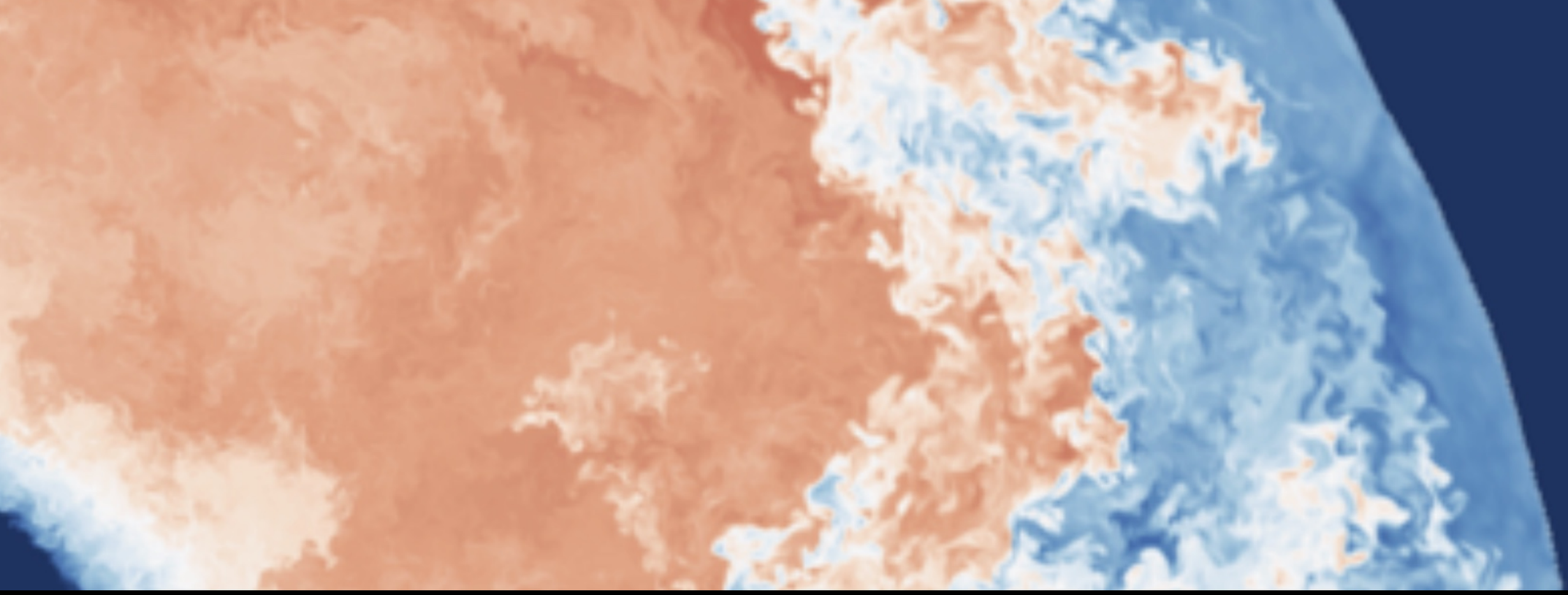


SIMULATING TURBULENCE-AIDED CORE-COLLAPSE SUPERNOVA EXPLOSIONS IN SPHERICAL SYMMETRY

MACKENZIE WARREN & SEAN COUCH
MICHIGAN STATE UNIVERSITY

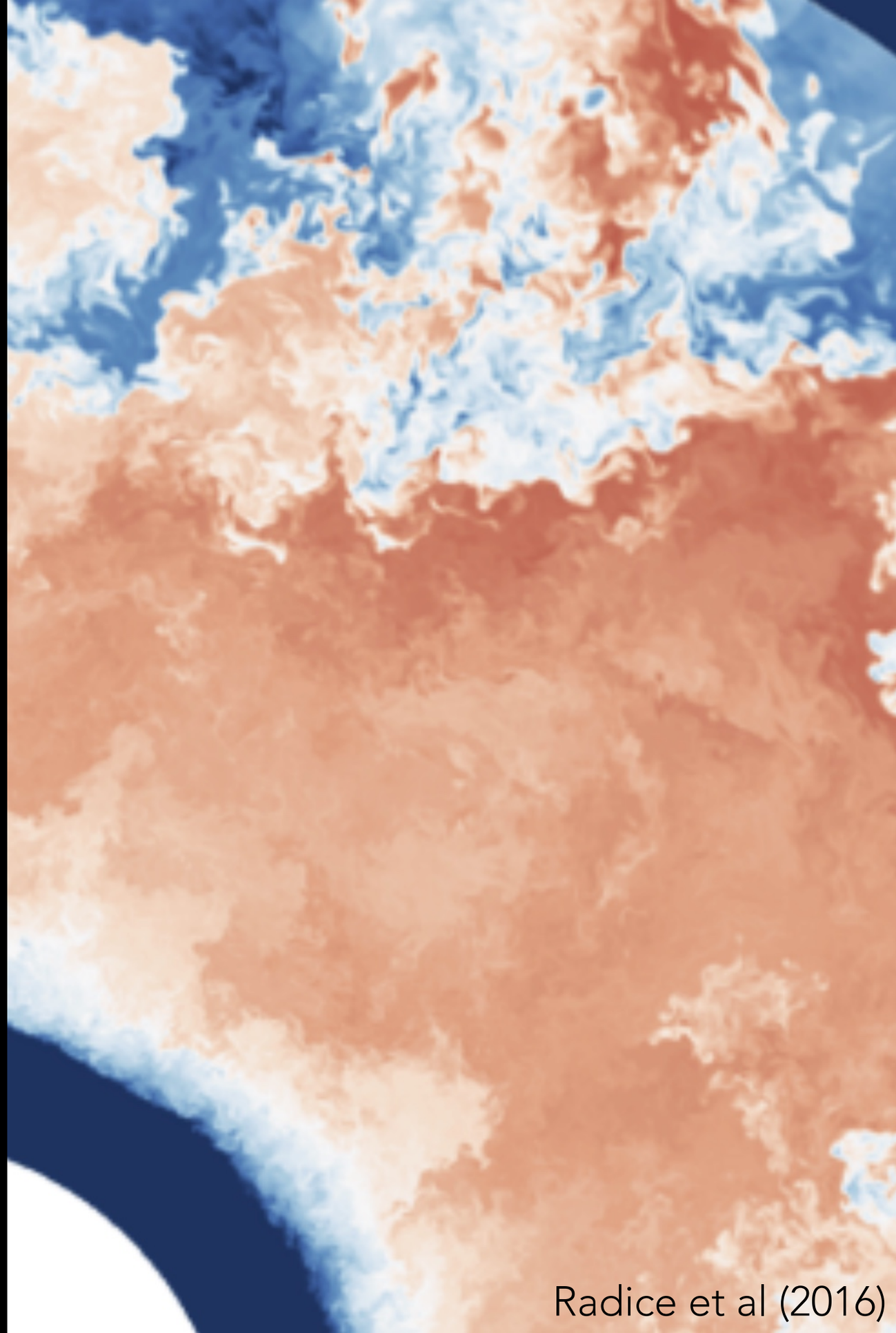
FORGING CONNECTIONS, MICHIGAN STATE UNIVERSITY
JUNE 27TH, 2017

JINA–CEE

MICHIGAN STATE UNIVERSITY

OUTLINE

- Explosion mechanism in 3D
- The case for spherical symmetry
- Modeling turbulence in spherical symmetry
- (Preliminary) Results
- What's next



Radice et al (2016)

EXPLOSION MECHANISM OF CCSNE

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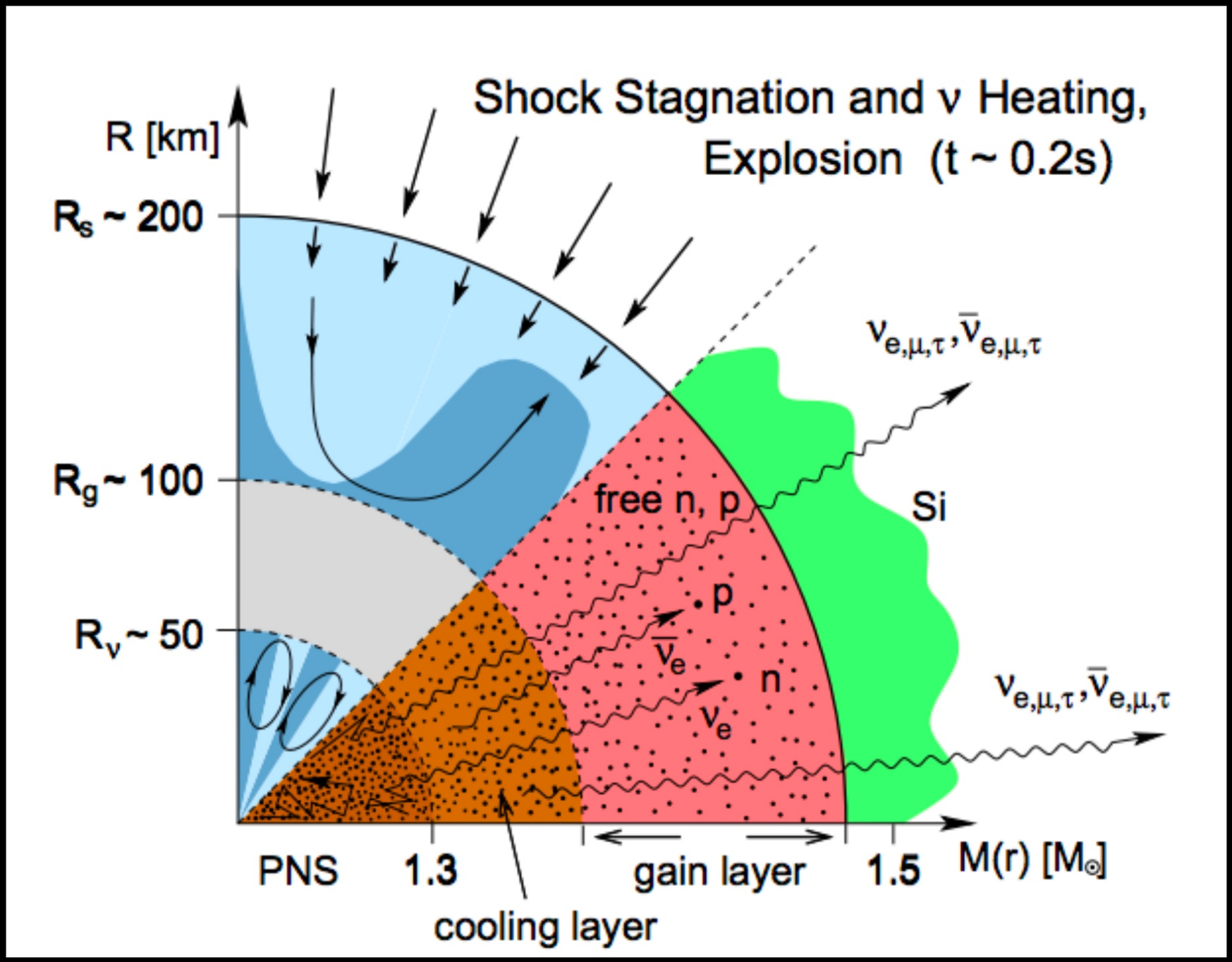
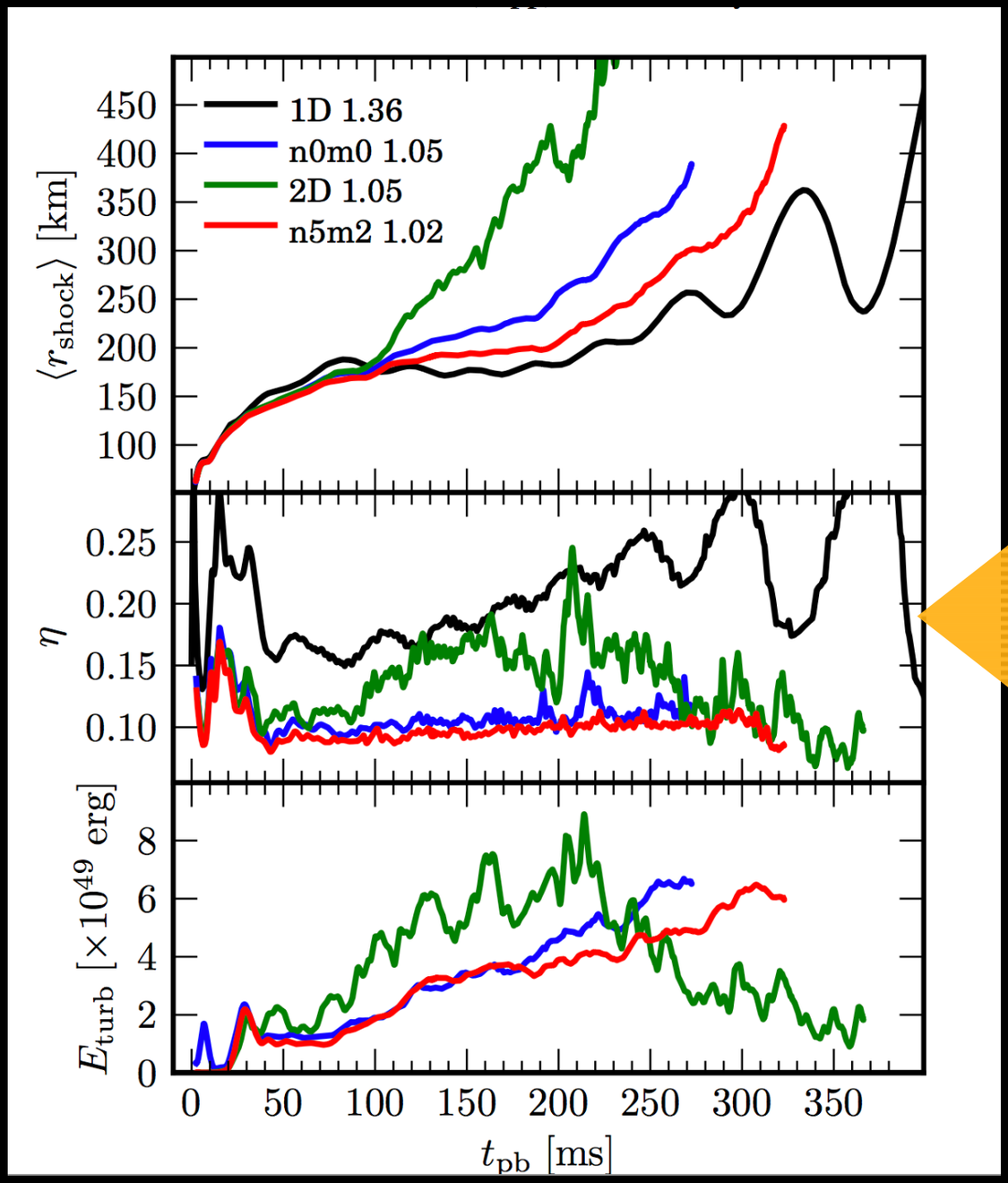


Janka (2012)

EXPLOSION MECHANISM OF CCSNE

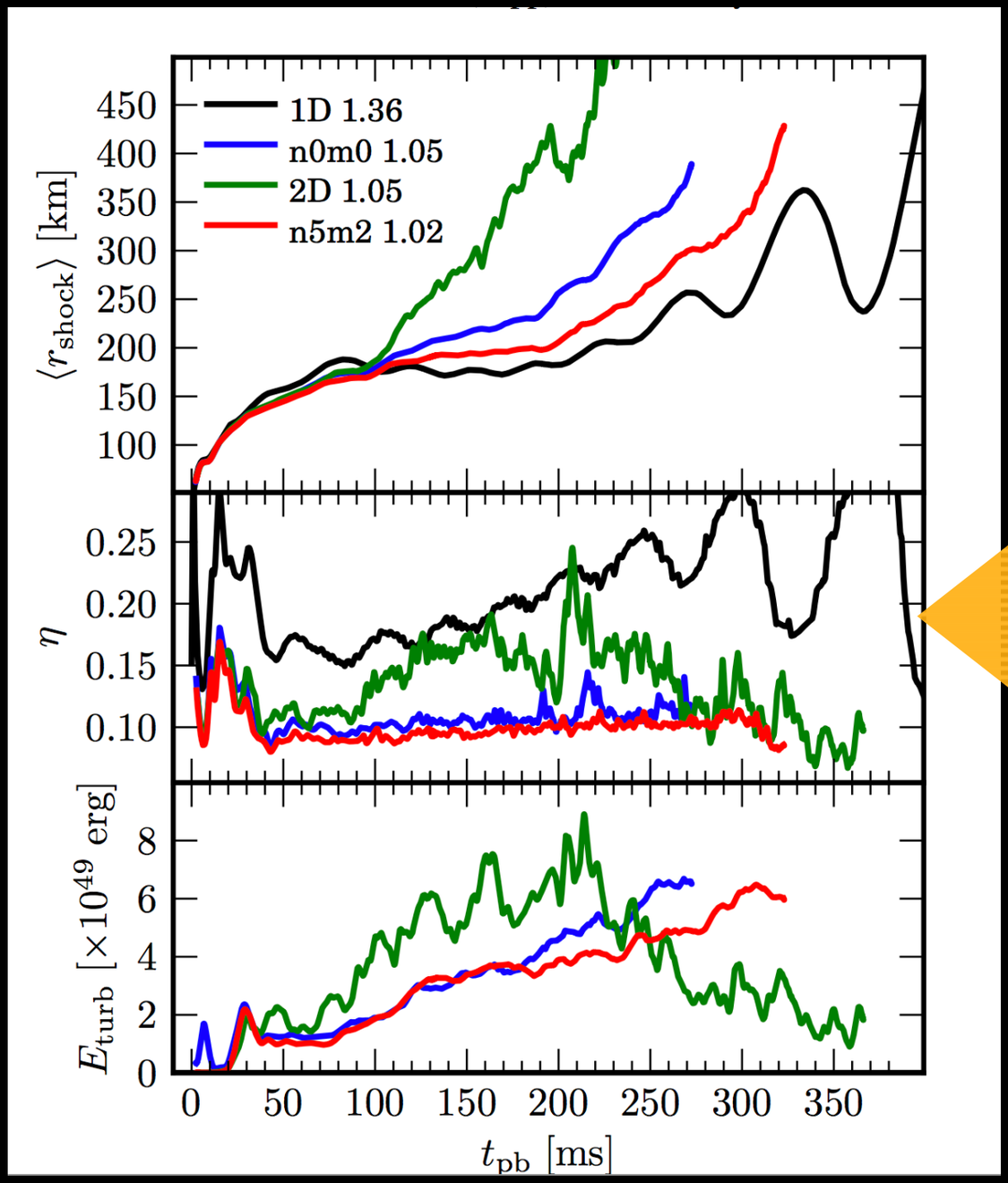


Couch & Ott (2015)

η is a measure of the neutrino heating

$$\eta = Q_{\rm net}(L_{\nu_e} + L_{\bar{\nu}_e})^{-1}$$

EXPLOSION MECHANISM OF CCSNE



Couch & Ott (2015)

η is a measure of the neutrino heating

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- 2D and 3D simulations require less neutrino heating to achieve explosion

ROLE OF TURBULENCE

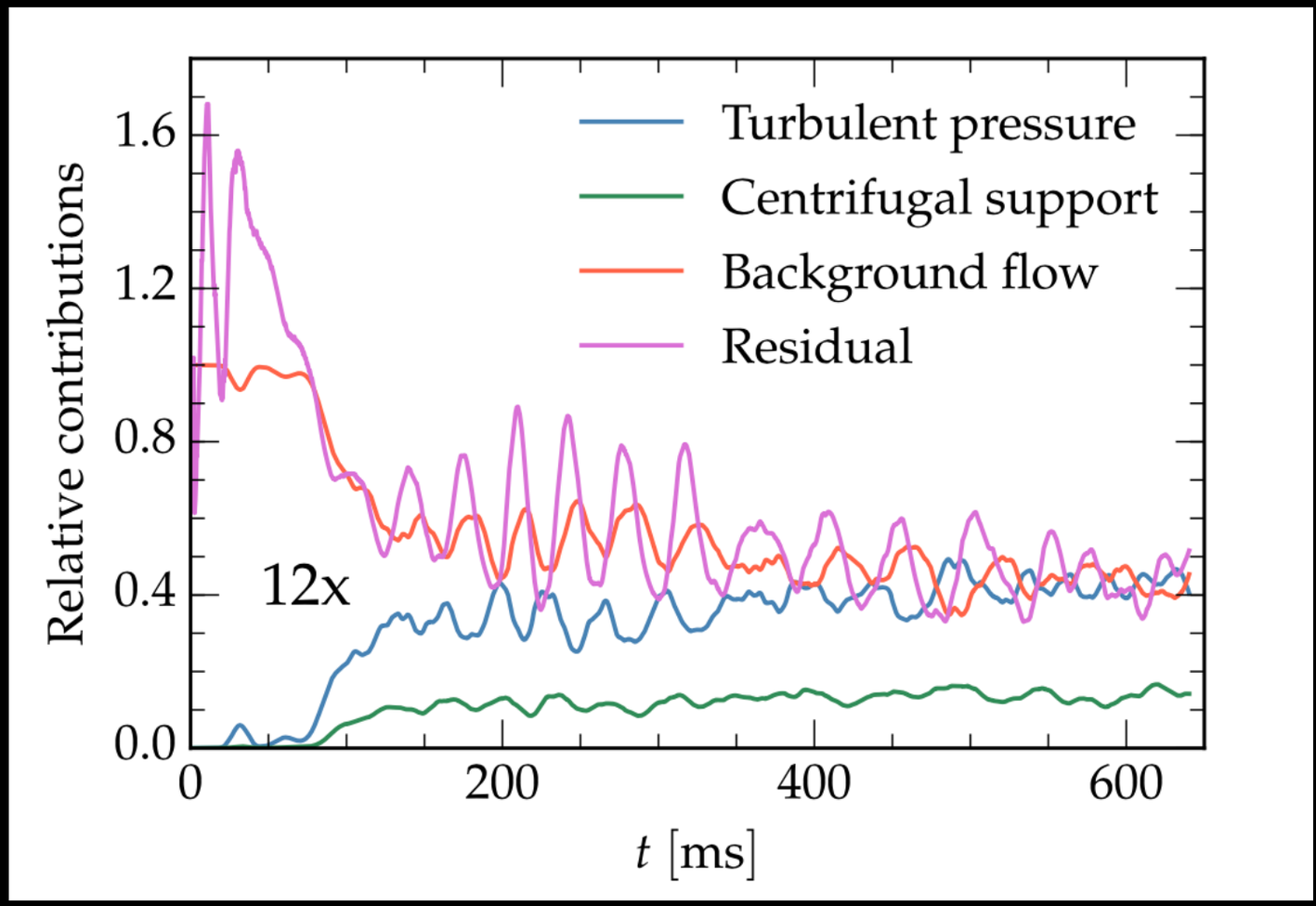
After Reynolds decomposition, get additional terms in hydro eqns

$$u \to v + v_{\rm turb}$$

$$\frac{\partial \rho v}{\partial t} + \frac{1}{r^2}\left(r^2 \rho v^2\right) + \frac{\partial}{\partial r}\left(P + \rho R_{rr}\right) = -\rho \frac{\partial \phi}{\partial r}$$

where $R_{rr} \sim v_{\rm turb}^2$

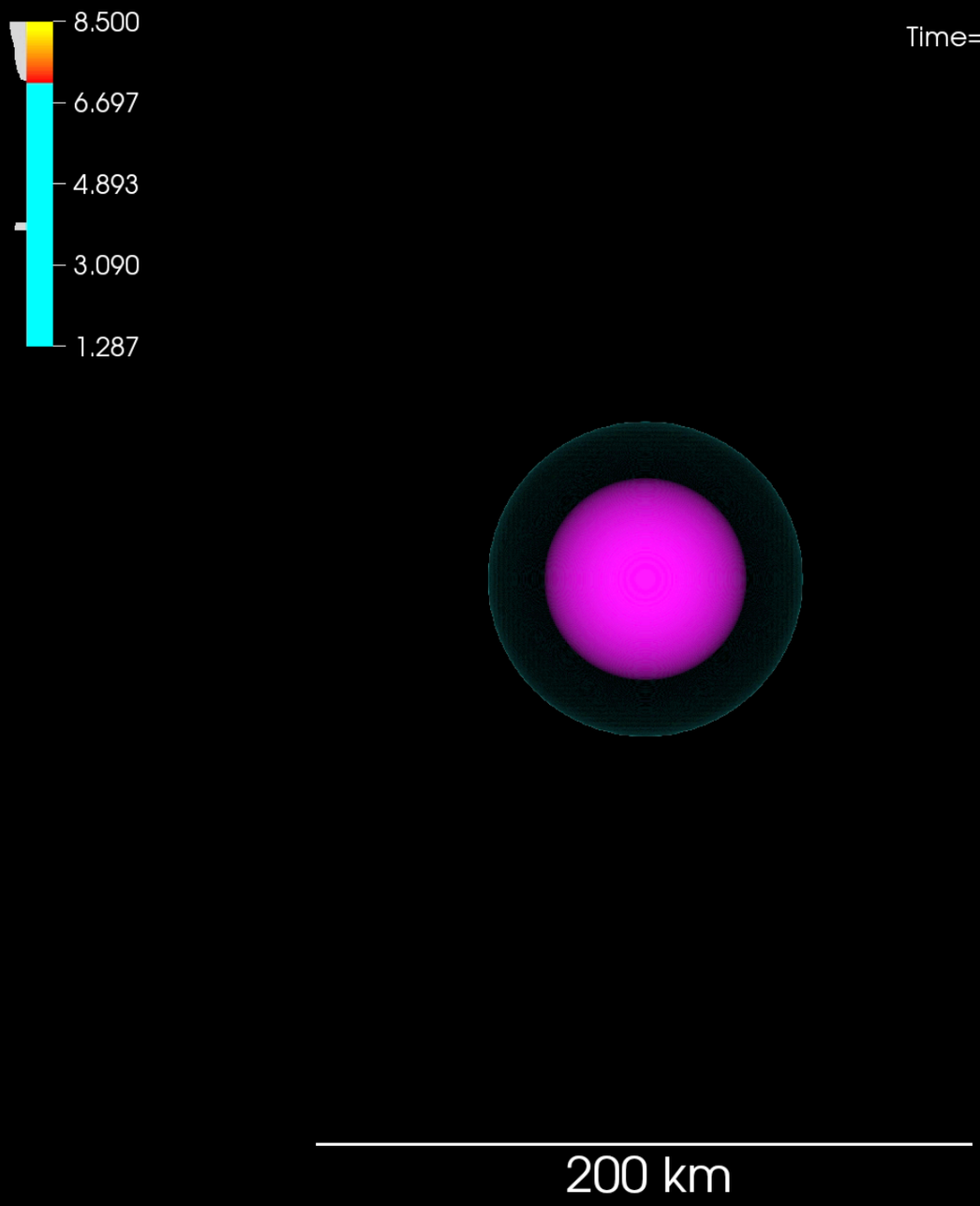
(and similarly for energy)



Radice et al (2016)

MAKING THE CASE FOR SPHERICAL SYMMETRY

THE CASE FOR SPHERICAL SYMMETRY



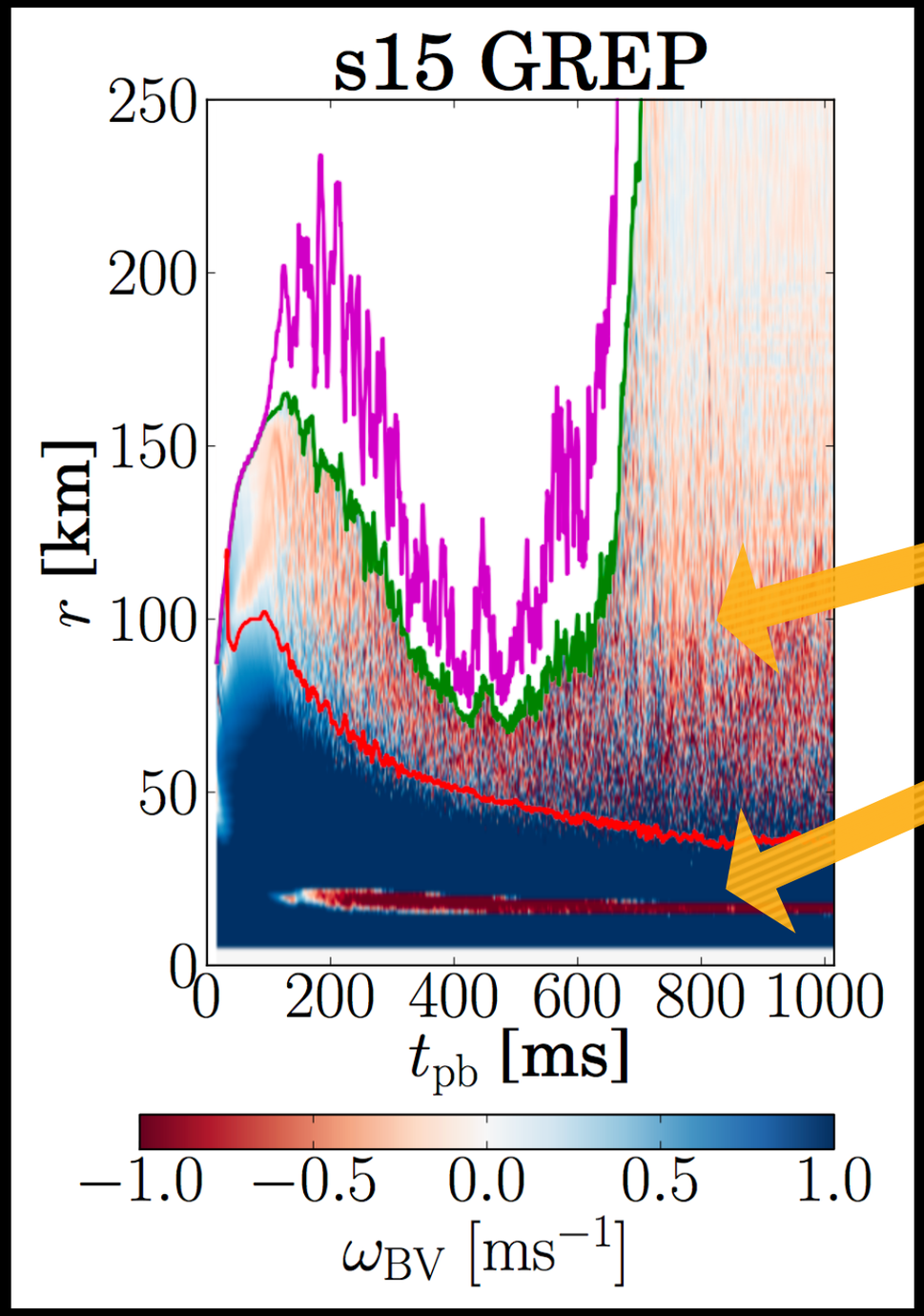
- Population studies
- Nuclear EOS
- Nucleosynthesis
- Neutrino physics
- New physics?

GOALS

- Reproduce physical explosion mechanism and local behavior of turbulence in spherical symmetry
- Better replicate local thermodynamics (and thus nucleosynthesis)
- By reproducing local conditions, also reproduce global quantities like SN1987A explosion energy, nickel mass, etc
- Provide predictions of explodability, nucleosynthesis, neutrino spectra & luminosities

MODELING TURBULENCE IN SPHERICAL SYMMETRY

MODELING CONVECTION IN CCSNE



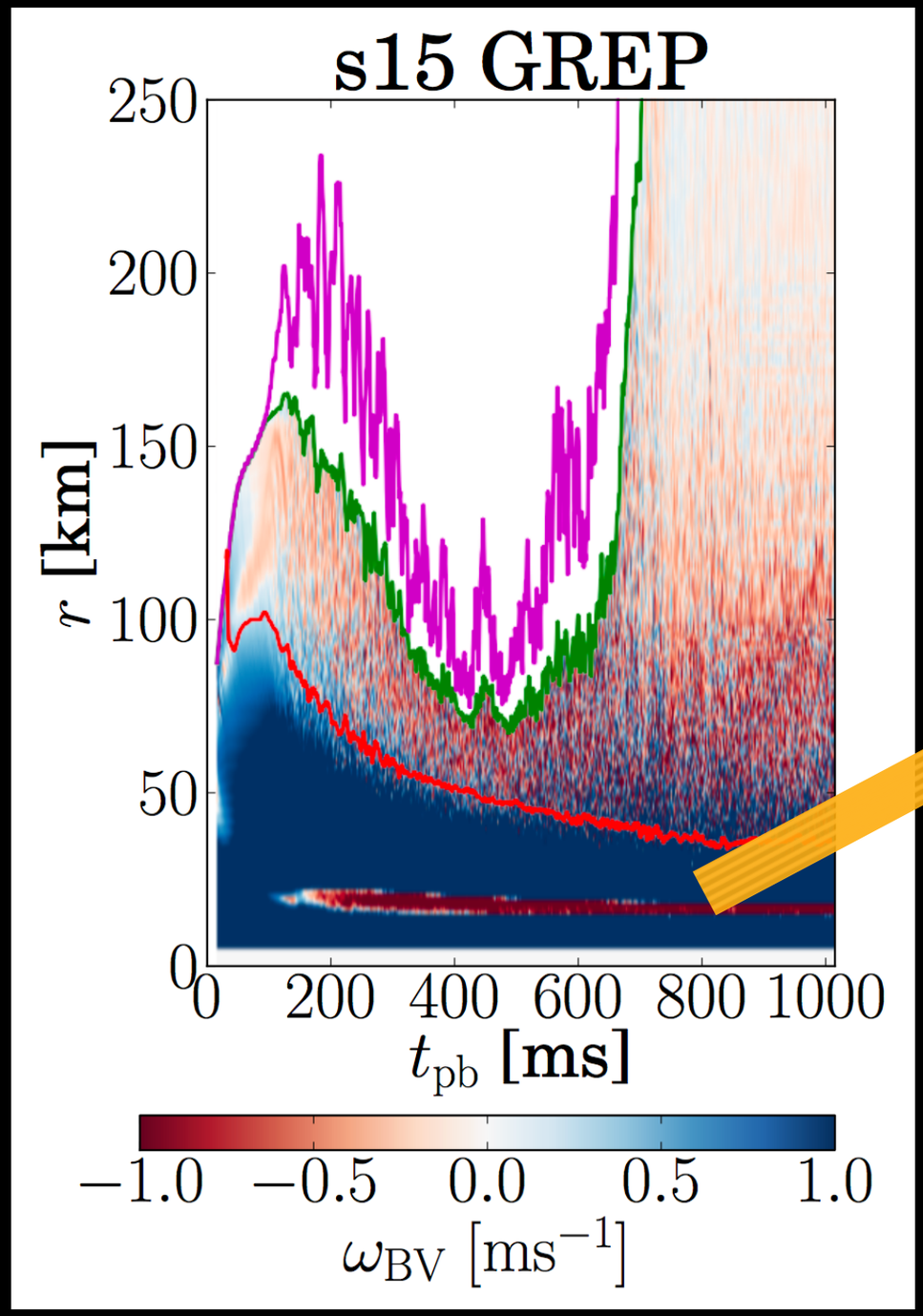
O'Connor & Couch (2015)

Two distinct regions of convection:

Gain region

PNS

PROTONEUTRON STAR CONVECTION



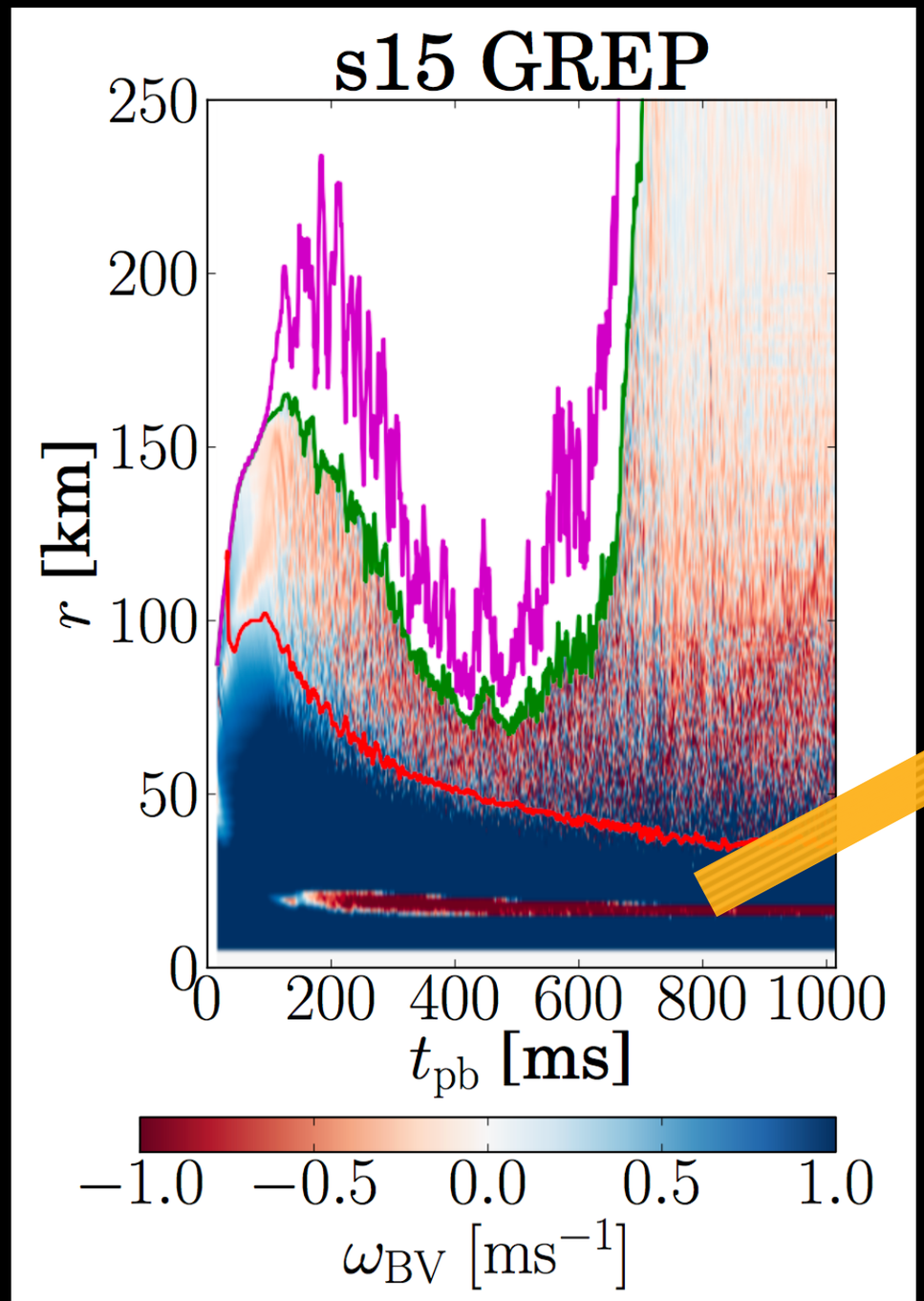
O'Connor & Couch (2015)

PNS Convection

Traditional MLT! Strength of convection set by gradients:

$$\omega_{BV}^2 = \frac{\partial \Phi}{\partial r}\left(\frac{d\ln\rho}{dr} - \frac{1}{c_s^2}\frac{d\ln P}{dr} - \frac{\chi_{Y_\ell}}{\chi_\rho}\frac{d\ln Y_\ell}{dr}\right)$$

PROTONEUTRON STAR CONVECTION



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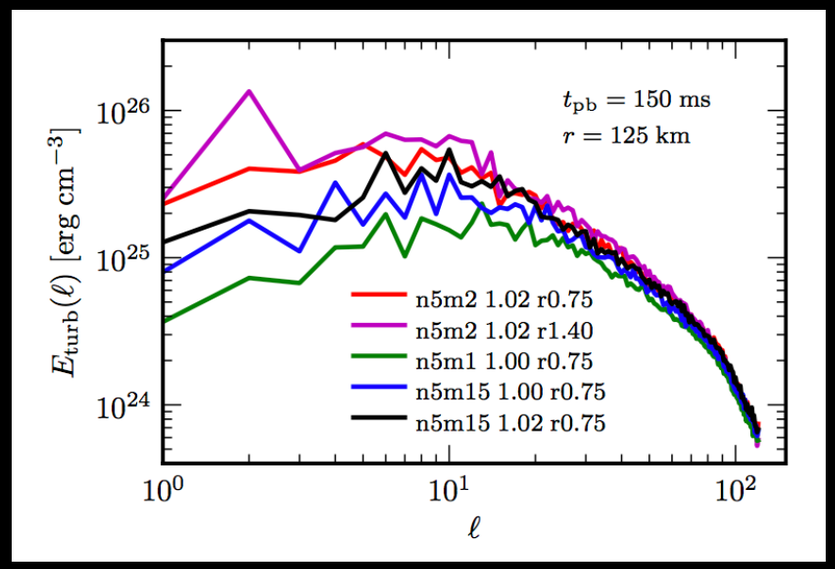

Couch & Ott (2015)

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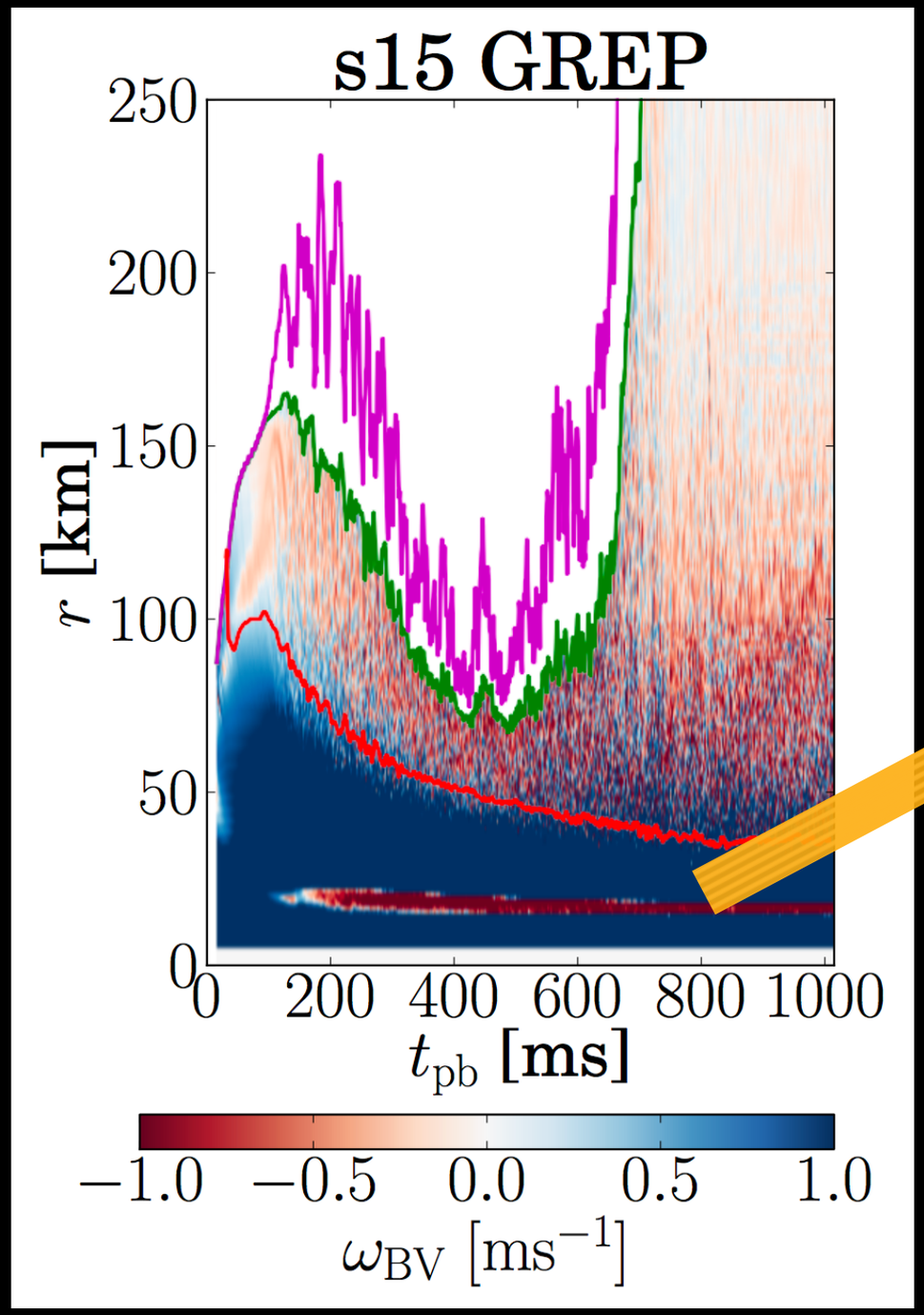

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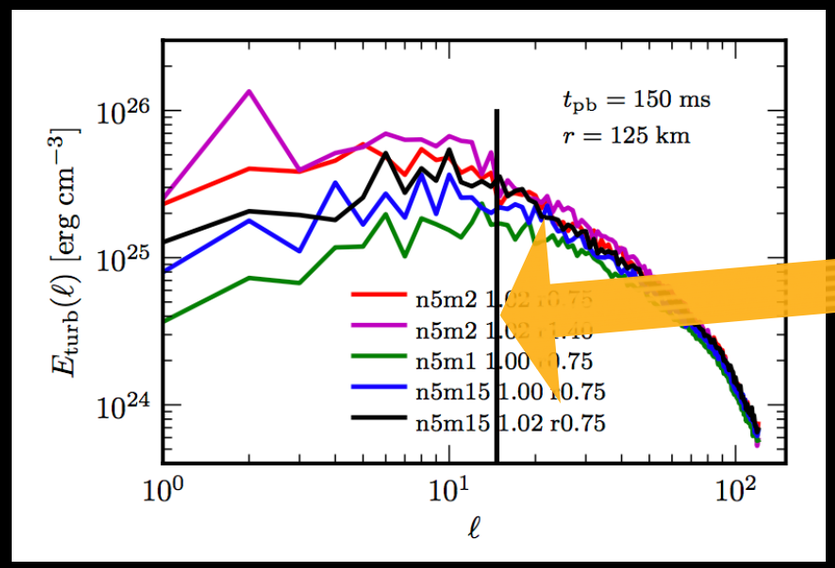
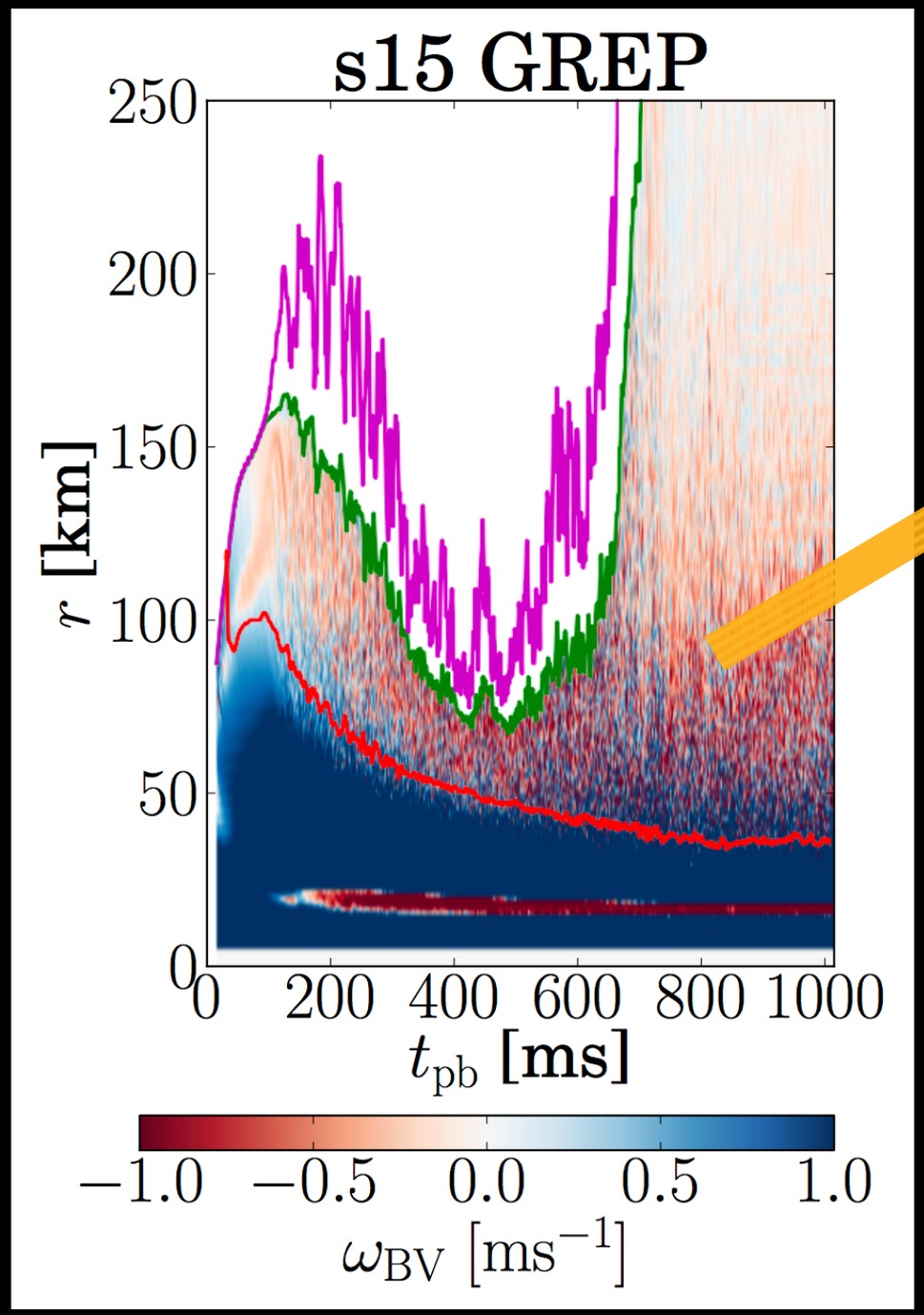


Couch & Ott (2015)

$$\Lambda_{\rm PNS} = \alpha_{\rm MLT} R_{\rm PNS}$$

$$v_{\rm turb}^2 \sim -\omega_{BV}\Lambda_{PNS}^2$$

GAIN REGION CONVECTION



O'Connor & Couch (2015)

Gain Region Convection

Turbulence and neutrino heating ~ equilibrium

$$\epsilon_\nu \sim v_{\rm turb}^3 / \Lambda_{\rm gain}$$

where $\Lambda_{\rm gain} = \beta_{\rm MLT} R_{\rm gain}$

TURBULENCE MODEL

- After Reynolds decomposition, get additional terms in hydro eqns

$$R_{rr} \sim v_{\mathrm{turb}}^2$$

(See Böhm-Vitense (1958))

$$\frac{\partial \rho v}{\partial t} + \frac{1}{r^2}\left(r^2 \rho v^2\right) + \frac{\partial}{\partial r}\left(P + \rho R_{rr}\right) = -\rho \frac{\partial \phi}{\partial r}$$

(and similarly for energy)

- Two parameters to fit: **α** and β to describe PNS and gain region convection respectively

NEUTRINO TRANSPORT:
- Leakage
- M1 spectral transport

(O'Connor & Couch arXiv:1511.07443)

HYDRO

NUCLEAR EQUATION OF STATE

FLASH CODE

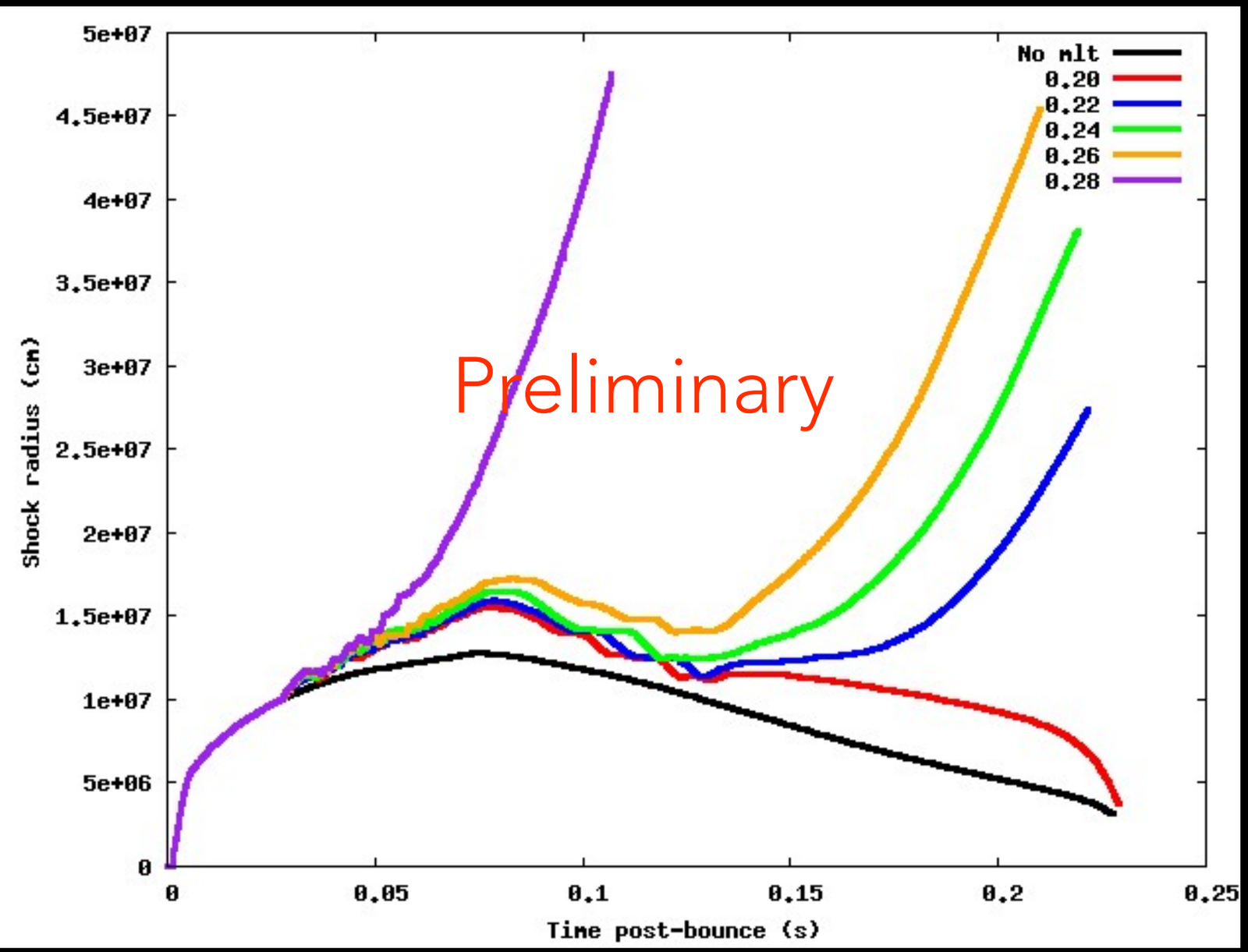
MULTIDIMENSIONAL: 1D → 3D

GR EFFECTIVE POTENTIAL

(Couch, Graziani, & Flocke 2013)

(PRELIMINARY) RESULTS

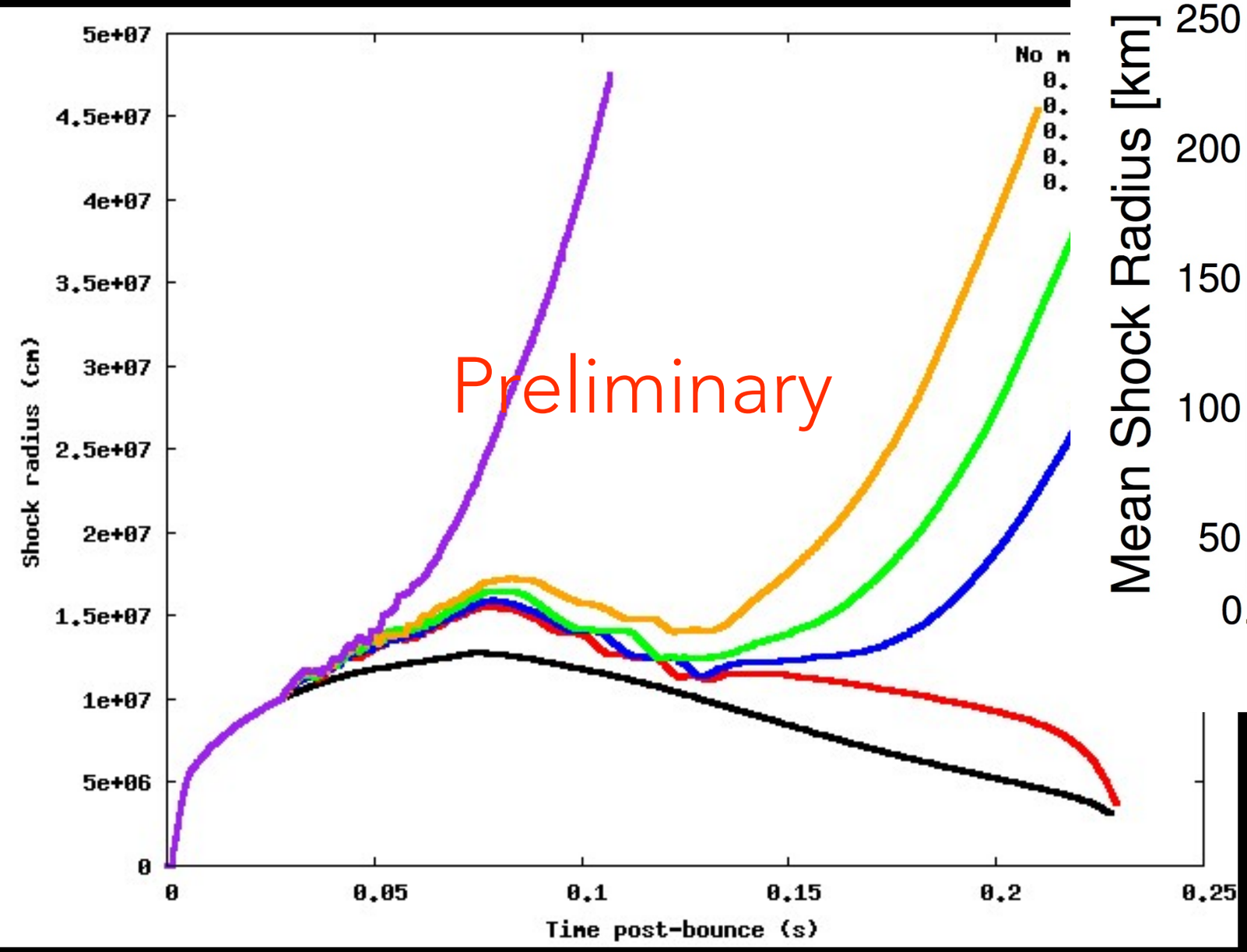
VARYING PARAMETERS: β



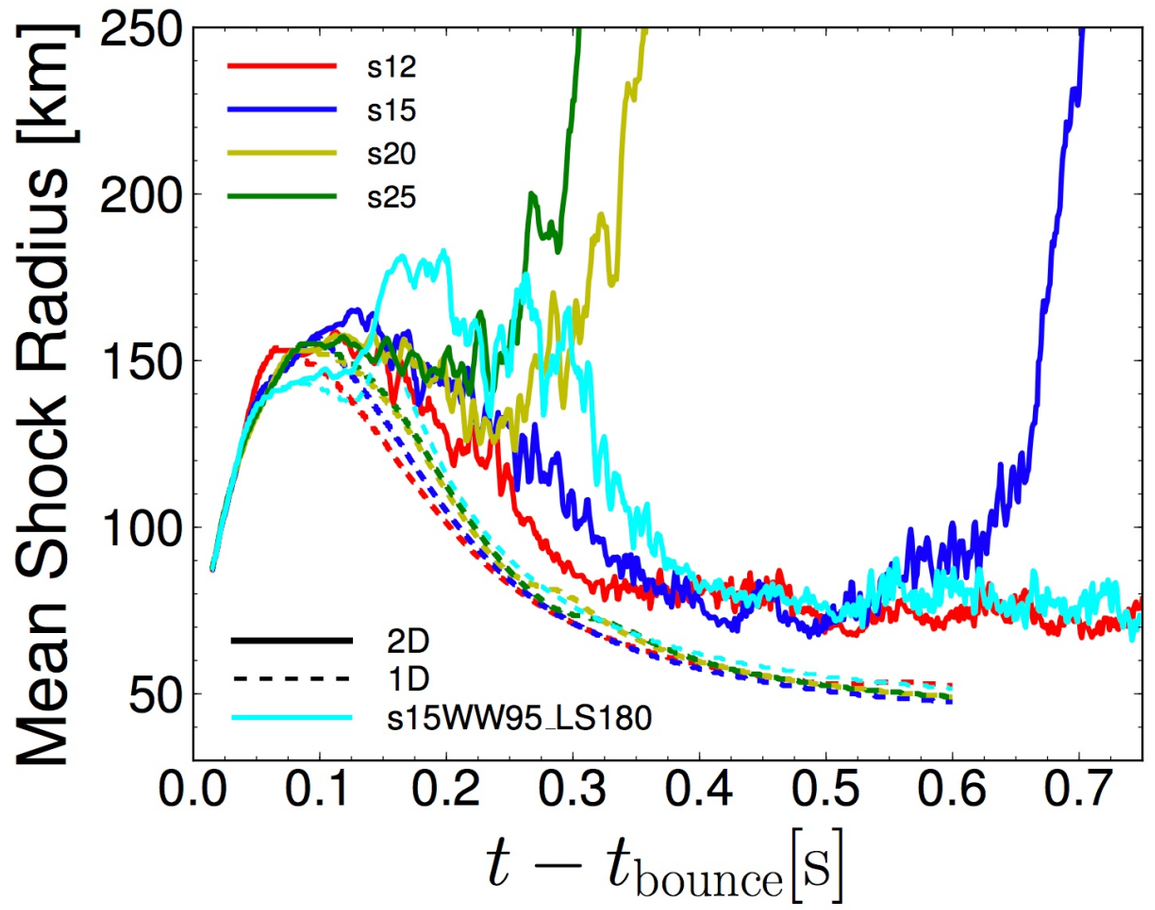
- 20 M◉ (HW 2007)
- LS220
- M1 neutrino transport
- GR Effective Potential

Warren & Couch (In prep)

COMPARING WITH MULTI-D 2D



Warren & Couch (In prep)

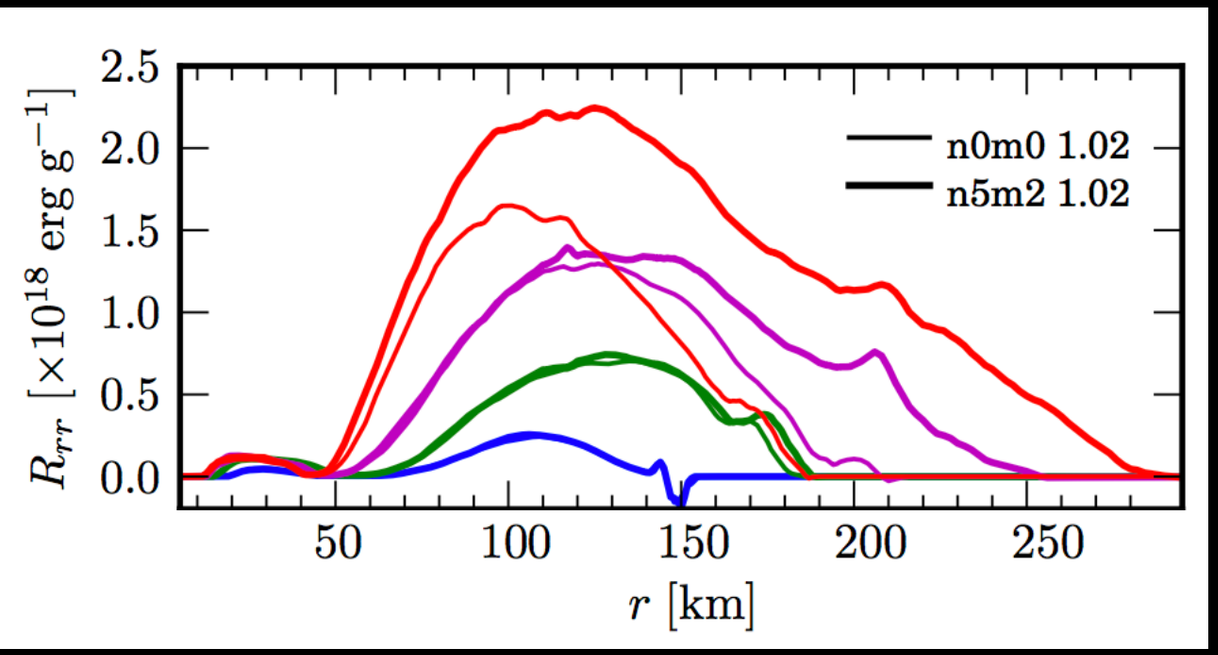


O'Connor & Couch (arXiv:1511.07443)

COMPARING WITH 3D

3D

$$R_{rr} \sim v_{\mathrm{turb}}^2$$



Couch & Ott (2015)

COMPARING WITH 3D

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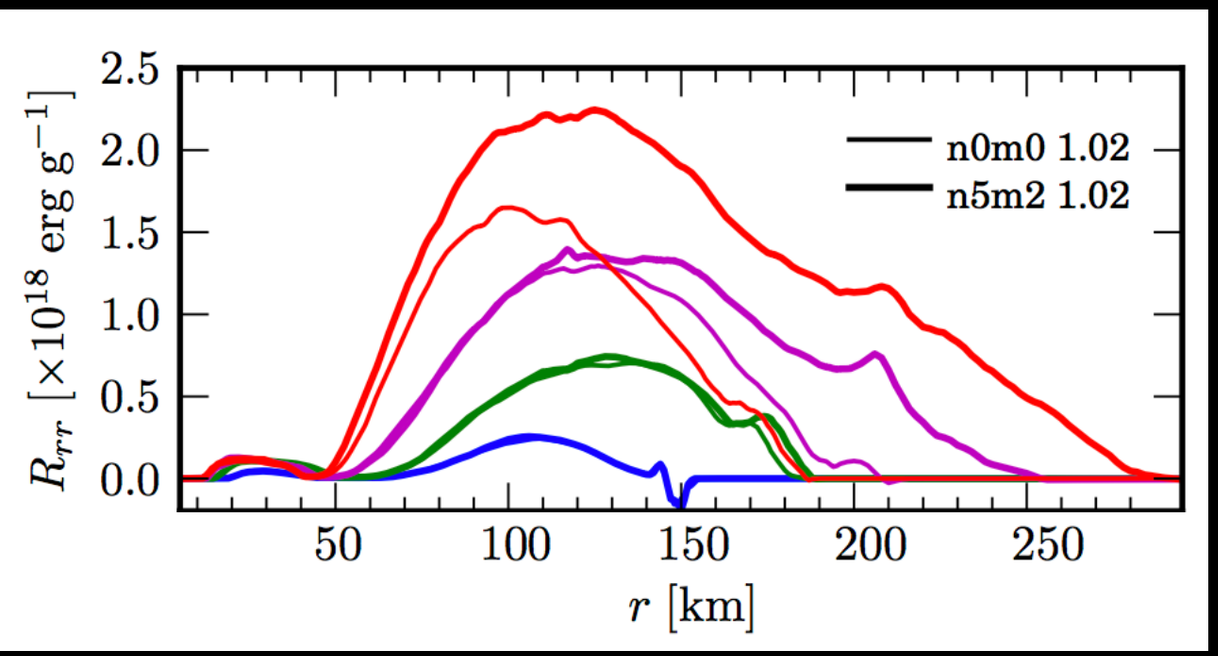
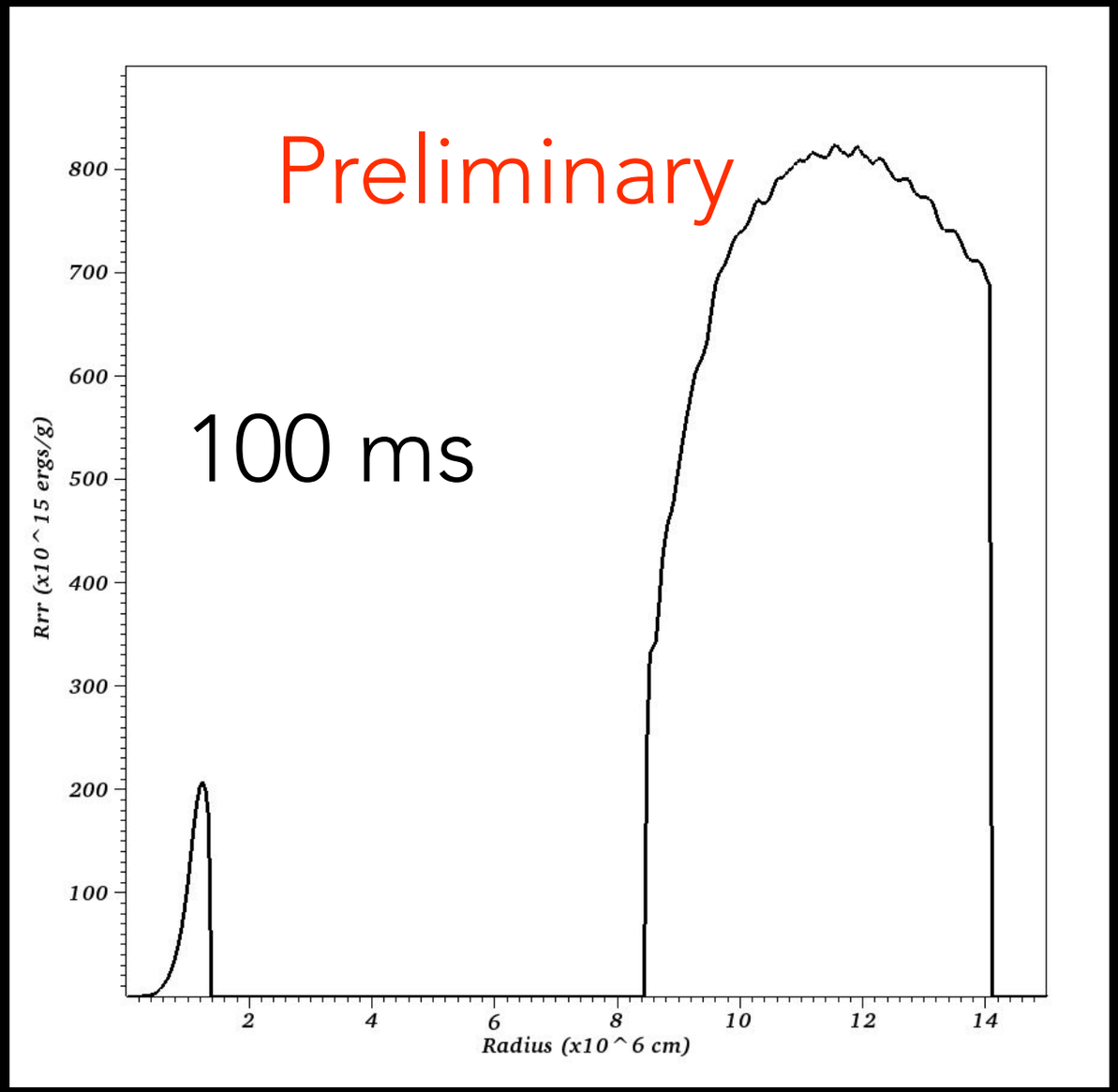


Couch & Ott (2015)



Warren & Couch (In prep)

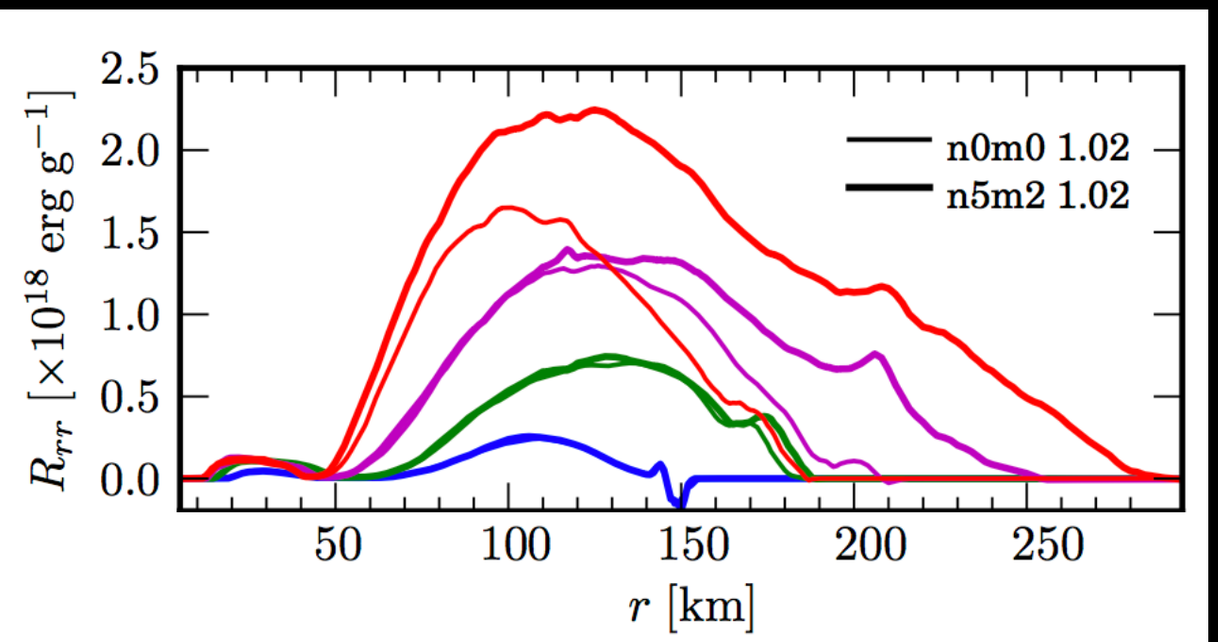
1D

β=0.22

COMPARING WITH 3D

3D

$$R_{rr} \sim v_{\mathrm{turb}}^2$$



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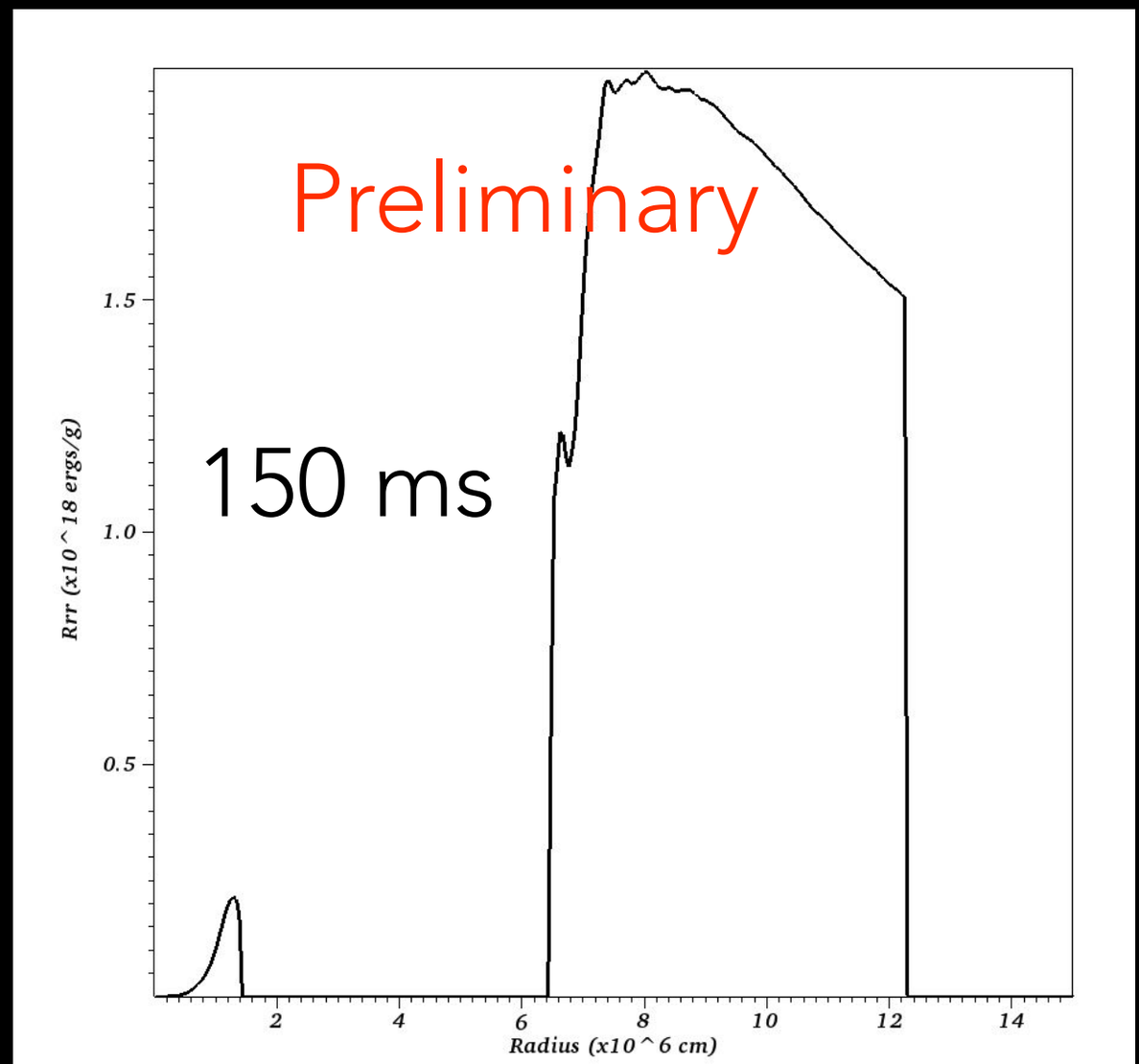

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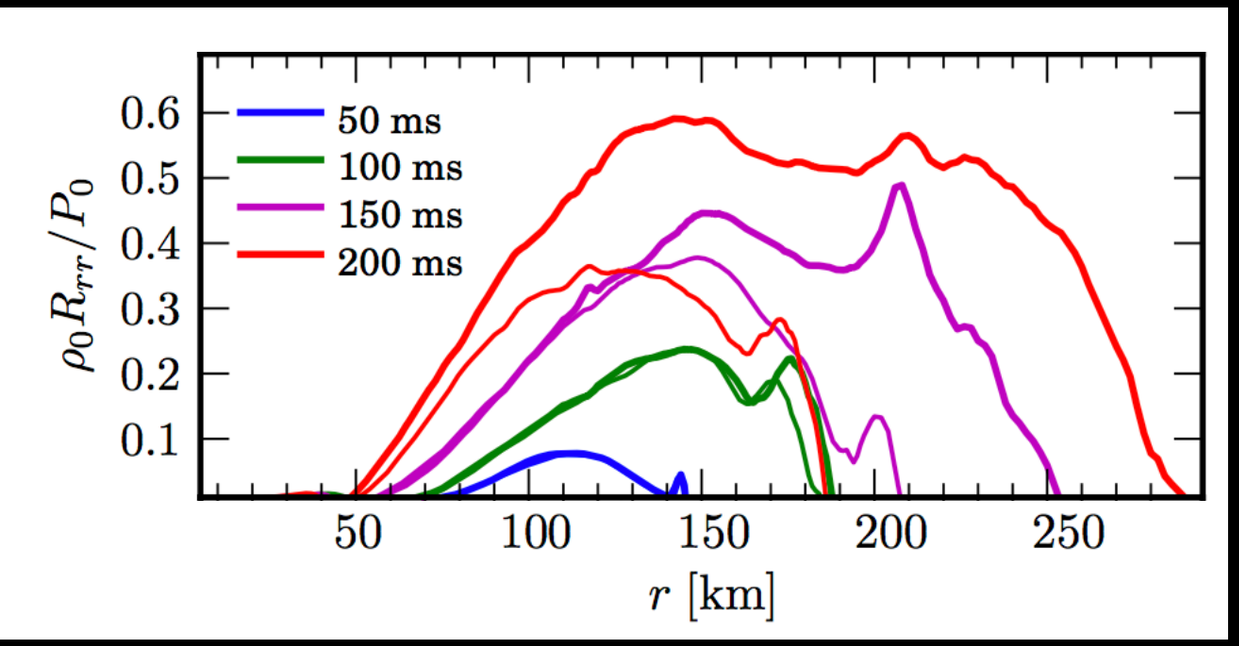

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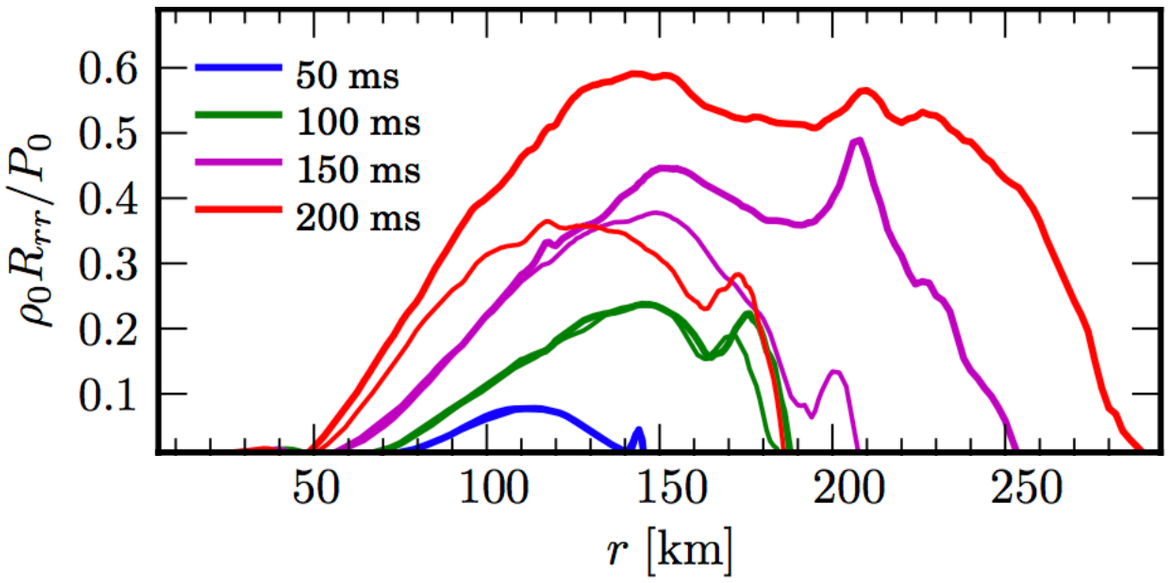

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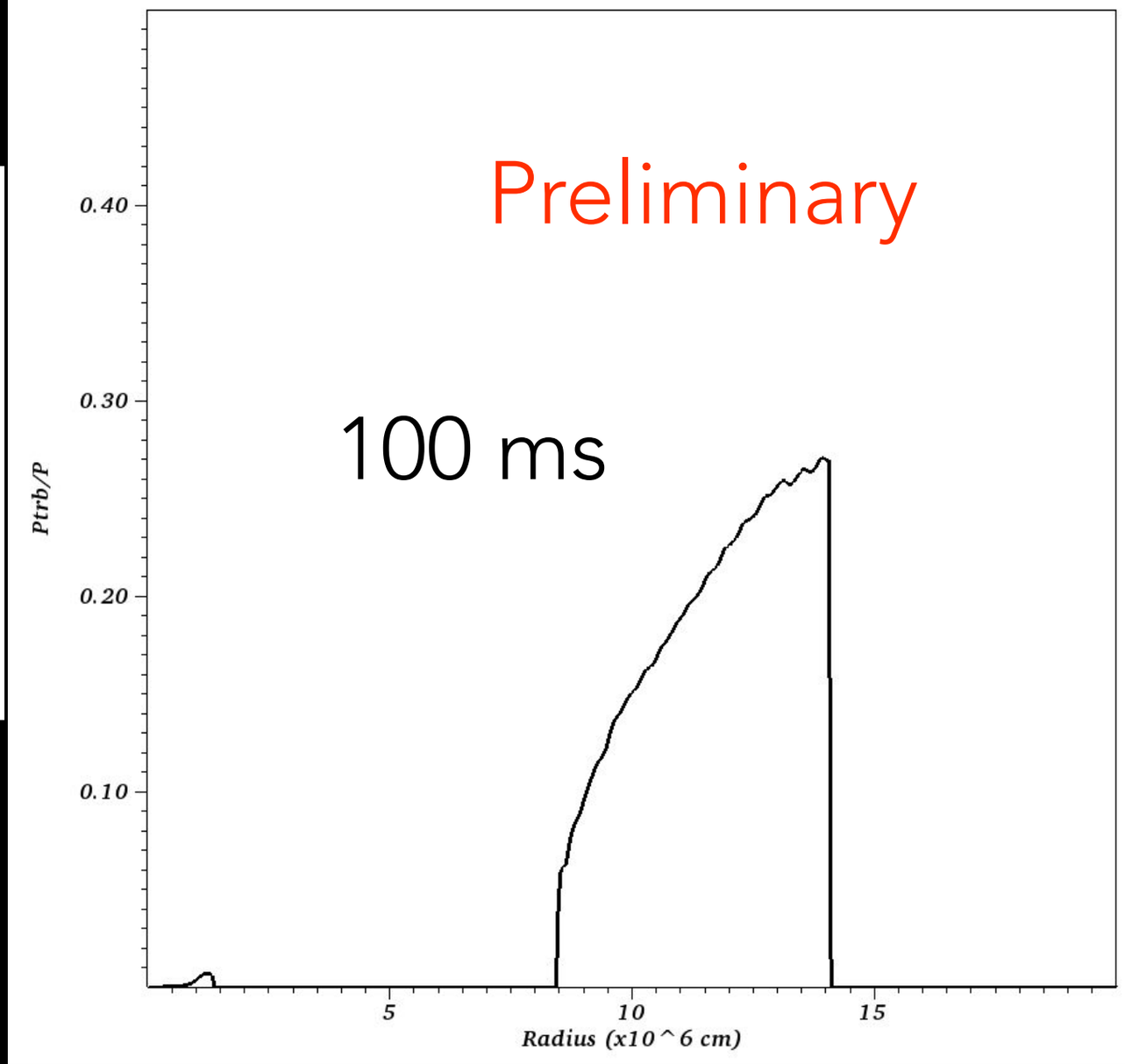

β=0.22 Warren & Couch (In prep)

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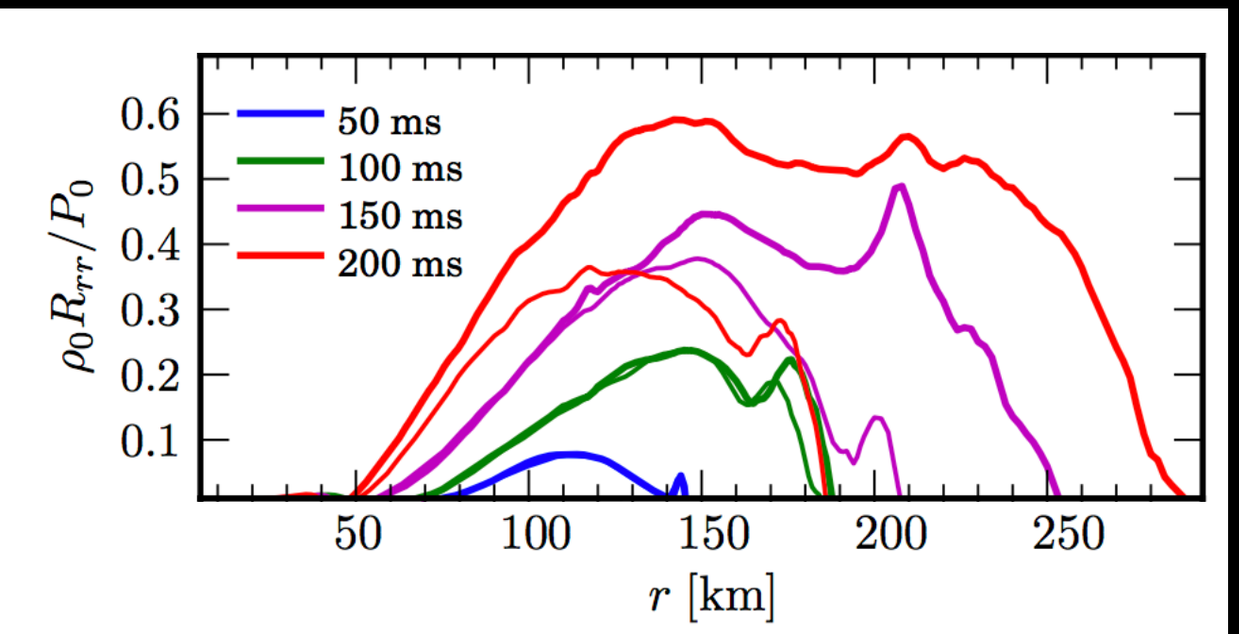

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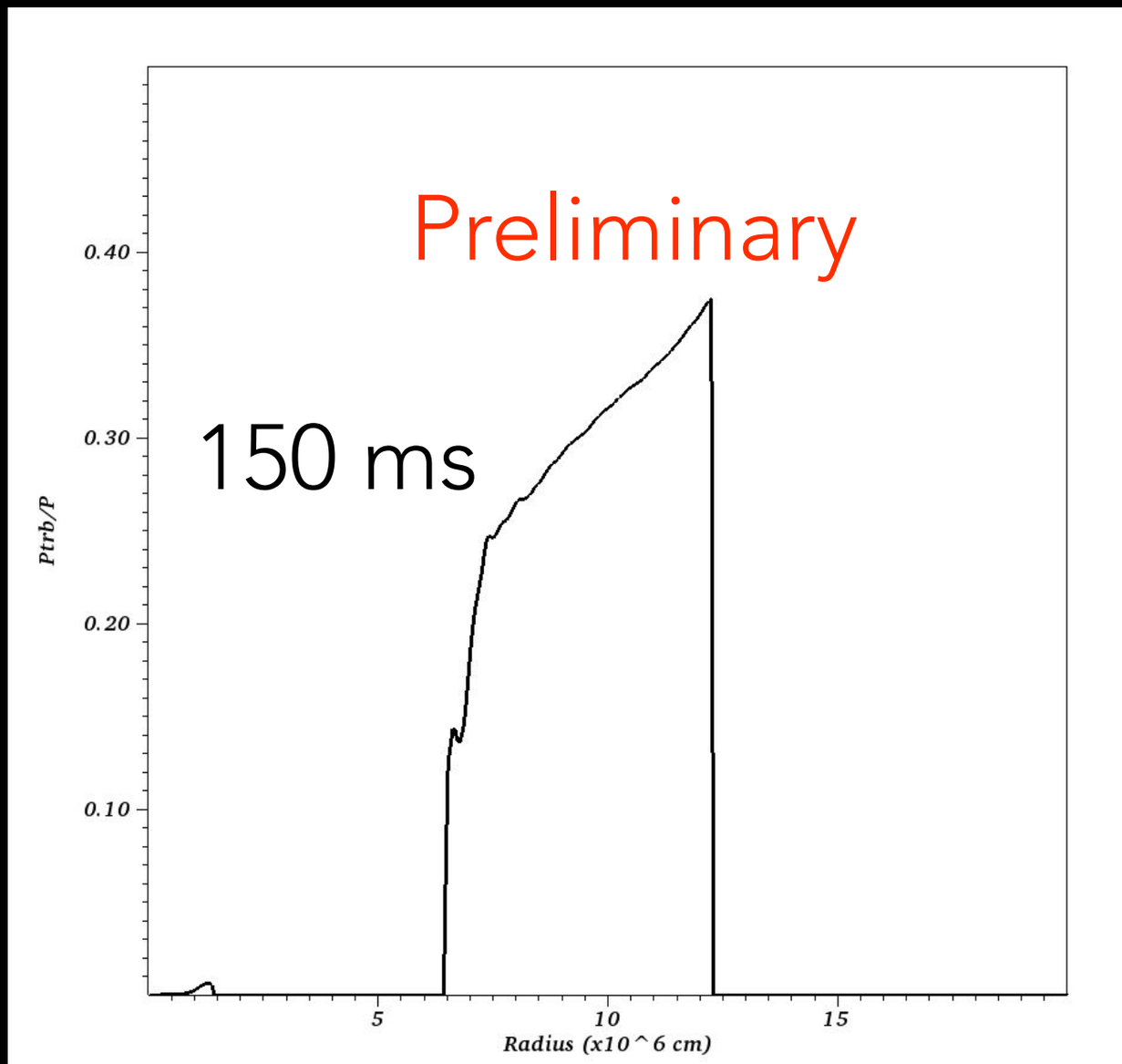


β=0.22

Warren & Couch (In prep)

WHAT'S NEXT?

New tool for exploring CCSNe sensitivities & nucleosynthesis, but many questions still to answer…

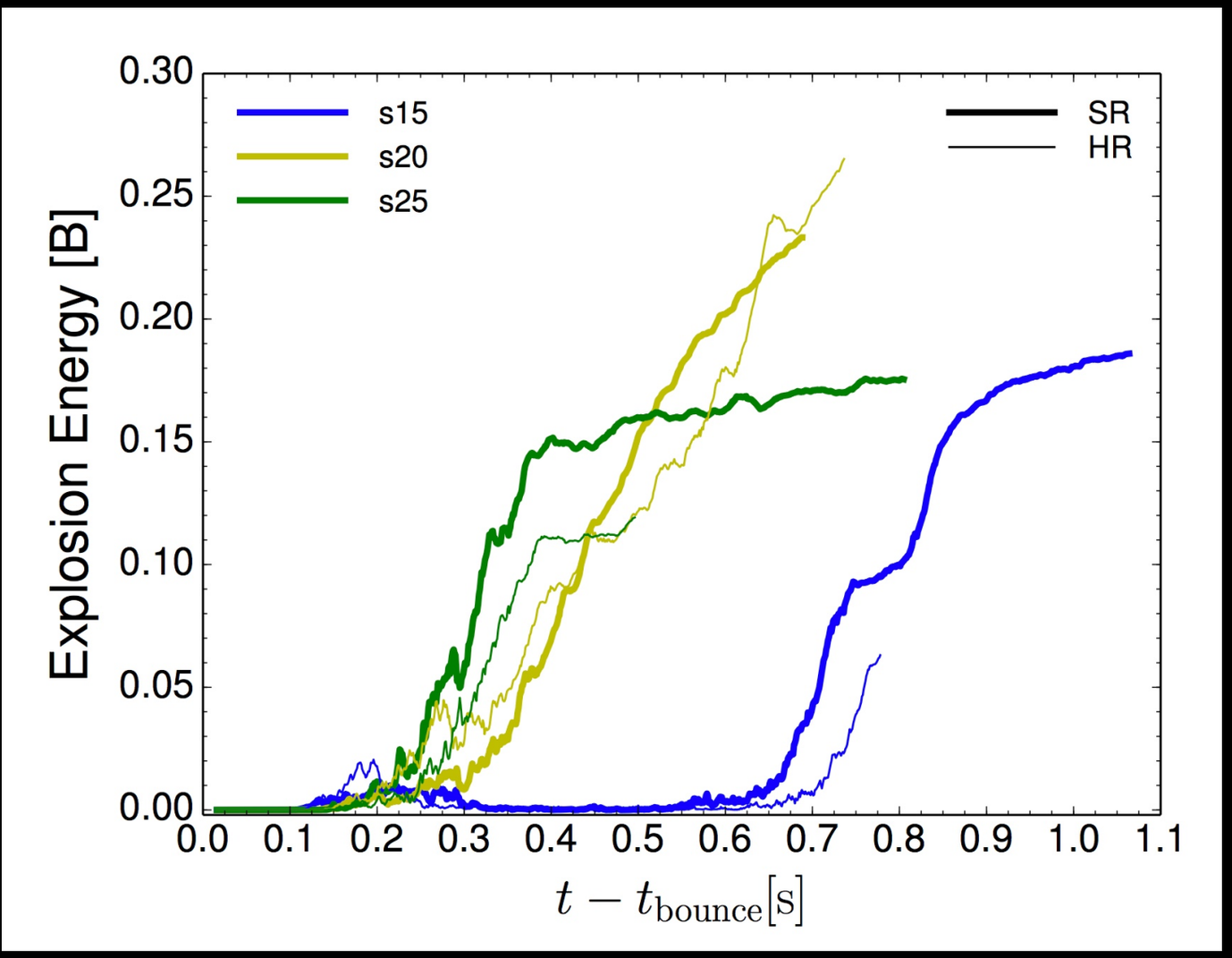
- How well does this method reproduce explosion mechanism seen in 3D? Will our fit match 3D results for different progenitors? Equations of state? Neutrino transport?
- Does fitting this model to 3D *also* reproduce quantities measure from 1987A?
- What would the universe look like with this model of explosion?
  - Which progenitors explode? What are their explosion energies, remnant masses, etc?
  - What nucleosynthesis results? What does this tell us about GCE?

THANK YOU!

EXPLODABILITY

COMPARING WITH MULTI-D

2D



O'Connor & Couch
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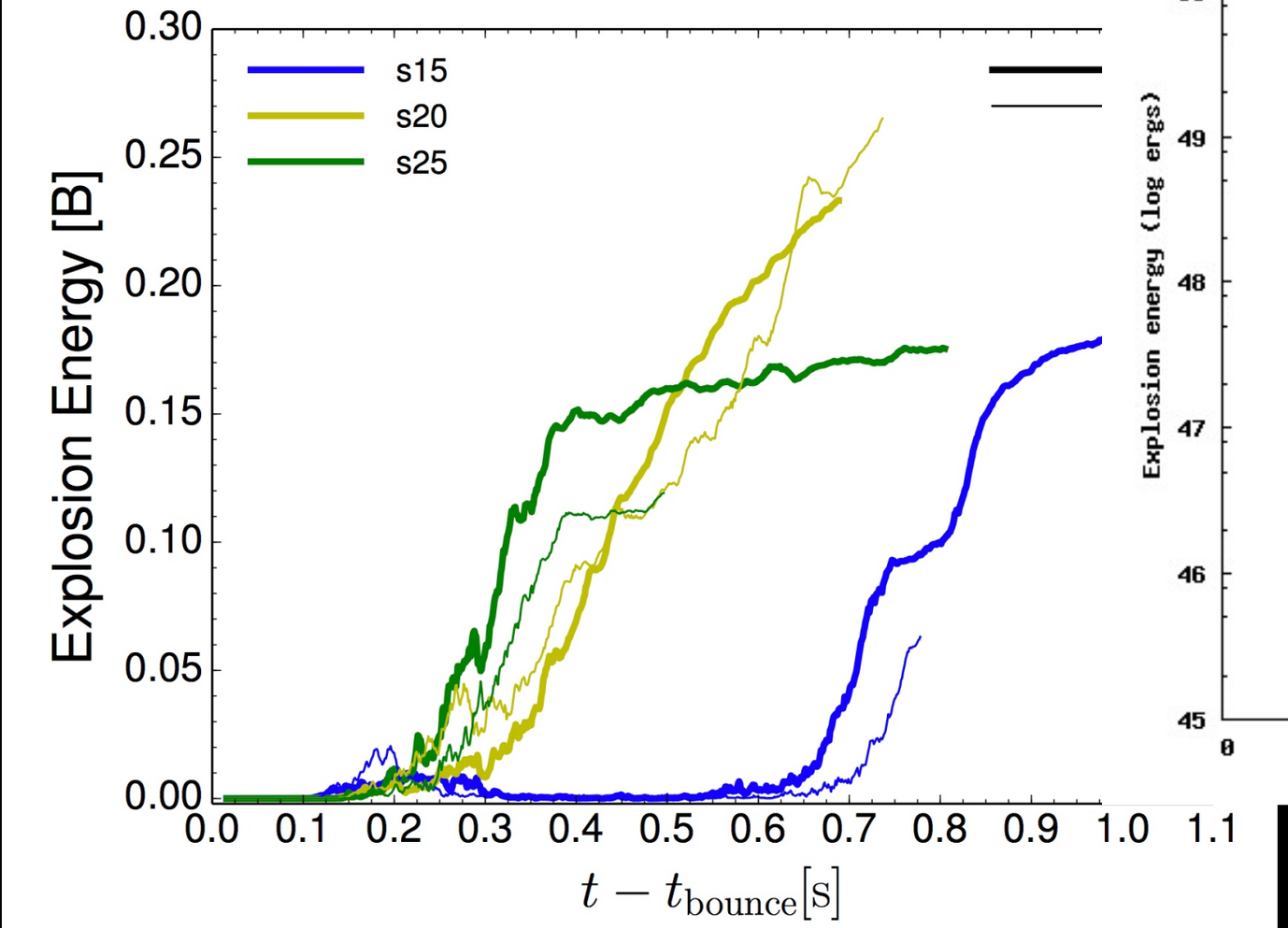

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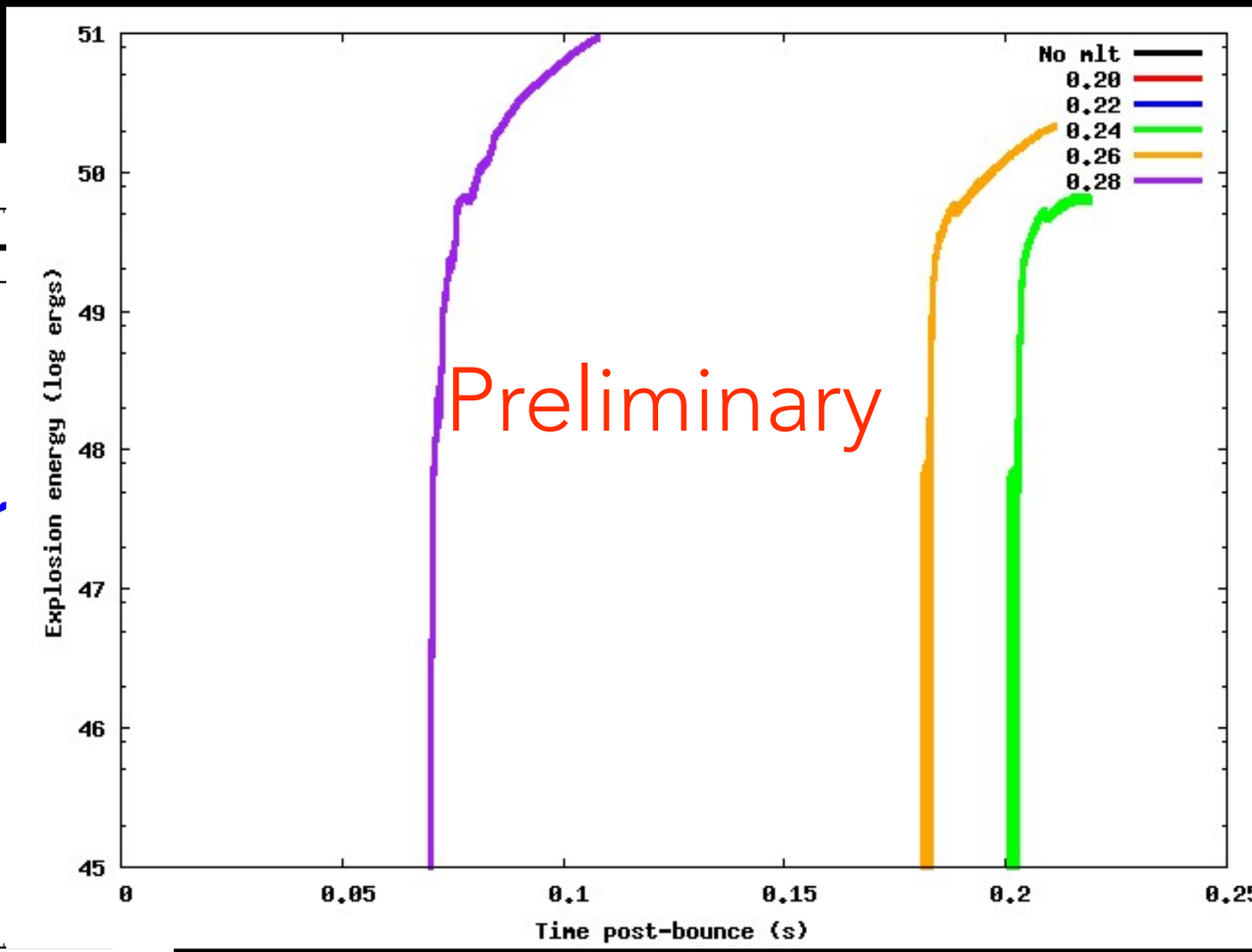

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