# Neutron Star Merger Simulations

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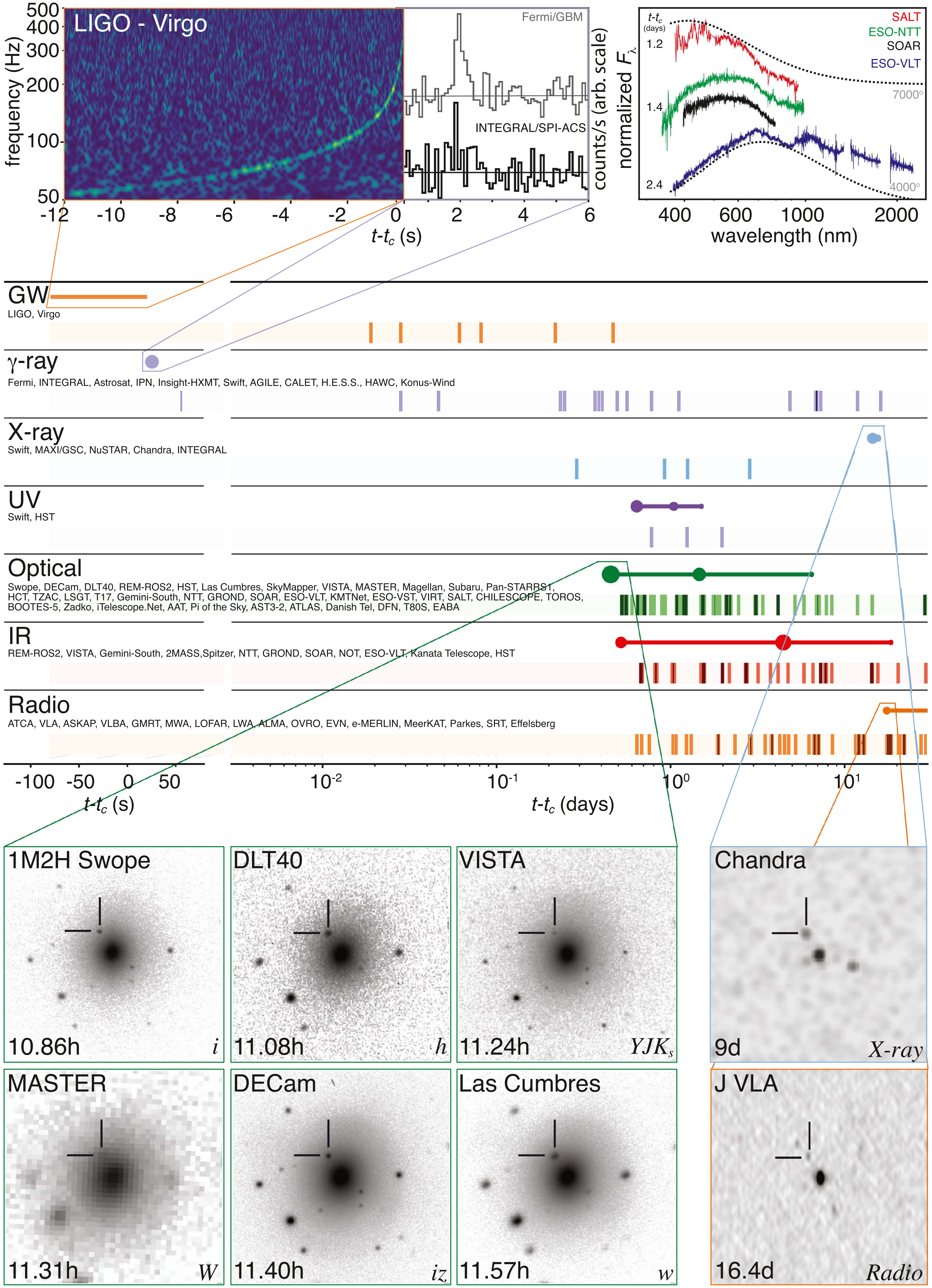
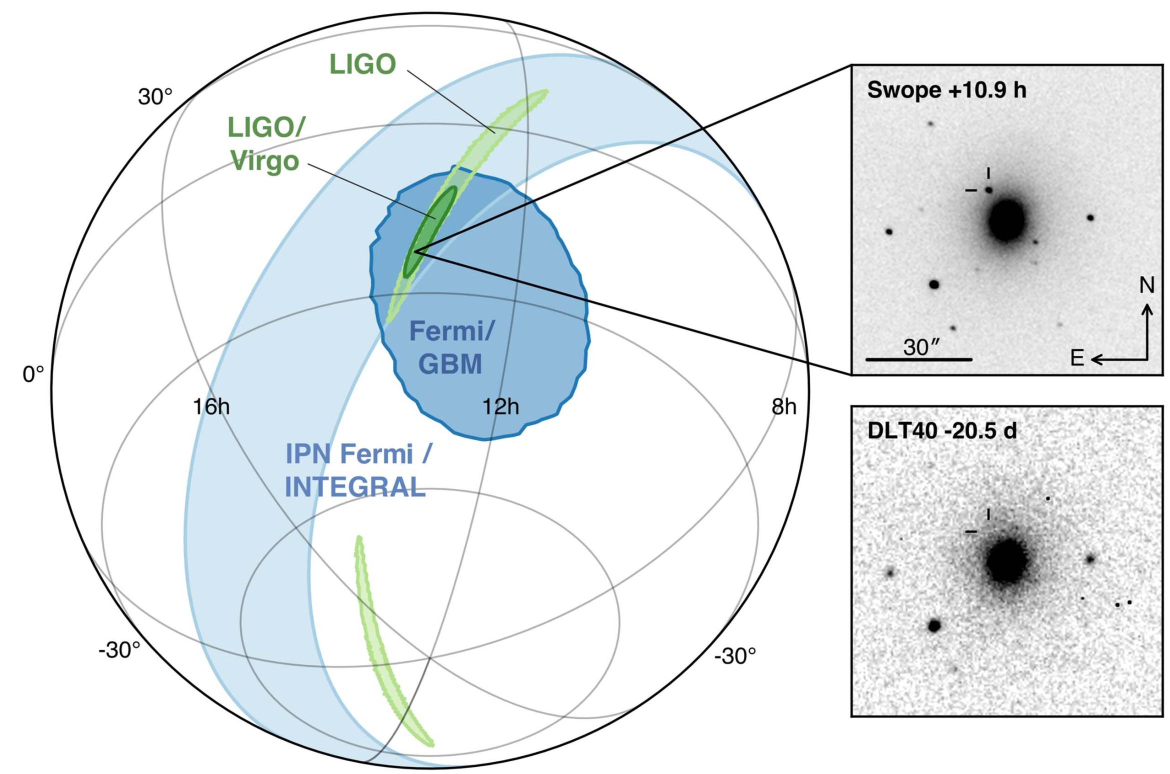
Compact Stars in the QCD Phase Diagram VII —NYC, June 11, 2018






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)

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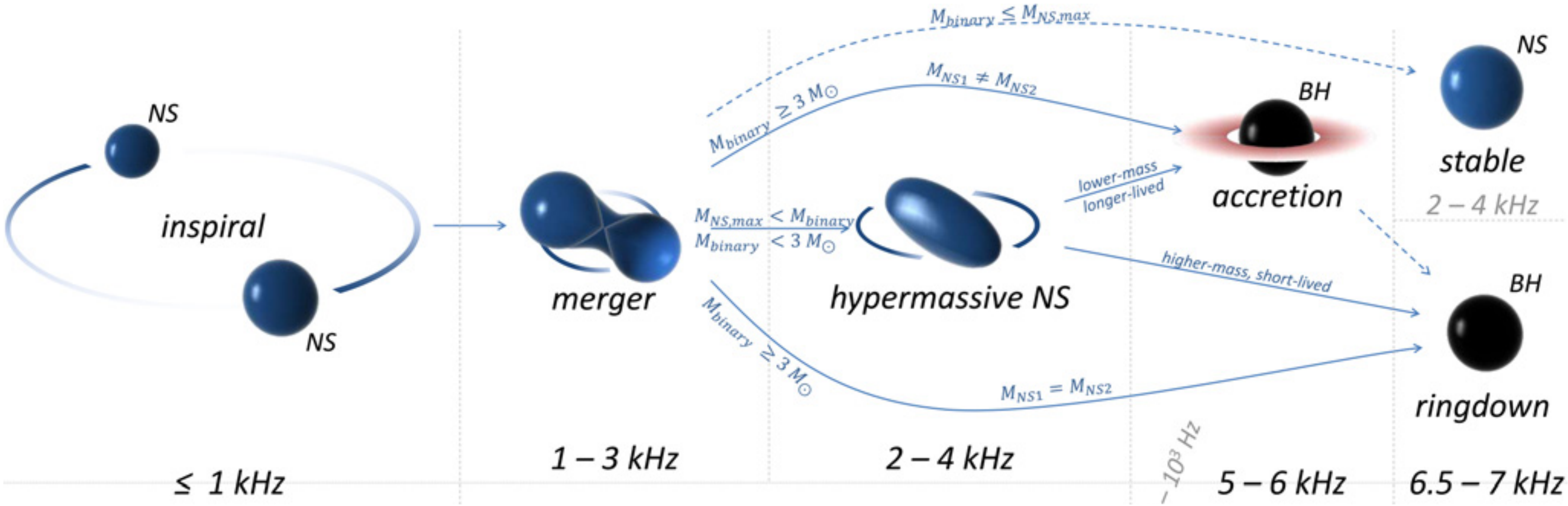
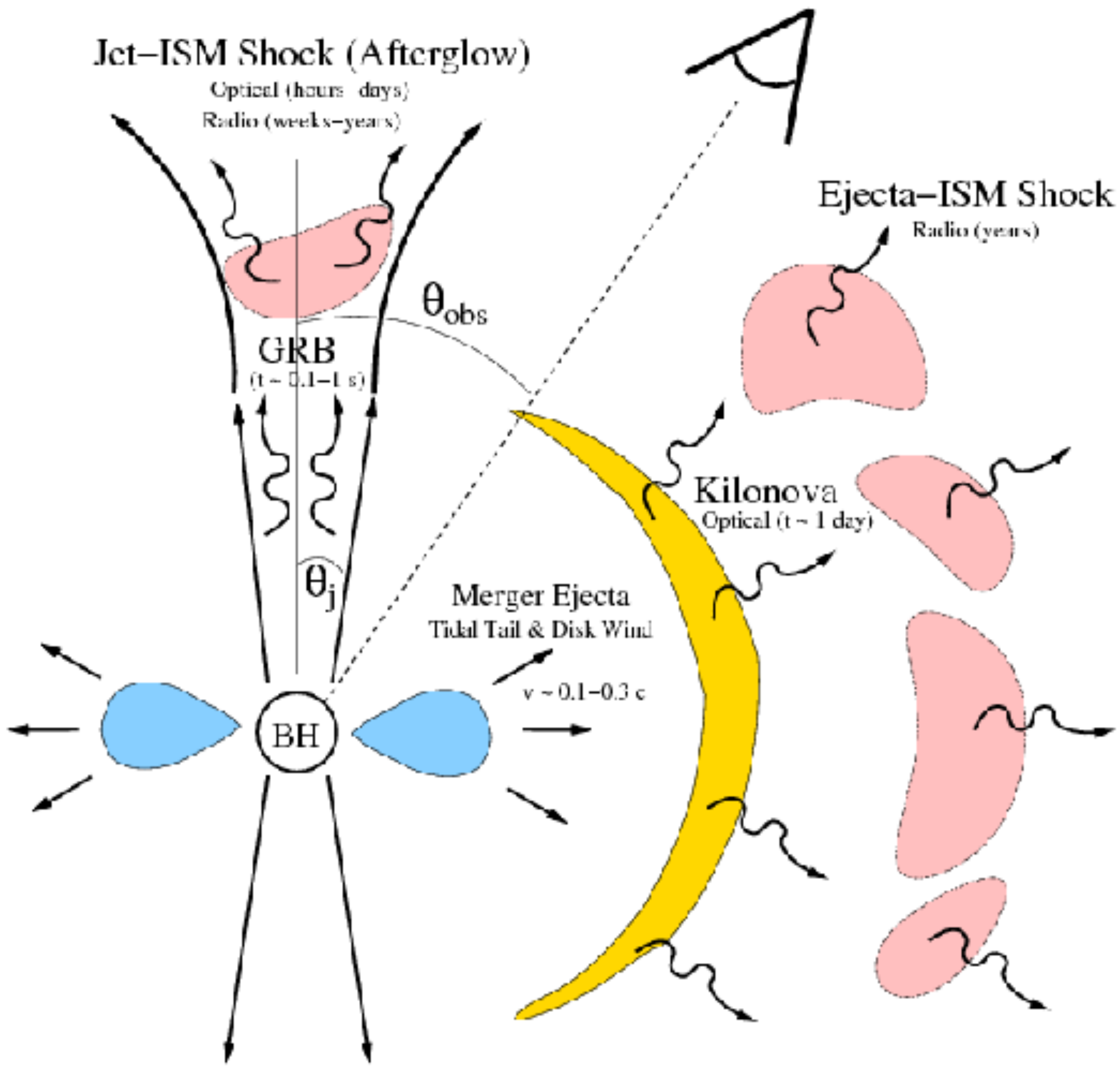
# Merger outcome




From Bartos, Brady, & Márka, CQG 30:123001 (2013)

# What happened?

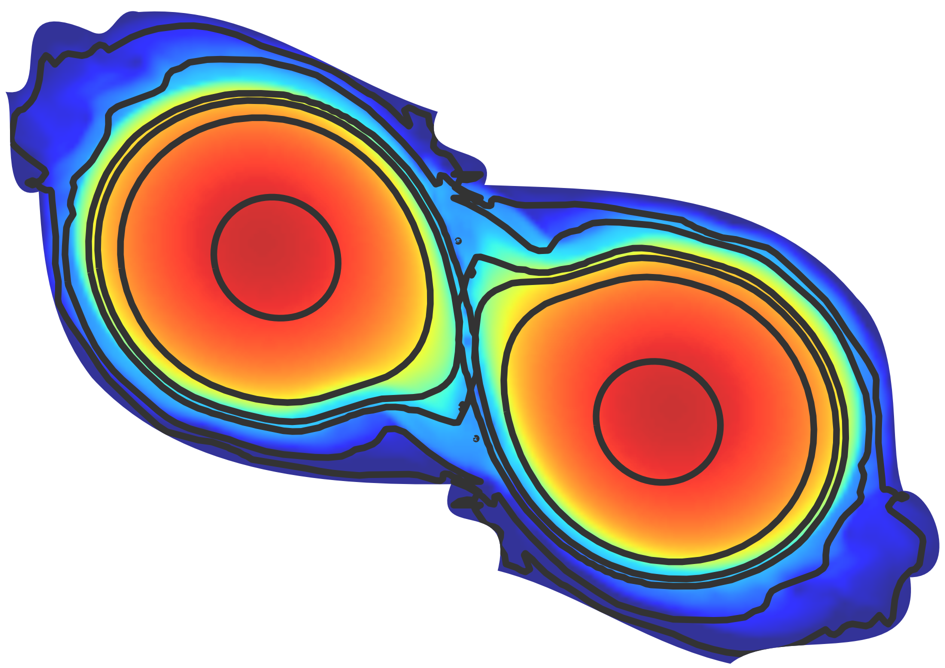



From Metzger & Berger 2012

- 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

# What have we learned about neutron stars?

# Tidal effects in NS mergers

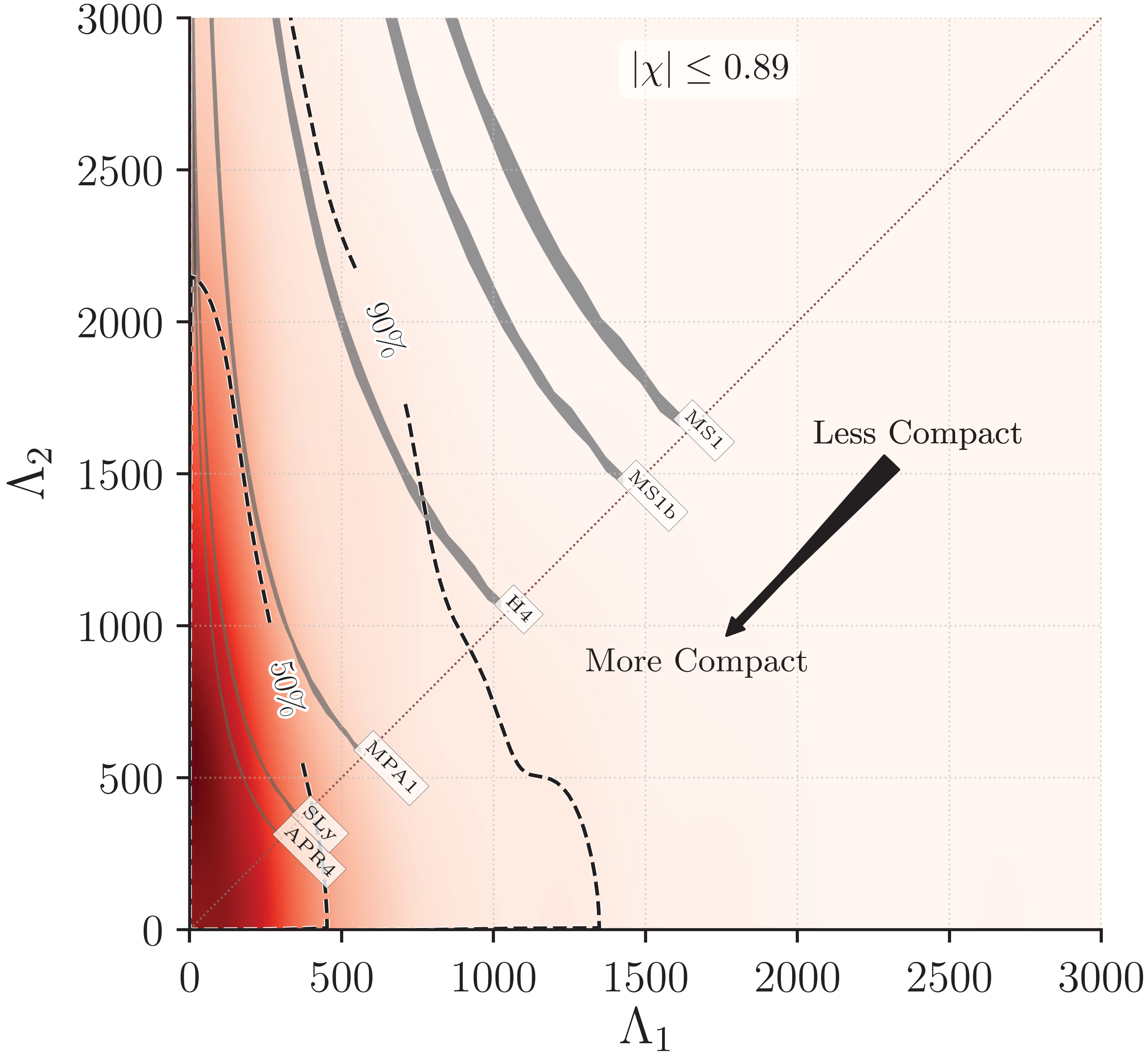


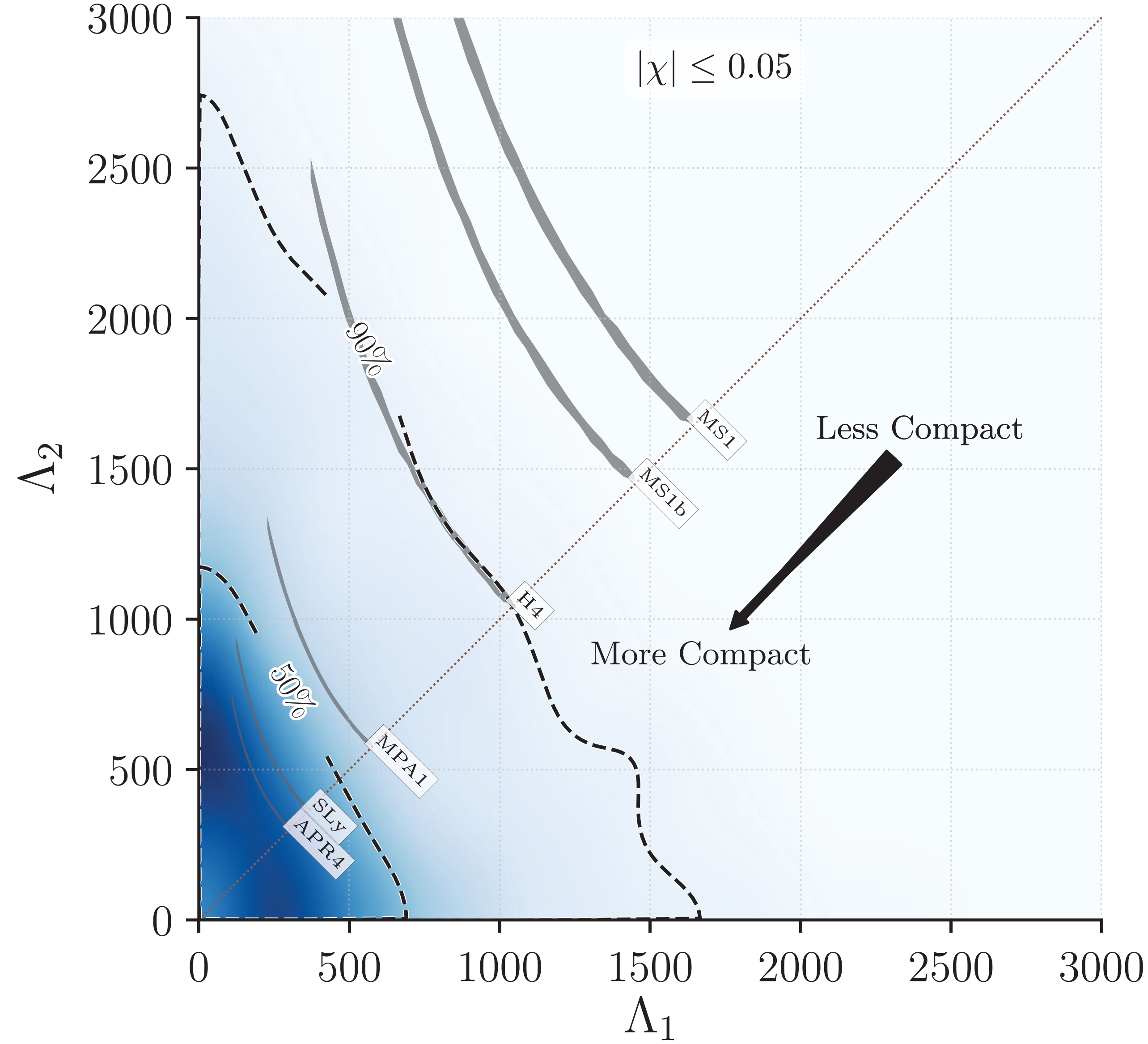
$$Q_{ij} = -\Lambda_2 \mathcal{E}_{ij}$$

- Part of the orbital energy goes into tidal deformation
- Accelerated inspiral
- Imprinted on the gravitational waves
- Constrains dimensionless tidal parameter

$$\boxed{\tilde{\Lambda}_2 = \frac{\Lambda_2}{M^5} \sim \frac{R^5}{M^5}}$$

# Constraints from GW170817



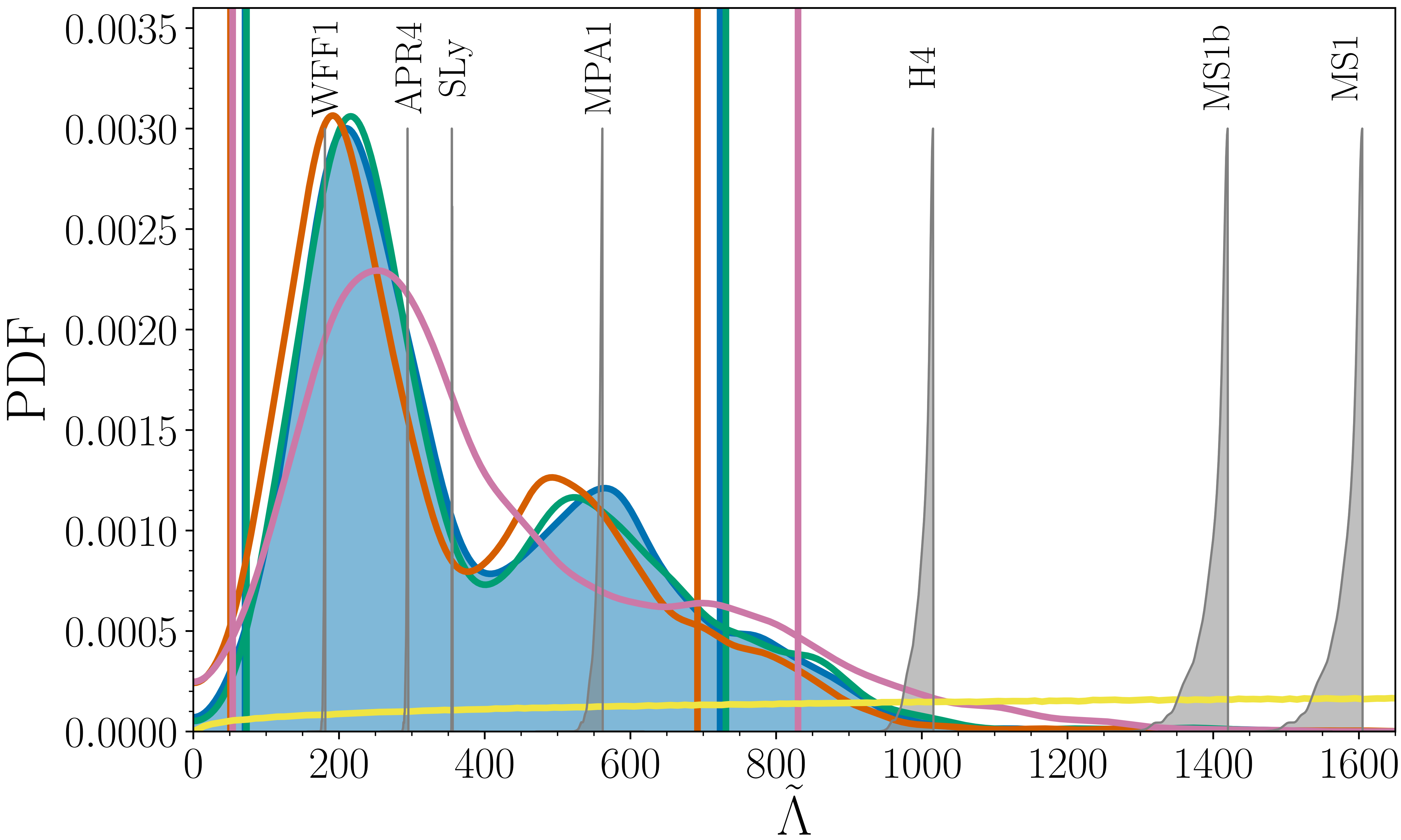




$$\frac{\bar{R}^5}{\bar{M}^5} \sim \tilde{\Lambda} = \frac{16}{13}\left[\frac{(M_A + 12M_B)M_A^4\tilde{\Lambda}_2^{(A)}}{(M_A+M_B)^5} + (A \leftrightarrow B)\right] \leq 800$$

See also De+ arXiv:1804.08583

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

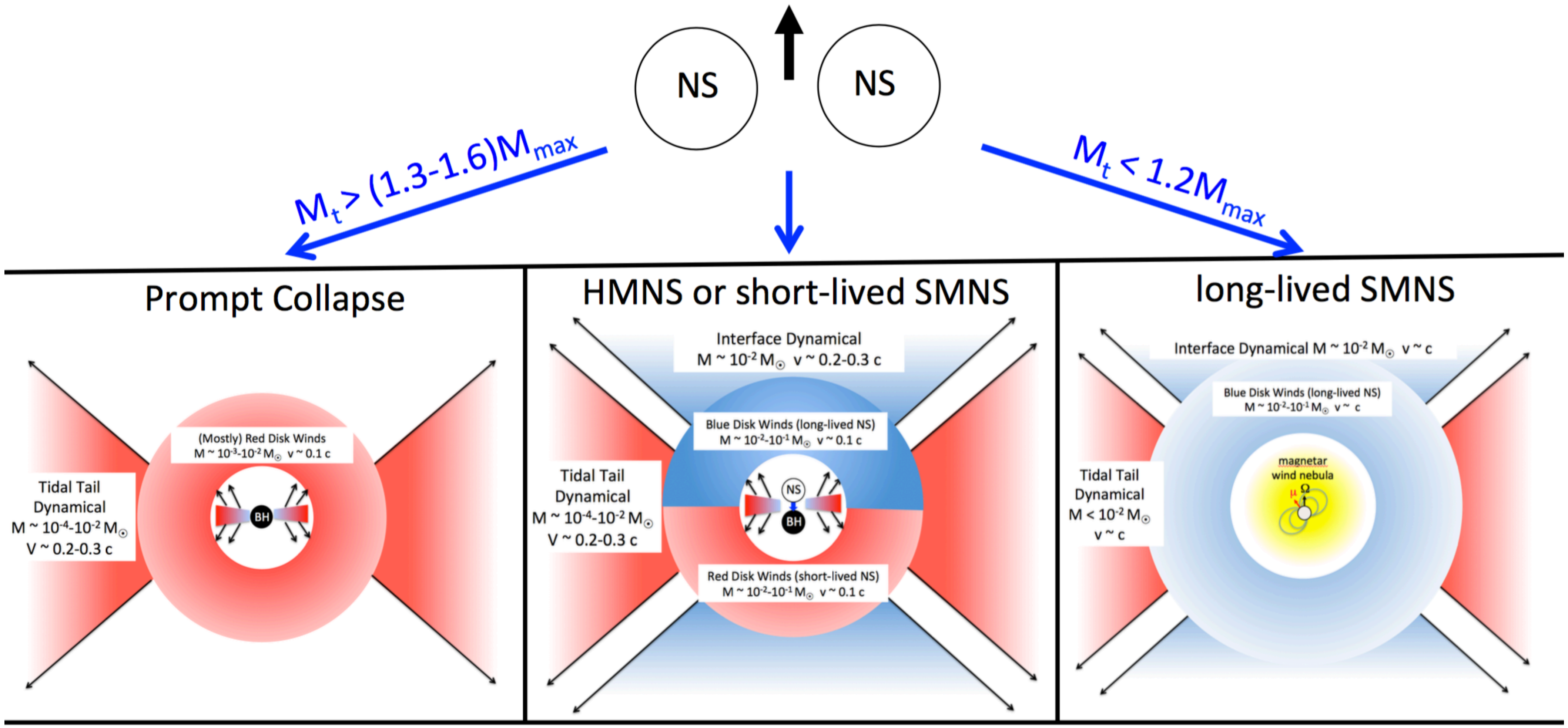
# Constraints from GW170817




See also De+ arXiv:1804.08583

LIGO/Virgo collaboration arXiv:1805.11579

# EOS constraints from GW+EM




From Margalit & Metzger 2017

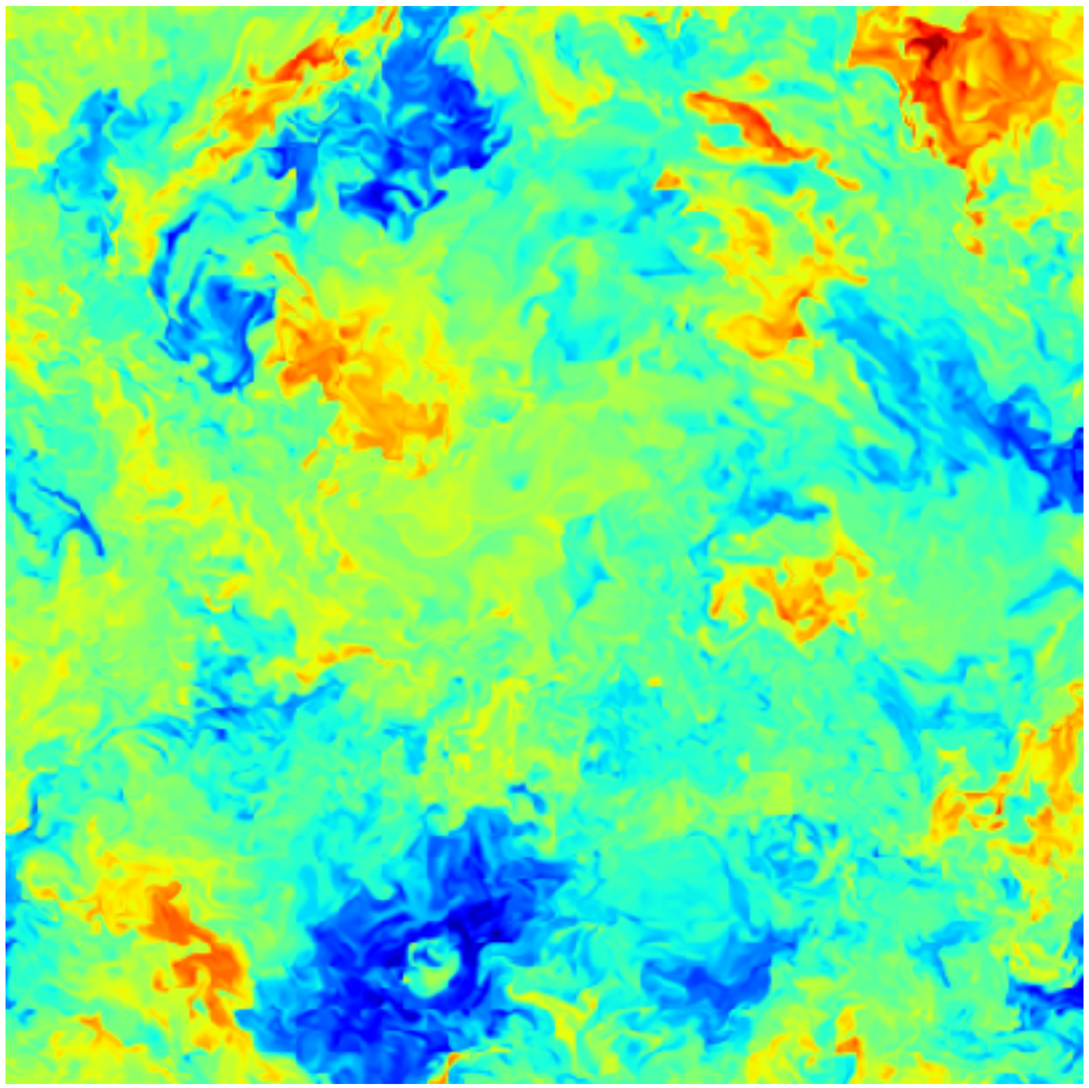
Assumption: no prompt BH formation —> EOS must be stiff enough

Assumption: no stable remnant —> EOS must soft enough

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

# WhiskyTHC

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

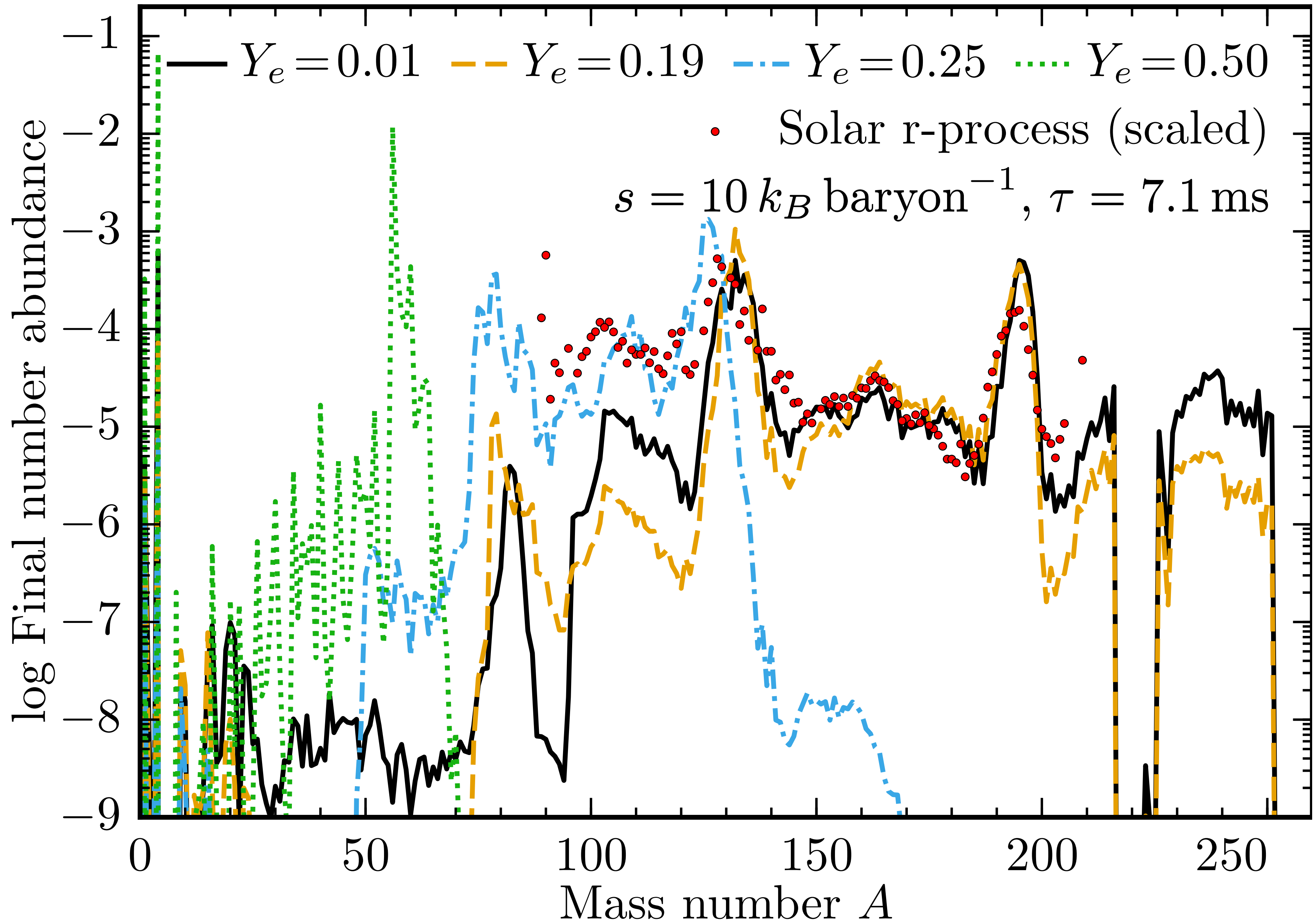


- Full-GR, dynamical spacetime*
- Nuclear EOS
- Effective neutrino treatment
- High-order hydrodynamics
- Open source!

* using the Einstein Toolkit metric solvers

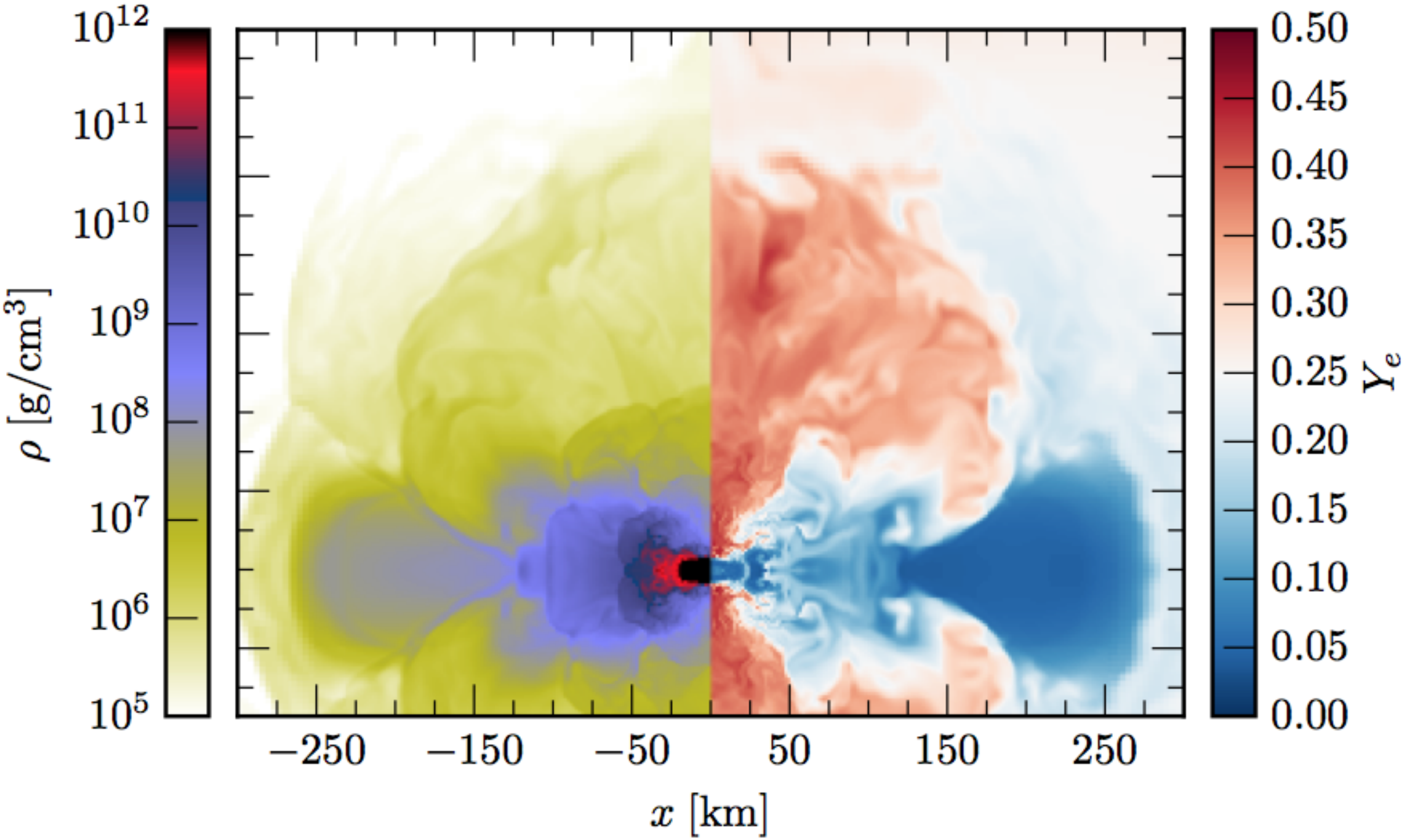
THC: Templated Hydrodynamics Code

# Strong and weak r-process




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

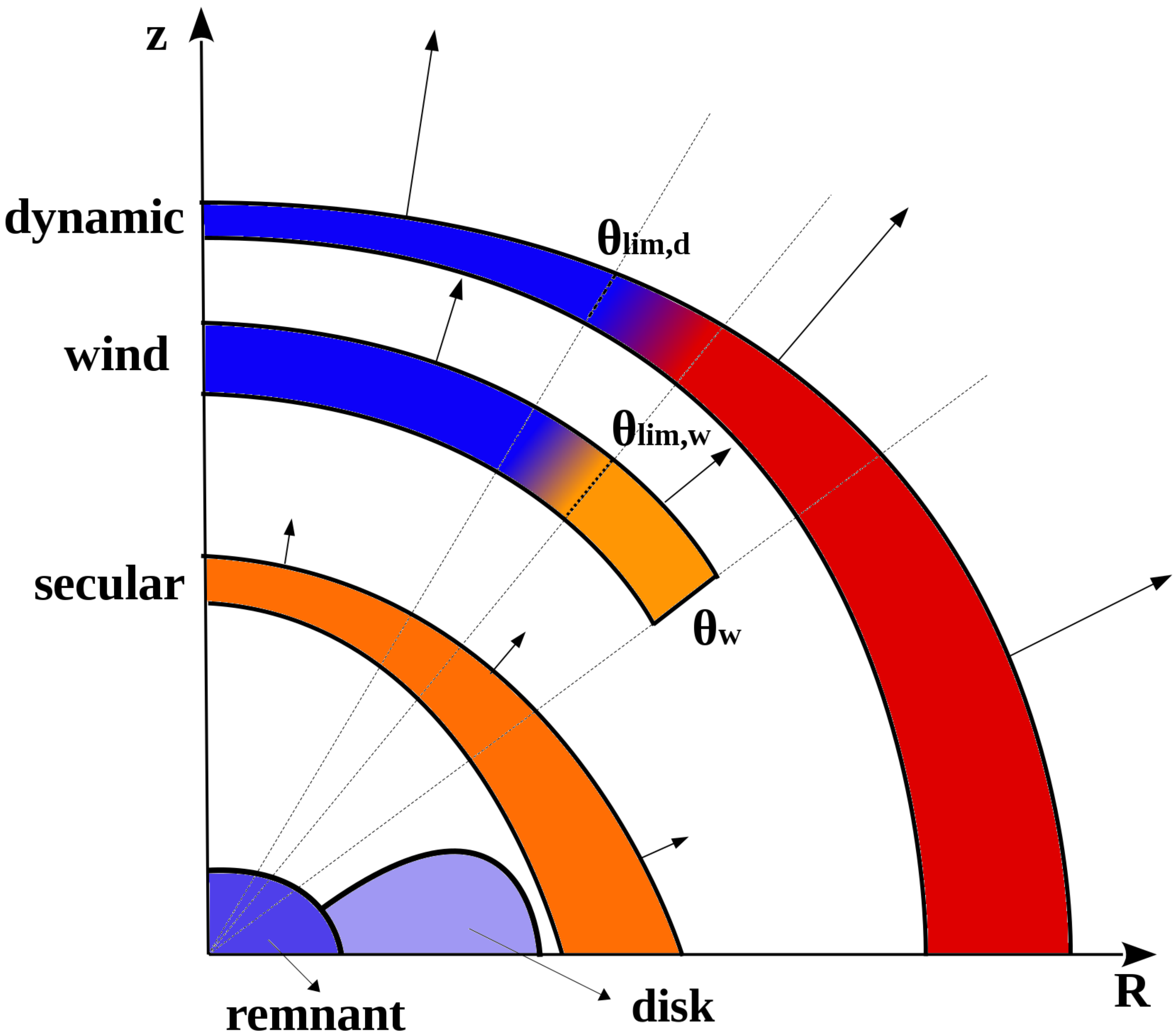
# Neutron rich outflows




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

**DR**, Galeazzi+ MRAS 460:3255 (2016)

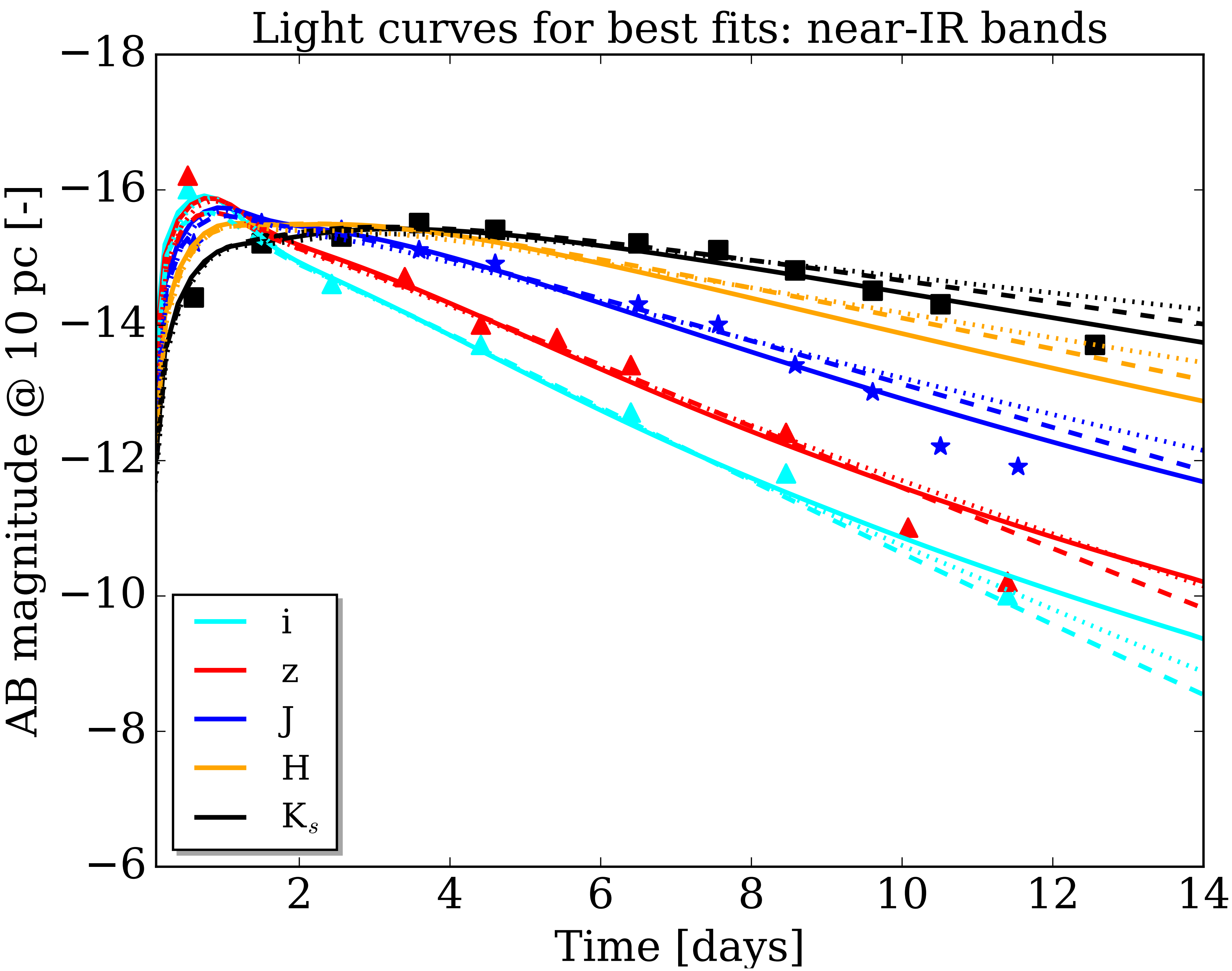
# Neutron rich outflows: model




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

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

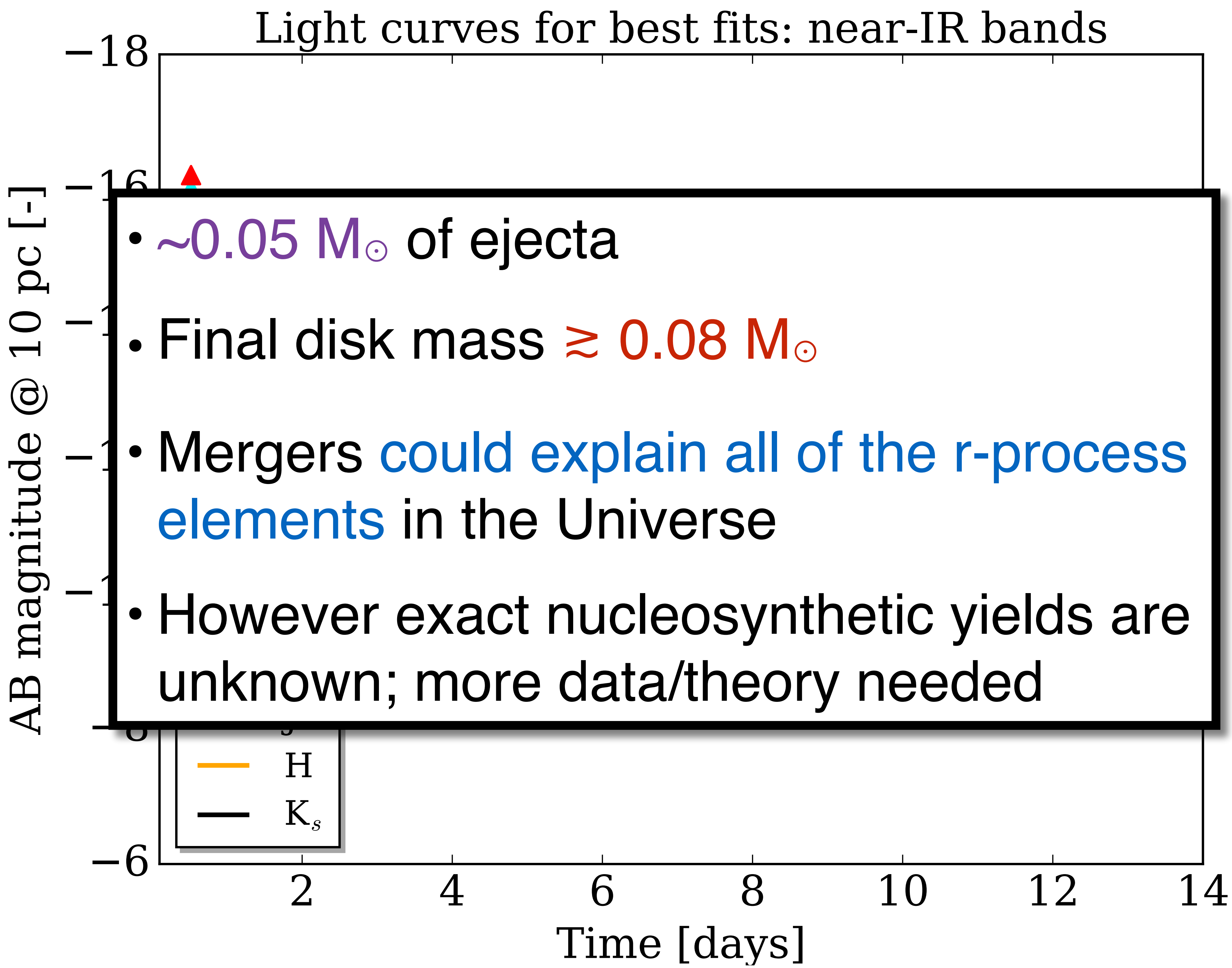
# Kilonova modeling




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

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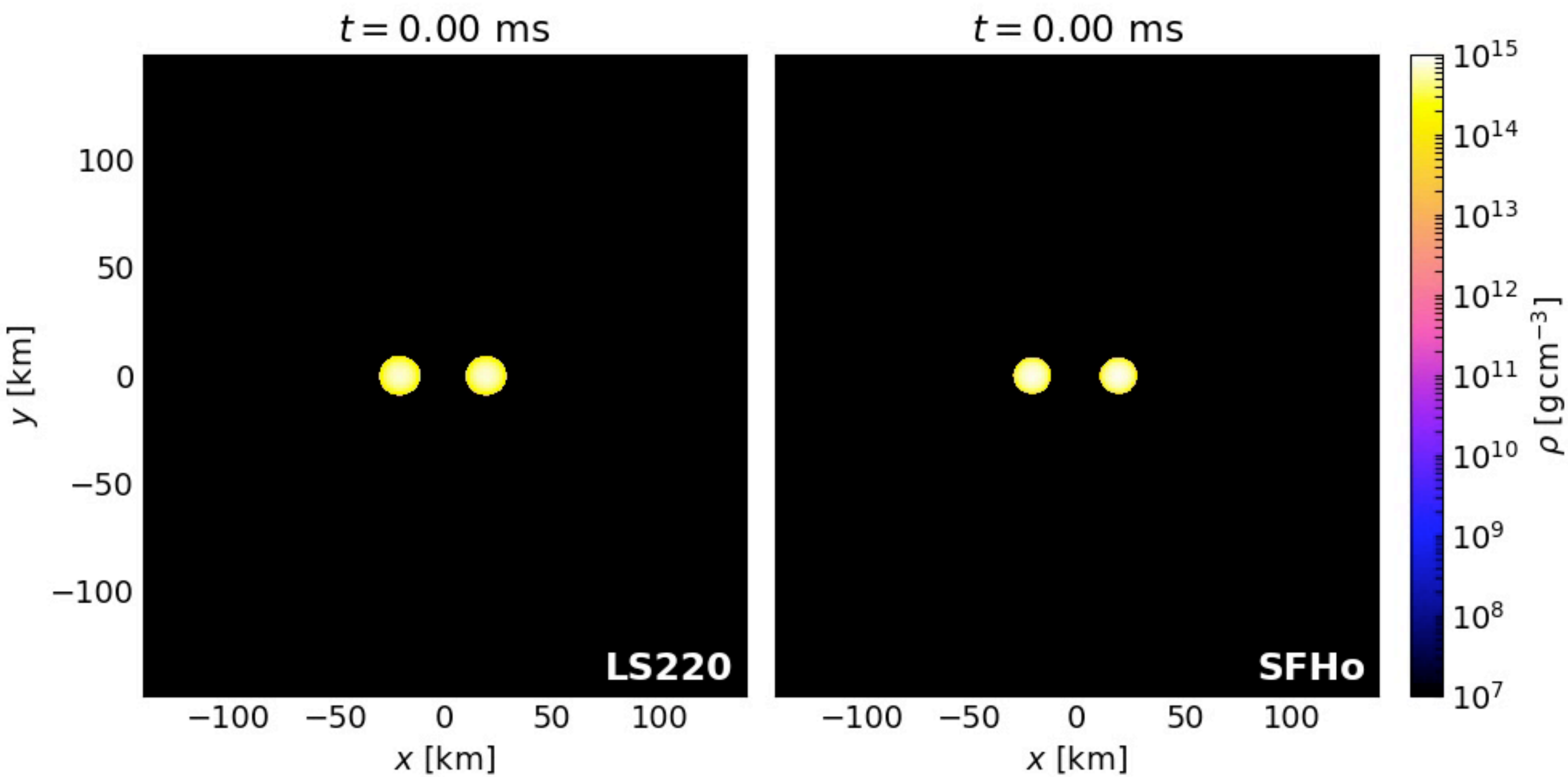
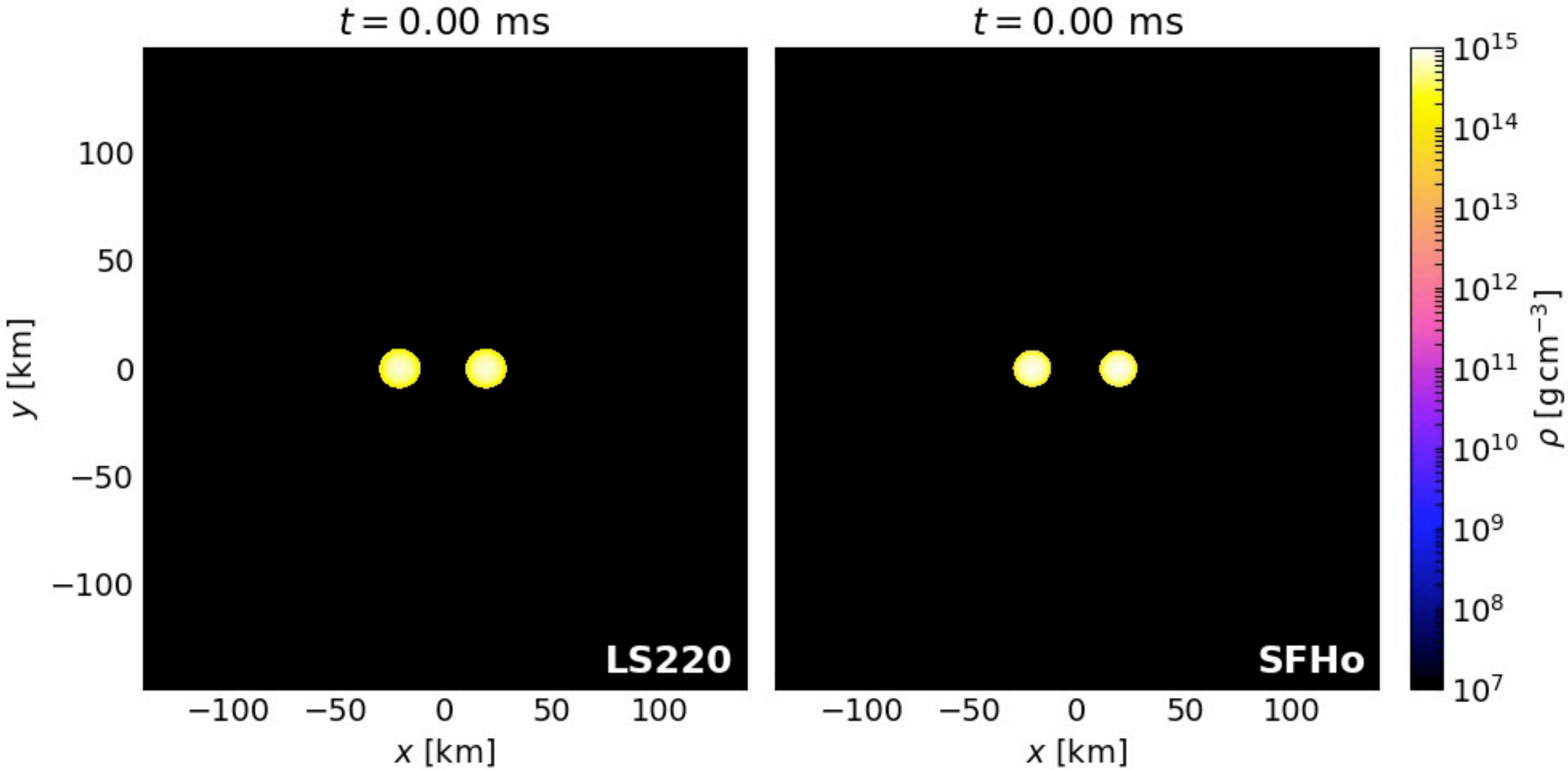
# Prompt collapse?




$(1.44 + 1.39)\ M_{\odot}$ — B1913 + 13

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

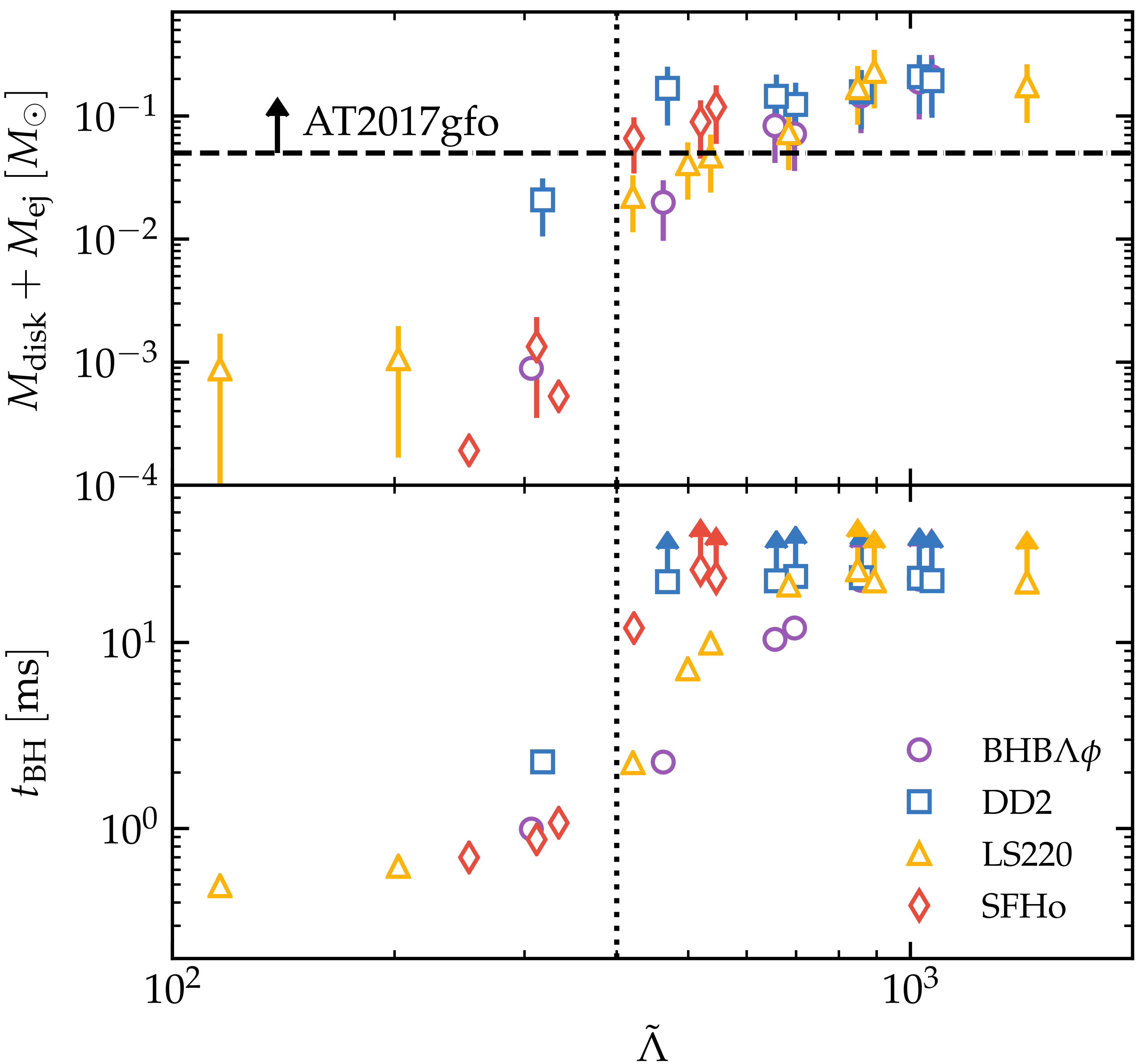
# Prompt collapse?




$(1.44 + 1.39)\ M_\odot$ — B1913 + 13

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

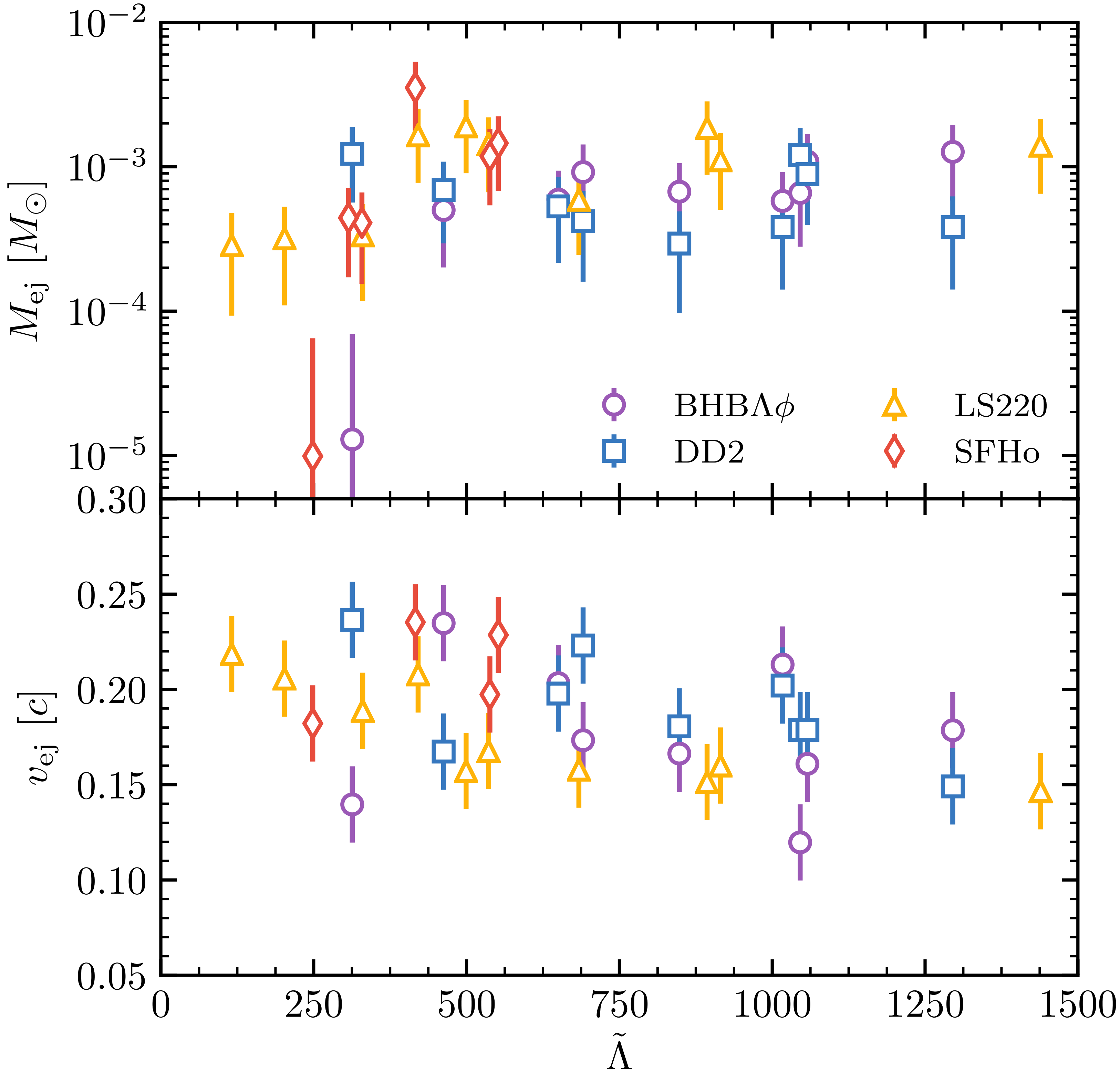
# GW170817: delayed BH formation




See also Bauswein+ 2017 ApJL 850:L34

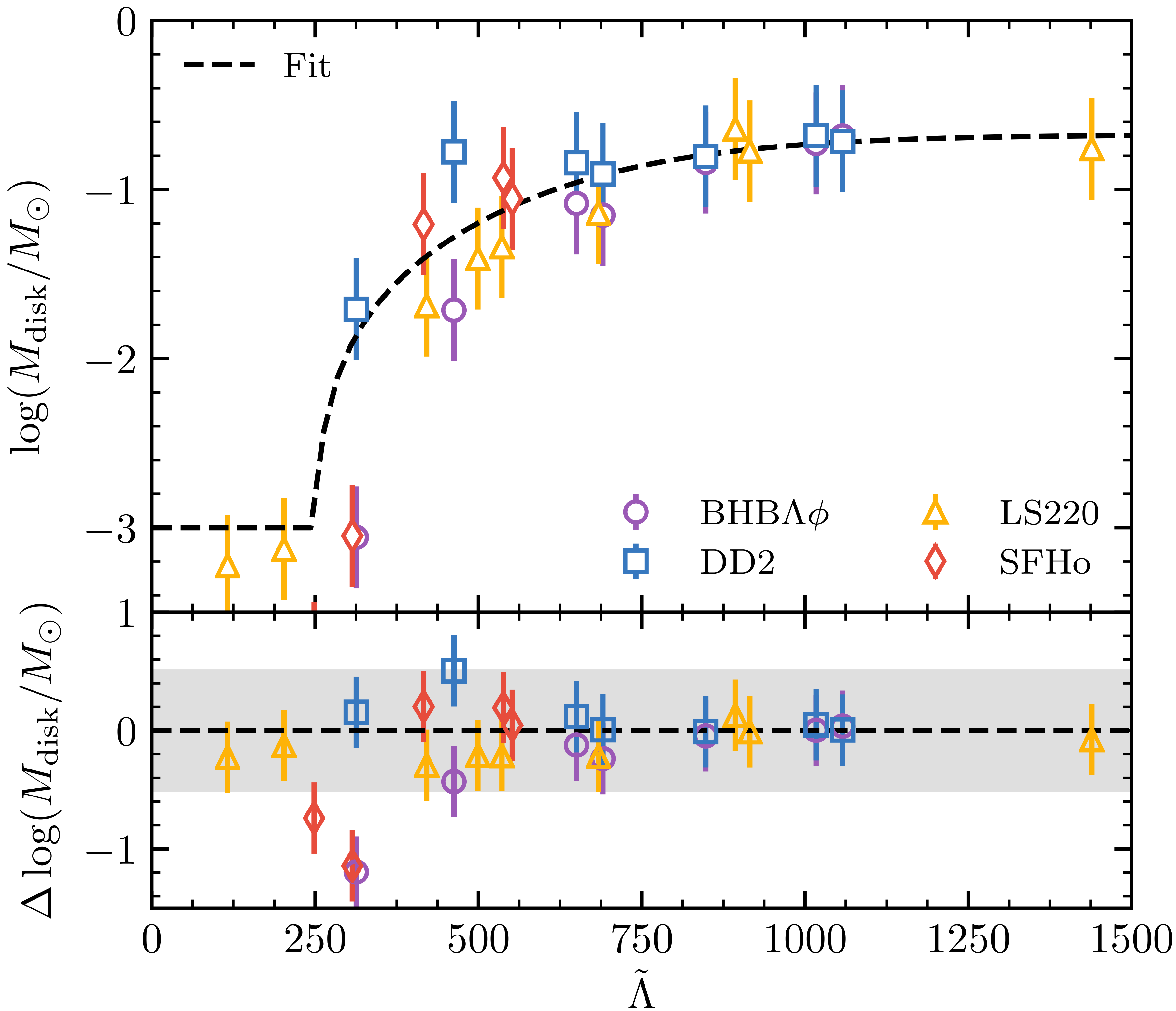
**DR**, Perego, Zappa, ApJL 852:L29 (2018)

# Dynamical ejecta mass



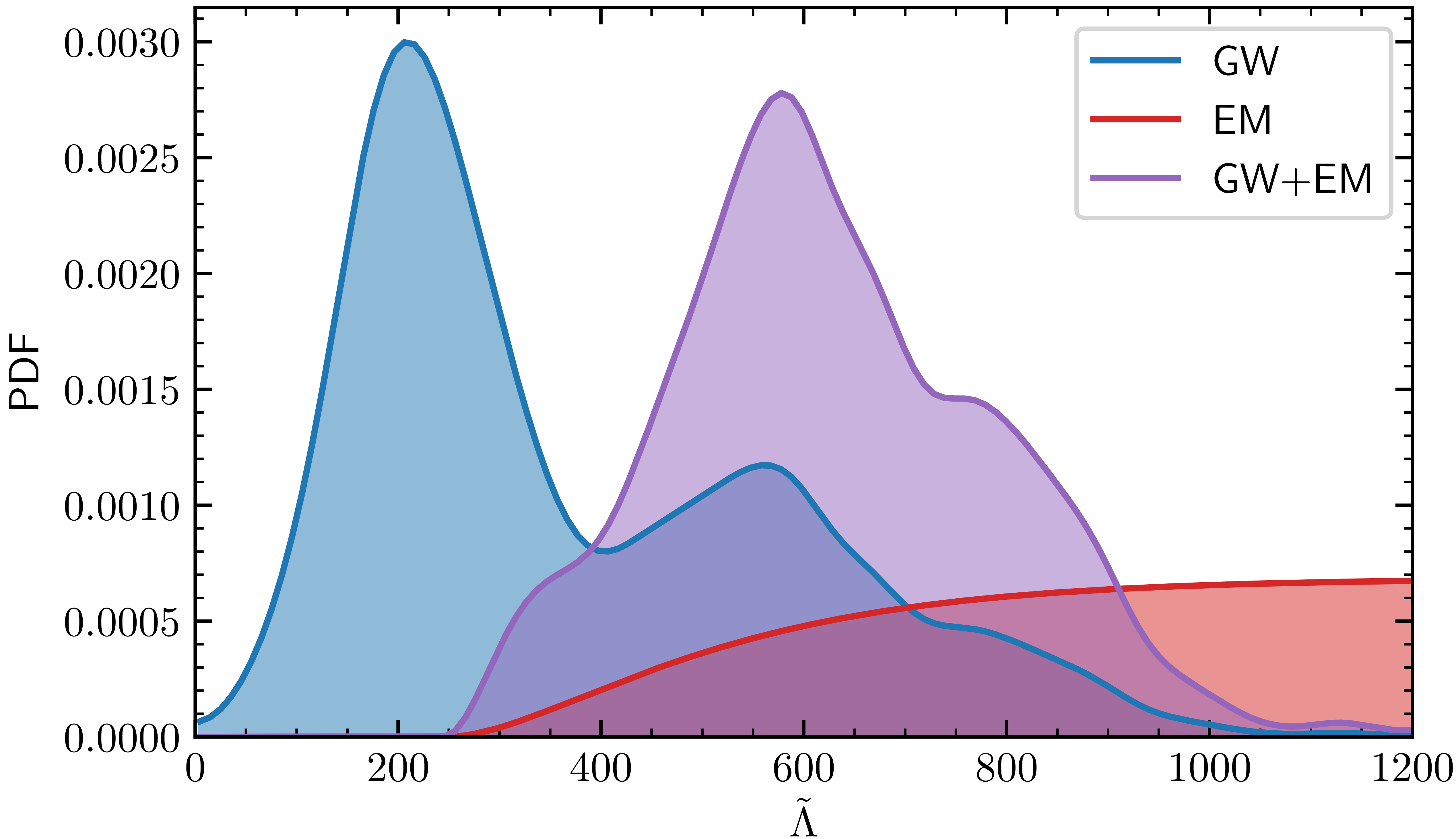

**DR** et al. (2018), in prep

# Disk masses



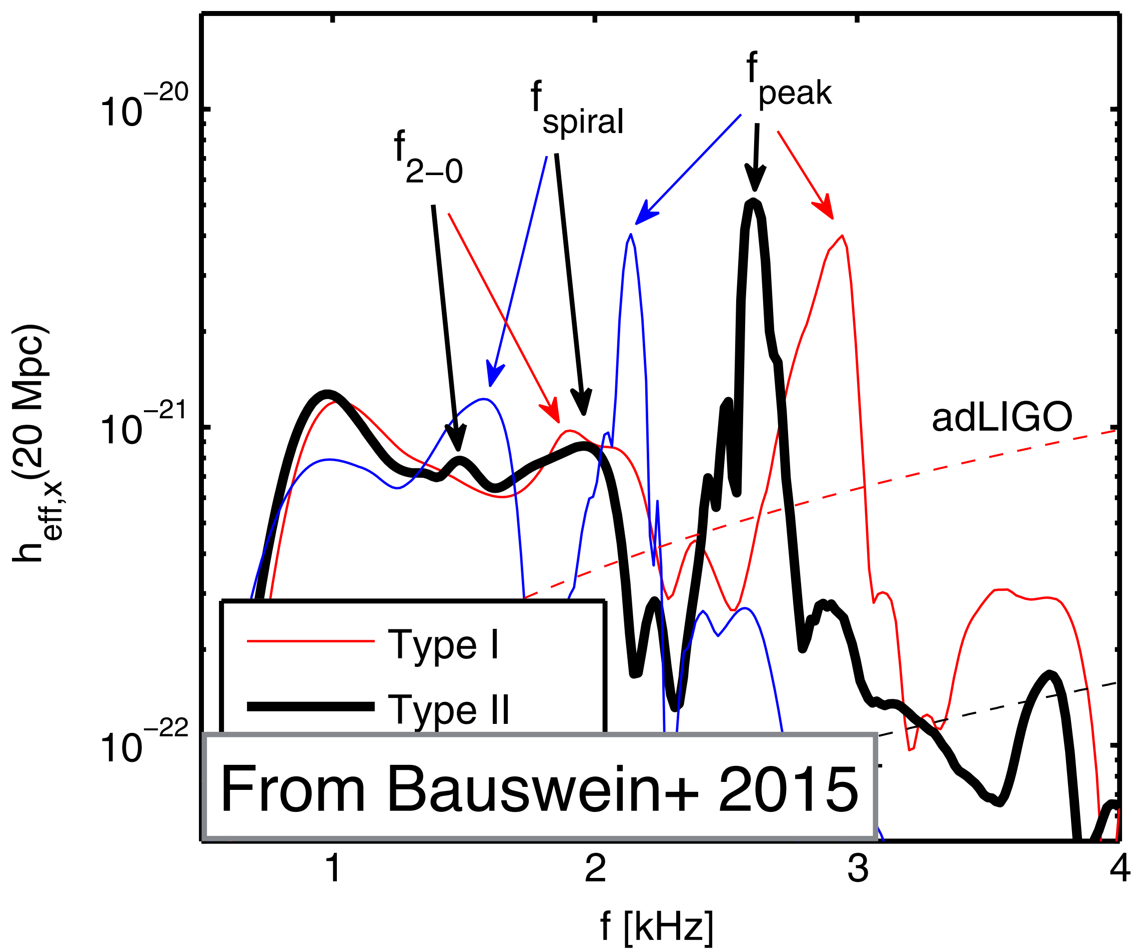

**DR** et al. (2018), in prep

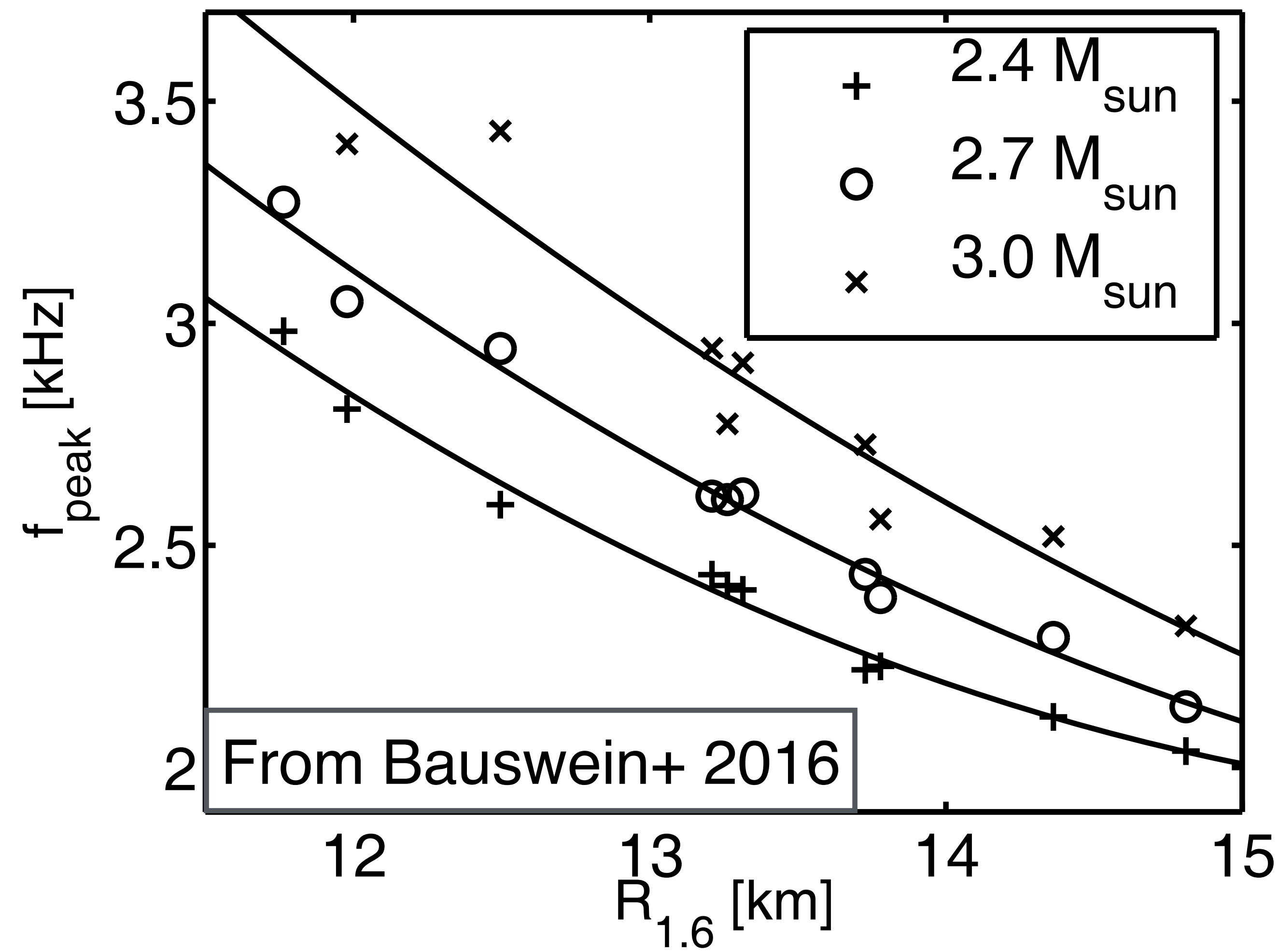
# Preliminary constraints



# Future prospects:
# post-merger signal

# Postmerger peak frequency

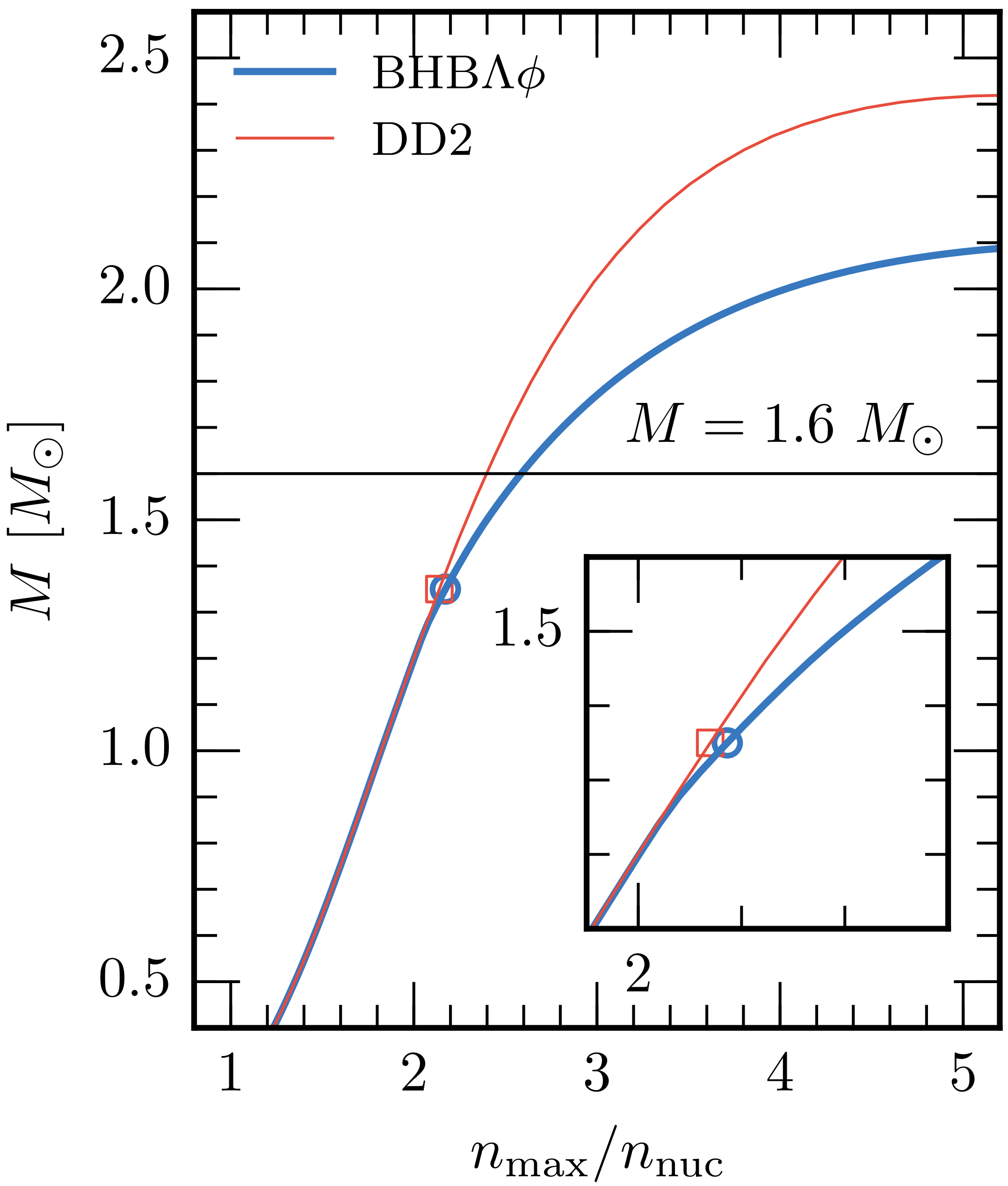



- Post-merger signal has a characteristic peak frequency
- $f_{peak}$ correlates with the NS radius
- Small statistical uncertainty, systematics not understood yet

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

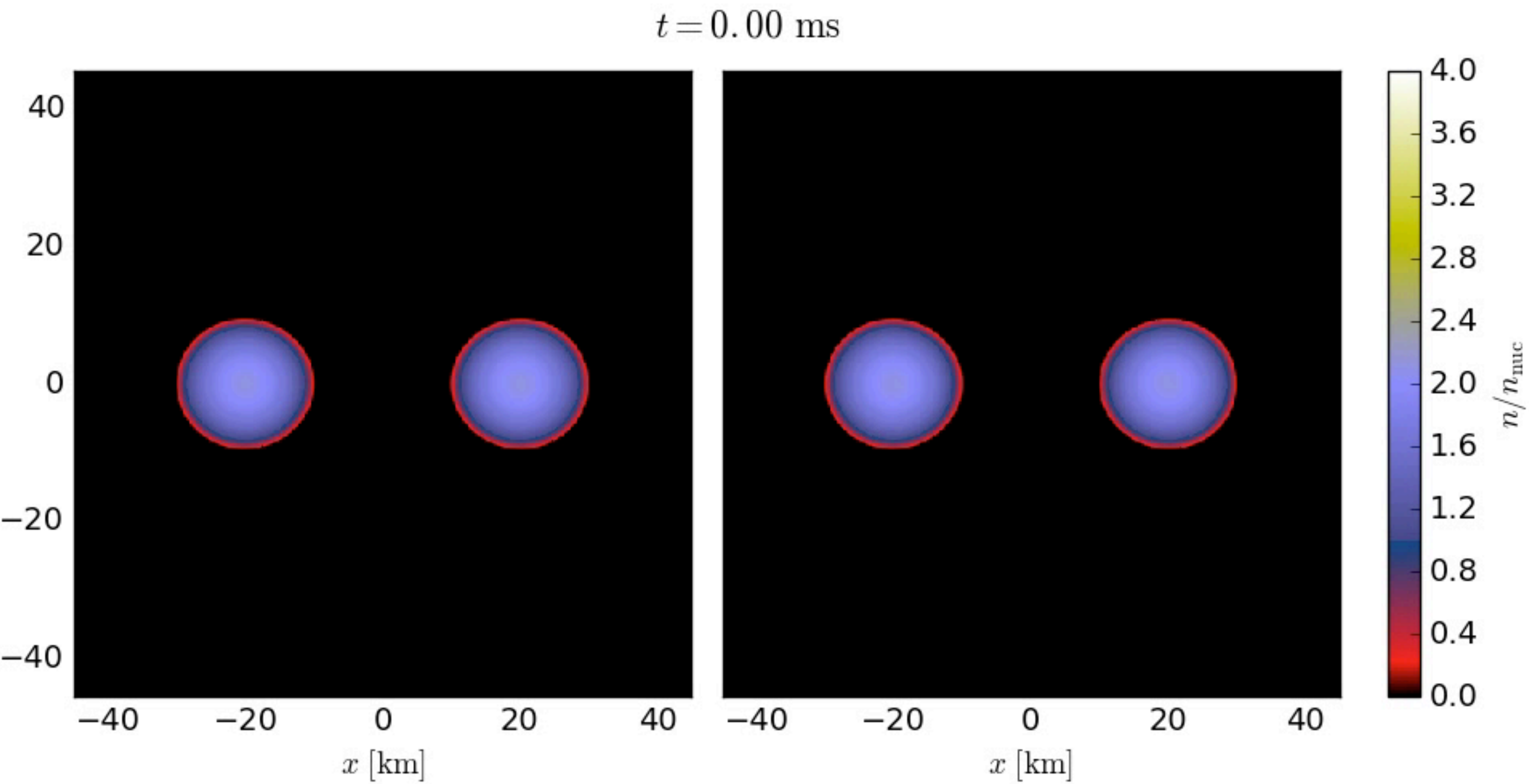
# Extreme-density physics




- Same EOS at low density; softening at high density
- Typical binaries have the same $\tilde{\Lambda}$!
- Different compactness, collapse time of remnant
- Can we tell them apart? Yes with the postmerger!

**DR**, Bernuzzi, Del Pozzo+, ApJL 842:L10 (2017)

# Effect on the evolution

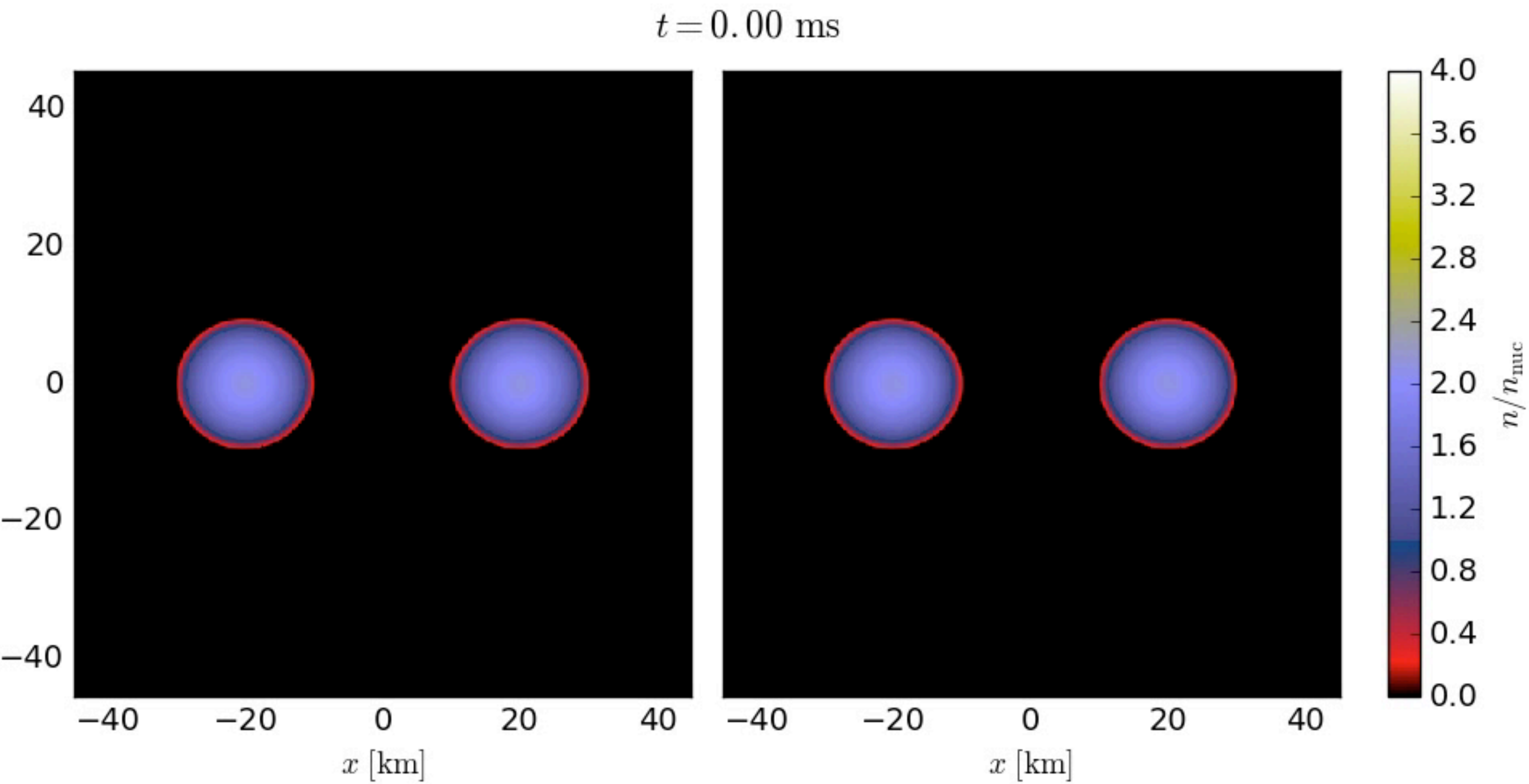



Hyperons

No Hyperons

**DR**, Bernuzzi, Del Pozzo+, ApJL 842:L10 (2017)

# Effect on the evolution

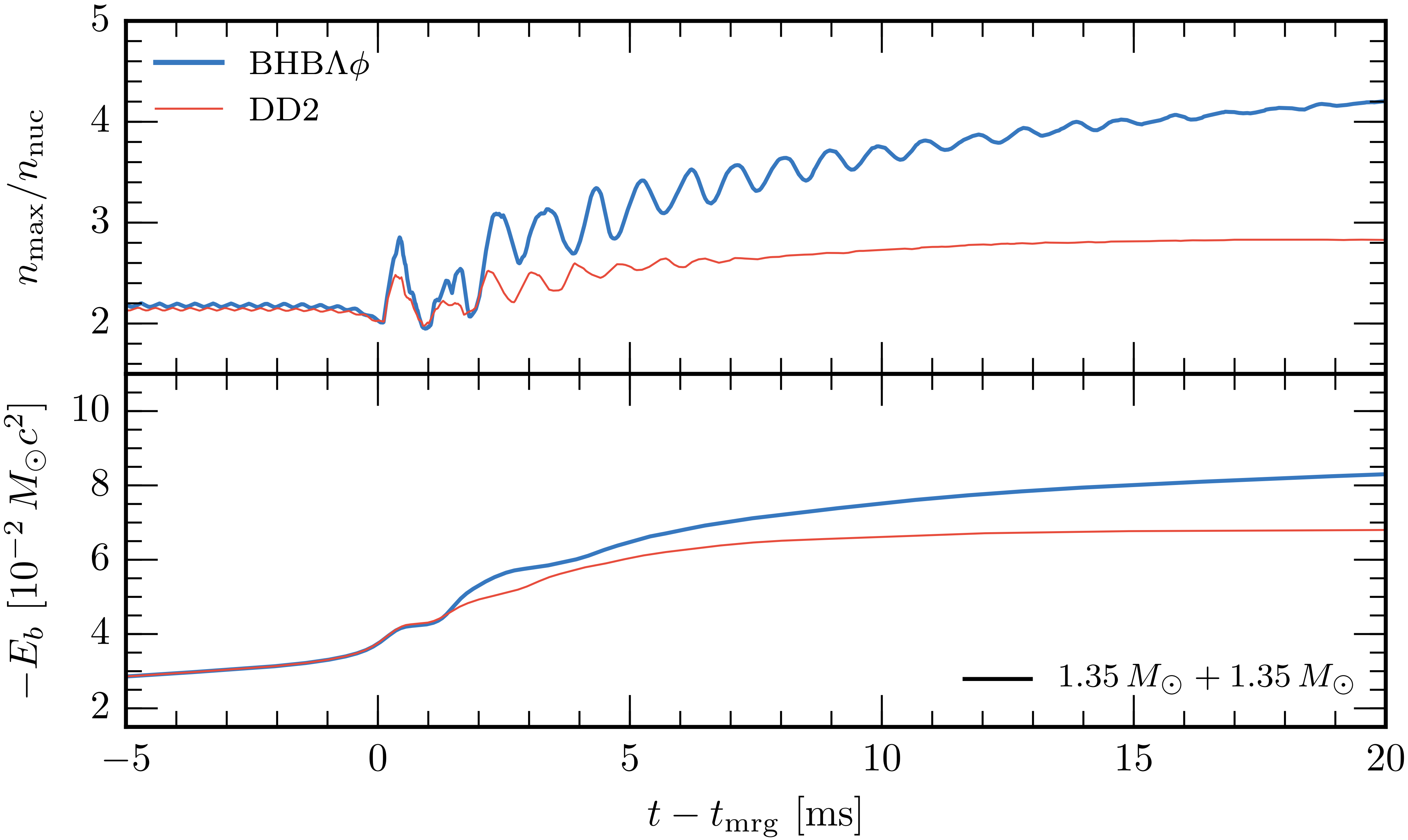



Hyperons

No Hyperons

**DR**, Bernuzzi, Del Pozzo+, ApJL 842:L10 (2017)

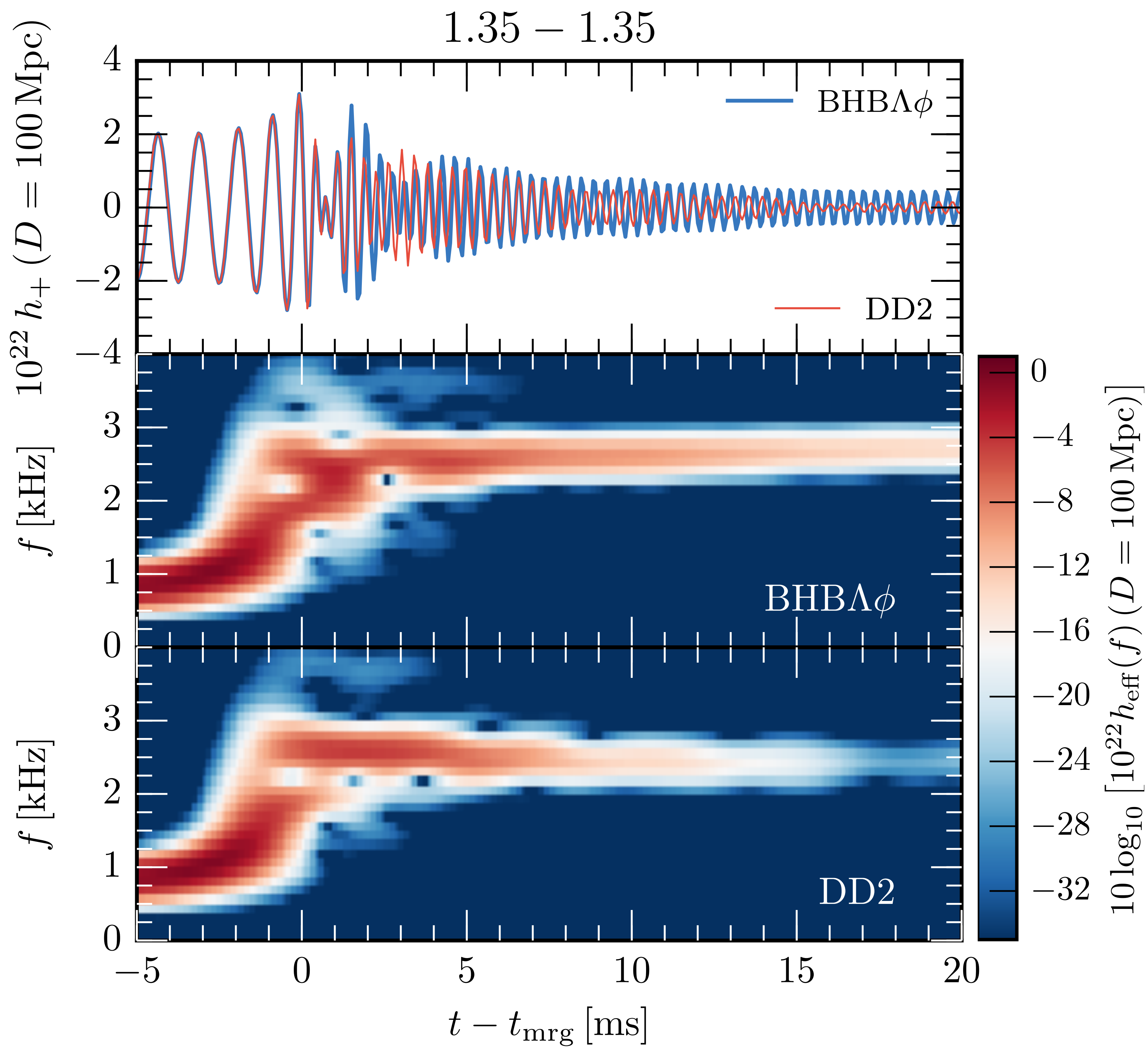
# Binding energy




High-density EOS encoded in the binding energy

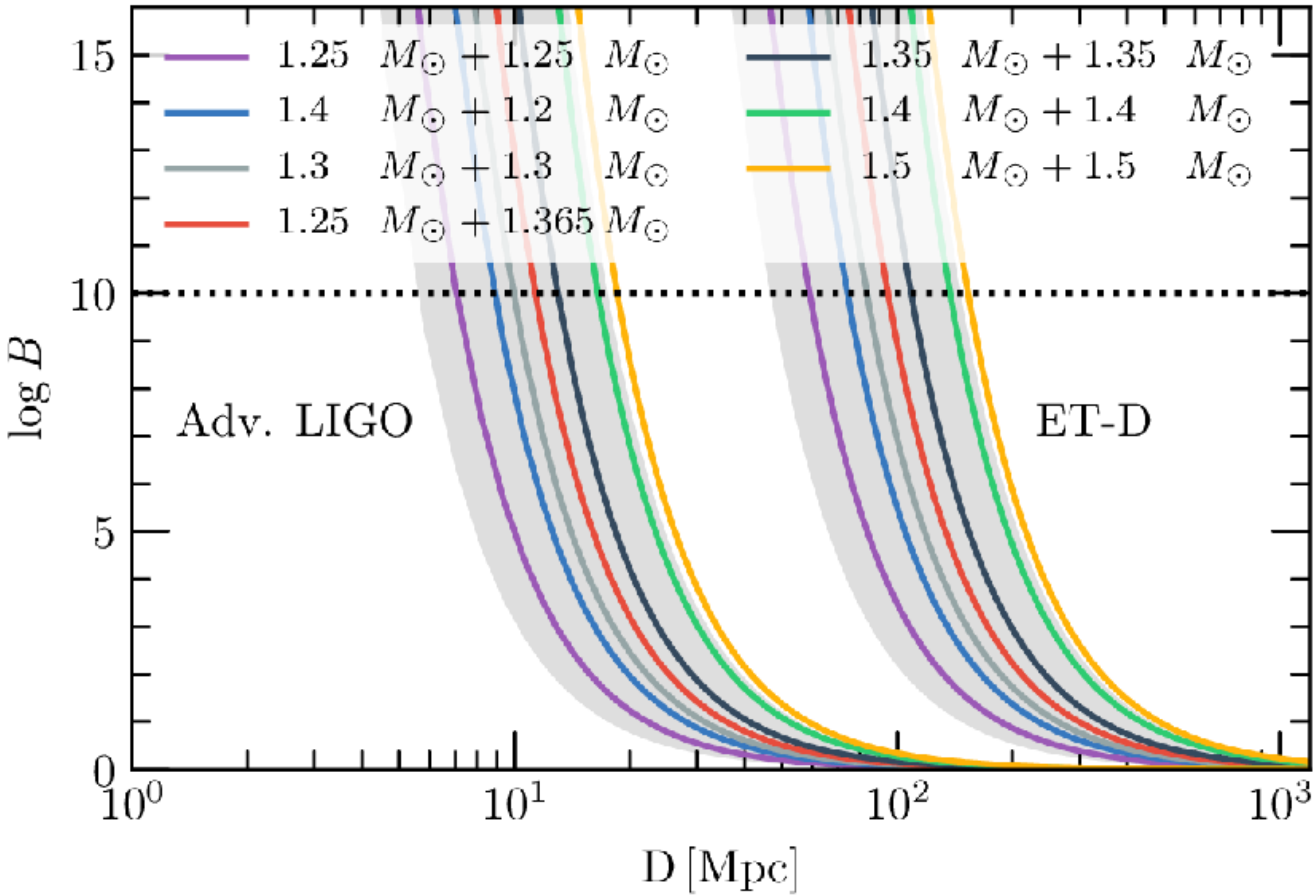
**DR**, Bernuzzi, Del Pozzo+, ApJL 842:L10 (2017)

# Gravitational waveform



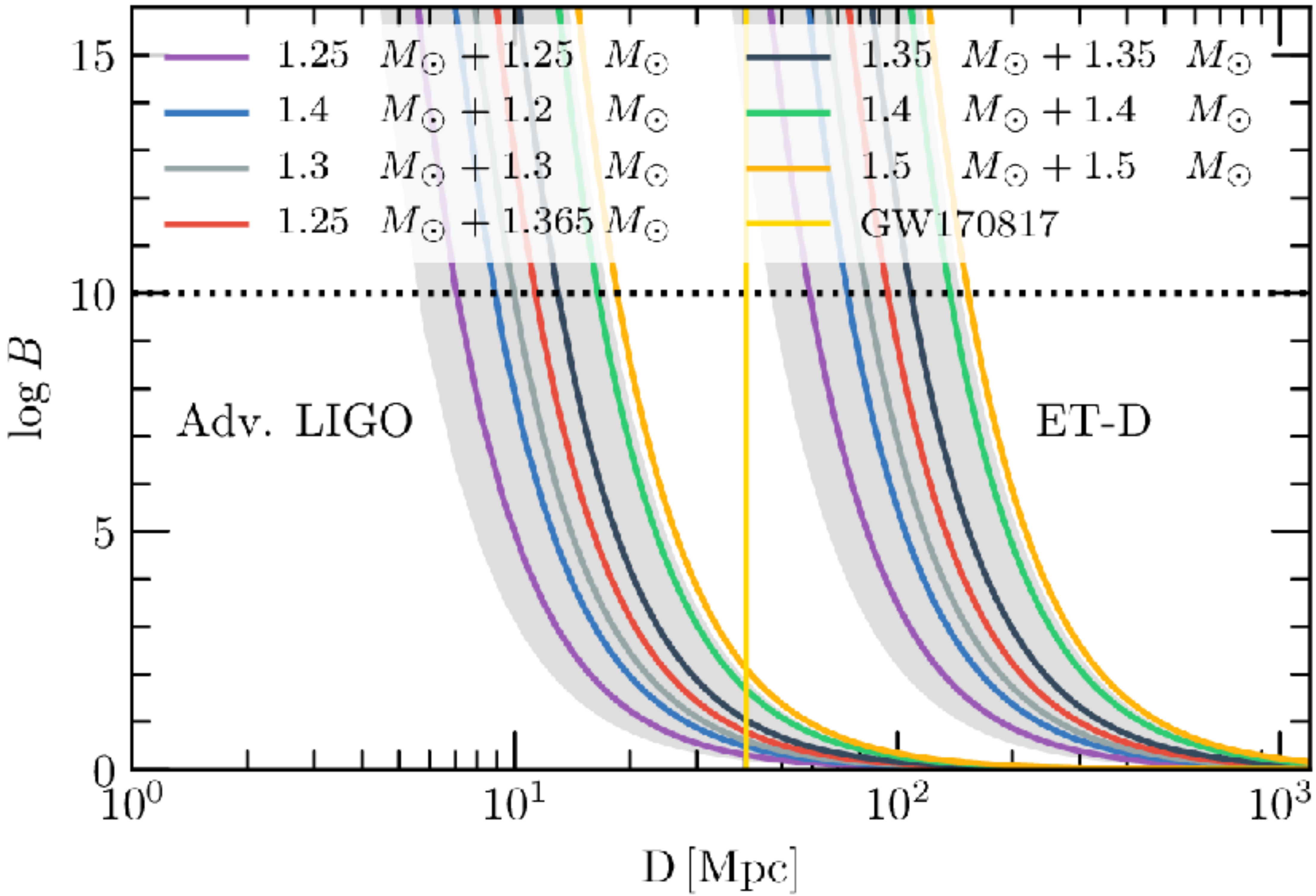

**DR**, Bernuzzi, Del Pozzo+, ApJL 842:L10 (2017)

# Detectability



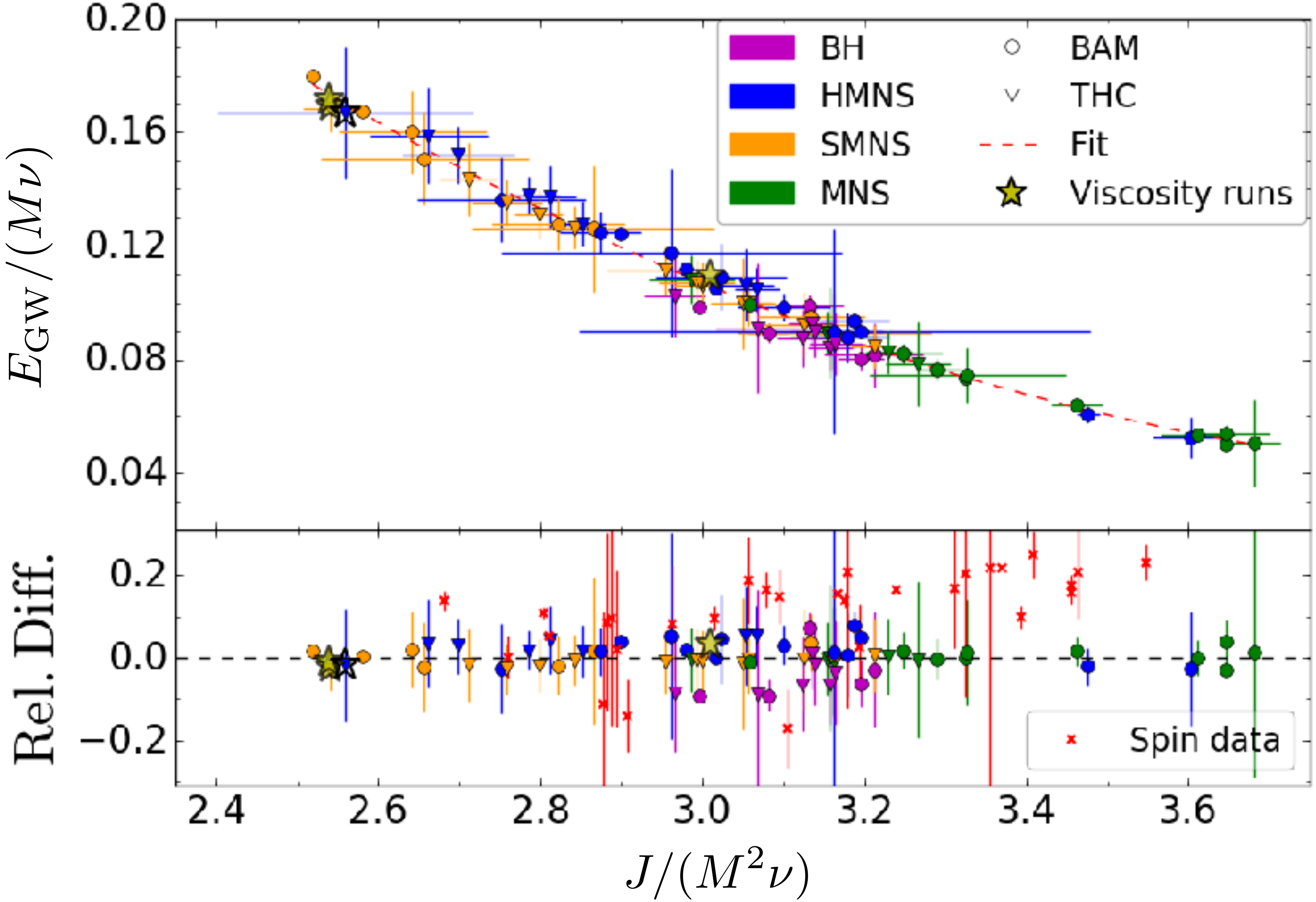

**DR**, Bernuzzi, Del Pozzo+, ApJL 842:L10 (2017)

# Detectability




**DR**, Bernuzzi, Del Pozzo+, ApJL 842:L10 (2017)

# GW luminosity in the postmerger

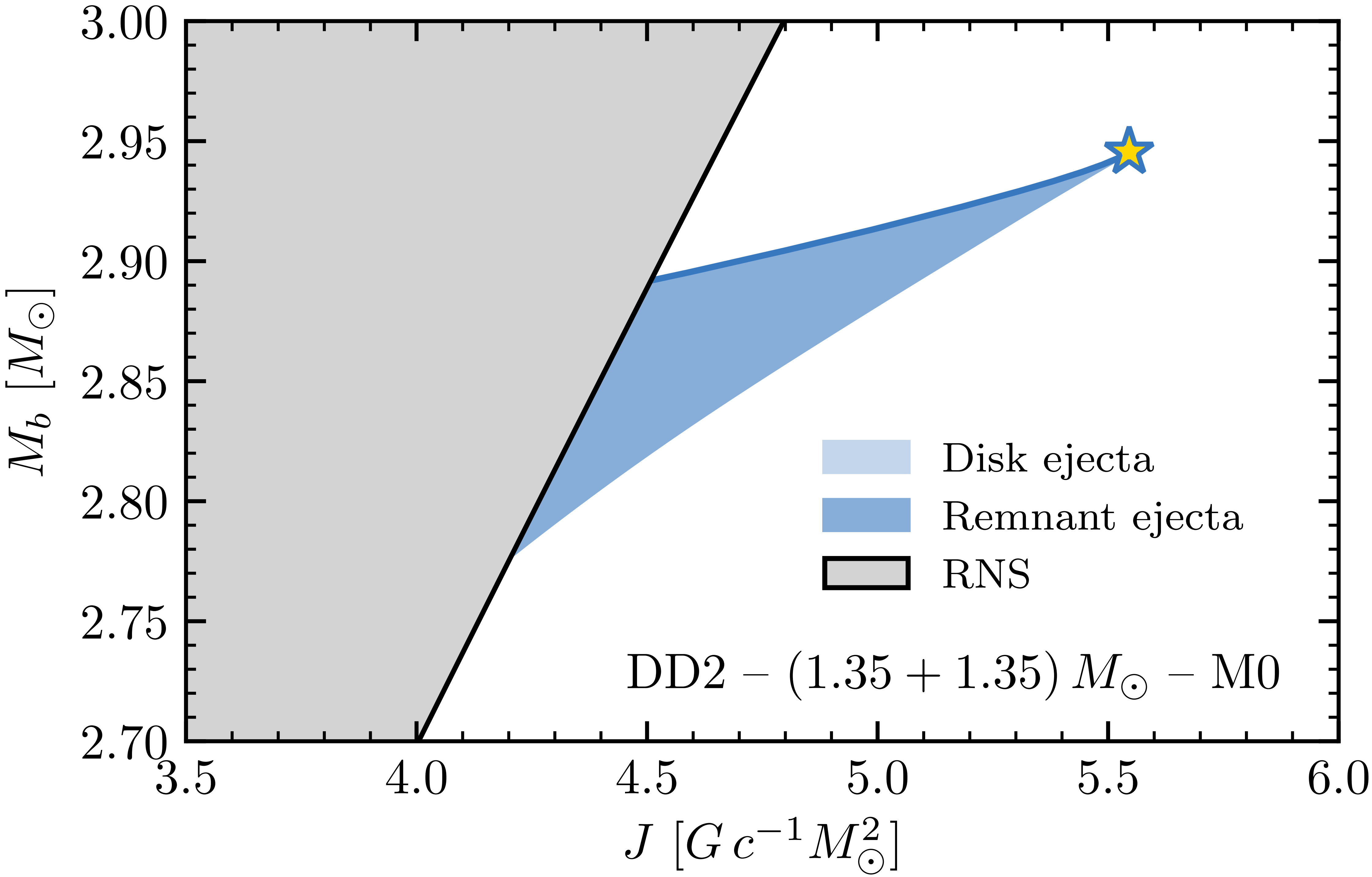





Zappa, Bernuzzi, **DR**+, RPL 120:111101 (2018)

# Future prospects:
# long-lived remnants

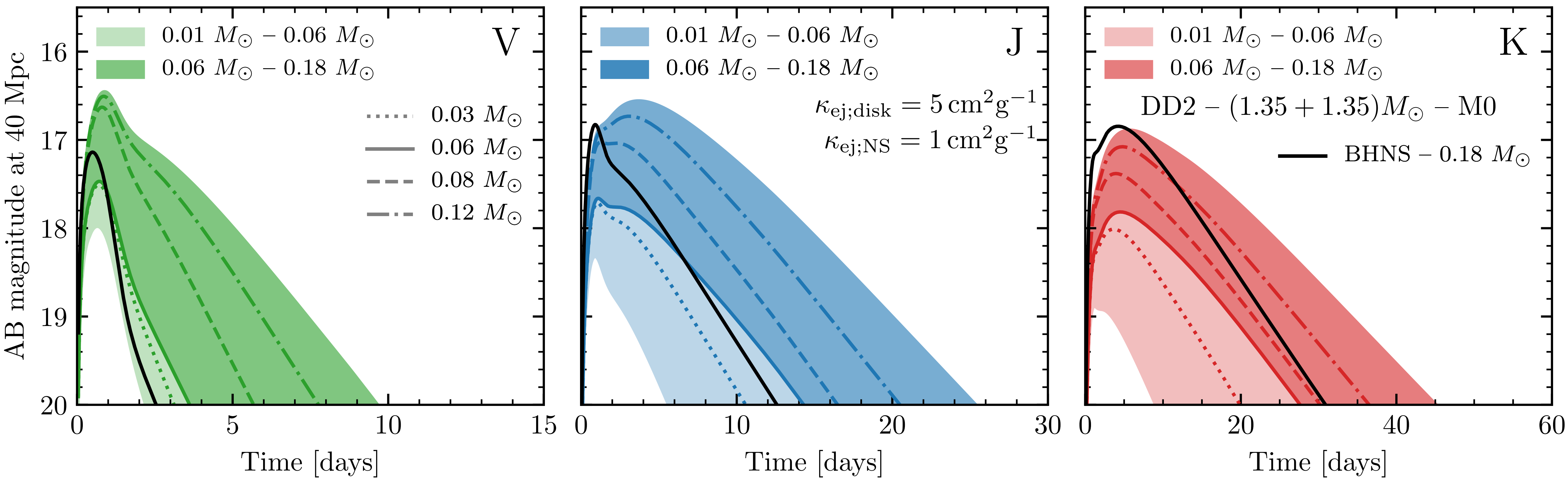
# Long-lived remnants (I)




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 phase is key to reveal the EOS at the highest densities
- The next GW event might look very differently!

http://www.computational-relativity.org