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Title: Next-Generation Simulations of The Remarkable Deaths of Massive Stars

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NEXT-GENERATION SIMULATIONS OF THE REMARKABLE DEATHS OF MASSIVE STARS

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Astronomy Colloquium

Dept. of Astronomy - UT Austin, October 26th, 2021

Los Alamos NATIONAL LABORATORY

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OVERVIEW

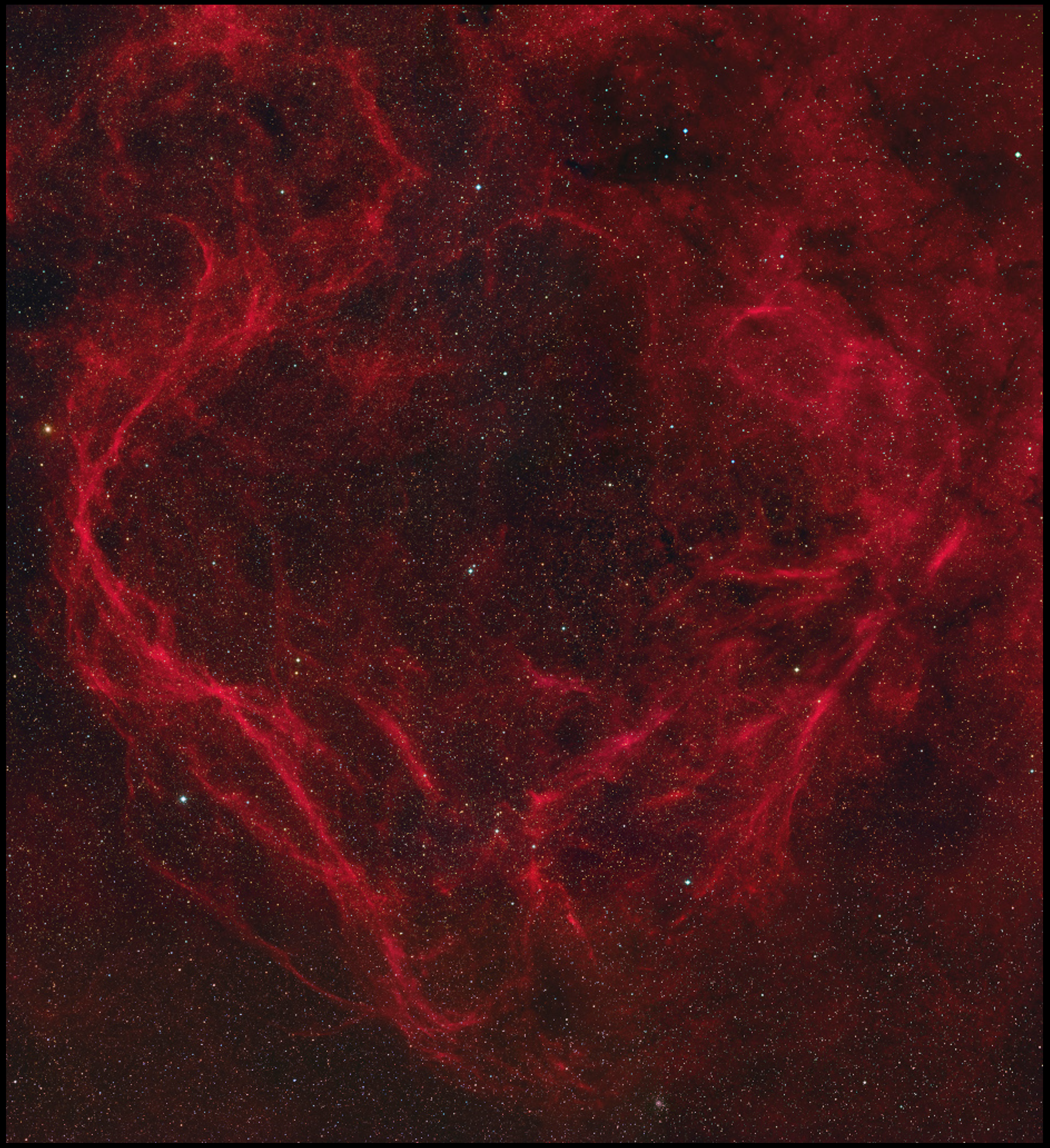
Introduction

- Core-Collapse Supernovae
- CCSN Explosion Mechanism
- The CCSN "Problem" and possible solutions

3D CCSN Progenitors

- 3D Simulations of a 15 $M_\odot$ star
- Landscape of 3D Progenitors
- 3D Rotating 16 $M_\odot$ star

Conclusions & Summary



RCW 114, an old supernova remnant with an estimated diameter of 100 lightyears.

INTRODUCTION

Core-Collapse Supernovae

CORE COLLAPSE SUPERNOVAE

Understanding core-collapse supernova explosions is crucial to many different problems of astronomy.

Galactic Chemical Evolution

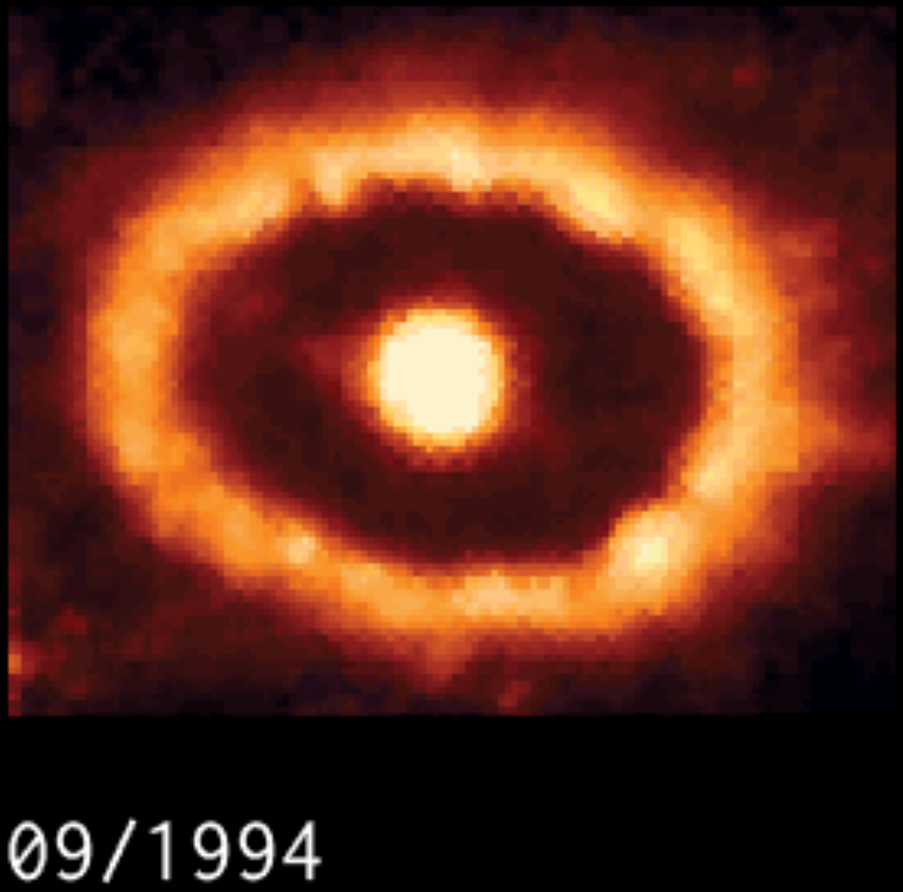
- Nucleosynthesis
- Stellar Feedback

Compact Object Formation

- Produce NS / stellar mass BHs

Multi-Messenger Astronomy

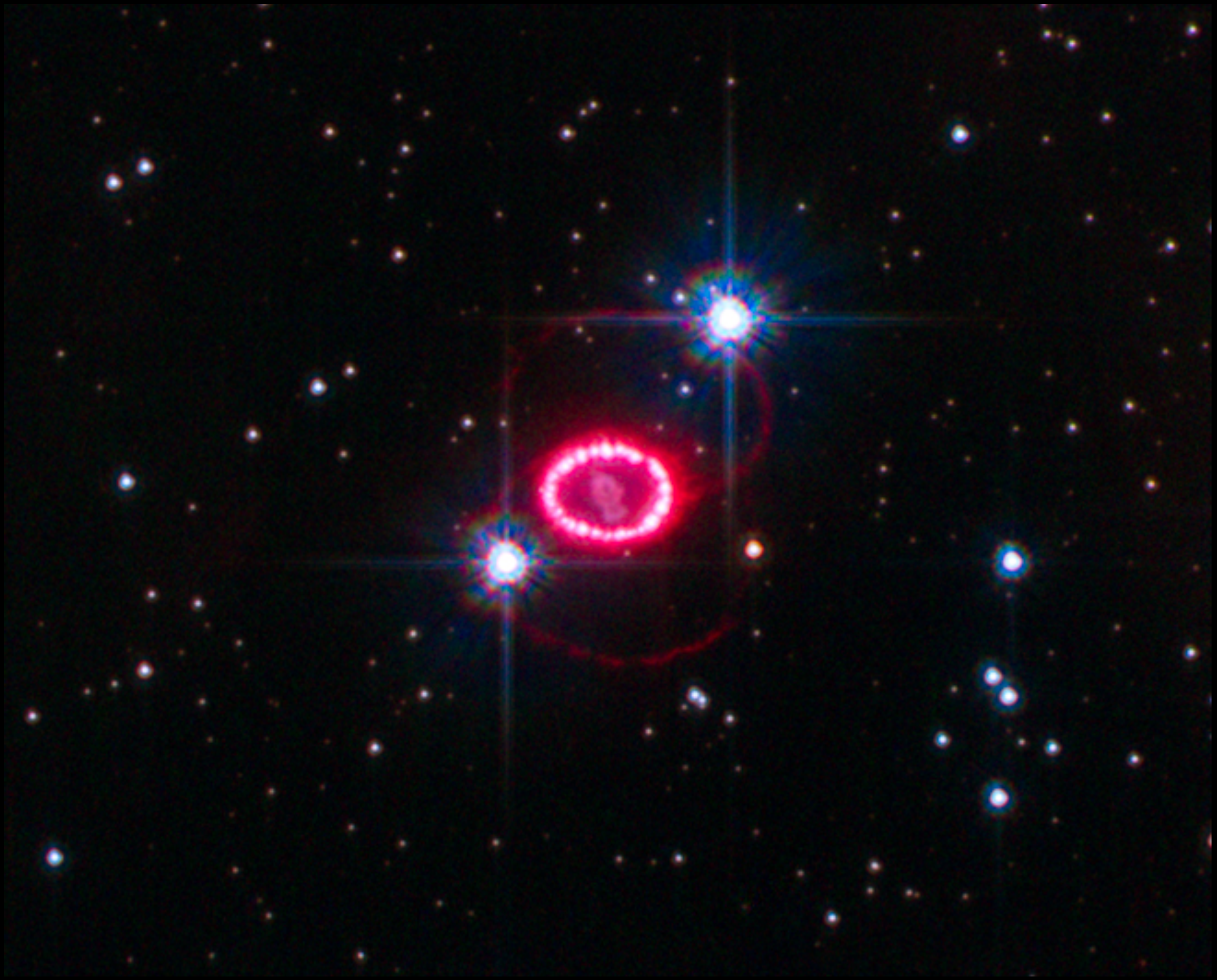
- Gravitational Waves
- Neutrino Emission



Credit: Larsson, J. et al. (2011).

CORE-COLLAPSE SUPERNOVA EXPLOSIONS

- ~3 per century for a Milky Way type galaxy (Li et al. 2012).
- More numerous than thermonuclear explosions (4x).
- Liberate ~ 10^{58} neutrinos.
- Kinetic energies on the order of 10^{51} erg!
- Produced by stars with masses about 8 times more than the Sun.

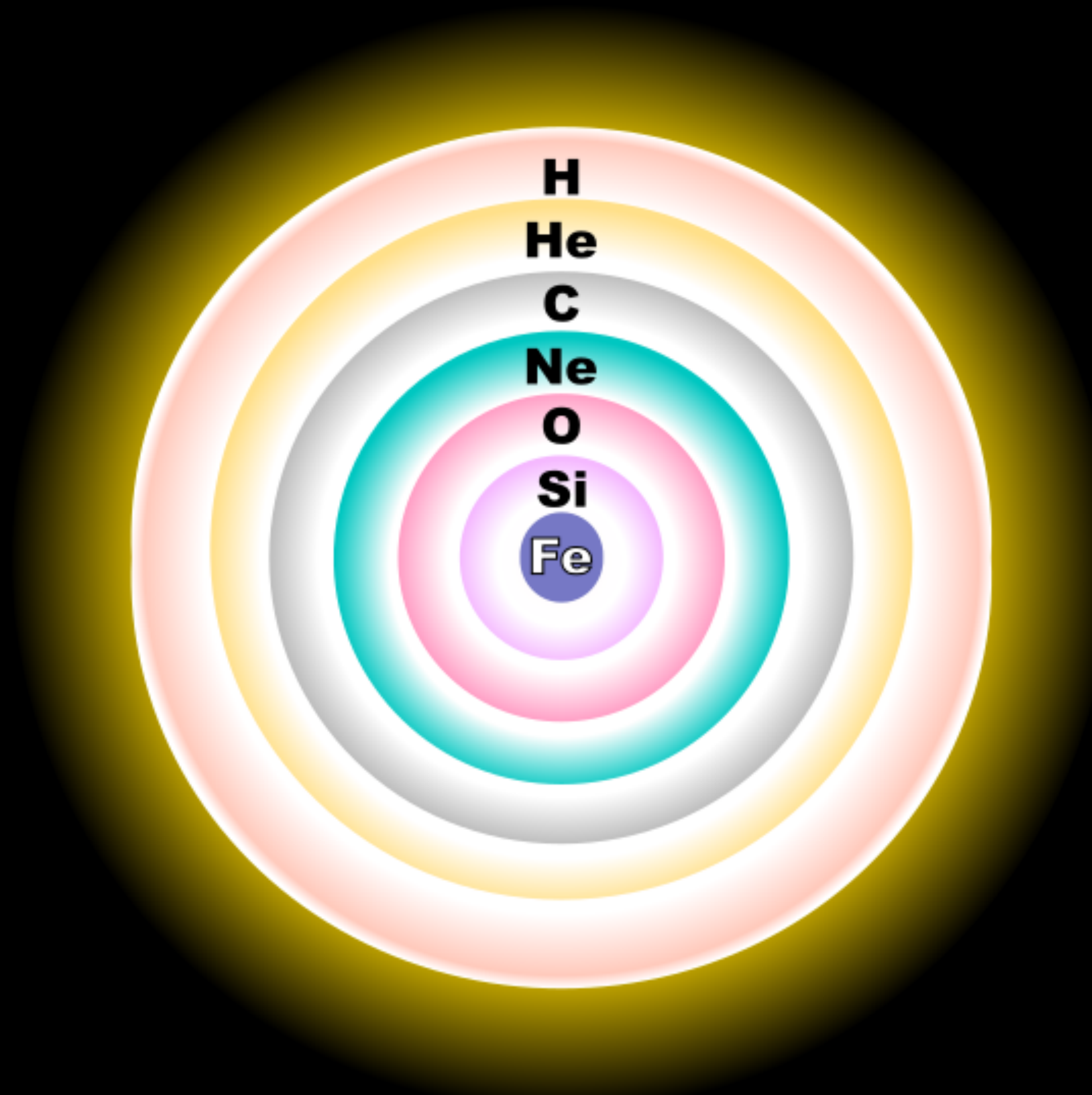


THE REMNANT OF SN 1987A. SOURCE: NASA GSFC.

CCSN Explosion Mechanism

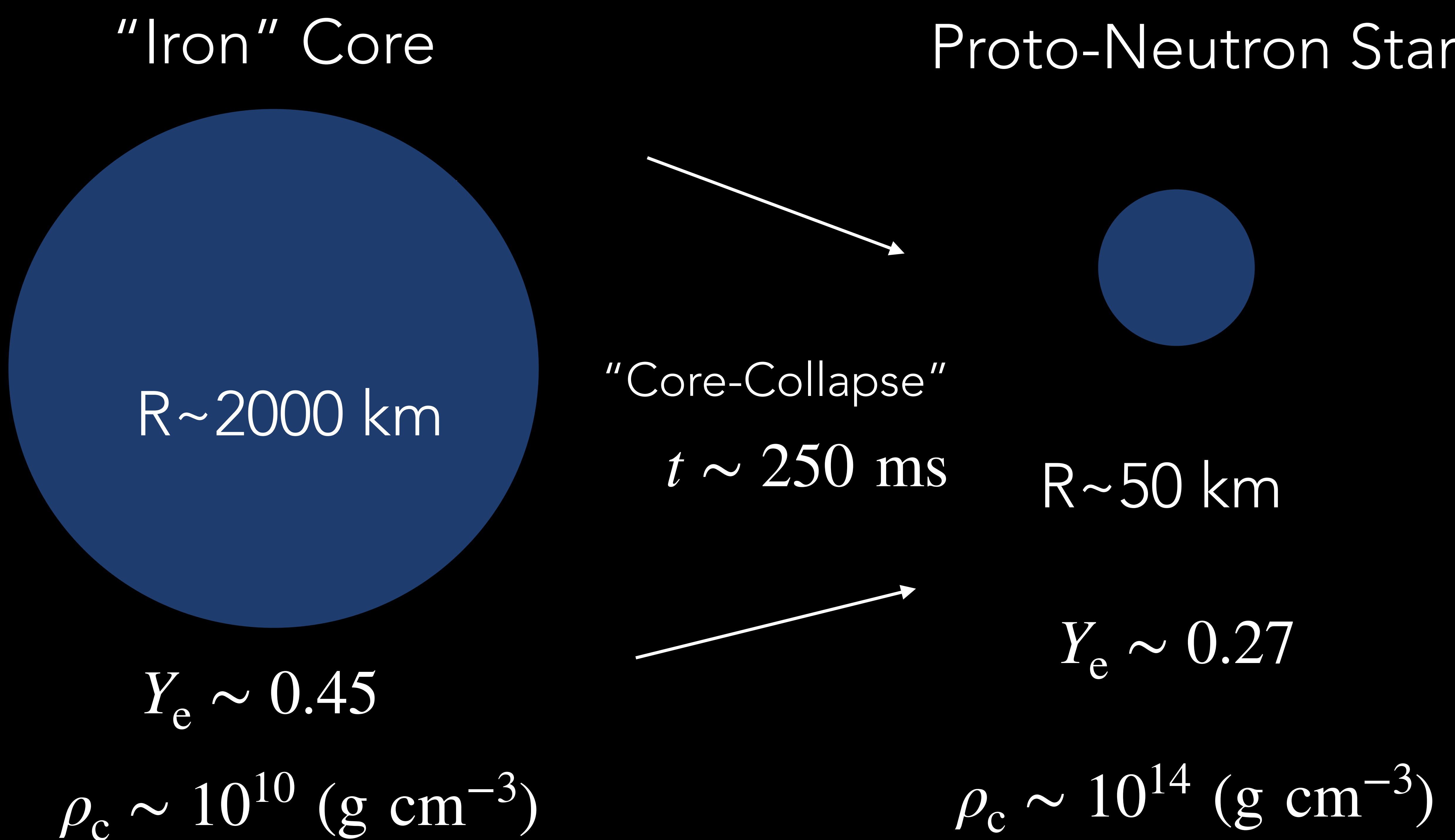
EVOLUTION TOWARDS IRON CORE-COLLAPSE IN A MASSIVE STAR

- Massive stars burn heavier and heavier elements.
- Form an inert core primarily of Fe peak elements.
- Core becomes gravitationally unstable as reactions remove pressure sources.
- Core collapses - rapidly !



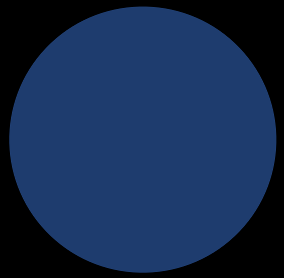
CREDIT: R. J. HALL

PHYSICS OF STELLAR CORE-COLLAPSE



PHYSICS OF STELLAR CORE-COLLAPSE

"Bounce"
Stiffening of Core
Launch Shock

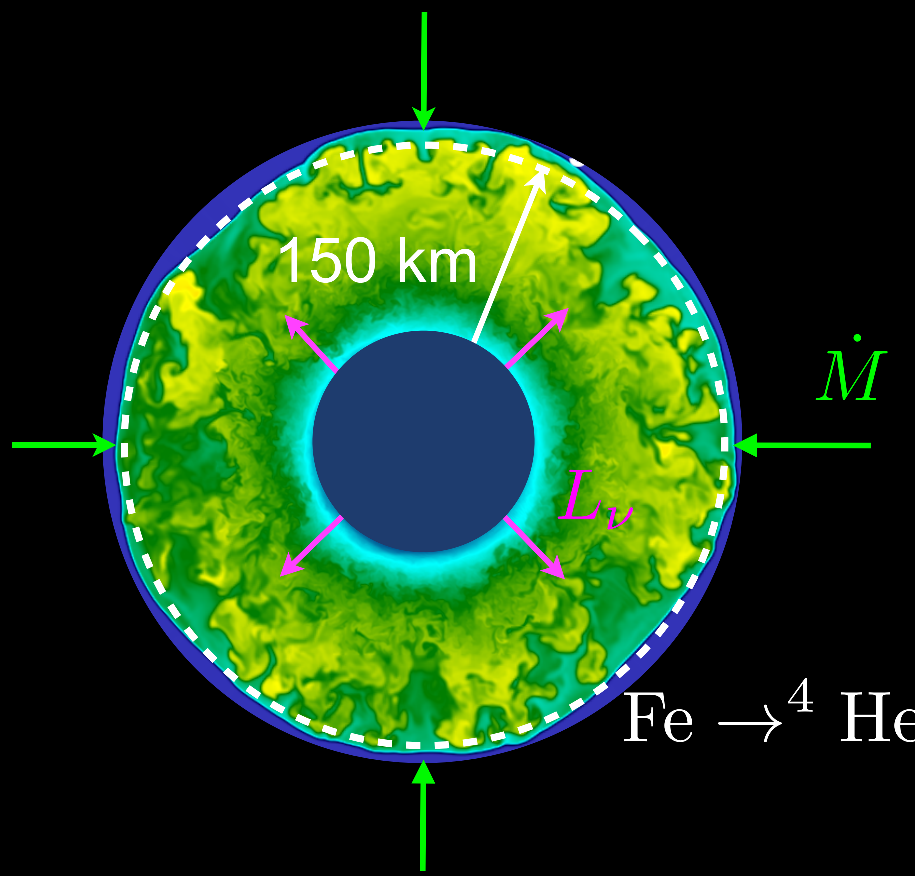


R~50 km

"Bounce" to
Stalled Shock

$t \sim 100$ ms

Stalled Shock



Entropy slice of explosion of 20 solar mass stars.
Credit: O' Connor & Couch (2018b).

Not enough energy to
promptly explode star.

REVIVAL OF THE STALLED SHOCK

Delayed Neutrino Heating Mechanism

- Needs ~10^{51} erg to unbind the star, explode.
- PNS contraction releases energy as neutrinos ~ 10^{53} erg / s !!
- Heating by neutrinos beneath the stalled shock via absorption.
- *Only* need a few % of released neutrinos to drive explosion (Bethe & Wilson 1985).

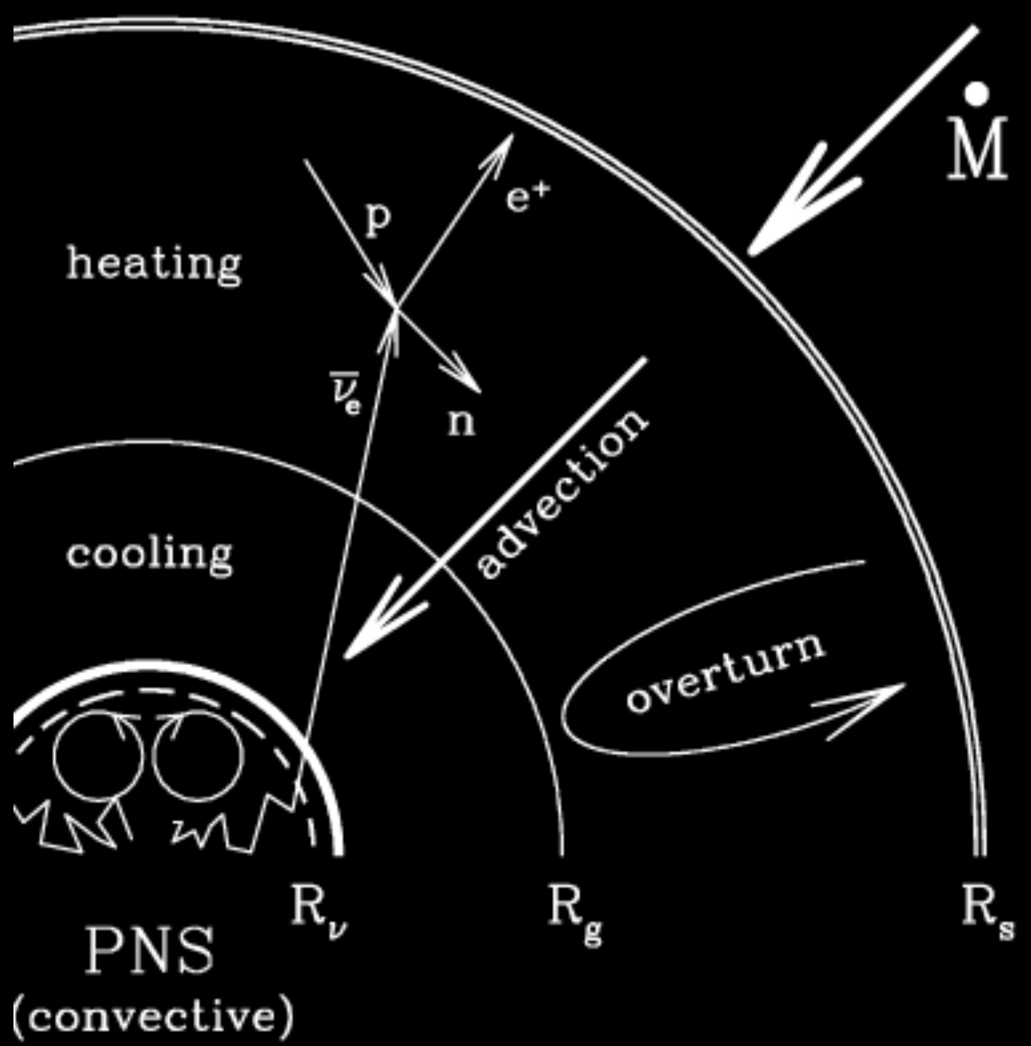


Diagram showing revival of stalled shock.
Credit: Janka (2011).

ERA OF 3D CCSN SIMULATIONS

<u>Fully-coupled!</u>

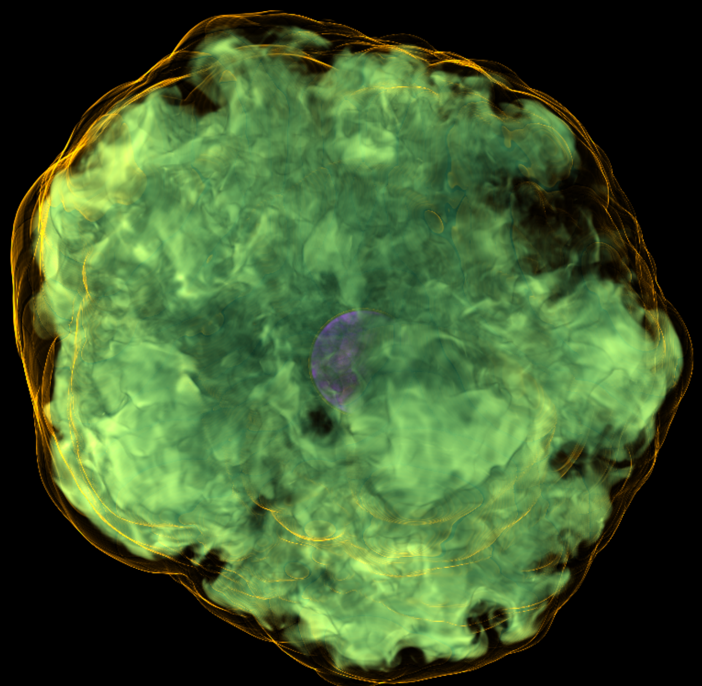
3D Magnetohydrodynamics

General Relativity

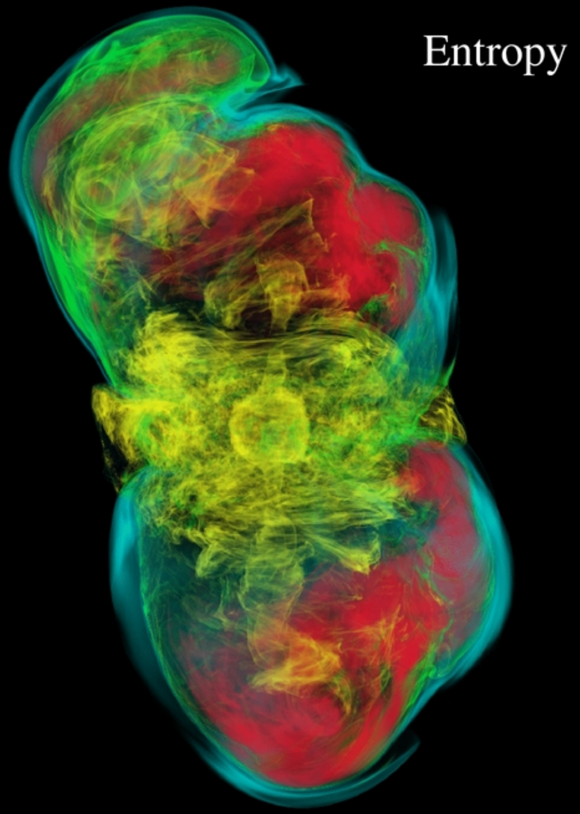
Boltzmann ν-transport

Microphysics
(Nuclear EOS, ν-interactions,
nuclear kinetics)

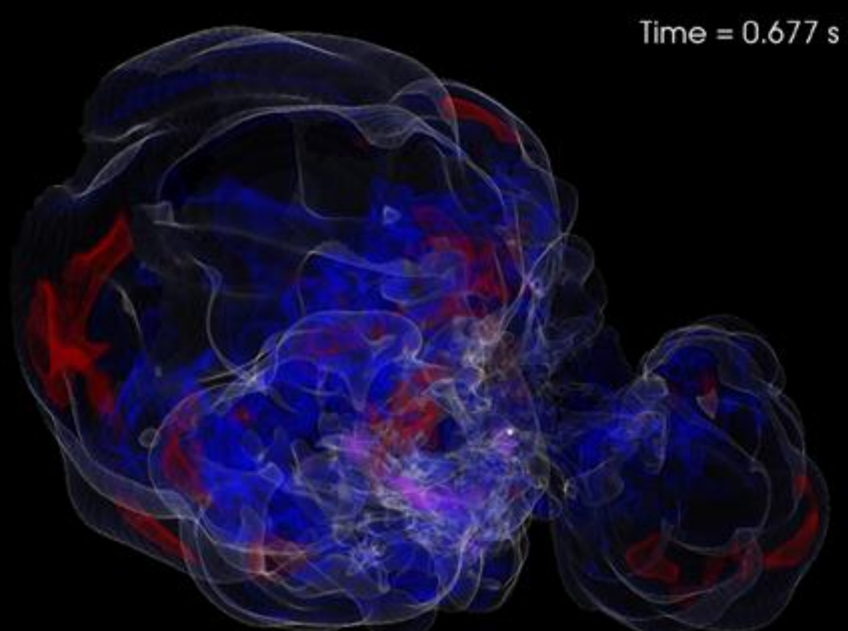
Credit: Sean Couch



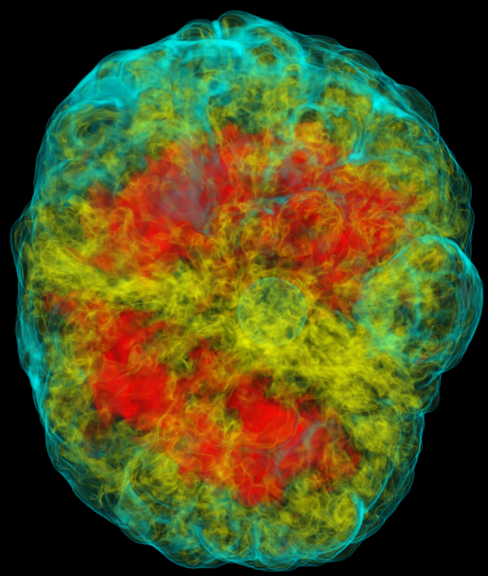
(Fields + 2021b, in prep.)



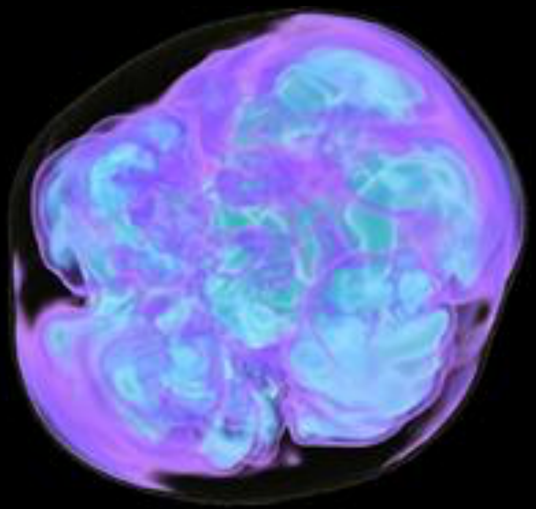
(Moesta + 2014)



(Vartanyan+ 2019)



(Roberts + 2016)



(Burrows + 2019)

Solved problem…right?

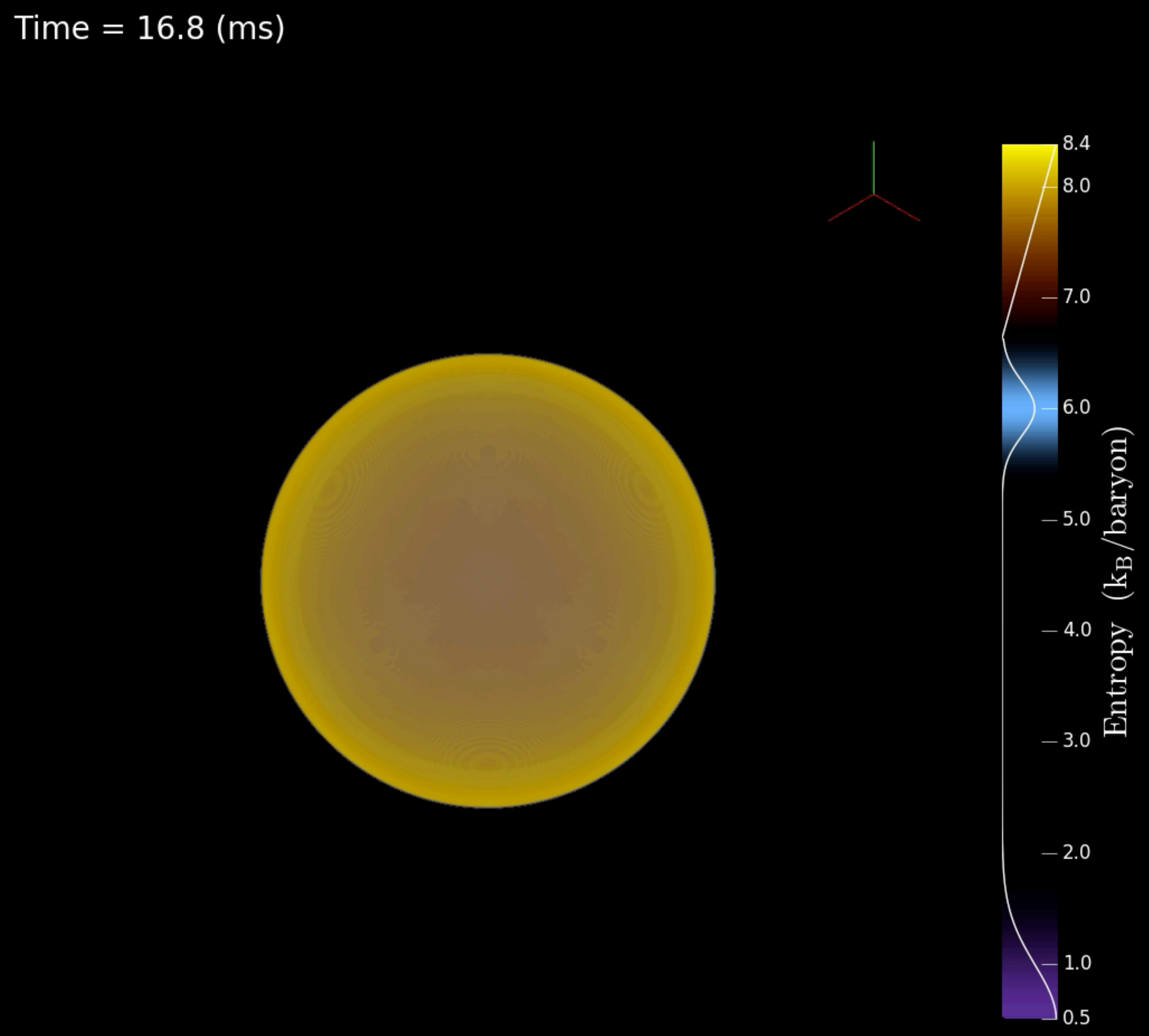
INTRODUCTION

The CCSN “Problem” and possible solutions

THE CORE-COLLAPSE 'PROBLEM'

How do we (try) to model stellar explosions?

- 1D Stellar Evolution Codes for pre-supernova evolution.
- Evolve explosion in 2/3D using multi-D hydro codes.
- Shock failed to be revived in some models.

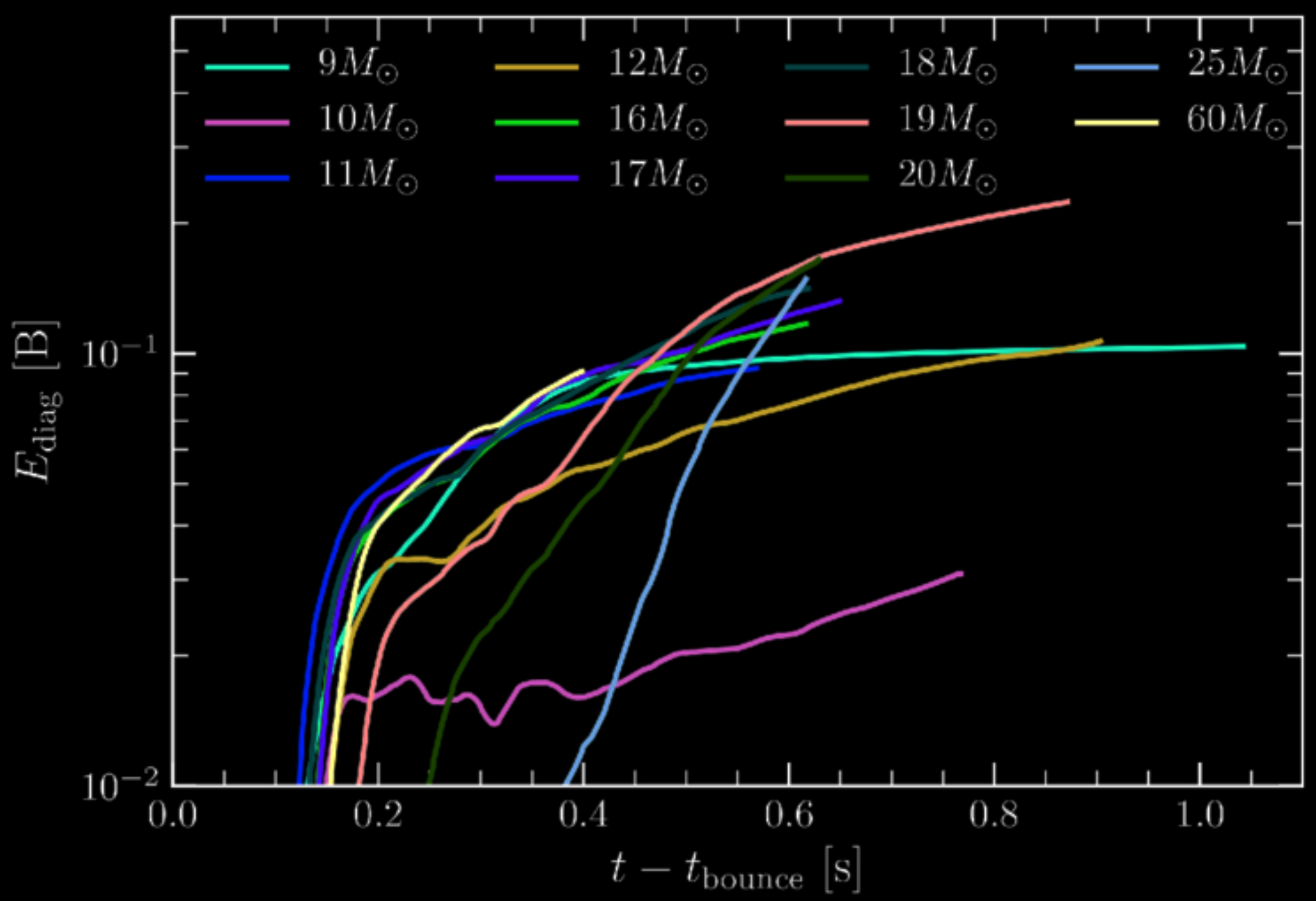


Failed explosion using spherically symmetric 1D model from Couch + 2018.

THE CORE-COLLAPSE 'PROBLEM'

How do we (try) to model stellar explosions?

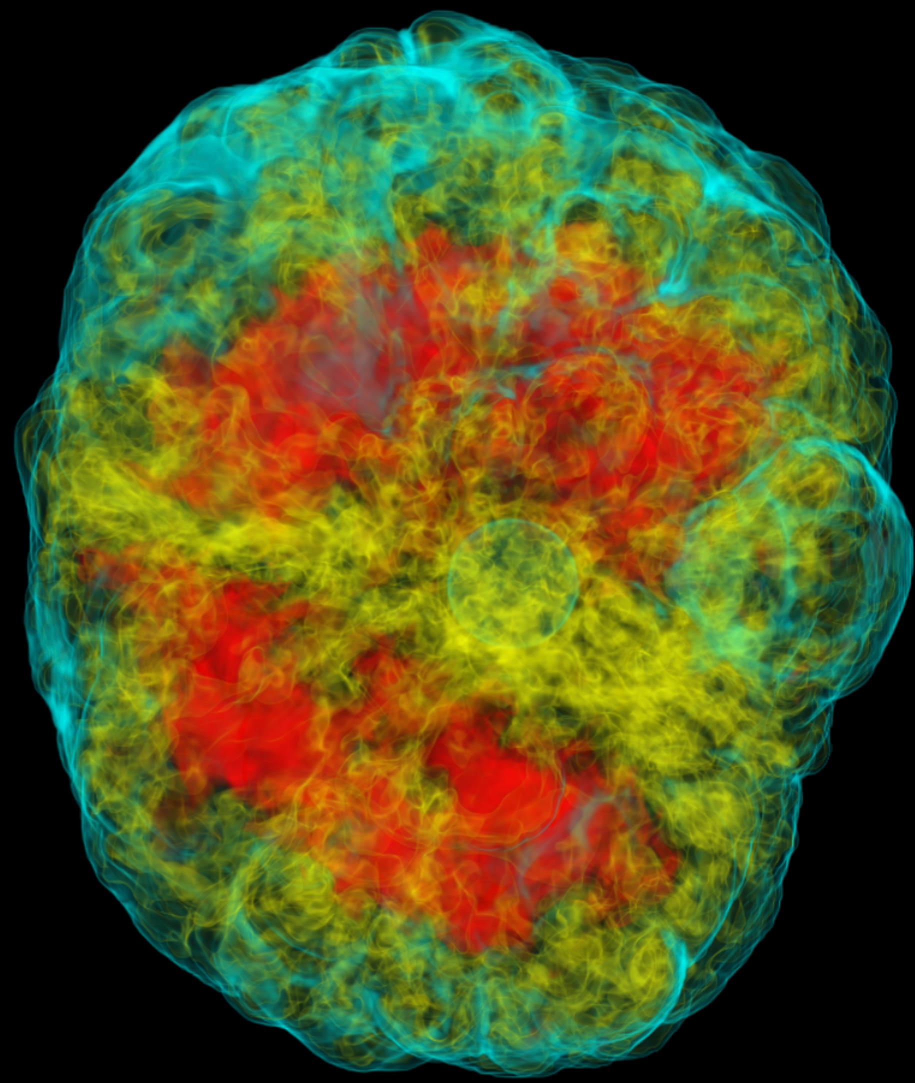
- Struggle to match range of Type IIP explosion energies of ~0.5-4B *(Kasen & Woosely 2015)*.
- 3D exploding models show low energies?
- Need to reach asymptotic plateau requires longer simulations *(Burrows+ 2019)*.



Evolution of explosion energy for 3D CCSN models from Burrows + 2019.

SOLUTION(S) TO THE CORE-COLLAPSE 'PROBLEM'?

- General Relativistic Gravity - More compact PNs lead to larger neutrino luminosities.
- Sophisticated Neutrino Transport - Full Transport + GR can result in explosion.
- Initial models/Perturbations - Pre-SN models are **not** spherical and can vary.

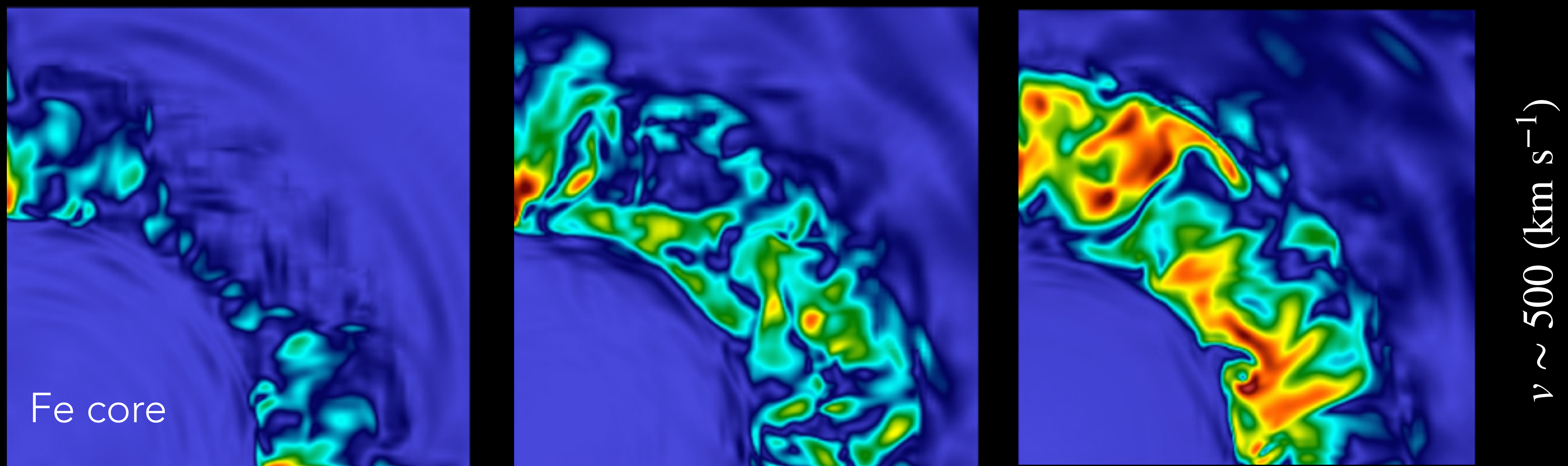


Volume rendering of the entropy distribution from *Roberts + 2016.*

INTRODUCTION

Deeper look in to the Pre-Supernova Models

PERTURBATIONS IN THE PRE-SUPERNOVA MODEL



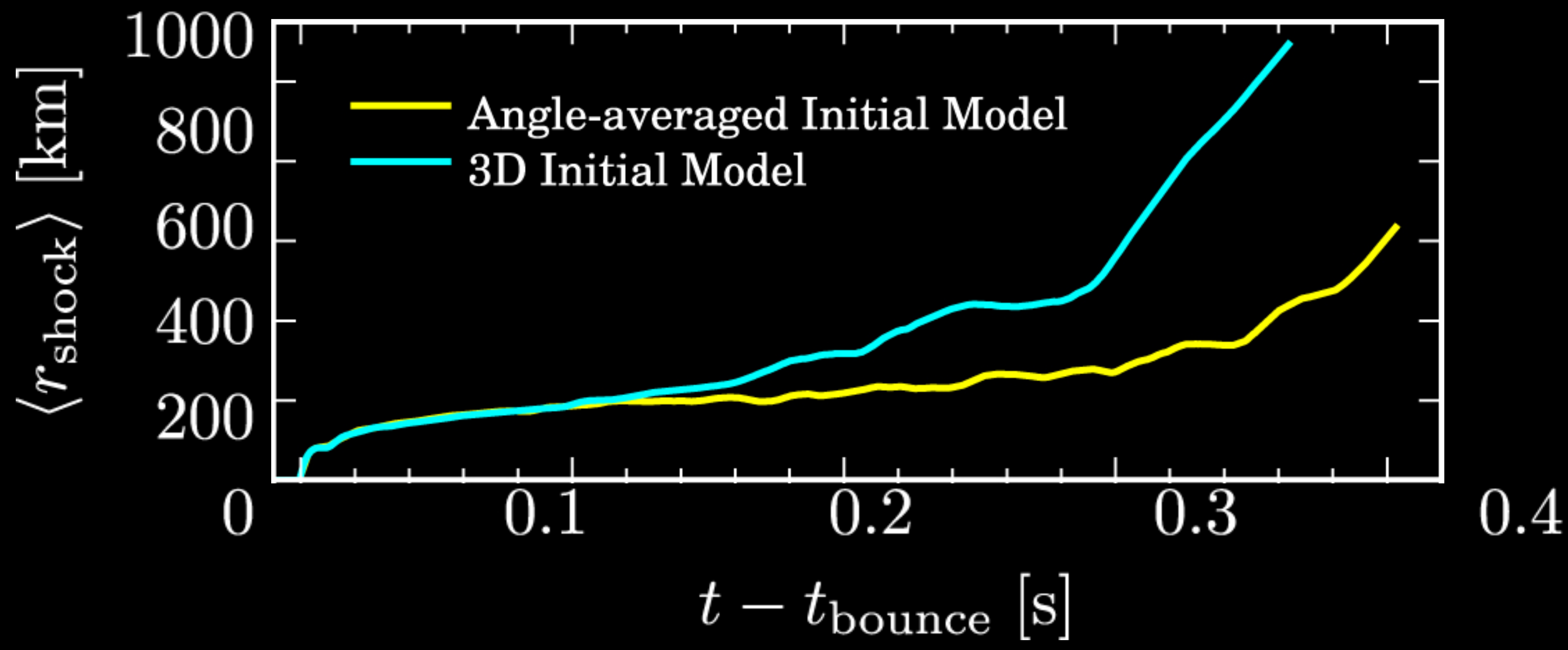
$t \sim 20$ (s) $t \sim 100$ (s) $t \sim 155$ (s)

(Couch + ApJL, 2015)

- 3D Octant model, ~ three minutes, evolved using 21 isotope network.

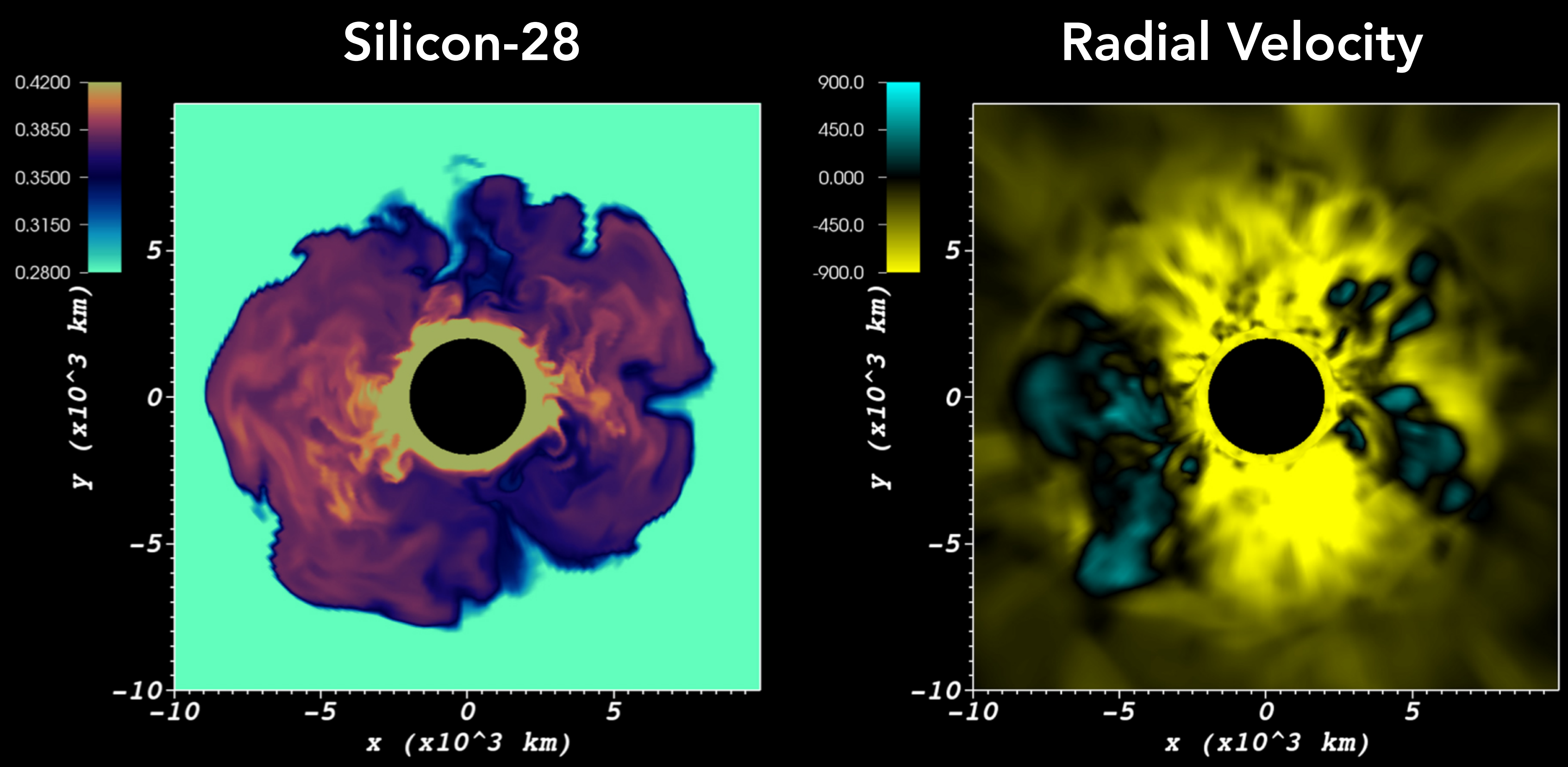
PERTURBATIONS IN THE PRE-SUPERNOVA MODEL

3D Initial model leads to faster, stronger explosion.



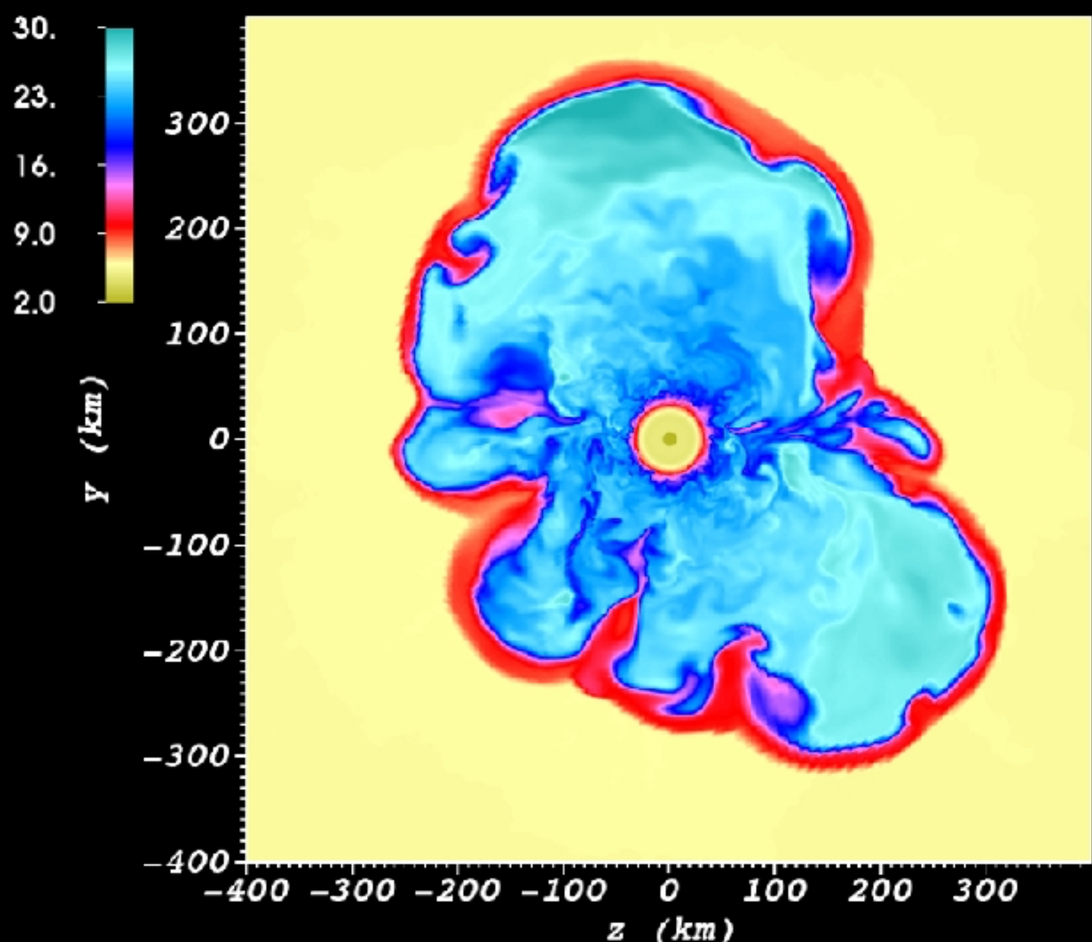
- Multi-D progenitors provide a solution to the core-collapse problem.

MULTI-DIMENSIONAL SIMULATIONS OF MASSIVE STARS

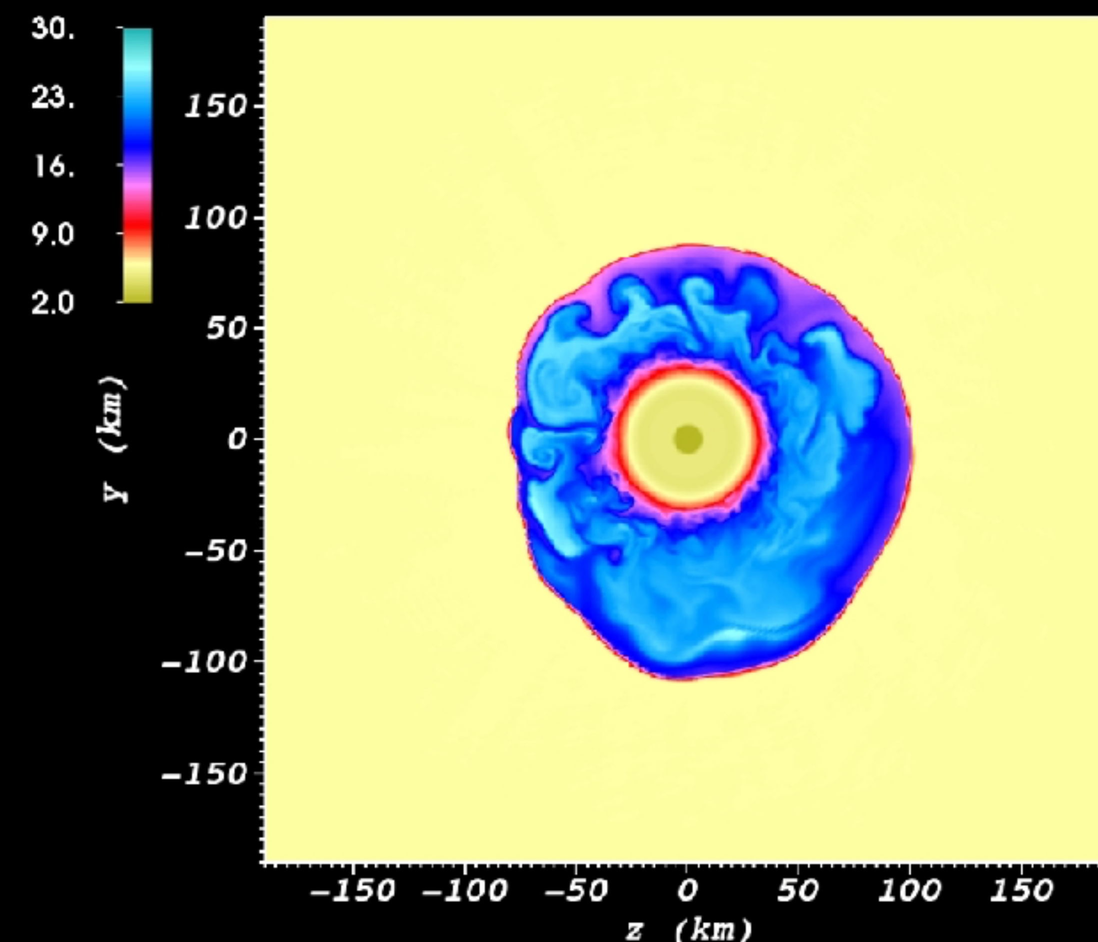


- 4pi simulations of oxygen shell burning find bipolar flow near collapse in simulation of 18 solar mass star. *(Muller +2016)*

IMPACT OF PROGENITORS ON EXPLOSION MECHANISM



3D initial progenitor



1D initial progenitor

(Muller + 2017)

IMPACT OF PROGENITORS ON EXPLOSION MECHANISM

How do 3D progenitors help facilitate explosion?

- **Large mach numbers** cause density fluctuations favorable for explosion.

$$\delta\rho/\rho \propto \mathscr{M}_{\mathrm{prog.}}$$

- **Increase mass in gain** region due to non-radial flow in post-shock region.

$$\dot{Q}_\nu \propto M_{\mathrm{gain}}$$

(Muller + 2017)

- **Increase in non-radial kinetic energy** at large scales.

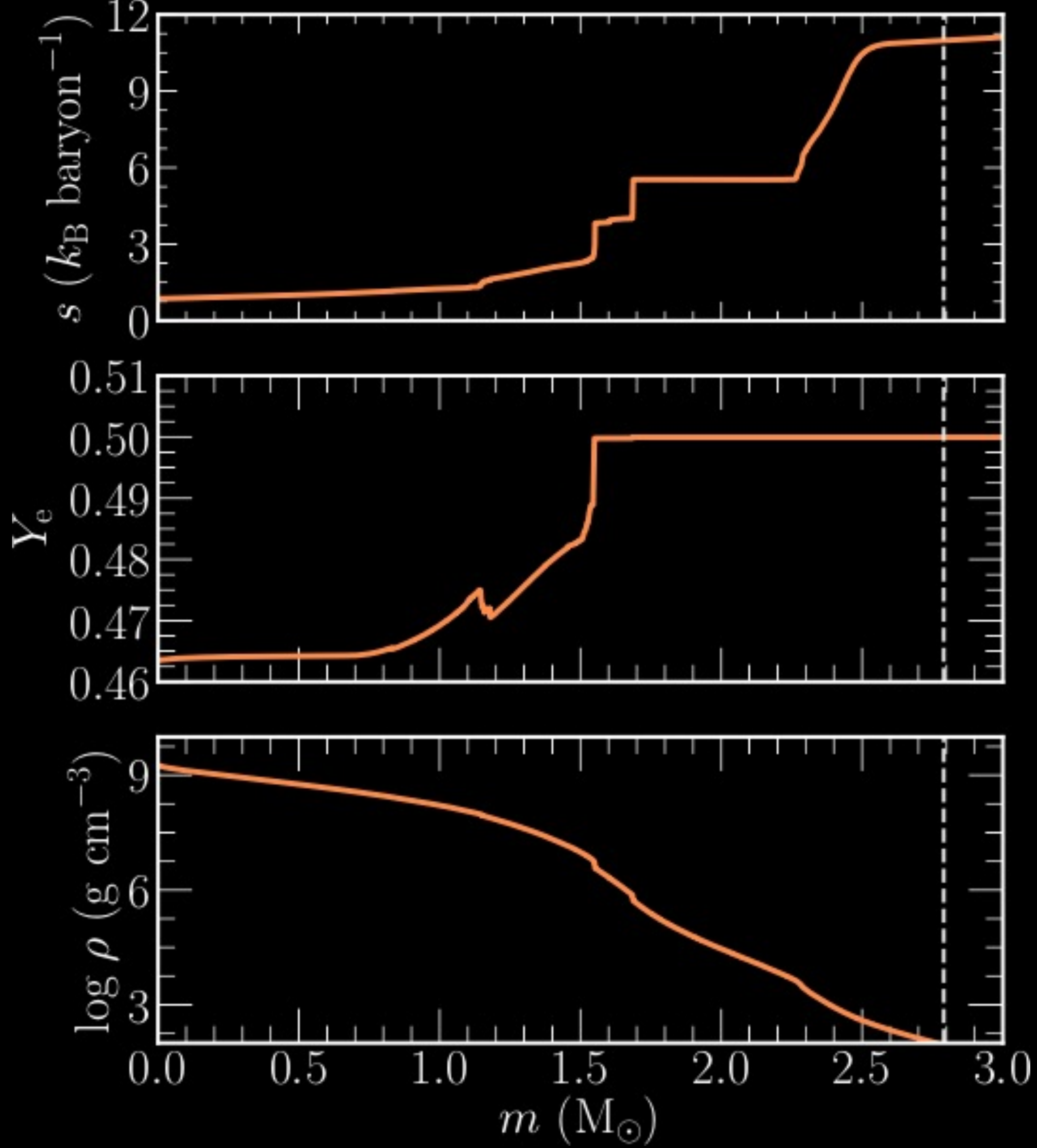
(Couch + 2014, 2015)

3D CCSN PROGENITORS

3D Simulations of a 15 $M_\odot$ star

MULTI-DIMENSIONAL SIMULATIONS OF MASSIVE STARS

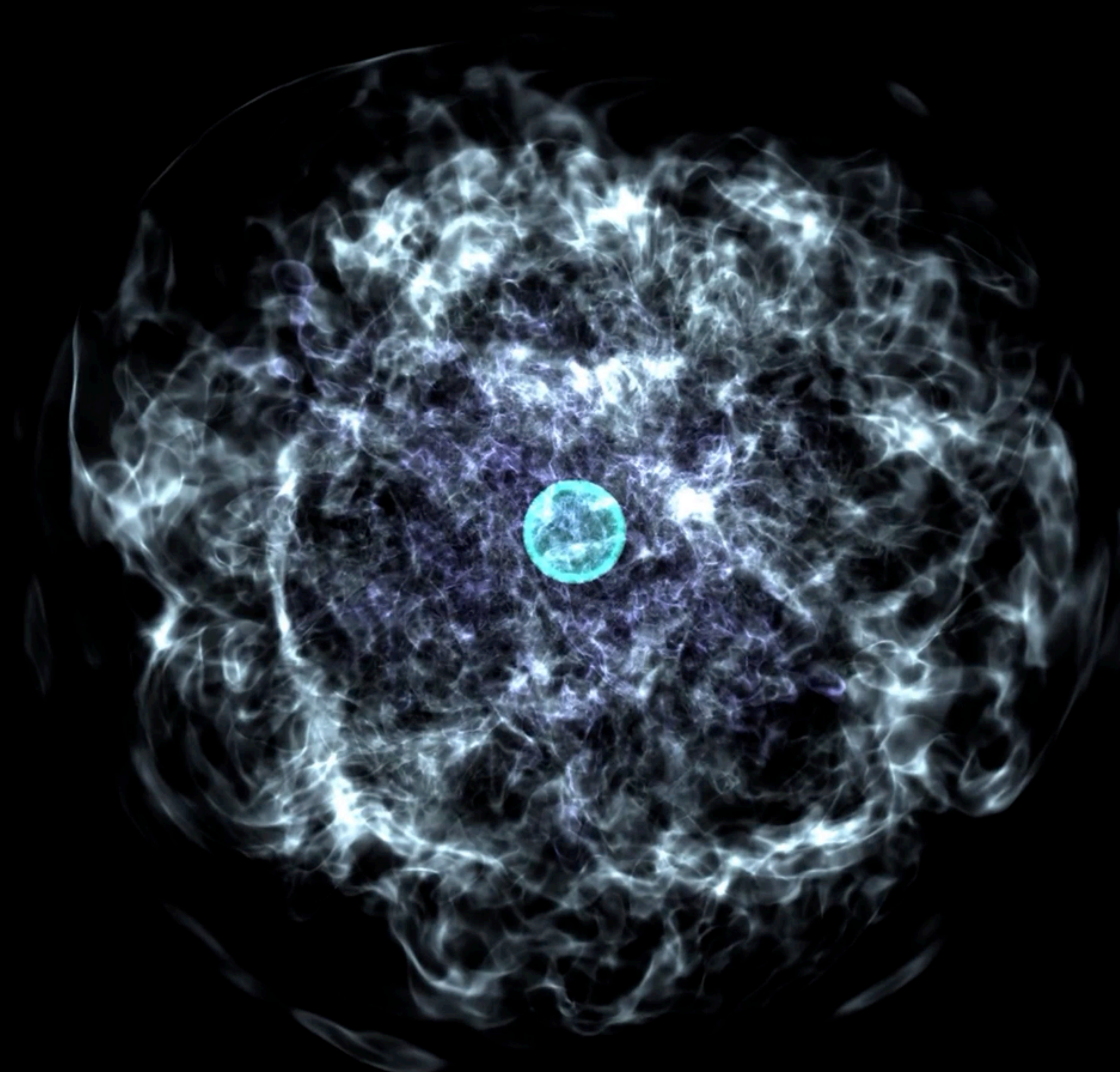
- 2/3D Hydrodynamic simulations using FLASH.
- Evolved ~**7 minutes** collapse using approximate network.
- 15 $M_\odot$ progenitor.



Stellar input model profiles from *Fields & Couch 2020.*

MULTI-DIMENSIONAL SIMULATIONS OF MASSIVE STARS

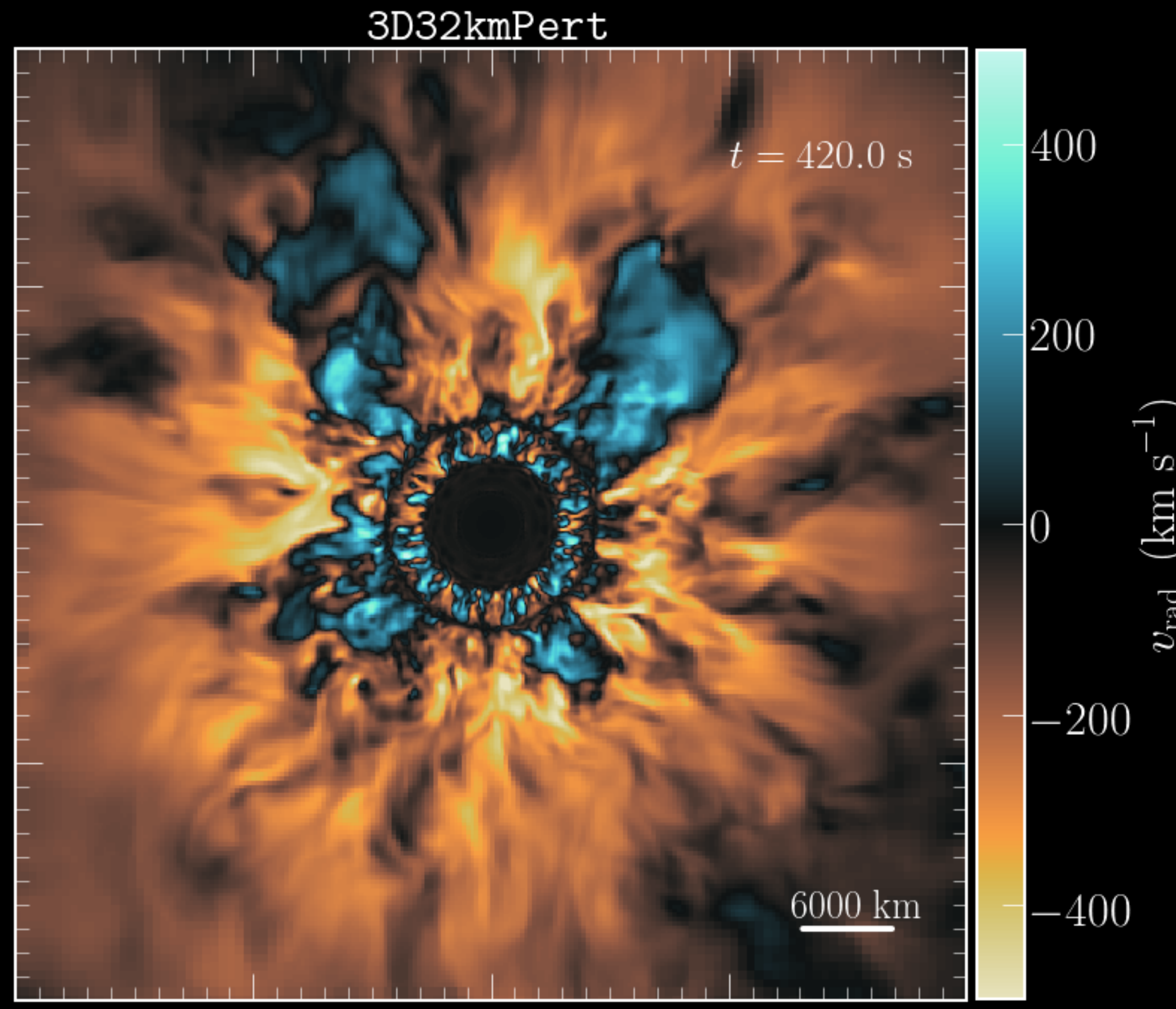
- 3D model evolved using FLASH.
- Shell convection occurring at many scales.
- Perturbations imply indirect **increase** in effective neutrino heating efficiency.



Volume rendering of the velocity field for 3D progenitor model near collapse ***(Fields & Couch 2020)***.

MULTI-DIMENSIONAL SIMULATIONS OF MASSIVE STARS

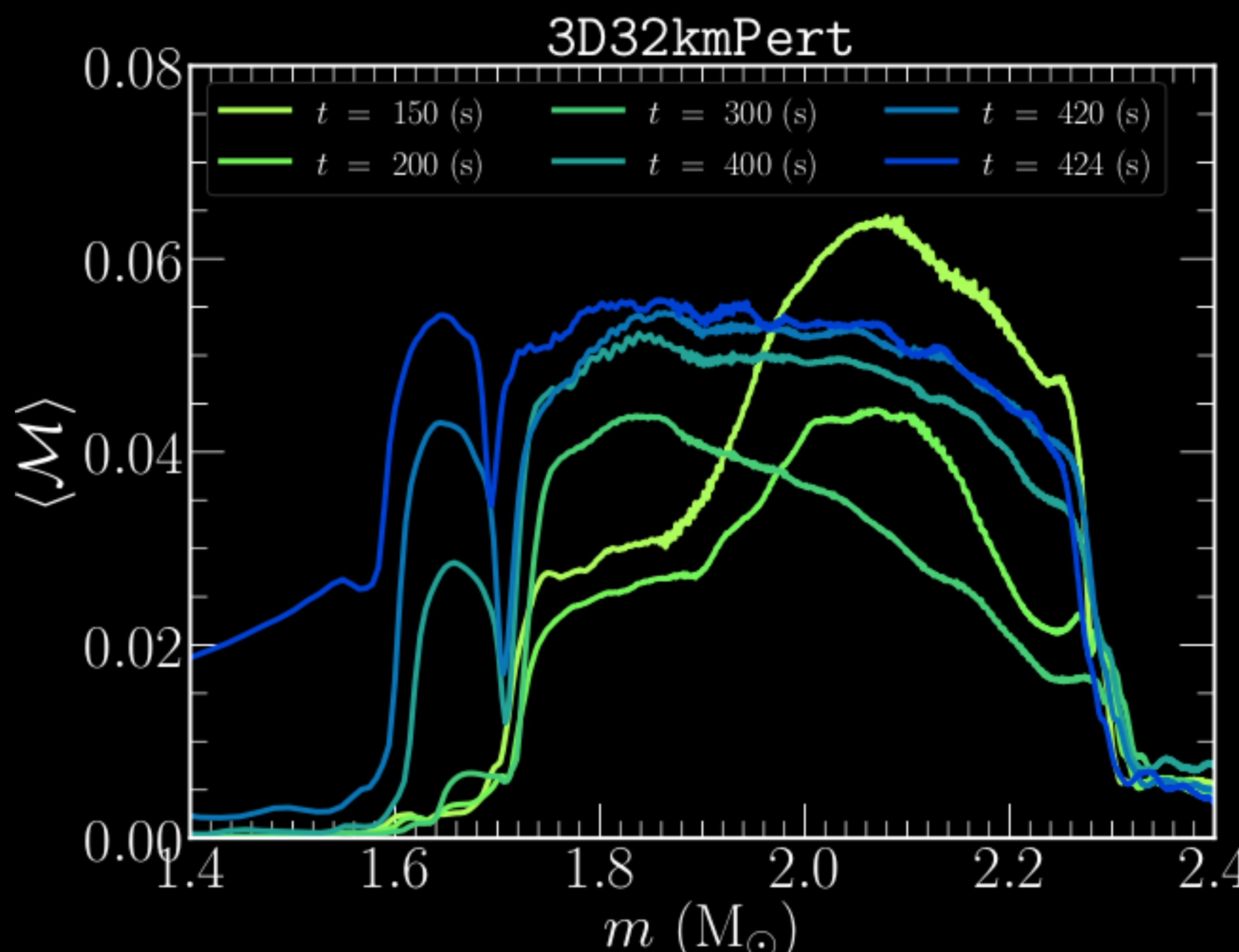
- 4 pi 3D model shows large scale plumes.
- Strong Si-shell convection.
- Convective speeds of several hundred km/s.



Slice of the radial velocity field of 3D progenitor model a few seconds before collapse ***(Fields & Couch 2020)***.

MULTI-DIMENSIONAL SIMULATIONS OF MASSIVE STARS

- Significant increase in Si-shell mach numbers at late time.
- Oxygen-shell reaches steady values early on.
- Values in O-shell lower than previous studies (Muller+2016)

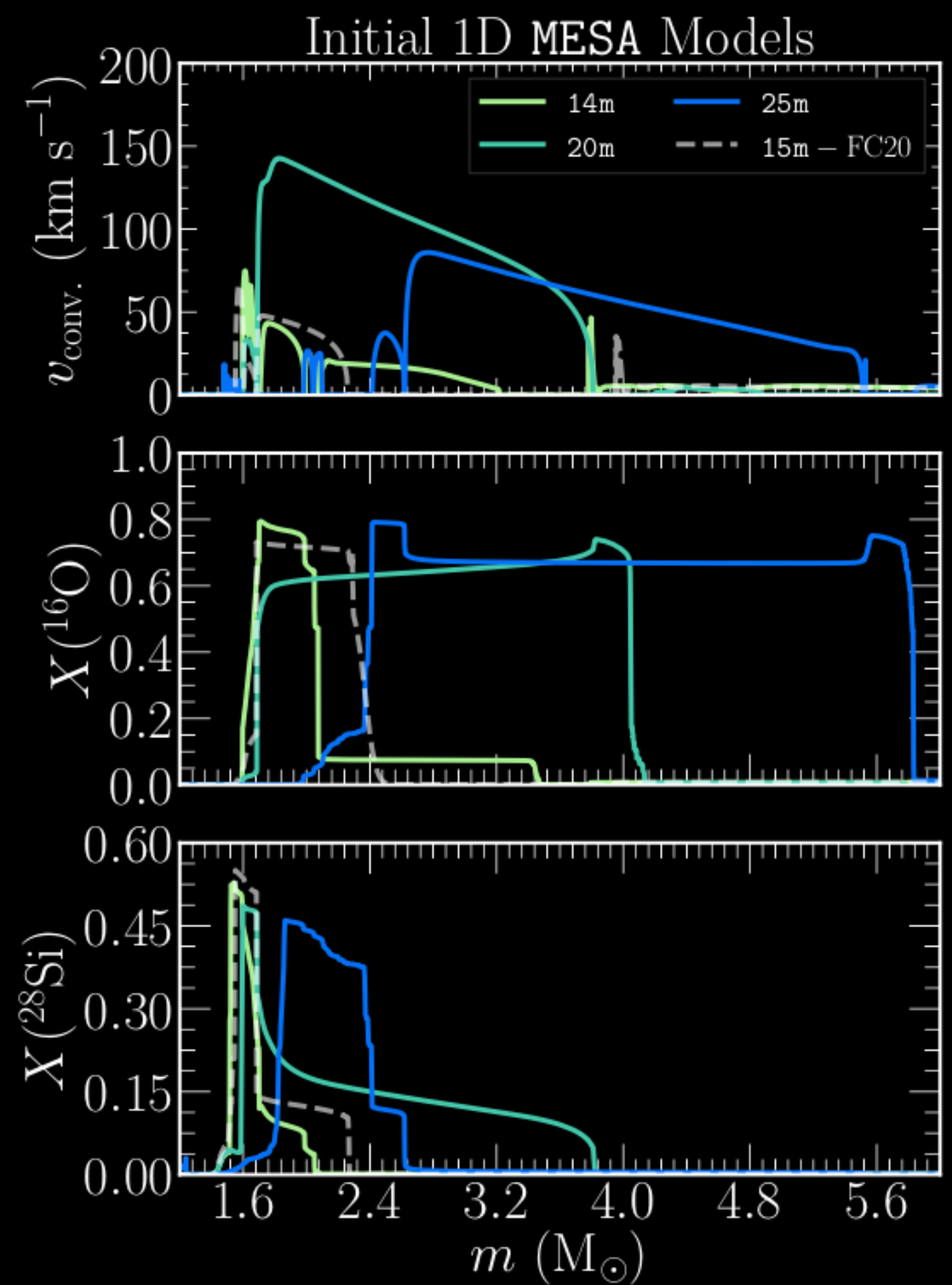


Angle average mach number profiles for 3D model at different times ***(Fields & Couch 2020)***.

Convection in multiple 3D Progenitor Models

MASSIVE STAR CONVECTION IN MULTIPLE PROGENITORS

- 3D simulations using FLASH for 14-,20-, and 25 $M_{\odot}$ models.
- Evolved ~**10 minutes** collapse using approximate network.

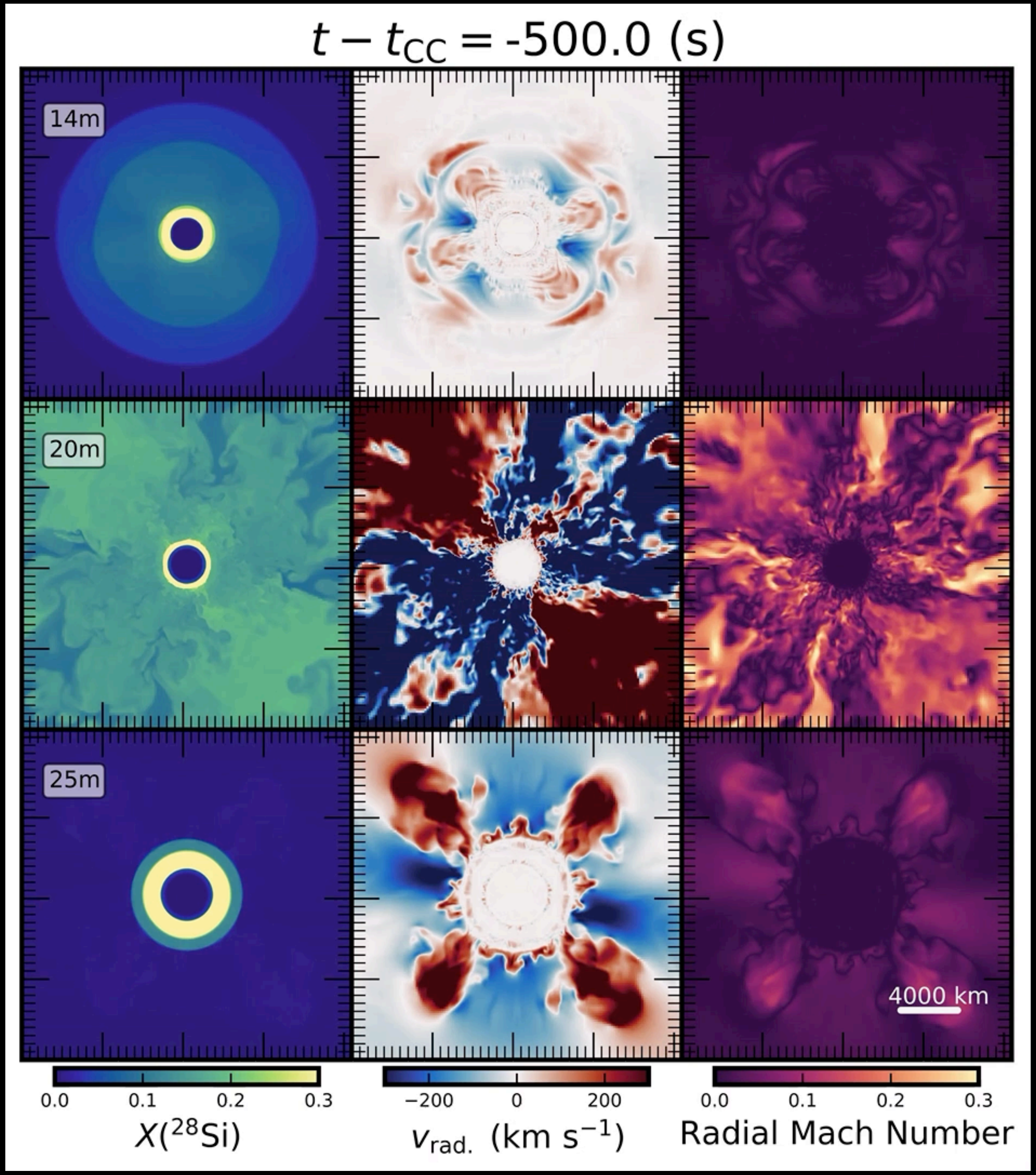


Initial 1D profile structure for 3D models.
*(**Fields & Couch 2021a**.)*

MASSIVE STAR CONVECTION IN MULTIPLE PROGENITORS

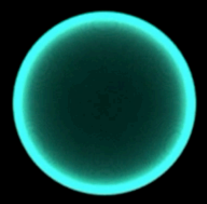
- Models vary in convective speeds!
- Large-scale flow observed in 20 $M_\odot$ model.

$$\delta\rho/\rho \propto \mathscr{M}_{\mathrm{prog.}}$$



SIMULATIONS OF MASSIVE STAR CONVECTION IN MULTIPLE PROGENITORS

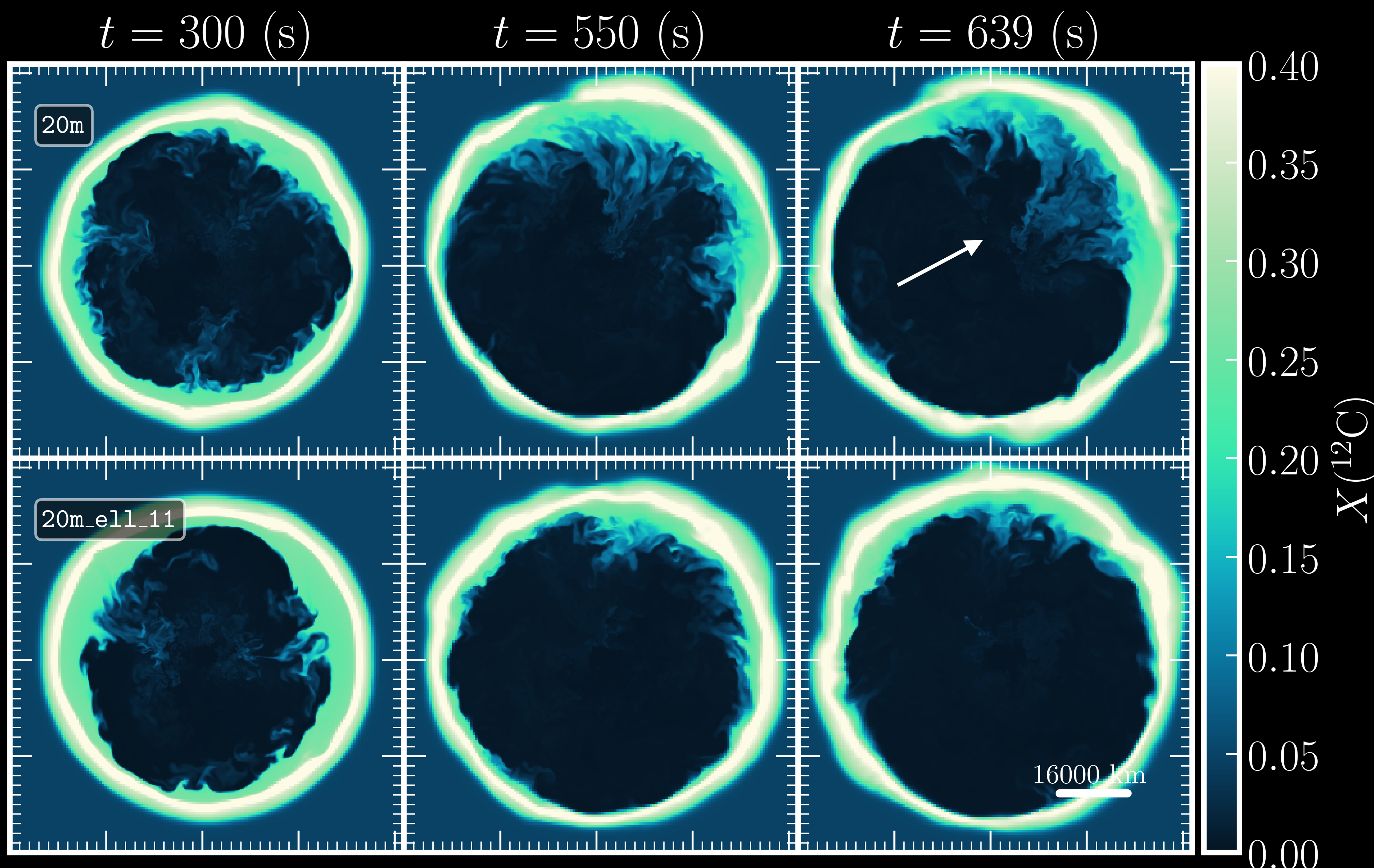
- Smaller O-shell Region, smaller mach numbers, ~0.04!
- Convection occurring at broad range of scales.



$$M_{\rm ZAMS} = 14M_{\odot}$$
$$t - t_{cc} = -300\ (s)$$

Volume rendering of the velocity field for 3D progenitor model near collapse ***(Fields + 2021a, in prep.)***.

MASSIVE STAR CONVECTION IN MULTIPLE PROGENITORS



(Fields + 2021a, in prep.).

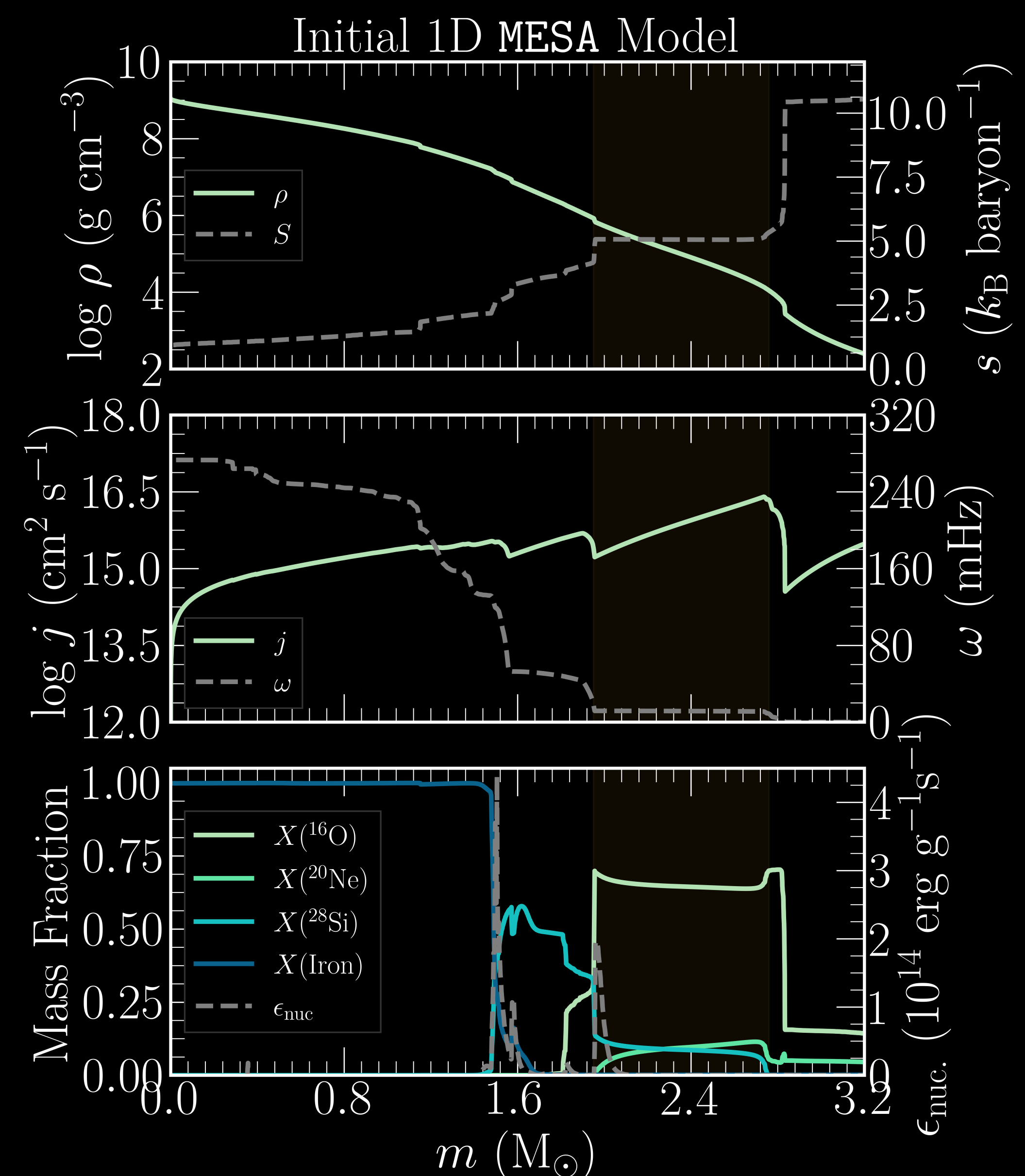
C-ingestion in the O-shell region affected by initial perturbations.

3D CCSN PROGENITORS

3D Evolution of a Rapidly Rotating $16M_\odot$ Star

CONVECTION IN RAPIDLY ROTATING PROGENITORS

- 3D simulations using FLASH for $16M_{\odot}$ model.
- Rotation initialized to 350 km/s at ZAMS.
- Evolved the final 10 minutes to iron core-collapse.
- Includes complete iron core.



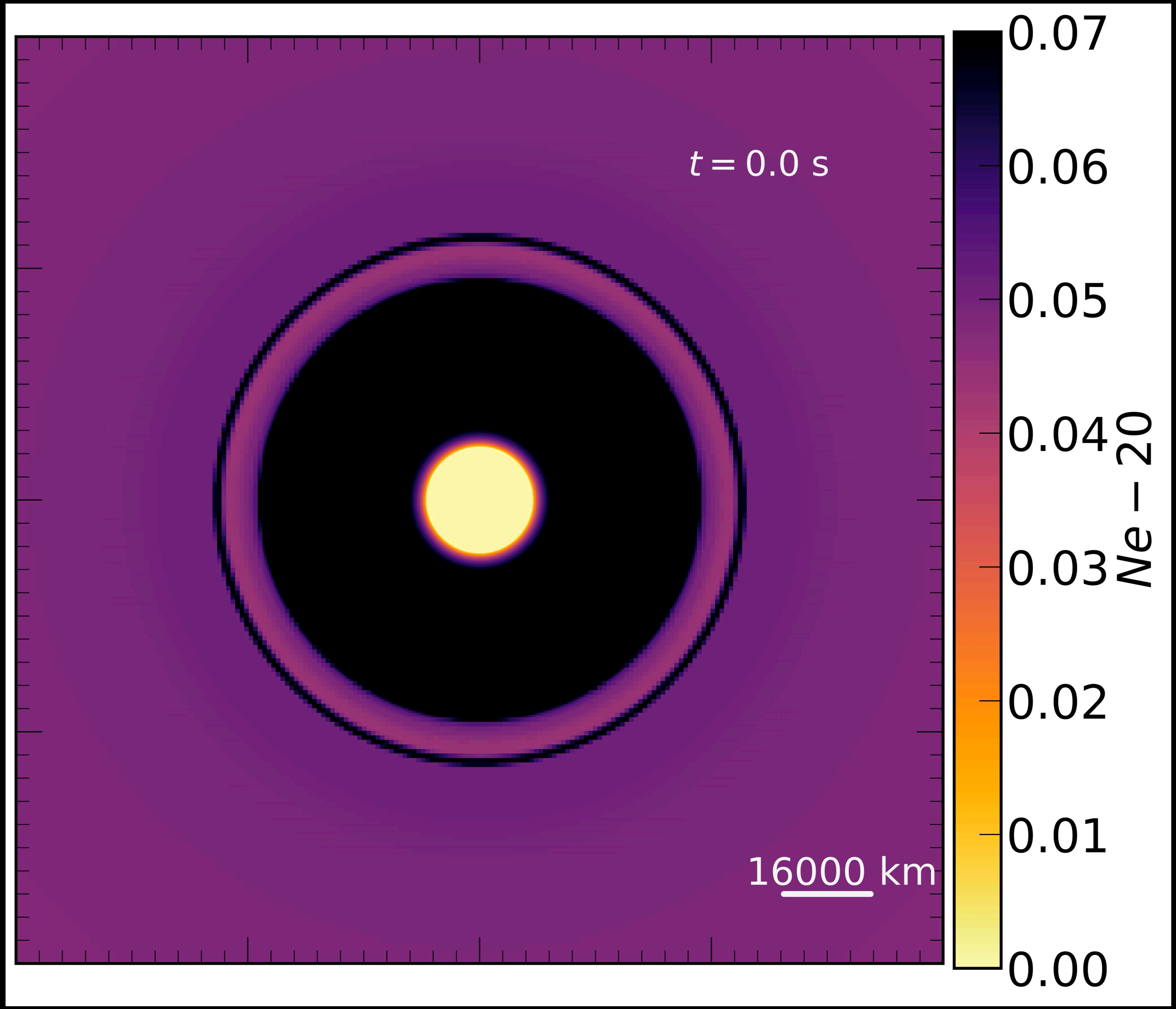
Initial 1D profile structure for 3D model.

(Fields 2021, in prep.)

MASSIVE STAR CONVECTION IN ROTATING PROGENITORS

Preliminary

- Broad convective scales
- Relatively weak Mach numbers ~0.04.
- Weak Si-shell convection.

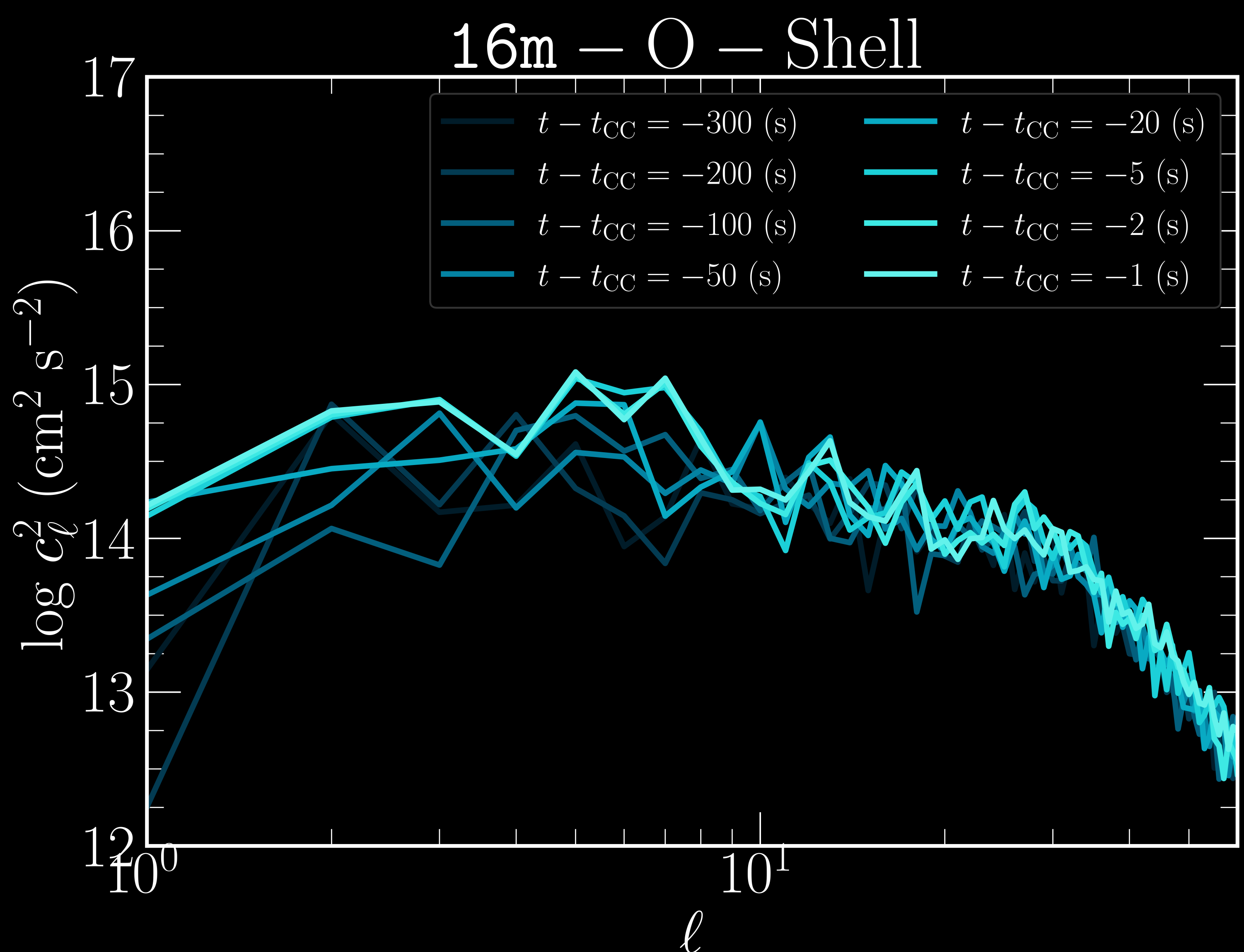


Slice in x-z plane of the Ne-20 mass fraction.
(Fields 2021, in prep.)

MASSIVE STAR CONVECTION IN ROTATING PROGENITORS

Preliminary

- Convection across a range of scales.
- Flow tends towards large scales at late times ($\ell = 3,5,7$).



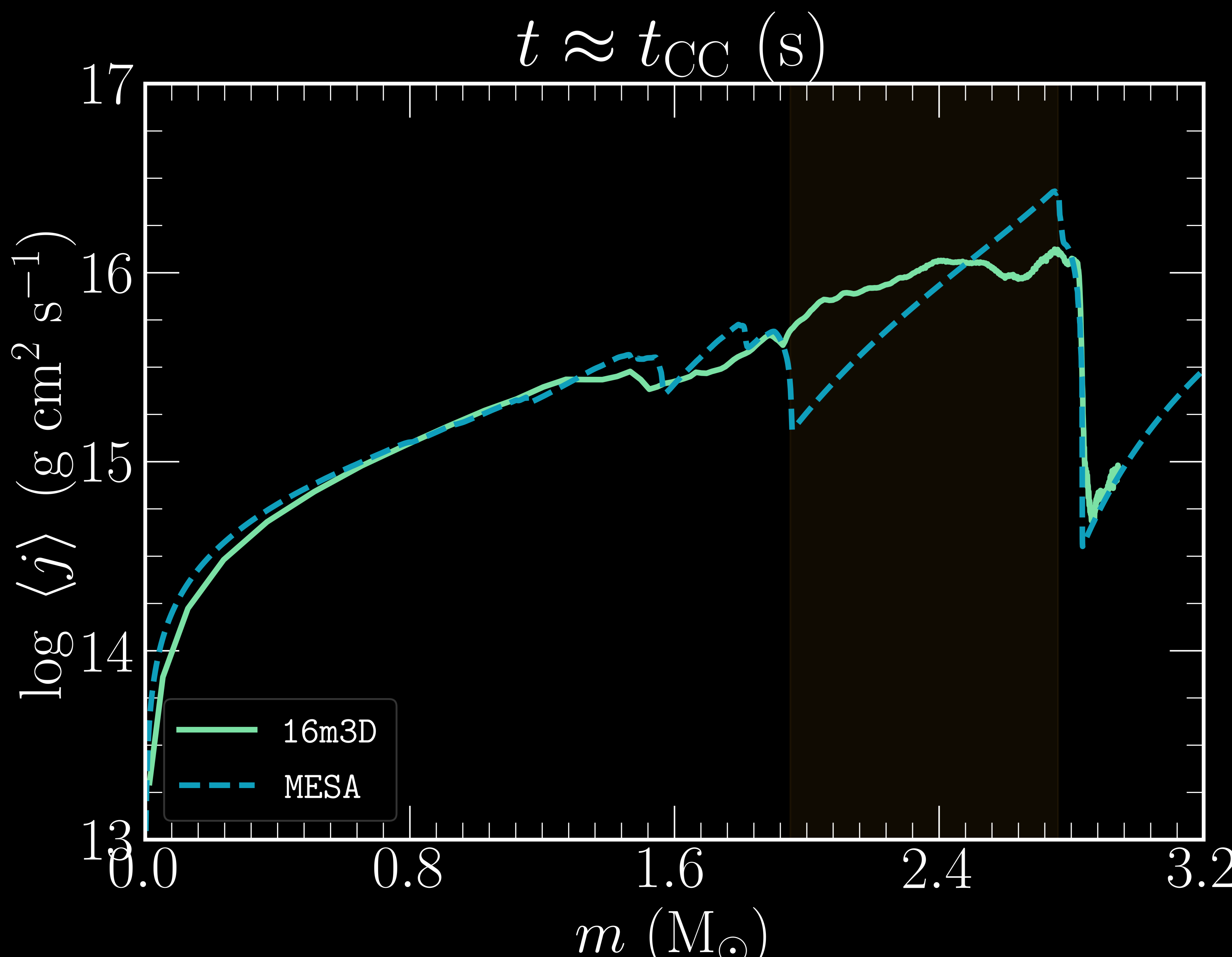
Spectrum of radial velocity field for 3D rotating progenitor.

(Fields 2021, in prep.)

MASSIVE STAR CONVECTION IN ROTATING PROGENITORS

Preliminary

- AM profile diverges from MESA.
- Implications for remnant.
- We find a NS spin period of $P \sim 1.42$ (ms) at collapse.
- MESA model finds $P \sim 1.41$ (ms).



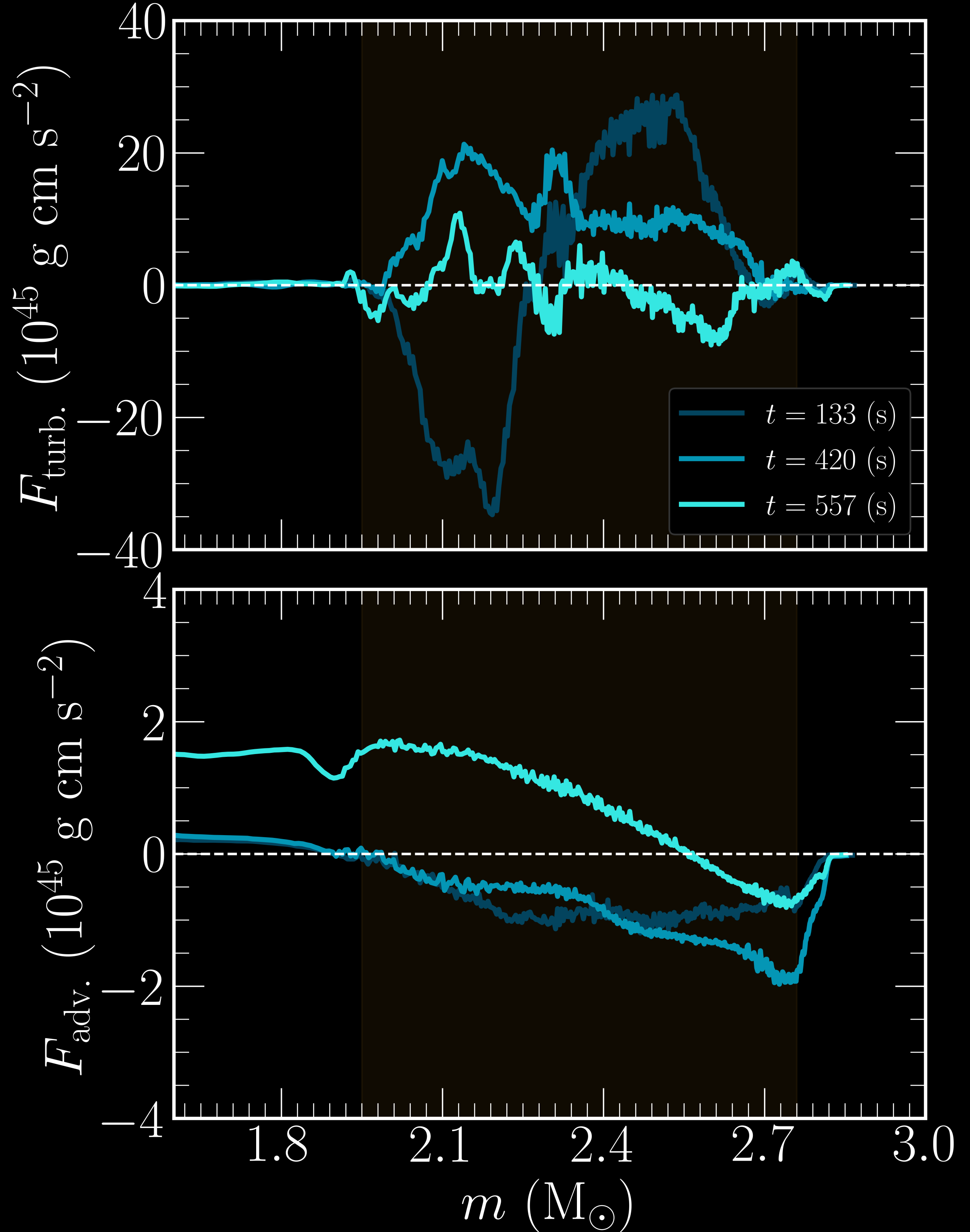
Angular momentum profiles for rotating 3D progenitor.

(Fields 2021, in prep.)

MASSIVE STAR CONVECTION IN ROTATING PROGENITORS

Preliminary

- Advective term in non-convective regions.
- Angular momentum flux components.
- Positive flux in the O-shell.



Angular momentum flux profiles.

(Fields 2021, in prep.)

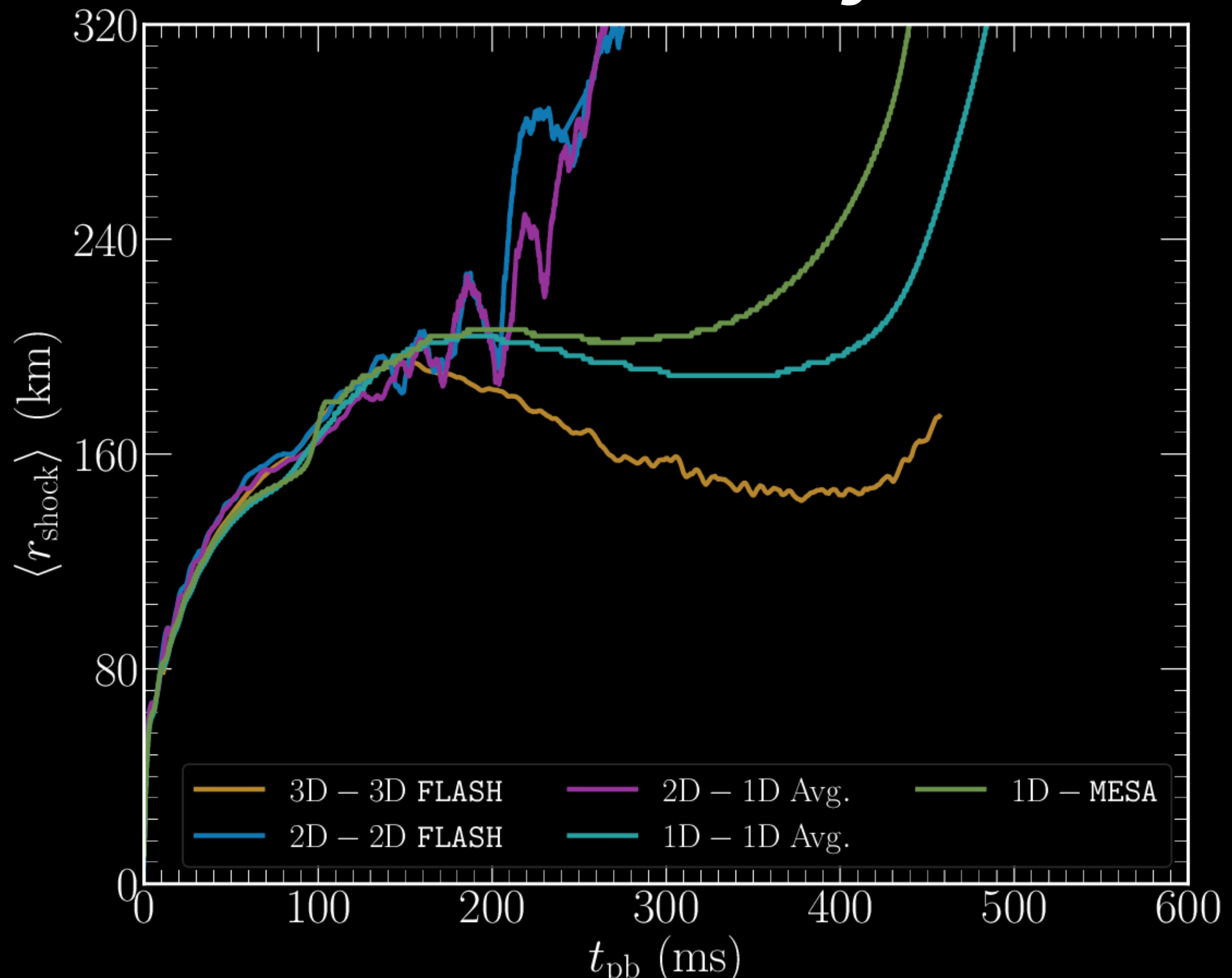
3D CCSN PROGENITORS

CCSNe using 3D Progenitors

CCSN EXPLOSIONS OF MULTI-D PROGENITORS

- 1/2/3D CCSN simulations.
- Use 2D/3D progenitors.
- Multi-group/species, energy/velocity dependent neutrino transport, **M1**.

Preliminary

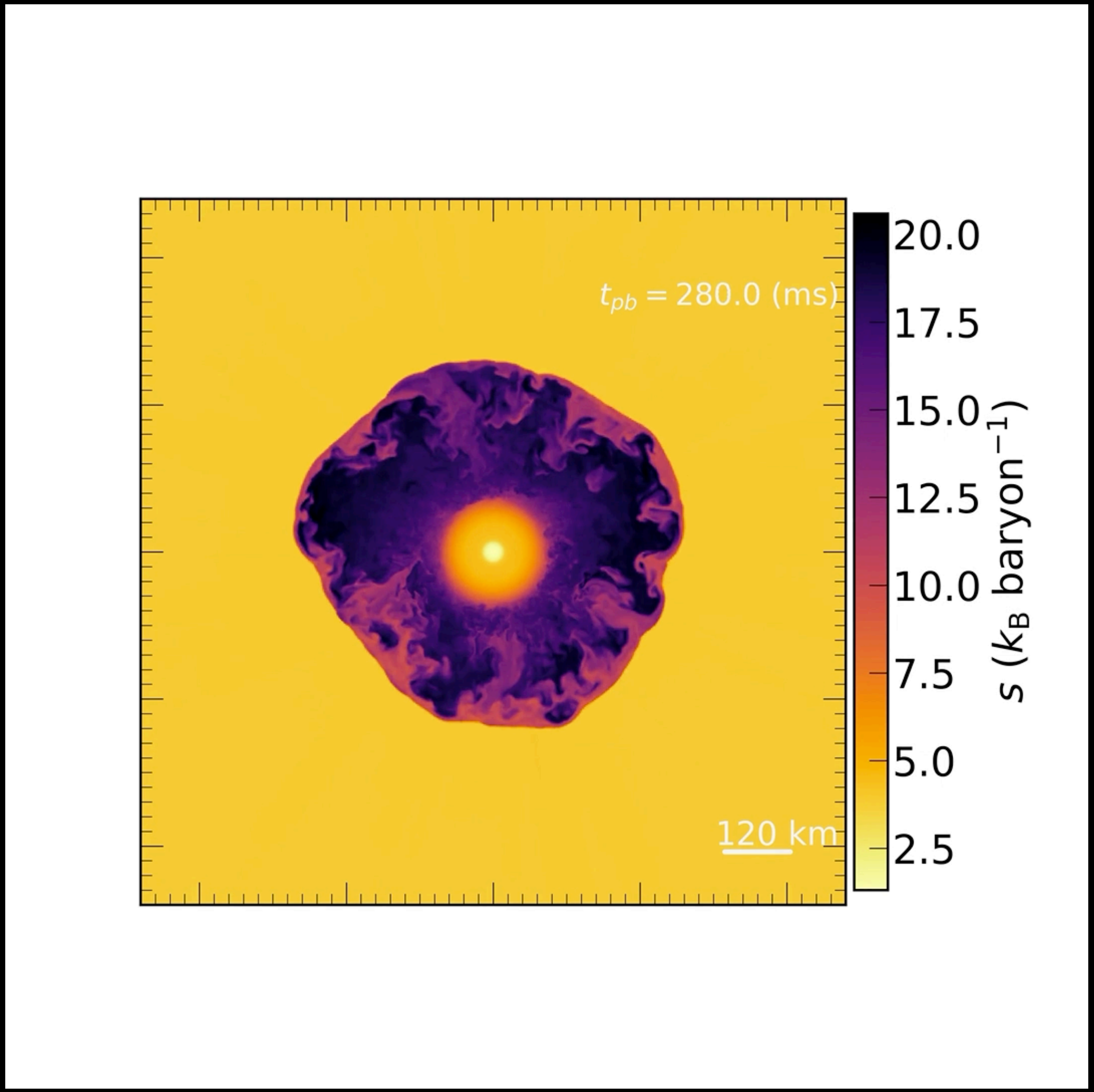


Mean shock radius evolution for multi-D CCSN models *(**Fields + 2021b, in prep.**)*.

CCSN EXPLOSIONS OF MULTI-D PROGENITORS

- 3D model approaching shock runaway.
- Large non-radial kinetic energy.
- Test for LESA, implications for NS kick, etc.

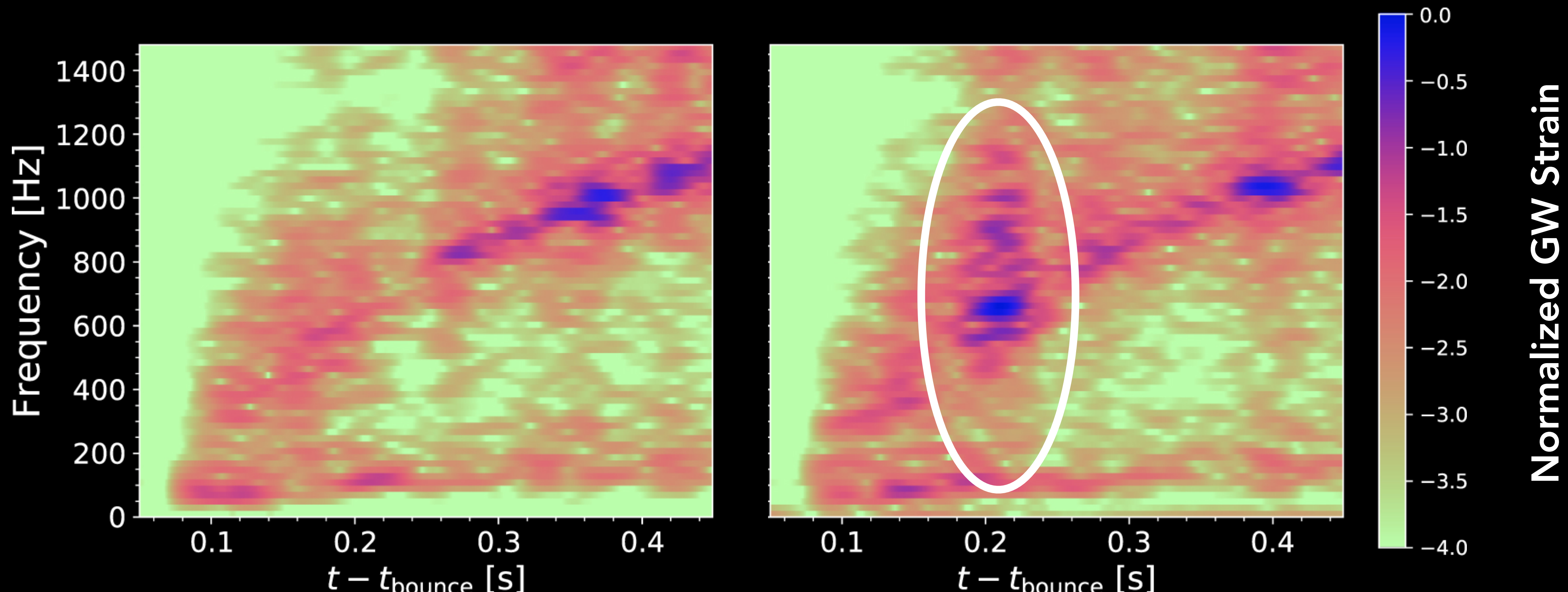
Preliminary



Slice of entropy in the x-y plane for 3D CCSN model ***(Fields + 2021b, in prep.)***.

IMPACT ON MULTI-MESSENGER ASTRONOMY

Impact of 3D progenitor on GW emission?

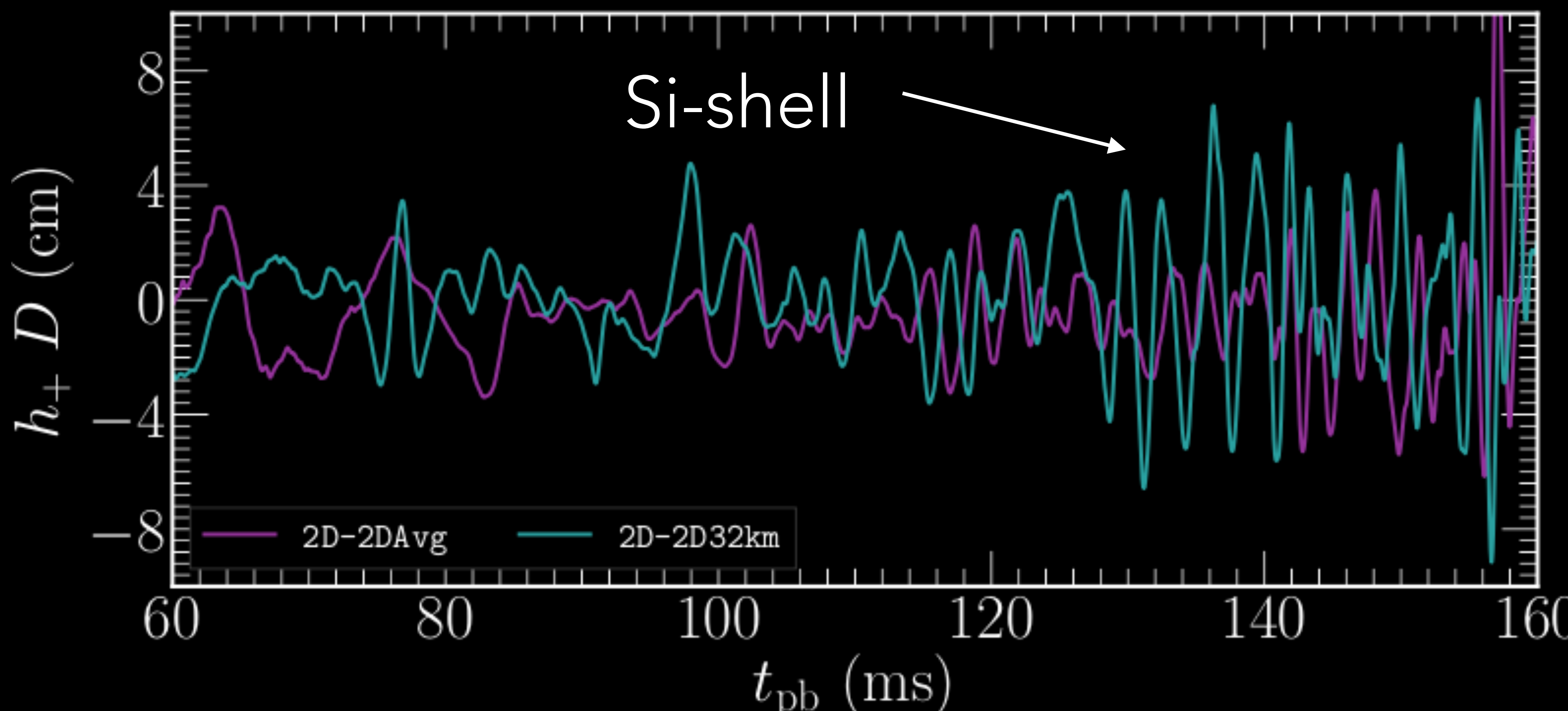


(O'Connor & Couch, 2018)

Si-shell perturbations shown in GW emission.

CCSN EXPLOSIONS OF MULTI-D PROGENITORS

Impact of perturbations on GW emission?

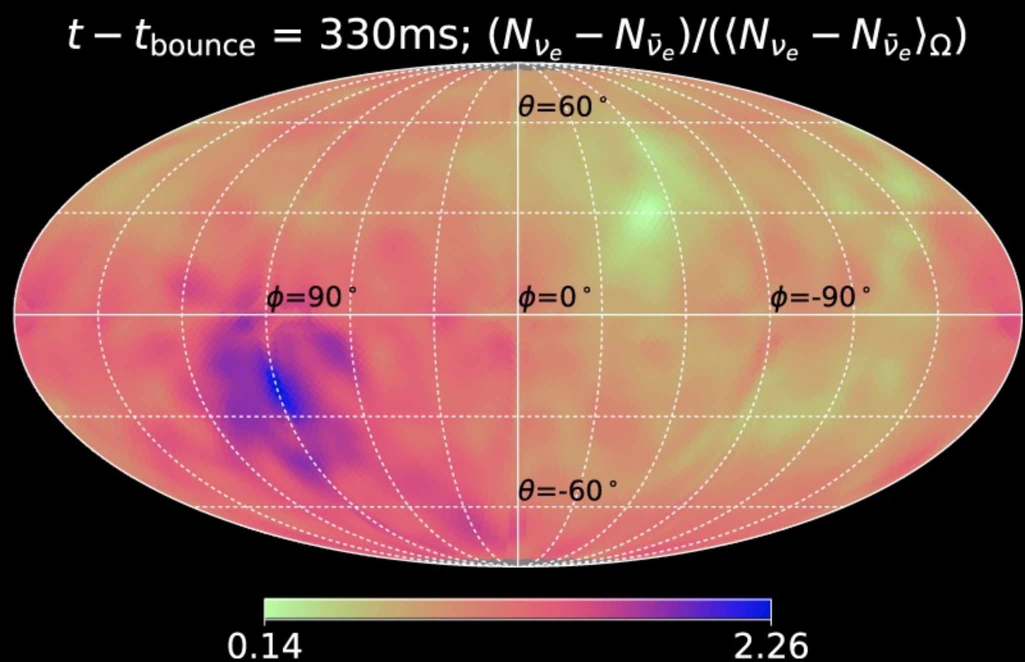


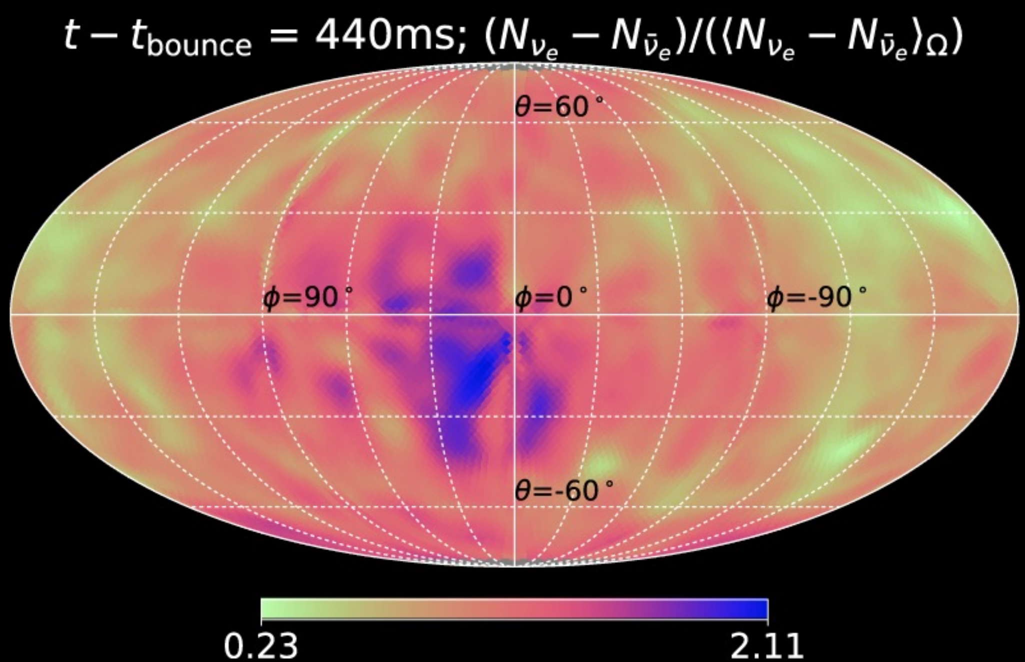
(Fields + 2021b, in prep.).

Si-shell perturbations shown in GW for $f_{\rm GW} \sim 150 - 600$ (Hz).

IMPACT ON MULTI-MESSENGER ASTRONOMY

Impact of 3D progenitor on neutrino emission?



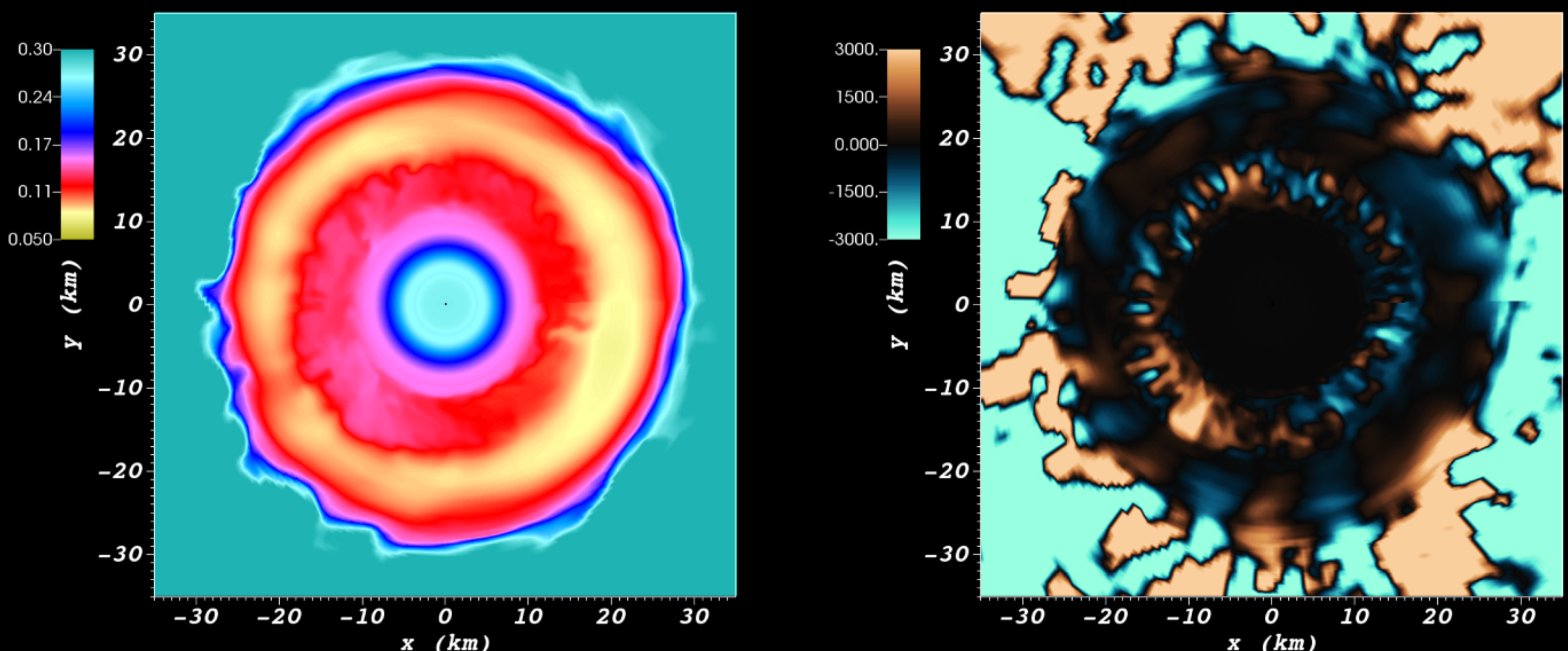


(O'Connor & Couch, 2018)

lepton-number emission self- sustained asymmetry - **LESA** found in 3D CCSN model.

IMPACT ON MULTI-MESSENGER ASTRONOMY

Y_e $\qquad\qquad$ $v_{\rm radial}$



(Muller+, 2020)

$M_{\rm ZAMS} = 18M_\odot \qquad t_{\rm pb} \sim 453\ ({\rm ms})$

Asymmetry in electron fraction, not in radial velocity - signature of **LESA.**

IMPACT ON MULTI-MESSENGER ASTRONOMY

MNRAS 000, 1–21 (2021) Preprint 27 September 2021 Compiled using MNRAS LaTeX style file v3.0

The Collapse and Three-Dimensional Explosion of Three-Dimensional Massive-star Supernova Progenitor Models

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(arxiv.org/abs/2109.10920)

Other groups using 3D progenitors as input. Check out this recent work!

CONCLUSIONS & SUMMARY

3D models of stellar convection necessary for accurate description of state of model near collapse

(Fields & Couch, 2020, ApJ; Fields & Couch 2021, ApJ)

- Convection occurring at many scales, large dominant mode near collapse
- 3D instabilities can affect flow properties and mass entrainment
- Mach number profiles show favorable conditions for explosion.

3D rotating progenitor models ALSO necessary

(Fields, 2021, in prep.)

- Redistribution of AM diverges from MESA model. Implications for remnant.
- Turbulent transport of AM in convective shell regions.

Multi-D models can provide input for successful CCSN models

- Larger non-radial kinetic energy when using multi-D progenitor input
- 3D CCSN model showed prompt convection, asymmetric shock runaway
- Explosion properties suggest robust impact on multi-messenger signals

THANK YOU

Questions?

Our data are online and available publicly!

doi.org/10.5281/zenodo.3976246

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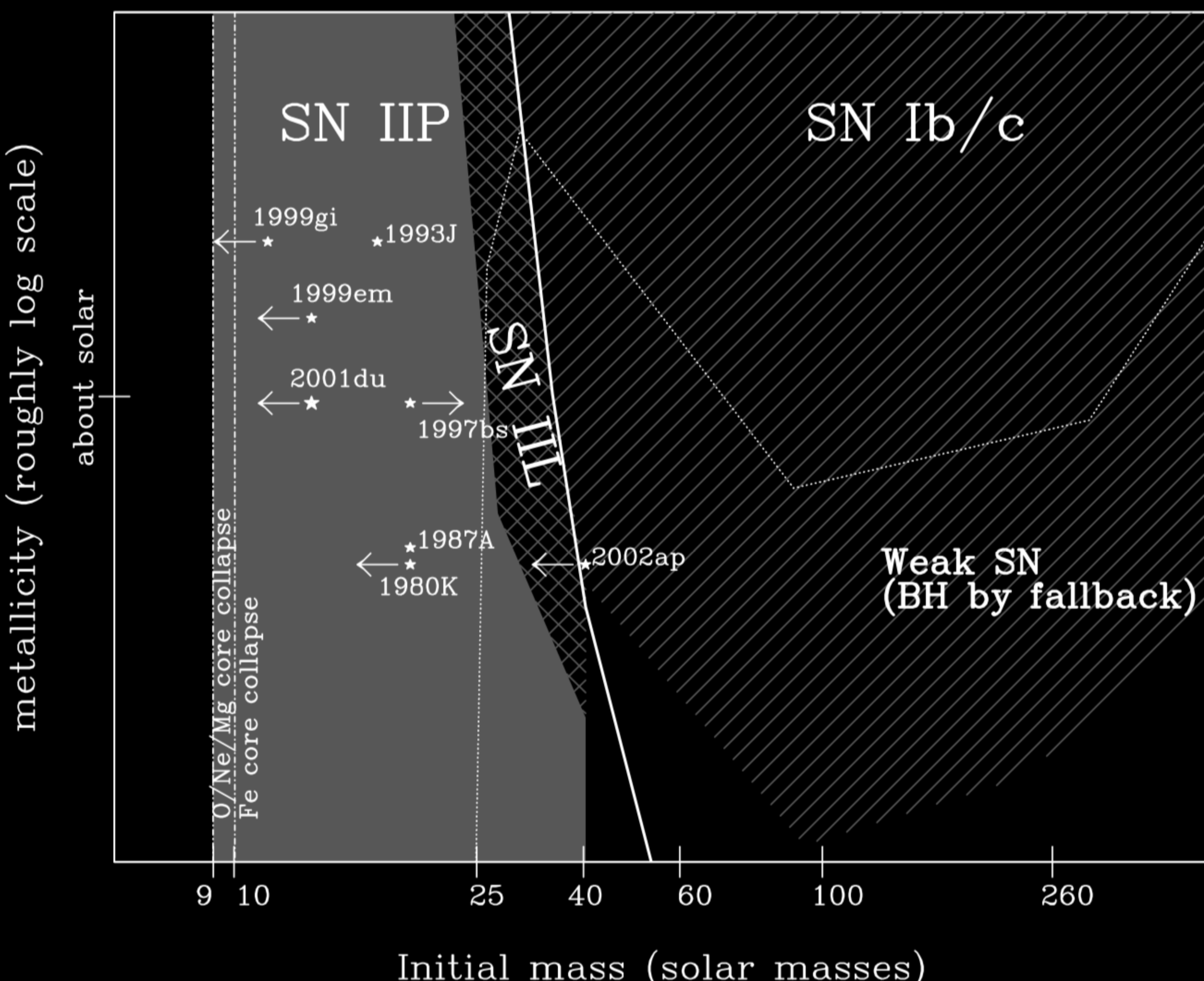
Los Alamos NATIONAL LABORATORY

@carlnotsagan

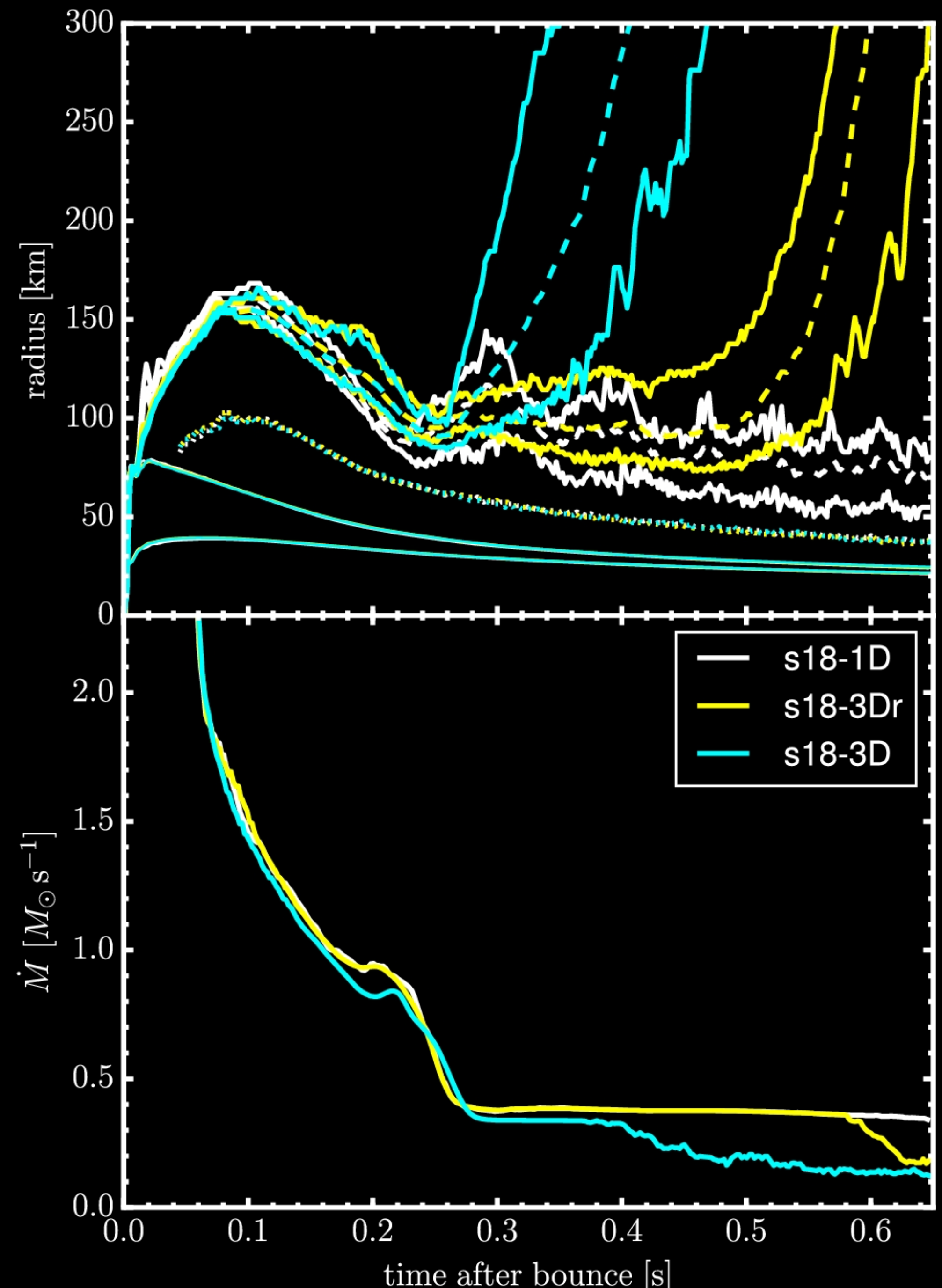
CORE COLLAPSE SUPERNOVAE - MASSIVE STAR TRANSIENTS



SN Populations from Heger+ 2003 models (Smartt + 2013)

IMPACT OF PROGENITORS ON EXPLOSION MECHANISM

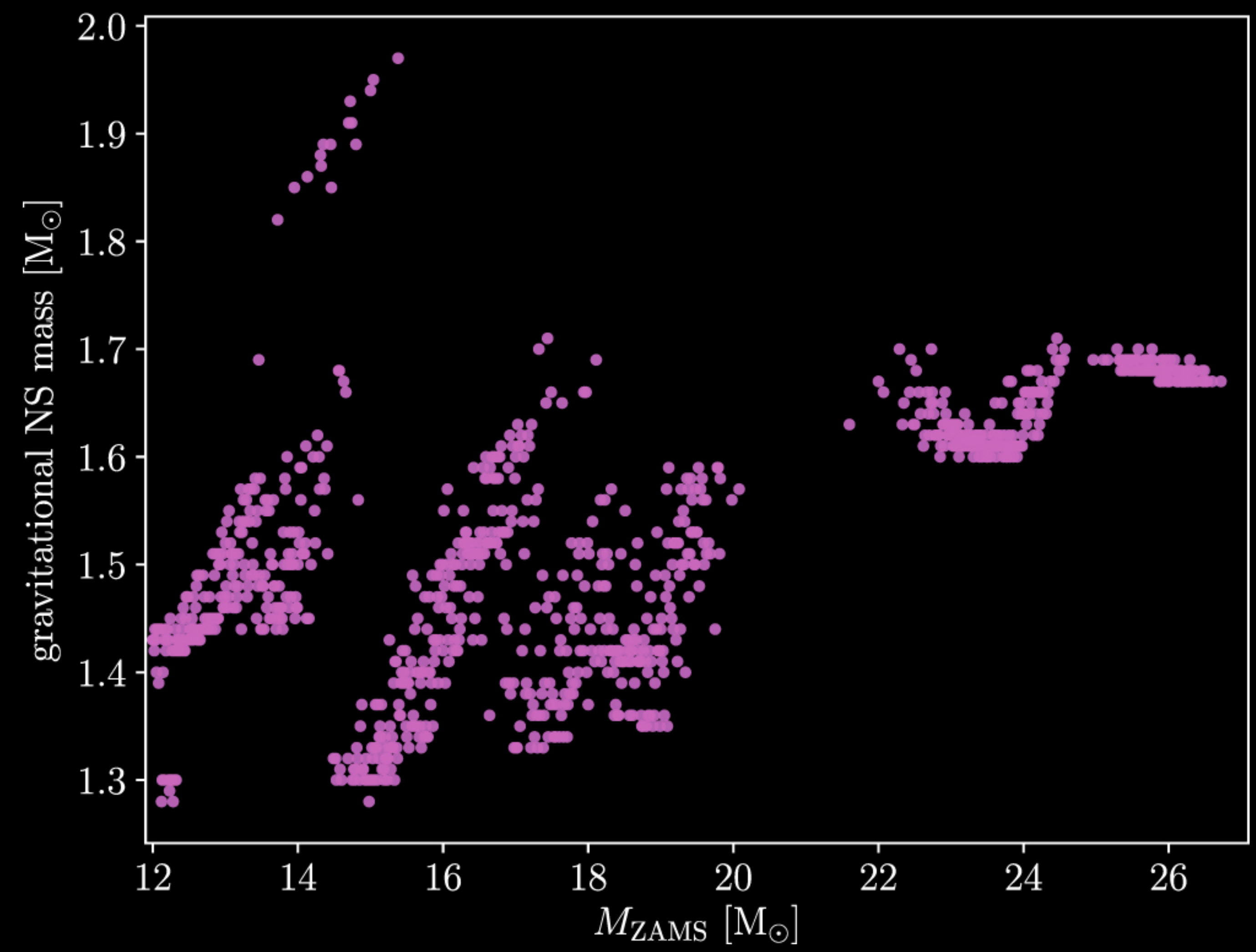
- Favorable impact found on the explosion mechanism.
- Reduced convection velocities results in later explosion.
- Impact partly due to accretion evolution.



(Muller + 2017)

COMPACT OBJECT FORMATION BY CORE-COLLAPSE SUPERNOVAE

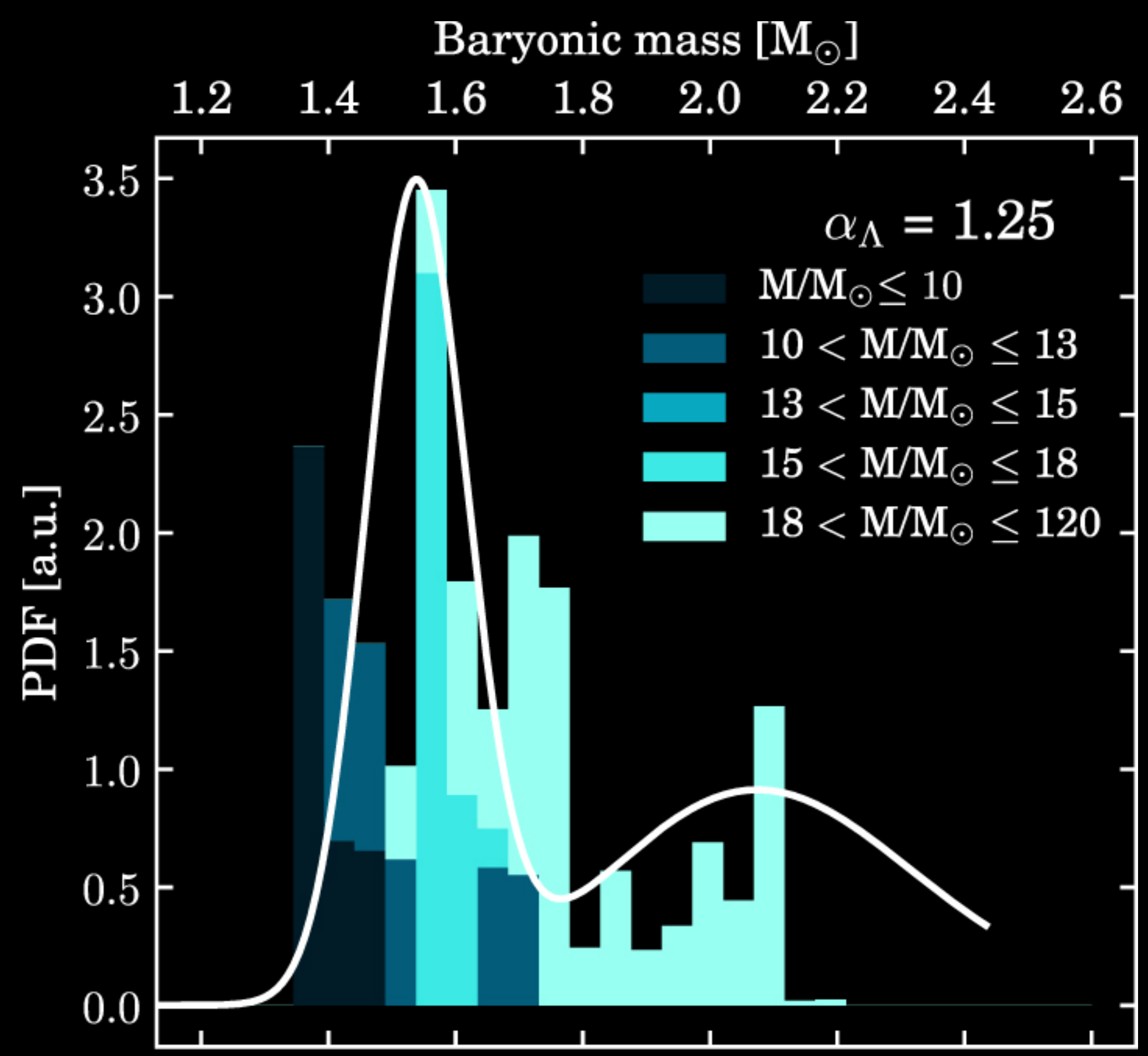
- Explosion models give wide range of NS masses.
- Complex interplay between burning shells in 1D!
- Variation is likely larger in 3D models.



Gravitational NS mass from 1D semi-analytical explosions. (Sukhbold + 2018)

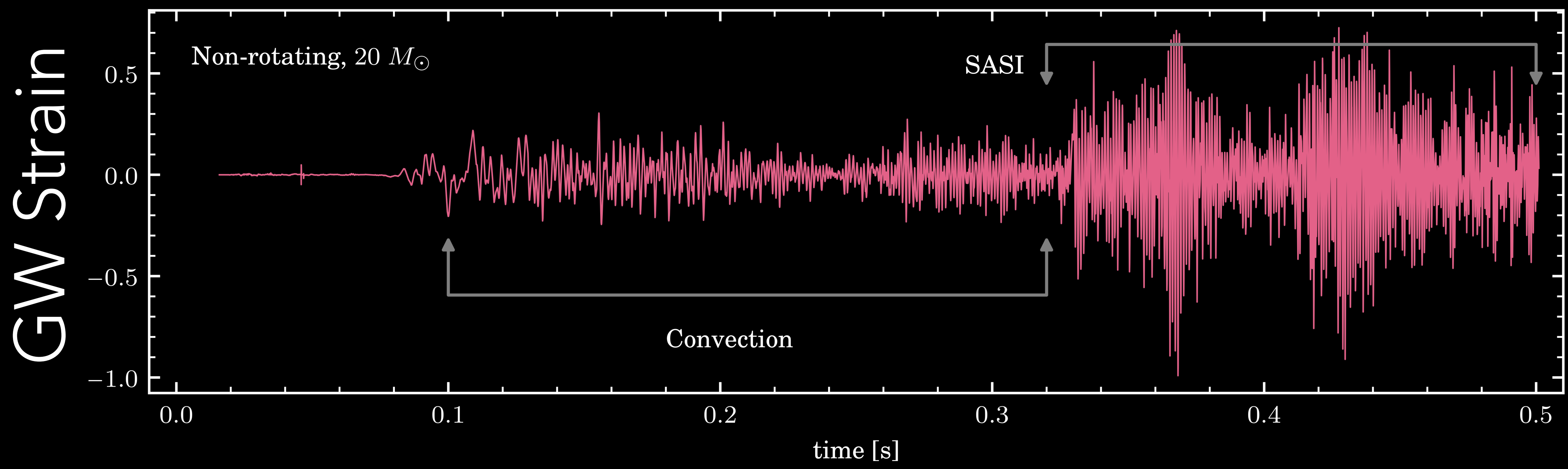
COMPACT OBJECT FORMATION BY CORE-COLLAPSE SUPERNOVAE

- 1D Models report a range of NS masses.
- Failed explosion suggest stellar mass black hole formation.
- Stochasticity due partially to input physics.
- Close to inferred observational distribution.



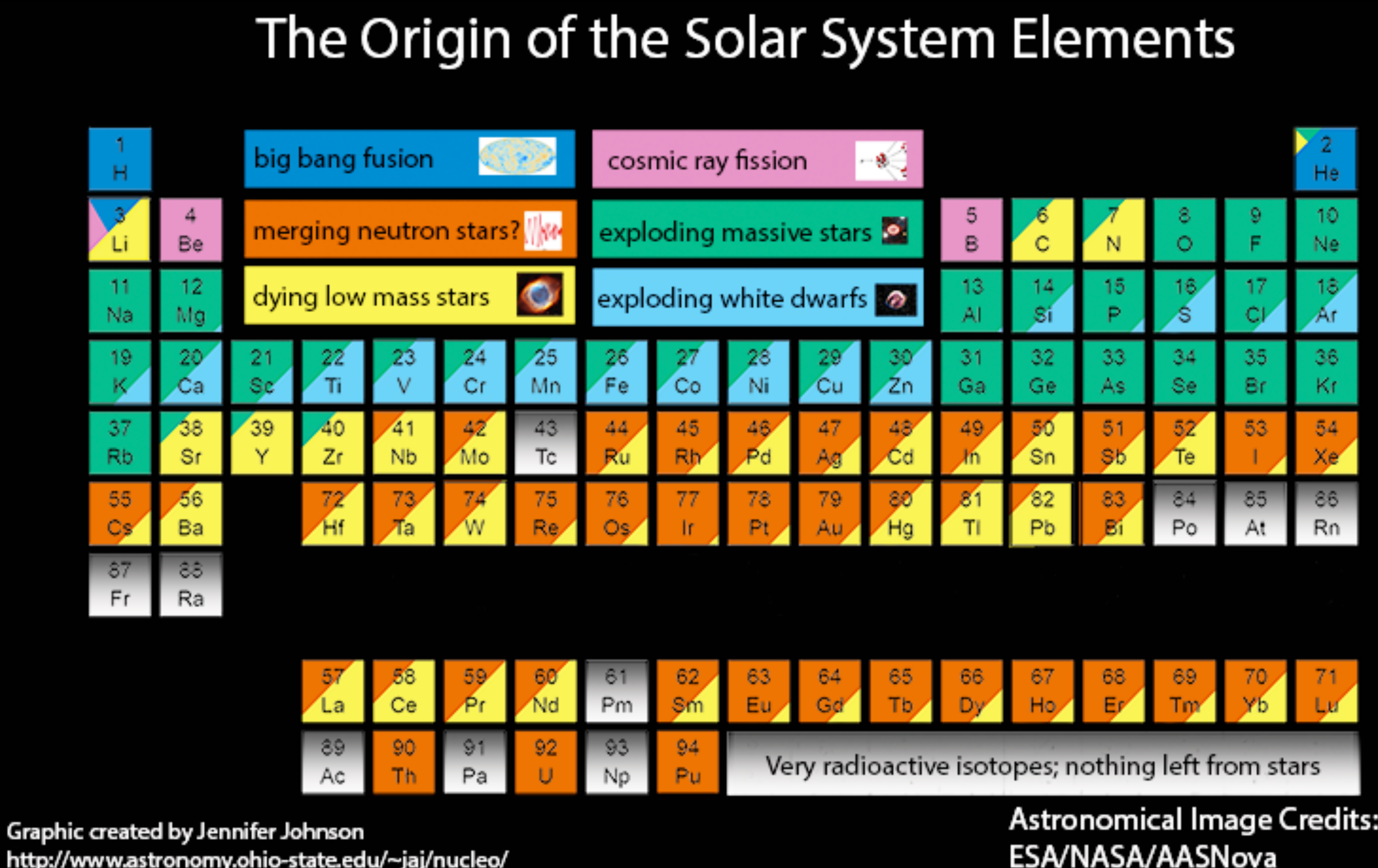
Resulting remnant mass PDF of 1D STIR CCSN explosions. (Couch + 2020)

MULTI-MESSENGER SIGNALS FROM CORE-COLLAPSE SUPERNOVAE



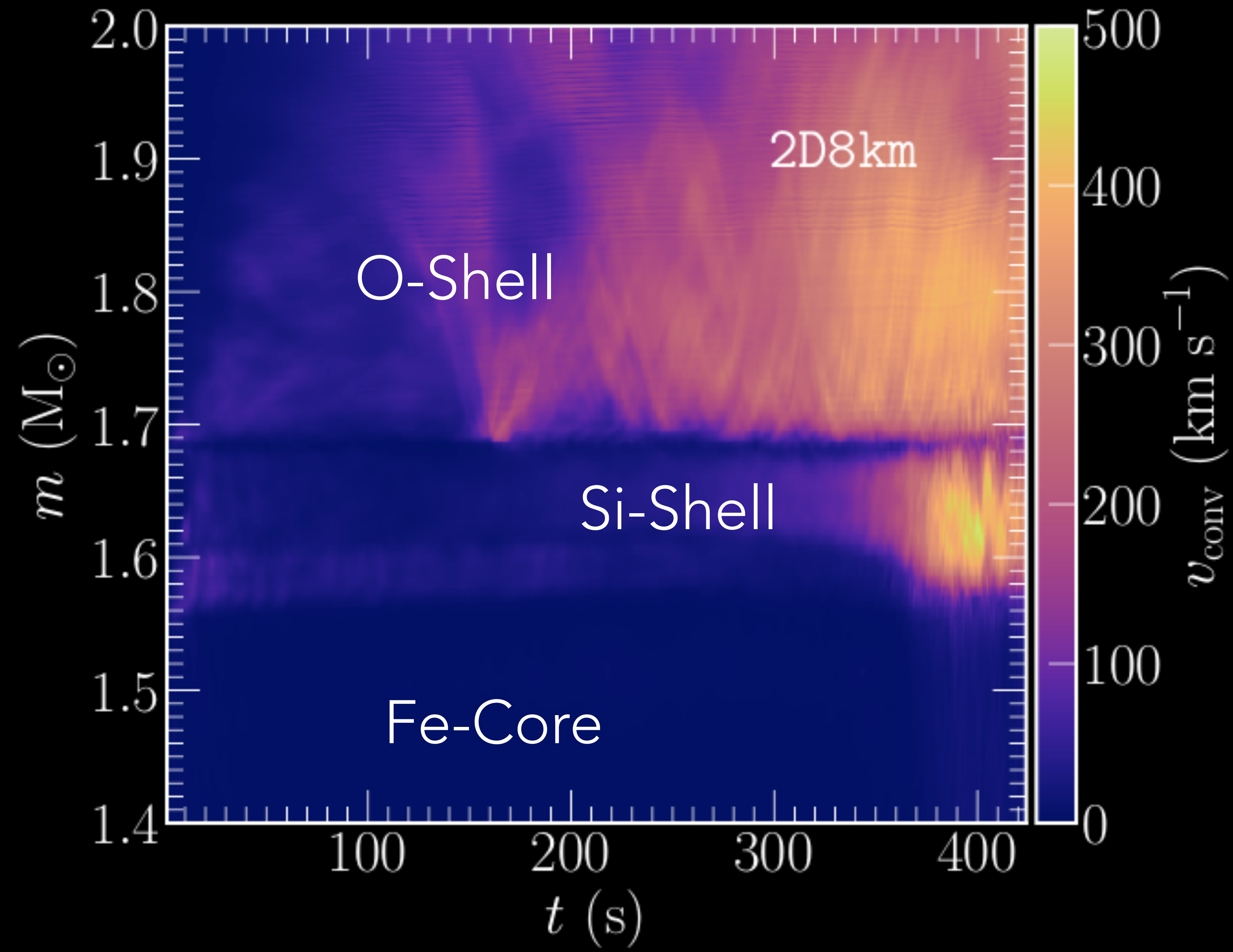
- Gravitational wave signals produced: **excitation of PNS caused by convection in gain region of shock**, *rotation*, other instabilities.
- Neutrino emission ~ thousands of events detectable by Super-Kamiokande like neutrino detectors within ~ 100 kpc.
- Combining this information can tell us unique information about the progenitor - possibly allow to break degeneracies.

CORE COLLAPSE SUPERNOVAE AND GALACTIC CHEMICAL EVOLUTION



MULTI-DIMENSIONAL SIMULATIONS OF MASSIVE STARS

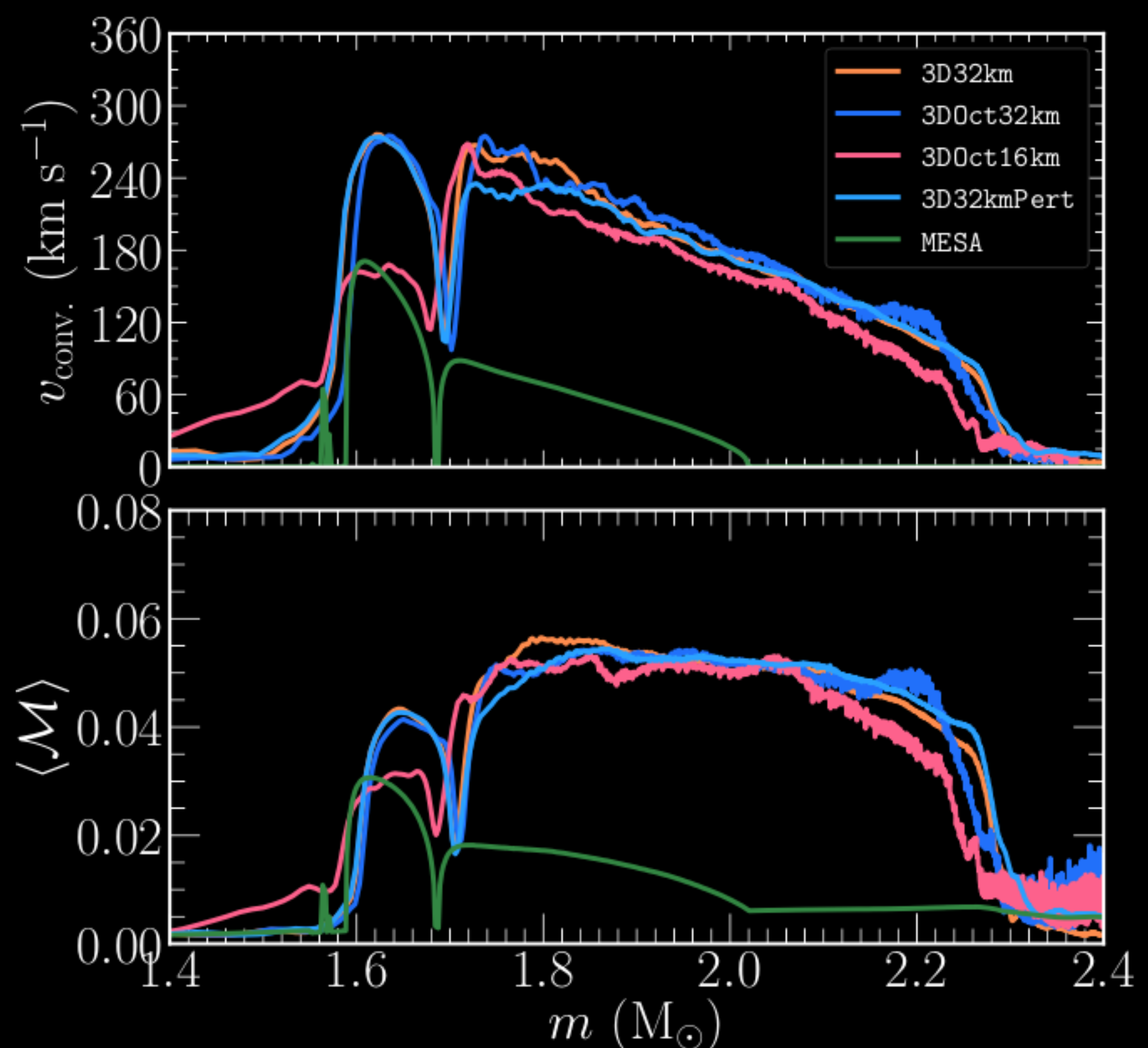
- 2D models shows large convective speeds.
- Late time merging of convective/non-convective regions.
- Convective speeds larger than 3D by factor of two.



Time evolution of convective velocity profiles for 2D model. ***(Fields & Couch 2020)***.

MULTI-DIMENSIONAL SIMULATIONS OF MASSIVE STARS

- 1D MESA model matches Si-shell convection well.
- Largely under predicts O-shell speeds and extent.
- 1D approximation good, in some cases.



Angle average mach number profiles for all models at different times ***(Fields & Couch 2020)***.