LA-UR-22-24718

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: colloquium 4/29

Issued: 2022-05-20

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

Colloquium, CCA, Flatiron Institute
April 29, 2022

Los Alamos
NATIONAL LABORATORY

@carlnotsagan

OVERVIEW

Introduction

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

3D CCSN Progenitors

- Landscape of 3D Progenitors
- 3D Rotating 16 $M_\odot$ star
- Signals from CCSNe

Conclusions & Summary

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

CCSNe = core-collapse supernovae

INTRODUCTION

Core-Collapse Supernovae

CORE-COLLAPSE SUPERNOVAE

The death of a massive star

Stellar Transients

- Core-Collapse Supernovae
- Collapsars, Gamma Ray Burst, SLSNe

Compact Object Formation

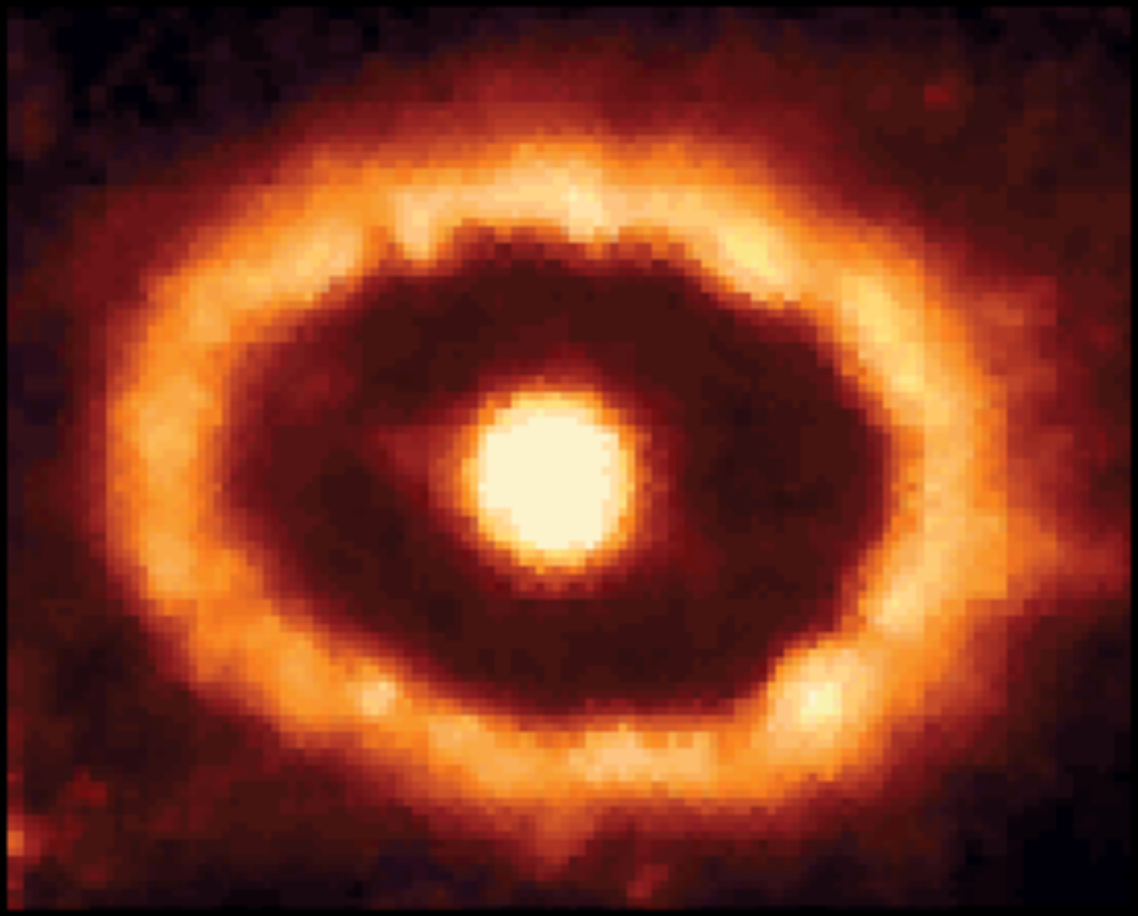
- Produce NS / stellar mass BHs

Galactic Chemical Evolution

- Nucleosynthesis
- Stellar Feedback

Multi-Messenger Astronomy

- Gravitational Waves
- Neutrinos
- Electromagnetic



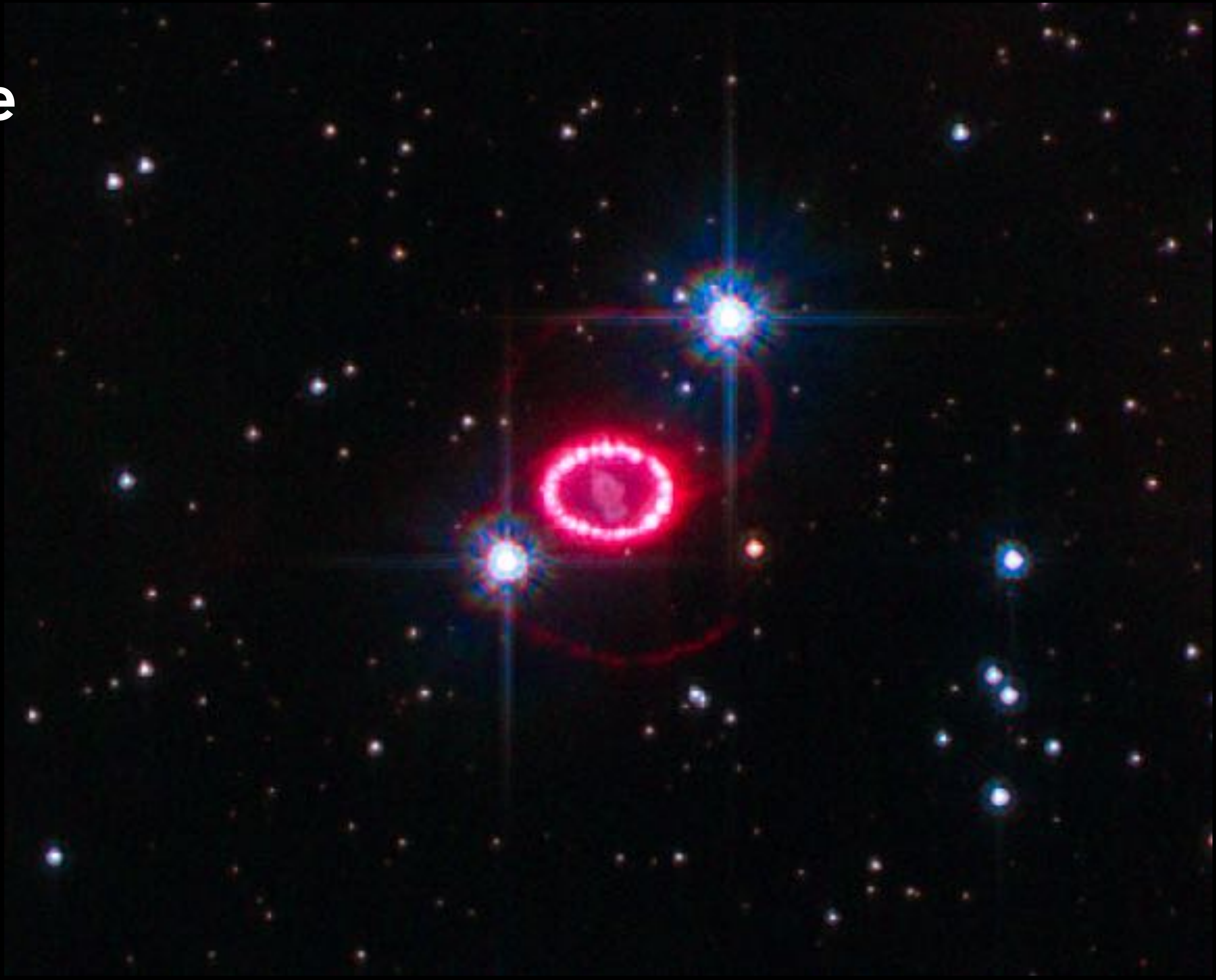
(Larsson + 2011)

09/1994

CORE-COLLAPSE SUPERNOVAE

Core-Collapse Supernovae

- ~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, **massive stars**.



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

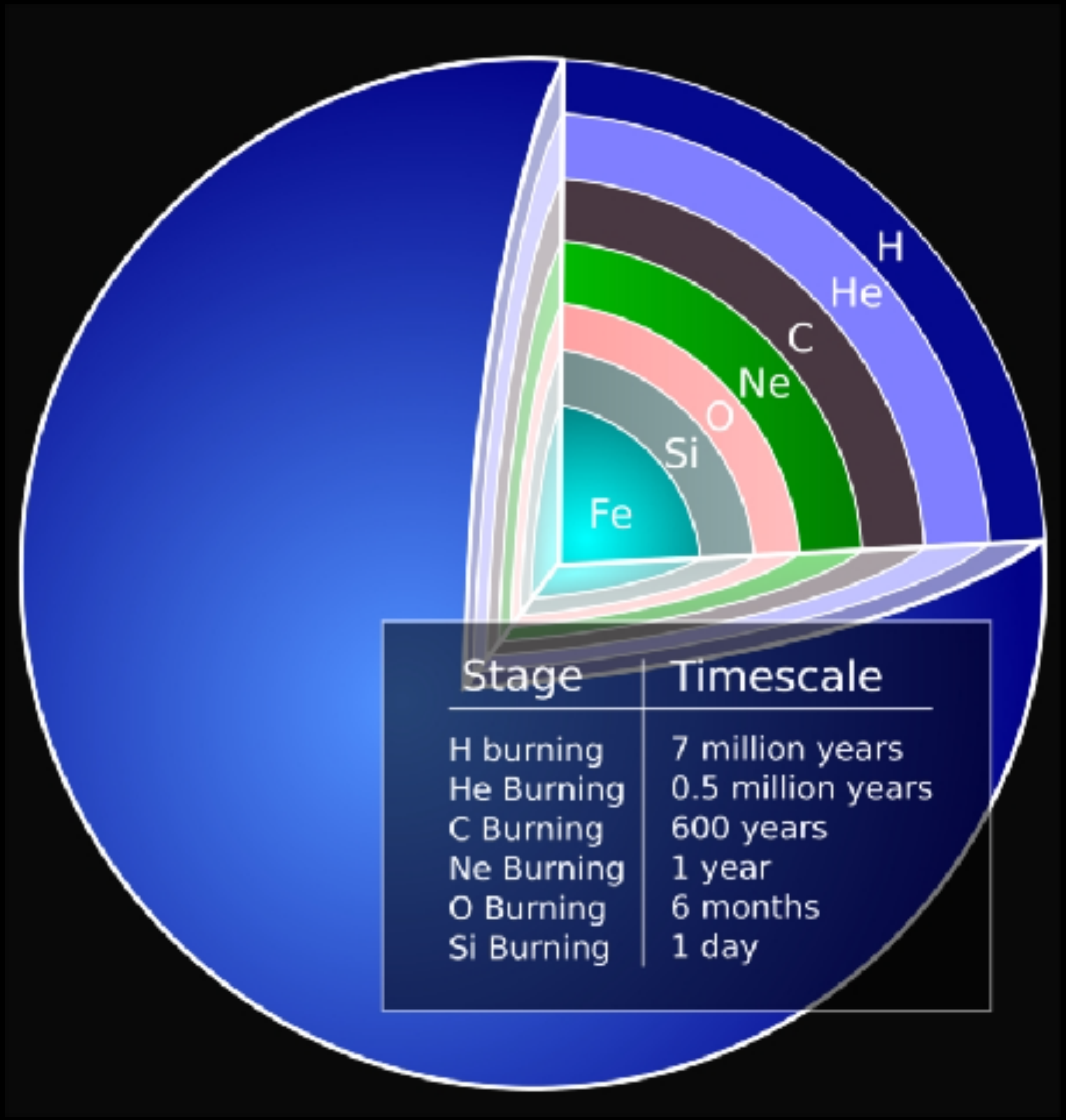
INTRODUCTION

The final moments of a massive star

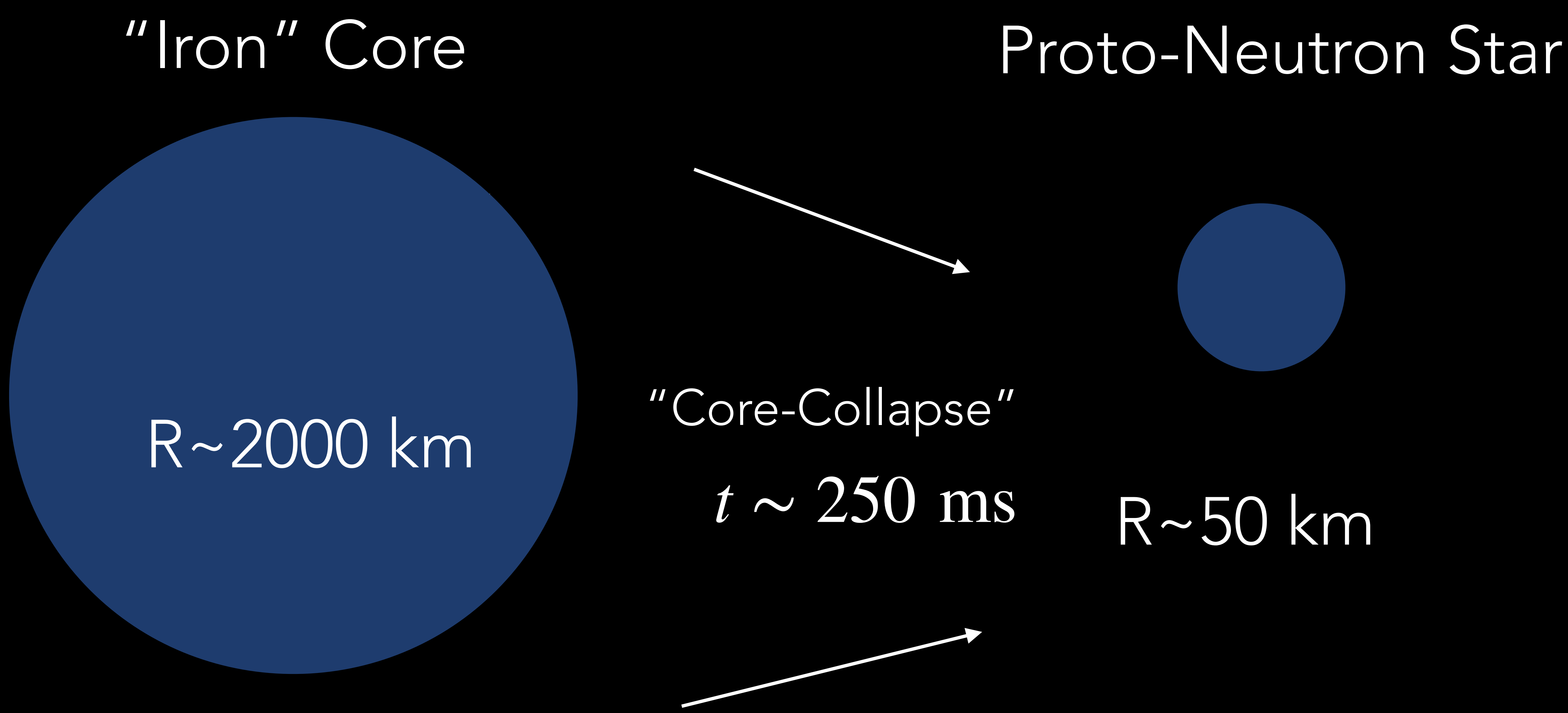
EVOLUTION TOWARDS IRON CORE-COLLAPSE IN A MASSIVE STAR

- 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 !

Interior of an evolved massive star



PHYSICS OF STELLAR CORE-COLLAPSE

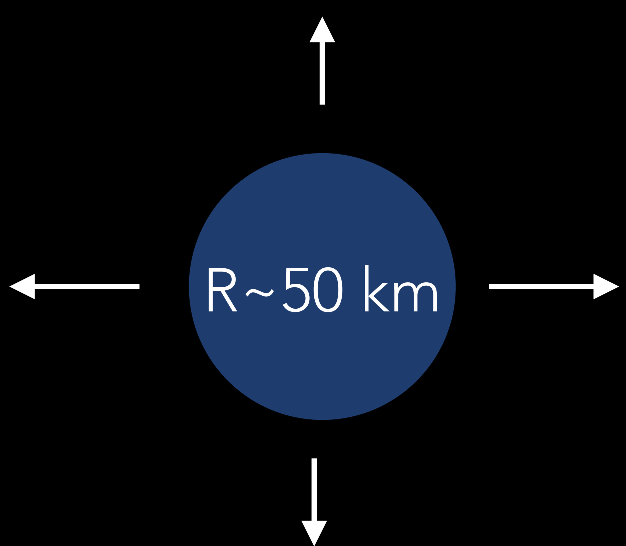


$\rho_c \sim 10^{10}$ (g cm^{-3})

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

PHYSICS OF STELLAR CORE-COLLAPSE

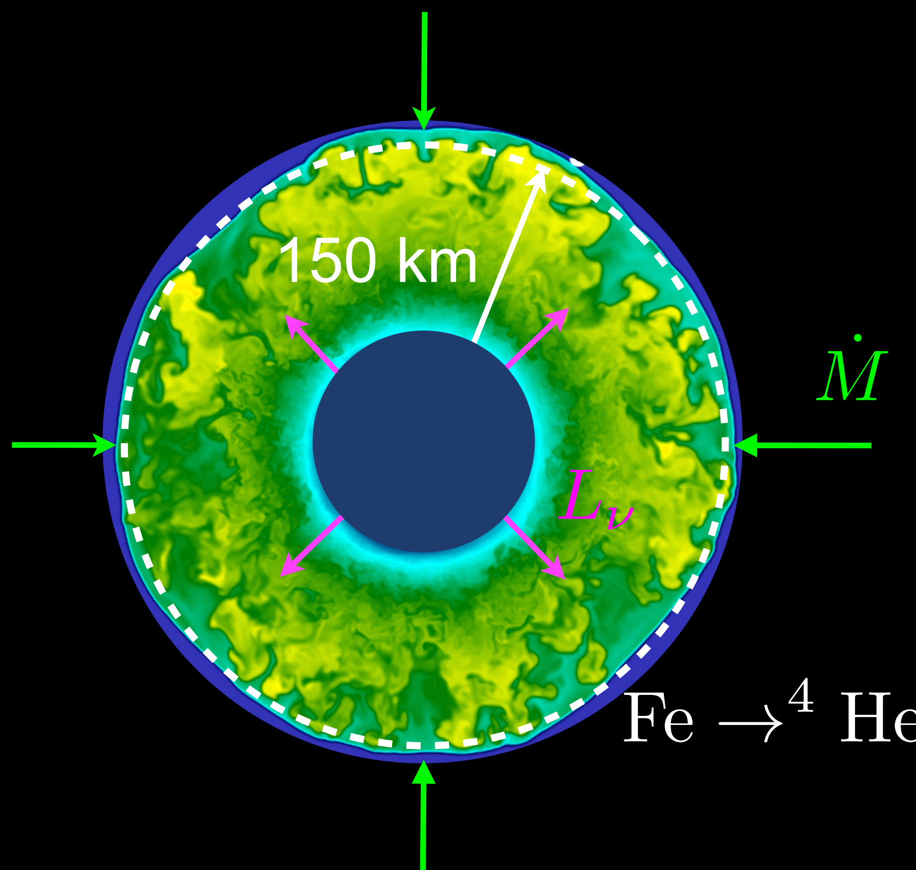
"Bounce"
Stiffening of Core
Launch Shock



"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).

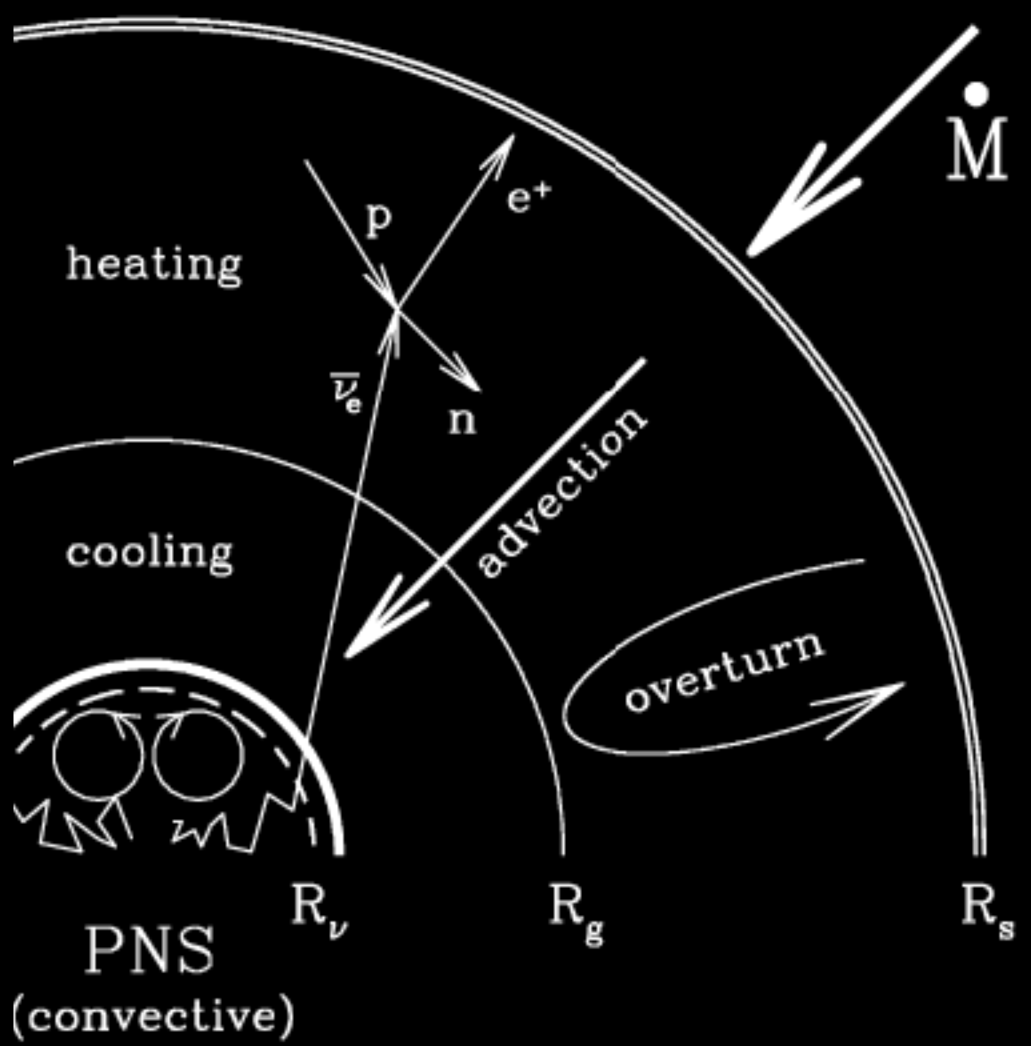


Diagram showing revival of stalled shock.
Credit: Janka (2011).

ERA OF 3D CCSN SIMULATIONS

<u>Fully-coupled!</u>

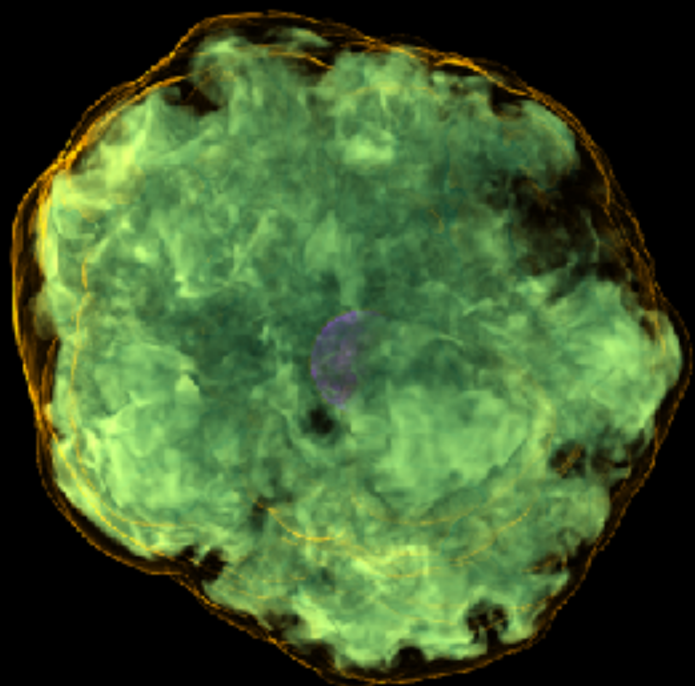
3D Magnetohydrodynamics

General Relativity

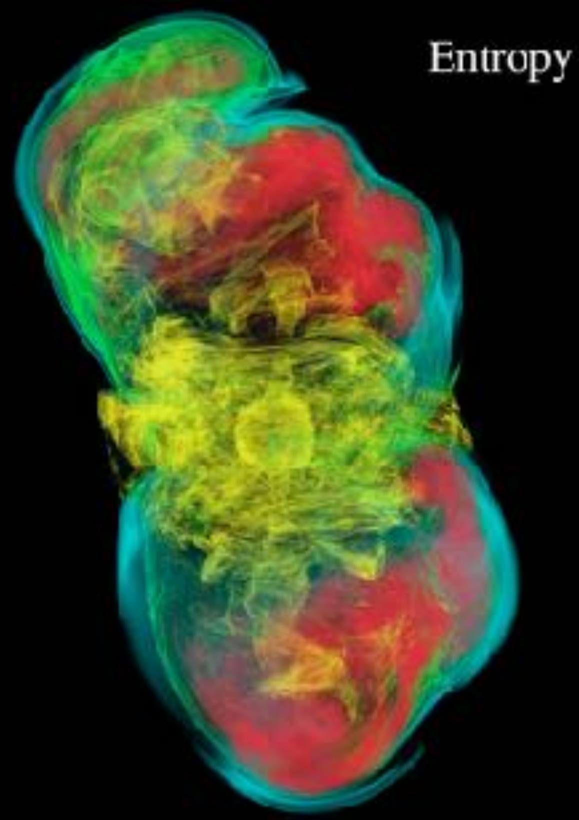
Boltzmann ν-transport

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

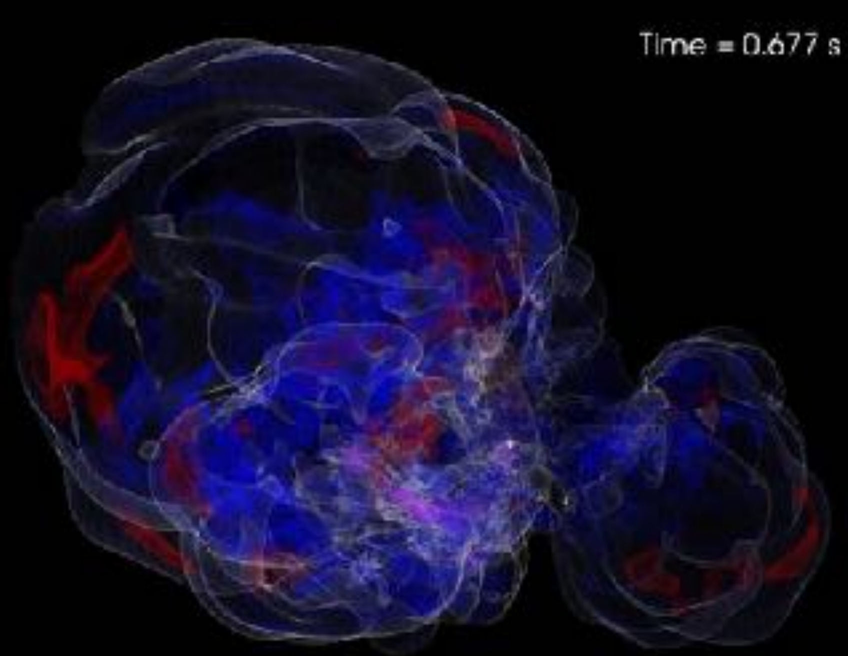
Credit: Sean Couch



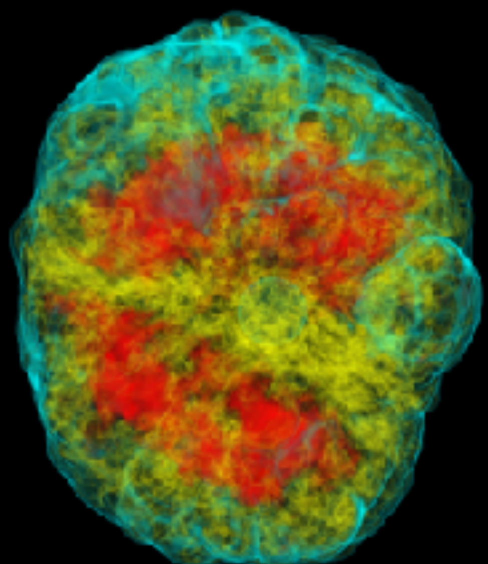
(Fields + 2022b, in prep.)



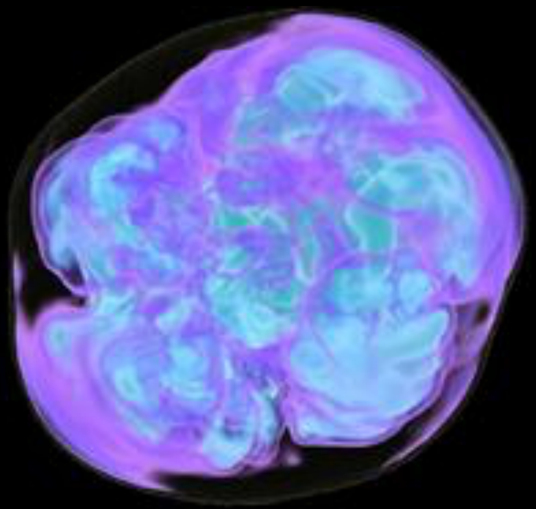
(Moesta + 2014)



(Vartanyan+ 2019)



(Roberts + 2016)



(Burrows + 2019)

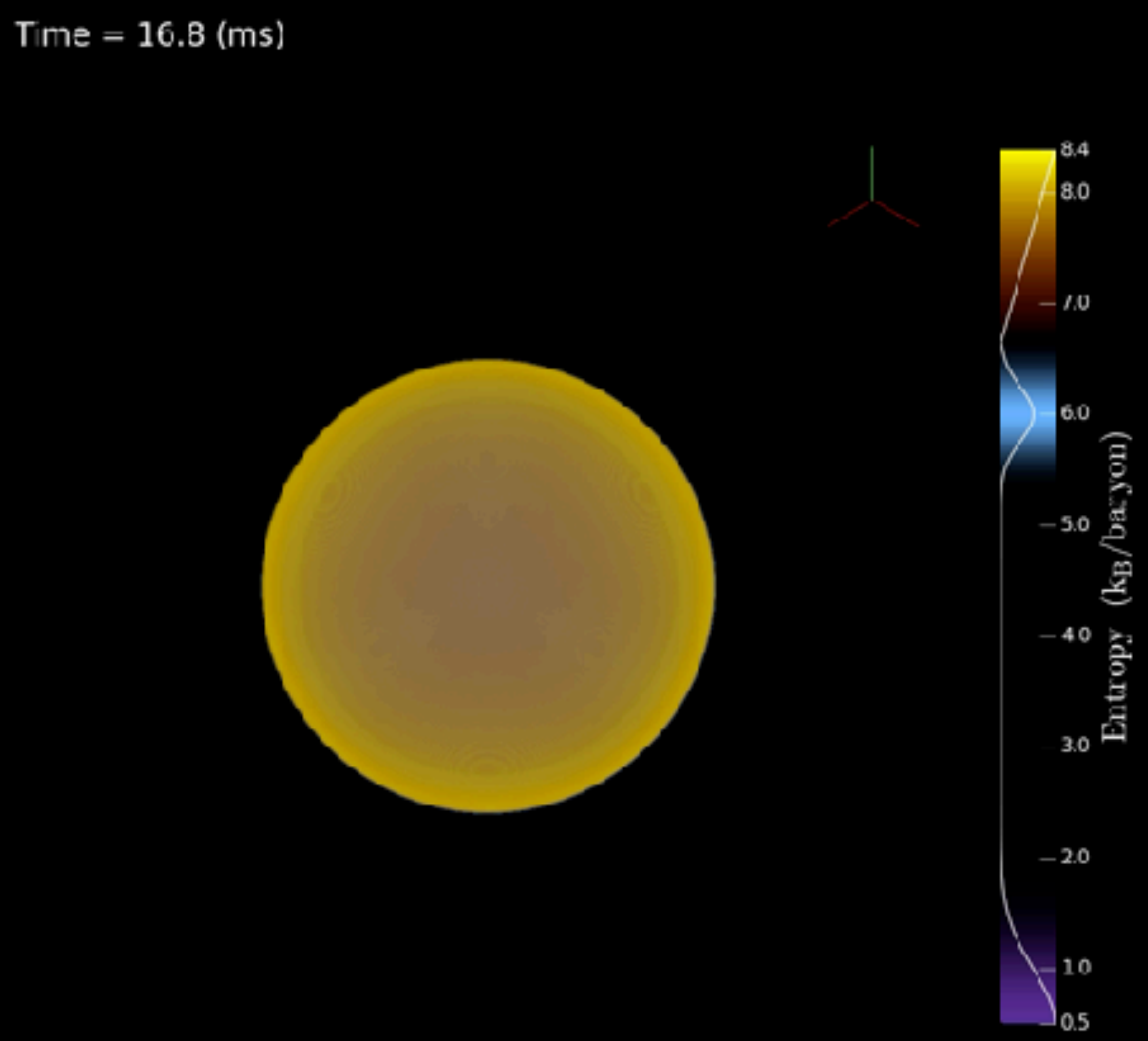
INTRODUCTION

Open challenges in modelling CCSNe 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'

Towards a definitive model of CCSNe

Explosion Energy

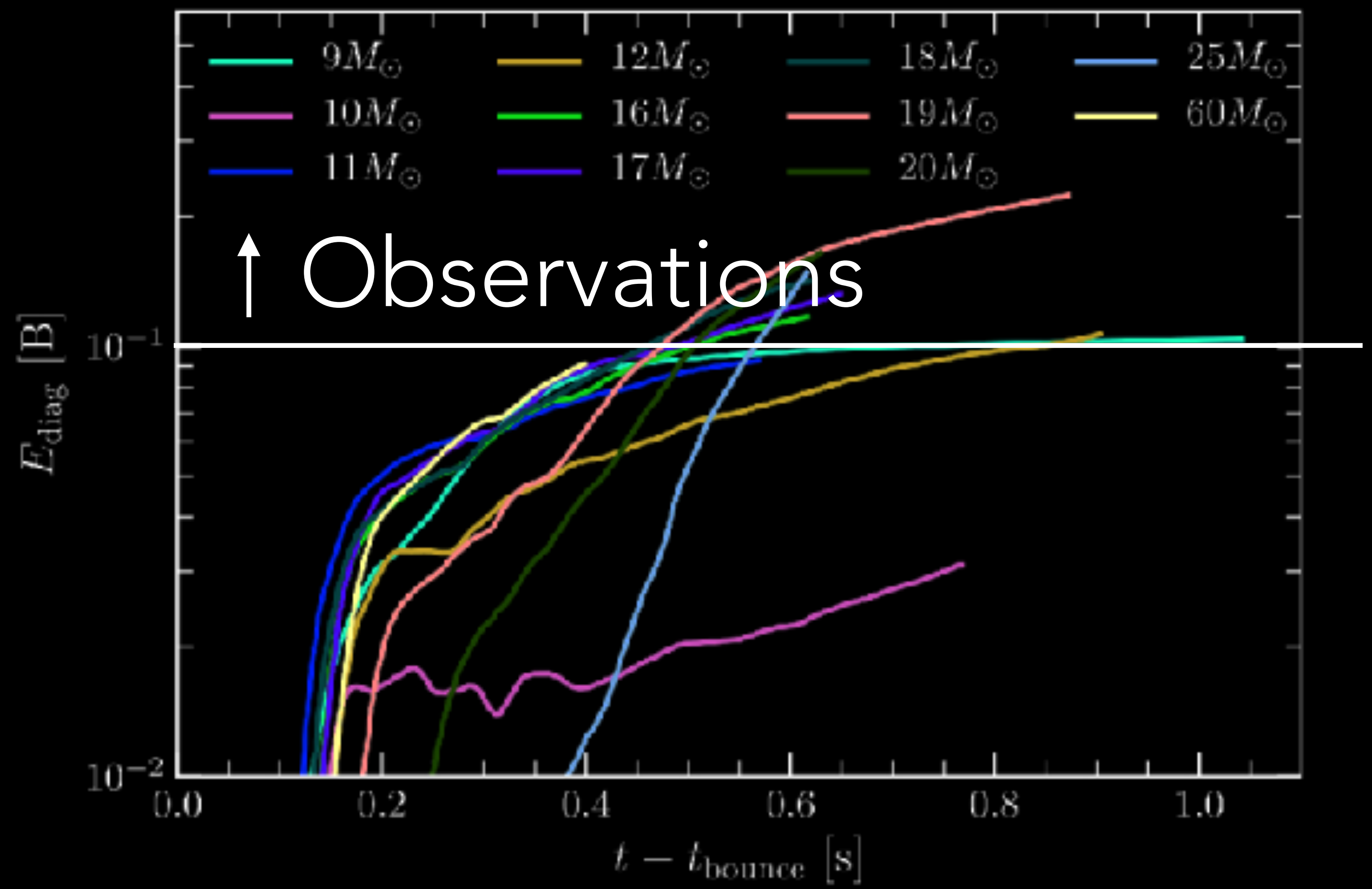
- Struggle to match range of Type IIP explosion energies of ~0.5-4B.

Shock Revival

- Models fail to explode in some cases.

Fate of Compact Remnants

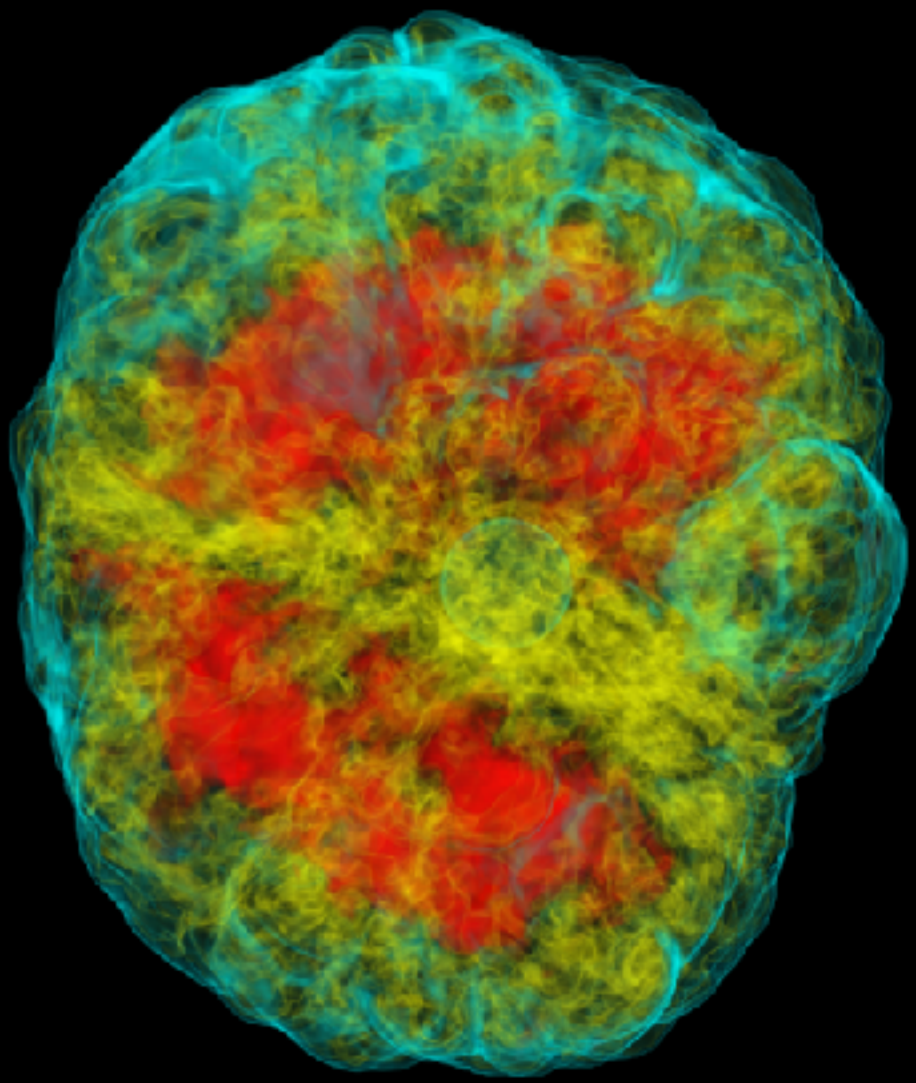
- Require long term simulations



(Burrows +, MNRAS, 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.

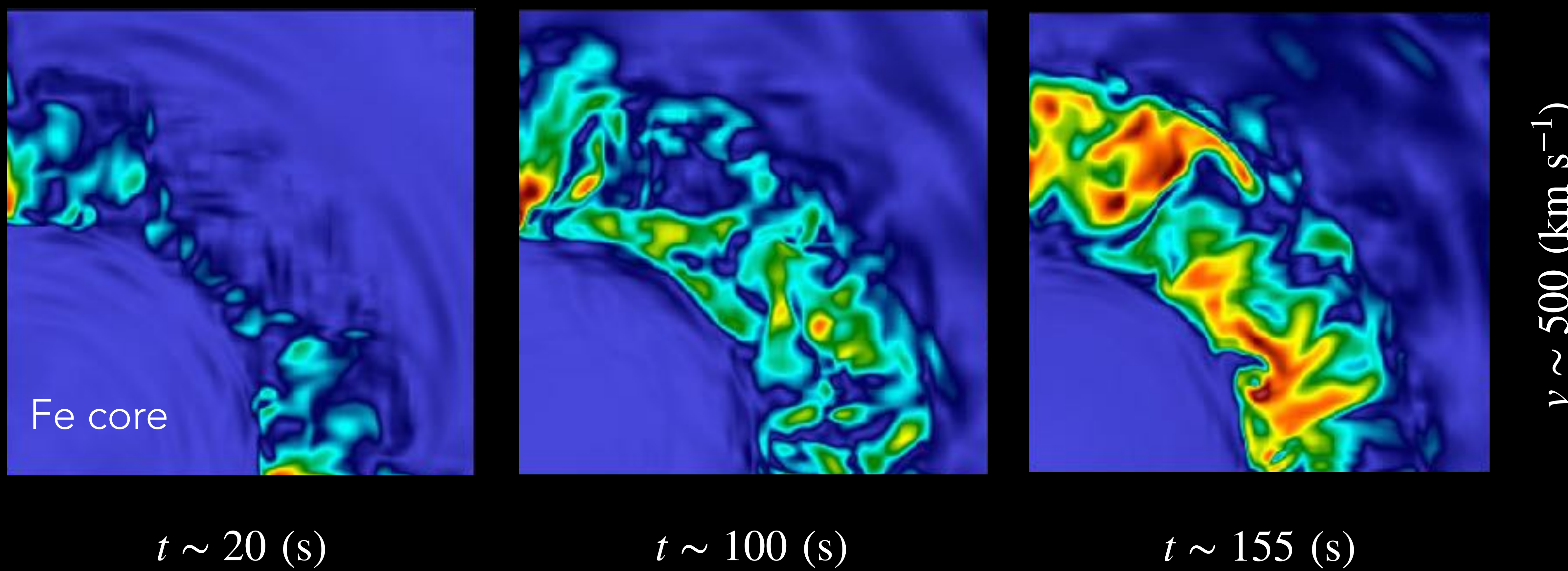


Volume rendering of the entropy distribution from *Roberts + 2016*.

INTRODUCTION

Deeper look in to the Pre-Supernova Models

PERTURBATIONS IN THE PRE-SUPERNOVA MODEL

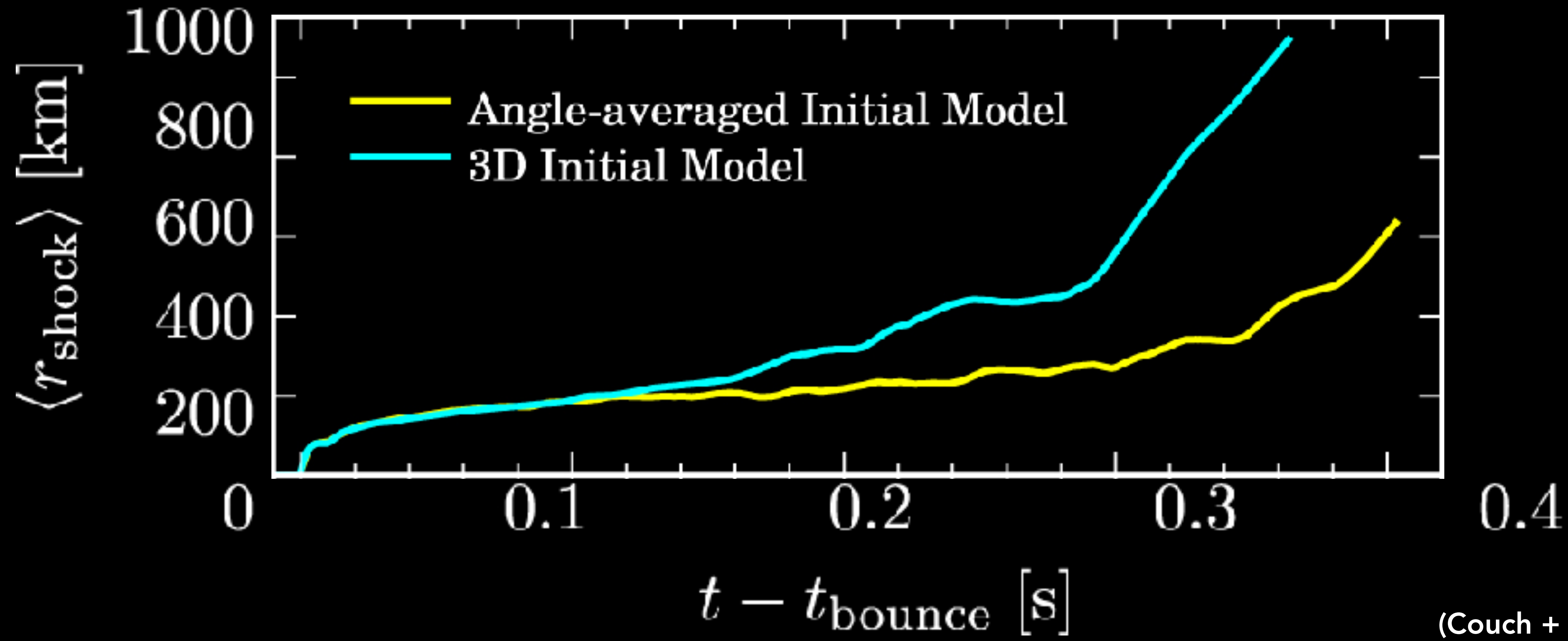


(Couch + ApJL, 2015)

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

PERTURBATIONS IN THE PRE-SUPERNOVA MODEL

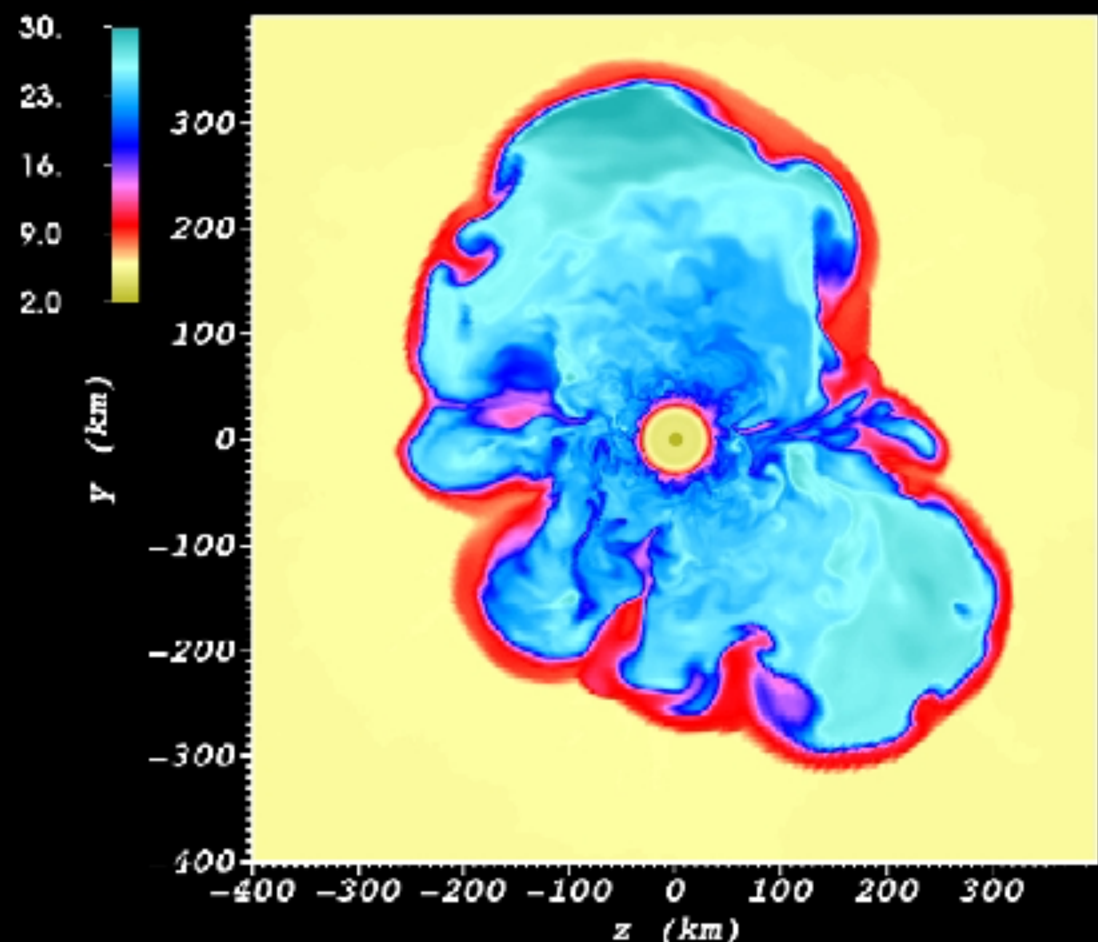
3D Initial model leads to faster, stronger explosion.



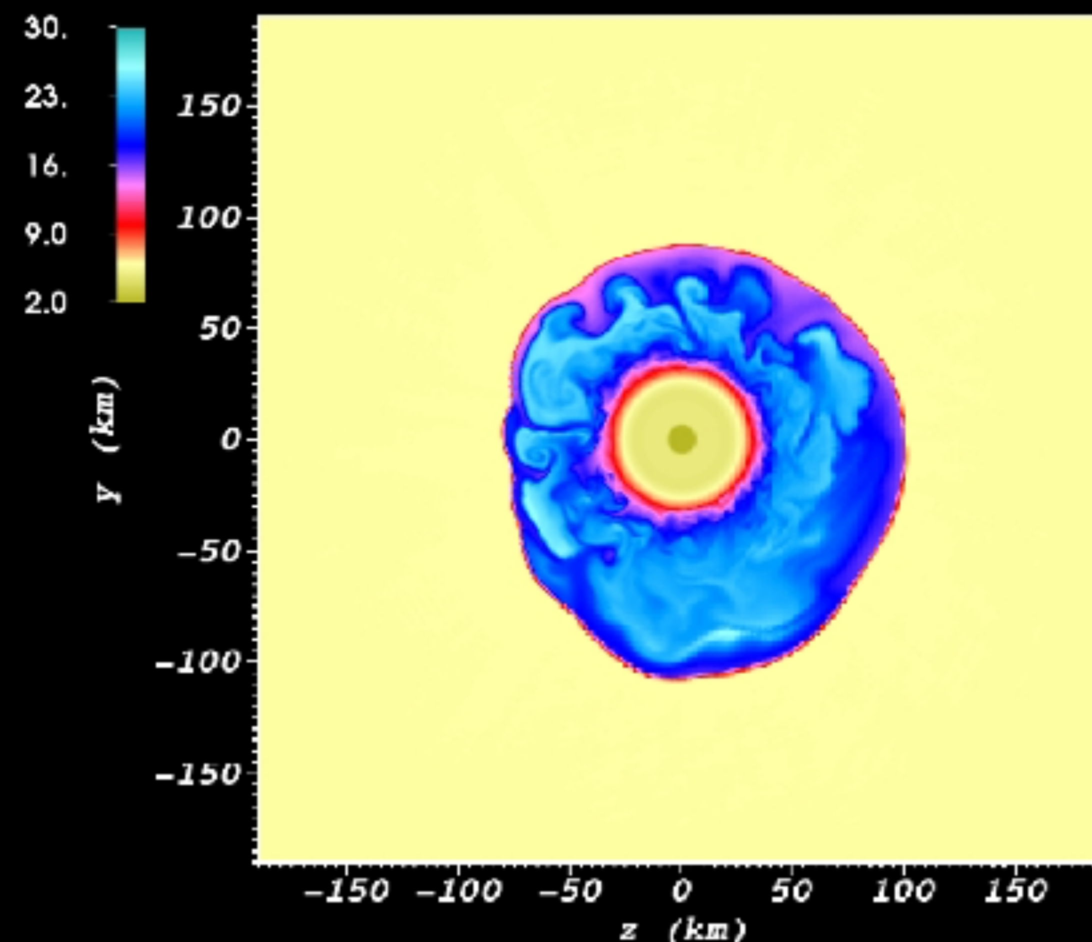
(Couch + ApJL, 2015)

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

IMPACT OF PROGENITORS ON EXPLOSION MECHANISM



3D initial conditions



1D initial conditions

(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.

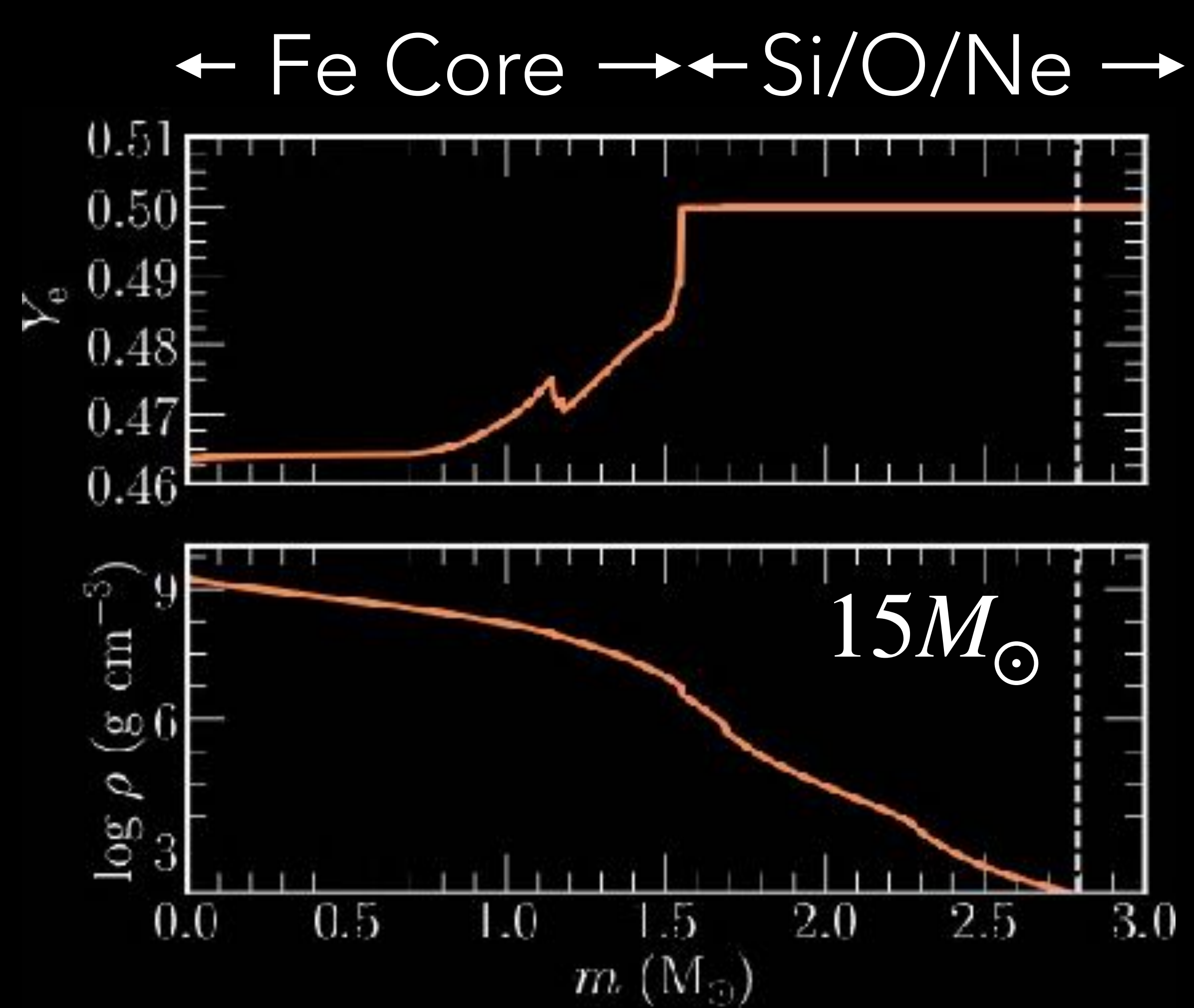
(Couch + 2014, 2015)

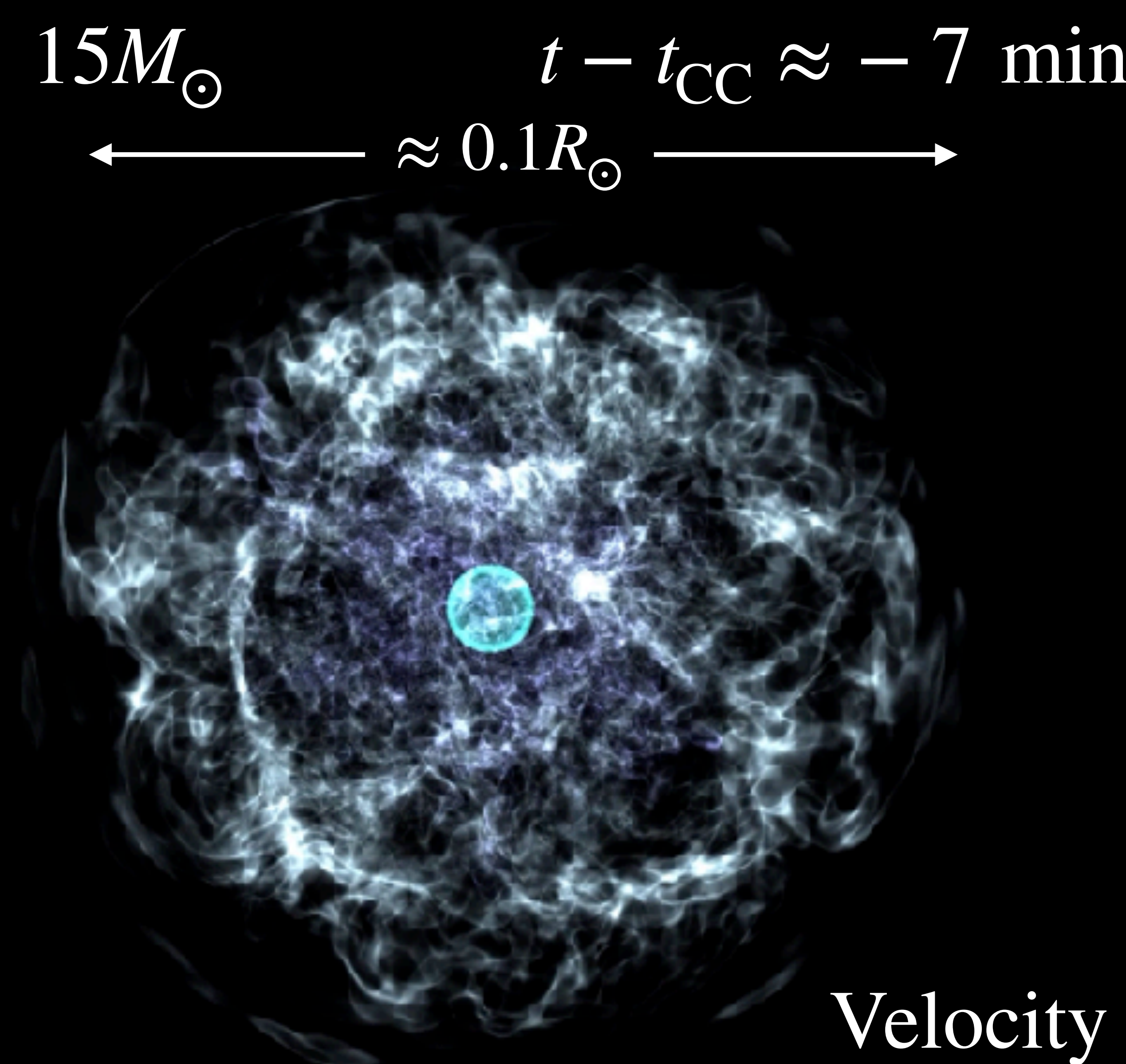
Convection in multiple 3D Progenitor Models

MASSIVE STAR CONVECTION IN MULTIPLE PROGENITORS

Our approach in modeling 3D stellar convection

Simplified initial conditions



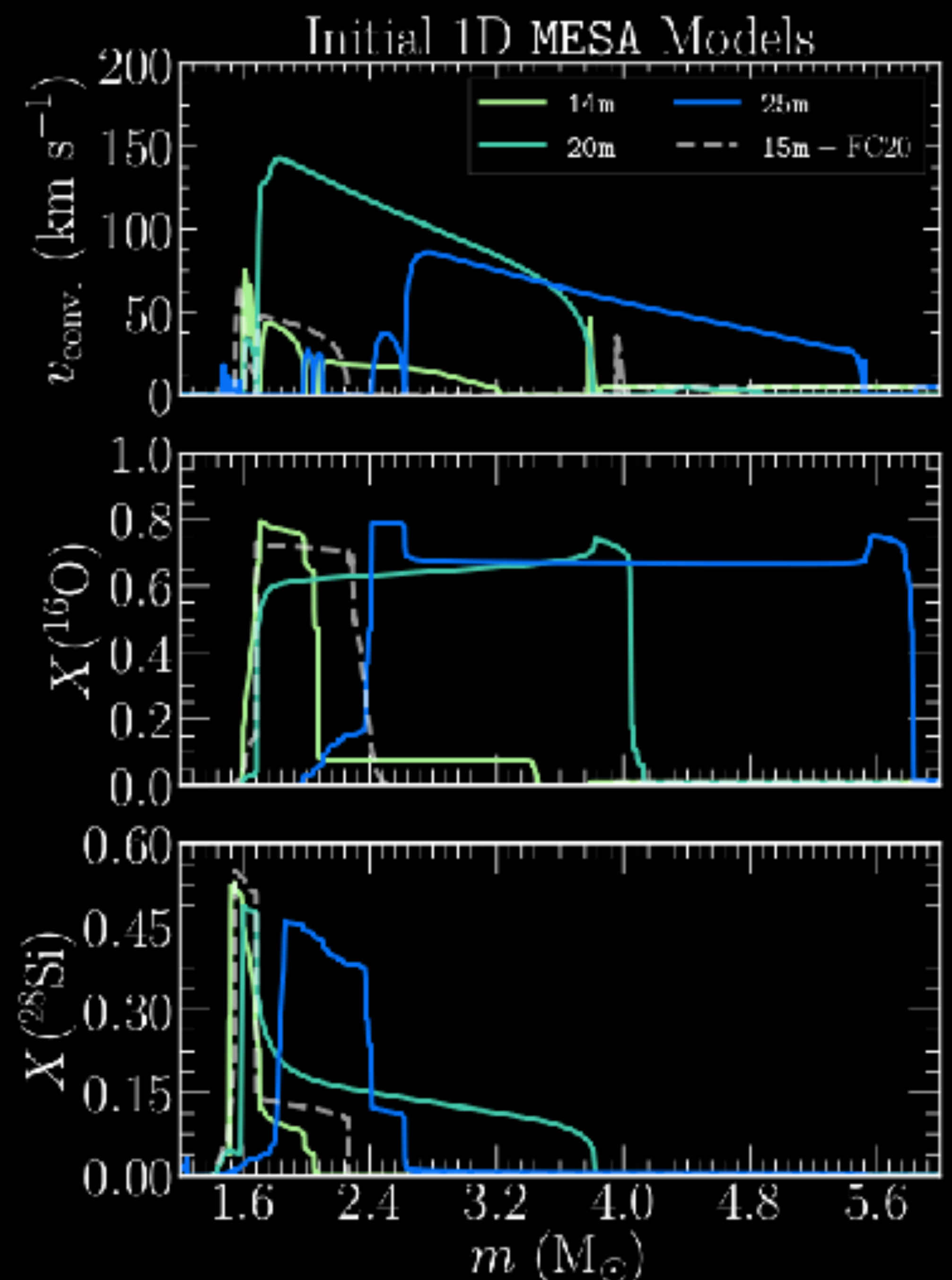


Oxygen shell burning in a massive star.
(Fields & Couch ApJ, 2020)

MASSIVE STAR CONVECTION IN MULTIPLE PROGENITORS

Surveying different progenitors

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



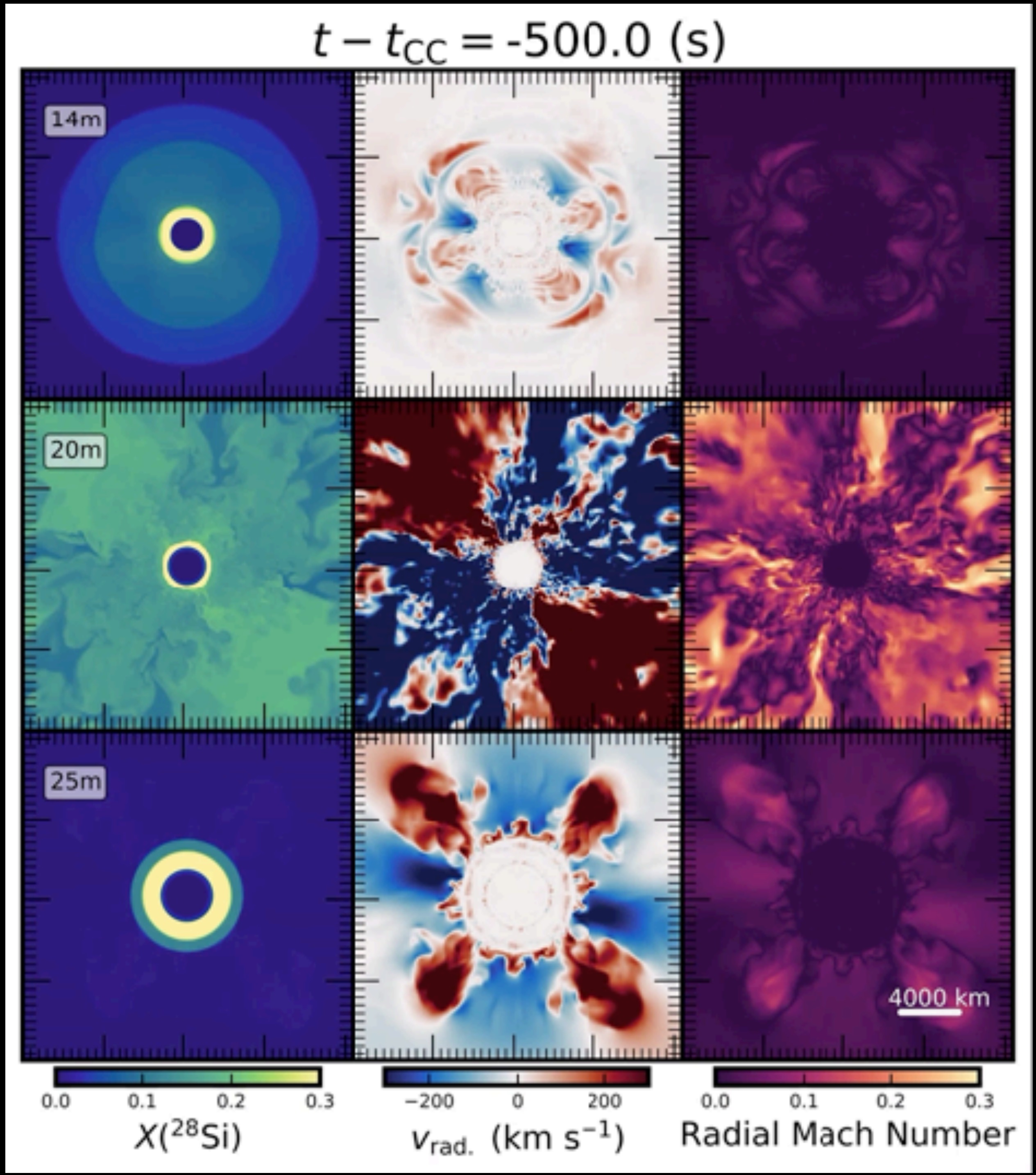
Initial 1D profile structure for 3D models.
(Fields & Couch ApJ, 2021)

MASSIVE STAR CONVECTION IN MULTIPLE PROGENITORS

Bulk properties of 3D stellar convection

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

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



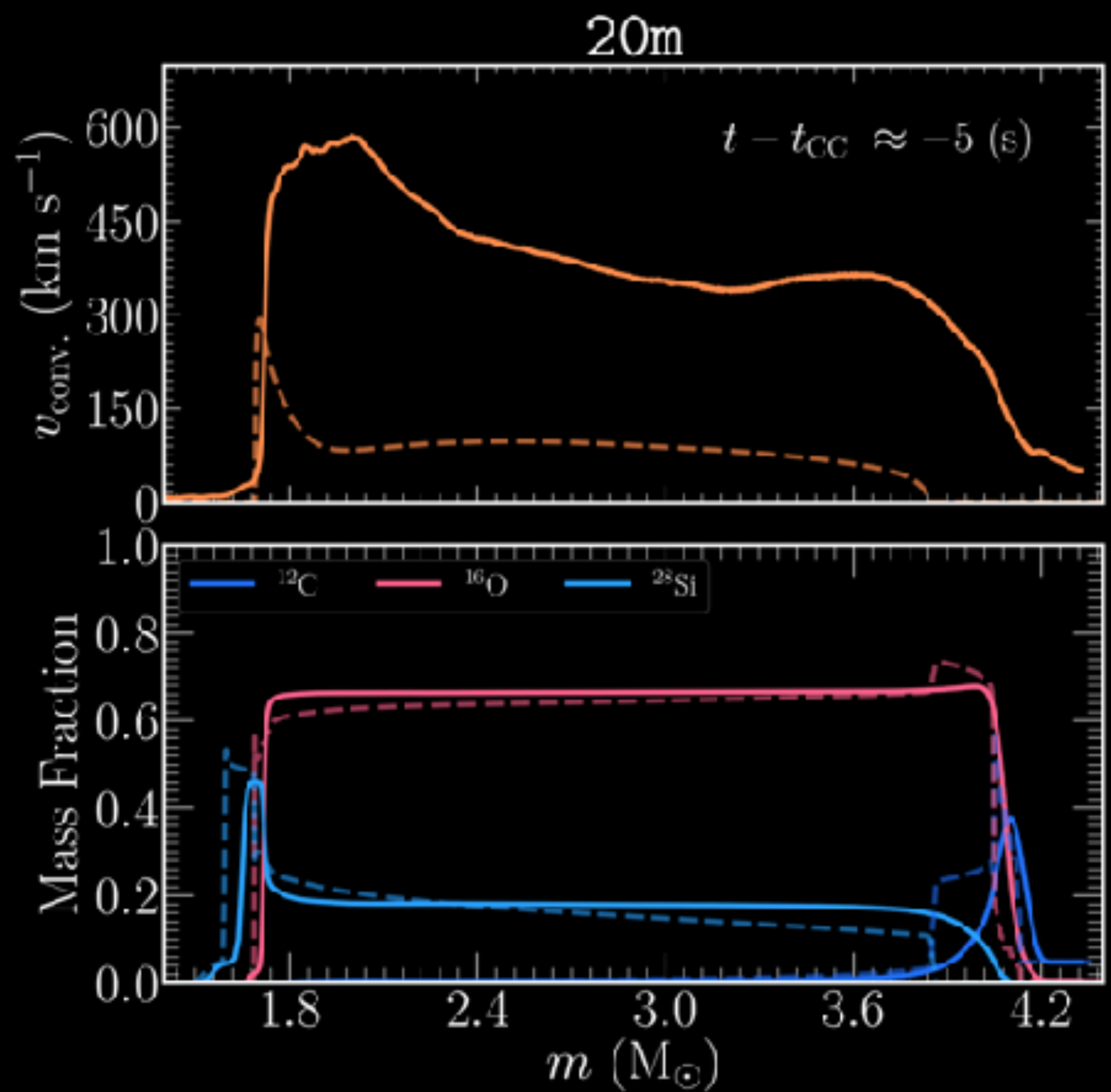
(Fields & Couch ApJ, 2021)

MASSIVE STAR CONVECTION IN MULTIPLE PROGENITORS

Using 3D simulations to inform 1D stellar models

3D Convection in FLASH

- Use 3D data to determine 1D convection parameters.
- Measure **mixing** at chemical boundaries.

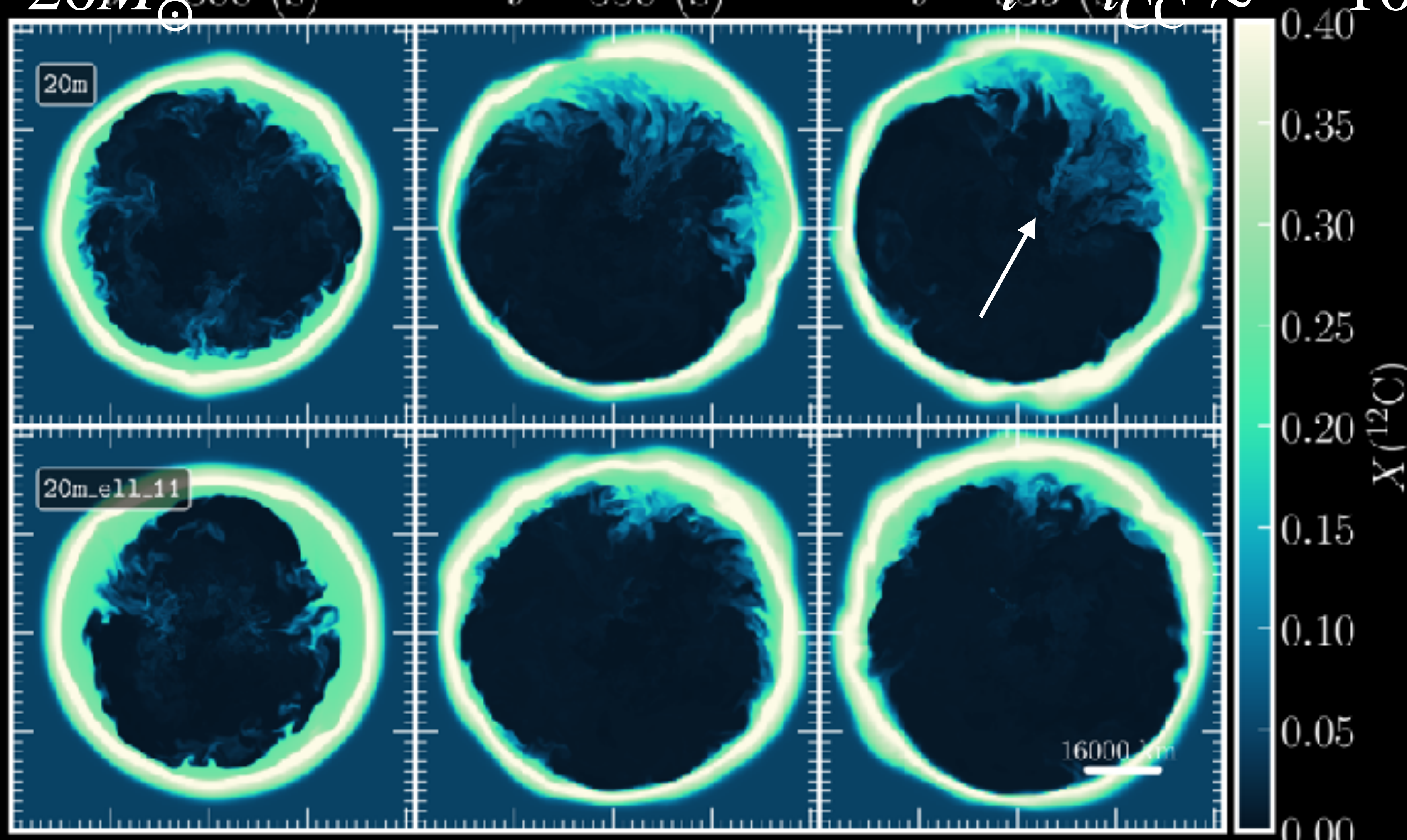


(Fields & Couch ApJ, 2021)

MASSIVE STAR CONVECTION IN MULTIPLE PROGENITORS

Measuring 3D mixing and chemical enrichment

$20M_\odot$ $t - t_{CC} \approx -10$ min



$\approx 0.1R_\odot$

(Fields & Couch ApJ, 2021)

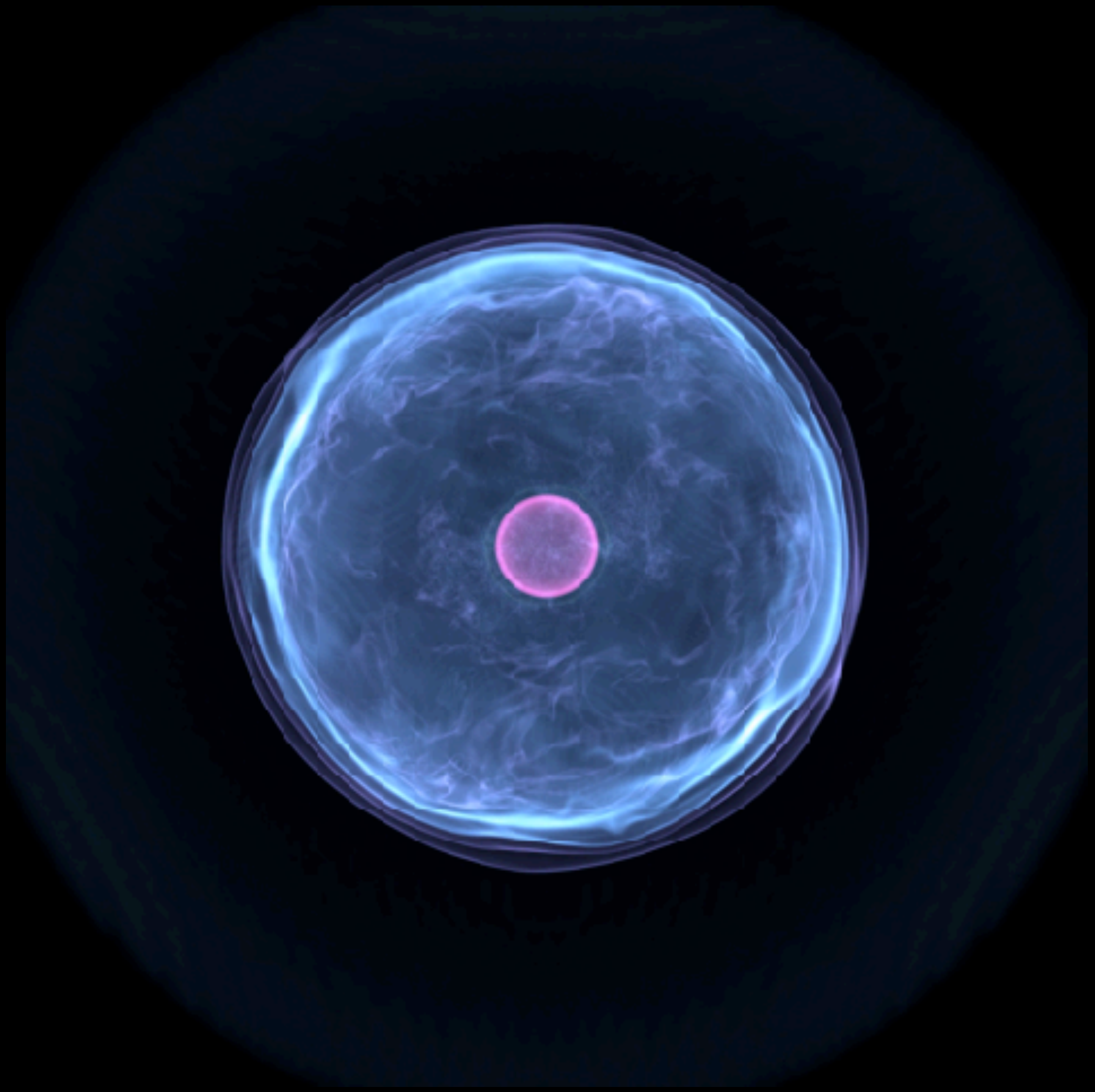
Entrainment can affect galactic **chemical evolution** models.

SIMULATIONS OF MASSIVE STAR CONVECTION + ROTATION

Angular momentum transport in 3D models

3D Rotating Convection in FLASH

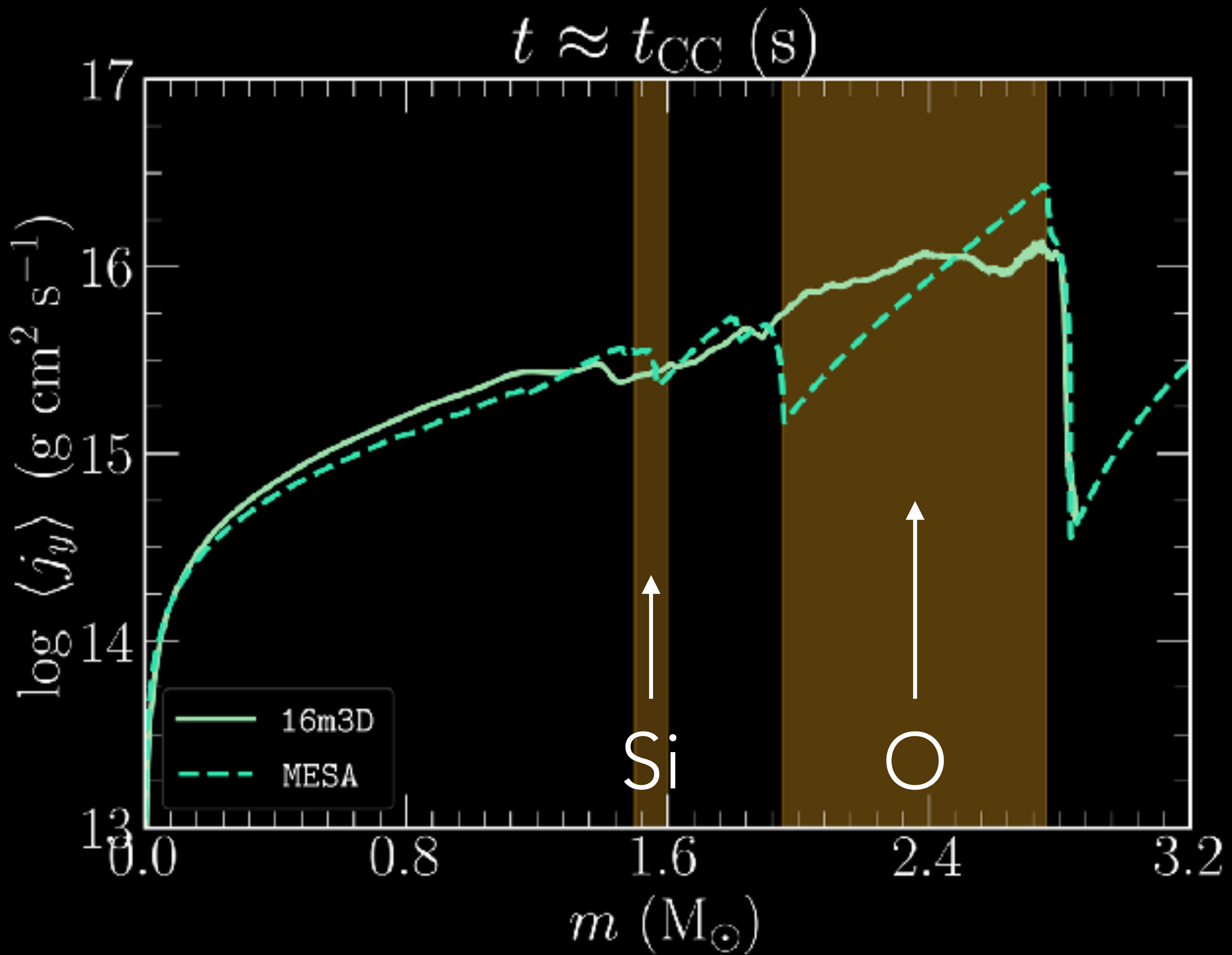
- Estimate **AM redistribution**.
- Differences lead to variation in PNS spin estimates ~1-5%.
- Impact **compact remnant** predictions.



(Fields ApJL, 2022)

SIMULATIONS OF MASSIVE STAR CONVECTION + ROTATION

- AM profile diverges from MESA in convective regions.



Angular momentum profiles for rotating 3D progenitor.

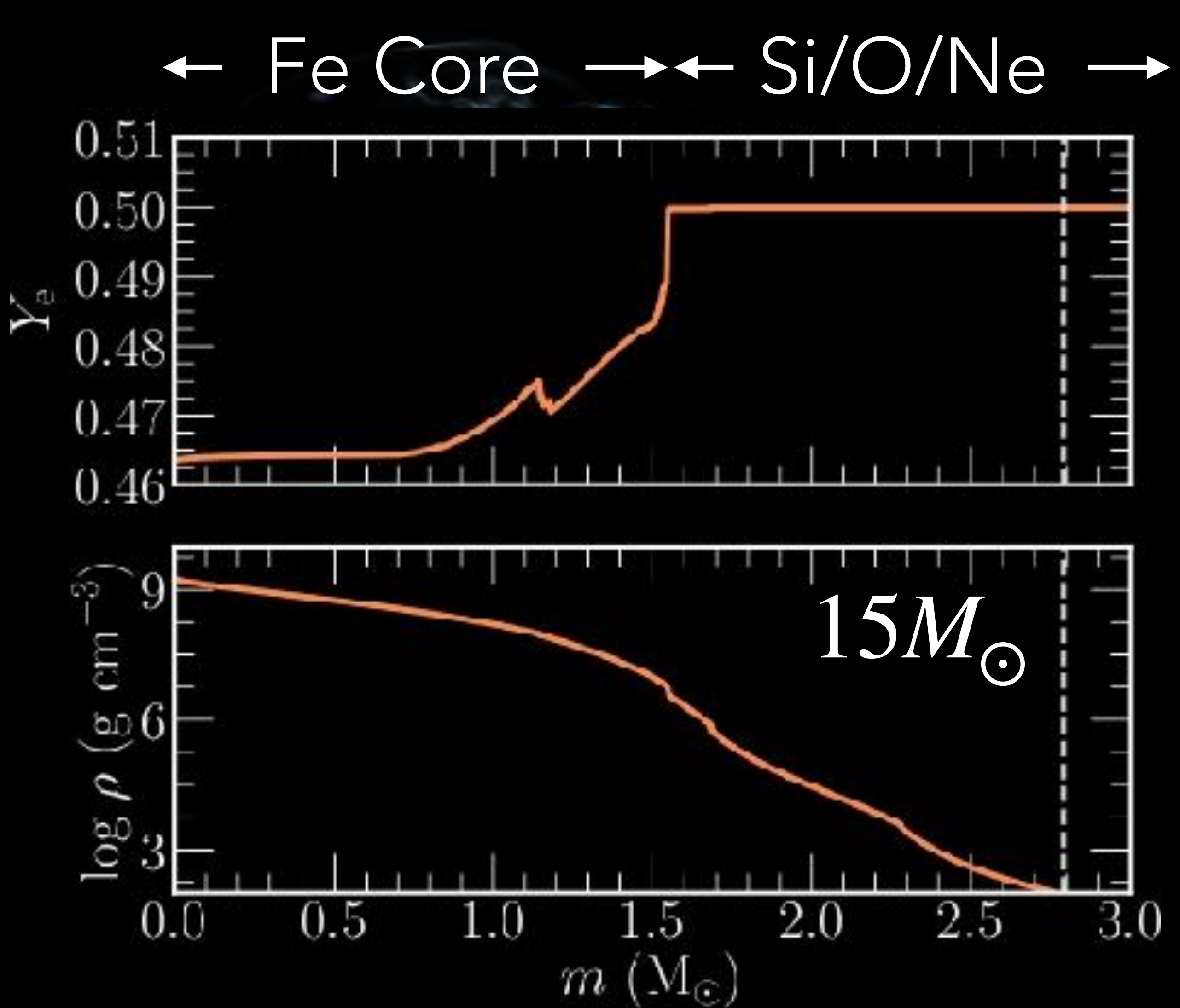
(Fields ApJL, 2022)

3D CCSN PROGENITORS

Building new models of stellar explosions

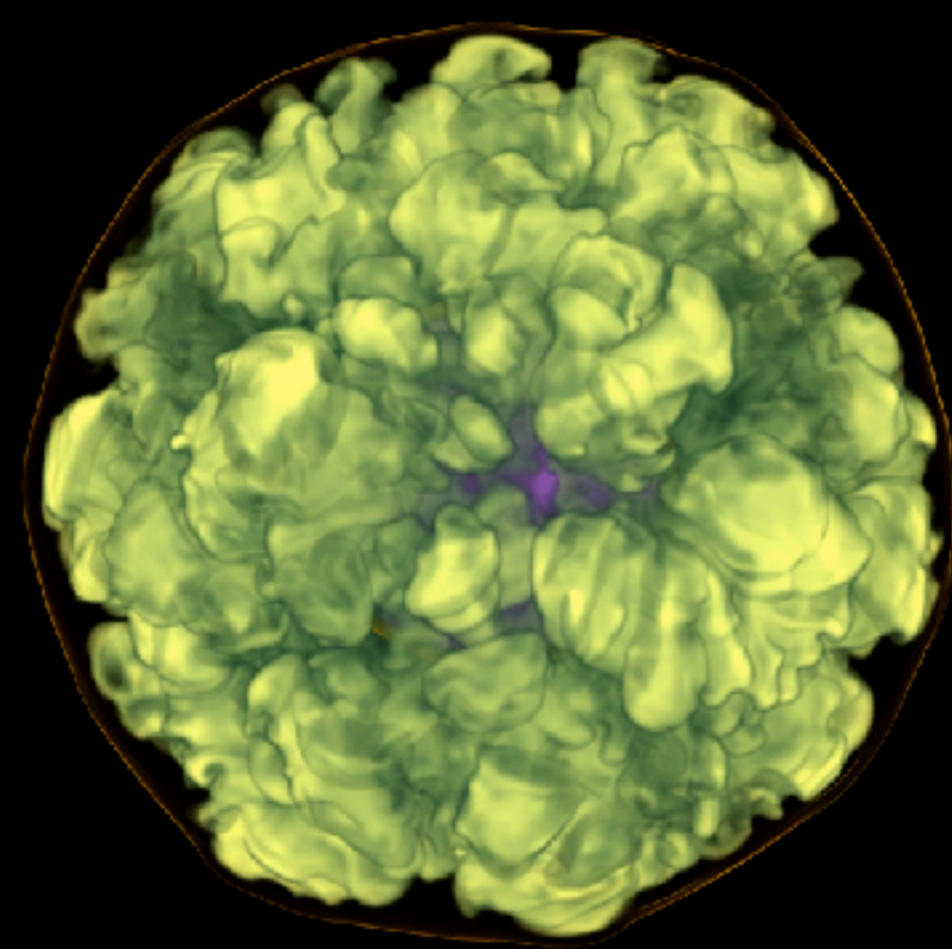
CCSN EXPLOSIONS OF MULTI-D PROGENITORS

CCSN explosion models from realistic conditions



Simplified 1D initial conditions
Complex 3D initial conditions

3D CCSN from 3D progenitor

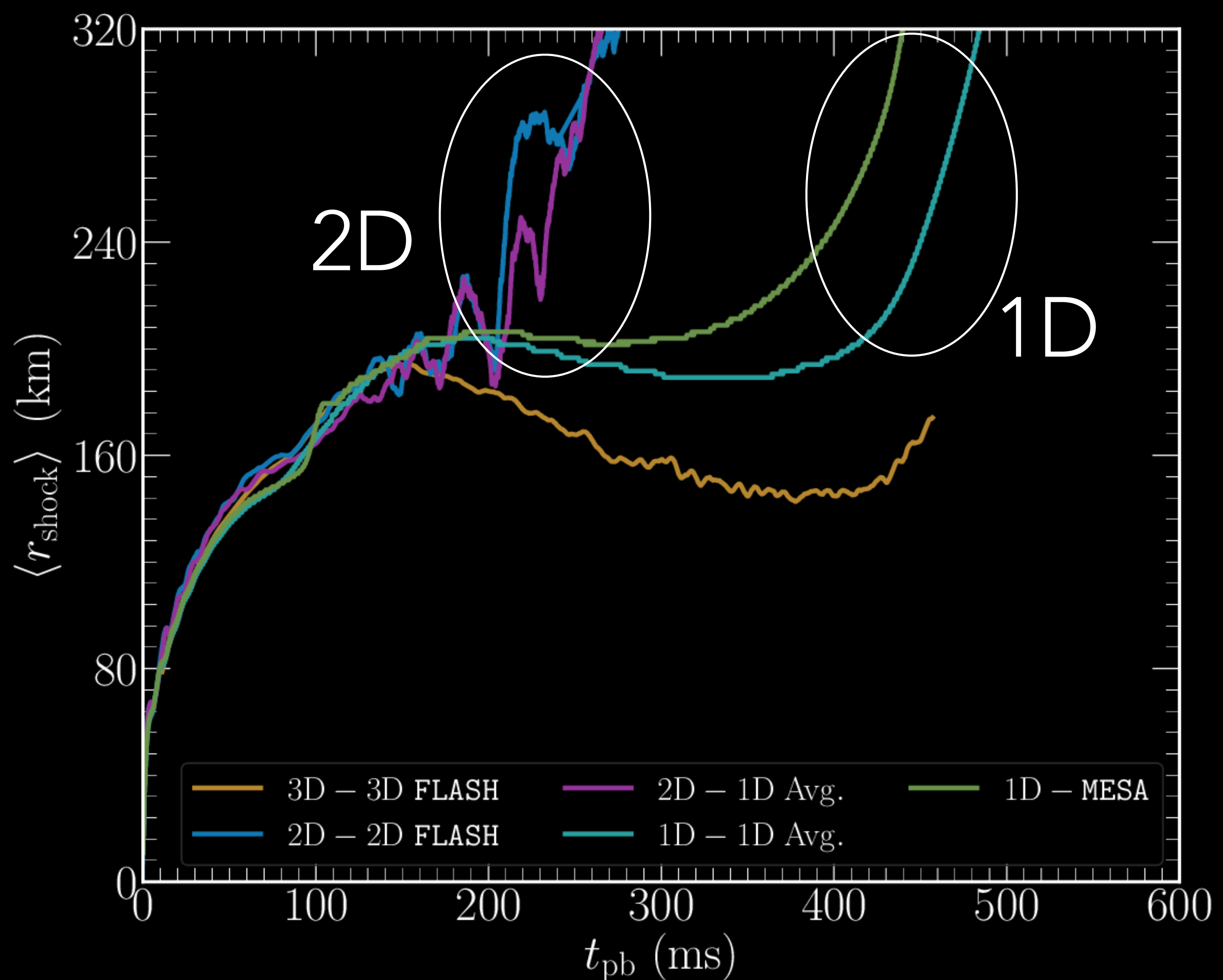


(Fields + 2022b, in prep.).

CCSN EXPLOSIONS OF MULTI-D PROGENITORS

CCSN explosion models from realistic conditions

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

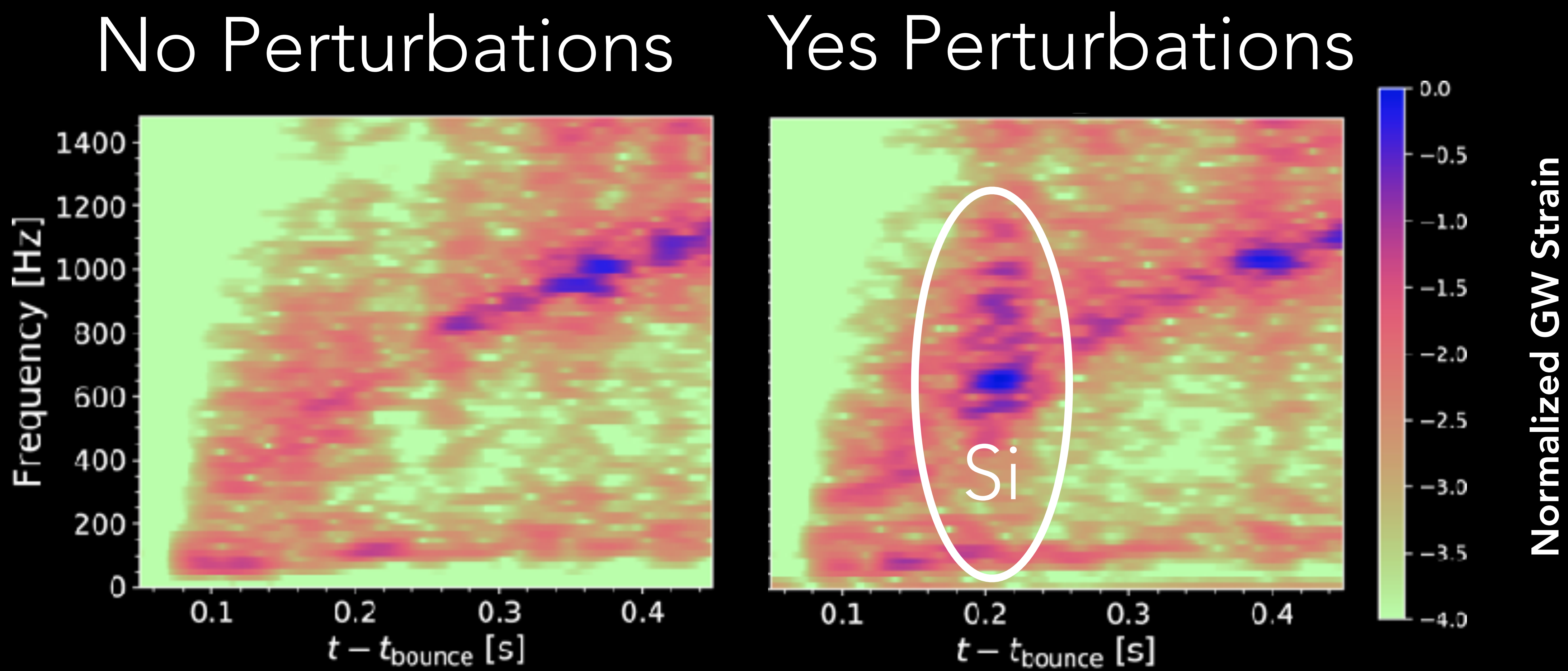


Mean shock radius evolution for multi-D CCSN models

(Fields + 2022b, in prep.).

IMPACT ON MULTI-MESSENGER SIGNALS

Impact of 3D progenitor on GW emission?

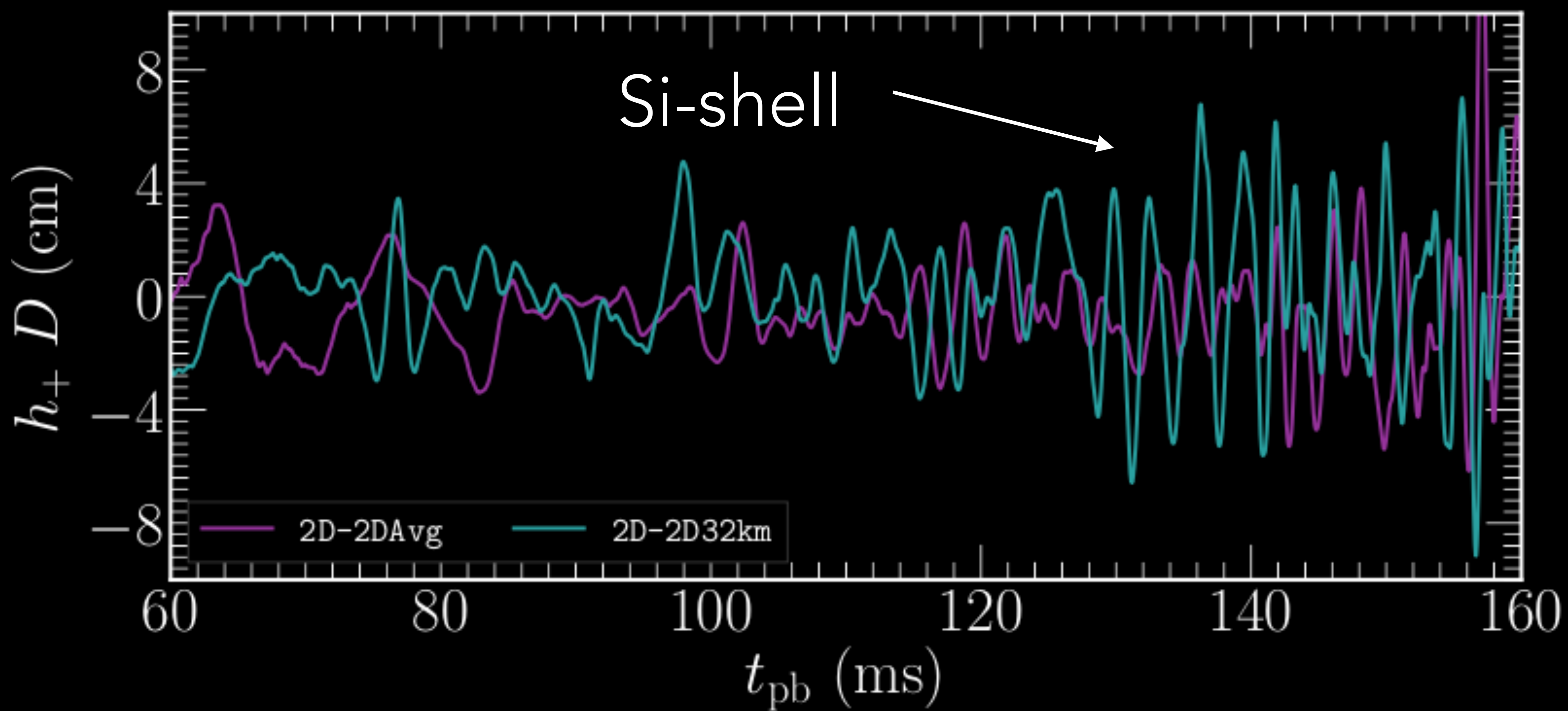


(O'Connor & Couch, 2018)

Si-shell perturbations shown in GW emission.

CCSN EXPLOSIONS OF MULTI-D PROGENITORS

GW Amplification via Realistic Explosion Models



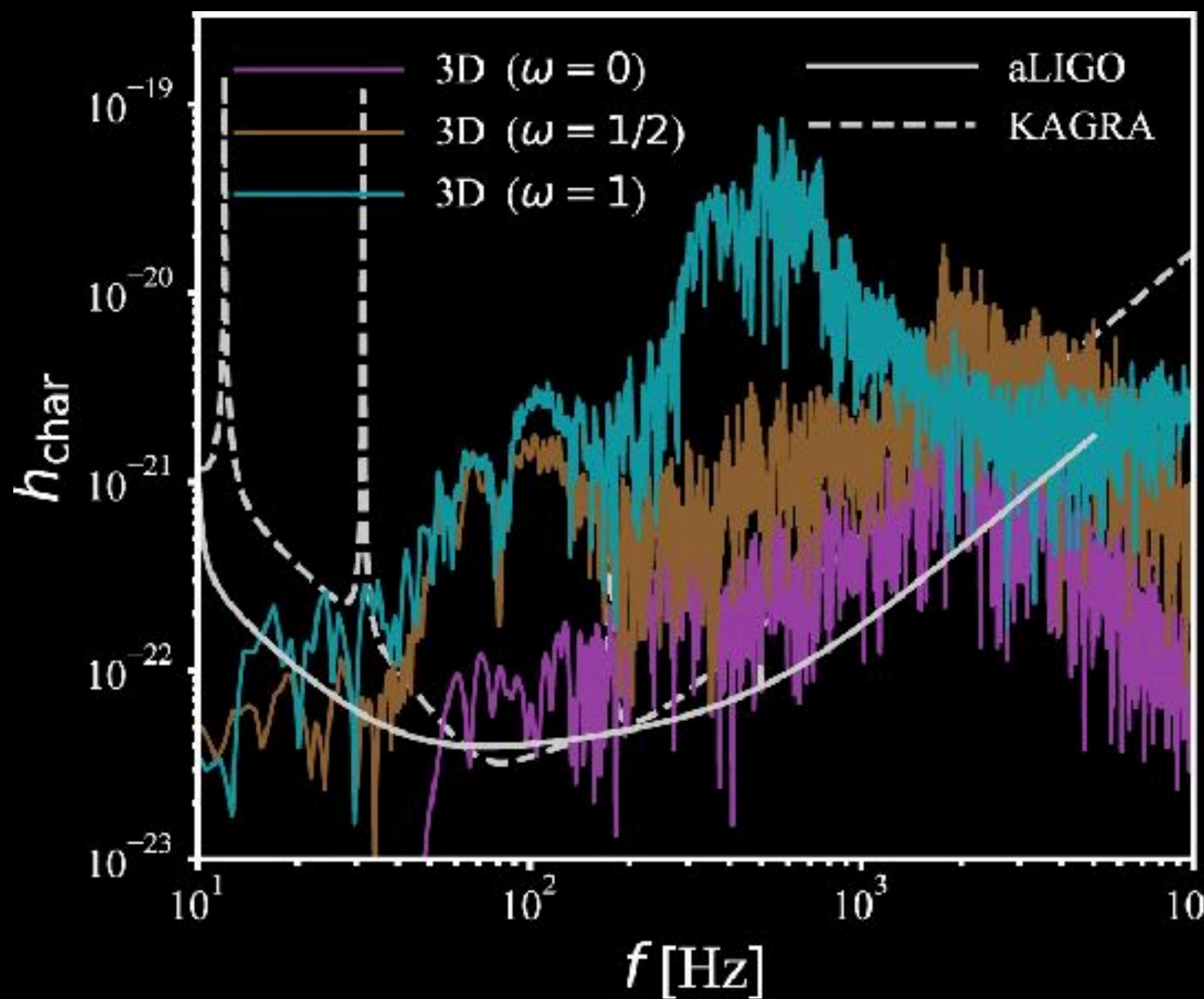
(Fields + 2022b, in prep.).

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

CCSN EXPLOSIONS OF MULTI-D PROGENITORS

Will current detectors hear these signals?

- 3D rotating explosion models.
- Detectable at 10 kpc (60 kpc w/LEN).
- Rotation can amplify signal.



(Pan+ 2021, ApJ).

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 ApJL, 2022)

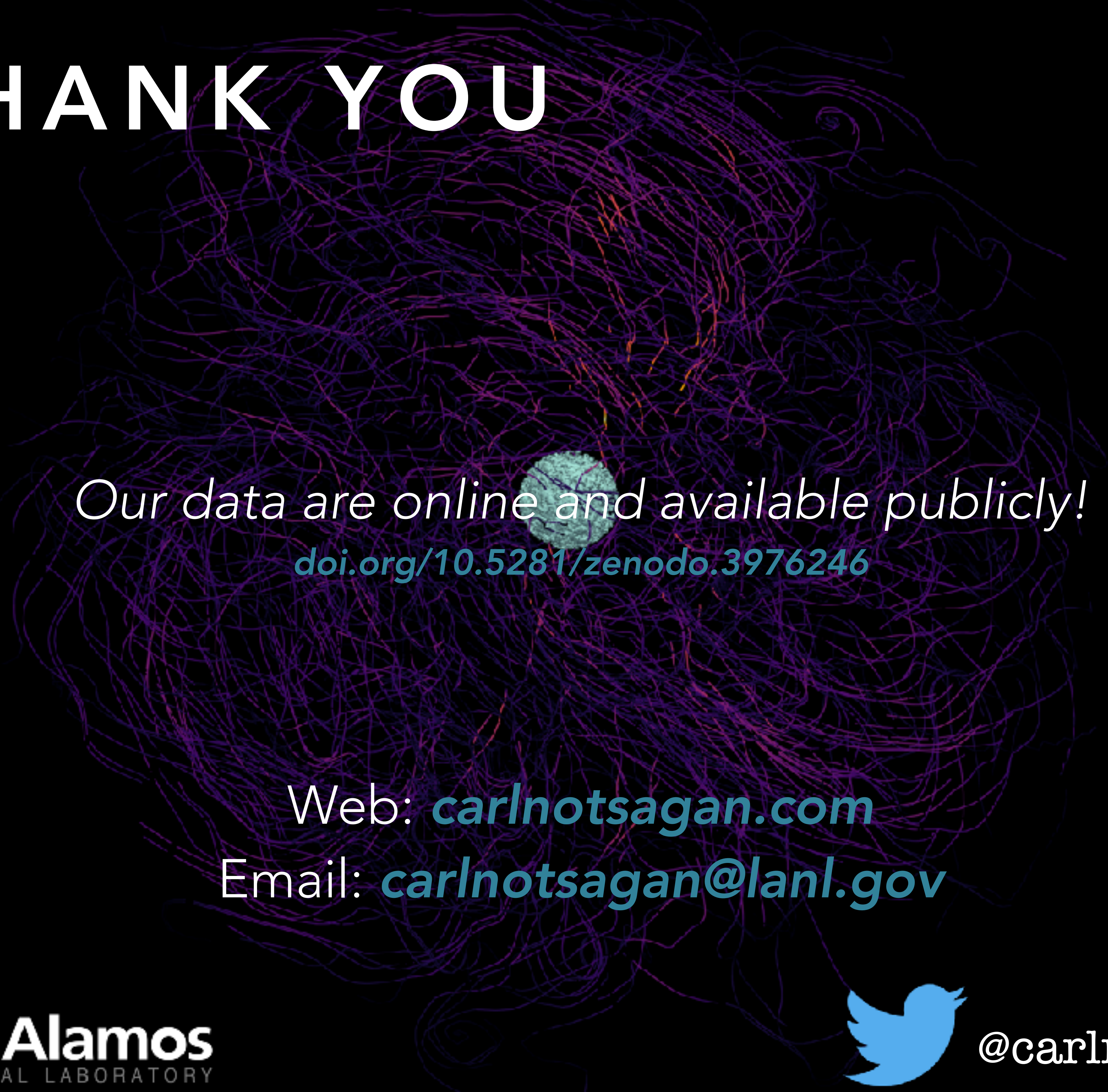
- Redistribution of AM diverges from MESA model. Implications for remnant.
- Turbulent transport of AM in convective shell regions.

Multi-D models can provide input for successful CCSN models

(Fields, 2022b, in prep.)

- 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



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

LOOKING FORWARD

Magnetic Fields

- Field amplification in pre-supernova phase and collapse
- Long term strength and topology during explosion

Neutrinos

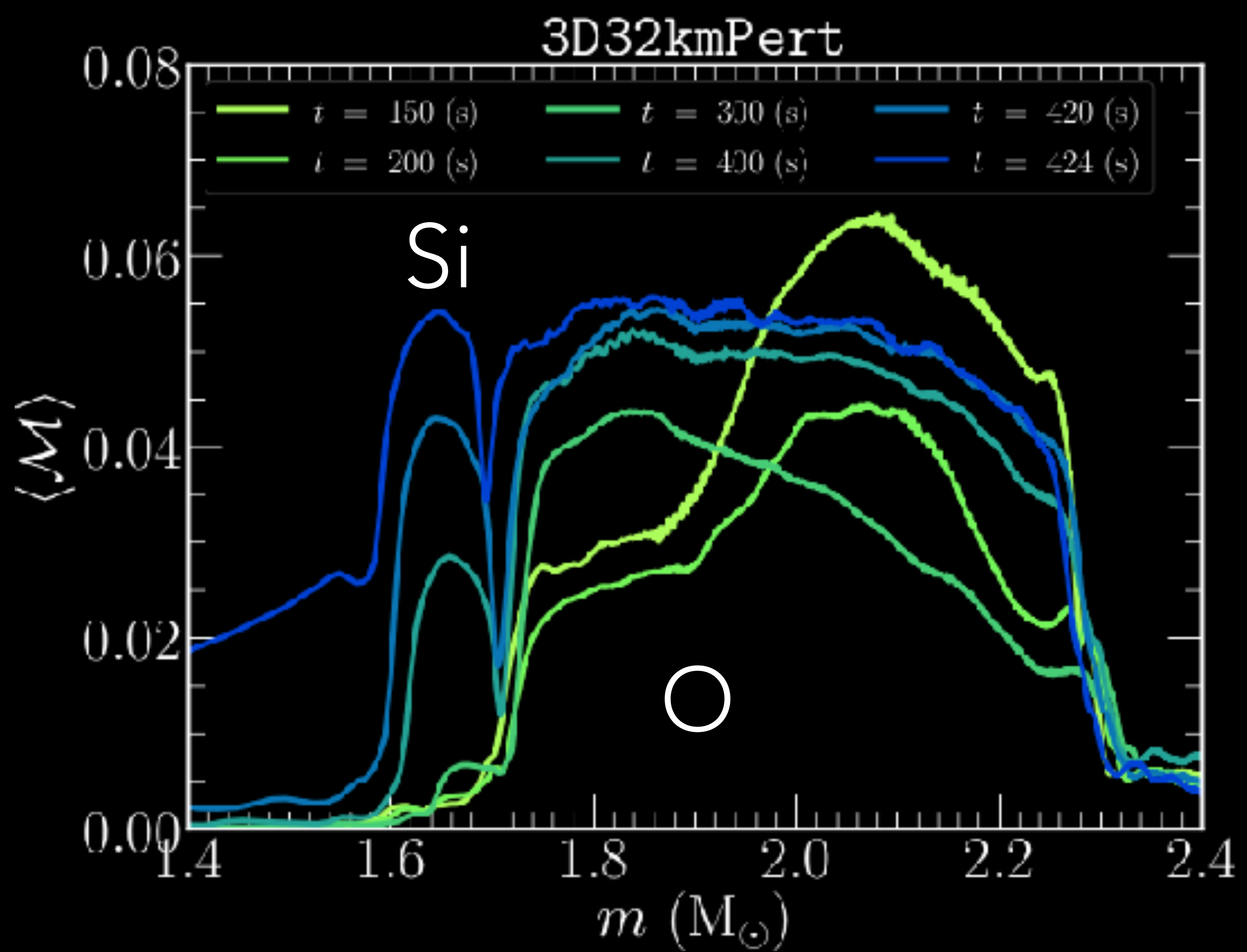
- Low energy neutrinos during pre-supernova phase - impact of 3D structure
- Coupling neutrino emission properties with GW signals of 3D explosions

Angular momentum transport

- 3D redistribution affecting our compact object estimates
- Feedback into AM transport assumed in 1D models

MULTI-DIMENSIONAL SIMULATIONS OF MASSIVE STARS

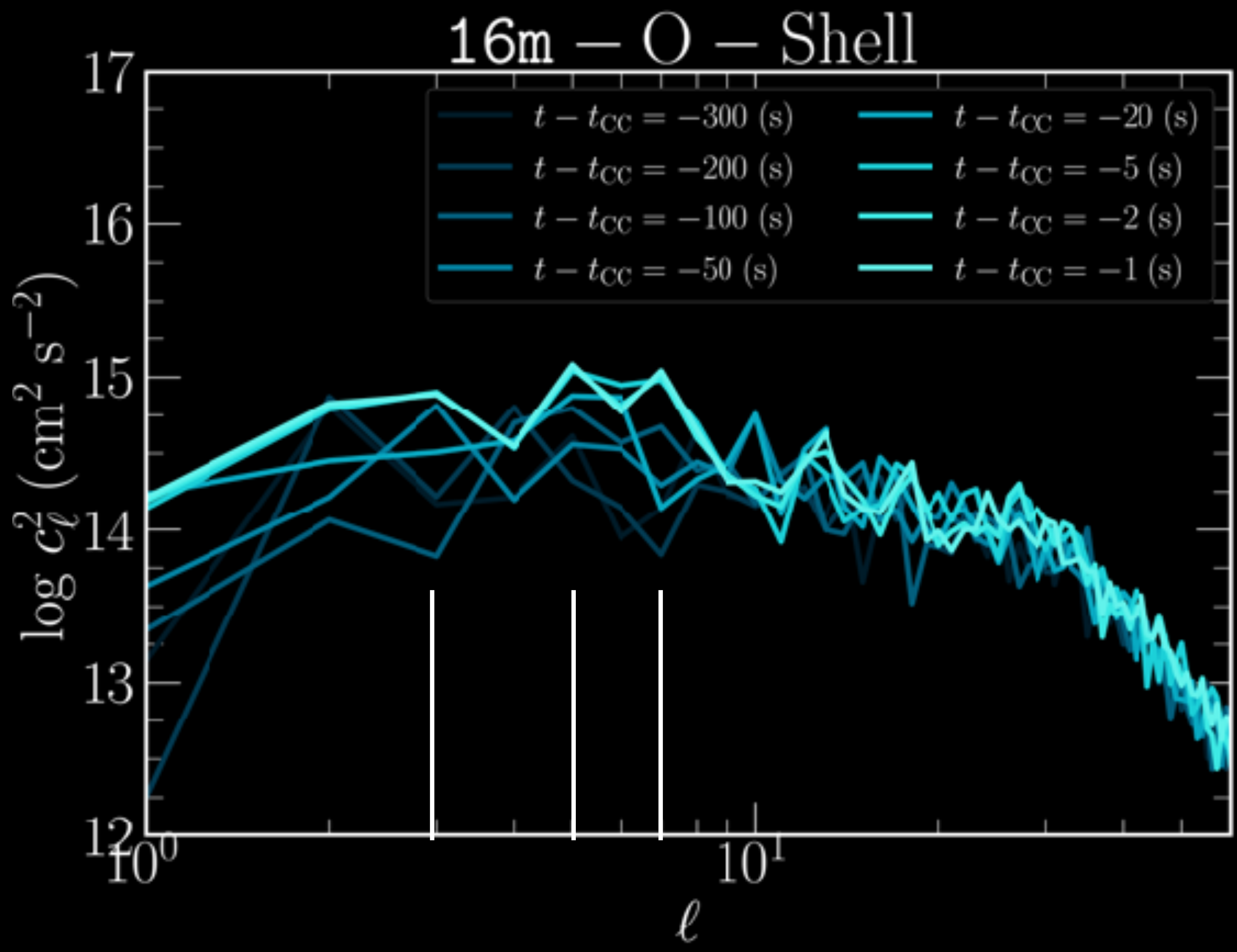
- Significant increase in Si-shell mach numbers at late time.
- Oxygen-shell reaches steady values early on.
- Values in O-shell lower than previous studies (Muller+2016)



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

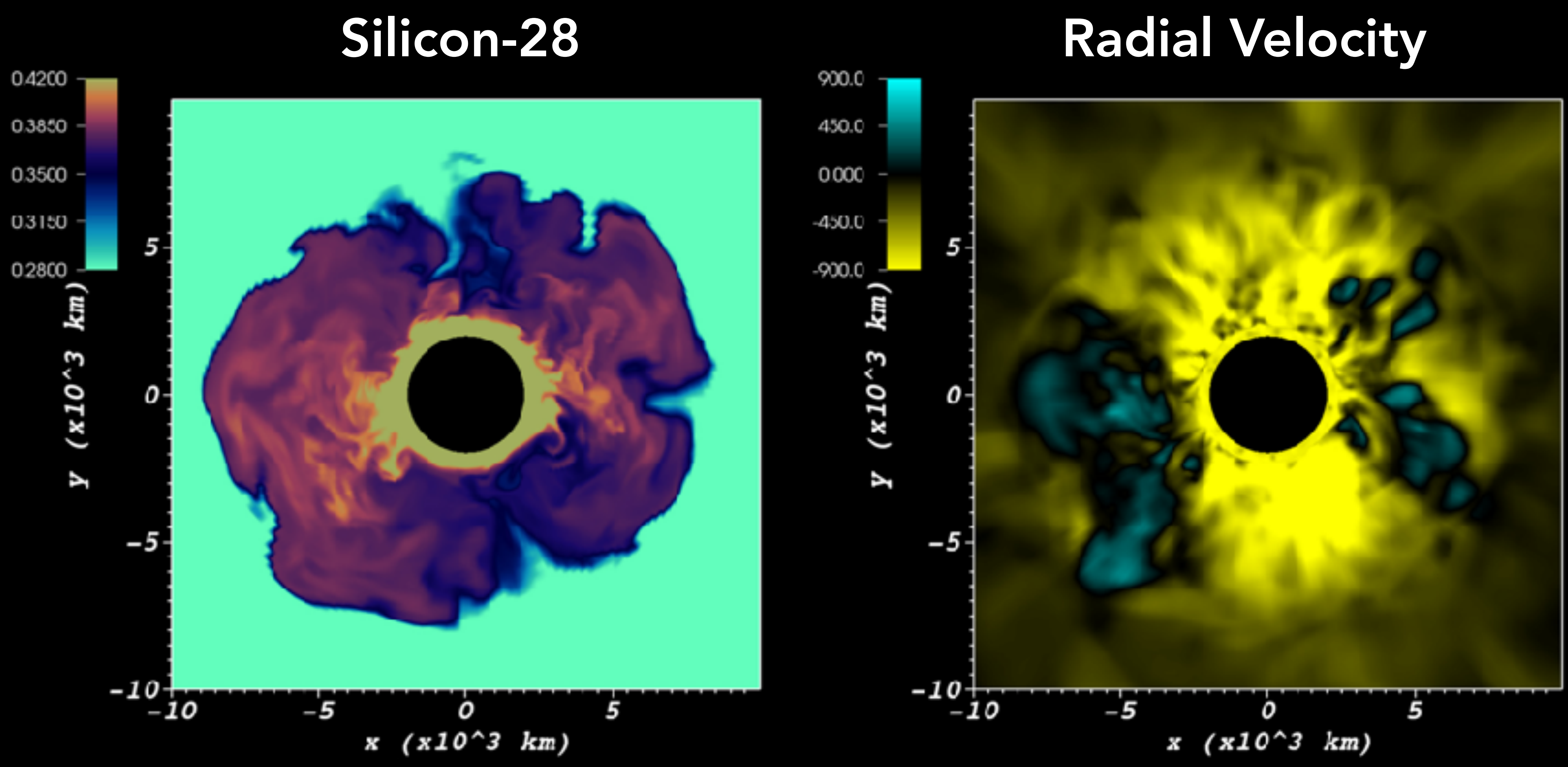
MASSIVE STAR CONVECTION IN ROTATING PROGENITORS

- 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 2022)

MULTI-DIMENSIONAL SIMULATIONS OF MASSIVE STARS

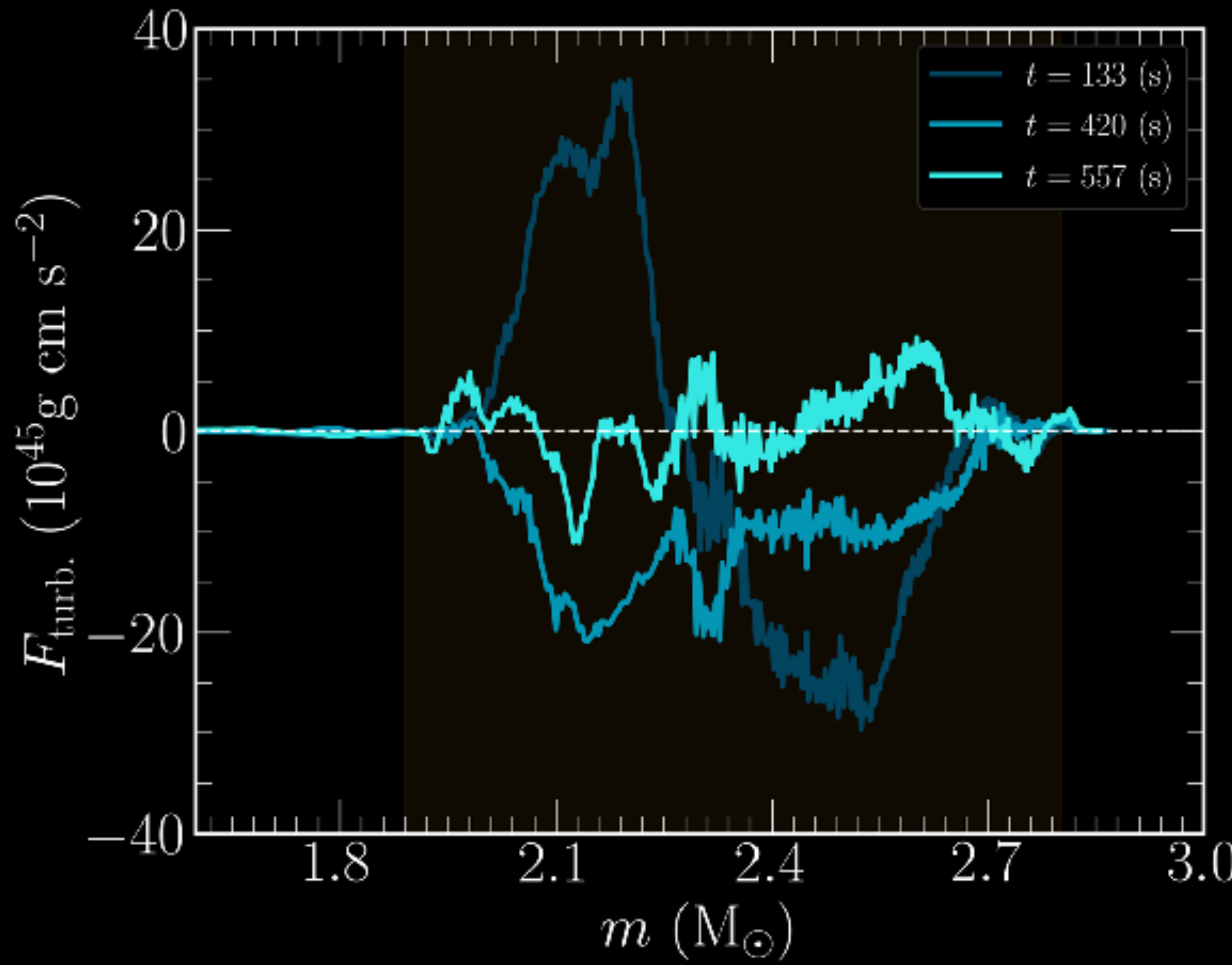


- 4pi simulations of oxygen shell burning find bipolar flow near collapse in simulation of 18 solar mass star. *(Muller +2016)*

MASSIVE STAR CONVECTION IN ROTATING PROGENITORS

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

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



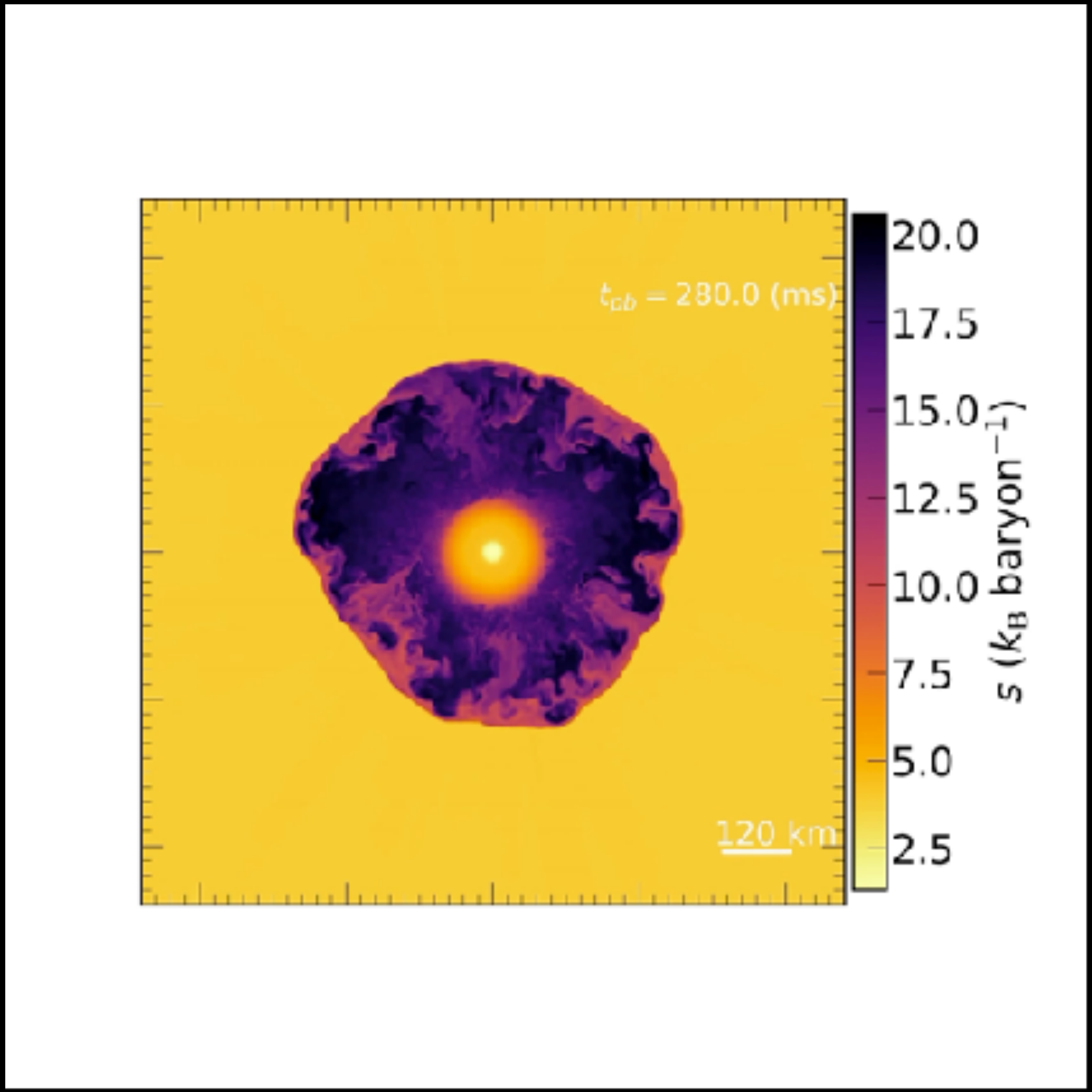
Angular momentum flux profiles.

***(Fields 2022*)**

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 + 2022b, in prep.)***.

MASSIVE STAR CONVECTION IN MULTIPLE PROGENITORS

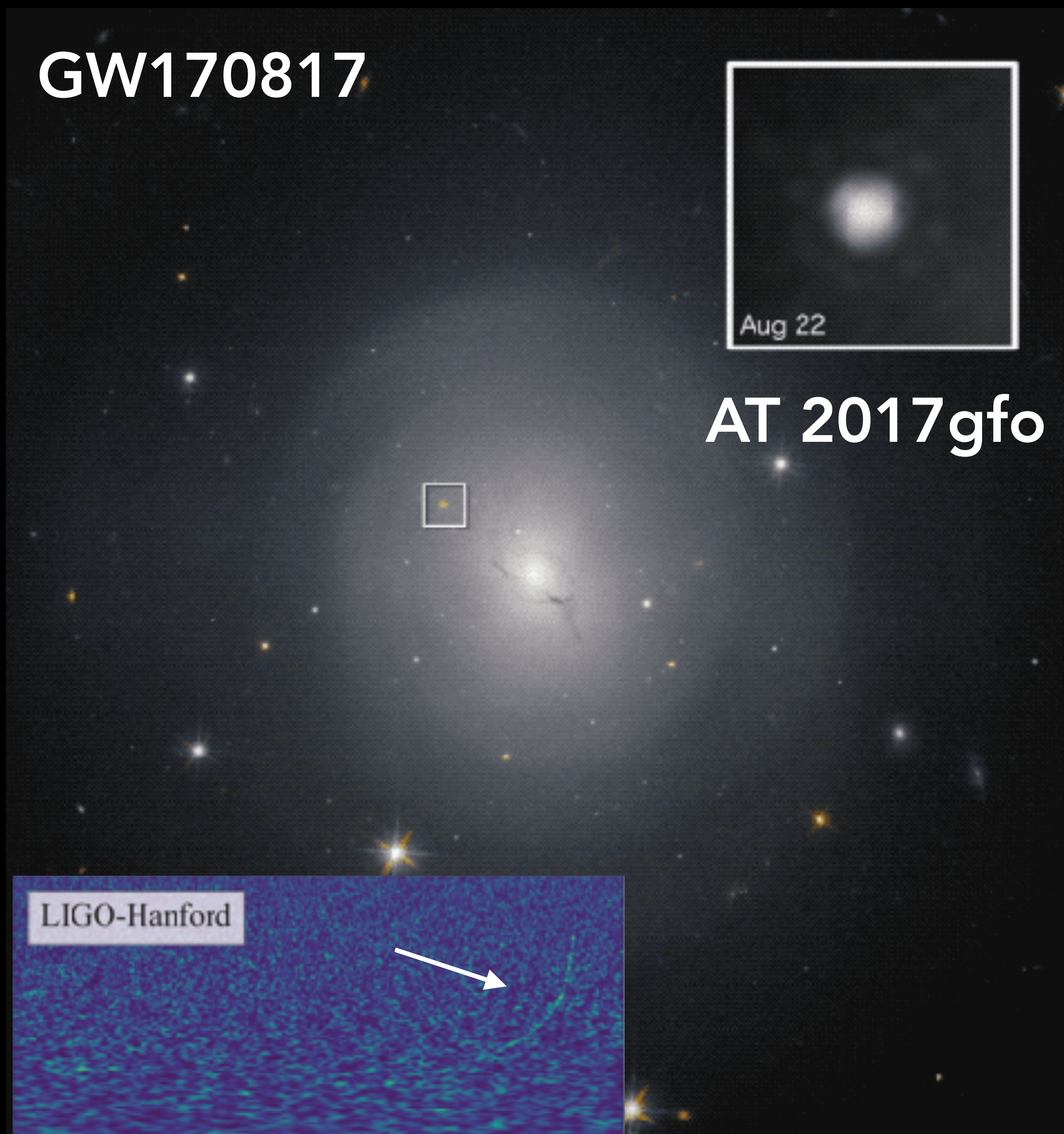
- Smaller O-shell Region, smaller mach numbers, ~0.04!
- Convection occurring at broad range of scales.

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

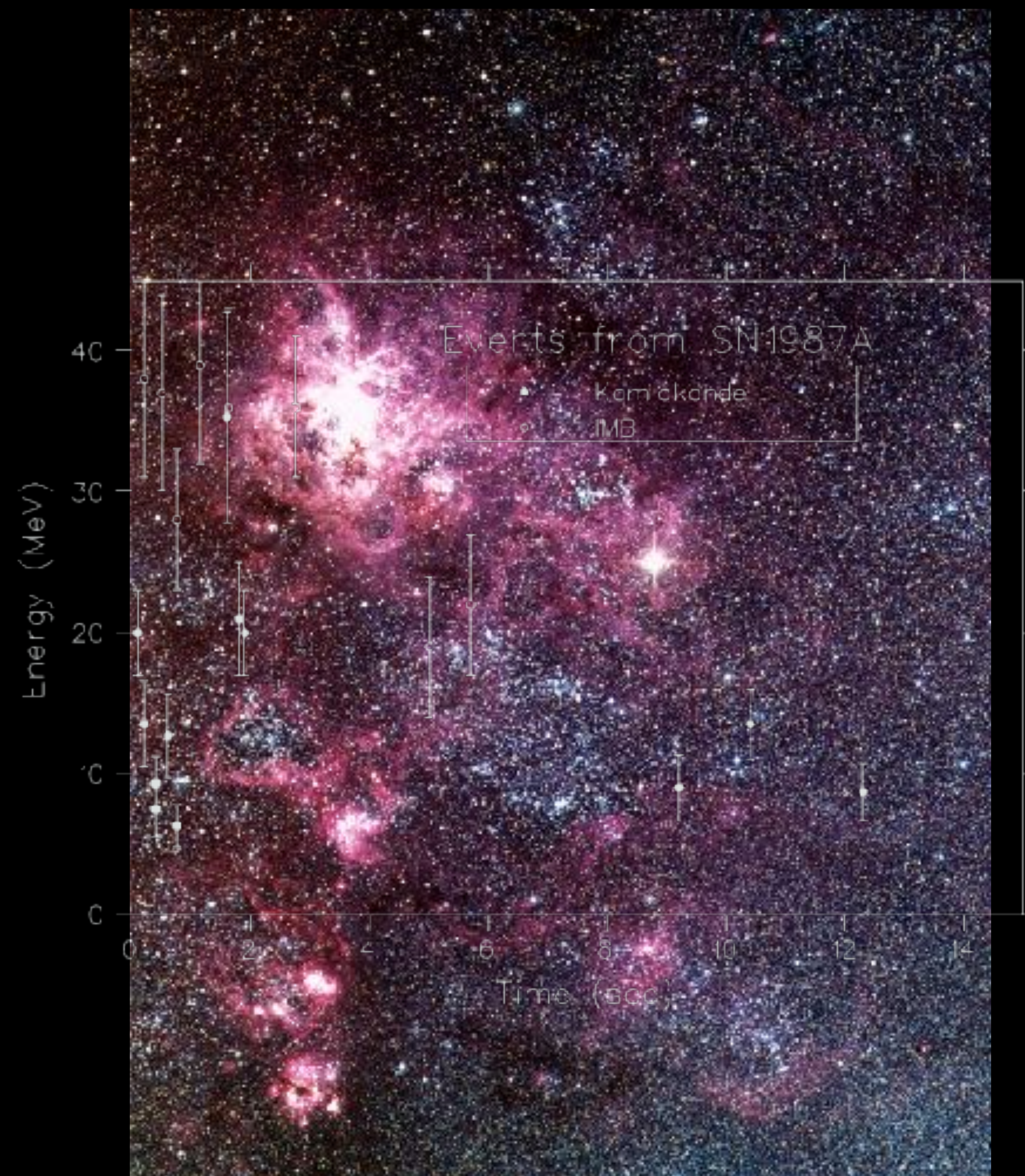
(Fields & Couch ApJ, 2021)

INTRODUCTION

Rely directly on our understanding of massive stars



Neutron Star Merger (Credit: NASA/ESA)



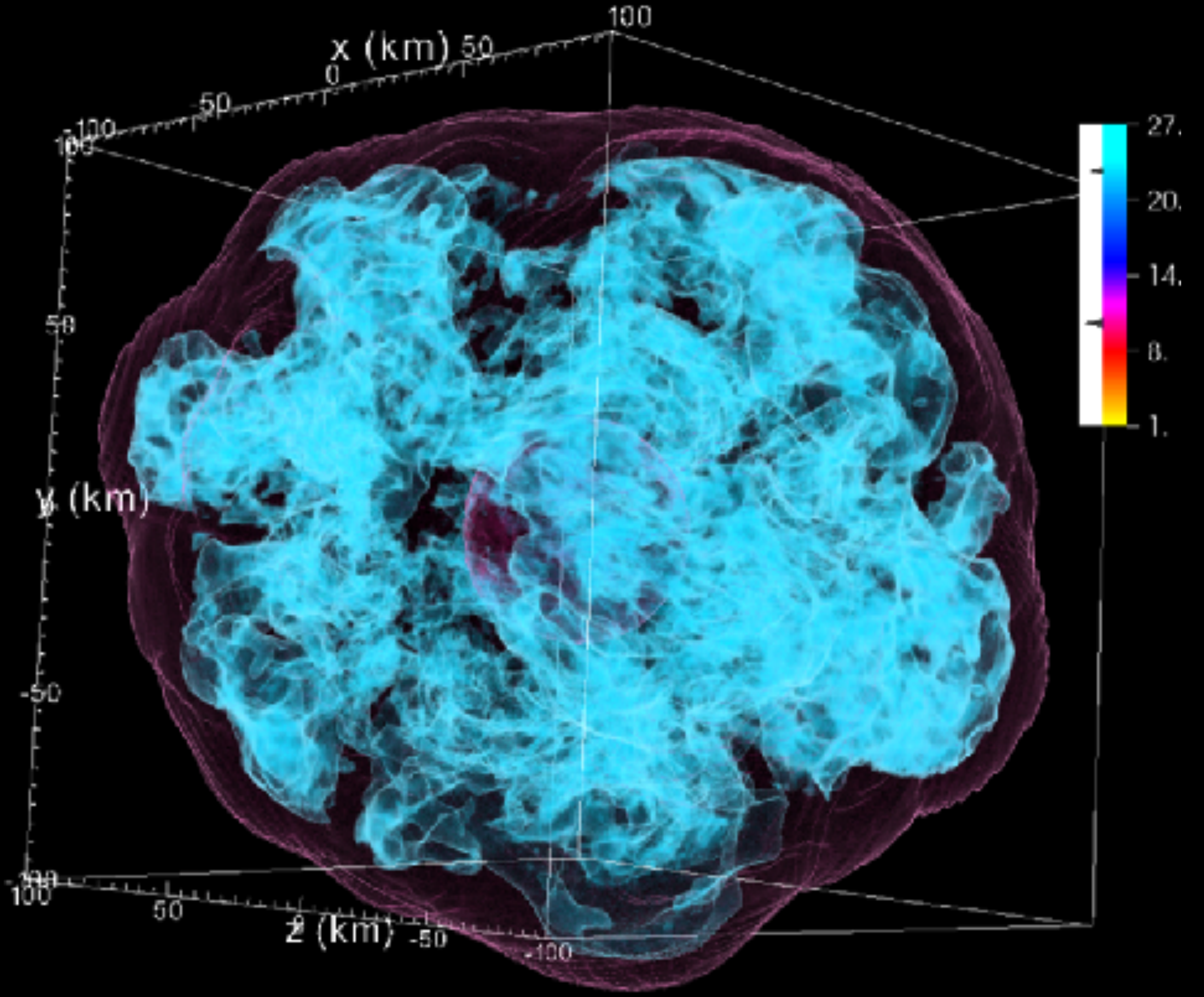
Supernova 1987A (Credit: ESO)

CCSN EXPLOSIONS OF MULTI-D PROGENITORS

What about magnetic fields…?

- Weak to moderate B fields can affect ordinary explosions.
- Field strength and topology prior to collapse not well constrained.

3D MHD CCSN Explosion



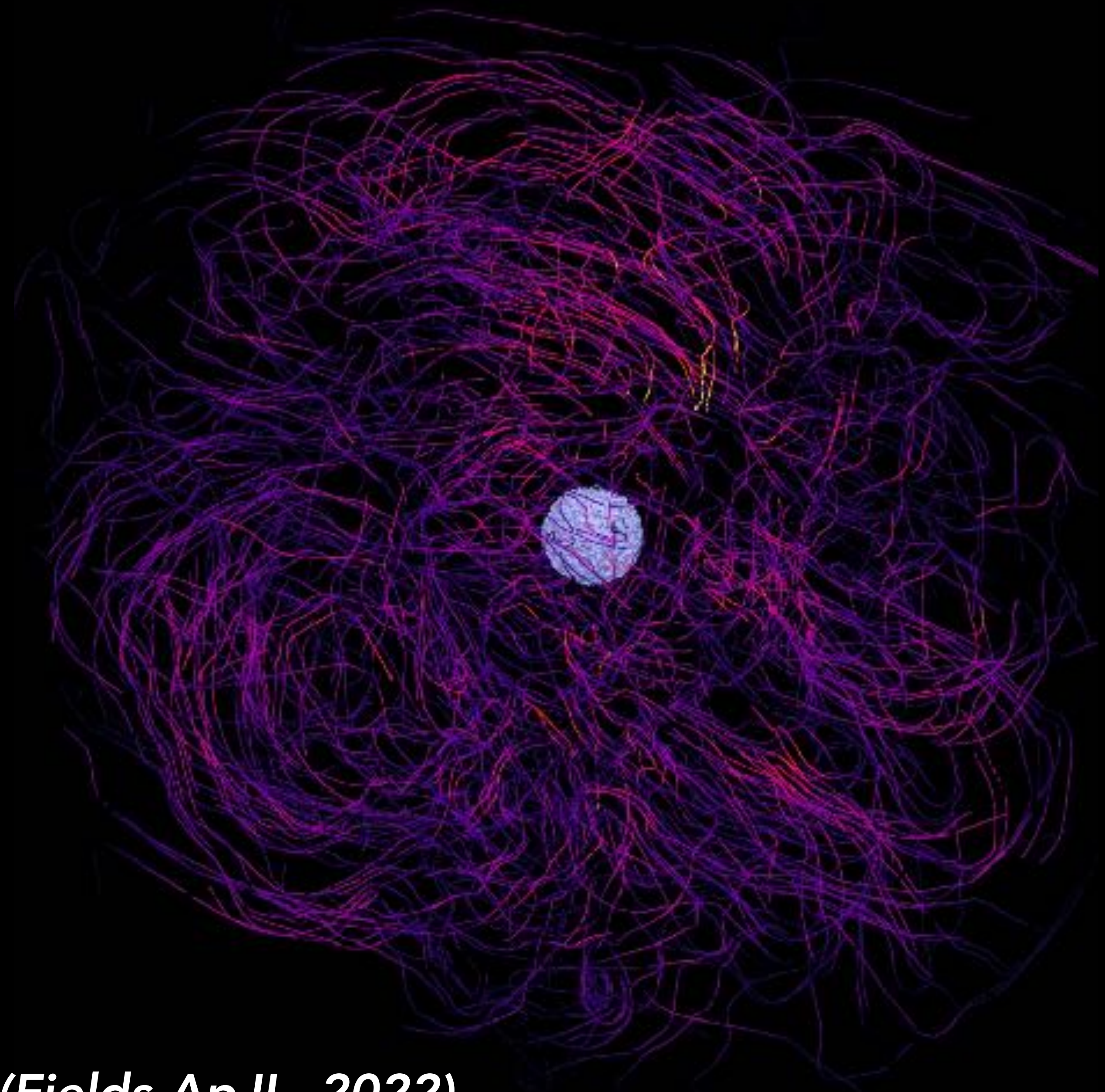
(Muller + ApJL, 2021)

CCSN EXPLOSIONS OF MULTI-D PROGENITORS

***Future Efforts**: Multi-Dimensional Magneto-Rotational Progenitor Models*

3D MHD Progenitors in FLASH

- Explore field strength, topology, amplification.
- Make estimates for compact remnants.
- Setup for 3D MHD explosions.



(Fields ApJL, 2022)