Dependence of neutrino heating in core-collapse supernovae on progenitor compactness

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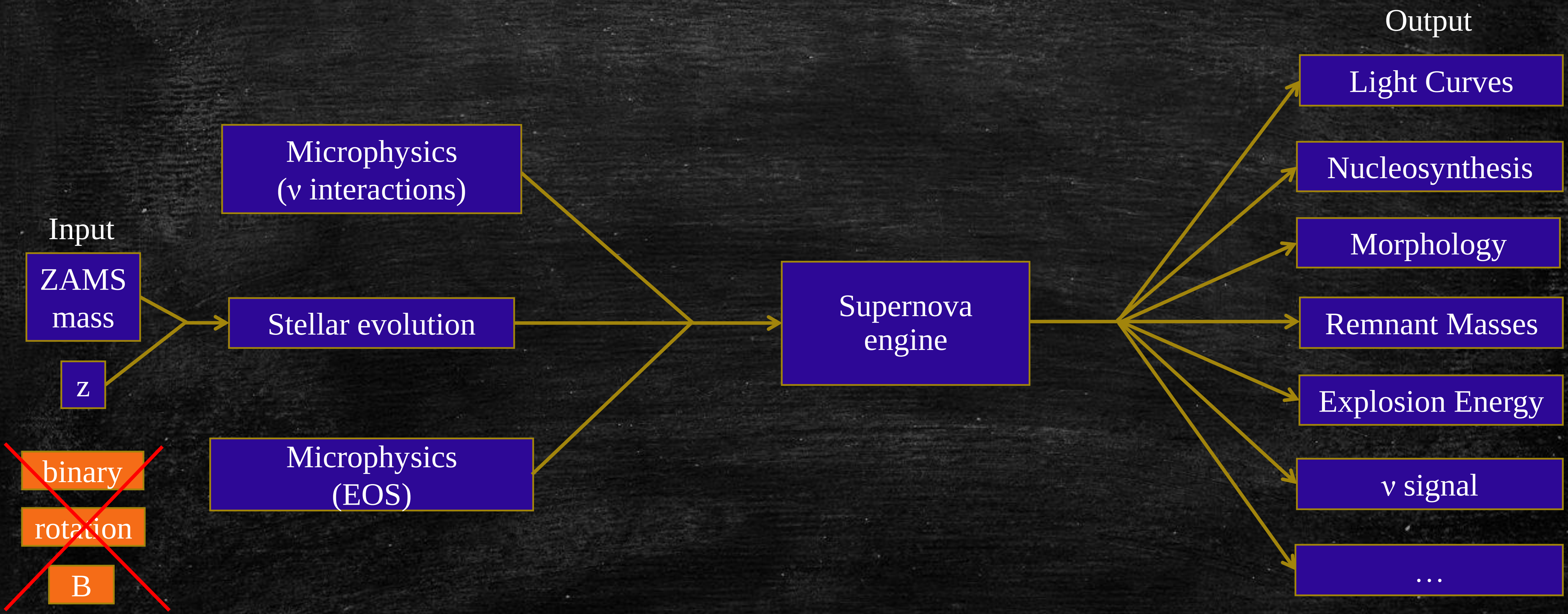
Galileo Galilei Institute: Neutrino Frontiers

July 19th 2024

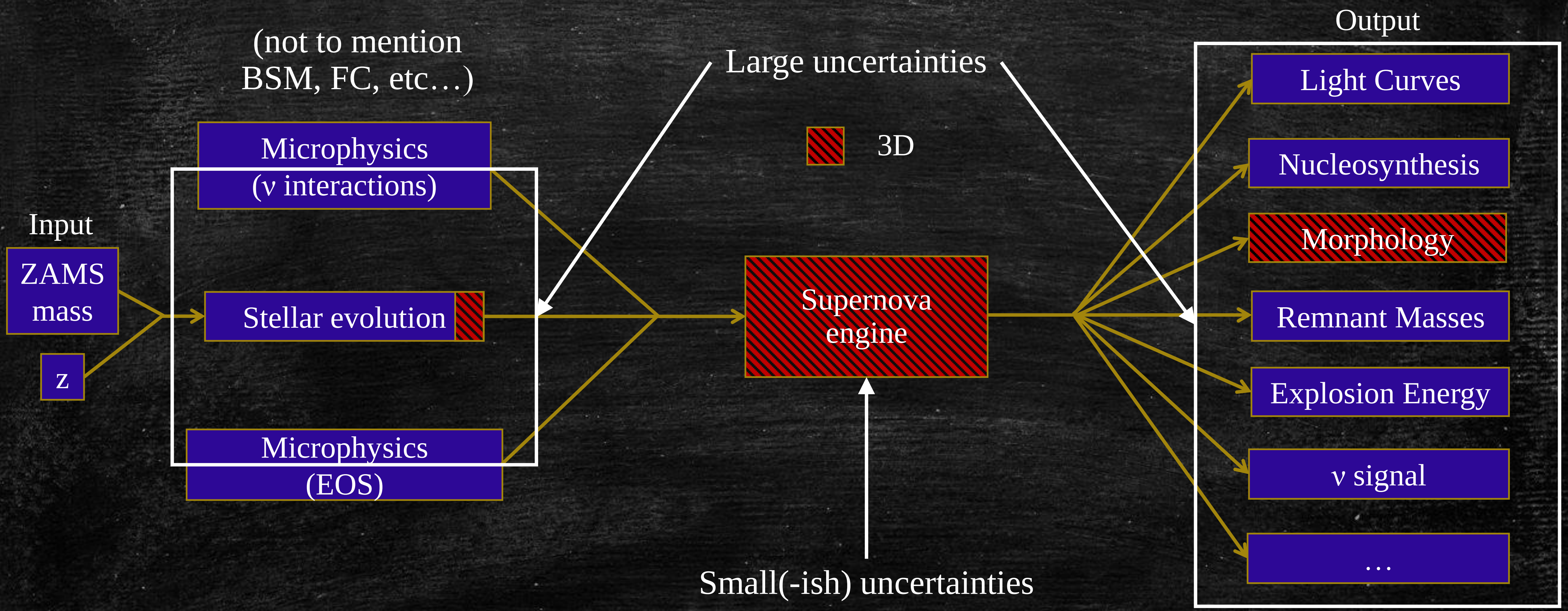
Network for Neutrinos, Nuclear Astrophysics, and Symmetries

PHYSICS FRONTIER CENTER

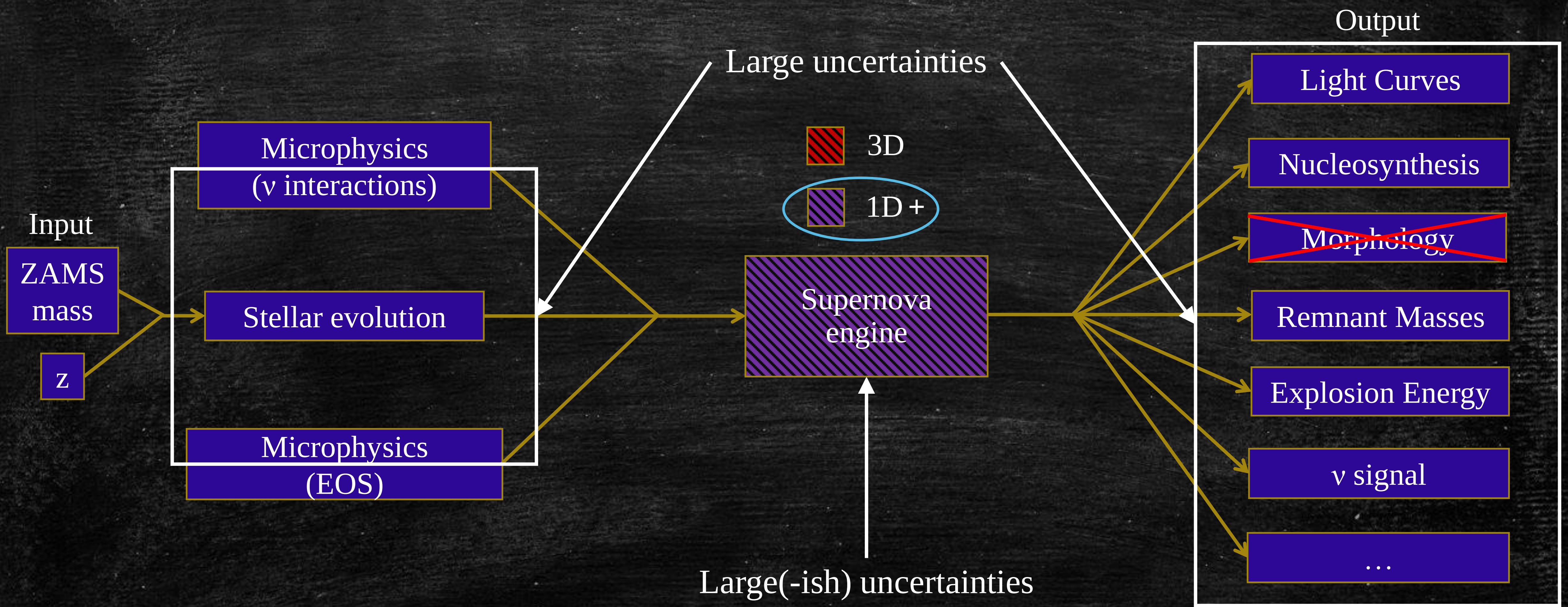
Overview of the CCSNe pipeline



Overview of the CCSNe pipeline



Overview of the CCSNe pipeline



CCSNe in 1D: why are they wrong?

- No convection, no SASI, no multi-dimensional effects (both in the hydrodynamics and neutrino transport). As a result: ***no explosions!***

CCSNe in 1D: why are they wrong? Why are they useful?

- No convection, no SASI, no multi-dimensional effects (both in the hydrodynamics and neutrino transport). As a result: ***no explosions!***

- Lower CPU cost than 3D (factor of 10^6)
- Large parametric studies: explodability, nucleosynthesis, light curves, neutrino signal, CNO, BSM physics, etc…

- Goal: cheap simulations with reliable physics
  - Commonly adopted approaches add extra energy into the simulation, using phenomenological or semi-analytical models : Pejcha (2012,2015), Perego (2015), Ertl (2016), Muller (2016)
  - Recent studies have taken a slightly different approach: Reynolds decomposition to model extra energy due to ν-driven convection (i.e. MLT): Murphy (2013), Couch (2020), Boccioli (2021), Sasaki (2023)

A compromise between 1D and 3D: 1D+ simulations

An (incomplete) summary of the characteristics of 1D+ models

- Reynolds decomposition is exact, the approximation enters in closing the equations. The simplest closure is provided by Mixing Length Theory
- Boussinesq approximation of low Mach numbers (not necessarily true near explosion)
- Turbulent eddies follow Kolmogorov spectrum
- Turbulence is driven by buoyancy and vertical shear. No horizontal shear, no negative turbulent flux (i.e. downward transport of energy)
- The form of the equations does not conserve energy (Muller 2019) (caveat, the energy is accounted for by the change in in free energy). No 1D model strictly speaking conserves energy!

A compromise between 1D and 3D: 1D+ simulations

I will be using a version of STIR (Couch 2020) that was implemented (*Boccioli 2021*) in GR1D (*).

STIR evolves an additional quantity: the turbulent energy $\rho v_{\rm turb}^2$

$$\frac{\partial \rho v_{\rm turb}^2}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}[r^2(\rho v_{\rm turb}^2 v_r - \rho D_{\rm K}\nabla v_{\rm turb}^2)]$$

$$= \rho v_{\rm turb}^2 \frac{\partial v_r}{\partial r} + \rho v_{\rm turb}\omega_{\rm BV}^2 \Lambda_{\rm mix} - \rho \frac{v_{\rm turb}^3}{\Lambda_{\rm mix}}$$

Shear

Buoyancy

Dissipation

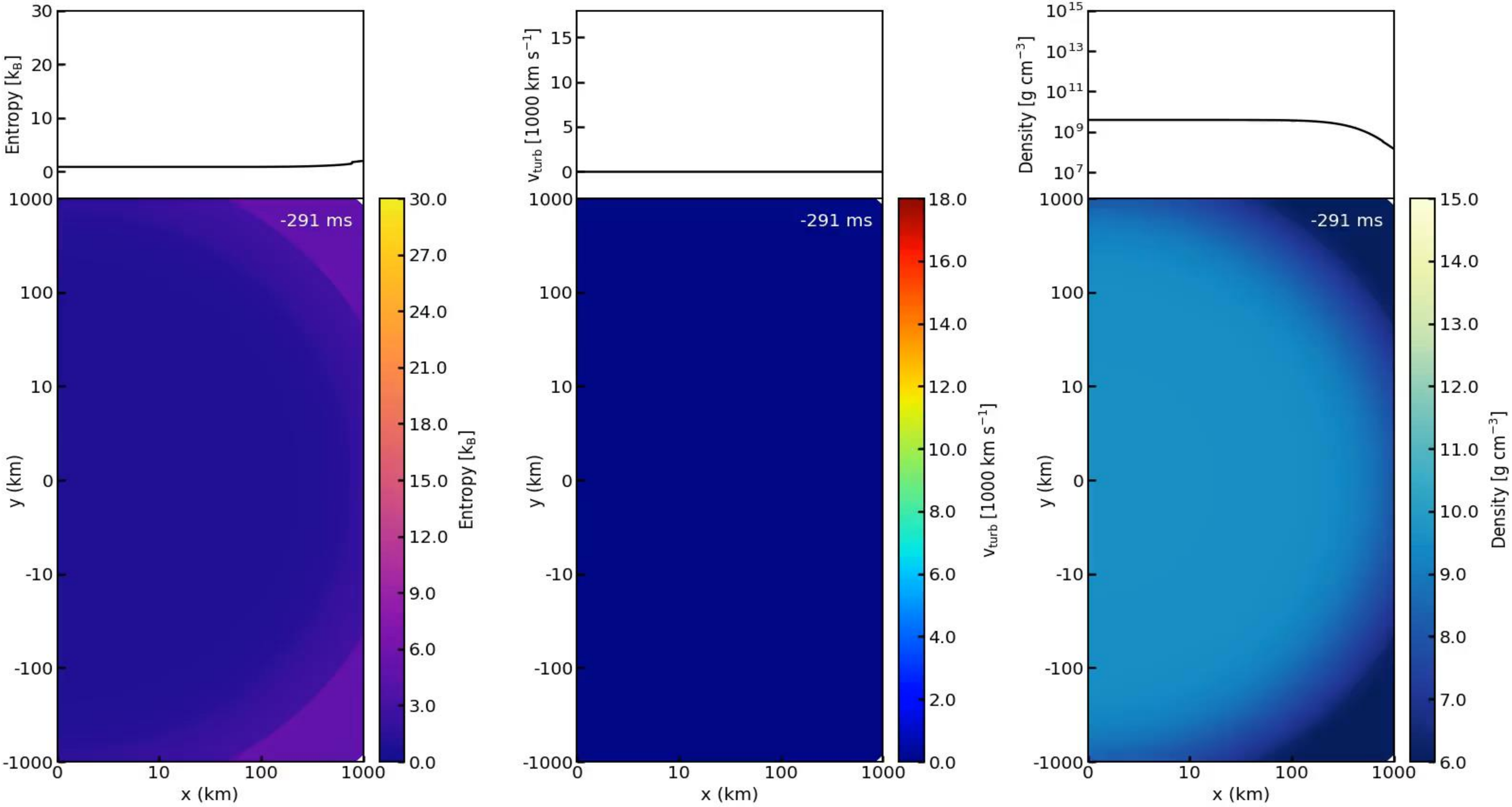
$$\Lambda_{\rm mix} = \alpha_{\rm MLT}\frac{P}{\rho g}$$

Calibration
to 3D simulations

$$\rho e_{\rm tot} = \rho \epsilon_{\rm int} + \frac{1}{2}\rho v^2 + \rho v_{\rm turb}^2$$

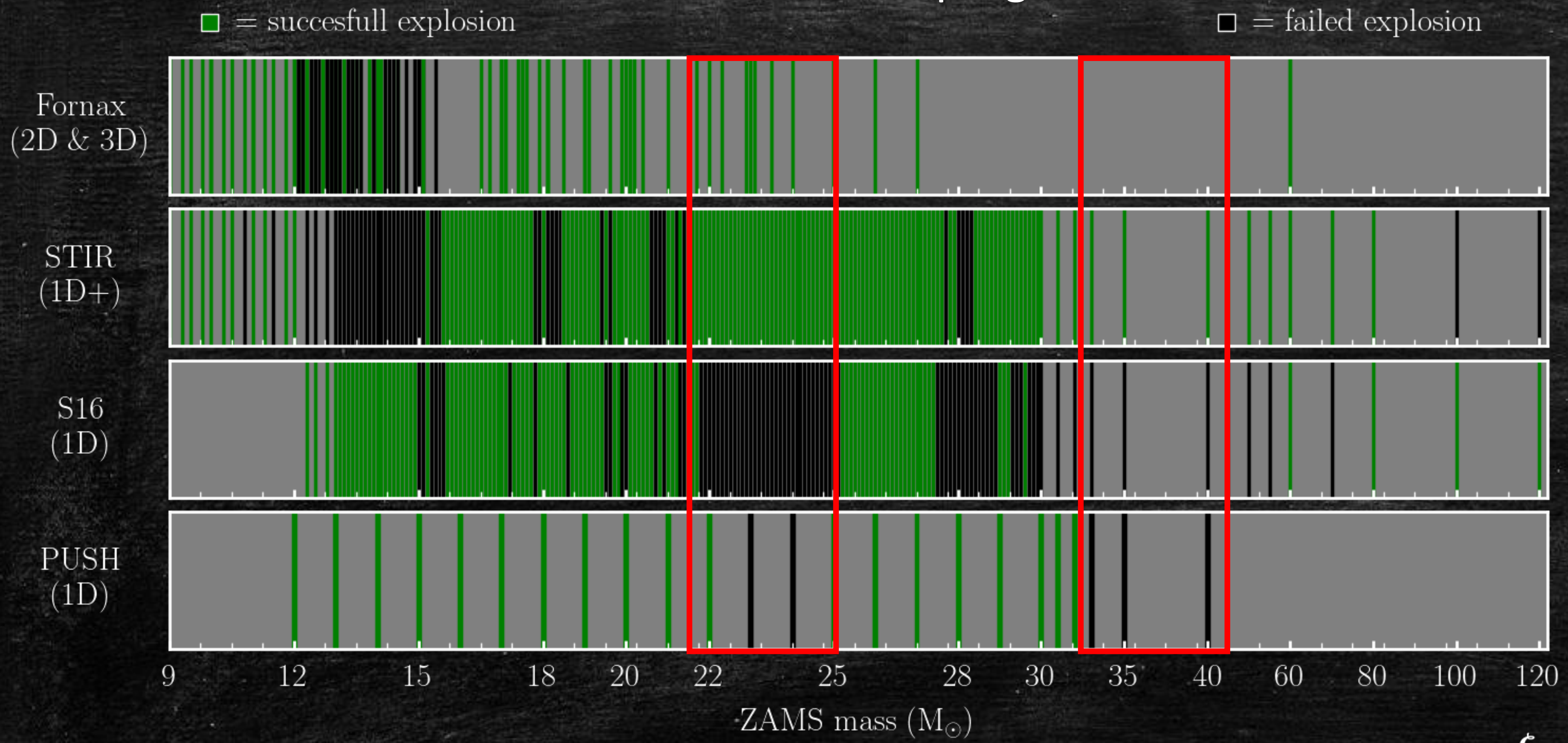
$$\frac{\partial \rho e_{\rm tot}}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}[r^2 v_r(\rho e_{\rm tot} + P + P_{\rm turb})] + \nabla\cdot F_e + \nabla\cdot F_K = -\rho v_r g + \dot{q}_\nu + \rho\epsilon_{\rm turb}$$

(*) https://github.com/evanoconnor/GR1D (O'Connor 2010, 2015)


Entropy [k_B]
-291 ms
y (km)
x (km)
v_{turb} [1000 km s^{-1}]
-291 ms
y (km)
x (km)
Density [g cm^{-3}]
-291 ms
y (km)
x (km)

1D vs. 1D+ vs. Multi-D

KEPLER progenitors



= $\xi_{2.0} \geq 0.5$

Wang et al. (2022)

Boccioli et al. (2023)

Sukhbold et al. (2016)
Ertl et al. (2016)

Ghosh et al. (2022)

$$\xi_M = \frac{M/M_\odot}{R(M_{\mathrm{bary}} = M)/1000\,\mathrm{km}}$$

STIR does not follow Ertl explosion criterion

A New Physically-Motivated Explosion Criterion

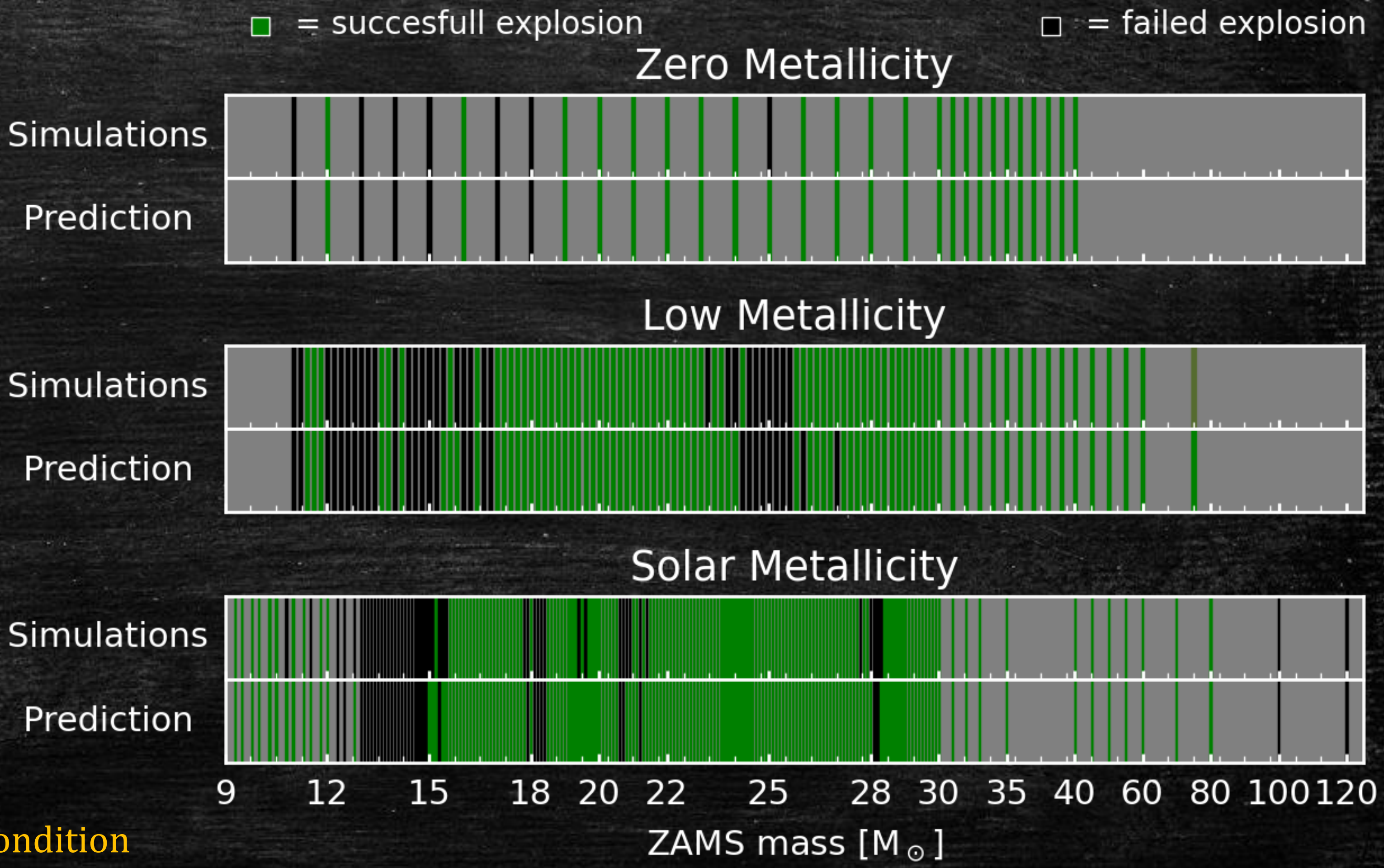
KEPLER progenitors

Boccioli et al. (2023)

If $\delta\rho^2_{\mathrm{Si/O}} / \rho^2_{\mathrm{Si/O}} > 0.08$ explosion (*)

If $\delta\rho^2_{\mathrm{Si/O}} / \rho^2_{\mathrm{Si/O}} > 0.078$ explosion

Wang et al. (2022)



Boccioli et al. (2024)

(*) = One must also add the condition
$\xi_{2.0} > 0.5$ at low metallicities/high compactnesses

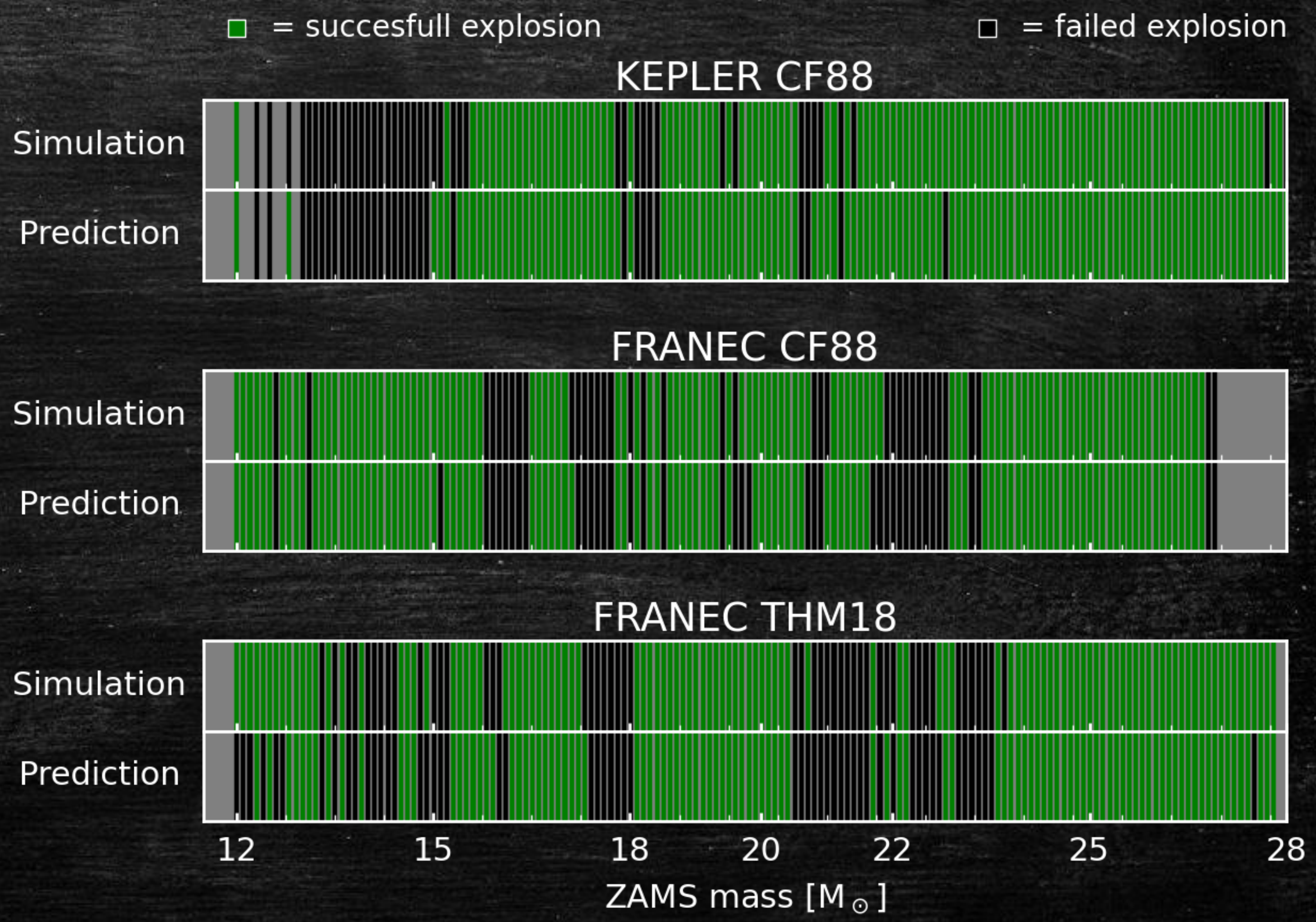
Warning: Uncertainties in Stellar Evolution Propagate!

Boccioli et al. (2023)

If $\delta\rho^2_{Si/O} \,/\, \rho^2_{Si/O} > 0.08$ explosion

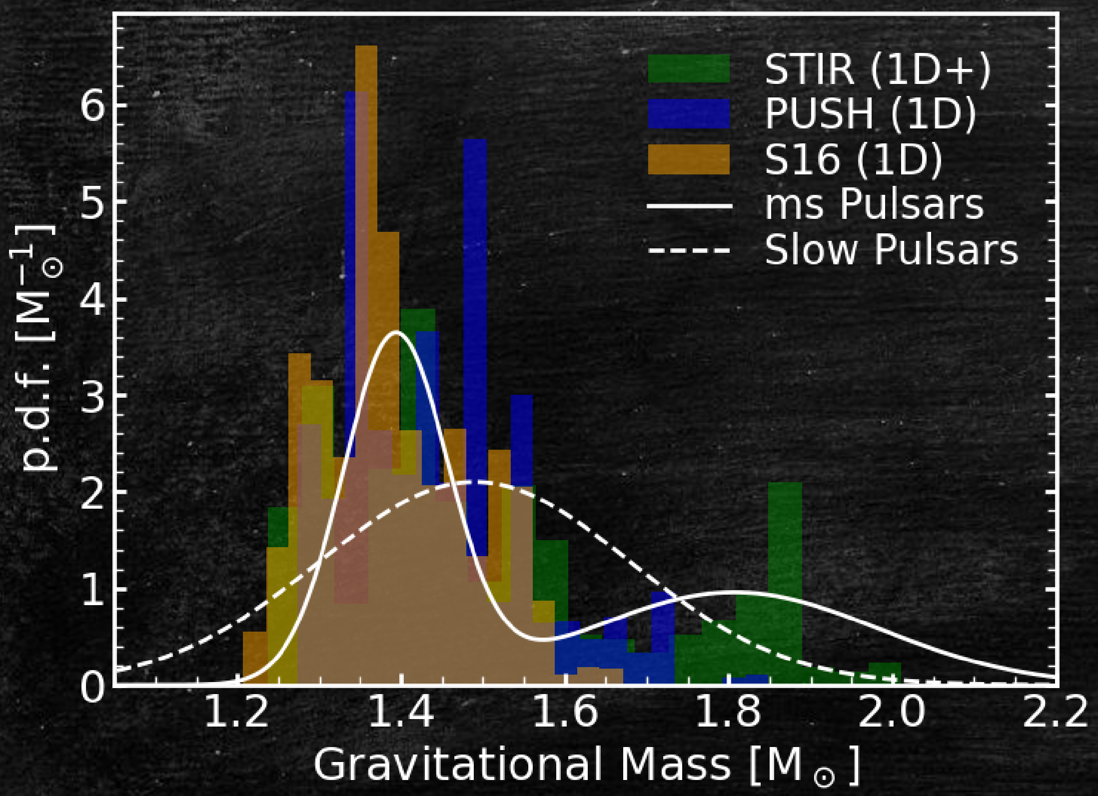
Different reaction rates for C12+C12:

- CF88
- THM18

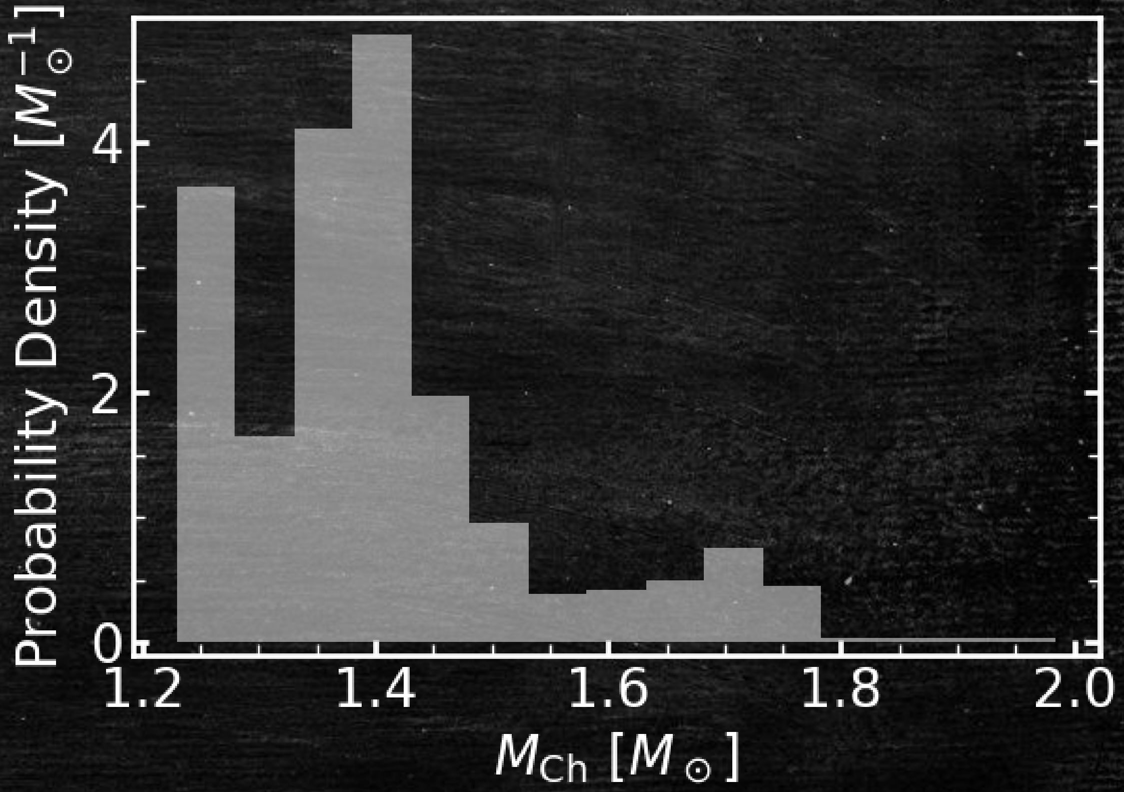


Remnant Masses: STIR (1D+) vs PUSH (1D) vs S16 (1D)

Neutron Star Birth Mass Distribution



Chandrasekhar Mass Distribution

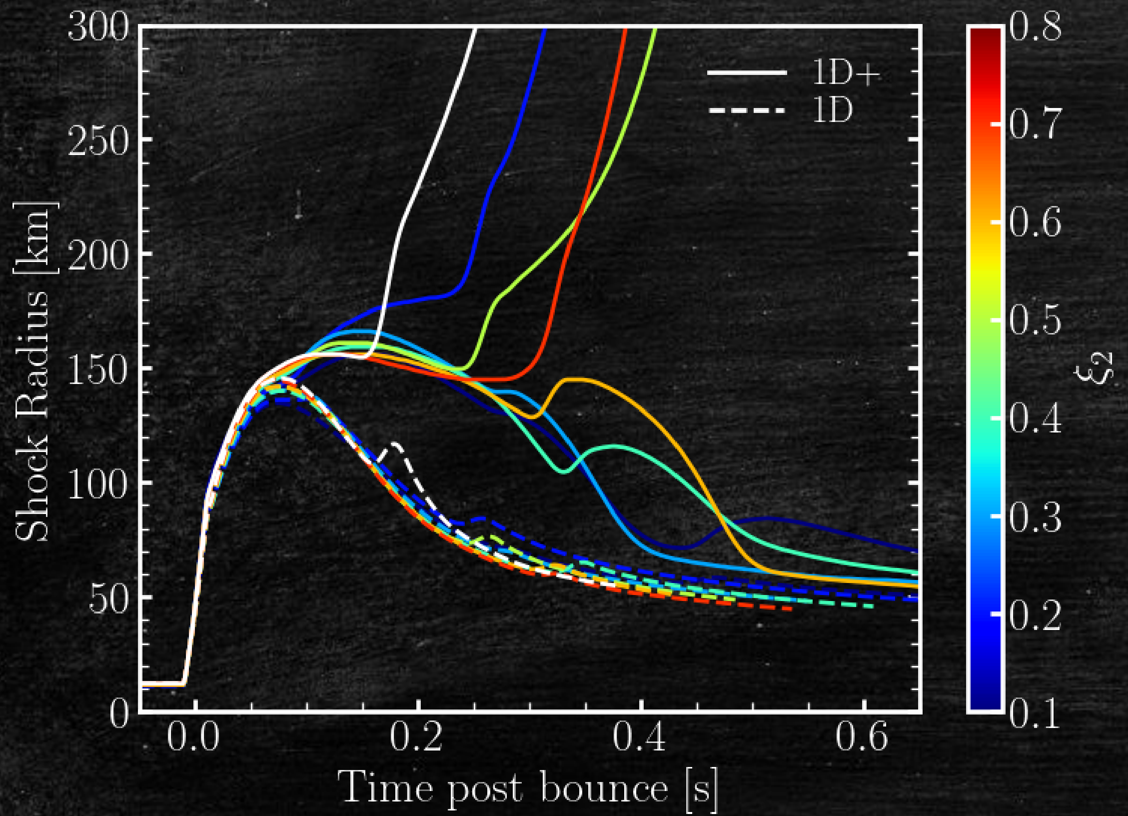


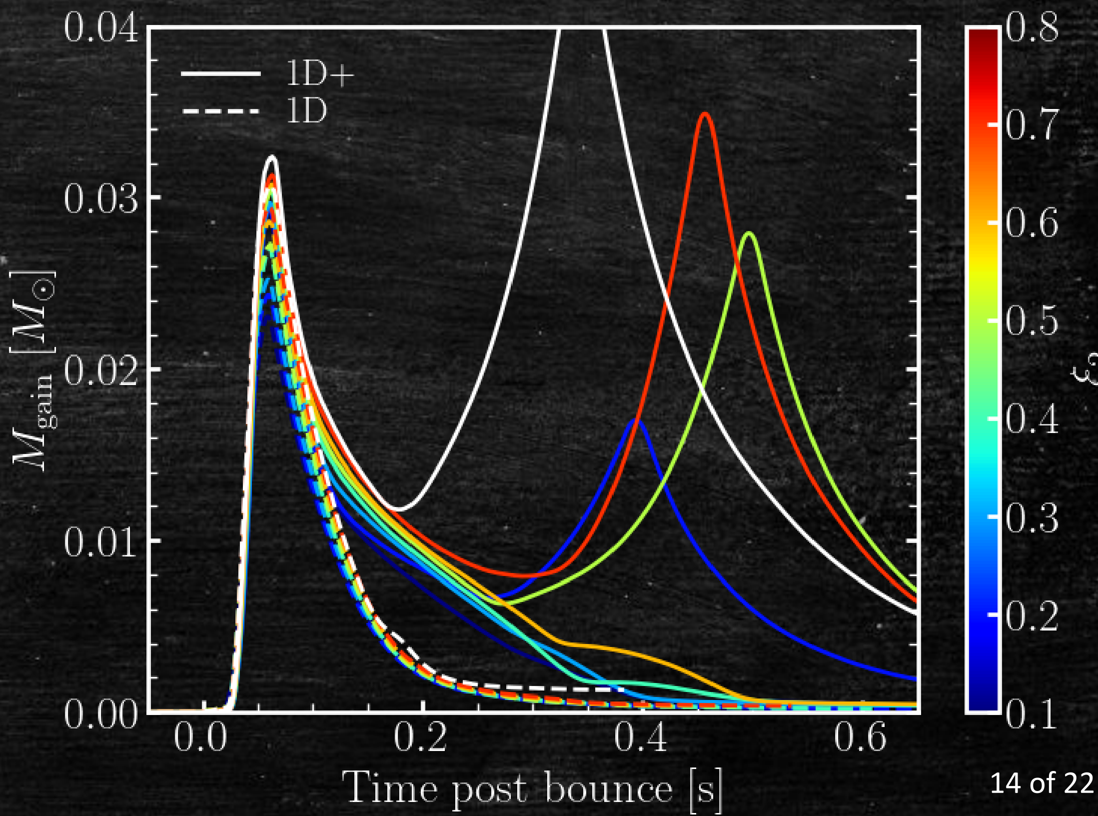
Neutrino heating in 1D and 1D+

$$\dot{Q}_\nu^{\mathrm{an}} = 1.75 \times 10^{51}\ \frac{\mathrm{erg}}{\mathrm{s}} \left(\frac{M_\mathrm{g}}{0.01\ M_\odot}\right)\left(\frac{\bar{R}_\mathrm{g}}{100\ \mathrm{km}}\right)^{-2} \sum_{\nu\in\{\nu_e,\bar{\nu}_e\}} \left(\frac{k_\mathrm{B}T_\nu}{4\ \mathrm{MeV}}\right)^2\left(\frac{L_\nu}{3\times10^{52}\ \mathrm{erg/s}}\right)$$

1D fast decrease
1D+ slow decrease

Janka (2012)





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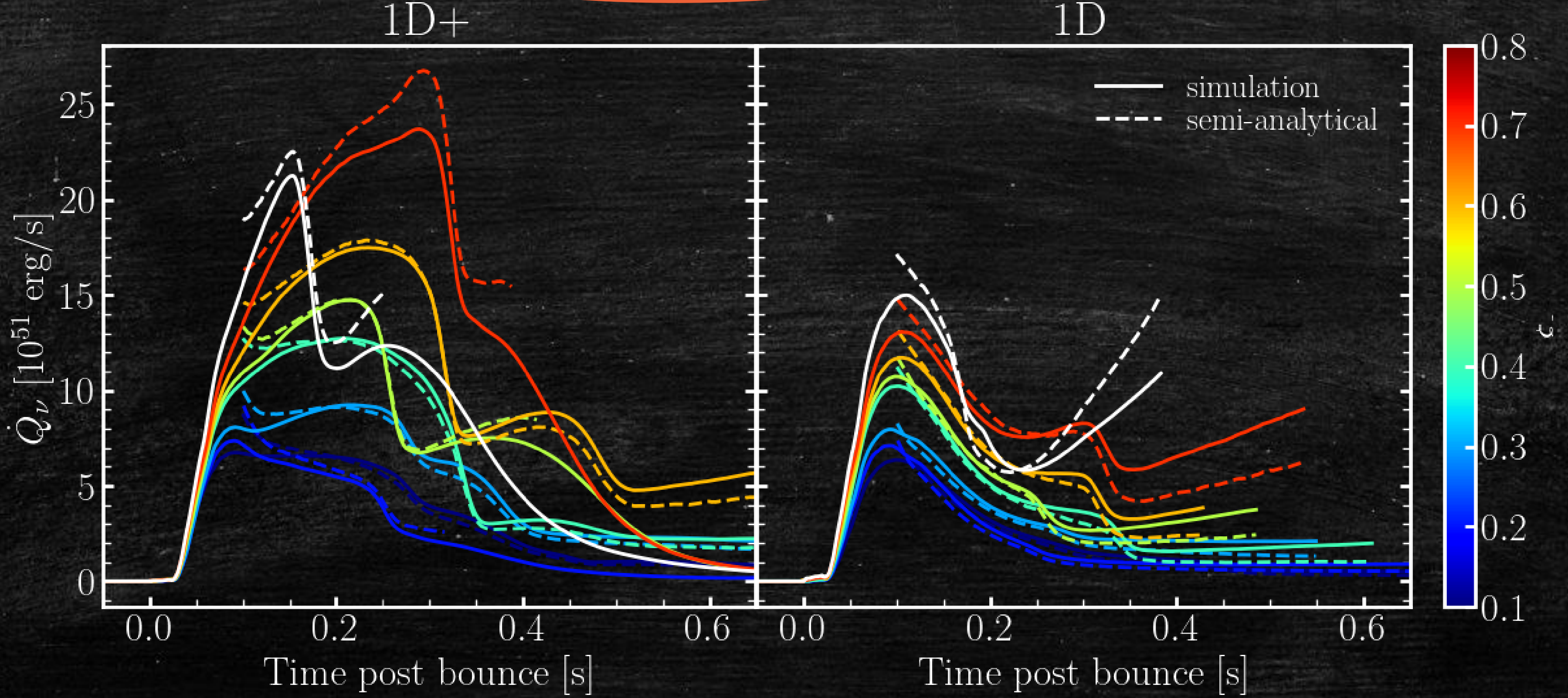
Dominates in 1D

Dominates in 1D+



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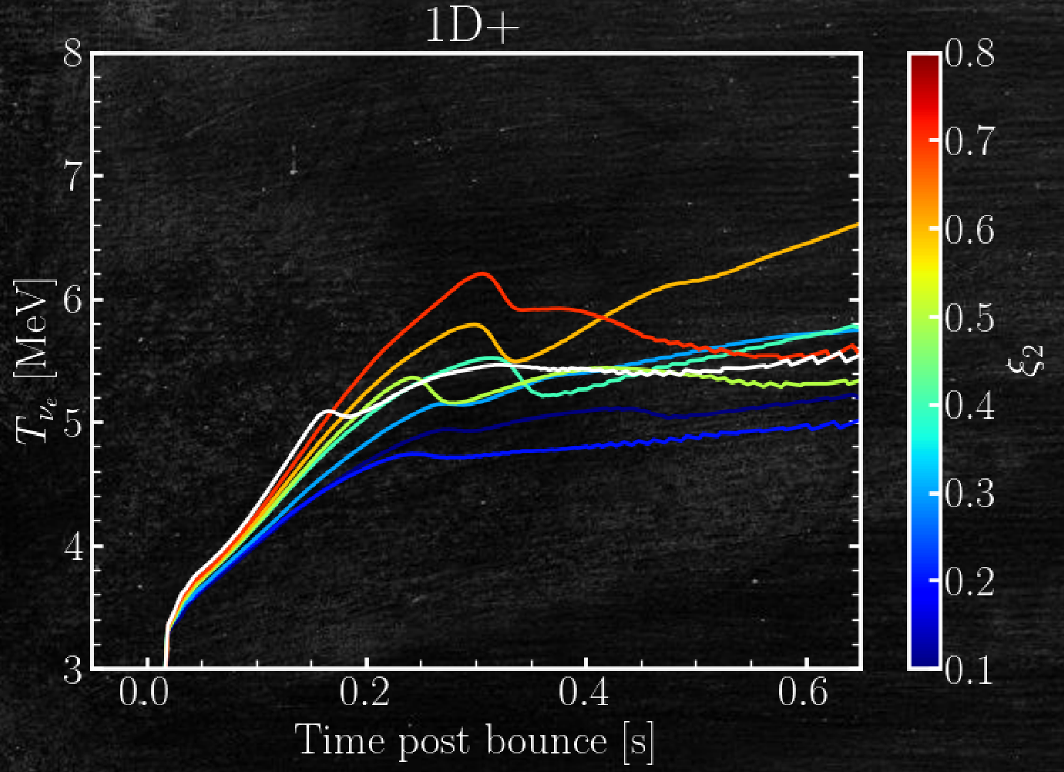
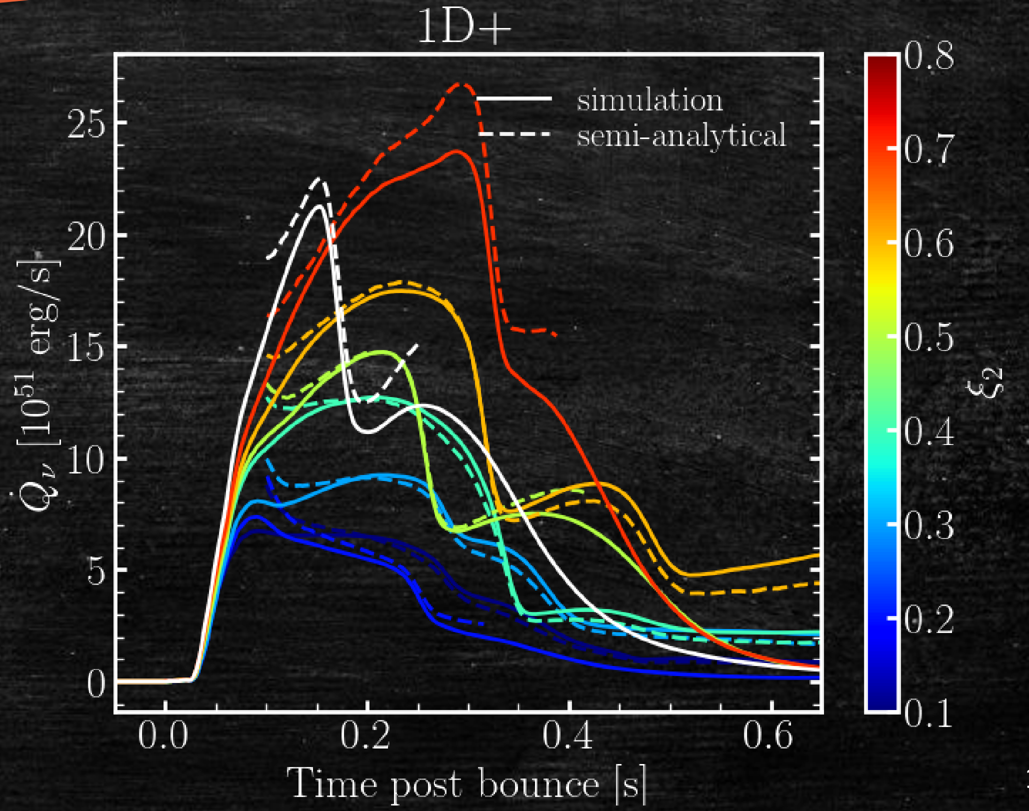
Dominates in 1D

Dominates in 1D+

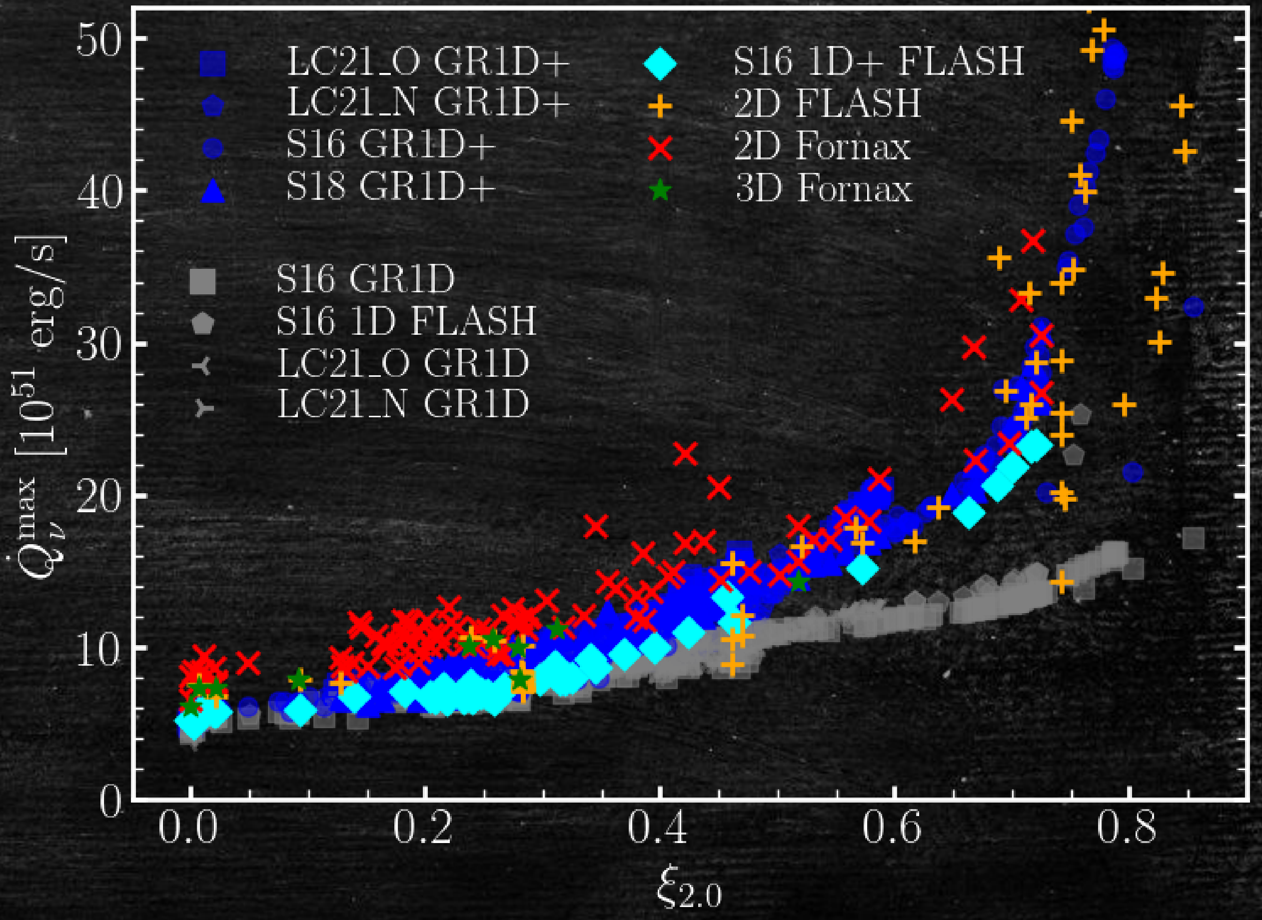




Neutrino heating in 1D, 1D+, 2D, and 3D

$$\dot{Q}_\nu = \int_{\text{gain}} \dot{q}_\nu \mathrm{d}V$$

- Progenitors with larger compactness develop a much larger neutrino heating
- 2D Fornax simulations have larger $\dot{Q}_\nu^{\max}$ compared to 3D Fornax and 2D FLASH simulations.



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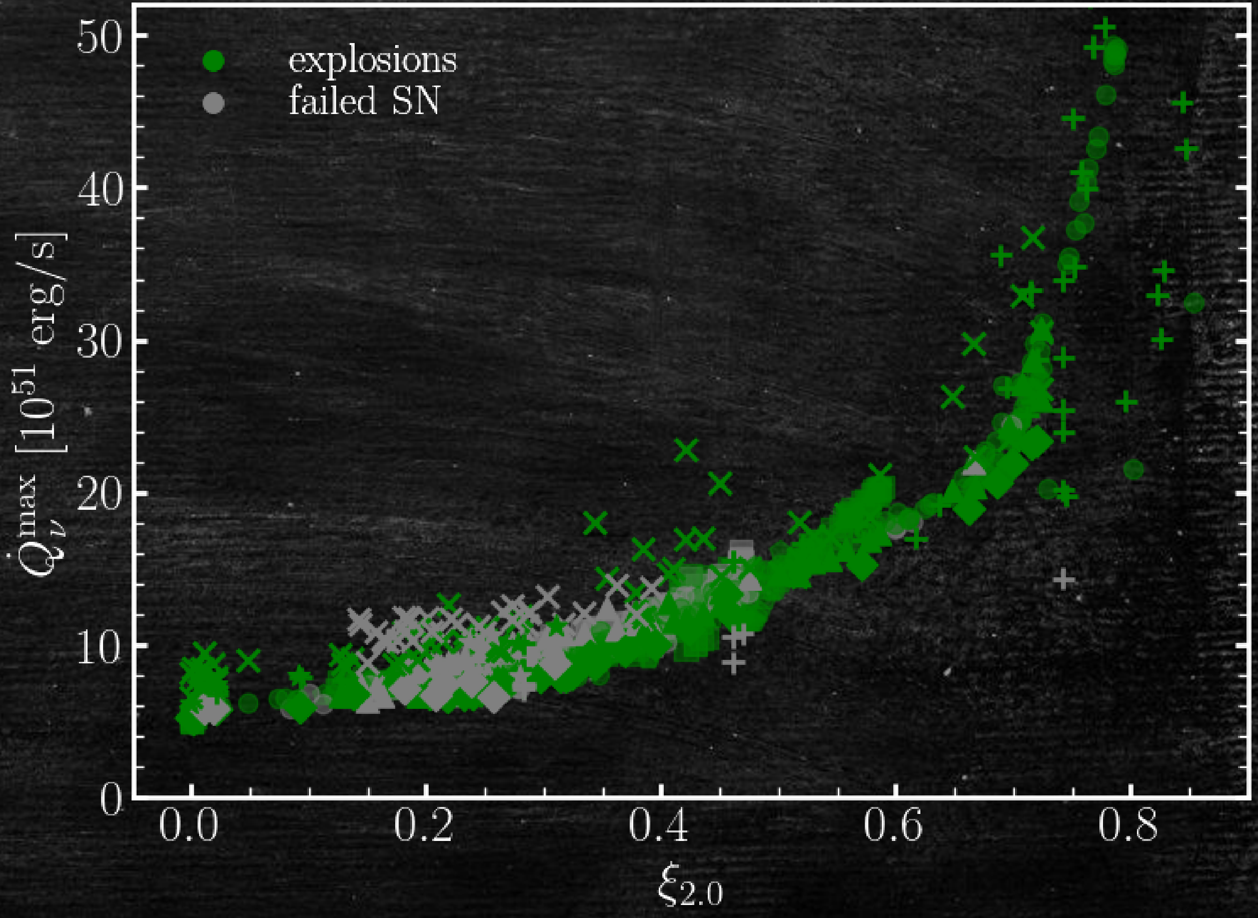
- Progenitors with larger compactness develop a much larger neutrino heating
- 2D Fornax simulations have larger $\dot{Q}_\nu^{\max}$ compared to 3D Fornax and 2D FLASH simulations.
- Progenitor with high compactness lead to successful explosions because they generate very large neutrino heating.



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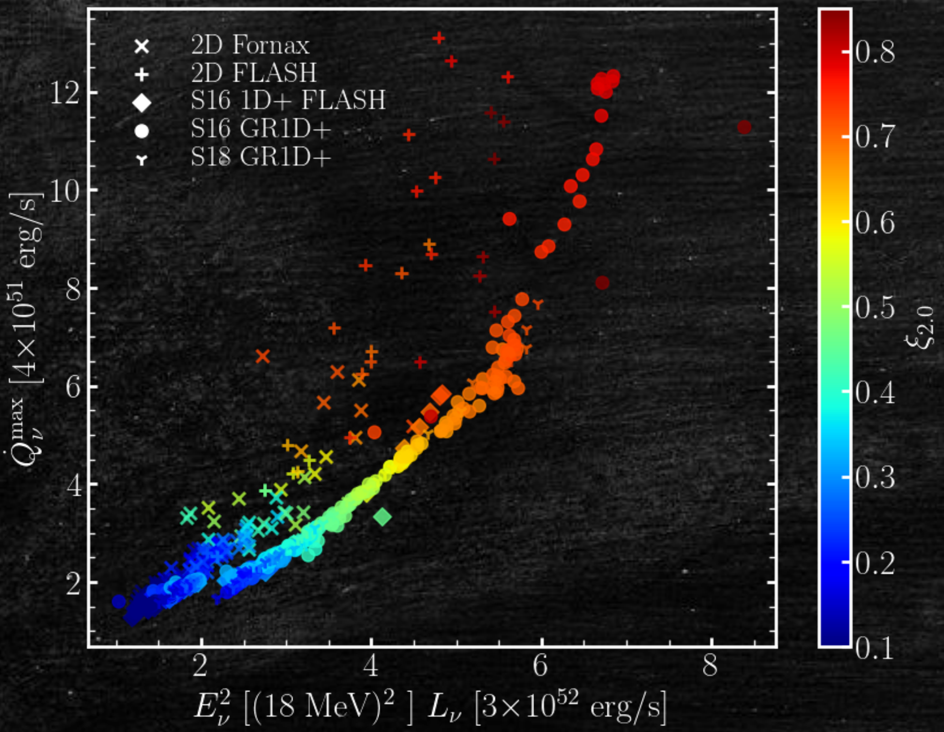
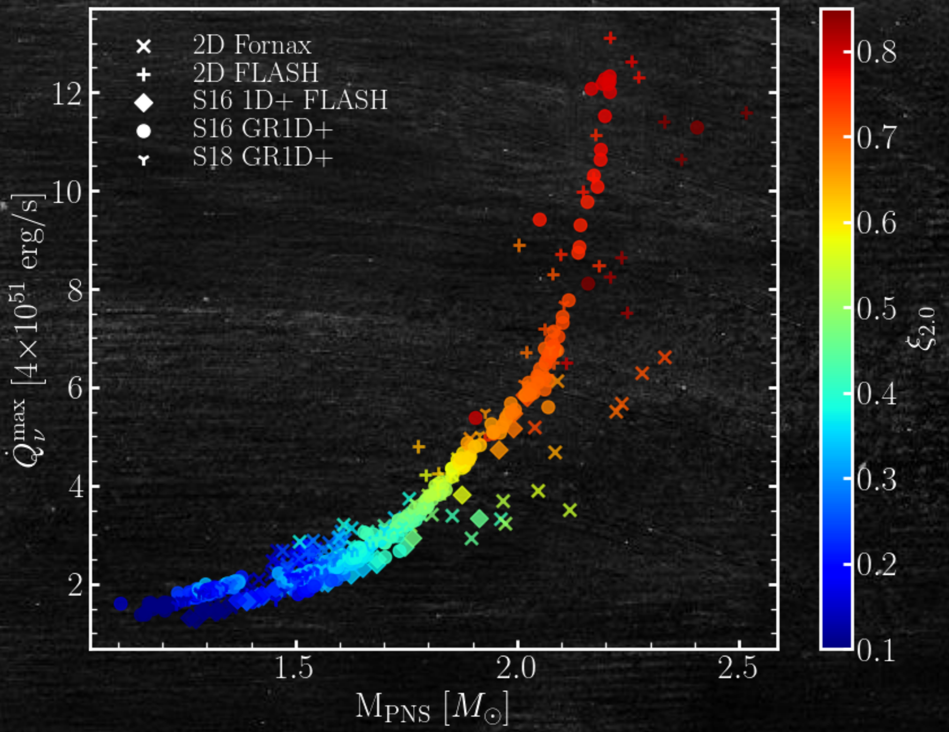
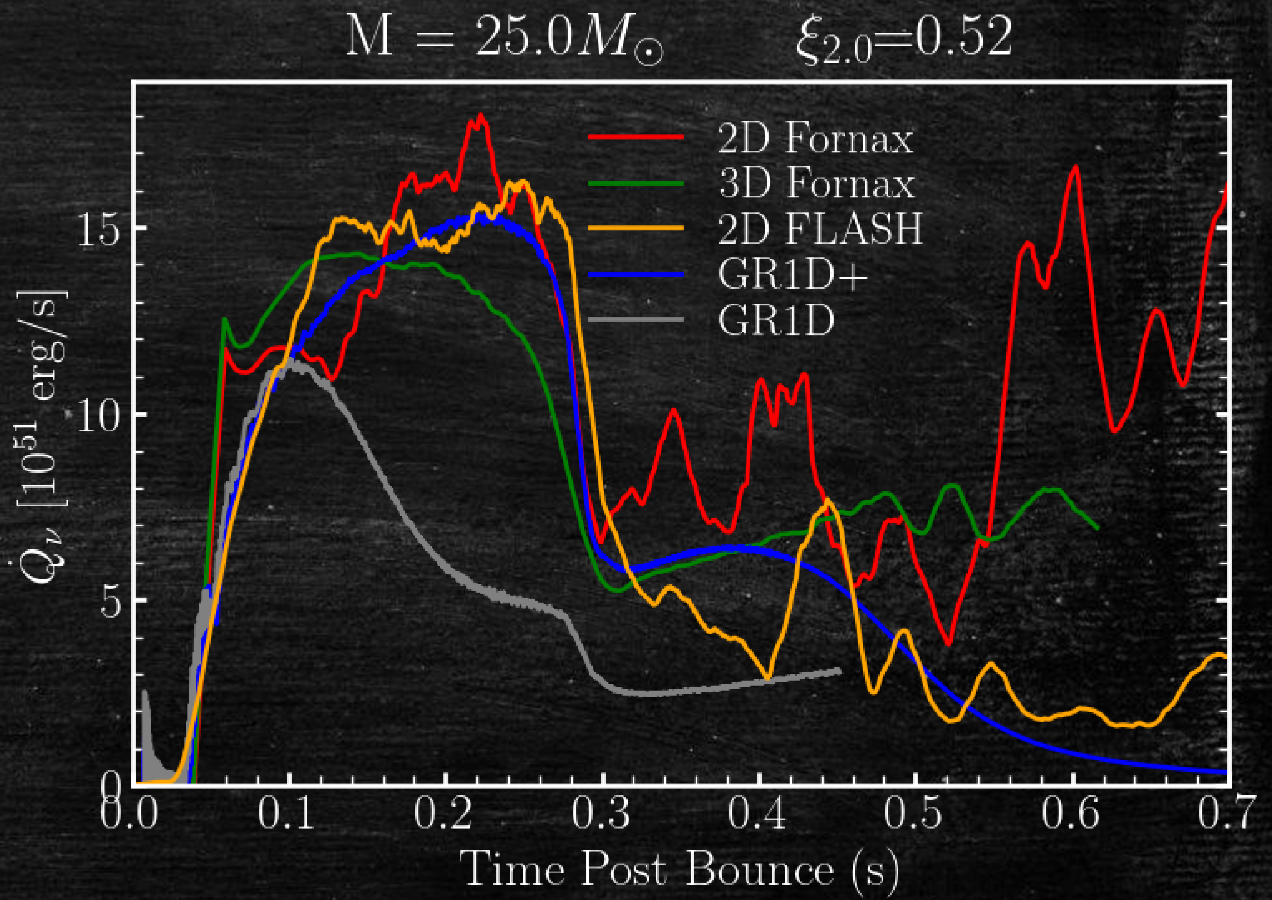
2D (and 3D) simulations have smaller neutrino energies
due to PNS convection (see also Nagakura (2020))





Comparison of simulations in 1D, 1D+, 2D, and 3D

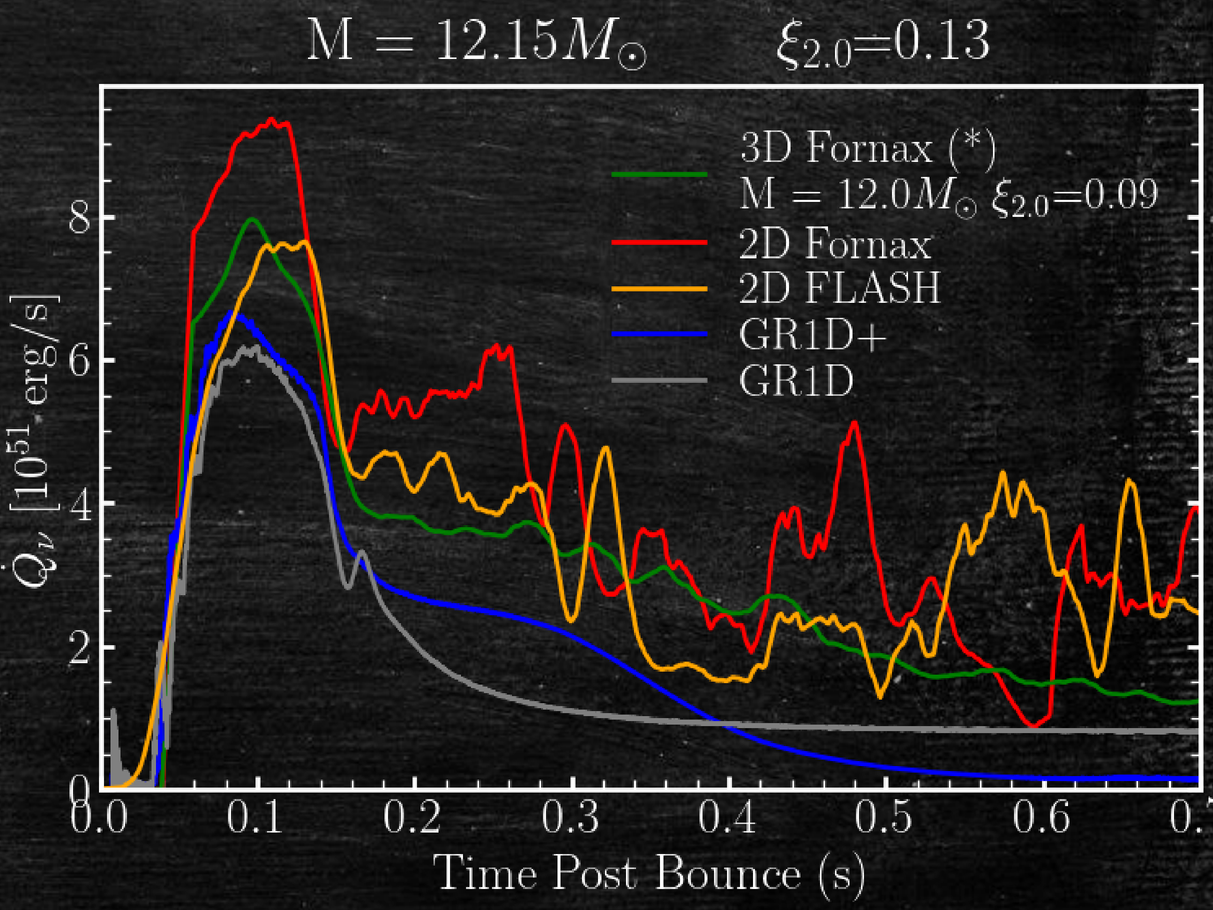
- This progenitor has a moderately large compactness $\xi_{2.0}$
- $\dot{Q}$ in 2D is very noisy. In 3D it is better behaved and tends to be smaller than in 2D at t > 0.2 s
- Fornax has large $\dot{Q}$ at late times (accretion and/or definition of the gain region)
- GR1D+ matches 2D simulations, especially FLASH since they have the same ν-transport.



Comparison of simulations in 1D, 1D+, 2D, and 3D

(*) = Note that the 3D simulation is for a different progenitor!

- This progenitor has a low compactness $\xi_{2.0}$
- $\dot{Q}$ in 3D Fornax(*) data is smaller than 2D, but compatible with 2D FLASH data!
- Fornax has large $\dot{Q}$ at late times (accretion and/or definition of the gain region)
- GR1D+ underestimates $\dot{Q}$ at very early times for low-compactness progenitors (prompt convection?)



Conclusions

- High-compactness progenitors explode because develop a much larger neutrino heating able to overcome the ram pressure of the infalling material

- Low-compactness progenitors explode when a sharp Si/O interface is accreted

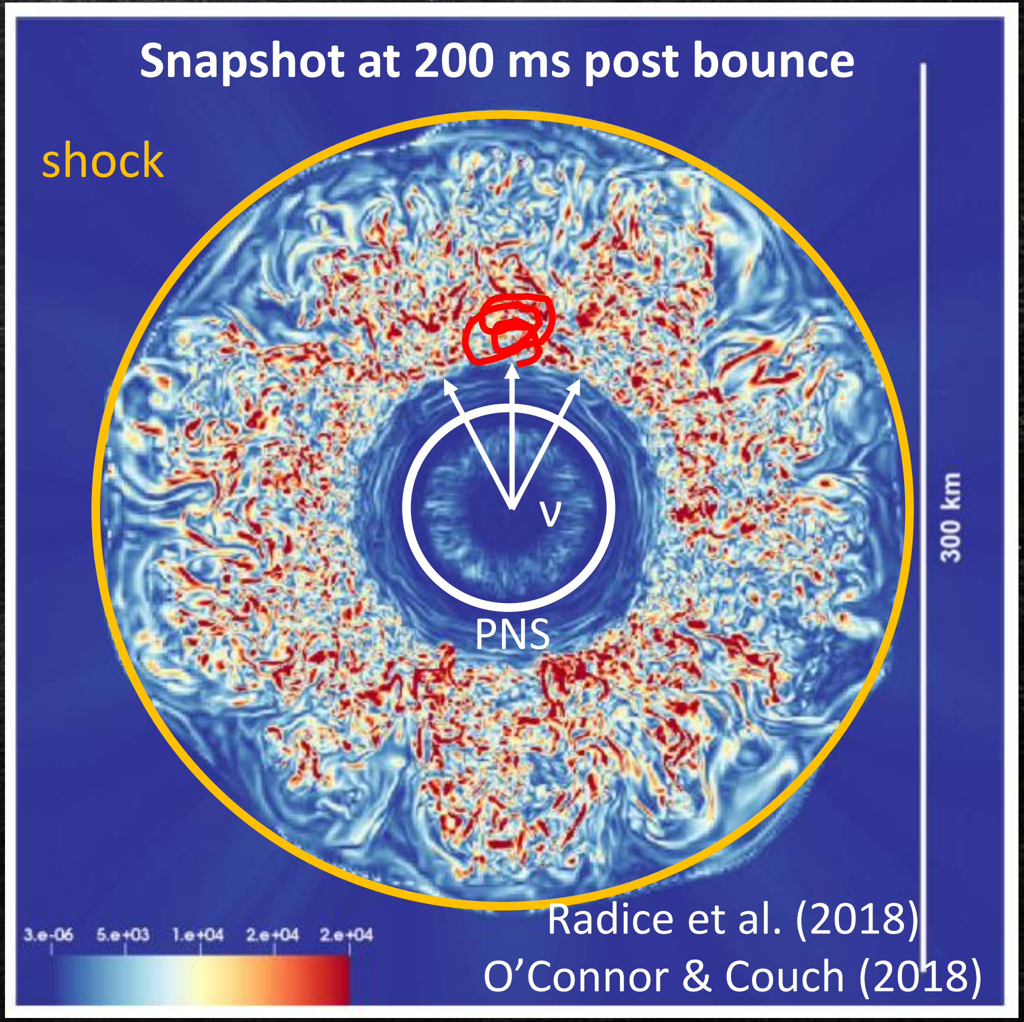
- 1D+ simulations develop similar neutrino heating (and qualitative explosion dynamics) to multi-D, with discrepancies at low compactness.

- 1D+ simulations struggle to produce reliable PNS convection

- More comparisons in 2D and 3D are necessary, especially regarding neutrino heating, since it plays a crucial role, particularly in leading to explosions of high-compactness progenitors

- 1D+ simulations are a powerful tool that can be used to perform large parameter and sensitivity studies, potentially to guide more accurate (and extremely more expensive) 3D simulations

Neutrino-Driven Convection



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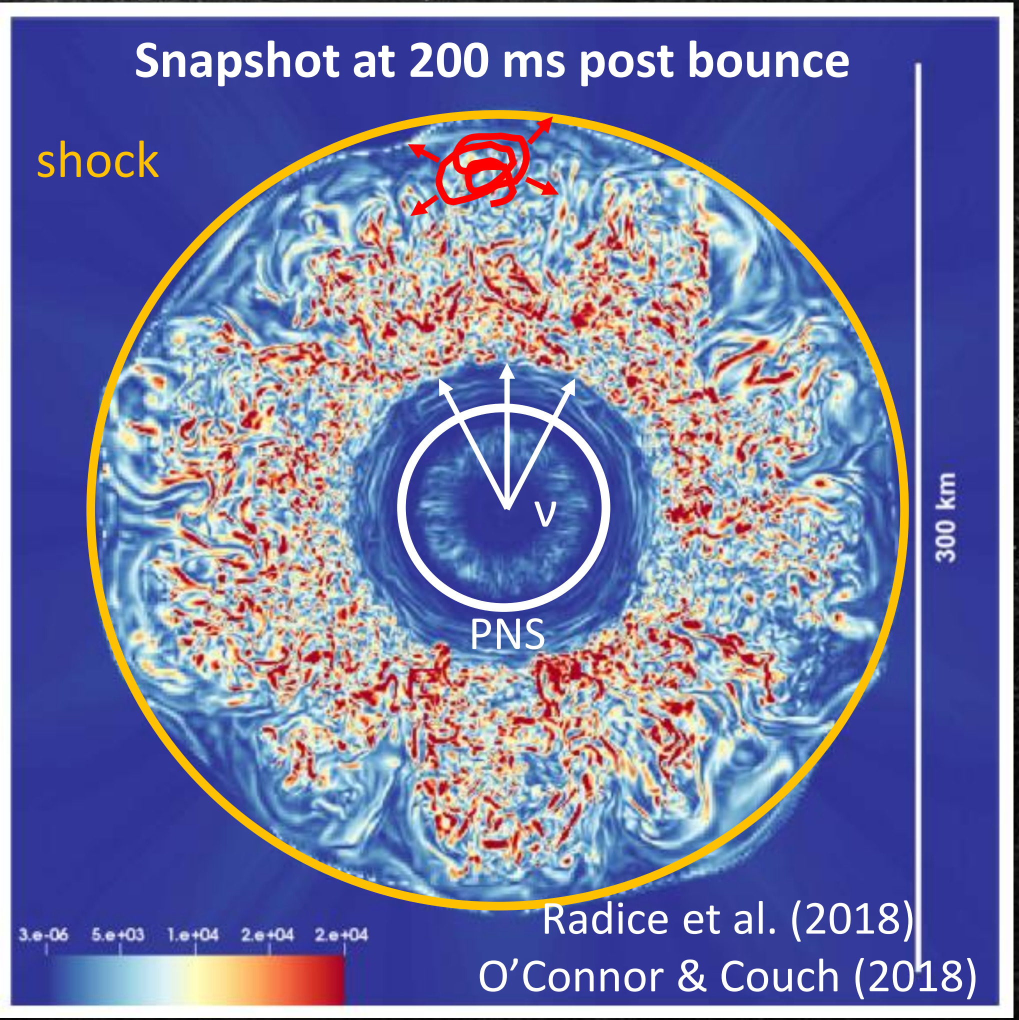


Neutrino-Driven Convection

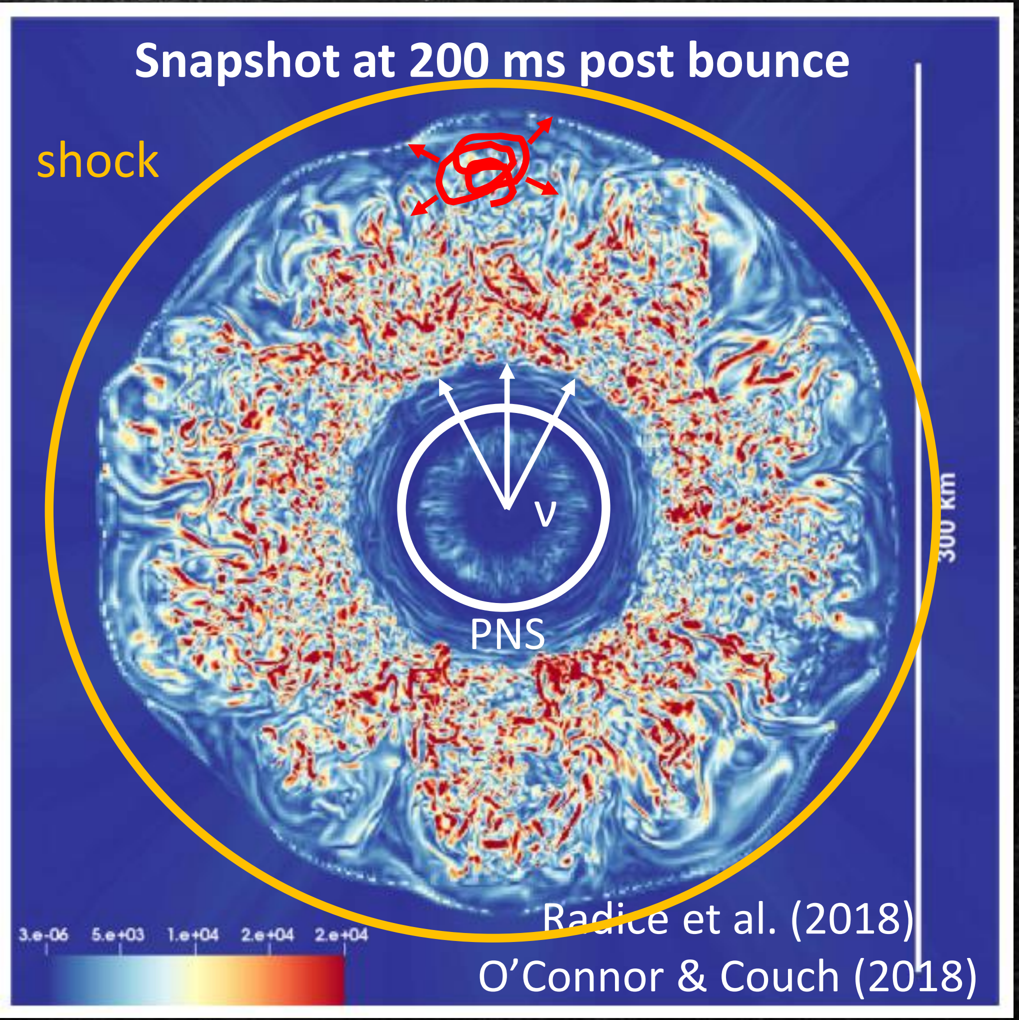
- 3D simulations:
  - ↑ They simulate convection self-consistently
  - ↓ They are computationally very expensive

- Spherically symmetric simulations (1D):
  - ↓ They cannot simulate convection
  - ↑ They are computationally very cheap

- We can find a compromise:
  - → Parametric model for convection -> 1D+

STIR Couch *et al* (2020)
Boccioli *et al* (2021)

But also: Murphy et al. (2013), Mabanta & Murphy (2018), etc...



Radice et al. (2018)
O'Connor & Couch (2018)

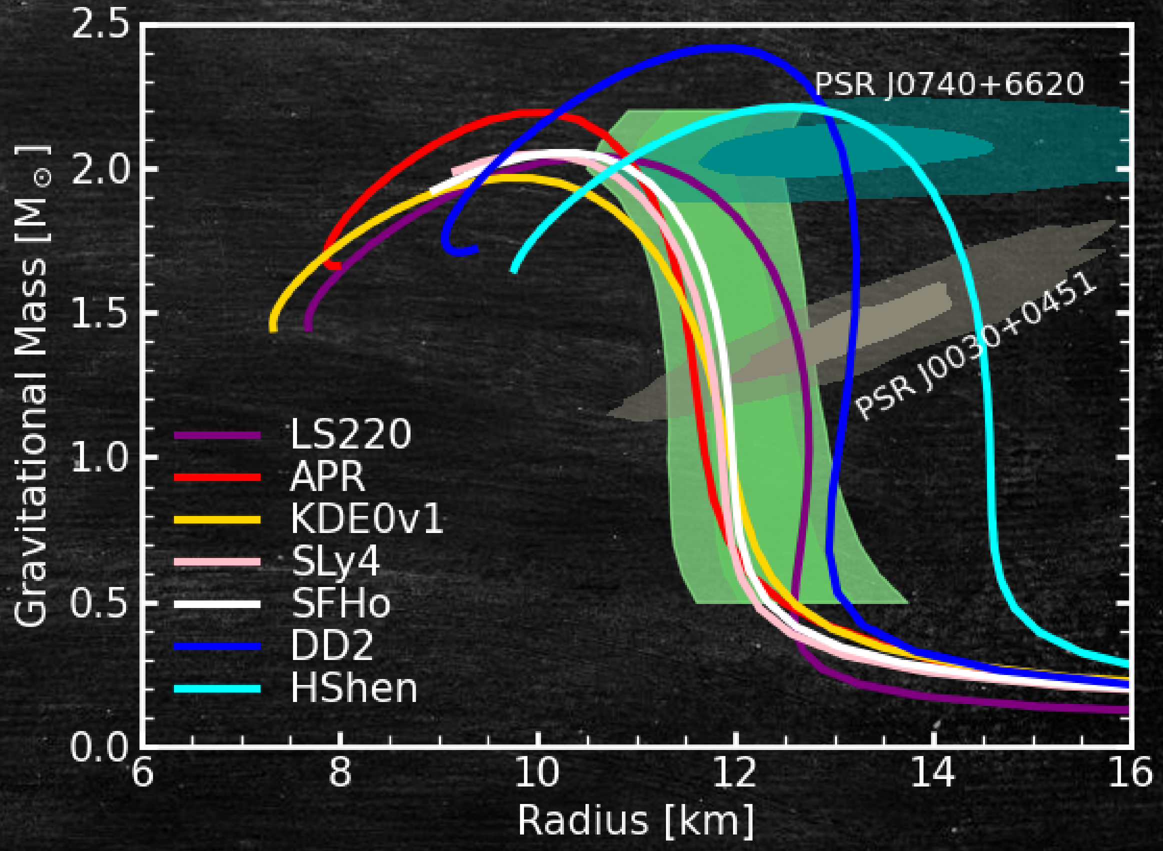
3) Details of the EOS used

Skyrme-type: *compressible liquid-drop model*

- LS220
- APR
- KDE0v1
- SLy4

RMF-type: *relativistic mean field model*

- SFHo
- DD2
- HShen



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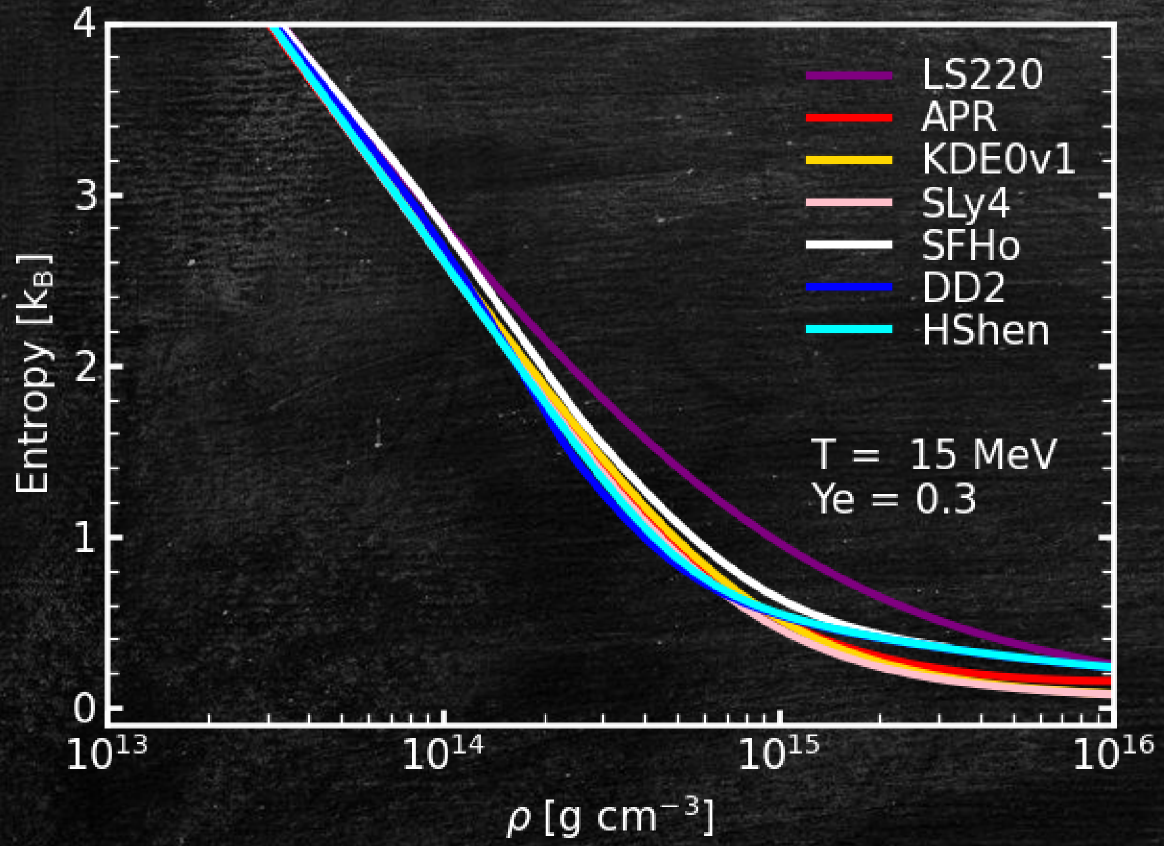
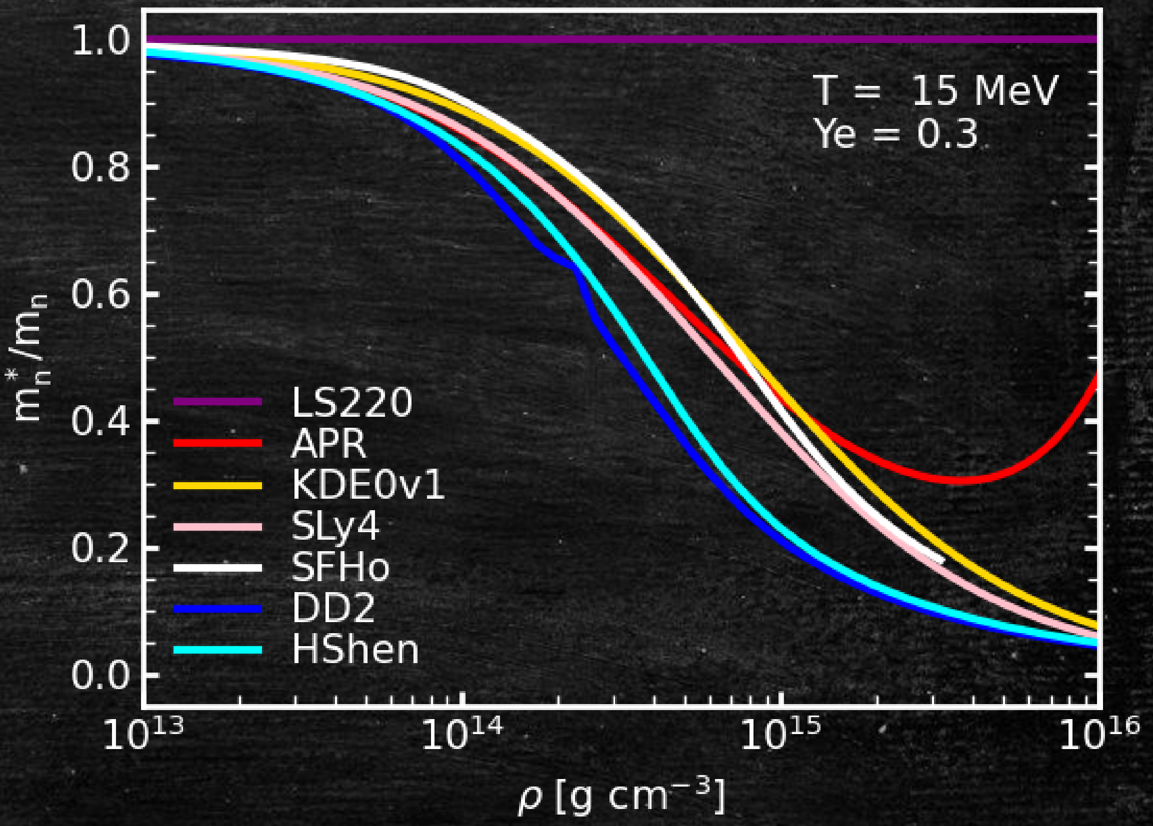
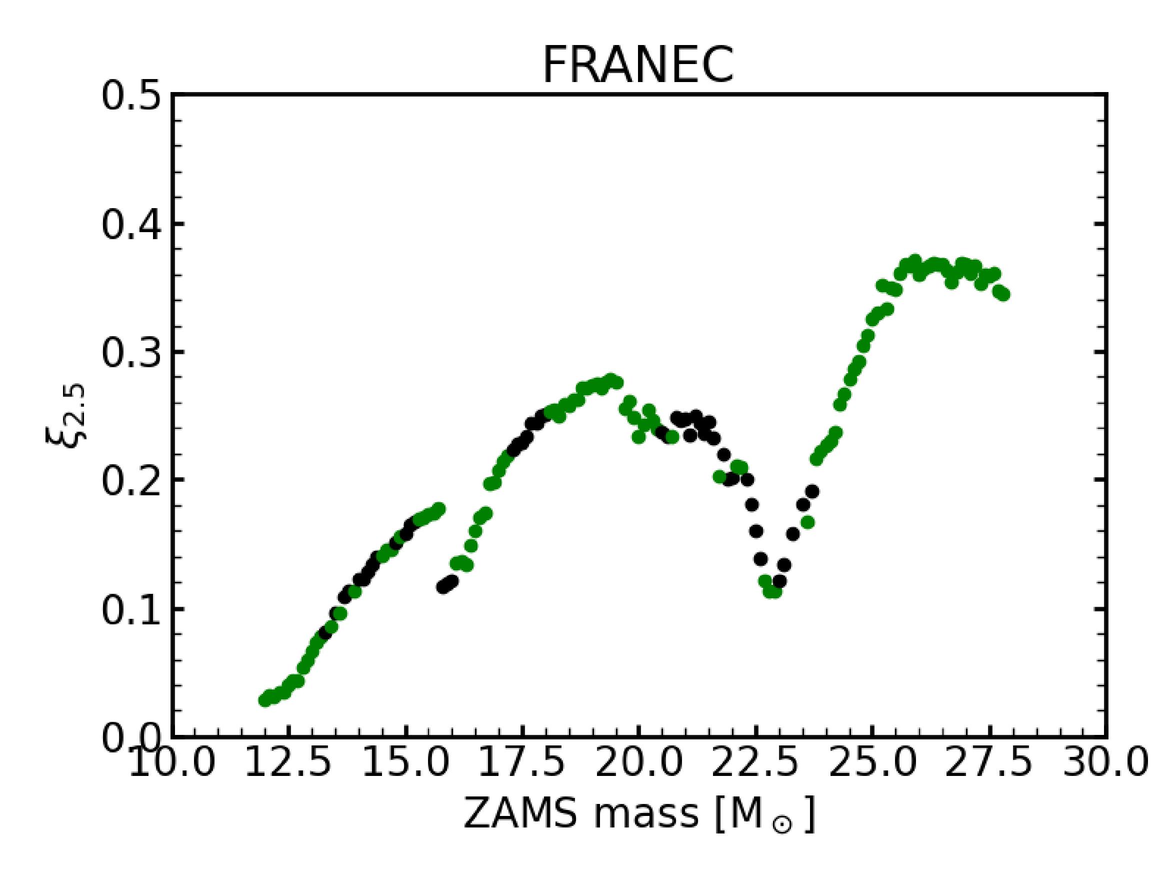
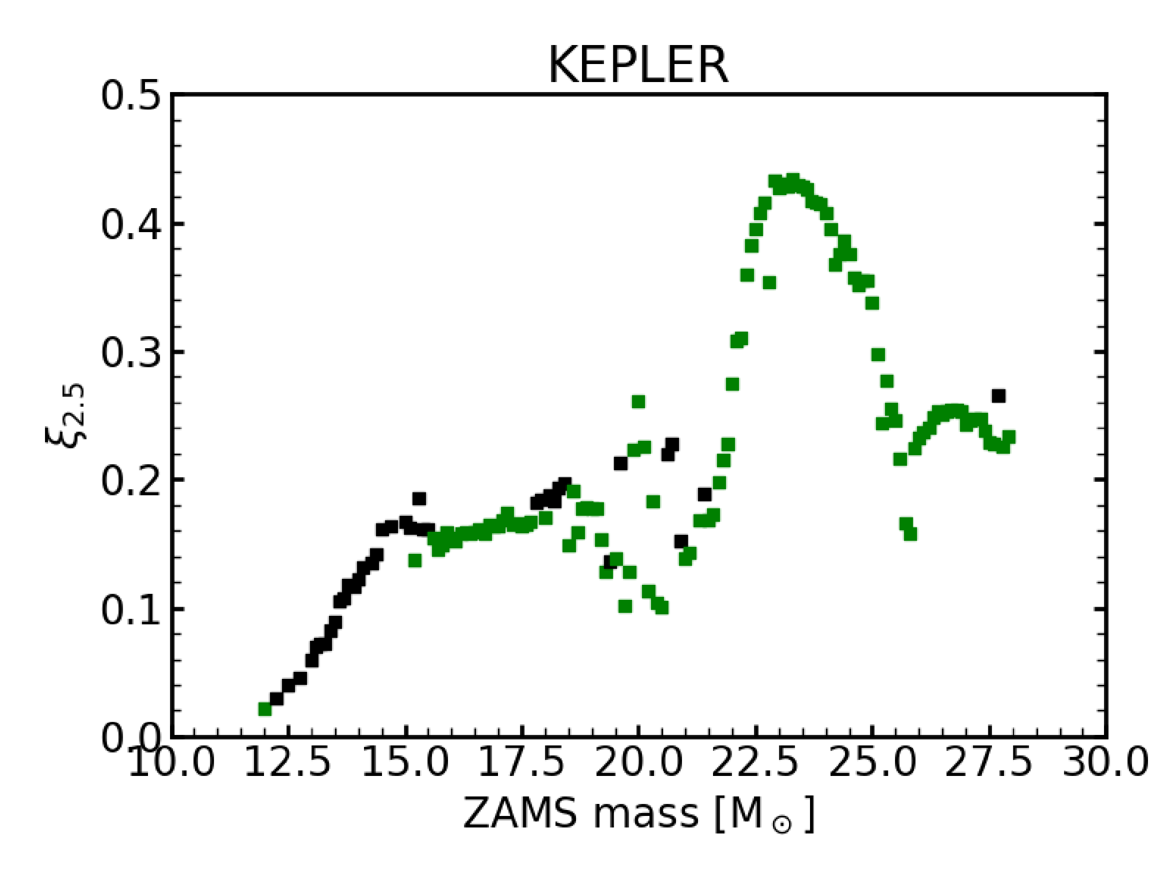


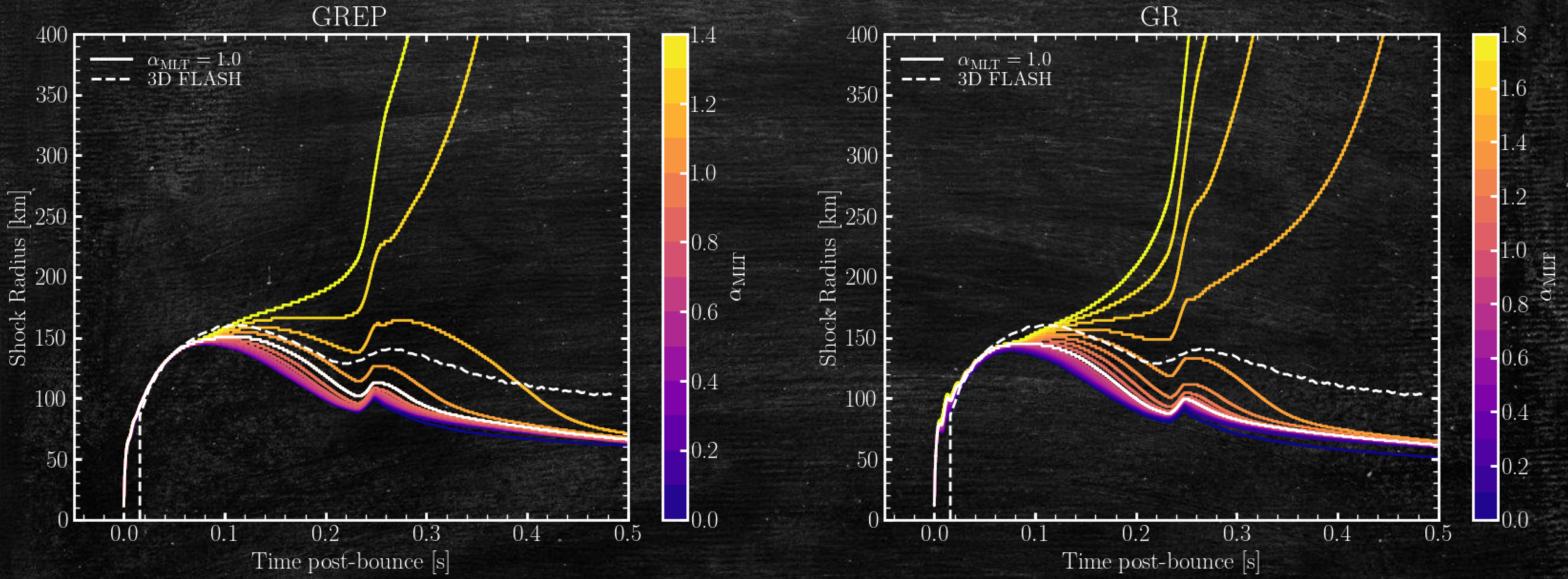


Compactness and explodability





Calibration to 3D Newtonian simulations: FLASH



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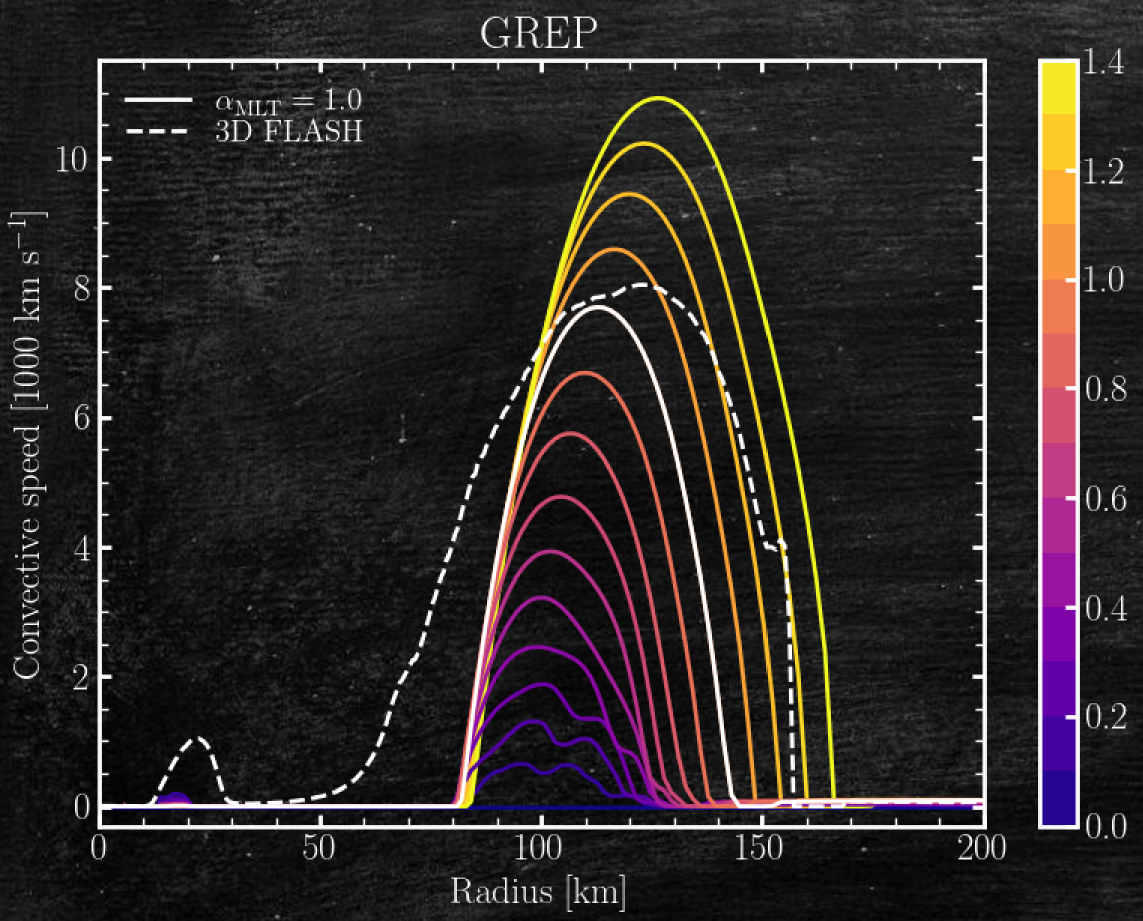

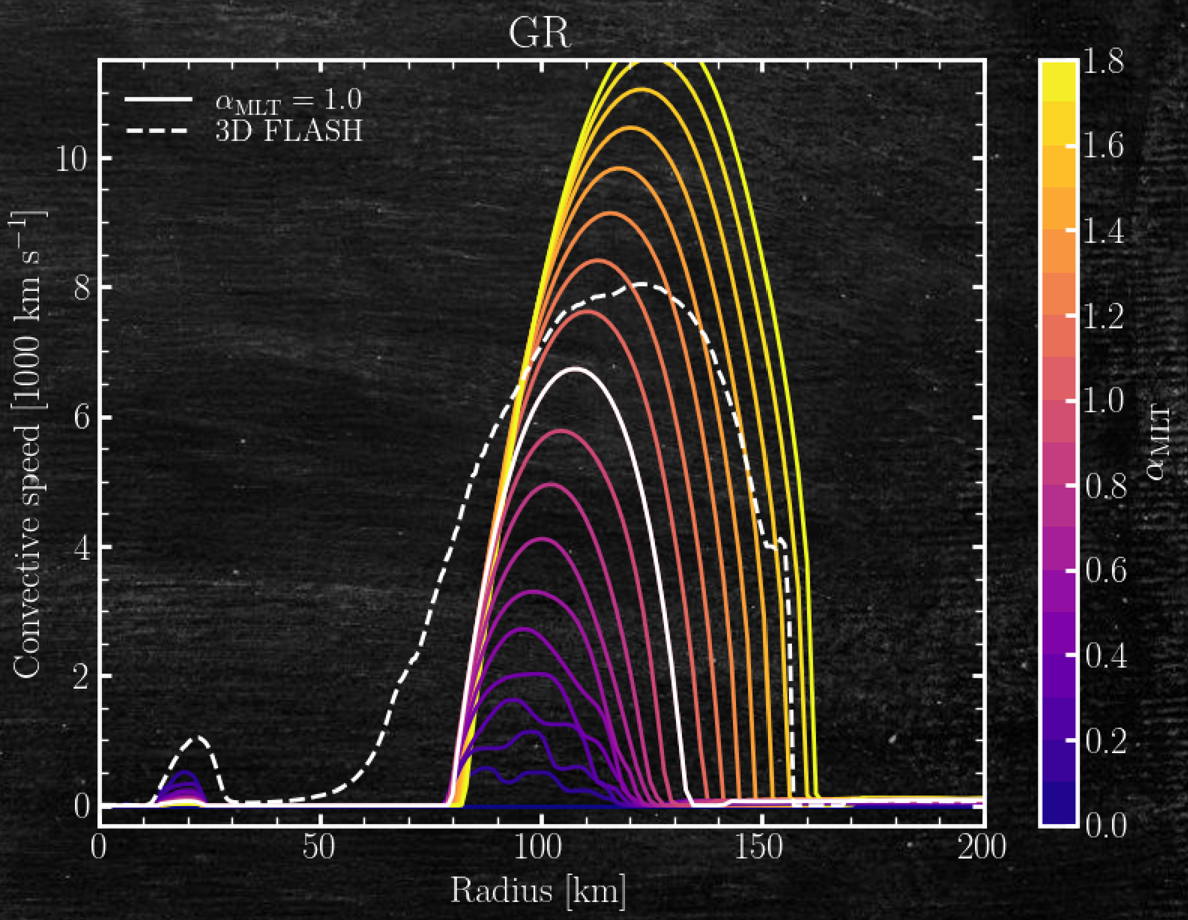

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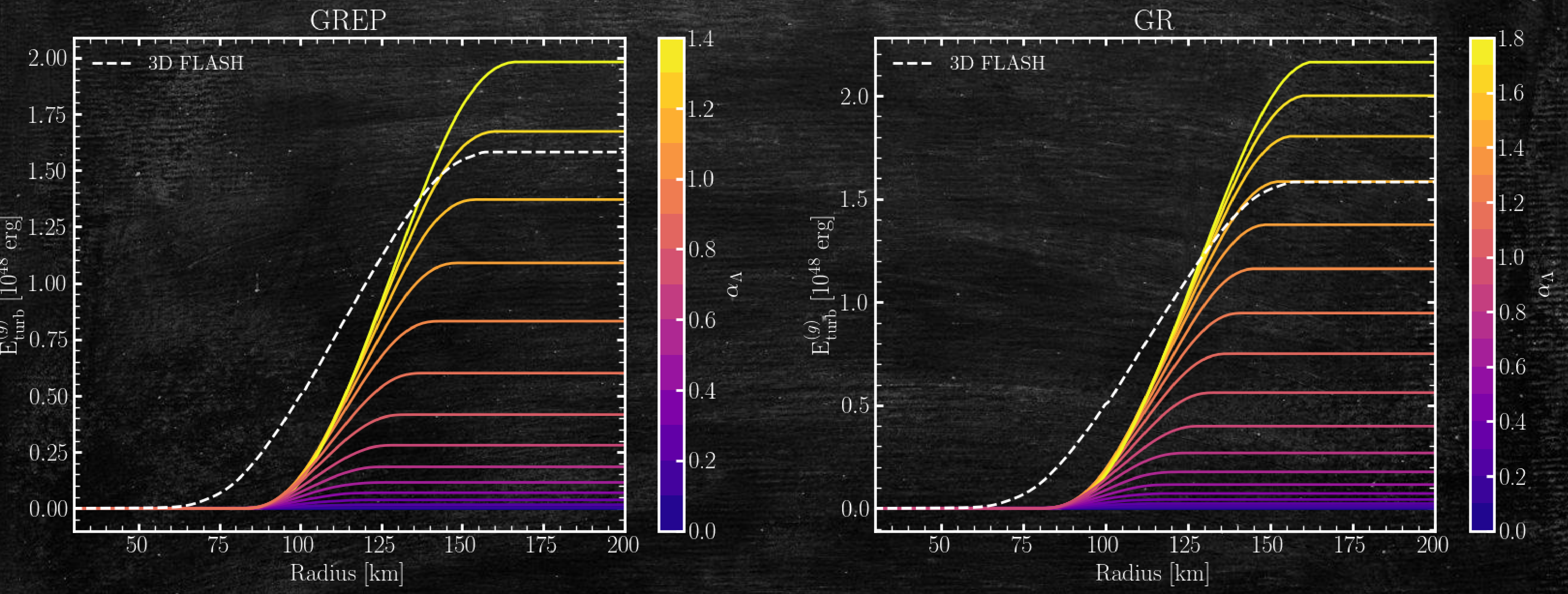
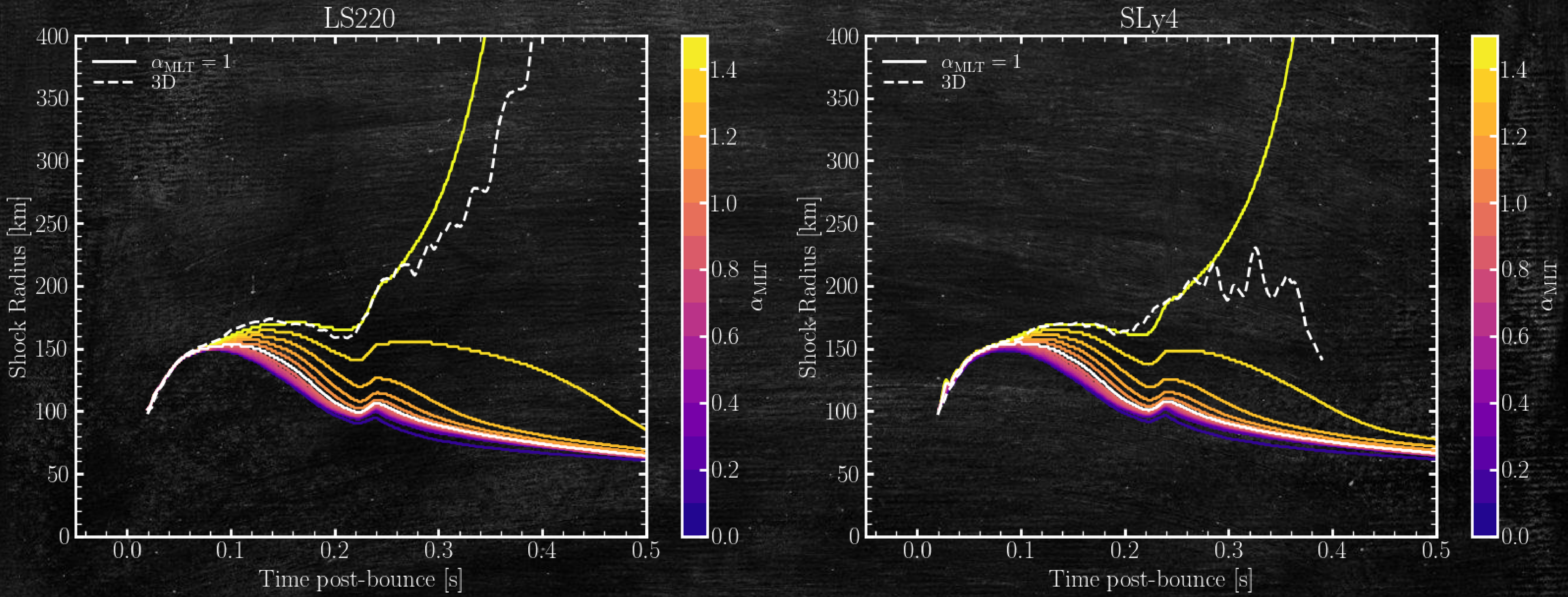
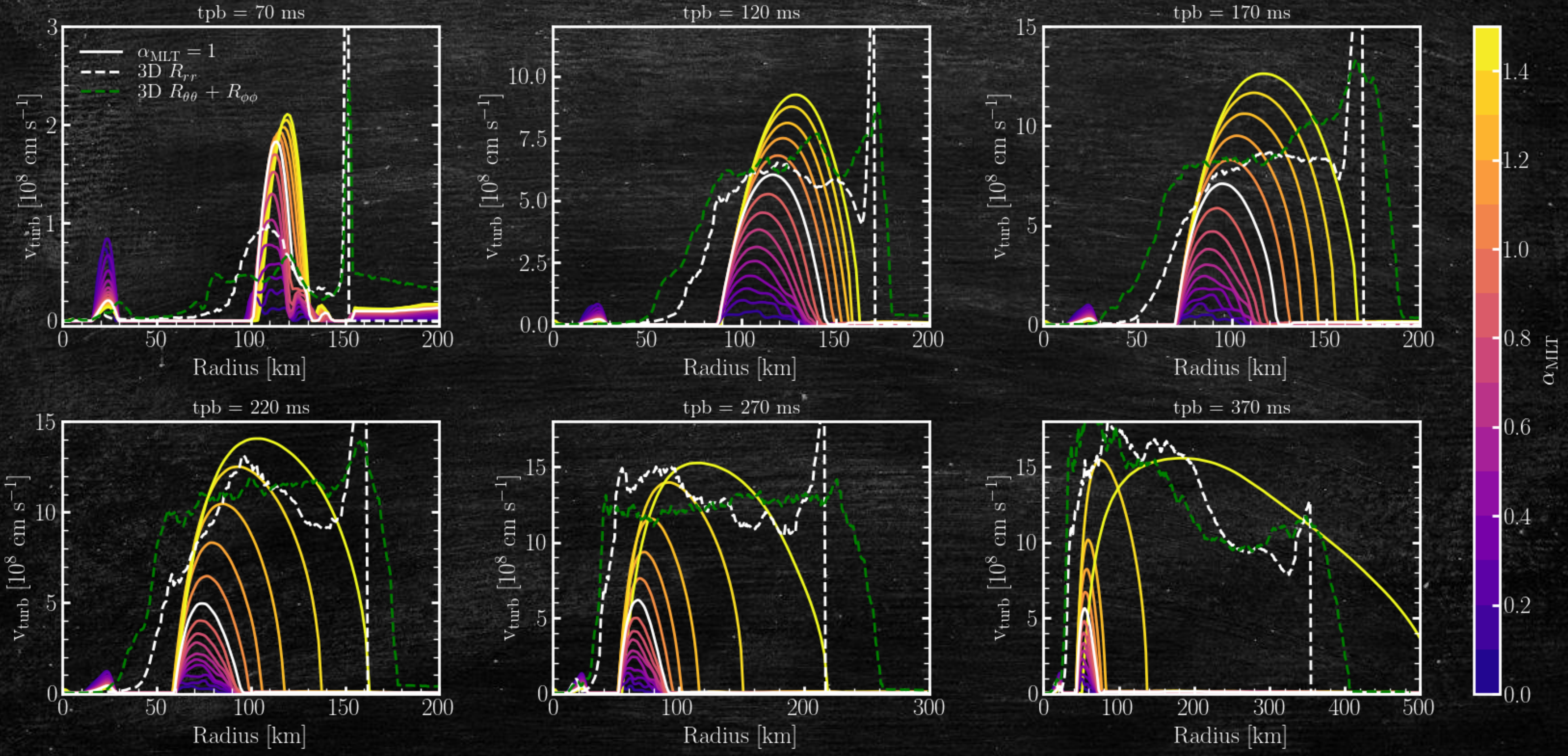


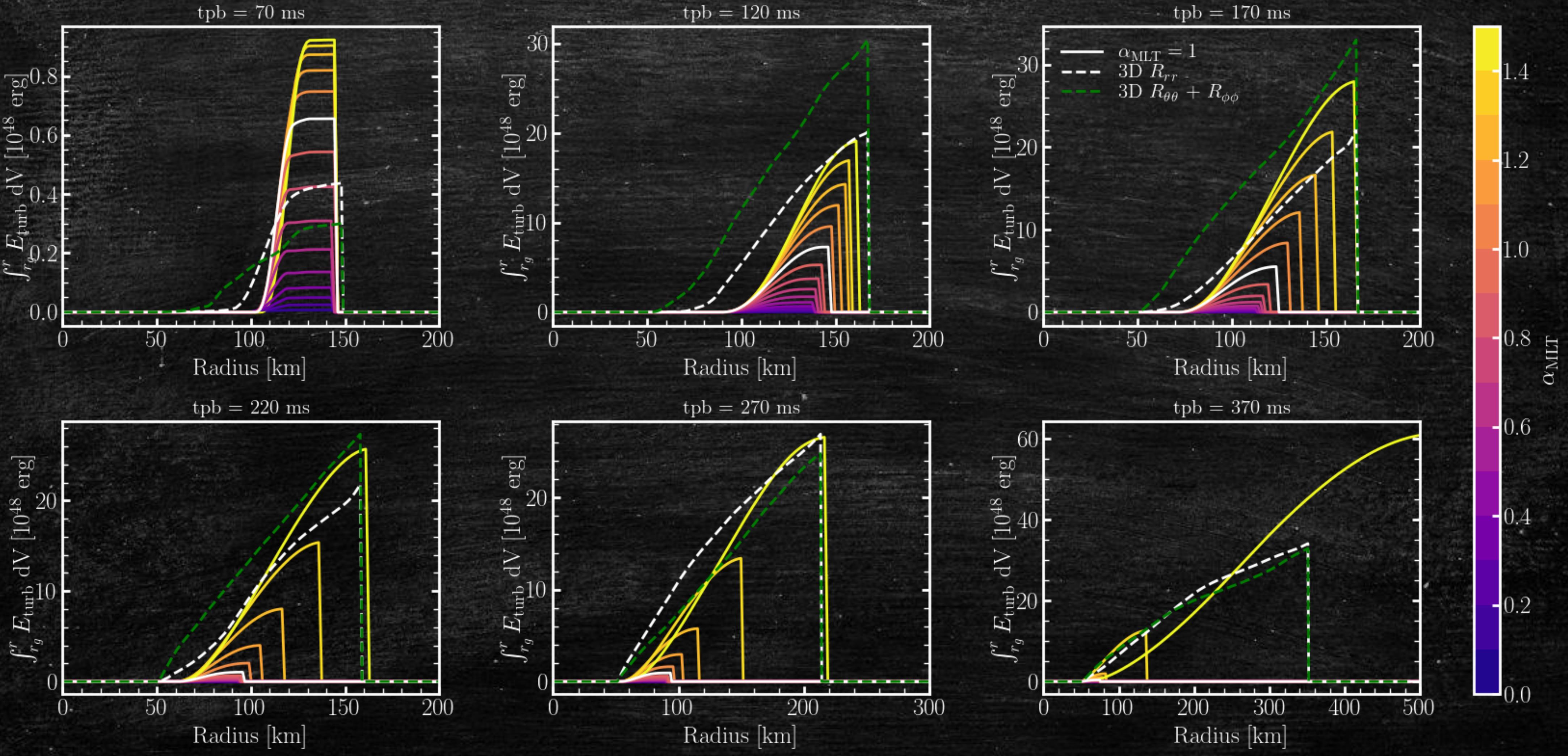
Calibration to 3D simulations: Zelmani



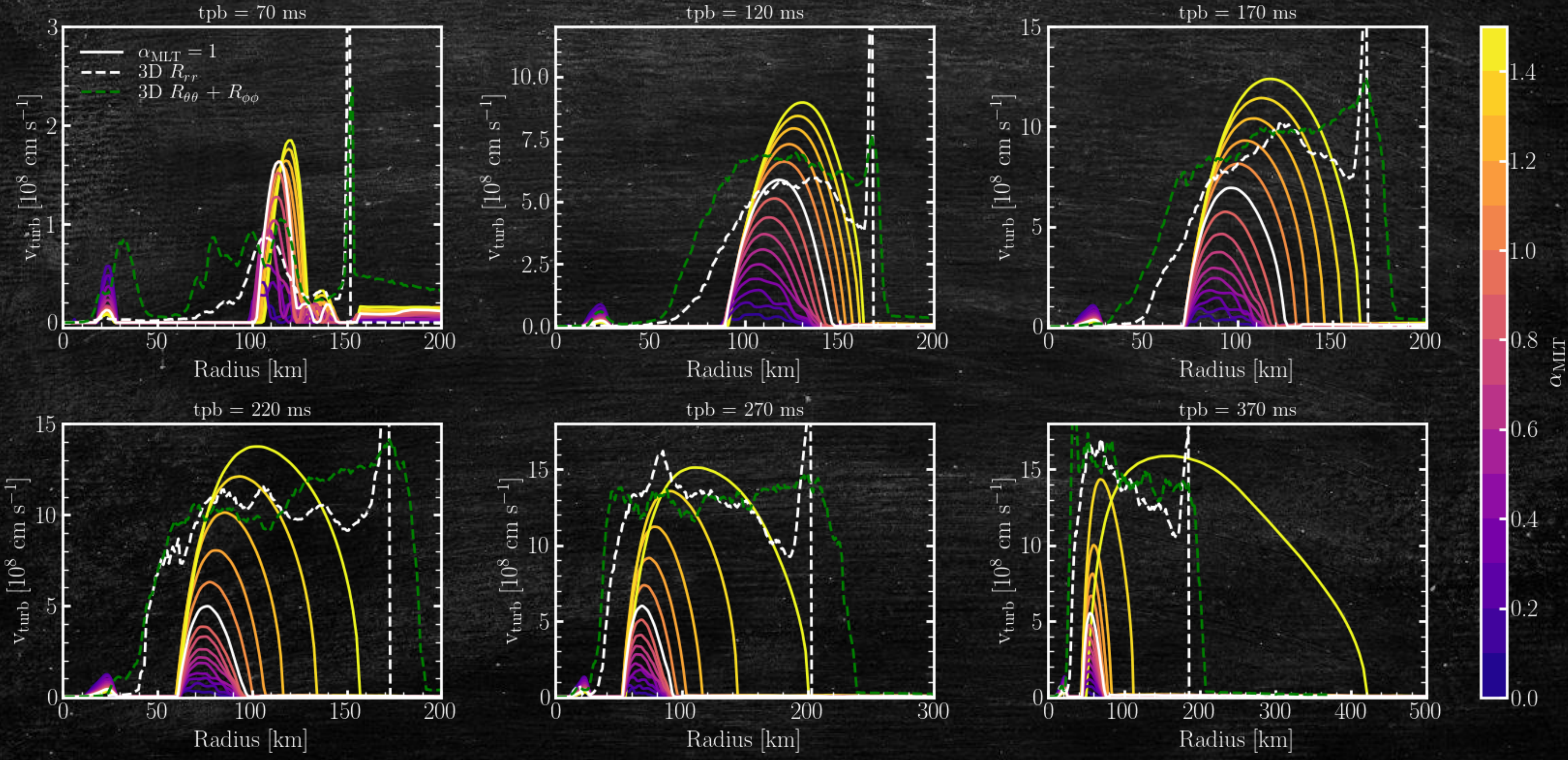
Calibration to 3D simulations: Zelmani LS220



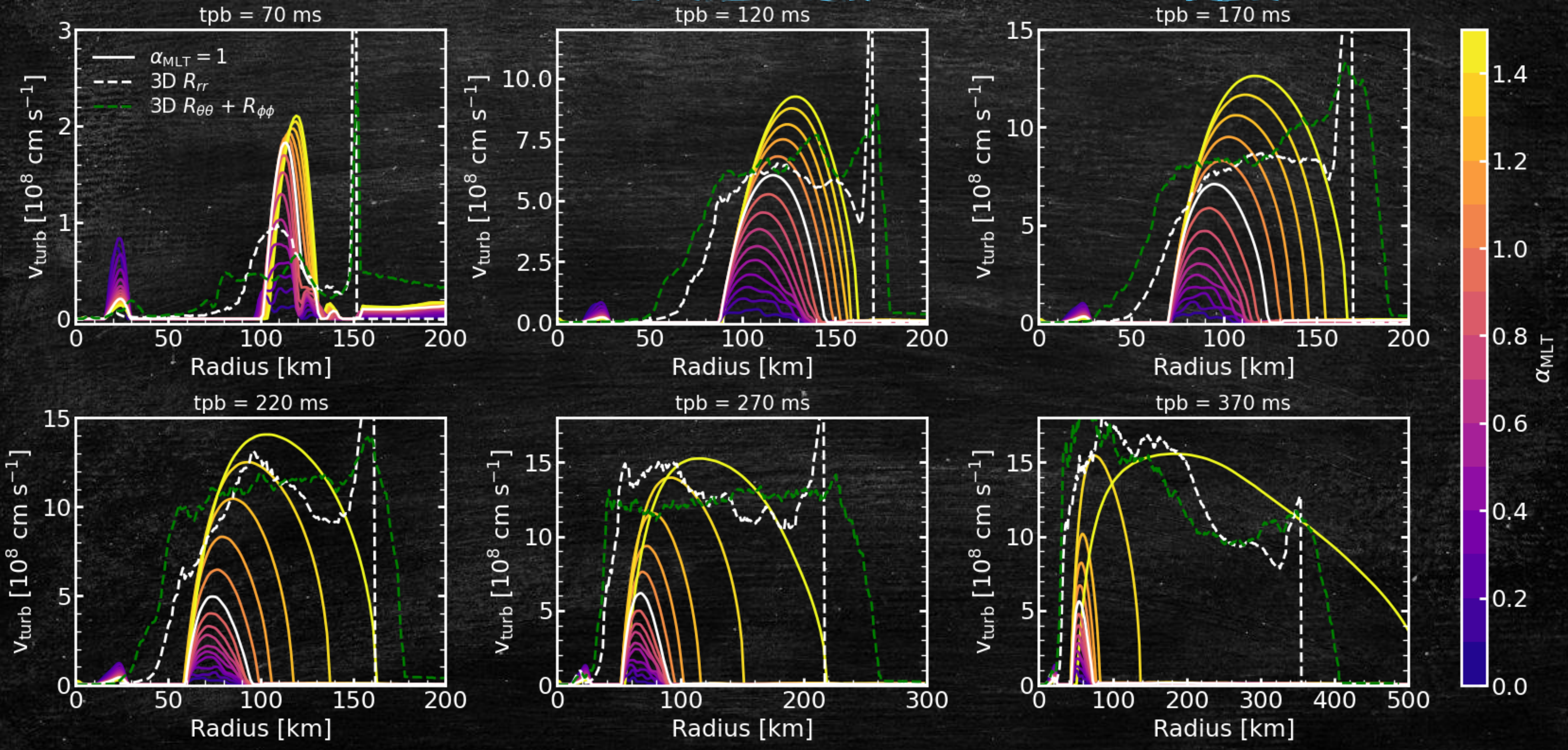
Calibration to 3D simulations: Zelmani LS220



Calibration to 3D simulations: Zelmani SLy4



Calibration to 3D simulations: Zelmani LS220



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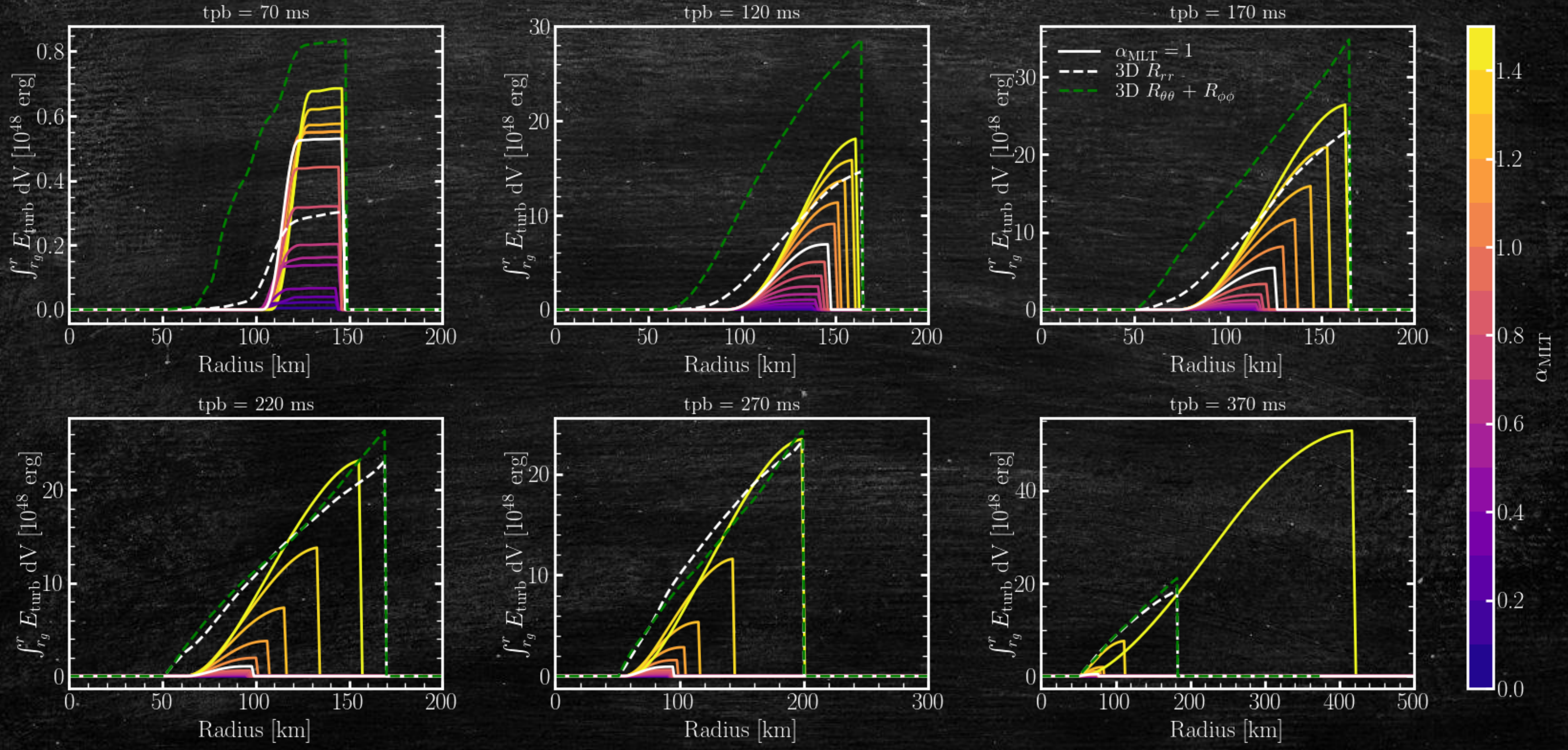
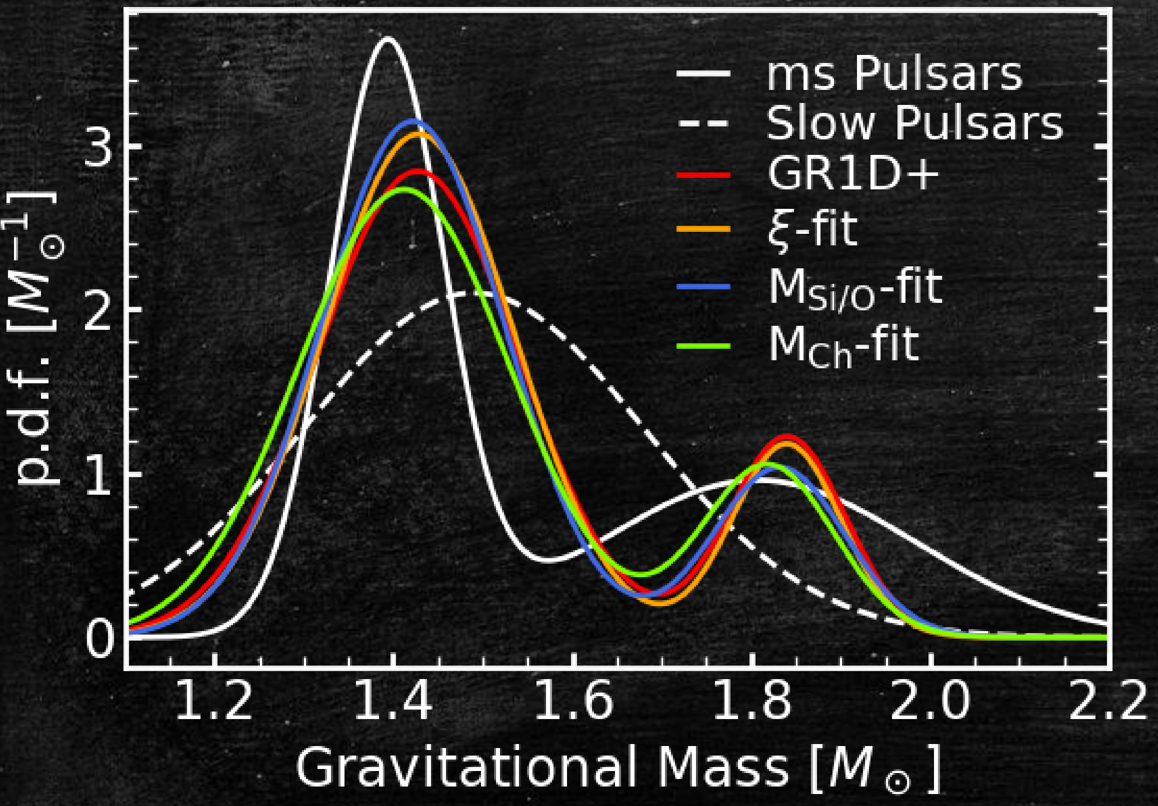


Remnant Mass distributions: 1D+ compared to predictions

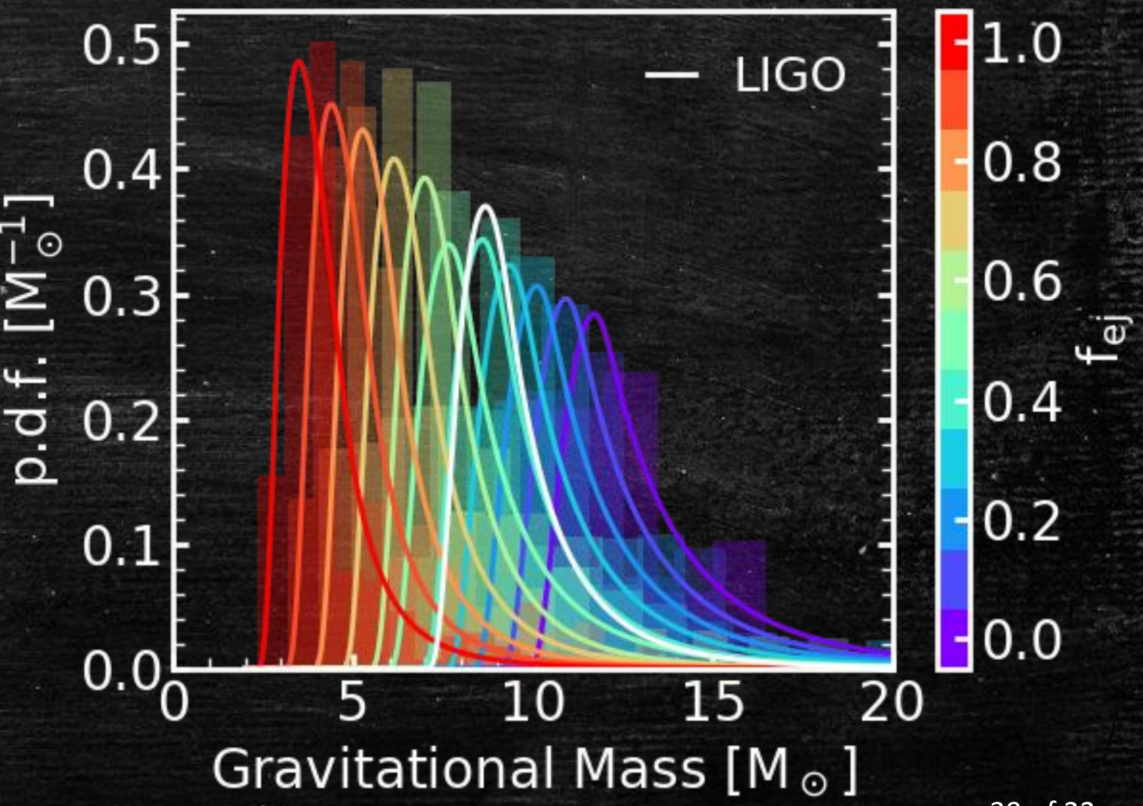
Combined Metallicities where IMF $\propto M^{-2.35}$

$$M_{BH} = M_{final} - f_{ej} M_H$$

Neutron Star Birth Mass Distribution



Black Hole Mass Distribution



Fits for the Neutron Star Mass