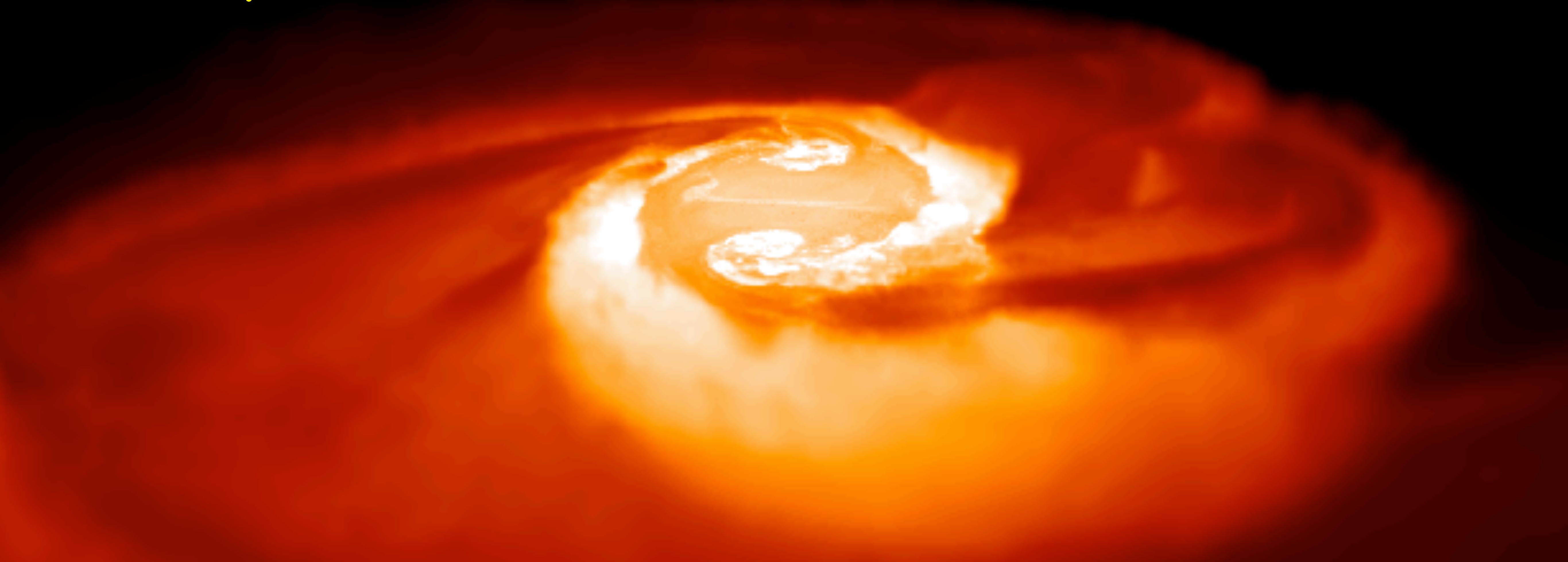
Bad Honnef, April 26 2013

Compact binary mergers as possible production sites for heavy nuclei



Stockholm University

Stephan Rosswog

Oskar Klein centre

I. Introduction

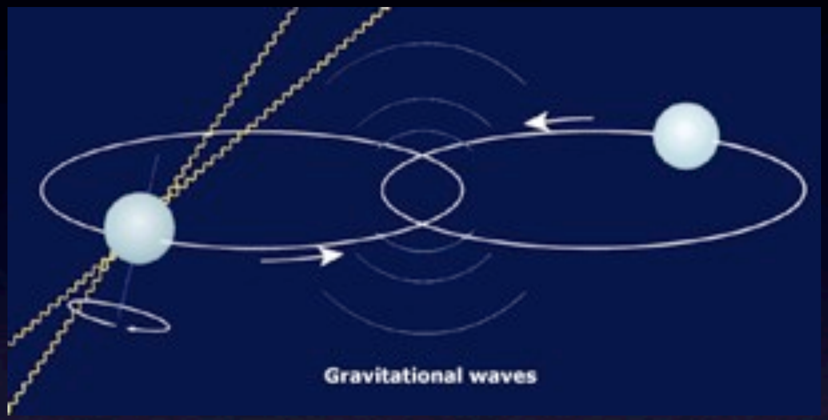
Russel Hulse

Joseph Taylor

Binary neutron star system PSR 1913+16

system parameters (Weisberg et al. 2010):

- orbital period: $P_0 = 7.75$ h $(v \sim 10^{-3}\ c)$



- pulsar period: $P_s = 59$ ms
- eccentricity: $e = 0.62$
- periastron advance: $(\delta\Phi)_{PSR} = 4°\ yr^{-1}$

  $\gg (\delta\Phi)_{Mercury} = 0.43''\ yr^{-1}$

- masses: $m_1 = 1.4398 \pm 0.0002\ M_{sol}$

  $m_2 = 1.3886 \pm 0.0002\ M_{sol}$

I. Introduction

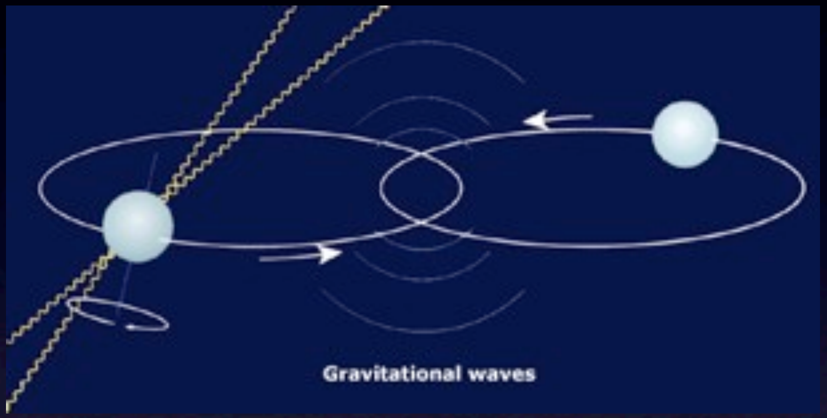
Russel Hulse

Joseph Taylor

Binary neutron star system PSR 1913+16

system parameters (Weisberg et al. 2010):

- orbital period: $P_o = 7.75$ h ($v \sim 10^{-3}$ c)
- pulsar period: $P_s = 59$ ms
- eccentricity: $e = 0.62$
- periastron advance: $(\delta\Phi)_{PSR} = 4° \ yr^{-1}$
  $\gg (\delta\Phi)_{Mercury} = 0.43'' \ yr^{-1}$
- masses: $m_1 = 1.4398 \pm 0.0002 \ M_{sol}$
  $m_2 = 1.3886 \pm 0.0002 \ M_{sol}$



- orbital decay due to gravitational wave emission in excellent agreement with predictions from general relativity

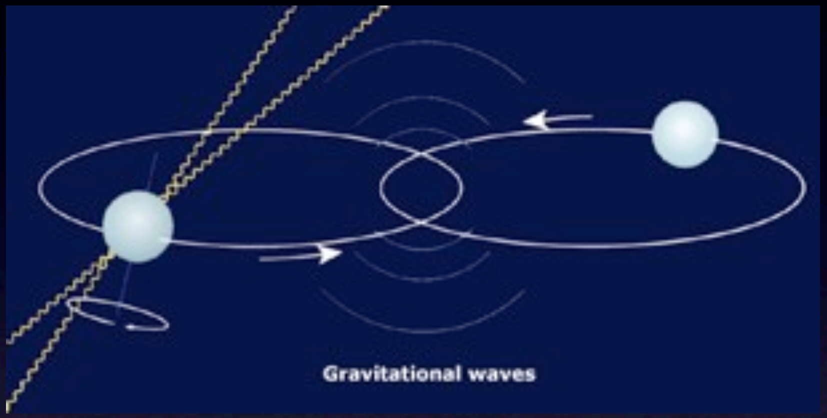
I. Introduction

Russel Hulse

Joseph Taylor

Binary neutron star system PSR 1913+16

system parameters (Weisberg et al. 2010):



- orbital period: $P_o = 7.75$ h ($v \sim 10^{-3}$ c)
- pulsar period: $P_s = 59$ ms
- eccentricity: $e = 0.62$
- periastron advance: $(\delta\Phi)_{PSR} = 4^\circ\ yr^{-1}$
  $\gg (\delta\Phi)_{Mercury} = 0.43''\ yr^{-1}$
- masses: $m_1 = 1.4398 \pm 0.0002\ M_{sol}$
  $m_2 = 1.3886 \pm 0.0002\ M_{sol}$

- orbital decay due to gravitational wave emission in excellent agreement with predictions from general relativity

→ merger in 3×10^8 years

Observed binary systems

- 5 “certain” systems (= both masses accurately measured)

Observed binary systems

- 5 "certain" systems (= both masses accurately measured)

- 5 more "likely" systems (= mass function consistent with ns)

  (see Lorimer, Living Reviews in Relativity (2008))

Observed binary systems

- 5 "certain" systems (= both masses accurately measured)
- 5 more "likely" systems (= mass function consistent with ns)

  (see Lorimer, Living Reviews in Relativity (2008))

- NO observed ns-bh system!

Observed binary systems

- 5 "certain" systems (= both masses accurately measured)

- 5 more "likely" systems (= mass function consistent with ns)

  (see Lorimer, Living Reviews in Relativity (2008))

- NO observed ns-bh system!

- estimated ns-ns rates:
  - based on observed systems: 1.5×10^{-5} - 2.9×10^{-4} (yr galaxy)$^{-1}$

    (95% conf. lev.; Kalogera et al. 2004)
  - from population synthesis: similar numbers

Observed binary systems

- 5 “certain” systems (= both masses accurately measured)

- 5 more “likely” systems (= mass function consistent with ns)

  (see Lorimer, Living Reviews in Relativity (2008))

- NO observed ns-bh system!

- estimated ns-ns rates:
  - based on observed systems: 1.5×10^{-5} - 2.9×10^{-4} $(\mathrm{yr\ galaxy})^{-1}$

    (95% conf. lev.; Kalogera et al. 2004)
  - from population synthesis: similar numbers

- ns-bh rates:
  - not accurately known
  - estimates from 10 times more (Bethe & Brown 1998) to 100 times less (Belczynski et al. 2007)

II. Why are such systems interesting?

II. Why are such systems interesting?

a) <u>Fundamental physics</u>

II. Why are such systems interesting?

a) Fundamental physics

- Tests of theory of gravity

II. Why are such systems interesting?

a) Fundamental physics

- Tests of theory of gravity

- **Direct** detection of gravitational waves (LIGO, VIRGO, GEO,...;

II. Why are such systems interesting?

a) Fundamental physics

- Tests of theory of gravity

- **Direct** detection of gravitational waves (LIGO, VIRGO, GEO,...; in advanced stages: detection out to z~0.1)

II. Why are such systems interesting?

a) Fundamental physics

- Tests of theory of gravity
- **Direct** detection of gravitational waves (LIGO, VIRGO, GEO,...; in advanced stages: detection out to z~0.1)
- Maximum neutron star mass: hadronic interaction at high

II. Why are such systems interesting?

a) Fundamental physics

- Tests of theory of gravity

- **Direct** detection of gravitational waves (LIGO, VIRGO, GEO,...; in advanced stages: detection out to z~0.1)

- Maximum neutron star mass: hadronic interaction at high density ($\rho \gg \rho_{nuc} \approx 2 \times 10^{14}$ g/cm^3)

II. Why are such systems interesting?

a) Fundamental physics

- Tests of theory of gravity

- **Direct** detection of gravitational waves (LIGO, VIRGO, GEO,...; in advanced stages: detection out to z~0.1)

- Maximum neutron star mass: hadronic interaction at high density ($\rho >> \rho_{nuc} \approx 2 \times 10^{14}$ g/cm^3)

b) Astrophysics

II. Why are such systems interesting?

a) Fundamental physics

- Tests of theory of gravity

- **Direct** detection of gravitational waves (LIGO, VIRGO, GEO,...; in advanced stages: detection out to z~0.1)

- Maximum neutron star mass: hadronic interaction at high density ($\rho \gg \rho_{nuc} \approx 2 \times 10^{14}$ g/cm^3)

b) Astrophysics

- Nucleosynthesis: are compact binary mergers sources of

II. Why are such systems interesting?

a) Fundamental physics

- Tests of theory of gravity

- **Direct** detection of gravitational waves (LIGO, VIRGO, GEO,...; in advanced stages: detection out to z~0.1)

- Maximum neutron star mass: hadronic interaction at high density ($\rho \gg \rho_{nuc} \approx 2 \times 10^{14}$ g/cm^3)

b) Astrophysics

- Nucleosynthesis: are compact binary mergers sources of rapid neutron capture ("r-process") nuclei?

II. Why are such systems interesting?

a) Fundamental physics

- Tests of theory of gravity

- **Direct** detection of gravitational waves (LIGO, VIRGO, GEO,...; in advanced stages: detection out to z~0.1)

- Maximum neutron star mass: hadronic interaction at high density ($\rho >> \rho_{nuc} \approx 2 \times 10^{14}$ g/cm^3)

b) Astrophysics

- Nucleosynthesis: are compact binary mergers sources of rapid neutron capture ("r-process") nuclei?

- Gamma-ray bursts: do they power (about 1/3 of) the el.mag.

II. Why are such systems interesting?

a) Fundamental physics

- Tests of theory of gravity
- **Direct** detection of gravitational waves (LIGO, VIRGO, GEO,...; in advanced stages: detection out to z~0.1)
- Maximum neutron star mass: hadronic interaction at high density ($\rho >> \rho_{nuc} \approx 2 \times 10^{14}$ g/cm^3)

b) Astrophysics

- Nucleosynthesis: are compact binary mergers sources of rapid neutron capture ("r-process") nuclei?
- Gamma-ray bursts: do they power (about 1/3 of) the el.mag. most luminous explosions in the Universe?

Direct gravitational wave (GW) detection

- LIGO & VIRGO detectors currently upgraded,

  increase sensitivity by factor > 10 (to $h \sim 10^{-22}$)

  grav. wave amplitude $h \propto 1/r$

  $\Rightarrow$ accessible volume enhanced by > factor 1000

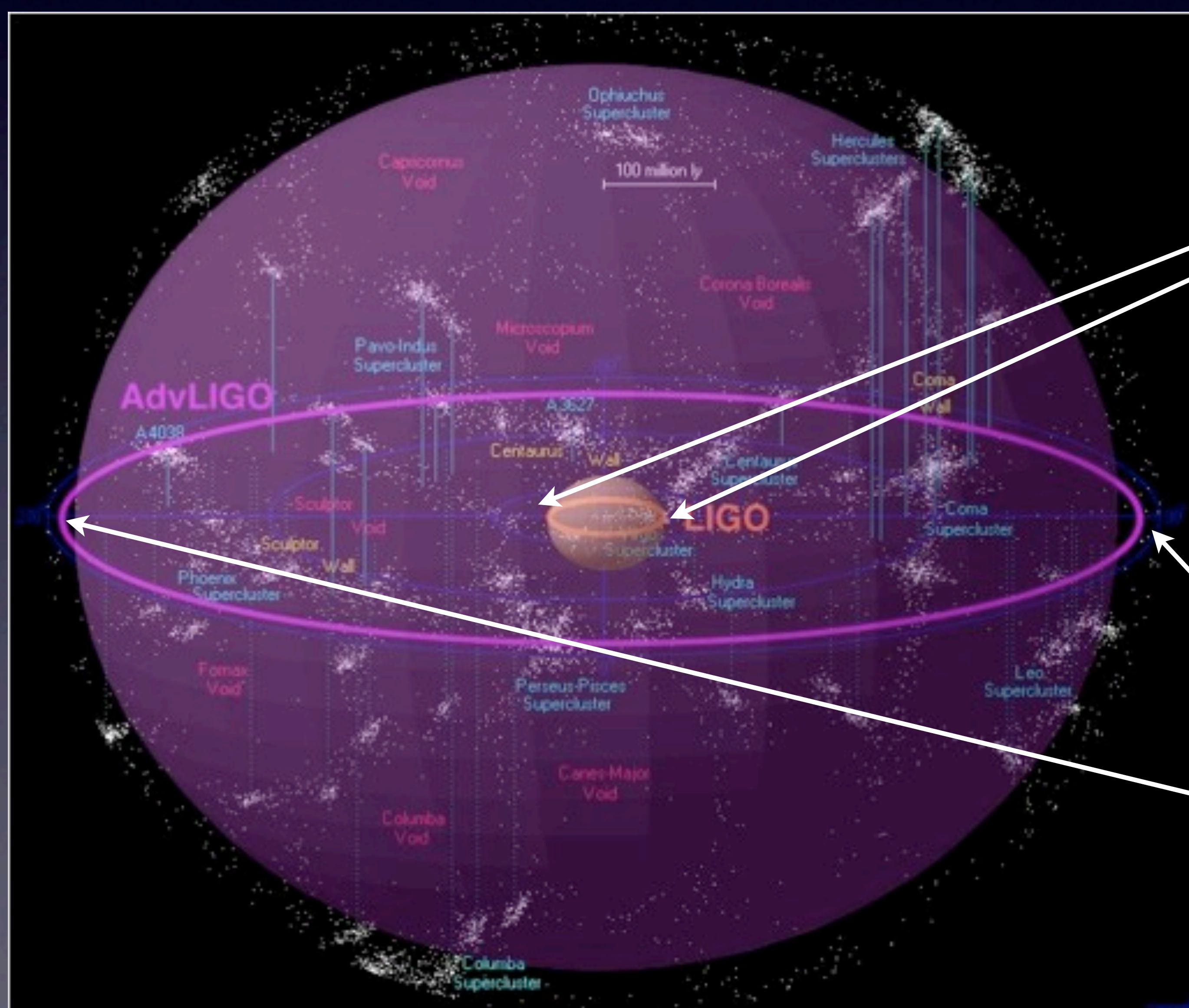
Direct gravitational wave (GW) detection

- LIGO & VIRGO detectors currently upgraded,

  increase sensitivity by factor > 10 (to $h \sim 10^{-22}$)

  grav. wave amplitude $h \propto 1/r$

  $\Rightarrow$ accessible volume enhanced by > factor 1000



initial LIGO

Advanced LIGO

- expected to be online ~2016

- expected to be online ~2016
- nsns and nsbh binary systems are main targets

- expected to be online ~2016

- nsns and nsbh binary systems are main targets

- expected detection rates (Abadie et al. 2010):
  - 0.4 - 400 yr^{-1} nsns
  - 0.2 - 300 yr^{-1} nsbh

- expected to be online ~2016

- nsns and nsbh binary systems are main targets

- expected detection rates (Abadie et al. 2010):
  - 0.4 - 400 yr^{-1} nsns
  - 0.2 - 300 yr^{-1} nsbh

large uncertainties!!

- expected to be online ~2016

- nsns and nsbh binary systems are main targets

- expected detection rates (Abadie et al. 2010):
  - 0.4 - 400 yr^{-1} nsns
  - 0.2 - 300 yr^{-1} nsbh

large uncertainties!!

- first detections may be ambiguous/near detection threshold, additional signatures may give confidence, enhancement of detection efficiency

- expected to be online ~2016
- nsns and nsbh binary systems are main targets
- expected detection rates (Abadie et al. 2010):
  - 0.4 - 400 yr^{-1} nsns
  - 0.2 - 300 yr^{-1} nsbh

large uncertainties!!

- first detections may be ambiguous/near detection threshold, additional signatures may give confidence, enhancement of detection efficiency
- "multi-messenger" approach will provide additional information on:
  - astrophysical events and their rates
  - their environment (host galaxies, ambient medium, ...)
  - the physics of the sources

- expected to be online ~2016

- nsns and nsbh binary systems are main targets

Which additional signatures are produced by compact object encounters?

signatures may give confidence, enhancement of detection efficiency

- "multi-messenger" approach will provide additional information on:
    - astrophysical events and their rates
    - their environment (host galaxies, ambient medium, ...)
    - the physics of the sources

Where are r-process nuclei produced in the cosmos?

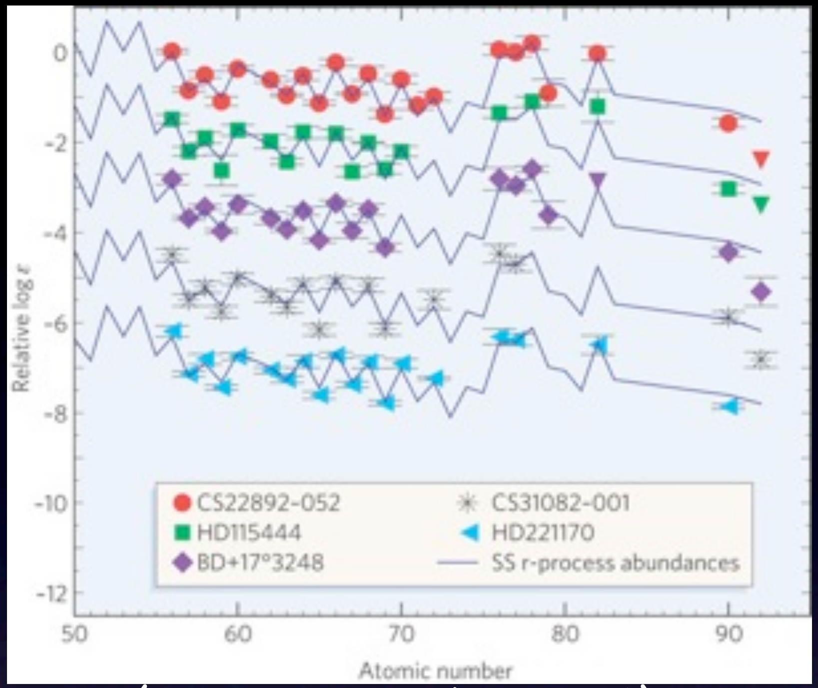
Where are r-process nuclei produced in the cosmos?

clues from metal-poor stars:

(at least) two sources:

a) "weak" (Z<56): varying abundance patterns

b) "strong" (Z>56): extremely robust abundance patterns



(Cowan & Sneden 2006)

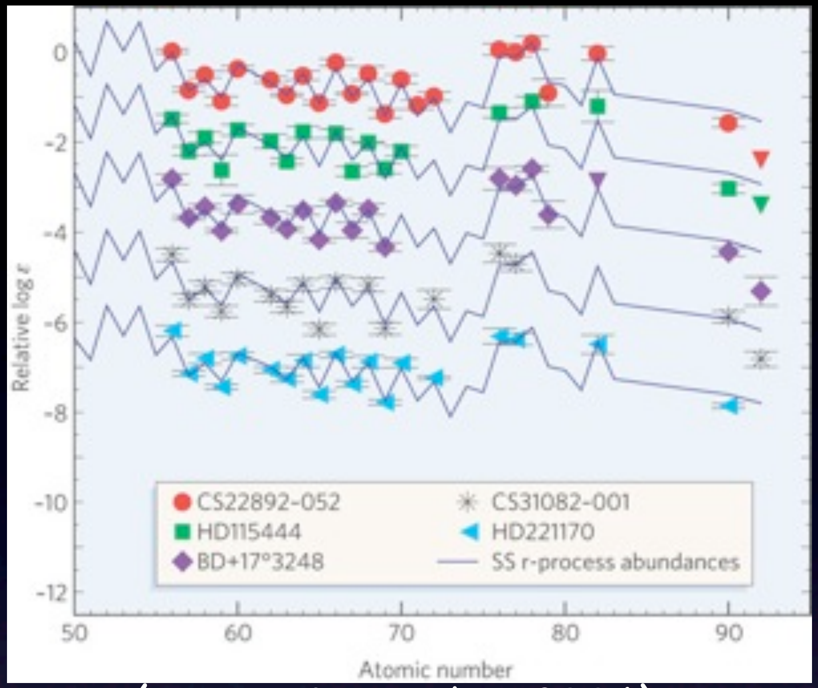
Where are r-process nuclei produced in the cosmos?

clues from metal-poor stars:

(at least) two sources:

a) "weak" (Z<56): varying abundance patterns

b) "strong" (Z>56): extremely robust abundance patterns



(Cowan & Sneden 2006)

requirements on astrophysical scenario

a) high temperatures ~ 10^9 K

b) high neutron to seed ratio, low Y_e

c) short time scales

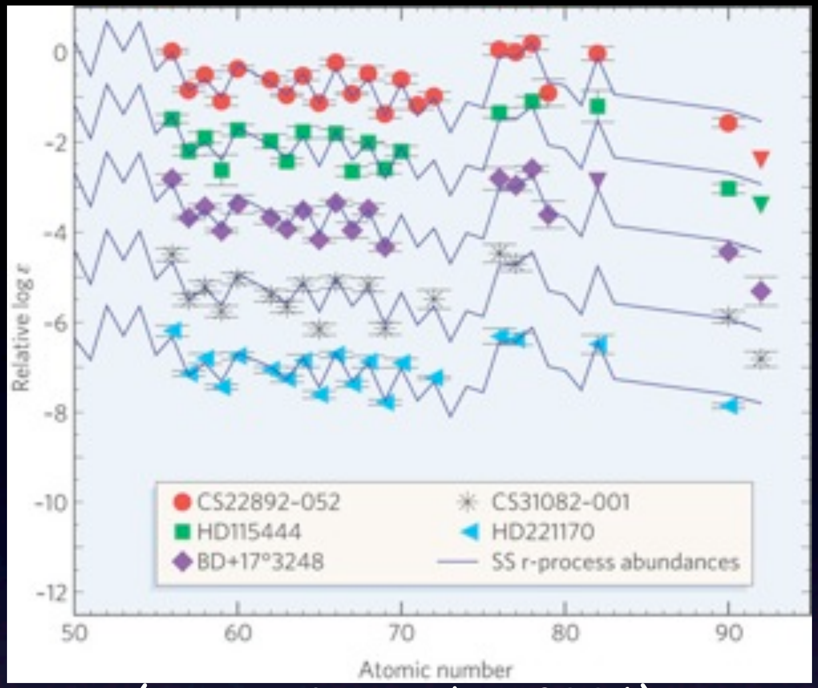
Where are r-process nuclei produced in the cosmos?

clues from metal-poor stars:

(at least) two sources:

a) "weak" (Z<56): varying abundance patterns

b) "strong" (Z>56): extremely robust abundance patterns



(Cowan & Sneden 2006)

requirements on astrophysical scenario

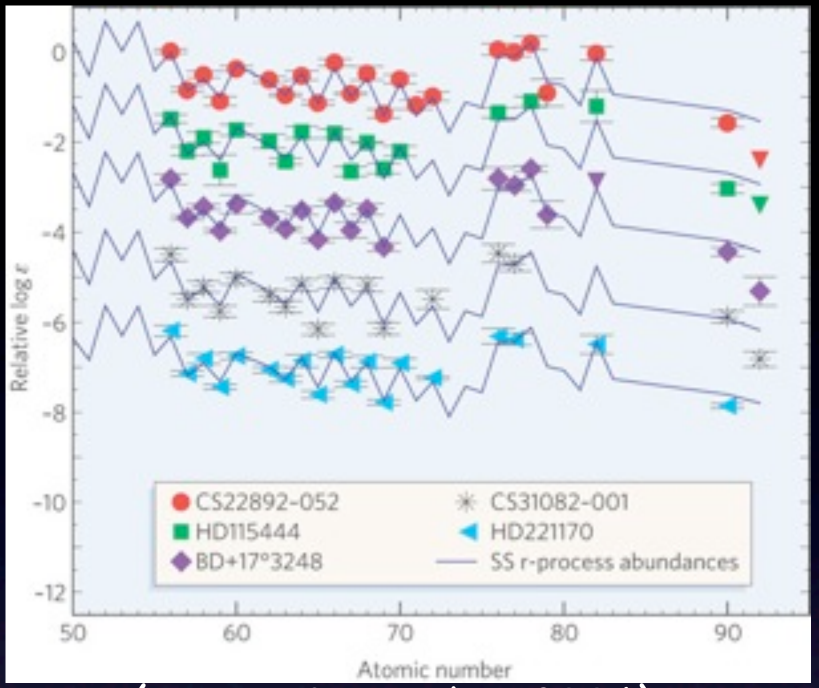
a) high temperatures ~ 10^9 K

b) high neutron to seed ratio, low Y_e

c) short time scales

"explosion in neutron-rich environment"

Where are r-process nuclei produced in the cosmos?



(Cowan & Sneden 2006)

clues from metal-poor stars:

(at least) two sources:

- a) "weak" (Z<56): varying abundance patterns
- b) "strong" (Z>56): extremely robust abundance patterns

requirements on astrophysical scenario

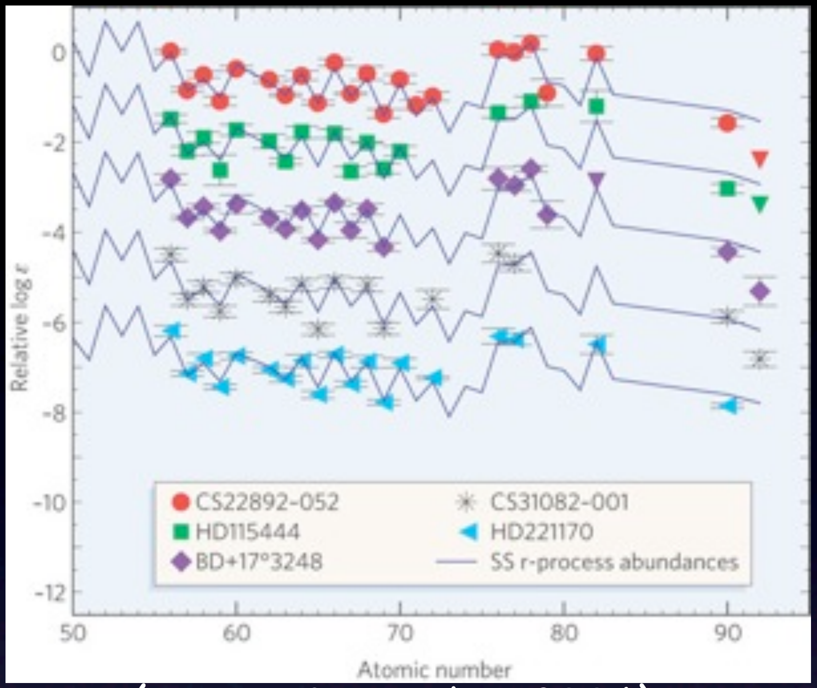
- a) high temperatures ~ 10^9 K
- b) high neutron to seed ratio, low Y_e
- c) short time scales

"explosion in neutron-rich environment"

core-collapse supernovae seem seriously challenged producing all the "r-process" material

(e.g. Roberts et al. 2010, Fischer et al. 2010, Arcones & Janka 2011)

Where are r-process nuclei produced in the cosmos?



(Cowan & Sneden 2006)

clues from metal-poor stars:
(at least) two sources:
a) "weak" (Z<56): varying abundance patterns
b) "strong" (Z>56): extremely robust abundance patterns

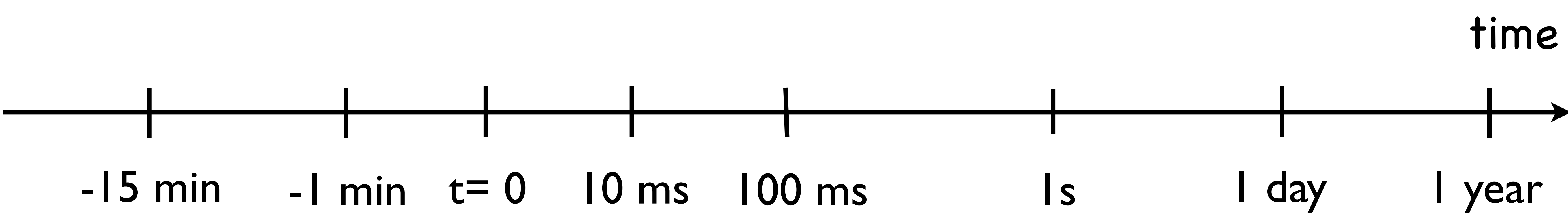
requirements on astrophysical scenario
a) high temperatures ~ 10^9 K
b) high neutron to seed ratio, low Y_e
c) short time scales

"explosion in neutron-rich environment"

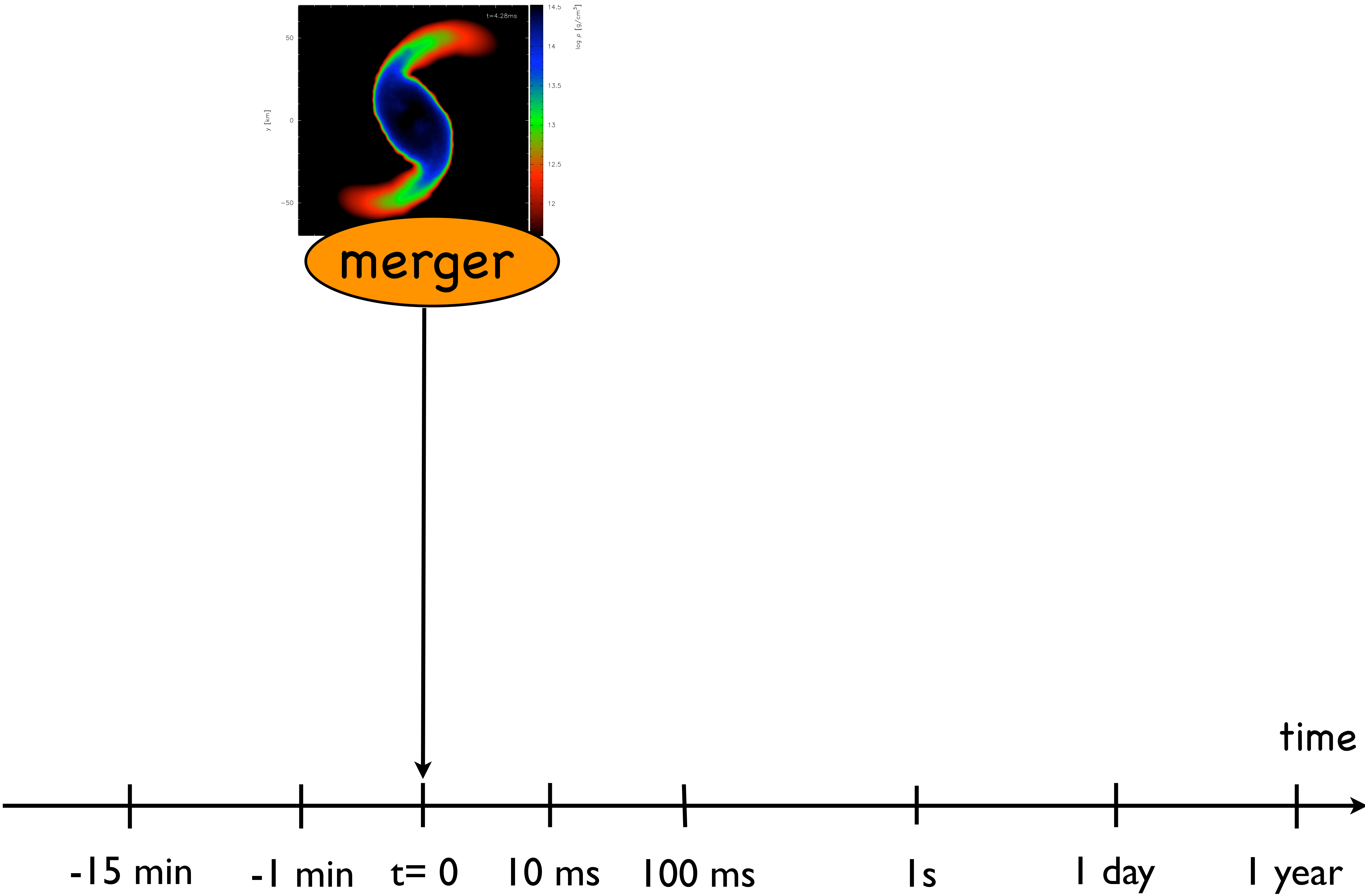
core-collapse supernovae seem seriously challenged producing all the "r-process" material
(e.g. Roberts et al. 2010, Fischer et al. 2010, Arcones & Janka 2011)

interesting alternative: decompression of neutron star matter, e.g. in a neutron star merger (Lattimer & Schramm 1974, Eichler et al. 1989, Freiburghaus et al. 1999, Roberts et al. 2011, Goriely et al 2011, Korobkin et al. 2012...)

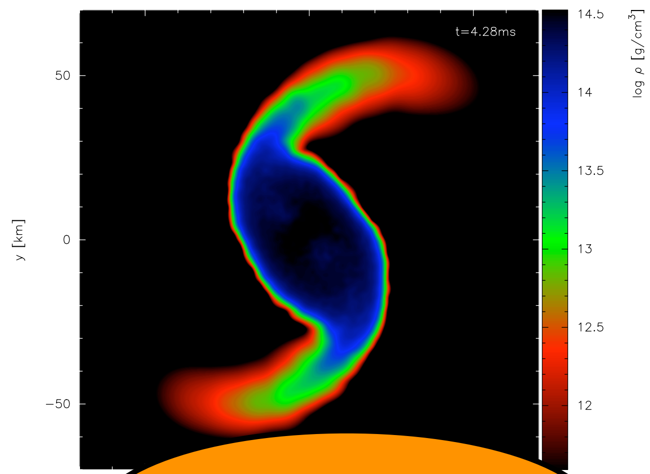
Compact binary mergers: multi-physics events



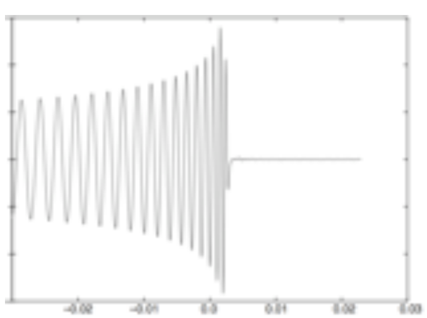
Compact binary mergers: multi-physics events



Compact binary mergers: multi-physics events



merger

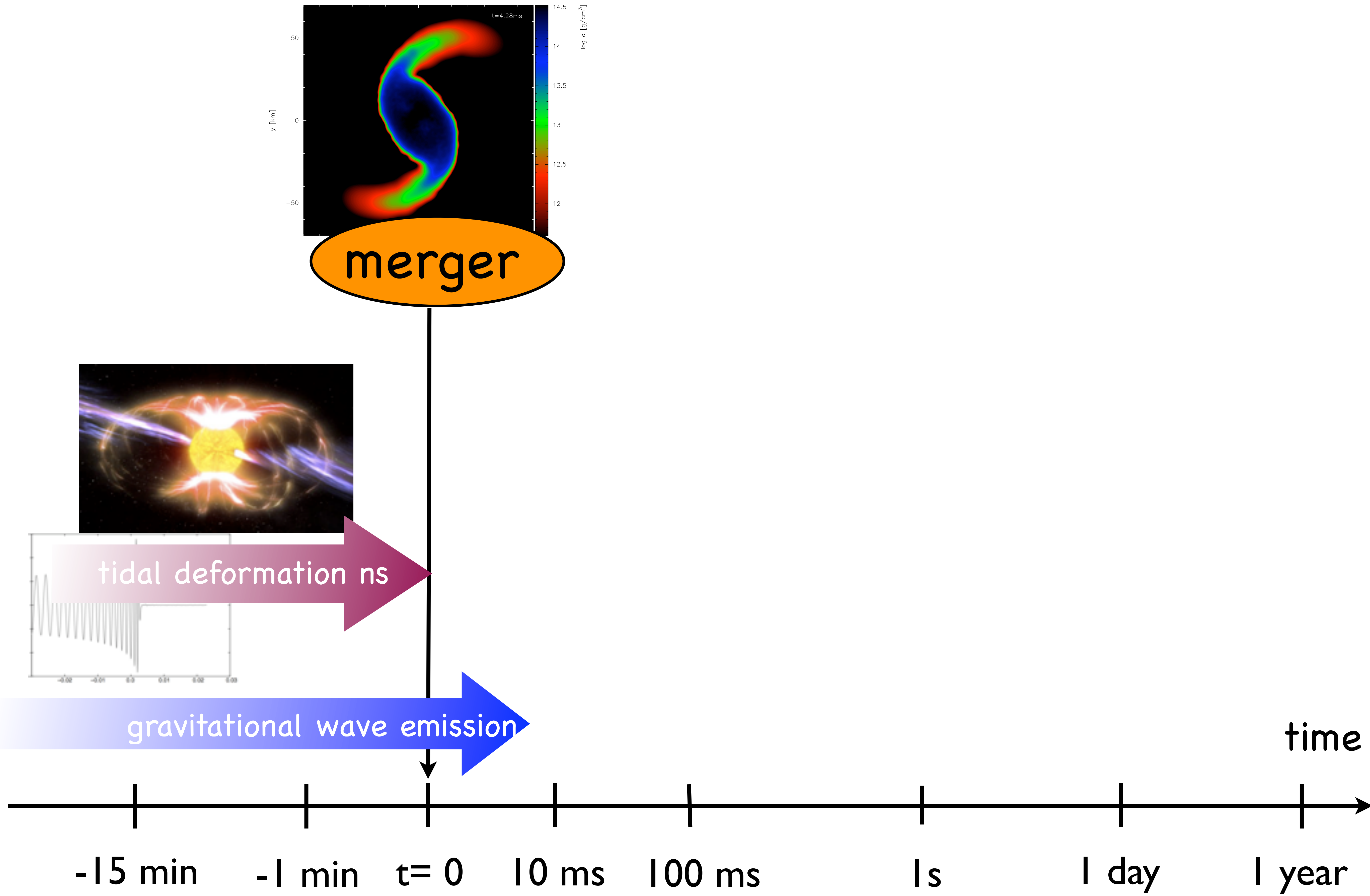


gravitational wave emission

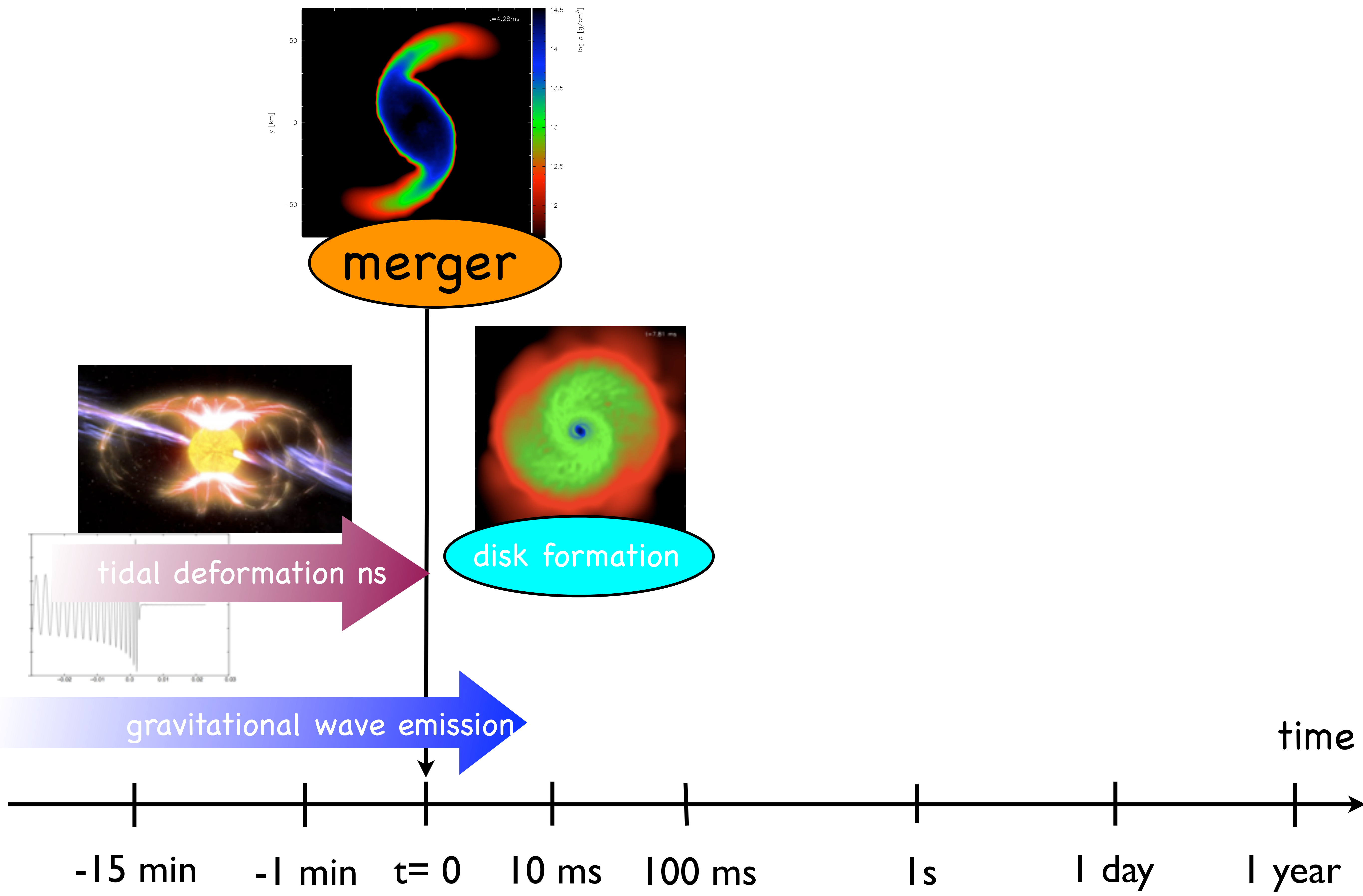
time

-15 min | -1 min | t= 0 | 10 ms | 100 ms | 1 s | 1 day | 1 year

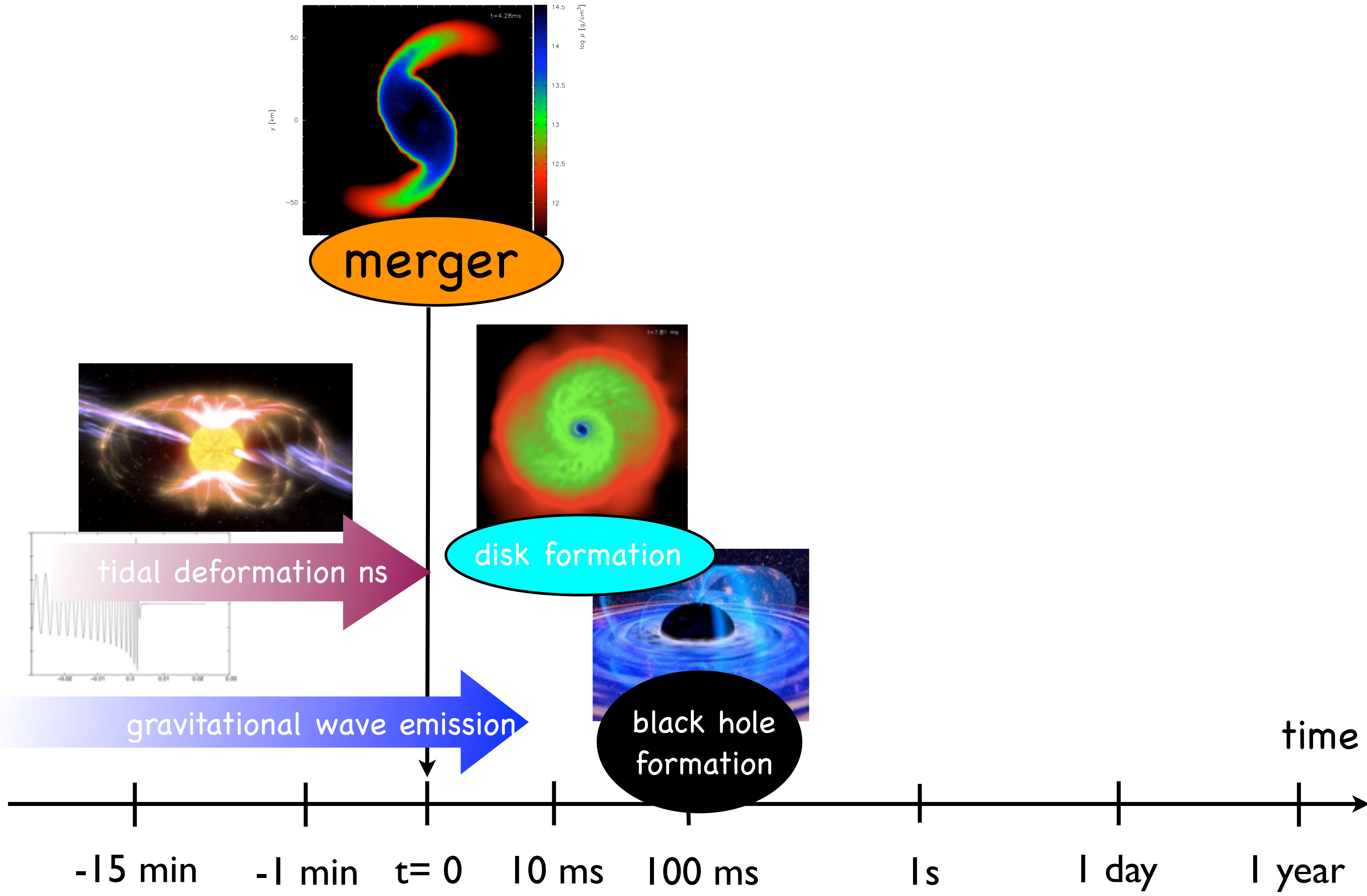
Compact binary mergers: multi-physics events



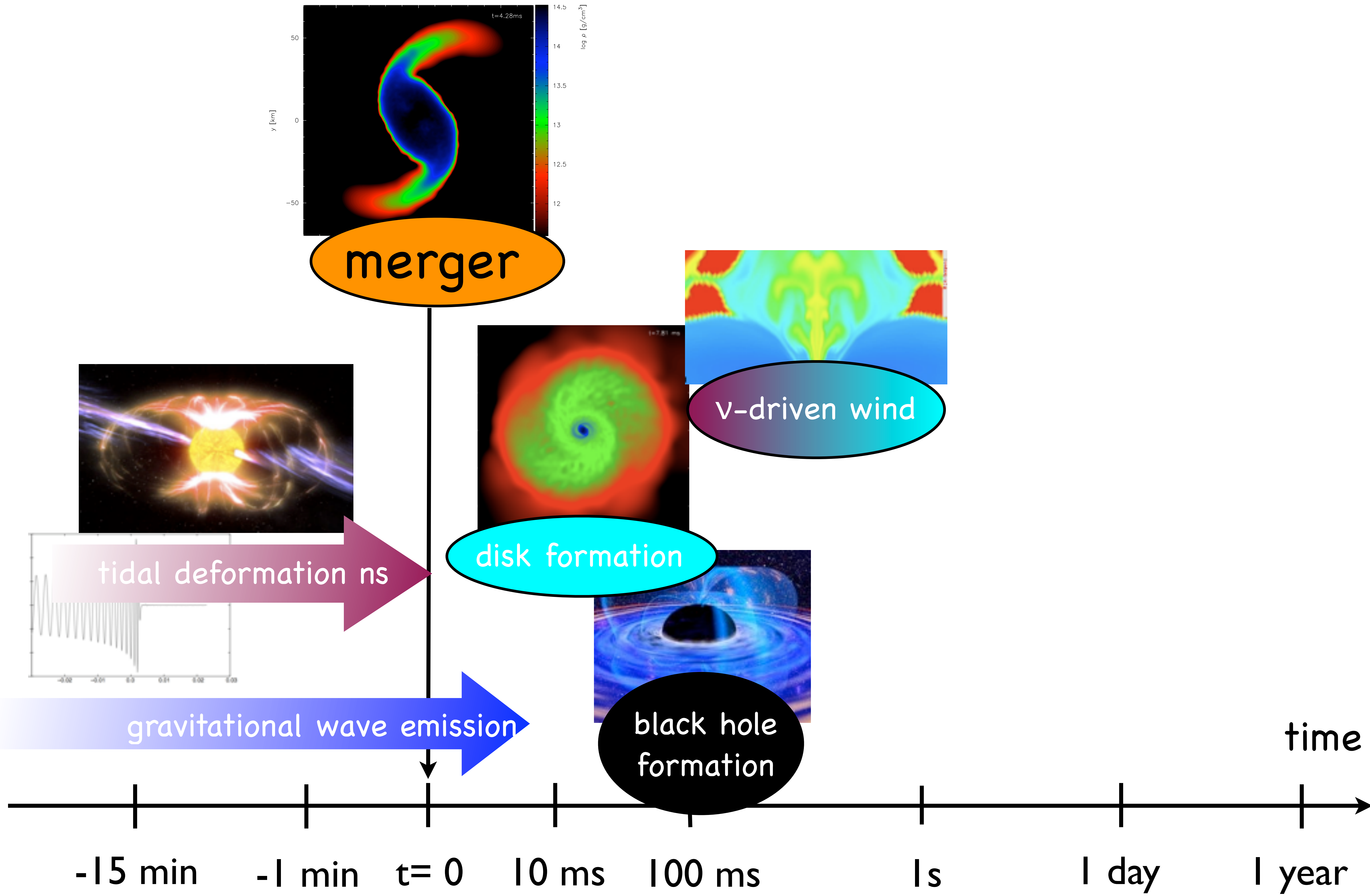
Compact binary mergers: multi-physics events



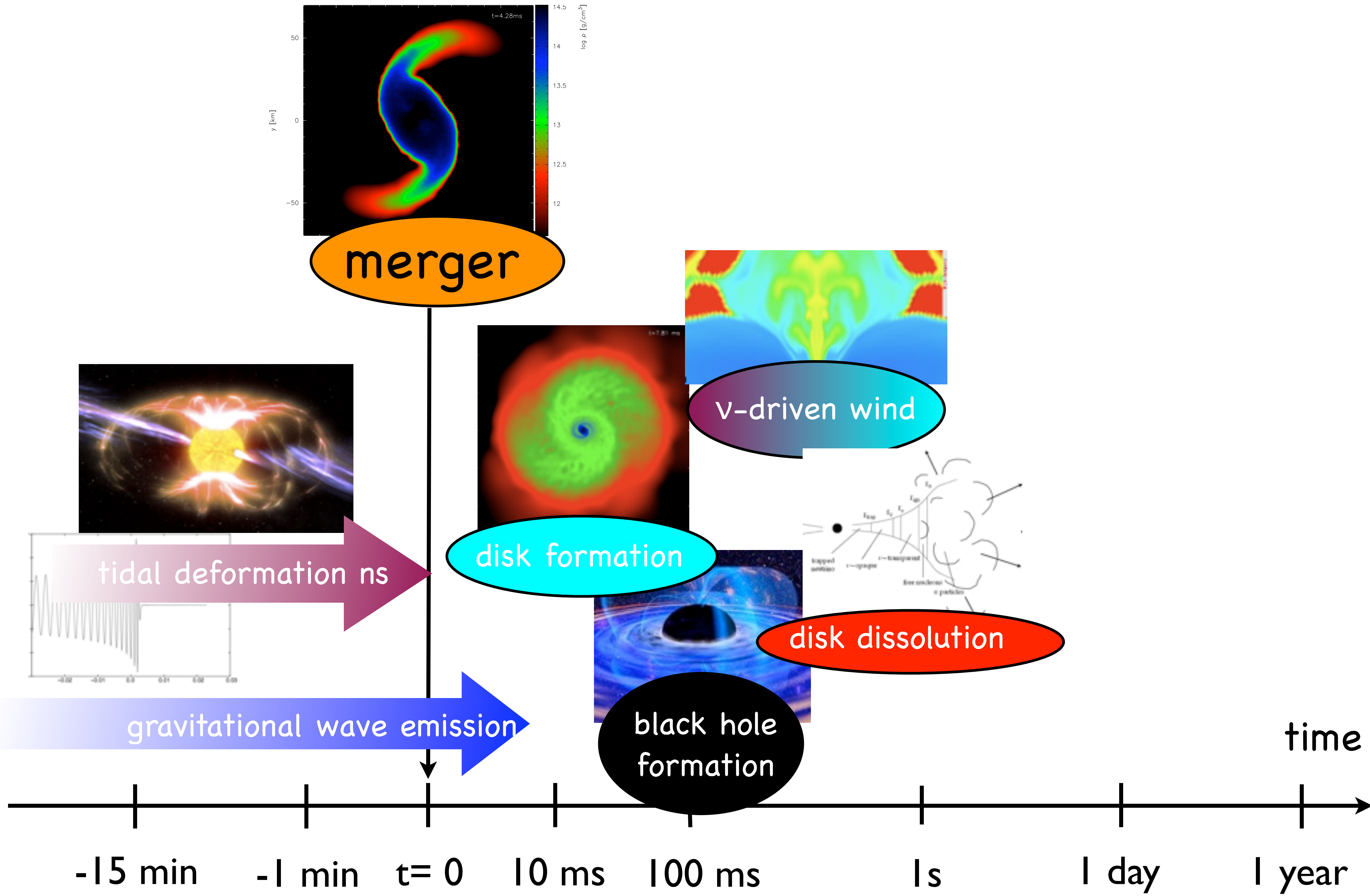
Compact binary mergers: multi-physics events



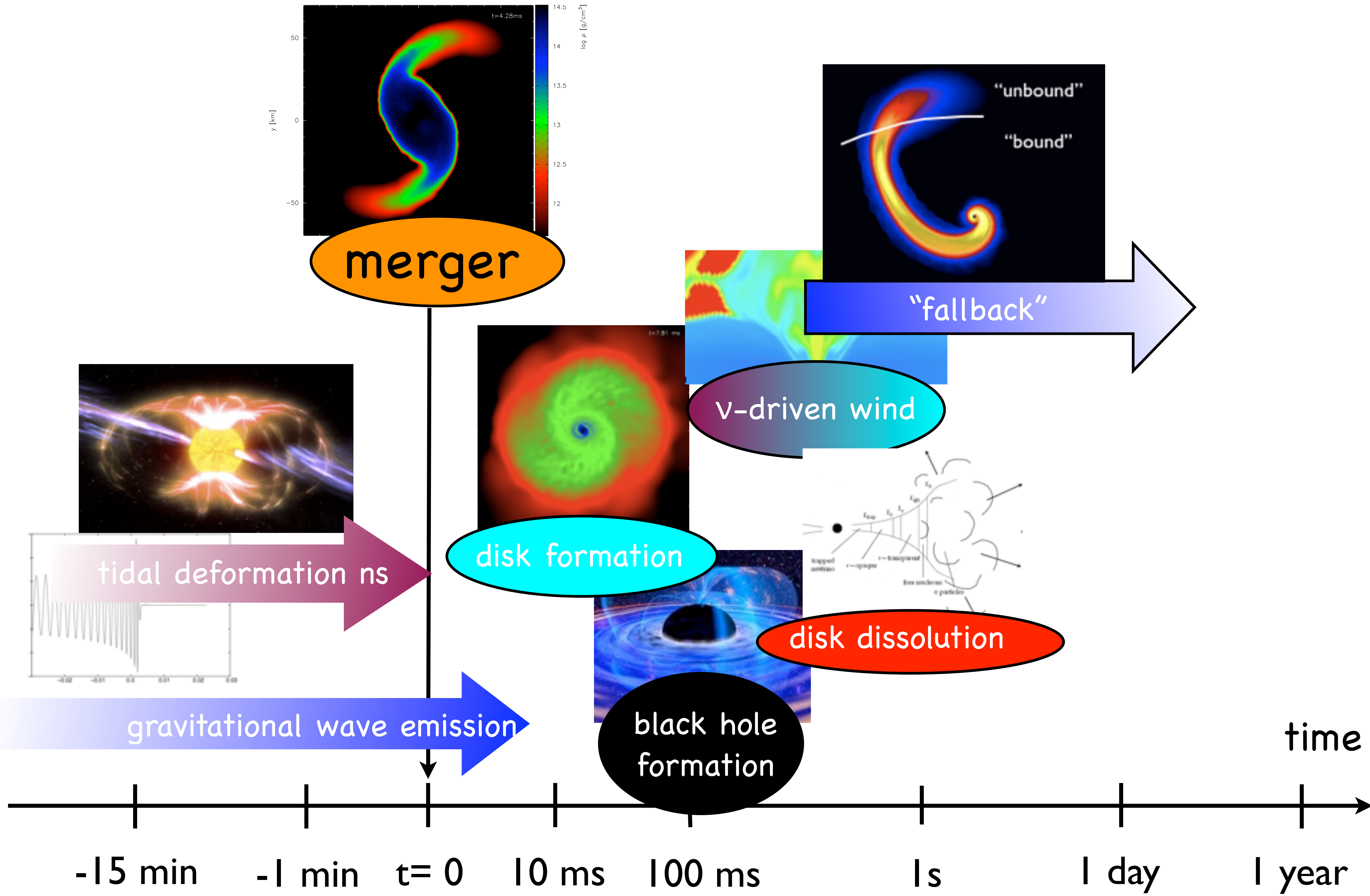
Compact binary mergers: multi-physics events



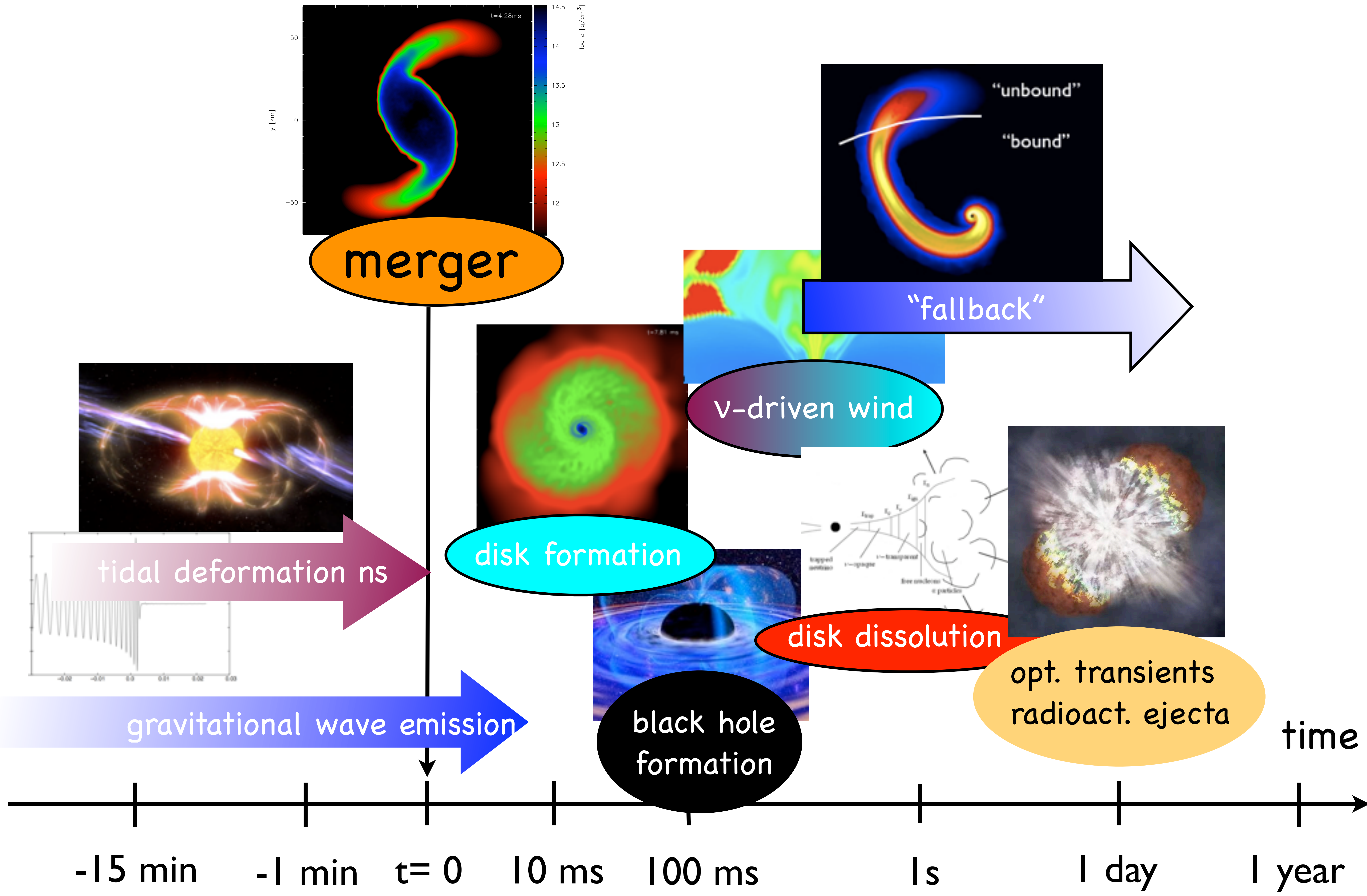
Compact binary mergers: multi-physics events



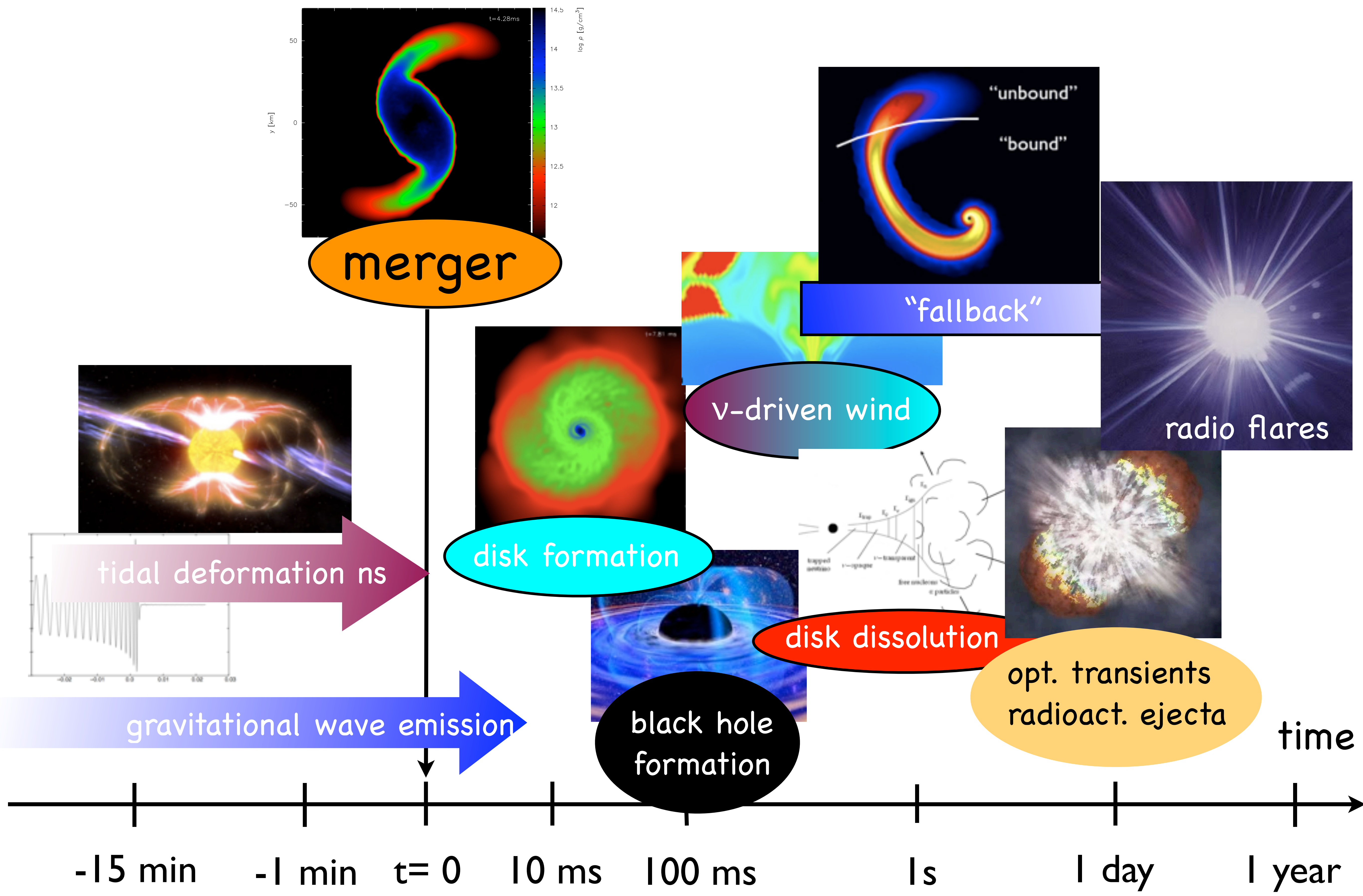
Compact binary mergers: multi-physics events



Compact binary mergers: multi-physics events

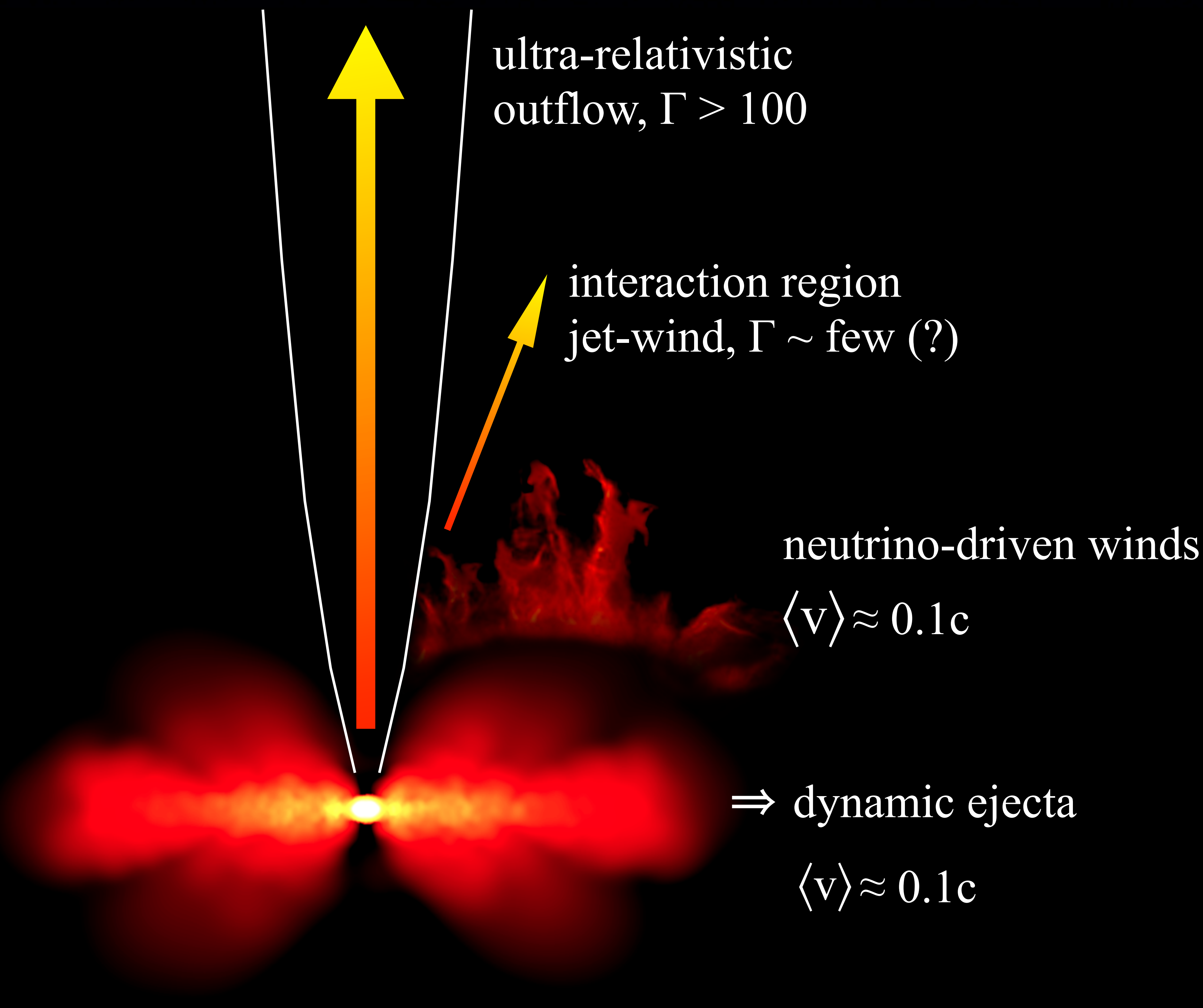


Compact binary mergers: multi-physics events

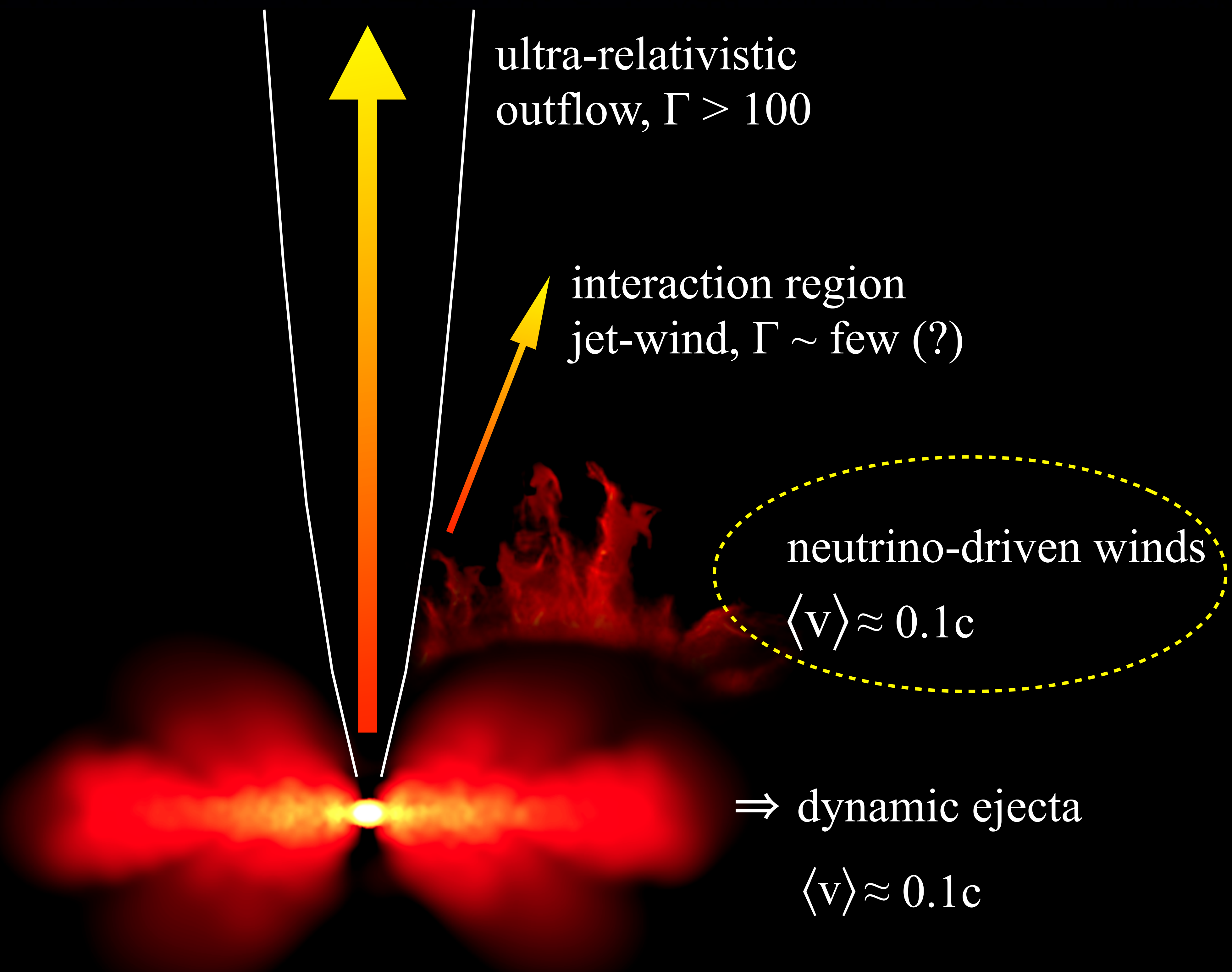


How does a compact binary merger enrich its environment with neutron-rich matter?

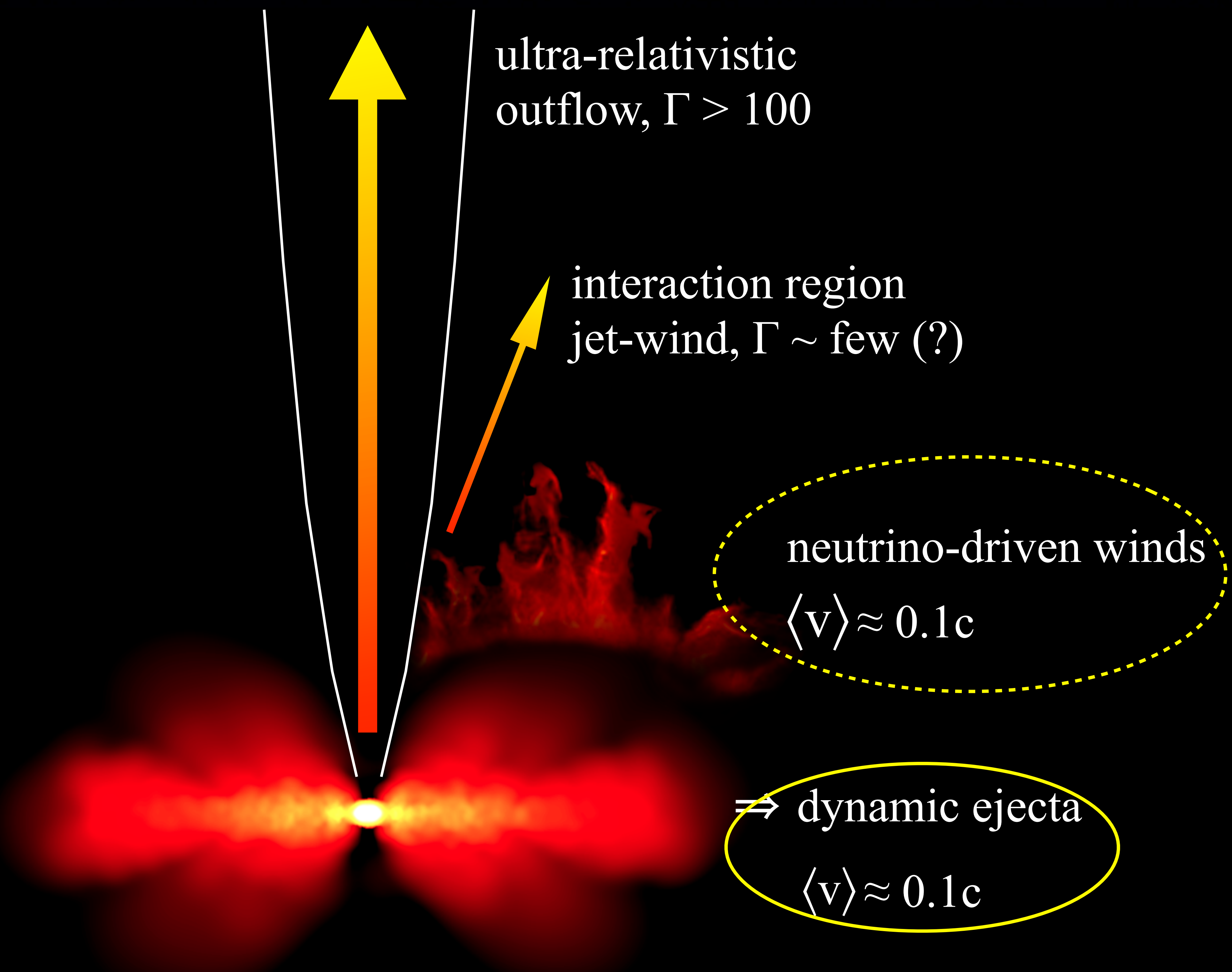
How does a compact binary merger enrich its environment with neutron-rich matter?



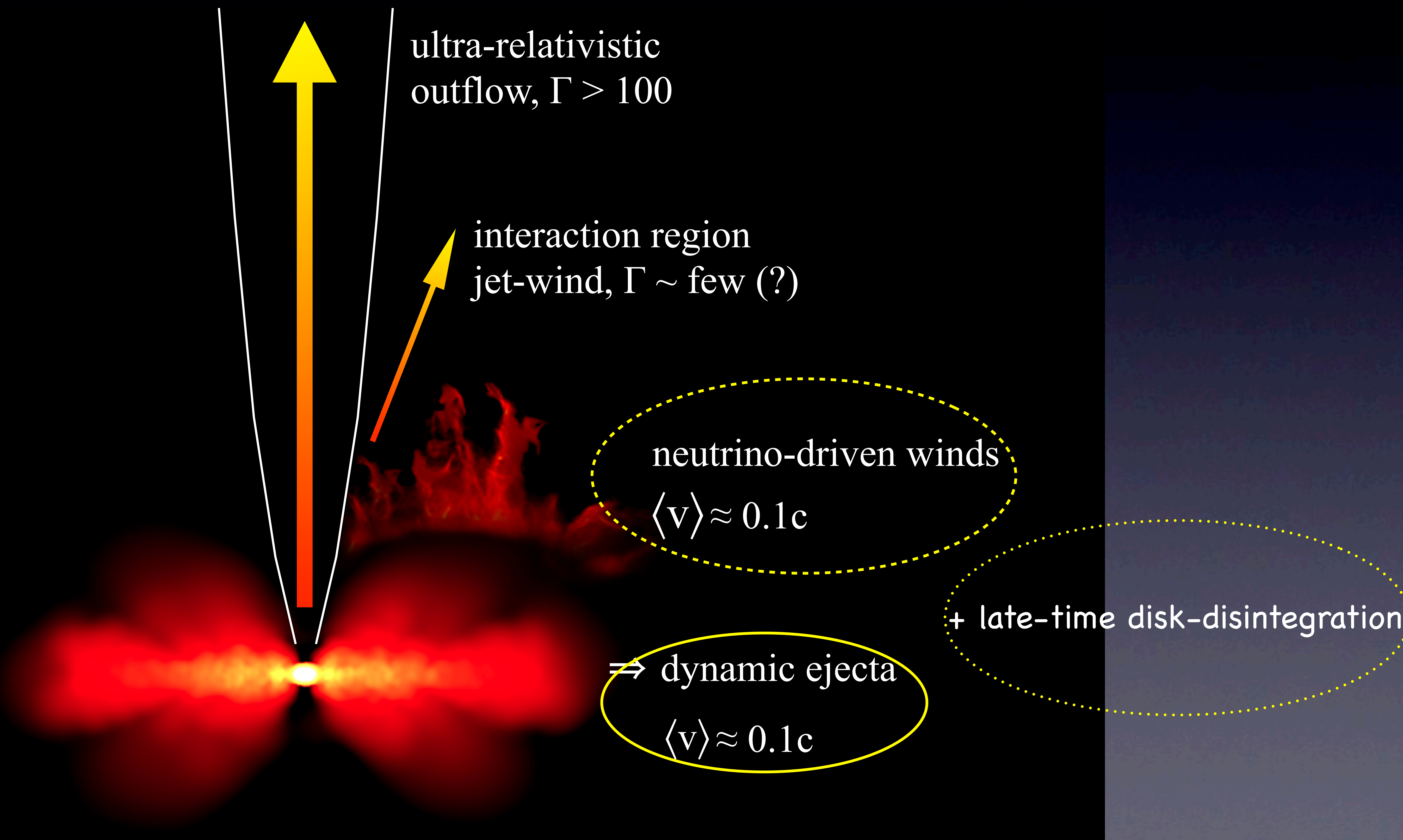
How does a compact binary merger enrich its environment with neutron-rich matter?



How does a compact binary merger enrich its environment with neutron-rich matter?



How does a compact binary merger enrich its environment with neutron-rich matter?



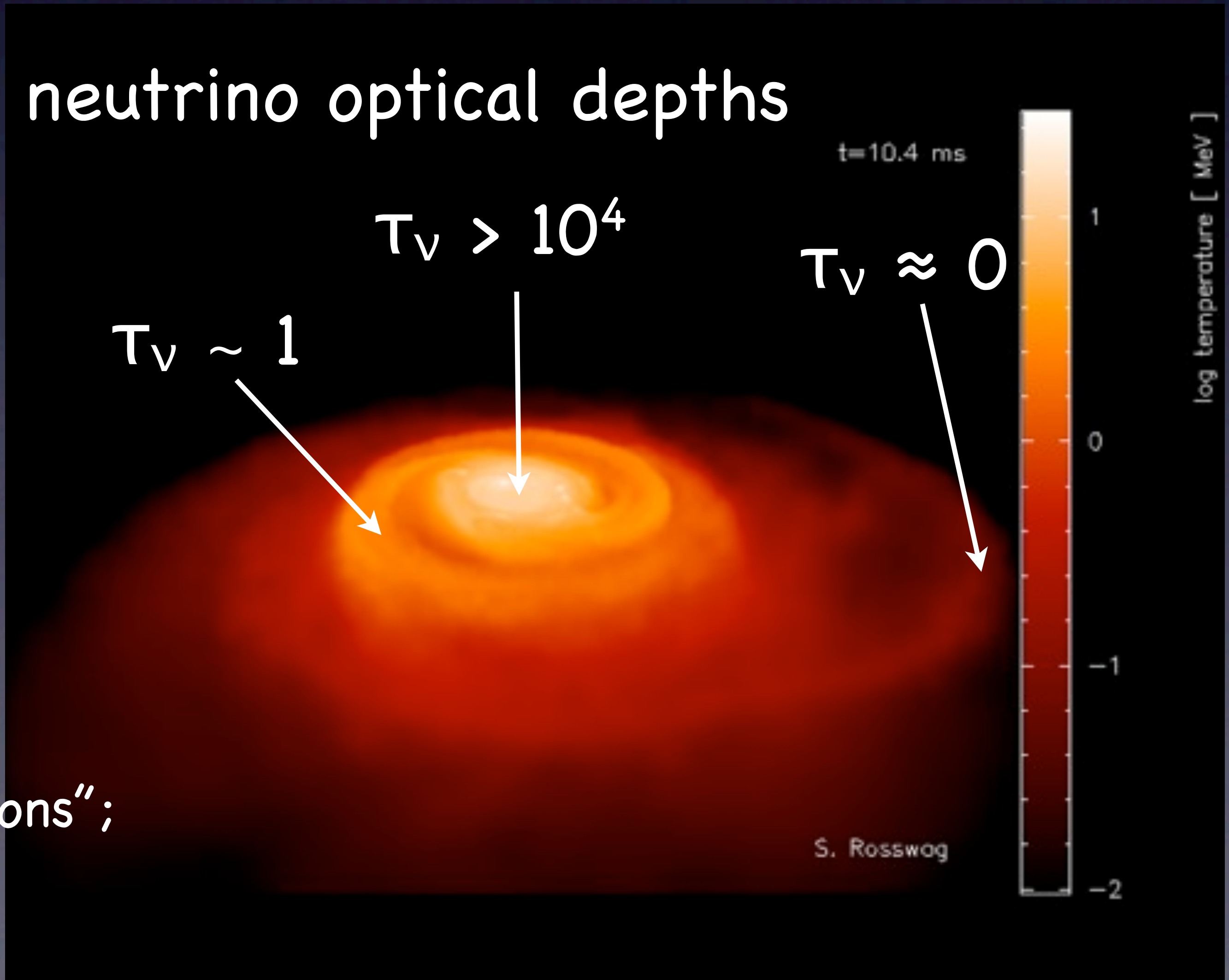
III. Recent results

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



References:

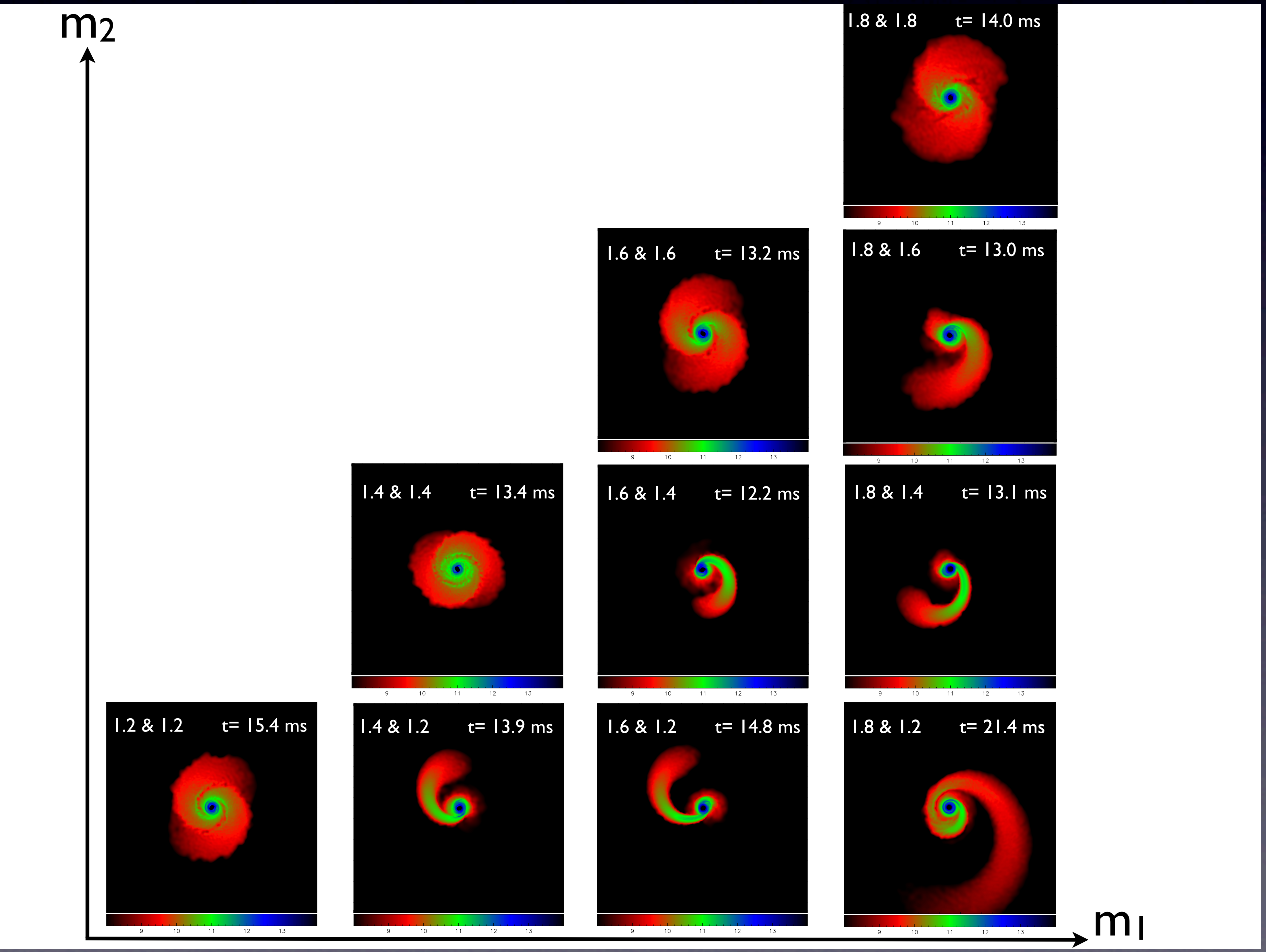
- SR & Davies, MNRAS 334, 481 (2002)
- SR & Liebendörfer, MNRAS 342, 673 (2003)
- "MAGnetohydrodynamics for Merger Applications"; SR & Price, MNRAS 379, 915 (2007))

systematic exploration of parameter space:

[1.0 M_{sol}, 2.0 M_{sol}] x [1.0 M_{sol} 2.0 M_{sol}] in 21 simulations

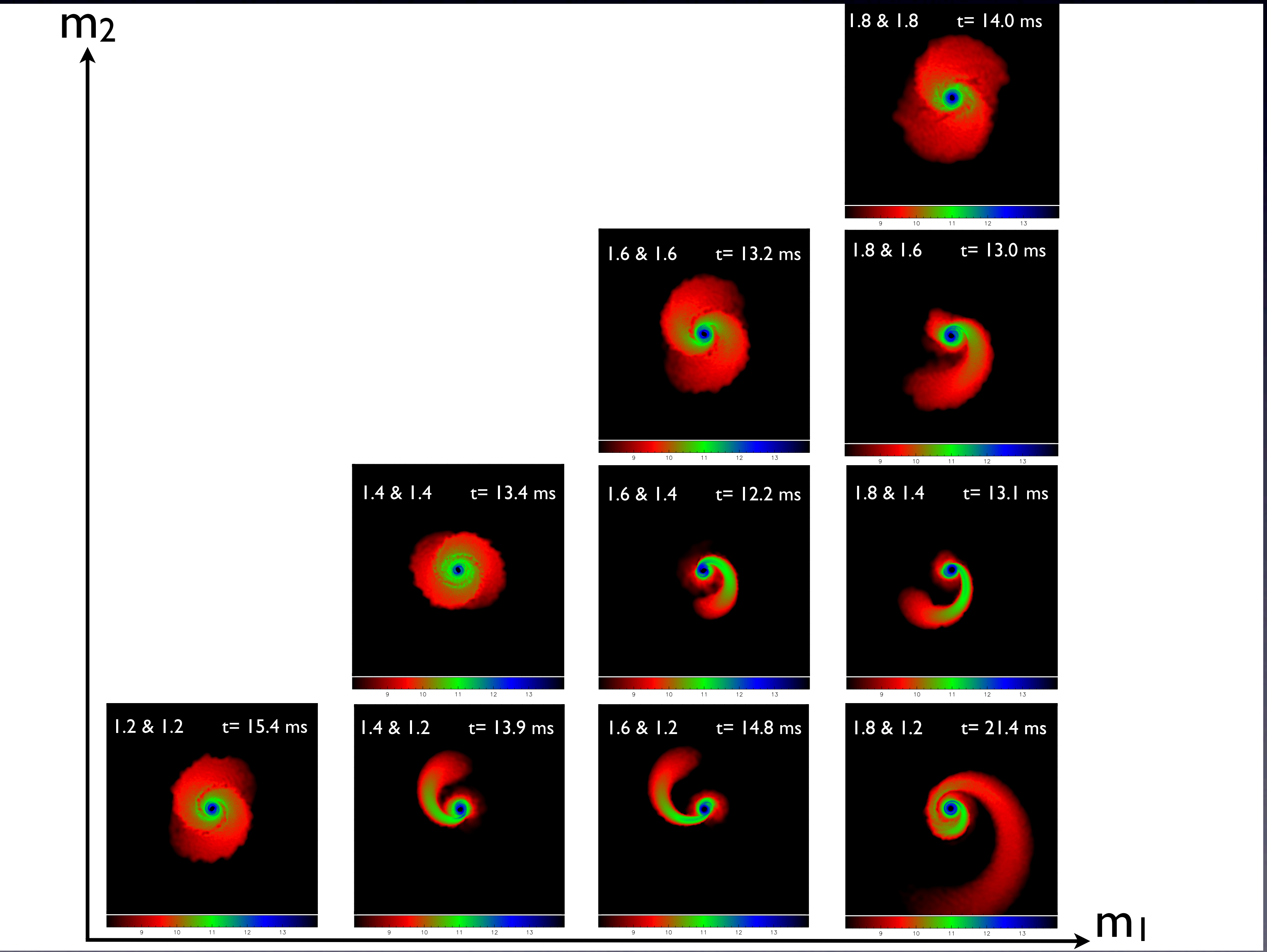
systematic exploration of parameter space:

[1.0 M_{sol}, 2.0 M_{sol}] x [1.0 M_{sol} 2.0 M_{sol}] in 21 simulations



systematic exploration of parameter space:

[1.0 M_{sol}, 2.0 M_{sol}] x [1.0 M_{sol} 2.0 M_{sol}] in 21 simulations



asymmetry in masses leads to:

- pronounced single tidal tail
- larger ejected masses
- larger ejecta velocities

⇒larger el.mag. luminos.

("macronovae", radio flares)

A. Double neutron star mergers

- masses close to 1.4 M_{sol}
- small asymmetry: m_1= 1.3 M_{sol}, m_2= 1.4 M_{sol}, q= 0.929
- stellar spins negligible (Bildsten et al. 1992, Kochanek 1992)

(visualized: temperature at given optical depth using)

A. Double neutron star mergers

- masses close to 1.4 M_{sol}
- small asymmetry: m_1= 1.3 M_{sol}, m_2= 1.4 M_{sol}, q= 0.929
- stellar spins negligible (Bildsten et al. 1992, Kochanek 1992)
- peak temperatures: ~ 40 MeV ($\approx 4 \times 10^{11}$ K) (in vortices)

(visualized: temperature at given optical depth using)

A. Double neutron star mergers

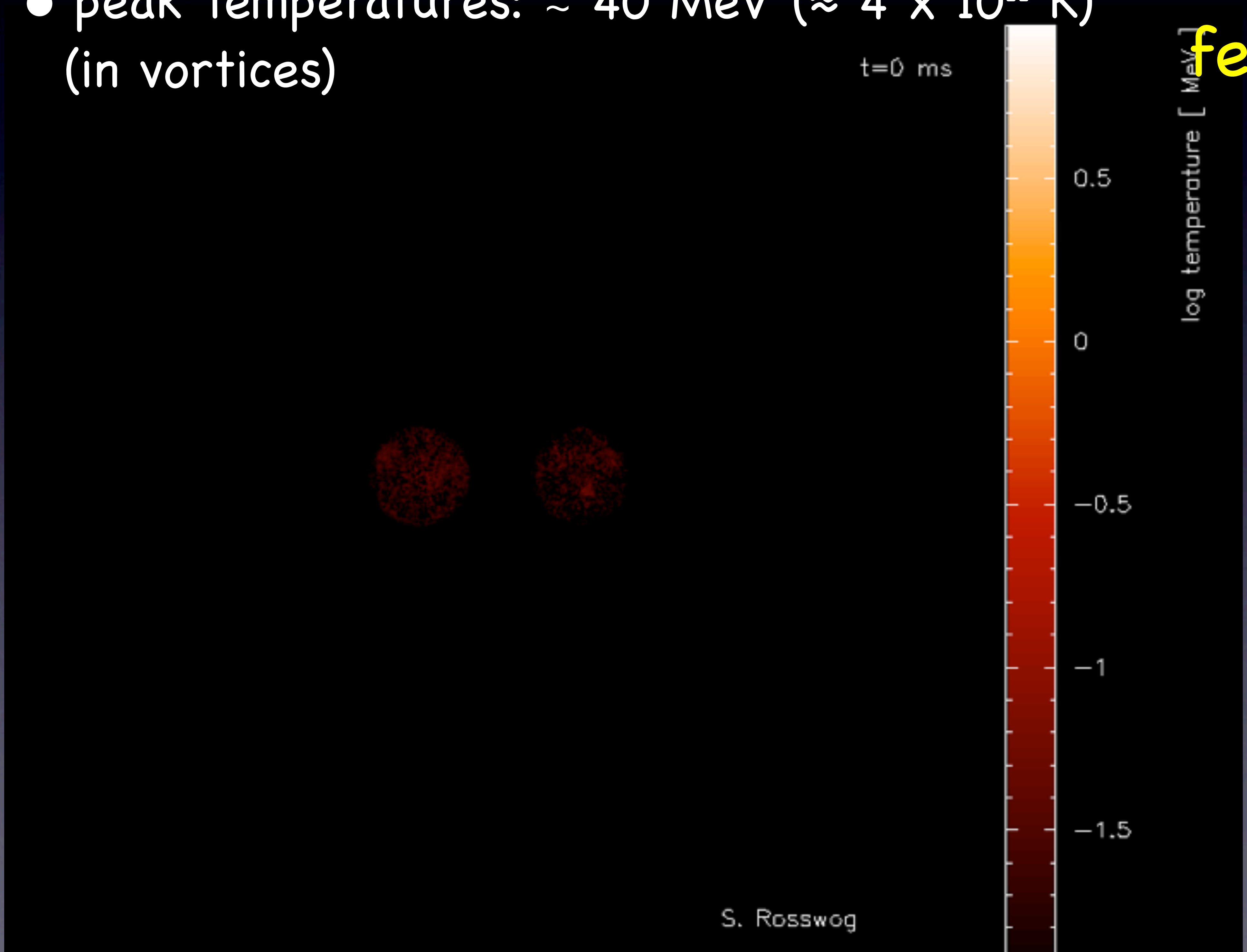
- masses close to 1.4 M_{sol}
- small asymmetry: m_1= 1.3 M_{sol}, m_2= 1.4 M_{sol}, q= 0.929
- stellar spins negligible (Bildsten et al. 1992, Kochanek 1992)
- peak temperatures: ~ 40 MeV (≈ 4 x 10^{11} K) (in vortices)

few milliseconds!

(visualized: temperature at given optical depth using)

A. Double neutron star mergers

- masses close to 1.4 M_{sol}
- small asymmetry: m_1= 1.3 M_{sol}, m_2= 1.4 M_{sol}, q= 0.929
- stellar spins negligible (Bildsten et al. 1992, Kochanek 1992)
- peak temperatures: ~ 40 MeV (≈ 4 x 10^{11} K) (in vortices)

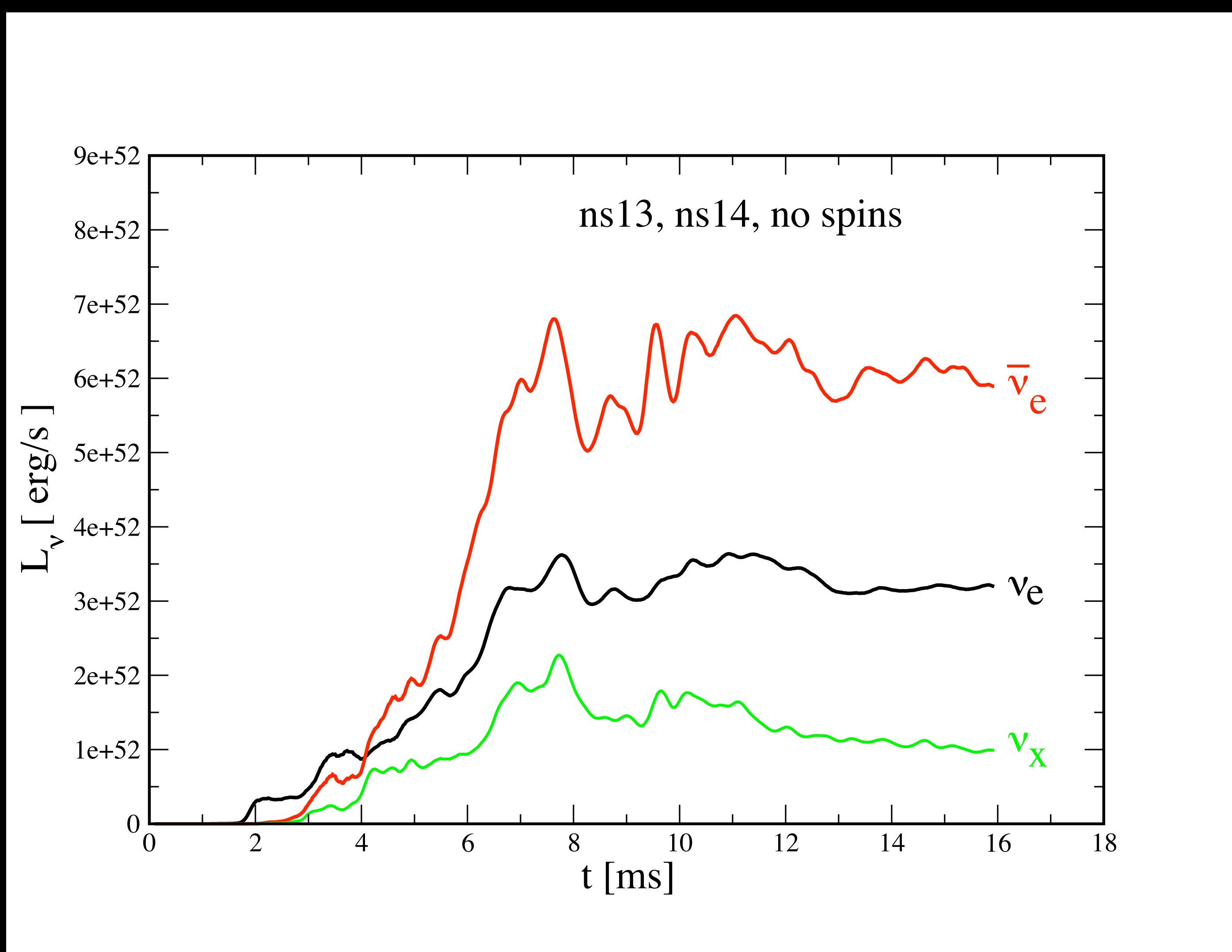


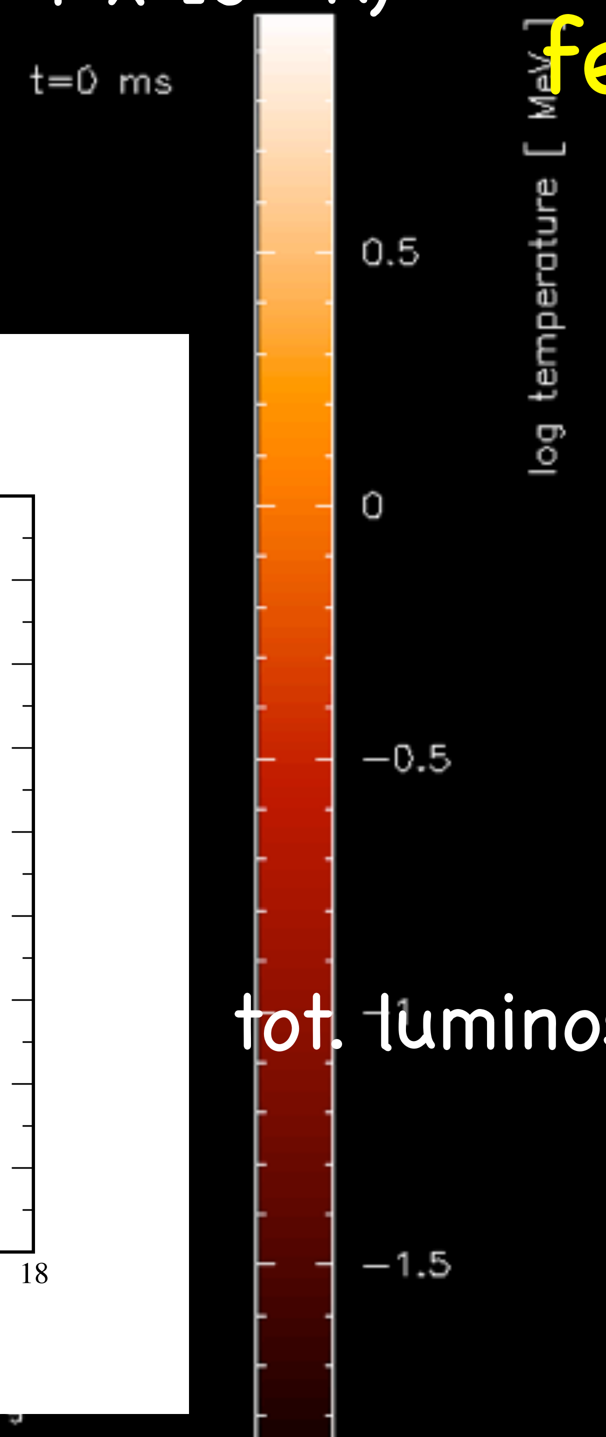
few milliseconds!

(visualized: temperature at given optical depth using)

A. Double neutron star mergers

- masses close to 1.4 M_{sol}
- small asymmetry: m_1= 1.3 M_{sol}, m_2= 1.4 M_{sol}, q= 0.929
- stellar spins negligible (Bildsten et al. 1992, Kochanek 1992)
- peak temperatures: ~ 40 MeV (≈ 4 x 10^{11} K) (in vortices)
- neutrino emission:





few milliseconds!

(visualized: temperature at given optical depth using)

tot. luminosity: ≈ 10^{53} erg/s

$E_{\nu e}$≈ 8 MeV

$E_{\bar{\nu} e}$≈ 14 MeV

$E_{\nu x}$≈ 26 MeV

- compact binary mergers are thought to produce (short) Gamma-ray Bursts

- compact binary mergers are thought to produce (short) Gamma-ray Bursts
- observed radiation is produced in ultra-relativistic outflows ($\Gamma \approx 300$), i.e. $v \approx 0.99998\,c$ (large energy + ms-variability + opt. thin)

- compact binary mergers are thought to produce (short) Gamma-ray Bursts
- observed radiation is produced in ultra-relativistic outflows ($\Gamma \approx 300$), i.e. $v \approx 0.99998\ c$ (large energy + ms-variability + opt. thin)

very non-trivial problem "Baryonic Pollution"

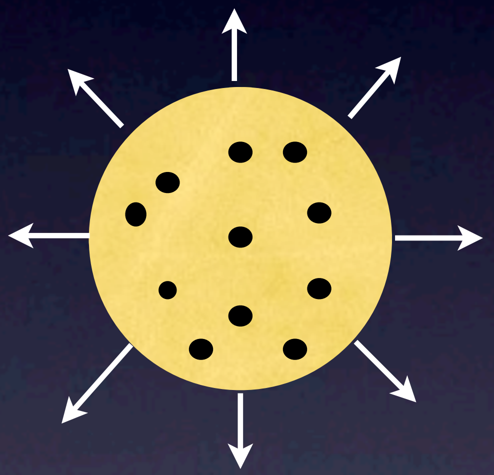
- compact binary mergers are thought to produce (short) Gamma-ray Bursts

- observed radiation is produced in ultra-relativistic outflows ($\Gamma \approx 300$), i.e. $v \approx 0.99998\ c$ (large energy + ms-variability + opt. thin)

very non-trivial problem "Baryonic Pollution"

- sphere with (thermal) energy E and baryonic mass expands to an asymptotic Lorentz factor

$$\Gamma_{\rm asym} \approx \frac{E}{mc^2}$$



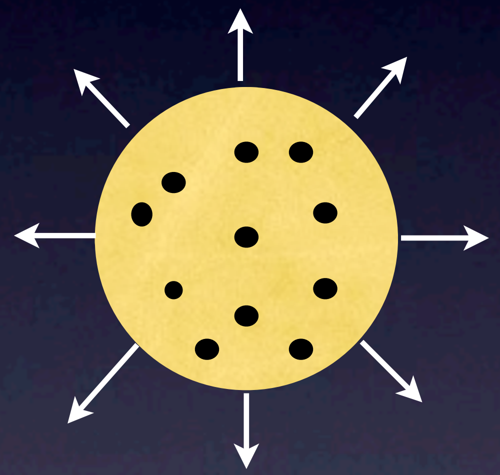
- compact binary mergers are thought to produce (short) Gamma-ray Bursts

- observed radiation is produced in ultra-relativistic outflows ($\Gamma \approx 300$), i.e. $v \approx 0.99998\, c$ (large energy + ms-variability + opt. thin)

very non-trivial problem <u>"Baryonic Pollution"</u>

- sphere with (thermal) energy E and baryonic mass expands to an asymptotic Lorentz factor

$$\Gamma_{\rm asym} \approx \frac{E}{mc^2}$$



- to reach a Lorentz factor $\Gamma_{\rm asym}$ it cannot be "loaded" with more mass than

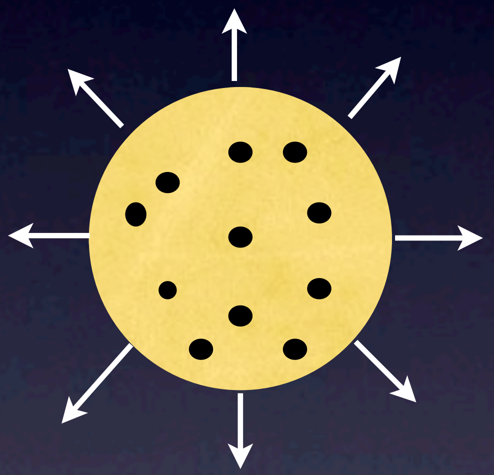
$$m_{\rm crit} = 2 \times 10^{-6} {\rm M}_\odot \, \frac{E/10^{51}{\rm erg}}{\Gamma_{\rm asym}/300}$$

- compact binary mergers are thought to produce (short) Gamma-ray Bursts

- observed radiation is produced in ultra-relativistic outflows ($\Gamma \approx 300$), i.e. $v \approx 0.99998$ c (large energy + ms-variability + opt. thin)

very non-trivial problem "Baryonic Pollution"

- sphere with (thermal) energy E and baryonic mass expands to an asymptotic Lorentz factor



$$\Gamma_{\rm asym} \approx \frac{E}{mc^2}$$

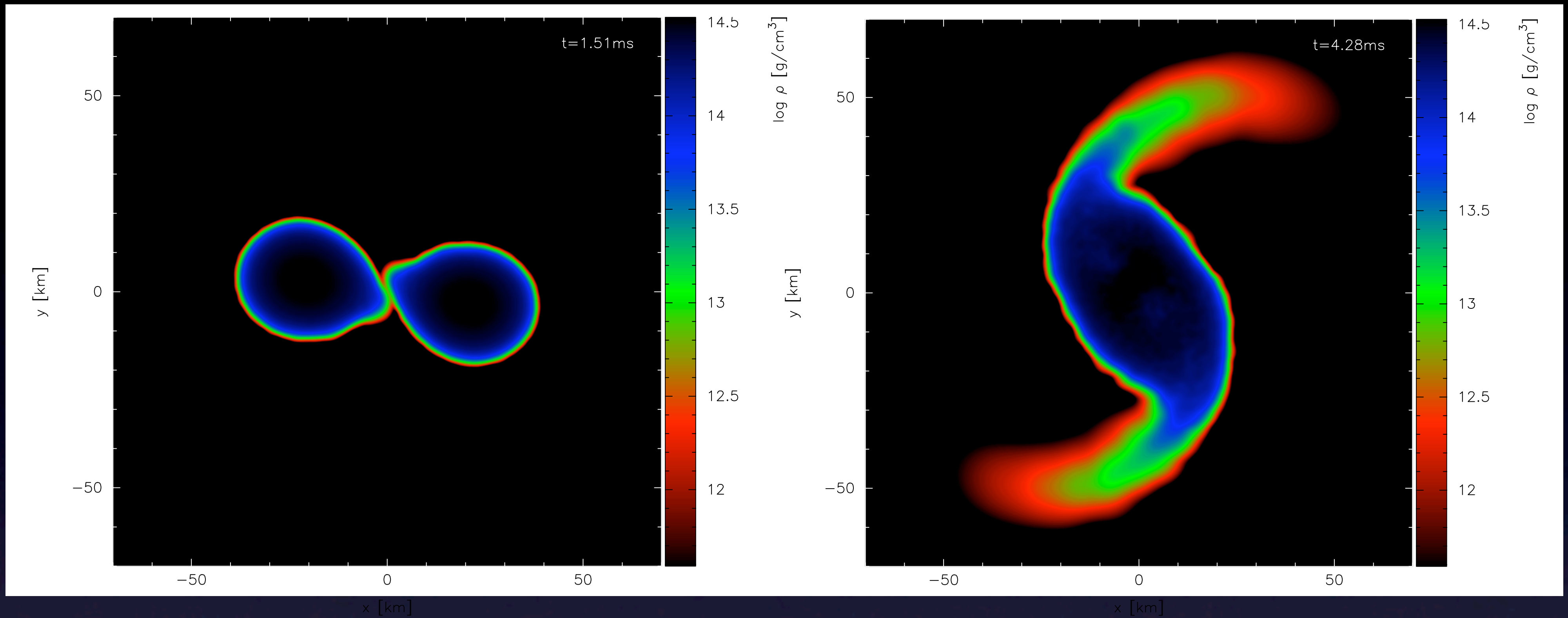
- to reach a Lorentz factor $\Gamma_{\rm asym}$ it cannot be "loaded" with more mass than

$$m_{\rm crit} = 2 \times 10^{-6} {\rm M}_\odot \frac{E/10^{51}{\rm erg}}{\Gamma_{\rm asym}/300}$$

→ How does Nature separate mass from energy?

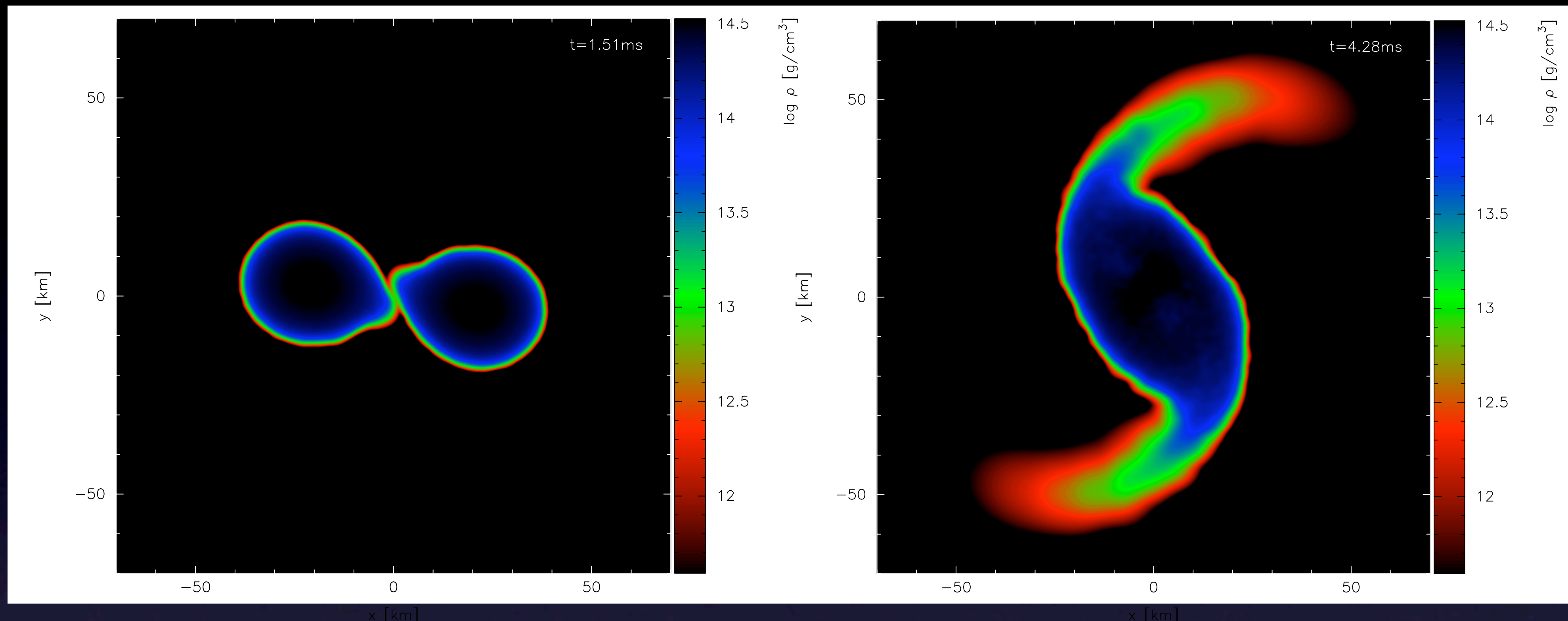
"Baryonic pollution"

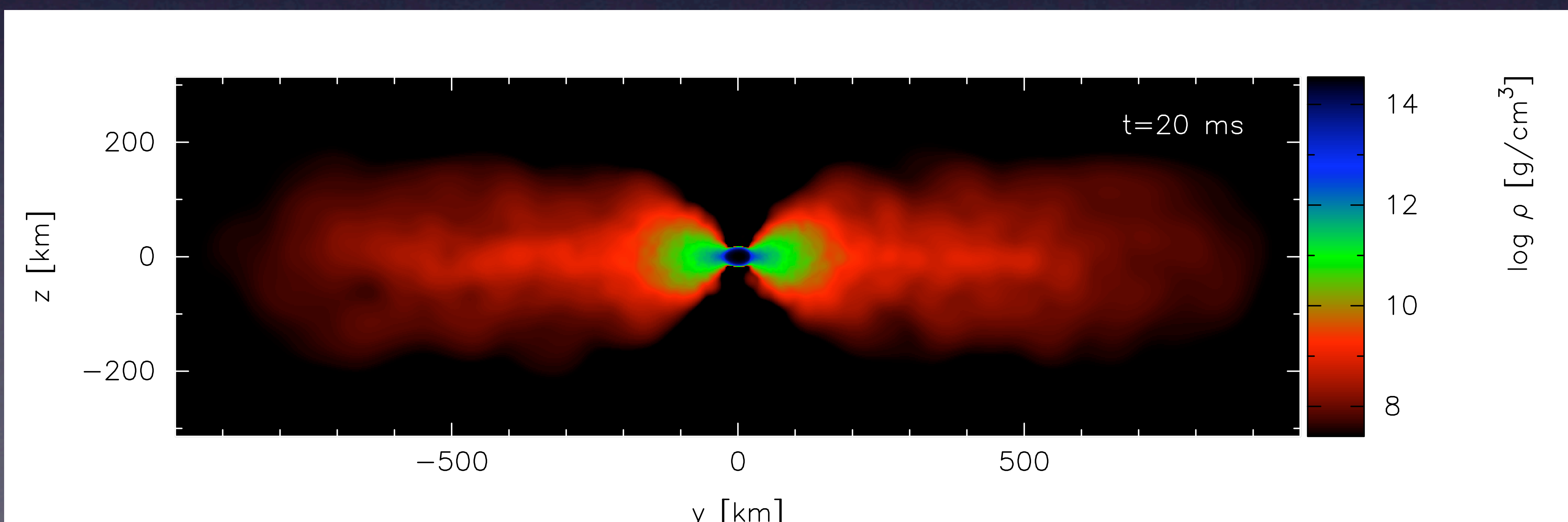
(S.R. 2006)



“Baryonic pollution”

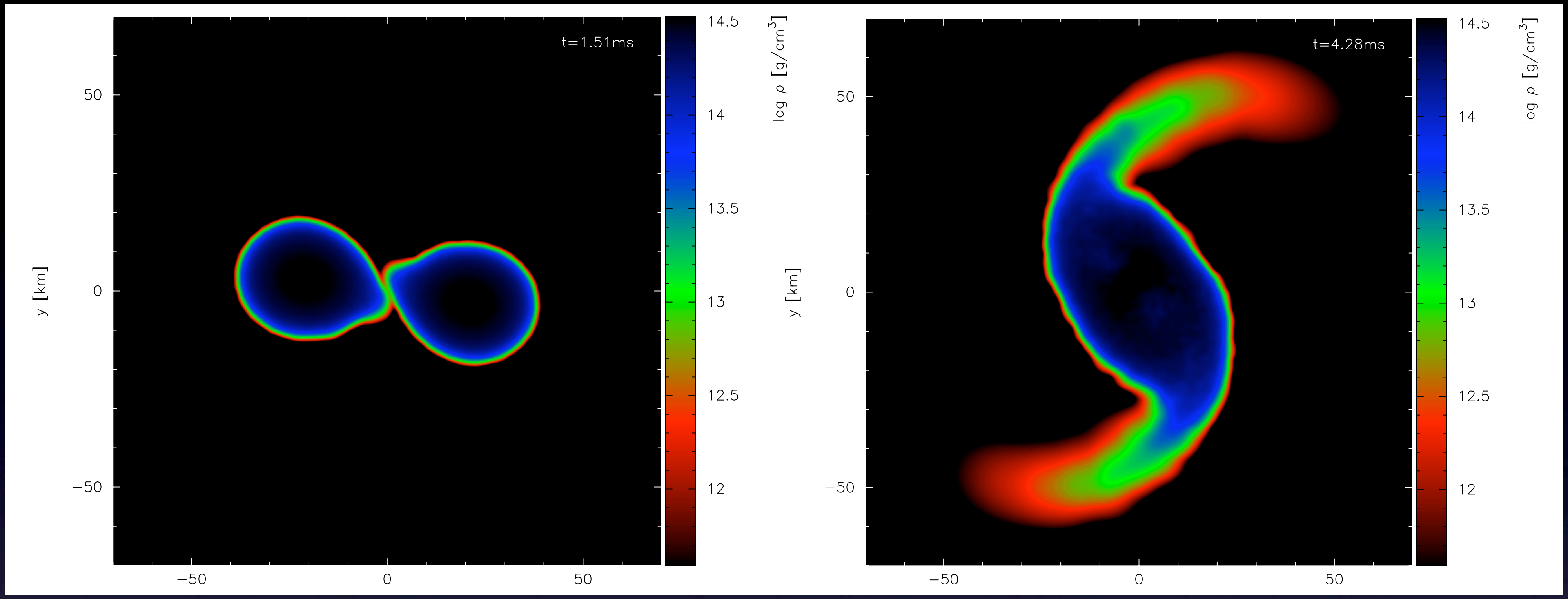
(S.R. 2006)



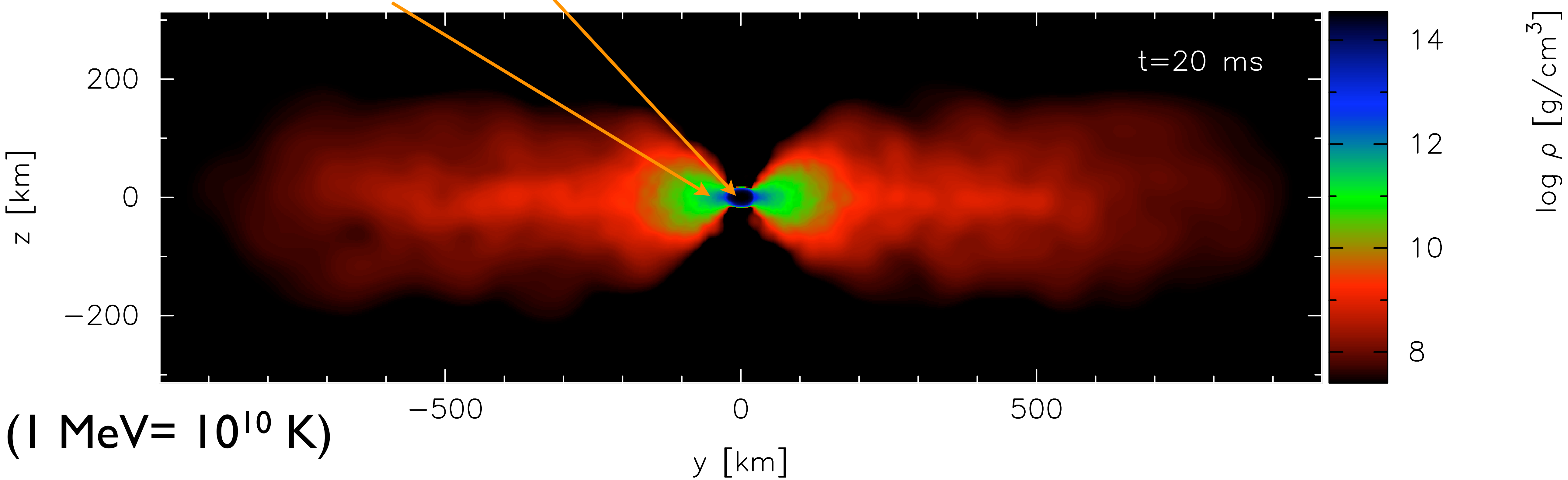


"Baryonic pollution"

(S.R. 2006)



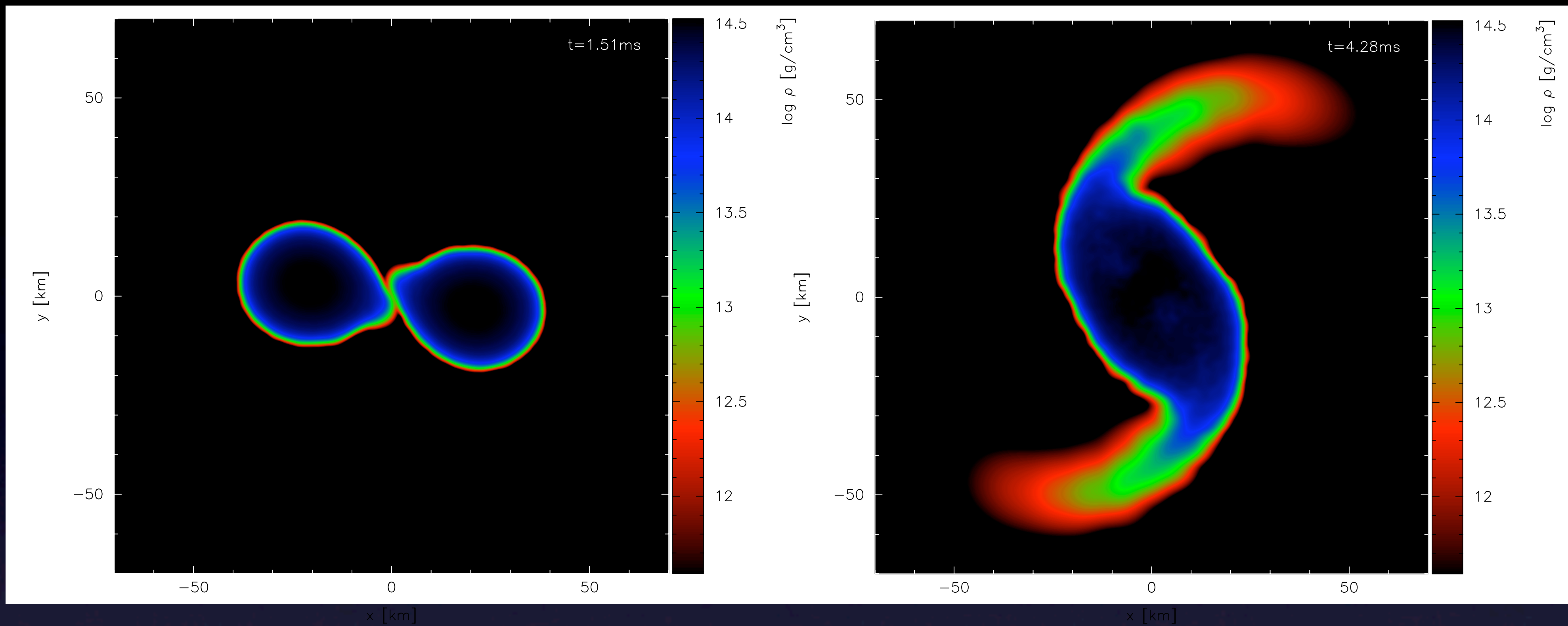
temperatures: ~ 4 MeV ~20 MeV



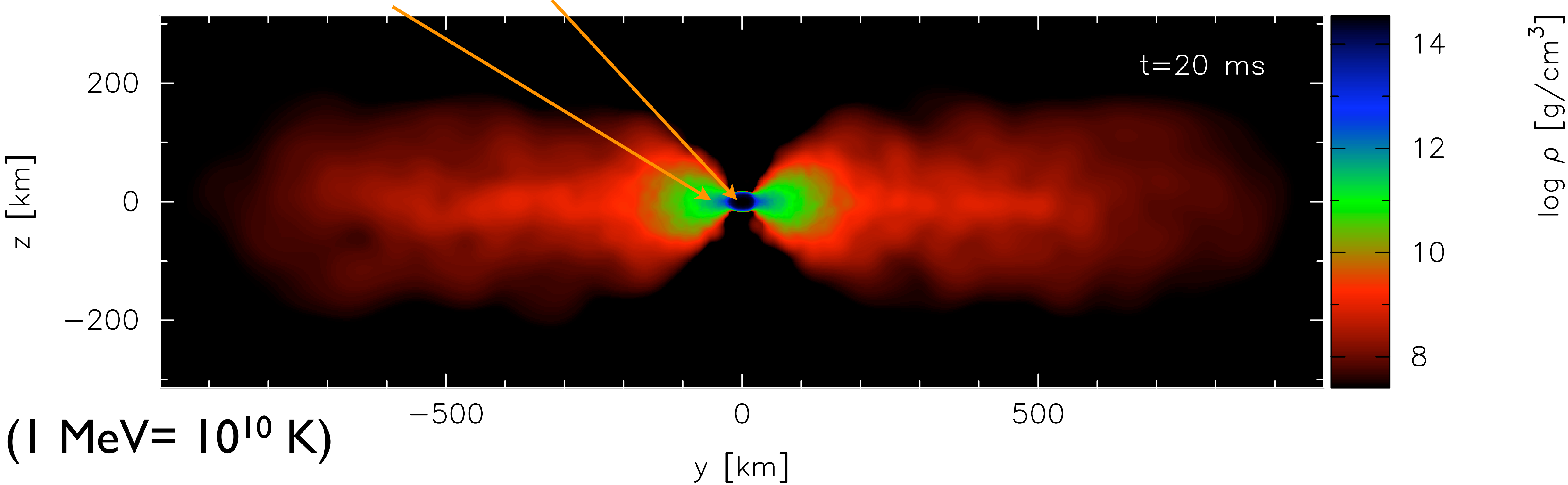
(1 MeV= 10^{10} K)

"Baryonic pollution"

(S.R. 2006)



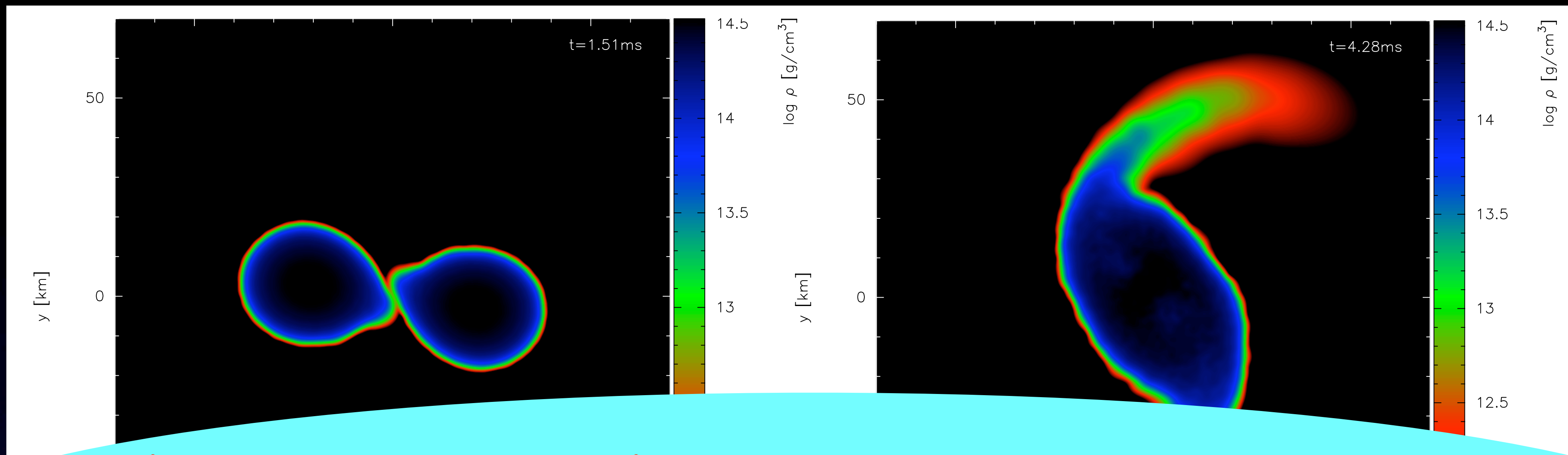
temperatures: ~ 4 MeV ~20 MeV ν-Luminosities: $L_\nu \sim 10^{53}$ erg/s



(1 MeV= 10^{10} K)

“Baryonic pollution”

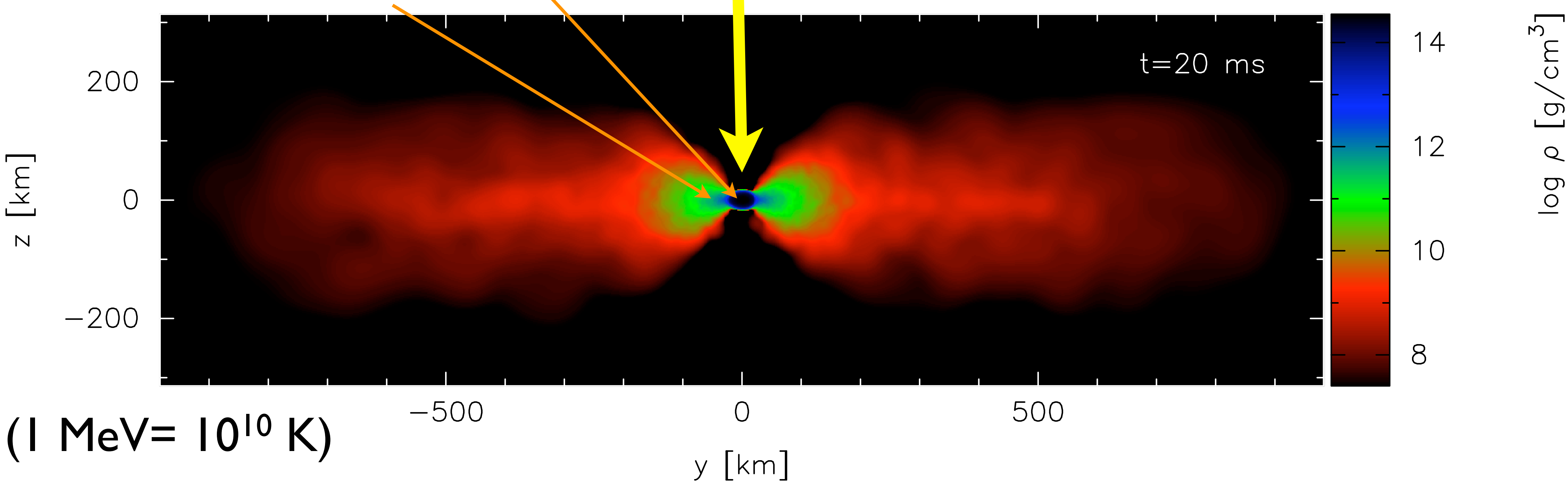
(S.R. 2006)



“baryon-free”: can ultra-relativistic outflow be launched here???

temperatures: ~ 4 MeV ~20 MeV

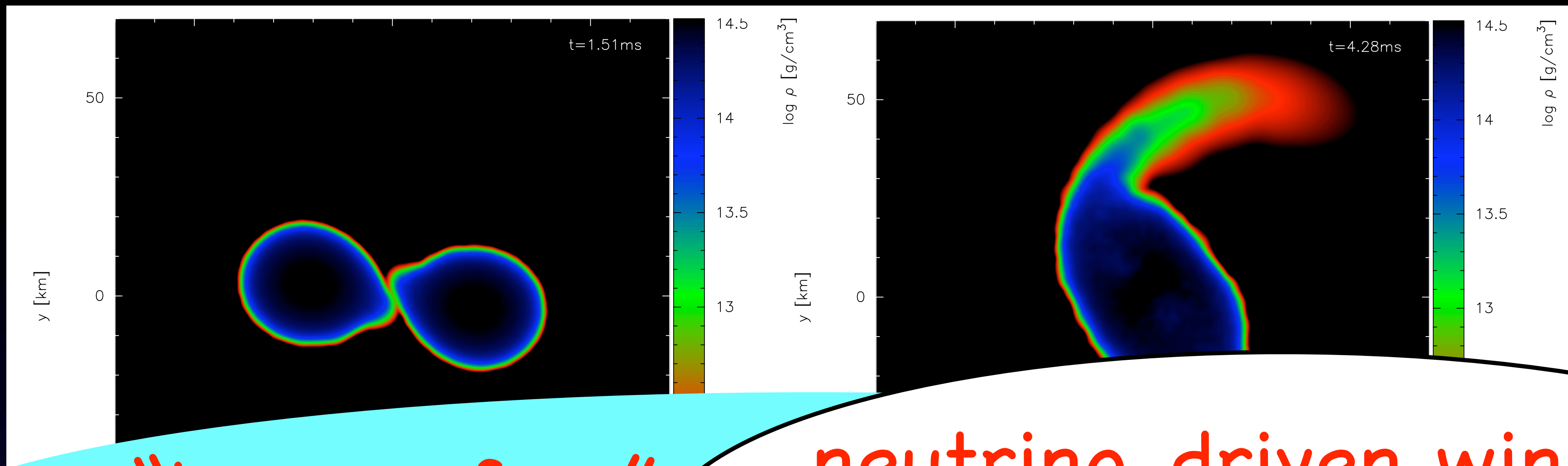
ν-Luminosities: $L_\nu \sim 10^{53}$ erg/s



(1 MeV= 10^{10} K)

“Baryonic pollution”

(S.R. 2006)



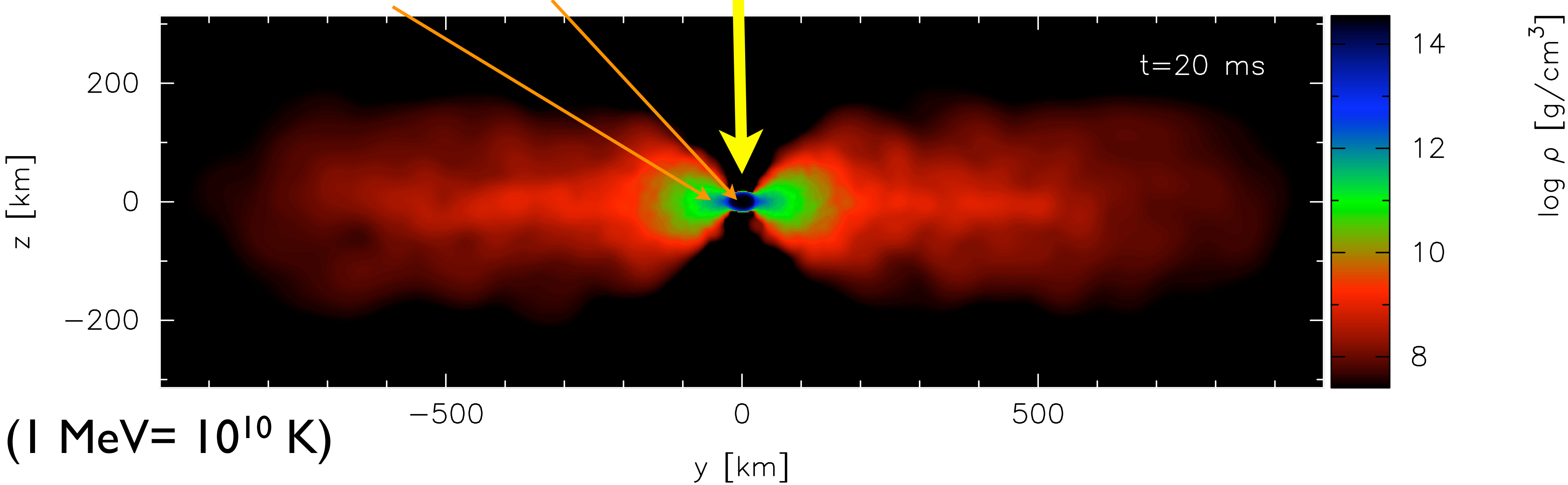
“baryon-free”

outflow be

neutrino-driven winds are likely to be important !!

temperatures: ~ 4 MeV ~20 MeV

ν-Luminosities: $L_\nu \sim 10^{53}$ erg/s



(1 MeV= 10^{10} K)

Neutrino-driven winds (Dessart et al. 2009)

- effects of neutrino-heating not accounted for in current SPH-code(s)
- approach:

  i) 3D merger simulation (MAGMA-code; SR&Price (2007))

  ii) mapping on 2D grid

  iii) use 2D neutrino-radiation-hydrodynamics calculation with VULCAN code (Livne et al. '04,Burrows et al. '07)

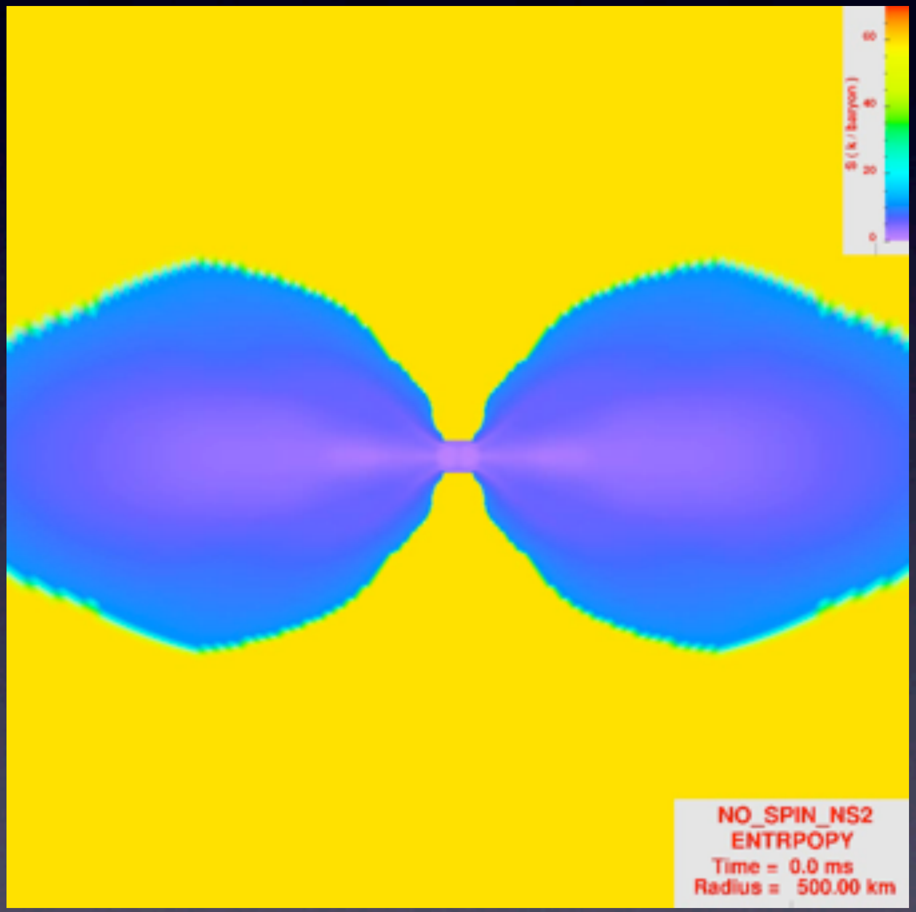
Neutrino-driven winds (Dessart et al. 2009)

- effects of neutrino-heating not accounted for in current SPH-code(s)
- approach:

  i) 3D merger simulation (MAGMA-code; SR&Price (2007))

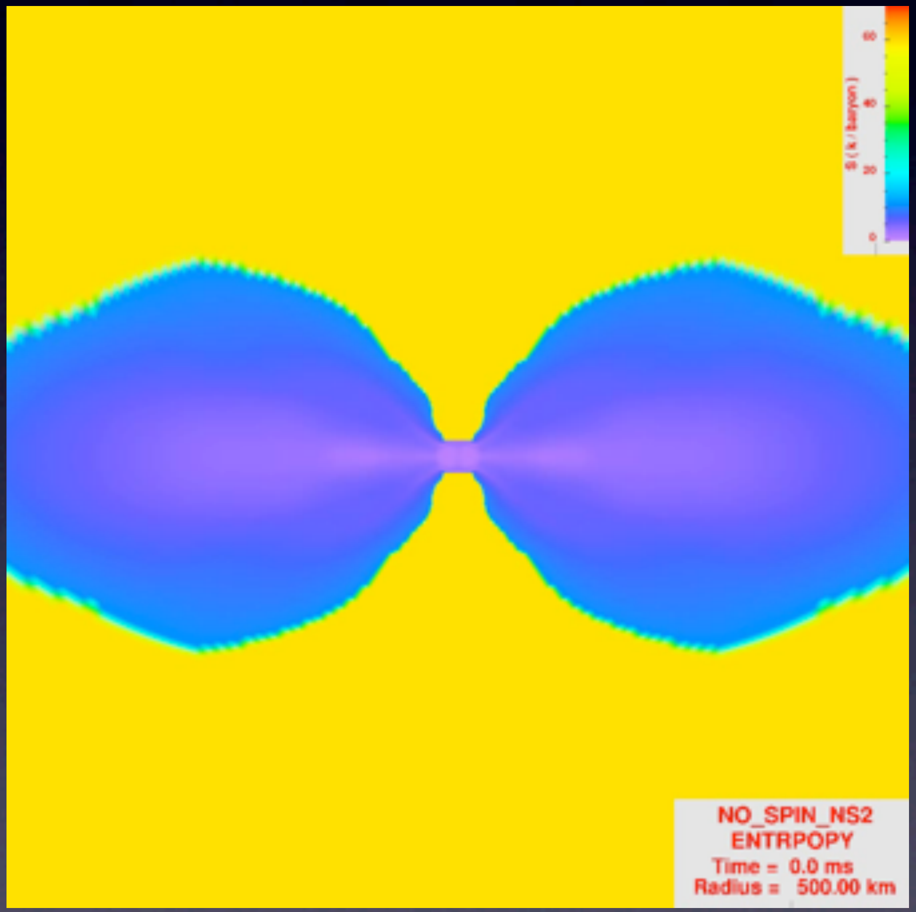
  ii) mapping on 2D grid

  iii) use 2D neutrino-radiation-hydrodynamics calculation with VULCAN code (Livne et al. ‘04,Burrows et al. ‘07)



Neutrino-driven winds (Dessart et al. 2009)

- effects of neutrino-heating not accounted for in current SPH-code(s)
- approach:
  - i) 3D merger simulation (MAGMA-code; SR&Price (2007))
  - ii) mapping on 2D grid
  - iii) use 2D neutrino-radiation-hydrodynamics calculation with VULCAN code (Livne et al. '04,Burrows et al. '07)



mass loss:

➡ driven by:

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

➡ rate: $$\frac{dM}{dt} \sim 10^{-3} \frac{M_\odot}{s}$$

Neutrino-driven winds (Dessart et al. 2009)

- effects of neutrino-heating not accounted for in current SPH-code(s)
- approach:

  i) 3D merger simulation (MAGMA-code; SR&Price (2007))

  ii) mapping on 2D grid

  iii) use 2D neutrino-radiation-hydrodynamics calculation with VULCAN code (Livne et al. '04,Burrows et al. '07)

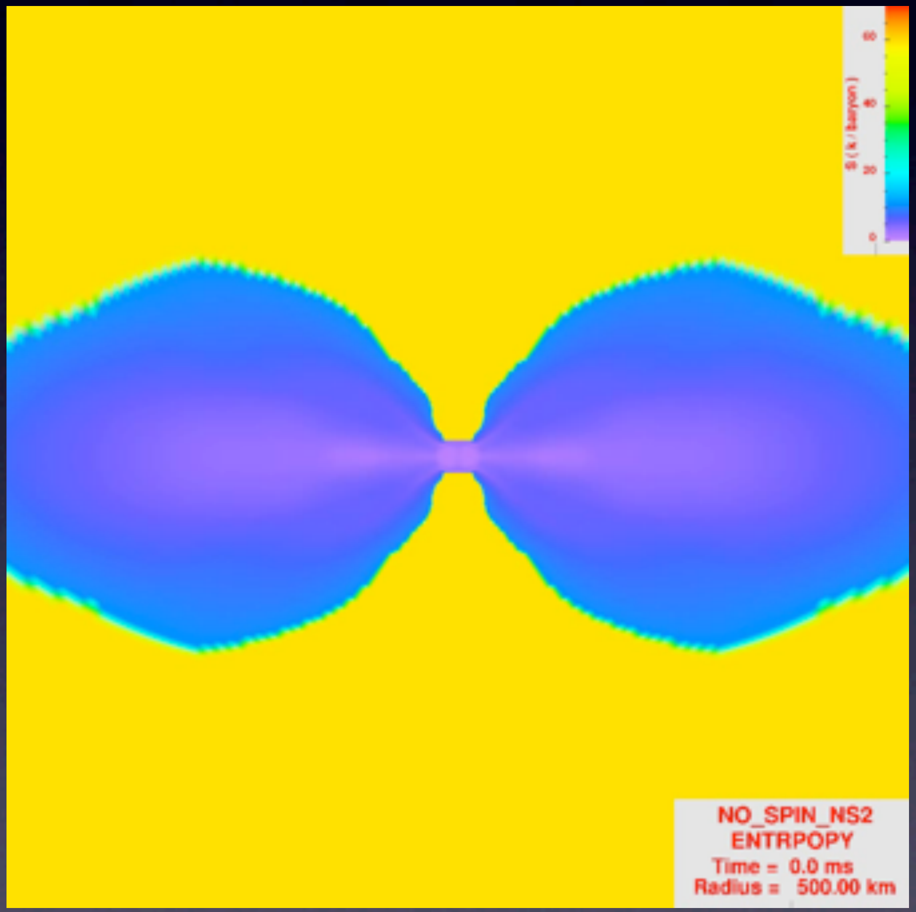
mass loss:

➡ driven by:

$$\begin{aligned} \nu_e + n &\rightarrow e + p \\ \bar{\nu}_e + p &\rightarrow e^+ + n \end{aligned}$$

➡ rate:

$$\frac{dM}{dt} \sim 10^{-3} \frac{M_\odot}{s}$$



strong, non-relativistic (≈ 0.1c) baryonic outflow,
no relativistic outflow possible as long as the central neutron star is alive!

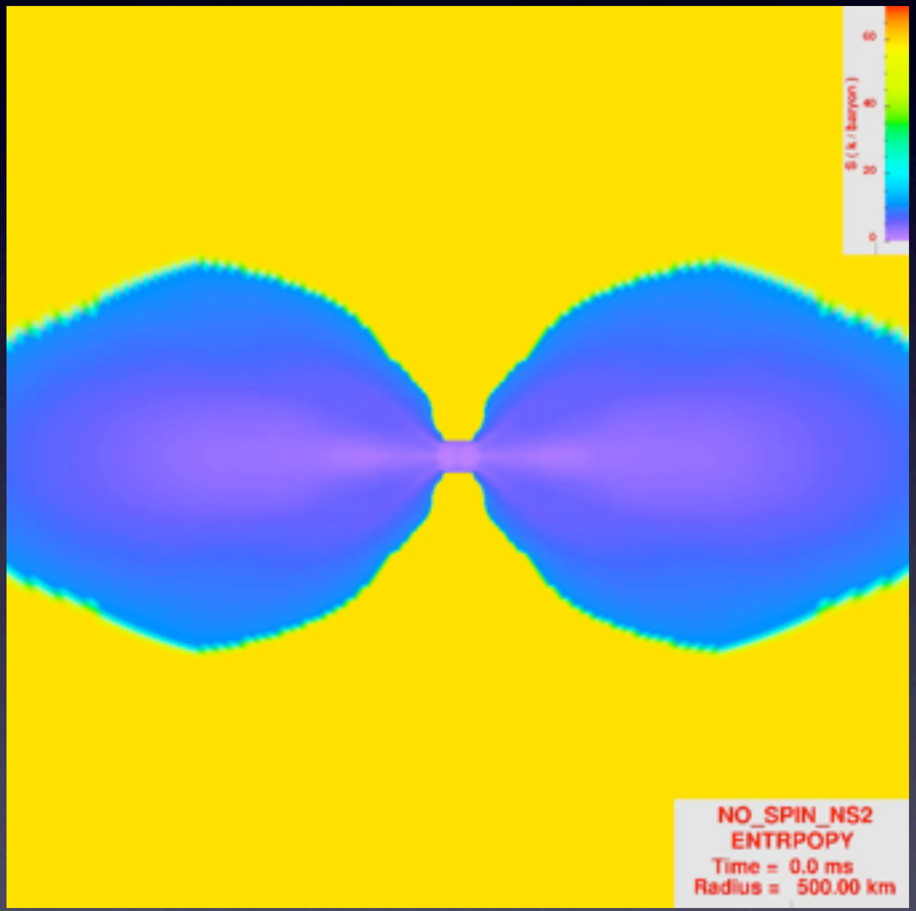
Neutrino-driven winds (Dessart et al. 2009)

- effects of neutrino-heating not accounted for in current SPH-code(s)
- approach:

i) 3D merger simulation (MAGMA-code; SR&Price (2007))

ii) mapping on 2D grid

iii) use 2D neutrino-radiation-hydrodynamics calculation with VULCAN code (Livne et al. '04, Burrows et al. '07)



mass loss:

➡ driven by:
$$\nu_e + n \rightarrow e + p$$
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

➡ rate:
$$\frac{dM}{dt} \sim 10^{-3} \frac{M_\odot}{s}$$

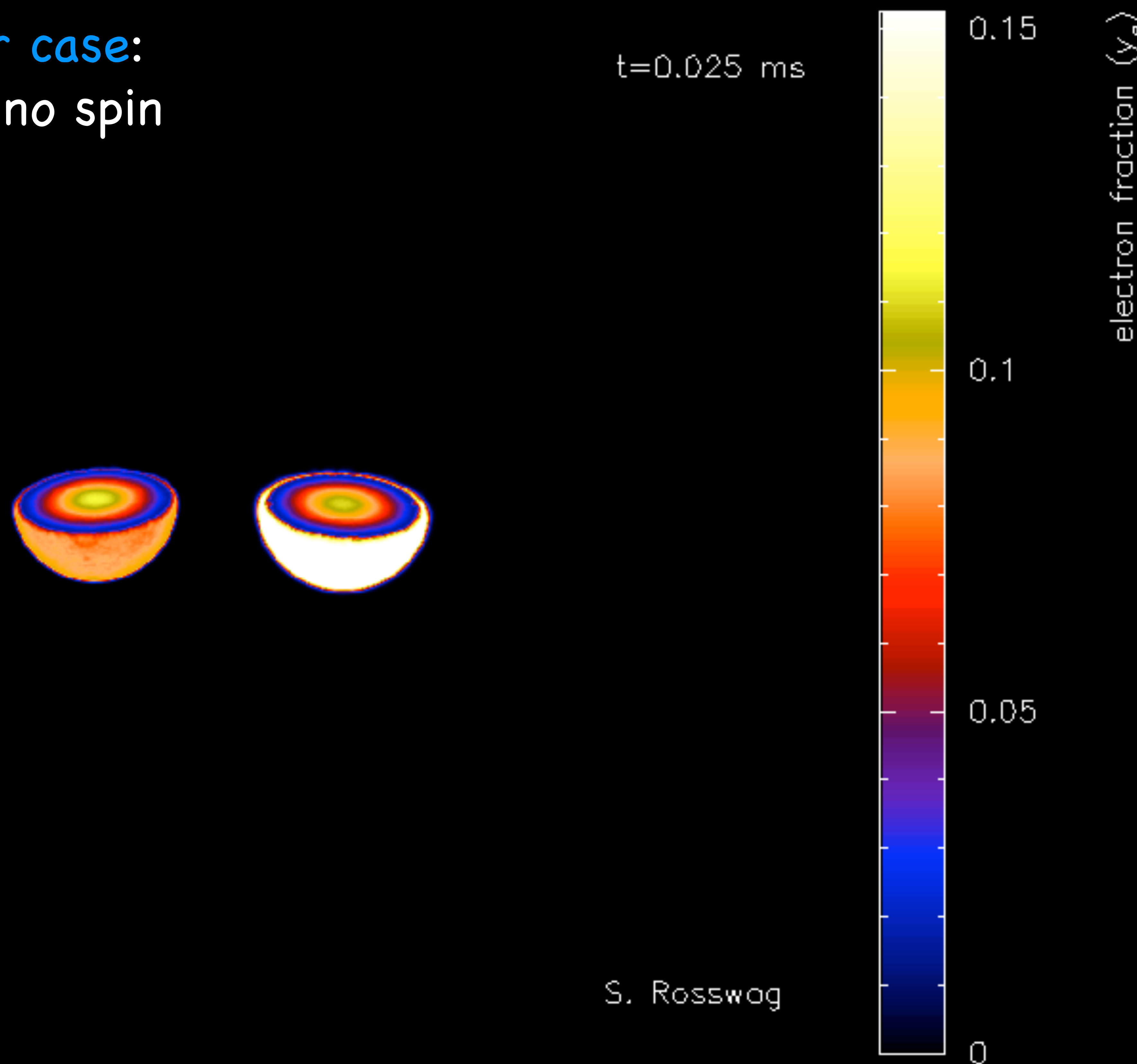
strong, non-relativistic (≈ 0.1c) baryonic outflow, no relativistic outflow possible as long as the central neutron star is alive!

relativistic outflow only after collapse to bh?

Dynamical mass ejection

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

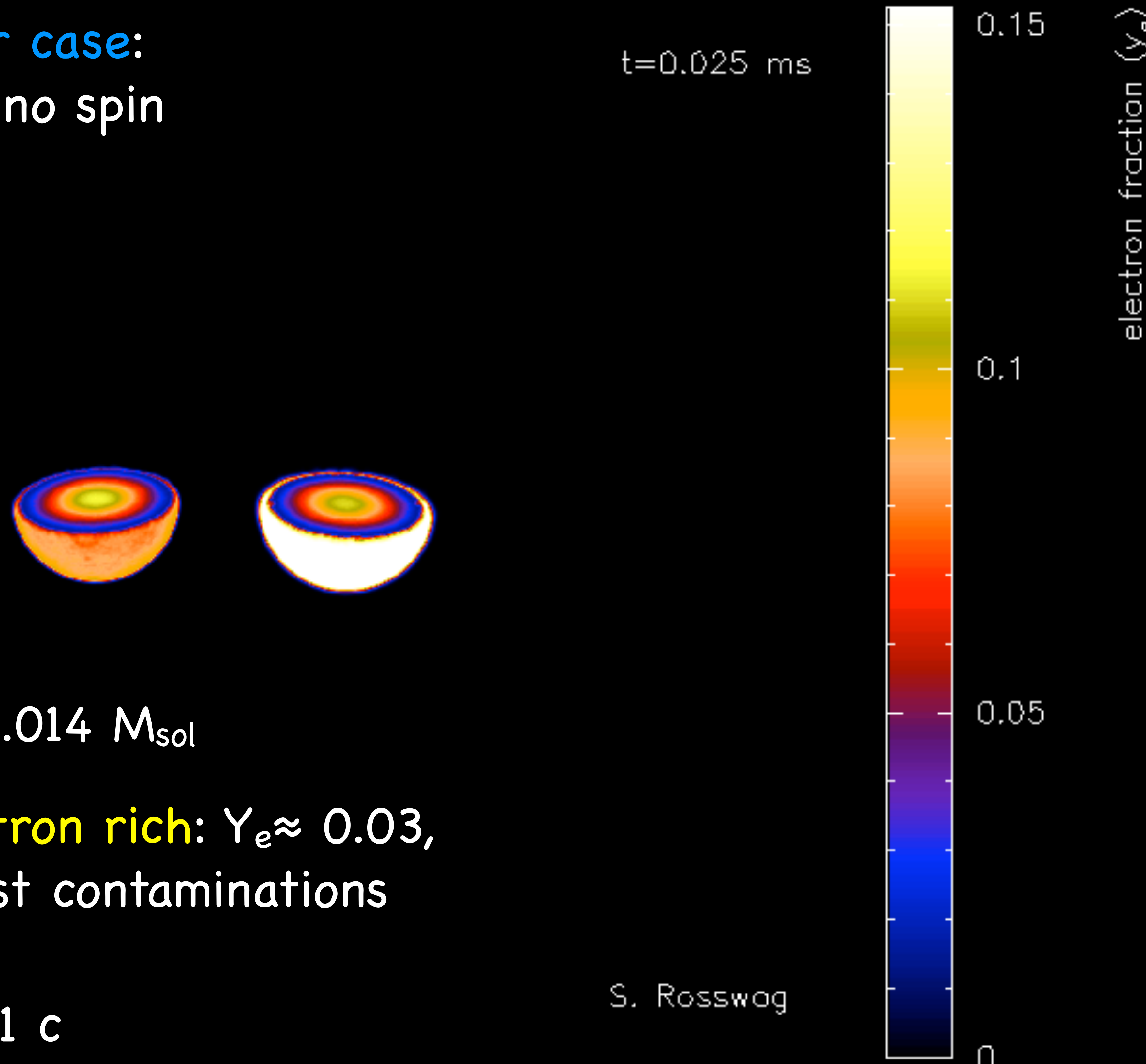
visualized:
Ye value at given optical depth



Dynamical mass ejection

visualized:
Ye value at given optical depth

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



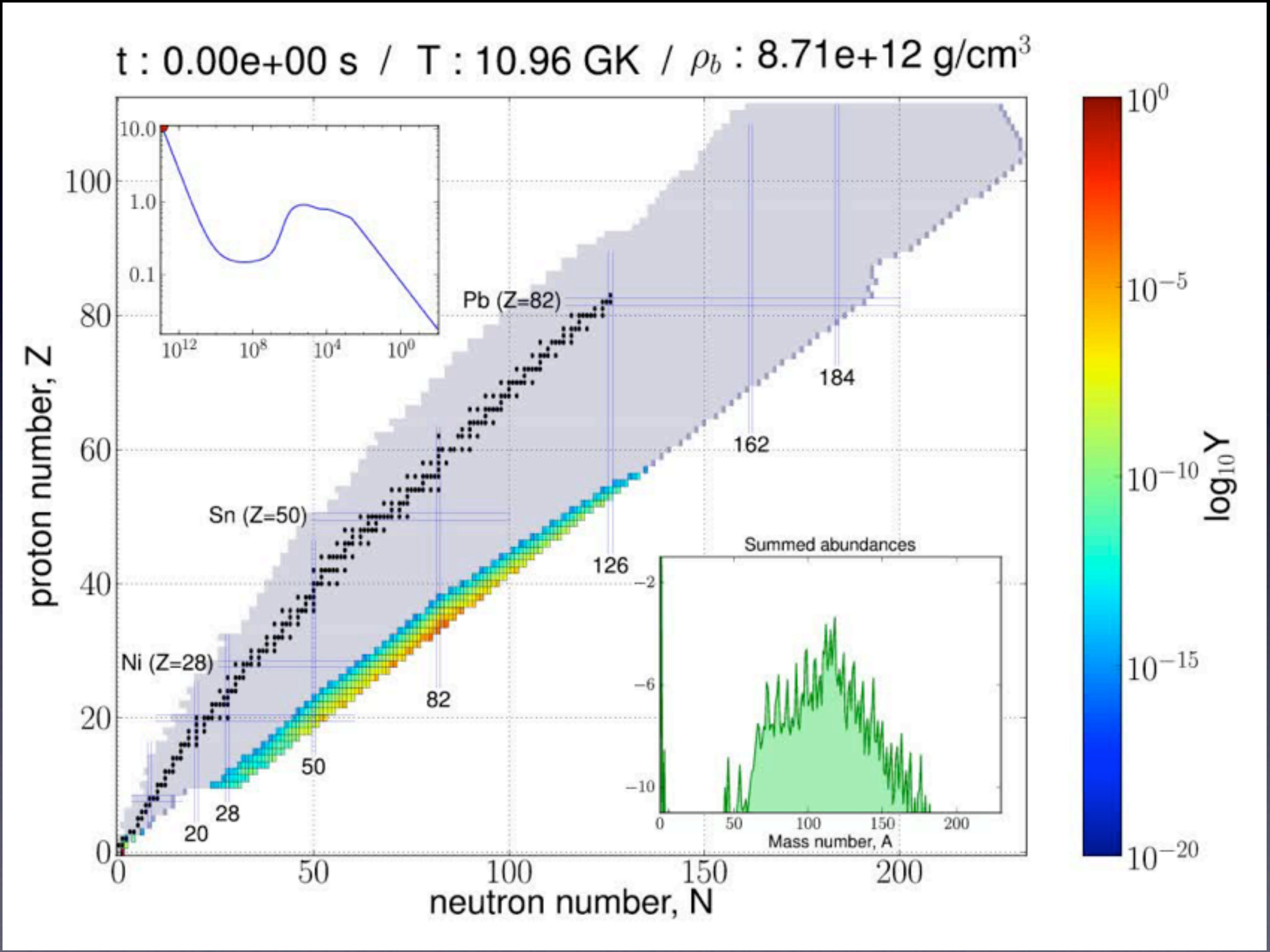
total amount: 0.014 M_{sol}

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

velocity $v \approx 0.1\ c$

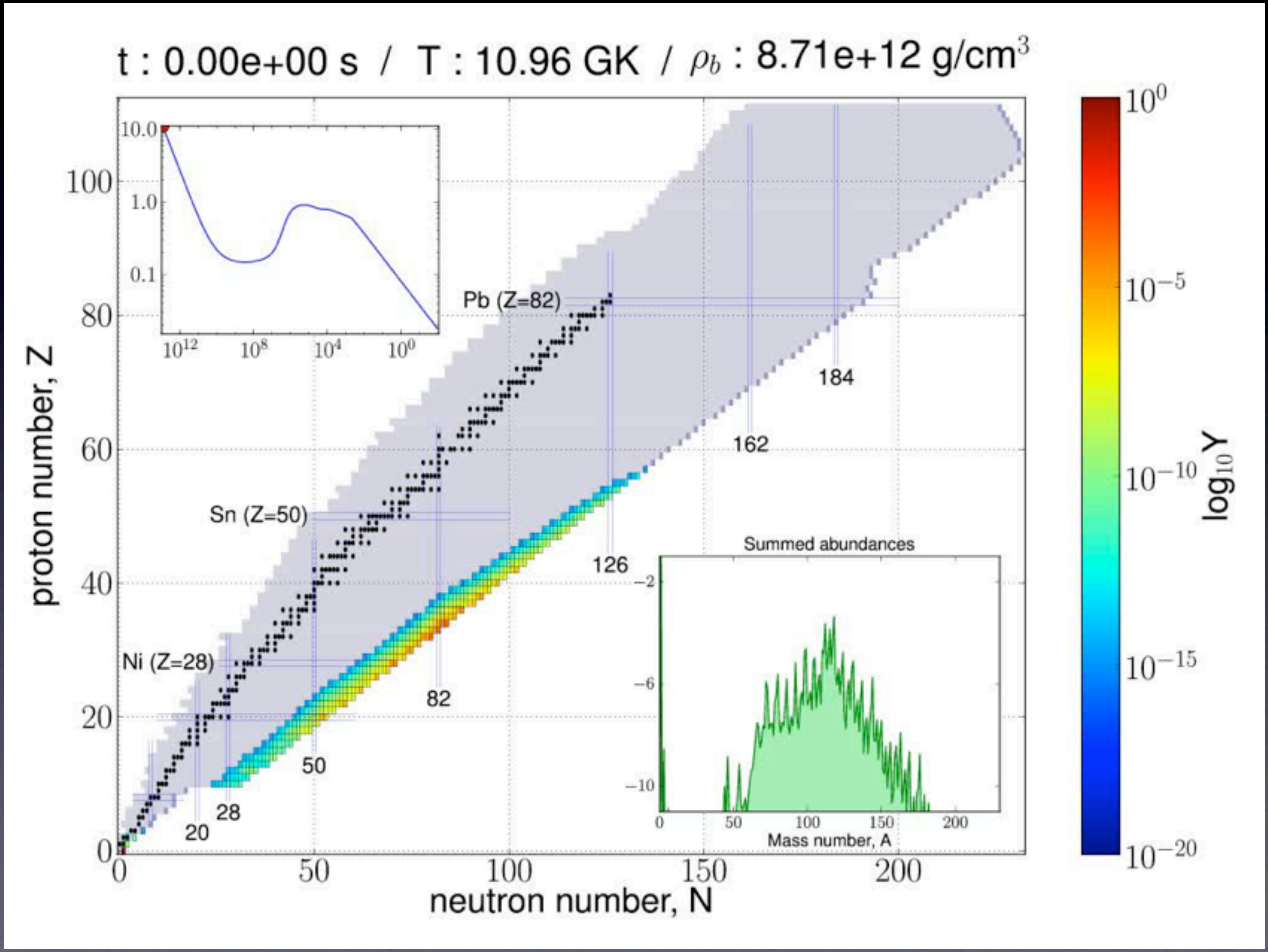
"r-process in action" (Korobkin, Rosswog, Arcones, Winteler 2012) dynamic ejecta

"r-process in action" (Korobkin, Rosswog, Arcones, Winteler 2012)

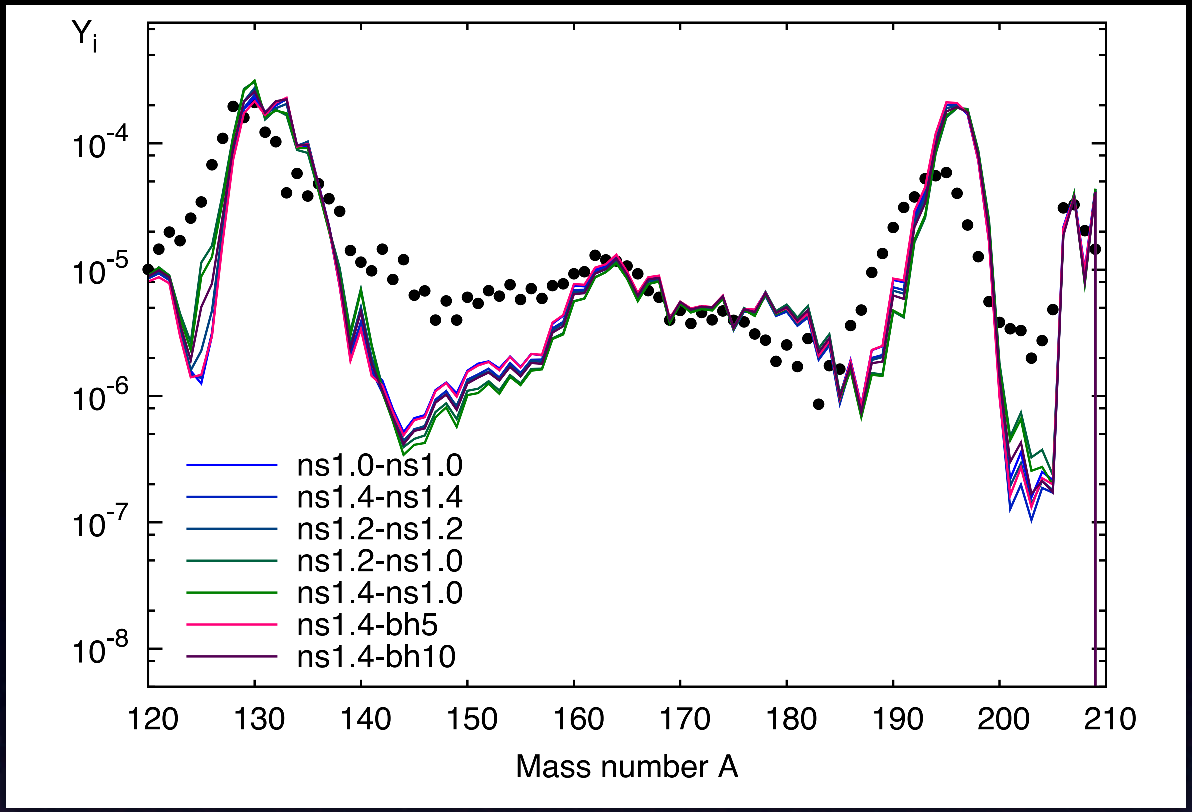


dynamic ejecta

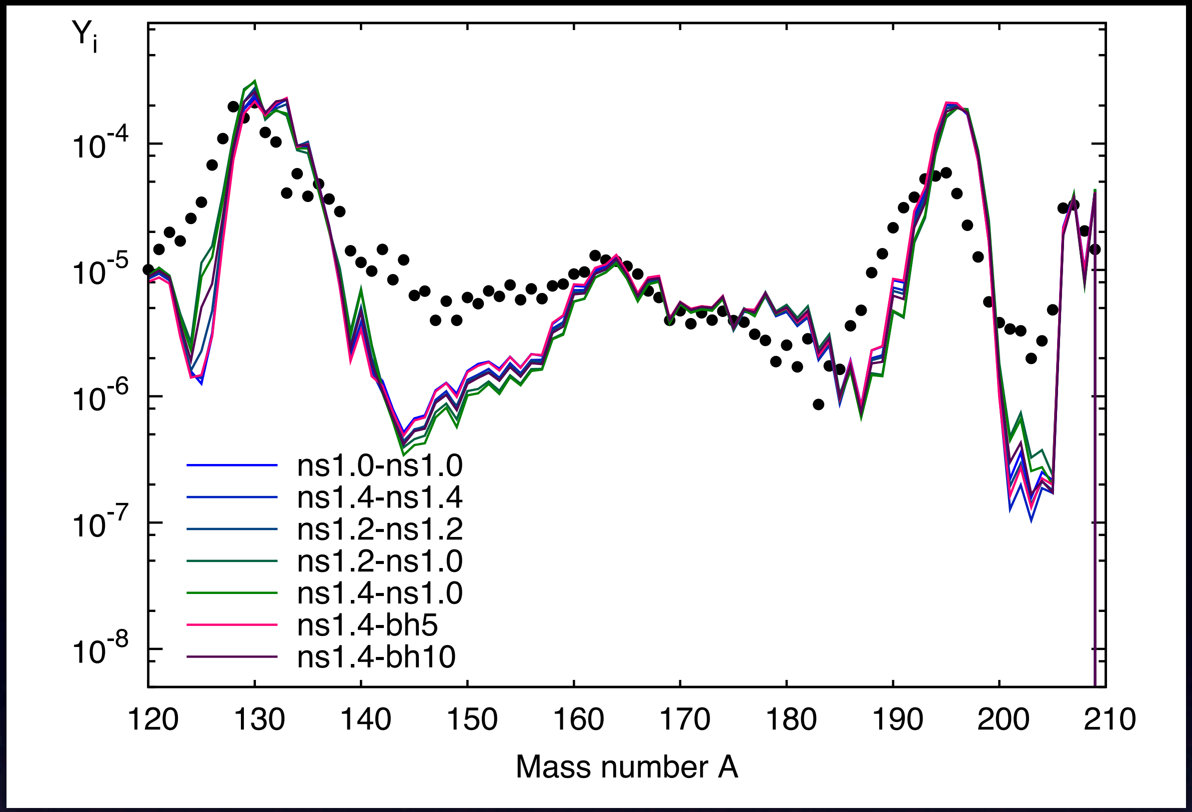
"r-process in action" (Korobkin, Rosswog, Arcones, Winteler 2012)



- final abundances

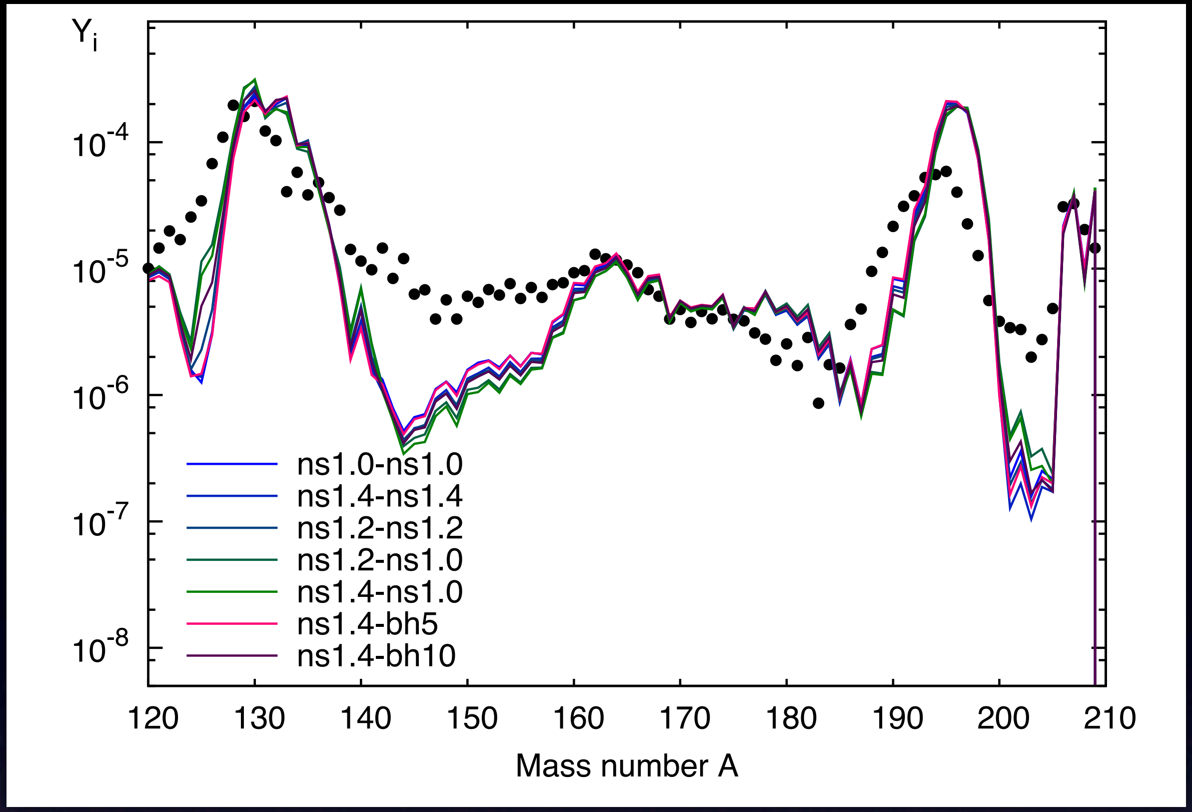


- final abundances



⇒ all 23 cases produce practically identical abundance patterns; independent of the properties of the merging compact binary system

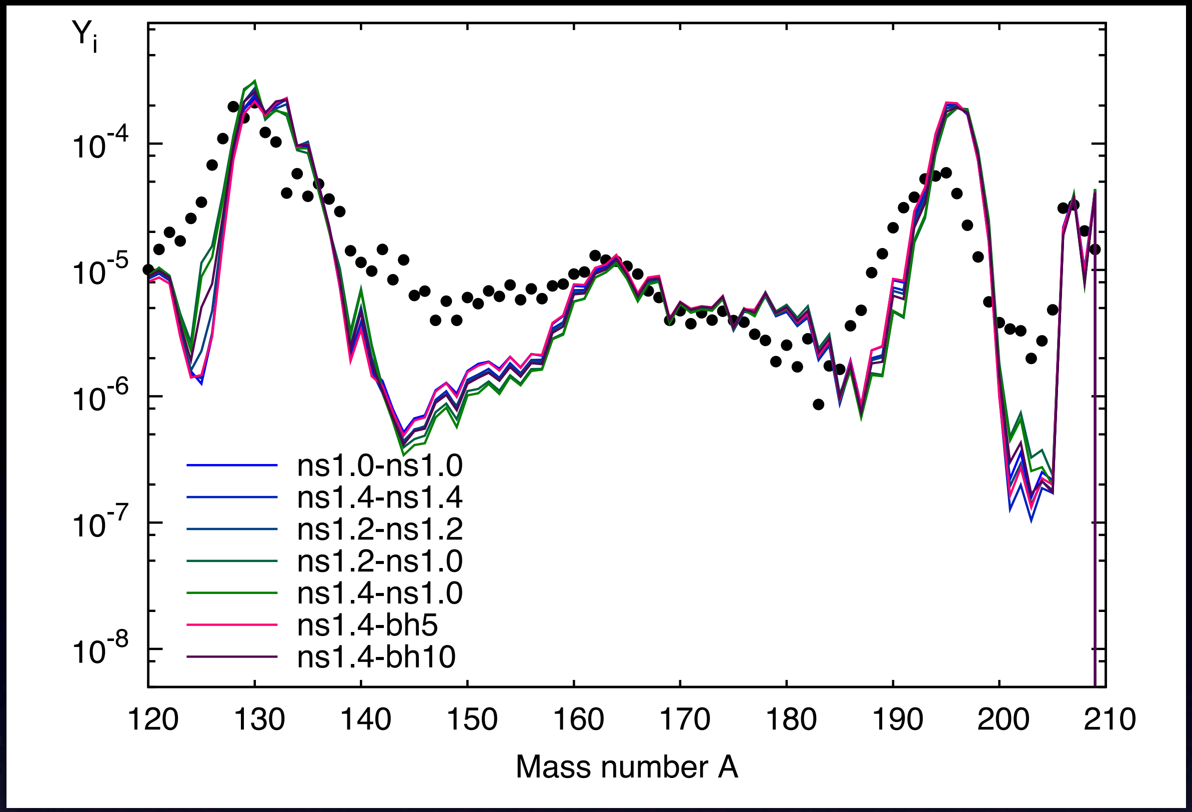
- final abundances



⇒ all 23 cases produce practically identical abundance patterns; independent of the properties of the merging compact binary system

⇒ but some sensitivity to nuclear physics near drip line (mass formula, fission distribution ...)

- final abundances

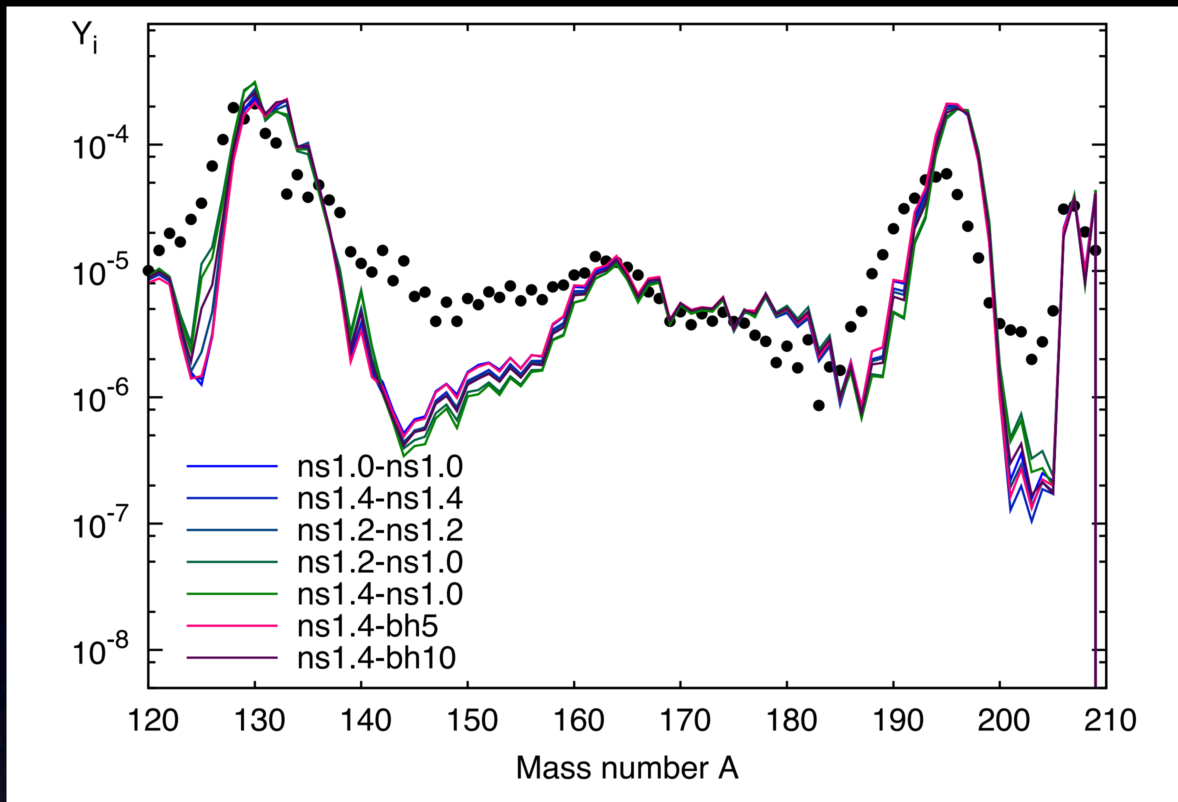


⇒ all 23 cases produce practically identical abundance patterns; independent of the properties of the merging compact binary system

⇒ but some sensitivity to nuclear physics near drip line (mass formula, fission distribution ...)

- enough ejected to be a major r-process source?

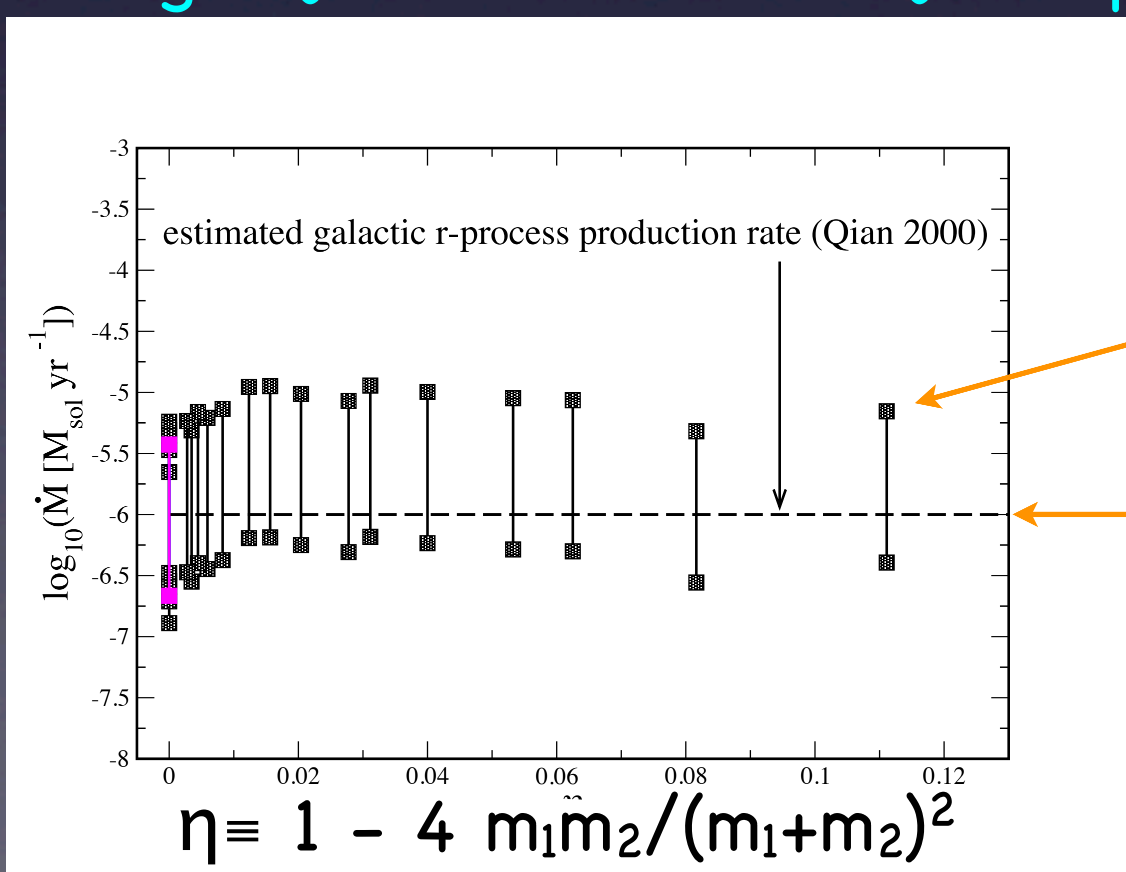
- final abundances



⇒ all 23 cases produce practically identical abundance patterns; independent of the properties of the merging compact binary system

⇒ but some sensitivity to nuclear physics near drip line (mass formula, fission distribution ...)

- enough ejected to be a major r-process source?



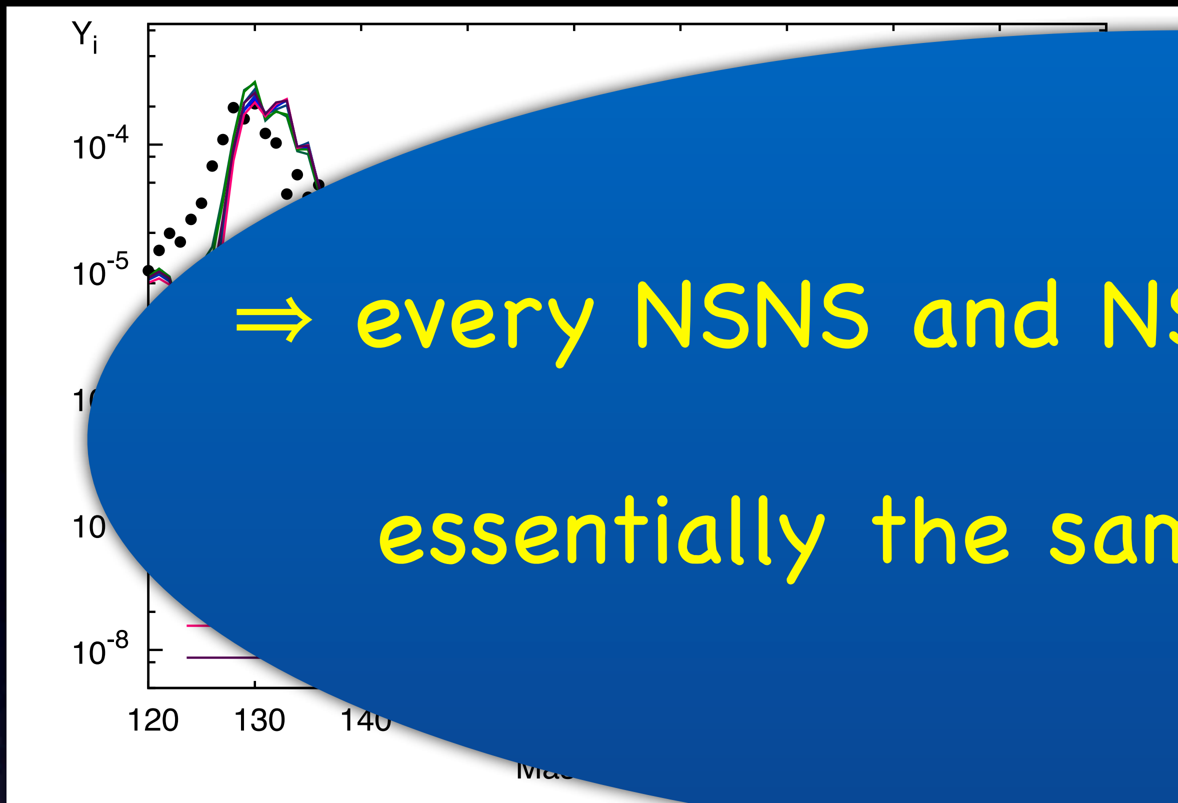
ejecta mass x rate interval

(95%, Kalogera et al. 2004)

galactic r-process production rate

(Qian 2000)

- final abundances



⇒ all 23 cases produce practically

abundance patterns;

properties

binary

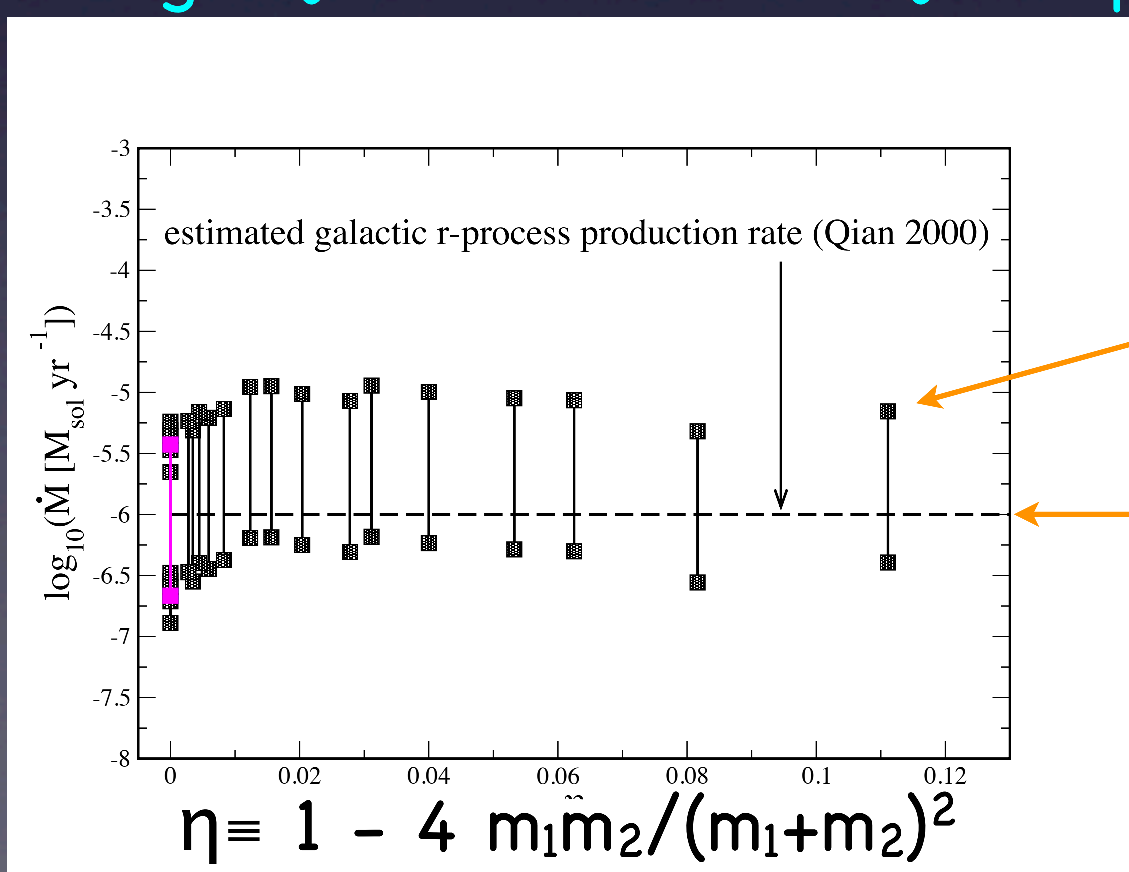
nuclear

line (mass

formula, fission distribution ...)

⇒ every NSNS and NSBH merger produces essentially the same abundance pattern!!

- enough ejected to be a major r-process source?



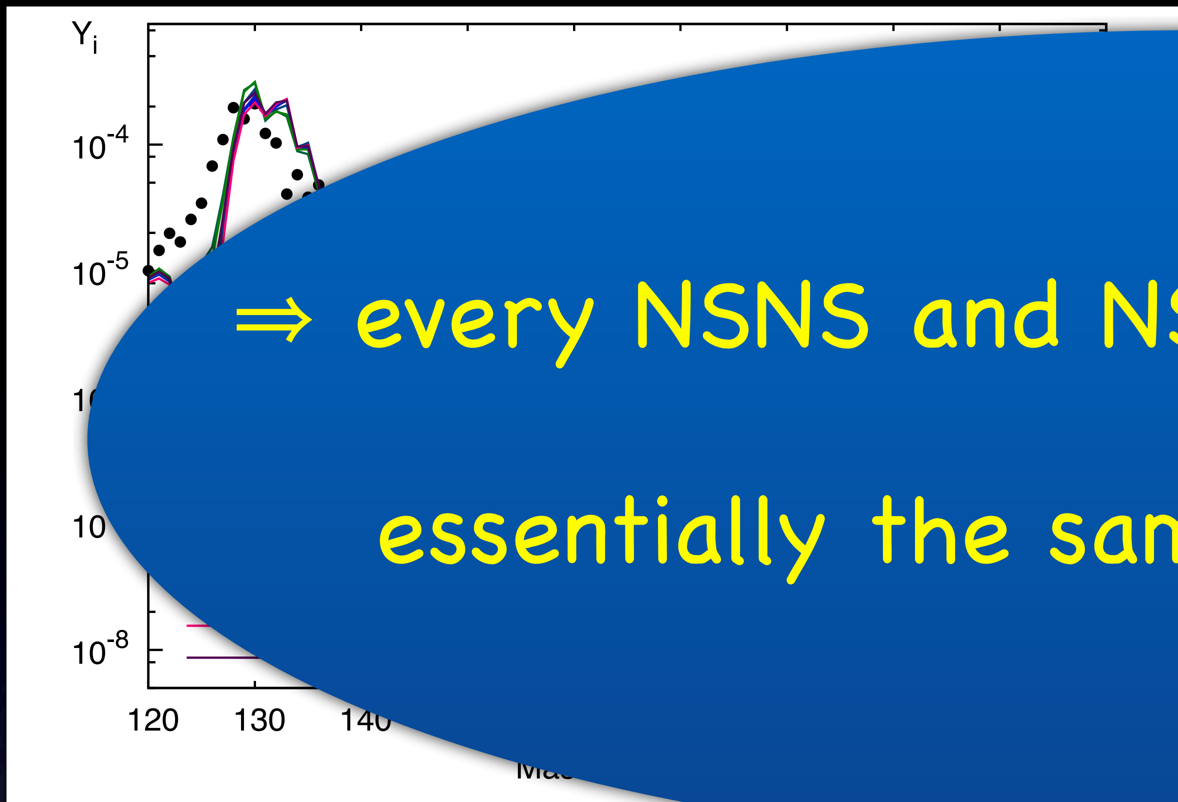
ejecta mass x rate interval

(95%, Kalogera et al. 2004)

galactic r-process production rate

(Qian 2000)

- final abundances



⇒ all 23 cases produce practically

... abundance patterns;

... properties

... binary

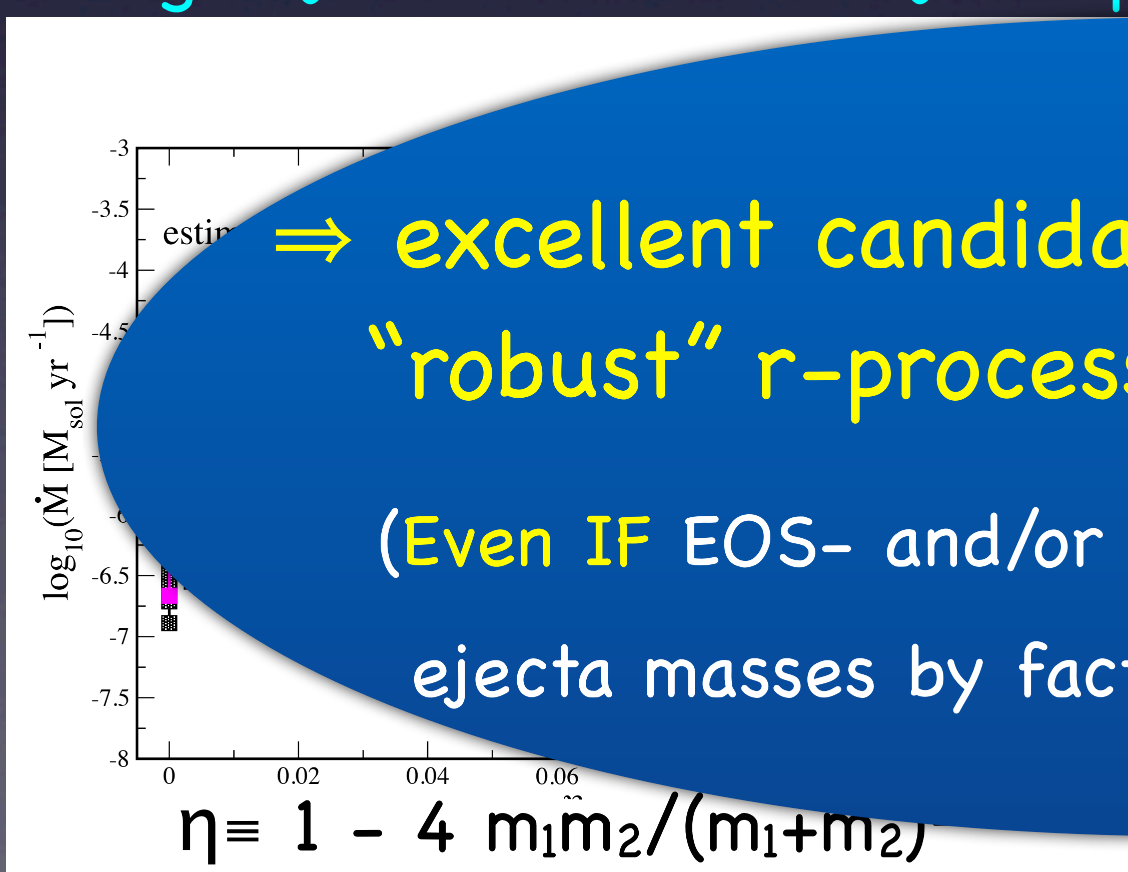
... nuclear

... line (mass

... formula, fission distribution ...)

⇒ every NSNS and NSBH merger produces essentially the same abundance pattern!!

- enough ejected to be a major r-process source?



... terval

... ction rate

⇒ excellent candidates for "robust" r-process component!!

(Even IF EOS- and/or GR-effects change the ejecta masses by factors of a few)

How good is the standard procedure "run network along hydrodynamic trajectory"?

How good is the standard procedure "run network along hydrodynamic trajectory"?

- standard procedure (Freiburghaus et al. 1999):
  - a) run hydrodynamics without network
  - b) take trajectory, density "as is", temperatures post-processed from entropy production
  - c) run network with this density-temperature history

How good is the standard procedure "run network along hydrodynamic trajectory"?

- standard procedure (Freiburghaus et al. 1999):
  a) run hydrodynamics without network
  b) take trajectory, density "as is", temperatures post-processed from entropy production
  c) run network with this density-temperature history

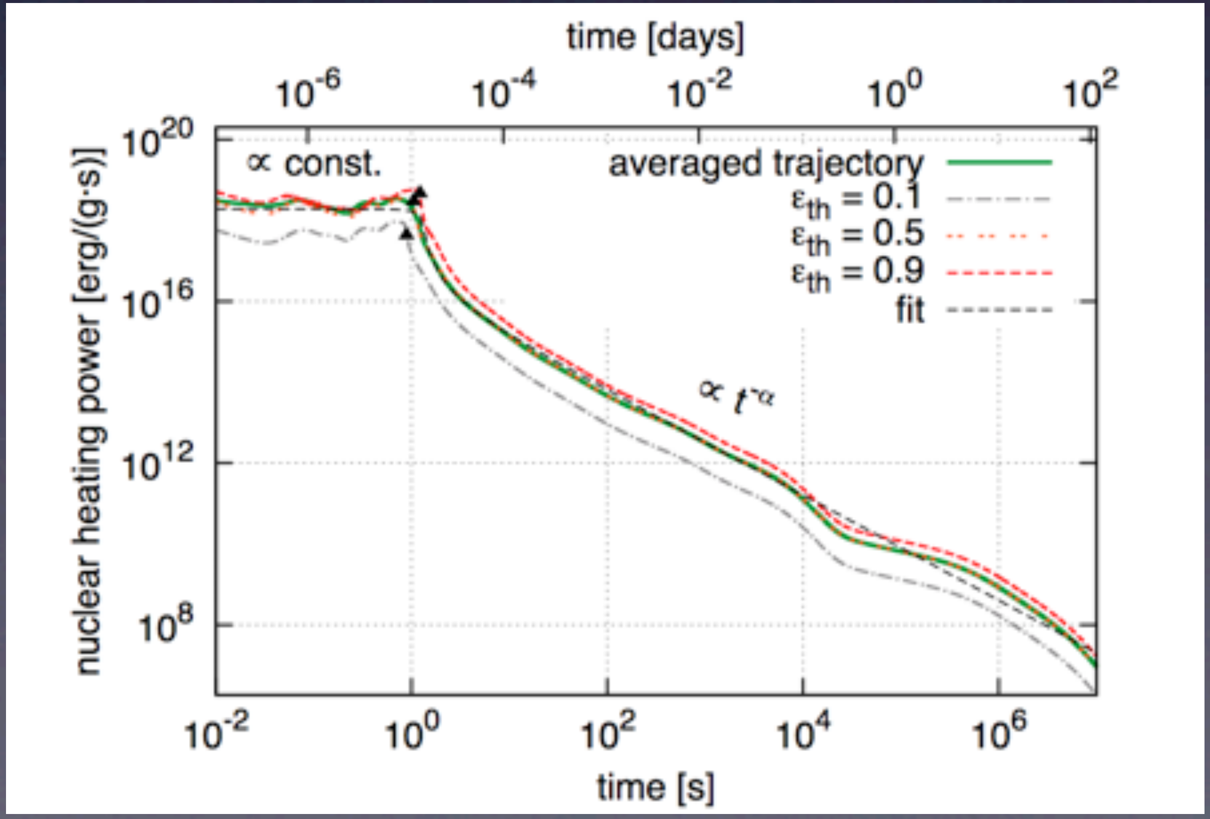
  ⇒ strictly speaking inconsistent (impact on density evolution ignored)

How good is the standard procedure "run network along hydrodynamic trajectory"?

- standard procedure (Freiburghaus et al. 1999):
  a) run hydrodynamics without network
  b) take trajectory, density "as is", temperatures post-processed from entropy production
  c) run network with this density-temperature history

  ⇒ strictly speaking inconsistent (impact on density evolution ignored)

- new approach (Korobkin, Rosswog + 2013)



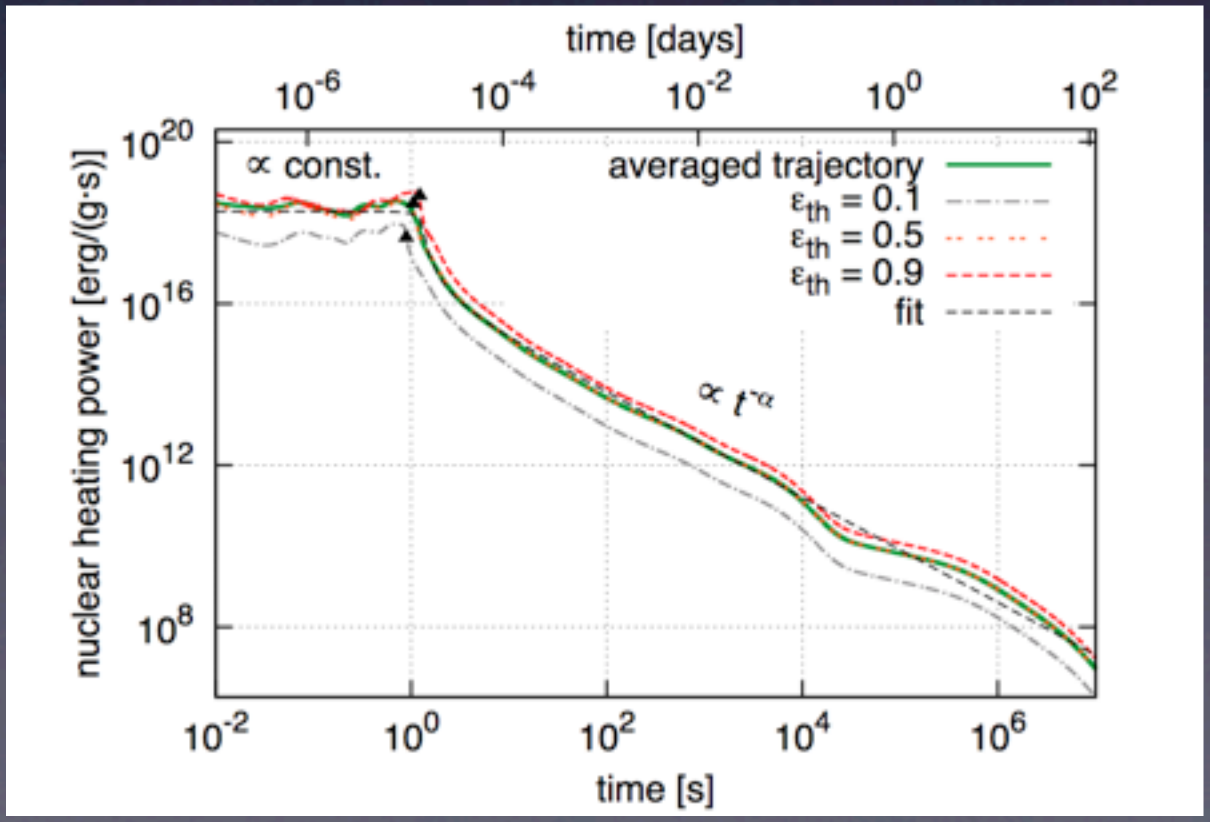
(figure from Korobkin et al. 2012)

How good is the standard procedure "run network along hydrodynamic trajectory"?

- standard procedure (Freiburghaus et al. 1999):
  a) run hydrodynamics without network
  b) take trajectory, density "as is", temperatures post-processed from entropy production
  c) run network with this density-temperature history

  ⇒ strictly speaking inconsistent (impact on density evolution ignored)

- new approach (Korobkin, Rosswog + 2013)



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

⇒ use fit formulae

⇒ implement heating in hydrodynamics

(figure from Korobkin et al. 2012)

- now compare:

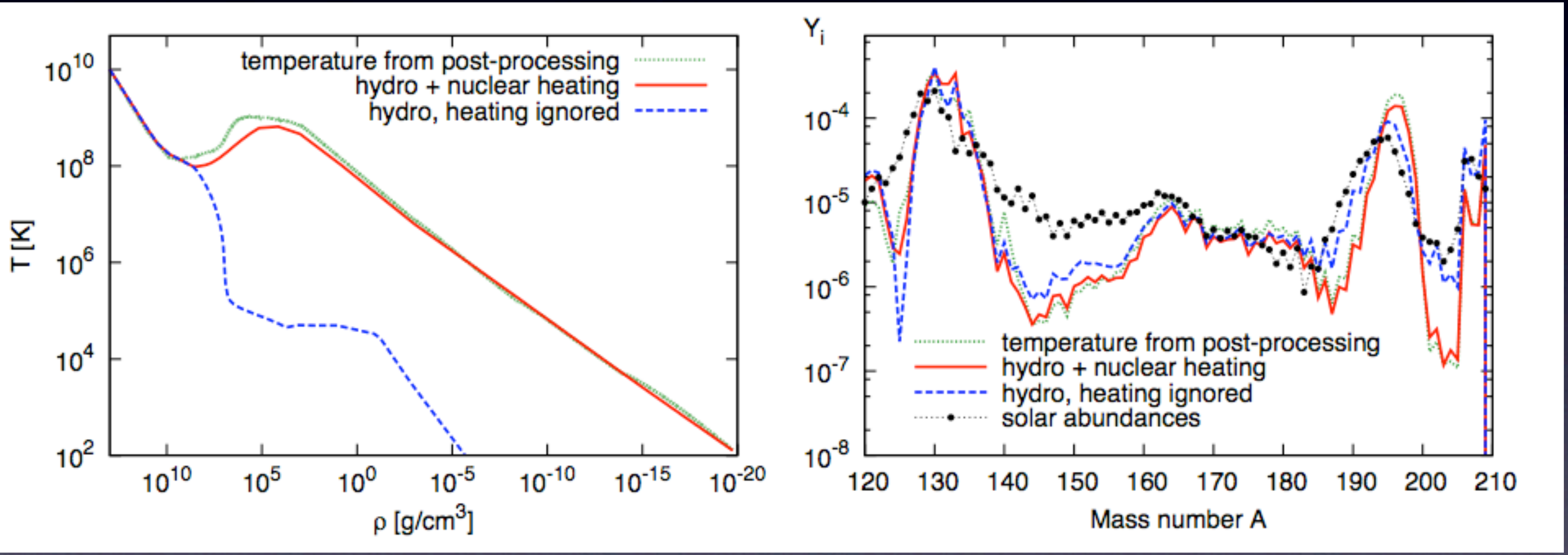
  a) ignore heating in hydro $\Rightarrow$ post-processing temperature & nucleosyn.

  b) include heating in hydro $\Rightarrow$ trajectories directly from hydro traject.

- now compare:

a) ignore heating in hydro ⇒ post-processing temperature & nucleosyn.

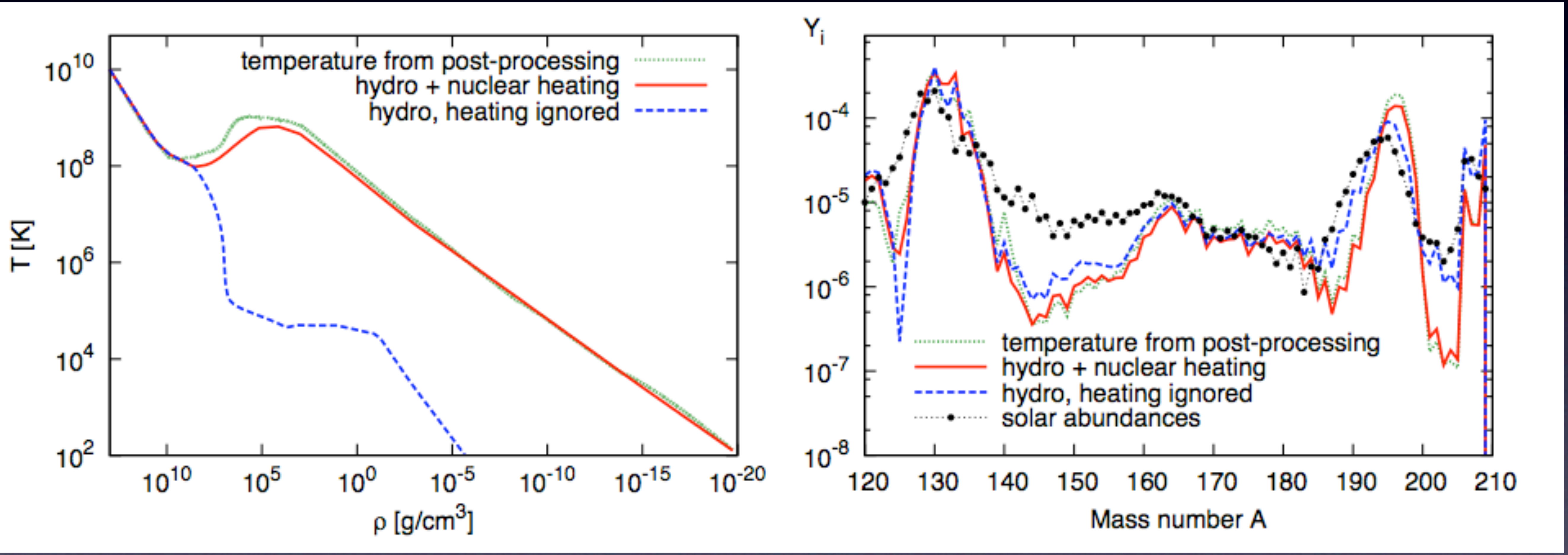
b) include heating in hydro ⇒ trajectories directly from hydro traject.



- now compare:

a) ignore heating in hydro ⇒ post-processing temperature & nucleosyn.

b) include heating in hydro ⇒ trajectories directly from hydro traject.



⇒ post-processing yields acceptable results!

Astrophysical impact of r-process:

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

Astrophysical impact of r-process:

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

- typical merger simulations are short (~20 ms), numerical time step restricted by CFL condition $\Delta t < \Delta x/c_s \sim 10^{-7}$ s

Astrophysical impact of r-process:

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

- typical merger simulations are short (~20 ms), numerical time step restricted by CFL condition $\Delta t < \Delta x/c_s \sim 10^{-7}$ s

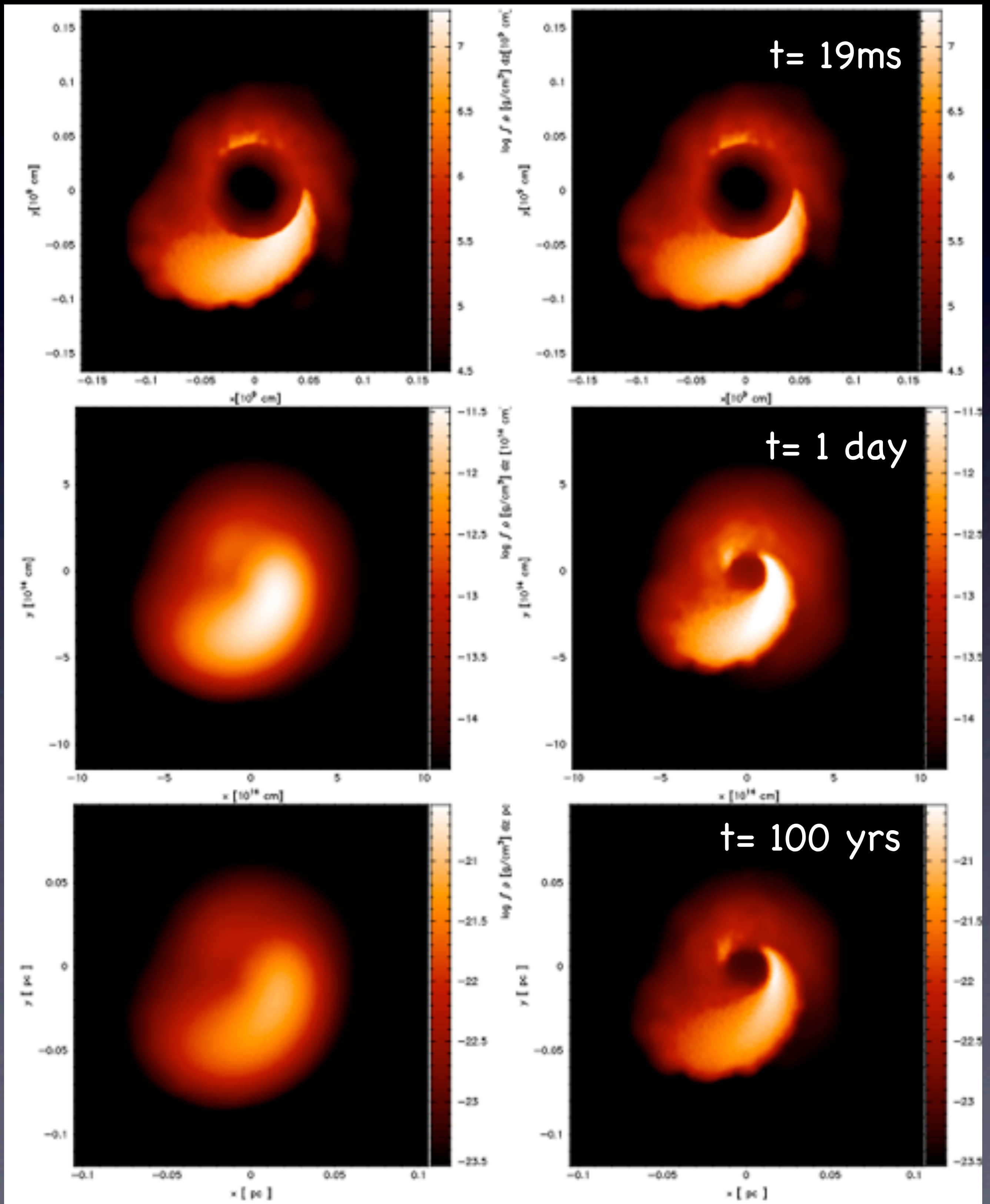
- we cut out high-density part, follow remnant evolution for as long as 100 years (at this point decel. by ambient medium)

Astrophysical impact of r-process:

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

- typical merger simulations are short (~20 ms), numerical time step restricted by CFL condition $\Delta t < \Delta x / c_s \sim 10^{-7}$ s

- we cut out high-density part, follow remnant evolution for as long as 100 years (at this point decel. by ambient medium)



(from Korobkin, Rosswog, ... 2013)

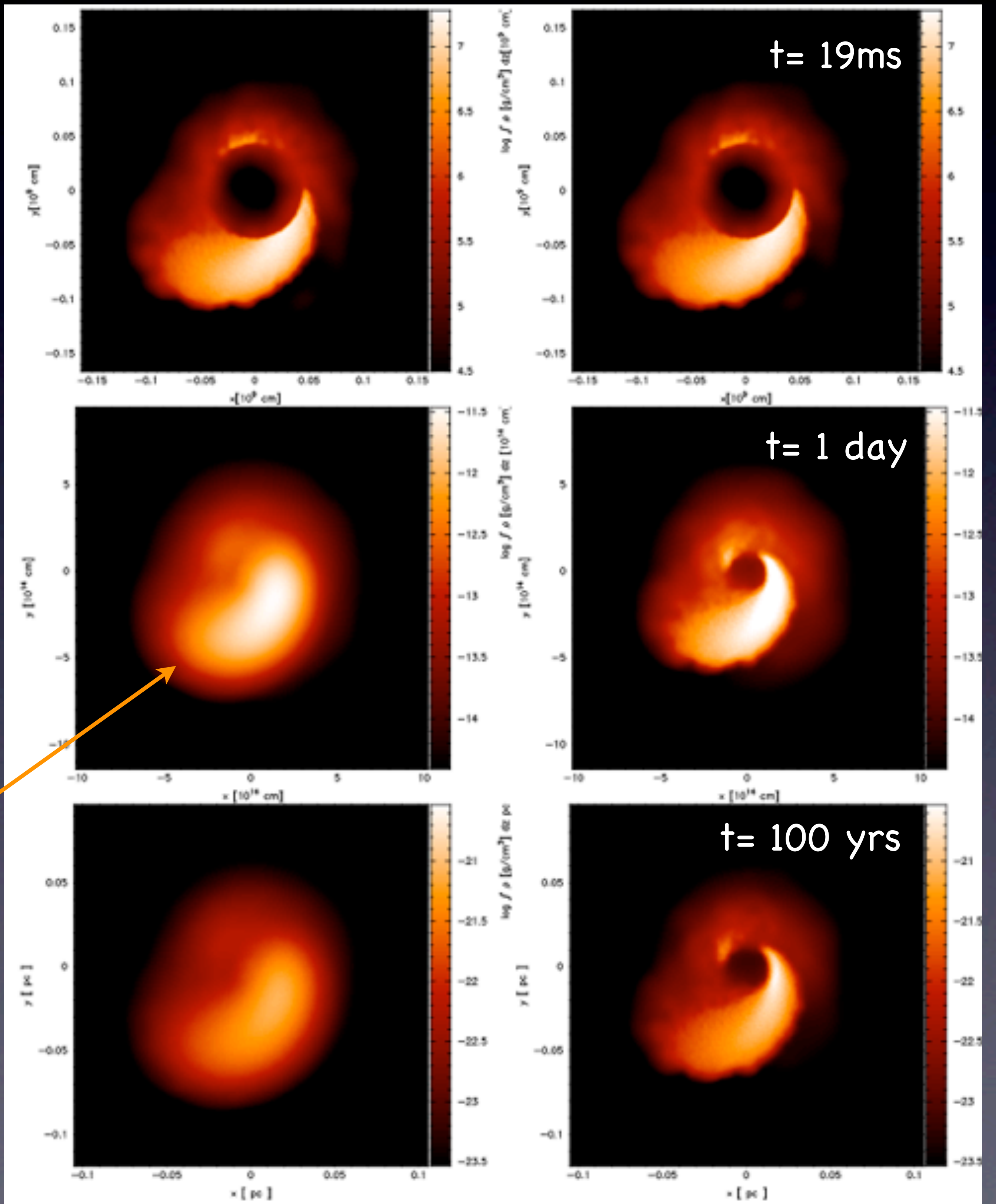
Astrophysical impact of r-process:

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

- typical merger simulations are short (~20 ms), numerical time step restricted by CFL condition $\Delta t < \Delta x / c_s \sim 10^{-7}$ s

- we cut out high-density part, follow remnant evolution for as long as 100 years (at this point decel. by ambient medium)

with radioactive heating



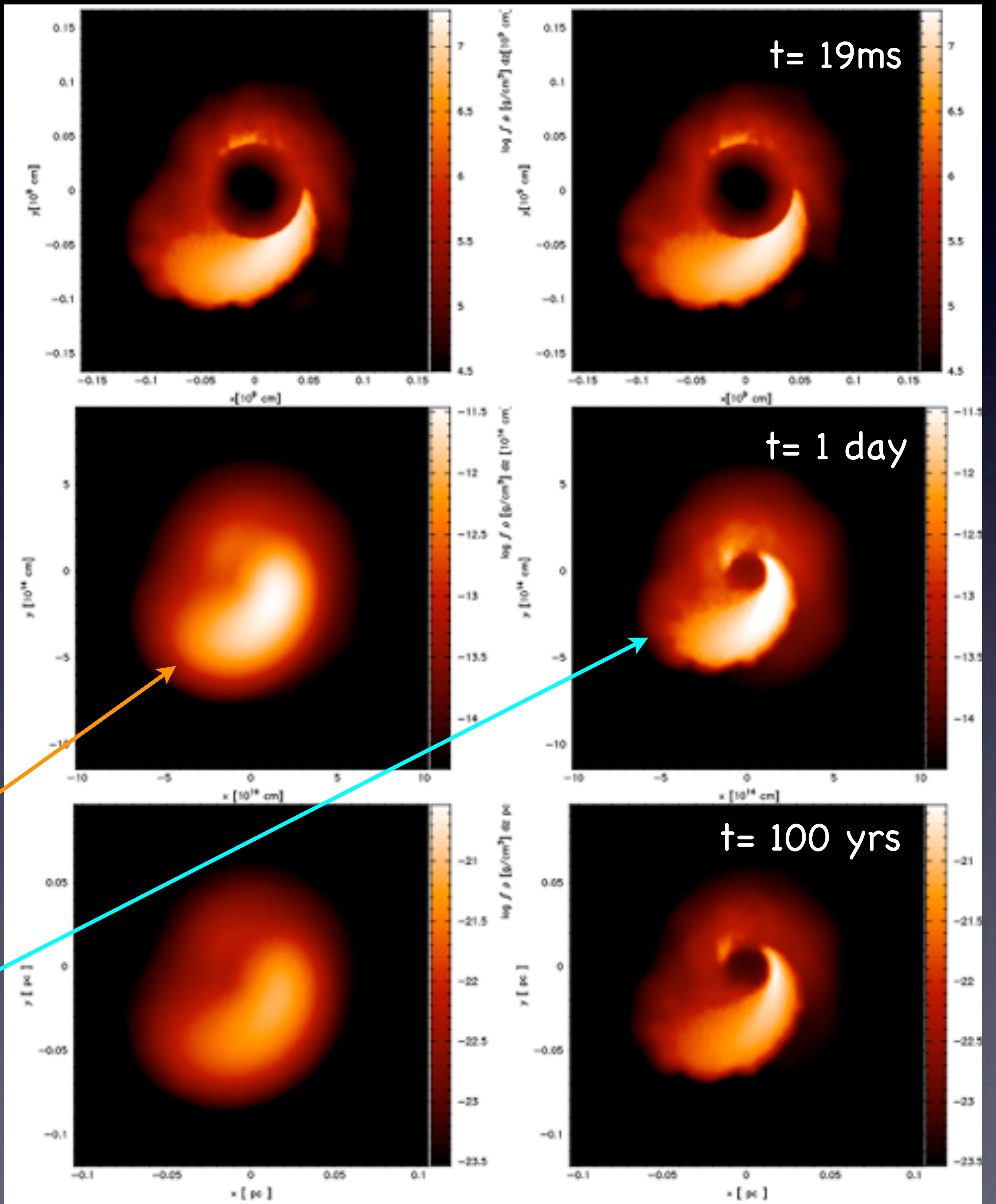
(from Korobkin, Rosswog, ... 2013)

Astrophysical impact of r-process:

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

- typical merger simulations are short (~20 ms), numerical time step restricted by CFL condition $\Delta t < \Delta x / c_s \sim 10^{-7}$ s

- we cut out high-density part, follow remnant evolution for as long as 100 years (at this point decel. by ambient medium)



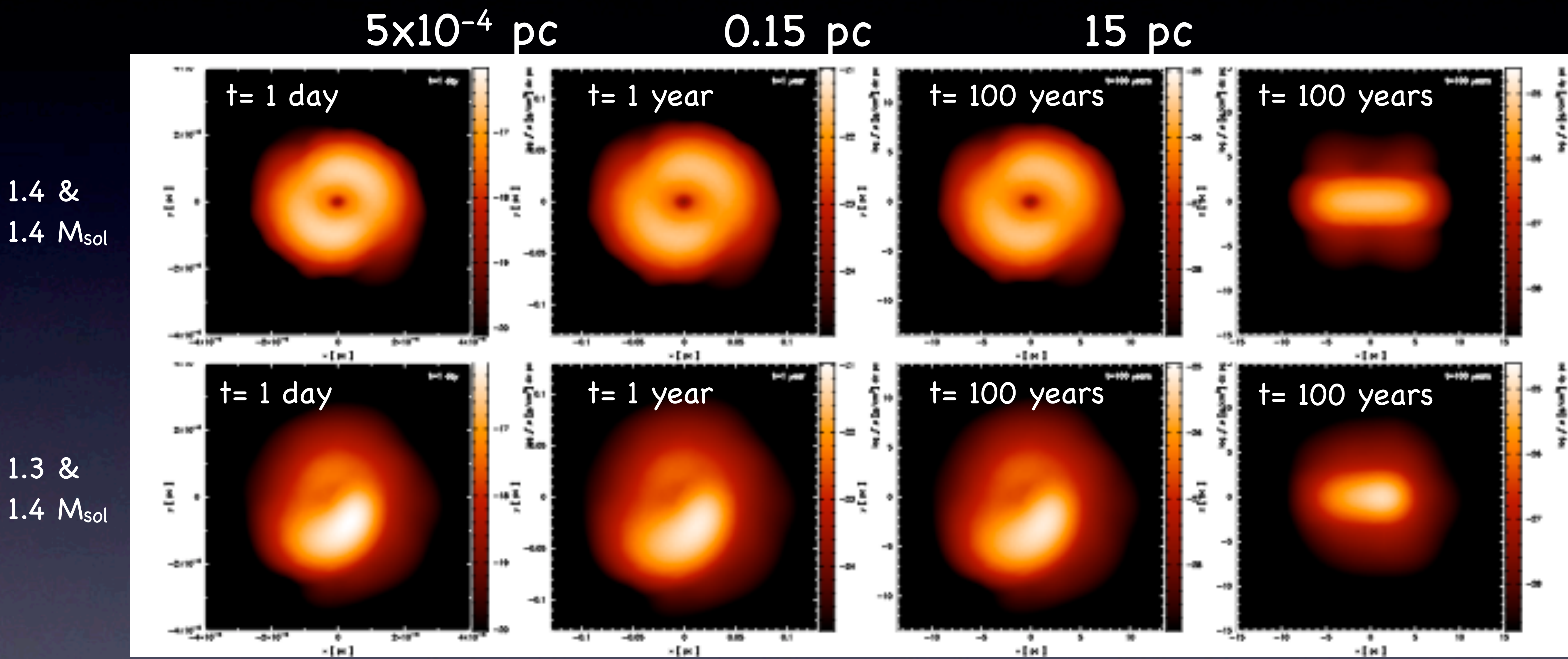
with radioactive heating

without radioactive heating

(from Korobkin, Rosswog, ... 2013)

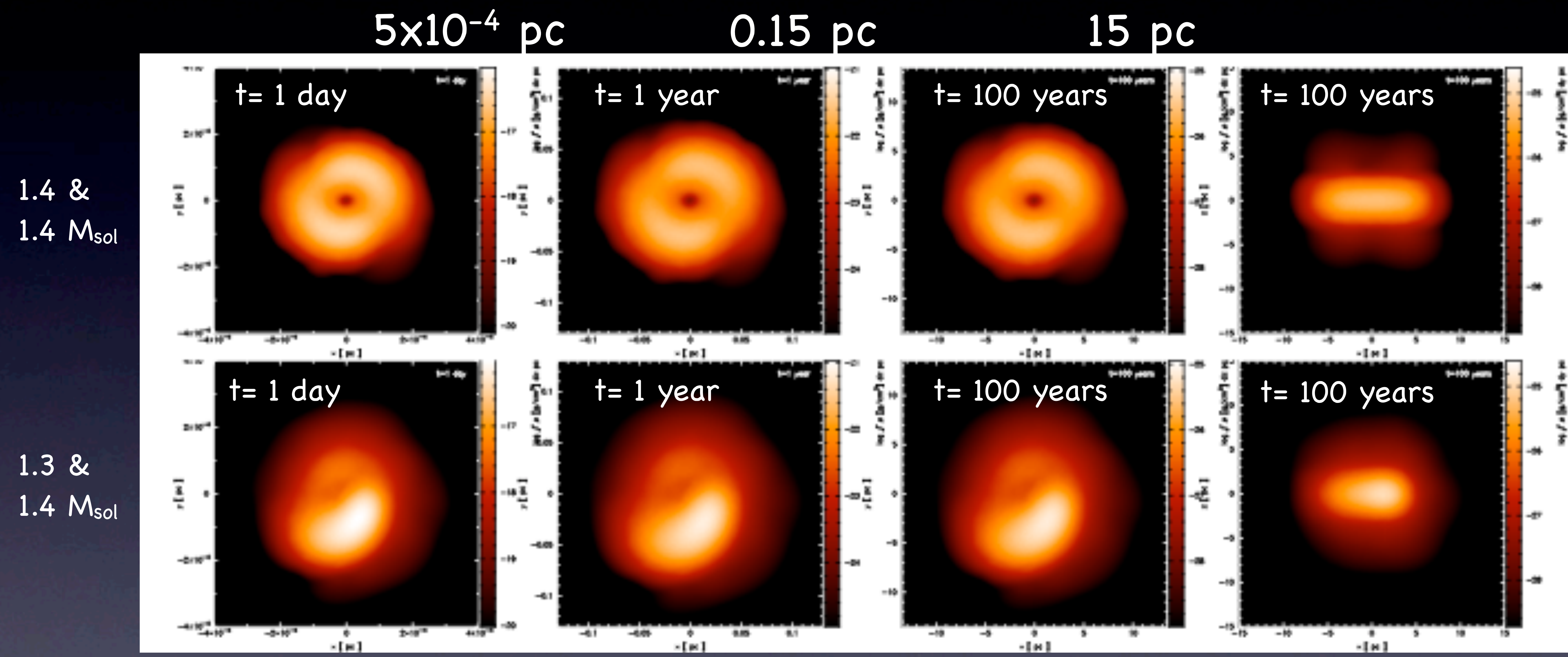
- during first century densities drop by ~40 orders of magnitude (few x 10^{14} to ~10^{-25} g/cm^3)

- during first century densities drop by ~40 orders of magnitude (few x 10^{14} to ~10^{-25} g/cm^3)



(from Korobkin, Rosswog... 2013)

- during first century densities drop by ~40 orders of magnitude (few x 10^{14} to ~10^{-25} g/cm^3)



(from Korobkin, Rosswog... 2013)

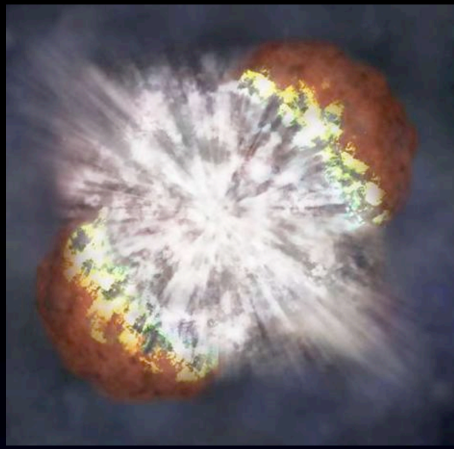
- self-similar solution
- remnant does not become spherical in first 100 years
- still carries memory of initial mass ratio

"r-process in action":

Electromagnetic signals from ejecta: Macronovae

(Li & Paczynski 1998, Kulkarni 2005, Rosswog 2005, Metzger et al. 2010... Roberts et al. 2011 ...

Rosswog, Piran, Nakar, 2013; Piran, Nakar, Rosswog, 2013; Korobkin, Rosswog +, 2013)

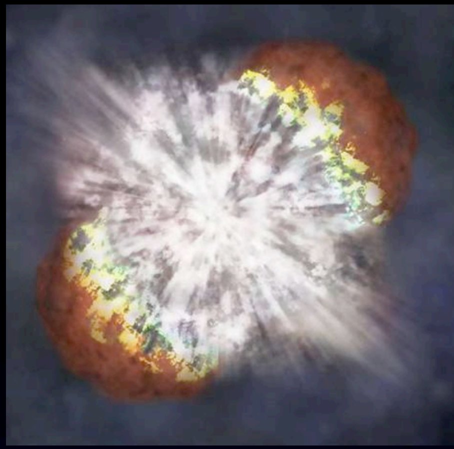


- radioactive decays in ejecta power el.mag. transients

"r-process in action":

Electromagnetic signals from ejecta: Macronovae

(Li & Paczynski 1998, Kulkarni 2005, Rosswog 2005, Metzger et al. 2010... Roberts et al. 2011 ... Rosswog, Piran, Nakar, 2013; Piran, Nakar, Rosswog, 2013; Korobkin, Rosswog +, 2013)

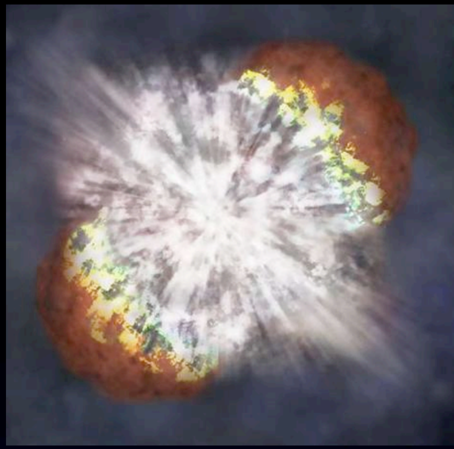


- radioactive decays in ejecta power el.mag. transients
- "supernova-like", but evolve faster and are dimmer

"r-process in action":

Electromagnetic signals from ejecta: Macronovae

(Li & Paczynski 1998, Kulkarni 2005, Rosswog 2005, Metzger et al. 2010... Roberts et al. 2011 ...
Rosswog, Piran, Nakar, 2013; Piran, Nakar, Rosswog, 2013; Korobkin, Rosswog +, 2013)



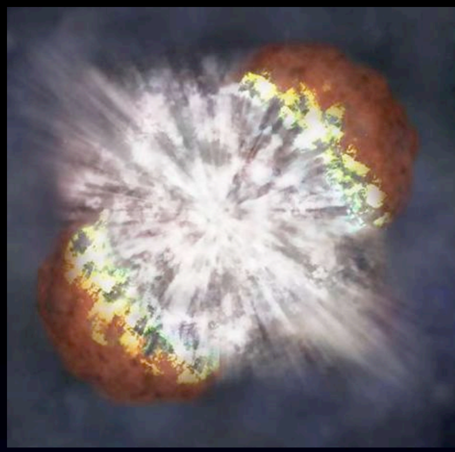
- radioactive decays in ejecta power el.mag. transients
- "supernova-like", but evolve faster and are dimmer
- from simulated ejecta properties:

"r-process in action":

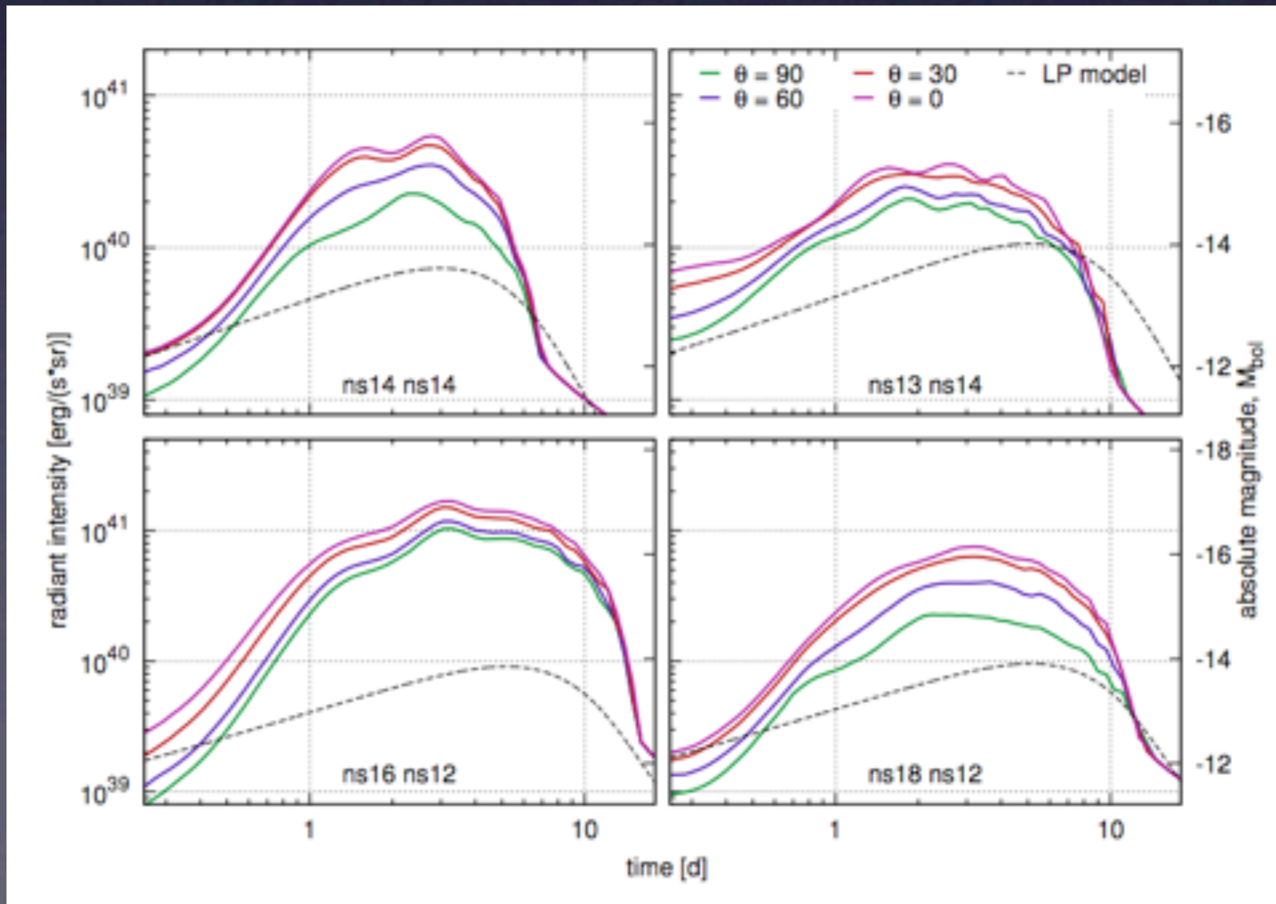
Electromagnetic signals from ejecta: Macronovae

(Li & Paczynski 1998, Kulkarni 2005, Rosswog 2005, Metzger et al. 2010... Roberts et al. 2011 ...

Rosswog, Piran, Nakar, 2013; Piran, Nakar, Rosswog, 2013; Korobkin, Rosswog +, 2013)



- radioactive decays in ejecta power el.mag. transients
- "supernova-like", but evolve faster and are dimmer
- from simulated ejecta properties:

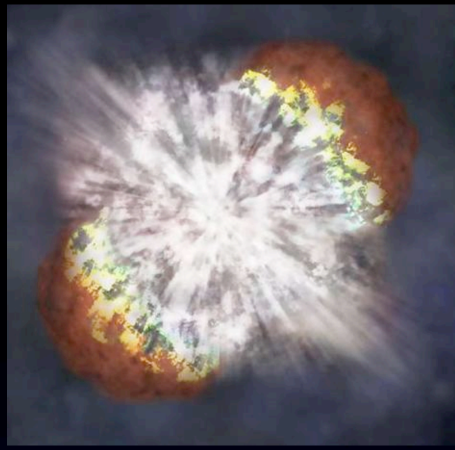


"r-process in action":

Electromagnetic signals from ejecta: Macronovae

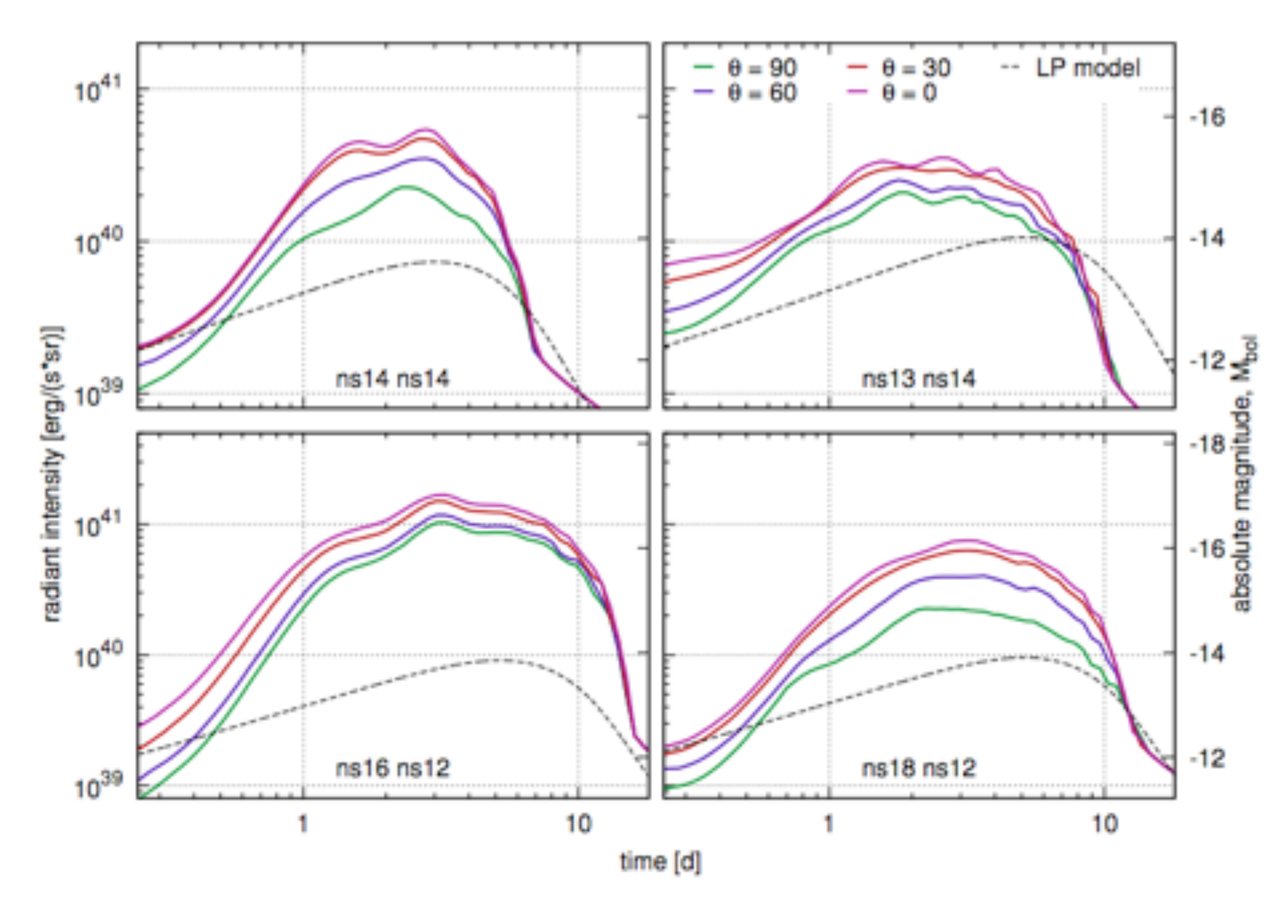
(Li & Paczynski 1998, Kulkarni 2005, Rosswog 2005, Metzger et al. 2010... Roberts et al. 2011 ...

Rosswog, Piran, Nakar, 2013; Piran, Nakar, Rosswog, 2013; Korobkin, Rosswog +, 2013)



- radioactive decays in ejecta power el.mag. transients
- "supernova-like", but evolve faster and are dimmer
- from simulated ejecta properties:

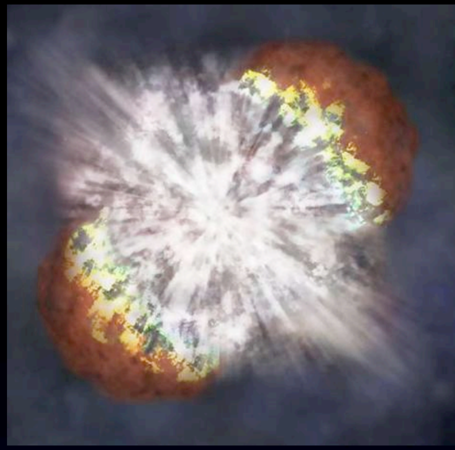
"typical" nsns merger:
peak after ≈ 3 days
with $L_{peak} \approx 5 \times 10^{41}$ erg/s
($\kappa = 1\ cm^2/g$)



"r-process in action":

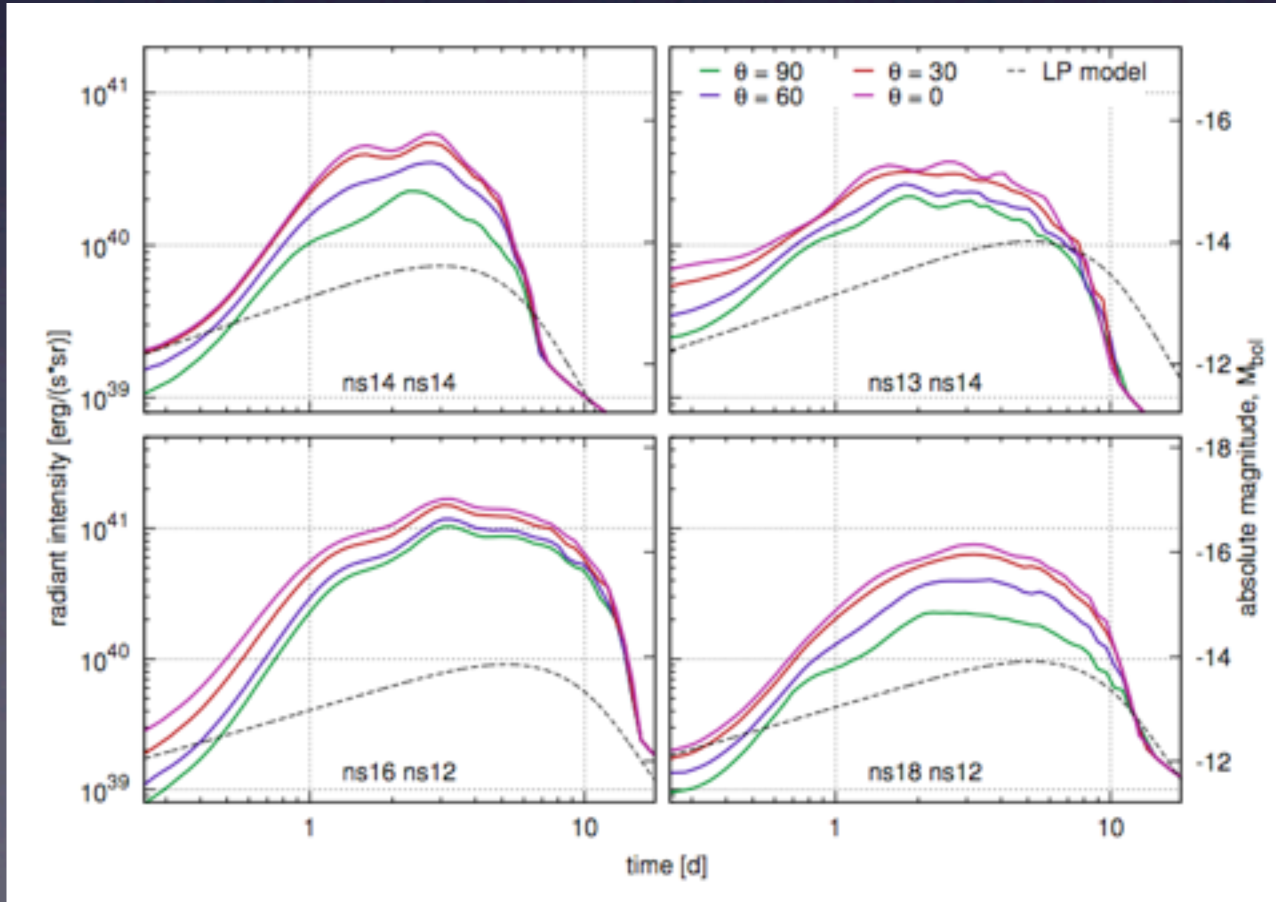
Electromagnetic signals from ejecta: Macronovae

(Li & Paczynski 1998, Kulkarni 2005, Rosswog 2005, Metzger et al. 2010... Roberts et al. 2011 ...
Rosswog, Piran, Nakar, 2013; Piran, Nakar, Rosswog, 2013; Korobkin, Rosswog +, 2013)



- radioactive decays in ejecta power el.mag. transients
- "supernova-like", but evolve faster and are dimmer
- from simulated ejecta properties:

"typical" nsns merger:
peak after ≈ 3 days
with L_{peak} ≈ 5 x 10^{41} erg/s
(κ = 1 cm^2/g)

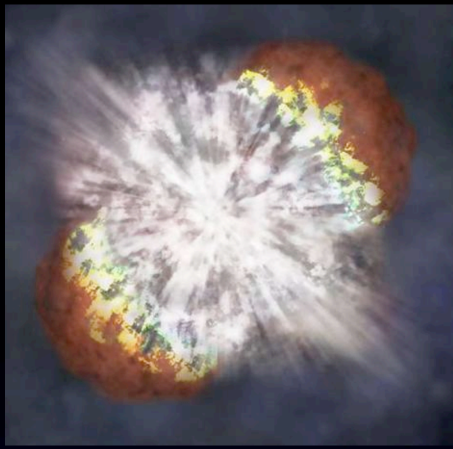


⇒ merger gravitational wave signal should be accompanied by such an "r-process powered transient"

"r-process in action":

Electromagnetic signals from ejecta: Macronovae

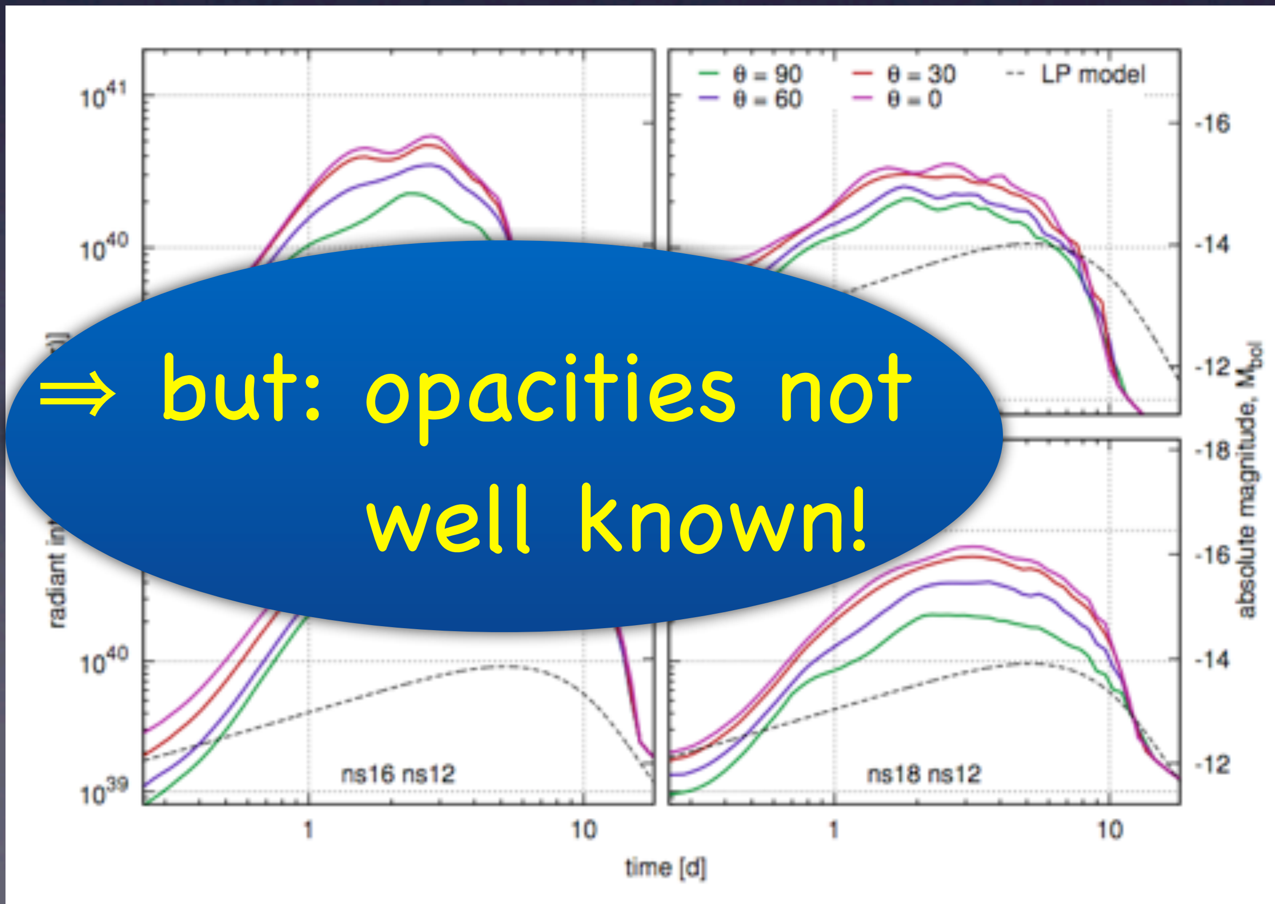
(Li & Paczynski 1998, Kulkarni 2005, Rosswog 2005, Metzger et al. 2010... Roberts et al. 2011 ... Rosswog, Piran, Nakar, 2013; Piran, Nakar, Rosswog, 2013; Korobkin, Rosswog +, 2013)



- radioactive decays in ejecta power el.mag. transients
- "supernova-like", but evolve faster and are dimmer
- from simulated ejecta properties:

"typical" nsns merger:
peak after ≈ 3 days
with $L_{peak} \approx 5 \times 10^{41}$ erg/s
($\kappa = 1\ cm^2/g$)

⇒ merger gravitational wave signal should be accompanied by such an "r-process powered transient"



⇒ but: opacities not well known!

A variation of the theme:

B. Dynamical compact object collisions

- recently (re-)suggested by Lee et al. (2010)
- e.g. in cores of Globular Clusters
- could contribute to observed sGRB rate

A variation of the theme:

B. Dynamical compact object collisions

- recently (re-)suggested by Lee et al. (2010)
- e.g. in cores of Globular Clusters
- could contribute to observed sGRB rate

"Isn't the cross-section of such objects way to small for an interesting rate?"

A variation of the theme:

B. Dynamical compact object collisions

- recently (re-)suggested by Lee et al. (2010)
- e.g. in cores of Globular Clusters
- could contribute to observed sGRB rate

"Isn't the cross-section of such objects way to small for an interesting rate?"

i) collision rate

$\propto$ (number density)^2

A variation of the theme:

B. Dynamical compact object collisions

- recently (re-)suggested by Lee et al. (2010)
- e.g. in cores of Globular Clusters
- could contribute to observed sGRB rate

"Isn't the cross-section of such objects way to small for an interesting rate?"

i) collision rate

$\propto$ (number density)^2

- ~10^6 stars
- 10^2 - 10^4 per galaxy
- centr. densities up to 10^8 stars/pc^3 >> 1 star/pc^3 (solar neighborhood)

A variation of the theme:

B. Dynamical compact object collisions

- recently (re-)suggested by Lee et al. (2010)
- e.g. in cores of Globular Clusters
- could contribute to observed sGRB rate

"Isn't the cross-section of such objects way to small for an interesting rate?"

i) collision rate

$\propto$ (number density)^2

ii) cross-section enhanced by "gravitational focussing"

- ~10^6 stars
- 10^2 - 10^4 per galaxy
- centr. densities up to 10^8 stars/pc^3 >> 1 star/pc^3 (solar neighborhood)

A variation of the theme:

B. Dynamical compact object collisions

- recently (re-)suggested by Lee et al. (2010)
- e.g. in cores of Globular Clusters
- could contribute to observed sGRB rate

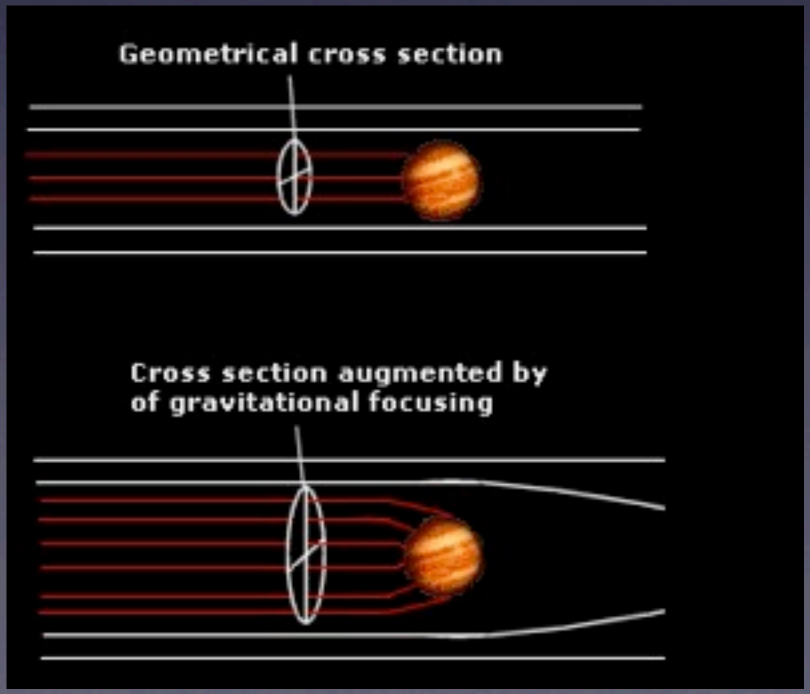
"Isn't the cross-section of such objects way to small for an interesting rate?"

i) collision rate

$\propto$ (number density)^2

ii) cross-section enhanced by "gravitational focussing"

- ~10^6 stars
- 10^2 - 10^4 per galaxy
- centr. densities up to 10^8 stars/pc^3 >> 1 star/pc^3 (solar neighborhood)



A variation of the theme:

B. Dynamical compact object collisions

- recently (re-)suggested by Lee et al. (2010)
- e.g. in cores of Globular Clusters
- could contribute to observed sGRB rate

"Isn't the cross-section of such objects way to small for an interesting rate?"

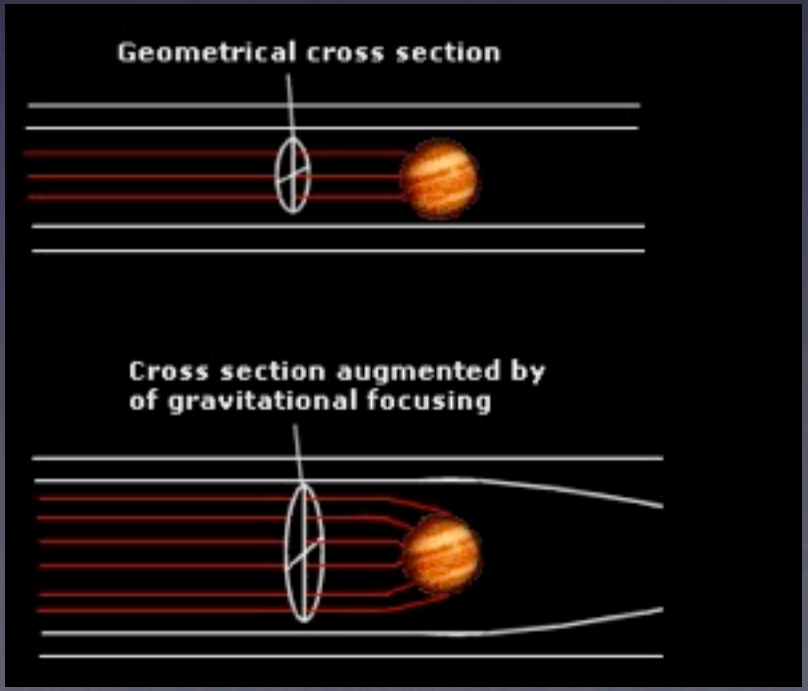
i) collision rate

$\propto$ (number density)^2

ii) cross-section enhanced by "gravitational focussing"

$$\sigma \approx \pi R^2 \left(1 + \left[\frac{v_{\rm esc}}{\Sigma}\right]^2\right)$$

- ~10^6 stars
- 10^2 - 10^4 per galaxy
- centr. densities up to 10^8 stars/pc^3 >> 1 star/pc^3 (solar neighborhood)



A variation of the theme:

B. Dynamical compact object collisions

- recently (re-)suggested by Lee et al. (2010)
- e.g. in cores of Globular Clusters
- could contribute to observed sGRB rate

"Isn't the cross-section of such objects way to small for an interesting rate?"

i) collision rate

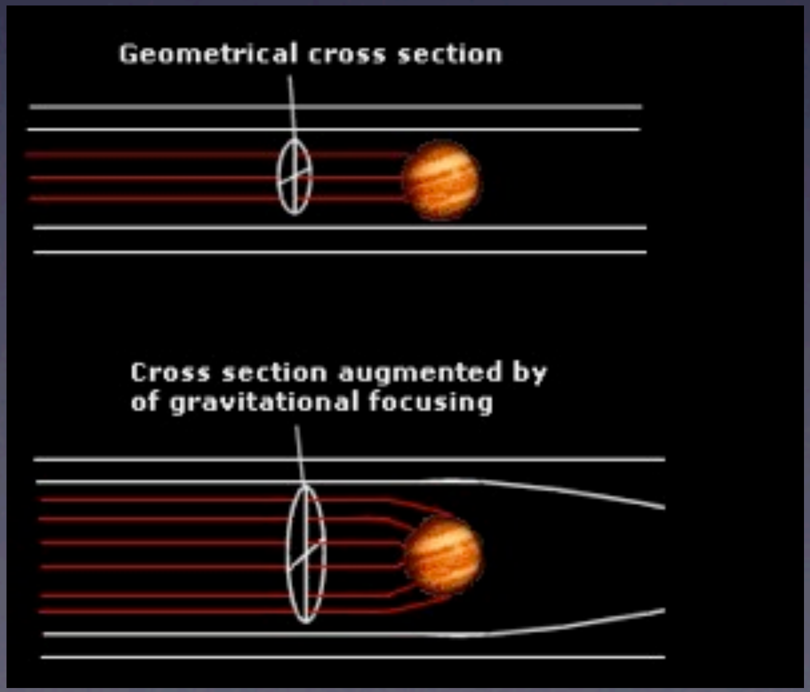
$\propto$ (number density)^2

ii) cross-section enhanced by "gravitational focussing"

surface escape velocity, ~ 0.3 c

$$\sigma \approx \pi R^2 \left(1 + \left[\frac{v_{\rm esc}}{\Sigma}\right]^2\right)$$

- ~10^6 stars
- 10^2 - 10^4 per galaxy
- centr. densities up to 10^8 stars/pc^3 >> 1 star/pc^3 (solar neighborhood)



A variation of the theme:

B. Dynamical compact object collisions

- recently (re-)suggested by Lee et al. (2010)
- e.g. in cores of Globular Clusters
- could contribute to observed sGRB rate

"Isn't the cross-section of such objects way to small for an interesting rate?"

i) collision rate

$\propto$ (number density)^2

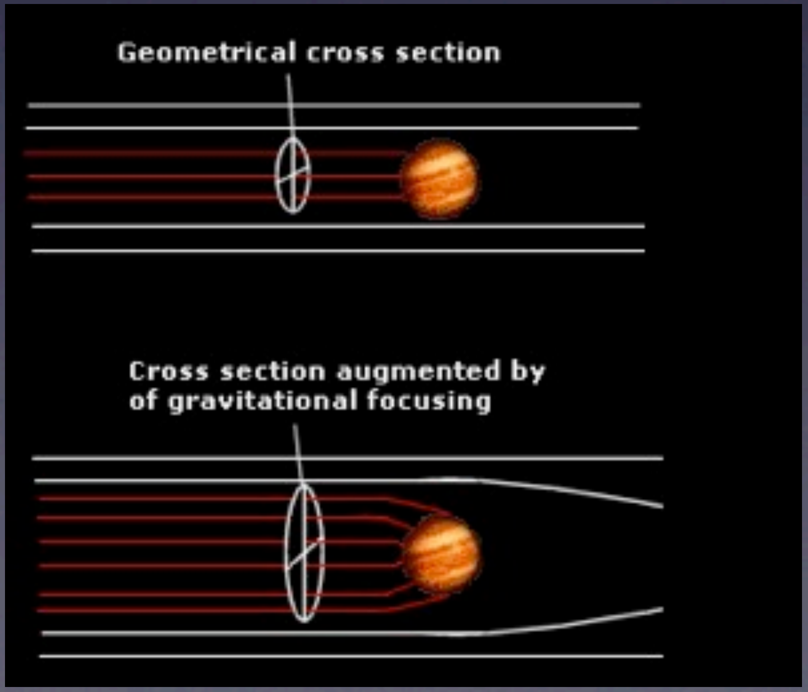
ii) cross-section enhanced by "gravitational focussing"

surface escape velocity, ~ 0.3 c

$$\sigma \approx \pi R^2 \left(1 + \left[\frac{v_{\rm esc}}{\Sigma}\right]^2\right)$$

velocity dispersion, ~ 10 km/s

- ~10^6 stars
- 10^2 - 10^4 per galaxy
- centr. densities up to 10^8 stars/pc^3 >> 1 star/pc^3 (solar neighborhood)



A variation of the theme:

B. Dynamical compact object collisions

- recently (re-)suggested by Lee et al. (2010)
- e.g. in cores of Globular Clusters
- could contribute to observed sGRB rate

- ~10^6 stars
- 10^2 - 10^4 per galaxy
- centr. densities up to 10^8 stars/pc^3 >> 1 star/pc^3 (solar neighborhood)

"Isn't the cross-section of such objects way to small for an interesting rate?"

i) collision rate

$\propto$ (number density)^2

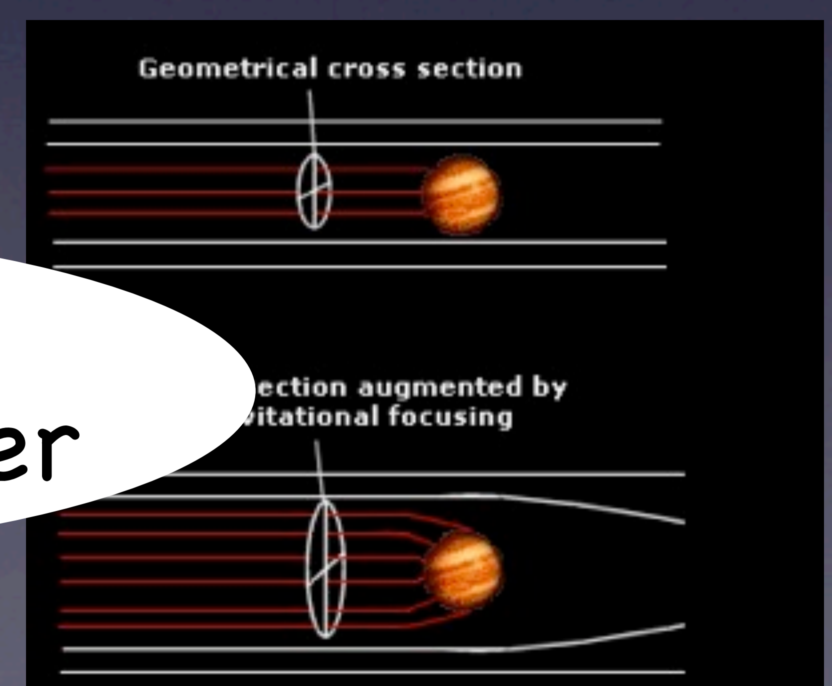
ii) cross-section enhanced by "gravitational focussing"

surface escape velocity, ~ 0.3 c

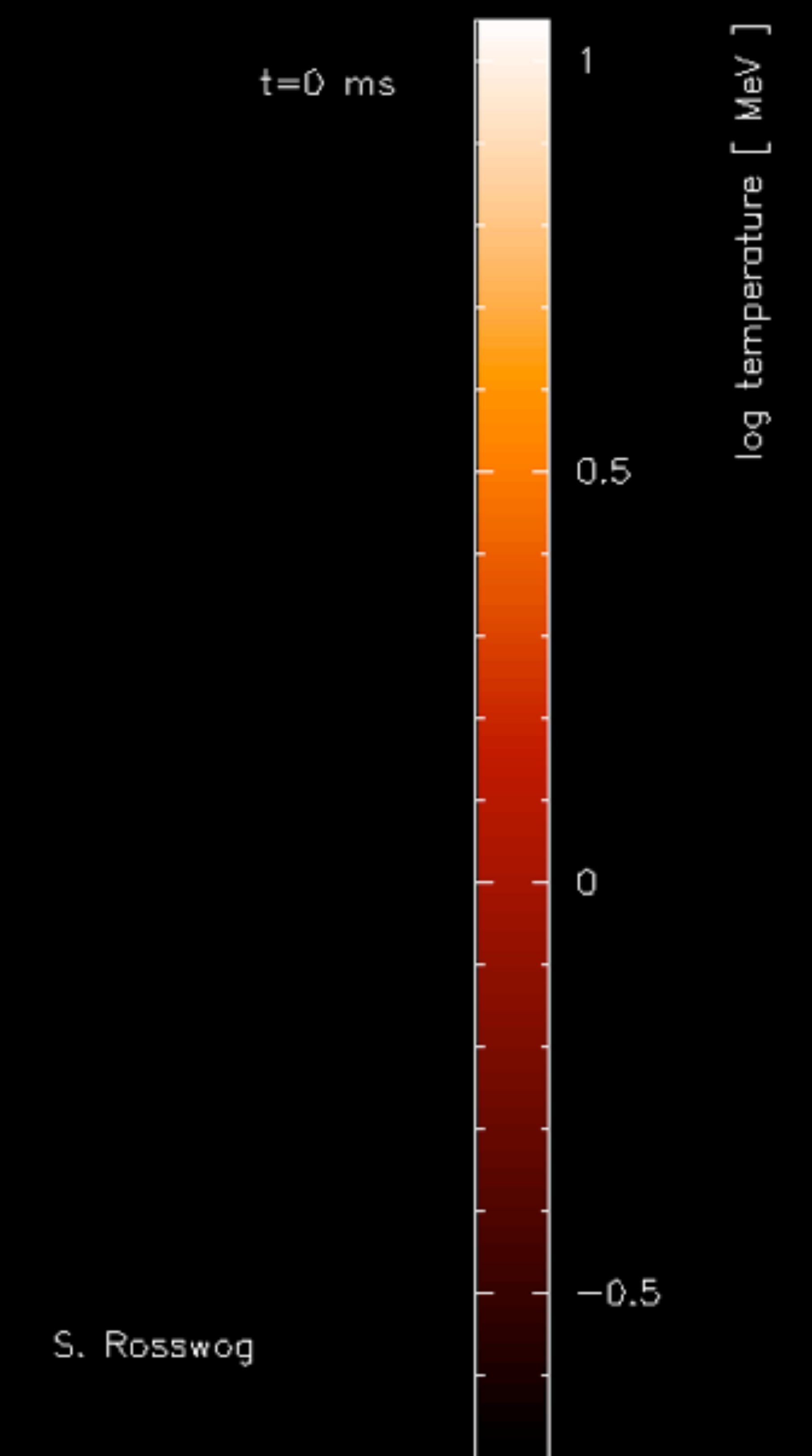
$\sigma \approx$

~ 10^8 for a ns in a globular cluster

velocity dispersion, ~ 10 km/s



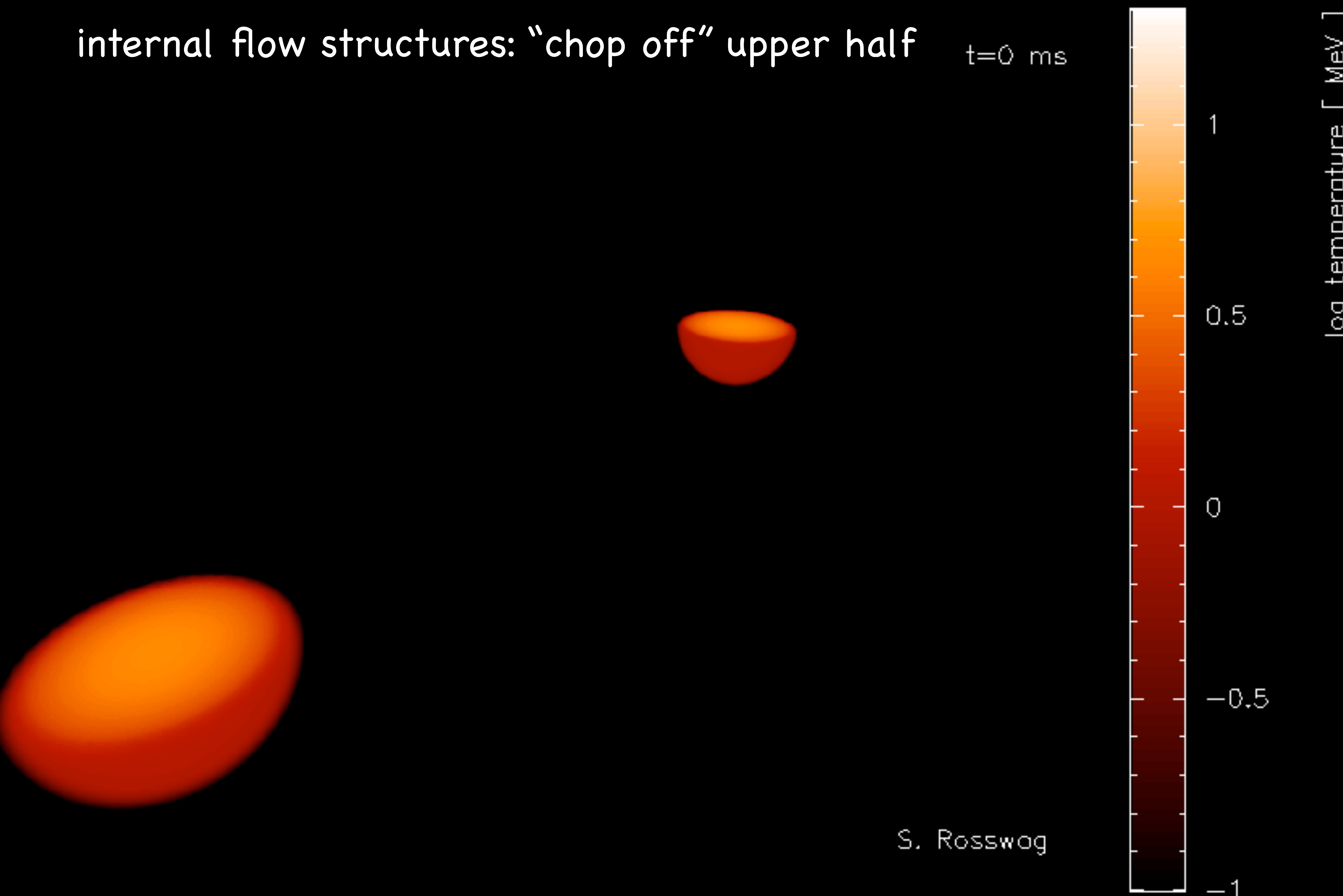
Example 1: $m_1 = 1.3\ M_{sol}$, $m_2 = 1.4\ M_{sol}$, $\beta=1$ "grazing impact"



(visualized: temperature at given optical depth)

- Example 2: slightly stronger than grazing impact (β=2)

internal flow structures: "chop off" upper half



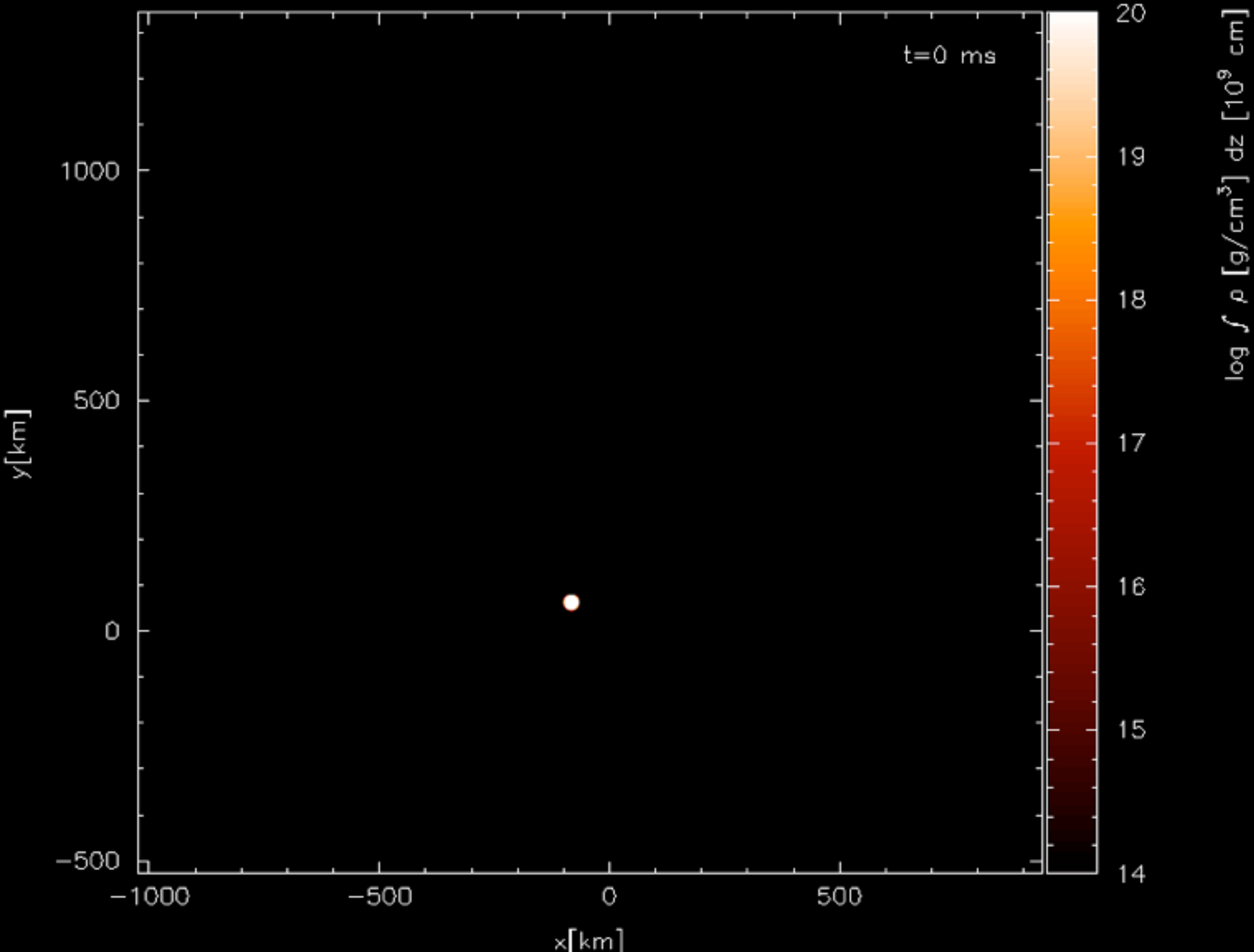
Example 3: neutron black hole collision m_{ns}= 1.3 M_{sol}, m_{bh}= 5 M_{sol}, β=1

"grazing impact"

(visualized:
column density)

Example 3: neutron black hole collision m_{ns}= 1.3 M_{sol}, m_{bh}= 5 M_{sol}, β=1

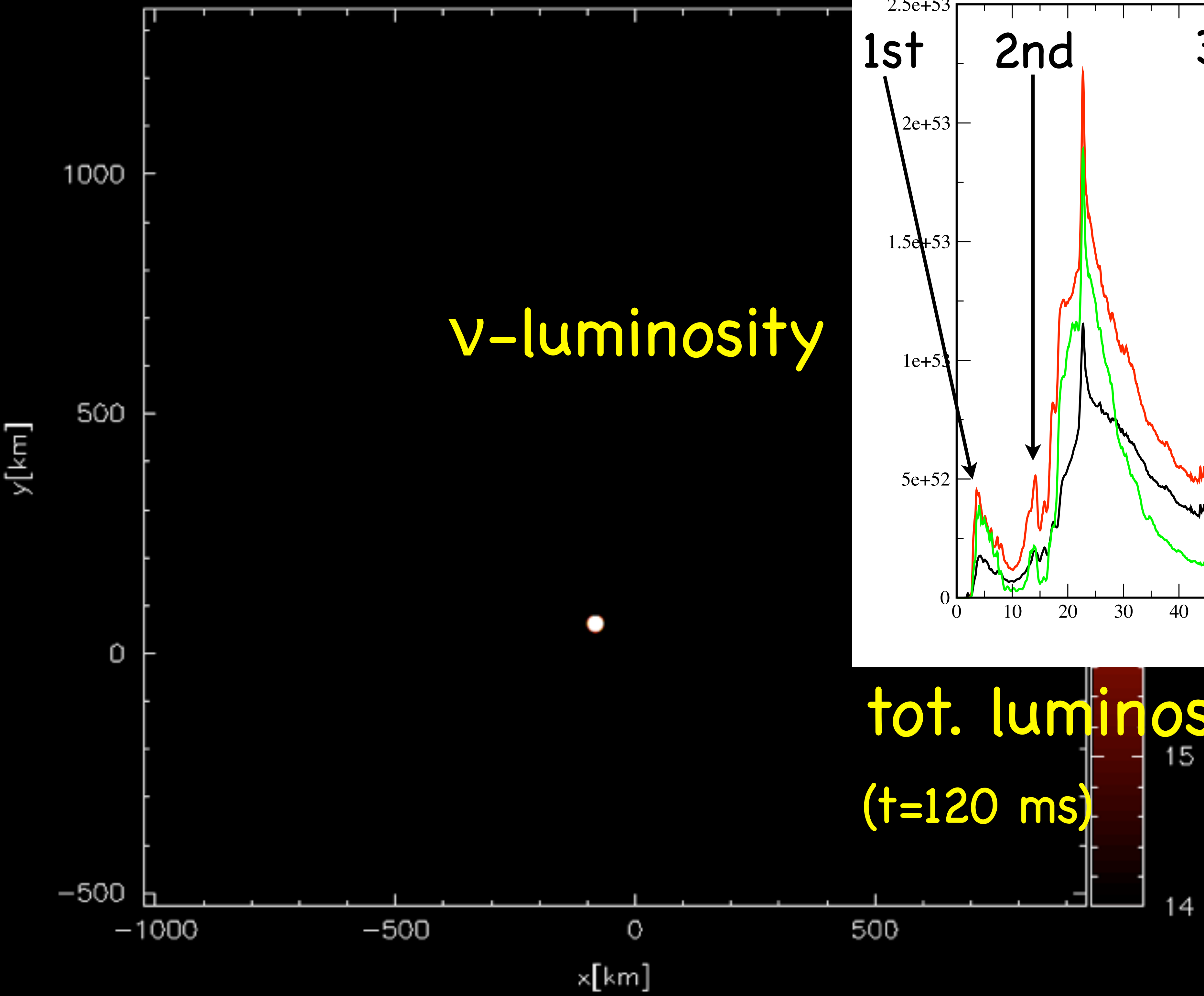
"grazing impact"



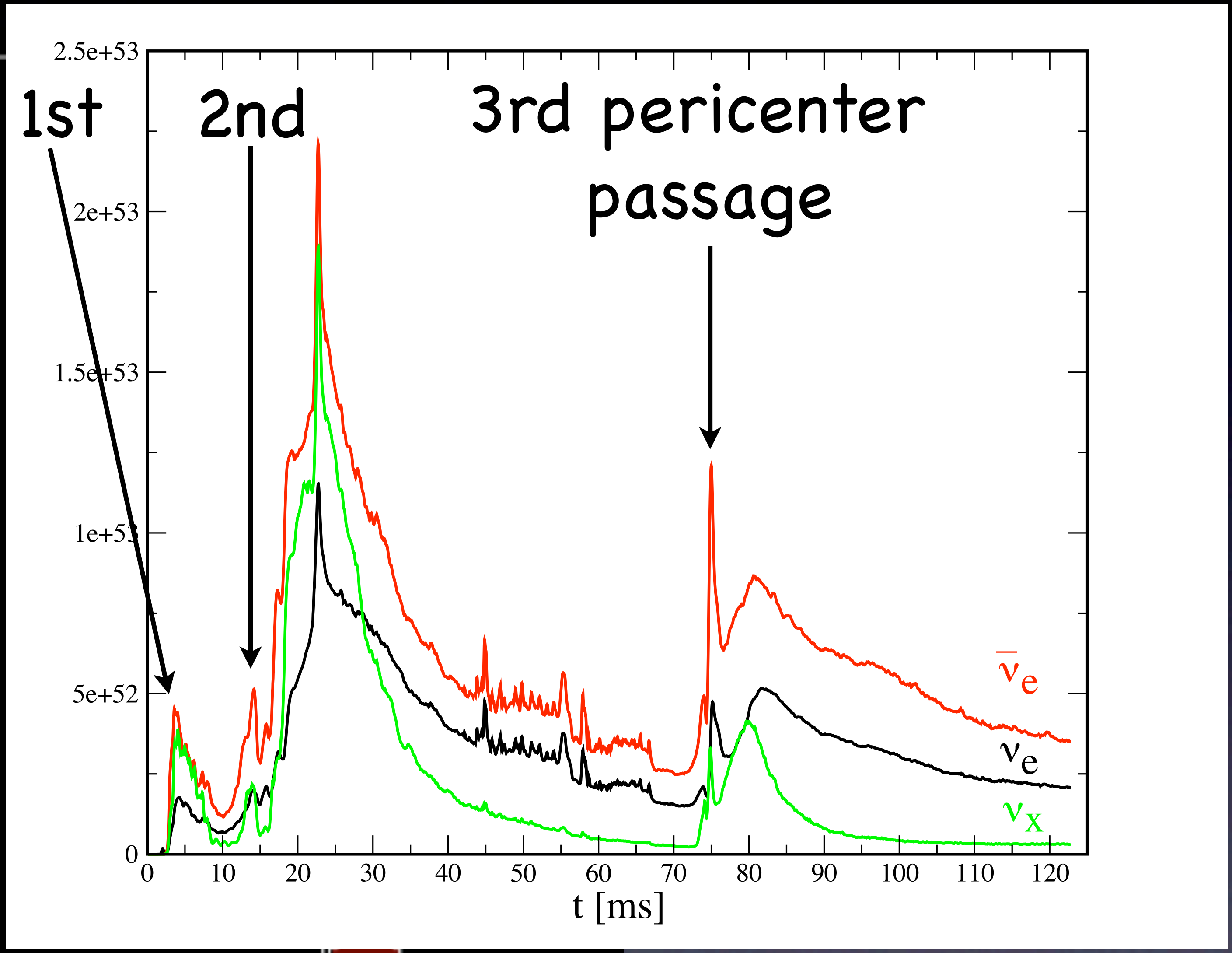
(visualized: column density)

Example 3: neutron black hole collision m_{ns}= 1.3 M_{sol}, m_{bh}= 5 M_{sol}, β=1

"grazing impact"



ν-luminosity



tot. luminosity: 6×10^{52} erg/s

(t=120 ms)

$E_{\nu_e} \approx$ 7 MeV

$E_{\bar{\nu}_e} \approx$ 8 MeV

$E_{\nu_x} \approx$ 14 MeV

rate constraints from ejecta masses:

- typical nsbh collision ejects ~0.15 M_{sol},
  typical nsns collision ~0.05 M_{sol}

rate constraints from ejecta masses:

- typical nsbh collision ejects ~0.15 M_{sol},
  typical nsns collision ~0.05 M_{sol}
- nsbh collisions should be 5 x more common (Lee et al. 2010)

rate constraints from ejecta masses:

- typical nsbh collision ejects ~0.15 M_{sol},
  typical nsns collision ~0.05 M_{sol}
- nsbh collisions should be 5 x more common (Lee et al. 2010)

} on average: 0.135 M_{sol} ejected per collision !

rate constraints from ejecta masses:

- typical nsbh collision ejects ~0.15 M_{sol}, typical nsns collision ~0.05 M_{sol}
- nsbh collisions should be 5 x more common (Lee et al. 2010)

} on average: 0.135 M_{sol} ejected per collision !

⇒ constraints from r-process nucleosynthesis: they must be rare!

($R_{collision}$ << 0.1 $R_{nsns-merger}$)

Summary

Summary

- compact binary mergers are prime targets of advanced, ground-based gravitational wave detectors, exp. operation ~2016

Summary

- compact binary mergers are prime targets of advanced, ground-based gravitational wave detectors, exp. operation ~2016
- additional signatures (apart from GWs) highly welcome:
  - boost confidence in detection
  - astrophysical environment (type of galaxy, redshift etc)
  - ...

Summary

- compact binary mergers are prime targets of advanced, ground-based gravitational wave detectors, exp. operation ~2016
- additional signatures (apart from GWs) highly welcome:
  - boost confidence in detection
  - astrophysical environment (type of galaxy, redshift etc)
  - ...
- dynamic ejecta are excellent candidates for heavy r-process; consistency with chem. evol. of Galaxies needs further studies

Summary

- compact binary mergers are prime targets of advanced, ground-based gravitational wave detectors, exp. operation ~2016
- additional signatures (apart from GWs) highly welcome:
  - boost confidence in detection
  - astrophysical environment (type of galaxy, redshift etc)
  - ...
- dynamic ejecta are excellent candidates for heavy r-process; consistency with chem. evol. of Galaxies needs further studies
- their radioactive decay is expected to produce short-lived transients ("Macronovae")

Summary

- compact binary mergers are prime targets of advanced, ground-based gravitational wave detectors, exp. operation ~2016
- additional signatures (apart from GWs) highly welcome:
  - boost confidence in detection
  - astrophysical environment (type of galaxy, redshift etc)
  - ...
- dynamic ejecta are excellent candidates for heavy r-process; consistency with chem. evol. of Galaxies needs further studies
- their radioactive decay is expected to produce short-lived transients ("Macronovae")
- compact binary mergers additionally release matter via at least two more channels:
  a) ν-driven winds
  b) dis-integrating (late-time) accretion disks

Summary

- compact binary mergers are prime targets of advanced, ground-based gravitational wave detectors, exp. operation ~2016
- additional signatures (apart from GWs) highly welcome:
  - boost confidence in detection
  - astrophysical environment (type of galaxy, redshift etc)
  - ...
- dynamic ejecta are excellent candidates for heavy r-process; consistency with chem. evol. of Galaxies needs further studies
- their radioactive decay is expected to produce short-lived transients ("Macronovae")
- compact binary mergers additionally release matter via at least two more channels:

  a) ν-driven winds

  b) dis-integrating (late-time) accretion disks

  $\Rightarrow$ could plausibly contribute to r-process production, but likely different properties than dynamic ejecta

Summary

- compact binary mergers are prime targets of advanced, ground-based gravitational wave detectors, exp. operation ~2016
- additional signatures (apart from GWs) highly welcome:
  - boost confidence in detection
  - astrophysical en… …y, redshift etc)
  - ...
- dynamic … process; consister… … studies
- their radi… …-lived transients ("Macronovae")

Thank you for your attention!

- compact binary mergers additionally release matter via at least two more channels:
  a) ν-driven winds
  b) dis-integrating (late-time) accretion disks

  ⇒ could plausibly contribute to r-process production, but likely different properties than dynamic ejecta