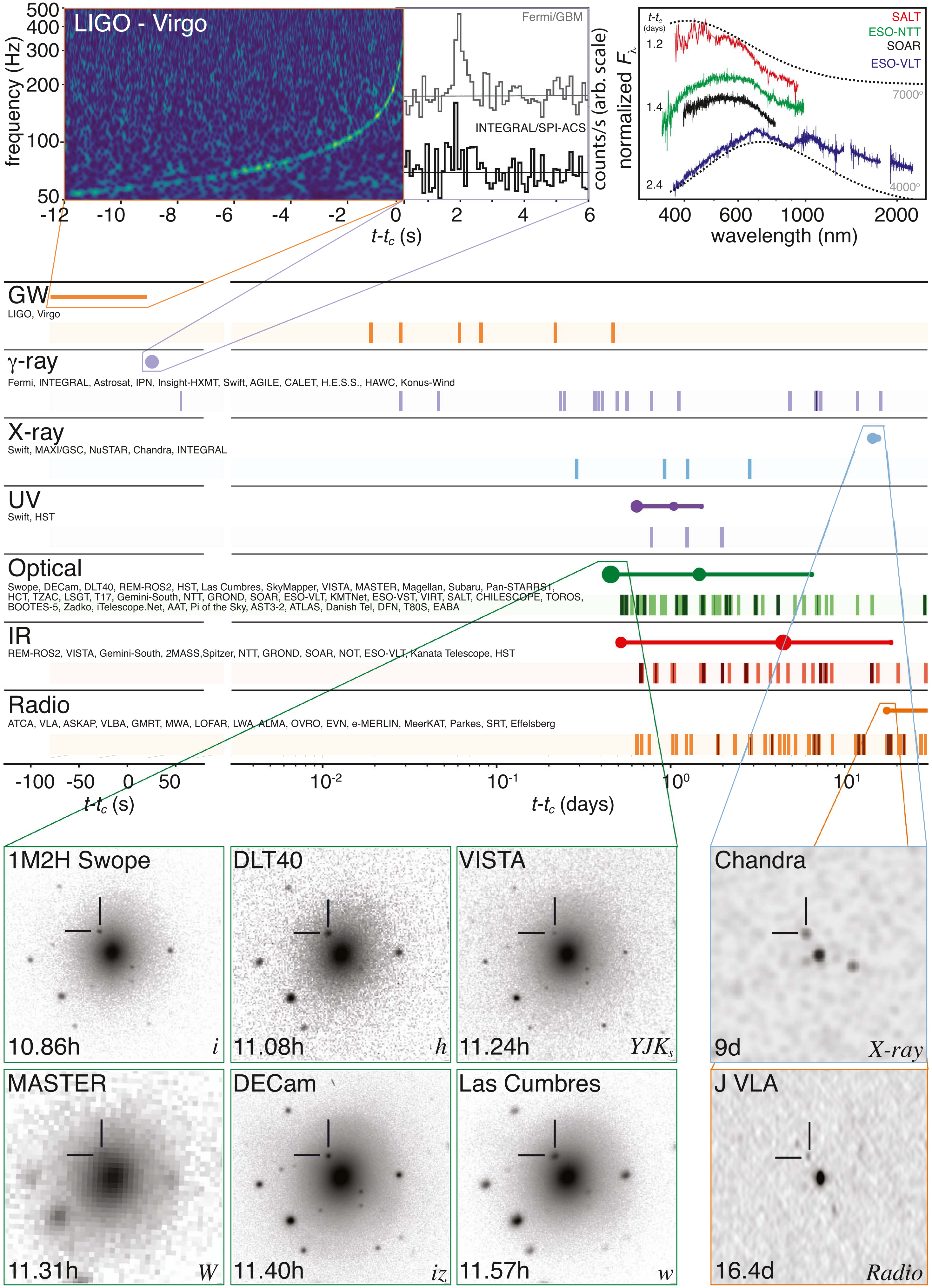
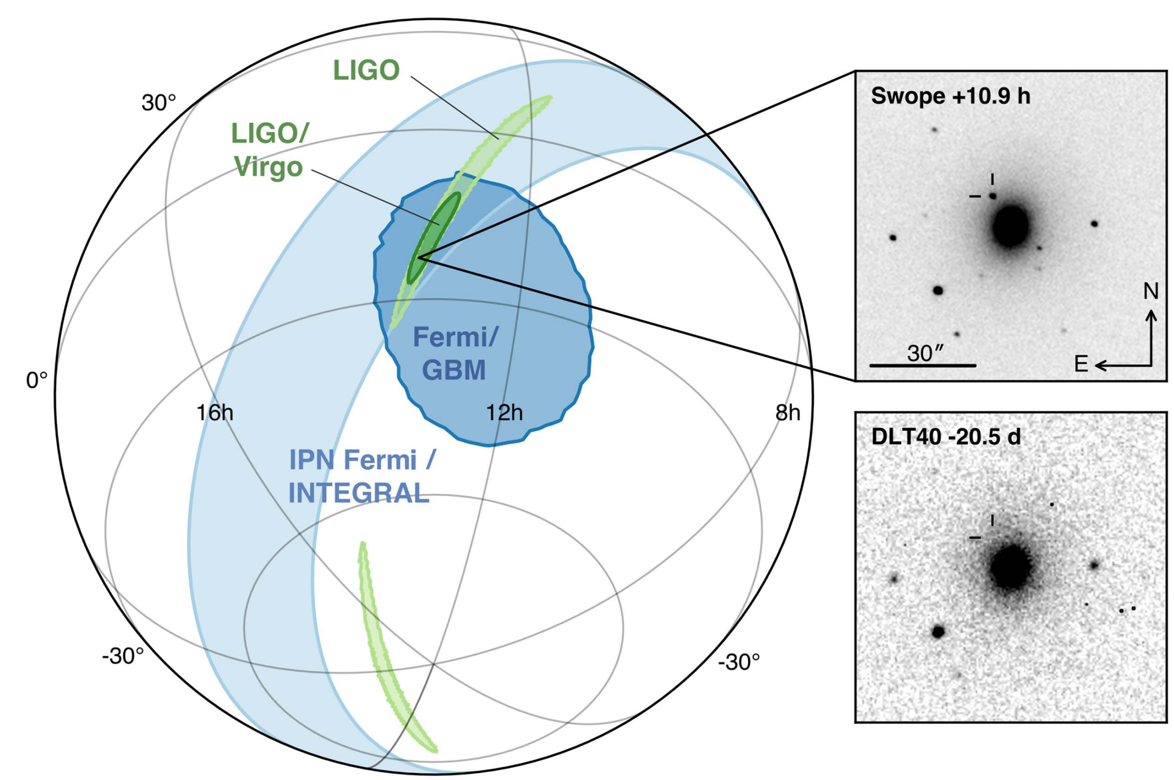
Discovery of gravitational waves and light from merging neutron stars: implications and open questions

David Radice[1,2]

[1] Research Associate, Princeton University
[2] Taplin Member, Institute for Advanced Study

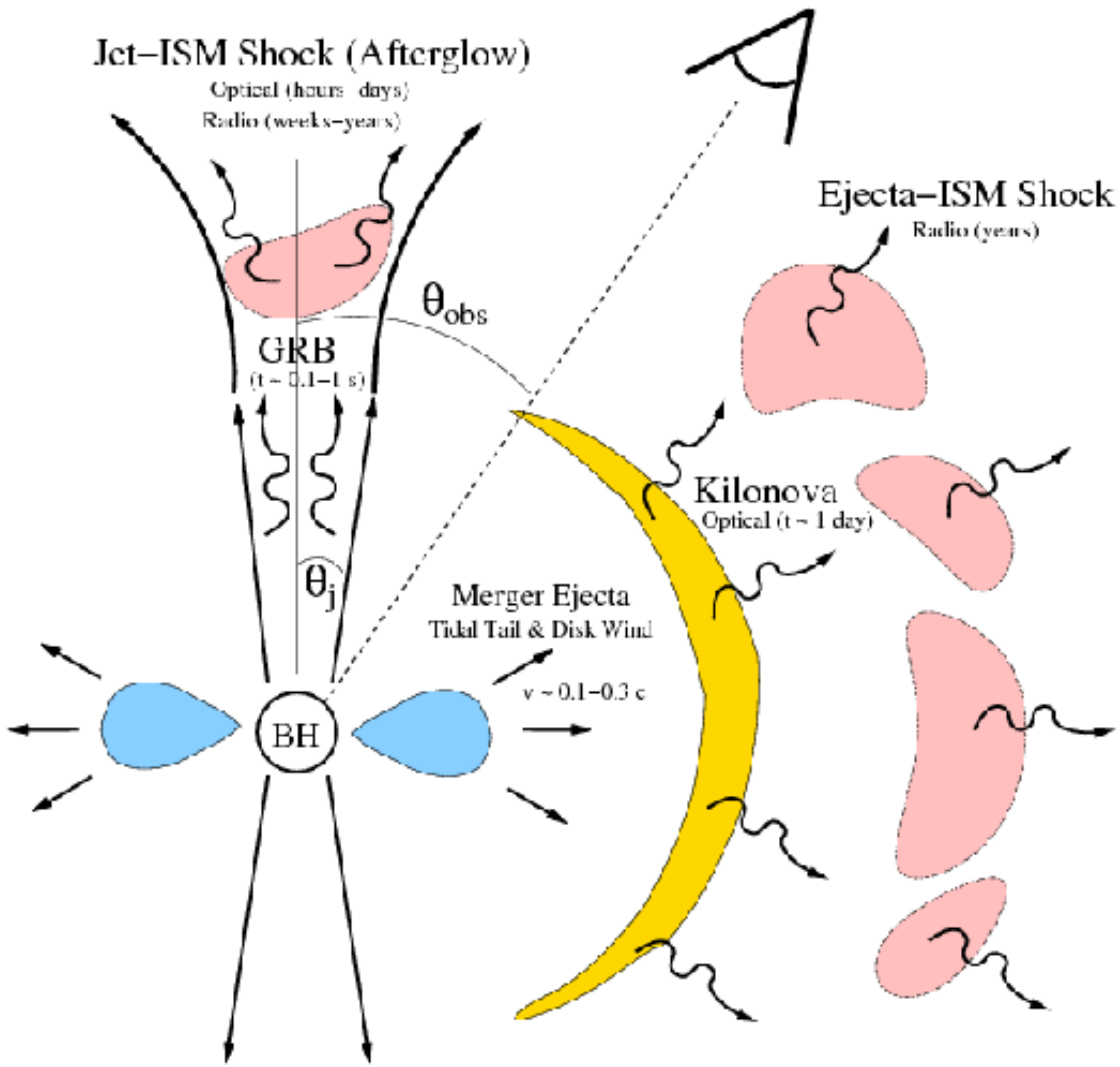
Neutron star mergers for non-experts:
GW170817 in the multi-messenger astronomy and FRIB eras





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)

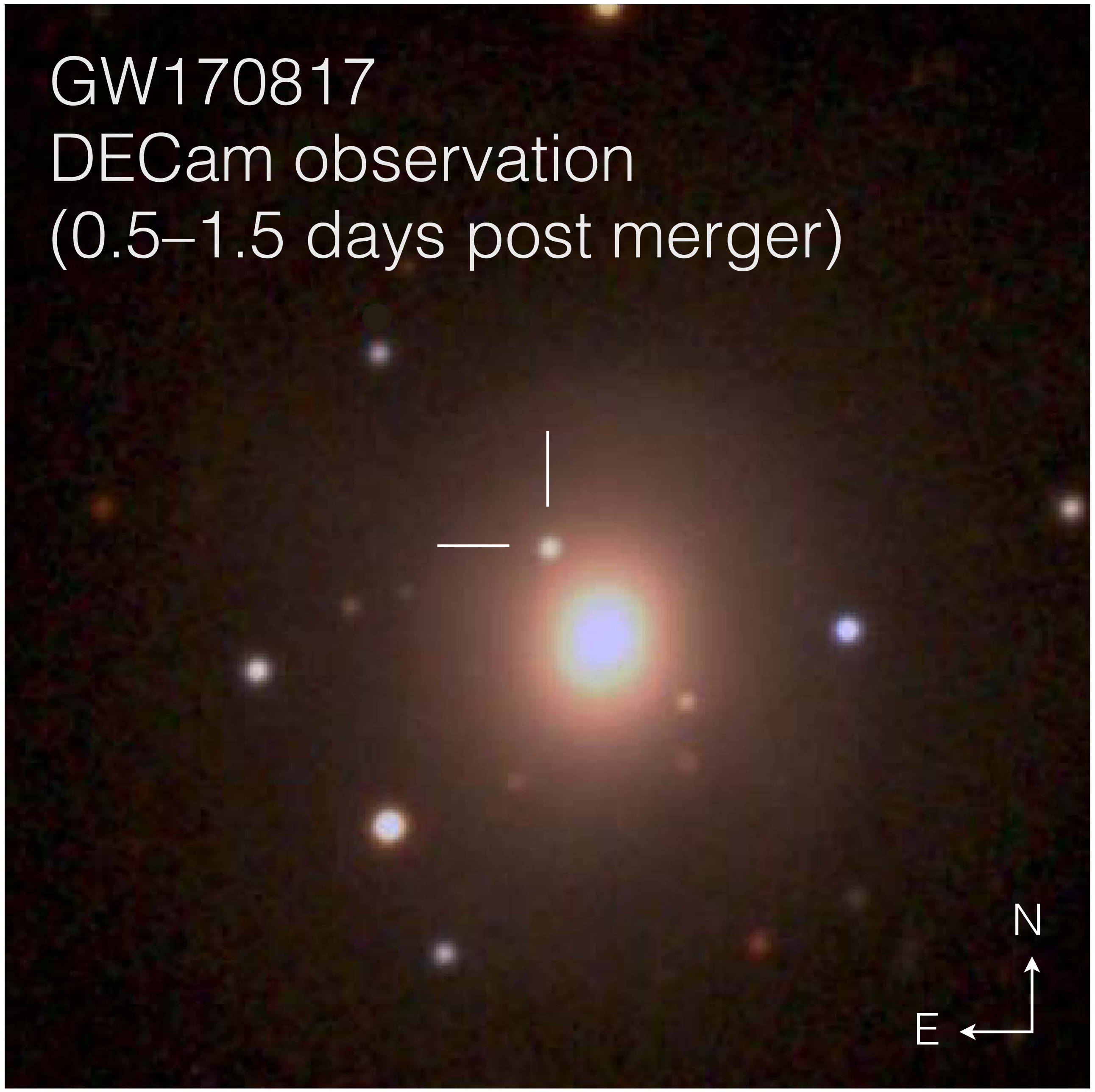
What happened?

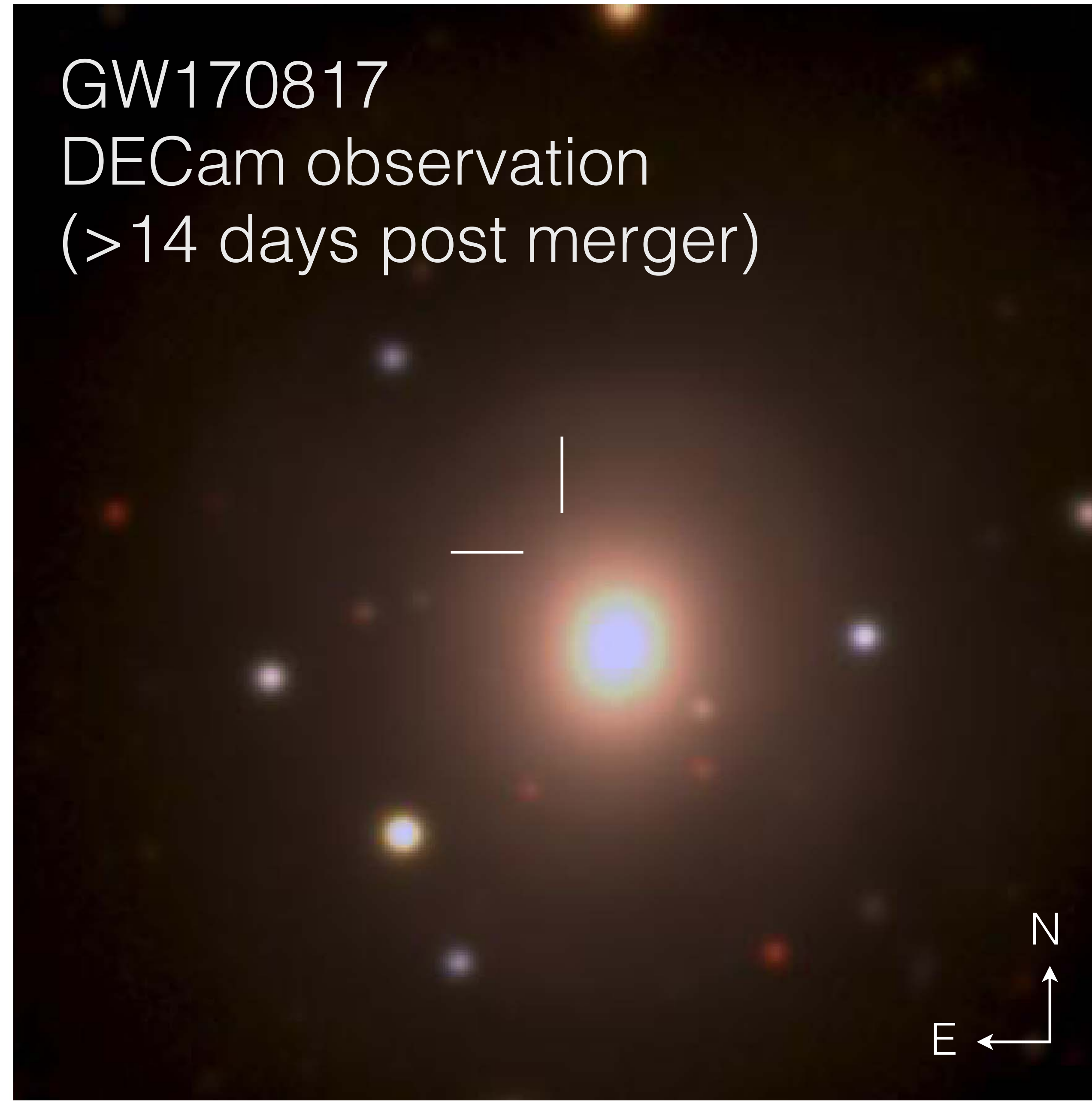


From Metzger & Berger 2012

- Fate of the remnant unknown, but likely a BH
- A short gamma-ray burst was launched. How?
- Synchrotron emission at late times: radio to X-ray Cocoon? Structured jet?
- Radioactive of neutron rich ejecta powers (~0.05 $M_\odot$ of ejecta) UV/optical/infrared

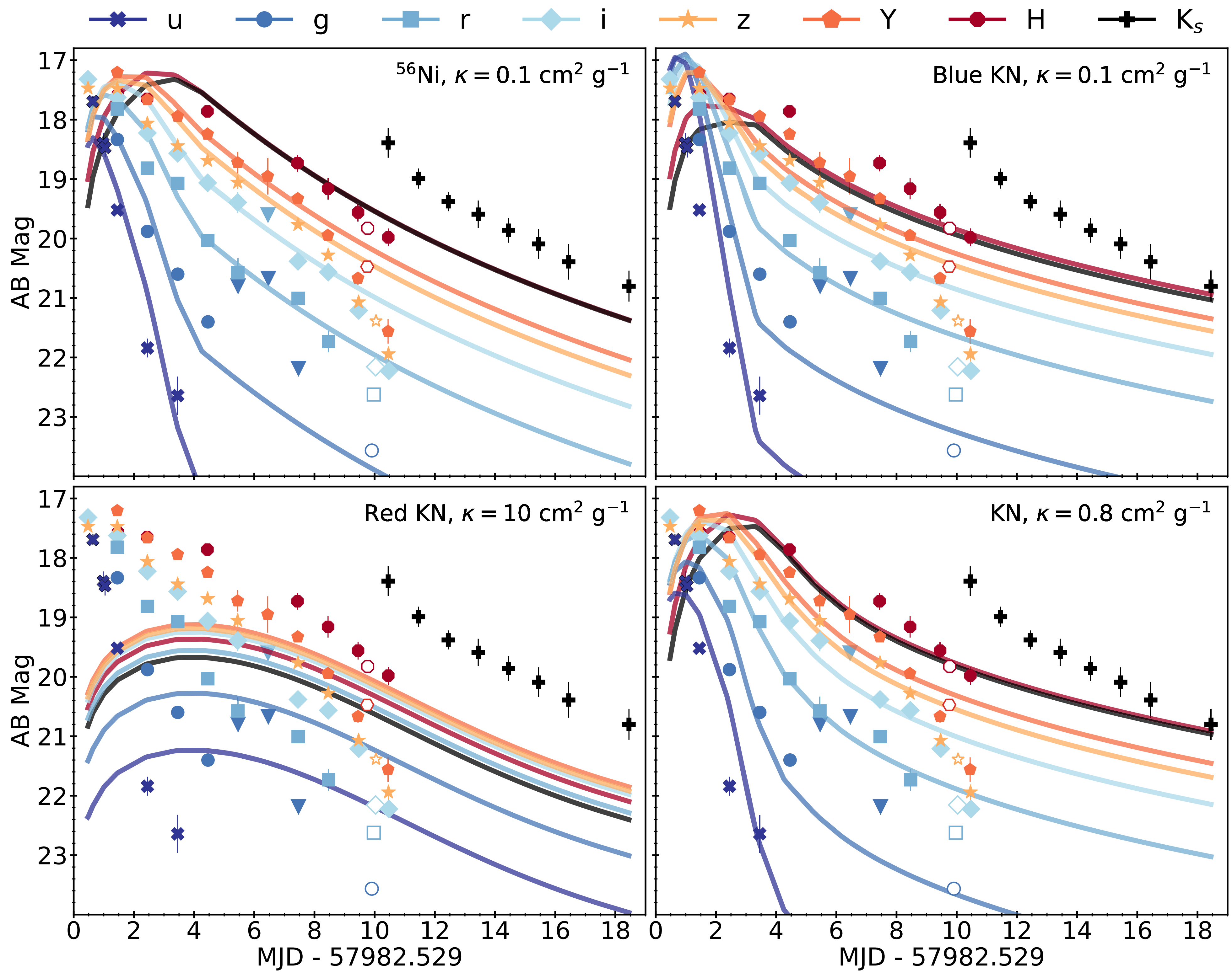
UVOIR





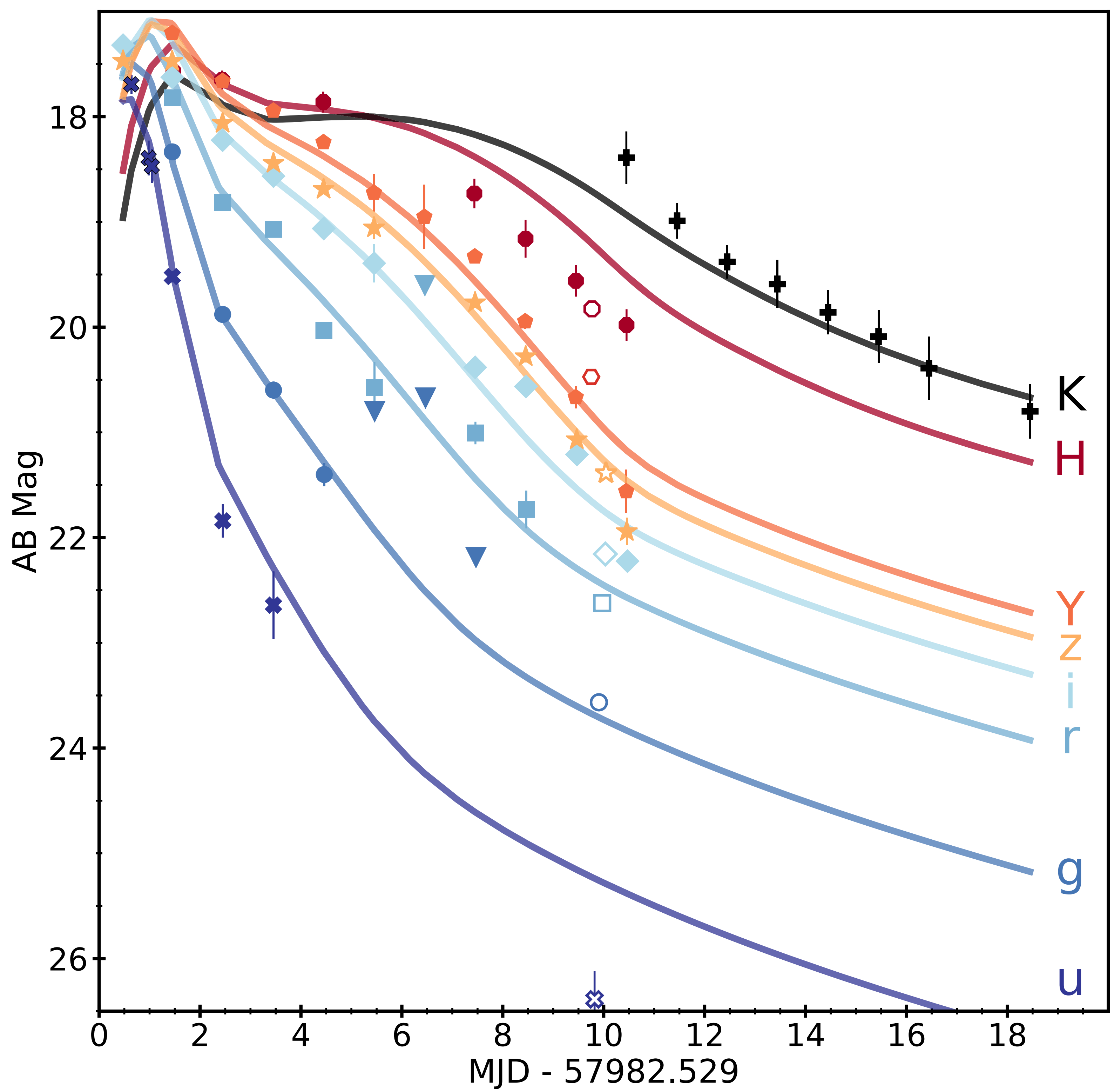
From Soares-Santos et al., ApJL 848:L16 (2017)

Multiple components!



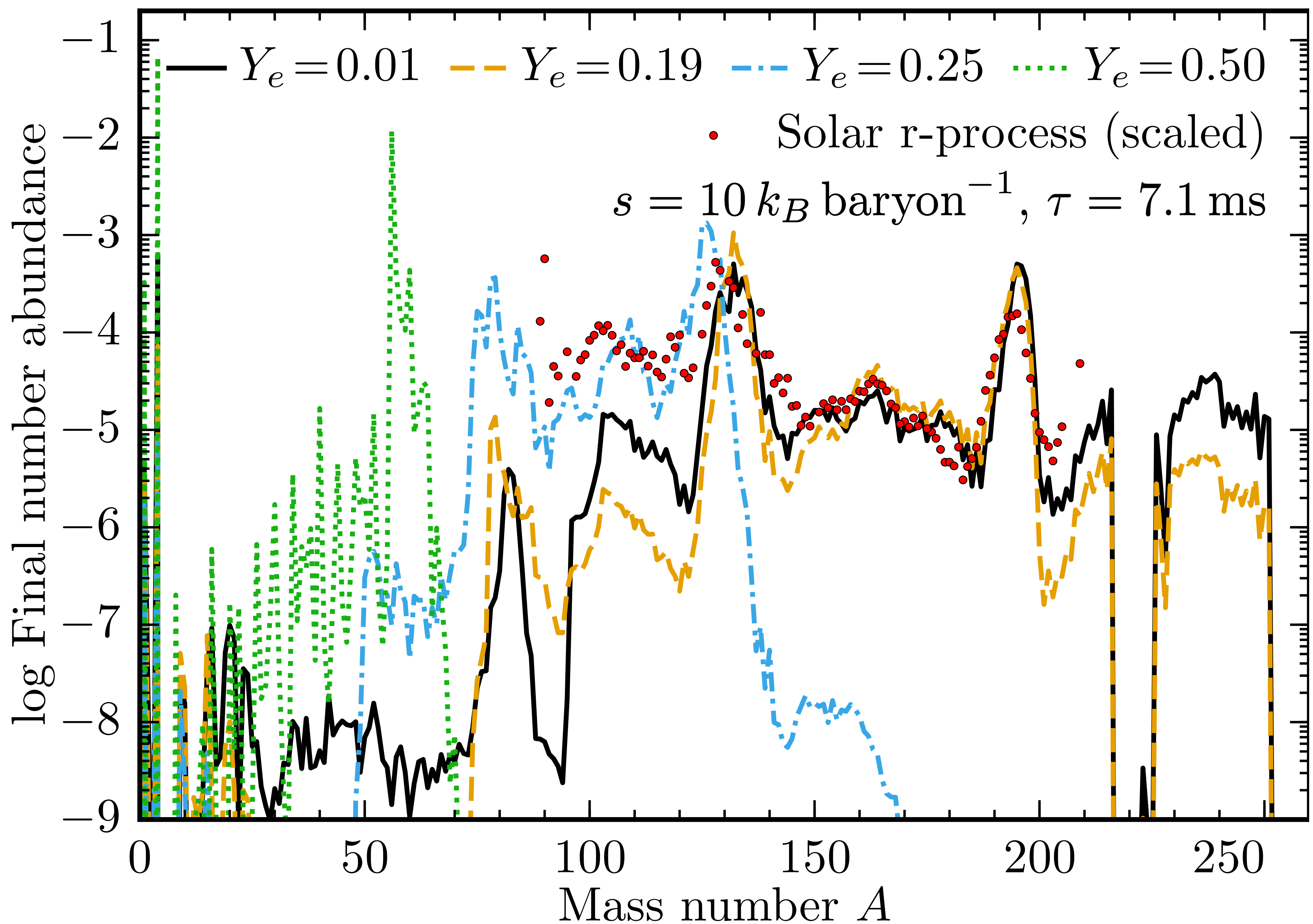
From Cowperthwaite et al., ApJL 848:L17 (2017)

Multiple components!



From Cowperthwaite et al., ApJL 848:L17 (2017)

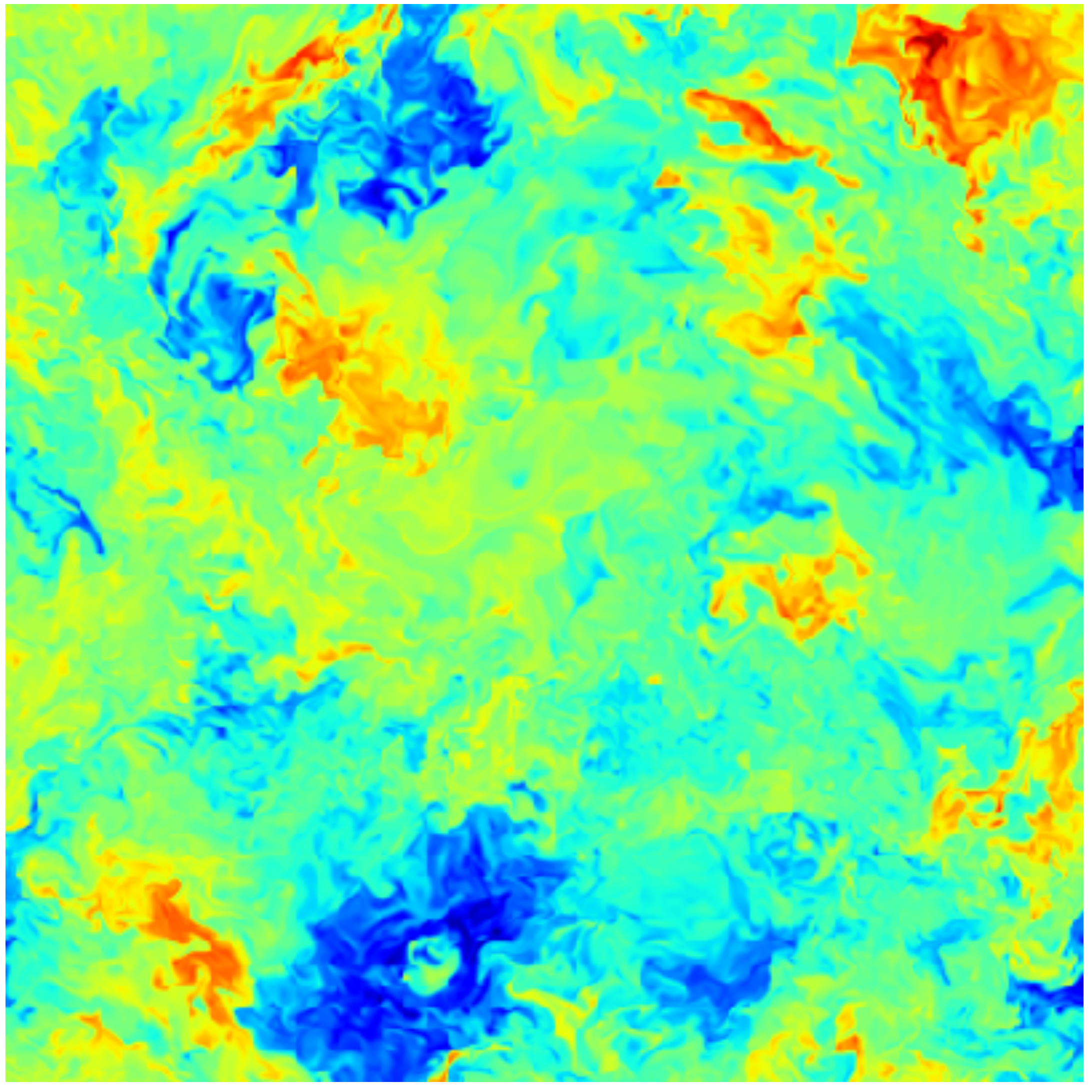
Strong and weak r-process



From Lippuner & Roberts, ApJ 815:82 (2015)

WhiskyTHC

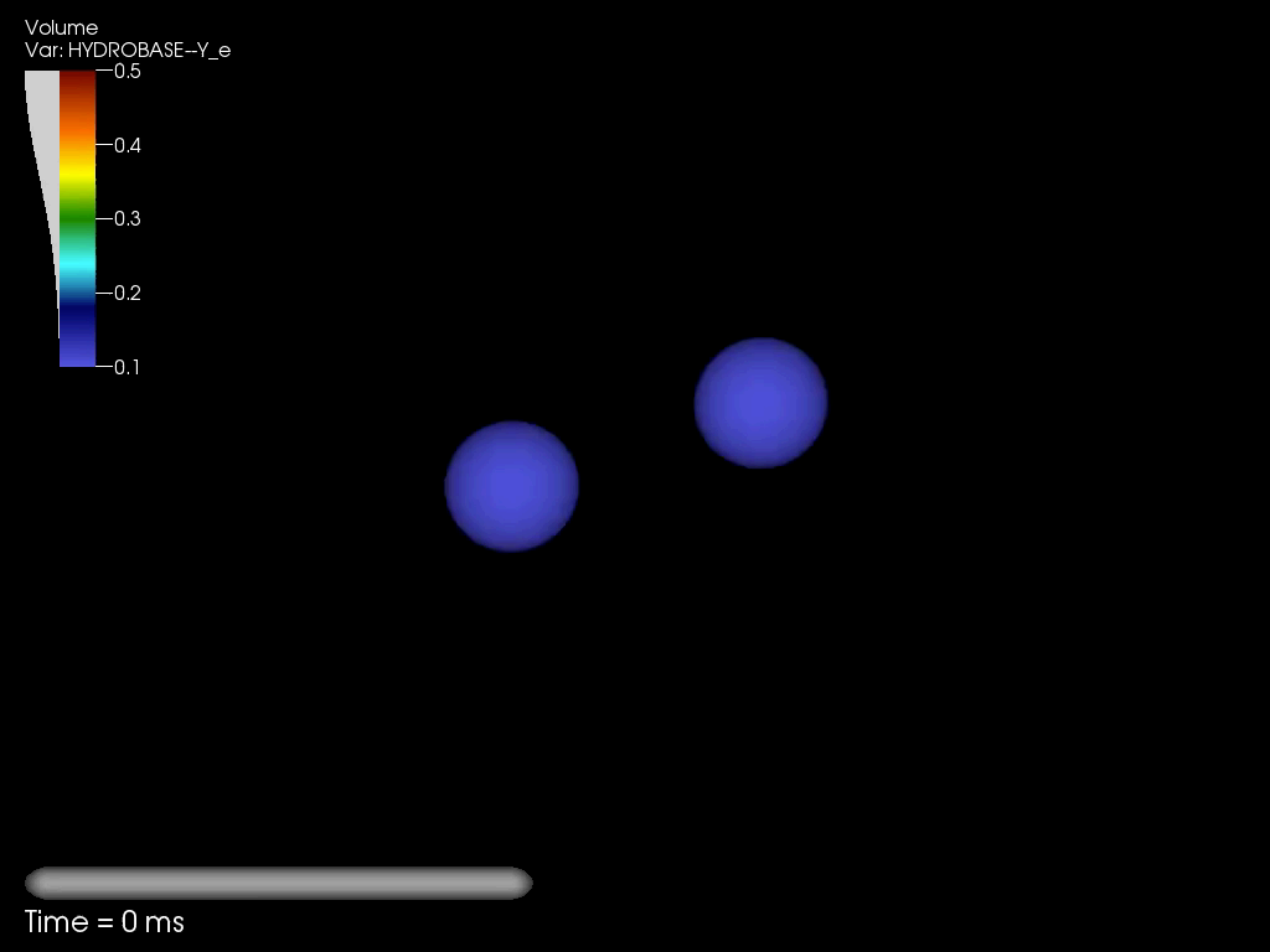
http://www.astro.princeton.edu/~dradice/whiskythc.html

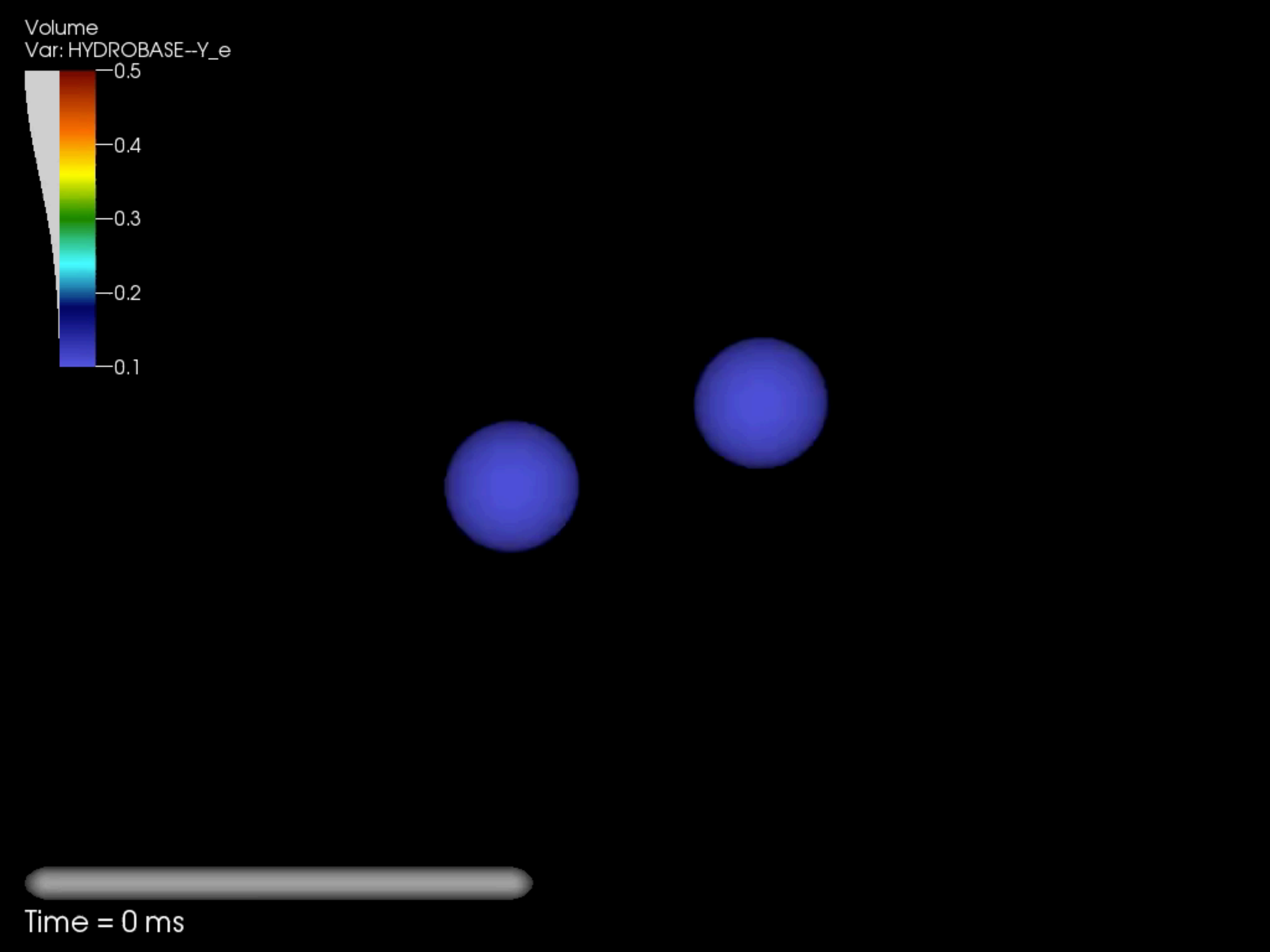


- Full-GR, dynamical spacetime*
- Nuclear EOS
- Effective neutrino treatment
- High-order hydrodynamics
- Open source!

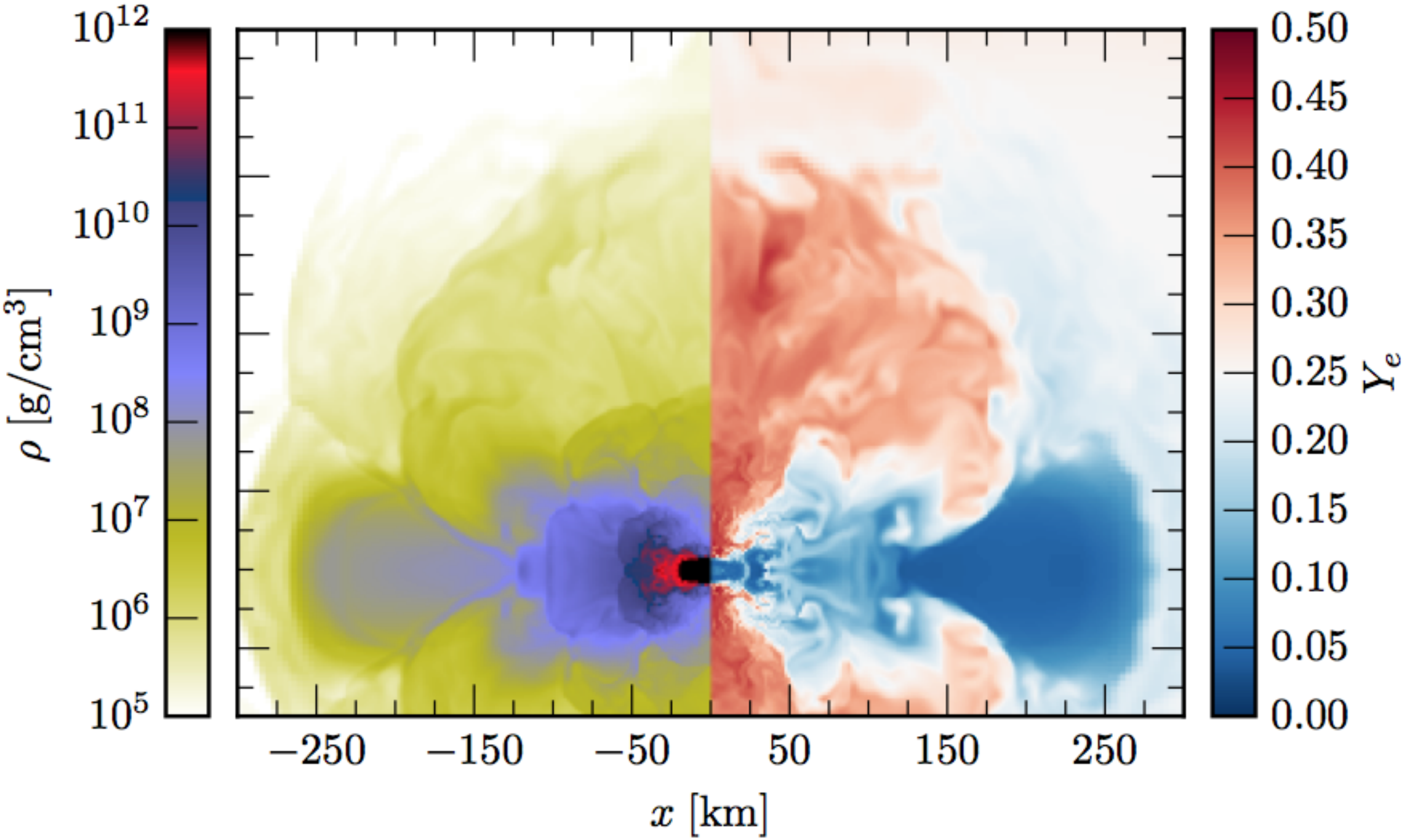
* using the Einstein Toolkit metric solvers

THC: Templated Hydrodynamics Code


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


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

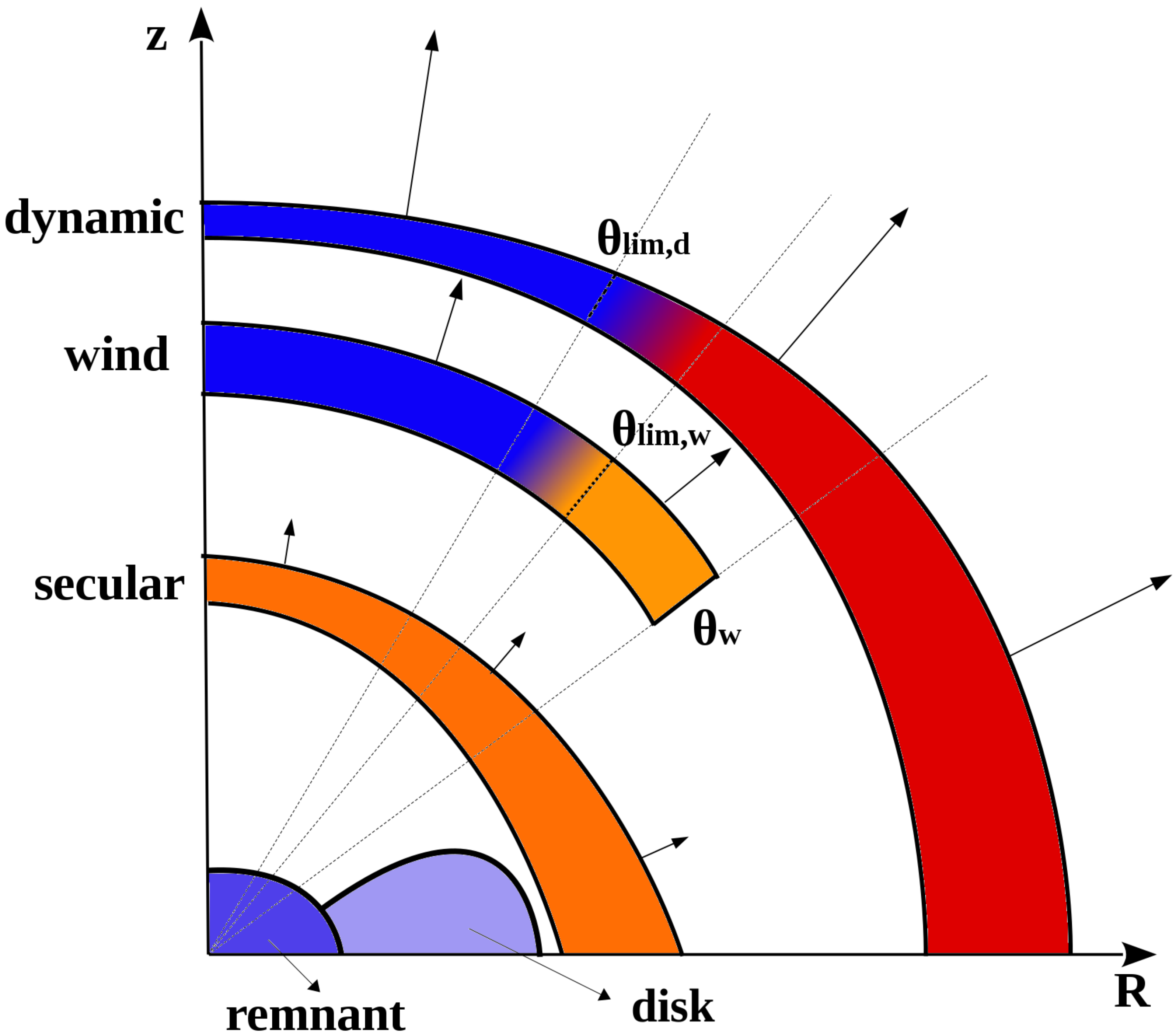
Neutron rich outflows



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

DR, Galeazzi+ MRAS 460:3255 (2016)

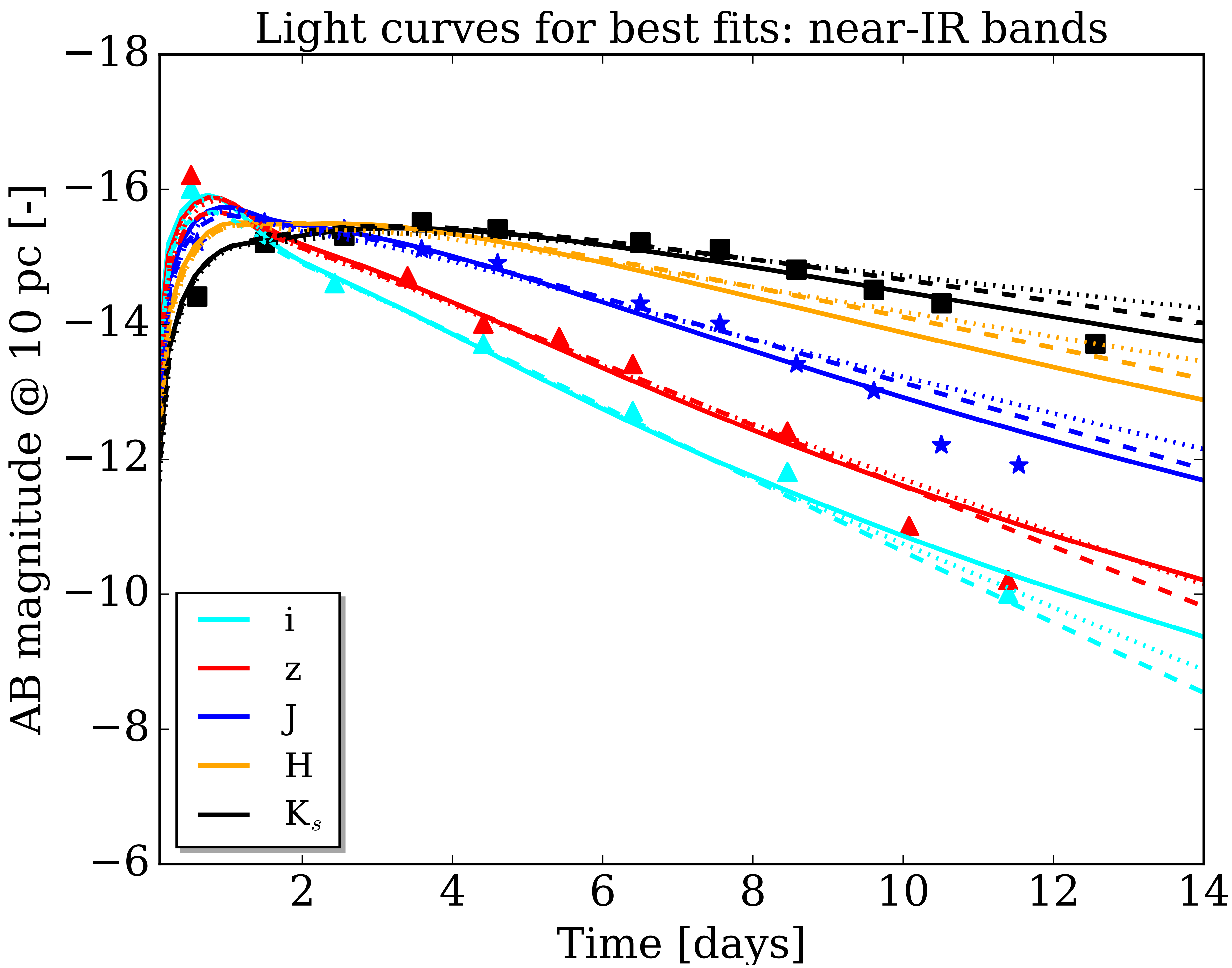
Neutron rich outflows: model



- Geometry and composition of the outflows from simulations
- Multiple ejecta components
- Ejecta masses from fitting AT2017gfo

Perego, **DR**, Bernuzzi, ApJL 850:37 (2017)

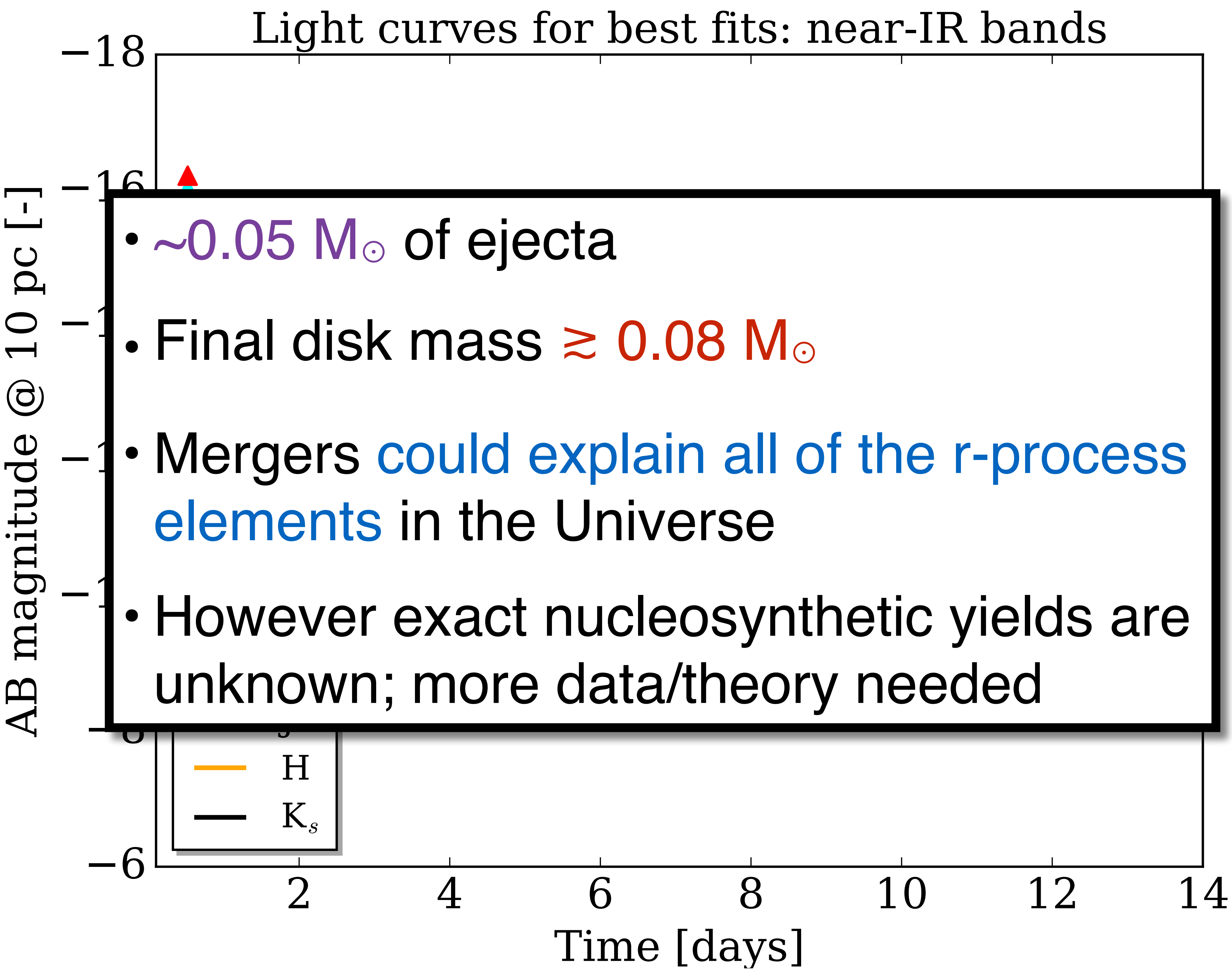
Kilonova modeling



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

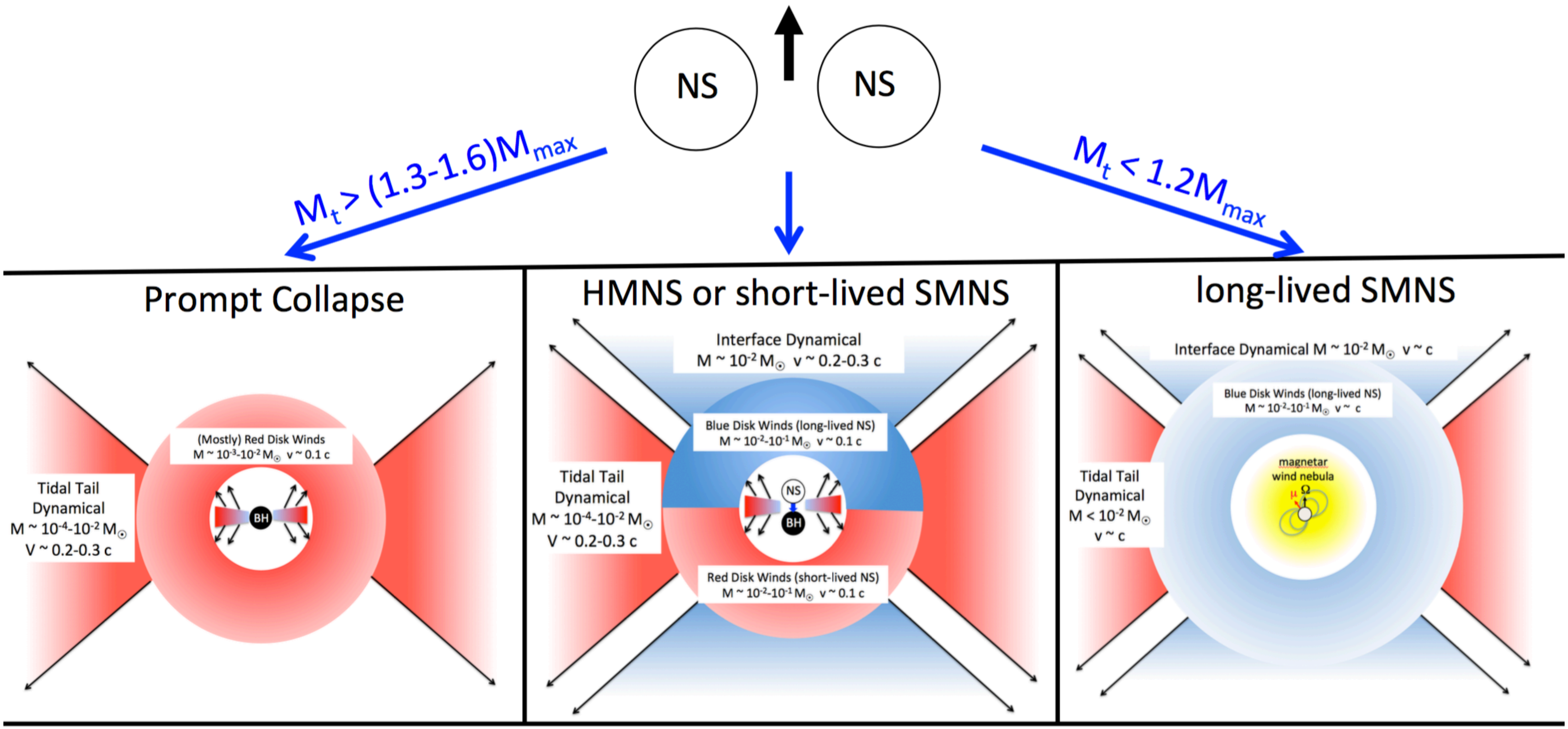


- ~0.05 $M_\odot$ of ejecta
- Final disk mass $\gtrsim$ 0.08 $M_\odot$
- Mergers could explain all of the r-process elements in the Universe
- However exact nucleosynthetic yields are unknown; more data/theory needed

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

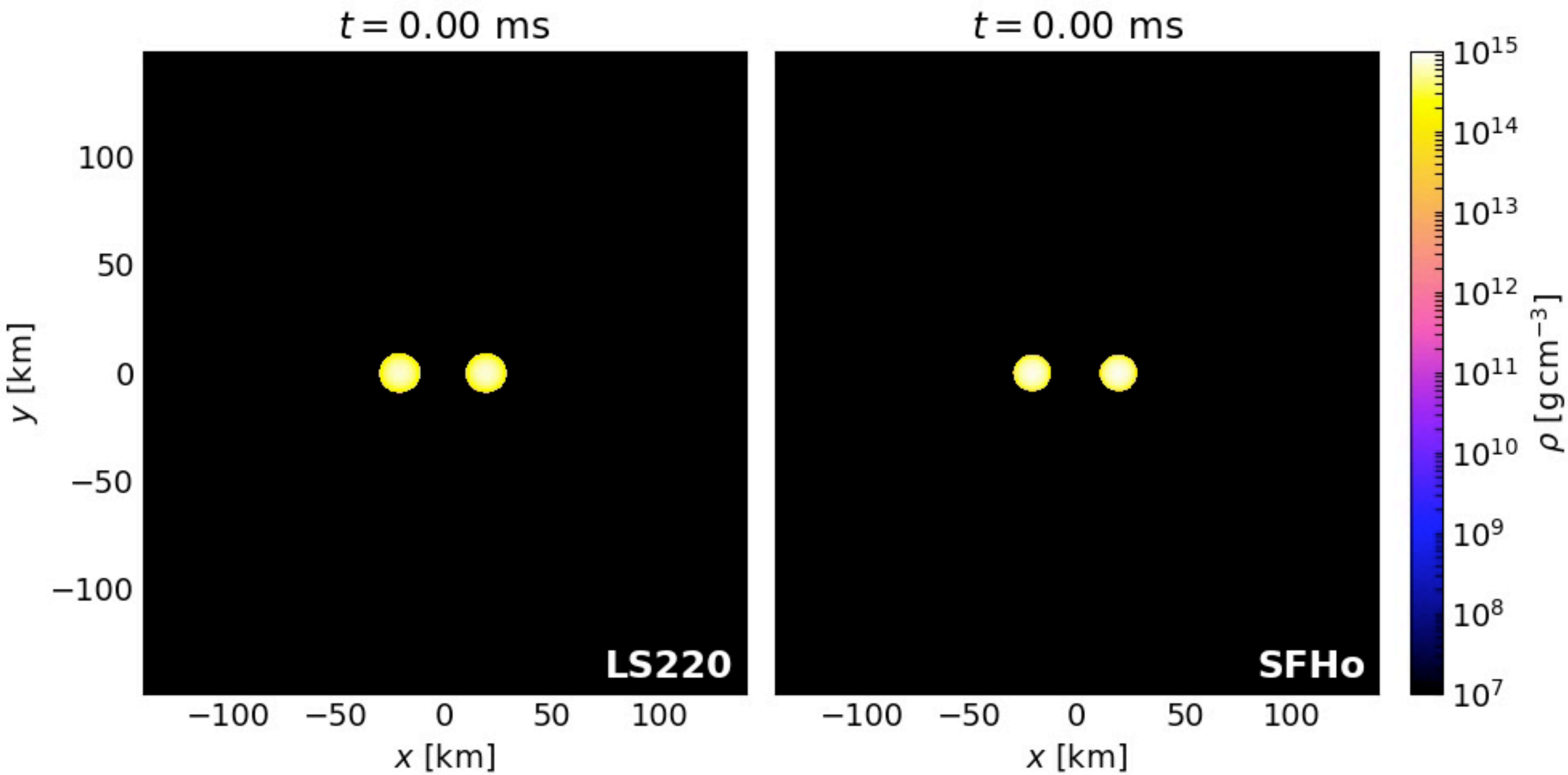
Fate of the remnant



From Margalit & Metzger 2017

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

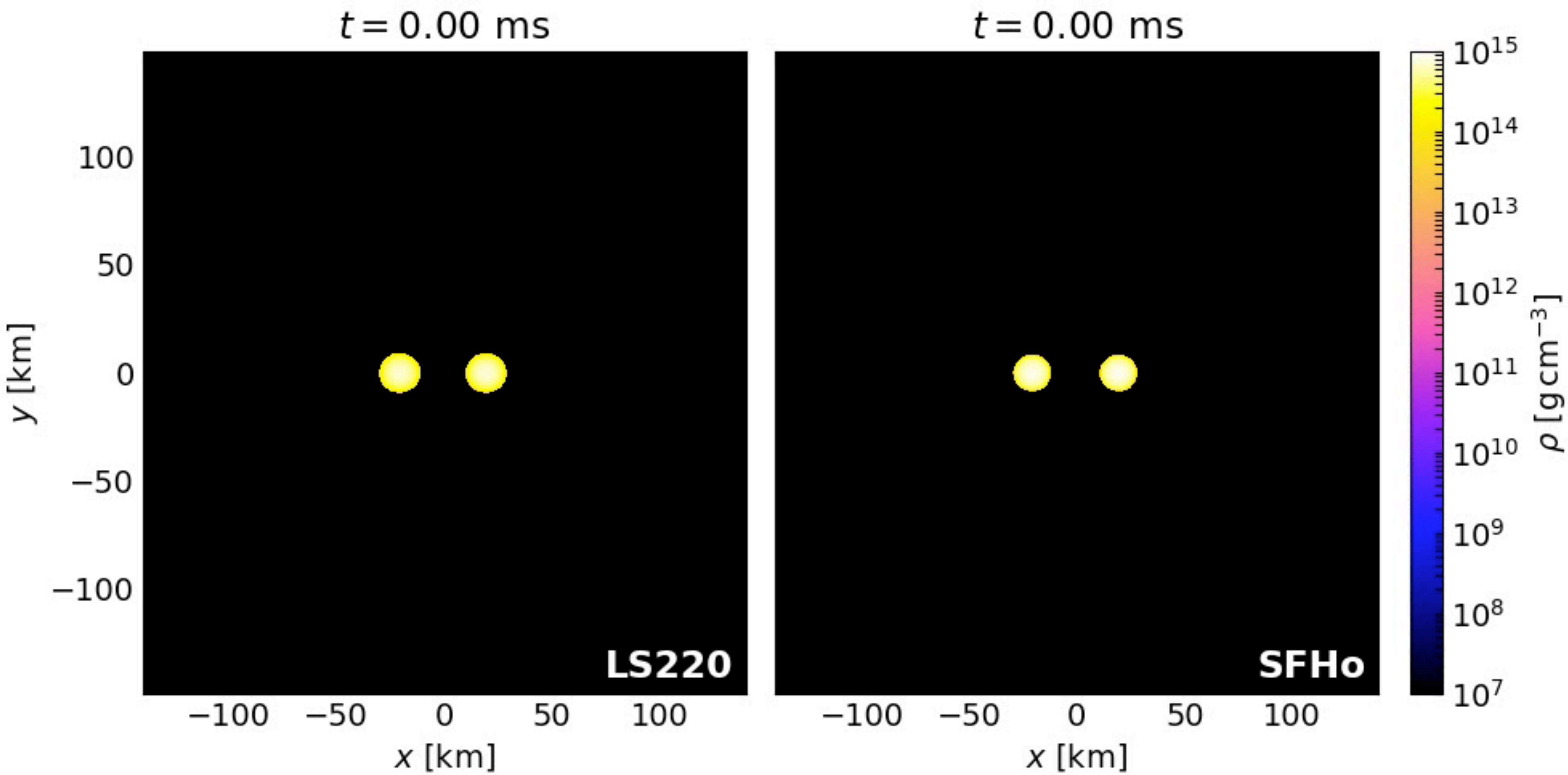
Prompt collapse?



$(1.44 + 1.39)\ M_\odot$ — B1913 + 13

DR, Perego, Zappa, ApJL 852:L29 (2018)

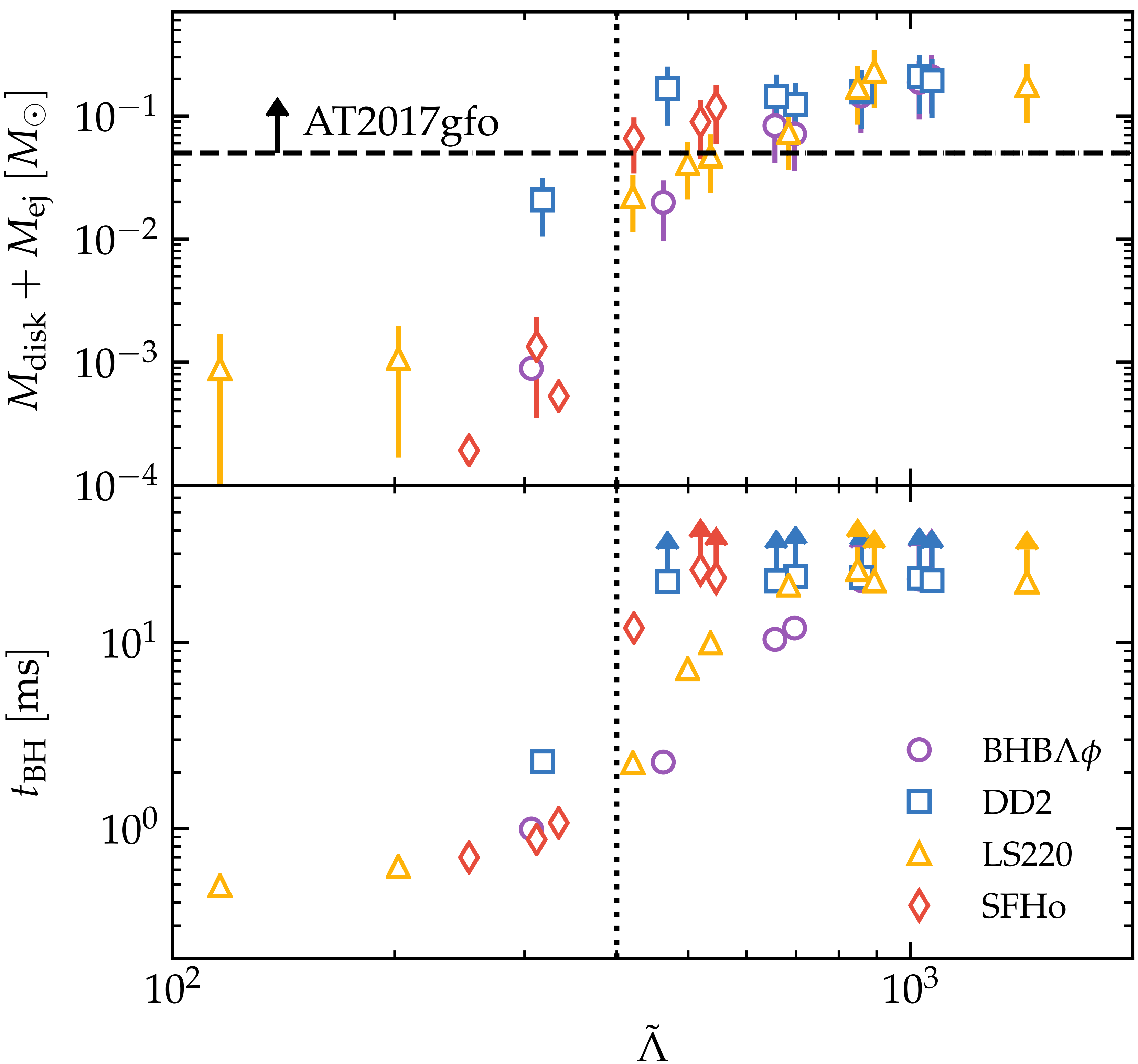
Prompt collapse?



$(1.44 + 1.39)\ M_\odot$ — B1913 + 13

DR, Perego, Zappa, ApJL 852:L29 (2018)

GW170817: not a prompt collapse



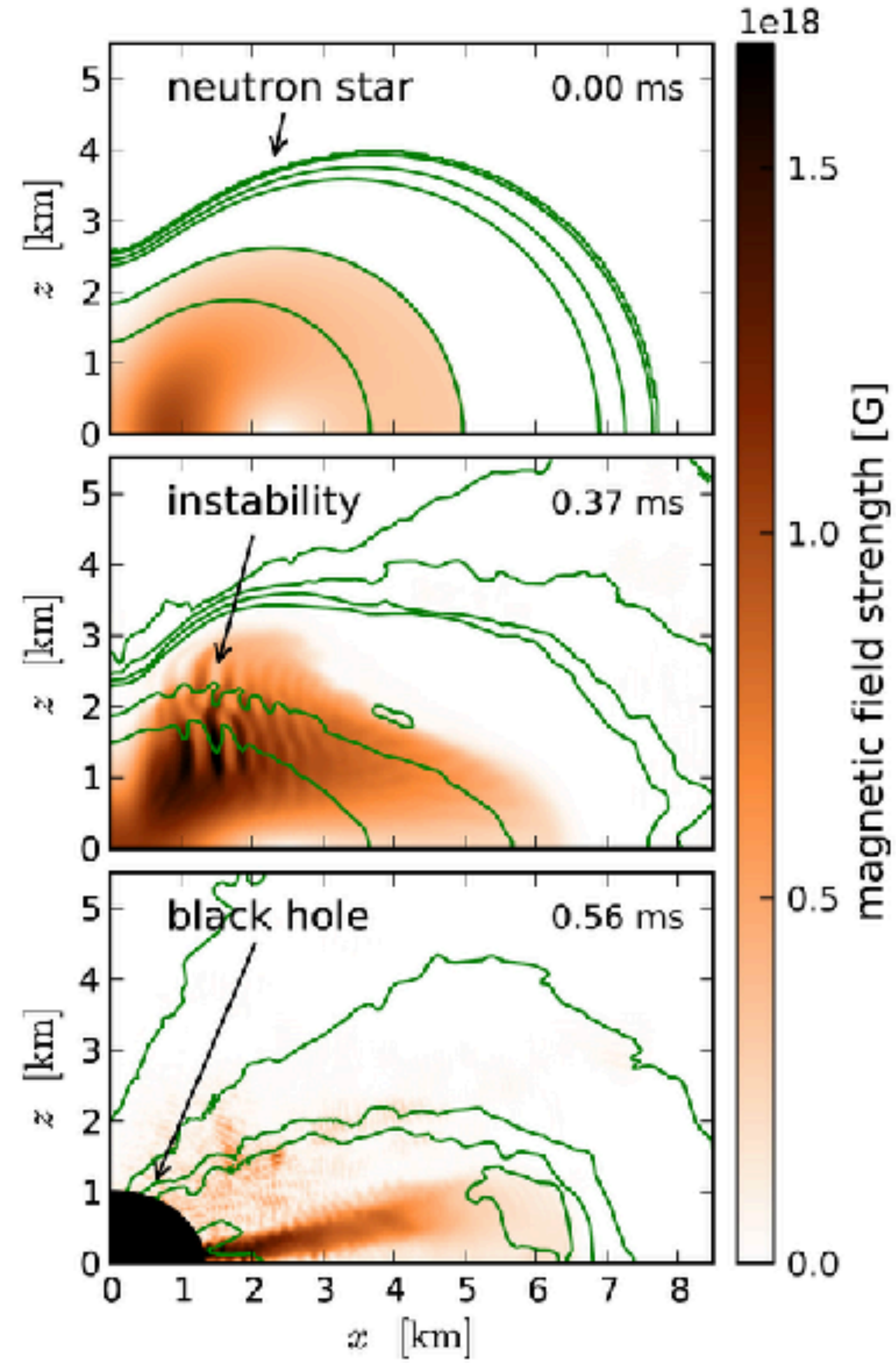
See also Bauswein+ 2017 ApJL 850:L34

DR, Perego, Zappa, ApJL 852:L29 (2018)

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, and/or idealized configurations
- Our approach: explicit subgrid-scale modeling with large-eddy simulations

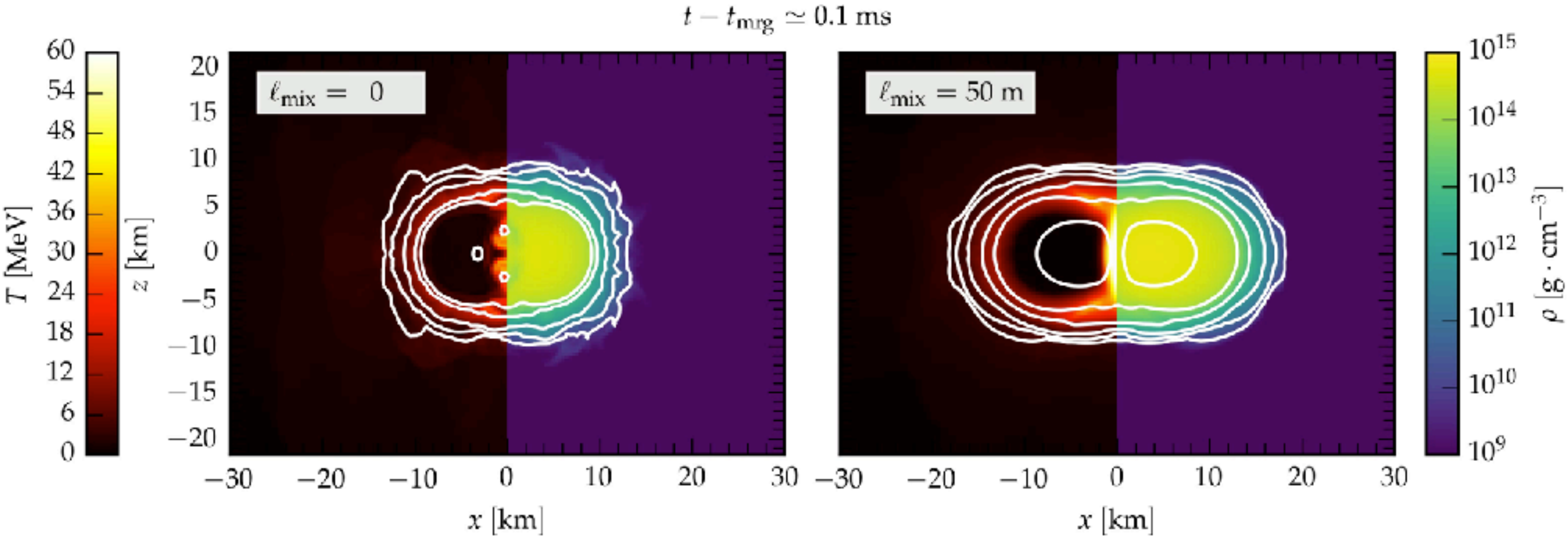


See also: Shibata & Kiuchi 2017, Kiuchi, Kyutoku+ 2017

From Siegel+ 2013

Angular momentum transport

$t_{\mathrm{visc}} = \infty$ $t_{\mathrm{visc}} \sim 15\,\mathrm{ms}$



See also: Shibata & Kiuchi 2017; Kiuchi, Kyotoku+ 2017

DR ApJL:838 L2 (2017)

Angular momentum transport

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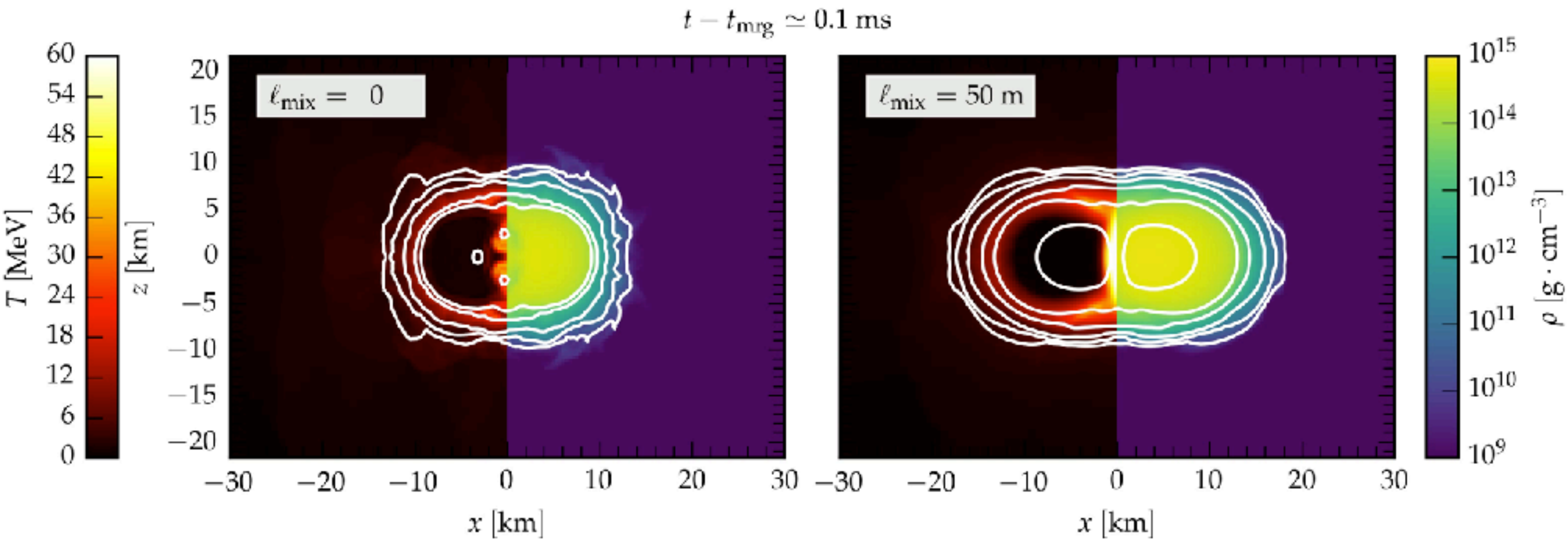
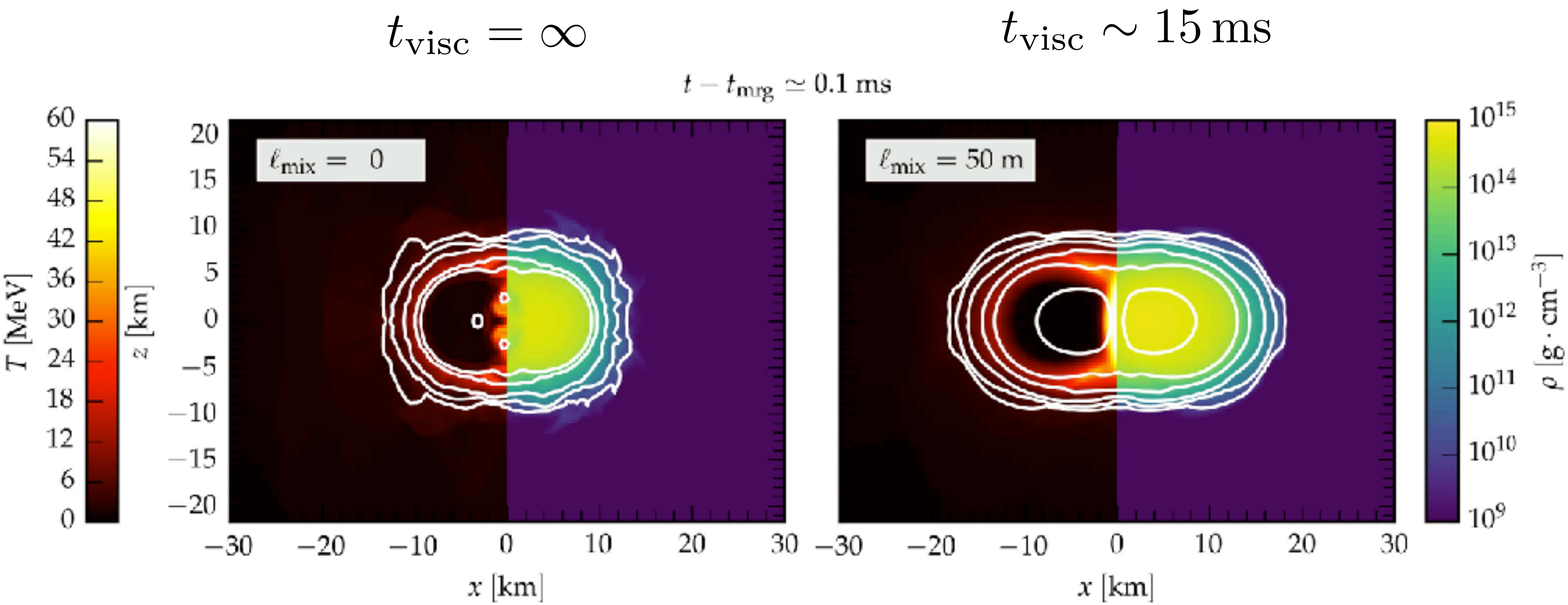


See also: Shibata & Kiuchi 2017; Kiuchi, Kyotoku+ 2017

DR ApJL:838 L2 (2017)

Angular momentum transport

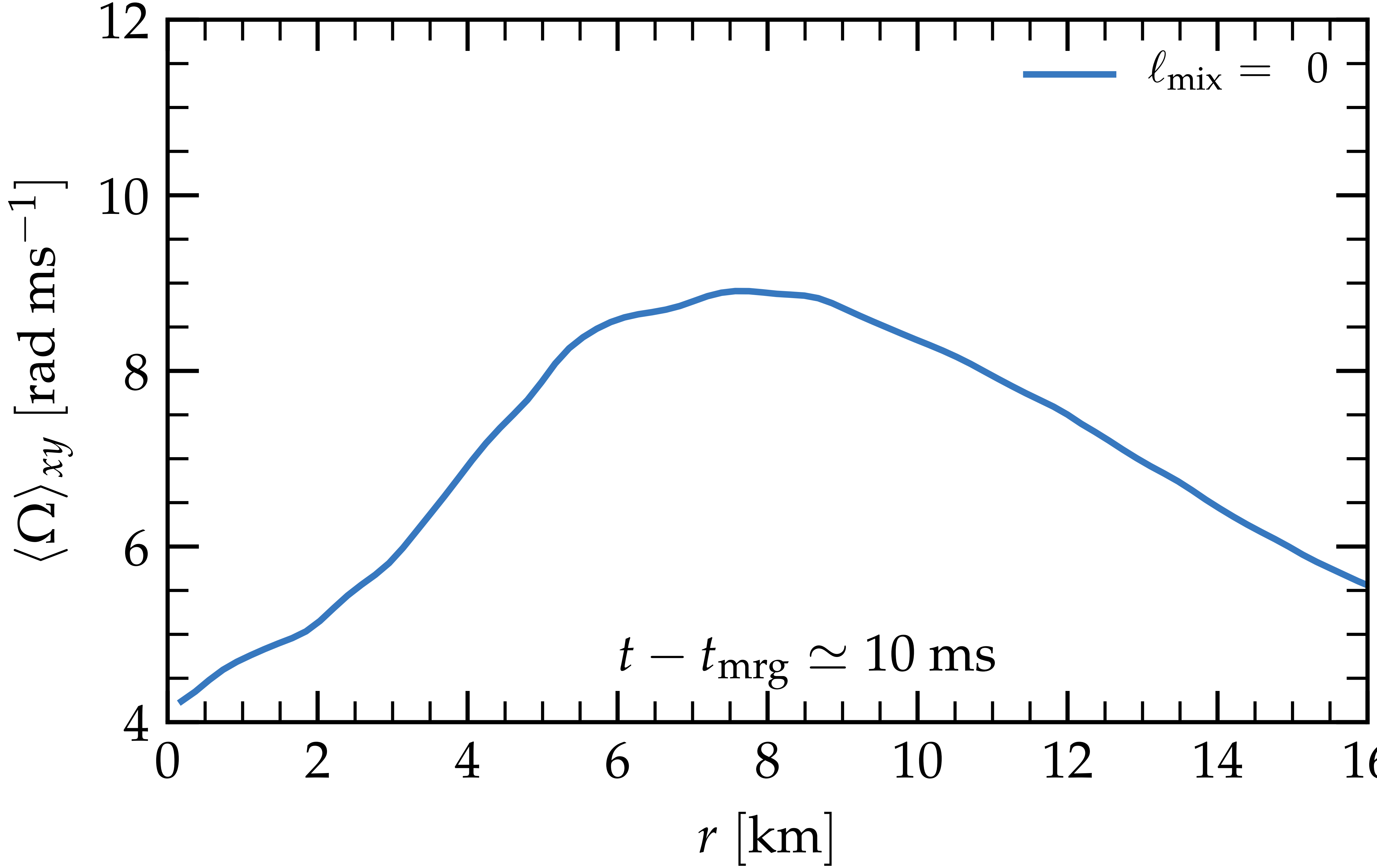


Delayed collapse!

See also: Shibata & Kiuchi 2017; Kiuchi, Kyotoku+ 2017

DR ApJL:838 L2 (2017)

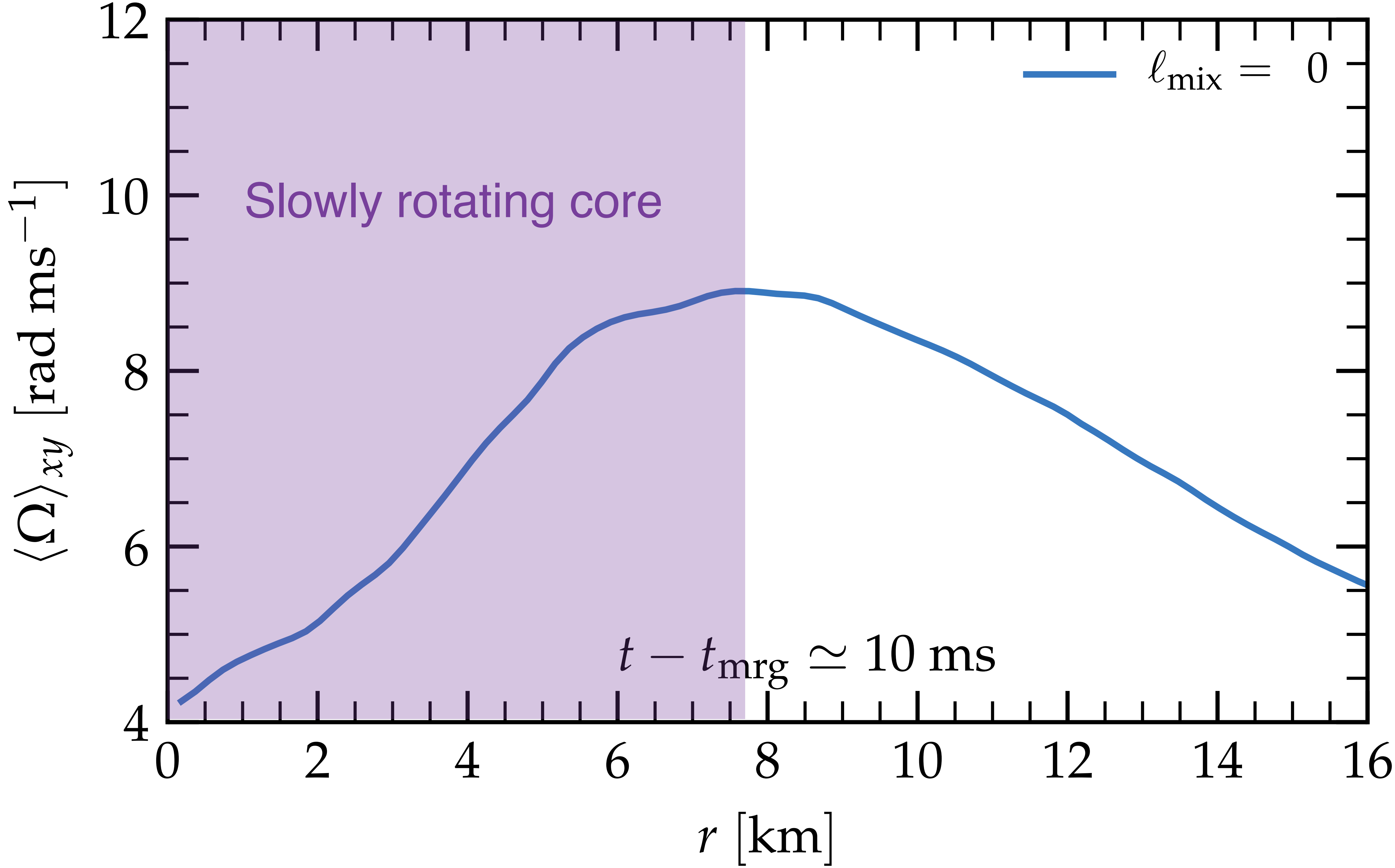
Rotational profile



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

DR ApJL:838 L2 (2017)

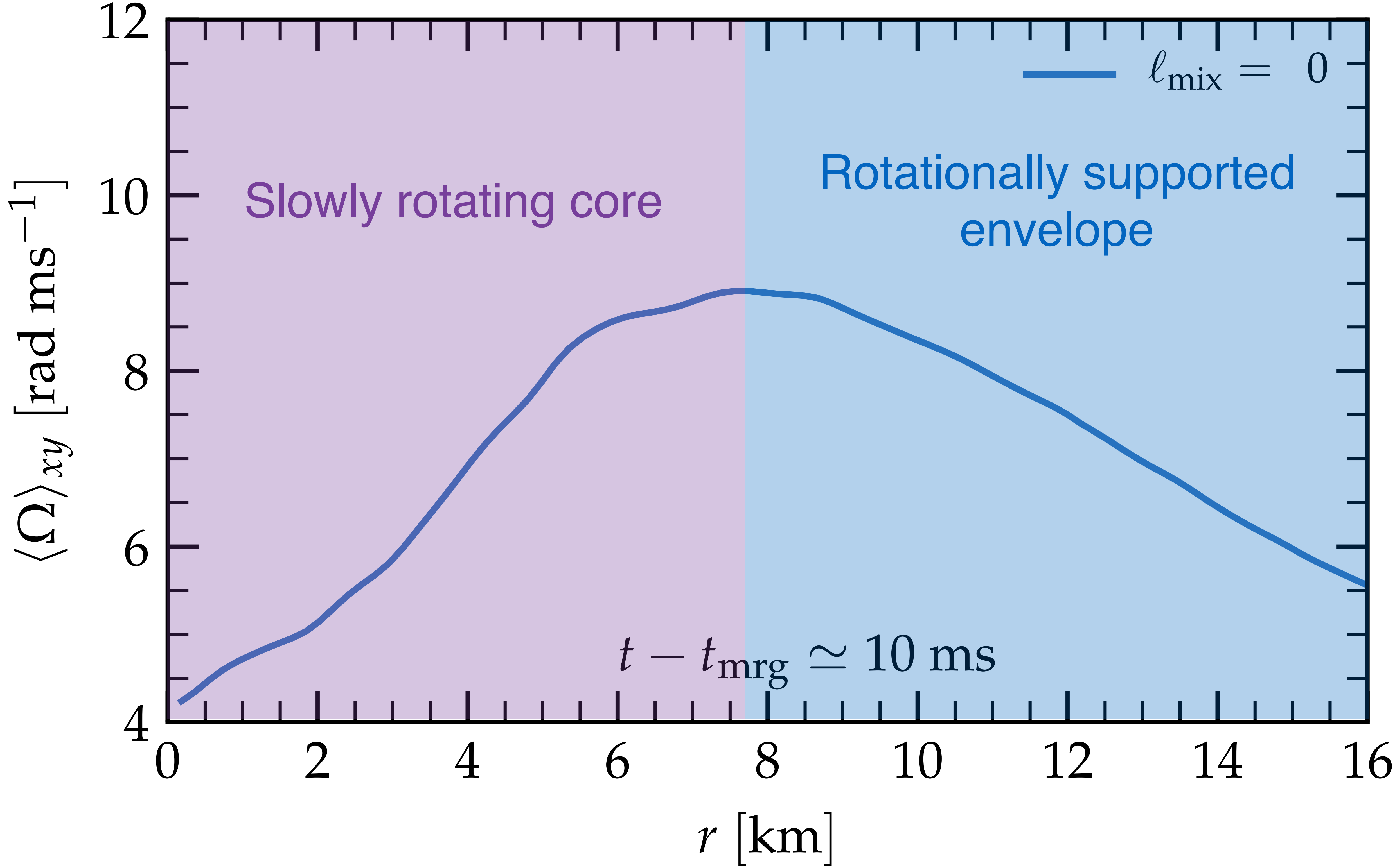
Rotational profile



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

DR ApJL:838 L2 (2017)

Rotational profile



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

DR ApJL:838 L2 (2017)

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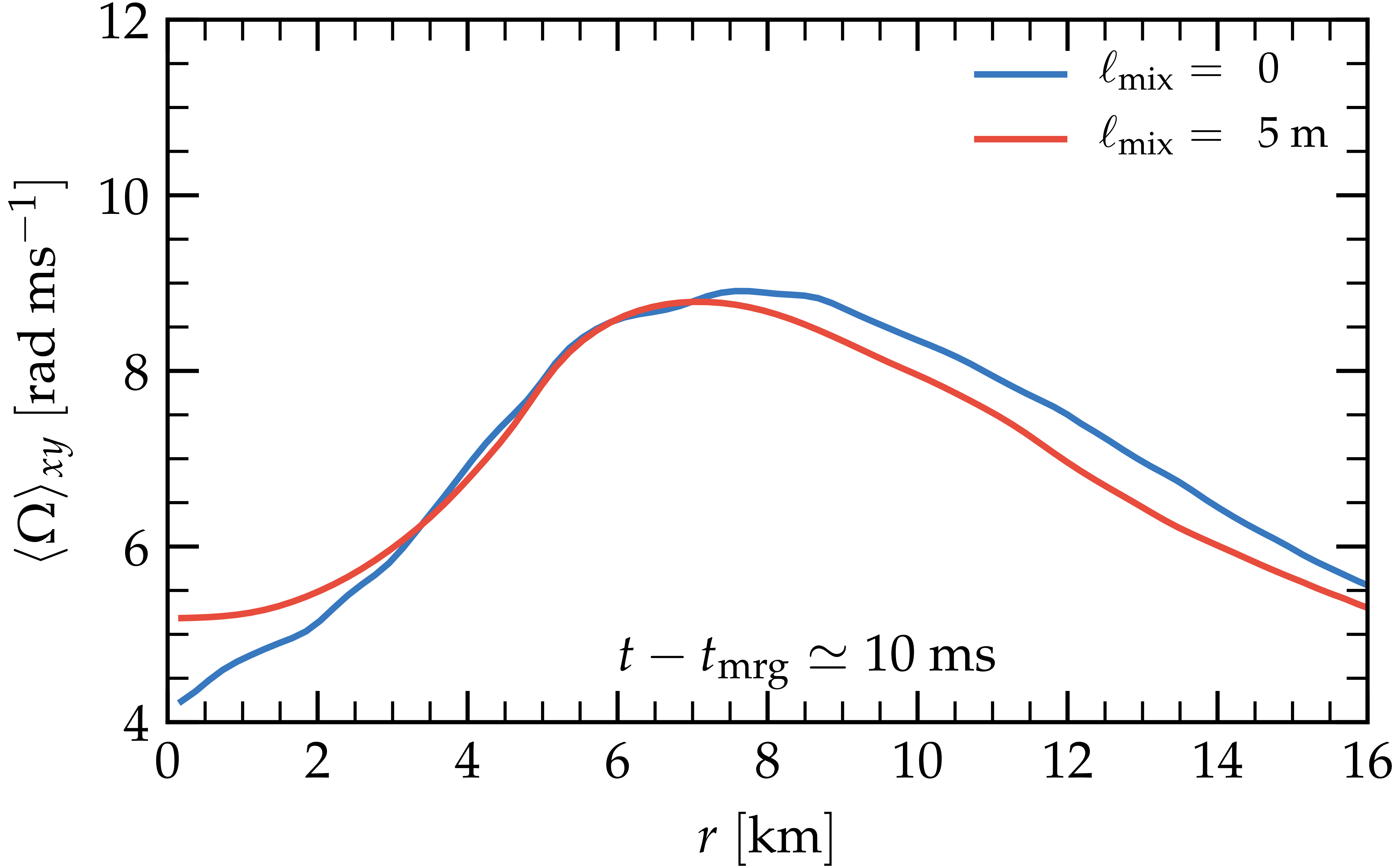

See also Shibata & Taniguchi 2006; Kastaun+ 2015, 2016; Hanauske+ 2016

DR ApJL:838 L2 (2017)

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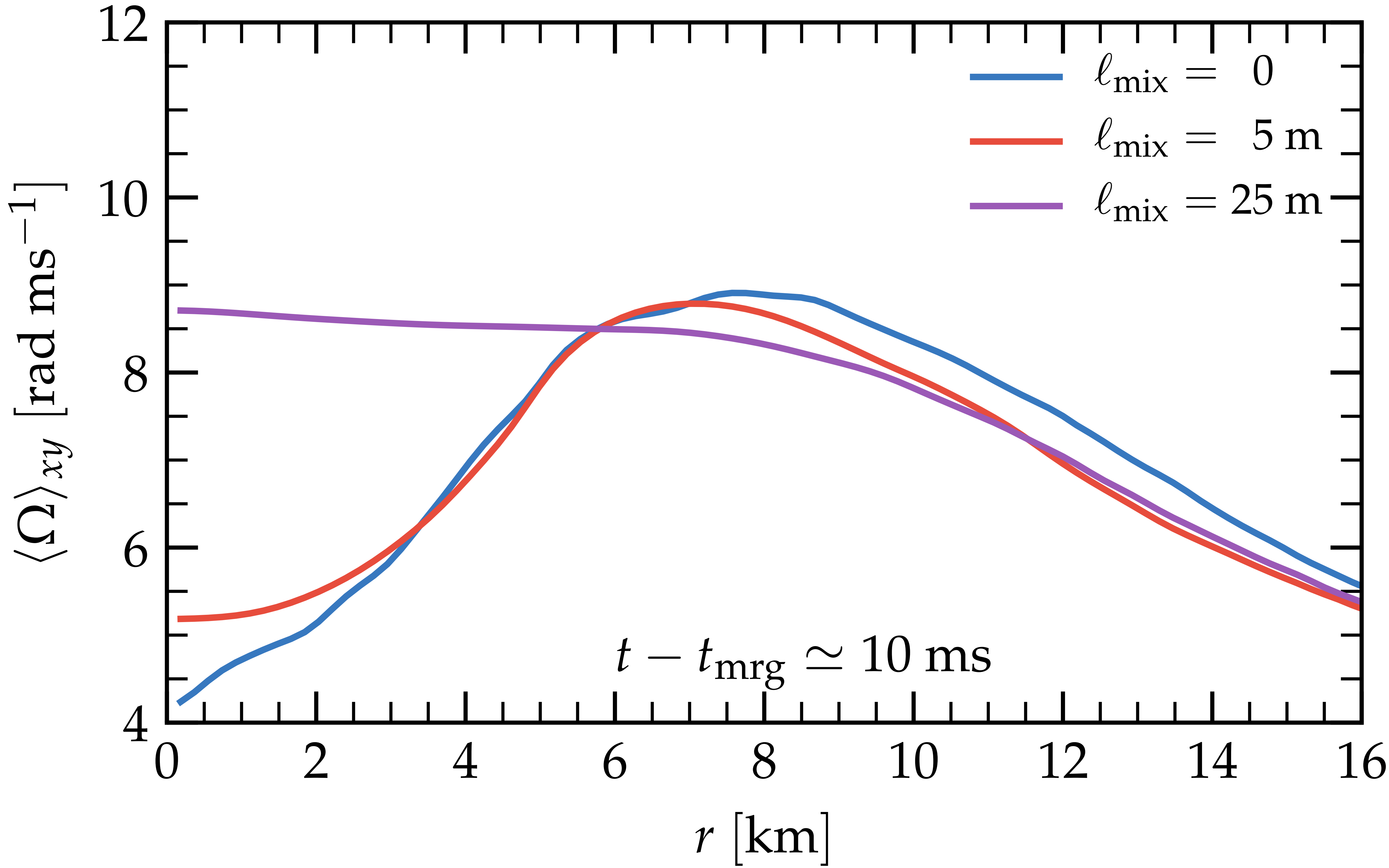

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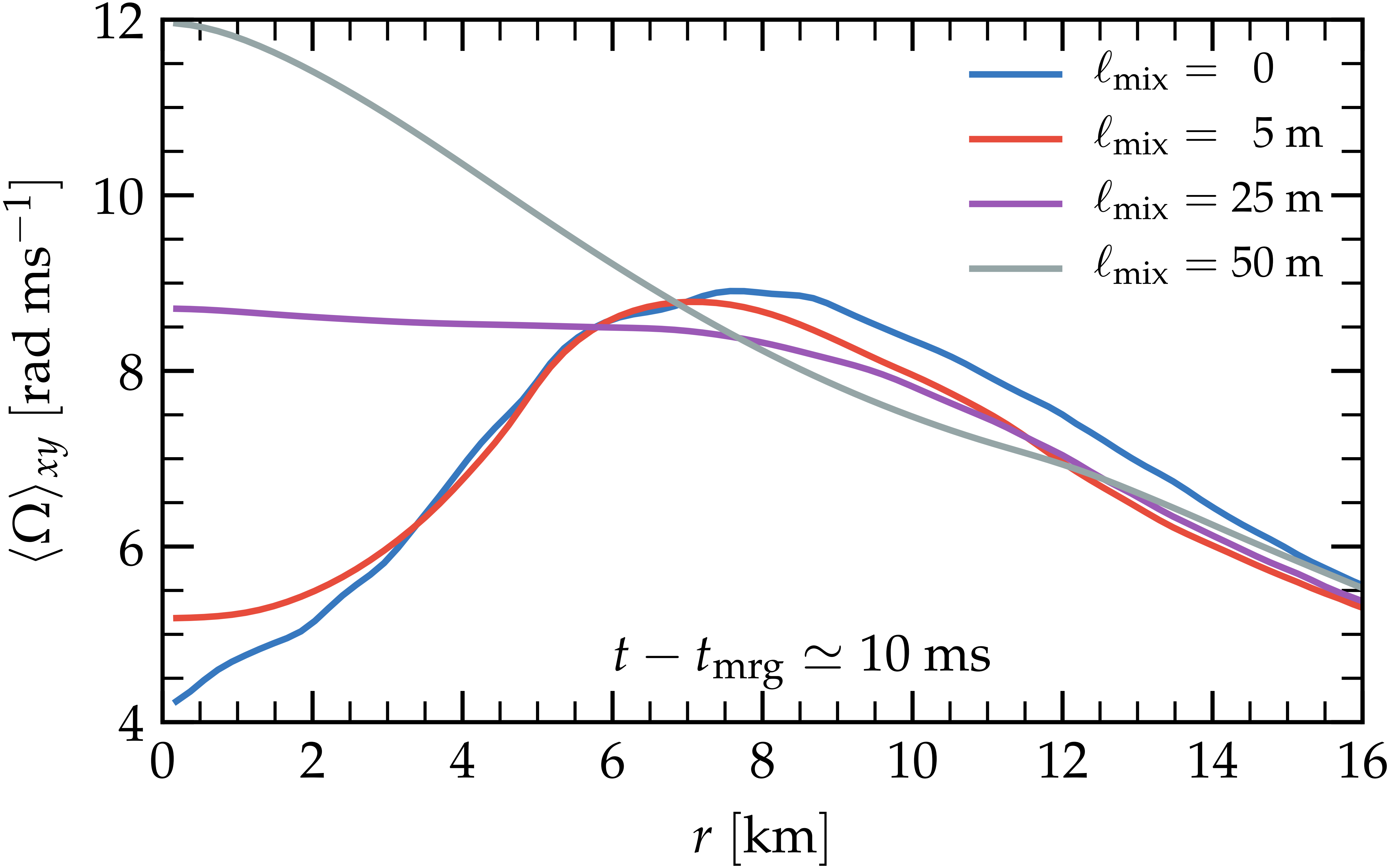
DR ApJL:838 L2 (2017)

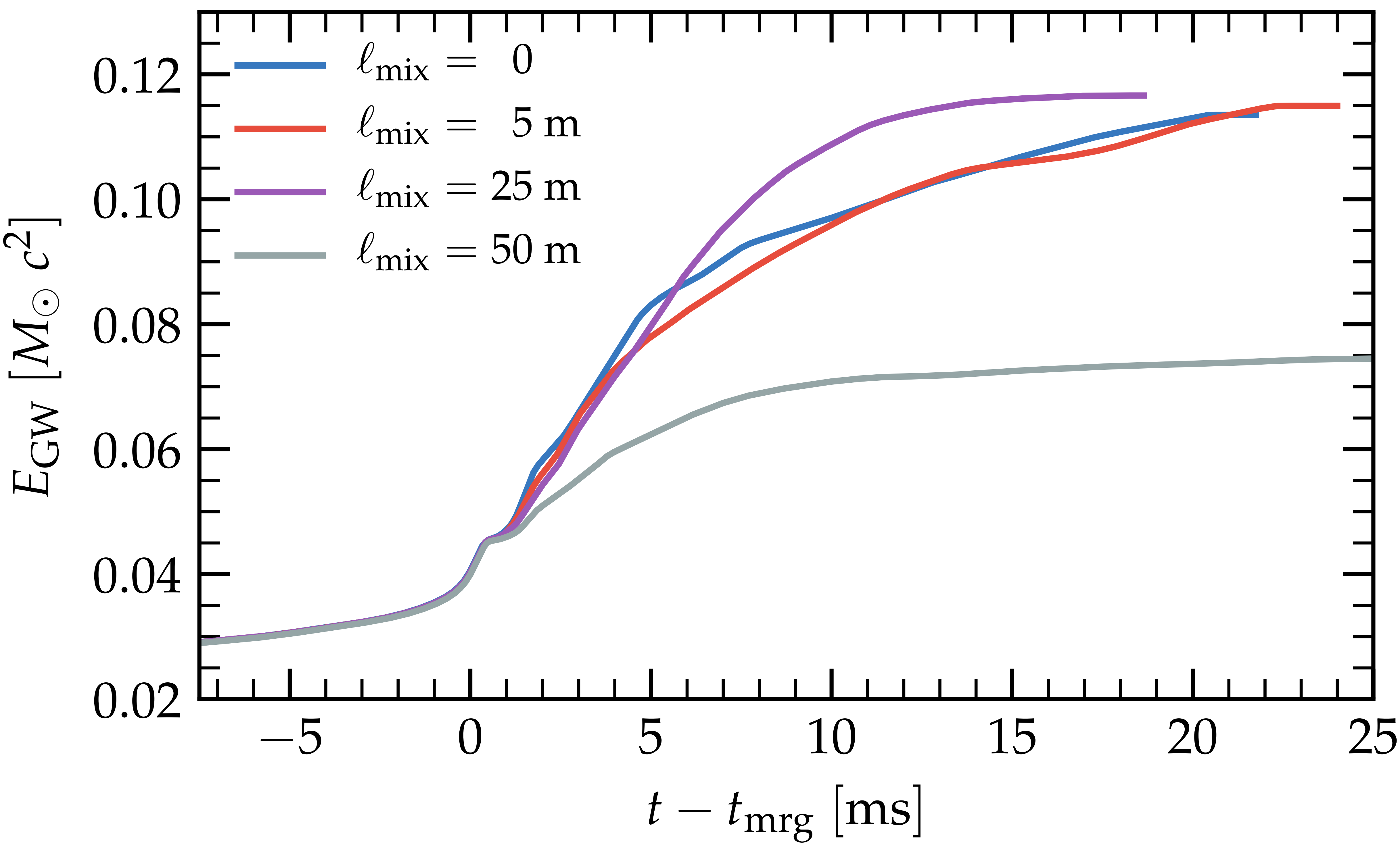
Rotational profile



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

DR ApJL:838 L2 (2017)

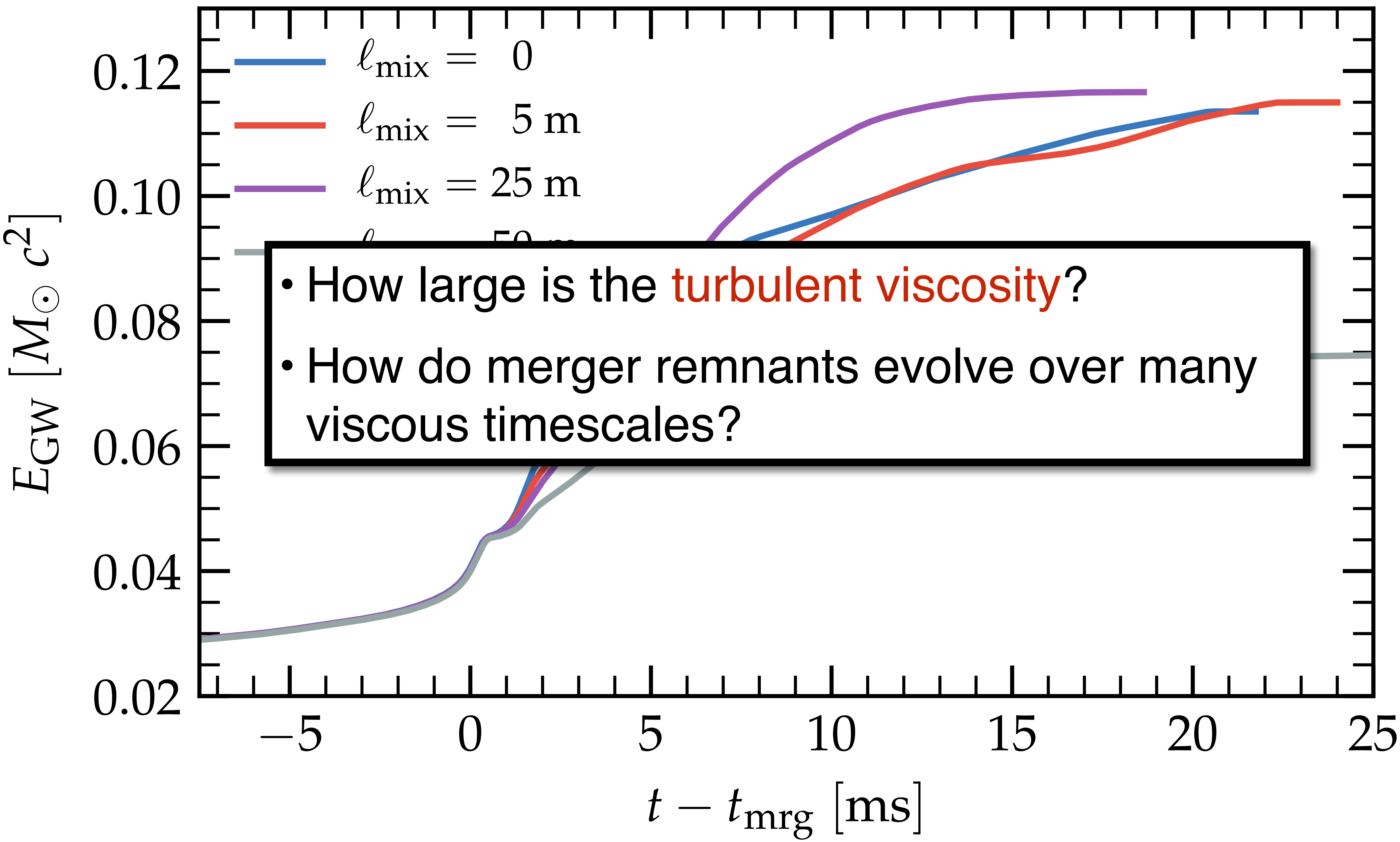
Gravitational waves



See also: Shibata & Kiuchi 2017; Kiuchi, Kyotoku+ 2017

DR ApJL:838 L2 (2017)

Gravitational waves



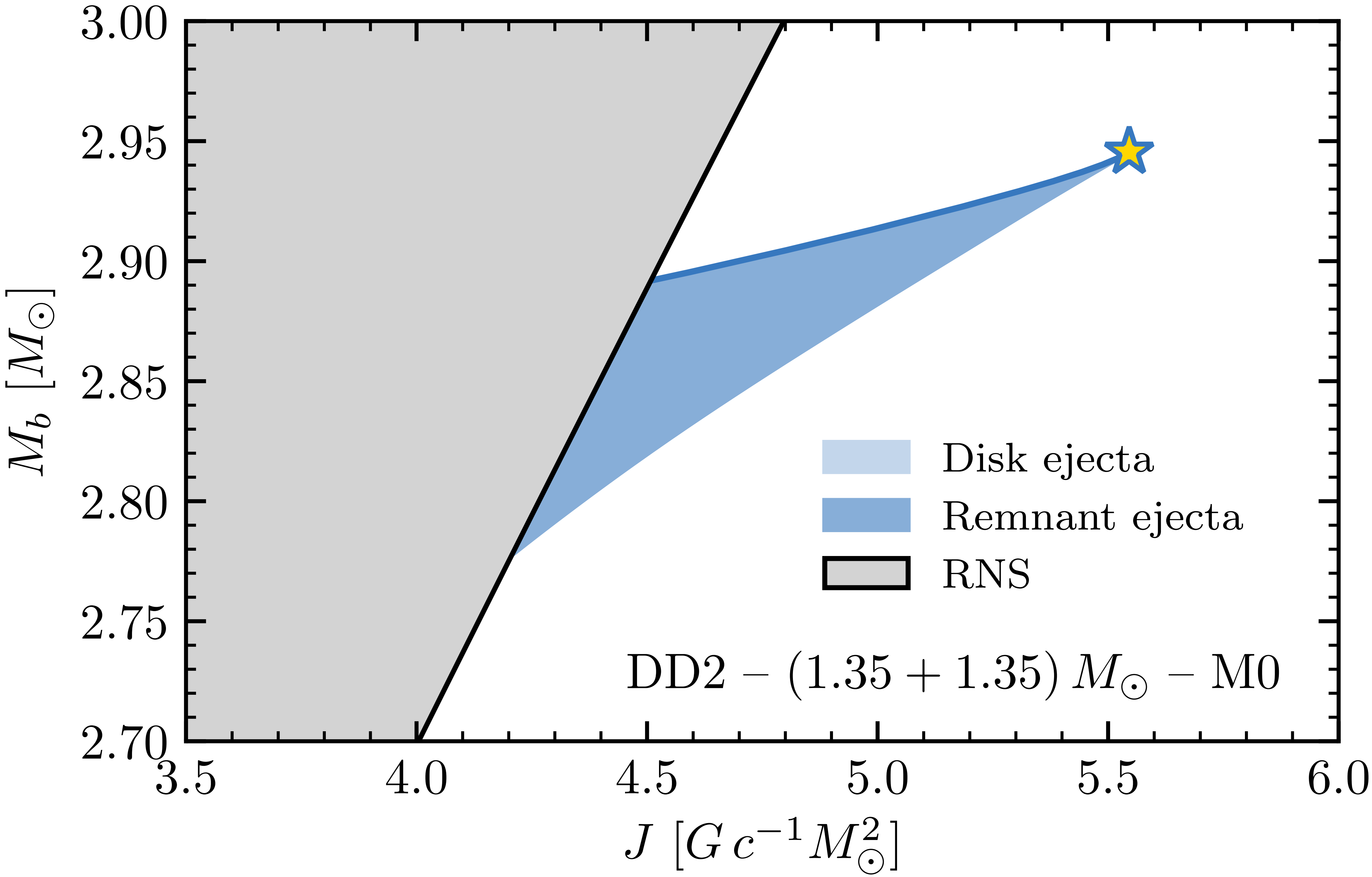
- How large is the turbulent viscosity?
- How do merger remnants evolve over many viscous timescales?

See also: Shibata & Kiuchi 2017; Kiuchi, Kyotoku+ 2017

DR ApJL:838 L2 (2017)

Future prospectives:
long-lived remnants

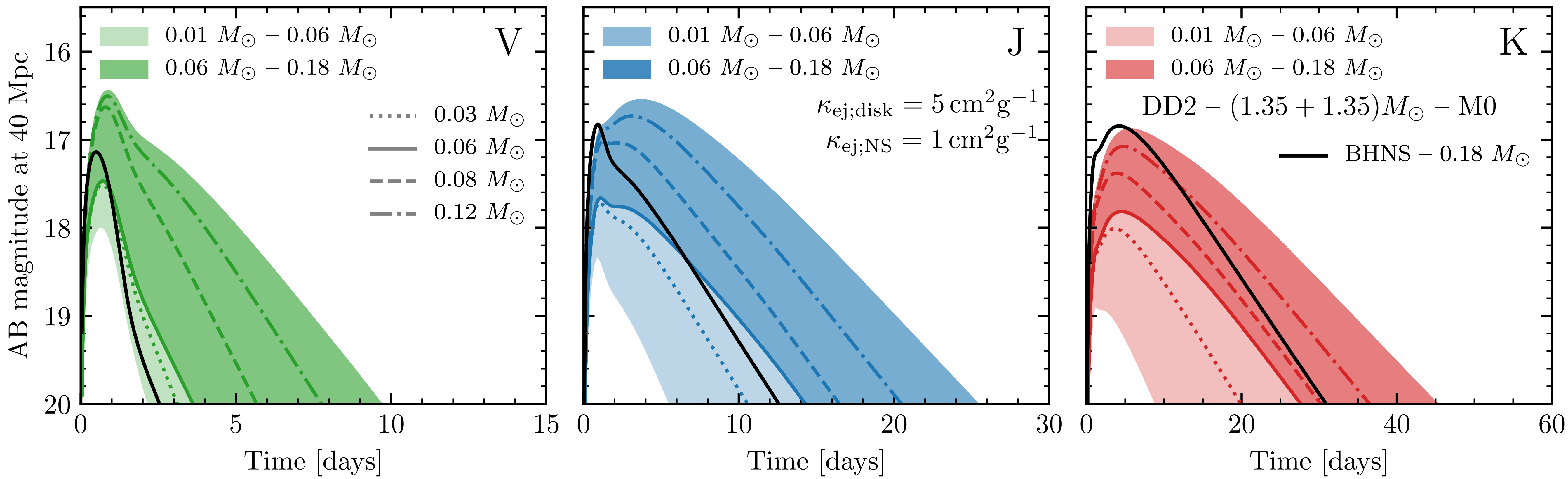
Long-lived remnants (I)



See also Fujibayashi, Kiuchi+ (2017)

DR, Perego, Bernuzzi, Zhang, arXiv:1803.10865

Long-lived remnants (II)



- Low-mass NS binaries exist* and likely form stable remnants
- Long-lived remnants are found to be unstable over the viscous timescale
- Smoking gun: a very bright kilonova with a blue component

* PSR J1411+2551; PSR J1946+2052

DR, Perego, Bernuzzi, Zhang, arXiv:1803.10865

Conclusions

- GW170817 *probably* made a BH, but not immediately
- Using numerical relativity to bridge the gap between EM and GW observations: starting to constrain the NS EOS
- The postmerger evolution of NS mergers is affected by turbulent angular momentum transport
- The next GW event might look very differently!