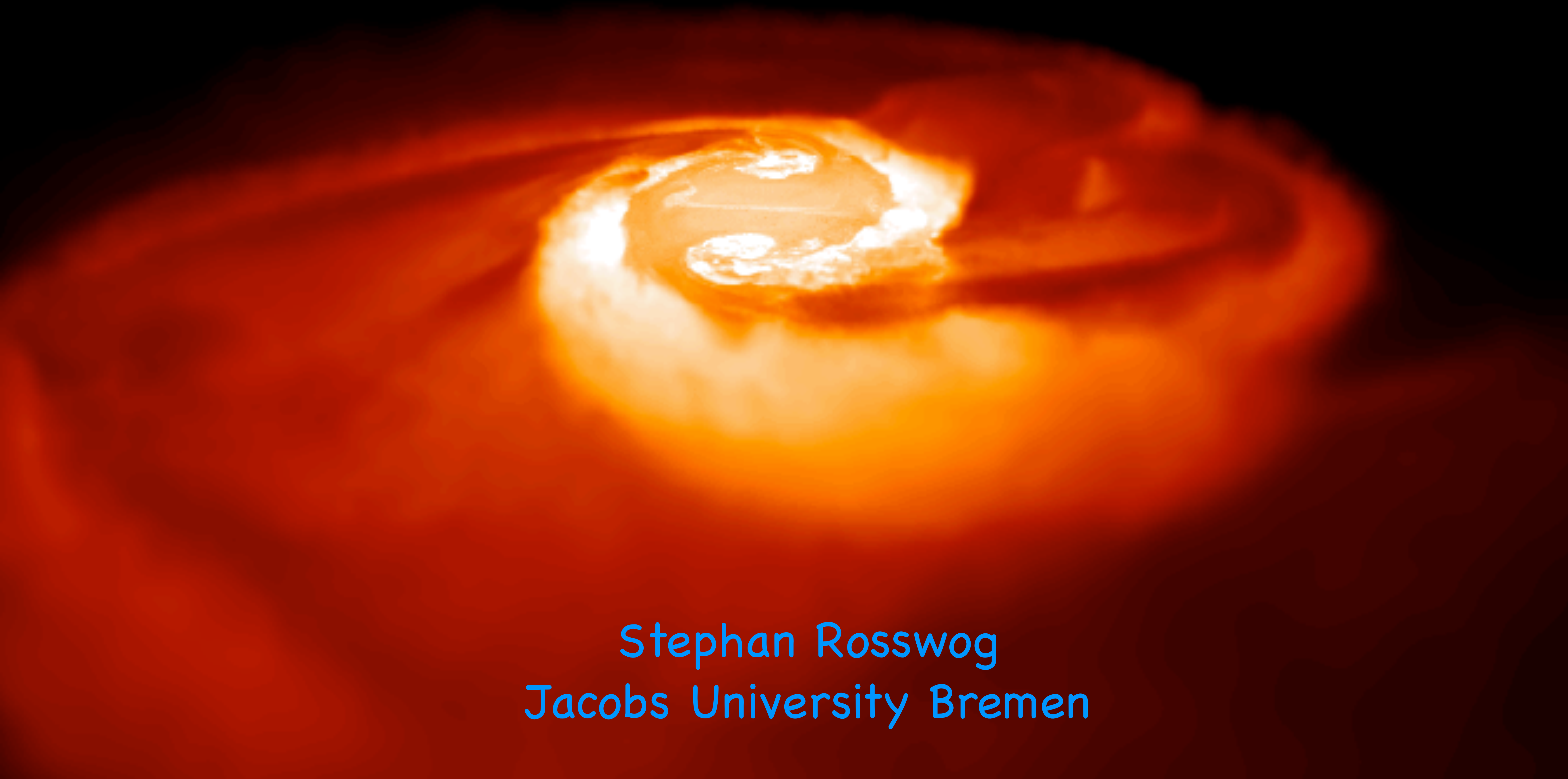
Munich, May 10, 2012

The multi-messenger picture of compact object encounters



Stephan Rosswog
Jacobs University Bremen

Munich, May 10, 2012

The multi-messenger picture of compact object encounters

References:

i) "The multi-messenger picture of compact object encounters", S. Rosswog, T. Piran, E. Nakar, arXiv:1204.6240

ii) "The electromagnetic signals of compact binary mergers", T. Piran, E. Nakar, S. Rosswog, arXiv:1204.6240

iii) "On the astrophysical robustness of neutron star merger r-process", O. Korobkin, S. Rosswog, A. Arcones, C. Winteler, to be submitted

I. Relevance of compact object mergers

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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)
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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?

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  ⇒ accessible volume enhanced by > factor 1000

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Which additional signatures are produced by compact object encounters?

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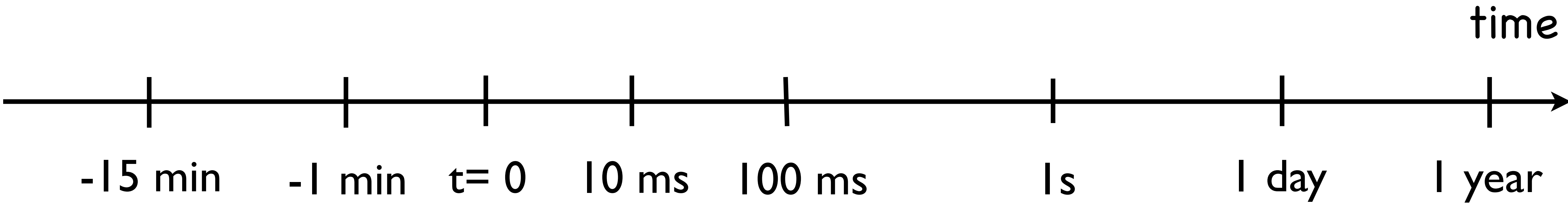
Compact binary mergers: multi-physics events



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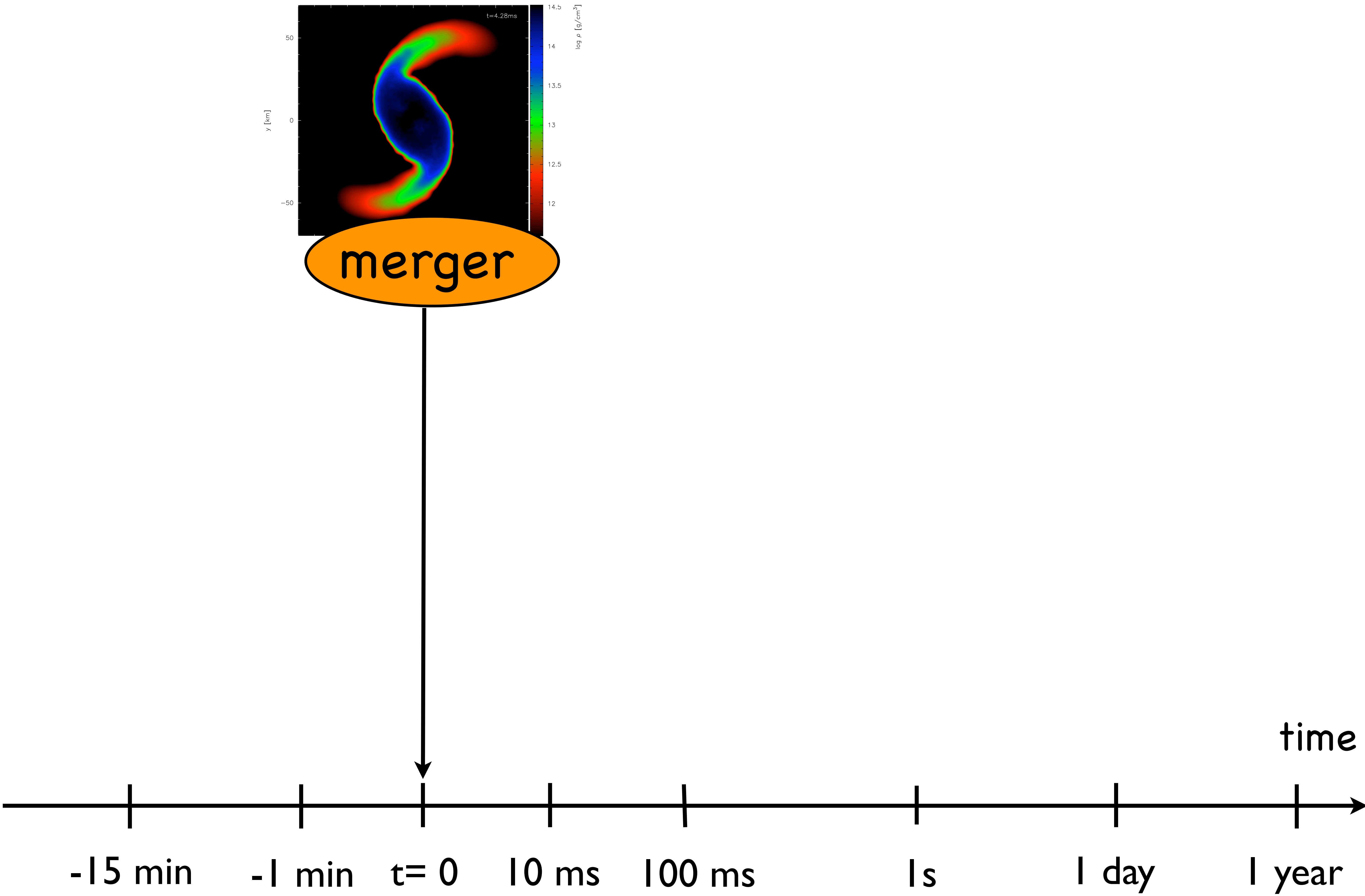

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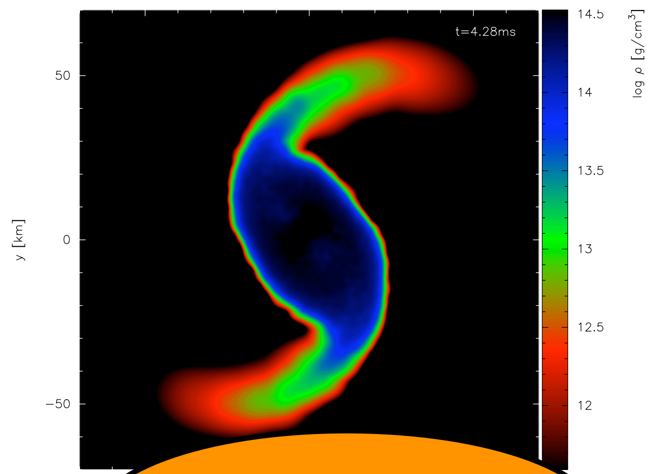
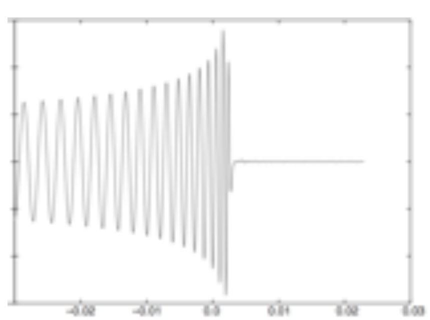


merger



gravitational wave emission

time

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

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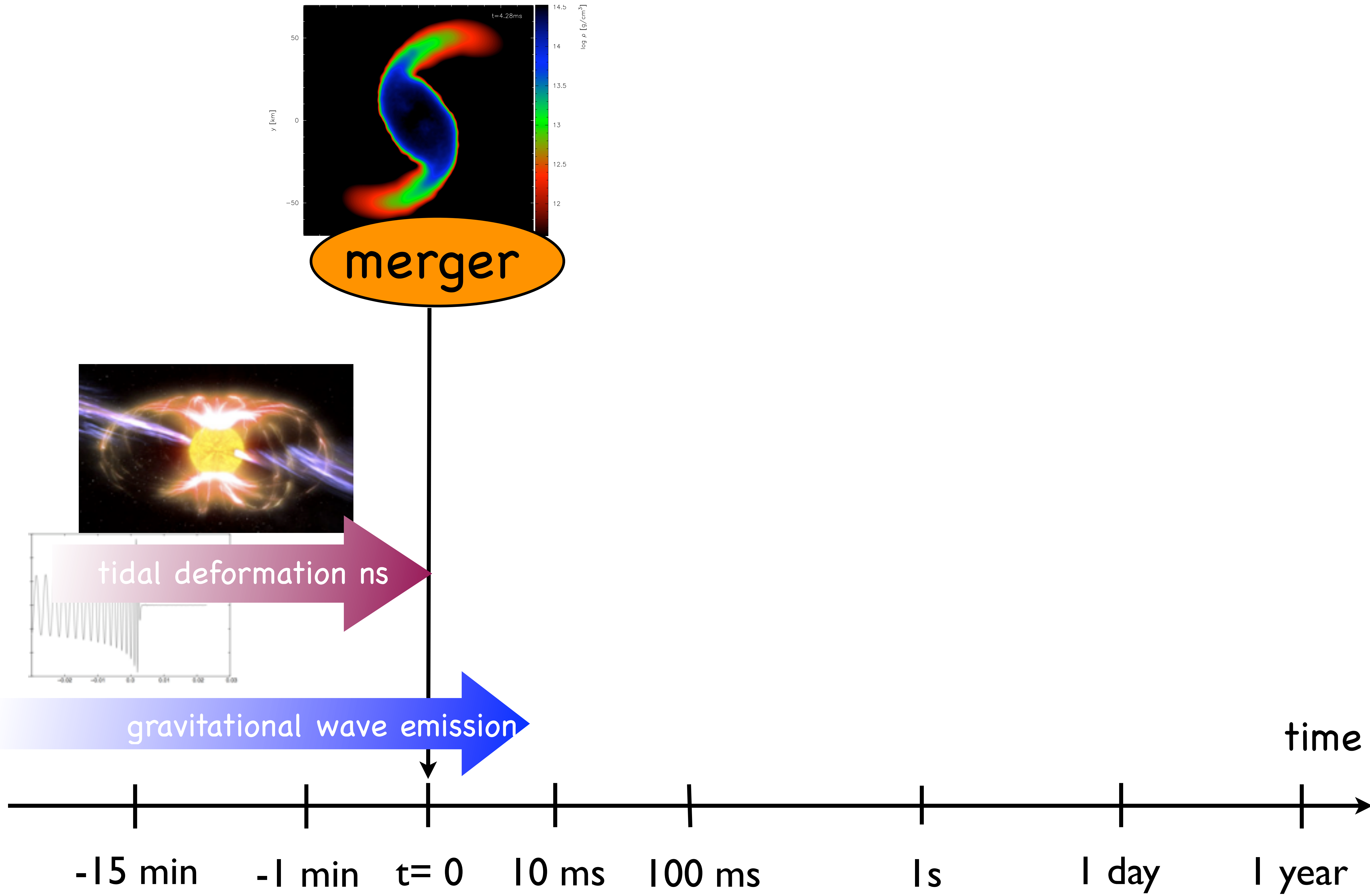

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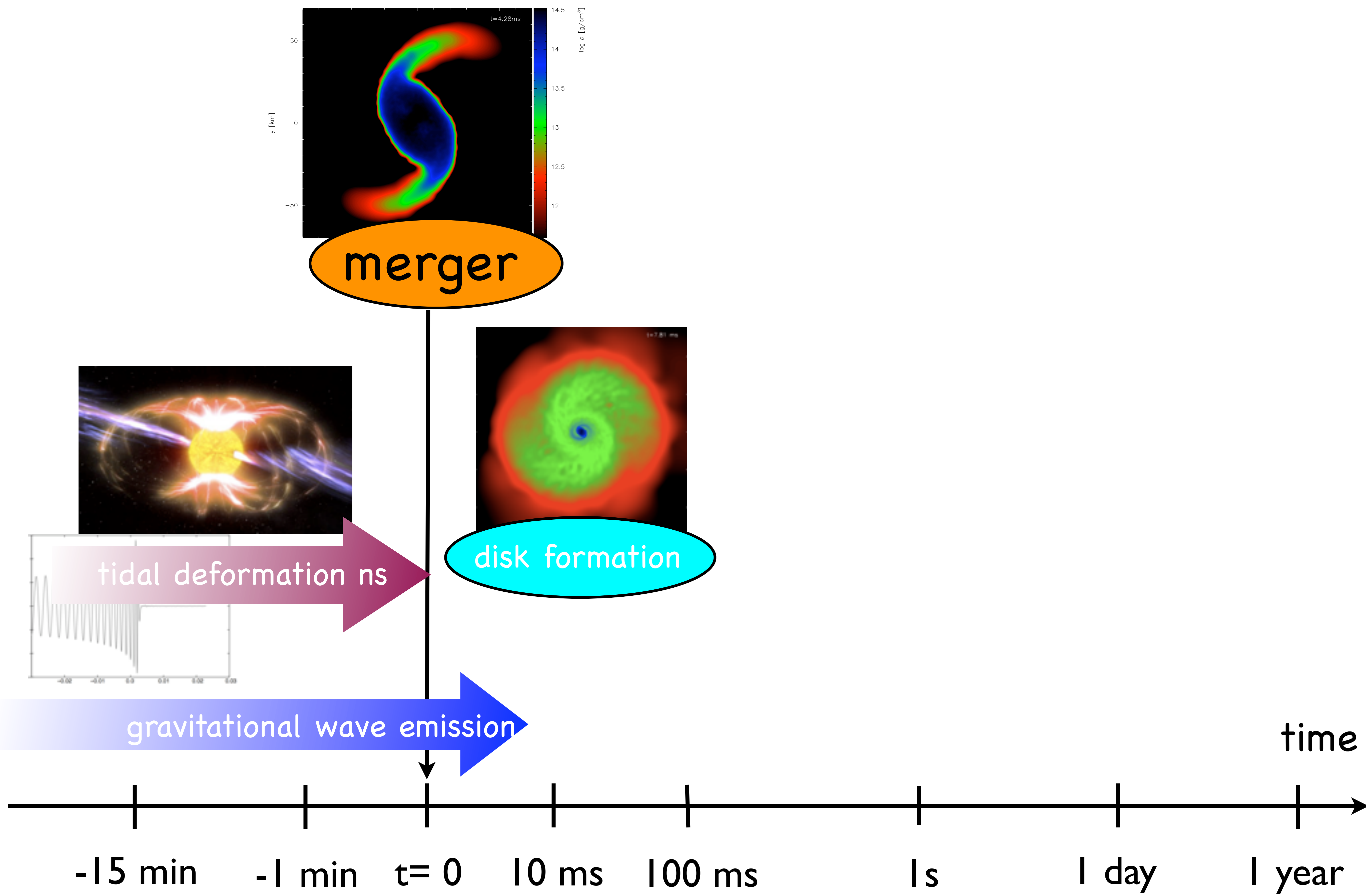

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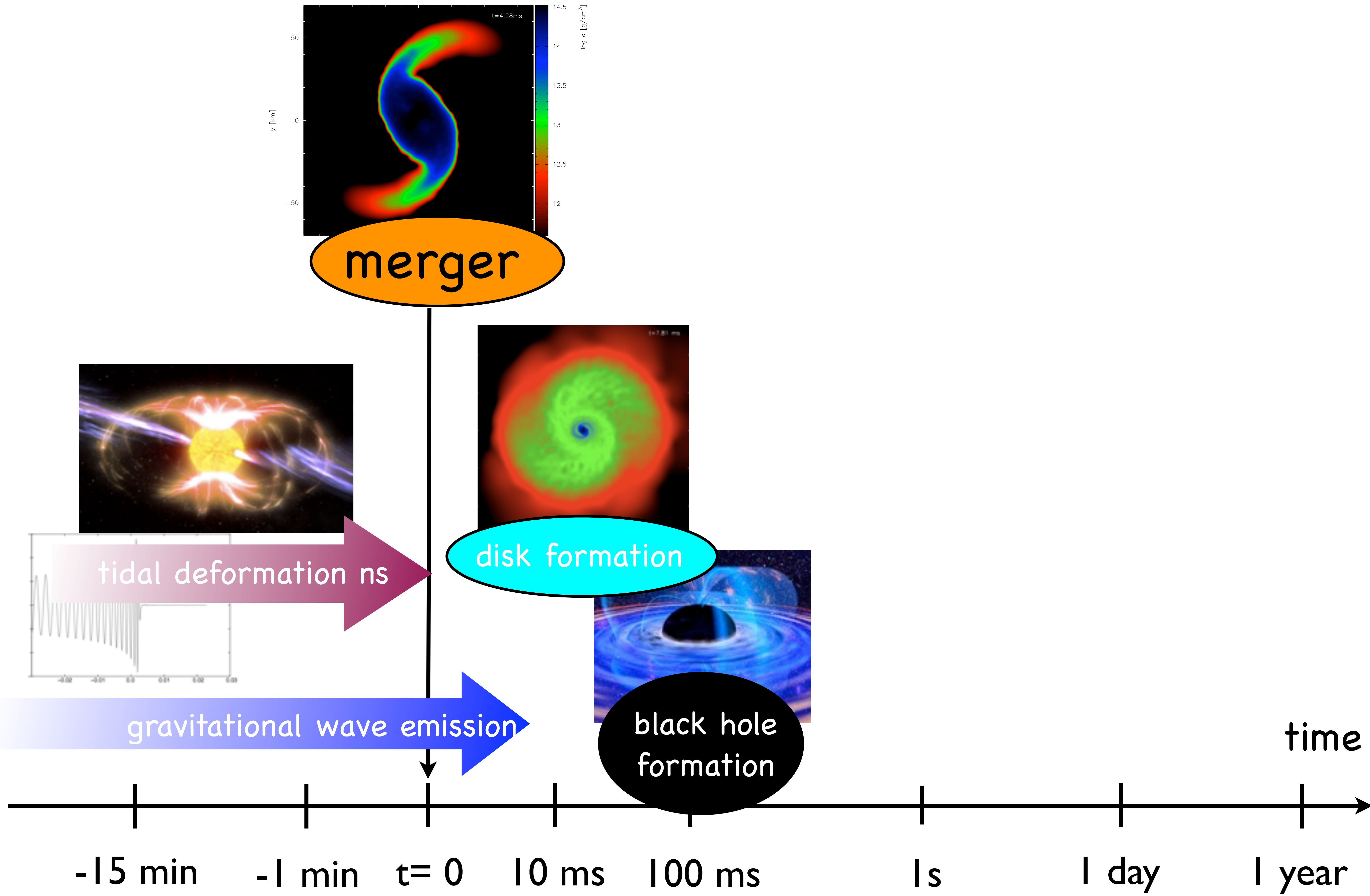

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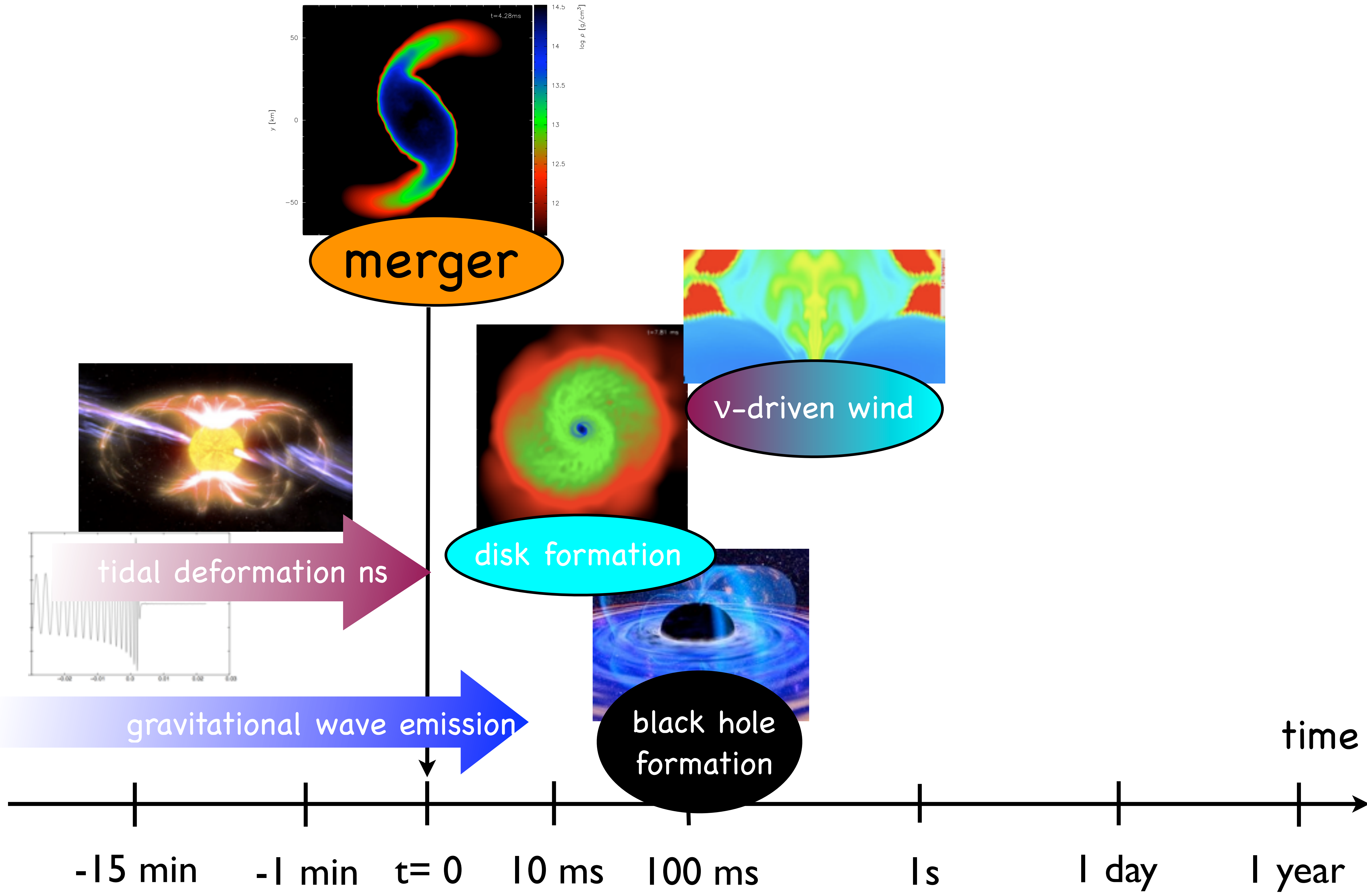

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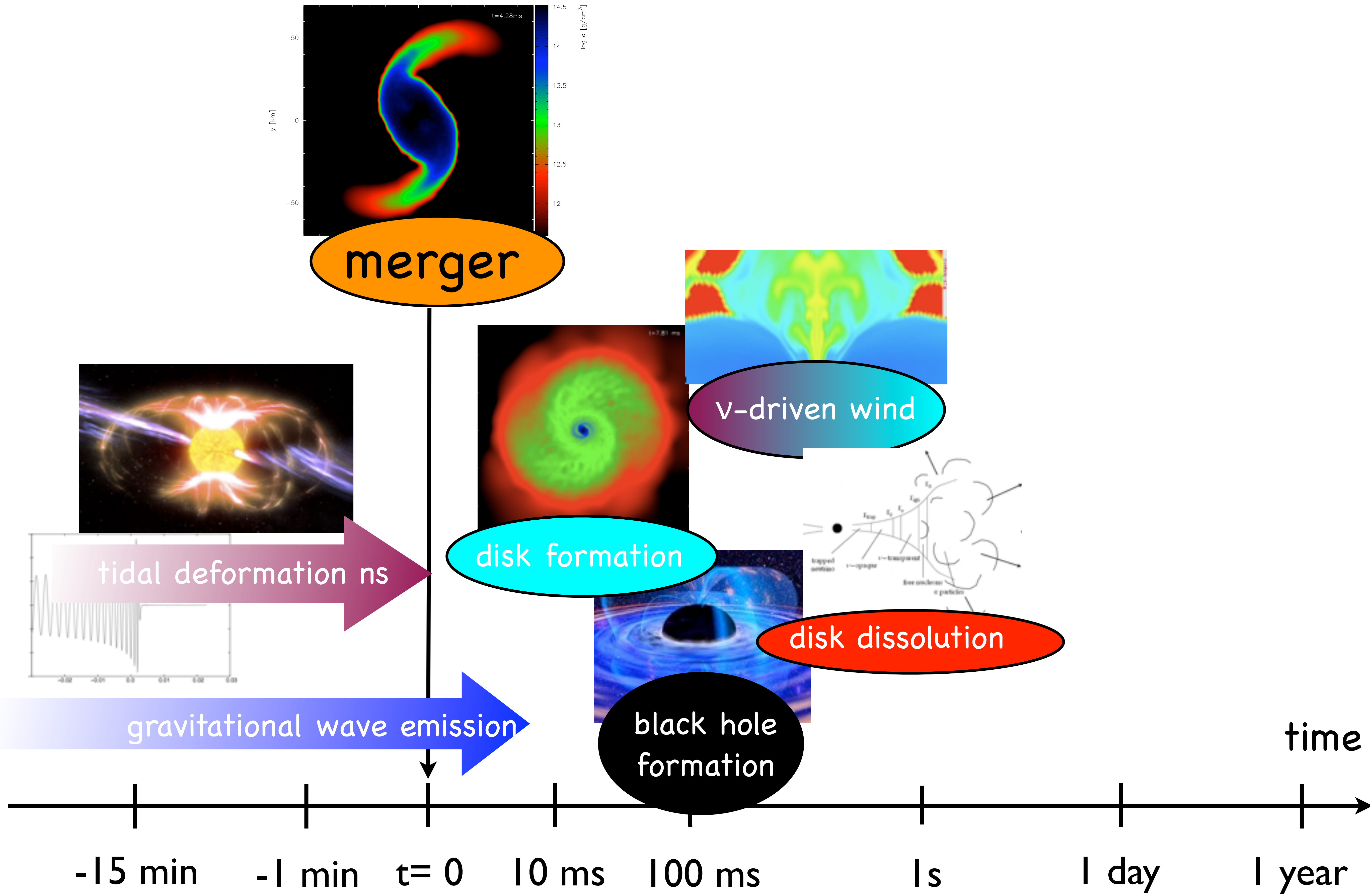

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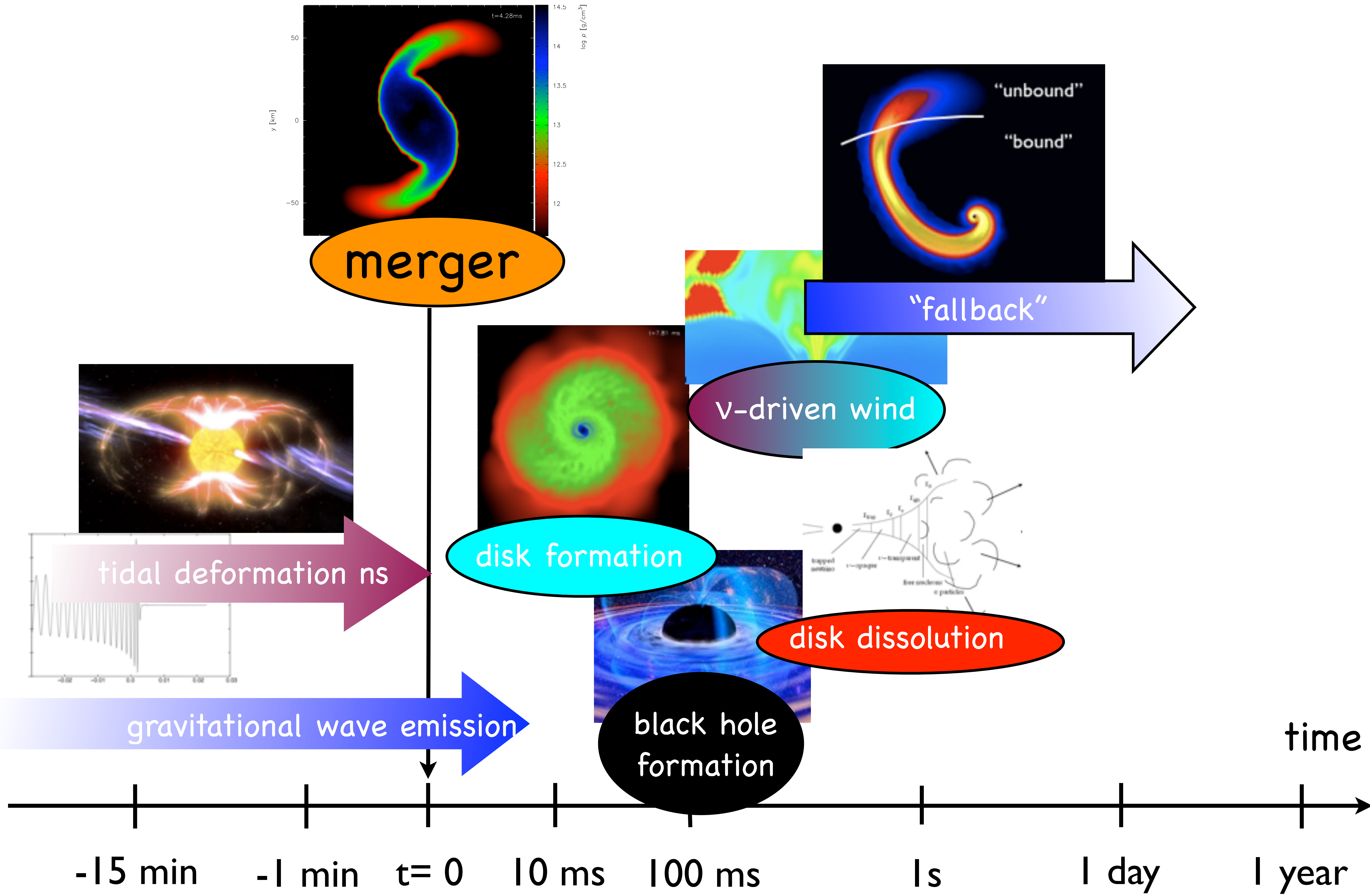

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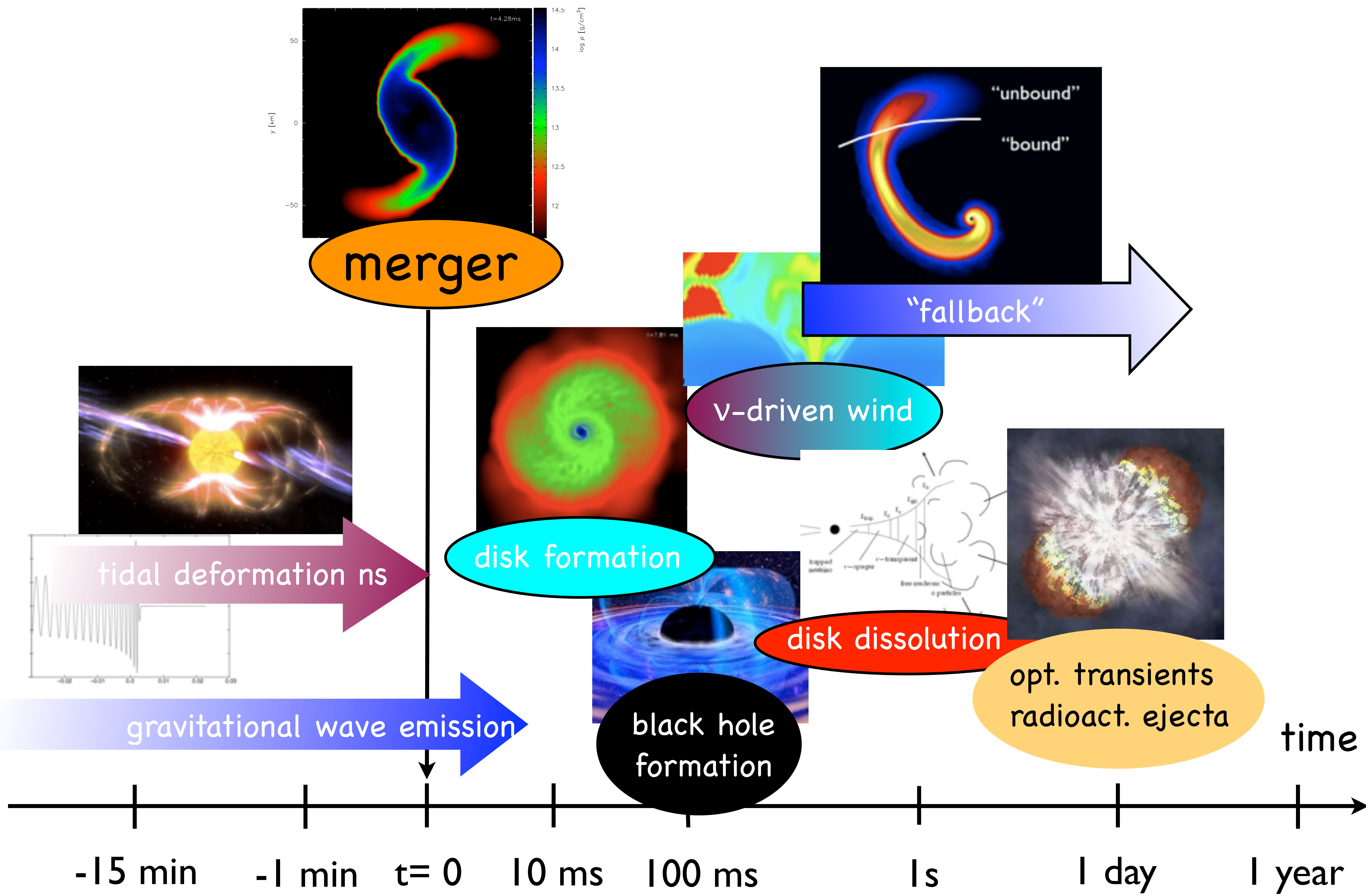

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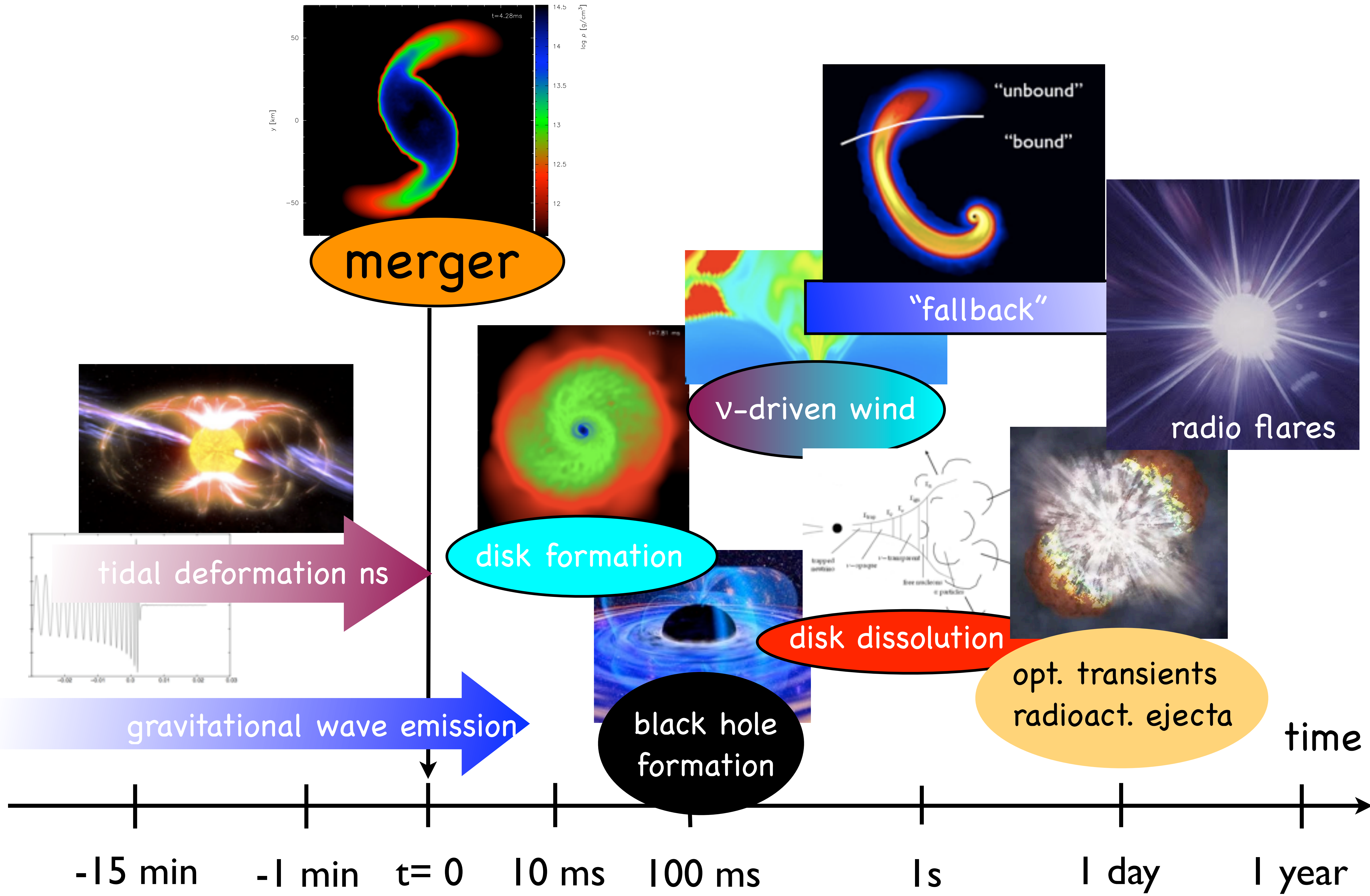

Various signatures

- gravitational waves
- neutrinos
- prob. short GRBs
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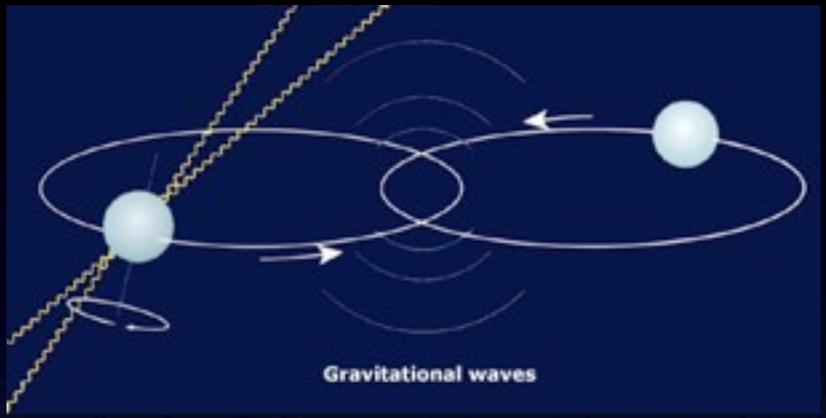
} related to ejecta properties

II. Results

1. Types of encounters

A) gravitational wave-driven nsns binary mergers

- main focus
- PSR 1913+16-like
- eccentricity ≈ 0 at merger



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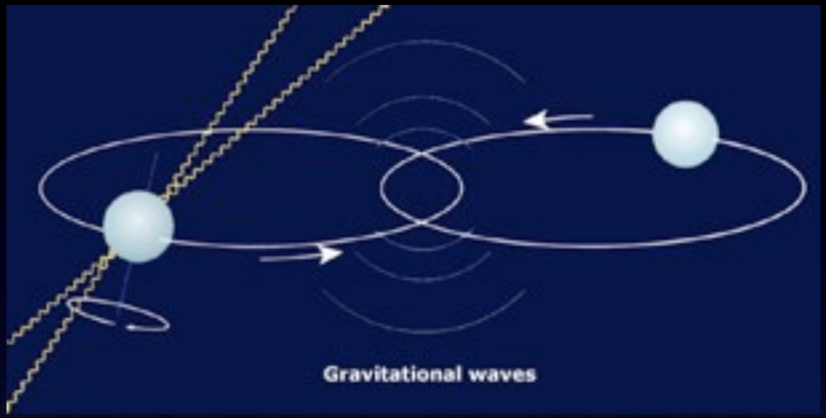
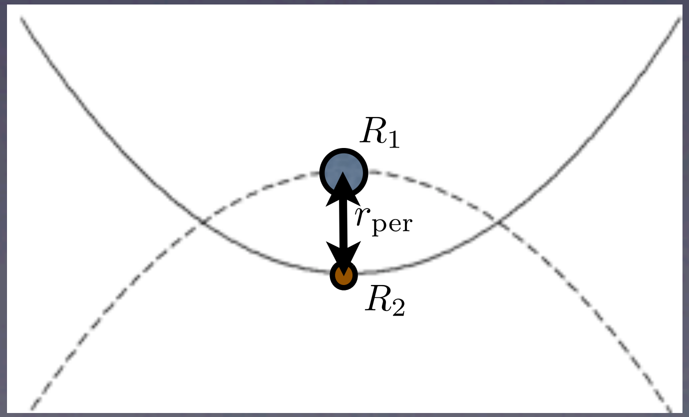


B) dynamic collisions

- e.g. in globular clusters/galactic nuclei (Lee et al.2010)
- study parabolic encounters with impact strength

$$\beta = \frac{R_1 + R_2}{r_{peri}}$$



"grazing": $\beta = 1$

"strong": $\beta > 1$

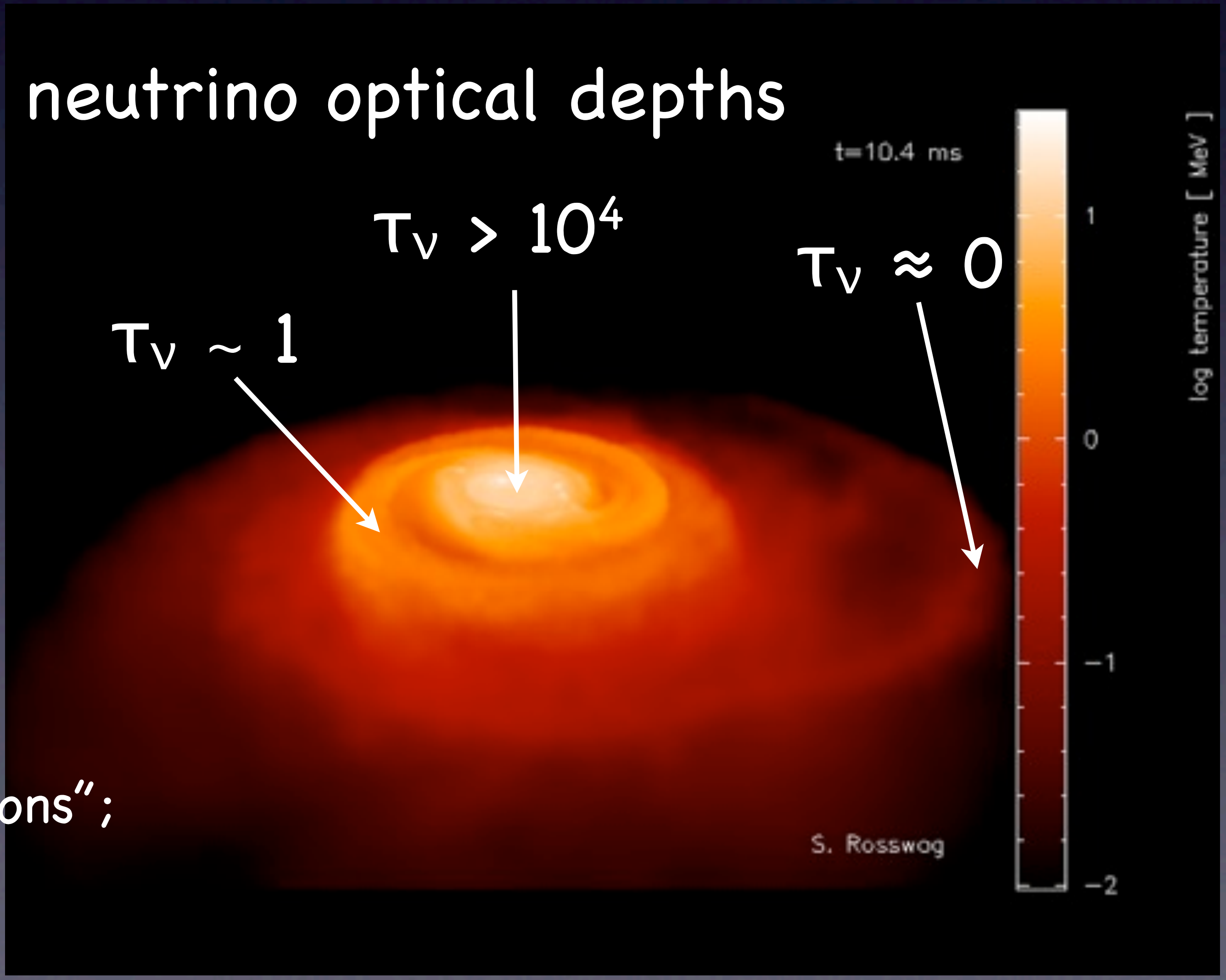
"weak": $\beta < 1$

2. 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))

3. Morphology

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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

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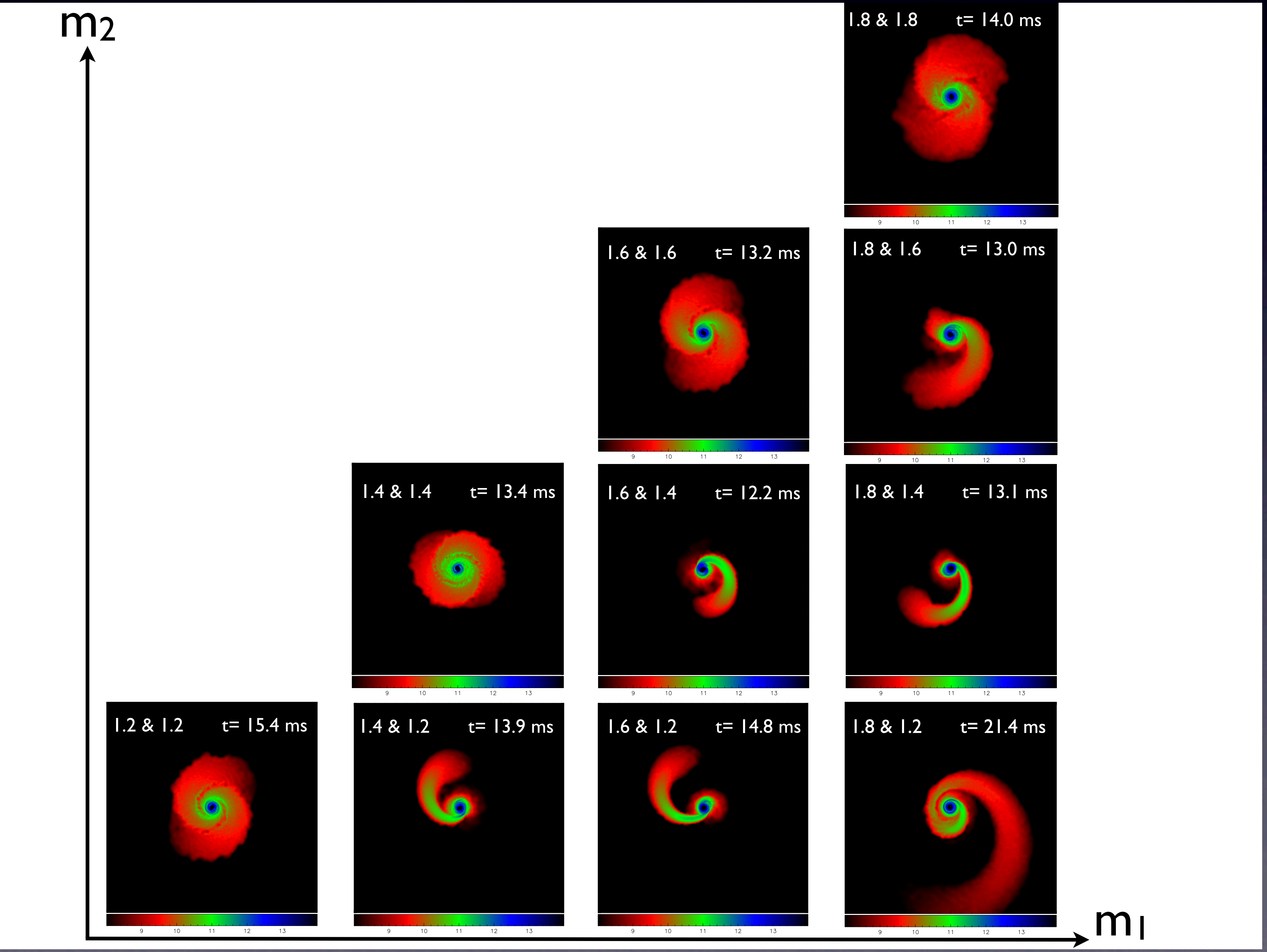

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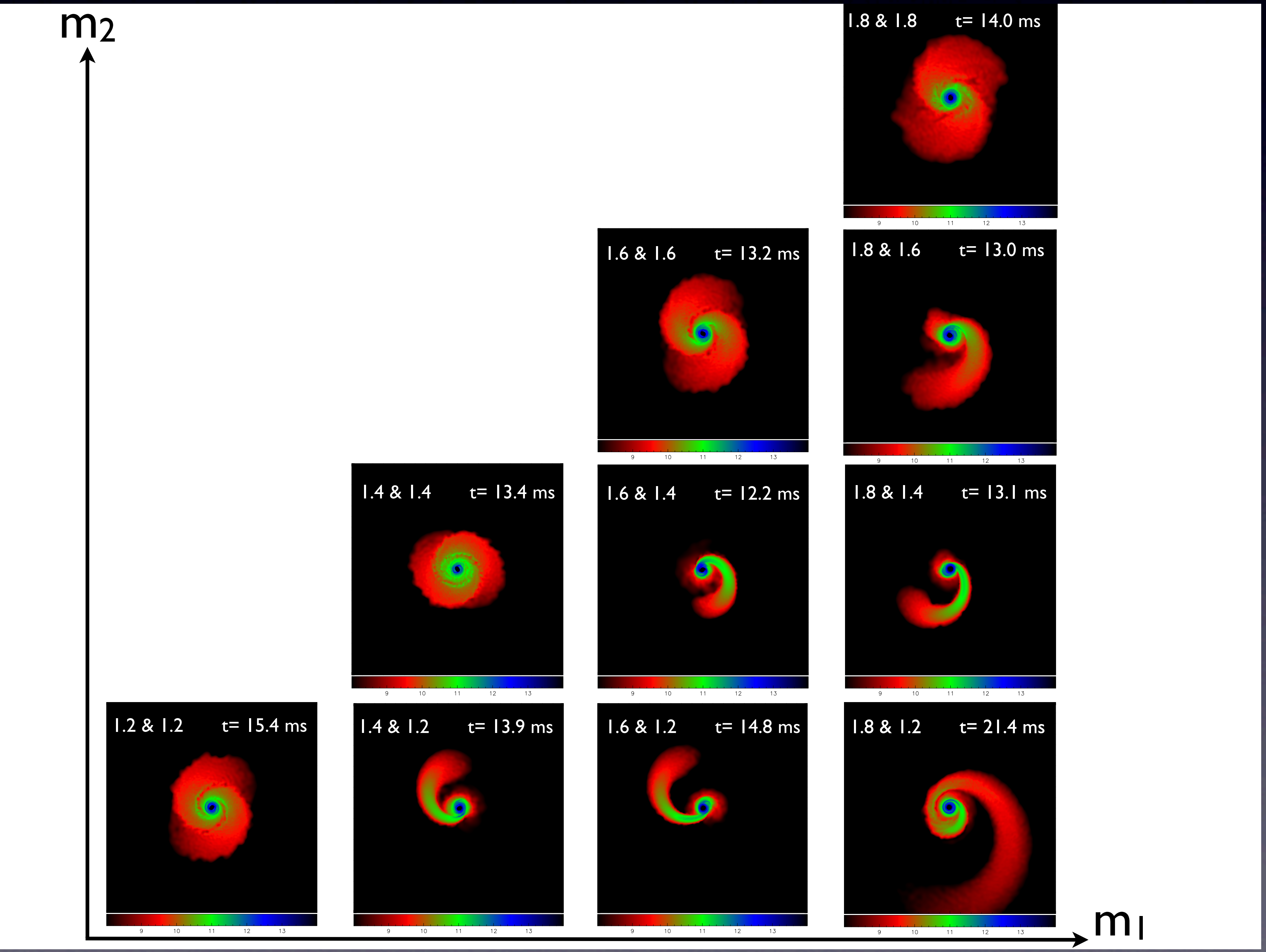

asymmetry in masses leads to:

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

⇒larger el.mag. luminos.

("macronovae", radio flares)

“standard case”

- masses close to 1.4 M_{sol}, slight asymmetry (1.3 and 1.4 M_{sol})
- zero initial spins
- stars in cold β-equilibrium
- simulated time ~ 15 ms
- visualized: log(T [MeV]) at given opt. depth

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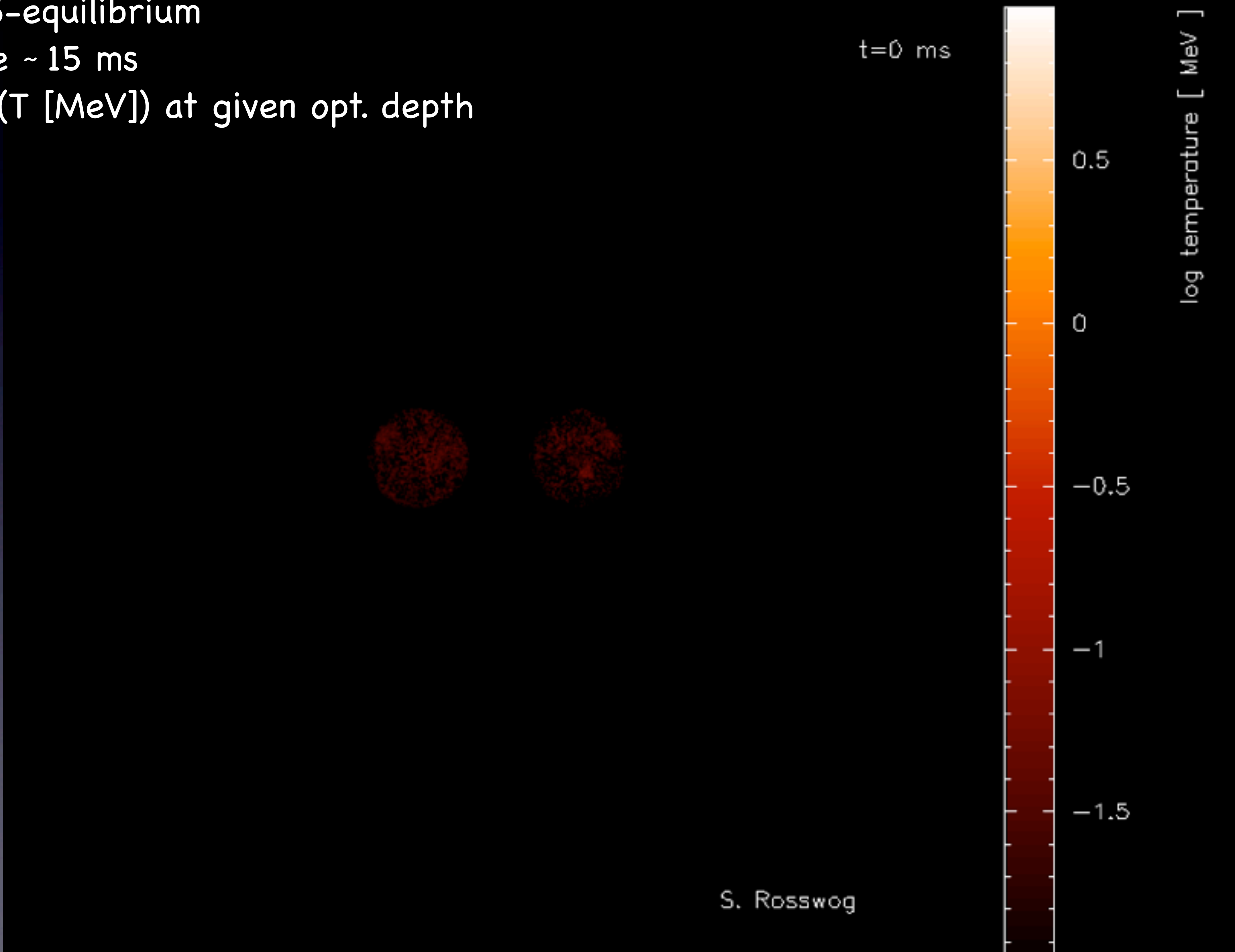

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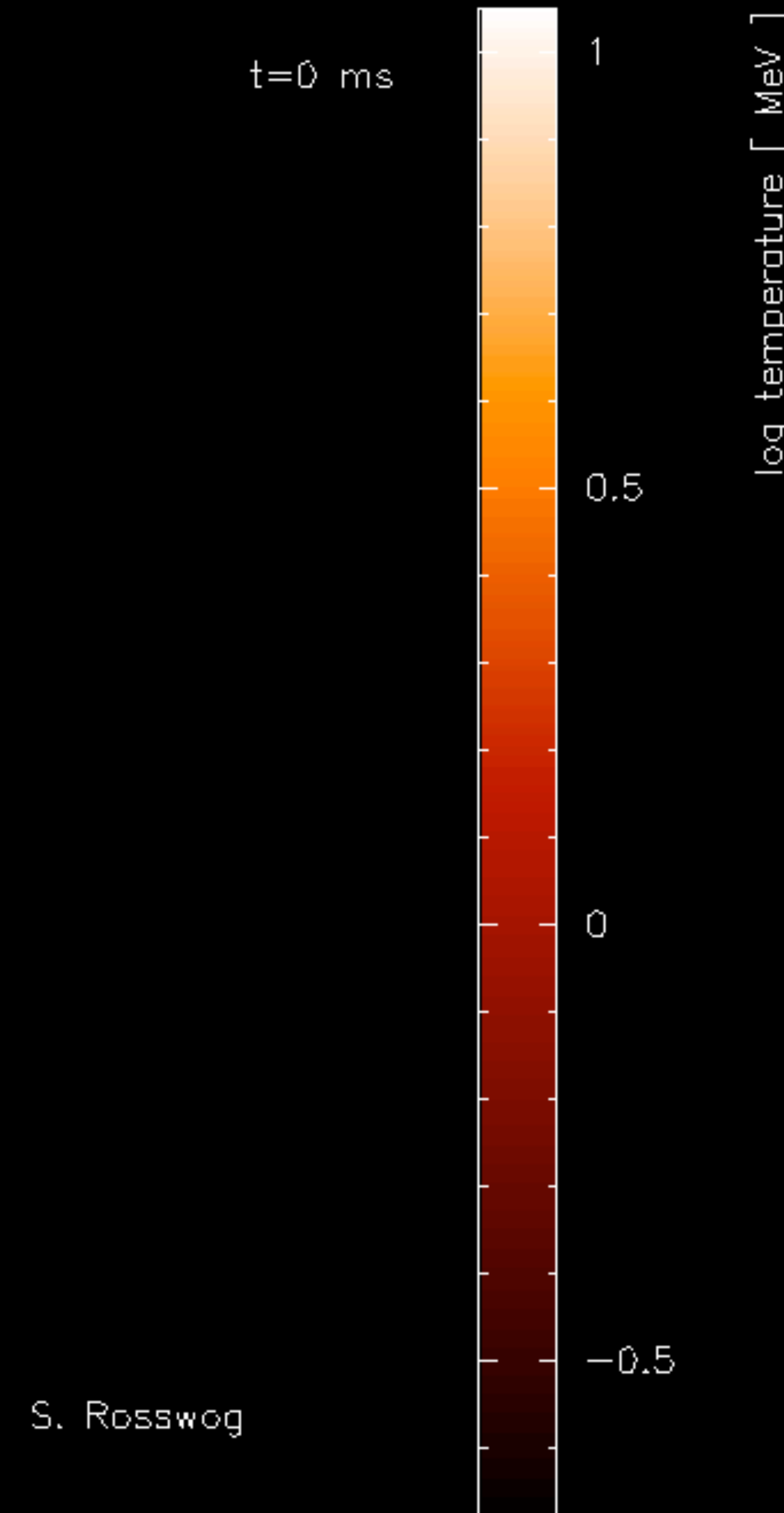
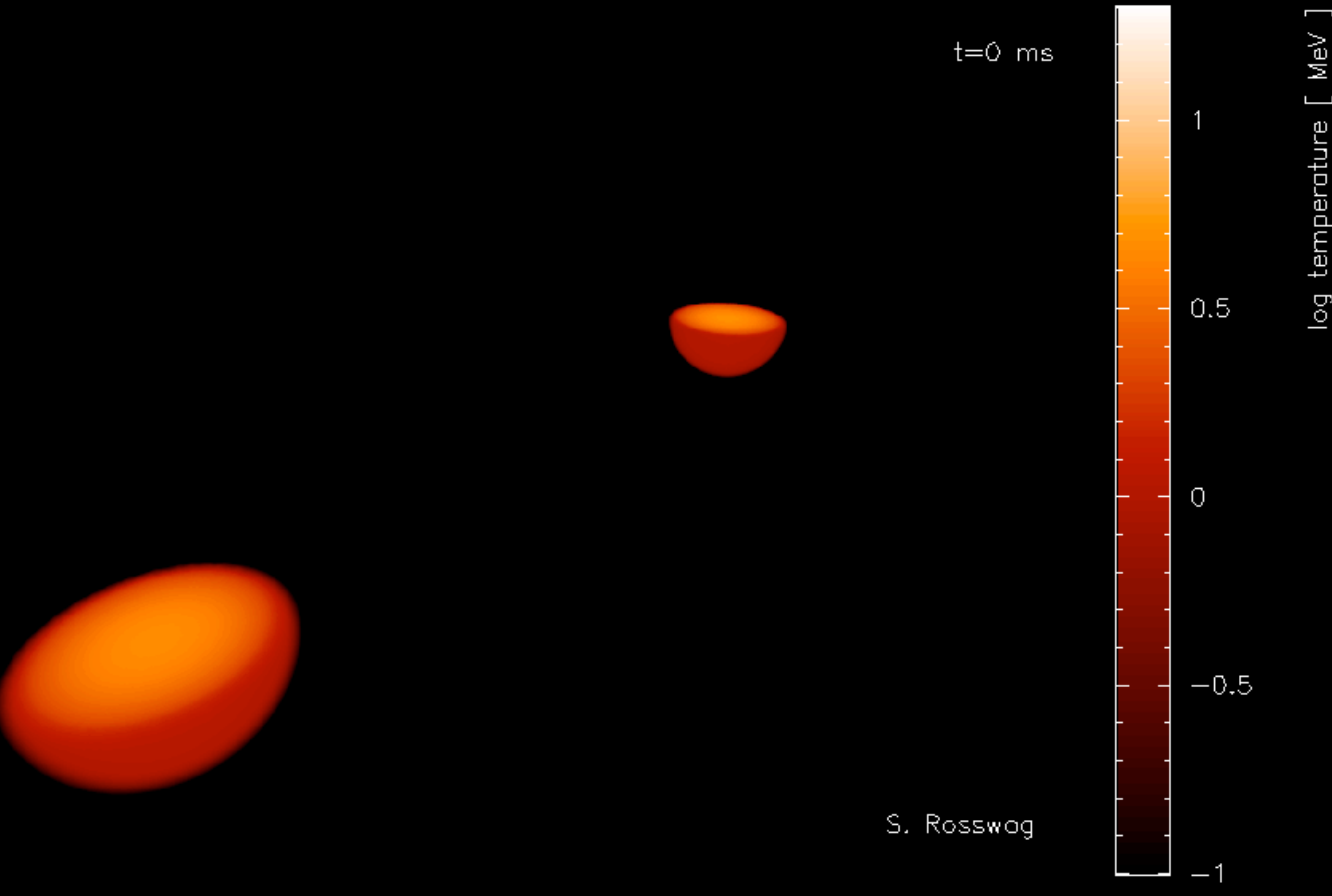
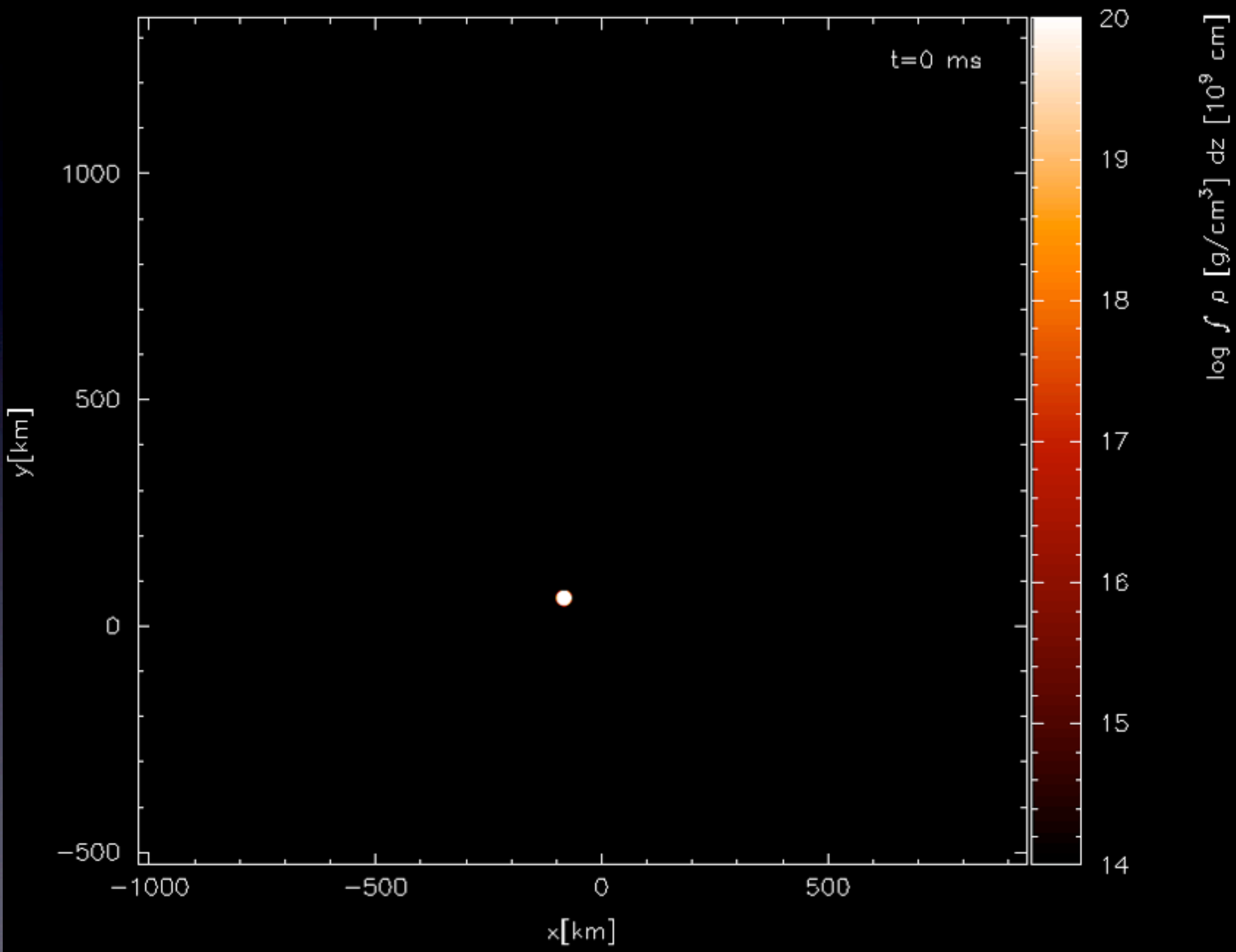


more central impact, $\beta=2$



neutron star (1.4 M_{sol}) - black hole (5 M_{sol}) collision, β=1 neutron star (1.4 M_{sol}) - black hole (5 M_{sol}) collision, β=1



4. Various outflows...

- outflows from hyper-accreting black hole: ultra-relativistic jets, mildly relativistic outflows
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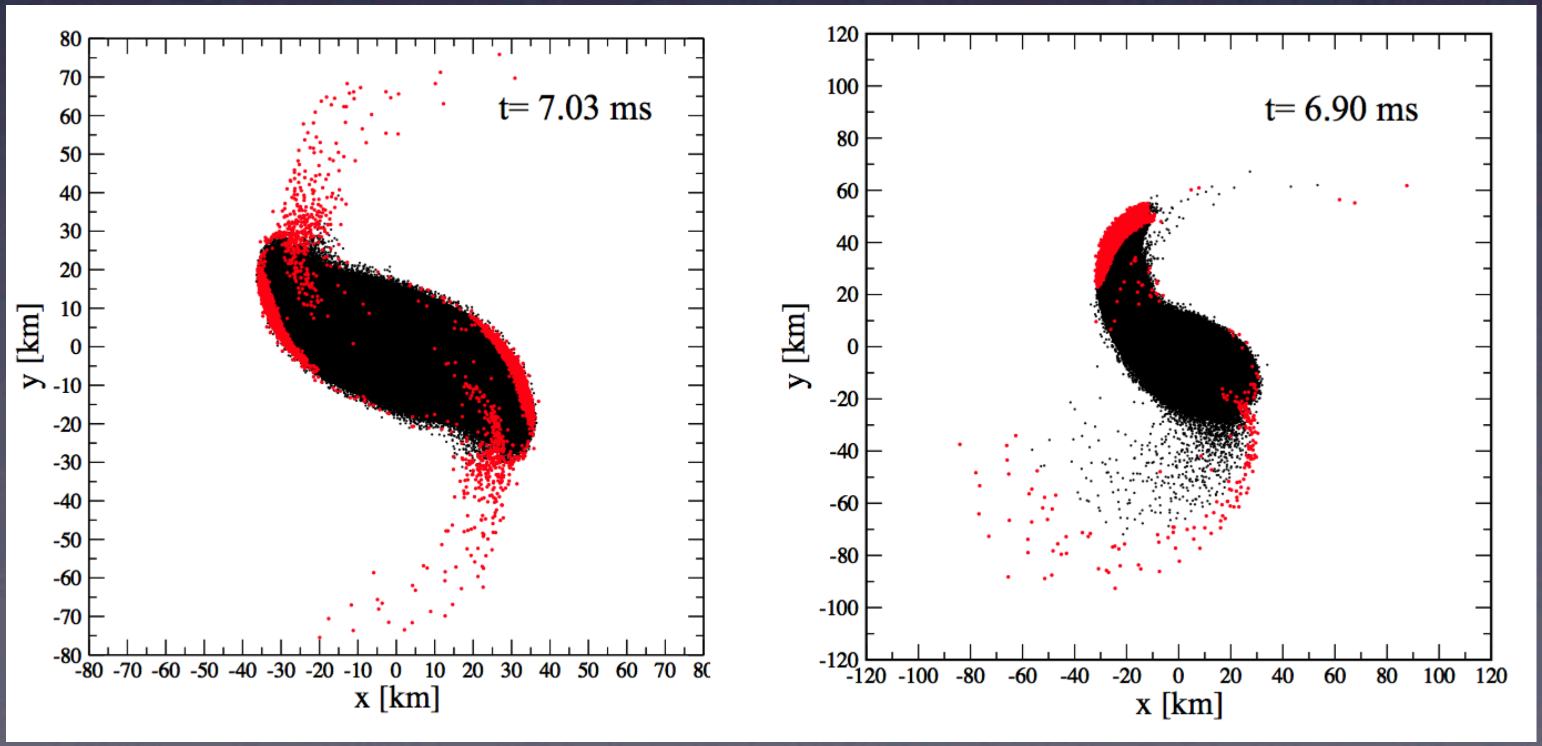

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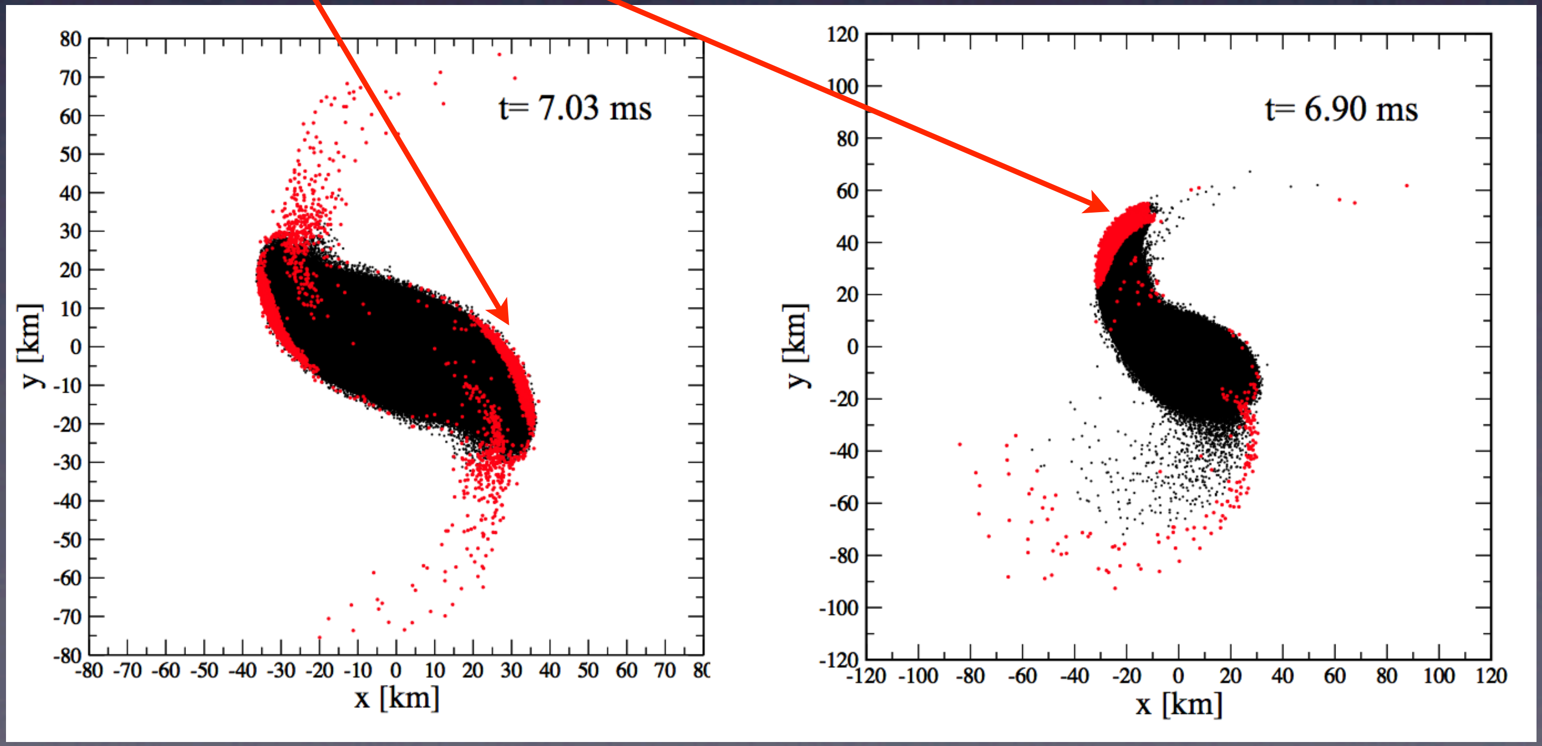
"tidal component"

- dynamic ejecta



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"interaction component"

"tidal component"

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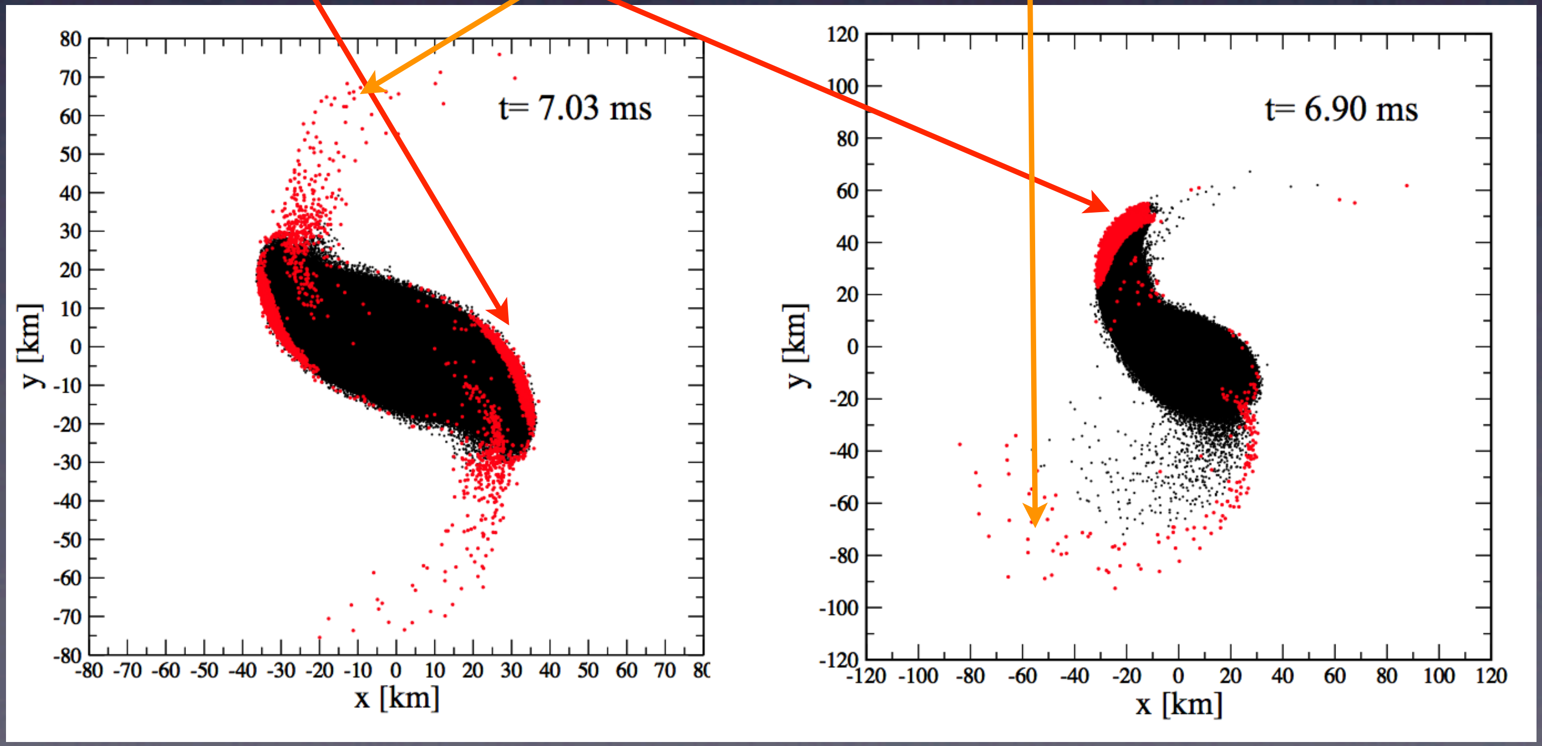

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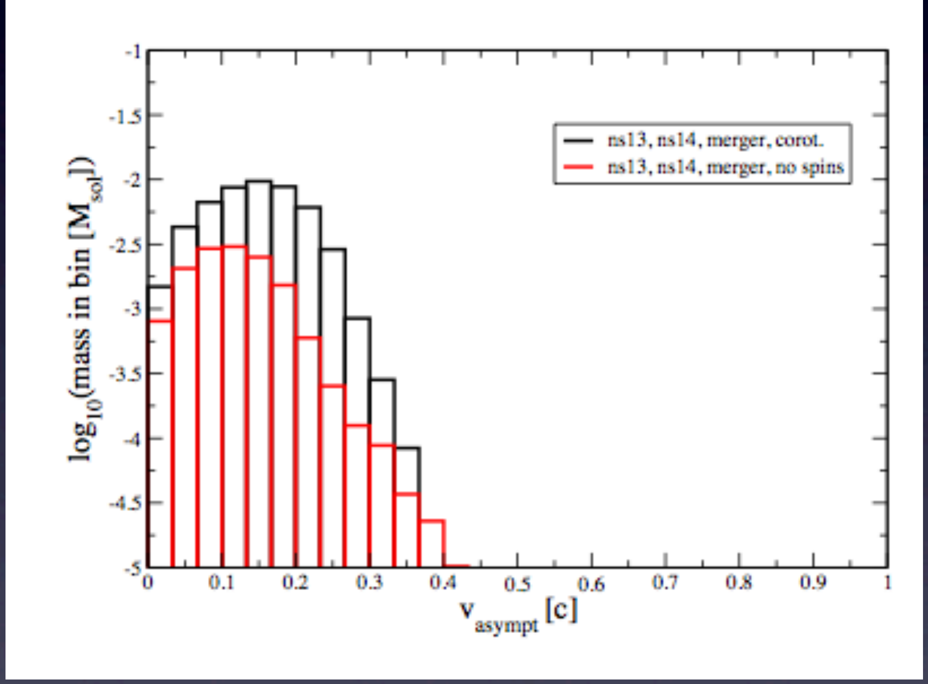

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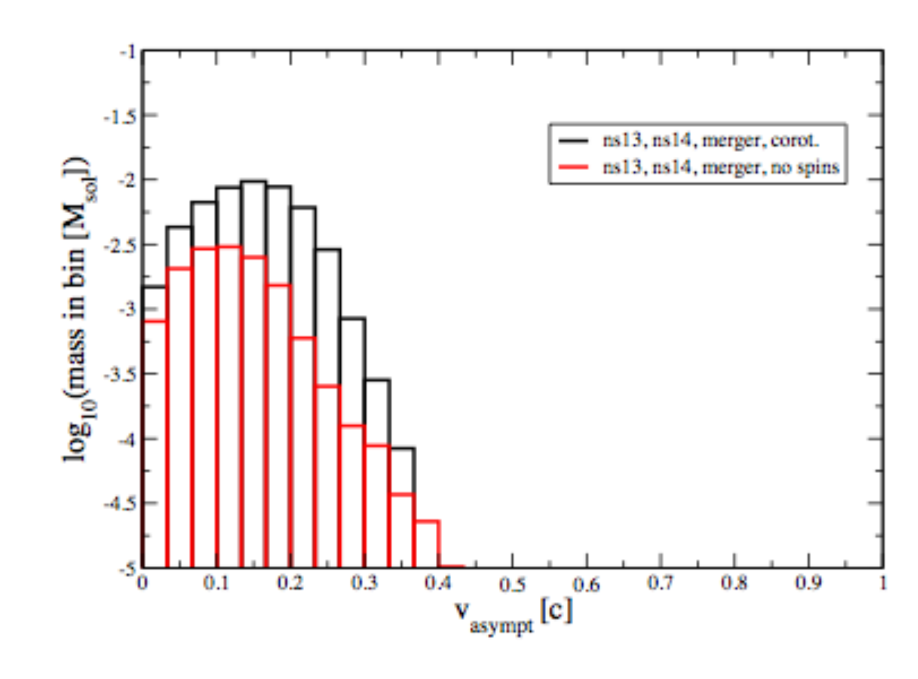

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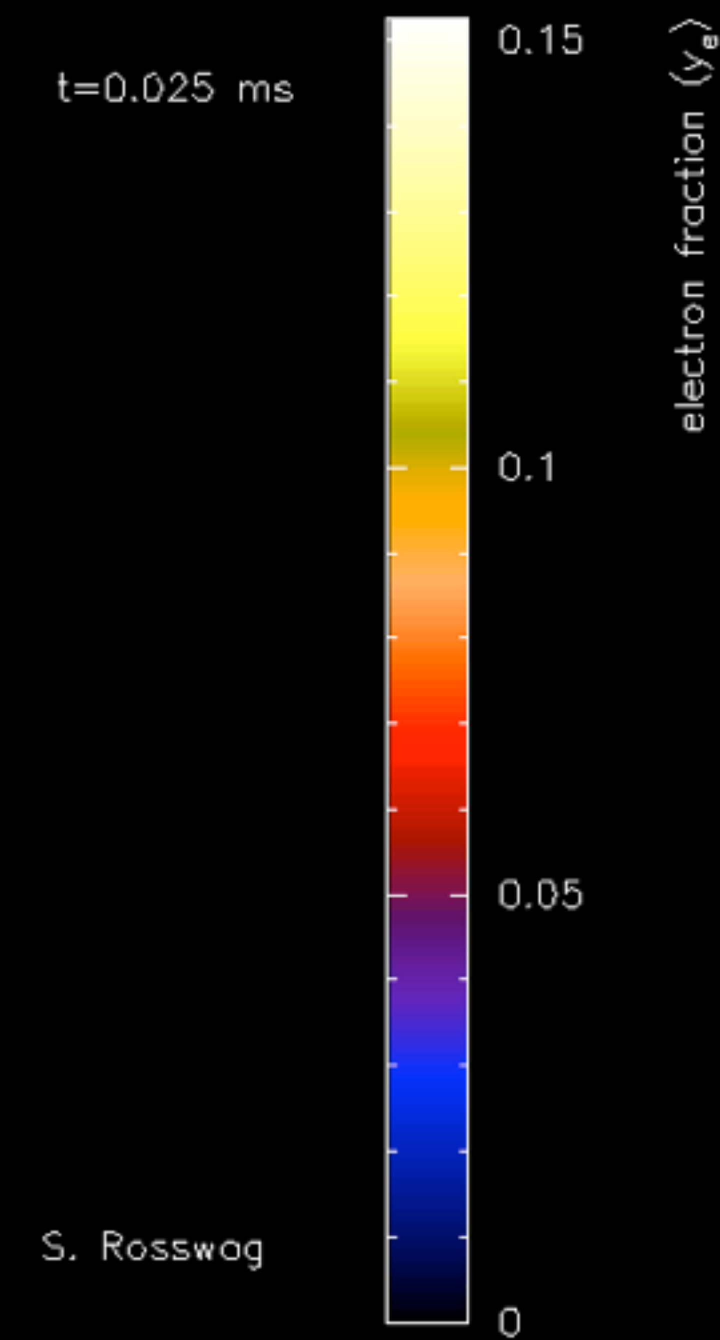

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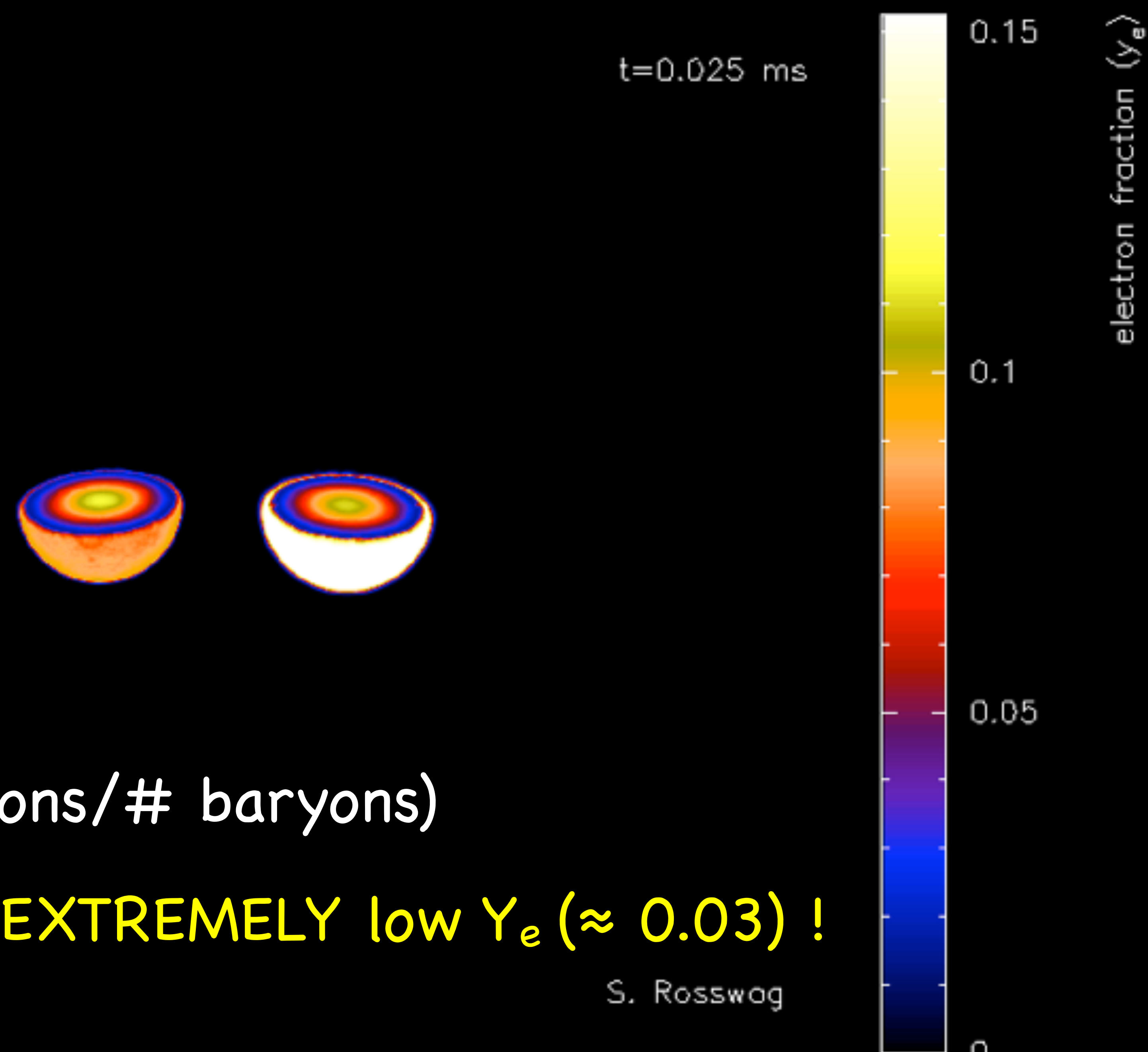

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  ⇒ bulk of matter ejected at EXTREMELY low Y_e (≈ 0.03) !

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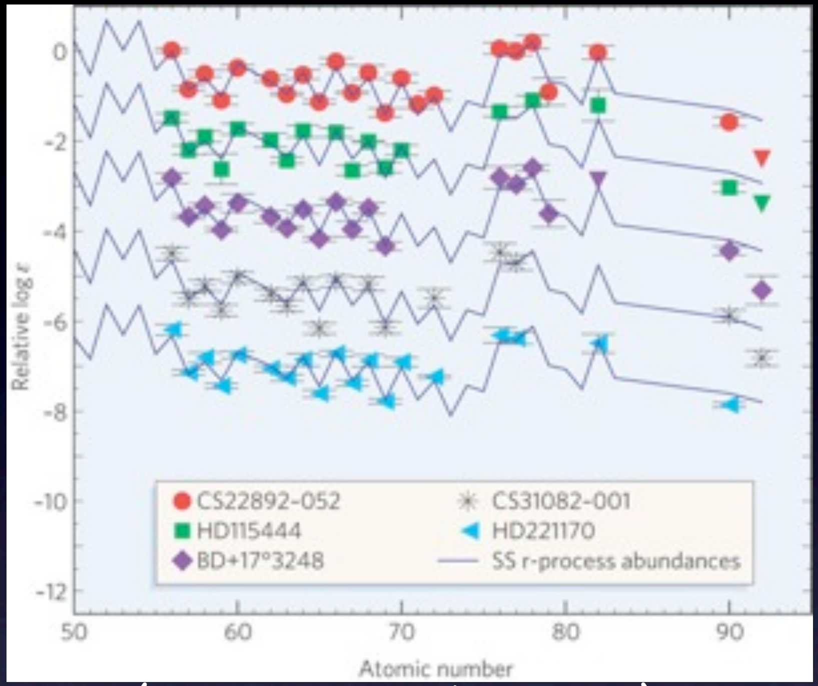

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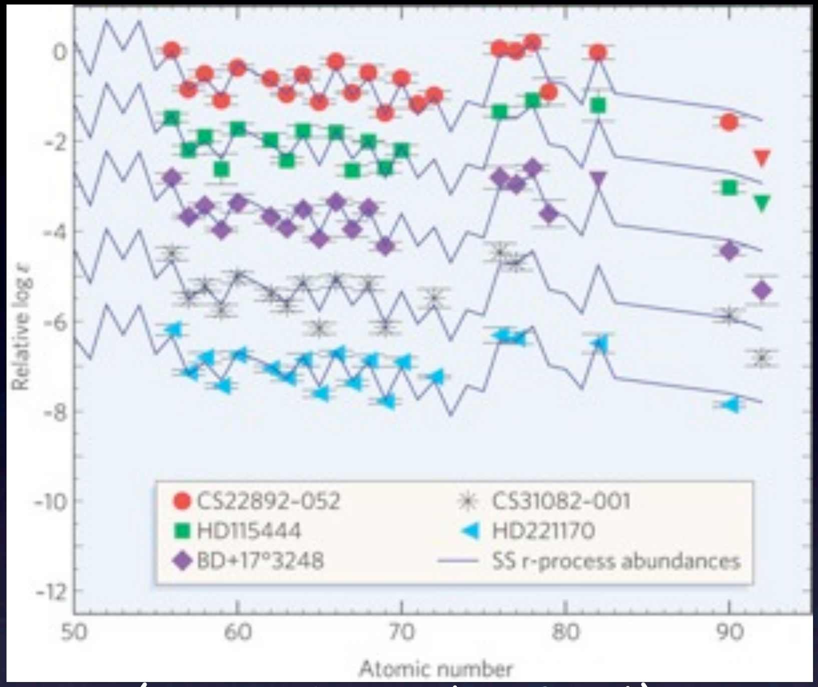

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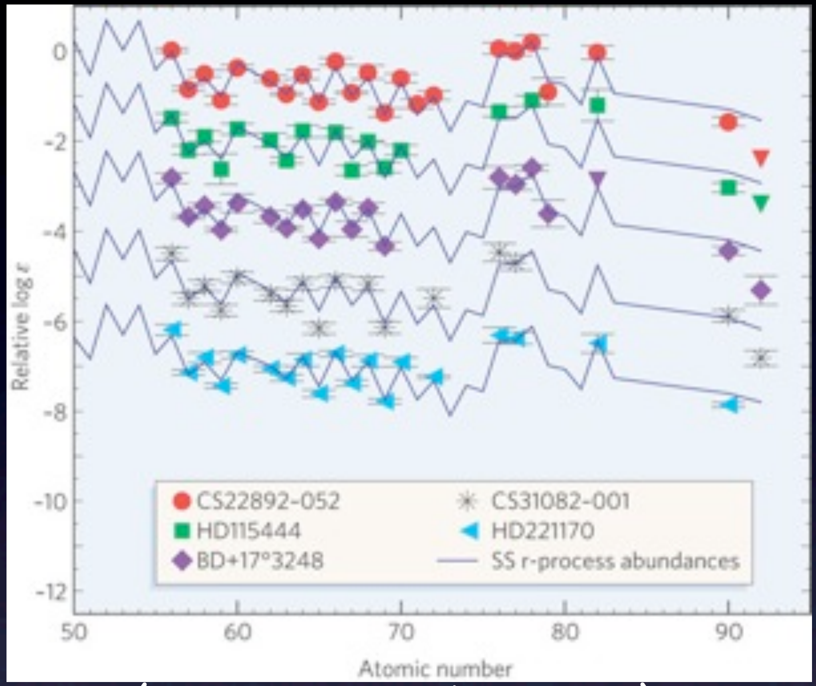

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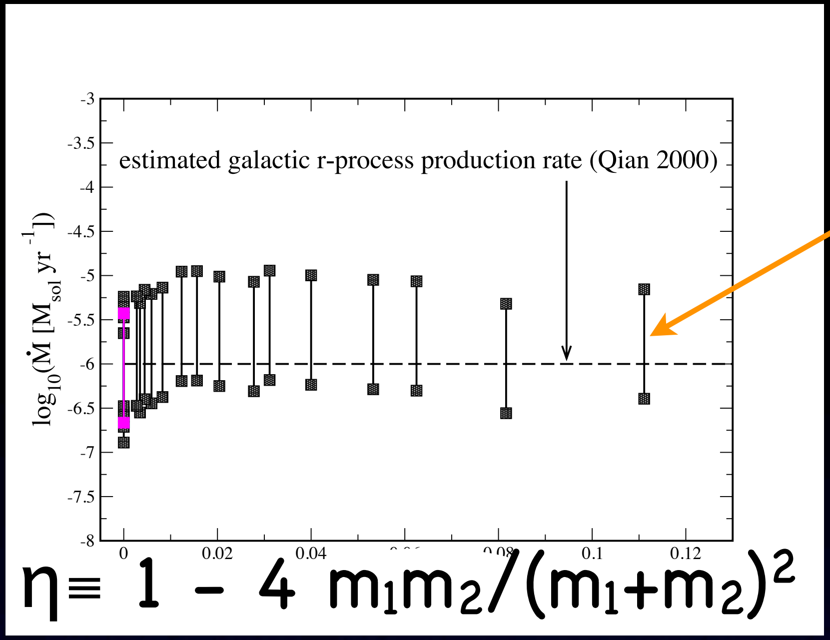
  (e.g. Arcones & Janka 2007, et al. 2010, Fischer et al. 2010)

- 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...)

- enough ejected to be interesting?



ejecta mass x rate interval

(95%, Kalogera et al. 2004)

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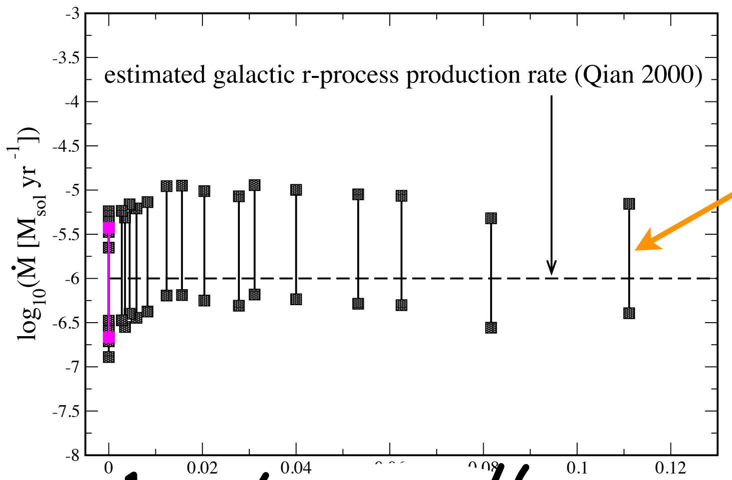

$\eta \equiv 1 - 4\, m_1 m_2/(m_1+m_2)^2$

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$\Rightarrow$ nsns mergers eject enough to be a major r-process source

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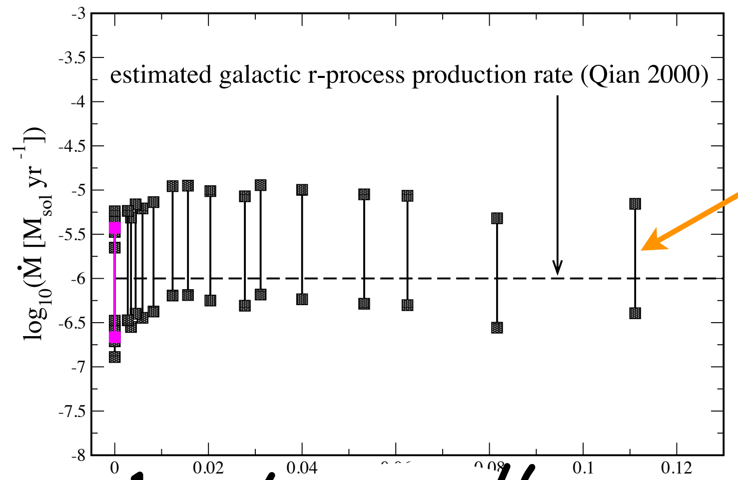

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ejecta mass x rate interval

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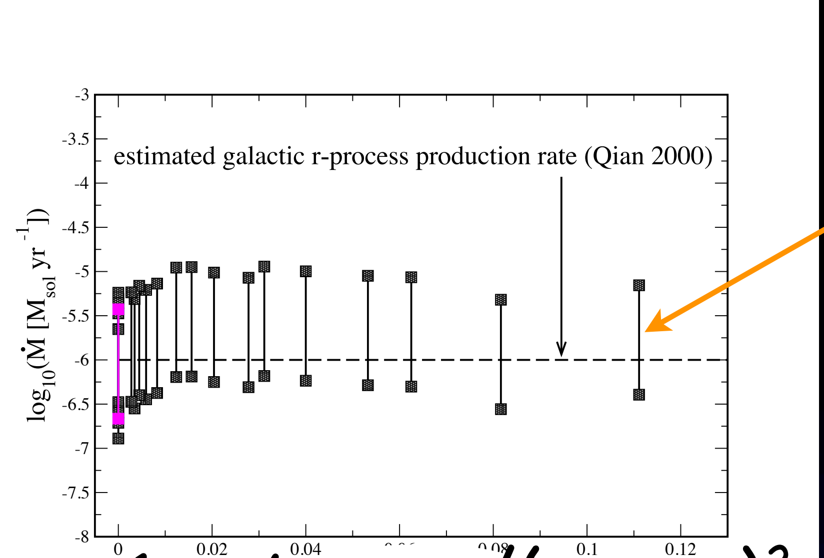
⇒ nsns mergers eject enough to be a major r-process source

⇒ collisions eject much more (up to 0.15 M_{sol}), must be rare (R_{coll} < 0.1 R_{merger})

- enough ejected to be interesting?



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ejecta mass x rate interval

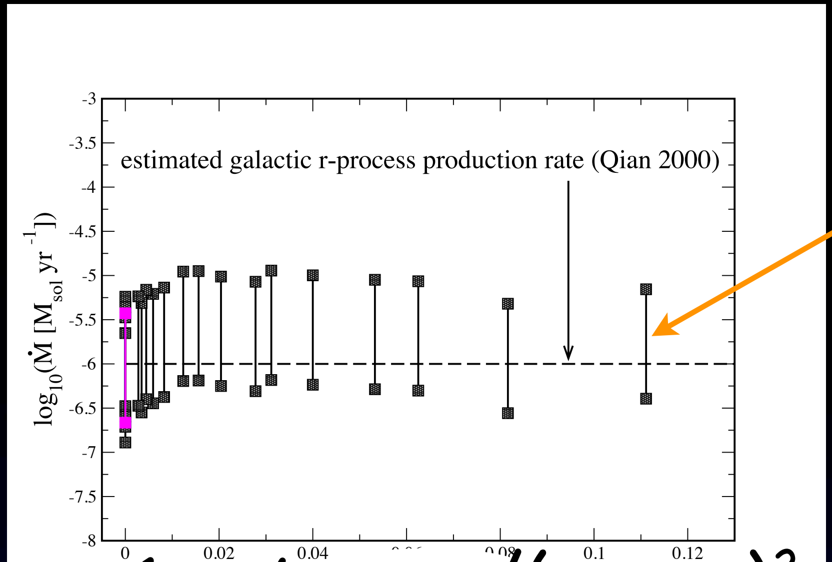
(95%, Kalogera et al. 2004)

⇒ nsns mergers eject enough to be a major r-process source

⇒ collisions eject much more (up to 0.15 M_{sol}), must be rare (R_{coll} < 0.1 R_{merger})

- r-process for neutron star merger ejecta

- enough ejected to be interesting?



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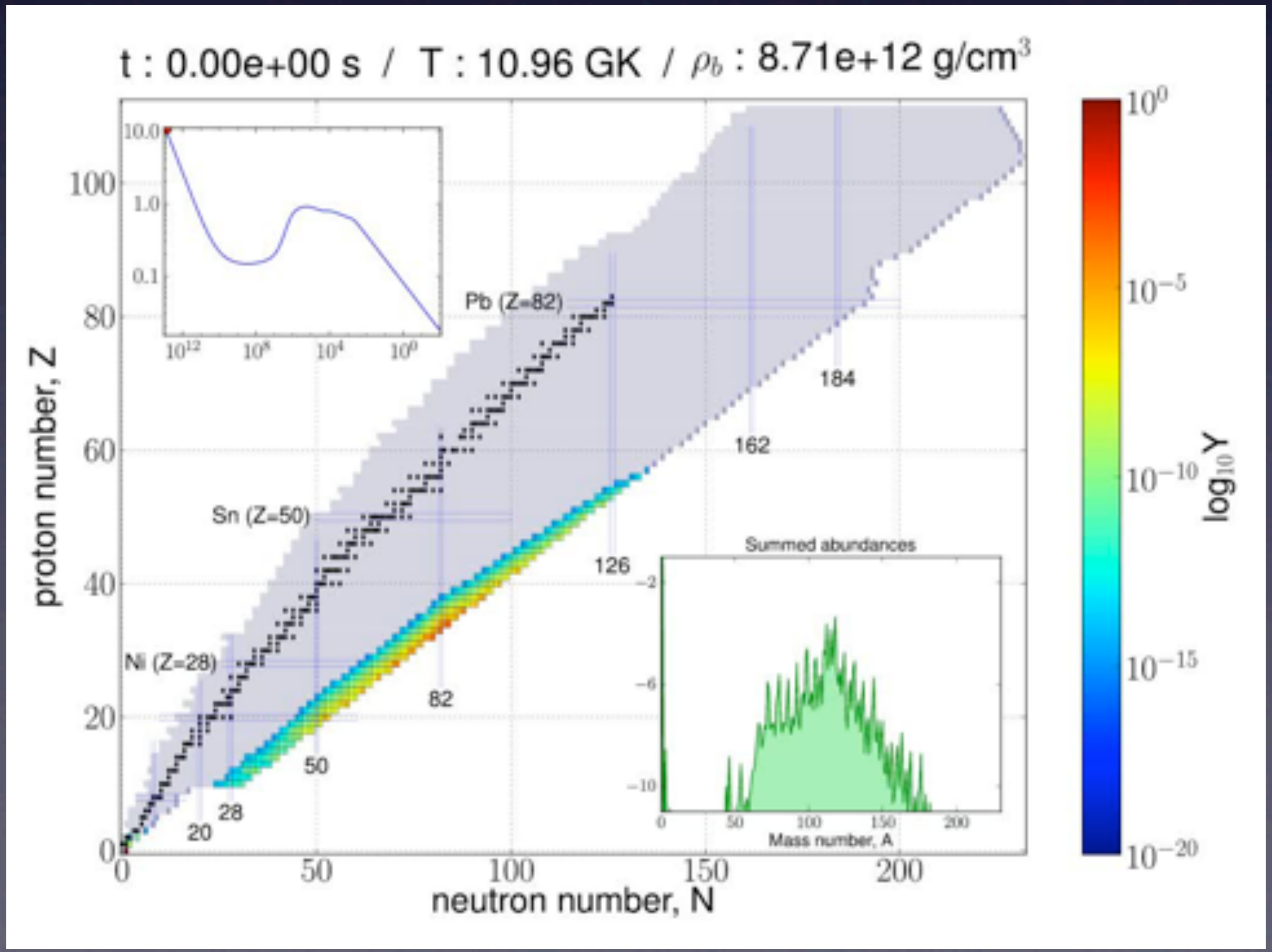
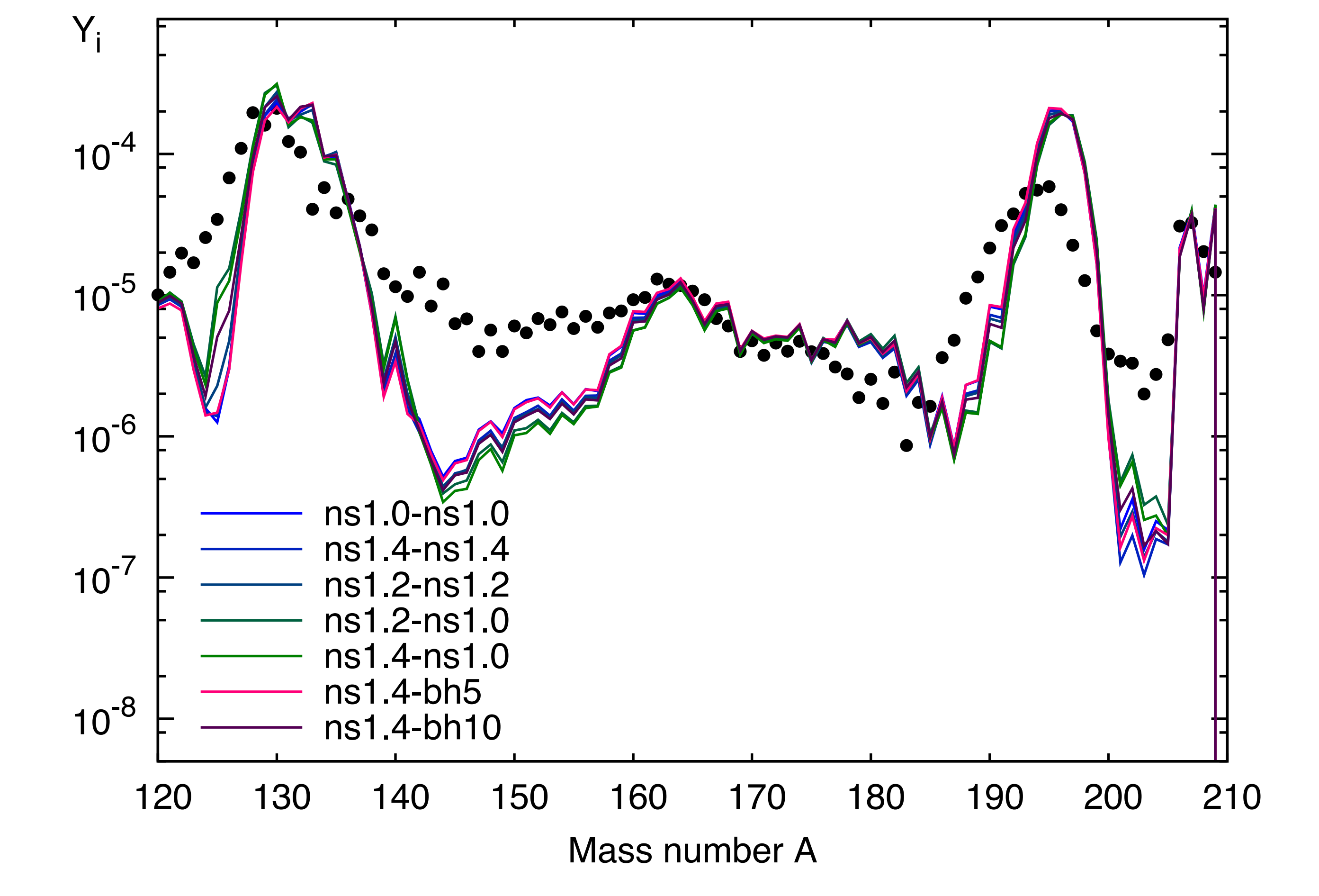


- final abundances



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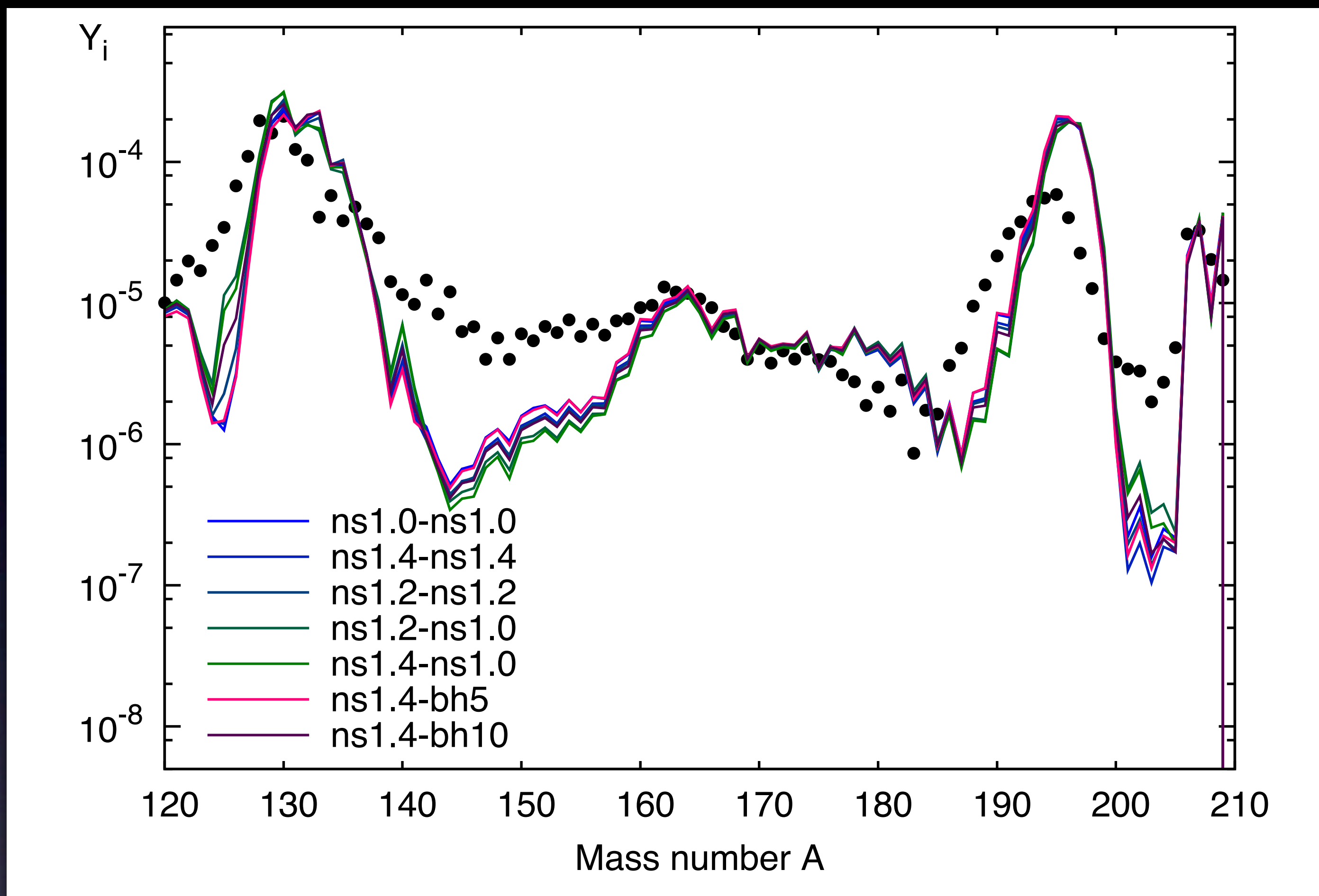

⇒ all 23 cases produce practically identical abundance patterns; independent of the properties of the merging compact binary system

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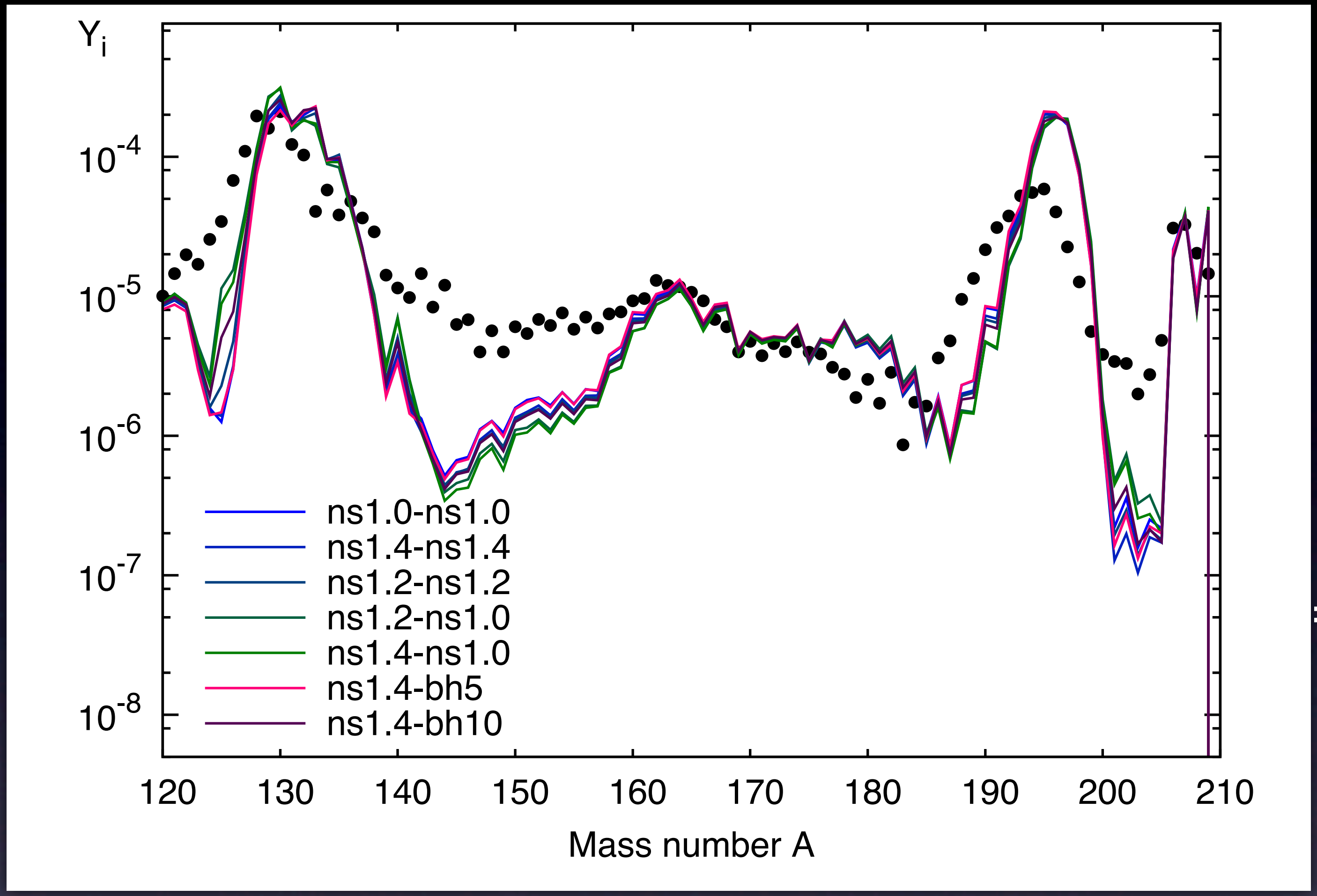

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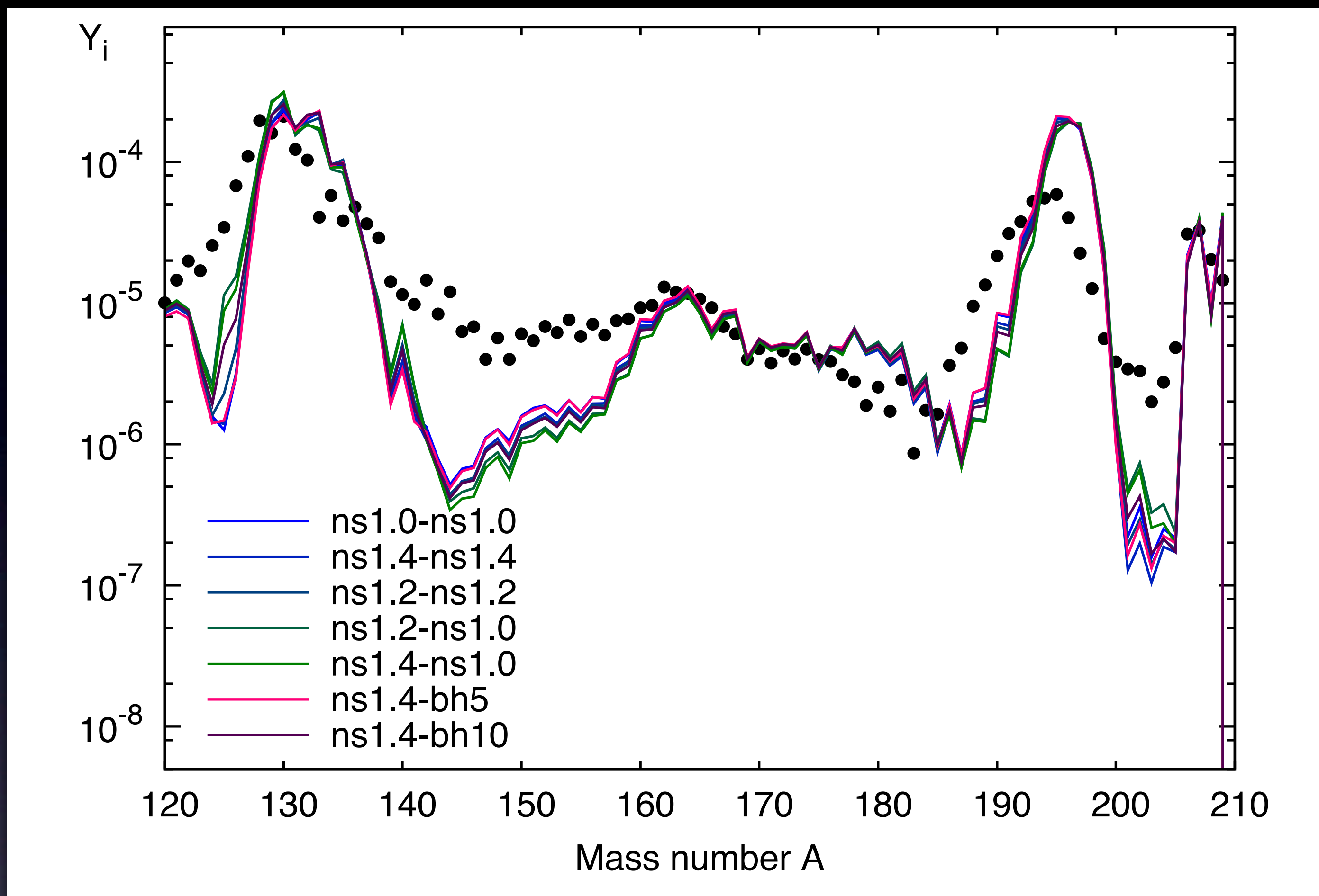

⇒ all 23 cases produce practically identical abundance patterns; independent of the properties of the merging compact binary system

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

⇒ excellent candidate for source of heavy r-process component!!

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

this work: Rosswog, Piran, Nakar, 2012, arXiv:1204.6240
Piran, Nakar, Rosswog, 2012, arXiv:1204.6242
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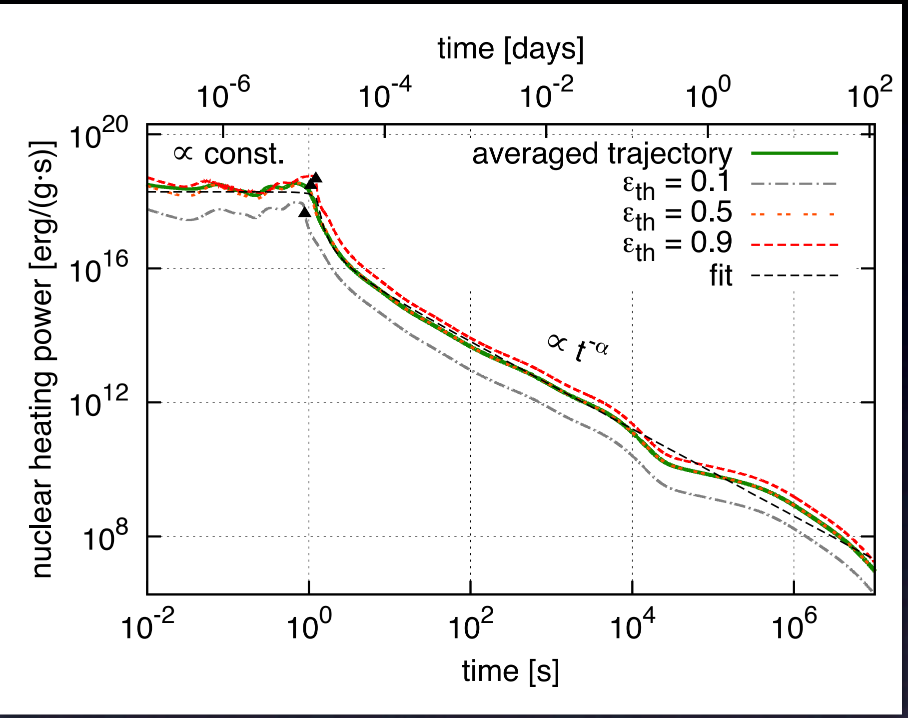

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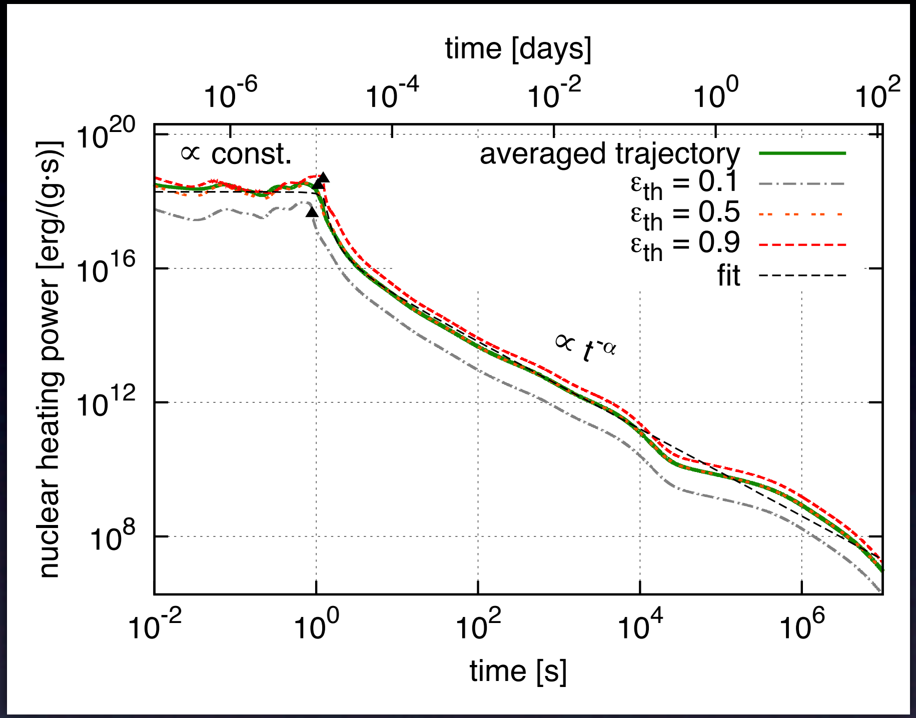
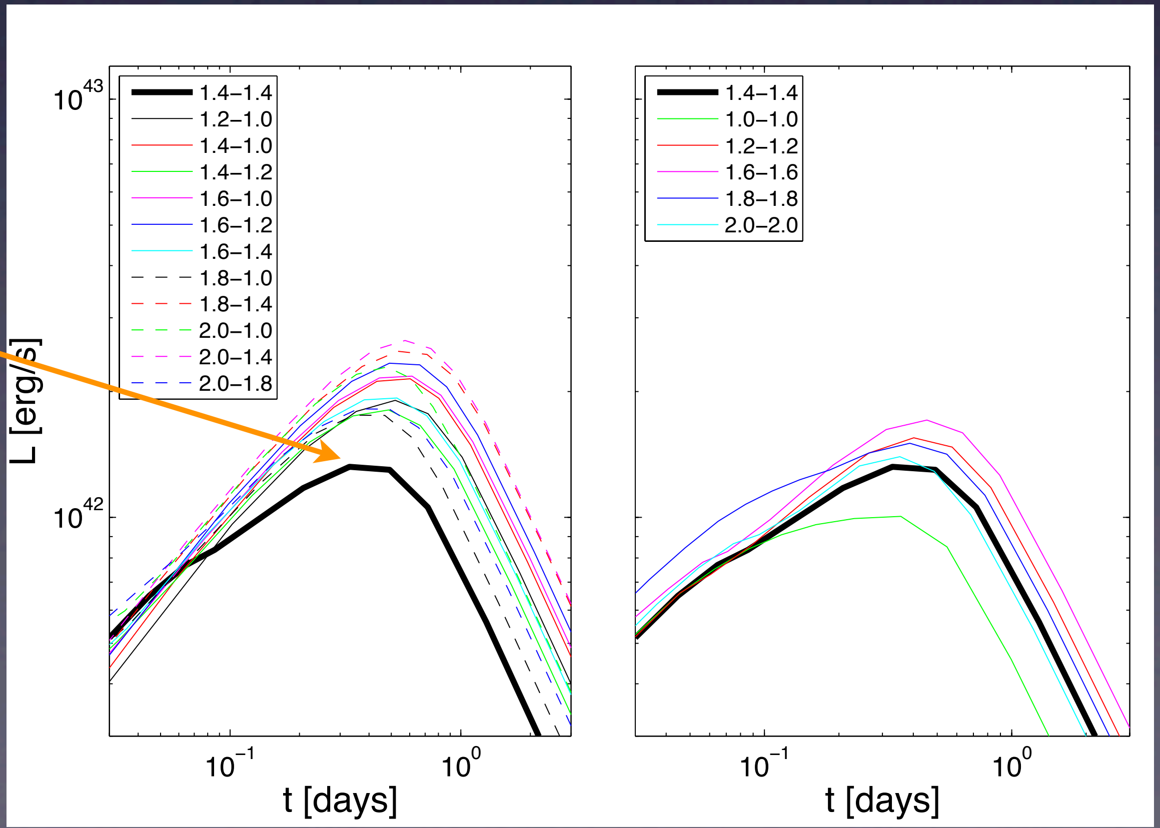


- from ejecta properties:

"standard" nsns merger:
peak after ≈ 0.4 days
with L_{peak} ≈ $2x10^{42}$ erg/s

practically all other cases are brighter and peak later (up to L≈ $6x10^{42}$ erg/s)



Electromagnetic signal II: Radio flares

(Nakar & Piran, Nature 478, 82 (2011)
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- ejecta carry a lot of kinetic energy:

mergers
- nsns: 2×10^{50} erg (1 ... 9×10^{50} erg)
- nsbh: $\approx 10^{51}$ erg

collisions
- nsns: 1 ... 4×10^{51} erg
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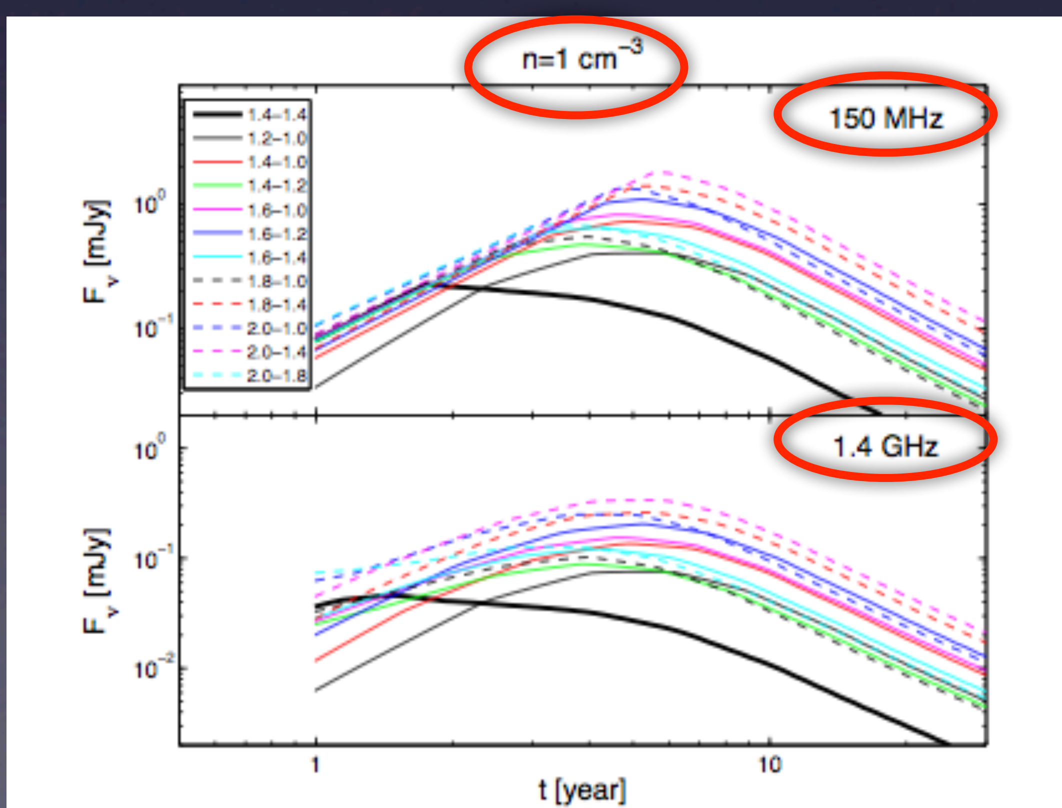
- nsbh: ≈ 10^{51} erg

collisions
- nsns: 1 ... 4×10^{51} erg
- nsbh: 6 ... 11×10^{51} erg

- interaction with ambient medium produces long-lived radio flares

ejecta properties from simulations + ($\varepsilon_e = \varepsilon_B = 0.1$; electron powerlaw dist. p= 2.5; merger at 10^{27} cm ≈ detection horizon adv. LIGO/Virgo; synchrotron)



- peak after ~years

- "standard case" ($2 \times 1.4\ M_{sol}$):
  - peak after ~ 1 year
    with 0.04 mJy at 1.4 GHz
    0.2 mJy at 150 MHz

- sensitive to ambient matter density

III. Summary

- ejecta properties important for
  a) nucleosynthesis b) "Macronovae" c) radio flares

- Nucleosynthesis:
  - nsns mergers are excellent candidates for "strong" r-process (heavy+robust)
  - seriously constrains collisions (<< 10% nsns merger rate)

- Electromagnetic signatures:

  - (probably) sGRB: "bright, but beamed"; s. also talk Fong
  - Macronovae:
    * "supernova-like" opt./UV transients, "dim, but isotropic"
    * powered by radioactivity, $L_{peak} \geq 10^{42}$ erg/s
    * rapid rise and decay (~0.4 day)
  - Radio flares:
    * dynamic ejecta mergers contain 10^{50}-10^{51} erg kinetic energy, at moderate velocities (~0.12 c)
    * produce radio flares in shocks with ambient medium
    * rise and remain bright on time scales ~years