LA-UR-21-32036
Approved for public release; distribution is unlimited.

Title: NEXT-GENERATION SIMULATIONS OF THE REMARKABLE DEATHS OF MASSIVE STARS

Author(s): Fields, Carl Edward Jr.

Intended for: talk

Issued: 2021-12-09

Disclaimer:
Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by Triad National Security, LLC for the National Nuclear Security Administration of U.S. Department of Energy under contract 89233218CNA000001. By approving this article, the publisher recognizes that the U.S. Government retains nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy. Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

NEXT-GENERATION SIMULATIONS OF THE REMARKABLE DEATHS OF MASSIVE STARS

DR. CARL E. FIELDS

(he/him)

Feynman Fellow, CCS-2/XCP-2
Los Alamos National Laboratory

AMNH Astrophysics Seminar
December 7th, 2021

Los Alamos NATIONAL LABORATORY

@carlnotsagan

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

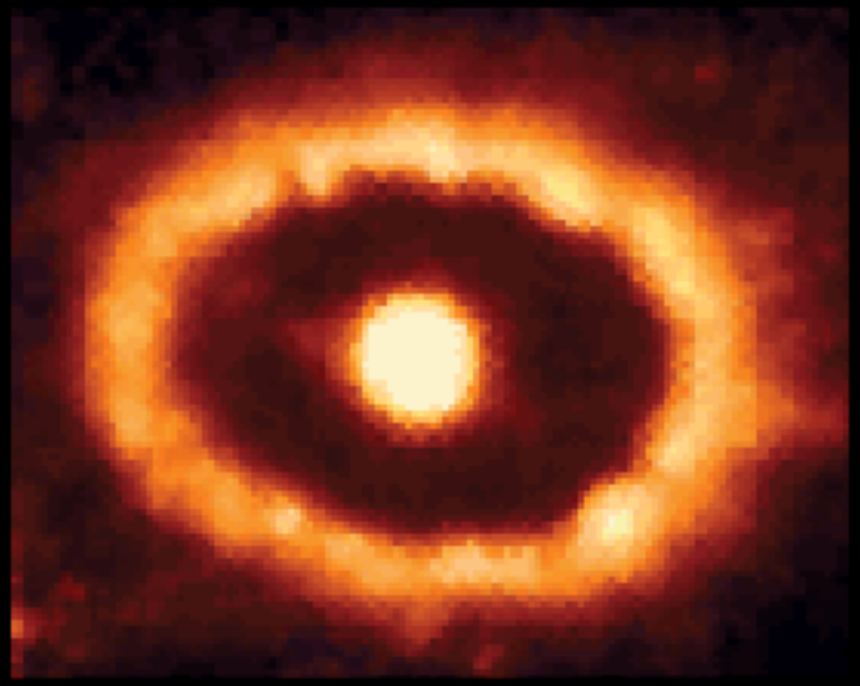
- Nucleosynthesis
- Stellar Feedback

Compact Object Formation

- Produce NS / stellar mass BHs

Multi-Messenger Astronomy

- Gravitational Waves
- Neutrino Emission

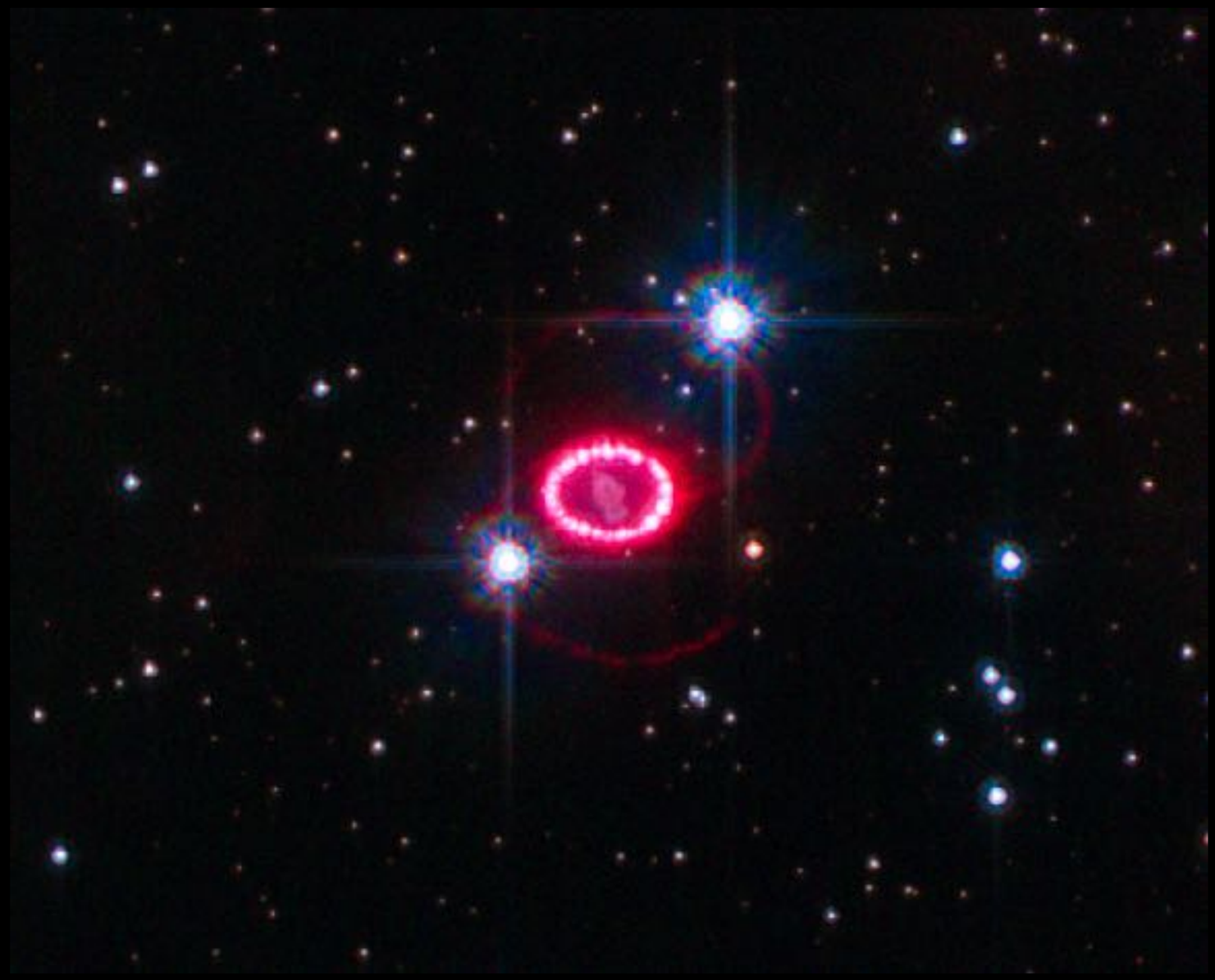


09/1994

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

CORE-COLLAPSE SUPERNOVA EXPLOSIONS

- ~3 per century for a Milky Way type galaxy (Li et al. 2012).
- 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.



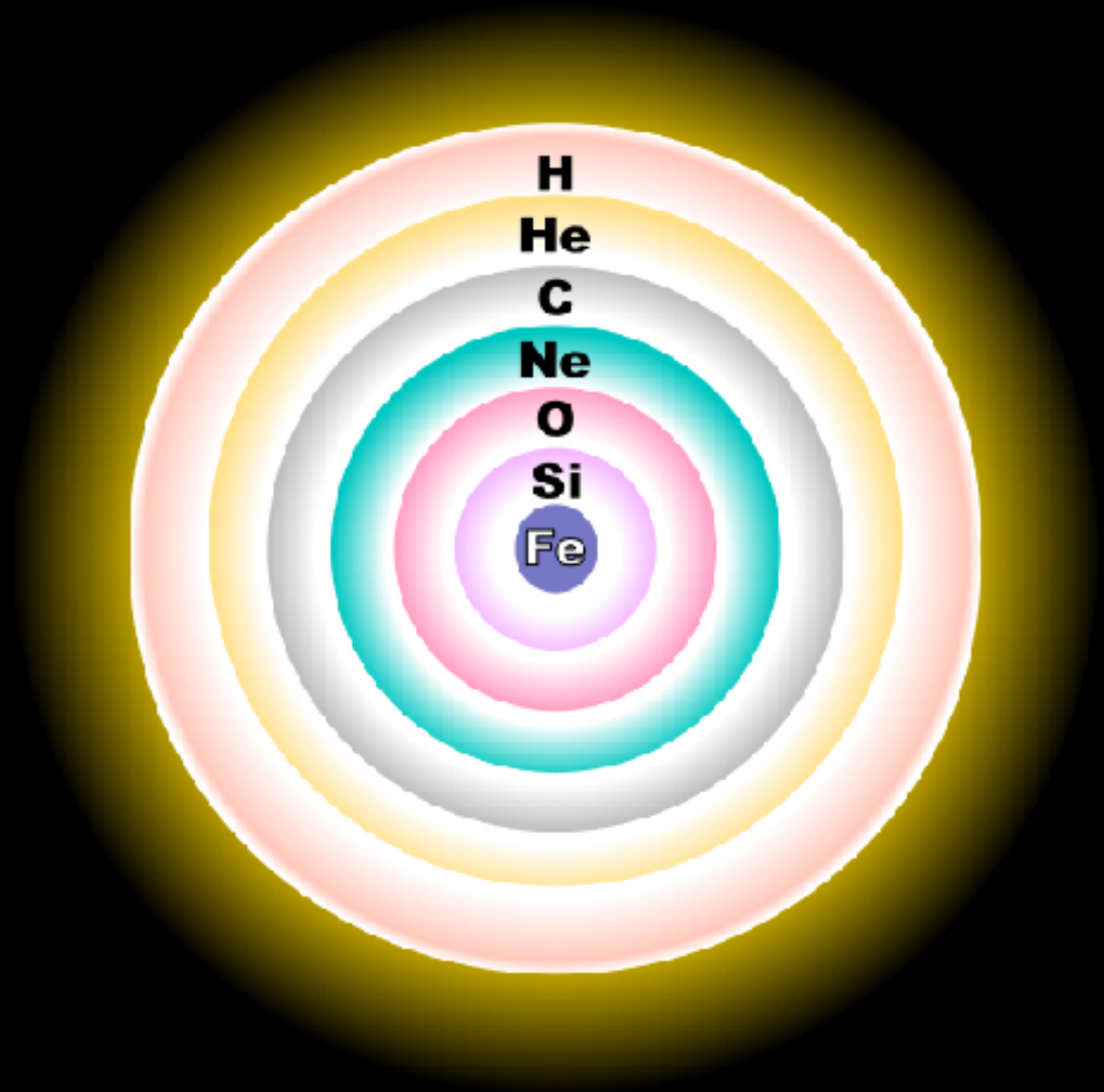
THE REMNANT OF SN 1987A. SOURCE: NASA GSFC.

INTRODUCTION

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

"Iron" Core

R~2000 km

$Y_e \sim 0.45$

$\rho_c \sim 10^{10}$ (g cm^{-3})

"Core-Collapse"

$t \sim 250$ ms

Proto-Neutron Star

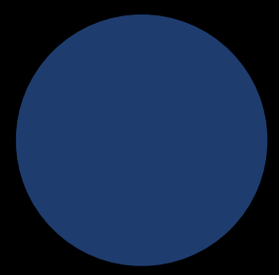
R~50 km

$Y_e \sim 0.27$

$\rho_c \sim 10^{14}$ (g cm^{-3})

PHYSICS OF STELLAR CORE-COLLAPSE

"Bounce"
Stiffening of Core
Launch Shock

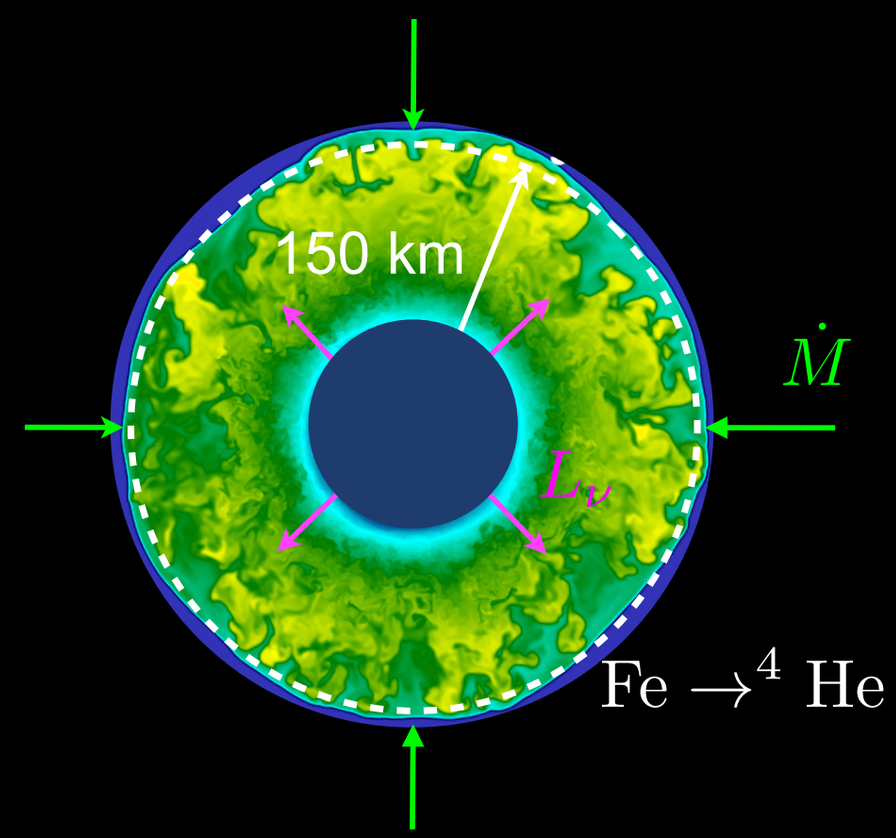


R~50 km

"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).

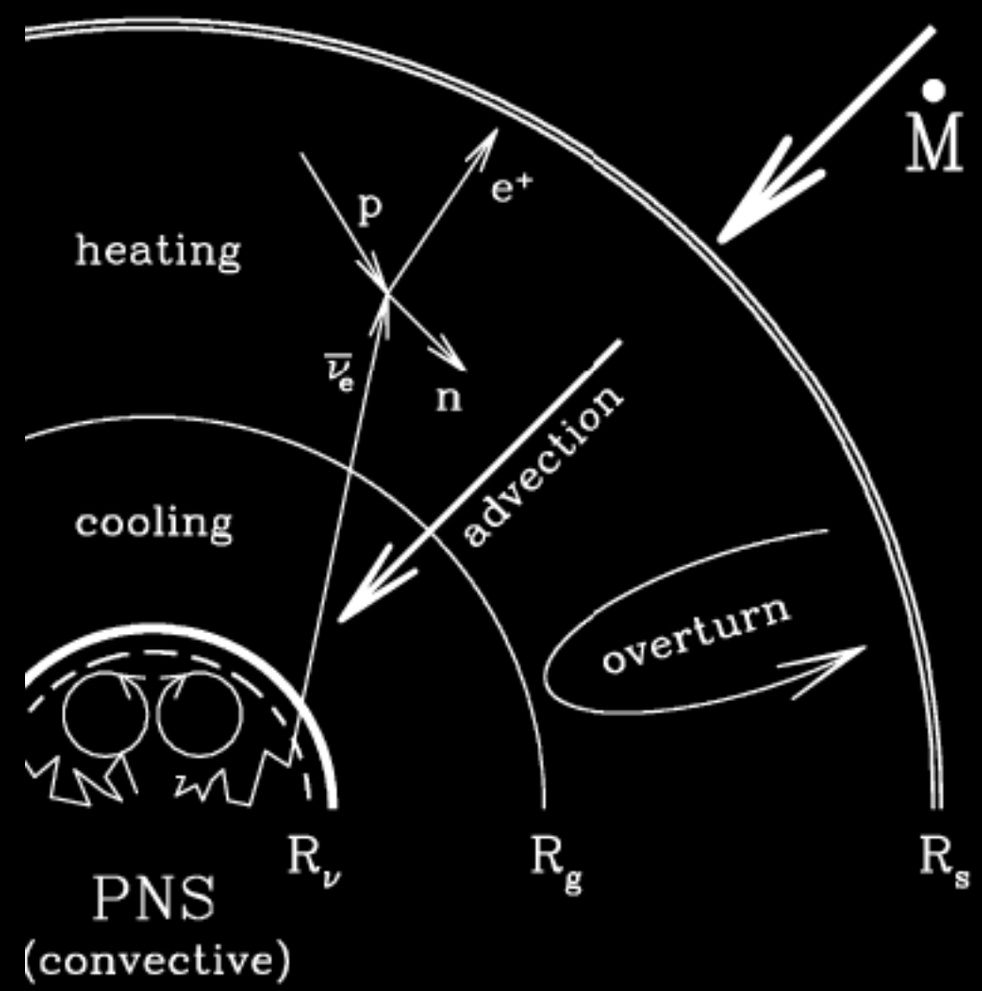


Diagram showing revival of stalled shock.
Credit: Janka (2011).

ERA OF 3D CCSN SIMULATIONS

<u>Fully-coupled!</u>

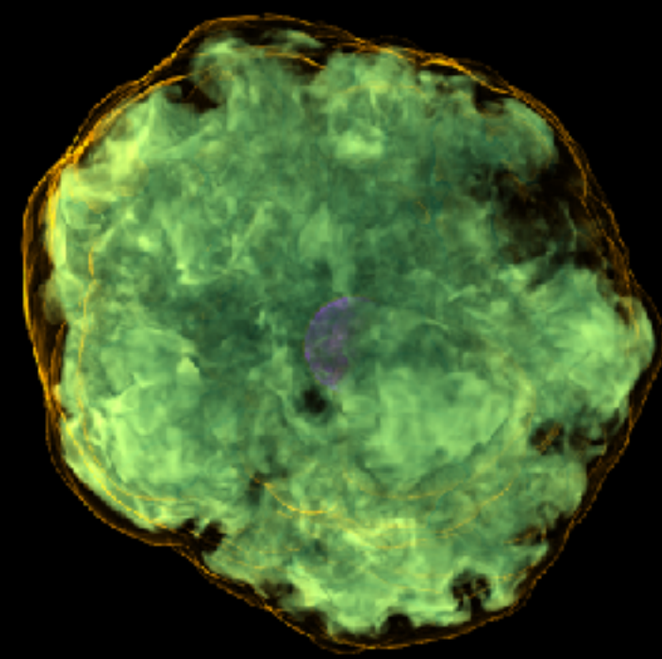
3D Magnetohydrodynamics

General Relativity

Boltzmann ν-transport

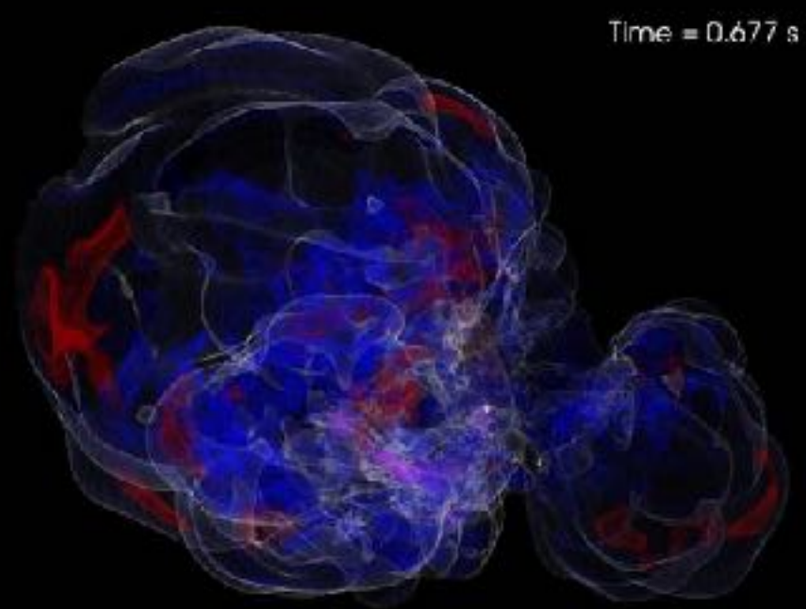
Microphysics
(Nuclear EOS, ν-interactions, nuclear kinetics)

Credit: Sean Couch

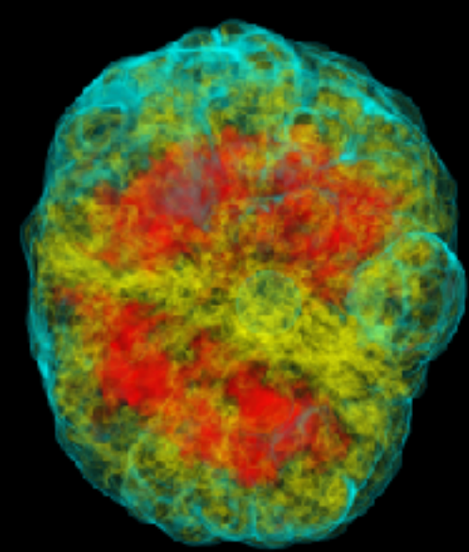


(Fields + 2022b, in prep.)

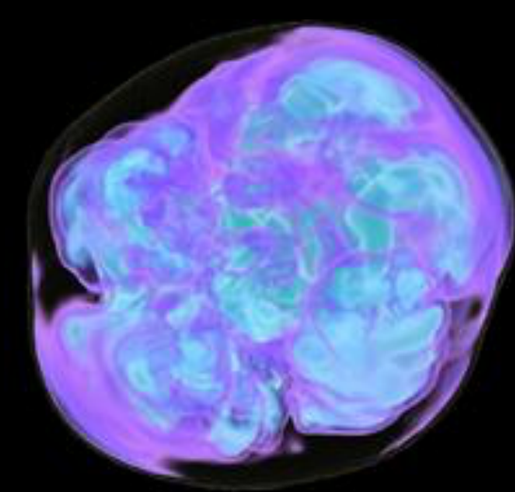
(Moesta + 2014)



(Vartanyan+ 2019)



(Roberts + 2016)



(Burrows + 2019)

Solved problem…right?

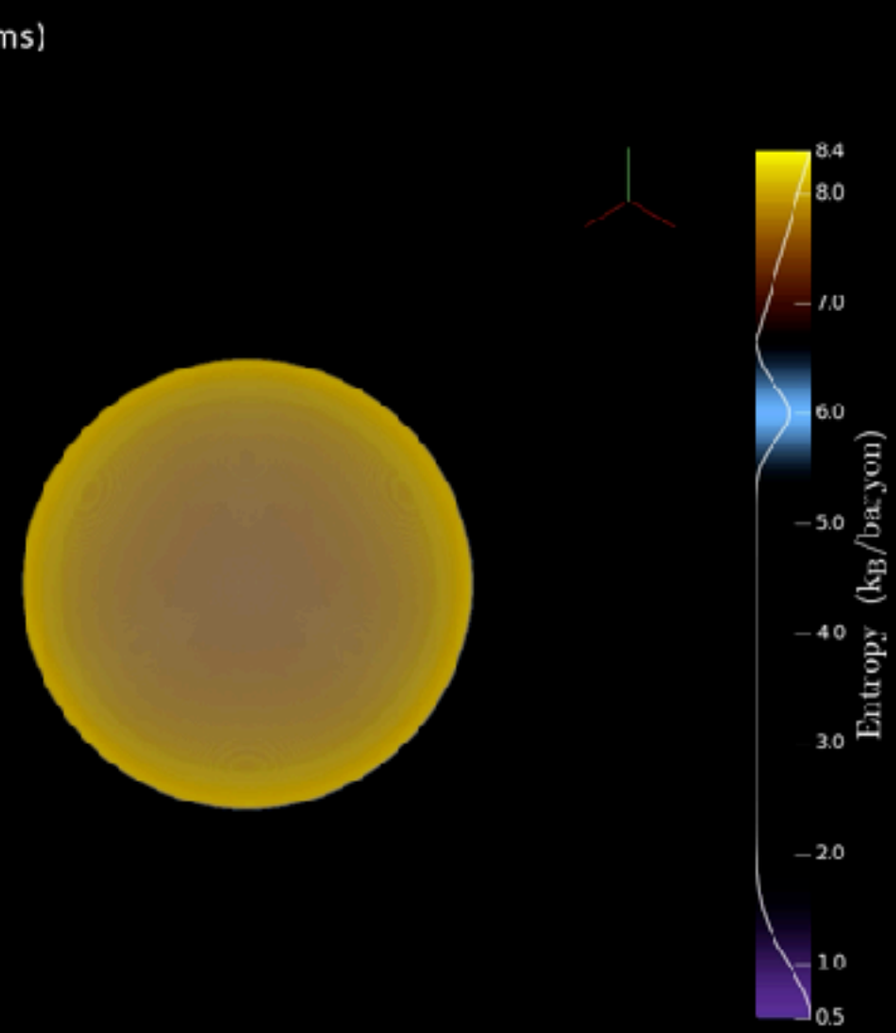
INTRODUCTION

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.

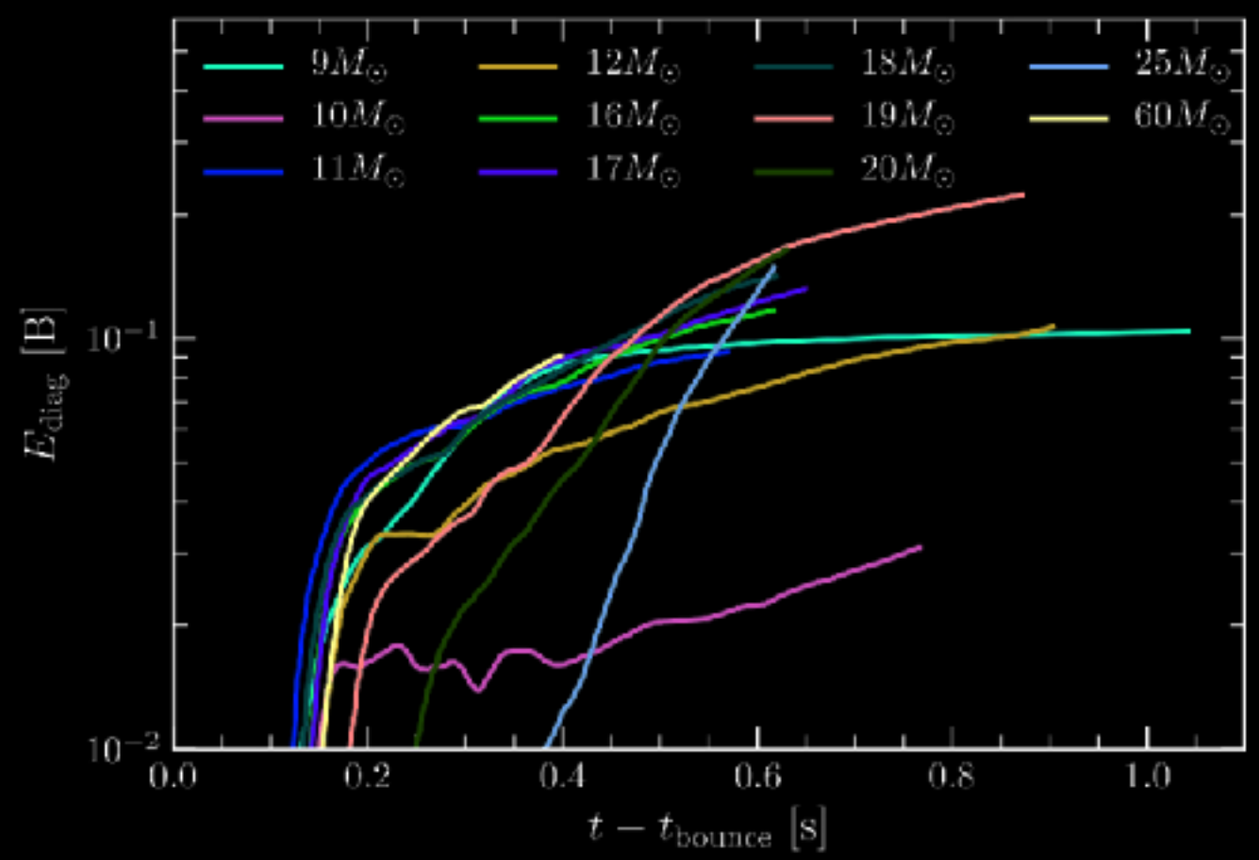


Failed explosion using spherically symmetric 1D model from Couch + 2018.

THE CORE-COLLAPSE 'PROBLEM'

How do we (try) to model stellar explosions?

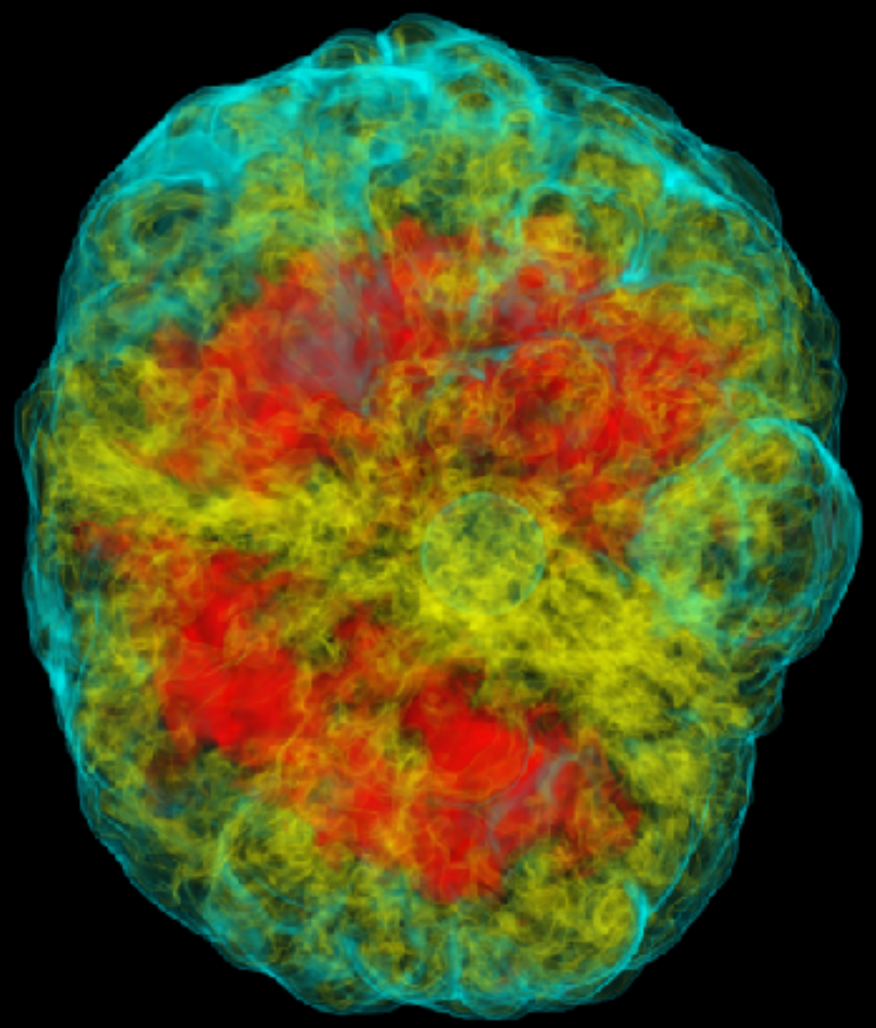
- Struggle to match range of Type IIP explosion energies of ~0.5-4B *(Kasen & Woosely 2015)*.
- 3D exploding models show low energies?
- Need to reach asymptotic plateau requires longer simulations *(Burrows+ 2019)*.



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.

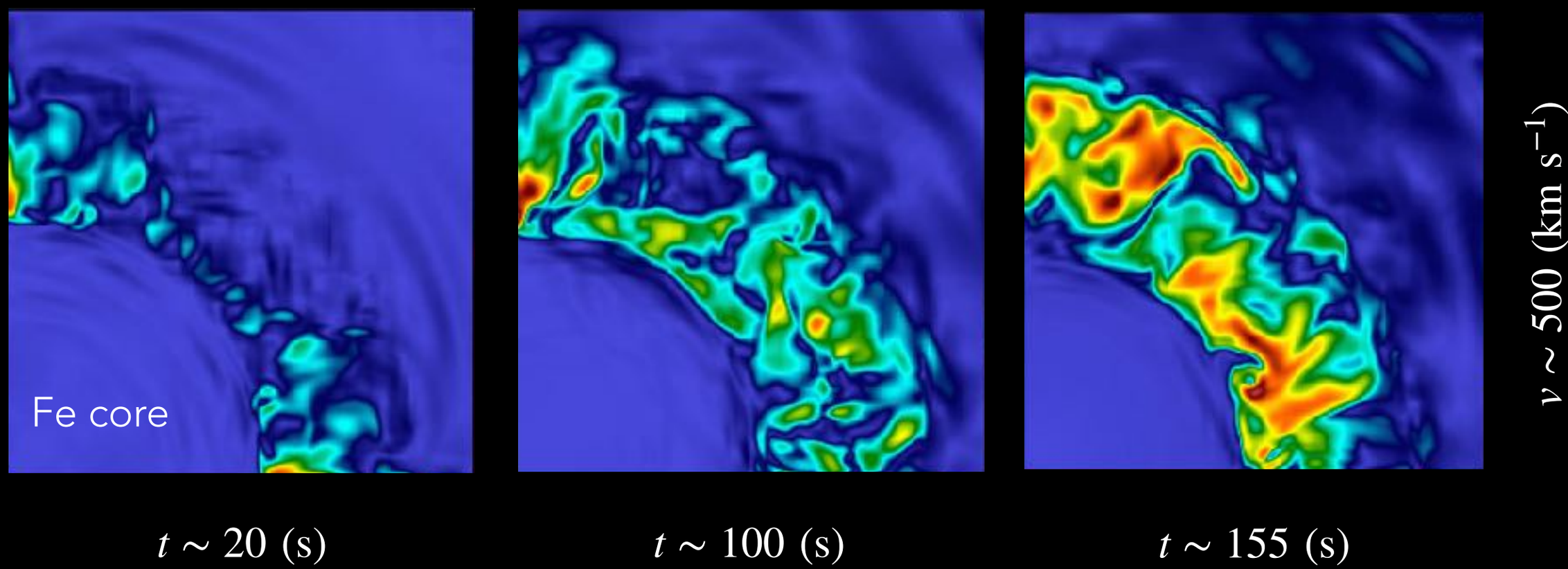


Volume rendering of the entropy distribution from *Roberts + 2016*.

INTRODUCTION

Deeper look in to the Pre-Supernova Models

PERTURBATIONS IN THE PRE-SUPERNOVA MODEL

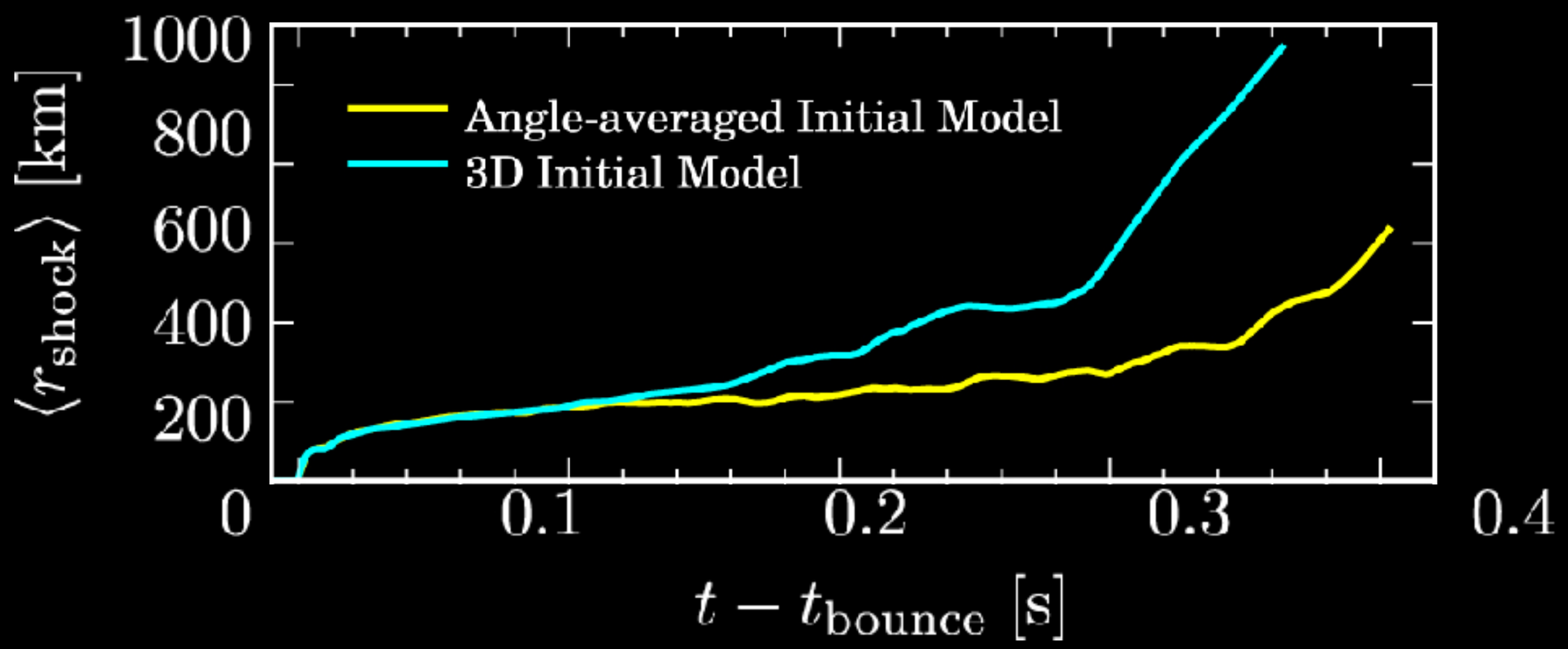


(Couch + ApJL, 2015)

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

PERTURBATIONS IN THE PRE-SUPERNOVA MODEL

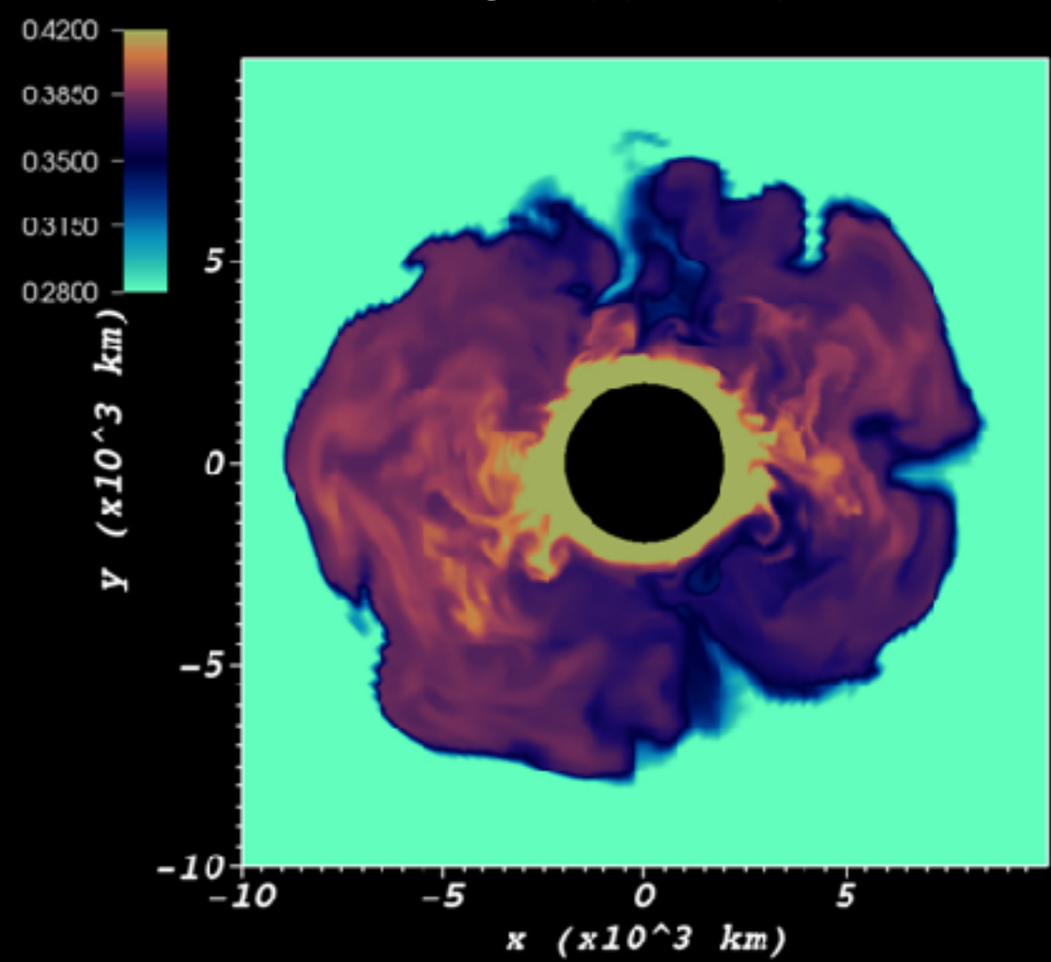
3D Initial model leads to faster, stronger explosion.



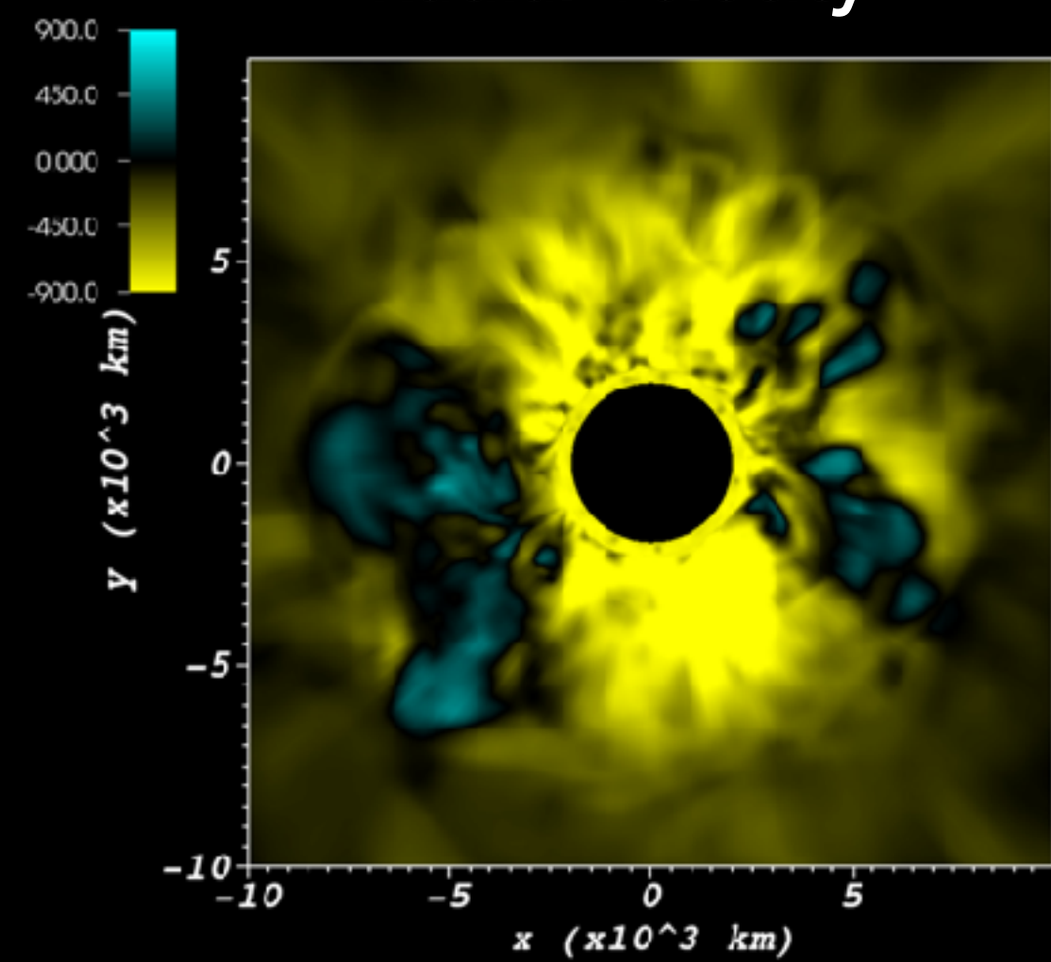
- Multi-D progenitors provide a solution to the core-collapse problem.

MULTI-DIMENSIONAL SIMULATIONS OF MASSIVE STARS

Silicon-28

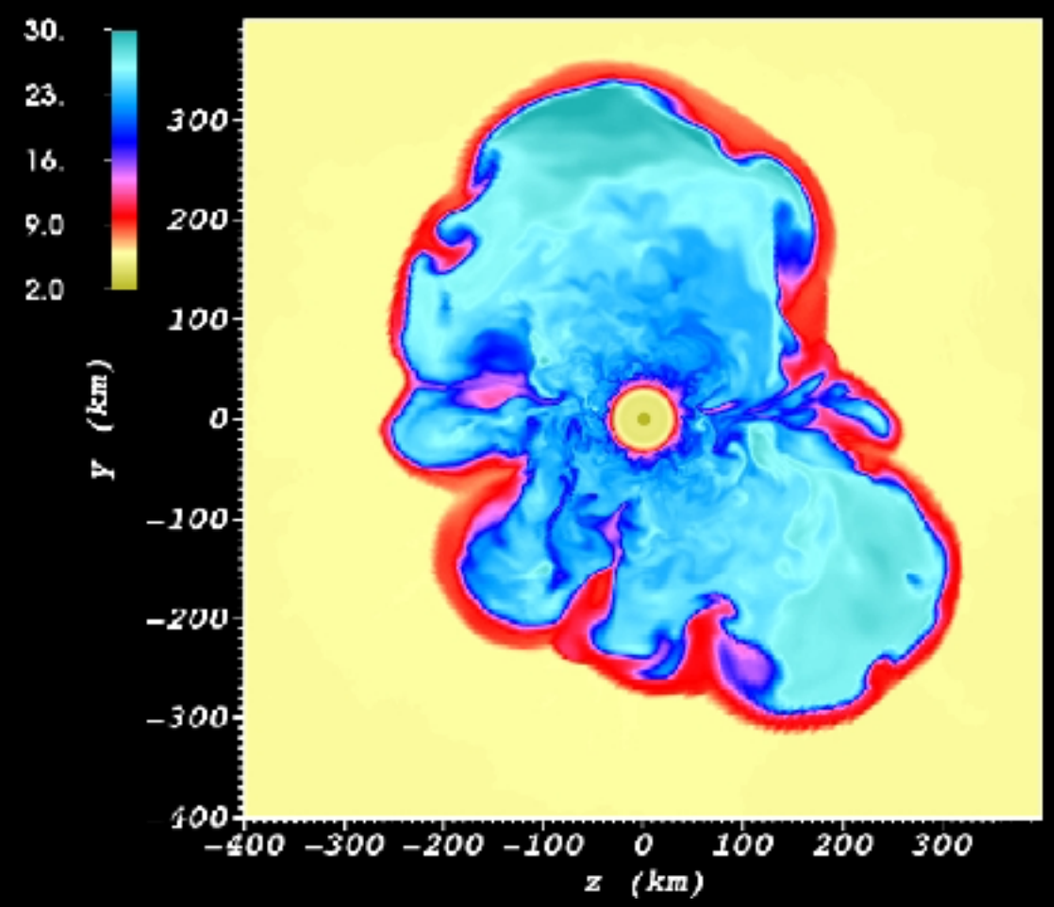


Radial Velocity

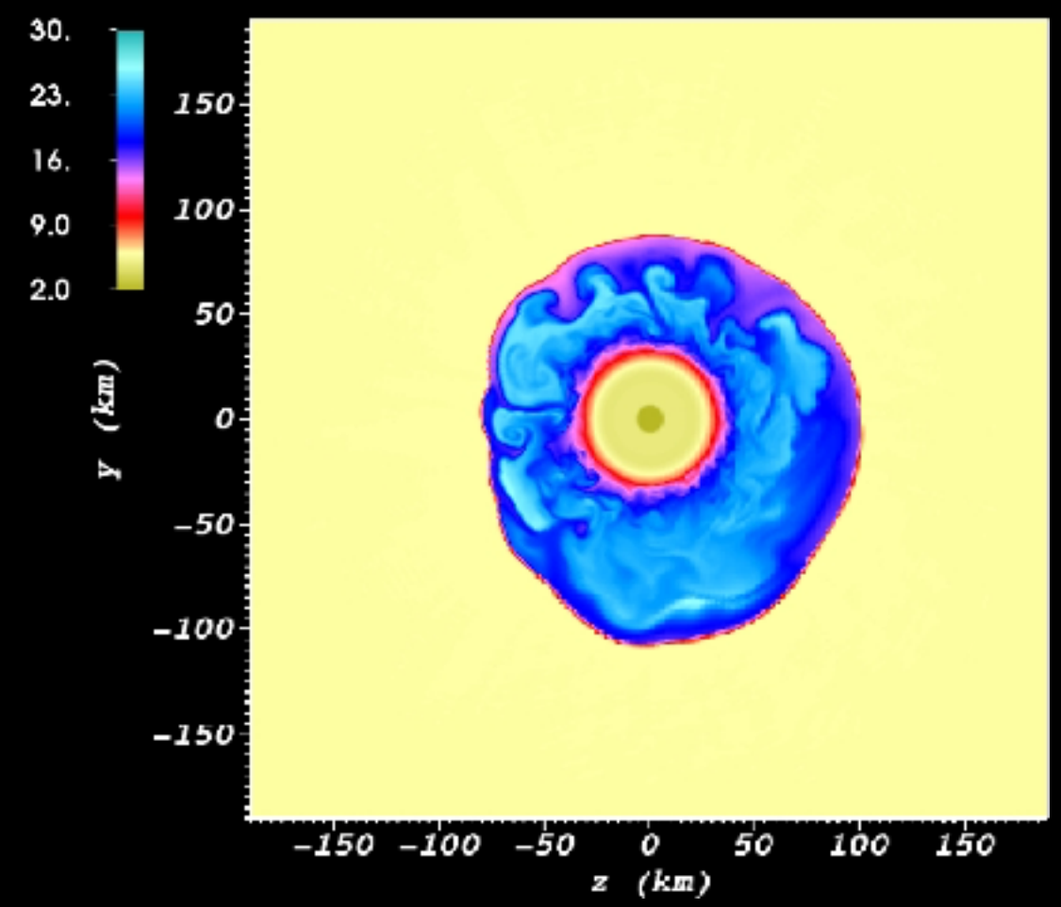


- 4pi simulations of oxygen shell burning find bipolar flow near collapse in simulation of 18 solar mass star. *(Muller +2016)*

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.

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

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

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

(Muller + 2017)

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

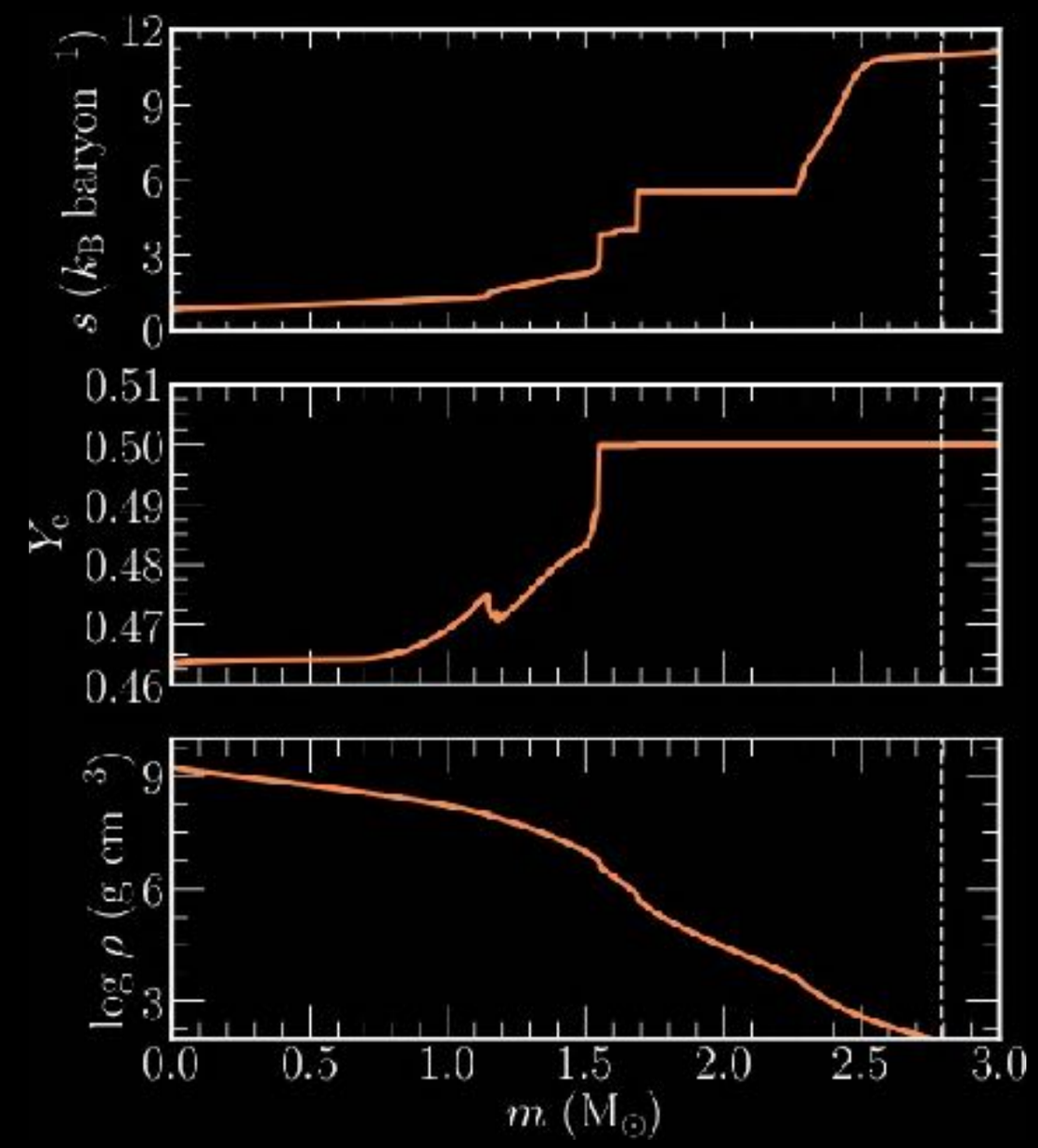
(Couch + 2014, 2015)

3D CCSN PROGENITORS

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

MULTI-DIMENSIONAL SIMULATIONS OF MASSIVE STARS

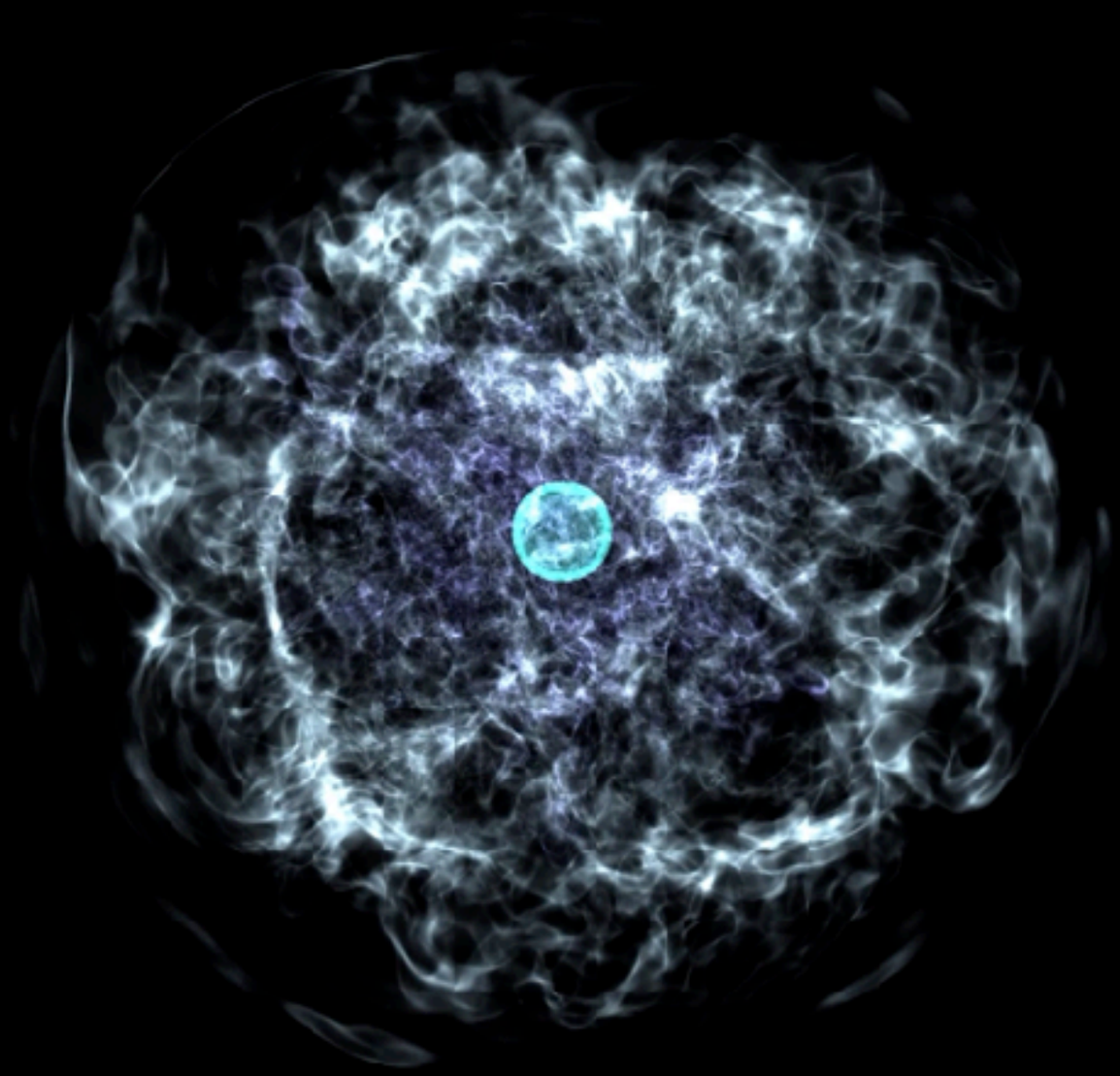
- 2/3D Hydrodynamic simulations using FLASH.
- Evolved ~**7 minutes** collapse using approximate network.
- 15 $M_\odot$ progenitor.



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

MULTI-DIMENSIONAL SIMULATIONS OF MASSIVE STARS

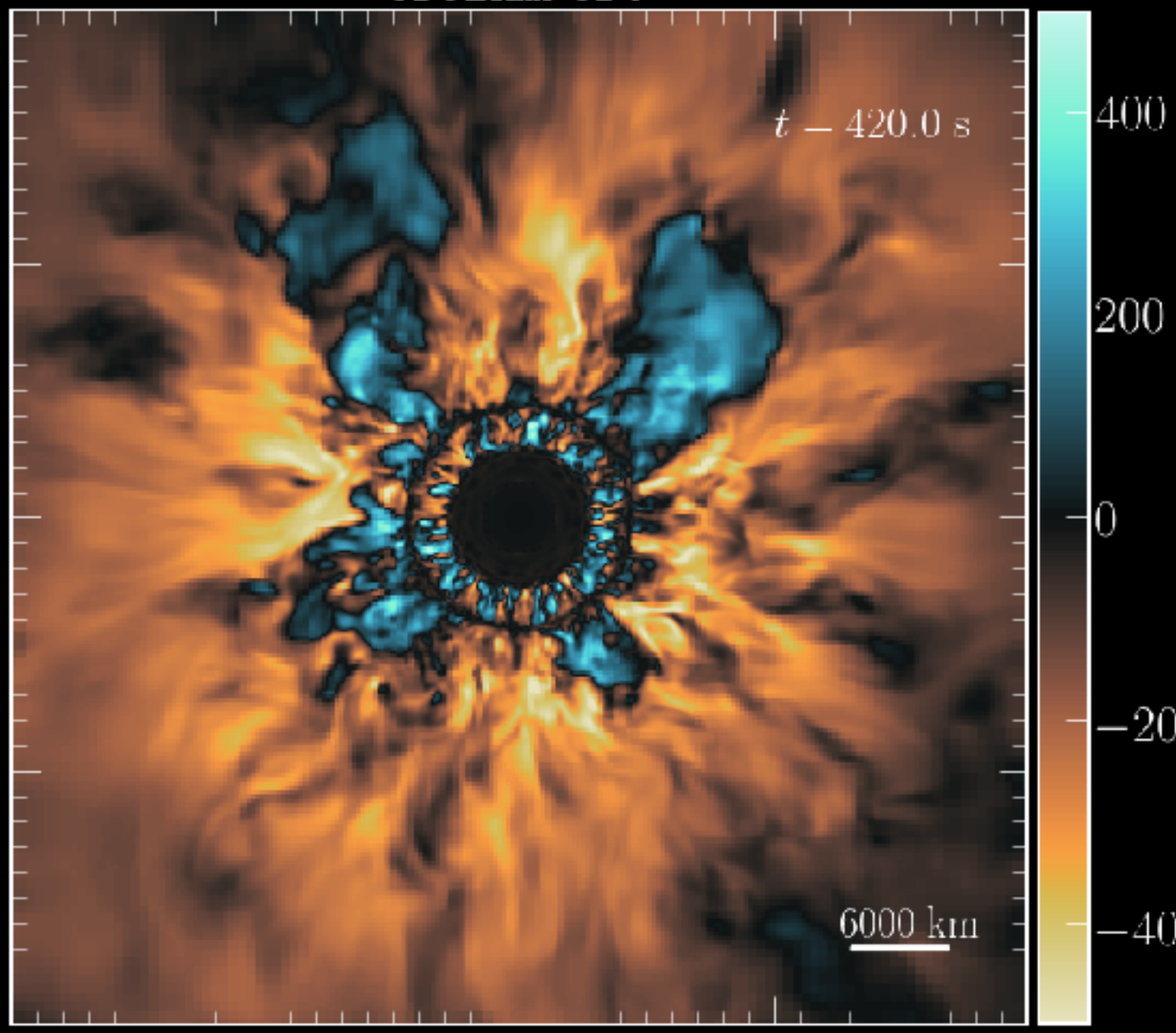
- 3D model evolved using FLASH.
- Shell convection occurring at many scales.
- Perturbations imply indirect **increase** in effective neutrino heating efficiency.



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

MULTI-DIMENSIONAL SIMULATIONS OF MASSIVE STARS

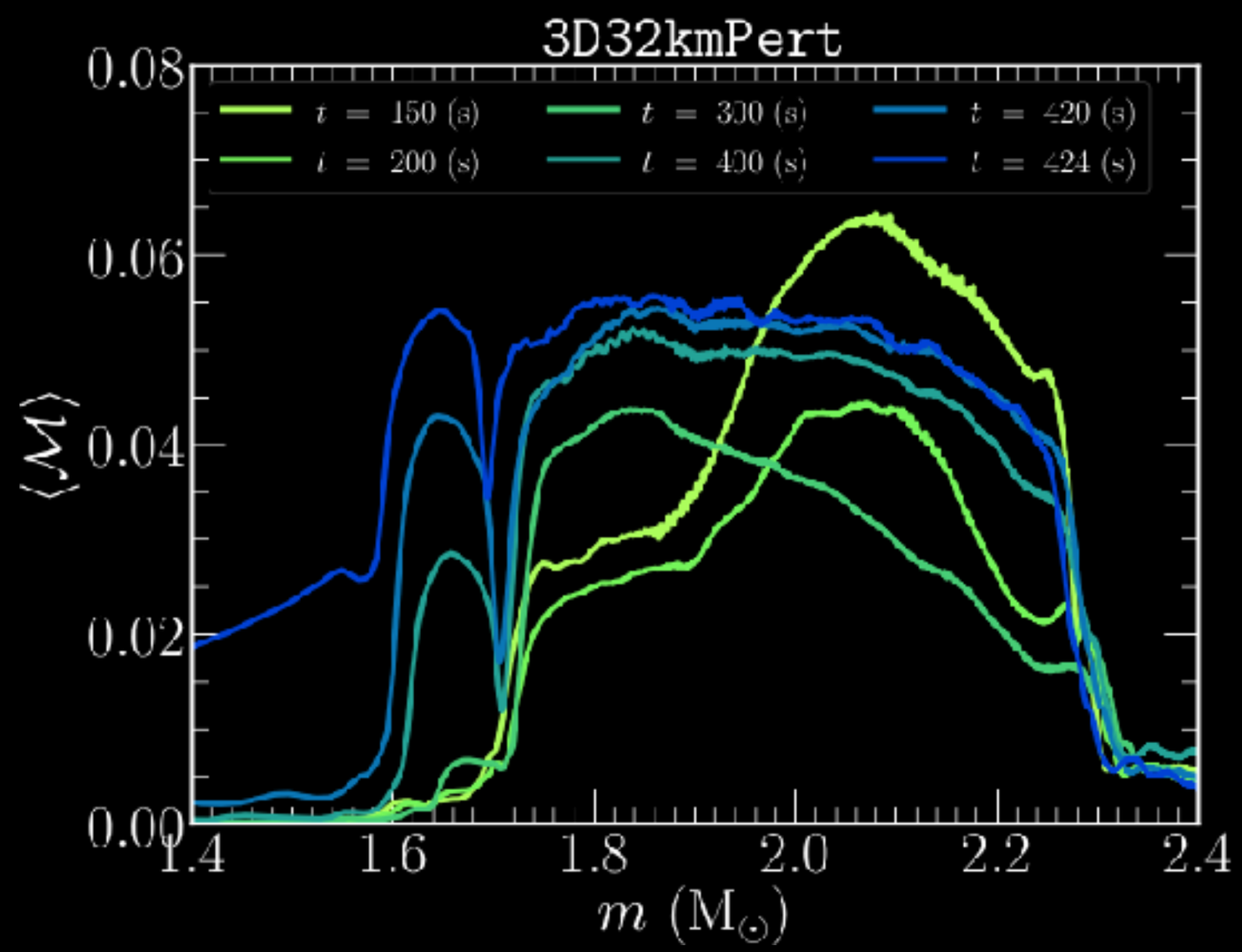
- 4 pi 3D model shows large scale plumes.
- Strong Si-shell convection.
- Convective speeds of several hundred km/s.



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

MULTI-DIMENSIONAL SIMULATIONS OF MASSIVE STARS

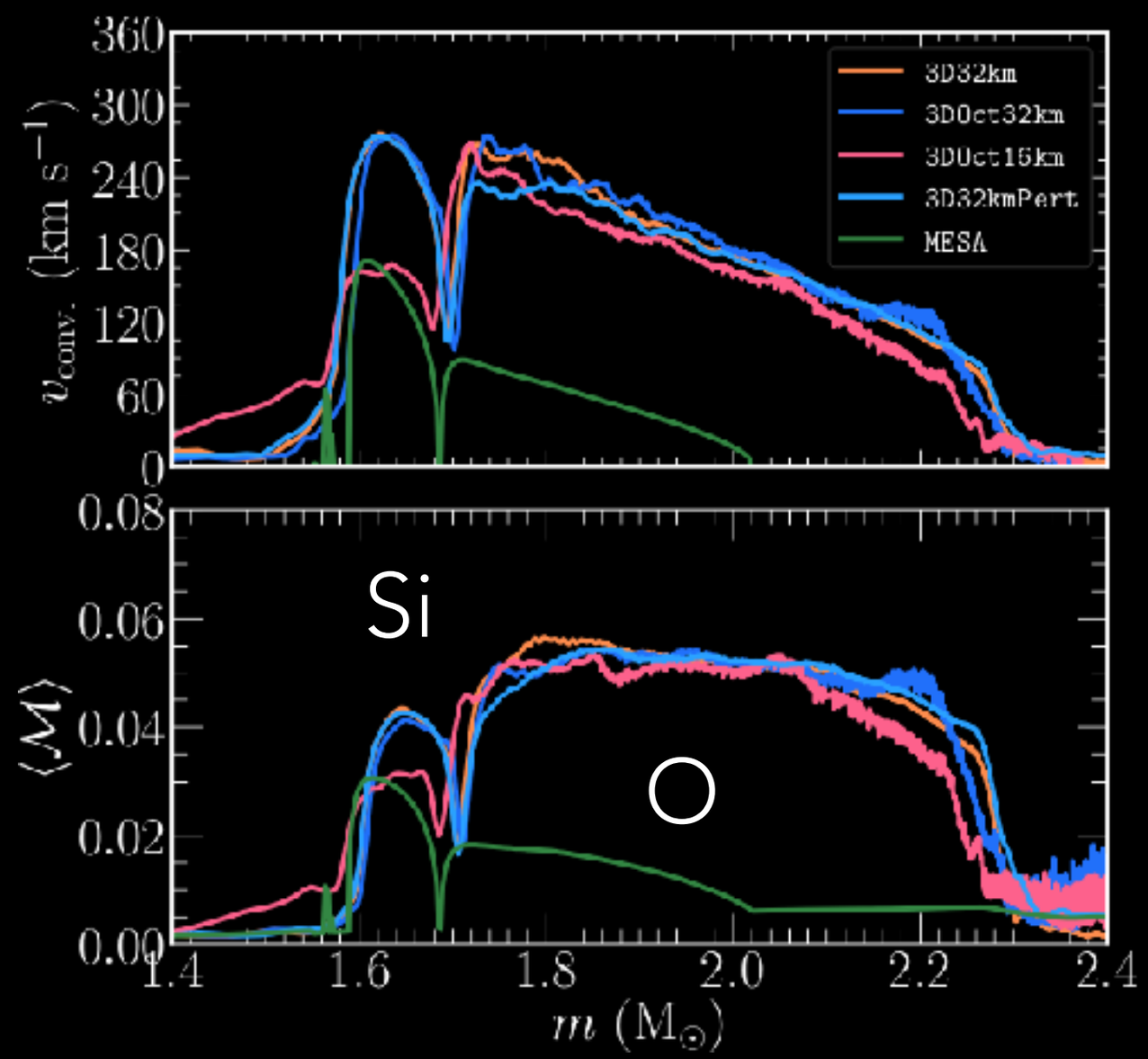
- Significant increase in Si-shell mach numbers at late time.
- Oxygen-shell reaches steady values early on.
- Values in O-shell lower than previous studies (Muller+2016)



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

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.

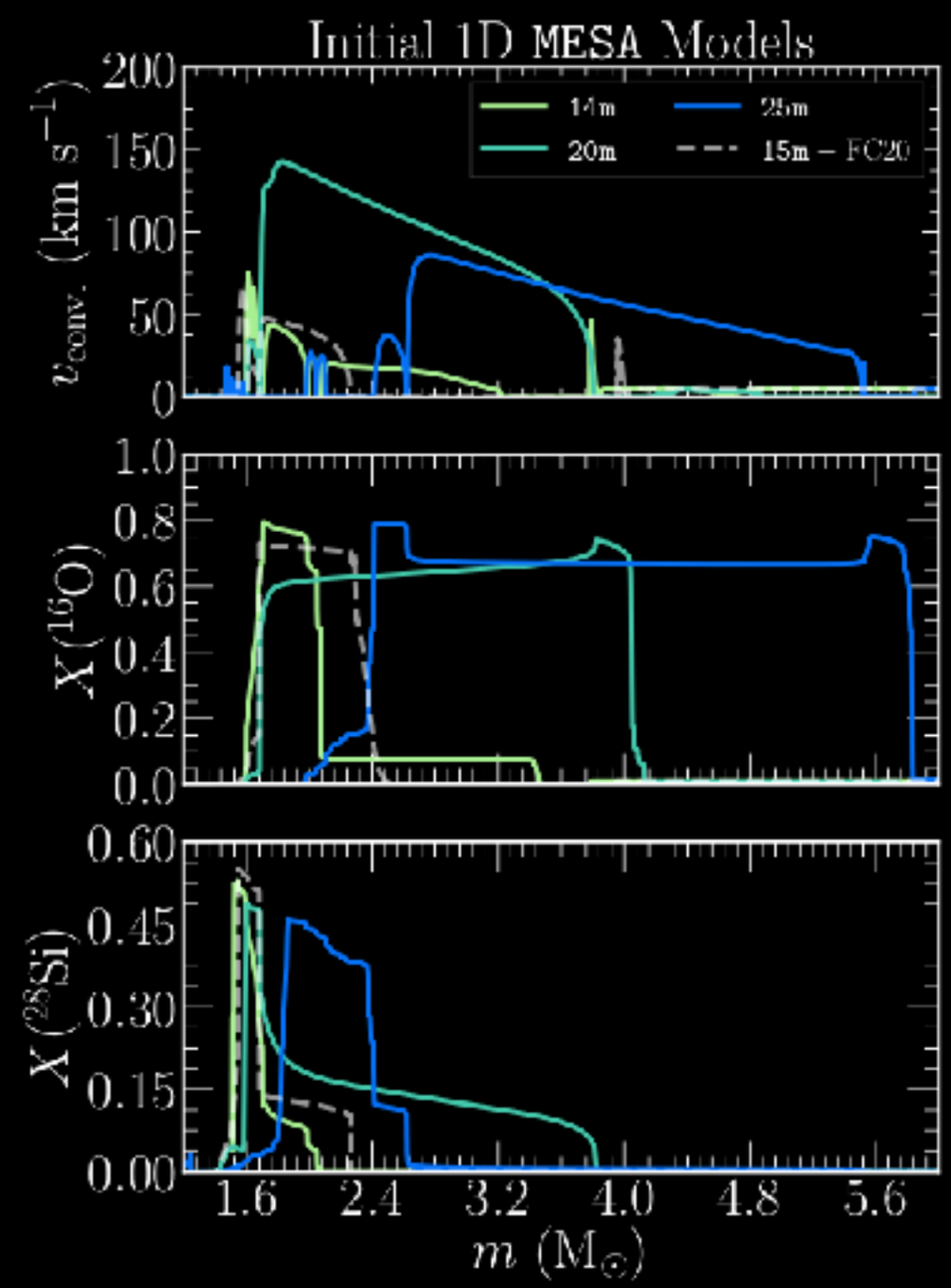


Angle average mach number profiles for all models at different times ***(Fields & Couch 2020)***.

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.



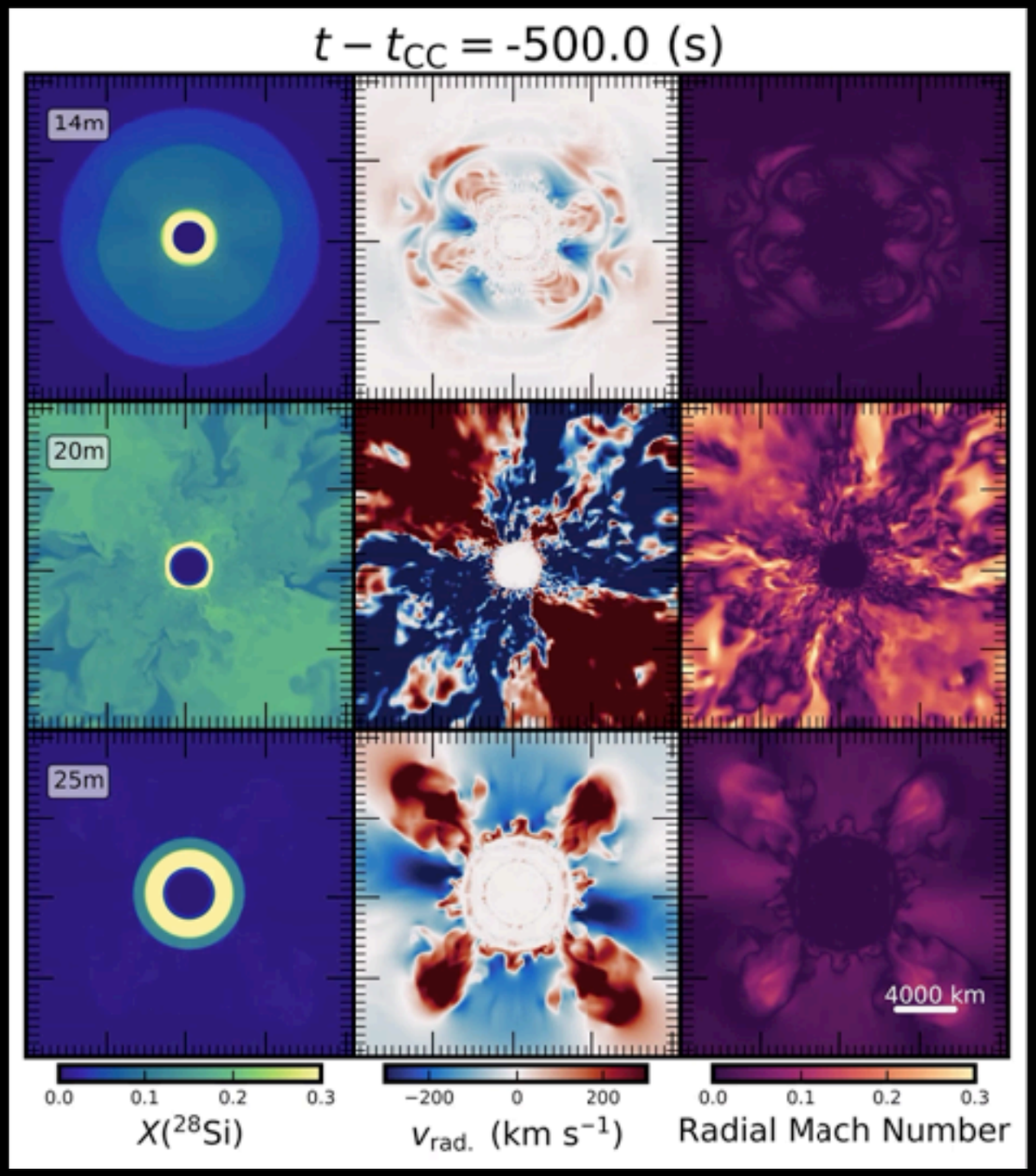
Initial 1D profile structure for 3D models.

(Fields & Couch 2021a.)

MASSIVE STAR CONVECTION IN MULTIPLE PROGENITORS

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

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



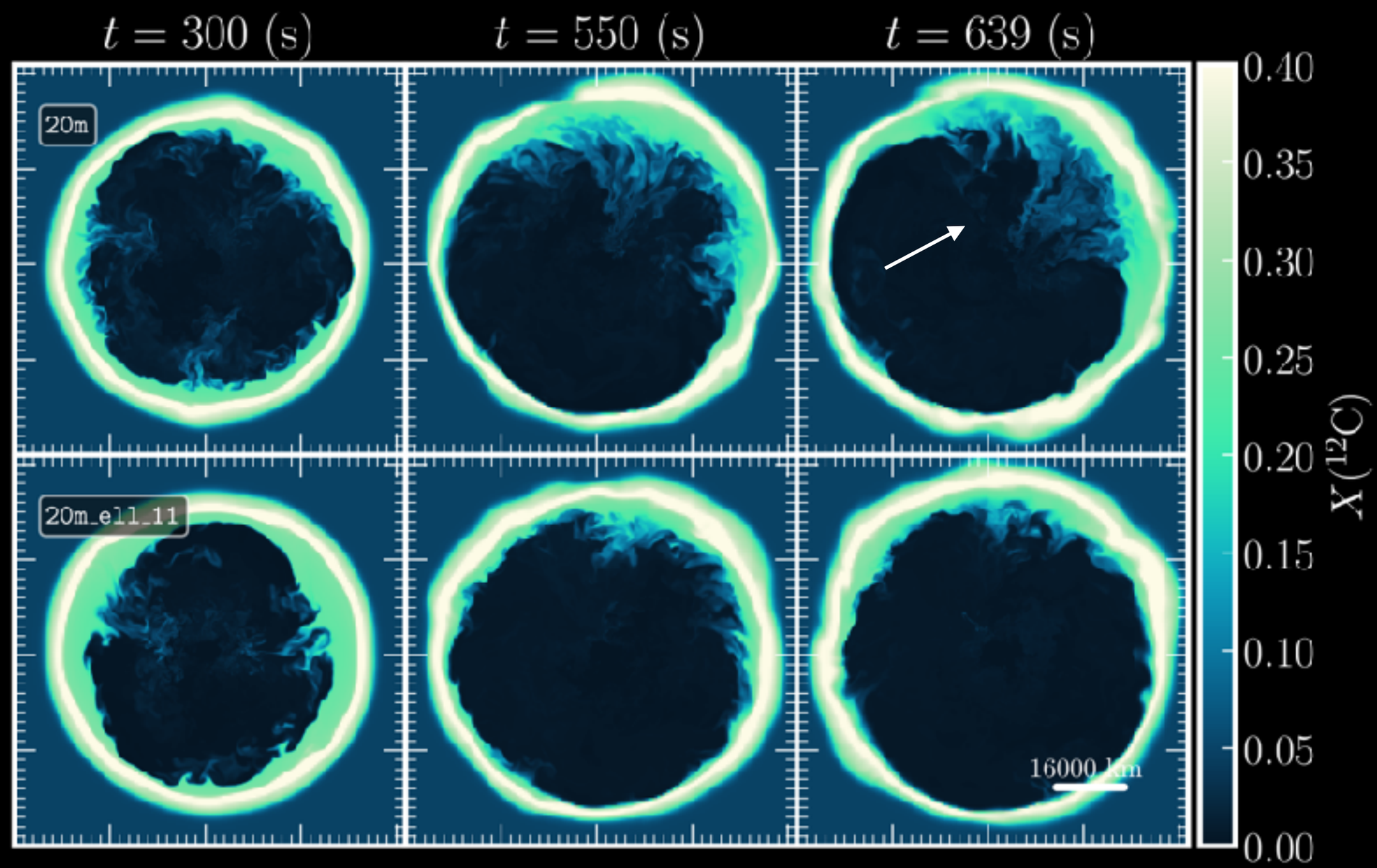
SIMULATIONS OF MASSIVE STAR CONVECTION IN MULTIPLE PROGENITORS

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

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

Volume rendering of the velocity field for 3D progenitor model near collapse ***(Fields & Couch 2021a.)***.

MASSIVE STAR CONVECTION IN MULTIPLE PROGENITORS



$$(5.2 - 7.5) \times 10^{-4} M_\odot \ \mathrm{yr}^{-1}$$

(Fields & Couch 2021a.).

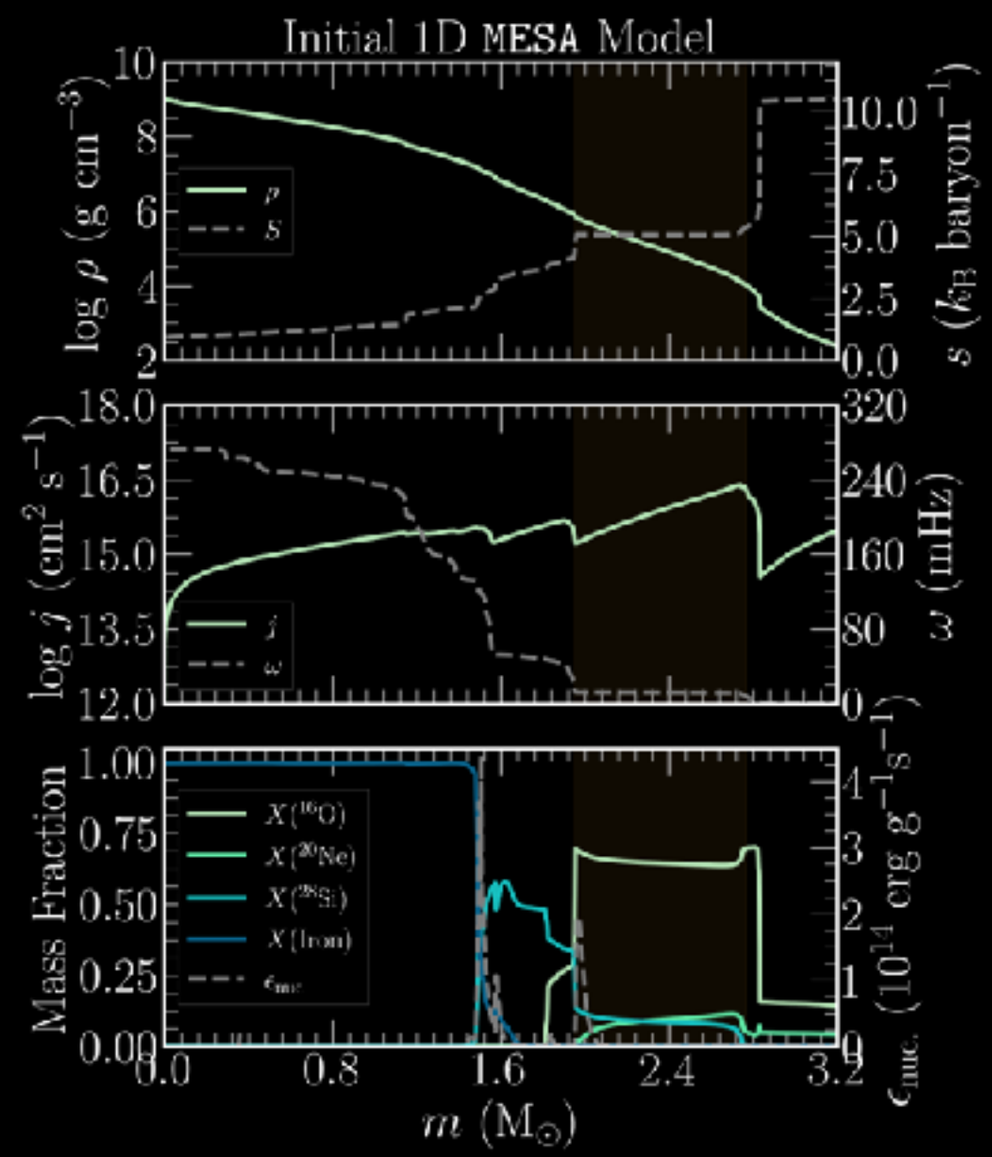
C-ingestion in the O-shell region affected by initial perturbations.

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.



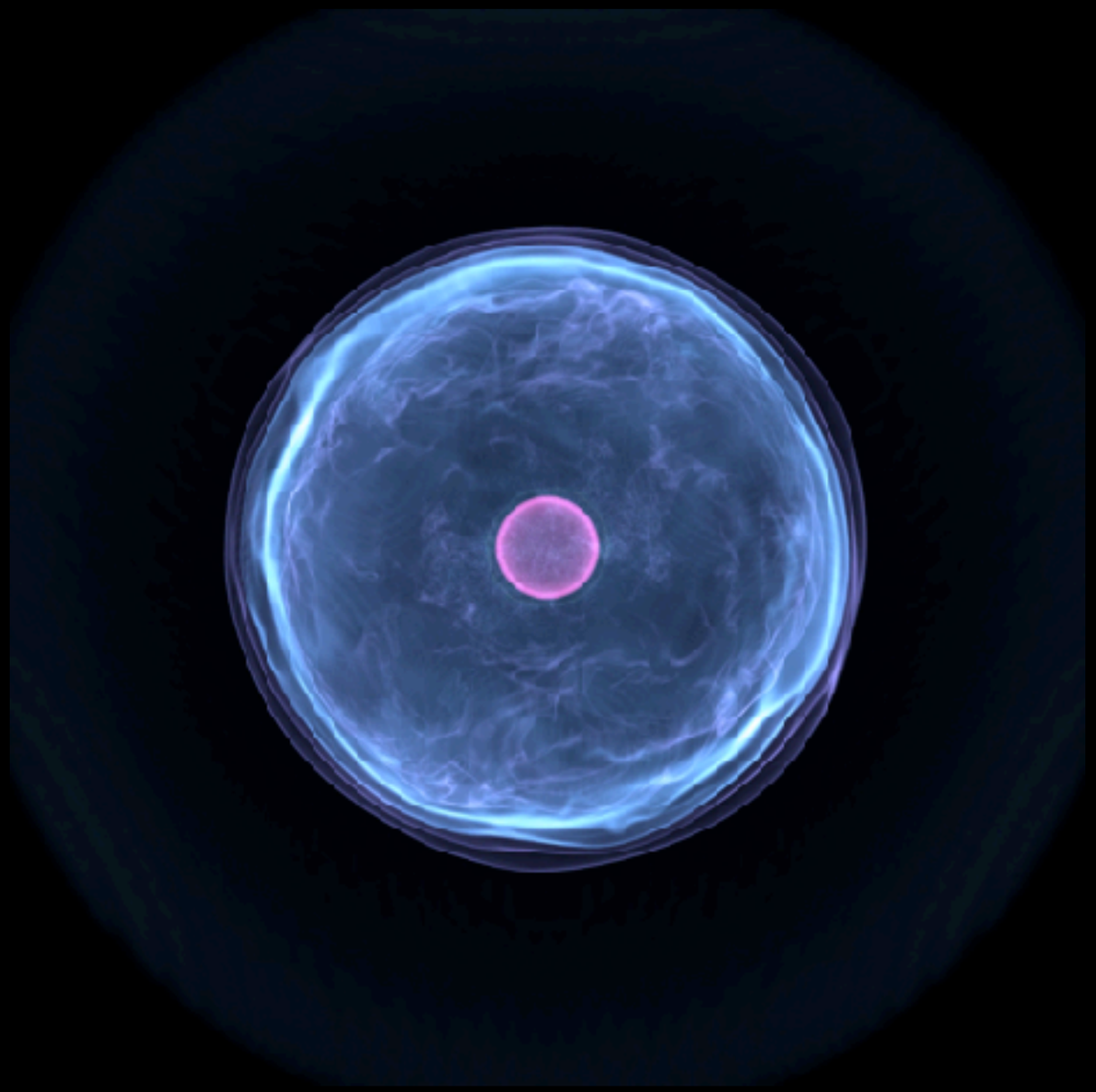
Initial 1D profile structure for 3D model.

(Fields 2021, in prep.)

MASSIVE STAR CONVECTION IN ROTATING PROGENITORS

Preliminary

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

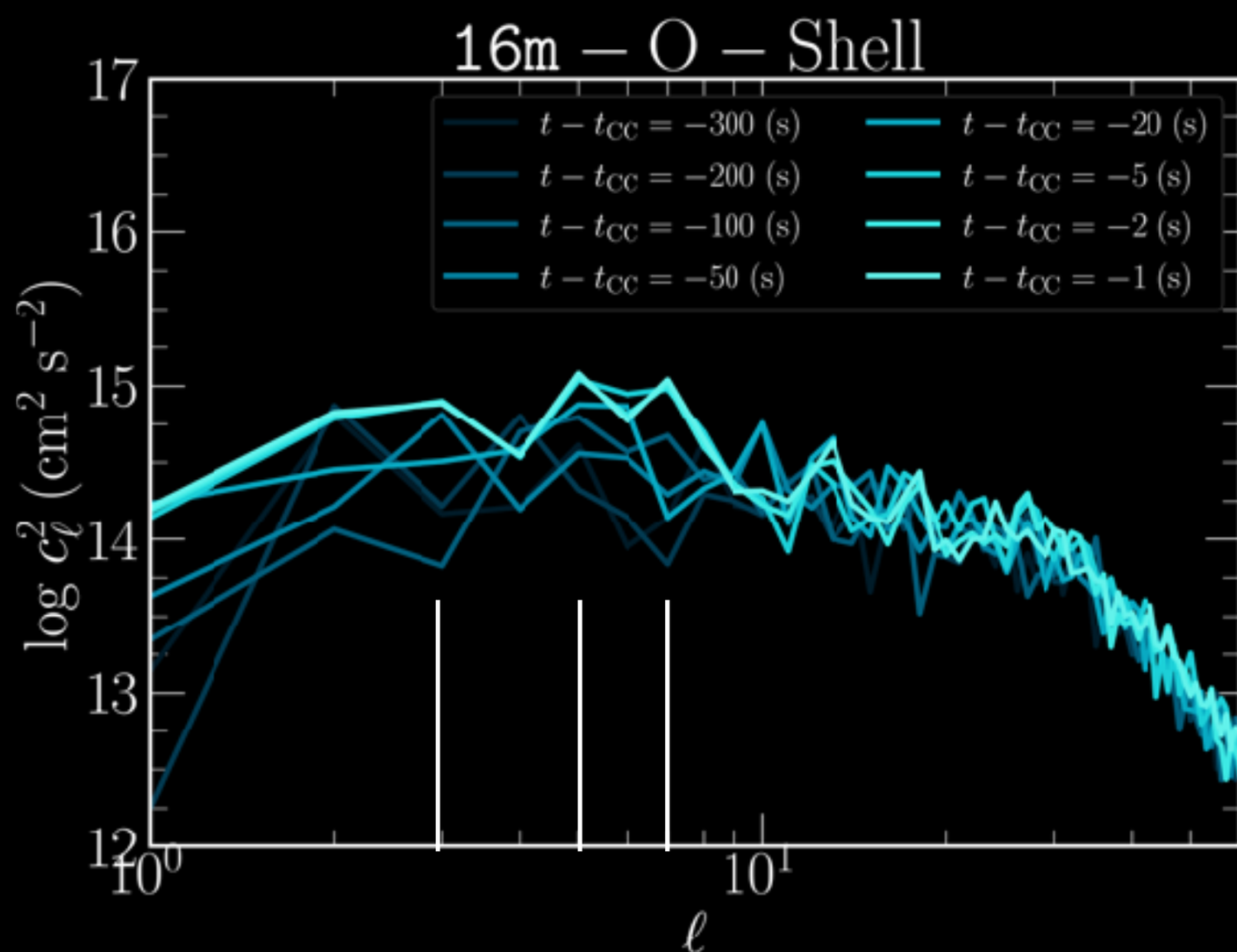


Volume rendering of the Ne-20 mass fraction.
(Fields 2021, in prep.)

MASSIVE STAR CONVECTION IN ROTATING PROGENITORS

Preliminary

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



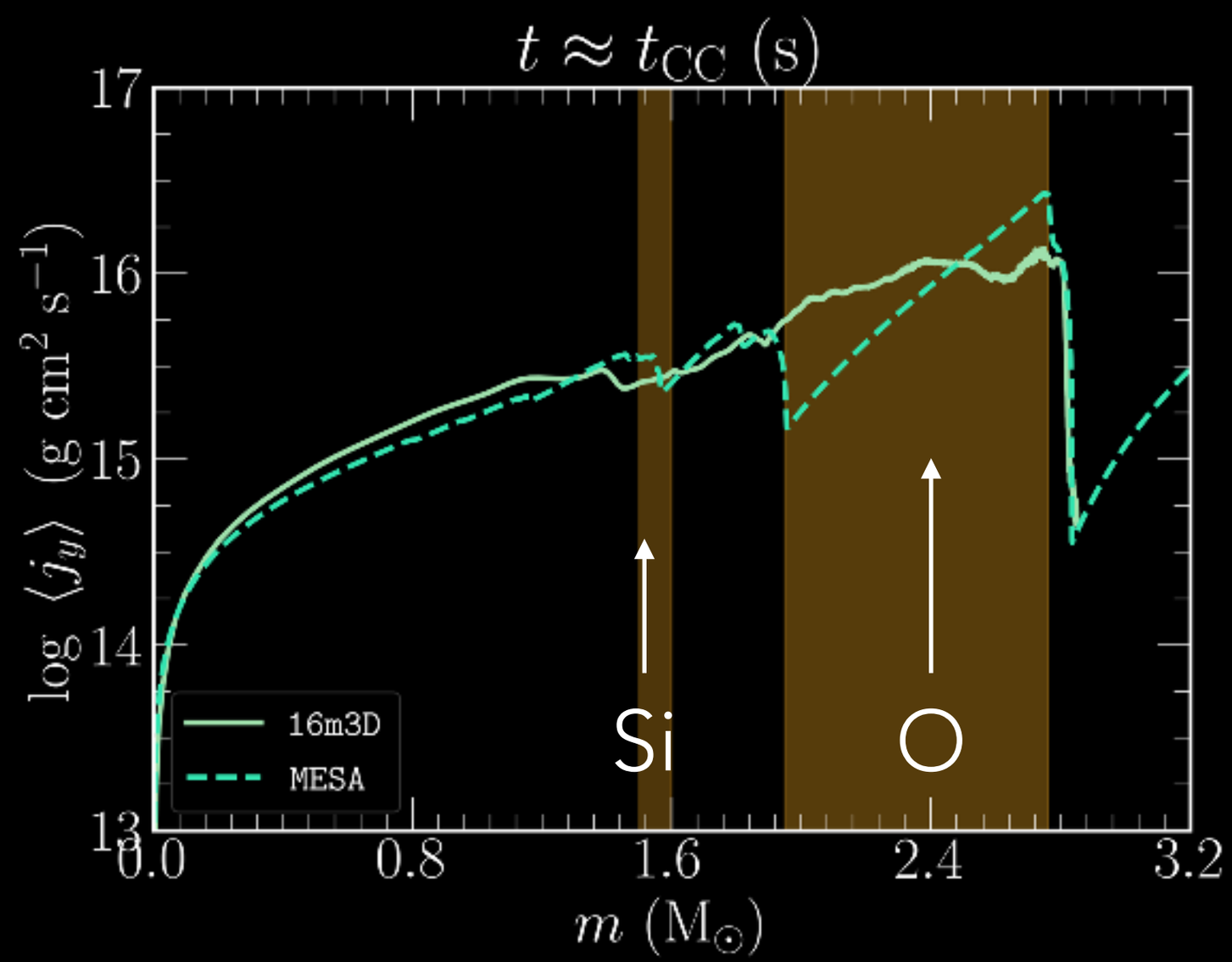
Spectrum of radial velocity field for 3D rotating progenitor.

(Fields 2021, in prep.)

MASSIVE STAR CONVECTION IN ROTATING PROGENITORS

Preliminary

- AM profile diverges from MESA in convective regions.
- 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.

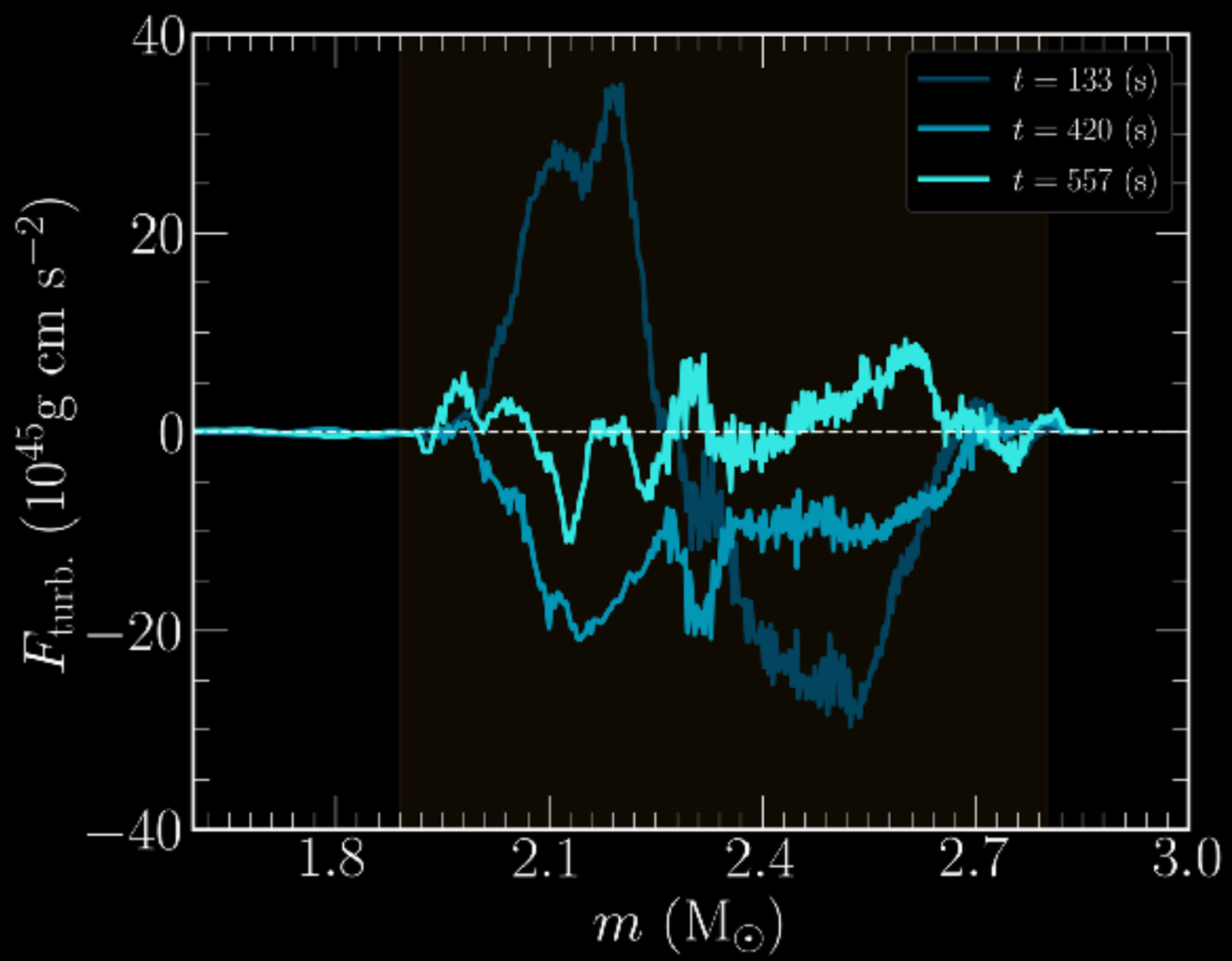
(Fields 2021, in prep.)

MASSIVE STAR CONVECTION IN ROTATING PROGENITORS

Preliminary

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

$$F_{\text{turb.}} = \left\langle \rho v_r'' j_y'' \right\rangle$$



Angular momentum flux profiles.

(Fields 2021, in prep.)

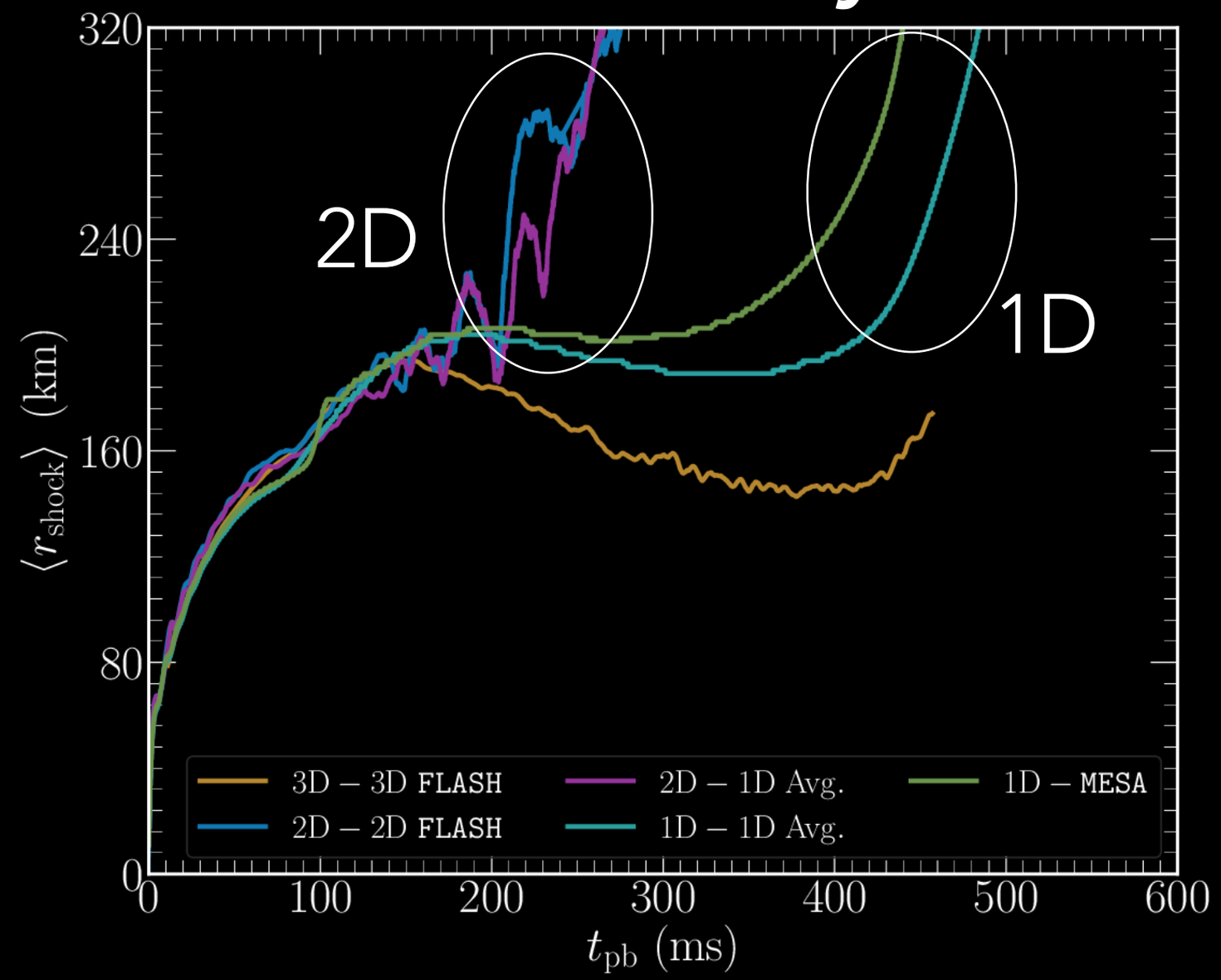
3D CCSN PROGENITORS

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



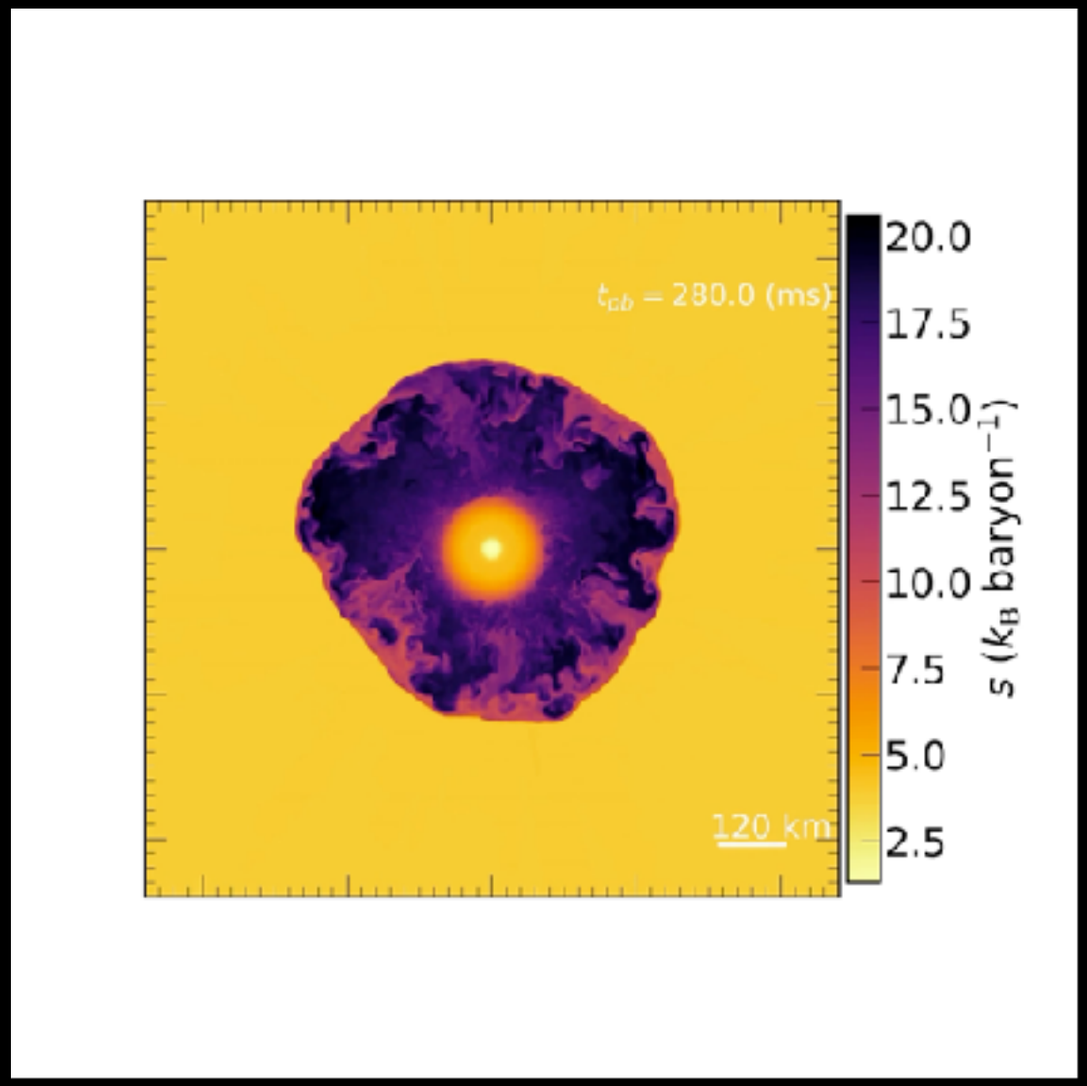
Mean shock radius evolution for multi-D CCSN models

(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



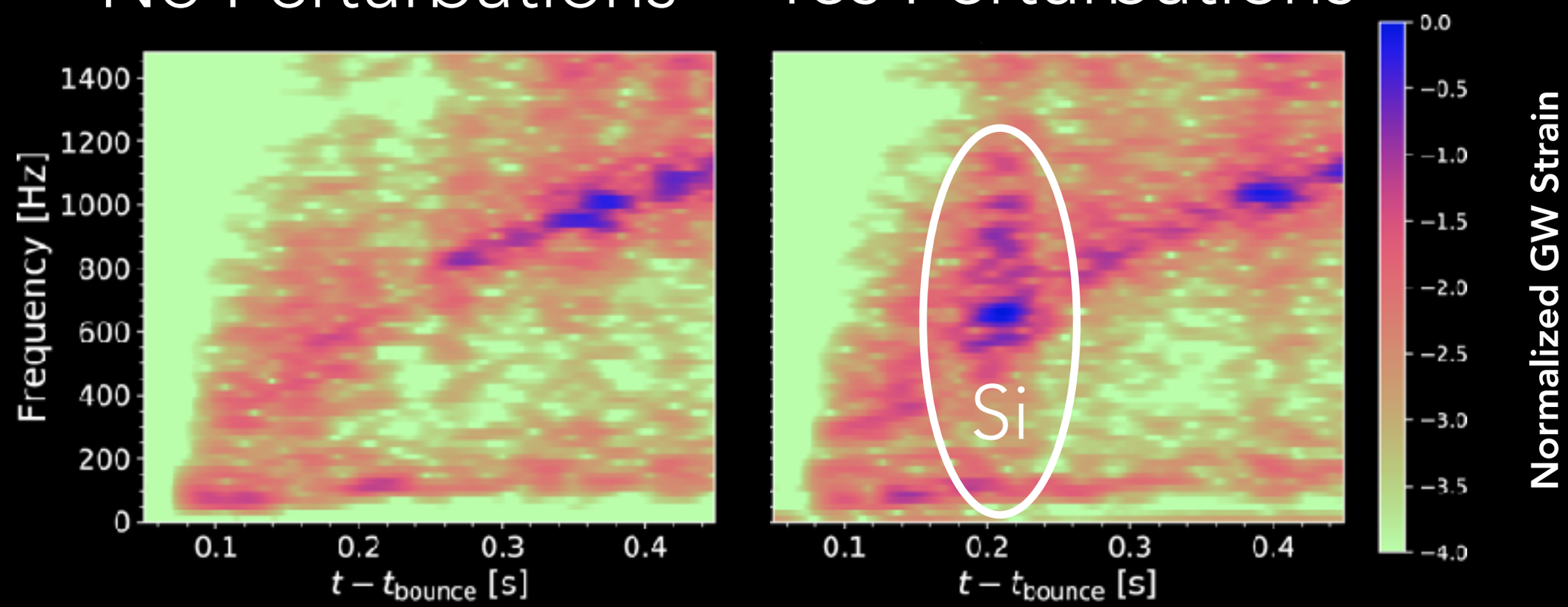
Slice of entropy in the x-y plane for 3D CCSN model

(Fields + 2021b, in prep.).

IMPACT ON MULTI-MESSENGER ASTRONOMY

Impact of 3D progenitor on GW emission?

No Perturbations Yes Perturbations

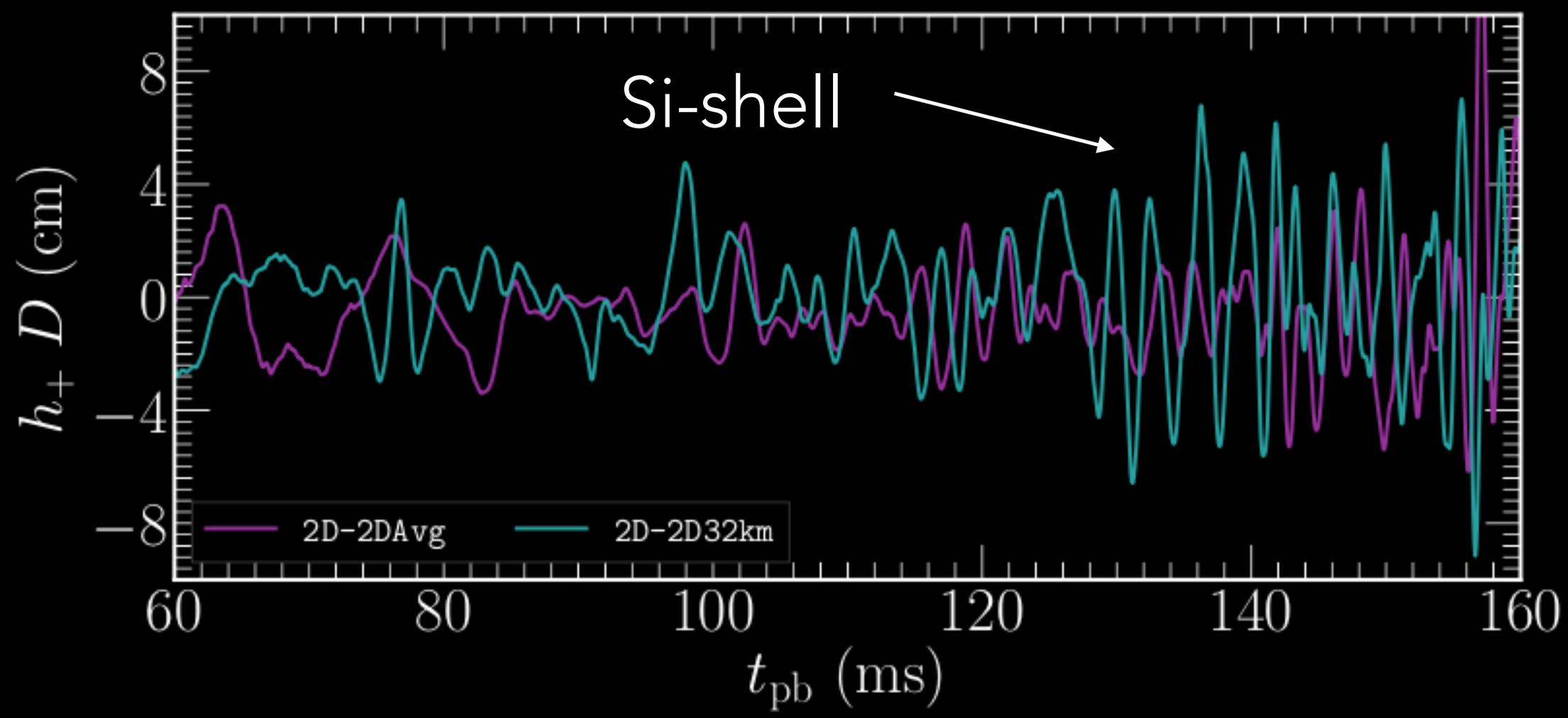


(O'Connor & Couch, 2018)

Si-shell perturbations shown in GW emission.

CCSN EXPLOSIONS OF MULTI-D PROGENITORS

Impact of perturbations on GW emission?

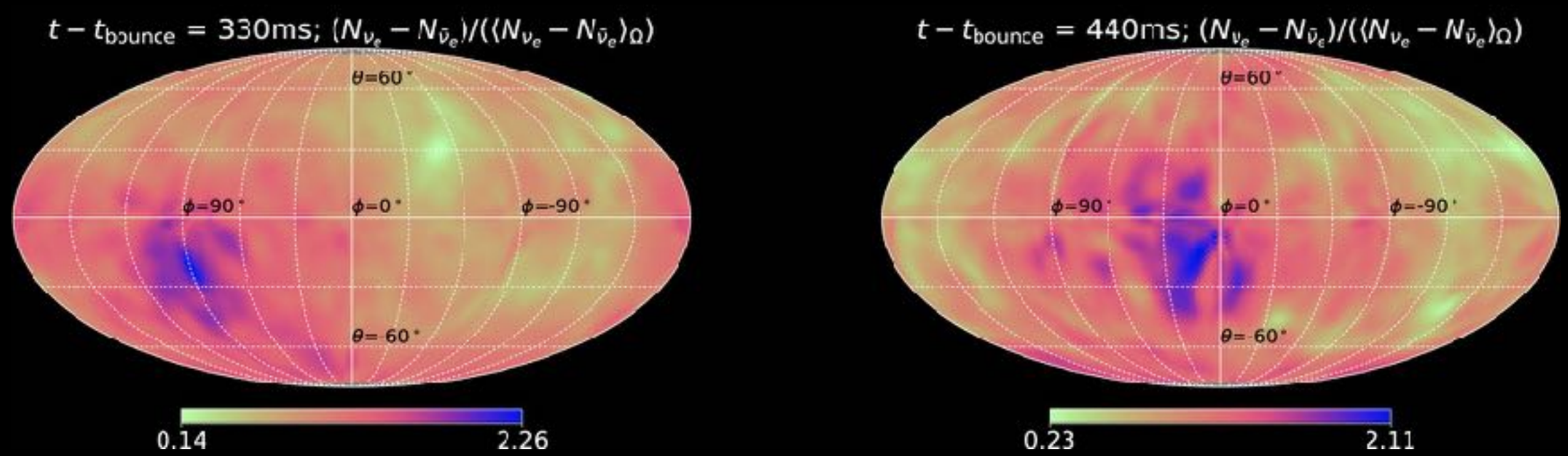


(Fields + 2021b, in prep.).

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?

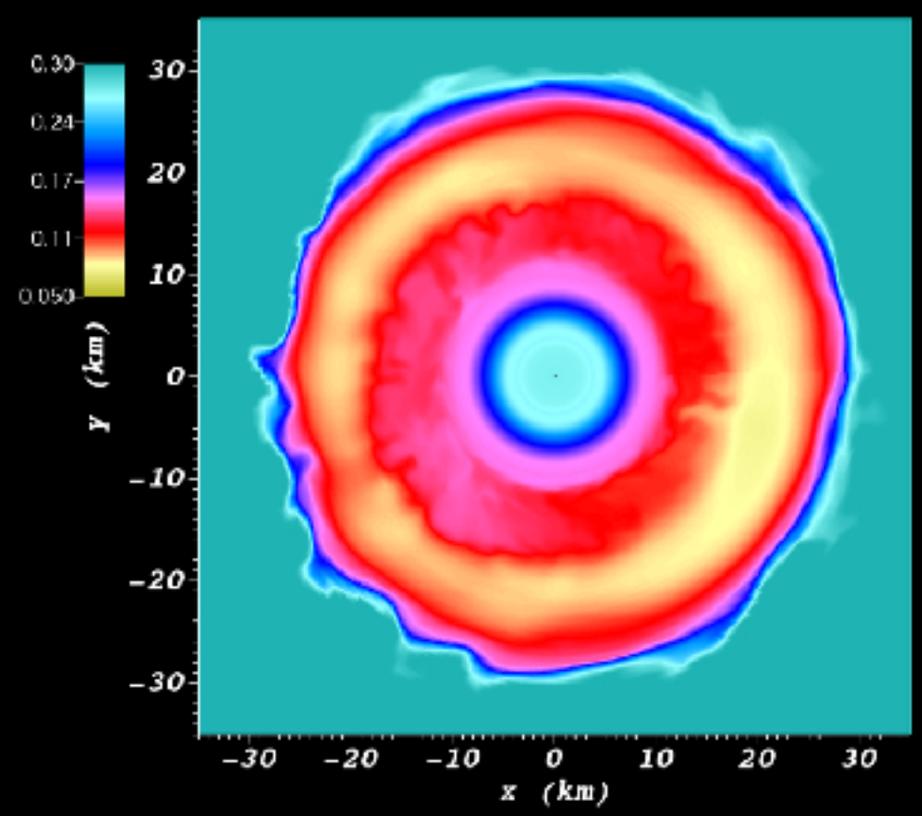


(O'Connor & Couch, 2018)

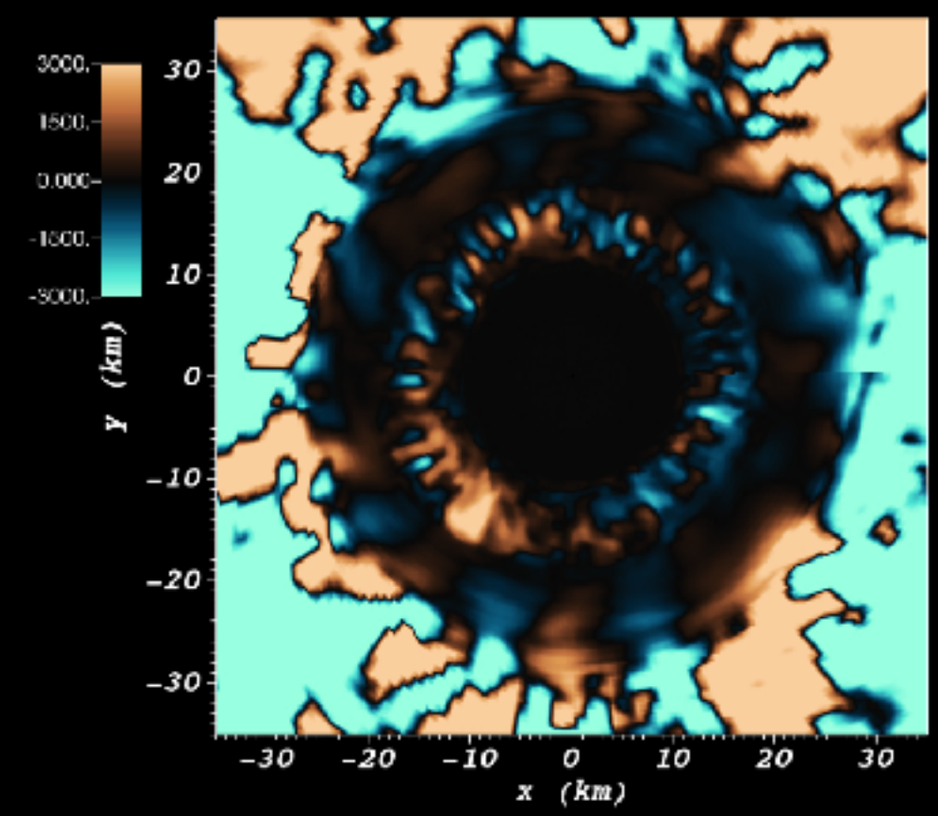
lepton-number emission self- sustained asymmetry
- **LESA** found in 3D CCSN model.

IMPACT ON MULTI-MESSENGER ASTRONOMY

Y_e



v_{radial}



(Muller+, 2020)

$M_{\mathrm{ZAMS}} = 18 M_{\odot}$ $\quad t_{\mathrm{pb}} \sim 453$ (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

David Vartanyan[1*], Matthew S. B. Coleman[2], Adam Burrows[2]
[1] Department of Physics and Astronomy, University of California, Berkeley, CA 94720, USA
[2] Department of Astrophysical Sciences, 4 Ivy Lane, Princeton University, Princeton, NJ 08544, USA

(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

Web: carlnotsagan.com
Email: carlnotsagan@lanl.gov

Los Alamos NATIONAL LABORATORY

@carlnotsagan