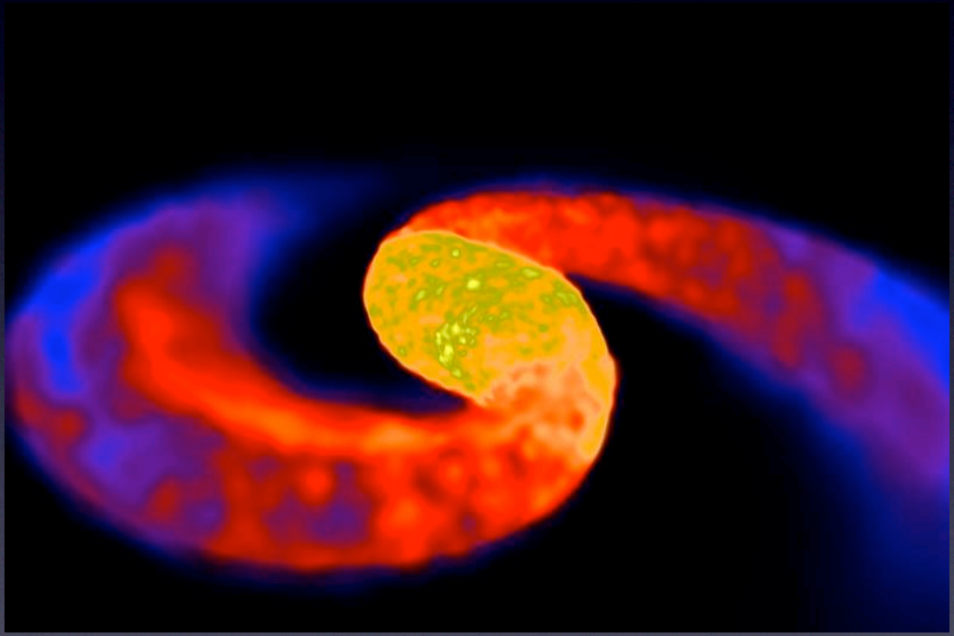
Annapolis, Nov 3, 2010

Compact Binary Mergers and Short GRBs: the emerging patchwork picture



(Price & Rosswog (2006))

Stephan Rosswog
Jacobs University Bremen

Overview

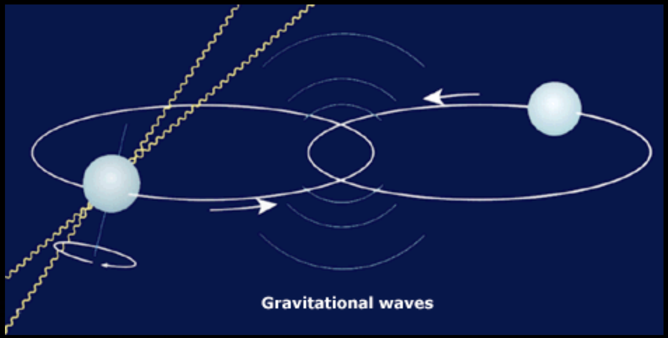
1. Introduction

2. Compact binary mergers: a multi-physics challenge
   ⟶ “patchwork picture”

3. Some “patches”:
   1. Tidal grinding of neutron star crust
   2. Merger and baryonic pollution
   3. Survival of the central object?
   4. Late-time activity/fallback

4. Summary

1. Relevance Compact Binary Mergers



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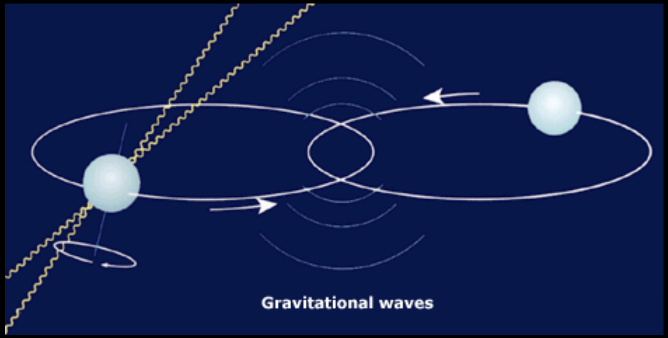

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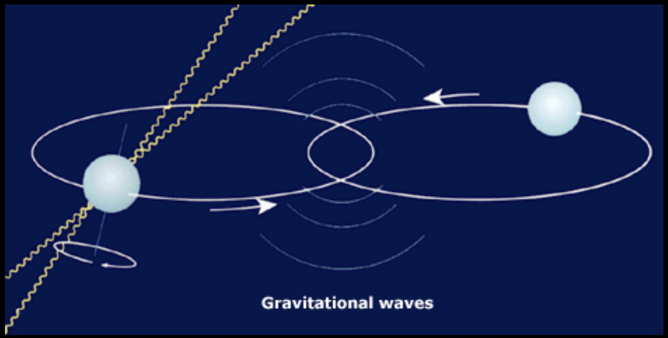

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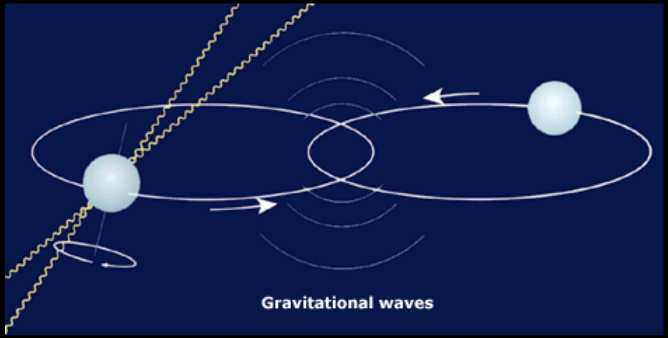

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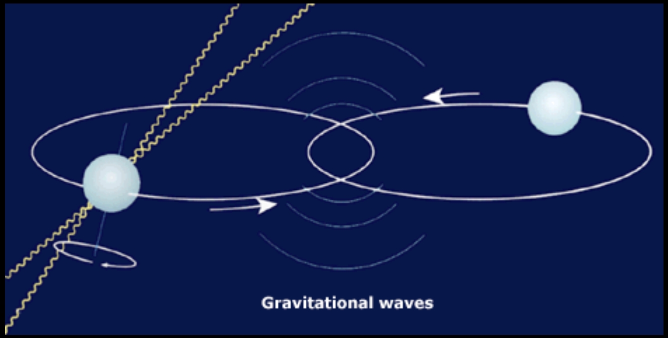

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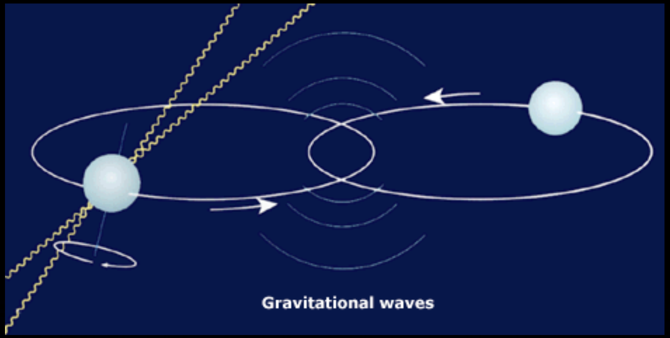

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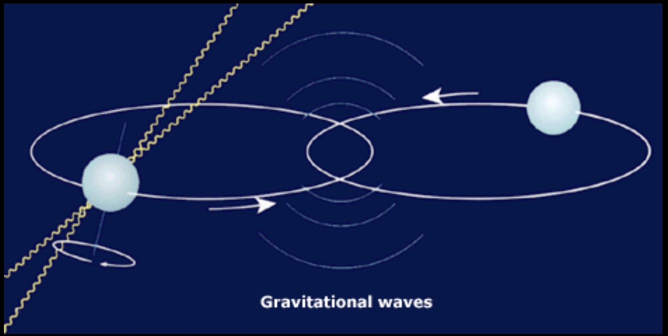

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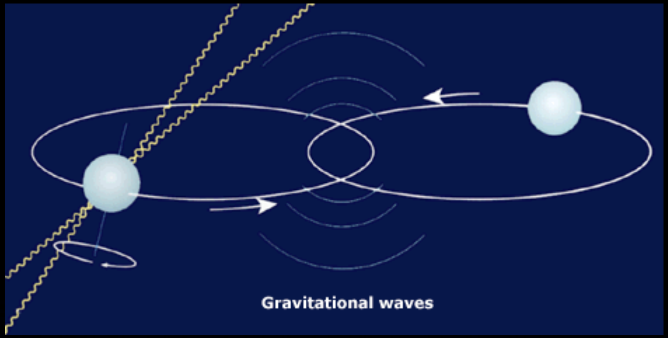

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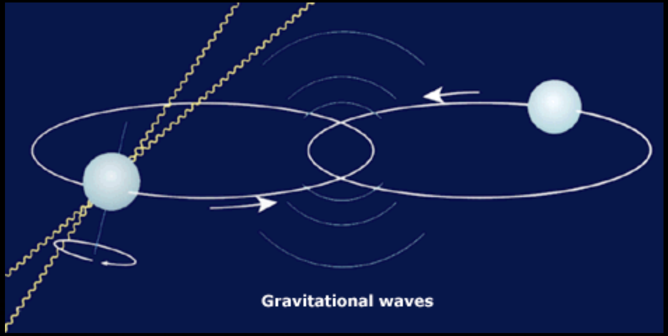

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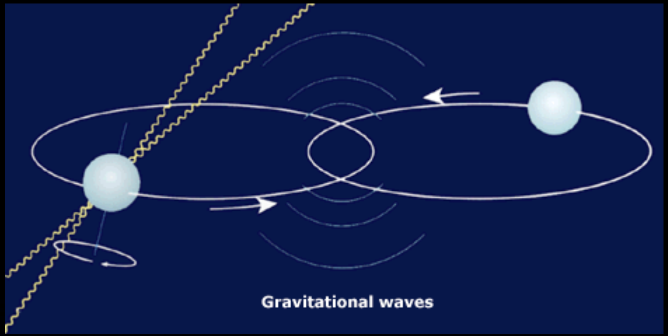

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- Prime candidate for central engine of (short) Gamma-ray bursts

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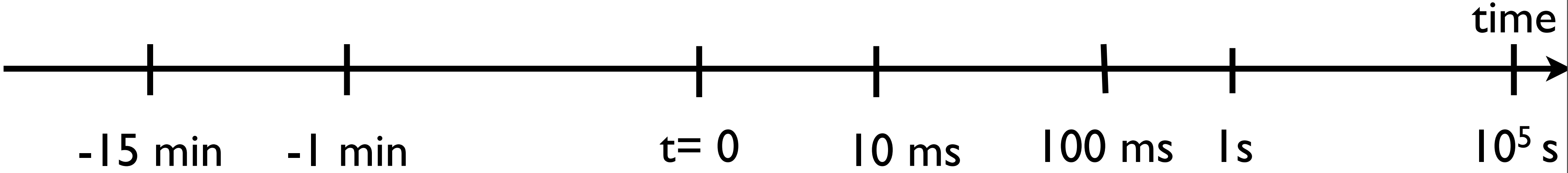

time

-15 min

-1 min

t= 0

10 ms

100 ms

1s

10^5 s

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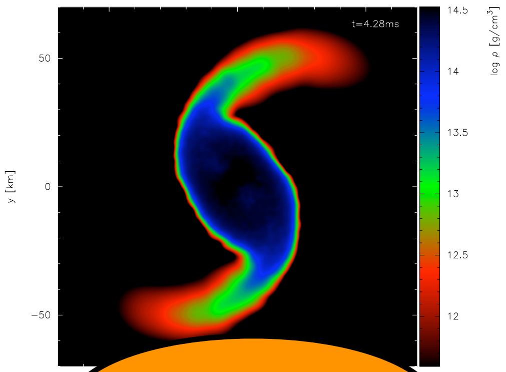

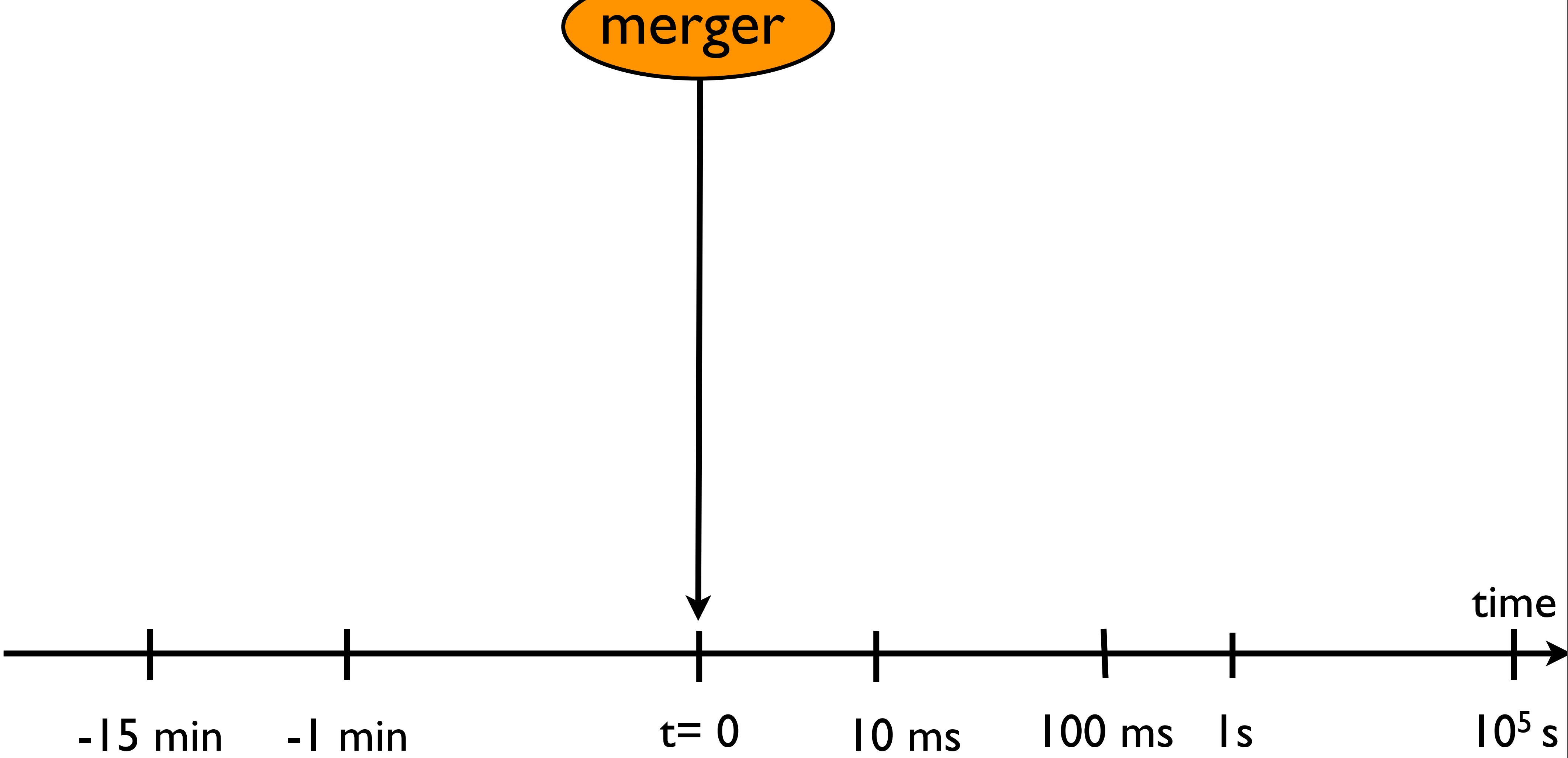

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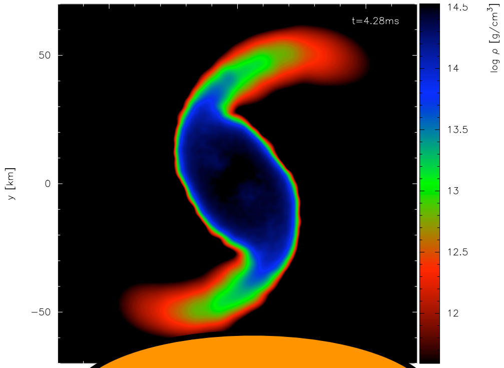

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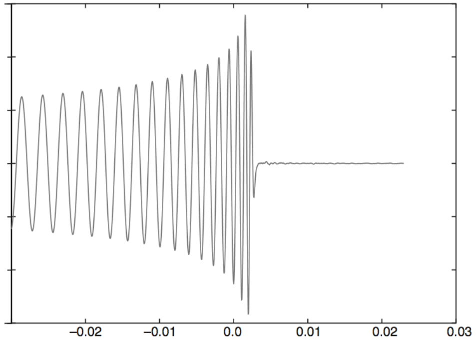

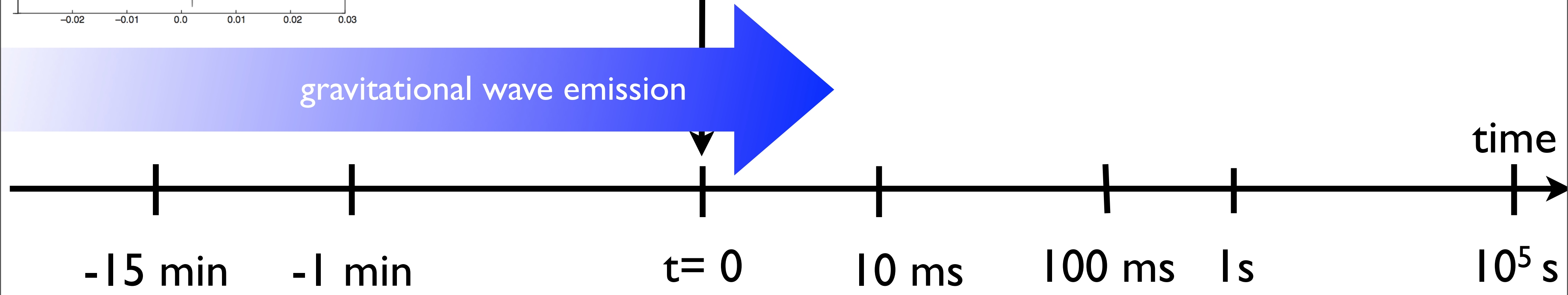

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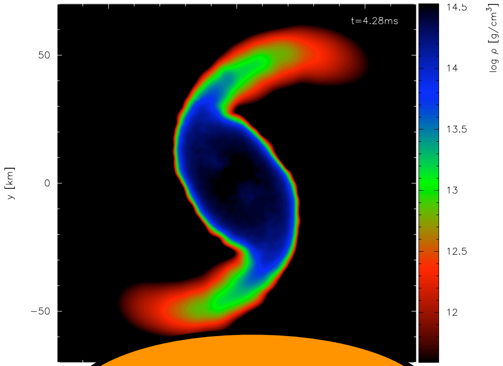

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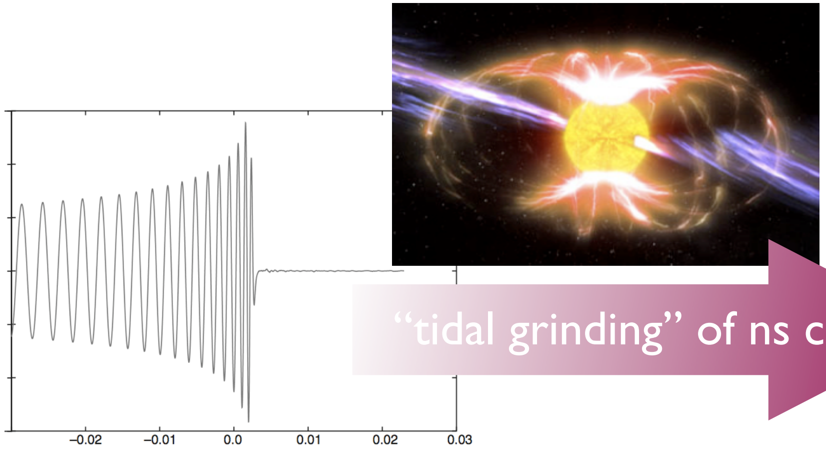

"tidal grinding" of ns crust

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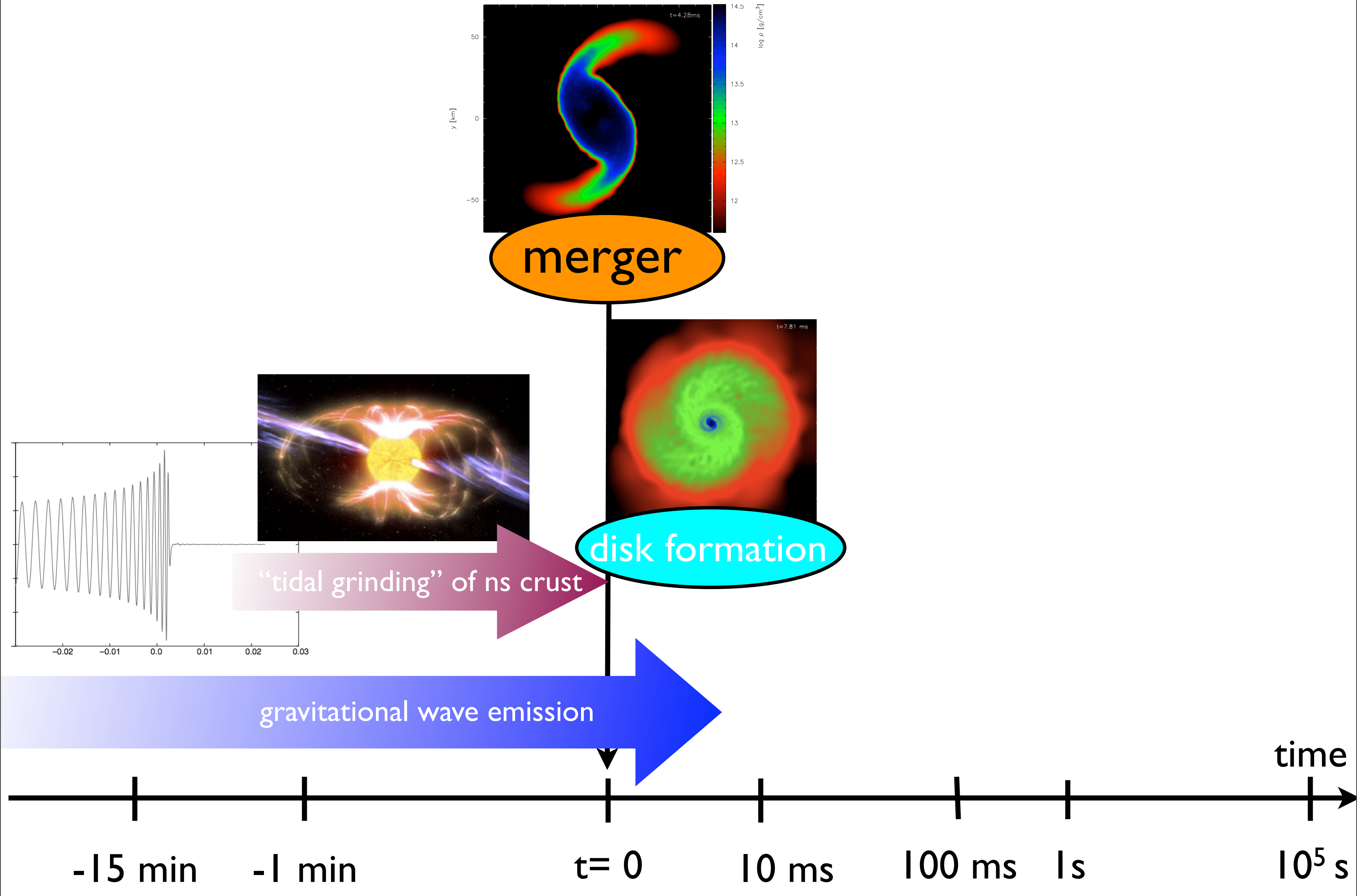

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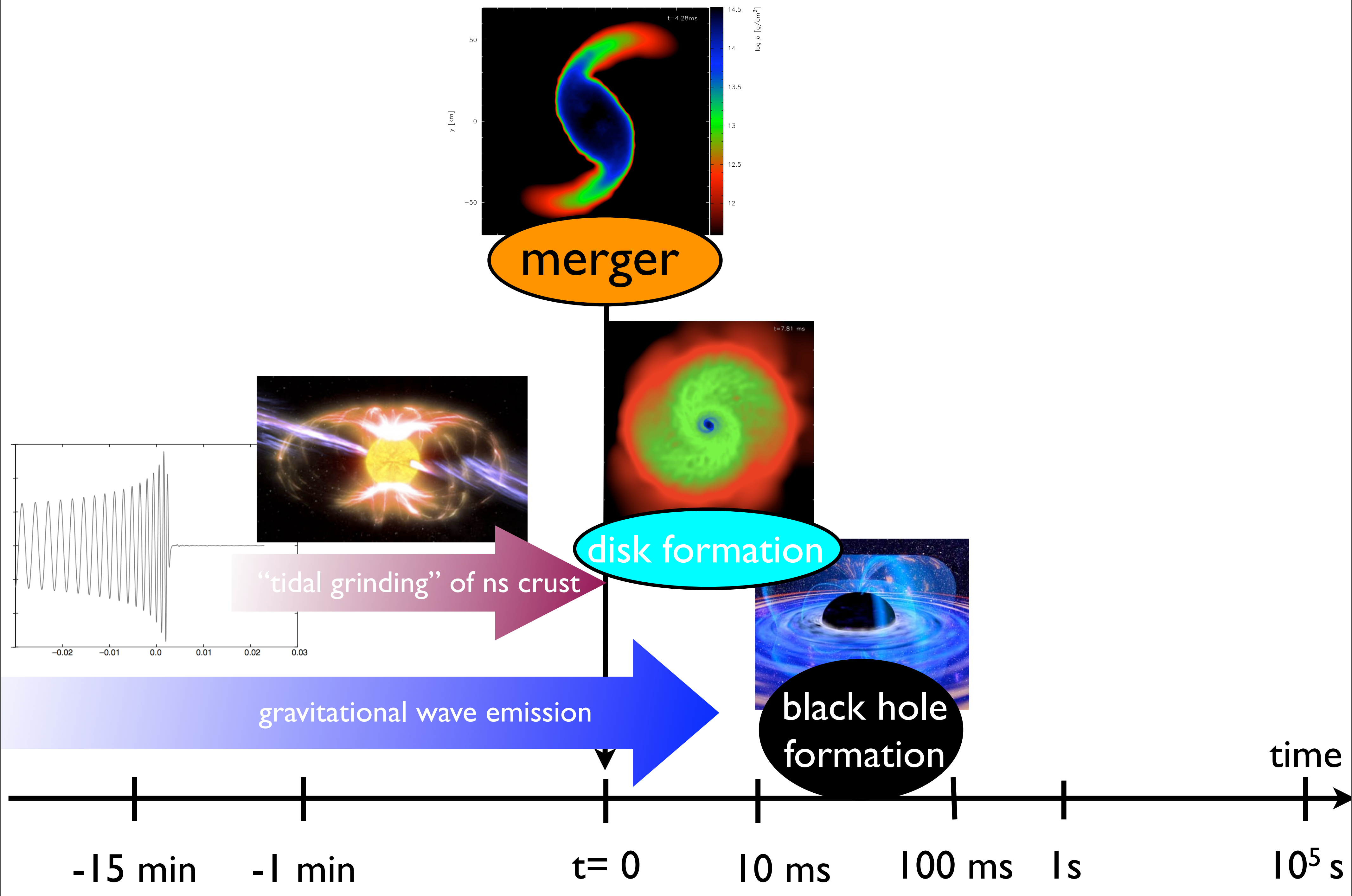

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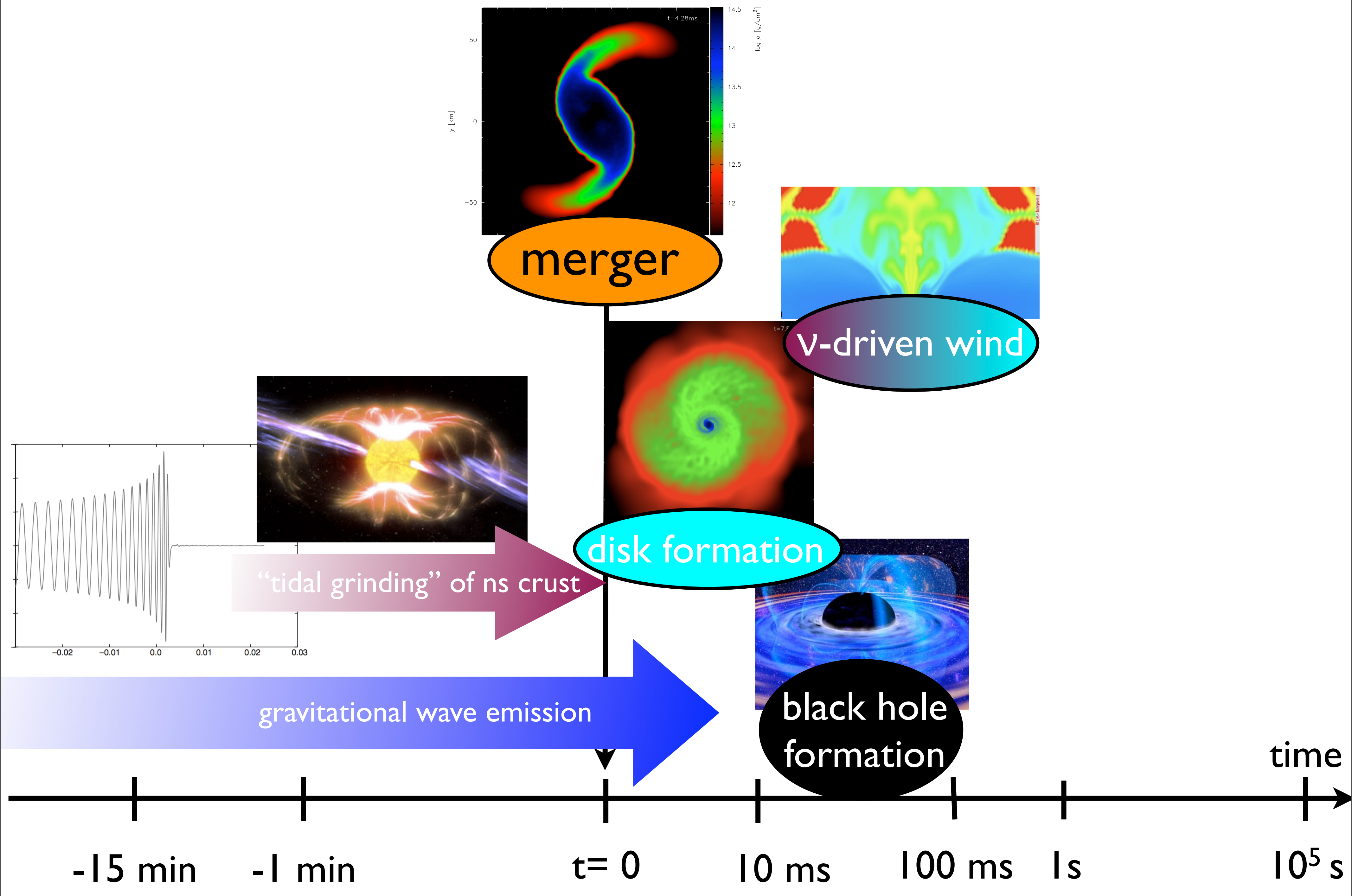

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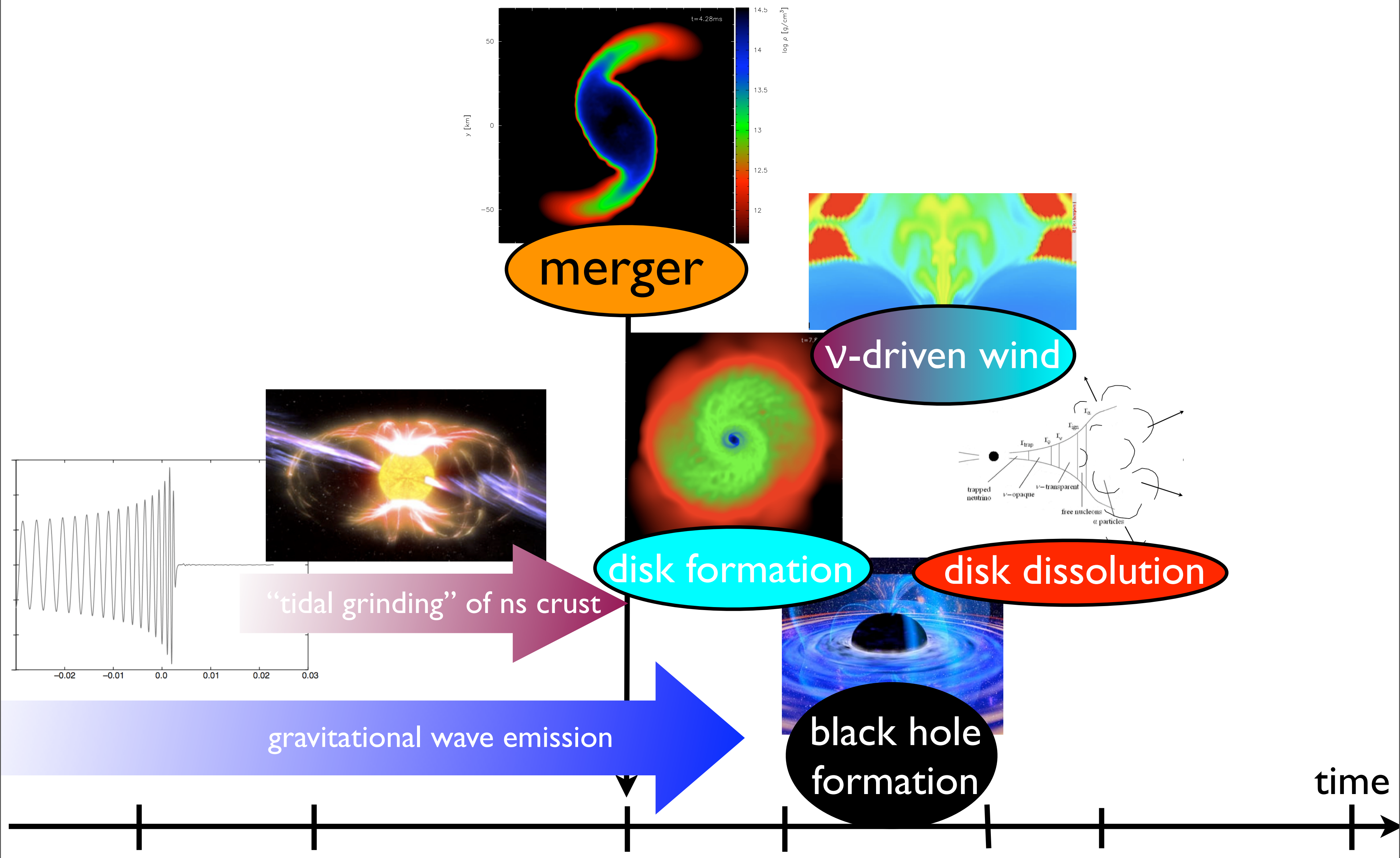

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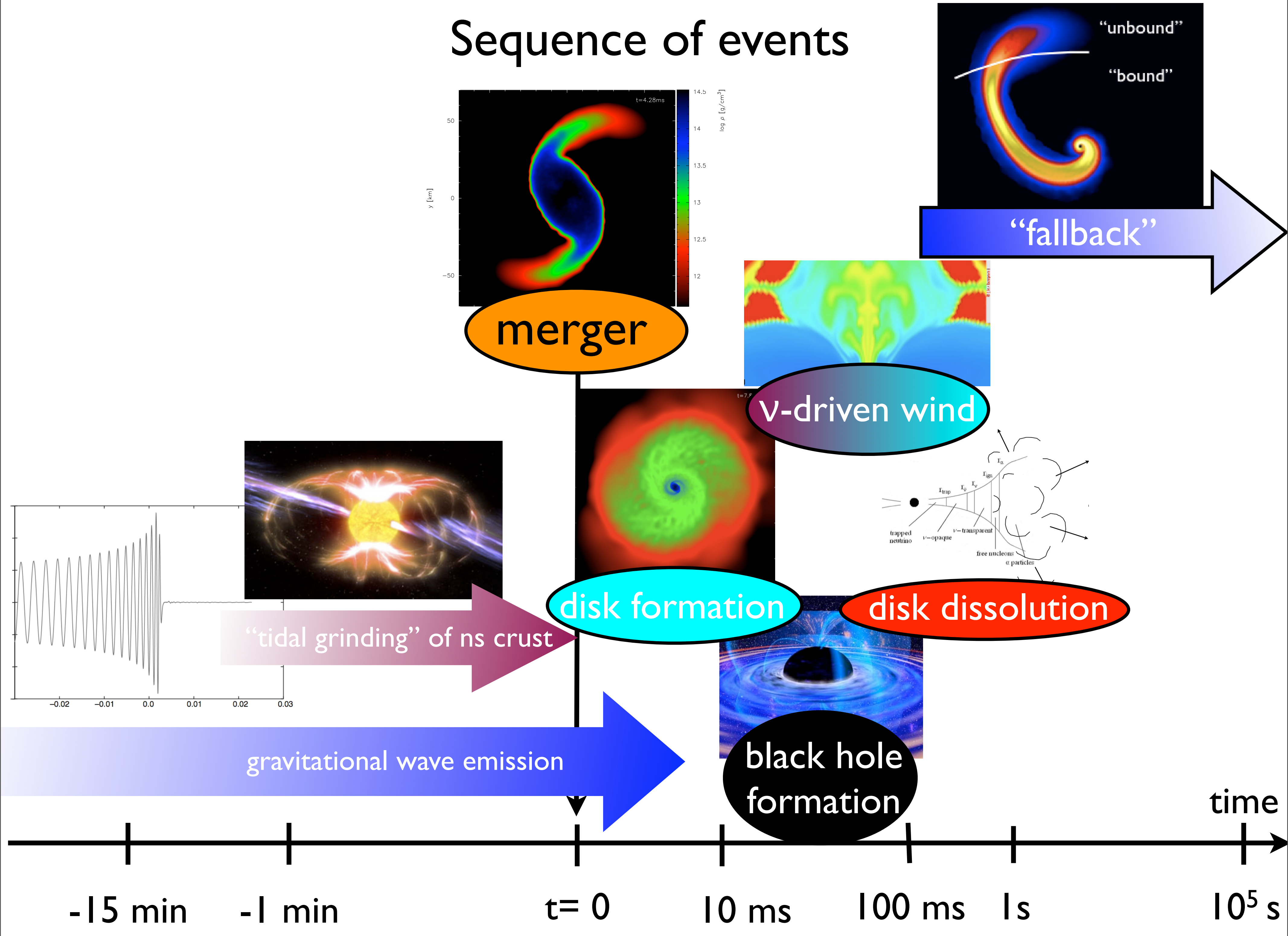

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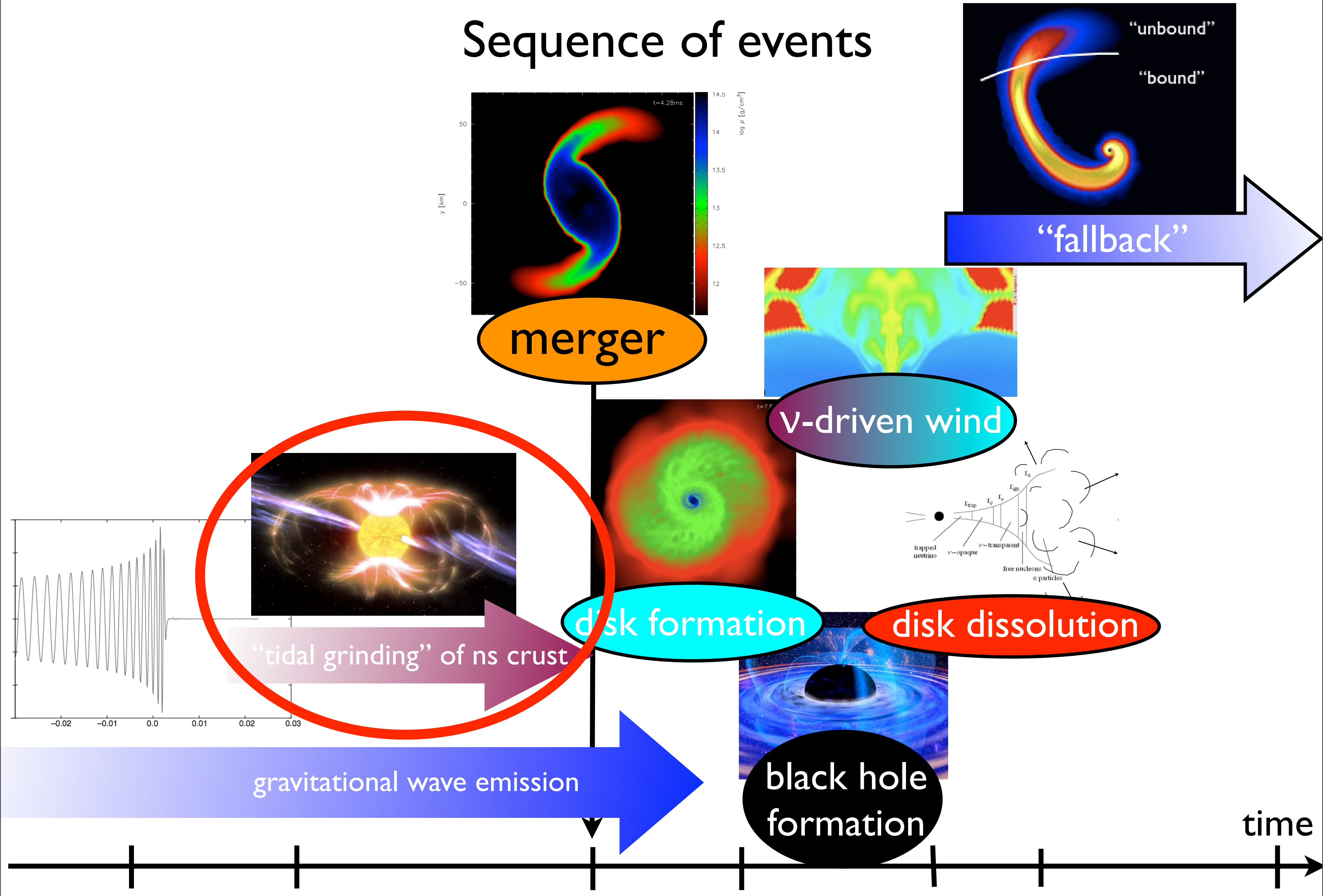

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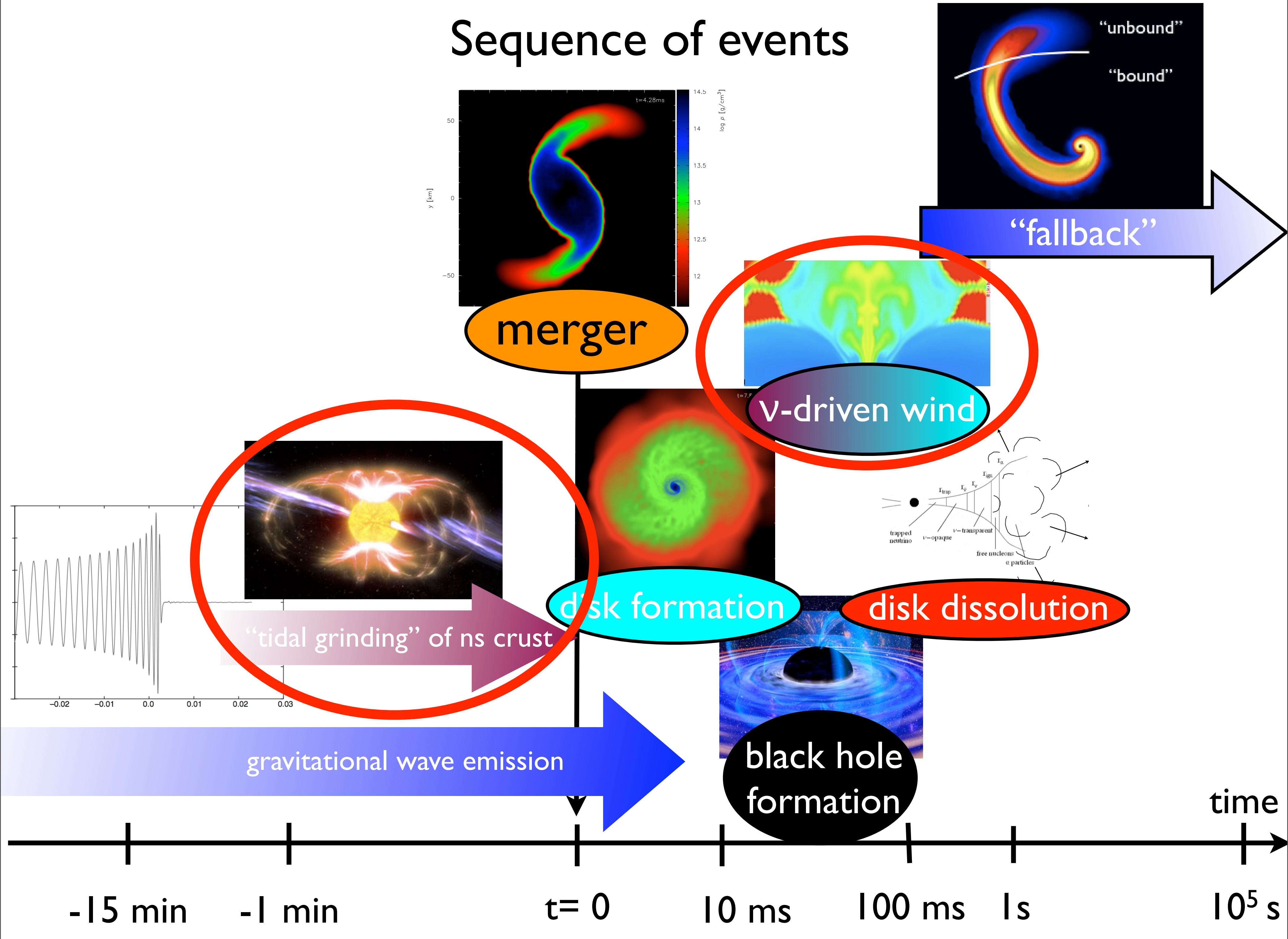

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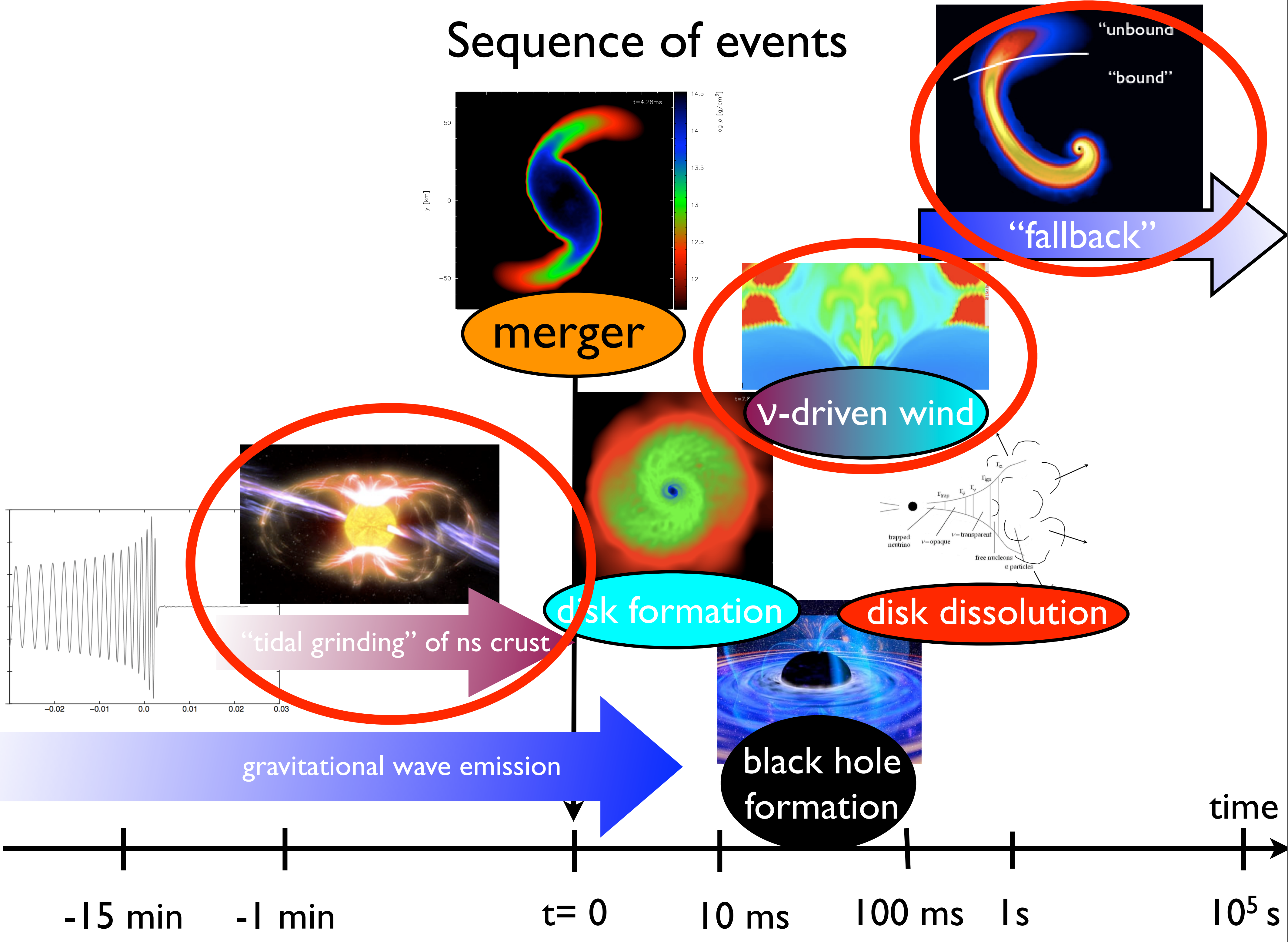

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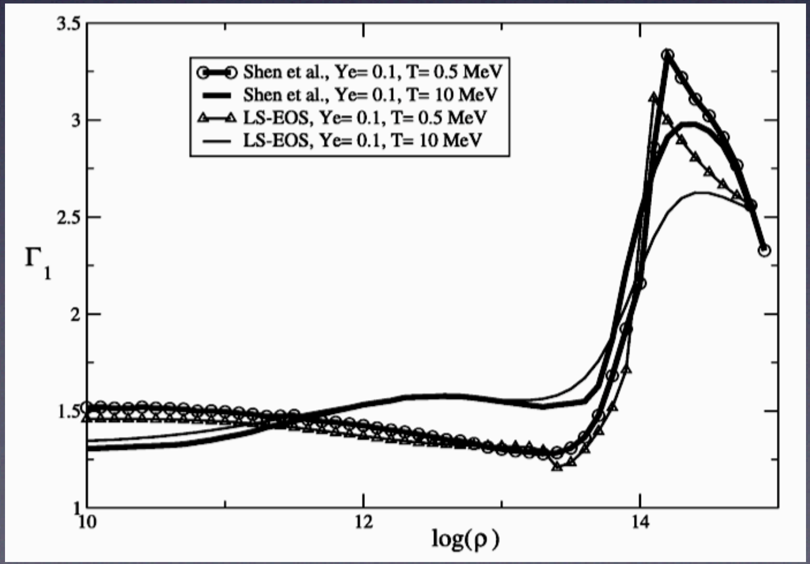

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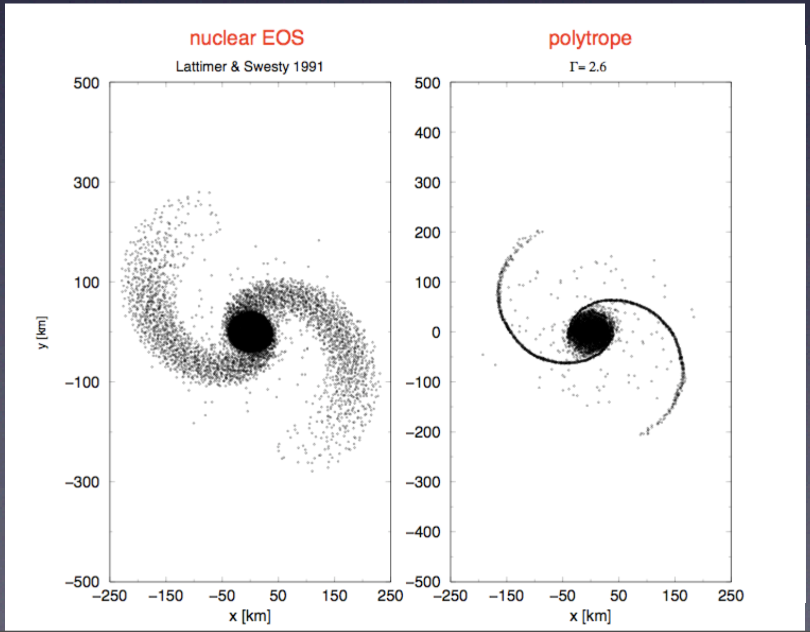

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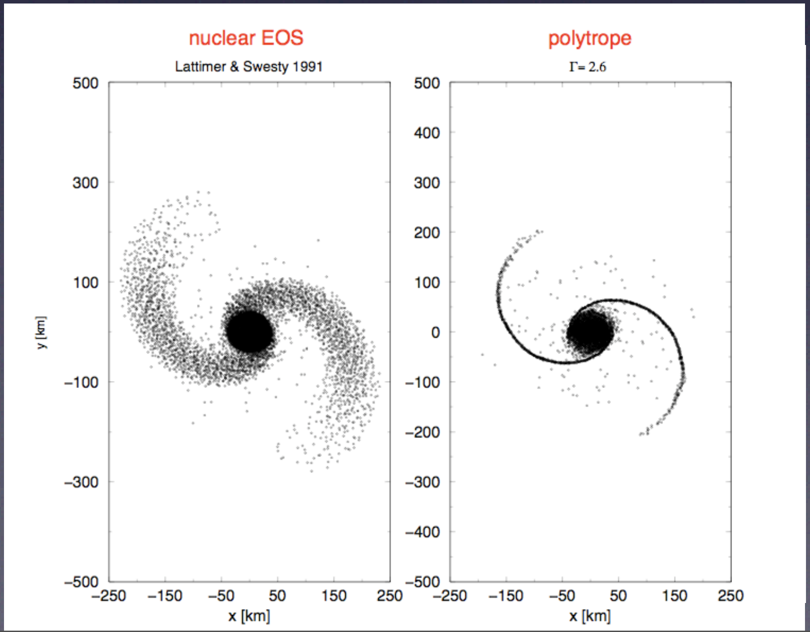

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→ for now have to rely on “patchwork picture”

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motivation: observed precursors of short GRBs, see Troja et al. (2010)

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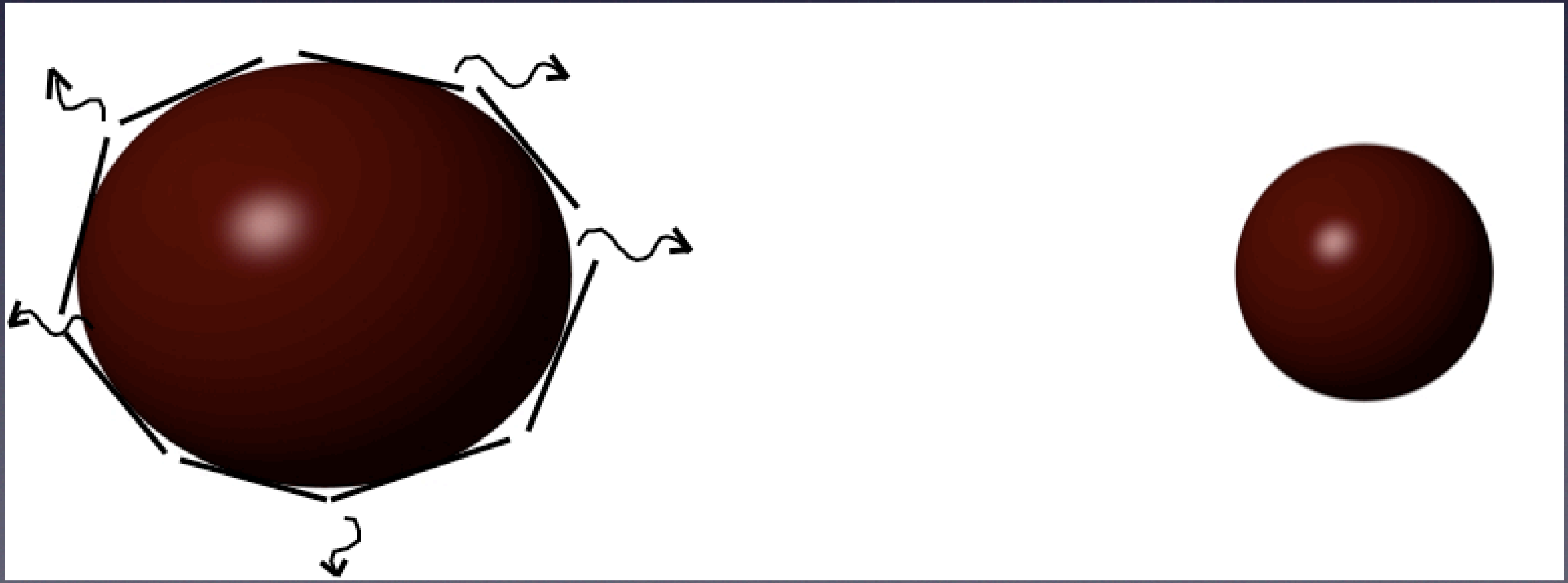

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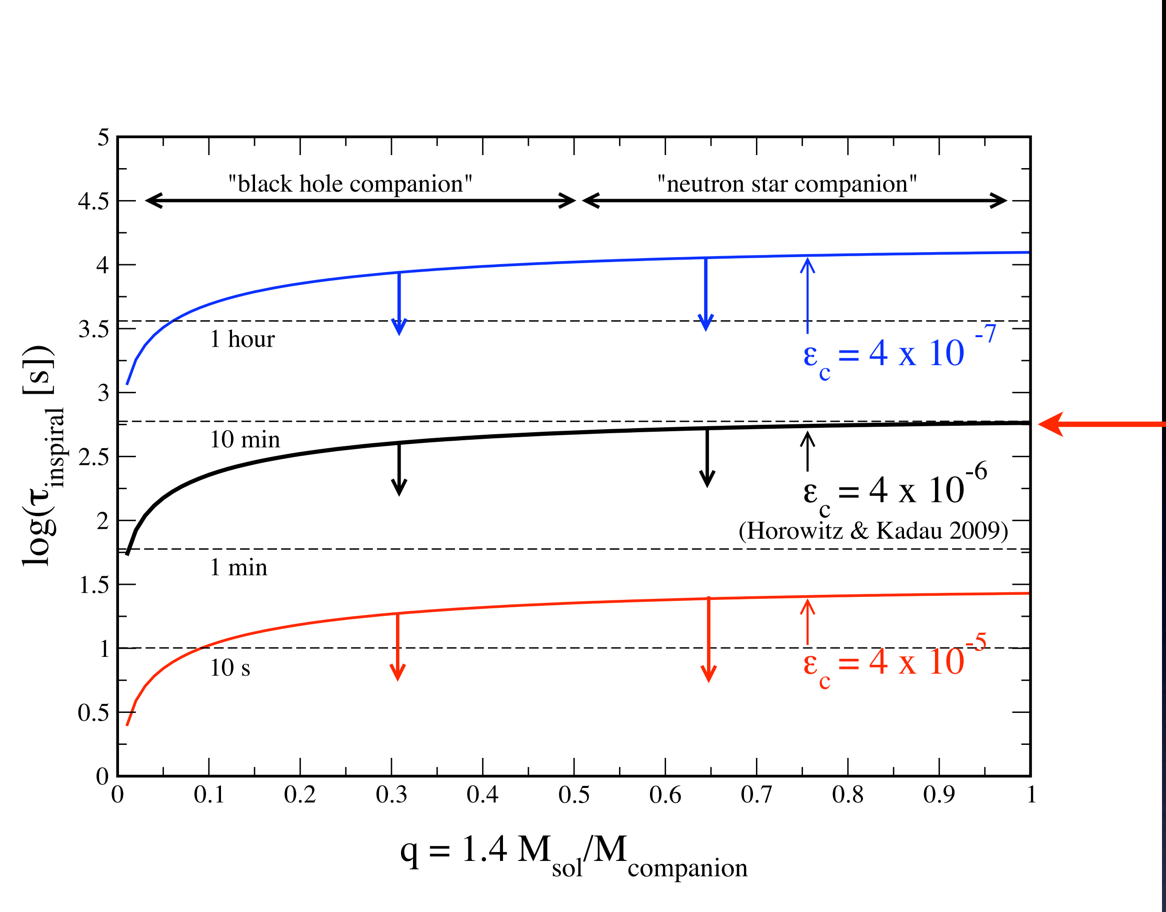
- "tidal grinding phase" until merger:

$$\tau_{\rm tg} < 62 \text{ min} \left(\frac{R_{\rm ns}}{10 \text{ km}}\right)^4 \epsilon_{\rm crit,-6}^{-4/3} \left(\frac{1.4 \text{ M}_\odot}{m_{\rm ns}}\right)^3$$

assume 1.4 M_{sol} star + companion



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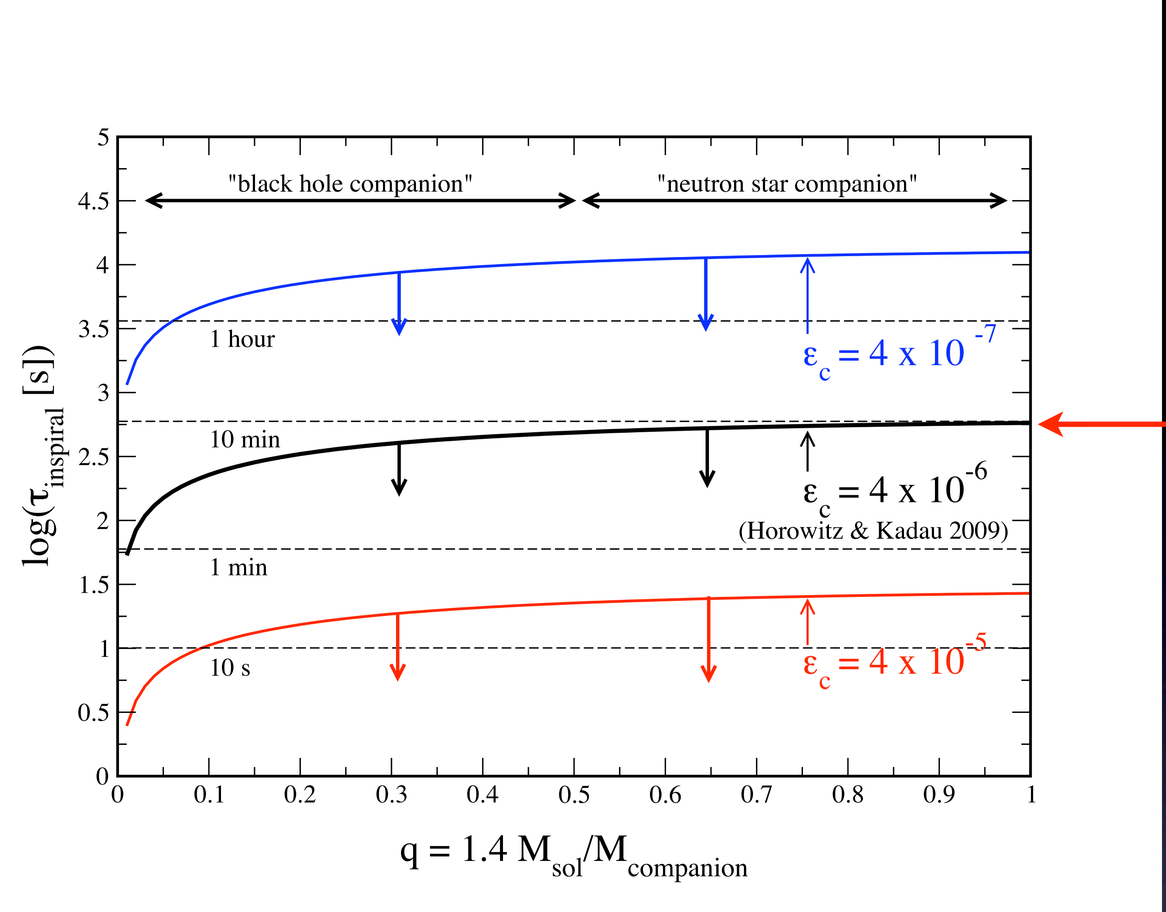

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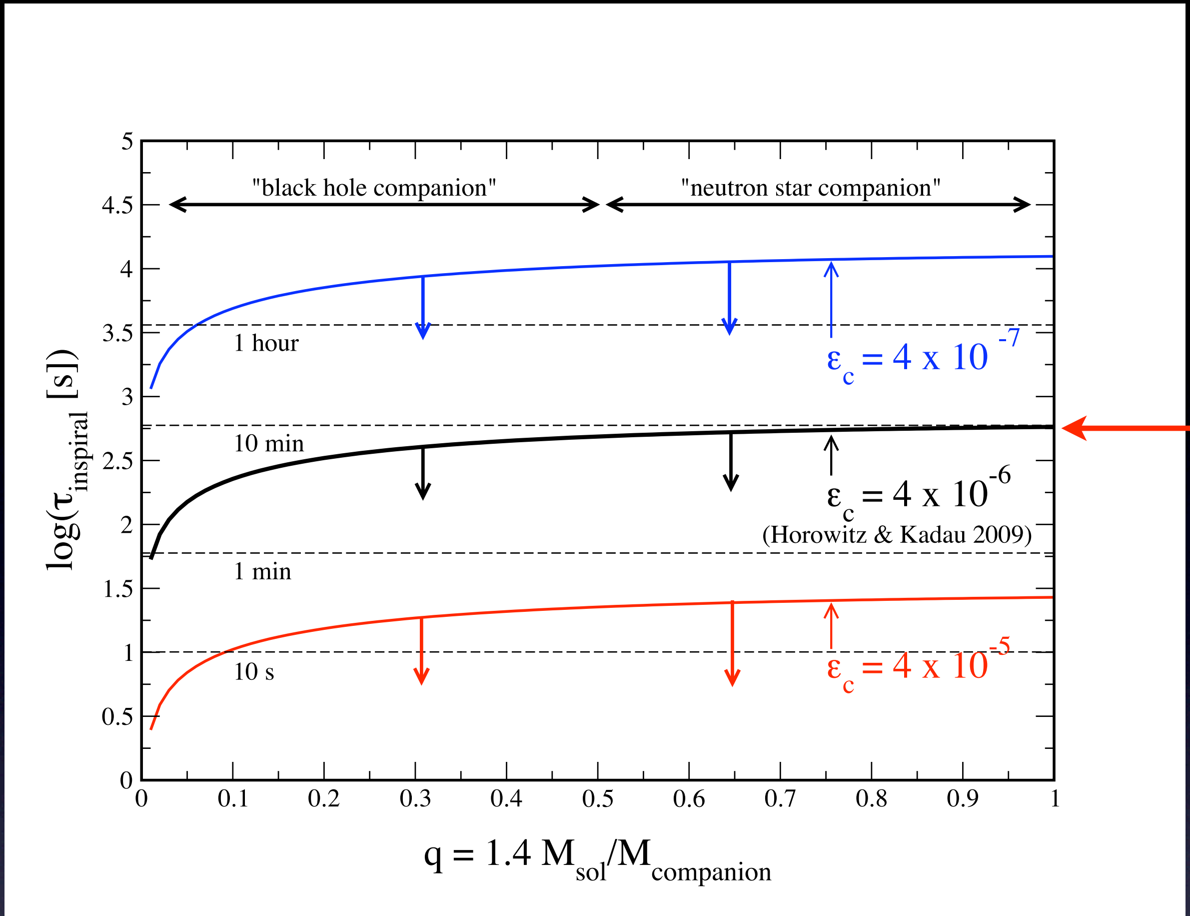

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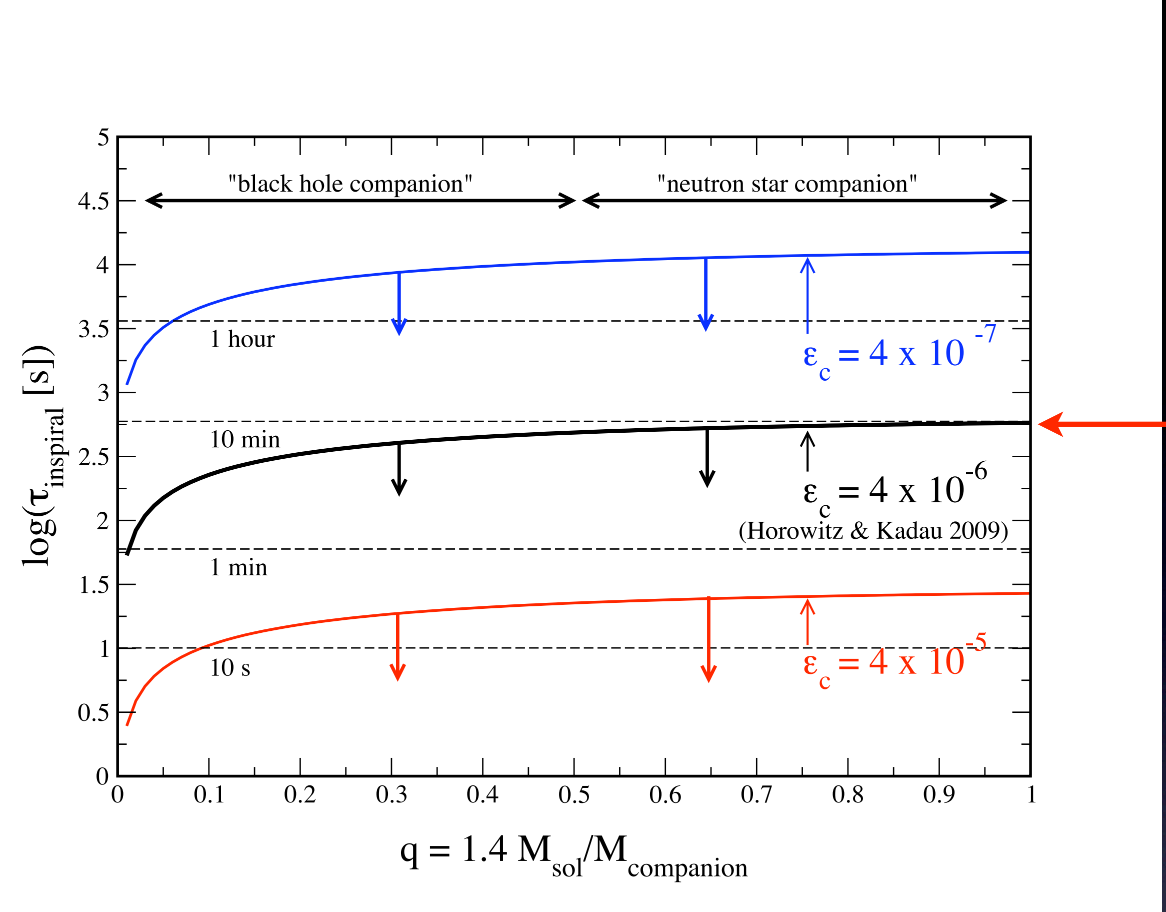

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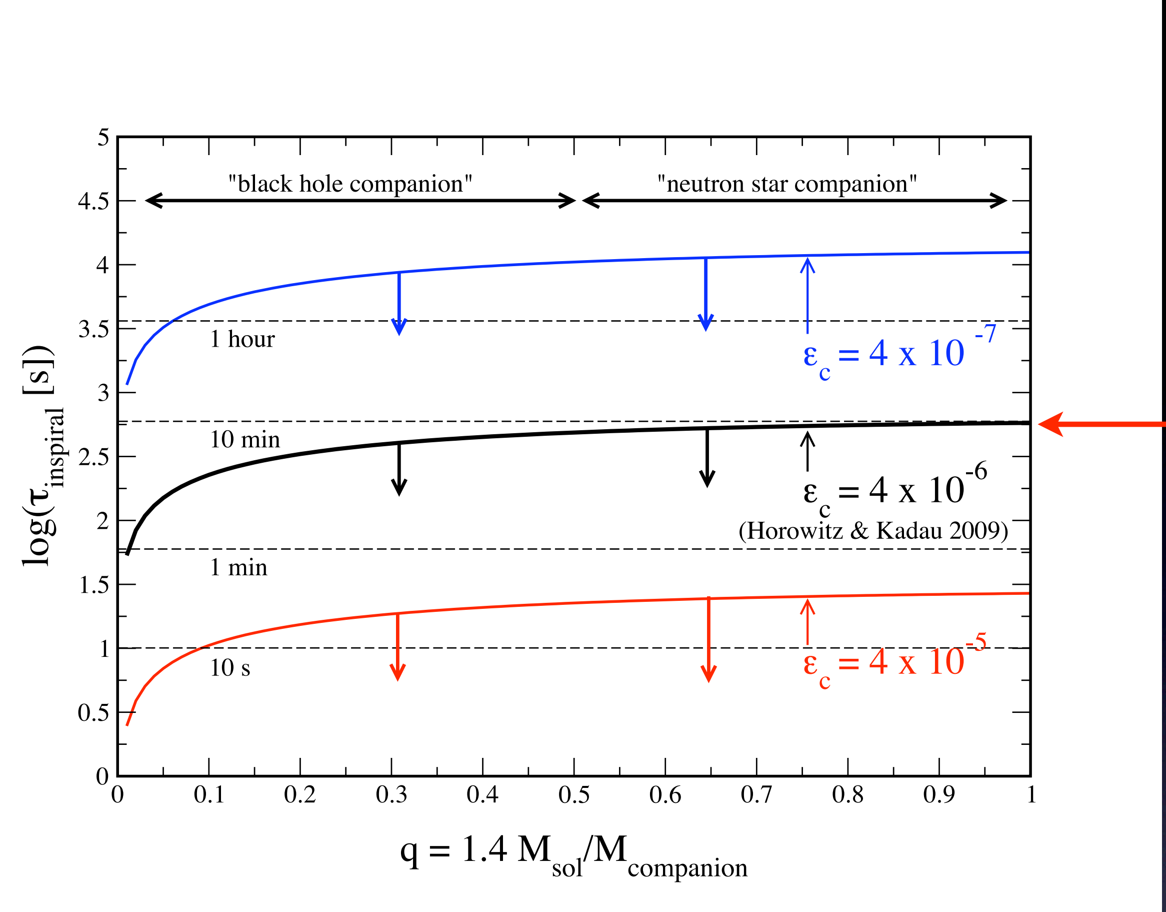

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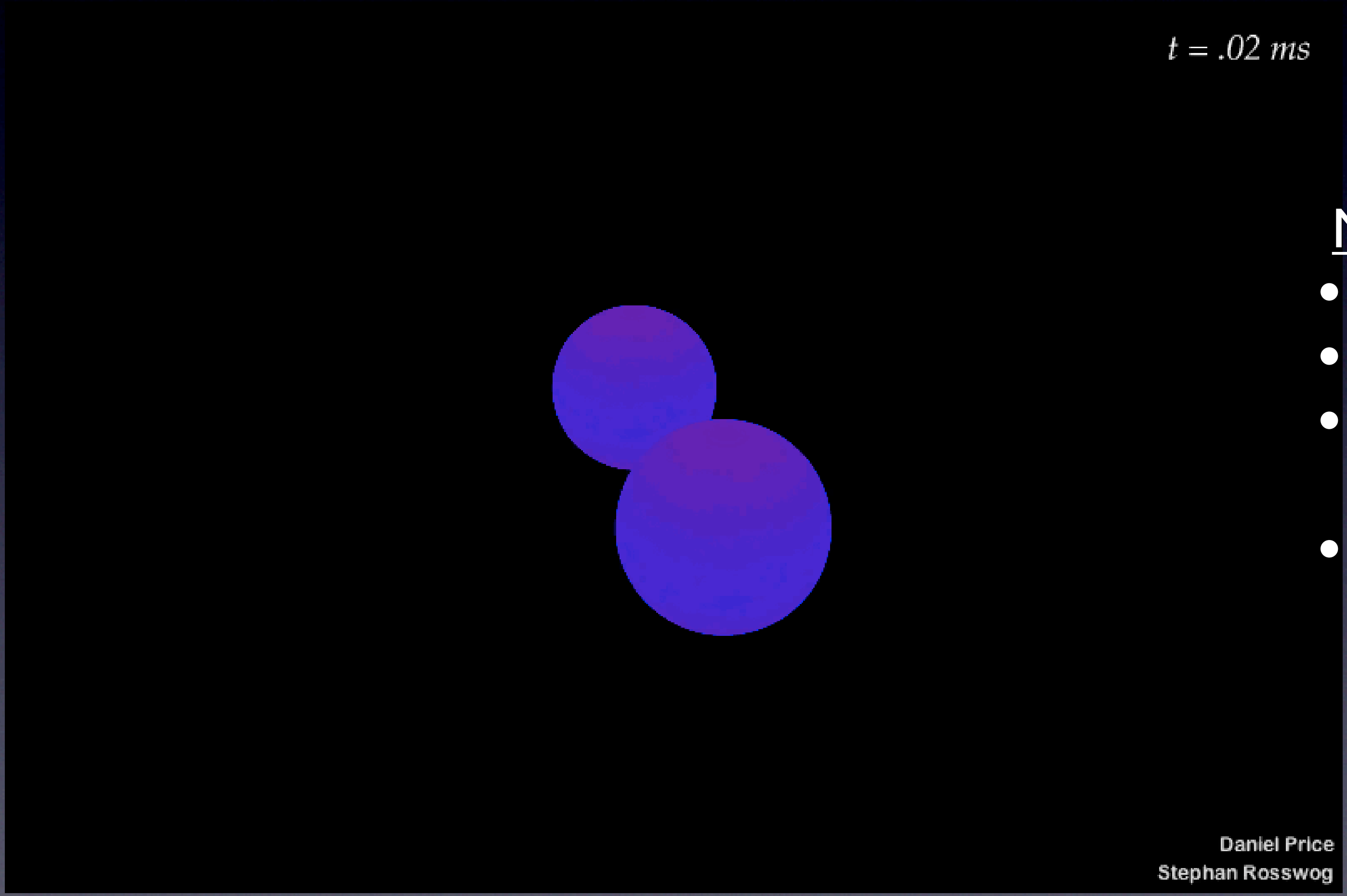
IF one of the neutron stars is highly magnetized:

- "tidal grinding" triggers a sequence of "magnetar-like" flares up to merger
- starting ~ 1 minute before merger
- flares will increase in energy $\Delta E \propto (\delta R)^2 \propto a^{-6} \propto \dfrac{1}{(t_{\rm merge} - t)^{3/2}}$

3.2 Merger and baryonic pollution



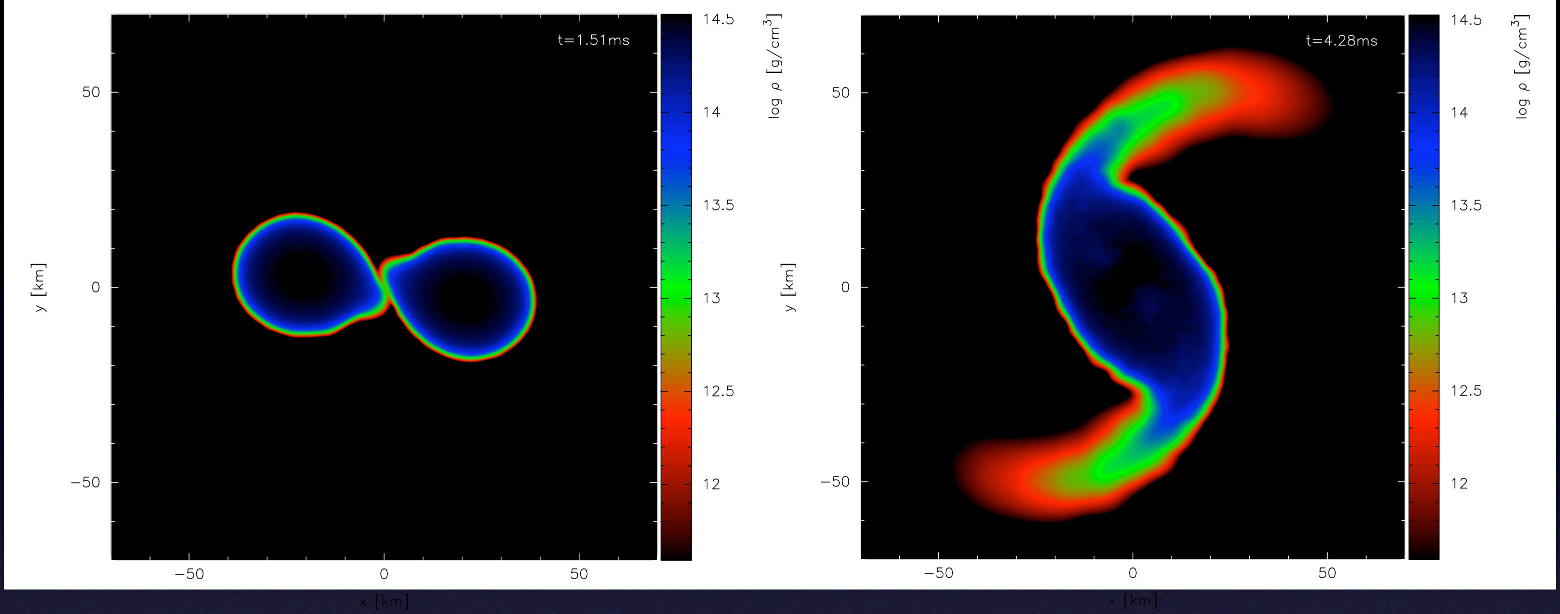
(Price & Rosswog, Science 312, 719, 2006)

MAGMA simulation includes:

- 3D magnetohydrodynamics
- nuclear equation of state
- opacity-dependent neutrino cooling
- self-gravity + gravitational wave emission

Previous merger calculations

(taken from Rosswog et al. 2006)



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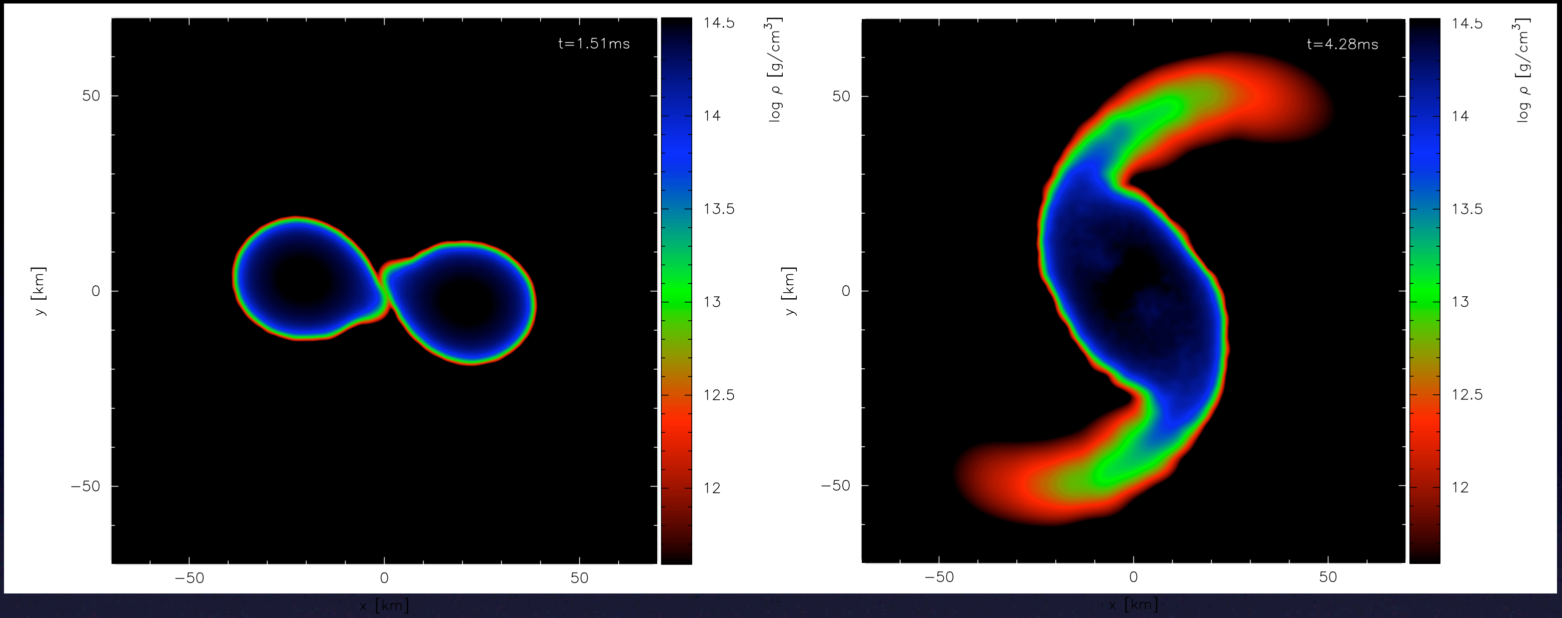

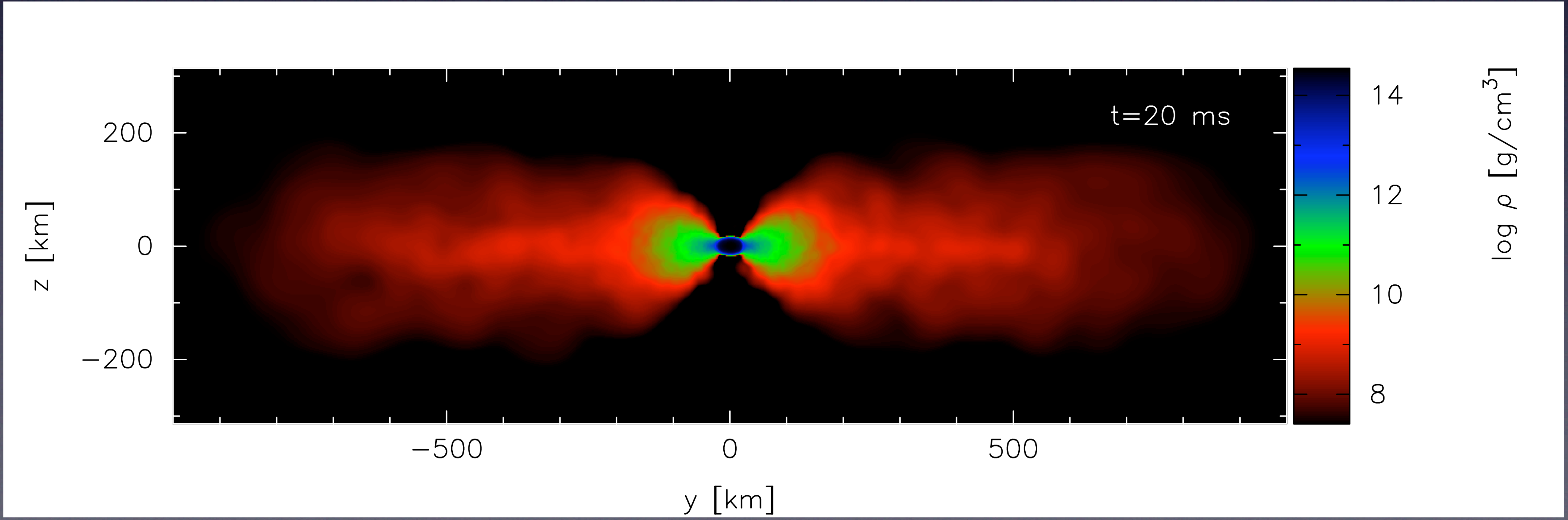

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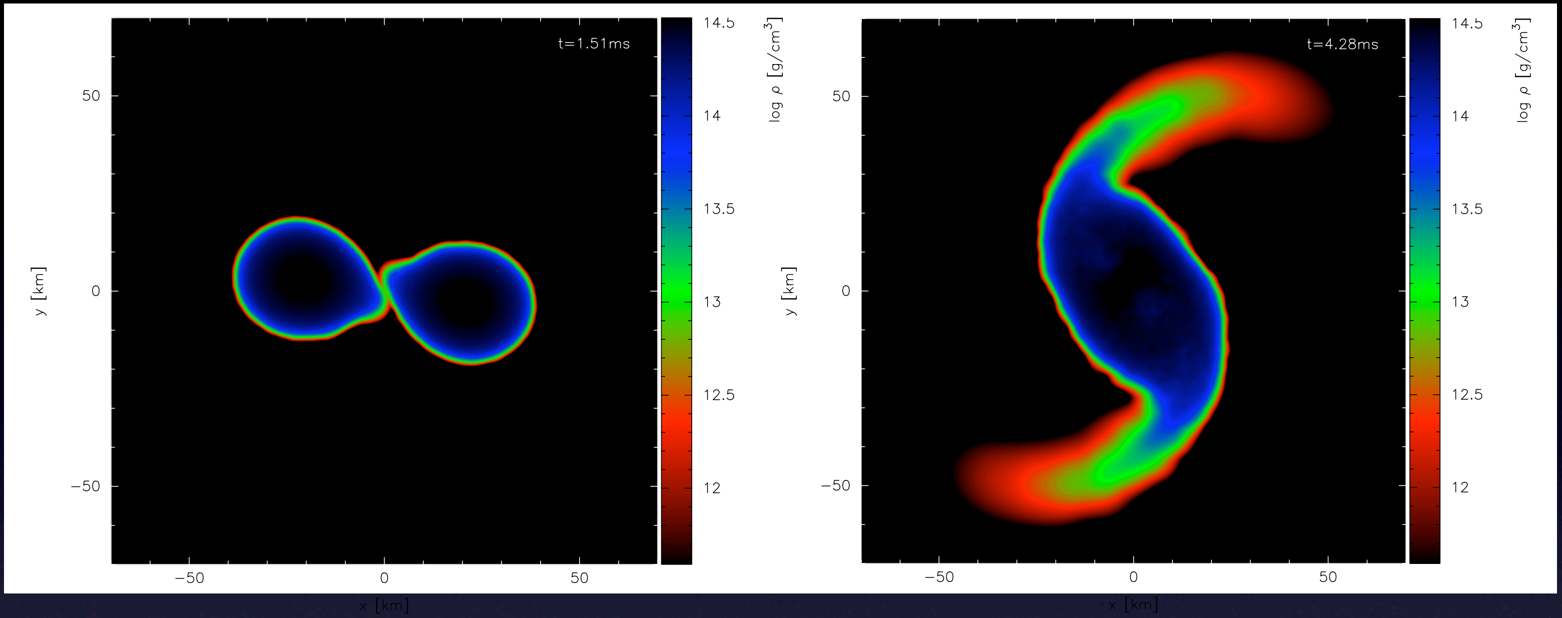
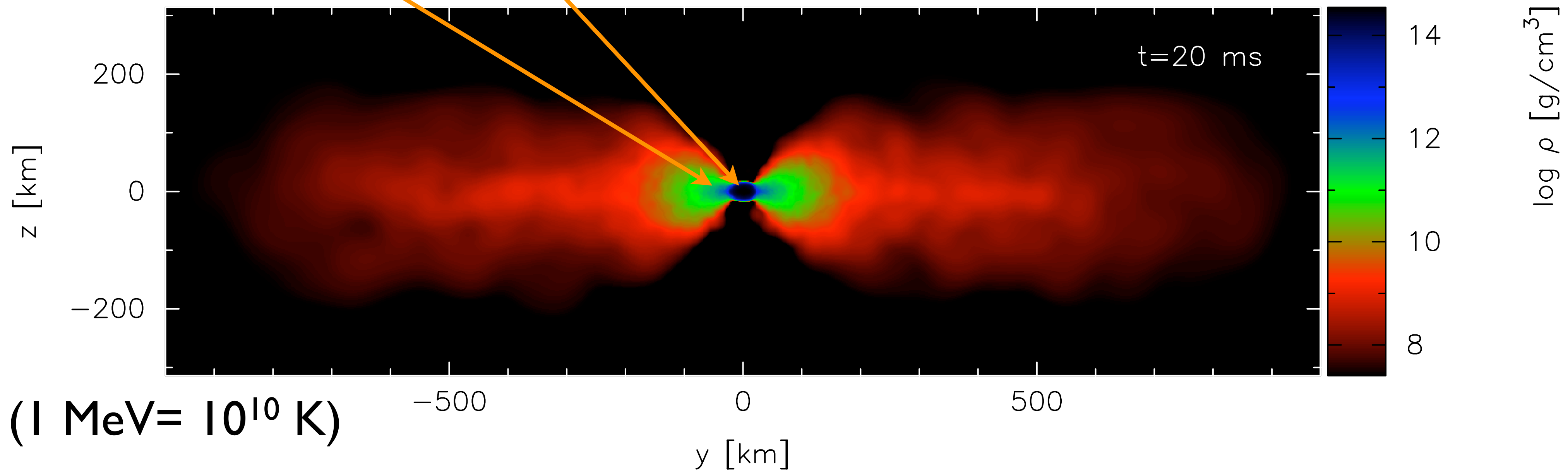


temperatures: ~ 4 MeV ~20 MeV



(1 MeV= 10^{10} K)

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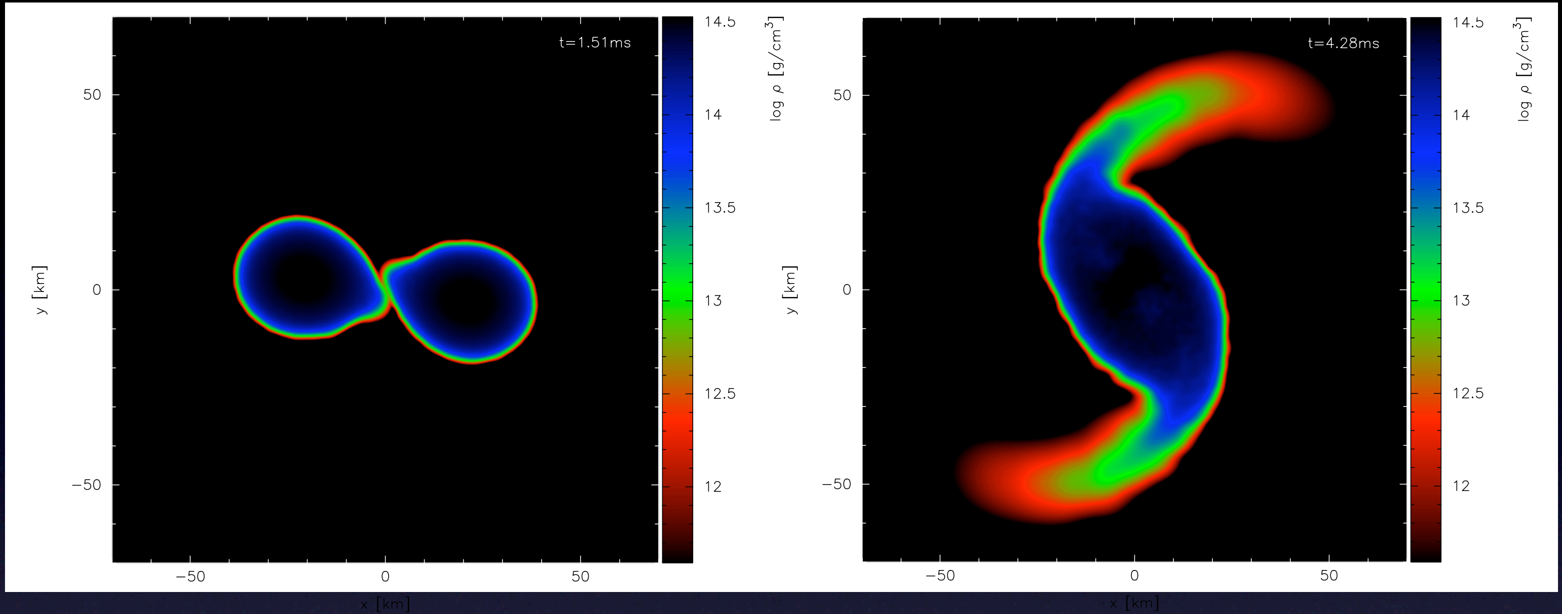
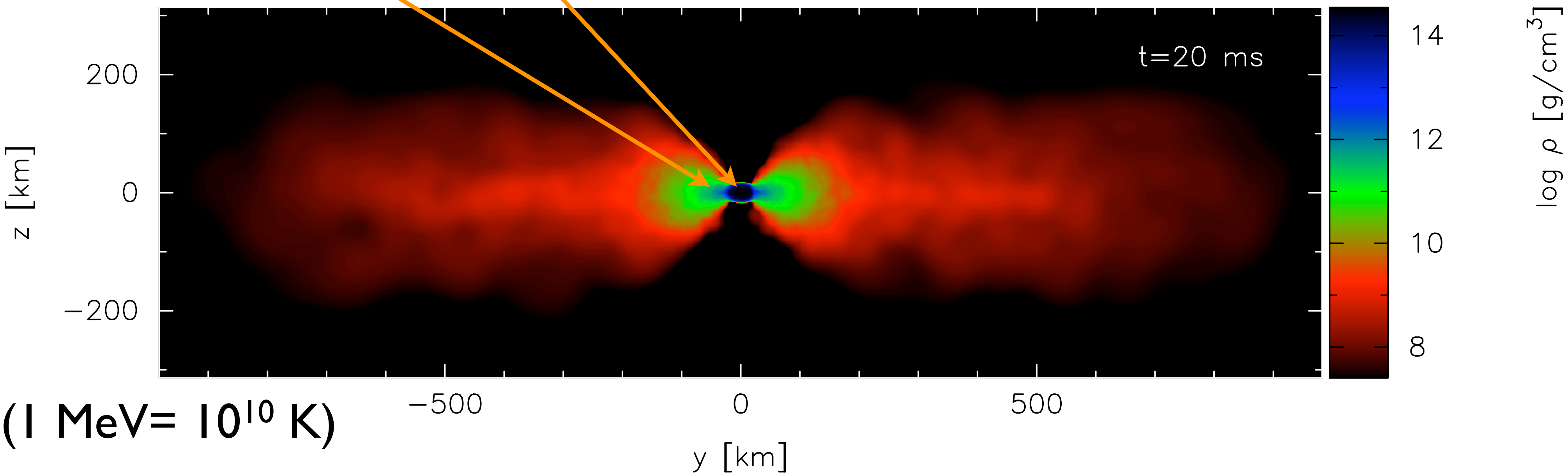


temperatures: ~ 4 MeV ~20 MeV

ν-Luminosities: $L_\nu \sim 2 \times 10^{53}$ erg/s



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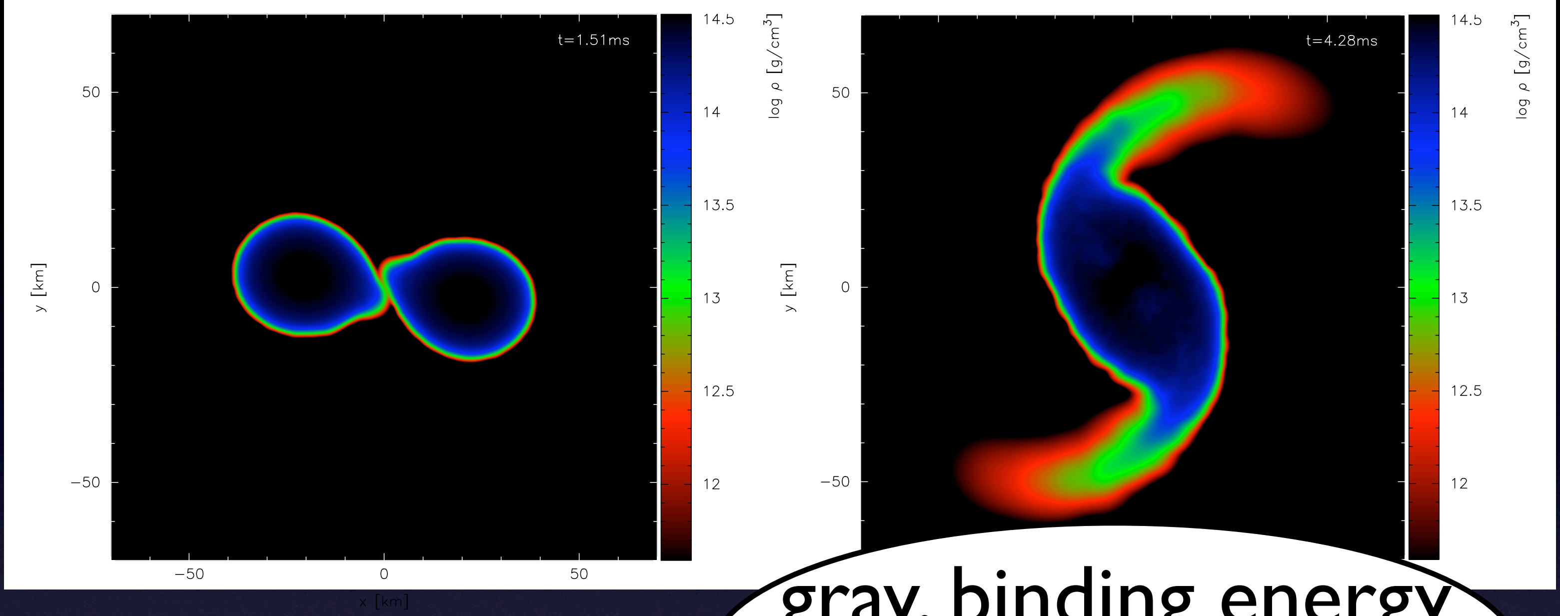
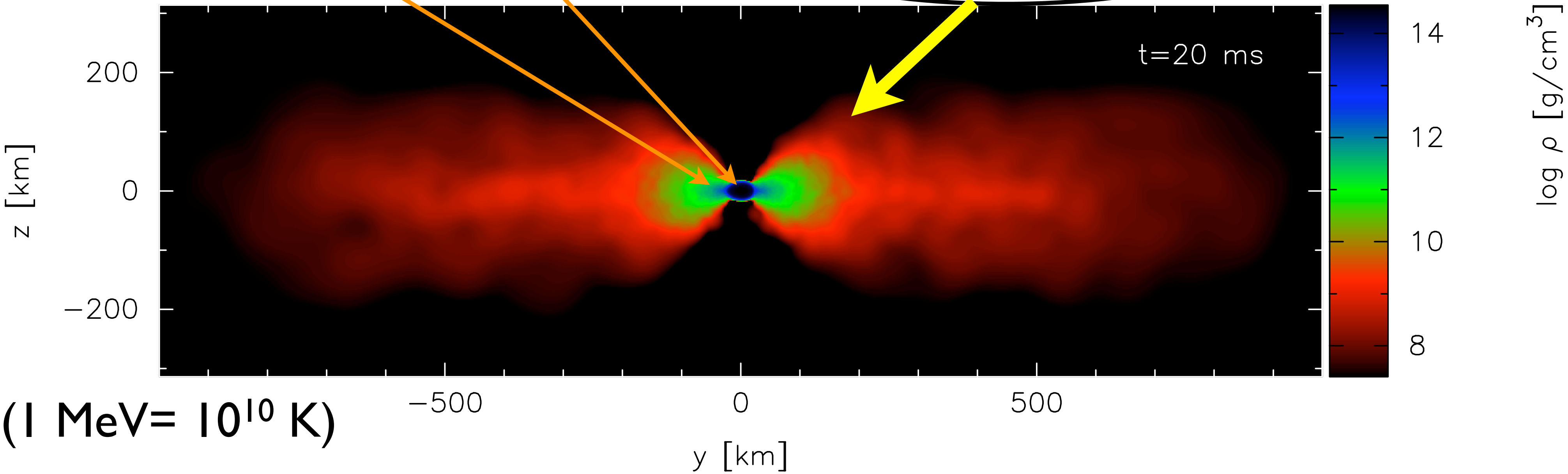


grav. binding energy

E_{grav} ~ 30 MeV/bar.

temperatures: ~ 4 MeV ~20 MeV

x 10^{53} erg/s



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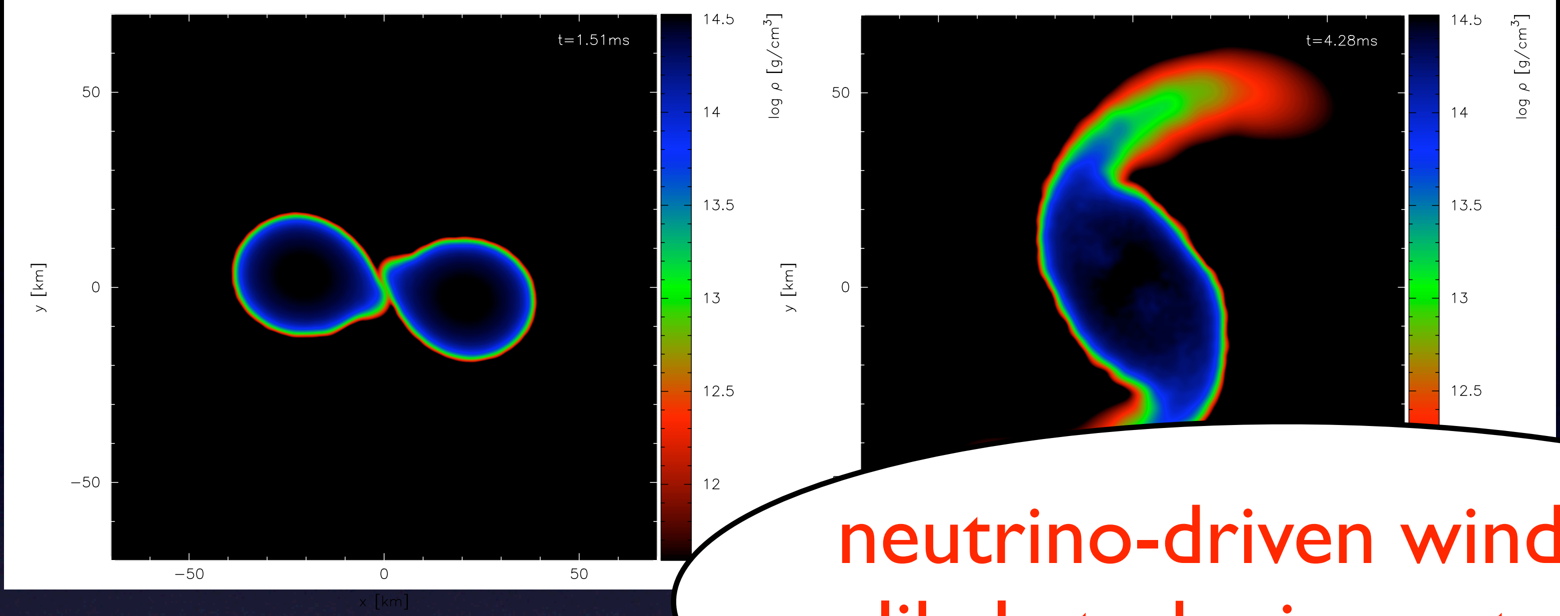

neutrino-driven winds are likely to be important !!

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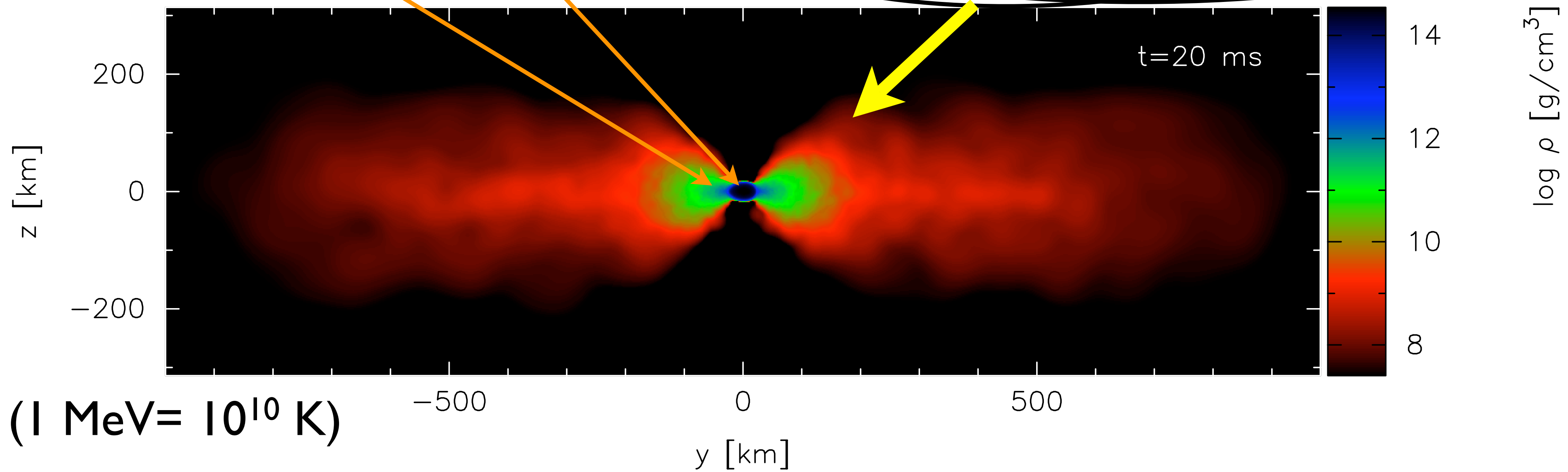

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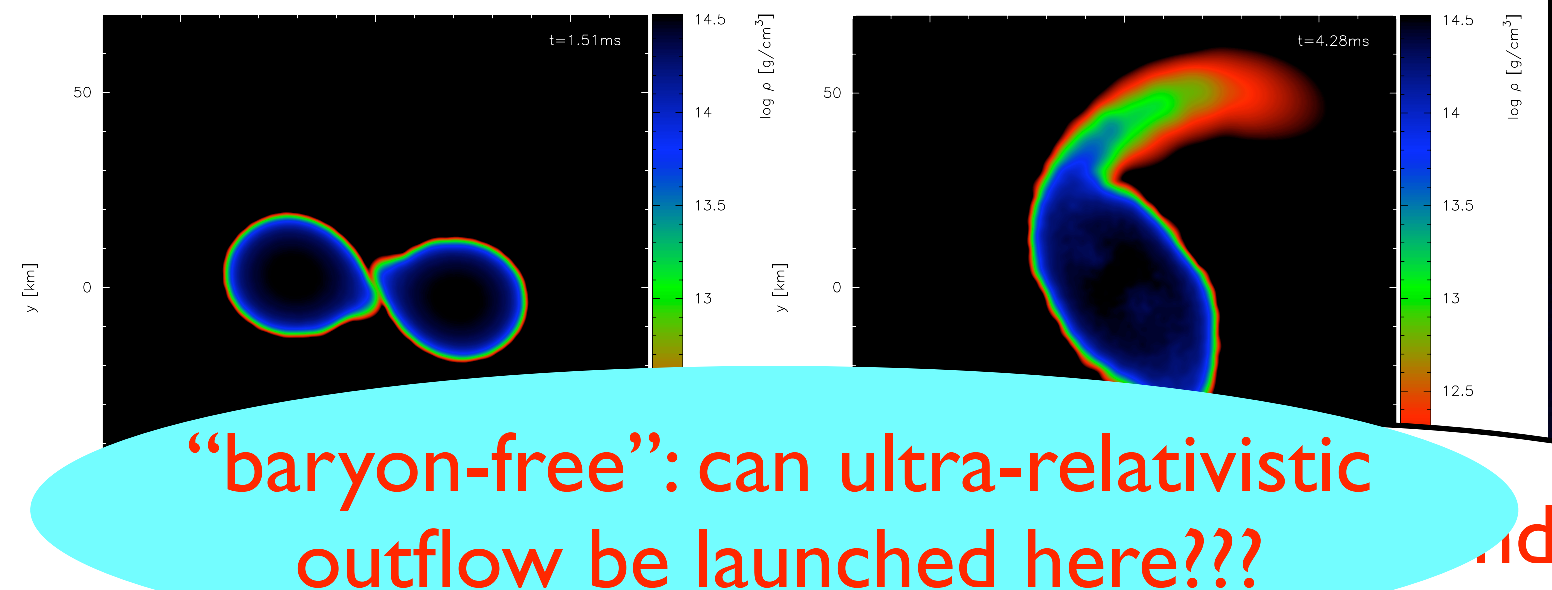
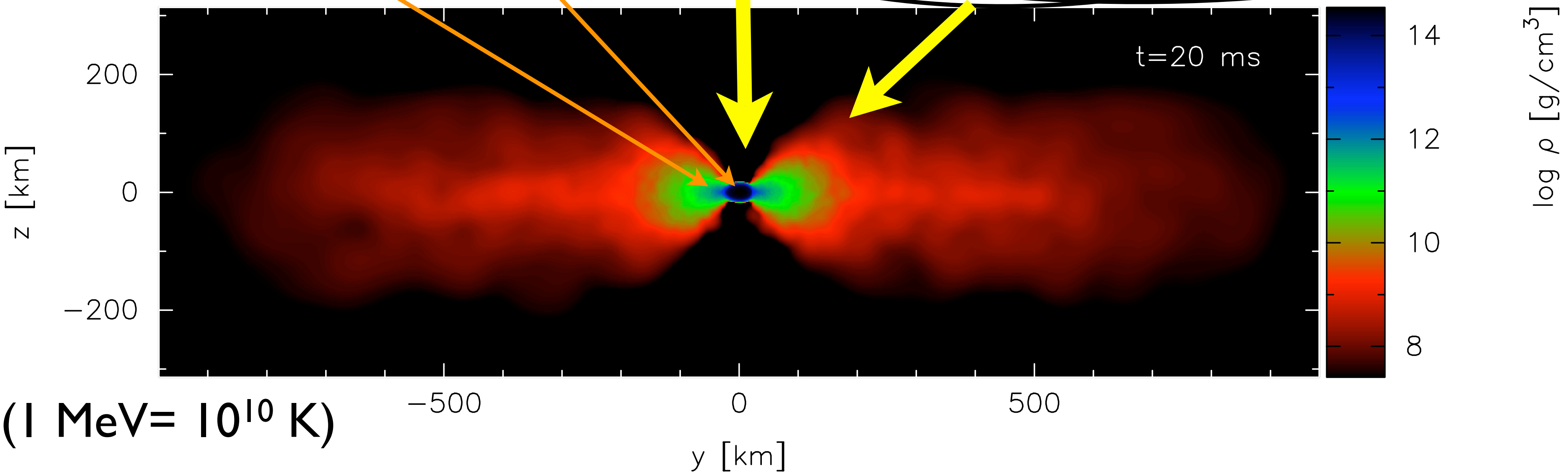


“baryon-free”: can ultra-relativistic outflow be launched here???

nds are
likely to be important !!

g/s

temperatures: ~ 4 MeV ~20 MeV



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Our approach

(Dessart, Ott, Burrows, Rosswog, Livne, ApJ 690, 1681, (2009))

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- step 1: simulate early phases with 3D MAGMA code
  (Rosswog&Price 2007)

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MAGMA

- 3D Smooth Particle Hydrodynamics
- Magnetic field evolution via Euler potentials
- nuclear equation of state (Shen et al. 1998)
- opacity dependent cooling via neutrinos
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- step 3: follow long-term evolution with supernova neutrino-hydrodynamics code VULCAN 2D

(Burrows et al. 2007)

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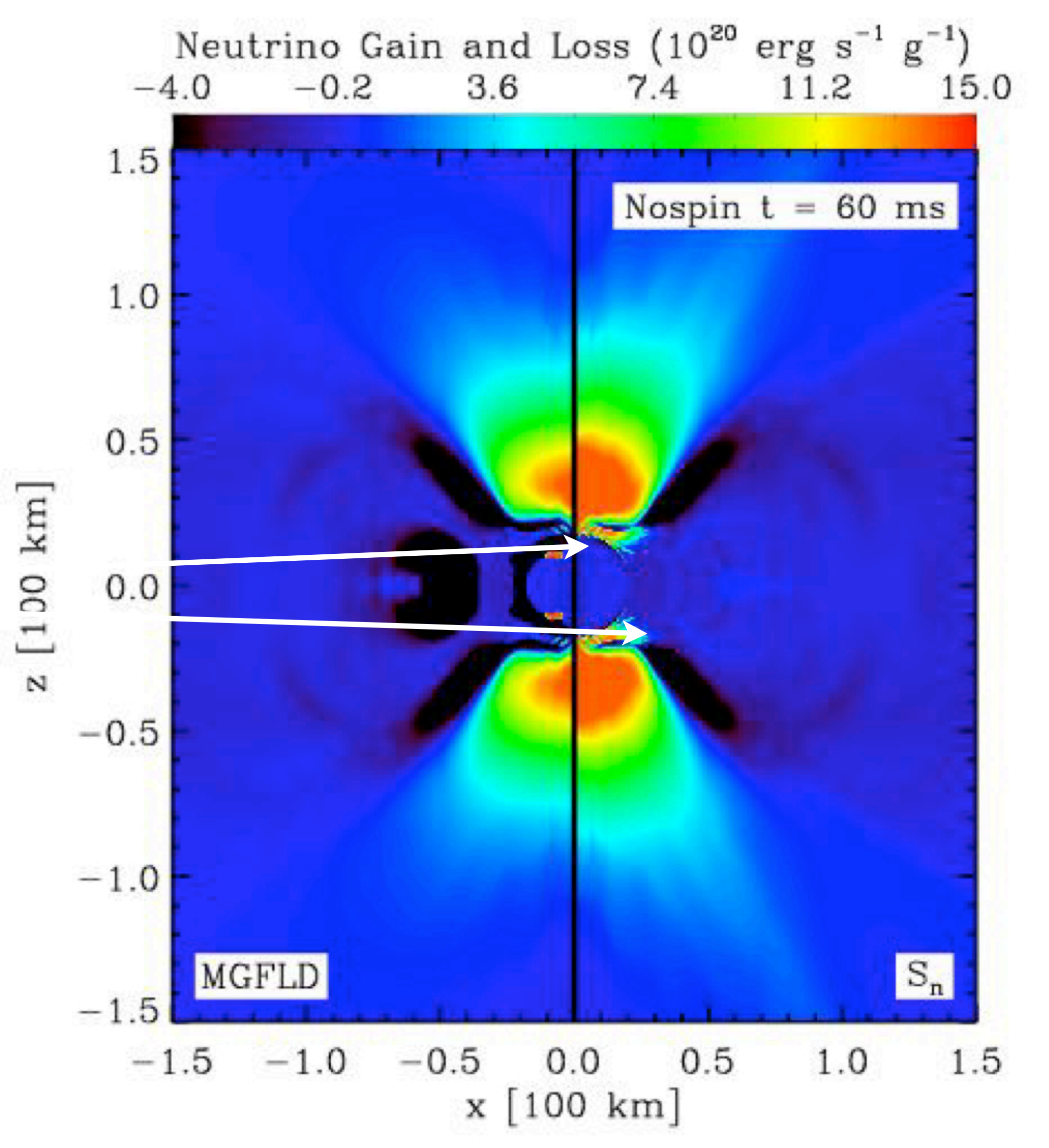
VULCAN 2D

- 2D "ALE" (Adaptive Lagrangian Eulerian)
- nuclear equation of state (Shen et al. 1998)
- state-of-the-art neutrino physics (emission, scattering, absorption)
  - during evolution: "Multi-group Flux Limited diffusion"
  - post-processing: "Multi-angle" or S_n-method
- heating via neutrino absorption & annihilation

- step 3: follow long-te
  neutrino-hydr

neutrino loss and gain at t= 60 ms:

major "gain regions":
- outer ns-crust
- funnel region



MGFLD: Multi-group flux-limited diffusion

S_n: short-characteristic method

- Step 3: dynamical evolution including neutrino heating and annihilation (VULCAN 2D)

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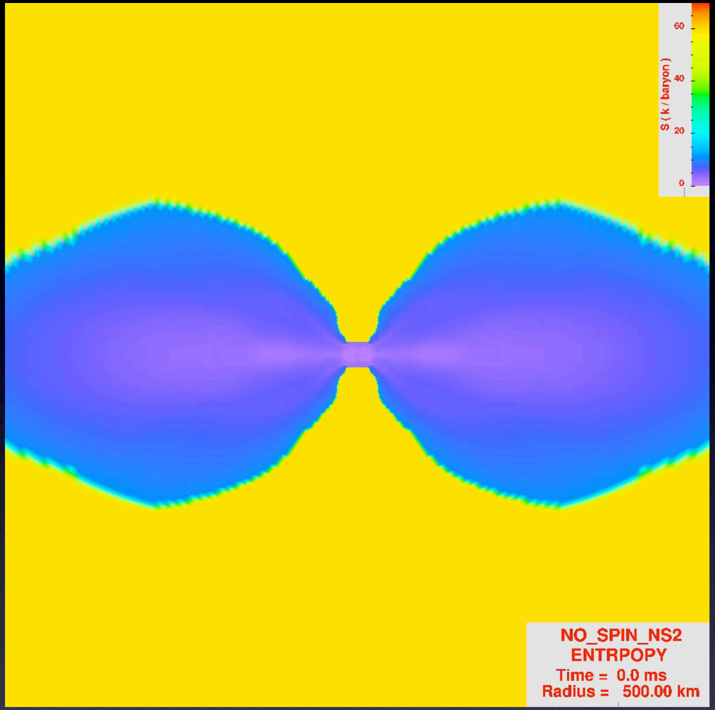
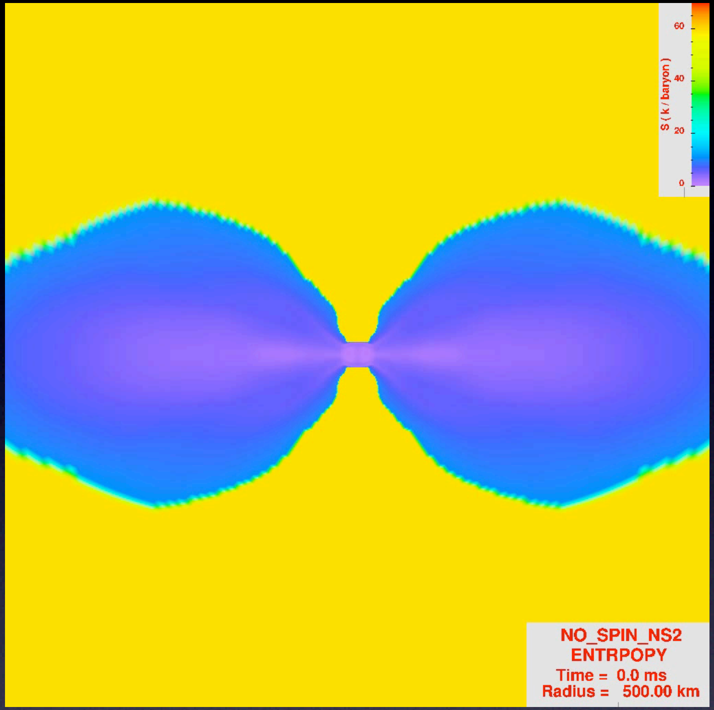


- Step 3: dynamical evolution including neutrino heating and annihilation (VULCAN 2D)

mass loss:

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

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



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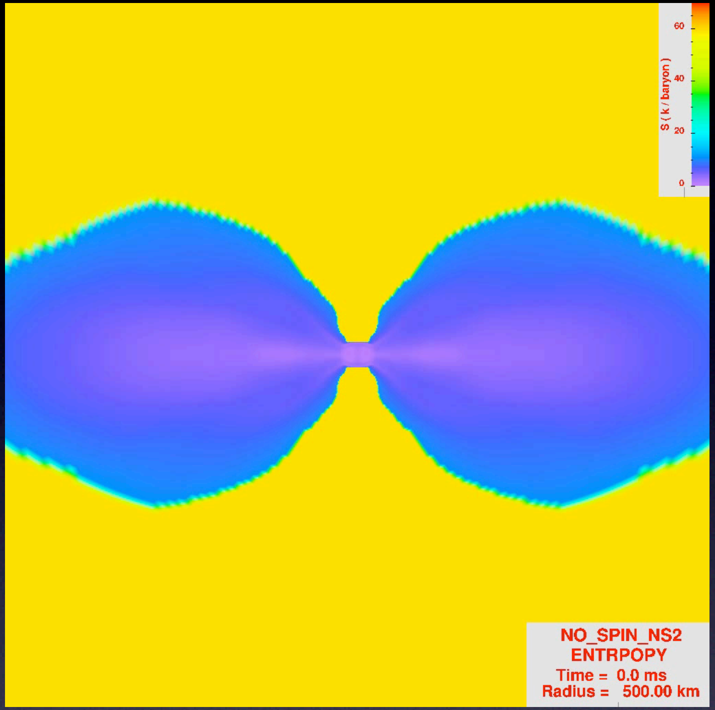

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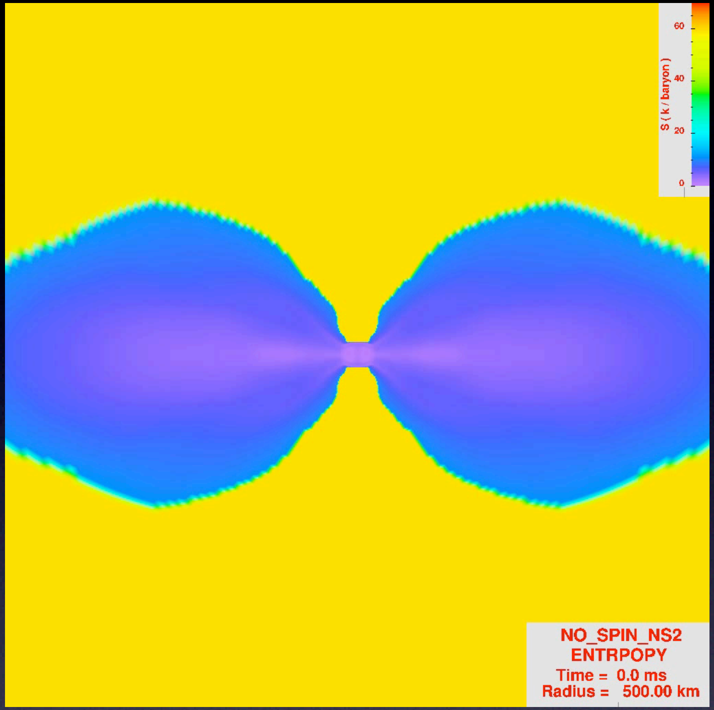

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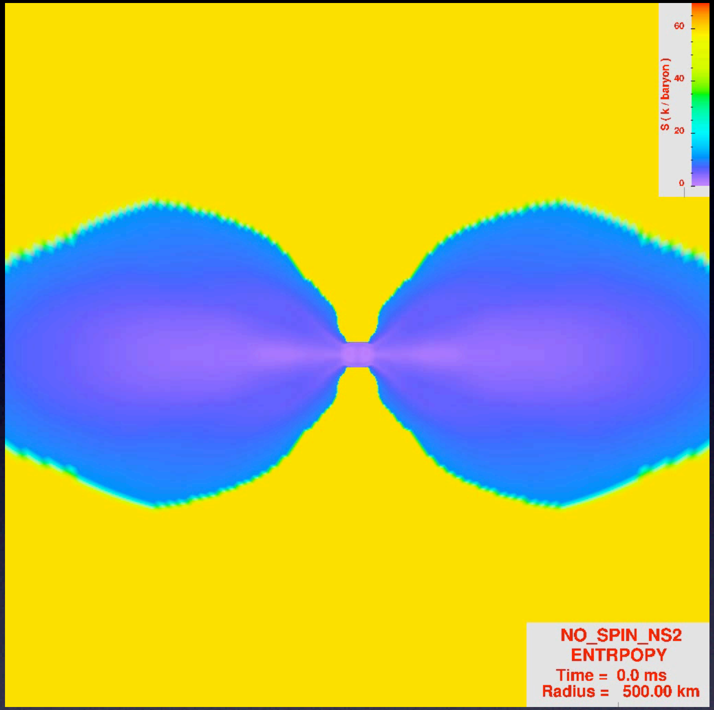

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➡ What happens after collapse to bh?

3.3 Can the central object avoid a collapse?

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- Demorest et al. Nature 467, 1081(2010): Shapiro delay for J 1614-2230

$$M_{\rm ns} = 1.97 \pm 0.04 M_\odot, \ \text{i.e.}\ M_{\rm ns,max} > 2 M_\odot$$

(cold, non-rotating!)

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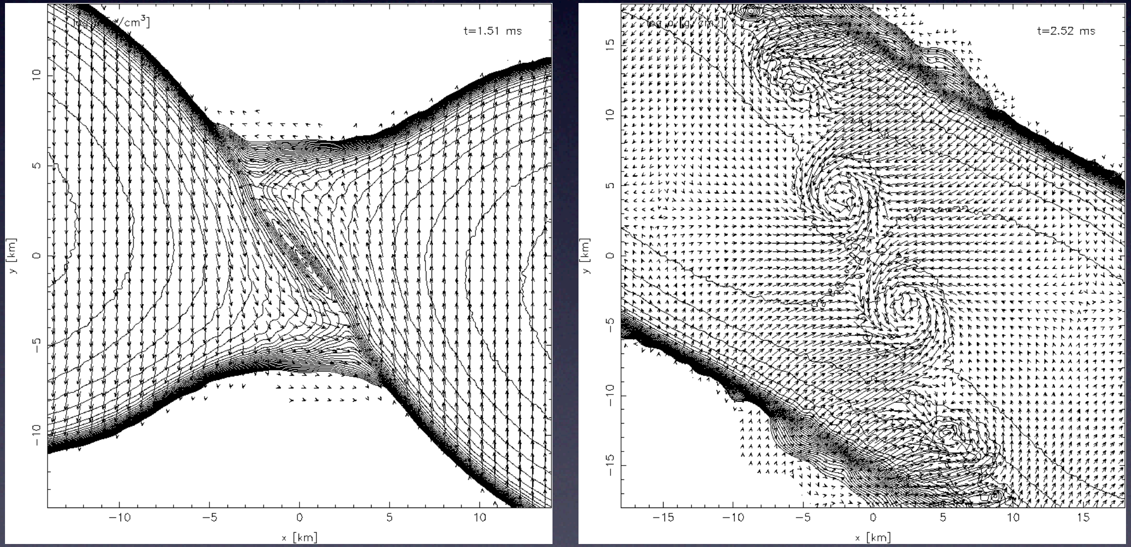

(from Rosswog 2007)

very efficient
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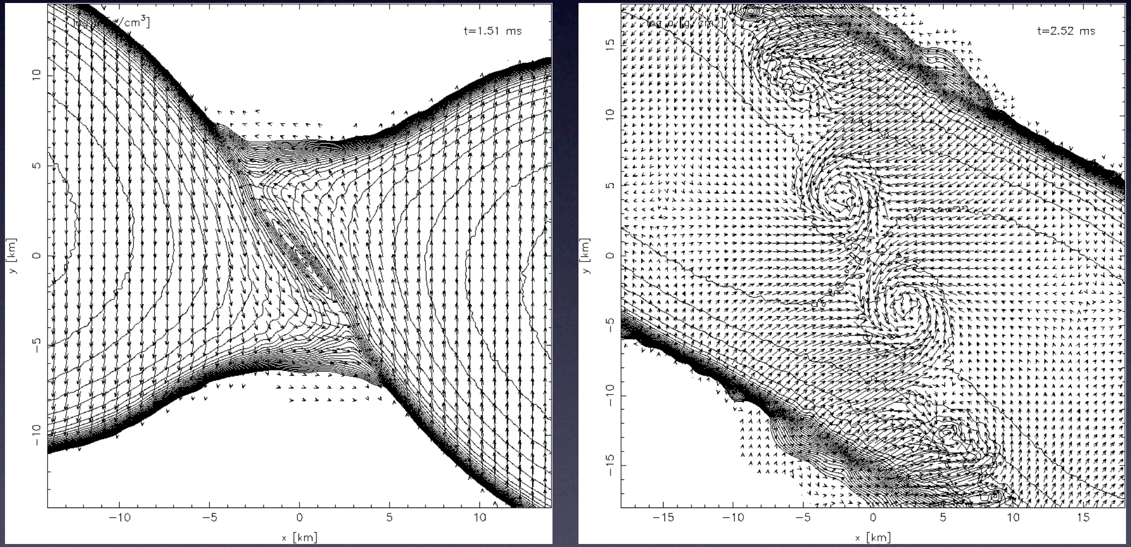

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- Shibata & Taniguchi (2006): threshold mass $M_{\rm thresh} \approx 1.35 M_{\rm ns,max} > 2.7 M_\odot$

$$M_{\rm c.o.} \quad < \quad M_{\rm thresh} : \text{direct collapse}$$

$$> \quad M_{\rm thresh} : \text{"hypermassive neutron star"}$$

→ many/most systems avoid direct collapse!

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Could enough mass be lost to prevent a final collapse?

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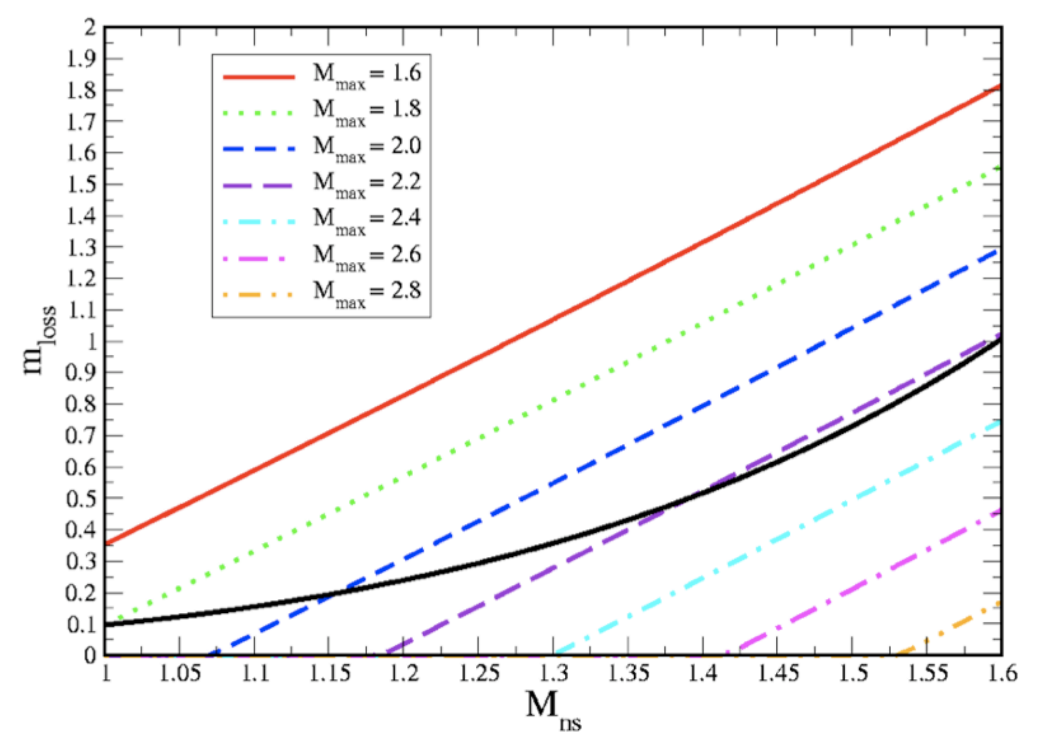
required baryonic mass loss



neutron star mass

(using grav. binding energy of Lattimer&Yahil 1989, from Rosswog, Rev. Mex. A.A. 27, 57, 2007,)

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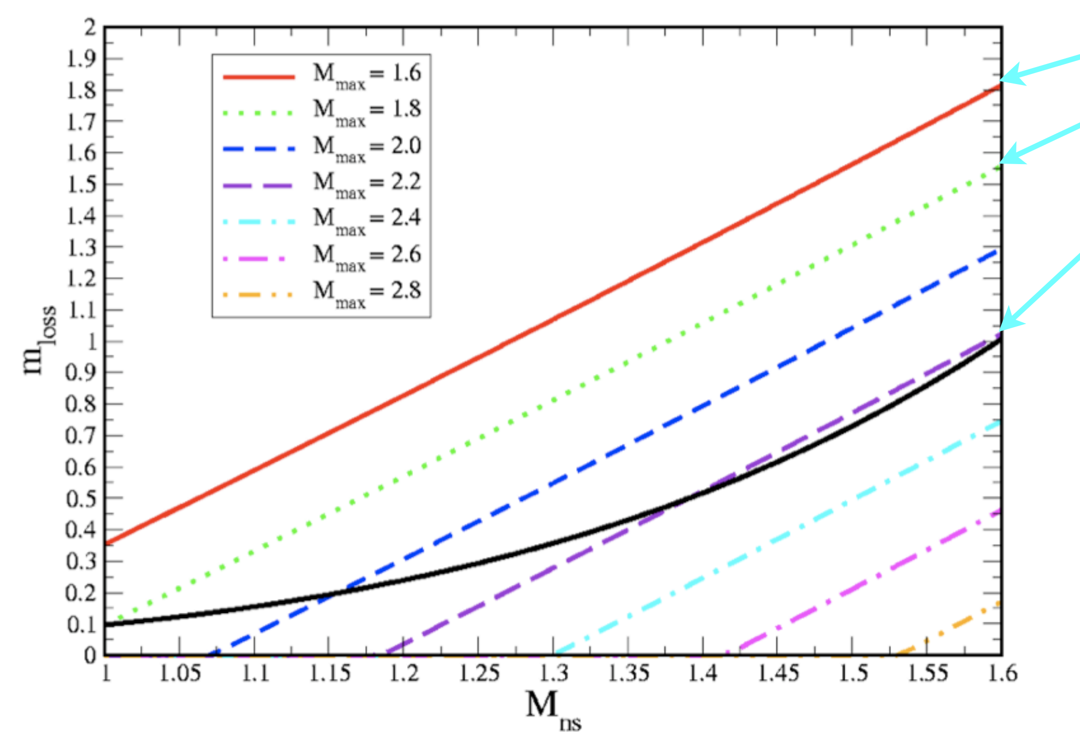

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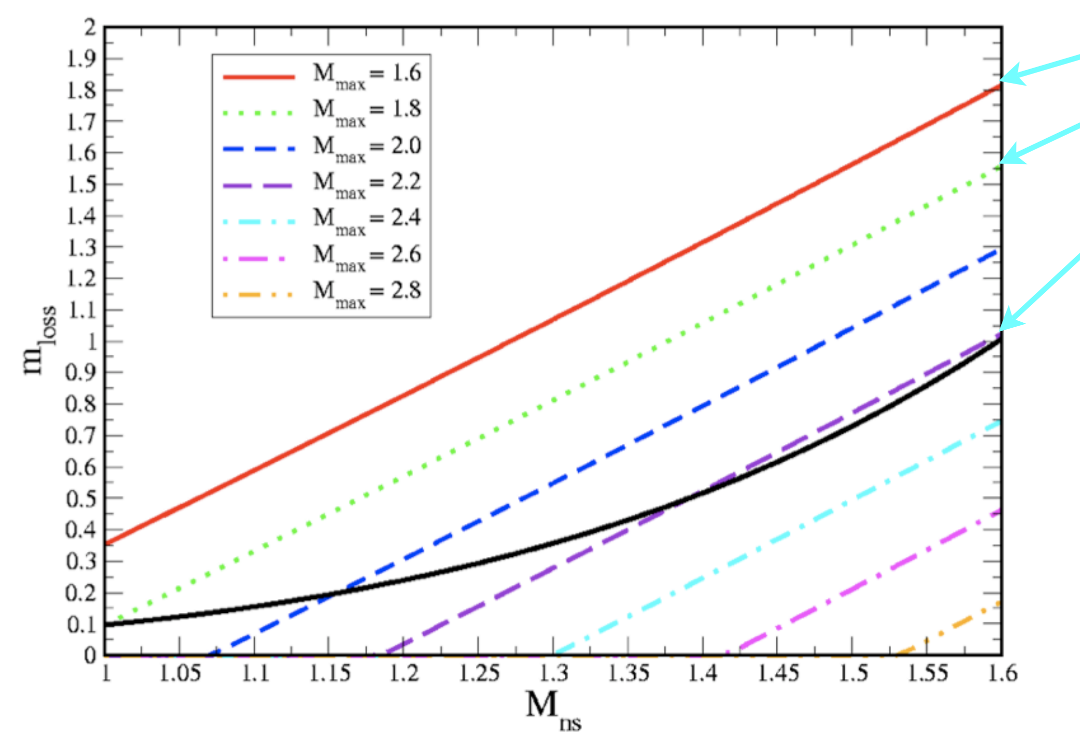

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for M_{ns}= 1.25:

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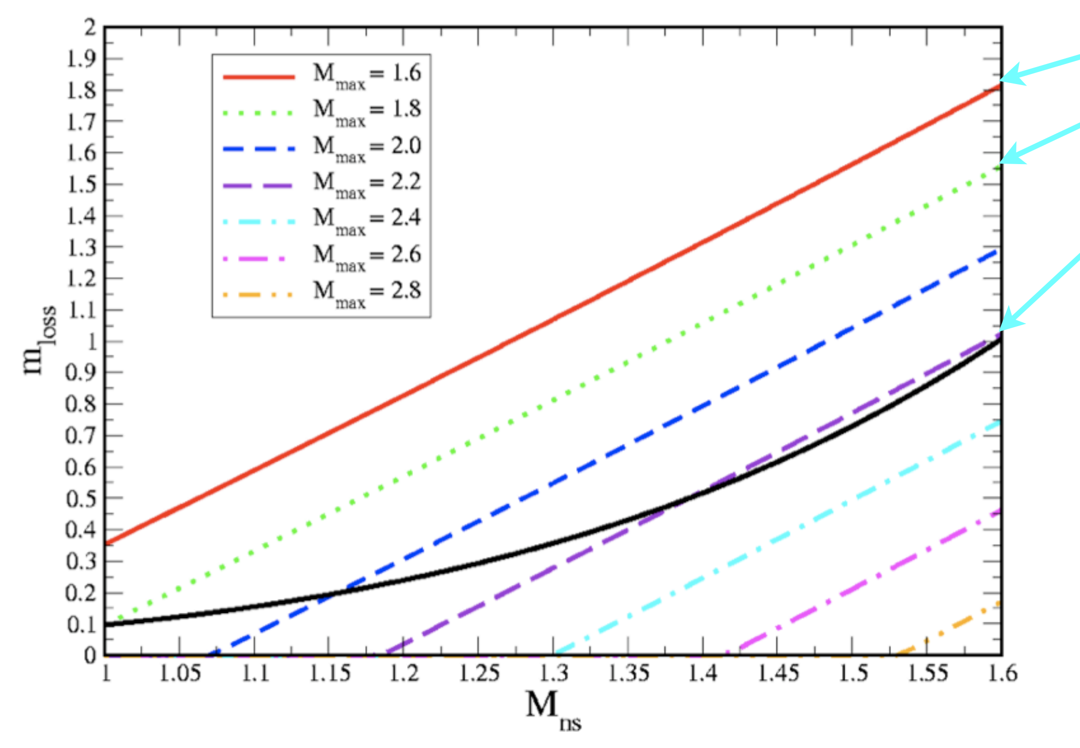

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$M_{ns,\ max}$= 2
M_{loss}= 0.4

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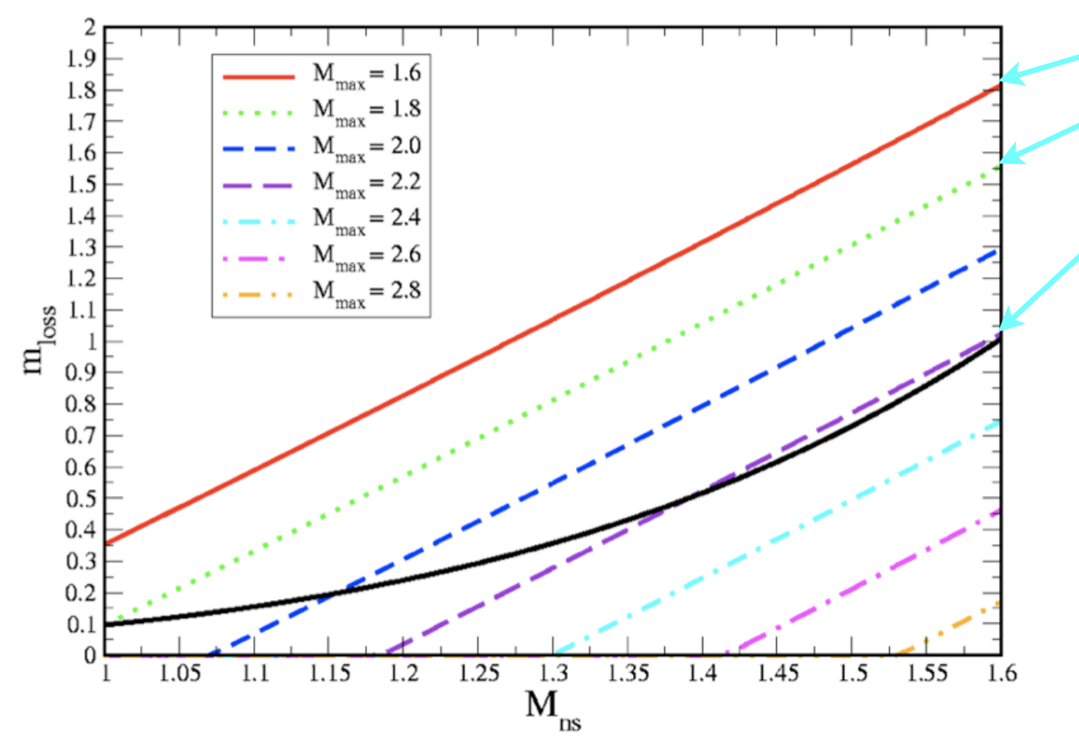

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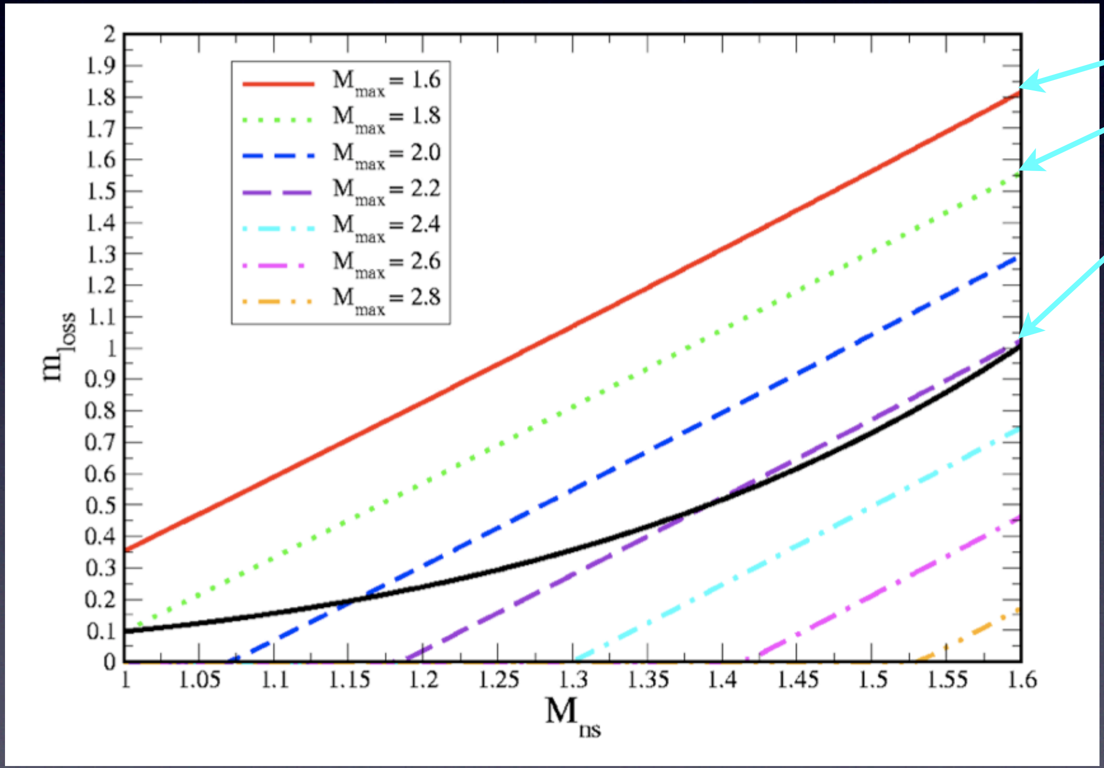

neutron star mass

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for M_{ns}= 1.25:

$M_{ns, max}$= 2
M_{loss}= 0.4

$M_{ns, max}$= 2.2
M_{loss}= 0.1

mass loss mechanisms:

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- neutrino-driven winds (enhanced by B-fields; Y_e~0.2-0.5): $\sim 0.1 M_\odot$
- viscous disk evolution (Beloborodov 08, Metzger+08, Lee+09):
  - ν-cooling becomes inefficient: advective disk
  - nucleons recombine into nuclei

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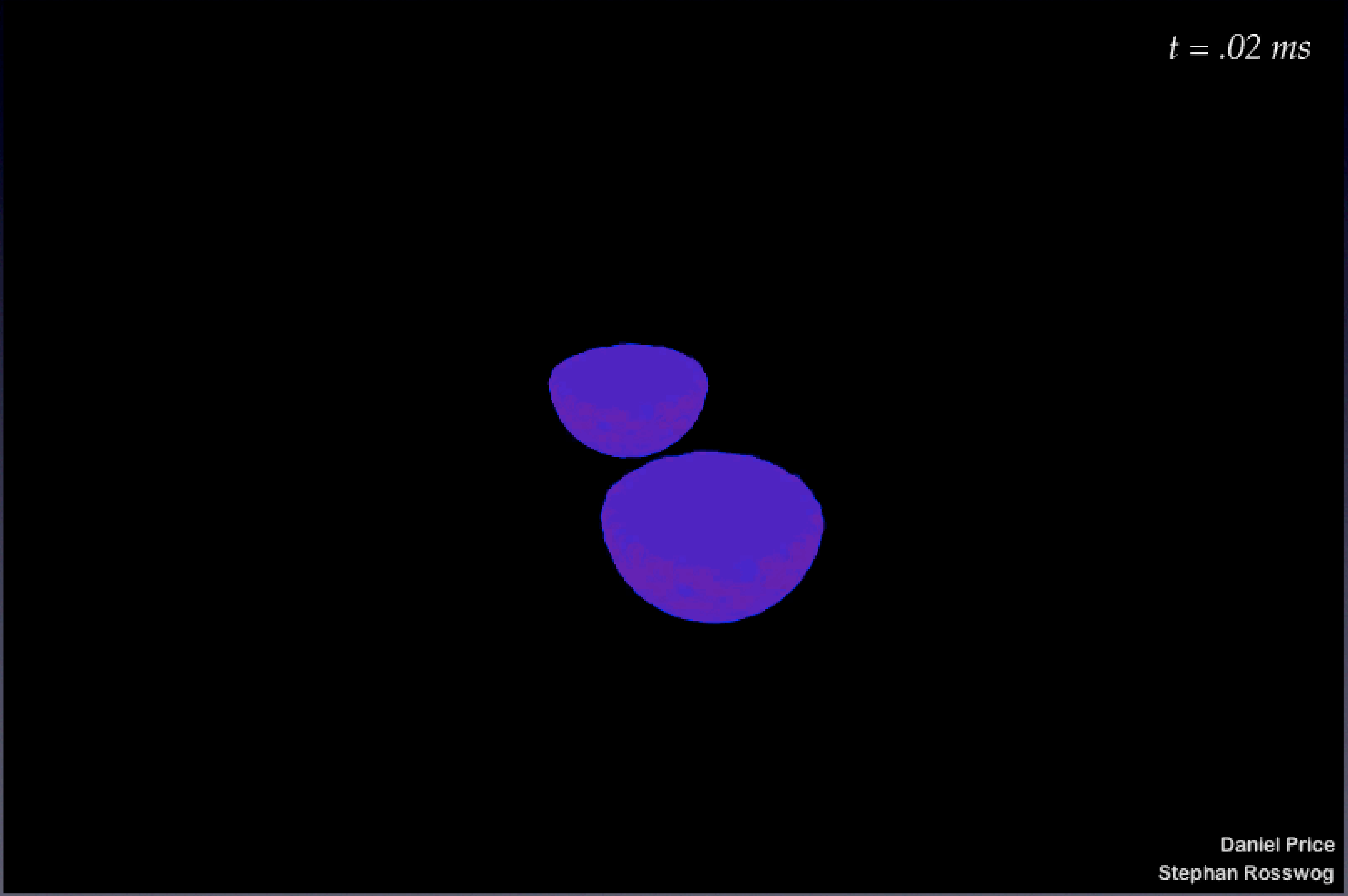
→ low-mass systems could possibly survive, "magnetar" formation cannot be excluded

(see talks O'Brien, Metzger this conference)

3.4 Late-time activity

gravitational torques launch matter $(\sim 0.02 - 0.08 M_\odot)$ unavoidably onto "fallback orbits"!



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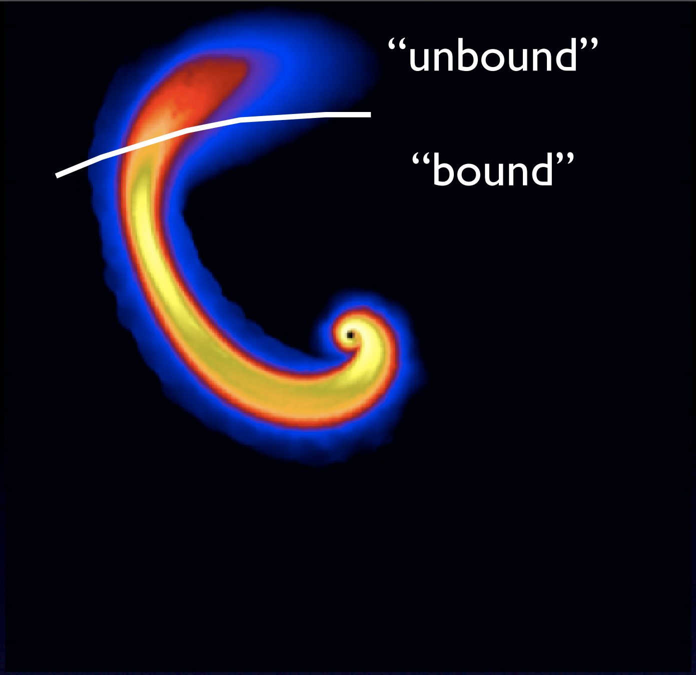
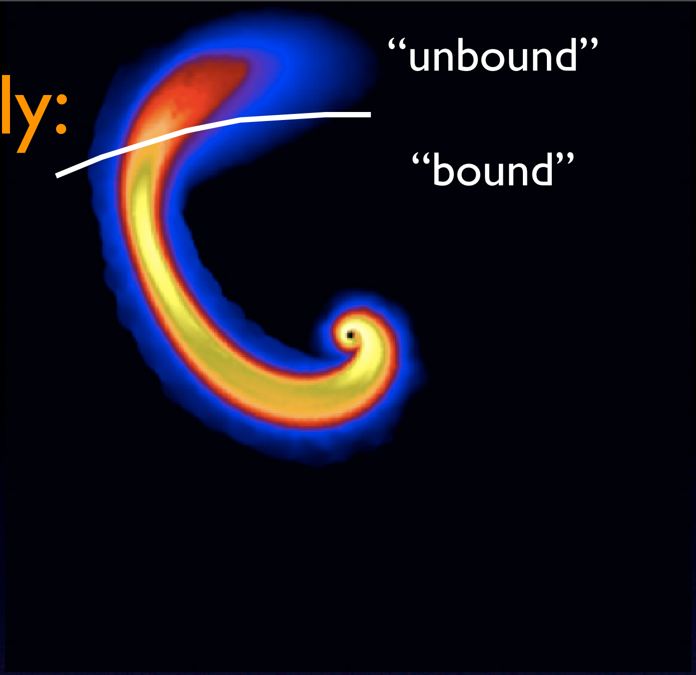
also the much longer

c) “fallback time scale” (Rosswog 2007)


“unbound”
“bound”

fallback time can be calculated analytically:



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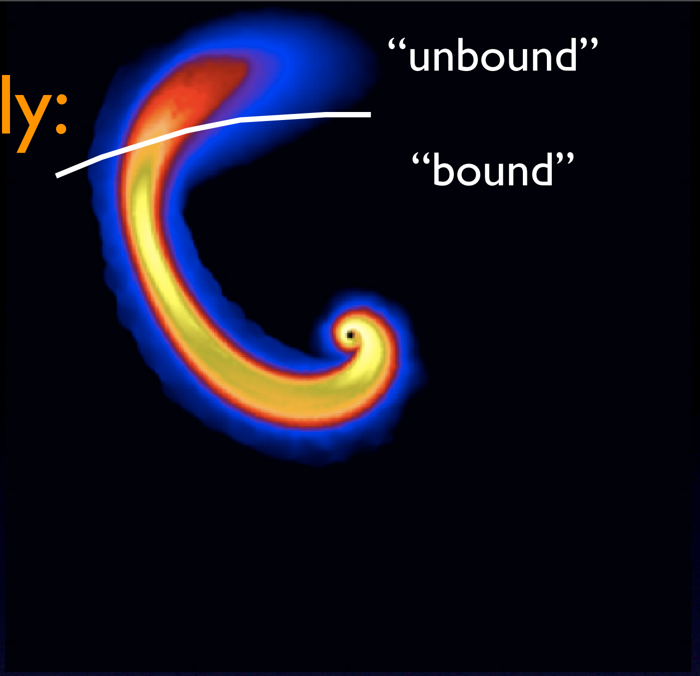
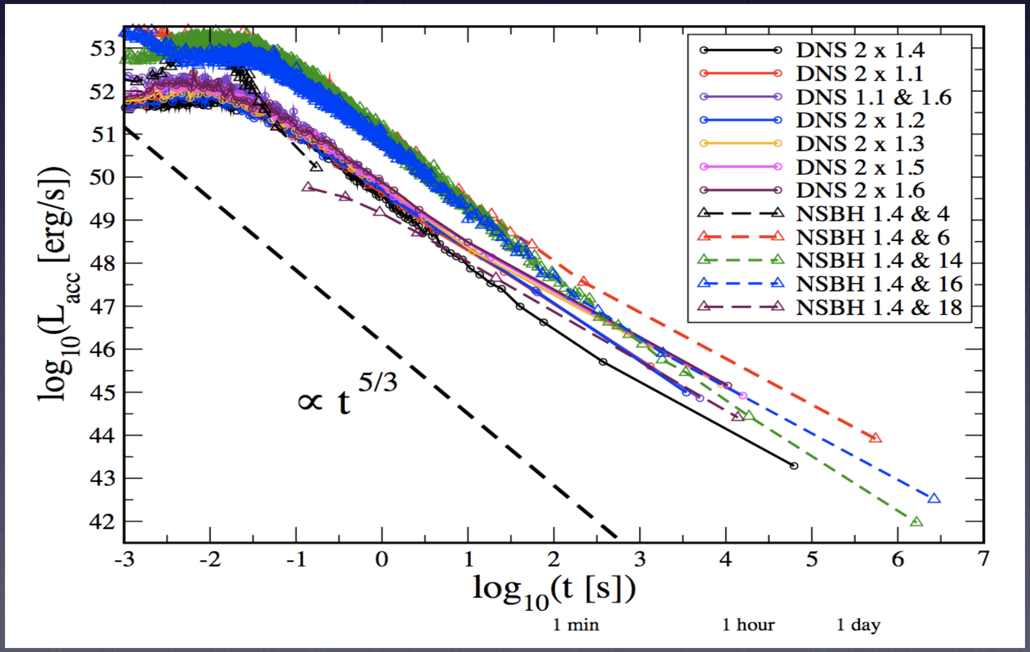


mech. fallback luminosity



(Rosswog, MNRAS 376, 148,

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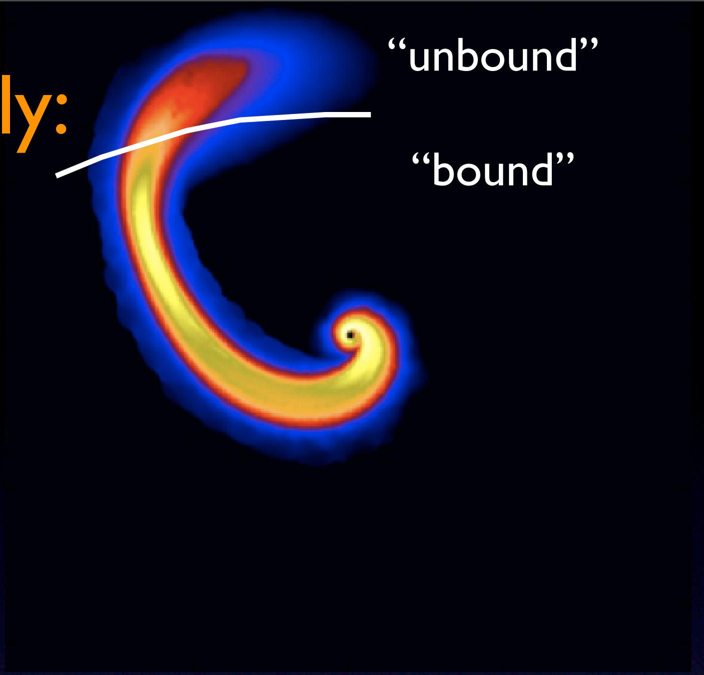

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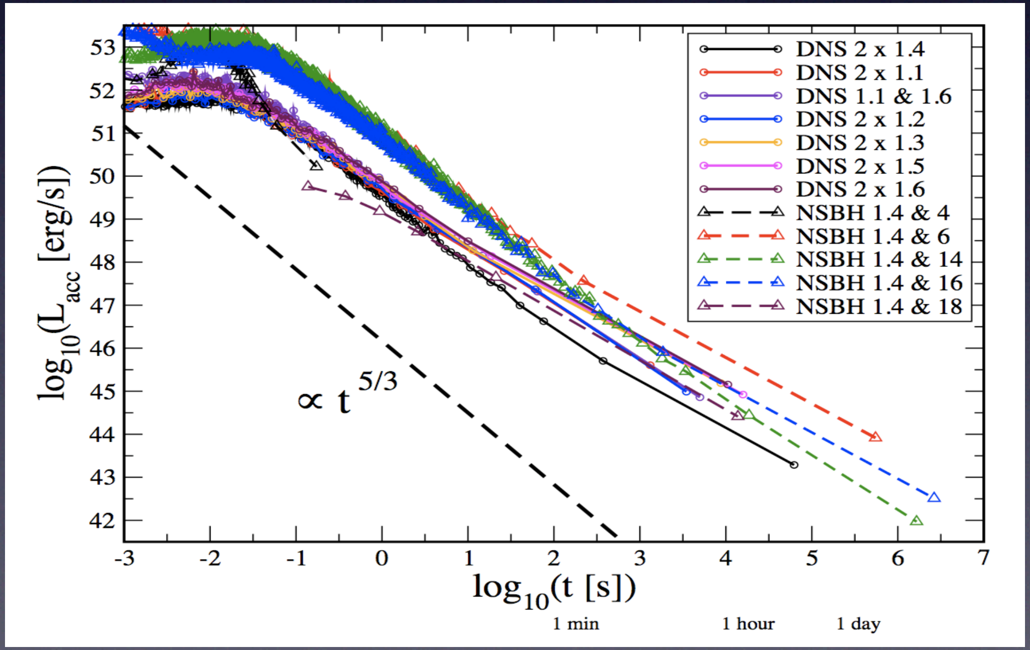

(Rosswog, MNRAS 376, l48,

can produce fallback for minutes to hours

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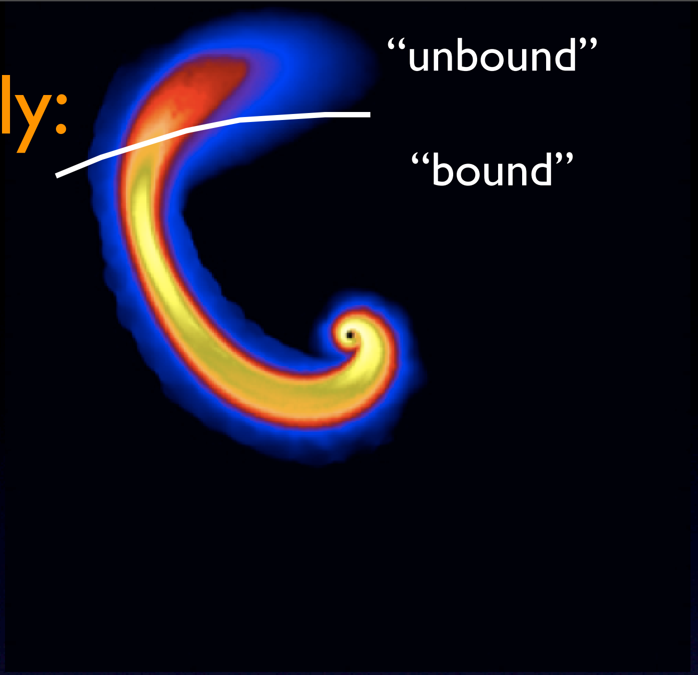

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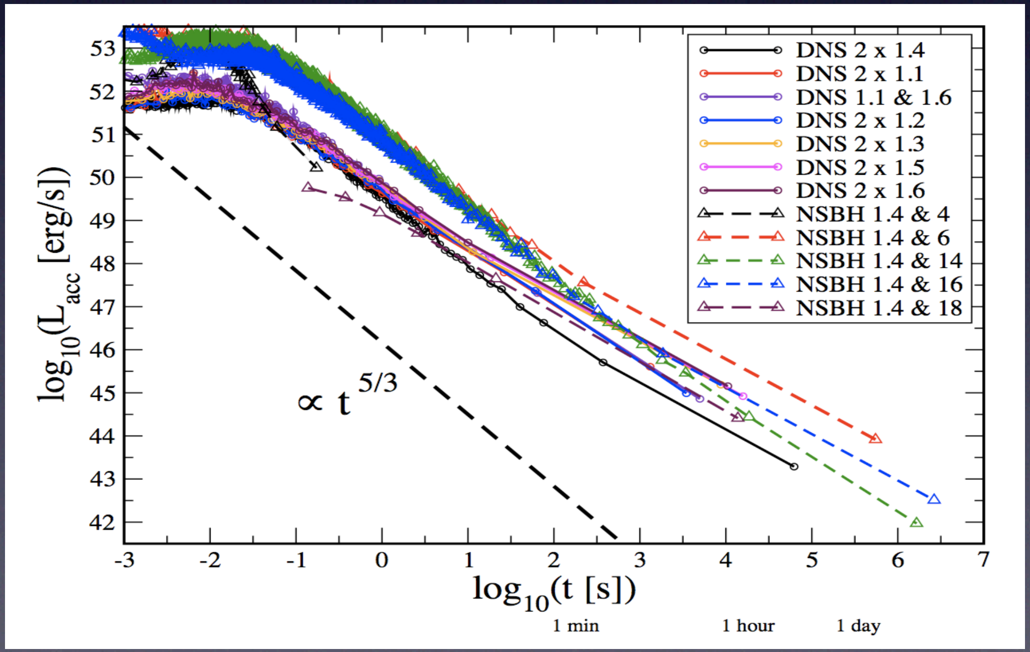

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really flares?

Puzzle:

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- magnetar-like remnants are plausible explanations for late-time activity

- BUT: how to avoid the baryonic pollution to produce the relativistic outflow in the first place???

4. Summary

- ~ 1 minute before merger neutron star suffers a "tidal grinding phase"
  - details complicated, but general prediction robust
  - IF at least one neutron star is highly magnetized, this should produce a sequence of "magnetar-like" flares with increasing strength
- (at least before collapse to a bh) neutrinos drive a very strong baryonic wind, that "pollutes" the most promising region to launch a burst; hard to see how ultra-relativistic could be launched
- low mass binary systems could possibly survive merger without bh formation: "magnetar-like" object
- late flares remain an open issue

- compact binary mergers are a good model,
  BUT: stay open-minded,
  whatever is not forbidden by physics will happen (at some rate)!