Towards the modeling of PBH-NS interactions with numerical relativity

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Kavli IPMU — Focus week on primordial black holes

Growth of a PBH inside a NS

The mass of PBH inside a NS grows as

$$\frac{\mathrm{d}M_\bullet}{\mathrm{d}t} \simeq \rho_{\rm nuc} A_\bullet c = 16\pi\rho_{\rm nuc}\frac{G^2 M_\bullet^2}{c^3}$$

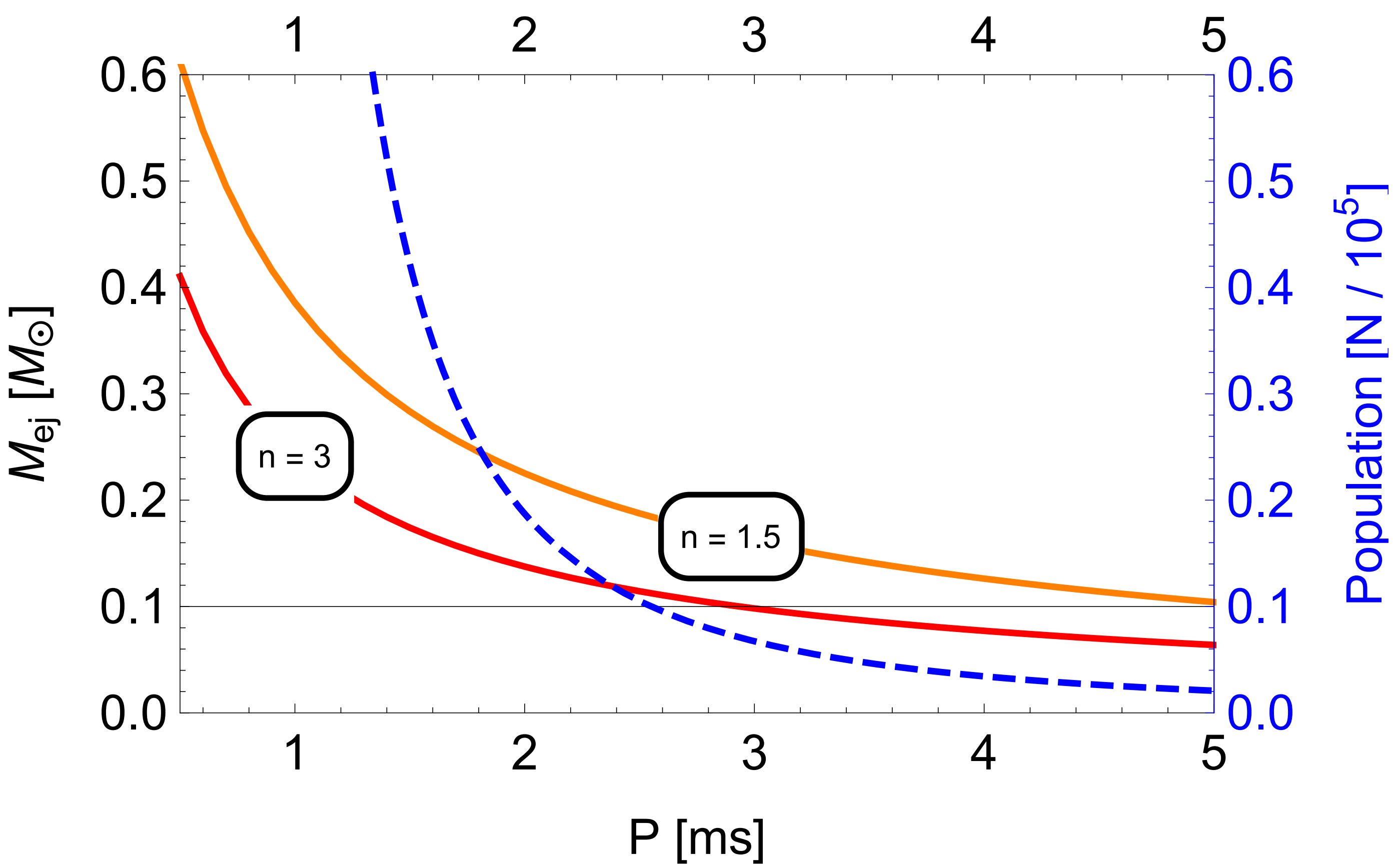
The NS implosion time

$$T = \left(16\pi\rho_{\rm nuc}\frac{G^2}{c^3}\right)^{-1}\left(\frac{1}{M_\bullet} - \frac{1}{M_{\rm NS}}\right) \simeq 0.2\ \mathrm{ms}\left(\frac{M_\bullet}{M_\odot}\right)^{-1}$$

The dynamical time of NS is $\lesssim$1 ms.

Evolution no longer quasi-steady when $M_\bullet \gtrsim 0.01 M_\odot$

What happens next?

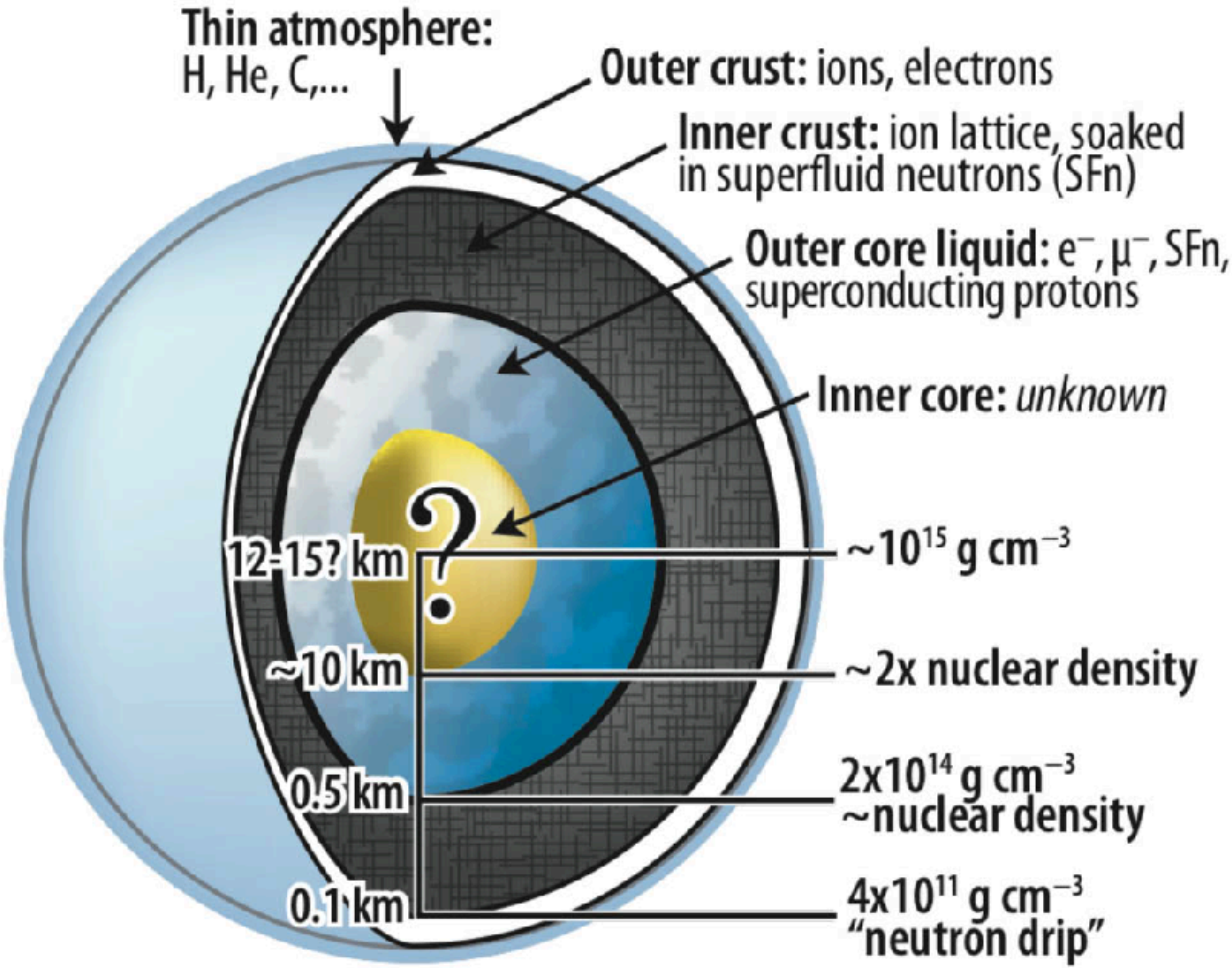


From Fuller, Kusenko, and Takhistov PRL (2017)

- Mass ejection / disk formation?
- Radioactively powered transient?
- Gamma-ray burst?

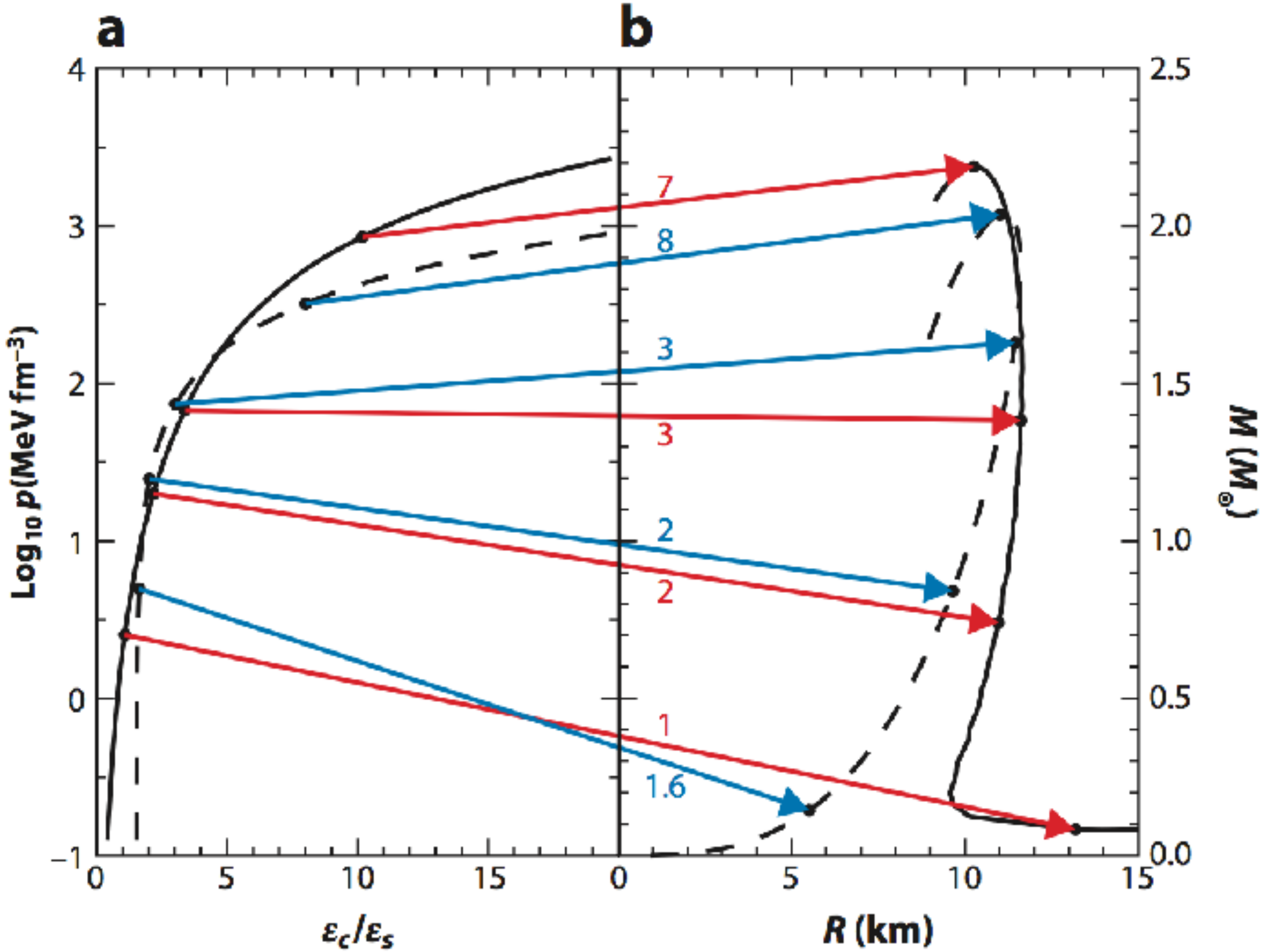
Main question: what are the EM/GW signatures?

See also Takhistov (2017)

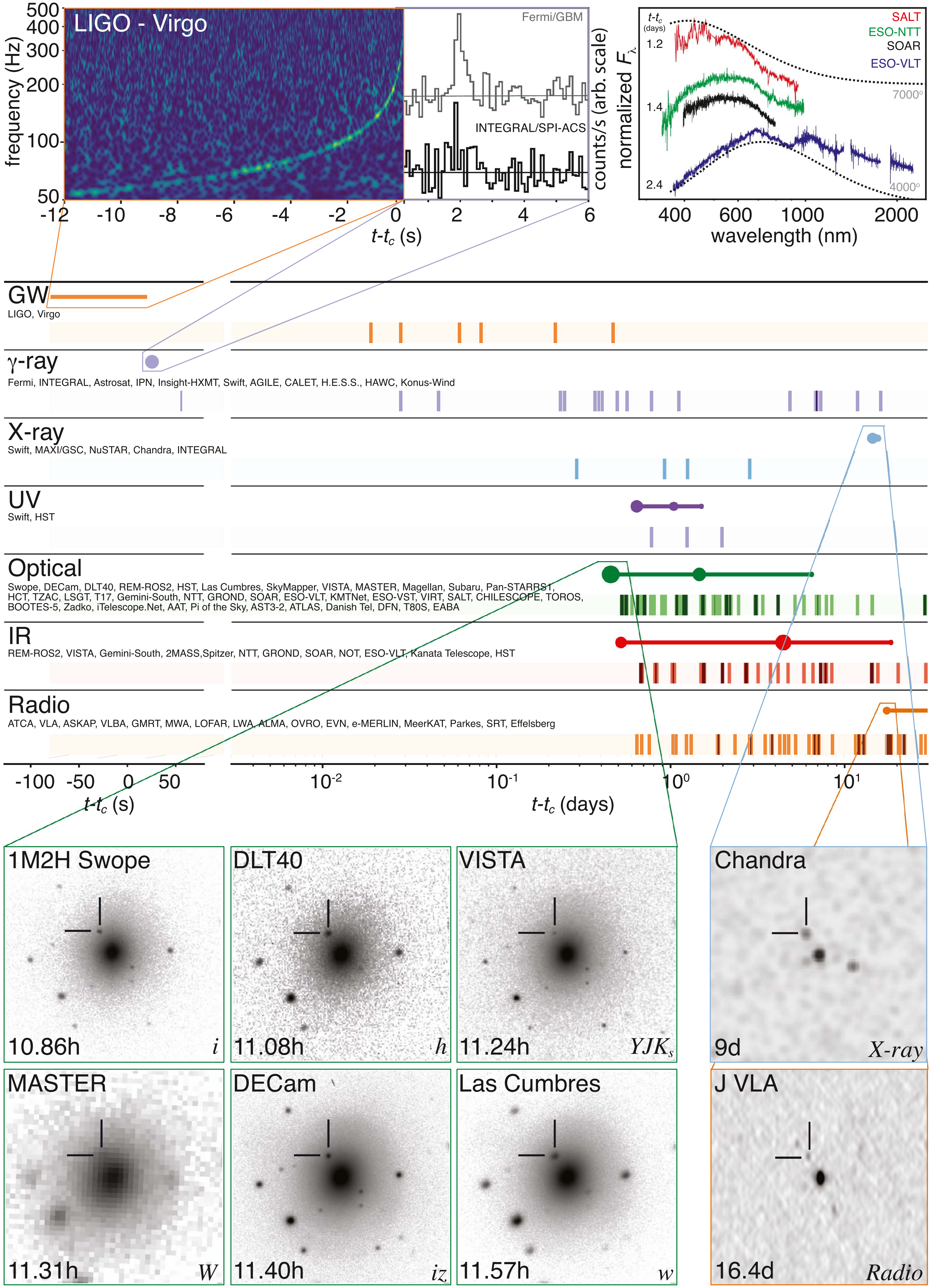


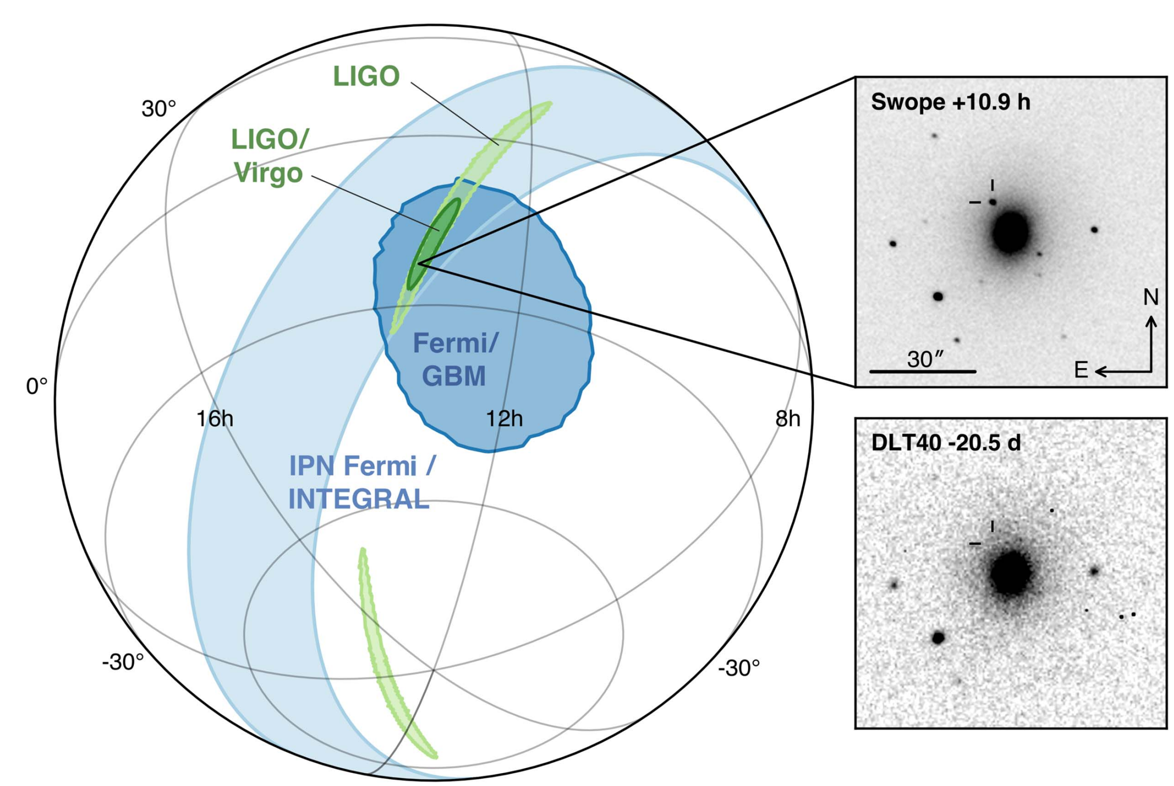
Credit: NASA/NICER

Neutron star equation of state



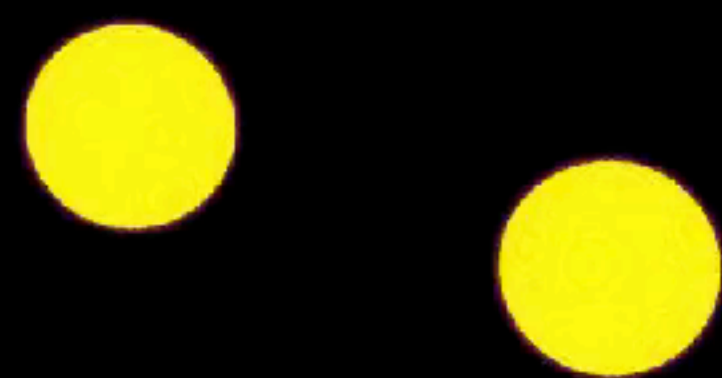
From Lattimer 2012





From LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech- NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT ApJL 848:L12 (2017)

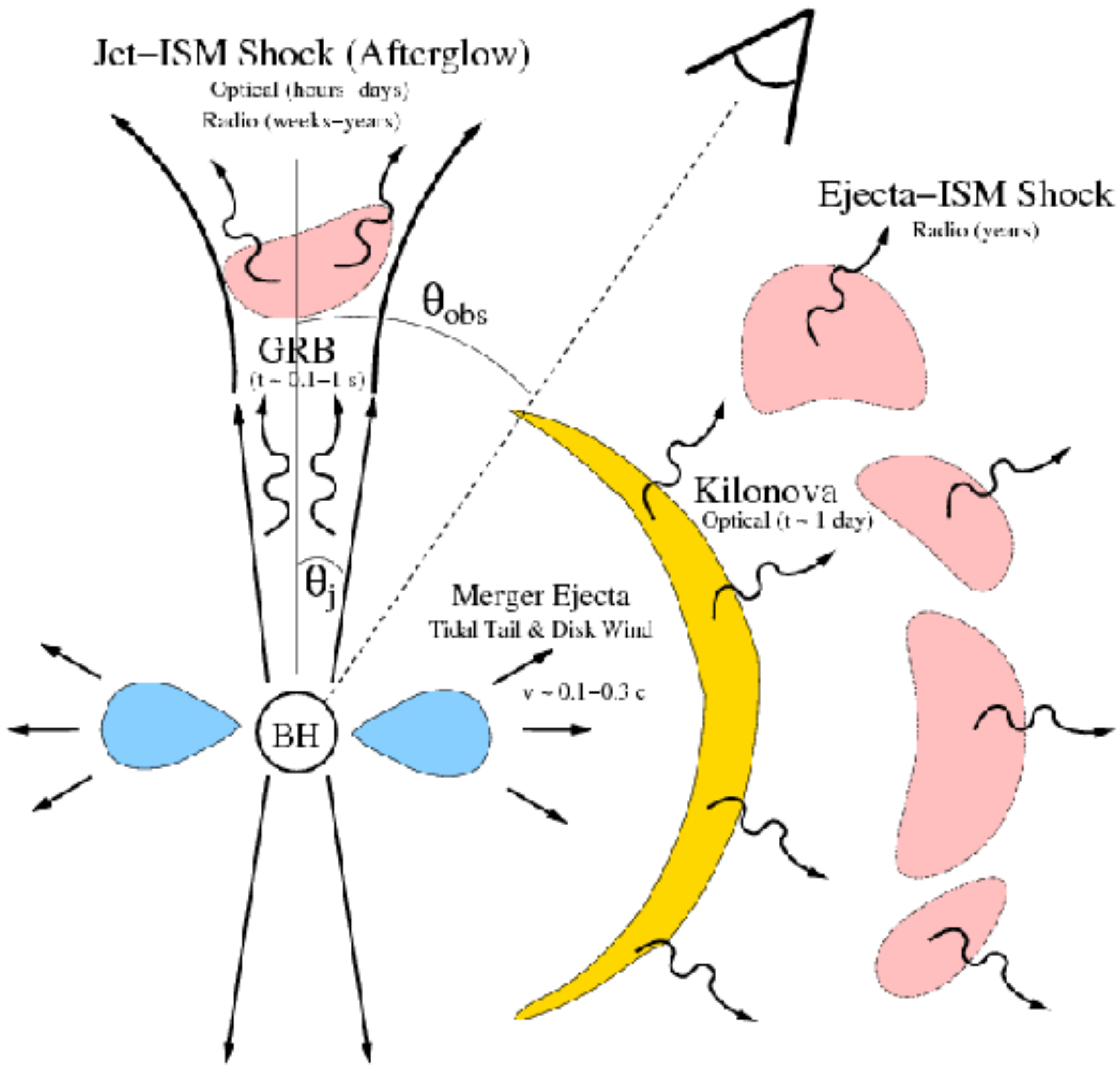
What happened?



LS220, 1.4 + 1.4 $M_{\odot}$

Simulation: **DR**, Visualization: Cosima Breu (Frankfurt)

What happened?

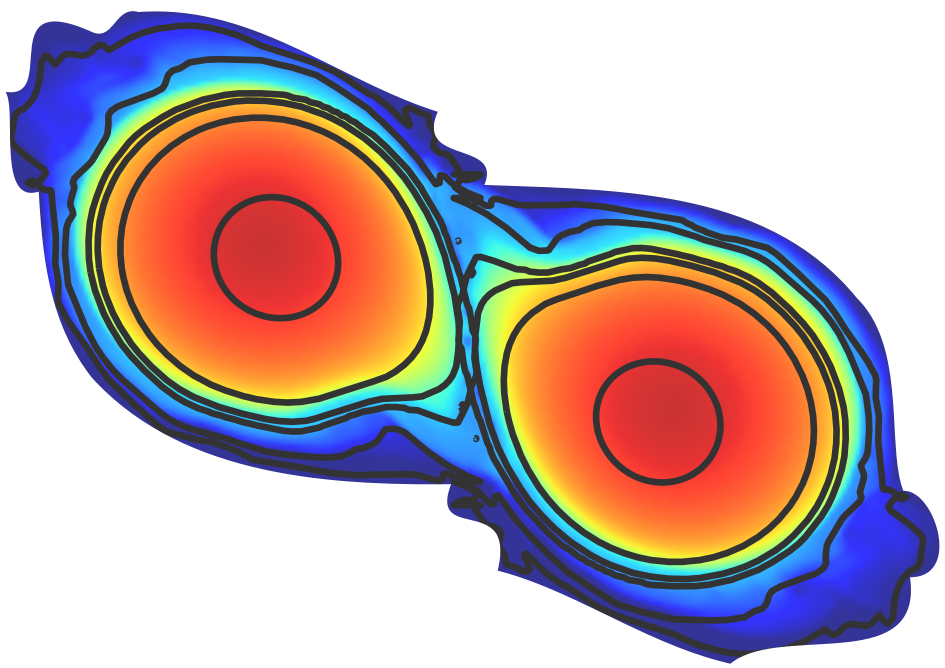


From Metzger & Berger 2012

- Fate of the remnant unknown, but likely a BH
- A short gamma-ray burst was launched. How?
- Radioactive of neutron rich ejeta powers UV/optical/infrared

What have we learned about neutron stars?

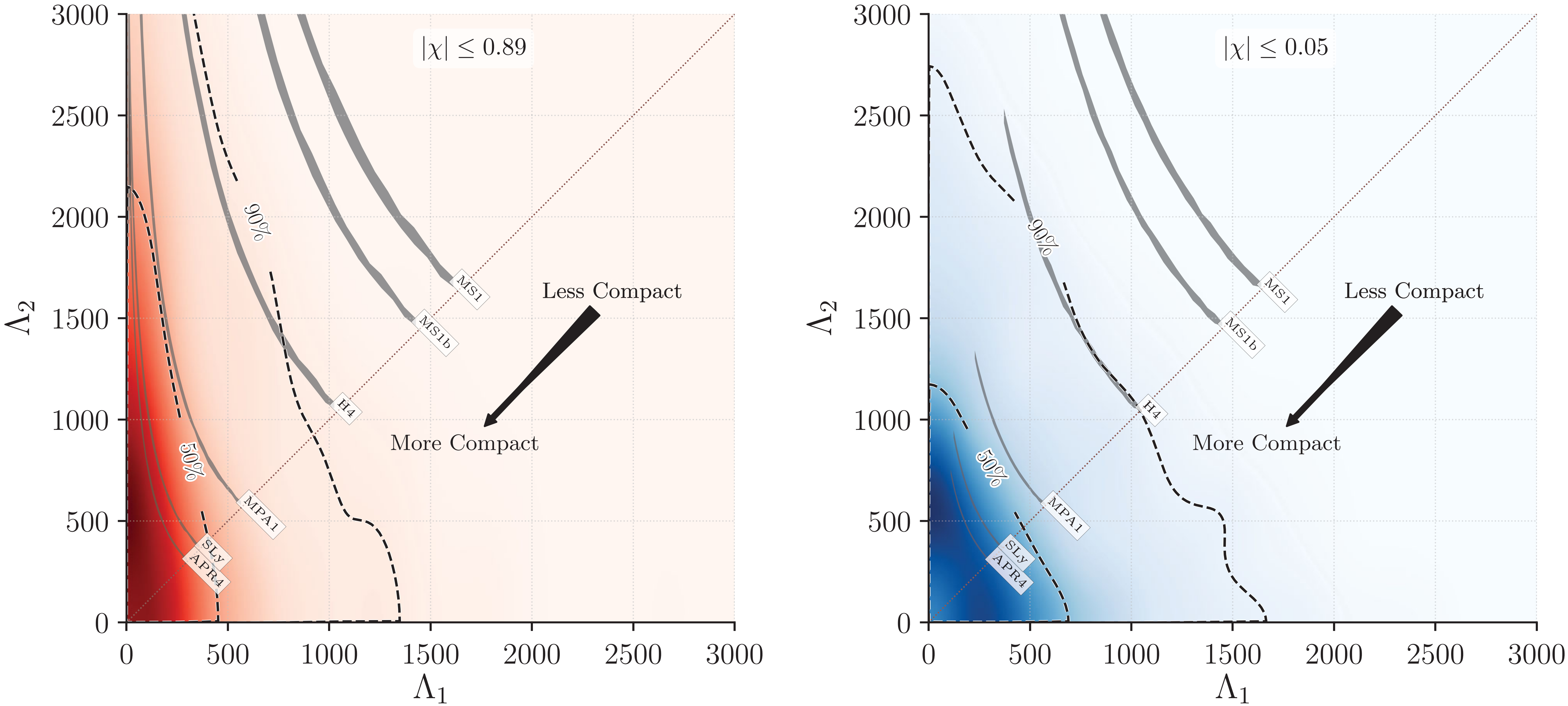
Tidal effects in NS mergers



$$Q_{ij} = -\Lambda_2 \mathcal{E}_{ij}$$

- Part of the orbital energy goes into tidal deformation
- Accelerated inspiral
- Imprinted on the gravitational waves
- Constrains dimensionless tidal parameter $\tilde{\Lambda}_2 = \frac{\Lambda_2}{M^5}$

Constraints from GW170817

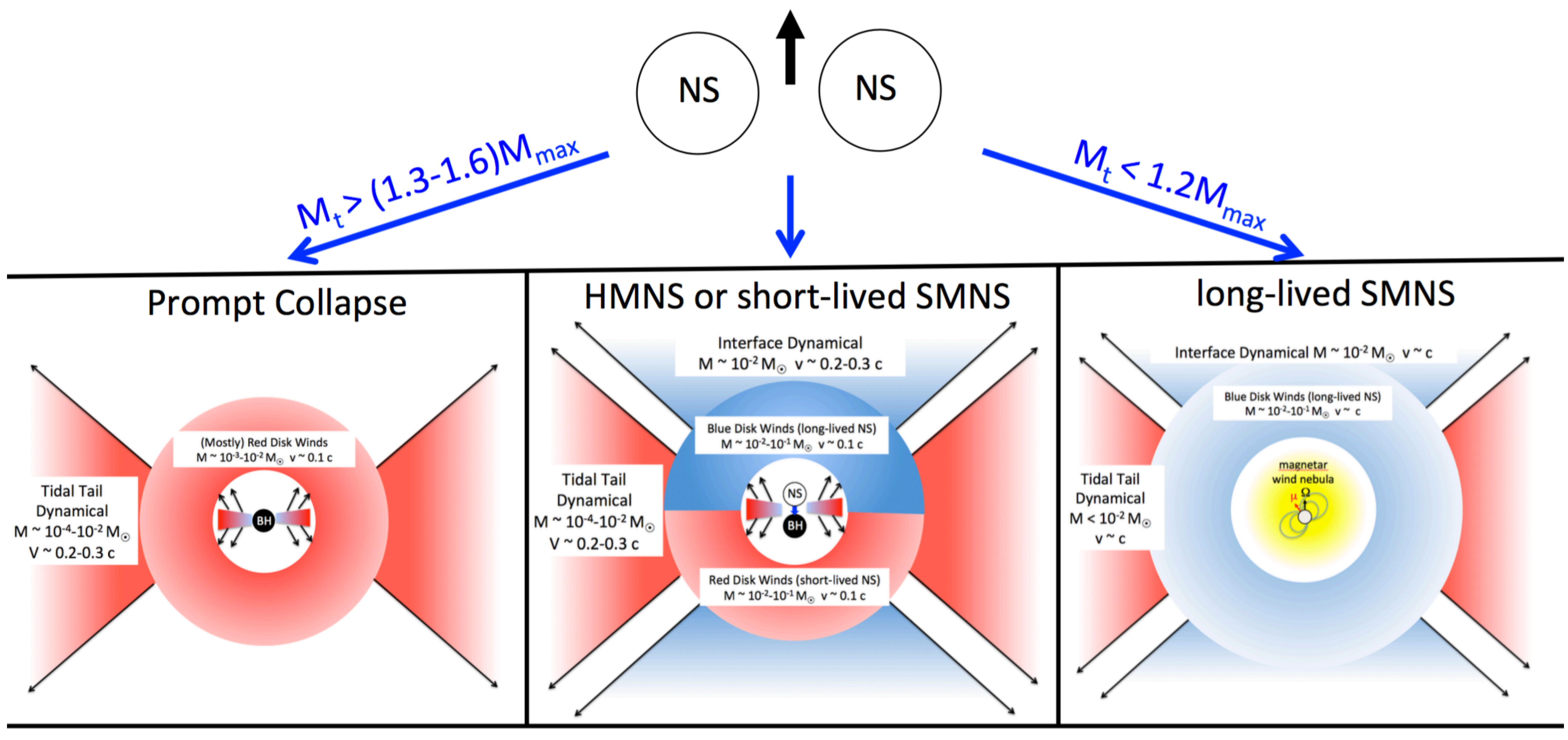


$$\tilde{\Lambda} = \frac{16}{13}\left[\frac{(M_A + 12M_B)M_A^4\tilde{\Lambda}_2^{(A)}}{(M_A+M_B)^5} + (A \leftrightarrow B)\right] \leq 800$$

From LIGO/Virgo collaboration, PRL 119, 161101 (2017)

This is the GW data.
Can we say something more
using the EM data?

Yes, with motivated assumptions



From Margalit & Metzger 2017

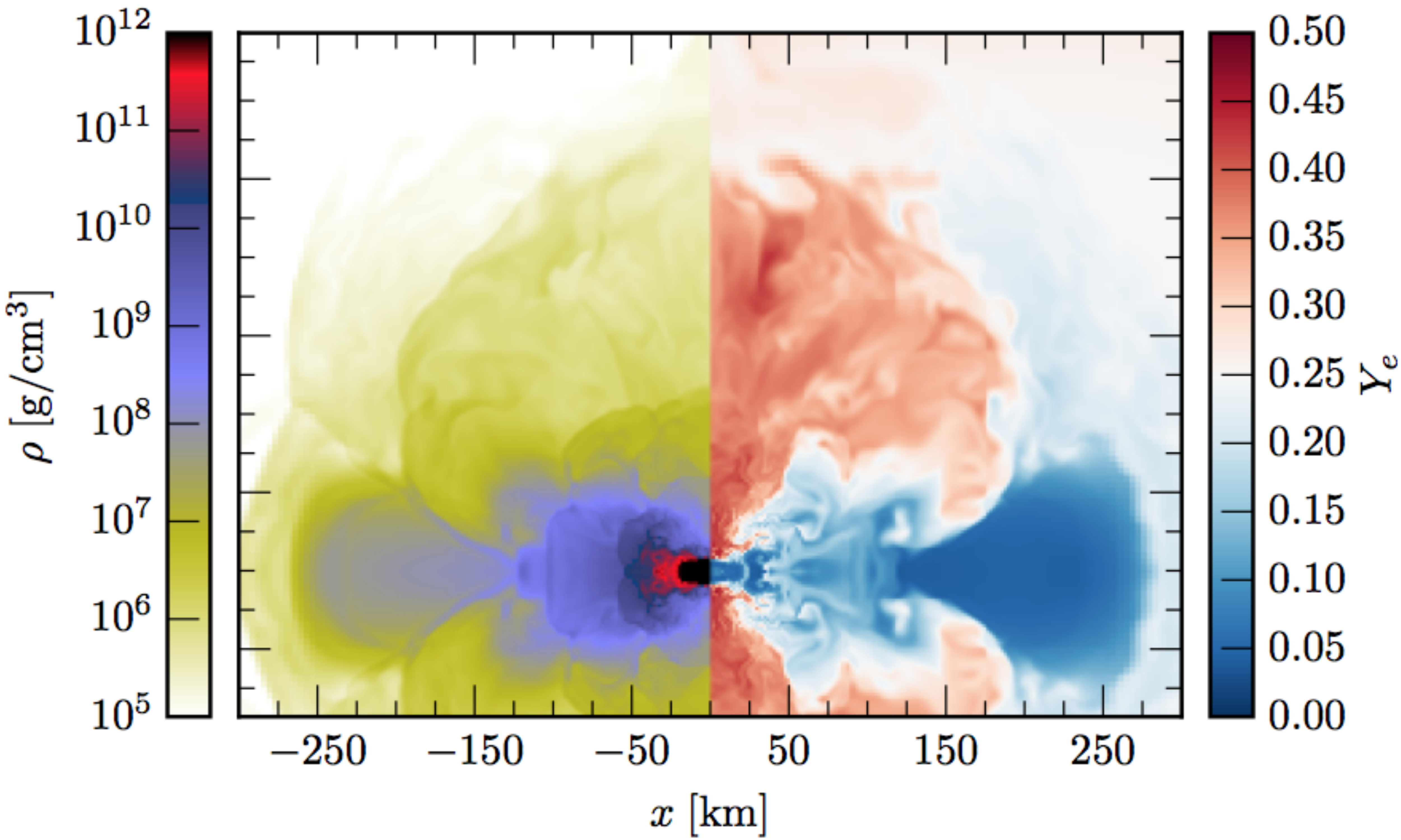
Assumption: no prompt BH formation —> EOS must be stiff enough

Assumption: no stable remnant —> EOS must soft enough

See also Bauswein+, Rezzolla+, Shibata+, Ruiz+ (2017)

Our approach: no assumptions,
use simulations.

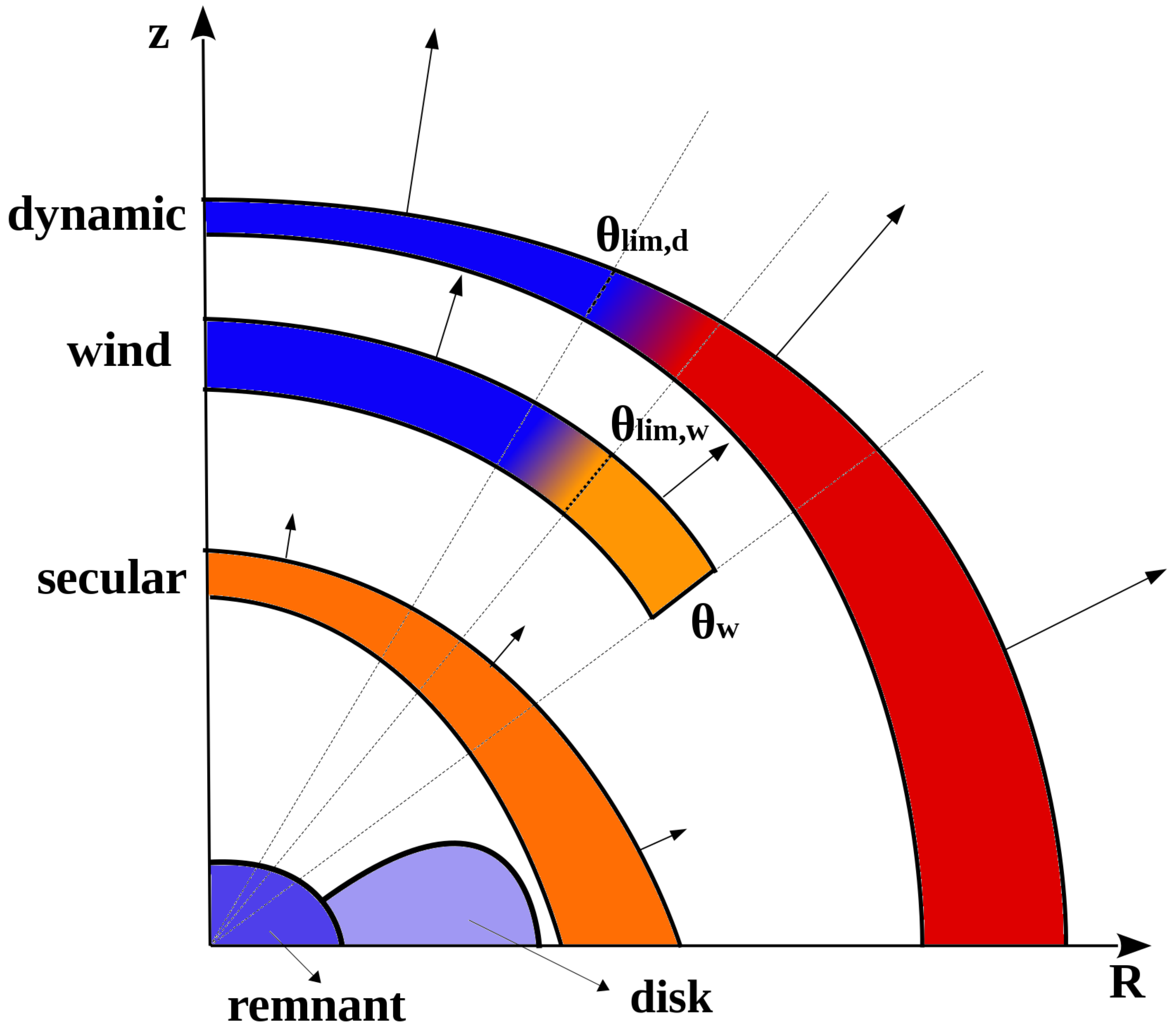
Neutron rich outflows



See also Wanajo+ 2014,
Sekiguchi+ 2015, 2016, Foucart+ 2016

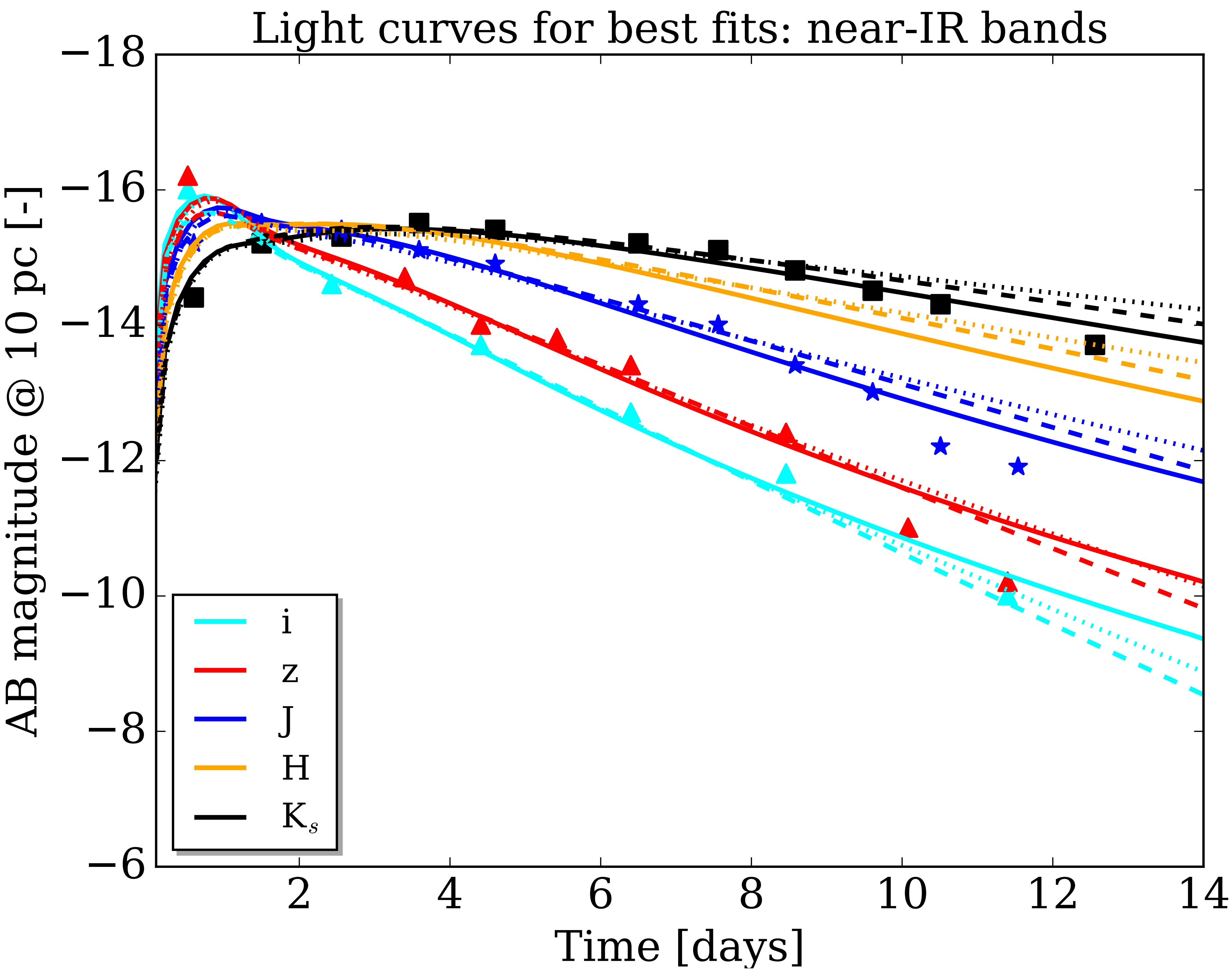
DR, Galeazzi+ MRAS 460:3255 (2016)

Neutron rich outflows



Perego, **DR**, Bernuzzi, arXiv:1711.03982

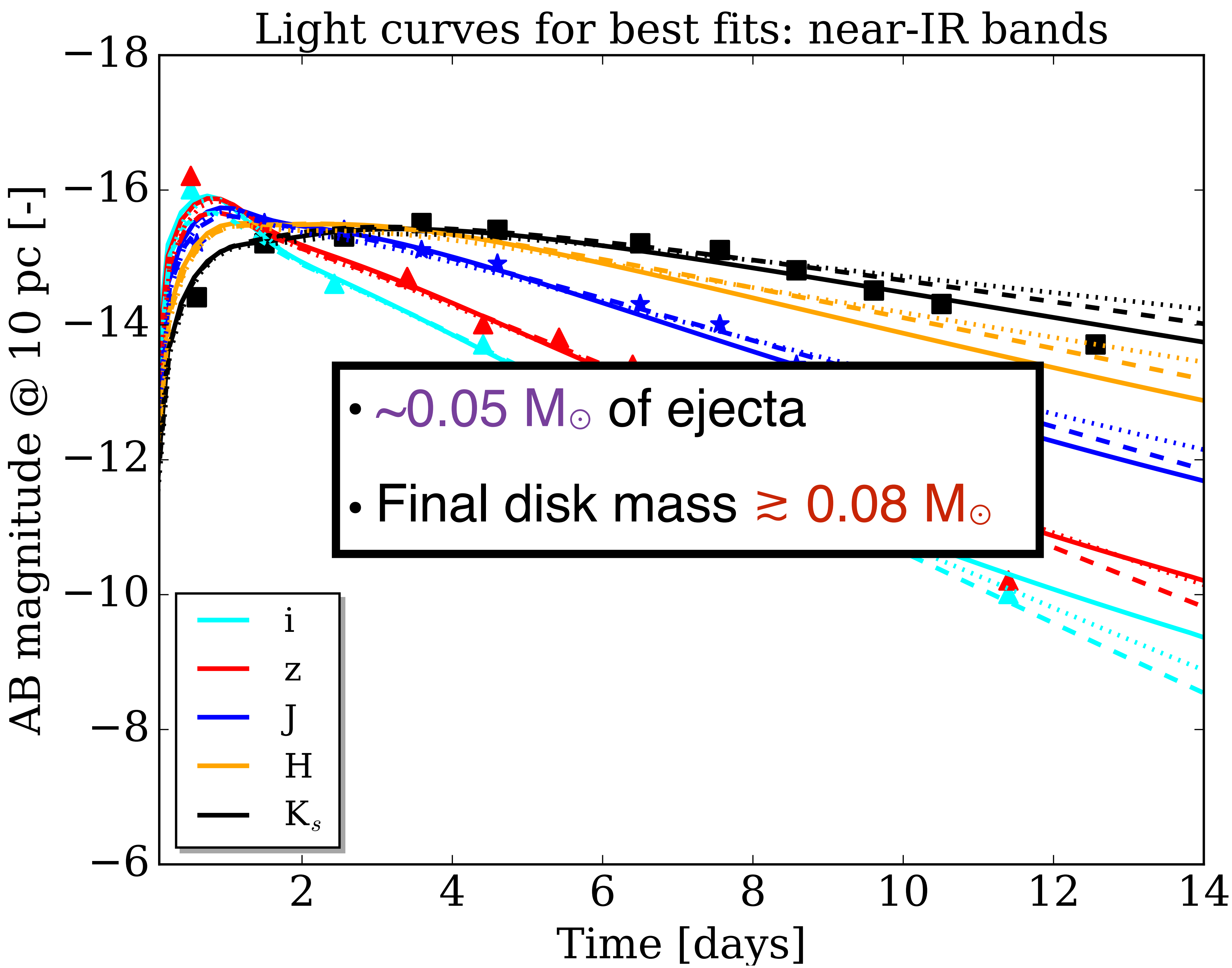
Kilonova modeling



See also: Chornock et al. 2017; Cowperthwaite et al. 2017; Drout et al. 2017; Nicholl et al. 2017; Rosswog et al. 2017; Tanaka et al. 2017; Tanvir et al. 2017; Villar et al. 2017

Perego, **DR**, Bernuzzi, arXiv:1711.03982

Kilonova modeling



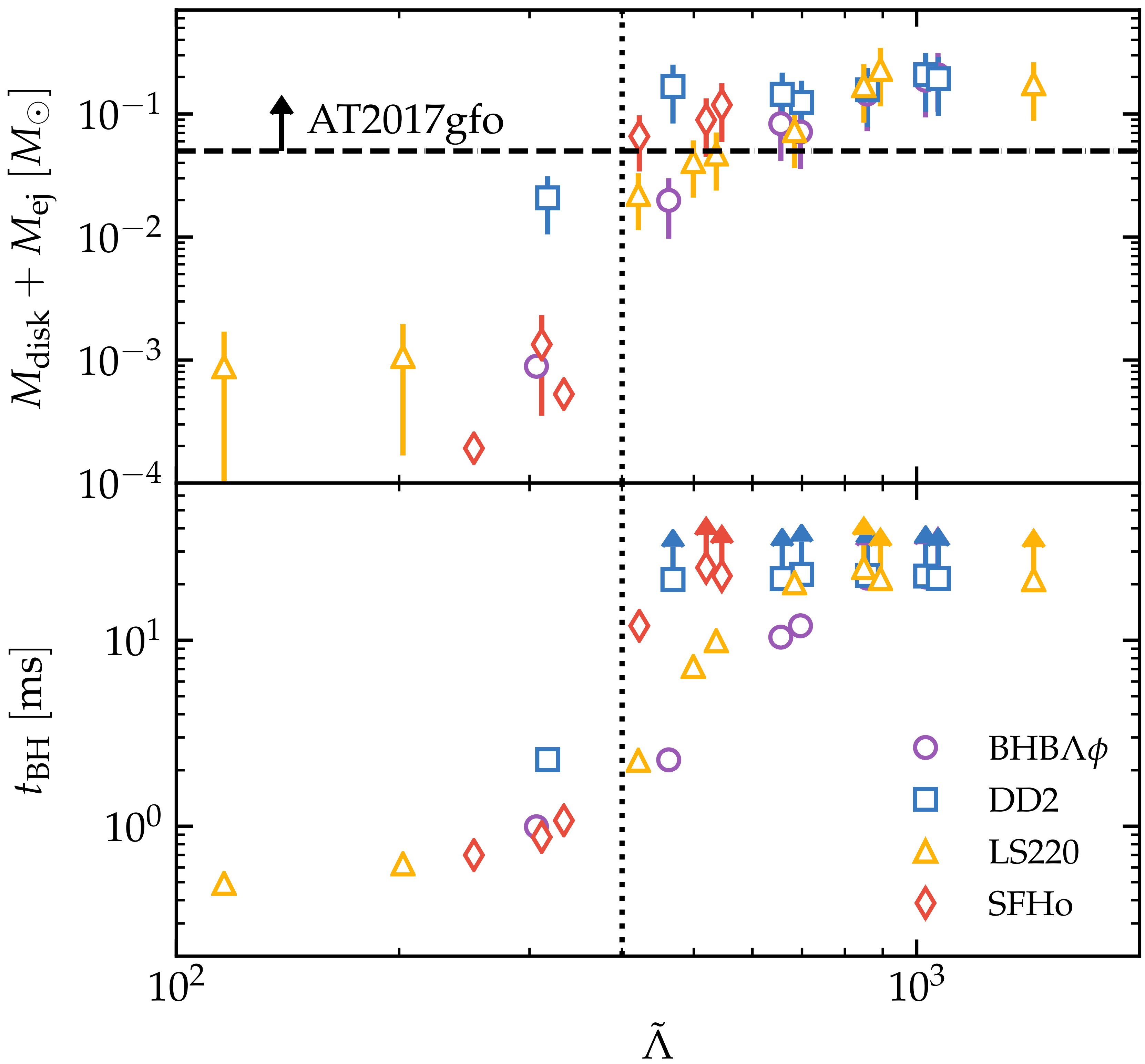
• ~0.05 M☉ of ejecta

• Final disk mass ≳ 0.08 M☉

Many other papers!

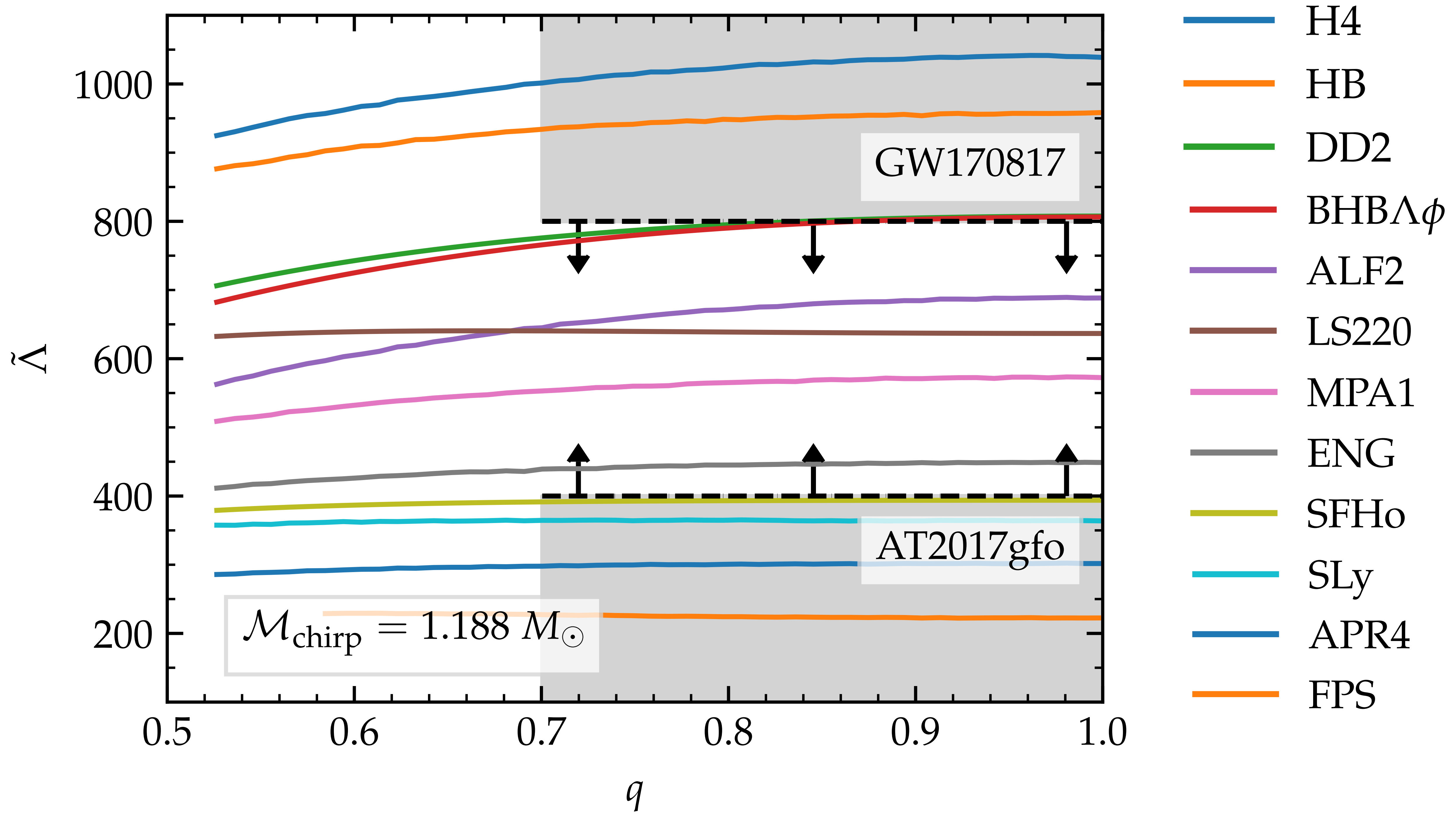
Perego, **DR**, Bernuzzi (2017)

Simulation results



Perego, **DR**, Bernuzzi, arXiv:1711.03982

NS EOS constraint



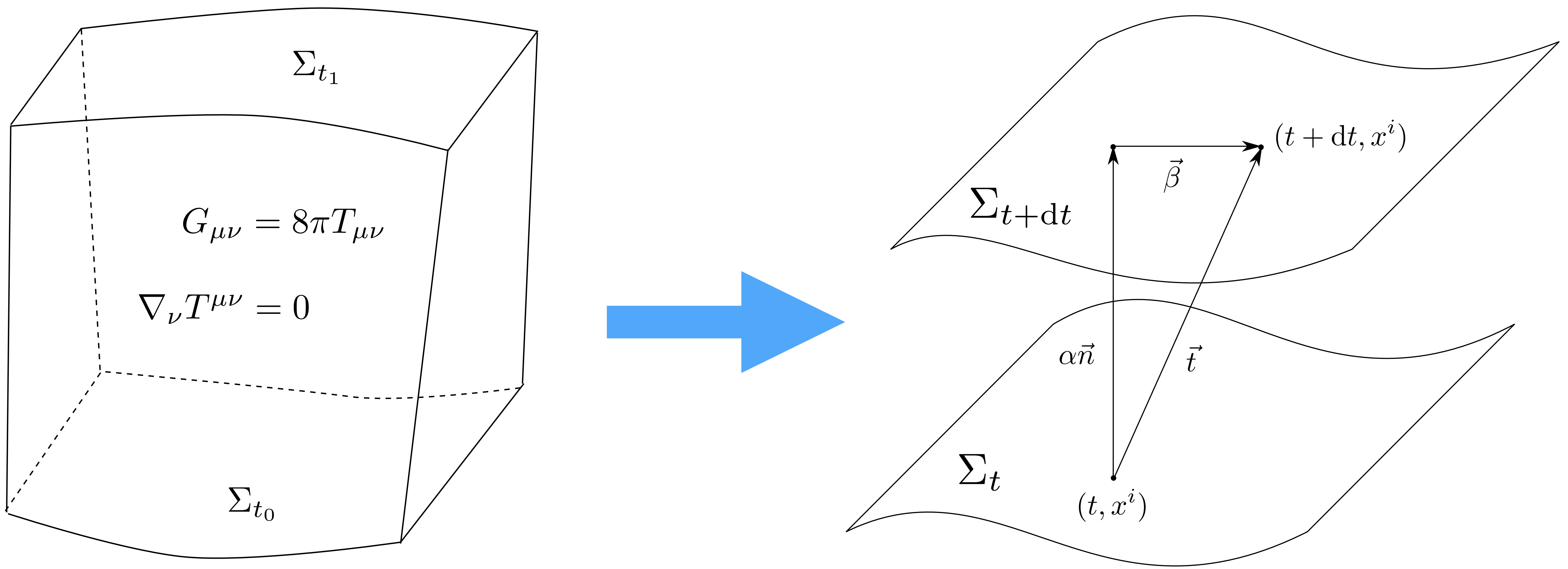
Perego, **DR**, Bernuzzi, arXiv:1711.03982

Back to PBH+NS.
Can numerical relativity be as successful here?

Technical challenges

- Need to handle dynamical spacetimes with singularities
- A 0.01 $M_\odot$ PBH is ~300 times smaller than a NS
- PBH dynamical time is also ~300 times faster!
- Our approach: use deeply nested AMR. Resolution for the PBH up to 2^{15} (= 32,768) times finer than on base grid.
- Start with 2 $M_\odot$ NS and a 2 $M_\odot$ PBH and decrease PBH mass. Currently running 0.03215 $M_\odot$.

3+1 formalism



- Dynamically adjusted spacetime foliation
- Solve Cauchy problem

BSSN formulation

Baumgarte, Shapiro, Shibata, and Nakamura

PHYSICAL REVIEW D VOLUME 52, NUMBER 10 15 NOVEMBER 1995

Evolution of three-dimensional gravitational waves: Harmonic slicing case

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(Received 7 April 1995)

PHYSICAL REVIEW D, VOLUME 59, 024007

Numerical integration of Einstein's field equations

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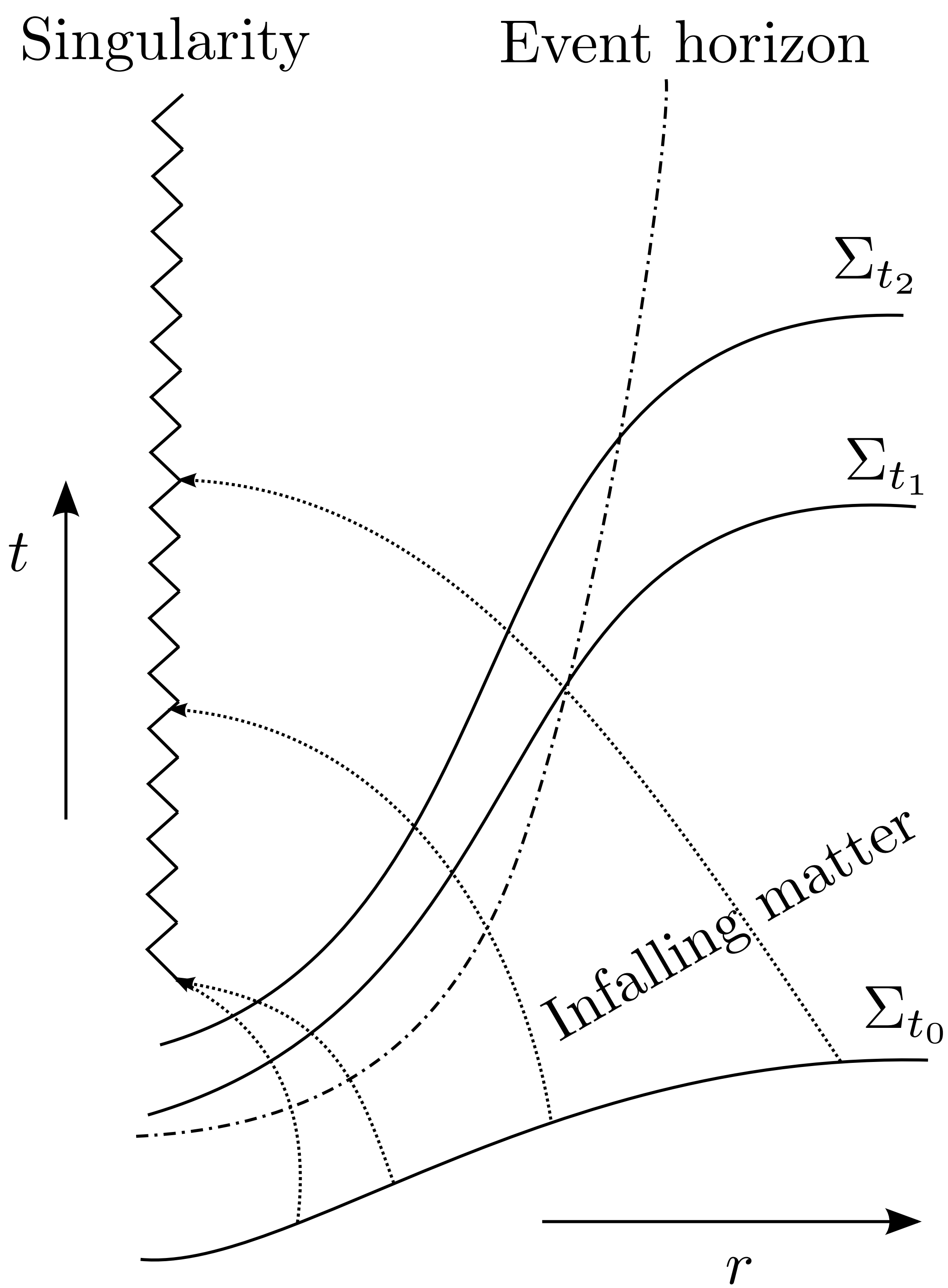
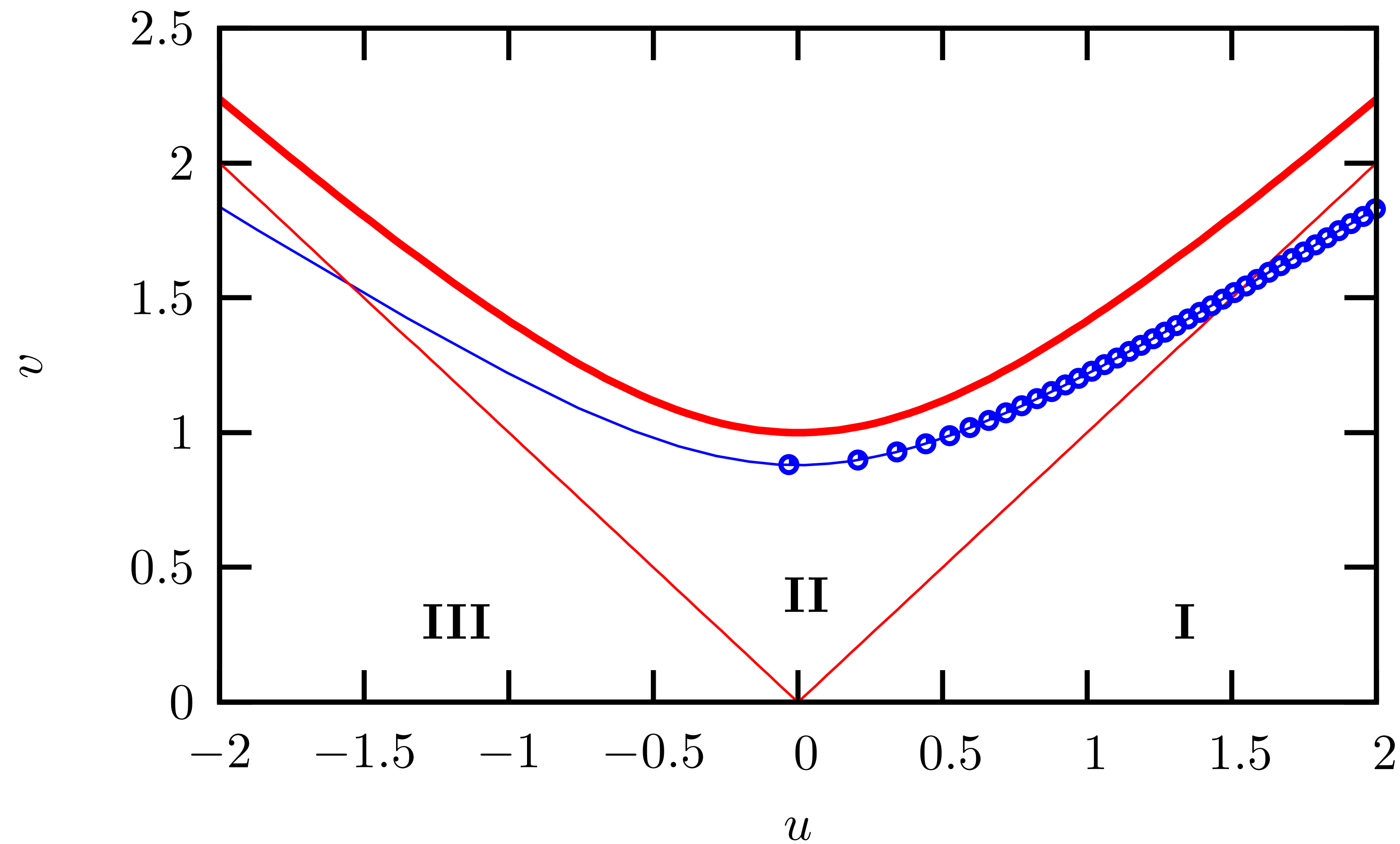
(Received 1 July 1998; published 7 December 1998)

Gauge conditions: punctures



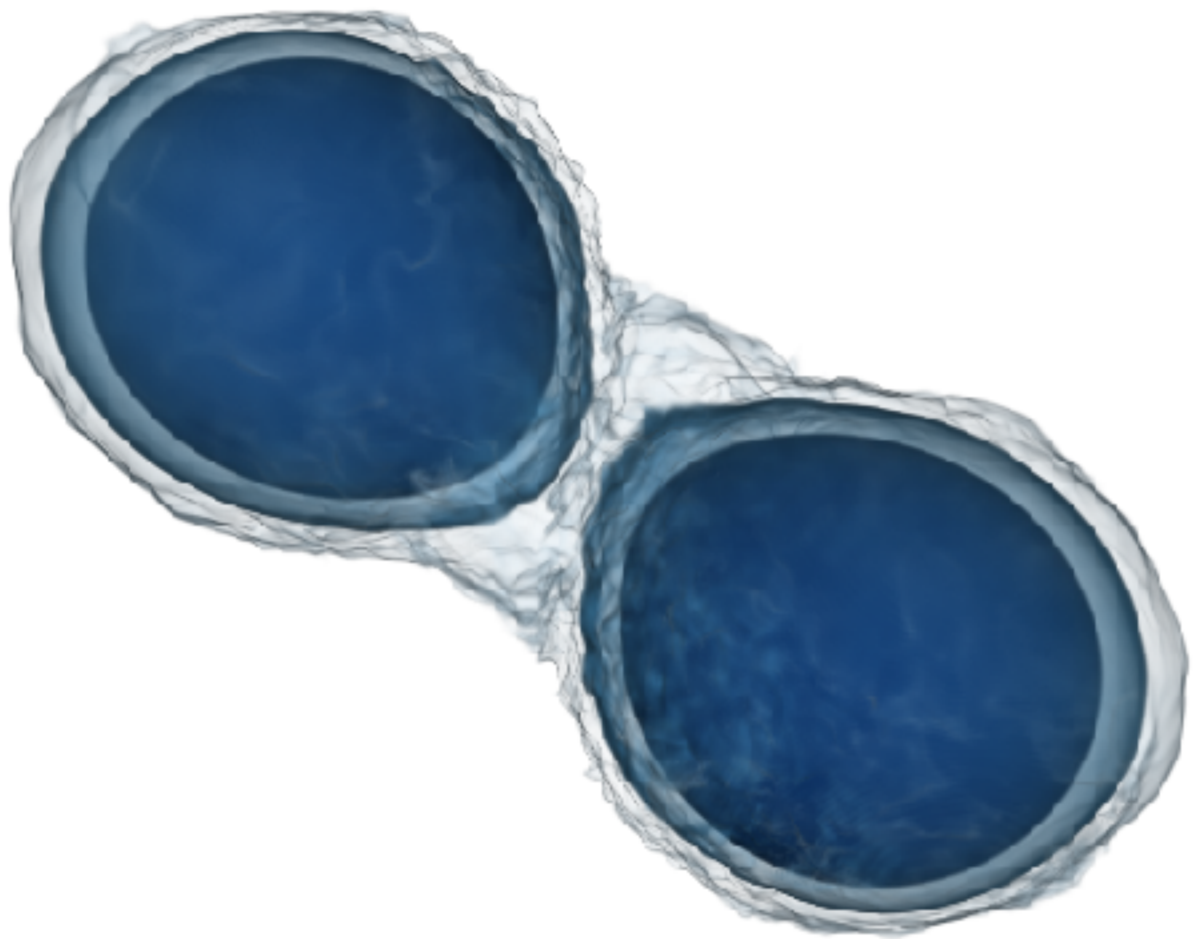


From Brown, Phys. Rev. D77:044018 (2008)

- Singularity avoidance
- Non-stationary evolution

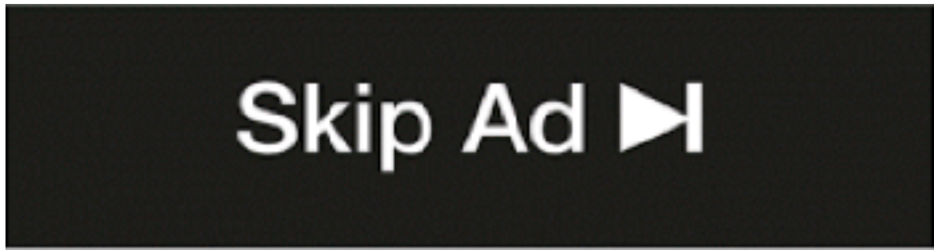
WhiskyTHC

http://www.astro.princeton.edu/~dradice/whiskythc.html

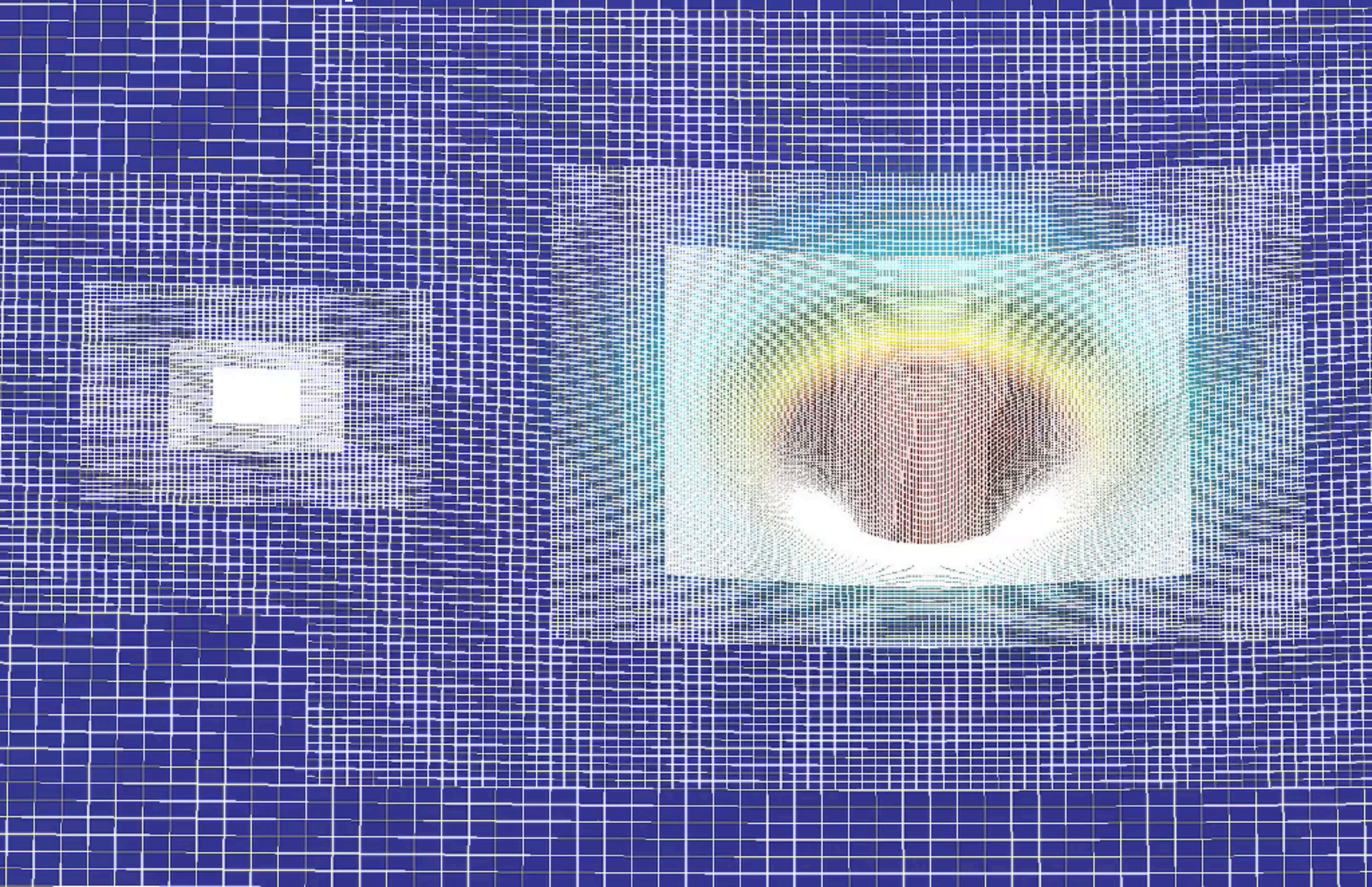


- Full-GR, dynamical spacetime
- Nuclear EOS
- Effective neutrino treatment
- High-order hydrodynamics
- Open source!

THC: Templated Hydrodynamics Code

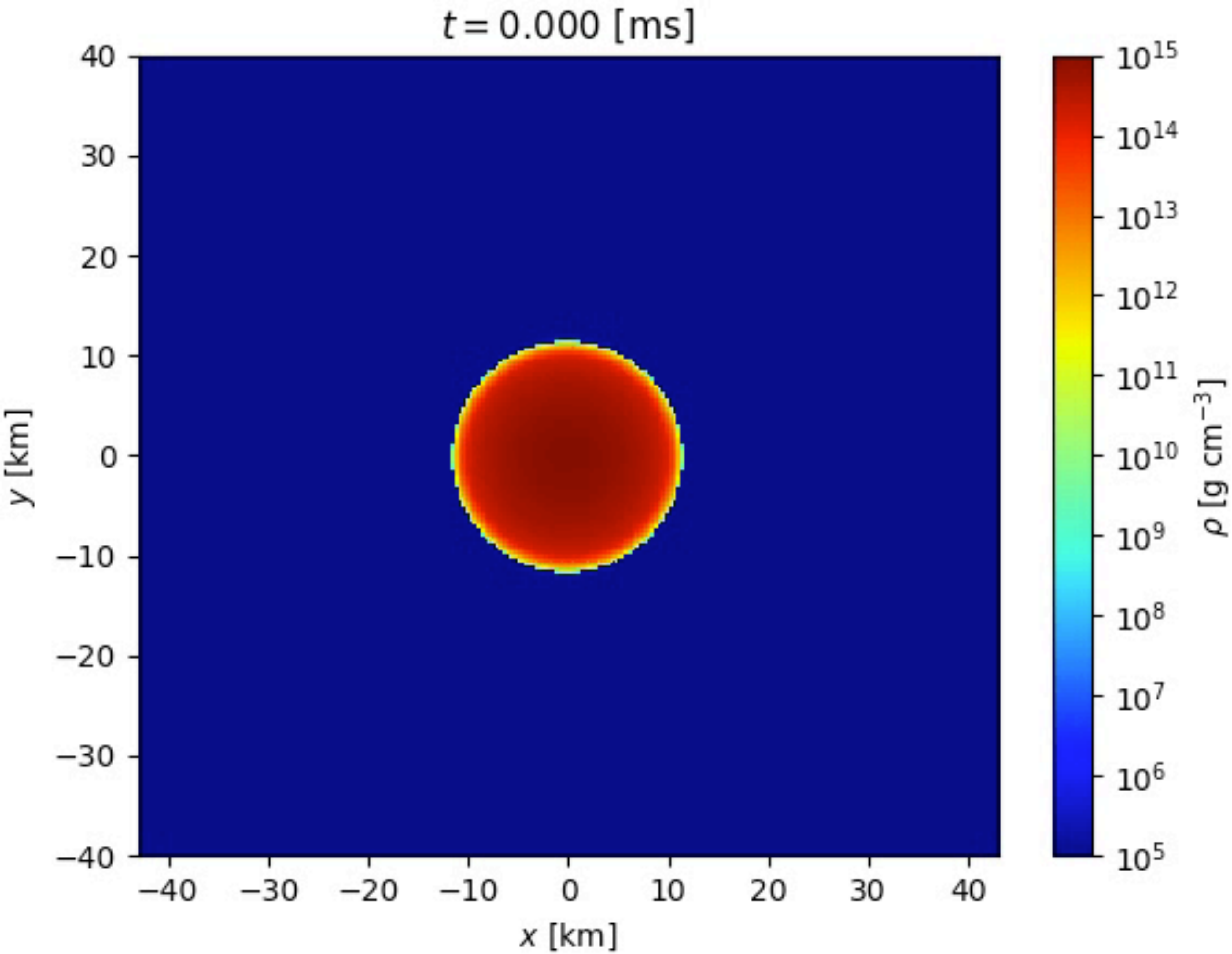


Adaptive mesh refinement



Preliminary results

PBH+NS: M = 2 M⊙


$t = 0.000$ [ms]
40
30
20
10
0
−10
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y [km]
−40
−30
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−10
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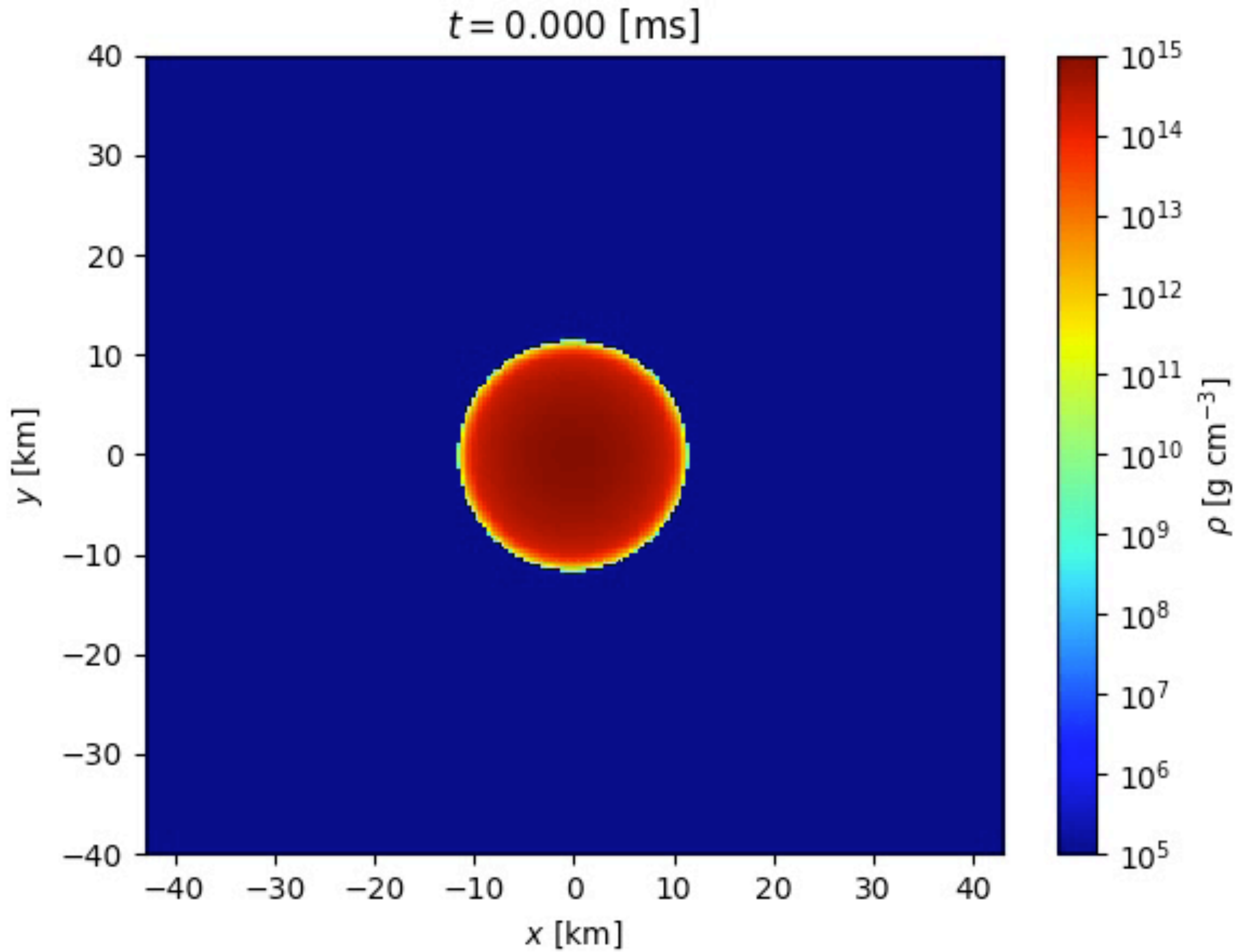
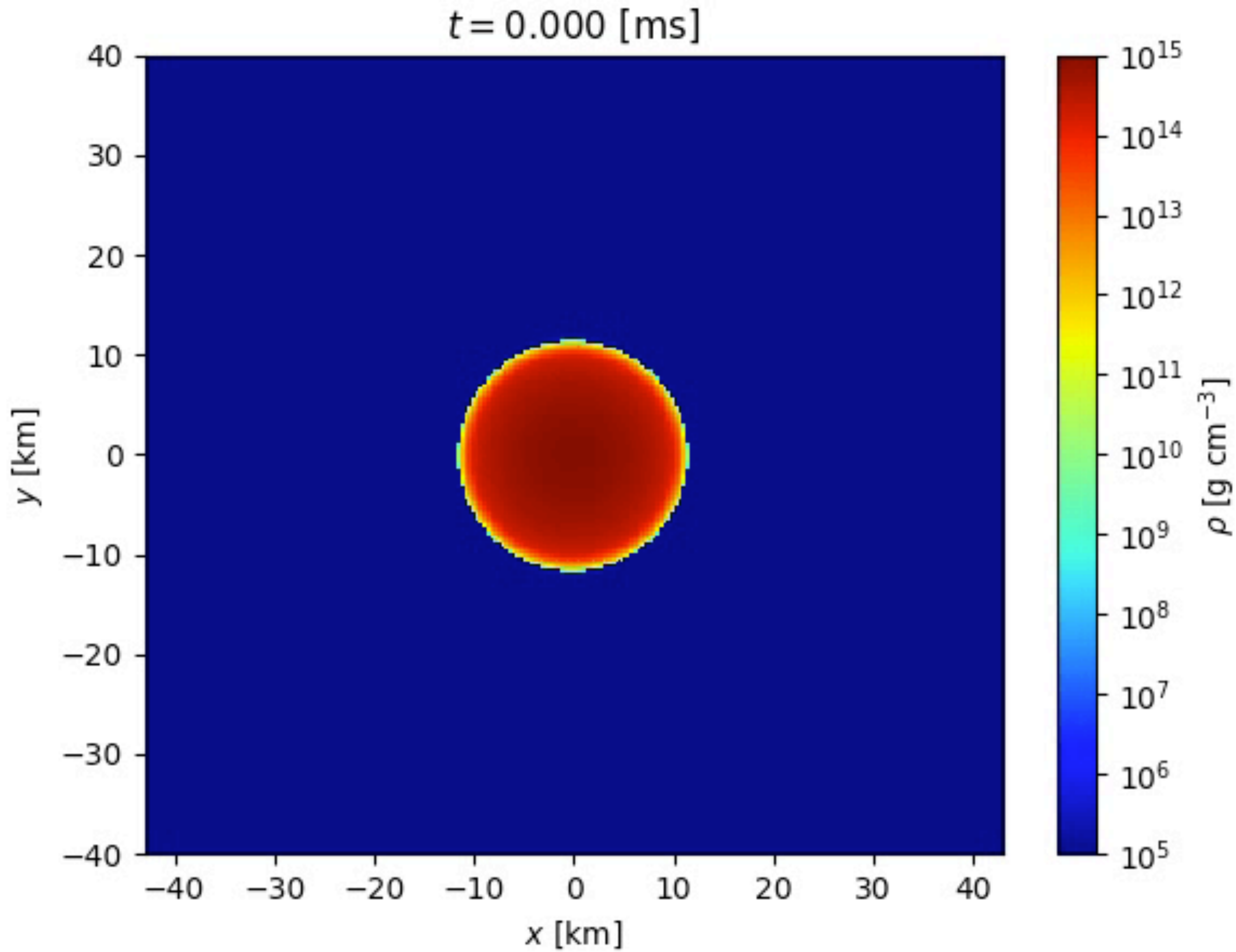
x [km]
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
ρ [g cm^{-3}]

PBH+NS: M = 0.125 $M_\odot$



PBH+NS: M = 0.0625 $M_\odot$



Conclusions & outlook

- Numerical relativity is a powerful tool for multimessenger astronomy
- The implosion of NS by PBH can produce a substantial amount of r-process material
- Expect a slowly evolving red kilonova