Numerical Simulations of Binary Neutron Star Mergers

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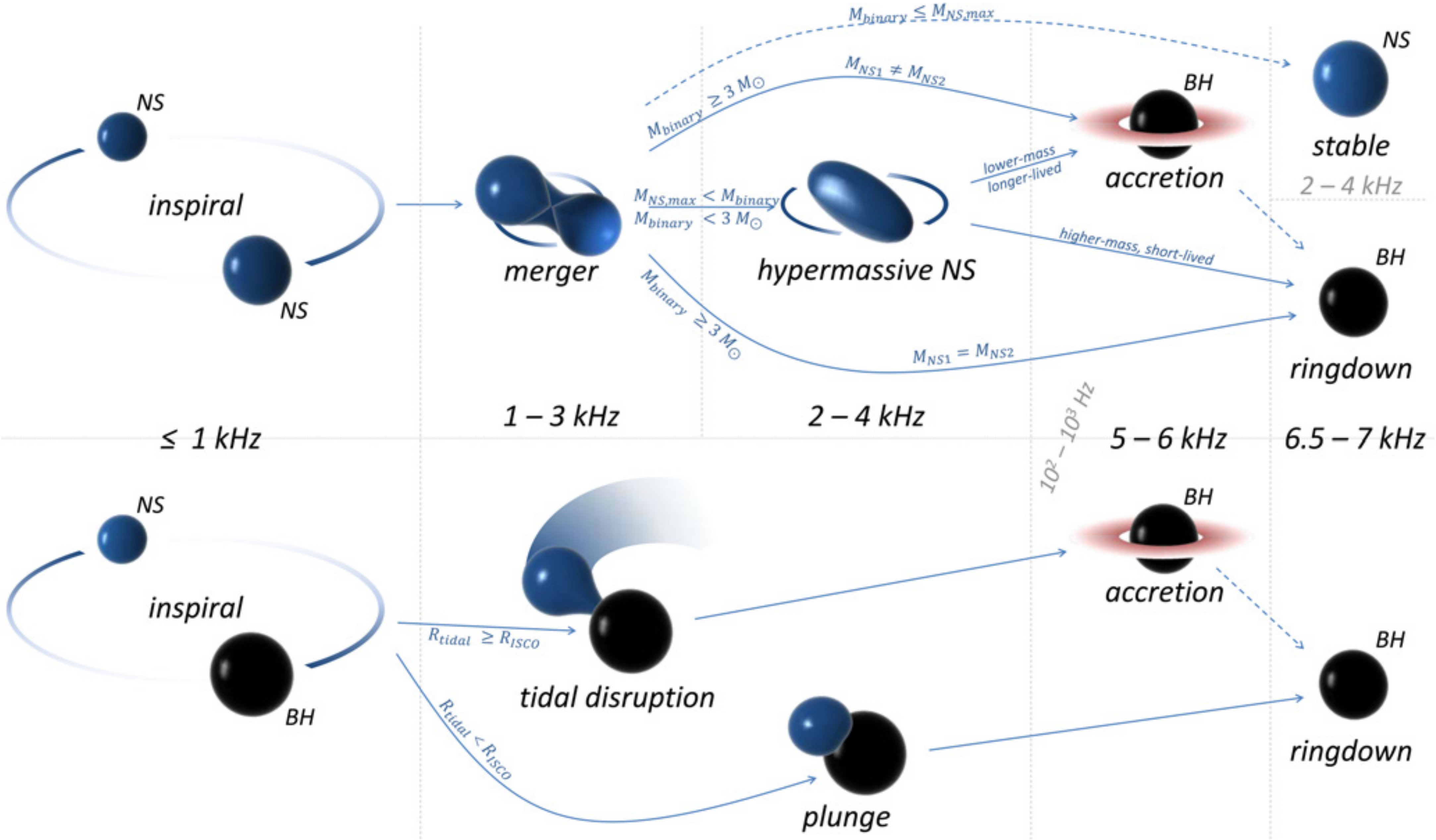
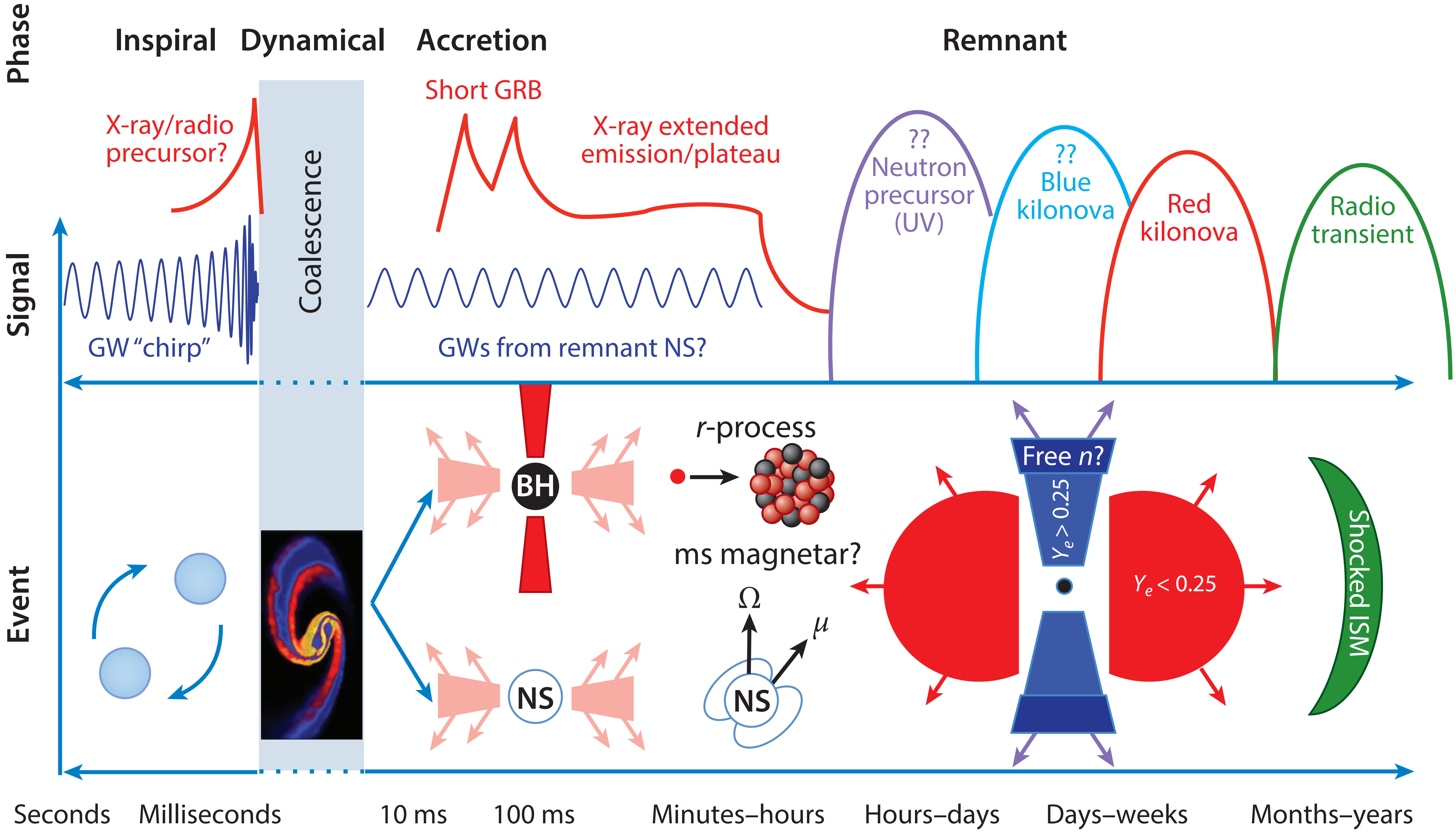
INT-2017-2b

Neutron Star Merger Evolution



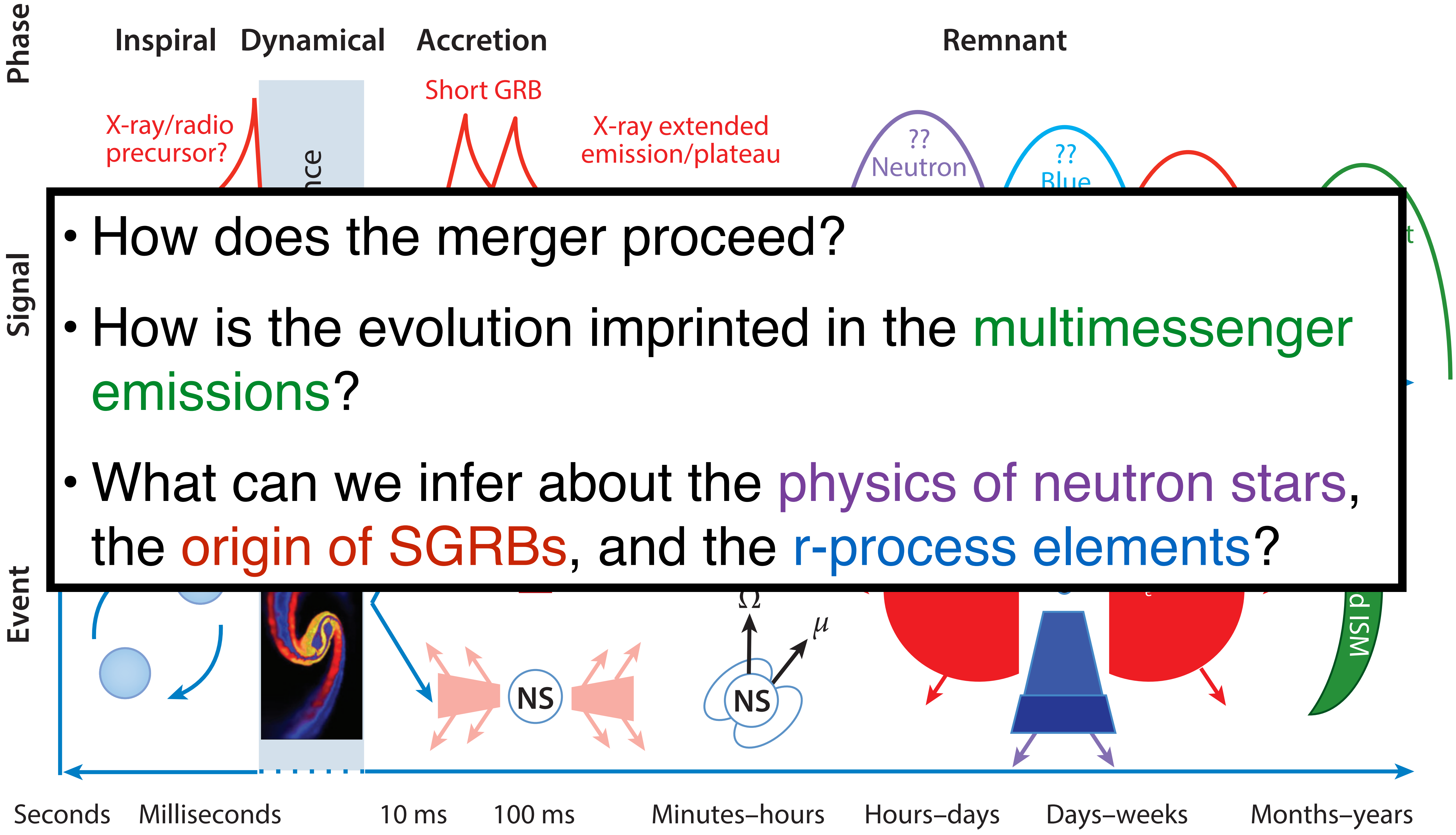
From Bartos, Brady, & Márka 2013

Multimessenger Emissions



From Fernández & Metzger 2016

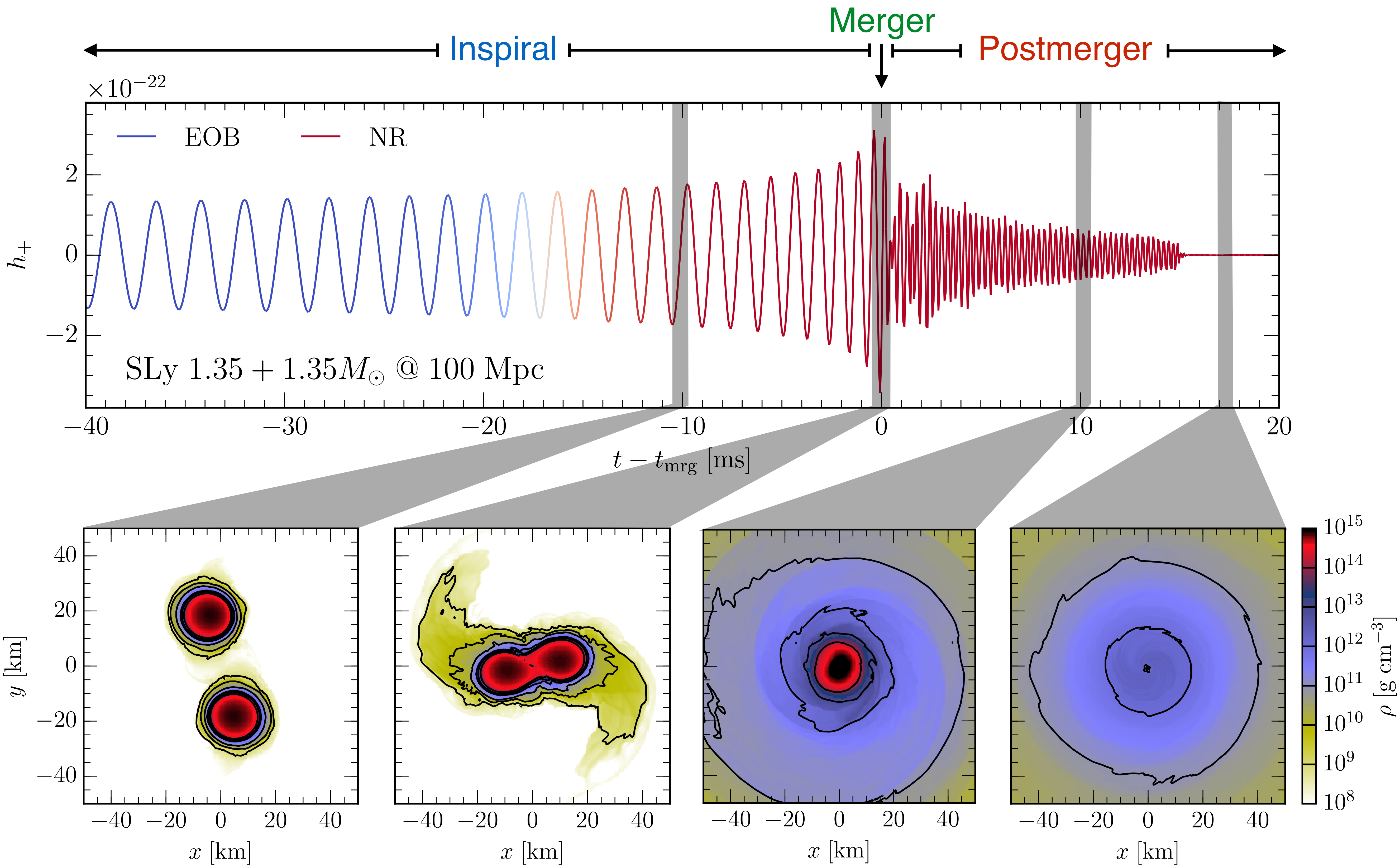
Multimessenger Emissions



- How does the merger proceed?
- How is the evolution imprinted in the multimessenger emissions?
- What can we infer about the physics of neutron stars, the origin of SGRBs, and the r-process elements?

From Fernández & Metzger 2016

Gravitational Waves



Inspiral

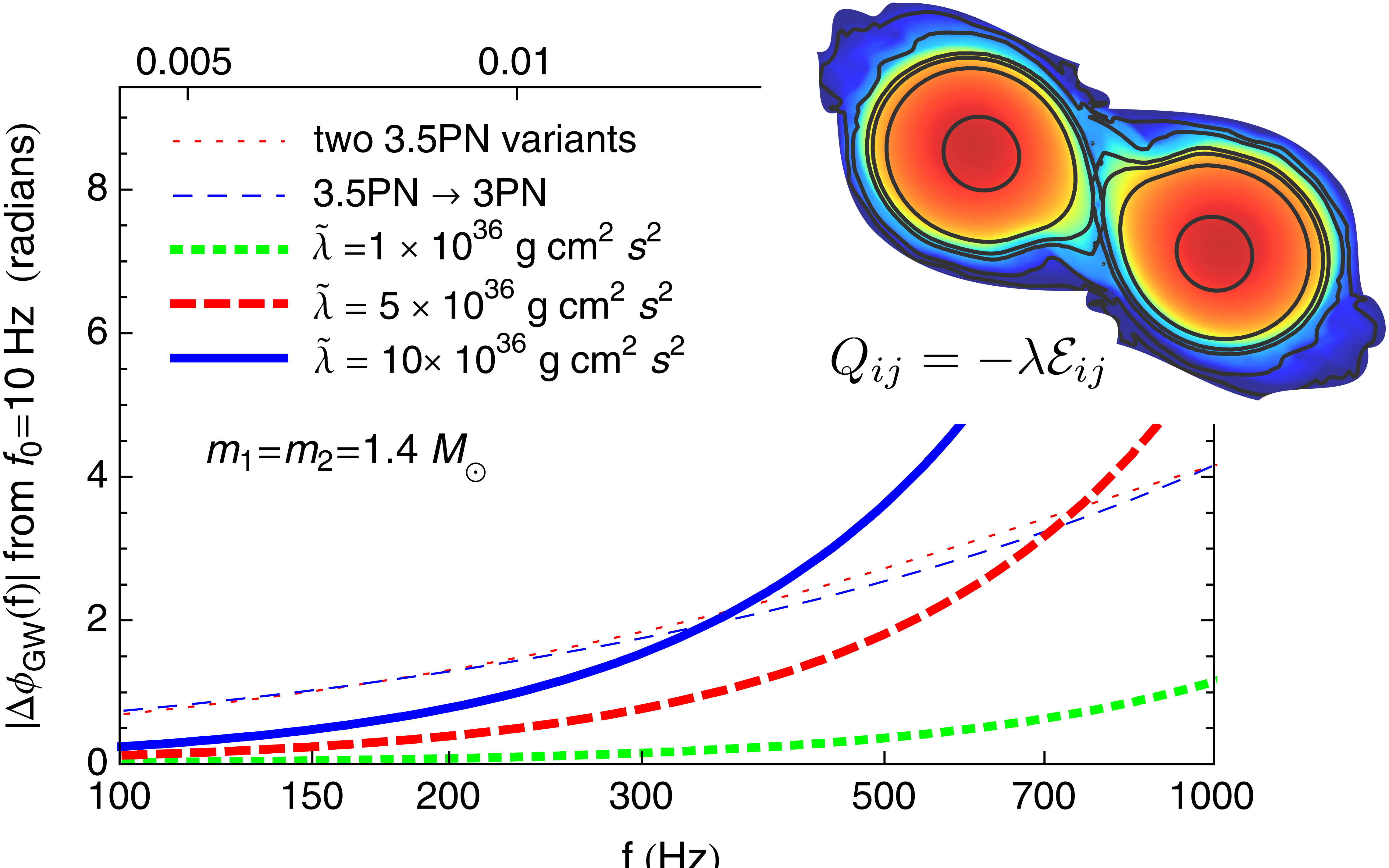
Merger

Postmerger

https://zenodo.org/record/46733

DR, Bernuzzi, Ott 2016

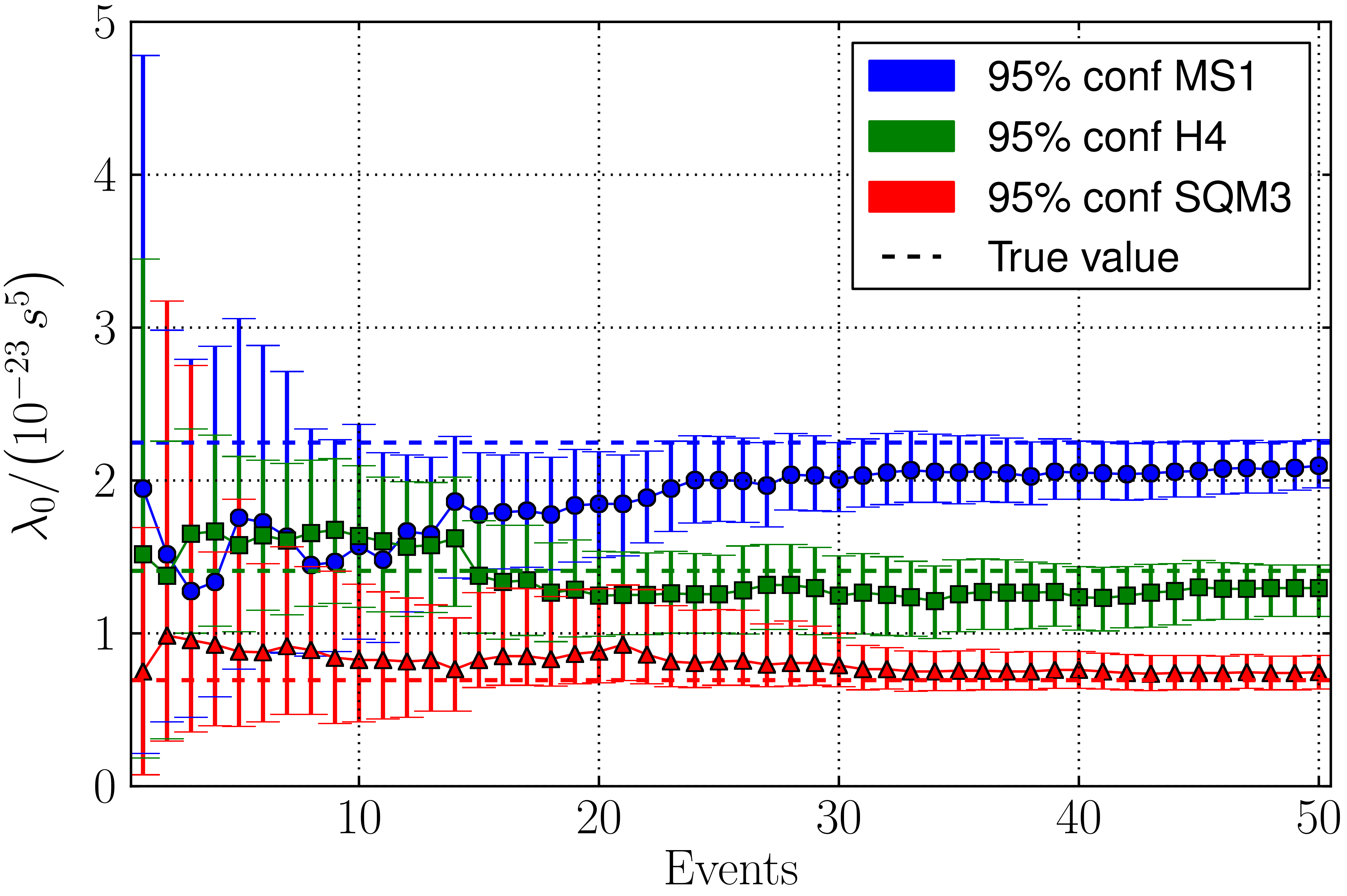
Tidal Effects (I)



$$Q_{ij} = -\lambda \mathcal{E}_{ij}$$

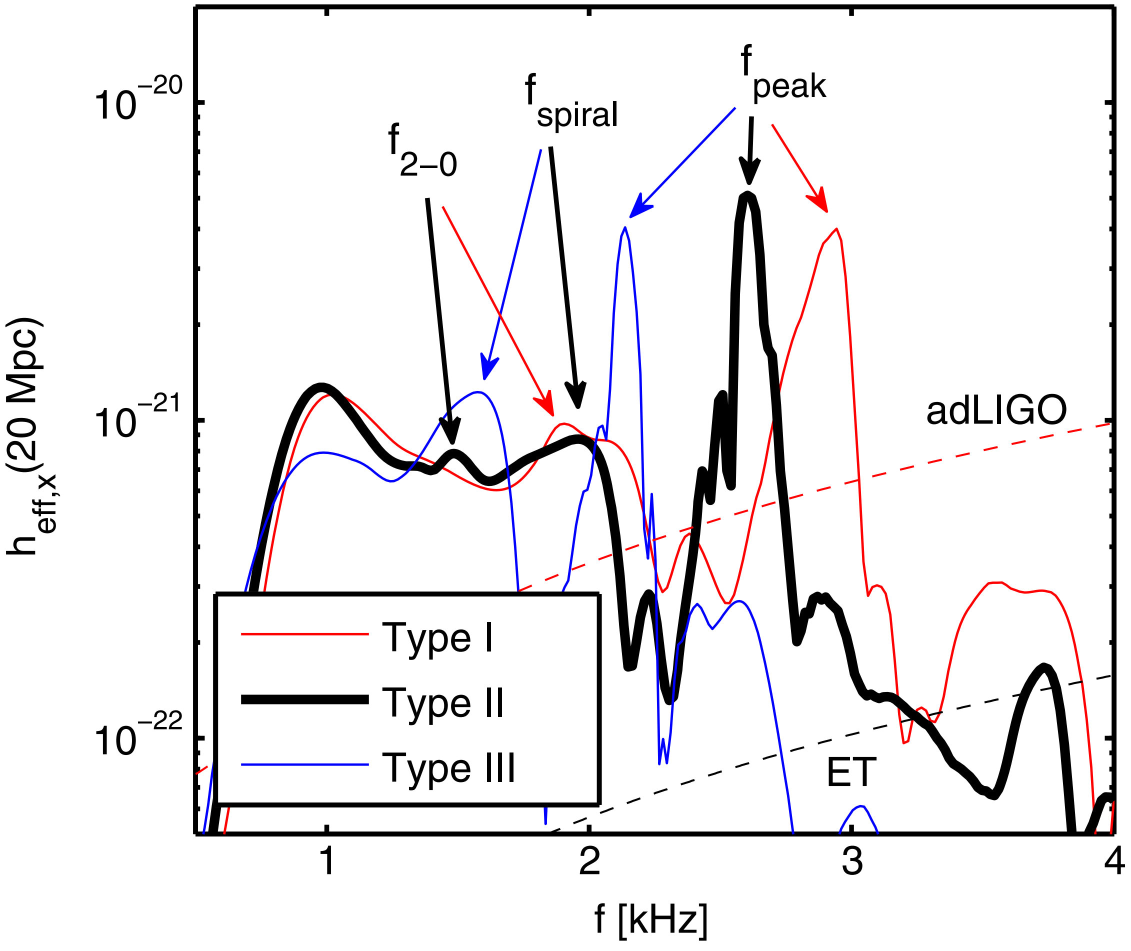
From Hinderer+ 2010

Tidal Effects (II)

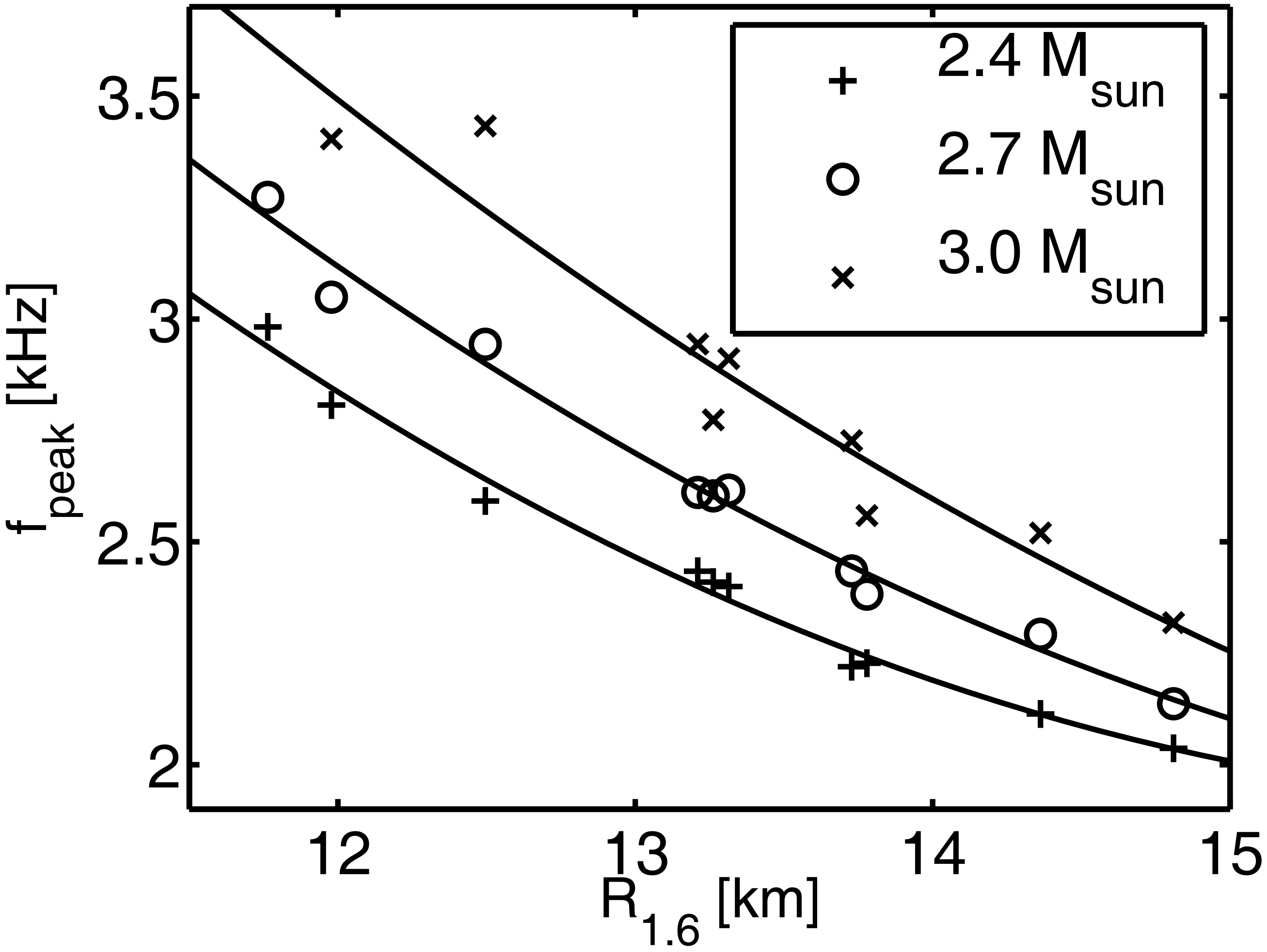


From Del Pozzo+ 2013

Postmerger Peak Frequency



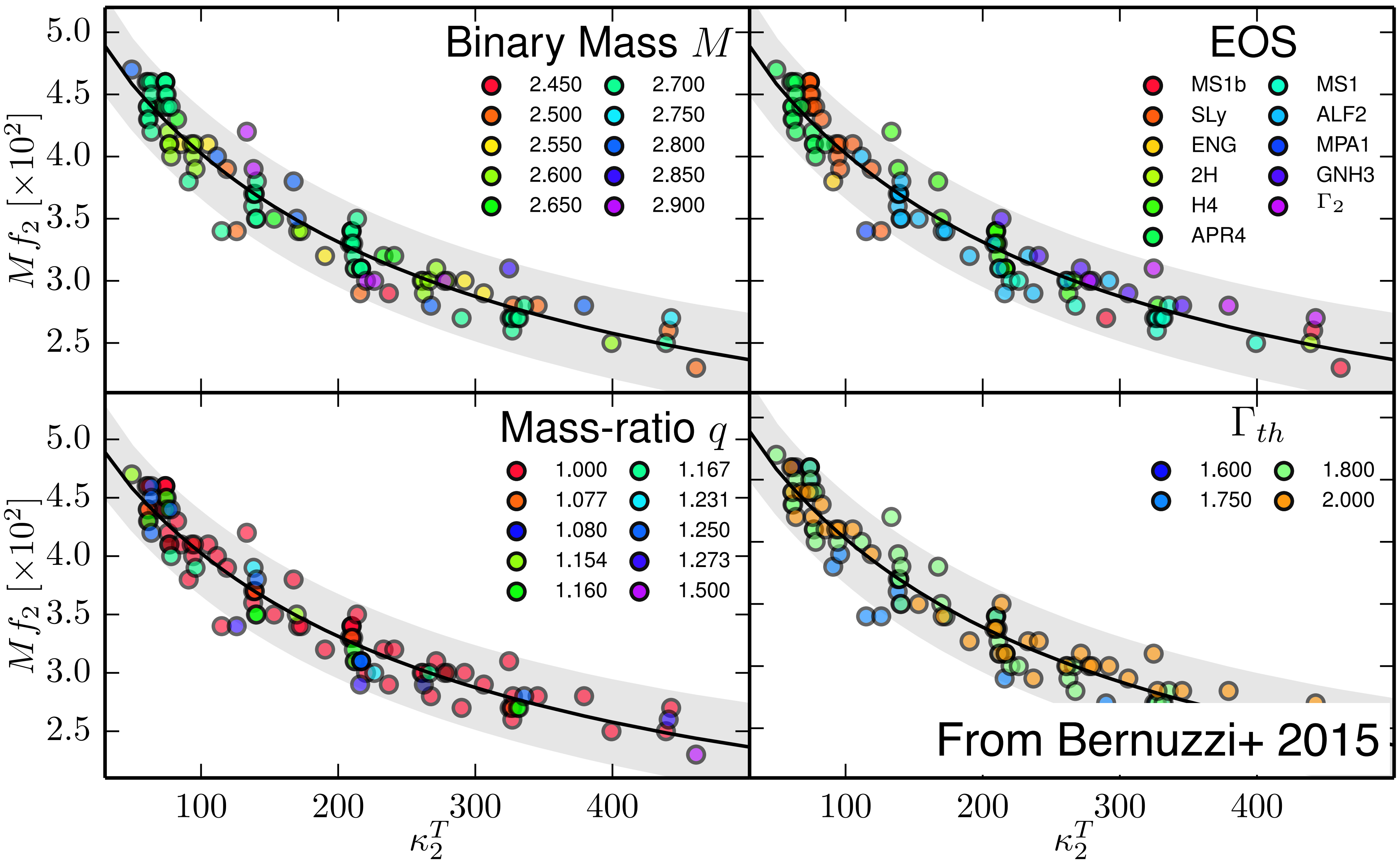
From Bauswein+ 2015



From Bauswein+ 2016

- Post-merger signal has a characteristic peak frequency
- Empirical correlations: f_{peak} vs. EOS properties
- Small statistical uncertainty: radii to within few hundred meters

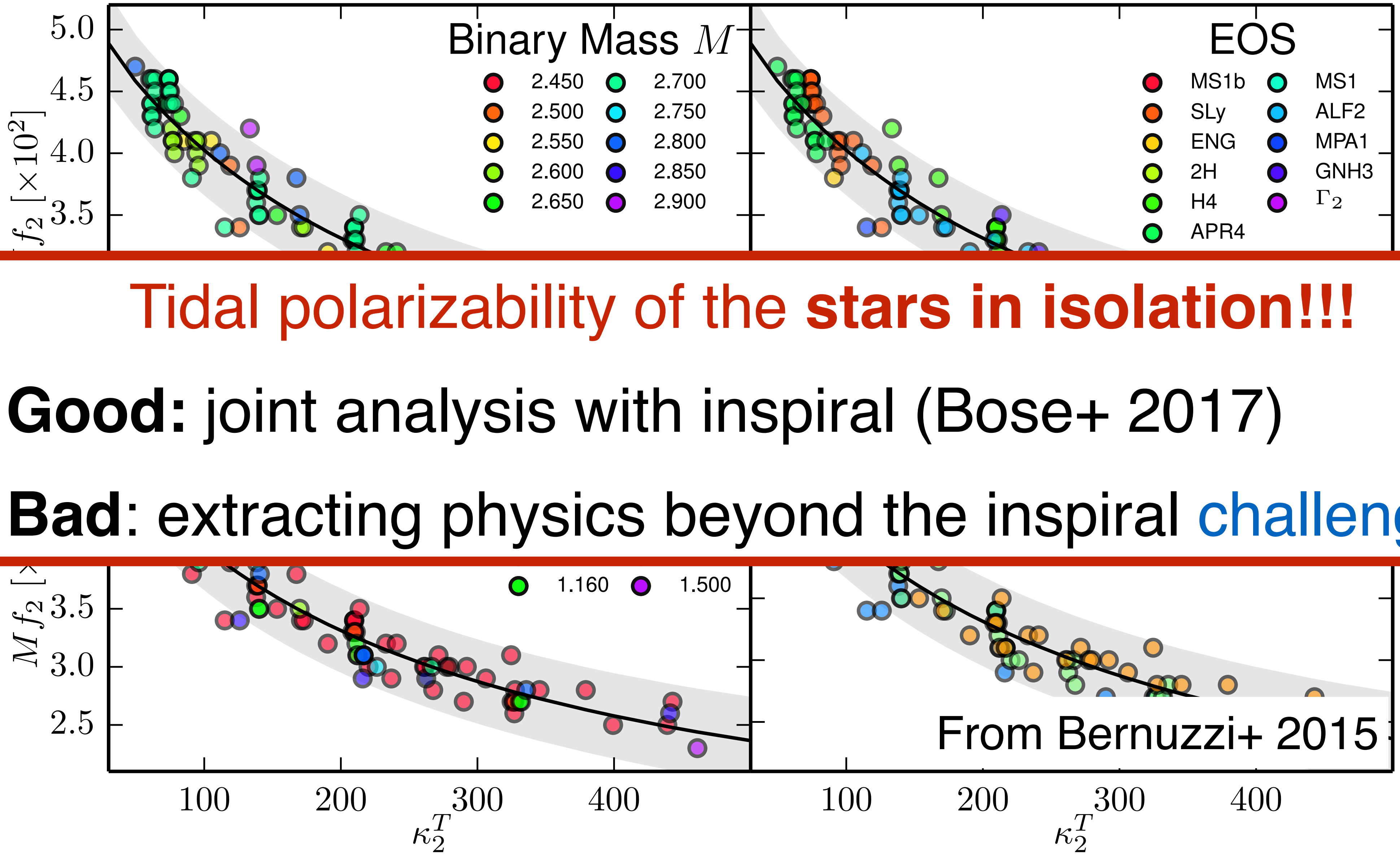
Postmerger: Universal Relations



Complementary measure of the tidal parameters

See also Takami+ 2014; Rezzolla & Takami 2016; Dietrich+ 2016; Bose+ 2017

Postmerger: Universal Relations



From Bernuzzi+ 2015

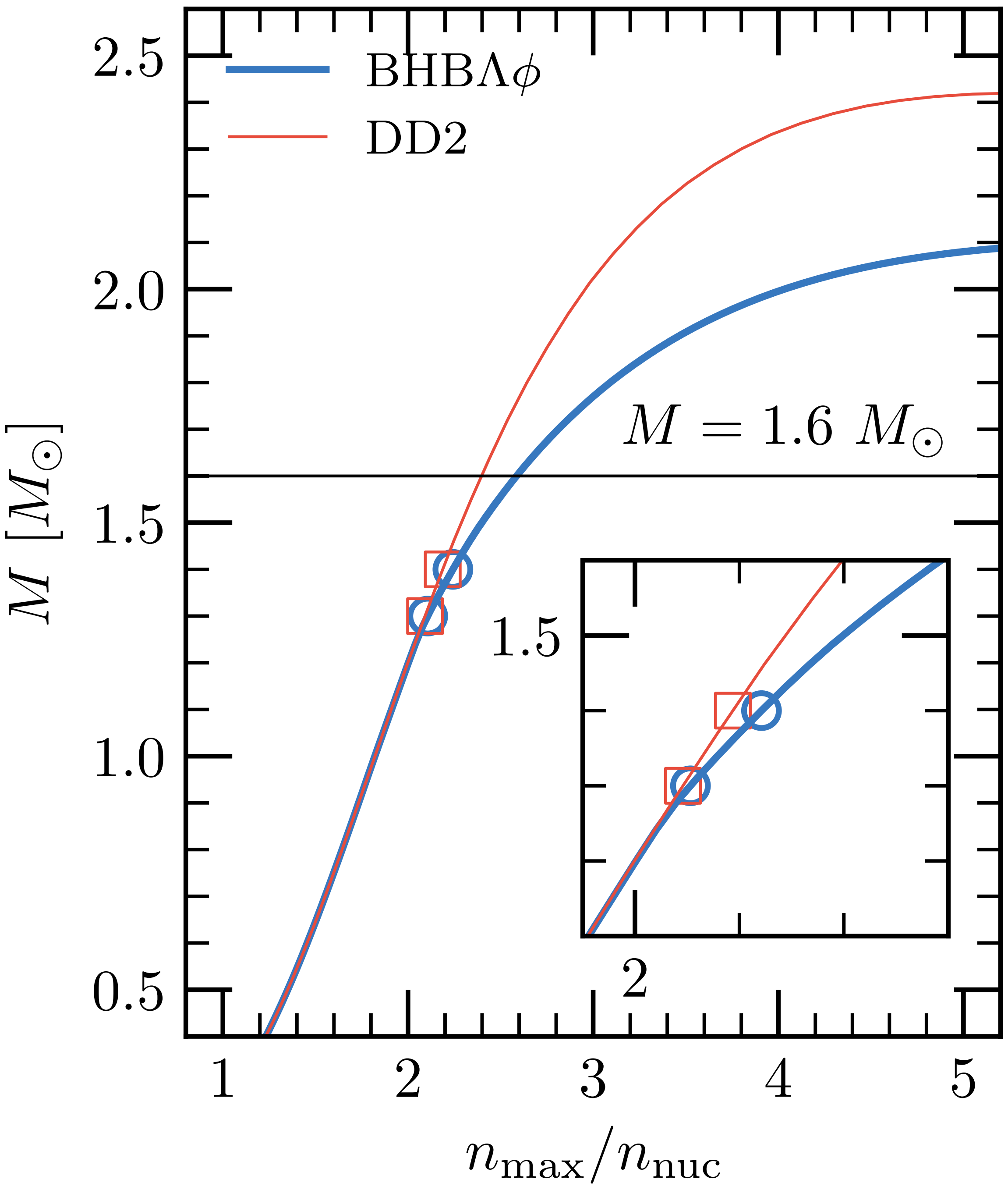
Tidal polarizability of the **stars in isolation!!!**

- **Good:** joint analysis with inspiral (Bose+ 2017)
- **Bad**: extracting physics beyond the inspiral challenging

Complementary measure of the tidal parameters

See also Takami+ 2014; Rezzolla & Takami 2016; Dietrich+ 2016; Bose+ 2017

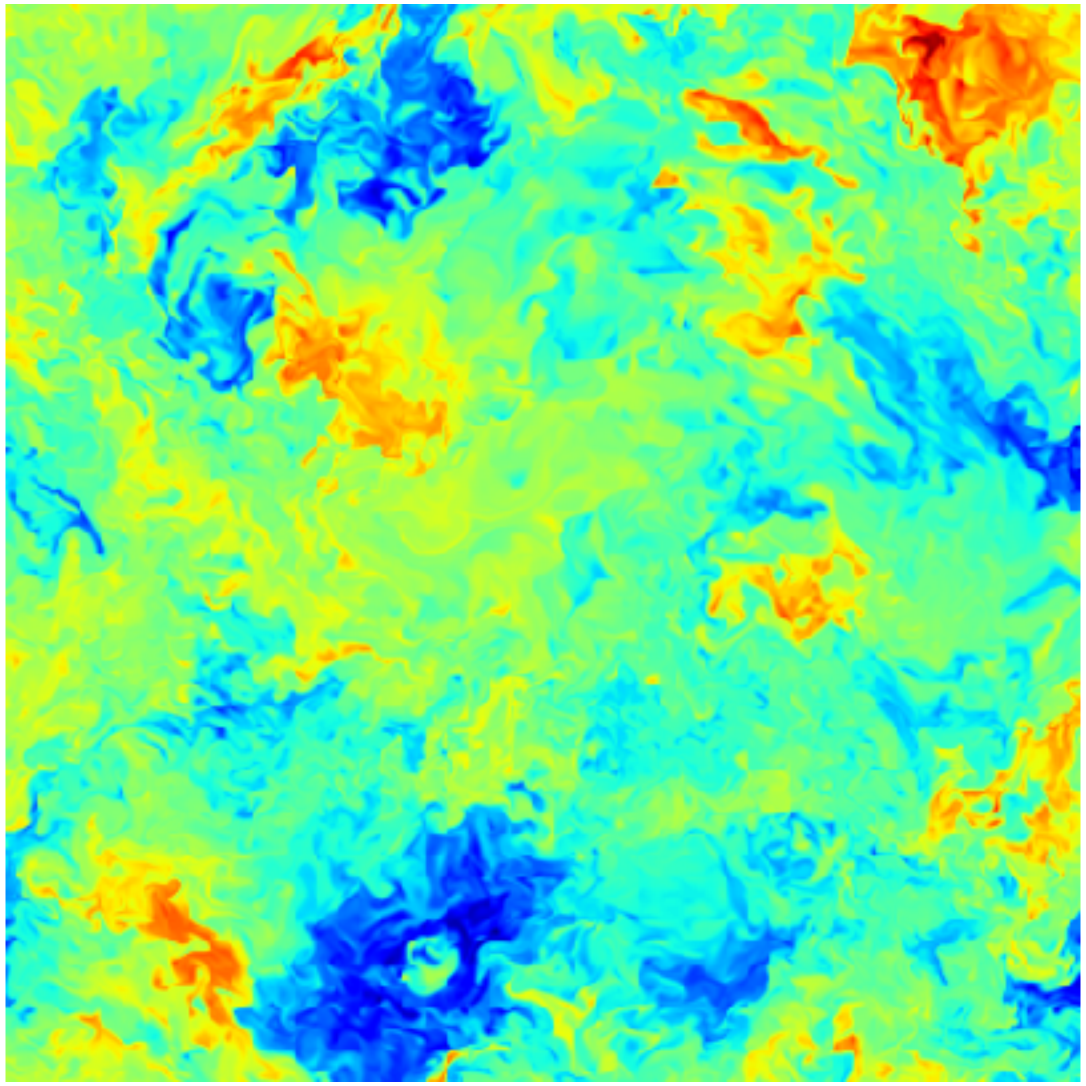
Extreme-Density Physics



- Neutron stars in binaries have masses clustered around ~1.35 $M_\odot$
- What happens if we change the EOS at high density?
- Different collapse time of remnant?
- What about $f_{\rm peak}$?
- What can we say about the EOS with GWs?

DR, Bernuzzi, Del Pozzo+ 2017

Einstein Toolkit / WhiskyTHC



Gravity: BSSN, Z4c;

GRHD: high-order FD; FV

Nuclear EOS

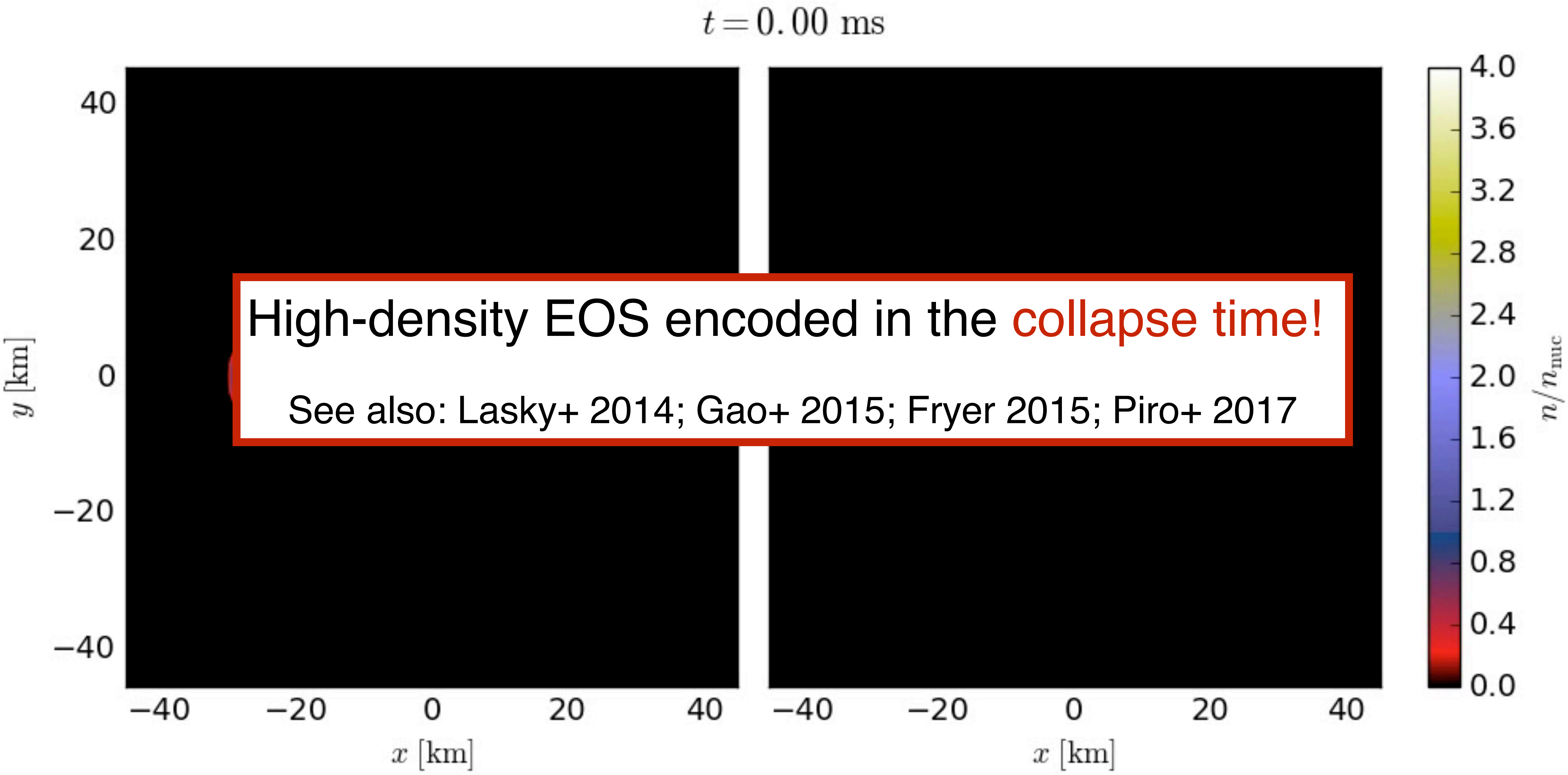
Neutrino radiation: leakage,
ray-by-ray moment-based transport

THC = Templated Hydrodynamics Code

To be released soon!

Skip Ad ⏭

1.4 $M_\odot$ vs 1.4 $M_\odot$



High-density EOS encoded in the collapse time!

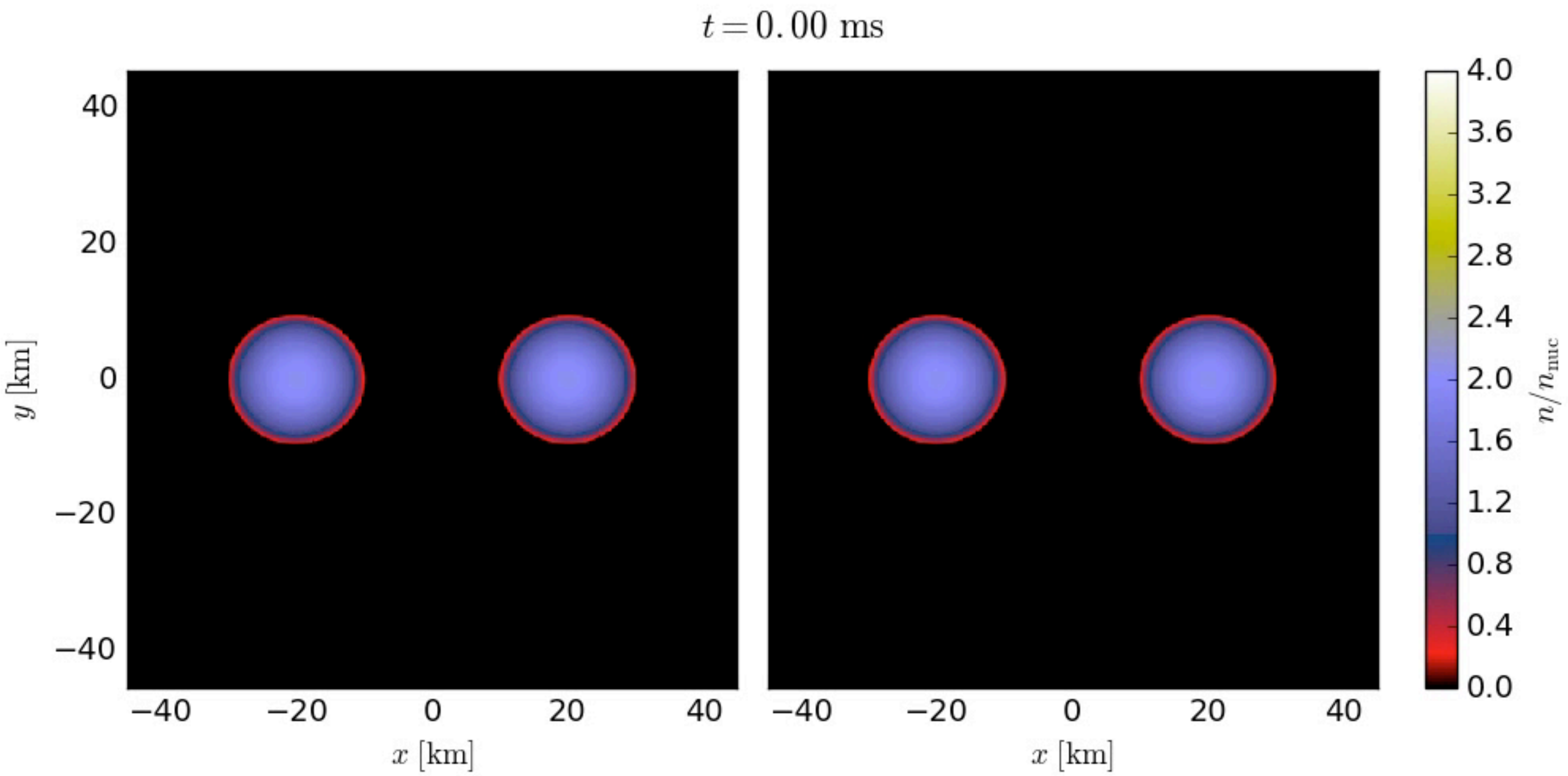
See also: Lasky+ 2014; Gao+ 2015; Fryer 2015; Piro+ 2017

Hyperons

No Hyperons

DR, Bernuzzi, Del Pozzo+ 2017

1.3 $M_\odot$ vs 1.3 $M_\odot$

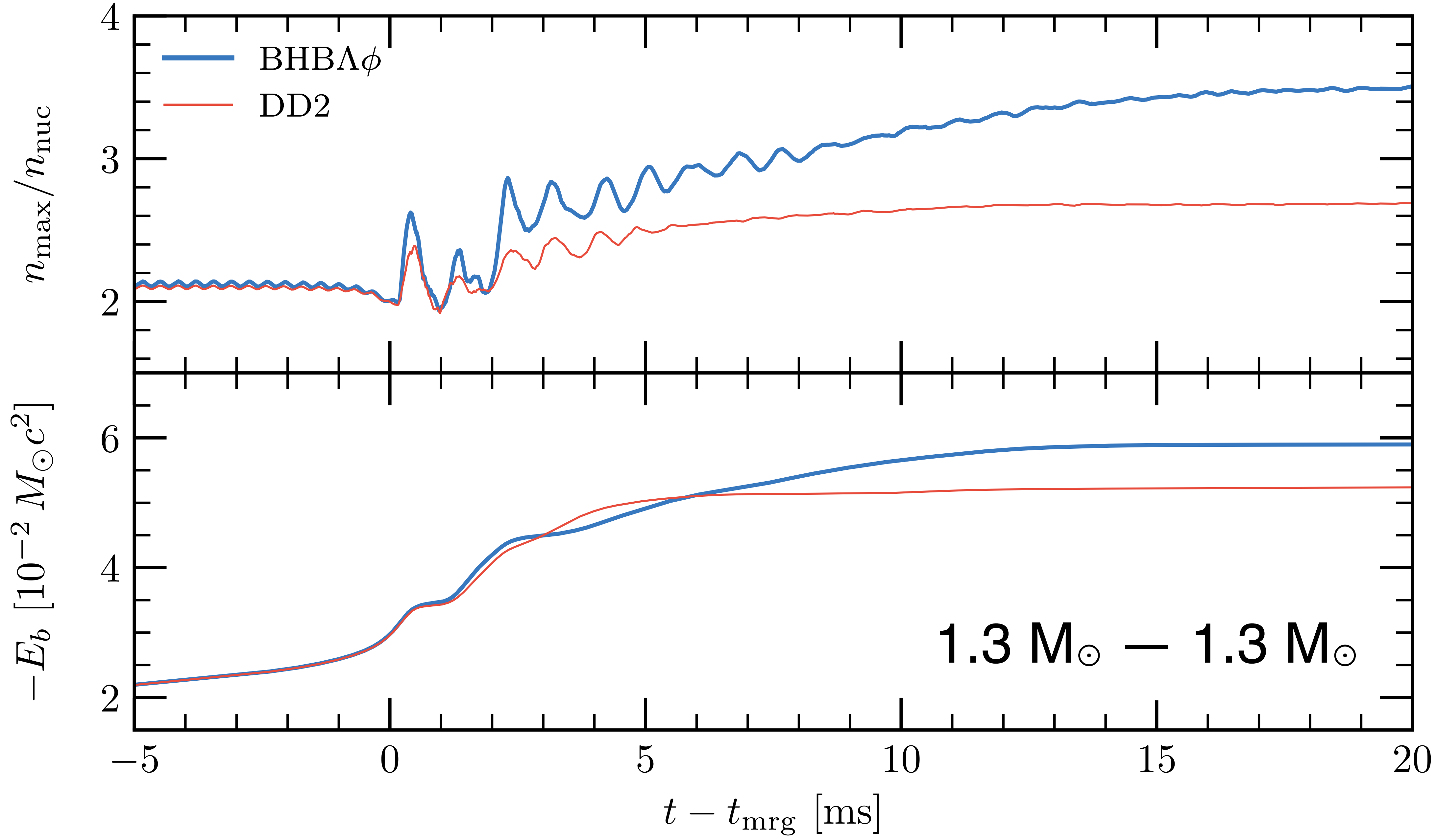


Hyperons

No Hyperons

DR, Bernuzzi, Del Pozzo+ 2017

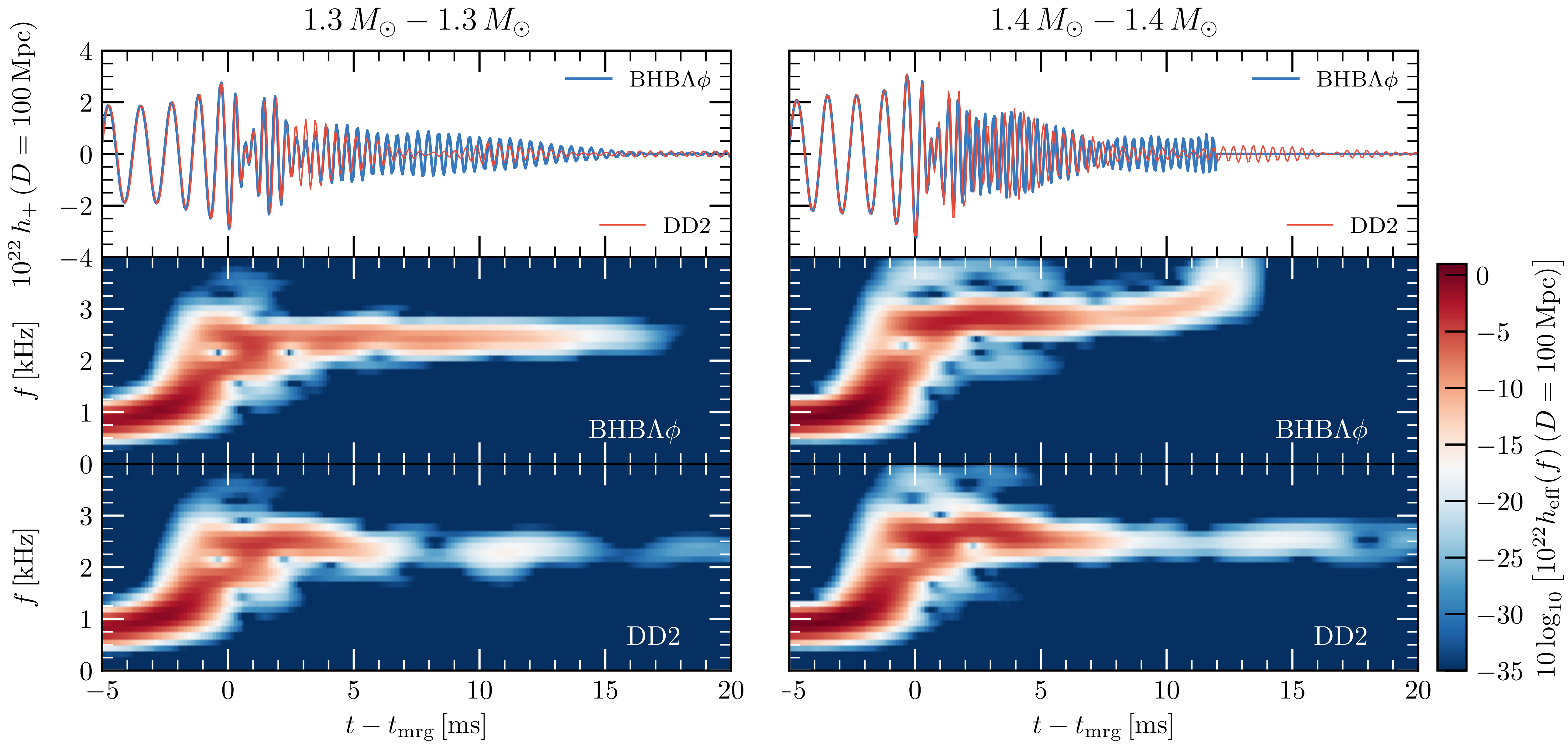
Binding Energy



High-density EOS encoded in the binding energy

DR, Bernuzzi, Del Pozzo+ 2017

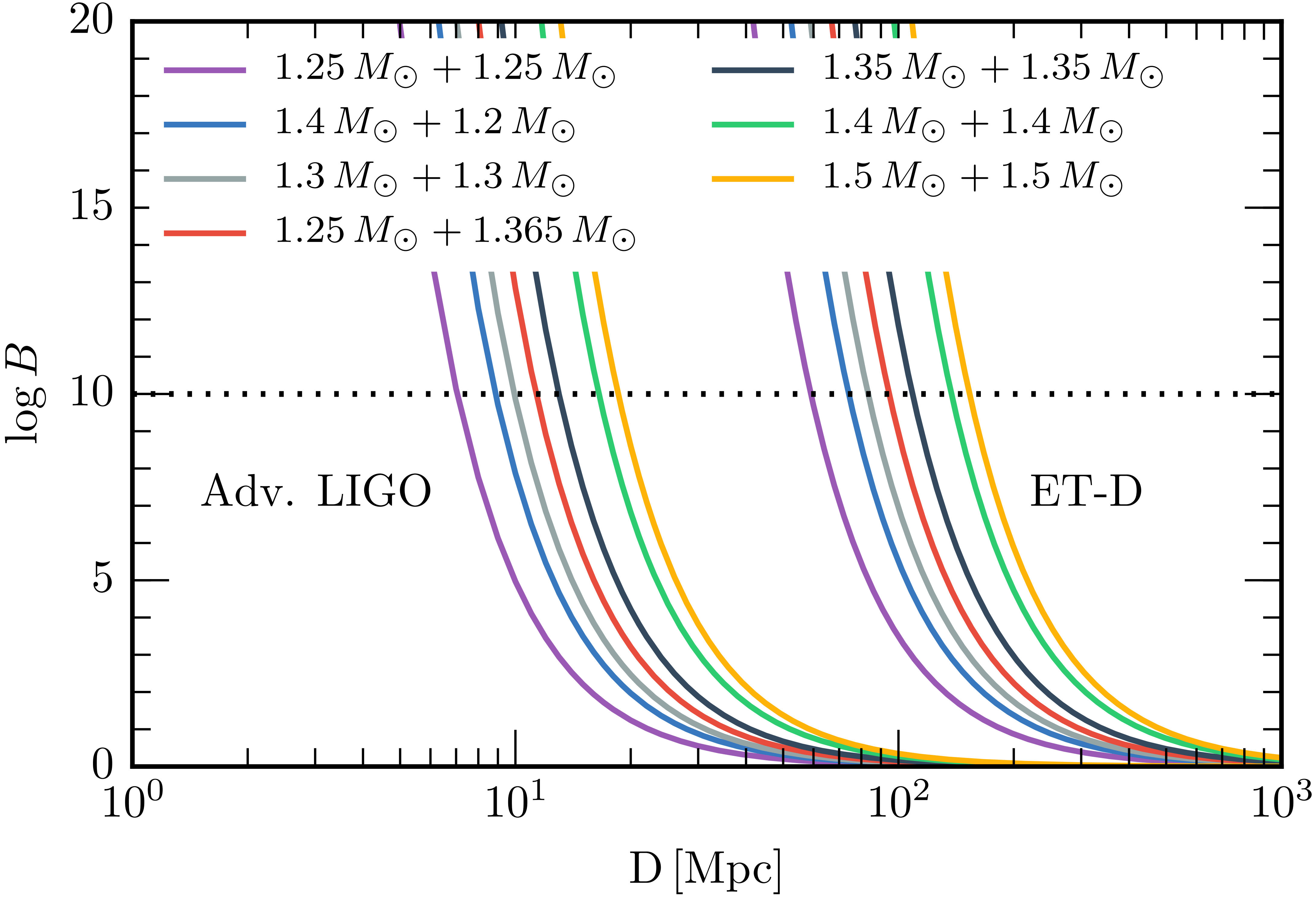
Gravitational Waves



- Frequency evolution: a black-hole formation signature
- EOS softening always imprinted as amplitude modulation

DR, Bernuzzi, Del Pozzo+ 2017

Detectability

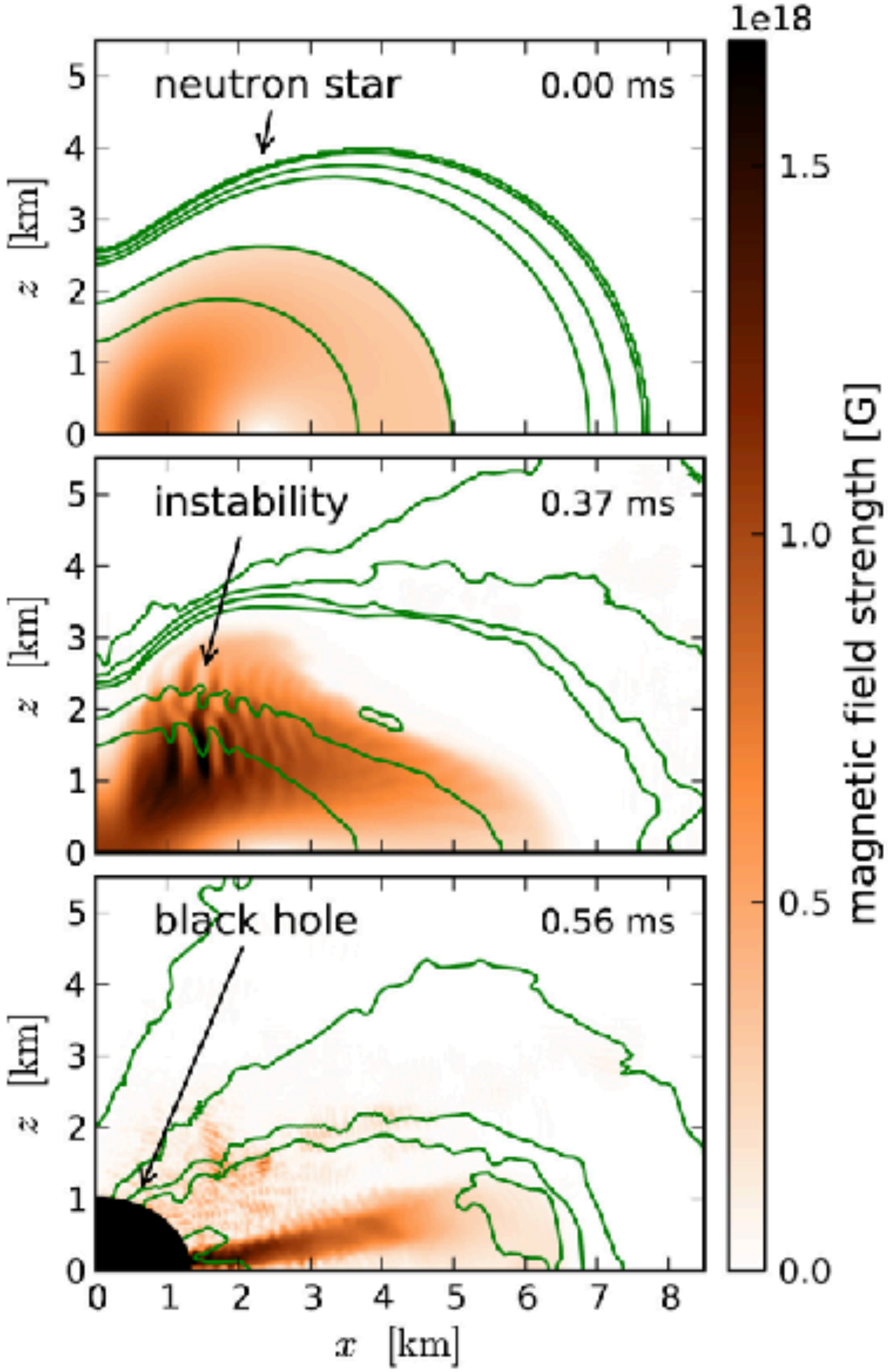


DR, Bernuzzi, Del Pozzo+ 2017

What About
Magnetic Fields?

Magneto-Turbulence Effects

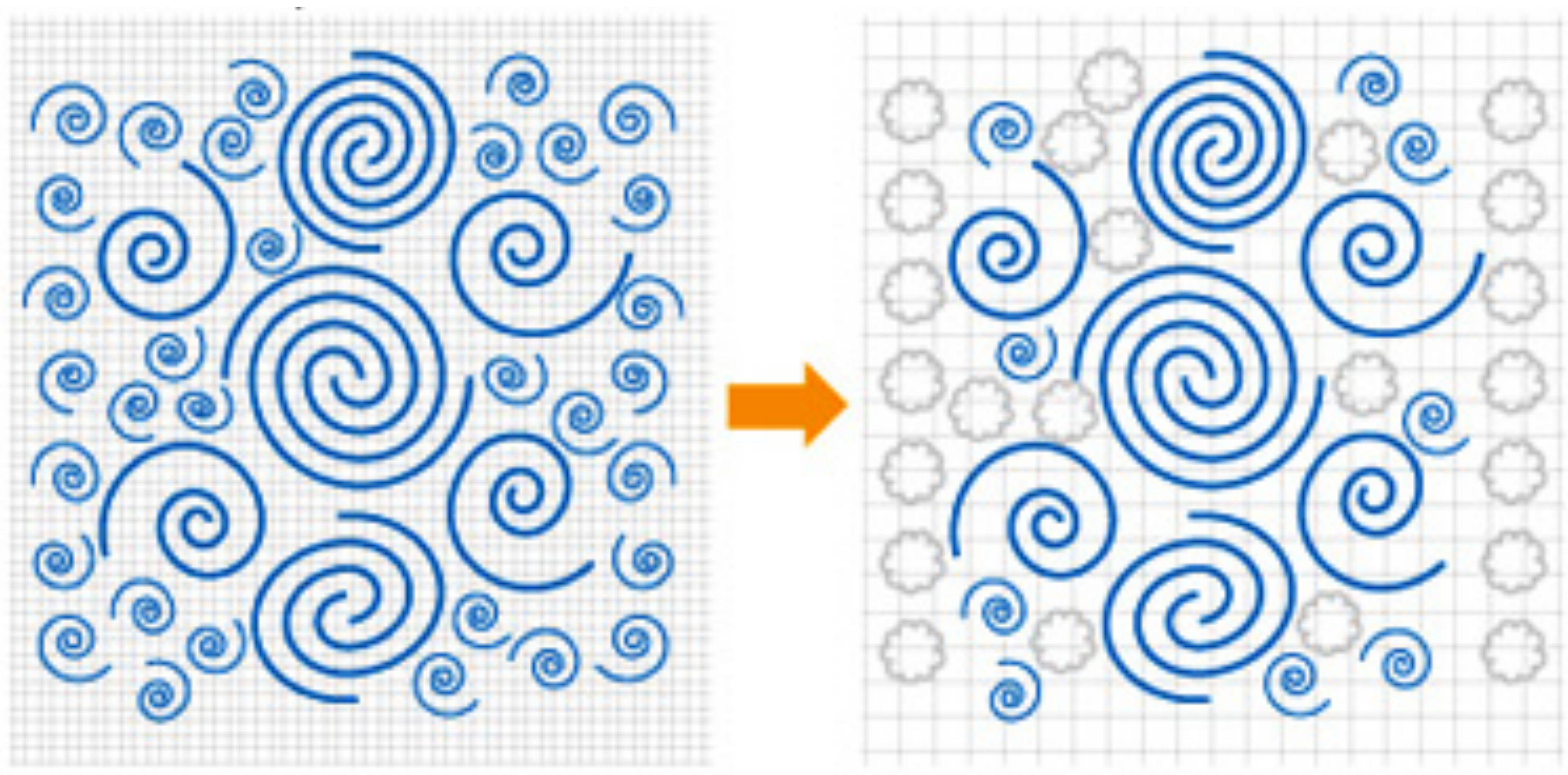
- MHD instabilities are known operate at a scale of few meters or less
- Resolution in global simulations is orders of magnitude too low
- Previous approach: neglect these effects or use unrealistically large B-fields & idealized configurations
- Our approach: explicit subgrid-scale modeling with large-eddy simulations



See also: Shibata & Kiuchi 2017

From Siegel+ 2013

Large-Eddy Simulations (LES)



From: T. Itami; http://www.cradle-cfd.com/tec/column04

Large scale flow is resolved, small scale flow is modeled

Relativistic LES

Special relativistic Euler equations

$$S_i = \rho h W^2 v_i \qquad\qquad \partial_t S_i + \partial_j (S_i v^j + p) = 0$$

Only large scales are resolved in a simulation

$$\partial_t \overline{S_i} + \partial_j (\overline{S_i v^j + p}) = 0$$

Small scales are modeled

$$\overline{S_i v^j} = \bar{S}_i \bar{v}^j + {\tau_i}^j \qquad\qquad \partial_t \bar{S}_i + \partial_j (\bar{S}_i \bar{v}^j + \overline{p}) = -\partial_j {\tau_i}^j$$

Turbulent-Viscosity Models

Rely on numerical viscosity; Implicit LES approach

$$\tau_{ij} = 0$$

Turbulence modeled as an effective viscosity: Smagorinsky (1963)

$$\tau_{ij} = -2\nu_T \overline{\rho h W^2} \left[\frac{1}{2}(\partial_i \bar{v}_j + \partial_j \bar{v}_i) - \frac{1}{3}\partial_k \bar{v}^k \delta_{ij} \right]$$

ν_T : turbulent viscosity

- Relativistic LES not relativistic viscous hydrodynamics
- Lorentz invariance is broken and only recovered as a limit*
- ν_T is not an intrinsic fluid quantity

* Eyink & Drivas 2017

Mixing Length Theory

Turbulent viscosity can be written in terms of characteristic speed and length

$$\nu_T = \ell_{\rm mix}\, c_s$$

$\ell_{\rm mix}$ is the correlation scale (typical eddy size) of the turbulence.

Two ways to estimate:

1. for MRI driven turbulence we assume

$$\ell_{\rm mix} \sim \lambda_{\rm MRI} \sim 3\,{\rm m}\, \left(\frac{\Omega}{4\ {\rm rad\ ms^{-1}}}\right)^{-1} \left(\frac{B}{10^{14}\ {\rm G}}\right)$$

2. equivalent choice [see Shibata & Kiuchi 2017] is

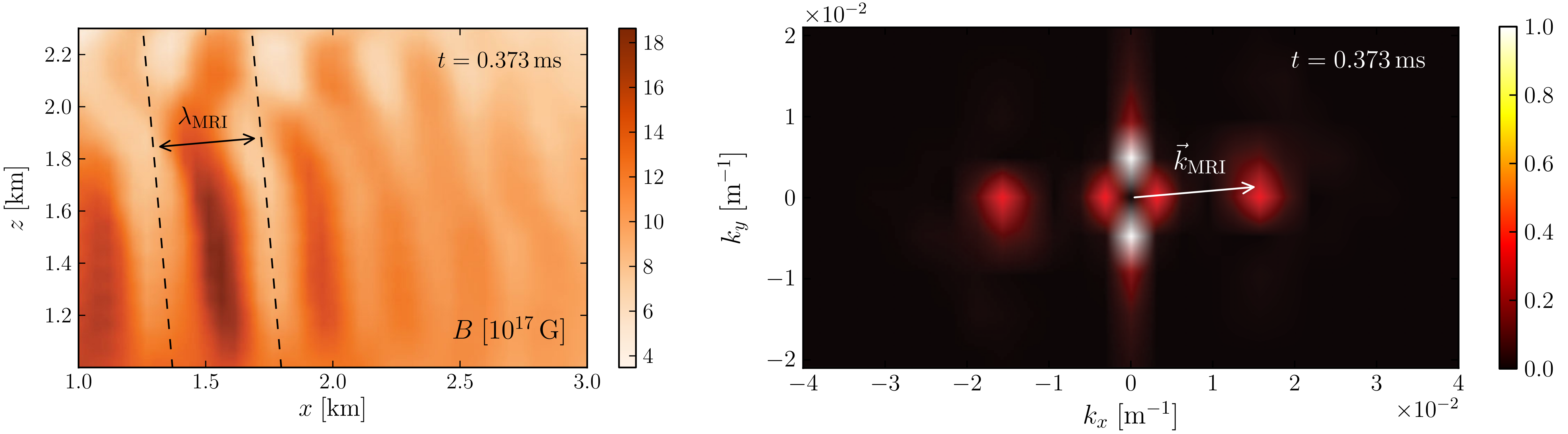
$$\ell_{\rm mix} \sim H_p \sim c_s/\Omega_s \sim 10\,{\rm km} \qquad \ell_{\rm mix} = \alpha\, c_s/\Omega$$

observations* and simulations+ show: $\alpha \gtrsim 0.1$

* King+ 2007 + Shi+ 2016

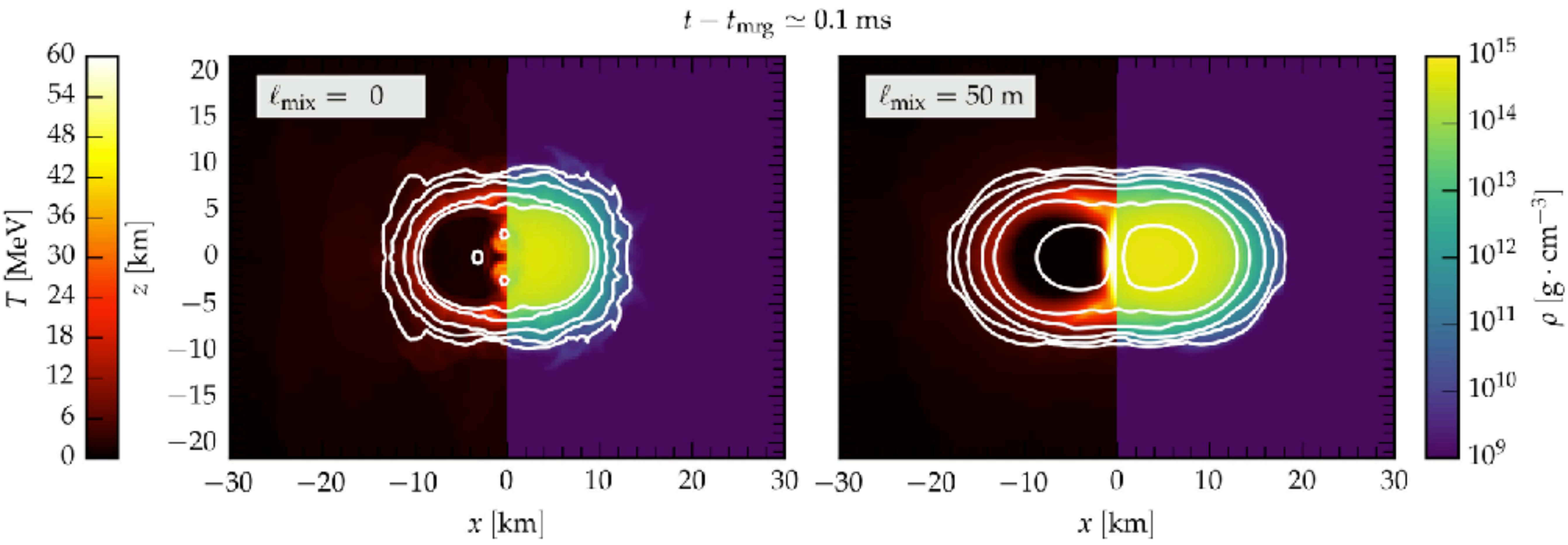
Mixing Length

- MRI studies focus on steady-state thin-disk flows
- HMNS evolution is non-steady (and not a thin disk),
- MRI must do something within few rotational periods to be relevant for GWs
- Current simulations of HMNS available support $\ell_{\rm mix} \sim \lambda_{\rm MRI}$
- Caveat: these simulations are too short! More work needed!



From Siegel+ 2013

Angular Momentum Transport



Delayed collapse?!?

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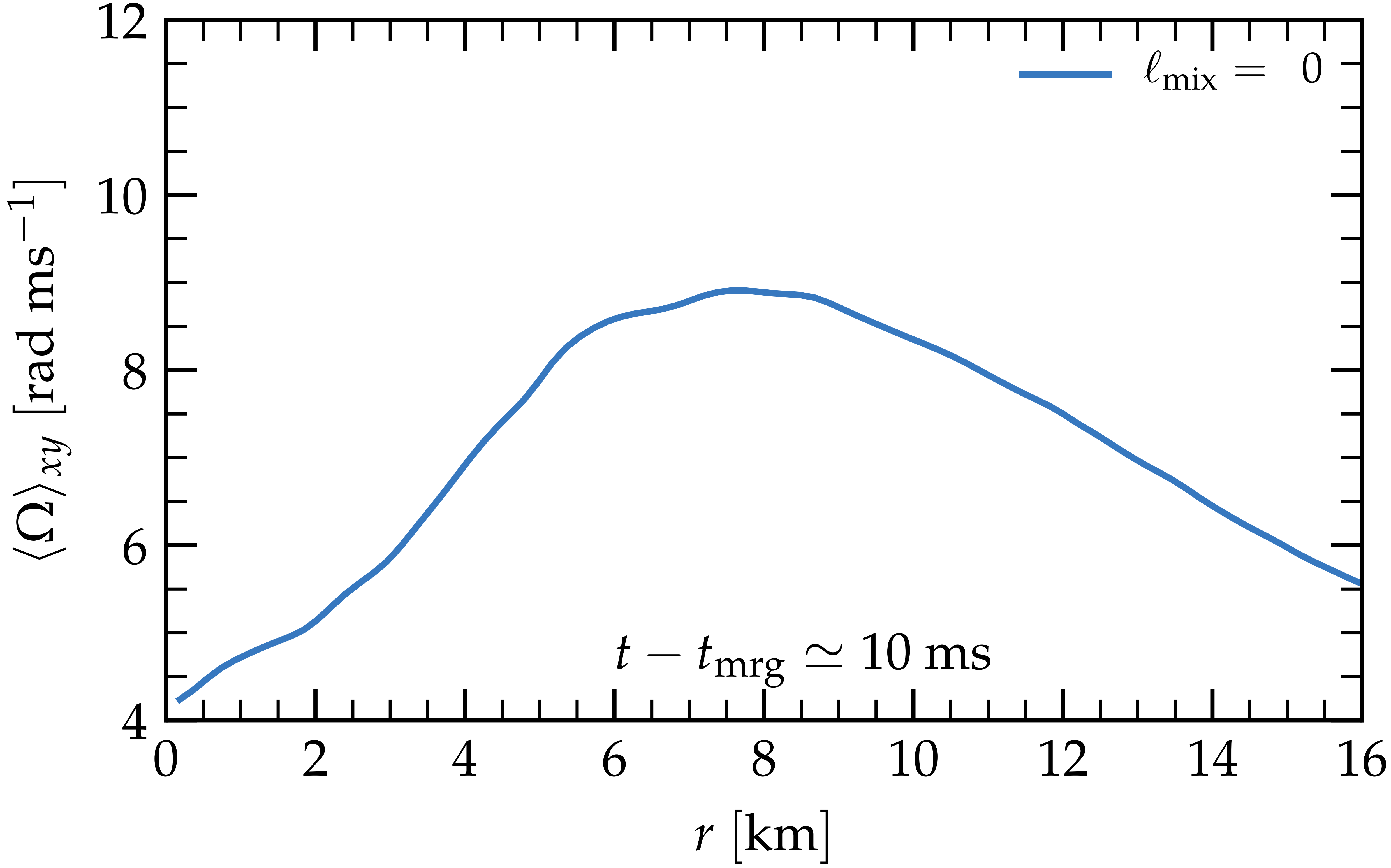
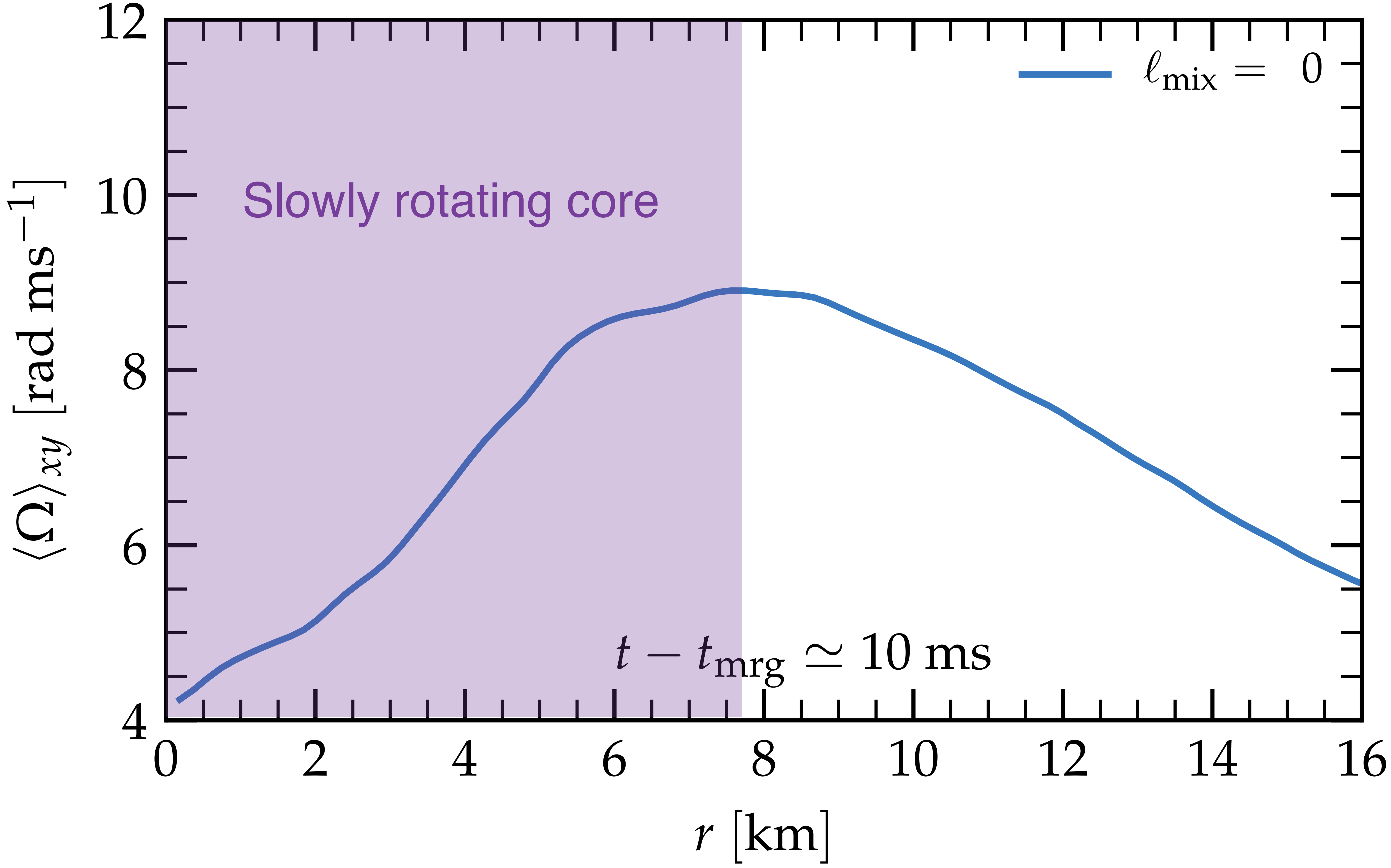
Rotational Profile



See also Shibata & Taniguchi 2006; Kastaun+ 2015, 2016; Hanauske+ 2016 **DR** 2017

Rotational Profile



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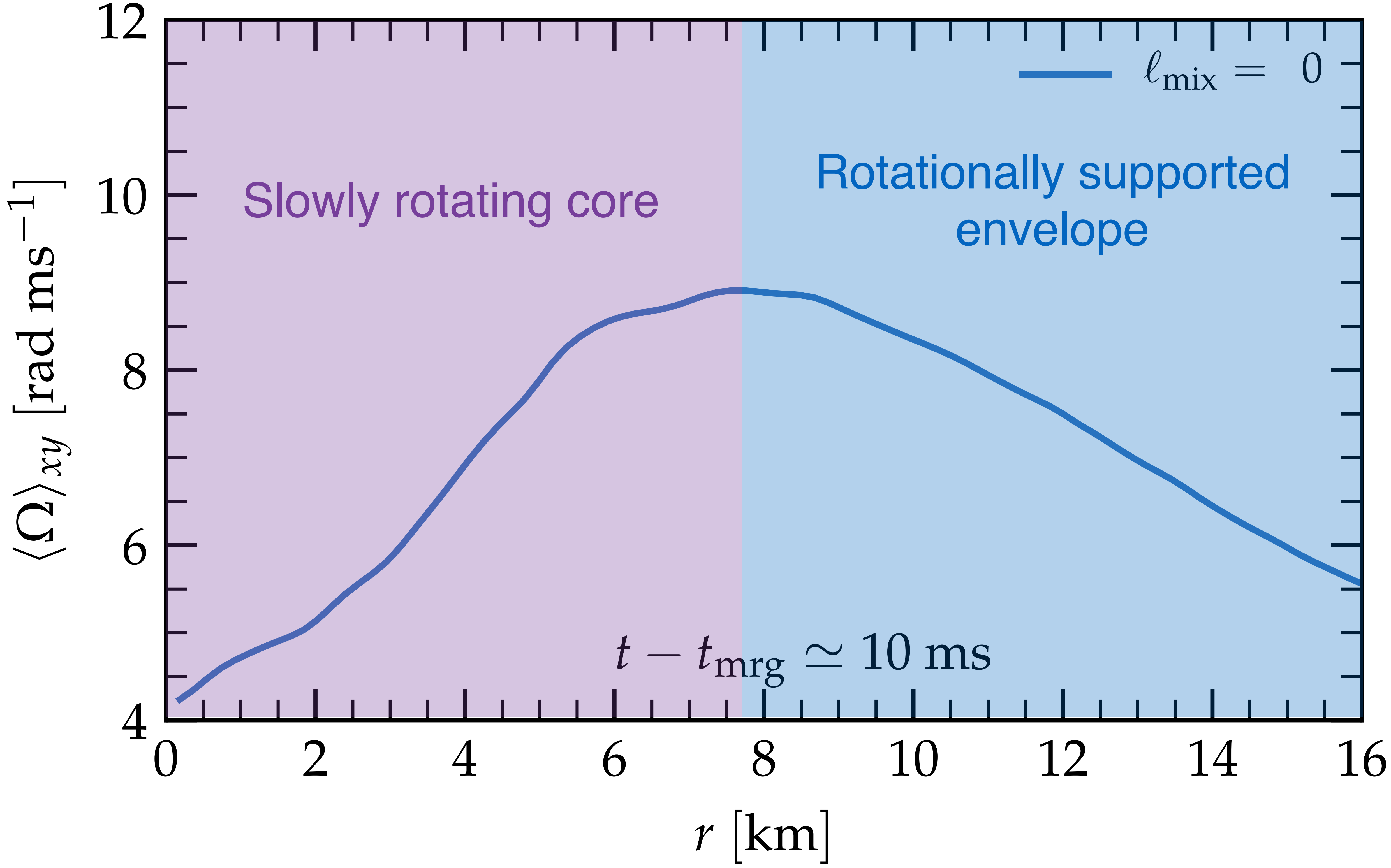
Rotational Profile



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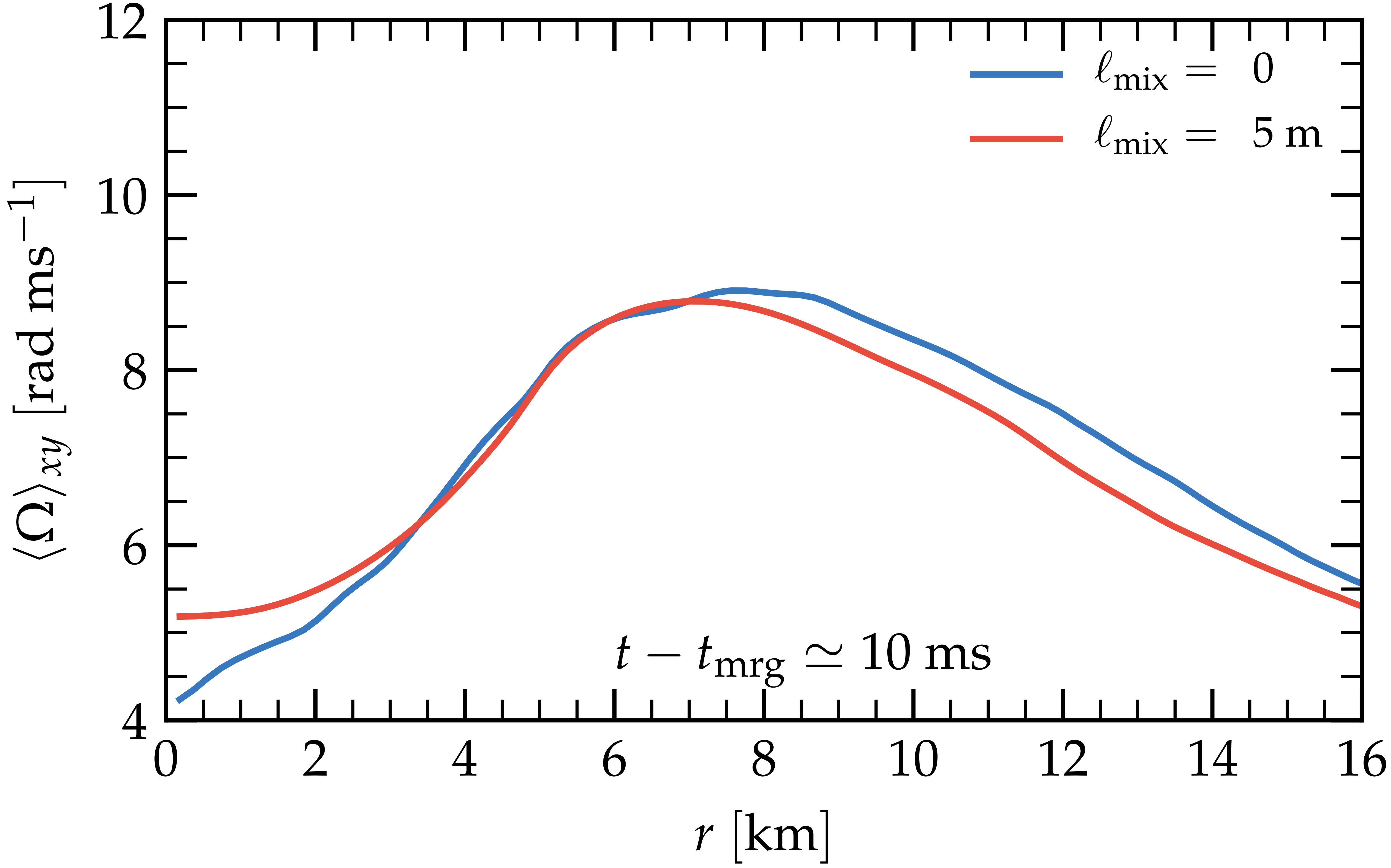

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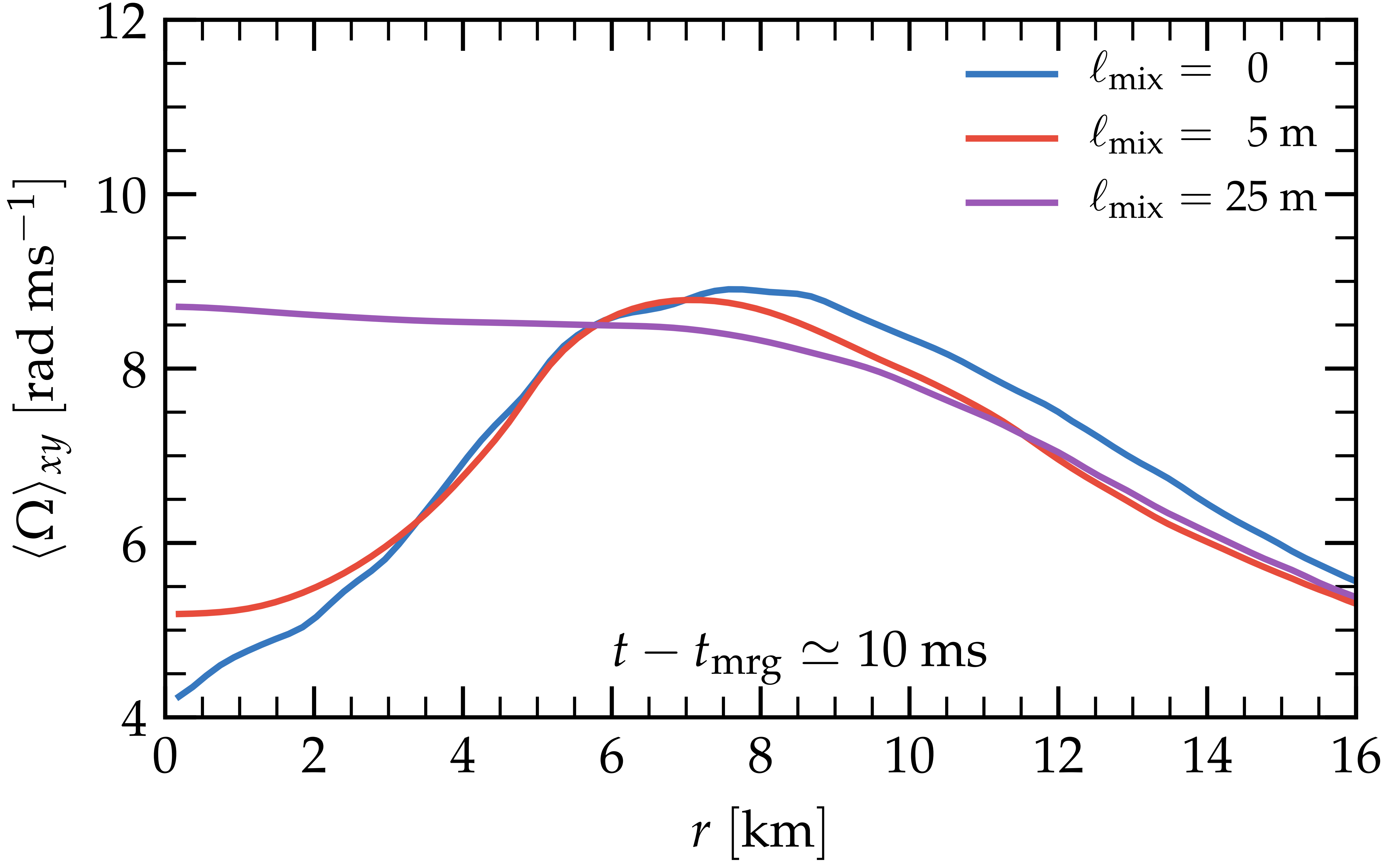

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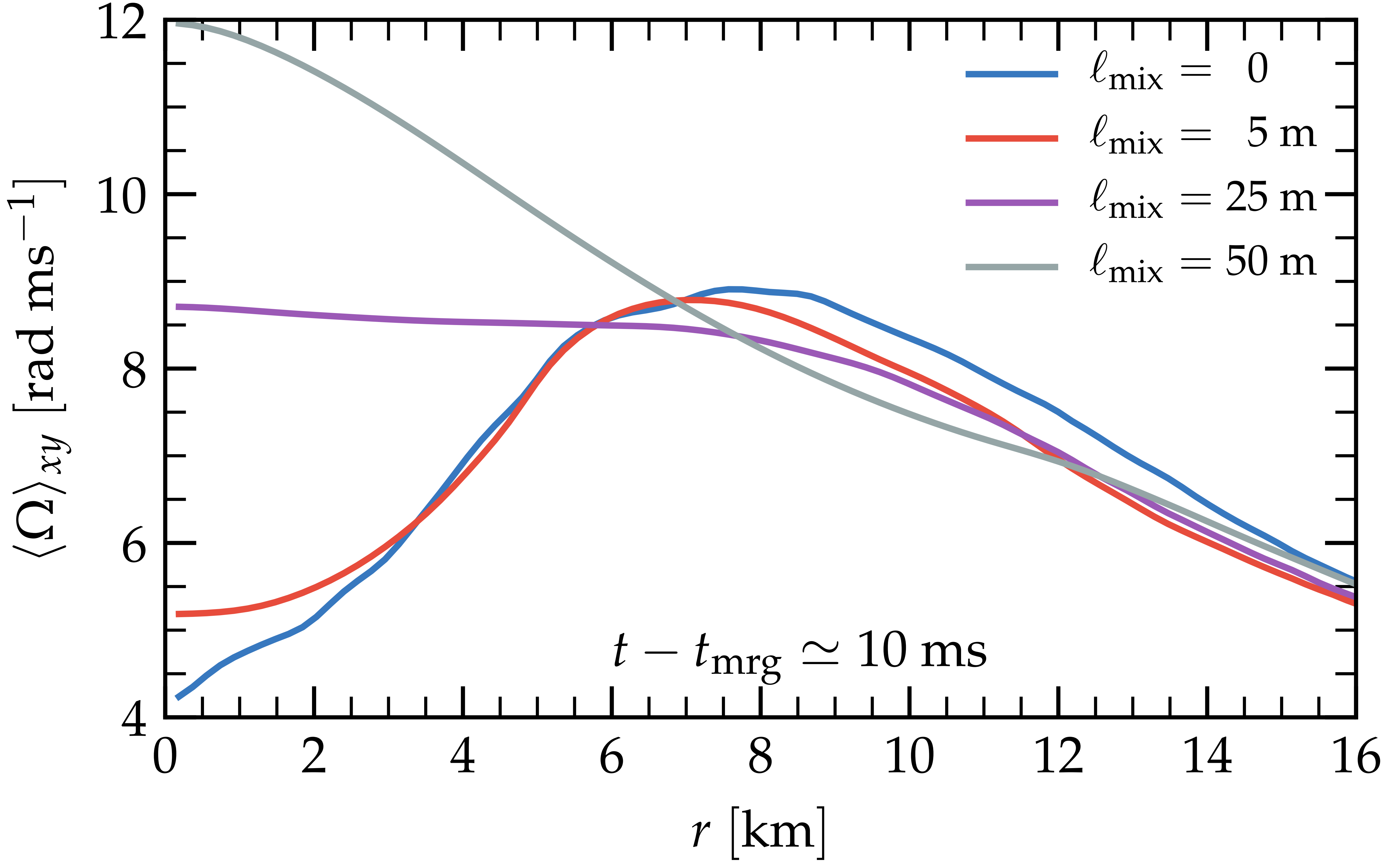
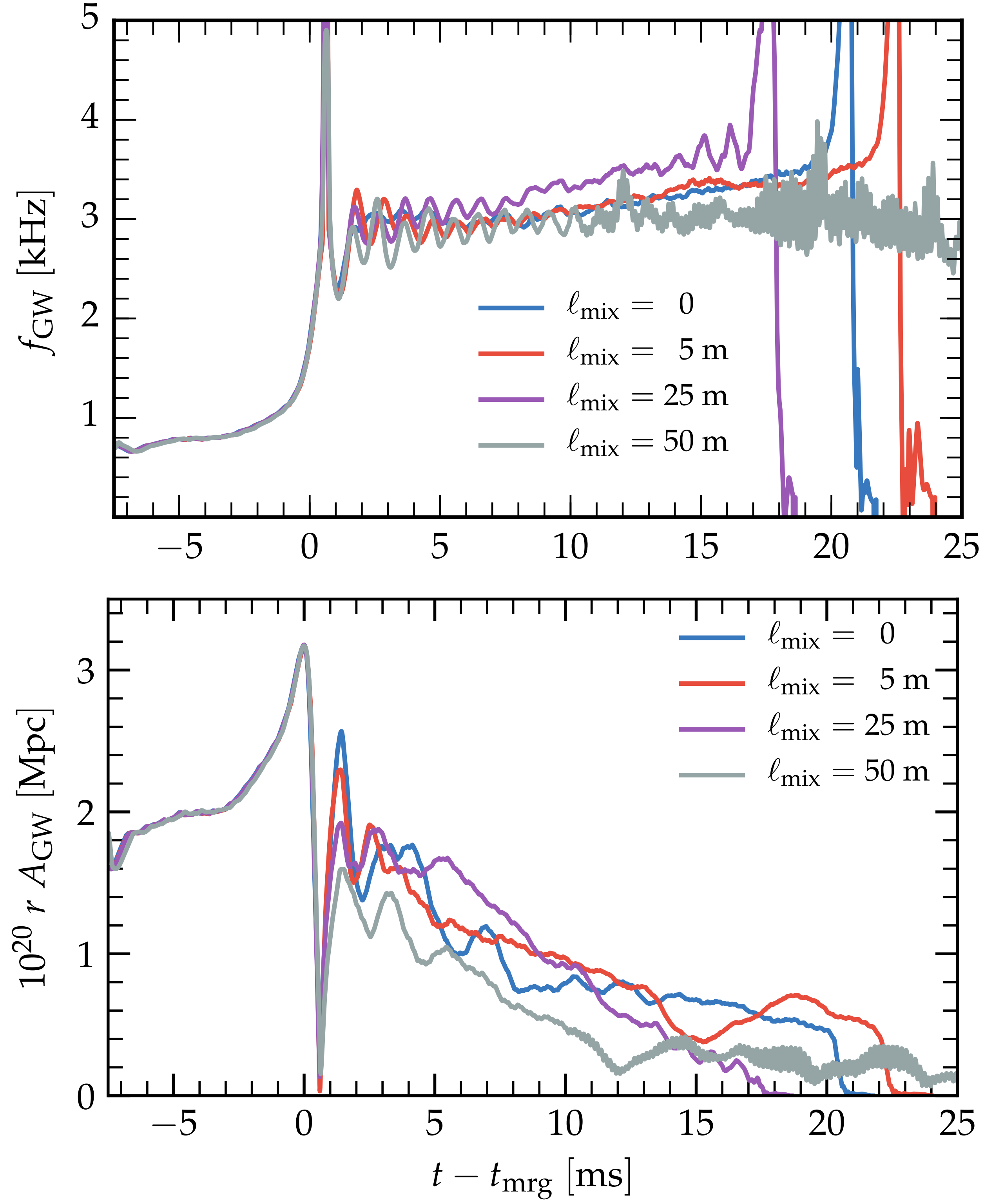
Rotational Profile

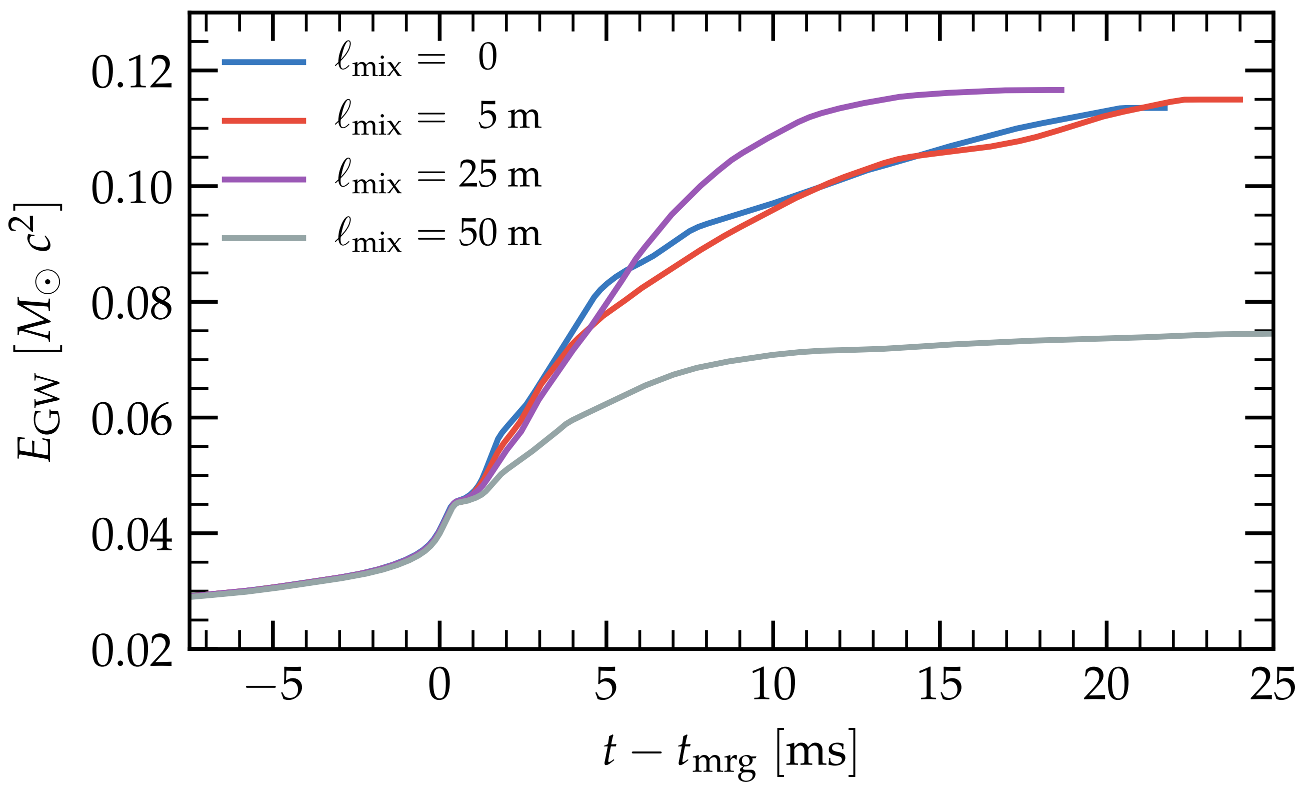


See also Shibata & Taniguchi 2006; Kastaun+ 2015, 2016; Hanauske+ 2016 **DR** 2017

Effect on the Waveforms

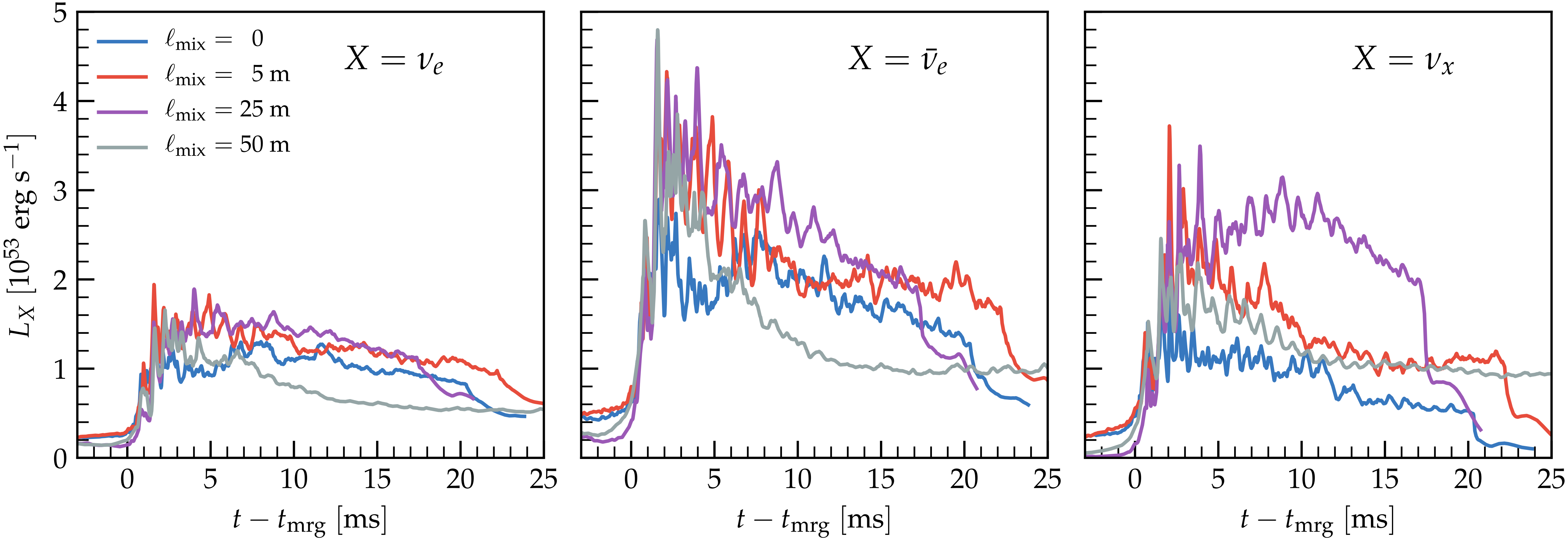


- f_{peak} is robust
- GW amplitude more sensitive
- MHD models needed



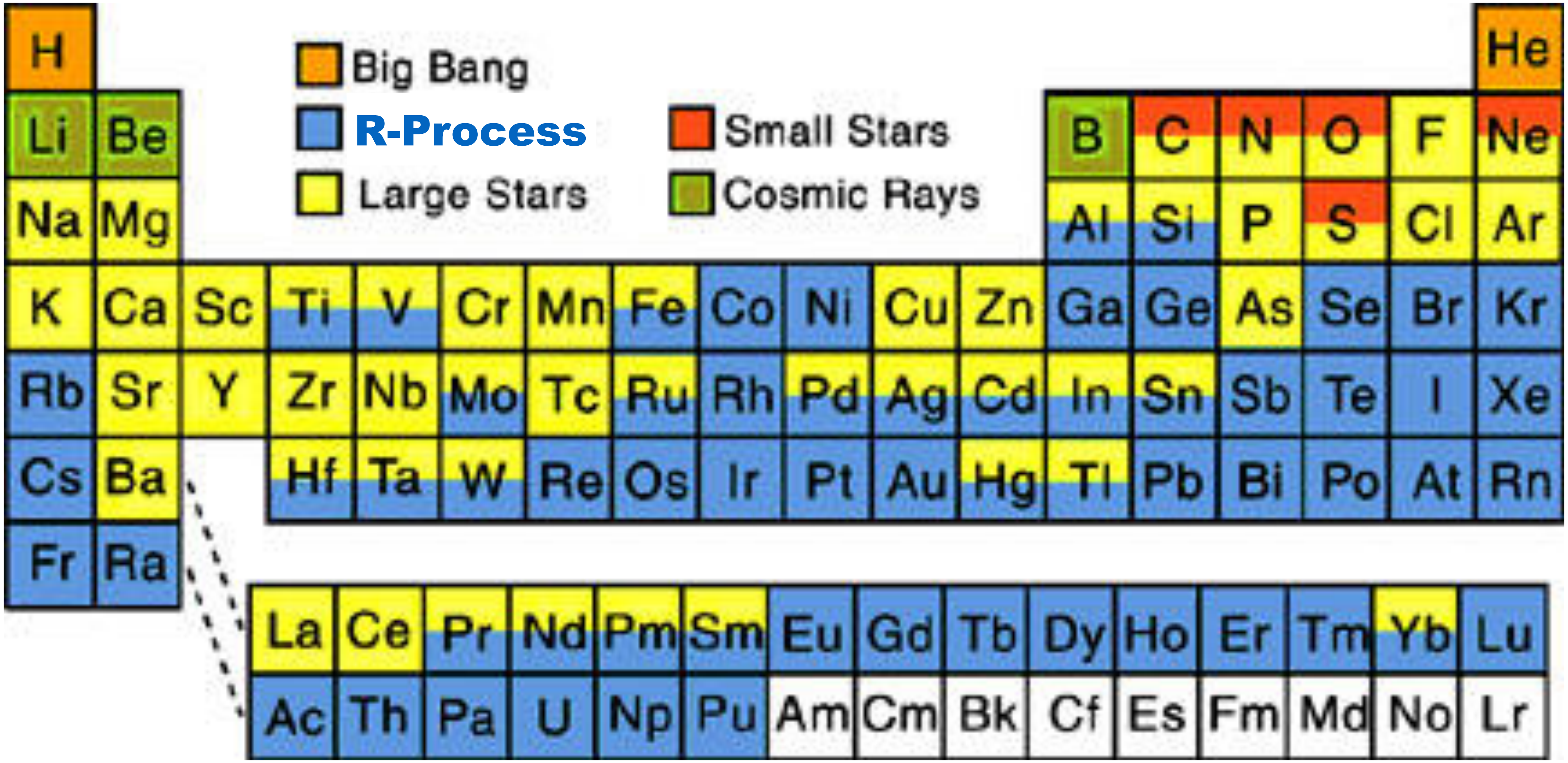
DR 2017

Effect on neutrino luminosity



- Inverted hierarchy compared to CCSNe: $L_{\nu_e} \lesssim L_{\bar{\nu}_e}$
- The remnant is re-leptonizing
- Turbulent dissipation some impact on luminosity: r-process?

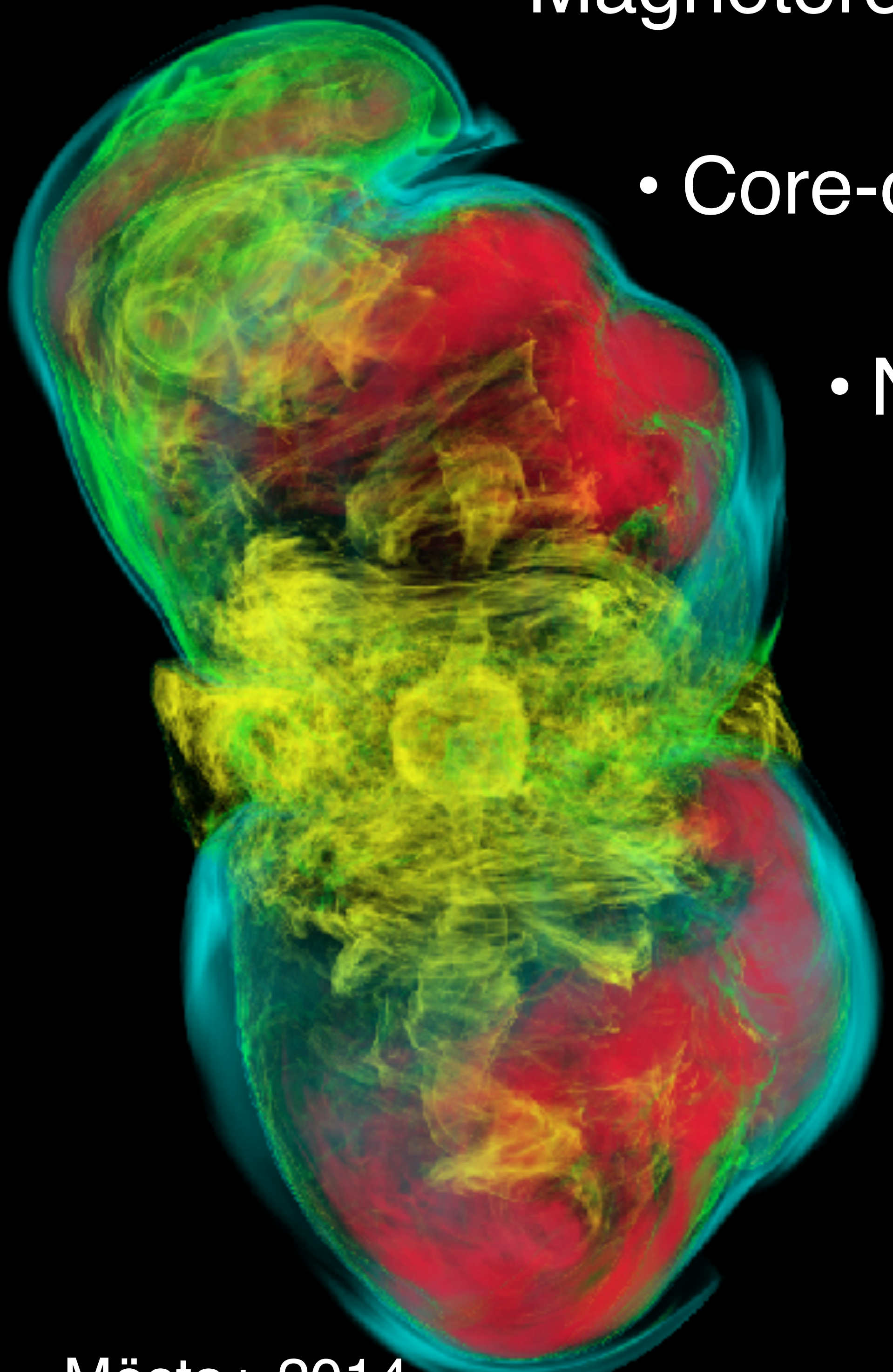
The Origin of the Elements

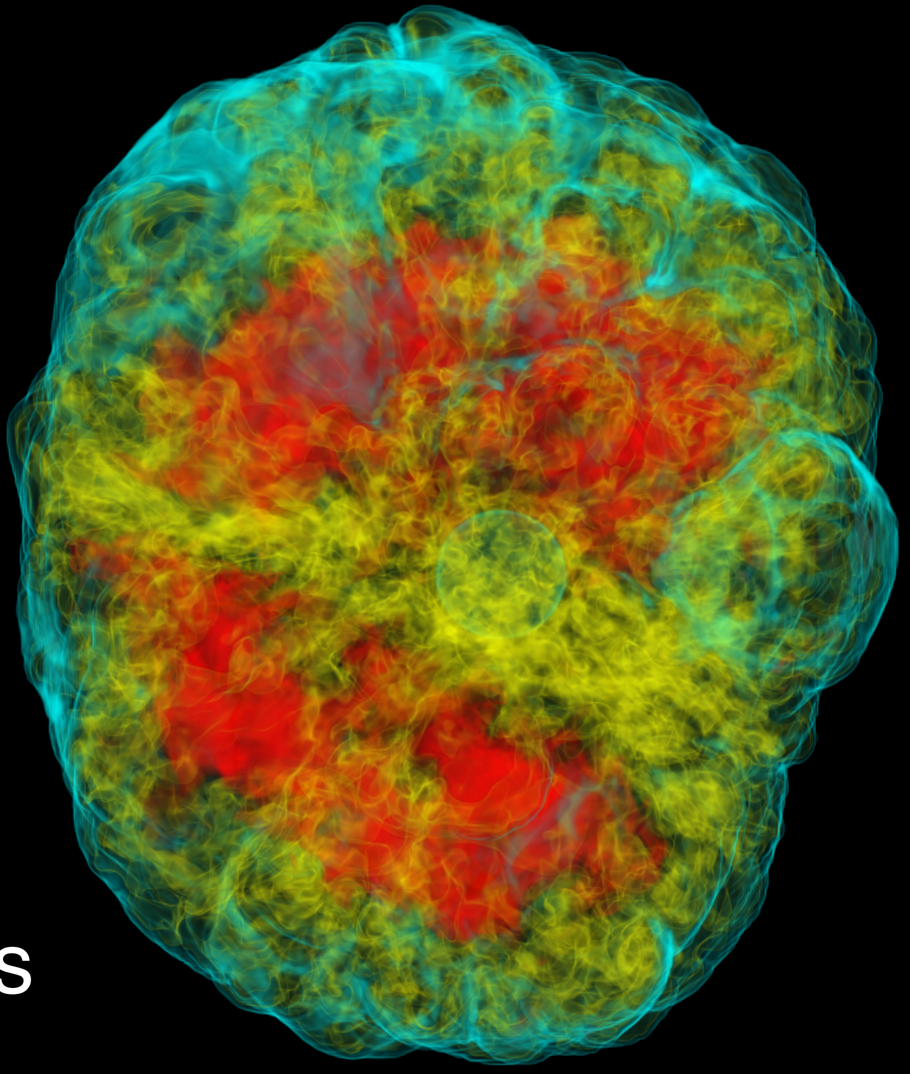


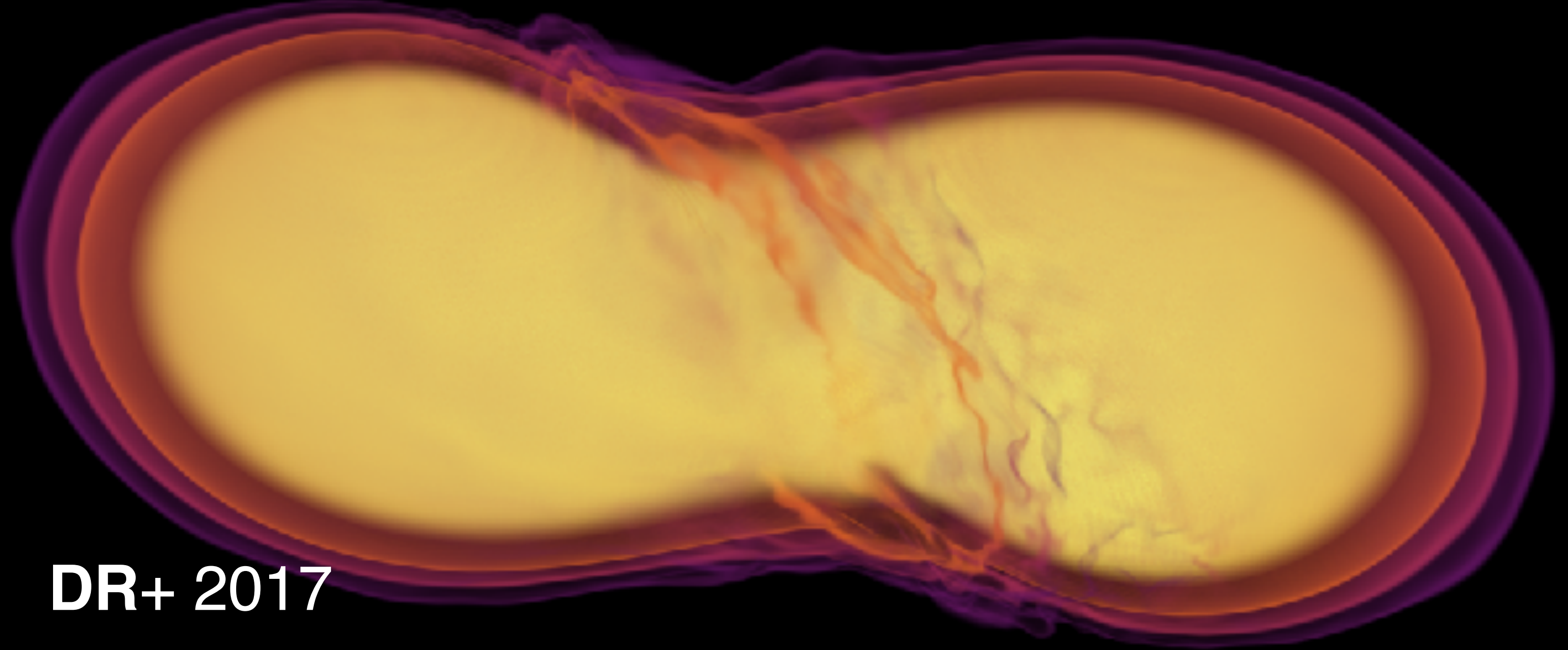
How are heavy elements formed?

R-process Sites

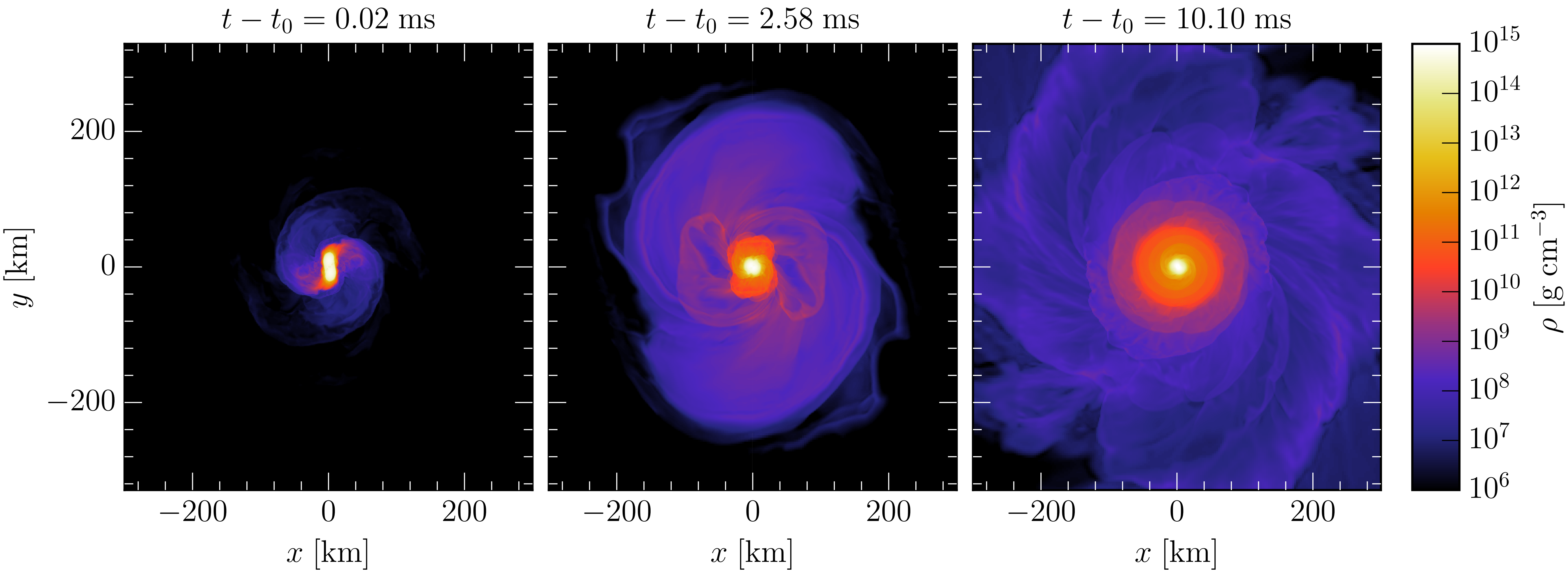
- Magnetorotational supernovae
- Core-collapse supernovae
- Neutron star mergers
- Nuclear explosions


Mösta+ 2014


Roberts+ 2016

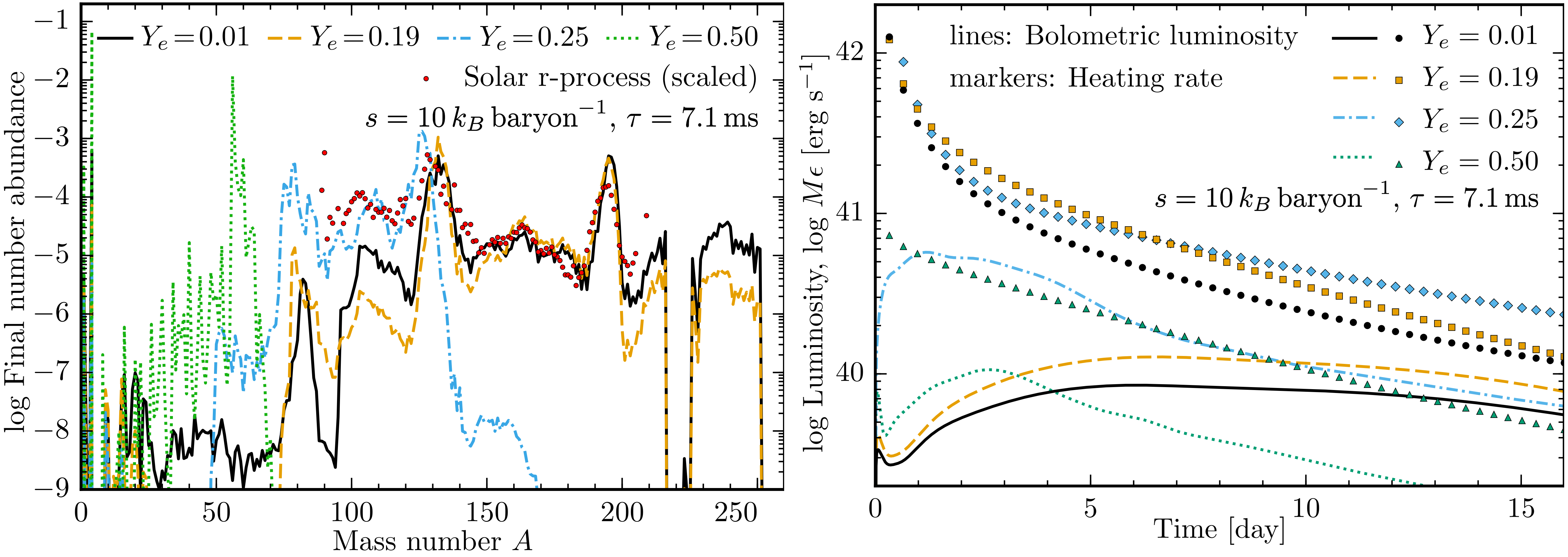

DR+ 2017

Compact Binary Mergers



- Neutron-rich outflows: the site of the r-process?
- Nucleosynthetic yields
- Radioactively powered transients

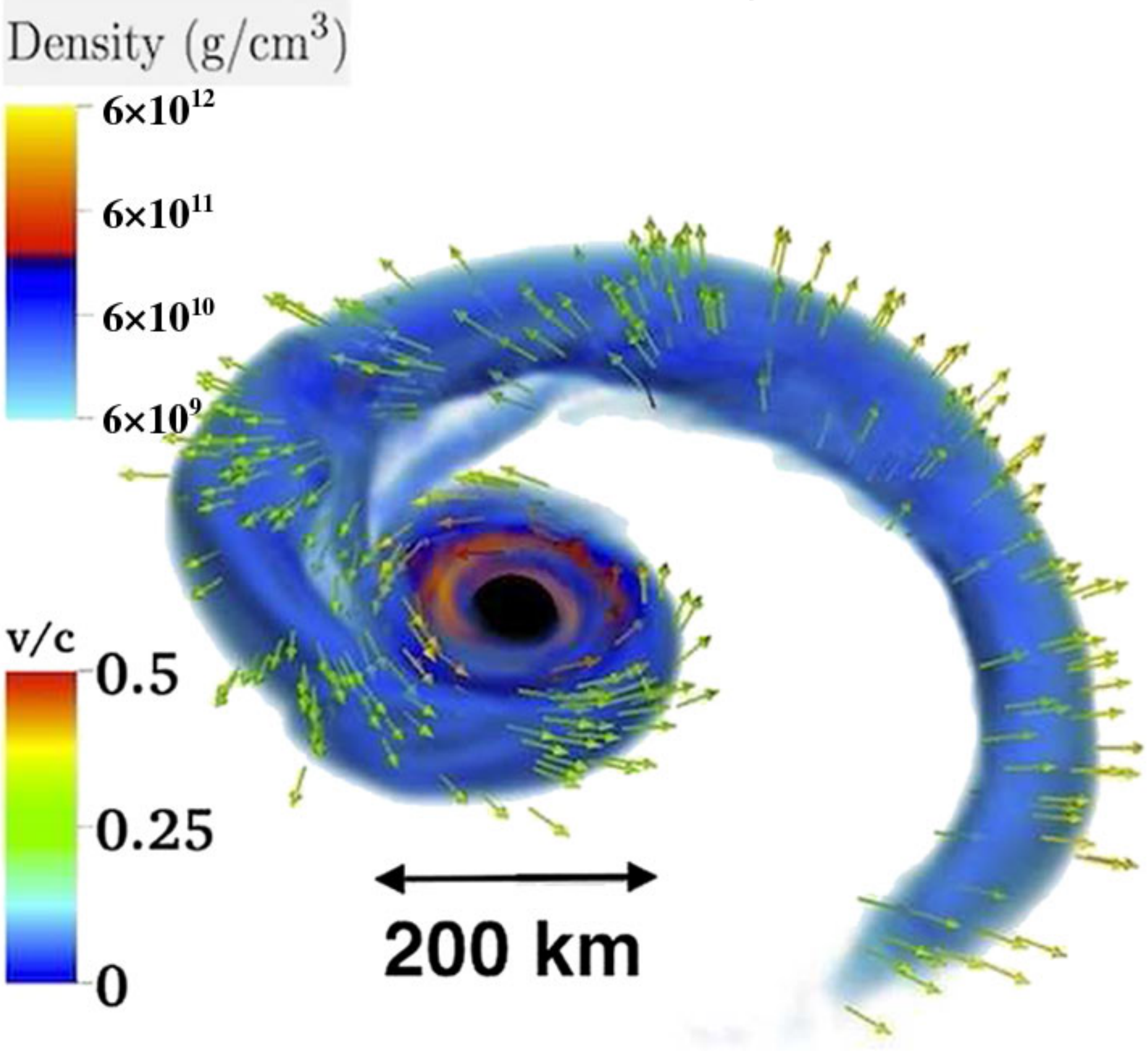
Strong and Weak R-process



From Lippuner & Roberts 2015

Nucleosynthetic yields, opacities, and radioactive heating: the composition is the most important parameter

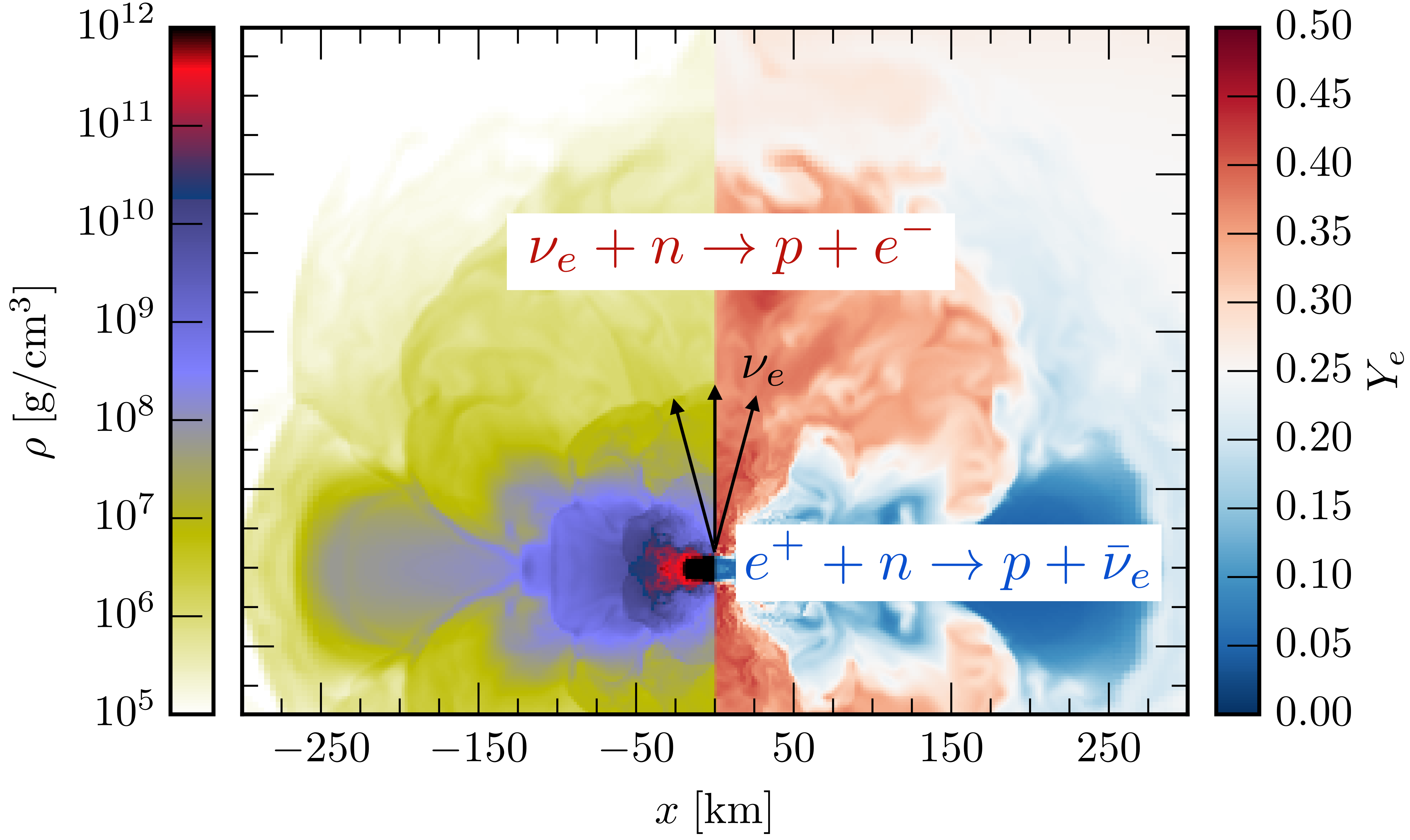
Neutron-Star Black-Hole Merger Outflows



From Foucart+ 2014

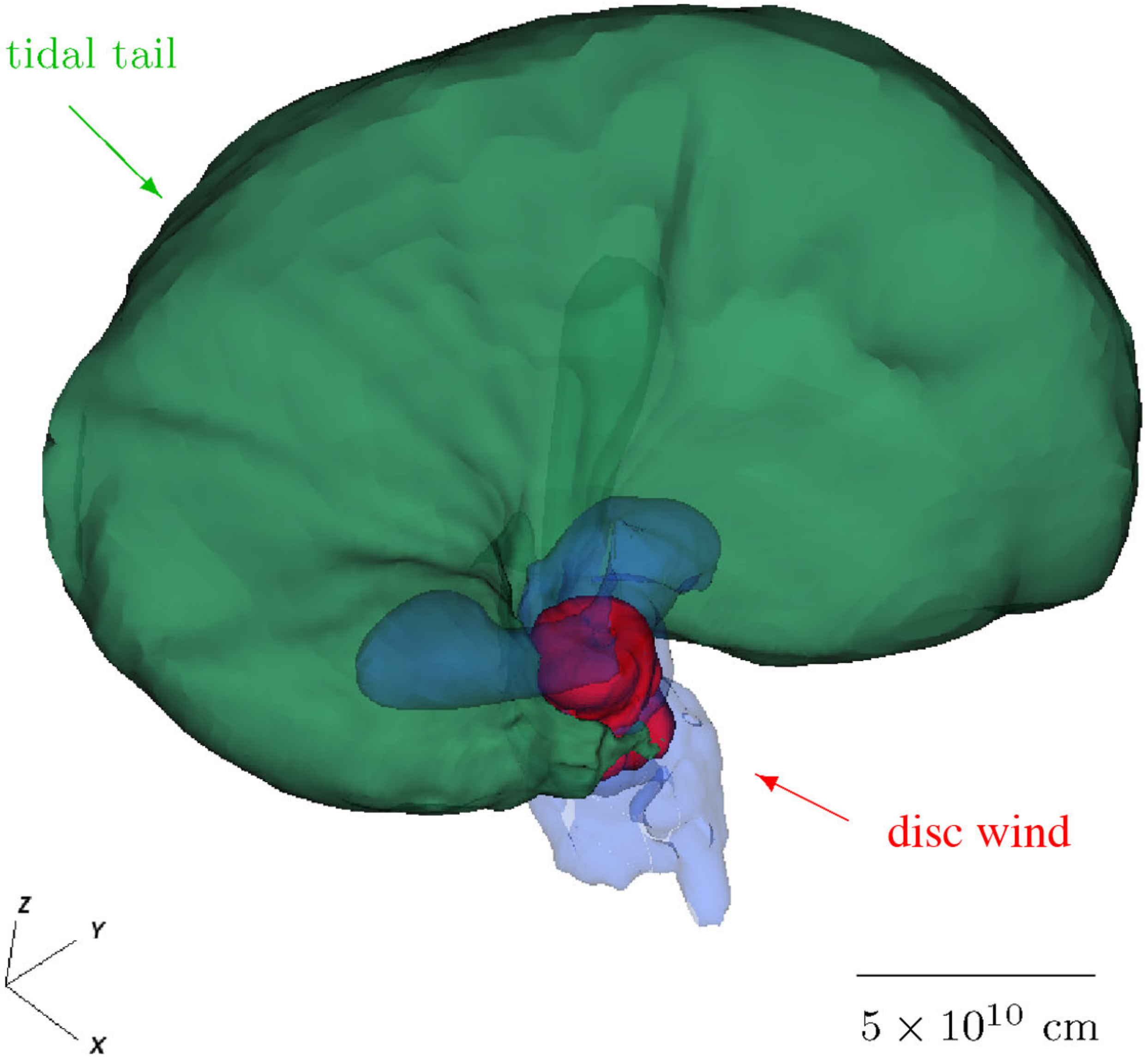
- Tidal disruption of NS
- Ejects ~up to 10^{-1} $M_\odot$
- Very neutron rich
- Crucially depends on R_{NS}, M_{NS}, M_{BH}, and a_{BH}

Neutron Star Merger Outflows

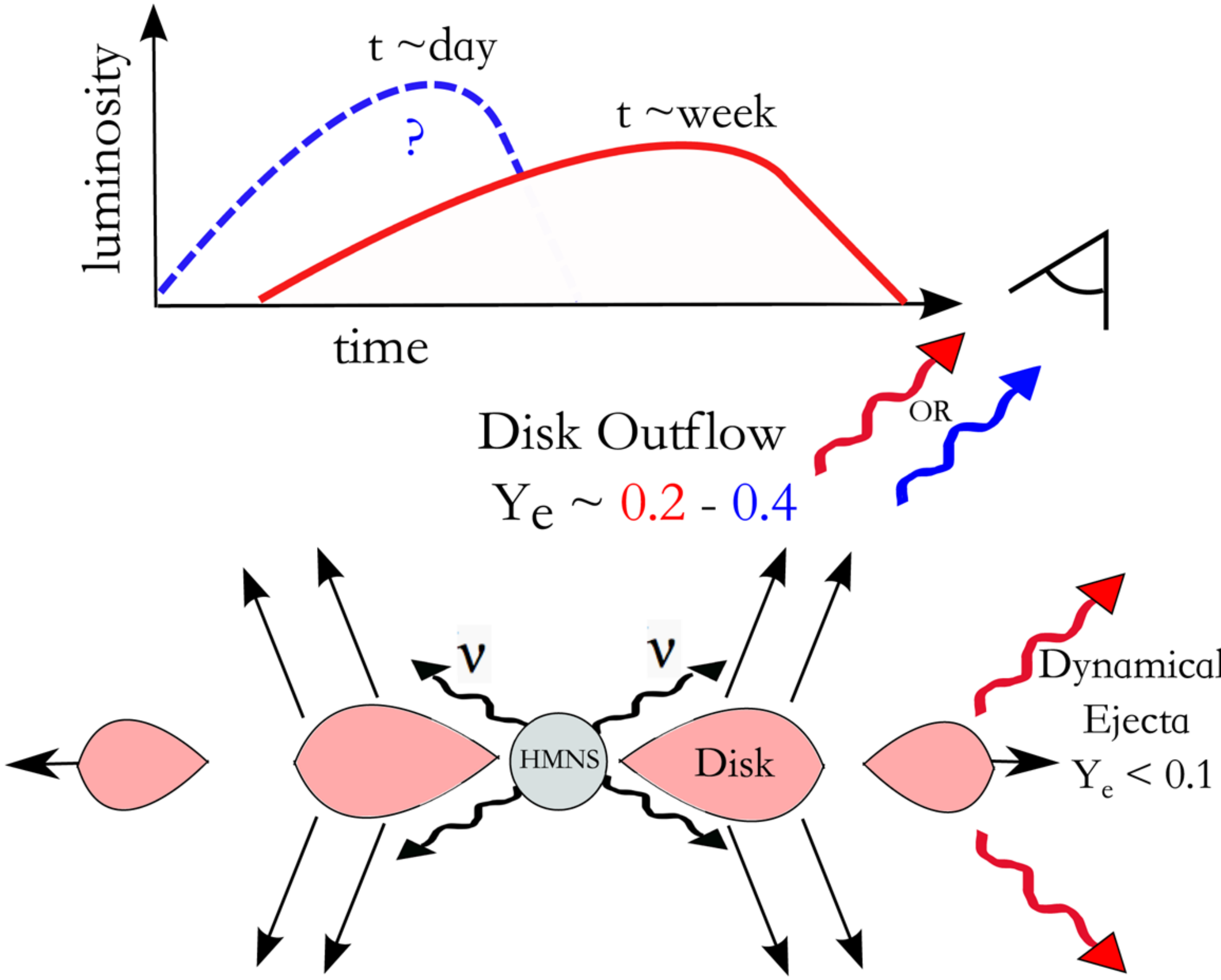


DR, Galeazzi, Lippuner+ 2016

Secular Ejecta



From Fernandez+ 2015

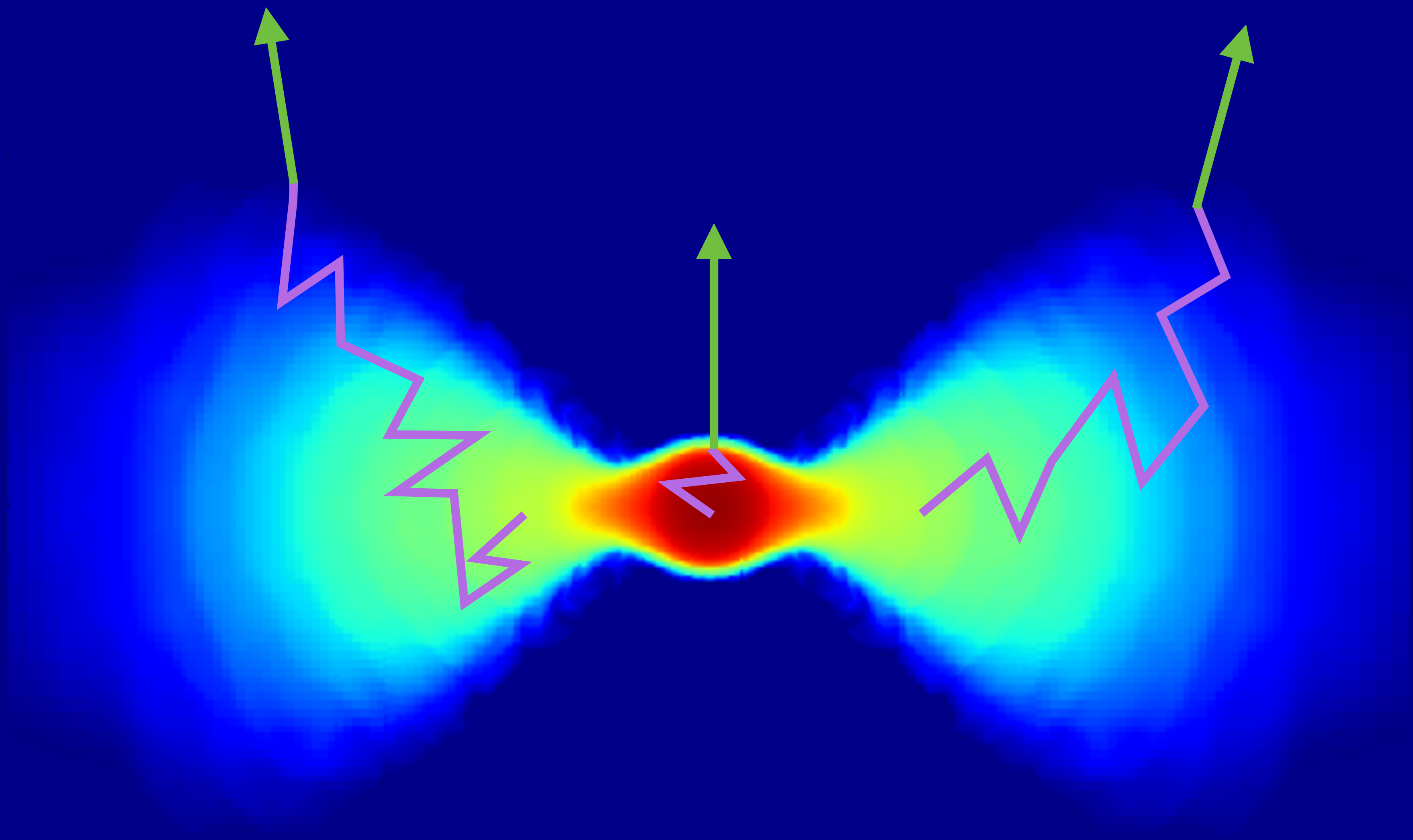


From Metzger+ 2014

Late-time ejecta can in some cases dominate yields and have an impact on the EM signal. Need to be included in emission models.

Approximate neutrino transport

1. Different treatment for trapped and free-streaming components



Trapped component: leakage

- Use effective emissivities weighted with the optical depth
- Leaked trapped neutrinos become free-streaming

Free-streaming component: M0

1. Free-streaming neutrinos stream radially out

$$\vec{J} = n_\nu \vec{k} \qquad\qquad \nabla \cdot \vec{J} = R_\nu^{\rm eff} - \kappa_a^{\rm eff} n_\nu$$

2. Assume $\vec{t}$ to be a Killing vector

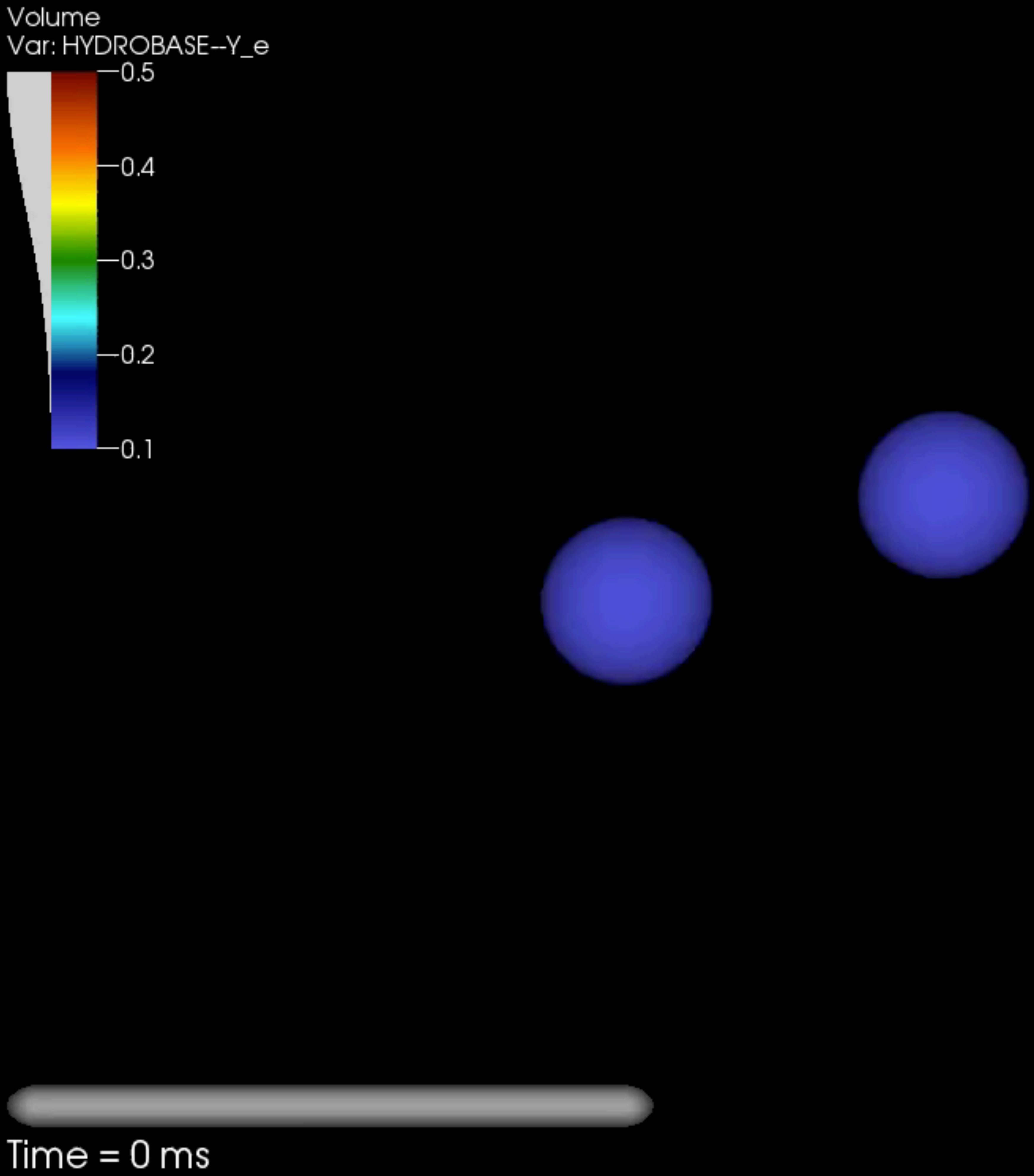
$$\vec{p}_\nu \cdot \vec{t} = {\rm const}$$

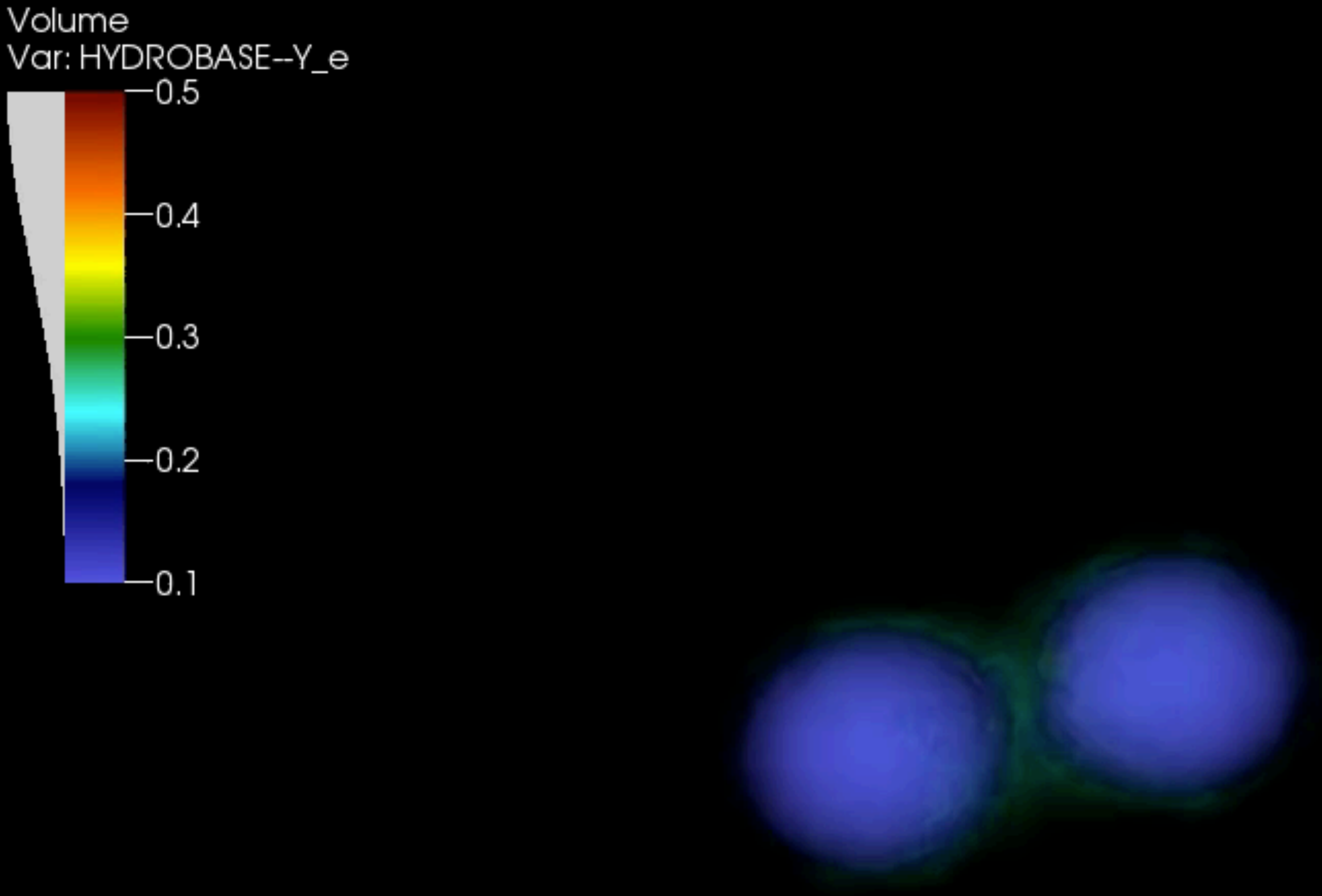
3. Use effective grey emissivities and opacities (no scattering)

4. Solve equations fully-implicitly on a radial grid “ray-by-ray”

- Mostly grey
- Idealized geometry
- Simple microphysics (no scattering!)

- Computationally inexpensive
- Clear physical interpretation
- No “radiation shocks”
- Velocity dependent terms
- Some spectral effects

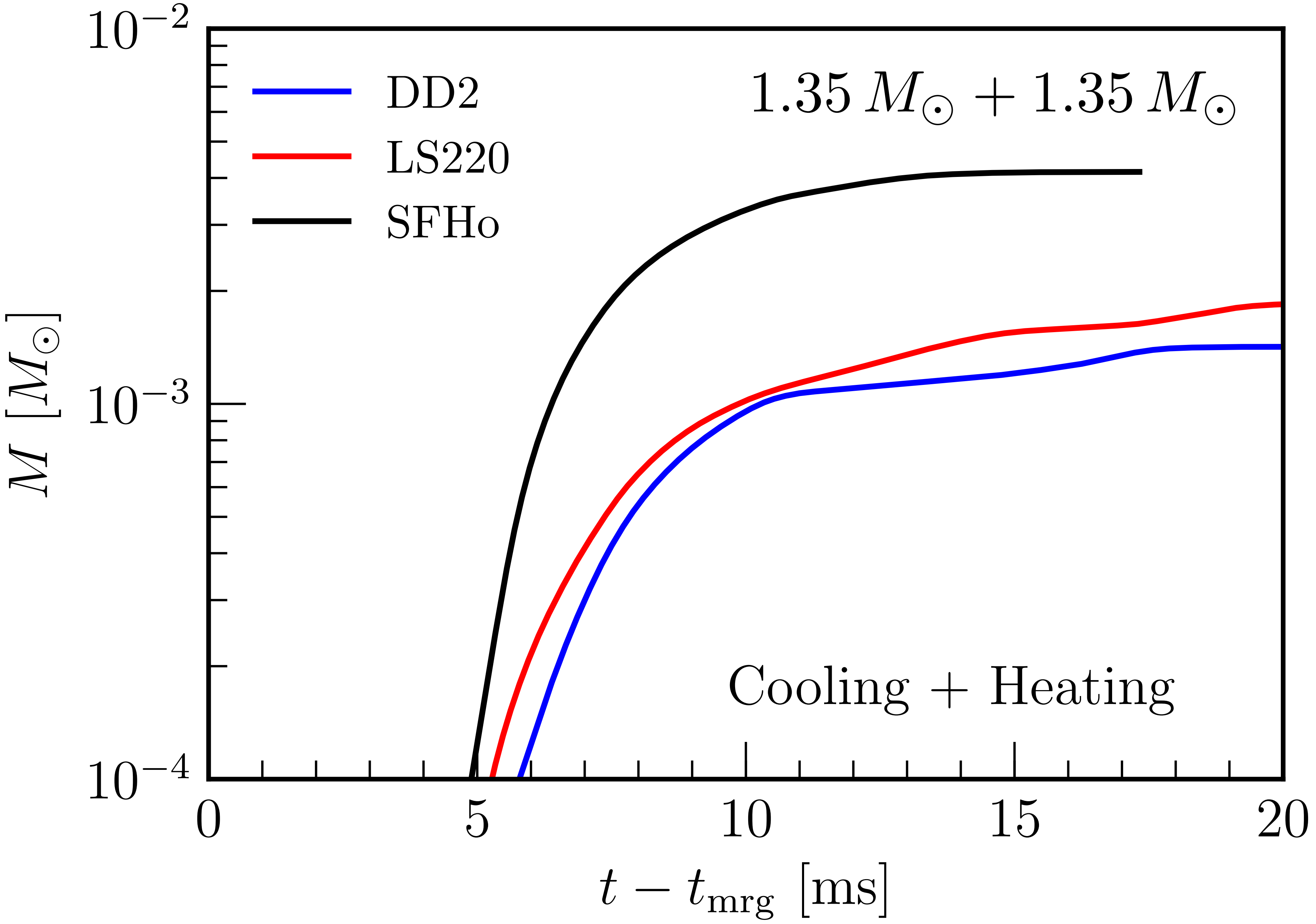

Volume
Var: HYDROBASE--Y_e
0.5
0.4
0.3
0.2
0.1
Time = 0 ms



R

Time = 7.38869 ms

Outflows

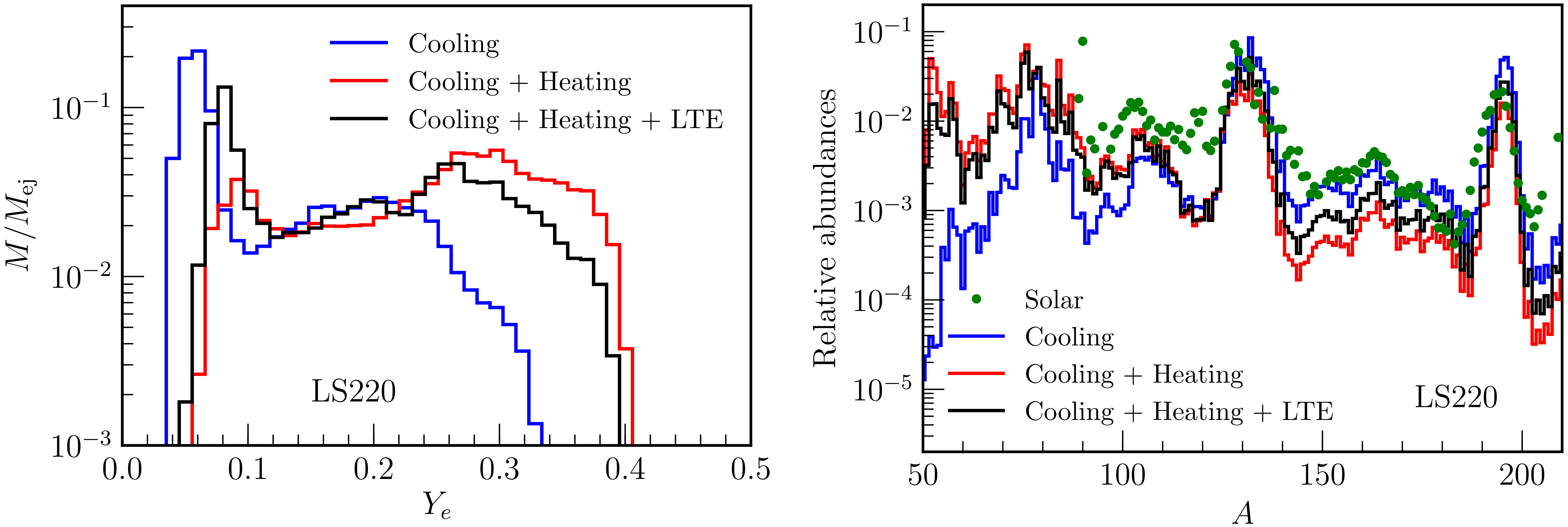


Record outflows at ~440 km

DR+ in prep

Impact of Neutrino Radiation

$1.35\,M_\odot + 1.35\,M_\odot$



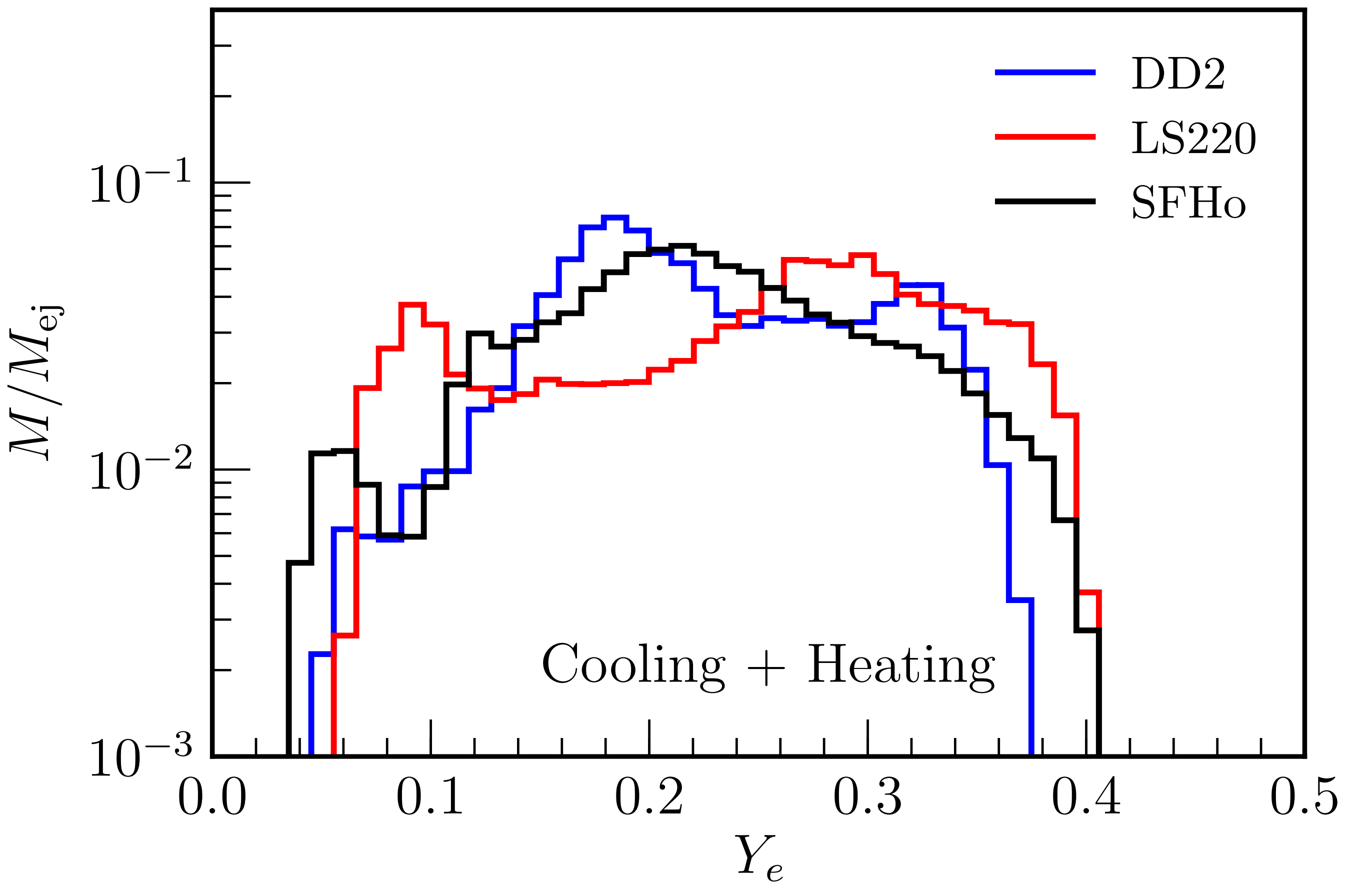
- The tidal tail is also irradiated
- Strong r-process yields are robust;
- but non-equilibrium effects are crucial: need spectral transport

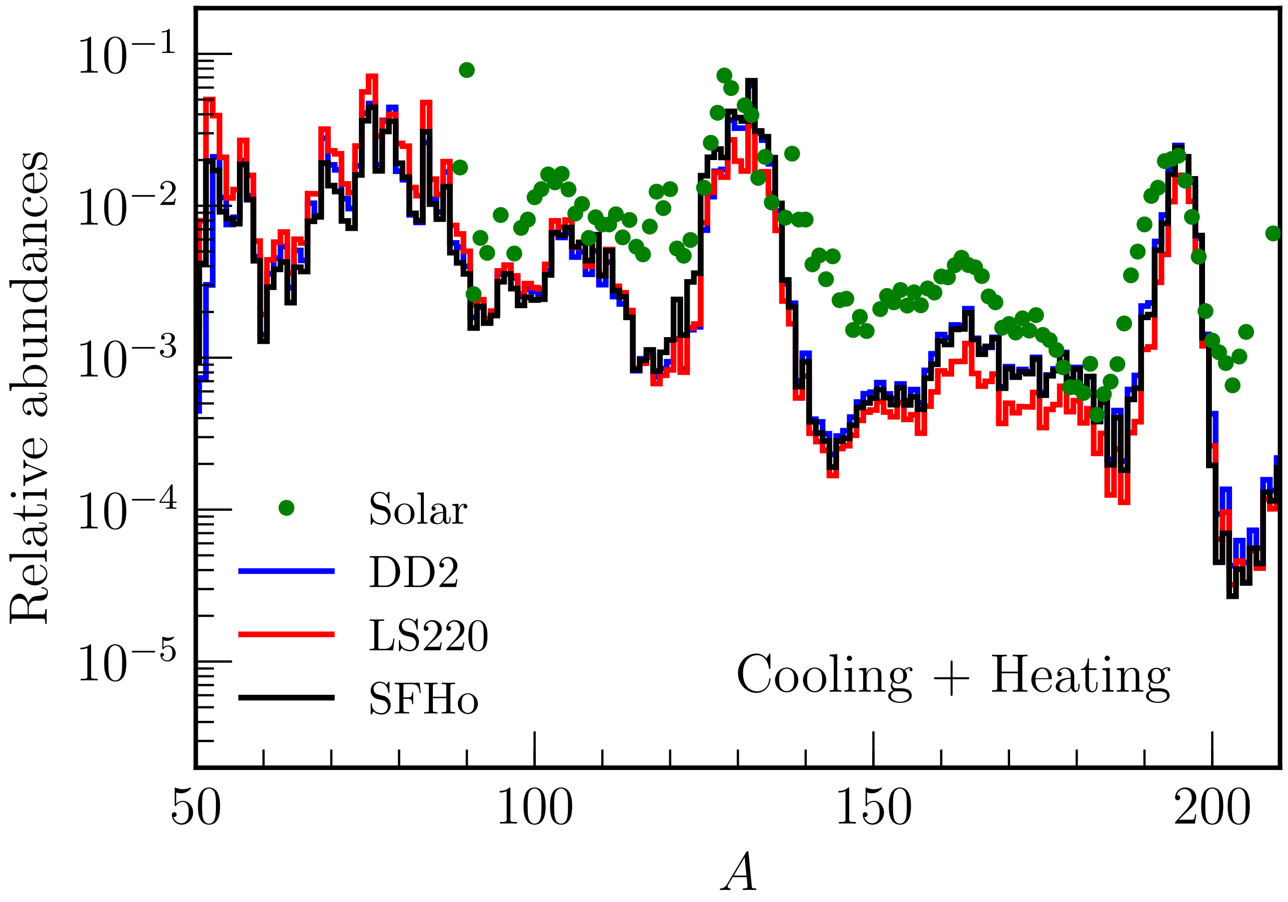
See also: Sekiguchi 2015, 2016, and Foucart+ 2015, 2016

DR+ in prep

Impact of Equation of State

$$1.35\,M_\odot + 1.35\,M_\odot$$





- Nuclear EOS affects composition and ejecta mass
- Relative abundances are robust

DR+ in prep

Uncertainties: Ejecta Mass

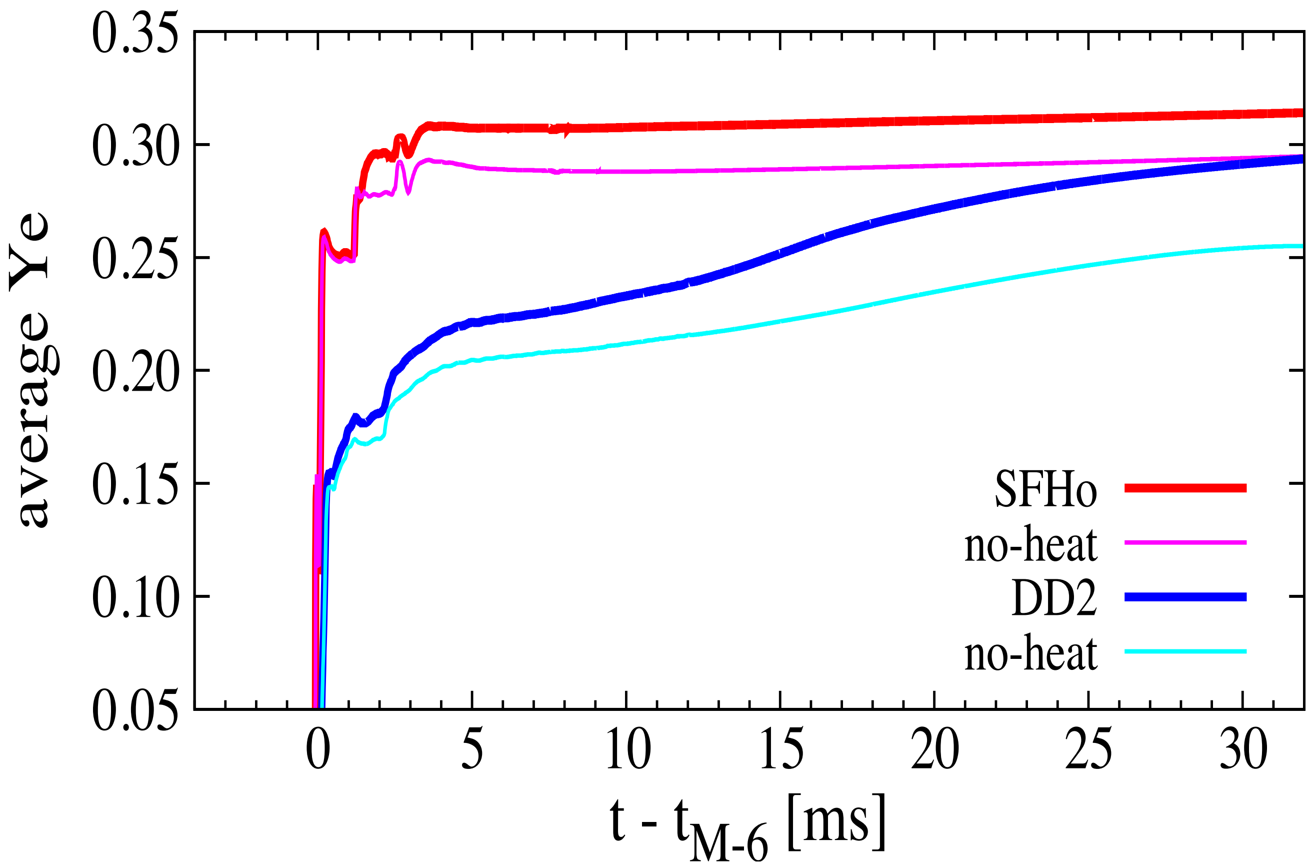
$$\mathrm{EOS: SFHo} \quad M = 1.35\,M_\odot$$

Simulation	Cooling	Heating	Ejecta Mass [Msun]
DR+ in prep	x	-	3.5×10^{-3}
DR+ in prep	x	x	4.1×10^{-3}
Palenzuela+ 2015	x	-	3.2×10^{-3}
Bauswein+ 2013	-	-	4.8×10^{-3}
Sekiguchi+ 2015	x	-	10.0×10^{-3}
Sekiguchi+ 2015	x	x	11.0×10^{-3}

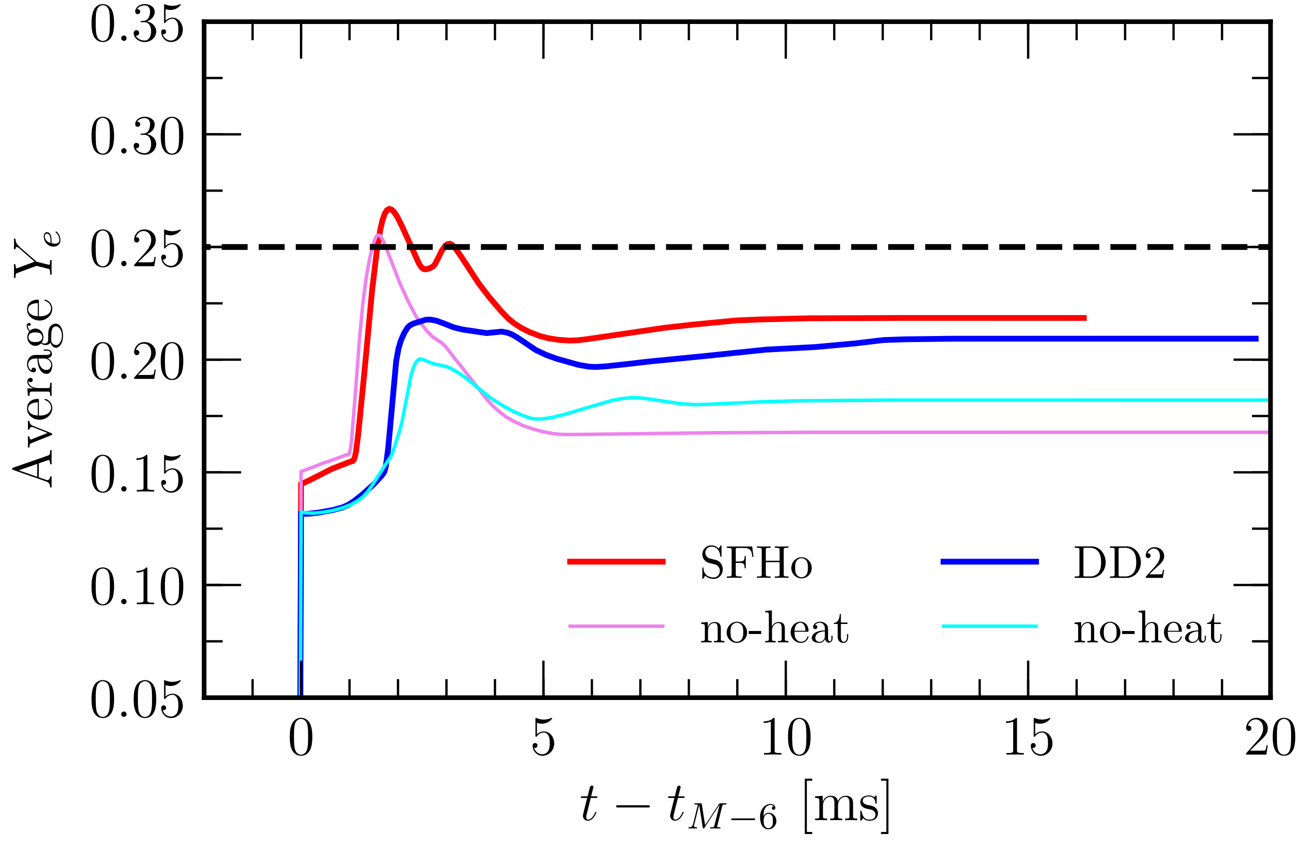
Factor of ~3 uncertainty in the ejecta mass!

Uncertainties: Composition

$$1.35\, M_{\odot} + 1.35\, M_{\odot}$$



From Sekiguchi+ 2015



From DR+ in prep

- Not yet a consensus on the exact composition
- Quantitative differences for nucleosynthesis, opacities

Conclusions

Conclusions

- Postmerger GWs: probing of extreme-density physics
- MHD turbulence effects: what is $\ell_{\rm mix}$?
- More work needed for fully-quantitative nucleosynthetic yield predictions: MHD turbulence, detailed microphysics