Kyoto, Nov 14 2013

The longterm evolution of neutron star merger ejecta

Stockholm University

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Oskar Klein centre

in collaboration with:

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Oleg Korobkin (Stockholm)

Doron Grossman (Jerusalem)
Friedrich-Karl Thielemann (Basel)

Tsvi Piran (Jerusalem)

Overview

I. Intro/Review

a) EM signals ⇔ GWs

b) Summary: compact binary mergers as producers of “heavy” r-process
⇒ “macronovae”

II. Remnant evolution

a) What is new?
b) Inclusion of nuclear heating
c) Effect on dynamics and nucleosynthesis
d) Remnant structure

III. EM emission

a) Procedure
b) Major results

VI. Summary

References:

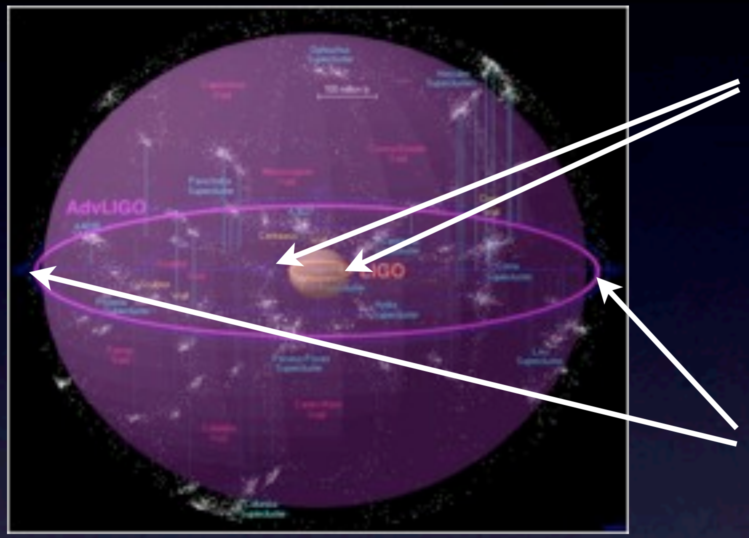
a) SR et al., arXiv13007.2939

b) Grossman et al., arXiv13007.2943

I. Intro/Review

Direct gravitational wave (GW) detection

- LIGO & VIRGO detector upgrade ⇒ access. volume increased by > factor 1000



initial LIGO

Advanced LIGO

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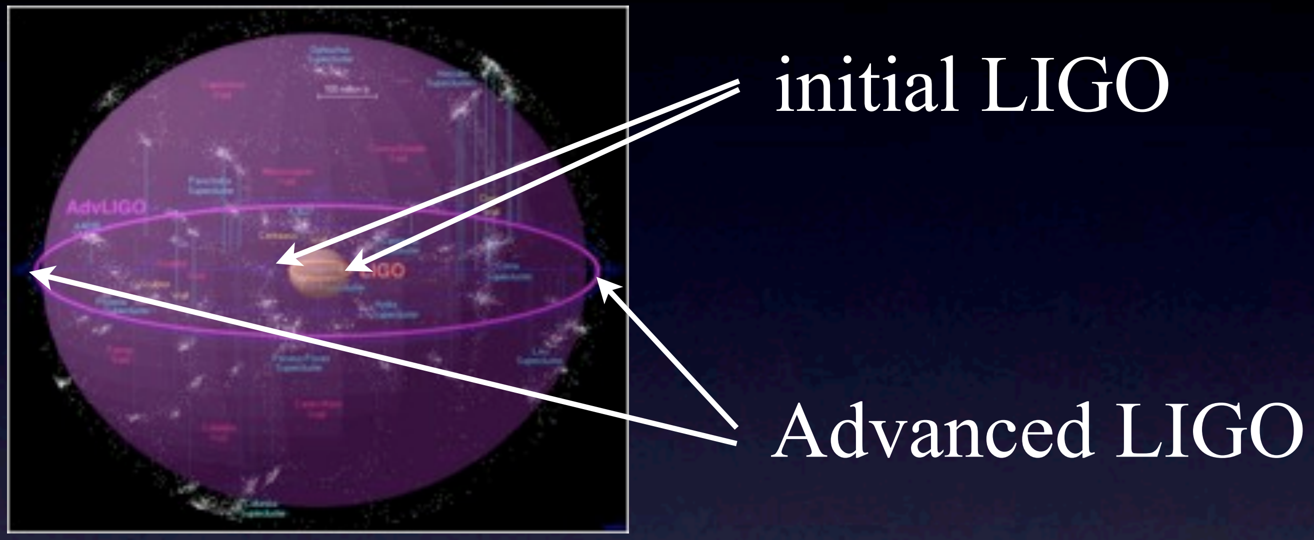

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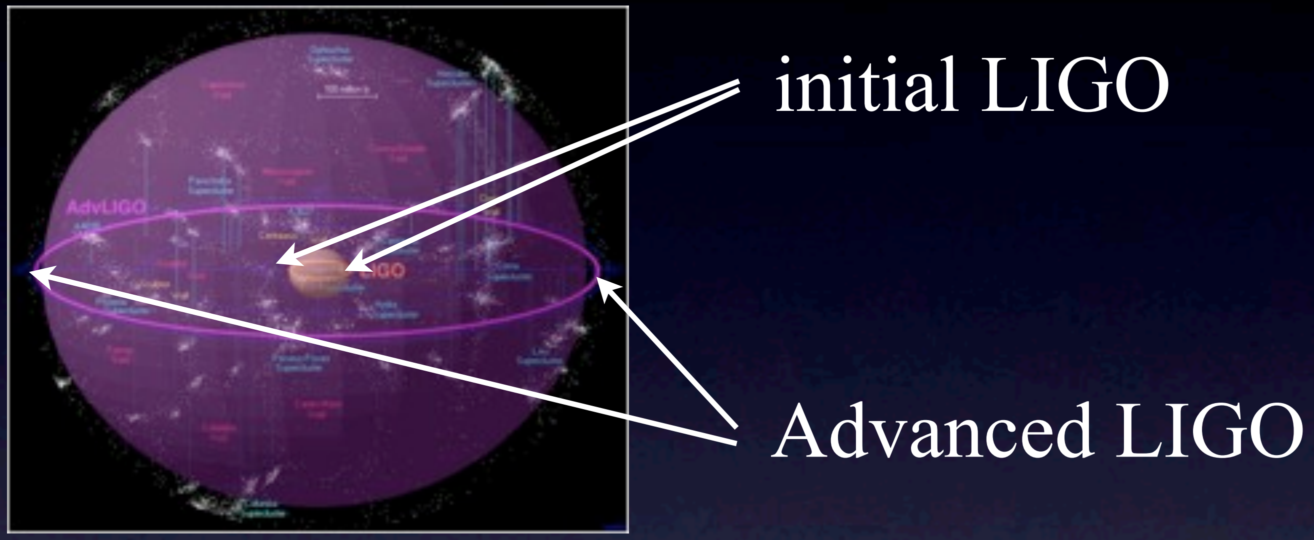

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  Gravitational waves
  - masses
  - spins
  - nuclear EOS
  - …

⇒ physics of binary system

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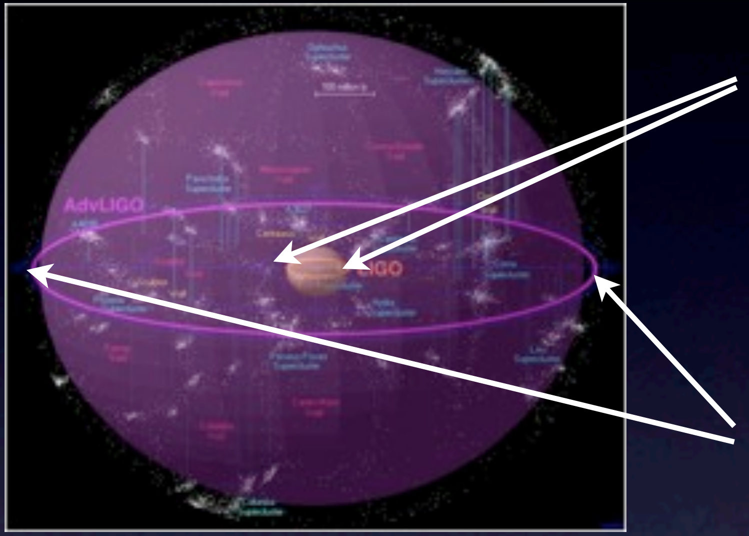

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⇒ physics of binary system

Electromagnetic signals

- redshift
- type of galaxy
- ambient medium
- ...

⇒ astronomical environment

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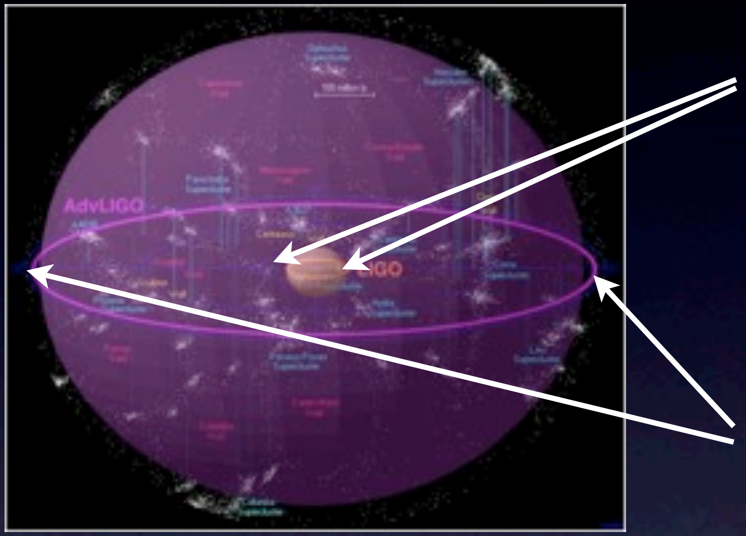

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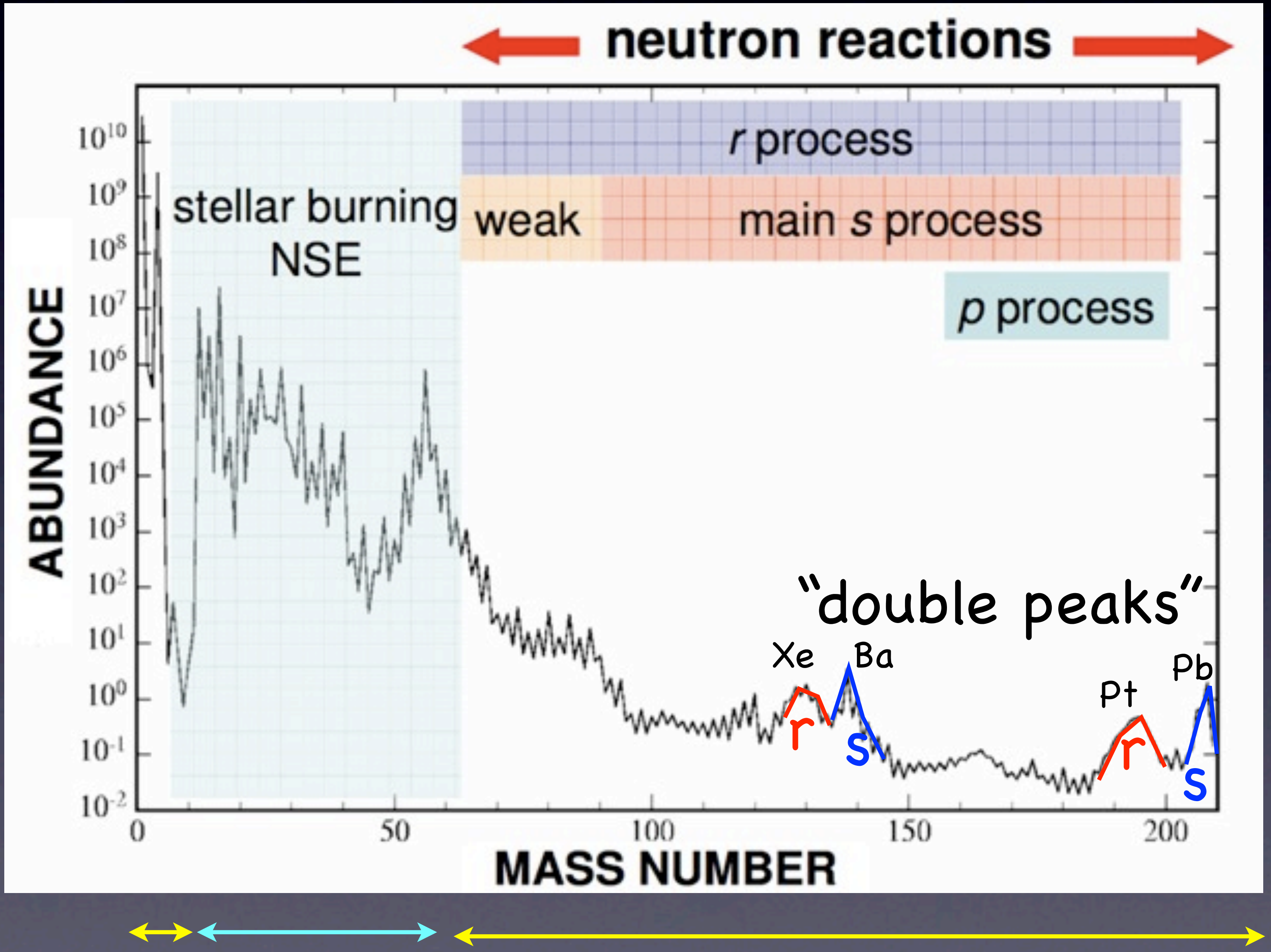
Advanced LIGO

Which additional signatures are produced by compact object encounters?

⇒ related to ejected mass

Rapid neutron capture nucleosynthesis ("r-process")

- Big Bang: elements up to ^{7}Li/^{7}Be
- hydrostatic stellar burning: up to "iron-group"
- beyond "iron group": mainly neutron capture processes



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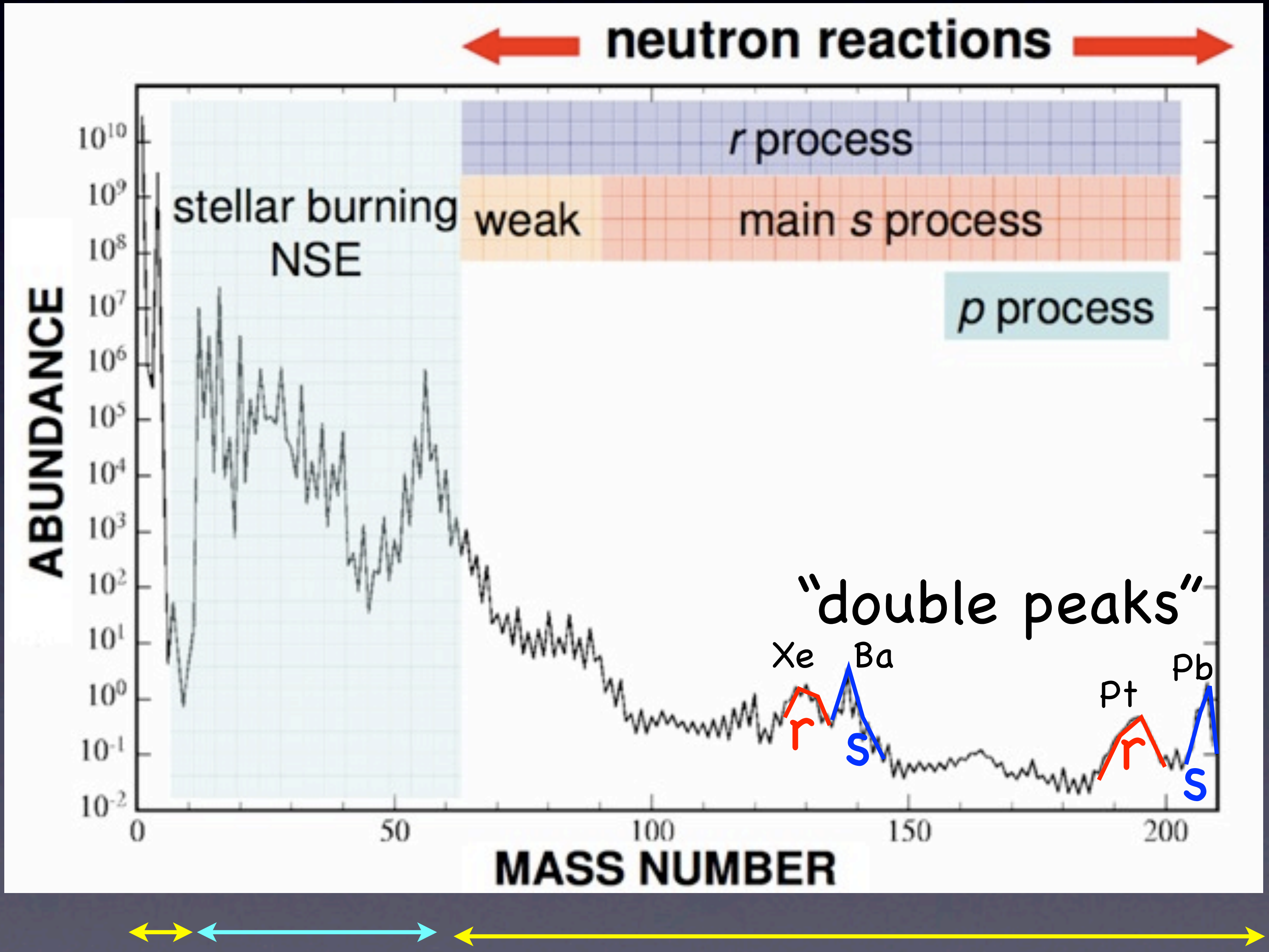

“Big Bang” “stellar burning” “neutron captures”

⇒ essentially two neutron capture processes in nature:

- rapid n-capture (“r-process”)
- slow n-capture (“s-process”)

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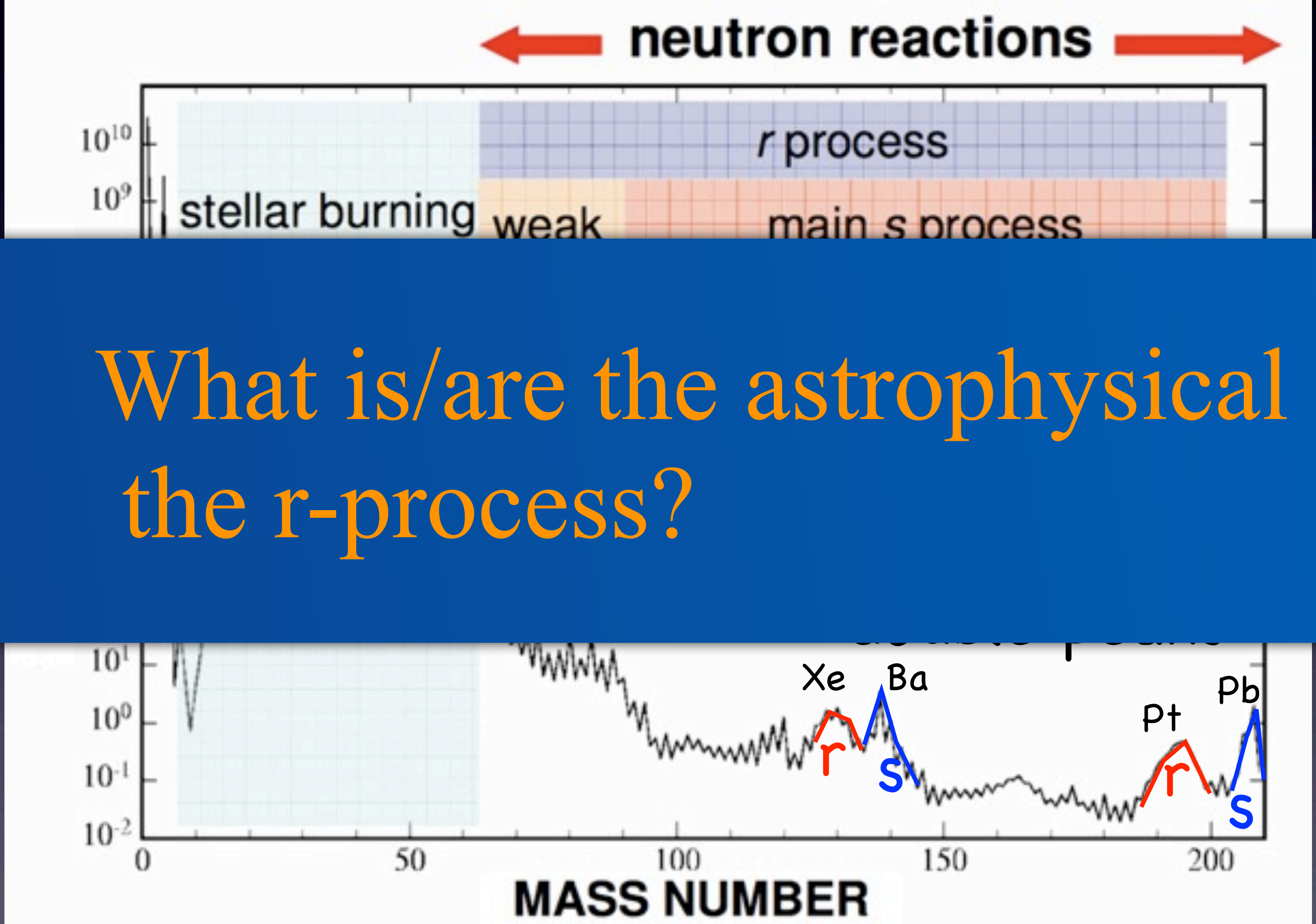

What is/are the astrophysical sources of the r-process?

⇒ essentially

- slow n-capture (“s-process”)

“Big Bang” “stellar burning” “neutron captures”

Neutron star mergers as r-process source?

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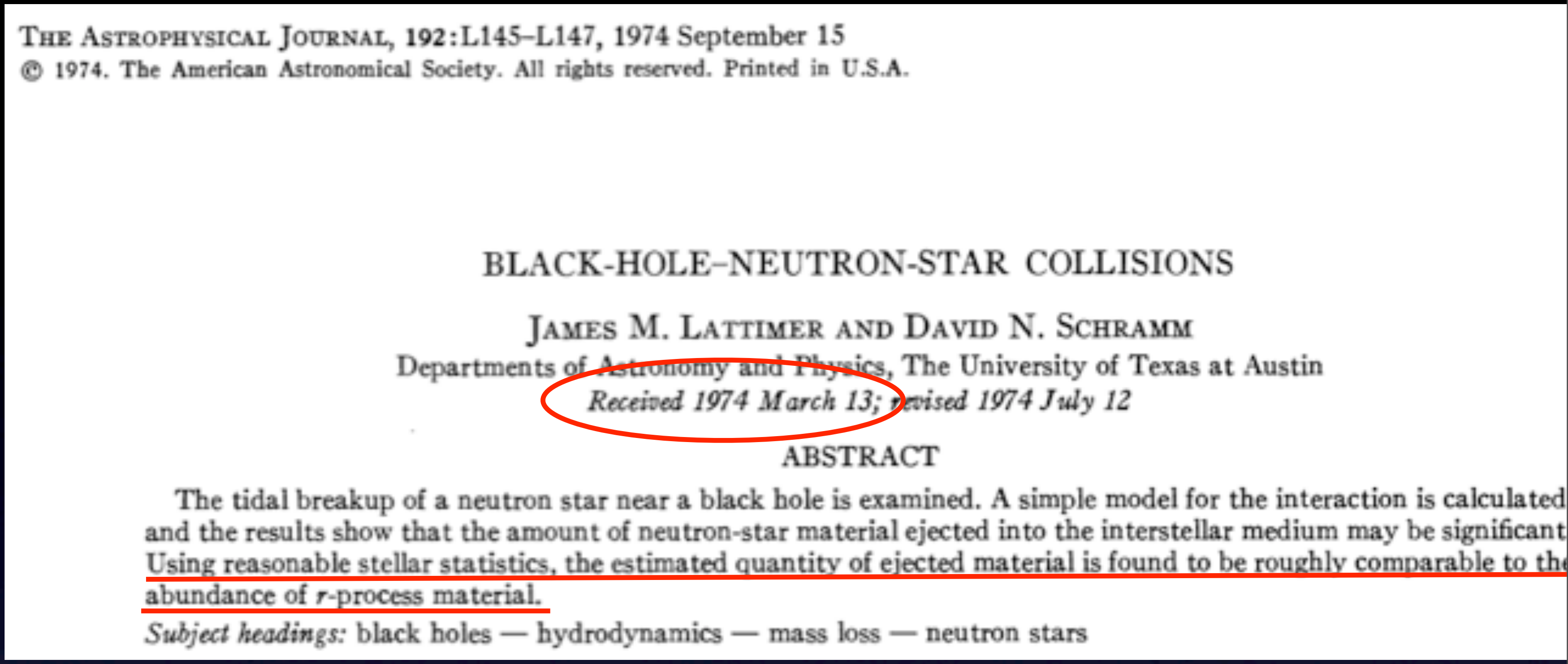

The Astrophysical Journal, 192:L145–L147, 1974 September 15

BLACK-HOLE–NEUTRON-STAR COLLISIONS

James M. Lattimer and David N. Schramm
Departments of Astronomy and Physics, The University of Texas at Austin

Received 1974 March 13; revised 1974 July 12

ABSTRACT

The tidal breakup of a neutron star near a black hole is examined. A simple model for the interaction is calculated and the results show that the amount of neutron-star material ejected into the interstellar medium may be significant. Using reasonable stellar statistics, the estimated quantity of ejected material is found to be roughly comparable to the abundance of *r*-process material.

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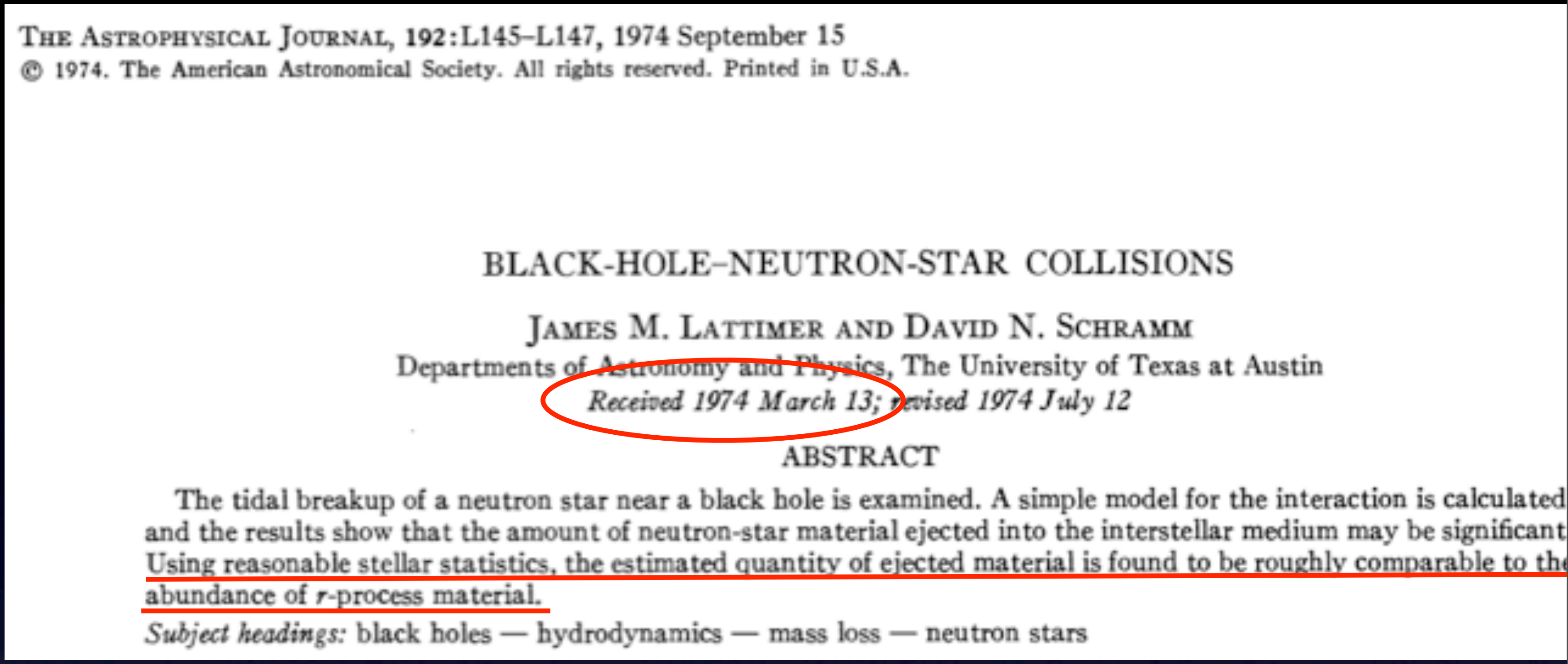

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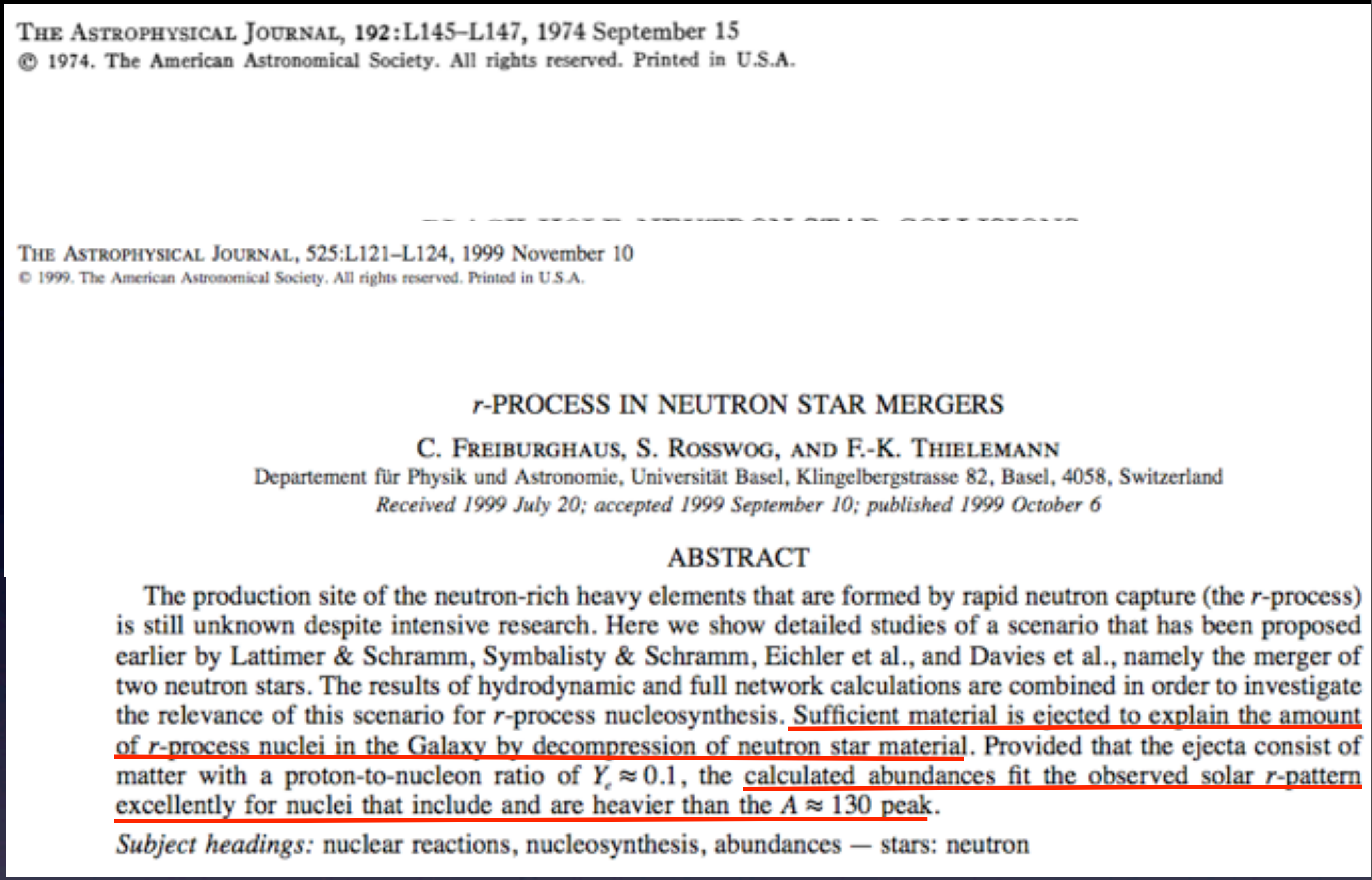

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r-PROCESS IN NEUTRON STAR MERGERS

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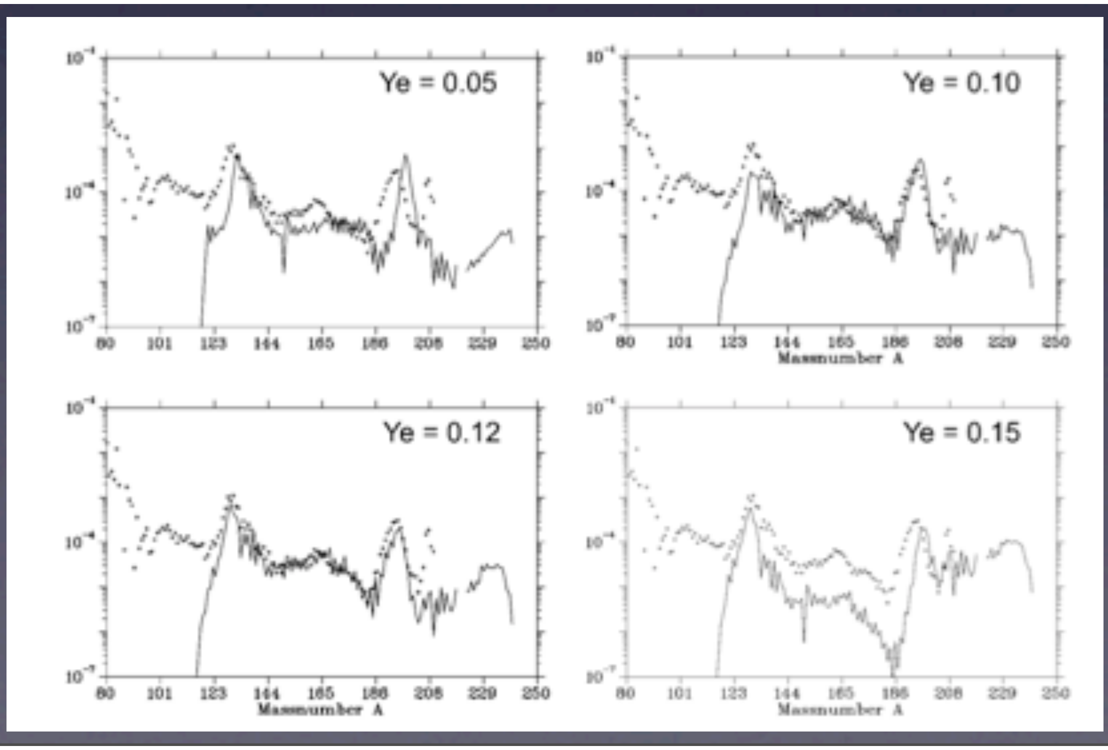

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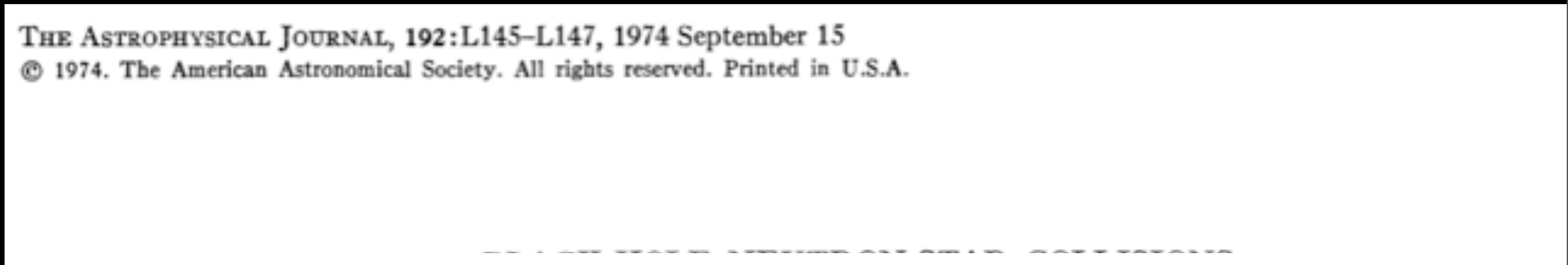

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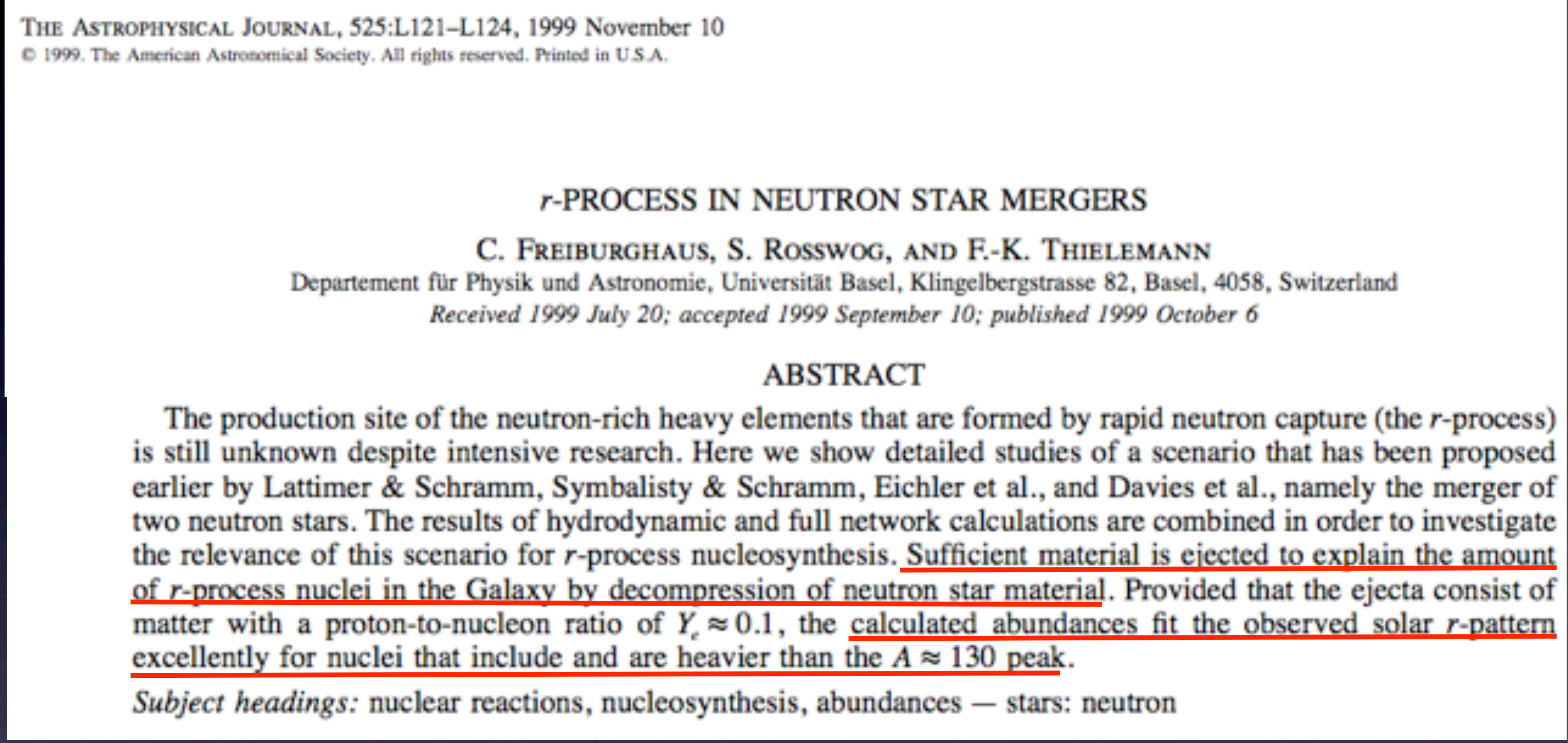

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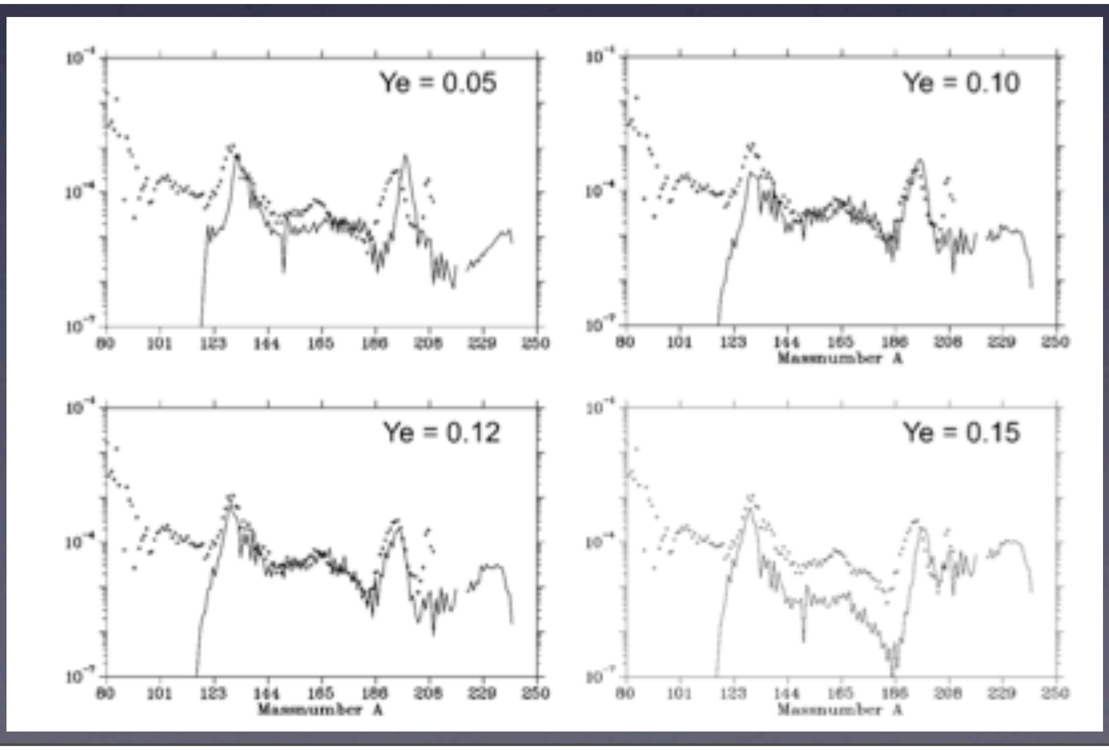
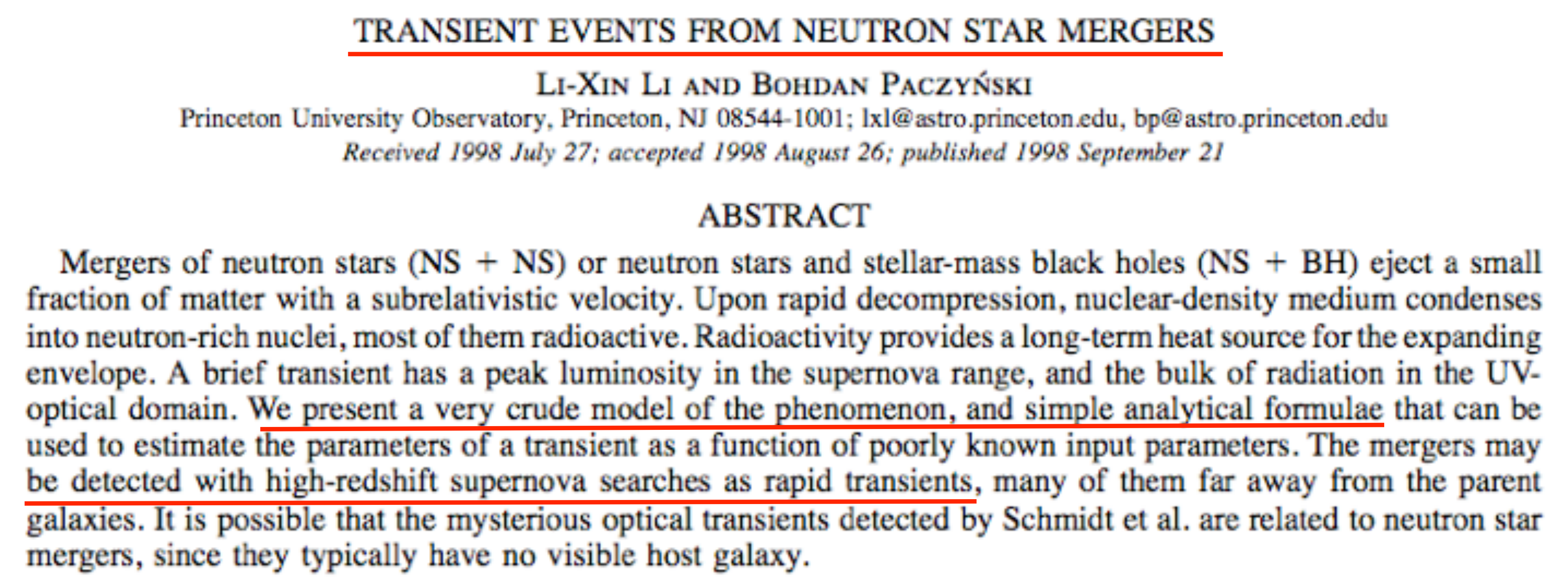


“Macro-”/”Kilonovae”



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

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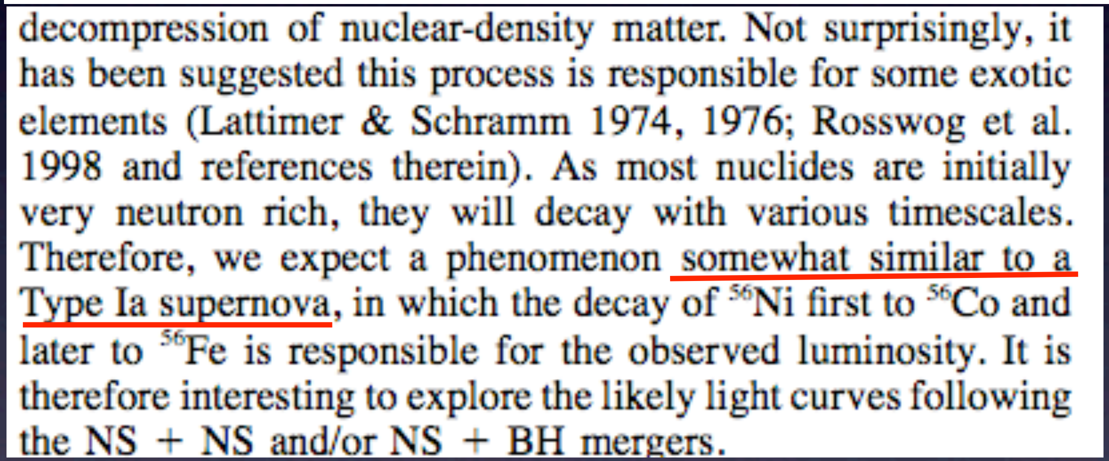
ABSTRACT

Mergers of neutron stars (NS + NS) or neutron stars and stellar-mass black holes (NS + BH) eject a small fraction of matter with a subrelativistic velocity. Upon rapid decompression, nuclear-density medium condenses into neutron-rich nuclei, most of them radioactive. Radioactivity provides a long-term heat source for the expanding envelope. A brief transient has a peak luminosity in the supernova range, and the bulk of radiation in the UV-optical domain. We present a very crude model of the phenomenon, and simple analytical formulae that can be used to estimate the parameters of a transient as a function of poorly known input parameters. The mergers may be detected with high-redshift supernova searches as rapid transients, many of them far away from the parent galaxies. It is possible that the mysterious optical transients detected by Schmidt et al. are related to neutron star mergers, since they typically have no visible host galaxy.



decompression of nuclear-density matter. Not surprisingly, it has been suggested this process is responsible for some exotic elements (Lattimer & Schramm 1974, 1976; Rosswog et al. 1998 and references therein). As most nuclides are initially very neutron rich, they will decay with various timescales. Therefore, we expect a phenomenon somewhat similar to a Type Ia supernova, in which the decay of ^{56}Ni first to ^{56}Co and later to ^{56}Fe is responsible for the observed luminosity. It is therefore interesting to explore the likely light curves following the NS + NS and/or NS + BH mergers.

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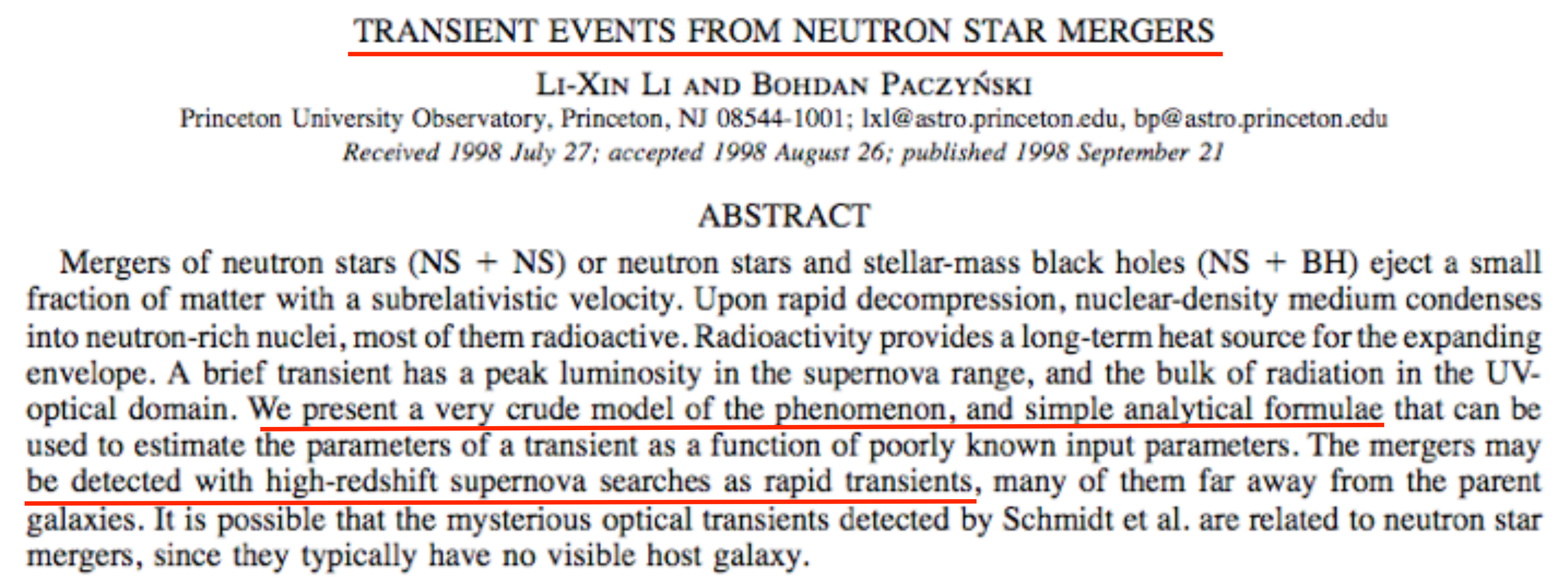

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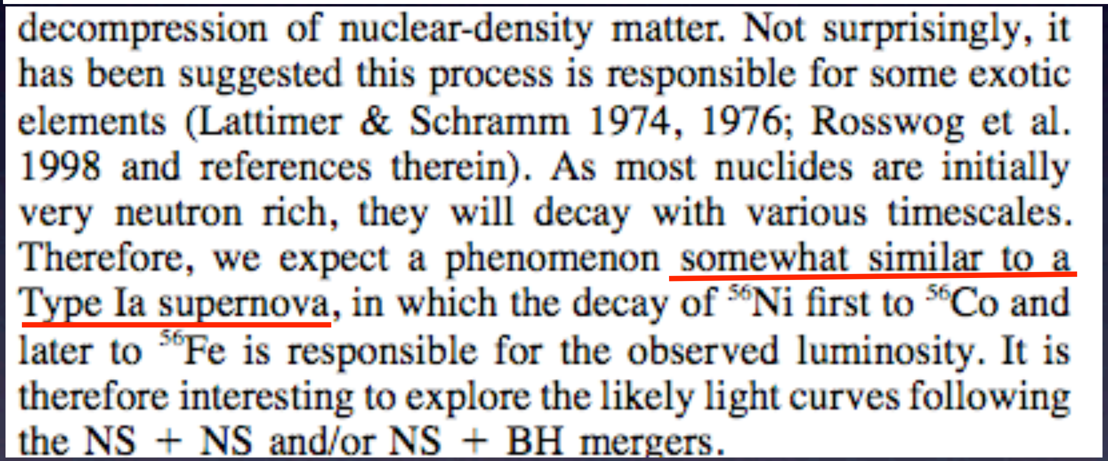

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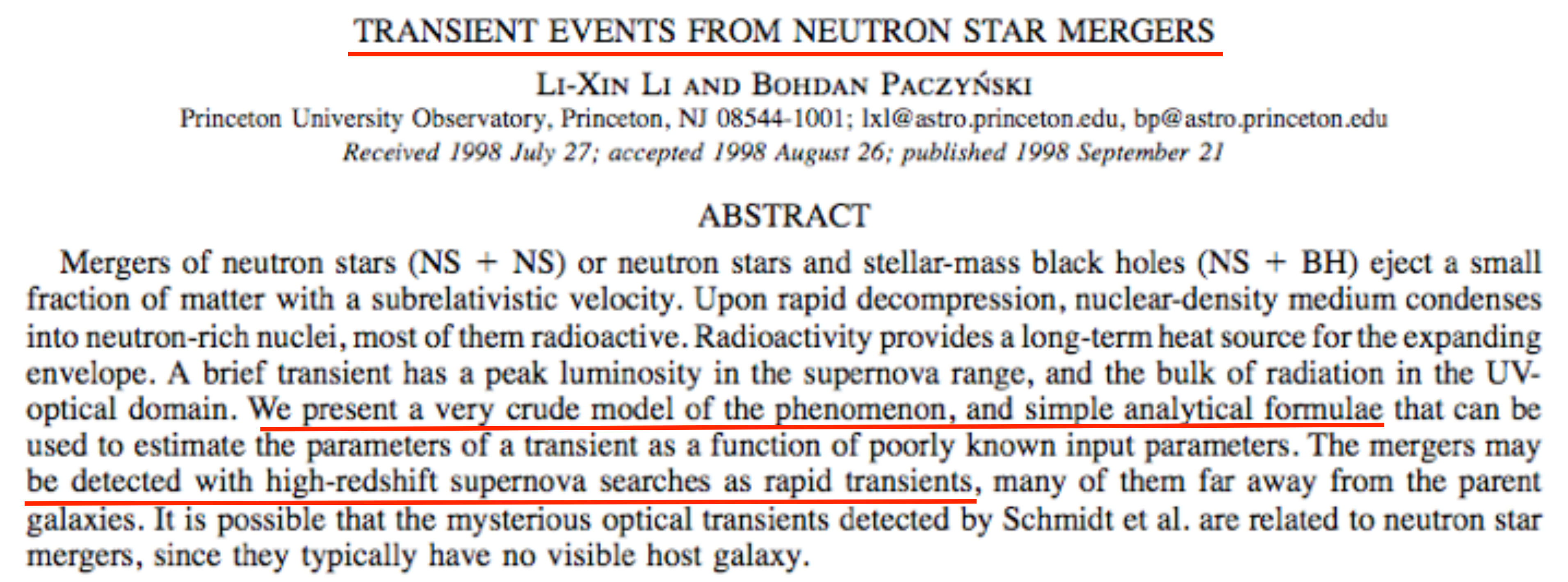

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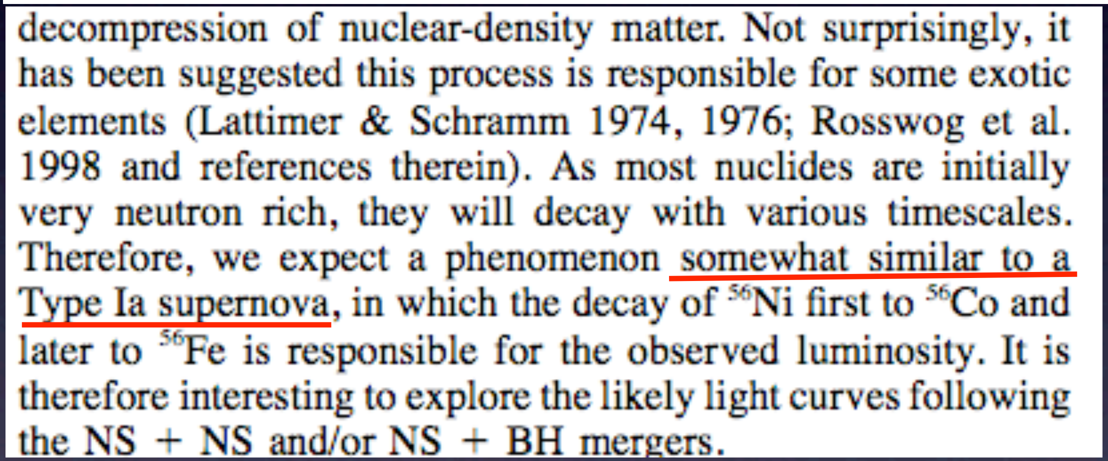

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- Kasen et al. 2013
- Barnes & Kasen 2013
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- Grossman et al. 2013
- Tanaka et al. 2013
- Tanaka & Hotokezaka 2013
- Hotokezaka et al. 2013

⇒ “VERY large opacities”

⇒ IR, not opt./UV

Channels to eject mass

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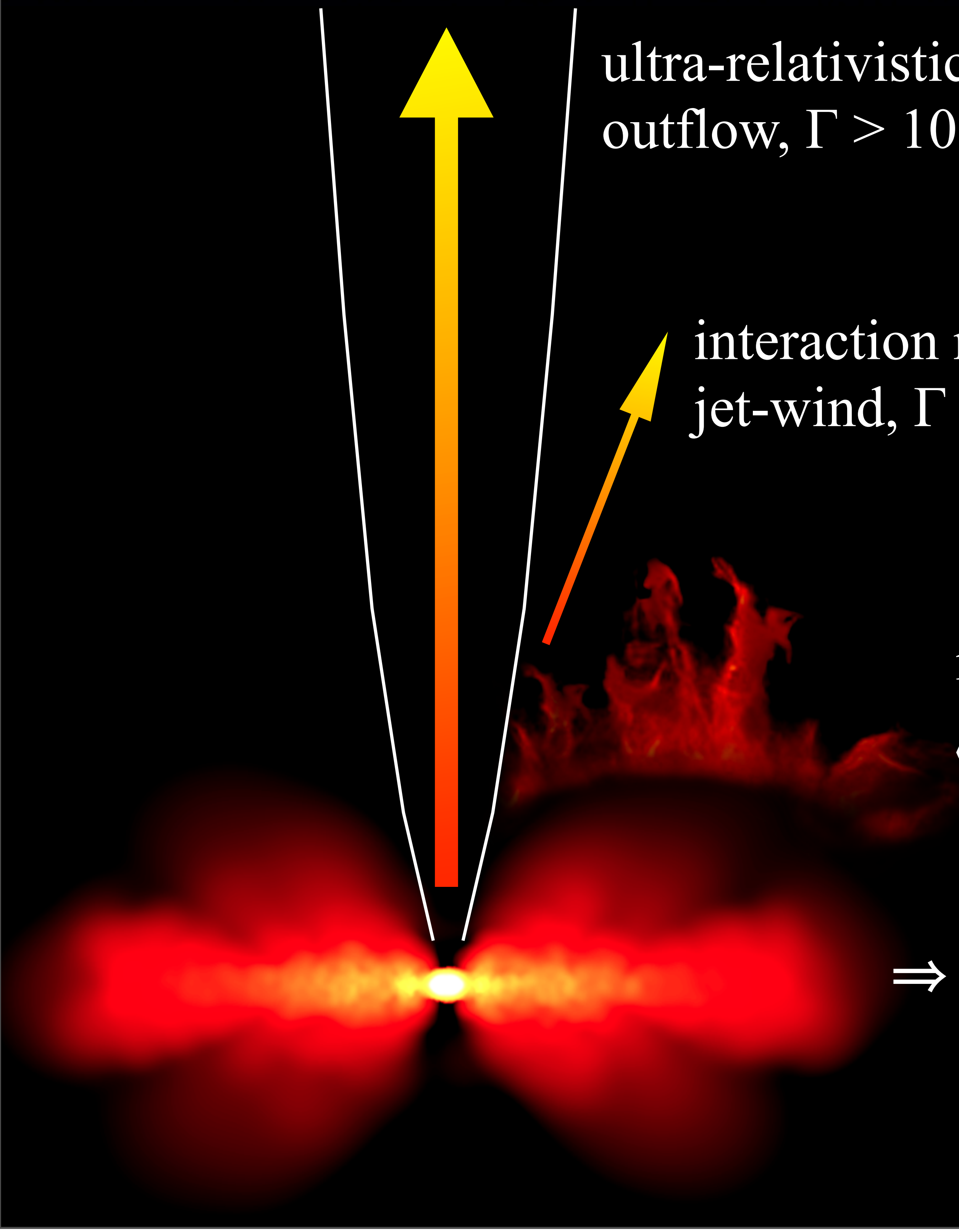

ultra-relativistic
outflow, $\Gamma > 100$

interaction region
jet-wind, $\Gamma \sim$ few (?)

neutrino-driven winds
$\langle v \rangle \approx 0.1c$

$\Rightarrow$ dynamic ejecta
$\langle v \rangle \approx 0.1c$

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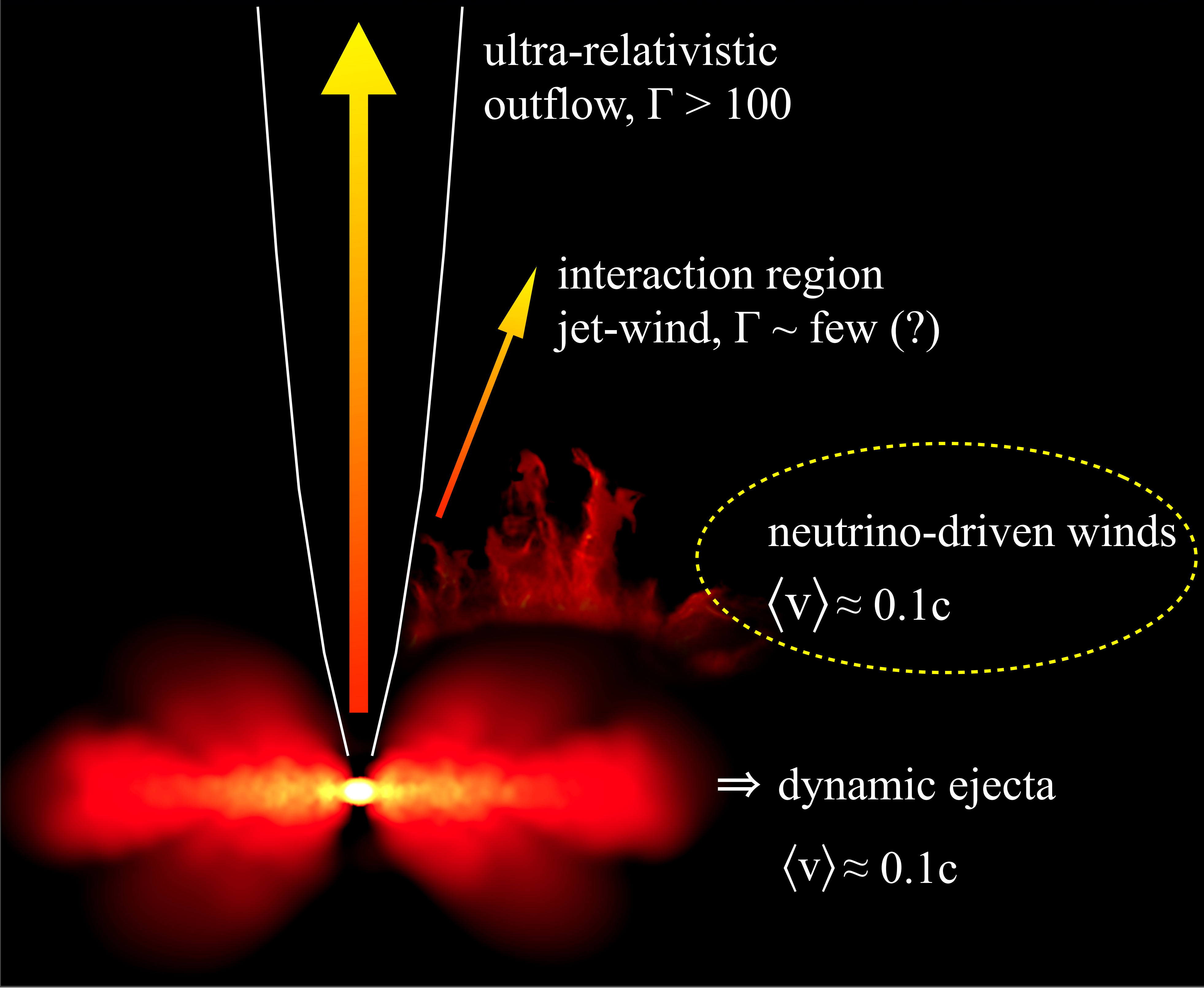

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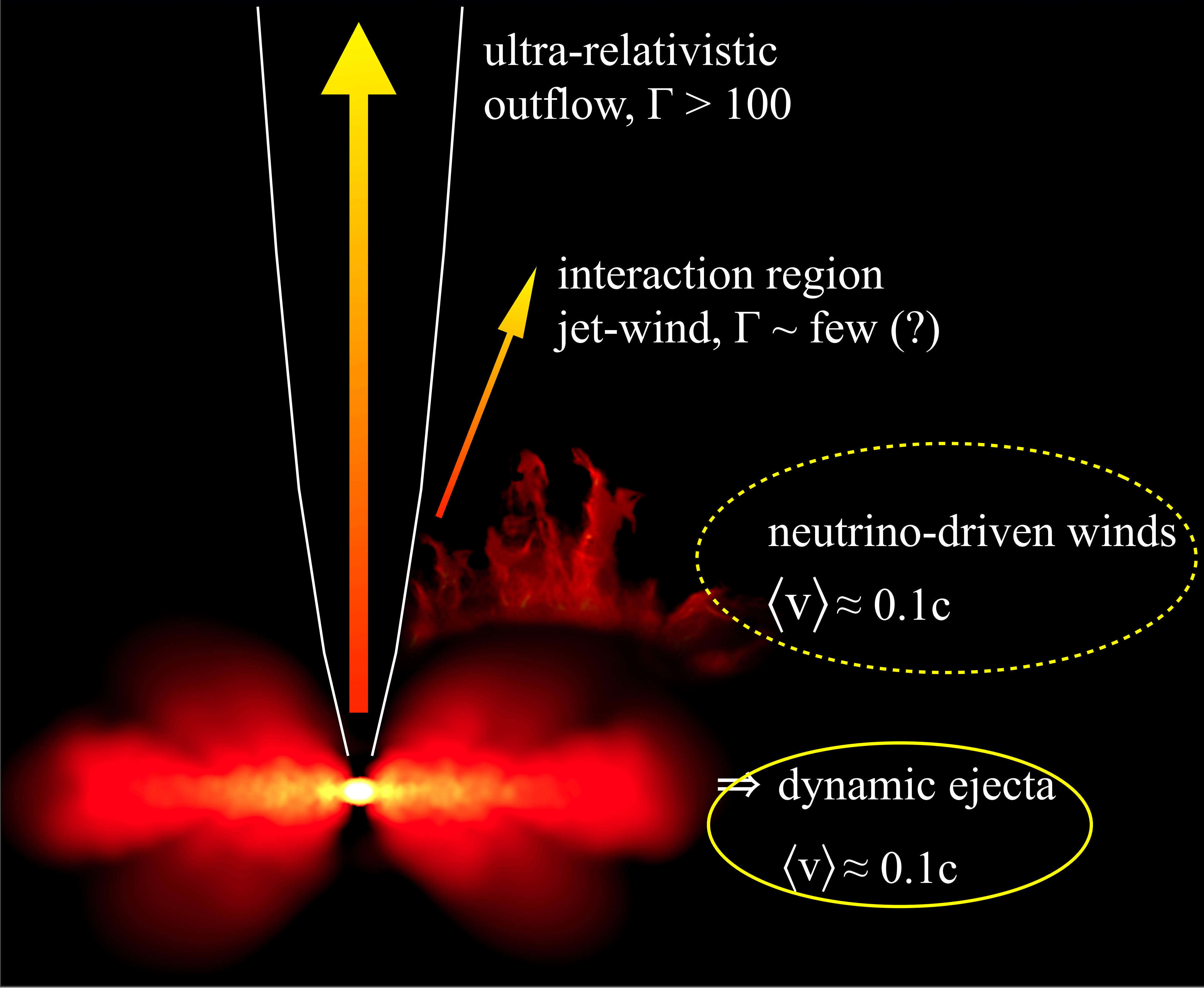

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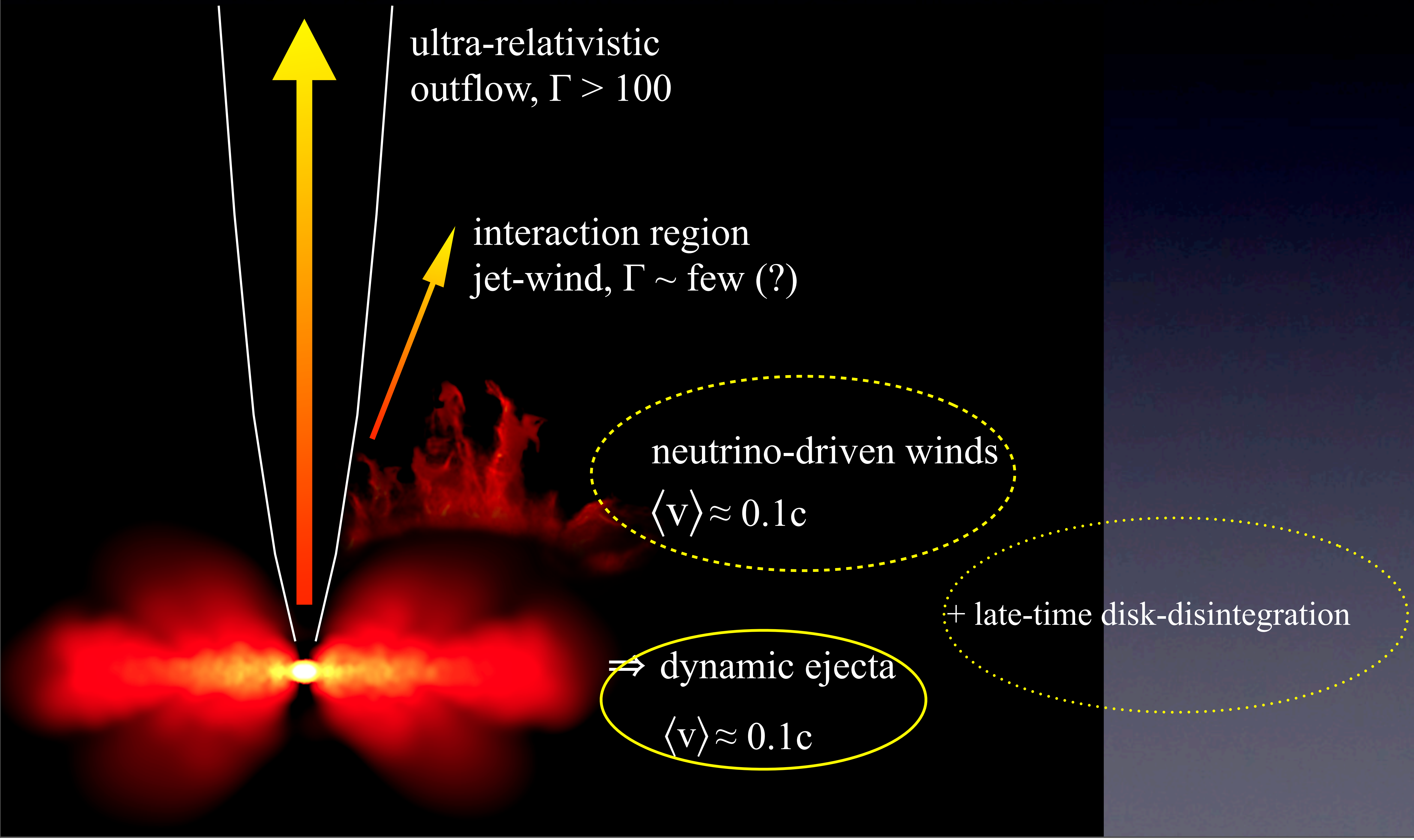

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+ late-time disk-disintegration

⇒ dynamic ejecta
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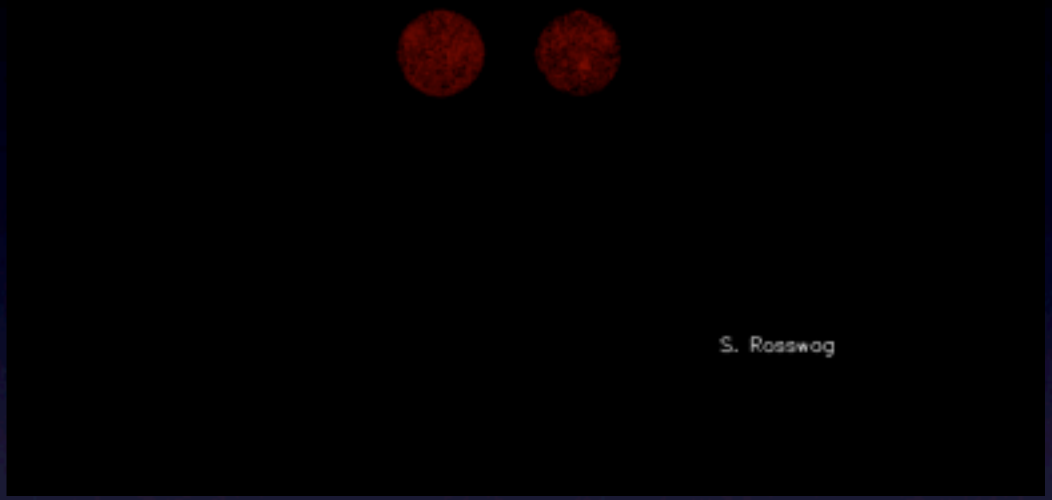
a) <u>"dynamic ejecta"</u>

(grav. torques, hydrodyn. interaction;

movie from Rosswog et al. 2013)



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typical merger case:
1.3 & 1.4 M_{sol}, no spin

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b) "neutrino-driven wind"

(neutrinos deposit energy via

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

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movie from Dessart et al. 2009,

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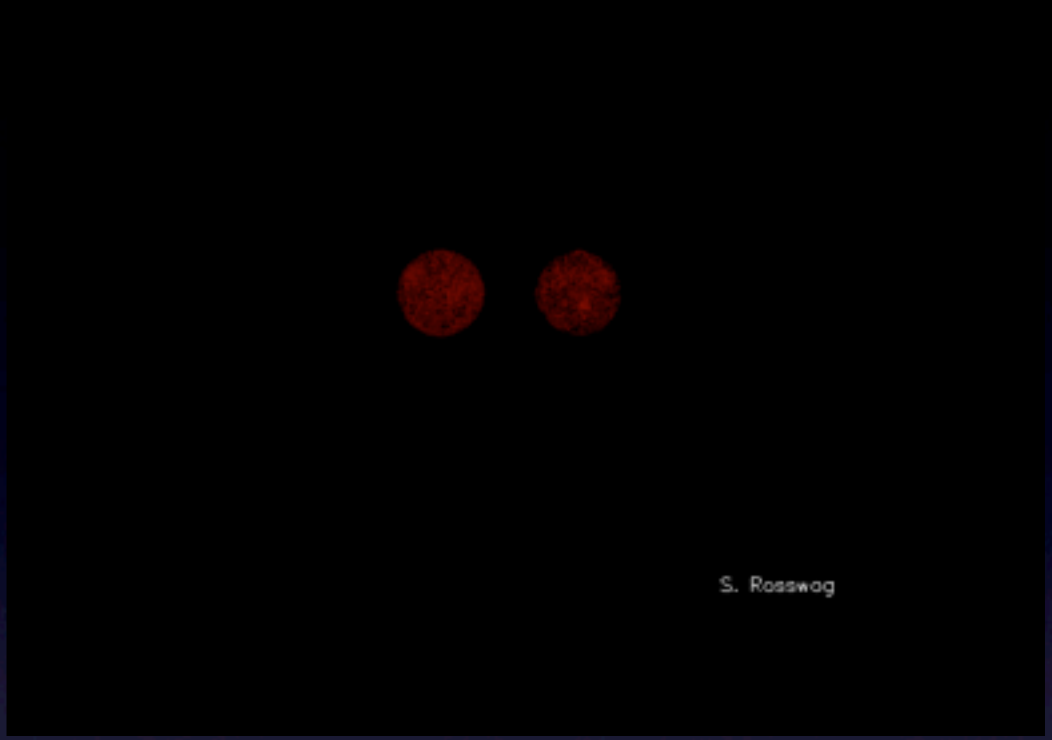

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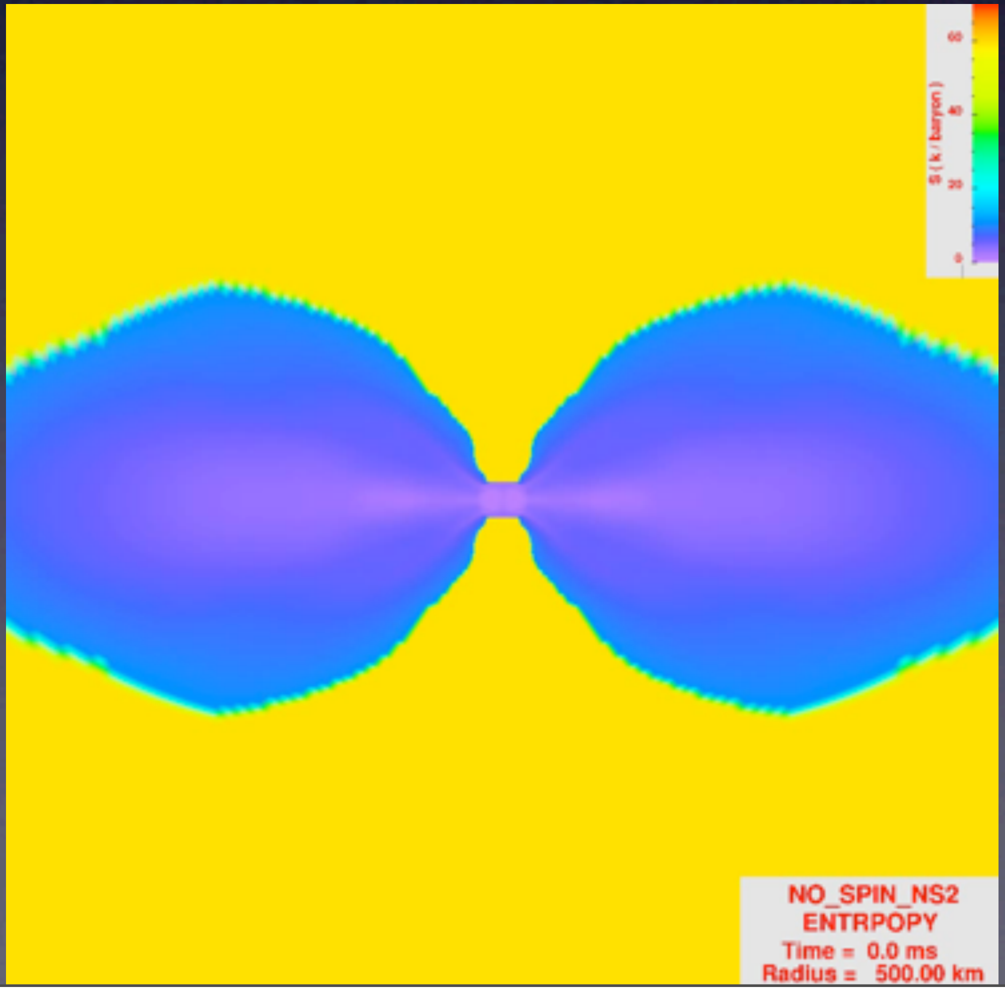

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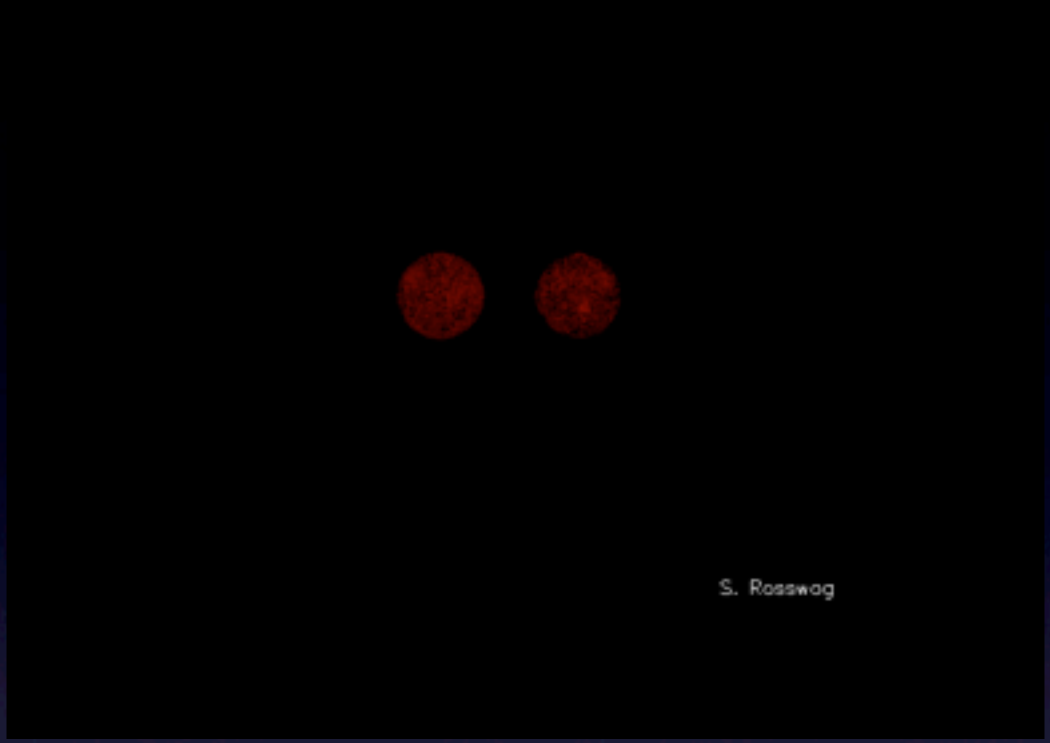

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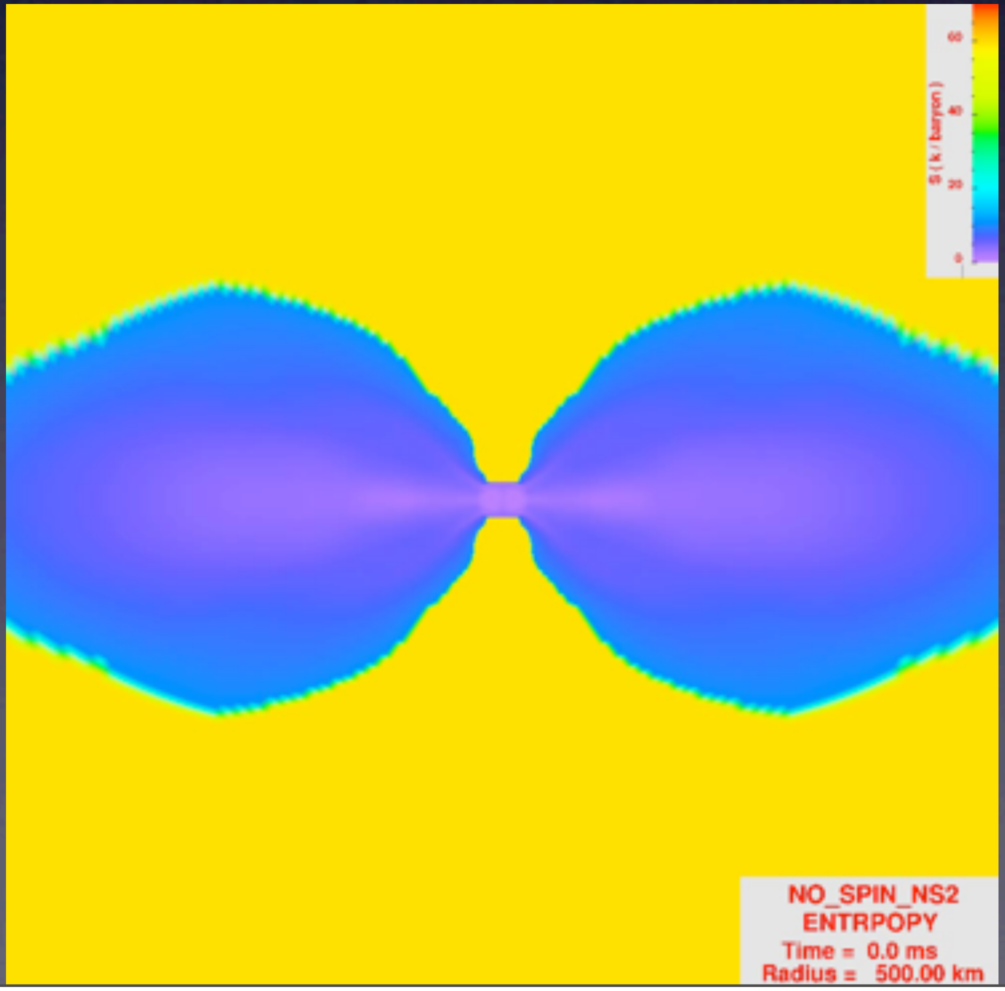

c) “accretion disk dissolves”

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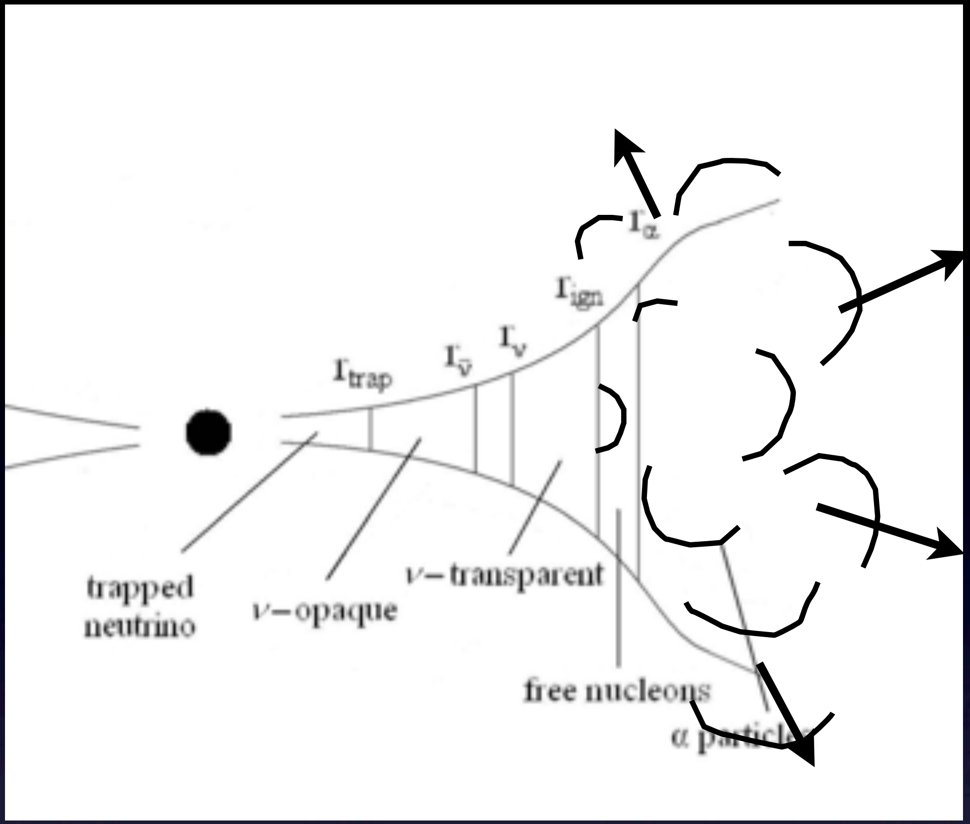

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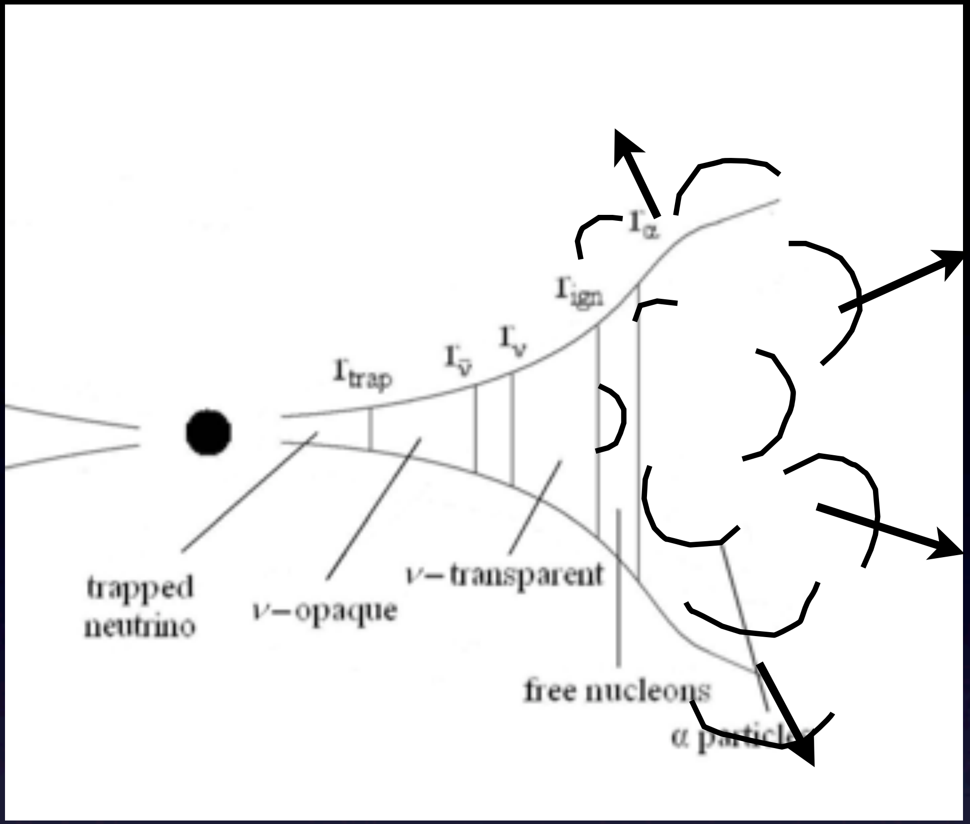

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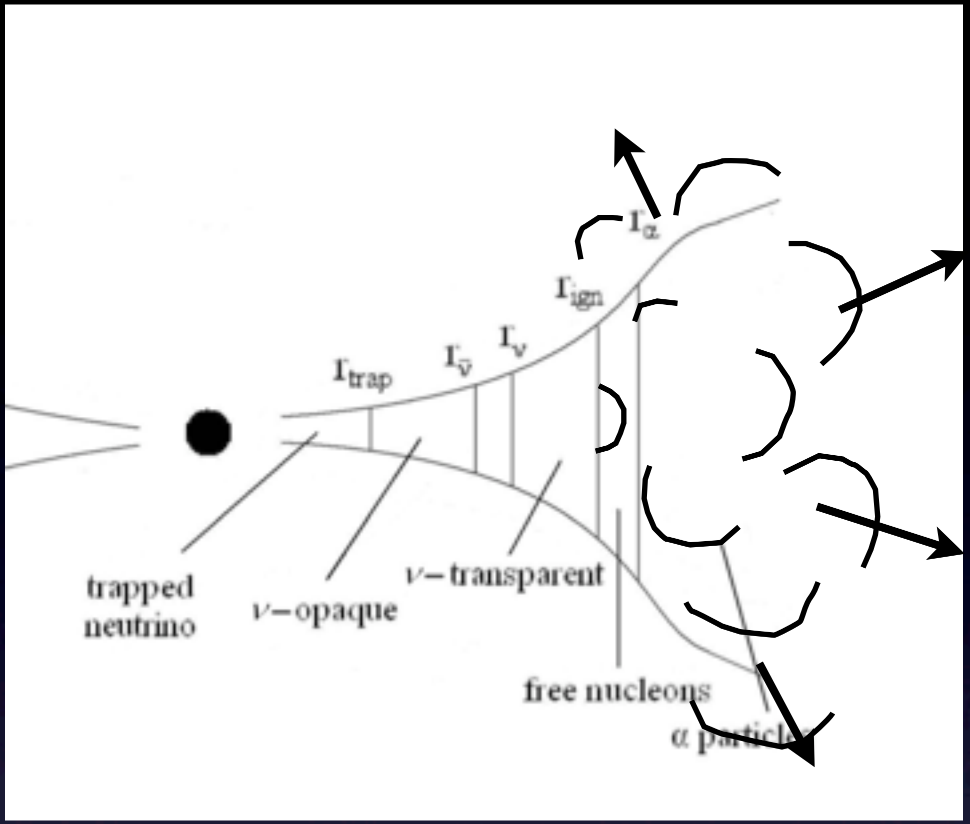

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⇒ m_{ej} ~ 0.02 M_{sol}

Qualitative differences/tendencies

“dynamic ejecta”

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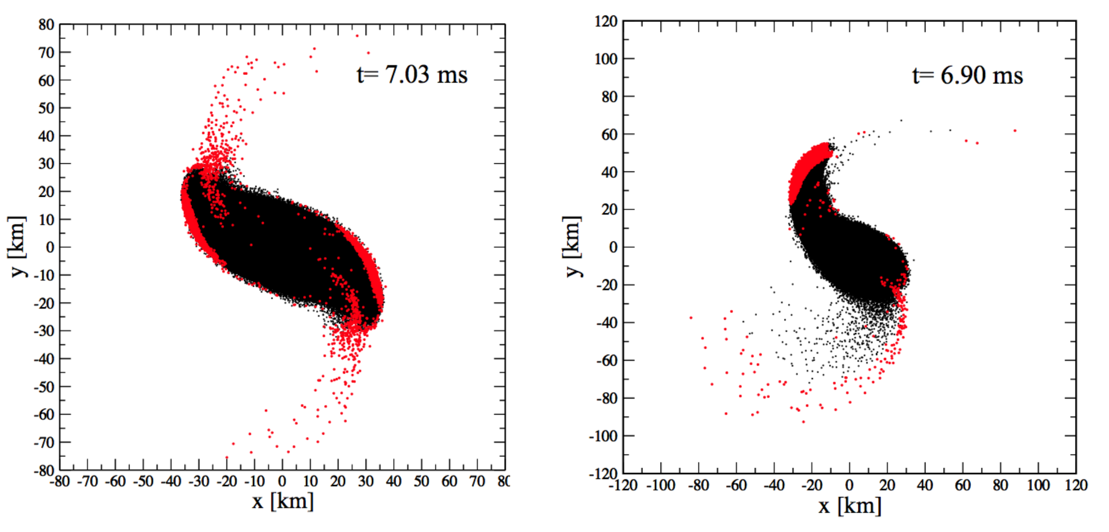
2 sources:



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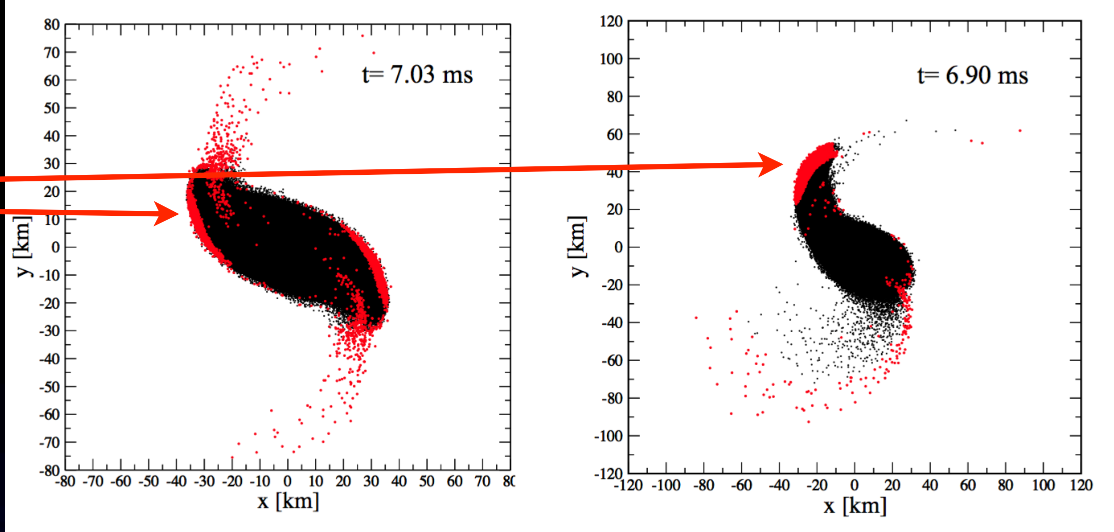

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2 sources: “tidal component”

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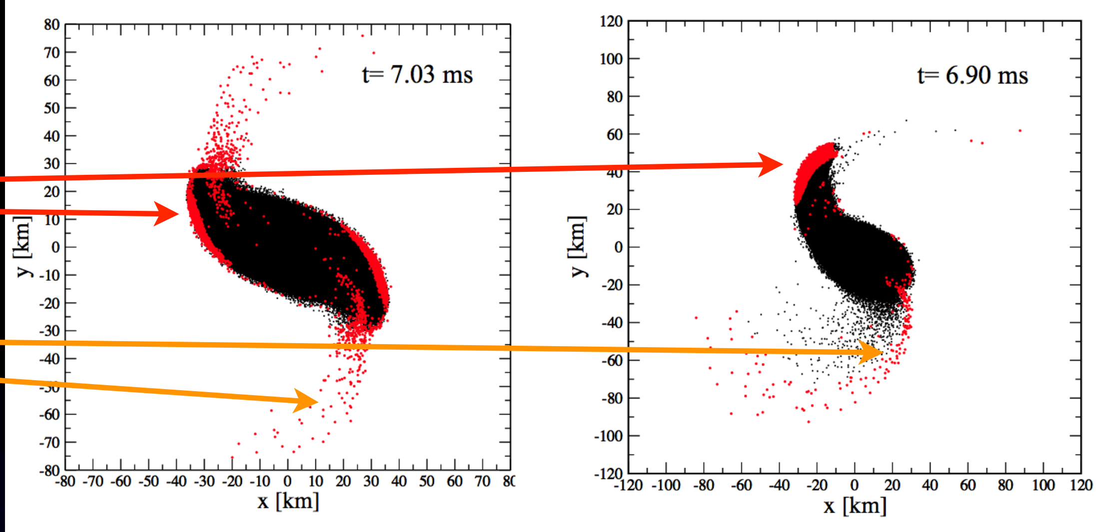

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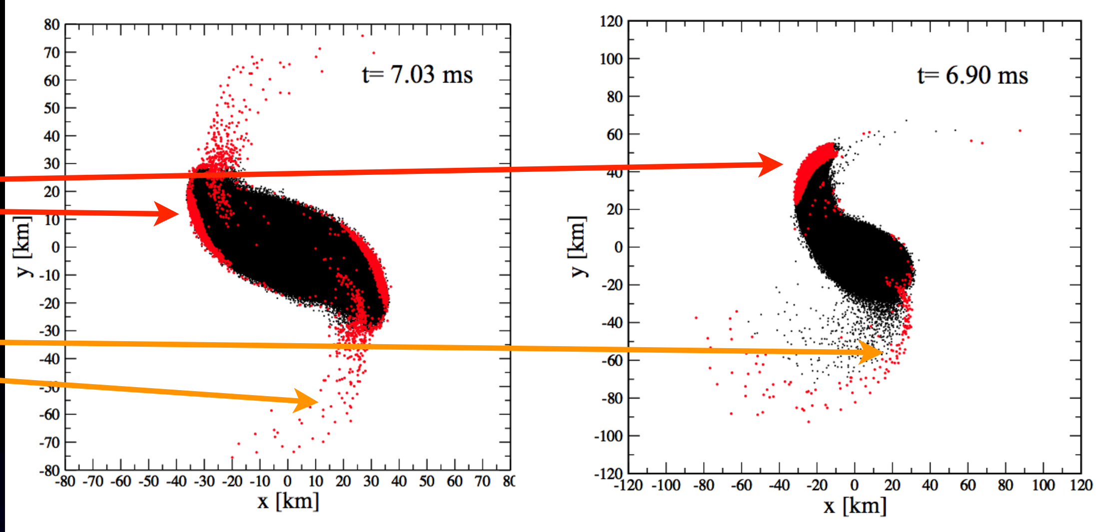

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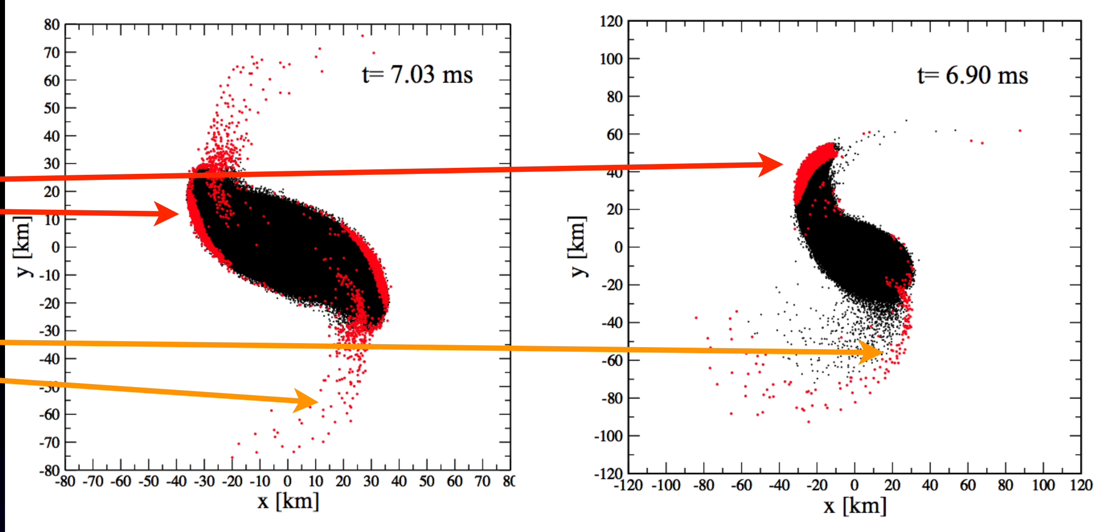

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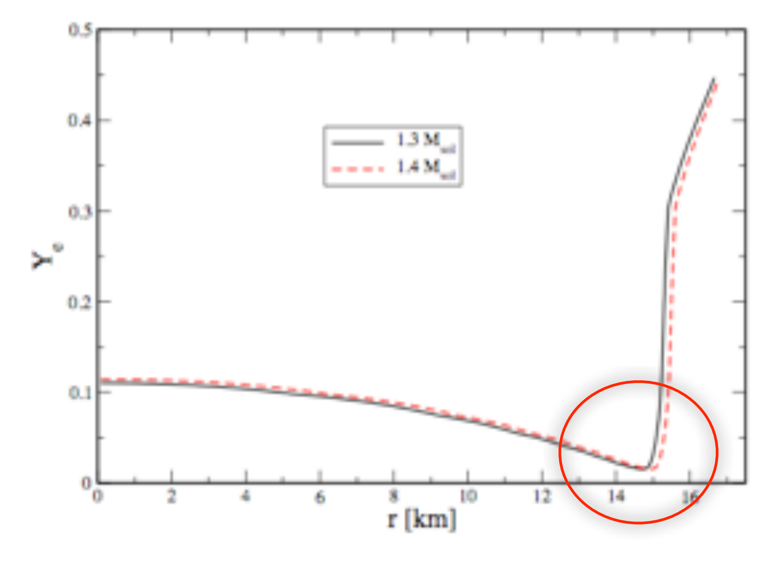

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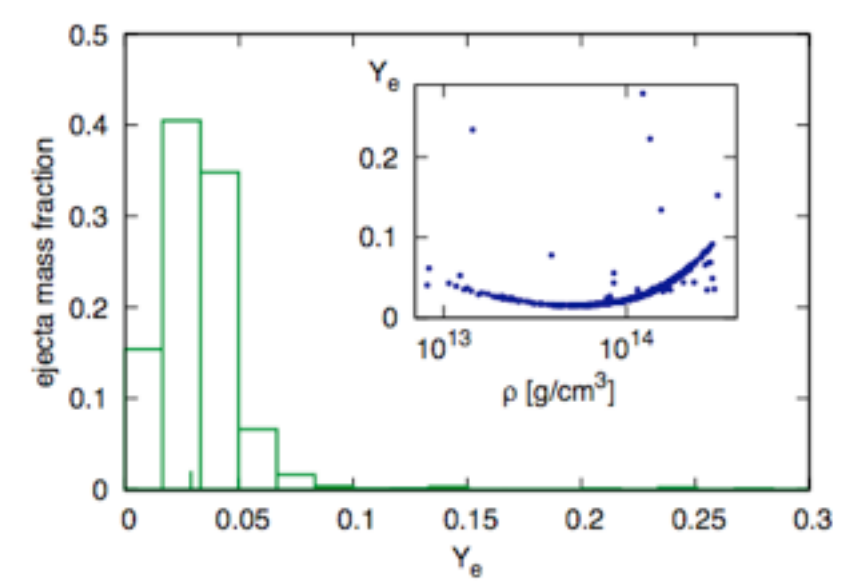

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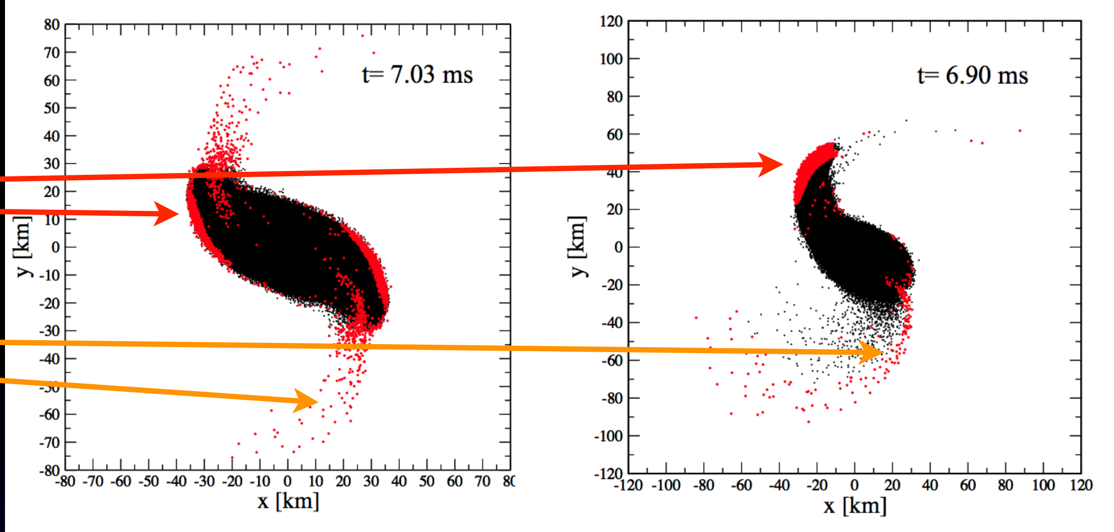

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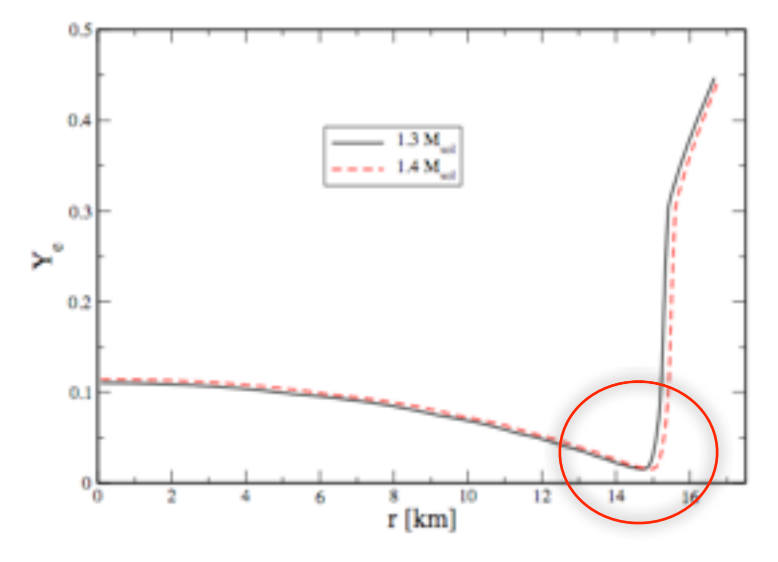

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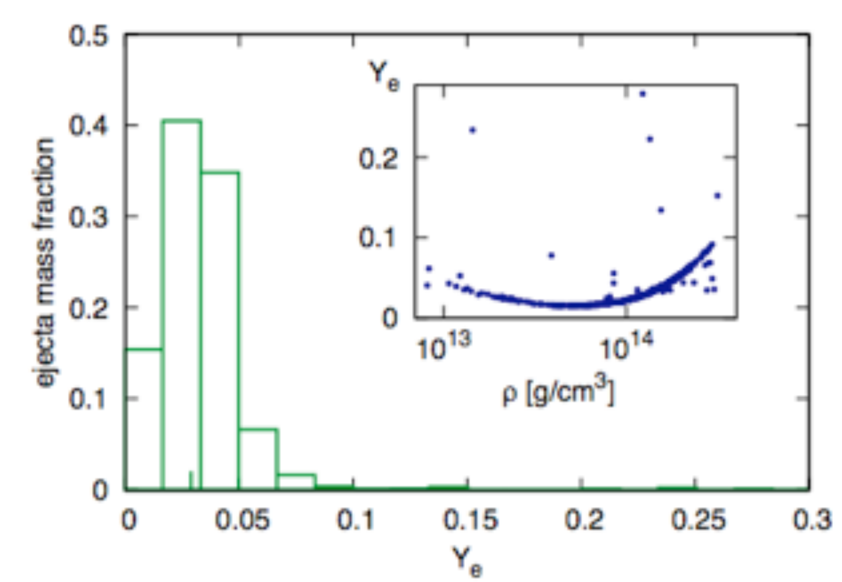

(Korobkin et al. 2013)

⇒ large neutron-to-seed ratio

⇒ very heavy nuclei up to/beyond platinum peak (A ~ 195)

⇒ very large opacities (Kasen et al. 2013)

⇒ late, dim macronova peak, IR

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sequence of ν/ν̄ capture for ν-wind,
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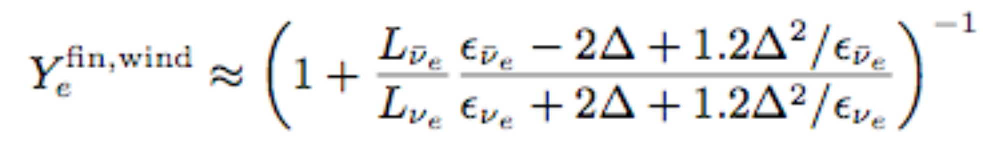

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from now on:
dynamic ejecta

Simulation ingredients:

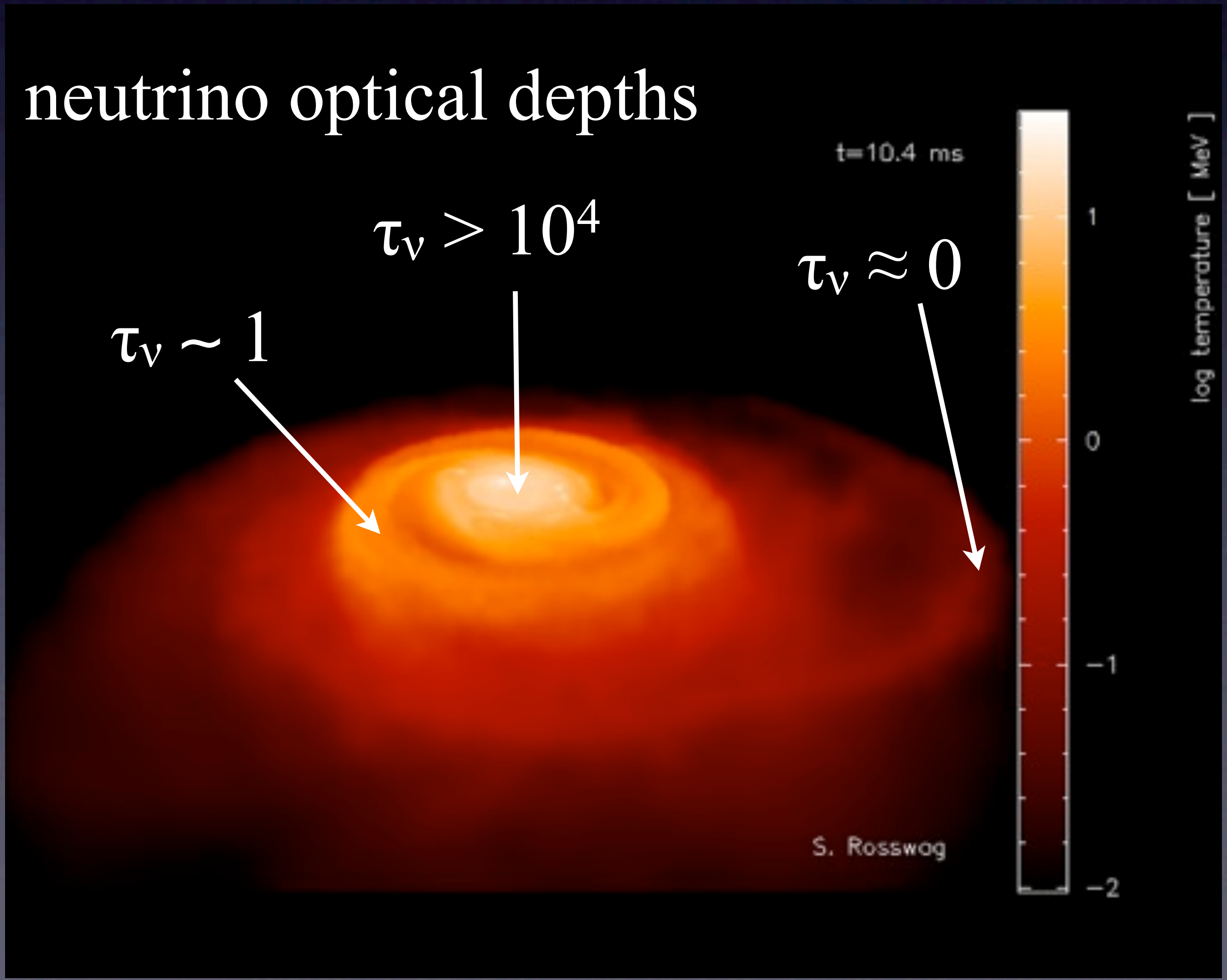
- 3D, Lagrangian Hydrodynamics (SPH) & (Newtonian) Gravity

- equation of state: density, temperature and composition dependent nuclear equation of state (Shen et al. 1998)

- neutrino emission:

  - opacity-dependent multi-flavour leakage scheme;

  - Y_e-change via electron/positron captures



neutrino optical depths

$\tau_\nu > 10^4$

$\tau_\nu \approx 0$

$\tau_\nu \sim 1$

References:

★ SR & Davies, MNRAS 334, 481 (2002)
★ SR & Liebendörfer, MNRAS 342, 673 (2003)
★ SR & Price, MNRAS 379, 915 (2007))

Dynamical mass ejection

typical merger case:
1.3 & 1.4 M_{sol}, no spin

visualized:
Ye value at given
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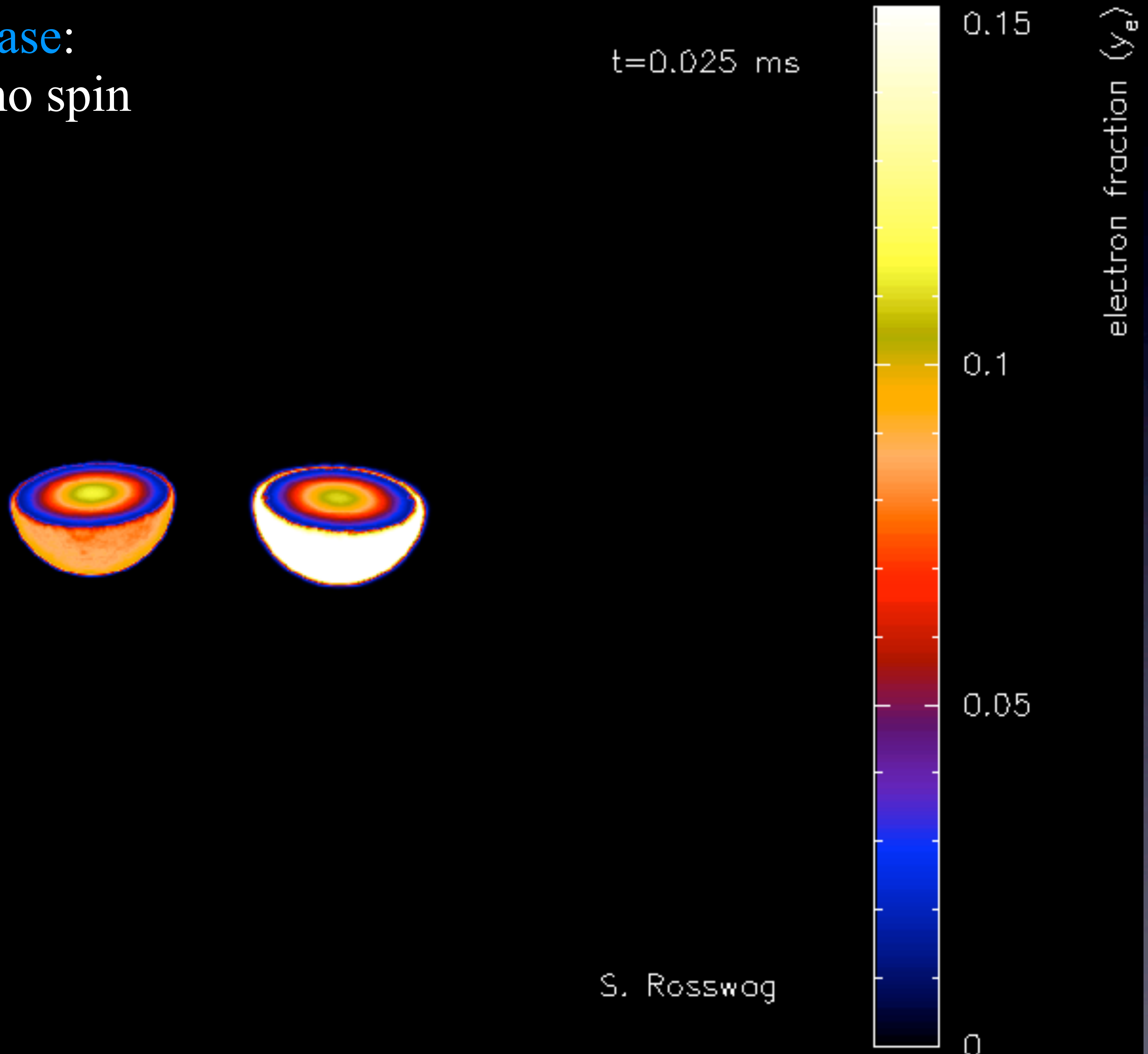

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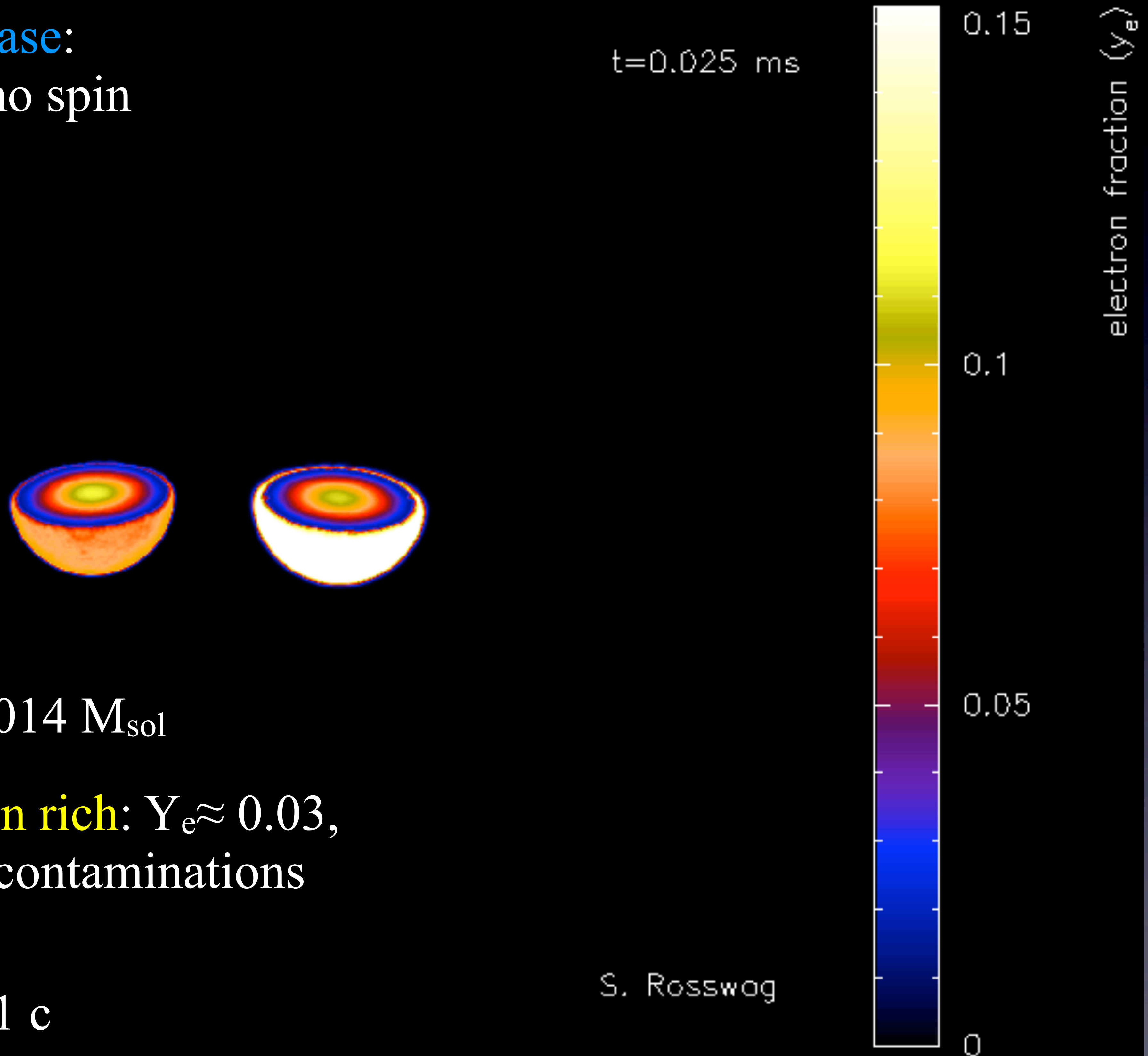


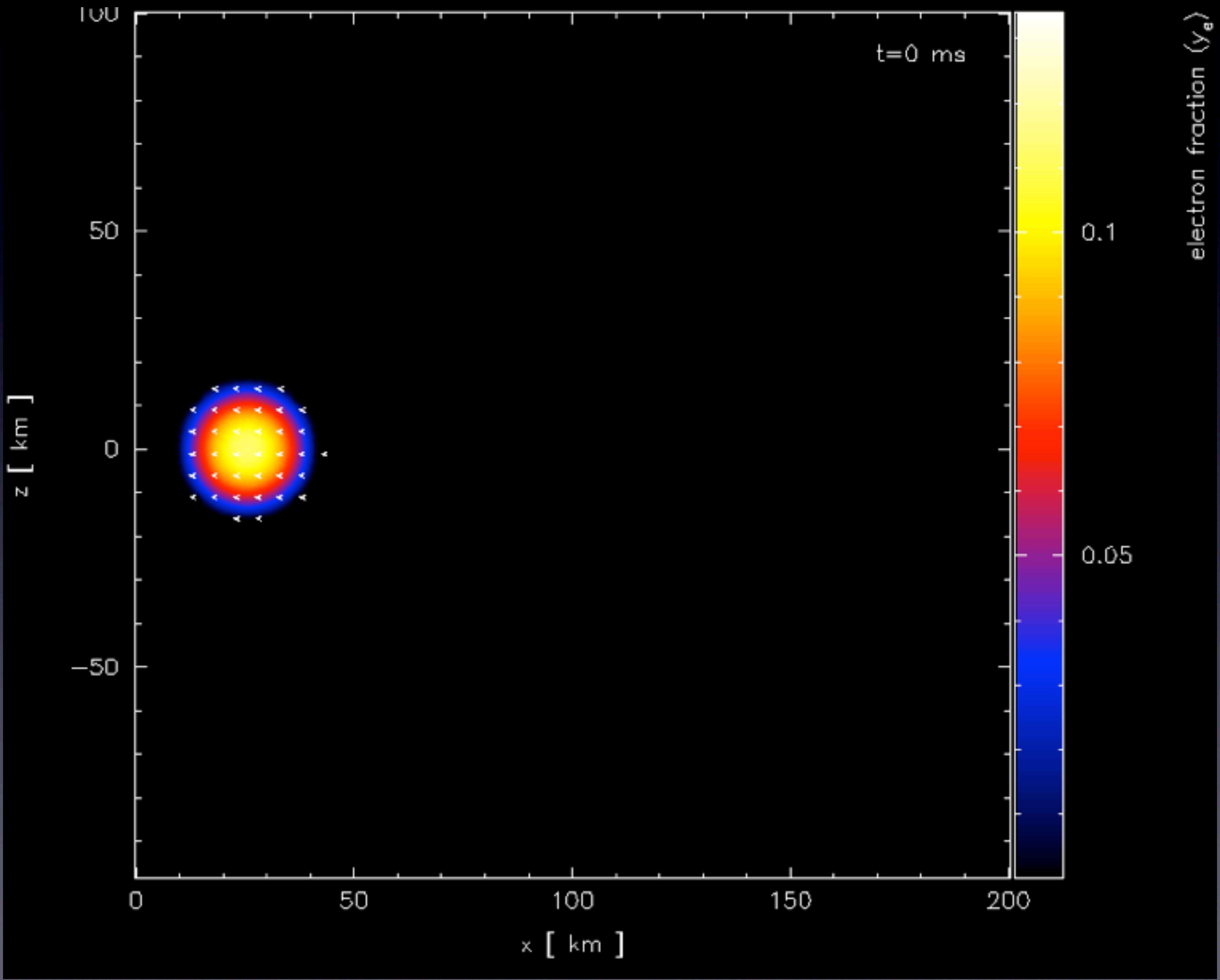
total amount: 0.014 M_{sol}

extremely neutron rich: $Y_e \approx 0.03$,
with small crust contaminations

velocity $v \approx 0.1\,c$

Disk formation: Y_e and velocity

$2 \times 1.4\ M_{sol}$



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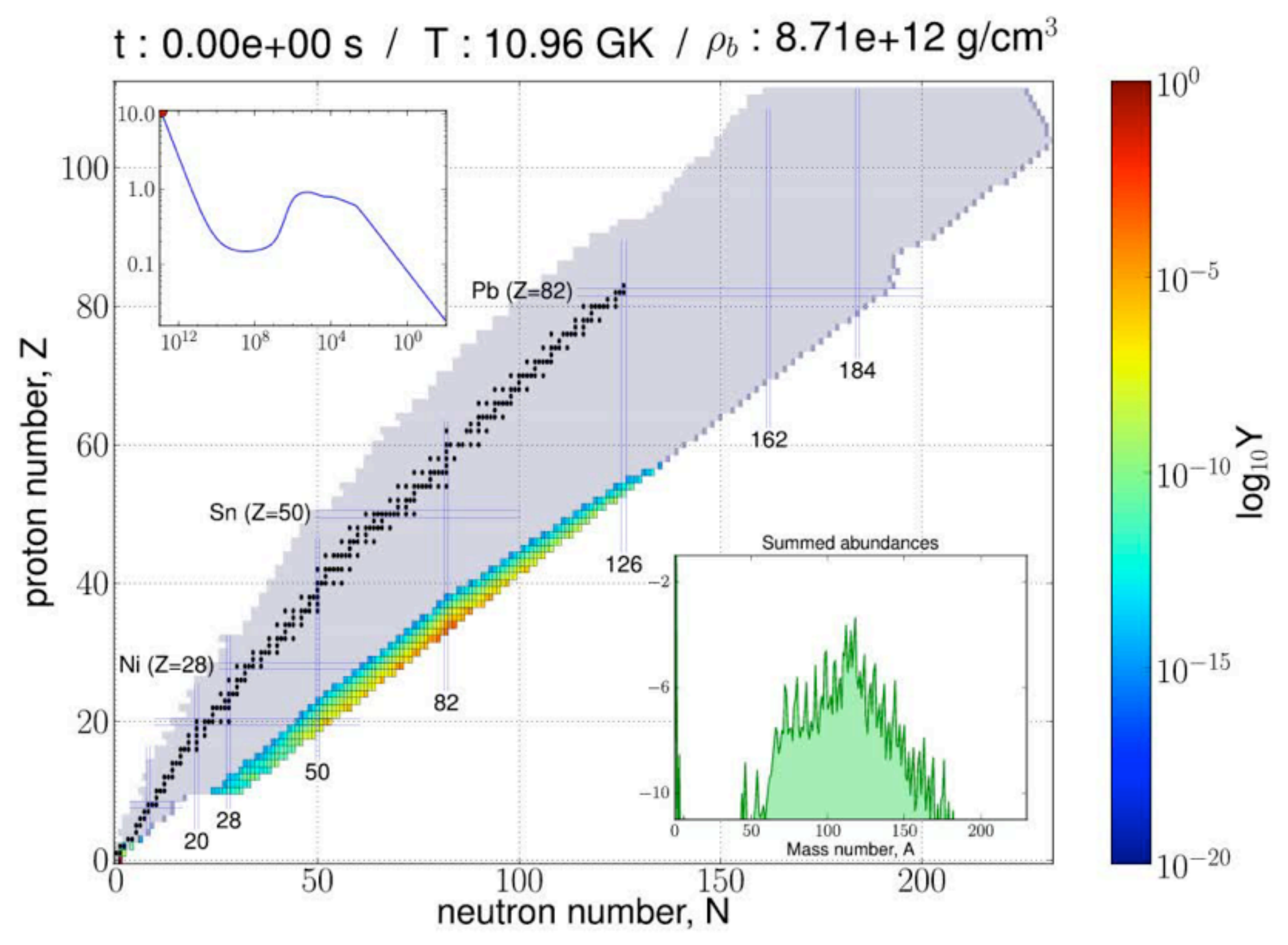

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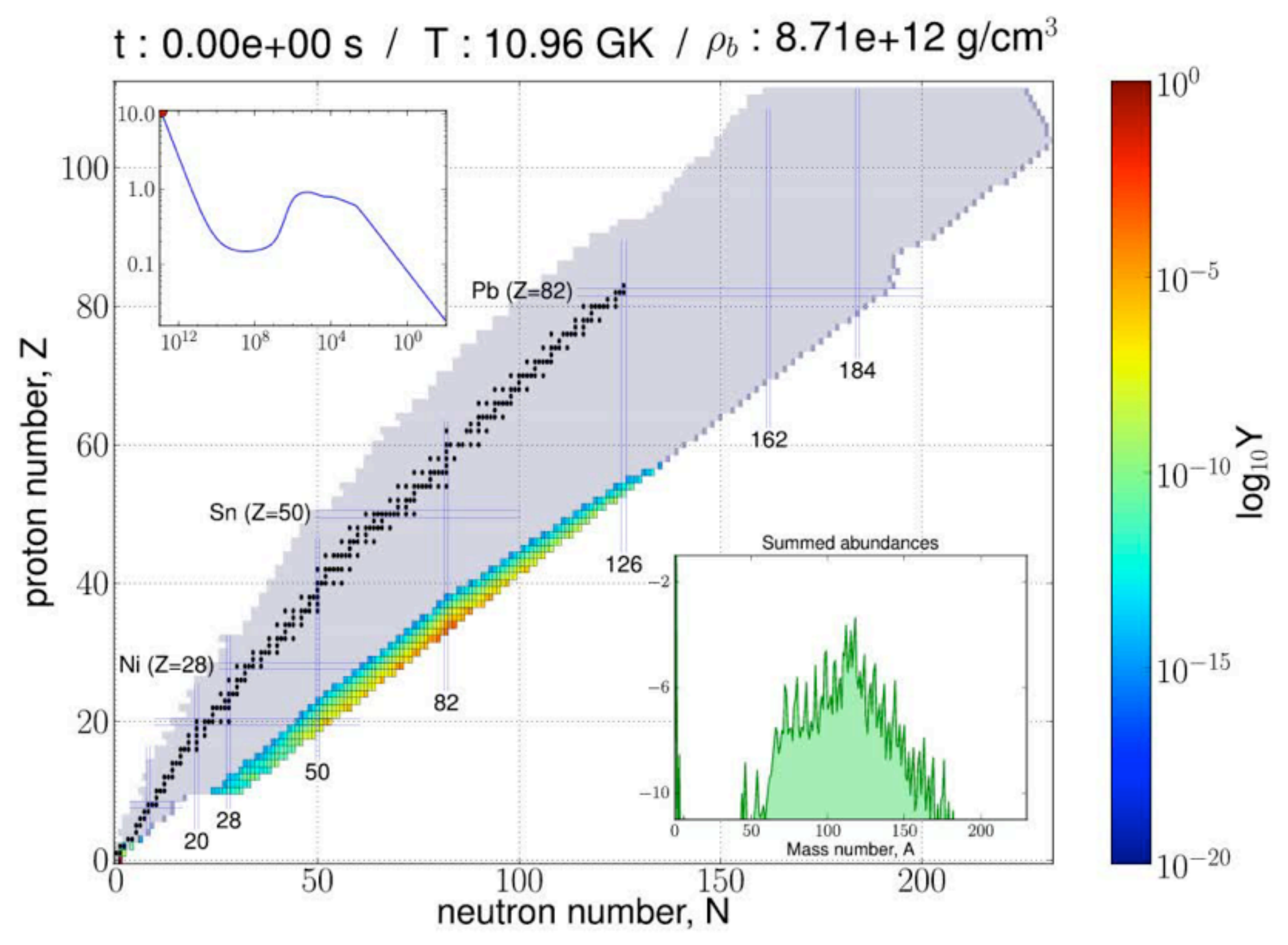

II. Remnant evolution

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e) radiative signature from 3D remnant geometry

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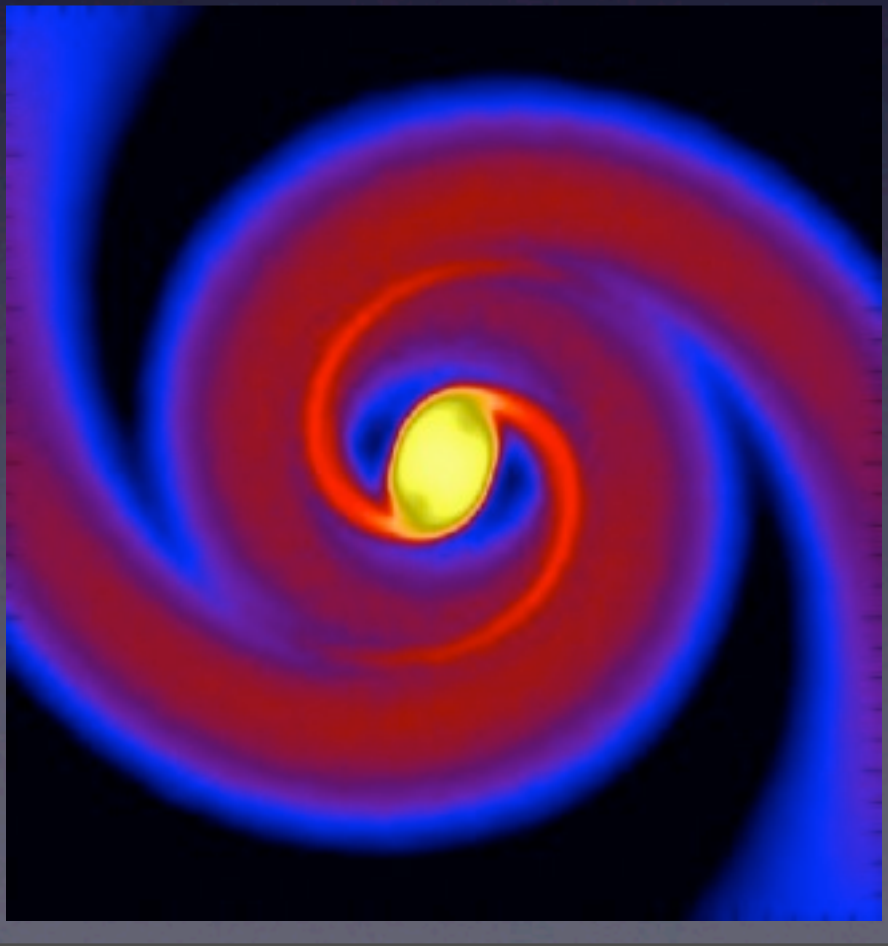

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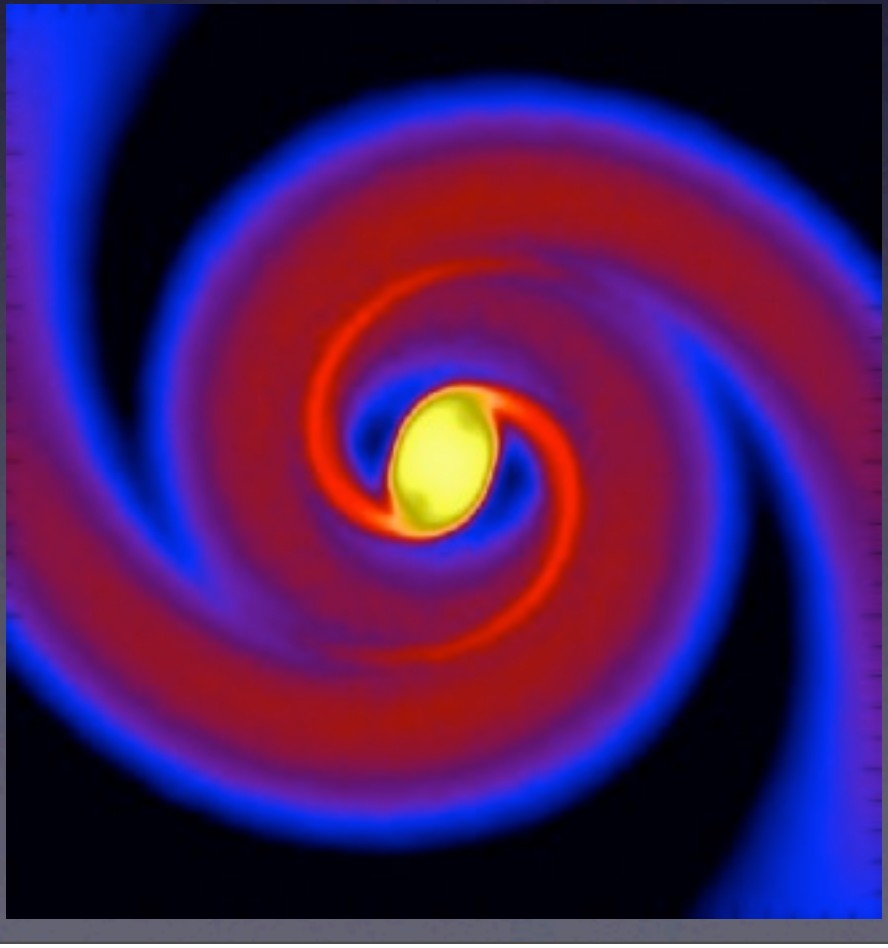

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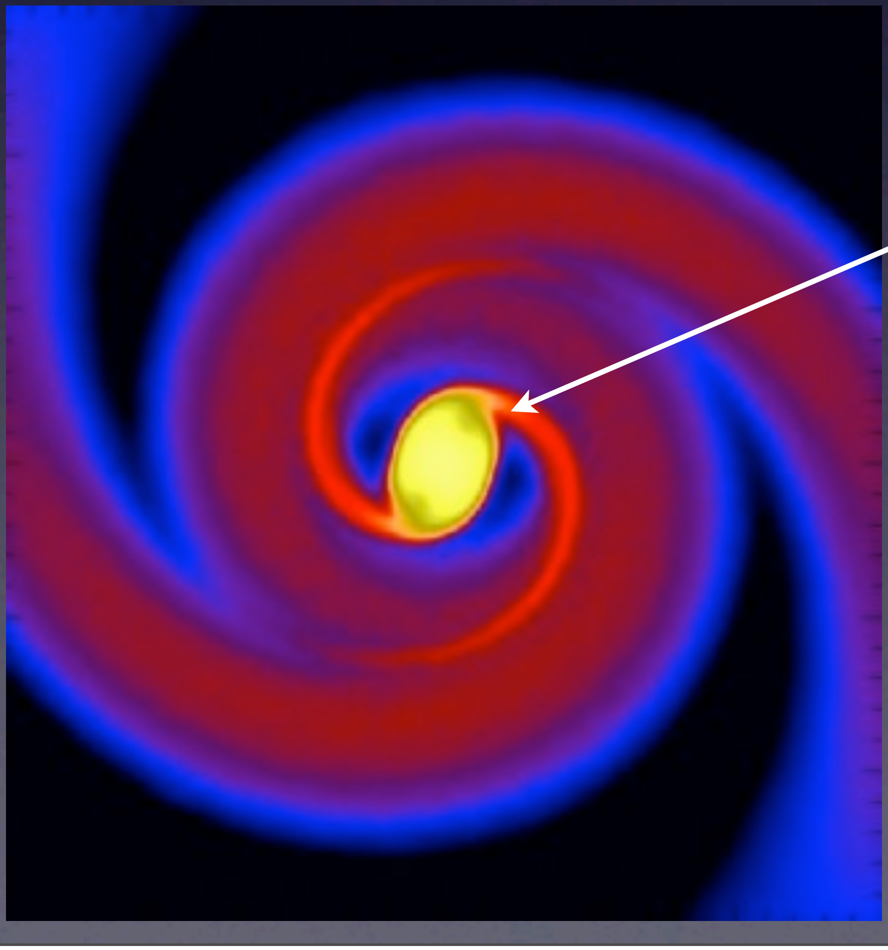

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⇒ merger simulations typically run up to ~ 20 ms

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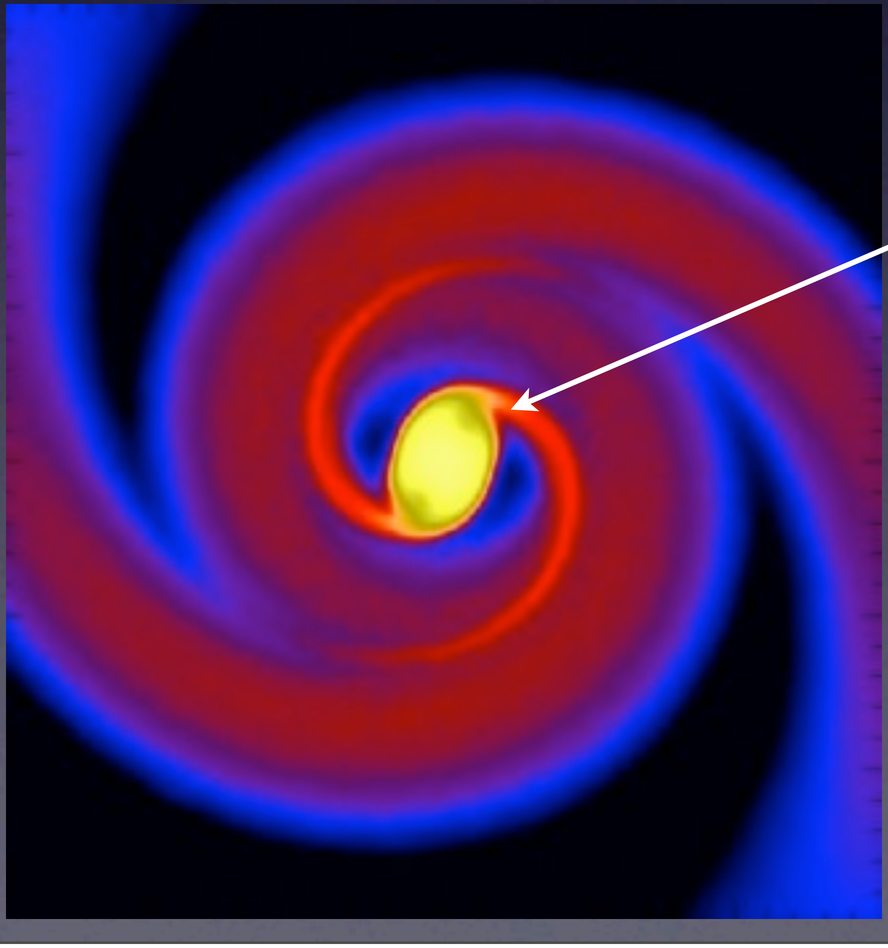

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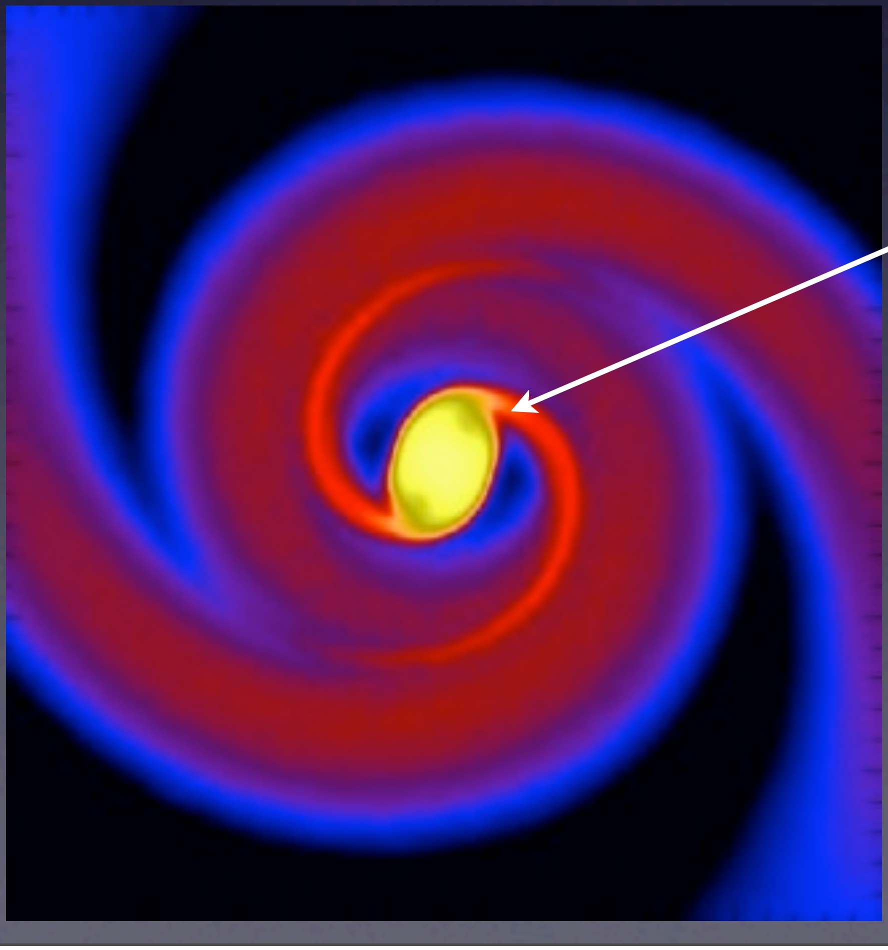

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⇒ our strategy:
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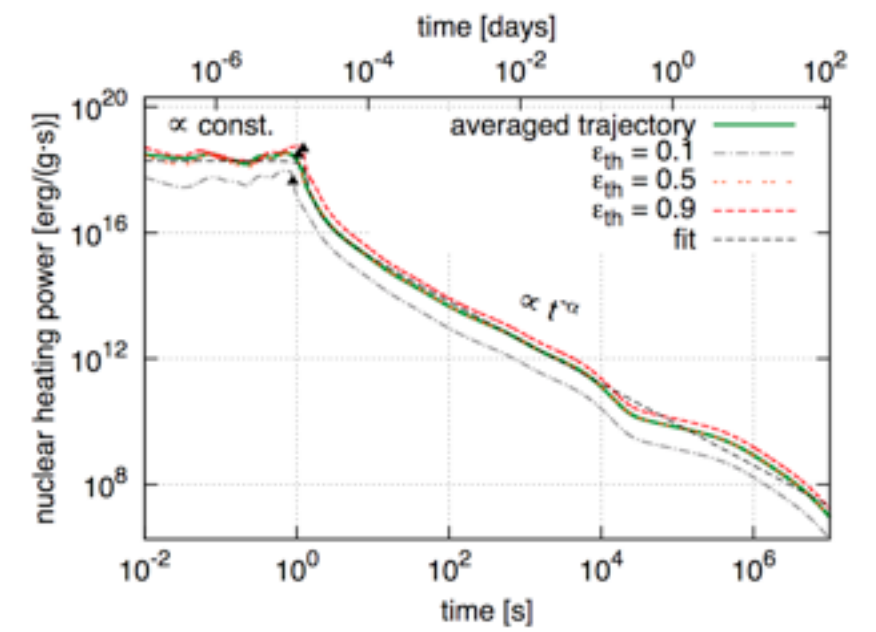
Implementing heating from radioactive decay into hydrodynamics



(figure from Korobkin et al. 2012)

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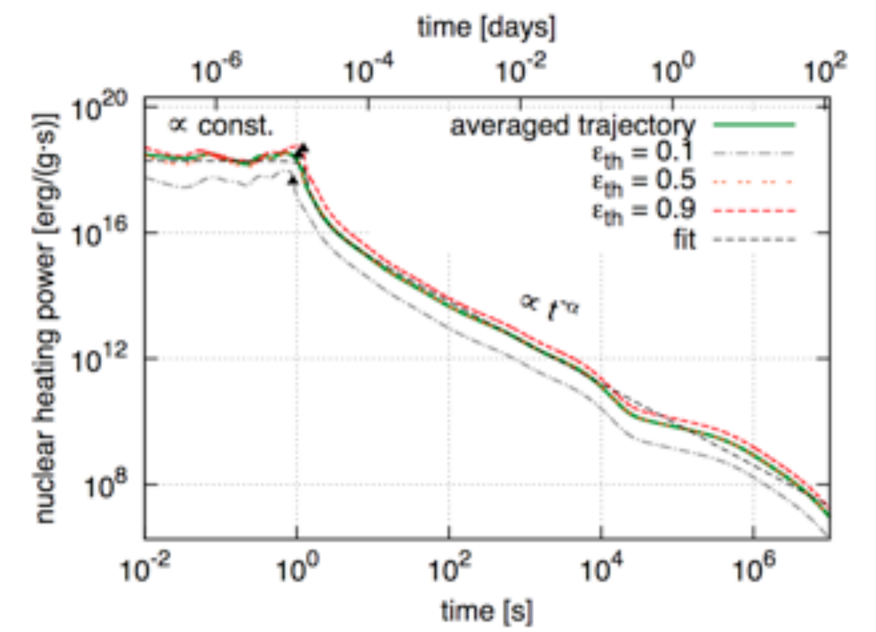

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heating history for ejecta trajectory
relatively simple:
“const. + power law”

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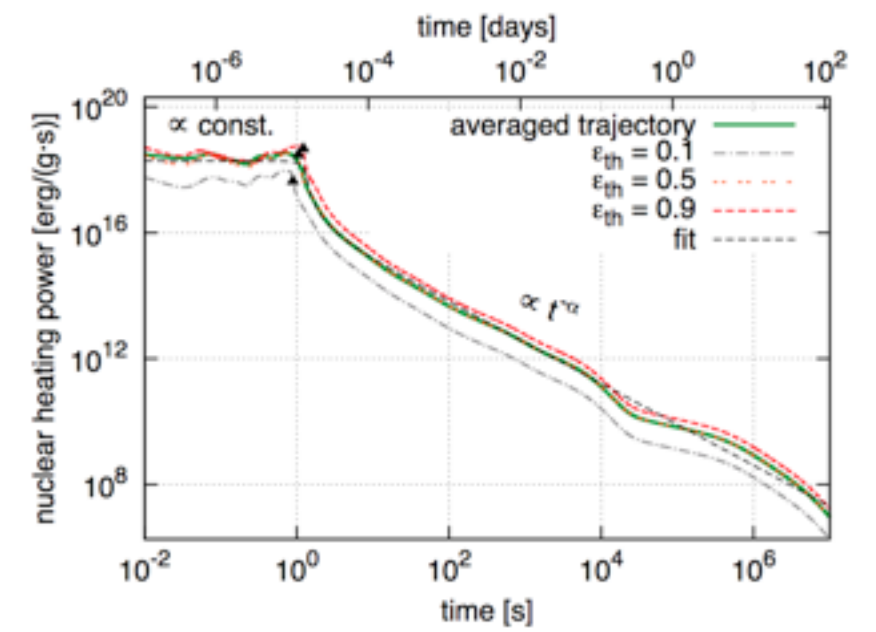

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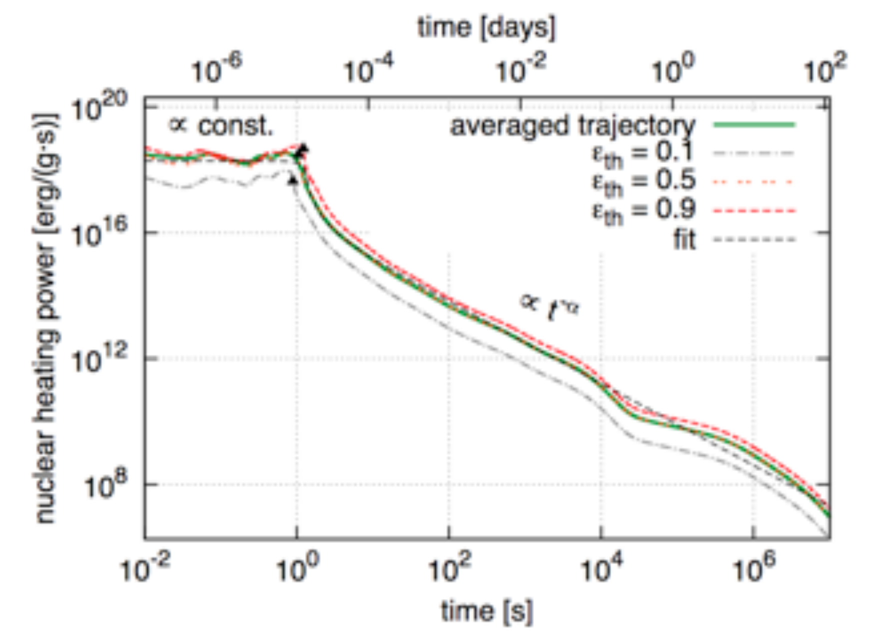

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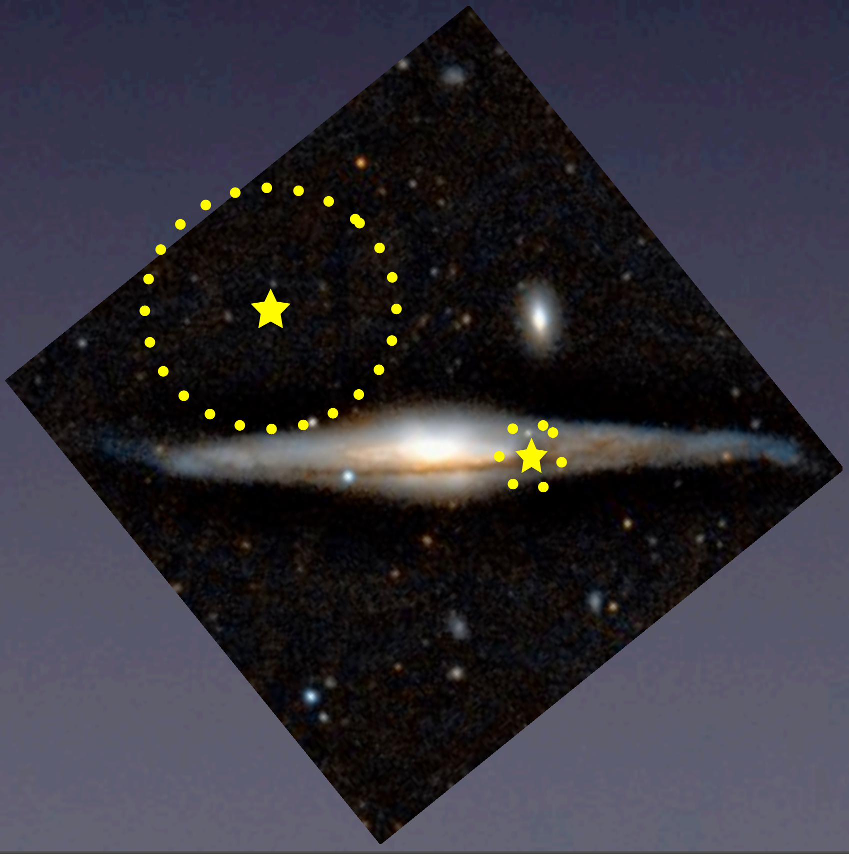

“swept up mass = ejected mass”

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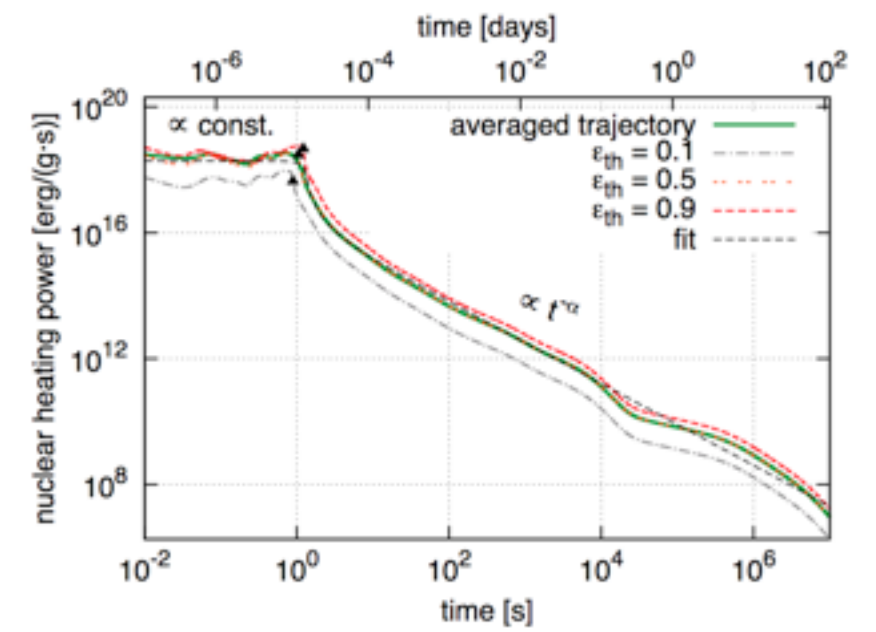

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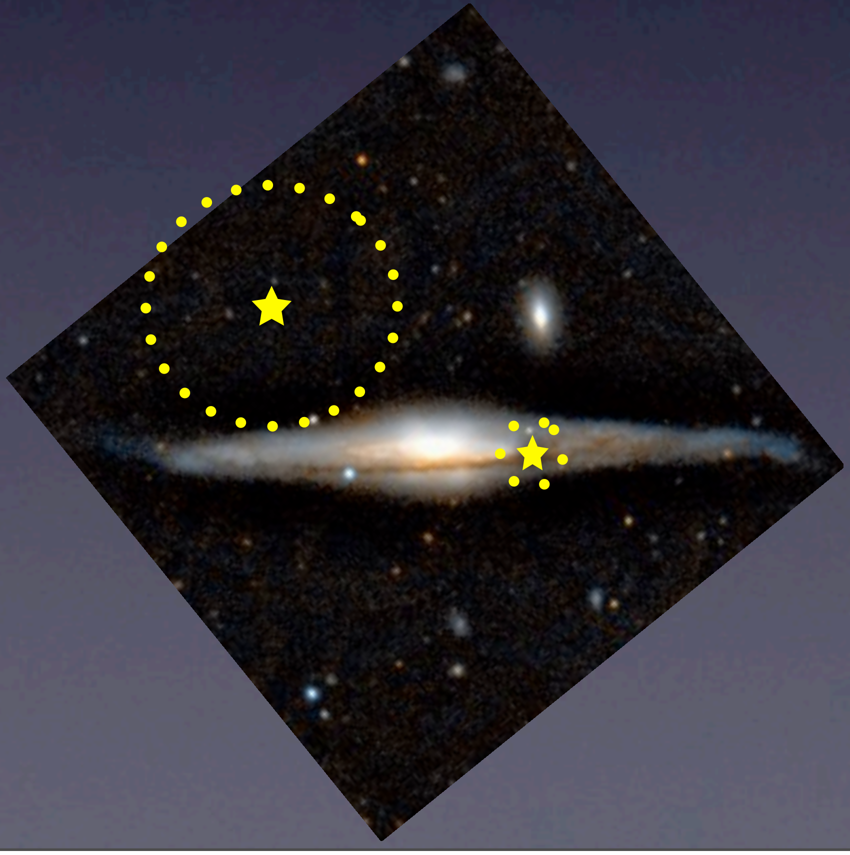
⇒ use fit formulae for $\dot{e}_{\rm nuc}, \bar{Z}, \bar{A}$

⇒ implement heating
in hydrodynamics

“When does matter start to be decelerated substantially?”

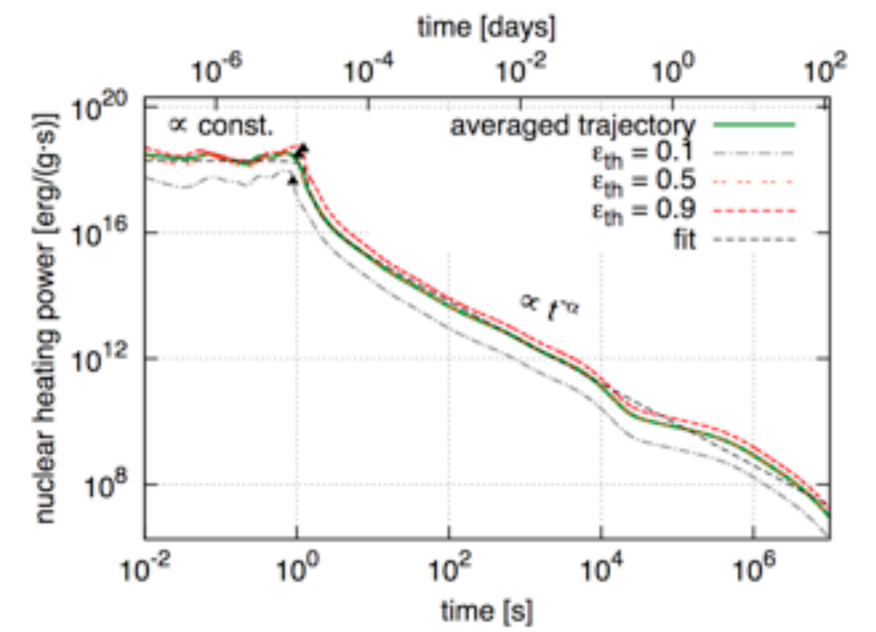


“swept up mass = ejected mass”

⇒ deceleration radius:

$$R_{\rm dec} = 0.5\ {\rm pc} \left(\frac{m_{\rm ej}}{10^{-2} M_\odot} \frac{1\ {\rm cm}^{-1/3}}{n_{\rm amb}} \right)^{1/3}$$

Implementing heating from radioactive decay into hydrodynamics



(figure from Korobkin et al. 2012)

heating history for ejecta trajectory relatively simple: “const. + power law”

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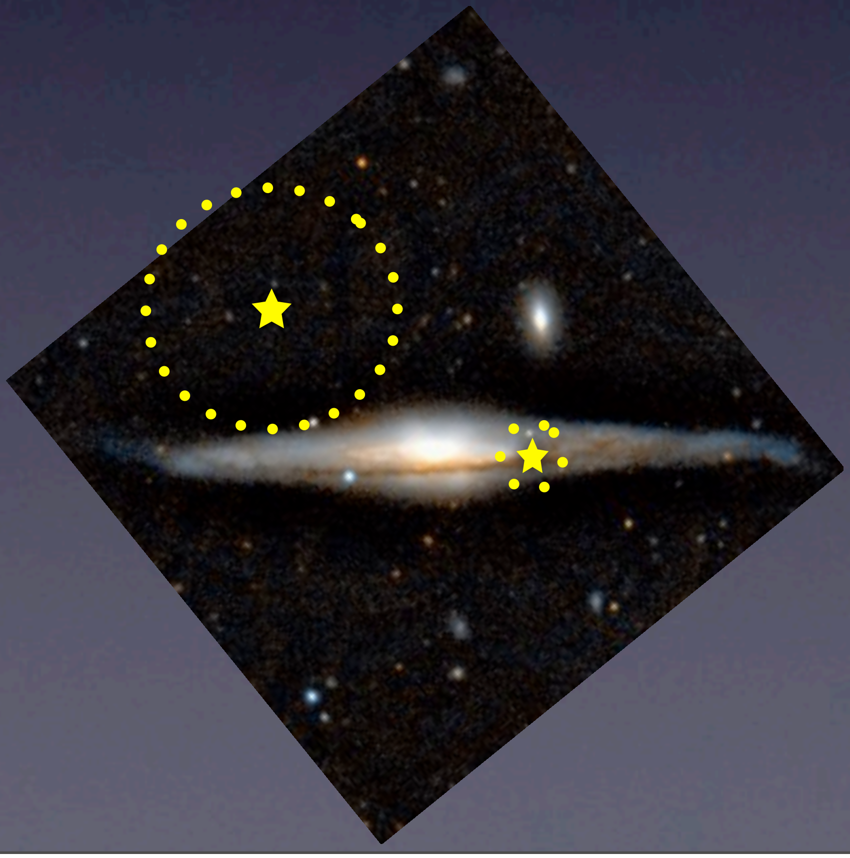

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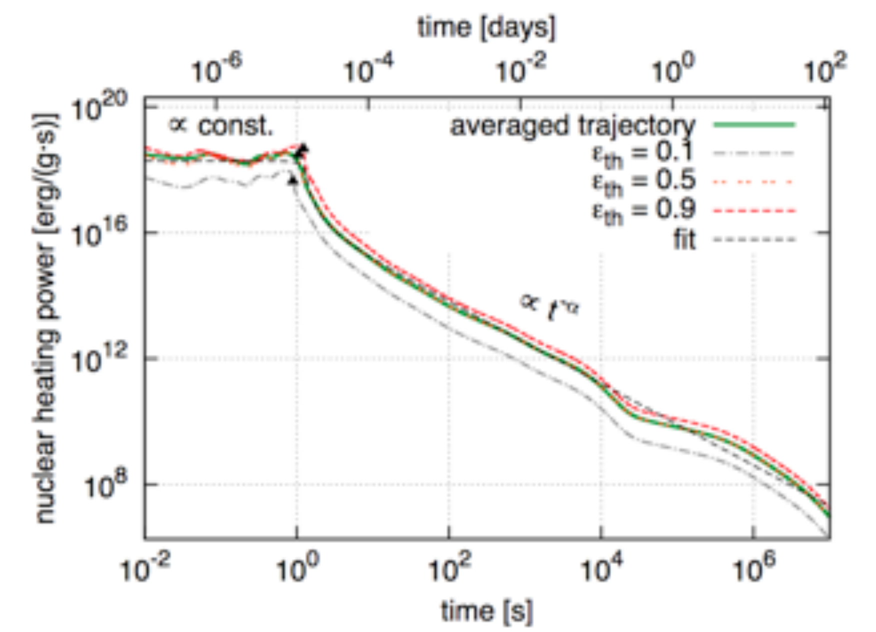
⇒ deceleration time:

$$\tau_{\rm dec} = 15 \text{ yrs} \left(\frac{m_{\rm ej}}{10^{-2} M_\odot} \frac{1 \text{ cm}^{-1/3}}{n_{\rm amb}} \right)^{1/3} \left(\frac{0.1 \text{ c}}{v_{\rm ej}} \right)$$

Implementing heating from radioactive decay into hydrodynamics



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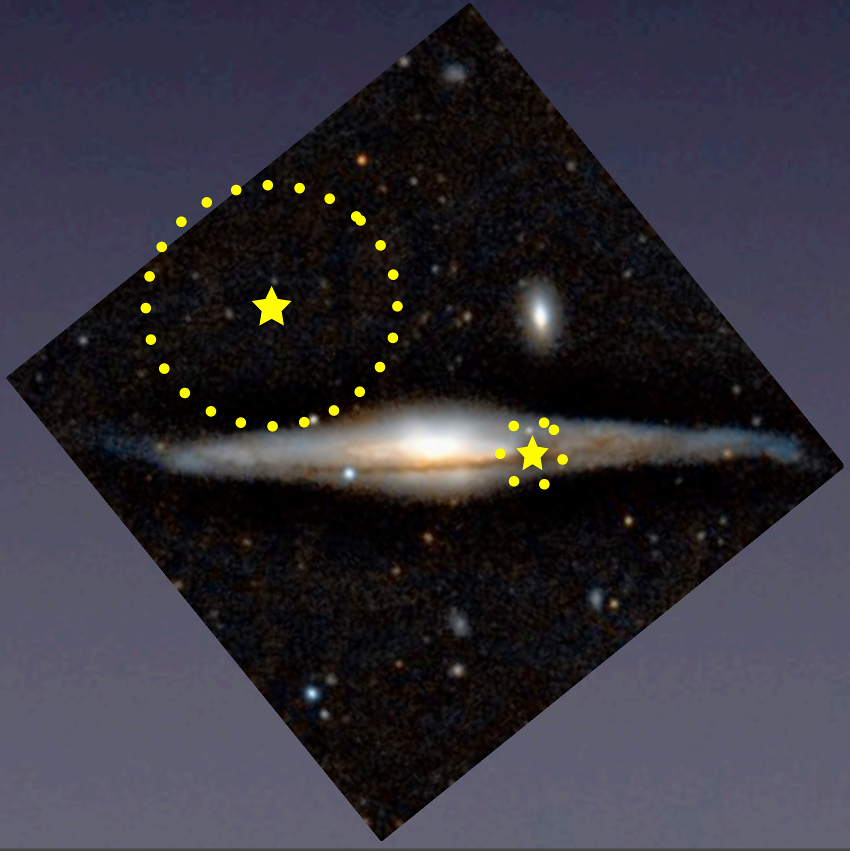
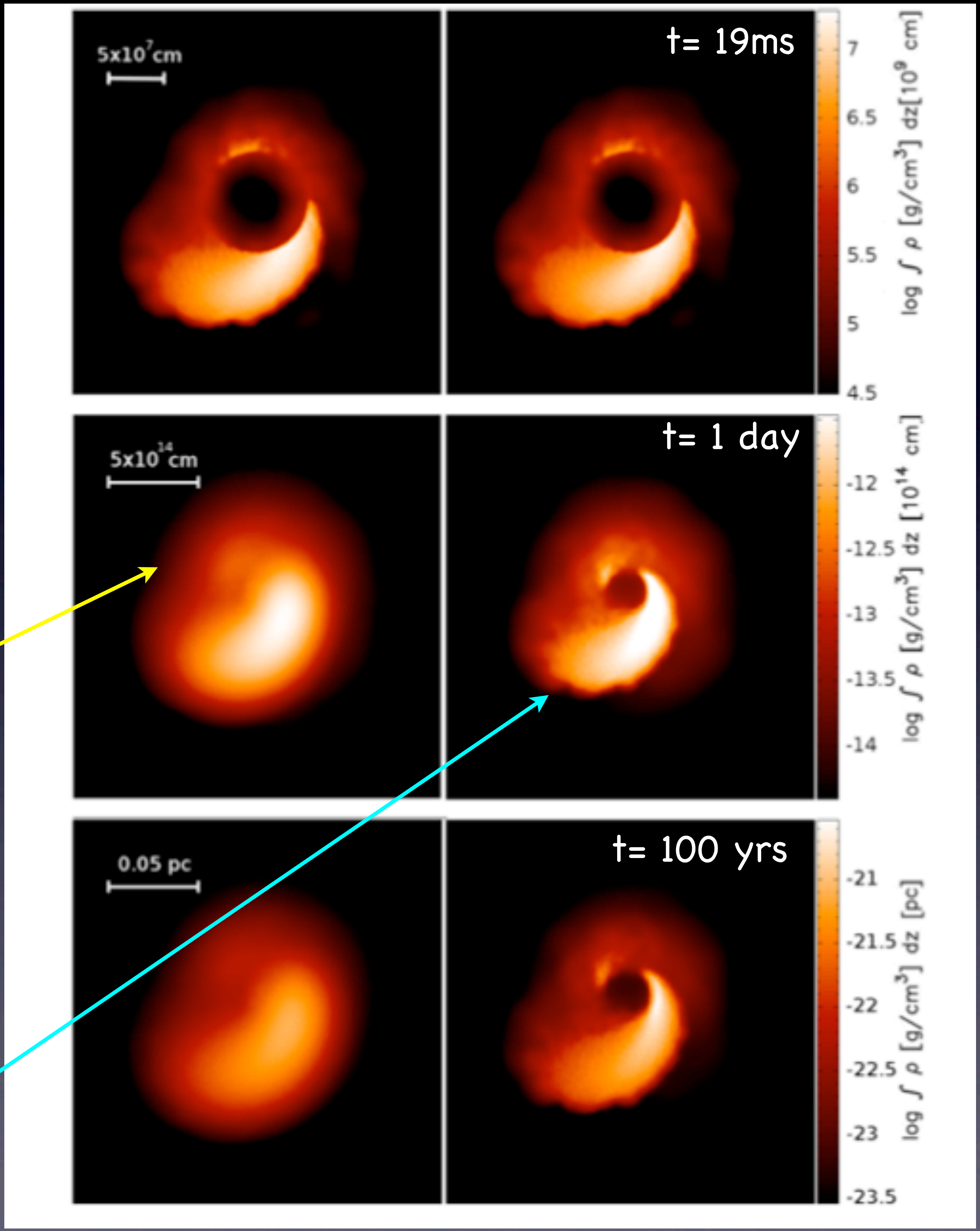


“swept up mass = ejected mass”

⇒ stop simulations after t = 100 years

(>> ~20 ms of usual merger simulation)

“How does the heating from radioactive decays impact on the further evolution of the remnant?”



with radioactive heating

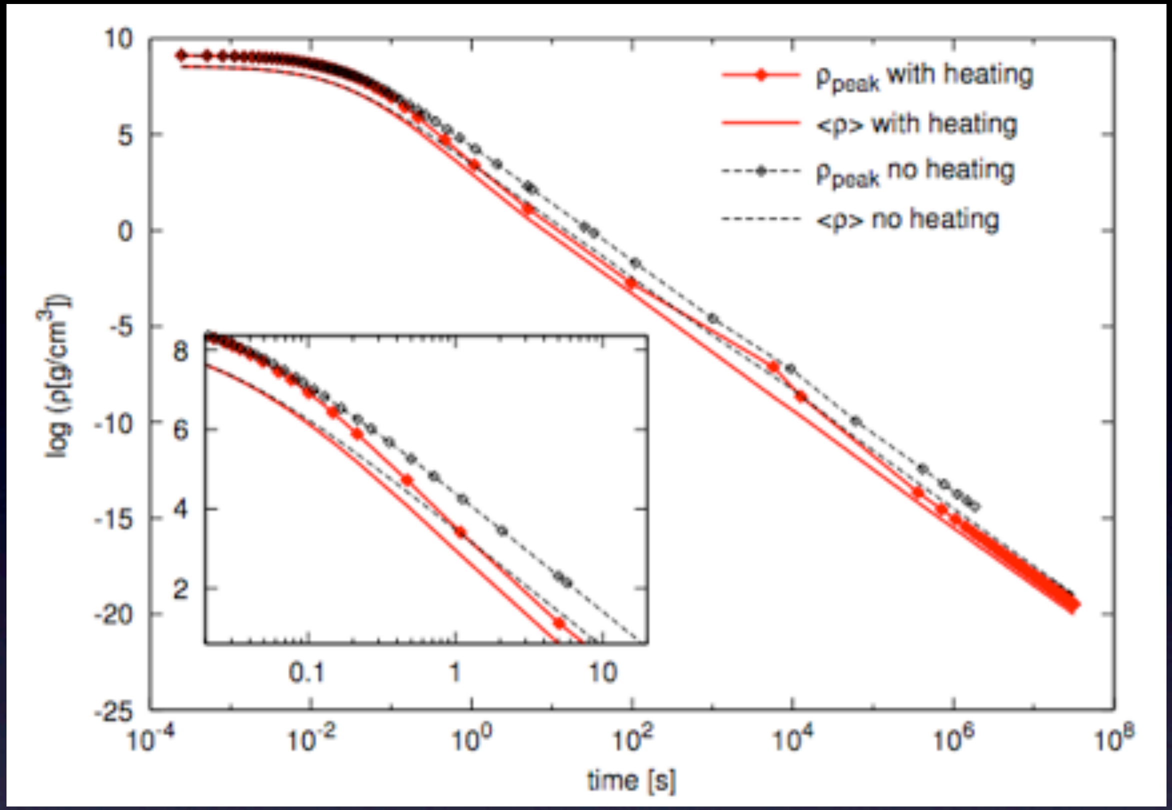
without radioactive heating

(from SR et al. 2013)

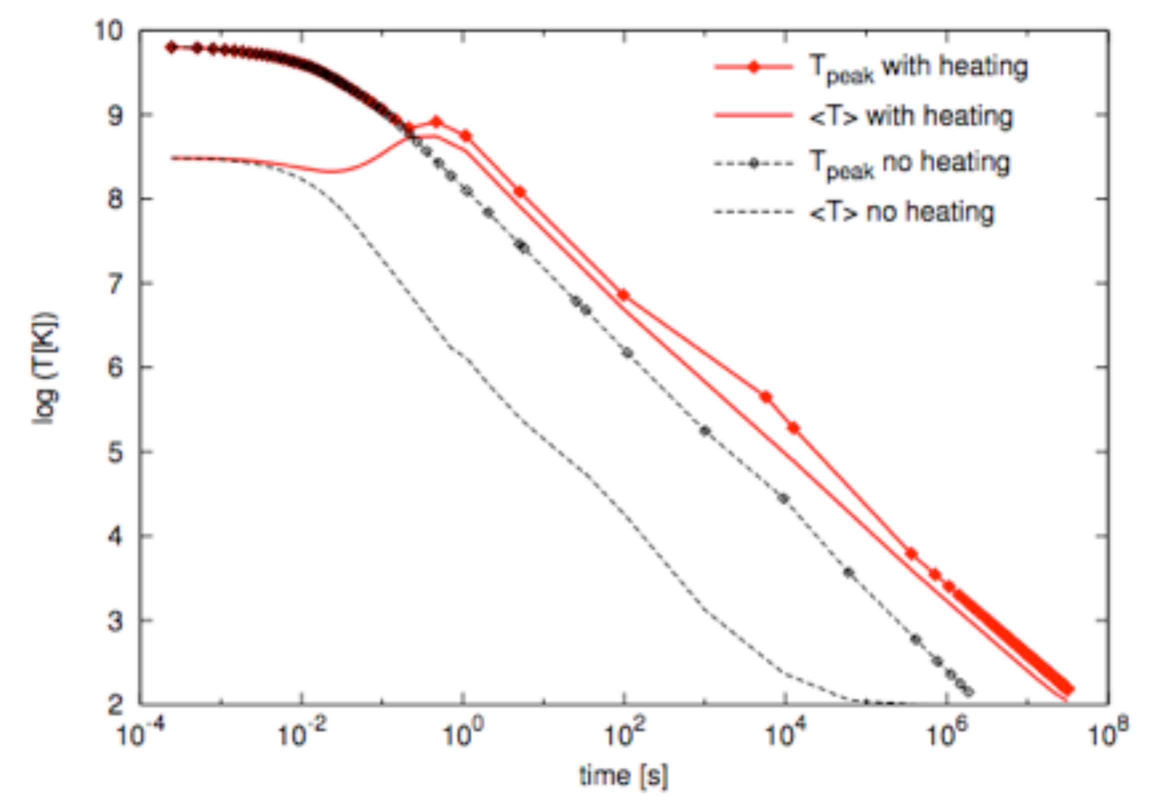
Effect of radioactive heating on density and temperature evolution

Effect of radioactive heating on density and temperature evolution

density

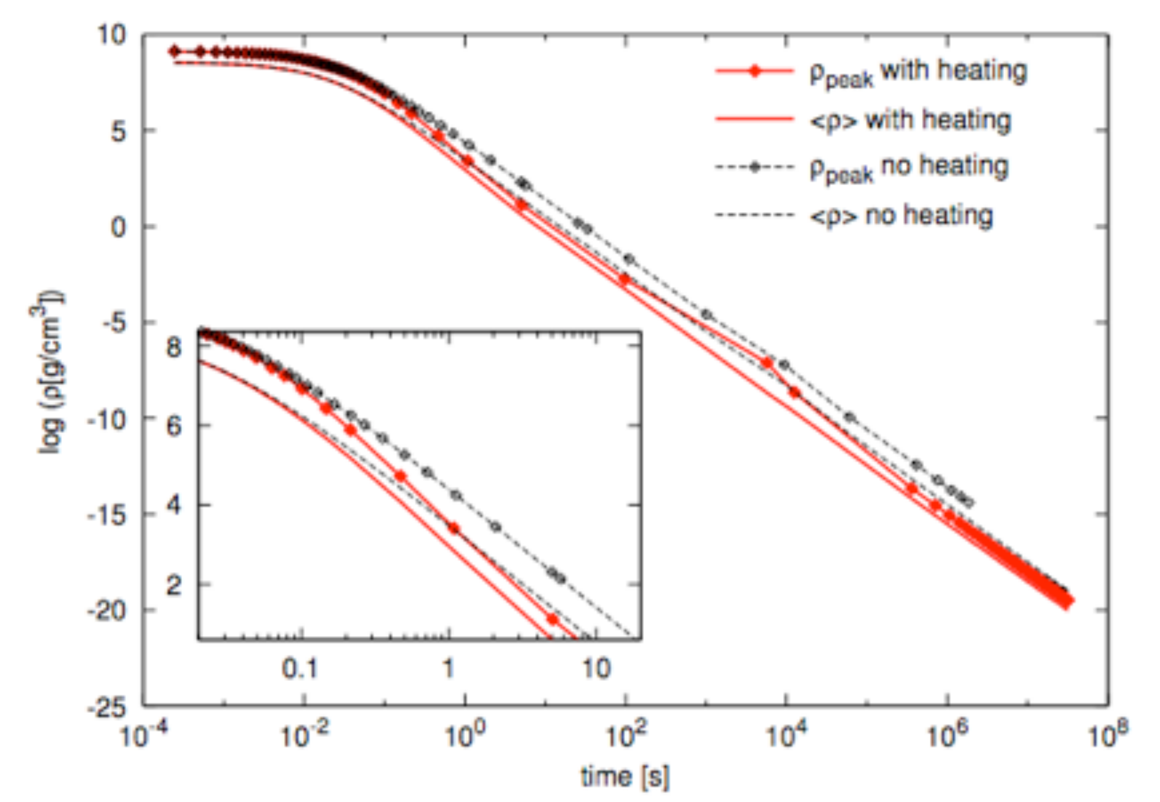


temperature

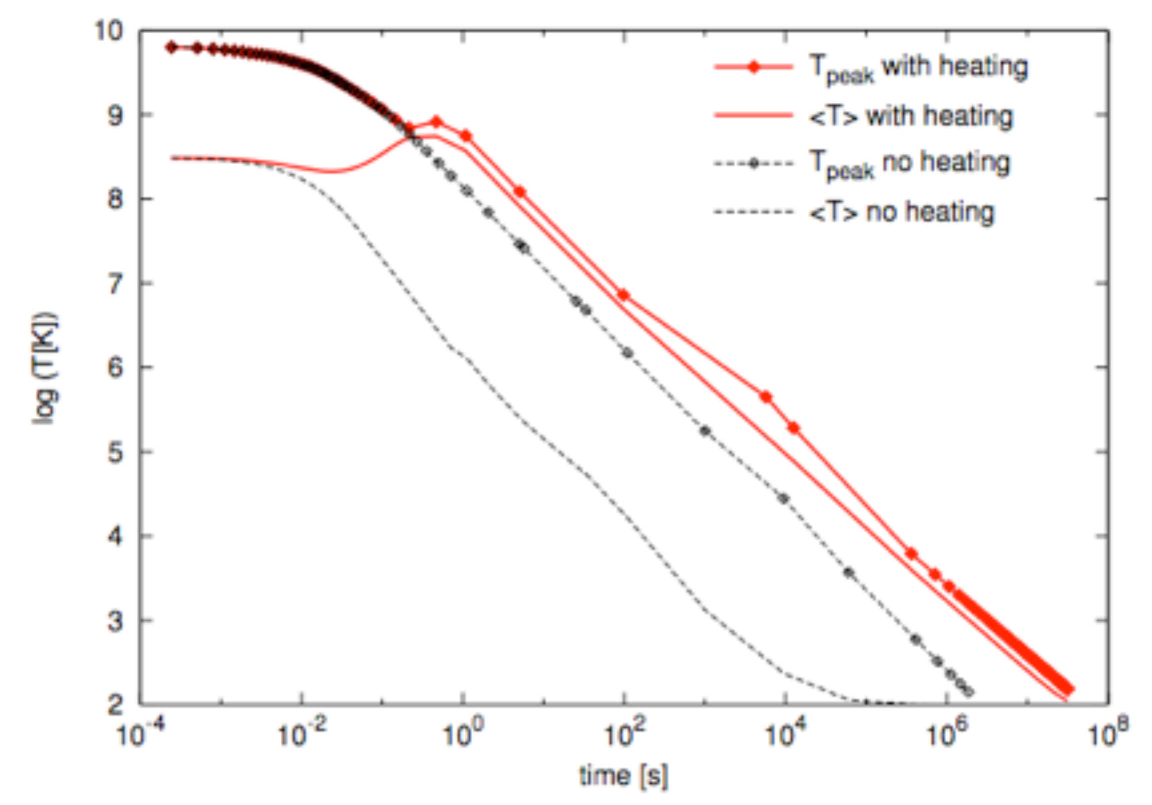


Effect of radioactive heating on density and temperature evolution

density



temperature

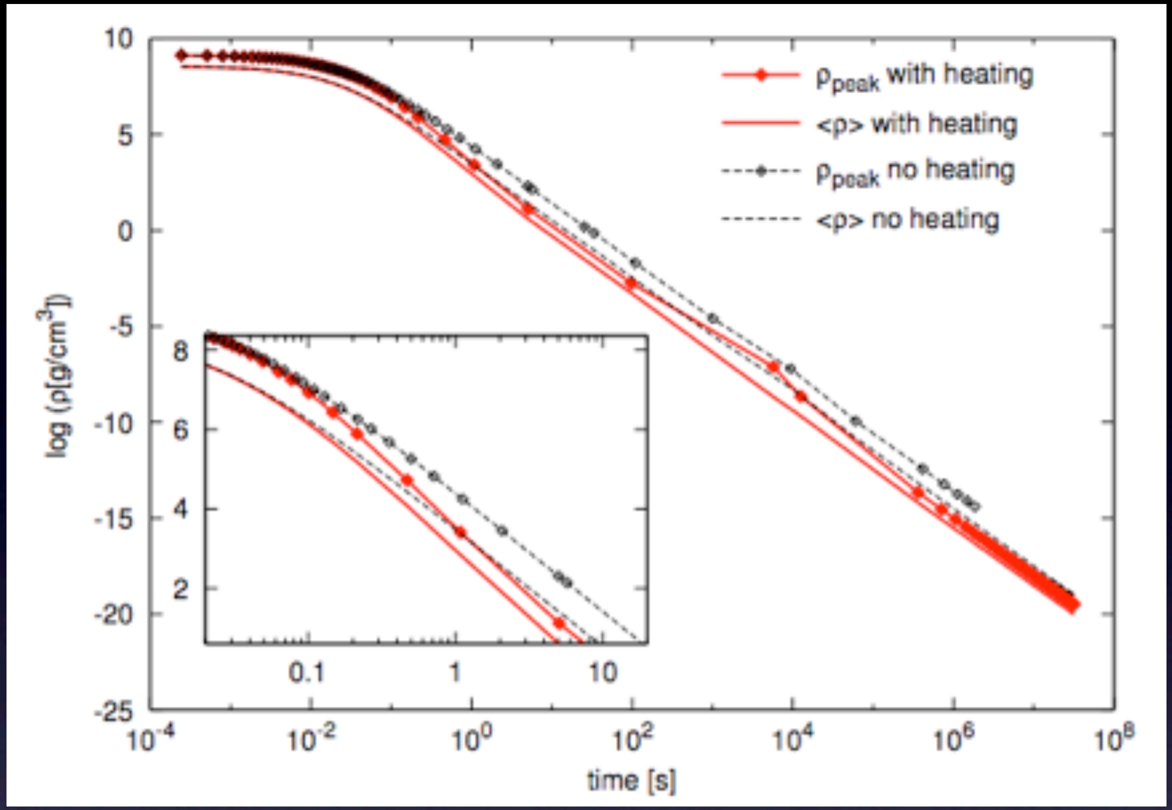


⇒ at any time larger than ~1s:

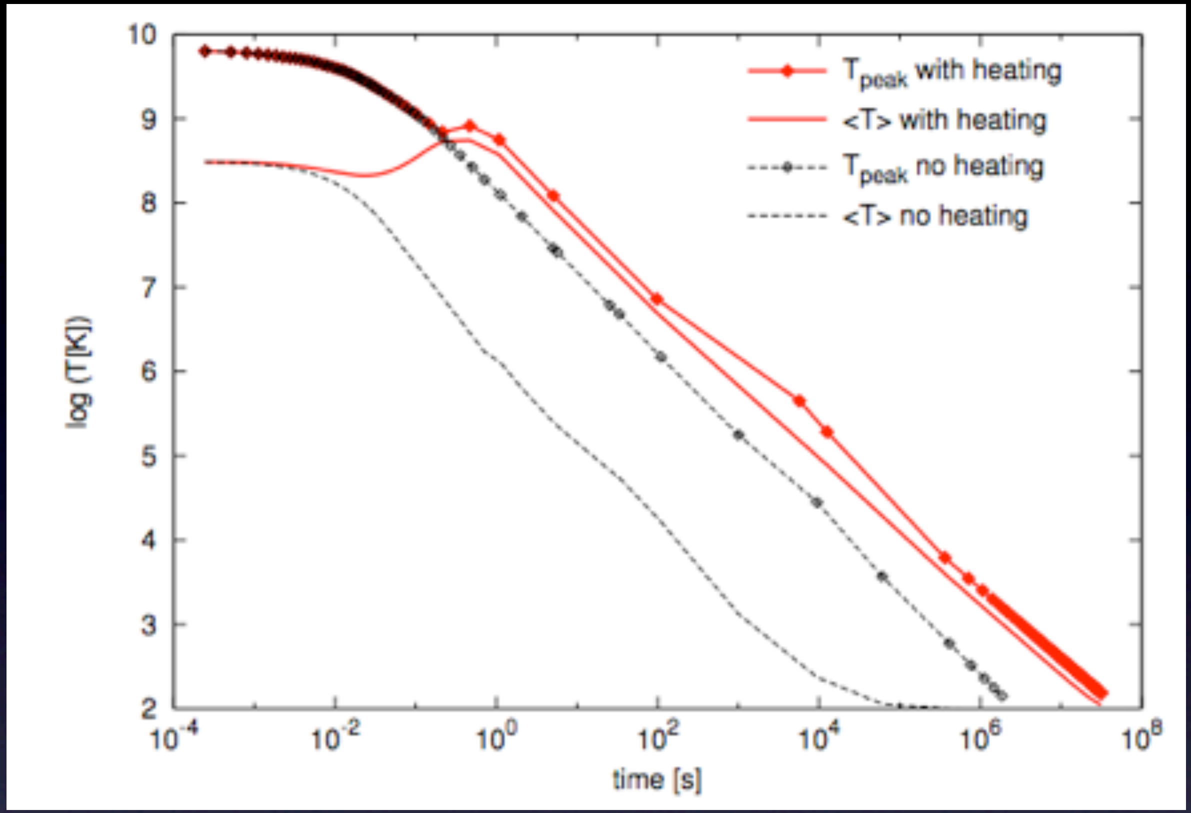
density lower/temperature higher by > 1 order of magnitude

Effect of radioactive heating on density and temperature evolution

density



temperature



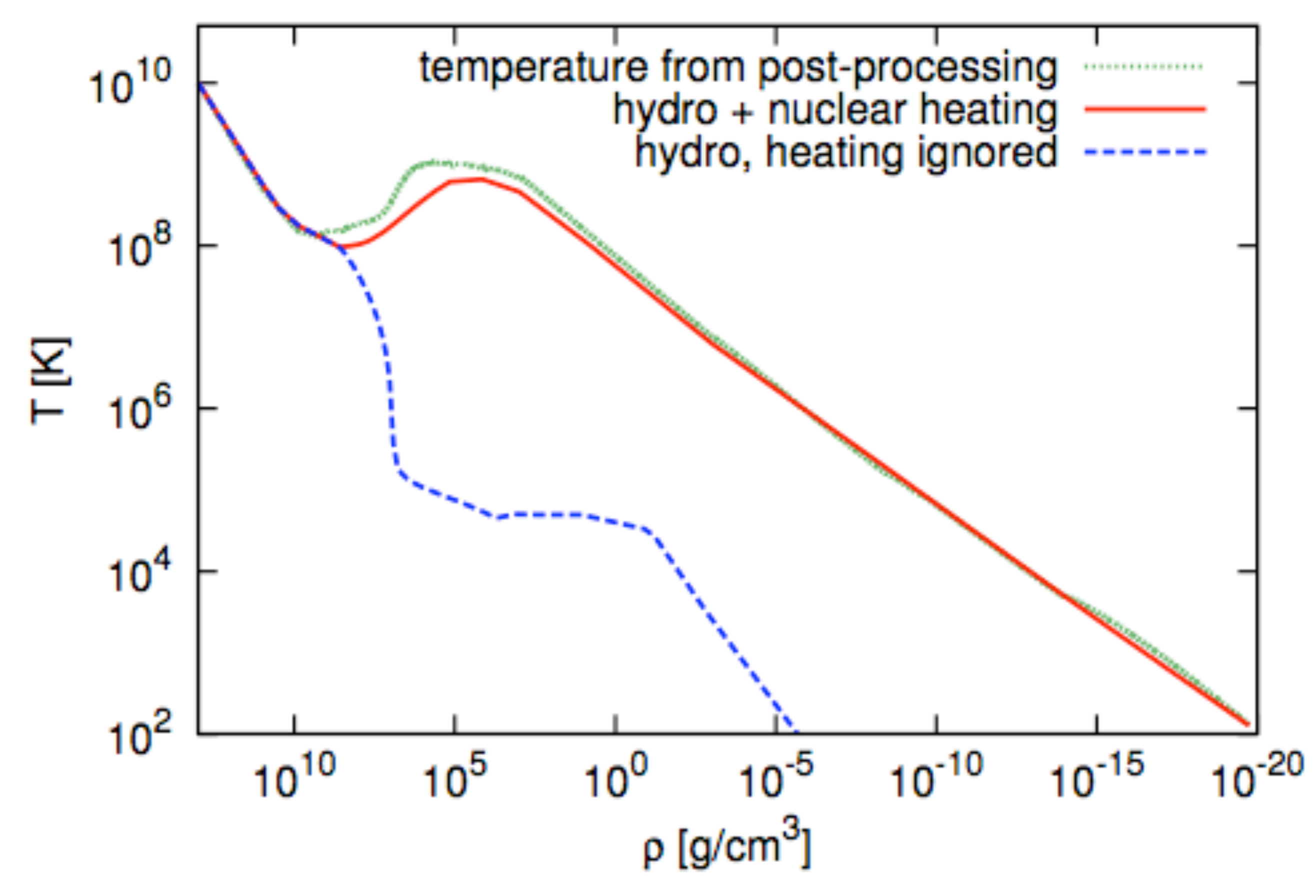
⇒ at any time larger than ~1s:
density lower/temperature higher by > 1 order of magnitude

⇒ Is standard procedure for nucleosynthesis post-processing

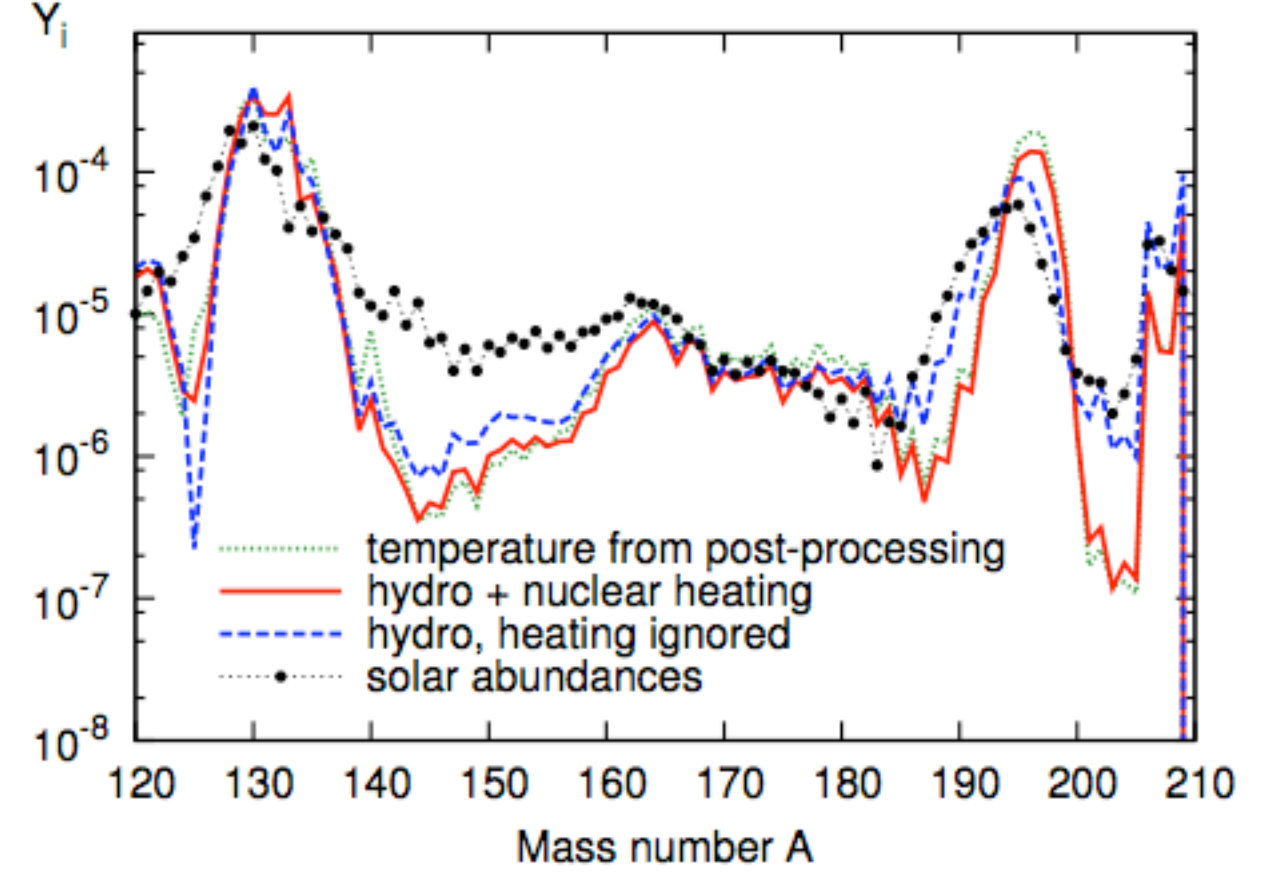
a) hydrodynamics WITHOUT heating
b) post-process temperature, *but not density*

justified?

temperature evolution



resulting nuclear abundances



⇒ differences seem acceptably small

Longterm hydrodynamic evolution: “100 years, but still in shape”

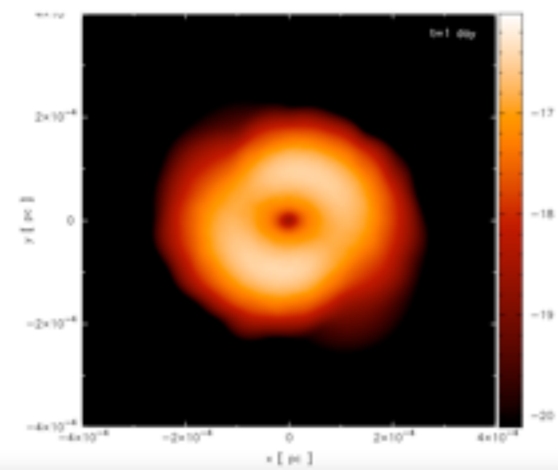
Longterm hydrodynamic evolution: “100 years, but still in shape”

$2 \times 1.4\mathrm{M}_\odot$

Longterm hydrodynamic evolution: “100 years, but still in shape”

after 1 day

$2 \times 1.4 M_\odot$

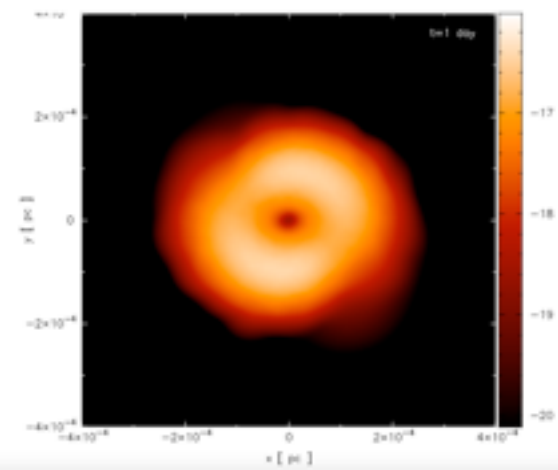


5×10^{-4} pc

Longterm hydrodynamic evolution: “100 years, but still in shape”

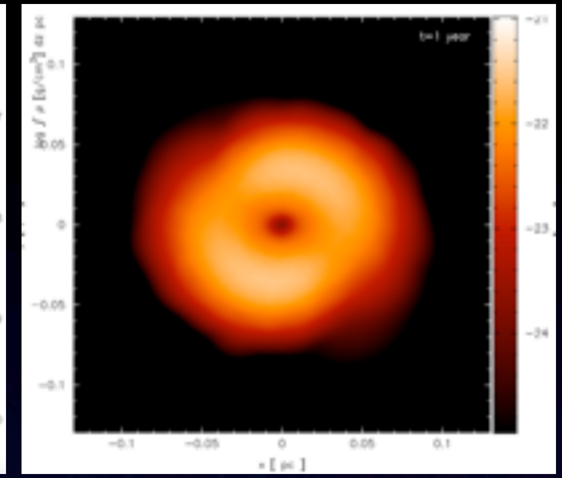
$2 \times 1.4M_\odot$

after 1 day



$5\text{x}10^{-4}$ pc

after 1 year



0.15 pc

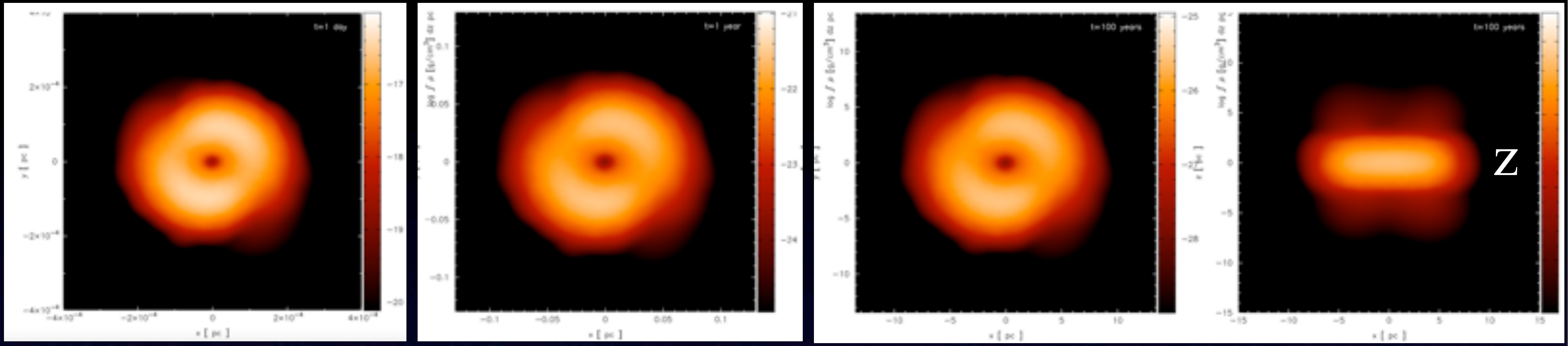
Longterm hydrodynamic evolution: “100 years, but still in shape”

$2 \times 1.4M_\odot$

after 1 day

after 1 year

after 100 years



z

5x10^{-4} pc

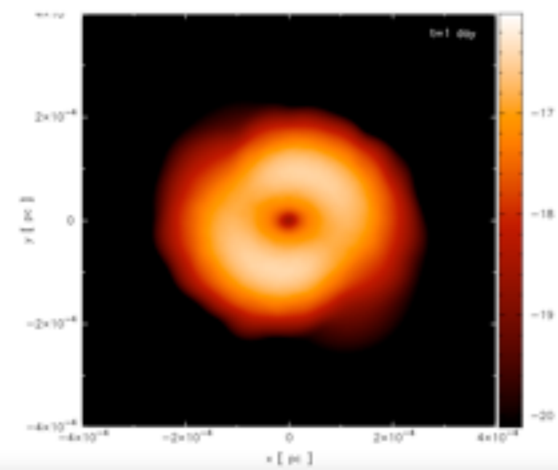
0.15 pc

15 pc

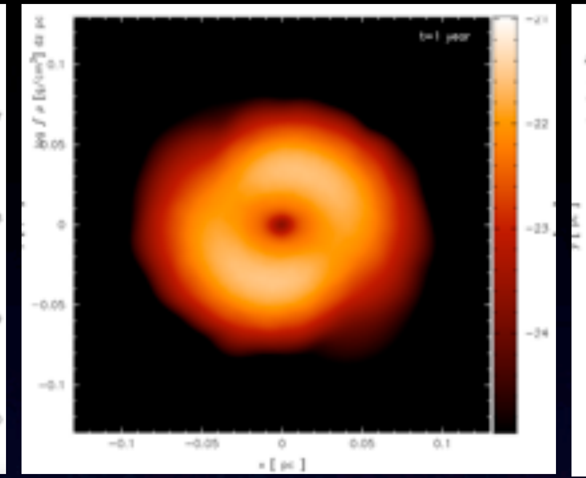
x

Longterm hydrodynamic evolution: “100 years, but still in shape”

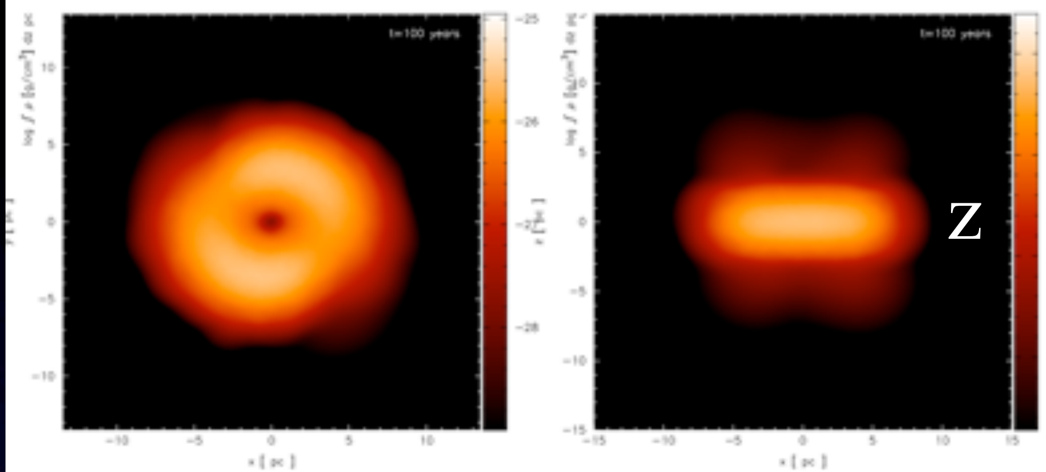
after 1 day



after 1 year



after 100 years



$2 \times 1.4 M_\odot$

z

5×10^{-4} pc

0.15 pc

15 pc

x

$1.3 \ \& \ 1.4 M_\odot$

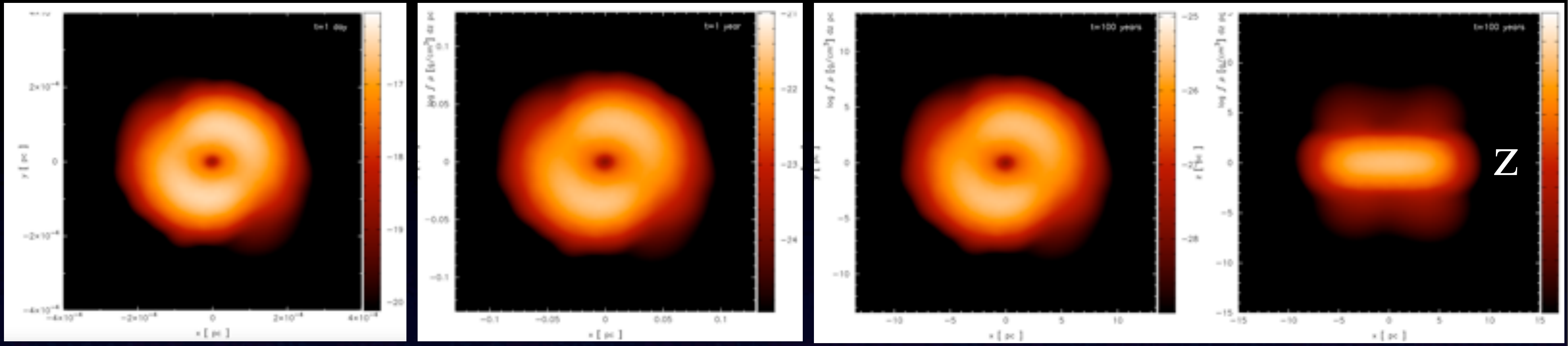
Longterm hydrodynamic evolution: “100 years, but still in shape”

after 1 day

after 1 year

after 100 years

$2 \times 1.4M_\odot$



z

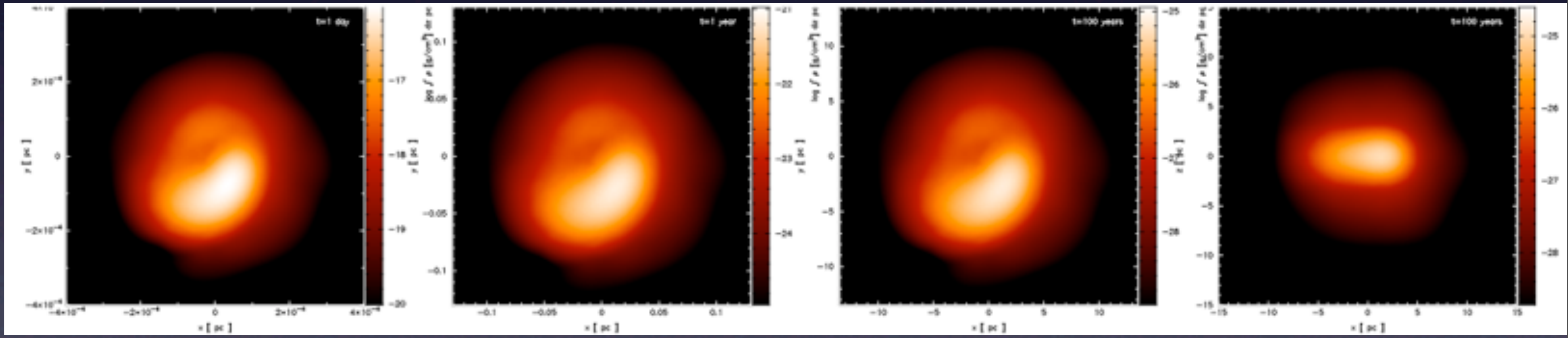
5×10^{-4} pc

0.15 pc

15 pc

x

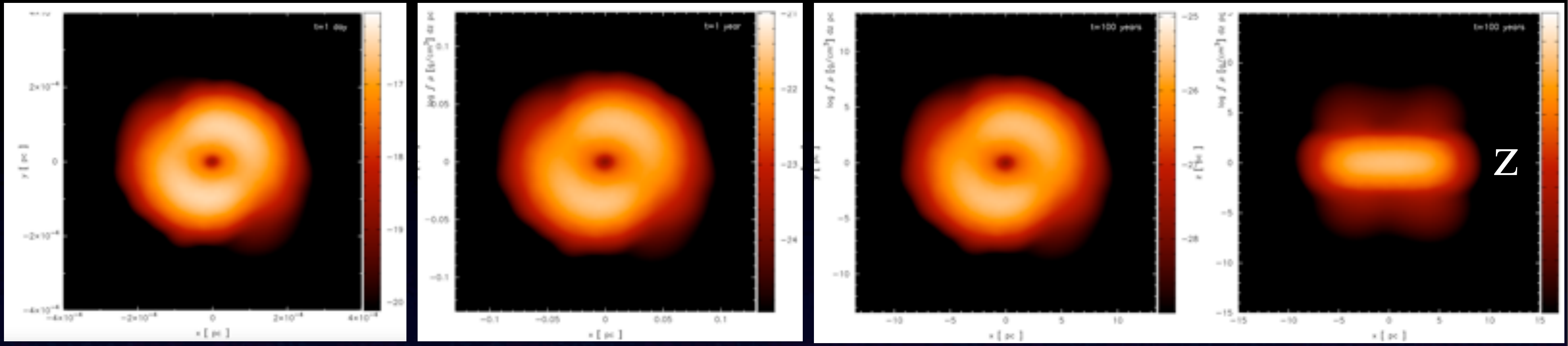
$1.3 \,\&\, 1.4M_\odot$



Longterm hydrodynamic evolution: “100 years, but still in shape”

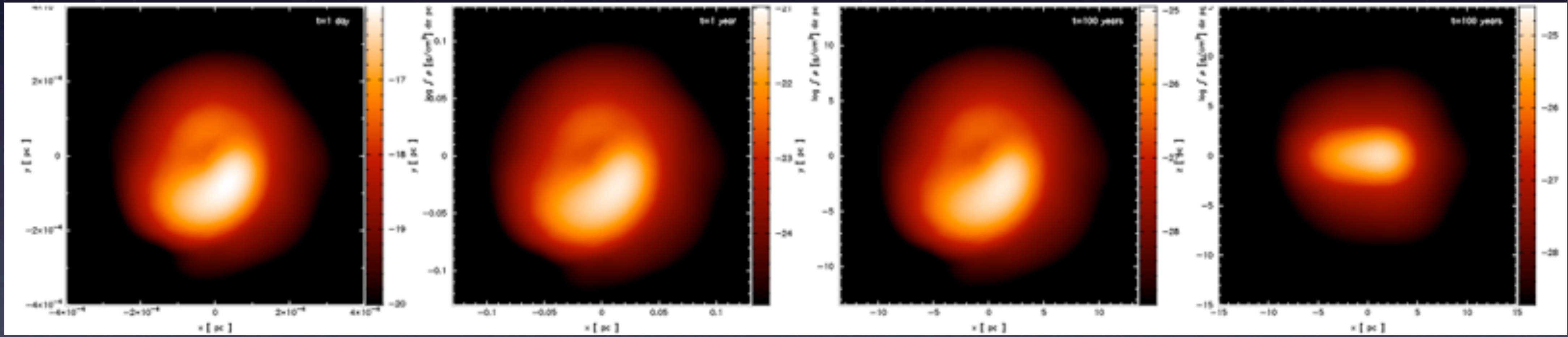
after 1 day　　after 1 year　　after 100 years

$2 \times 1.4M_\odot$



$5x10^{-4}$ pc　　0.15 pc　　15 pc　　x

$1.3\ \&\ 1.4M_\odot$



- self-similar solution, after 100 s: better than 1% homologous
- remnant does not become spherical in first 100 years
- still carries memory of initial mass ratio

Density evolution:

Density evolution:

from:

- a) few times nucl. matter density (“neutron star”) ⇒ Shen-EOS
- b) white dwarf densities ⇒ Helmholtz EOS (Timmes 2000)
- c) ISM-like densities ⇒ ideal gas + rad.

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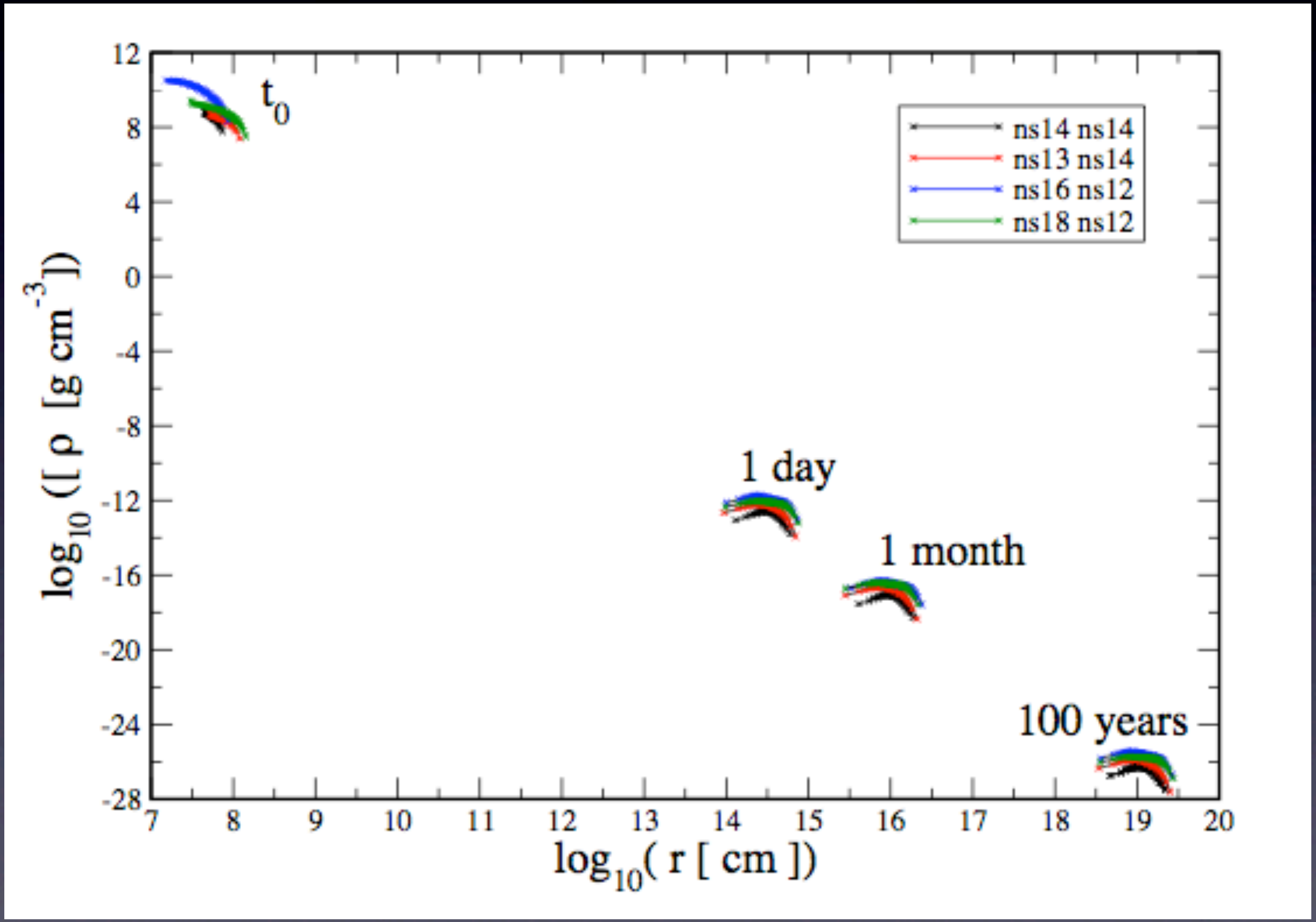
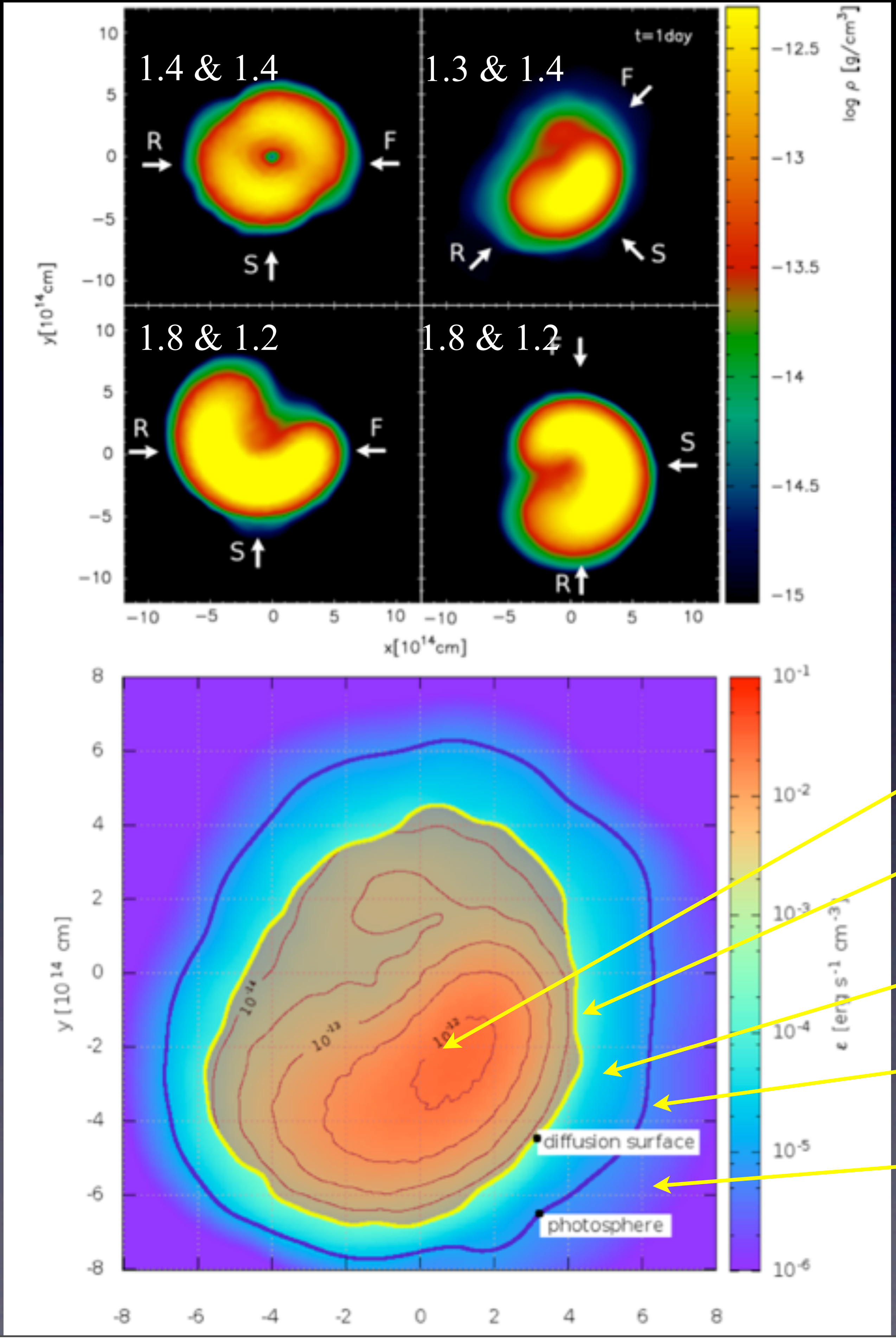


⇒ during first century densities drop by ~40 orders of magnitude

(few x 10^{14} to ~10^{-25} g/ccm)

Extracting the radiative signature from expanding remnant



input/assumptions:

- opacities: $\kappa = 10\ \mathrm{cm^2/g}$
  (Kasen et al. 2013;
  Tanaka & Hotokezaka 2013)
- heating rate directly from our network calculations
- radiation ≈ BB

"trapped component"
$\tau > \tau_{\rm diff}$

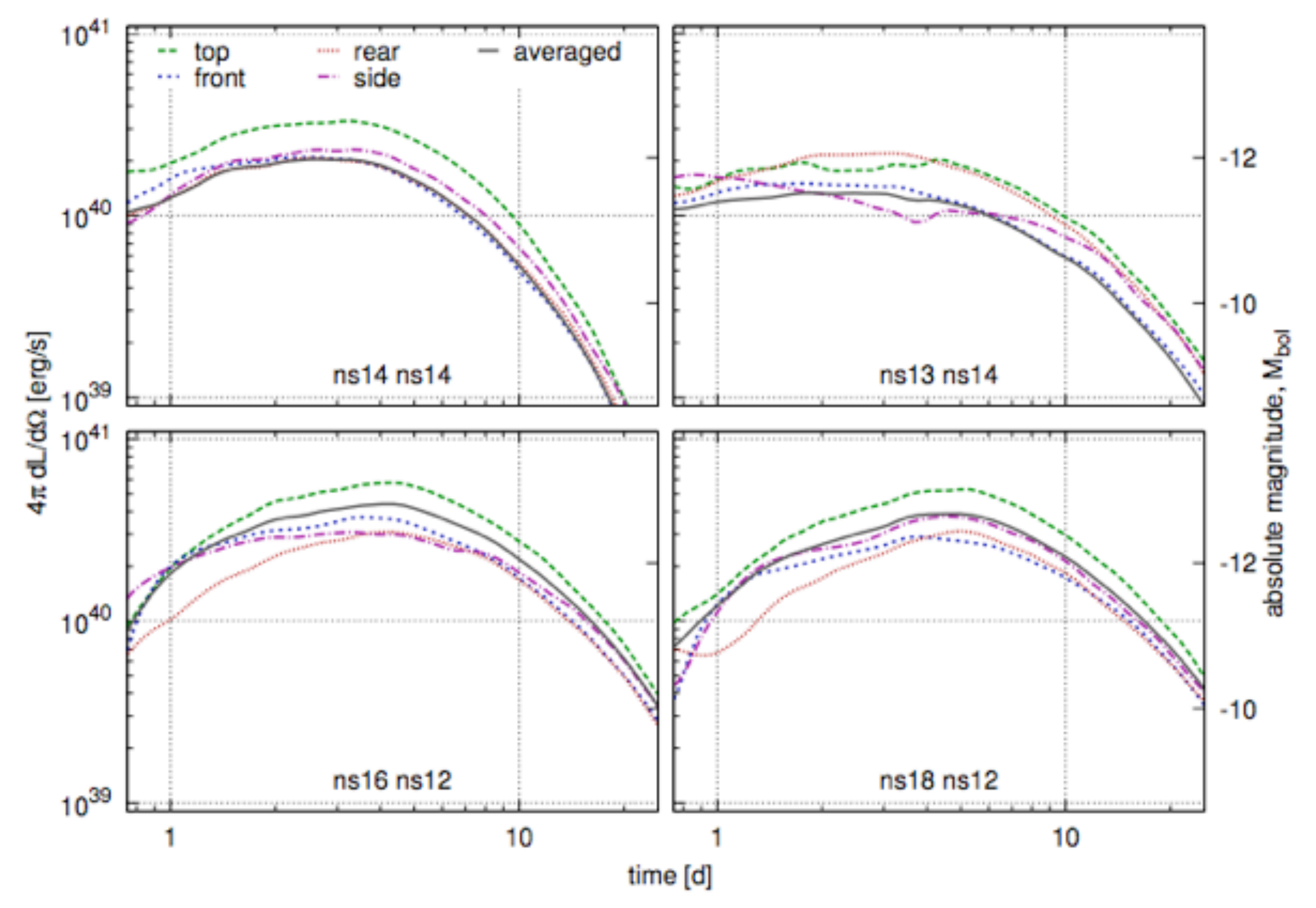
"diffusion surface":
$\tau_{\rm diff} = \tau_{\rm dyn}$

"radiating volume"
$\tau_{\rm diff} < \tau < 2/3$

"Photosphere":
$\tau_{\rm diff} = \tau_{\rm dyn}$

"photons from escaping with energies set by nuclear reactions; not considered"
$\tau < \tau_{\rm diff}$

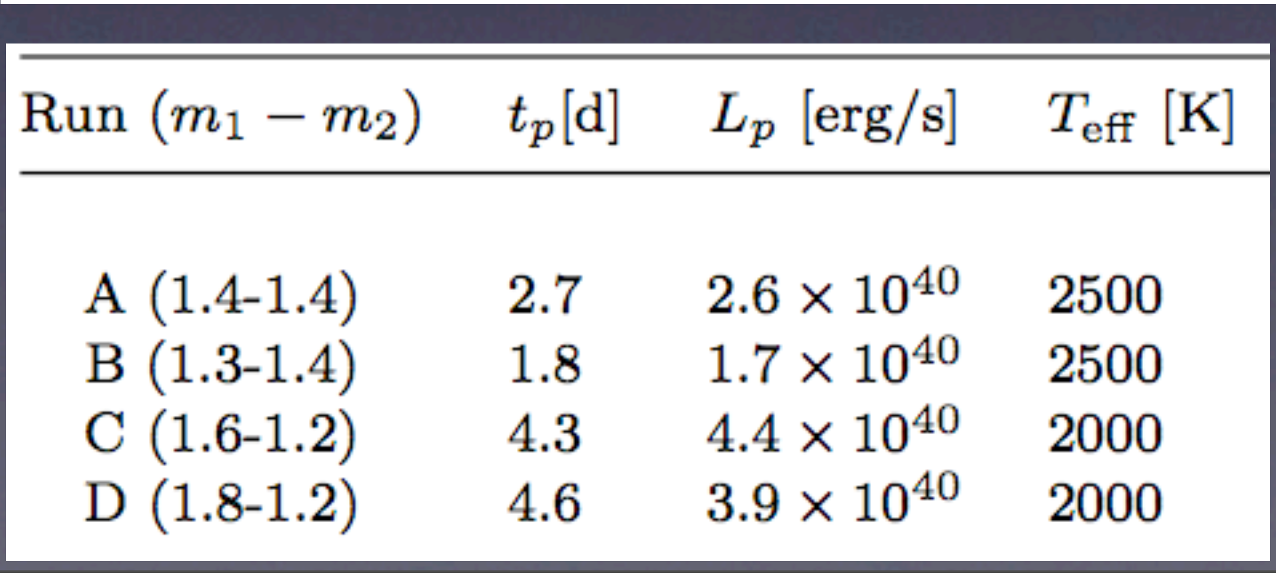
$$\frac{dL}{d\Omega}(\mathbf{k}) = \int_{\tau(\mathbf{r})>\mathbf{2/3},\mathbf{k}\cdot\mathbf{n}>\mathbf{0}}^{\tau(\mathbf{r})<\mathbf{ct}/\zeta(\mathbf{r})} \mathbf{k}\cdot\mathbf{n}\,\dot{\epsilon}(\mathbf{t})\rho(\mathbf{r})\mathbf{d}^{\mathbf{3}}\mathbf{r}$$



Tendencies:

i) asymmetric systems are brighter

ii) ~ factor of 2 between “top” and “front” view



Run $(m_1 - m_2)$	t_p[d]	L_p [erg/s]	$T_{\rm eff}$ [K]
A (1.4-1.4)	2.7	2.6×10^{40}	2500
B (1.3-1.4)	1.8	1.7×10^{40}	2500
C (1.6-1.2)	4.3	4.4×10^{40}	2000
D (1.8-1.2)	4.6	3.9×10^{40}	2000

“flat” peak at ~ 3days:

$L_p \approx$ 3 x 10^{40} erg/s

$T_{\rm eff} \approx$ 2500 K

Summary

- compact binary mergers are likely sources of r-process
- they eject (at least) via three different channels:

  a) dynamic ejecta
  b) ν-driven winds
  c) “accretion disk dissolutions”

  ⇒ different properties

- likely all relevant for nucleosynthesis and el.mag. transients
- better understanding of “macronovae” required

Summary

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- they eject (at least)

  a) dynami
  b) ν-driv
  c) “accre

Thank you for your attention!

- likely all releva ients
- better understanding of “macronovae” required