Importance of cooling in triggering the collapse of hypermassive neutron stars

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Motivation

- HMNSs arise following the merger of binary neutron stars when the total mass < 1.3-1.35 $M_{TOV,limit}$ (Shibata, Taniguchi, PRD 73, 064027)

- HMNSs are born hot and rapidly differentially rotating

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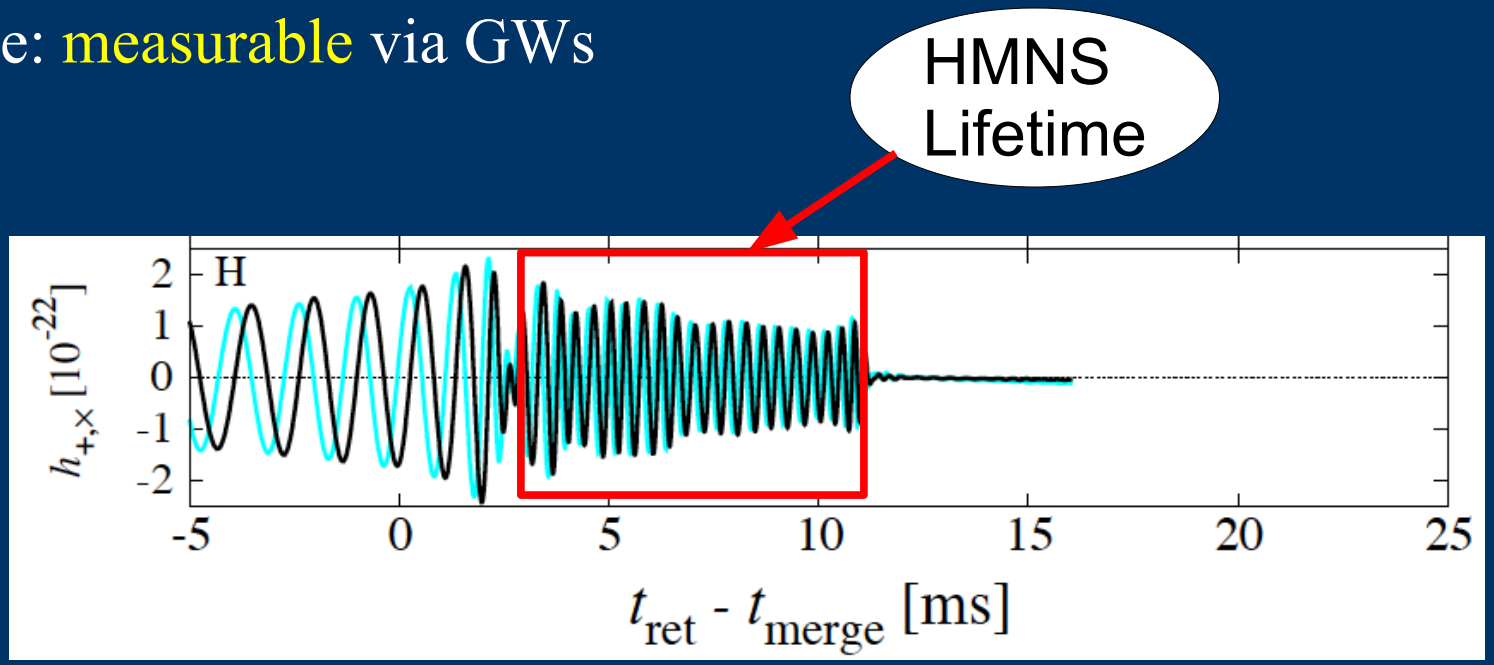

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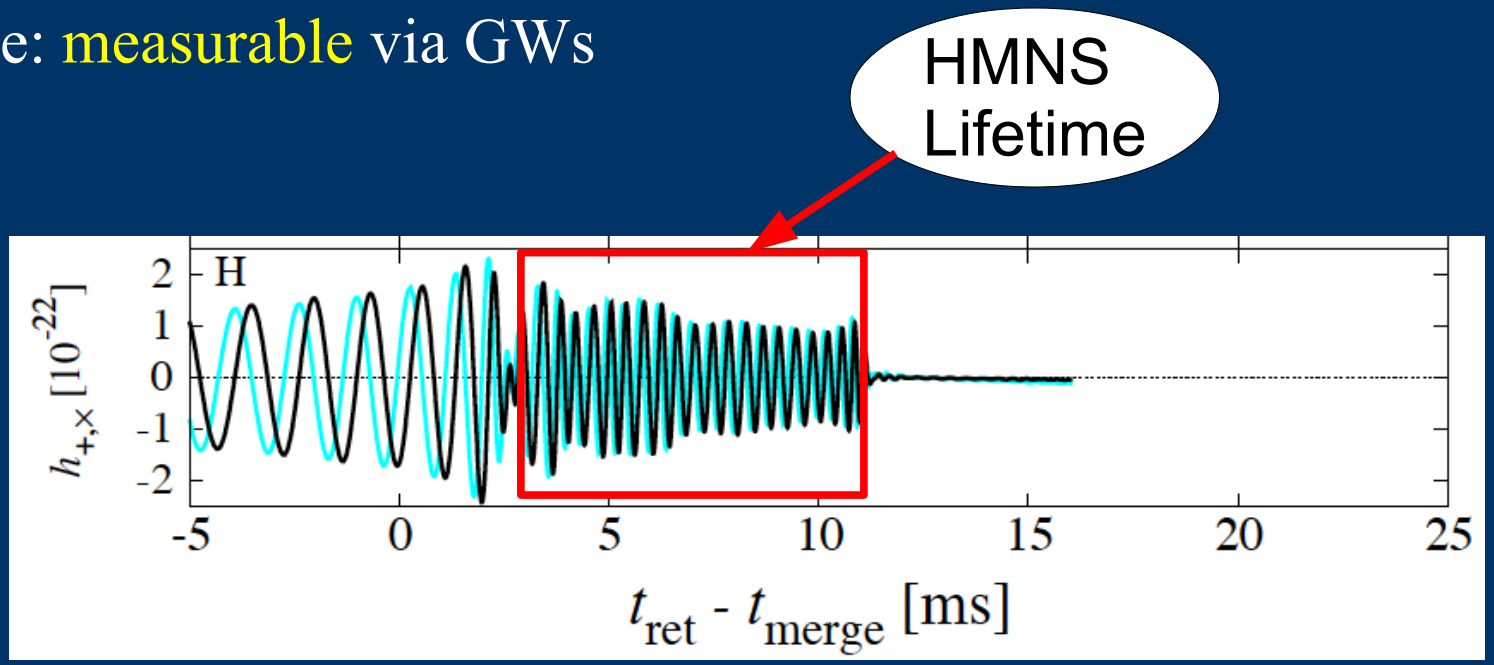

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- GW observations: can constrain B-field strength, bar modes, cooling mechanisms, temperatures, etc.

Background: Thermal or Centrifugal support?

- Recent works seem to be pointing in different directions.

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- Question: Is thermal support important or not?

HMNS Relevant Timescales

- GW timescale

$$t_{\rm GW} \equiv \frac{J}{dJ/dt} \approx \frac{1}{MR^2\Omega^4 e^2} = \frac{R^4}{\epsilon^4 e^2 M^3}$$

$$\epsilon = \frac{\Omega}{\Omega_{\rm breakup}}$$

HMNS Relevant Timescales

- GW timescale

$$t_{\rm GW} \approx 200 \left(\frac{\epsilon}{0.5}\right)^{-4} \left(\frac{e}{0.75}\right)^{-2} \left(\frac{R}{20{\rm km}}\right)^{4} \left(\frac{M}{2.8 M_\odot}\right)^{-3} {\rm ms}$$

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- Alfven (magnetic braking) timescale

$$t_{\rm A} \approx \frac{R}{v_A} \approx \frac{R\sqrt{4\pi\rho}}{B}$$

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- Neutrino cooling timescale

$$t_{\rm cool} \approx 3\frac{R^2}{\lambda_n c}$$

$$\lambda_n^{-1} = n\sigma_n$$

$$\sigma_{\rm scat} \approx \frac{1}{4}\sigma_0\left(\frac{E_\nu}{m_e c^2}\right)^2,$$

$$\sigma_{\rm abs} \approx 1.42\sigma_0\left(\frac{E_\nu}{m_e c^2}\right)^2$$

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- Neutrino cooling timescale

$$t_{\rm cool} \approx 400 \left(\frac{M}{2.8 M_\odot}\right) \left(\frac{R}{20{\rm km}}\right)^{-1} \left(\frac{E_\nu}{10{\rm MeV}}\right)^{2} {\rm ms}$$

Cooling timescale comparable to other timescales

Fully GRHD simulations accounting for HMNS cooling with an effective emissivity

- Goal: Assess the importance of shock-induced thermal pressure support in an HMNS formed following the merger of a NSNS

- Binary NS initial data (LORENE generated and publicly available):
  a) equal-mass, n=1 polytropic
  b) circular orbit and irrotational
  c) quasiequilibrium
  d) satisfy the conformal-thin-sandwich equations

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  - Continue without cooling
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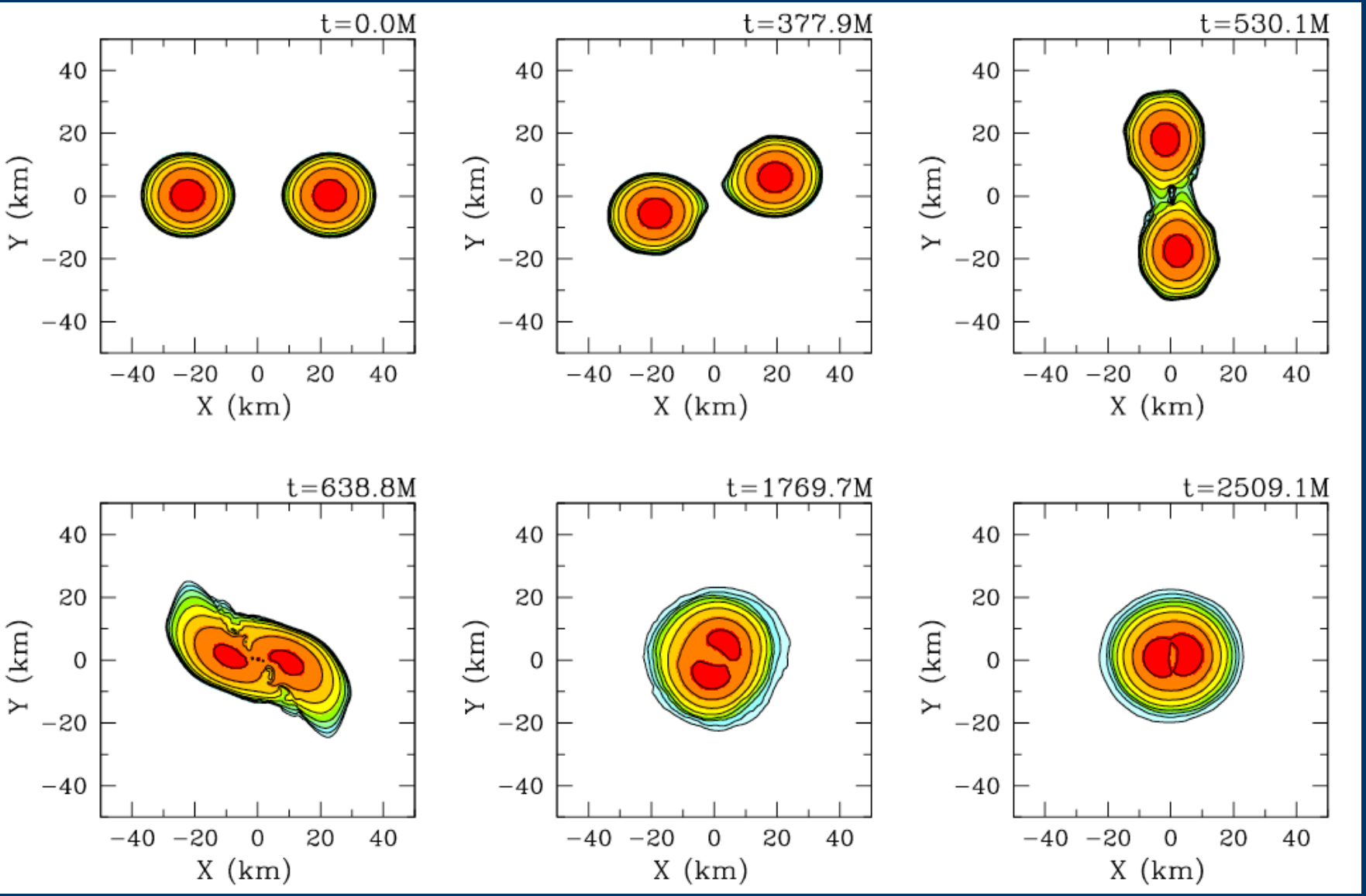
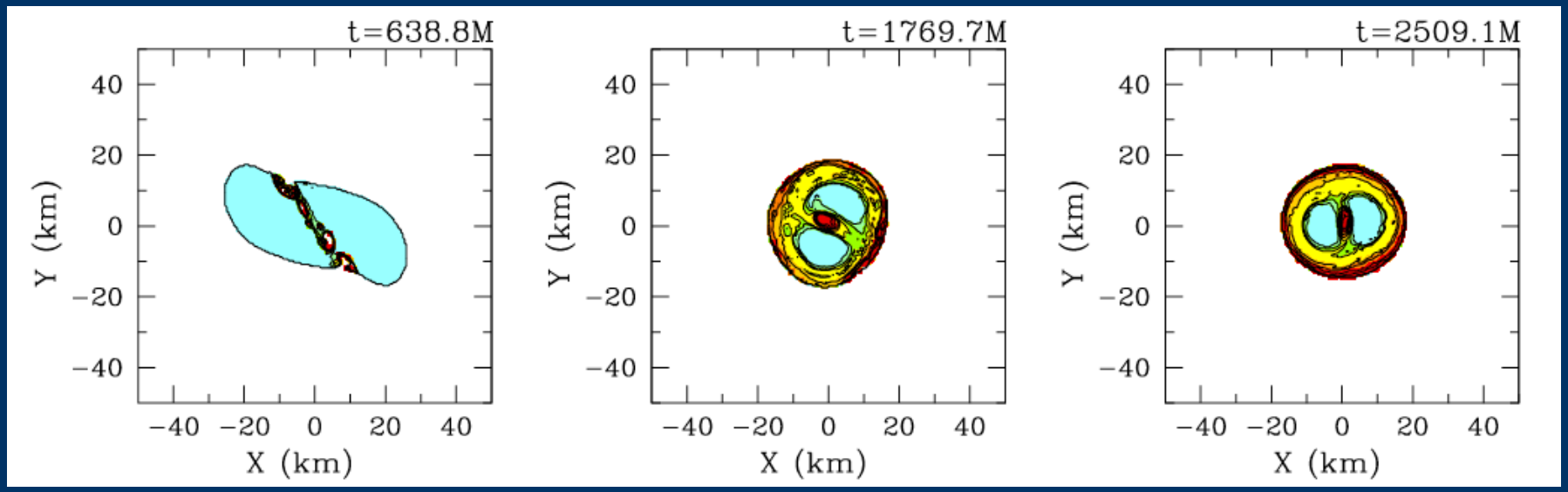
Compare

Inspiral, merger and HMNS formation: Orbital-plane rest-mass density



Merger and HMNS formation: Entropy parameter $K=(P_{th}+P_{cold})/P_{cold}$



Red: K ≈ 1.6
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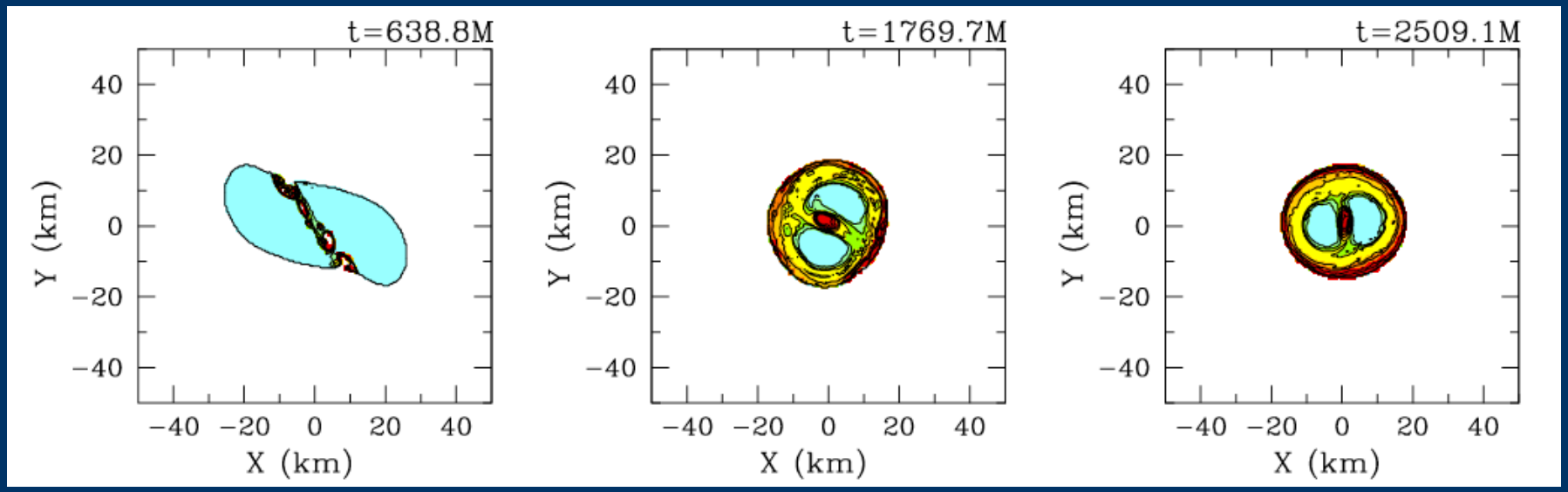

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Total of 40%-60% additional pressure!

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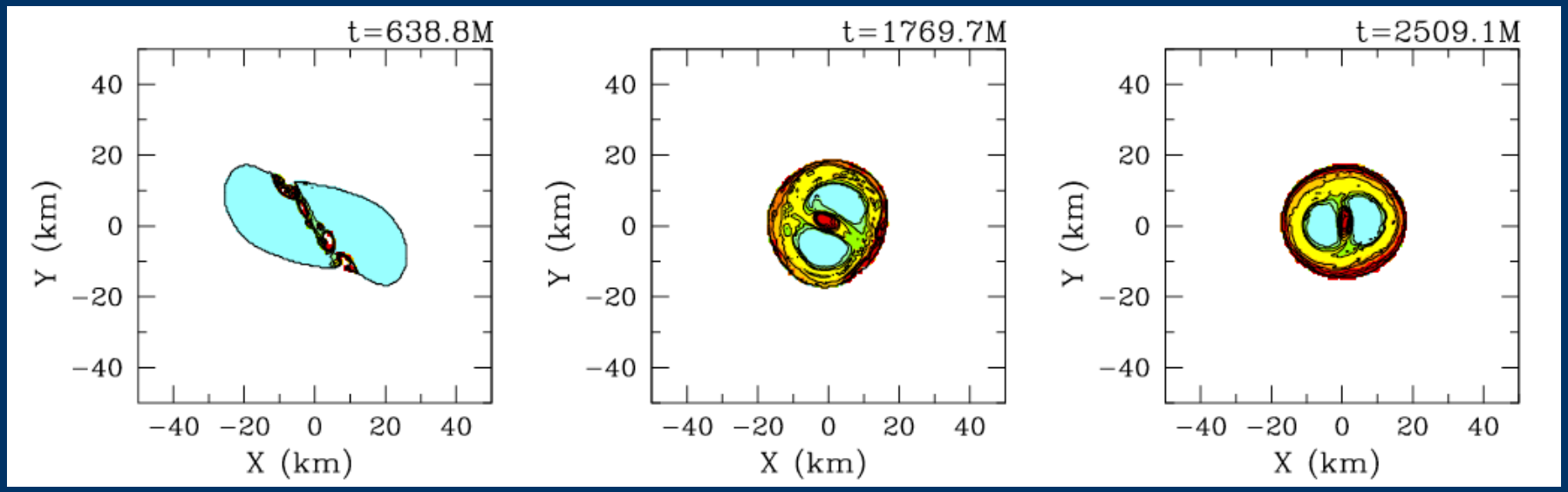

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Comparable to the GW time scale!

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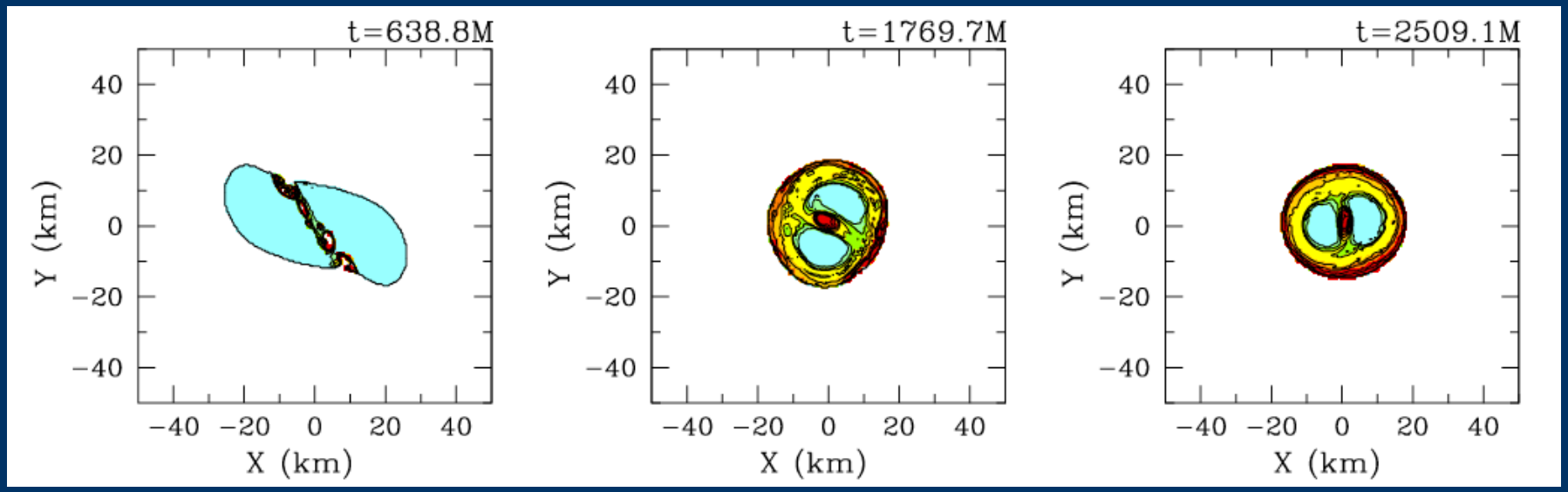

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Will the HMNS collapse if cooled?

Cooling study: HMNS collapses following cooling

- Choose t_{cool} sufficiently longer than t_{dyn}, but short enough for computational efficiency.

Case Name[a]	Cooling?	Cooling time scale, τ/M
A	No	∞
B1	Yes	150
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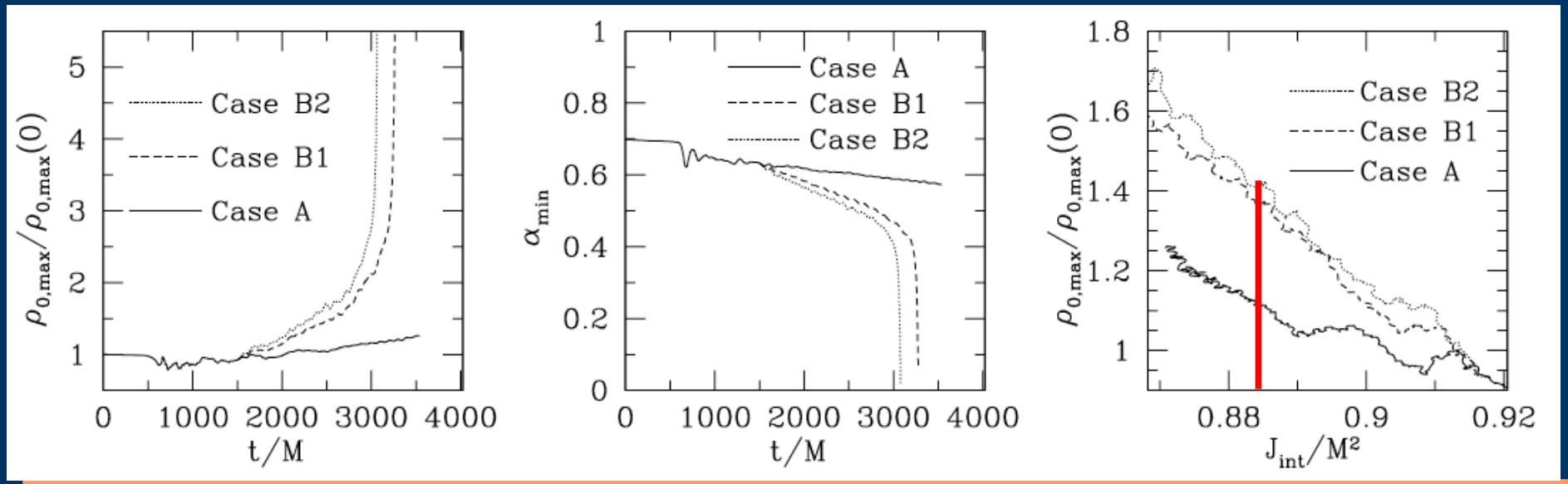
- Results



Summary

We demonstrated a few simple points of principle:

- $t_{cool} \sim t_{GW} \sim t_{Alfven}$ is possible
- $P_{thermal}$ can be an important source of support against collapse for HMNSs formed following the merger of binary NSs.
- Cooling physics is important to include in NSNS merger calculations to accurately determine the lifetime of HMNSs, and to extract physical information (cooling mechanisms, B-fields, bar instabilities etc.) from GW observations.

Fully GRHD simulations accounting for HMNS cooling with an effective emissivity

- Radiative Cooling:
  - Perfect fluid stress-energy tensor: $T^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu + P g^{\mu\nu}$
    $\varepsilon = \rho_0(1 + \epsilon_{\rm th} + \epsilon_{\rm cold})$
  - Contract the energy momentum conservation $\nabla_\alpha T^{\alpha\beta} = G^\beta$ with u^α to derive

$$\frac{d}{d\tau}\epsilon_{\rm th} = \frac{P_{\rm th}}{\rho_0^2}\frac{d}{d\tau}\rho_0 - \frac{1}{\rho_0}u^\alpha G_\alpha$$

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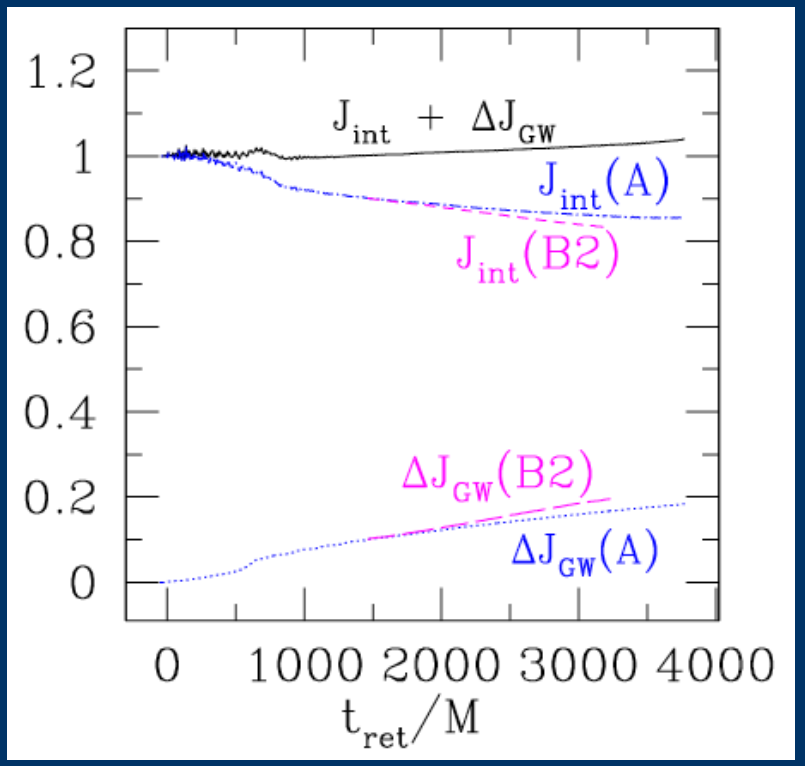
  - Choose $\frac{1}{\rho_0}u^\alpha G_\alpha = \frac{\epsilon_{\rm th}}{\tau_c}$
  - Eventually: $\frac{d}{d\tau}\epsilon_{\rm th} = \left[\frac{(\Gamma_{\rm th}-1)}{\rho_0}\frac{d\rho_0}{d\tau} - \frac{1}{\tau_c}\right]\epsilon_{\rm th}$

Exponential cooling

Cooling study: Additional effects due to cooling

Angular momentum



- Angular momentum is conserved to within 3%.
- Cases with cooling emit GWs more strongly.
- Thus, cooling accelerates the collapse by the combined action of two effects:
  a) it drains thermal support
  b) HMNS remnant becomes more compact, emitting GWs more strongly → angular momentum is removed faster.