Title: Numerical study of black hole spacetimes

Date: May 28, 2008 02:00 PM

URL: http://pirsa.org/08050036

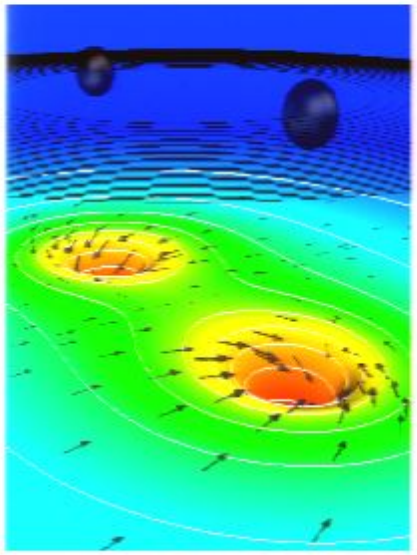
Abstract: The last years have seen tremendous progress in simulations of inspiral and coalescence of binary black holes. I will present recent results of the Caltech/Cornell collaboration simulating inspiral and collision of two black holes. Furthermore, while currently no talk on numerical relativity seems to be complete without a discussion of binary black hole coalescence, there are many more aspects of Einstein\'s equations that can be probed numerically. I will discuss some of these unexpected and intriguing features, among them black holes with five horizons and super-extremal black holes.

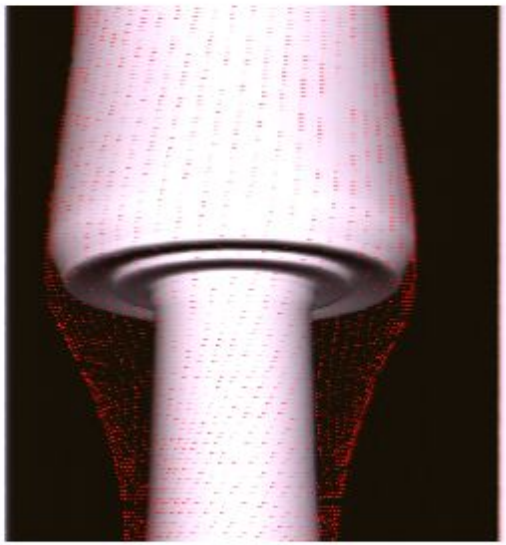
Numerical study of black hole spacetimes

Harald Pfeiffer

California Institute of Technology

Perimeter Institute, May 28, 2008





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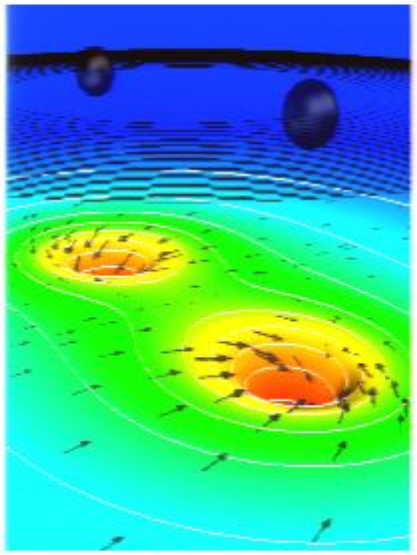
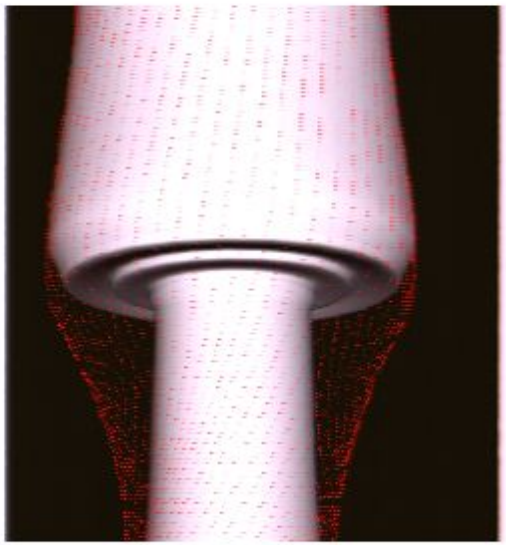


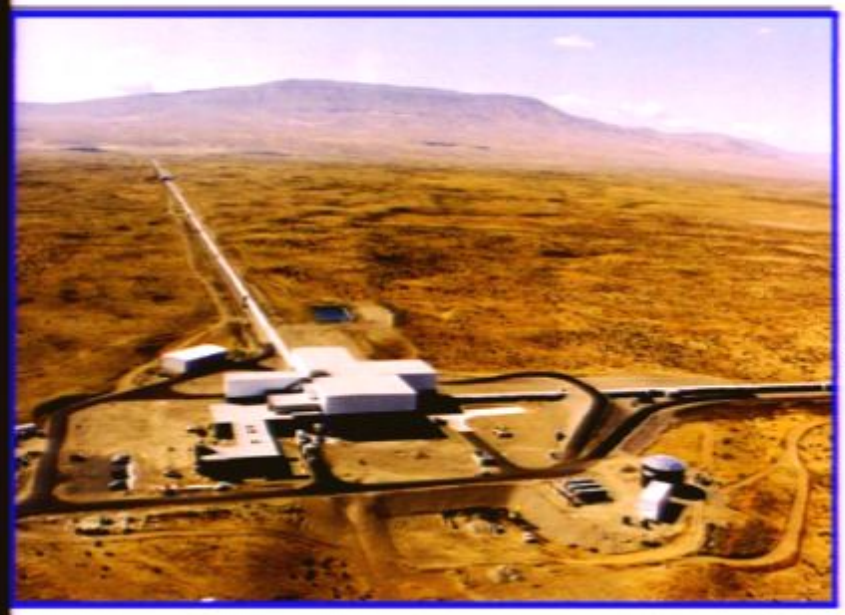


Gravitational Waves

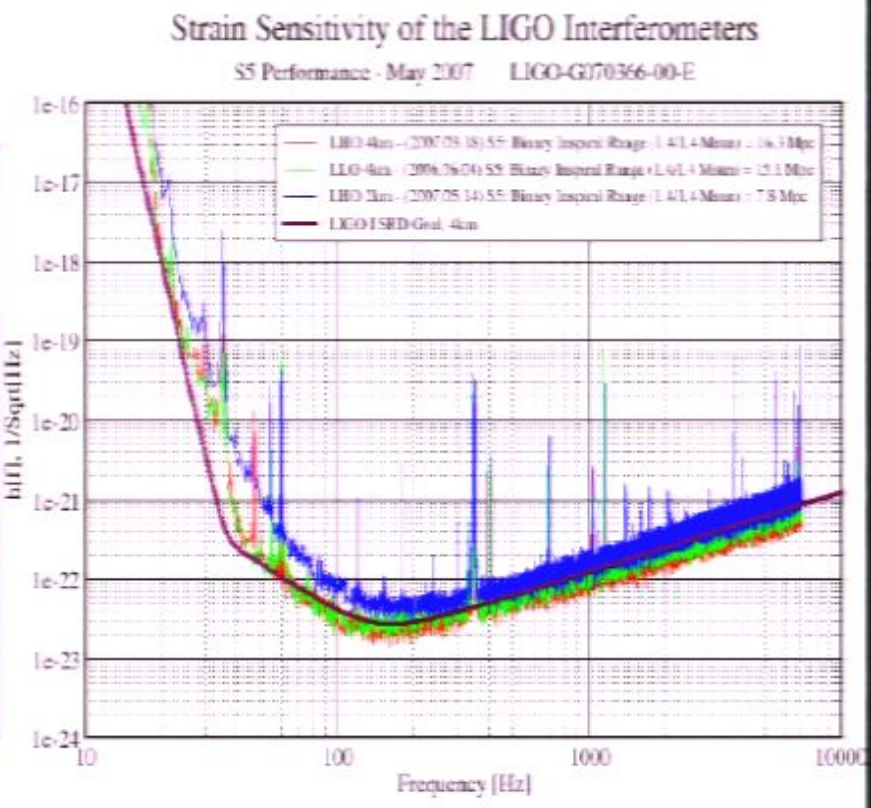
- Einstein's equations admit wave-solutions

$$g_{ab} = \eta_{ab} + h_{ab} \qquad \Box \bar{h}_{ab} = 0$$

- Efforts are underway to detect these gravitational waves

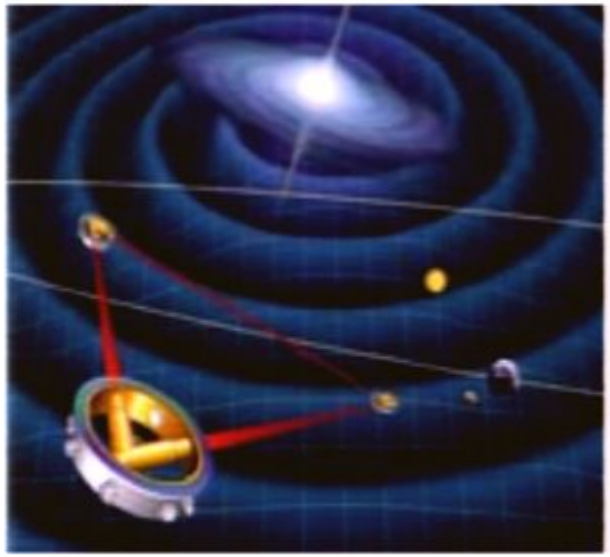


LIGO Hanford



Gravitational wave detectors

LISA (planned)



LIGO (2 sites)

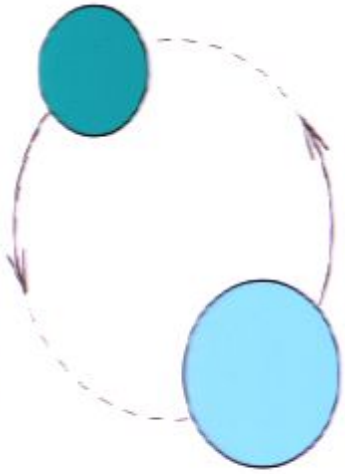
VIRGO

GEO 600

Gravitational Wave Sources

- Generated by changing quadrupole moments

$$h_{ij} = \frac{1}{r}\ddot{Q}_{ij}$$



- **Compact object binaries**

$$\Omega^2 r^3 = GM. \quad f_{\rm GW} = 2\frac{\Omega}{2\pi}$$

- Close to merger

$$r \sim 10GM/c^2 \;\Rightarrow\; f_{\rm GW} \sim 2\text{kHz}\left(\frac{M}{M_\odot}\right)^{-1}$$

- $M = 1 \cdots 100 M_\odot \;\Rightarrow$ LIGO
- $M = 10^4 \cdots 10^7 M_\odot \;\Rightarrow$ LISA

Matched Filtering

- Tiny signal, $h = \frac{\Delta L}{L} \sim 10^{-21}$
- Detector output s, waveform template h_T

$$\mathrm{SNR} = \frac{<s.h_T>}{(<h_T.h_T>)^{1/2}}.$$

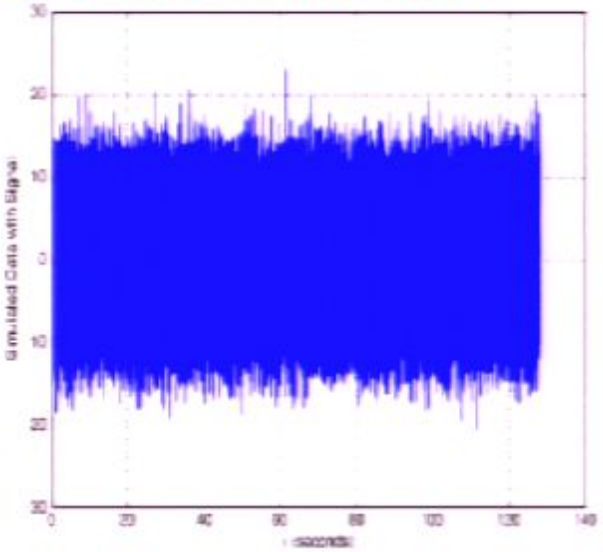
$$<a.b> = \int df \, \frac{\tilde{a}(f)\tilde{b}^*(f)}{S_h(f)}$$

- **Phase of h_T crucial**

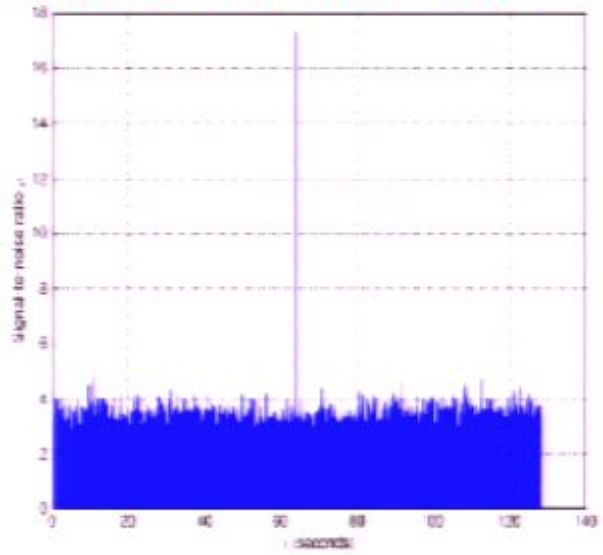
$$\delta\phi \lesssim 1/\mathrm{SNR}$$

SNR $= 8 \ldots 50$ for advanced LIGO

Simulated detector output

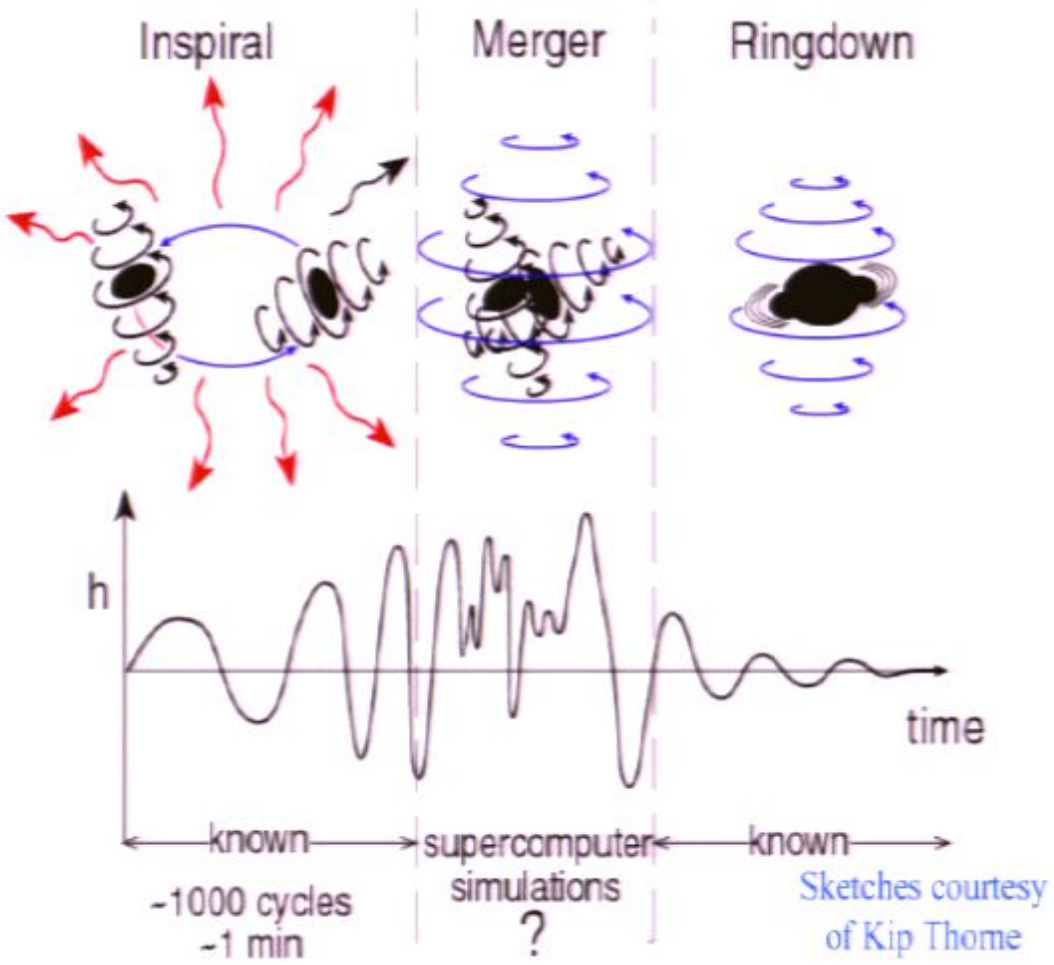


SNR vs. coalescence time



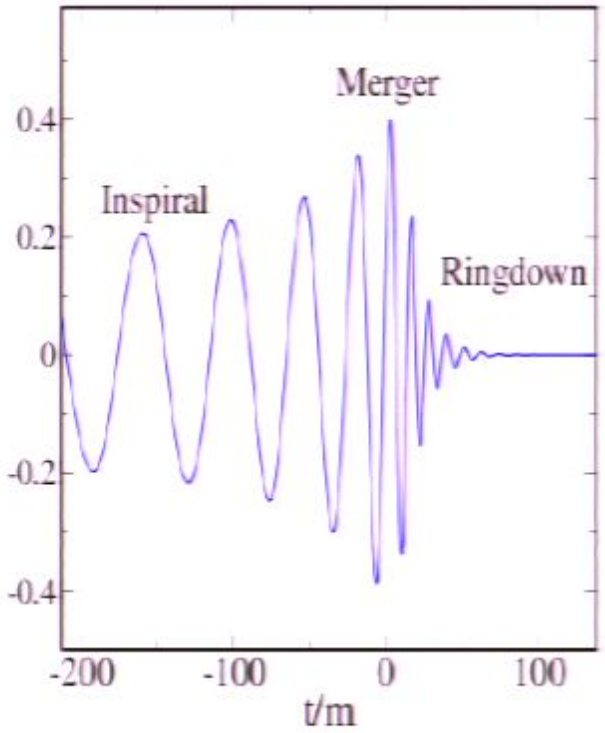
(D. Brown)

Stages of binary black hole evolution



Tools for computing the waveform

- Inspiral
  - $v \ll c$: perturbative expansion in v/c (post-Newtonian expansion)
  - v/c large: Numerical relativity
- Merger
  - Numerical relativity
- Ringdown
  - BH perturbation theory
  - Numerical relativity



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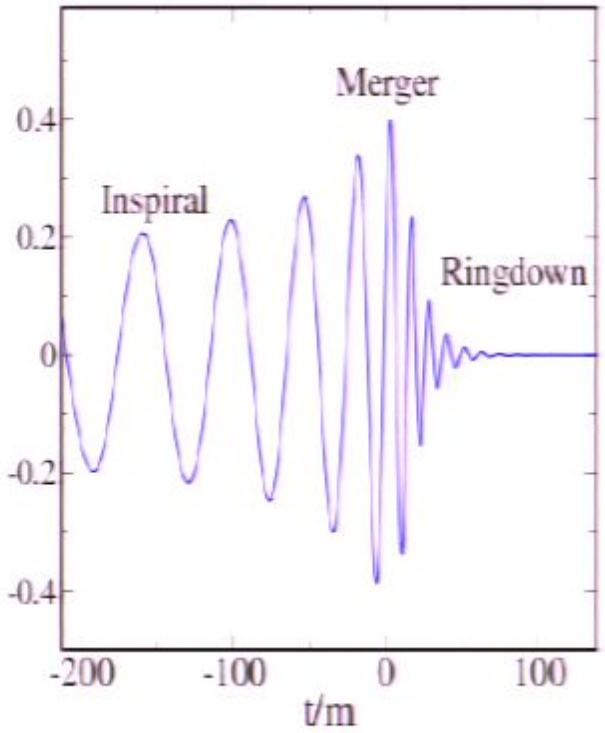
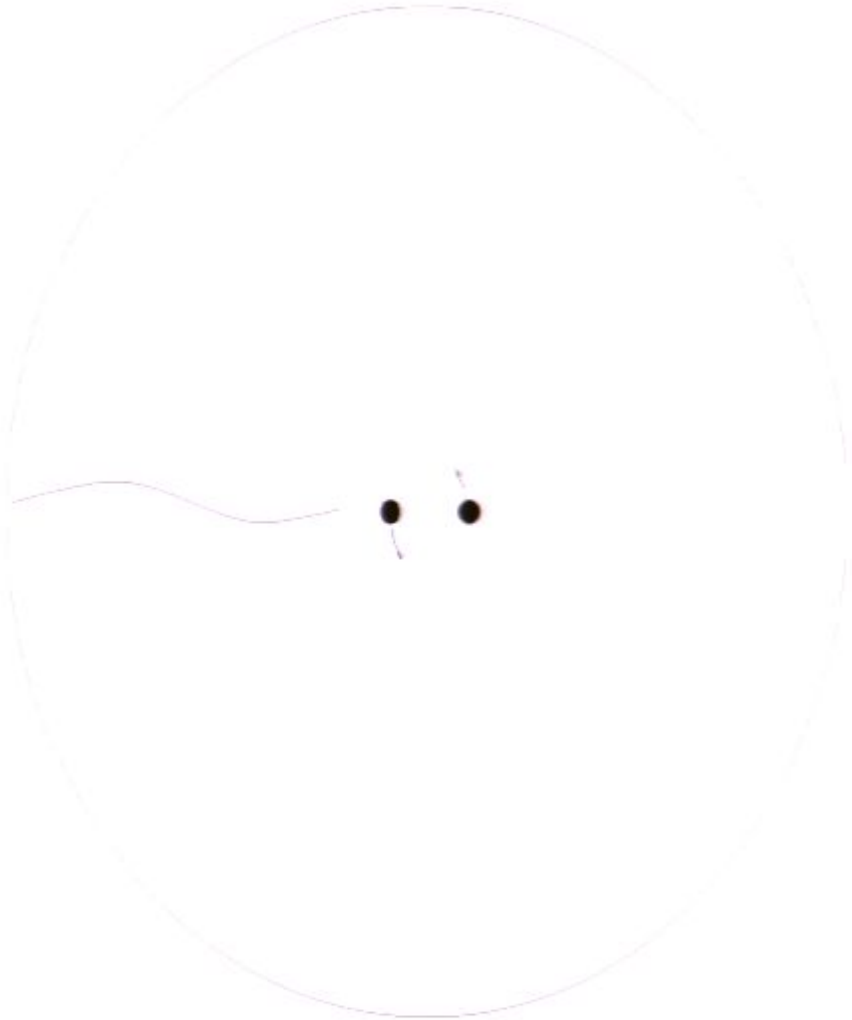
- Tasks for Numerical relativity:
  - simulate "late" inspiral and merger
  - determine what "**late**" means



BBH Simulations – Overview

Problem characteristics

- Multiple length scales
  - Size of BH's ~ 1
  - Separation ~ 10
  - Wavelength $\lambda \sim 100$
  - Wave extraction at several λ
- Gravitational wave flux small
  - $\dot{E}/E \sim 10^{-5}$
  - $\dot{E}$ drives inspiral
- High accuracy required
  - Absolute phase error $\delta\phi \ll 1$
- Solutions are smooth



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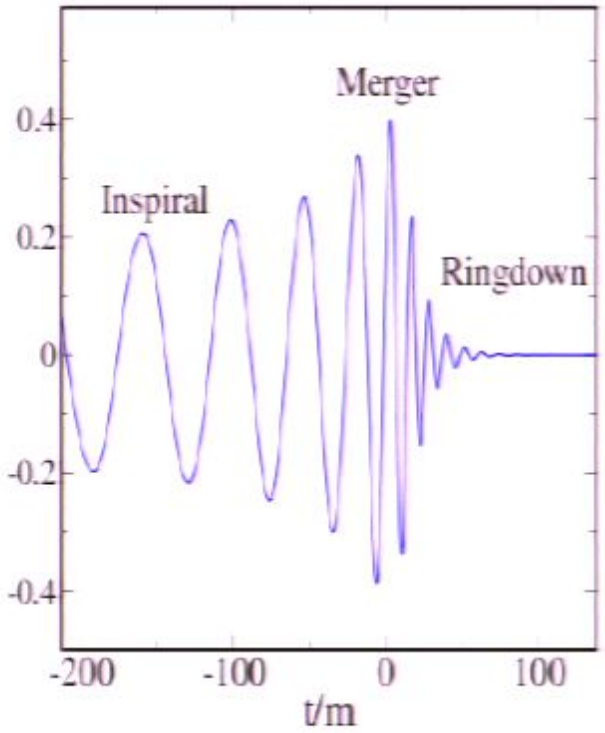

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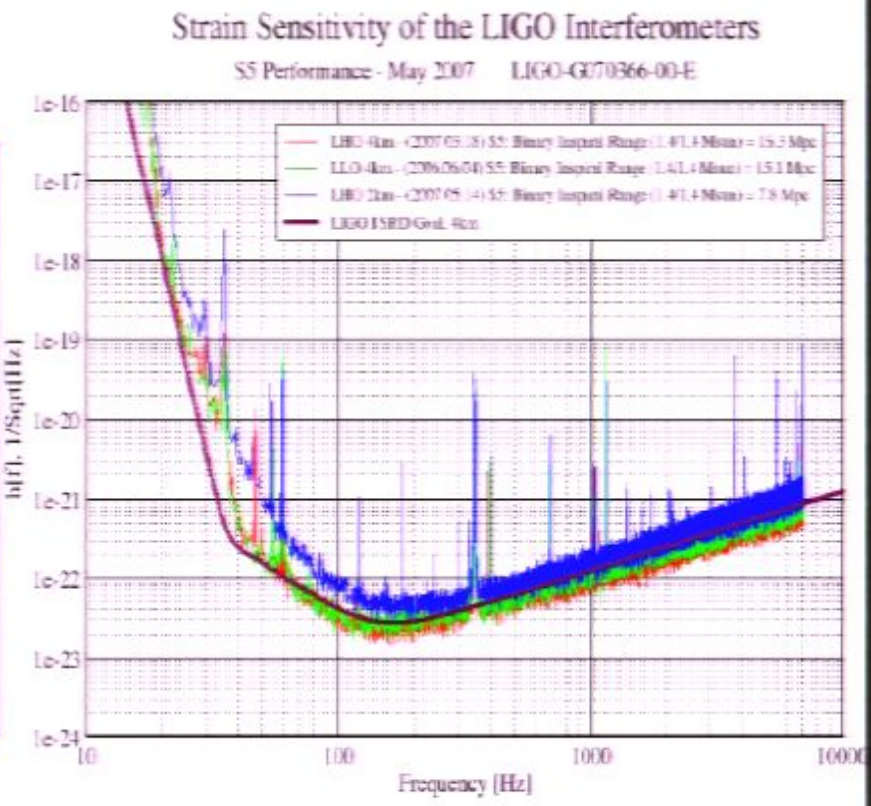

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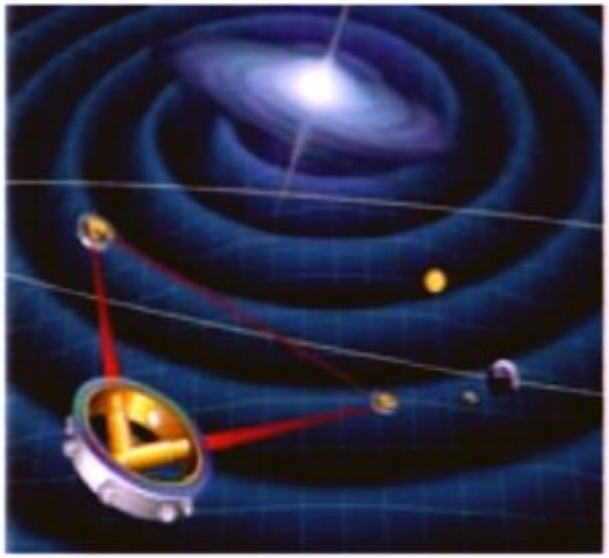

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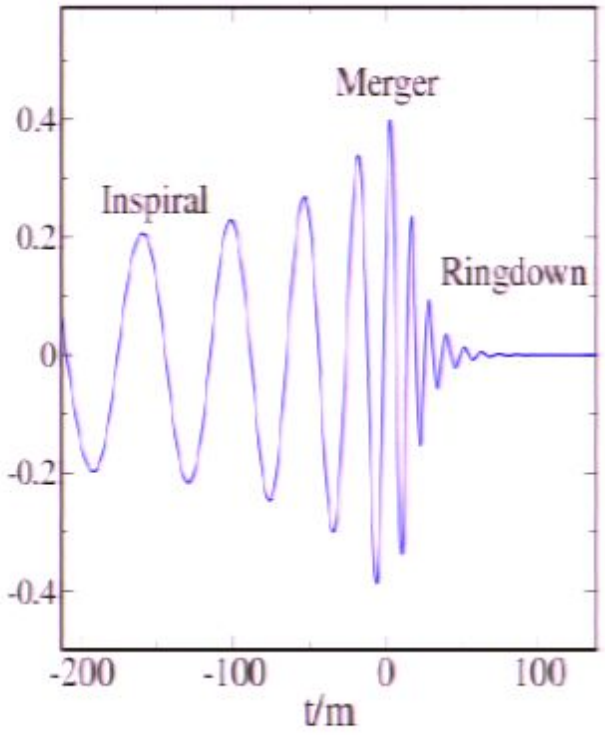

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Computational approaches

- Finite difference AMR
  - Albert-Einstein Institut (Berlin), Goddard, Jena (Germany), LSU, Penn State, Princeton, Rochester
  - Impressive short inspirals with mergers (BH-kicks)
  - Accurate long inspirals difficult
- Multi-domain spectral methods
  - Cornell/Caltech collaboration
  - Impressive long inspirals
  - Merger difficult, but possible

Computational Framework I

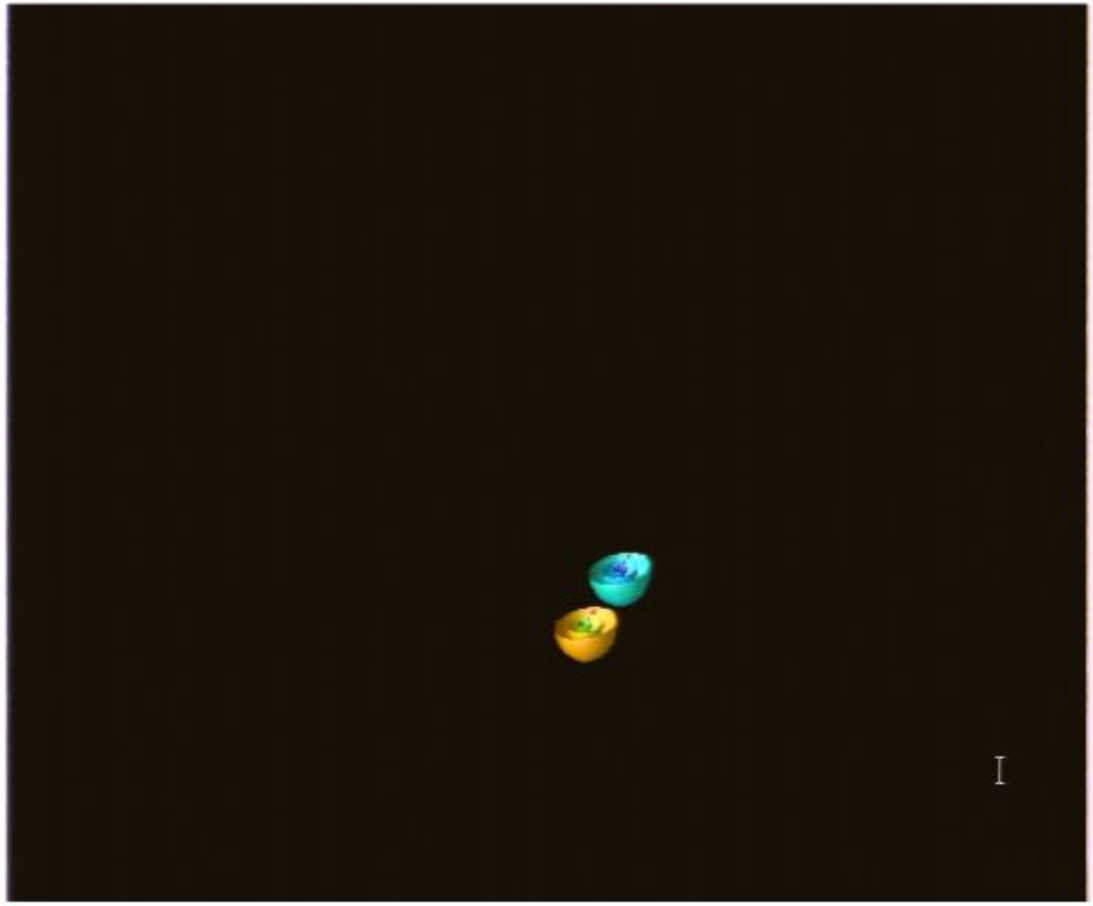
- Pseudo-spectral code

$$u(x,t) = \sum_{k=1}^{N} \tilde{u}_k(t)\Phi_k(x)$$

- Evaluate derivatives in spectral space,
  non-linear terms in physical space
- Elliptic problems
  Solve large set of algebraic equations for $\tilde{u}_k$ (HP et *al.* 2003)
- Hyperbolic problems
  Evolve $\tilde{u}_k(t)$ with method of lines
- Principal code developers Larry Kidder, Mark Scheel, HP; 250,000 lines

Computational Framework II

- Domain-decomposition



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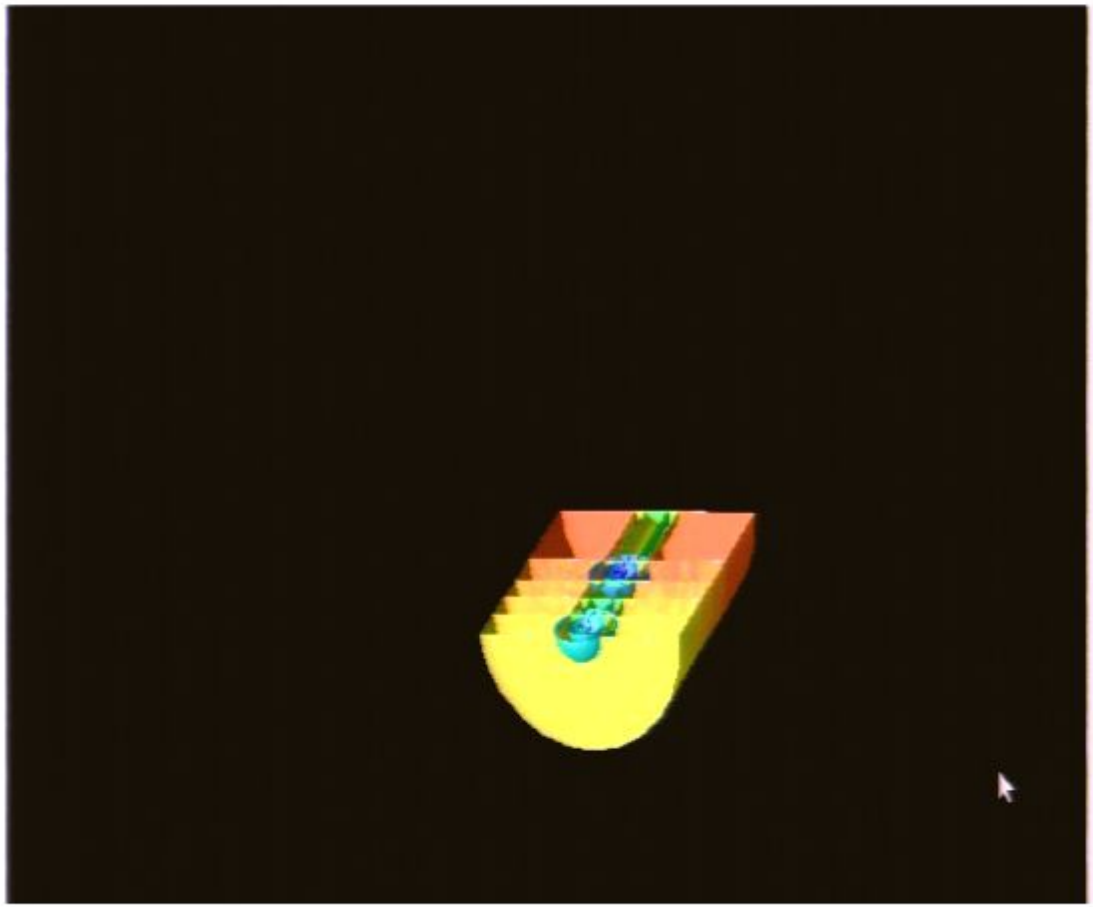

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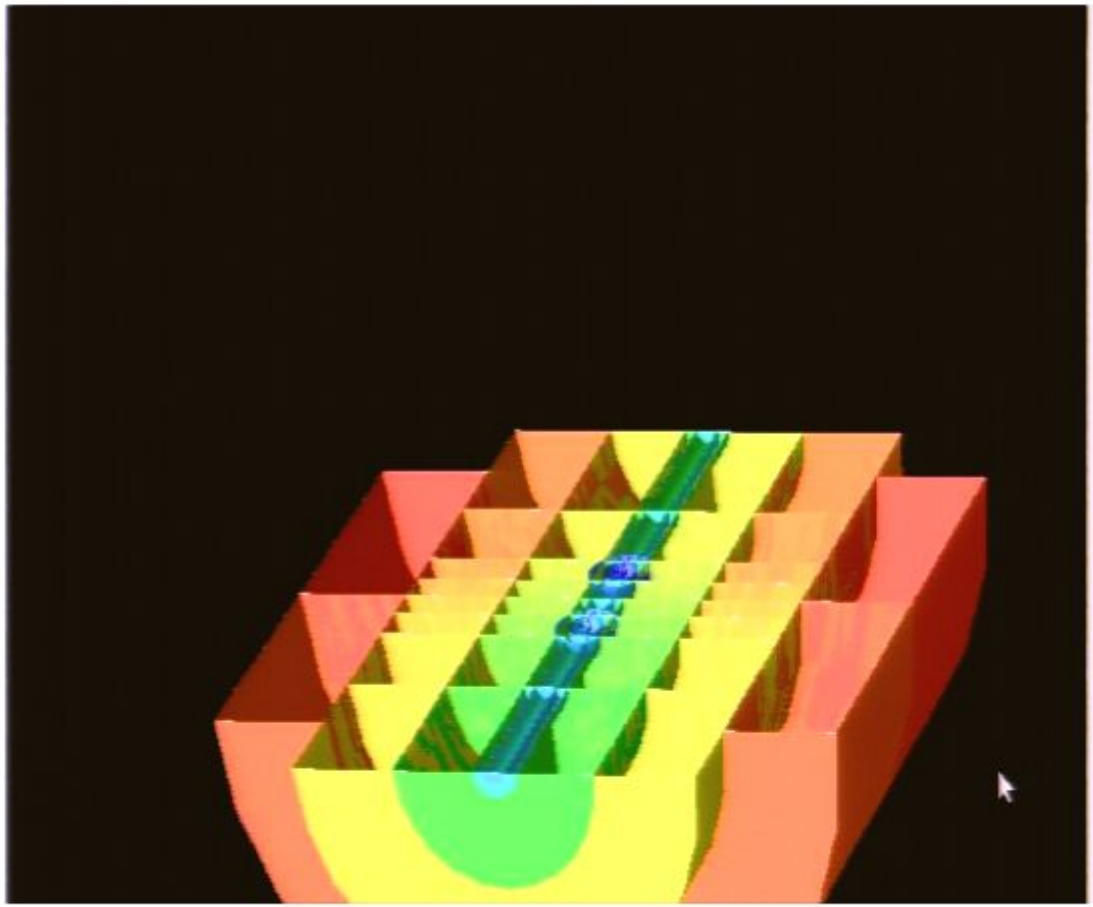

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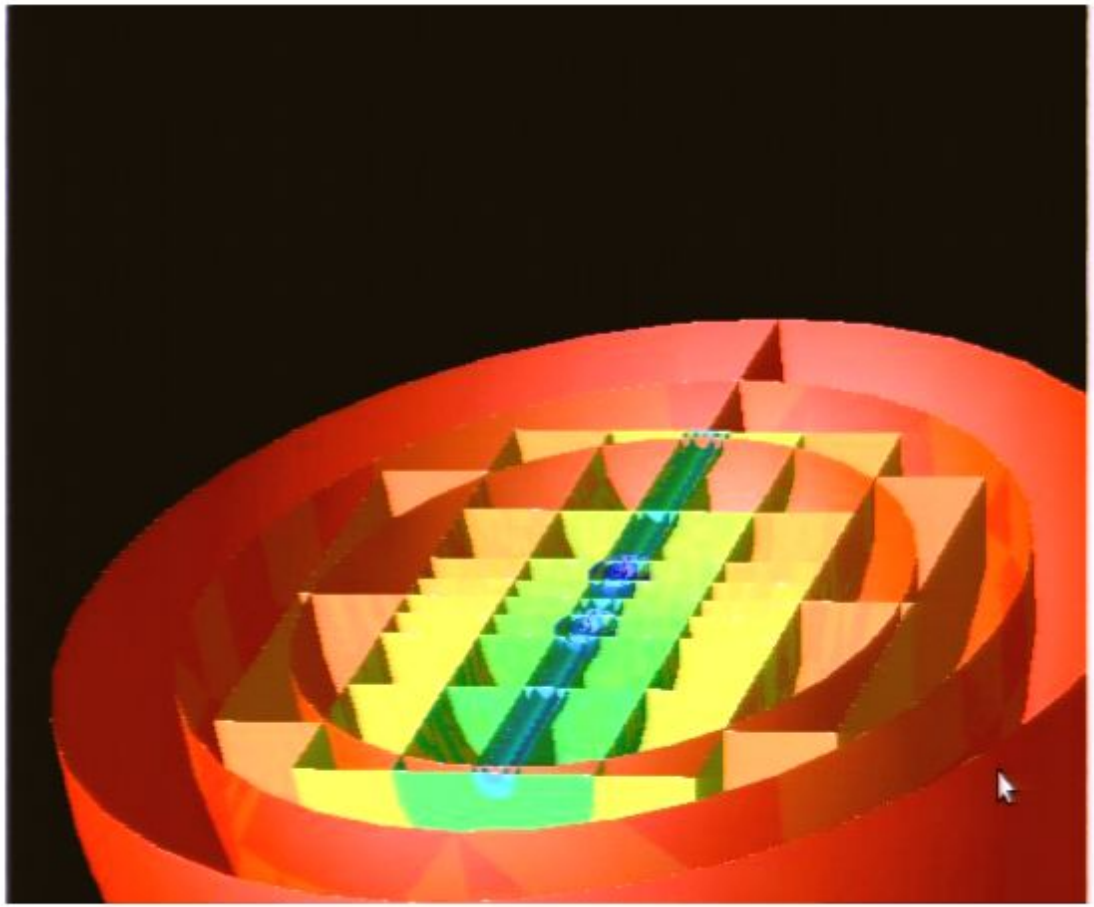

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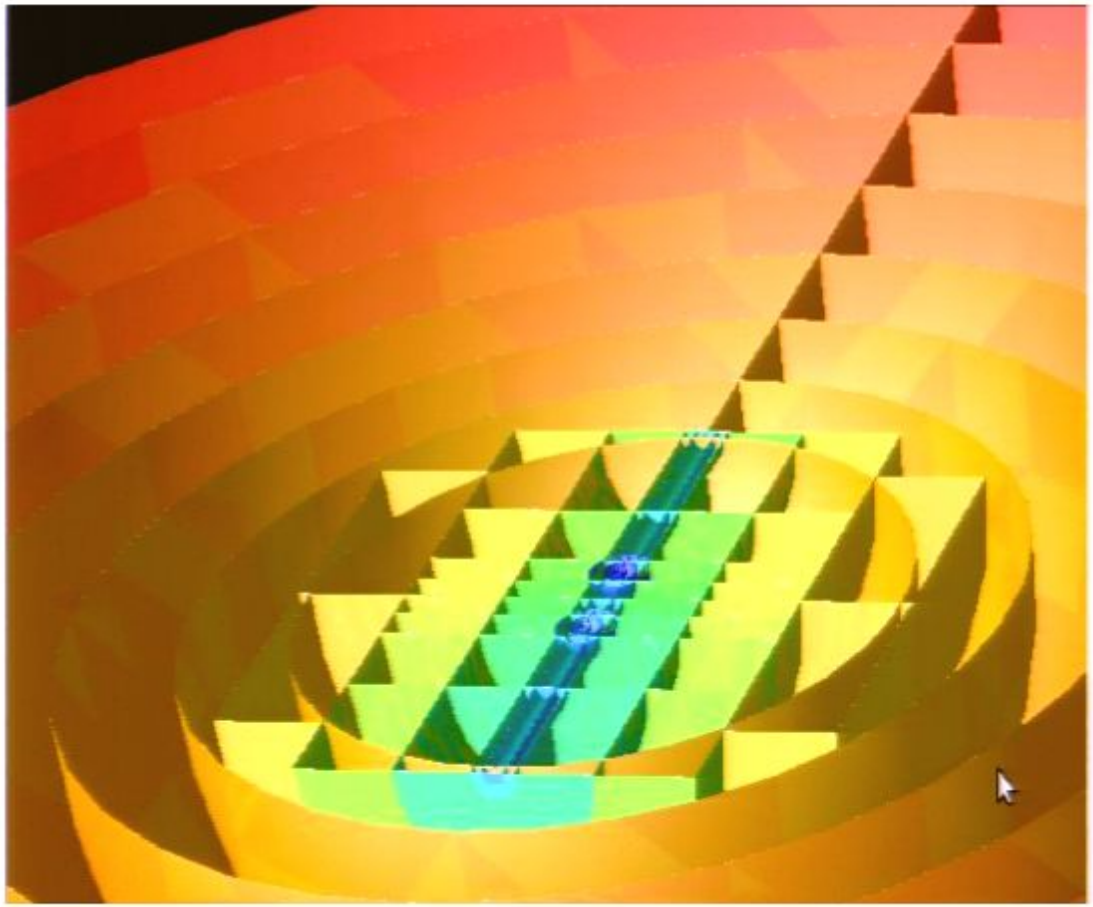
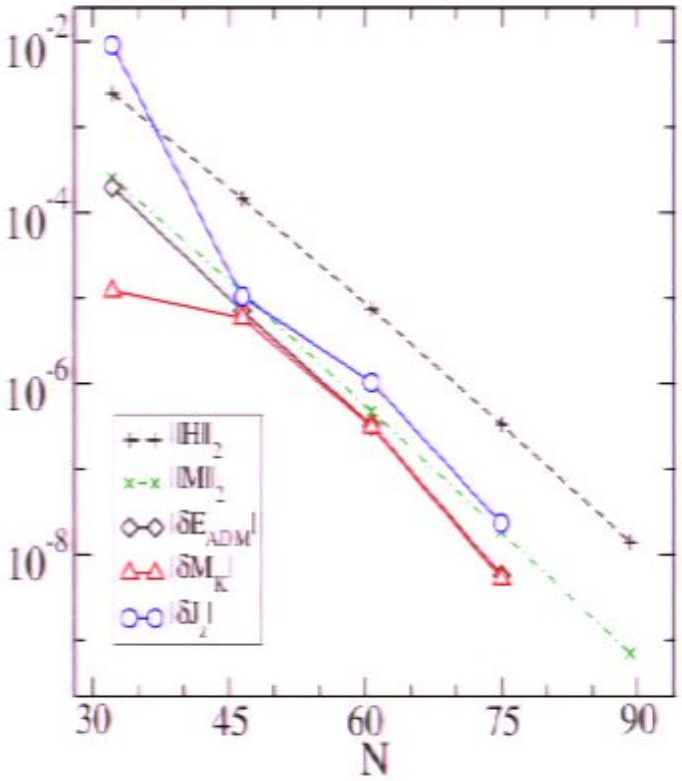
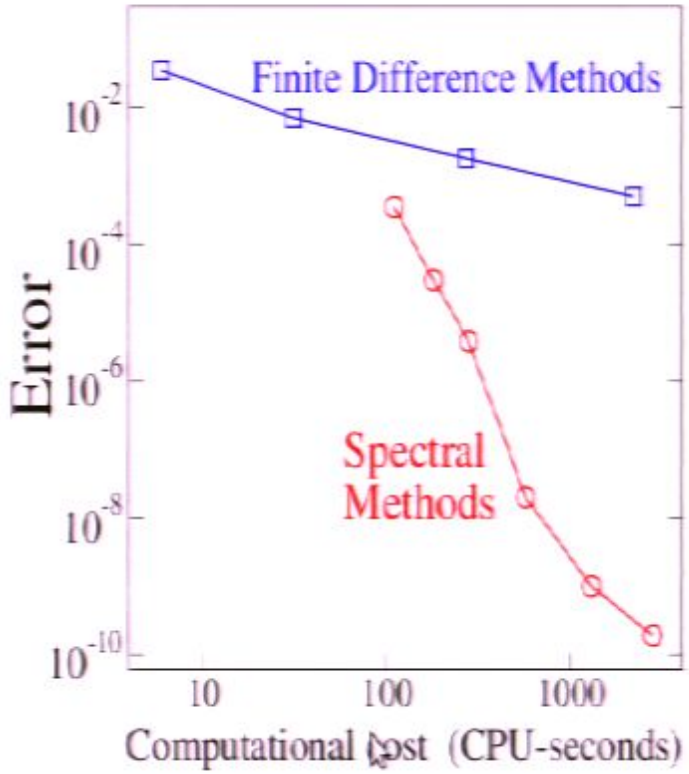


Why spectral methods?

Smooth solutions ⇒ exponential convergence



Cook, HP 2004



HP et *al.* 2003

Computational Framework III

- Domain-decomposition using simple topologies (DUST)

Building blocks

- I_1 interval
- S_1 circle
- S_2 sphere
- B_2 disk
- B_3 ball

Tensor-product

$\otimes$

Composite topologies

- n-dim Block $I_1 \otimes I_1 \otimes \cdots \otimes I_1$
- Cylinder $B_2 \otimes I_1$, $I_1 \otimes S_1 \otimes I_1$
- Sphere B_3, $I_1 \otimes S_2$
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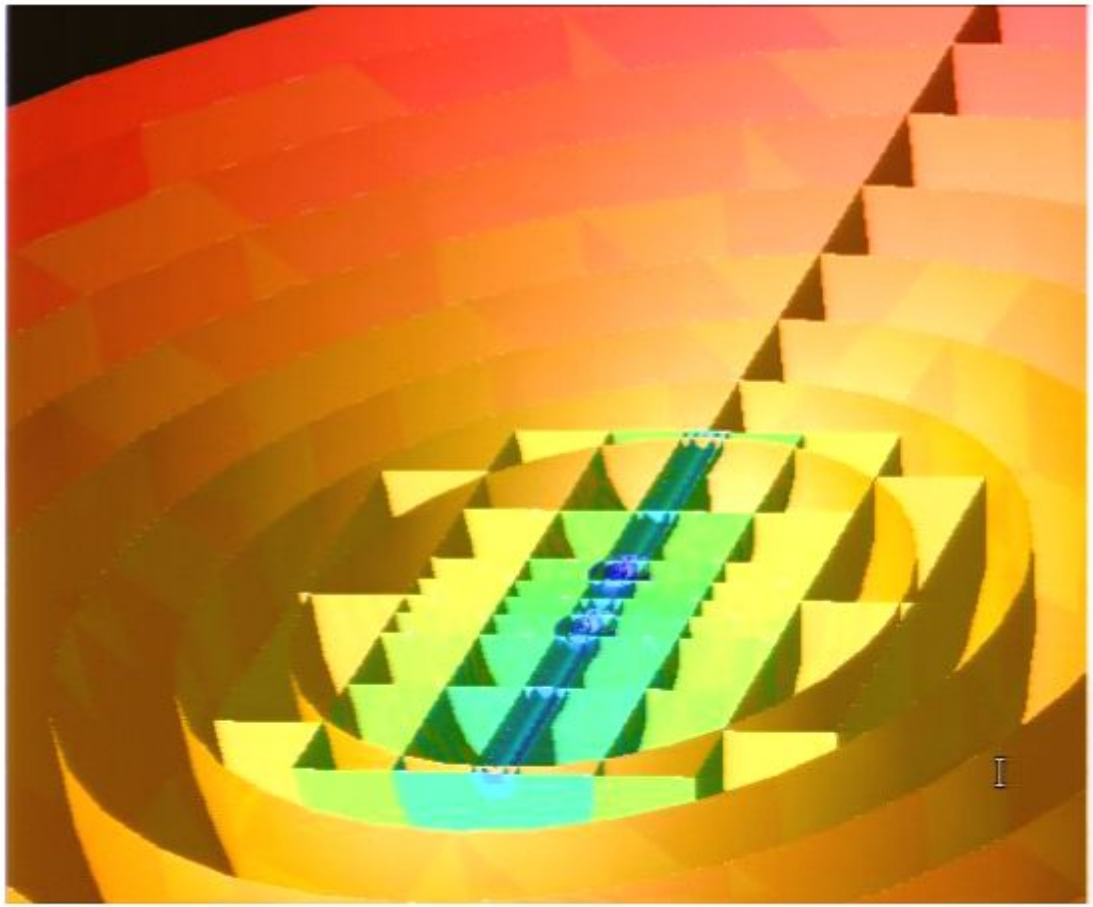

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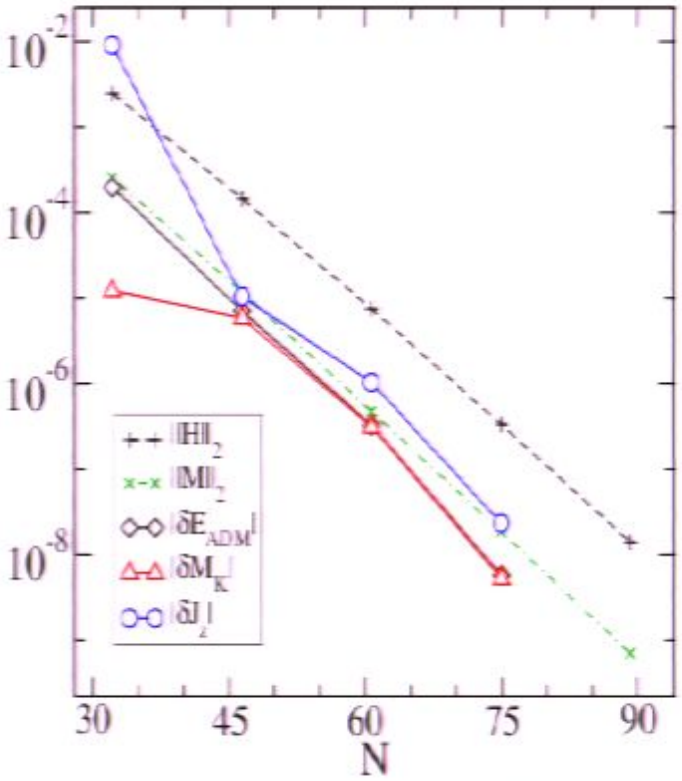

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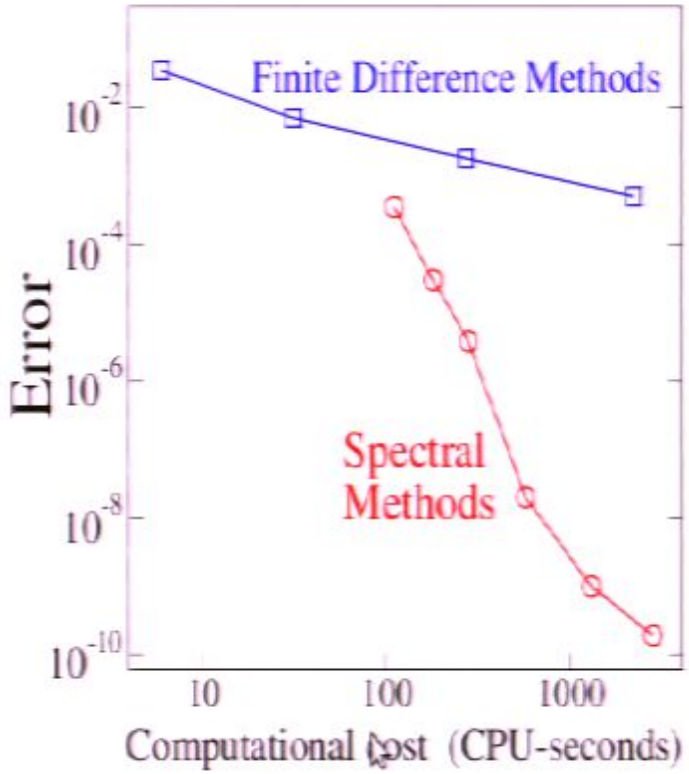

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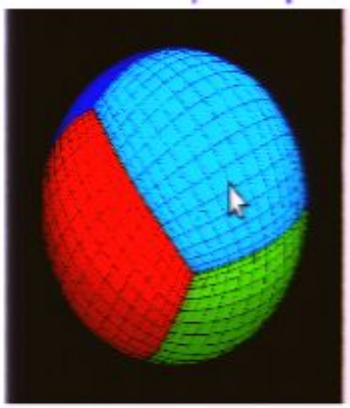
Combine several subdomains to get desired shape/topology

Six distorted squares = sphere



Evolution equations

- Einstein's equations

$$0 = R_{ab}[g_{ab}] = -\frac{1}{2}\Box g_{ab} + \nabla_{(a}\Gamma_{b)} + \text{lower order terms.} \qquad \Gamma_a = -g_{ab}\Box x^b.$$

- Generalized harmonic coordinates $g_{ab}\Box x^b \equiv H_a(x^a, g_{ab})$
  (Friedrich 1985, Pretorius 2005; note that $H \equiv 0$ has been used since 1920's)

$$\Box g_{ab} = \text{lower order terms.}$$

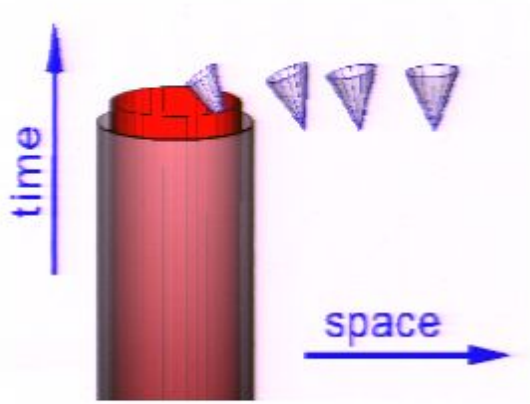
  $\Rightarrow$ Constraint $C_a \equiv H_a - g_{ab}\Box x^b = 0$

- Constraint damping (Gundlach, et *al.*, Pretorius, 2005)

$$\Box g_{ab} = \gamma\left[t_{(a}C_{b)} - \frac{1}{2}g_{ab}t^c C_c\right] + \text{lower order terms}$$

$$\partial_t C_a \sim -\gamma C_a.$$

Boundary conditions



- **Black hole singularity excision**
  - Place artificial inner boundary just inside horizon
  - Causality $\Rightarrow$ pure outflow condition, no BC applied (Unruh, 80's)
  - Technical details require dual coordinate frames (Scheel et *al.*, 2006)
- **Outer boundary**
  - Constraint preserving (Kidder et *al.* 05; Sarbach, Tiglio 05; Lindblom et al. 06)
  - Transparent to outgoing gravitational waves (Lindblom et *al.*, 2006)
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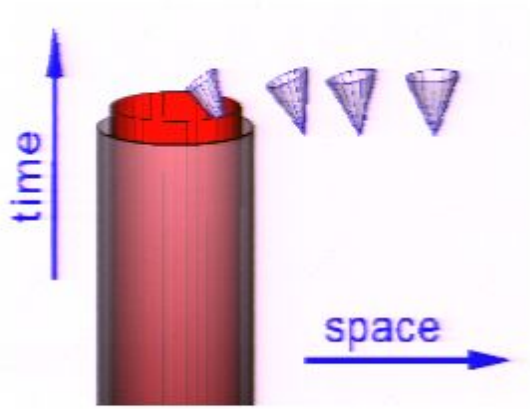

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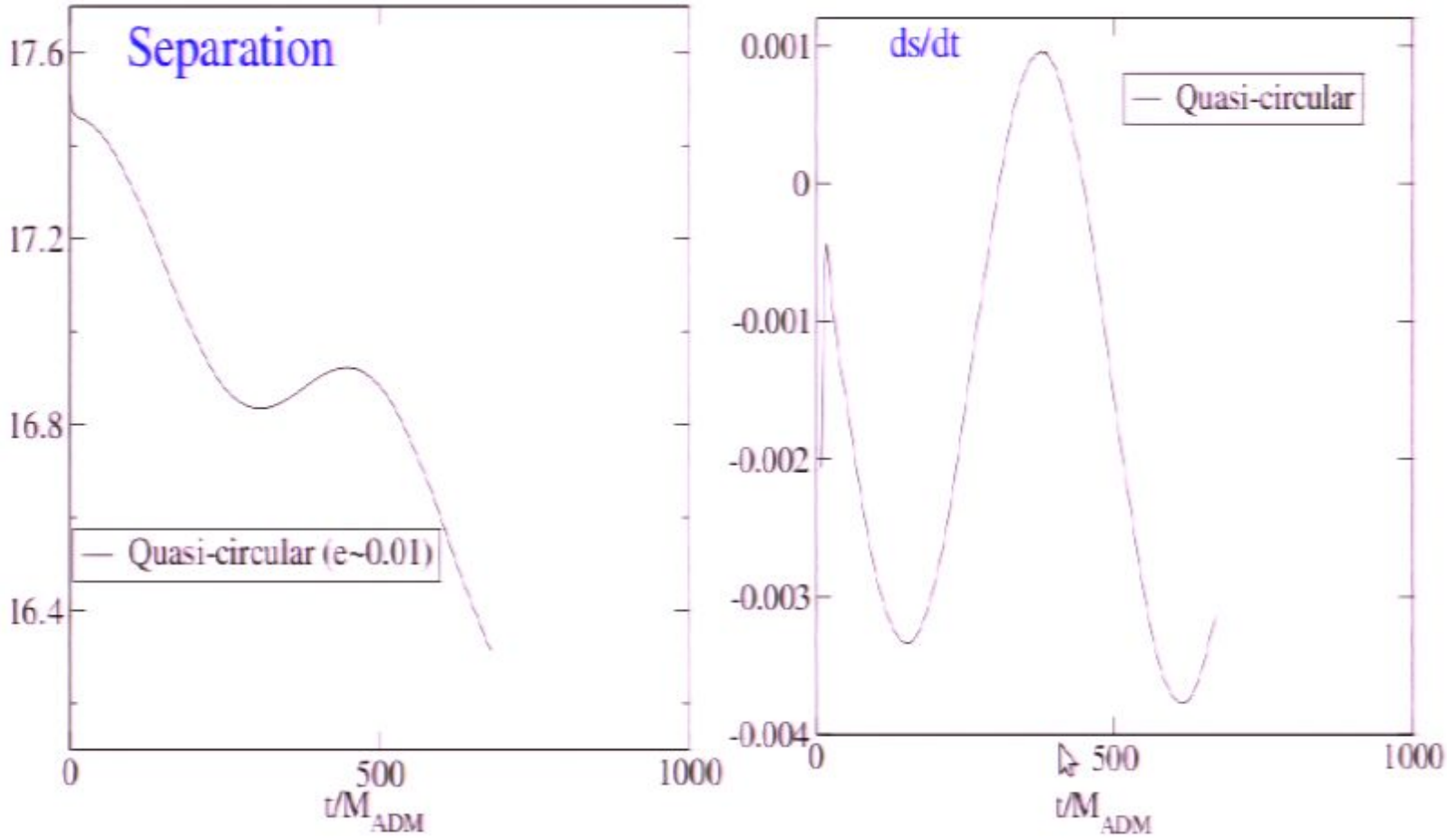
Iteratively control eccentricity (HP et *al.*, 2007)



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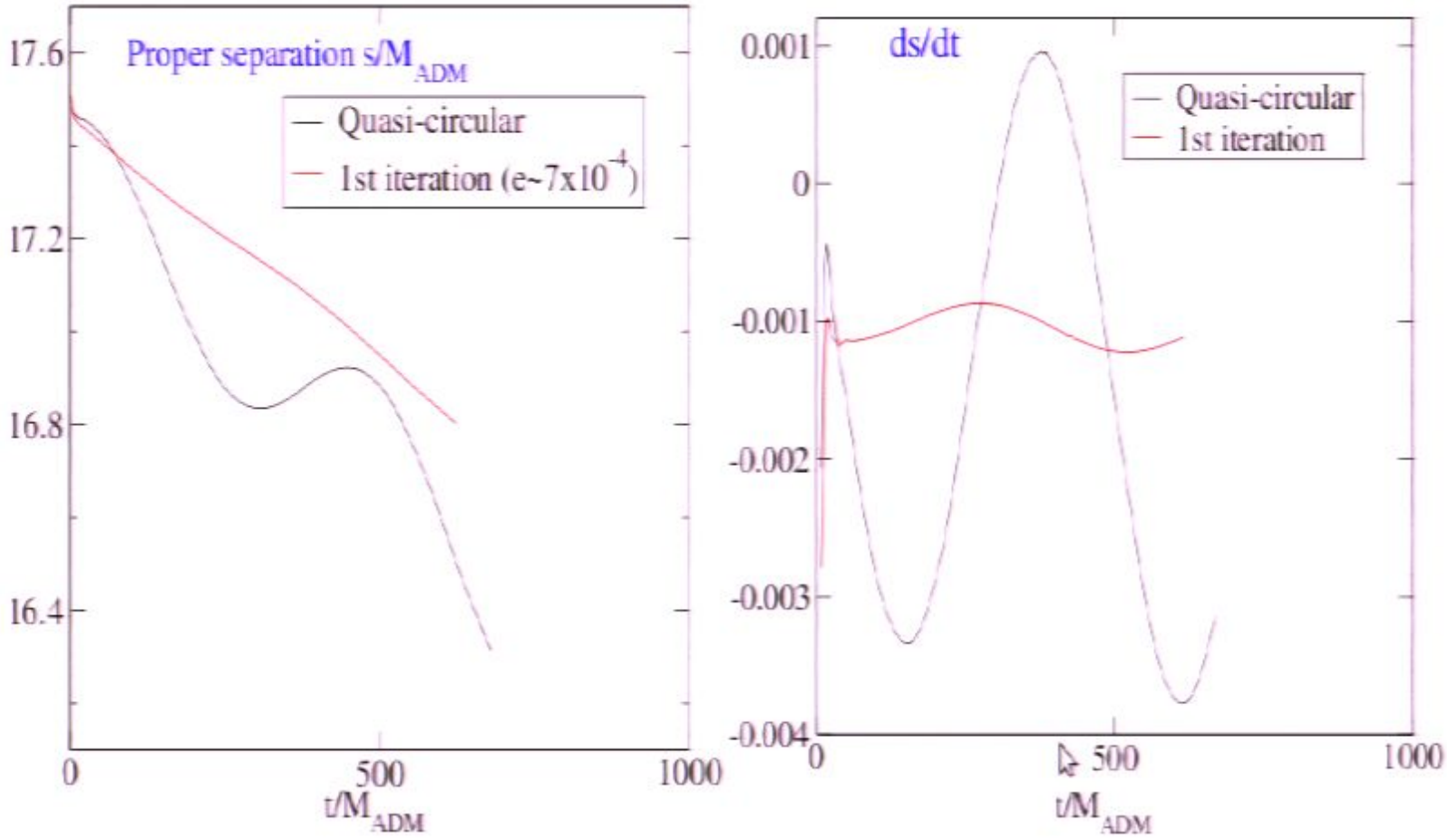

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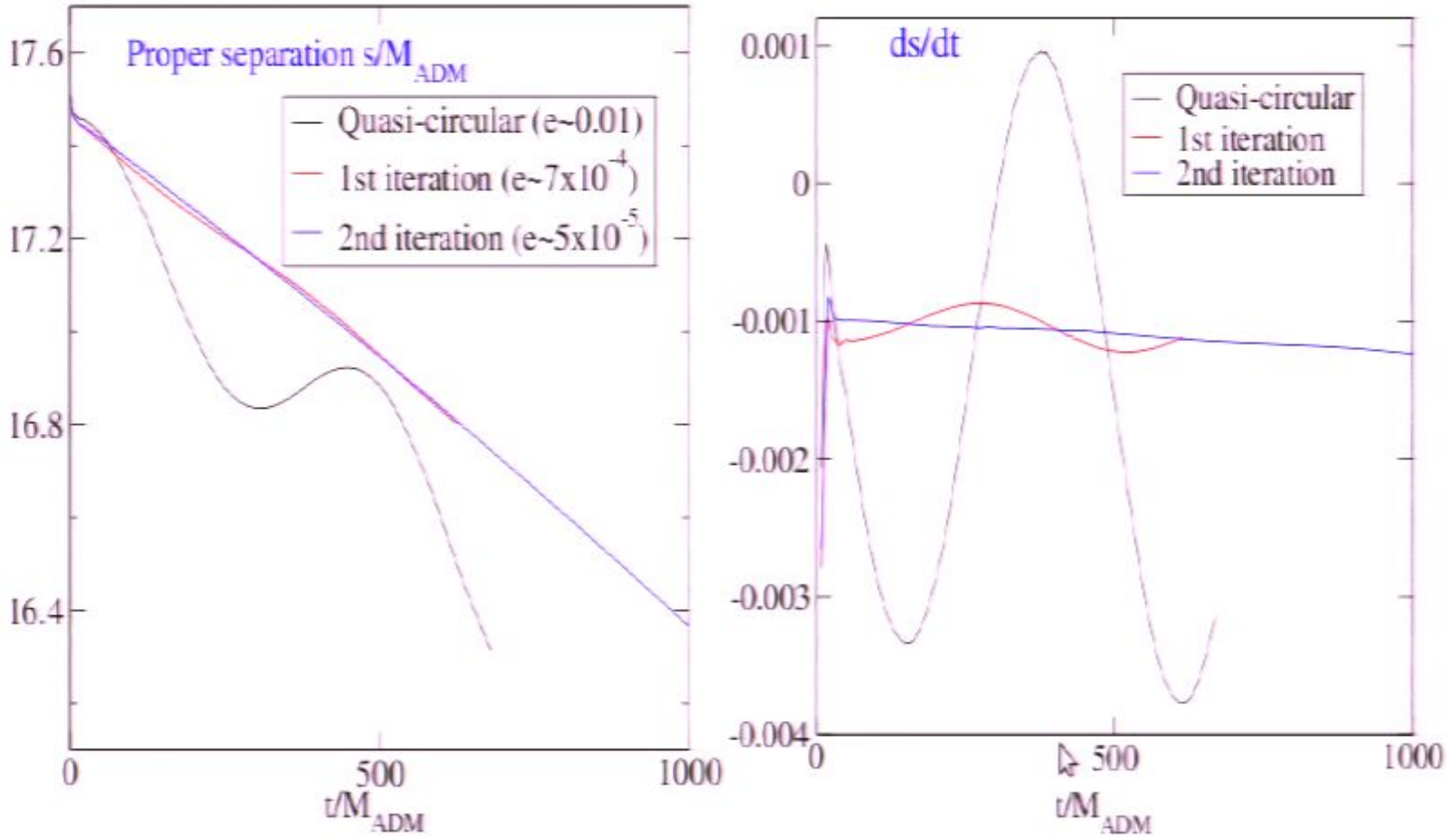
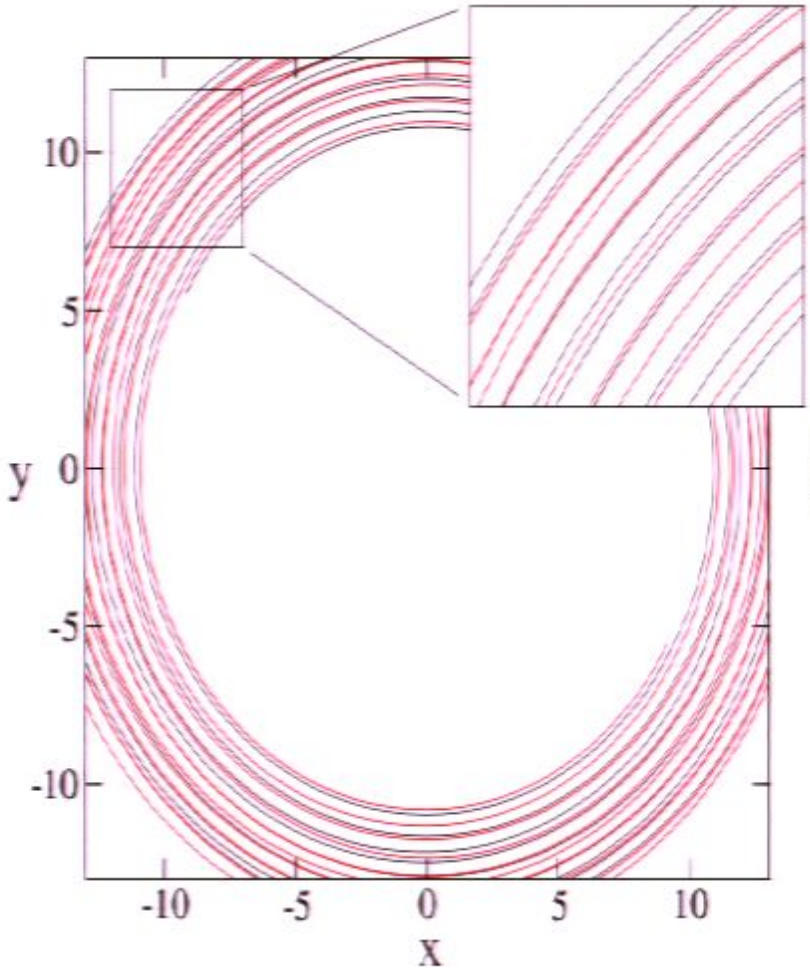
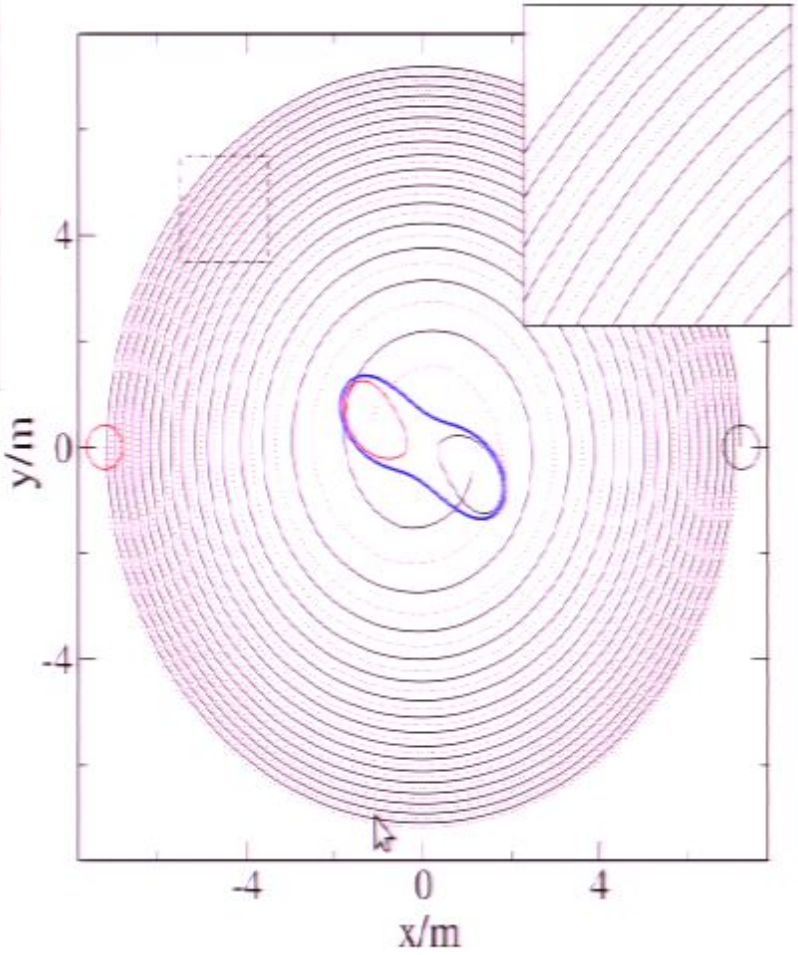


Orbital trajectory

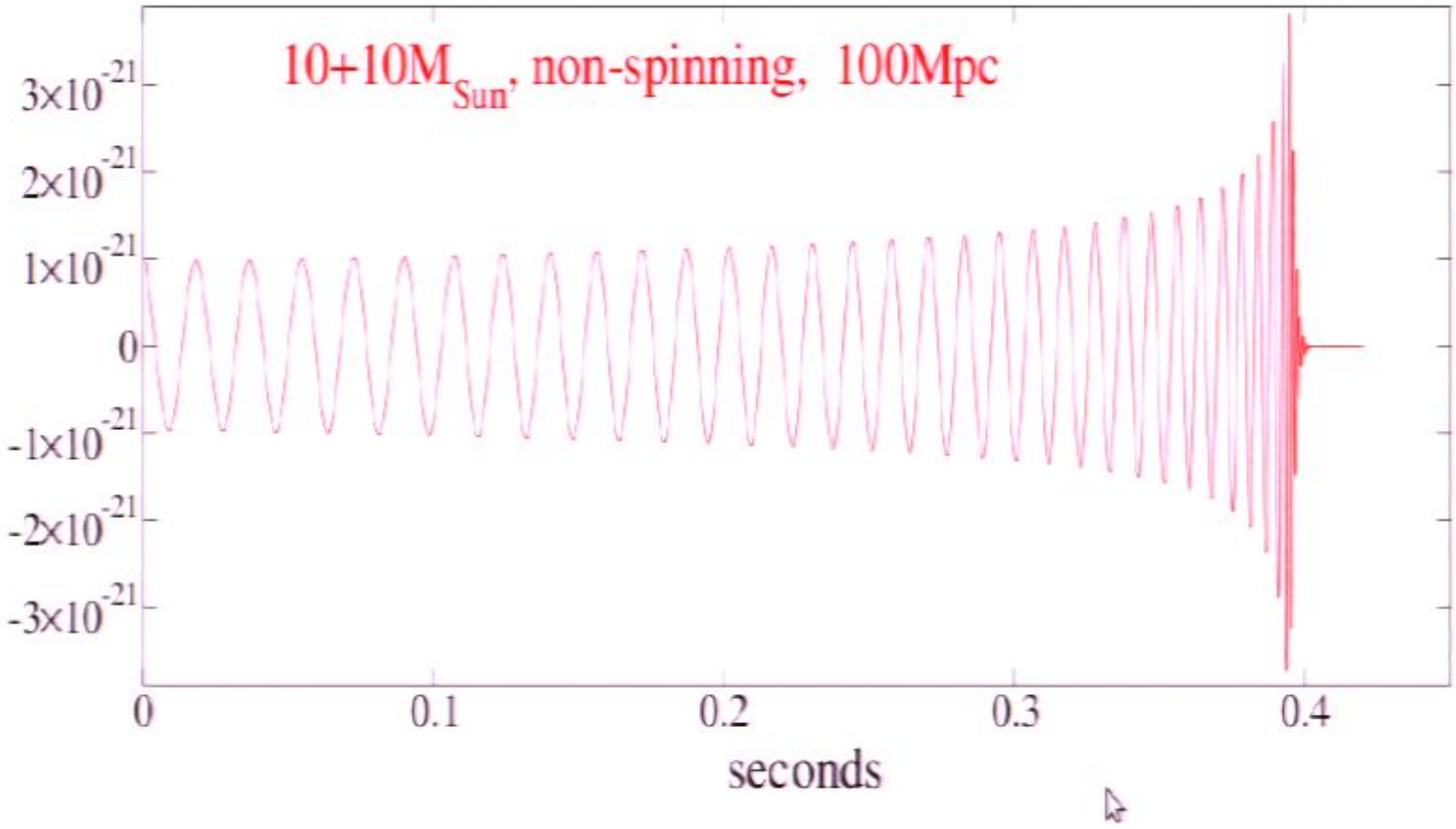
$e = 0.01$



$e = 5 \times 10^{-5}$



At last – a waveform!!



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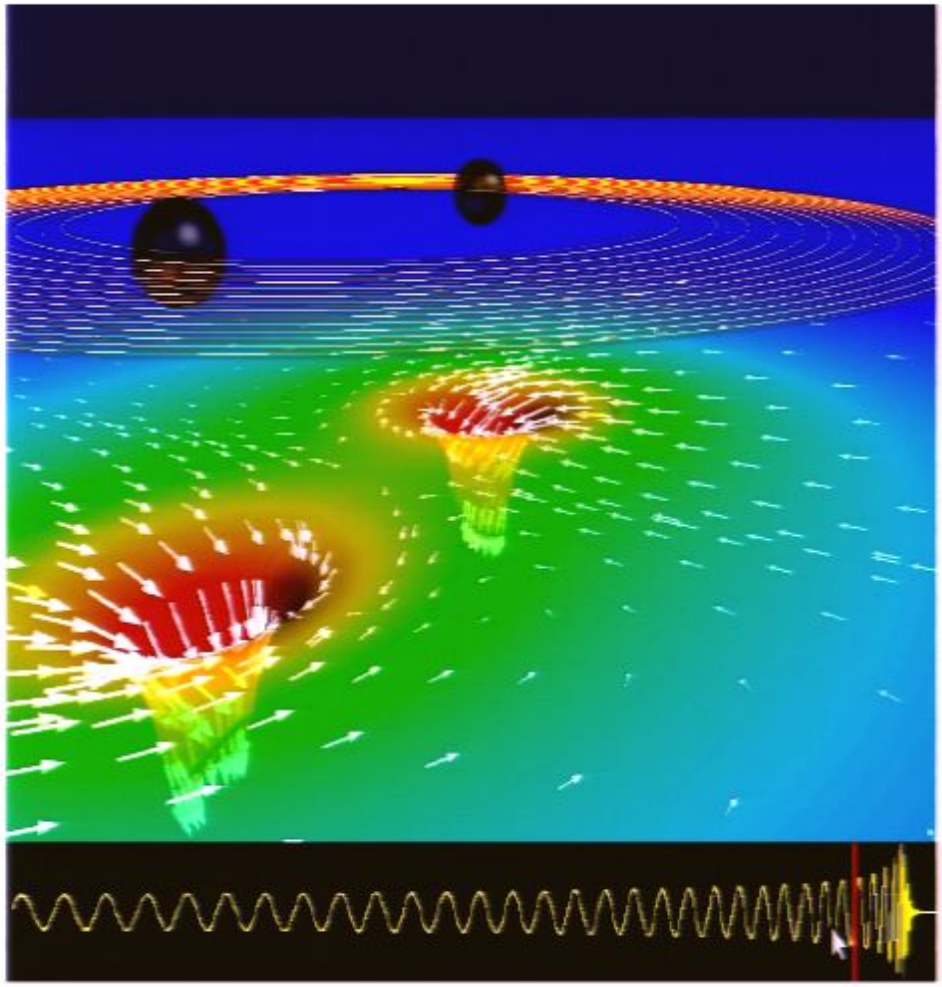

www.black-holes.org/explore2.html

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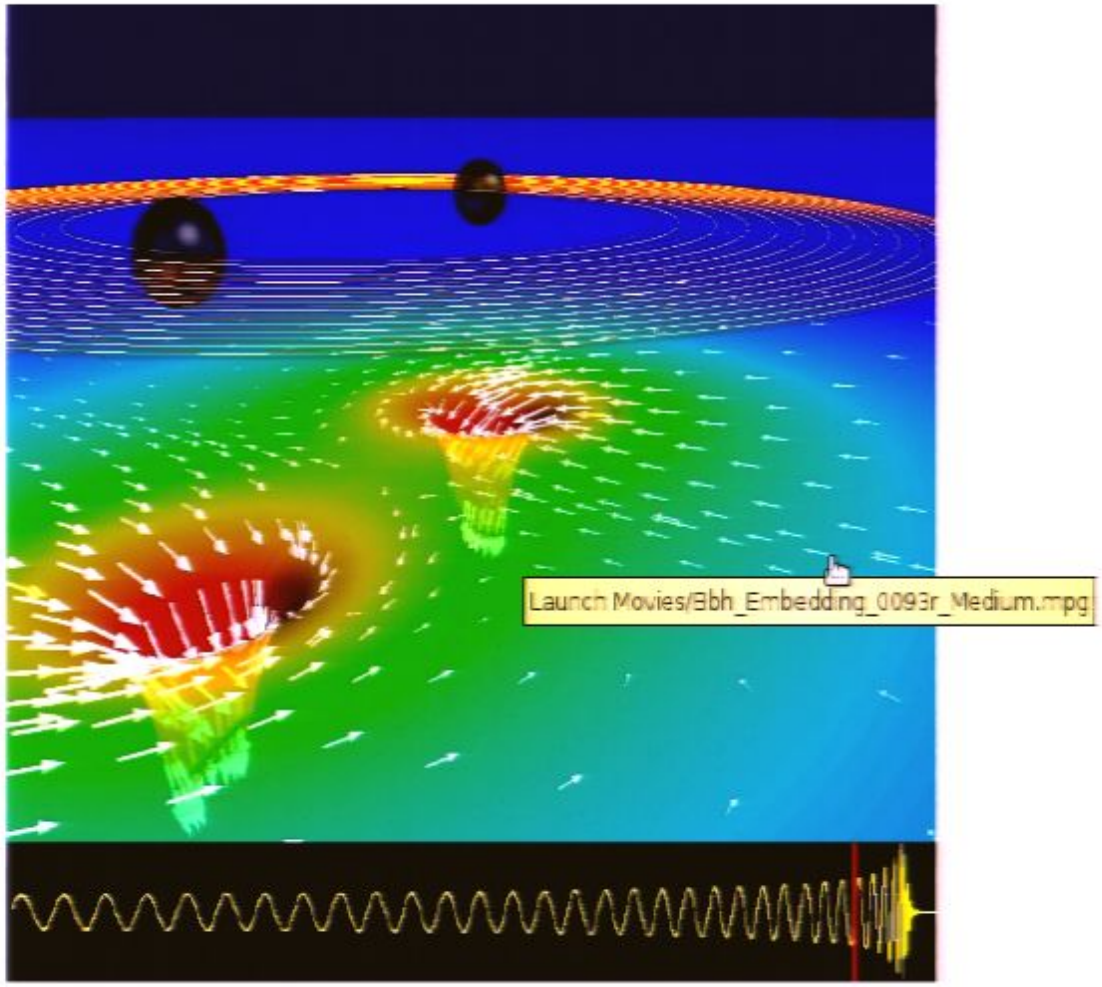

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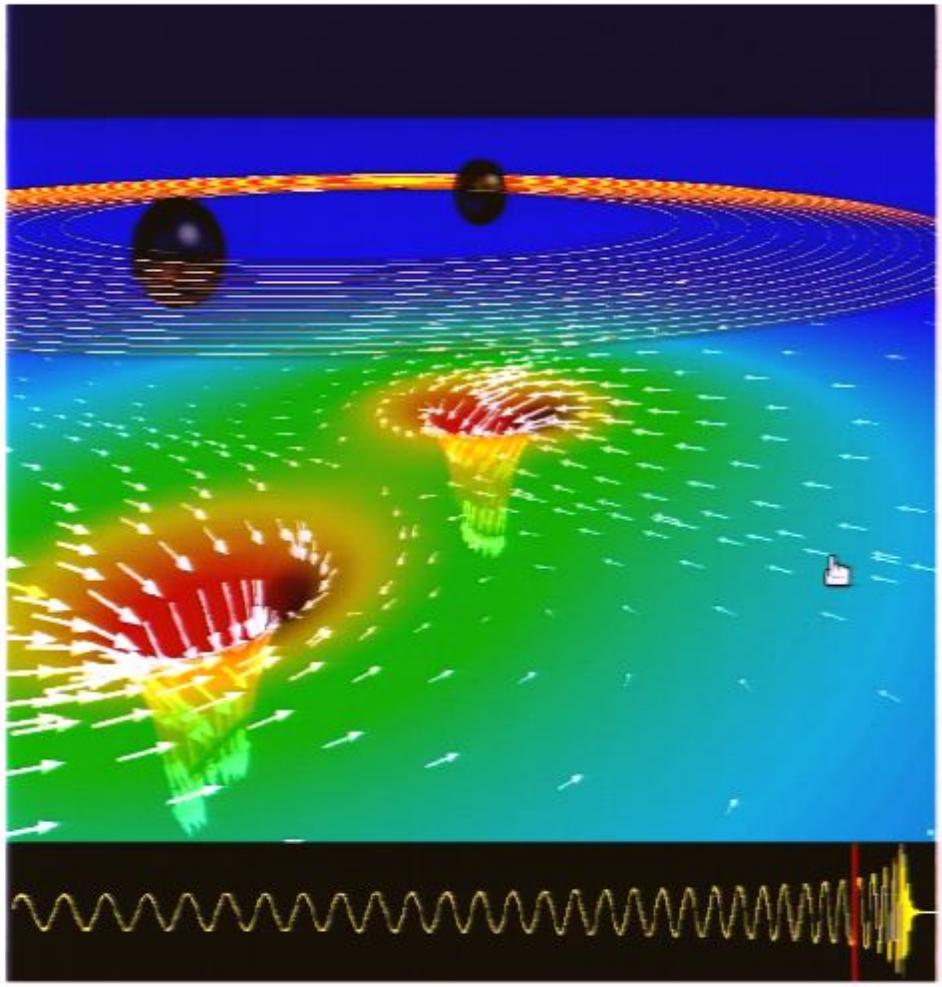

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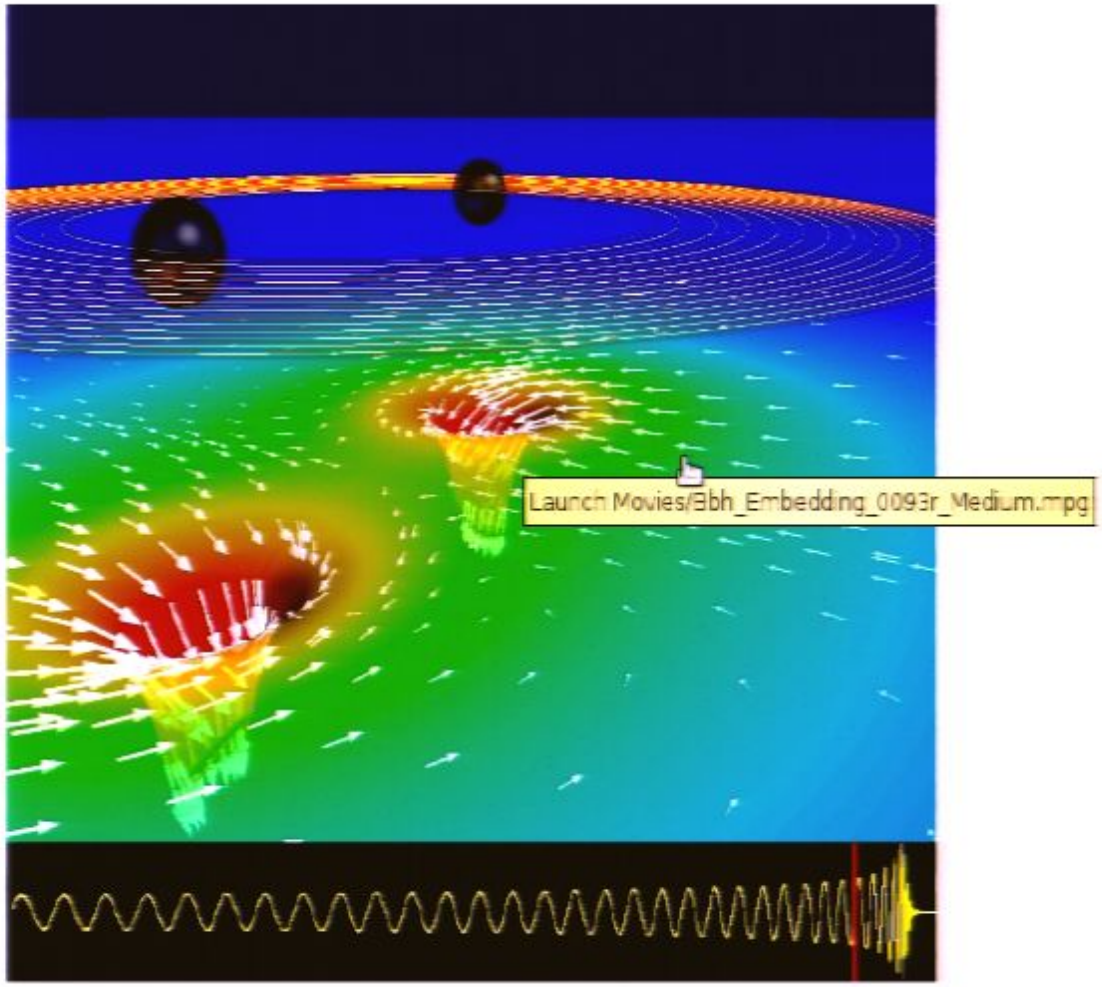

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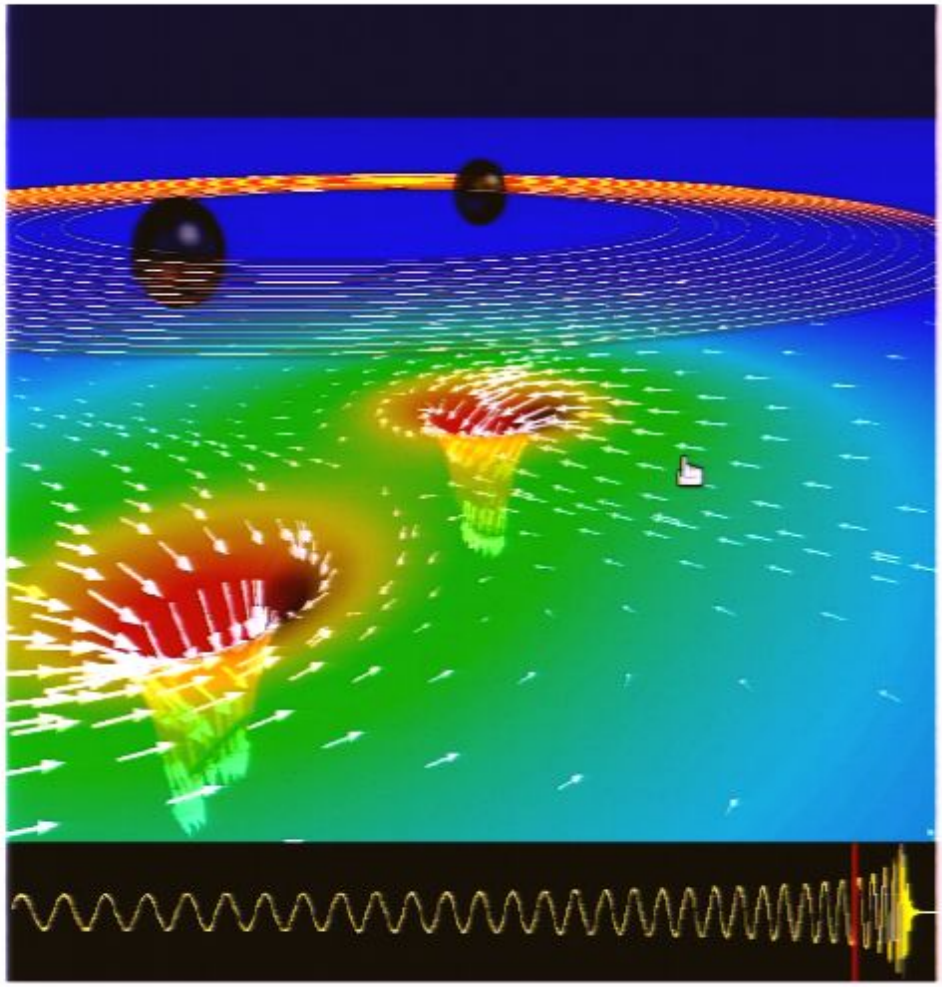

www.black-holes.org/explore2.html

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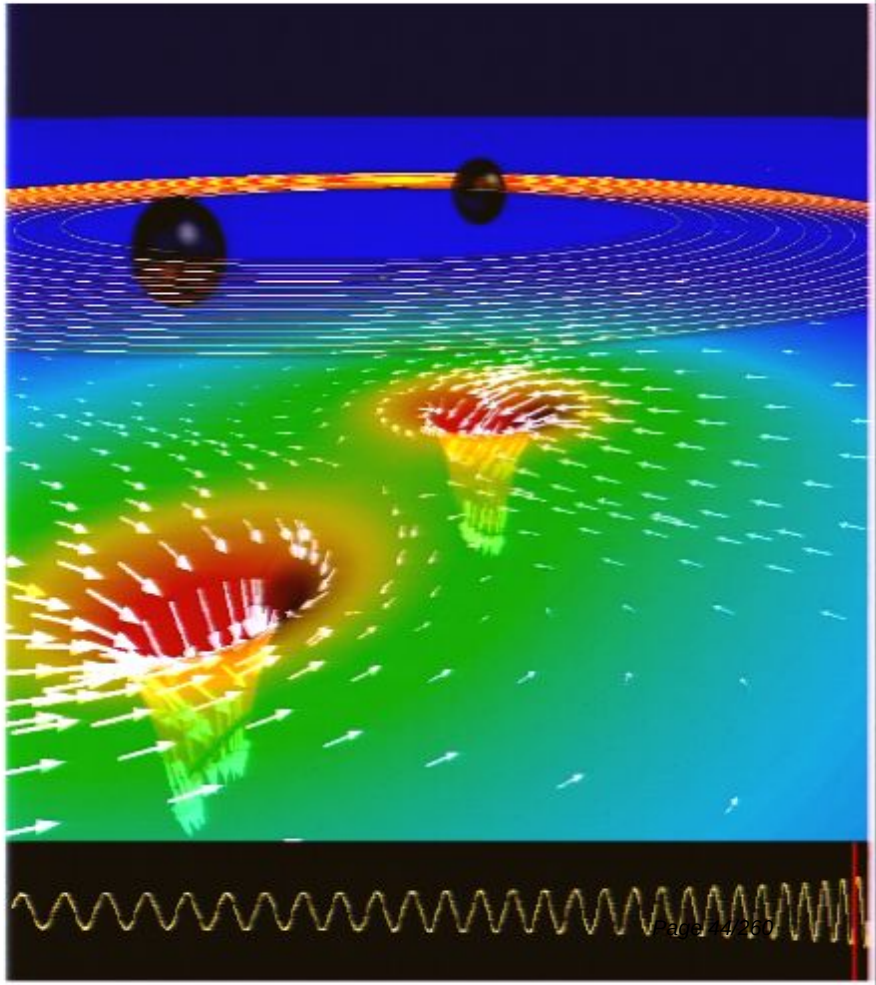
File Edit View Go Help

Previous Next 27 of 67 Best Fit

Movies I



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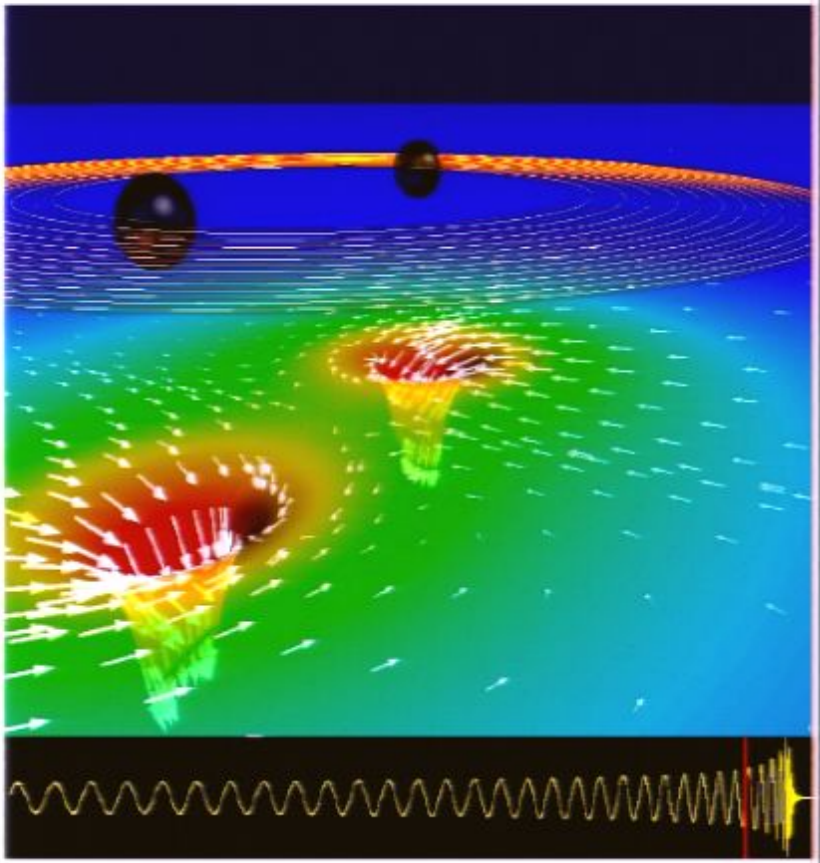
1.33 GHz

Numerical study of black hole spacetimes

File Edit View Go Help

Previous Next 27 of 67 Best Fit

Movies I



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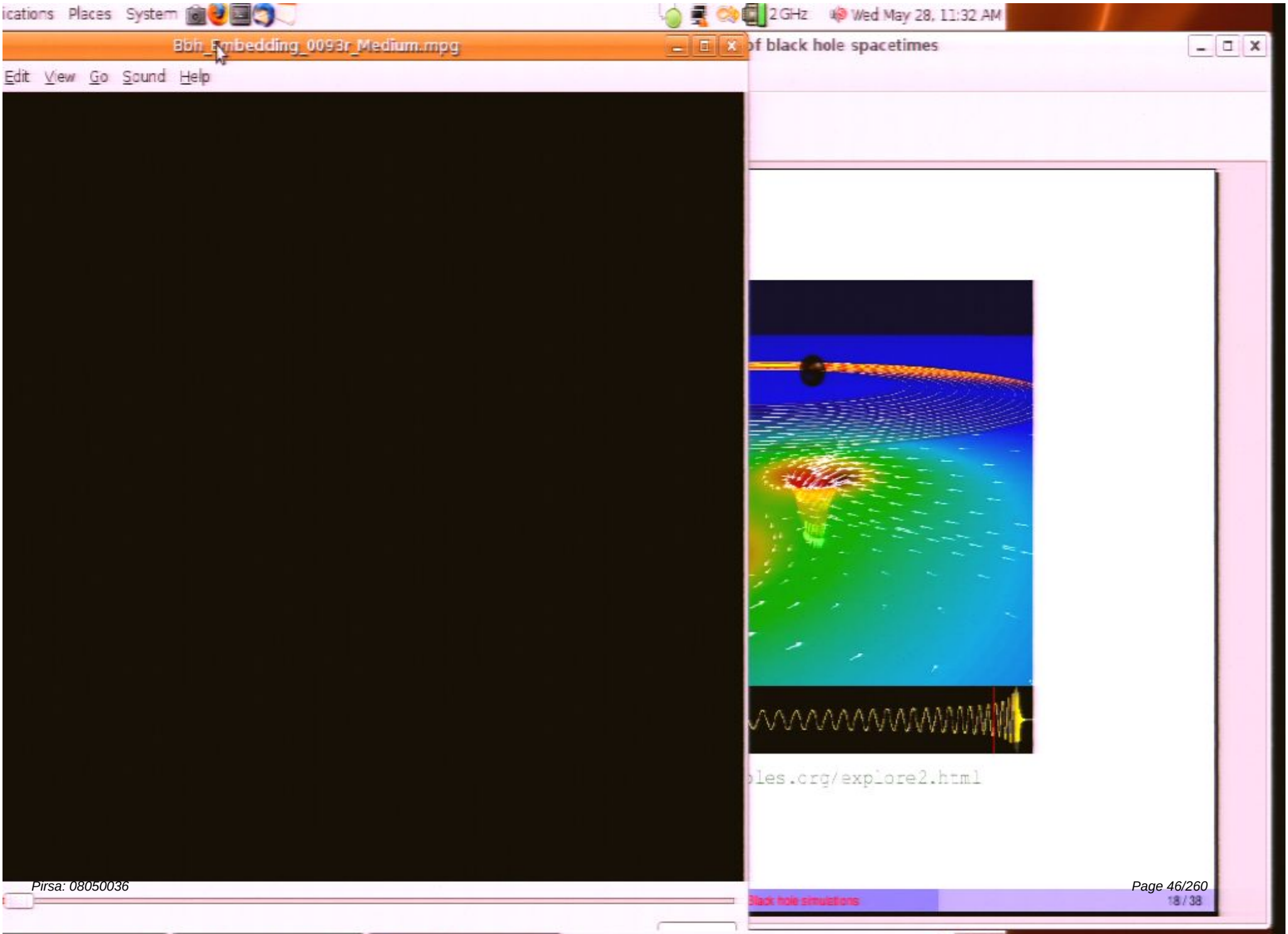
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Black hole simulations
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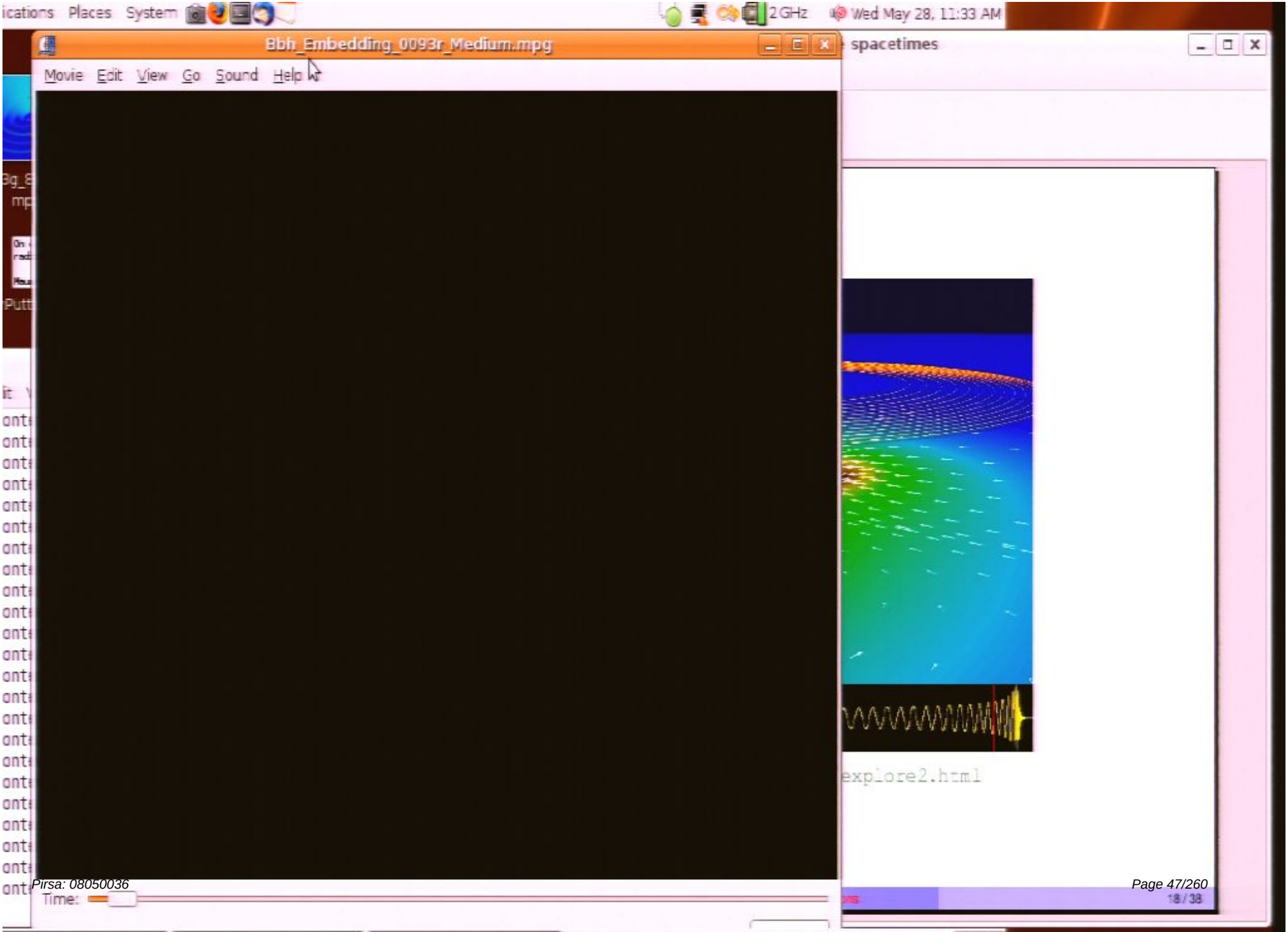
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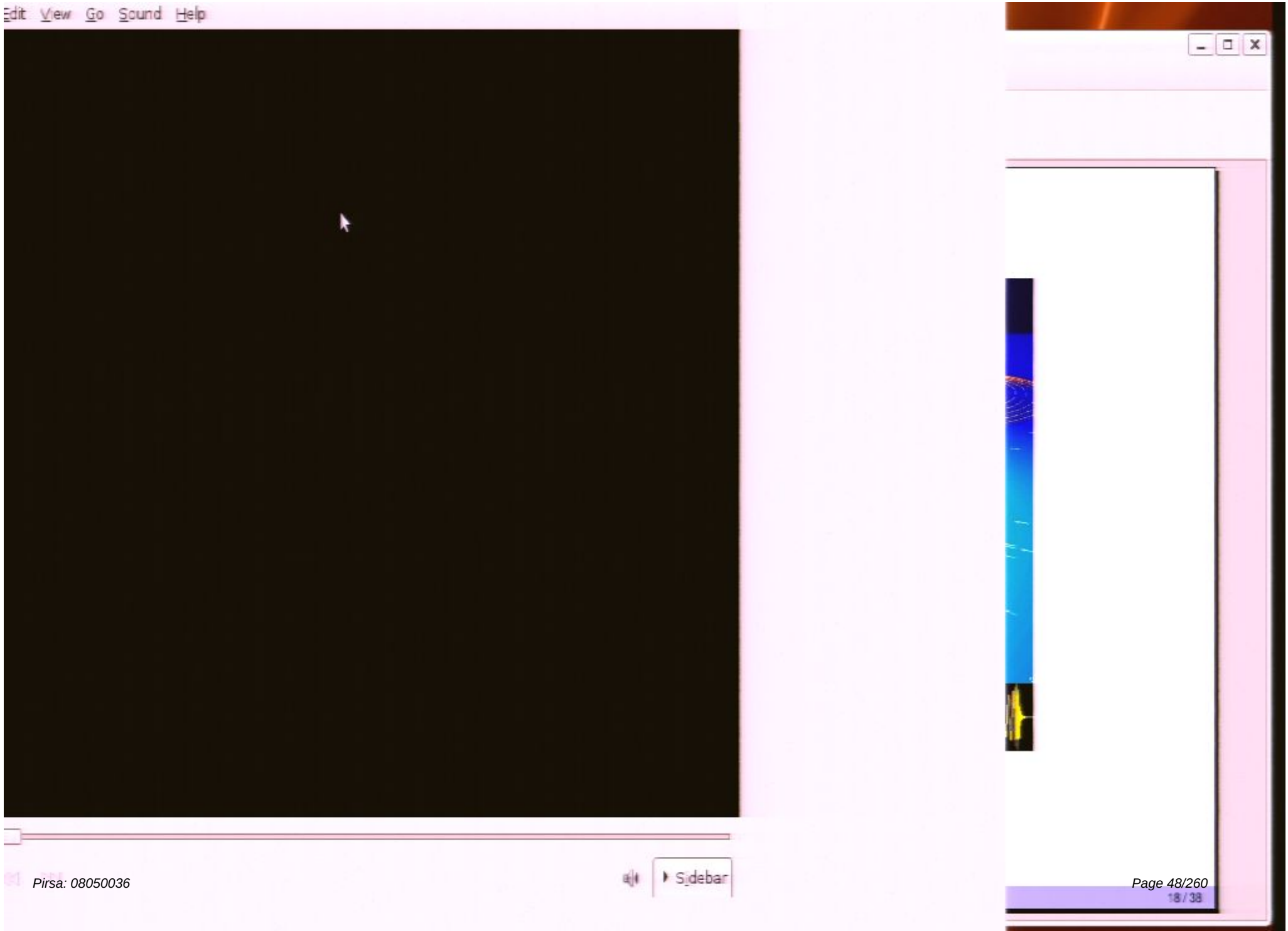
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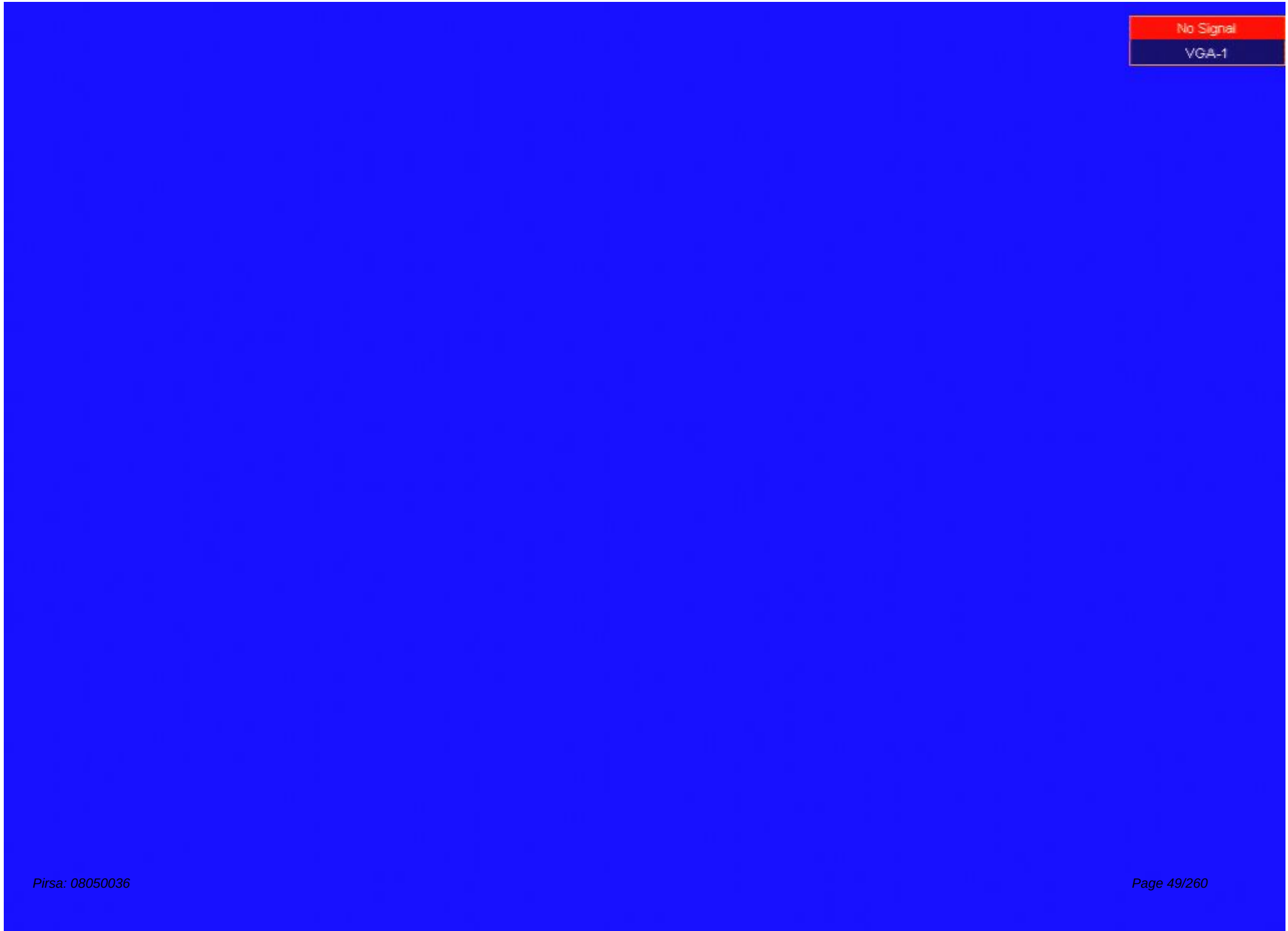
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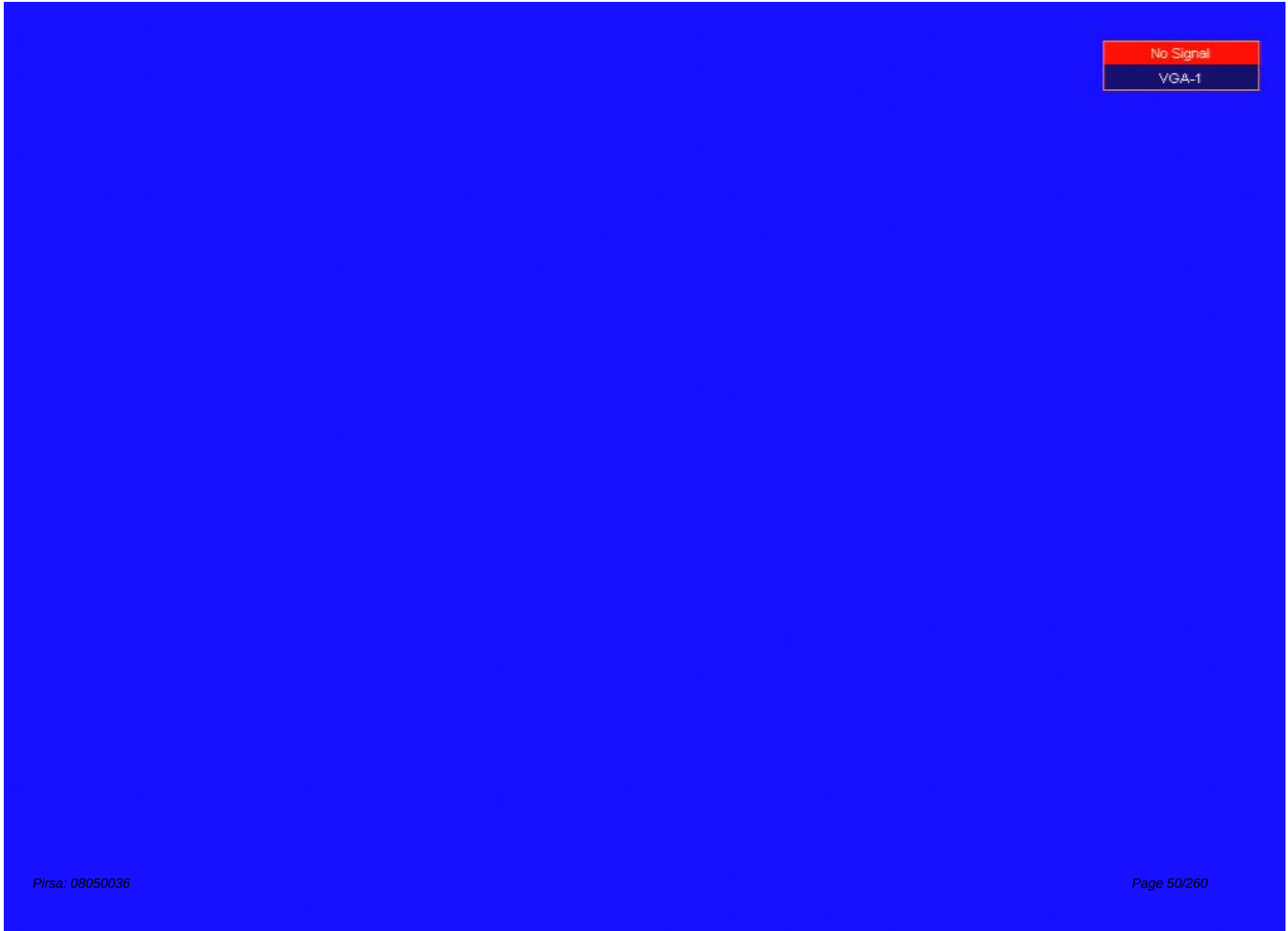
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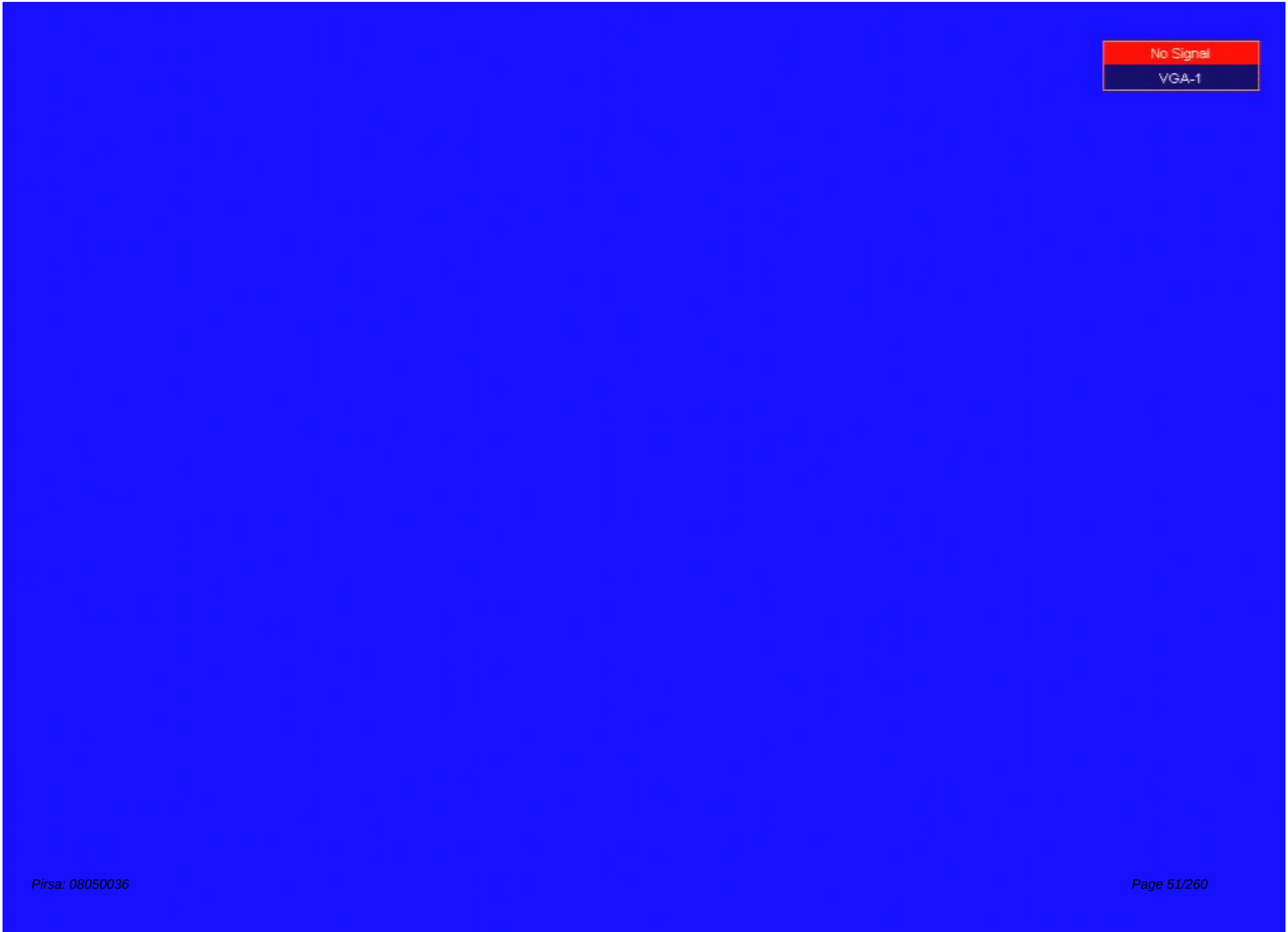
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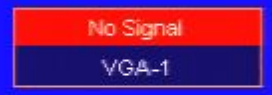
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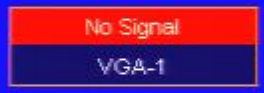
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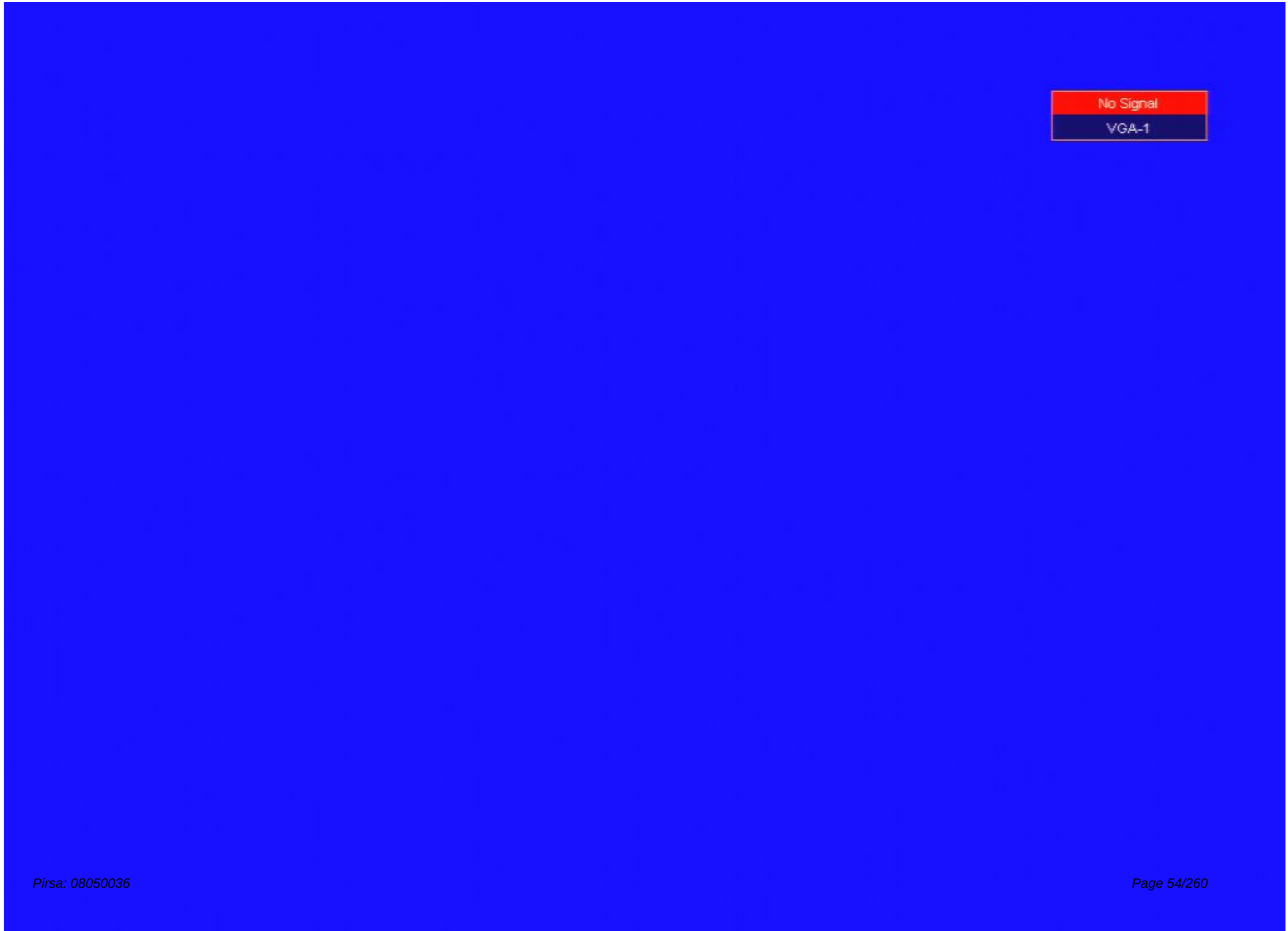
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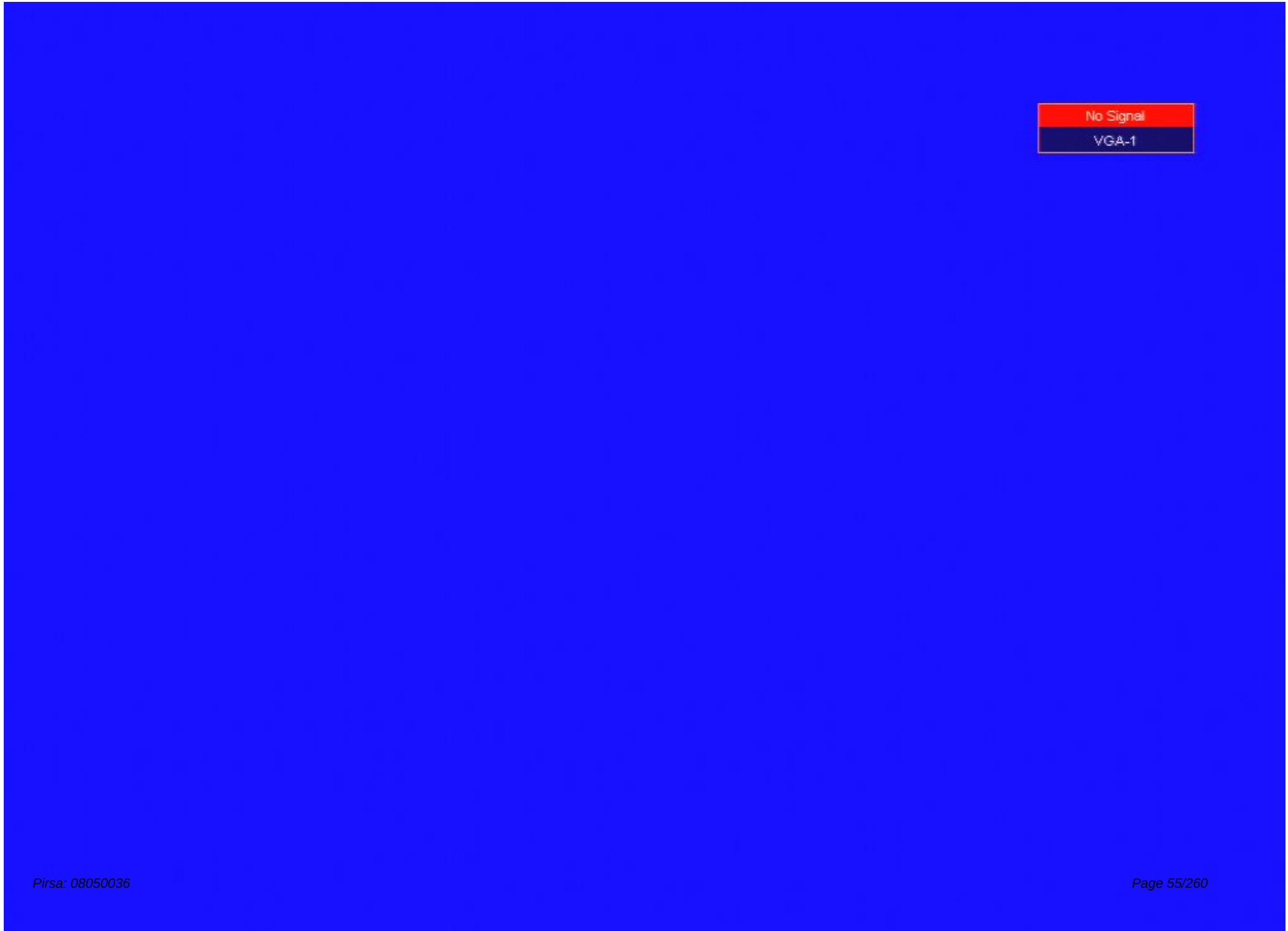
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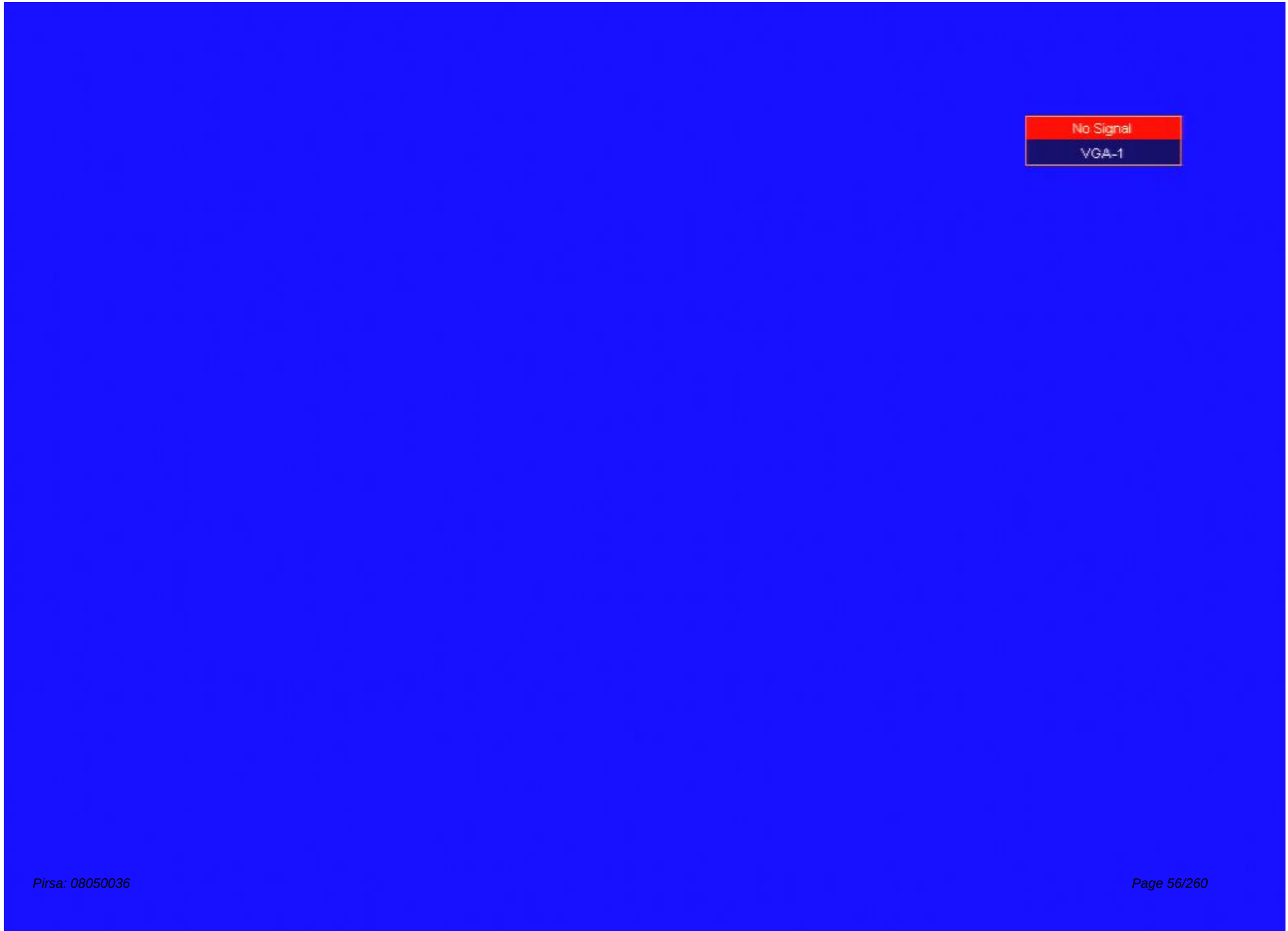
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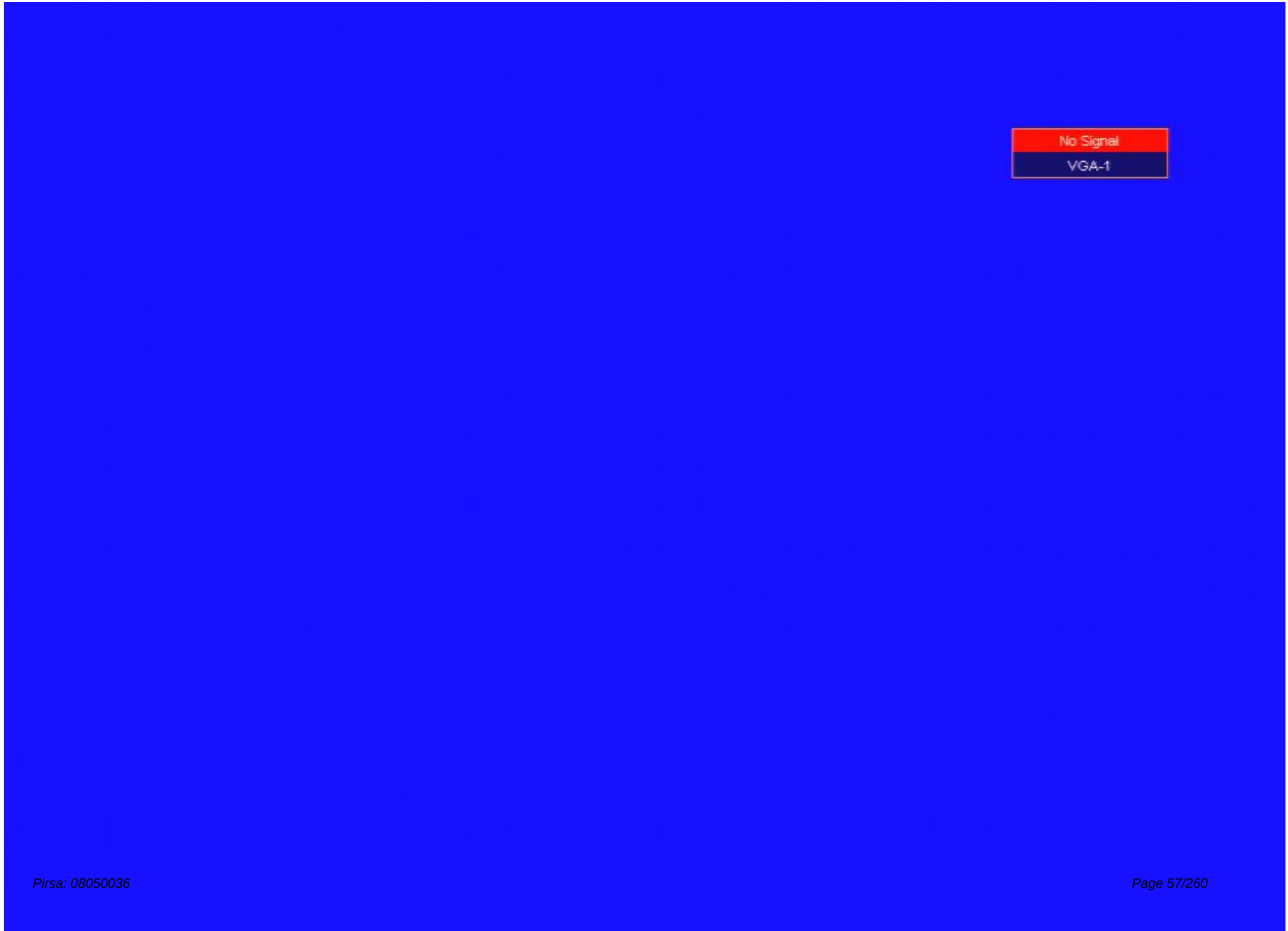
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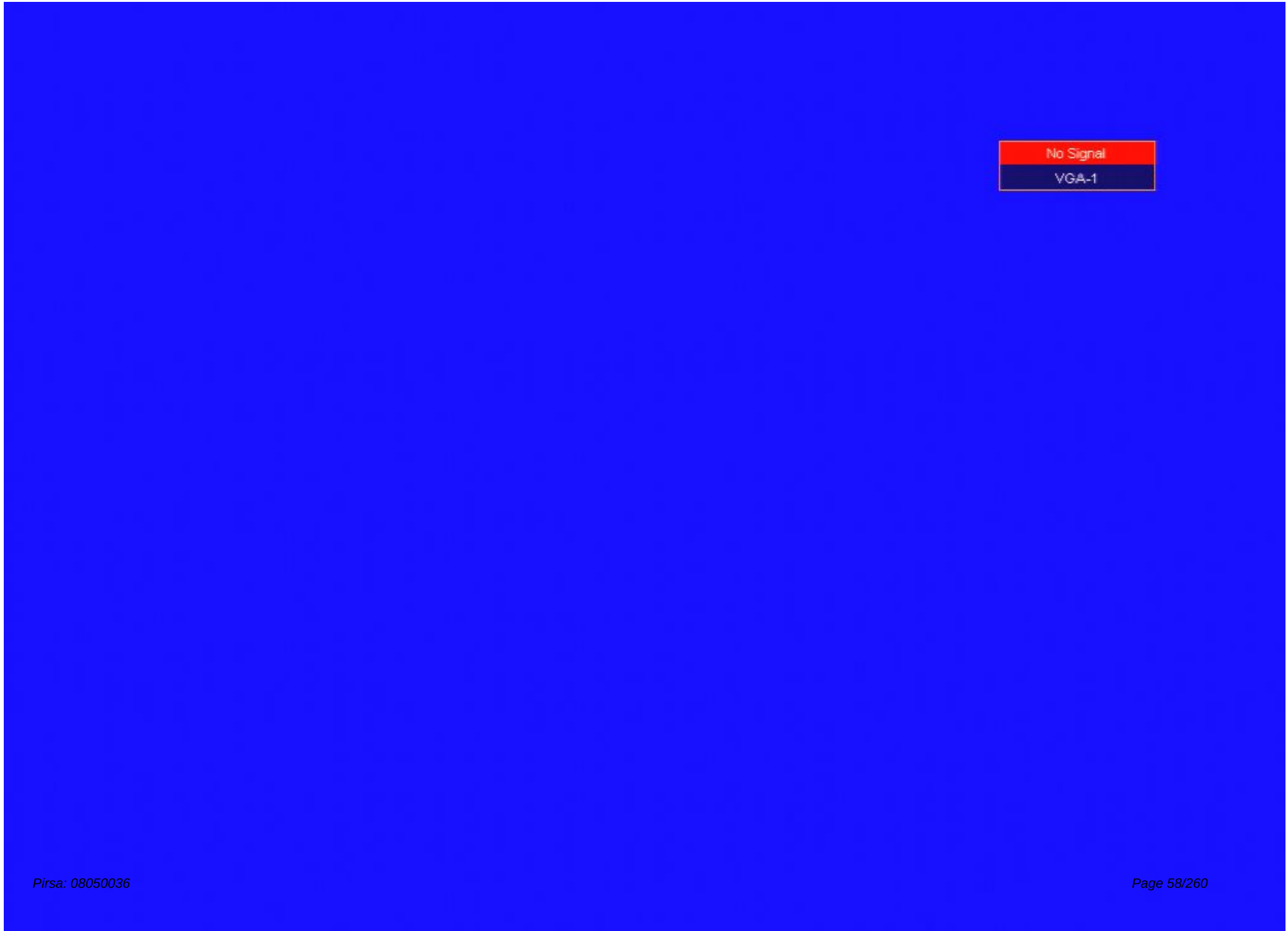
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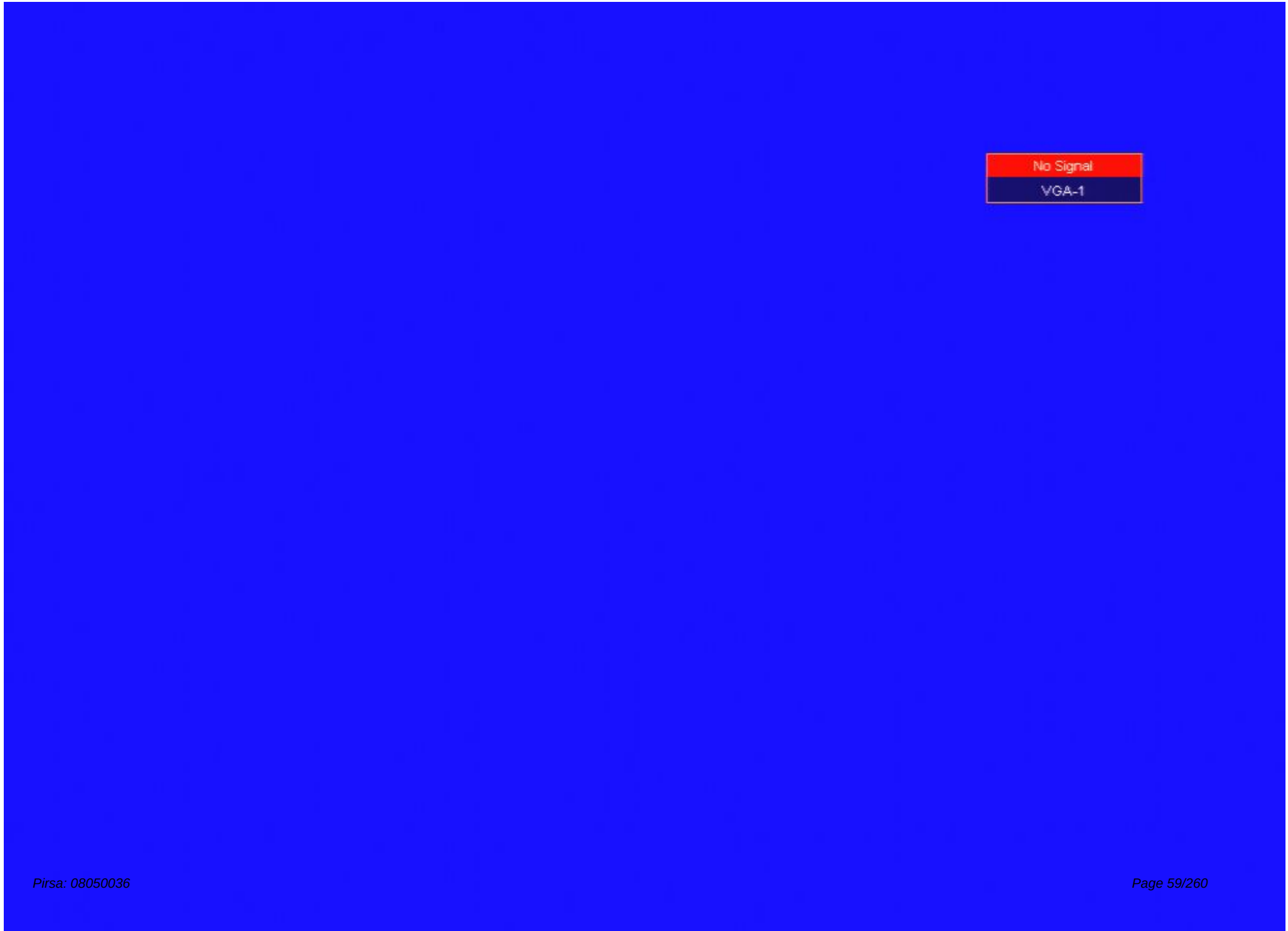
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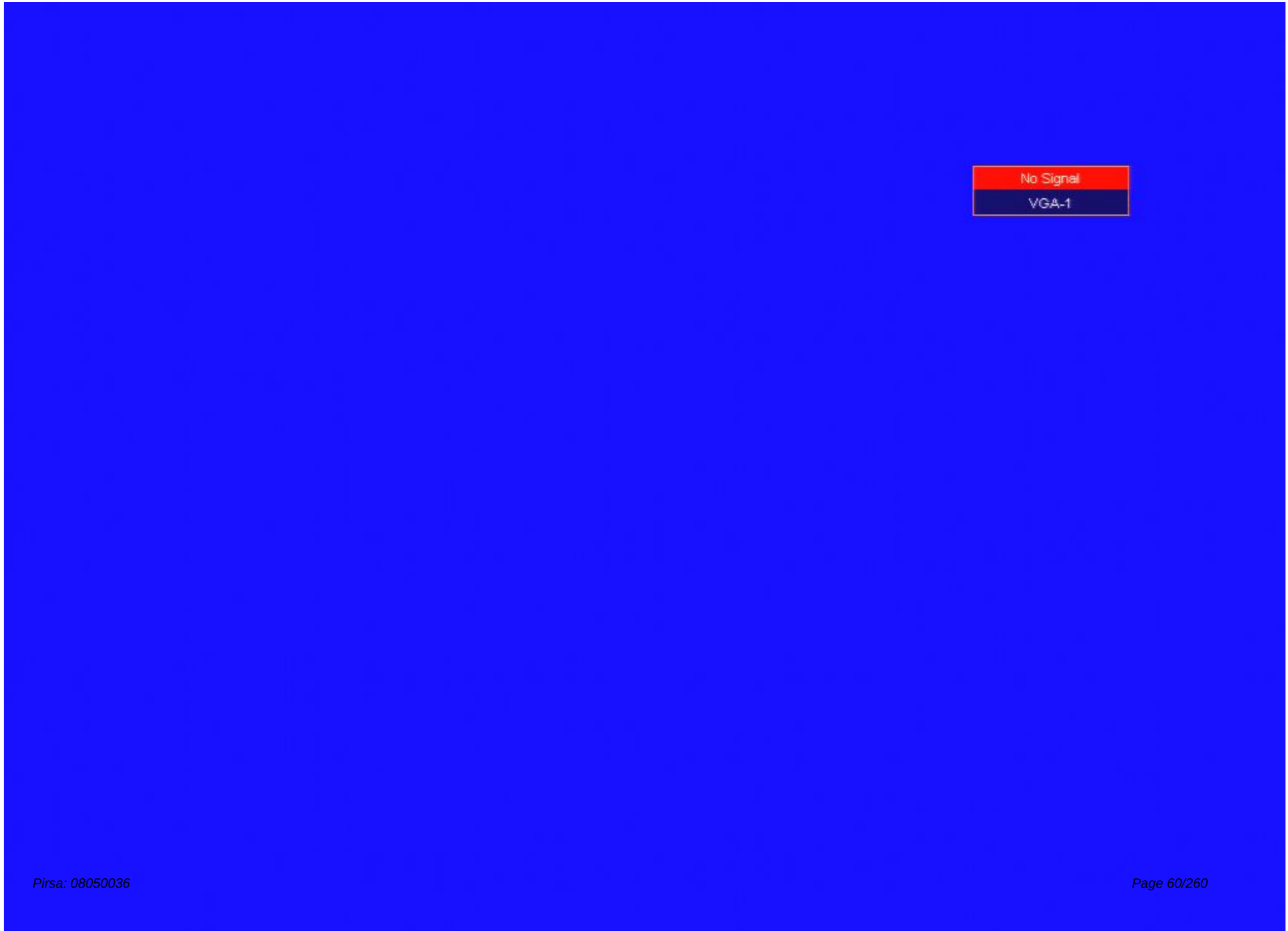
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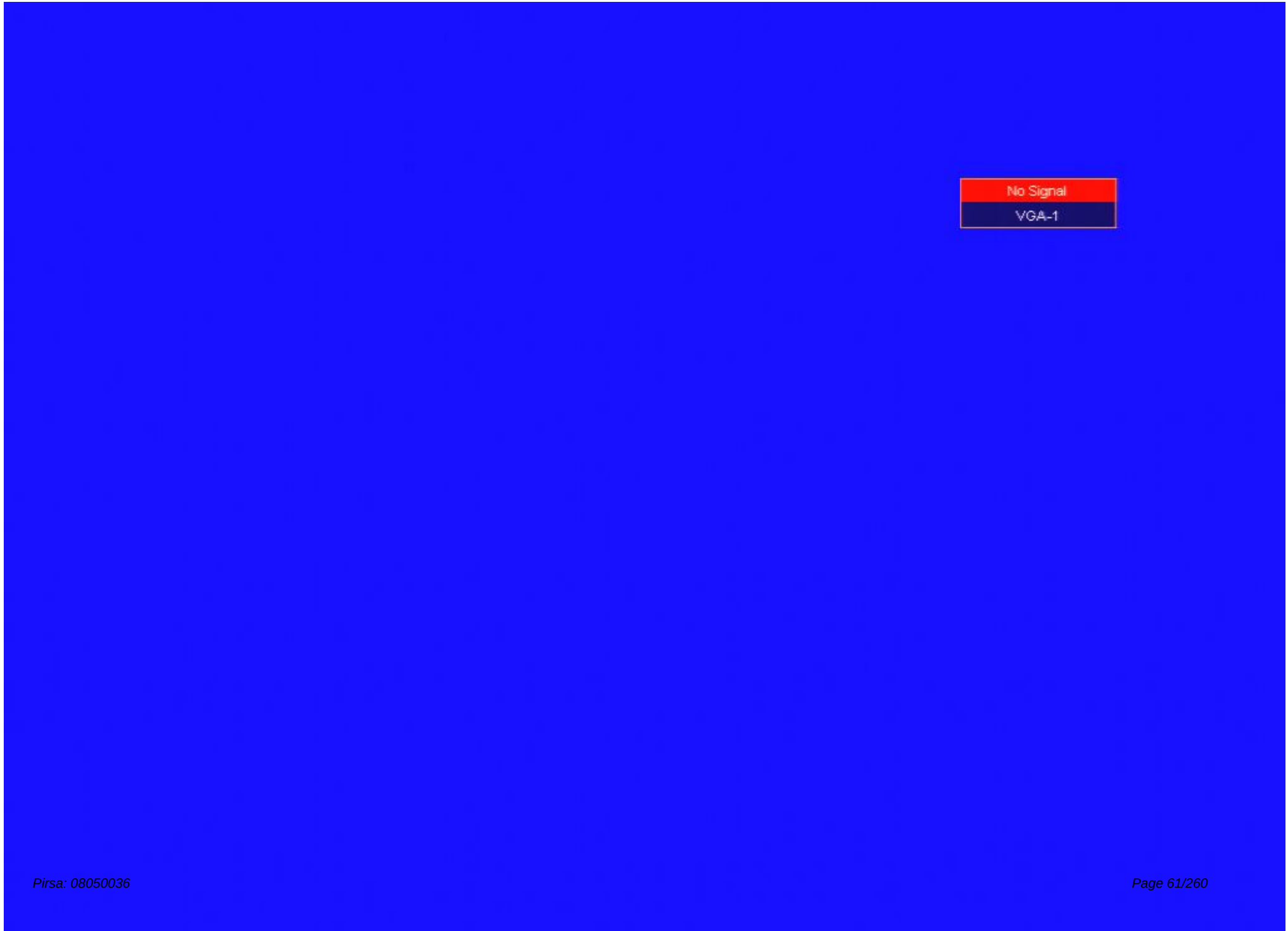
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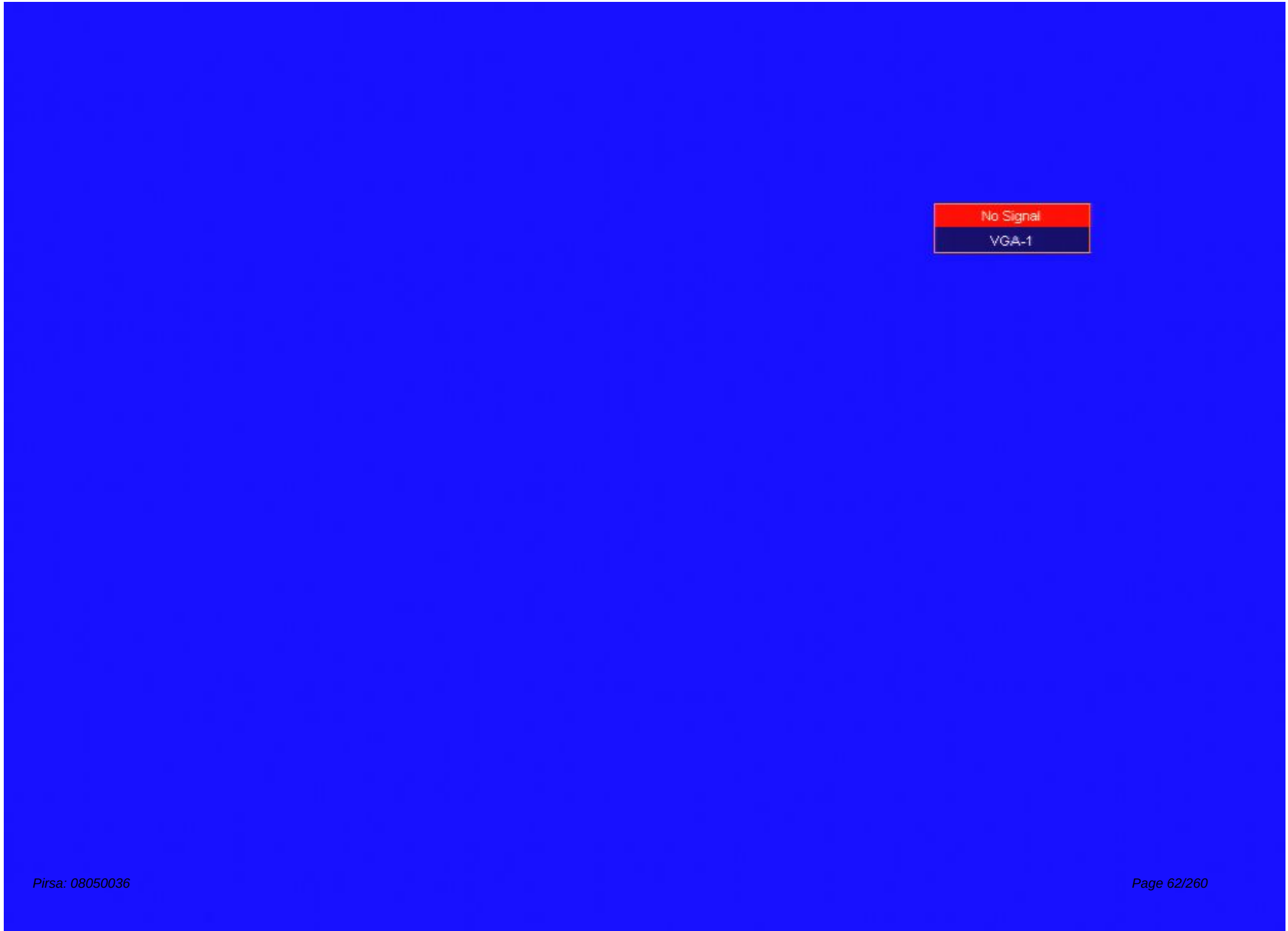
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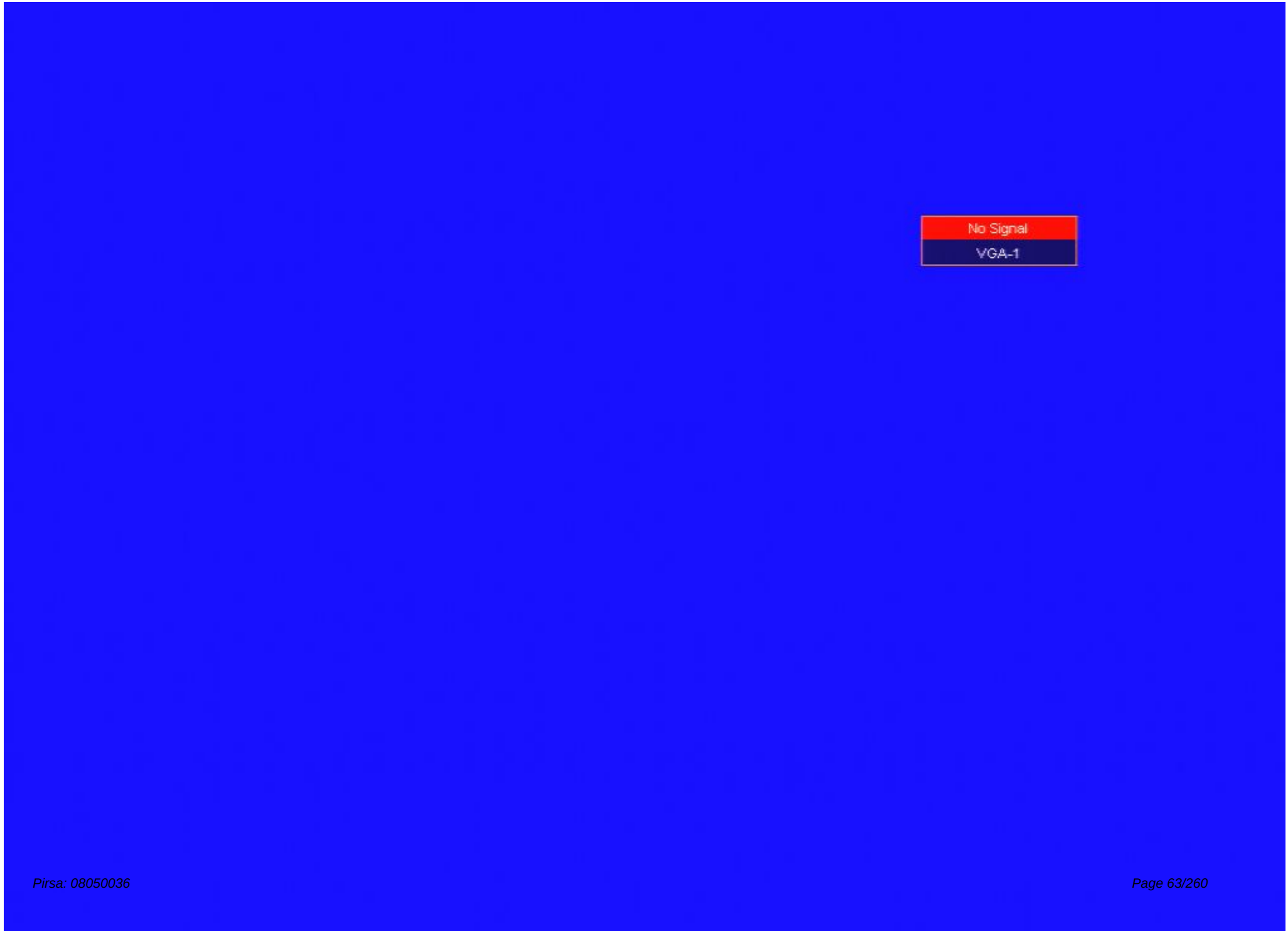
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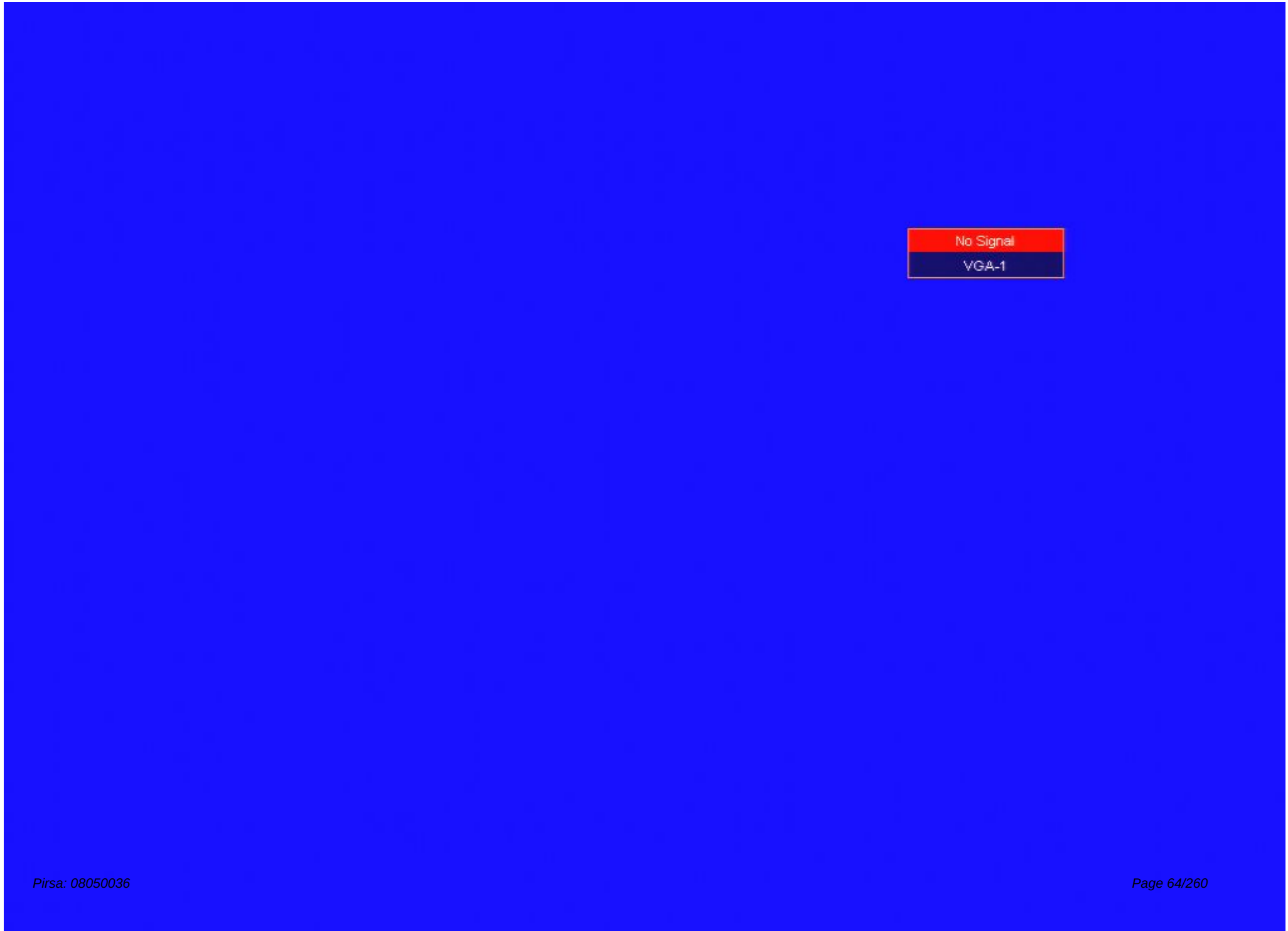
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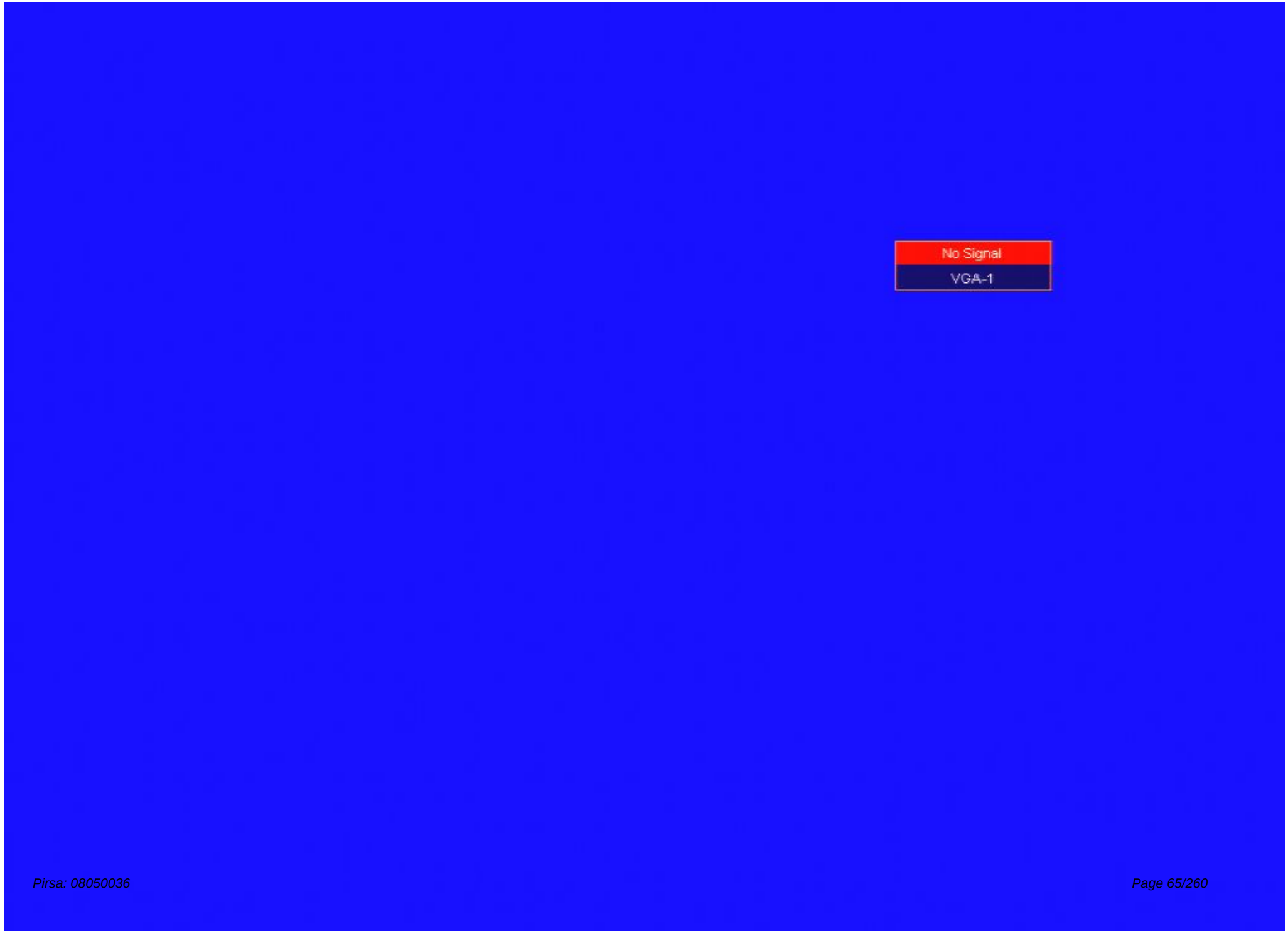
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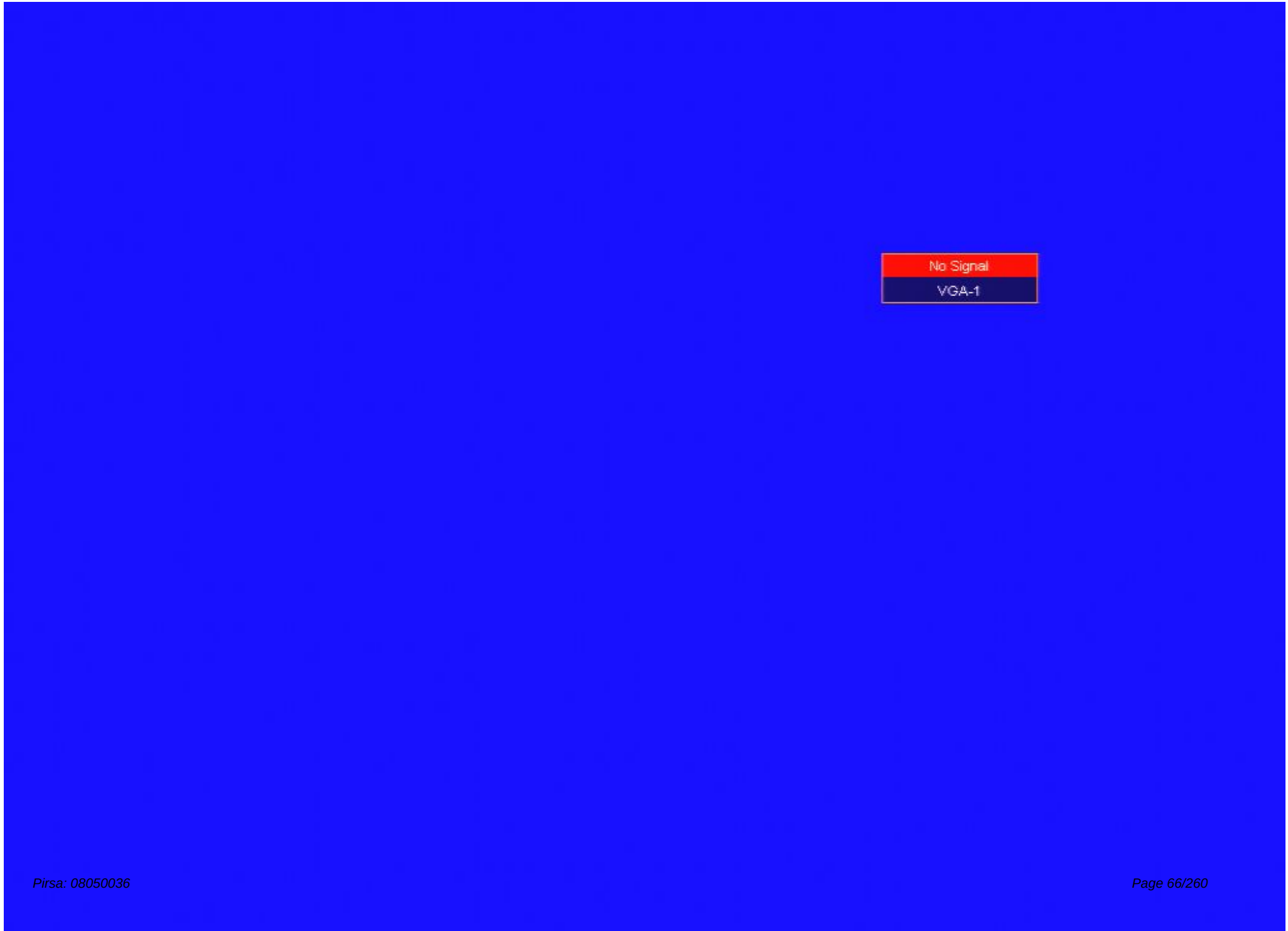
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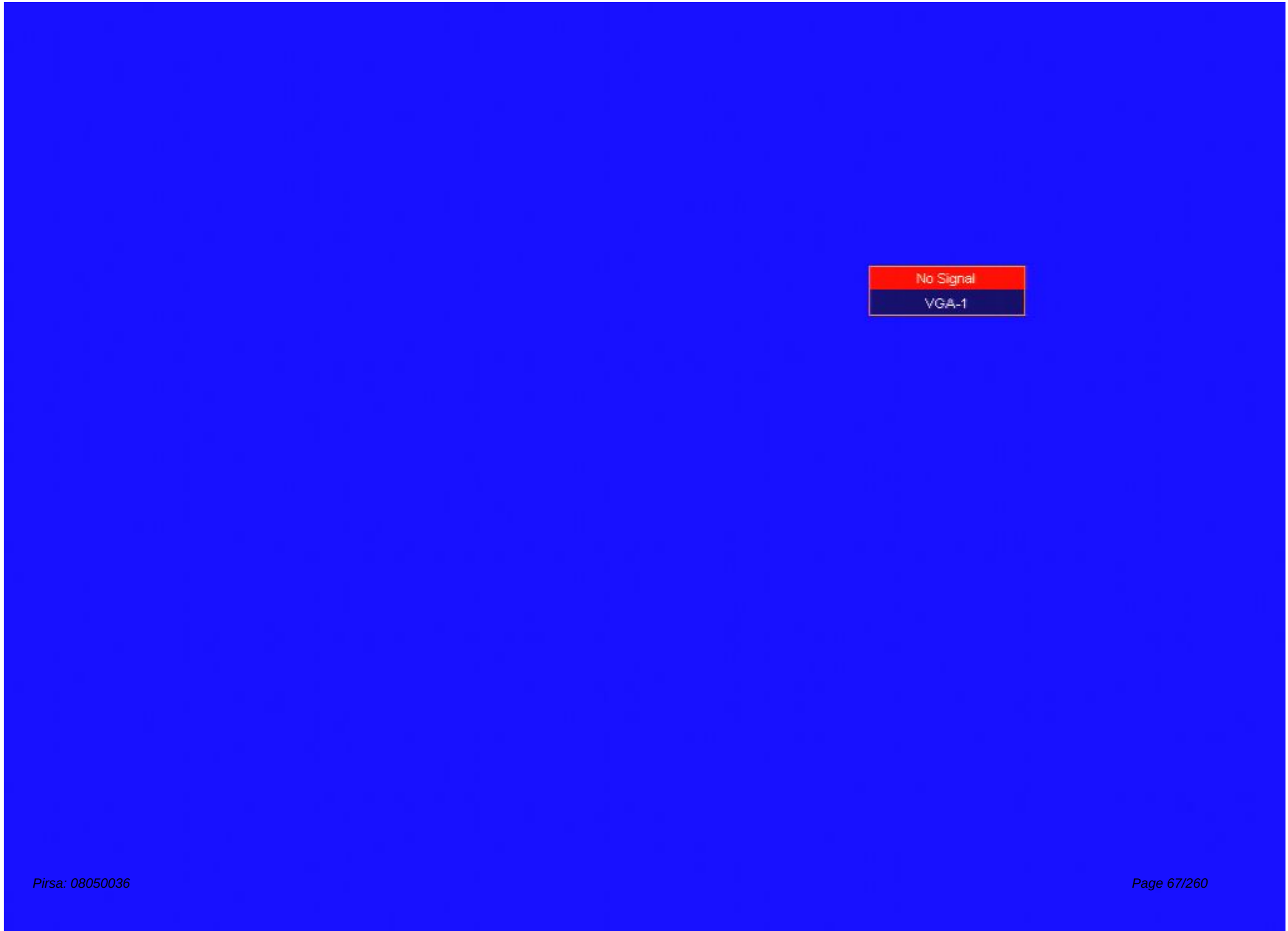
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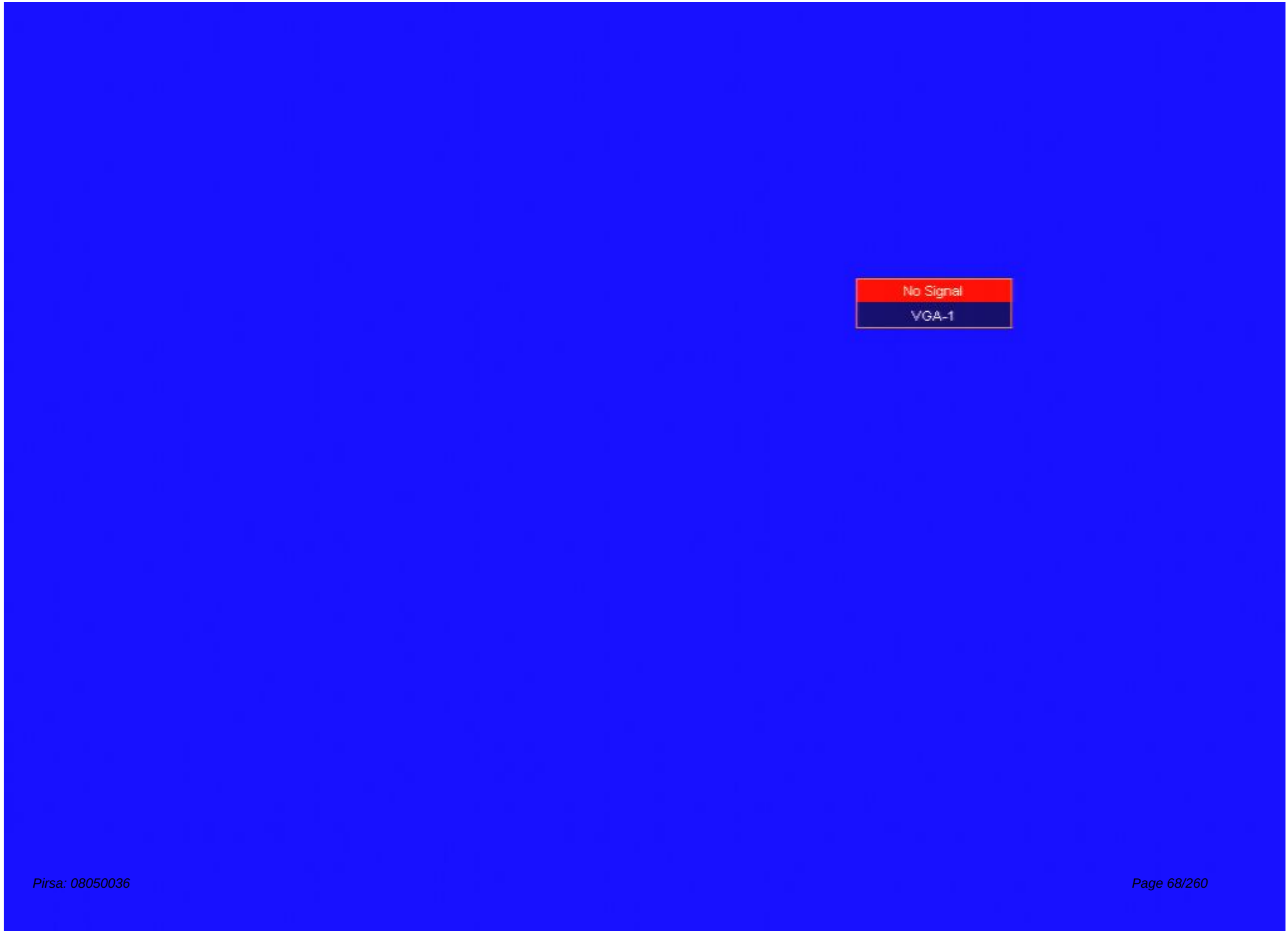
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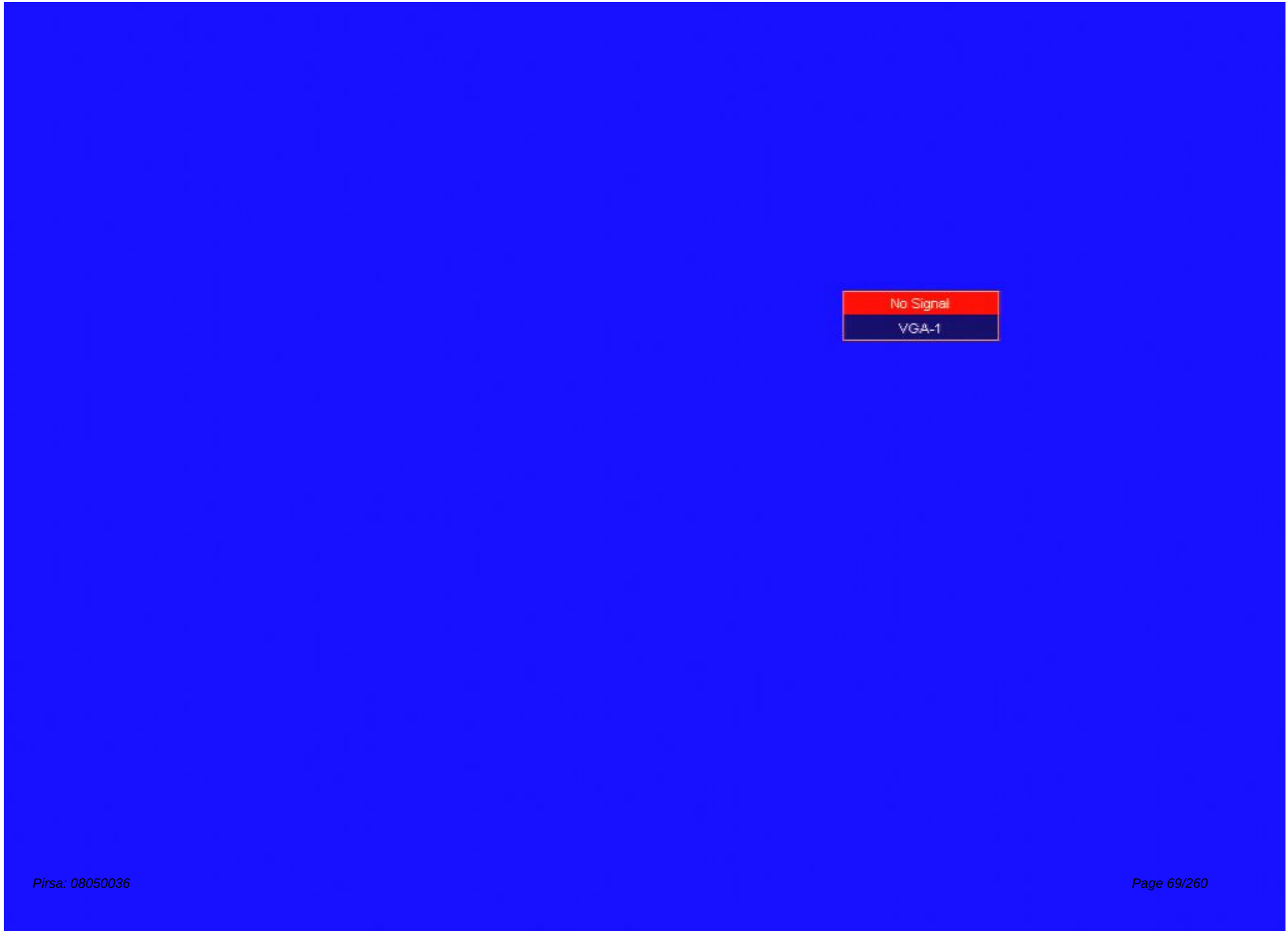
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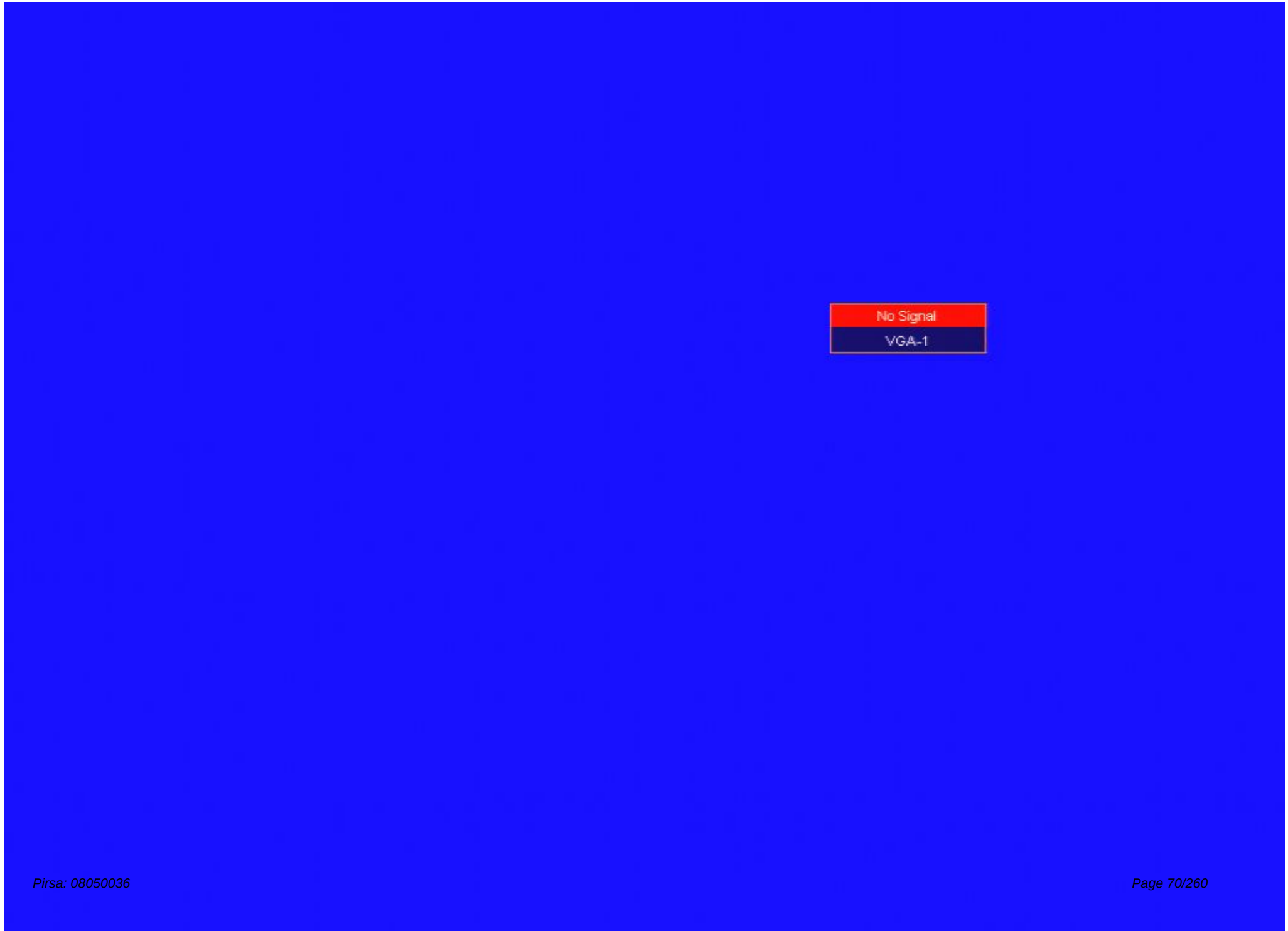
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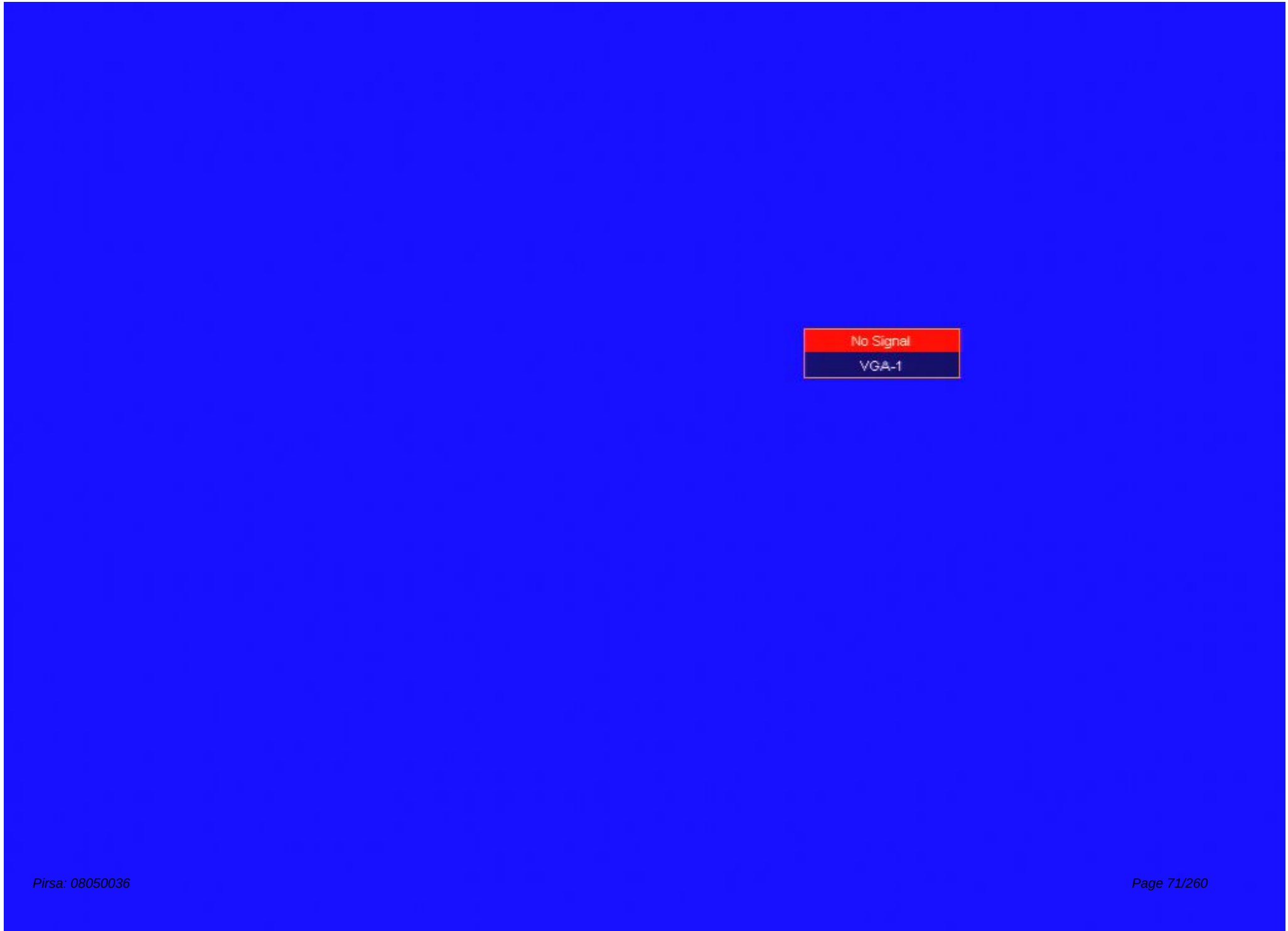
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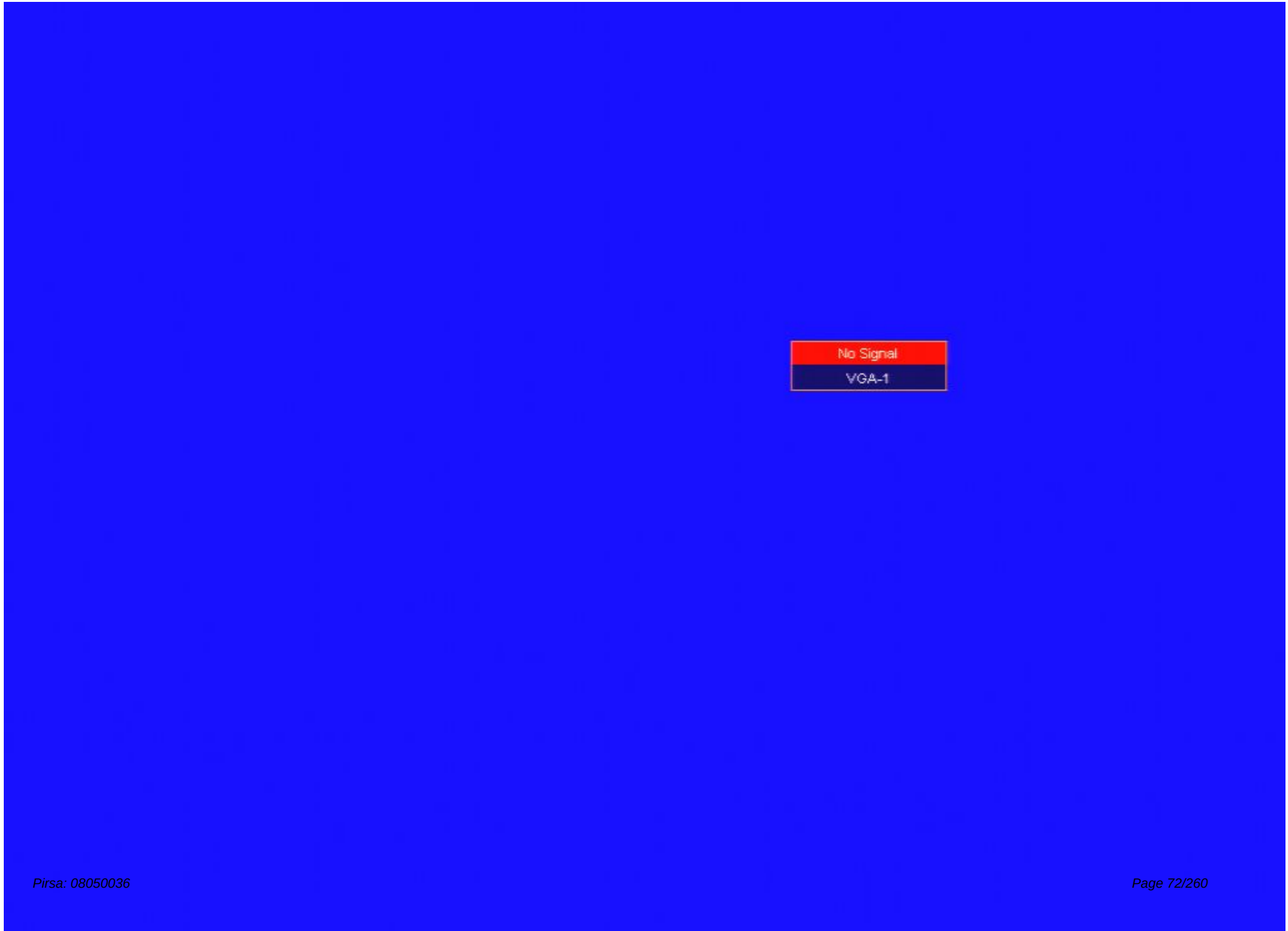
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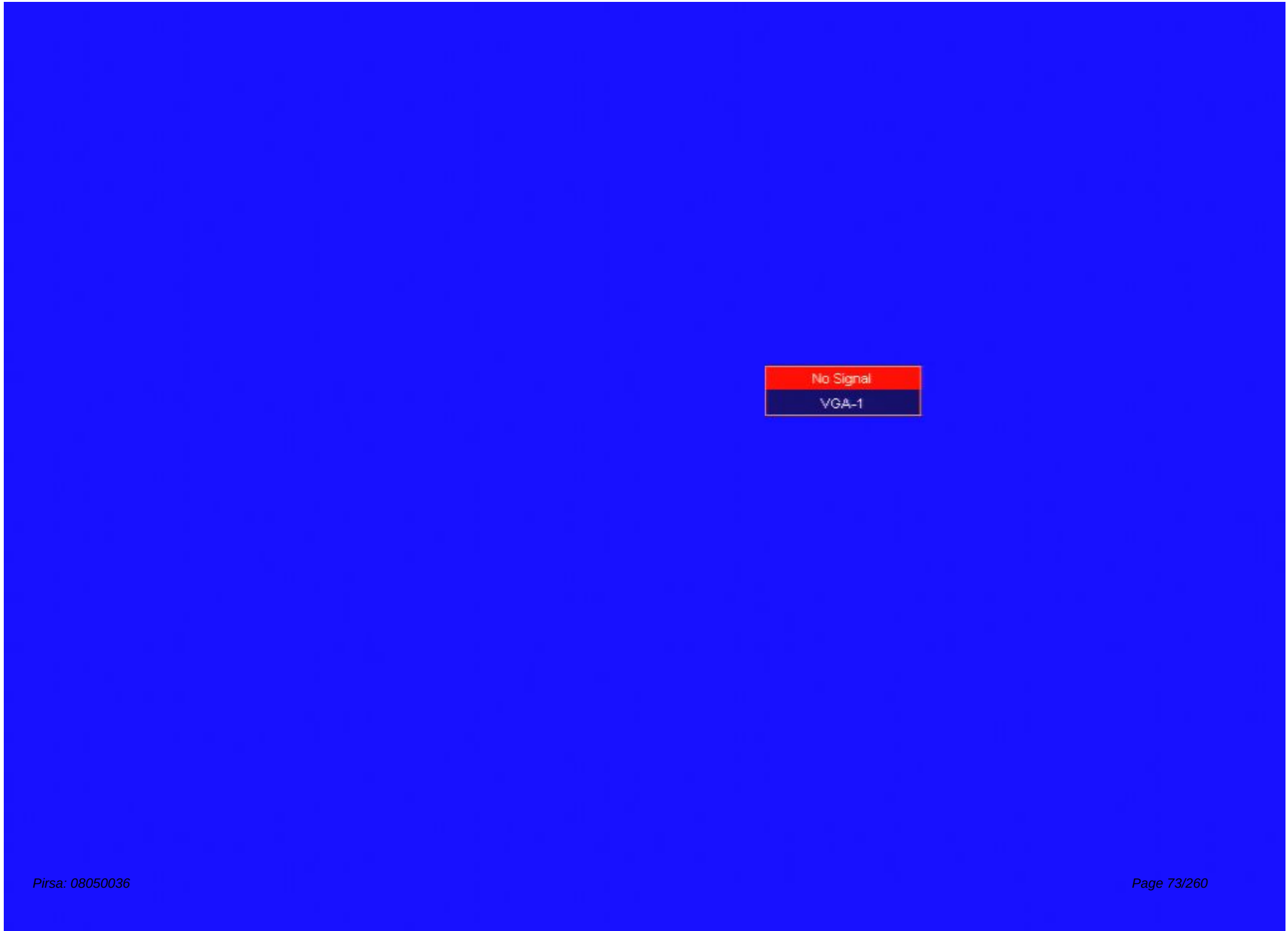
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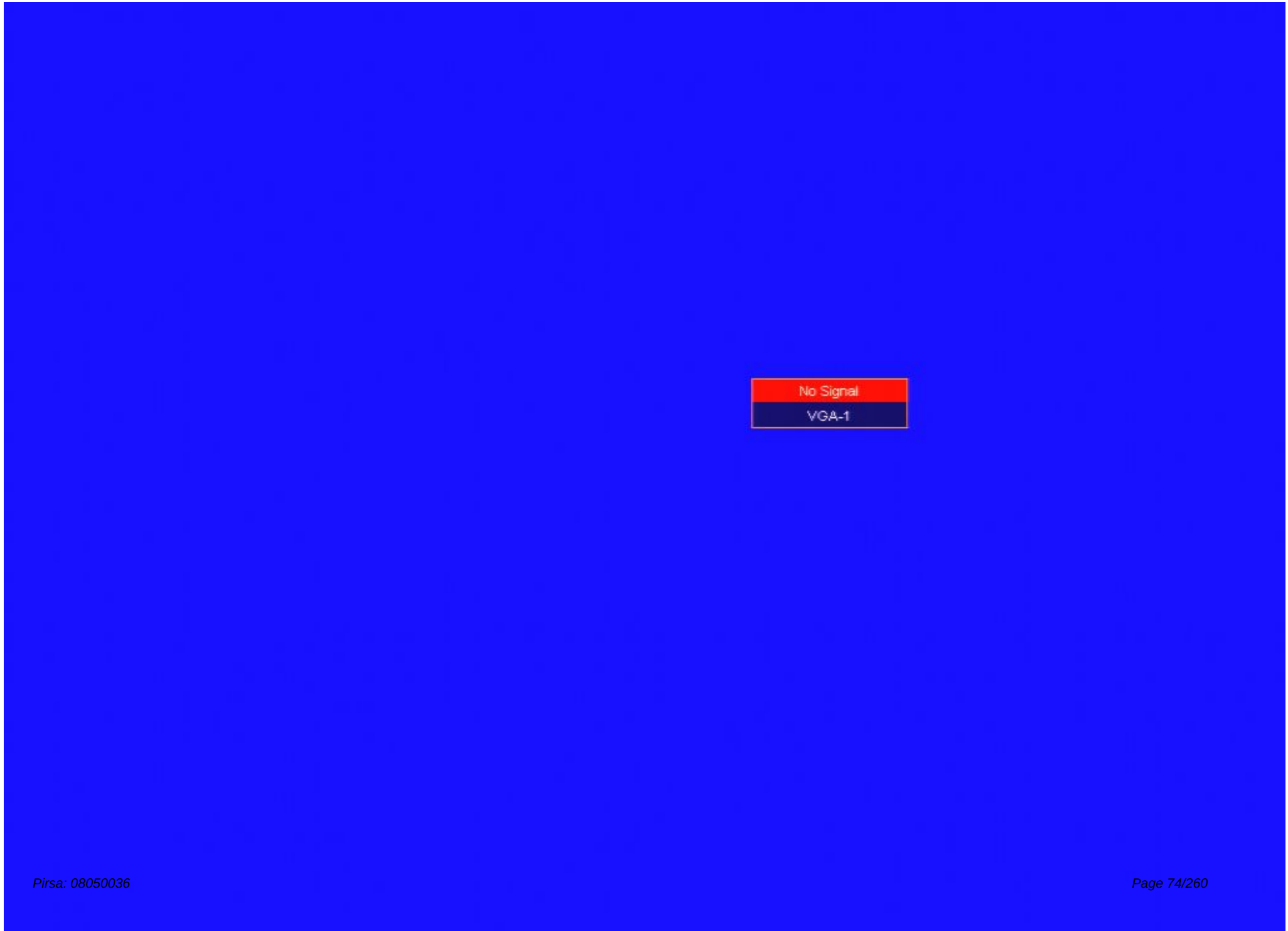
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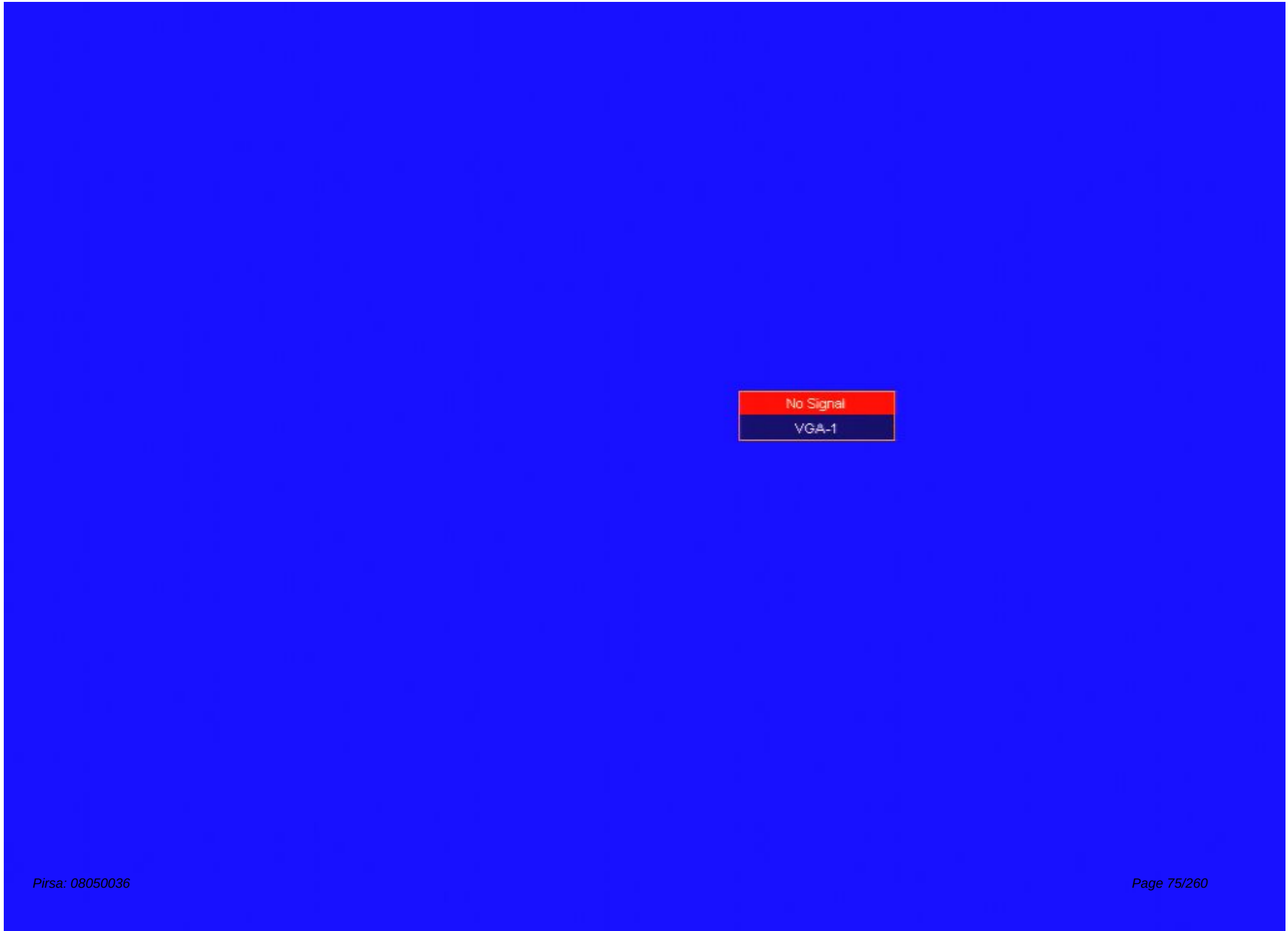
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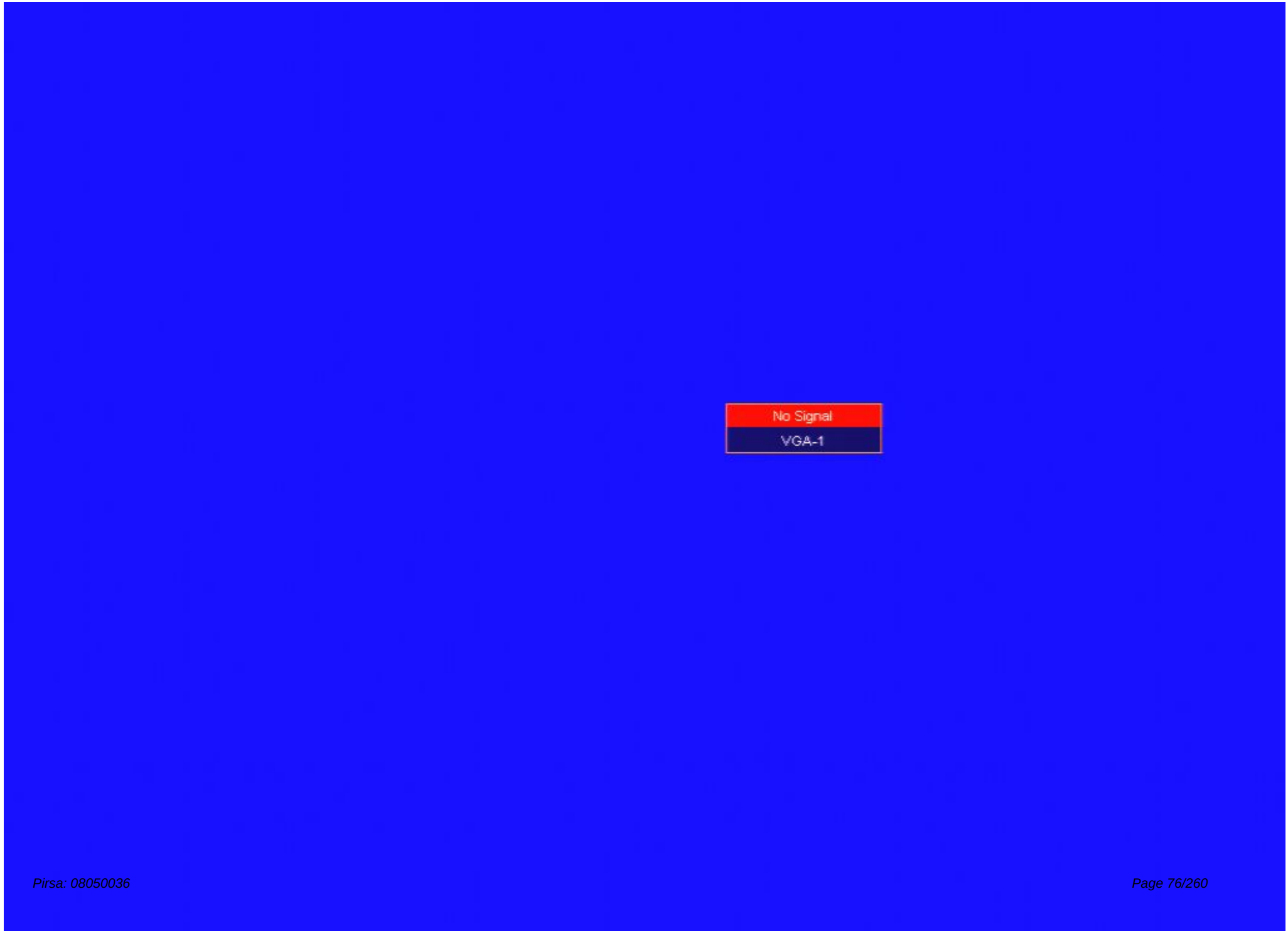
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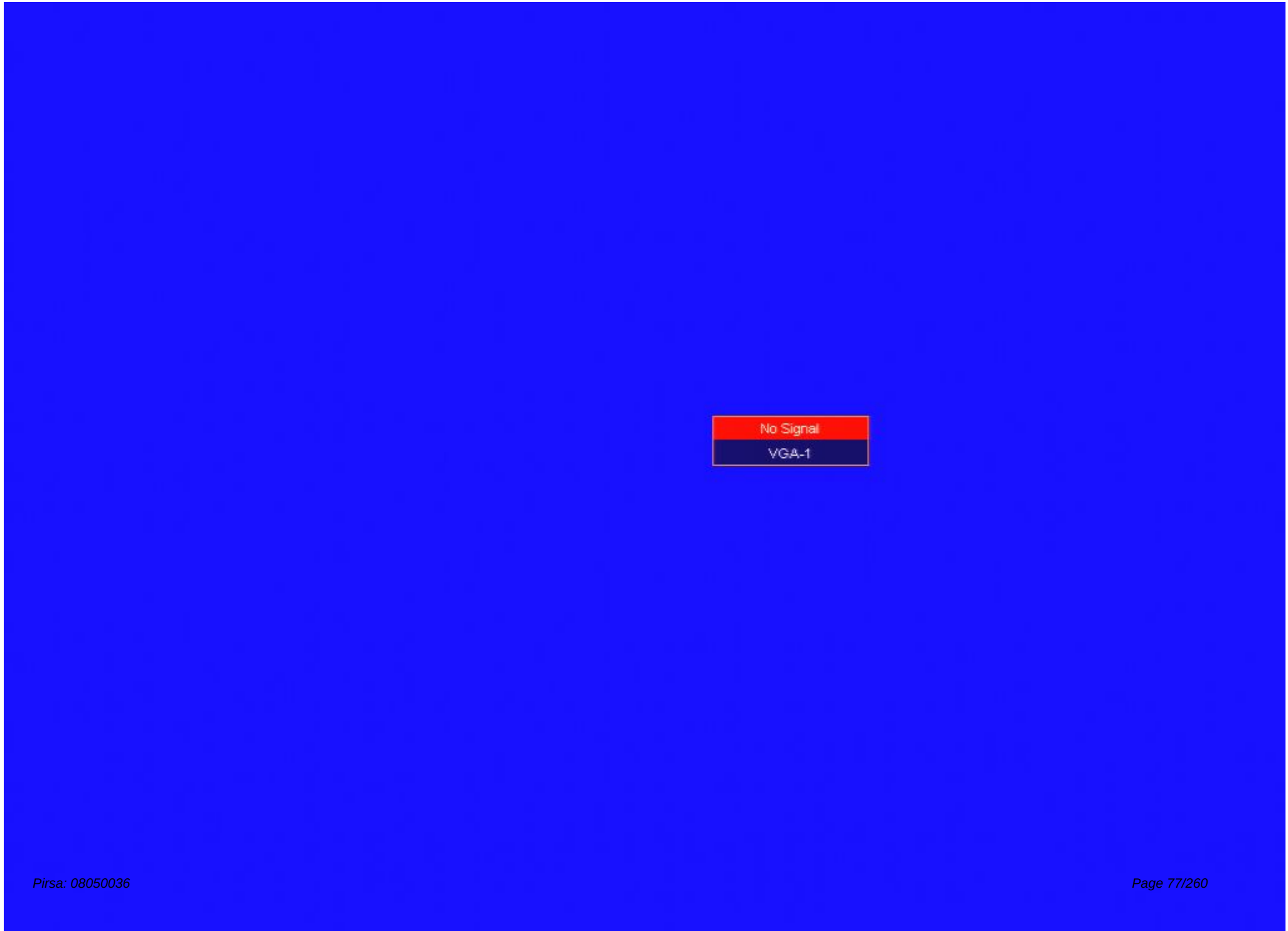
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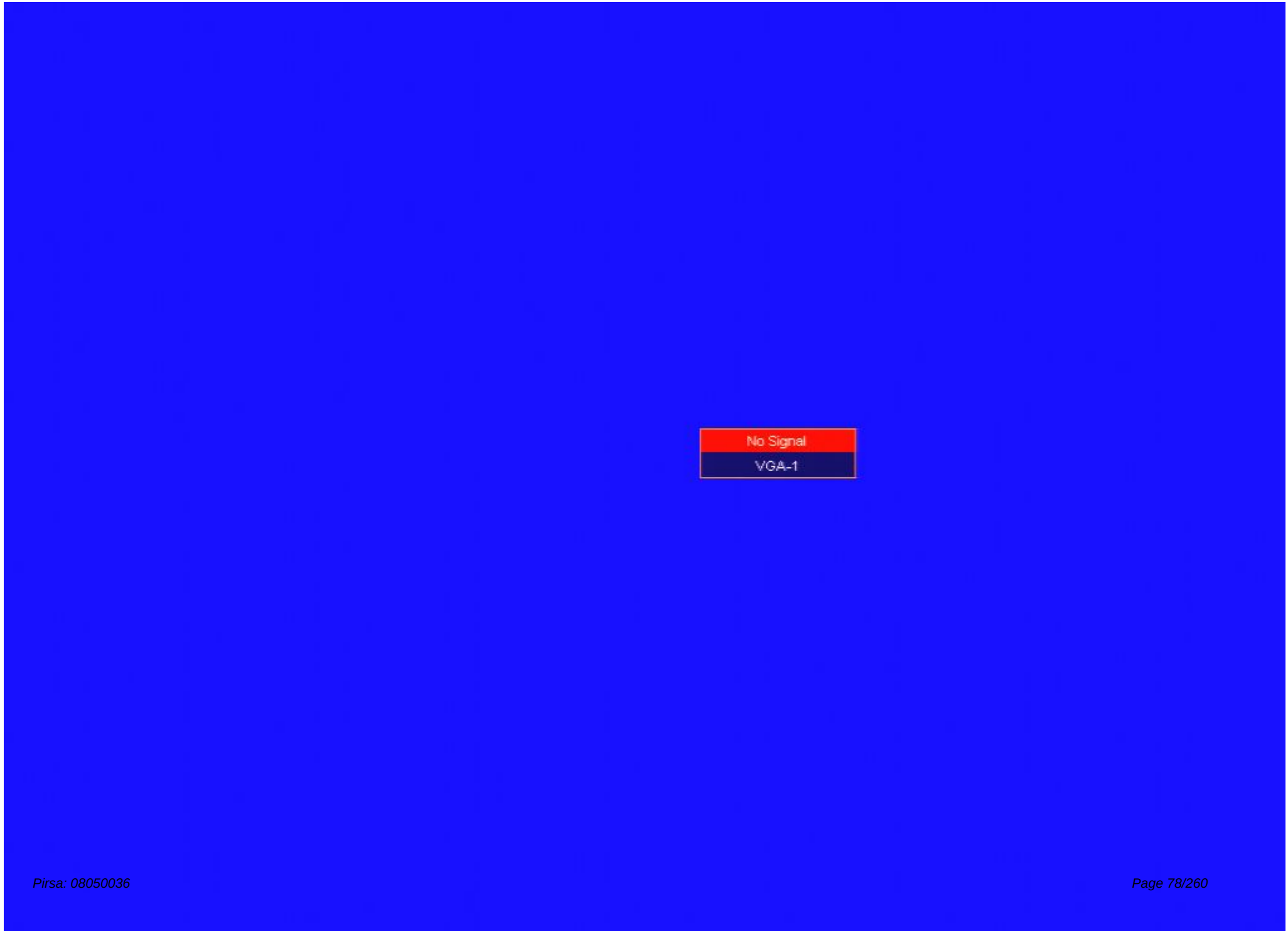
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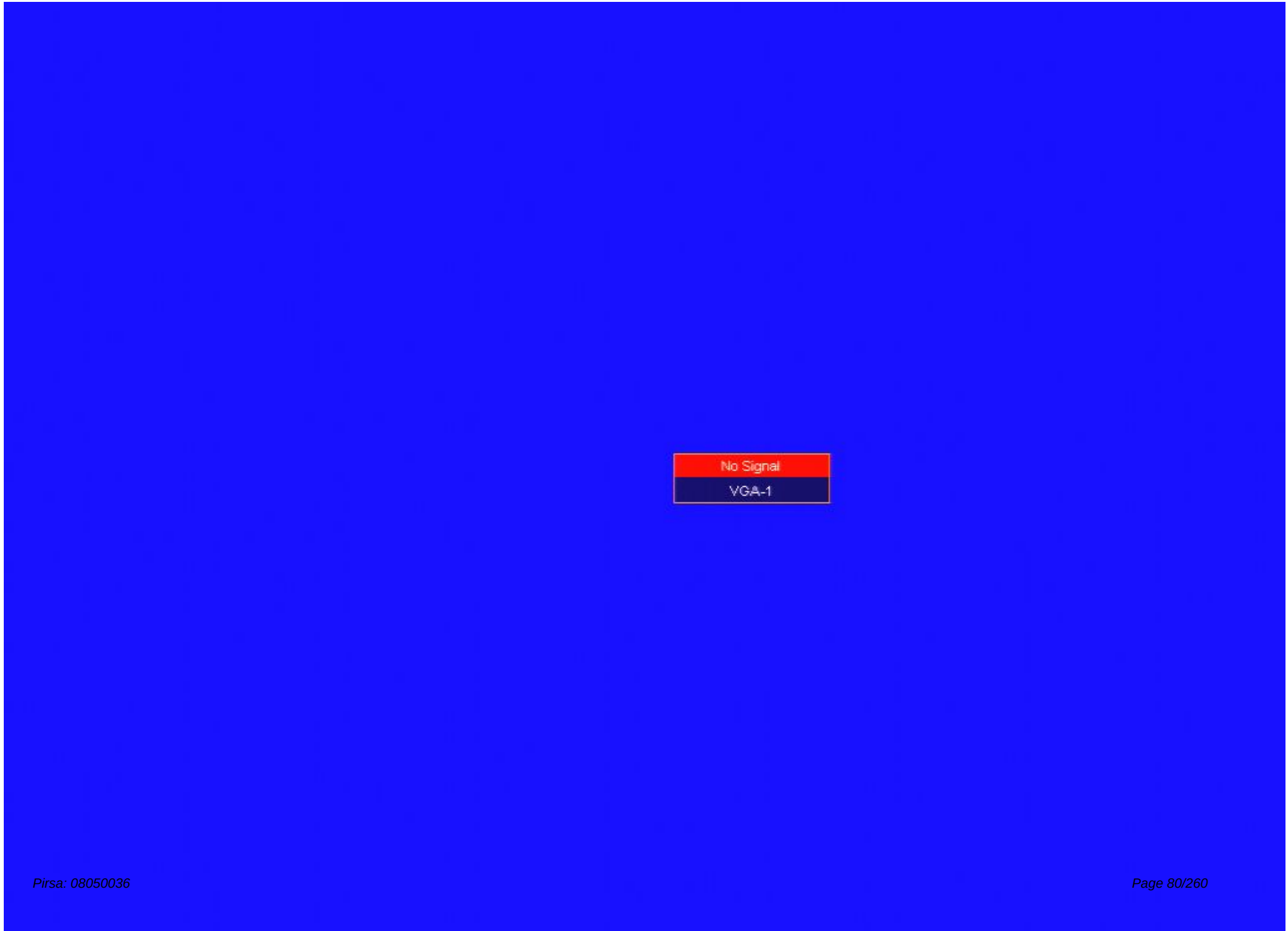
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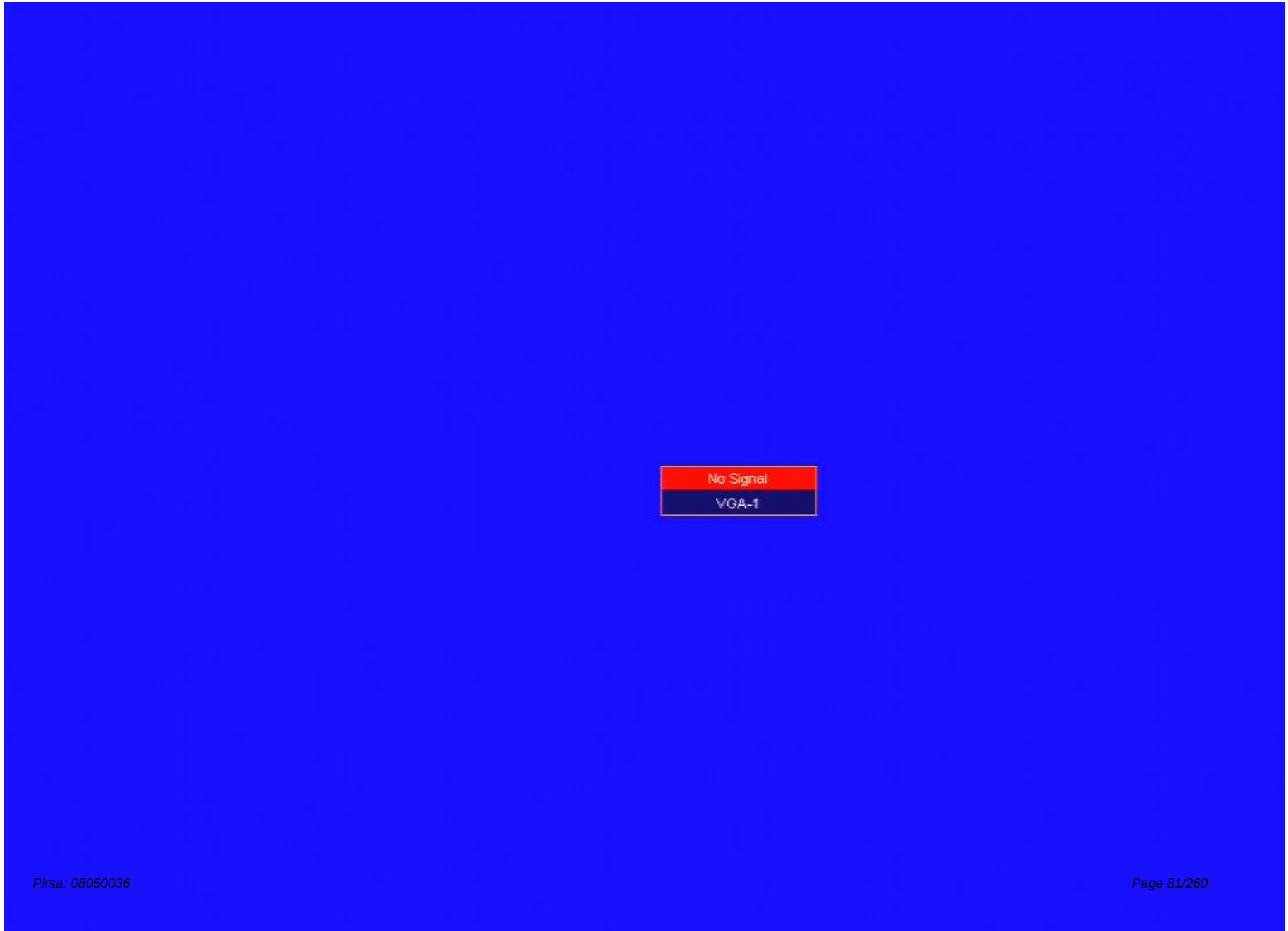
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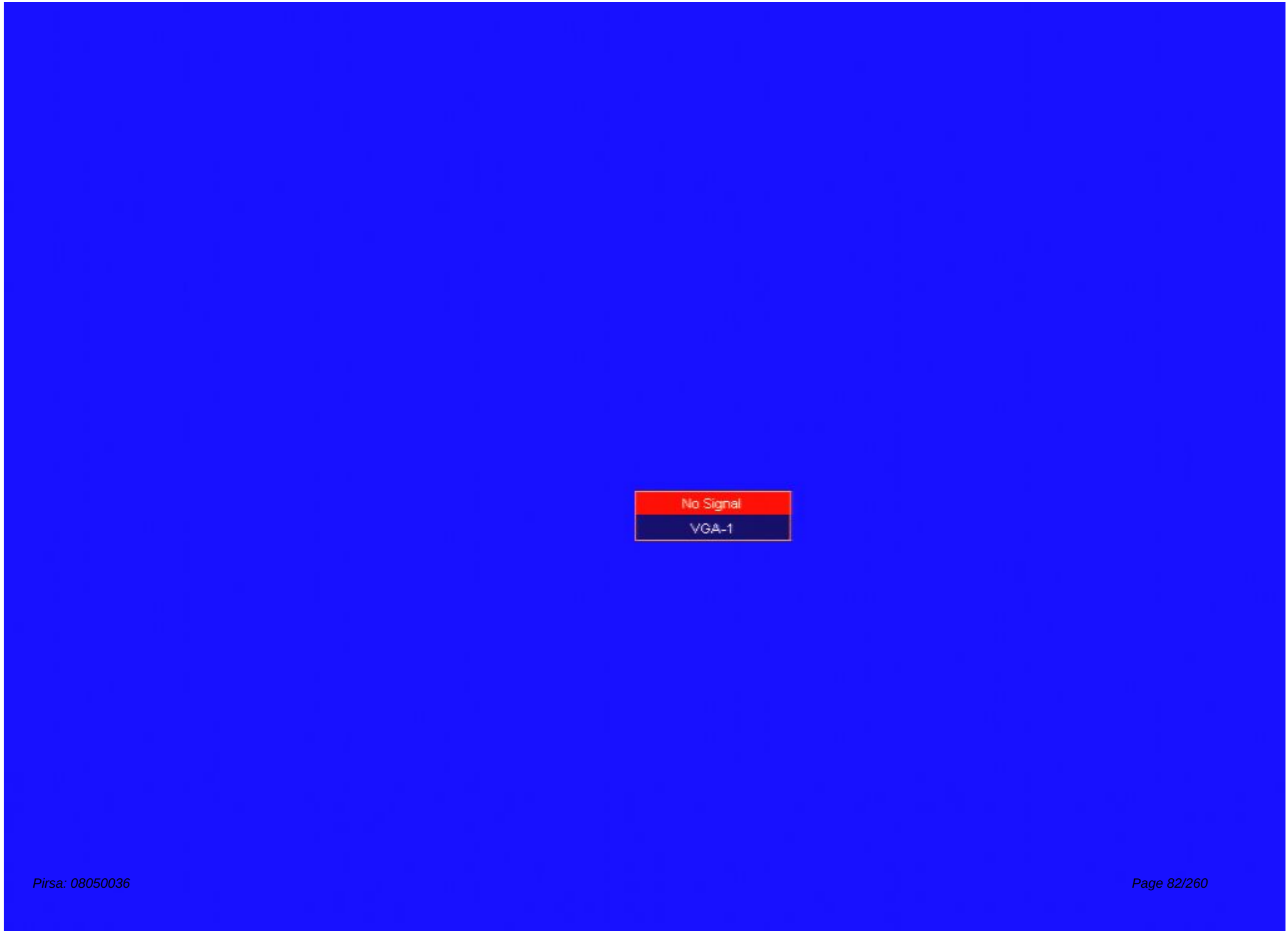
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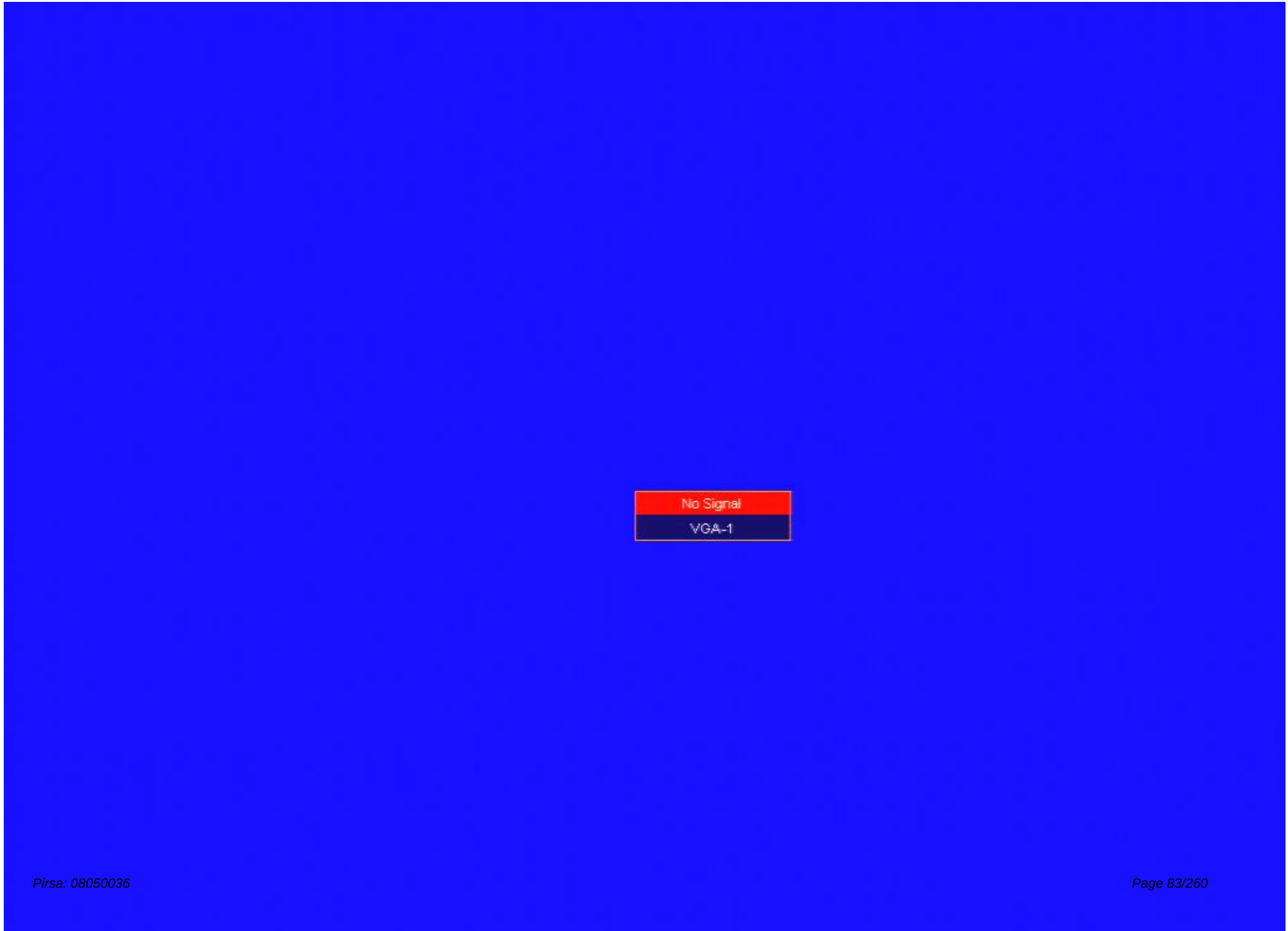
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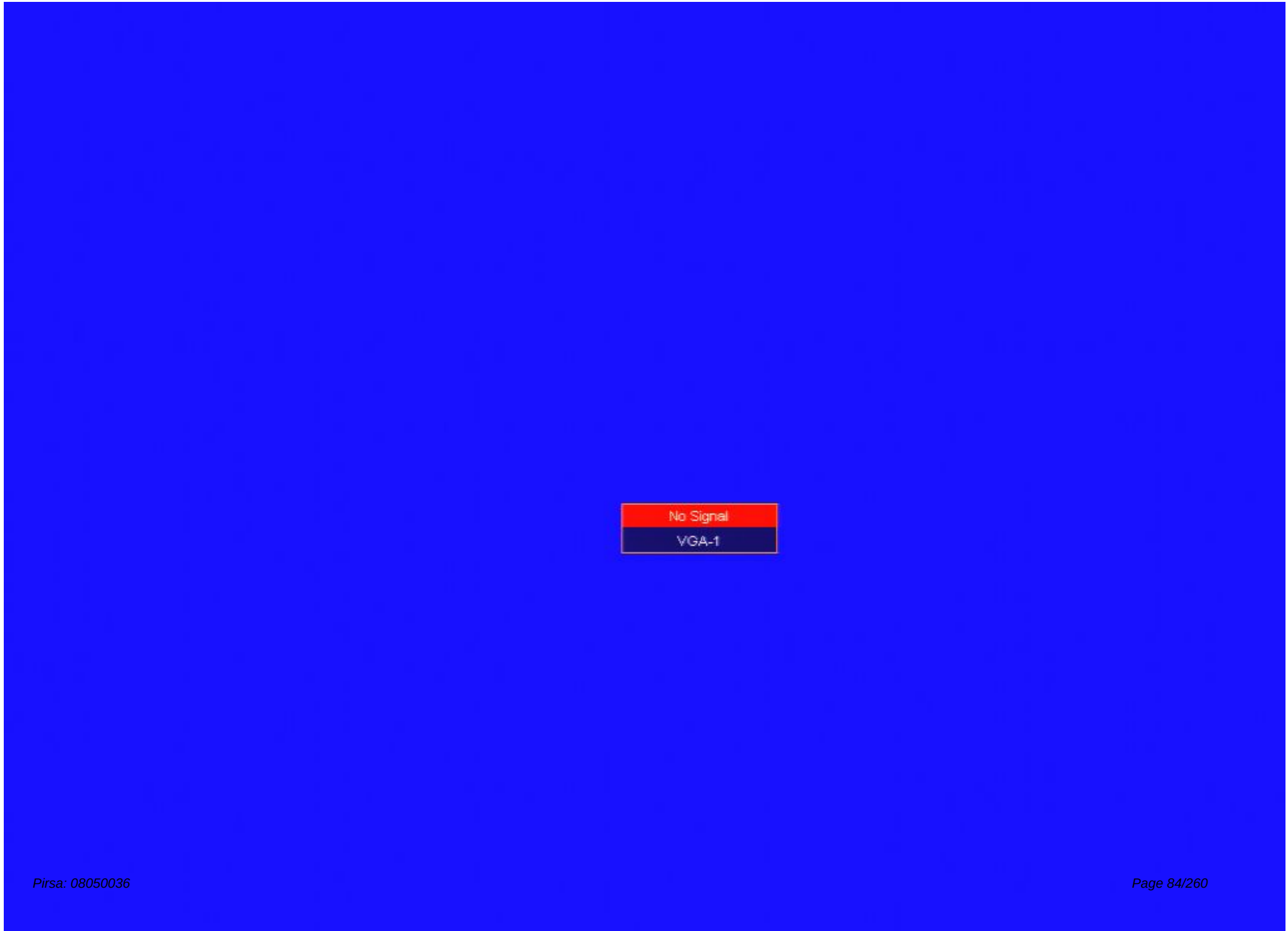
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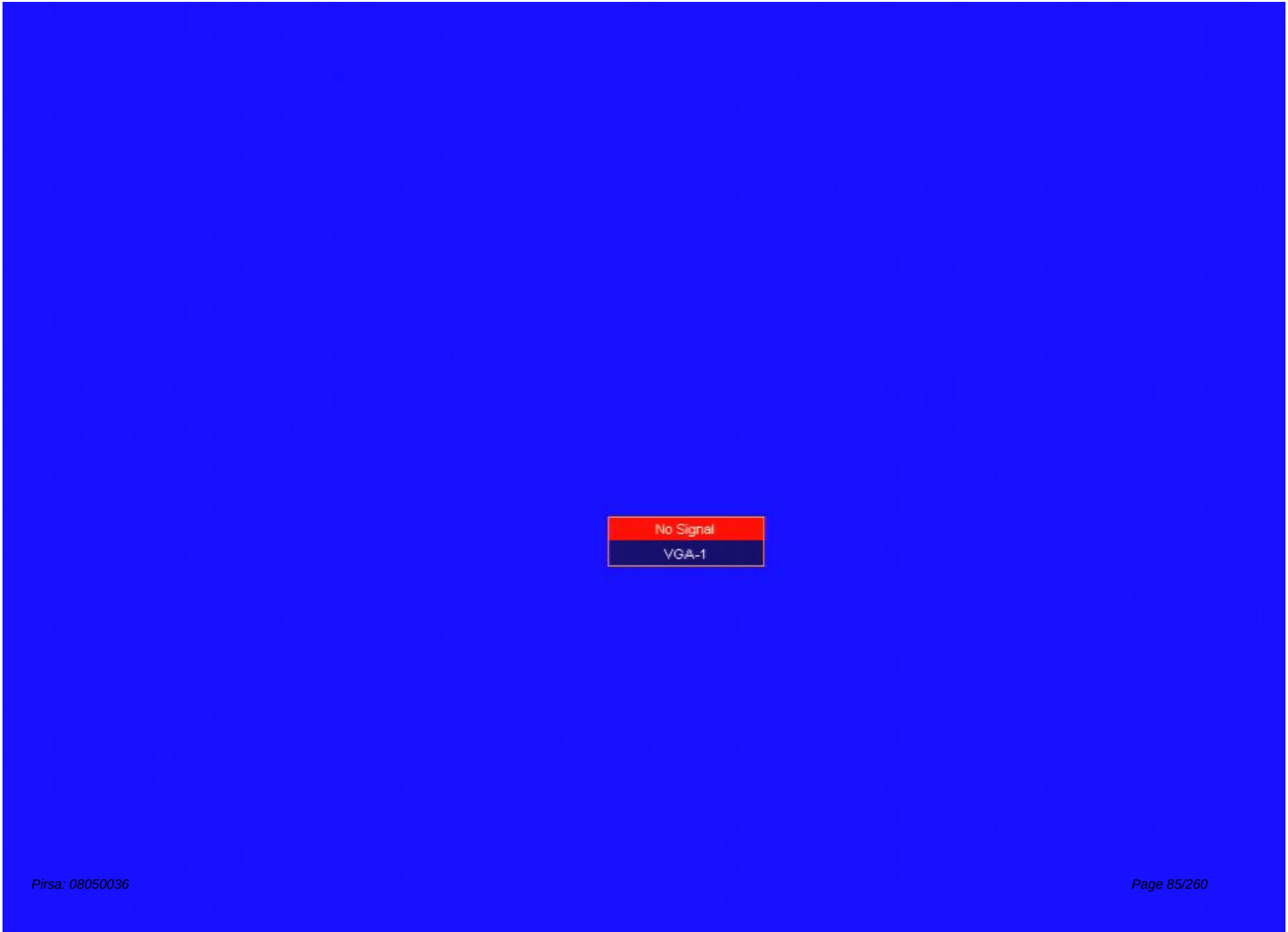
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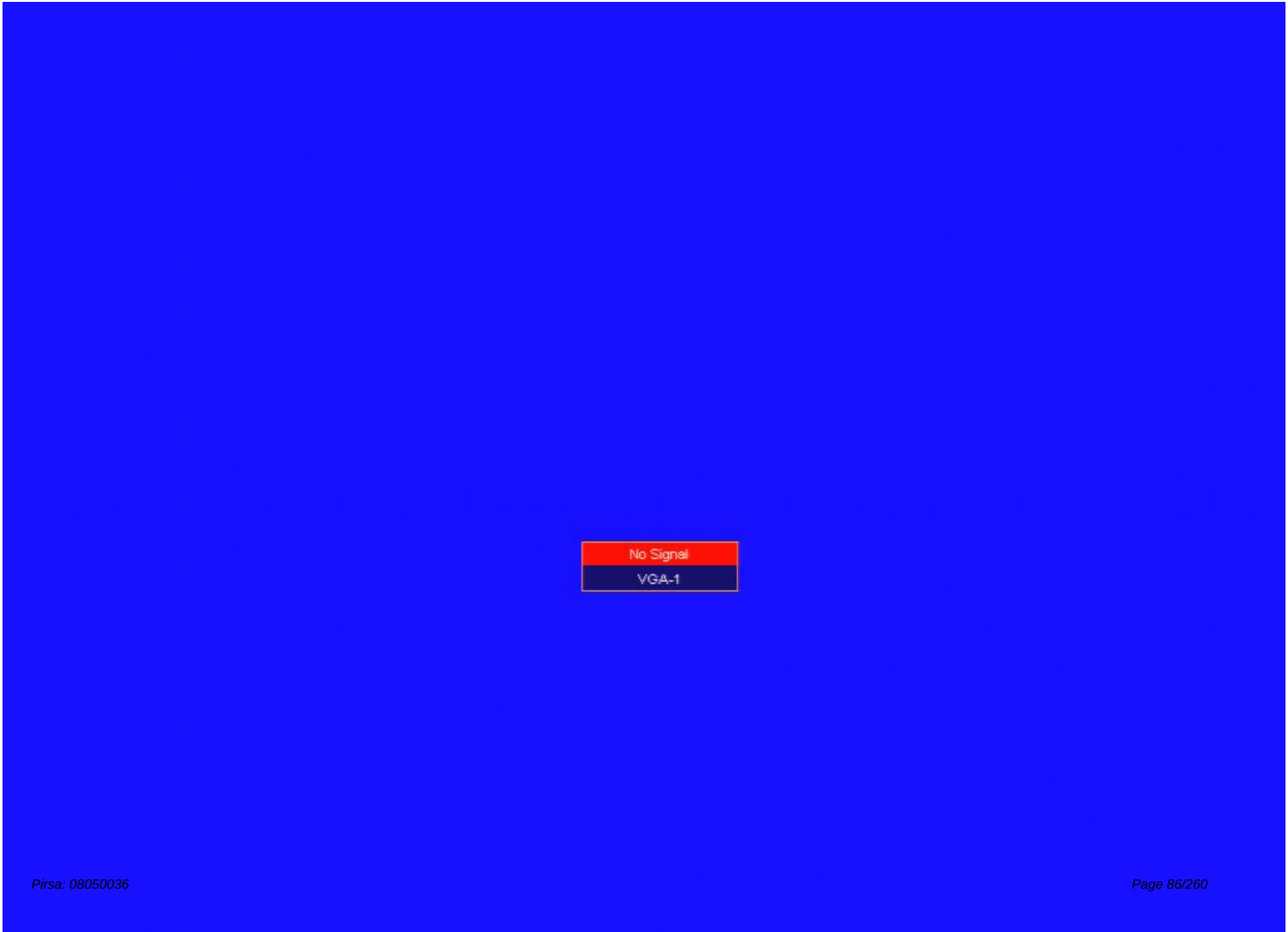
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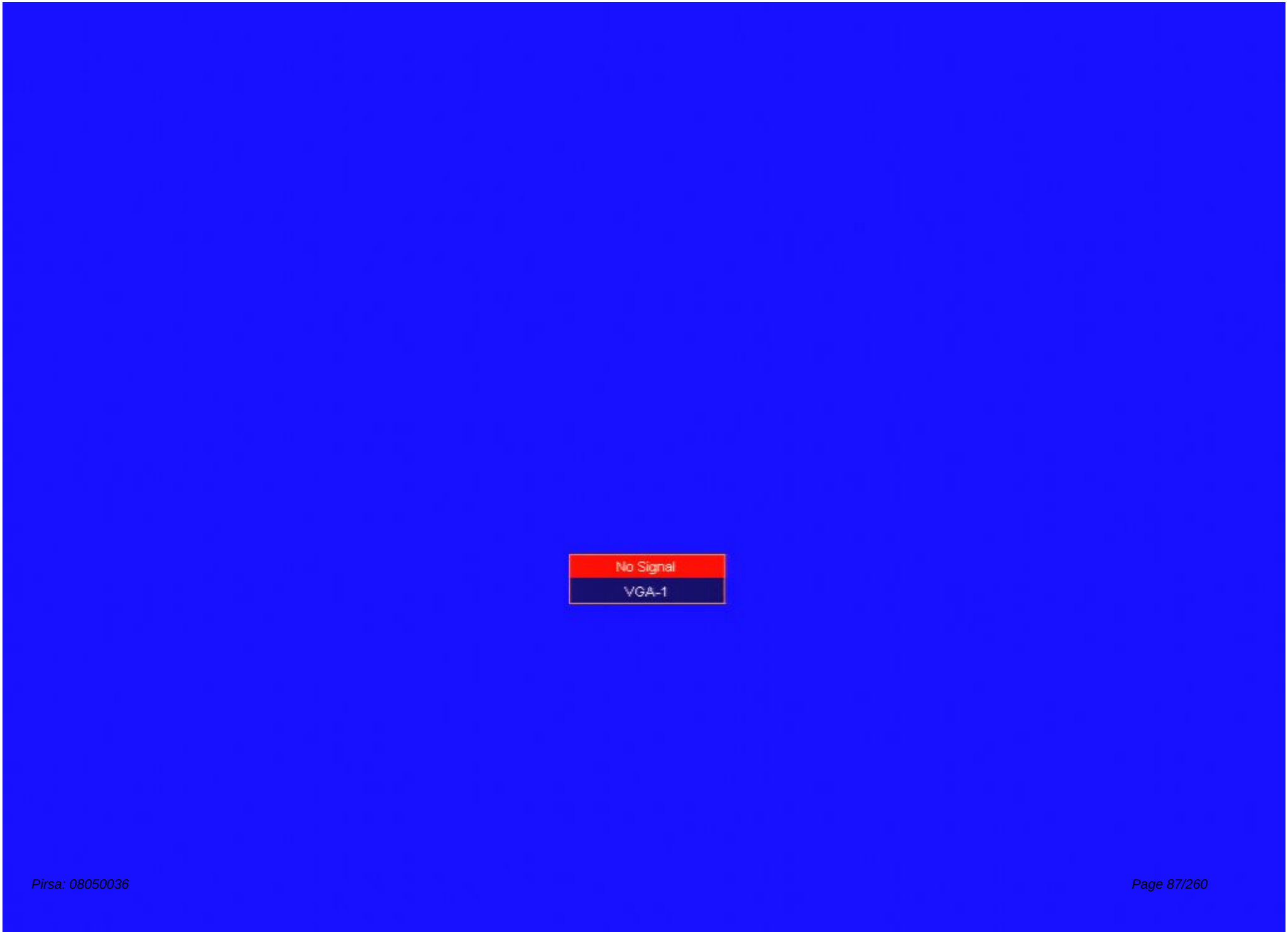
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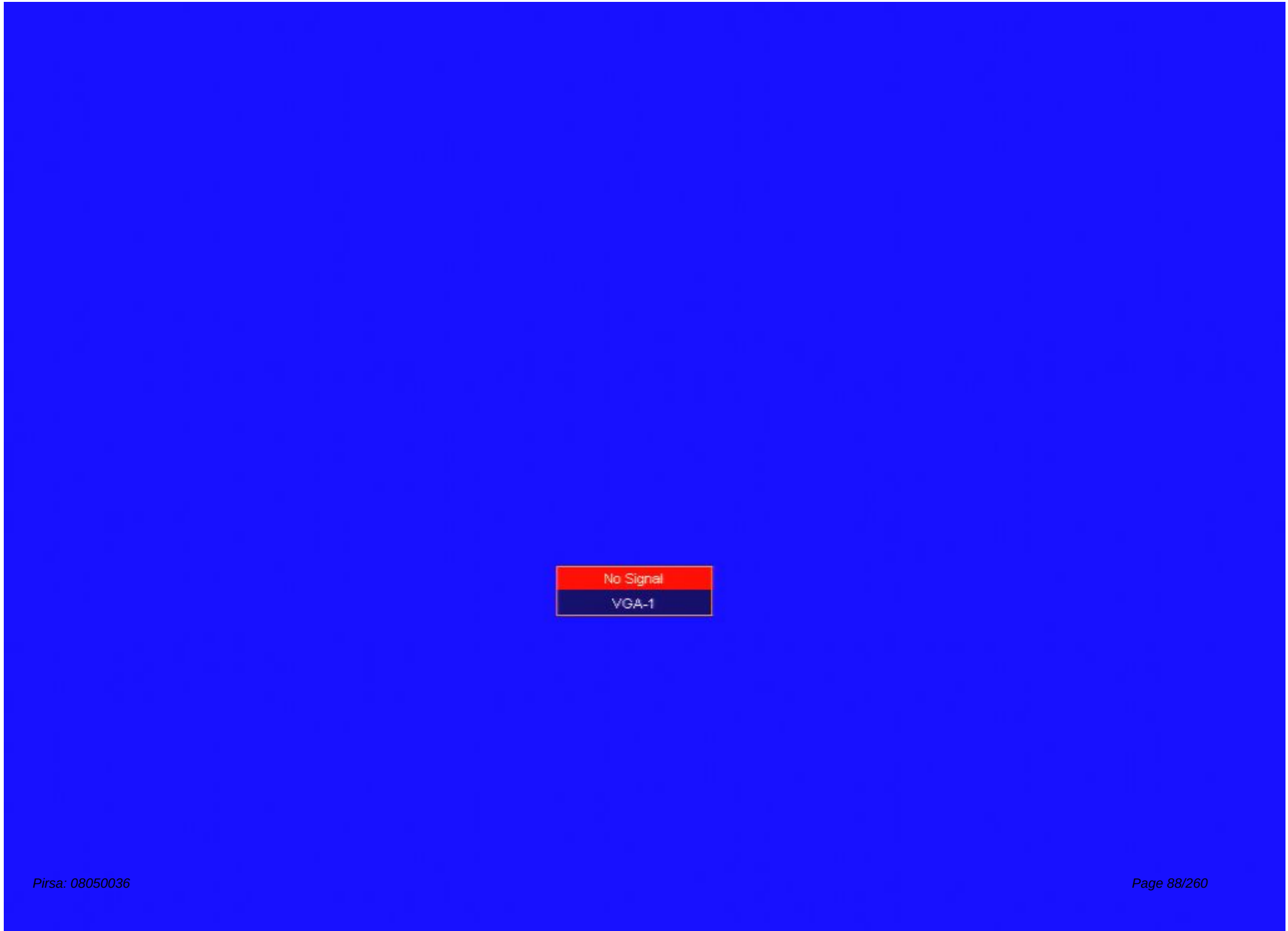
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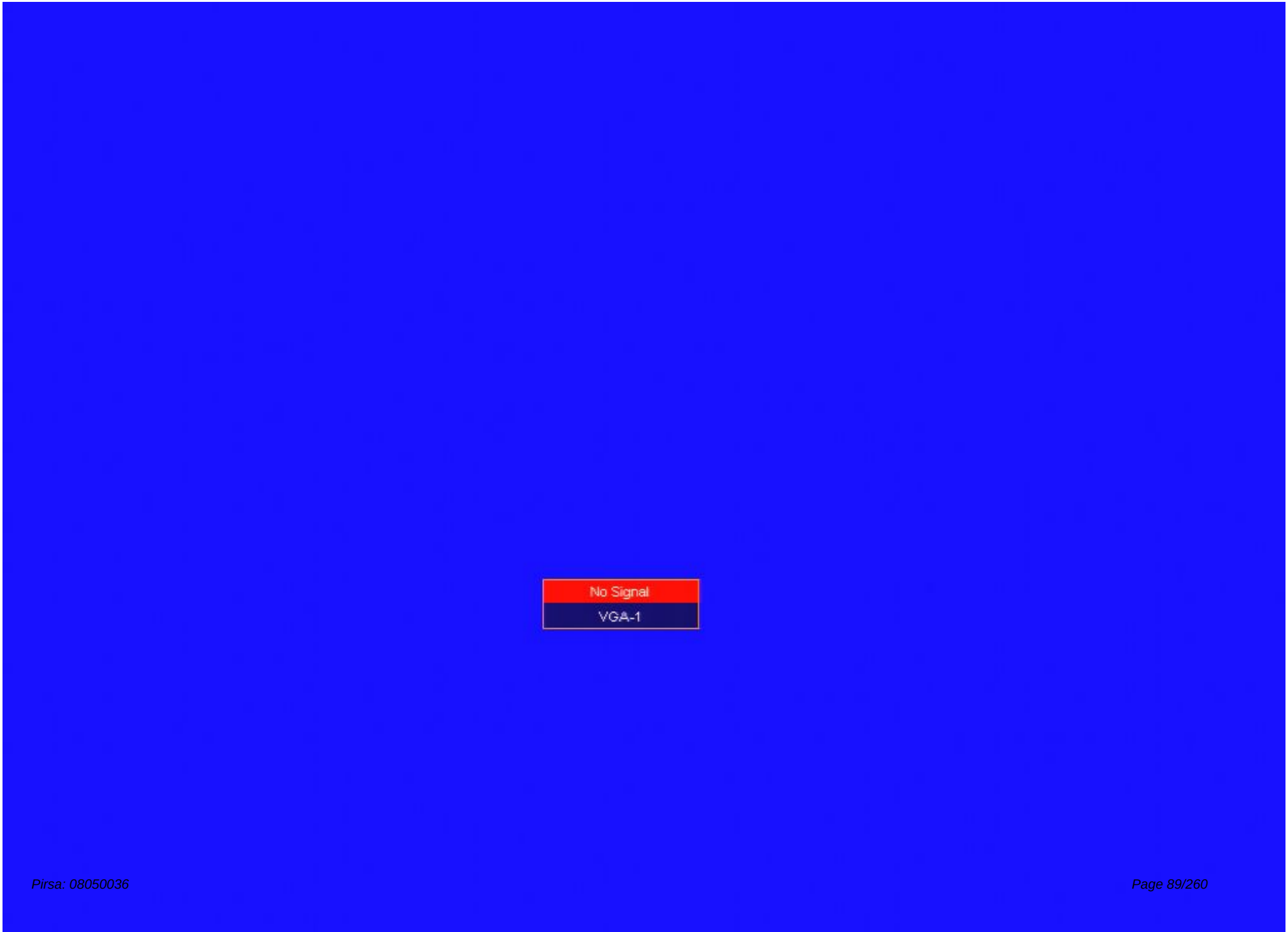
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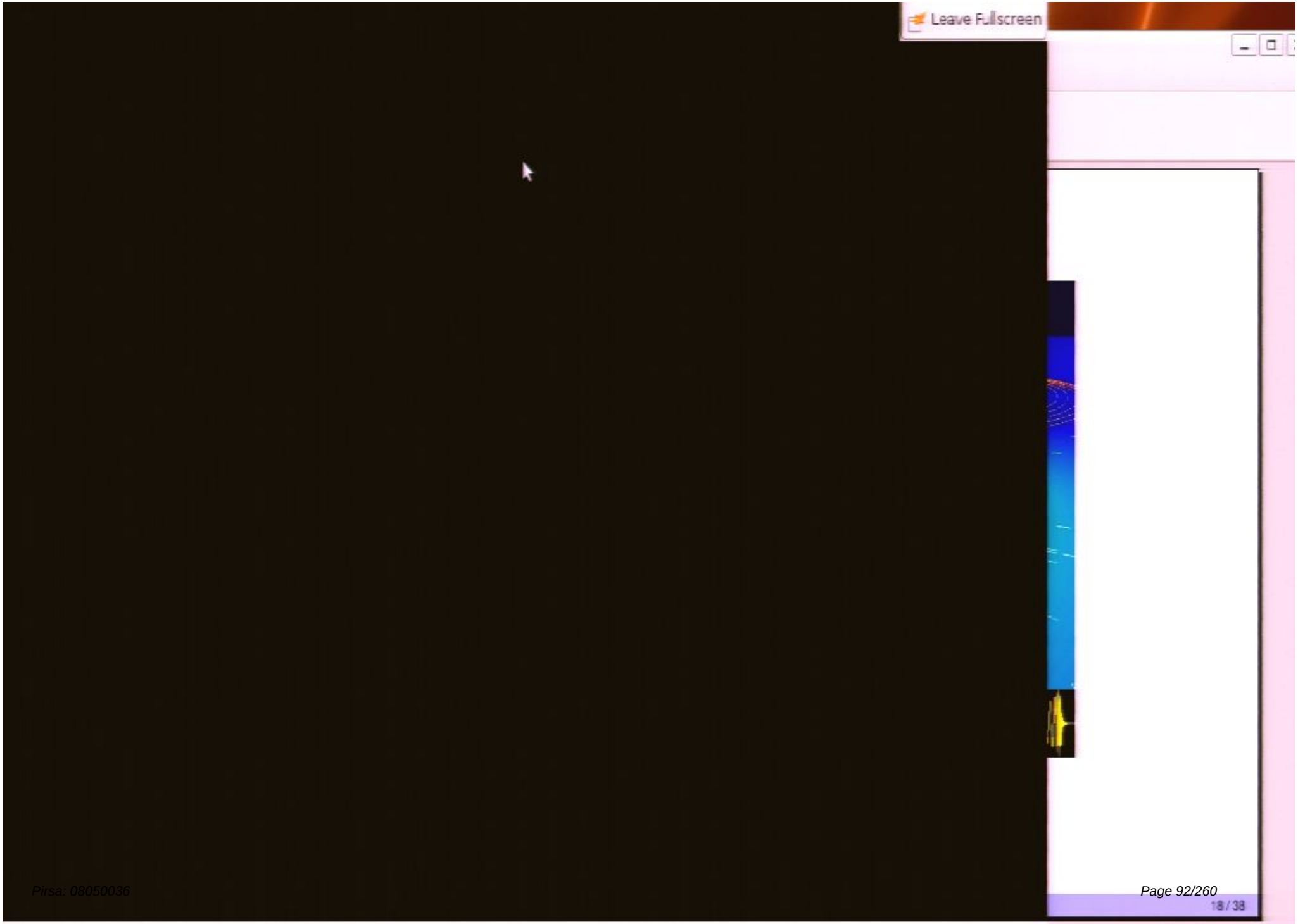
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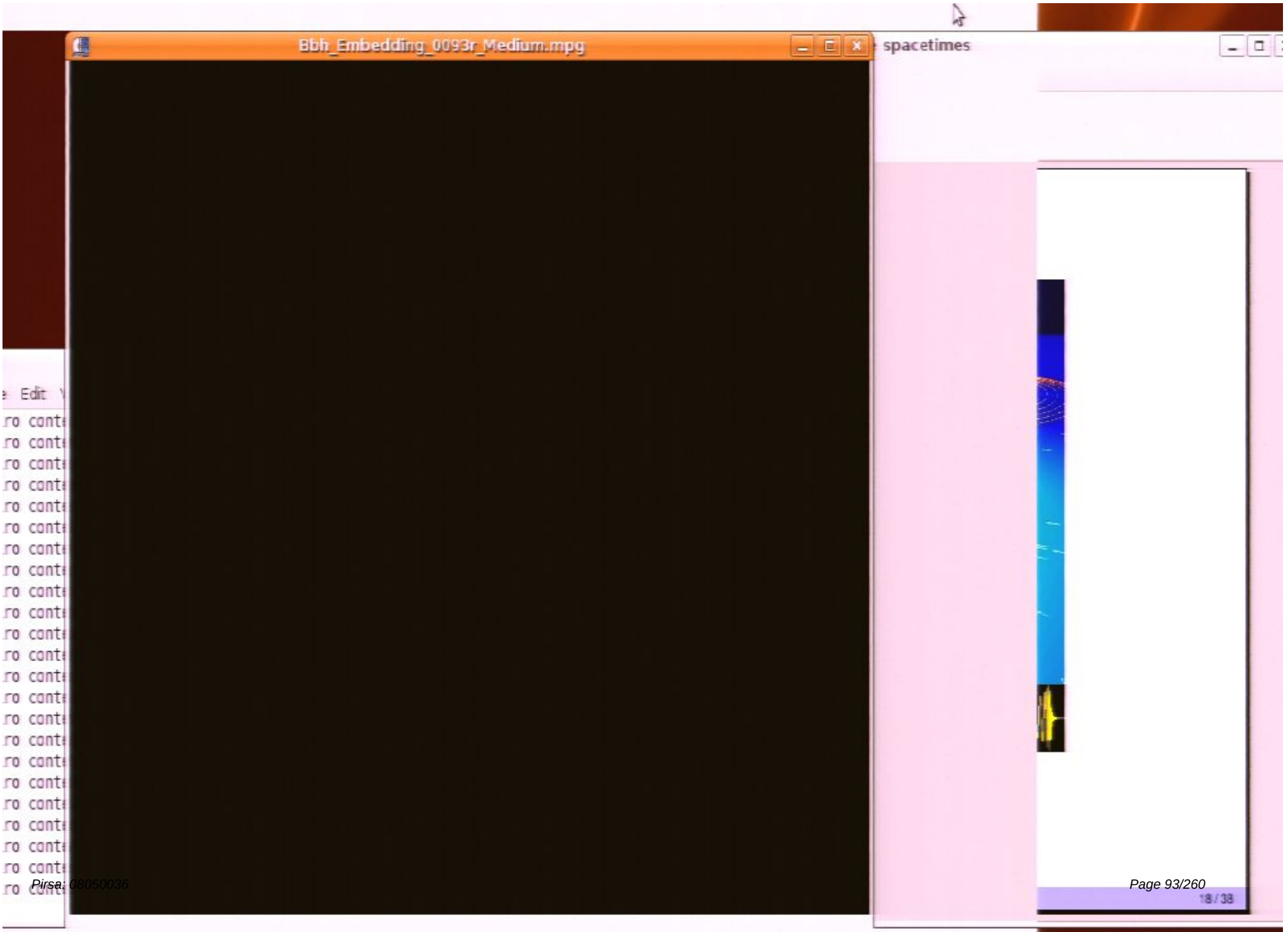
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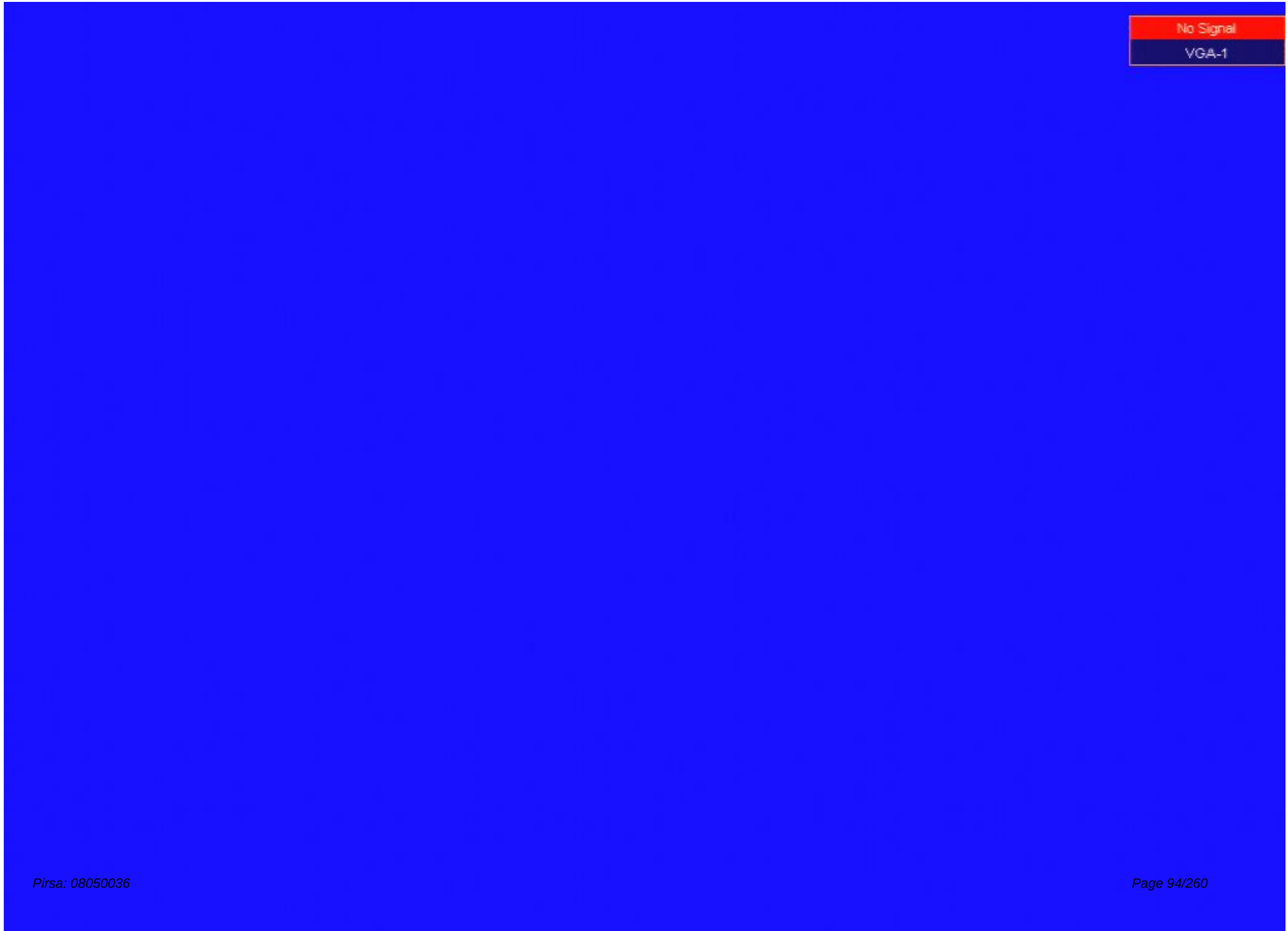
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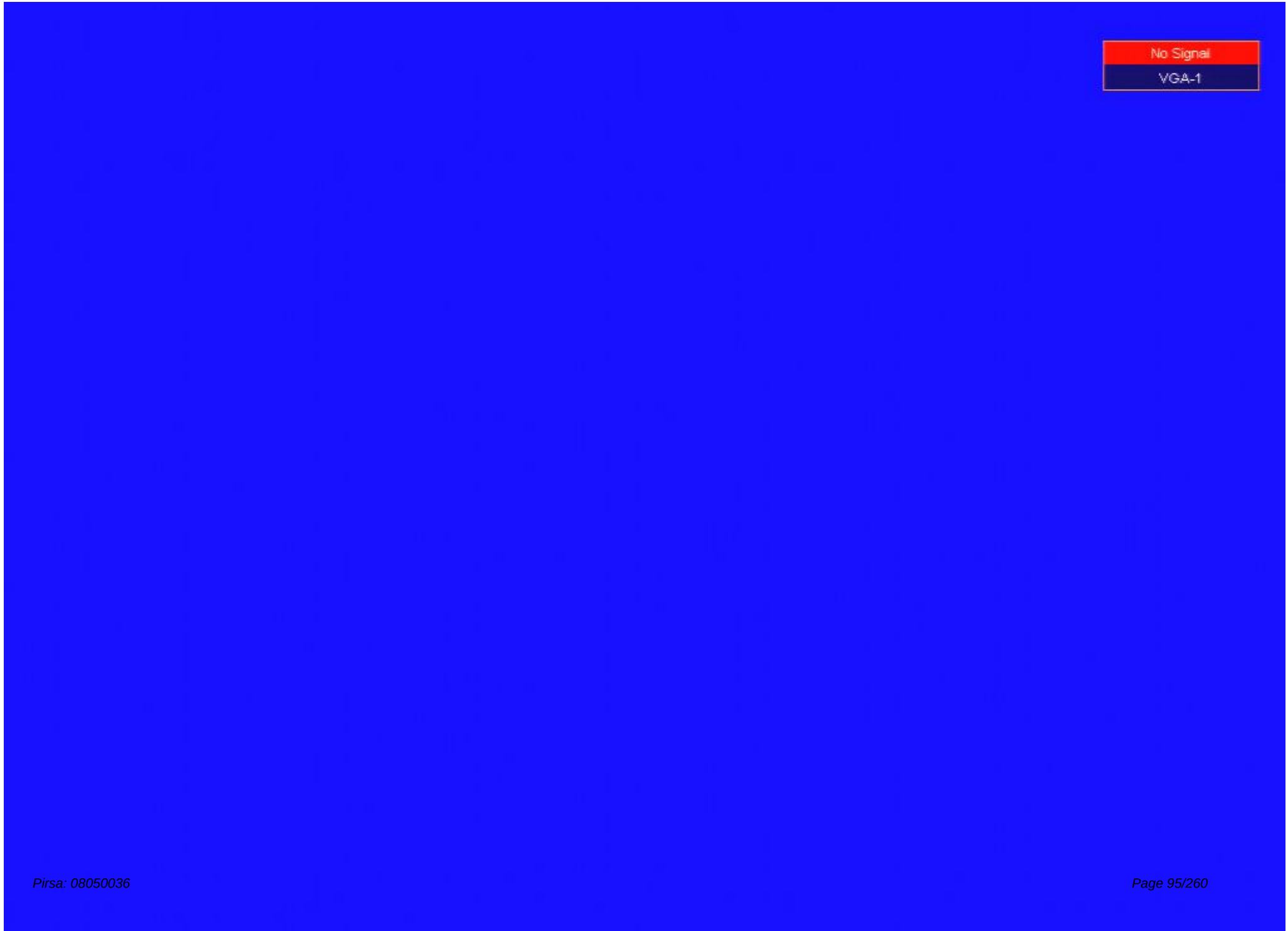
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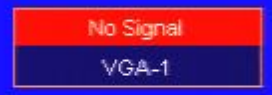
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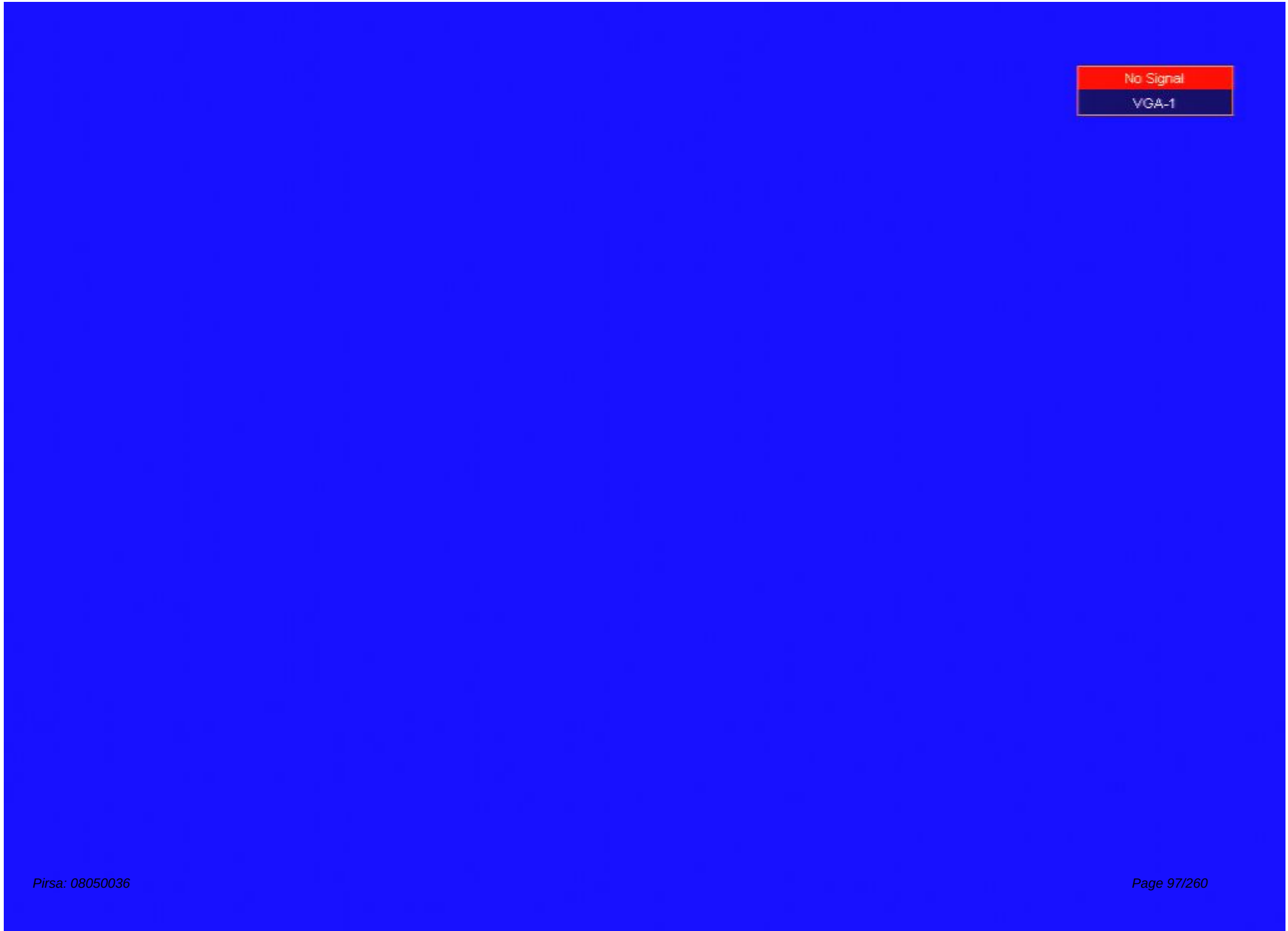
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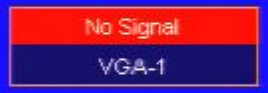
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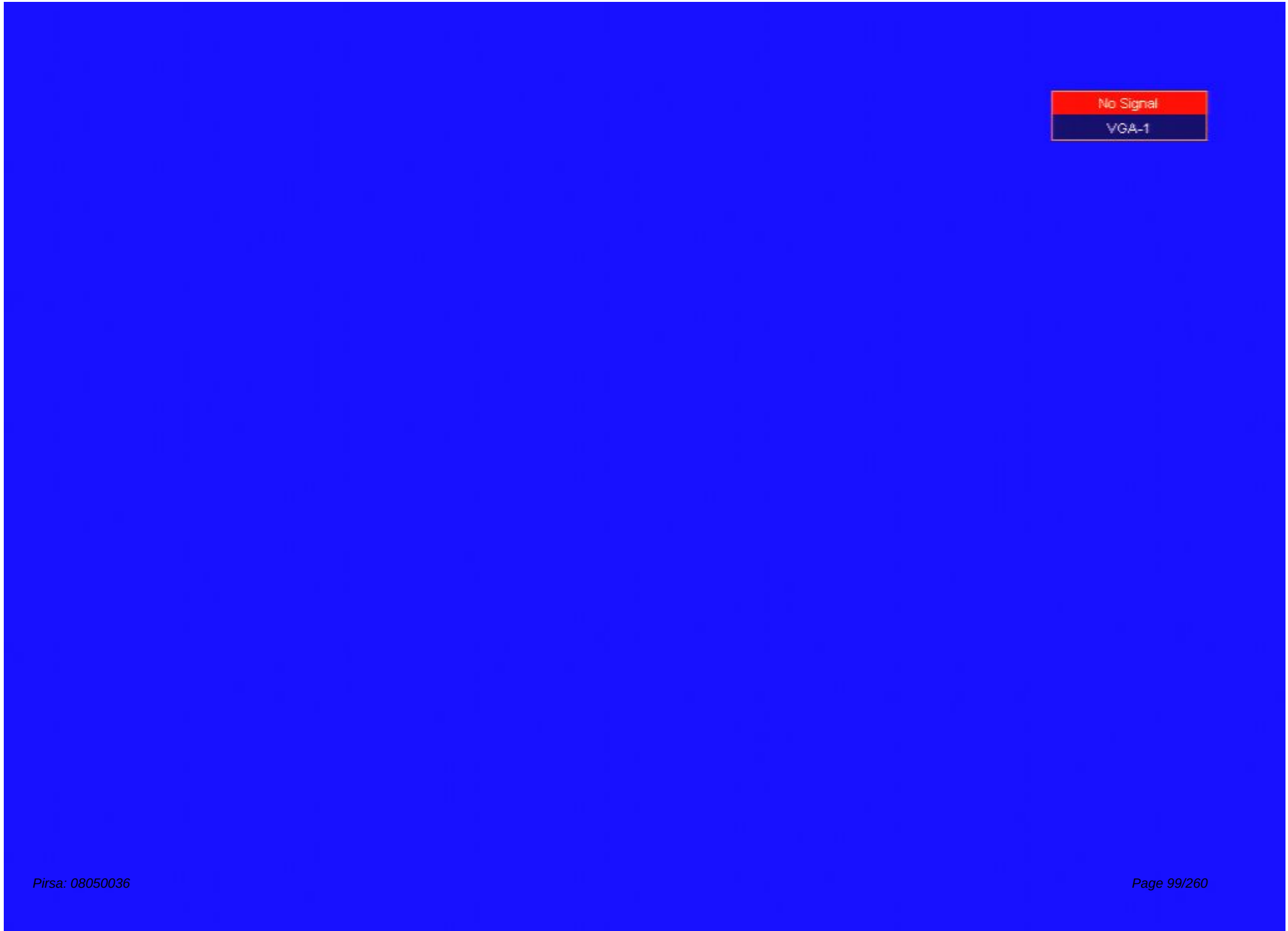
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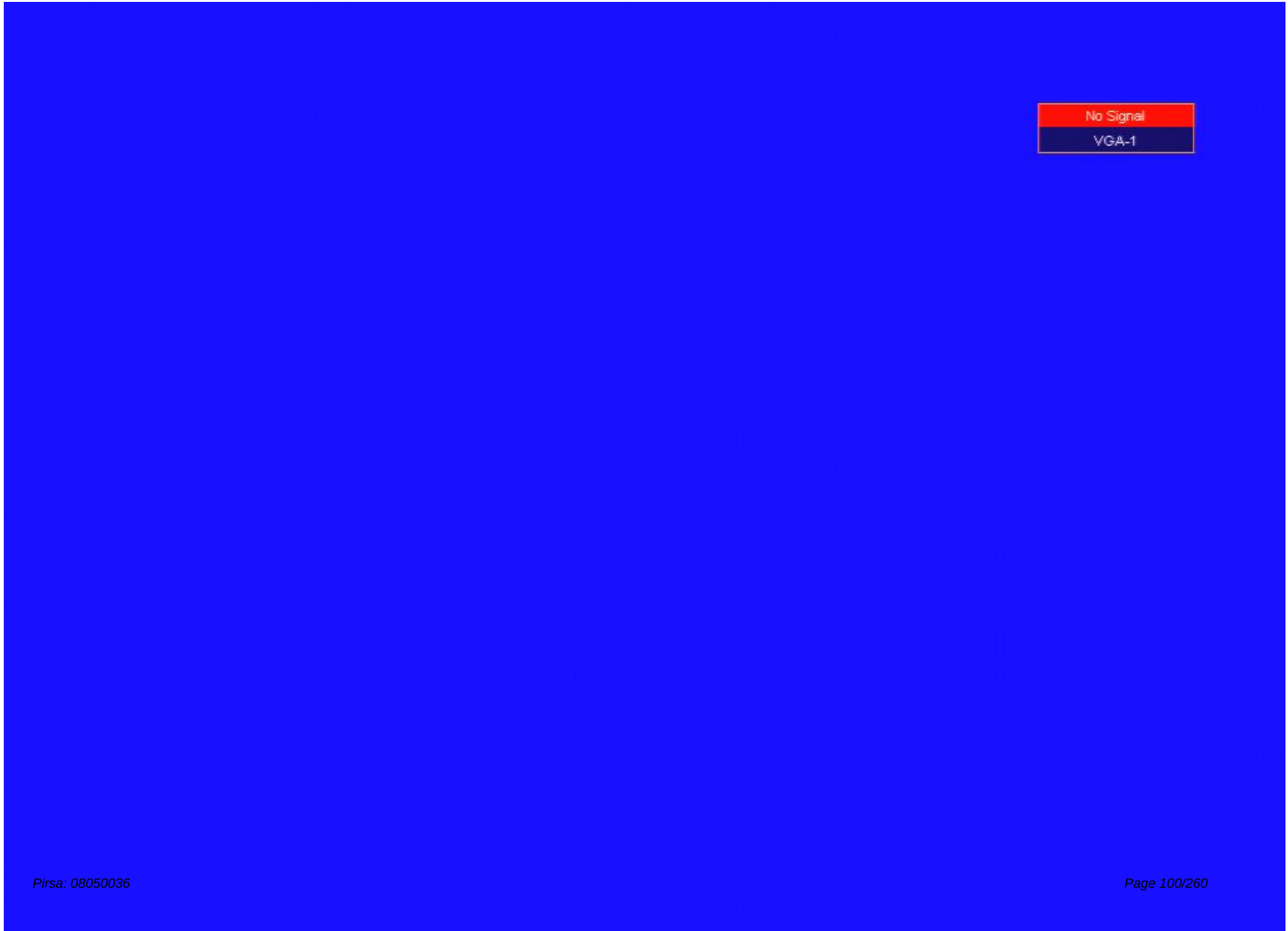
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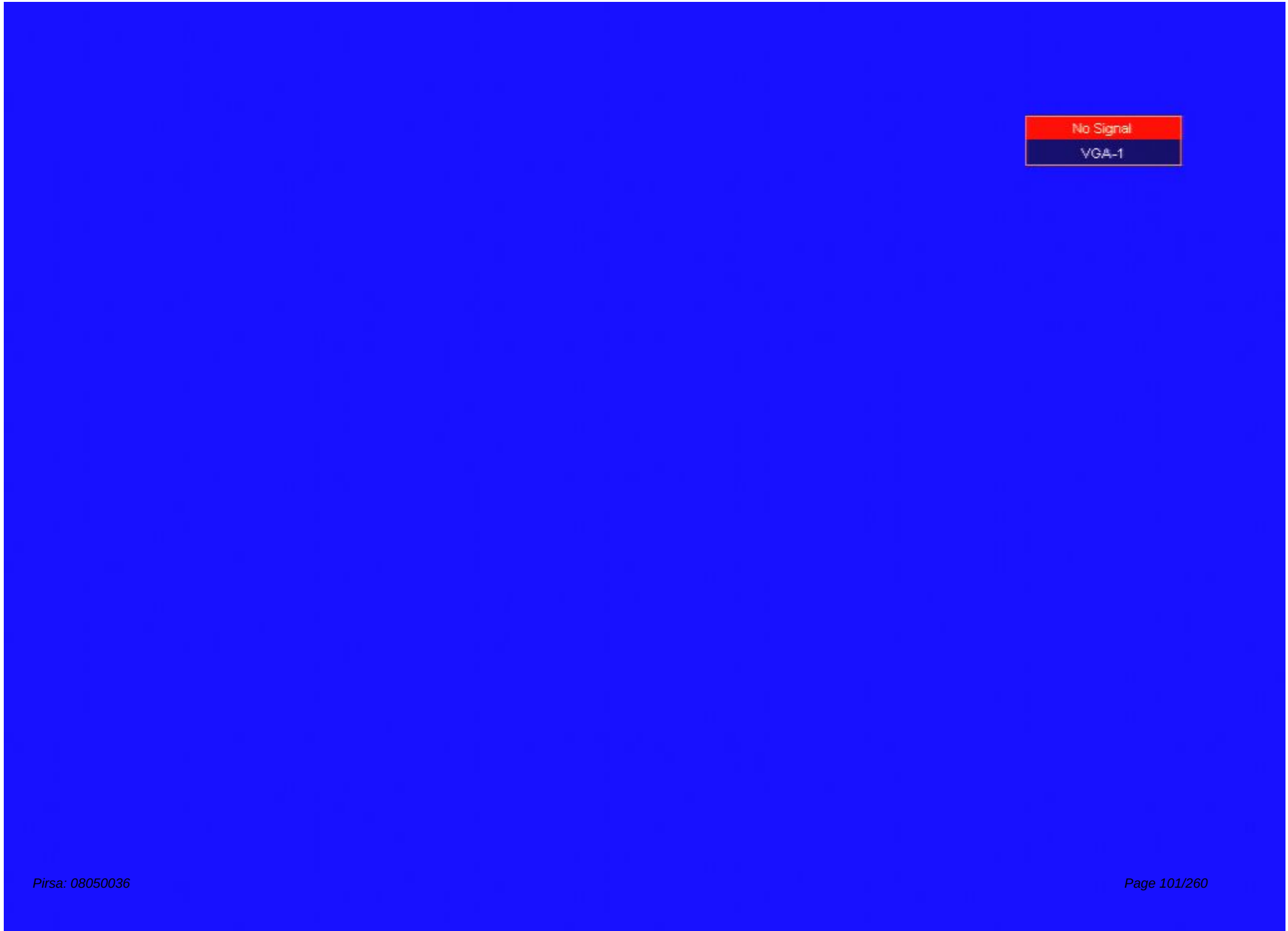
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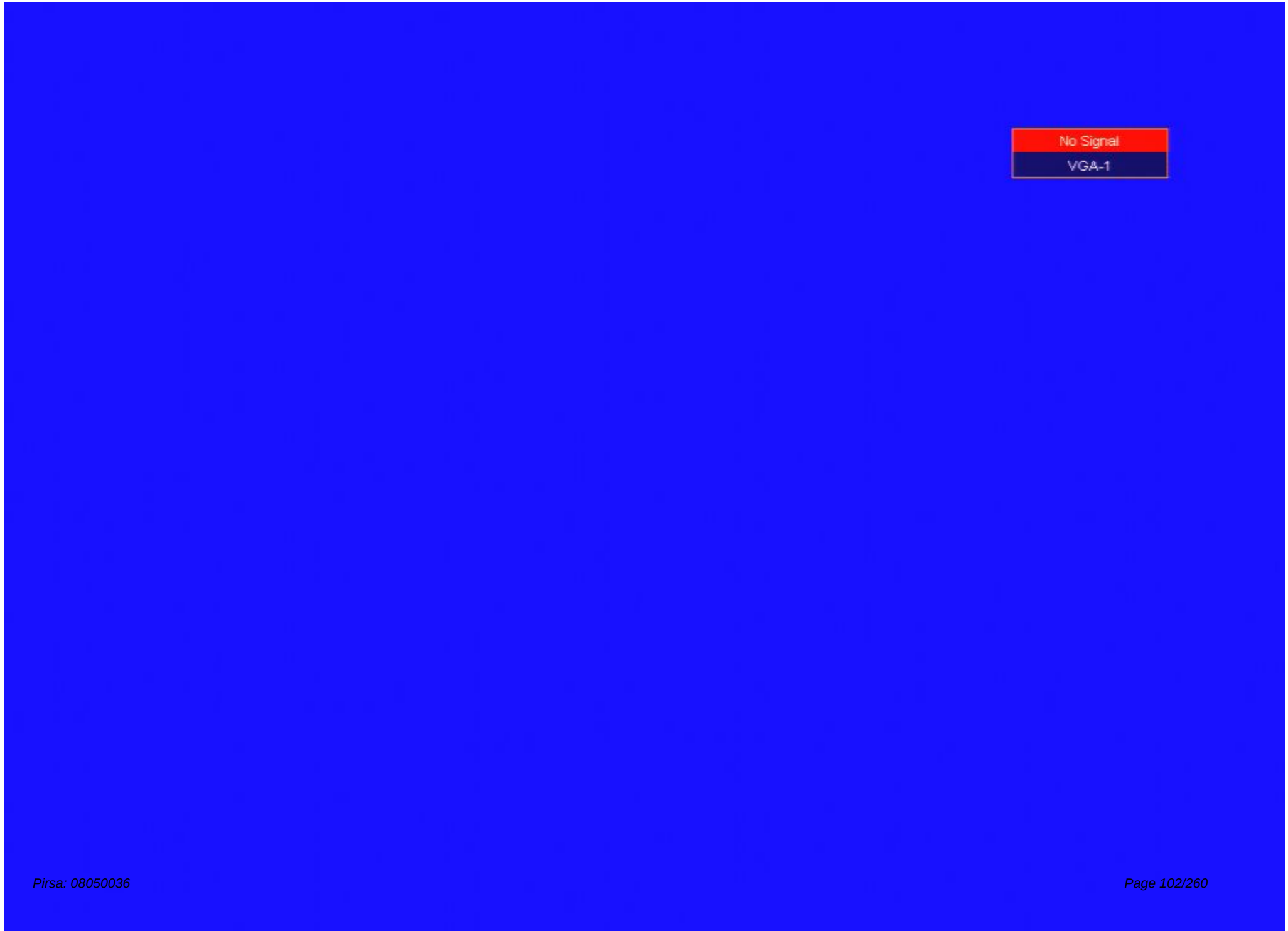
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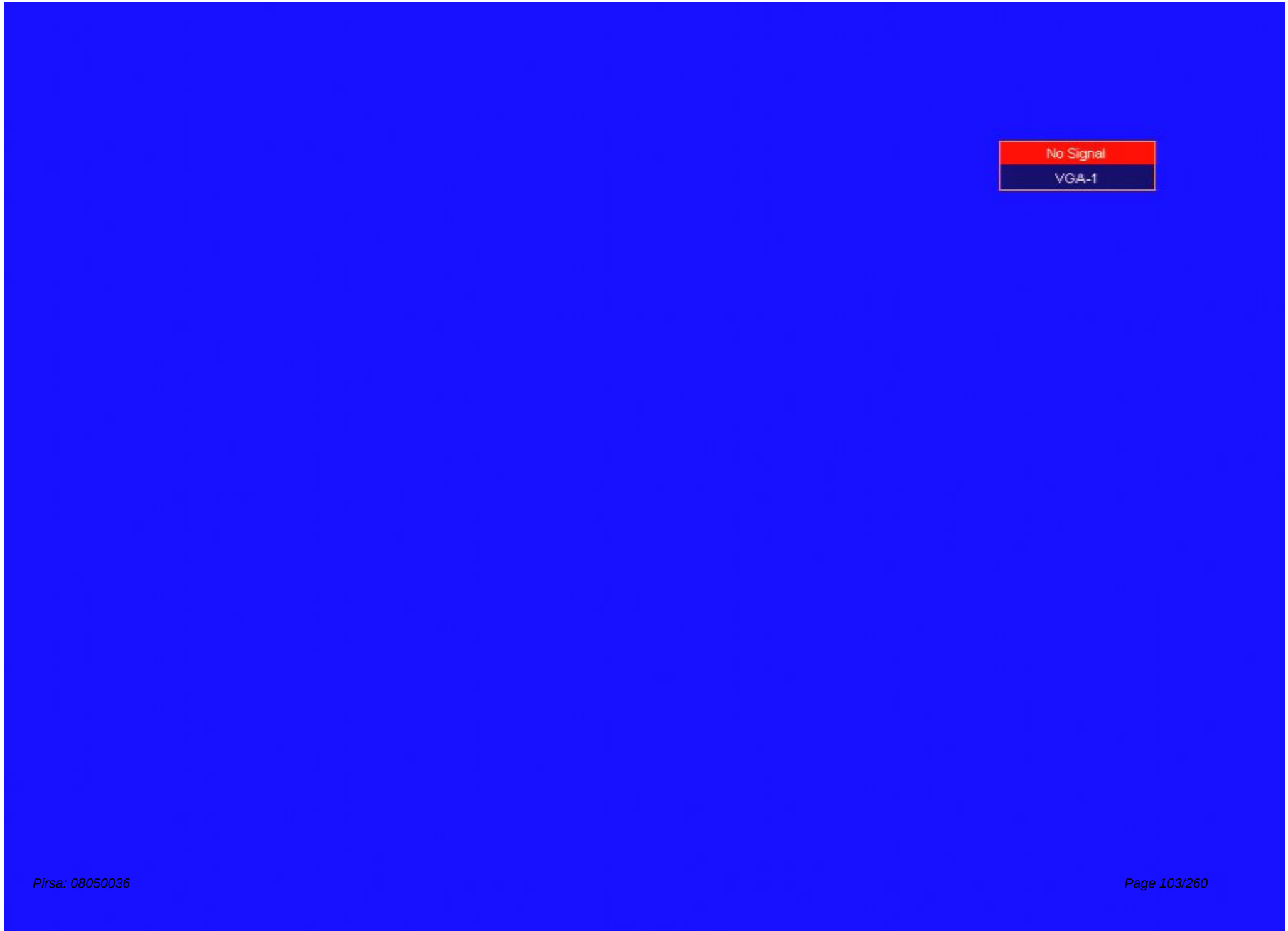
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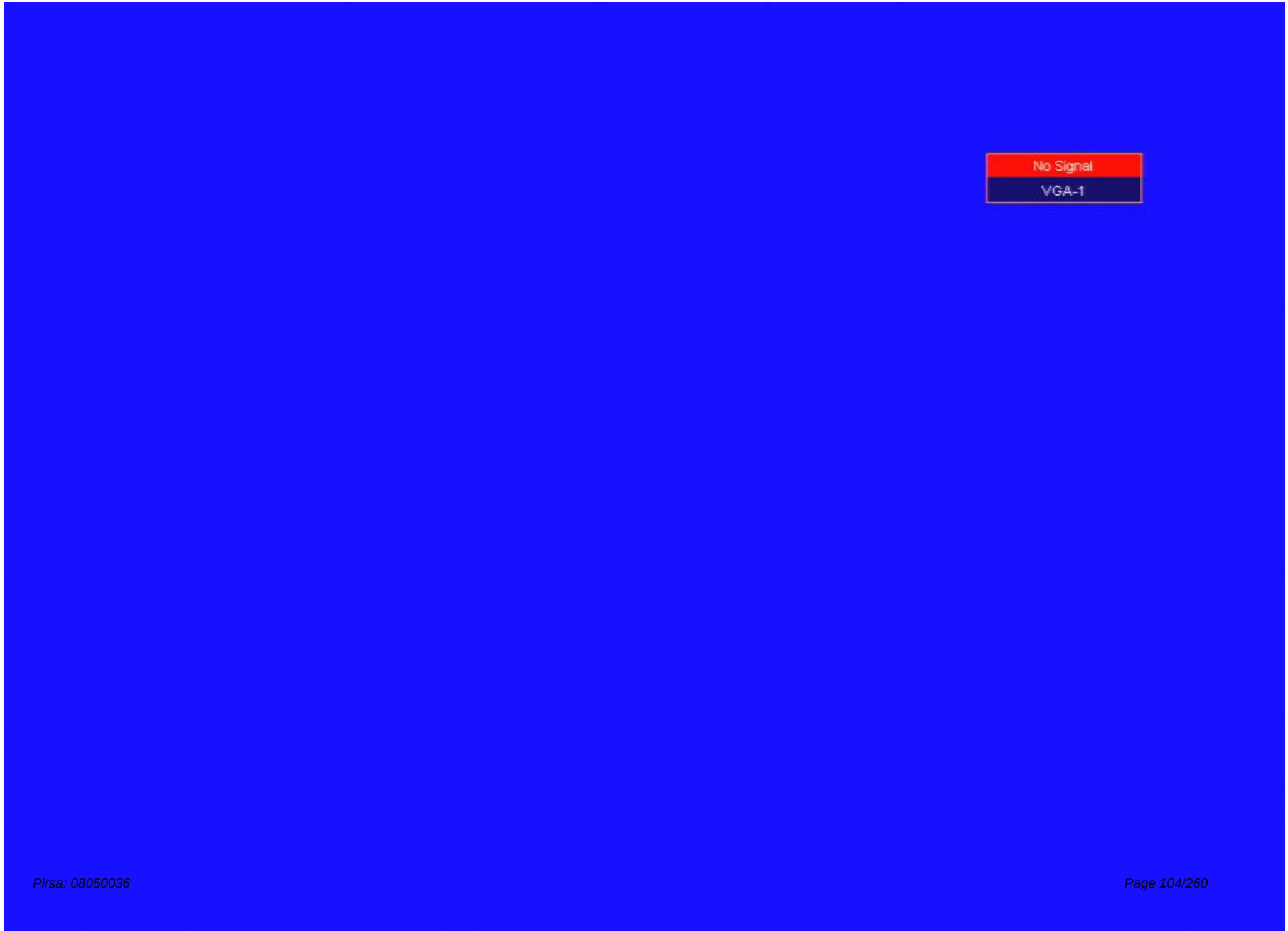
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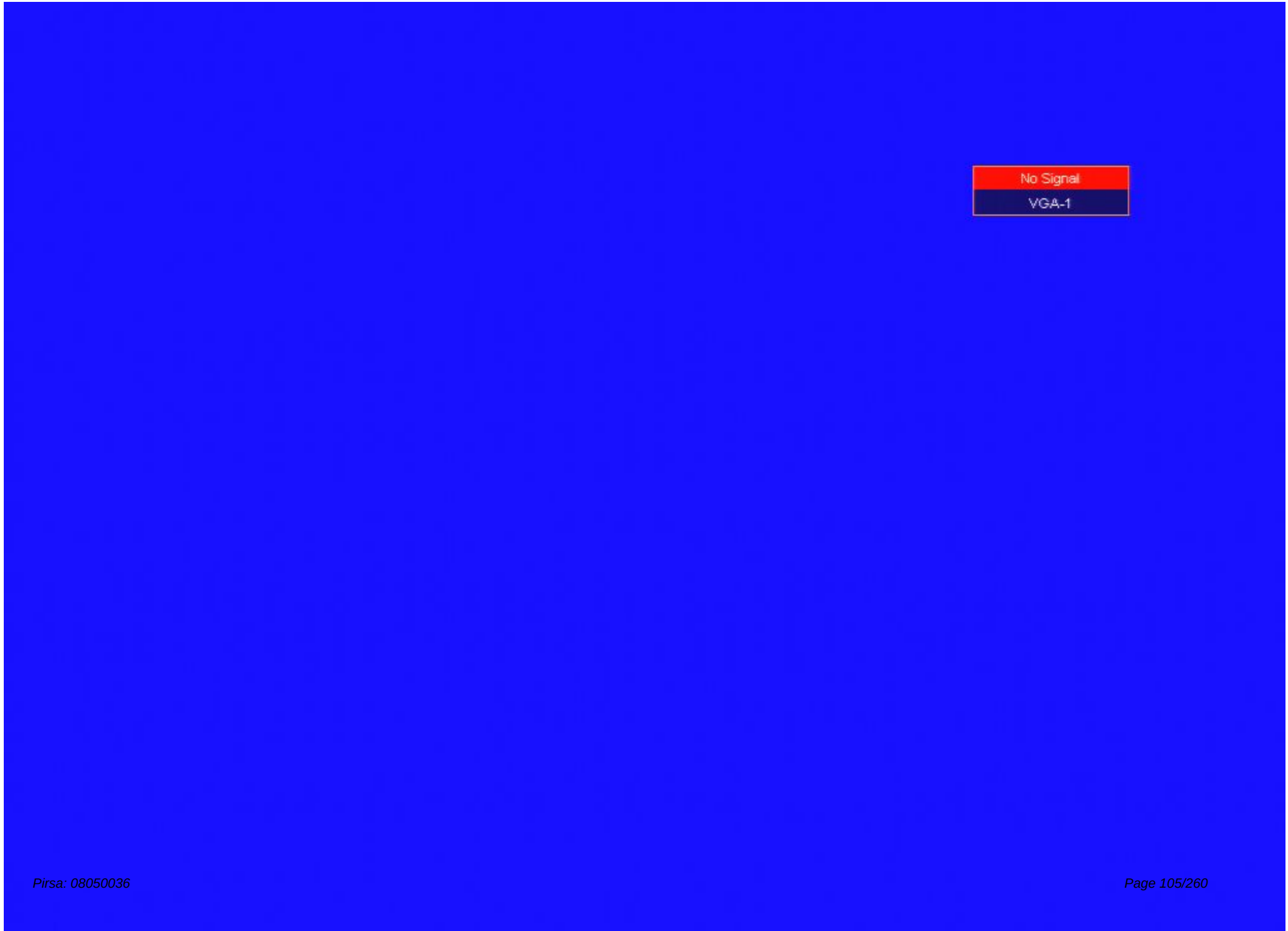
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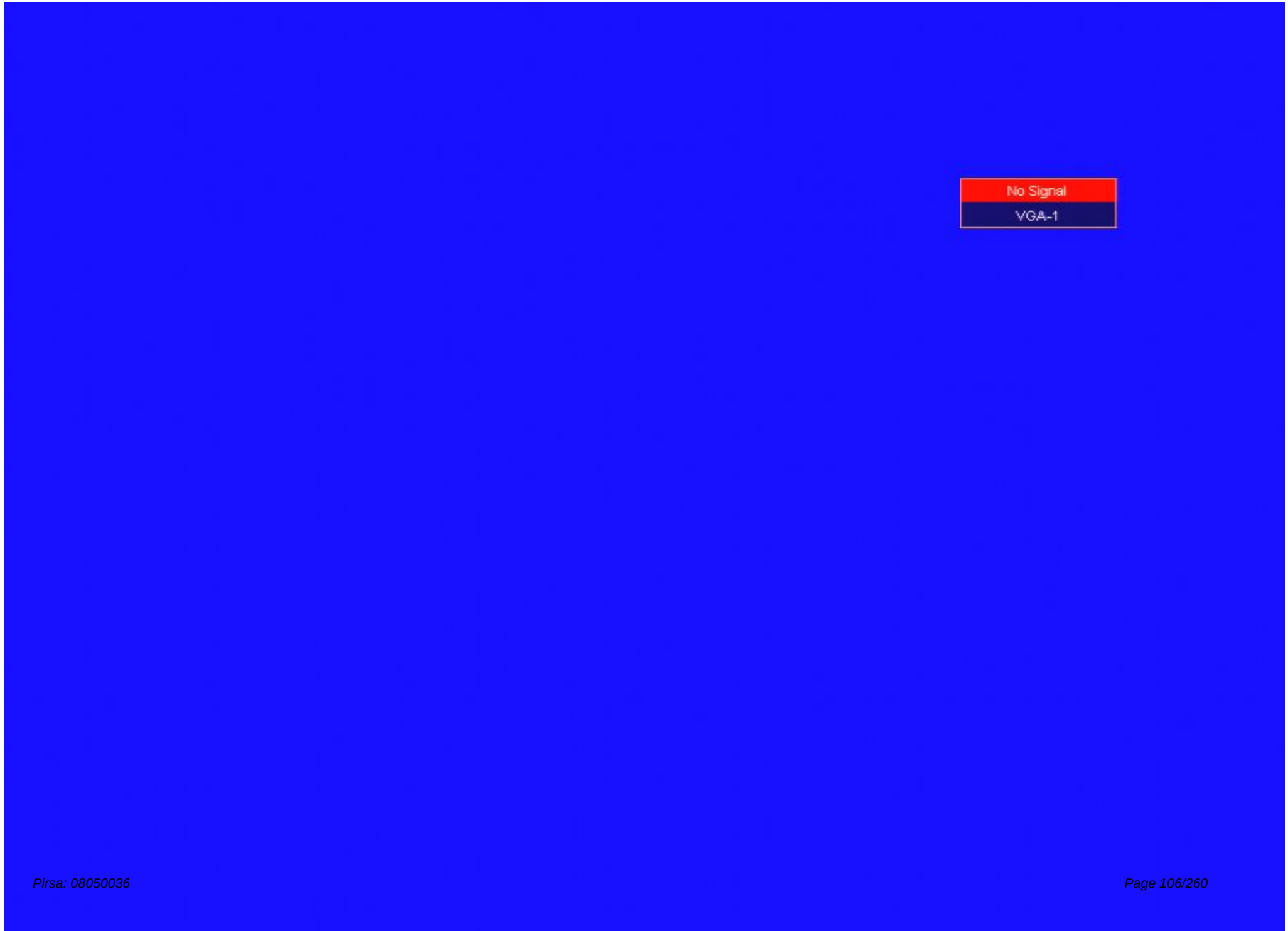
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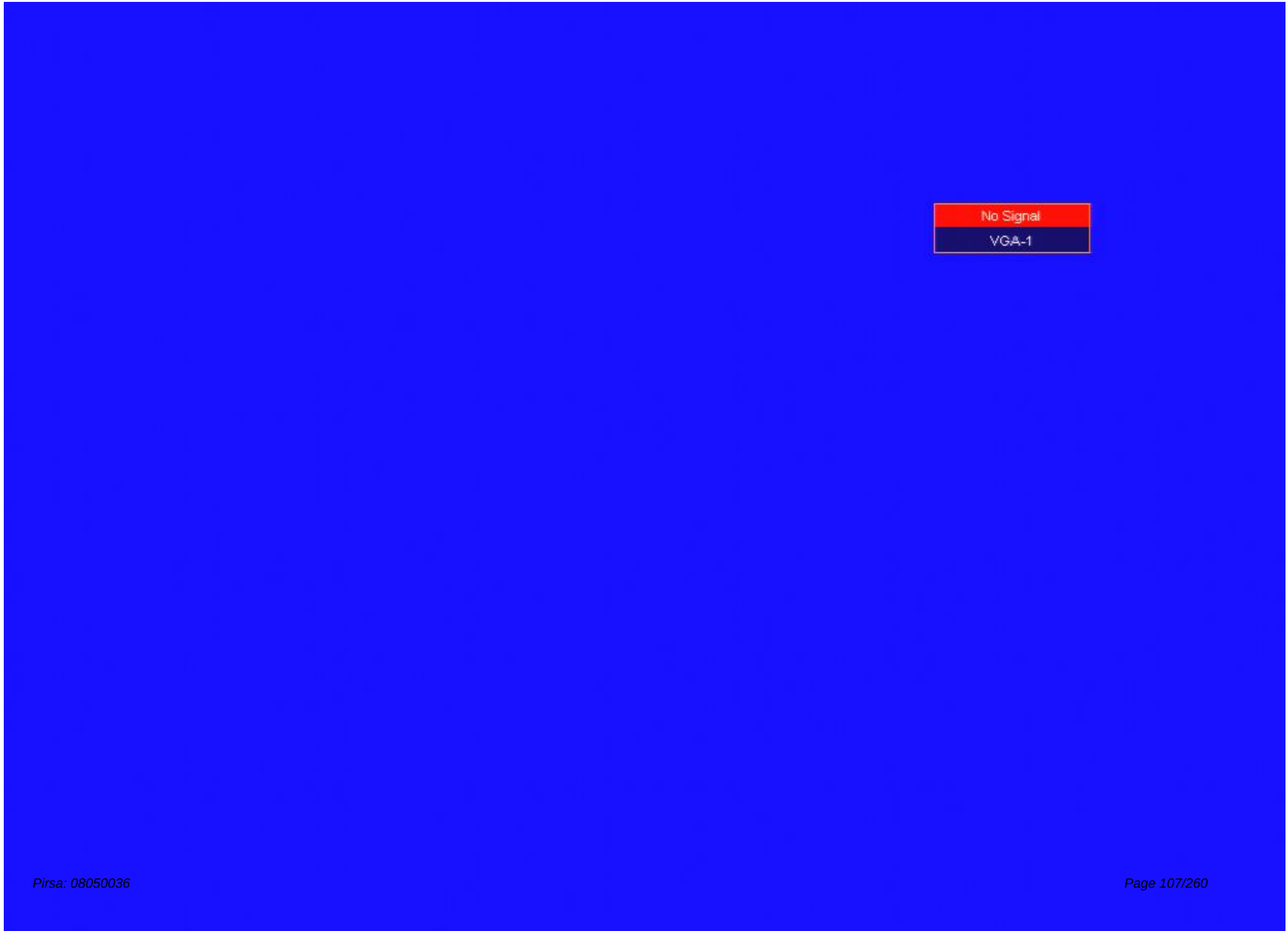
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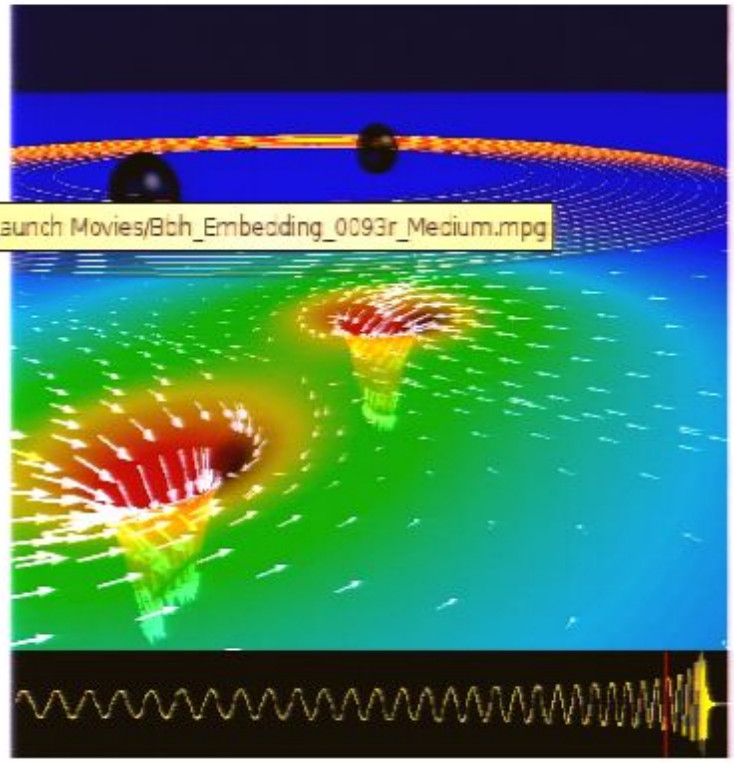

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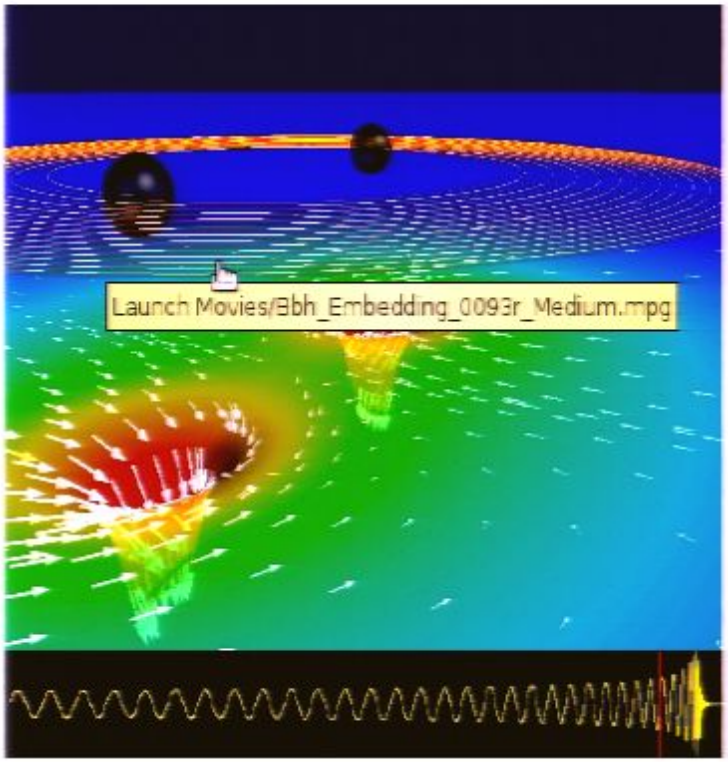

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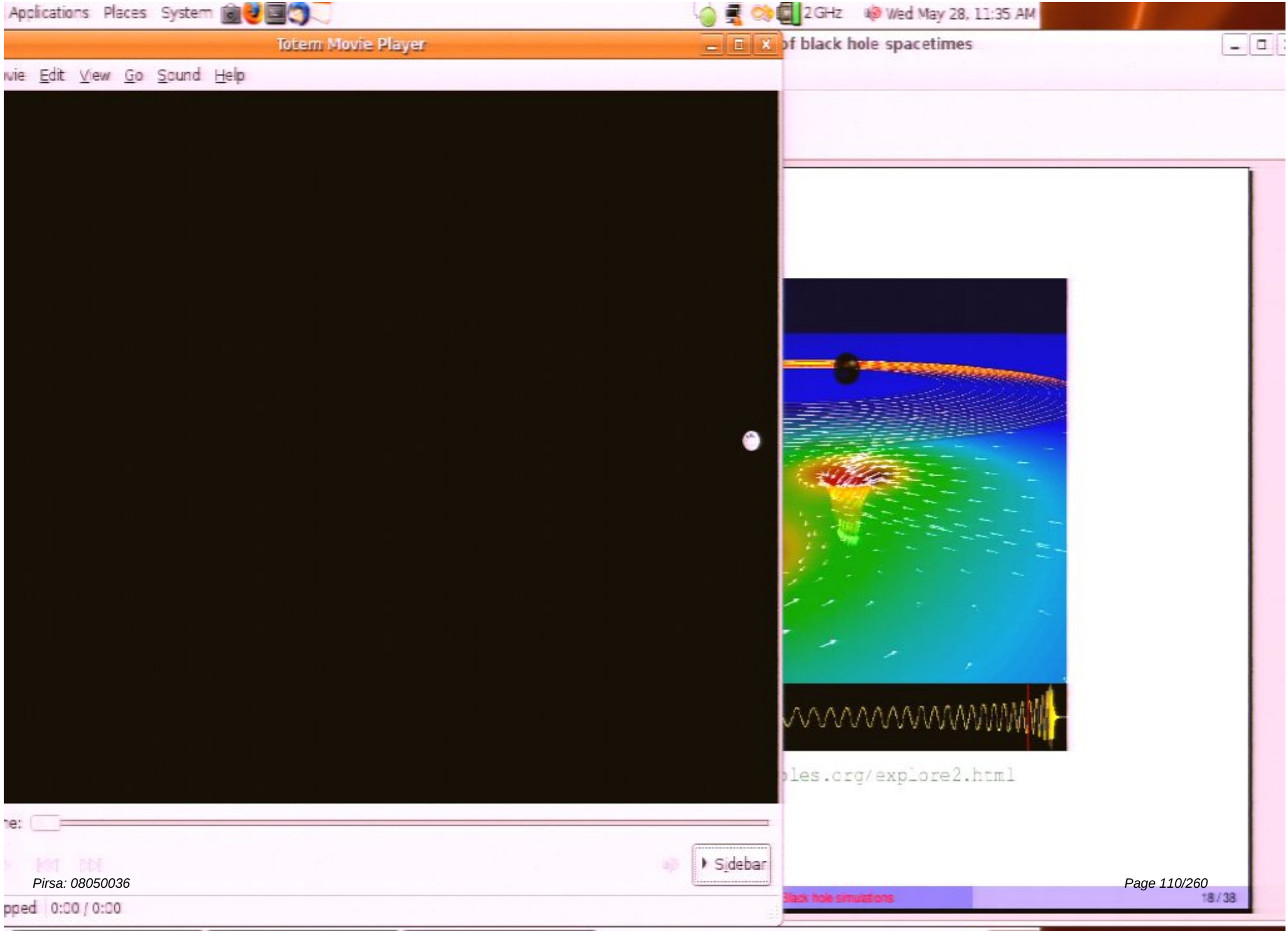
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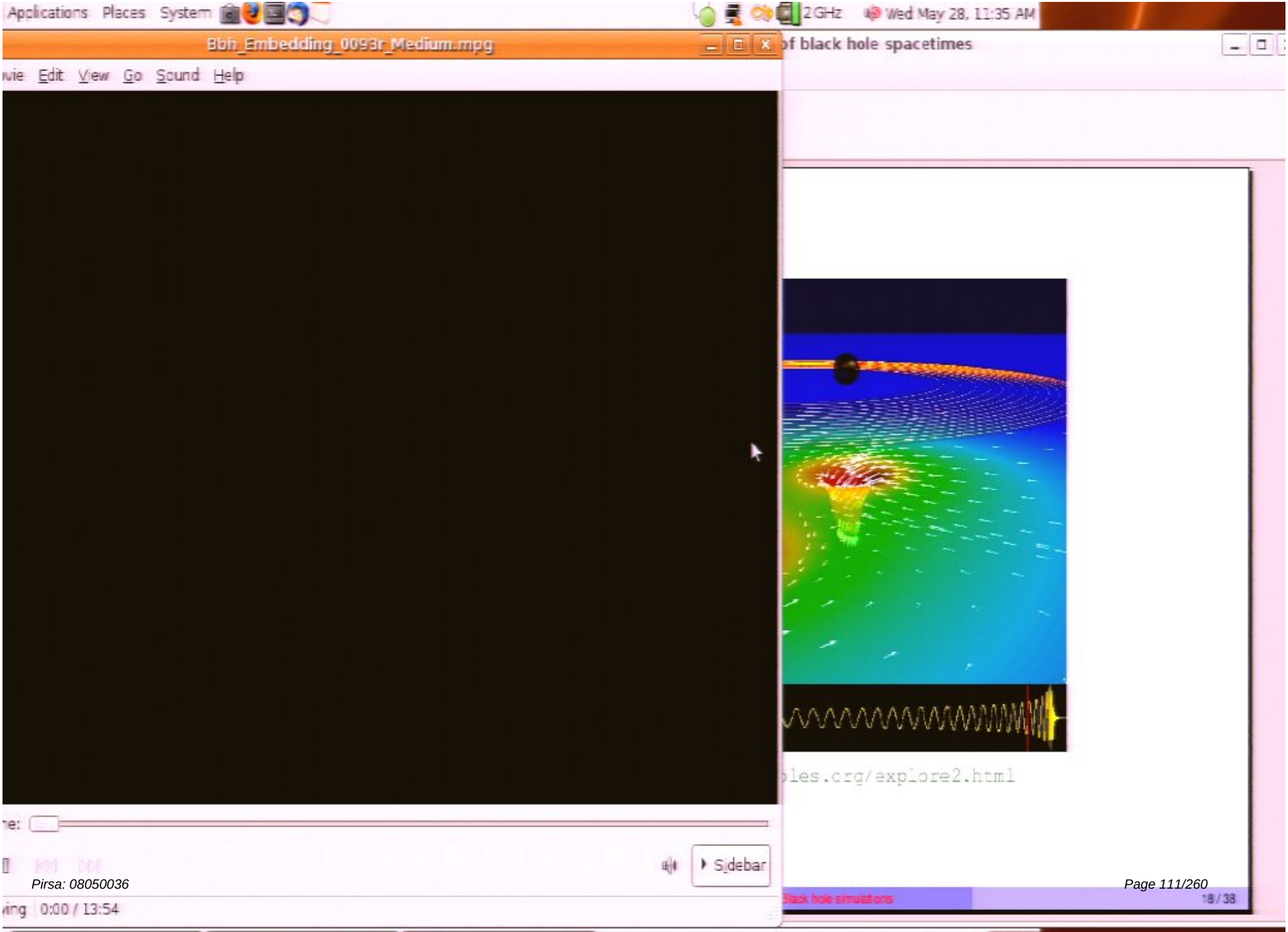
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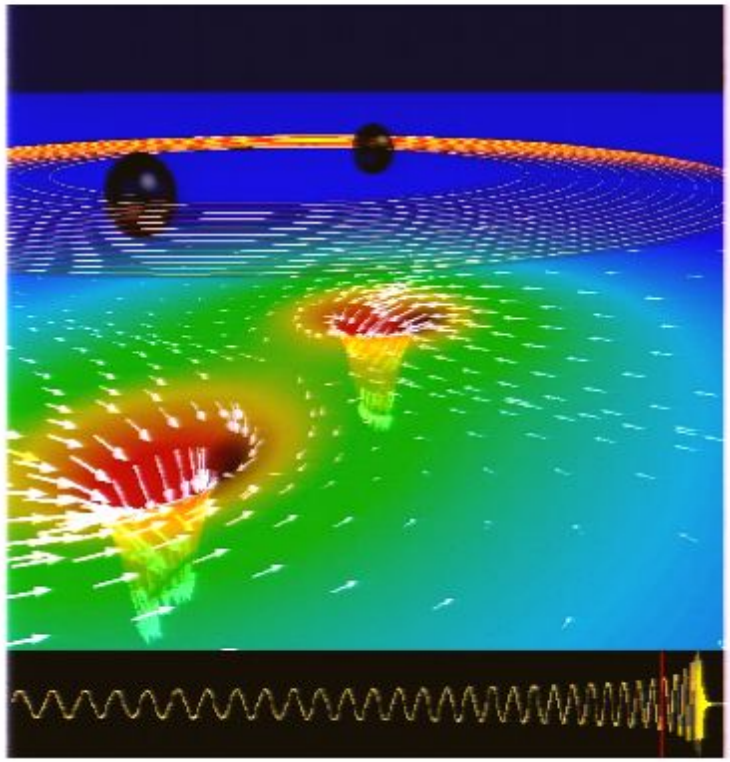

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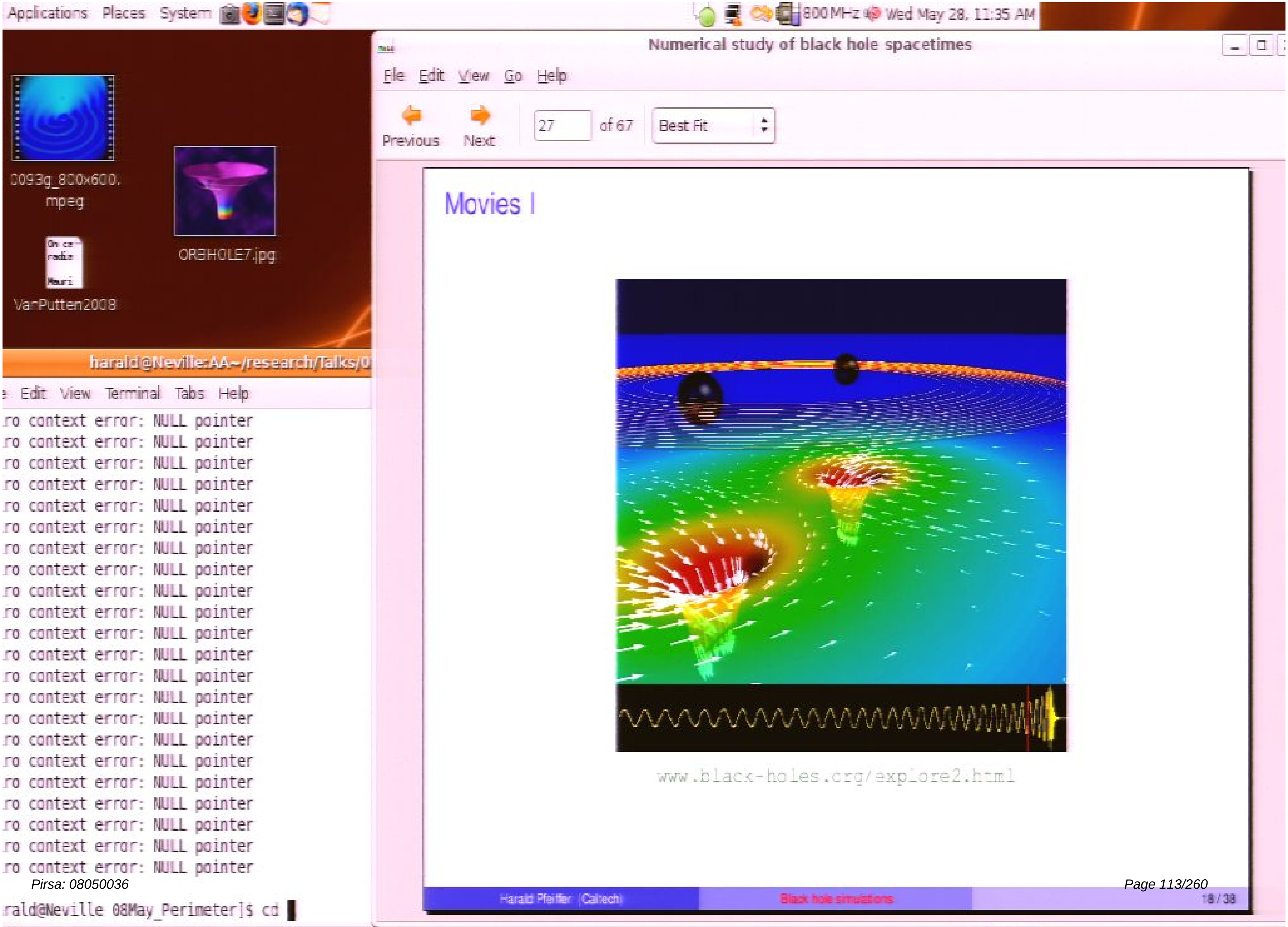
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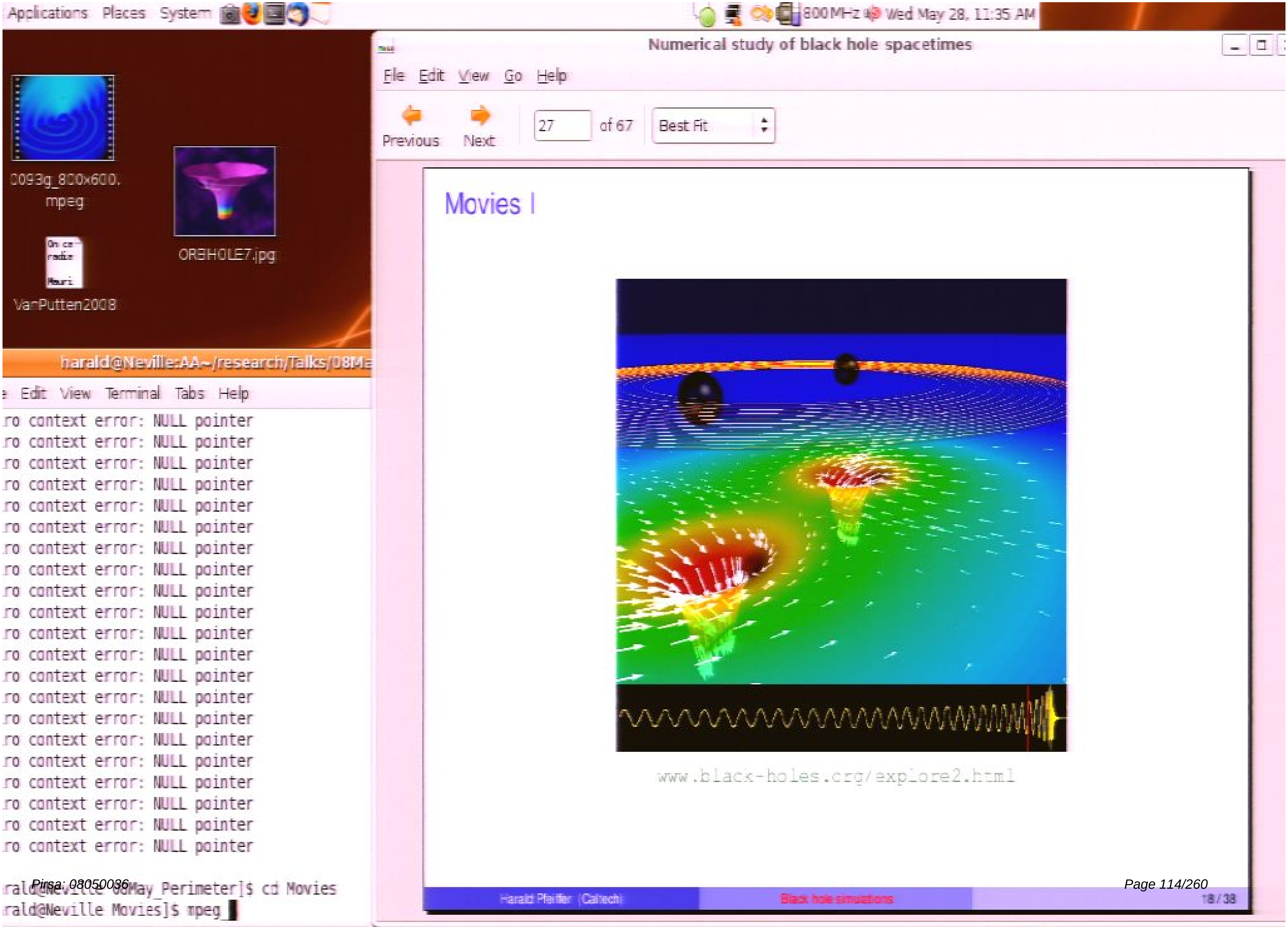
rald@Neville 08May_Perimeter]$ cd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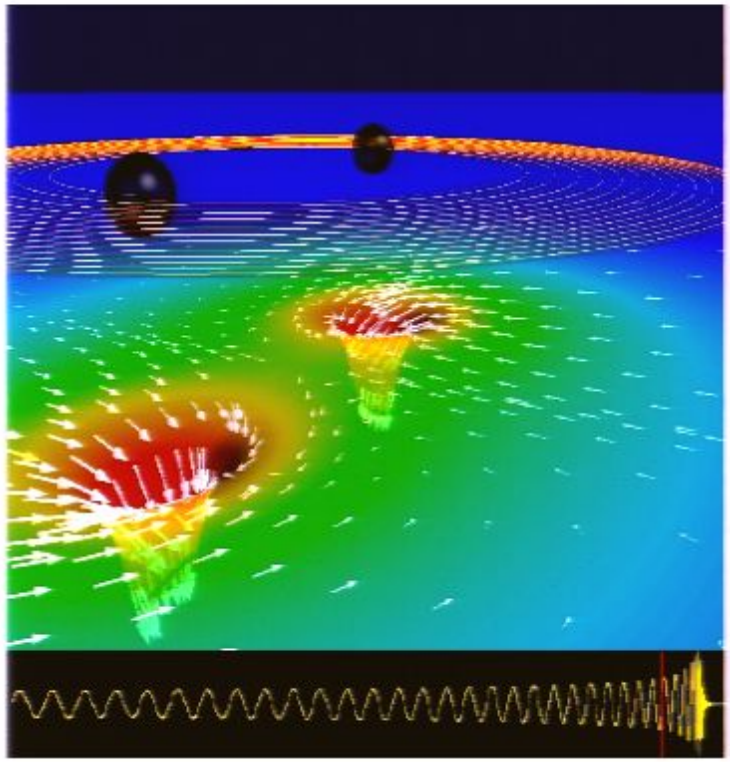

www.black-holes.org/explore2.html

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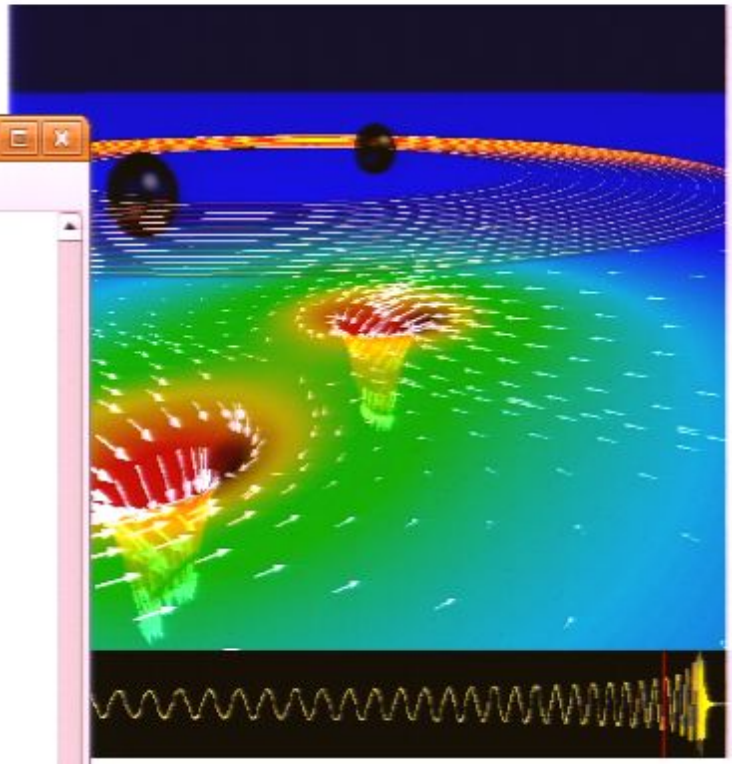

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rald@Neville 08May_Perimeter]$ cd Movies
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rald@Neville Movies]$ mpeg_play Embedd
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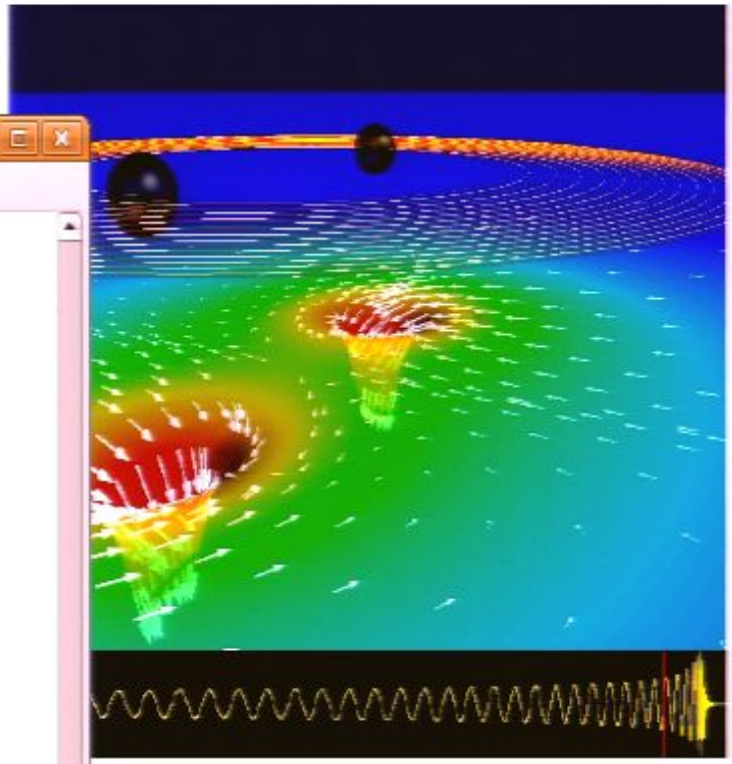

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rald@Neville Movies]$ mpeg_play Bbh_Embedding_0093r_
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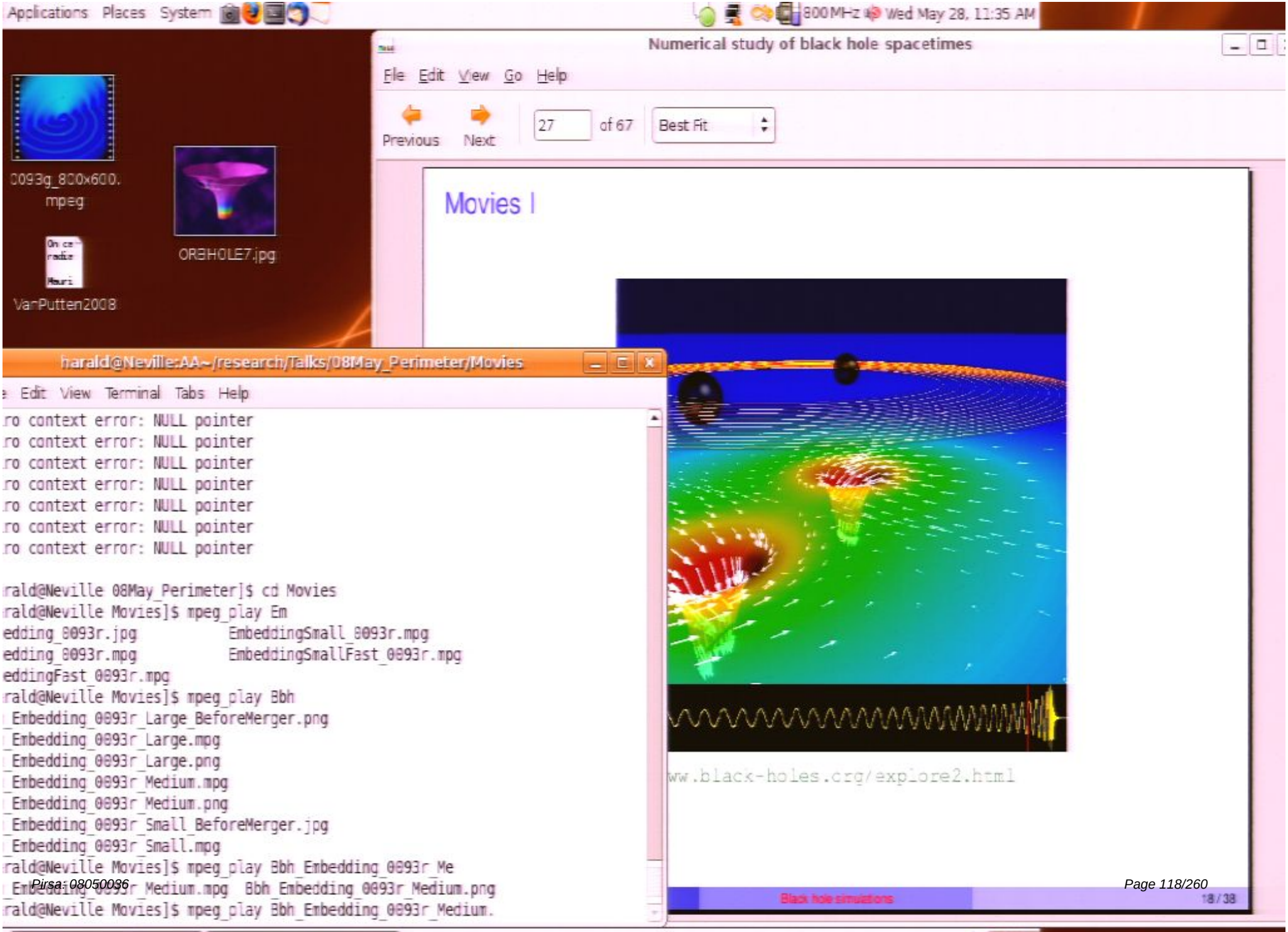
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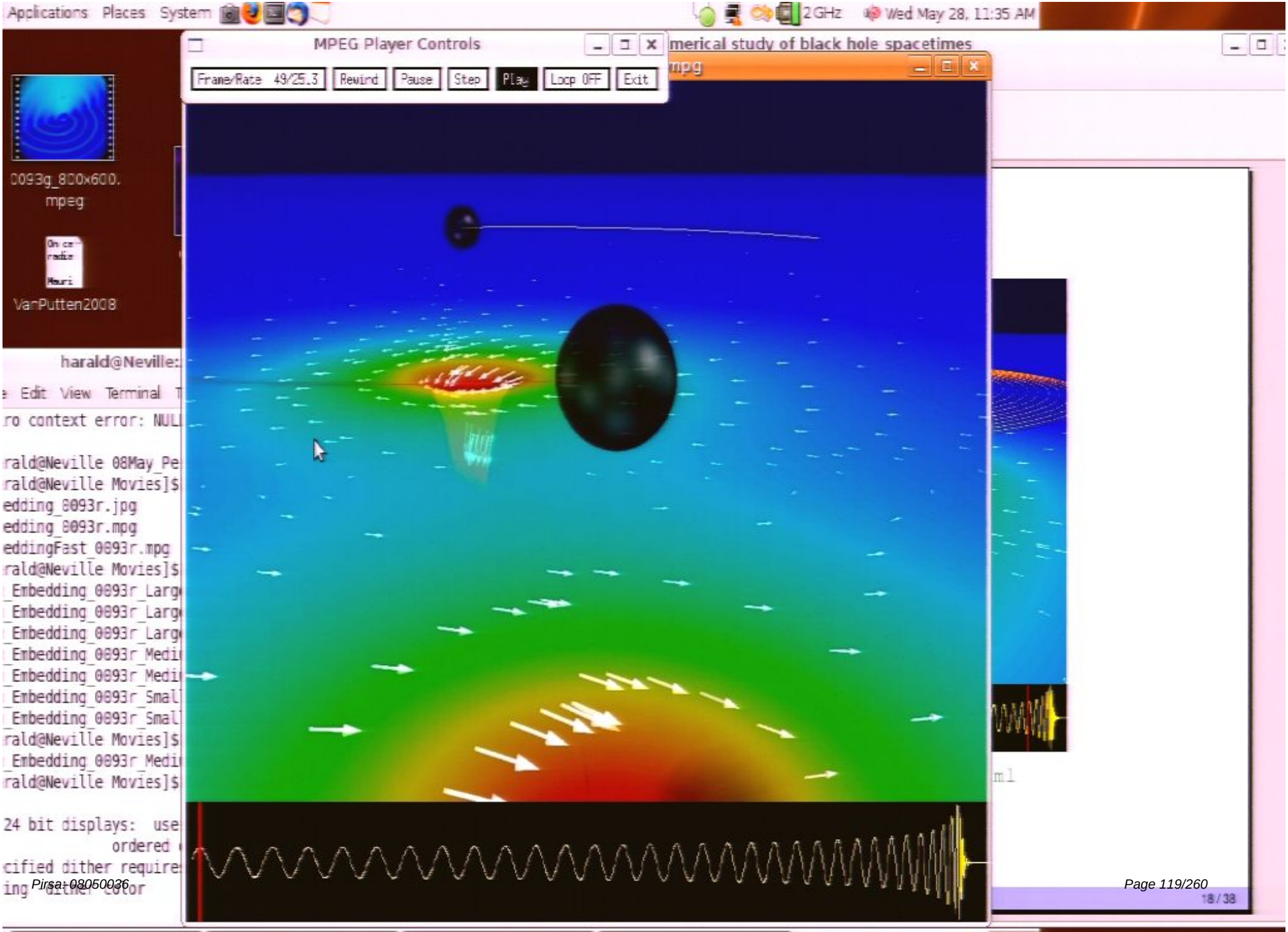
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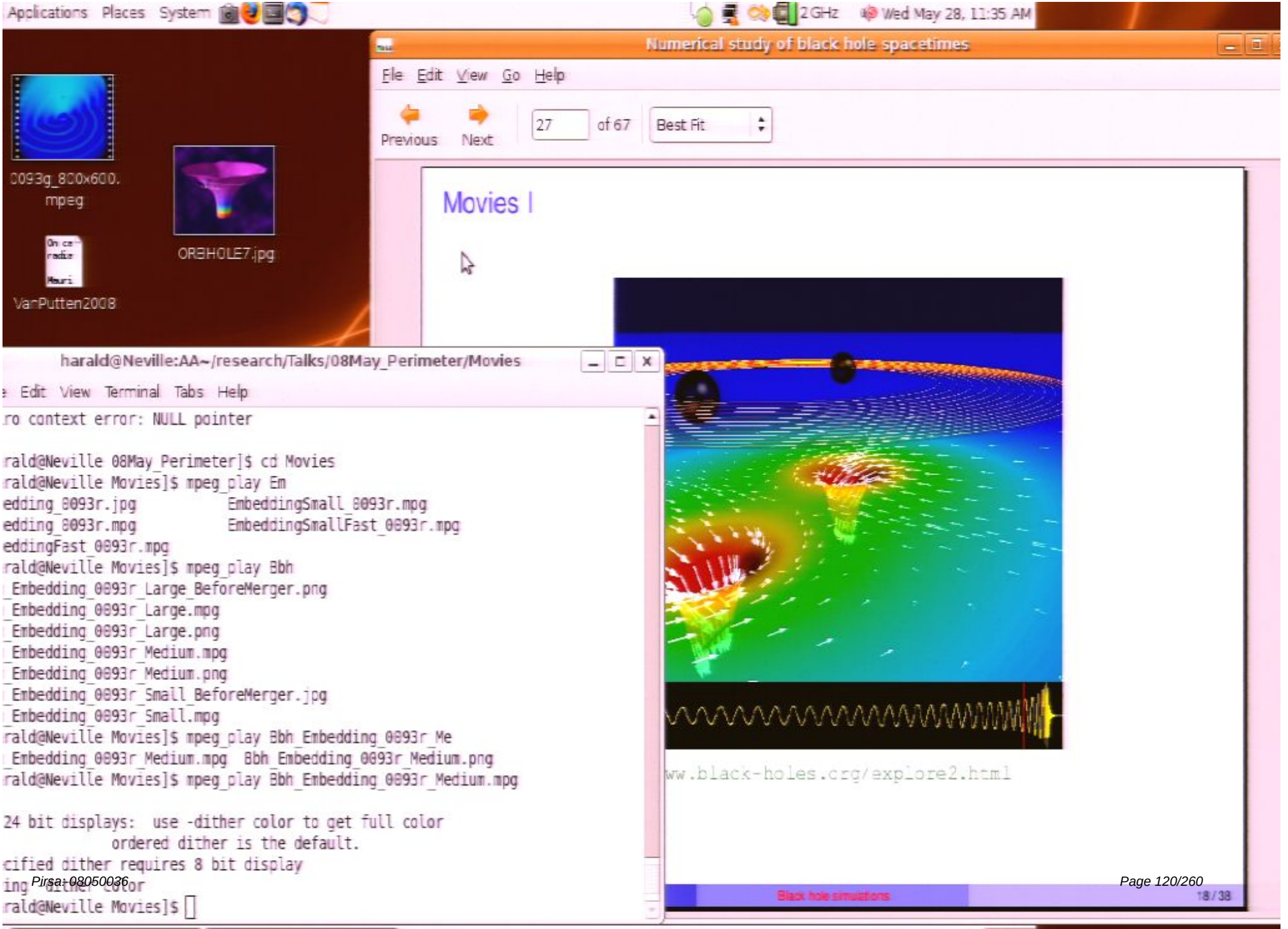
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rald@Neville 08May_Perimeter]$ cd Movies
rald@Neville Movies]$ mpeg_play Em
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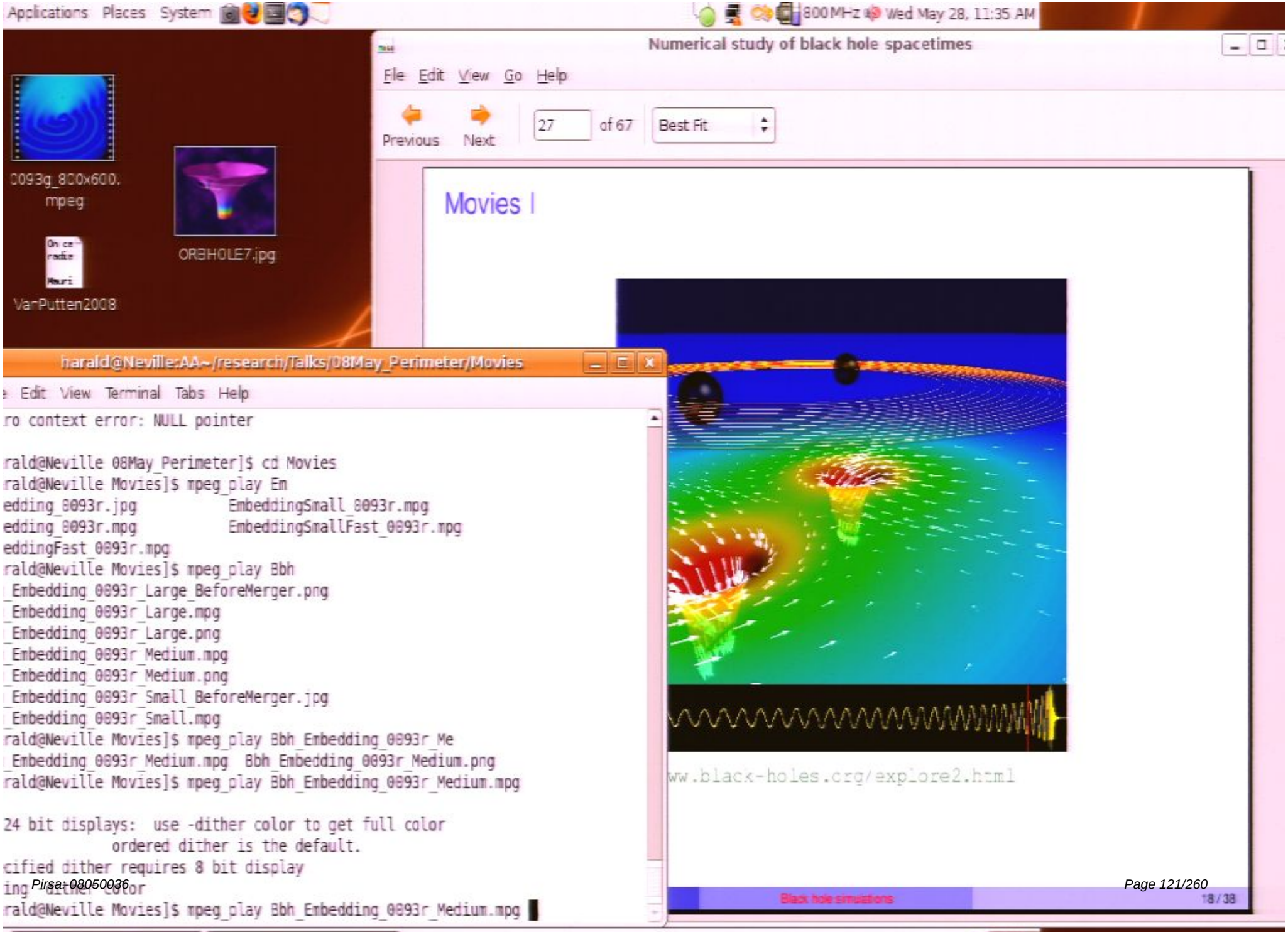
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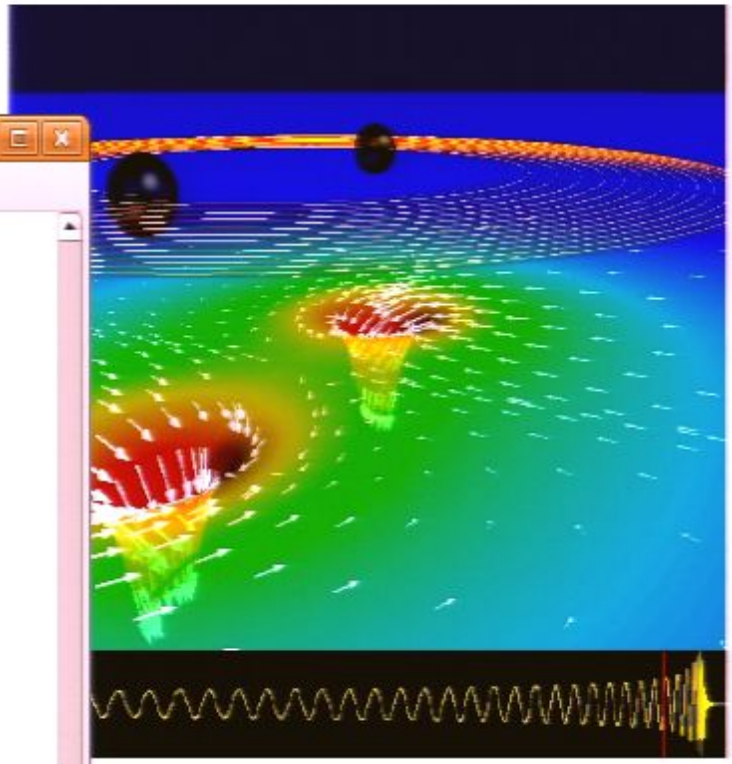

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rald@Neville 08May_Perimeter]$ cd Movies
rald@Neville Movies]$ mpeg_play Em
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rald@Neville Movies]$ mpeg_play Bbh
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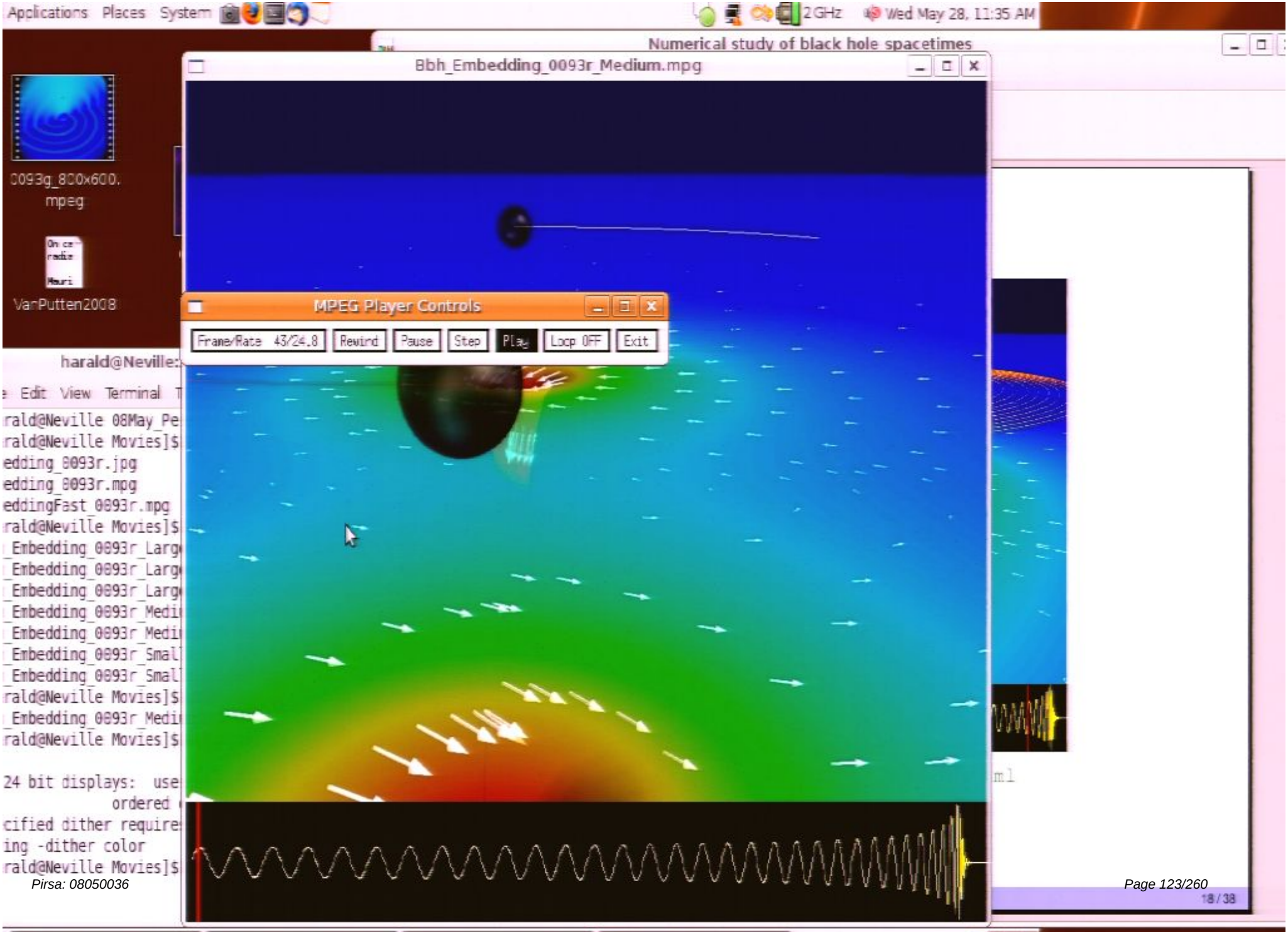
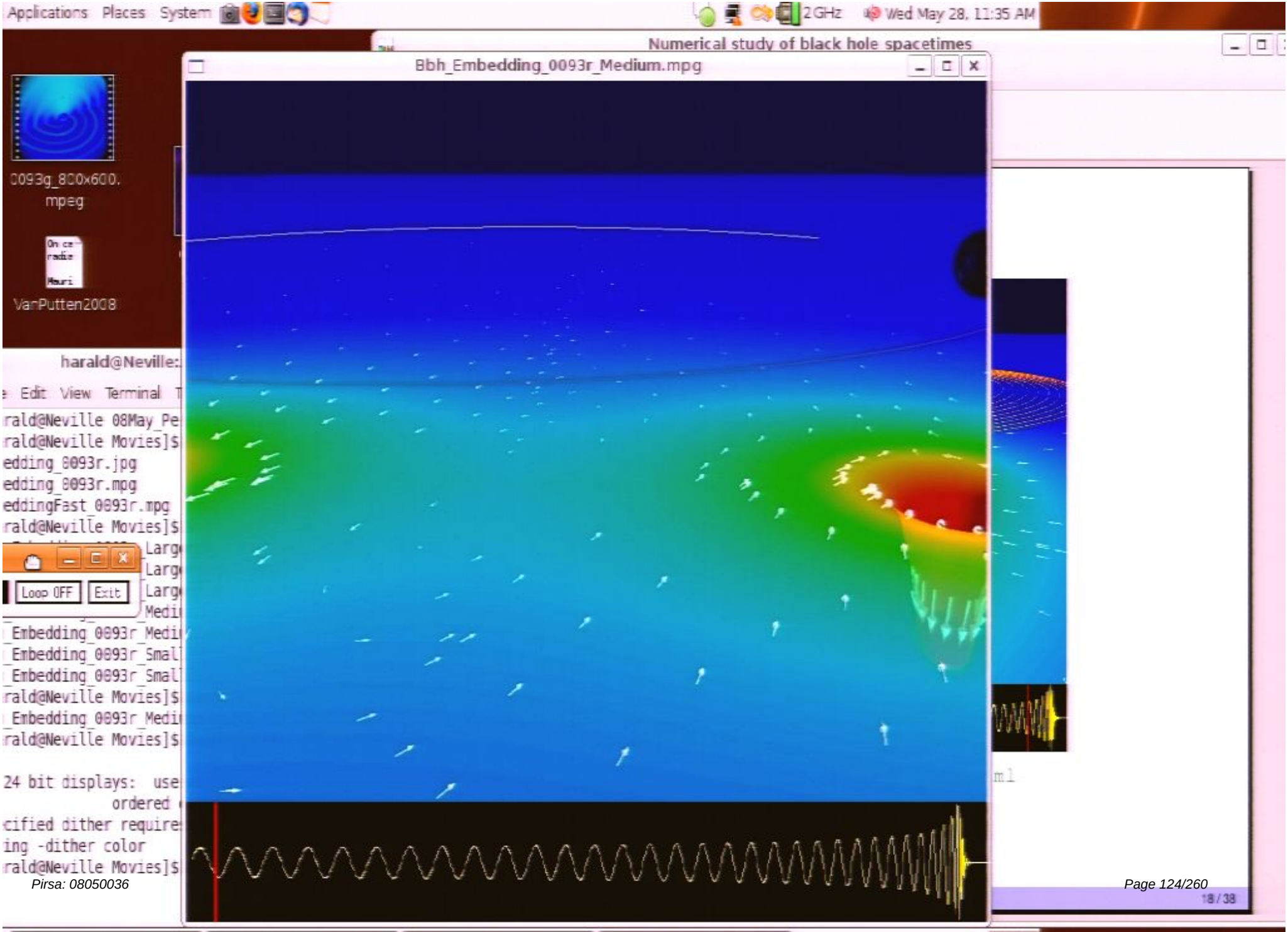
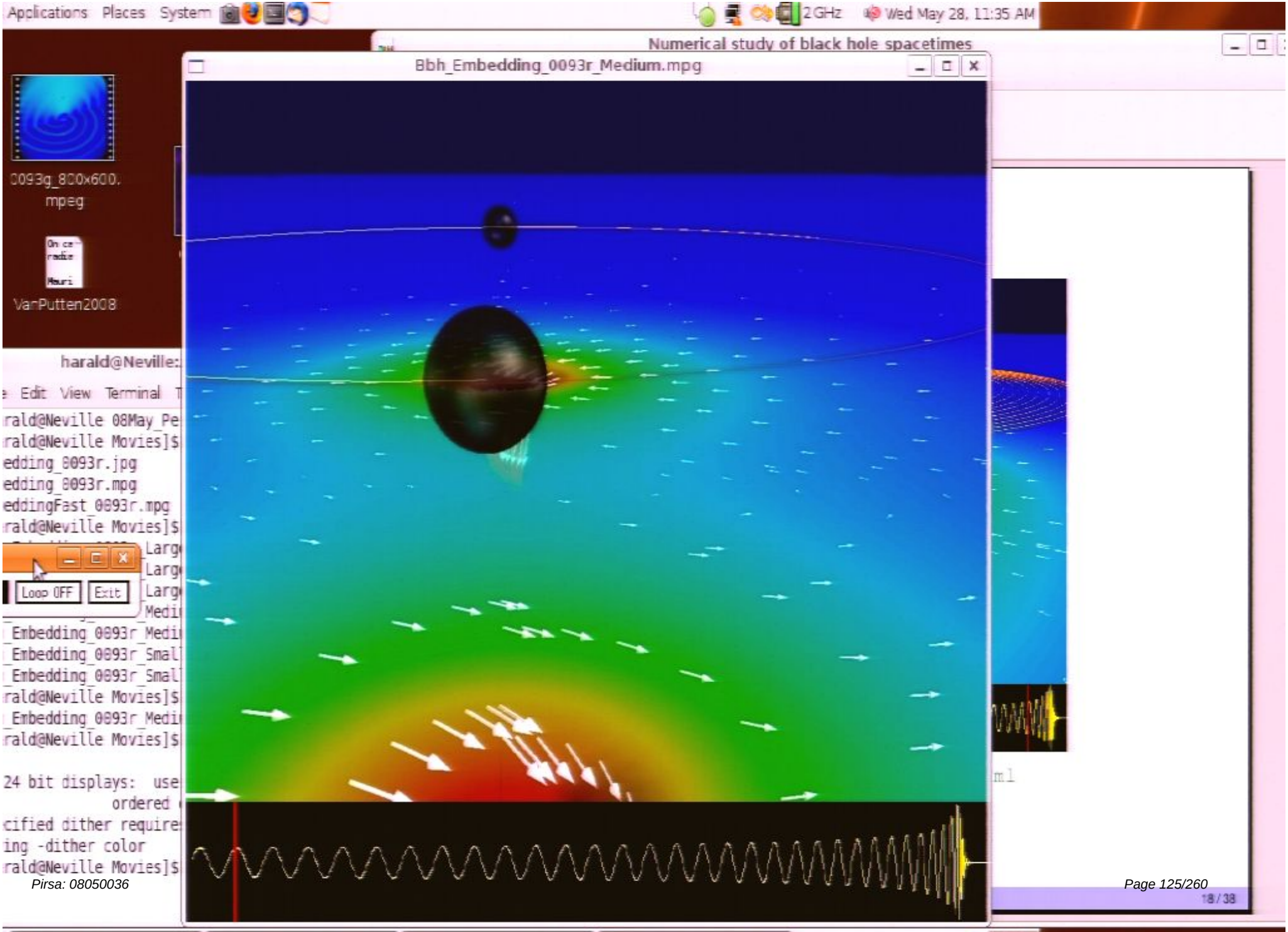
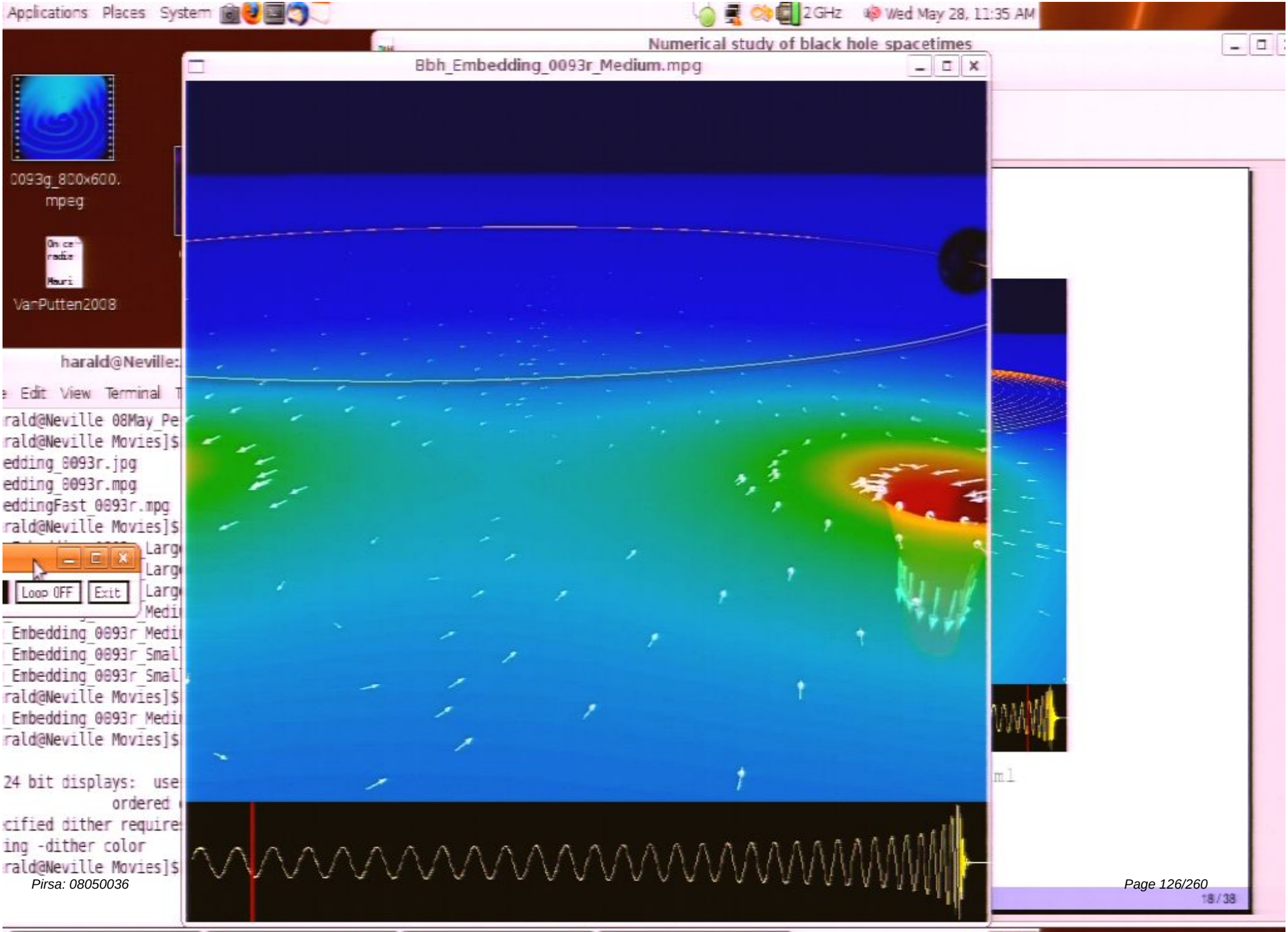
_Embedding_0093r_Small.mpg
rald@Neville Movies]$ mpeg_play Bbh_Embedding_0093r_Me
_Embedding_0093r_Medium.mpg  Bbh_Embedding_0093r_Medium.png
rald@Neville Movies]$ mpeg_play Bbh_Embedding_0093r_Medium.mpg

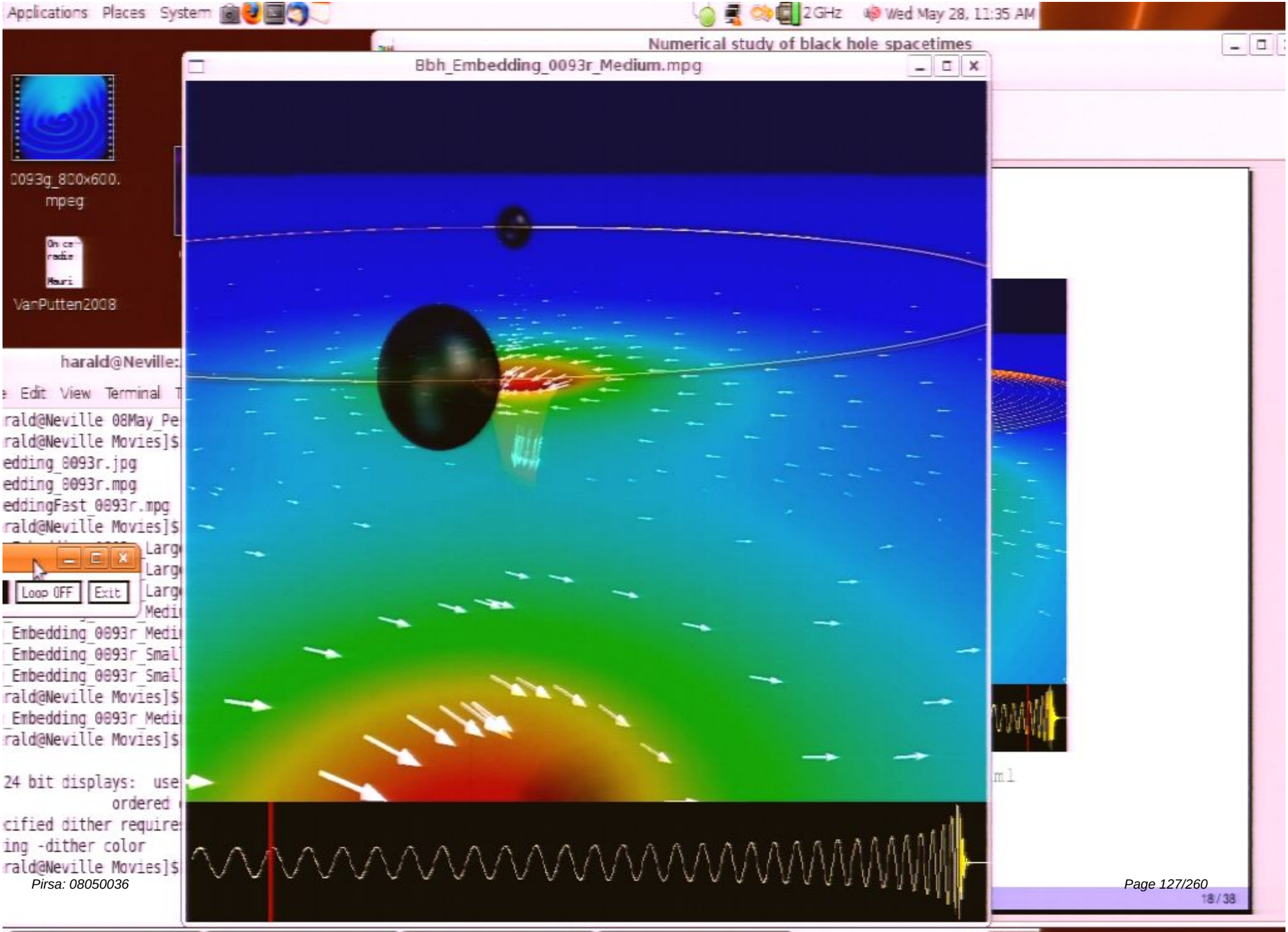
24 bit displays:  use -dither color to get full color
            ordered dither is the default.
cified dither requires 8 bit display
ing "dither" color
rald@Neville Movies]$ mpeg_play -dither co Bbh_Embedding_0093r_Medium.mpg
```

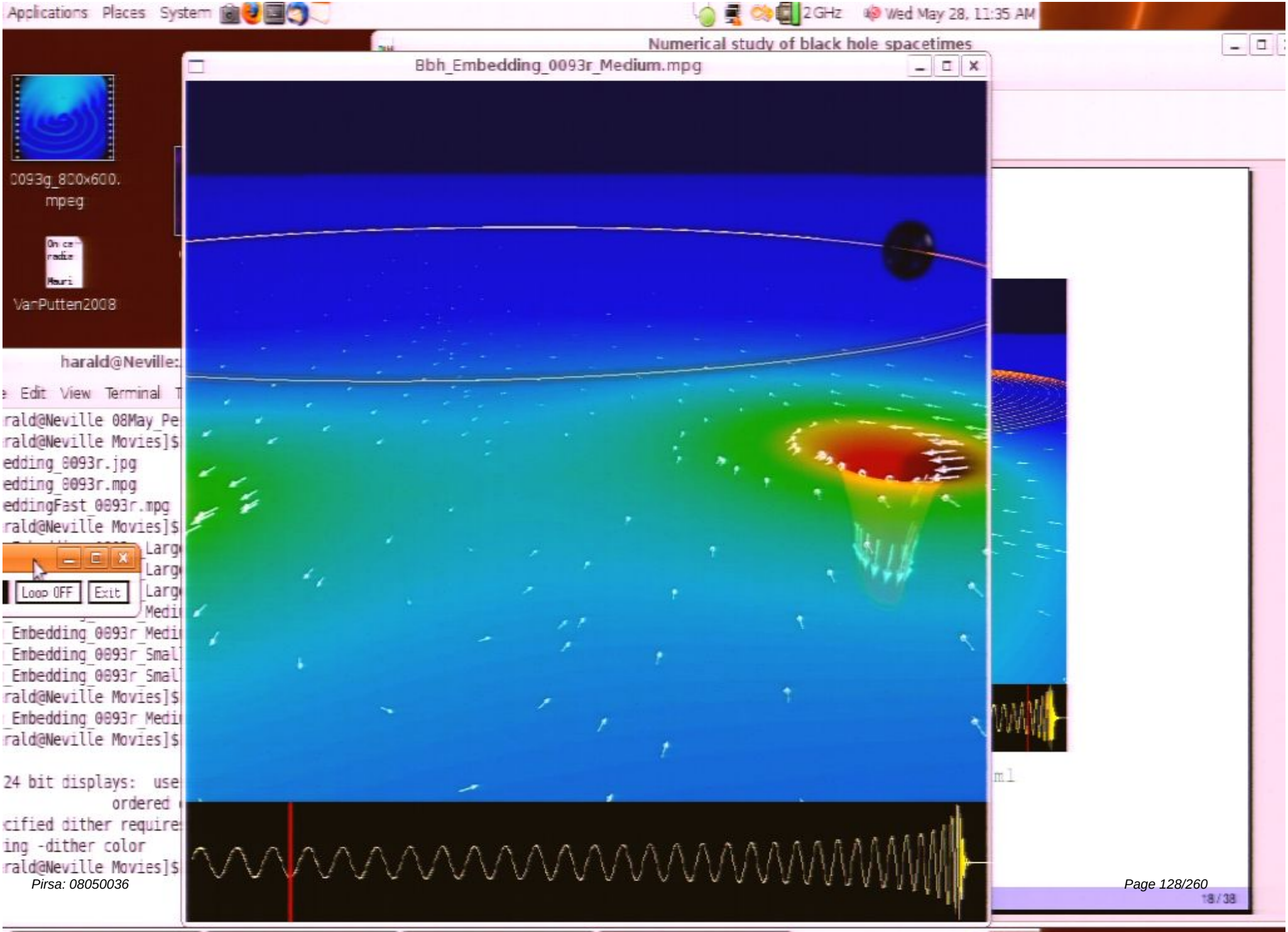

Applications Places System
2 GHz
Wed May 28, 11:35 AM
Numerical study of black hole spacetimes
Bbh_Embedding_0093r_Medium.mpg
MPEG Player Controls
Frame/Rate 43/24.8
Rewind
Pause
Step
Play
Loop OFF
Exit
0093g_800x600.mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
18 / 38

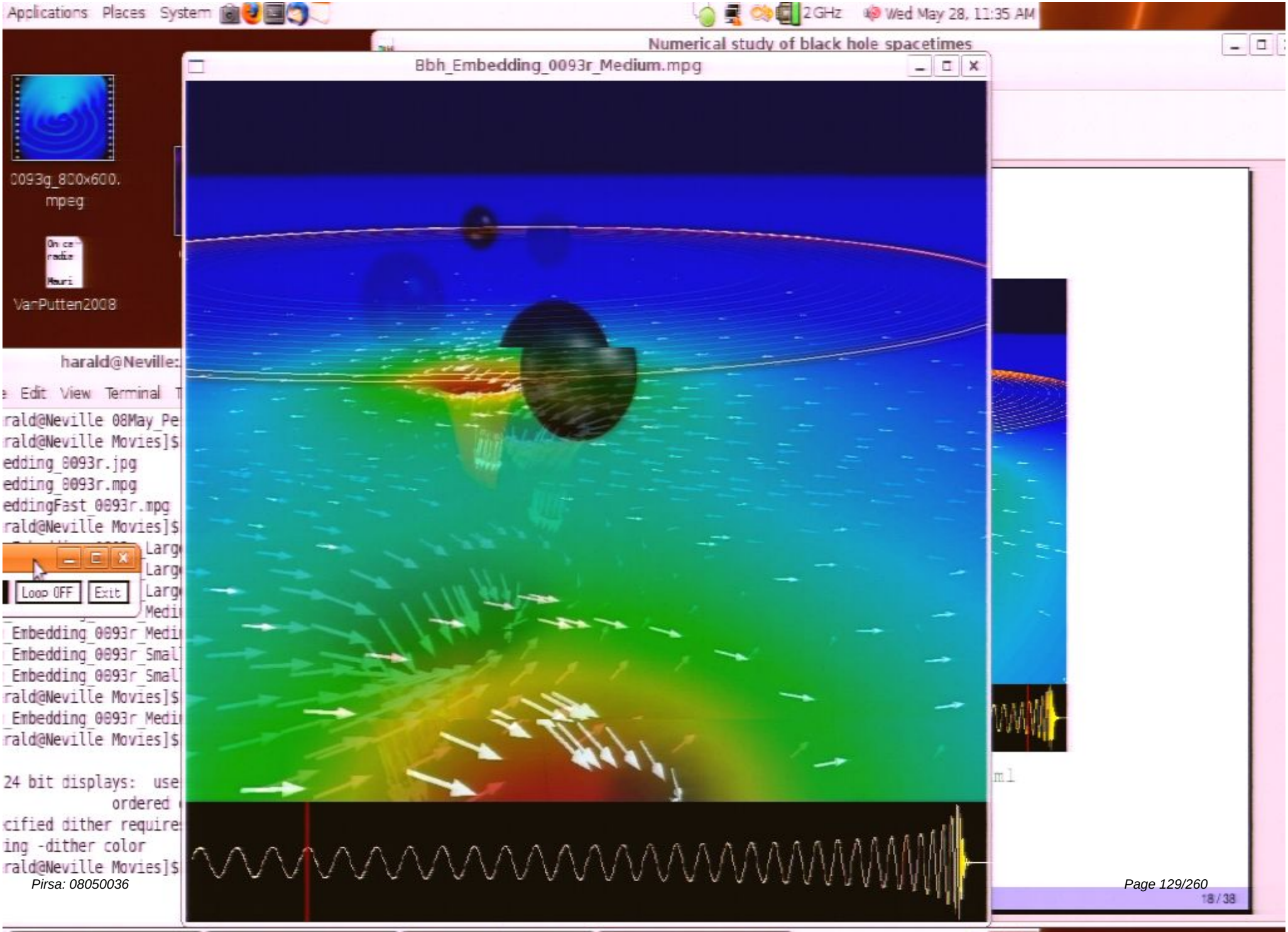

Applications Places System
2 GHz
Wed May 28, 11:35 AM
Numerical study of black hole spacetimes
Bbh_Embedding_0093r_Medium.mpg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
Loop OFF
Exit
18 / 38

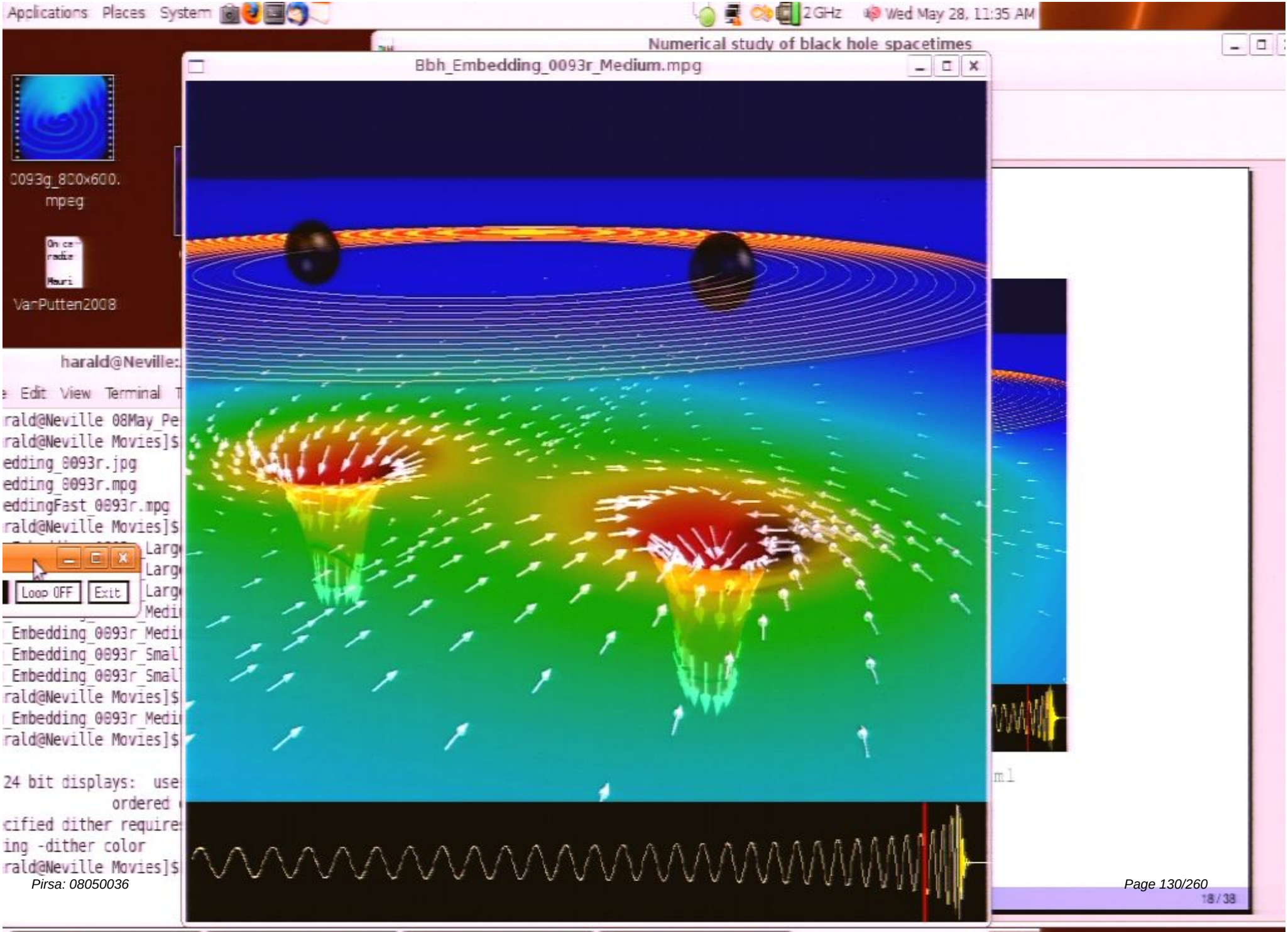

Applications Places System
2 GHz
Wed May 28, 11:35 AM
Numerical study of black hole spacetimes
Bbh_Embedding_0093r_Medium.mpg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
Loop OFF
Exit
18 / 38

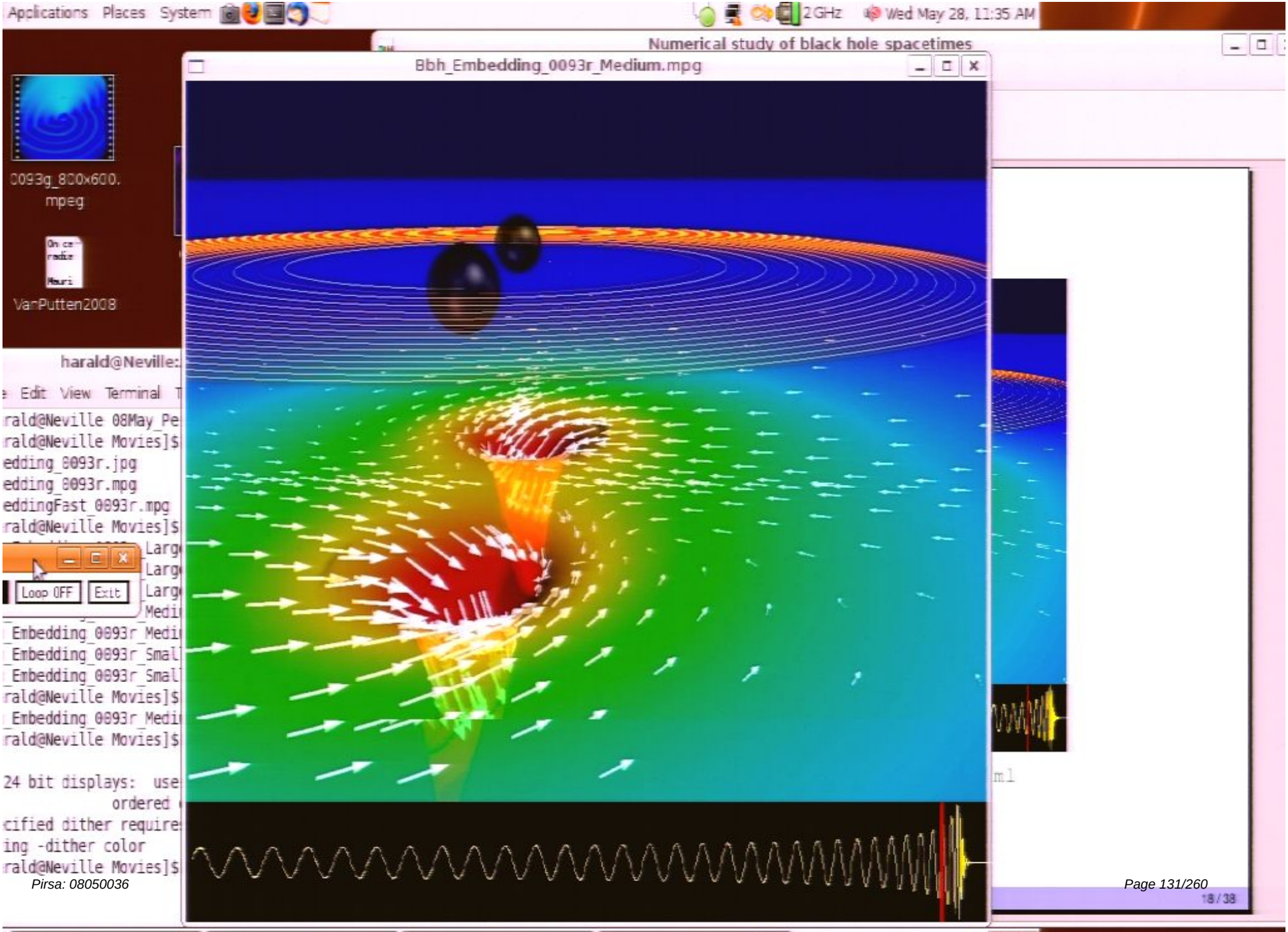

Applications Places System
2 GHz
Wed May 28, 11:35 AM
Numerical study of black hole spacetimes
Bbh_Embedding_0093r_Medium.mpg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
Loop OFF
Exit
18 / 38

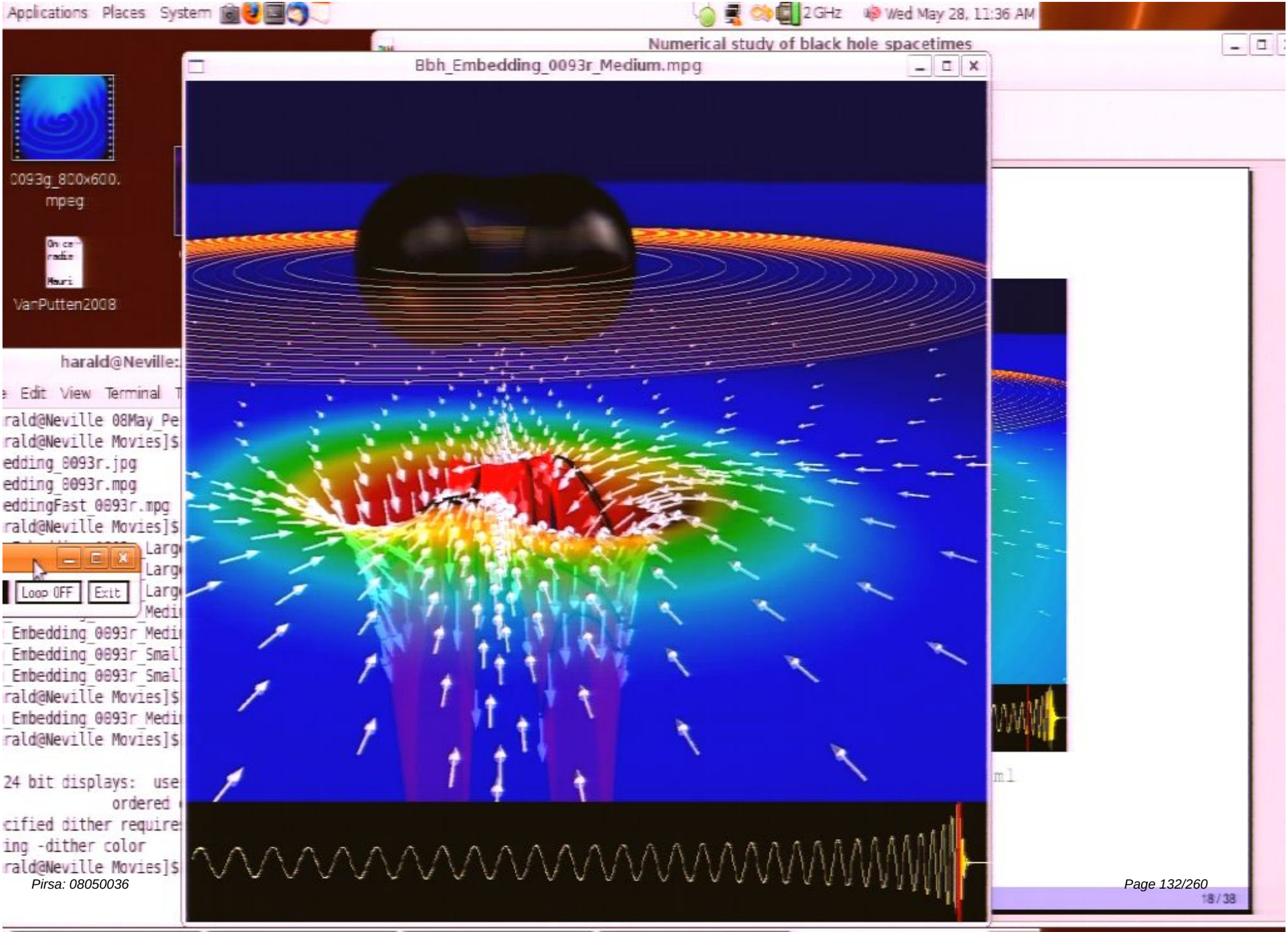

Applications Places System
2 GHz
Wed May 28, 11:35 AM
Numerical study of black hole spacetimes
Bbh_Embedding_0093r_Medium.mpg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
Loop OFF
Exit
18 / 38

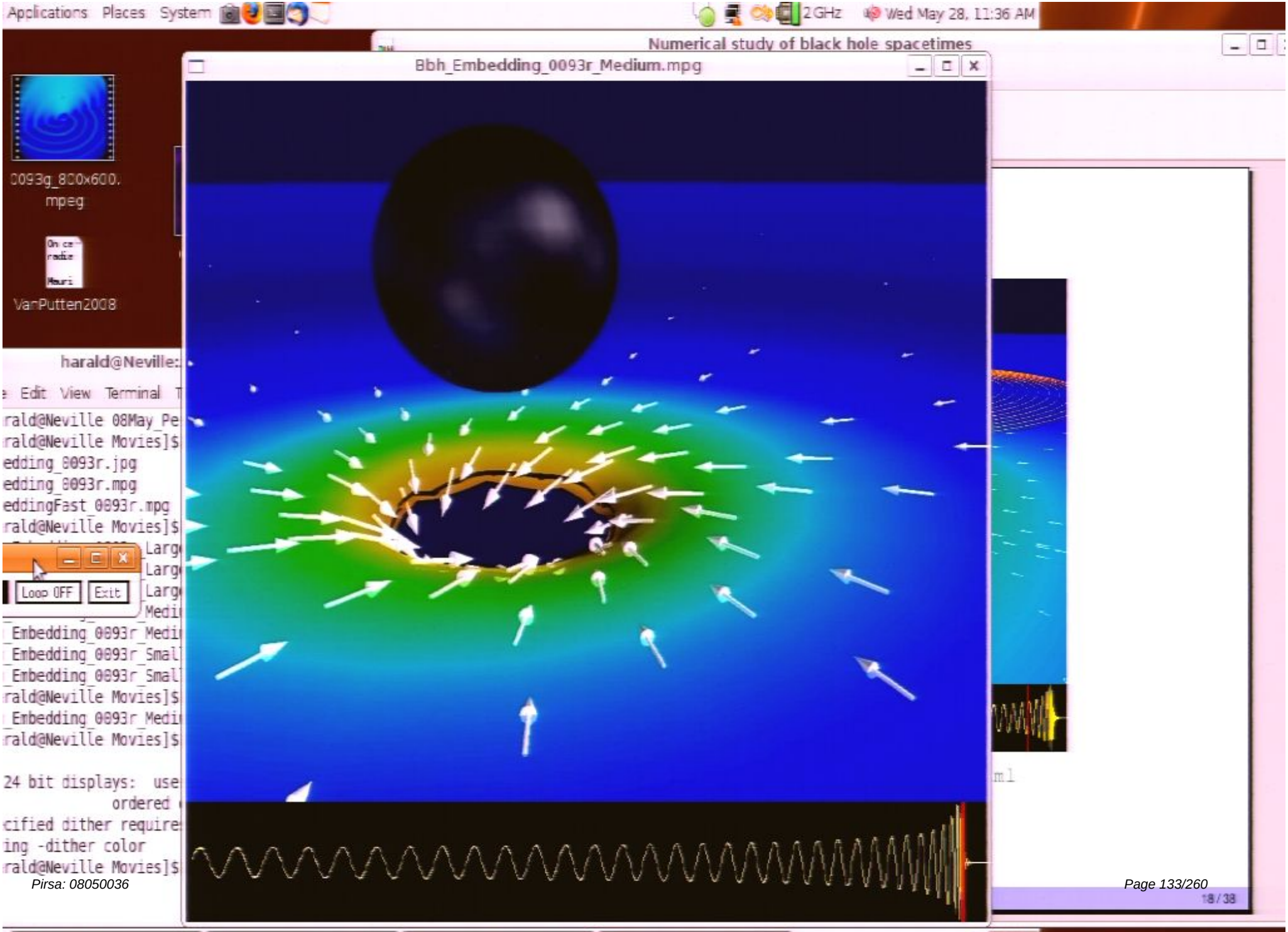

Applications Places System
2 GHz
Wed May 28, 11:35 AM
Numerical study of black hole spacetimes
Bbh_Embedding_0093r_Medium.mpg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
Loop OFF
Exit
Pirsa: 08050036
Page 128/260

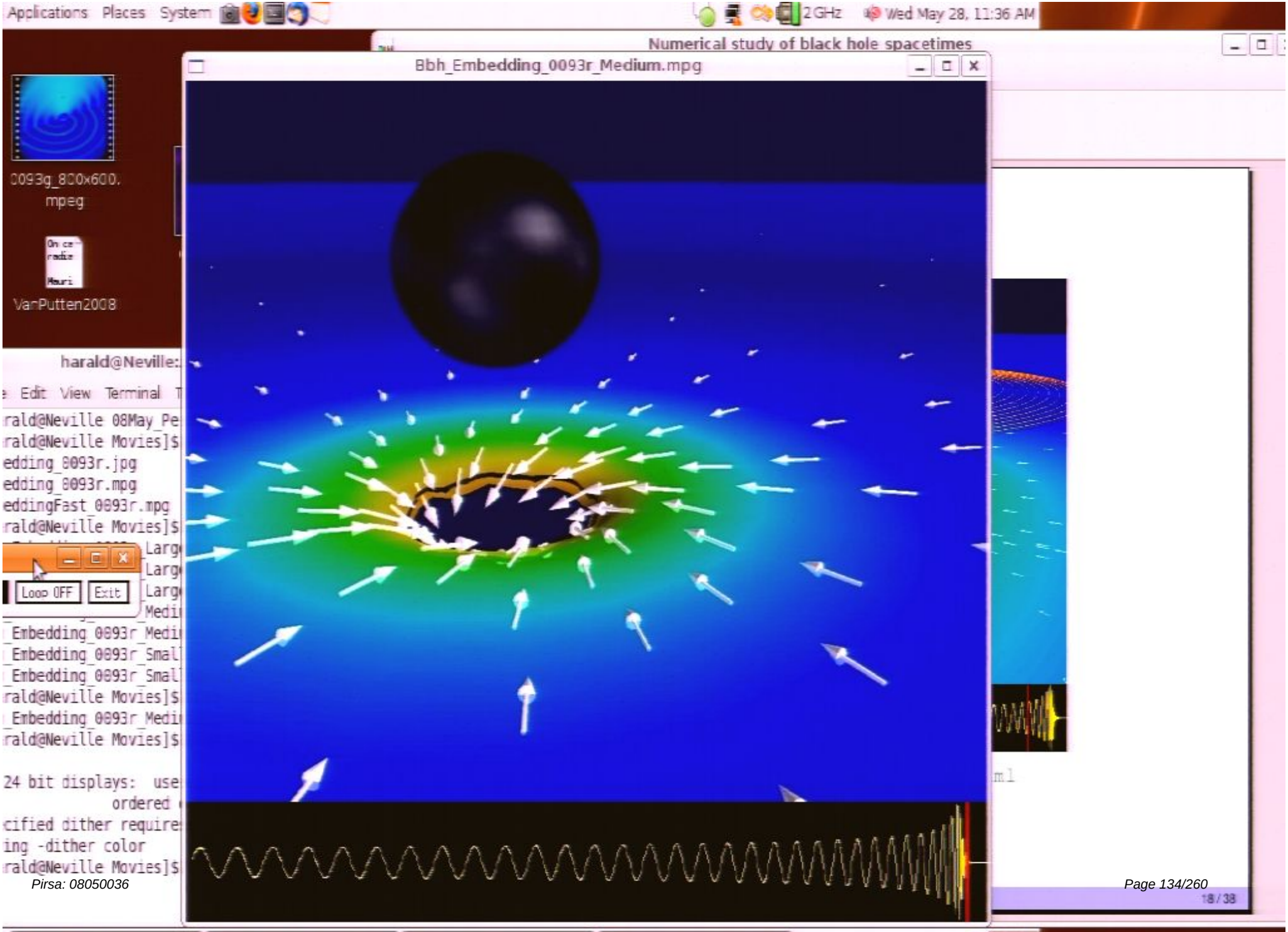

Applications Places System
2 GHz
Wed May 28, 11:35 AM
Numerical study of black hole spacetimes
Bbh_Embedding_0093r_Medium.mpg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
Loop OFF
Exit
18 / 38

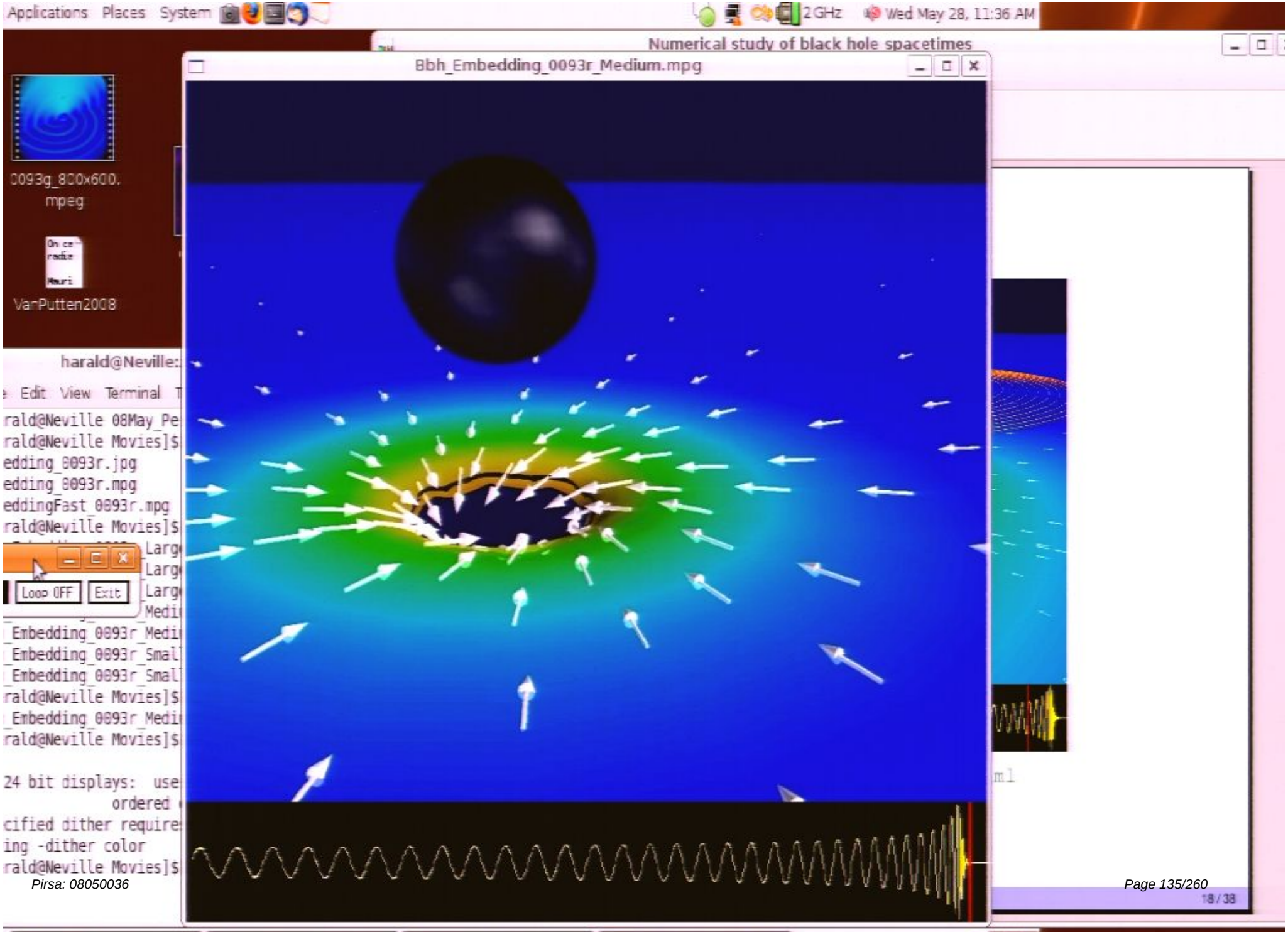

Applications Places System
2 GHz
Wed May 28, 11:35 AM
Numerical study of black hole spacetimes
Bbh_Embedding_0093r_Medium.mpg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
Loop OFF
Exit
18 / 38

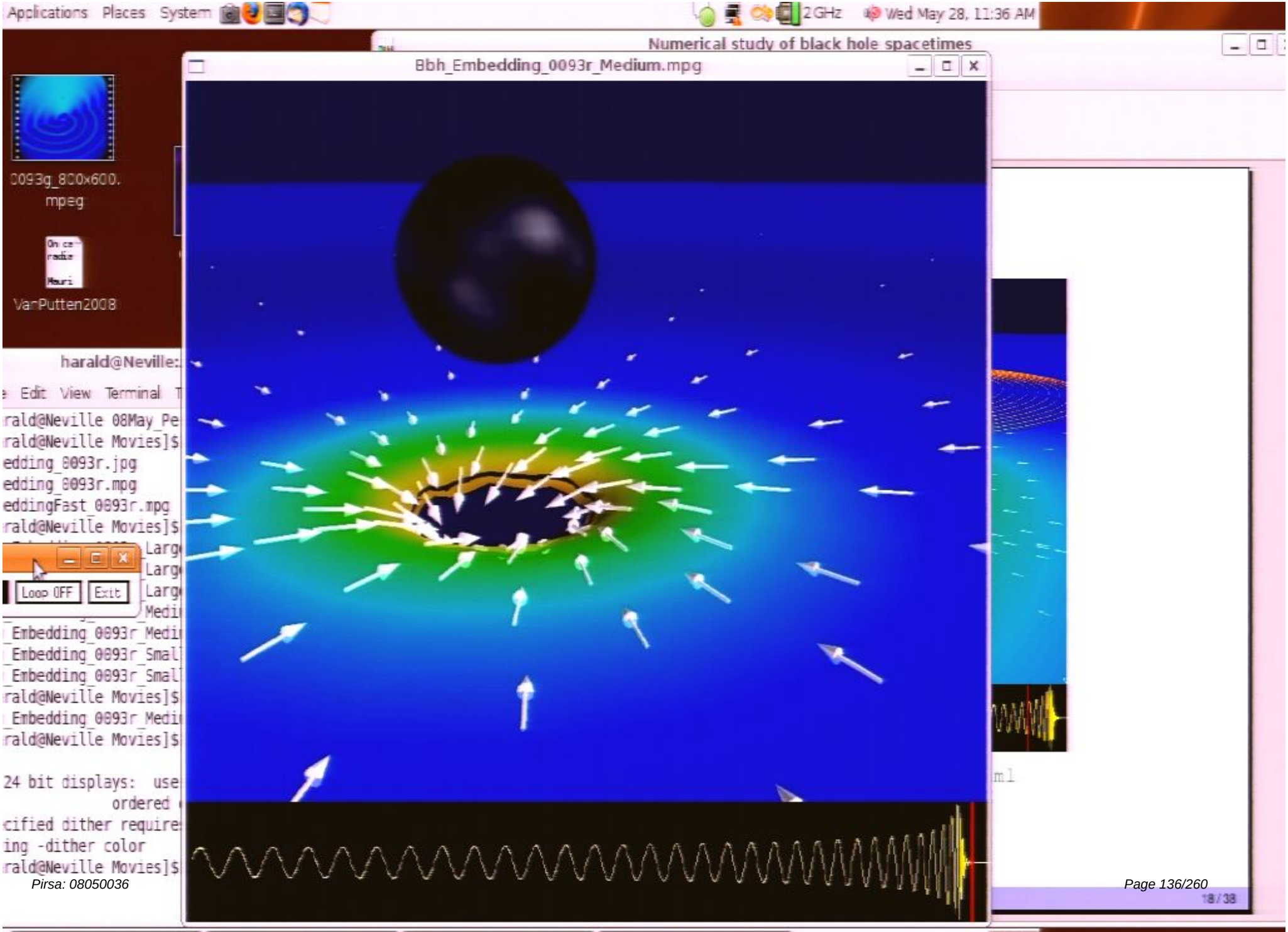

Applications Places System
2 GHz
Wed May 28, 11:35 AM
Numerical study of black hole spacetimes
Bbh_Embedding_0093r_Medium.mpg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
Loop OFF
Exit
18 / 38

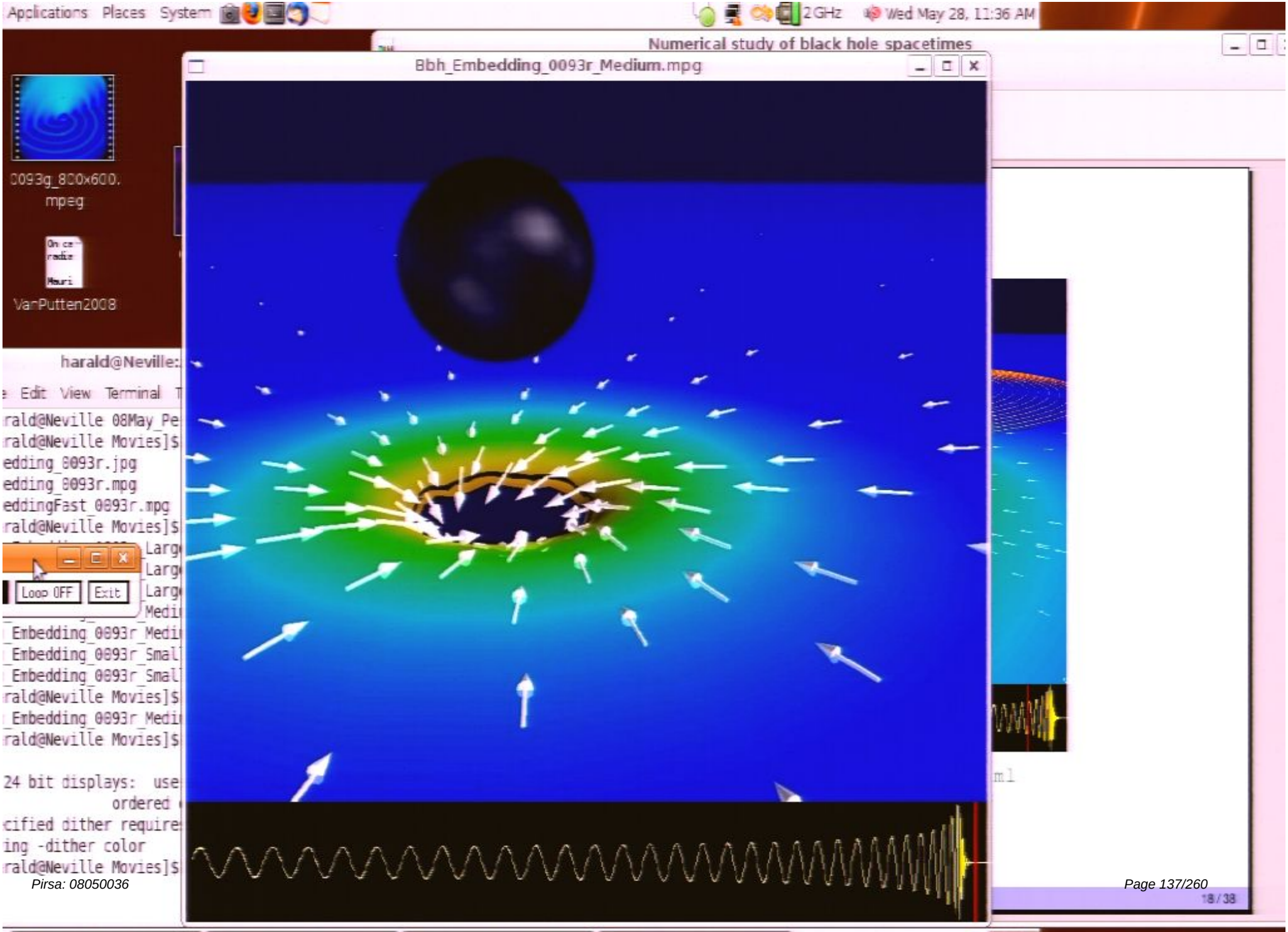

Applications Places System
2 GHz
Wed May 28, 11:36 AM
Numerical study of black hole spacetimes
Bbh_Embedding_0093r_Medium.mpg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
Loop OFF
Exit
18 / 38

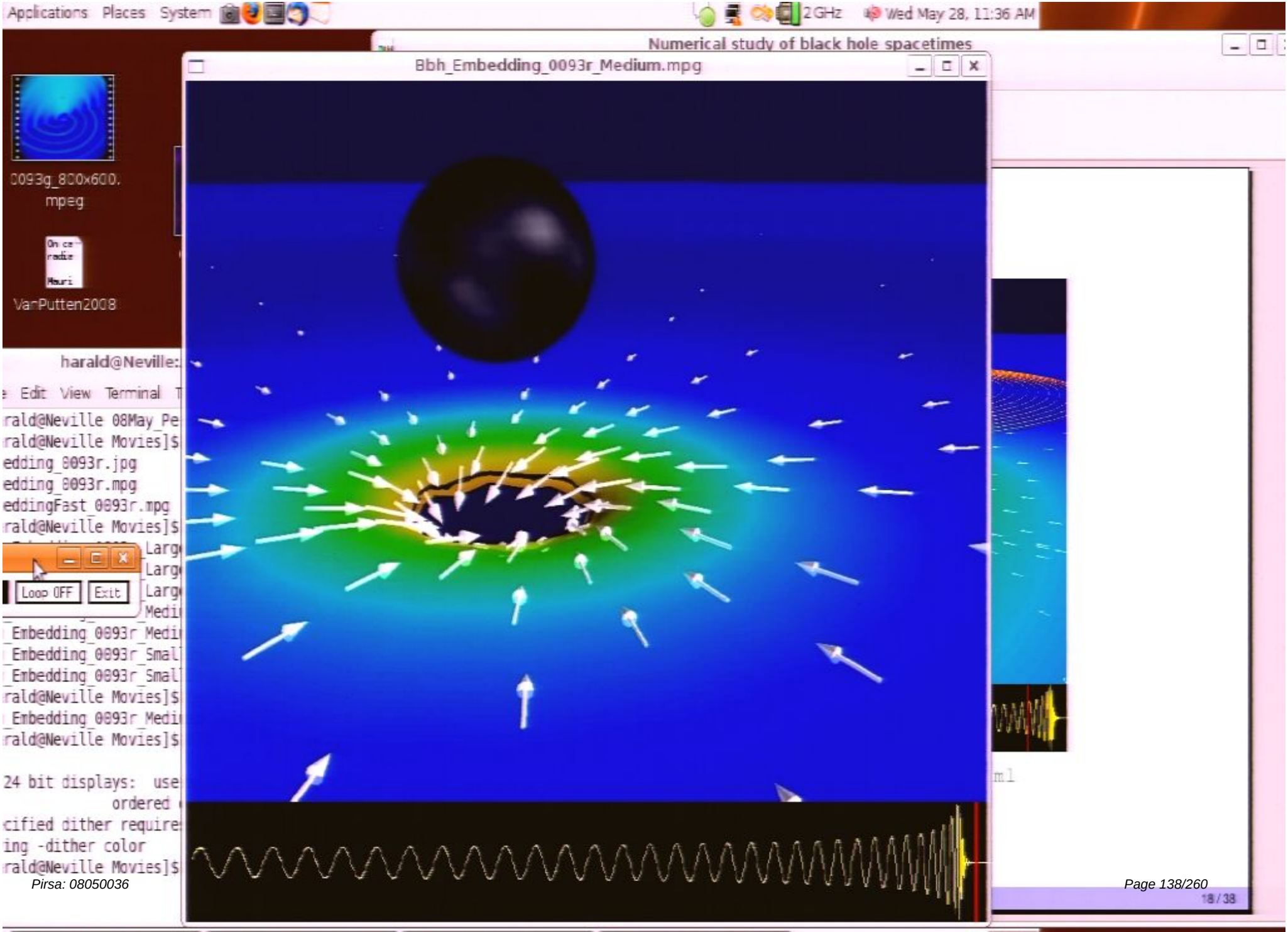

Applications Places System
2 GHz
Wed May 28, 11:36 AM
Numerical study of black hole spacetimes
Bbh_Embedding_0093r_Medium.mpg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
Loop OFF
Exit
18 / 38

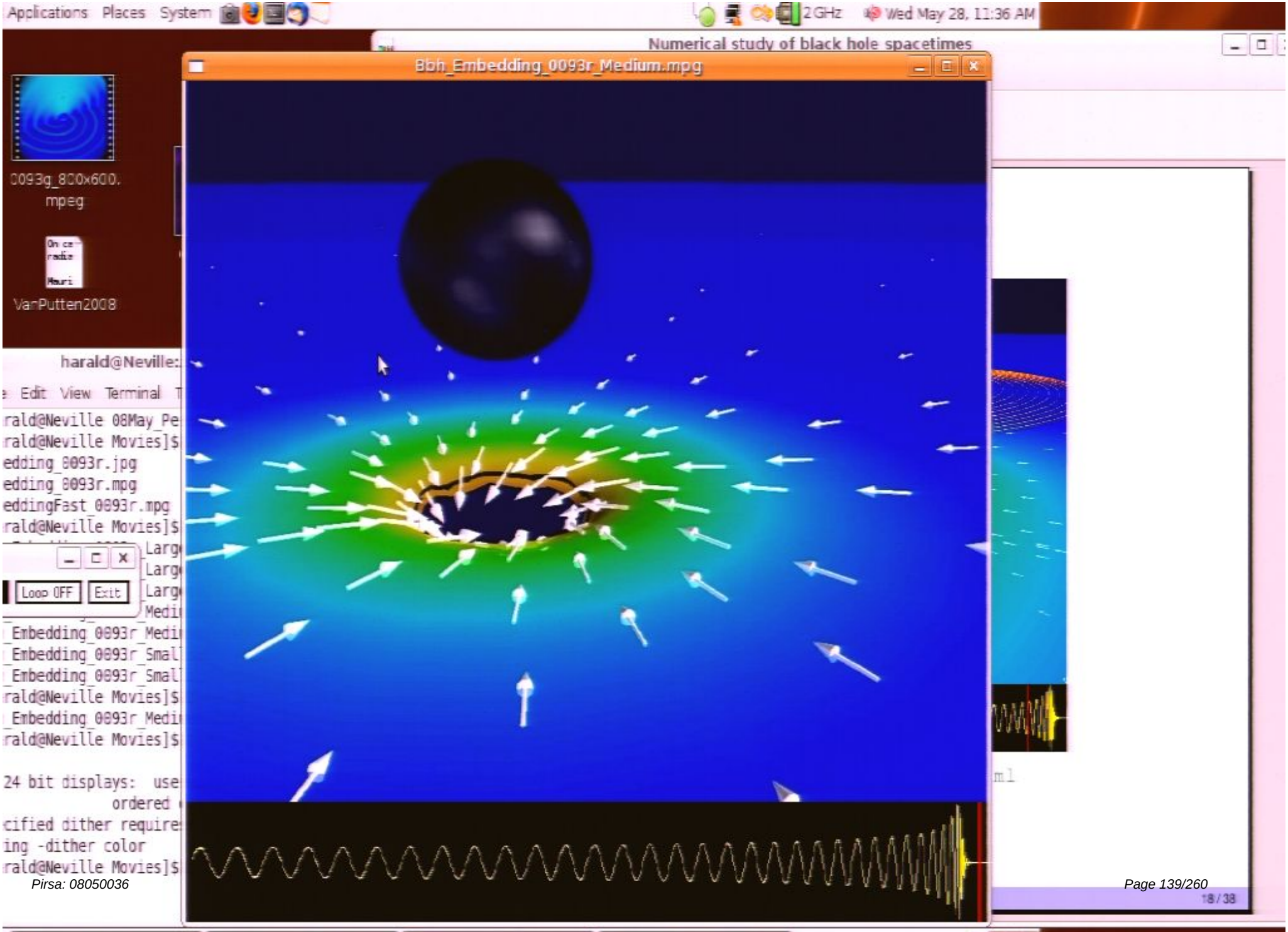

Applications Places System
2 GHz
Wed May 28, 11:36 AM
Numerical study of black hole spacetimes
Bbh_Embedding_0093r_Medium.mpg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
Loop OFF
Exit
18 / 38

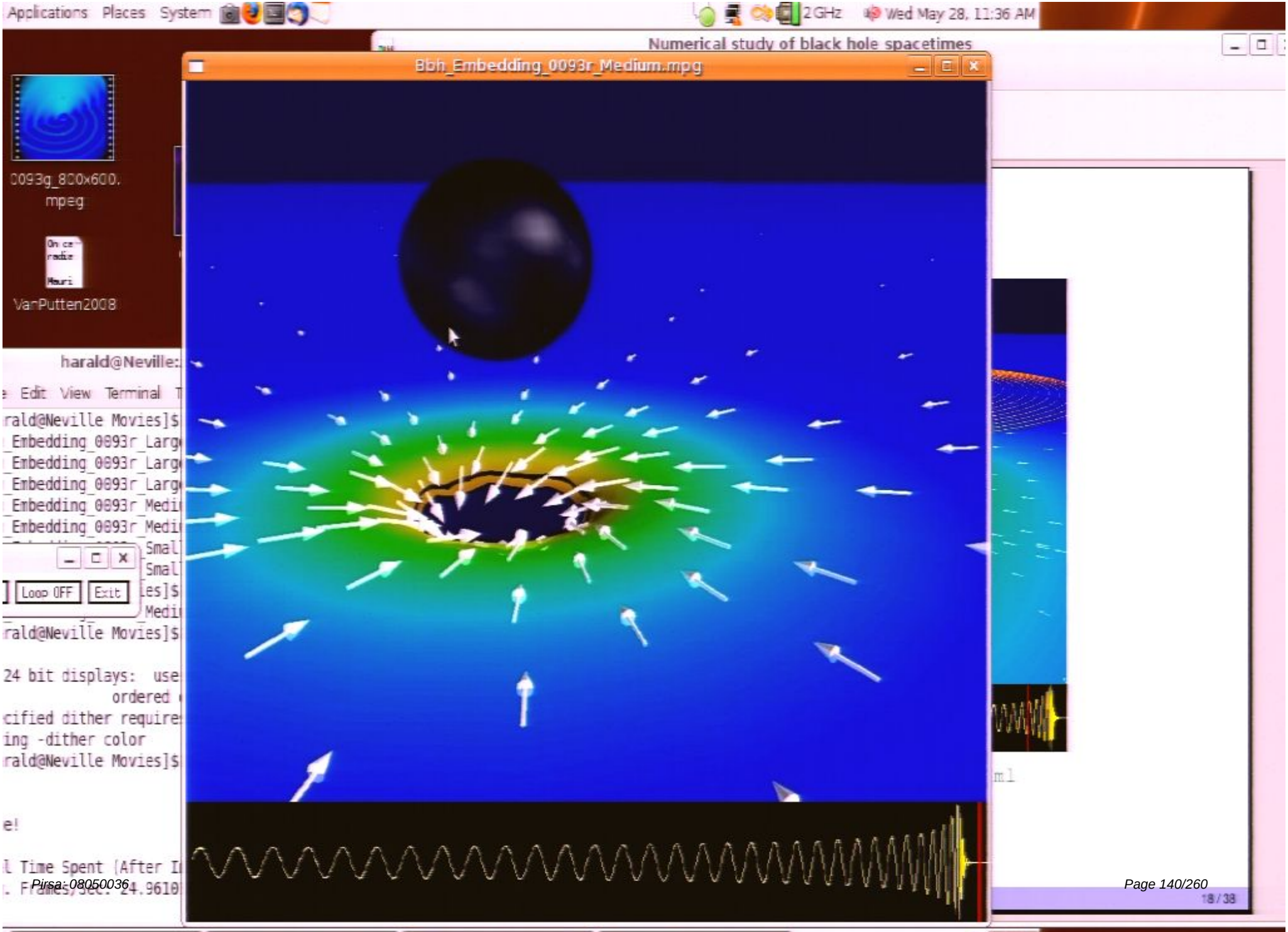

Applications Places System
2 GHz
Wed May 28, 11:36 AM
Numerical study of black hole spacetimes
Bbh_Embedding_0093r_Medium.mpg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
Loop OFF
Exit
18 / 38

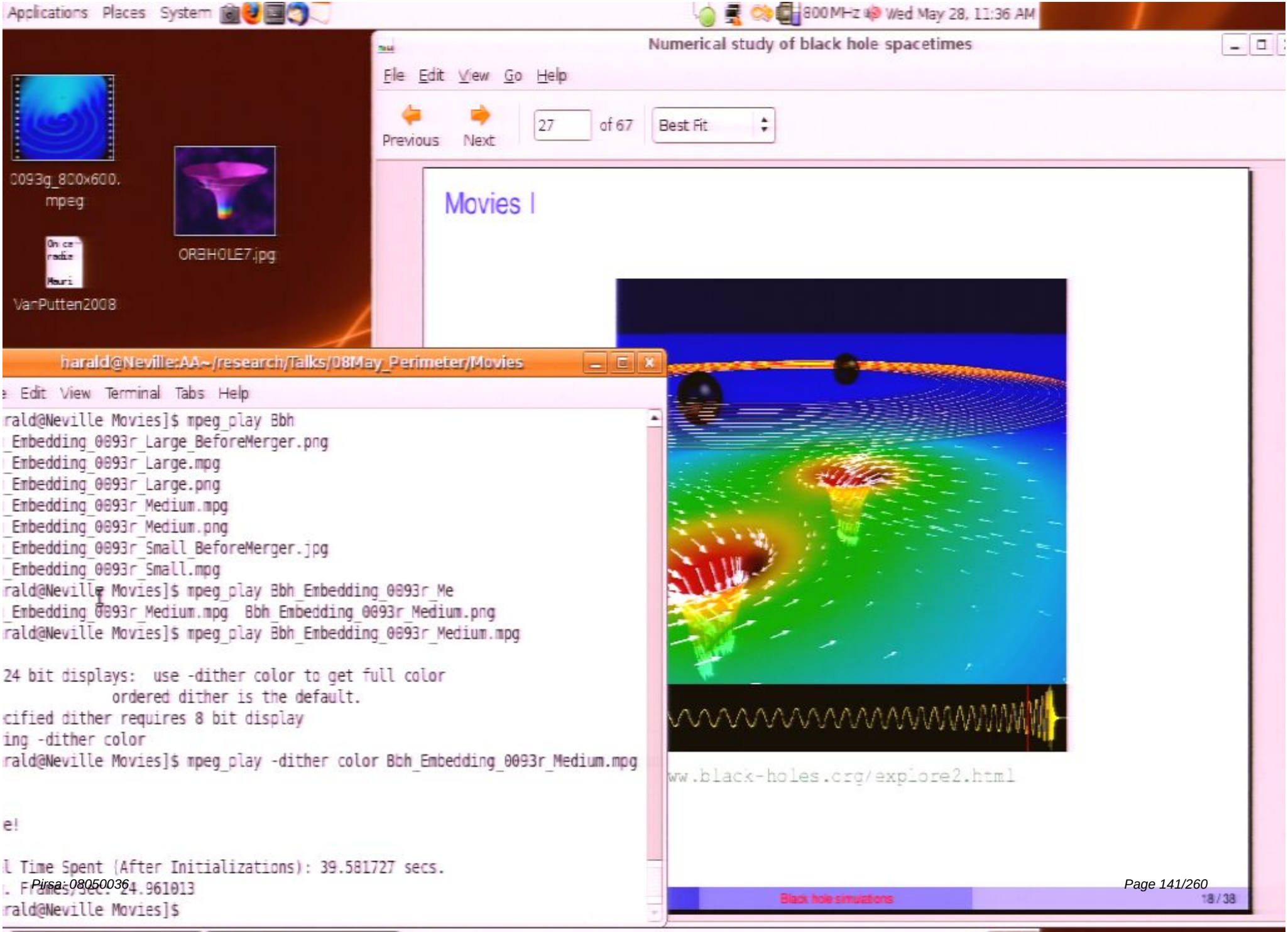

Applications Places System
2 GHz
Wed May 28, 11:36 AM
Numerical study of black hole spacetimes
Bbh_Embedding_0093r_Medium.mpg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
Loop OFF
Exit
Pirsa: 08050036
Page 136/260

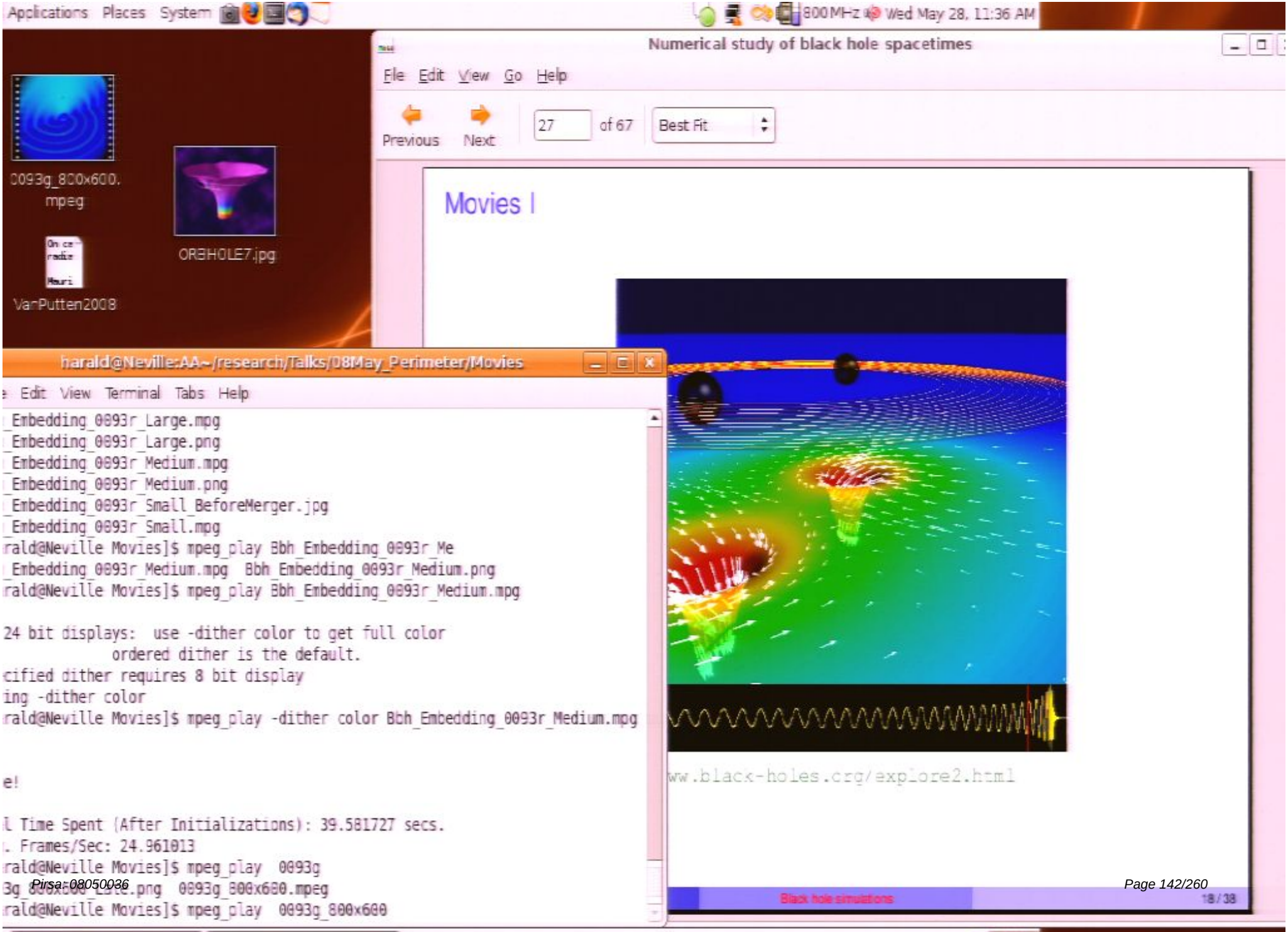

Applications Places System
2 GHz
Wed May 28, 11:36 AM
Numerical study of black hole spacetimes
Bbh_Embedding_0093r_Medium.mpg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
Loop OFF
Exit
18 / 38

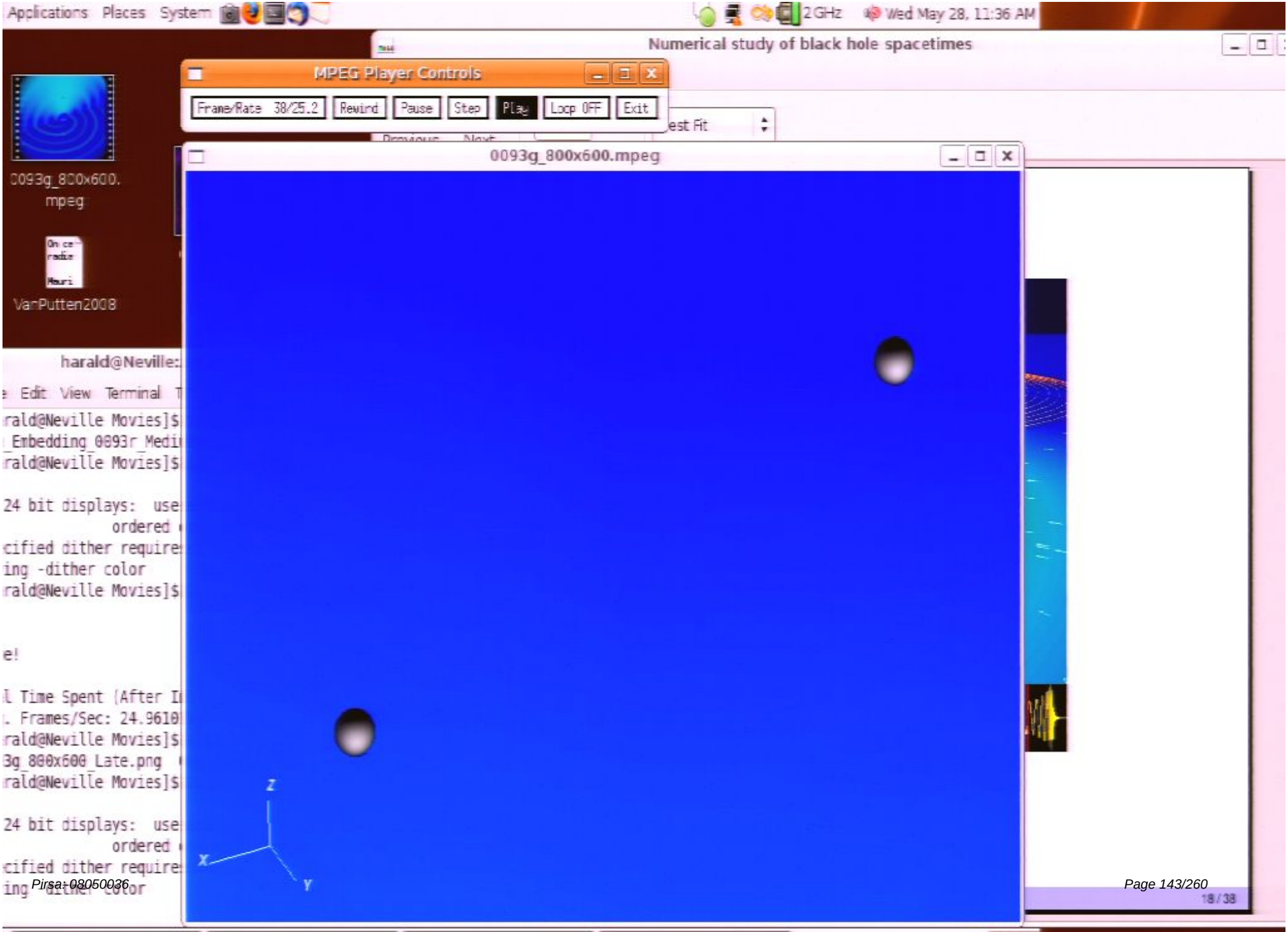

Applications Places System
2 GHz
Wed May 28, 11:36 AM
Numerical study of black hole spacetimes
Bbh_Embedding_0093r_Medium.mpg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
Loop OFF
Exit
18 / 38

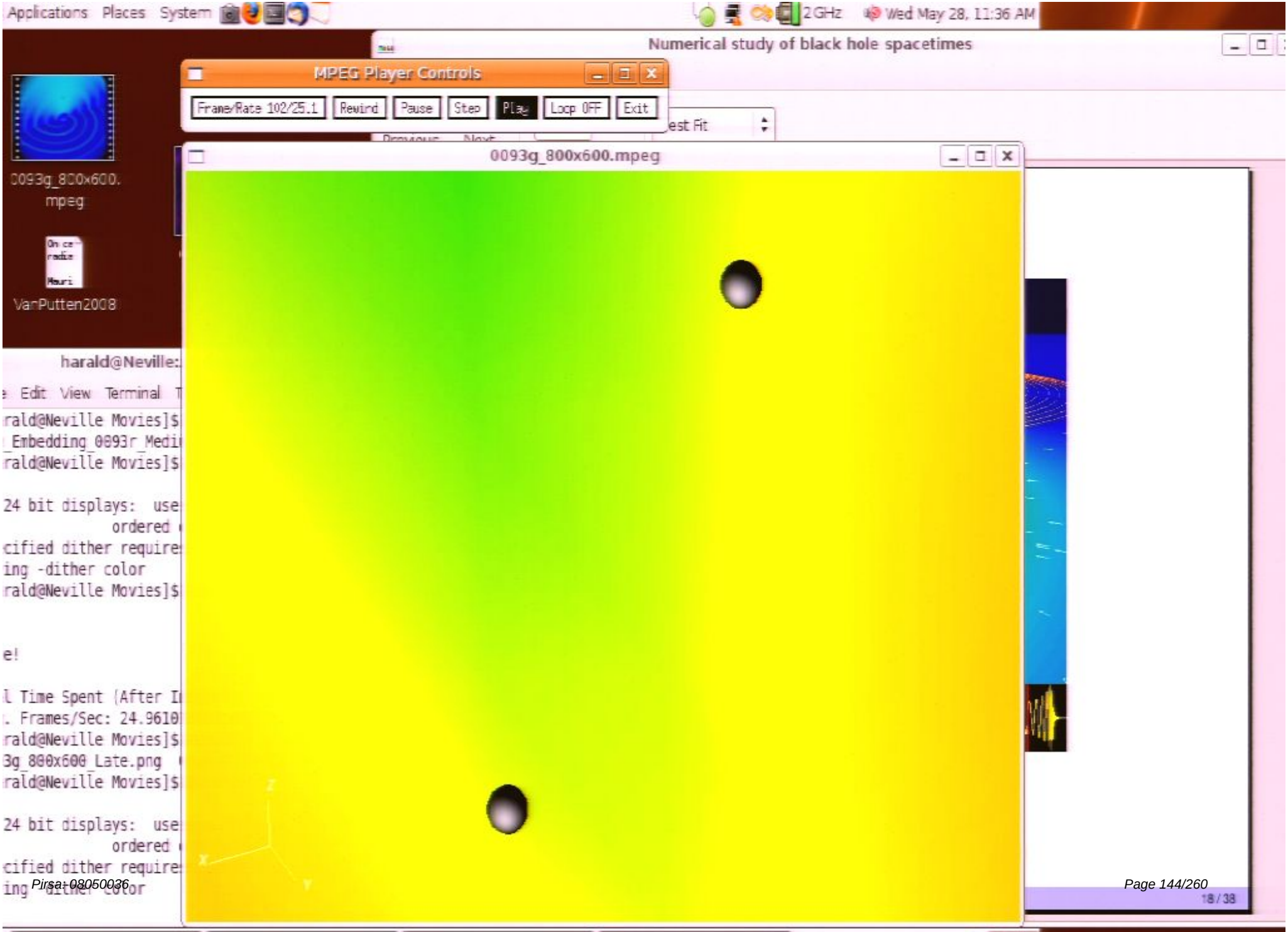

Applications Places System
2 GHz
Wed May 28, 11:36 AM
Numerical study of black hole spacetimes
Bbh_Embedding_0093r_Medium.mpg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
Loop OFF
Exit
18 / 38

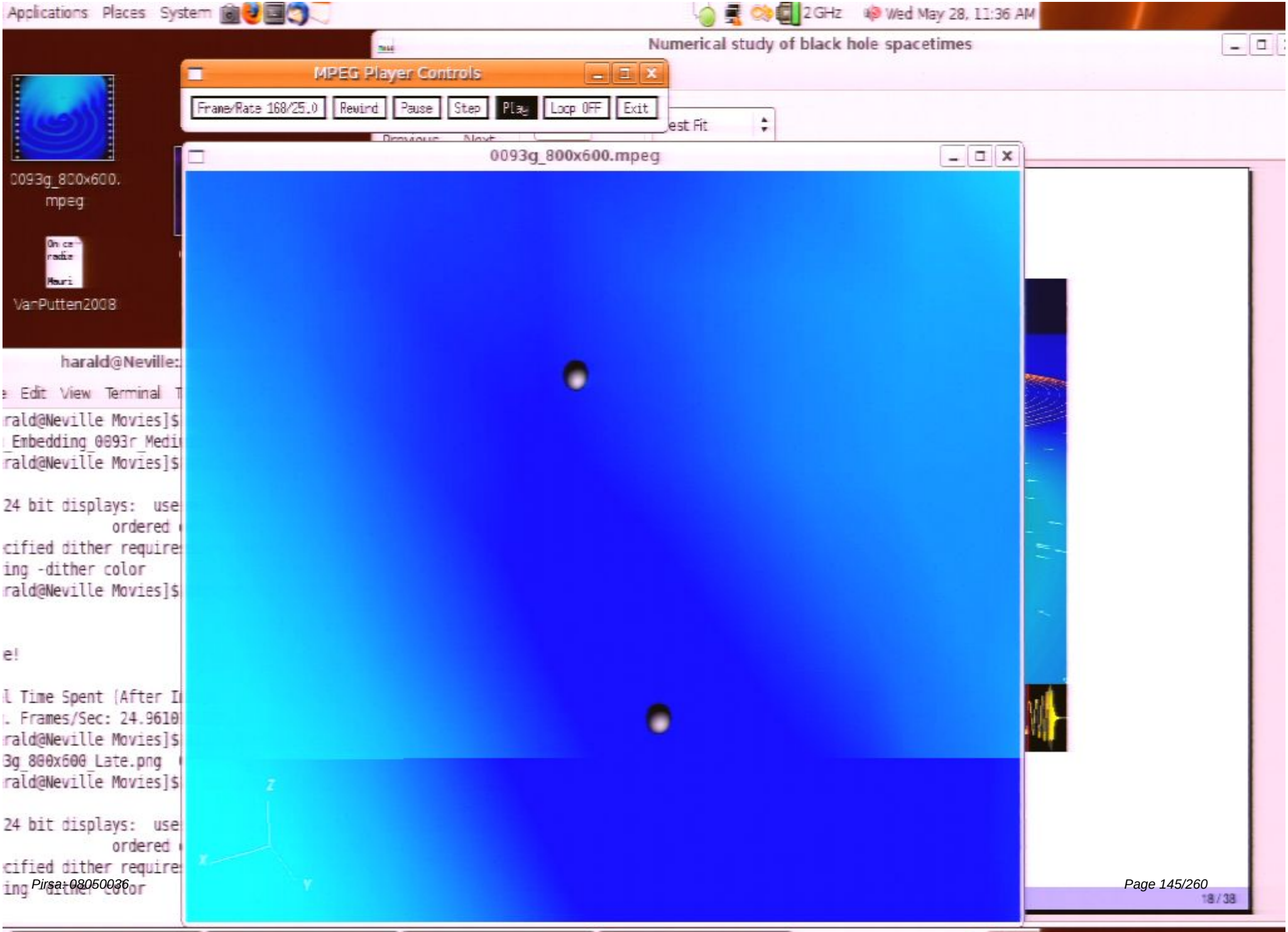

Applications Places System
2 GHz
Wed May 28, 11:36 AM
Numerical study of black hole spacetimes
Bbh_Embedding_0093r_Medium.mpg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
Loop OFF
Exit
24 bit displays: use
ordered
ing -dither color
Time Spent (After I
18 / 38

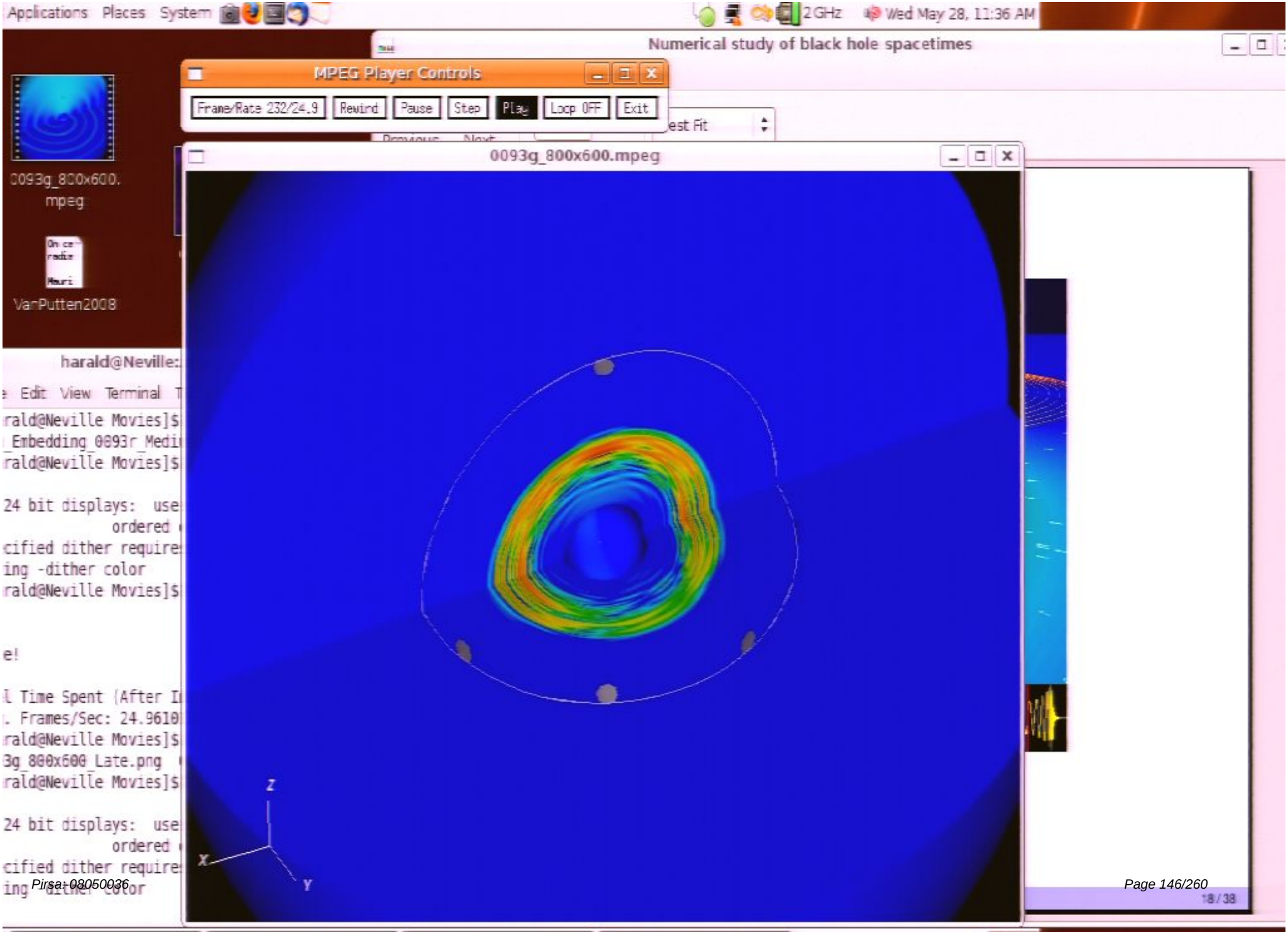

Applications Places System
800 MHz Wed May 28, 11:36 AM
0093g_800x600.mpeg
ORBHOLE7.jpg
VanPutten2008
Numerical study of black hole spacetimes
File Edit View Go Help
Previous Next
27 of 67
Best Fit
Movies I
harald@Neville:AA~/research/Talks/08May_Perimeter/Movies
Edit View Terminal Tabs Help
rald@Neville Movies]$ mpeg_play Bbh
_Embedding_0093r_Large_BeforeMerger.png
_Embedding_0093r_Large.mpg
_Embedding_0093r_Large.png
_Embedding_0093r_Medium.mpg
_Embedding_0093r_Medium.png
_Embedding_0093r_Small_BeforeMerger.jpg
_Embedding_0093r_Small.mpg
rald@Neville Movies]$ mpeg_play Bbh_Embedding_0093r_Me
_Embedding_0093r_Medium.mpg Bbh_Embedding_0093r_Medium.png
rald@Neville Movies]$ mpeg_play Bbh_Embedding_0093r_Medium.mpg
24 bit displays: use -dither color to get full color
ordered dither is the default.
cified dither requires 8 bit display
ing -dither color
rald@Neville Movies]$ mpeg_play -dither color Bbh_Embedding_0093r_Medium.mpg
e!
l Time Spent (After Initializations): 39.581727 secs.
. Frames/Sec: 24.961013
rald@Neville Movies]$
ww.black-holes.org/explore2.html
Black hole simulations
18 / 38

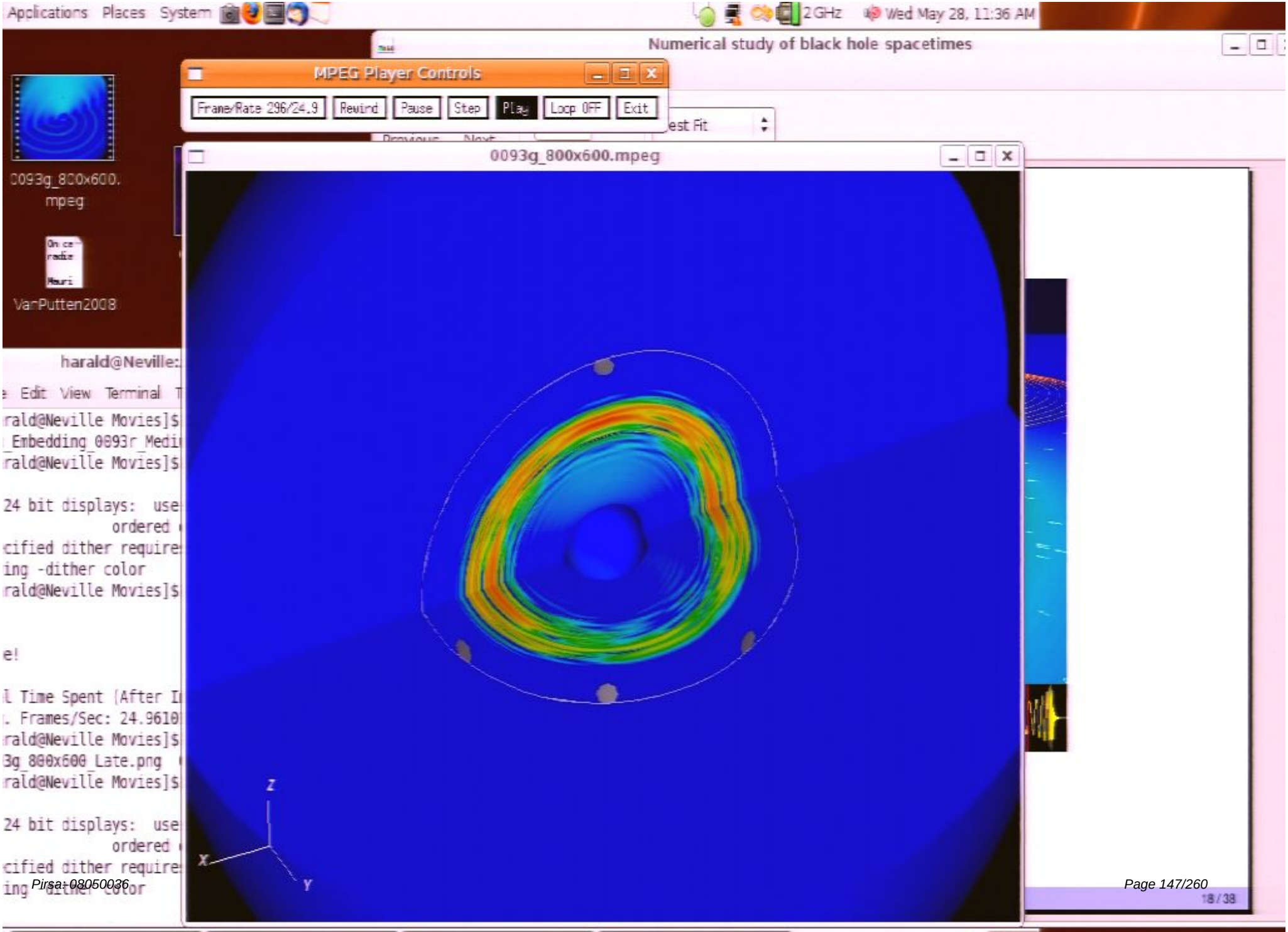

Applications Places System
800 MHz Wed May 28, 11:36 AM
0093g_800x600.mpeg
ORBHOLE7.jpg
VanPutten2008
Numerical study of black hole spacetimes
File Edit View Go Help
Previous Next
27 of 67
Best Fit
Movies I
harald@Neville:AA~/research/Talks/08May_Perimeter/Movies
Edit View Terminal Tabs Help
_Embedding_0093r_Large.mpg
_Embedding_0093r_Large.png
_Embedding_0093r_Medium.mpg
_Embedding_0093r_Medium.png
_Embedding_0093r_Small_BeforeMerger.jpg
_Embedding_0093r_Small.mpg
rald@Neville Movies]$ mpeg_play Bbh_Embedding_0093r_Me
_Embedding_0093r_Medium.mpg Bbh_Embedding_0093r_Medium.png
rald@Neville Movies]$ mpeg_play Bbh_Embedding_0093r_Medium.mpg
24 bit displays: use -dither color to get full color
ordered dither is the default.
cified dither requires 8 bit display
ing -dither color
rald@Neville Movies]$ mpeg_play -dither color Bbh_Embedding_0093r_Medium.mpg
e!
l Time Spent (After Initializations): 39.581727 secs.
. Frames/Sec: 24.961013
rald@Neville Movies]$ mpeg_play 0093g
3g_800x600_Lite.png 0093g_800x600.mpeg
rald@Neville Movies]$ mpeg_play 0093g_800x600
ww.black-holes.org/explore2.html
Black hole simulations
18 / 38

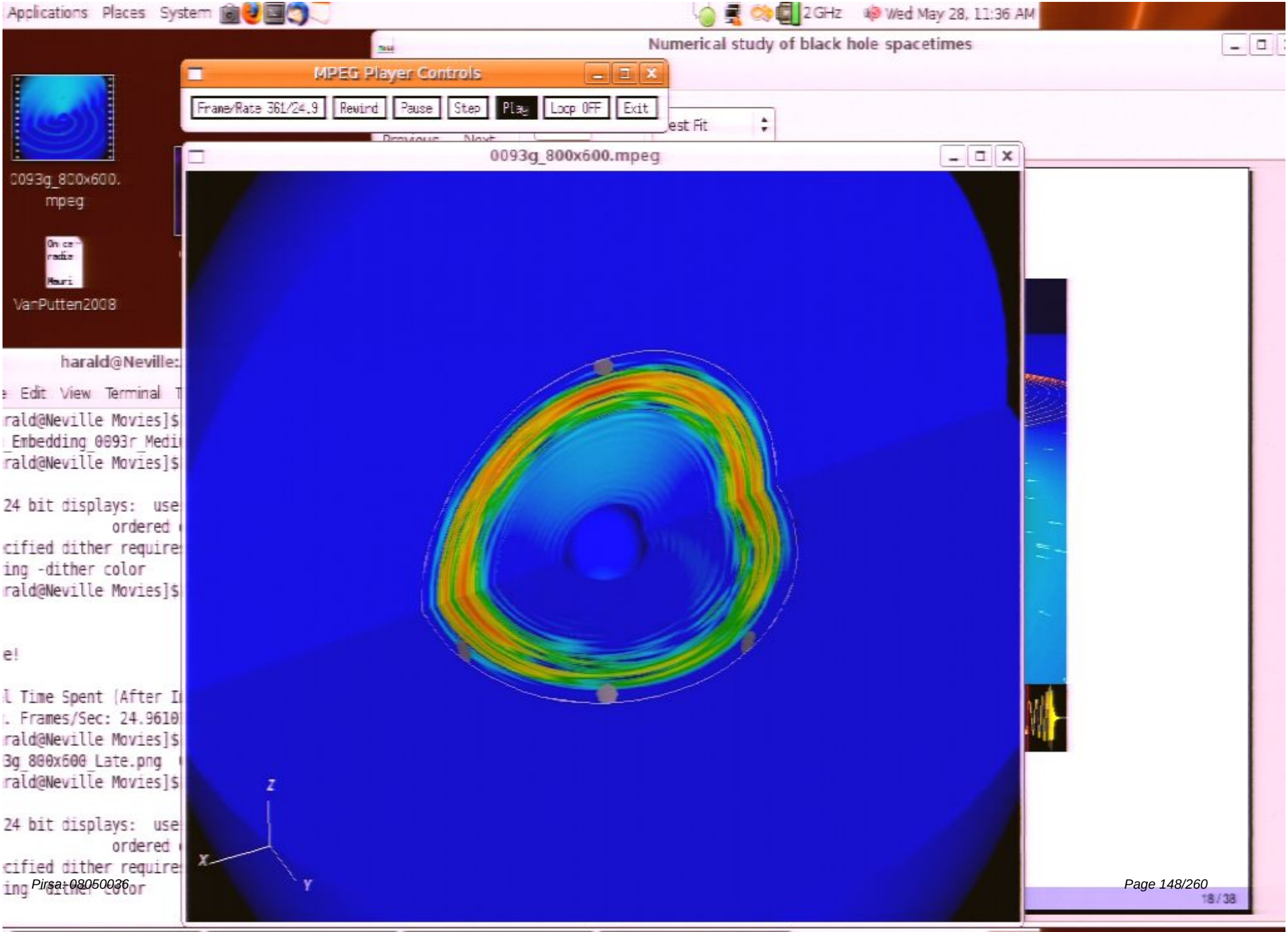

Applications Places System
2 GHz
Wed May 28, 11:36 AM
Numerical study of black hole spacetimes
MPEG Player Controls
Frame/Rate 38/25.2
Rewind
Pause
Step
Play
Loop OFF
Exit
0093g_800x600.mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
Z
X
Y
18 / 38

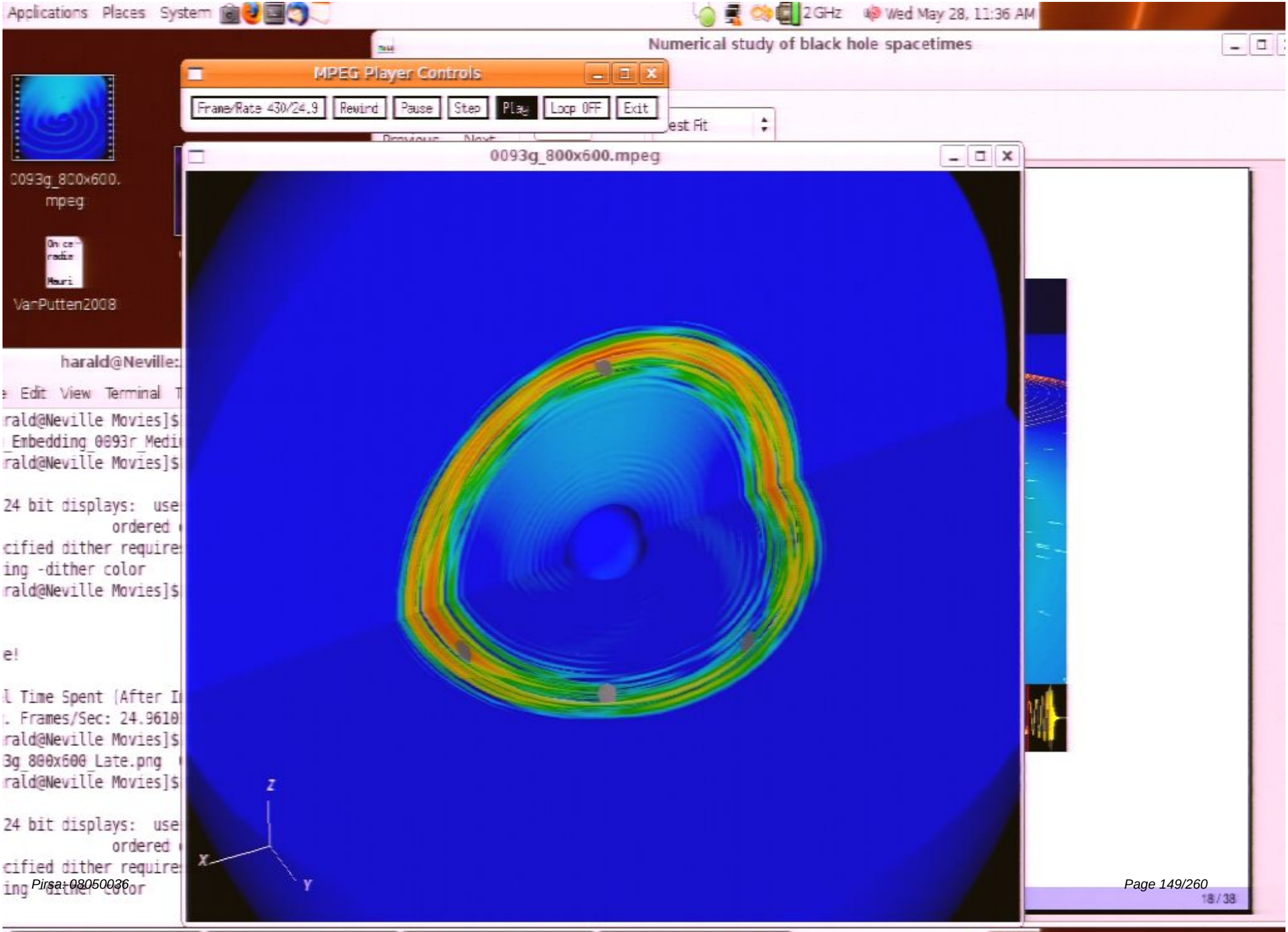

Applications Places System
2 GHz
Wed May 28, 11:36 AM
Numerical study of black hole spacetimes
MPEG Player Controls
Frame/Rate 102/25.1
Rewind
Pause
Step
Play
Loop OFF
Exit
0093g_800x600.mpeg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
rald@Neville Movies]$
_Embedding_0093r_Medi
rald@Neville Movies]$
24 bit displays: use
ordered
cified dither require
ing -dither color
rald@Neville Movies]$
e!
l Time Spent (After I
. Frames/Sec: 24.9610
rald@Neville Movies]$
3g_800x600_Late.png
rald@Neville Movies]$
24 bit displays: use
ordered
cified dither require
ing -dither color
18 / 38

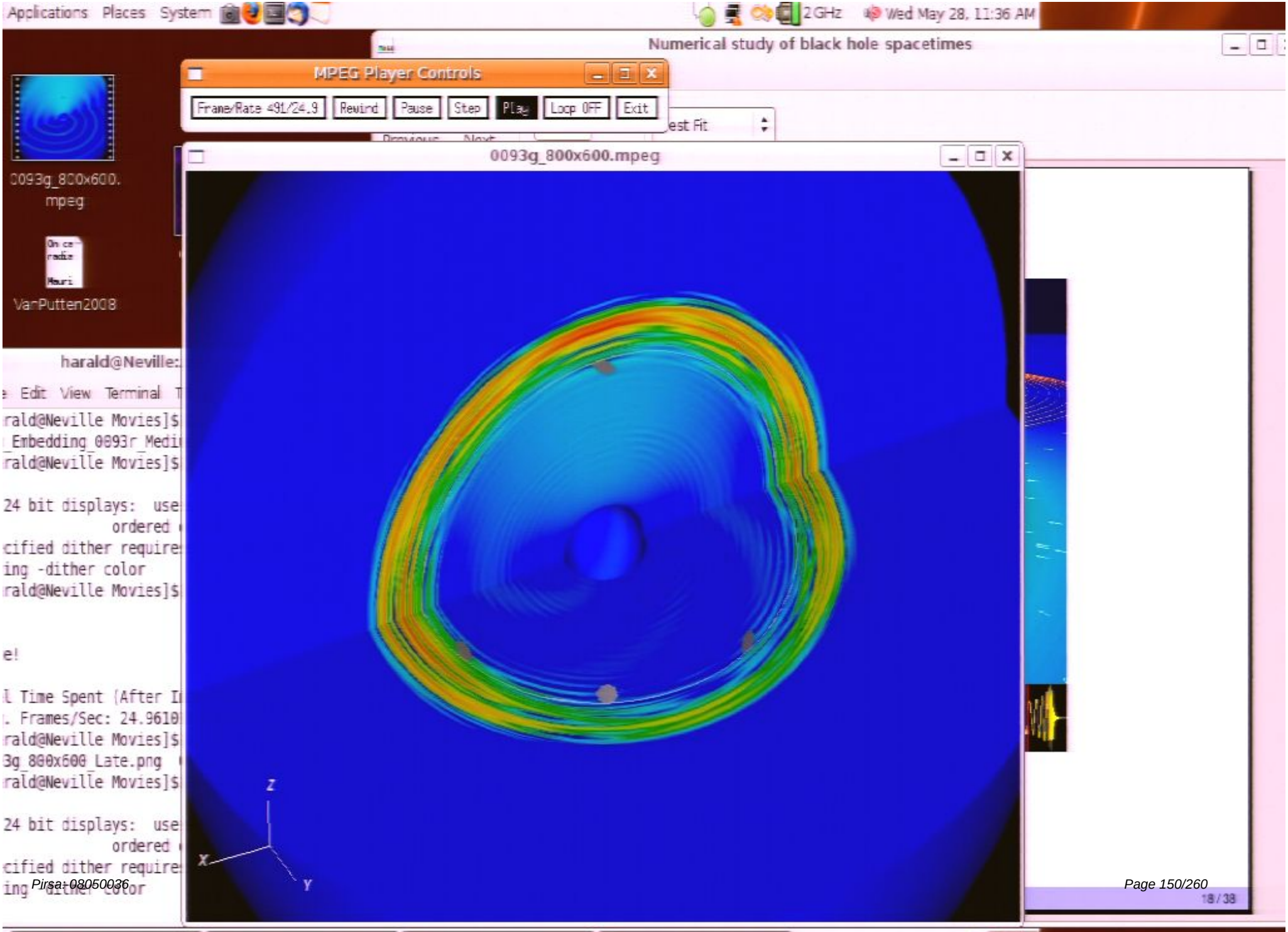

Applications Places System
2 GHz
Wed May 28, 11:36 AM
Numerical study of black hole spacetimes
MPEG Player Controls
Frame/Rate 168/25.0
Rewind
Pause
Step
Play
Loop OFF
Exit
0093g_800x600.mpeg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
rald@Neville Movies]$
Embedding_0093r_Medi
rald@Neville Movies]$
24 bit displays: use
ordered
cified dither require
ing -dither color
rald@Neville Movies]$
e!
l Time Spent (After I
. Frames/Sec: 24.9610
rald@Neville Movies]$
3g_800x600_Late.png
rald@Neville Movies]$
24 bit displays: use
ordered
cified dither require
ing -dither color
18 / 38

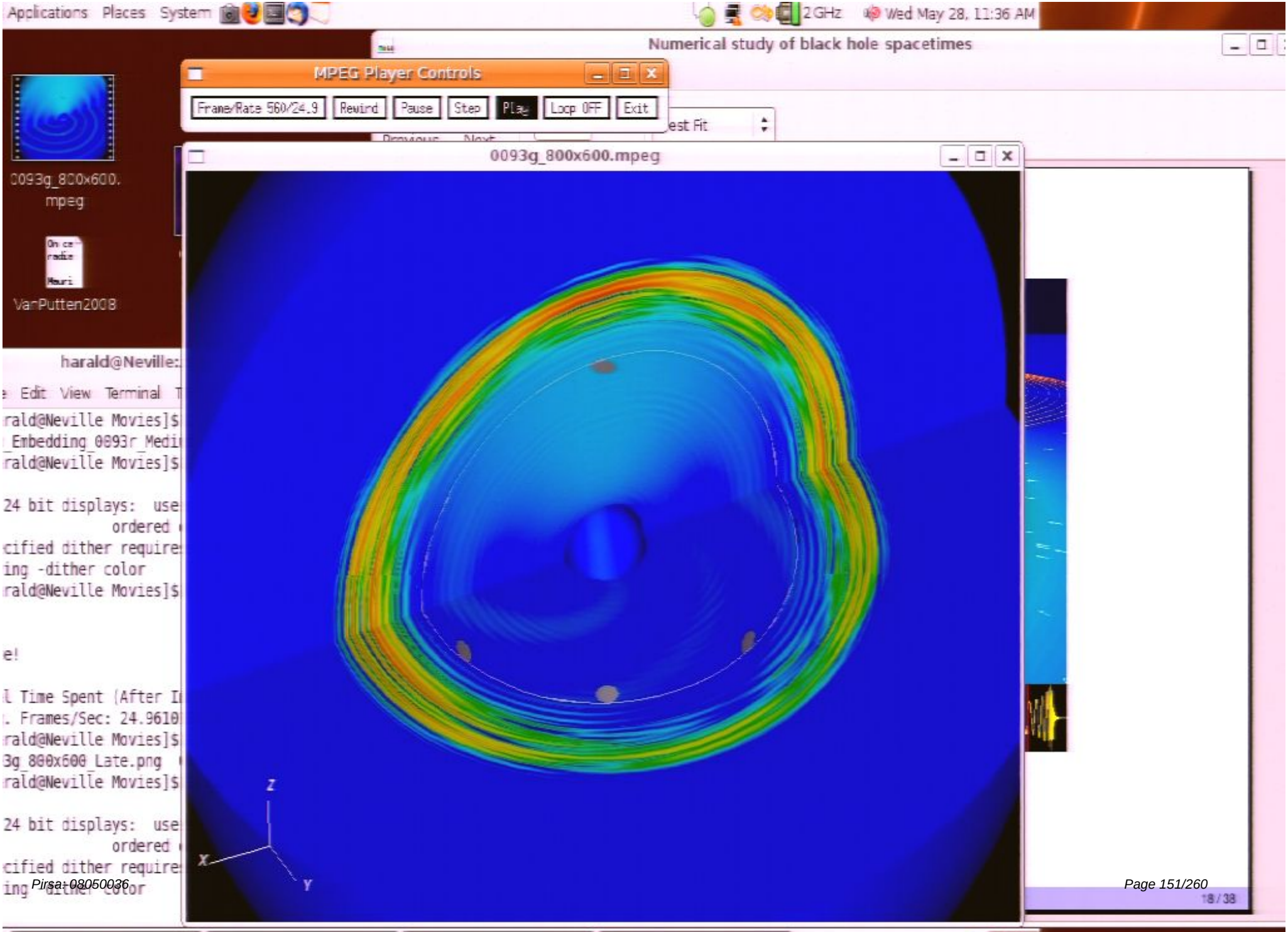

Applications Places System
2 GHz
Wed May 28, 11:36 AM
Numerical study of black hole spacetimes
MPEG Player Controls
Frame/Rate 232/24.9
Rewind
Pause
Step
Play
Loop OFF
Exit
0093g_800x600.mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
Z
X
Y

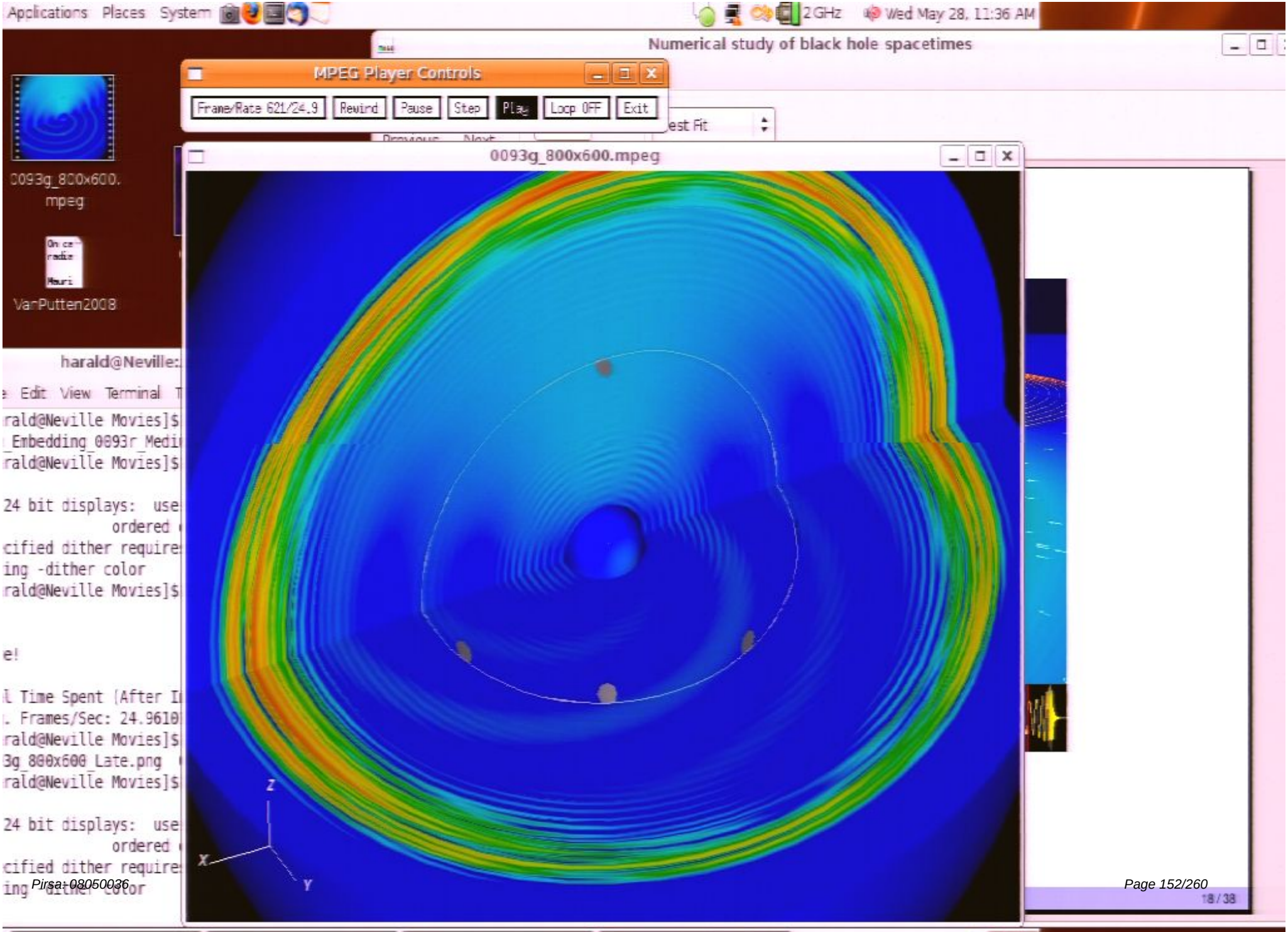

Applications Places System
2 GHz
Wed May 28, 11:36 AM
Numerical study of black hole spacetimes
MPEG Player Controls
Frame/Rate 296/24.9
Rewind
Pause
Step
Play
Loop OFF
Exit
0093g_800x600.mpeg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
Z
X
Y


Applications Places System
2 GHz
Wed May 28, 11:36 AM
Numerical study of black hole spacetimes
MPEG Player Controls
Frame/Rate 361/24.9
Rewind
Pause
Step
Play
Loop OFF
Exit
0093g_800x600.mpeg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
Z
X
Y


Applications Places System
2 GHz
Wed May 28, 11:36 AM
Numerical study of black hole spacetimes
MPEG Player Controls
Frame/Rate 430/24.9
Rewind
Pause
Step
Play
Loop OFF
Exit
0093g_800x600.mpeg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
Z
X
Y


Applications Places System
2 GHz
Wed May 28, 11:36 AM
Numerical study of black hole spacetimes
MPEG Player Controls
Frame/Rate 491/24.9
Rewind
Pause
Step
Play
Loop OFF
Exit
0093g_800x600.mpeg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
Z
X
Y


Applications Places System
2 GHz
Wed May 28, 11:36 AM
Numerical study of black hole spacetimes
MPEG Player Controls
Frame/Rate 560/24.9
Rewind
Pause
Step
Play
Loop OFF
Exit
0093g_800x600.mpeg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
24 bit displays: use
ordered
ing -dither color
e!
Time Spent (After I
Frames/Sec: 24.9610
3g_800x600_Late.png
24 bit displays: use
ordered
ing -dither color
Z
X
Y
18 / 38


Applications Places System
2 GHz
Wed May 28, 11:36 AM
Numerical study of black hole spacetimes
MPEG Player Controls
Frame/Rate 621/24.9
Rewind
Pause
Step
Play
Loop OFF
Exit
0093g_800x600.mpeg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
ralD@Neville Movies]$
Embedding 0093r Medi
ralD@Neville Movies]$
24 bit displays: use
ordered
cified dither require
ing -dither color
ralD@Neville Movies]$
e!
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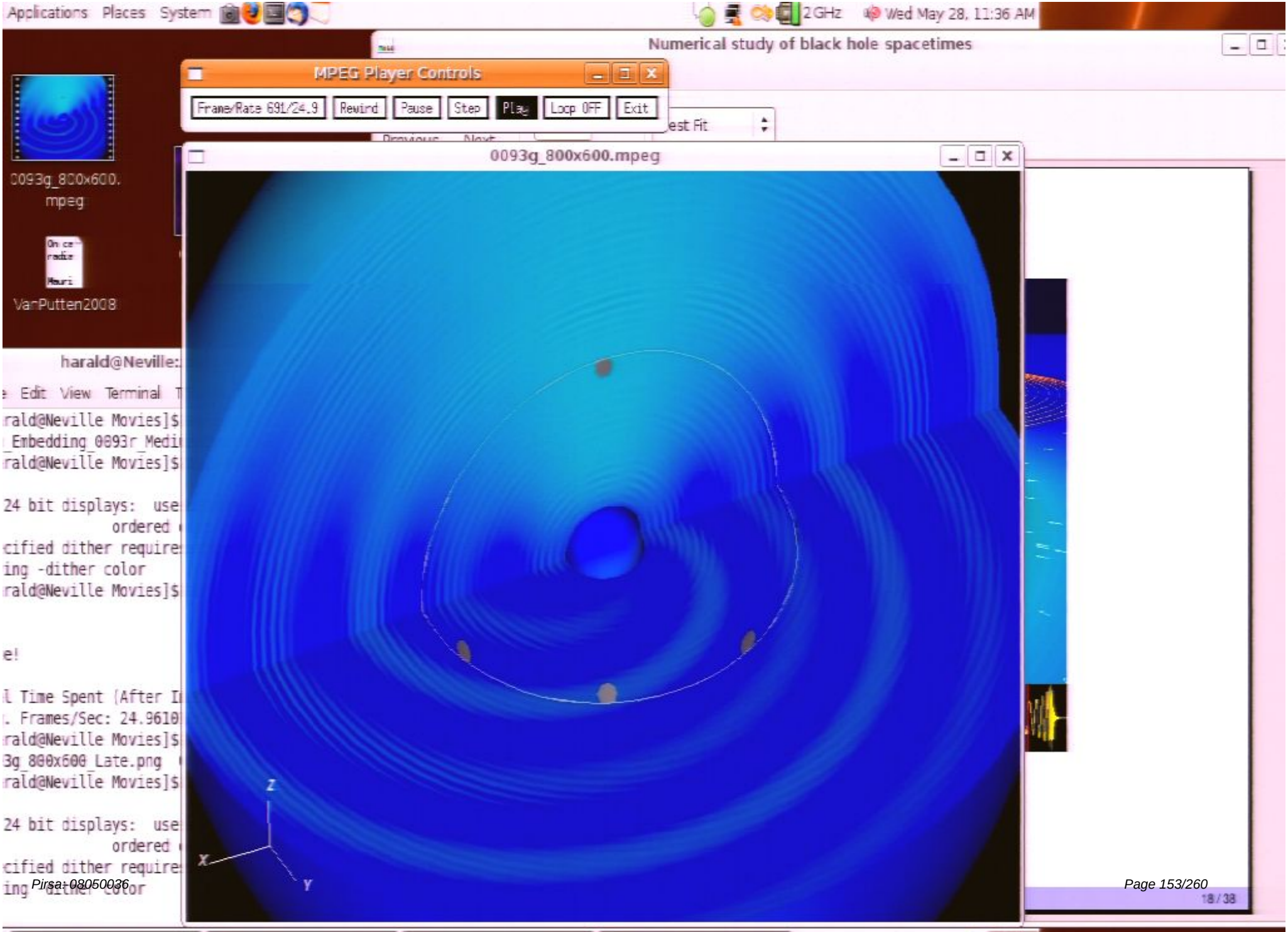
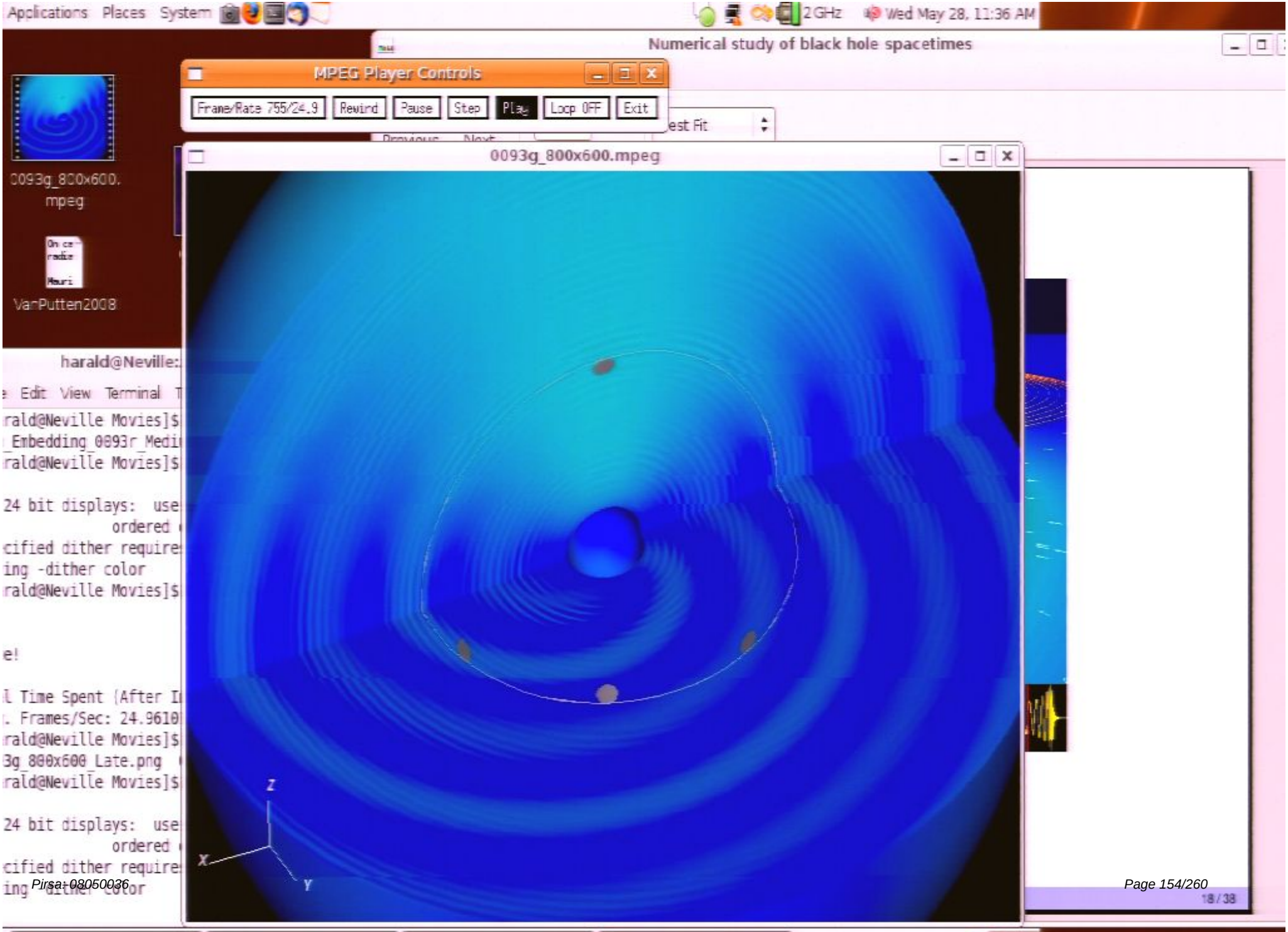
ralD@Neville Movies]$
3g_800x600_Late.png
ralD@Neville Movies]$
24 bit displays: use
ordered
cified dither require
ing -dither color
Z
X
Y
18 / 38


Applications Places System
2 GHz
Wed May 28, 11:36 AM
Numerical study of black hole spacetimes
MPEG Player Controls
Frame/Rate 691/24.9
Rewind
Pause
Step
Play
Loop OFF
Exit
0093g_800x600.mpeg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
Z
X
Y


Applications Places System
2 GHz
Wed May 28, 11:36 AM
Numerical study of black hole spacetimes
MPEG Player Controls
Frame/Rate 755/24.9
Rewind
Pause
Step
Play
Loop OFF
Exit
0093g_800x600.mpeg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
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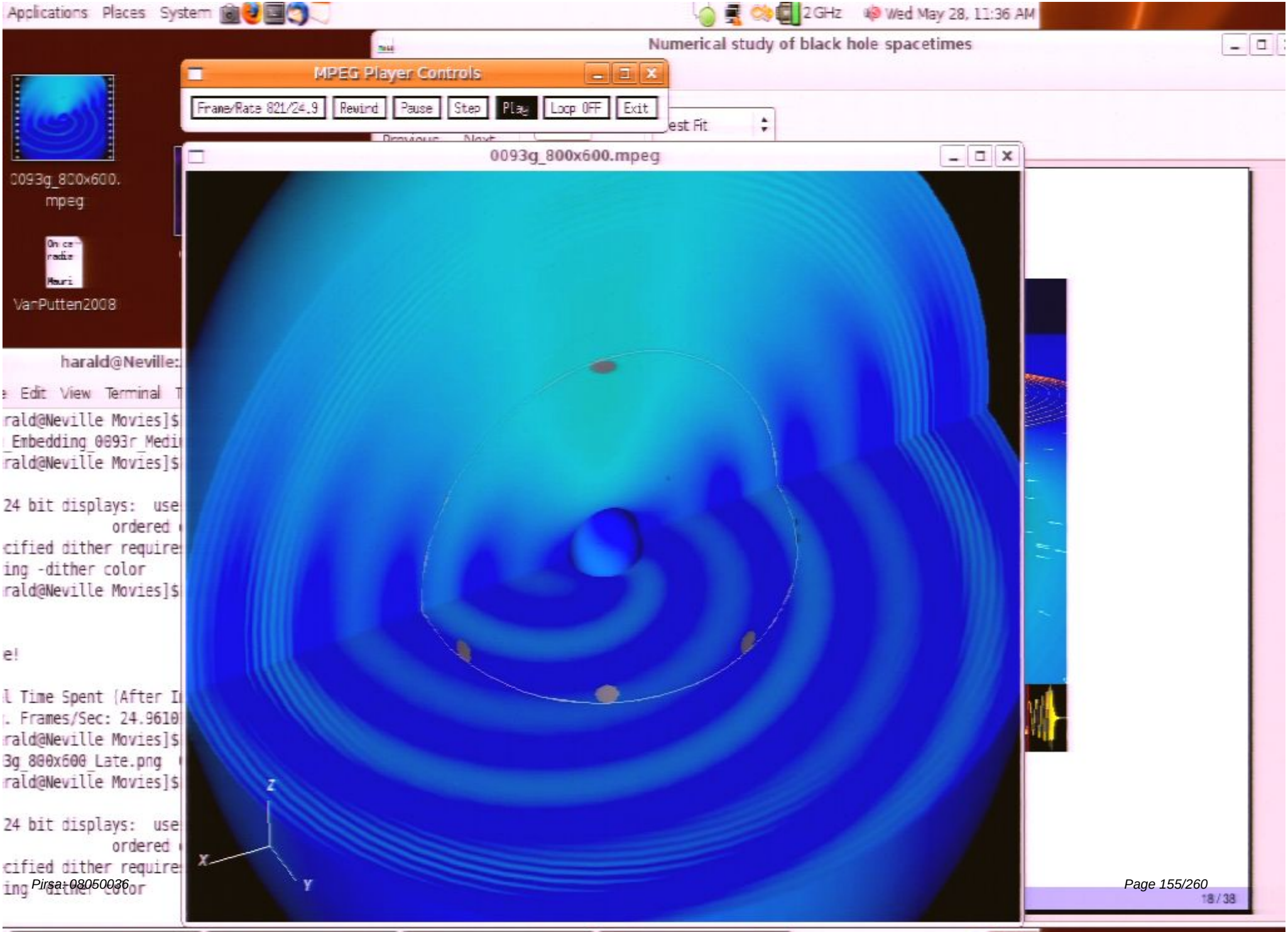
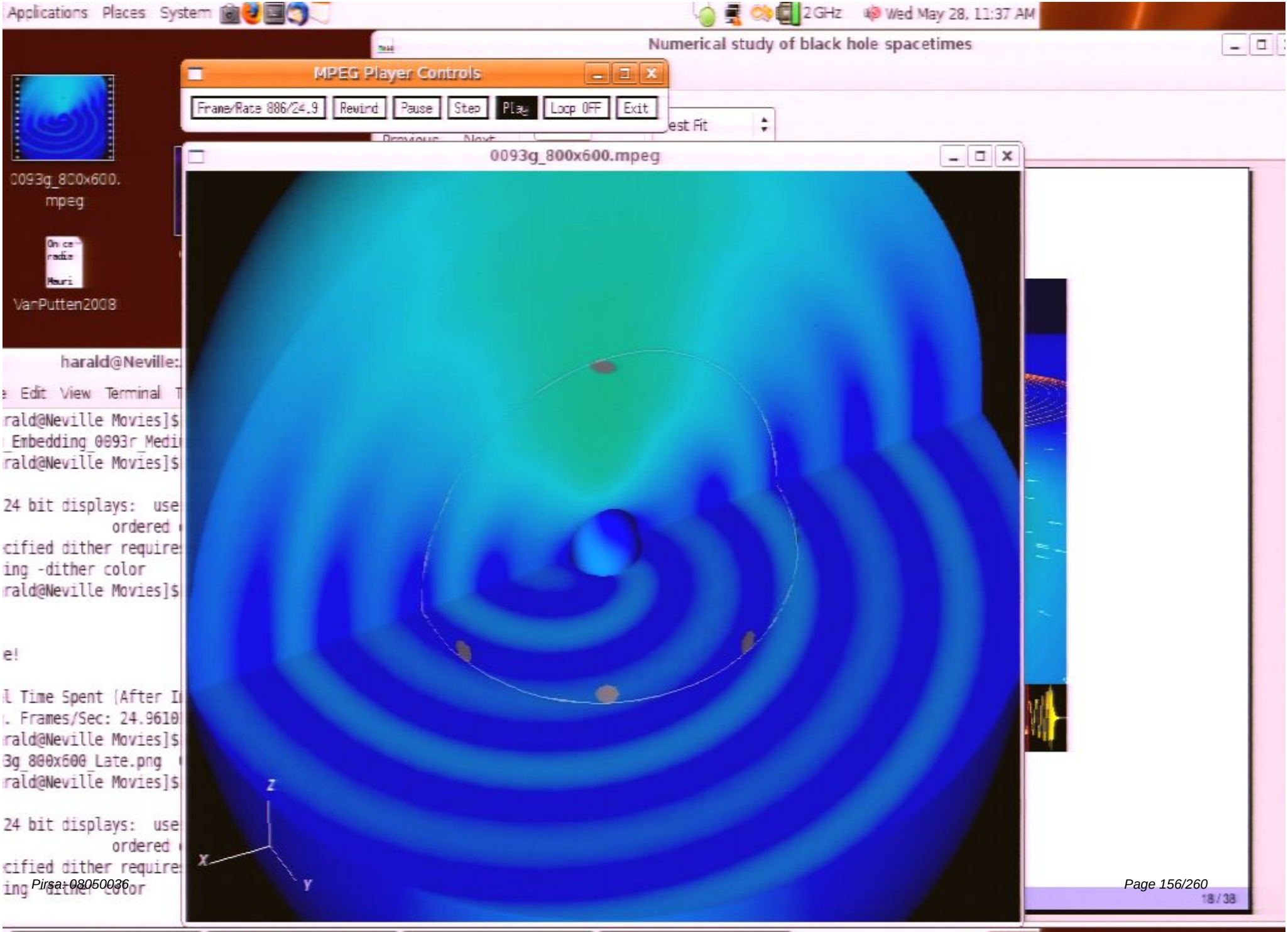
Y


Applications Places System
2 GHz
Wed May 28, 11:36 AM
Numerical study of black hole spacetimes
MPEG Player Controls
Frame/Rate 821/24.9
Rewind
Pause
Step
Play
Loop OFF
Exit
0093g_800x600.mpeg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
Z
X
Y


Applications Places System
2 GHz
Wed May 28, 11:37 AM
Numerical study of black hole spacetimes
MPEG Player Controls
Frame/Rate 886/24.9
Rewind
Pause
Step
Play
Loop OFF
Exit
0093g_800x600.mpeg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
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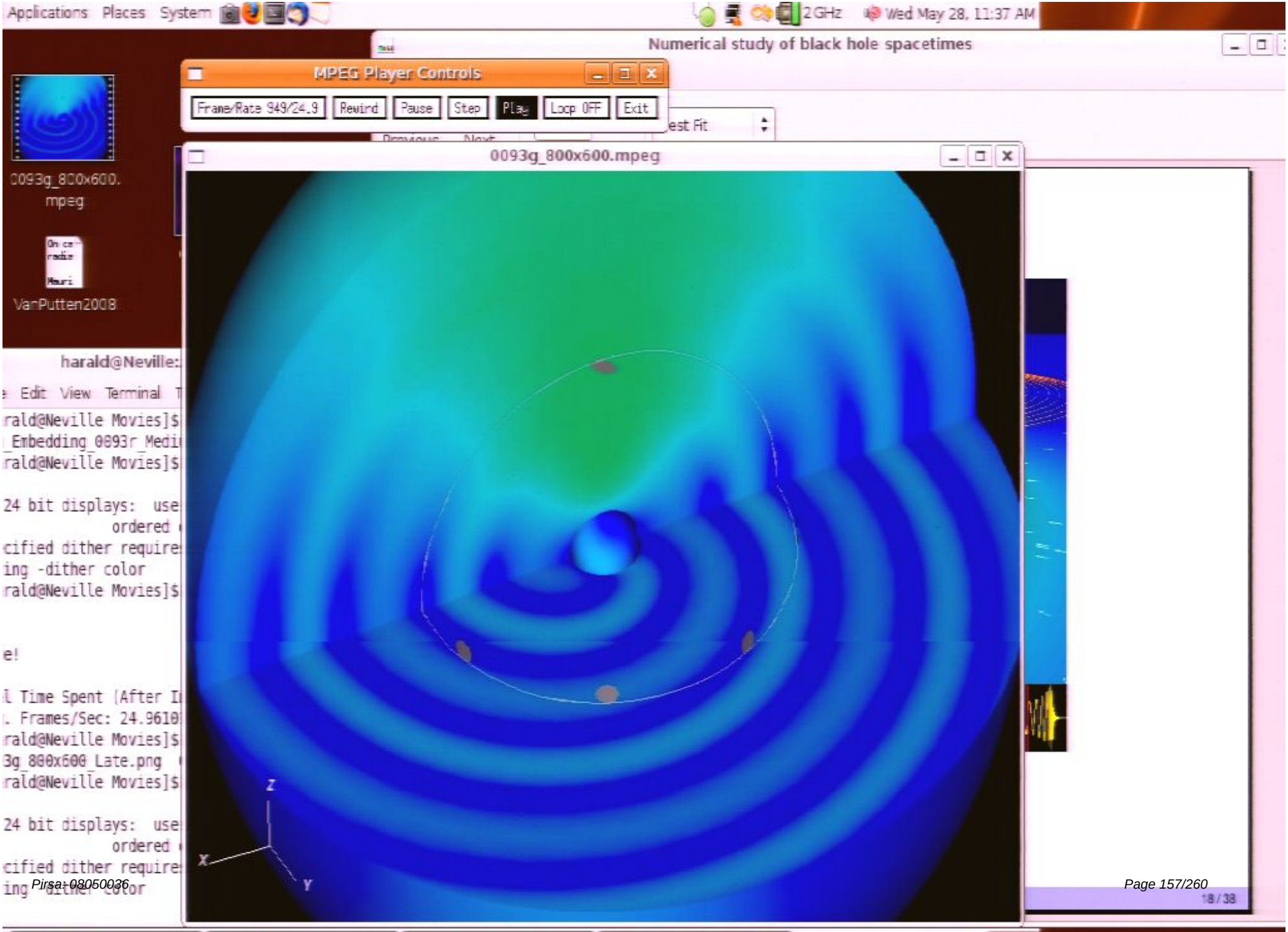
X
Y


Applications Places System
2 GHz
Wed May 28, 11:37 AM
Numerical study of black hole spacetimes
MPEG Player Controls
Frame/Rate 949/24.9
Rewind
Pause
Step
Play
Loop OFF
Exit
0093g_800x600.mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
Z
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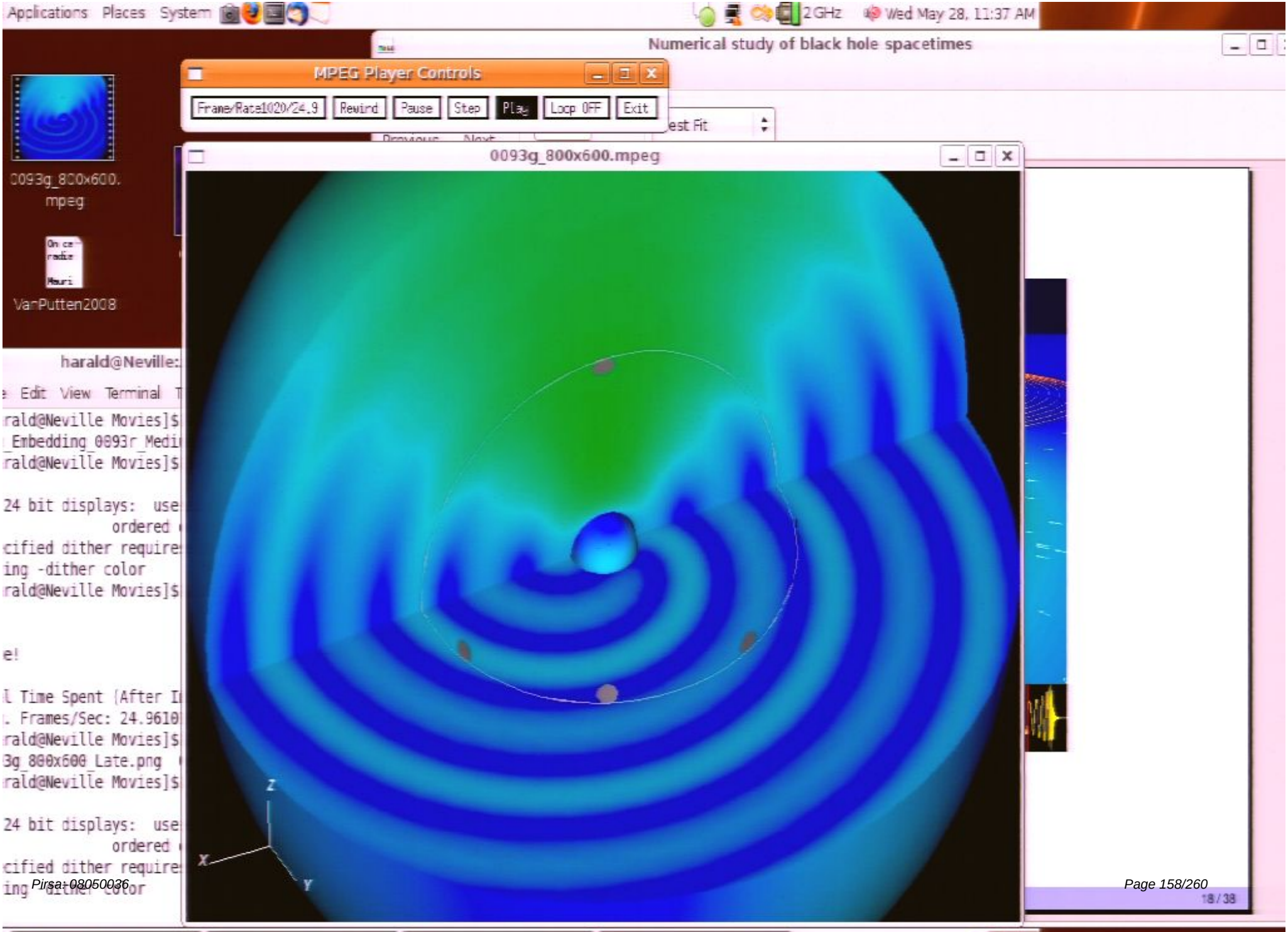
Y


Applications Places System
2GHz
Wed May 28, 11:37 AM
Numerical study of black hole spacetimes
MPEG Player Controls
Frame/Rate1020/24.9
Rewind
Pause
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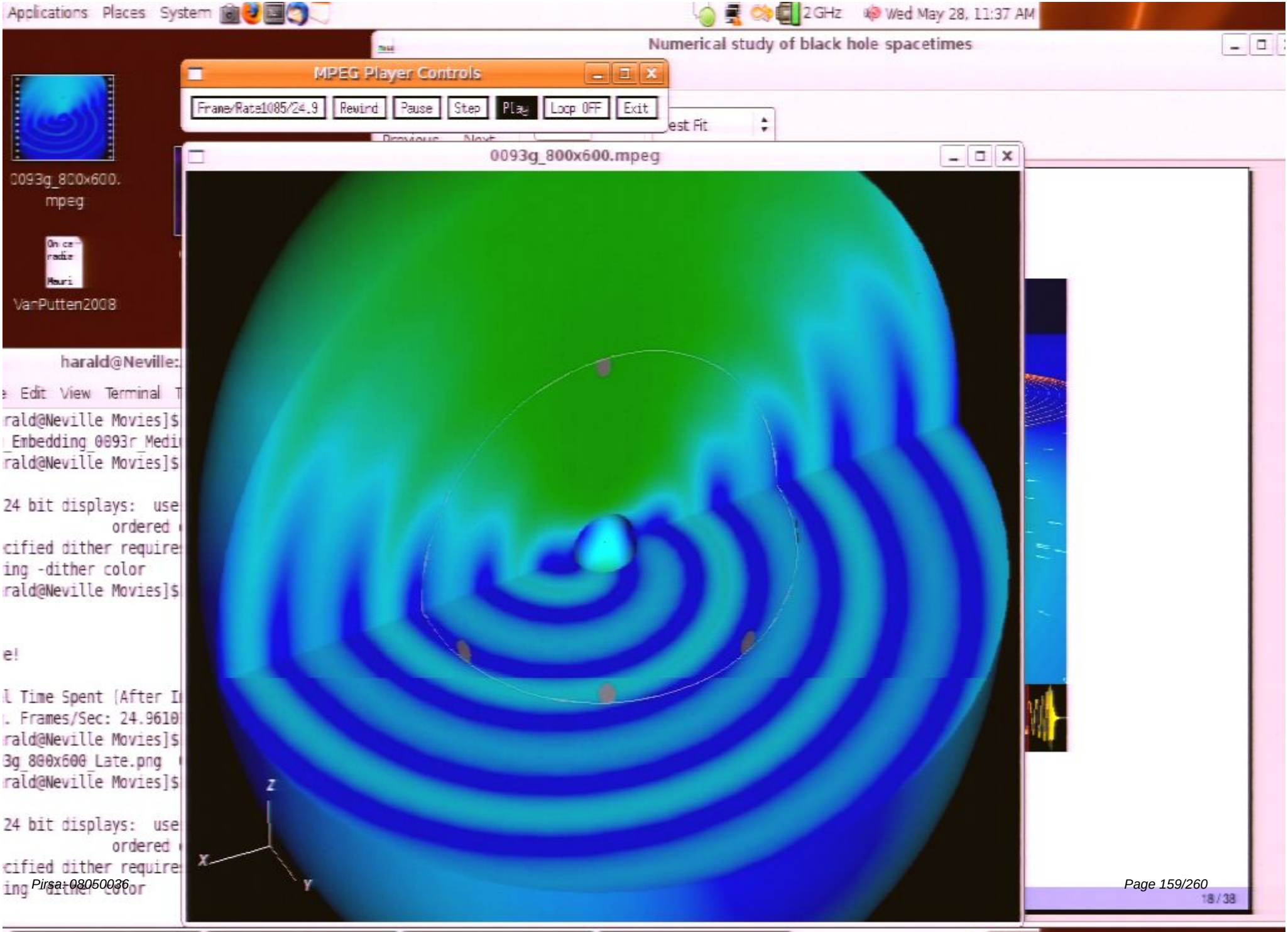
Play
Loop OFF
Exit
0093g_800x600.mpeg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
Z
X
Y


Applications Places System
2 GHz
Wed May 28, 11:37 AM
Numerical study of black hole spacetimes
MPEG Player Controls
Frame/Rate1085/24.9
Rewind
Pause
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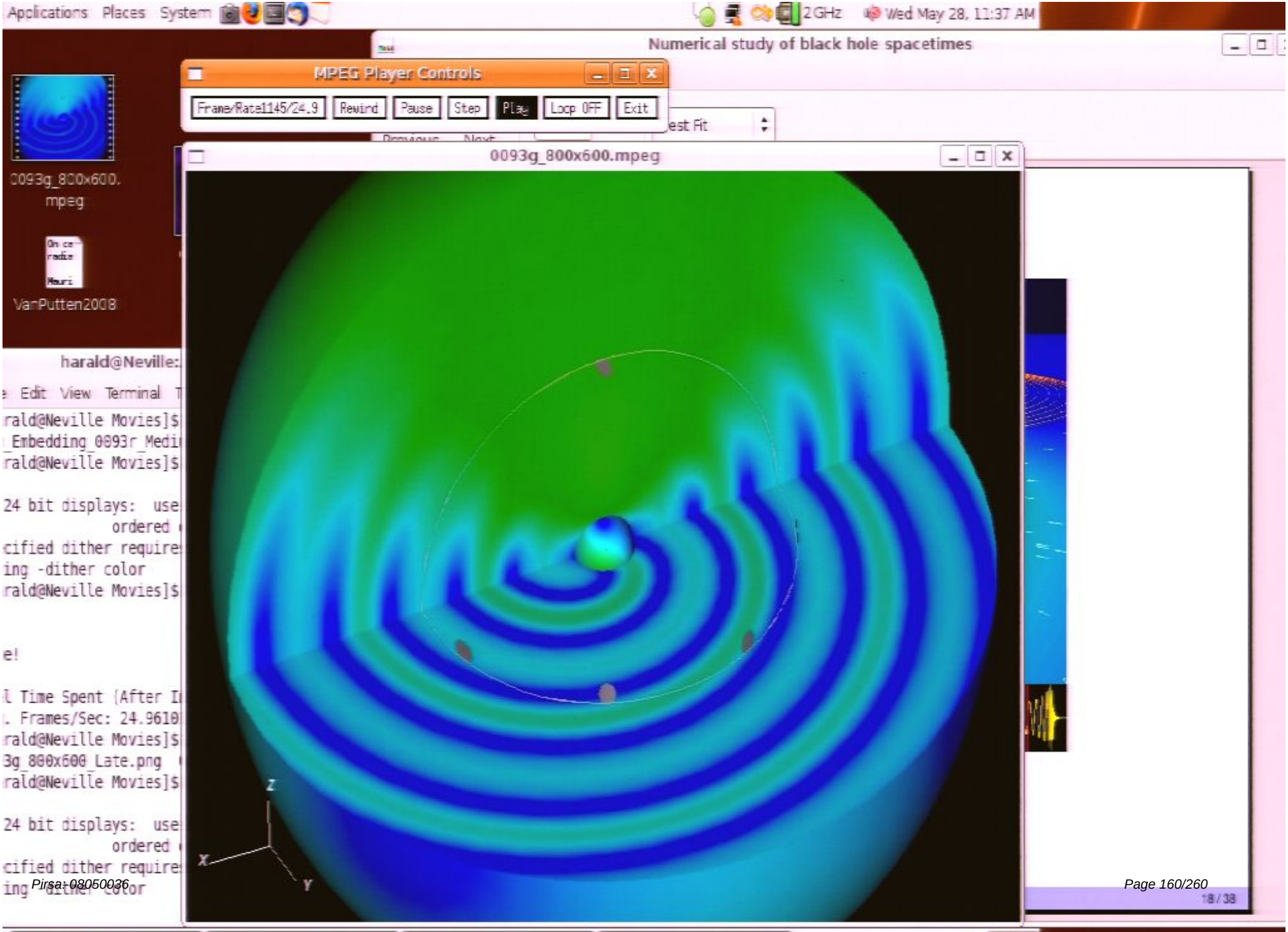
Play
Loop OFF
Exit
0093g_800x600.mpeg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
Z
X
Y


Applications Places System
2 GHz
Wed May 28, 11:37 AM
Numerical study of black hole spacetimes
MPEG Player Controls
Frame/Rate1145/24.9
Rewind
Pause
Step
Play
Loop OFF
Exit
0093g_800x600.mpeg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
Z
X
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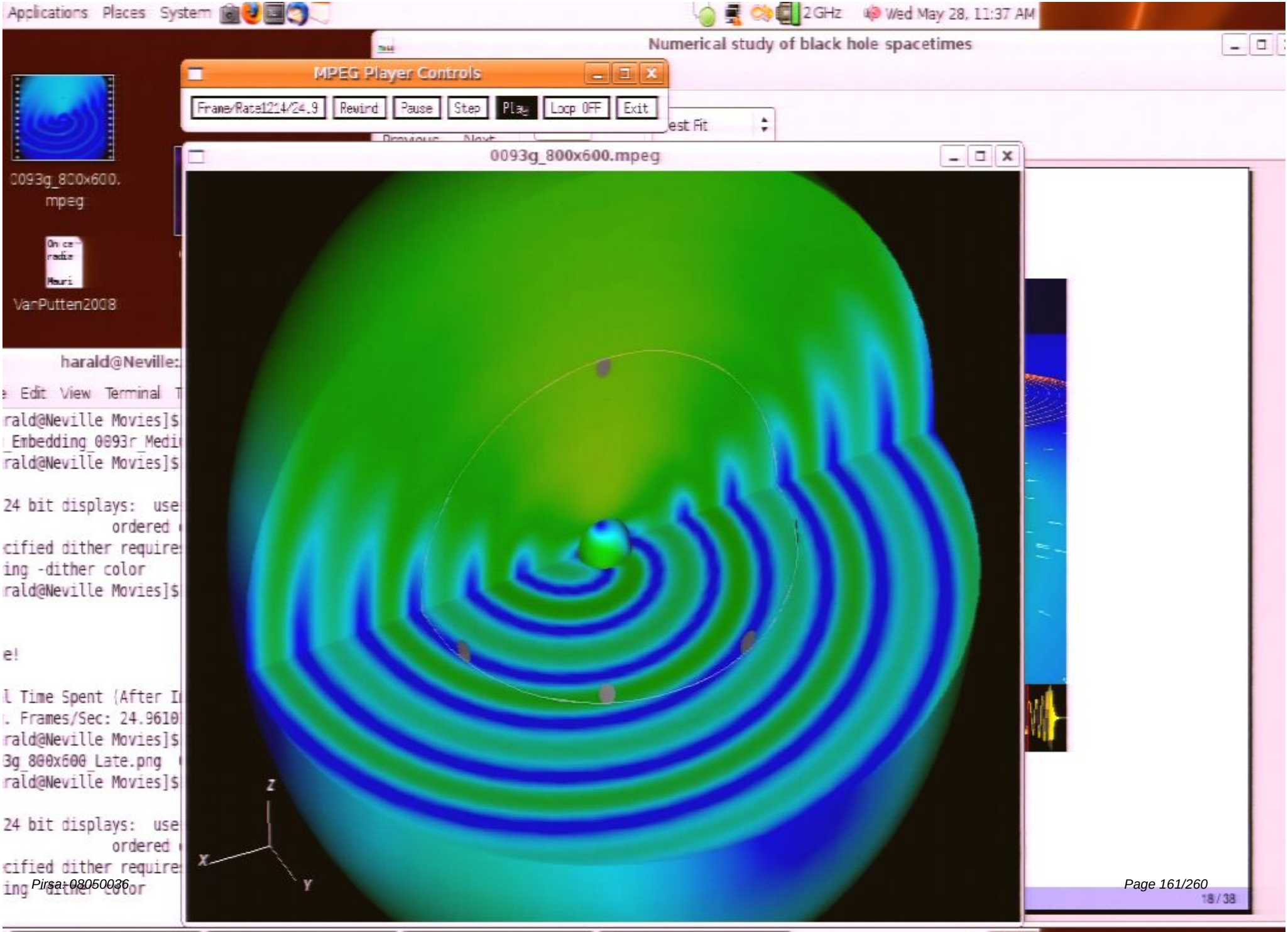
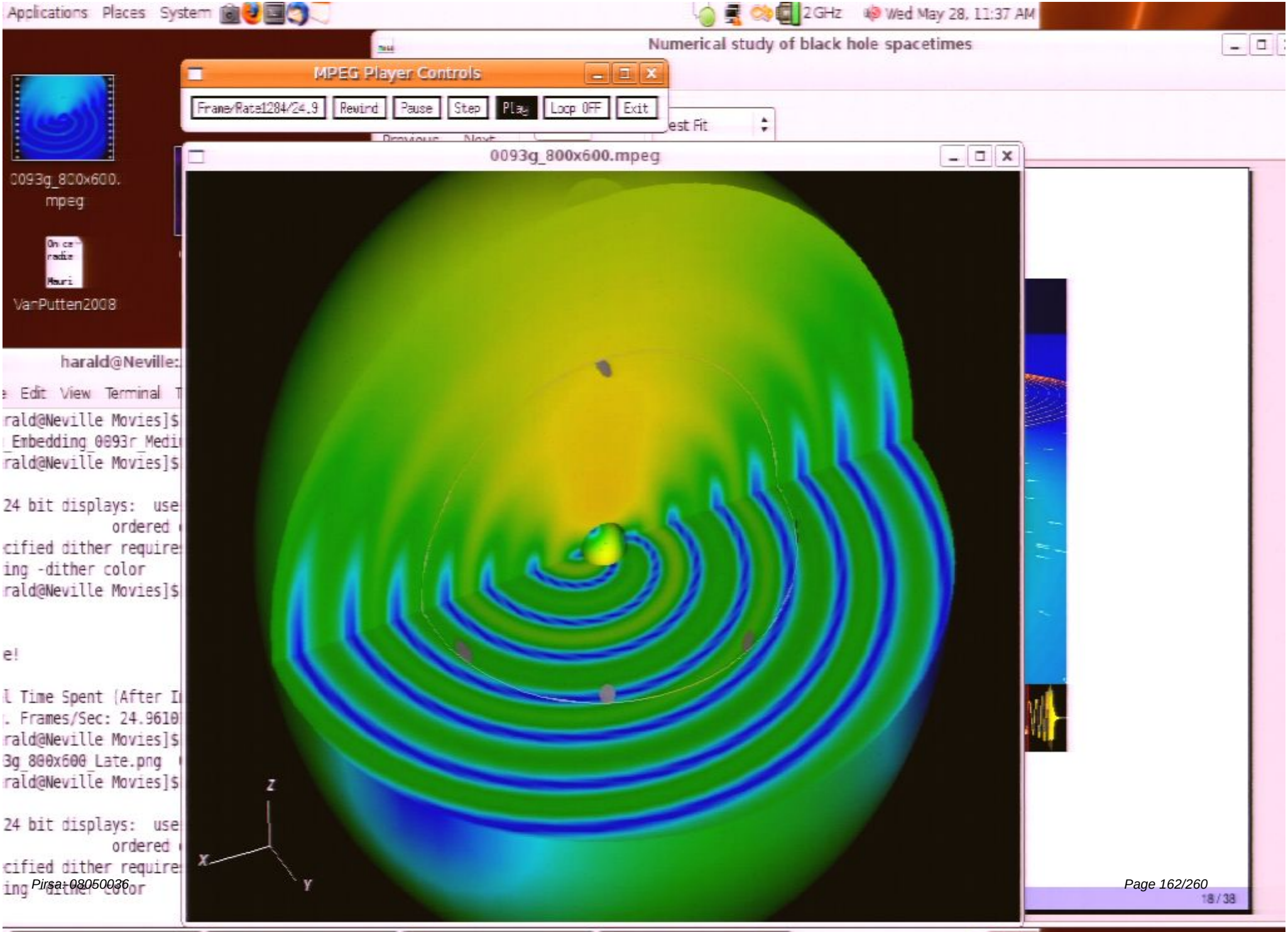
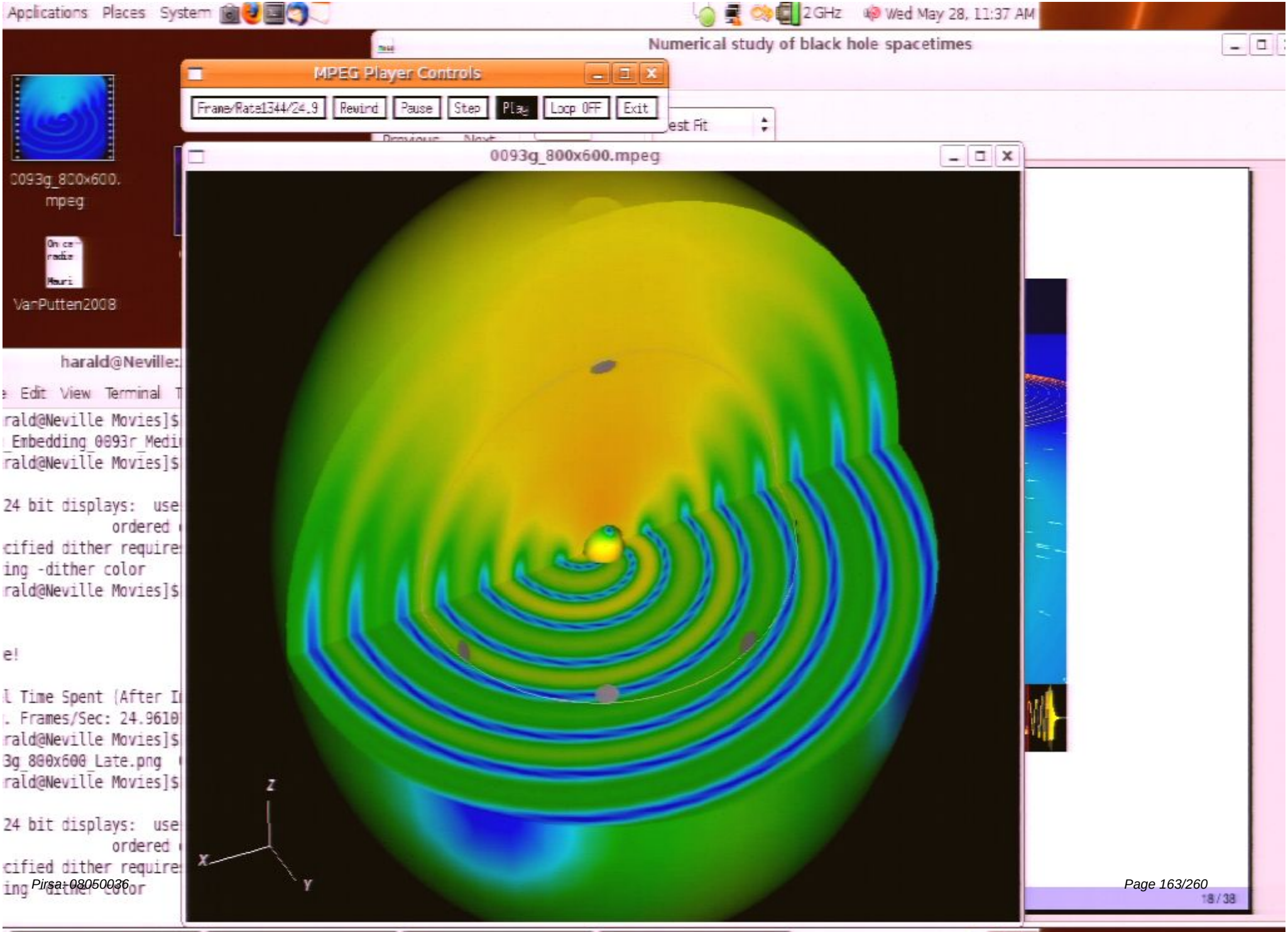

Applications Places System
2 GHz
Wed May 28, 11:37 AM
Numerical study of black hole spacetimes
MPEG Player Controls
Frame/Rate1214/24.9
Rewind
Pause
Step
Play
Loop OFF
Exit
0093g_800x600.mpeg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
Z
X
Y
18 / 38


Applications Places System
2 GHz
Wed May 28, 11:37 AM
Numerical study of black hole spacetimes
MPEG Player Controls
Frame/Rate1284/24.9
Rewind
Pause
Step
Play
Loop OFF
Exit
0093g_800x600.mpeg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
Z
X
Y


Applications Places System
2 GHz
Wed May 28, 11:37 AM
Numerical study of black hole spacetimes
MPEG Player Controls
Frame/Rate1344/24.9
Rewind
Pause
Step
Play
Loop OFF
Exit
0093g_800x600.mpeg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
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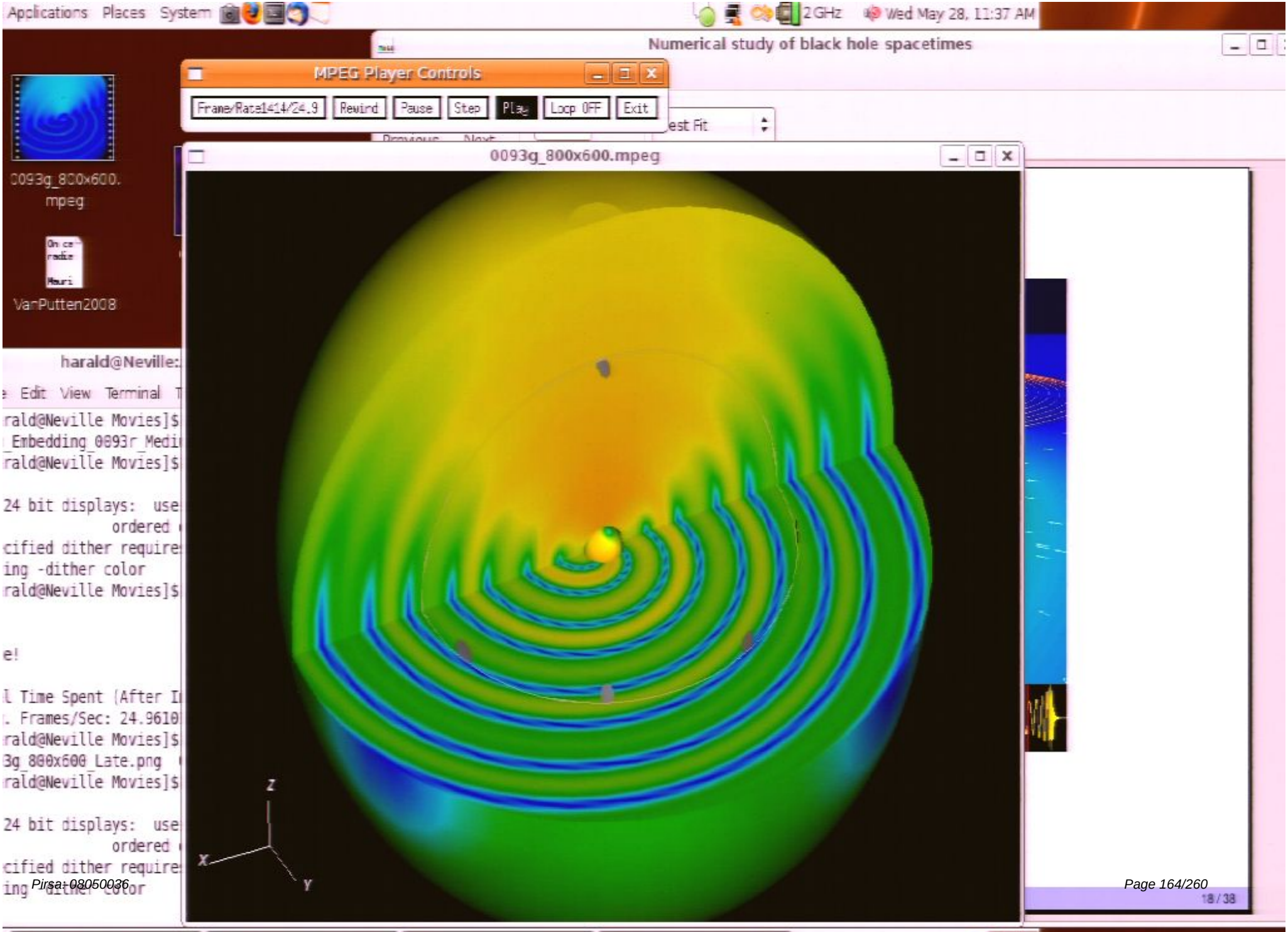
Applications Places System
2 GHz
Wed May 28, 11:37 AM
Numerical study of black hole spacetimes
MPEG Player Controls
Frame/Rate1414/24.9
Rewind
Pause
Step
Play
Loop OFF
Exit
0093g_800x600.mpeg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
Z
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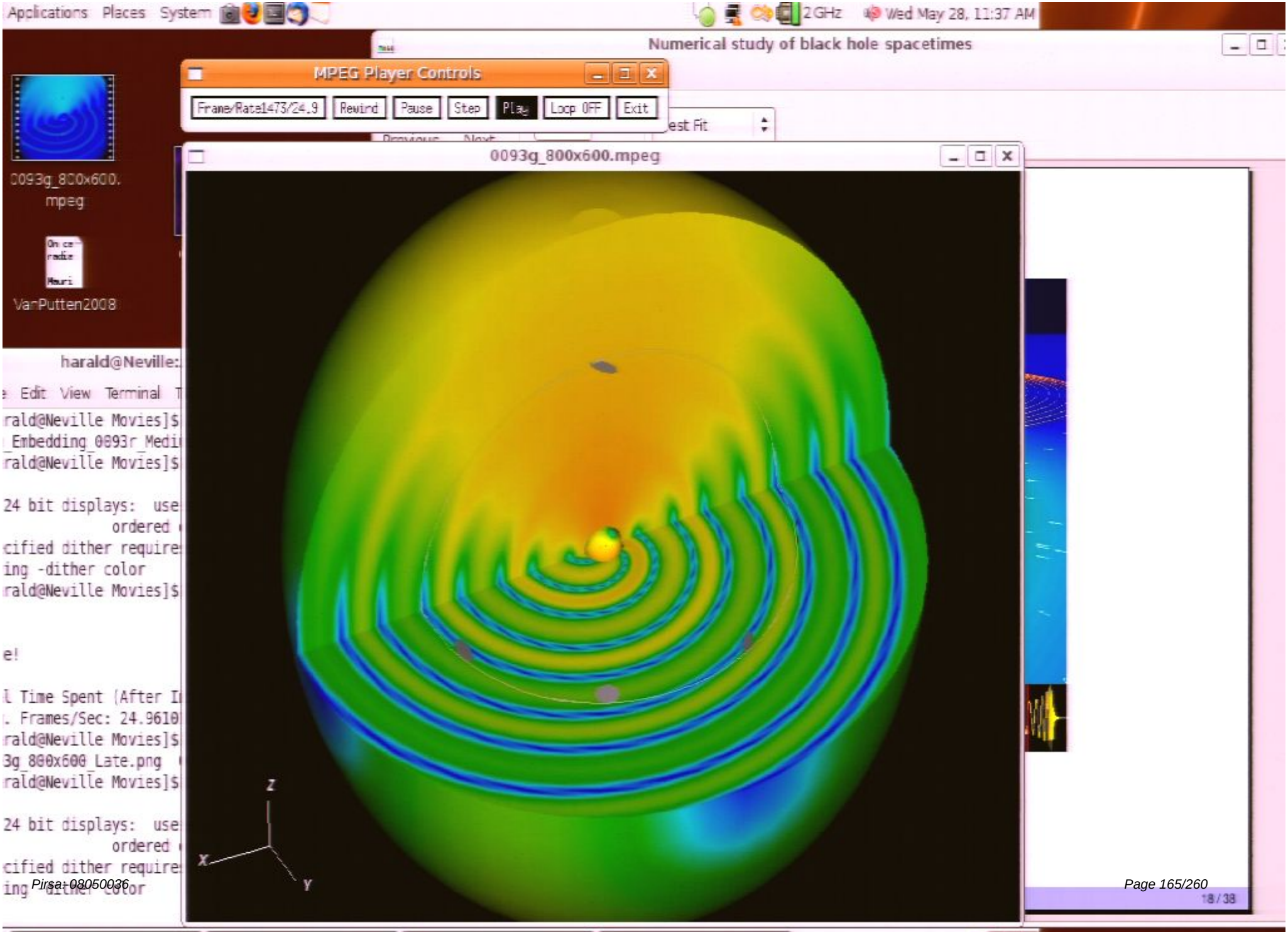
Y


Applications Places System
2 GHz
Wed May 28, 11:37 AM
Numerical study of black hole spacetimes
MPEG Player Controls
Frame/Rate1473/24.9
Rewind
Pause
Step
Play
Loop OFF
Exit
0093g_800x600.mpeg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
rald@Neville Movies]$
_Embedding_0093r_Medi
rald@Neville Movies]$
24 bit displays: use
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ing -dither color
rald@Neville Movies]$
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. Frames/Sec: 24.9610
rald@Neville Movies]$
3g_800x600_Late.png
rald@Neville Movies]$
24 bit displays: use
ordered
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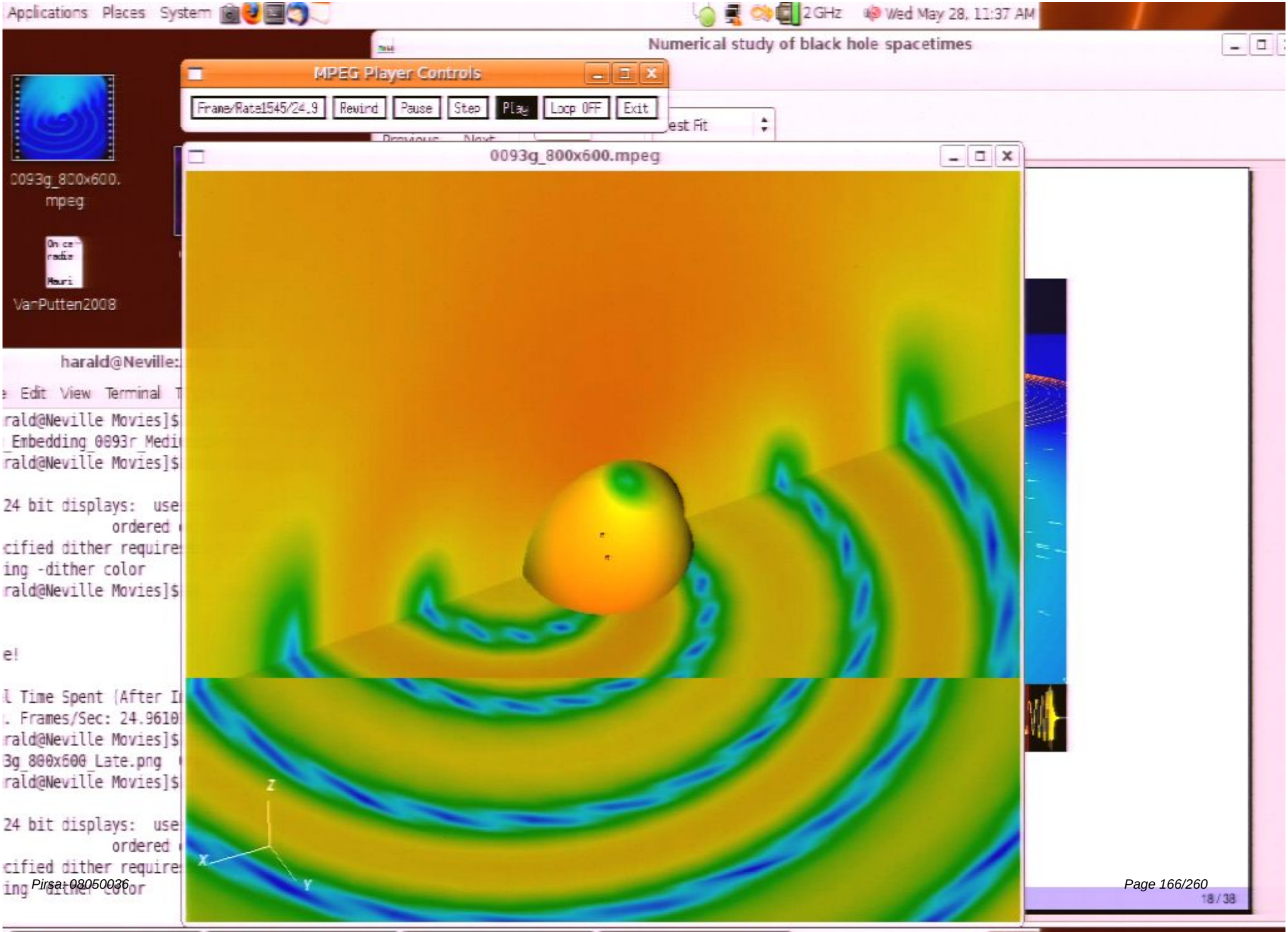
ing -dither color
Z
X
Y
18 / 38


Applications Places System
2 GHz
Wed May 28, 11:37 AM
Numerical study of black hole spacetimes
MPEG Player Controls
Frame/Rate1545/24.9
Rewind
Pause
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Play
Loop OFF
Exit
0093g_800x600.mpeg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
rald@Neville Movies]$
Embedding_0093r_Medi
rald@Neville Movies]$
24 bit displays: use
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rald@Neville Movies]$
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. Frames/Sec: 24.9610
rald@Neville Movies]$
3g_800x600_Late.png
rald@Neville Movies]$
24 bit displays: use
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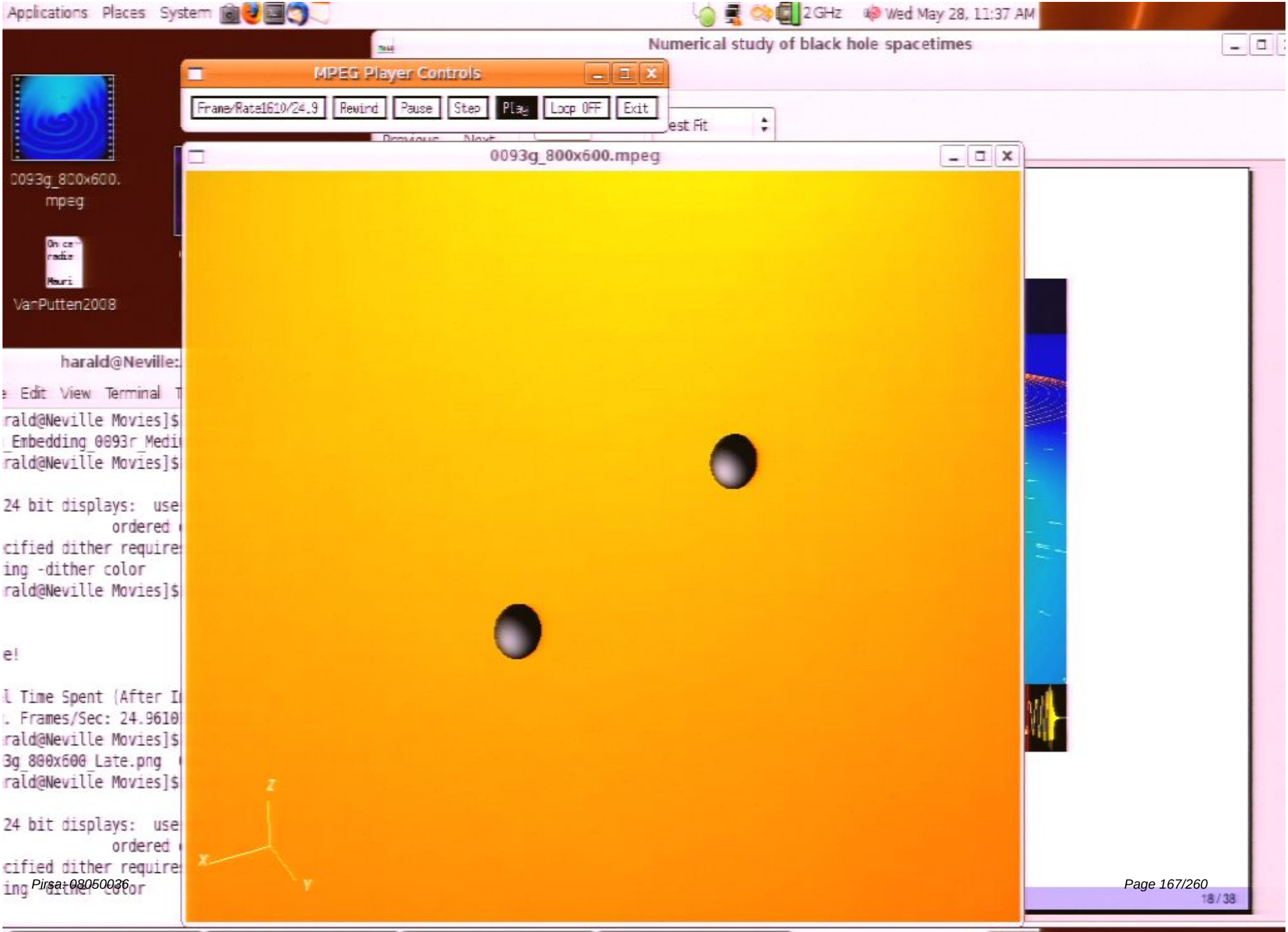
18 / 38


Applications Places System
2 GHz
Wed May 28, 11:37 AM
Numerical study of black hole spacetimes
MPEG Player Controls
Frame/Rate1610/24.9
Rewind
Pause
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Play
Loop OFF
Exit
0093g_800x600.mpeg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
rald@Neville Movies]$
_Embedding_0093r_Medi
rald@Neville Movies]$
24 bit displays: use
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rald@Neville Movies]$
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rald@Neville Movies]$
3g_800x600_Late.png
rald@Neville Movies]$
24 bit displays: use
ordered
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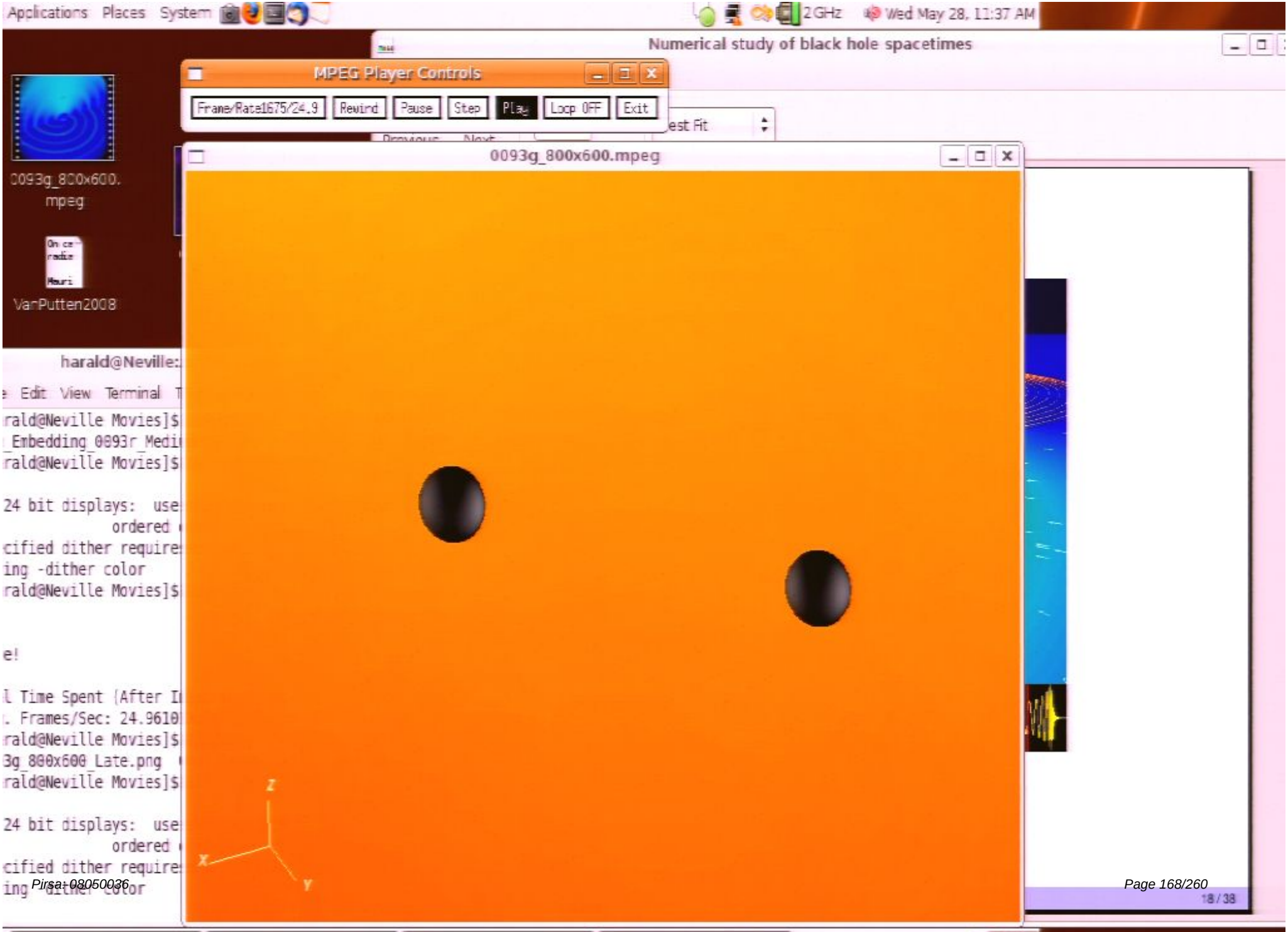
ing -dither color
Z
X
Y
18 / 38


Applications Places System
2 GHz
Wed May 28, 11:37 AM
Numerical study of black hole spacetimes
MPEG Player Controls
Frame/Rate1675/24.9
Rewind
Pause
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Play
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0093g_800x600.mpeg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
rald@Neville Movies]$
_Embedding_0093r_Medi
rald@Neville Movies]$
24 bit displays: use
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rald@Neville Movies]$
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. Frames/Sec: 24.9610
rald@Neville Movies]$
3g_800x600_Late.png
rald@Neville Movies]$
24 bit displays: use
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cified dither require
ing -dither color
Z
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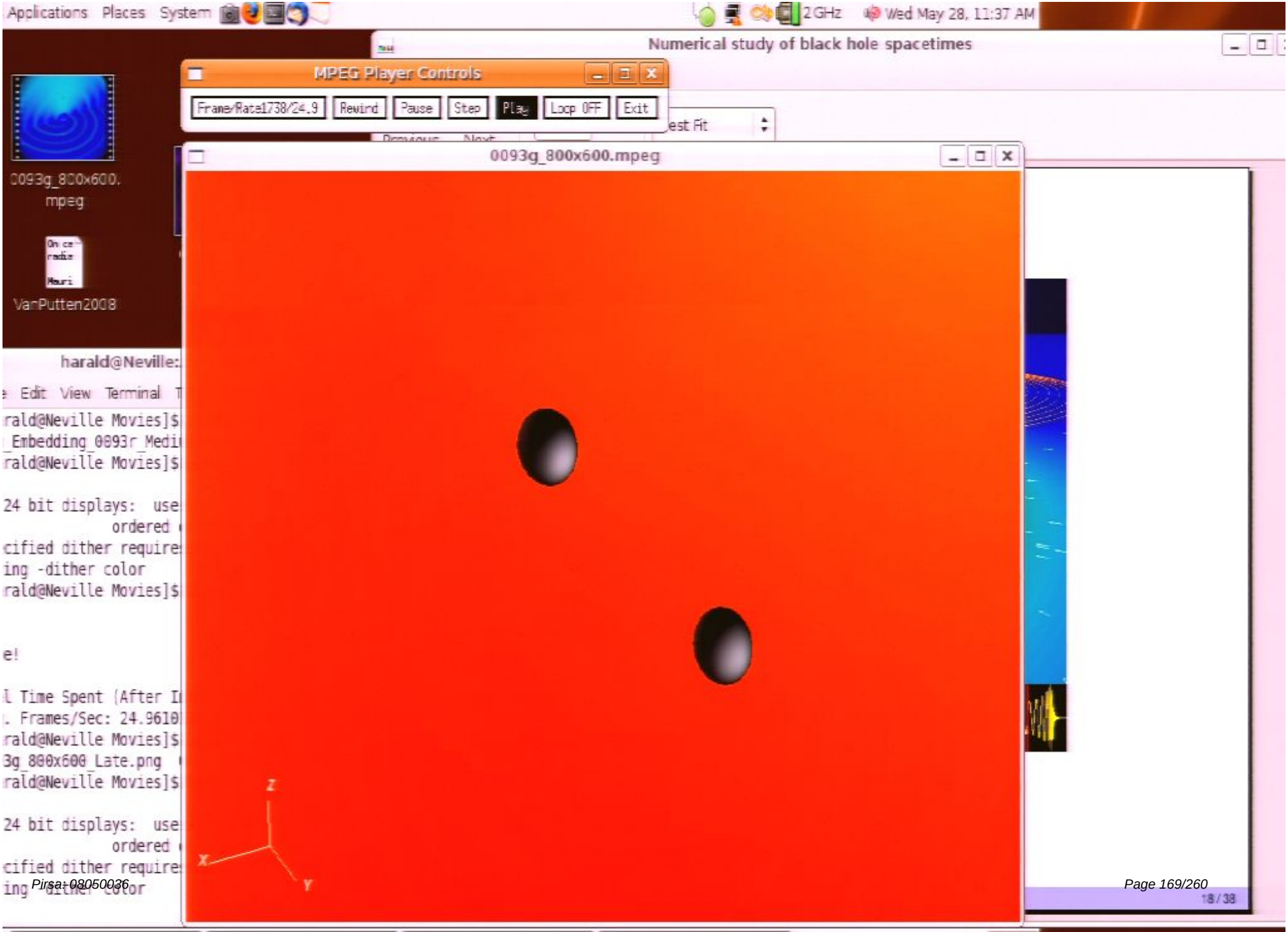
18 / 38


Applications Places System
2 GHz
Wed May 28, 11:37 AM
Numerical study of black hole spacetimes
MPEG Player Controls
Frame/Rate1738/24.9
Rewind
Pause
Step
Play
Loop OFF
Exit
0093g_800x600.mpeg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
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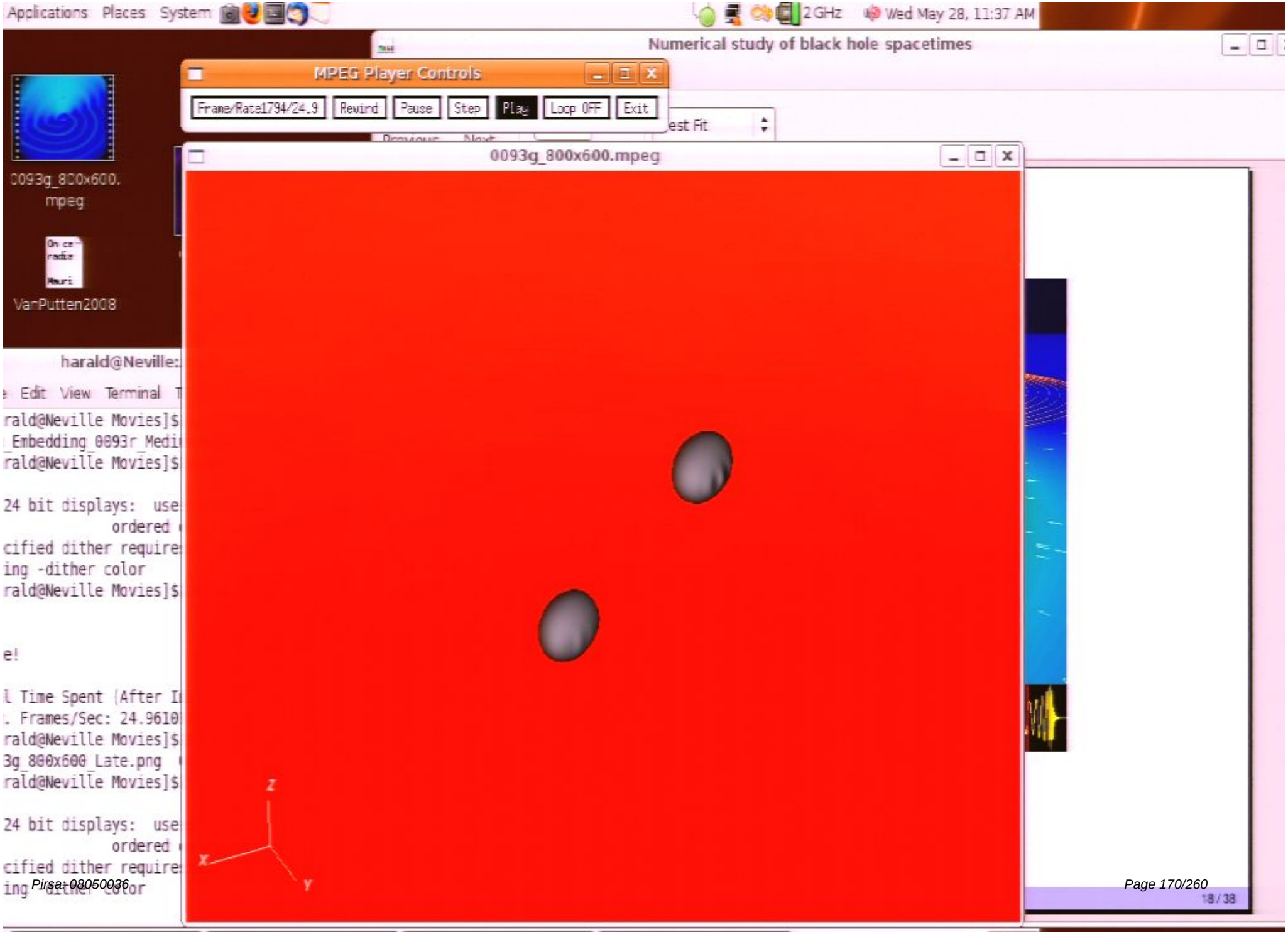
Y


Applications Places System
2 GHz
Wed May 28, 11:37 AM
Numerical study of black hole spacetimes
MPEG Player Controls
Frame/Rate1794/24.9
Rewind
Pause
Step
Play
Loop OFF
Exit
0093g_800x600.mpeg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
rald@Neville Movies]$
_Embedding_0093r_Medi
rald@Neville Movies]$
24 bit displays: use
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rald@Neville Movies]$
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rald@Neville Movies]$
3g_800x600_Late.png
rald@Neville Movies]$
24 bit displays: use
ordered
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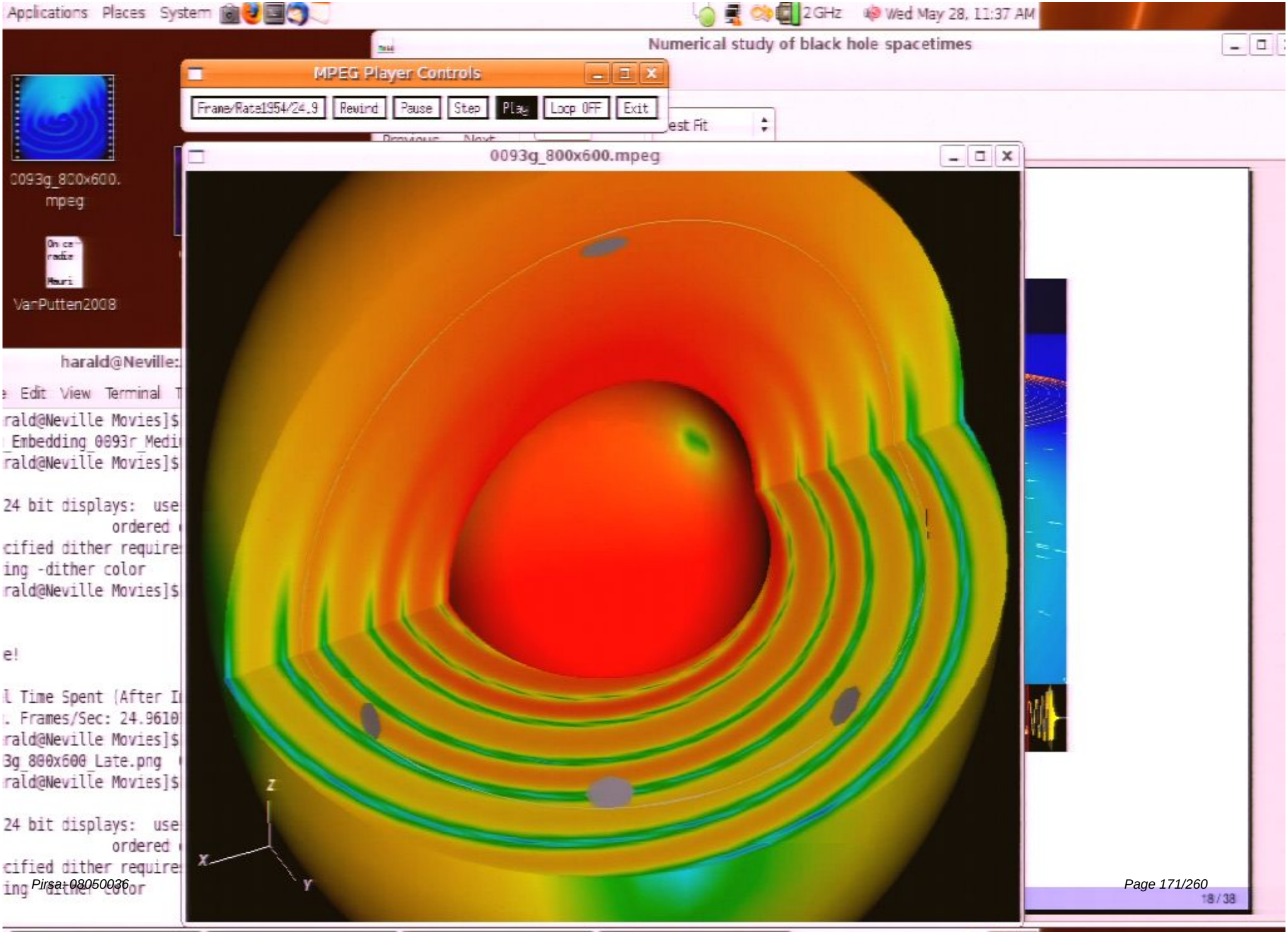
ing -dither color
Z
X
Y
18 / 38


Applications Places System
2 GHz
Wed May 28, 11:37 AM
Numerical study of black hole spacetimes
MPEG Player Controls
Frame/Rate1954/24.9
Rewind
Pause
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Play
Loop OFF
Exit
0093g_800x600.mpeg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
rald@Neville Movies]$
_Embedding_0093r_Medi
rald@Neville Movies]$
24 bit displays: use
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rald@Neville Movies]$
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rald@Neville Movies]$
3g_800x600_Late.png
rald@Neville Movies]$
24 bit displays: use
ordered
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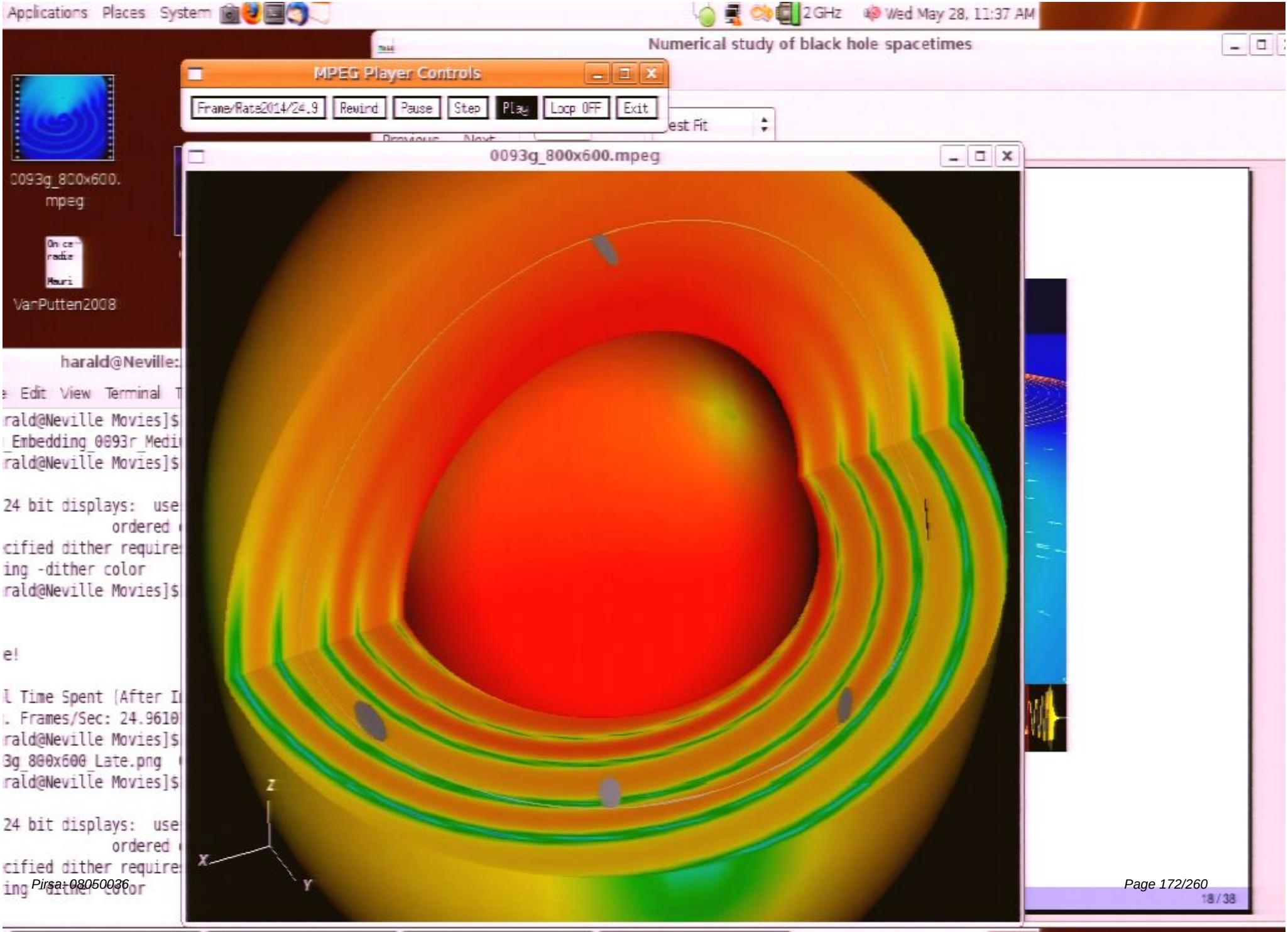
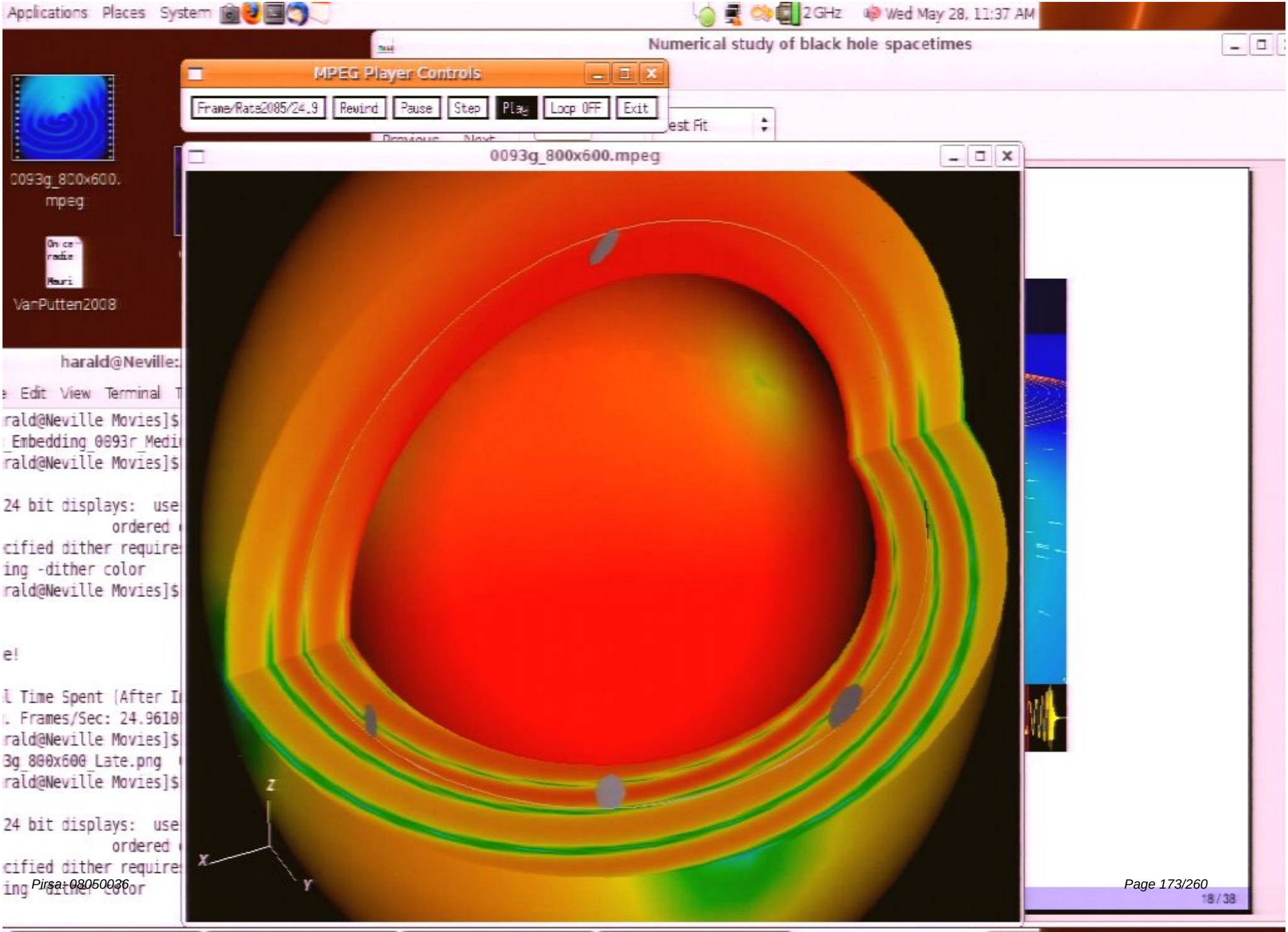
Z
X
Y
18 / 38


Applications Places System
2 GHz
Wed May 28, 11:37 AM
Numerical study of black hole spacetimes
MPEG Player Controls
Frame/Rate2014/24.9
Rewind
Pause
Step
Play
Loop OFF
Exit
0093g_800x600.mpeg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
Z
X
Y
18 / 38


Applications Places System
2 GHz
Wed May 28, 11:37 AM
Numerical study of black hole spacetimes
MPEG Player Controls
Frame/Rate2085/24.9
Rewind
Pause
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Loop OFF
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0093g_800x600.mpeg
0093g_800x600.
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harald@Neville:
Edit View Terminal
rald@Neville Movies]$
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rald@Neville Movies]$
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rald@Neville Movies]$
3g_800x600_Late.png
rald@Neville Movies]$
24 bit displays: use
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Z
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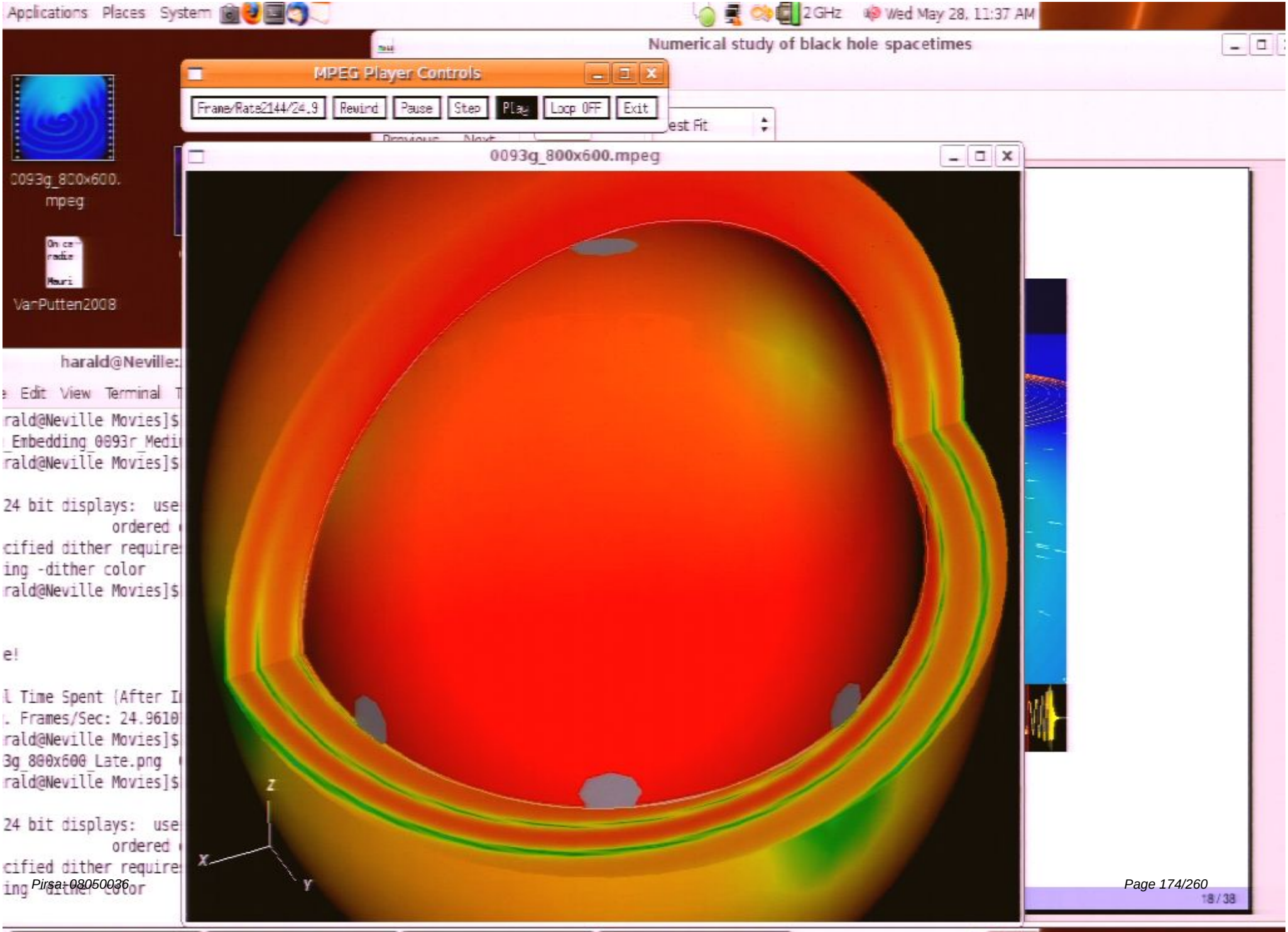
18 / 38


Applications Places System
2 GHz
Wed May 28, 11:37 AM
Numerical study of black hole spacetimes
MPEG Player Controls
Frame/Rate2144/24.9
Rewind
Pause
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Loop OFF
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0093g_800x600.mpeg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
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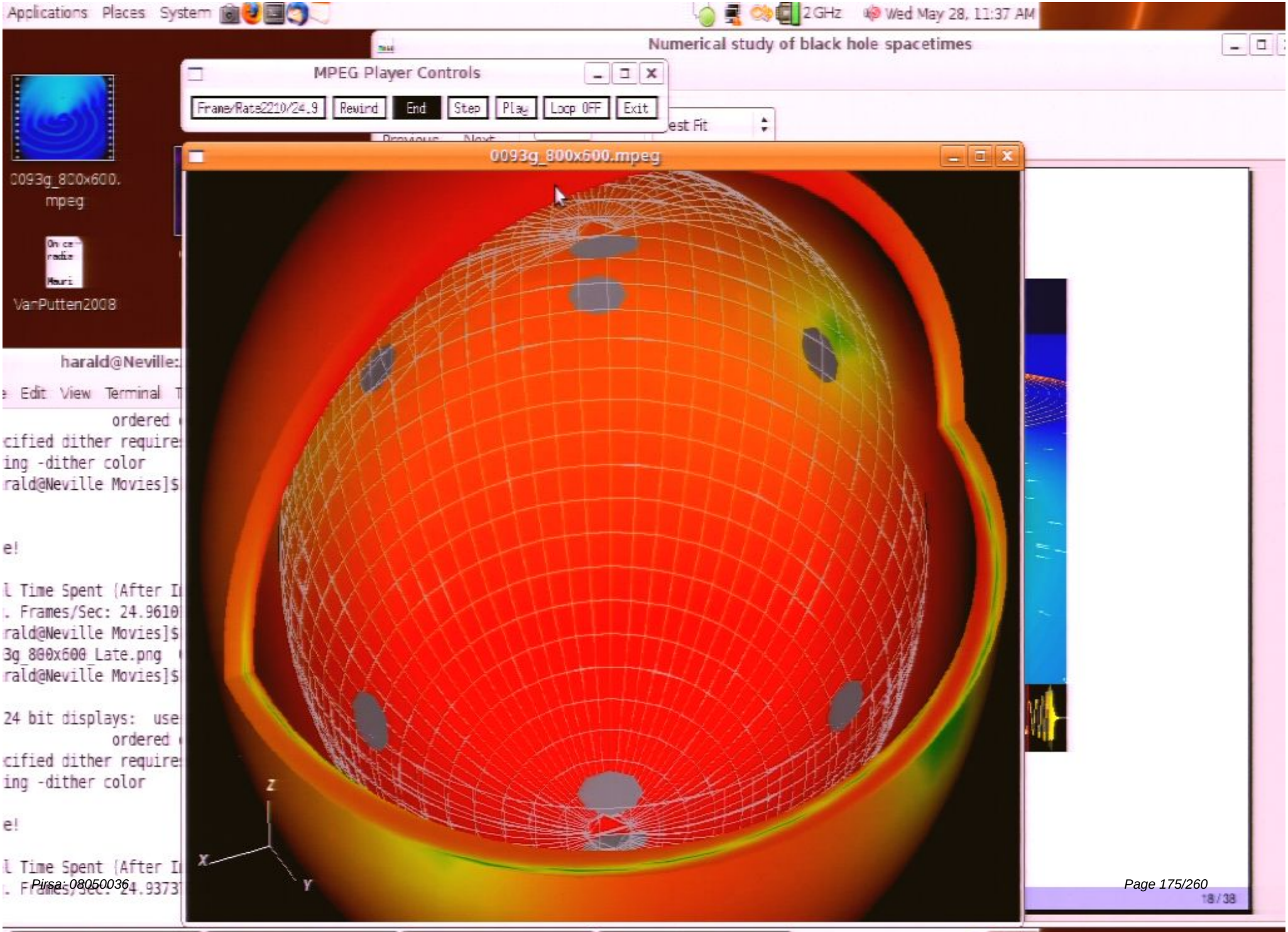
Applications Places System
2 GHz
Wed May 28, 11:37 AM
Numerical study of black hole spacetimes
MPEG Player Controls
Frame/Rate2210/24.9
Rewind
End
Step
Play
Loop OFF
Exit
0093g_800x600.mpeg
0093g_800x600.
mpeg
VanPutten2008
harald@Neville:
Edit View Terminal
ordered
cified dither require
ing -dither color
rald@Neville Movies]$
e!
l Time Spent (After I
. Frames/Sec: 24.9610
rald@Neville Movies]$
3g_800x600_Late.png
rald@Neville Movies]$
24 bit displays: use
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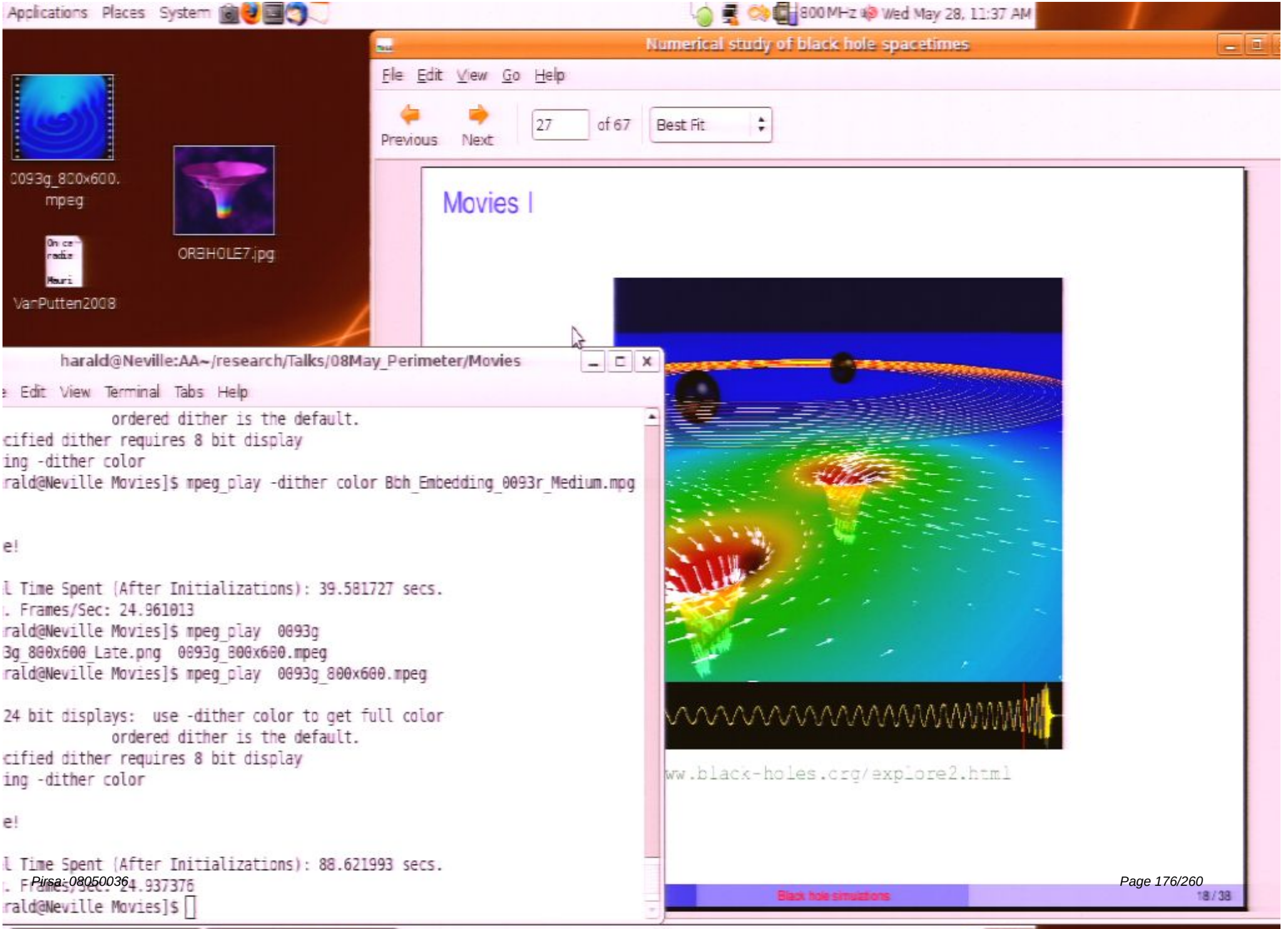
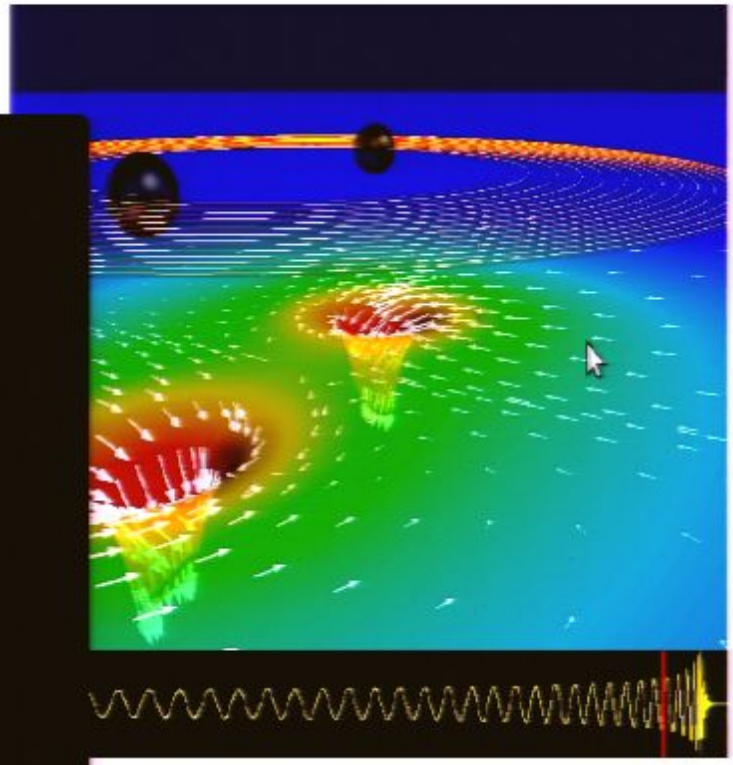
cified dither require
ing -dither color
e!
l Time Spent (After I
. Frames/Sec: 24.9373
Z
X
Y
18 / 38


Applications Places System
800 MHz Wed May 28, 11:37 AM
0093g_800x600.mpeg
ORBHOLE7.jpg
VanPutten2008
Numerical study of black hole spacetimes
File Edit View Go Help
Previous Next
27 of 67
Best Fit
Movies I
harald@Neville:AA~/research/Talks/08May_Perimeter/Movies
Edit View Terminal Tabs Help
ordered dither is the default.
cified dither requires 8 bit display
ing -dither color
rald@Neville Movies]$ mpeg_play -dither color Bch_Embedding_0093r_Medium.mpg
e!
l Time Spent (After Initializations): 39.581727 secs.
. Frames/Sec: 24.961013
rald@Neville Movies]$ mpeg_play 0093g
3g_800x600_Late.png 0093g_800x600.mpeg
rald@Neville Movies]$ mpeg_play 0093g_800x600.mpeg
24 bit displays: use -dither color to get full color
ordered dither is the default.
cified dither requires 8 bit display
ing -dither color
e!
l Time Spent (After Initializations): 88.621993 secs.
. Frames/Sec: 24.937376
rald@Neville Movies]$
ww.black-holes.org/explore2.html
Black hole simulations
18 / 38

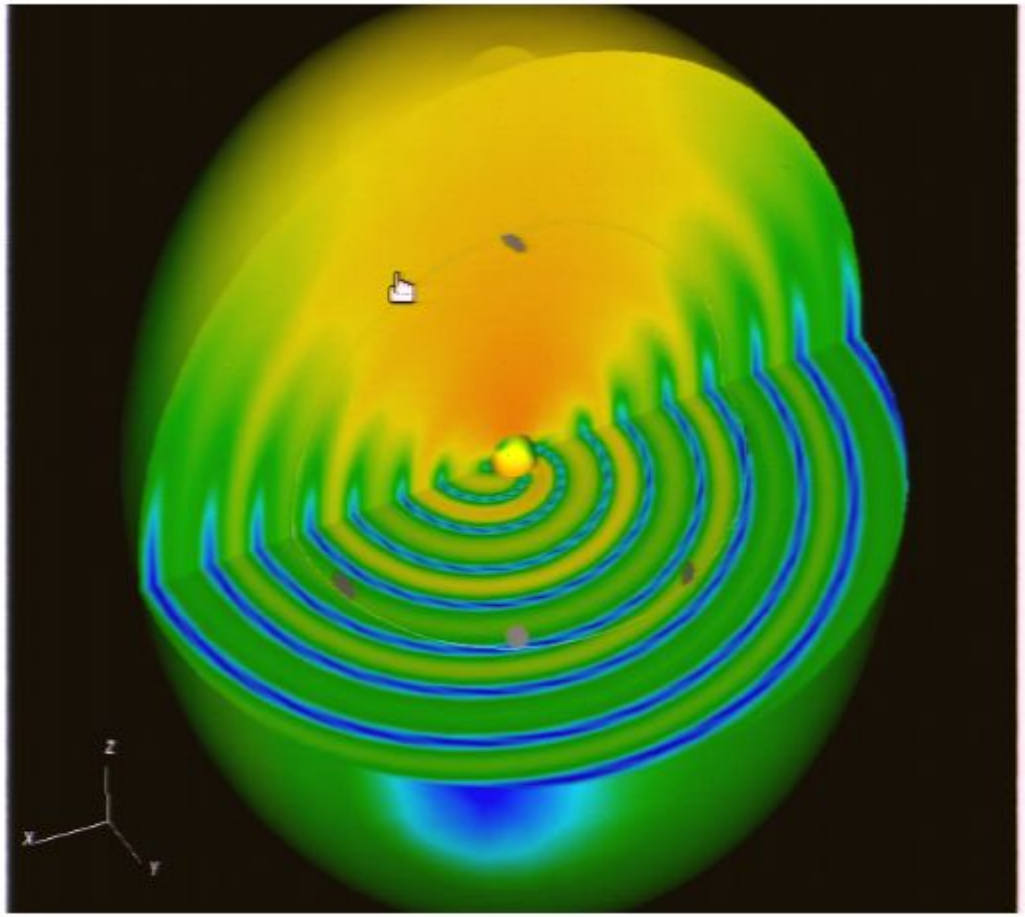
Movies I



ww.black-holes.org/explore2.html

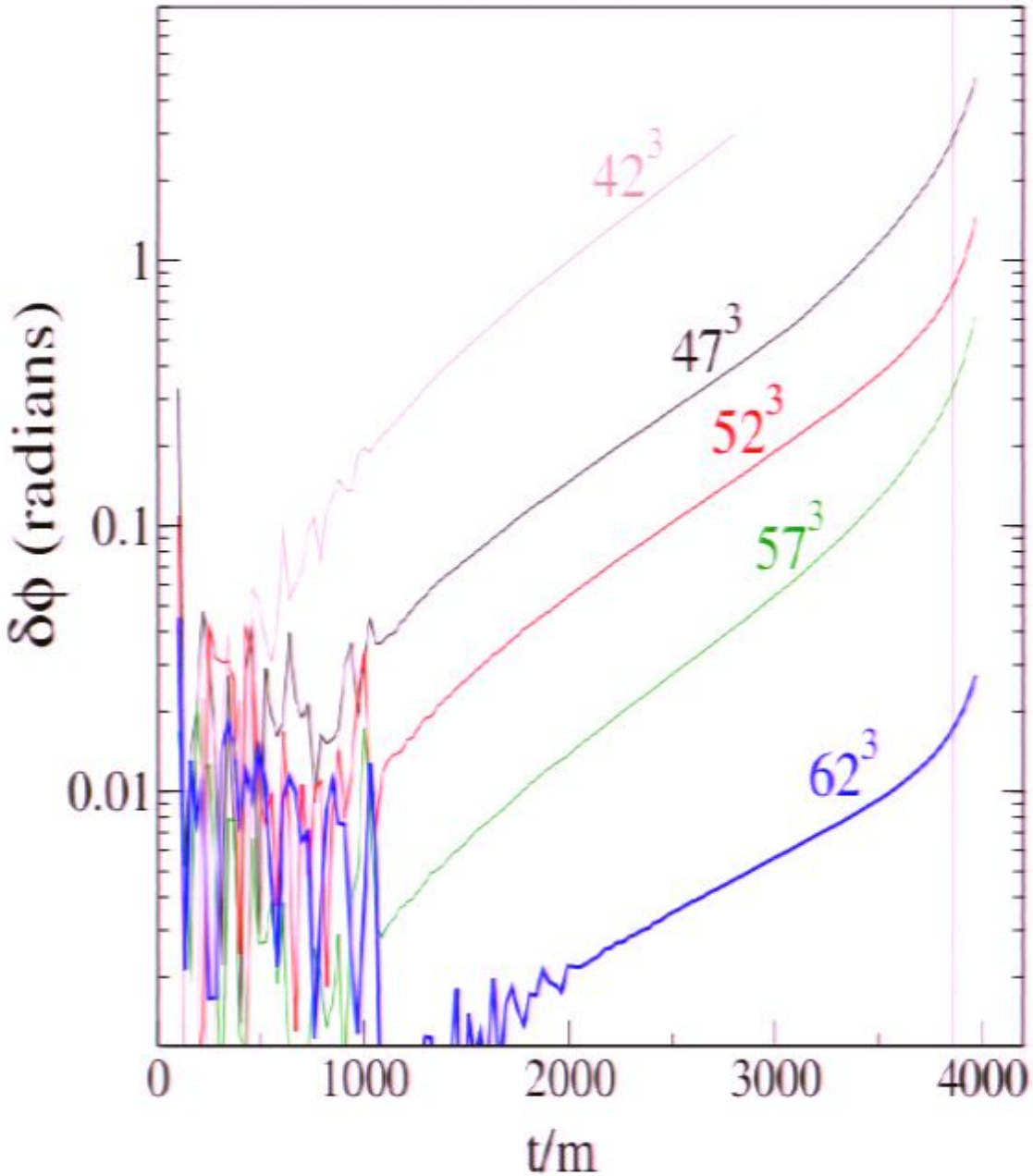
Black hole simulations 18 / 38

Movies II



www.black-holes.org/explore2.html

Phase-Accuracy (out of 200 radians)



Post-Newtonian theory

Blanchet, Damour, Iyer, Schäfer, Jaranowski, Faye; Will, Wiseman, Kidder, ...

- Expansion in velocity $v = v/c$
- For a binary in a circular orbit
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  - GW-Flux $F(v) = \frac{32\mu^2}{5} v^{10} \left(1 + \sum_{k=1}^{7} b_k v^k\right)$
- Energy-balance gives time-evolution:

$$\frac{dE}{dt} = -F \quad \Rightarrow \quad \frac{dv}{dt} = -\frac{F}{dE/dv}$$

- **Difficulty:** $v/c \sim 0.3$ during late inspiral
  - Slow convergence
  - Uncontrolled higher-order terms seizable!

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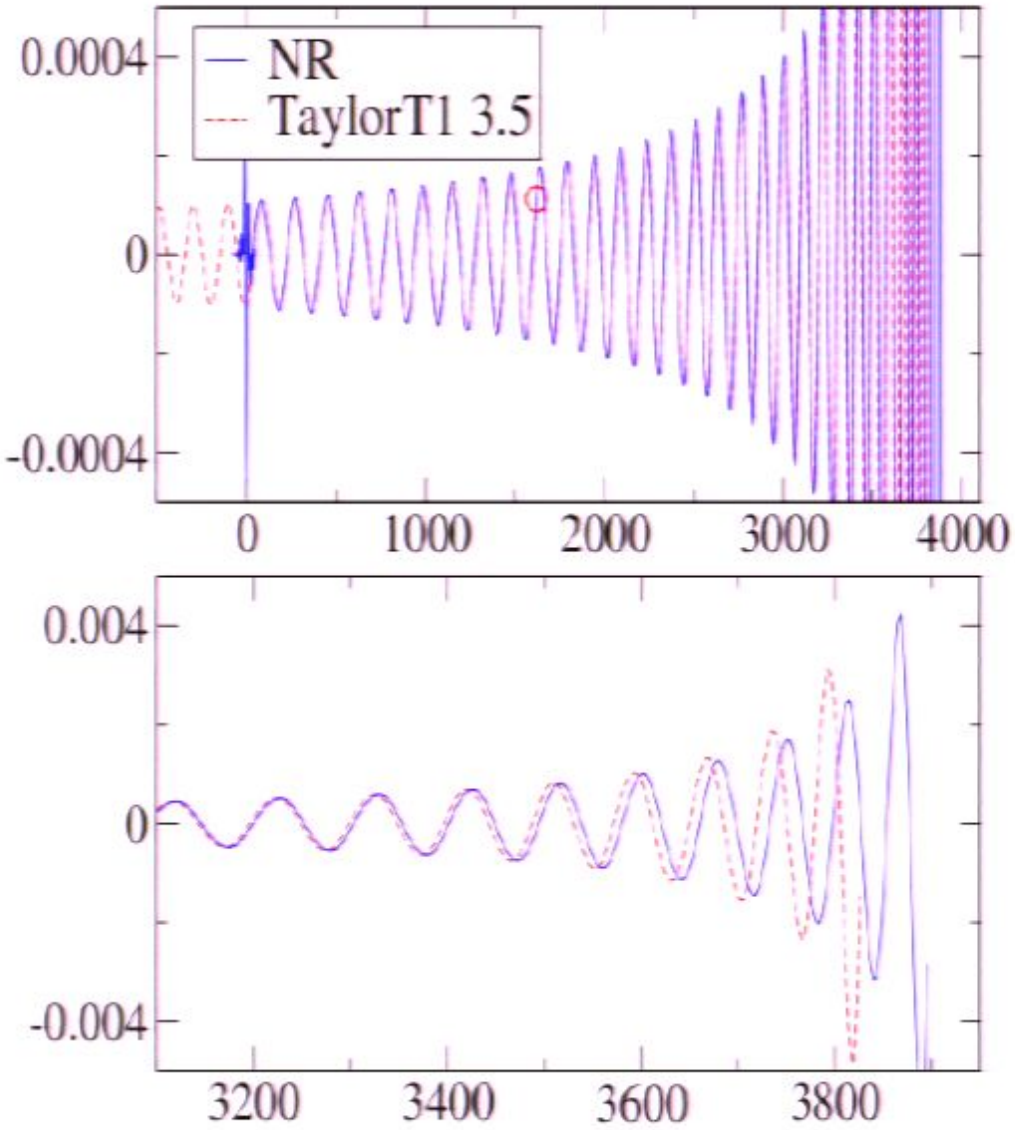

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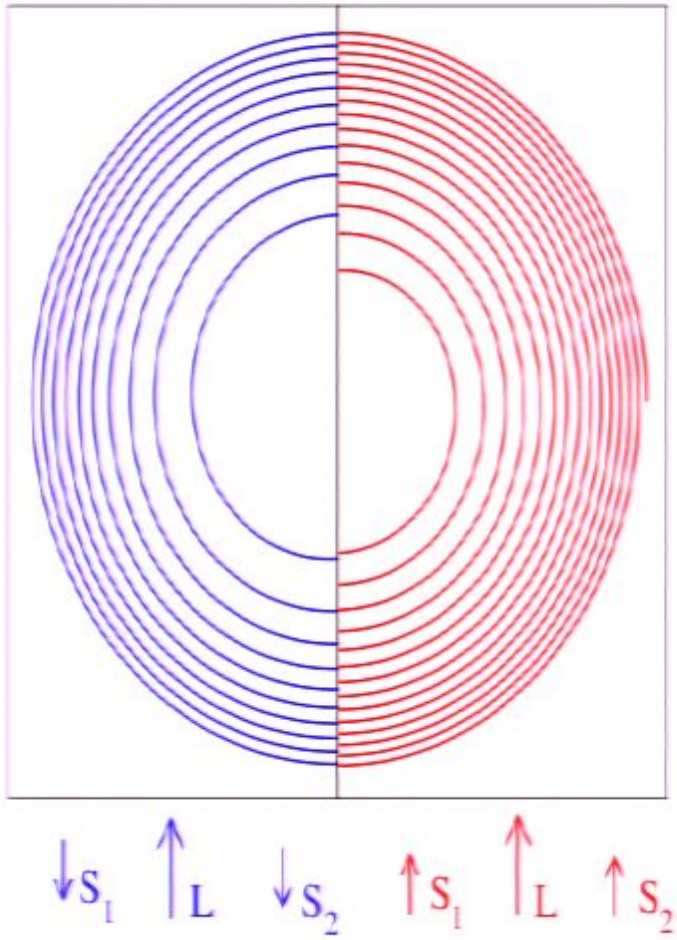

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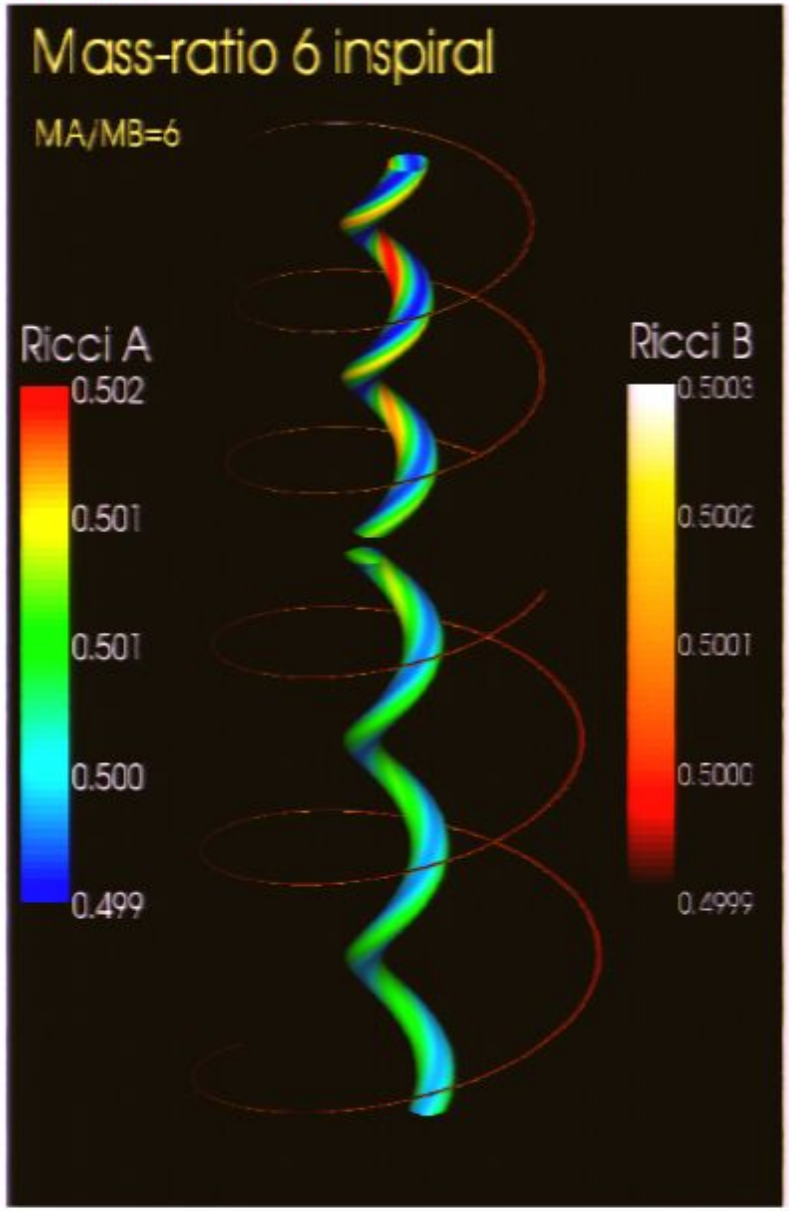

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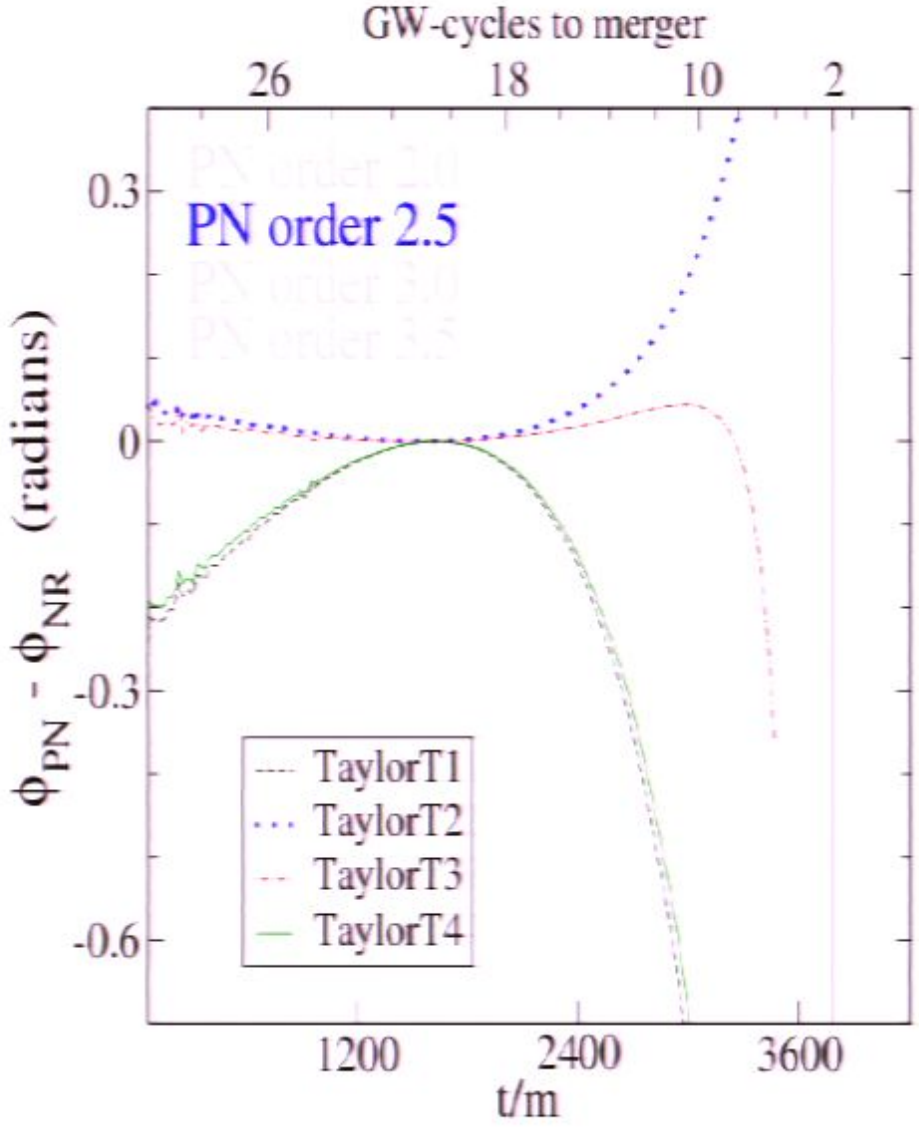
Boyle et *al.*, 2007



PN-approximants

- Different treatment of uncontrolled higher-order terms, e.g.
  - Use of energy-balance equation (Damour, Iyer, Sathyaprakash, 01)

$$\frac{dv}{dt} = -\frac{F}{dE/dv} \qquad \text{TaylorT1}$$

$$\frac{dv}{dt} = -\text{Series}\left[\frac{F}{dE/dv}, v\right] \qquad \text{TaylorT4}$$

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  - Padé-resummation of F(v) (Damour et *al.* 98; Buonanno et *al.* 98)
  - Effective-One-Body formalism (Damour and collaborators)

Post-Newtonian theory

Blanchet, Damour, Iyer, Schäfer, Jaranowski, Faye; Will, Wiseman, Kidder, ...

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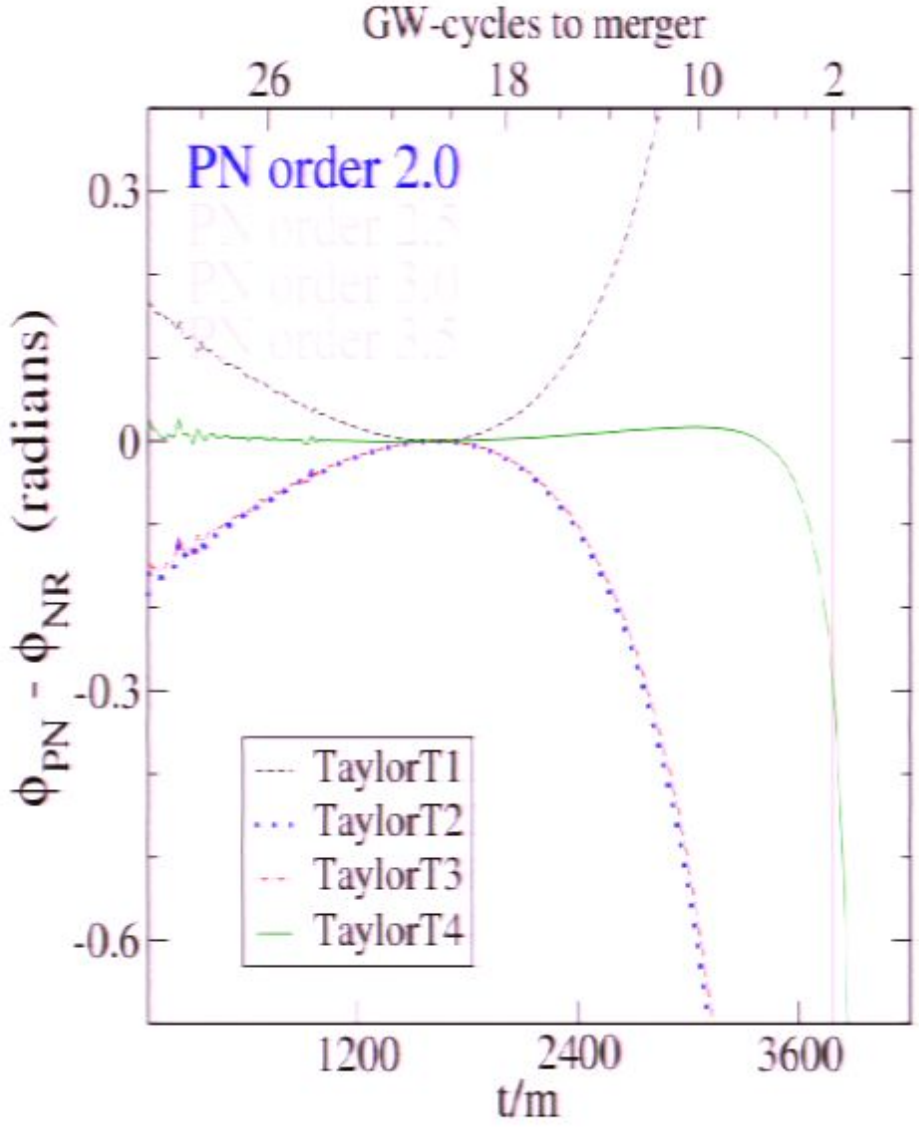

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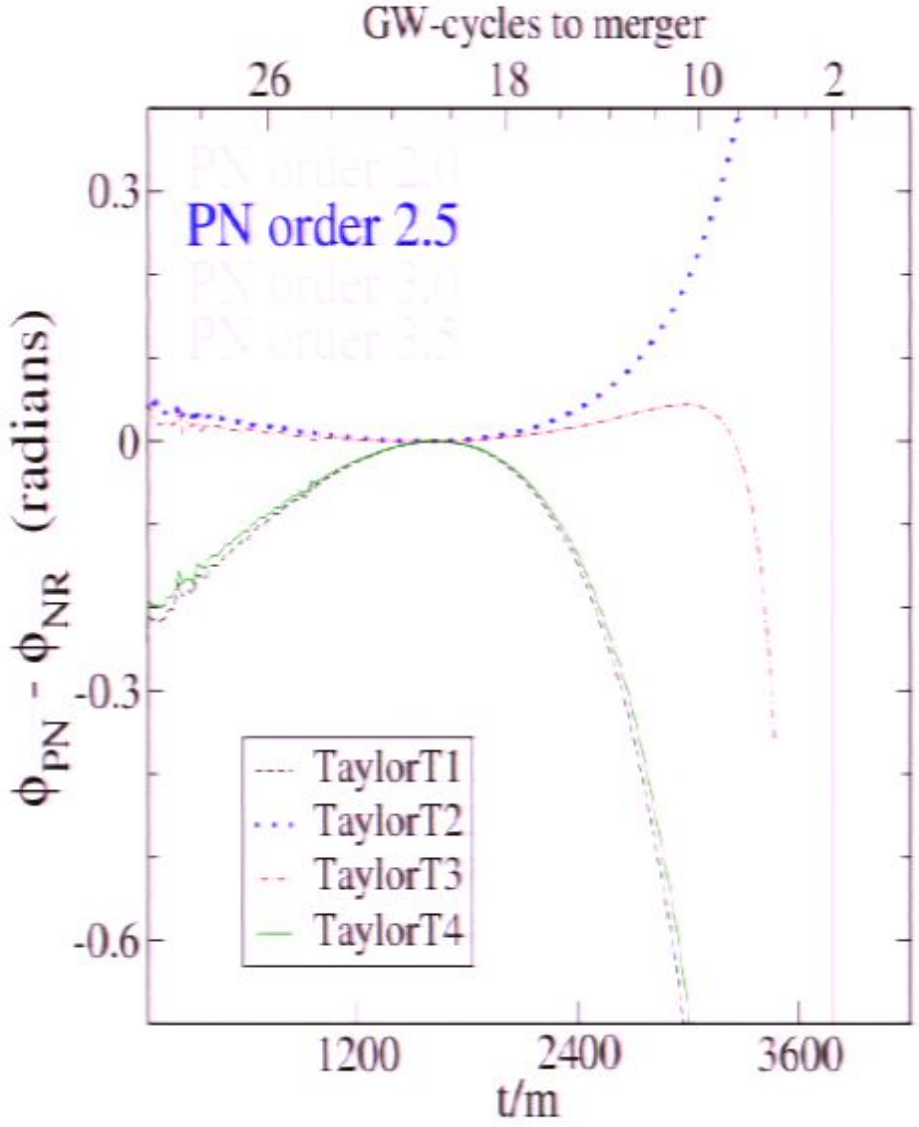

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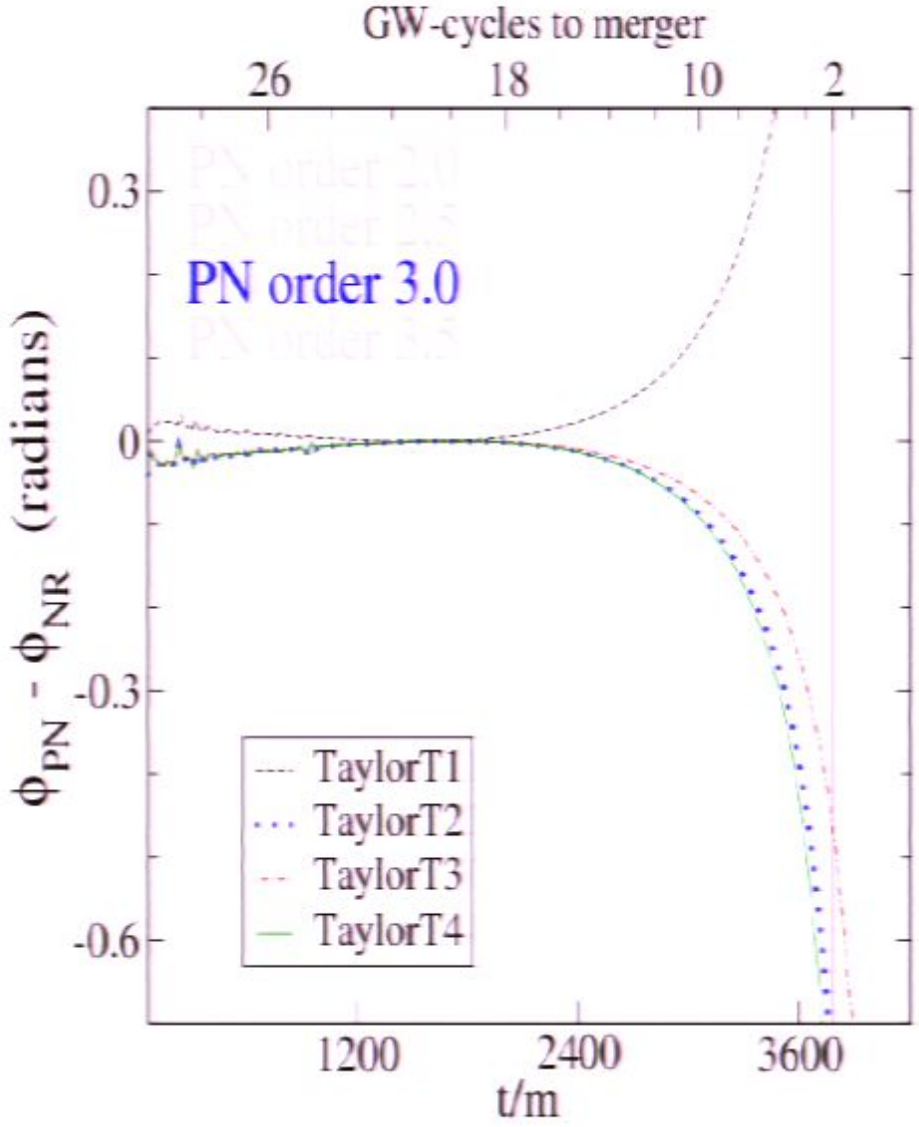

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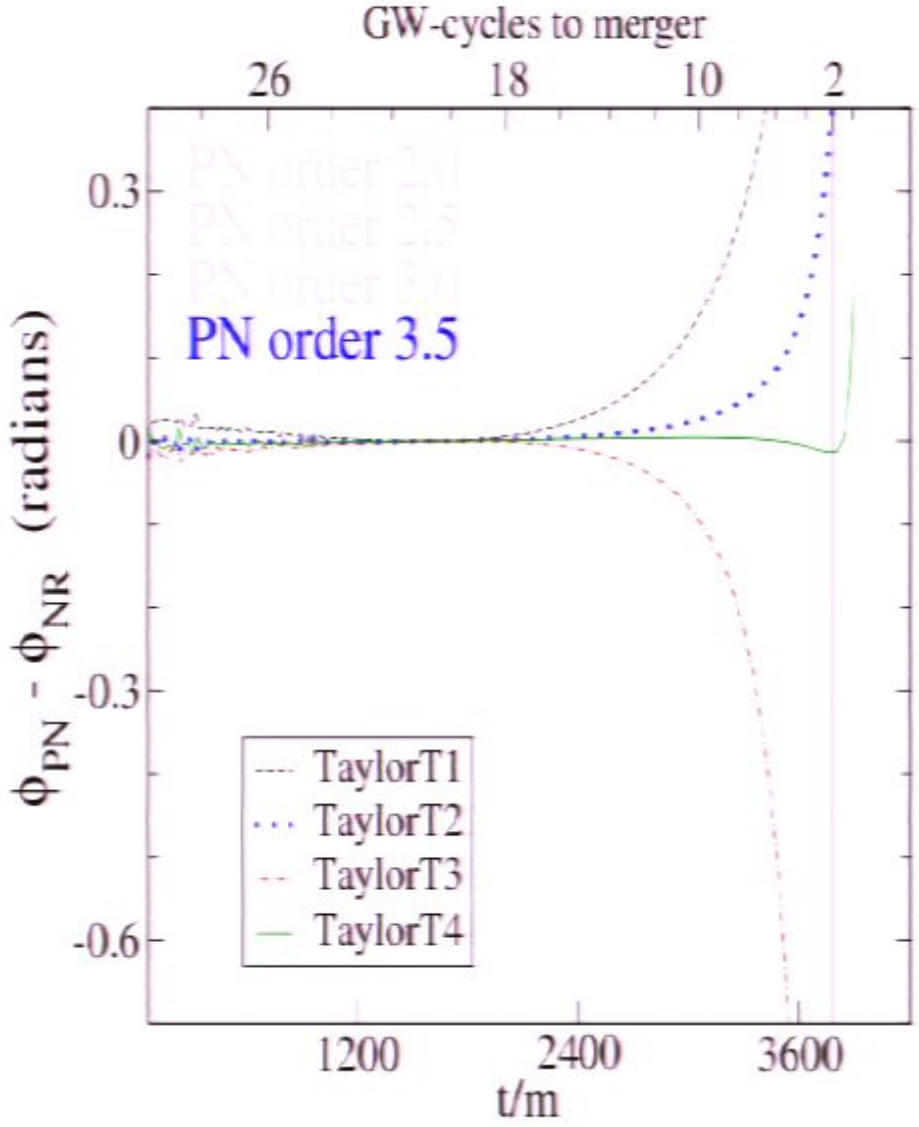

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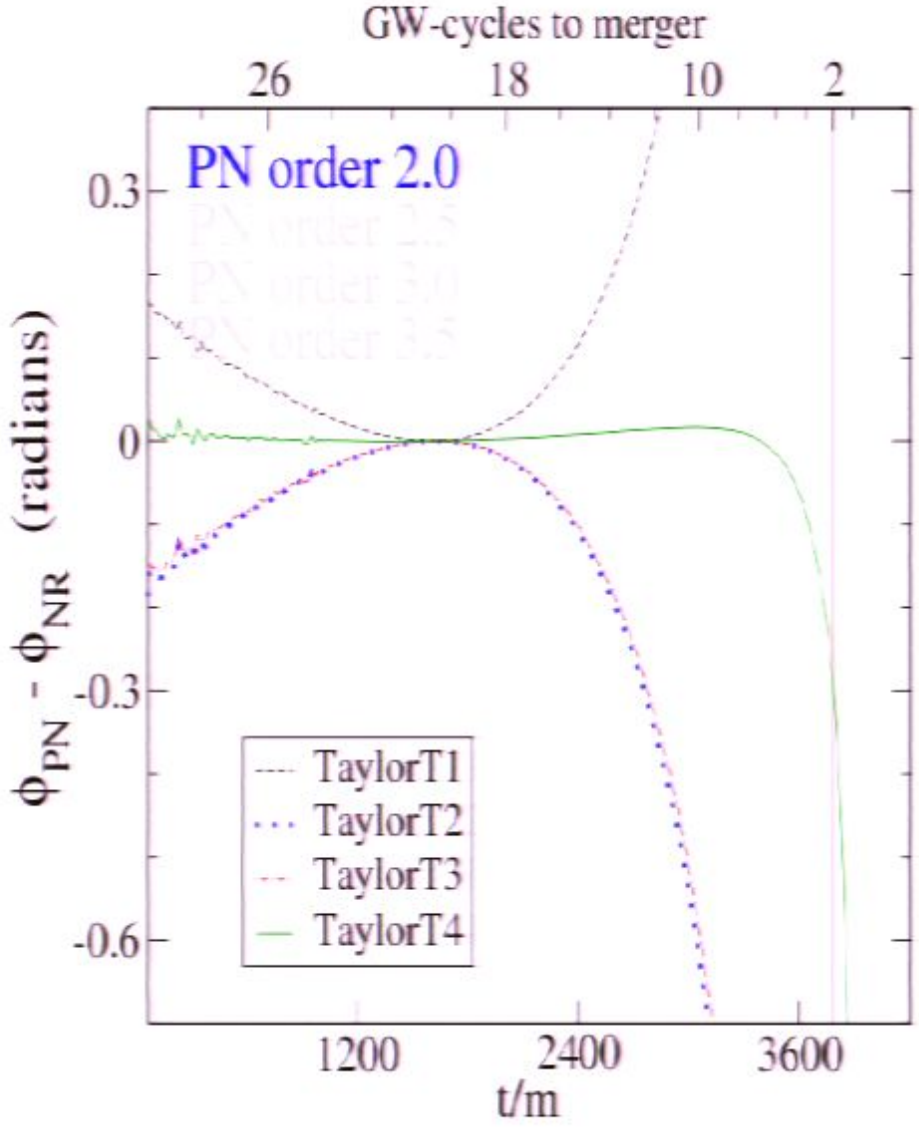

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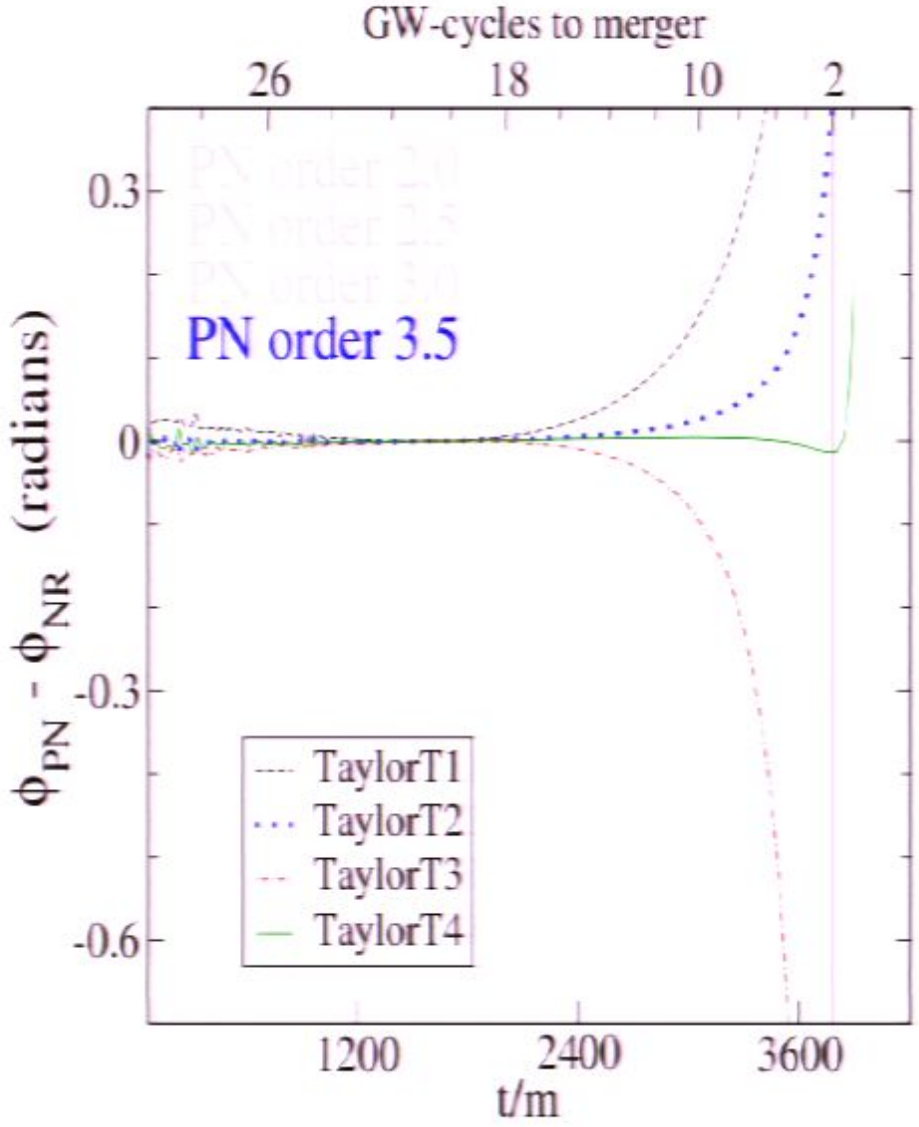

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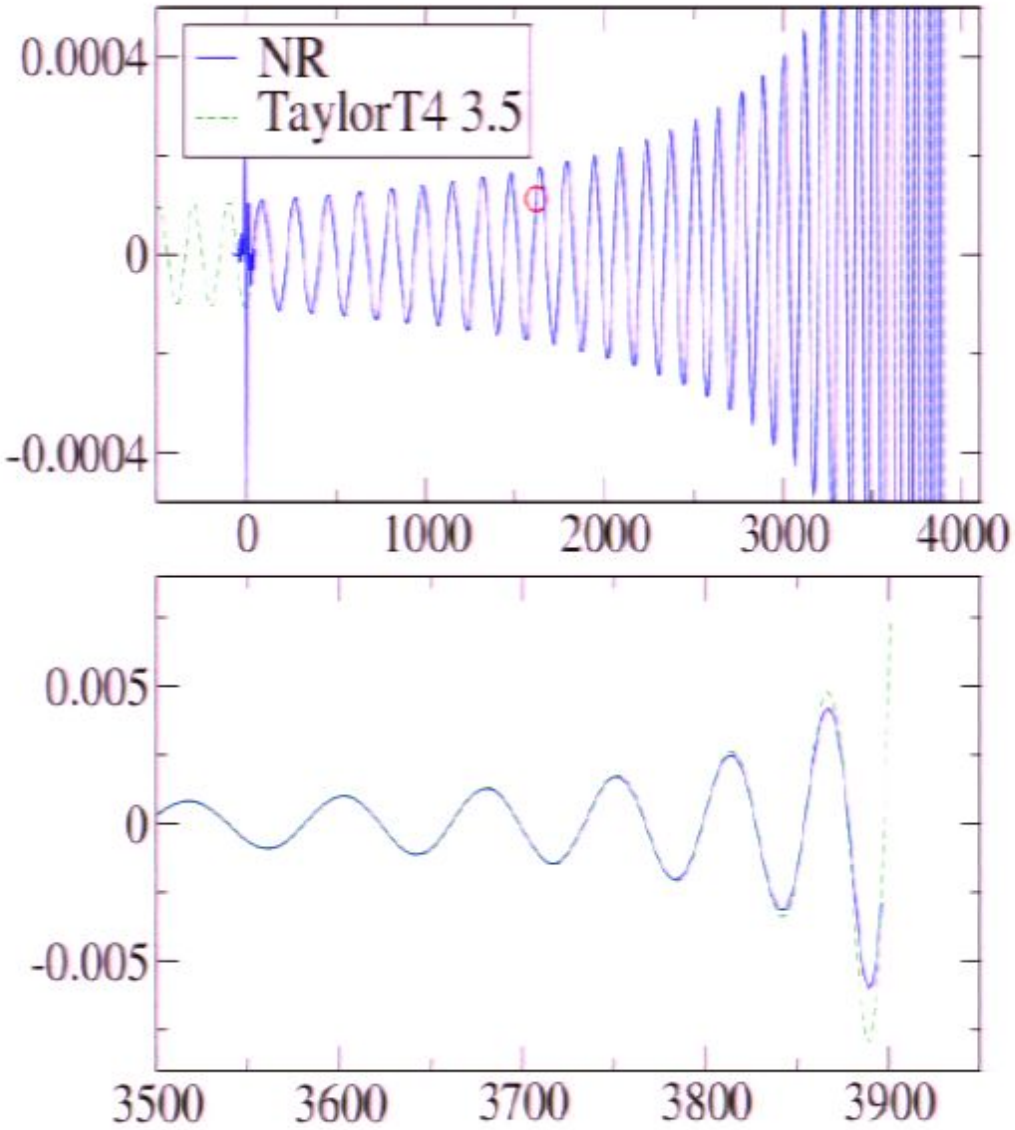

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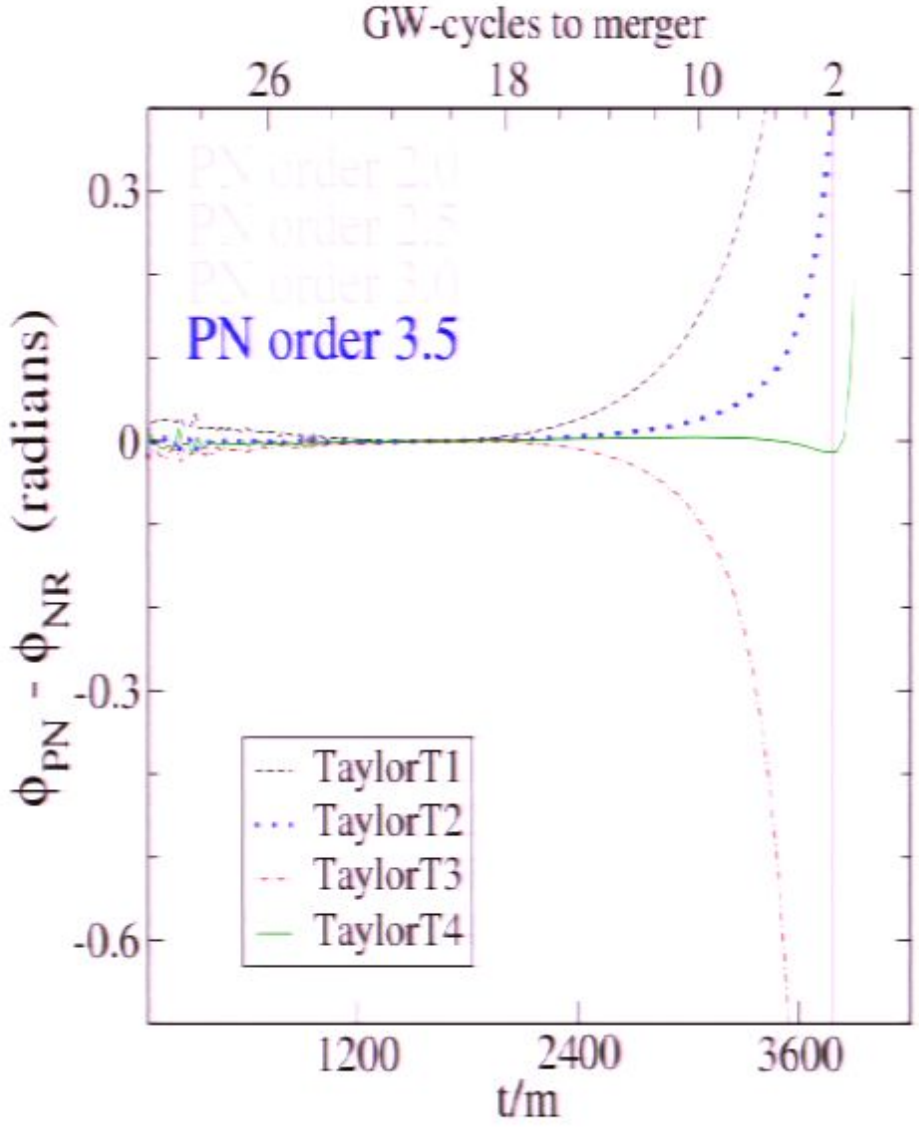

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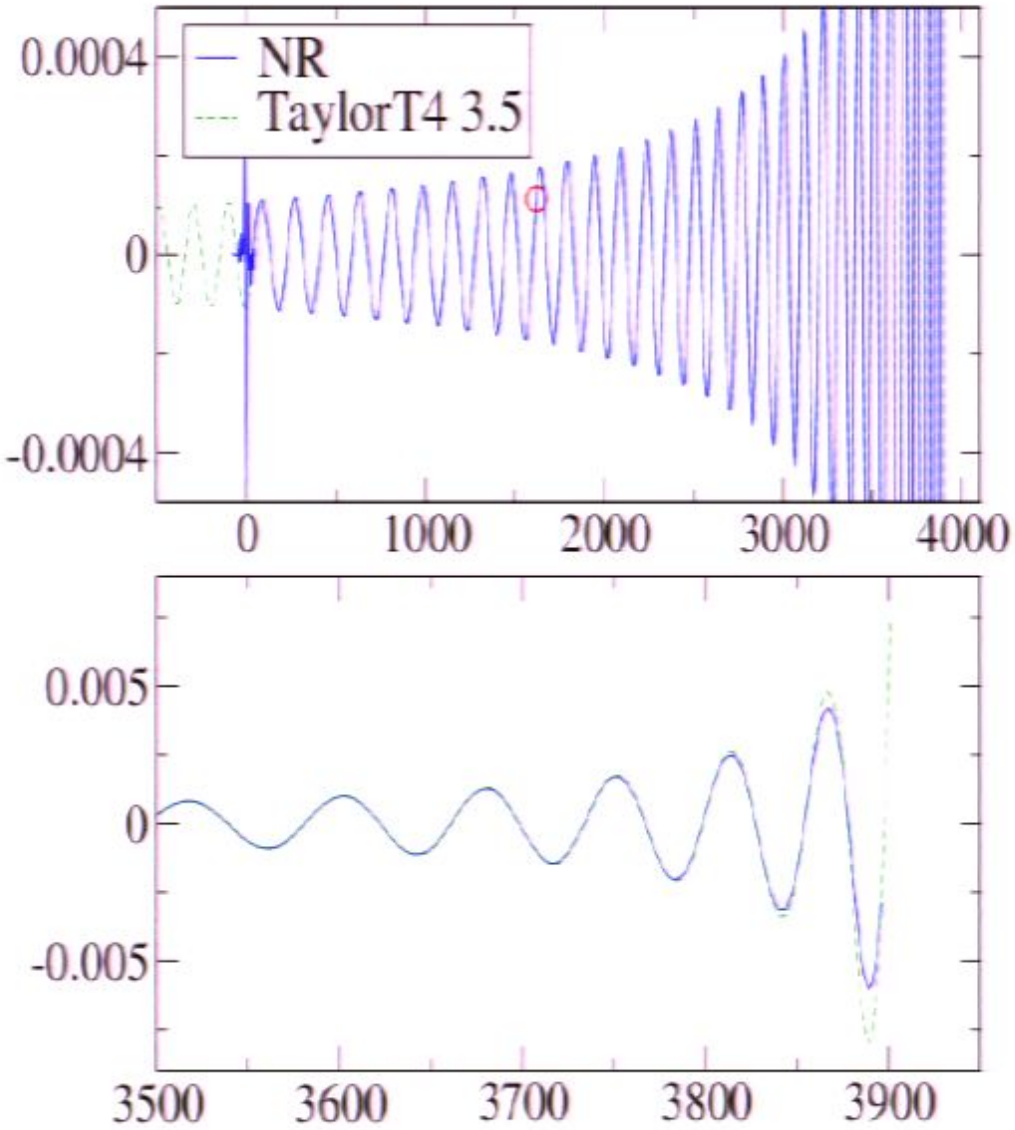

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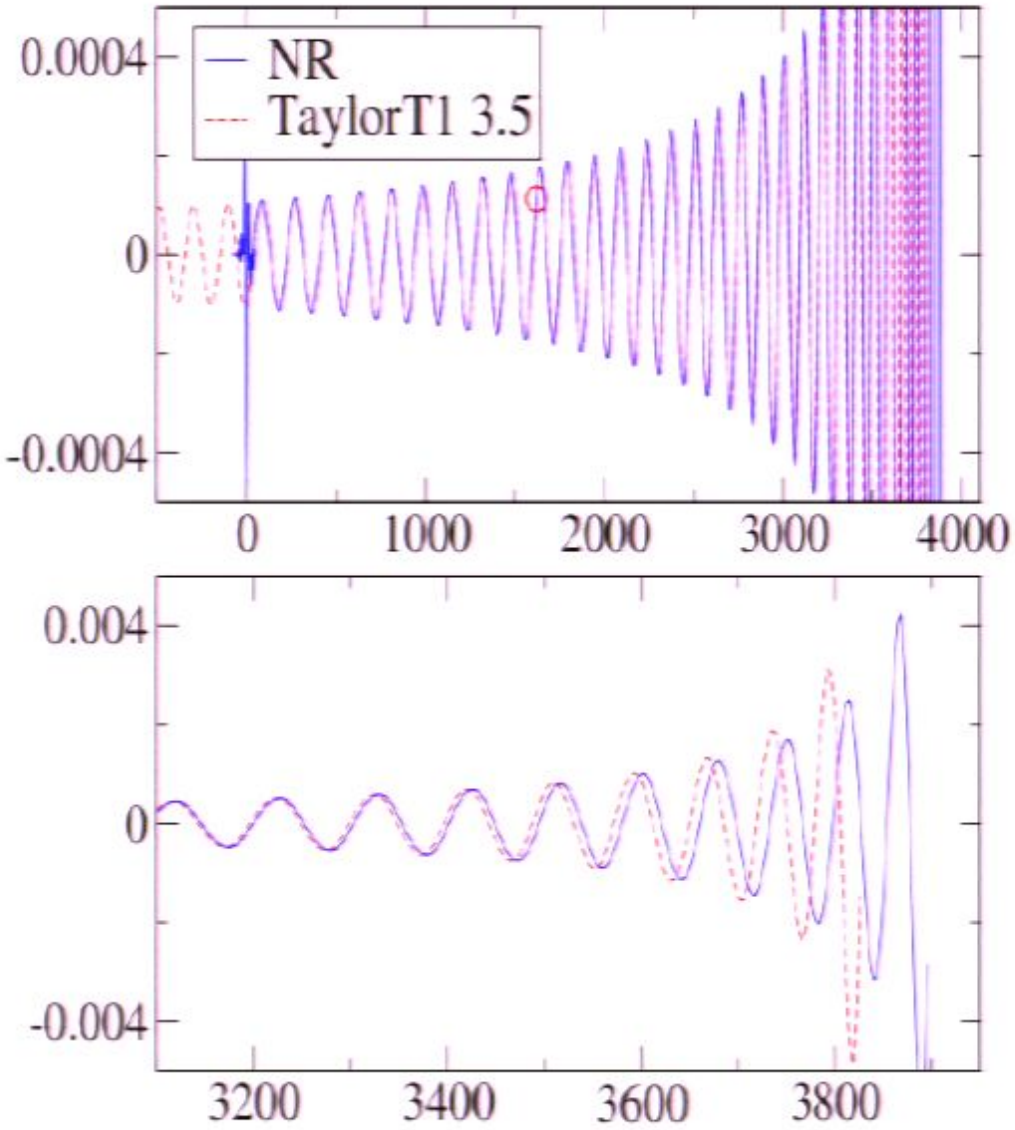

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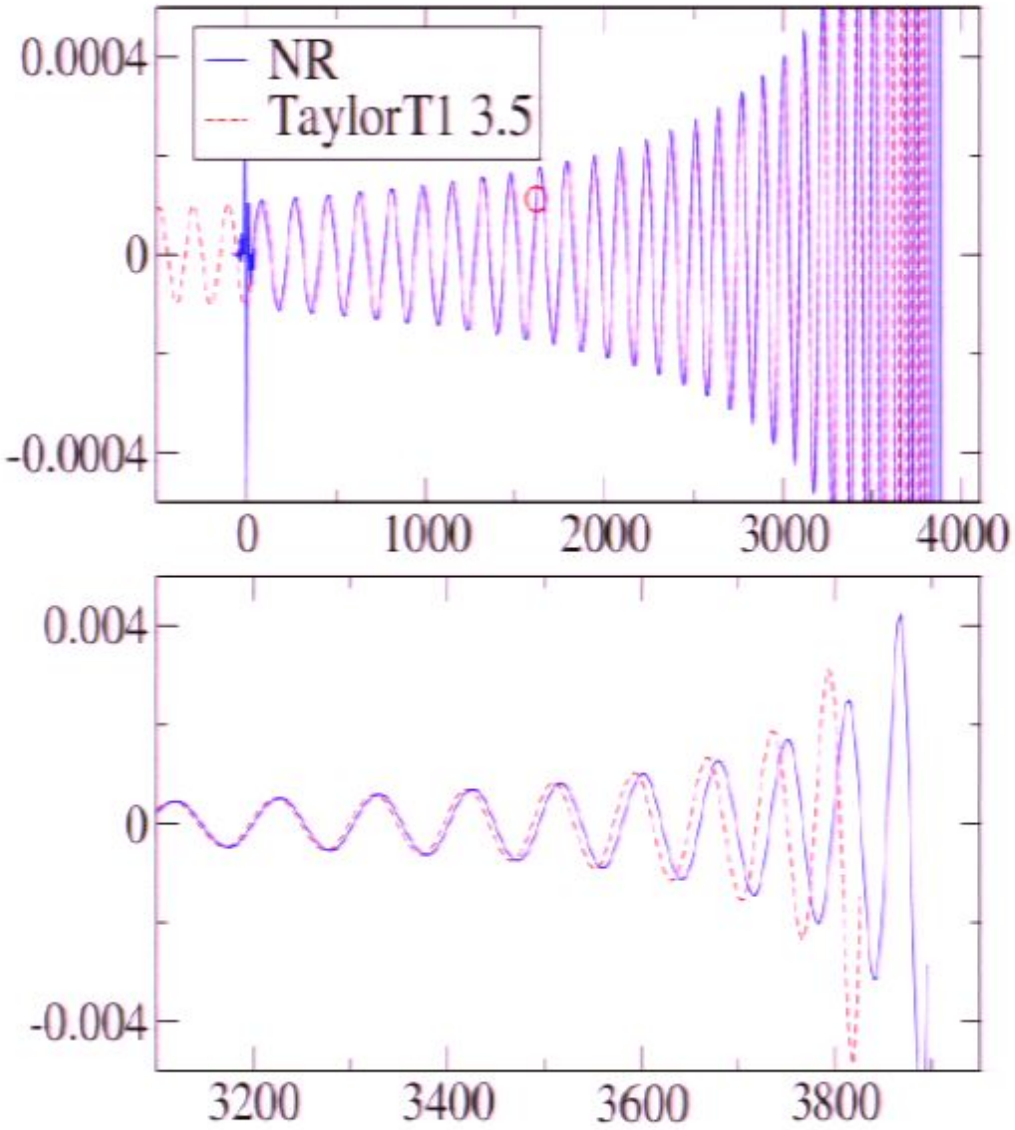

- *Some* PN-approximants match extremely well.
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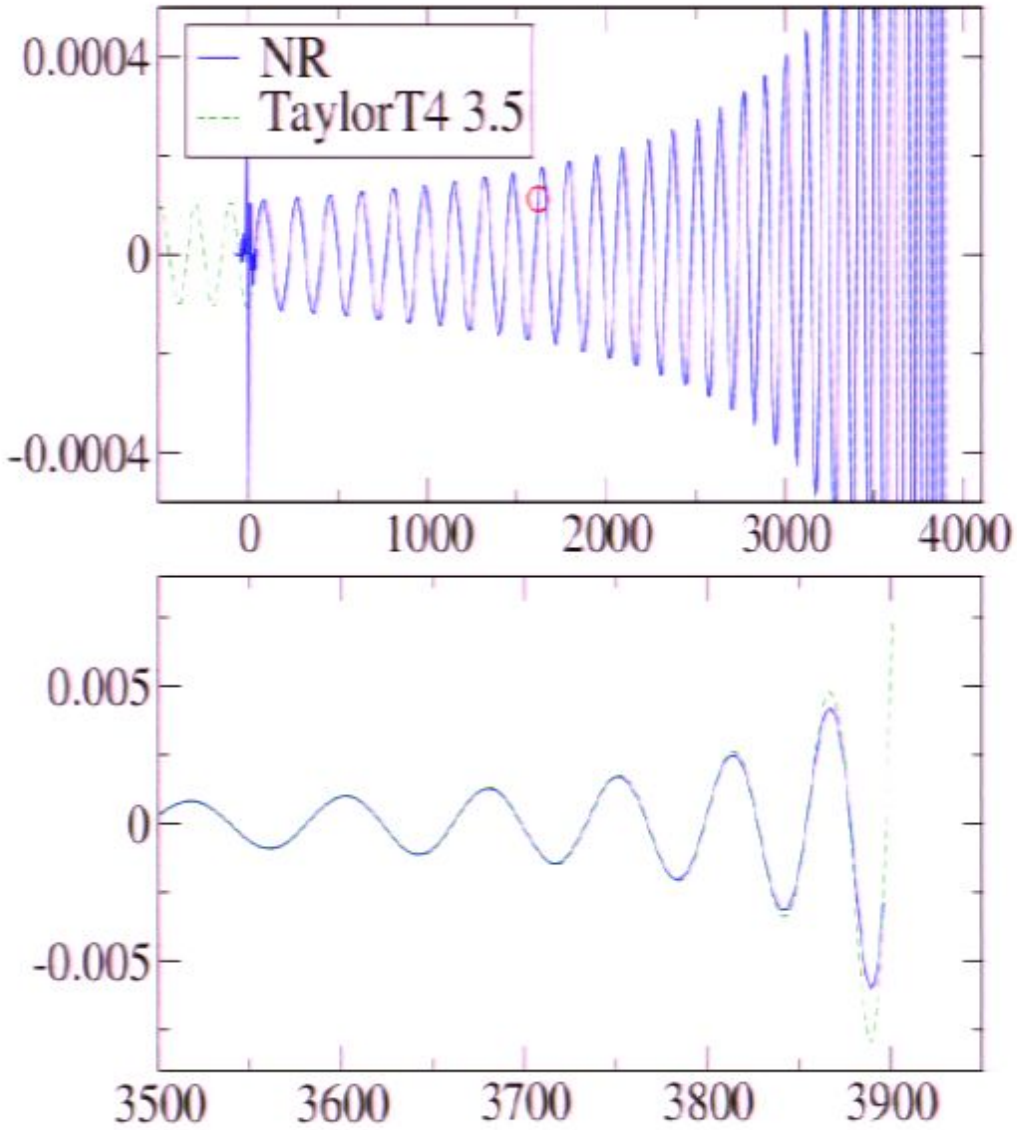

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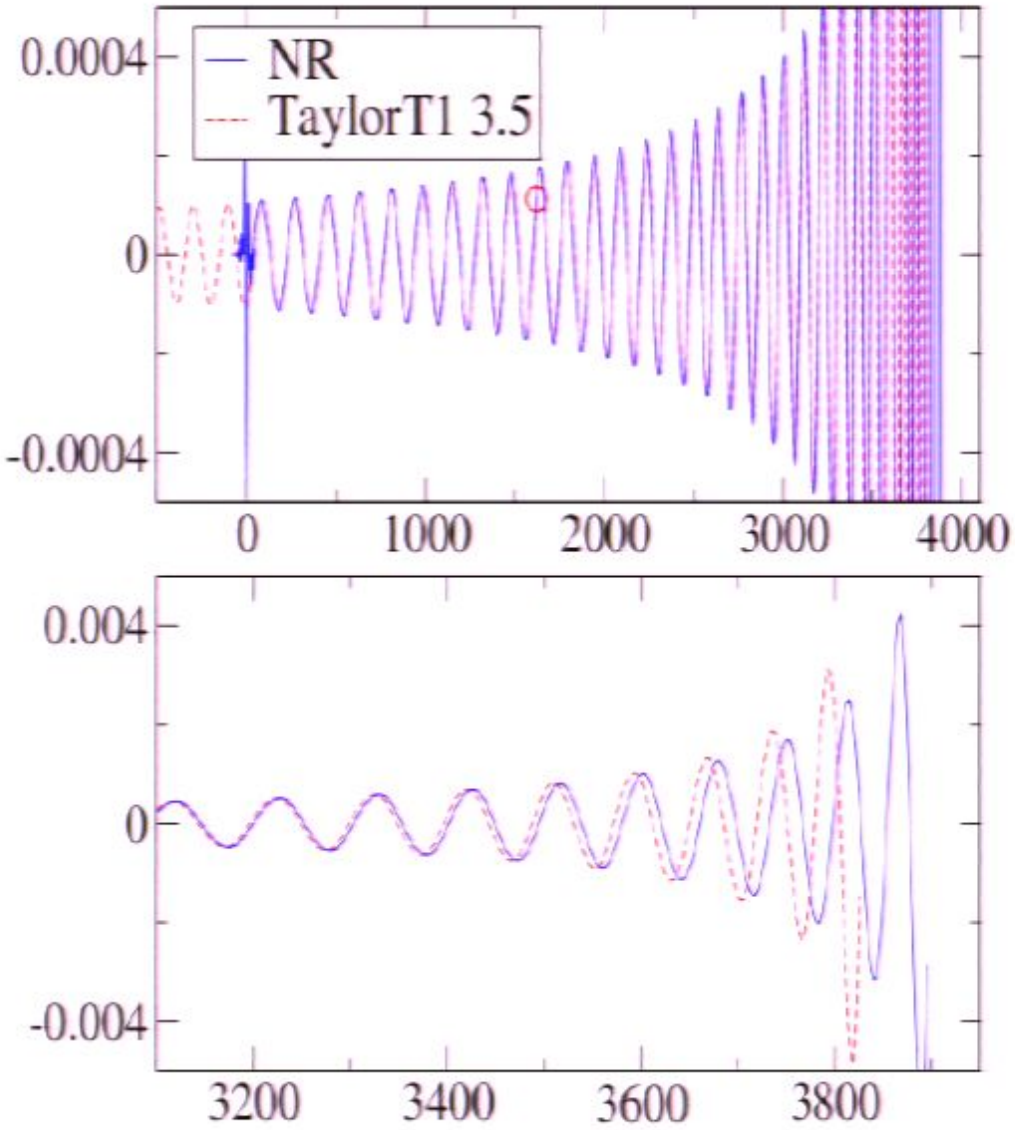

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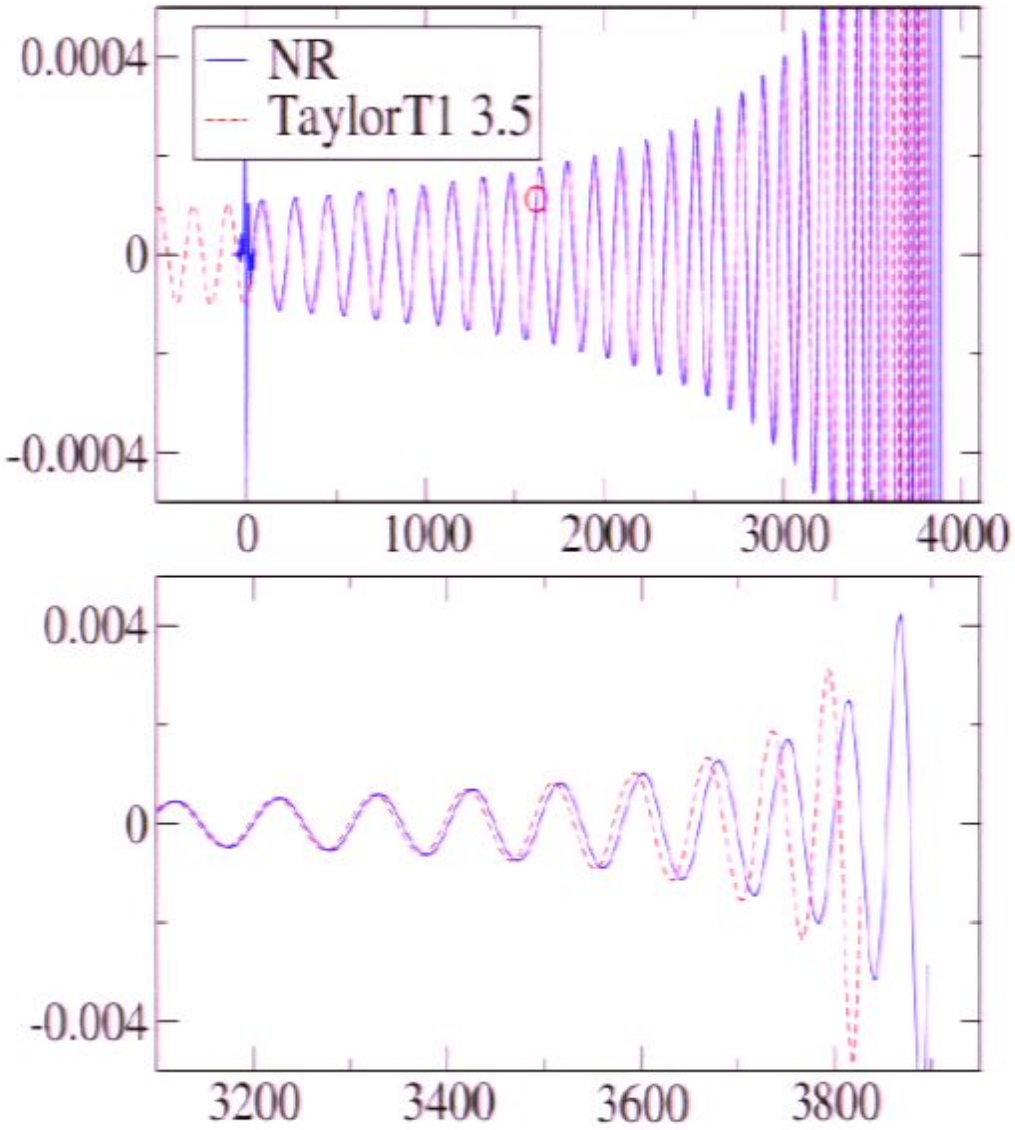

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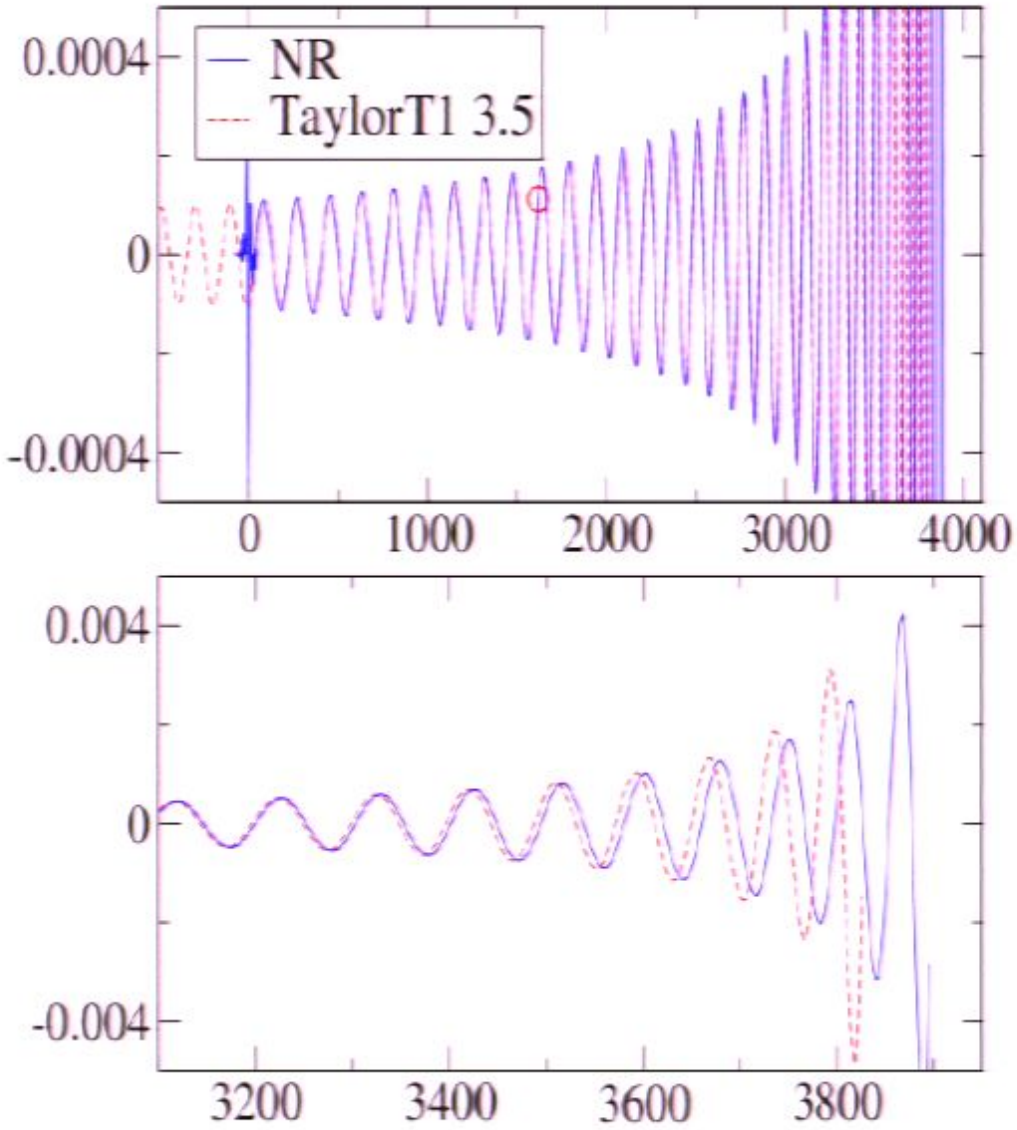
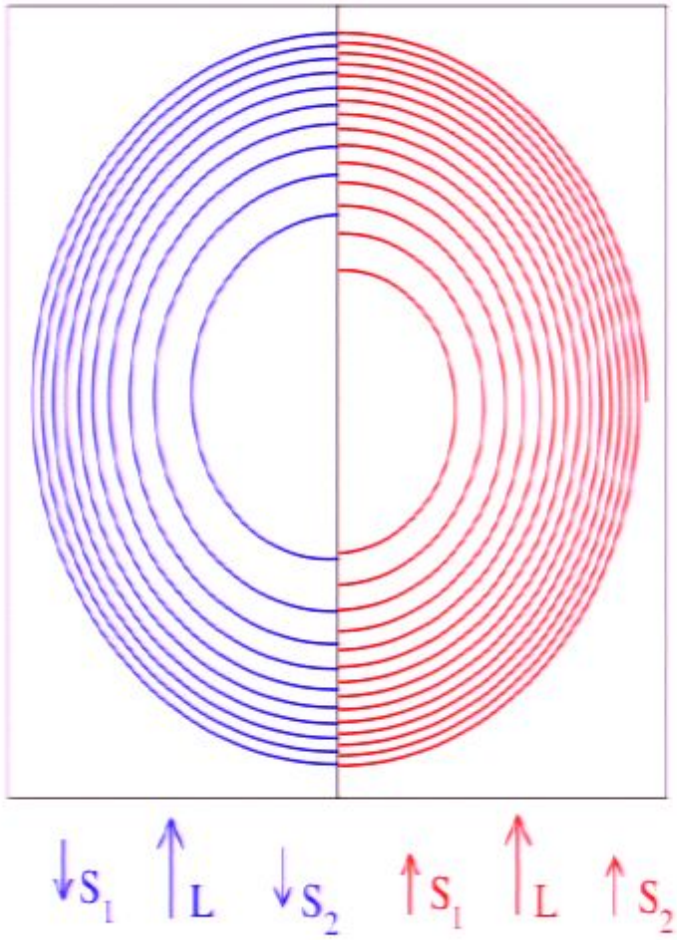


- *Some* PN-approximants match extremely well.
- No a priori knowledge; NR must tell which one.
- Equal mass, no spin most favorable for PN:
  - Spinning PN only known to lower order.
  - Non-equal mass binary has more cycles in strong-field regime.
- PN has great potential as basis for fitting formulae.

In the pipeline

Spinning BHs

(Trajectory of BH A)



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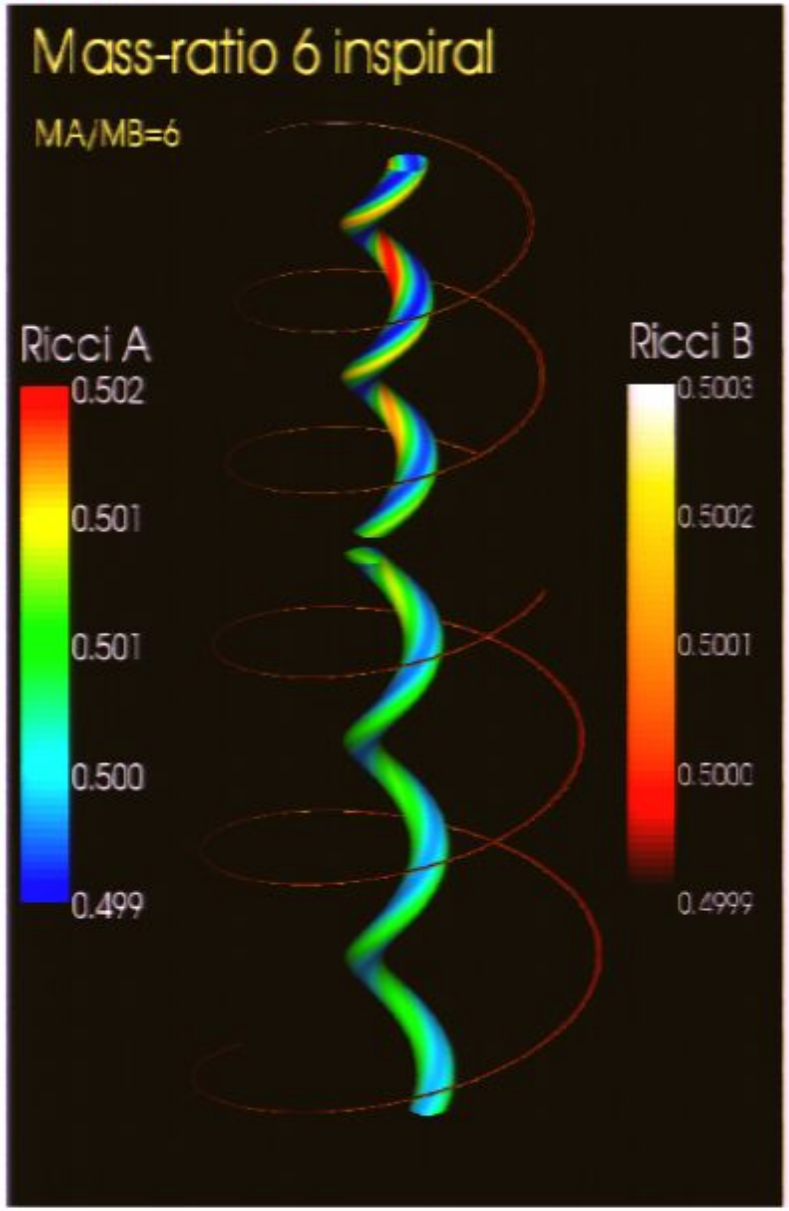
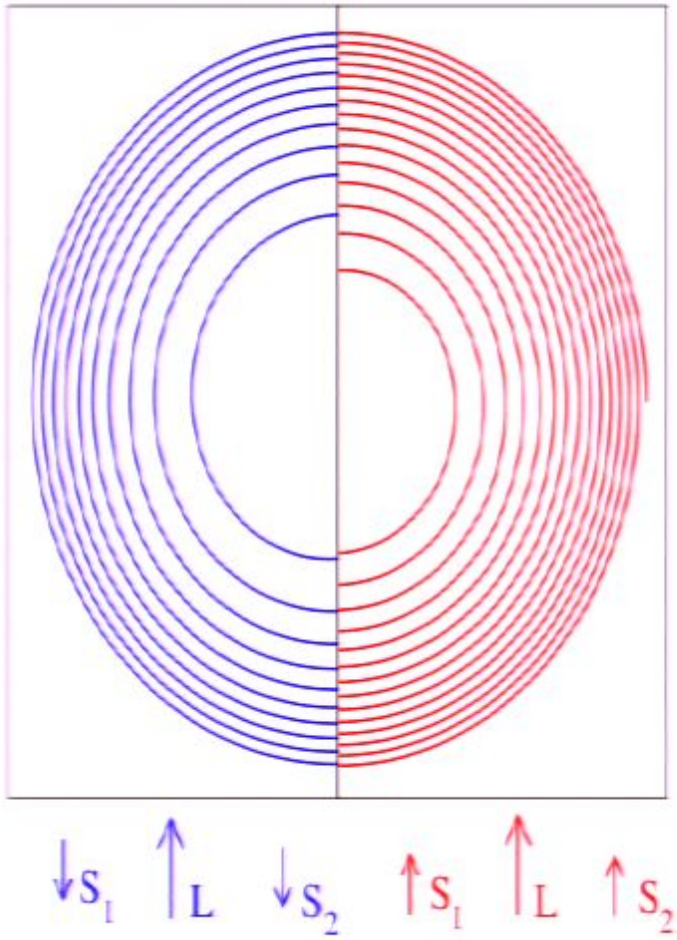


Properties of Einstein's Equations

In the pipeline

Spinning BHs

(Trajectory of BH A)



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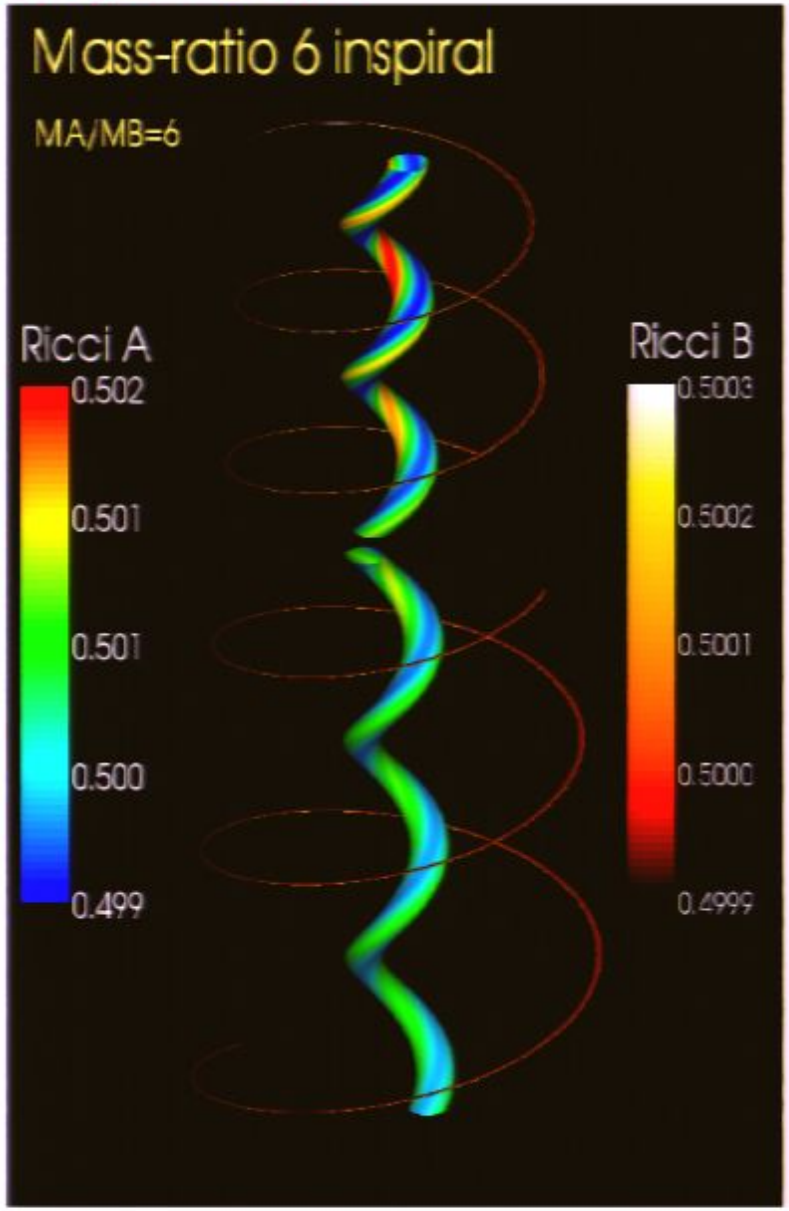

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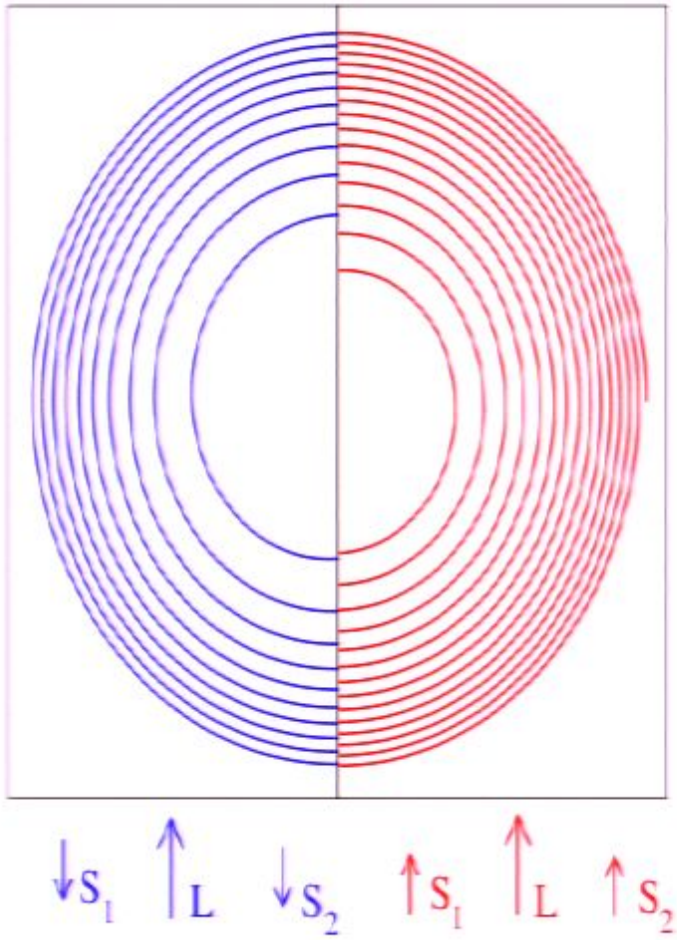

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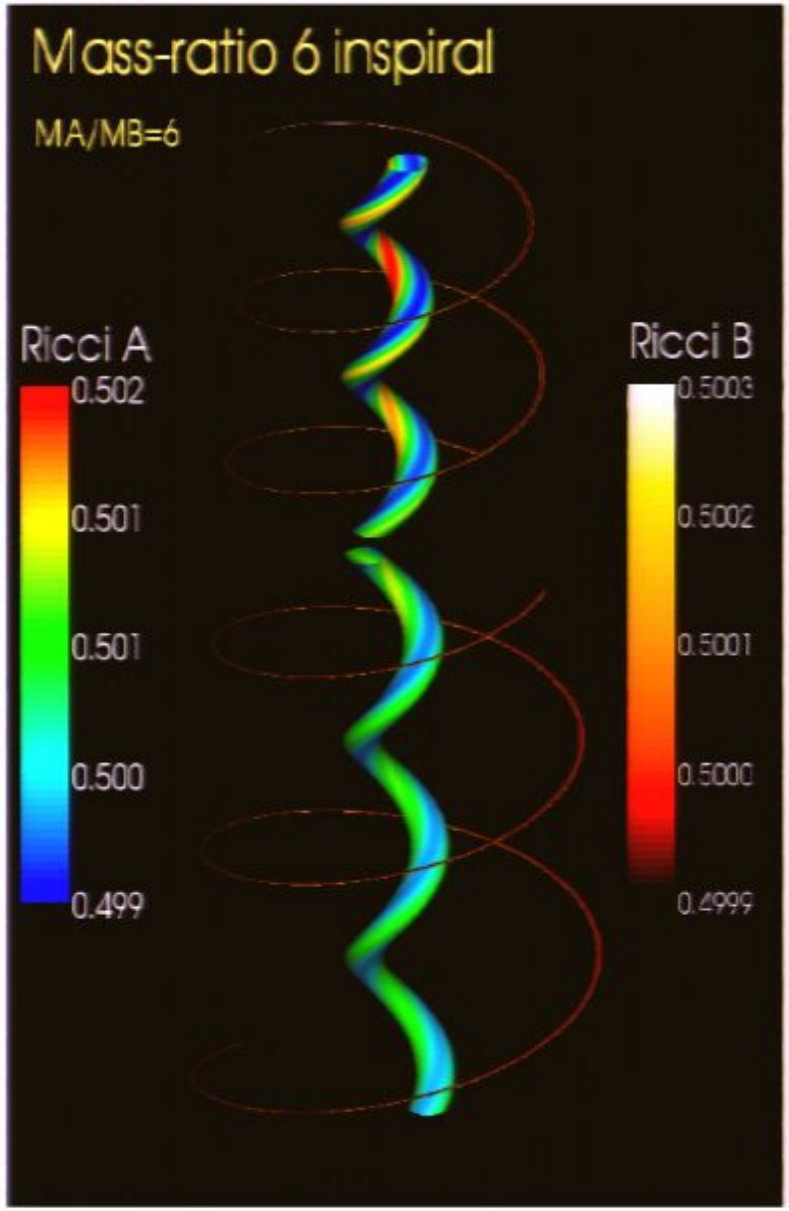
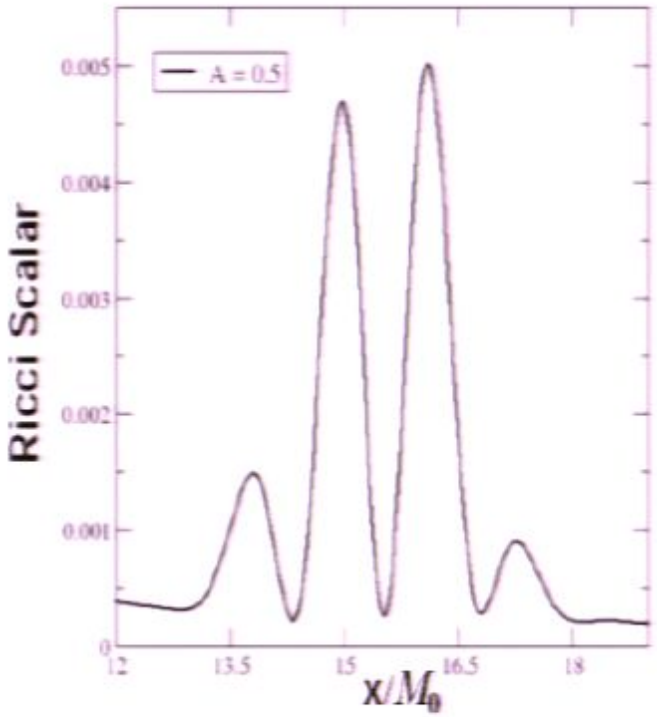


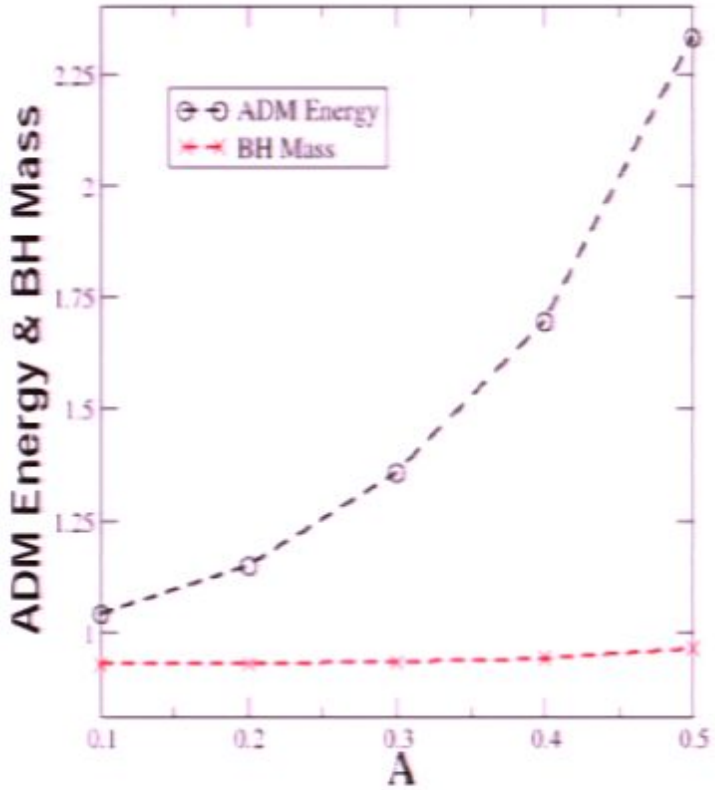
Properties of Einstein's Equations

Distorted Kerr black holes

- With Tony Chu & Mike Cohen
  (Caltech grad students)

- Initial data: Kerr black hole with *incoming* spherical gravitational wave
  (r=15M, width 1.25, even parity, m=2).

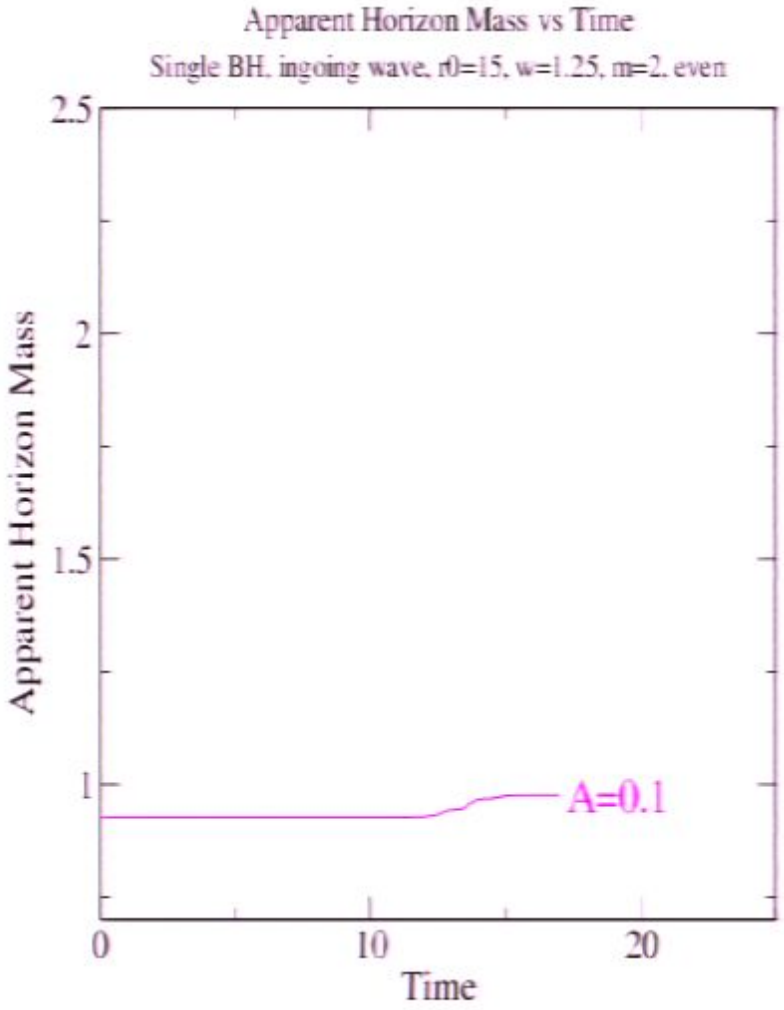




Apparent Horizon Area vs. Time

- Apparent horizon: Surface w/ zero expansion of outgoing null-geodesics

$M \equiv \sqrt{A/16\pi}$



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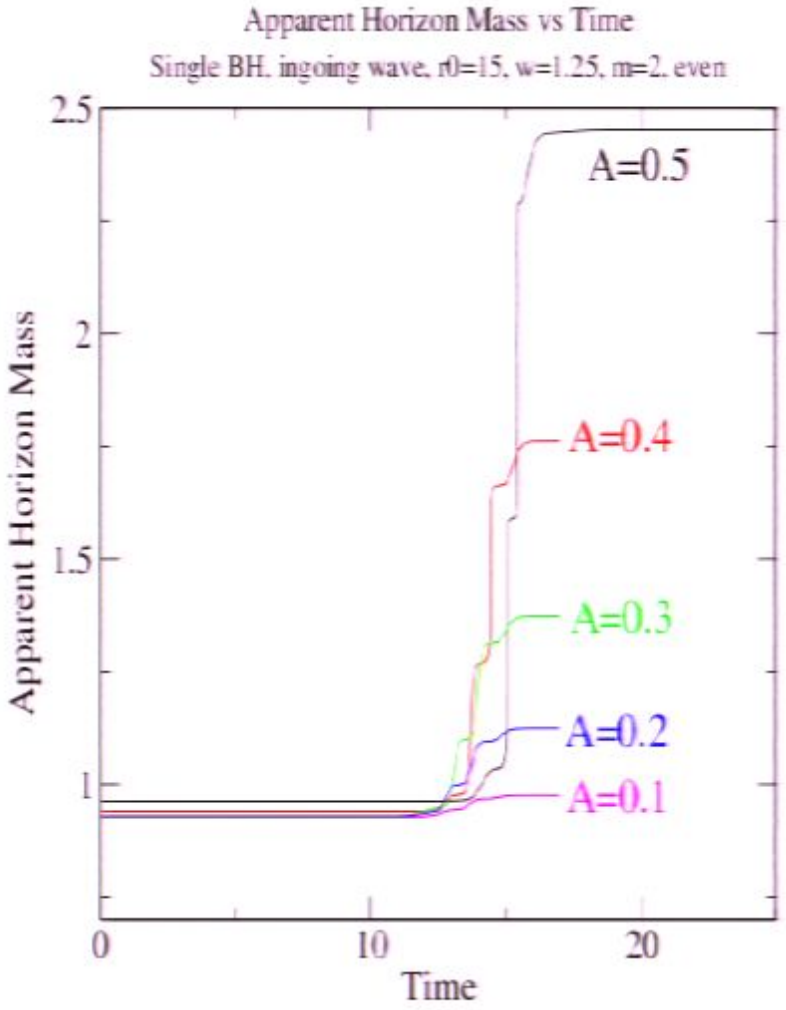

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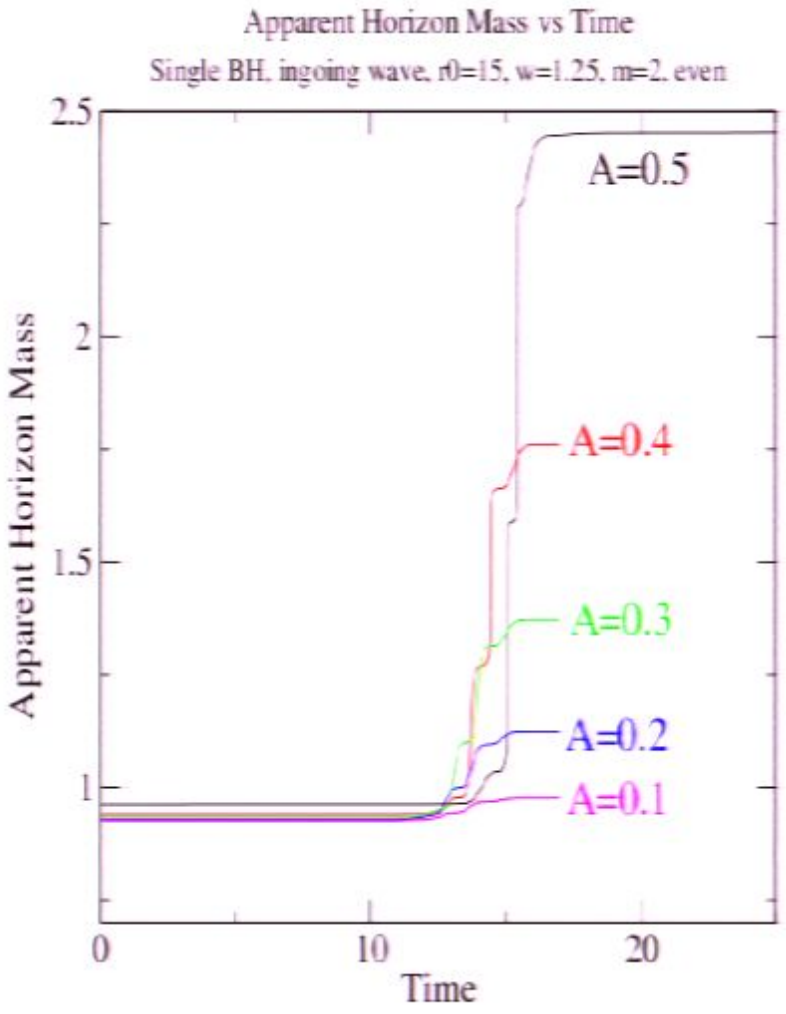

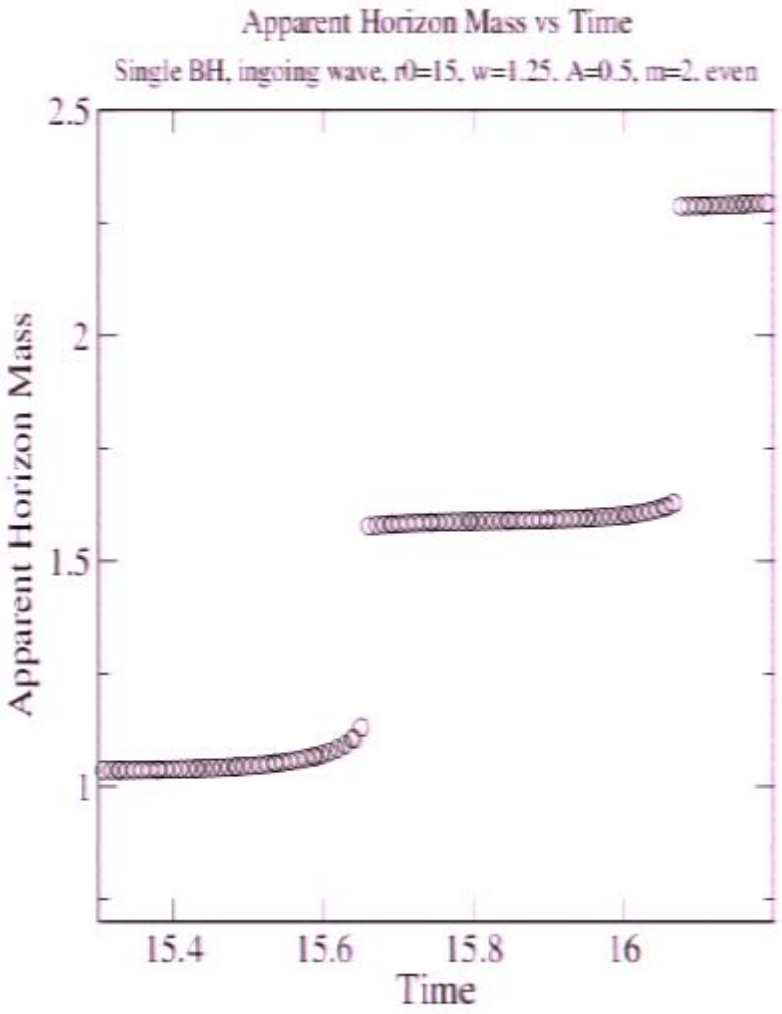

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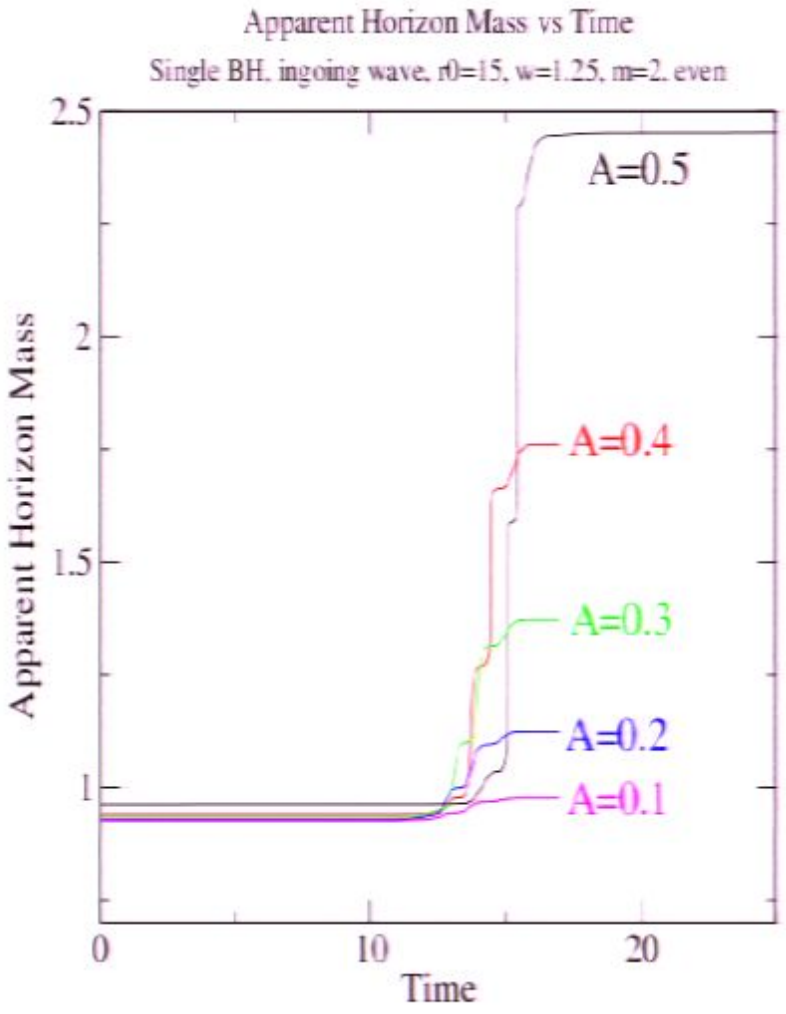

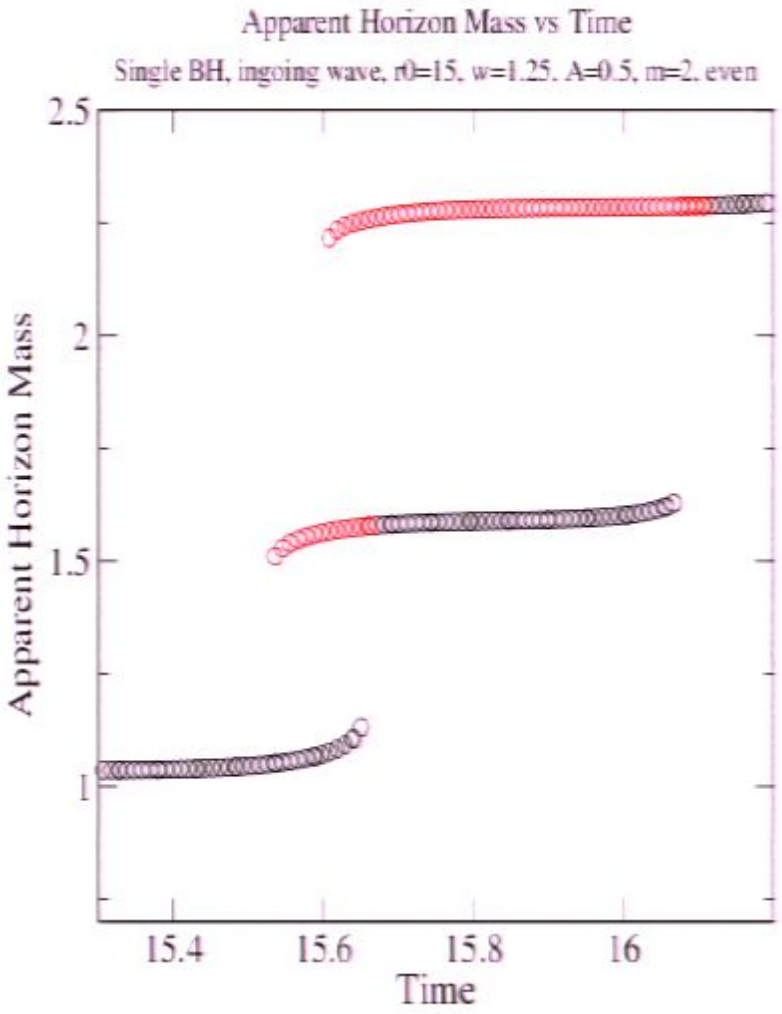

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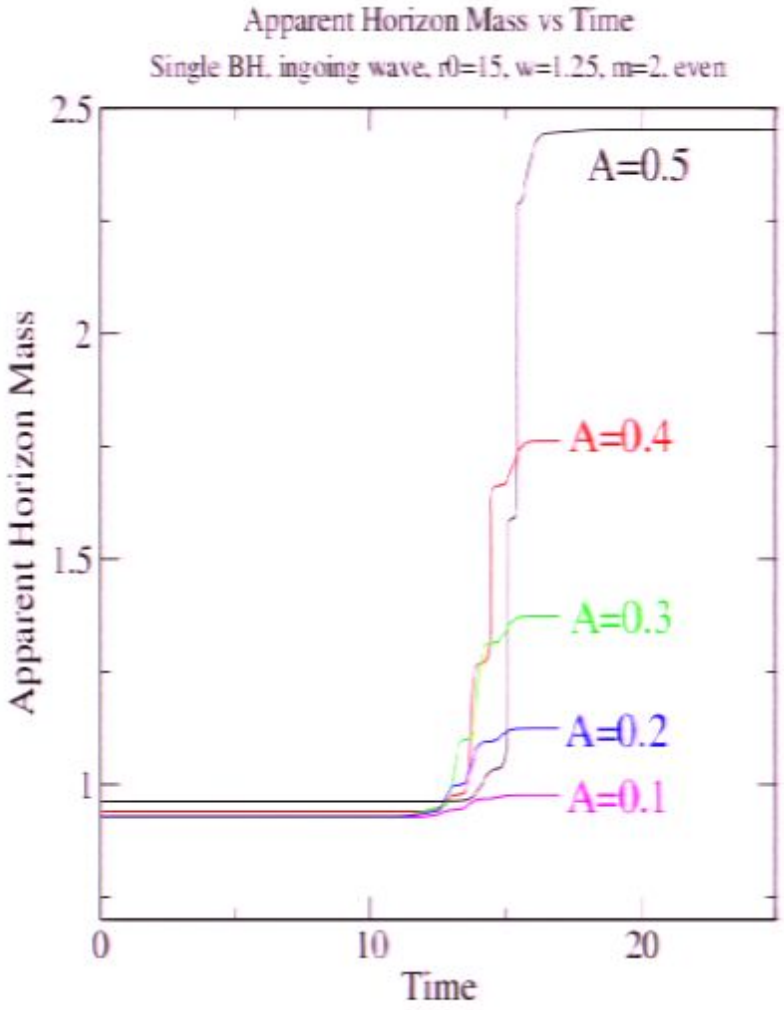

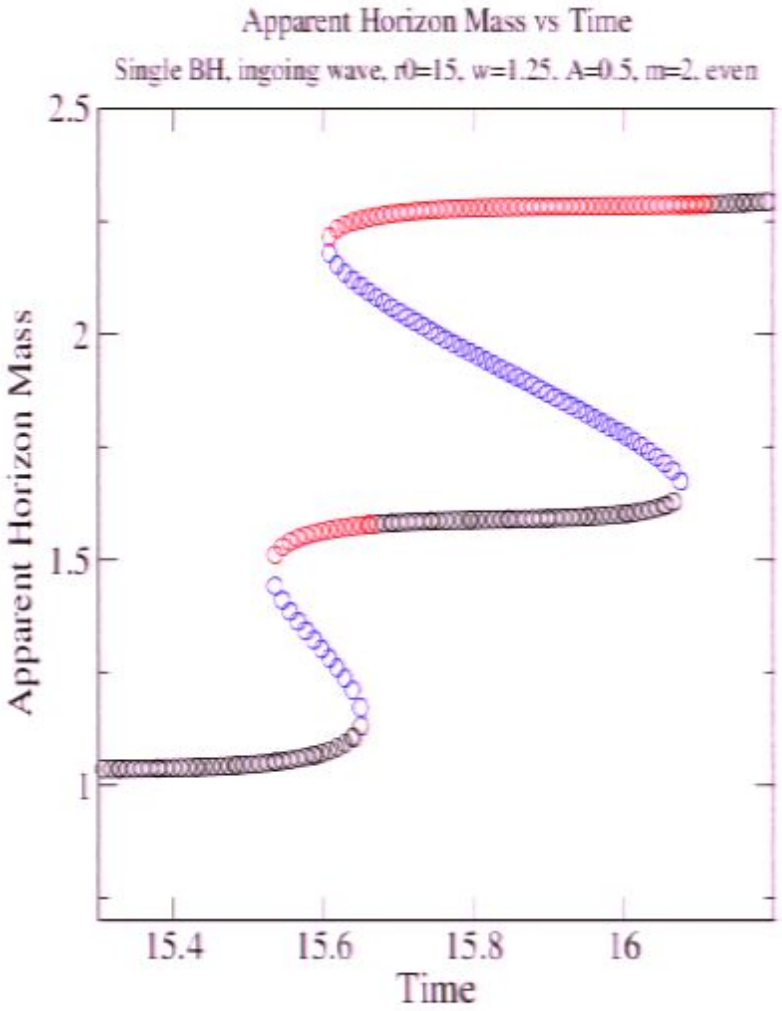

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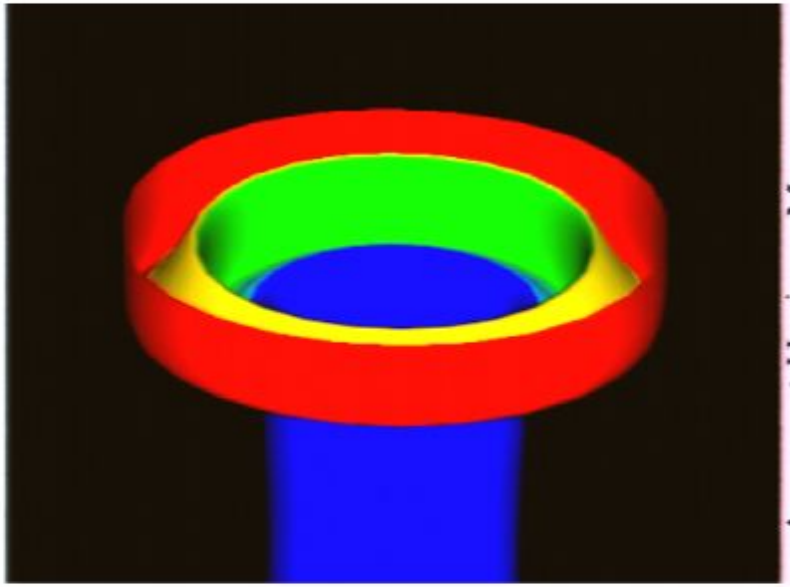

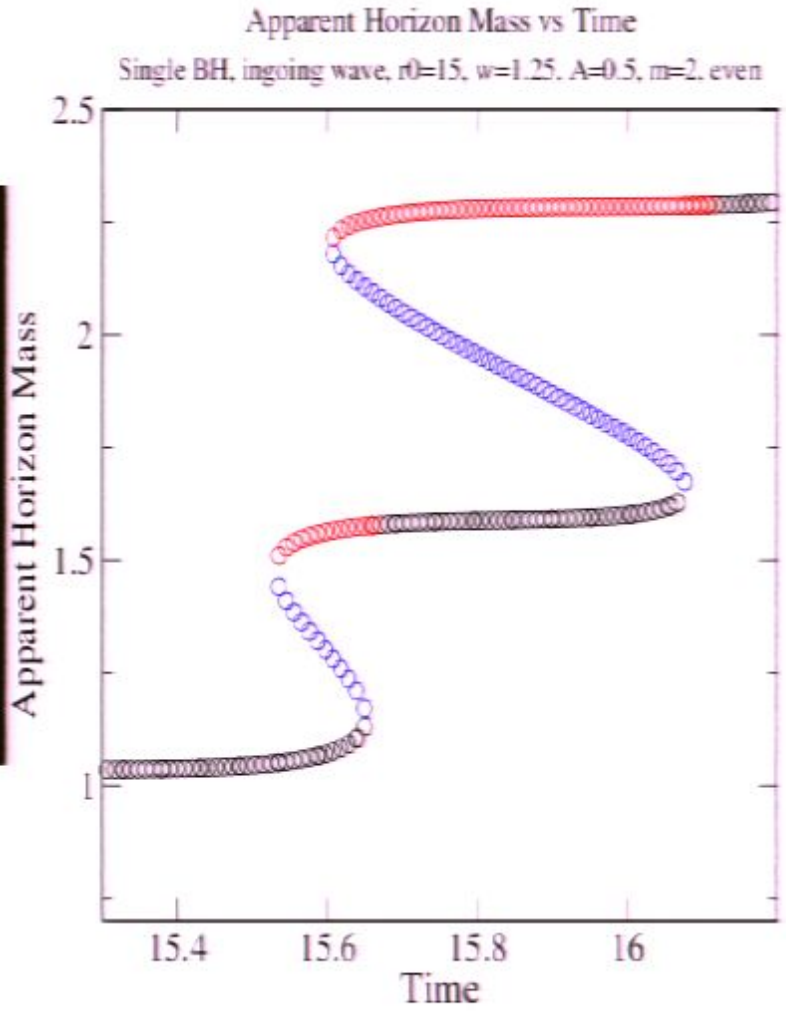

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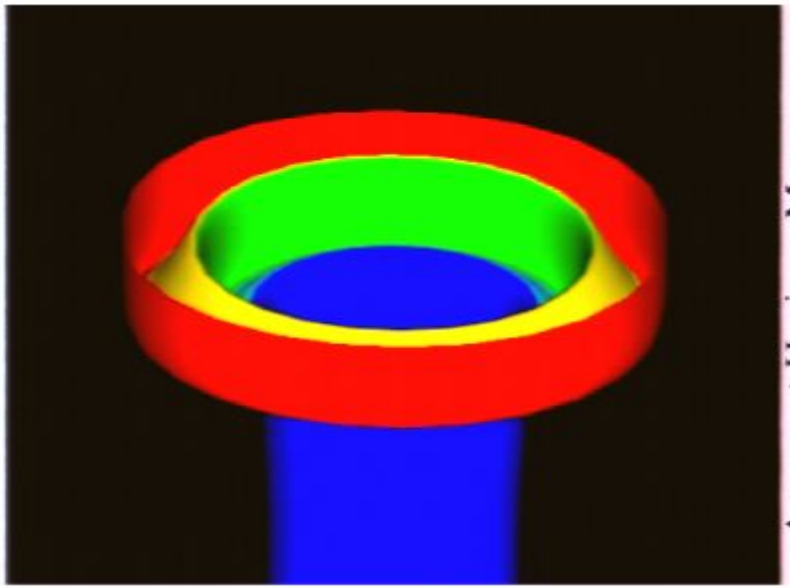

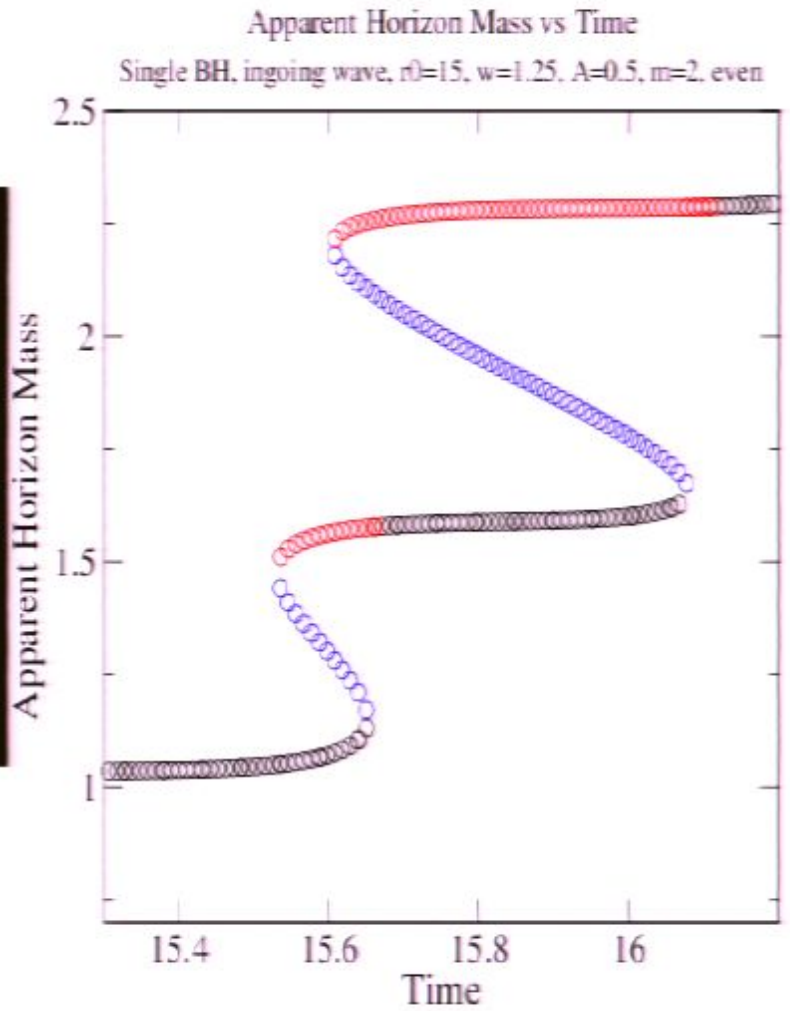

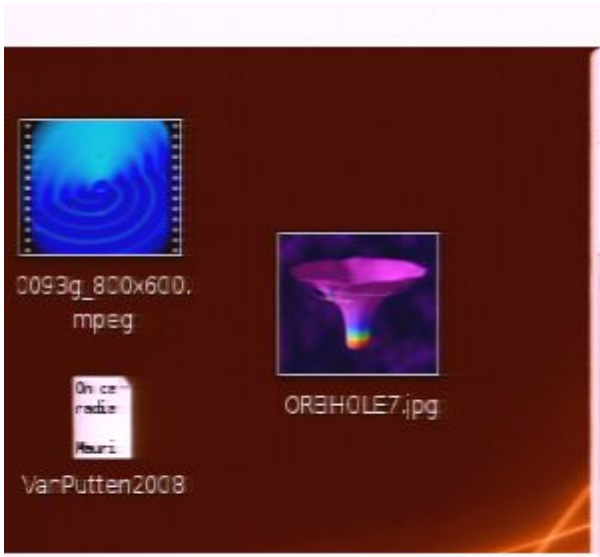

2 GHz

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Previous Next 51 of 67 Best Fit

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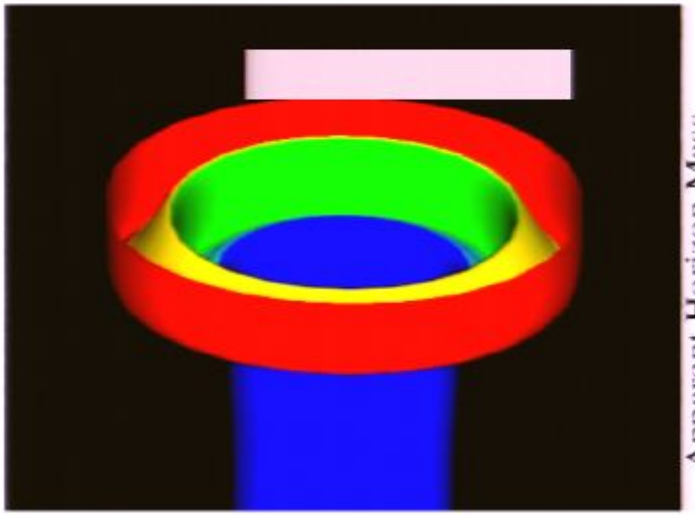

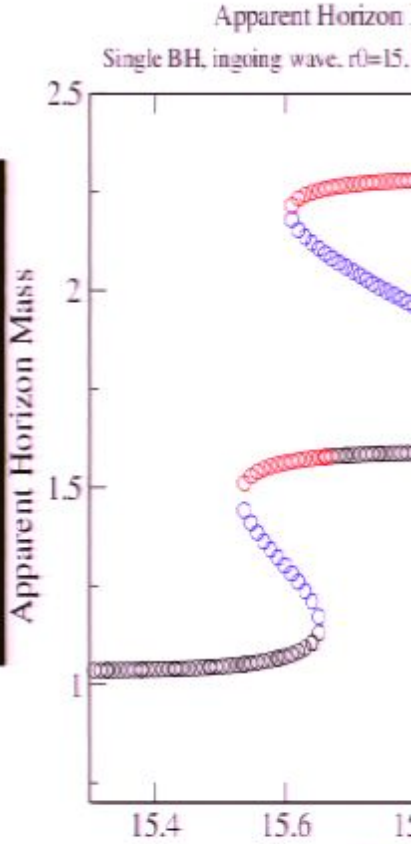

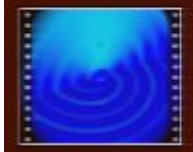

VanPutten2008

harald@Neville:AA~/research/Talks/08Ma

2 GHz

Numerical study of black hole spacetimes

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Previous Next 51 of 67 Best Fit

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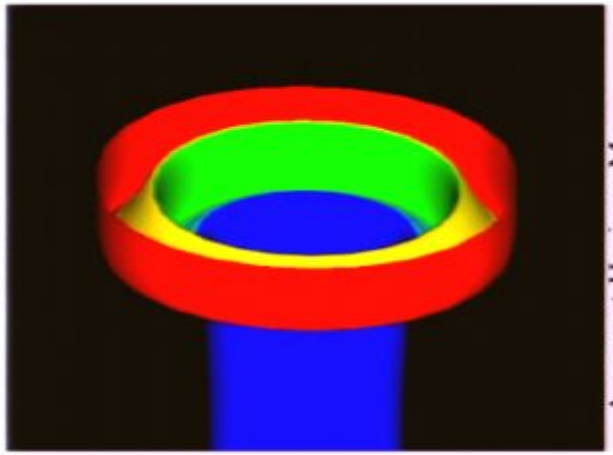
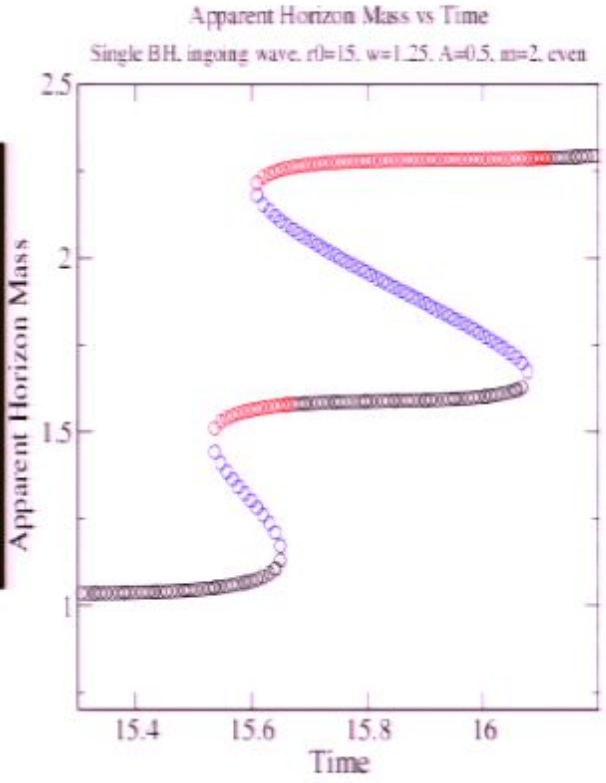
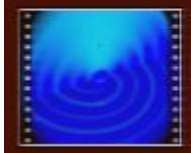




Harald Pfeiffer (Caltech) Black hole simulations 28 / 38



harald@Neville:AA~/research/Talks/08Ma

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2 GHz

Numerical study of black hole spacetimes

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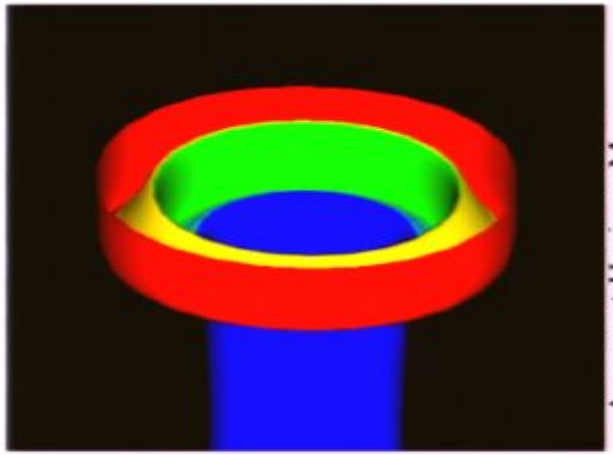
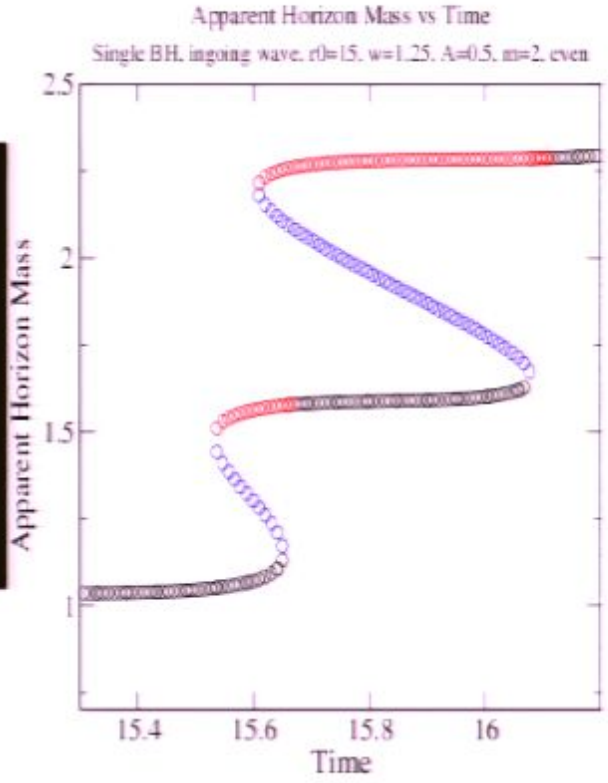
Apparent Horizon Area vs. Time

- Apparent horizon: Surface w/ zero expansion of outgoing null-geodesics

$$M \equiv \sqrt{A/16\pi}$$





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Applications Places System 800 MHz Wed May 28, 11:51 AM

0093g_800x600.mpeg

ORBHOLE7.jpg

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Numerical study of black hole spacetimes

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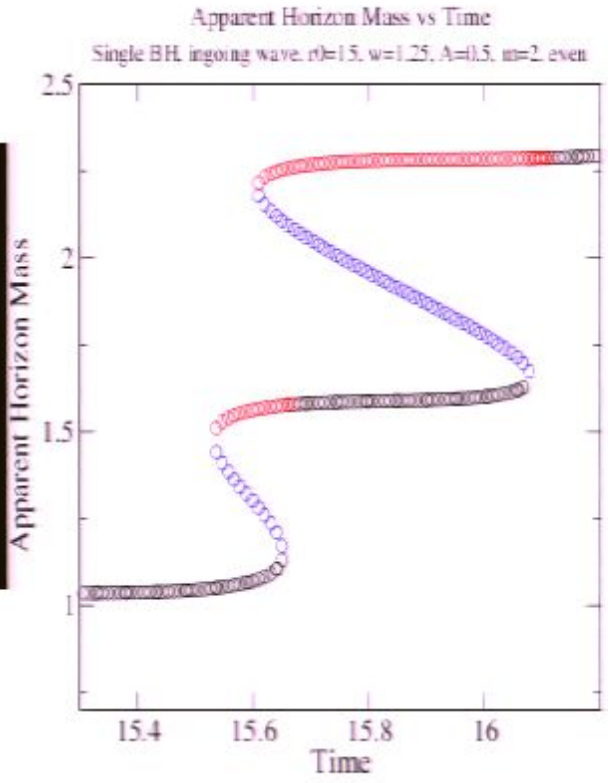
Apparent Horizon Area vs. Time

- Apparent horizon: Surface w/ zero expansion of outgoing null-geodesics

$M \equiv \sqrt{A/16\pi}$



Black hole simulations 28 / 38

harald@Neville:AA~/research/Talks/08May_Perimeter/Movies

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rald@Neville Movies]$
rald@Neville Movies]$
rald@Neville Movies]$
rald@Neville Movies]$ ls *m
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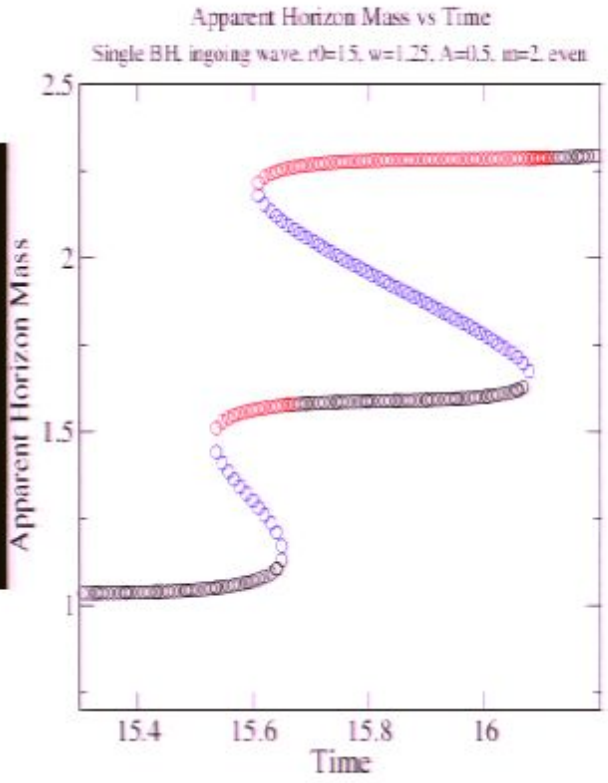
Apparent Horizon Area vs. Time

- Apparent horizon: Surface w/ zero expansion of outgoing null-geodesics

$M \equiv \sqrt{A/16\pi}$



Black hole simulations 28 / 38

harald@Neville:AA~/research/Talks/08May_Perimeter/Movies

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rald@Neville Movies]$
rald@Neville Movies]$ ls *mpg
_Embedding_0093r_Large.mpg        ProlateCriticalCollapse.mpg
_Embedding_0093r_Medium.mpg       RePsi4_0093r.mpg
_Embedding_0093r_Small.mpg        Shibata_APR-135-165.mpg
edding_0093r.mpg                  Shibata_APR-140-140.mpg
eddingFast_0093r.mpg              TrKBlowup.mpg
eddingSmall_0093r.mpg             viz_shiftingall_21.mpg
eddingSmallFast_0093r.mpg         viz_shiftingall_ImPsi4_20.mpg
torius_qc_15_EMI_psi4r_z_log.mpg
rald@Neville Movies]$
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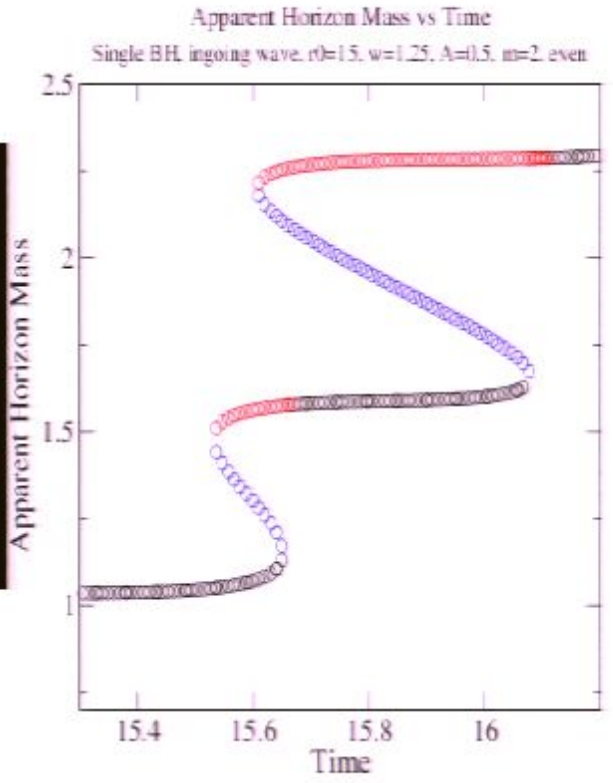
Apparent Horizon Area vs. Time

- Apparent horizon: Surface w/ zero expansion of outgoing null-geodesics

$M \equiv \sqrt{A/16\pi}$



Black hole simulations 28 / 38

harald@Neville:AA~/research/Talks/08May_Perimeter

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rald@Neville Movies]$ ls *mpg
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 Embedding_0093r_Medium.mpg       RePsi4_0093r.mpg
 Embedding_0093r_Small.mpg        Shibata_APR-135-165.mpg
edding_0093r.mpg                  Shibata_APR-140-140.mpg
eddingFast_0093r.mpg              TrKBlowup.mpg
eddingSmall_0093r.mpg             viz_shiftingall_21.mpg
eddingSmallFast_0093r.mpg         viz_shiftingall_ImPsi4_20.mpg
torius_qe_19_Lm1_psi4r_z_log.mpg
rald@Neville Movies]$ cd ..
rald@Neville 08May_Perimeter]$ ls *mpg
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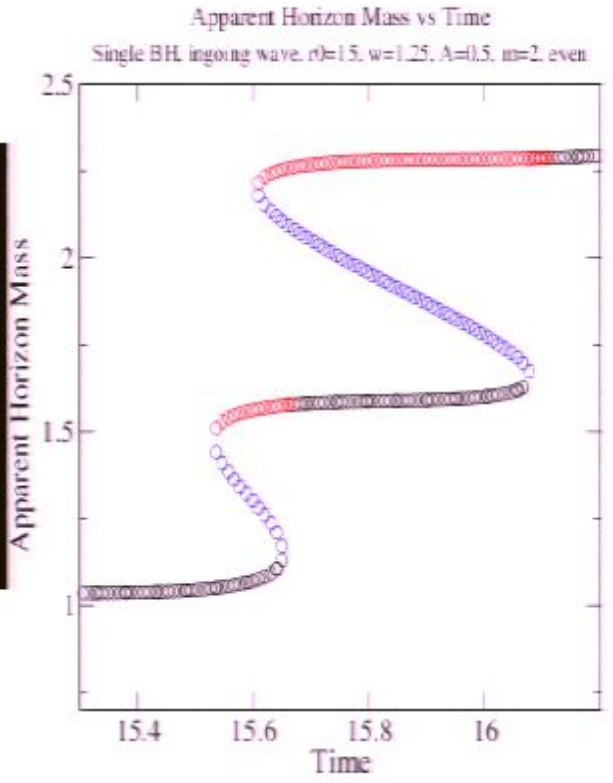
Previous Next 51 of 67 Best Fit

Apparent Horizon Area vs. Time

- Apparent horizon: Surface w/ zero expansion of outgoing null-geodesics

$M \equiv \sqrt{A/16\pi}$



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harald@Neville:AA~/research/Talks/08May_Perimeter

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rald@Neville Movies]$
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rald@Neville Movies]$
rald@Neville Movies]$ ls *mpg
_Embedding_0093r_Large.mpg        ProlateCriticalCollapse.mpg
_Embedding_0093r_Medium.mpg       RePsi4_0093r.mpg
_Embedding_0093r_Small.mpg        Shibata_APR-135-165.mpg
edding_0093r.mpg                  Shibata_APR-140-140.mpg
eddingFast_0093r.mpg              TrKBlowup.mpg
eddingSmall_0093r.mpg             viz_shiftingall_21.mpg
eddingSmallFast_0093r.mpg         viz_shiftingall_ImPsi4_20.mpg
torius_qe_19_Lm1_psi4r_z_log.mpg
rald@Neville Movies]$ cd ..
rald@Neville 08May_Perimeter]$ ls *mpg
 *mpg: No such file or directory
rald@Neville 08May_Perimeter]$
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Applications Places System 800 MHz Wed May 28, 11:51 AM

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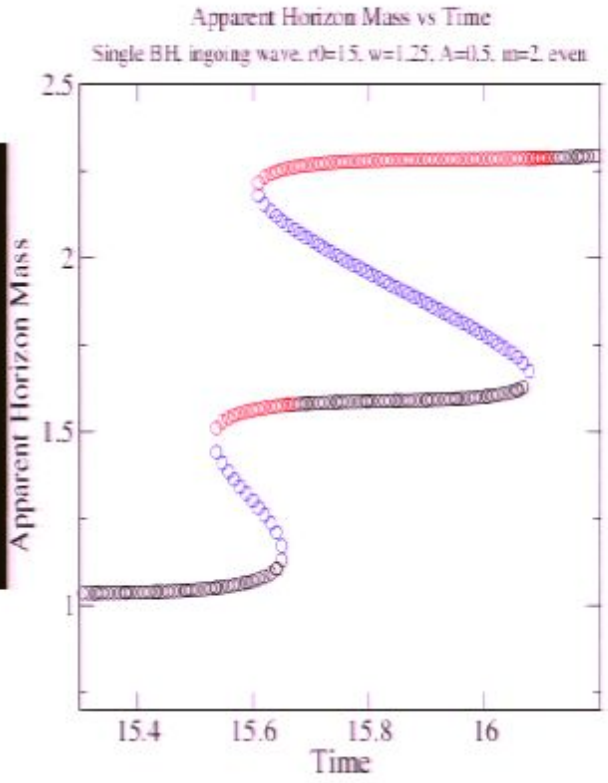
Apparent Horizon Area vs. Time

- Apparent horizon: Surface w/ zero expansion of outgoing null-geodesics

$M \equiv \sqrt{A/16\pi}$



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harald@Neville:AA~/research/Talks/08May_Perimeter

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rald@Neville Movies]$
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rald@Neville Movies]$ ls *mpg
_Embedding_0093r_Large.mpg        ProlateCriticalCollapse.mpg
_Embedding_0093r_Medium.mpg       RePsi4_0093r.mpg
_Embedding_0093r_Small.mpg        Shibata_APR-135-165.mpg
edding_0093r.mpg                  Shibata_APR-140-140.mpg
eddingFast_0093r.mpg              TrKBlowup.mpg
eddingSmall_0093r.mpg             viz_shiftingall_21.mpg
eddingSmallFast_0093r.mpg         viz_shiftingall_ImPsi4_20.mpg
torius_qe_19_Lm1_psi4r_z_log.mpg
rald@Neville Movies]$ cd ..
rald@Neville 08May_Perimeter]$ ls *mpg
 *mpg: No such file or directory
rald@Neville 08May_Perimeter]$ ls *mpeg
rald@Neville 08May_Perimeter]$
```

Applications Places System 800 MHz Wed May 28, 11:52 AM

0093g_800x600.mpeg

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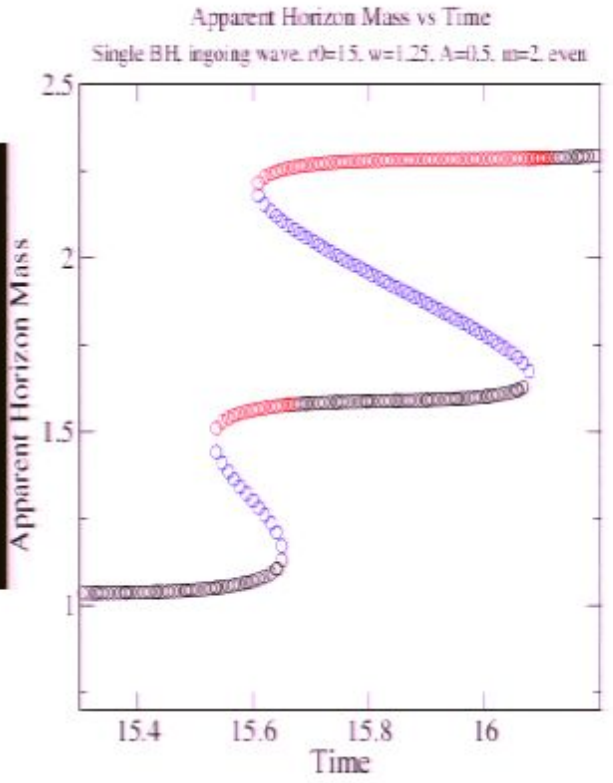
Apparent Horizon Area vs. Time

- Apparent horizon: Surface w/ zero expansion of outgoing null-geodesics

$M \equiv \sqrt{A/16\pi}$



Black hole simulations 28 / 38

harald@Neville:AA~/research/Talks/08May_Perimeter

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rald@Neville Movies]$
rald@Neville Movies]$
rald@Neville Movies]$
rald@Neville Movies]$ ls *mpg
_Embedding_0093r_Large.mpg        ProlateCriticalCollapse.mpg
_Embedding_0093r_Medium.mpg       RePsi4_0093r.mpg
_Embedding_0093r_Small.mpg        Shibata_APR-135-165.mpg
edding_0093r.mpg                  Shibata_APR-140-140.mpg
eddingFast_0093r.mpg              TrKBlowup.mpg
eddingSmall_0093r.mpg             viz_shiftingall_21.mpg
eddingSmallFast_0093r.mpg         viz_shiftingall_ImPsi4_20.mpg
torius_qe_19_lml_psi4r_z_log.mpg
rald@Neville Movies]$ cd ..
rald@Neville 08May_Perimeter]$ ls *mpg
 *mpg: No such file or directory
rald@Neville 08May_Perimeter]$ ls *mpeg
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rald@Neville 08May_Perimeter]$ mpeg_play 5HorizonSlicing.
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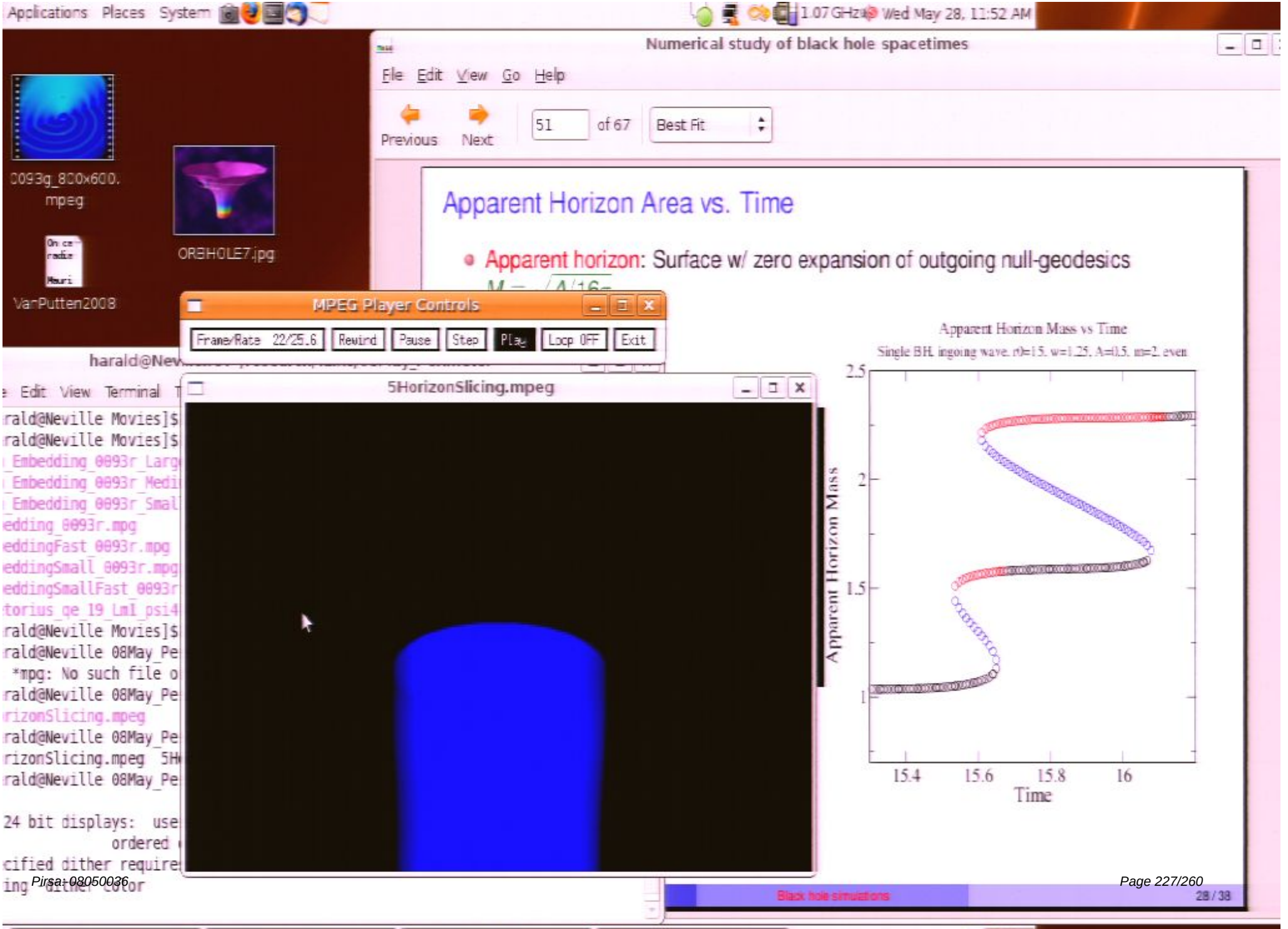
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1.07 GHz Wed May 28, 11:52 AM
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Numerical study of black hole spacetimes
File Edit View Go Help
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Best Fit
Apparent Horizon Area vs. Time
Apparent horizon: Surface w/ zero expansion of outgoing null-geodesics
MPEG Player Controls
Frame/Rate 22/25.6
Rewind
Pause
Step
Play
Loop OFF
Exit
5HorizonSlicing.mpeg
Apparent Horizon Mass vs Time
Single BH, ingoing wave, r0=1.5, w=1.25, A=0.5, m=2, even
Apparent Horizon Mass
Time
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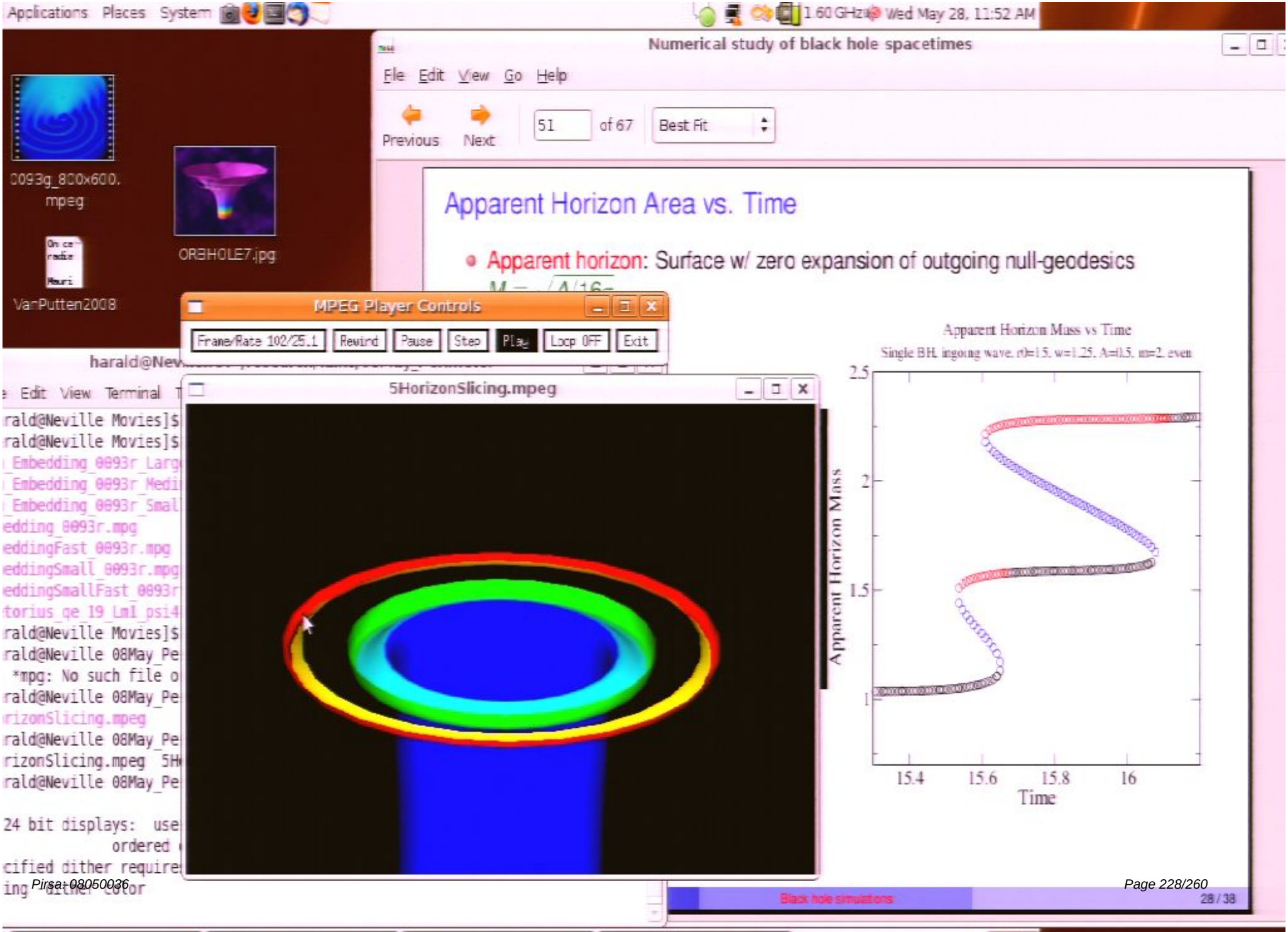
Black hole simulations
28 / 38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Best Fit
Apparent Horizon Area vs. Time
Apparent horizon: Surface w/ zero expansion of outgoing null-geodesics
MPEG Player Controls
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5HorizonSlicing.mpeg
Apparent Horizon Mass vs Time
Single BH, ingoing wave, r0=1.5, w=1.25, A=0.5, m=2, even
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harald@Neville Movies]$
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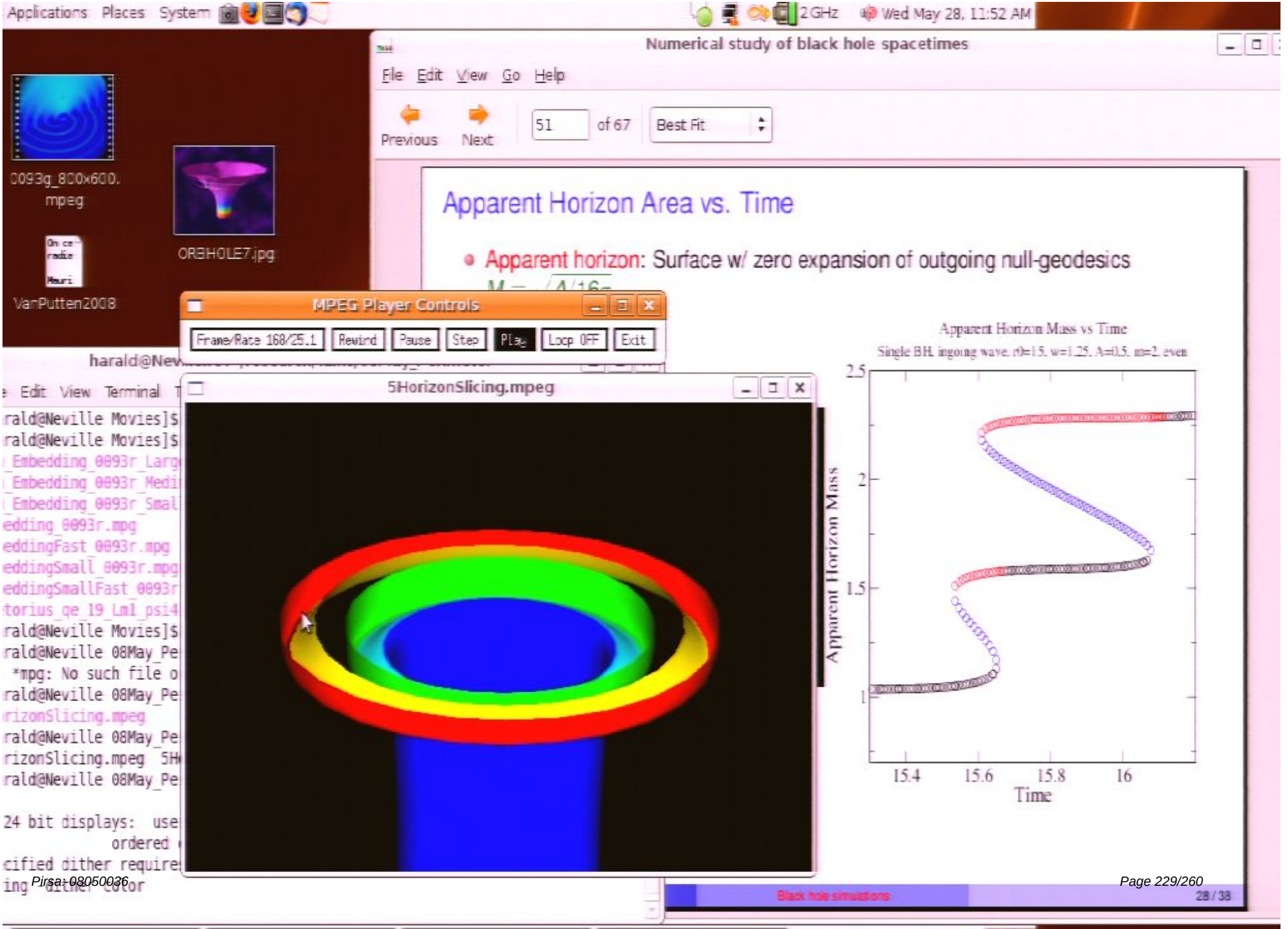
Black hole simulations
28 / 38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File Edit View Go Help
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of 67
Best Fit
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Apparent Horizon Area vs. Time
Apparent horizon: Surface w/ zero expansion of outgoing null-geodesics
MPEG Player Controls
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Apparent Horizon Mass vs Time
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harald@Neville Movies]$
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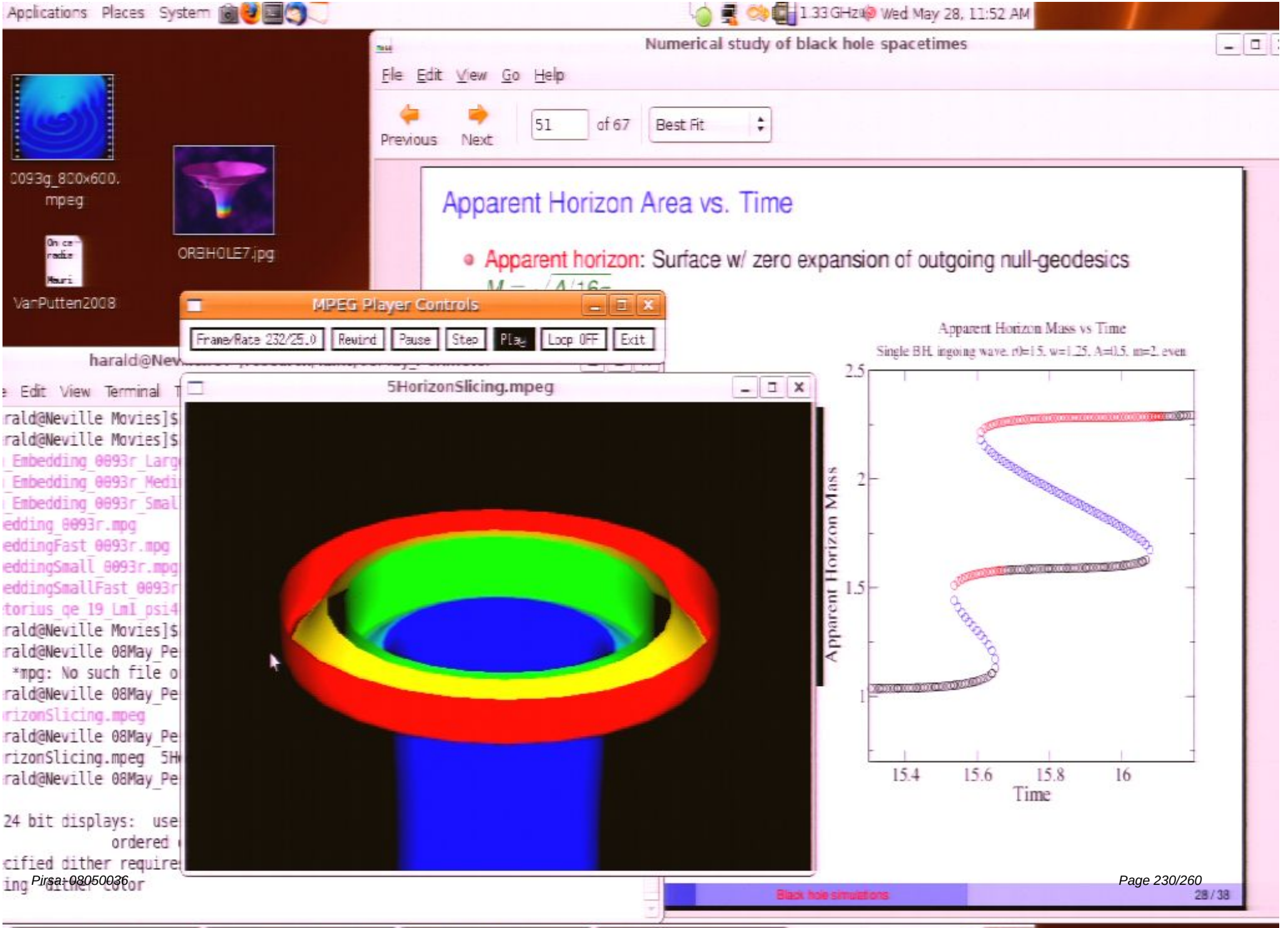
Black hole simulations
28 / 38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File Edit View Go Help
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Best Fit
Apparent Horizon Area vs. Time
Apparent horizon: Surface w/ zero expansion of outgoing null-geodesics
MPEG Player Controls
Frame/Rate 232/25.0
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5HorizonSlicing.mpeg
Apparent Horizon Mass vs Time
Single BH, ingoing wave, r0=1.5, w=1.25, A=0.5, m=2, even
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harald@Neville Movies]$
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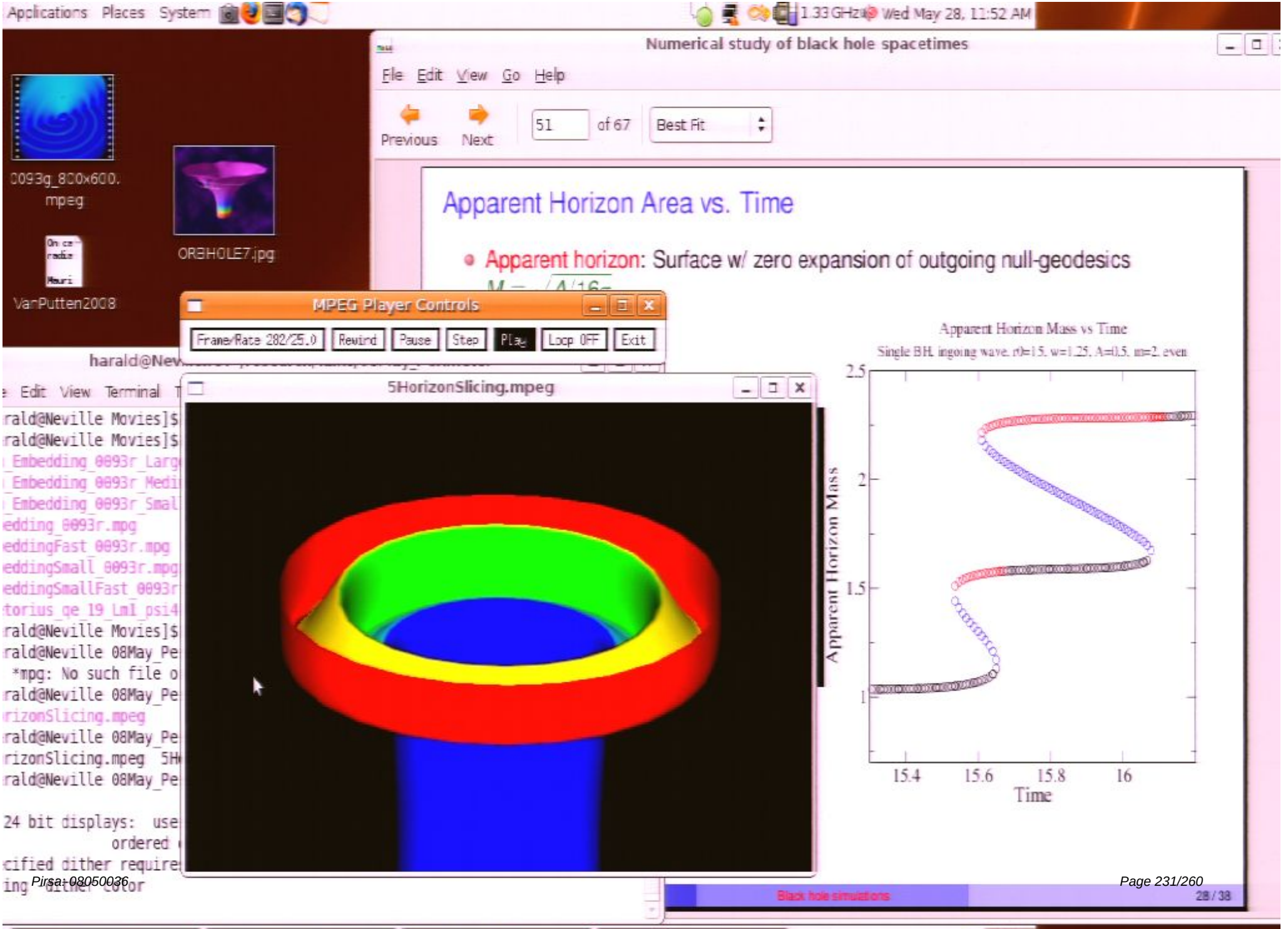
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Best Fit
Apparent Horizon Area vs. Time
Apparent horizon: Surface w/ zero expansion of outgoing null-geodesics
MPEG Player Controls
Frame/Rate 282/25.0
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Exit
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Apparent Horizon Mass vs Time
Single BH, ingoing wave, r0=1.5, w=1.25, A=0.5, m=2, even
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Edit View Terminal
harald@Neville Movies]$
harald@Neville 08May_Pe
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Black hole simulations
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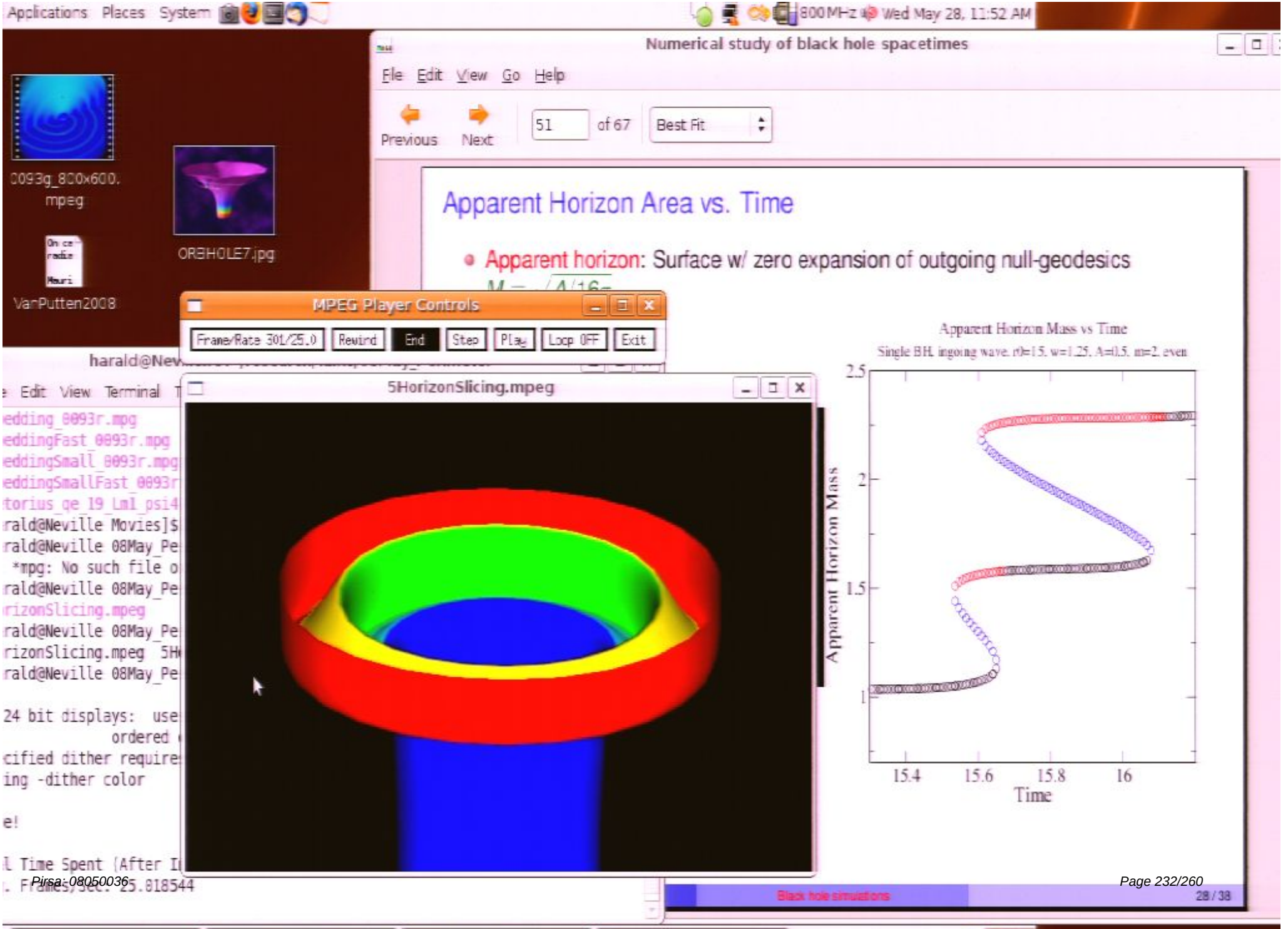
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Numerical study of black hole spacetimes
File Edit View Go Help
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Best Fit
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VanPutten2008
Apparent Horizon Area vs. Time
Apparent horizon: Surface w/ zero expansion of outgoing null-geodesics
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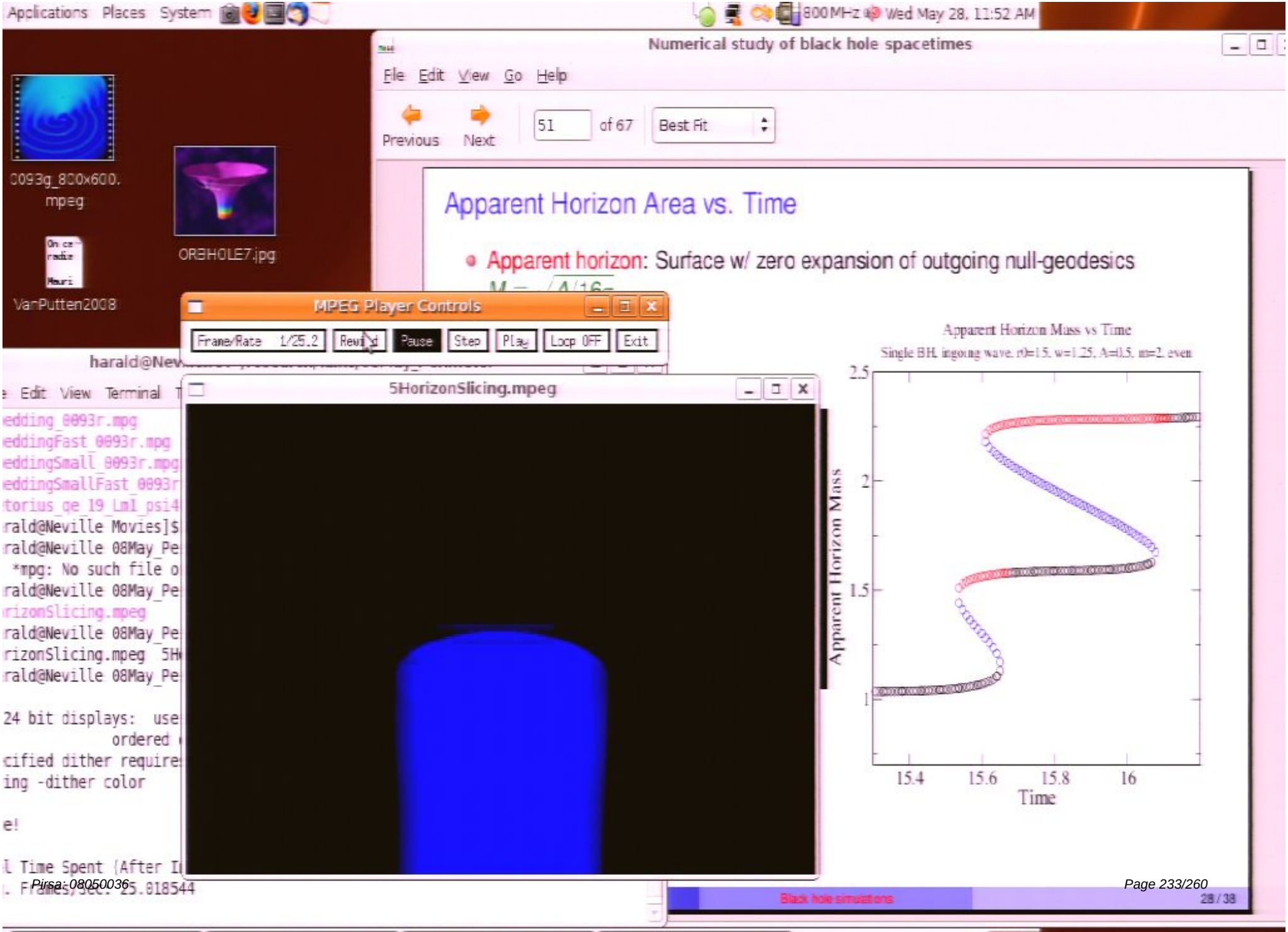
28 / 38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File Edit View Go Help
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Best Fit
Apparent Horizon Area vs. Time
Apparent horizon: Surface w/ zero expansion of outgoing null-geodesics
MPEG Player Controls
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Play
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Exit
5HorizonSlicing.mpeg
Apparent Horizon Mass vs Time
Single BH, ingoing wave, r0=1.5, w=1.25, A=0.5, m=2, even
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Edit View Terminal
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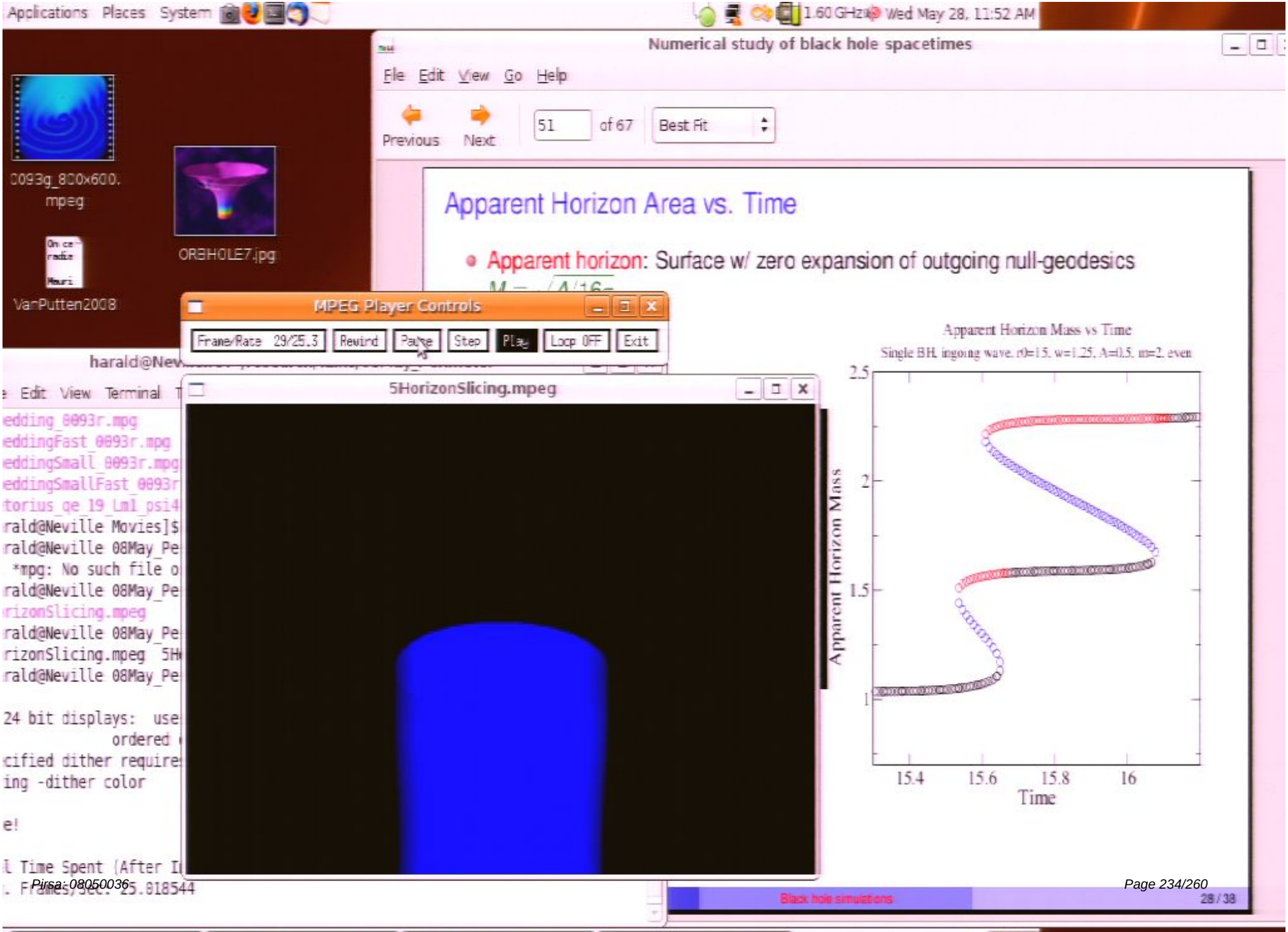
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Numerical study of black hole spacetimes
File Edit View Go Help
Previous Next
51 of 67
Best Fit
0093g_800x600.mpeg
ORBHOLE7.jpg
VanPutten2008
Apparent Horizon Area vs. Time
Apparent horizon: Surface w/ zero expansion of outgoing null-geodesics
MPEG Player Controls
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5HorizonSlicing.mpeg
Apparent Horizon Mass vs Time
Single BH, ingoing wave, r0=1.5, w=1.25, A=0.5, m=2, even
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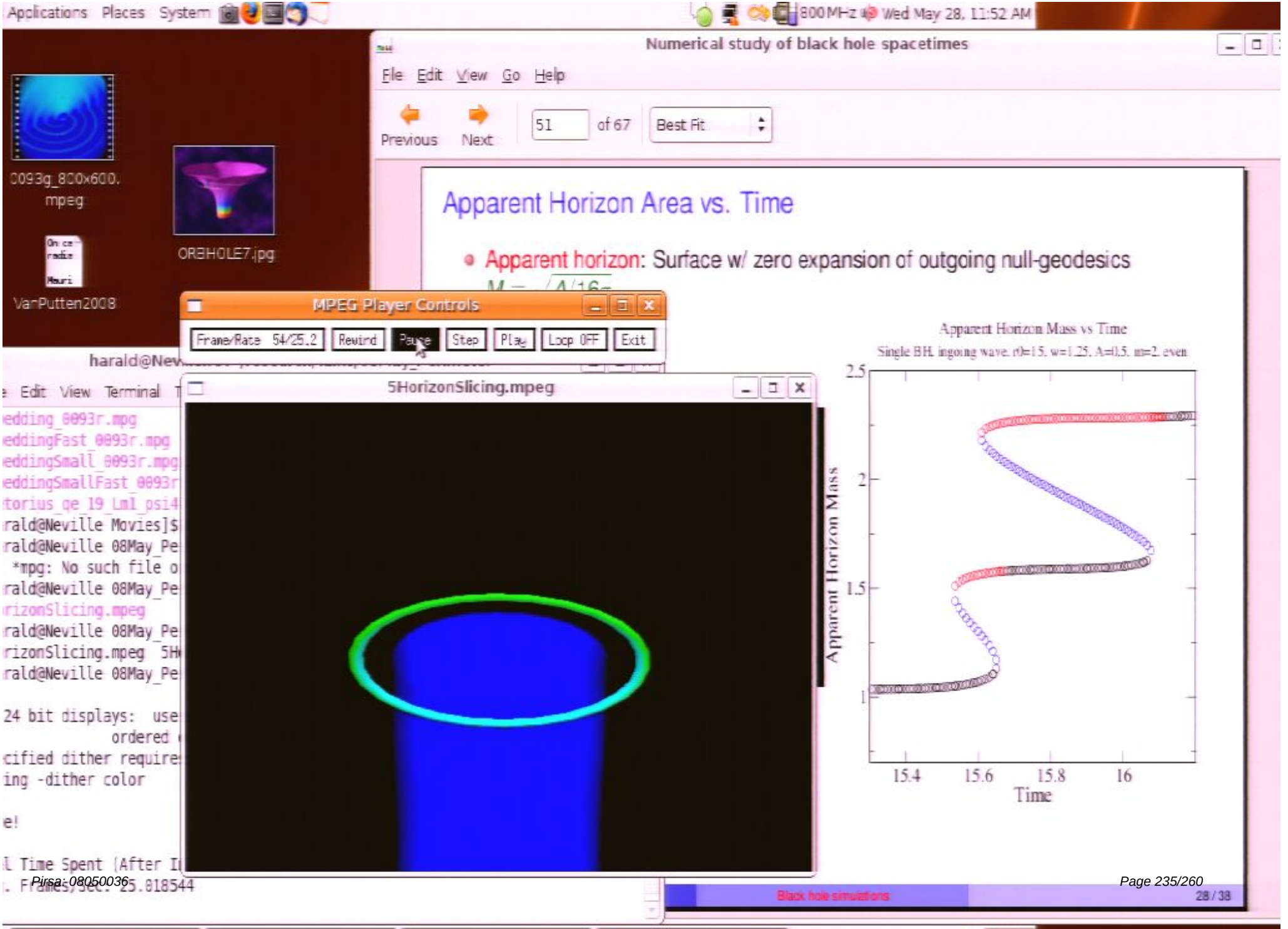
Black hole simulations
28 / 38


Applications Places System
800 MHz Wed May 28, 11:52 AM
Numerical study of black hole spacetimes
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51 of 67
Best Fit
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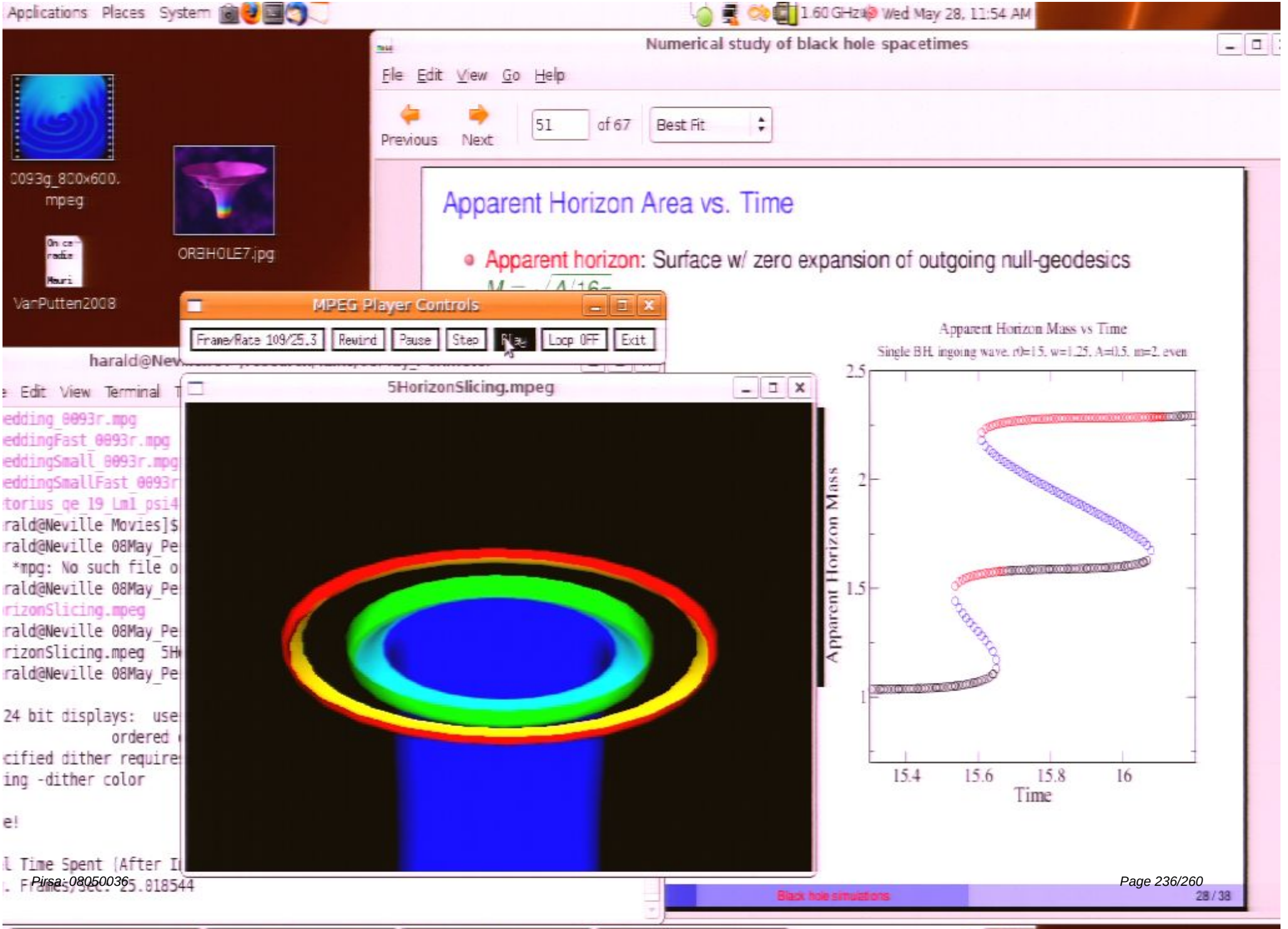
Black hole simulations
28 / 38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Numerical study of black hole spacetimes
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Best Fit
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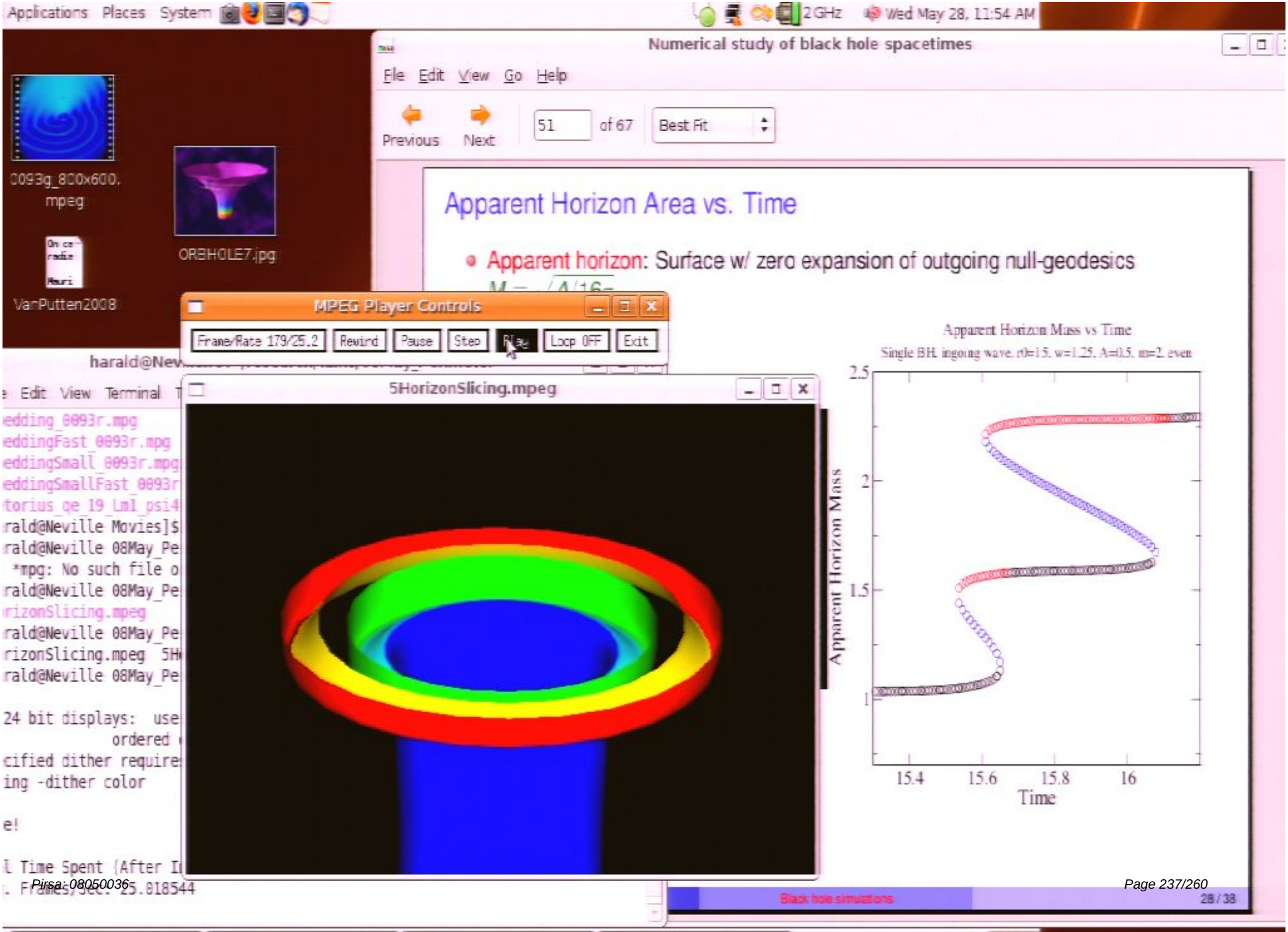
Frames/Sec: 25.018544
Black hole simulations
28 / 38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Numerical study of black hole spacetimes
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51
of 67
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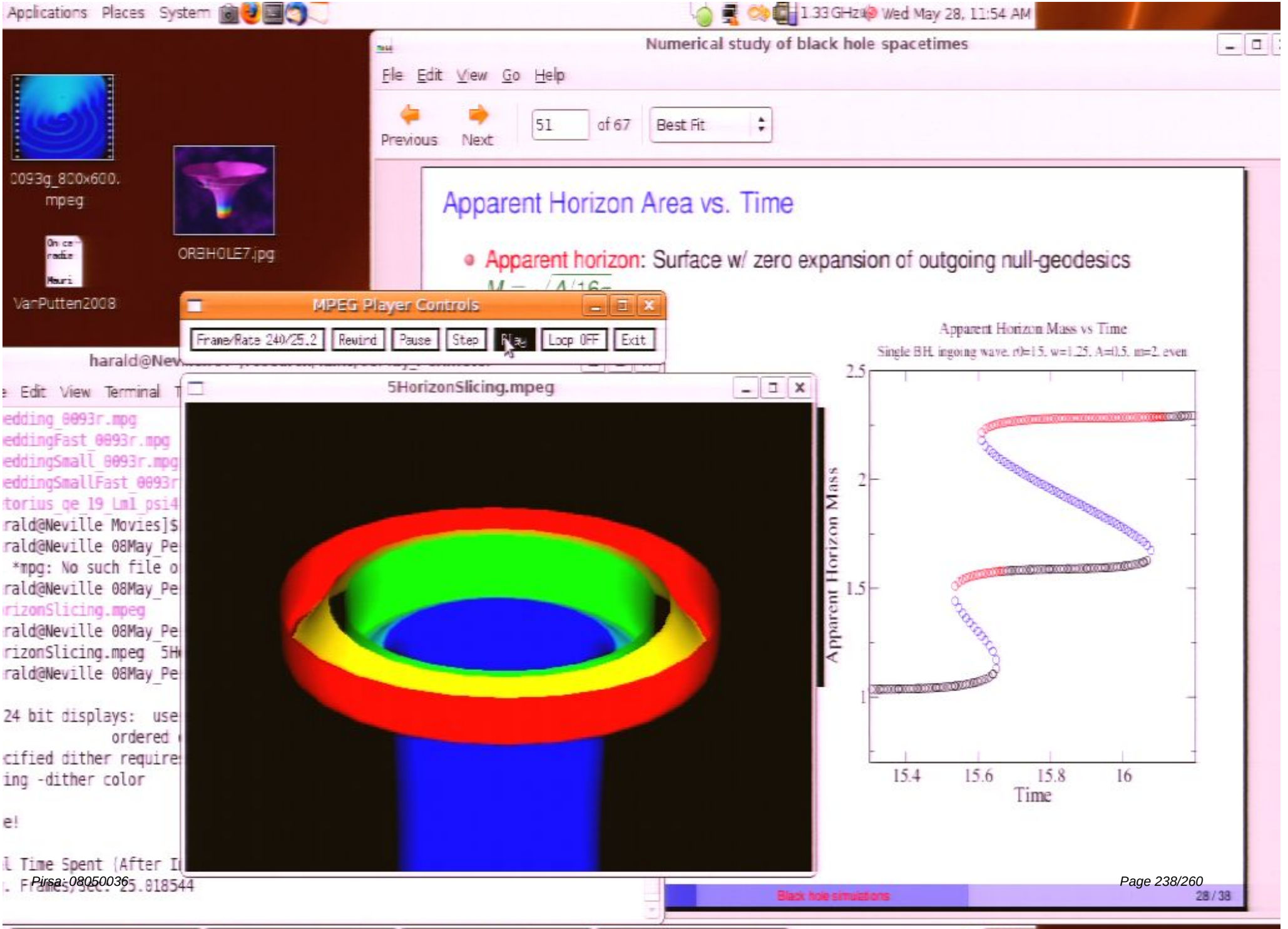
Black hole simulations
28 / 38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Numerical study of black hole spacetimes
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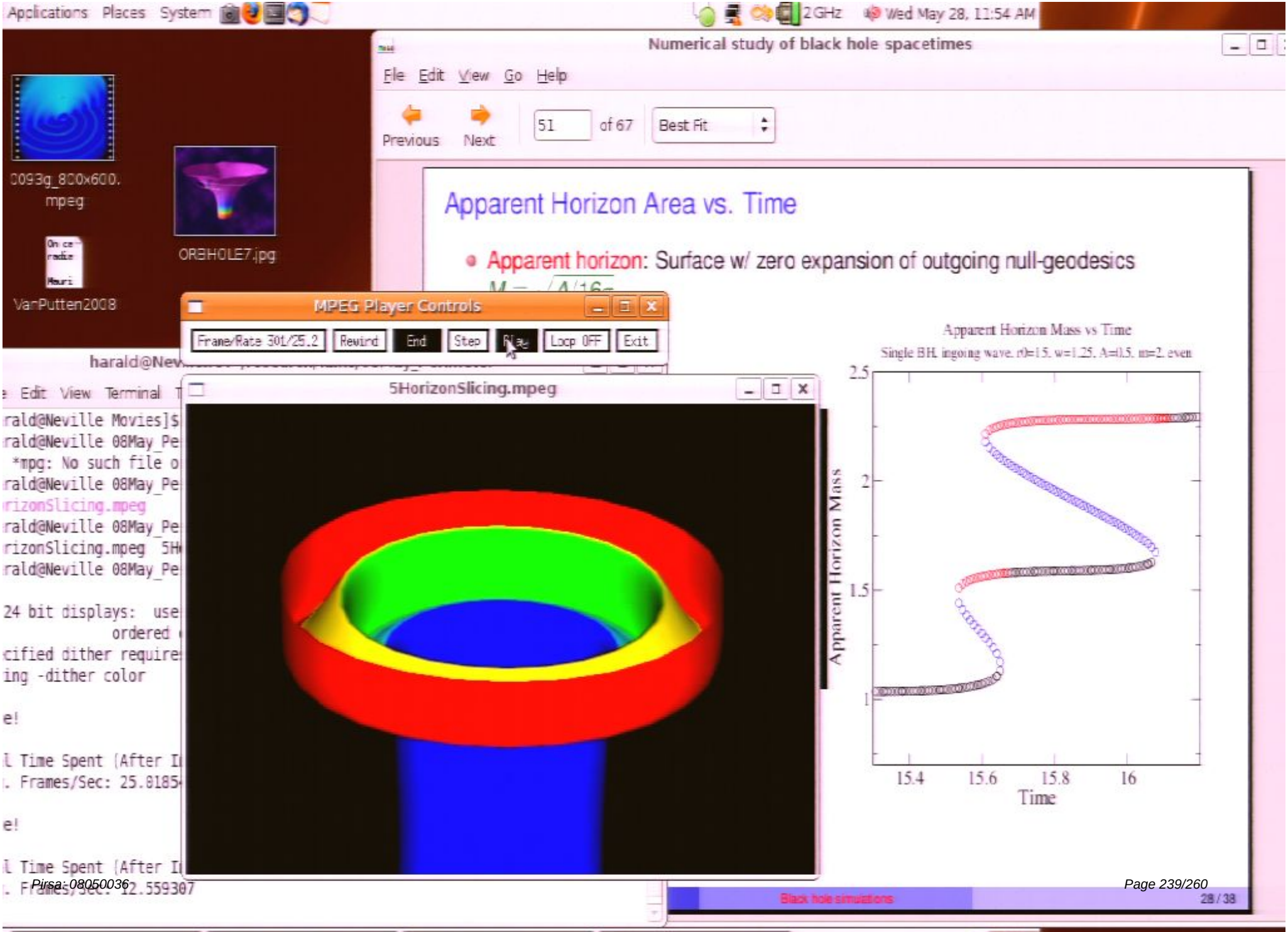
Black hole simulations
28 / 38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Numerical study of black hole spacetimes
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Black hole simulations
28 / 38

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ORBHOLE7.jpg

VanPutten2008

Numerical study of black hole spacetimes

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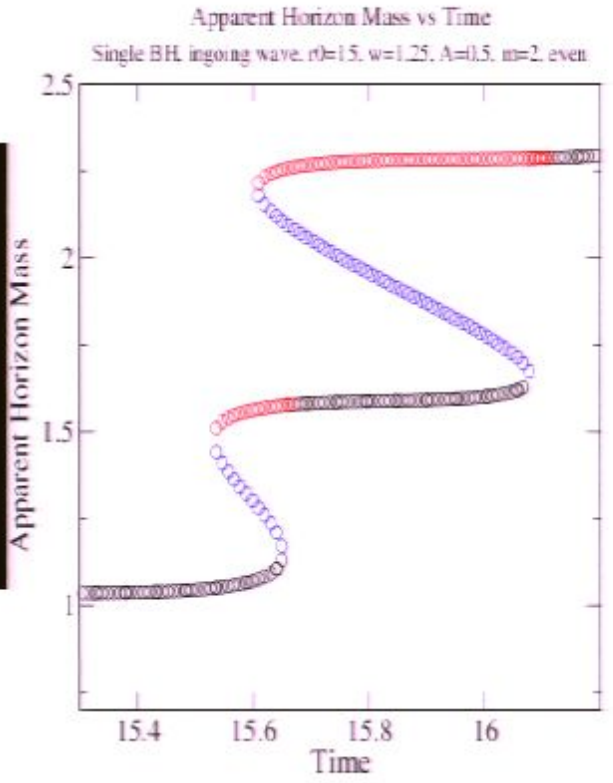
Previous Next 51 of 67 Best Fit

Apparent Horizon Area vs. Time

- Apparent horizon: Surface w/ zero expansion of outgoing null-geodesics

$$M \equiv \sqrt{A/16\pi}$$



Black hole simulations 28 / 38

harald@Neville:AA~/research/Talks/08May_Perimeter

Edit View Terminal Tabs Help

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rald@Neville Movies]$ cd ..
rald@Neville 08May_Perimeter]$ ls *mpg
 *mpg: No such file or directory
rald@Neville 08May_Perimeter]$ ls *mpeg
rizonSlicing.mpeg
rald@Neville 08May_Perimeter]$ mpeg_play 5Ho
rizonSlicing.mpeg  5HorizonSlicing.png
rald@Neville 08May_Perimeter]$ mpeg_play 5HorizonSlicing.mpeg

24 bit displays:  use -dither color to get full color
            ordered dither is the default.
cified dither requires 8 bit display
ing -dither color

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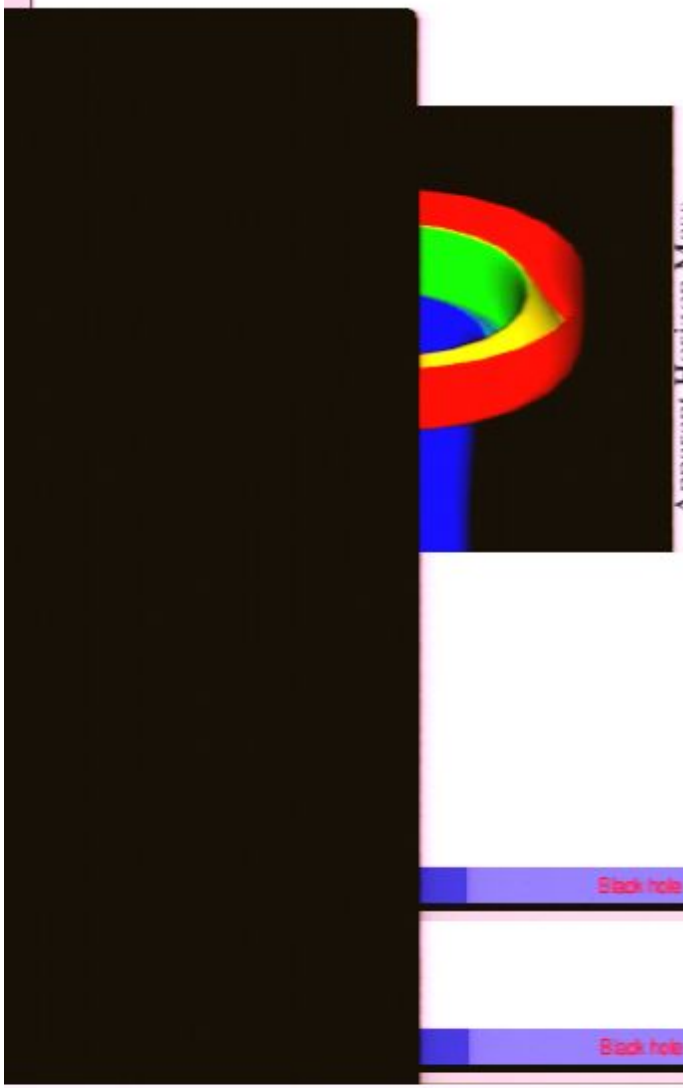
l Time Spent (After Initializations): 12.031076 secs.
. Frames/Sec: 25.018544

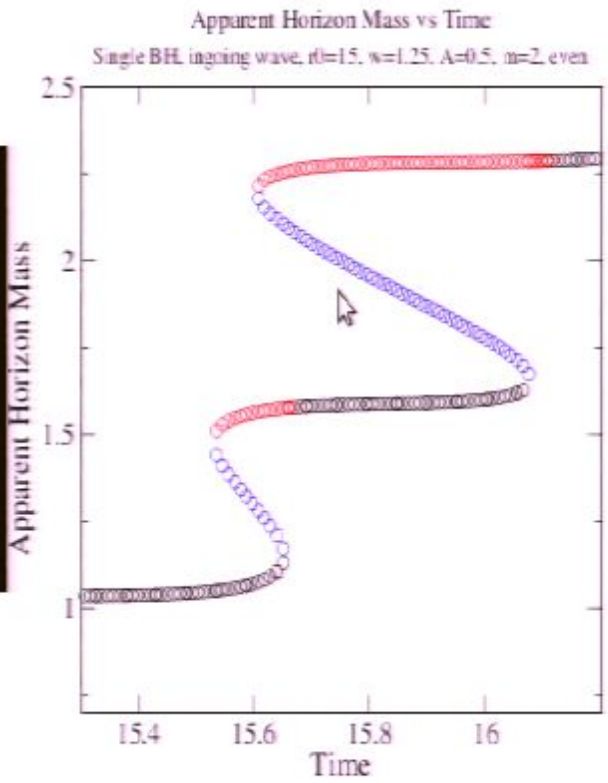
e!

l Time Spent (After Initializations): 23.966291 secs.
. Frames/Sec: 12.559307
rald@Neville 08May_Perimeter]$
```

Apparent Horizon Area vs. Time

- Apparent horizon: Surface w/ zero expansion of outgoing null-geodesics
  $M \equiv \sqrt{A/16\pi}$





Black hole simulations 28 / 38

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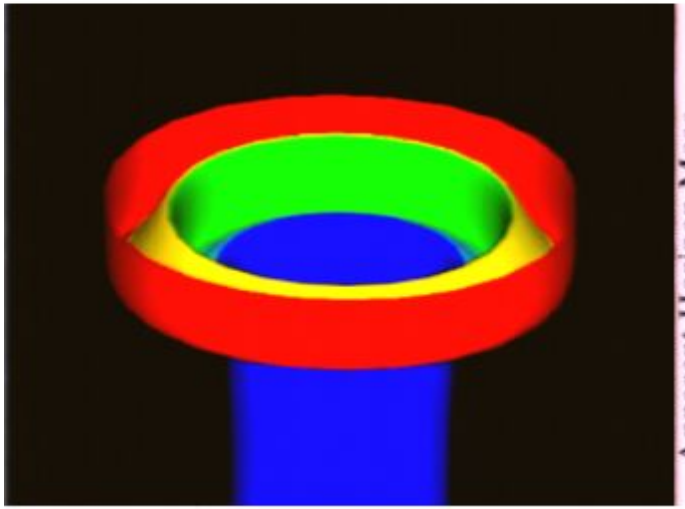
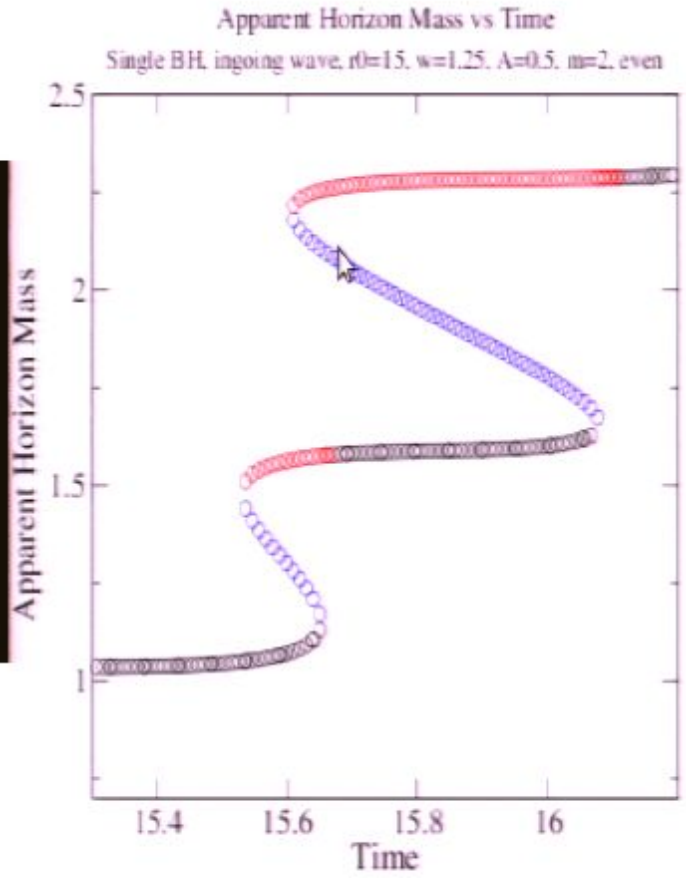
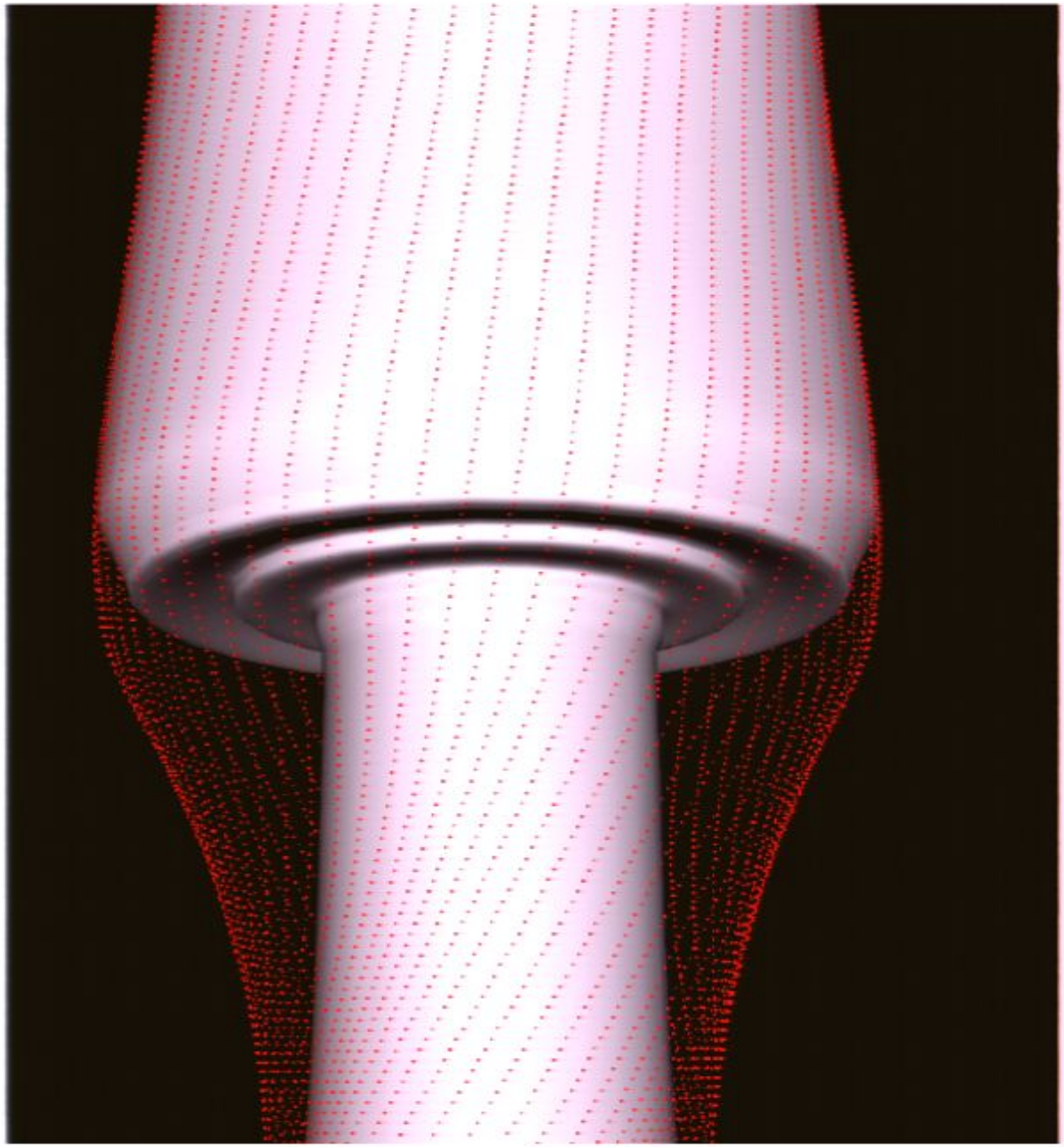


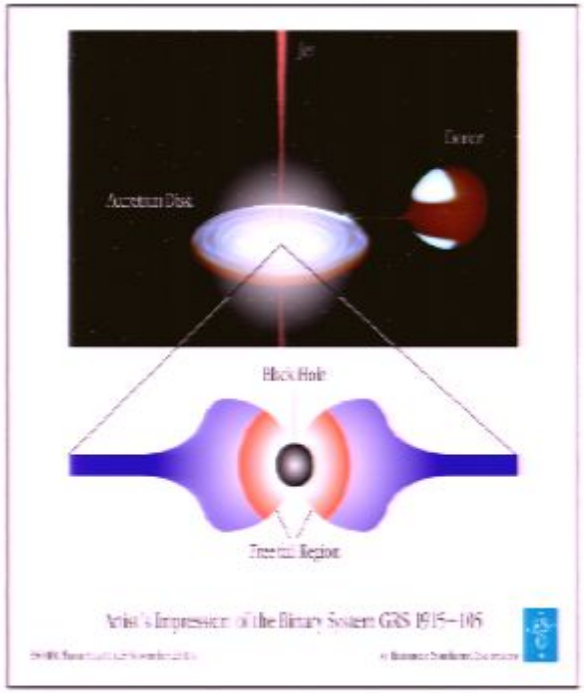


Event horizon



Black holes with near-extremal spins

- GRS 1915+105: $S/M^2 \gtrsim 0.98$ (McClintock et al. 2006)



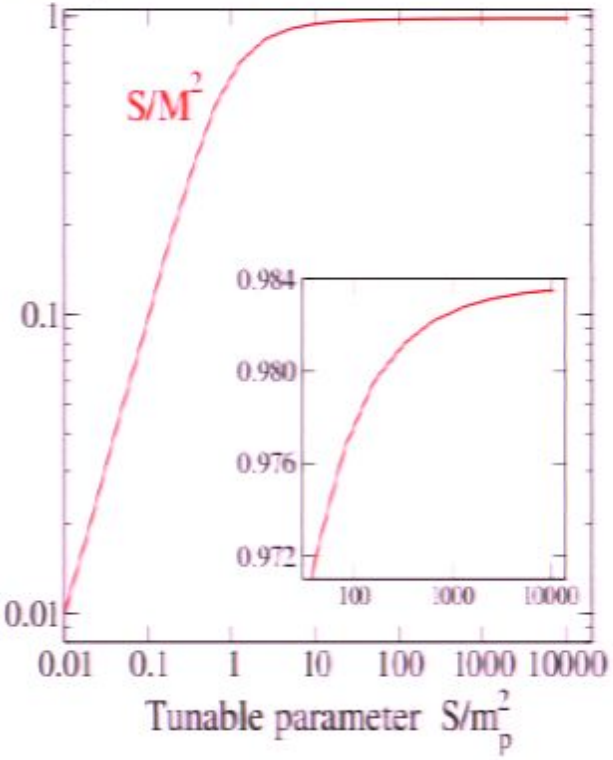
- Constraints non-linear, cannot just superpose analytical Kerr metrics to get high spin BBH.

- With Geoffrey Lovelace, Rob Owen (Caltech grads, now Cornell post-docs) & Tony Chu (Caltech grad)

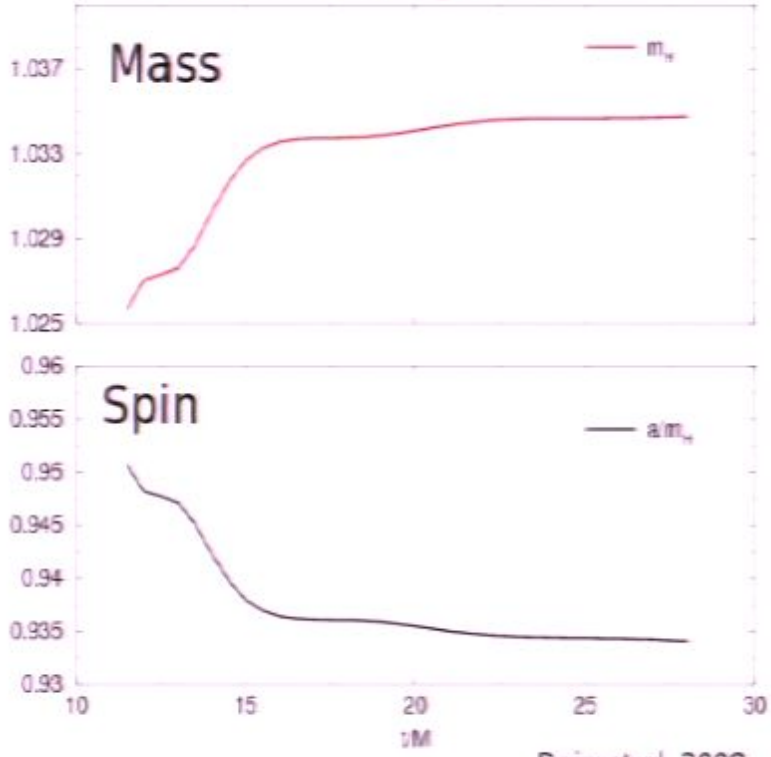
First attempt: Puncture initial data

- Most widely used BBH initial data: Just one elliptic PDE

Spin at initial time (Cook & York, 1990)



Relaxation during evolution



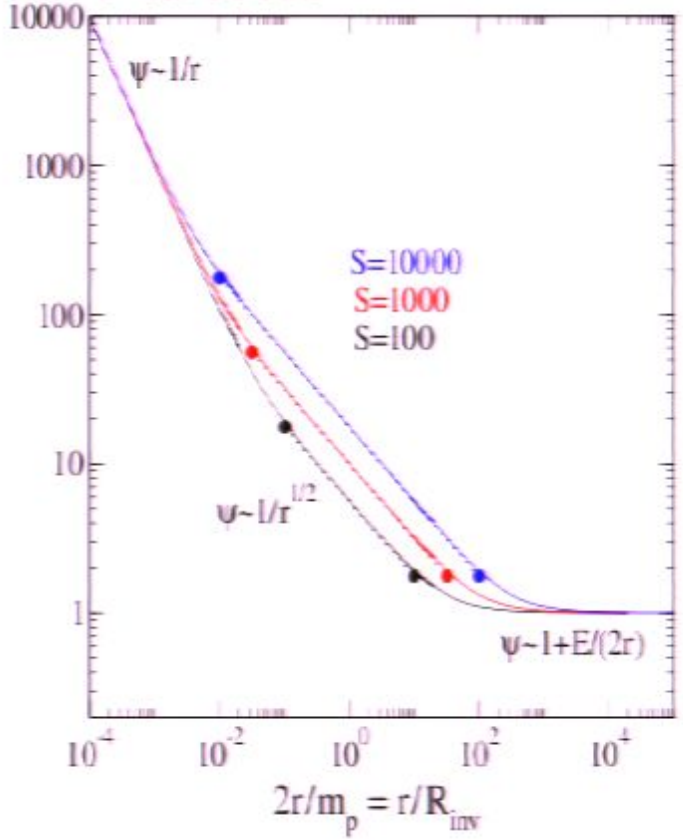
Dain et al. 2008

- Maximal *relaxed* spin ~ 0.93 — not large enough.

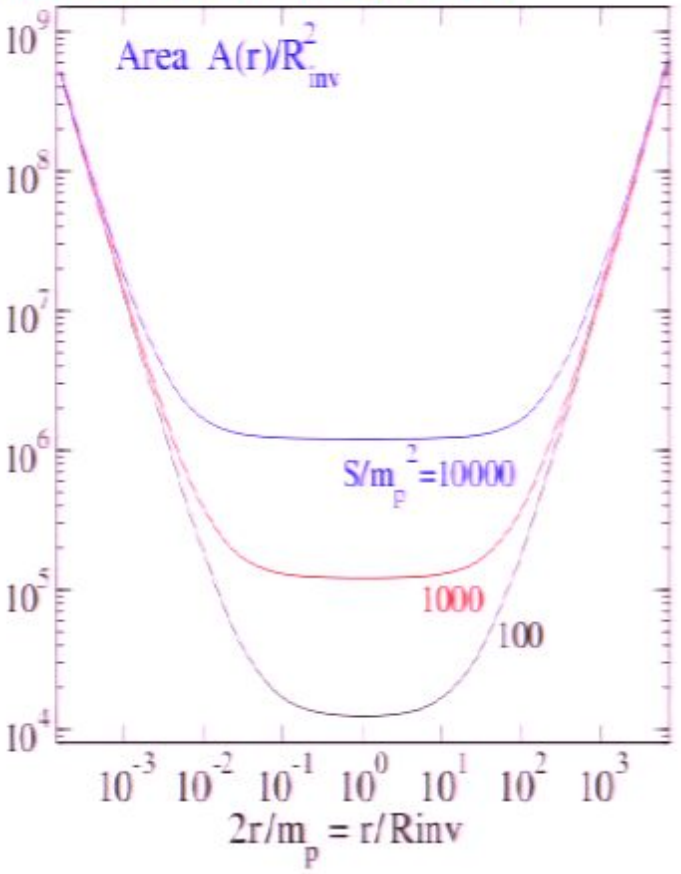
But intriguing properties of initial data geometry

$$g_{ij} = \Psi^4 \delta_{ij}, \quad \nabla^2 \Psi + \frac{9}{4} \frac{S^2 \cos^2\theta}{r^6} \Psi^{-7} = 0, \quad \text{BCs: } \Psi(r=\infty) = 1, \quad \Psi \to \frac{m_p}{2r} \text{ as } r \to 0$$

Numerical solution



Area of coordinate spheres



Four spherical shells
cover radii $10^{-4} < r < 10^{9}$

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$g_{ij} = \Psi^4 \delta_{ij}, \quad \nabla^2 \Psi + \frac{9}{4} \frac{S^2 \cos^2\theta}{r^6} \Psi^{-7} = 0, \quad$ BCs: $\Psi(r = \infty) = 1, \quad \Psi \to \frac{m_p}{2r}$ as $r \to 0$

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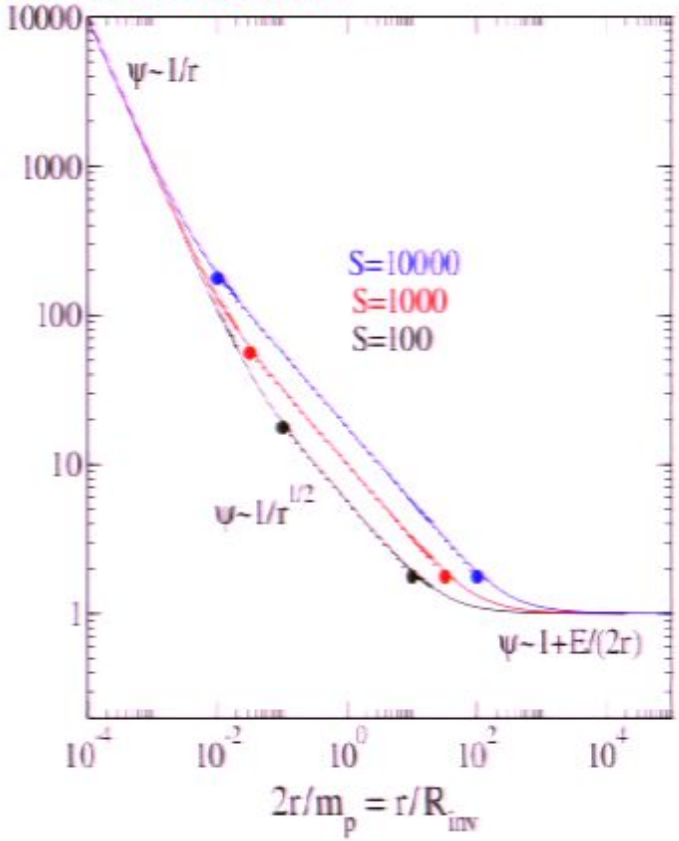

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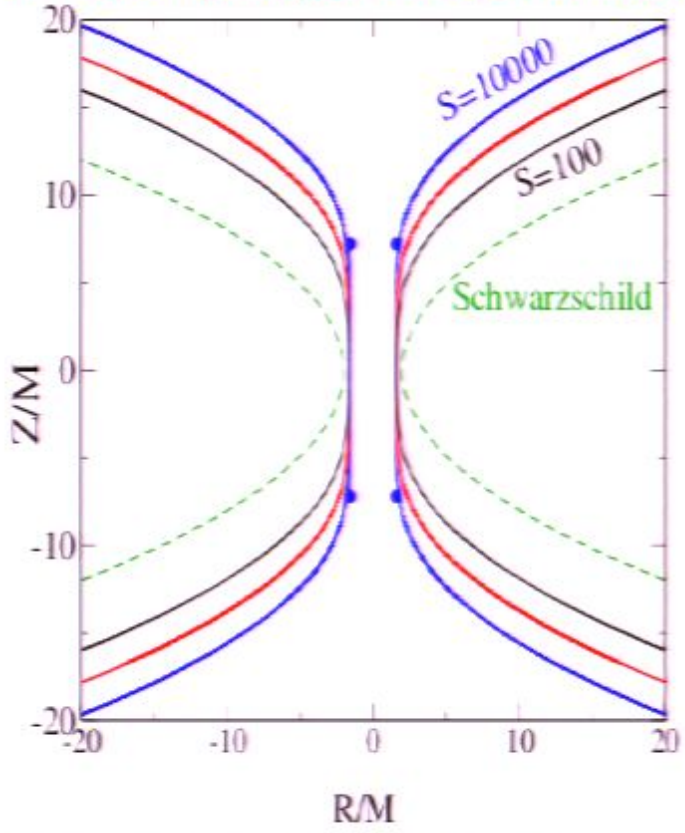
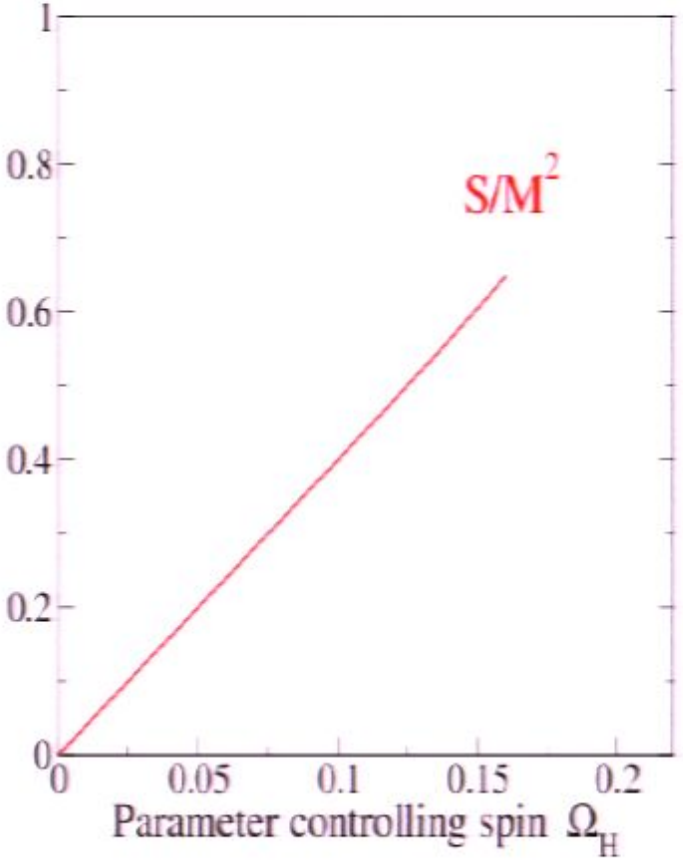
Embedding diagram of equatorial plane



Lengthening cylindrical throat
Analytic approximation of throat region matches well

Second attempt: Quasi-equilibrium initial data (Cook, HP, 2002-2006)

- Based on:
  1) time-independence ⇒ Five coupled elliptic PDE's
  2) BH's in equilibrium [vanishing shear of horizon] ⇒ BCs at excision surfaces
  3) Simplicity (conformal flatness, maximal slicing)



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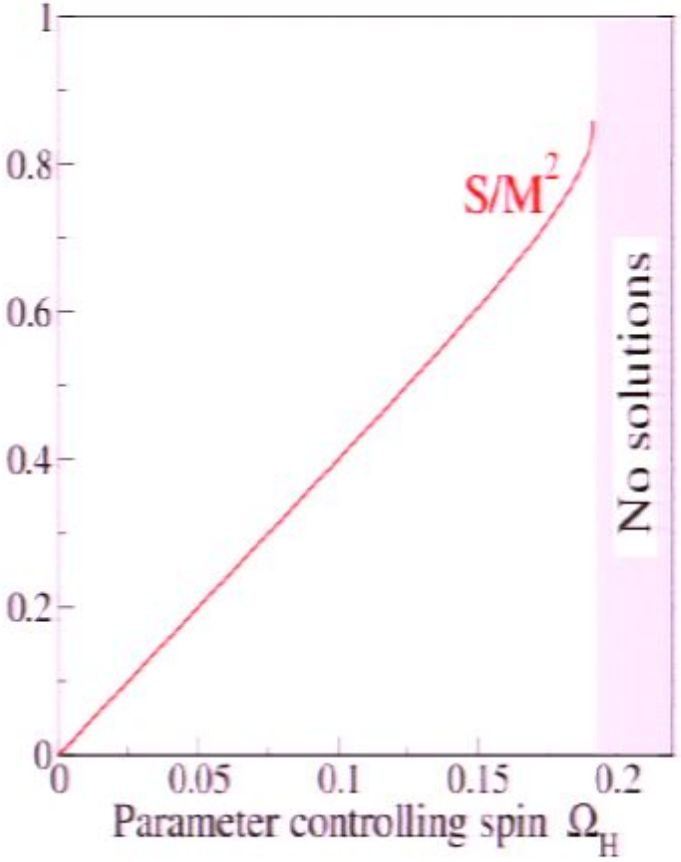

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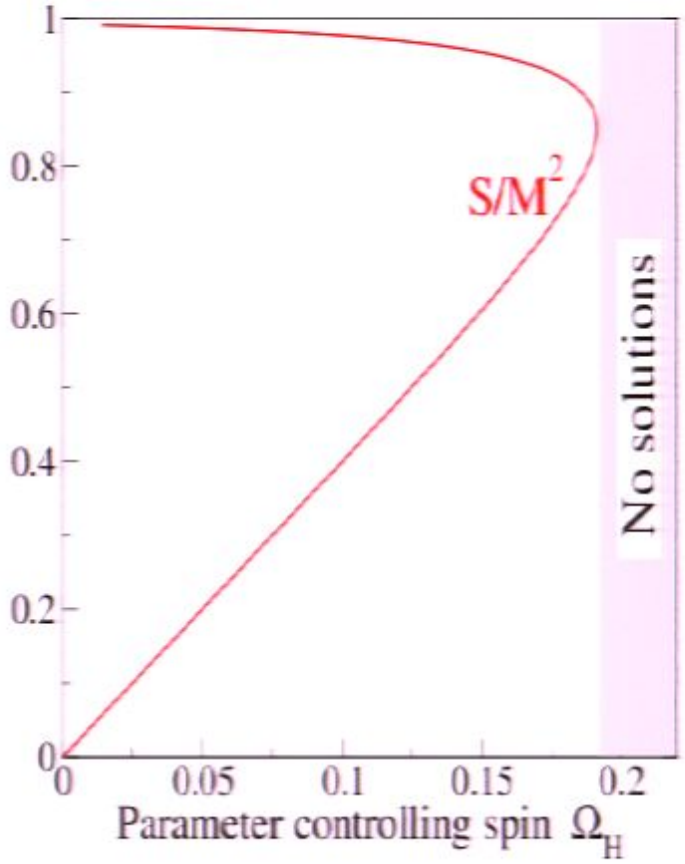

- **Two** solutions for **same** Ω_H (HP, York, 2005).
- Novel discovery, previously always unique solution of constraints.
- With model-problem, behavior can be traced to a term which makes the linearized operator indefinite (Walsh, 2007; Baumgarte, O'Murchadha, HP, 2007.)

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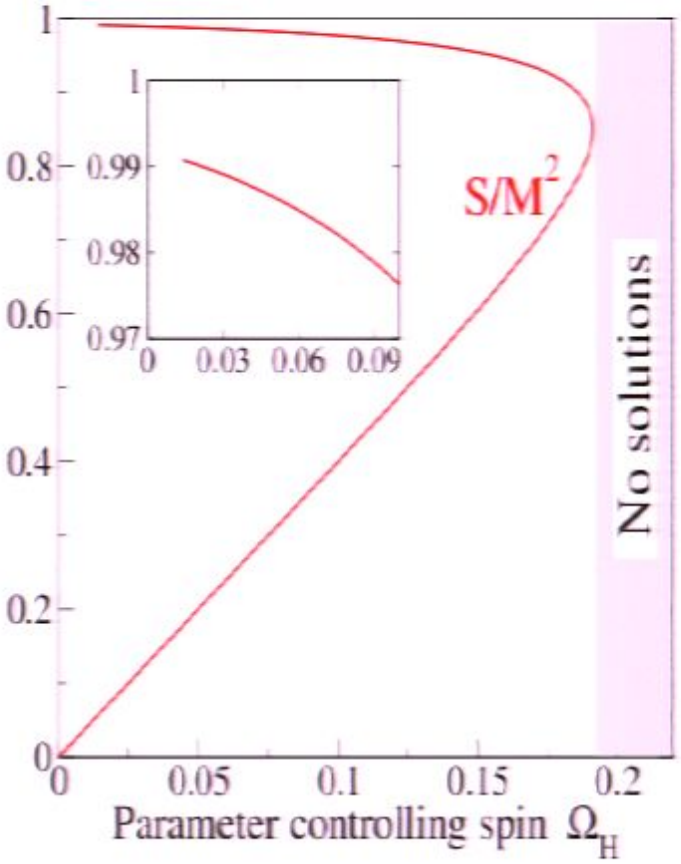

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- Maximal *initial* spin ~ 0.99, but expect spin to relax to ~ 0.94.

Third attempt

- Same quasi-equilibrium formalism as in 2nd attempt
- Adapted remaining choices:

$$\tilde{g}_{\bar{i}\bar{j}} = \delta_{\bar{i}\bar{j}} + \left(g^{\mathrm{Kerr.A}}_{\bar{i}\bar{j}} - \delta_{\bar{i}\bar{j}}\right) + \left(g^{\mathrm{Kerr.B}}_{\bar{i}\bar{j}} - \delta_{\bar{i}\bar{j}}\right)$$

$$K = K^{\mathrm{Kerr.A}} + K^{\mathrm{Kerr.B}}$$

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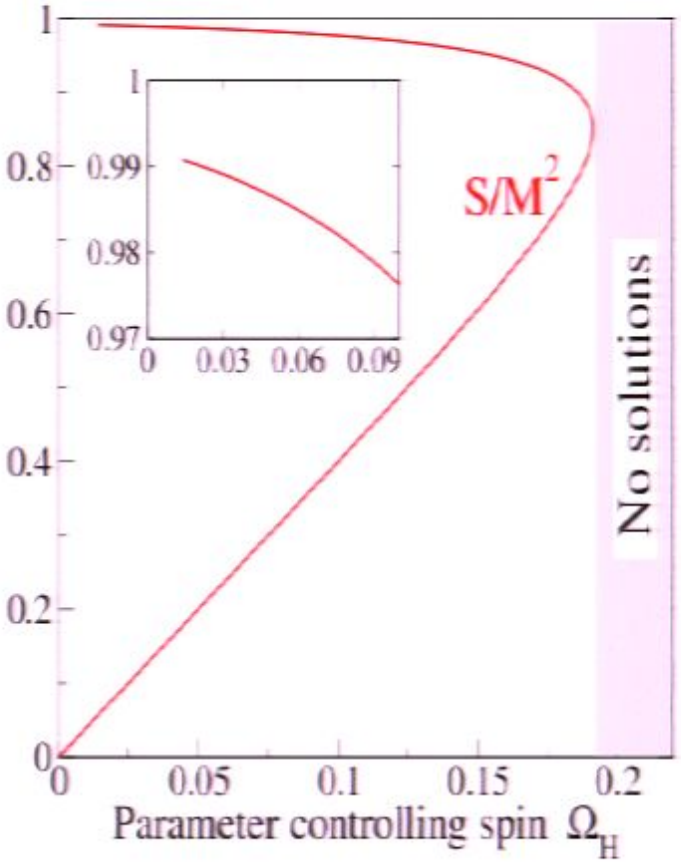

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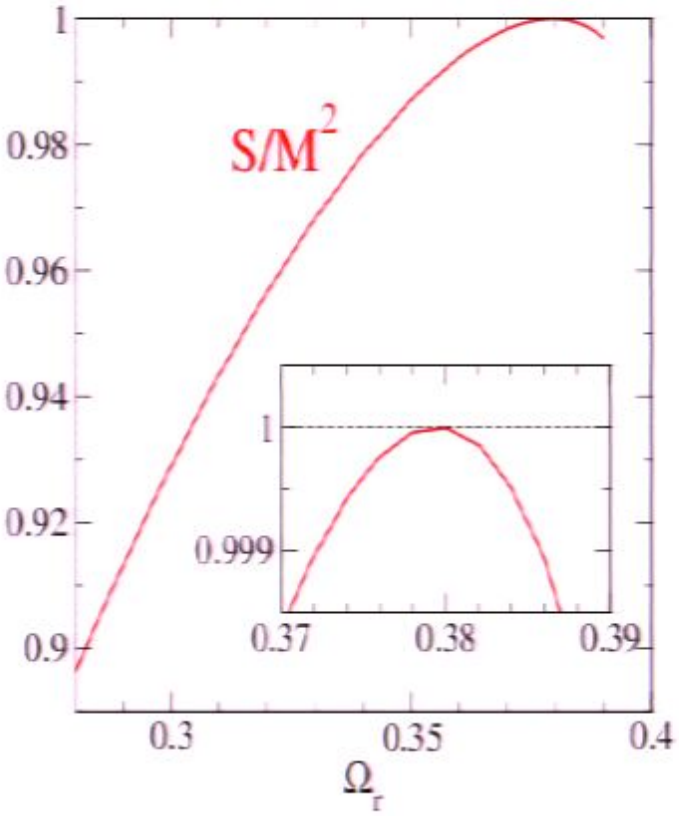
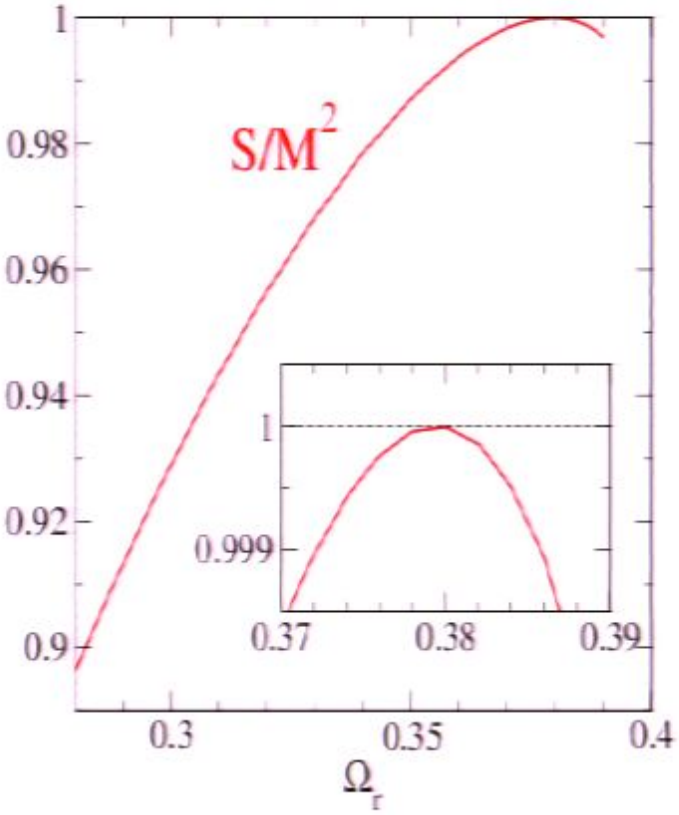
Third attempt



$$M^2 = M_{\text{irr}}^2 + \frac{S^2}{4M_{\text{irr}}^2}$$

$$M_{\text{irr}} = \sqrt{A_{\text{AH}}/16\pi}$$

Third attempt



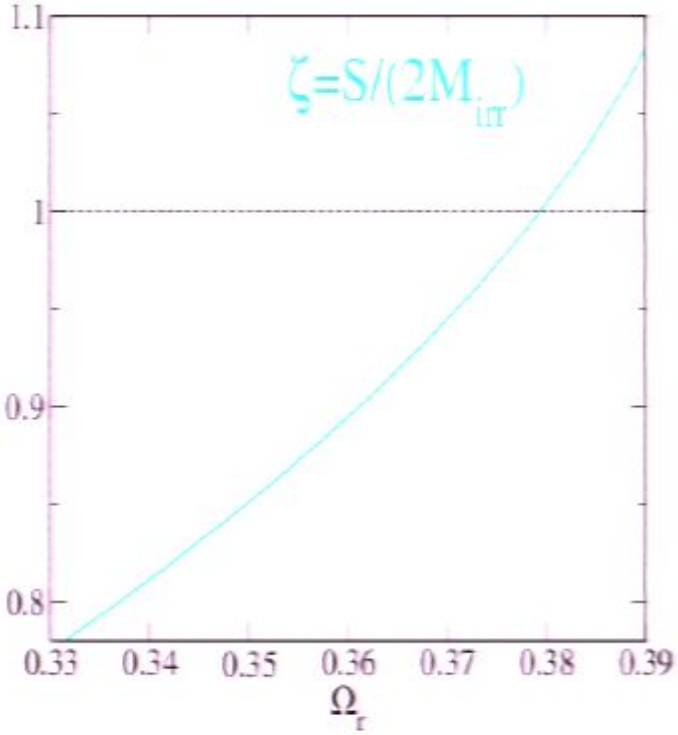
$$M^2 = M_{\mathrm{irr}}^2 + \frac{S^2}{4M_{\mathrm{irr}}^2}$$

$$M_{\mathrm{irr}} = \sqrt{A_{\mathrm{AH}}/16\pi}$$

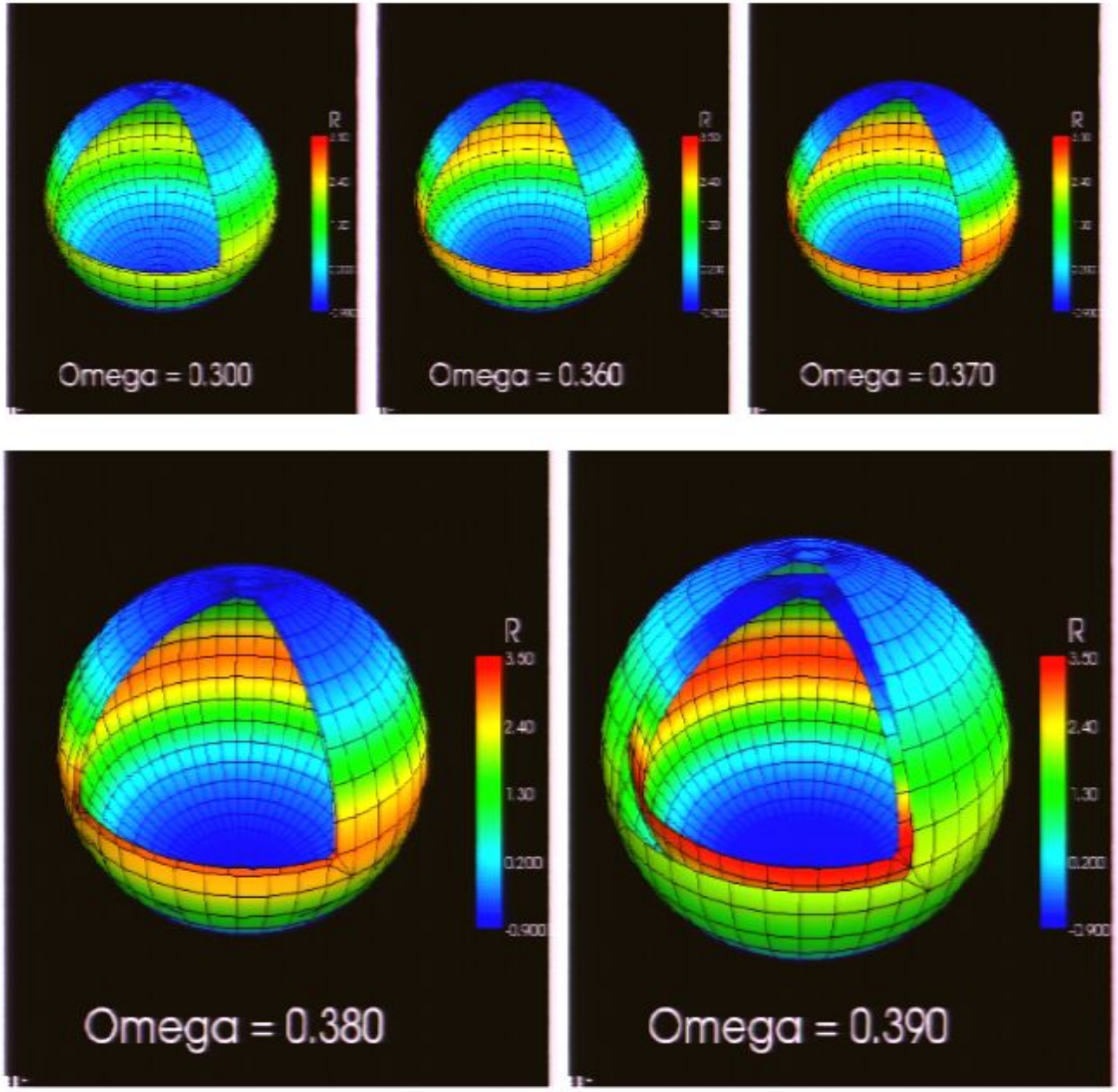
- Extremality parameter $\zeta = \dfrac{S}{2M_{\mathrm{irr}}}$

$$\frac{S}{M^2} = 1 - \frac{(1-\zeta)^2}{1+\zeta^2} \leq 1$$

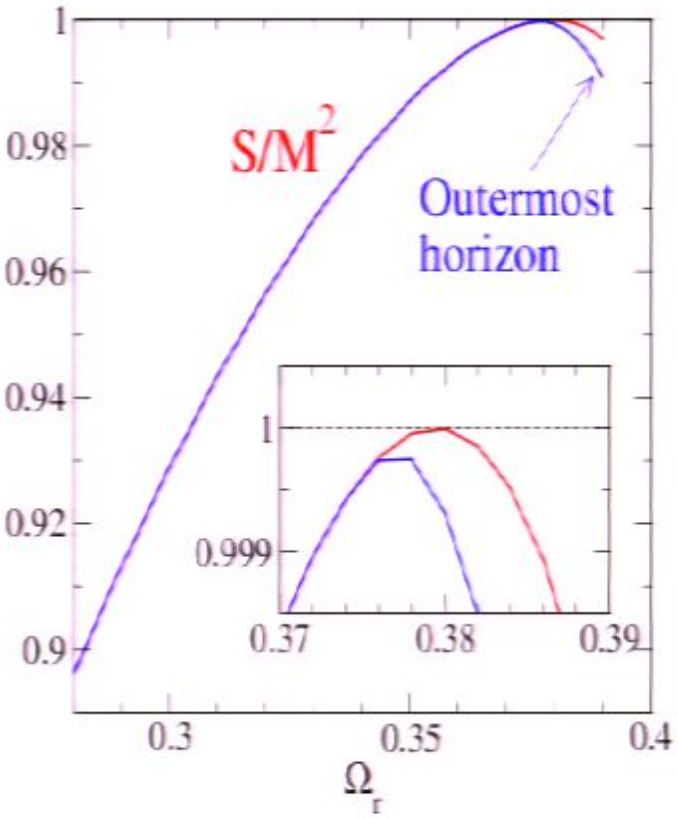
- Kerr: $\zeta \leq 1$ w/ equality for extremal BH

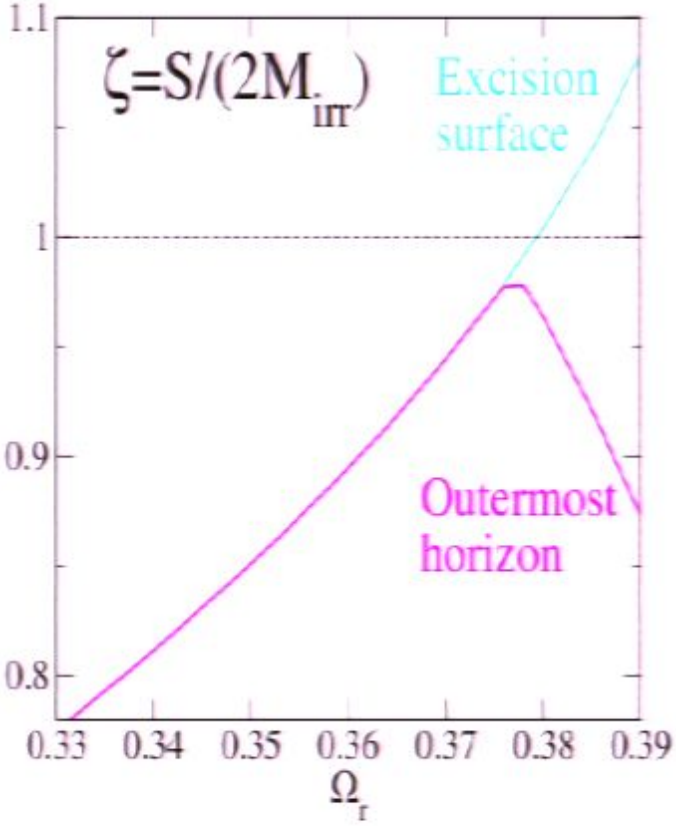


A new horizon outside the excision boundary



Super-extremal black holes?

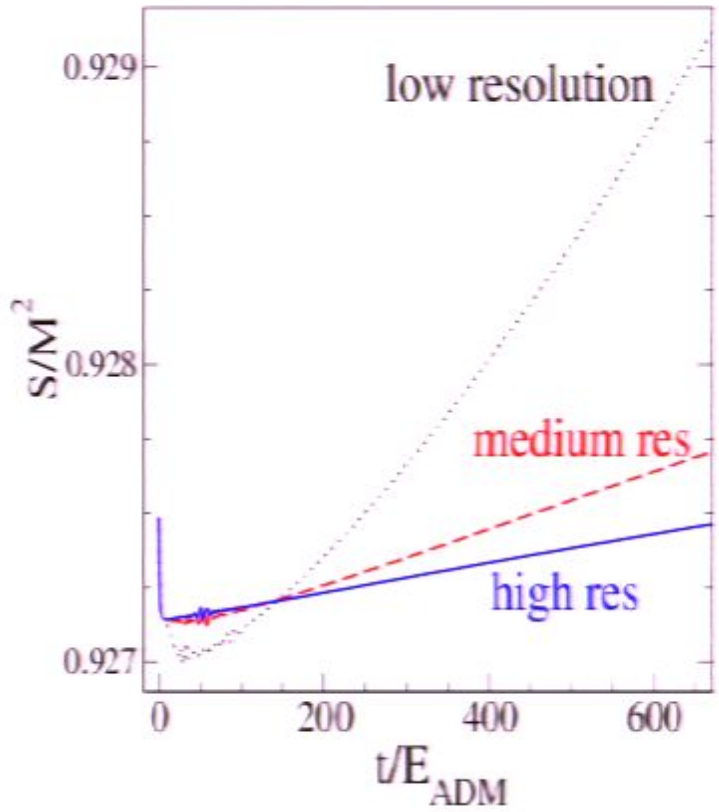




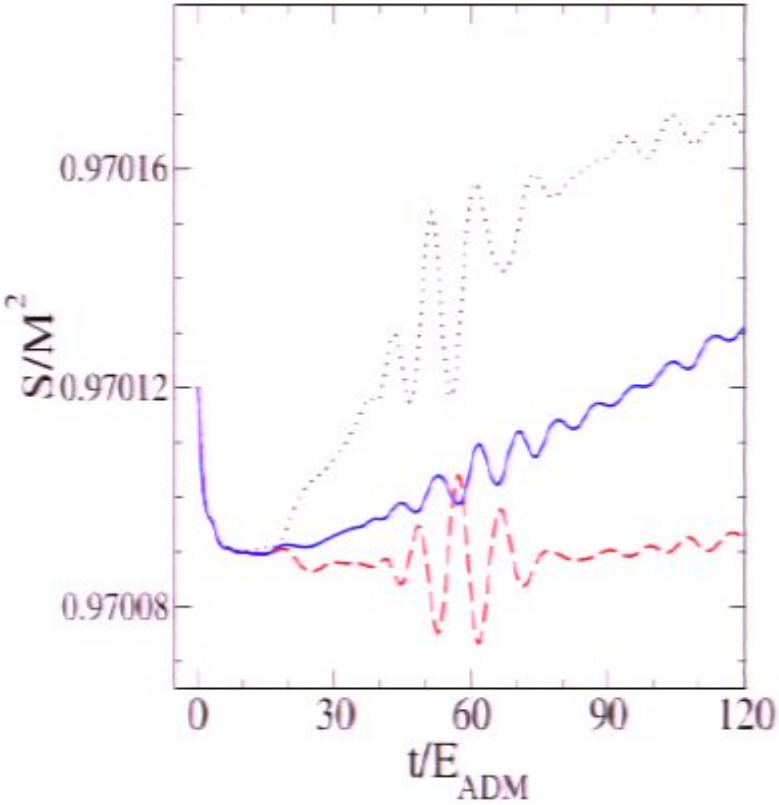
- No super-extremal black holes.
- But nearly-extremal spin, $S/M^2 \approx 0.9998$!!

Virtually no spin relaxation

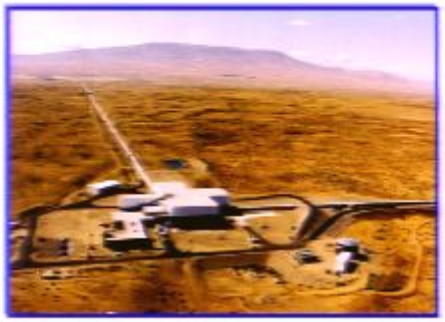
Orbiting binary black hole



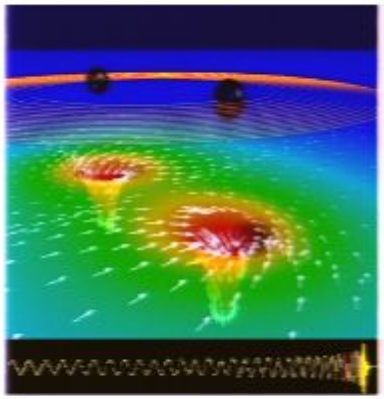
Head-On collision from rest



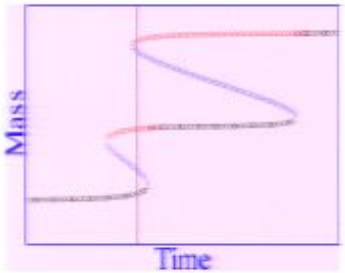
Summary

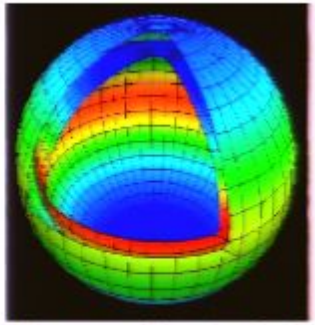


- GW-detectors require accurate **templates**
- **Spectral Einstein Code *SpEC***
  - Elliptic & hyperbolic
  - Efficient & flexible domain-decompostion
  - 15 orbits & merger, $\delta\phi \lesssim$ few $\times\ 10^{-2}$ radians



- **PN-NR comparison**
  - Large PN-truncation error in last 20 GW-cycles
  - Only simulations can find good PN approximants
  - Non-equal masses, spins underway





- **BHs with multiple apparent horizons**
- **BBH with nearly-extremal spins**
  - $S/M^2 = 0.9998$; plenty surprises
- **Collaborators**: Mike Boyle, Tony Chu, Lee Lindblom, Oliver Rinne, Mark Scheel (Caltech); Larry Kidder, Geoffrey Lovelace, Abdul Mroue, Rob Owen, Saul Teukolsky (Cornell); Duncan Brown (Syracuse), Greg Cook (Wake Forest)