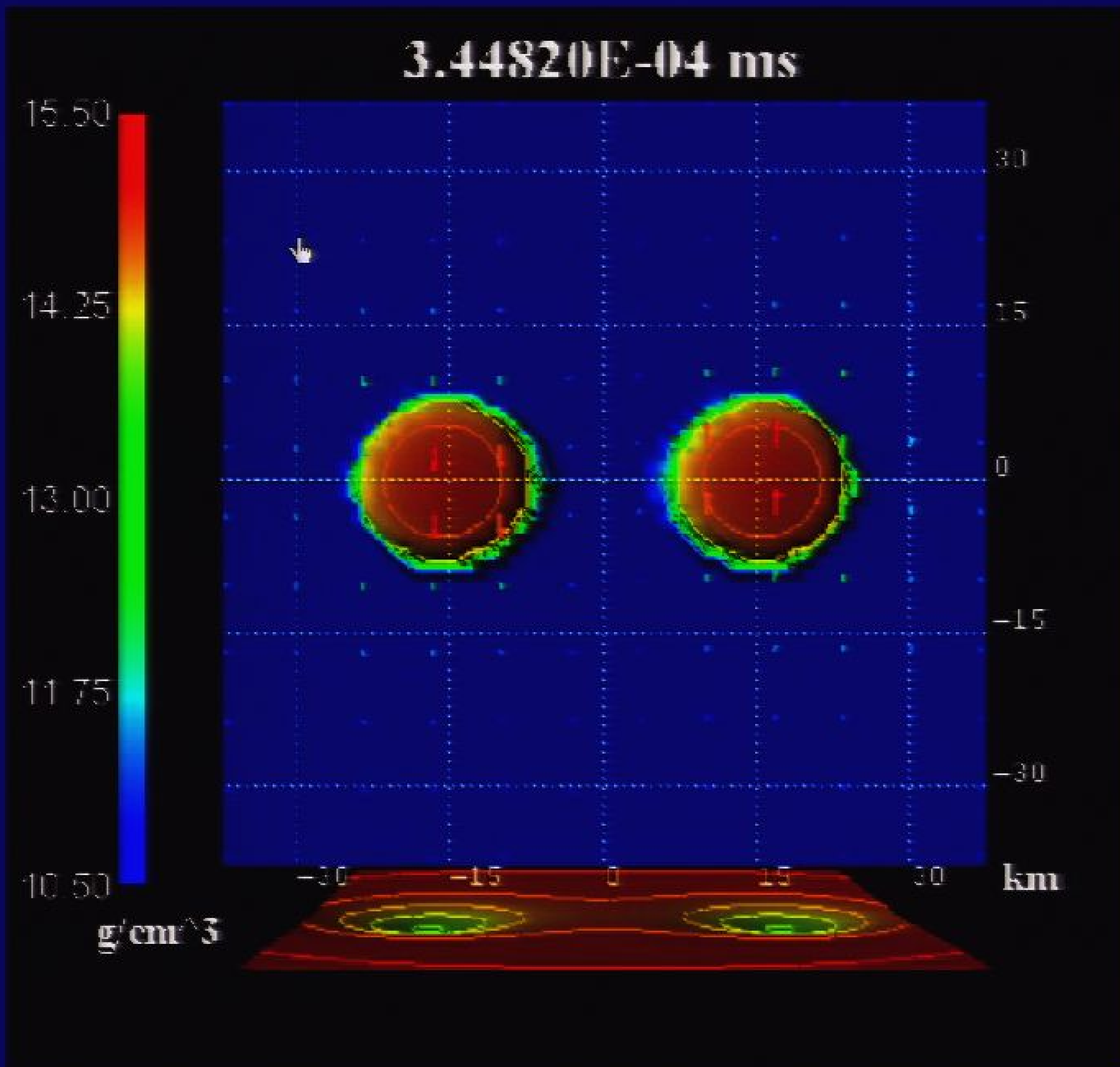
Title: Nucleosynthesis and Short Gamma-Ray Burst Central Engines

Date: Jun 22, 2011 11:00 AM

URL: http://pirsa.org/11060029

Abstract: Massive accretion disks may form from the merger of neutron star (NS)-NS or black hole-NS binaries, or following the accretion-induced collapse (AIC) of a white dwarf. These disks, termed `hyper-accreting' due to their accretion rates up to several solar masses per second, may power the relativistic jets responsible for short duration gamma-ray bursts. Using 1D time-dependent calculations of hyper-accreting disks, I show that a generic consequence of the disk's late-time evolution is the development of a powerful outflow, powered by viscous heating and the recombination of free nuclei into Helium. These outflows - in additional to any material dynamically-ejected during the merger - synthesize heavy radioactive elements as they expand into space. Nuclear heating from the r-process is not yet incorporated in merger simulations, yet has important consequences both for the dynamics of late `fall-back' accretion and in powering a supernova-like transient (`kilonova') 1 day following the merger or AIC.

Numerical Simulation - Two 1.4 $M_{\odot}$ NSs



Courtesy M. Shibata (Tokyo U)

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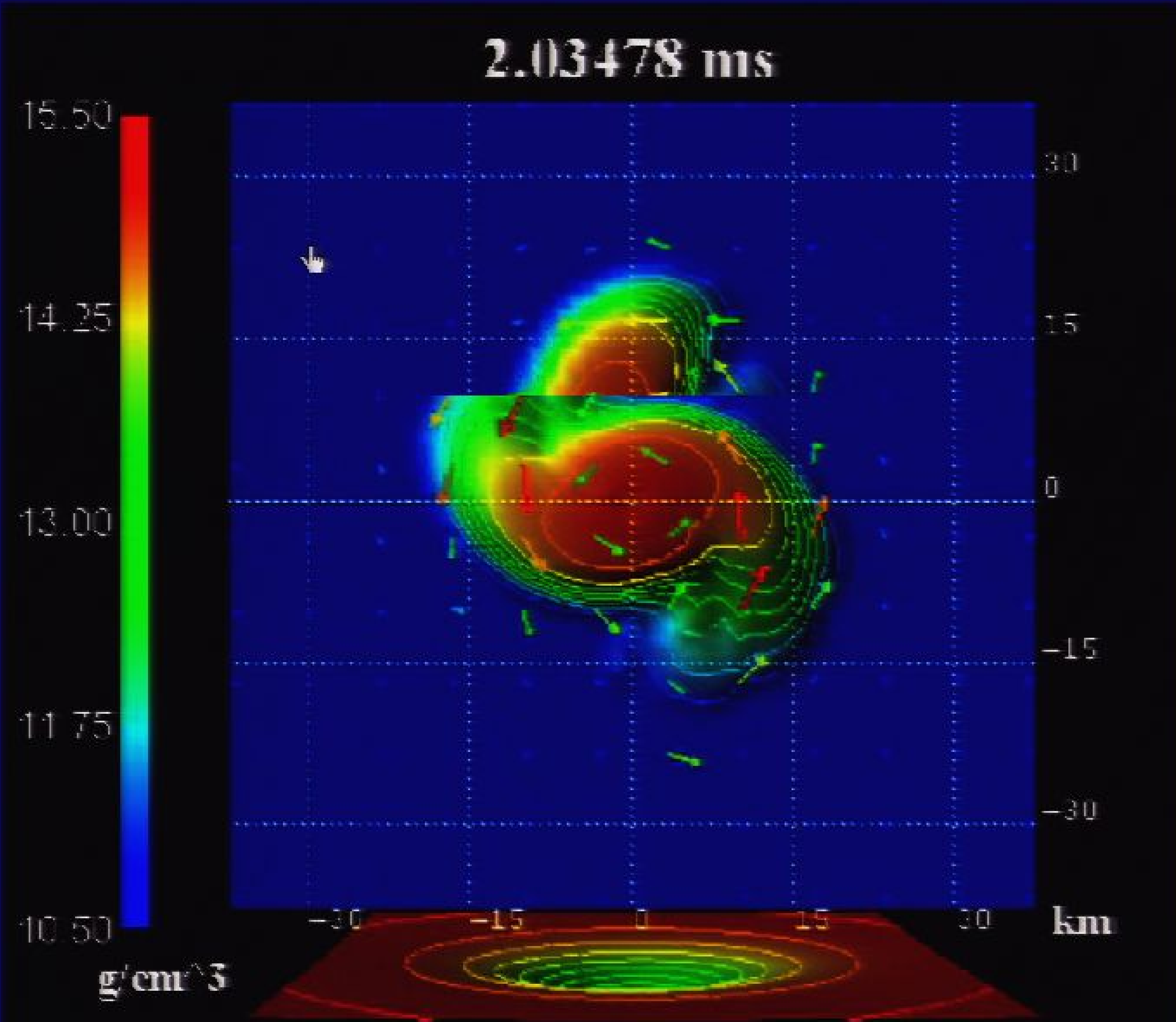

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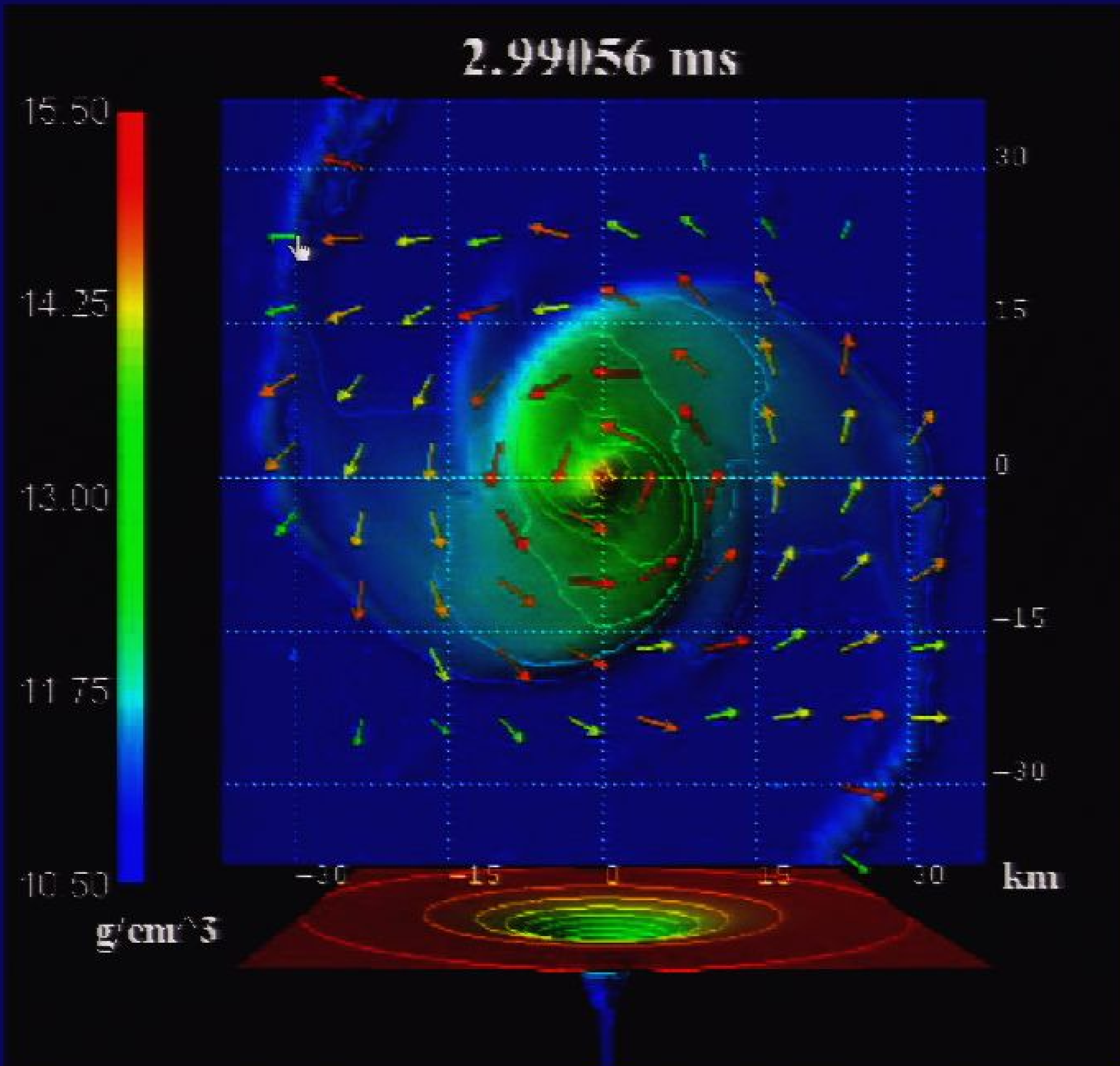

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Electromagnetic Counterparts of NS-NS/NS-BH Mergers

Short Gamma-Ray Burst

Blinnikov+84; Paczynski 86; Goodman 86; Eichler+89

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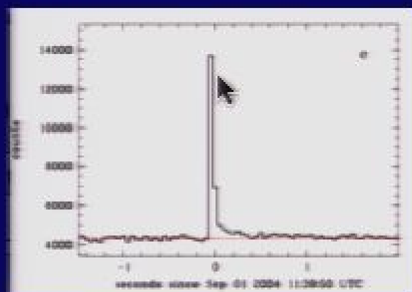

Bright, but Beamed

Depends On & Informs:

- jet efficiency $L_{\rm jet} = \varepsilon_{\rm jet}\dot{M}c^2$
- remnant disk $E_{\rm GRB} \propto M_{\rm acc} \propto M_{\rm disk}$
- jet baryon loading $\Gamma_{\rm jet} = E_{\rm GRB}/M_{\rm jet}c^2$

  (e.g. neutrino driven disk winds)

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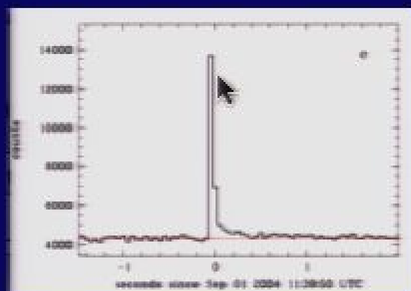

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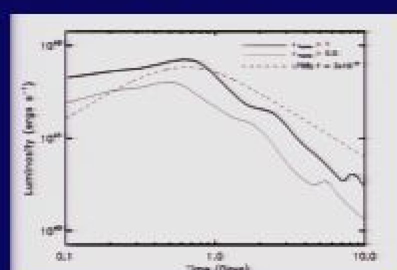
Thermal Transient (Kilonova) Powered by Radioactive Ejecta

Li & Paczynski 98; Rosswog 05; Metzger et al. 08, 10

⇒



Depends On & Informs:

- ejecta mass, velocity, entropy & composition (e.g. Y_e)
- r-process nucleosynthesis (nuclear properties far from β-stability)
- radiative transfer through "exotic" heavy nuclei

Dimmer, but Isotropic

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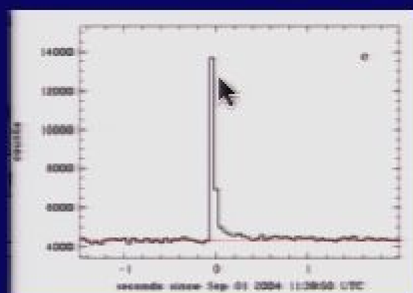

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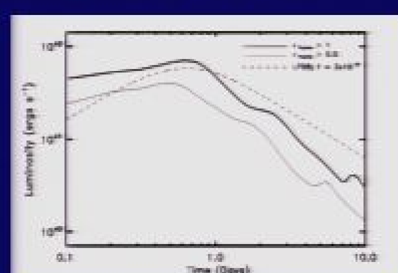

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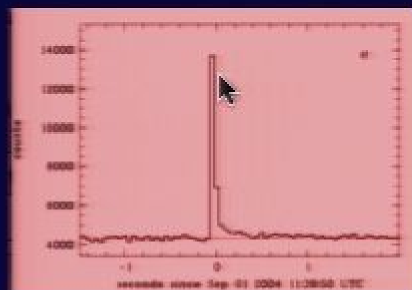

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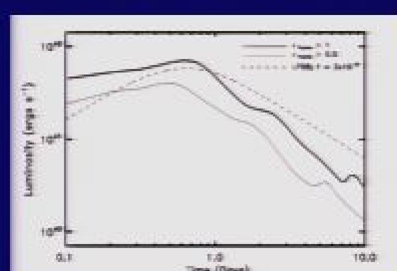

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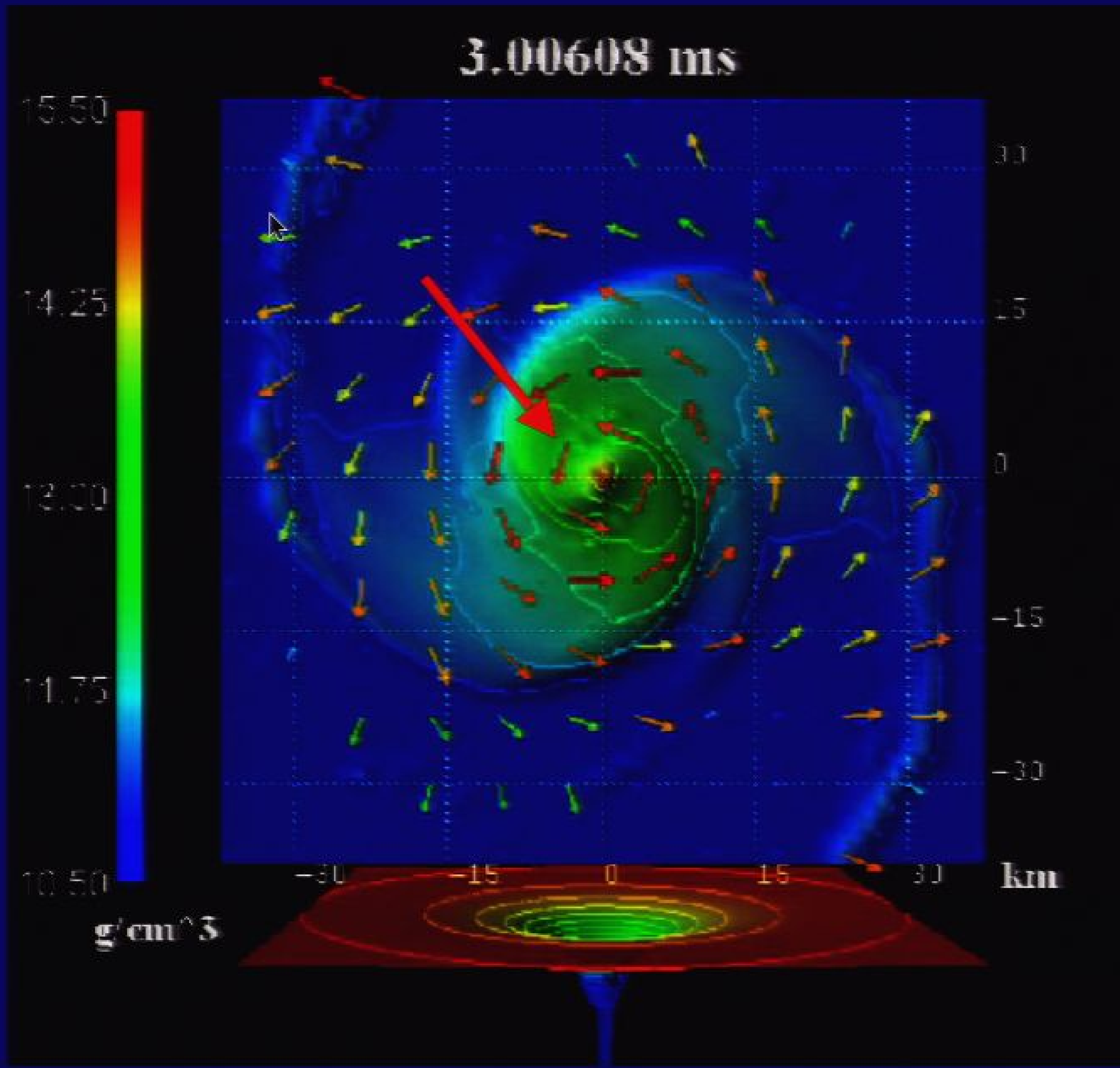
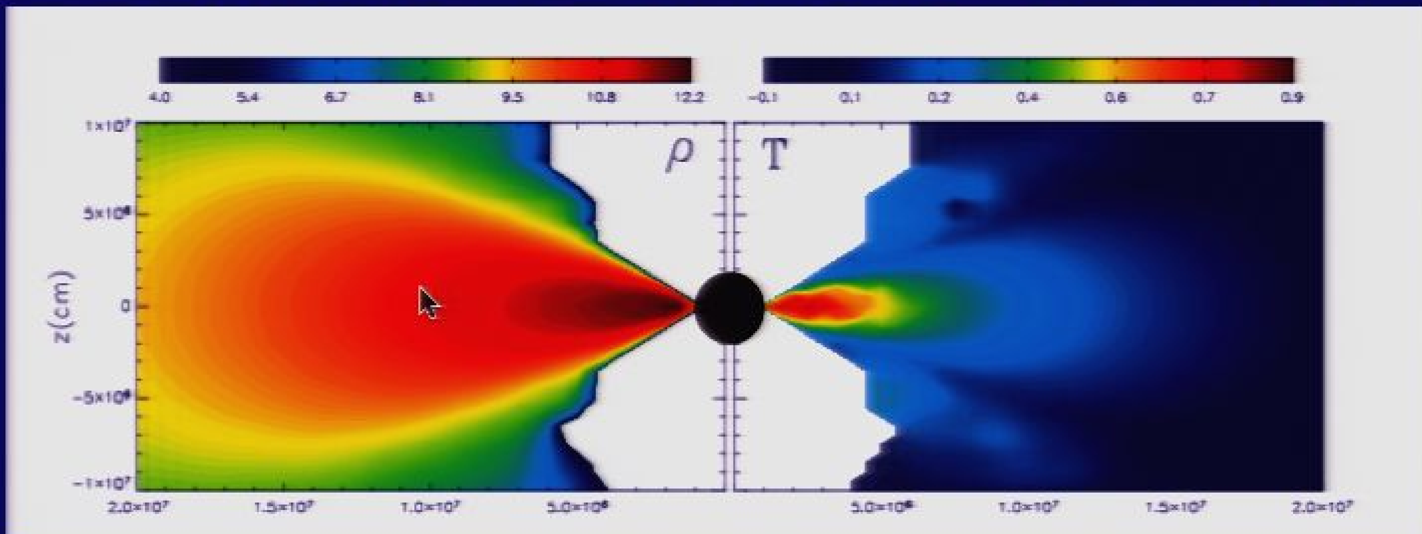


Courtesy M. Shibata (Tokyo U)

Remnant Accretion Disk

(e.g. Ruffert & Janka 1999; Lee et al. 2004; Shibata & Taniguchi 2006; Faber et al. 2006; Chawla et al. 2010; Duez et al. 2010)



Lee et al. 2004

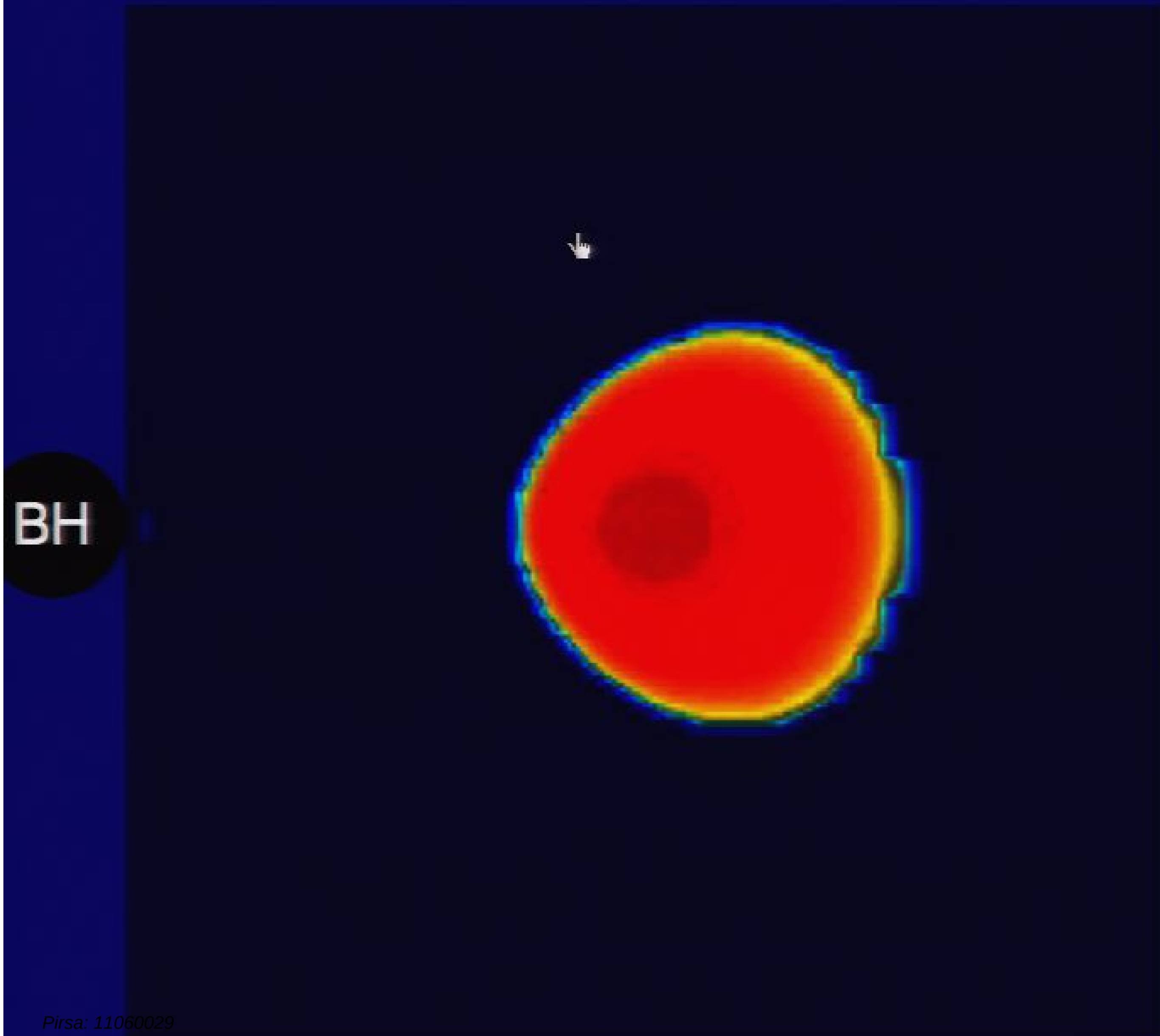
- Disk **Mass ~ 10^{-3} - 0.1 $M_\odot$** & **Size ~ 10-100 km**
- Midplane Hot (T > MeV) & Dense (ρ ~ 10^8-10^{12} g cm^{-3})
- Cooling via Neutrinos: (τ_γ >>1, τ_ν ~ 0.01-100)
- Neutron-Rich Equilibrium $e^+ + n \rightarrow \bar{\nu}_e + p$ vs. $e^- + p \rightarrow \nu_e + n$

Accretion Rate $\dot{M} \sim 10^{-2} - 10\, M_\odot\, \mathrm{s}^{-1}$

$$t_{visc} \sim 0.1 \left(\frac{M_\bullet}{3M_\odot}\right)^{1/2} \left(\frac{\alpha}{0.1}\right)^{-1} \left(\frac{R_d}{100\text{ km}}\right)^{3/2} \left(\frac{H/R}{0.5}\right)^{-2} \text{ s}$$

Short GRB Central Engine?

Spreading Accretion Disk



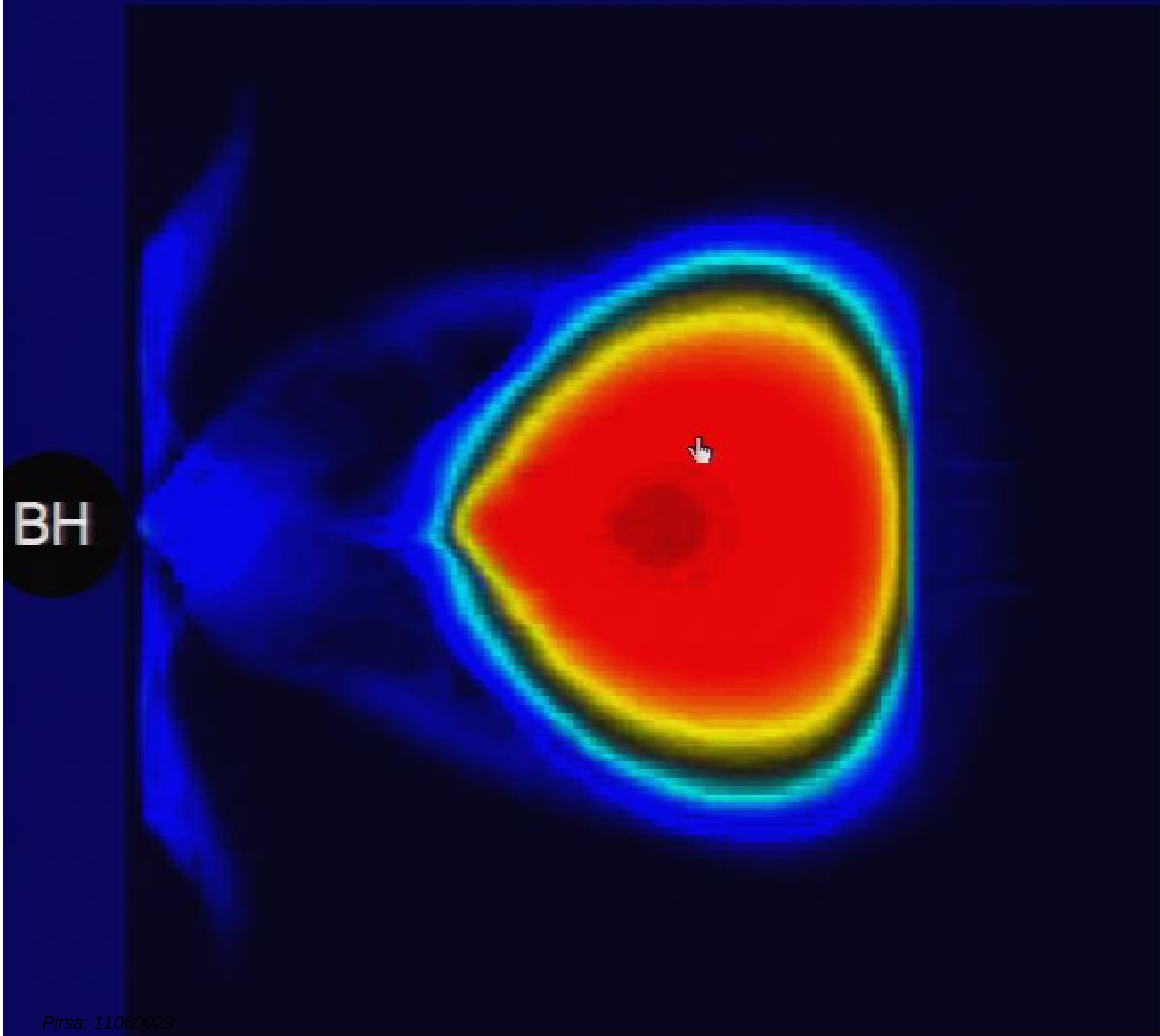
MHD Turbulence
Redistributes
Angular
Momentum

$$J \approx M_d (G M_{BH} R_d)^{1/2}$$
$$\Rightarrow R_d\big|_J \propto M_d^{-2}$$

Accretion
⇔
Expansion to Larger Radii

Hawley & Balbus (2002)

Spreading Accretion Disk



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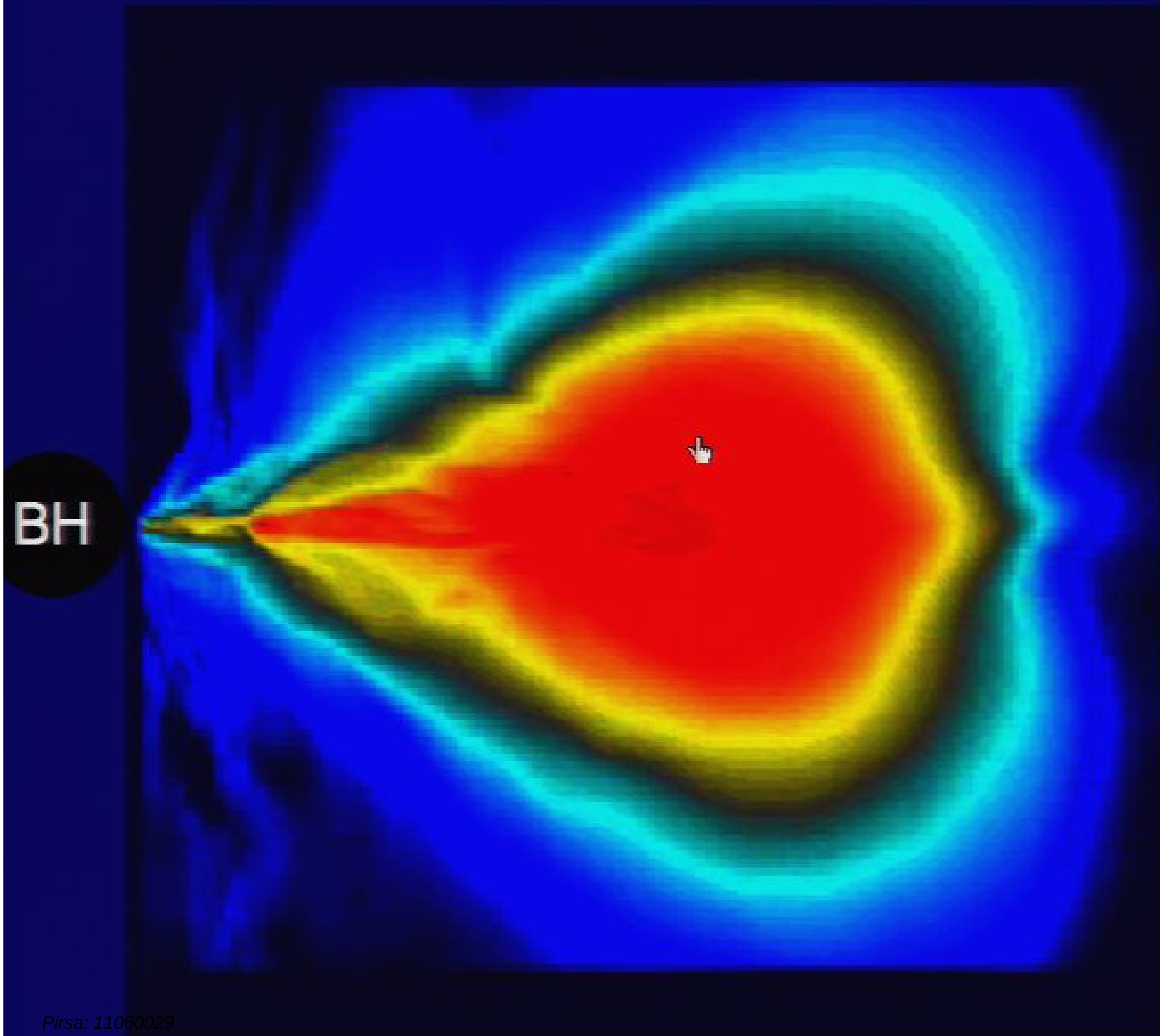

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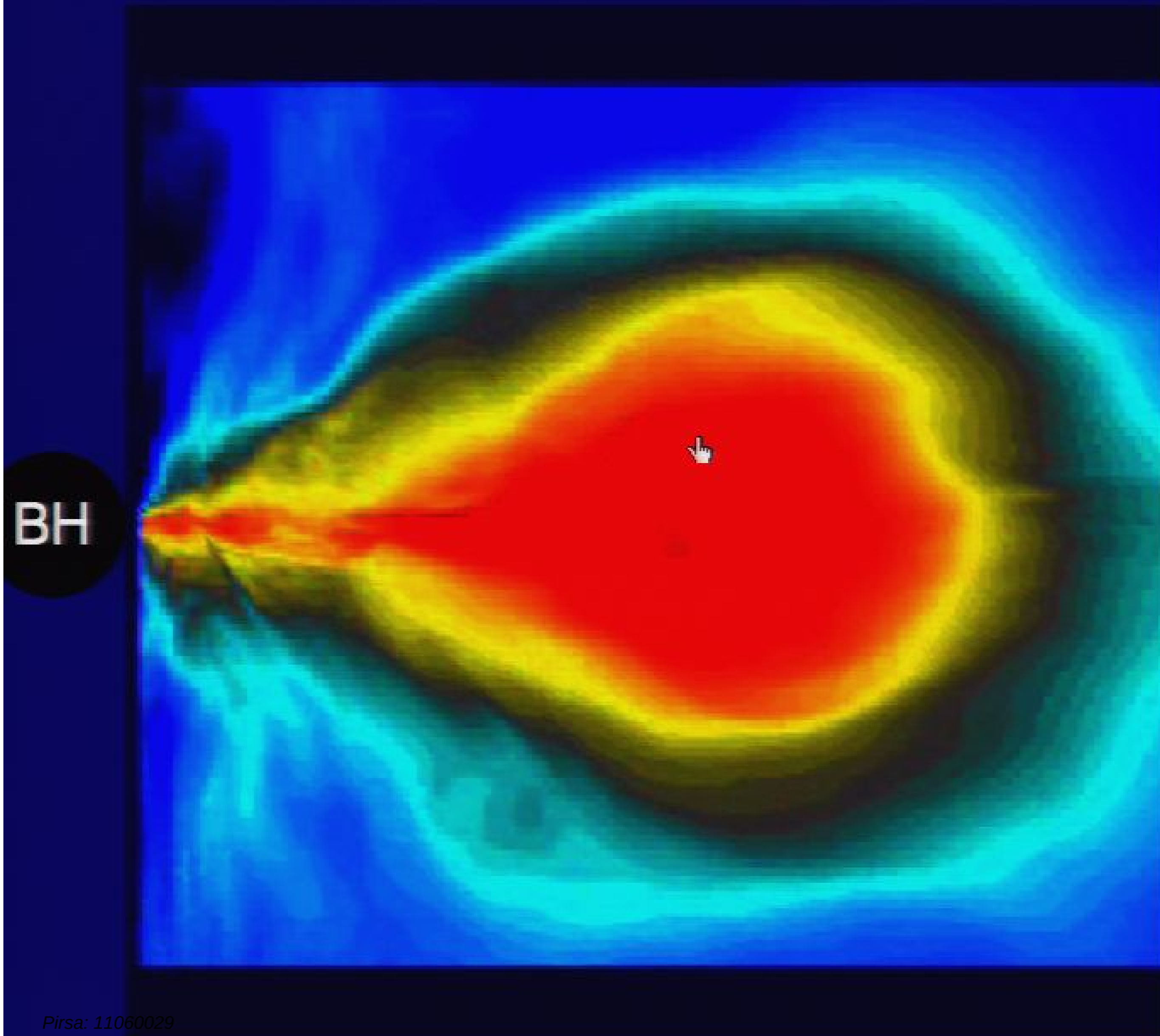

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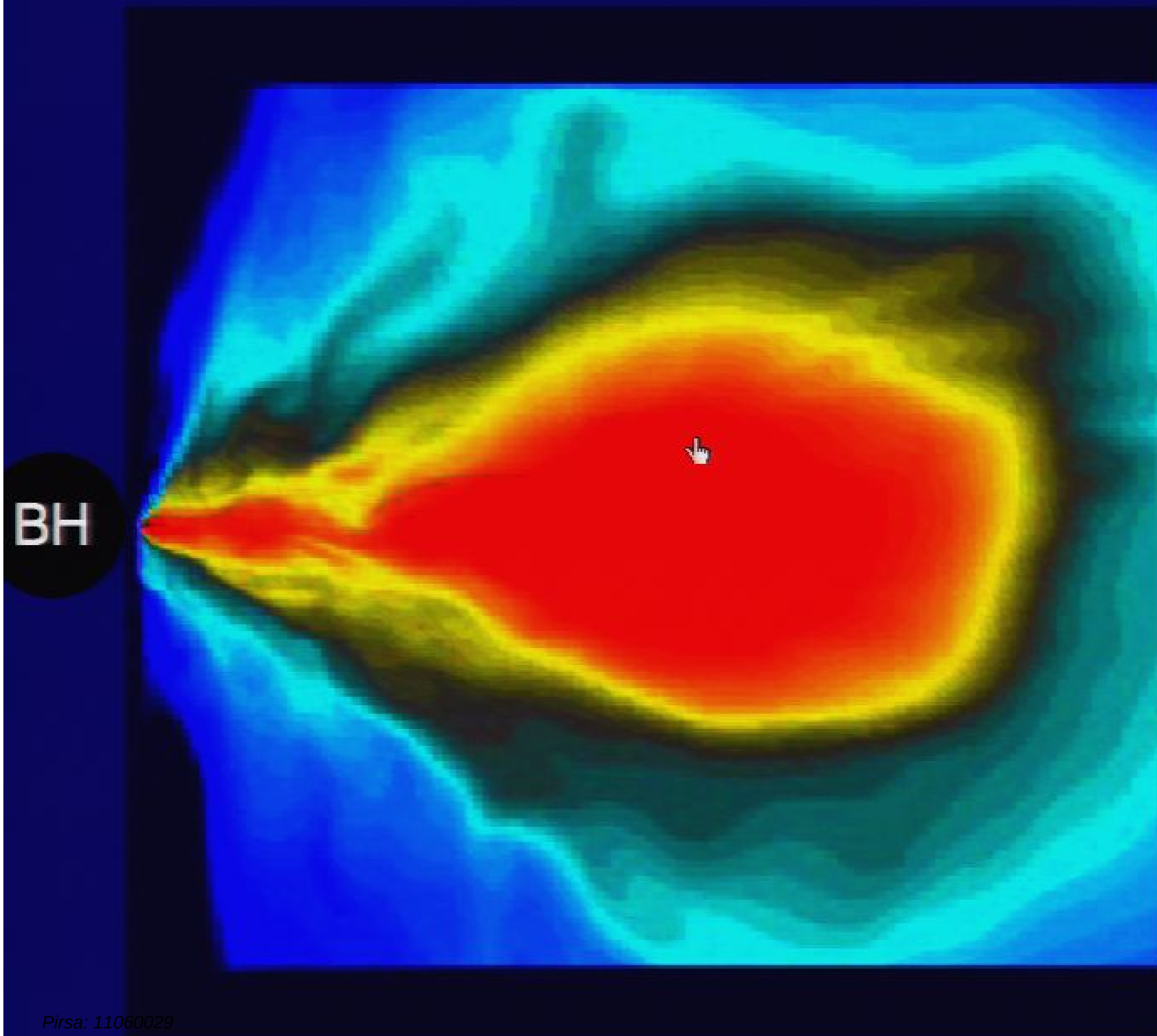

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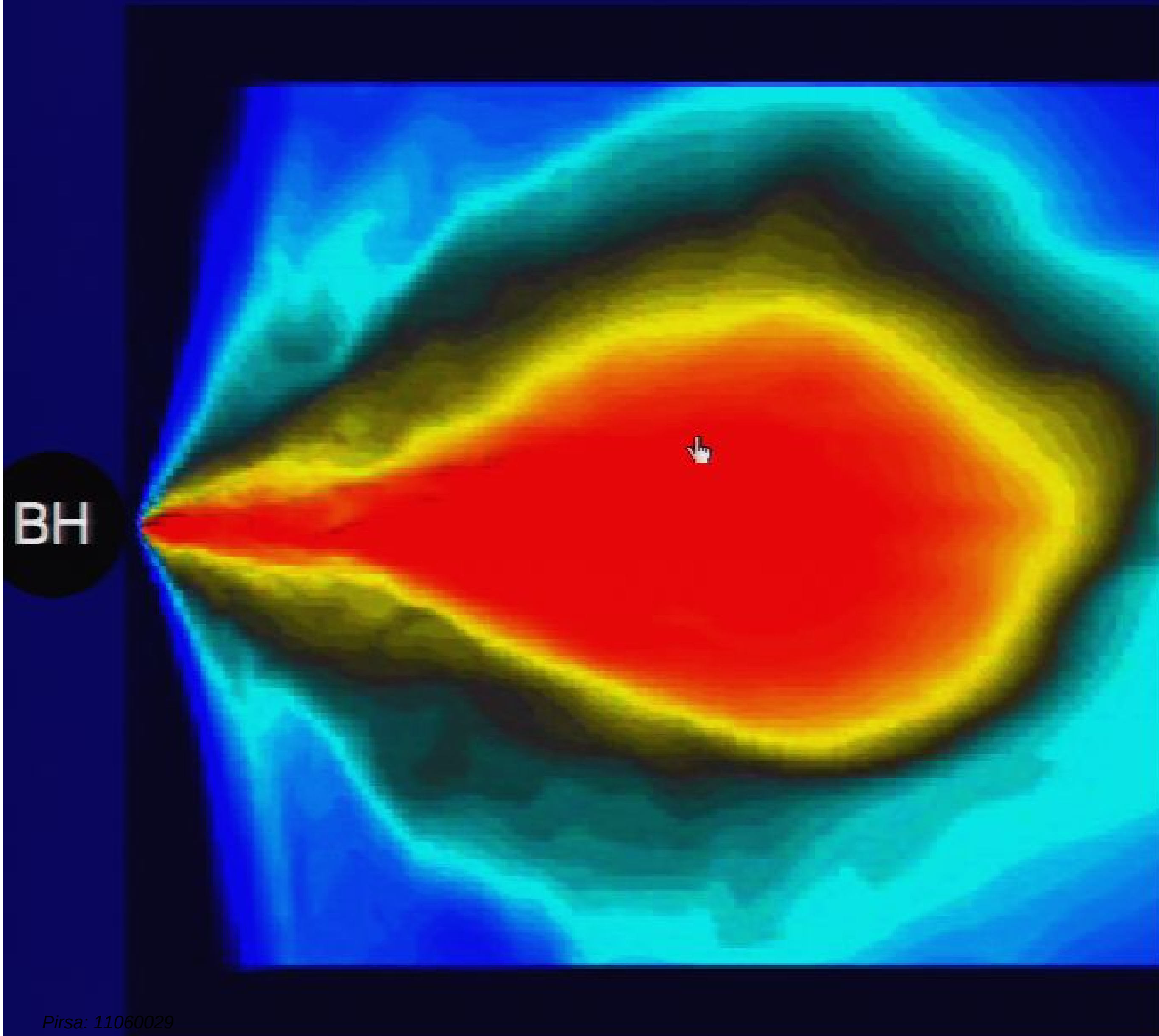

MHD Turbulence Redistributes Angular Momentum

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$\Leftrightarrow$

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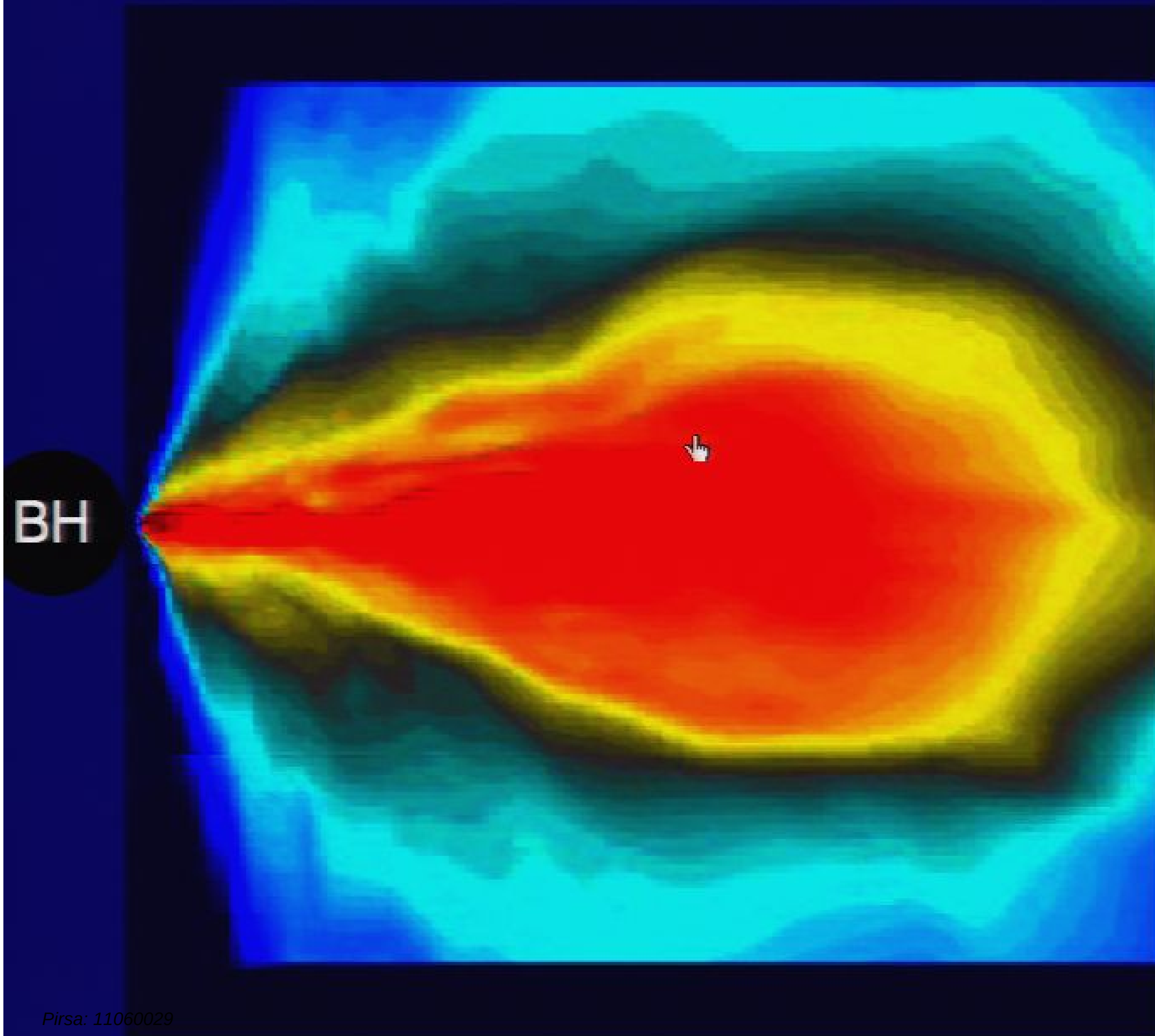

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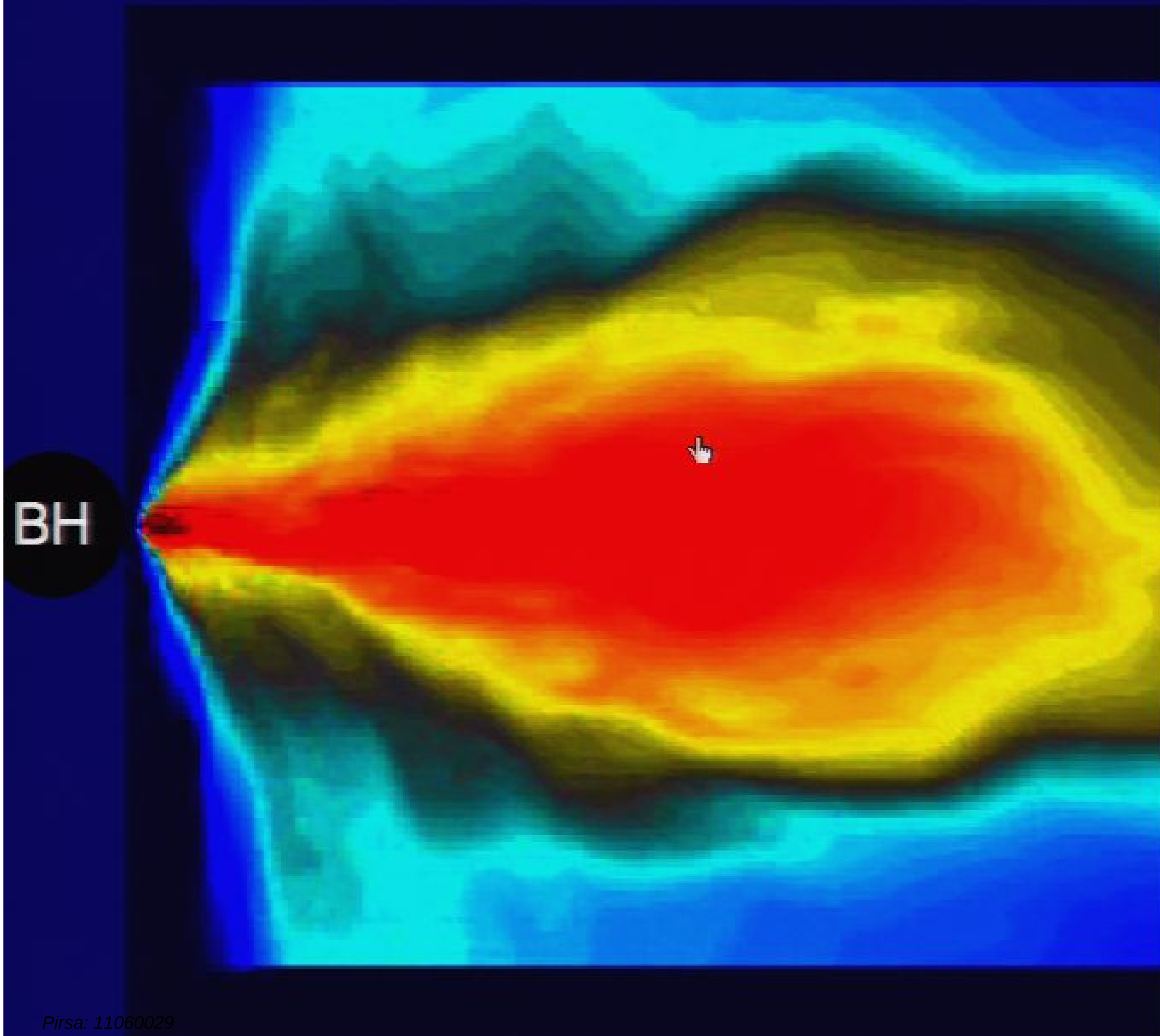

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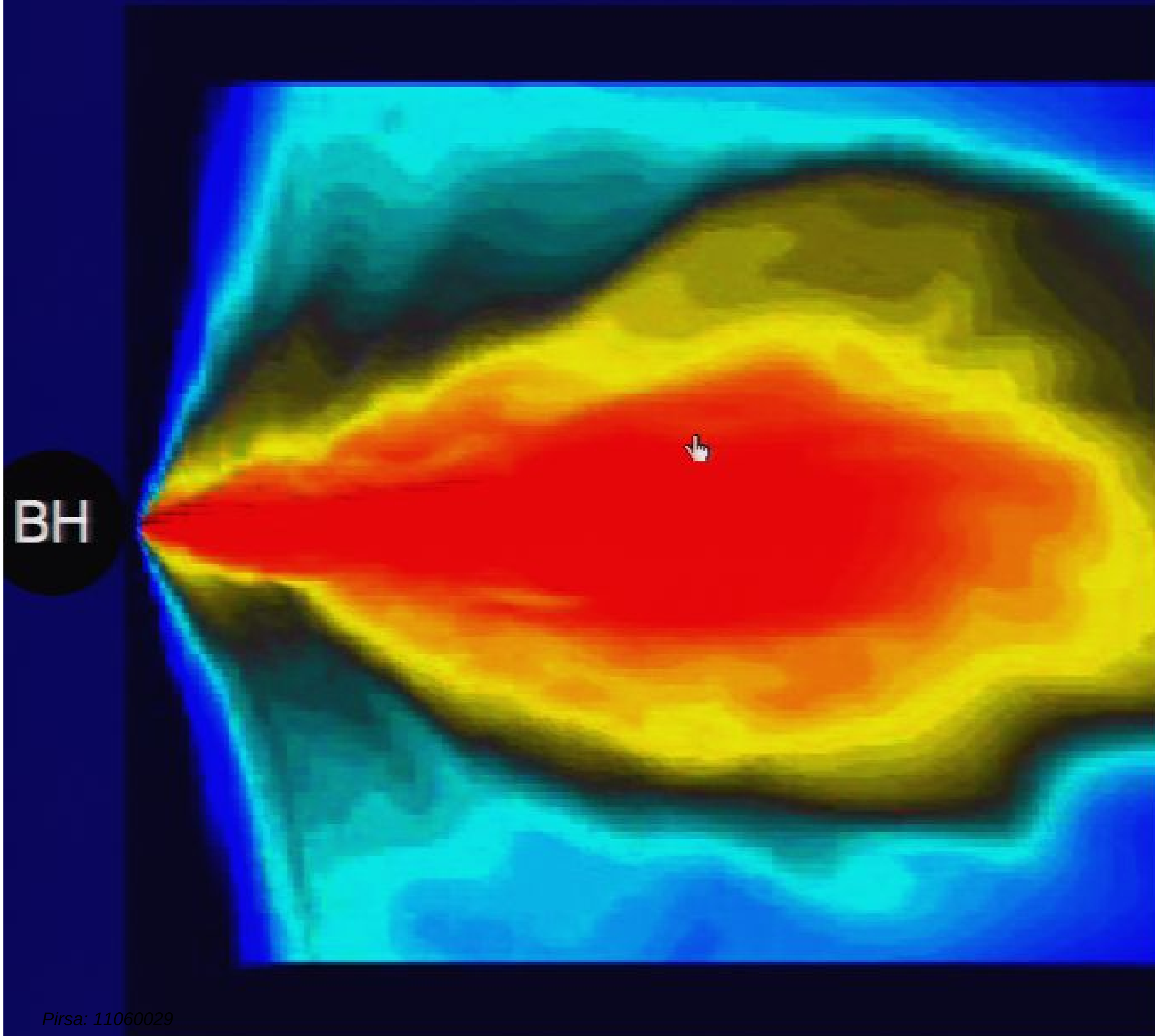

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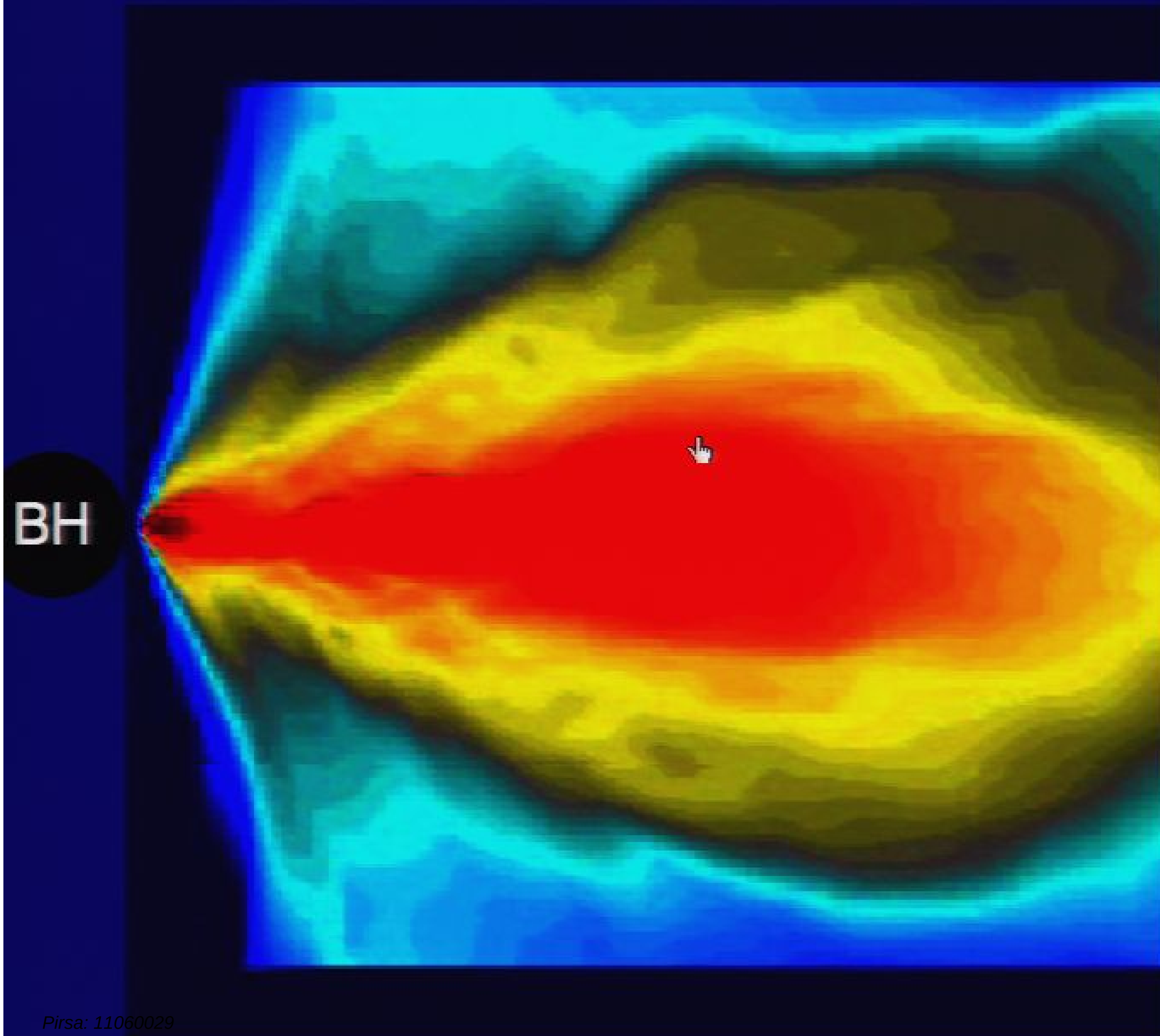

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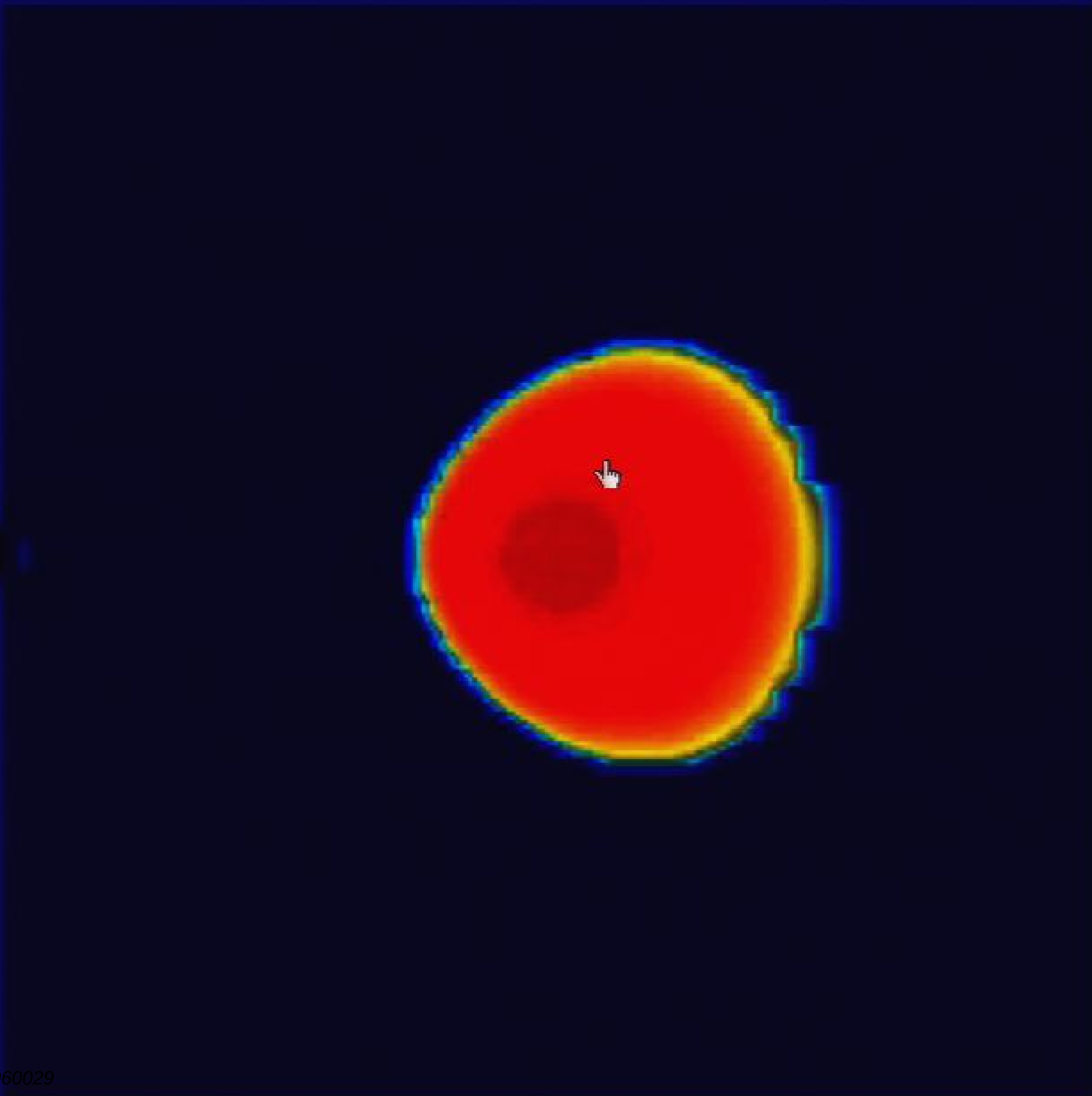

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Viscous Evolution of the Remnant Disk

Metzger, Piro & Quataer 2008, 2009

Angular Momentum

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{r}\frac{\partial}{\partial r}\left[r^{1/2}\frac{\partial}{\partial r}\left(\nu \Sigma r^{1/2}\right)\right]$$

$$\nu = \alpha c_s H$$

Entropy

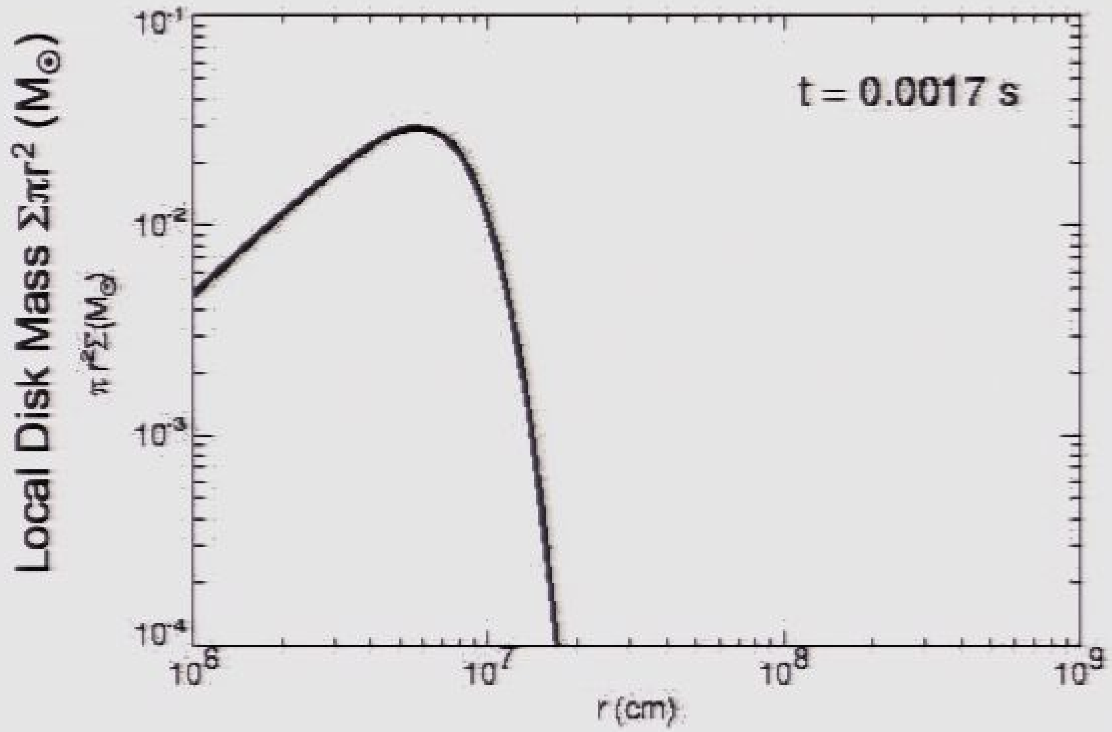
$$T\frac{dS}{dt} = \dot{q}_{visc} - \dot{q}_{\nu}$$

Heating

Cooling

Nuclear Composition

$$\frac{dY_e}{dt} = (\lambda_{e^+ n \rightarrow p\nu} + \lambda_{e^- p \rightarrow n\nu})\left[1 - Y_e - \left(\frac{1 - X_f}{2}\right)\right]$$



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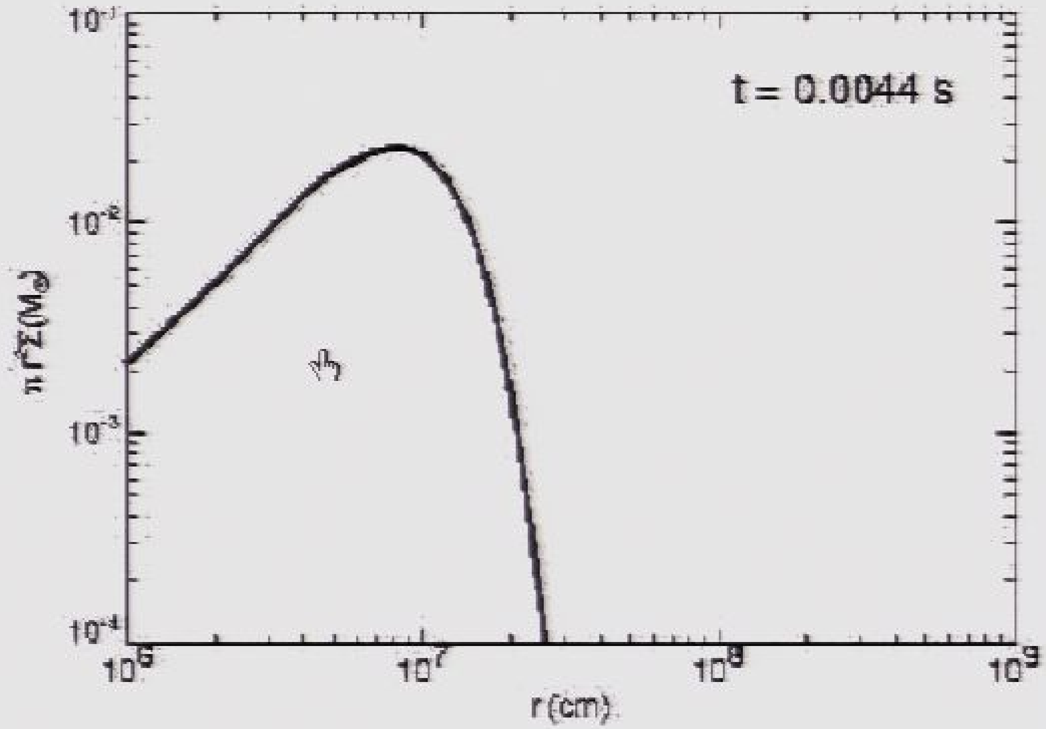

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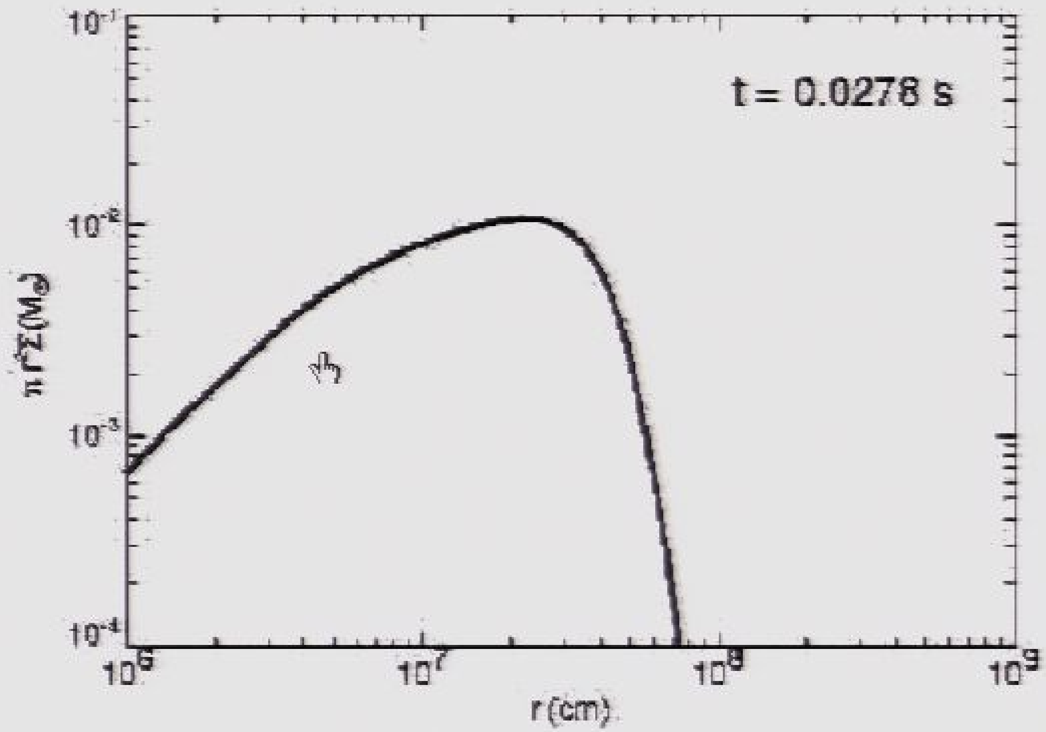

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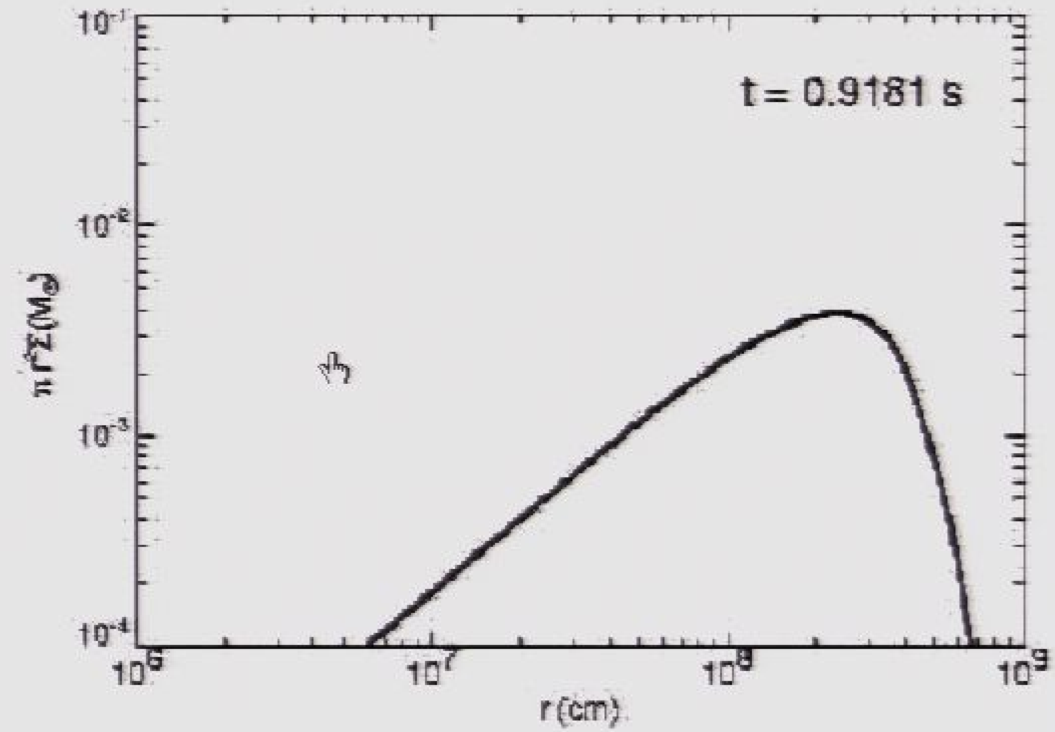

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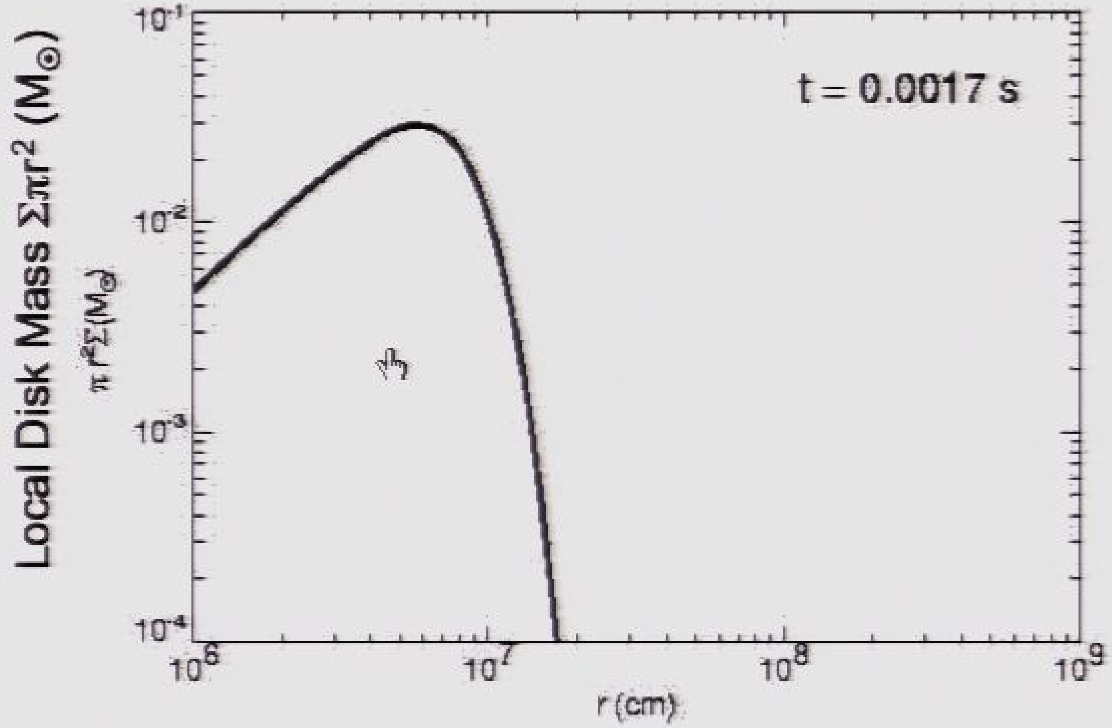
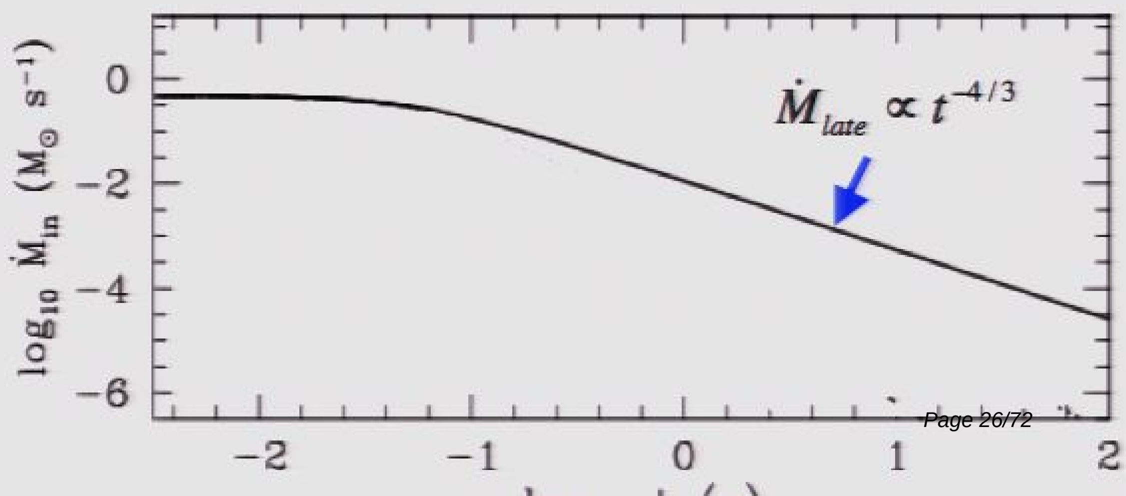
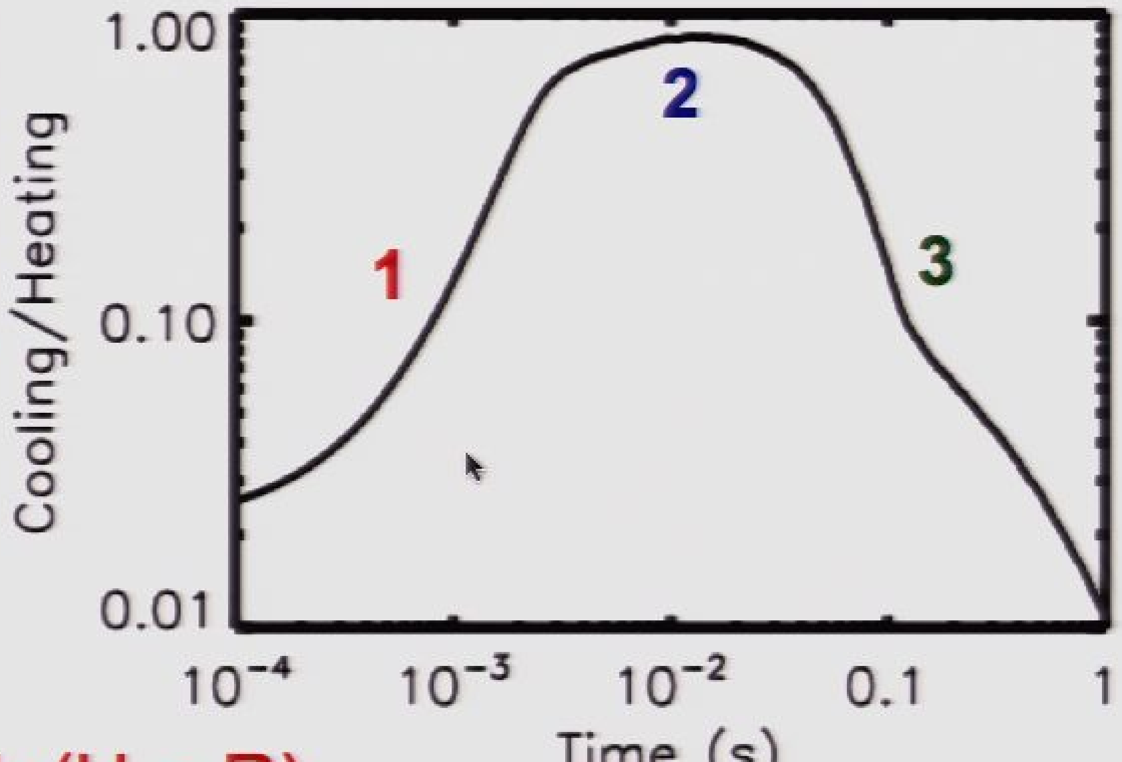




Three Accretion Phases

Metzger, Piro & Quataert 08, 09



1) **High $\dot{M}$ Thick Disk** (H ~ R)
   - matter accretes before cooling (neutrino trapped)

2) **Neutrino-Cooled Thin Disk** (H ~ 0.2 R)
   - geometrically thin; tightly gravitationally bound
   - neutrino luminosity $L_\nu \sim 0.1 \dot{M} c^2$

3) **Low $\dot{M}$ Thick Disk** (H ~ R)
   - radiatively inefficient (neutrino cooling << viscous heating)

Late-Time Disk Winds ("Evaporation")

After $t \sim 0.1\text{-}1$ seconds, $R \sim 500$ km & $T < 1$ MeV

- **Recombination: n + p ⇒ He**

  $E_{BIND} \sim GM_{BH}m_n/2R \sim 3$ MeV nucleon^{-1}

  $\Delta E_{NUC} \sim 7$ MeV nucleon^{-1}

- **Thick Disks Marginally Bound**

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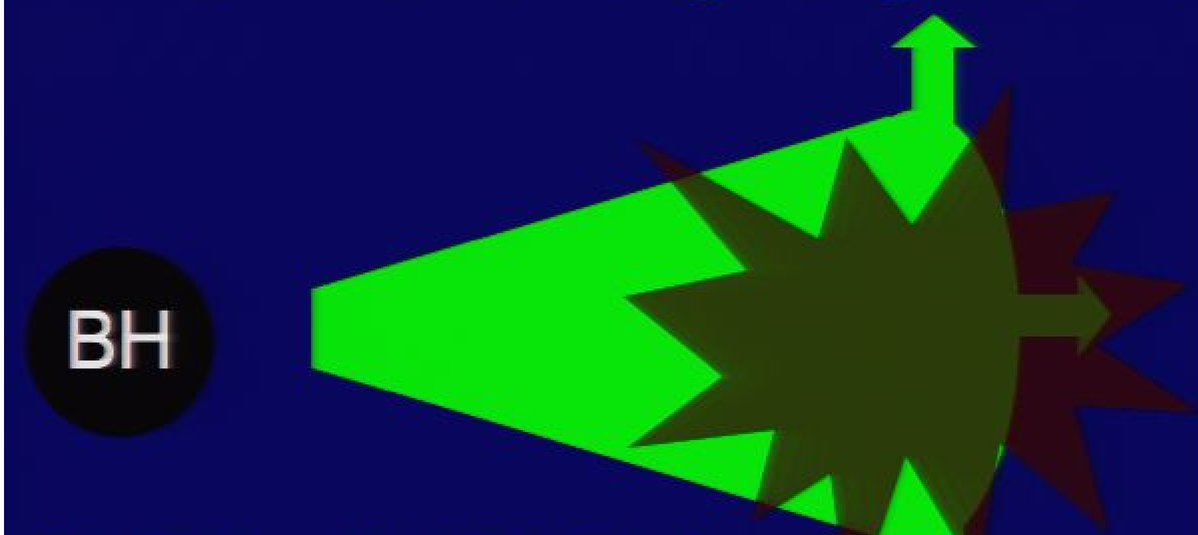
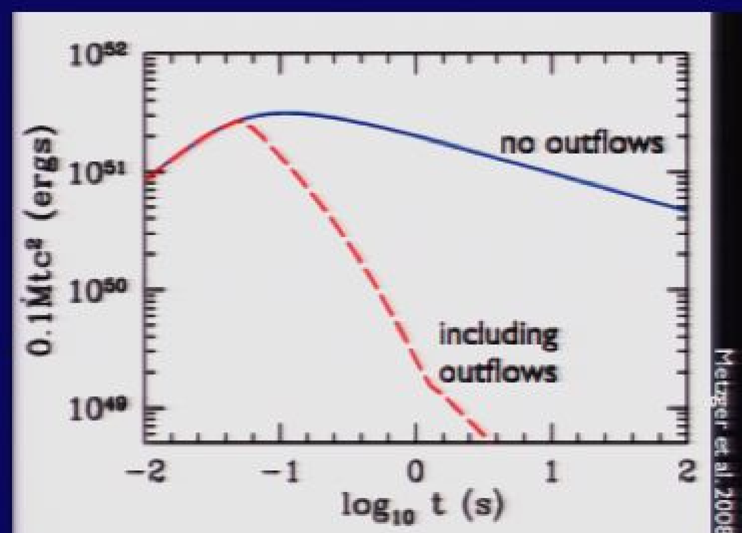
} ⇒ **Powerful Winds Blow Apart Disk**

(see also Lee et al. 2009)



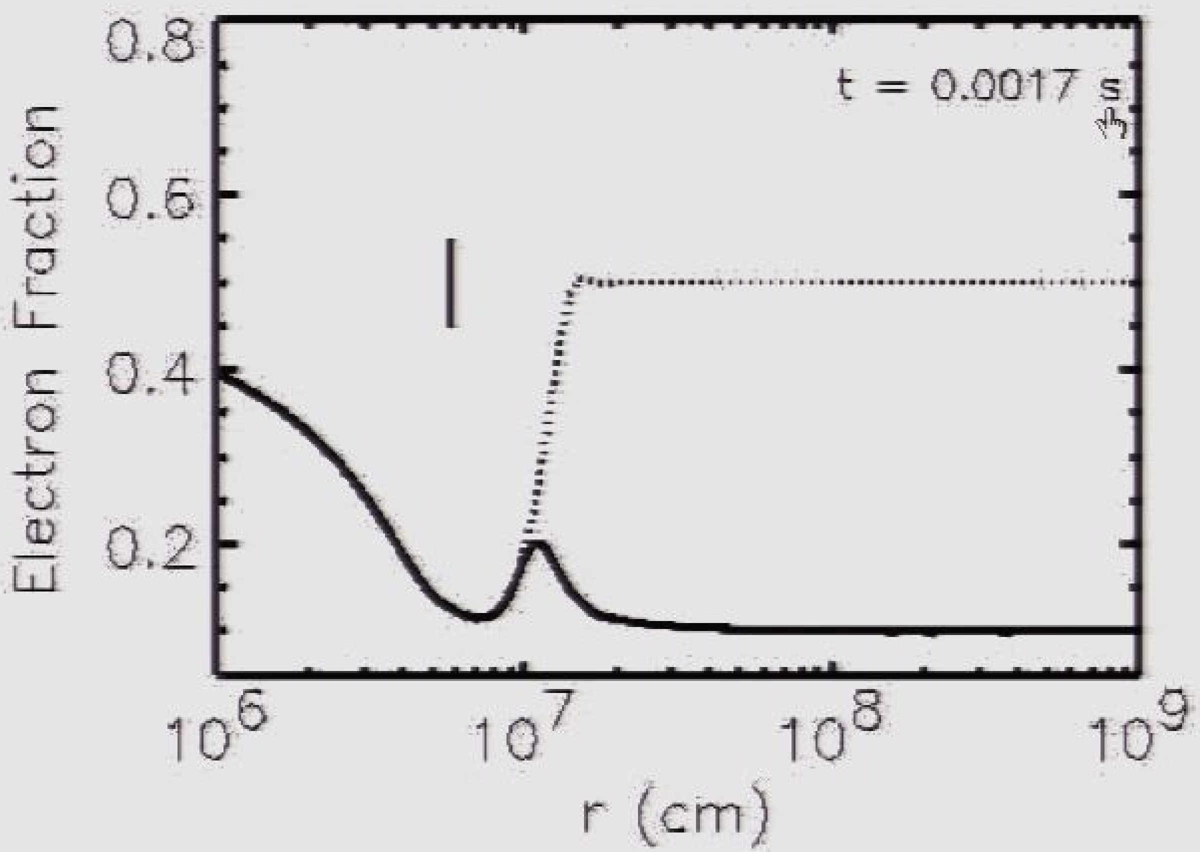
~20-50% of Initial Disk Ejected Back into Space!



Accretion of the Initial Disk Cannot Power Late Time Activity in SGRBs

Neutron Rich Freeze Out ("Little Bang")

Metzger, Piro & Quataert 2009



Weak Interactions

$$e^- + p \rightarrow \nu_e + n$$

$$e^+ + n \rightarrow \bar{\nu}_e + p$$

Drive $Y_e \Rightarrow Y_e^{eq}$ Until Freeze-Out

Y_e^{eq} ....

Y_e ——

Thickening / Freeze-Out Begins at the Outer Disk and Moves Inwards

Limited β-equilibrium assumed in most multi-D disk simulations !

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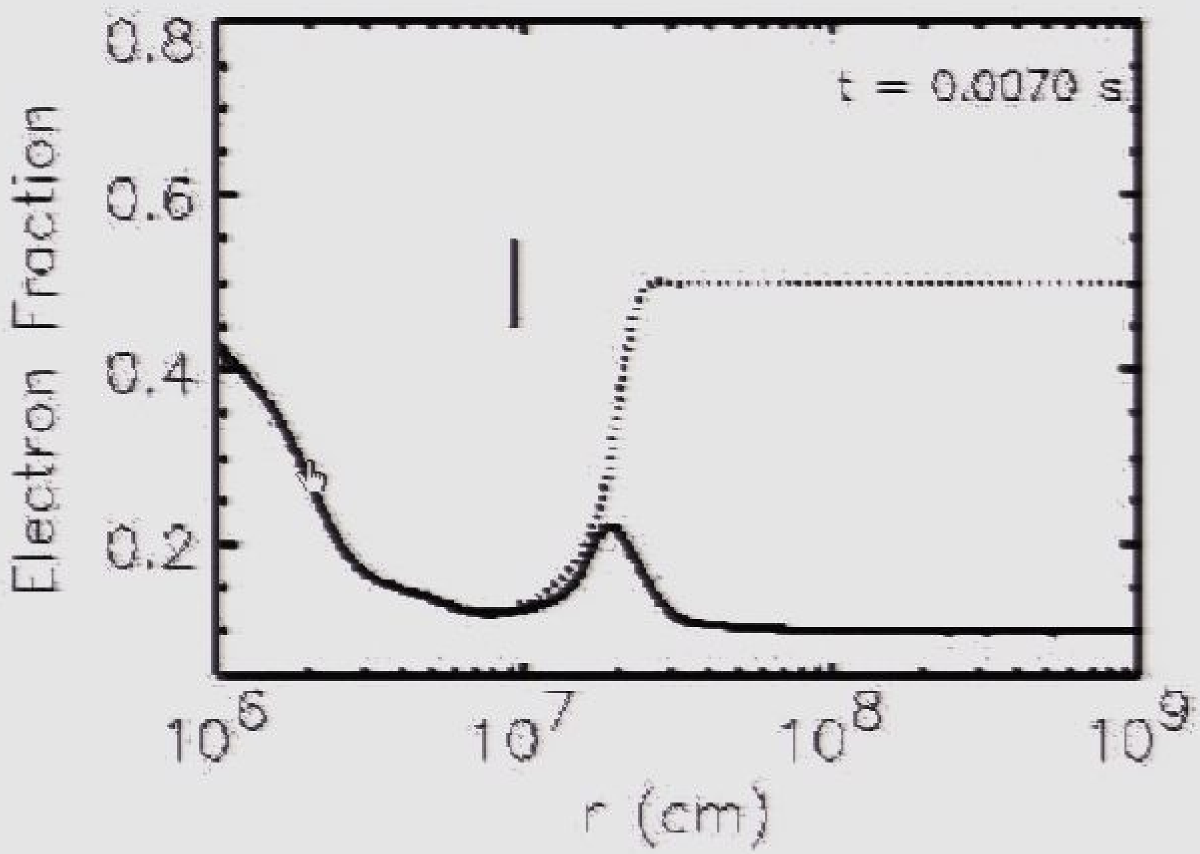

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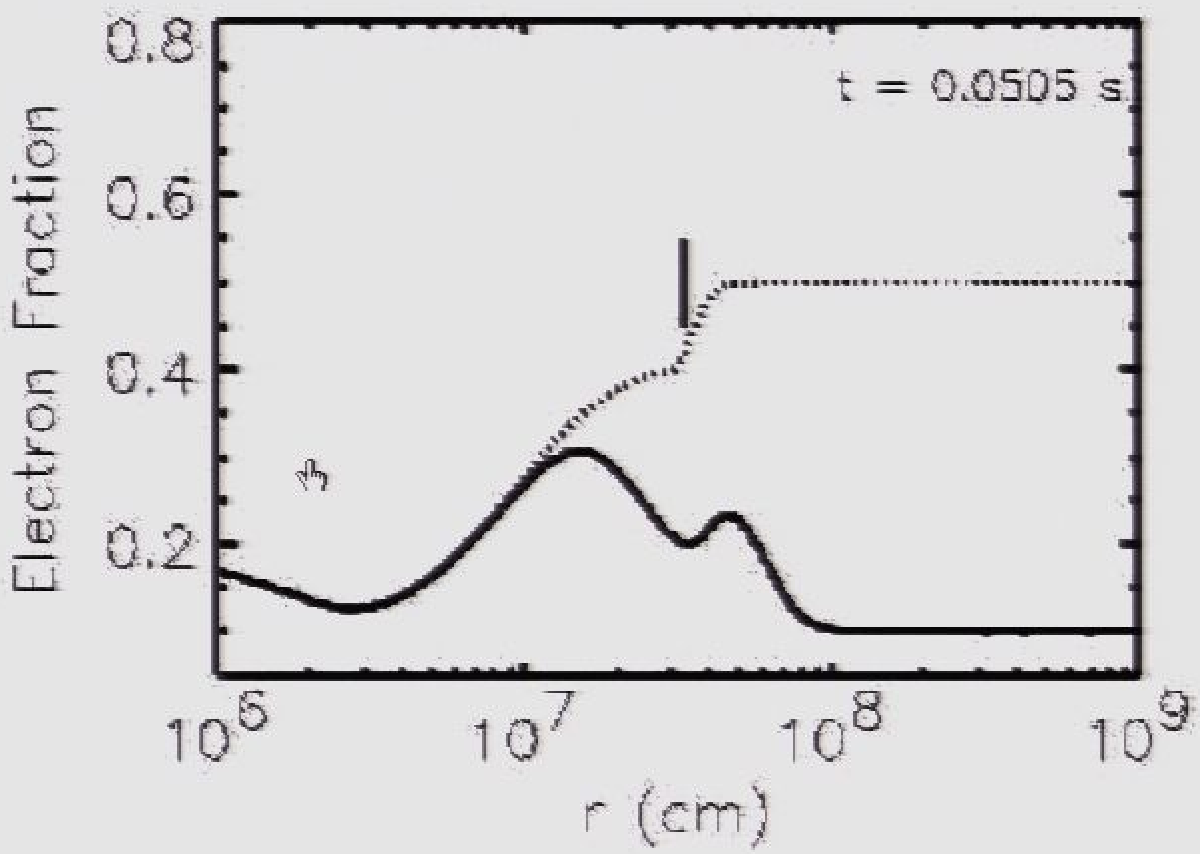
Neutron Rich Freeze Out ("Little Bang")

Metzger, Piro & Quataert 2009



Weak Interactions

$$e^- + p \rightarrow \nu_e + n$$

$$e^+ + n \rightarrow \bar{\nu}_e + p$$

Drive $Y_e \Rightarrow Y_e^{eq}$ Until Freeze-Out

Y_e^{eq} ....

Y_e ——

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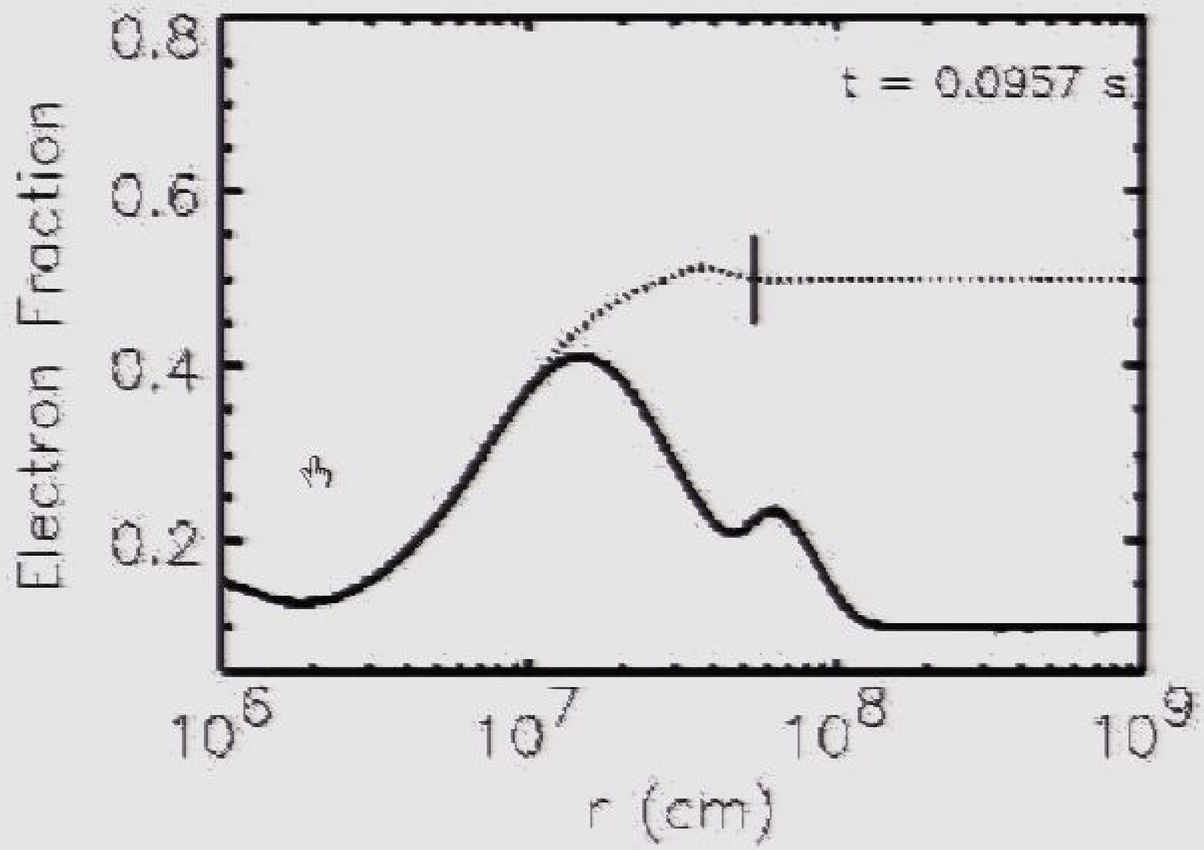

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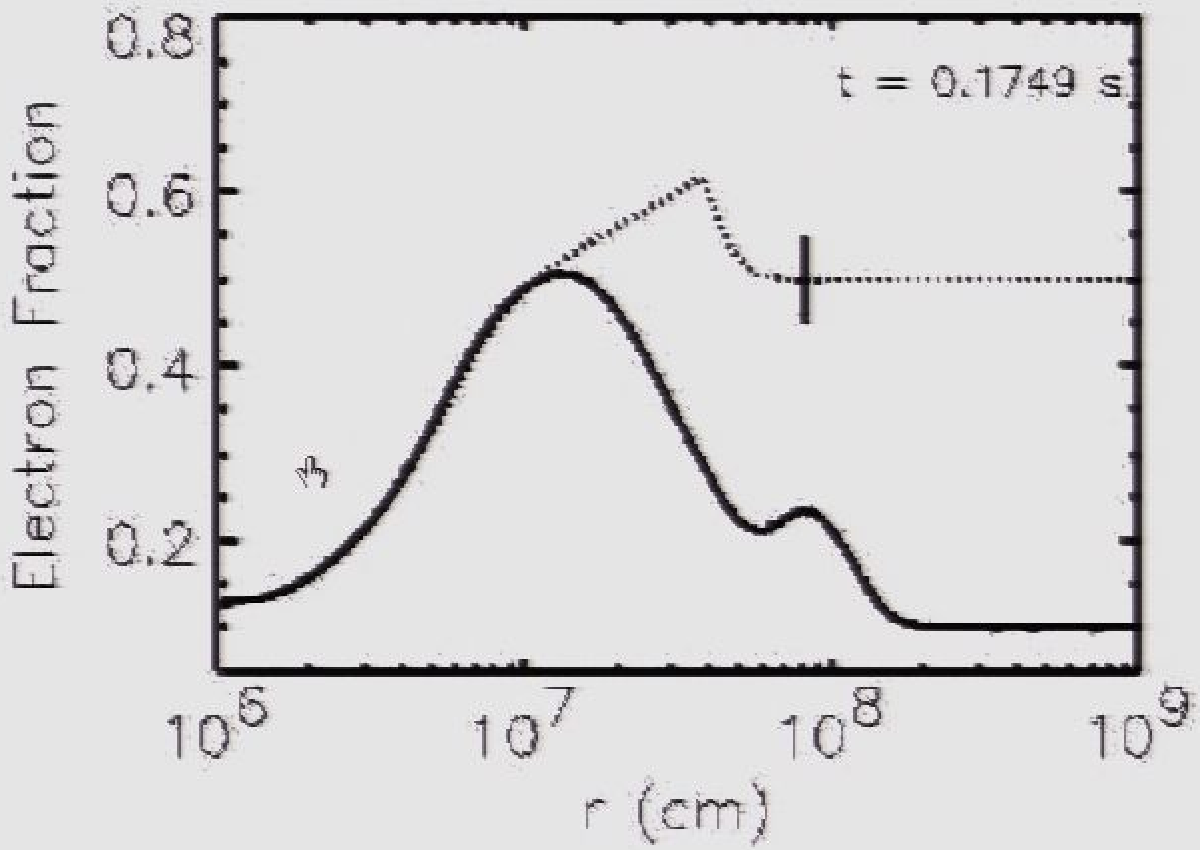

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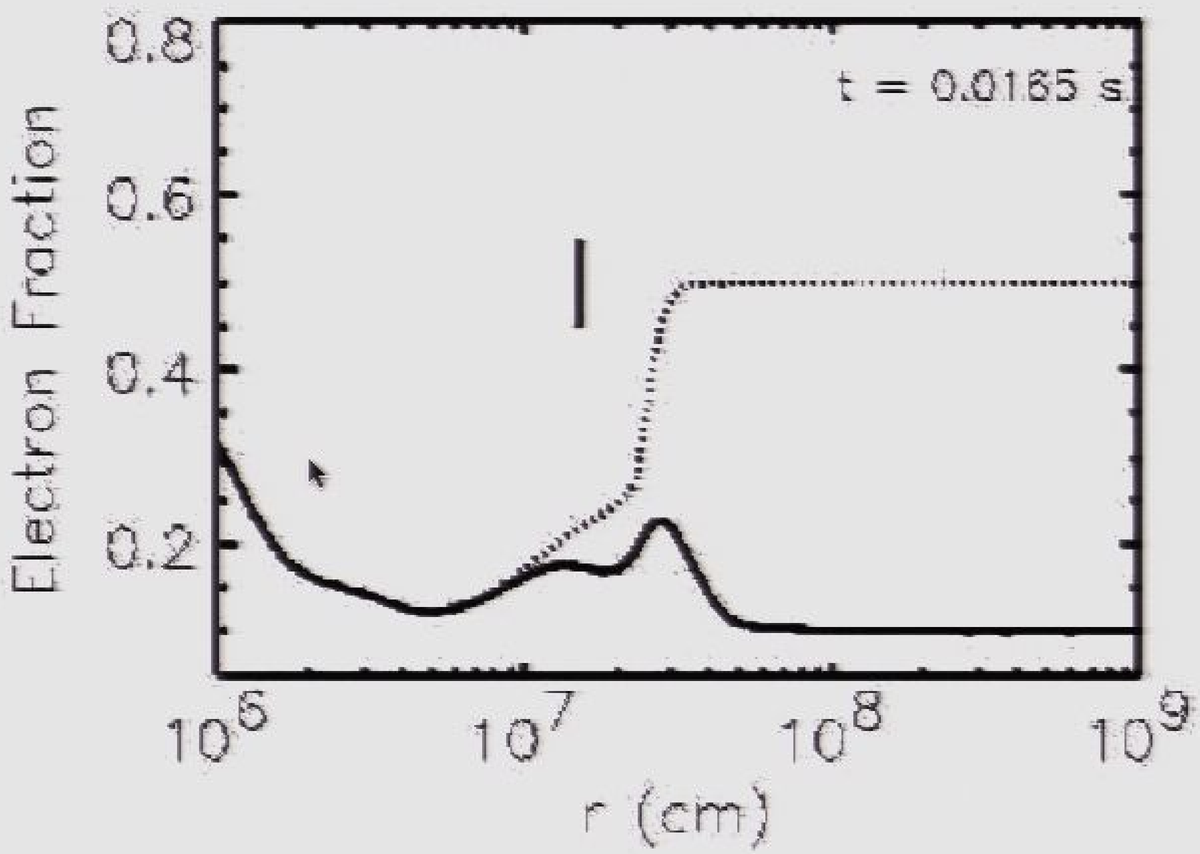

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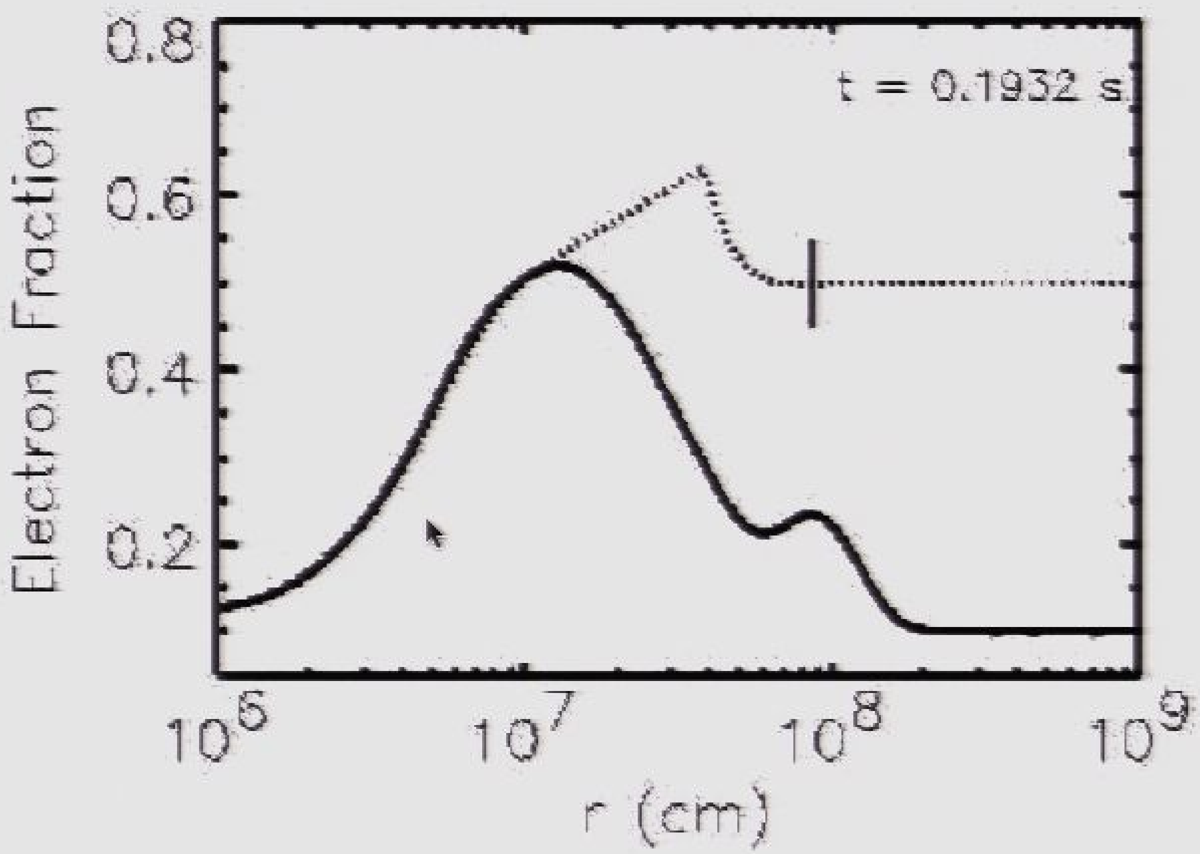

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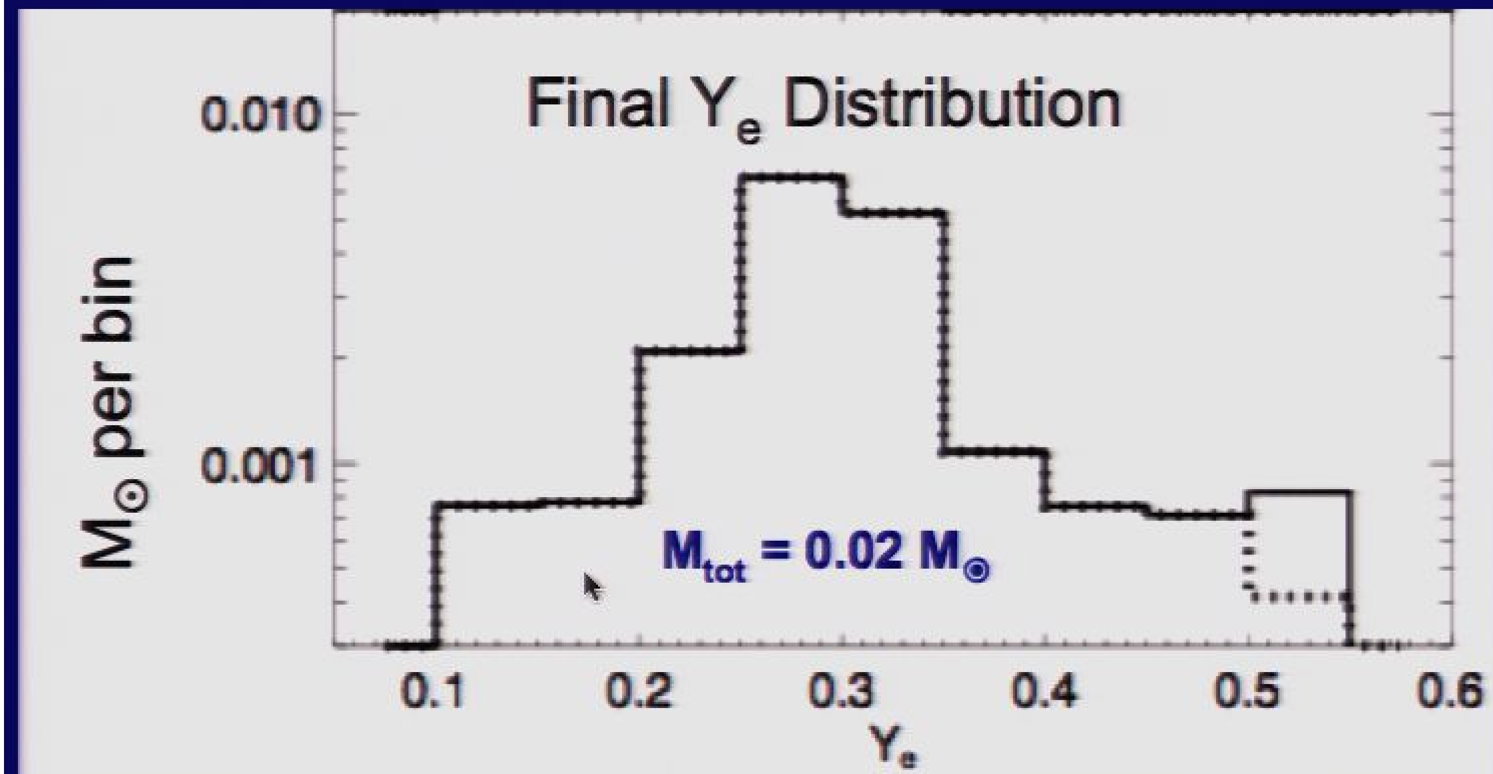

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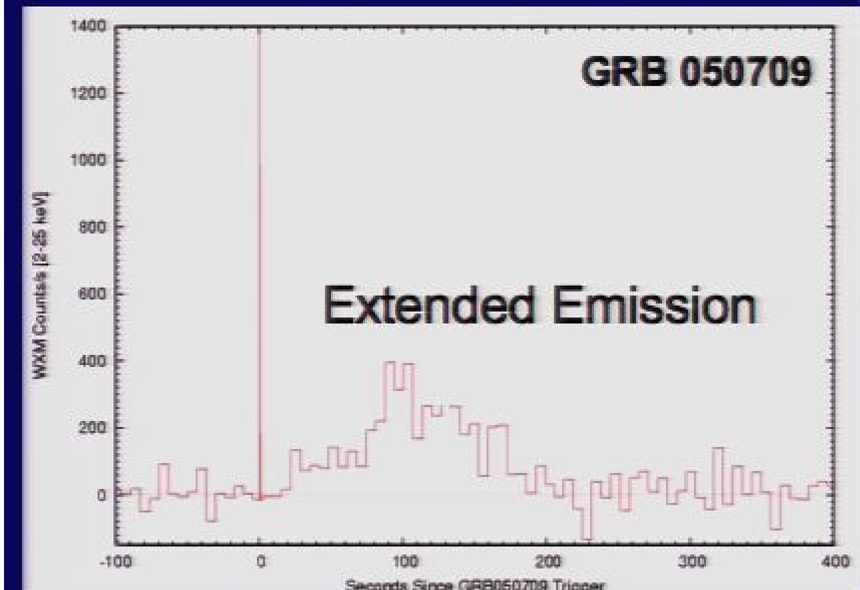
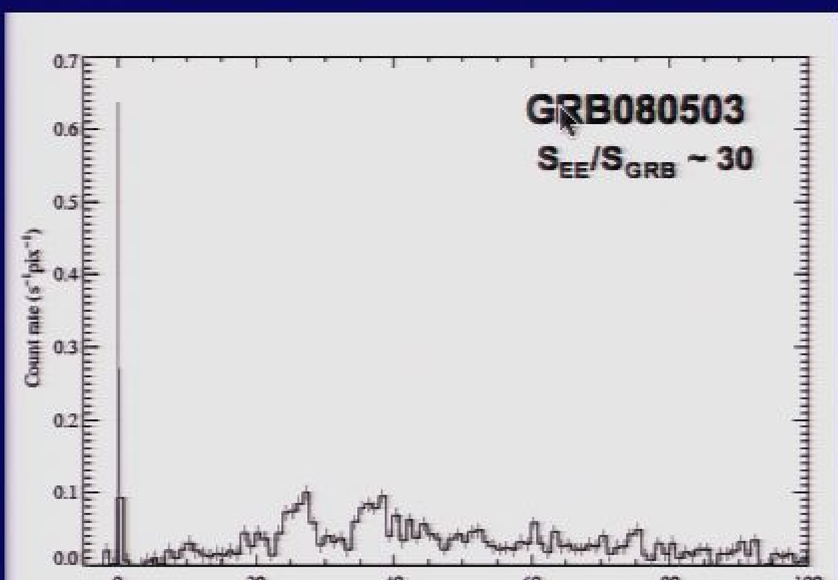
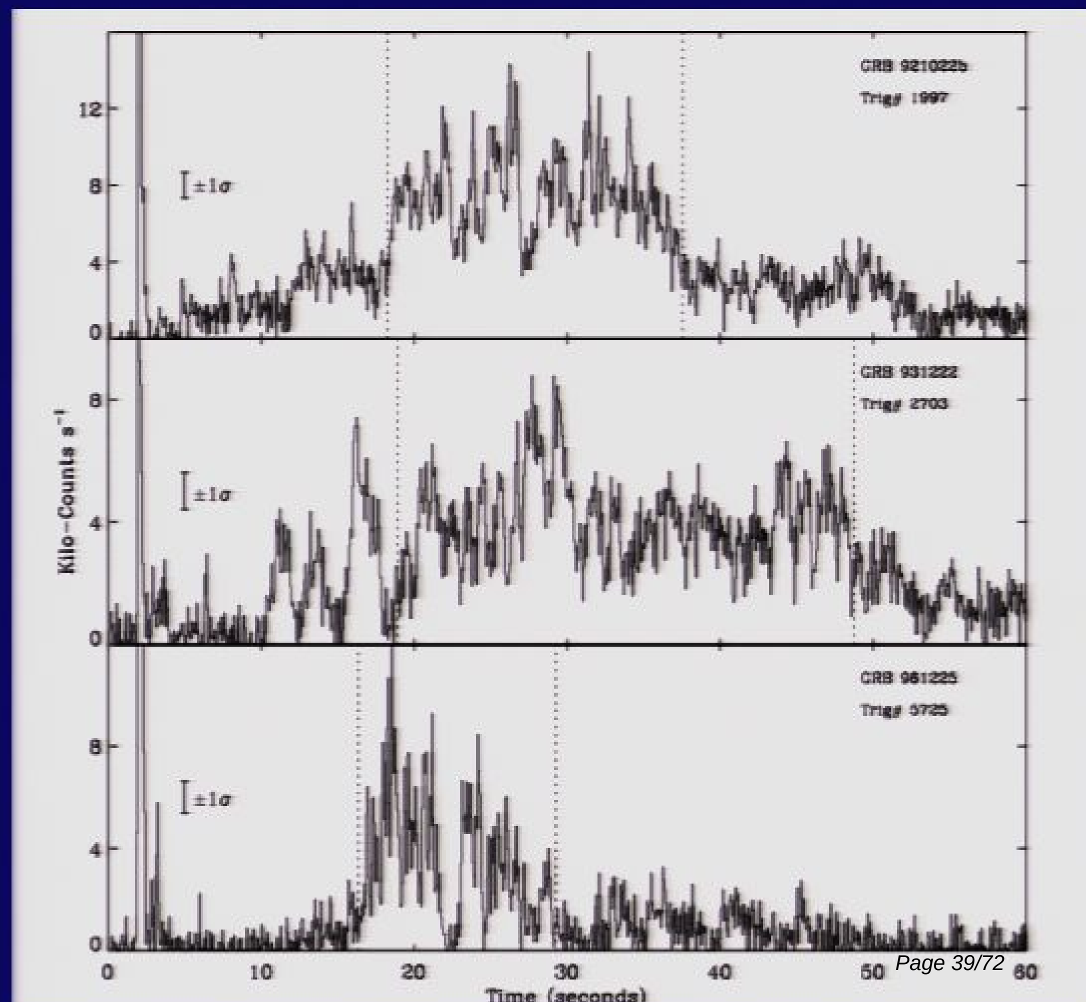
Mystery of Short GRBs with Extended Emission

- 1/4 Swift Short Bursts have X-ray Tails
- Rapid Variability ⇒ Ongoing Engine Activity
- Energy up to ~30 times Burst Itself!



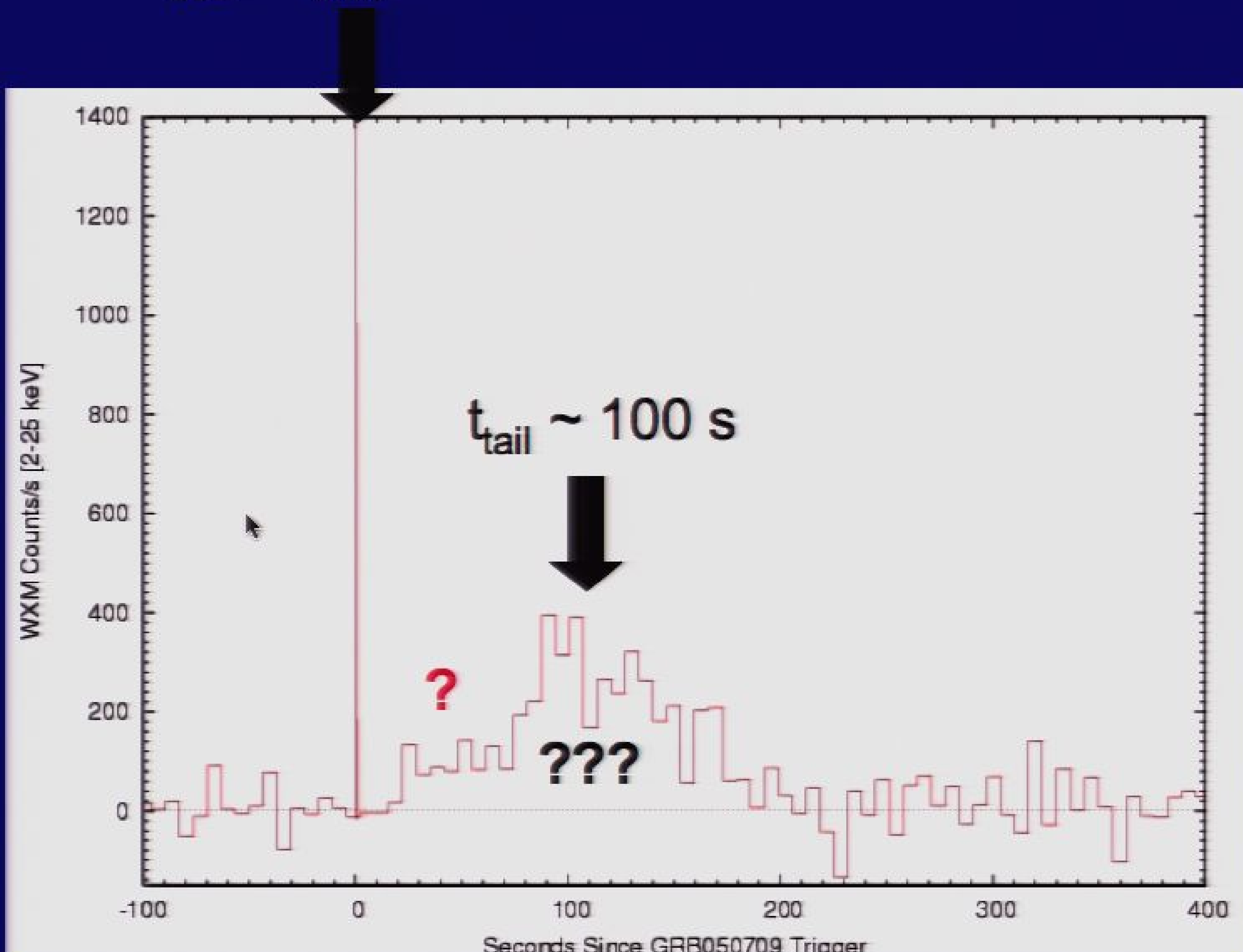




Perley, BDM et al. 2009

Why Two Timescales? Why the Delay?

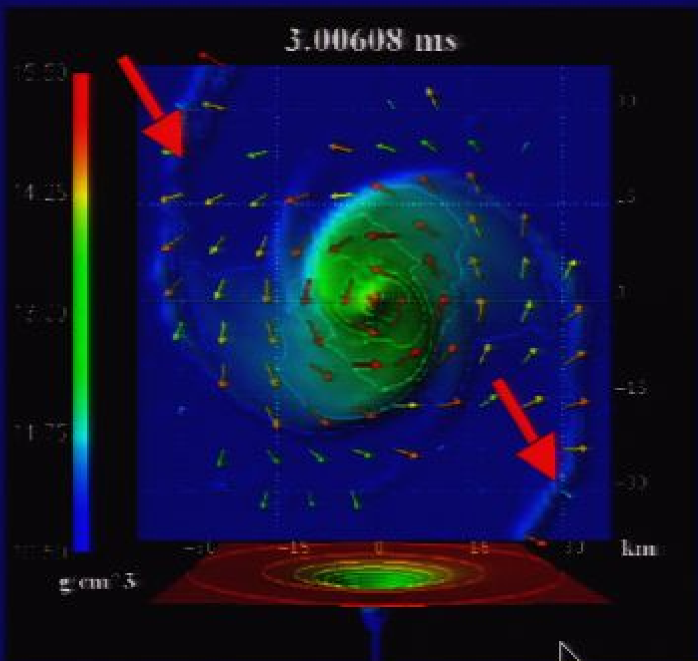
$t_{acc} \sim t_{disk} \sim 0.1\text{-}1$ s



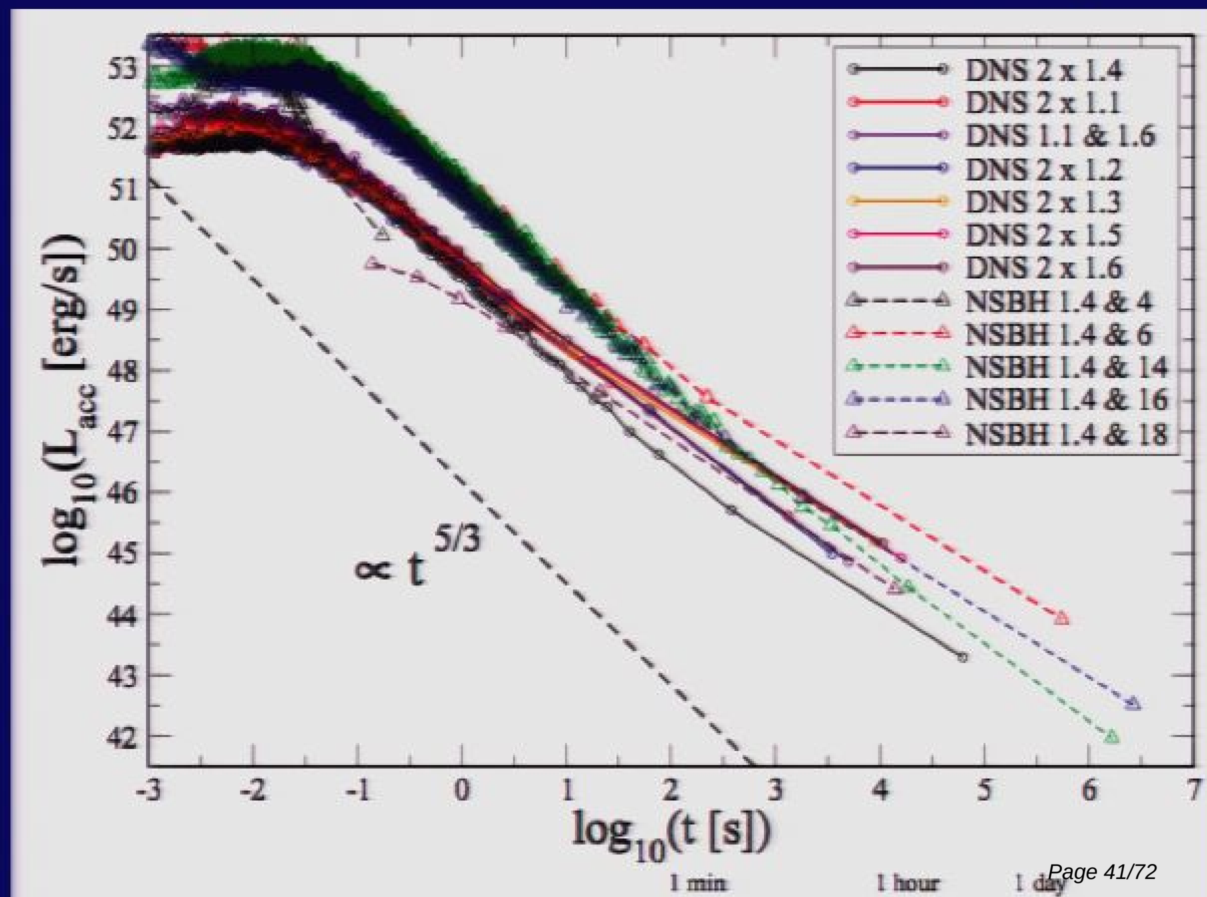
Late Time Fall Back Accretion

Tidal Tails

(e.g. Faber et al. 2006, Lee & Ramirez-Ruiz 2007)



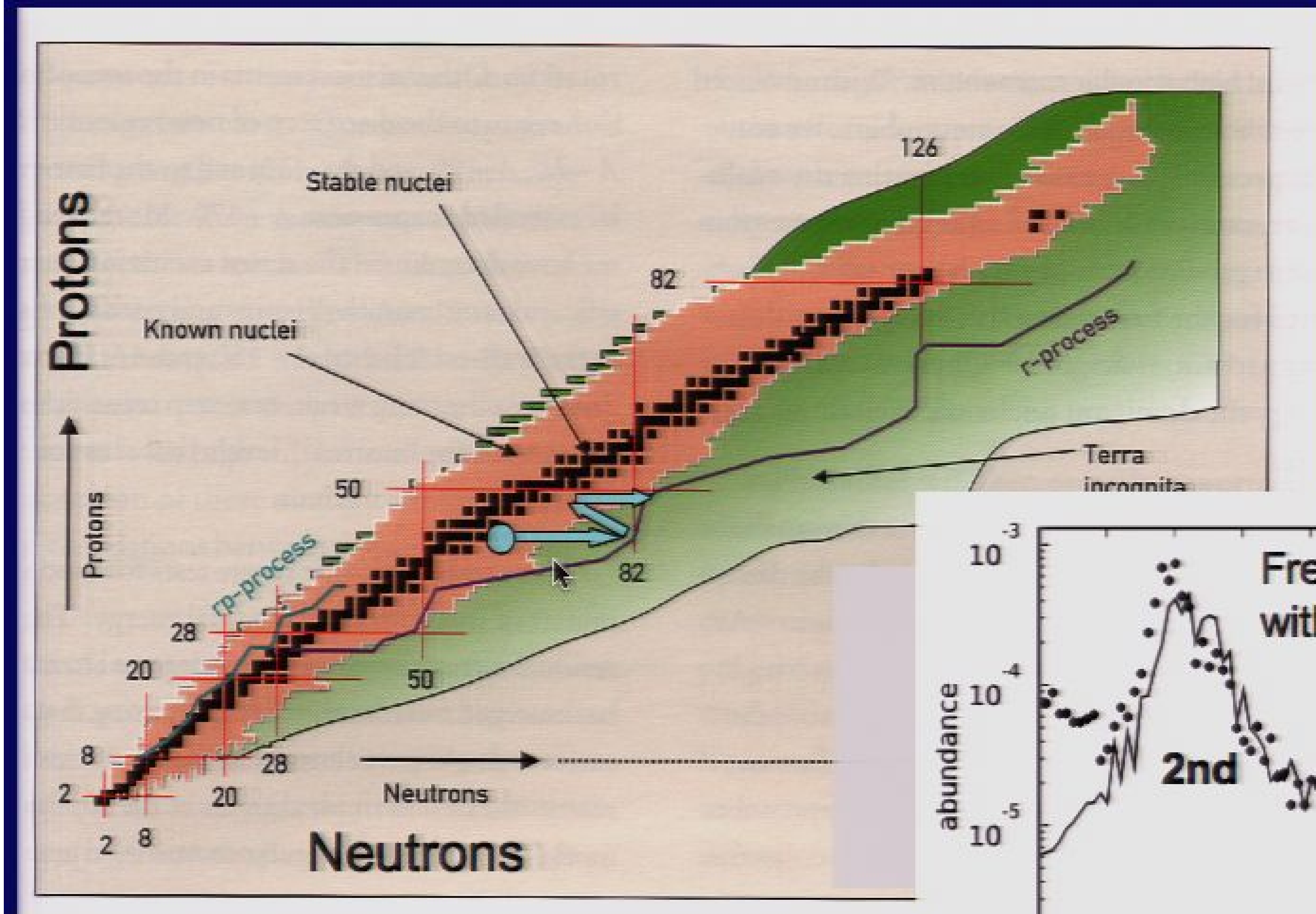
Fallback Accretion Luminosity



Rapid Neutron Capture (R - Process) Heating

Decompressing NS Matter ⇒ A ~ 100 Nuclei + Free Neutrons

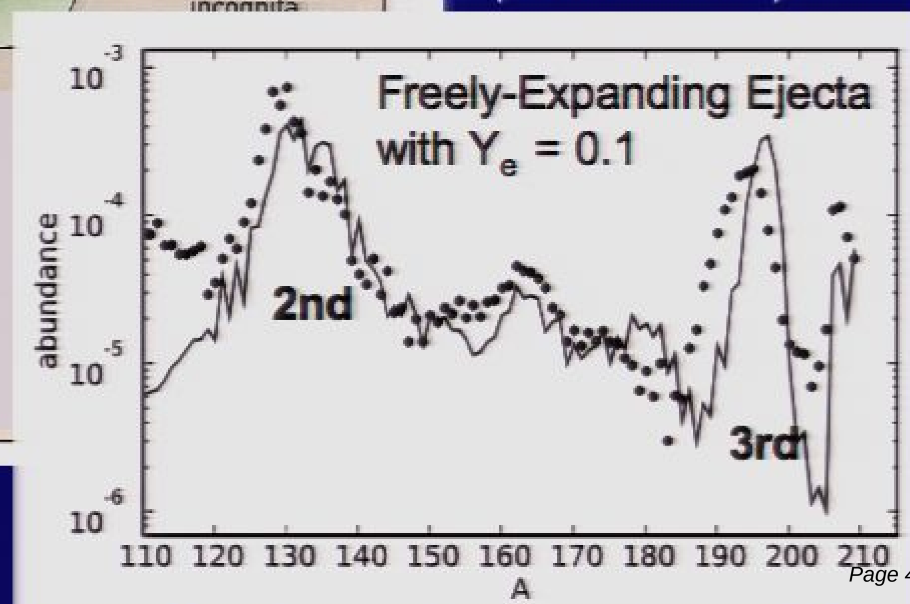
(Lattimer et al. 1977; Meyer 1989; Freiburghaus et al. 1999):



R-Process Network

(Martinez-Pinedo 2008)

- neutron captures
(Rauscher & Thielemann 2000)
- photo-dissociations
- α- and β-decays
- fission reactions
(Panov et al. 2009).



BDM, Martinez-Pinedo et al. 2010
(Cf. Freiburghaus et al. 1999)

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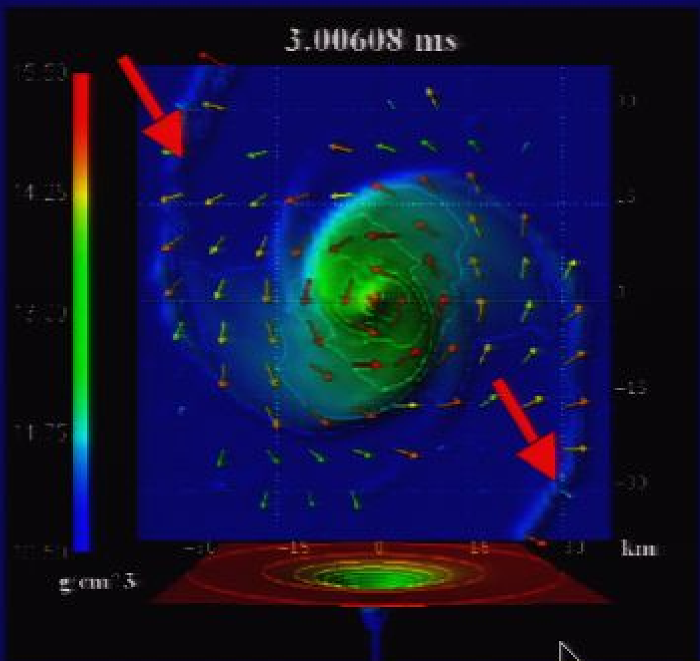
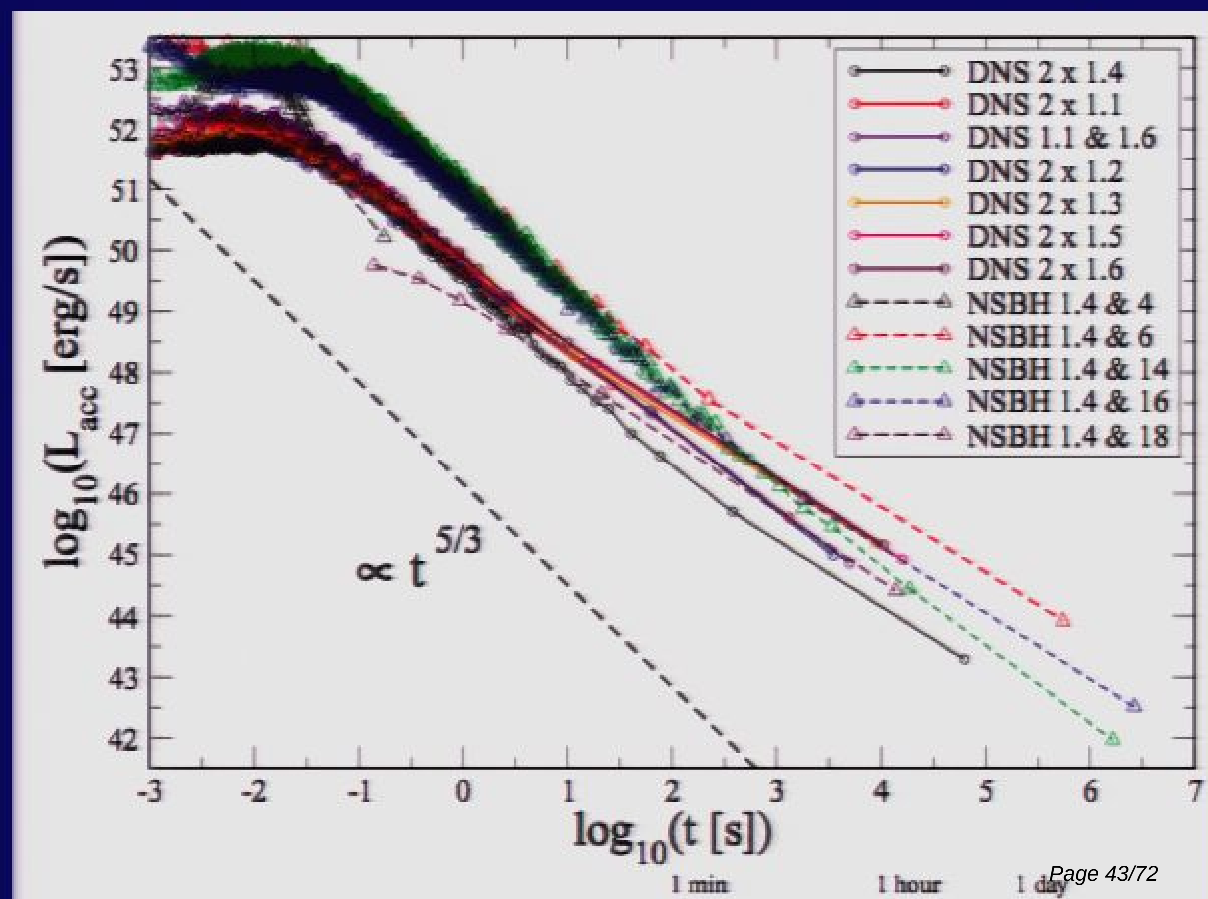


Fallback Accretion Luminosity



Rosswog 2007

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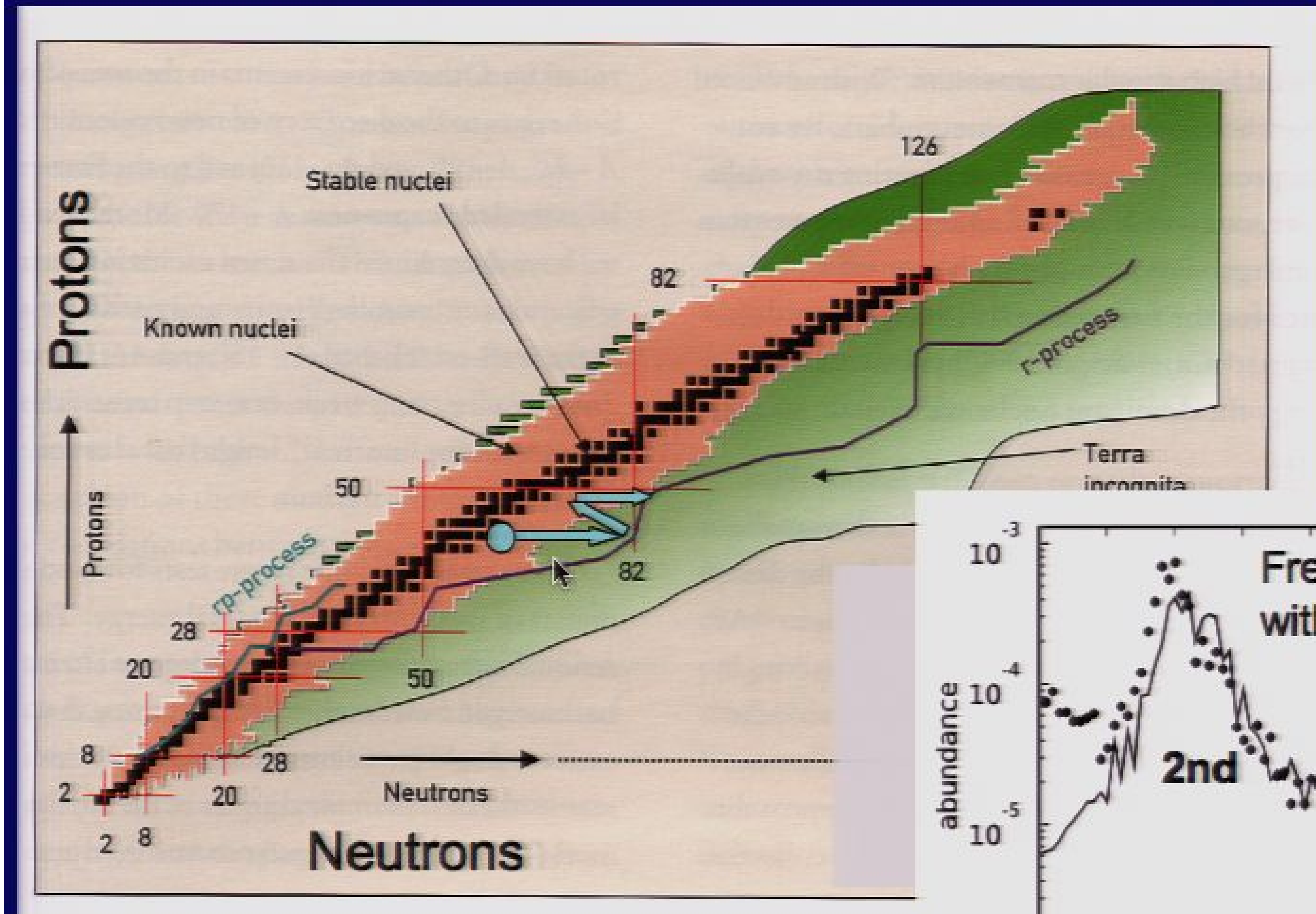

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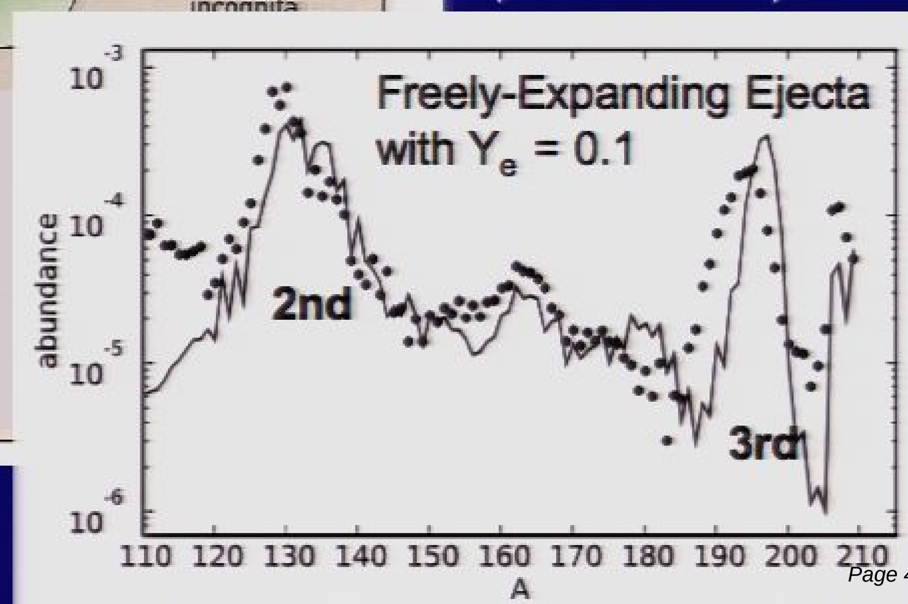
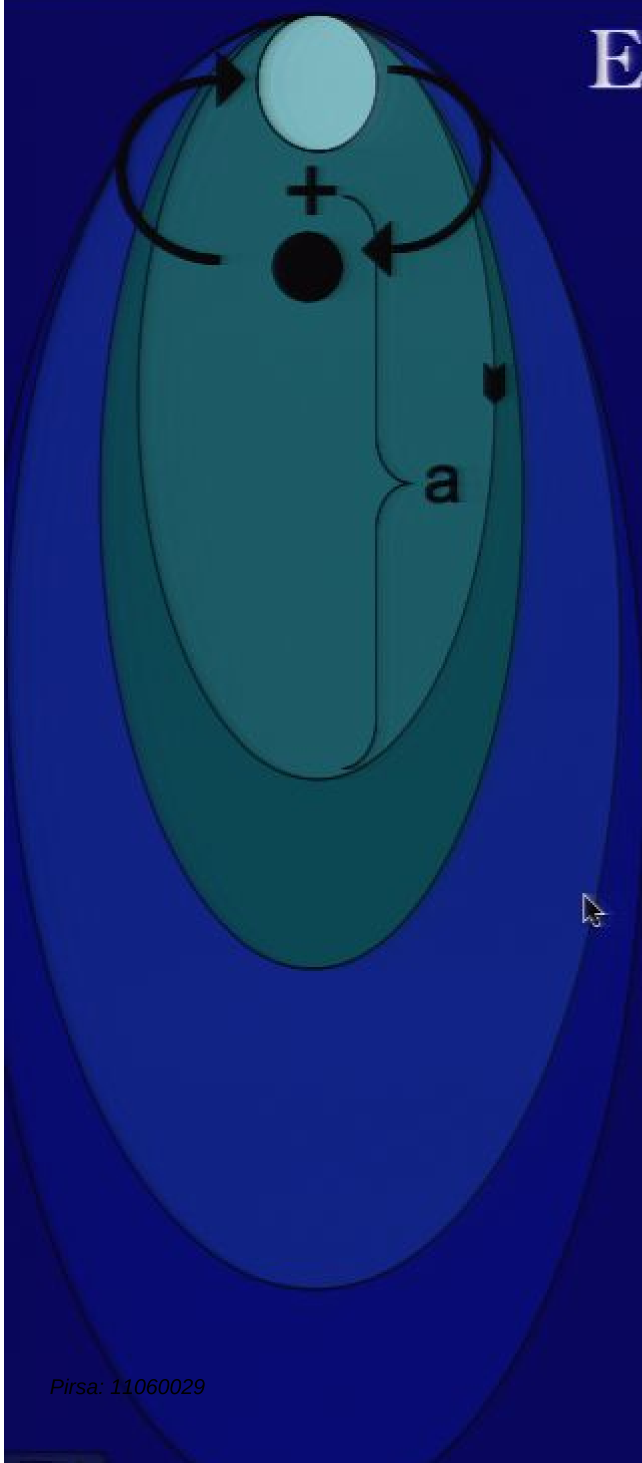


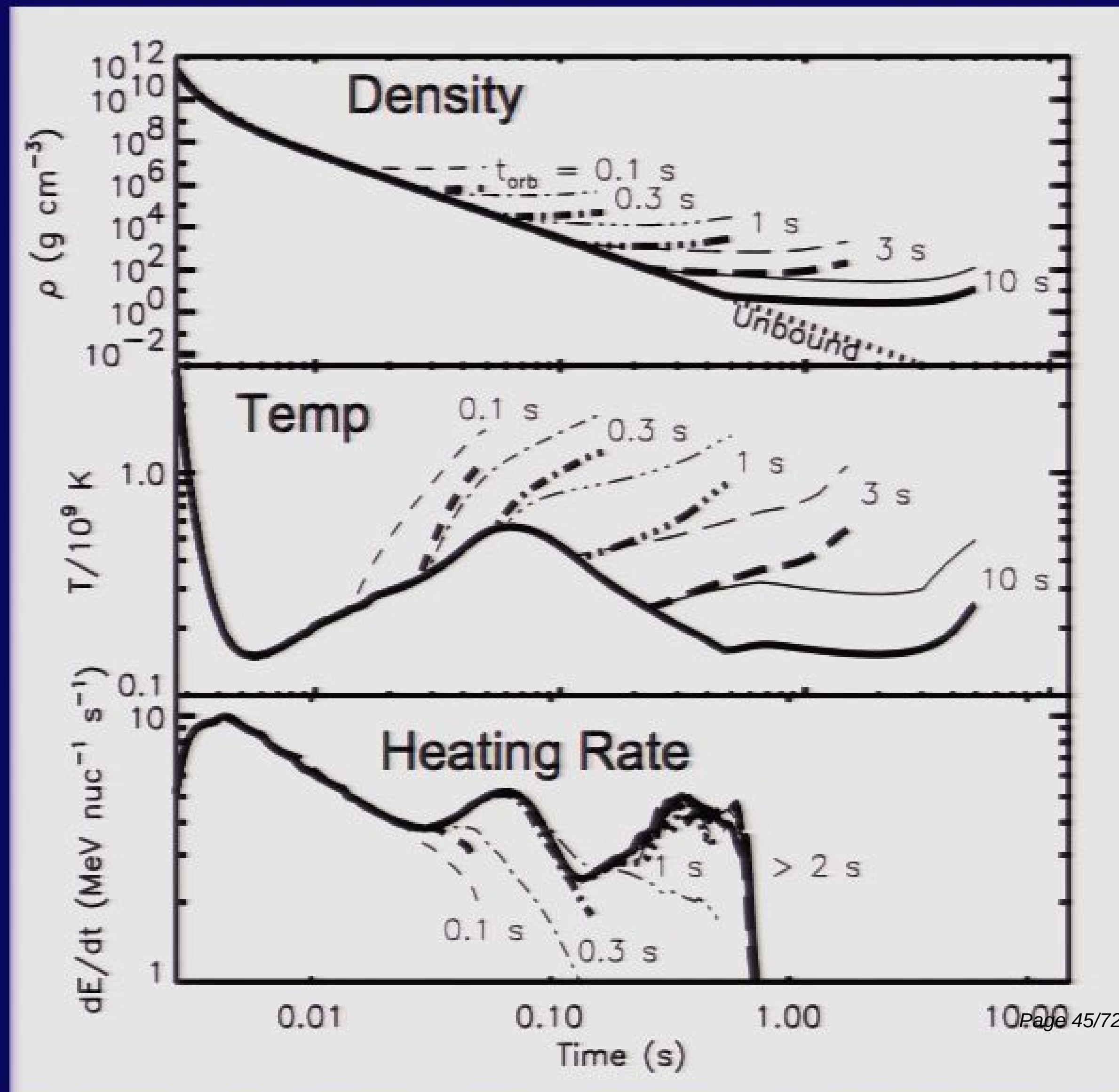
BDM, Martinez-Pinedo et al. 2010
(Cf. Freiburghaus et al. 1999)

Effects of r-Process on Fall-Back Accretion

Metzger, Arcones, Quataert, & Martinez-Pinedo 2010



Nucleosynthesis along Lagrangian Orbits



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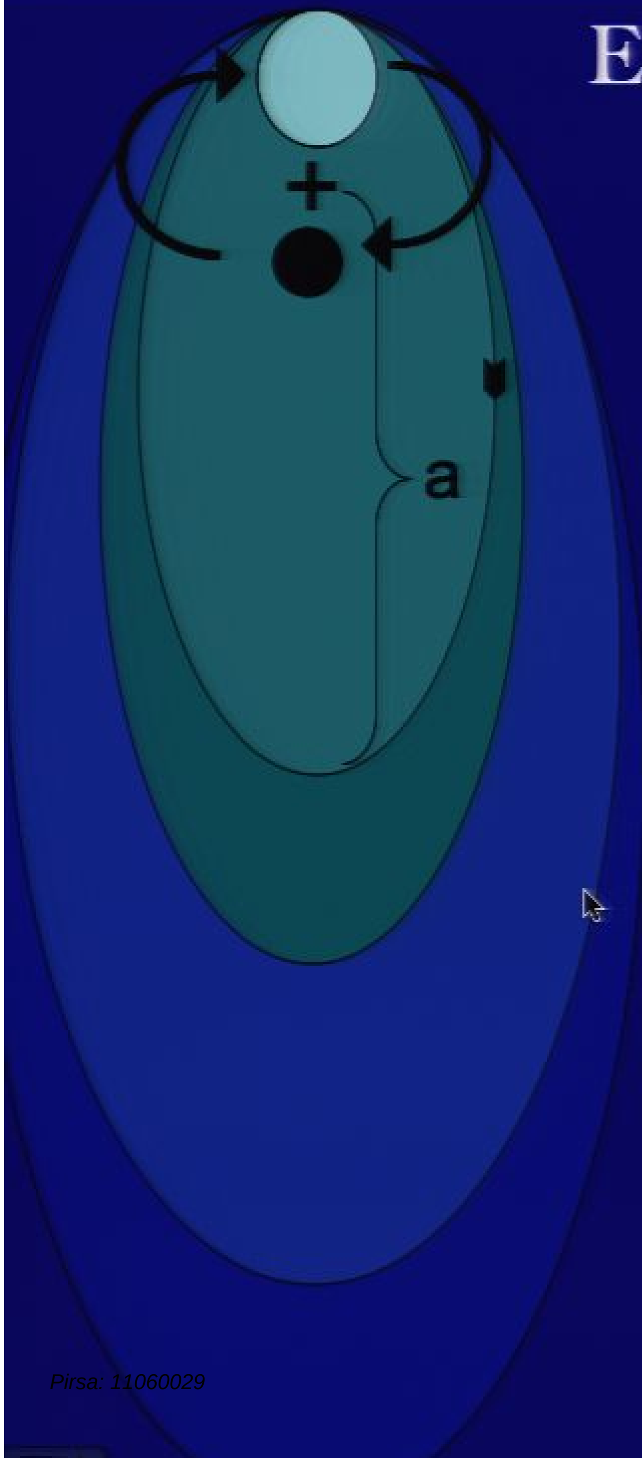
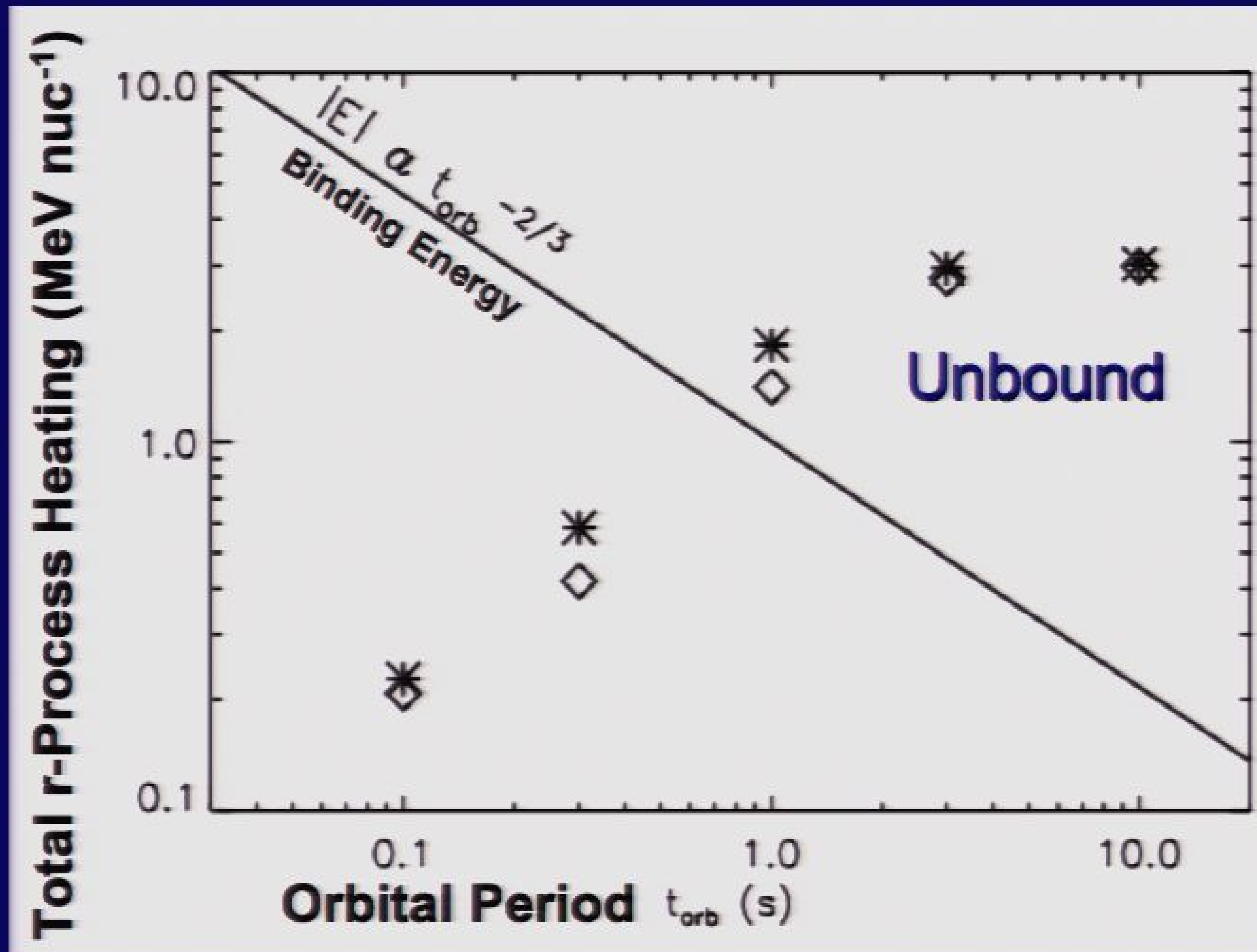
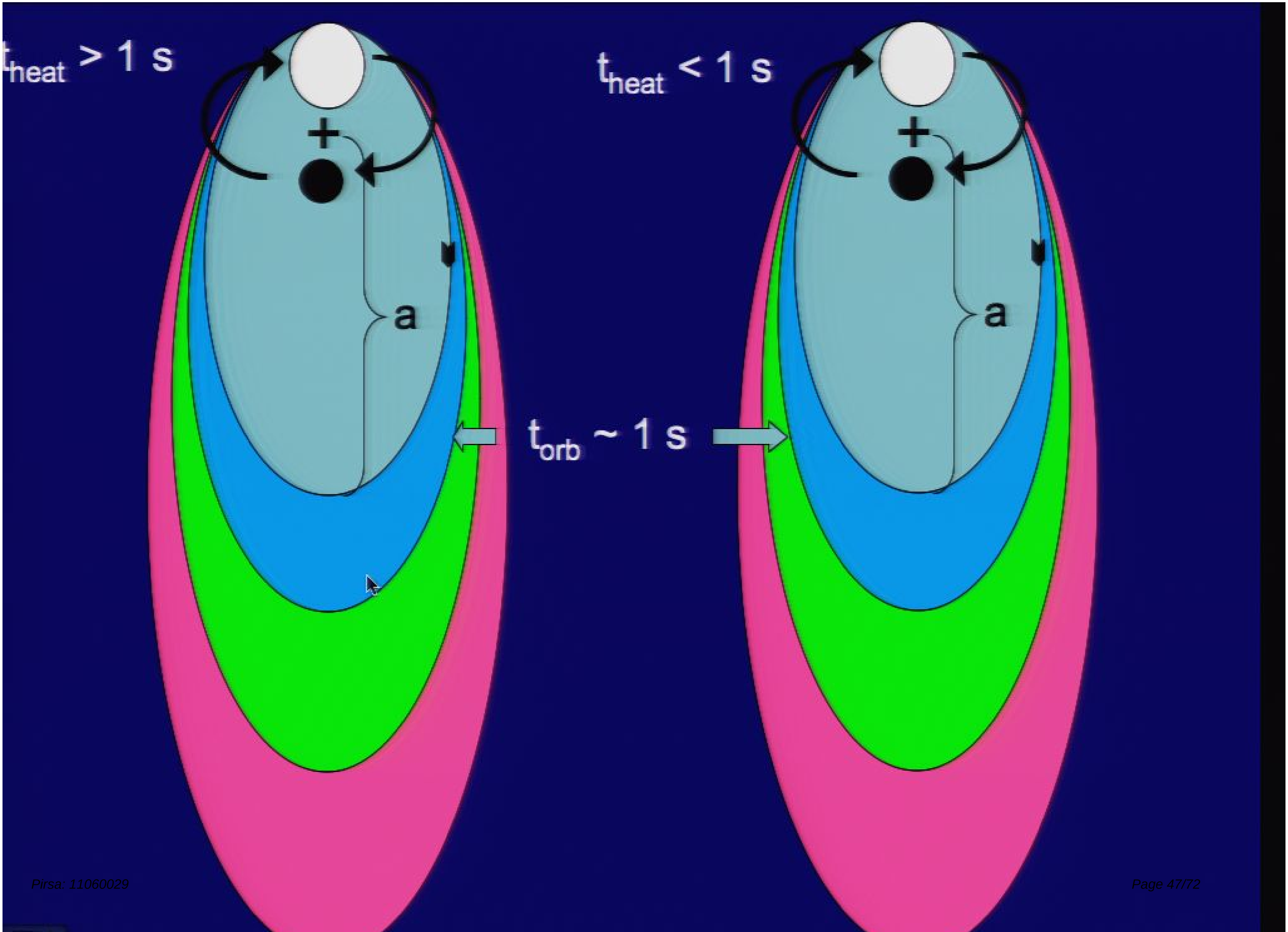
Metzger, Arcones, Quataert, & Martinez-Pinedo 2010

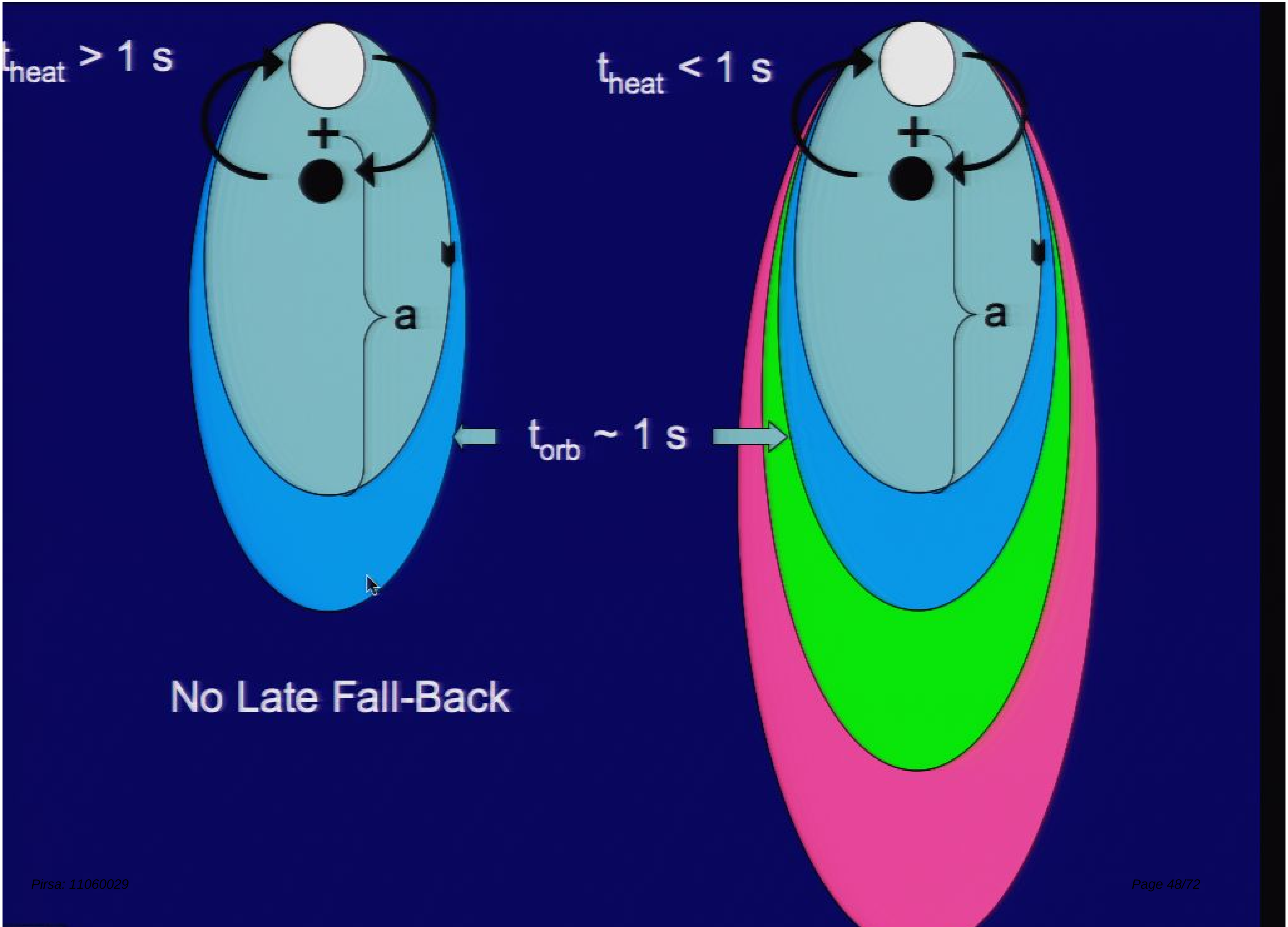




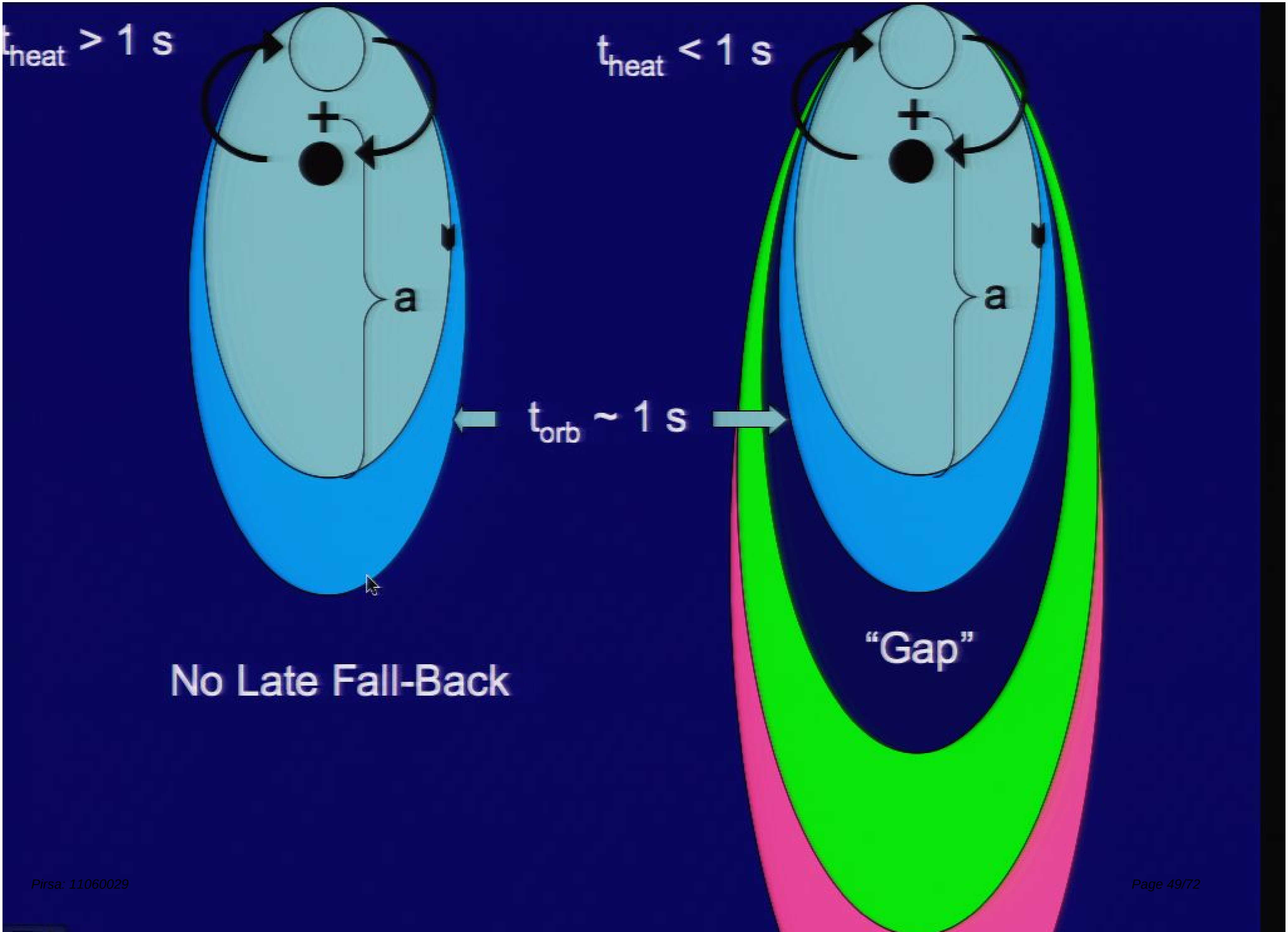
Binding Energy of Merger Ejecta

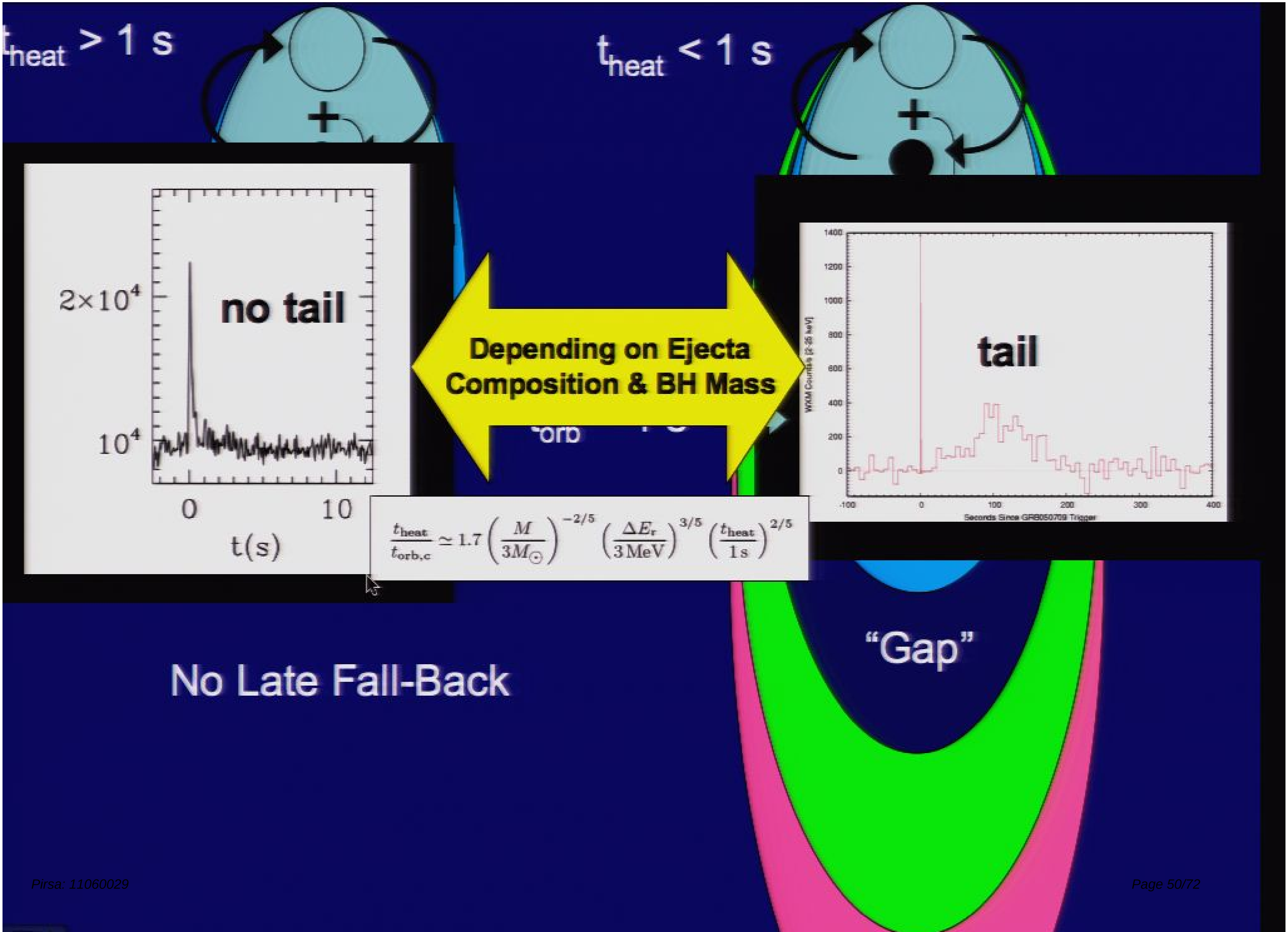
$$|E| = \frac{GMm_{\rm n}}{2a} \simeq 1.0 \left(\frac{M}{3M_{\odot}}\right)^{2/3} \left(\frac{t_{\rm orb}}{1\,{\rm s}}\right)^{-2/3} \frac{\rm MeV}{\rm nucleon}$$


$t_{heat} > 1$ s
$t_{heat} < 1$ s
+
a
+
a
$t_{orb} \sim 1$ s



t_{heat} > 1 s
t_{heat} < 1 s
a
a
t_{orb} ~ 1 s
No Late Fall-Back


t_heat > 1 s
t_heat < 1 s
a
a
t_orb ~ 1 s
"Gap"
No Late Fall-Back



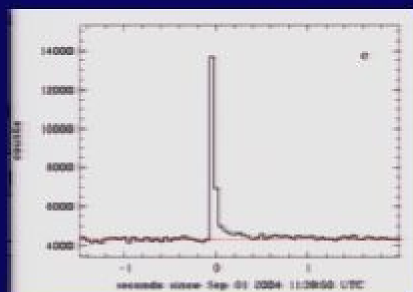
$t_{heat} > 1$ s
$t_{heat} < 1$ s
no tail
2×10^4
10^4
0
10
t(s)
Depending on Ejecta
Composition & BH Mass
tail
WXM Counts [2-25 keV]
Seconds Since GRB050709 Trigger
$\frac{t_{heat}}{t_{orb,c}} \simeq 1.7 \left(\frac{M}{3M_\odot}\right)^{-2/5} \left(\frac{\Delta E_r}{3\,MeV}\right)^{3/5} \left(\frac{t_{heat}}{1\,s}\right)^{2/5}$
"Gap"
No Late Fall-Back

Electromagnetic Counterparts of NS-NS/NS-BH Mergers

Short Gamma-Ray Burst

Blinnikov+84; Paczynski 86; Goodman 86; Eichler+89

⇒



Bright, but Beamed

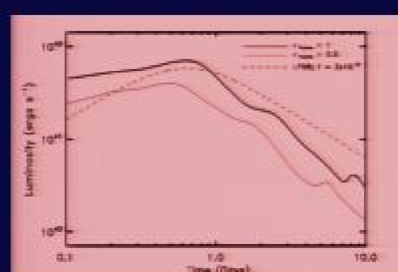
Depends On & Informs:

- jet efficiency $L_{jet} = \varepsilon_{jet} \dot{M} c^2$
- remnant disk $E_{GRB} \propto M_{acc} \propto M_{disk}$
- jet baryon loading $\Gamma_{jet} = E_{GRB} / M_{jet} c^2$
  (e.g. neutrino driven)

Thermal Transient (Kilonova) Powered by Radioactive Ejecta

Li & Paczynski 98; Rosswog 05; Metzger et al. 08, 10

⇒



Depends On & Informs:

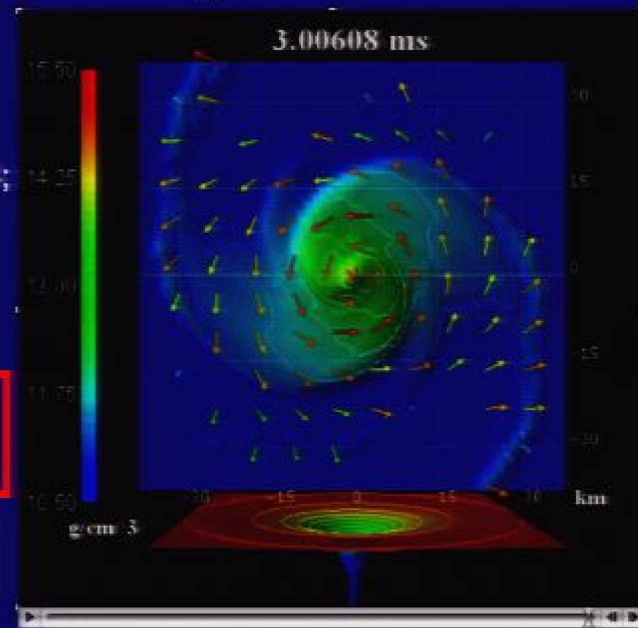
- ejecta mass, velocity, entropy & composition (e.g. Y_e)
- r-process nucleosynthesis (nuclear properties far from β-stability)
- origin of the heaviest elements

Dimmer, but Isotropic

Sources of Neutron-Rich Ejecta

Tidal Tails (Dynamical Ejecta)

(e.g. Janka et al. 1999; Lee & Kluzniak 1999; Ruffert & Janka 2001; Rosswog et al. 2004; Rosswog 2005; Shibata & Taniguchi 2006; Giacomazzo et al. 2009; Duez et al. 2010)



Full GR / Simple EOS

Current Sims: $M_{ej} \sim 0 - 0.1\ M_{\odot}$

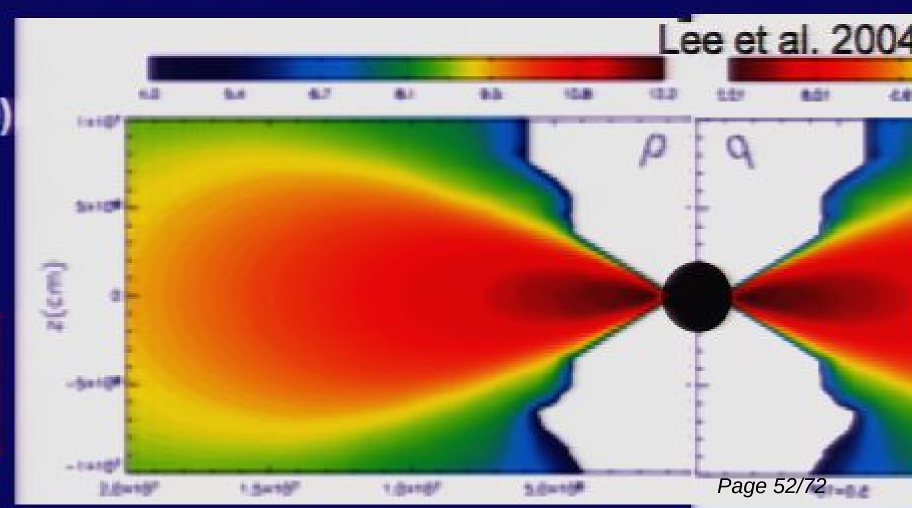
Newtonian / Realistic EOS

Accretion Disk Outflows

Neutrino-Driven Winds (Early)
(McLaughlin & Surman 05; BDM+08; Rosswog et al. 2009)

Thermonuclear-Driven Winds (Late)
(Metzger, Piro & Quataert 2008, 2009; Lee et al. 2009)

$M_{ej} \sim M_{disk}/3 \sim 10^{-3} - 10^{-2}\ M_{\odot}$



Neutron-Rich Freeze-Out $Y_e \sim 0.1$-0.4 (BDM + 2009)

Californium-254 and Supernovae*

G. R. Burbidge and F. Hoyle,† *Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California*

and

E. M. Burbidge, R. F. Christy, and W. A. Fowler, *Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California*

(Received May 17, 1956)

- B^2FH: Type I SN light curves powered by ^{254}Cf
- Today: Type Ia SNe powered by ^{56}Ni & ^{56}Co

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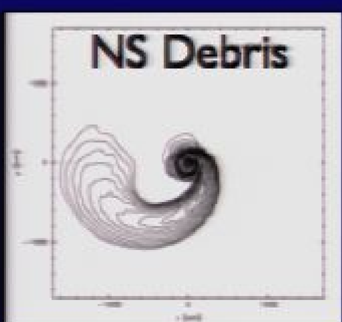

TRANSIENT EVENTS FROM NEUTRON STAR MERGERS

LI-XIN LI AND BOHDAN PACZYŃSKI

Princeton University Observatory, Princeton, NJ 08544-1001; lxl@astro.princeton.edu, bp@astro.princeton.edu

Received 1998 July 27; accepted 1998 August 26; published 1998 September 21

$$t_{peak} \approx 0.5\,\mathrm{days}\left(\frac{v}{0.1c}\right)^{-1/2}\left(\frac{M_{\rm ej}}{10^{-2}M_\odot}\right)^{1/2}$$

$$L_{peak} \approx 5\times10^{41}\mathrm{ergs\ s^{-1}}\left(\frac{f}{10^{-6}}\right)\left(\frac{v}{0.1c}\right)^{1/2}\left(\frac{M_{\rm ej}}{10^{-2}M_\odot}\right)^{1/2}$$

} "mini-supernova"

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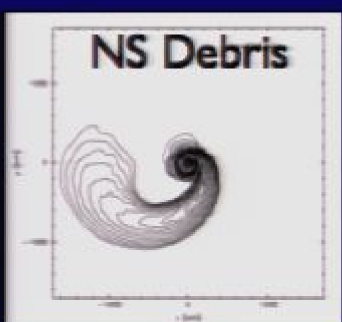

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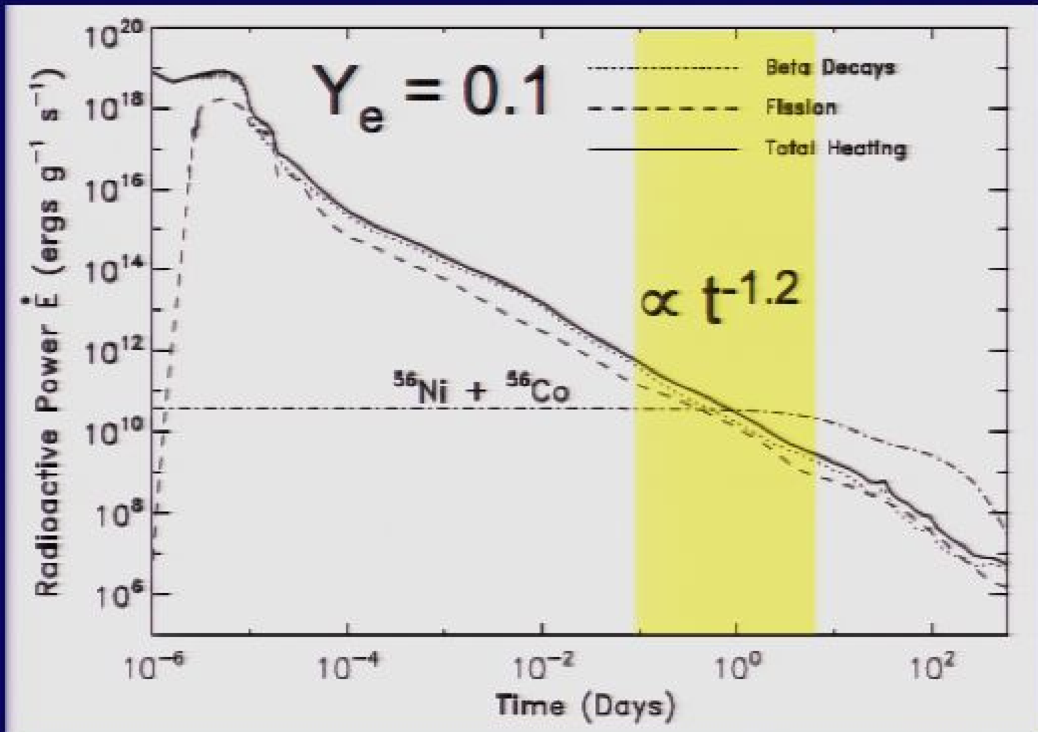
Radioactive Heating of NS Merger Ejecta



@ t ~ 1 day :

- R-process & Ni heating similar
- ~1/2 Fission, ~1/2 β-Decays
- Dominant β-Decays:

^{132,134,135}I, ^{128,129}Sb, ^{129}Te, ^{135}Xe

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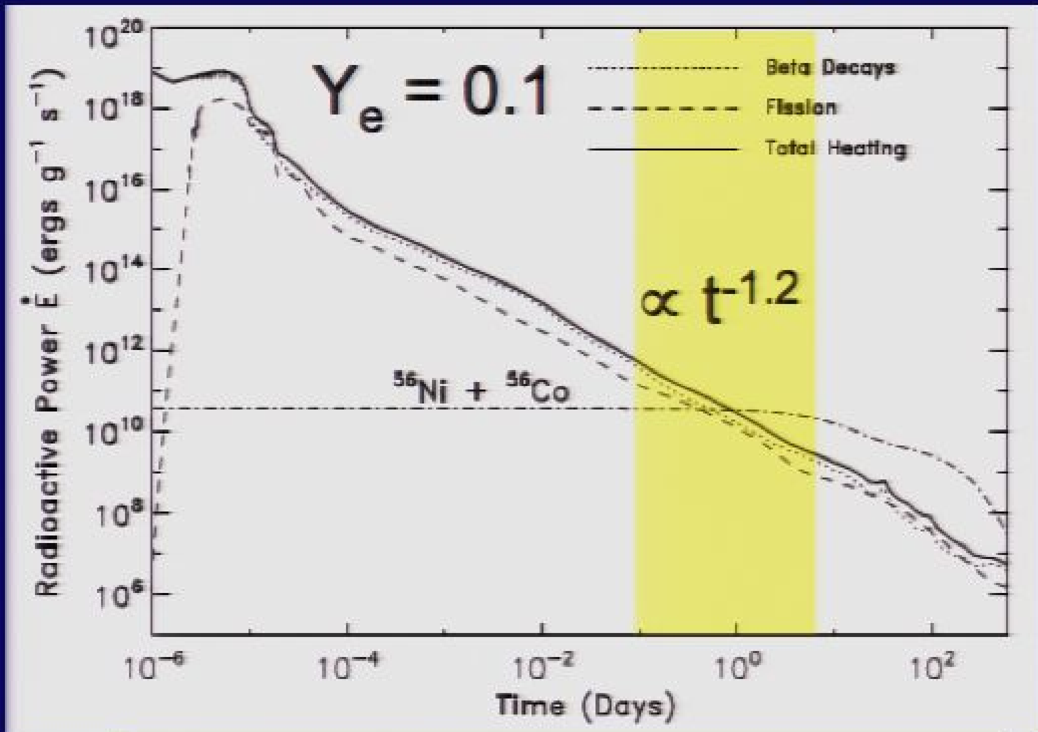

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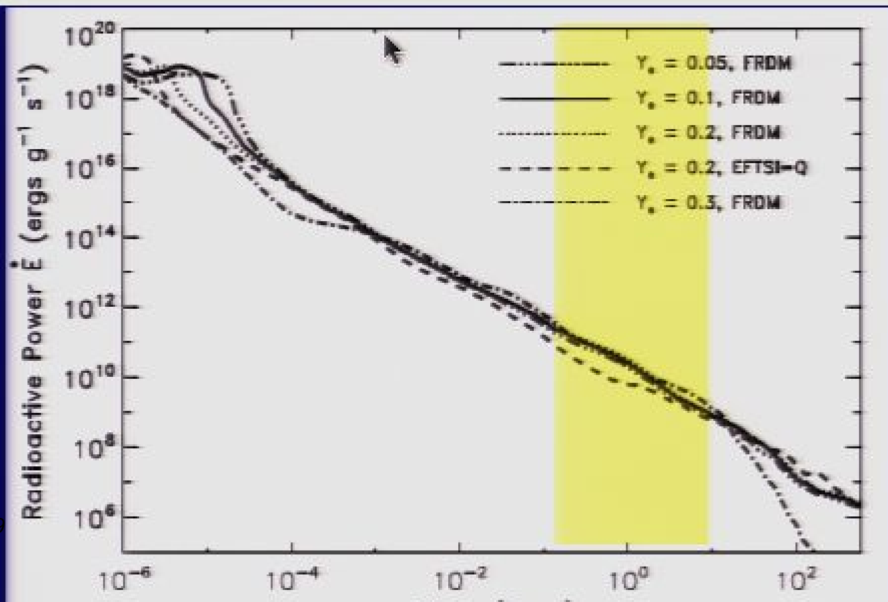
$f_{LP} = 3 \times 10^{-6}$



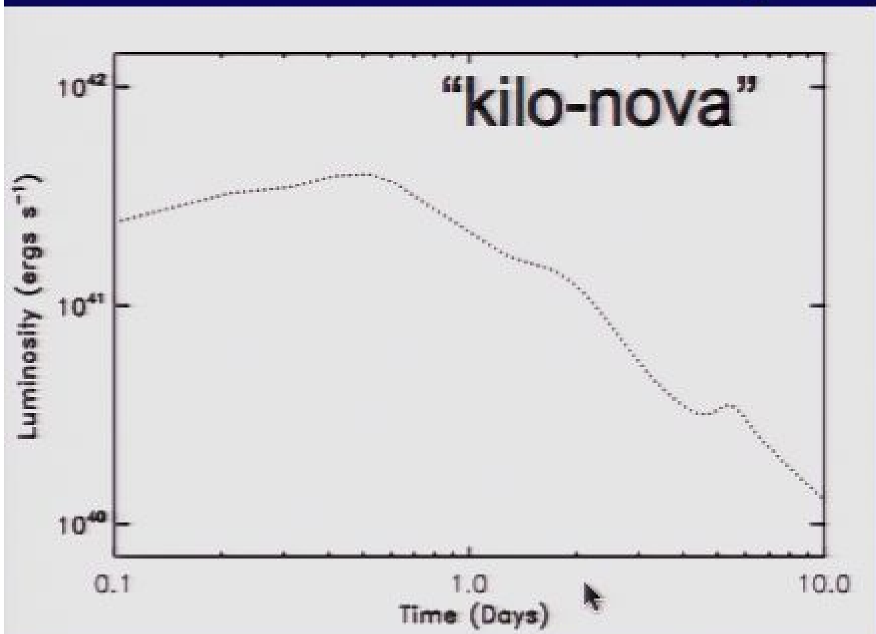
Results Robust to:

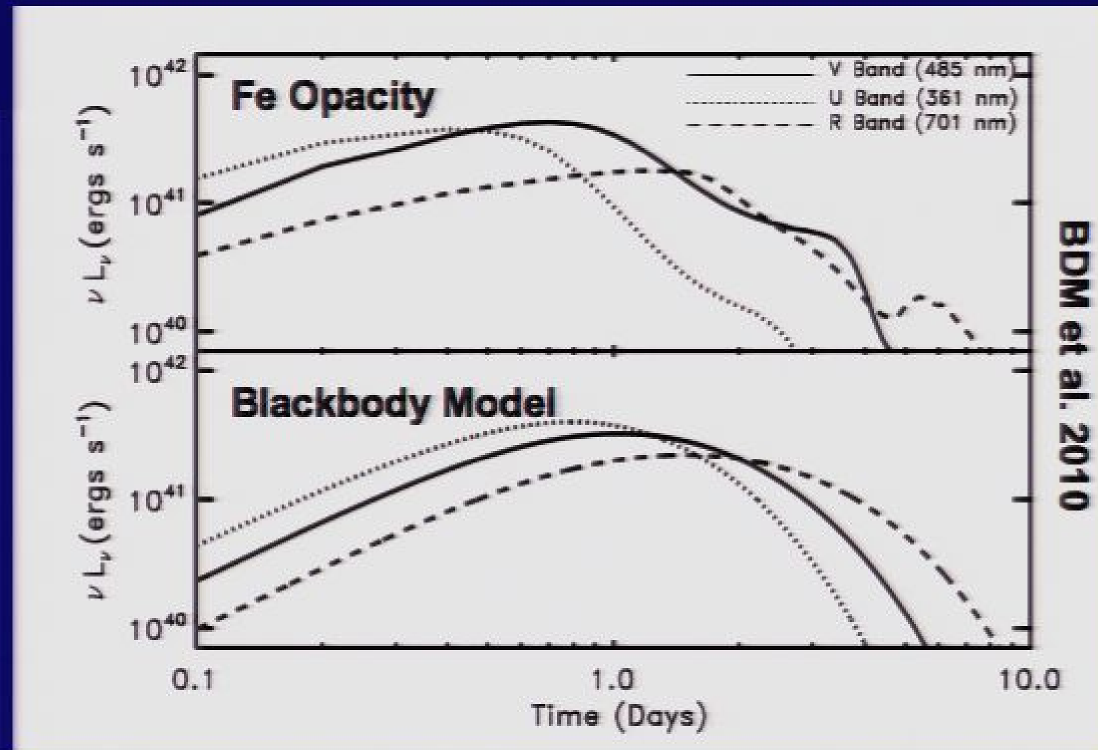
- ejecta composition (Y_e = 0.05 - 0.3)
- nuclear mass model
- outflow trajectory (dynamically-ejected or wind-driven)
- Agrees w Roberts et al. (2011)

Light Curves

Color Evolution

Bolometric Luminosity





Monte Carlo Radiative Transfer (SEDONA; Kasen et al. 2006)

Peak Brightness M_V= -15 @ t ~ 1 day for M_{ej} = 10^{-2} $M_\odot$

CAVEAT: Fe composition assumed for opacity

What *does* a pure r-process photosphere look like?

Three Detection Methods

1) Gravitational-Wave Triggered Follow-Up

V < 22-24 to probe entire Advanced LIGO merger volume (for $M_V = -15$)

Positional Uncertainty > 10 degrees
(e.g. Nissanke et al. 2011)

} ⇒ Wide-Field, Sensitive Telescope (e.g. LSST)

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2) Short Gamma-Ray Burst Follow-Up

Upper Limits

GRB 070724A
(Kocevski et al. 2009)

$M_{ej} < 0.1 M_\odot$

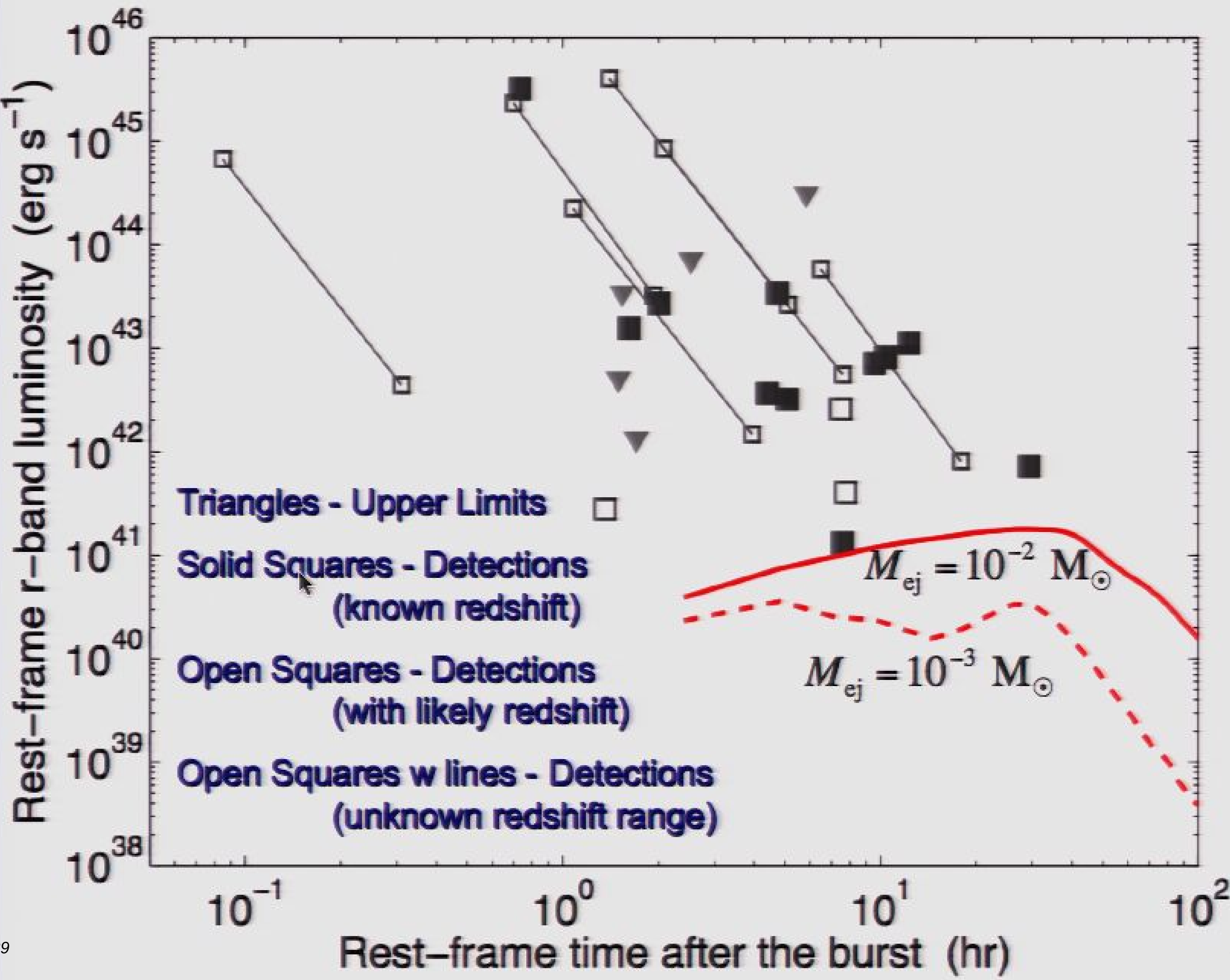
GRB 050509b
(Hjorth et al. 2005)

$M_{ej} < 10^{-3} M_\odot$

GRB 080503
(Perley, BDM, et al. 2009)
Possible Detection

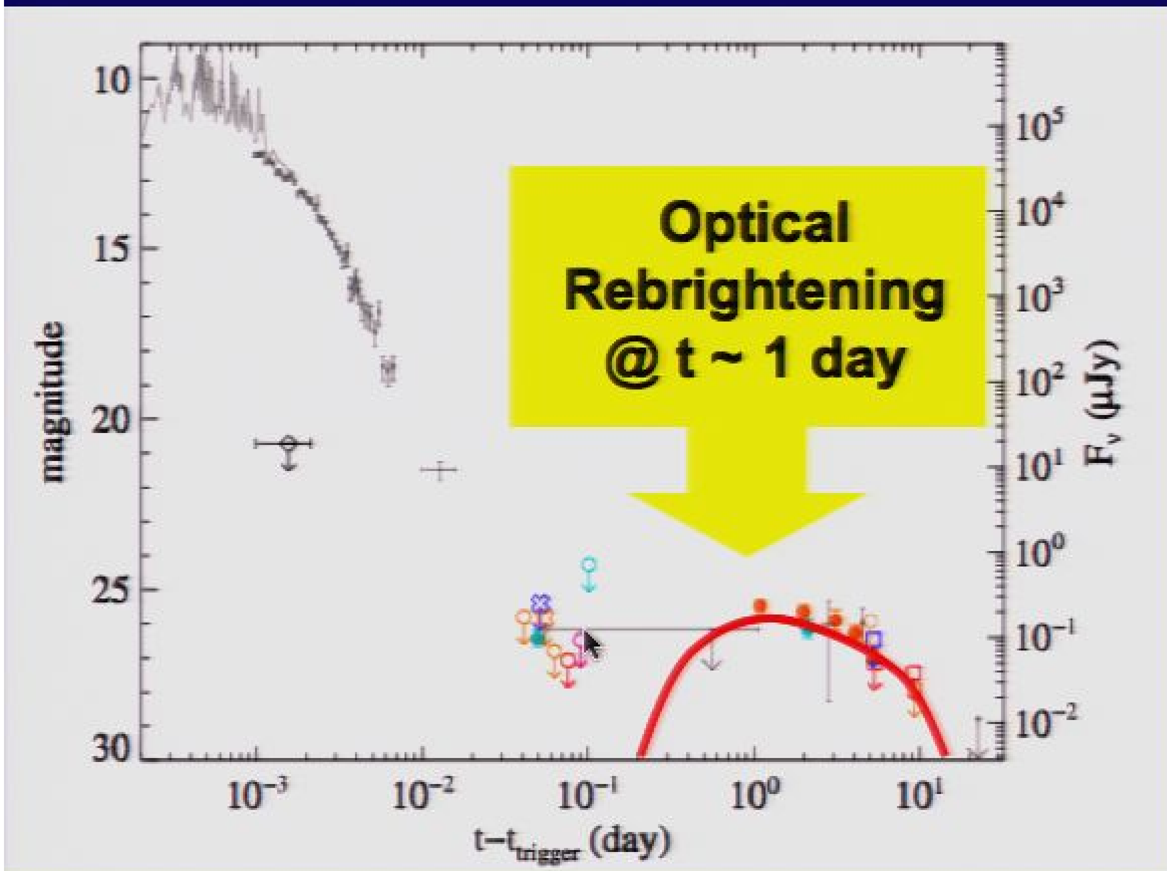
Fundamental Obstacle? Bright Optical Afterglow

Early Optical Follow-Up of Short GRBs (from Edo Berger)



GRB 080503: Candidate Kilonova

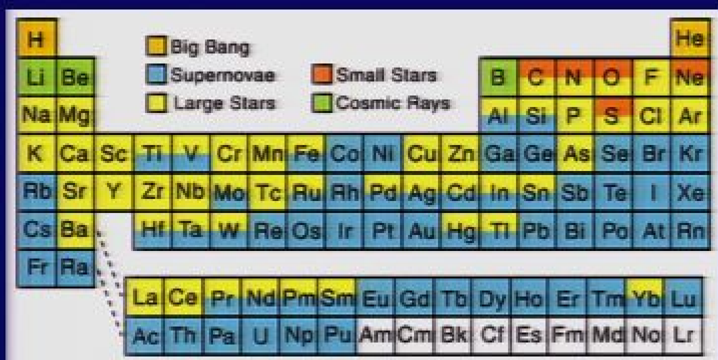
(Perley, BDM et al. 2009)



Best-Fit Kilonova Parameters: $v \sim 0.1$ c, $M_{ej} \sim$ few $10^{-2}\ M_{\odot}$, **z ~ 0.1**

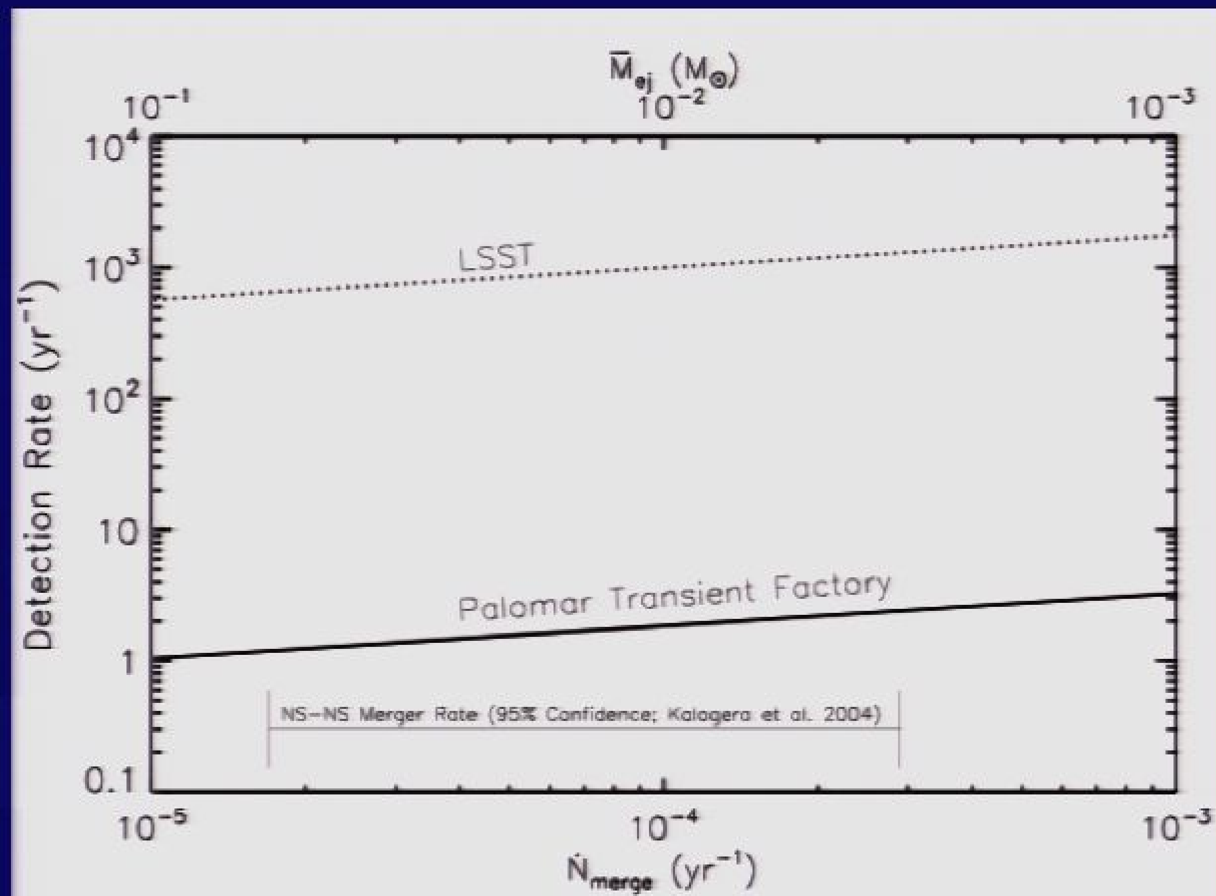
"Direct" Probe of the R-Process Origin

- ***Unknown*** origin of 1/2 of elements more massive than Fe
- Rival Models: Core Collapse Supernovae and NS Mergers



Galactic R-Process Production Rate:

$$\dot{M}_R \sim 10^{-6} M_\odot \, \mathrm{yr}^{-1}$$



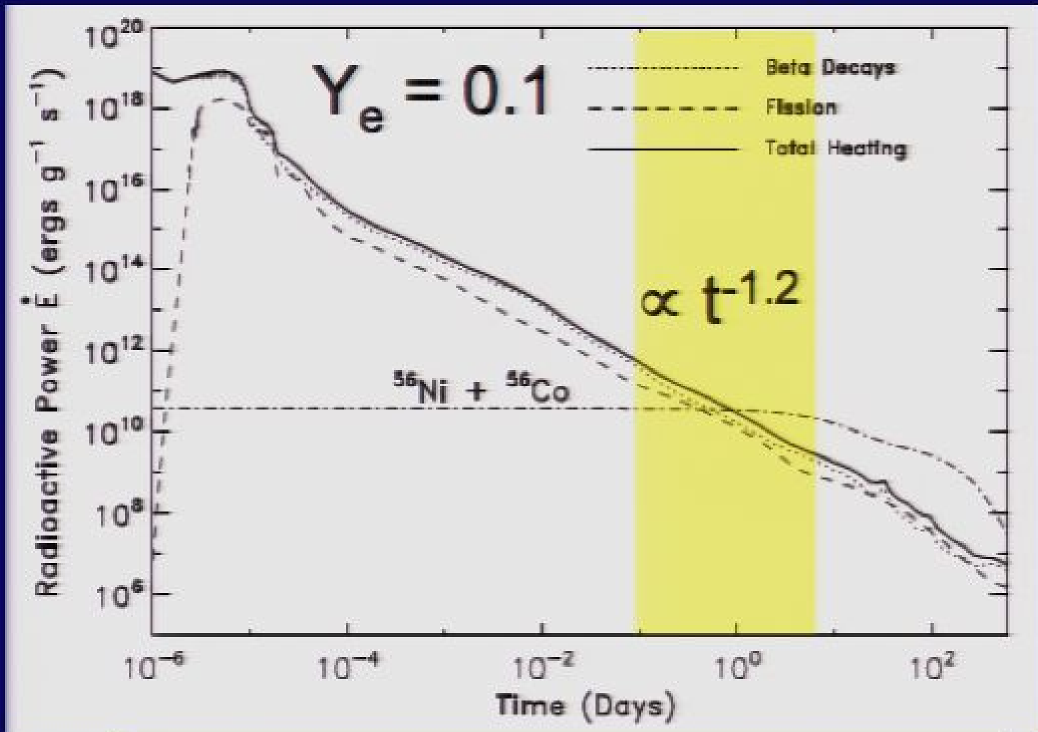
Fixes Merger Rate to Avg. Ejecta Mass:

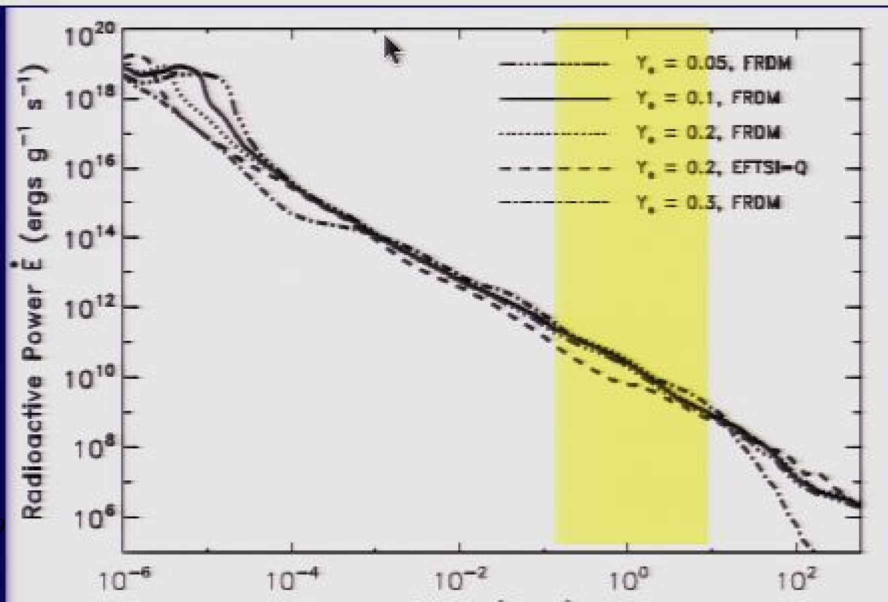
$$\dot{N}_{\mathrm{merge}} = 10^{-4}\,\mathrm{yr}^{-1}(\bar{M}_{\mathrm{ej}}/10^{-2}M_\odot)^{-1}$$

Conclusions

- Nuclear energy is released following NS mergers as matter expands to lower densities. Depending on when and where this occurs, nuclear heating can have a surprisingly large effect on observables.
- Part of this energy (~50-80%) is released abruptly and can be captured with an appropriate EOS (dynamical ejecta) or by assuming NSE (disk). The rest is released over a longer timescale (~seconds) by the r-process, which requires separate techniques to capture.
- NS merger disks viscously spread and cool after forming. Weak freeze-out and nuclear recombination begin on the outside, moving in, evaporating the disk and ejecting ~1/3 of its mass in winds.
- R-process heating in the ejecta on ~ second timescales affects what mass falls back to the black hole. This may have implications for the mysterious late time X-ray flaring after short GRBs.
- Residual decay heating of material ejected during the merger powers an optical transient lasting ~ 1 day, with properties . This is a promising EM counterpart to mergers detected by LIGO/Virgo.

Radioactive Heating of NS Merger Ejecta





@ t ~ 1 day :

- **R-process & Ni heating similar**
- **~1/2 Fission, ~1/2 β-Decays**
- **Dominant β-Decays:** ^{132,134,135}**I**, ^{128,129}**Sb**, ^{129}**Te**, ^{135}**Xe**

$f_{LP} = 3 \times 10^{-6}$

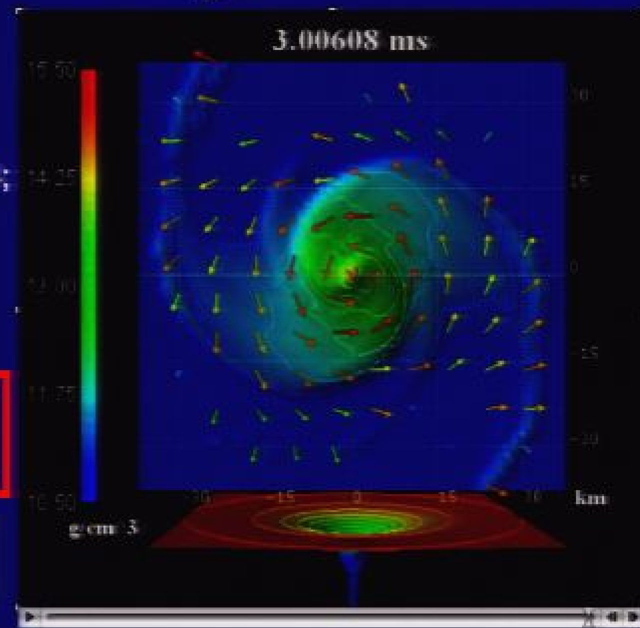
Results Robust to:

- ejecta composition (Y_e = 0.05 - 0.3)
- nuclear mass model
- outflow trajectory (dynamically-ejected or wind-driven)
- Agrees w Roberts et al. (2011)

Sources of Neutron-Rich Ejecta

Tidal Tails (Dynamical Ejecta)

(e.g. Janka et al. 1999; Lee & Kluzniak 1999; Ruffert & Janka 2001; Rosswog et al. 2004; Rosswog 2005; Shibata & Taniguchi 2006; Giacomazzo et al. 2009; Duez et al. 2010)



Full GR / Simple EOS

Current Sims: $M_{ej} \sim 0 - 0.1\ M_{\odot}$

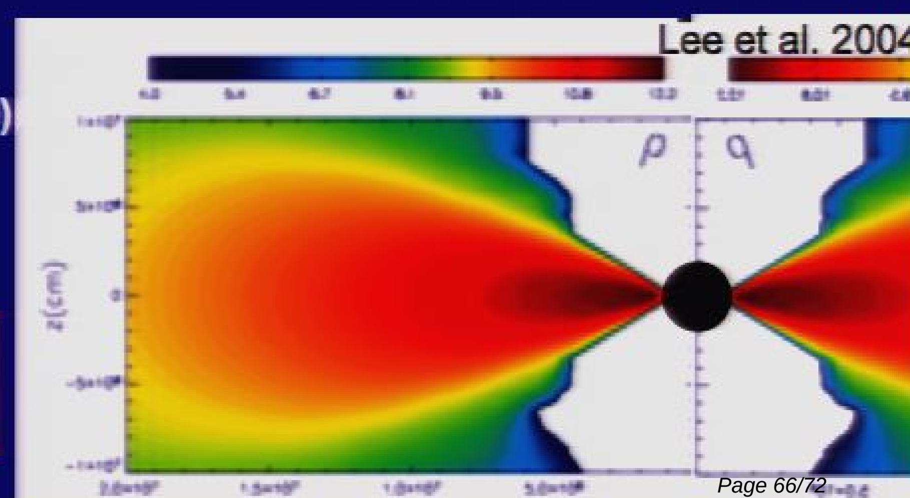
Newtonian / Realistic EOS

Accretion Disk Outflows

Neutrino-Driven Winds (Early)
(McLaughlin & Surman 05; BDM+08; Rosswog et al. 2009)

Thermonuclear-Driven Winds (Late)
(Metzger, Piro & Quataert 2008, 2009; Lee et al. 2009)

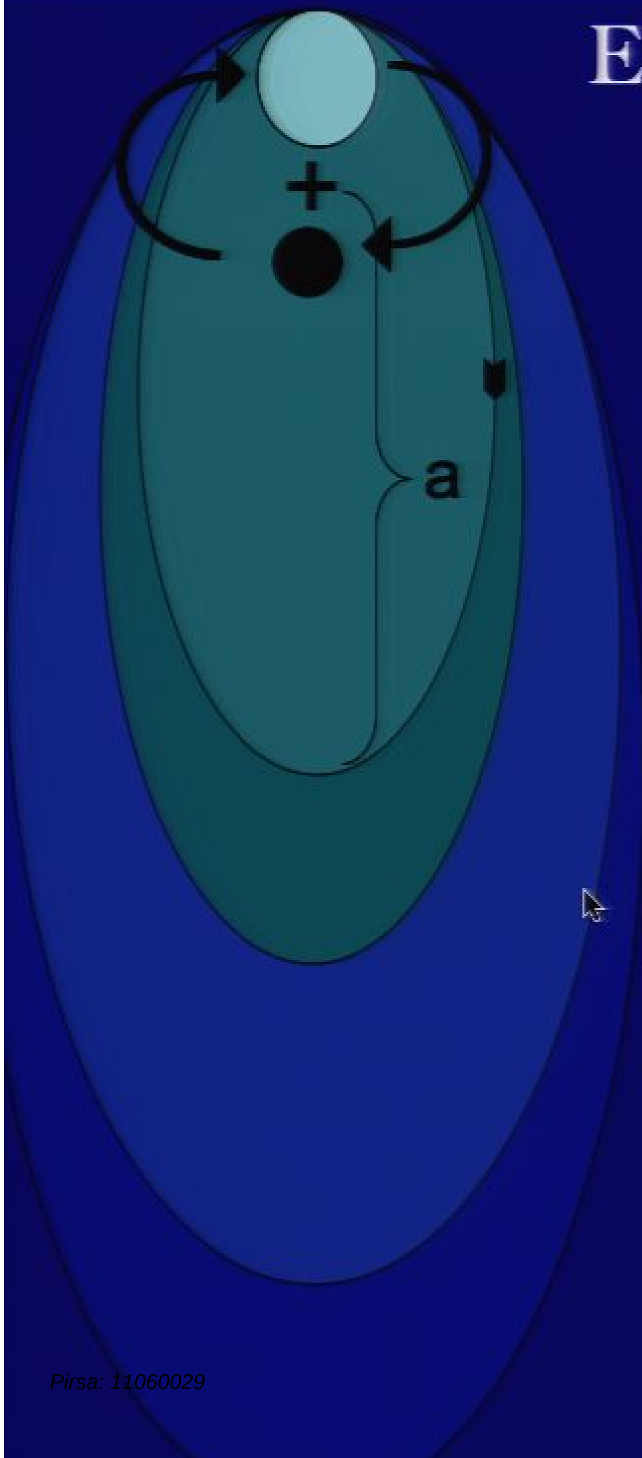
$M_{ej} \sim M_{disk}/3 \sim 10^{-3} - 10^{-2}\ M_{\odot}$



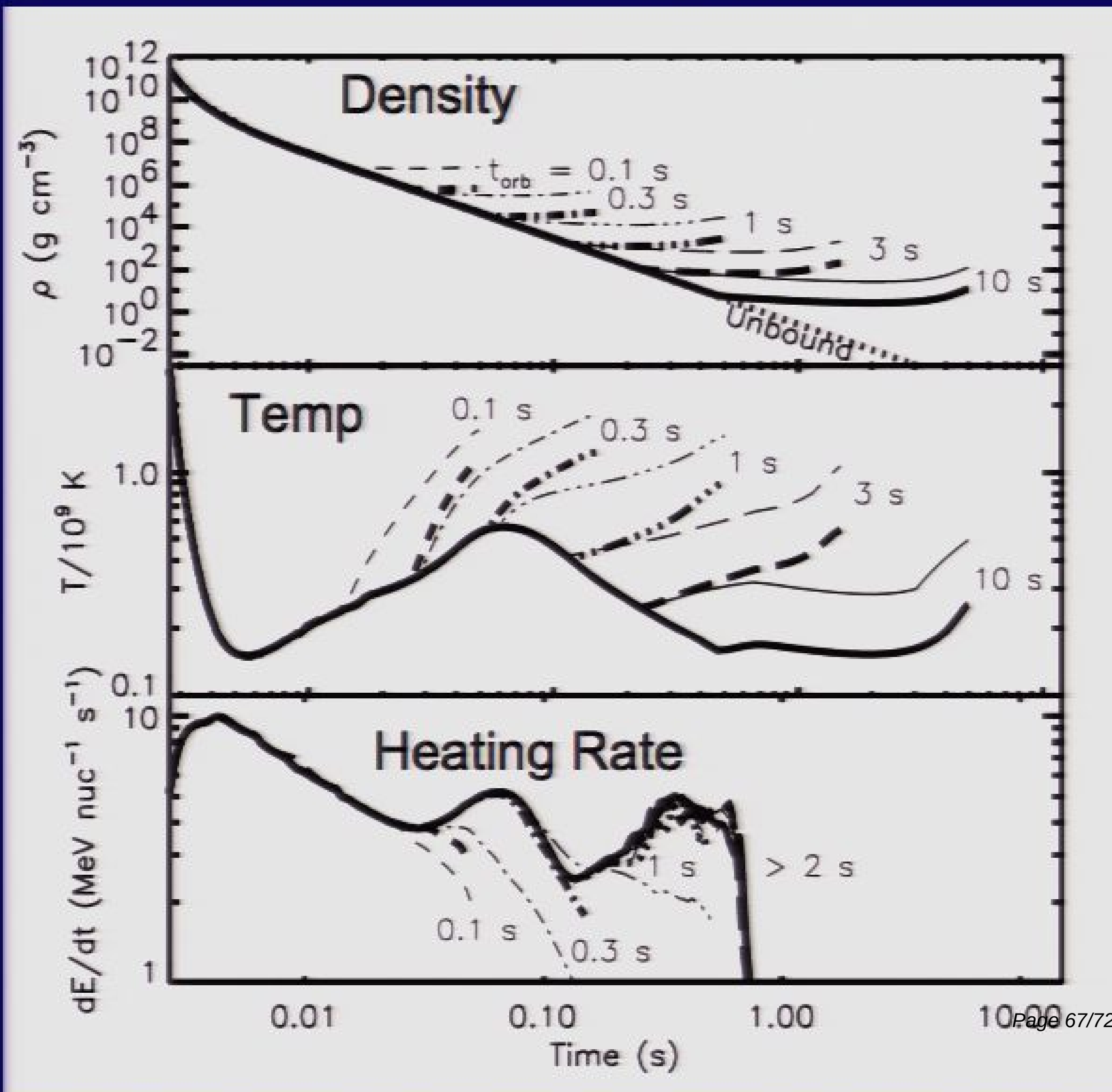
Neutron-Rich Freeze-Out $Y_e \sim 0.1$-0.4 (BDM + 2009)

Effects of r-Process on Fall-Back Accretion

Metzger, Arcones, Quataert, & Martinez-Pinedo 2010



Nucleosynthesis along Lagrangian Orbits



Late-Time Disk Winds ("Evaporation")

After t ~ 0.1-1 seconds, R ~ 500 km & T < 1 MeV

- **Recombination: n + p ⇒ He**

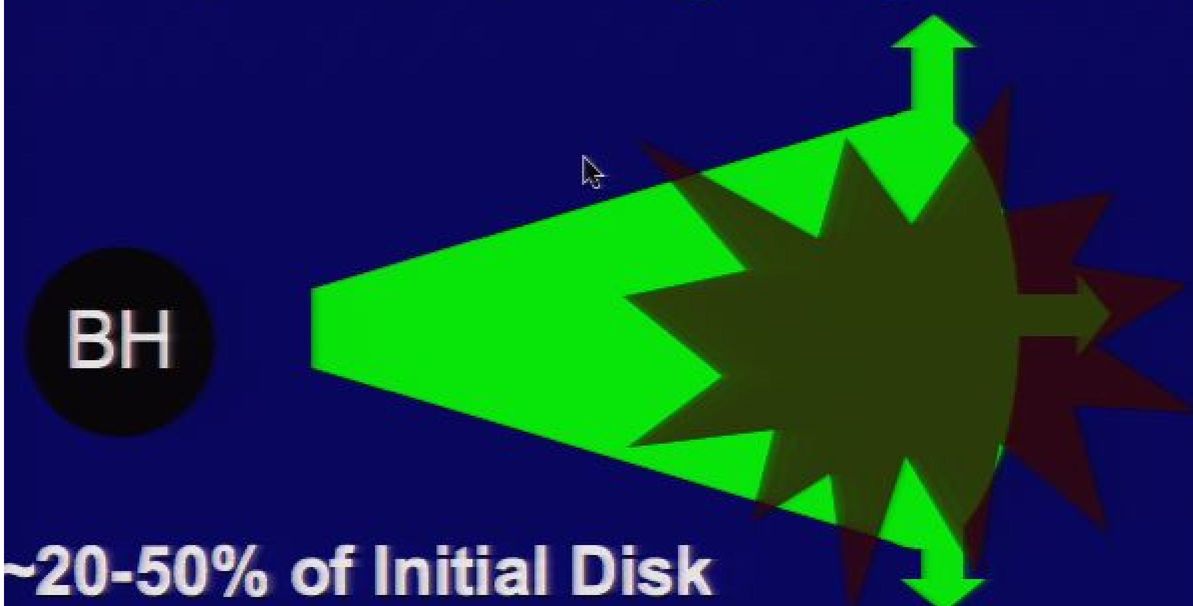
  $E_{BIND} \sim GM_{BH}m_n/2R \sim 3$ MeV nucleon^{-1}

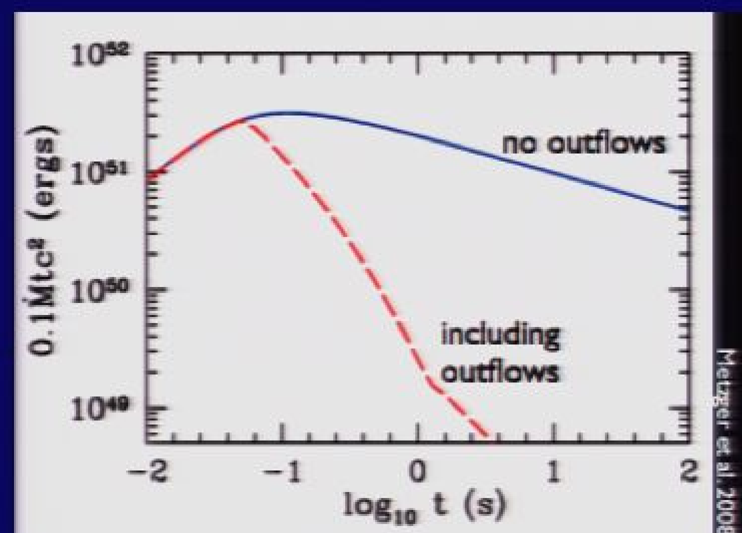
  $\Delta E_{NUC} \sim 7$ MeV nucleon^{-1}

- **Thick Disks Marginally Bound**

⇒ **Powerful Winds Blow Apart Disk**

(see also Lee et al. 2009)





Accretion of the Initial Disk Cannot Power Late Time Activity in SGRBs

~20-50% of Initial Disk Ejected Back into Space!

Viscous Evolution of the Remnant Disk

Metzger, Piro & Quataer 2008, 2009

Angular Momentum

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{r}\frac{\partial}{\partial r}\left[r^{1/2} \frac{\partial}{\partial r}\left(\nu \Sigma r^{1/2} \right) \right]$$

$$\nu = \alpha c_s H$$

Entropy

BH

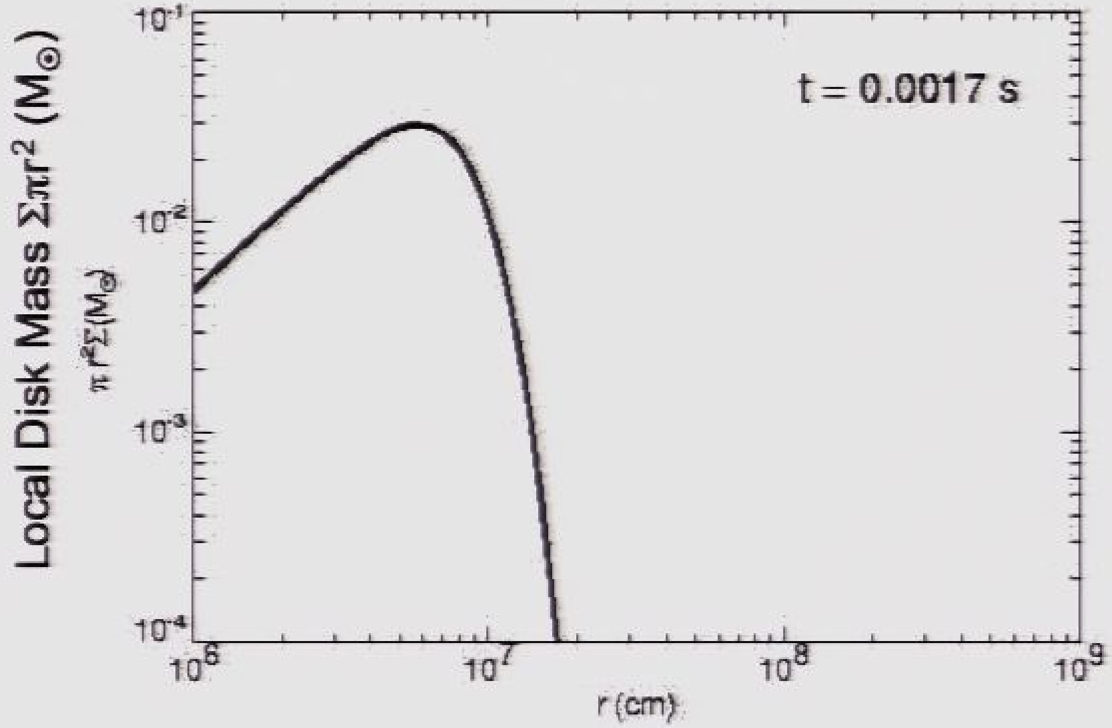
$$T\frac{dS}{dt} = \dot{q}_{visc} - \dot{q}_{\nu}$$

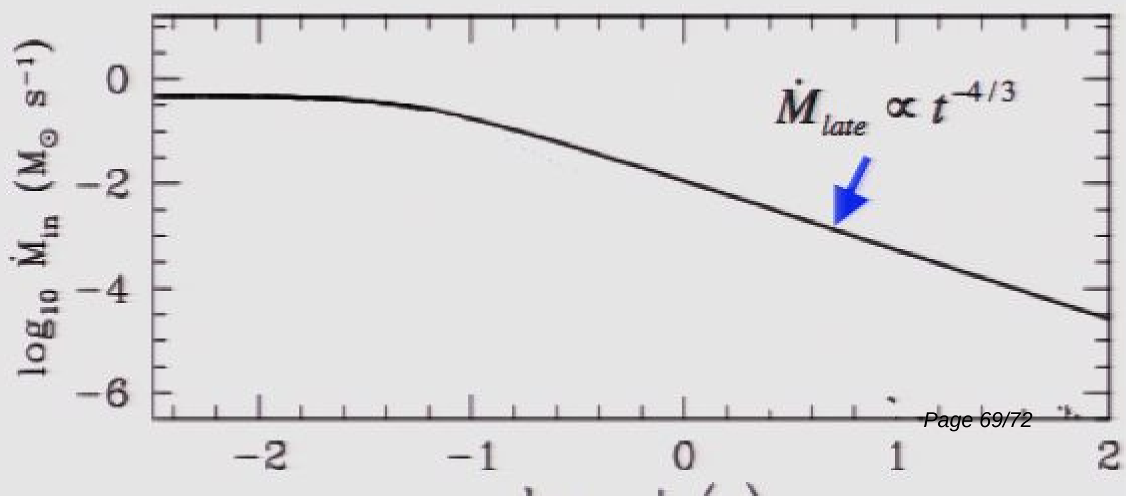
Heating

Cooling

Nuclear Composition

$$\frac{dY_e}{dt} = (\lambda_{e^+ n \to p\nu} + \lambda_{e^- p \to n\nu})\left[1 - Y_e - \left(\frac{1 - X_f}{2}\right)\right]$$





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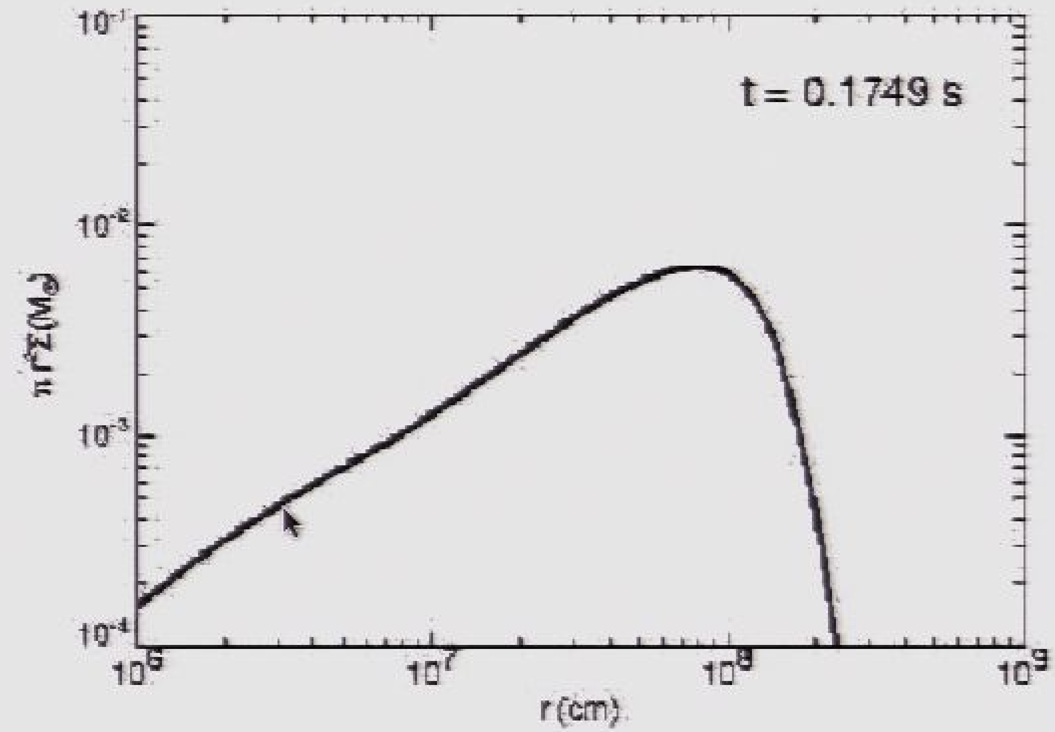

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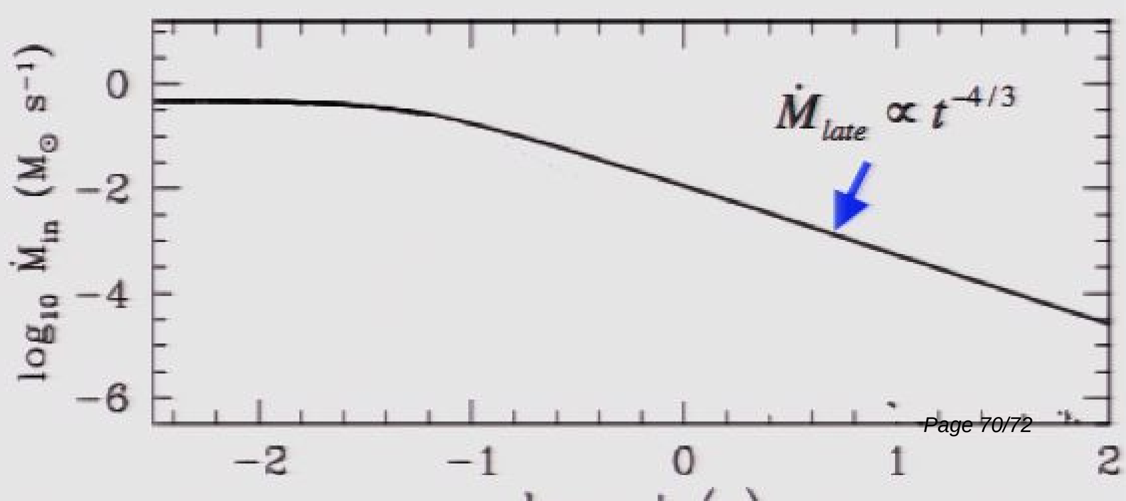

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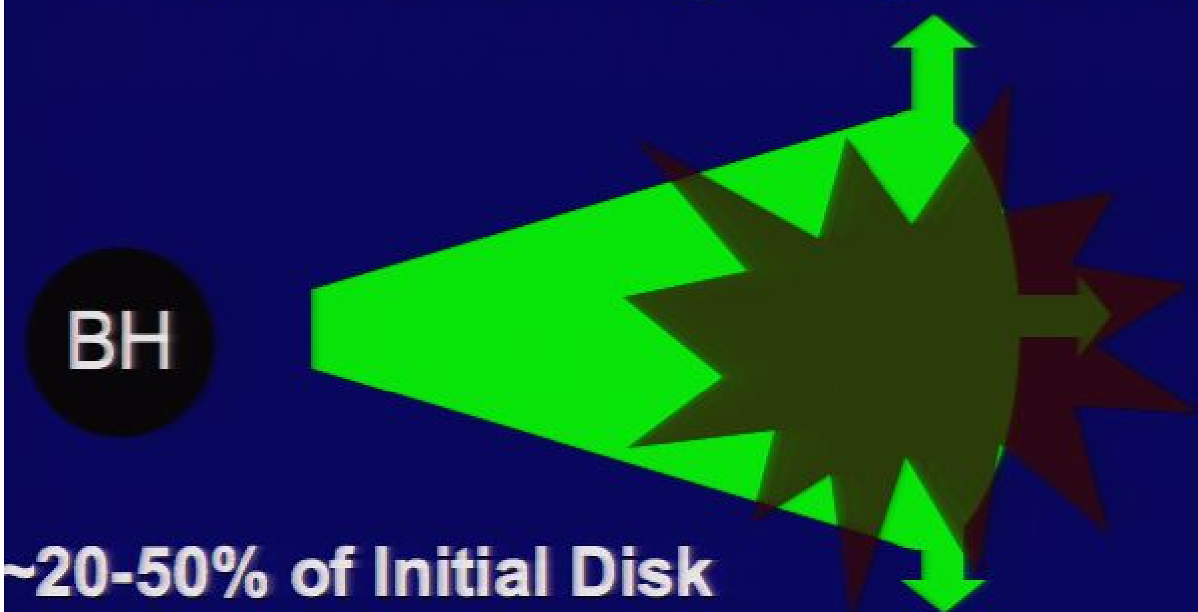

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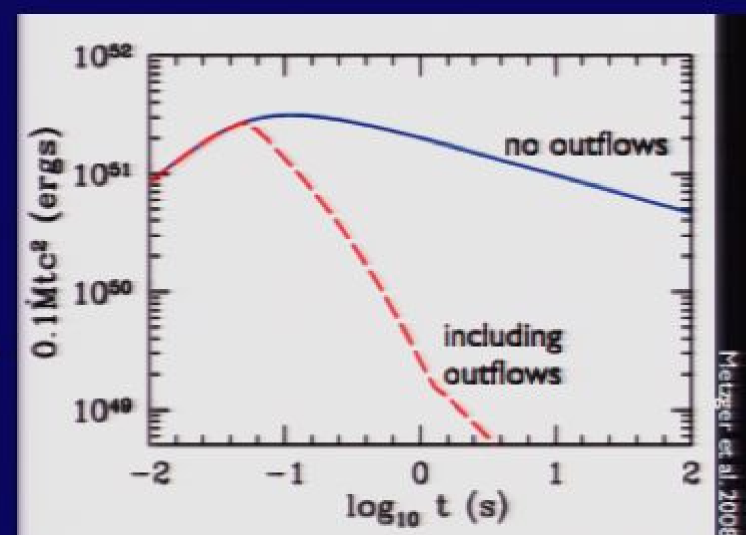
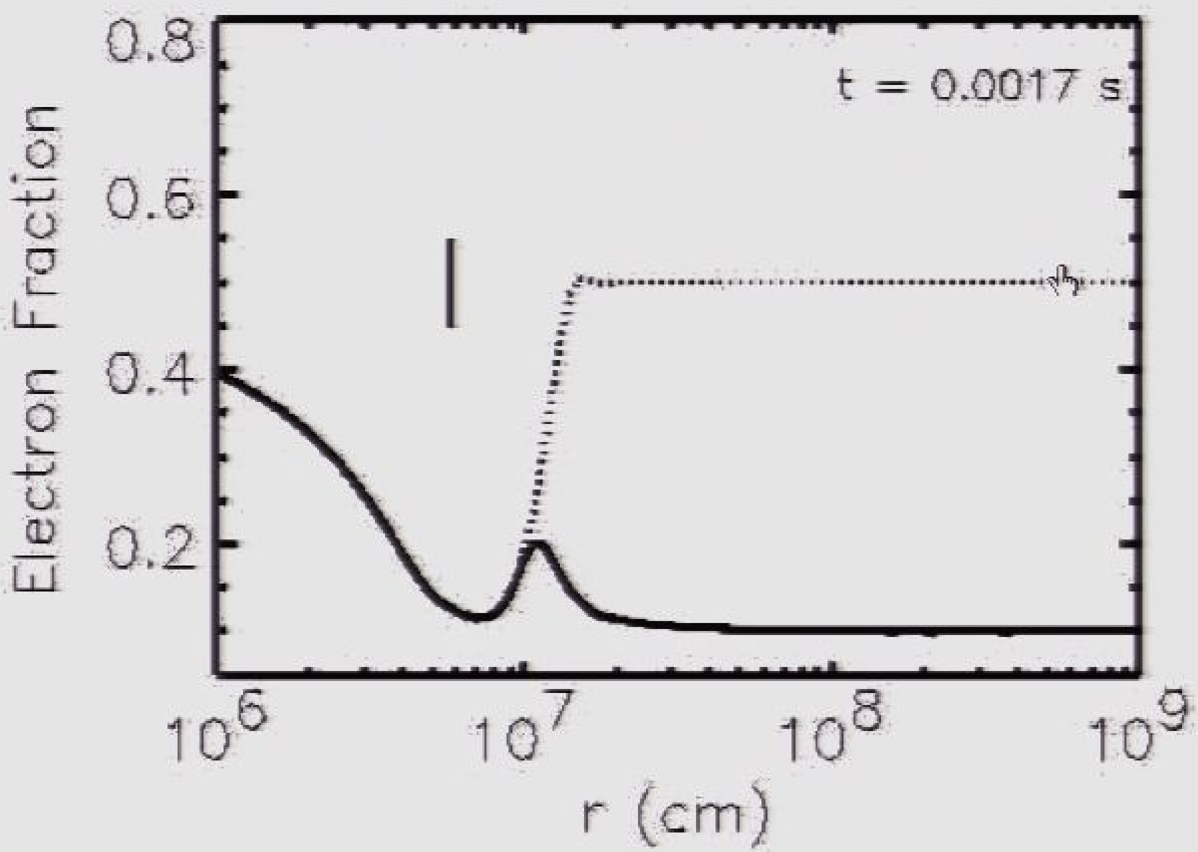


Accretion of the Initial Disk Cannot Power Late Time Activity in SGRBs

Neutron Rich Freeze Out ("Little Bang")

Metzger, Piro & Quataert 2009



Weak Interactions

$$e^- + p \rightarrow \nu_e + n$$

$$e^+ + n \rightarrow \bar{\nu}_e + p$$

Drive $Y_e \Rightarrow Y_e^{eq}$ Until Freeze-Out

Y_e^{eq} ....

Y_e ———

Thickening / Freeze-Out Begins at the Outer Disk and Moves Inwards

Limited β-equilibrium assumed in most multi-D disk simulations !