Microphysics effects in core-collapse supernovae and neutron star mergers

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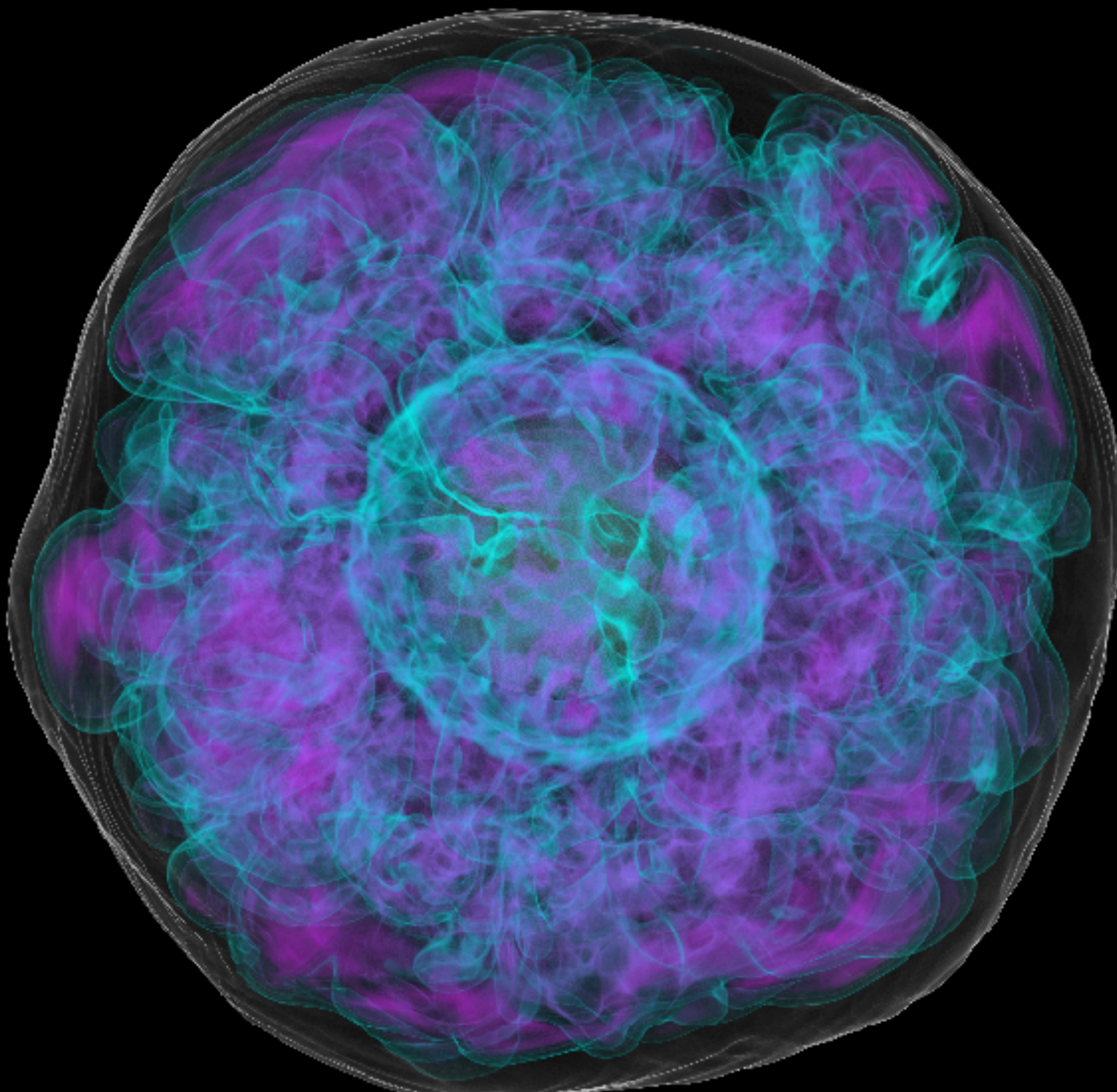
[2] Taplin Member, Institute for Advanced Study

Physics of Core-Collapse Supernovae and Compact Star Formations
Waseda University — March 21, 2018

Core-collapse supernovae

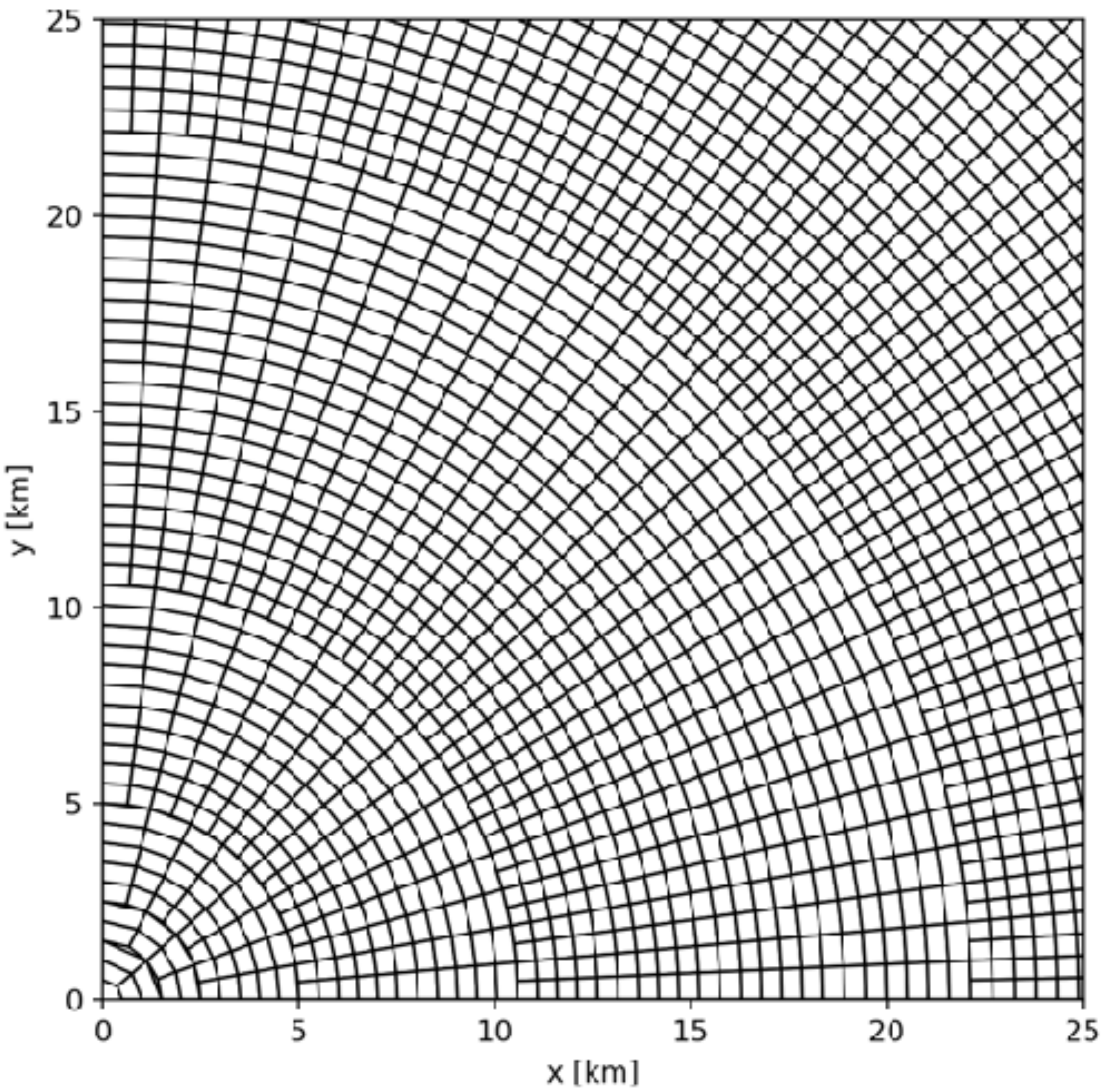


Current efforts in Princeton*

- Explosion mechanism: crucial physical dependencies
  [Burrows, Vartanyan, …, **DR** 2018 — Vartanyan, Burrows, **DR** et al., 2018]
- Low-mass progenitors: electron-capture vs regular CCSNe
  [**DR**, Burrows, et al. 2017]
- Neutrinos: synthetic signals for galactic events
  [Seadrow, … **DR** et al., in prep 2018]
- Gravitational waves: what can we learn?
  [Morozova, **DR** et al. 2018]
- Stay tuned for 3D results!

* and collaborators at LANL, LLNL

Fornax

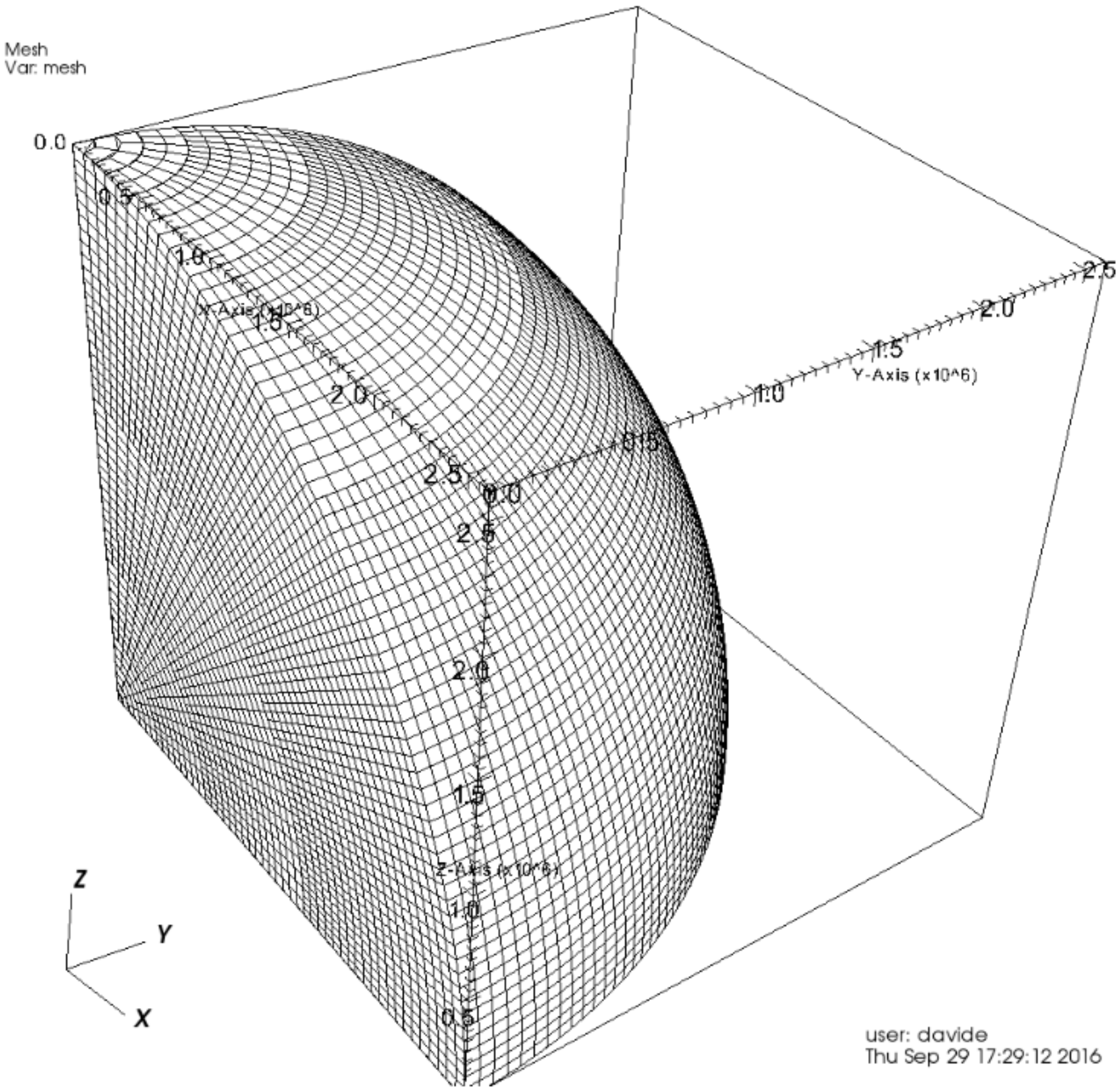


- A new CCSN code
- Spherical dendritic grid
- Multi-dimensional M1 neutrino O(v/c) transport
- Newtonian with effective GR potential
- 1D, 2D, and 3D

See also Just's talk

Dolence, Skinner, … **DR** in prep 2018

Fornax



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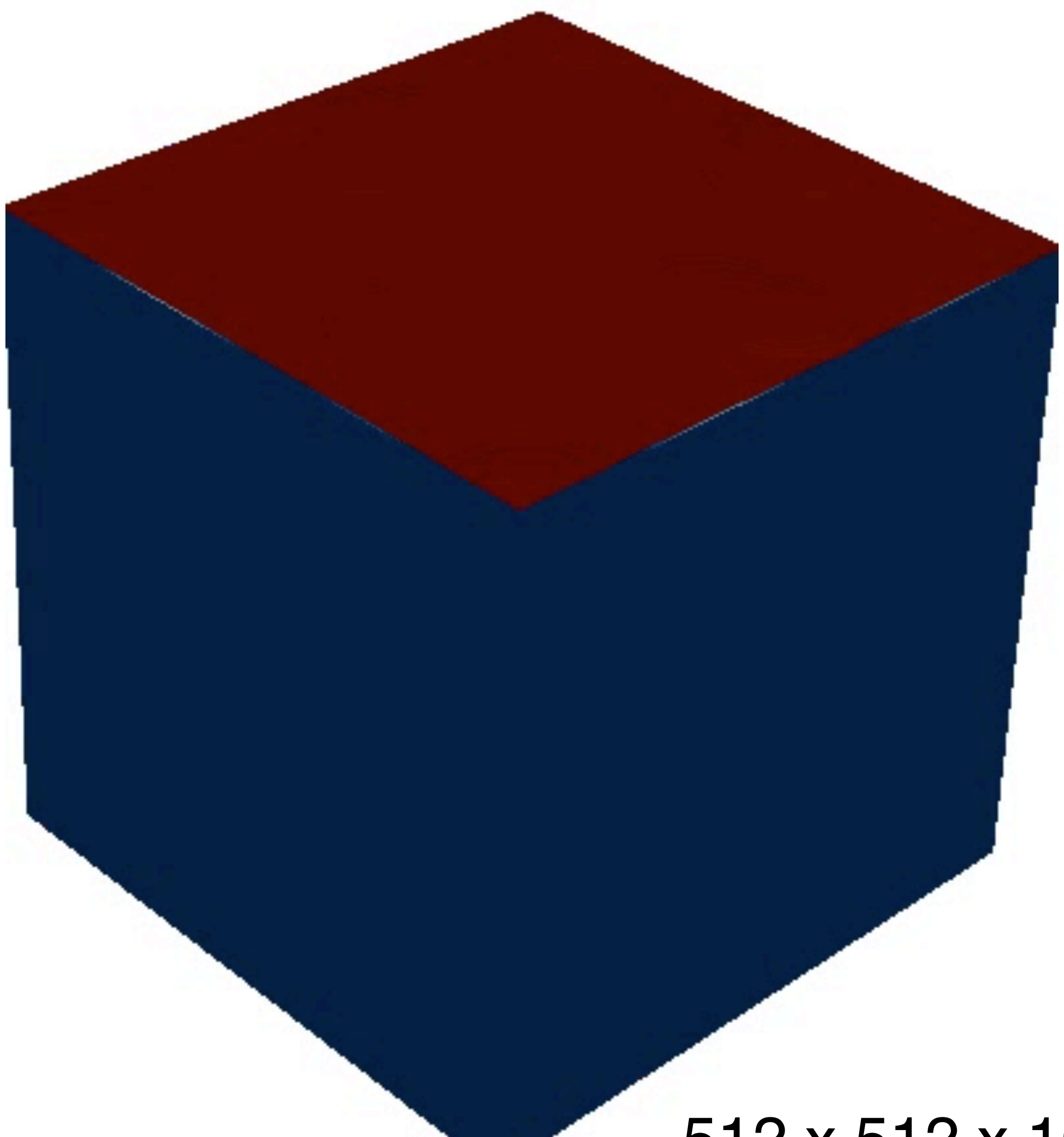
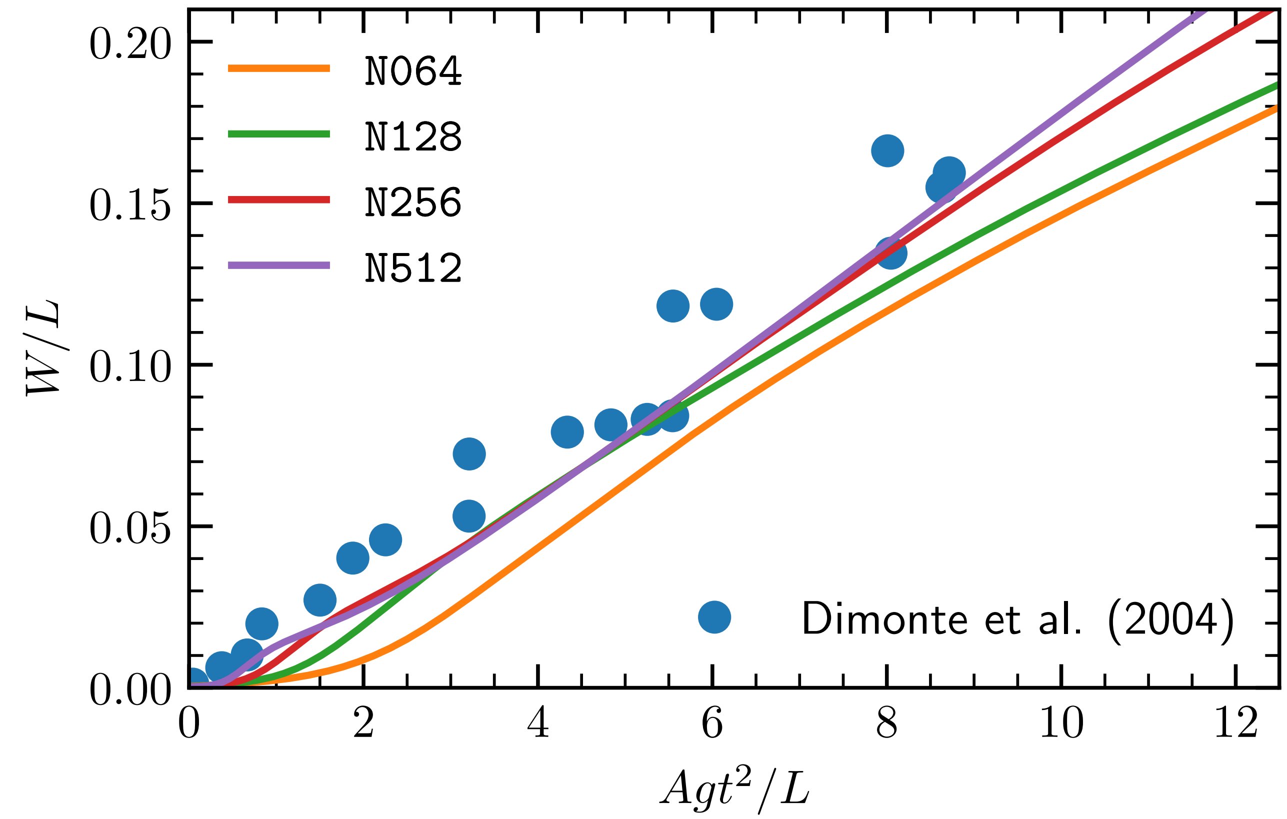
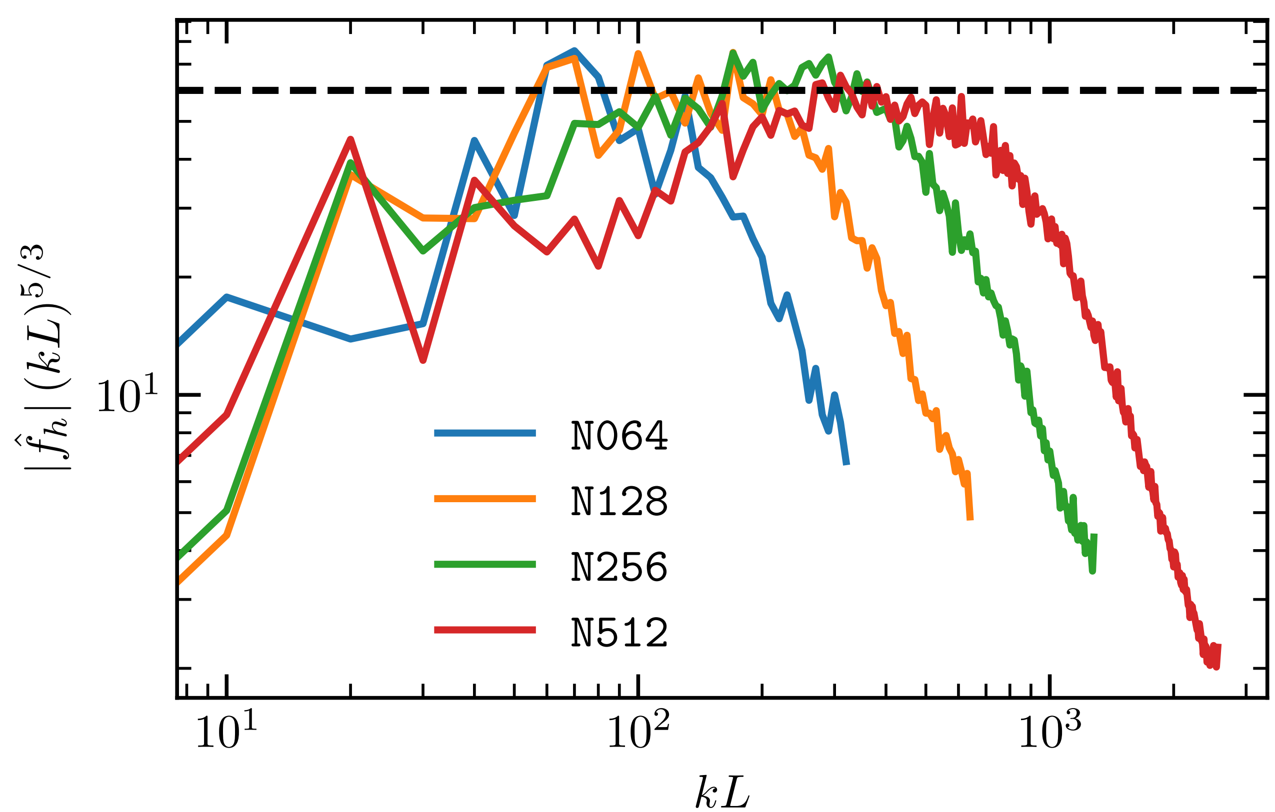
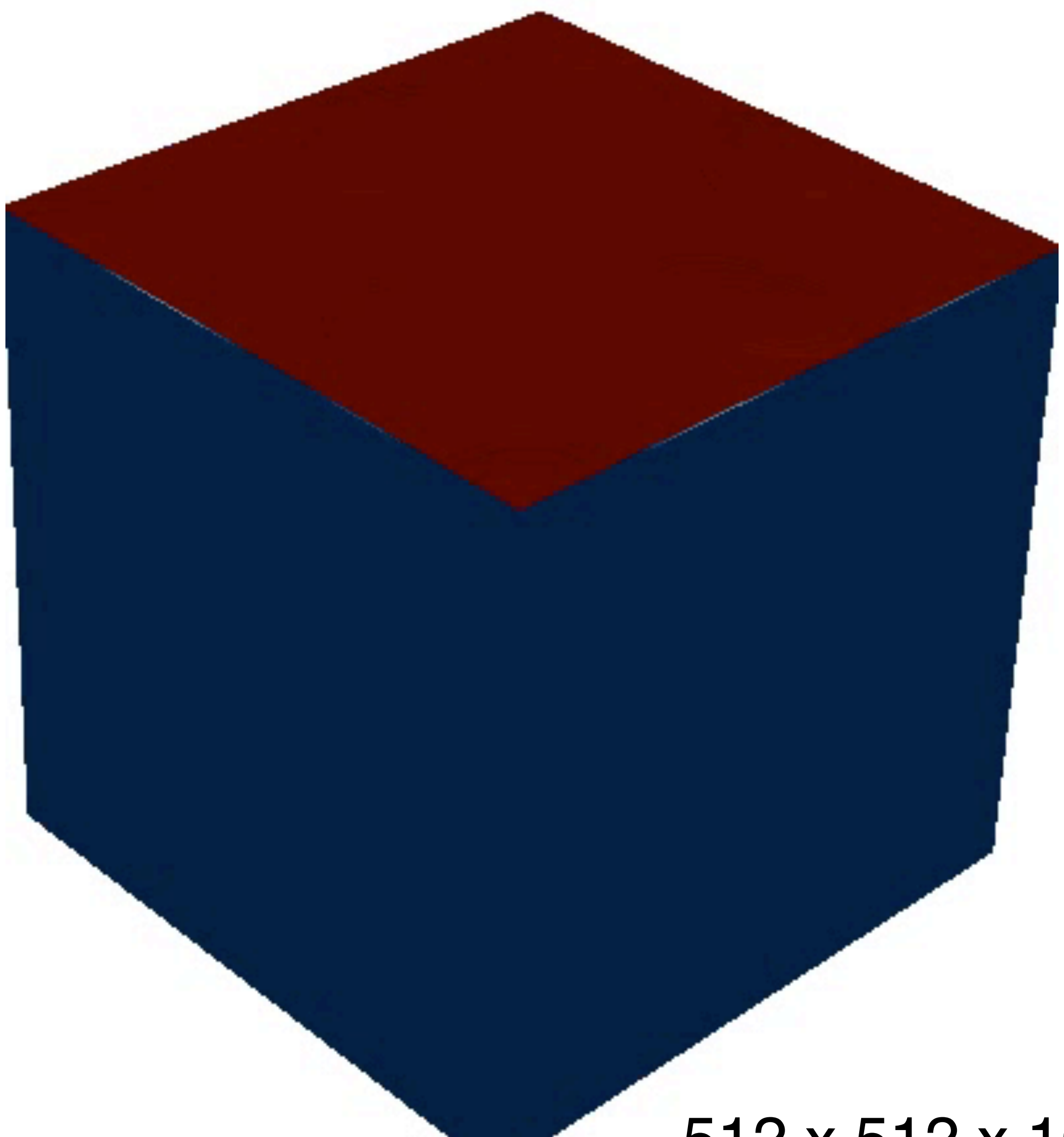




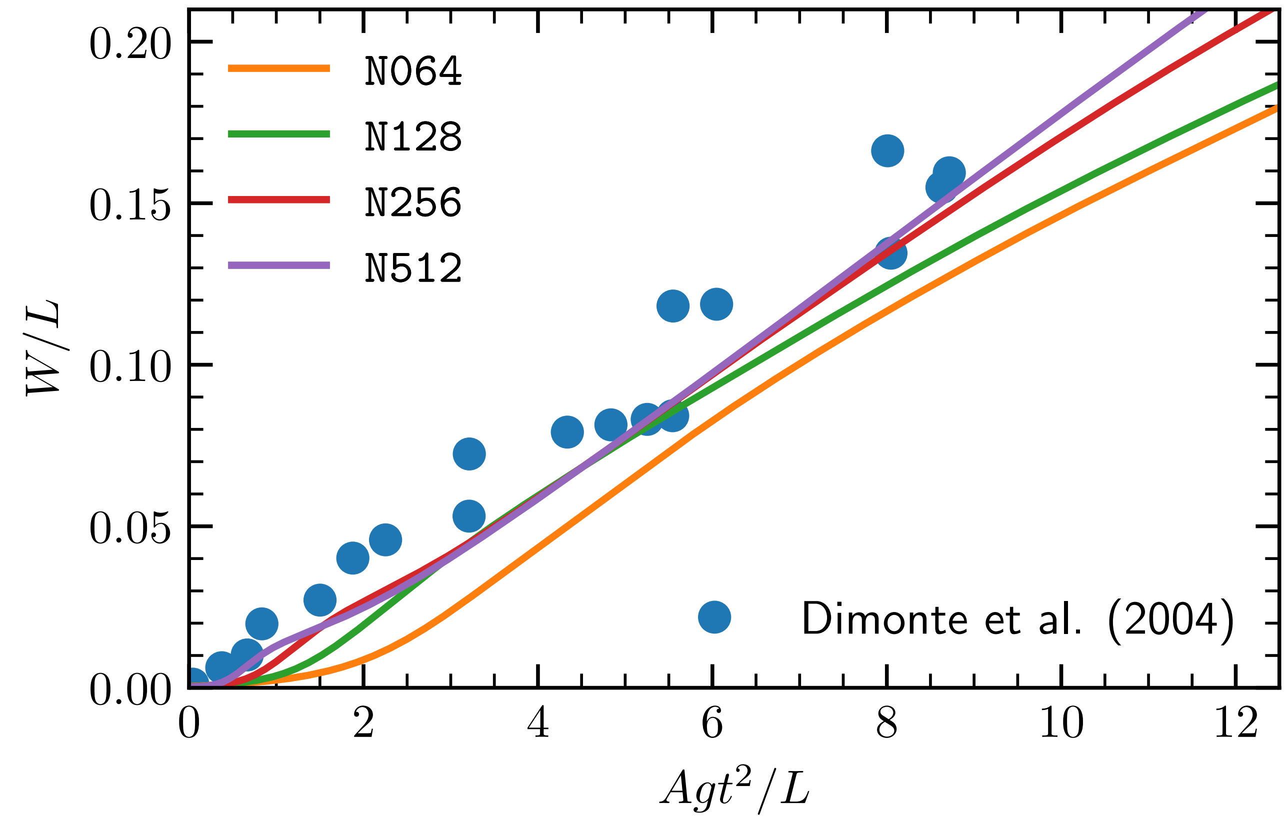


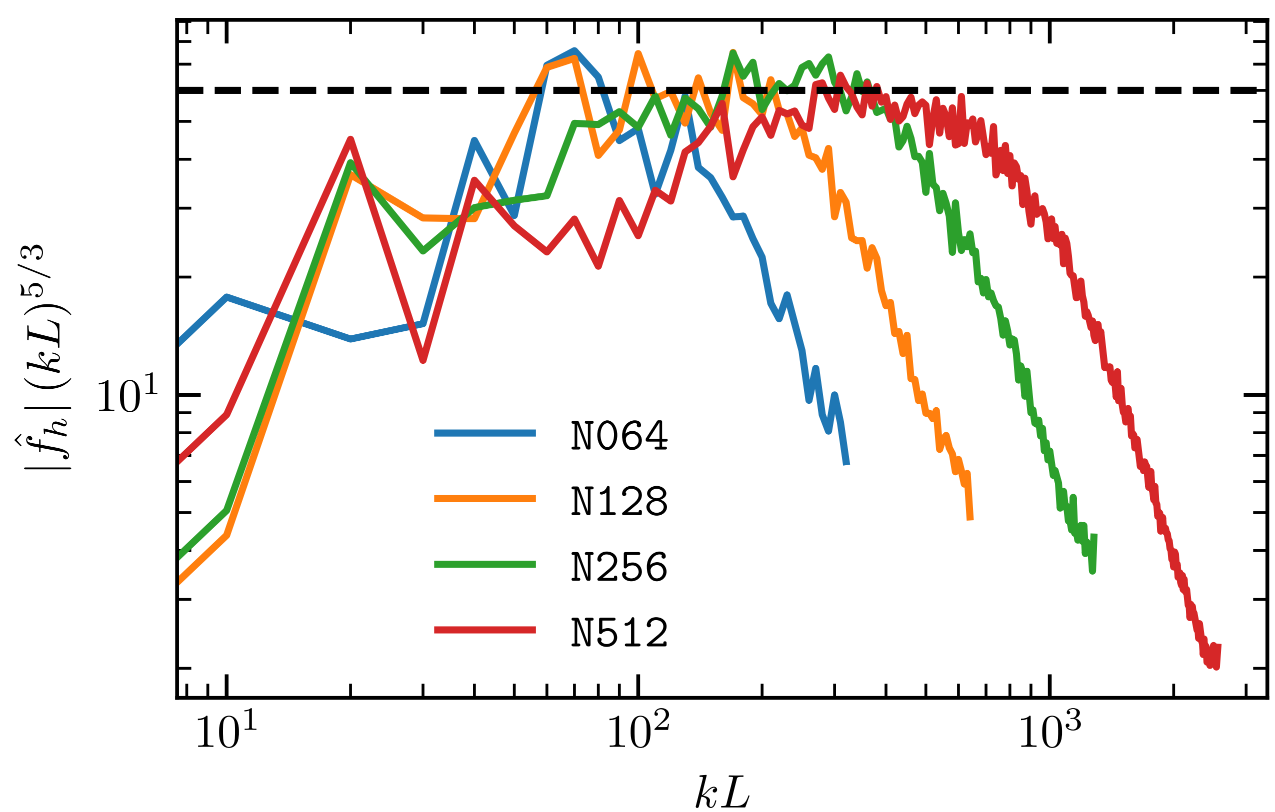
Dolence, Skinner, … **DR** in prep 2018

t = 0.0



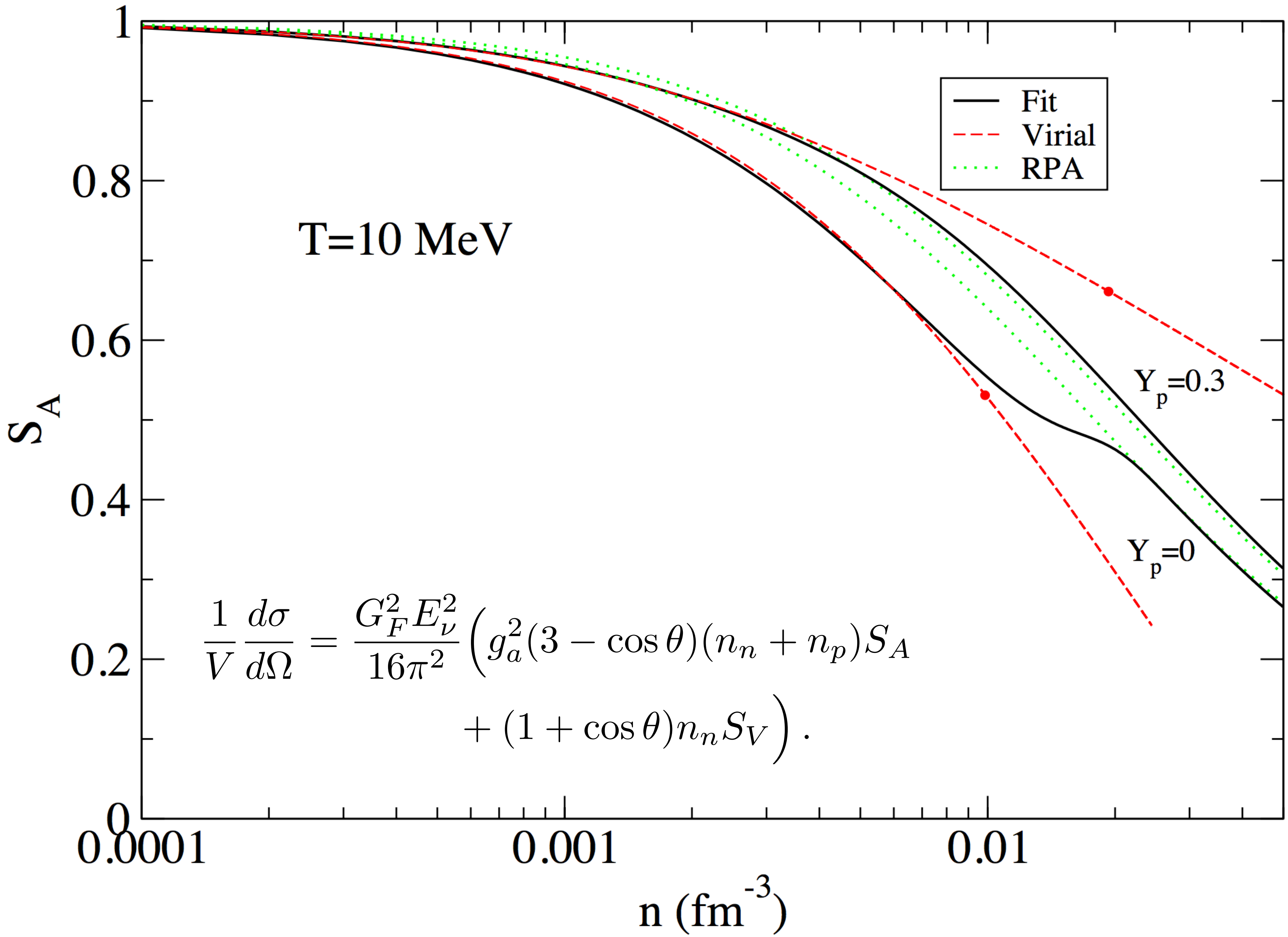
512 x 512 x 1024





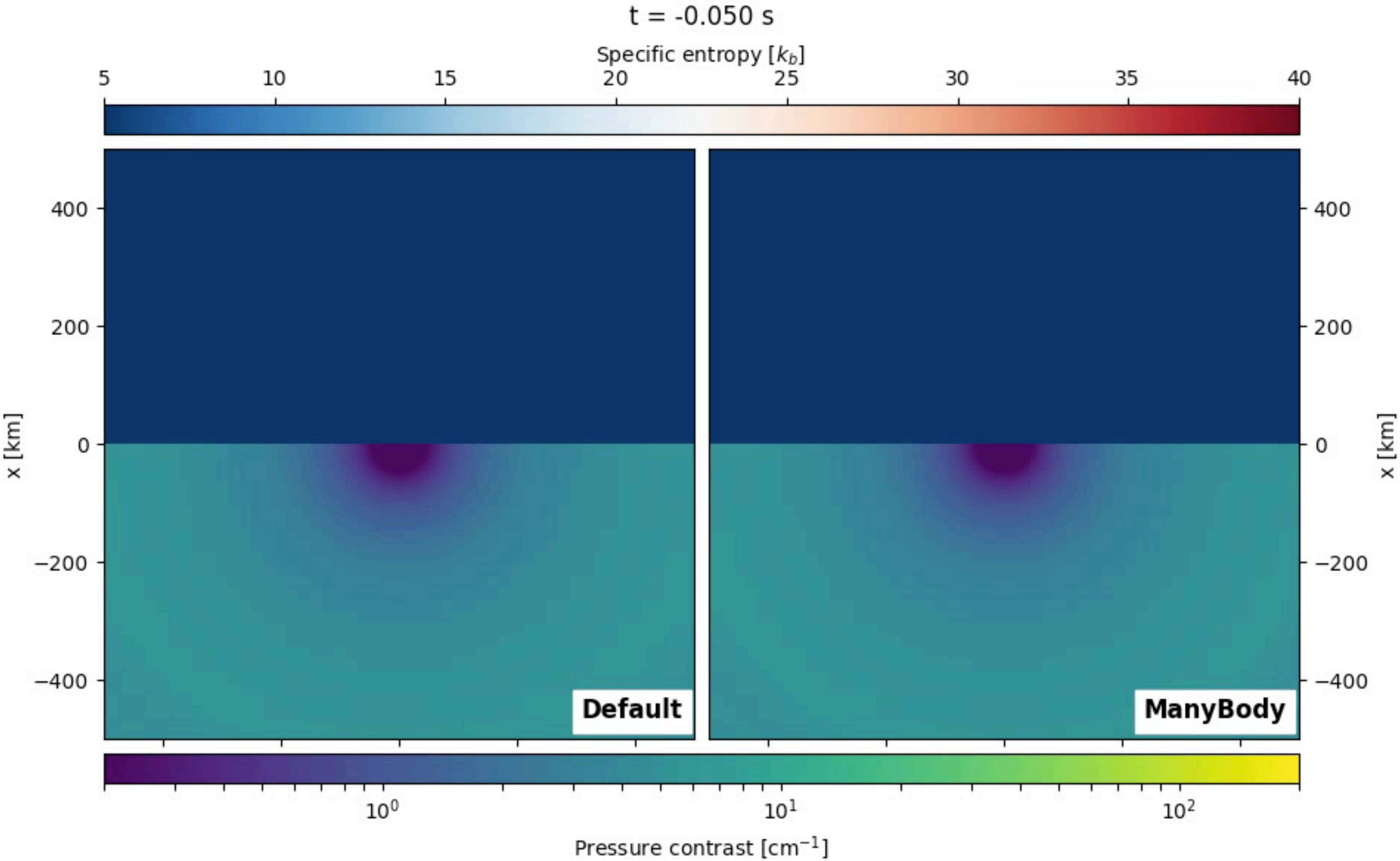
Dolence, Skinner, … **DR** in prep 2018

Many-body effects



From Horowitz et al. 2017

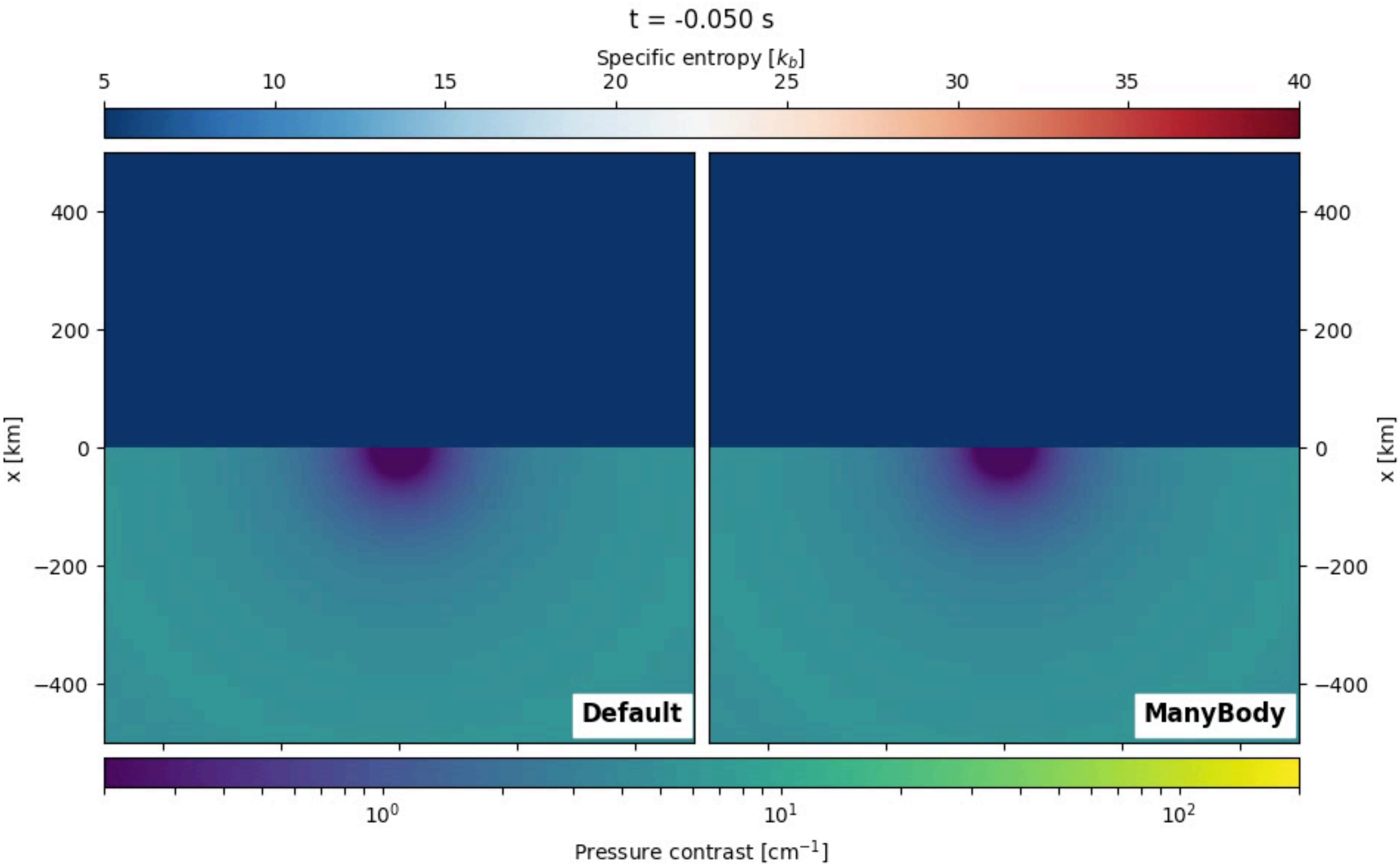
Many-body effects



s9.0-LS220

DR, Burrows, et al 2017
Burrows, … **DR** 2018

Many-body effects



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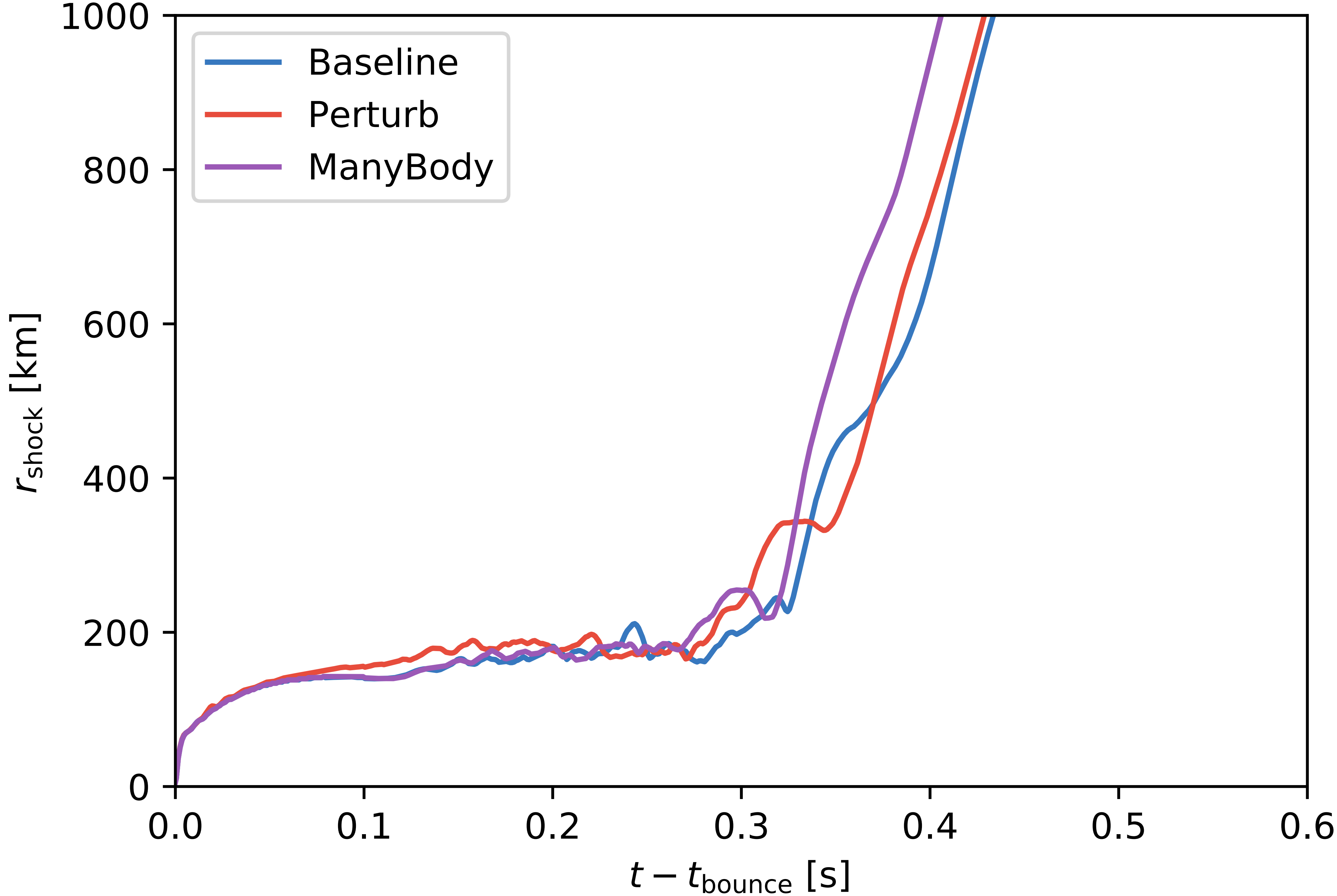
Many-body effects



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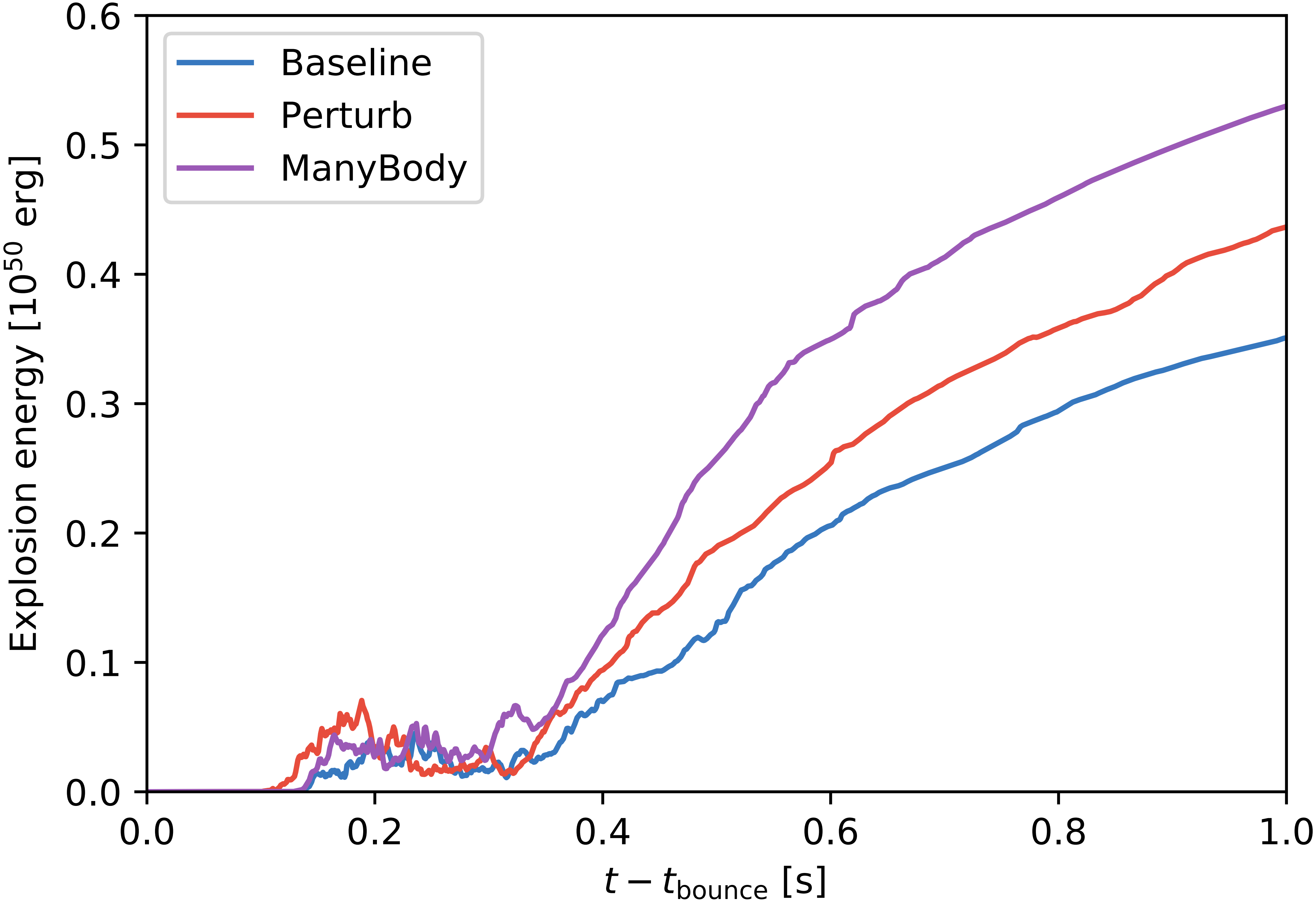

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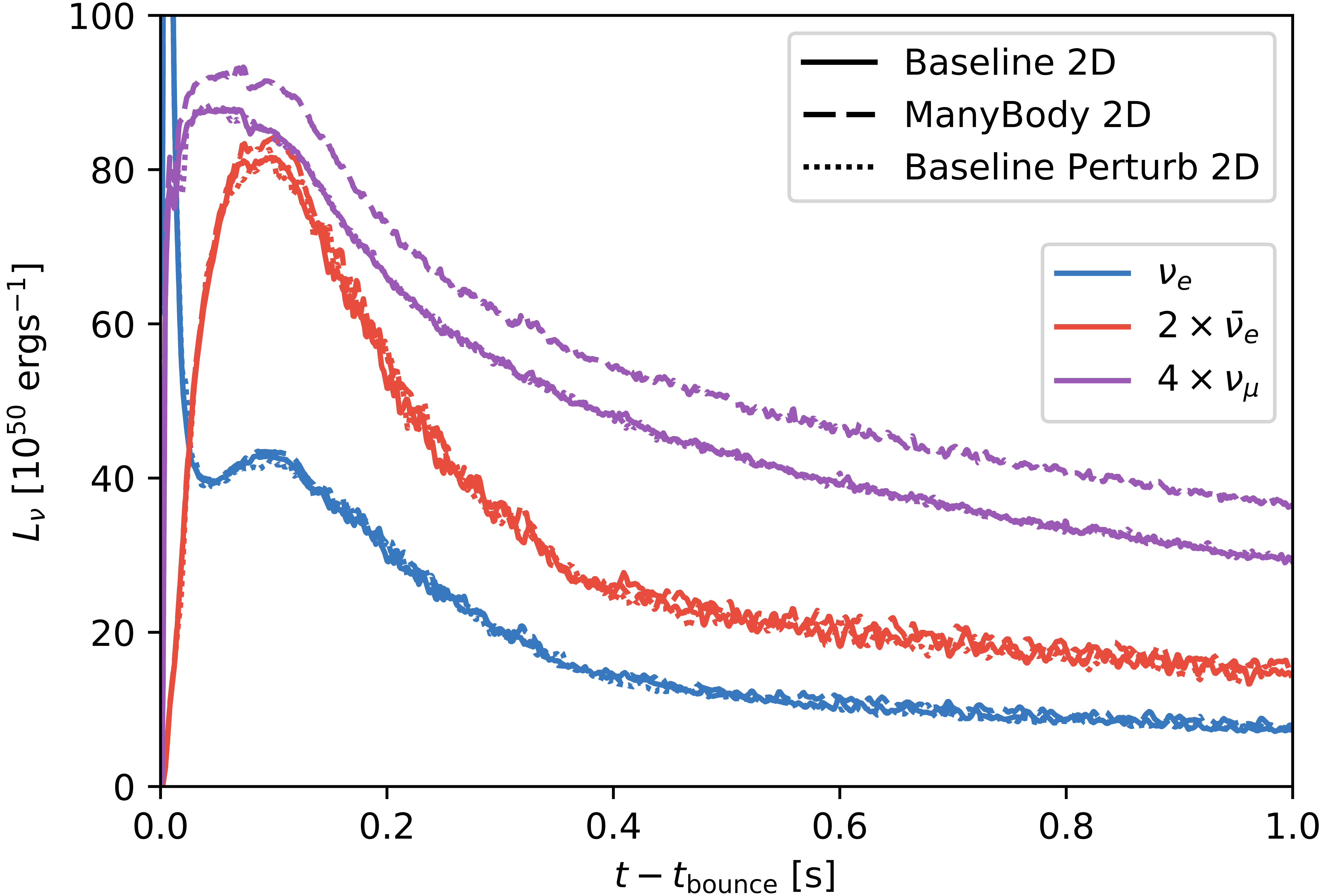

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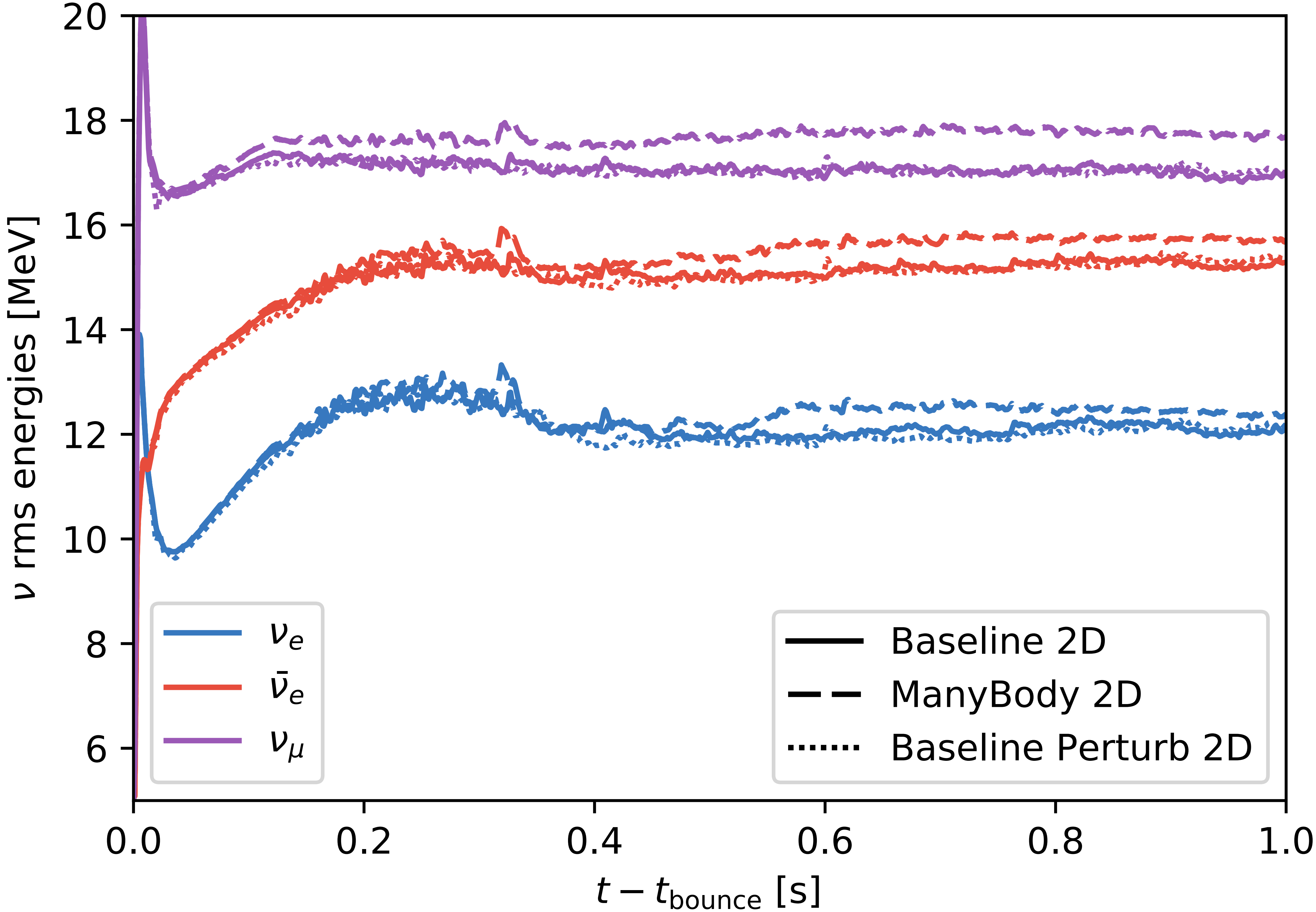

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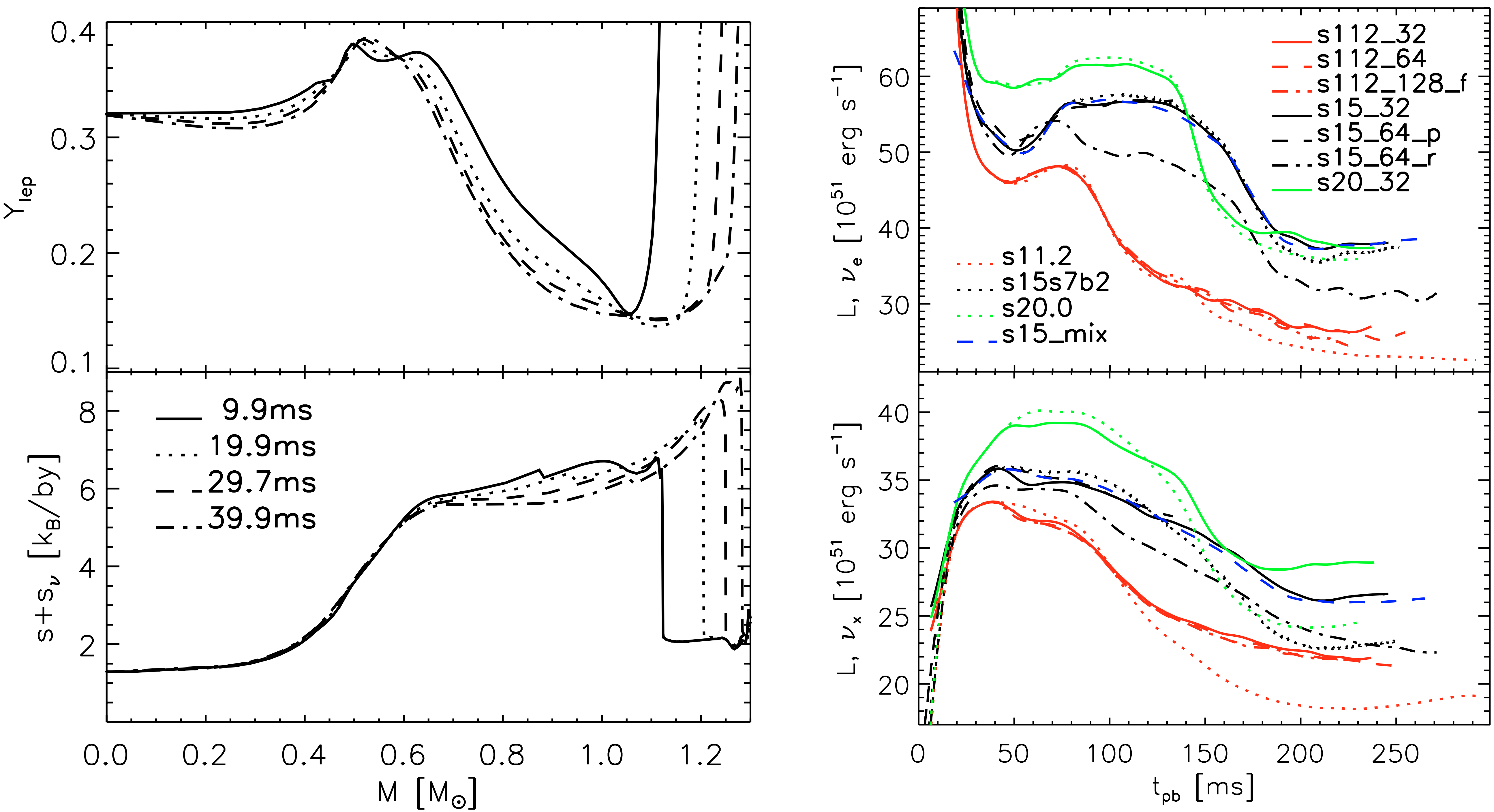
DR, Burrows, et al 2017
Burrows, … **DR** 2018

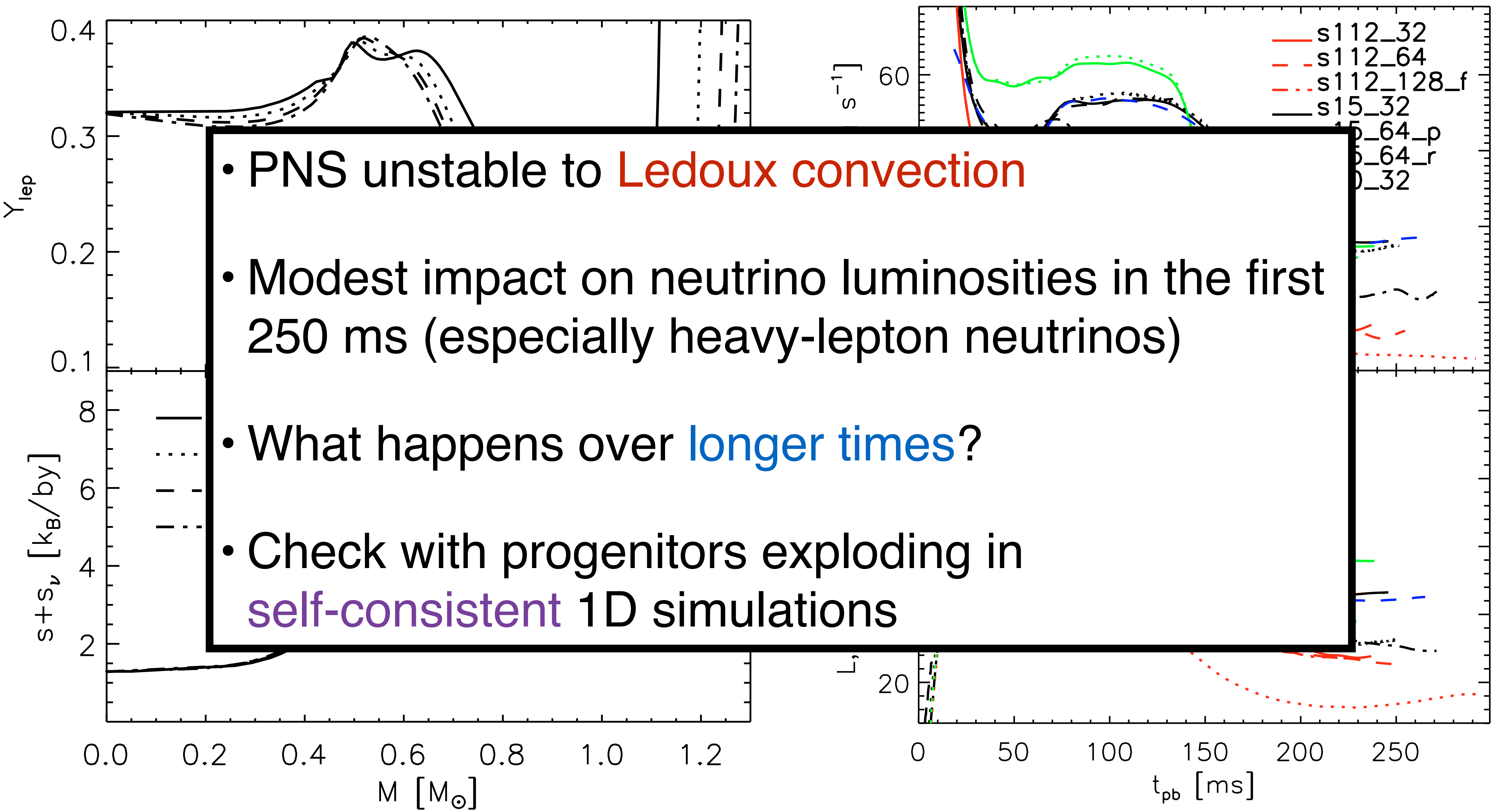
Protoneutron star convection



From Buras et al 2006

See also Dessart, Burrows et al. 2006

Protoneutron star convection

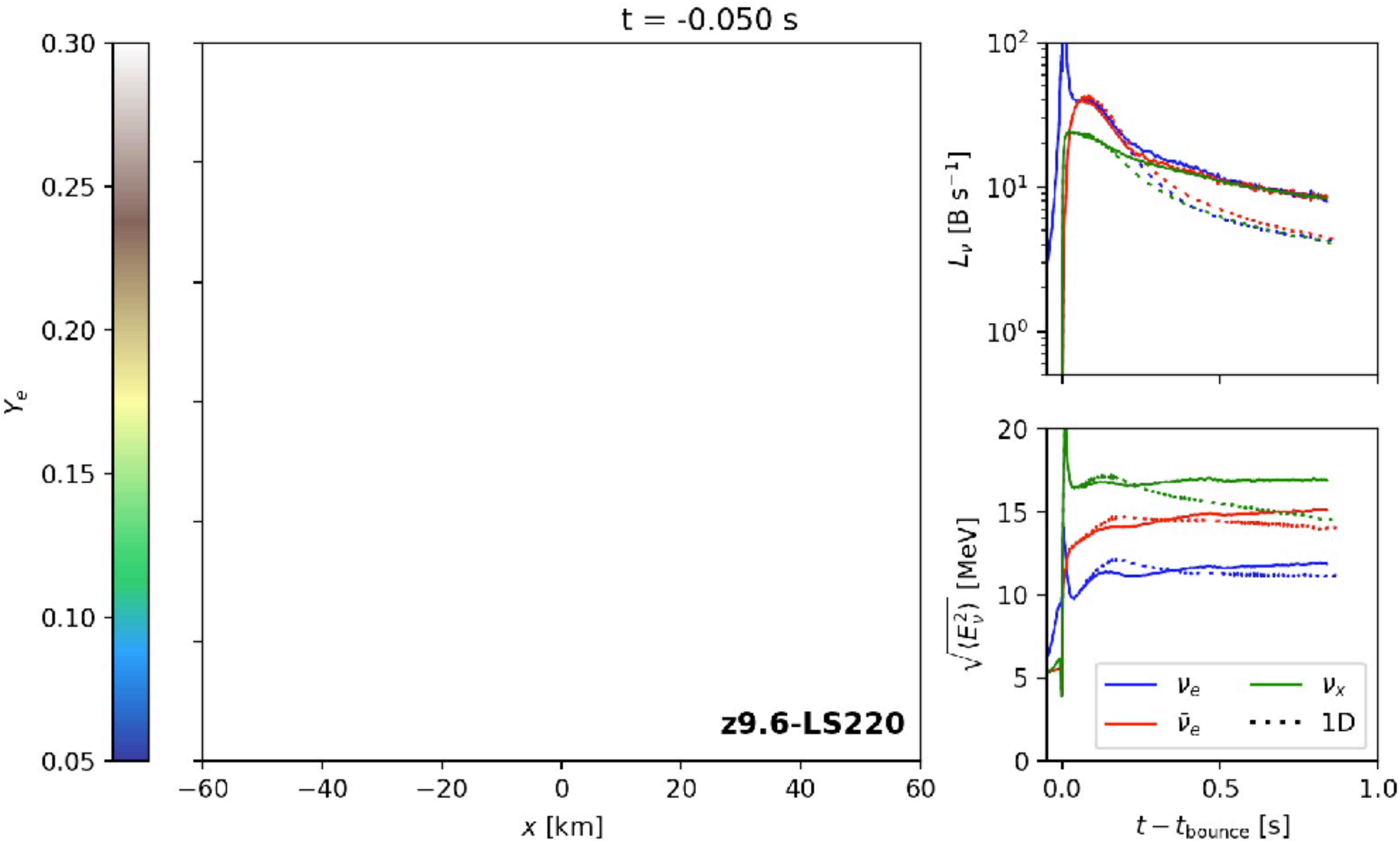


- PNS unstable to Ledoux convection
- Modest impact on neutrino luminosities in the first 250 ms (especially heavy-lepton neutrinos)
- What happens over longer times?
- Check with progenitors exploding in self-consistent 1D simulations

From Buras et al 2006

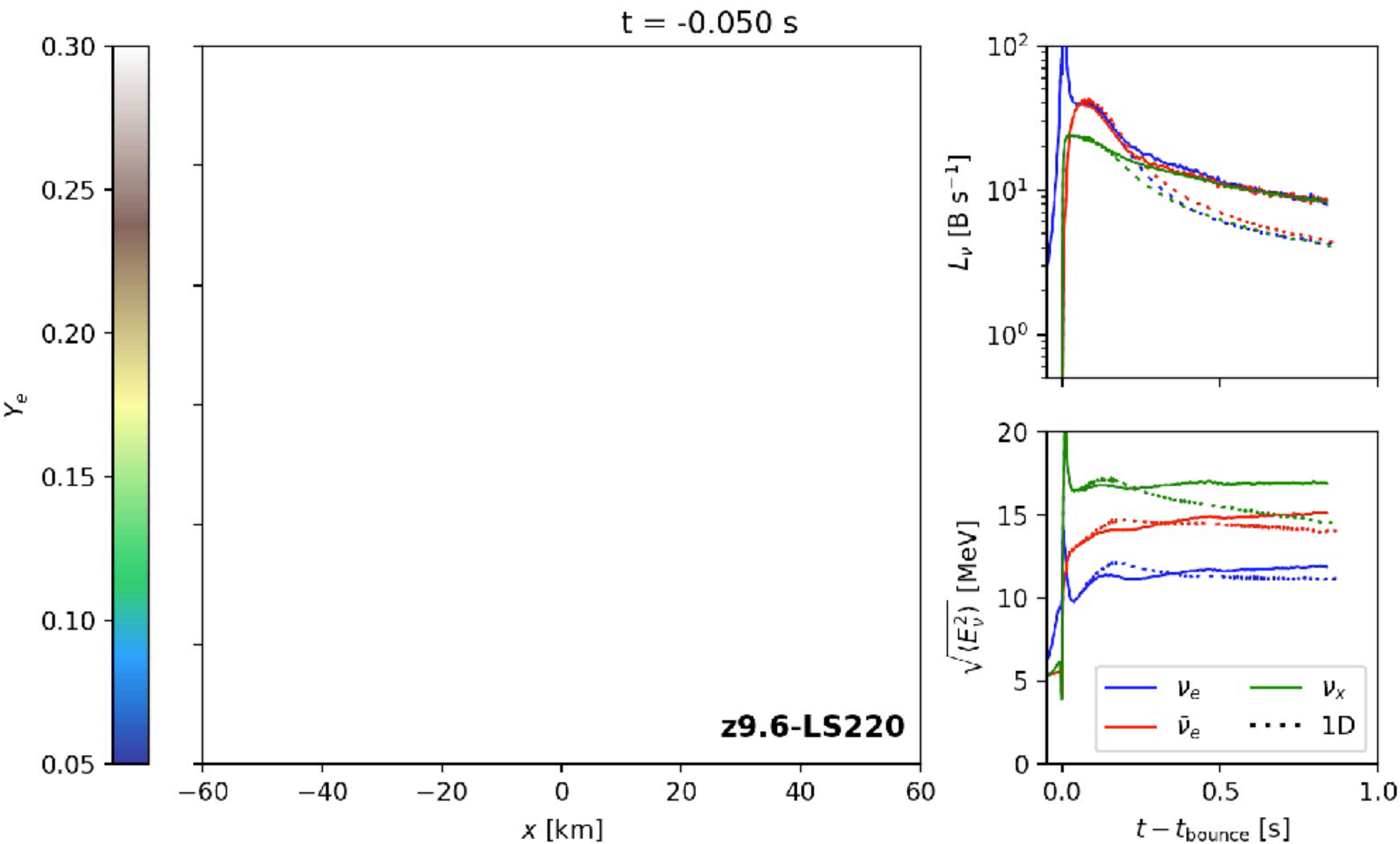
See also Dessart, Burrows et al. 2006

Protoneutron star convection



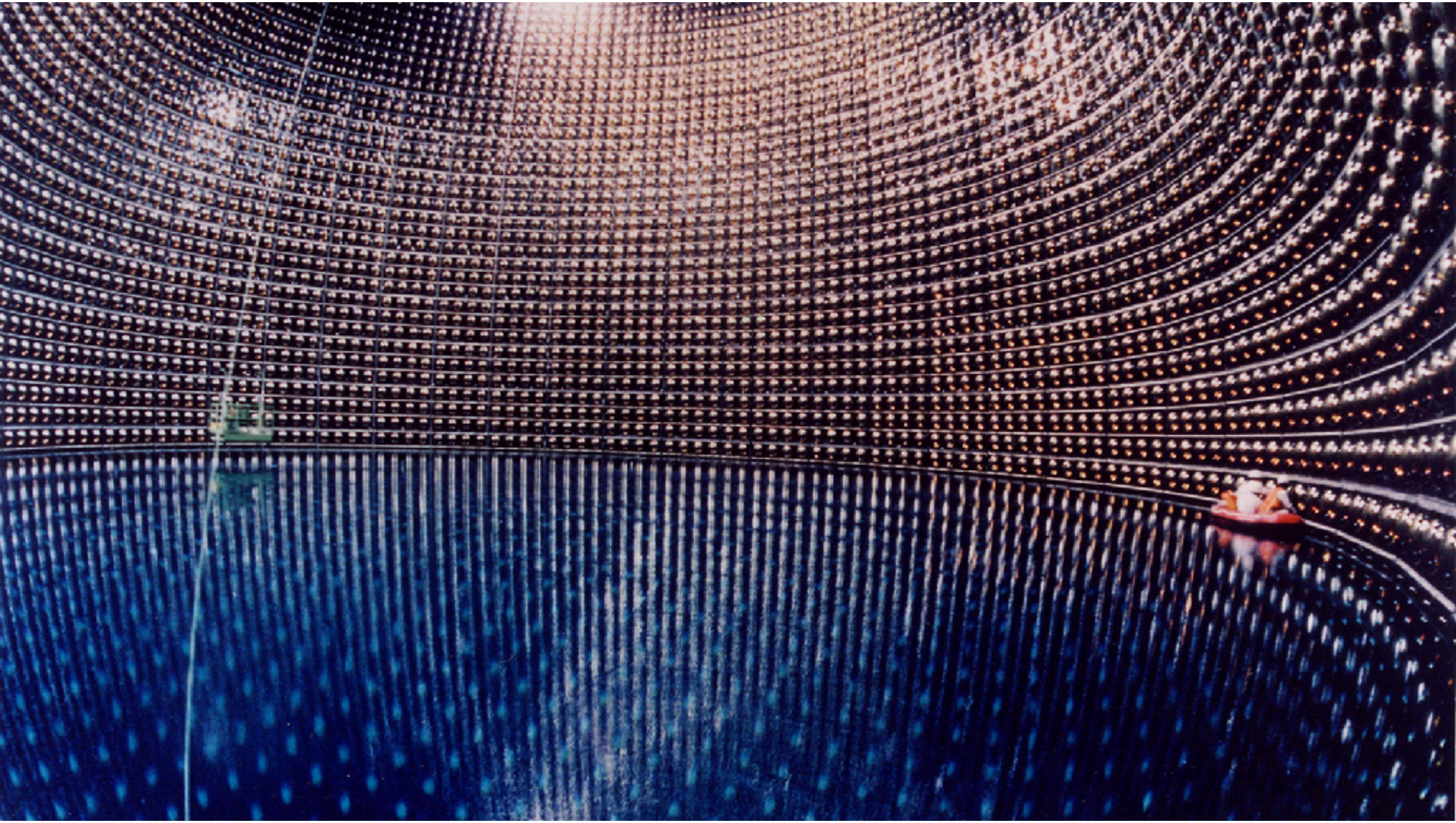
DR, Burrows, et al 2017

Protoneutron star convection



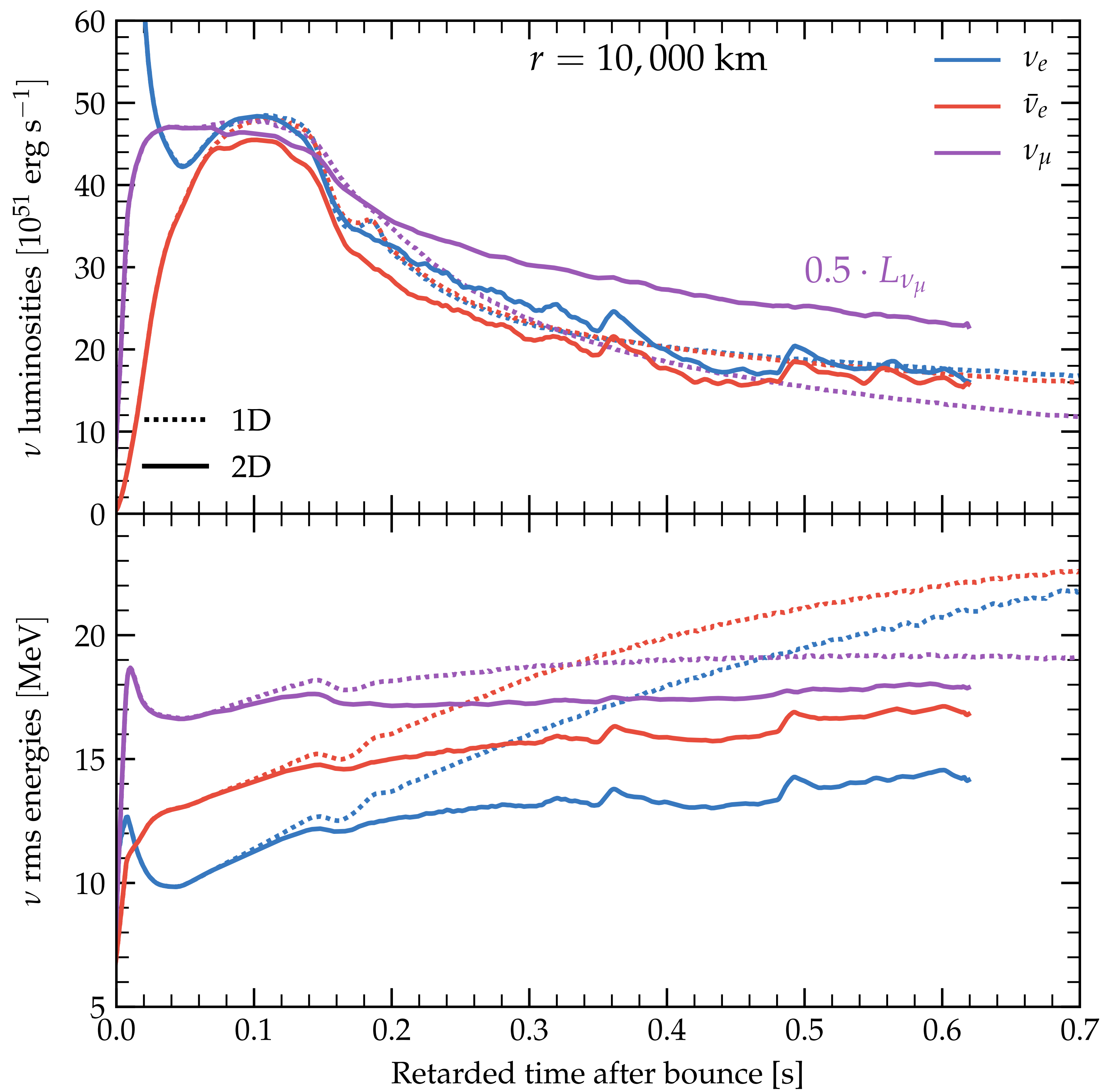
DR, Burrows, et al 2017

Neutrino signals



Super-Kamiokande— Credit: Symmetry Magazine

Neutrino "light" curves



s11.0-LS220

DR, Burrows, et al 2017

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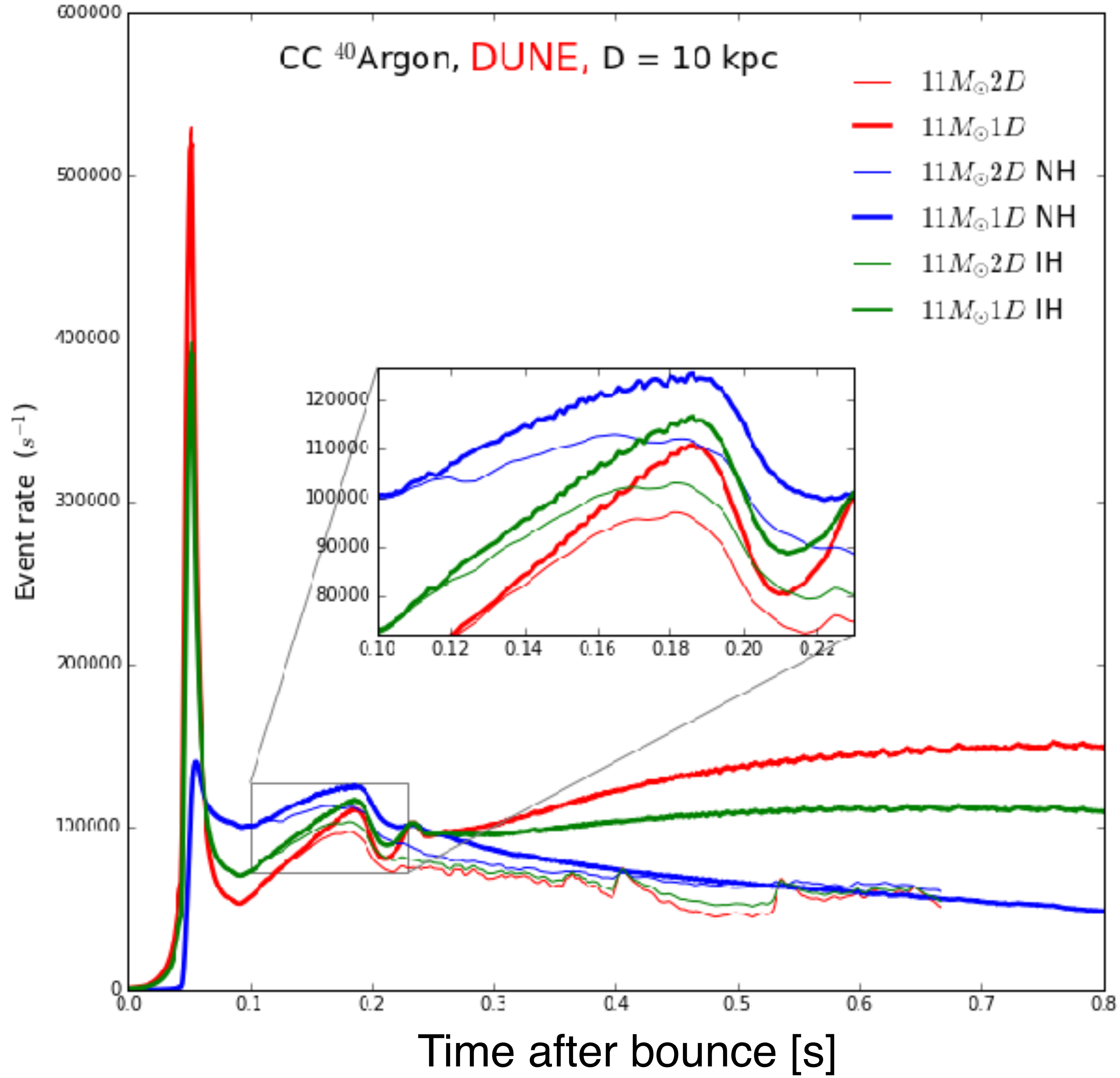
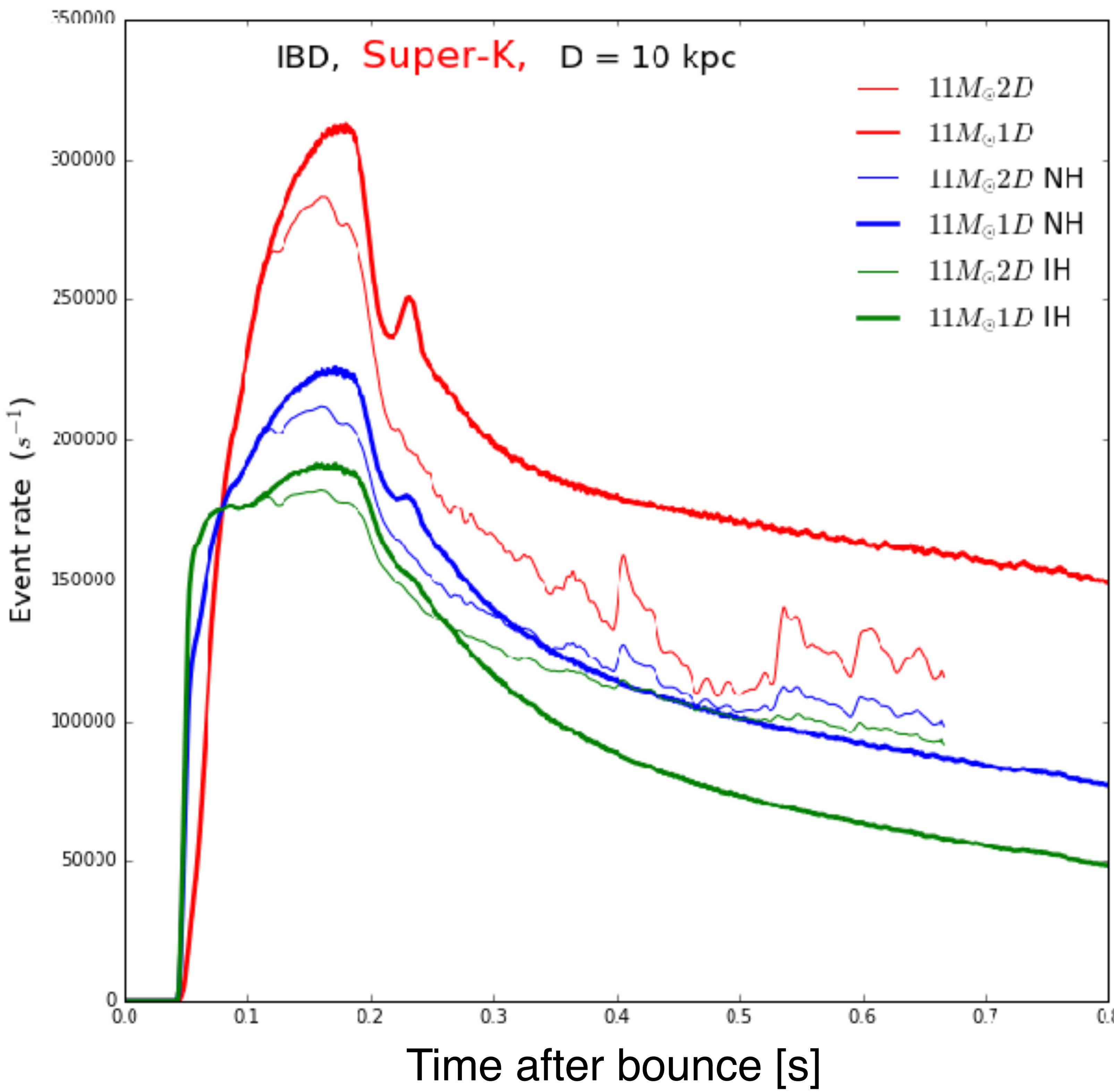


s11.0-LS220

Seadrow, …, **DR** et al., in prep 2018

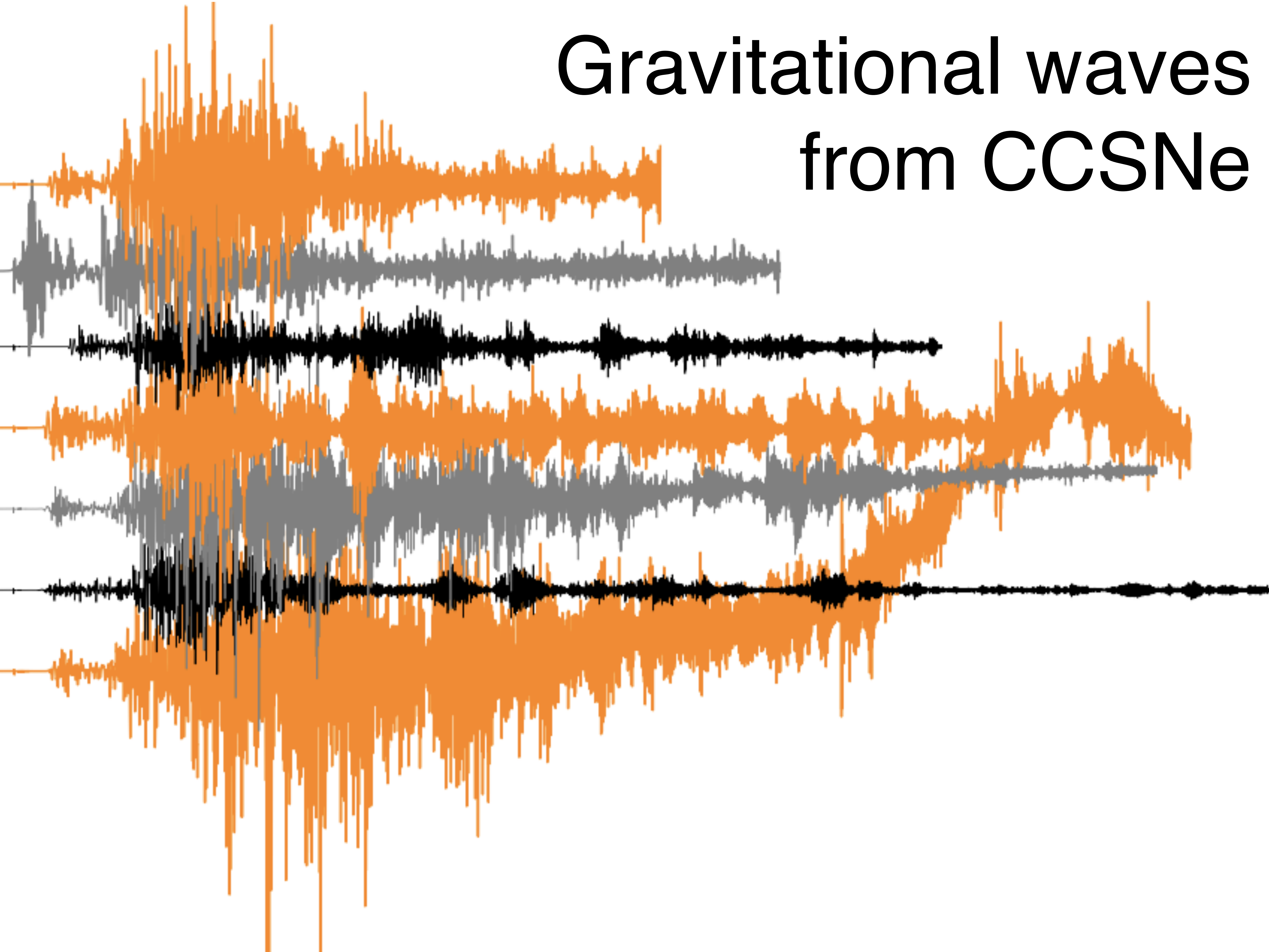
Neutrino “light” curves



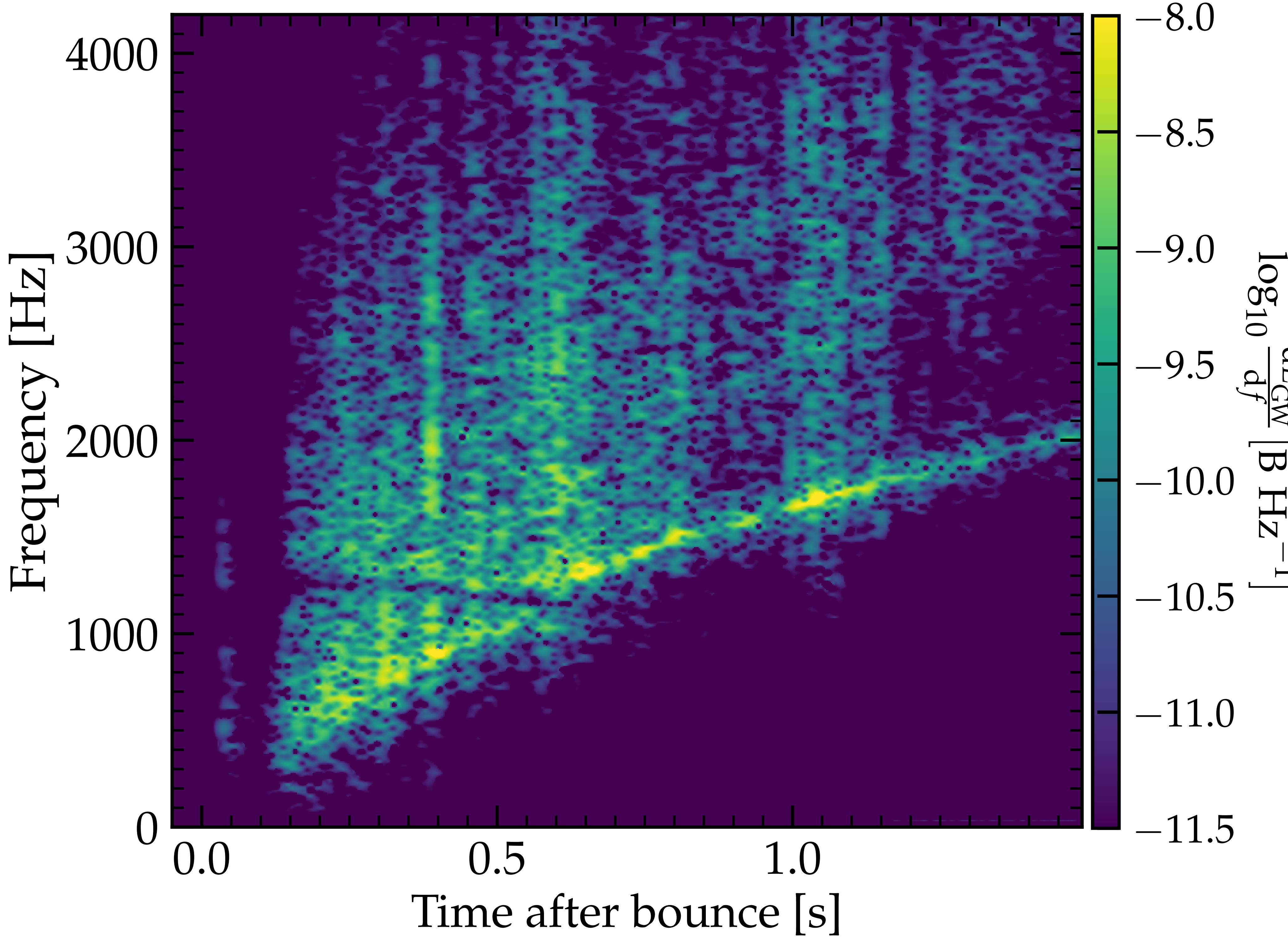
s11.0-LS220

Seadrow, …, **DR** et al., in prep 2018

Gravitational waves from CCSNe

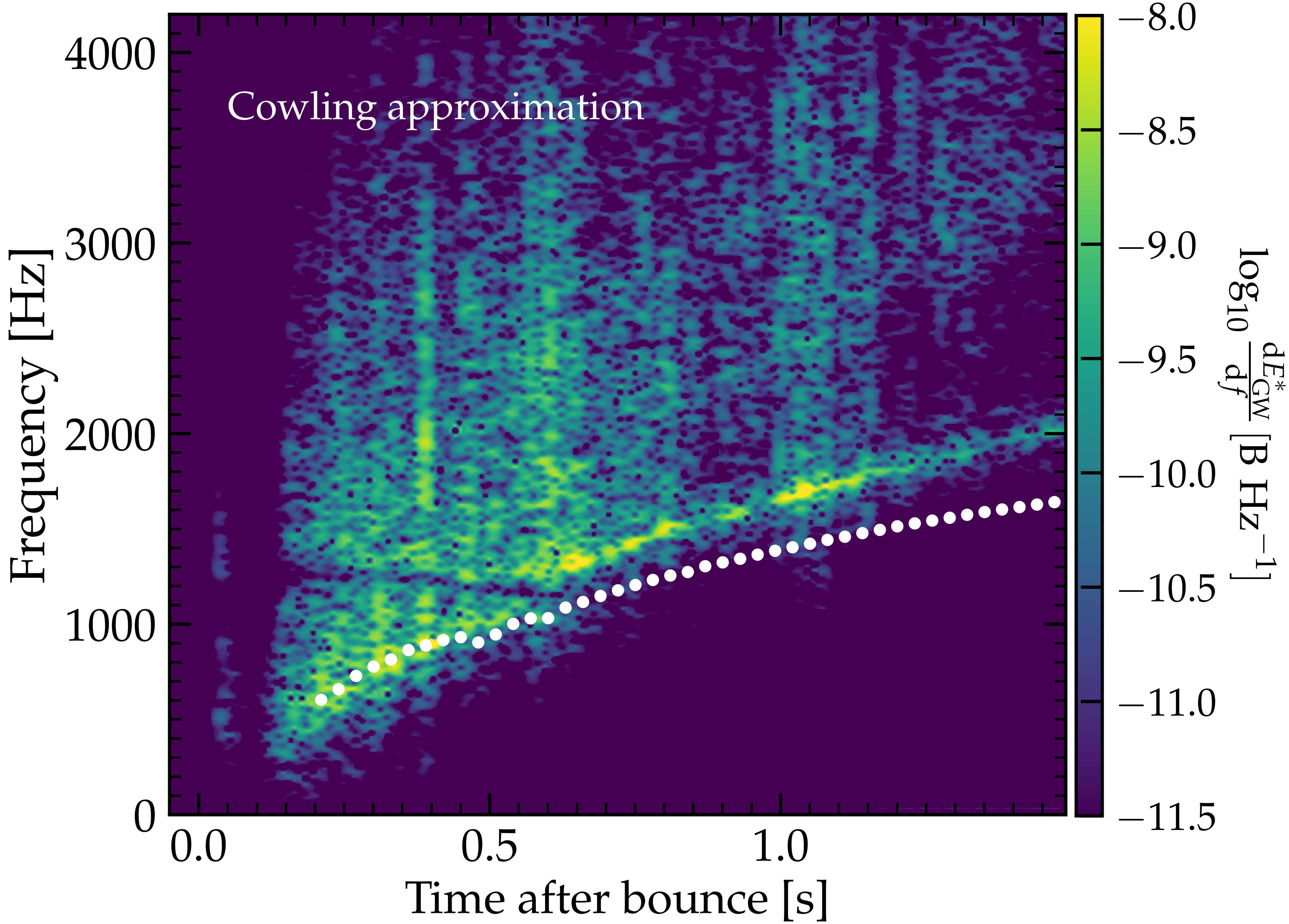


Gravitational-wave spectrum



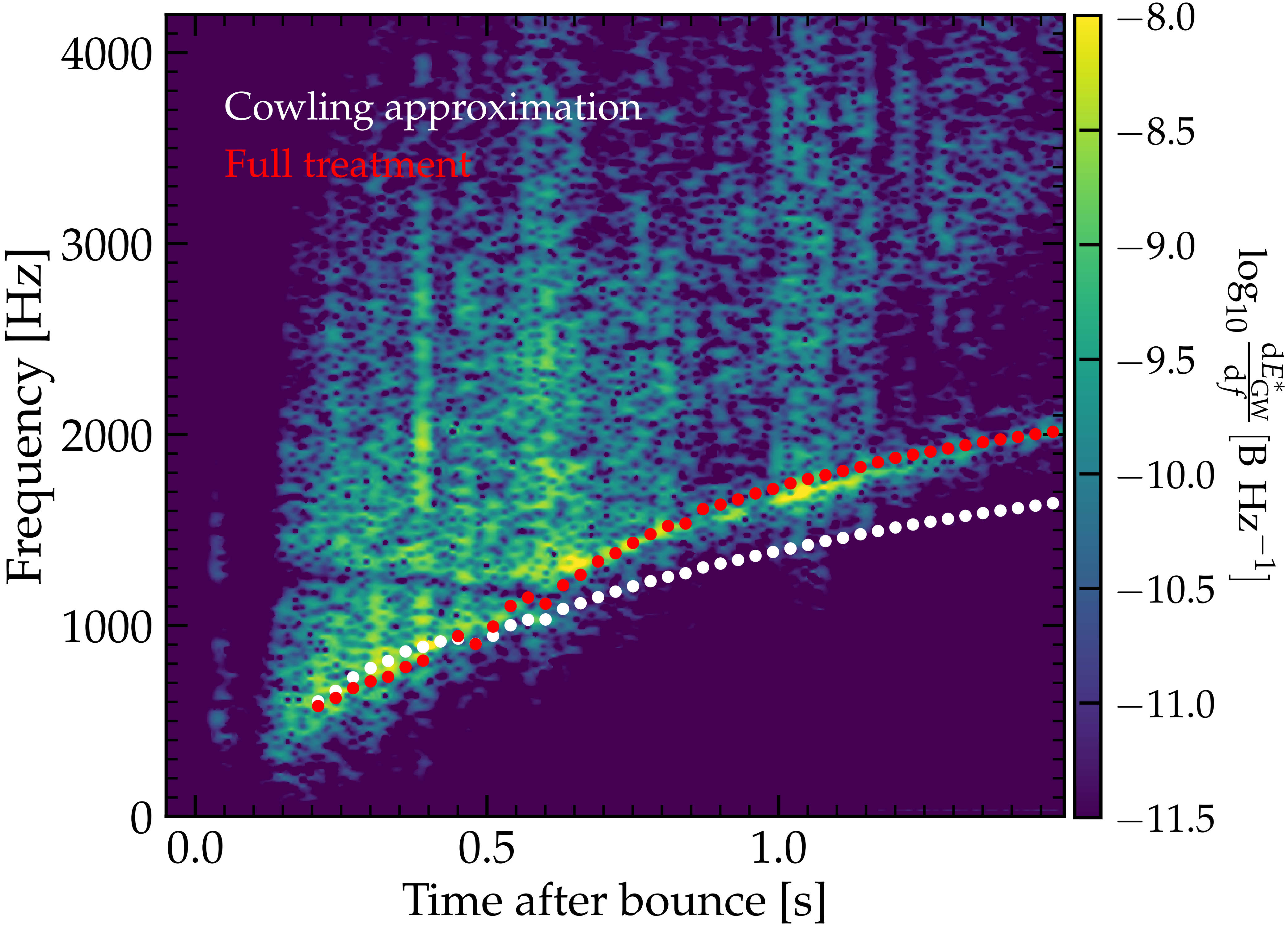
Morozova, **DR**, Burrows, Vartanyan, arXiv:1801.01914

Gravitational-wave spectrum



From Morozova, **DR**, Burrows, Vartanyan, arXiv:1801.01914

Gravitational-wave spectrum

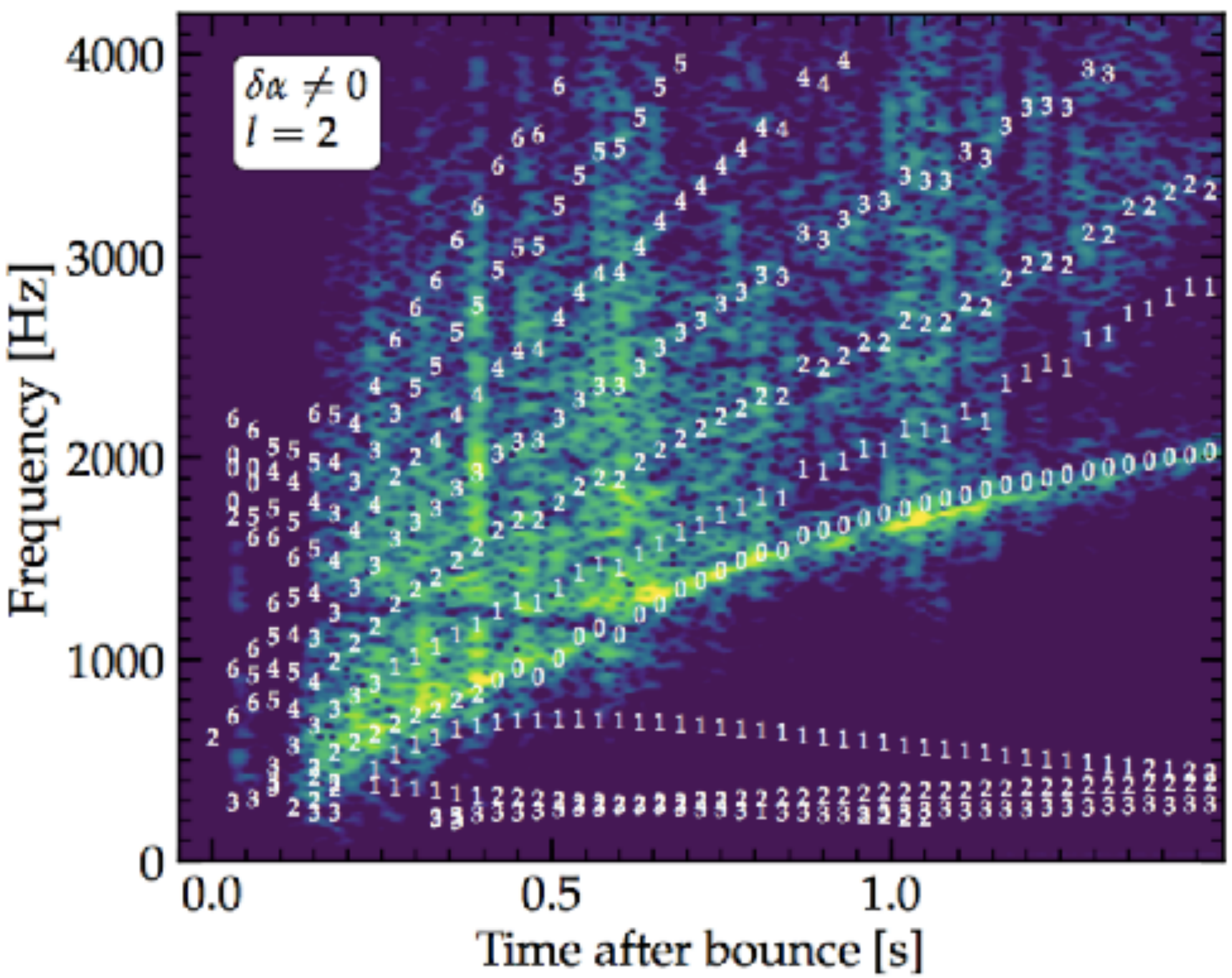


From Morozova, **DR**, Burrows, Vartanyan, arXiv:1801.01914

Amplitude and frequency

Frequency

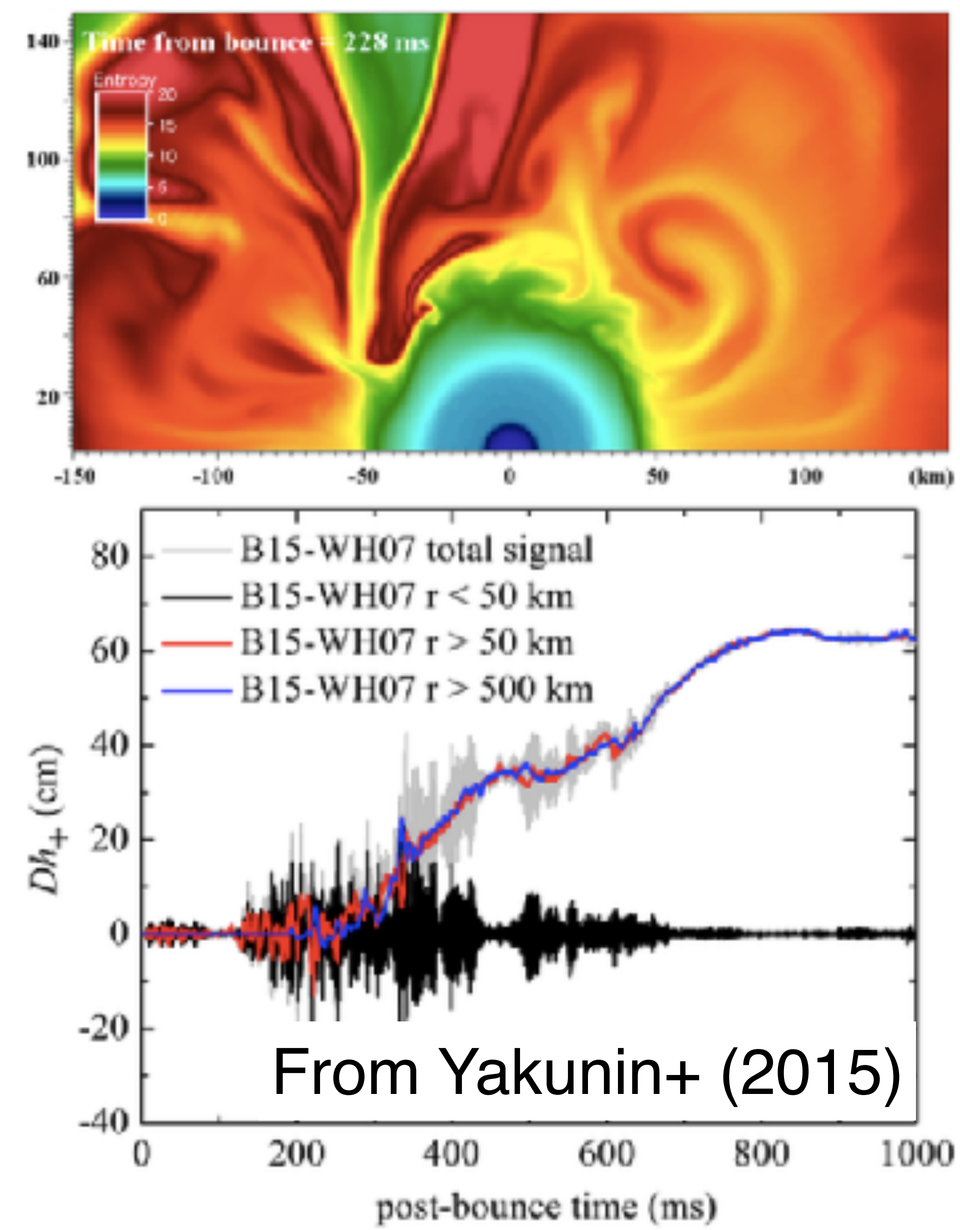
is defined by the structure of the proto-neutron star



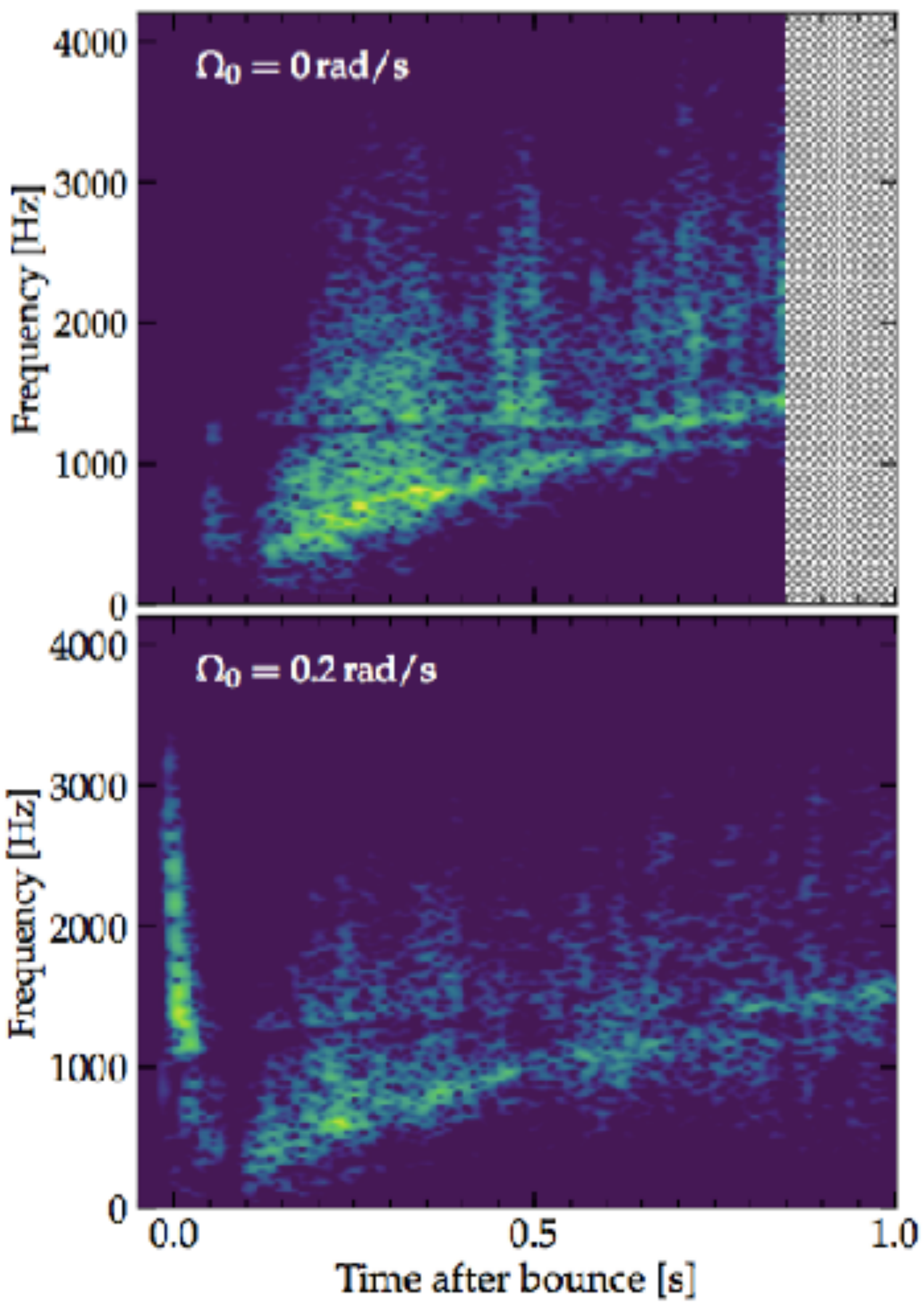
Morozova, **DR**, Burrows, Vartanyan, arXiv:1801.01914

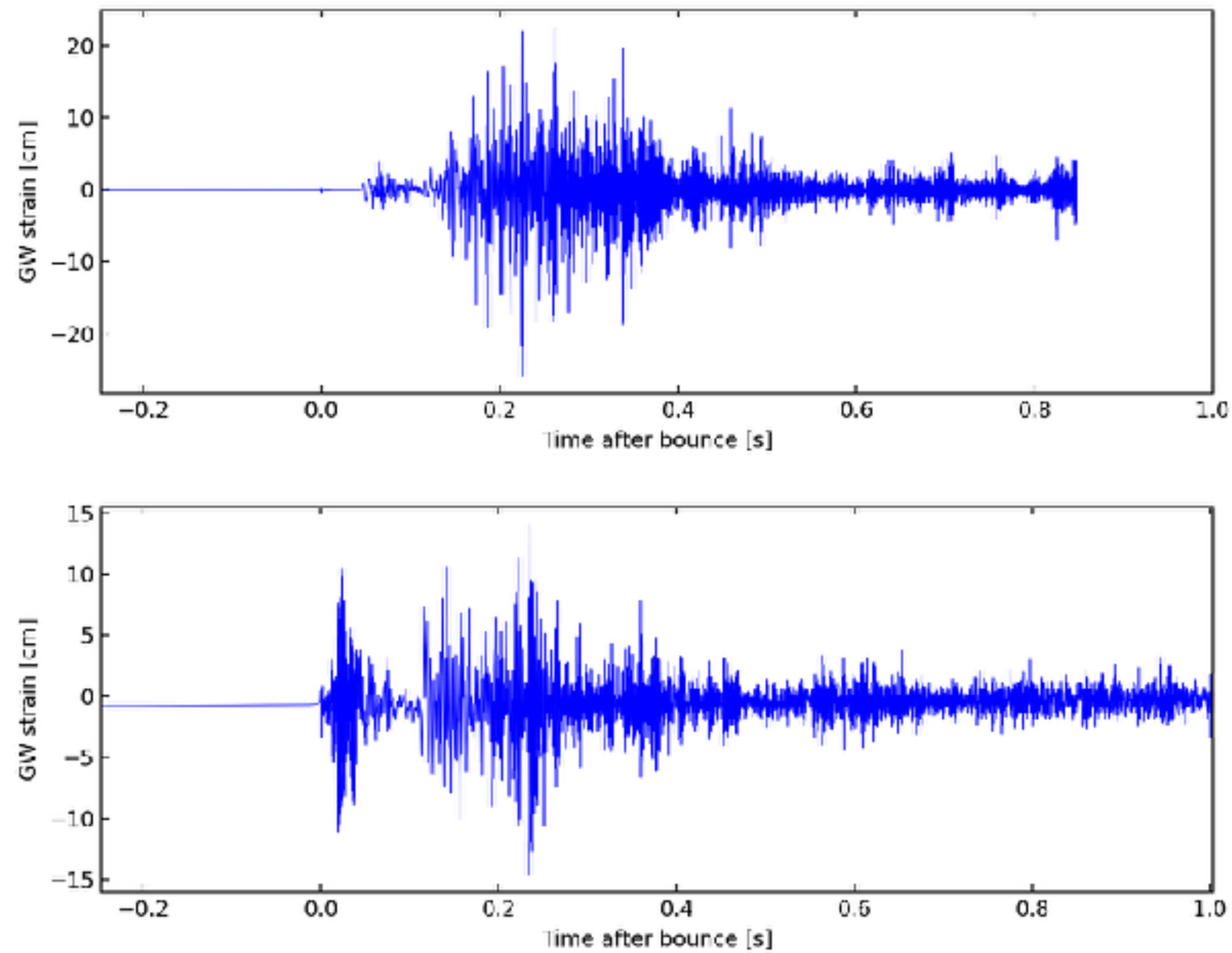
Amplitude

is defined by the character of the excitation



Effect of rotation

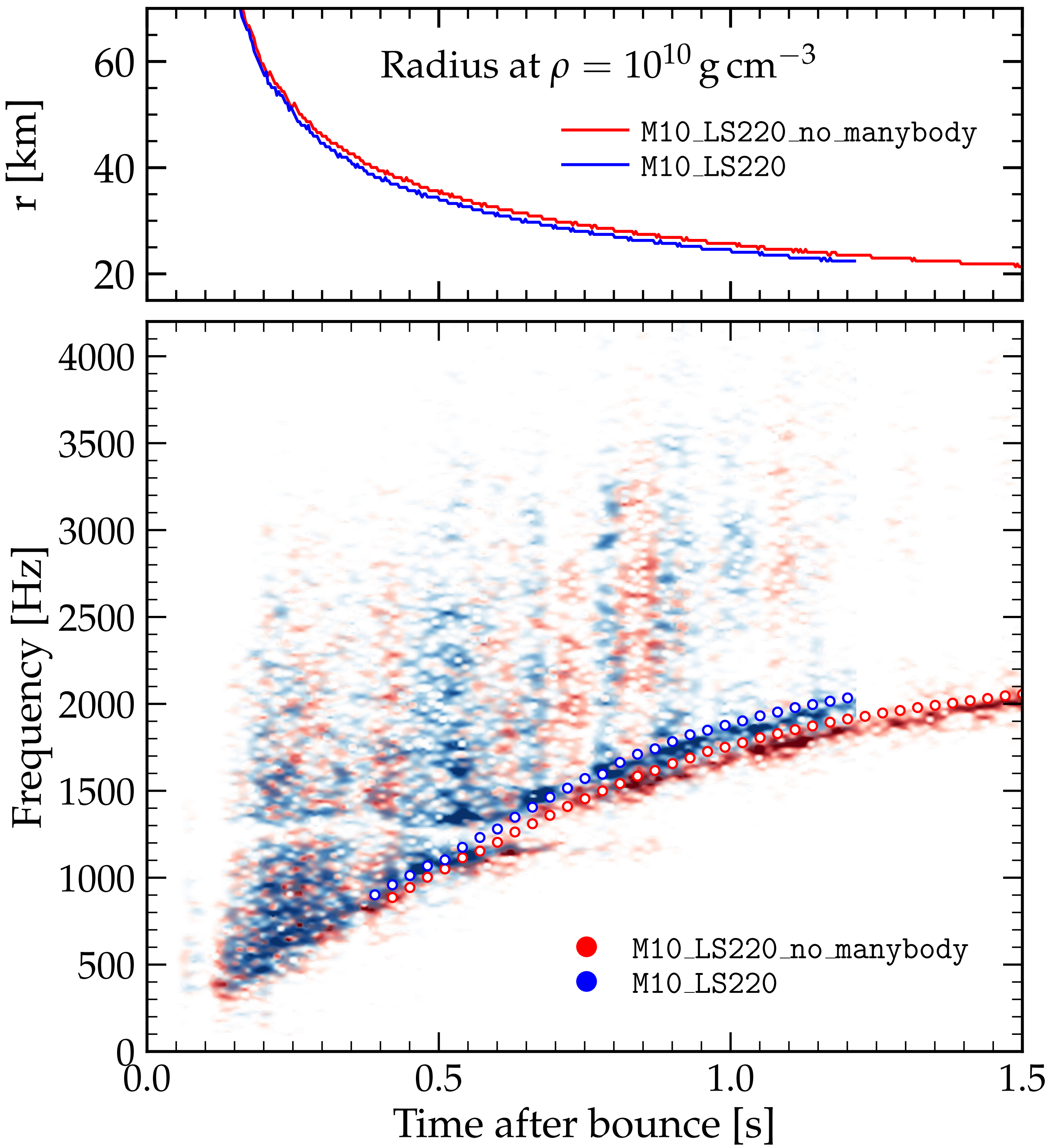




* The bounce signal is stronger, because the collapse is not symmetric
* The dominant frequency is nearly the same

Morozova, **DR**, Burrows, Vartanyan, arXiv:1801.01914

Protoneutron star seismology

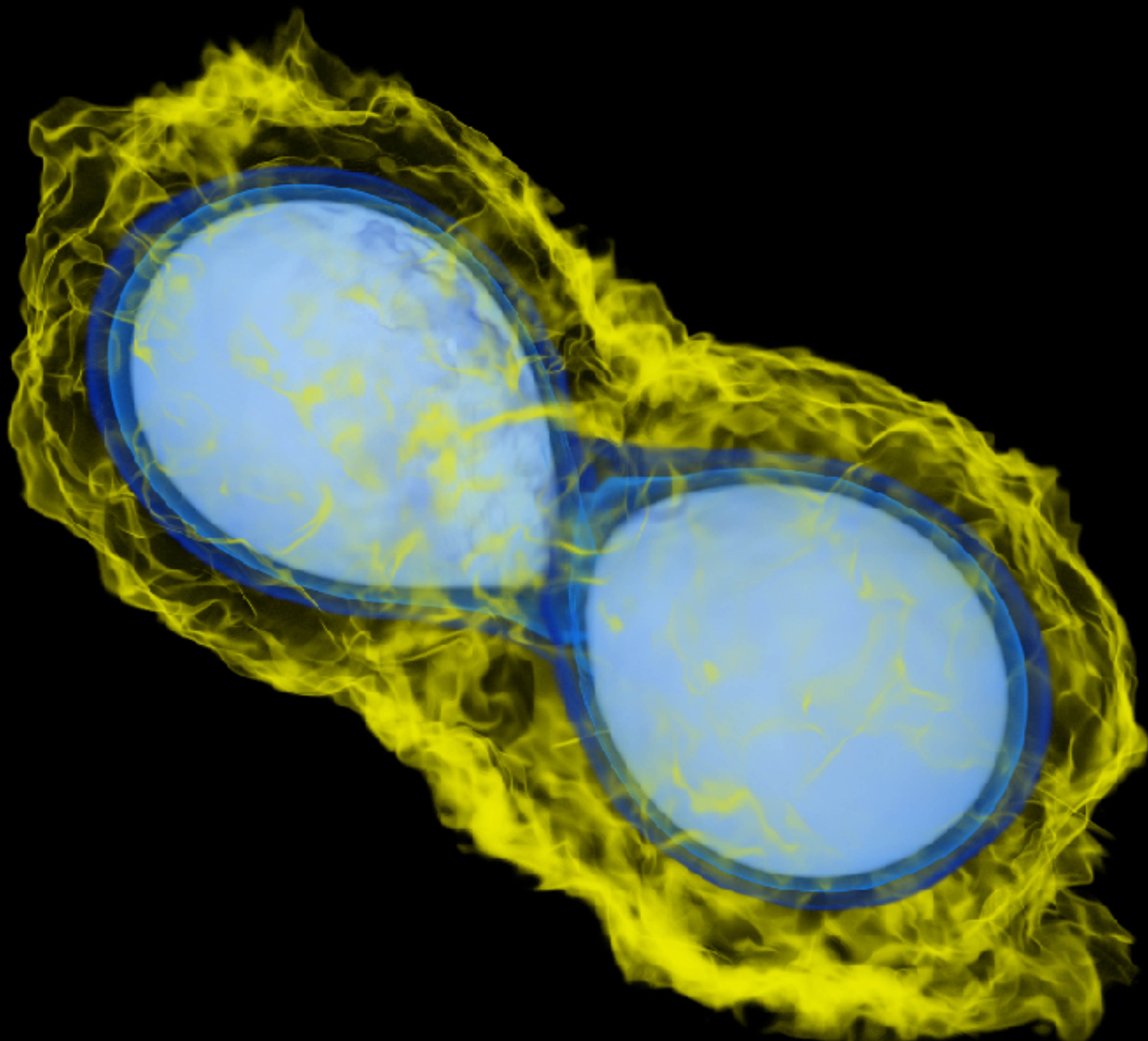


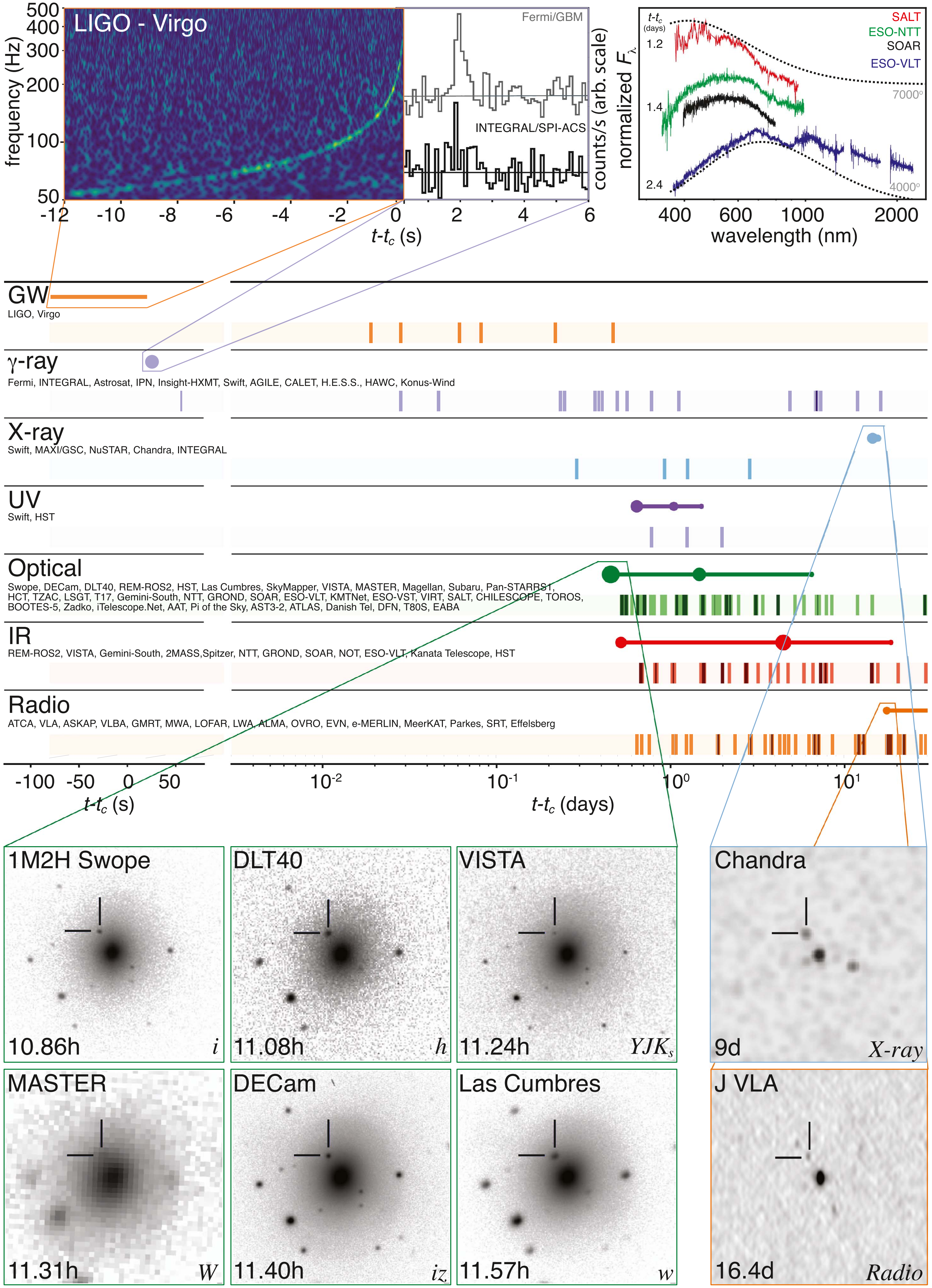
- GW signal: l=2, m=0; f-mode of the PNS
- Infer PNS radius
- Accretion history is encoded in the neutrino signal
- Learn about EOS and transport properties of warm nuclear matter

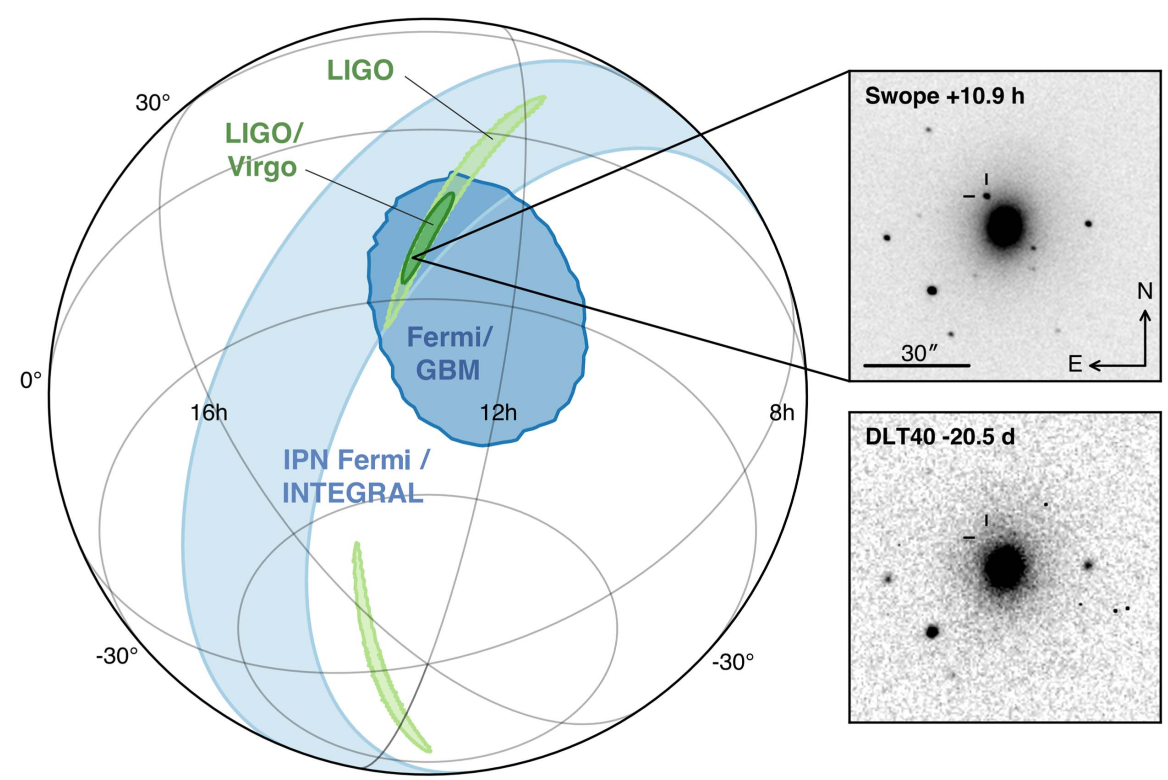
See also talk of Sotani

Morozova, **DR**, Burrows, Vartanyan, arXiv:1801.01914

Neutron star mergers

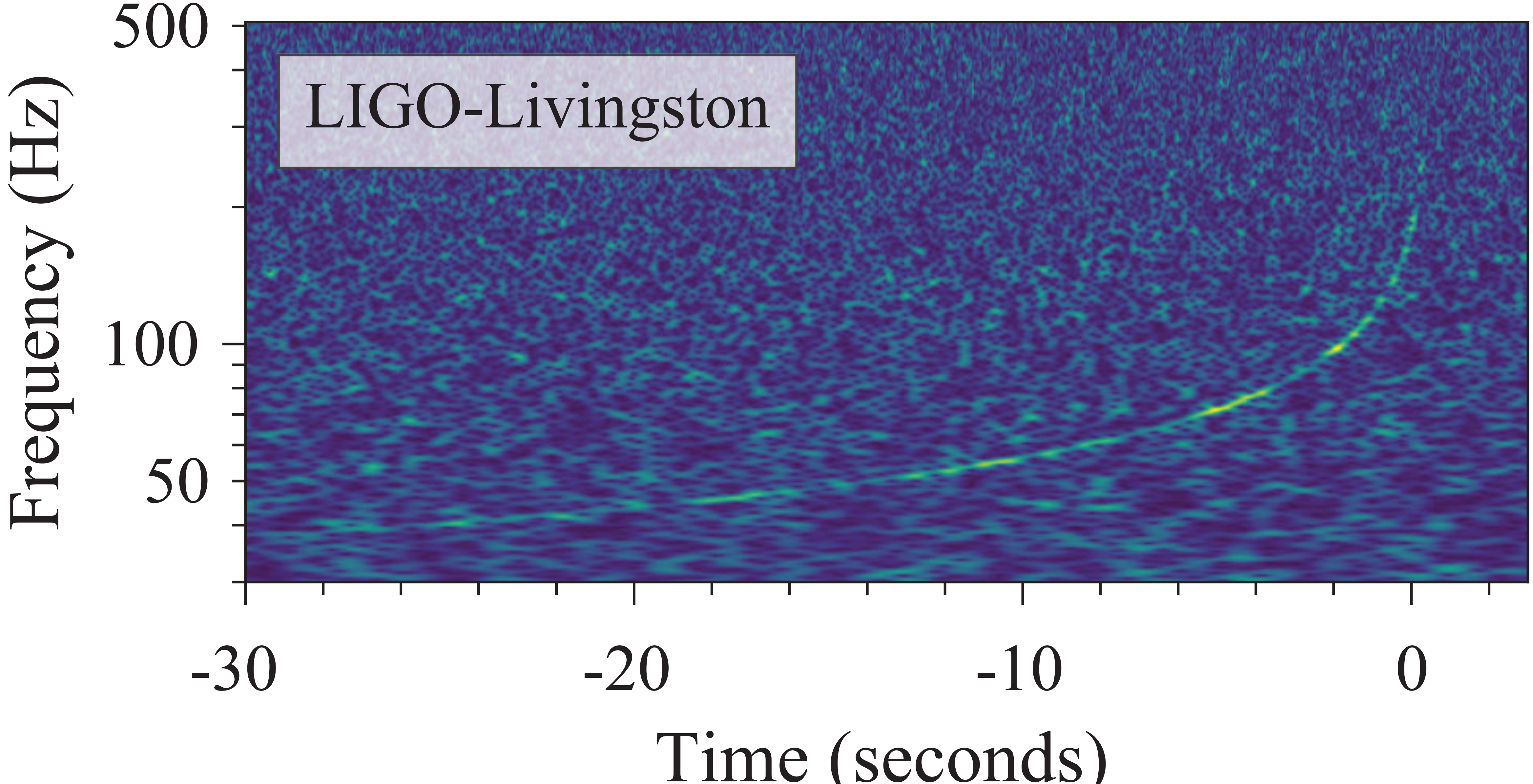






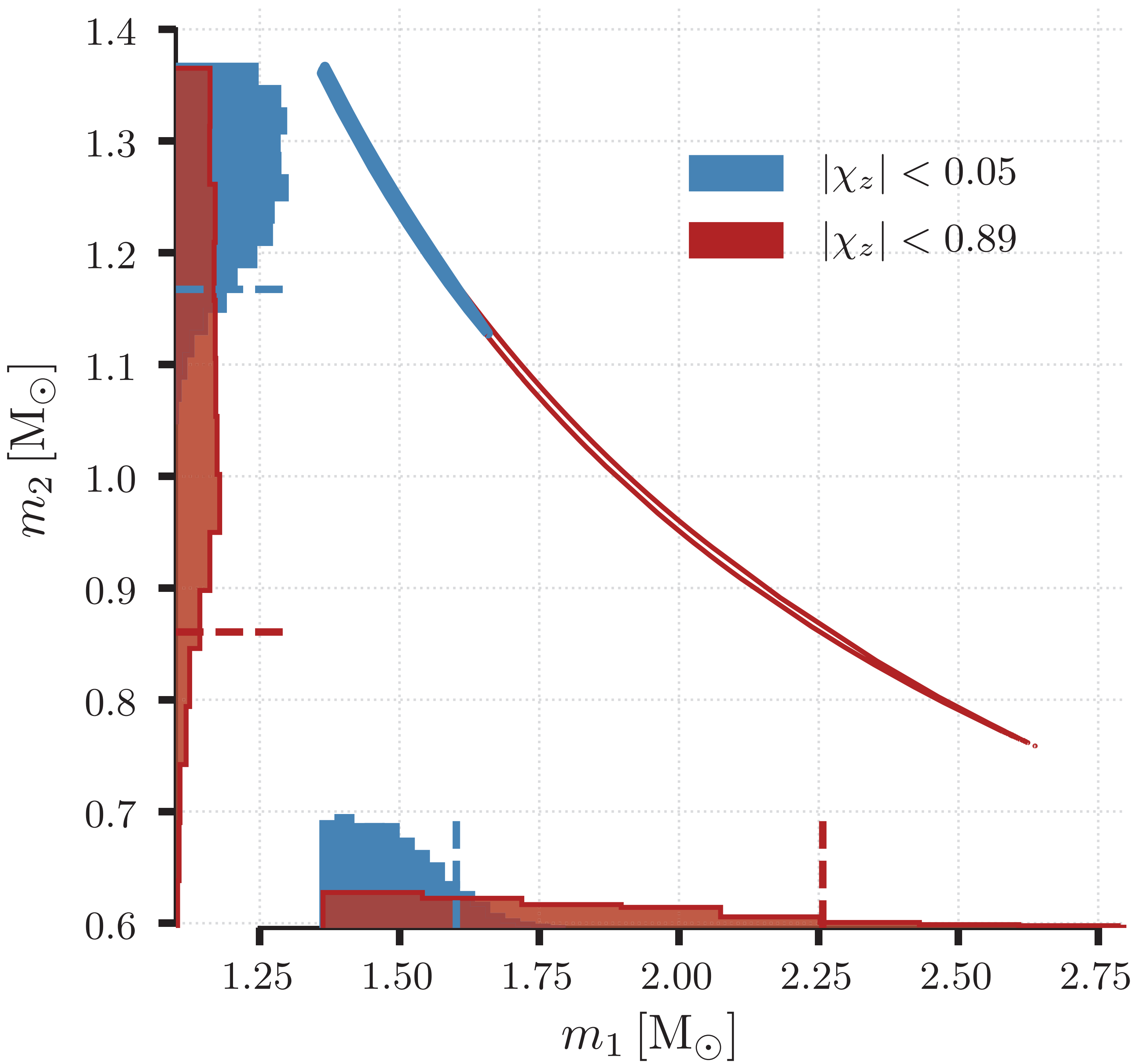
From LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM 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)

Gravitational waves



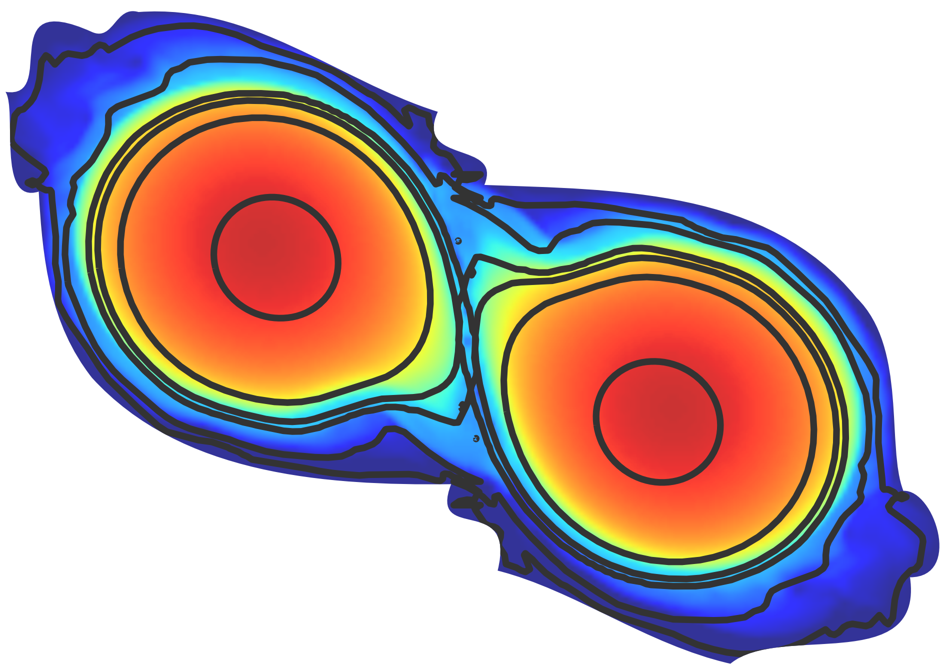
From LIGO/Virgo collaboration, PRL 119:161101 (2017)

Parameter estimation



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

Tidal effects in NS mergers

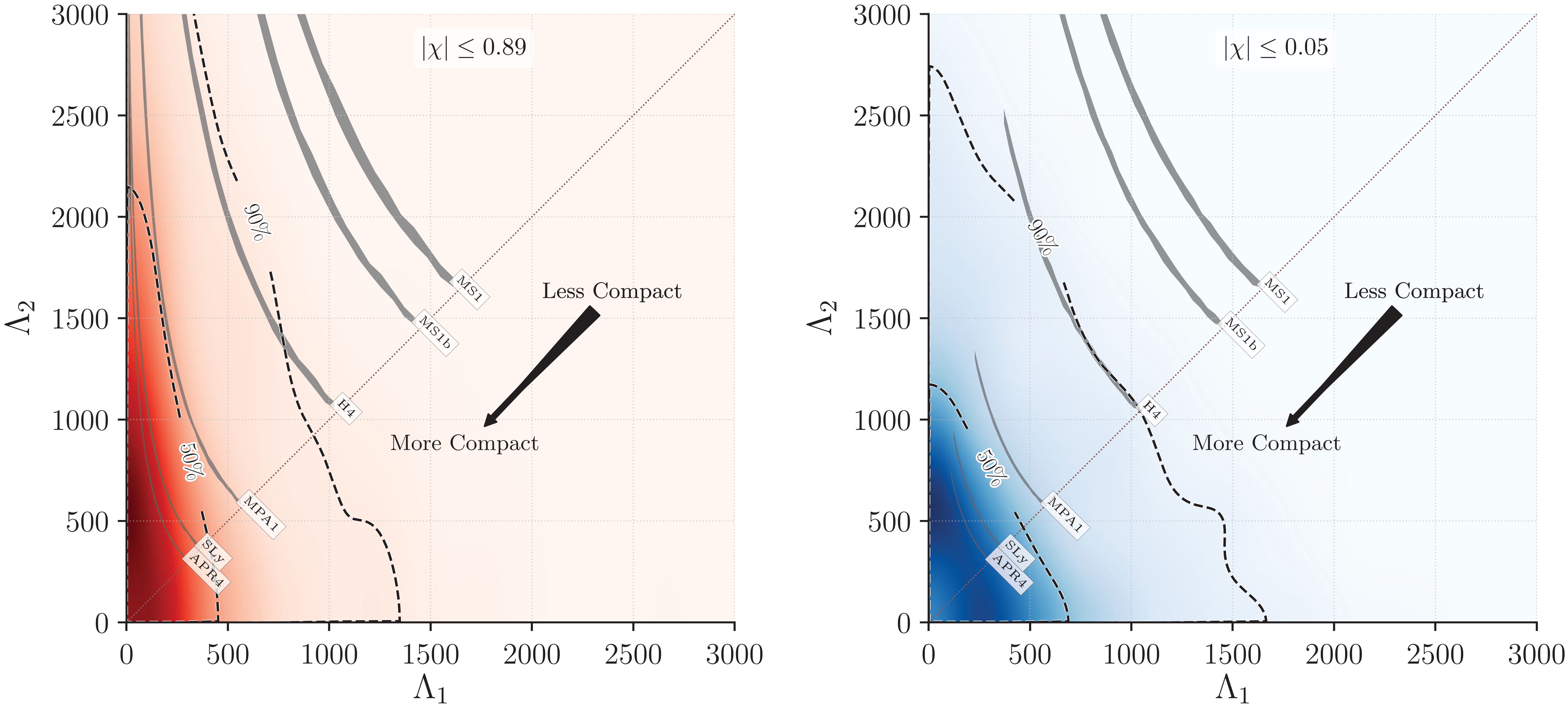


$$Q_{ij} = -\Lambda_2 \mathcal{E}_{ij}$$

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

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

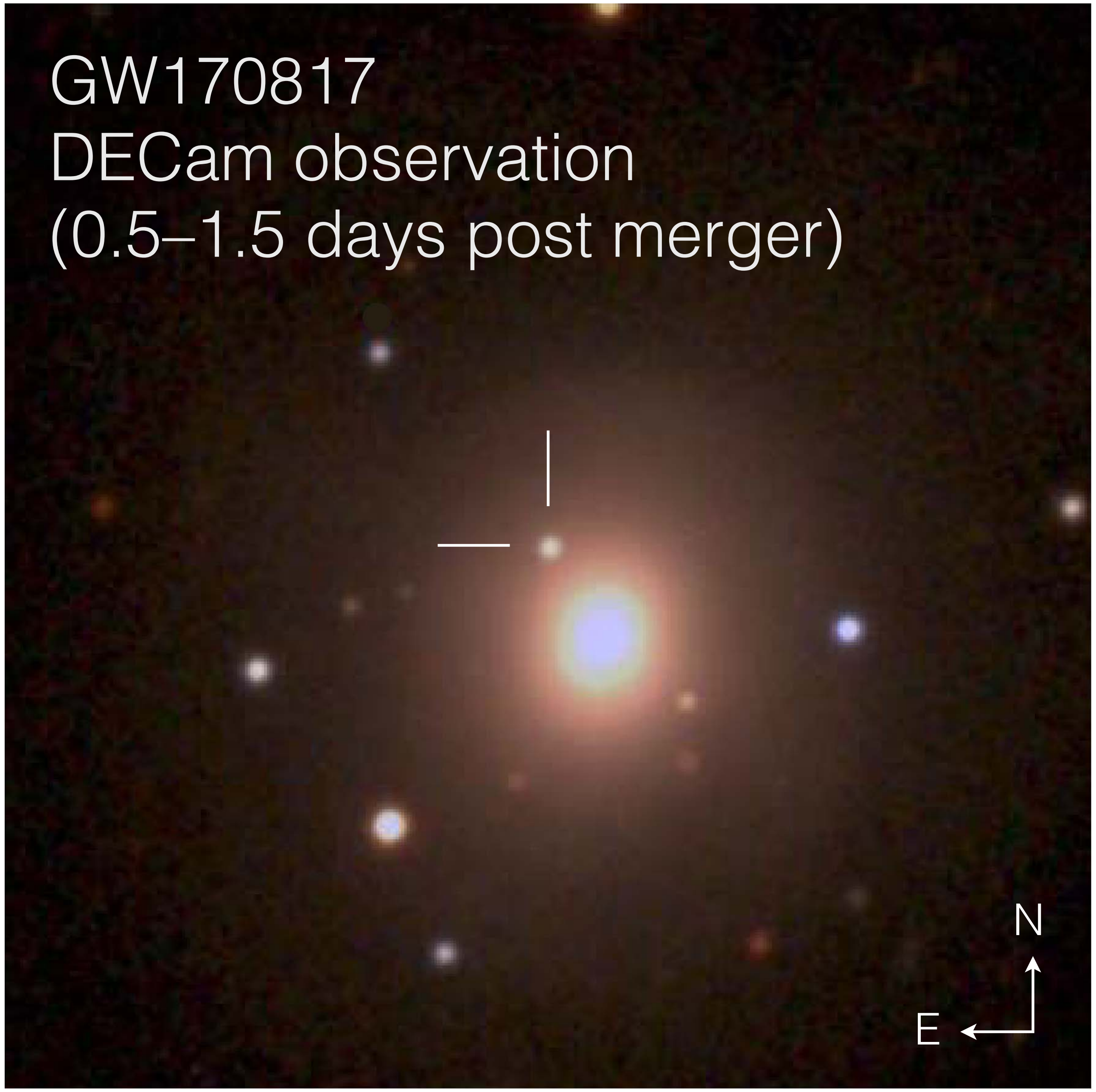
Constraints from GW170817

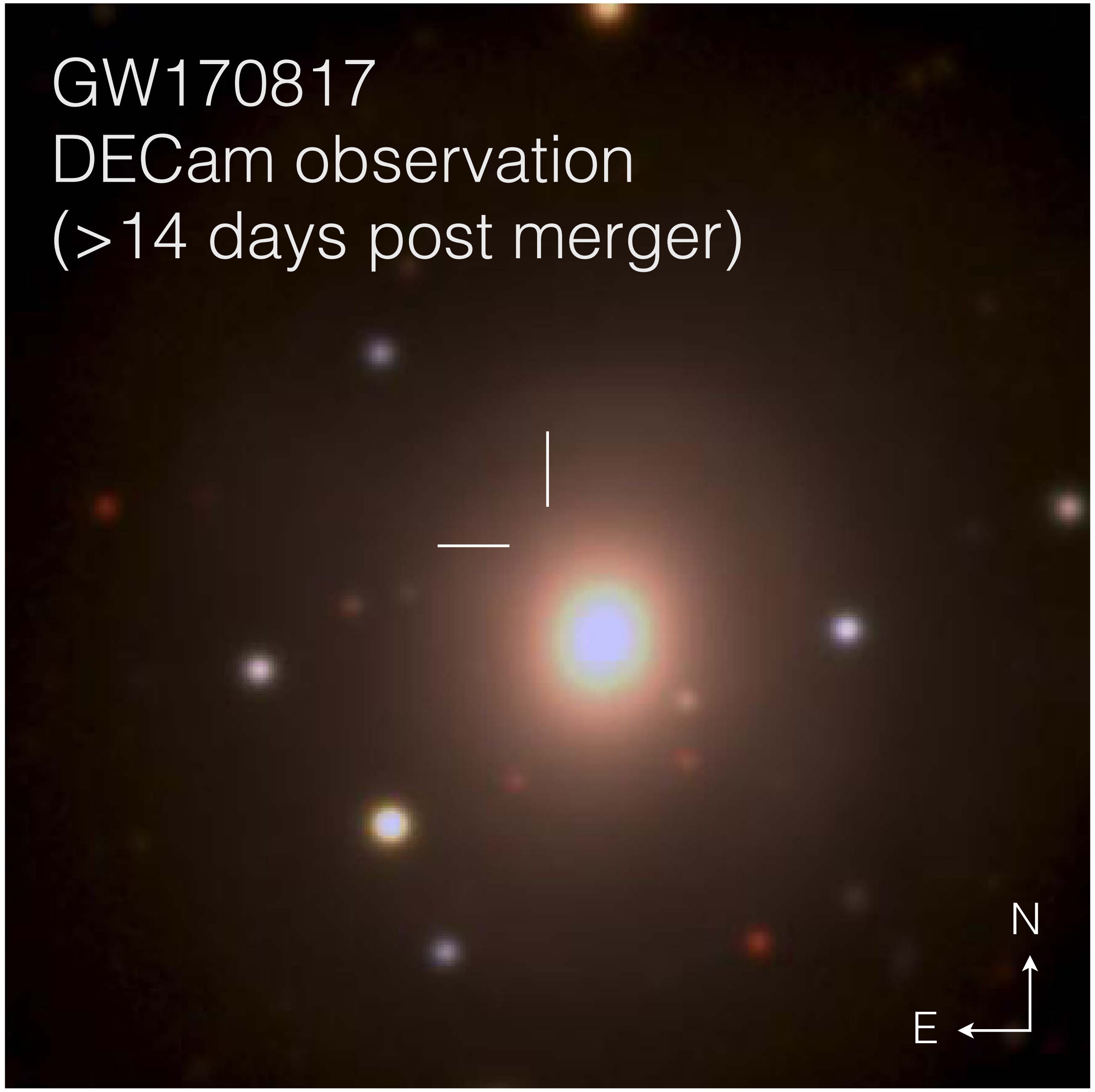


$$\frac{\bar{R}^5}{\bar{M}^5} \sim \tilde{\Lambda} = \frac{16}{13}\left[\frac{(M_A + 12M_B)M_A^4\tilde{\Lambda}_2^{(A)}}{(M_A+M_B)^5} + (A \leftrightarrow B)\right] \leq 800$$

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

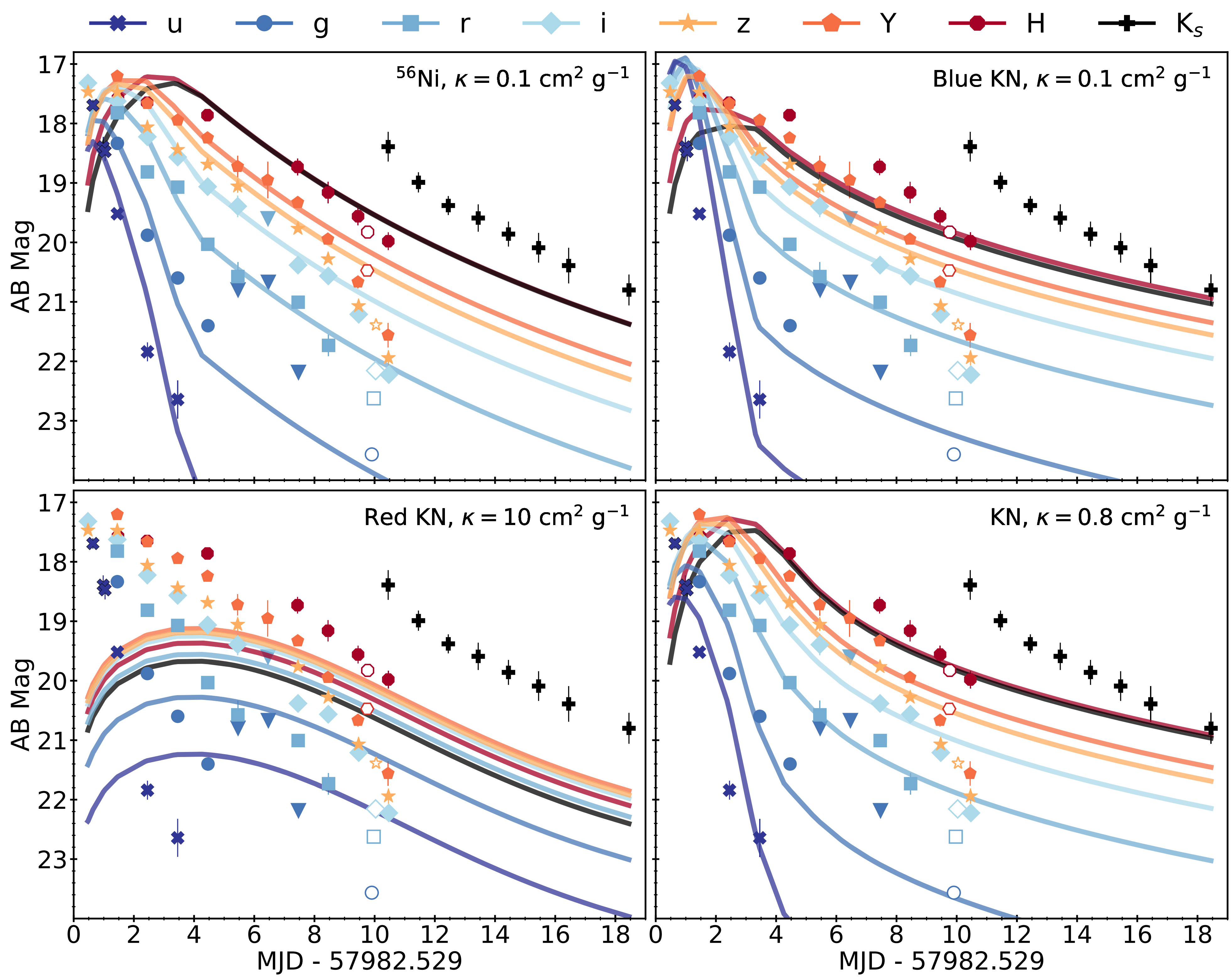
UVOIR





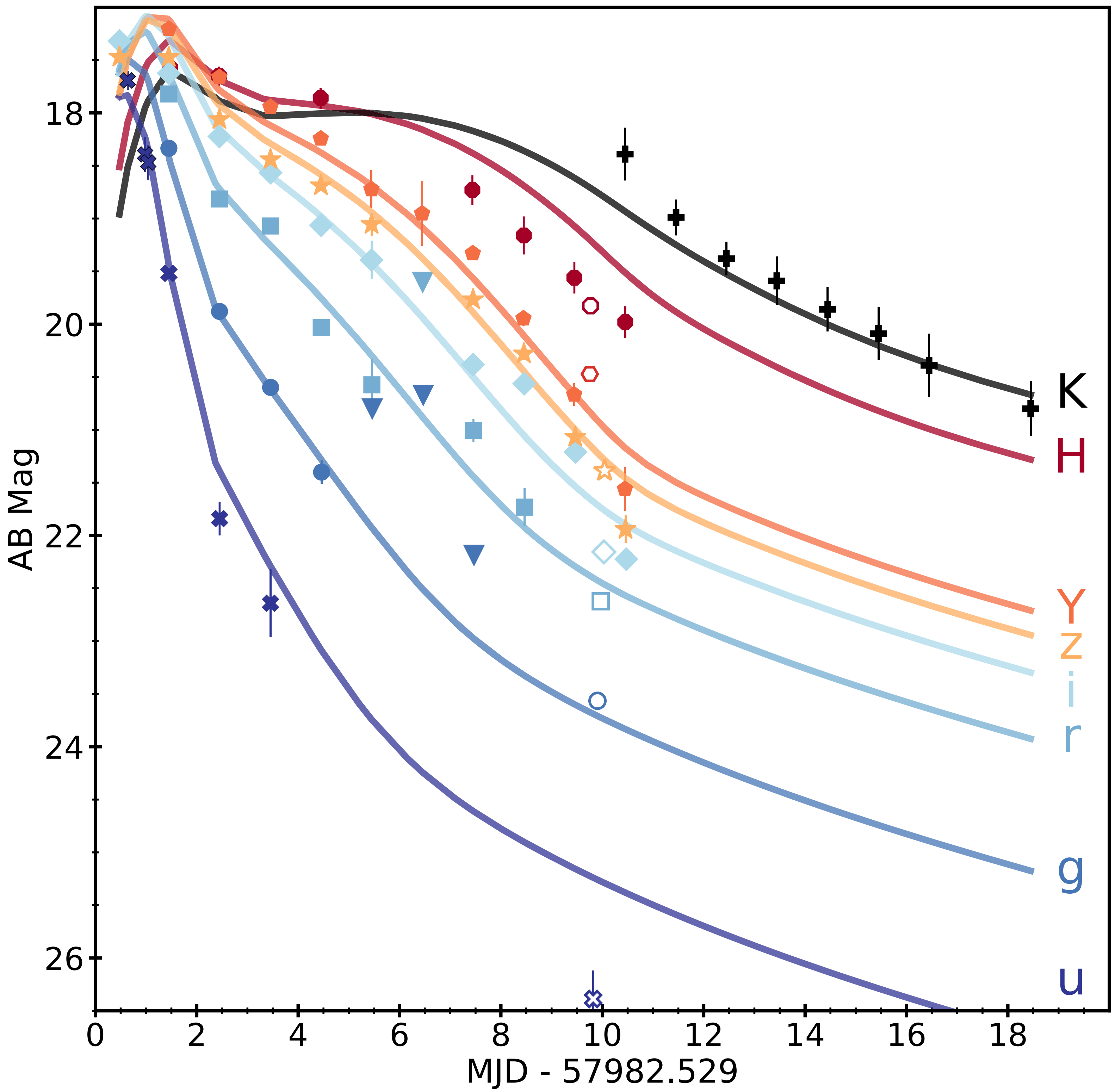
From Soares-Santos et al., ApJL 848:L16 (2017)

Multiple components!



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

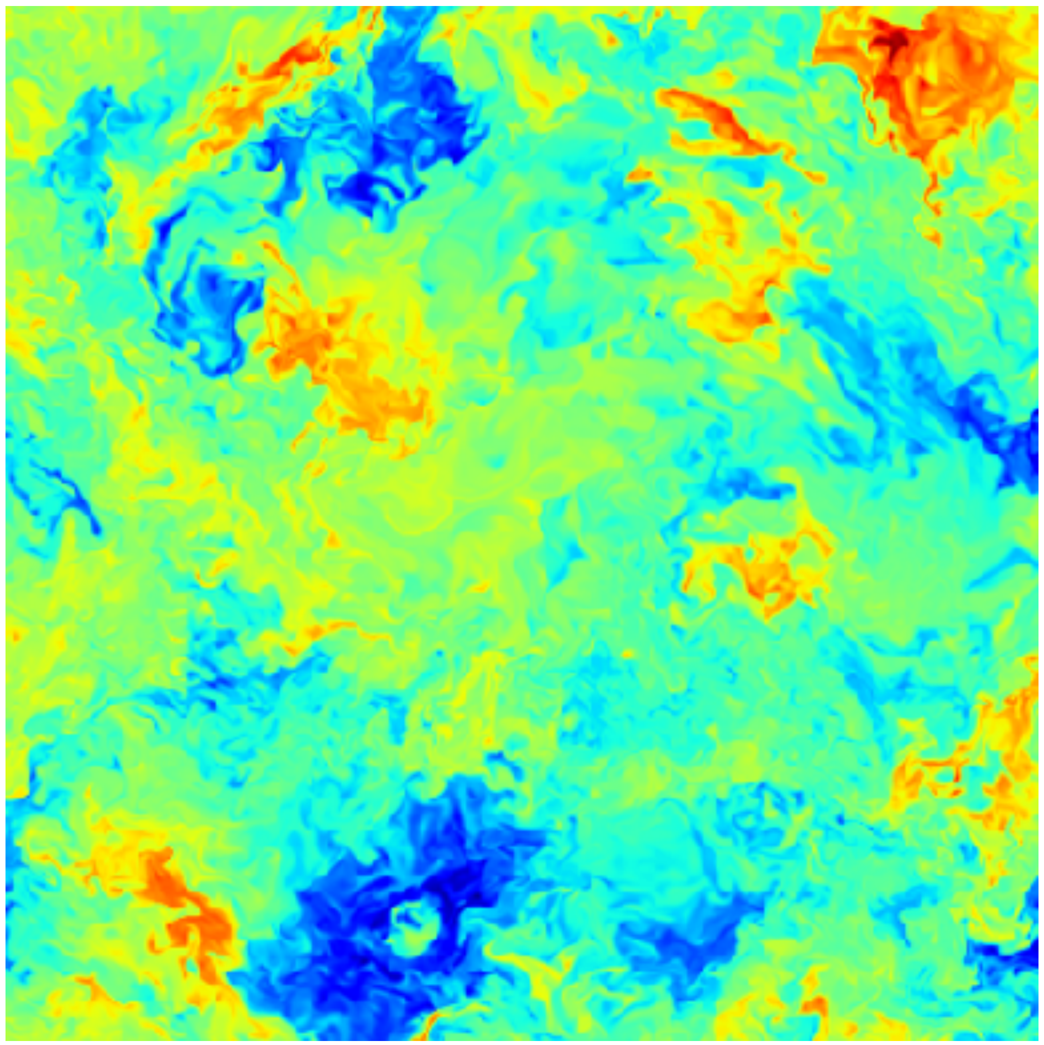
Multiple components!



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

WhiskyTHC

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



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

* using the Einstein Toolkit metric solvers

THC: Templated Hydrodynamics Code

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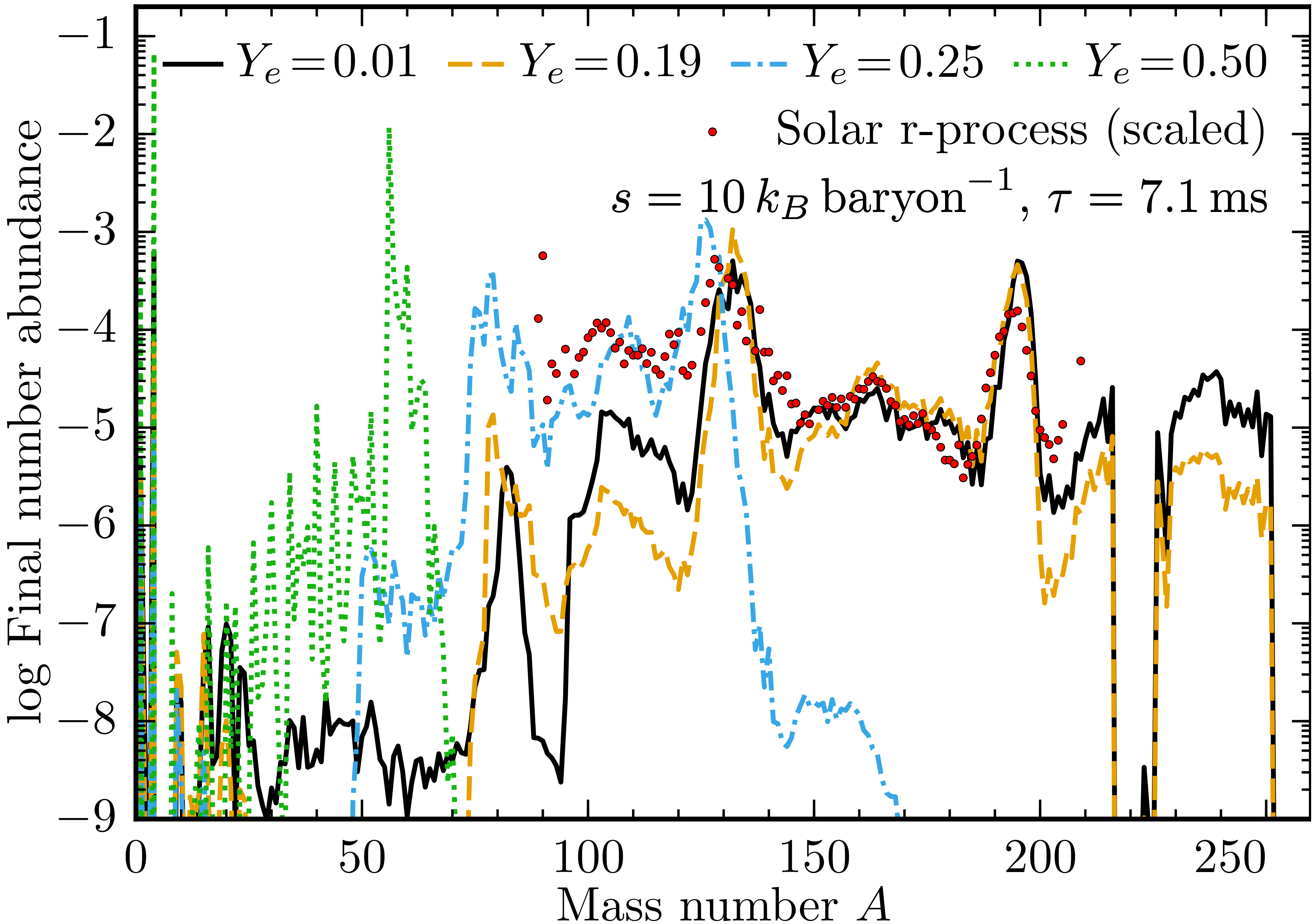
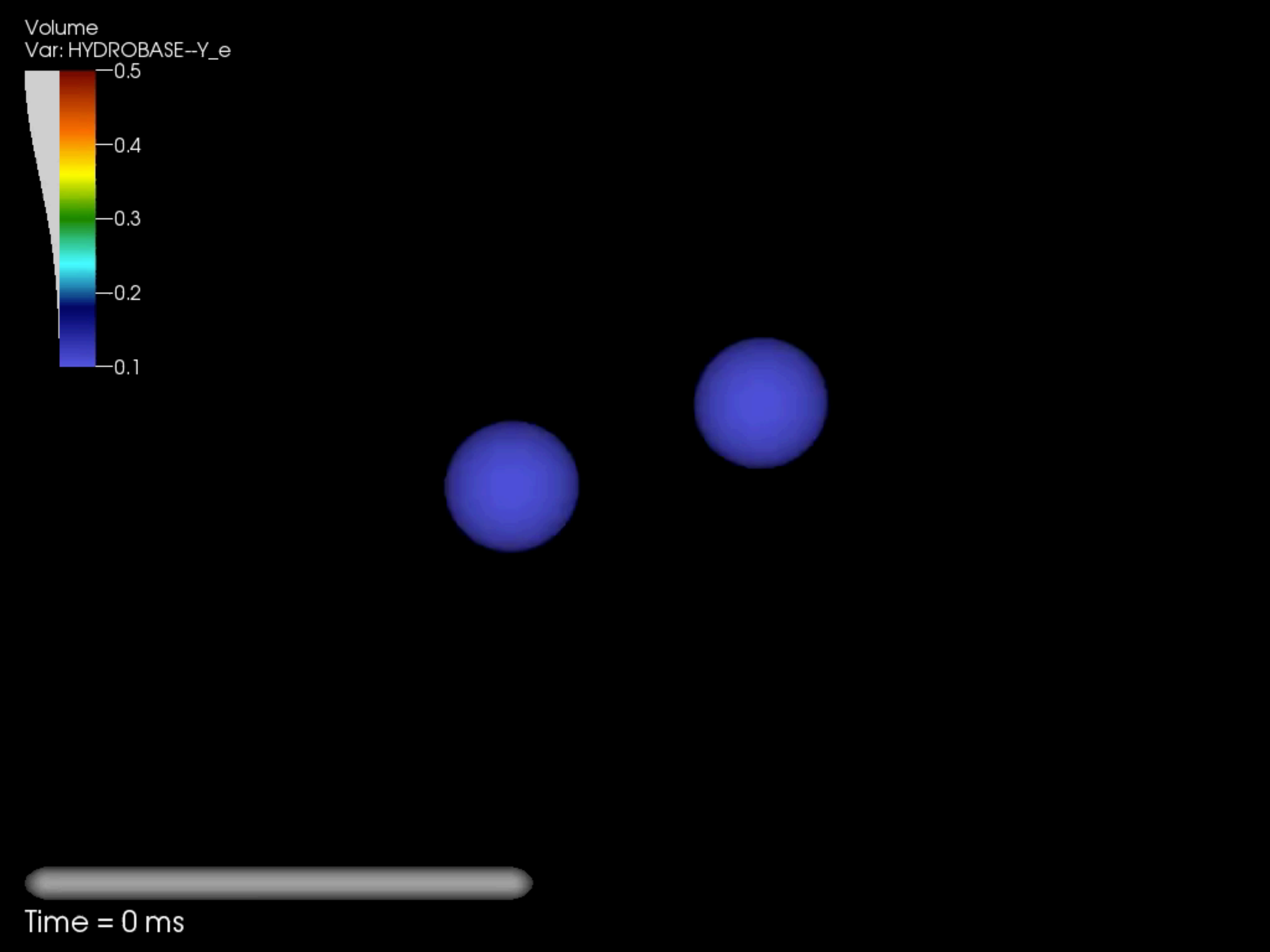
Strong and weak r-process



From Lippuner & Roberts, ApJ 815:82 (2015)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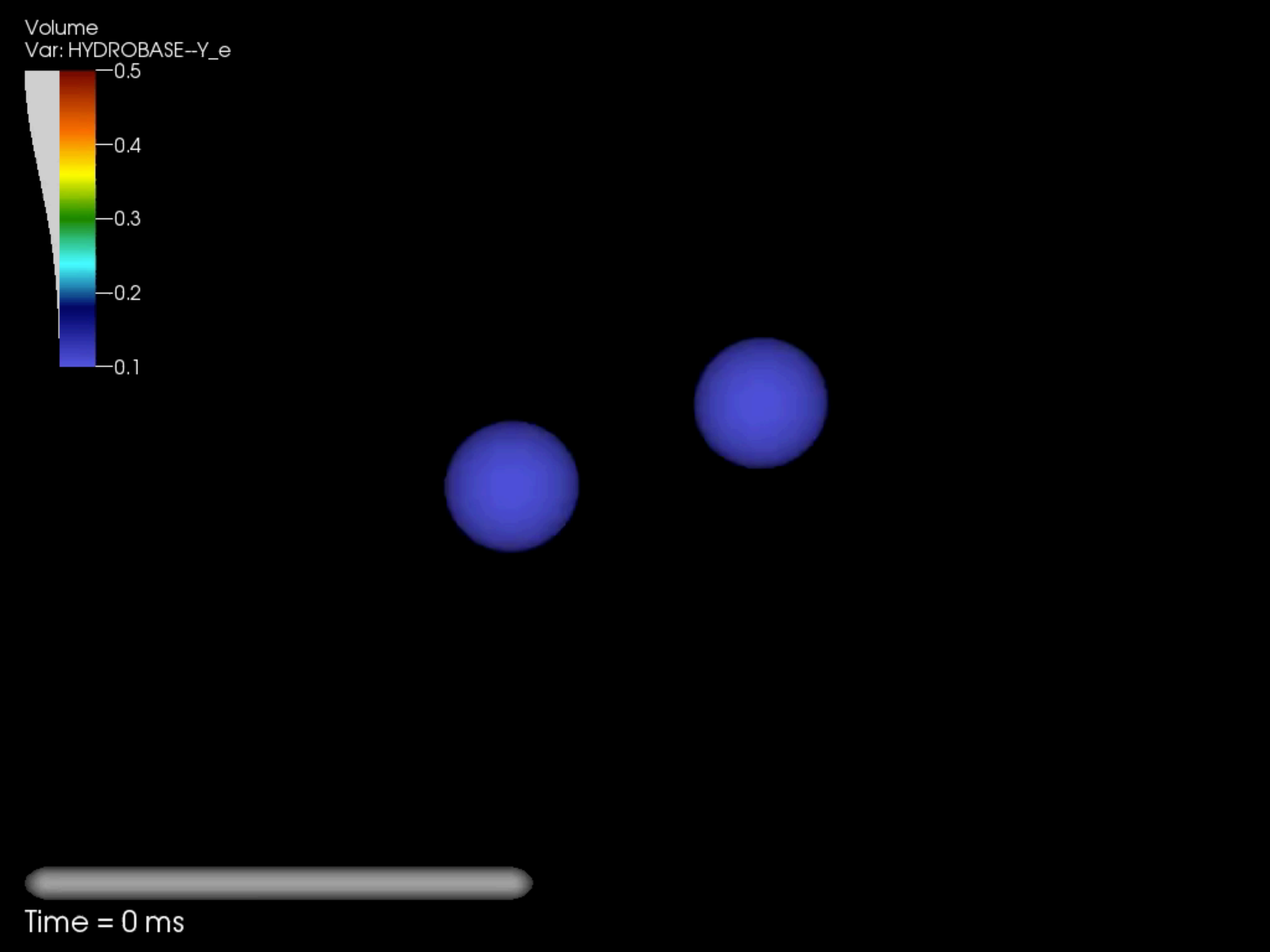
0.4
0.3
0.2
0.1
Time = 0 ms


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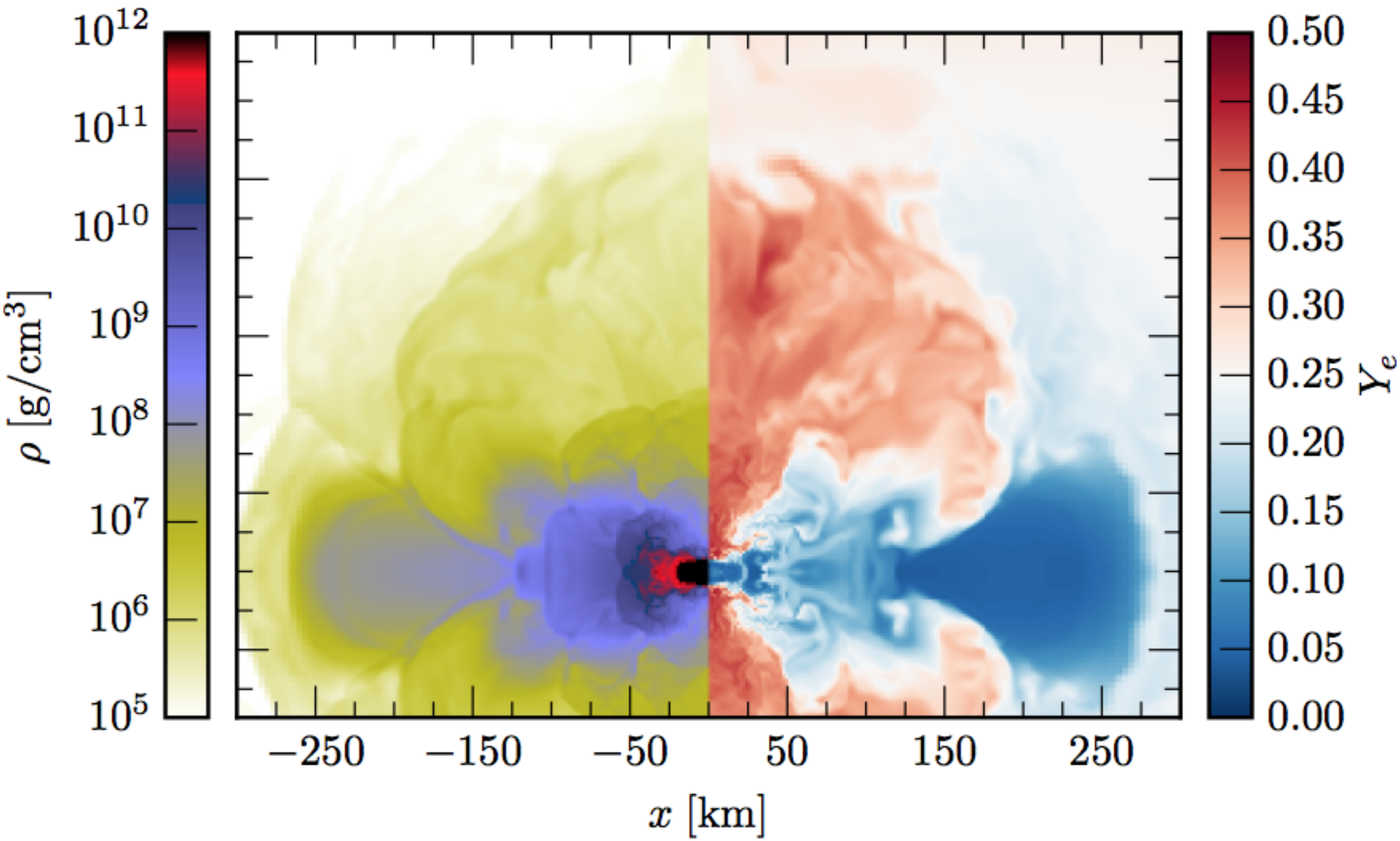
0.3
0.2
0.1
Time = 0 ms

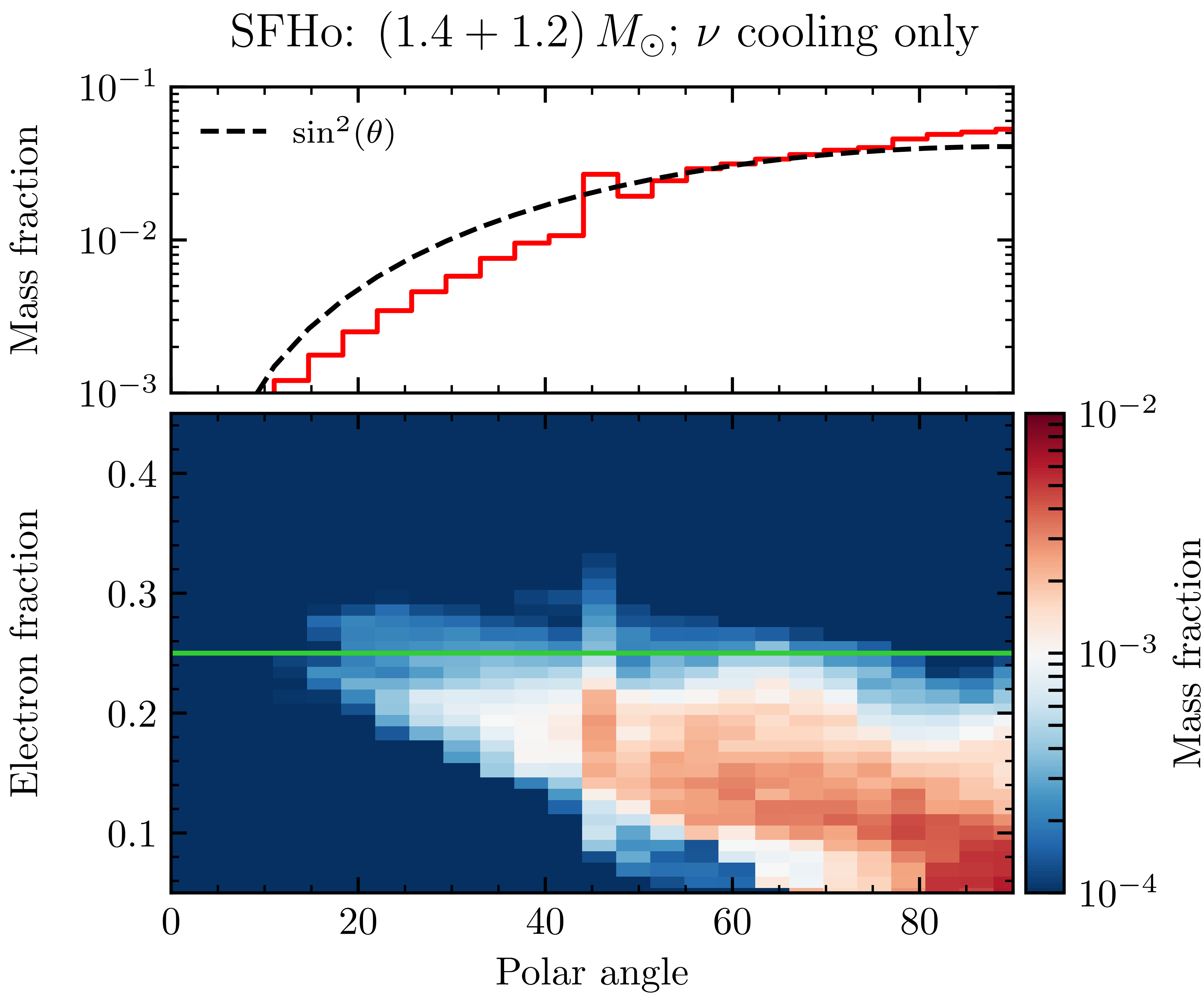
Neutron rich outflows



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

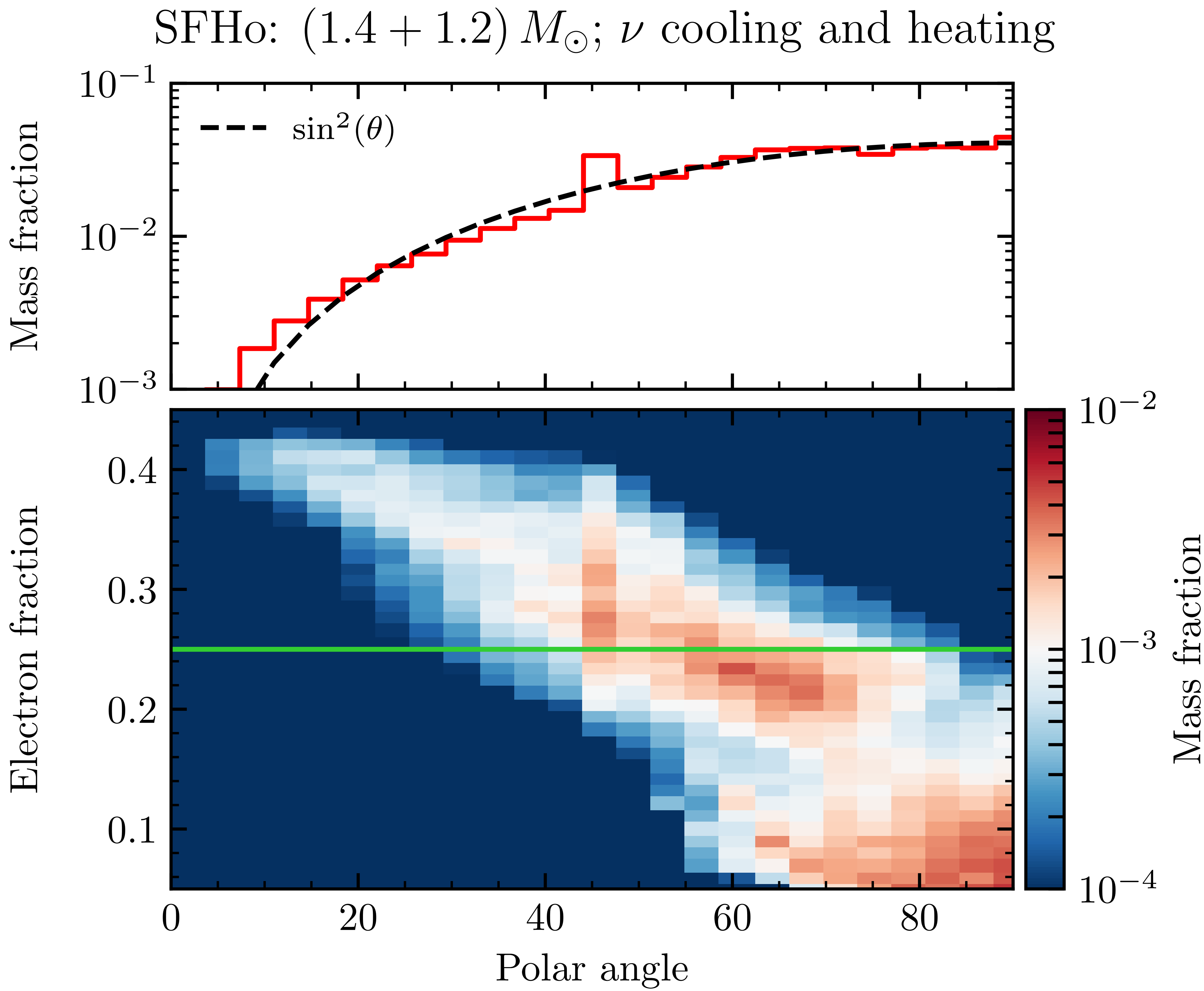
DR, Galeazzi+ MRAS 460:3255 (2016)

Dynamic ejecta: role of neutrinos



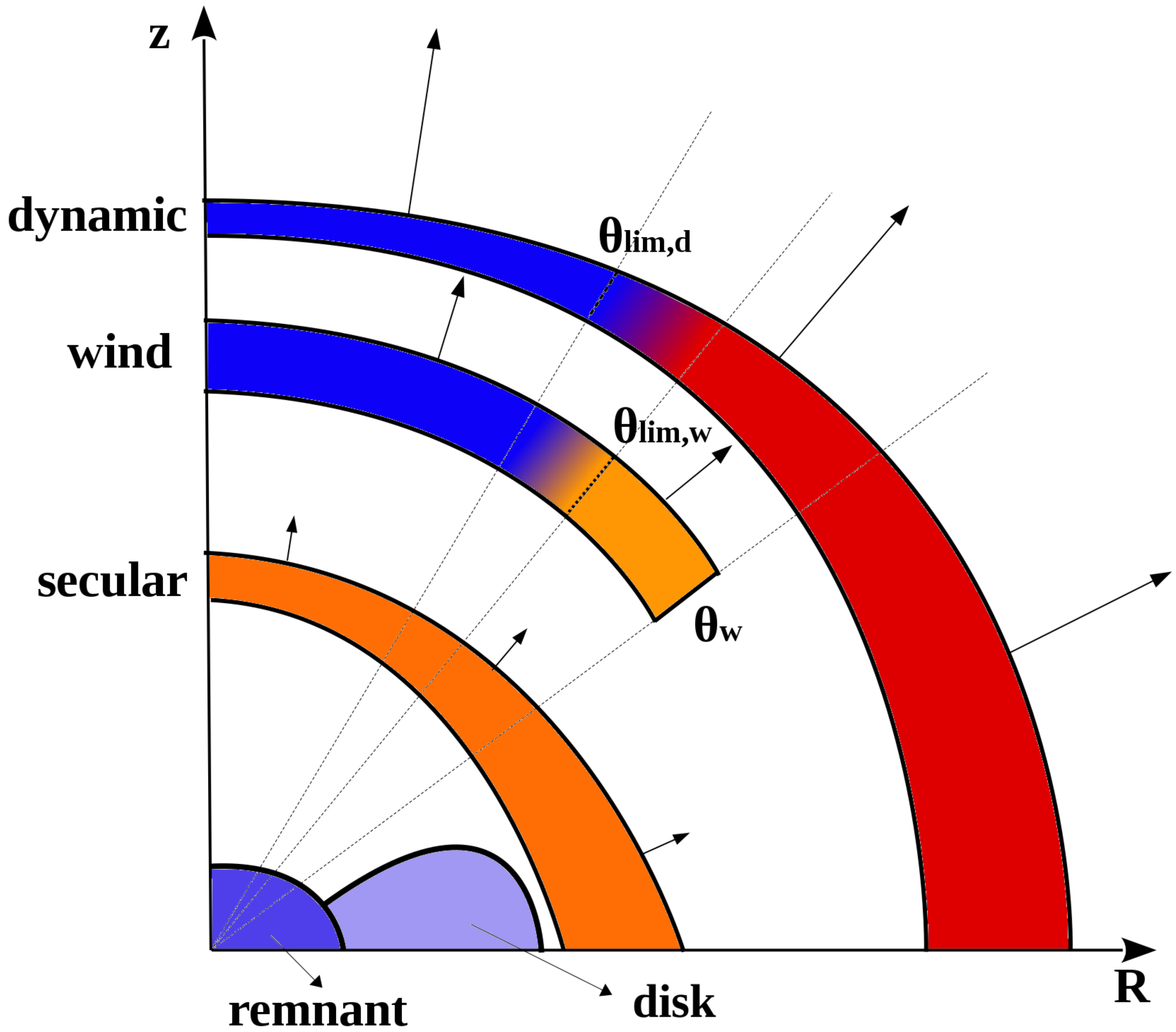
Perego, **DR**, Bernuzzi, arXiv:1711.03982

Dynamic ejecta: role of neutrinos



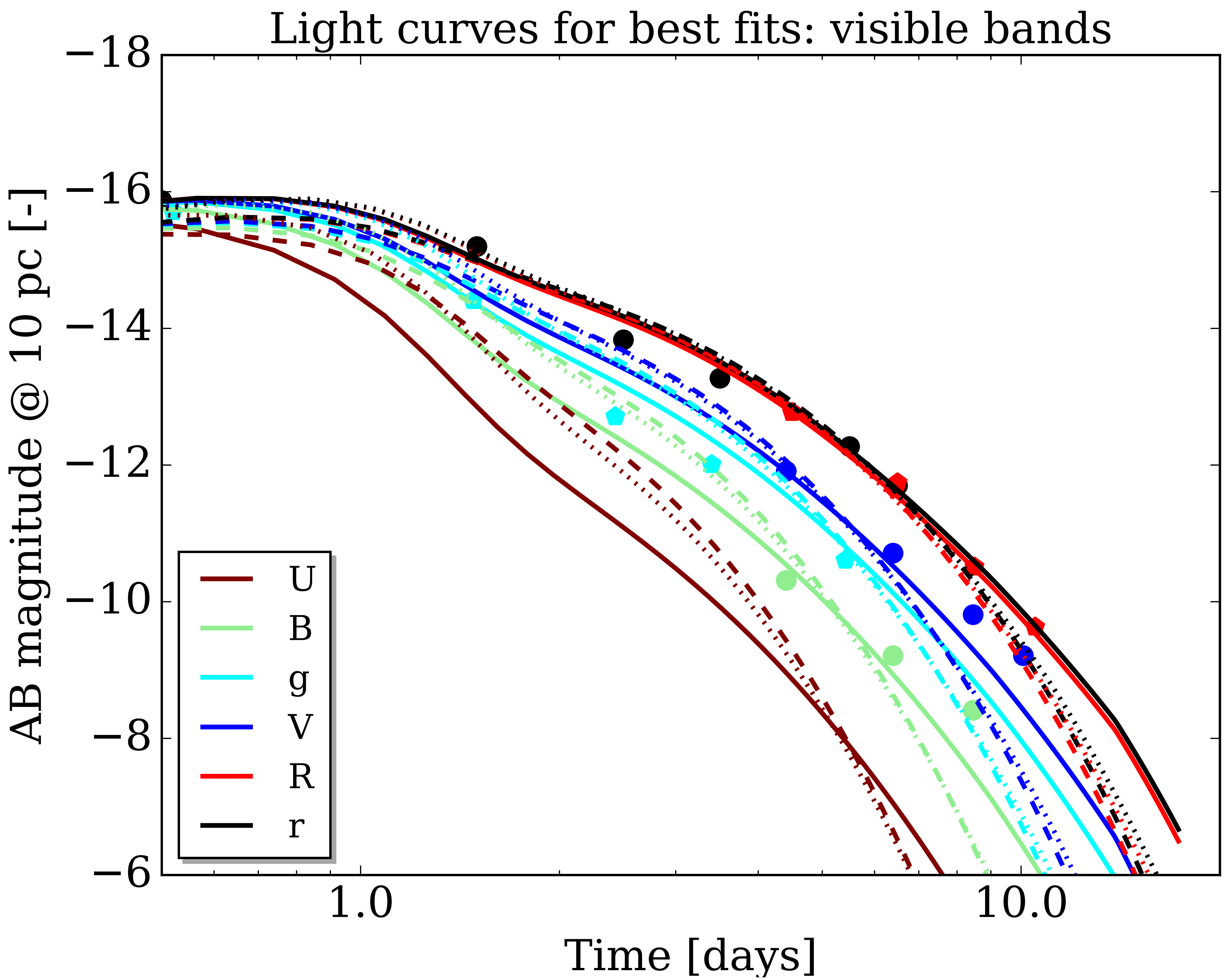
Perego, **DR**, Bernuzzi, arXiv:1711.03982

Neutron rich outflows: model



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

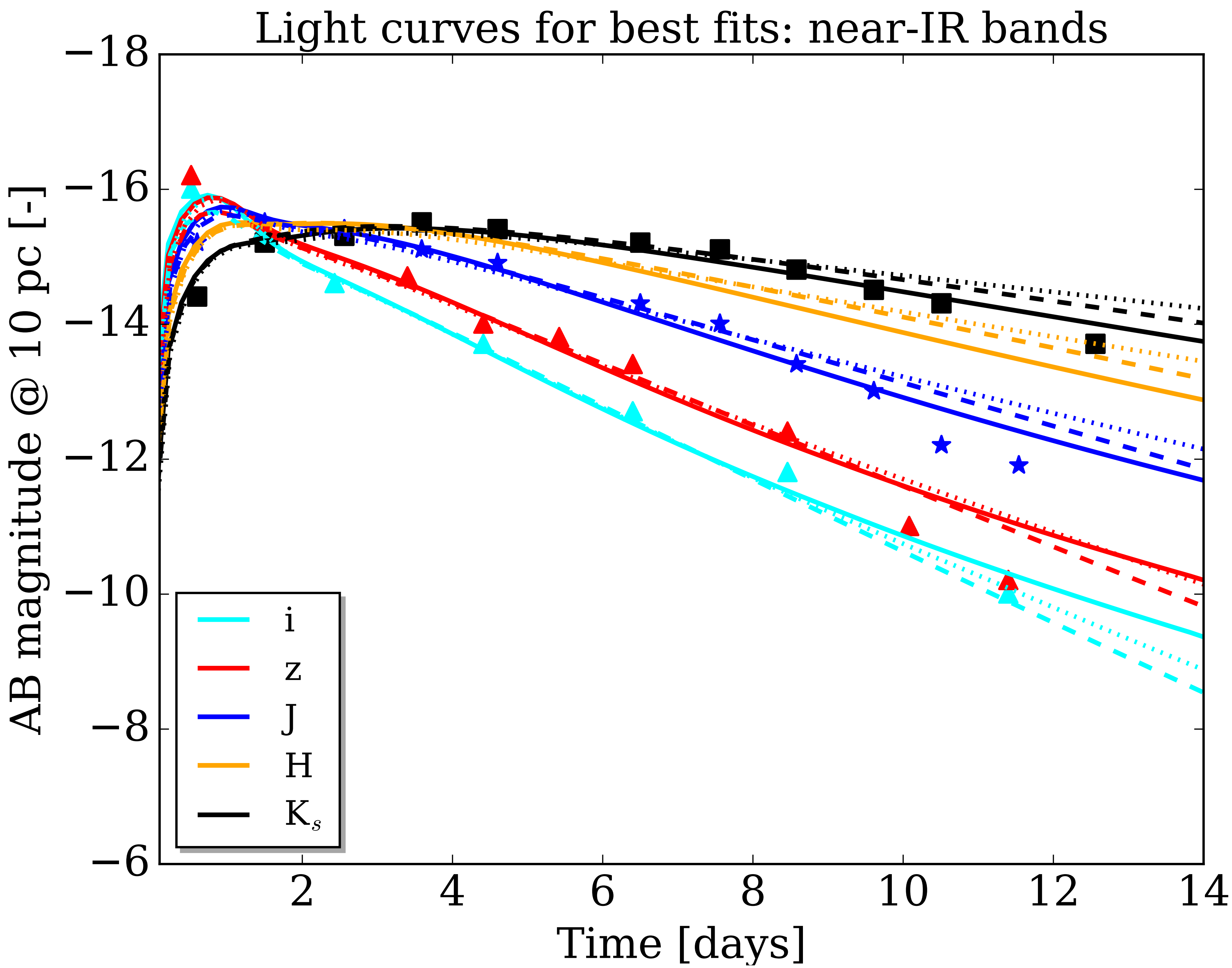
Kilonova modeling (I)



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

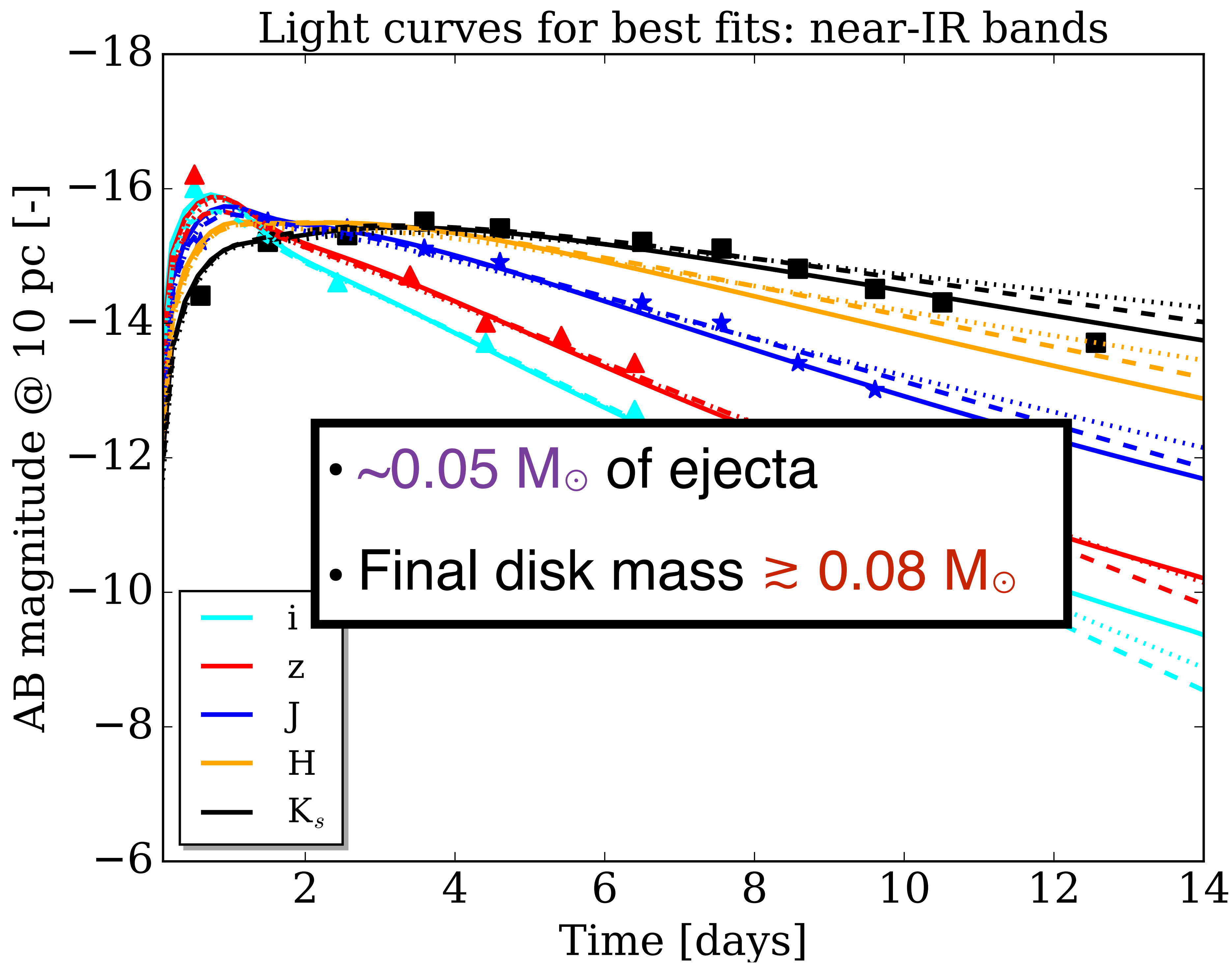
Kilonova modeling (II)



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

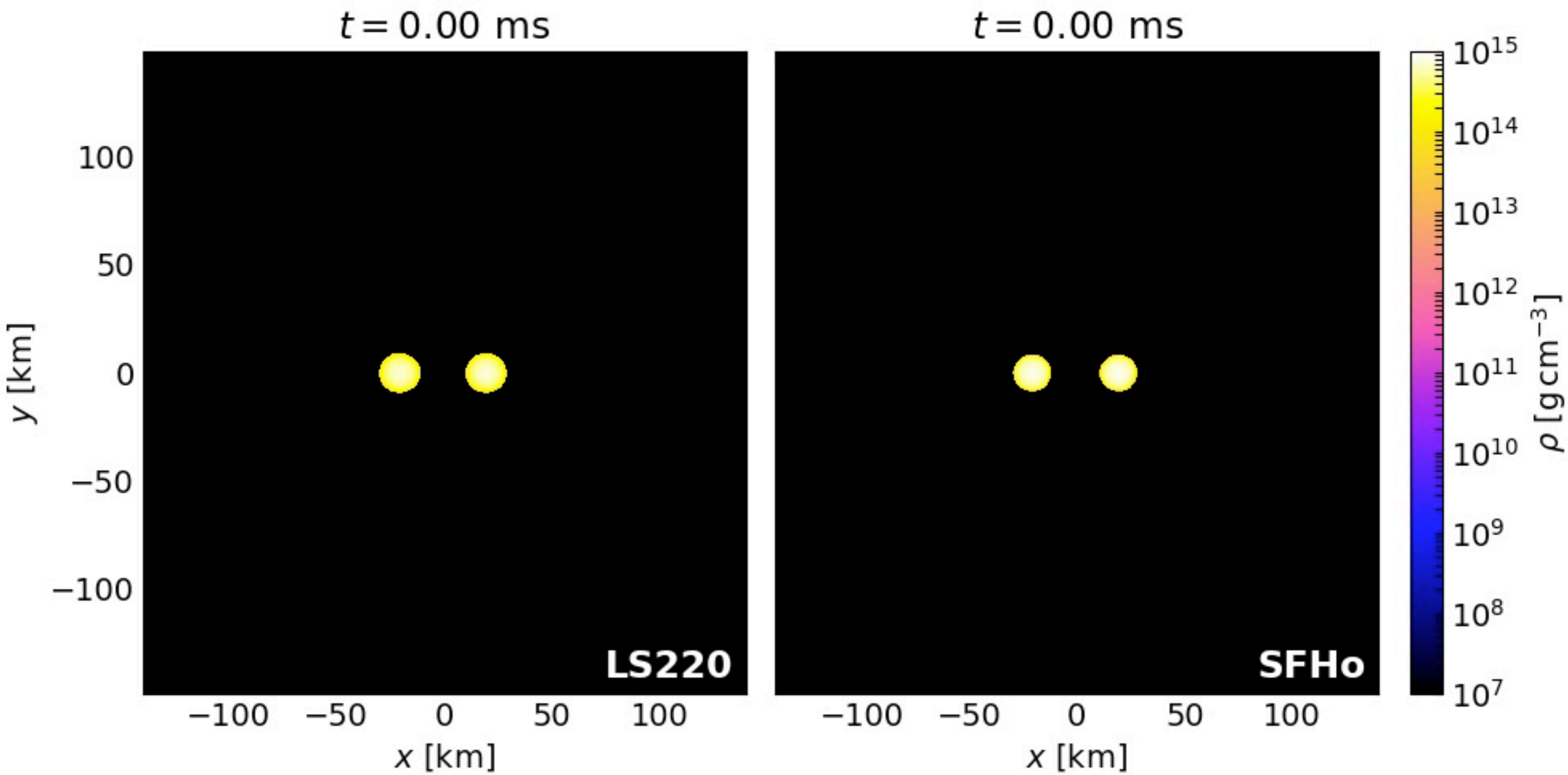
Kilonova modeling (II)



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

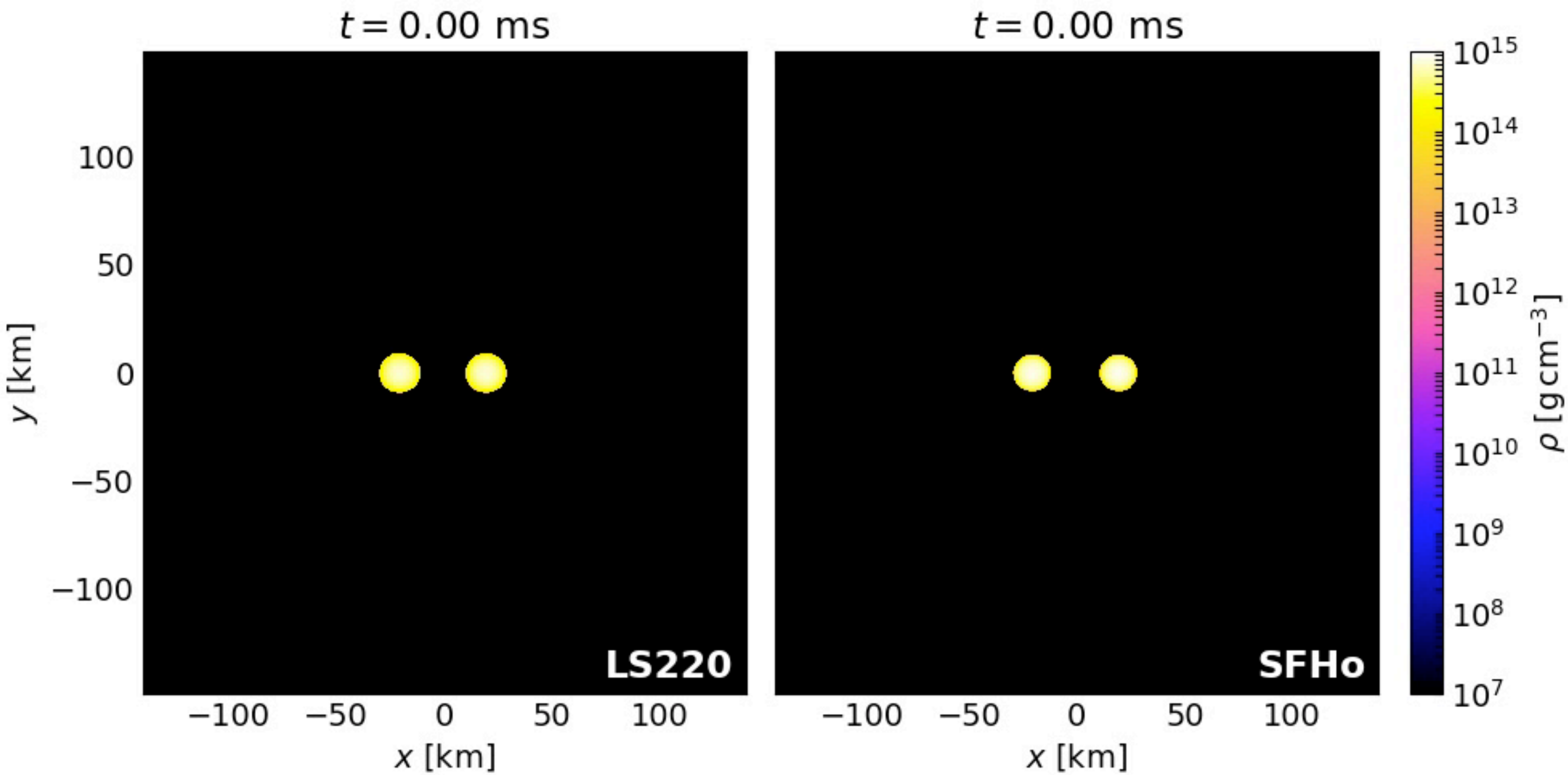
Prompt collapse?



$(1.44 + 1.39)\ M_\odot$ — B1913 + 13

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

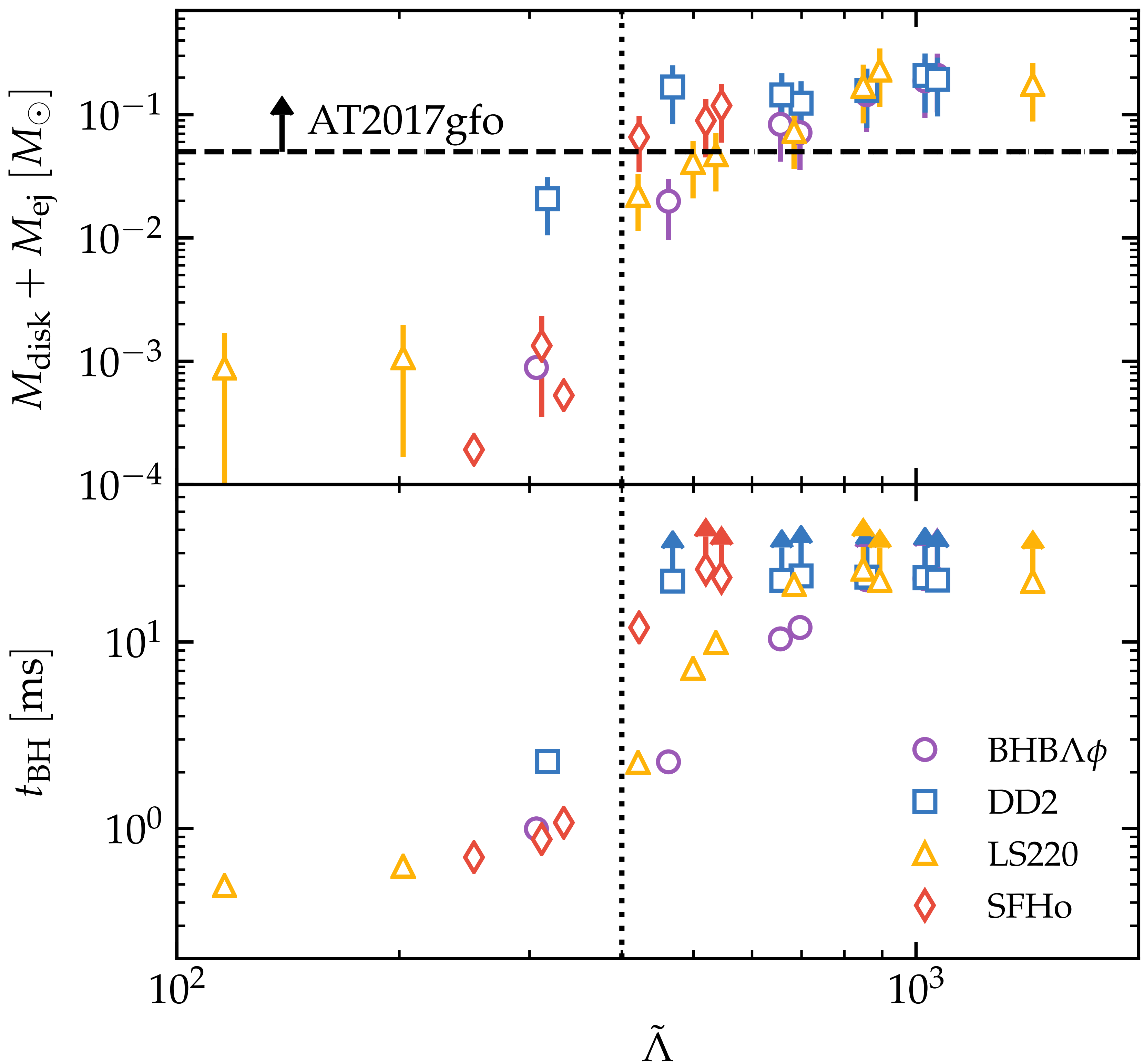
Prompt collapse?



$(1.44 + 1.39)\ M_\odot$ — B1913 + 13

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

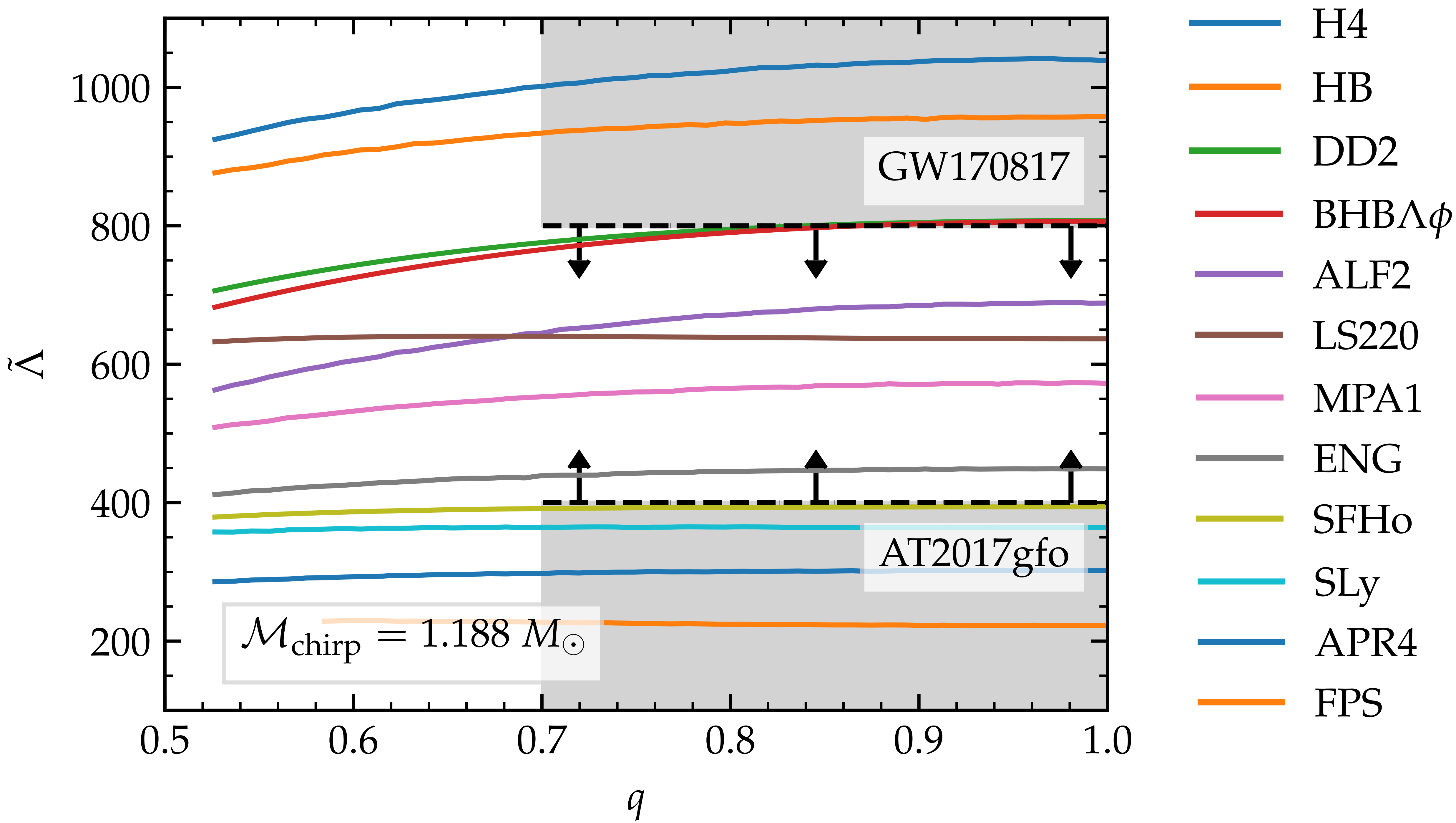
Constraining the nuclear EOS



See also Bauswein+ 2017 ApJL 850:L34

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

Constraining the nuclear EOS



See also:
Margalit & Metzger, Bauswein+, Rezzolla+, Ruiz+ (2017)

DR, Perego+ ApJL 852:L29 (2018)

Conclusions

Core-collapse supernovae

- Sensitivity to microphysics
- Protoneutron star convection is important
- Neutrino and GW signatures

Neutron star mergers

- Neutrinos play important role for EM counterparts
- Prompt collapse excluded for GW170817
- Complementary constrain on $\tilde{\Lambda}$