Title: Fully General Relativistic Simulations of Black Hole-Neutron Star Mergers: A Current Overview

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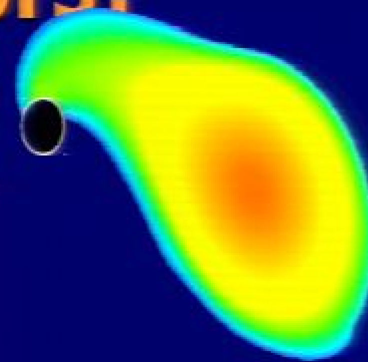
Abstract: Black hole-neutron star binary (BHNS) mergers are likely sources for detectable gravitational radiation and candidate engines for short-hard gamma-ray bursts. However, accurate modeling of these mergers requires fully general relativistic simulations, incorporating both relativistic hydrodynamics for the matter and Einstein's field equations for the (strong) gravitational fields. I will review techniques and results from recent fully general relativistic BHNS merger simulations. These simulations examine the effects of the BH:NS mass ratio, BH spin, and NS equation of state, focusing on both the gravitational waveforms and remnant disk.

BHNSs: SGRB progenitors?



- Short-hard gamma-ray burst (SGRB) progenitor
  - Plausible scenario:

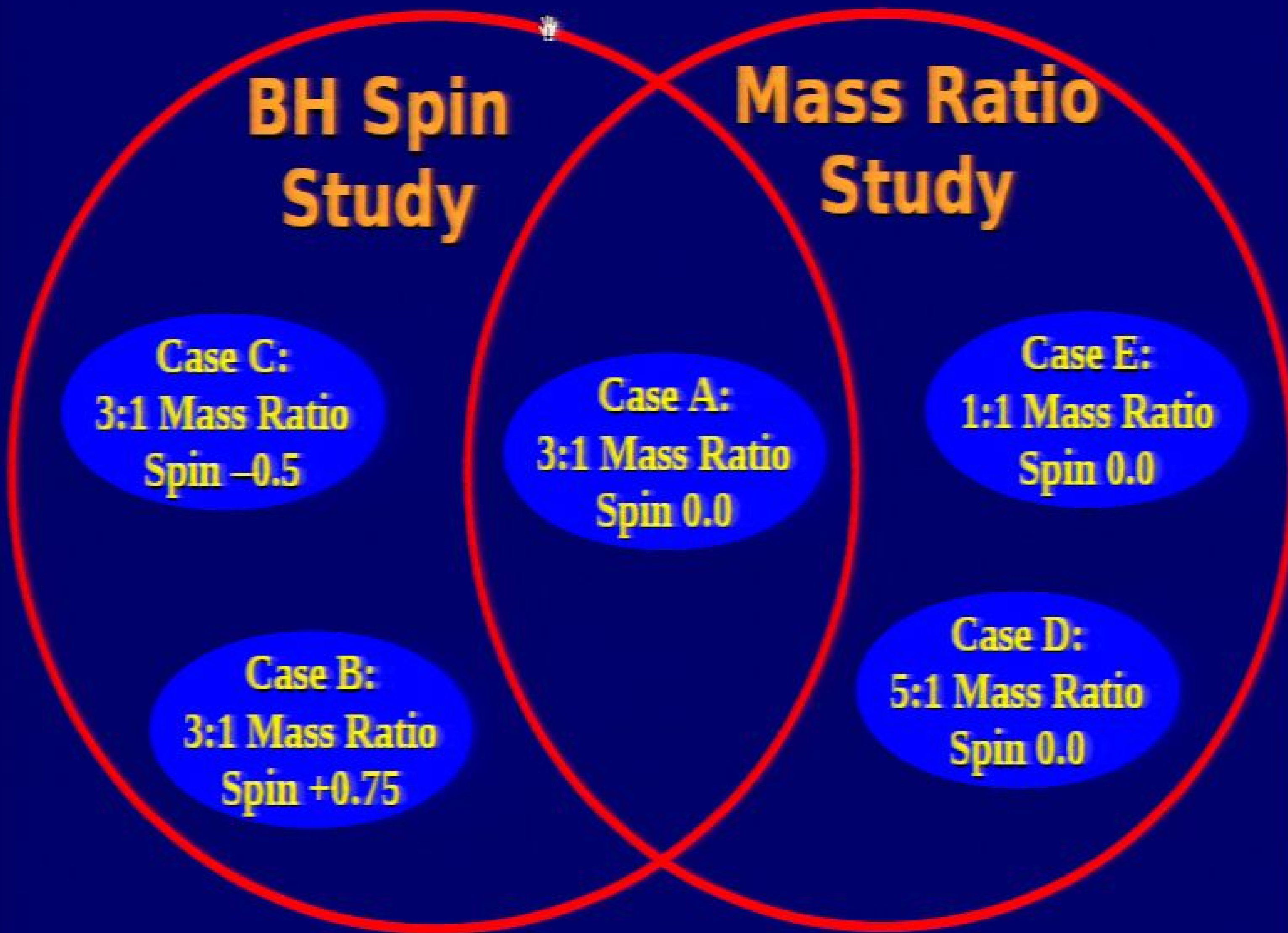
    SGRB engine:
    - BH+NS binary inspiral
    - Tidal disruption of NS → massive, high temp. disk
    - Huge amount of EM energy radiated (lasting ~10 – 10[3] ms) -> SGRB!
  - So, SGRB engine **may need substantial disk, *not* direct plunge** into BH
    - i.e., tidal disruption @ orbital separation $d \gtrsim r_{\rm ISCO}$.

    grav. force @ NS surf. → $\frac{M_{\rm NS}}{R_{\rm NS}^2} \sim \frac{M_{\rm BH}}{d^3} R_{\rm NS}$ ← BH tidal force

$$\mathcal{C} = \frac{M_{\rm NS}}{R_{\rm NS}}, \quad q = \frac{M_{\rm BH}}{M_{\rm NS}} \Longrightarrow \frac{d}{M_{\rm BH}} \sim q^{-2/3}\mathcal{C}^{-1}$$

  - $d \gtrsim r_{\rm ISCO}$ → NS tidally disrupts before BH ISCO → Substantial disk?
  - *Note:* Test particle around Kerr BH → $r_{\rm ISCO}$ decreases as aligned spin increases
    - → Expect more disk as aligned spin increases

Example: Illinois Case Studies



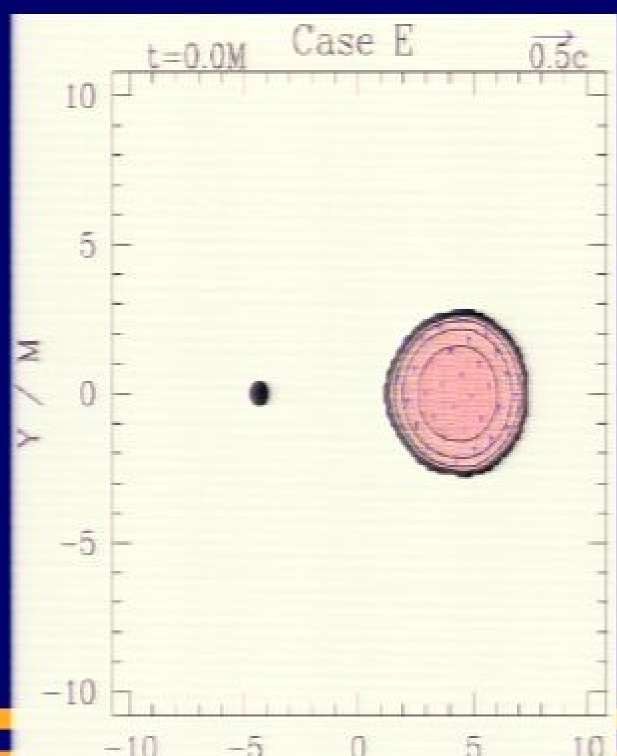
BHNS Initial Data

Conformal Thin-Sandwich

- Chawla et al.
- Cornell
- Illinois

Puncture

- Japan



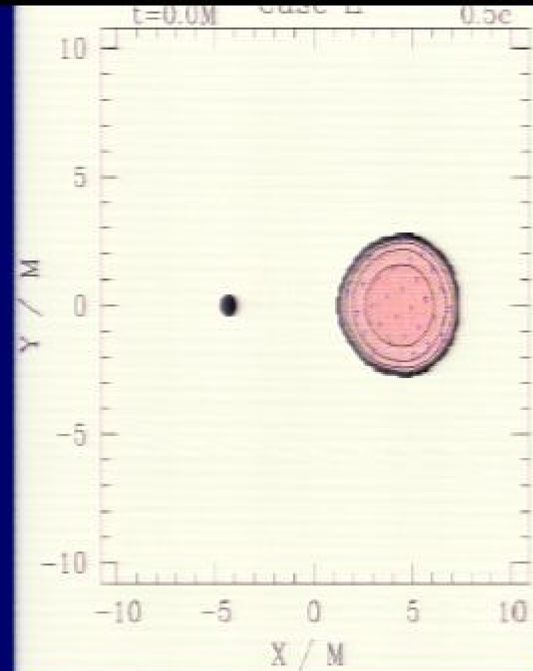
BH

- Default case: BH spin parameter=0,
- 3:1 Mass ratio
  - ~7:1 preferred by pop. synth.

NS

- Default case: Irrotational NS with n=1 ($\Gamma = 2$) polytropic EOS (*irr.* ← *tidal locking time>>inspiral*)

BHNS Initial Data



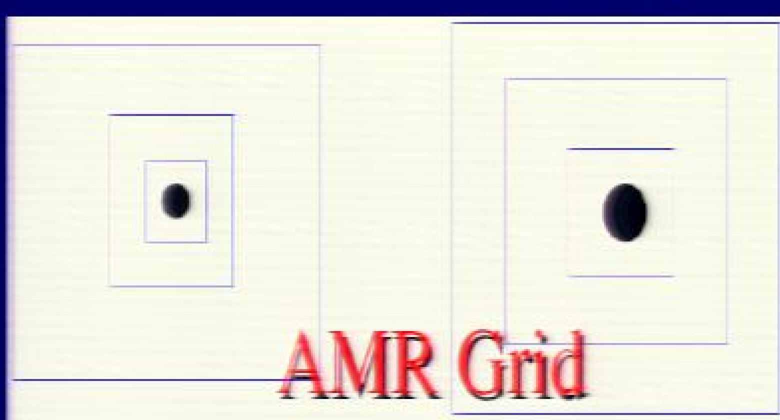
- Default case: Irrotational NS with n=1 ($\Gamma = 2$) polytropic EOS (*irr. ← tidal locking time>>inspiral*)
  - Other EOSs, irrotational NS: Japan, Cornell
- Conformal thin-sandwich (CTS) initial data (all except Japan)
  - CTS: GR soln for quasieq. binaries in circular orbit
  - Models BH spin, mass via boundary condition on AH
    - $-0.5 < J_{BH} / M_{BH}^2 < 0.75$
    - Puncture evolutions: Fill with smoothly extrapolated data from exterior ("junk" initial data)
      - [Etienne et al. PRD **76**, 101503(R) (2007)]
      - [Brown et al. PRD **76**, 081503(R) (2007)]
      - [Brown et al. PRD **79**, 044023 (2009)]
  - Magnetic fields added by Chawla et al. (2010)
- Moving puncture framework initial data (Japan)
  - So far, nonspinning BH initial data only
  - Extra degree of freedom, allows for better match to PN
    - Corresponding reduction in eccentricity

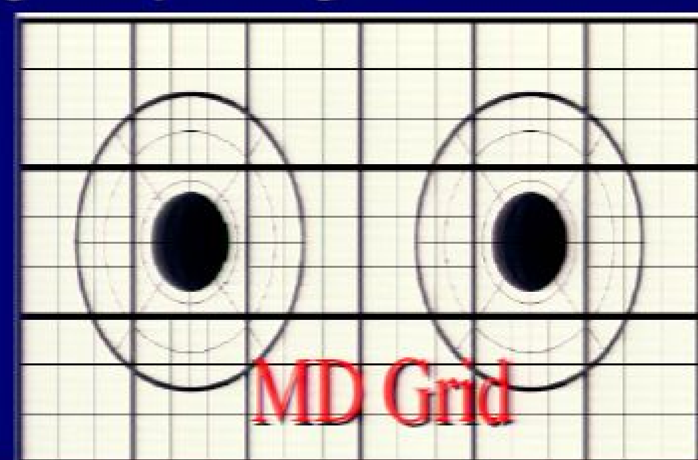
Have BHNS Initial Data
Next Step: Evolve!

- Basic Equations
  - Gravitational fields $G^{\mu\nu} = 8\pi T^{\mu\nu}$
    - Generalized Harmonic formalism
      - Cornell, Chawla et al
    - BSSN (Baumgarte-Shapiro Shibata-Nakamura) formalism
      - Illinois, Japan
  - Fluids
    - General Relativistic Hydrodynamics
    - Magnetic fields added (MHD approximation)
      - Chawla et al
      - Illinois (*in progress*)

Evolution Codes

- Time evolution: 4^{th} order finite differences (RK4)
- Einstein's equations for metric (BSSN/GH formalism)
  - Spatial derivatives: 4^{th} order+ finite differences ← Cornell: Spectral!
- Coordinates: "puncture gauge" or "generalized harmonic coordinates"
  - Puncture coords avoid BH physical singularity → stability!
  - Generalized harm. coords use excision: BC @ BH
- General relativistic hydro/MHD equations: conservative, HRSC scheme
  - Reconstruction: 2^{nd} or 3^{rd} order accurate, for smooth flows
  - MHD: div B
- Chawla, Illinois, Japan: AMR infrastructure
- Cornell: Multi-Domain (MD) spectral grid + hydro unigrid





Cornell Movie Details

- BH spin 0.5, 80 degrees inclined to orbital *J*
  - → First precessing case!
- 3:1 mass ratio, EOS not mentioned

- ~3% disk at end of simulation
  - Less disk than same case, but with aligned BH spin
- Final spin: 20 degrees inclined to orbital *J*

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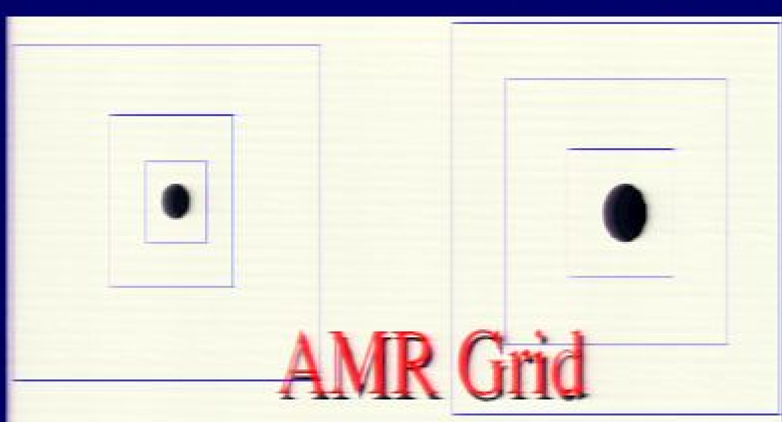

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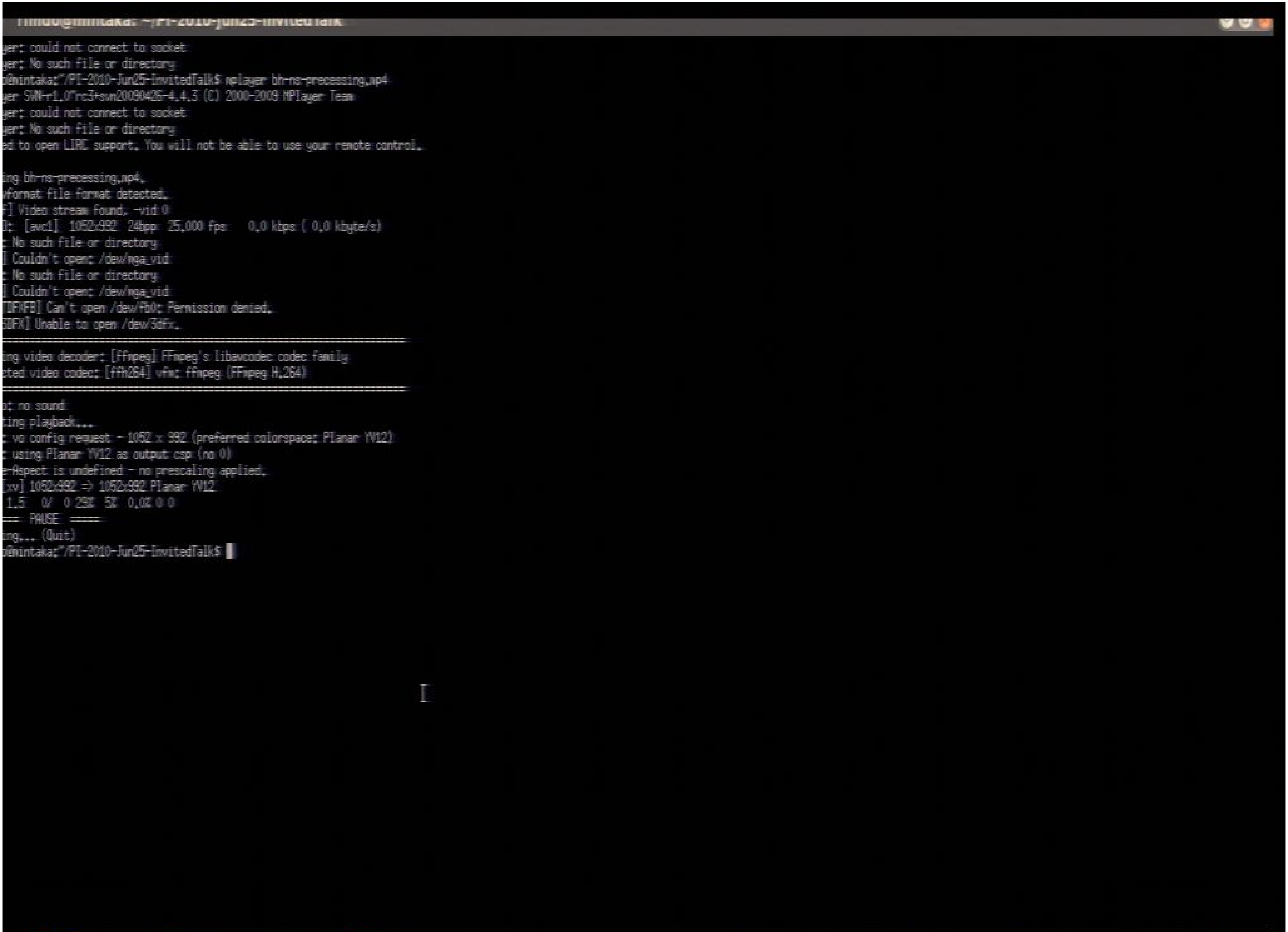

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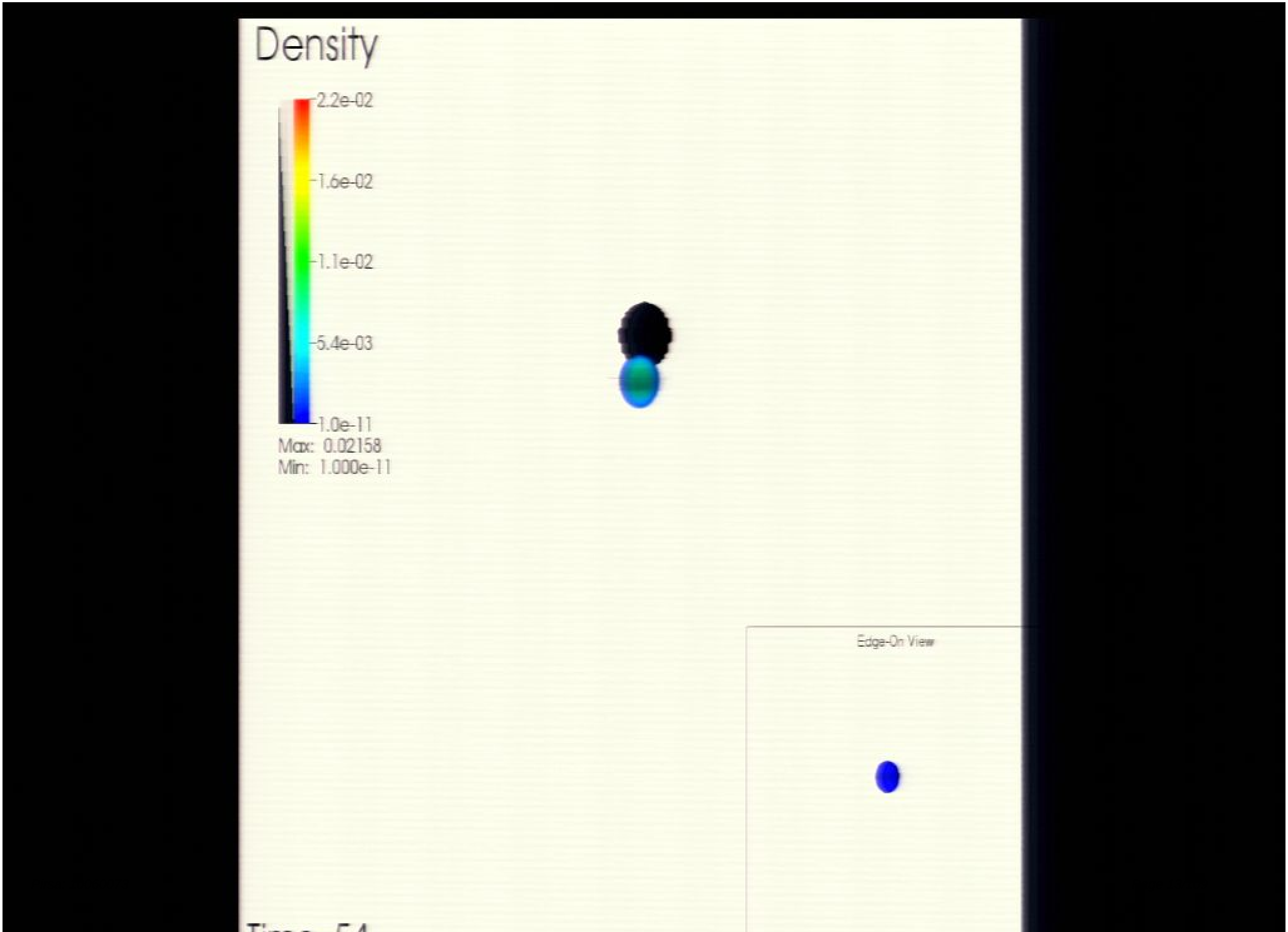
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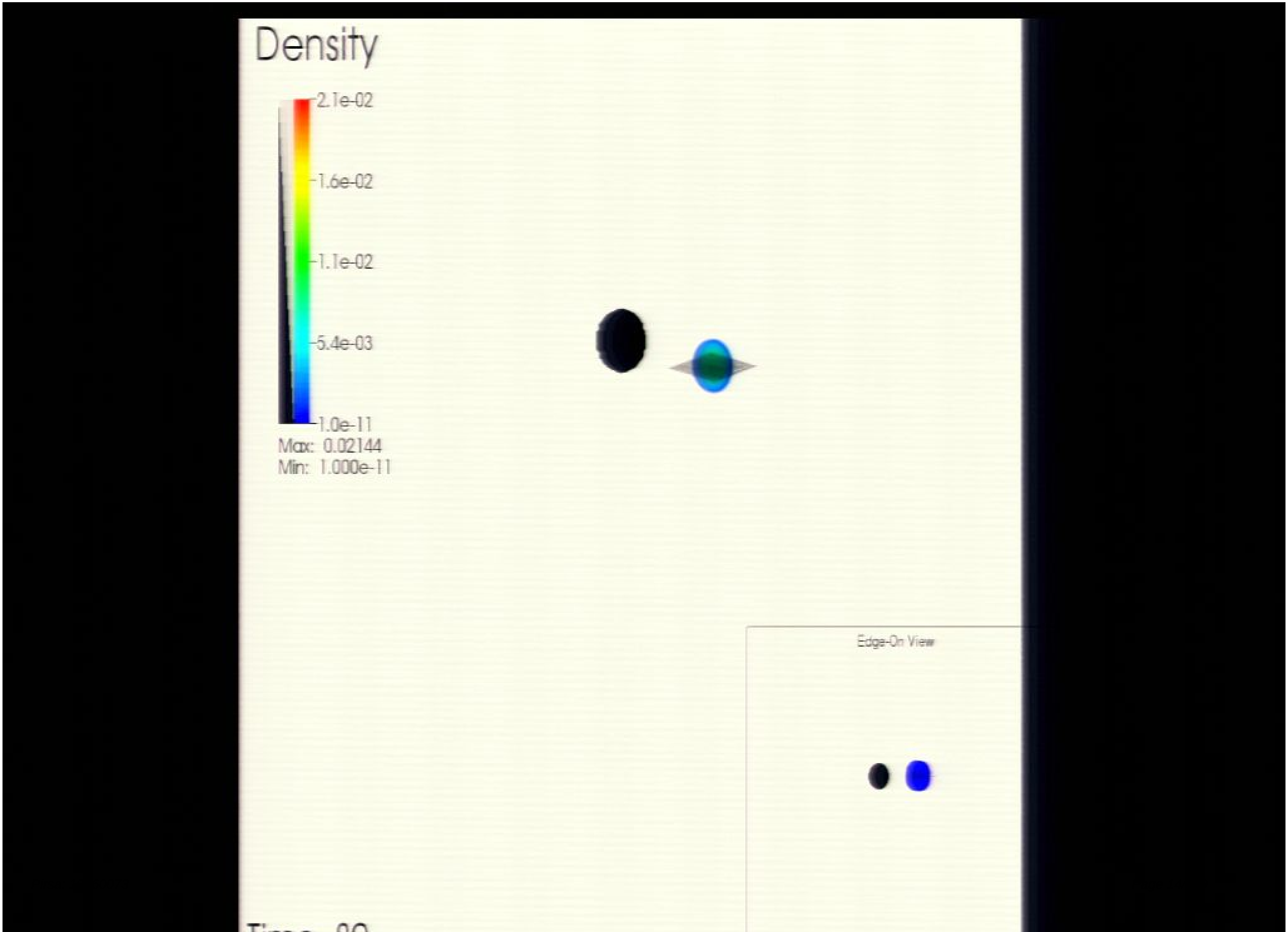
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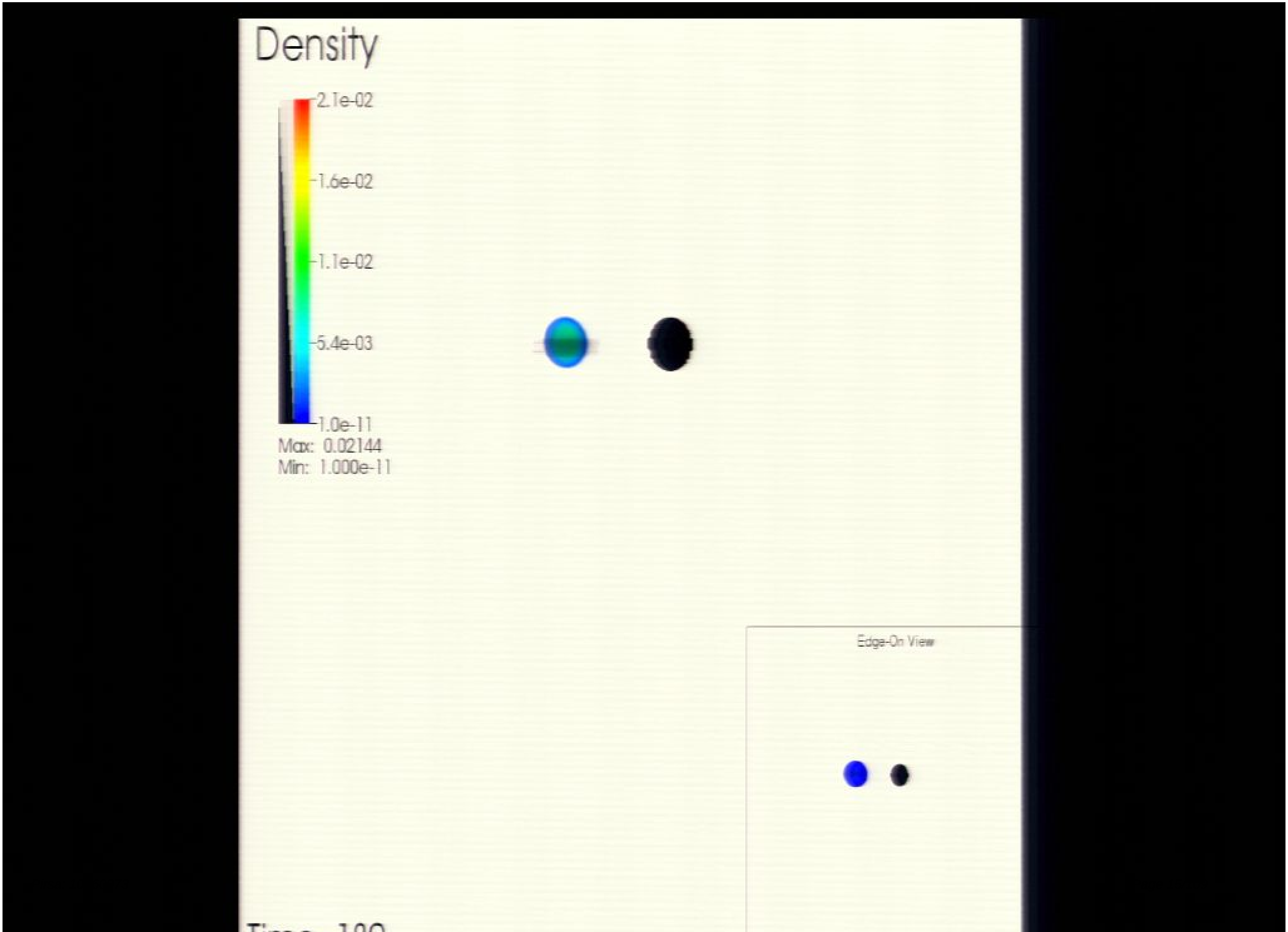
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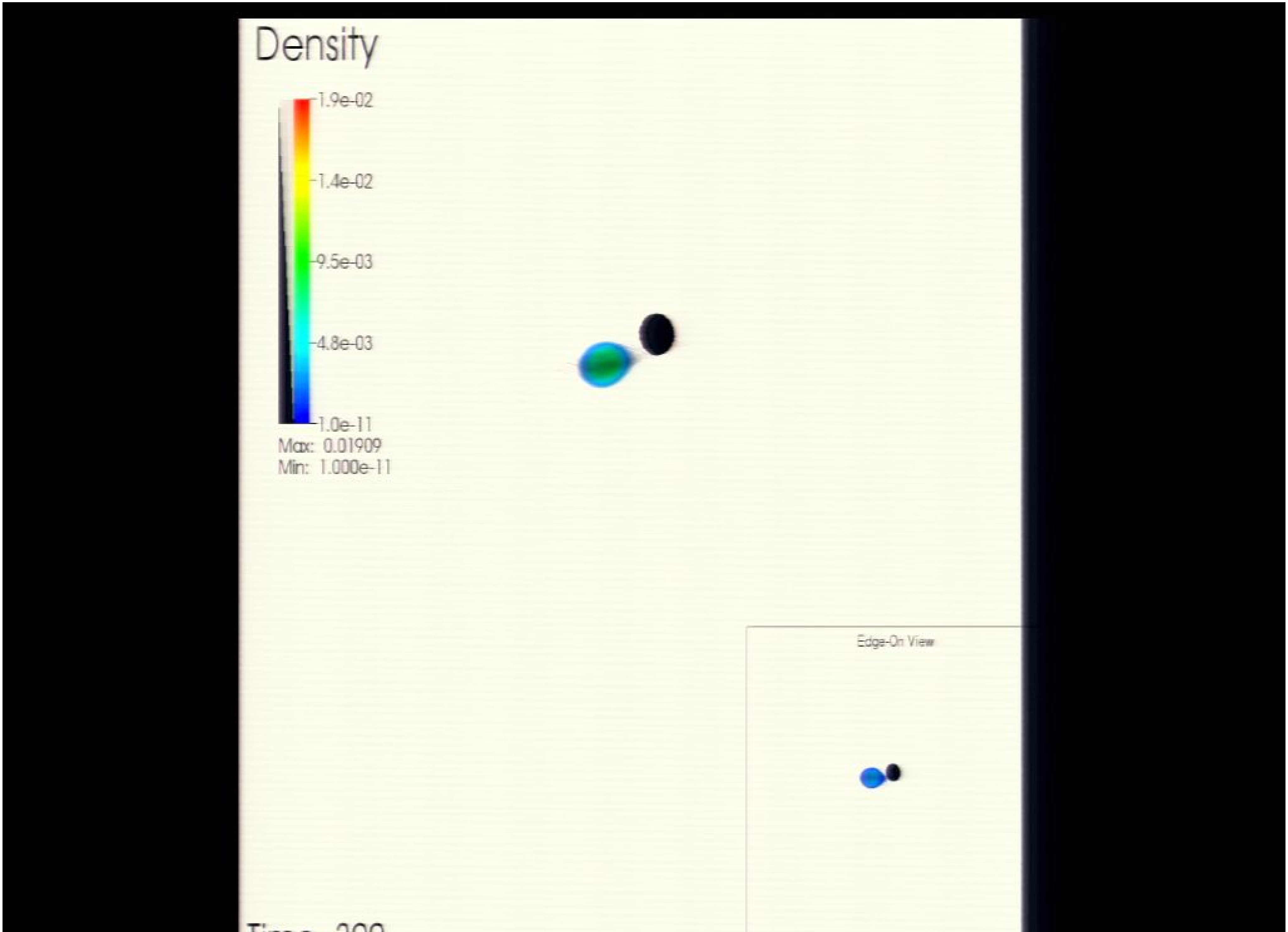
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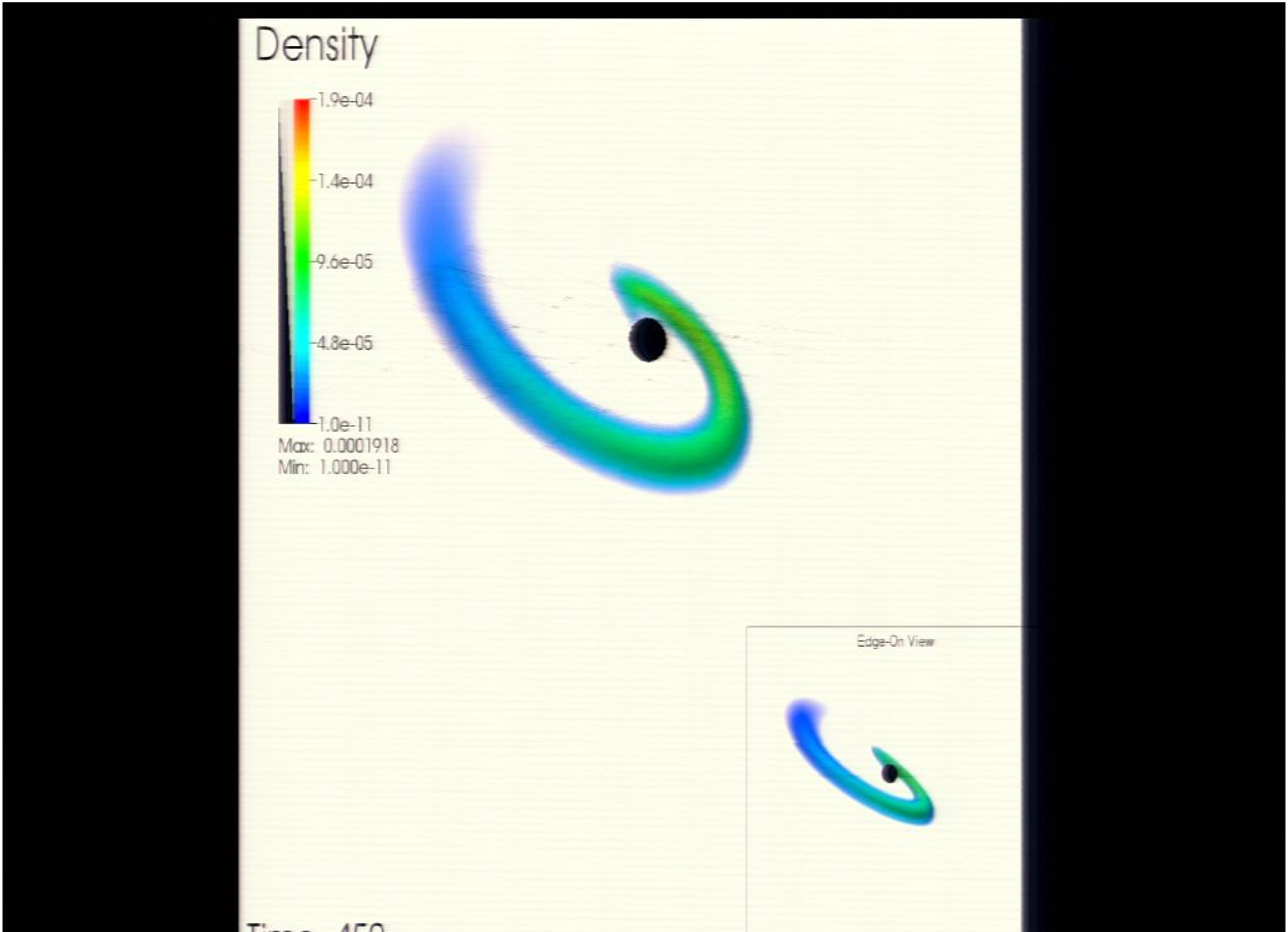

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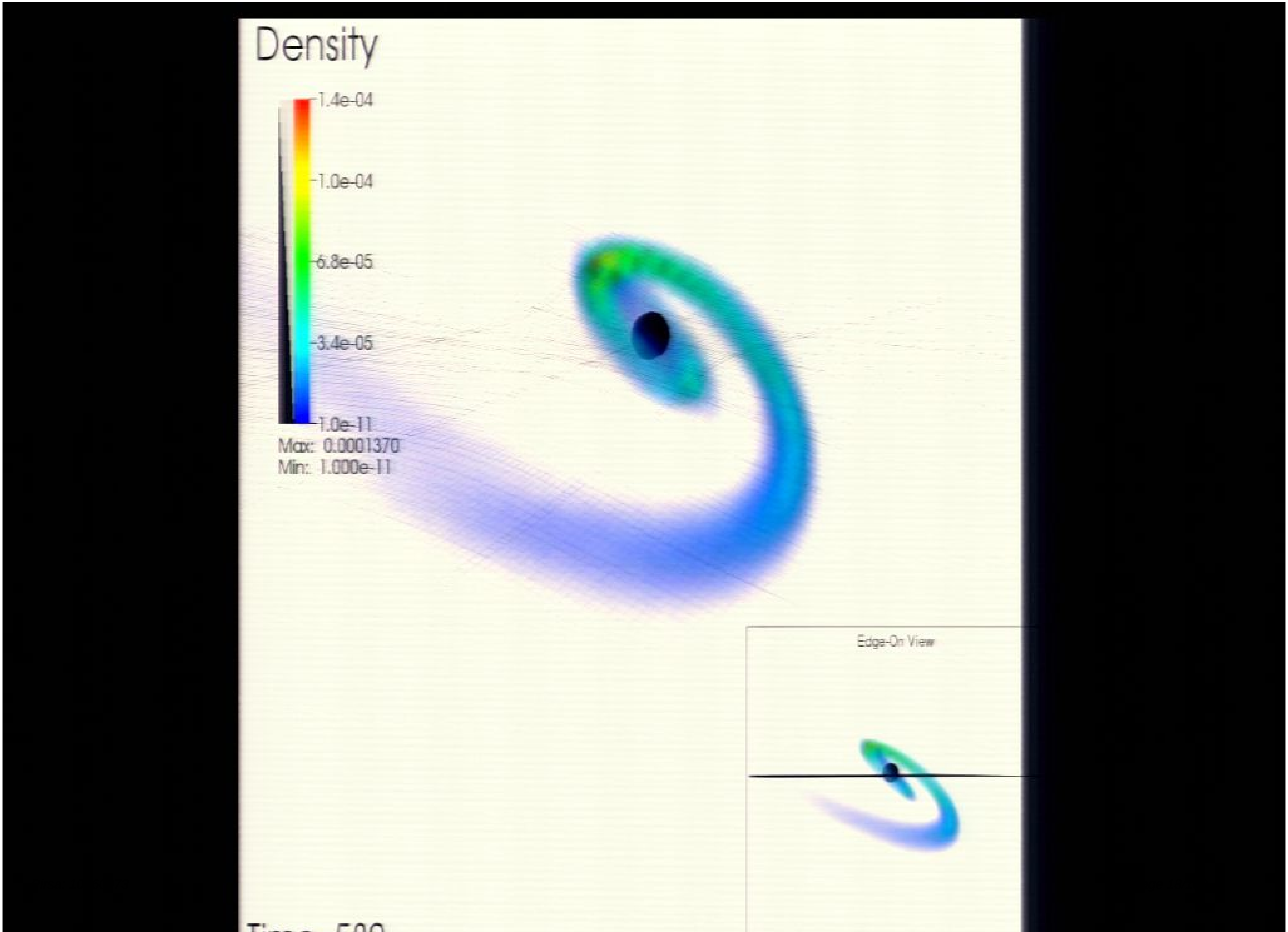
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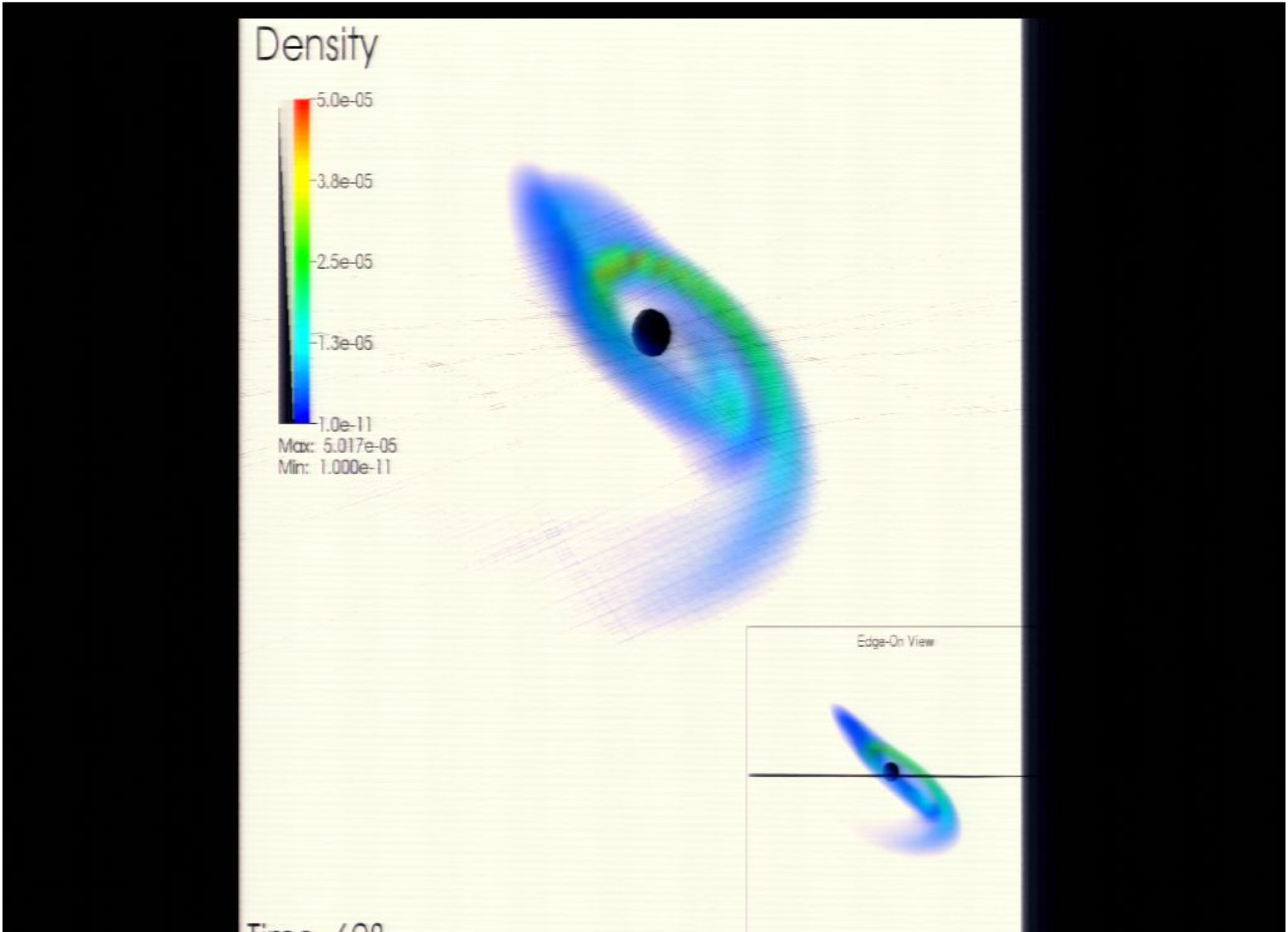
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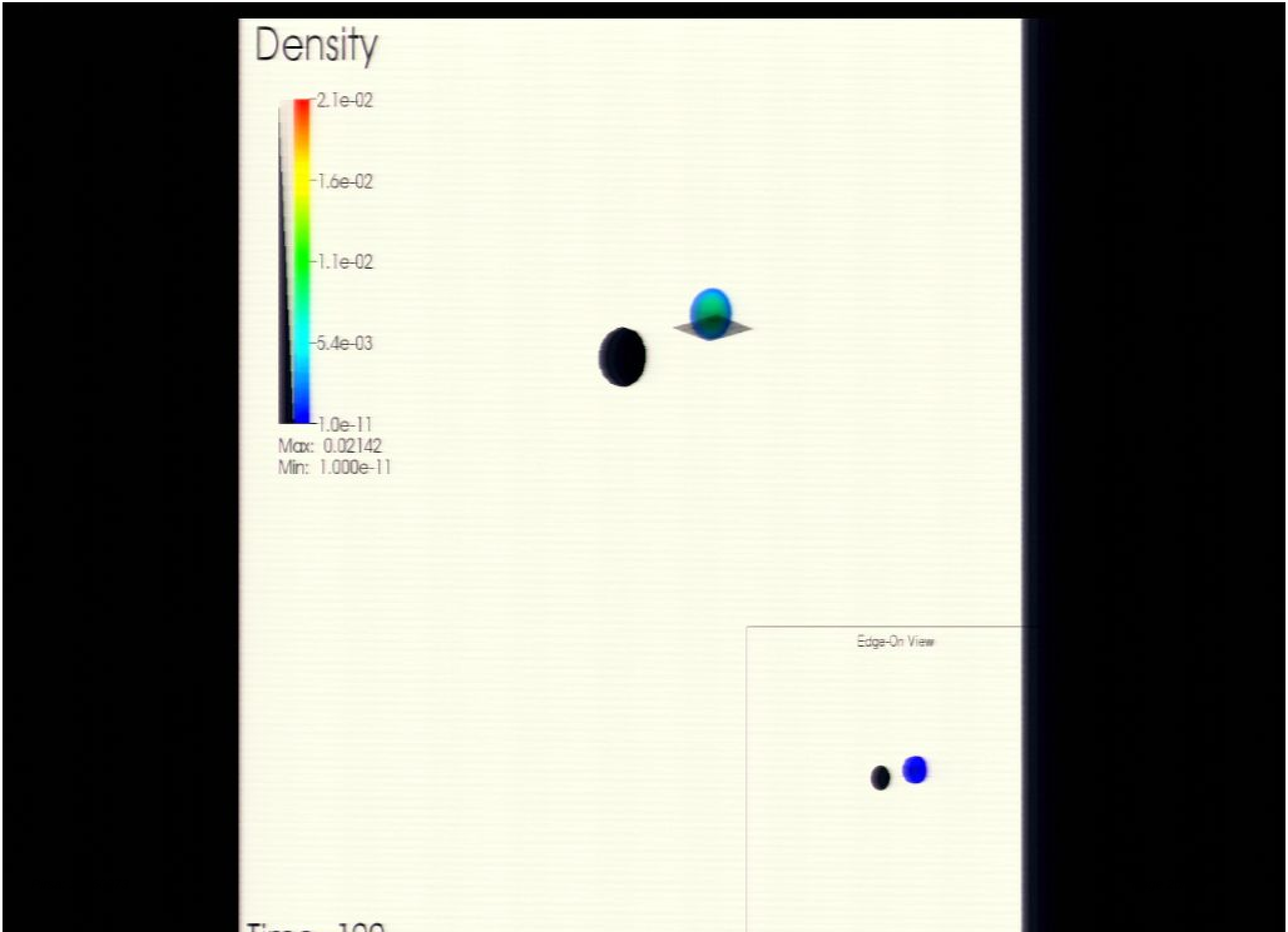
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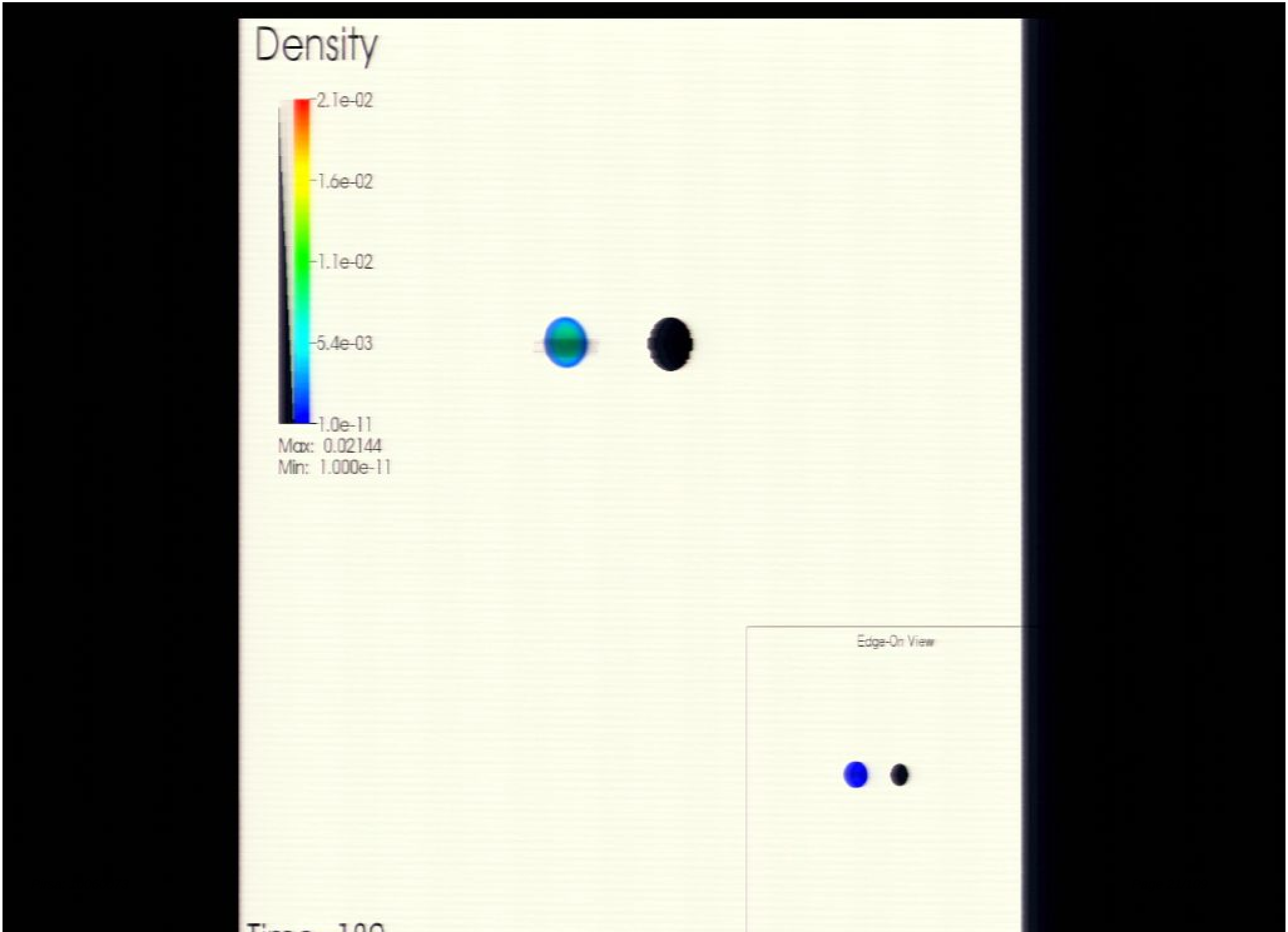
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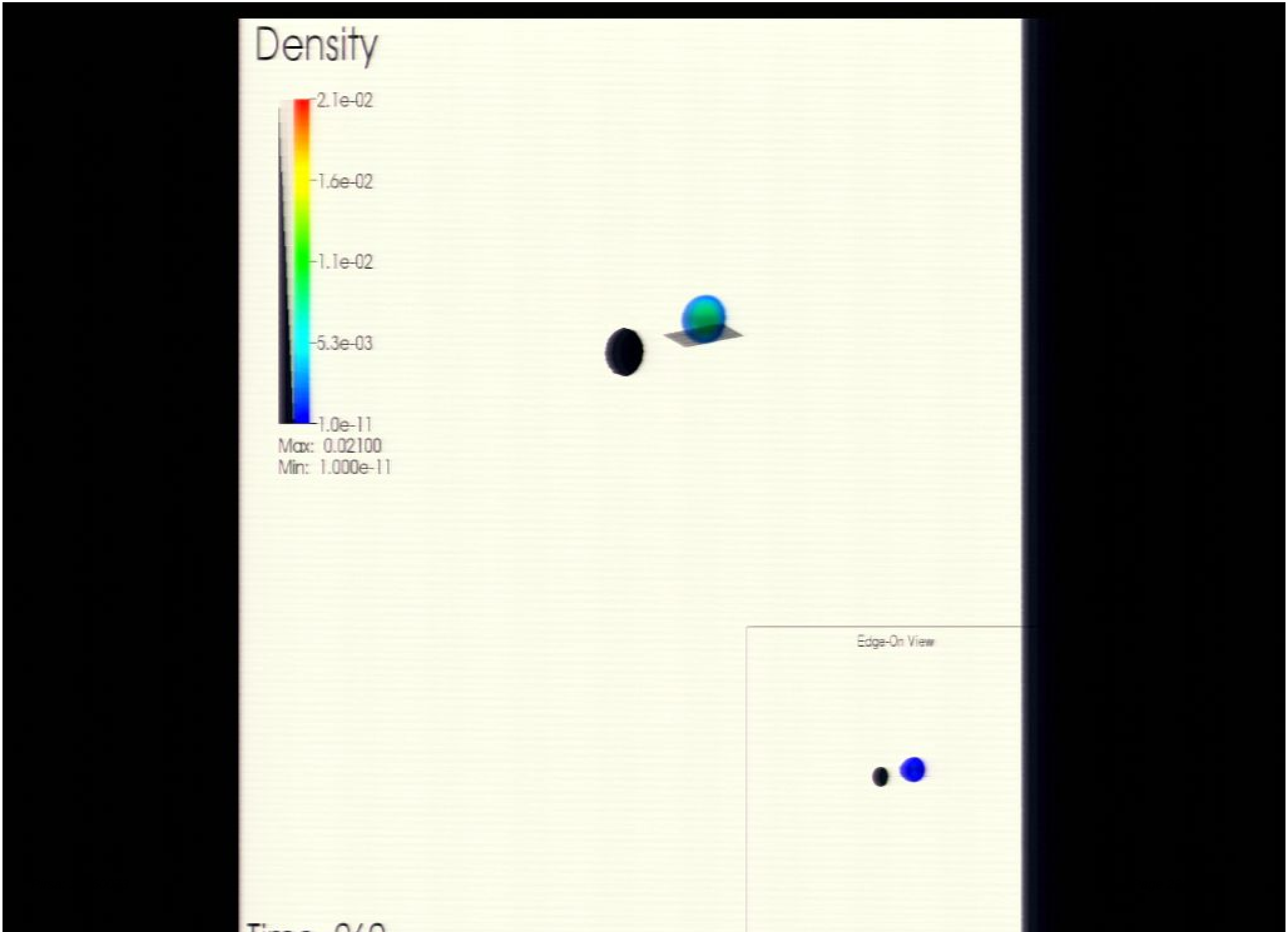
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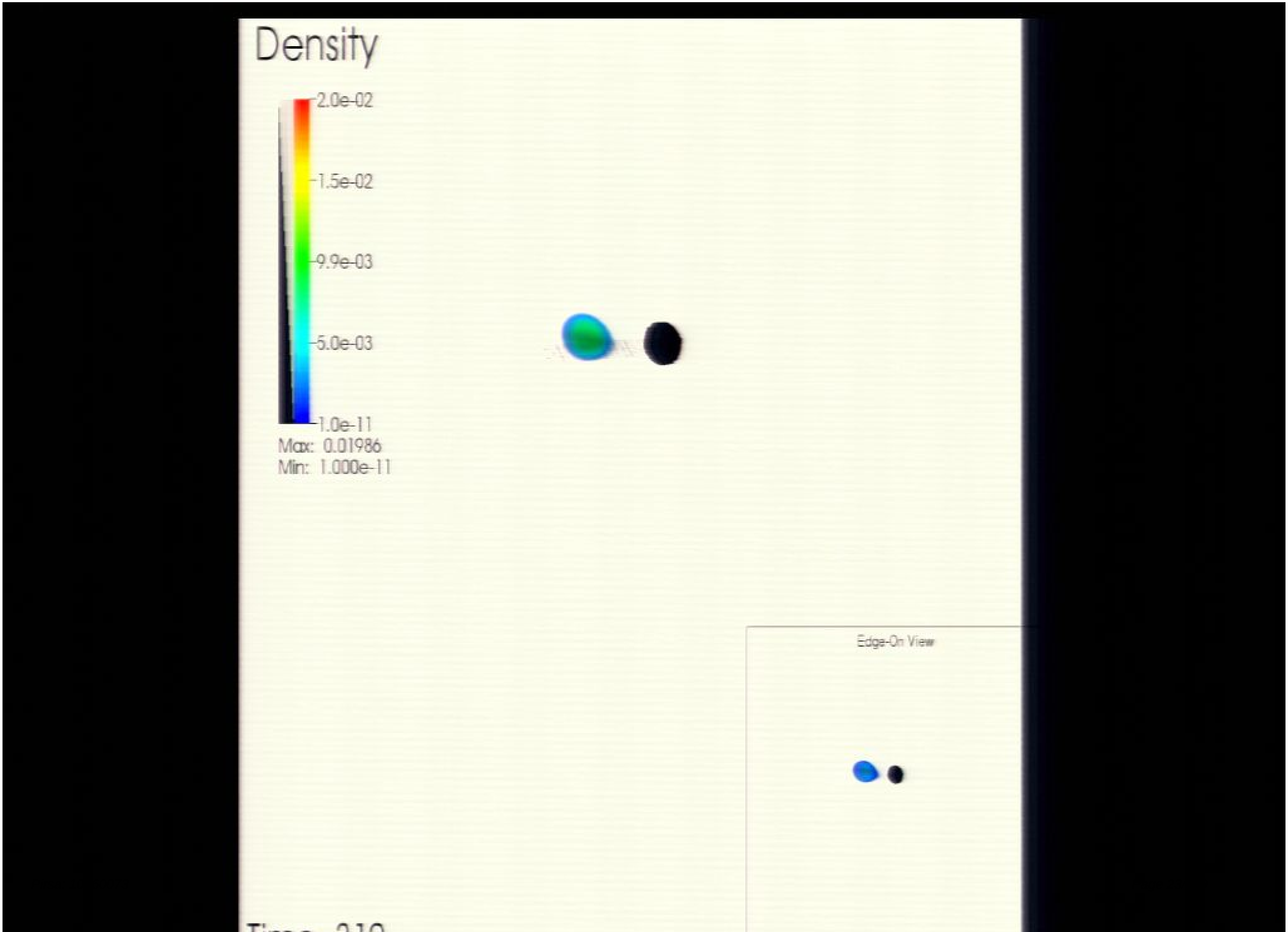

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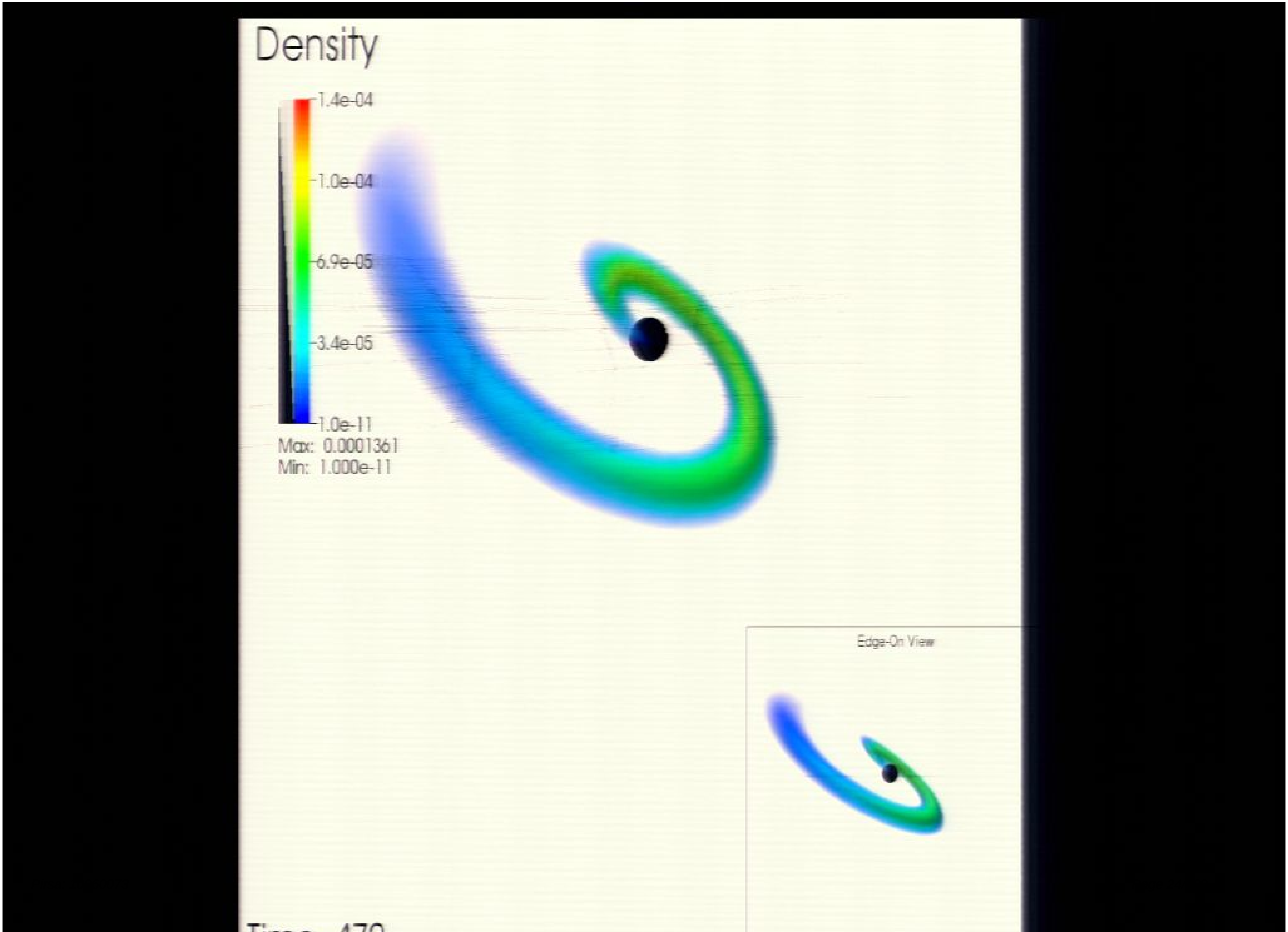
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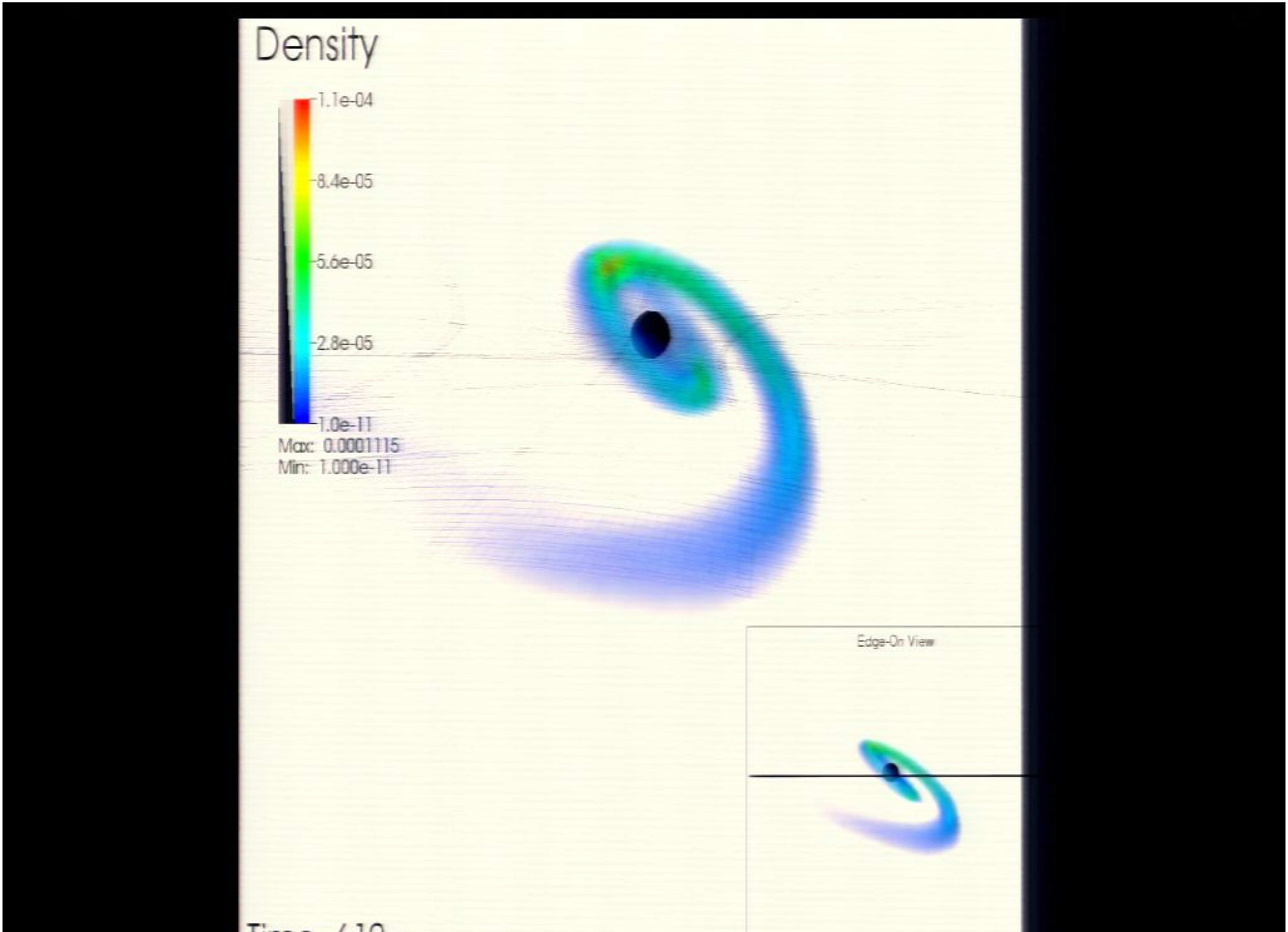
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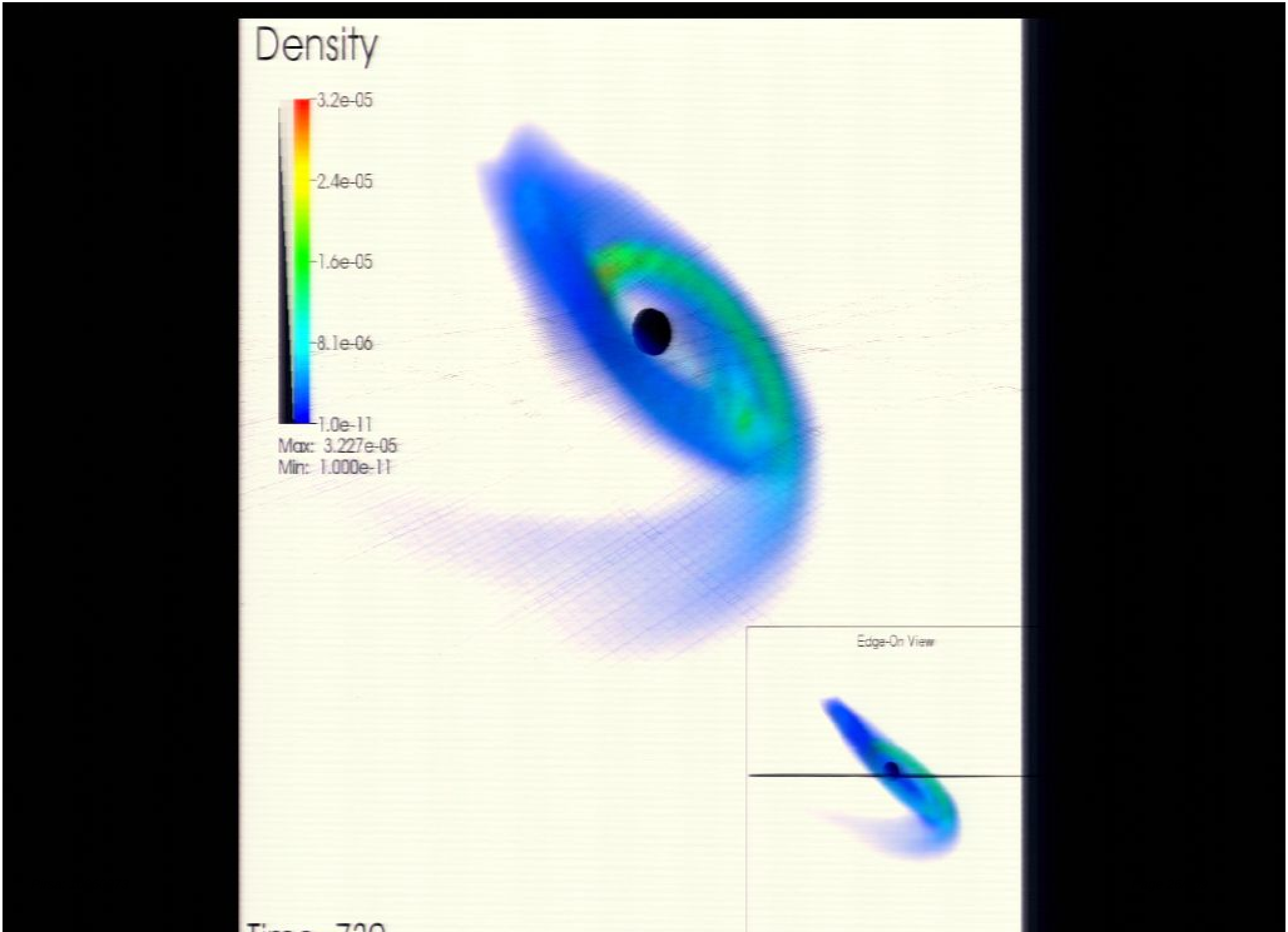
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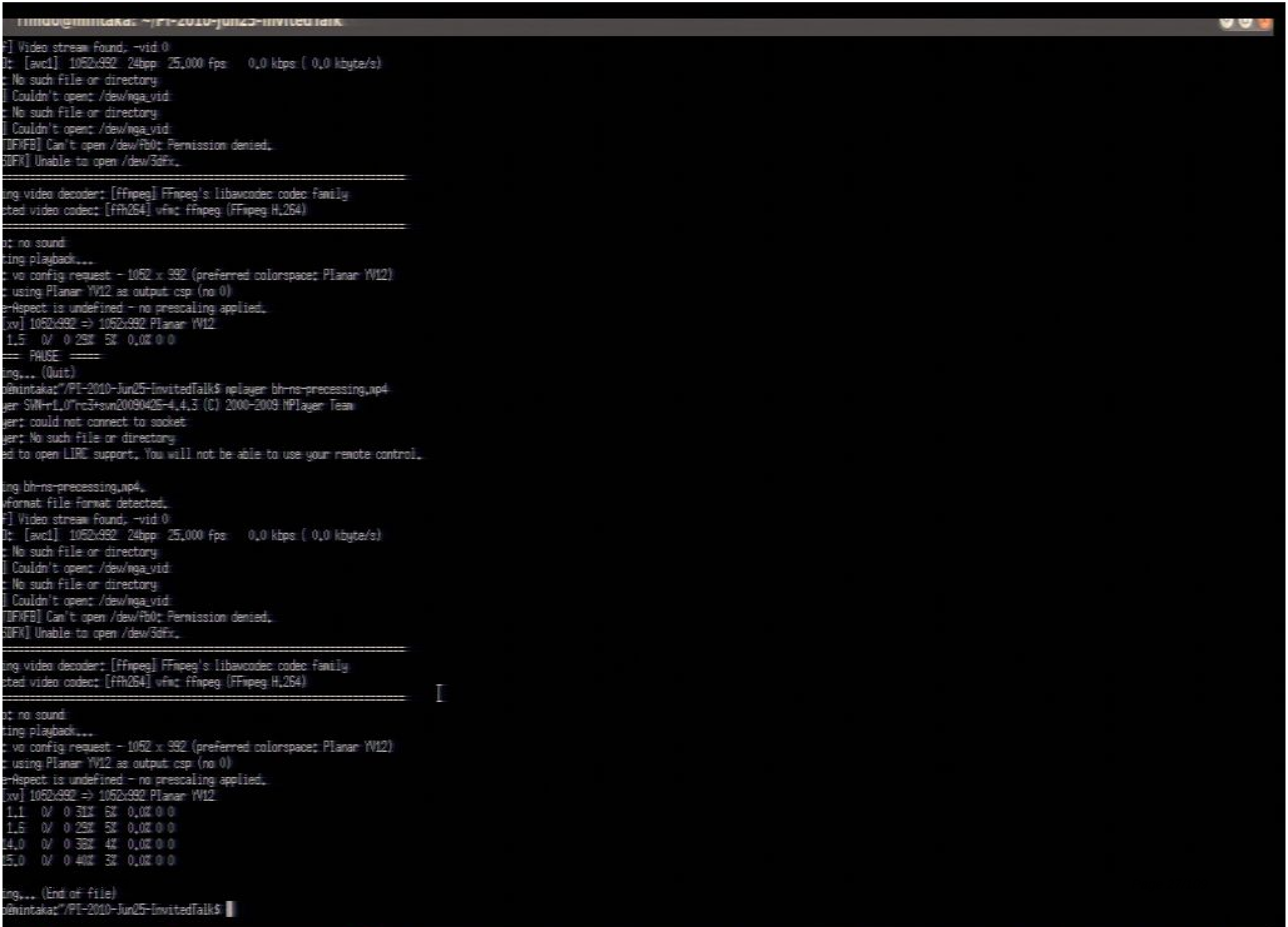
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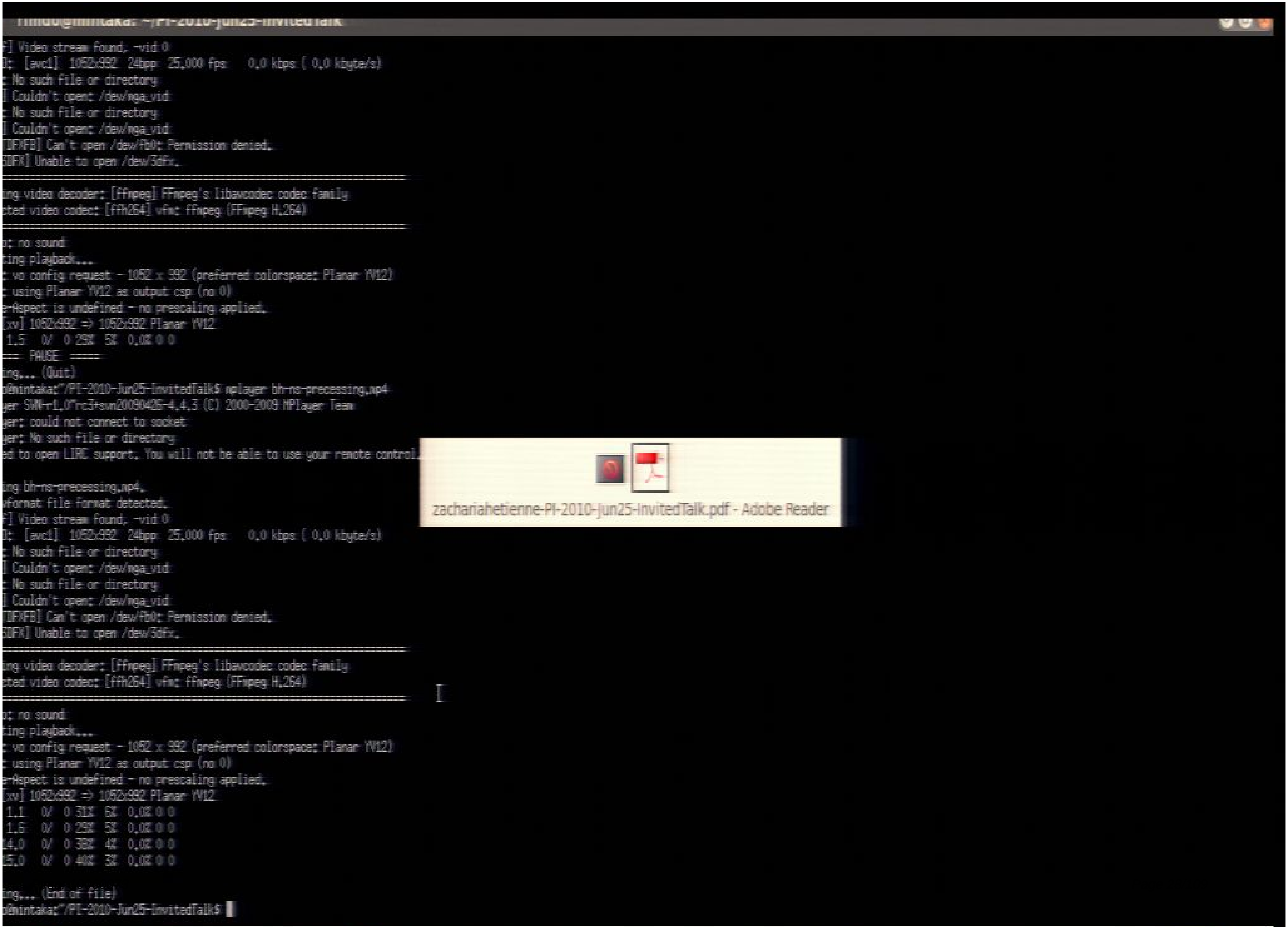
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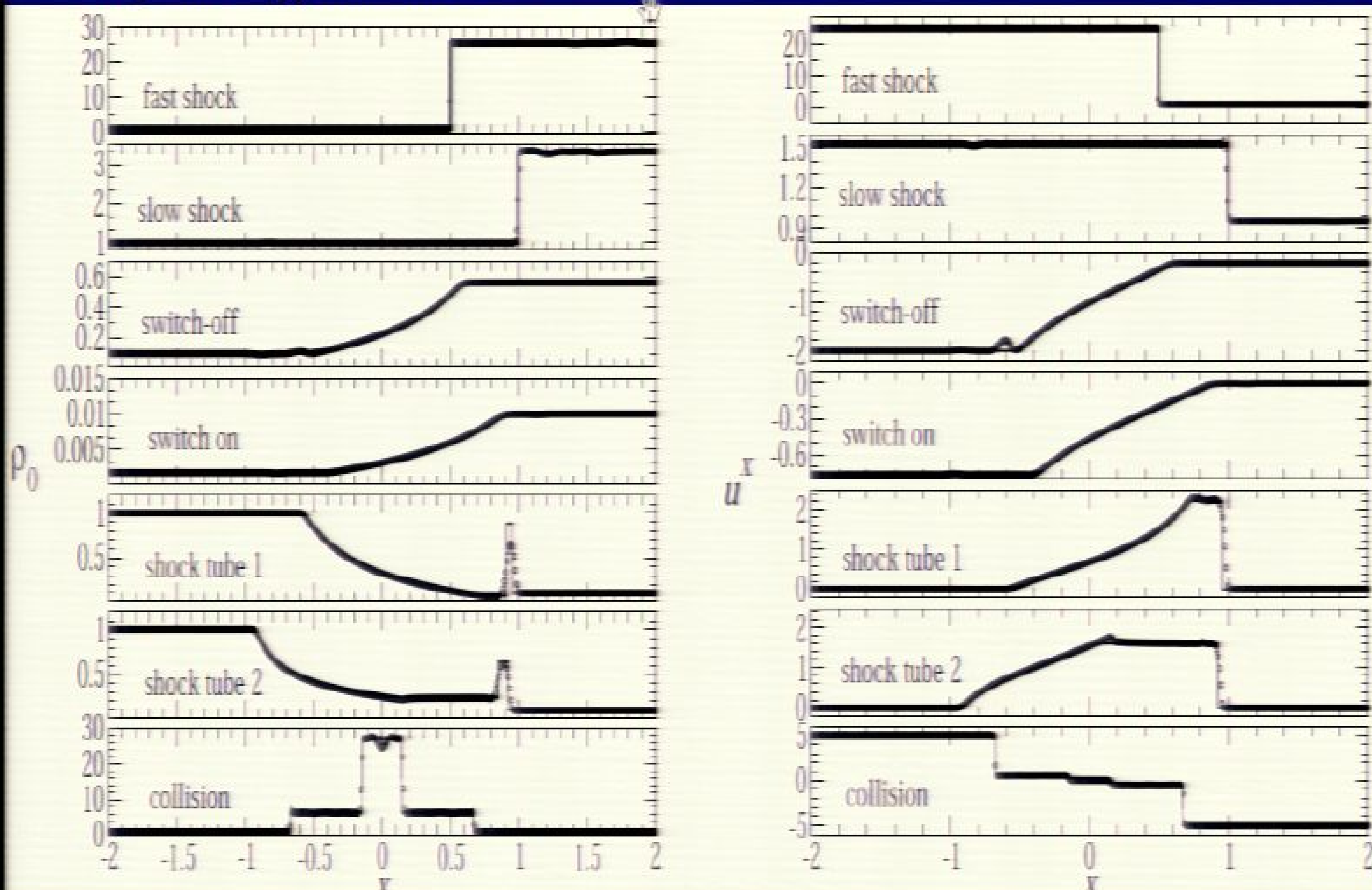
Illinois Non-AMR Code Validation Tests

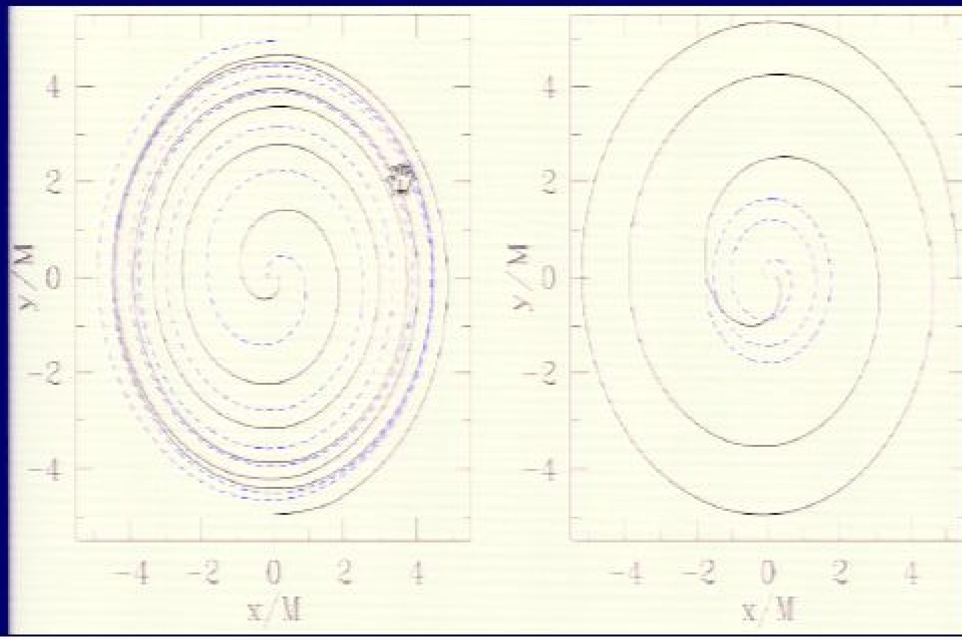
- Tests with analytic solutions
  - Shock tube, OS collapse, Bondi flow
- Tests against other codes (Japan)
  - Magnetized hypermassive NSs



[Duez et al. PRD 72 (2005) 024028]

Illinois AMR Code Tests, Part I: BHBH Binary

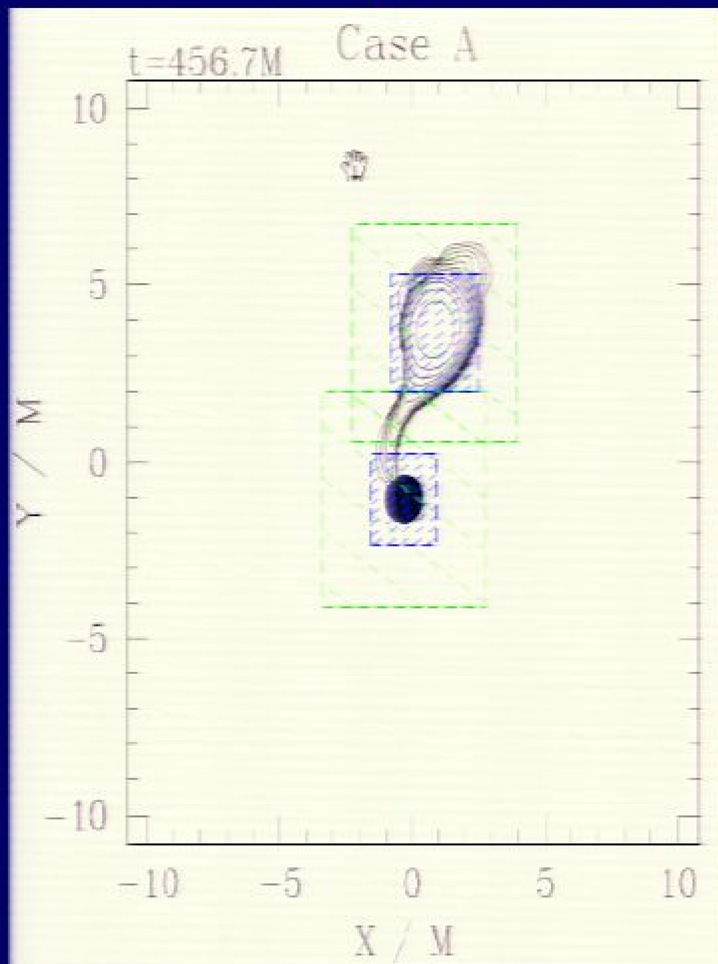
- BHBH: equal & unequal mass (Equal: 7 orbits, Unequal 3:1: 5 orbits)
- (9 ref. levels)



	equal mass (known value)	unequal mass ($q = 3$) (known value)
$M_{\rm BH}/M$	0.96 (0.95)	0.981 (0.978)
$J_{\rm BH}/M_{\rm BH}^2$	0.685 (0.686)	0.541 (0.545)
$v_{\rm kick}$	—	174 ($\sim$ 175) km s^{-1}
δE	4×10^{-4}	-2×10^{-4}
δJ	4×10^{-3}	9×10^{-4}

Where $\delta E \equiv (M - M_f - \Delta E_{\rm GW})/M$.

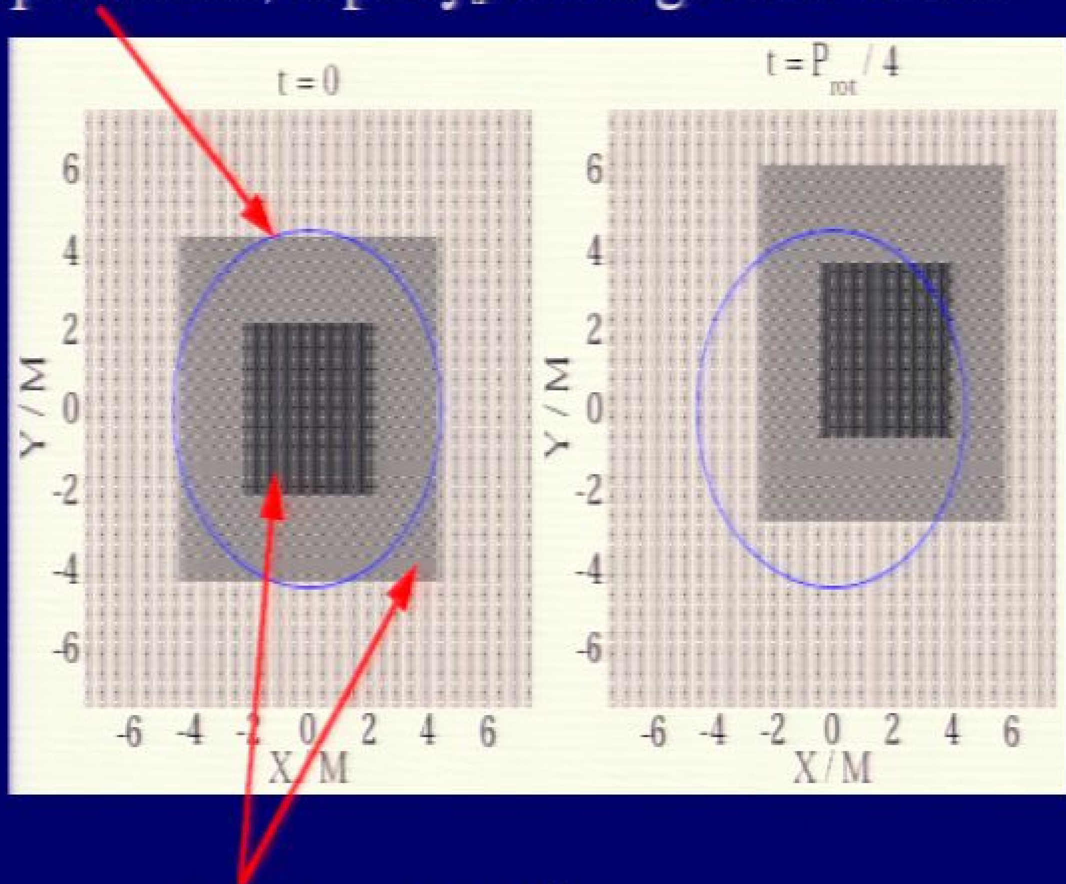
Illinois AMR Code Tests, Part II: AMR+Matter



- Typical BHNS during merger phase
- Matter crosses refinement boundaries!
- Unigrid → Hydro. scheme preserves rest mass
- AMR → Rest mass conservation not guaranteed. **How much error?**

Illinois AMR Code Tests, Part II: AMR+Matter

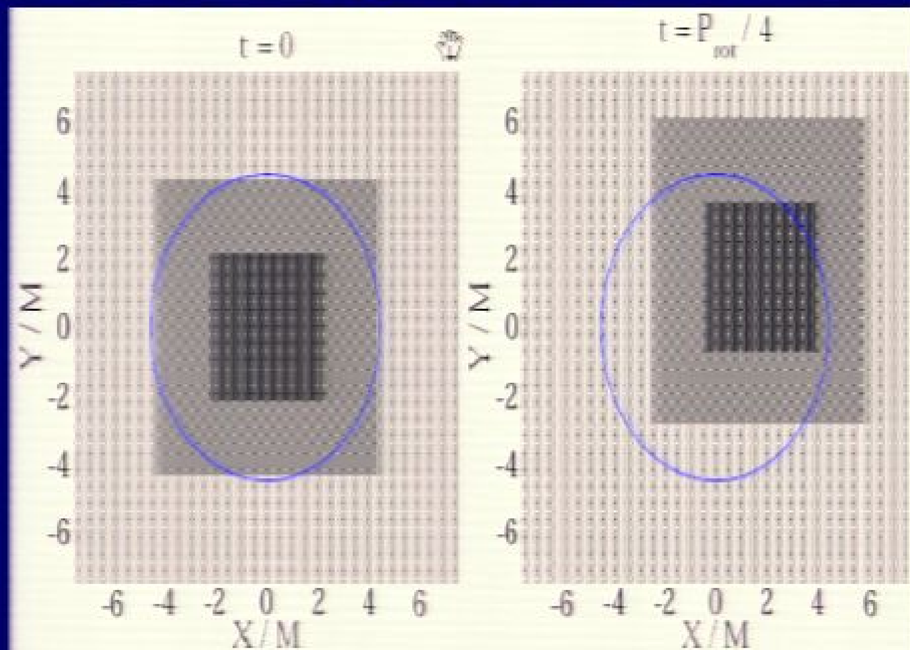
Equilibrium, rapidly rotating neutron star

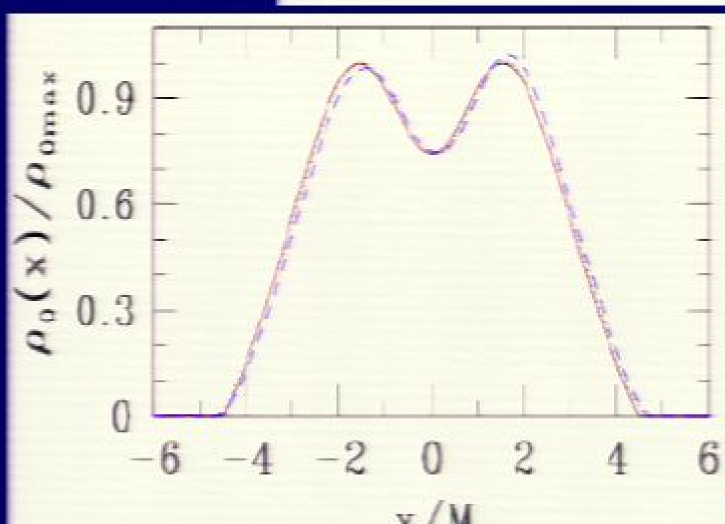


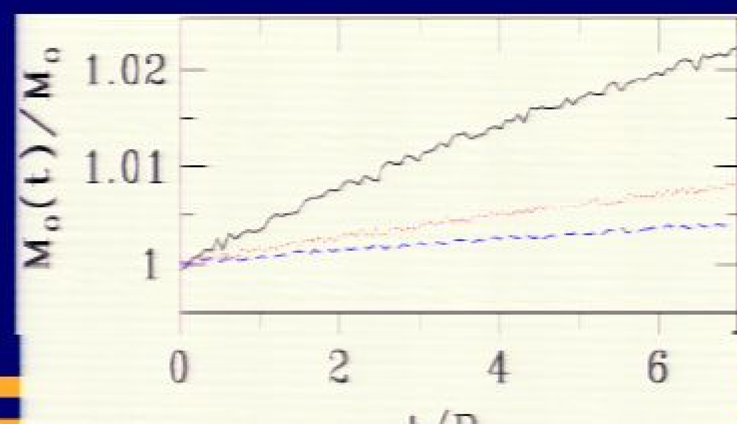
Moving AMR boxes:
(darker → higher resolution)

Illinois AMR Code Tests, Part II: AMR+Matter

- Equil., rapidly rotating star maintains equilibrium, many rotation periods
- Rest-mass violation error converges to zero @ >2nd order, <1%

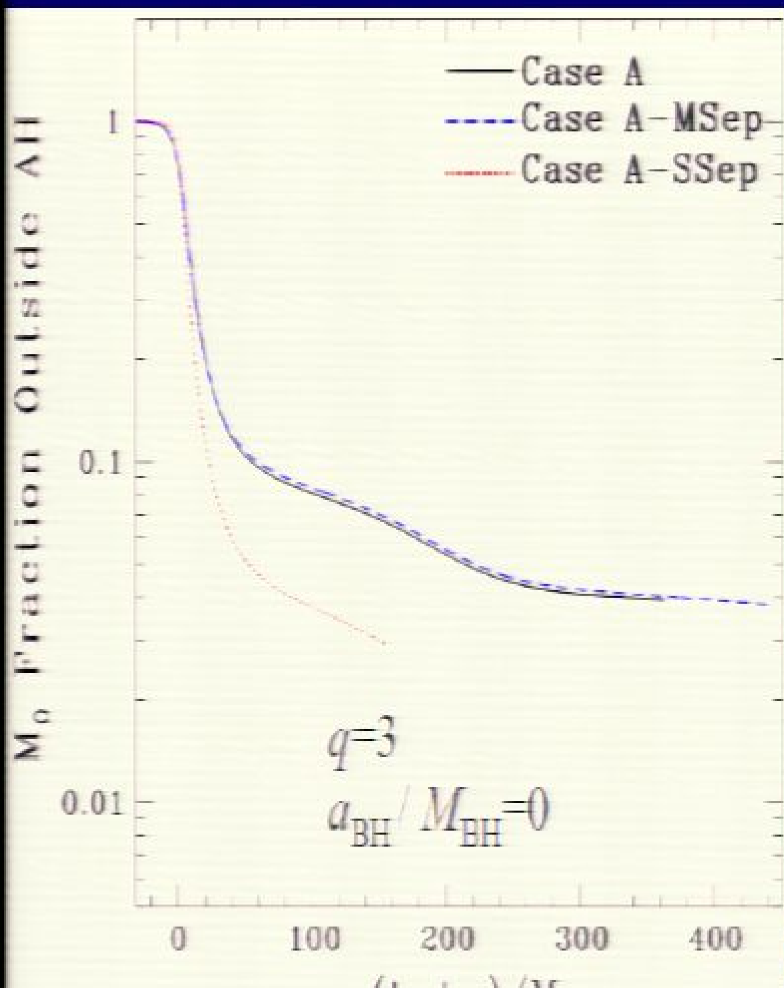


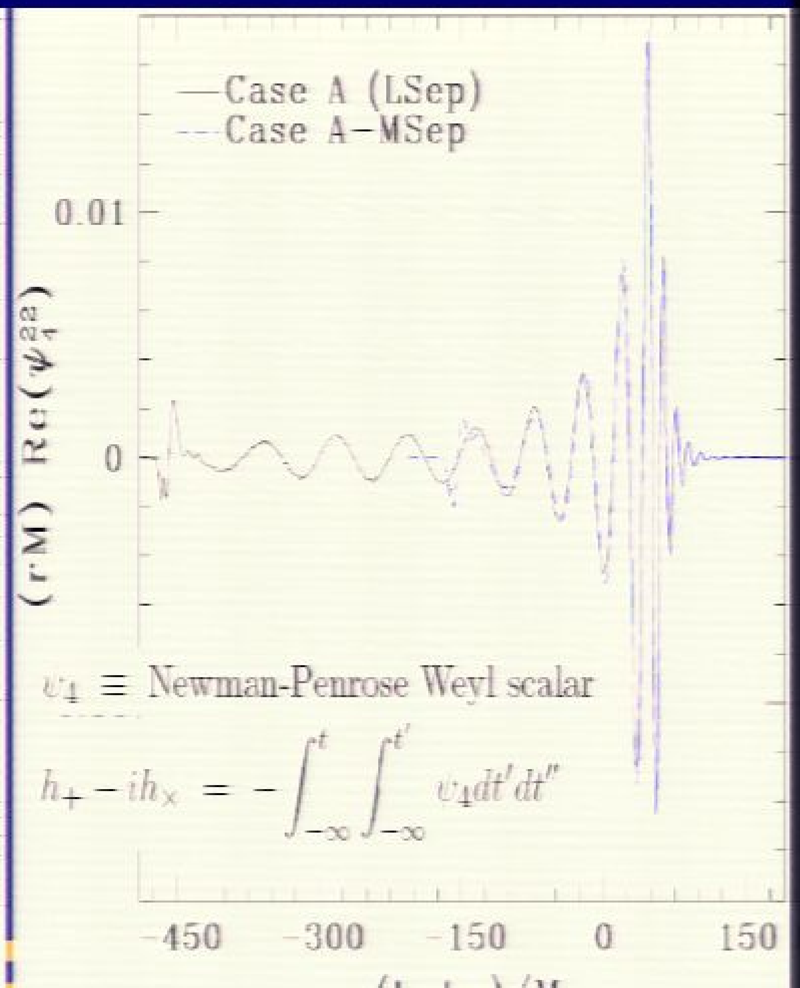




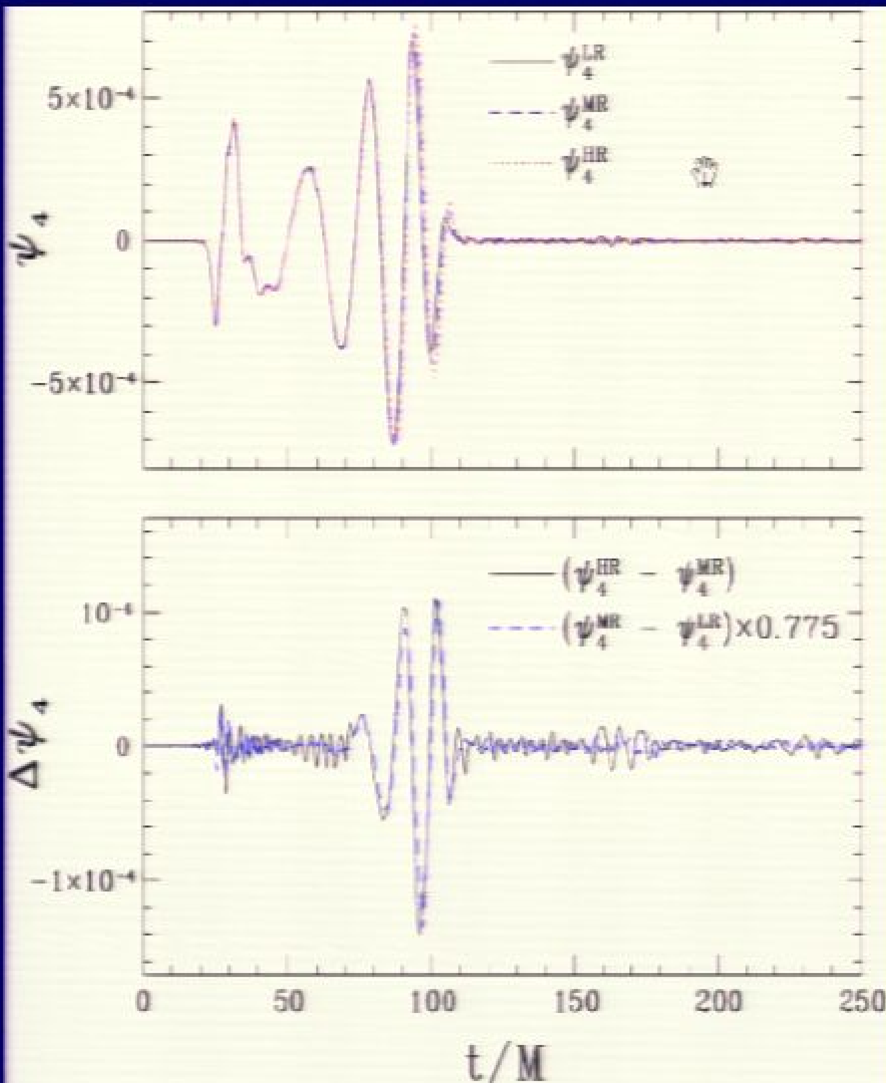
Illinois Code Tests, Part III: BHNS Initial Data

- CTS imposes circularity condition on binary orbit ← HKV
  - Smaller seps → Radial infall increases → Circular data inconsistent!
- Have CTS initial data at very small separations
  - How far apart must we start binaries to ensure consistent results?
- Code test: evolve same binary config. at diff. separations





Illinois Code Tests, Part IV: BHNS Convergence



$q=3,\ a_{BH}/M_{BH}=0.75,\ D_0=5.5M$

Resolution in the innermost refinement box:

In a typical BHNS simulation:

Normalized constraint violations $\sim 10^{-3} - 10^{-2}$

$\delta E = (M_i - M_f - \Delta E_{GW})/M_i \sim 10^{-4}$

Other Groups' Code Tests

- Japan:
  - Convergence tests
    - rest mass violation convergence with AMR+NSNS: 2nd order
    - BHNS: second order convergence
  - Self-consistency:
    - *J* & *E* conservation; BHNS vs post-Newtonian
- Cornell:
  - Convergence tests:
    - Field sector: spectral, well-tested with BHBH
    - Matter (no AMR): NS tests; second-order convergent BHNS
  - Self-consistency: *J* & *E* conservation
- LSU/BYU/PI/etc:
  - Evolve TOV star unigrid, ~2.4 order convergence
  - Spherical accretion onto stationary Schw. BH
    - converges to analytic as more AMR levels added
  - AMR spherical blast wave: HDC improves div B =0
  - Convergence for BHNS unpublished

BHNS Evolutions: Case Studies

BH Spin Study
- Illinois

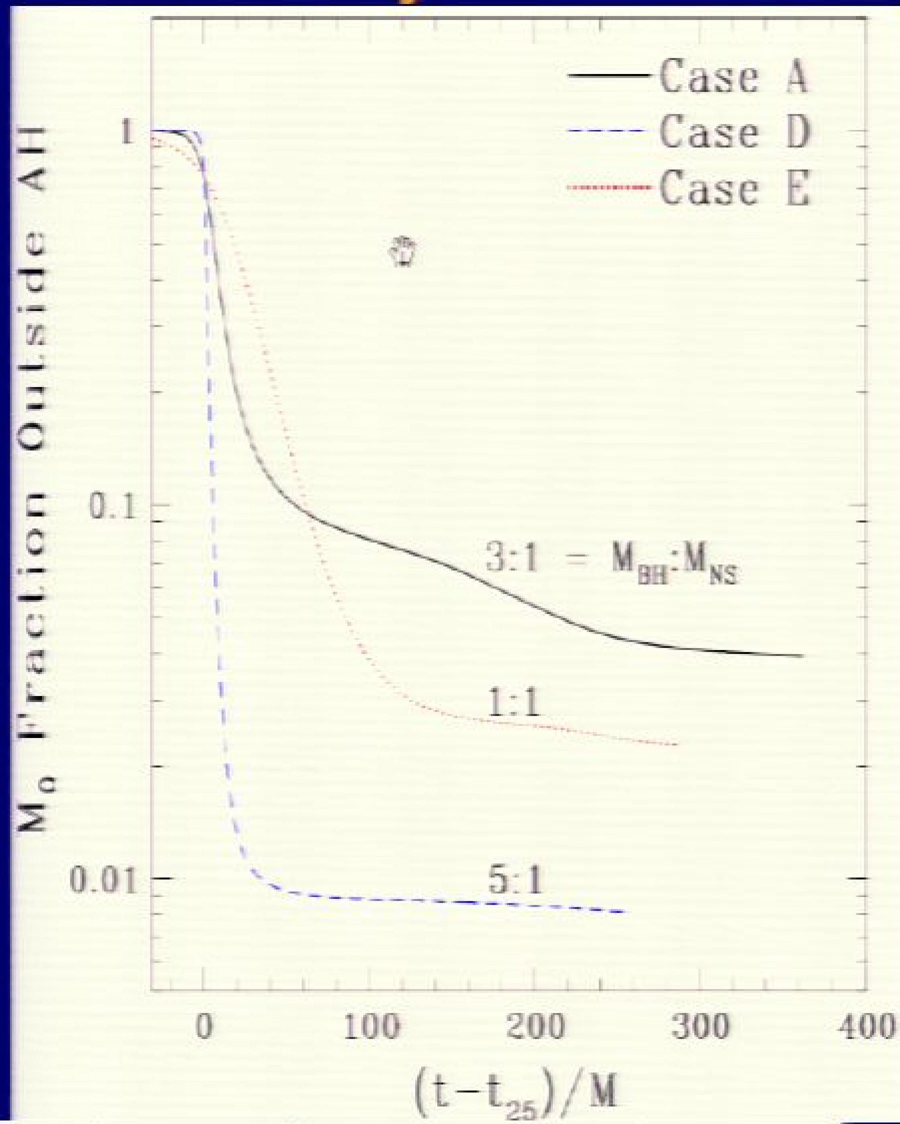
NS Compaction Study
- Cornell
- Japan

Mass Ratio Study
- Illinois
- Japan

Equation of State Study
- Cornell

Magnetic Field Study
- Chawla et al. (LSU,BYU,IU,PI, UG,ULI)

Mass Ratio Study: Accretion History



Case	J_{BH}/M^2_{BH}	$M_{BH}:M_{NS}$	N_{orb}	M_{disk}/M_0
E	0.0	1:1	2.25	$\lesssim 2.3\%$
A	0.0	3:1	4.5	$\lesssim 3.9\%$
D	[illegible]	[illegible]	[illegible]	[illegible]

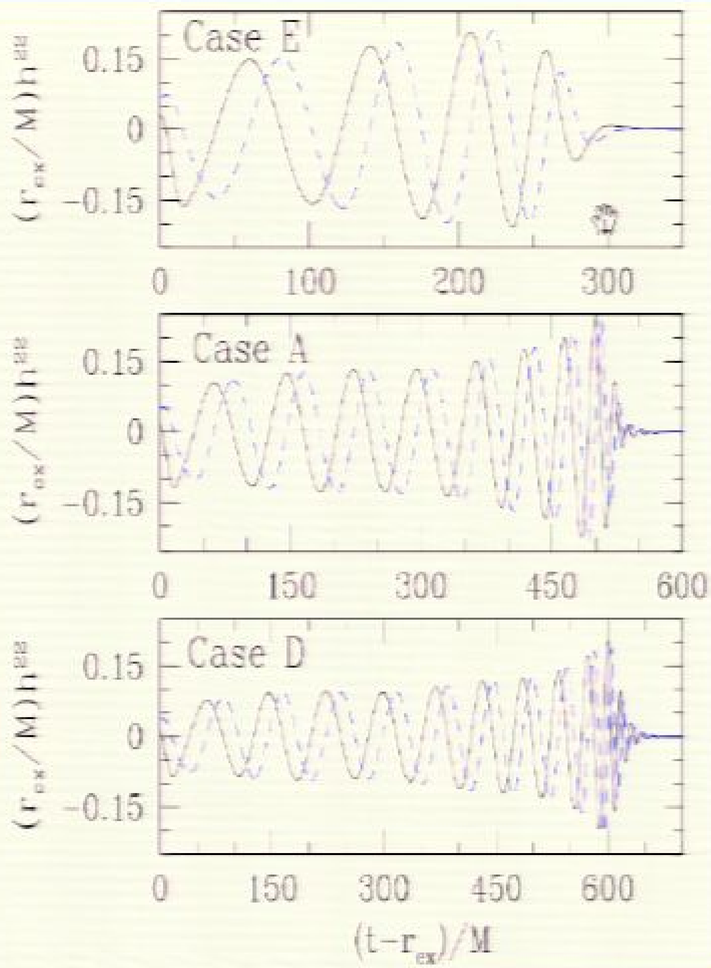
→ SGRB?

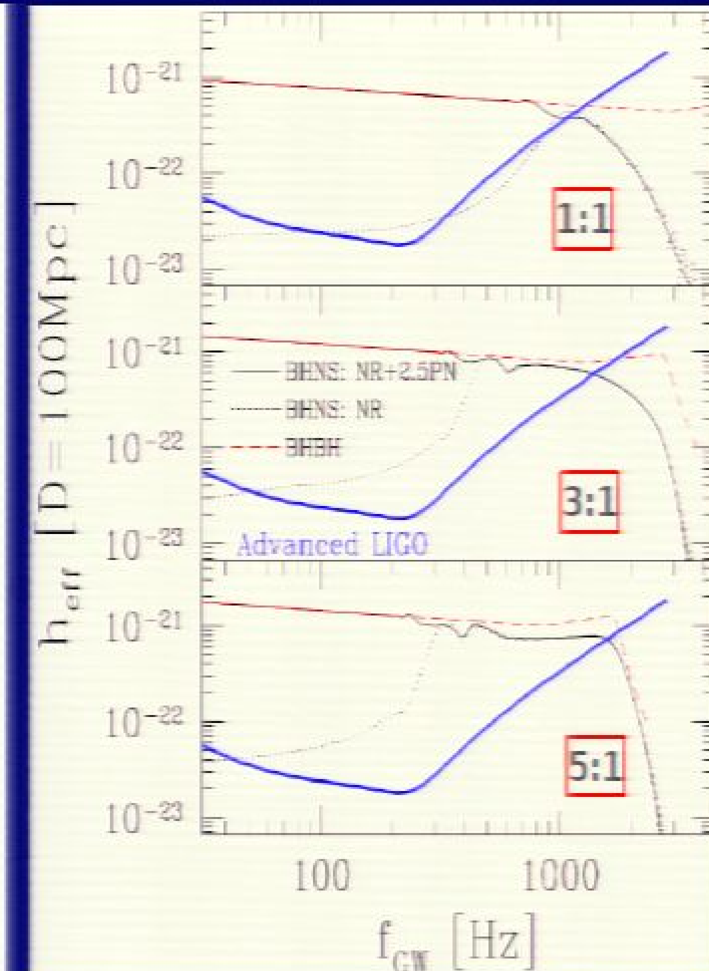
Mass Ratio vs Disk Mass Multi-Group Comparison

Group	BH:NS Mass Ratio	$(M/R)_{NS}$	EOS	Disk Mass
Illinois	1.0	0.145	$\Gamma = 2$	2.3%
Japan	1.5	–	–	2.3%
Japan	2.0	–	–	1.0%
Illinois	3.0	–	–	3.9%
Japan	–	–	–	Tiny
Japan	4.0	–	–	–
Illinois	5.0	–	–	–
Japan	–	–	–	–

- Discrepancy:
  - Total energy in disk: up to ~4% of NS mass → ~1% total E
    - E, J spuriously lost:
      - E: 0.01% Illinois, 1% Japan;
      - J: 1 – 2% Illinois, Japan

M_{BH}:M_{NS} Mass Ratio Study: Gravitational Wave Analysis





Solid lines: h_{+}, dash lines: $h_{\times}$

$r_{ex} = 30M - 80M$

Initial $M\Omega = 0.033$

Case	J_{BH}/M_{BH}^2	$M_{BH} : M_{NS}$	N_{orb}	M_{disk}/M_0
E	0.0	1:1	2.25	$\lesssim 2.3\%$
A	0.0	3:1	4.5	$\lesssim 3.9\%$
D	0.0	5:1	6.25	$\lesssim 0.8\%$

BHNS Evolutions: Illinois BH Spin Study

BH Spin Study

Case C:
3:1 Mass Ratio
Spin –0.5

Case A:
3:1 Mass Ratio
Spin 0.0

Case B:
3:1 Mass Ratio
Spin +0.75

BHNS Evolutions:
Illinois BH Spin Study

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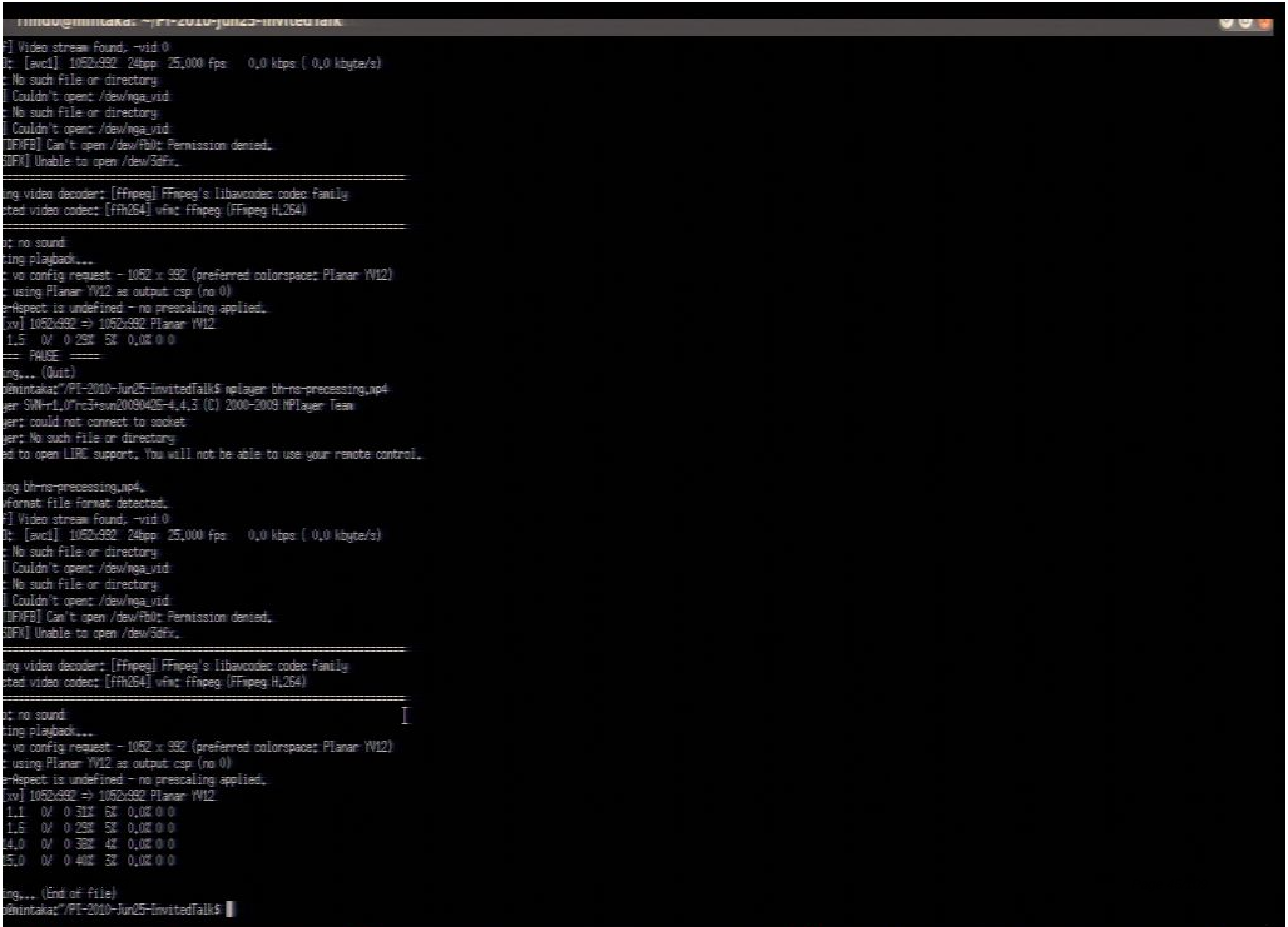

F] Video stream found, -vid 0
0: [avc1] 1052x992 24bpp 25.000 fps 0.0 kbps (0.0 kbyte/s)
: No such file or directory
] Couldn't open: /dev/mga_vid
: No such file or directory
] Couldn't open: /dev/mga_vid
TDFXFB] Can't open /dev/fb0: Permission denied.
3DFX] Unable to open /dev/3dfx.
ing video decoder: [ffmpeg] FFmpeg's libavcodec codec family
cted video codec: [ffh264] vfm: ffmpeg (FFmpeg H.264)
o: no sound
ting playback...
: vo config request - 1052 x 992 (preferred colorspace: Planar YV12)
: using Planar YV12 as output csp (no 0)
e-Aspect is undefined - no prescaling applied.
[xv] 1052x992 => 1052x992 Planar YV12
1.5 0/ 0 29% 5% 0.0% 0 0
=== PAUSE ====
ing... (Quit)
@mintaka:~/PI-2010-Jun25-InvitedTalk$ mplayer bh-ns-precessing.mp4
yer SVN-r1.0~rc3+svn20090426-4.4.3 (C) 2000-2009 MPlayer Team
yer: could not connect to socket
yer: No such file or directory
ed to open LIRC support. You will not be able to use your remote control.
ing bh-ns-precessing.mp4.
format file format detected.
F] Video stream found, -vid 0
0: [avc1] 1052x992 24bpp 25.000 fps 0.0 kbps (0.0 kbyte/s)
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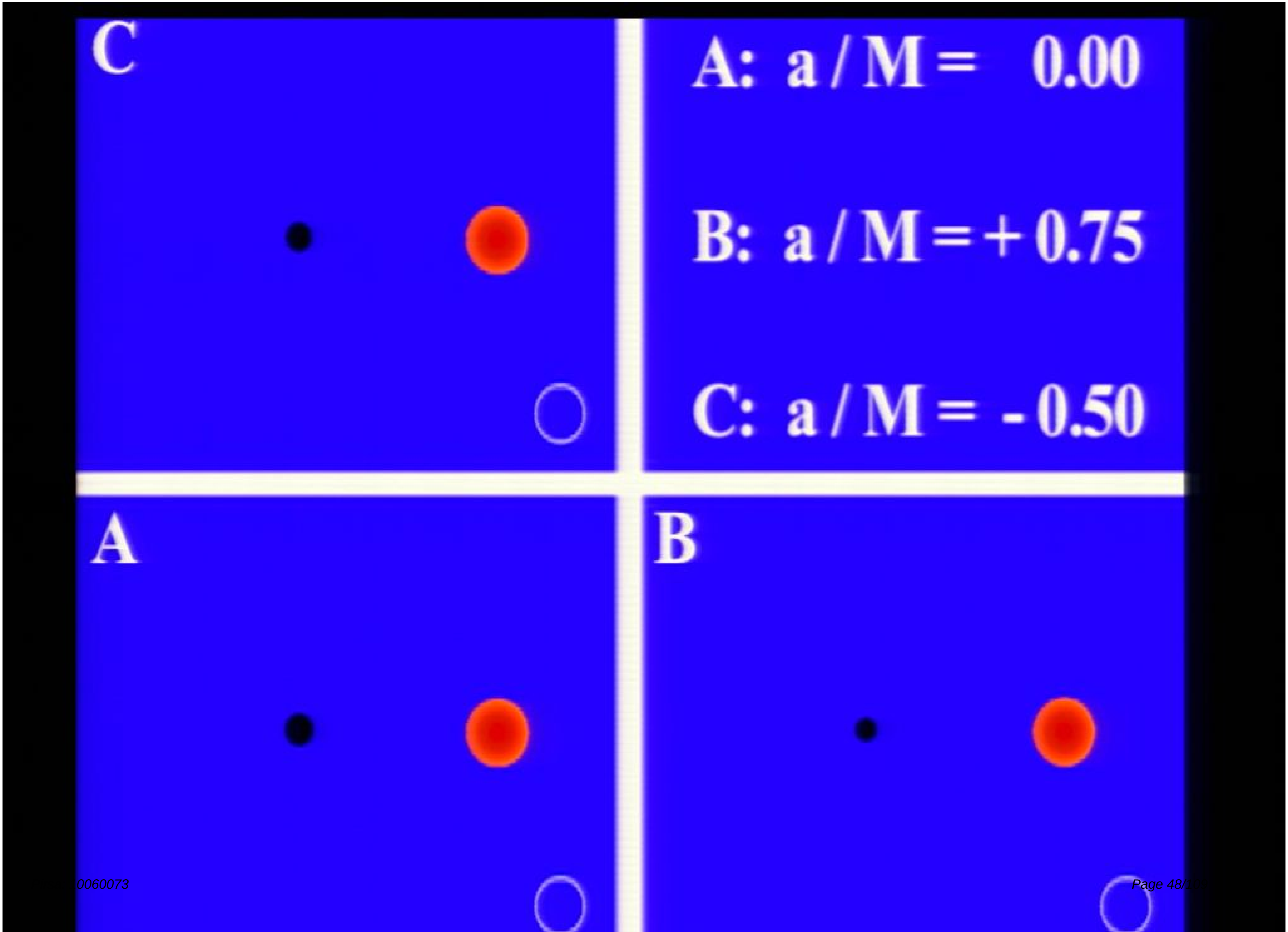
1.1 0/ 0 31% 6% 0.0% 0 0
1.6 0/ 0 29% 5% 0.0% 0 0
14.0 0/ 0 38% 4% 0.0% 0 0
15.0 0/ 0 40% 3% 0.0% 0 0
ing... (End of file)
@mintaka:~/PI-2010-Jun25-InvitedTalk$

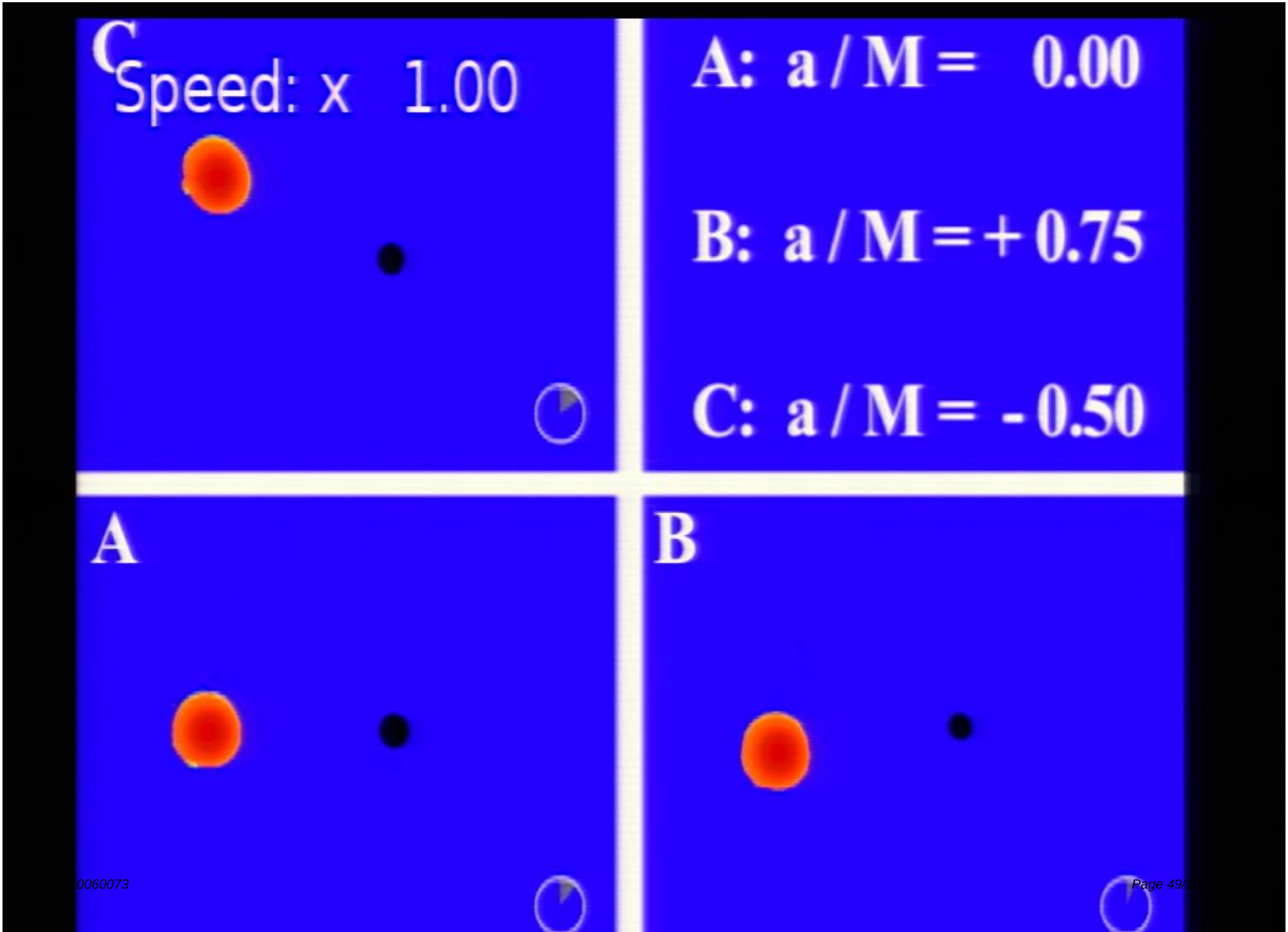
Initial Black Hole Spin:

$$a / M = J_{BH} / M_{BH}^2$$

$$(q = 3.00)$$

[redacted]


C
A: a / M = 0.00
B: a / M = + 0.75
C: a / M = - 0.50
A
B


C
Speed: x 1.00
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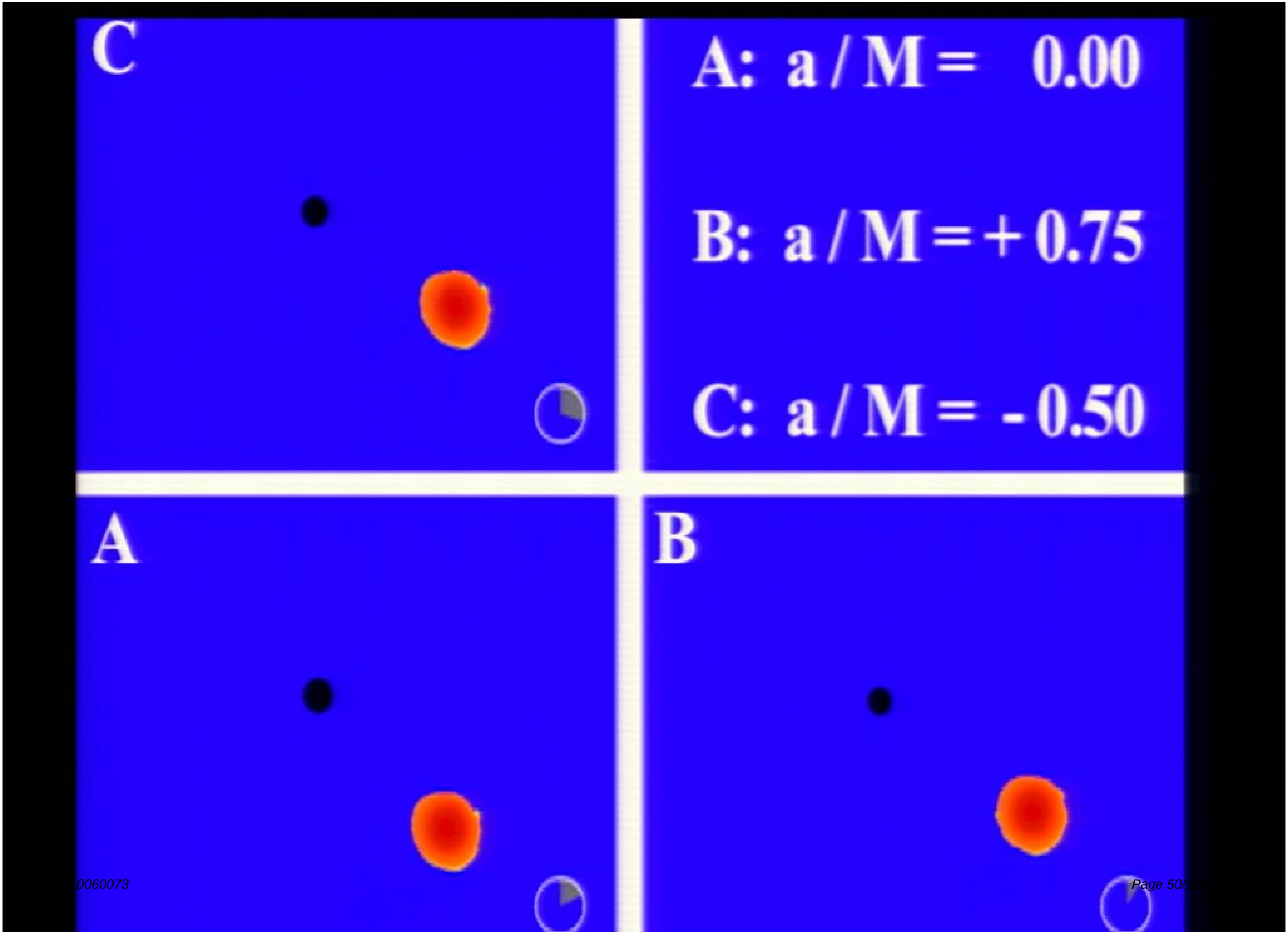
A
B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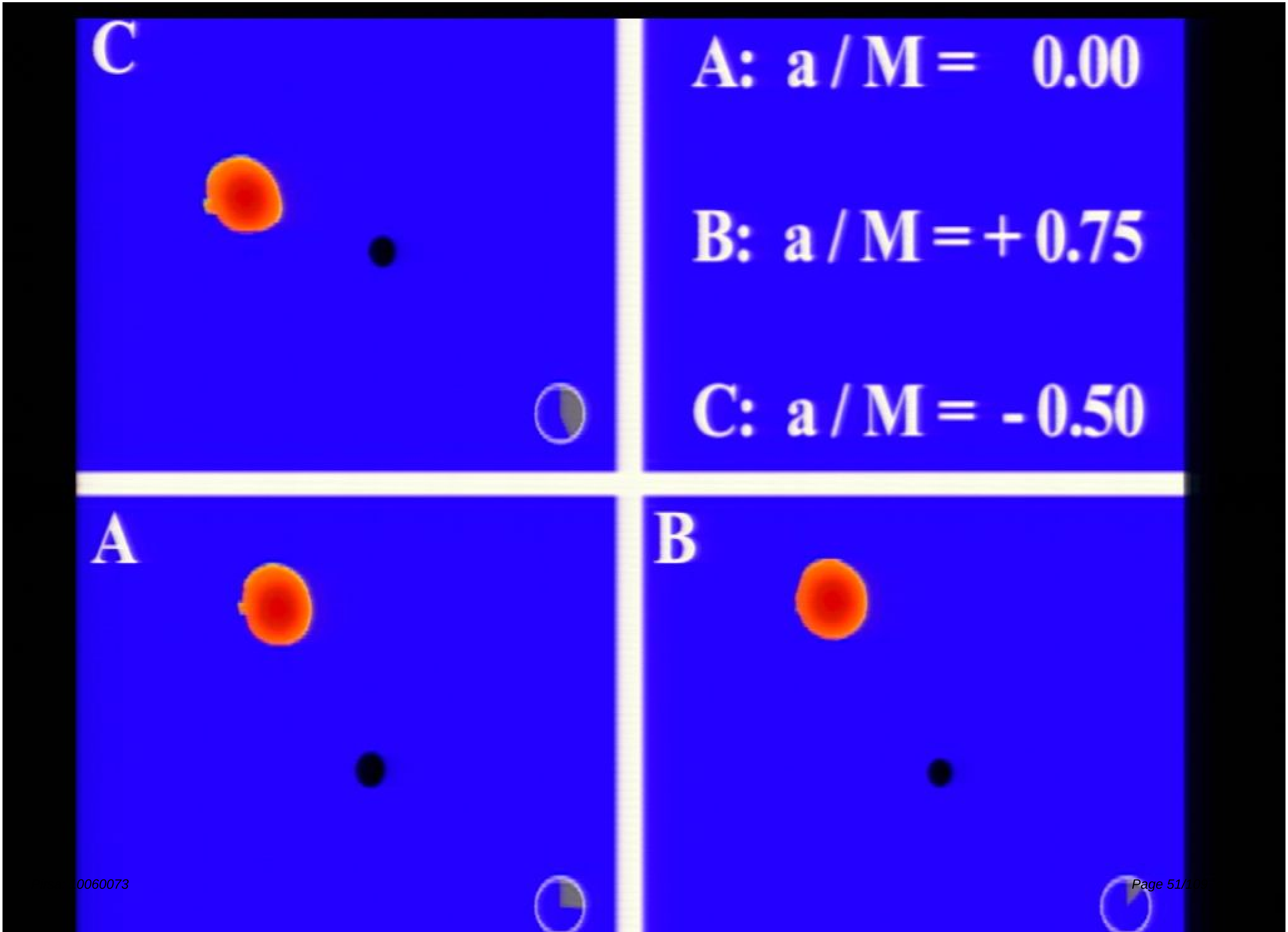
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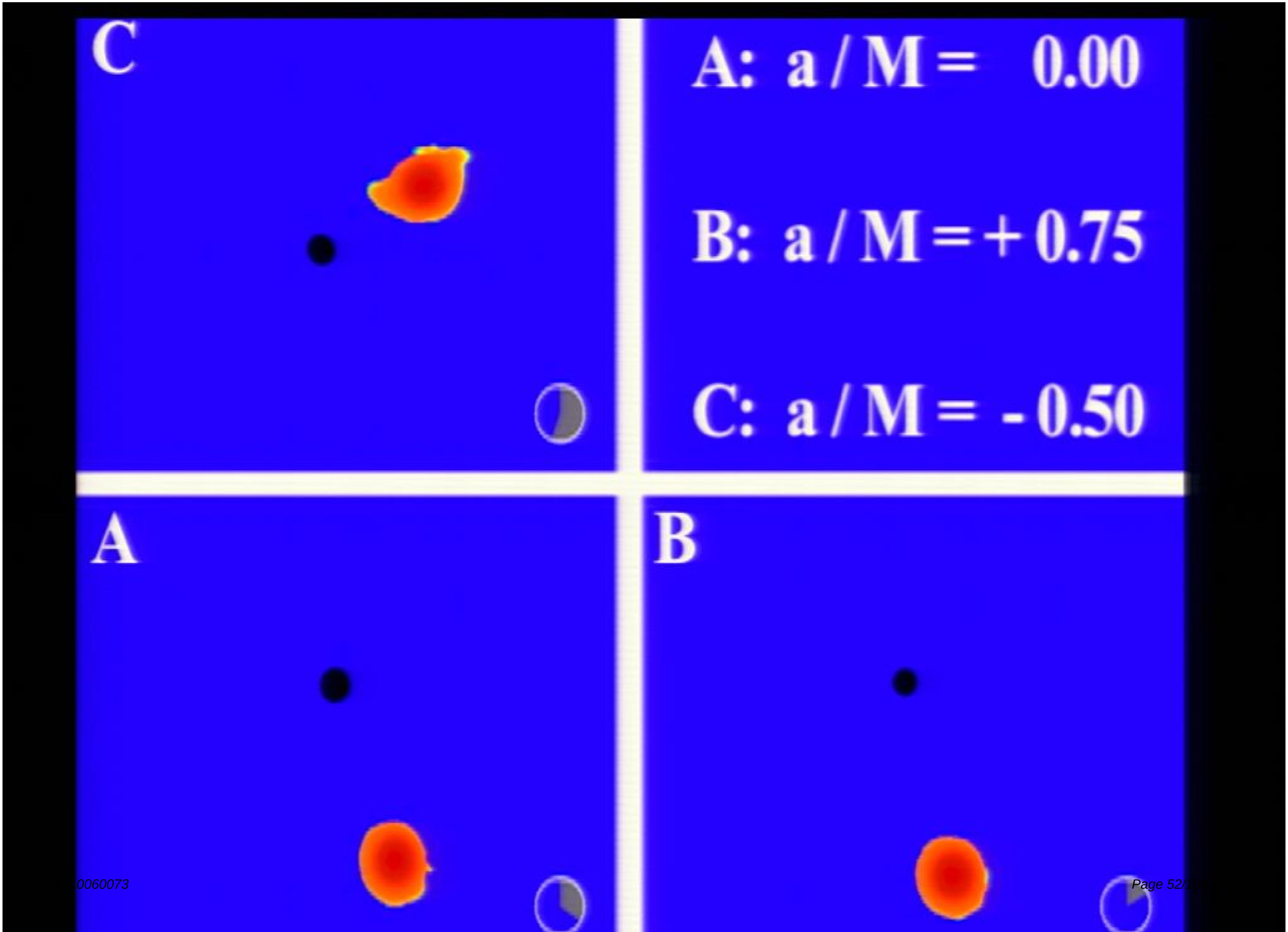
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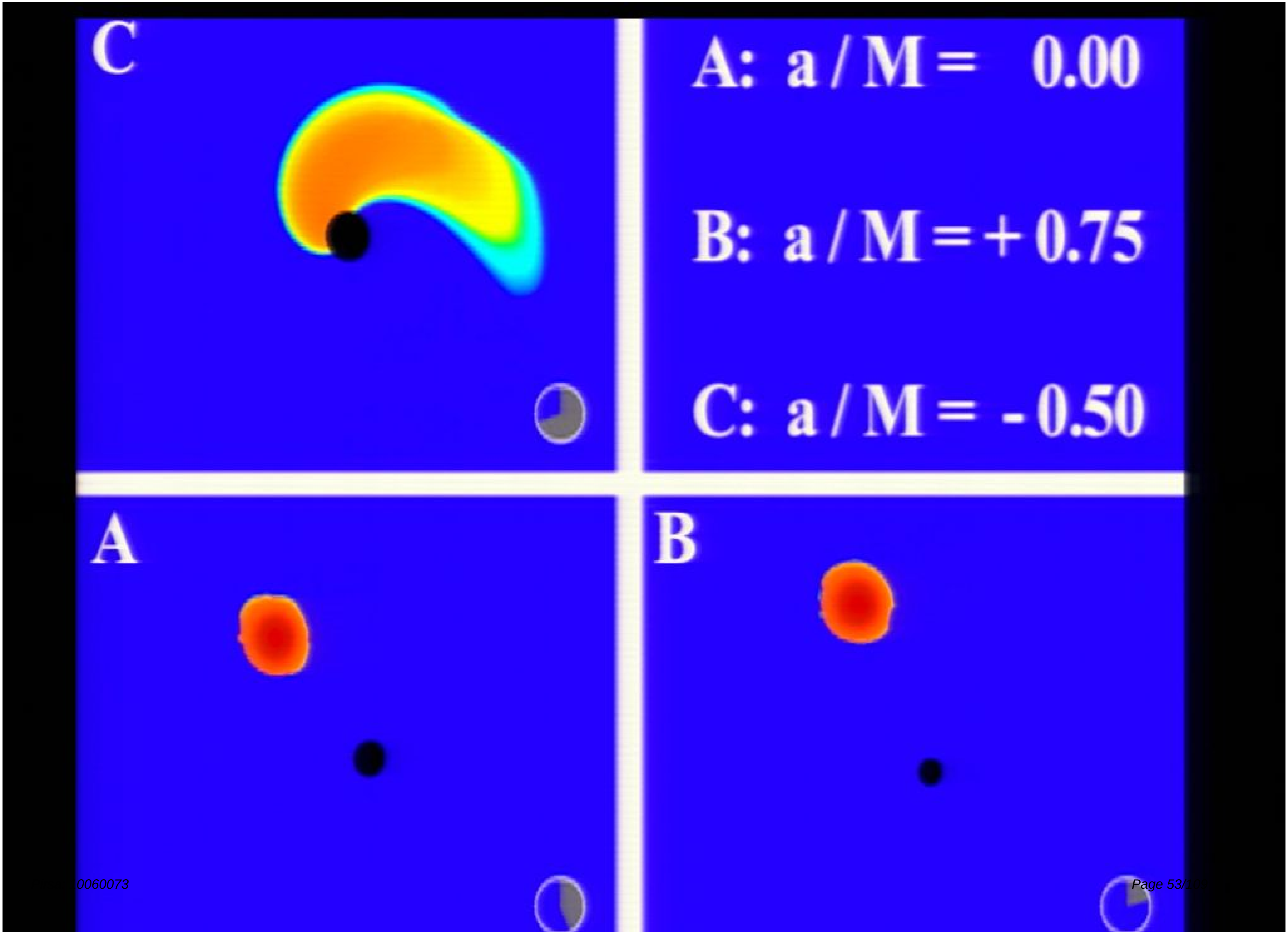
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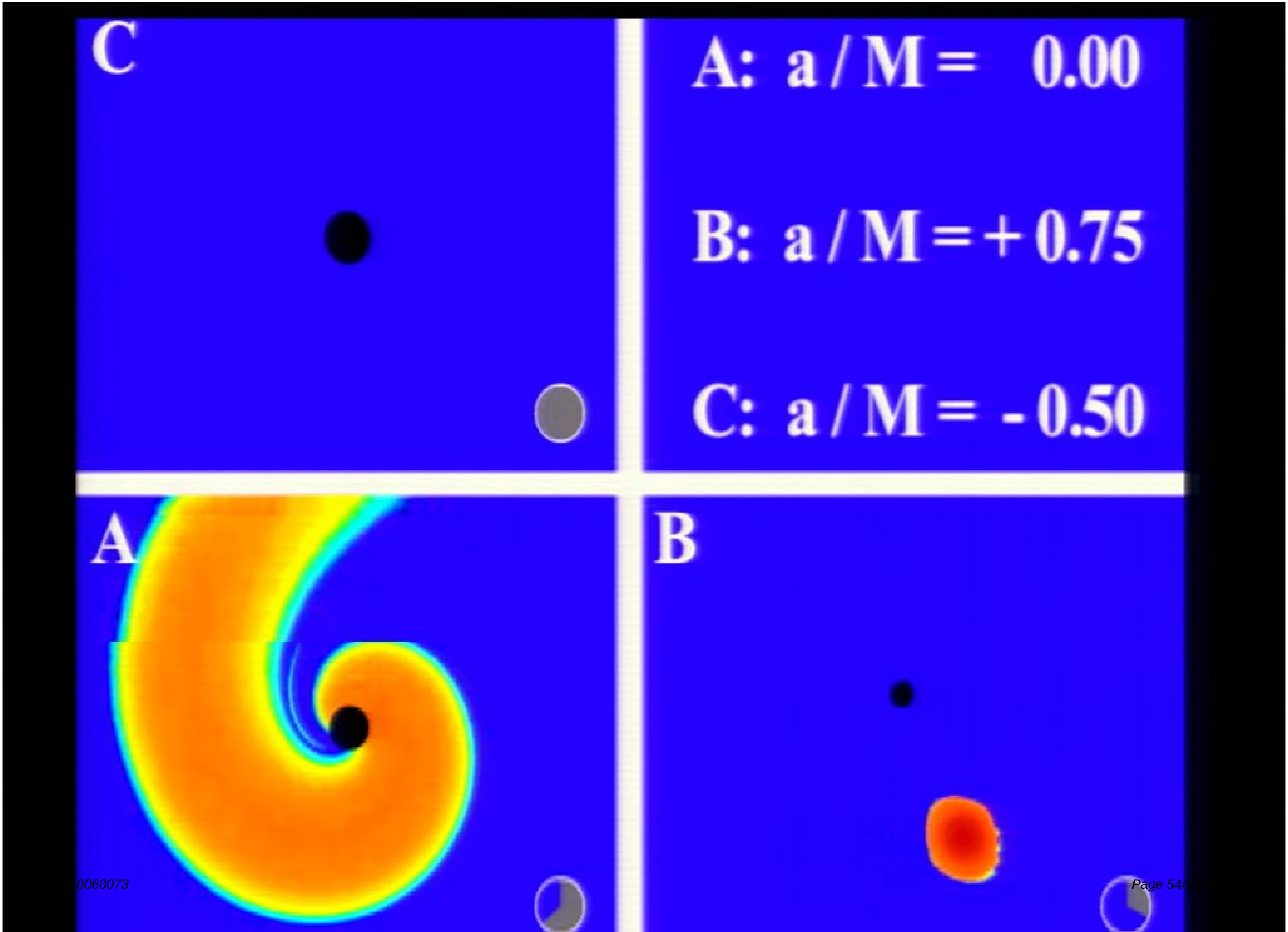
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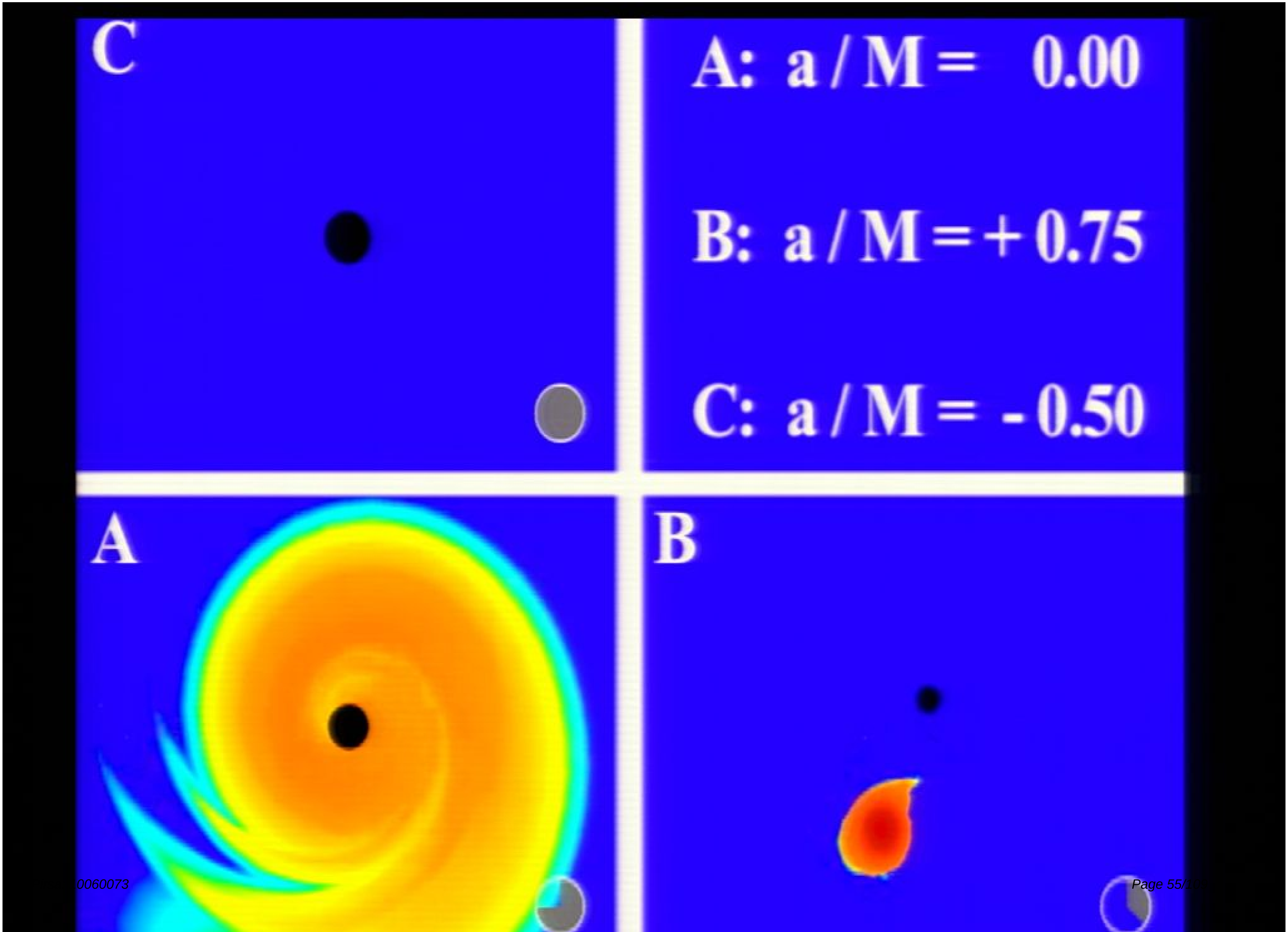
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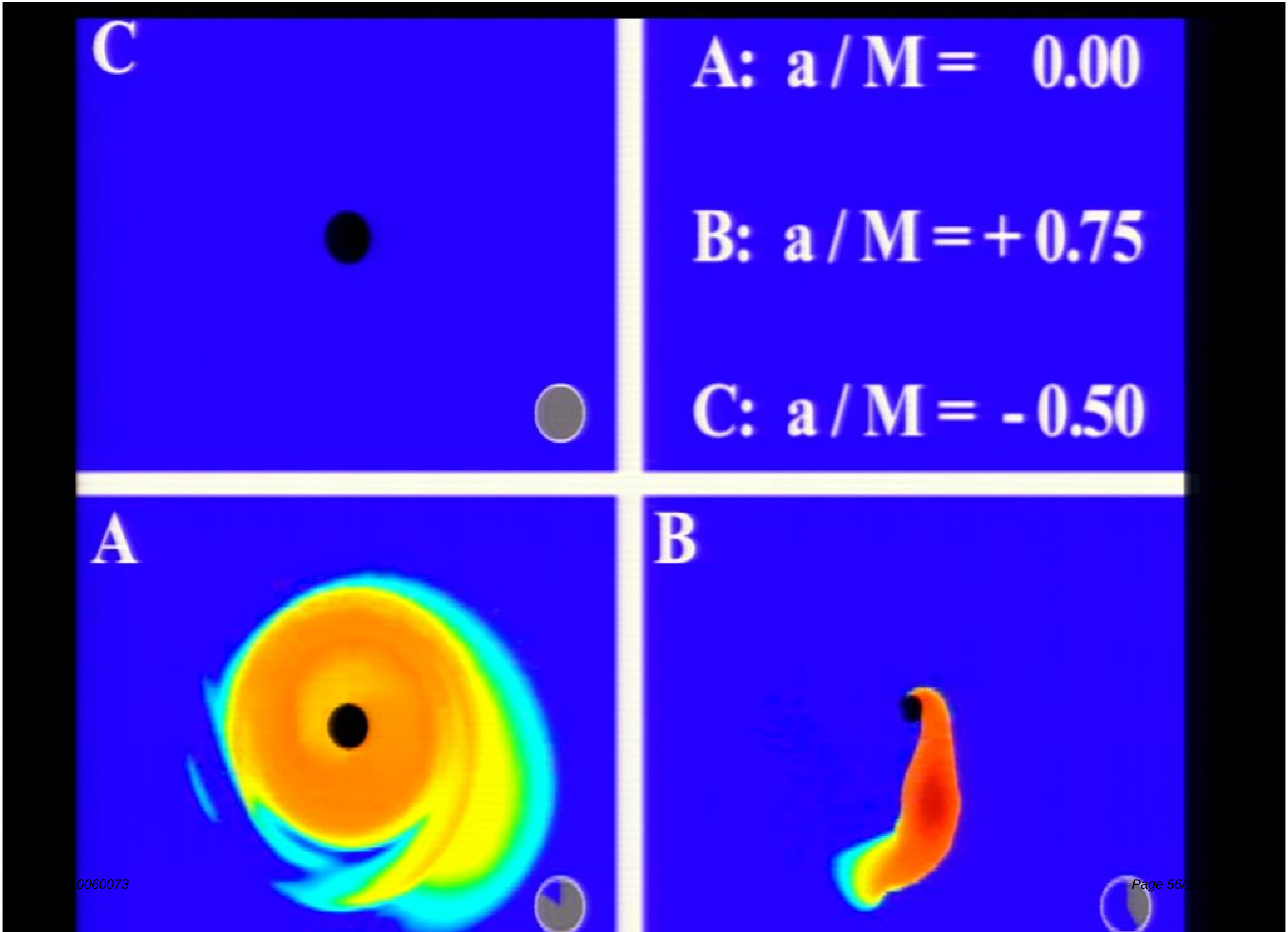
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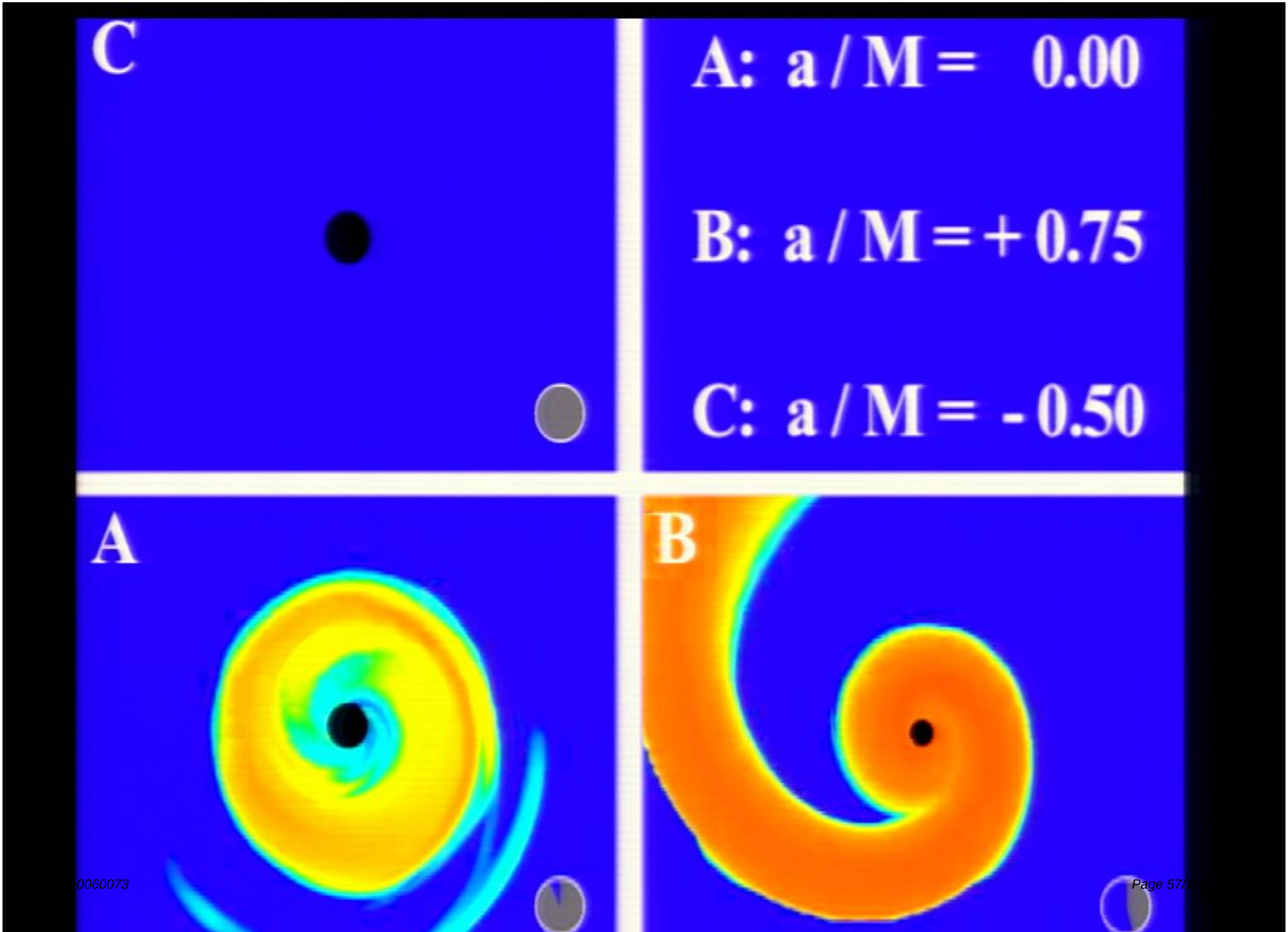
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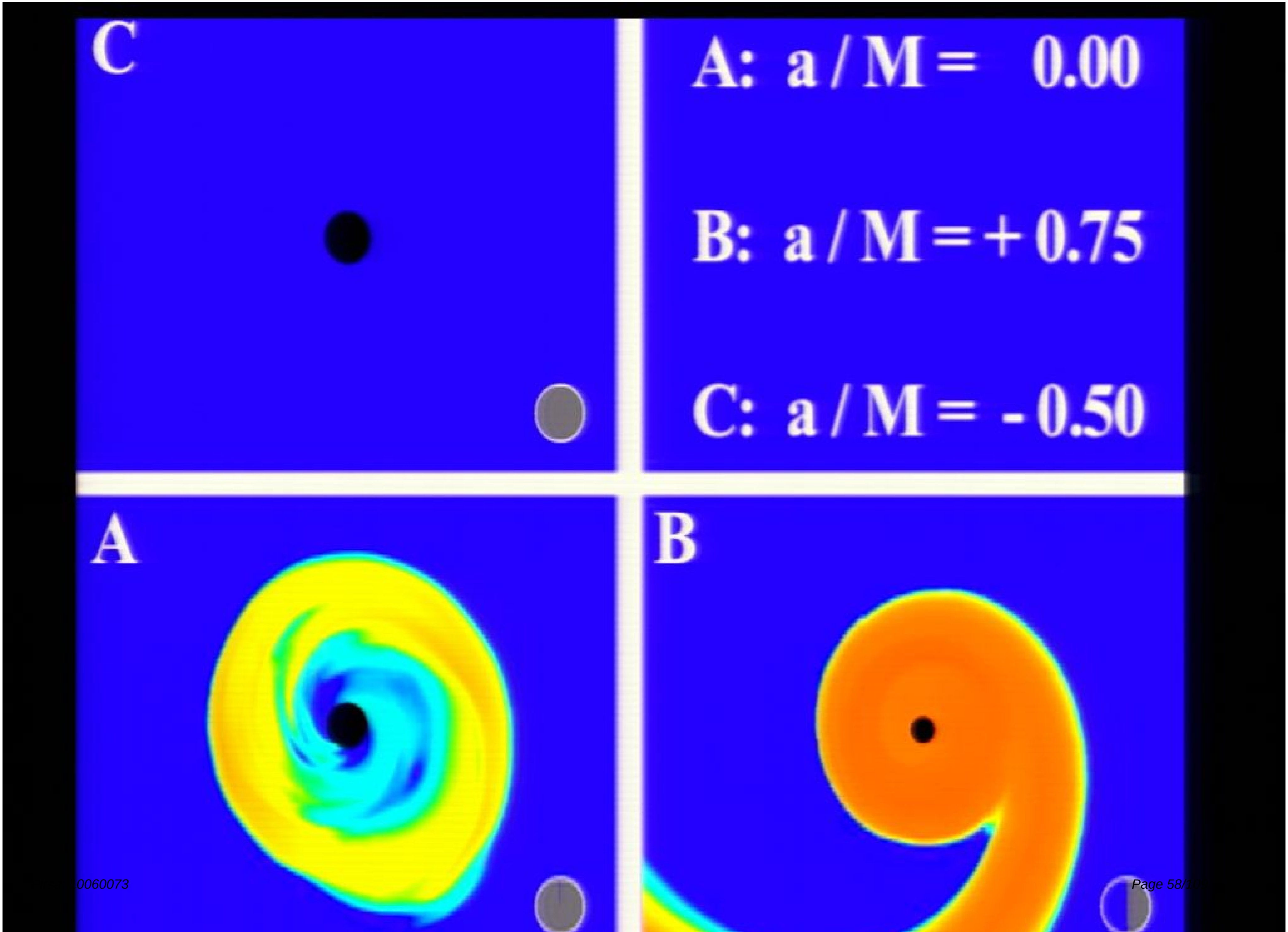
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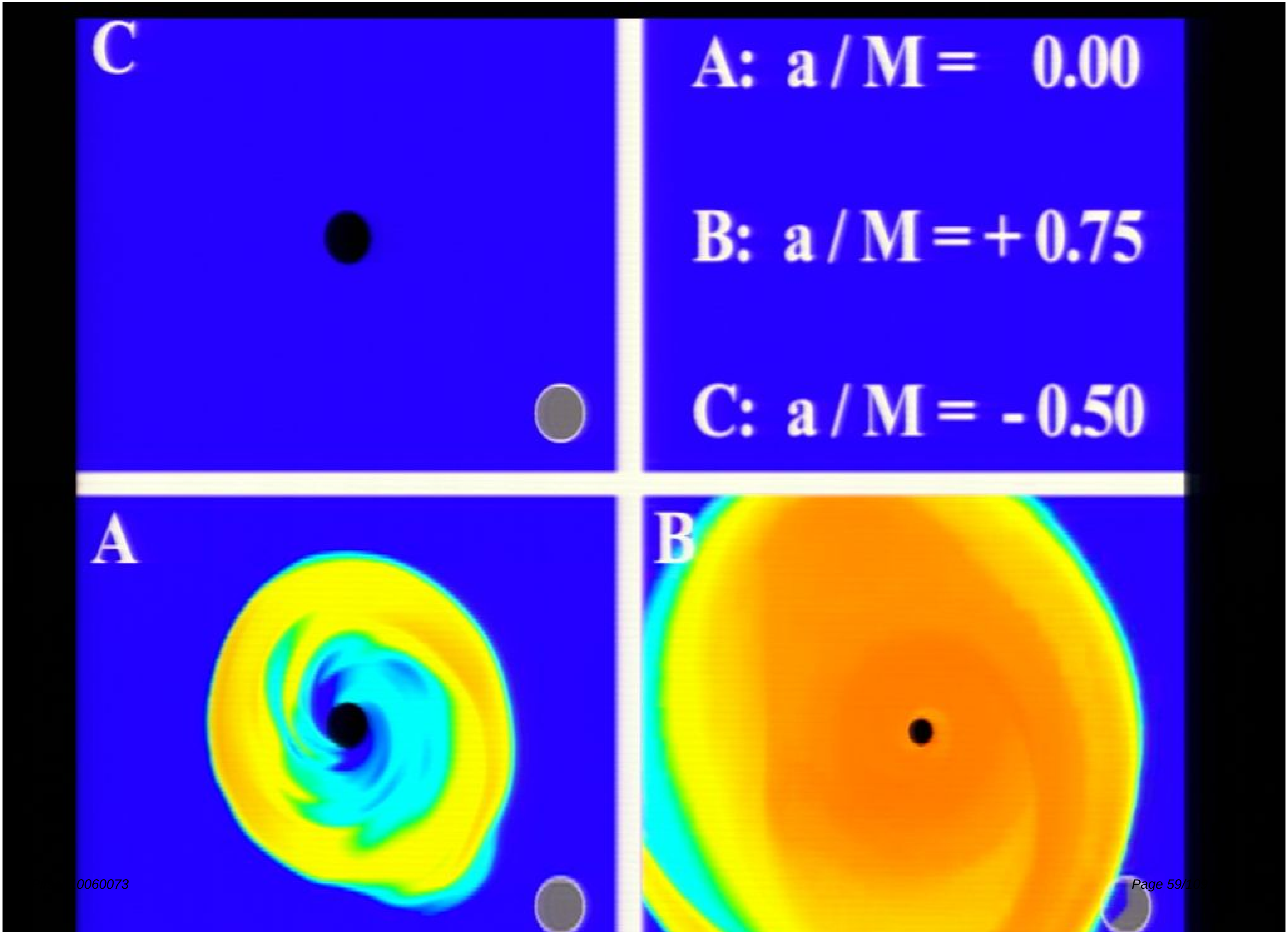
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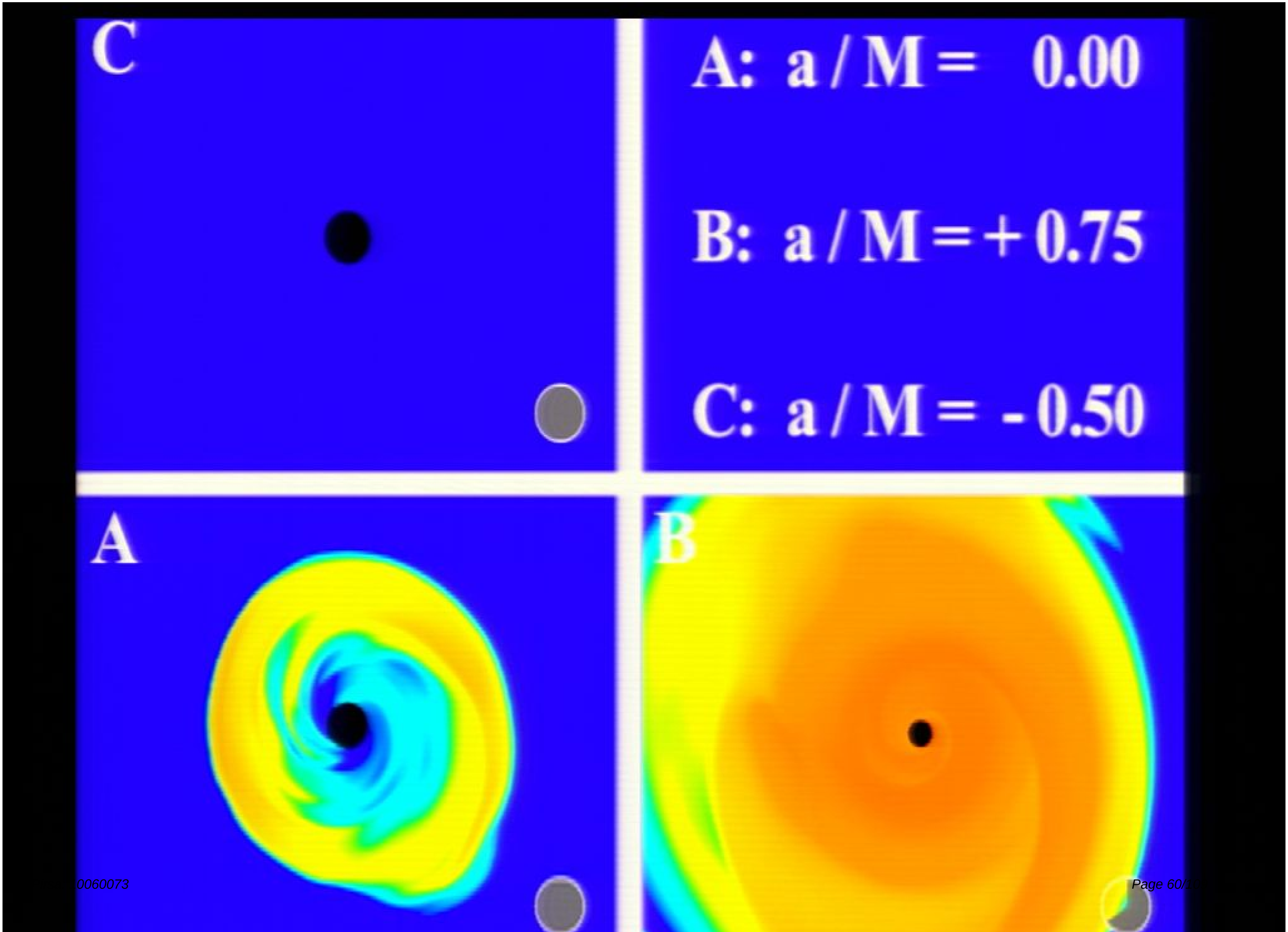
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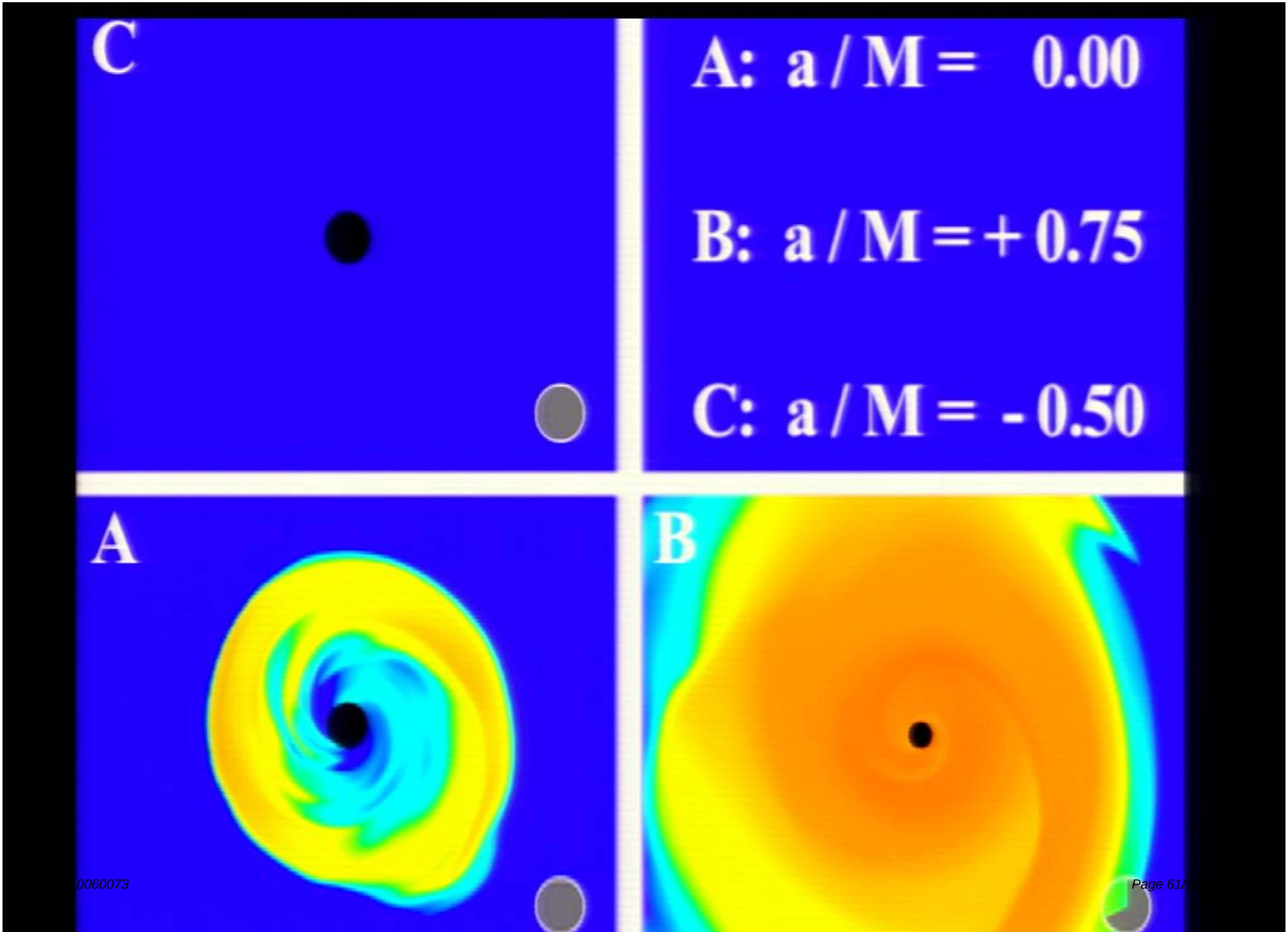
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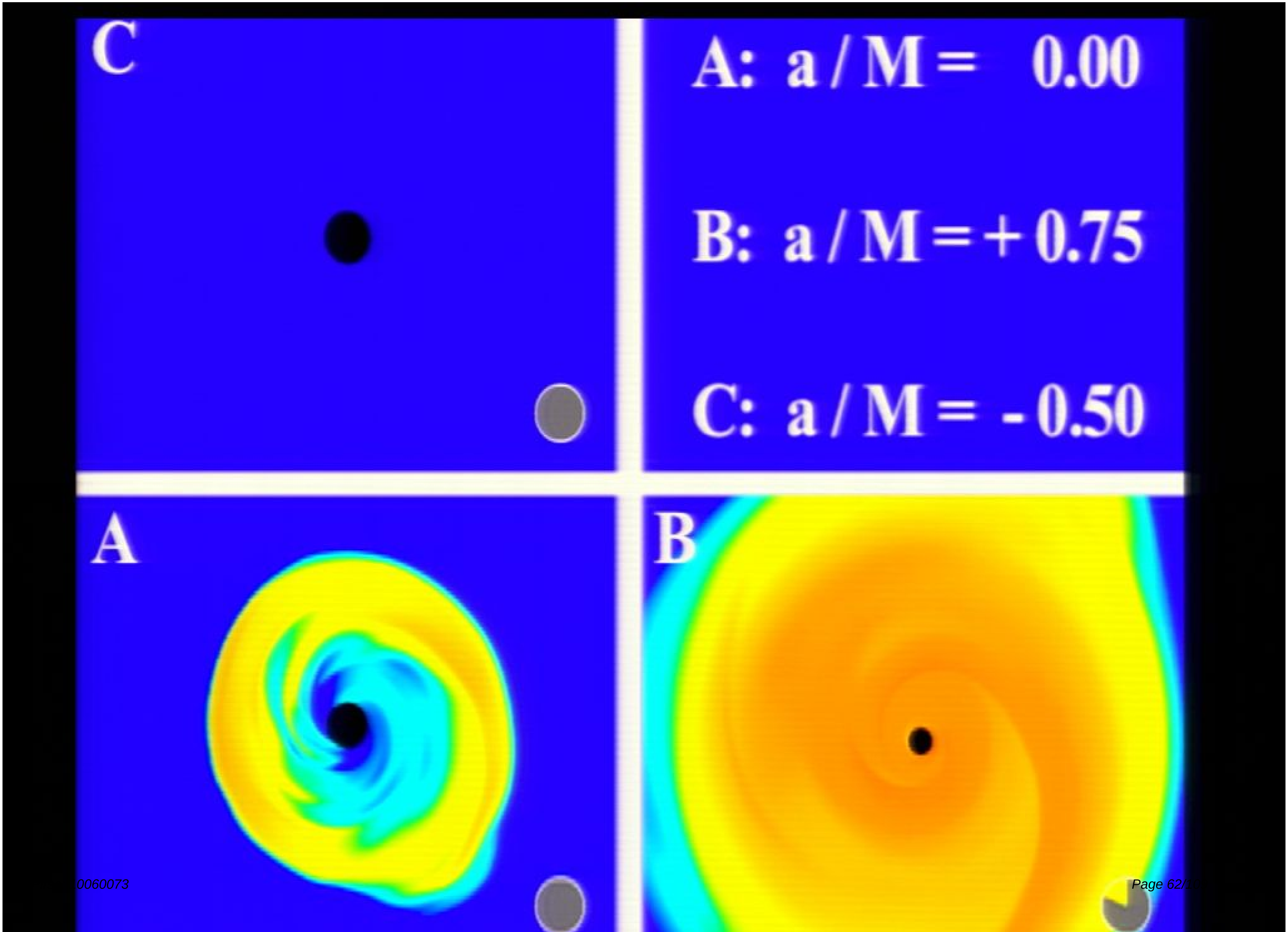
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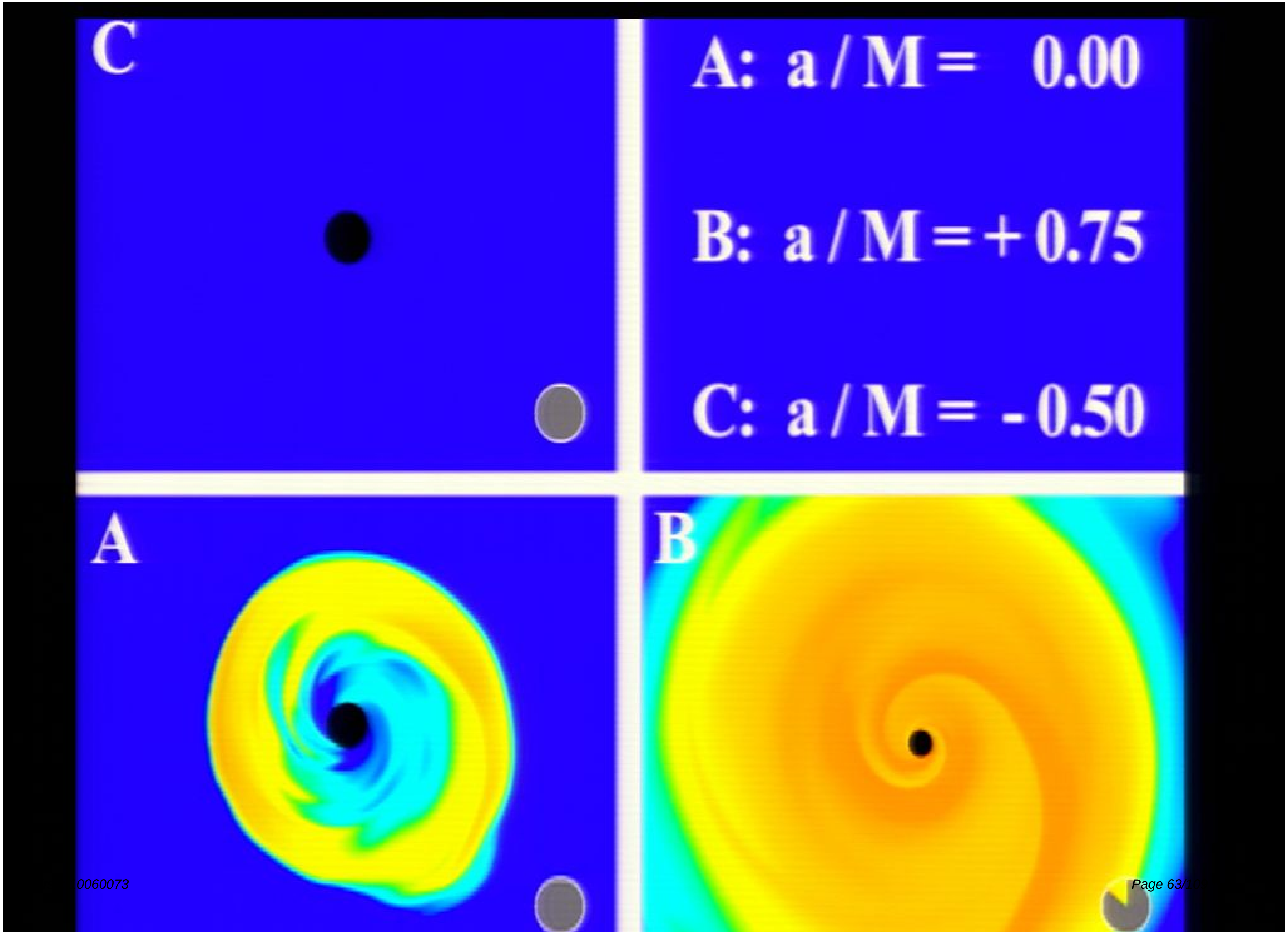
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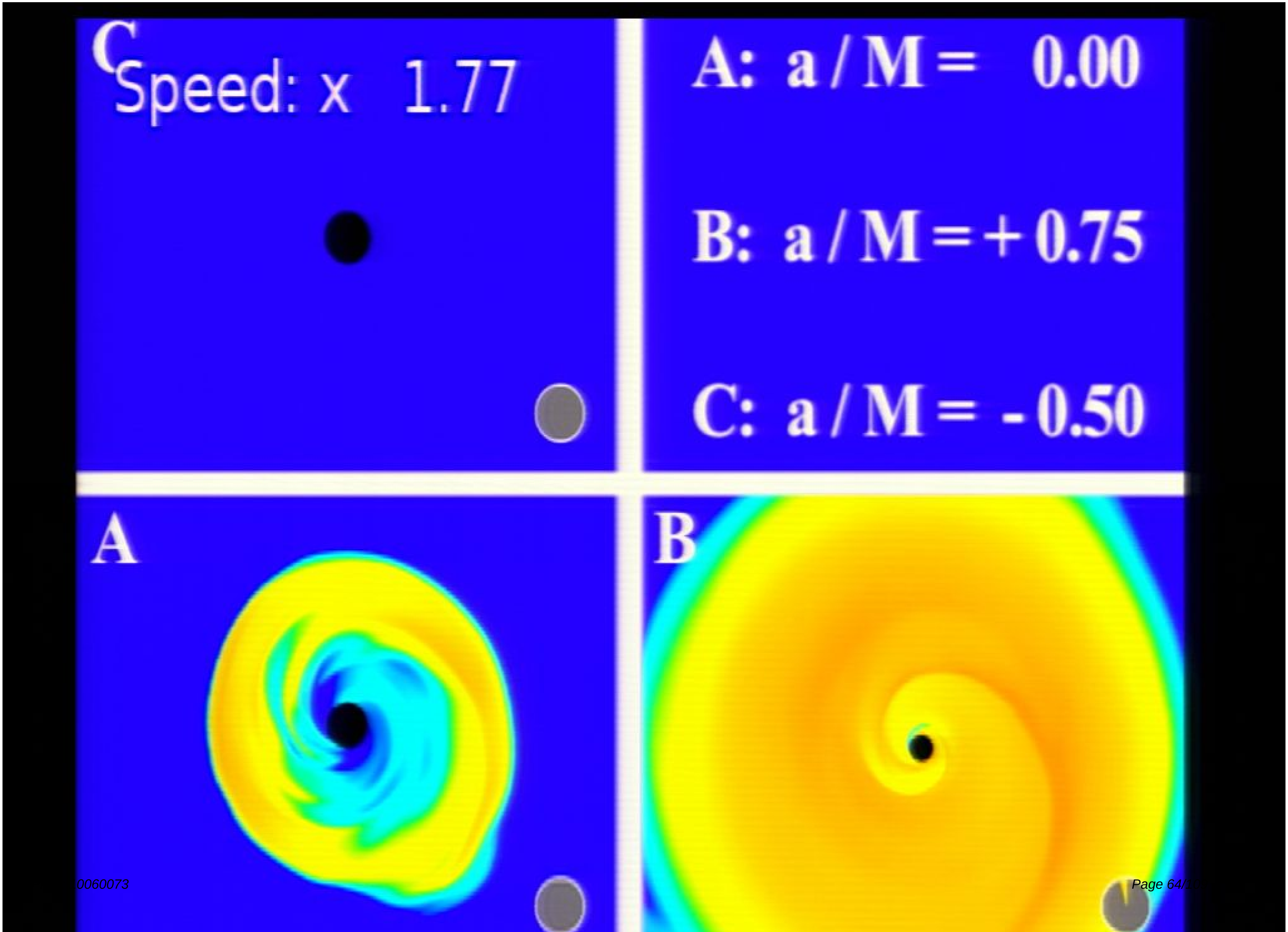
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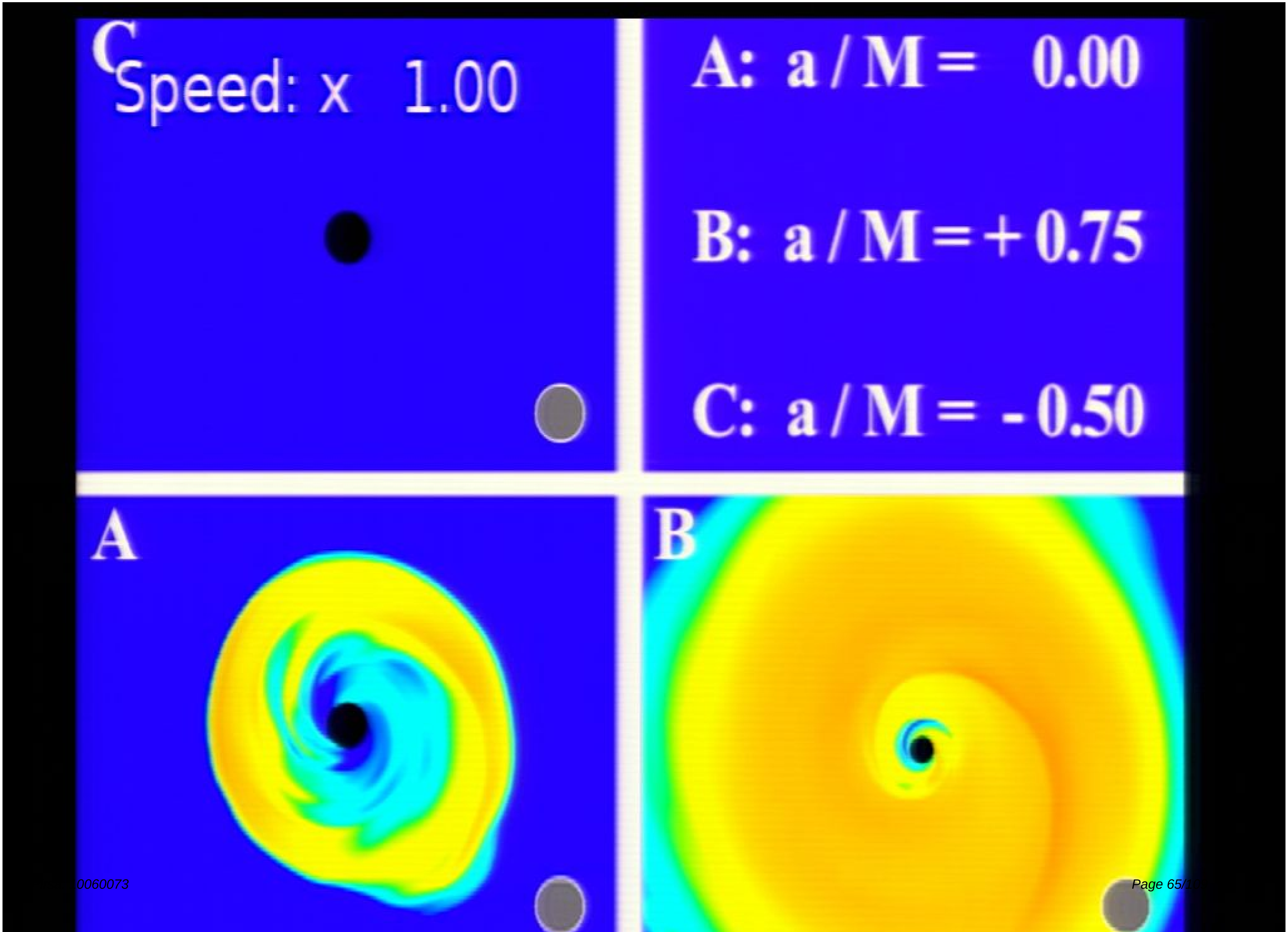
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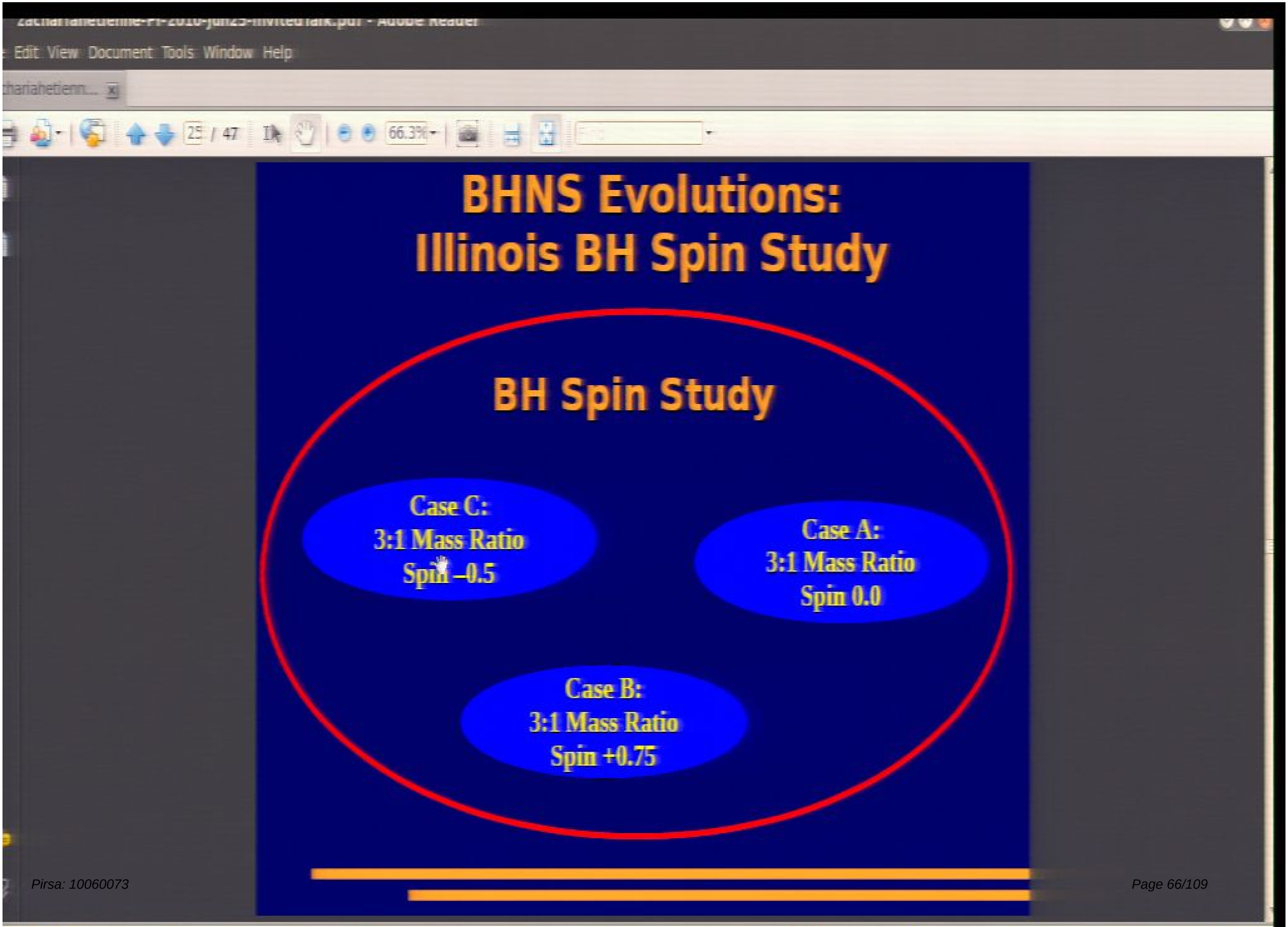

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BHNS Evolutions:
Illinois BH Spin Study
BH Spin Study
Case C:
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Spin –0.5
Case A:
3:1 Mass Ratio
Spin 0.0
Case B:
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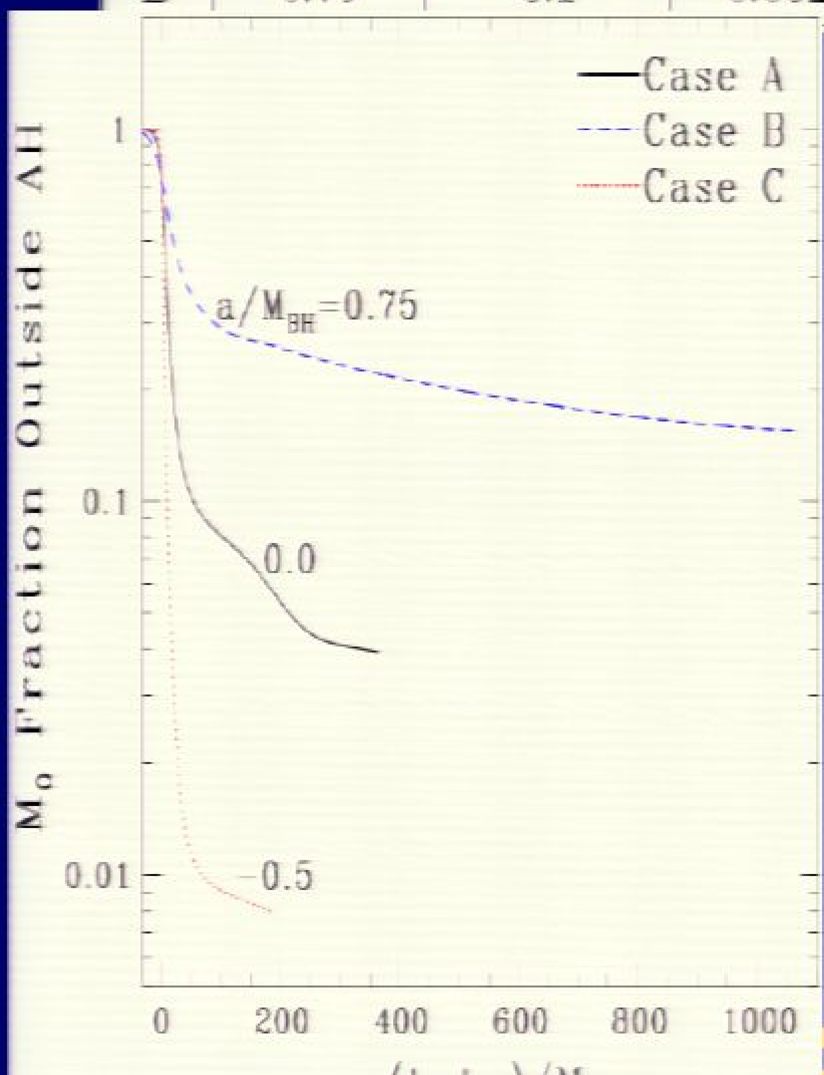
Spin +0.75

Vary BH Spin: Accretion History

Case	J_{BH}/M_{BH}^2	$M_{BH}:M_{NS}$	$M\Omega(t=0)$	N_{orb}	M_{disk}/M_0
C	-0.50	3:1	0.0338	3.25	$\lesssim 0.8\%$
A	0.00	3:1	0.0333	4.5	$\lesssim 3.9\%$
B	0.75	3:1	0.0328	6.5	$\lesssim 15\%$

SGRB?



$$a/M_{BH} = J_{BH}/M_{BH}^2$$

EOS vs. Disk Mass, waveform effects Cornell Results

Group	BH:NS Mass Ratio	$(M/R)_{NS}$	EOS	BH Spin	Disk Mass
Cornell	3.0	0.146	$\Gamma = 2.0$	0.5	8%
–	–	0.147	Shen ("realistic")	–	7%
–	–	0.144	$\Gamma = 2.75$	–	13%

- Gamma=2.75: Huge tidal tail → Larger disk
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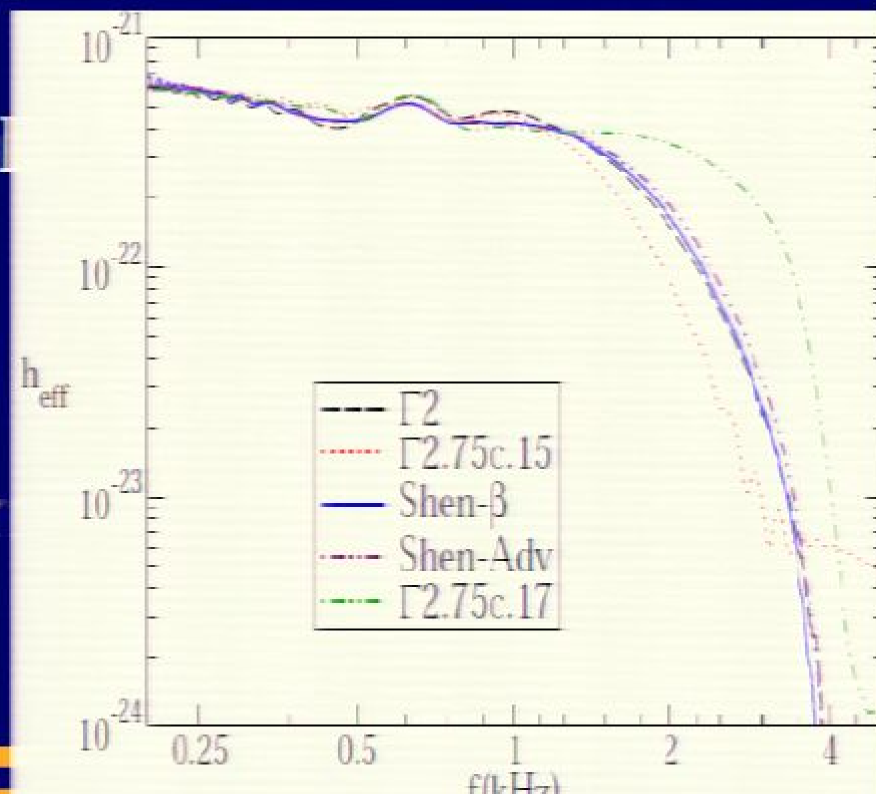
  - → similar disk mass



NS Compaction vs. Disk Mass
Multi-Group Comparison

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–	–	0.173	–	–	2%
Japan	2.0	0.145	$\Gamma = 2.0$	0.0	1.0%
–	–	0.160	–	–	0.06%
–	–	0.178	–	–	Tiny

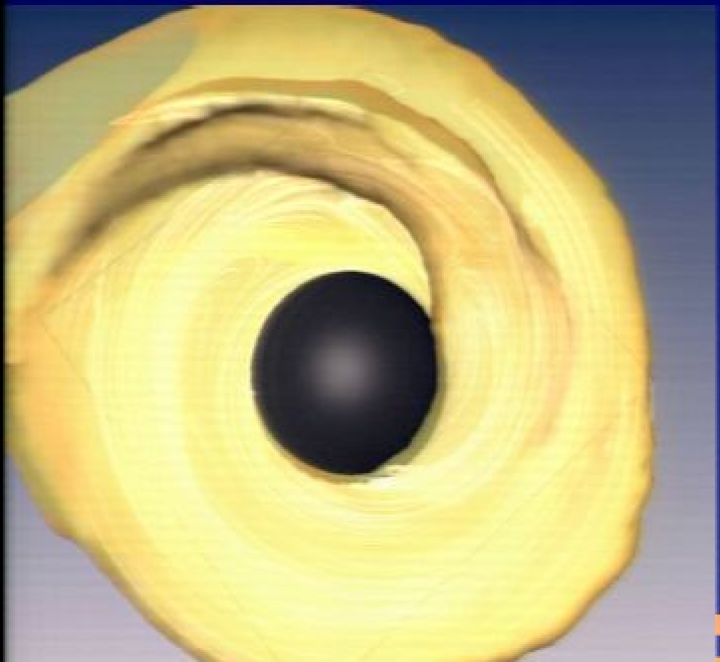
Final disk mass strongly dependent on NS compaction

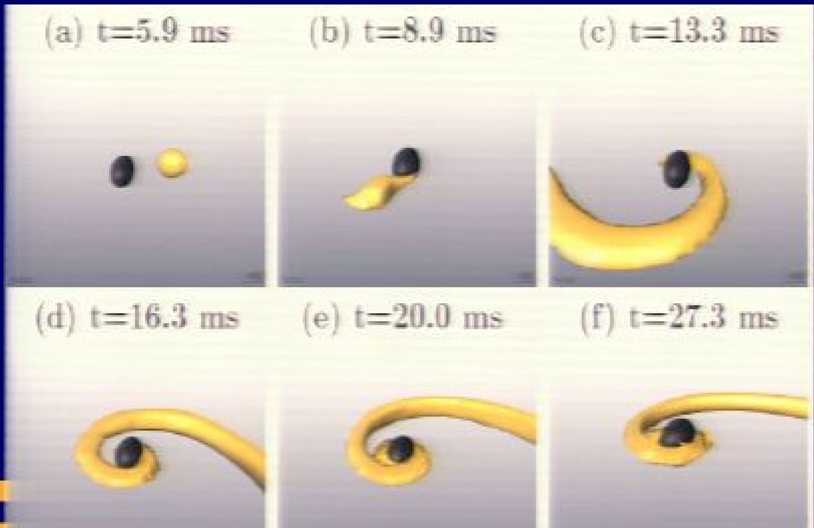
Higher compaction, lower disk → Closer to BHBH

Effects of Magnetized NS Chawla et al. Results (LSU,BYU,IU,PI,UG,ULI)

BH:NS Mass Ratio	$(M/R)_{NS}$	EOS	BH Spin	$\max(\lvert\mathbf{B}\rvert_{\text{Initial}})$	Disk Mass (end of sim.)
5.0	0.1	$\Gamma = 2.0$	0.5	0	7%
–	–	–	–	10^{12} G	7%

- No significant effect from B field





Future Directions

- Incorporate more physics to better model disk; Can BHNSs produce GRBs?
  - Neutrino radiation
  - EM radiation
- Improve software
  - Long-term disk evolution: implicit timestepping scheme?
  - Work to better understand discrepancies between codes
    - *Need an Apple-to-Apples code validation test for GRMHD!*

Fin

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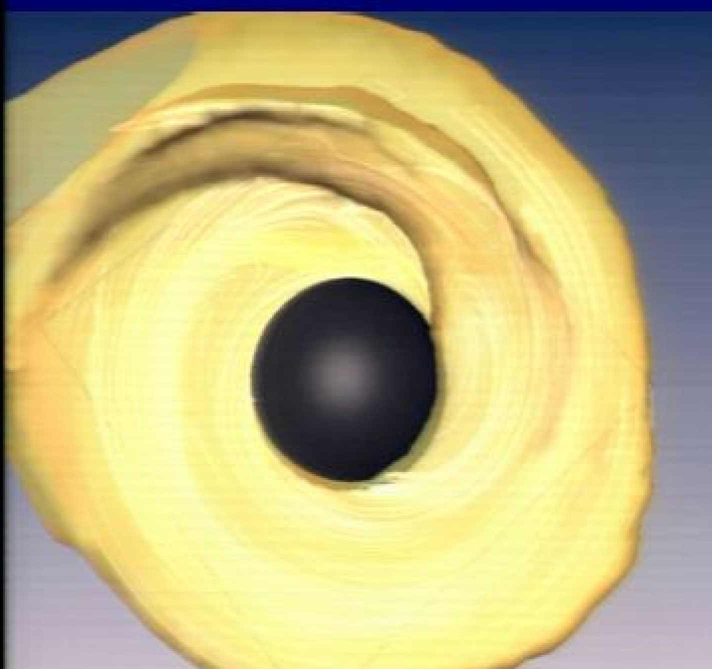

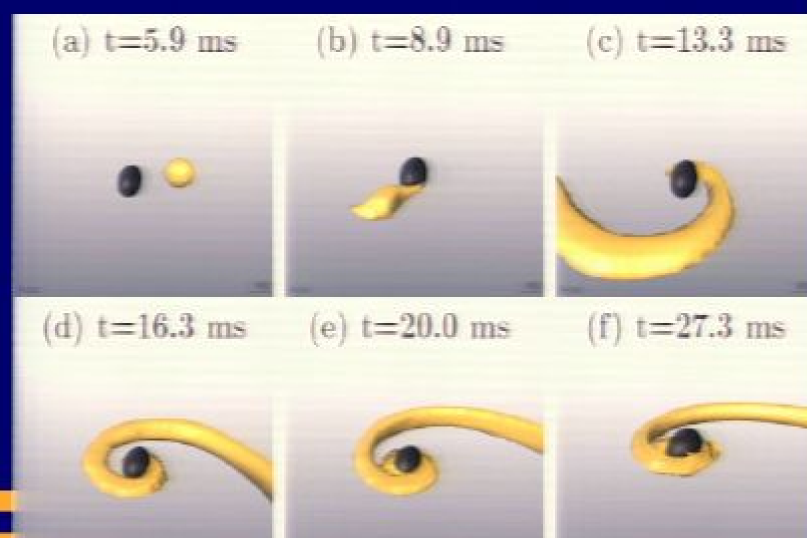

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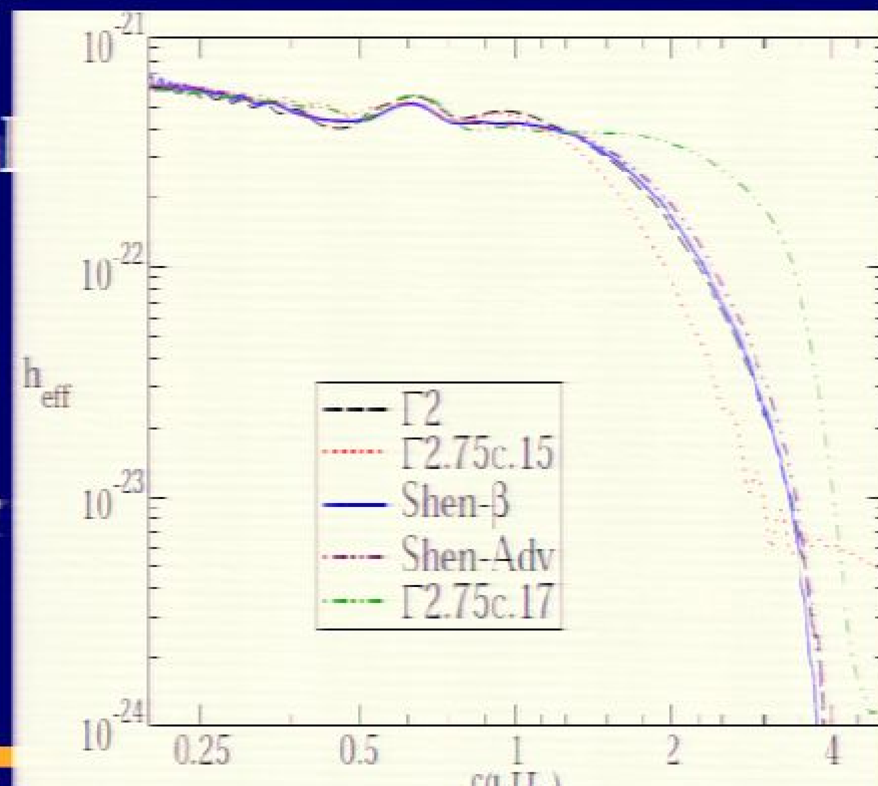

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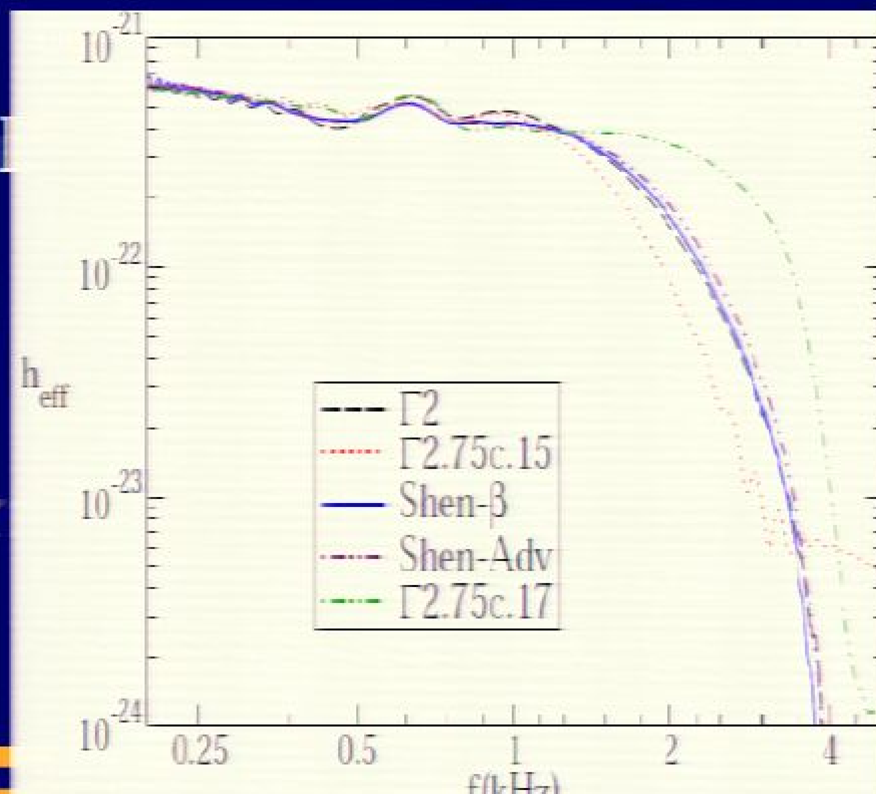
EOS vs. Disk Mass, waveform effects
Cornell Results

Group	BH:NS Mass Ratio	$(M/R)_{NS}$	EOS	BH Spin	Disk Mass
Cornell	3.0	0.146	$\Gamma = 2.0$	0.5	8%
–	–	0.147	Shen ("realistic")	–	7%
–	–	0.144	$\Gamma = 2.75$	–	13%

- Gamma=2.75: Huge tidal tail → Larger disk
- Nuclear-theory-based Shen EOS similar to Gamma=2 EOS in lower density NS regions
  - → similar disk mass

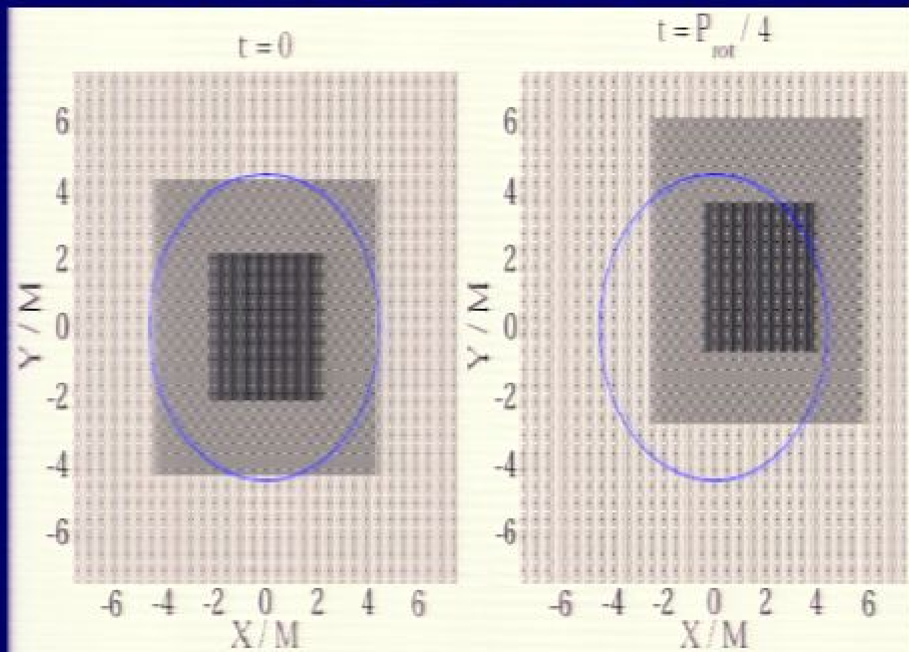


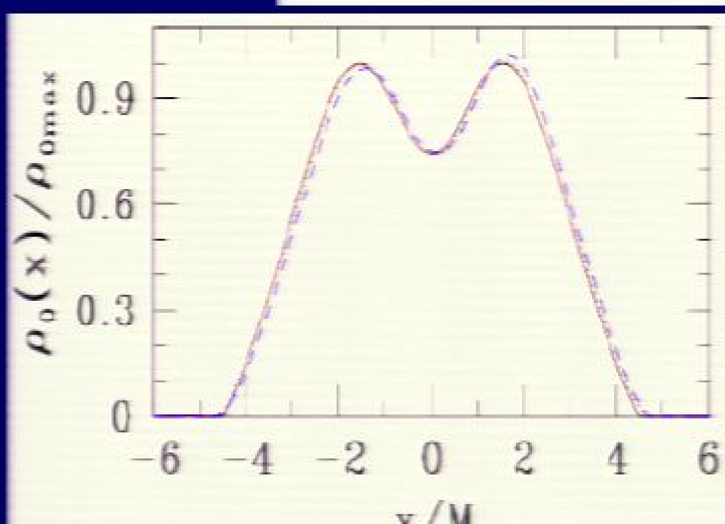
Future Directions

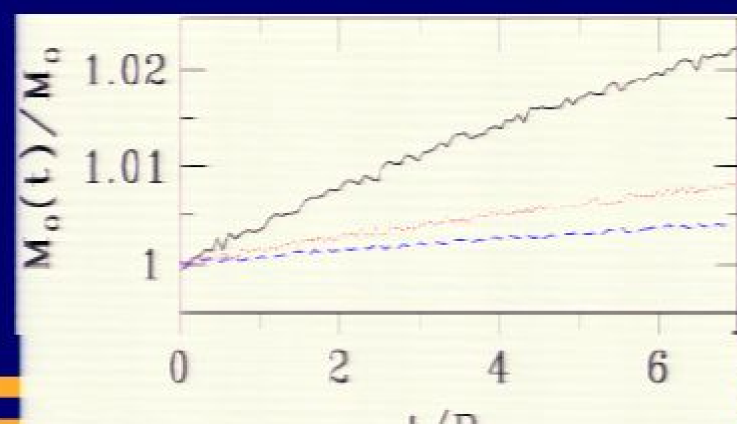
- Incorporate more physics to better model disk; Can BHNSs produce GRBs?
  - Neutrino radiation
  - EM radiation
- Improve software
  - Long-term disk evolution: implicit timestepping scheme?
  - Work to better understand discrepancies between codes
    - *Need an Apple-to-Apples code validation test for GRMHD!*

Illinois AMR Code Tests, Part II: AMR+Matter

- Equil., rapidly rotating star maintains equilibrium, many rotation periods
- Rest-mass violation error converges to zero @ >2^{nd} order, <1%







Have BHNS Initial Data
Next Step: Evolve!

- Basic Equations
  - Gravitational fields $G^{\mu\nu} = 8\pi T^{\mu\nu}$
    - Generalized Harmonic formalism
      - Cornell, Chawla et al
    - BSSN (Baumgarte-Shapiro Shibata-Nakamura) formalism
      - Illinois, Japan
  - Fluids
    - General Relativistic Hydrodynamics
    - Magnetic fields added (MHD approximation)
      - Chawla et al
      - Illinois (*in progress*)

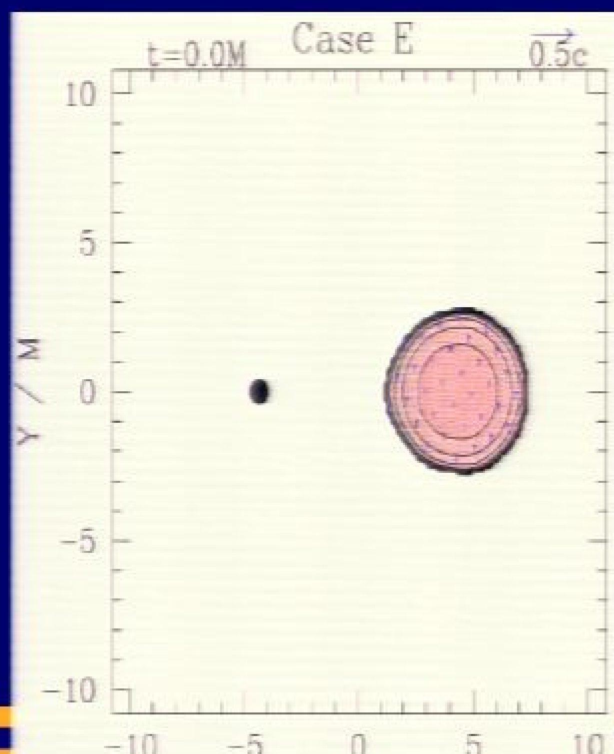
BHNS Initial Data

Conformal Thin-Sandwich

- Chawla et al.
- Cornell
- Illinois

Puncture

- Japan



BH

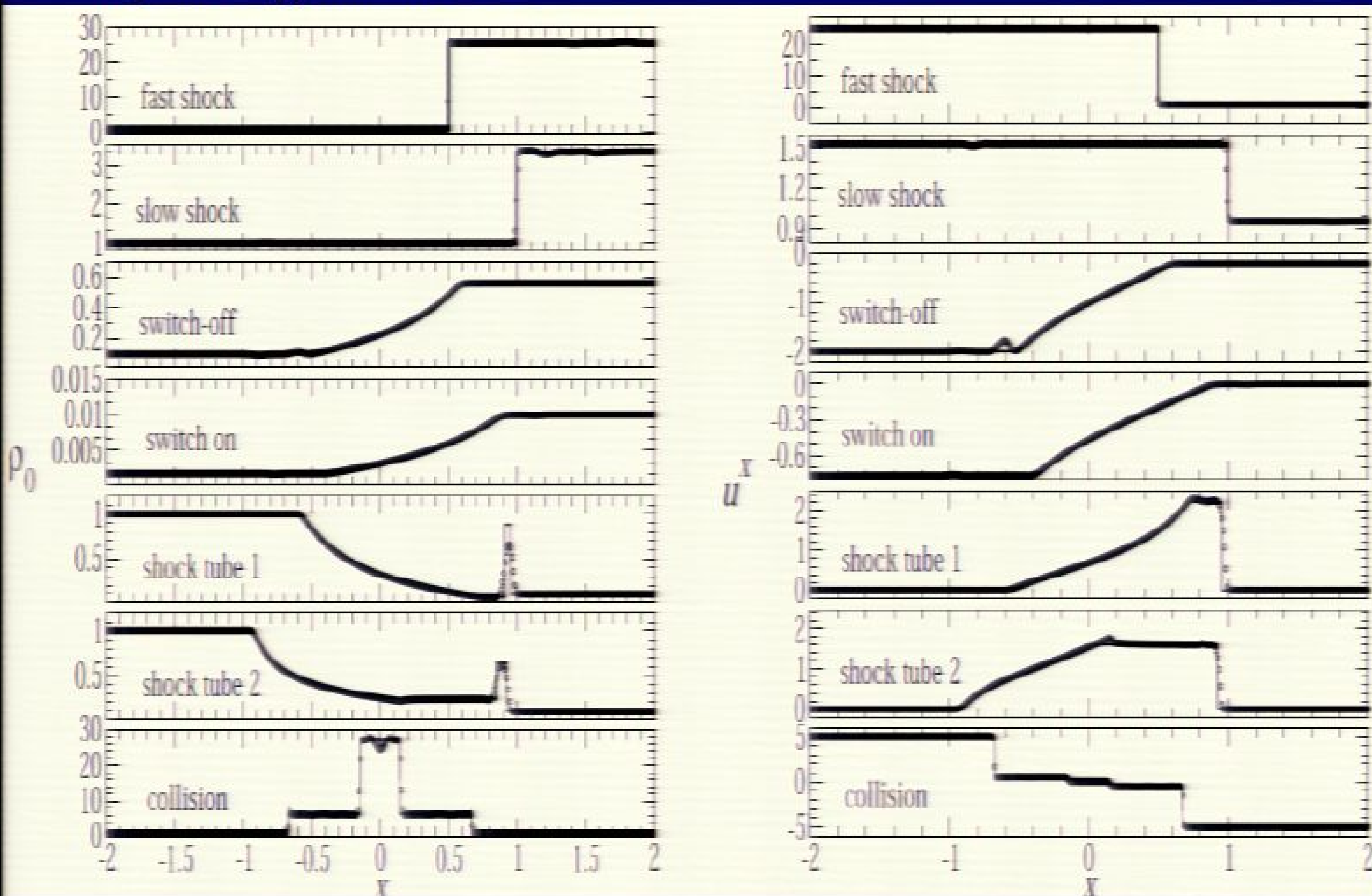
- Default case: BH spin parameter=0,
- 3:1 Mass ratio
  - ~7:1 preferred by pop. synth.

NS

- Default case: Irrotational NS with n=1 ($\Gamma = 2$) polytropic EOS (*irr.* ← *tidal locking time>>inspiral*)

Illinois Non-AMR Code Validation Tests

- Tests with analytic solutions
  - Shock tube, OS collapse, Bondi flow
- Tests against other codes (Japan)
  - Magnetized hypermassive NSs



[Duez et al. PRD 72 (2005) 024028]

BHNS Evolutions: Case Studies

BH Spin Study
- Illinois

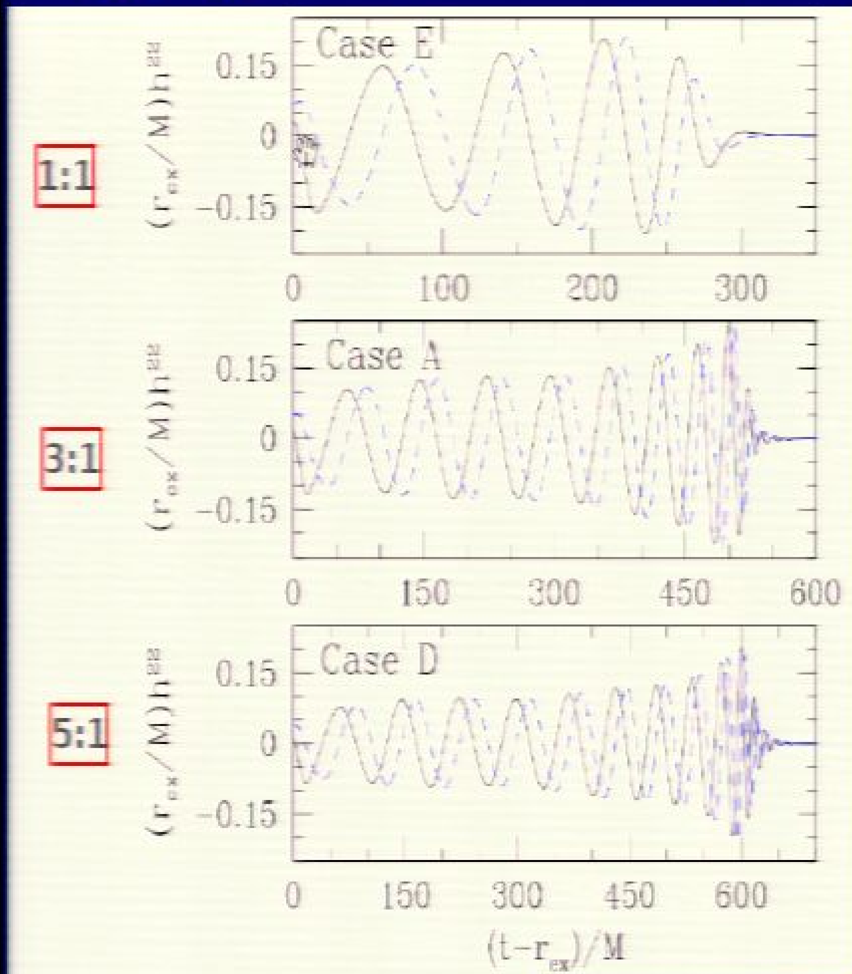
Mass Ratio Study
- Illinois
- Japan

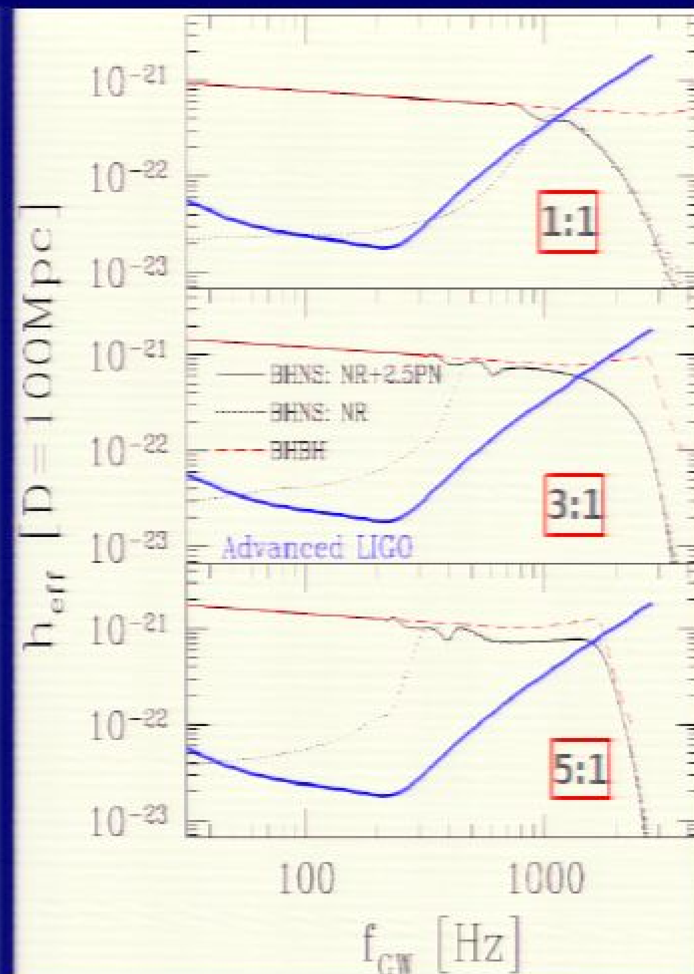
NS Compaction Study
- Cornell
- Japan

Equation of State Study
- Cornell

Magnetic Field Study
- Chawla et al. (LSU,BYU,IU,PI, UG,ULI)

M_{BH}:M_{NS} Mass Ratio Study: Gravitational Wave Analysis





Solid lines: h_+ , dash lines: $h_\times$

$r_{ex} = 30M - 80M$

Initial $M\Omega = 0.033$

Case	J_{BH}/M_{BH}^2	$M_{BH} : M_{NS}$	N_{orb}	M_{disk}/M_0
E	0.0	1:1	2.25	$\lesssim 2.3\%$
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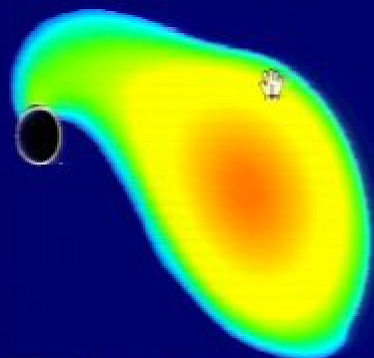
Fully General Relativistic Simulations of Black Hole-Neutron Star Binary Mergers: A Current Overview



Zachariah B. Etienne

References

Relativistic Simulations of Black Hole-Neutron Star Mergers: Effects of black-hole spin . Etienne, Liu, Shapiro, & Baumgarte. PRD **79**, 044024 (2009).

Fully General Relativistic Simulations of Black Hole-Neutron Star Mergers. Etienne, Faber, Liu, Shapiro, Taniguchi, & Baumgarte. PRD **77**, 084002 (2008).

Equation of state effects in black hole-neutron star mergers. Duez, Foucart, Kidder, Ott, & Teukolsky. CQG **27**. 114106 (2010).

Evolving black hole-neutron star binaries in general relativity using pseudospectral and finite difference methods. Duez, Foucart, Kidder, Pfeiffer, Scheel, & Teukolsky. PRD **78**. 104015 (2008).

Gravitational waves from black hole-neutron star binaries I: Classification of waveforms. Shibata, Kyutoku, Yamamoto, & Taniguchi. PRD **79**. 044030 (2009).

Simulating coalescing compact binaries by a new code SACRA. Yamamoto, Shibata, & Taniguchi. PRD **78**. 064054 (2008).

Mergers of Magnetized Neutron Stars with Spinning Black Holes: Disruption, Accretion and Fallback. Chawla, Anderson, Besselman, Lehner, Liebling, Motl, & Neilsen. arXiv:1006.2839

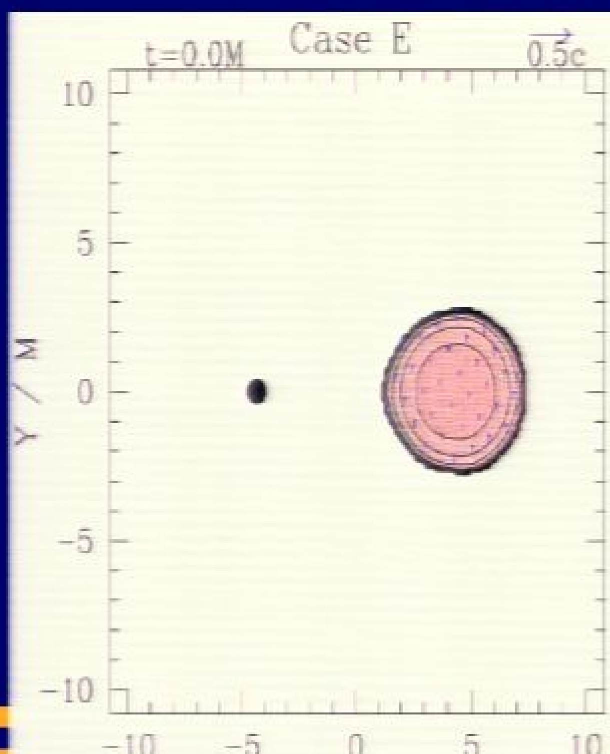
BHNS Initial Data

Conformal Thin-Sandwich

- Chawla et al.
- Cornell
- Illinois

Puncture

- Japan



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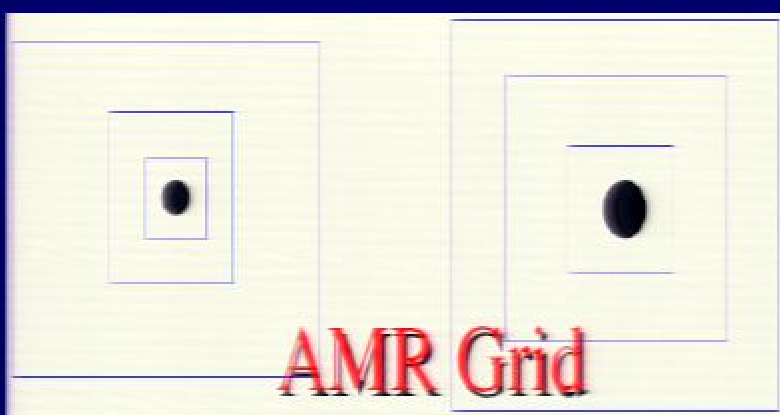
NS

- Default case: Irrotational NS with n=1 ($\Gamma = 2$) polytropic EOS (*irr. ← tidal locking time>>inspiral*)

Evolution Codes

- Time evolution: 4^{th} order finite differences (RK4)
- Einstein's equations for metric (BSSN/GH formalism)
  - Spatial derivatives: 4^{th} order+ finite differences ← Cornell: Spectral!
- Coordinates: "puncture gauge" or "generalized harmonic coordinates"
  - Puncture coords avoid BH physical singularity → stability!
  - Generalized harm. coords use excision: BC @ BH
- General relativistic hydro/MHD equations: conservative, HRSC scheme
  - Reconstruction: 2^{nd} or 3^{rd} order accurate, for smooth flows
  - MHD: div B
- Chawla, Illinois, Japan: AMR infrastructure
- Cornell: Multi-Domain (MD) spectral grid + hydro unigrid



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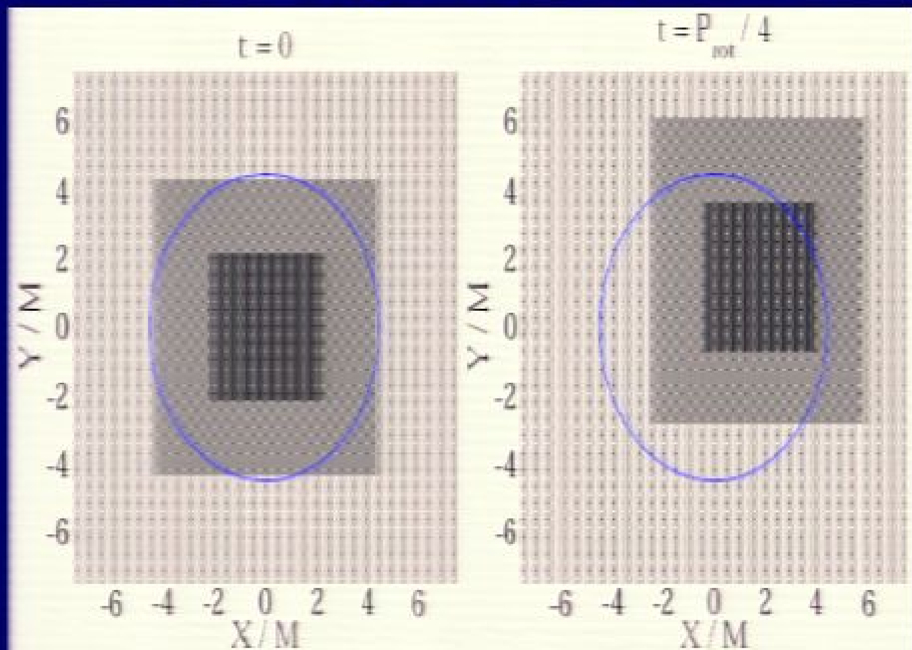
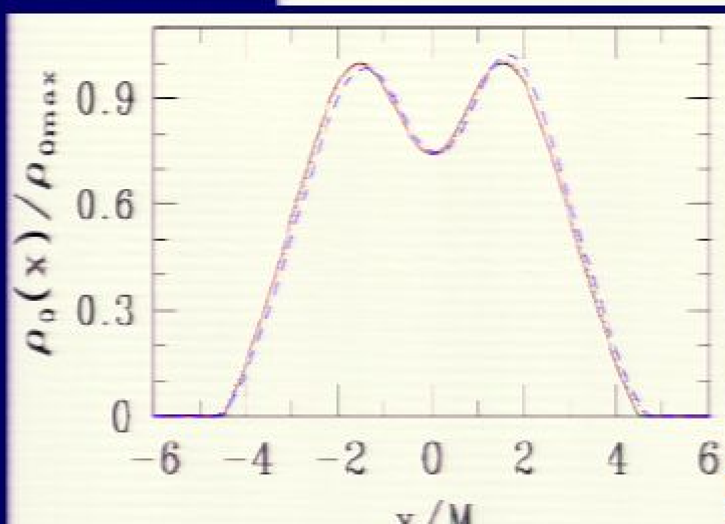
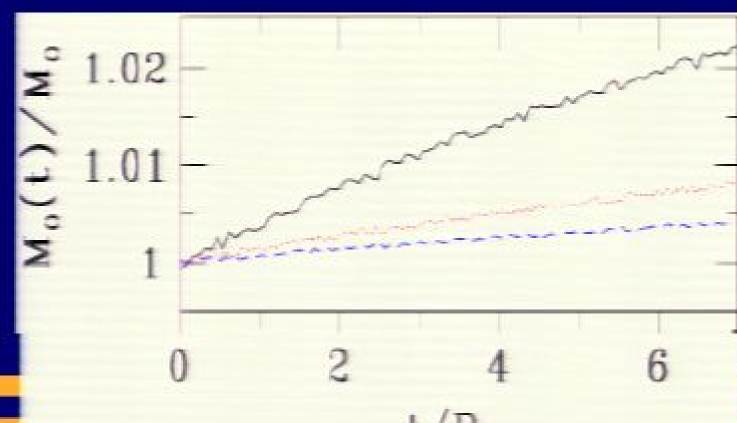
- Rest-mass violation error converges to zero @ >2nd order, <1%







Other Groups' Code Tests

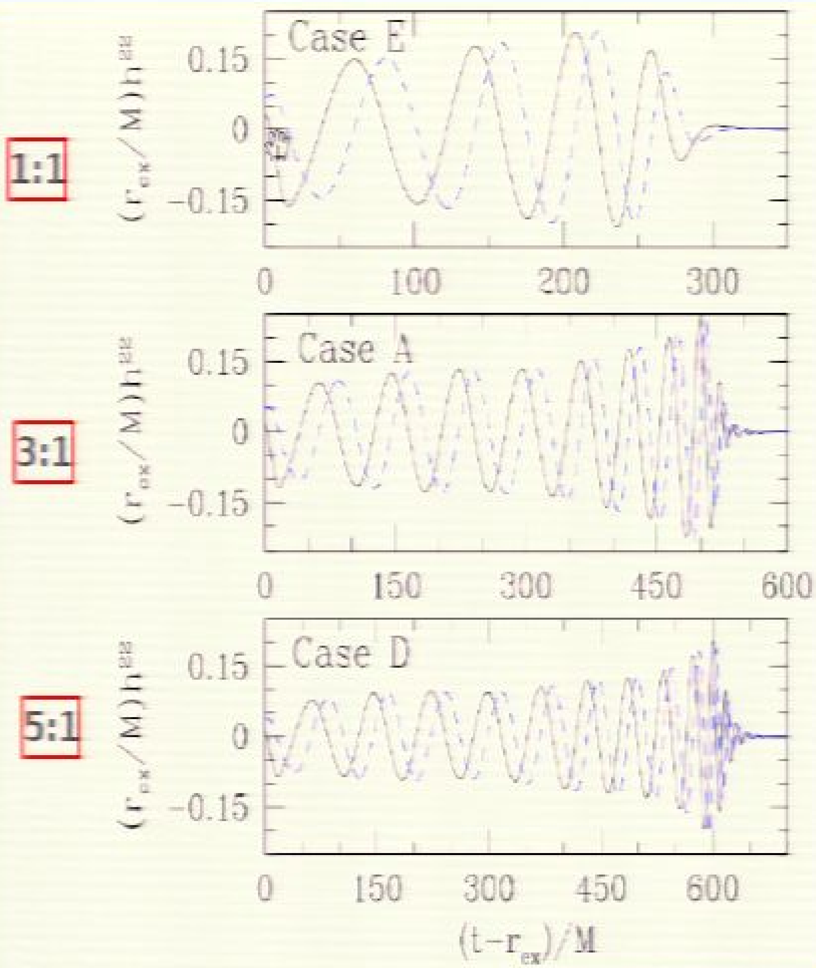
- Japan:
  - Convergence tests
    - rest mass violation convergence with AMR+NSNS: 2^{nd} order
    - BHNS: second order convergence
  - Self-consistency:
    - *J* & *E* conservation; BHNS vs post-Newtonian
- Cornell:
  - Convergence tests:
    - Field sector: spectral, well-tested with BHBH
    - Matter (no AMR): NS tests; second-order convergent BHNS
  - Self-consistency: *J* & *E* conservation
- LSU/BYU/PI/etc:
  - Evolve TOV star unigrid, ~2.4 order convergence
  - Spherical accretion onto stationary Schw. BH
    - converges to analytic as more AMR levels added
  - AMR spherical blast wave: HDC improves div B =0
  - Convergence for BHNS unpublished

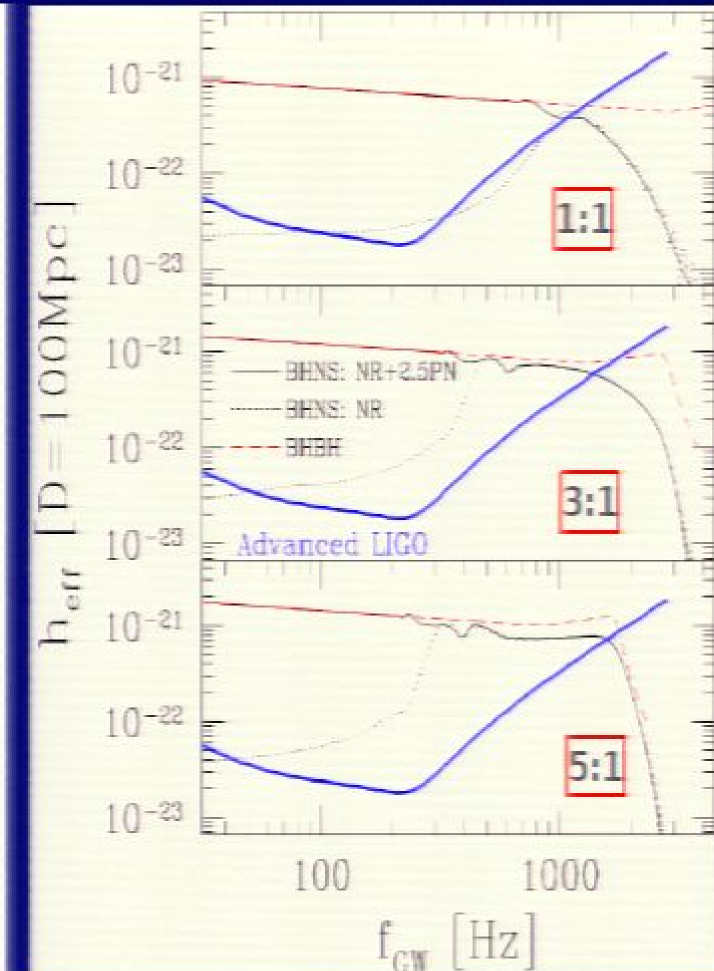
Mass Ratio vs Disk Mass
Multi-Group Comparison

Group	BH:NS Mass Ratio	$(M/R)_{NS}$	EOS	Disk Mass
Illinois	1.0	0.145	$\Gamma = 2$	2.3%
Japan	1.5	–	–	2.3%
Japan	2.0	–	–	1.0%
Illinois	3.0	–	–	3.9%
Japan	–	–	–	Tiny
Japan	4.0	–	–	–
Illinois	5.0	–	–	–
Japan	–	–	–	–

- Discrepancy:
  - Total energy in disk: up to ~4% of NS mass → ~1% total *E*
    - *E*, *J* spuriously lost:
      - *E*: 0.01% Illinois, 1% Japan;
      - *J*: 1 – 2% Illinois, Japan

M_{BH}:M_{NS} Mass Ratio Study: Gravitational Wave Analysis





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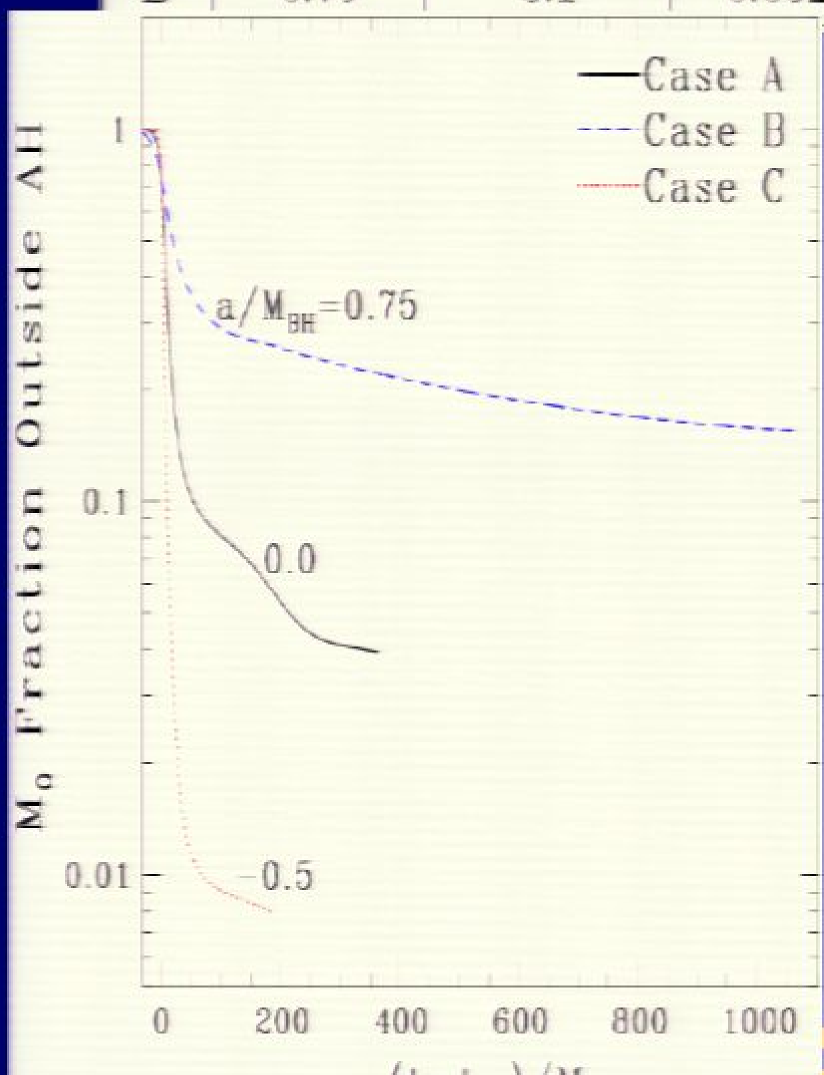
Vary BH Spin: Accretion History

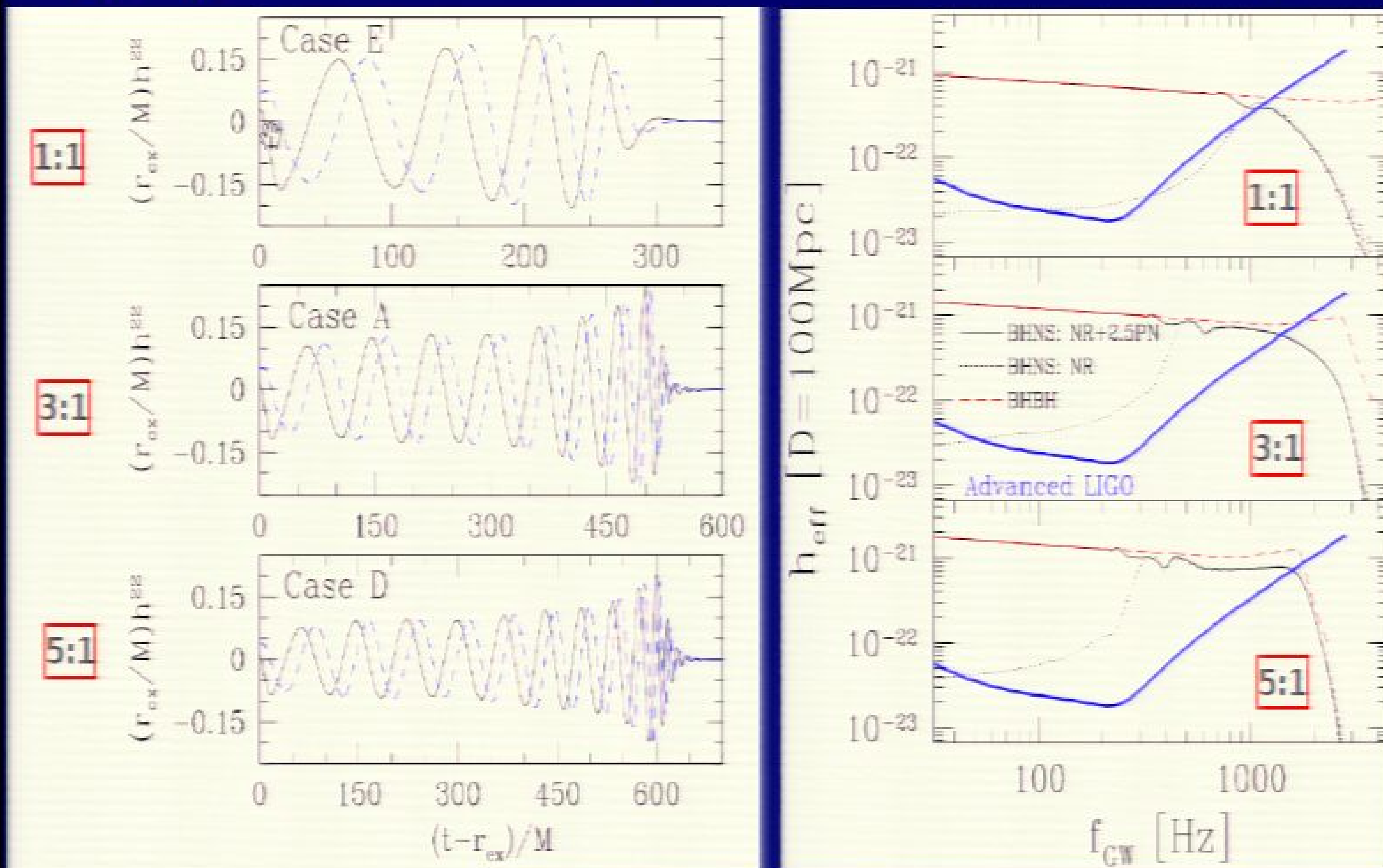
Case	J_{BH}/M_{BH}^2	$M_{BH} : M_{NS}$	$M\Omega(t=0)$	N_{orb}	M_{disk}/M_0
C	-0.50	3:1	0.0338	3.25	$\lesssim 0.8\%$
A	0.00	3:1	0.0333	4.5	$\lesssim 3.9\%$
B	0.75	3:1	0.0328	6.5	$\lesssim 15\%$

→ SGRB?



$$a/M_{BH} = J_{BH}/M_{BH}^2$$

M_{BH}:M_{NS} Mass Ratio Study: Gravitational Wave Analysis



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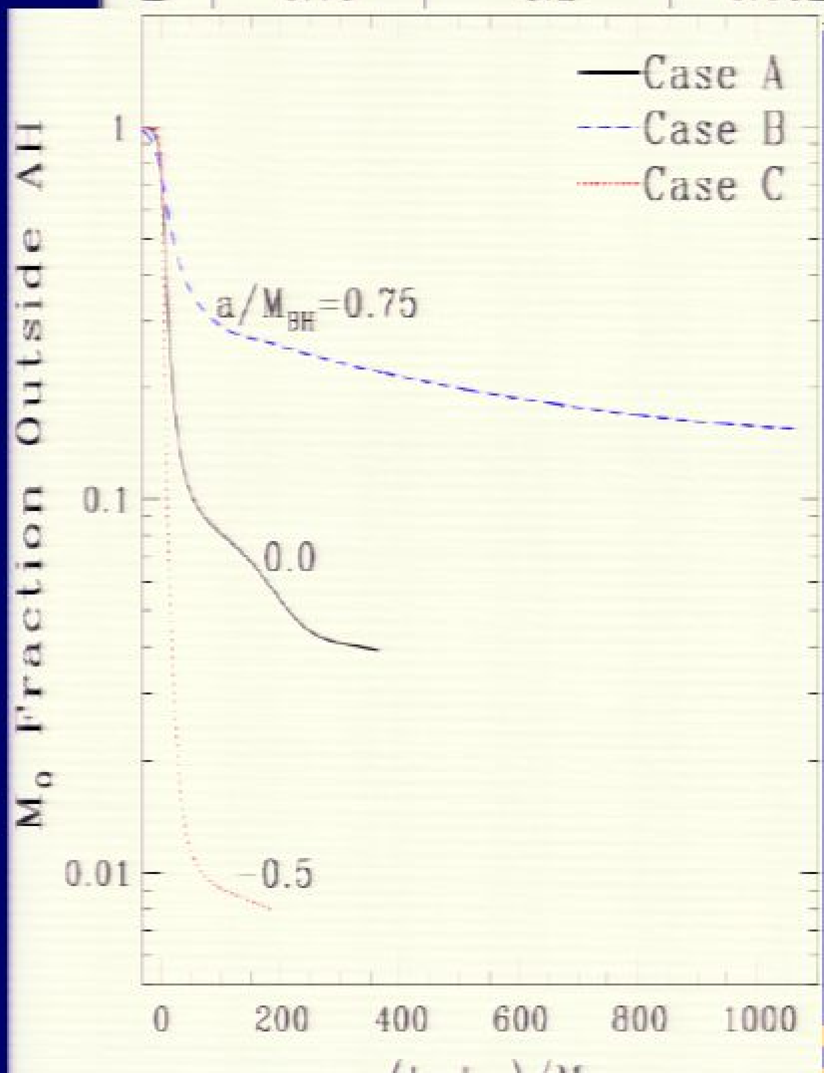
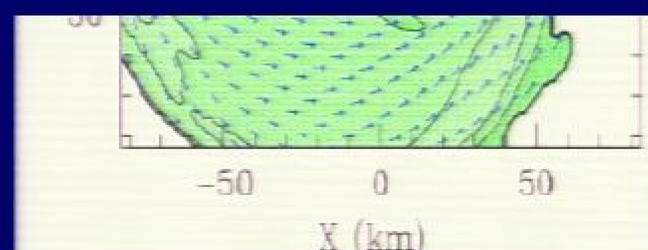


$$a/M_{BH} = J_{BH}/M_{BH}^2$$

8

- For typical disk, assuming $M_0 = 1.4 M_\odot$
  - we get: $\rho_0 \sim 10^{11} - 10^{12} \mathrm{g/cm}^3$
    $T \sim 10^{10} - 10^{11} K$
  - Approx scalings from BH disk sim's predict: $E_\gamma \sim 10^{47} - 10^{50}$ ergs



[Setiawan, Ruffert, & Janka 2006]

Disk Temperature Estimate

- EOS: Initial: $P = P_{\rm cold} = K\rho_0^{\Gamma=2}$ at $t=0$,
  Adiabatic evolution: $P = (\Gamma - 1)\rho_0\epsilon$ at $t>0$.
- Split internal energy into 2 parts ($\epsilon_{\rm th}$ from shock heating)

$$\epsilon = \epsilon_{\rm cold} + \epsilon_{\rm th}, \text{ where}$$
$$\epsilon_{\rm cold} = -\int P_{\rm cold}\, d\left(\frac{1}{\rho_0}\right) = \frac{K}{\Gamma-1}\rho_0^{\Gamma}$$

- Estimate temperature as follows:
  (cf. Popham, Woosley, & Fryer (1999))

$$\epsilon_{\rm th} \sim \frac{3kT}{2m_n} + f\frac{aT^4}{\rho_0}$$
$$f = \frac{7}{8} \text{ for } e^+, e^-, \nu, \bar{\nu}\text{'s}; \; f = 1 \text{ for } \gamma\text{'s}$$

- For typical disk, assuming $M_0 = 1.4 M_\odot$
  - we get: $\rho_0 \sim 10^{11} - 10^{12}\,{\rm g/cm^3}$
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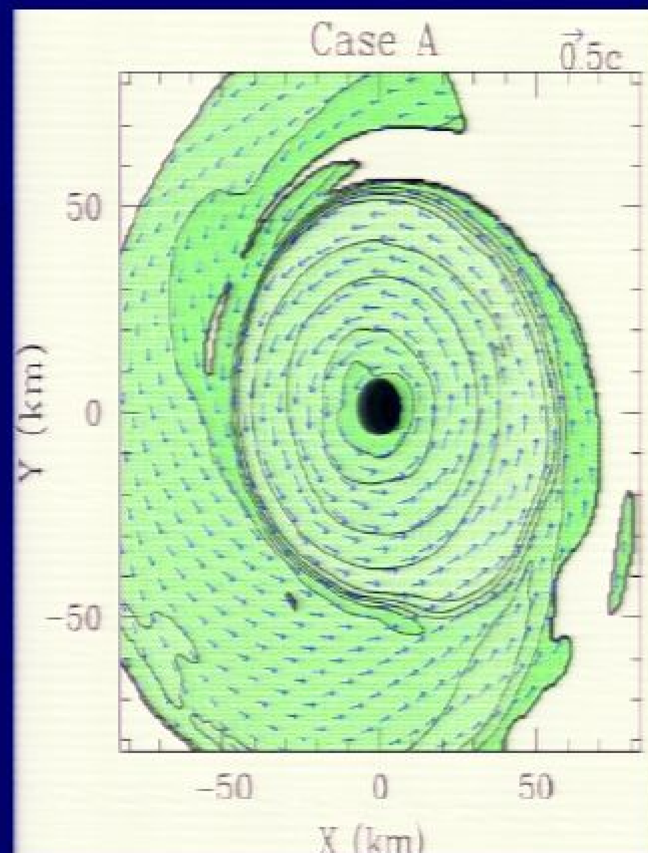

[Setiawan, Ruffert, & Janka 2006]


No Signal
VGA-1


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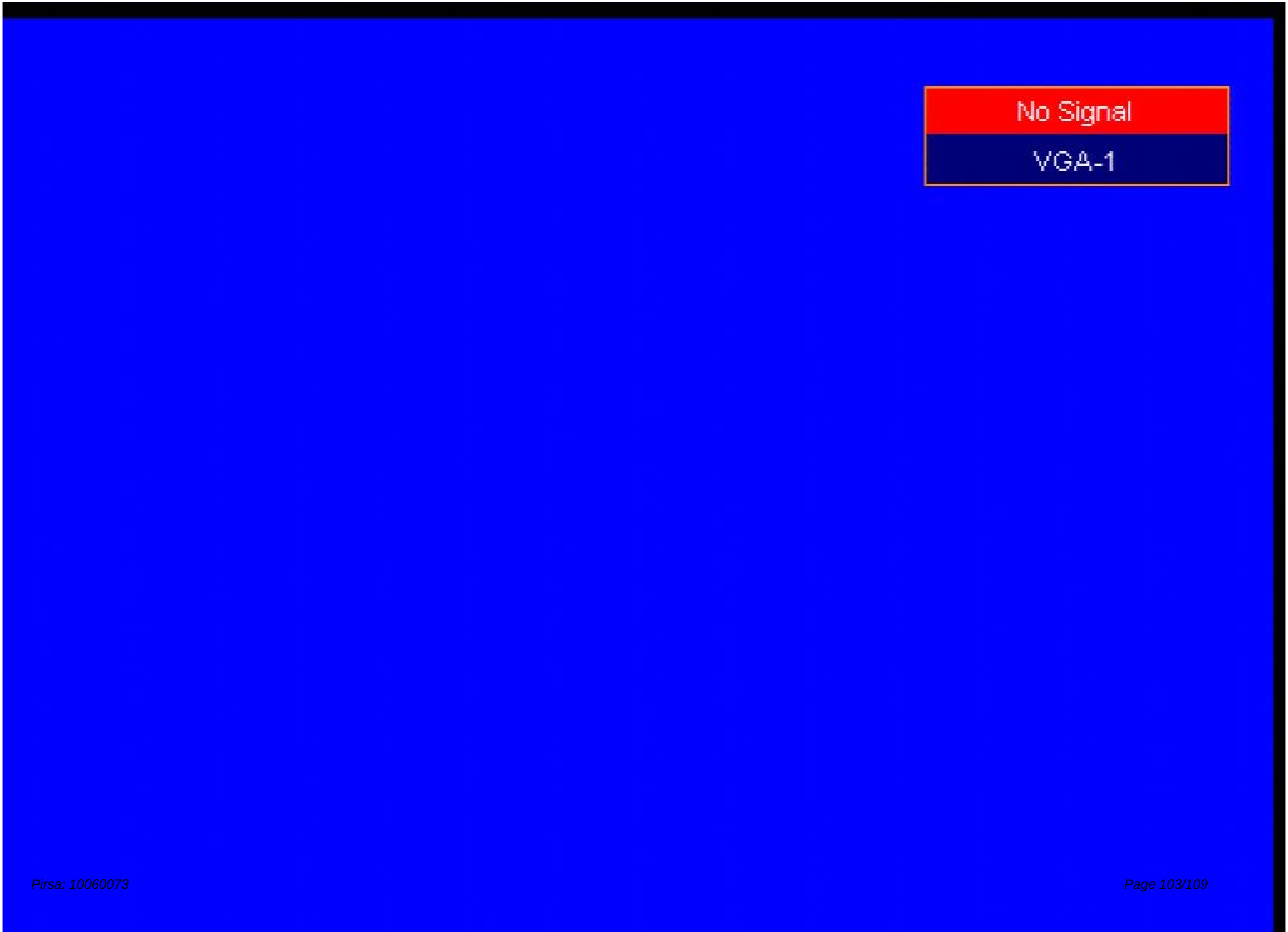
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