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Title: THE NEXT GENERATION OF STELLAR ASTROPHYSICS

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THE NEXT GENERATION OF STELLAR ASTROPHYSICS

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(he/him)

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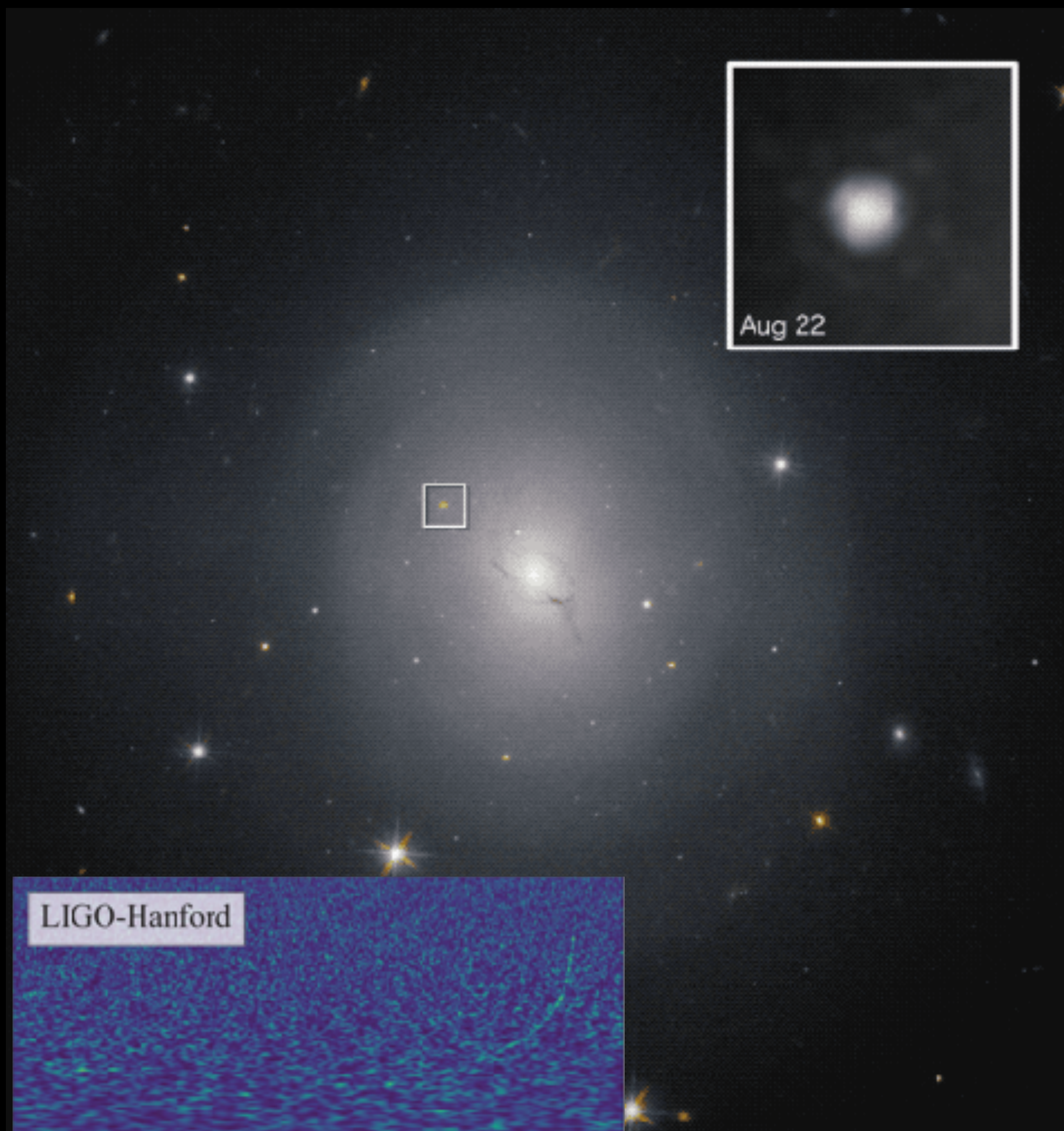
University of Arizona, Colloquium
February, 28, 2023

Los Alamos NATIONAL LABORATORY

@carlnotsagan

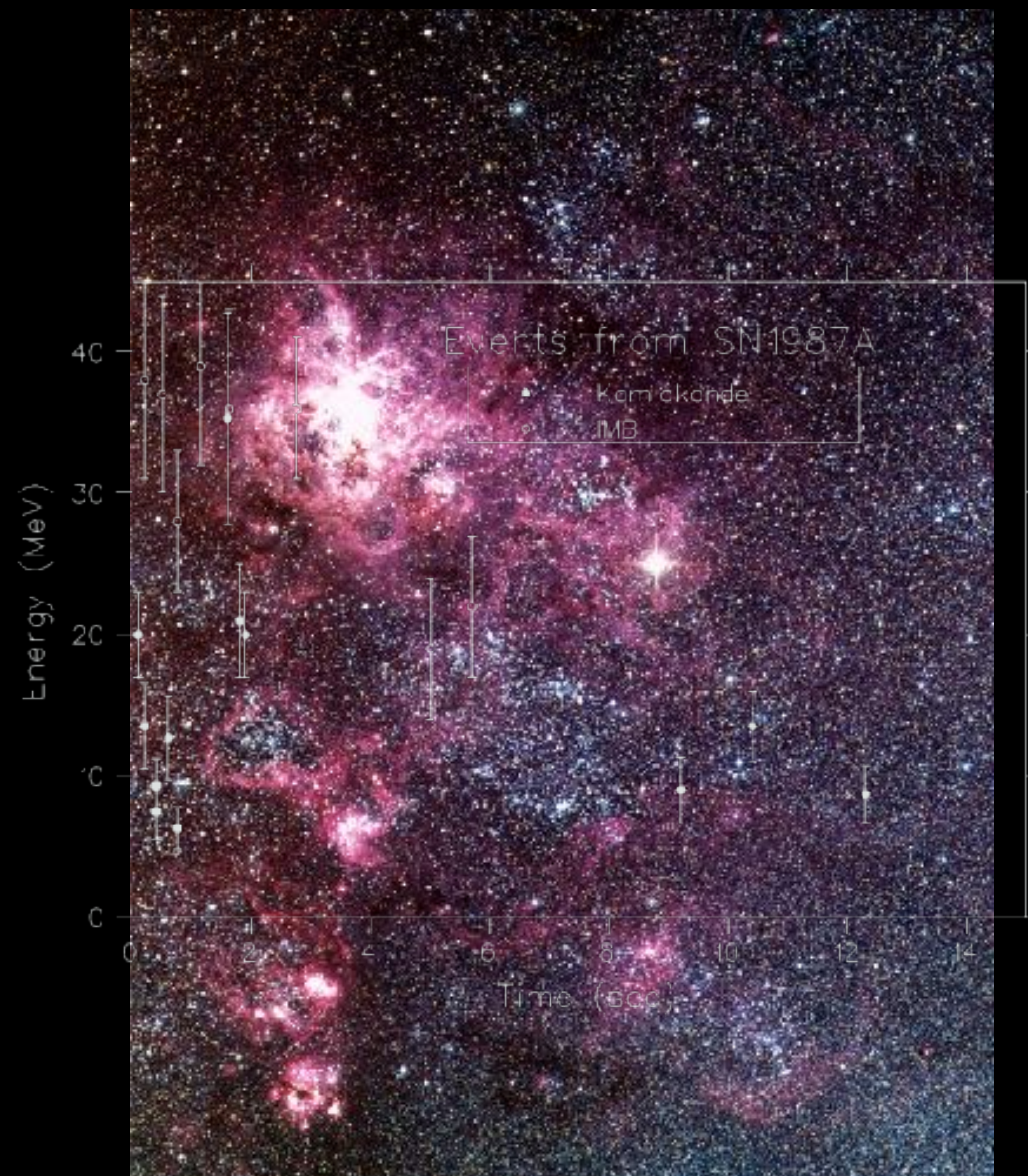
INTRODUCTION

Rely directly on our understanding of stars



GW170817

(Credit: NASA/ESA)

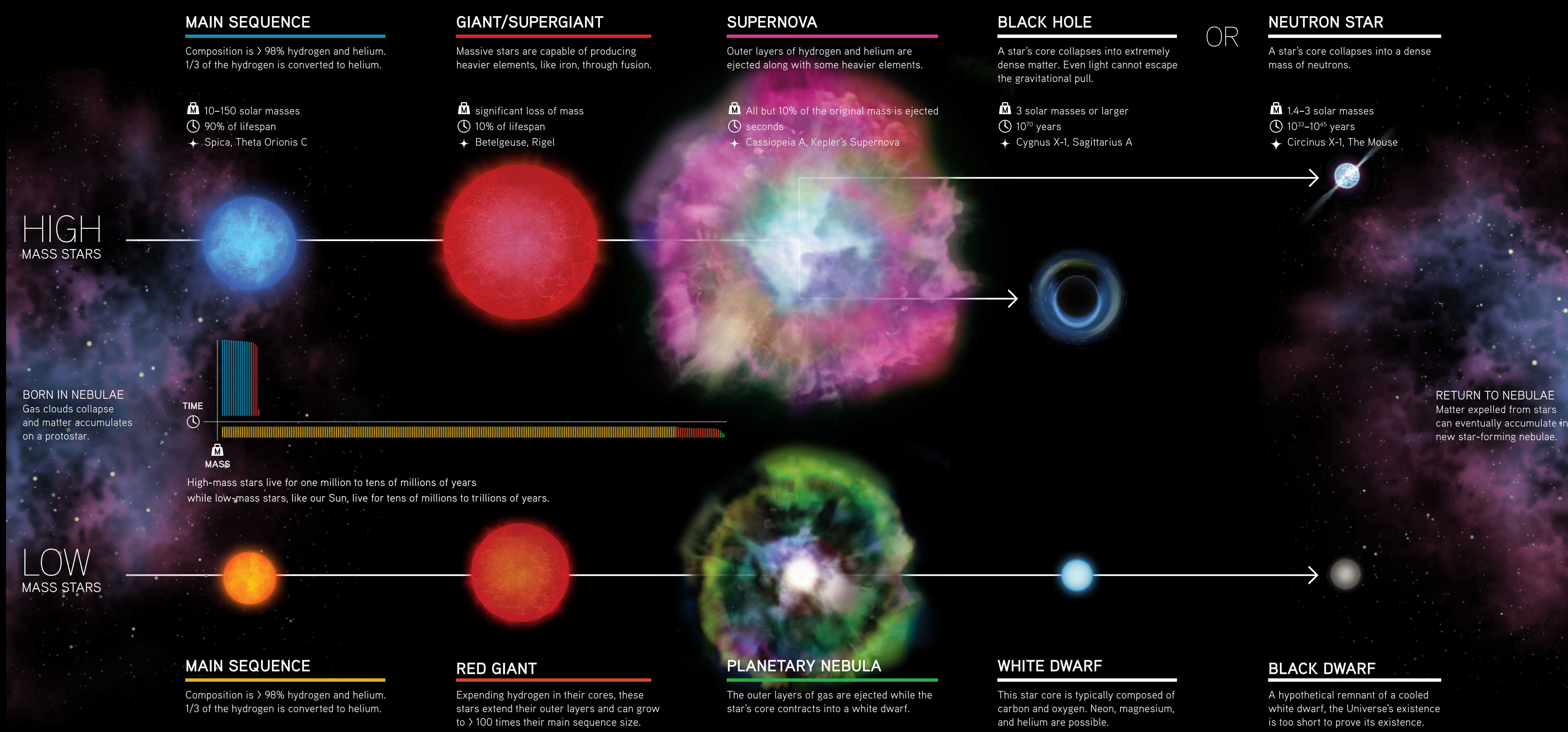


Supernova 1987A

(Credit: ESO)

INTRODUCTION

THE LIFE CYCLES OF STARS



STELLAR LIFE CYCLES. CREDIT: KHAN ACADEMY

INTRODUCTION

A New Generation of Computational Tools

- Advancements in hardware (CPUs, GPUs, architecture)
- Advancements in computational methods
- State-of-the-art tools required in concert with experiment and observation

Stellar Evolution Toolkit

Multi-Physics Hydrodynamics

Multi-Physics Low Mach Hydrodynamics

INTRODUCTION

Current and Next Generational Facilities

- **Require** astrophysical observations
- **Require** nuclear physics experiments
- **Require** new computational models

LIGO

Hyper-Kamiokande

OVERVIEW

Stellar Models in 1D

- Measuring stellar parameters
- Connections to observational data

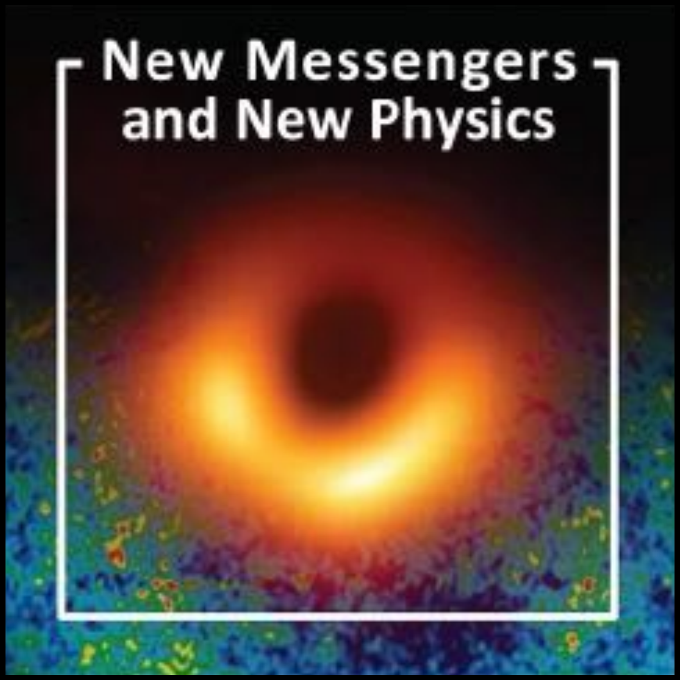
Stellar Convection

- Novel approach to modeling convection
- Informing 1D stellar models
- Astrophysical observables

Stellar Explosions

- Simulations of CCSNe from 3D progenitors
- Multi-messenger signals from CCSNe
- Late-time compact remnants

Collaborative Vision



Astro 2020

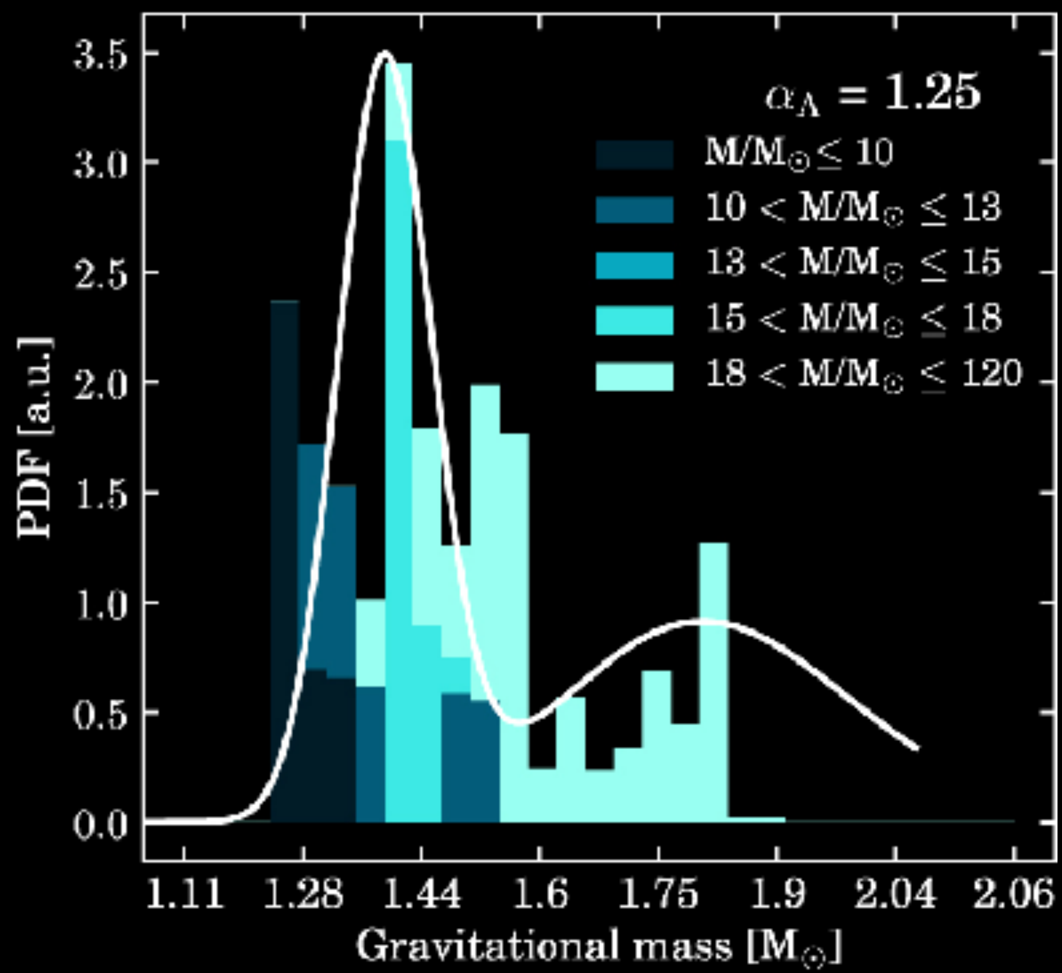
2015 Long Range Plan for Nuclear Science

FOUNDATIONS

Stellar models are powerful and necessary tools

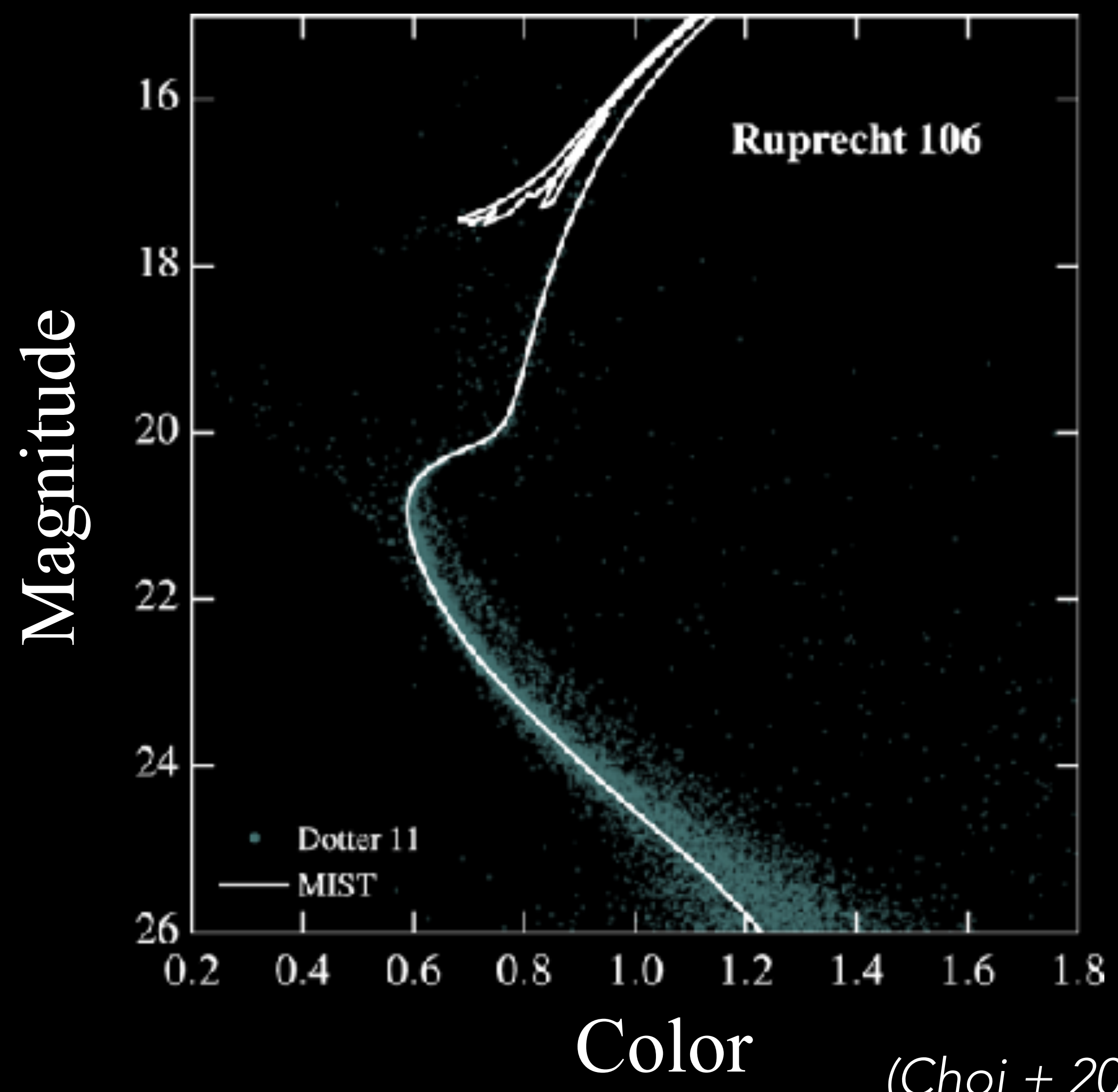
STELLAR MODELS IN 1D

NS mass distribution



(Couch + 2020)

Globular Clusters



(Choi + 2016)

STELLAR MODELS IN 1D

Connecting stellar models and observables

Input for Stellar Models

- Mass loss
- Convection
- Nuclear data
- Angular momentum
- Magnetic fields

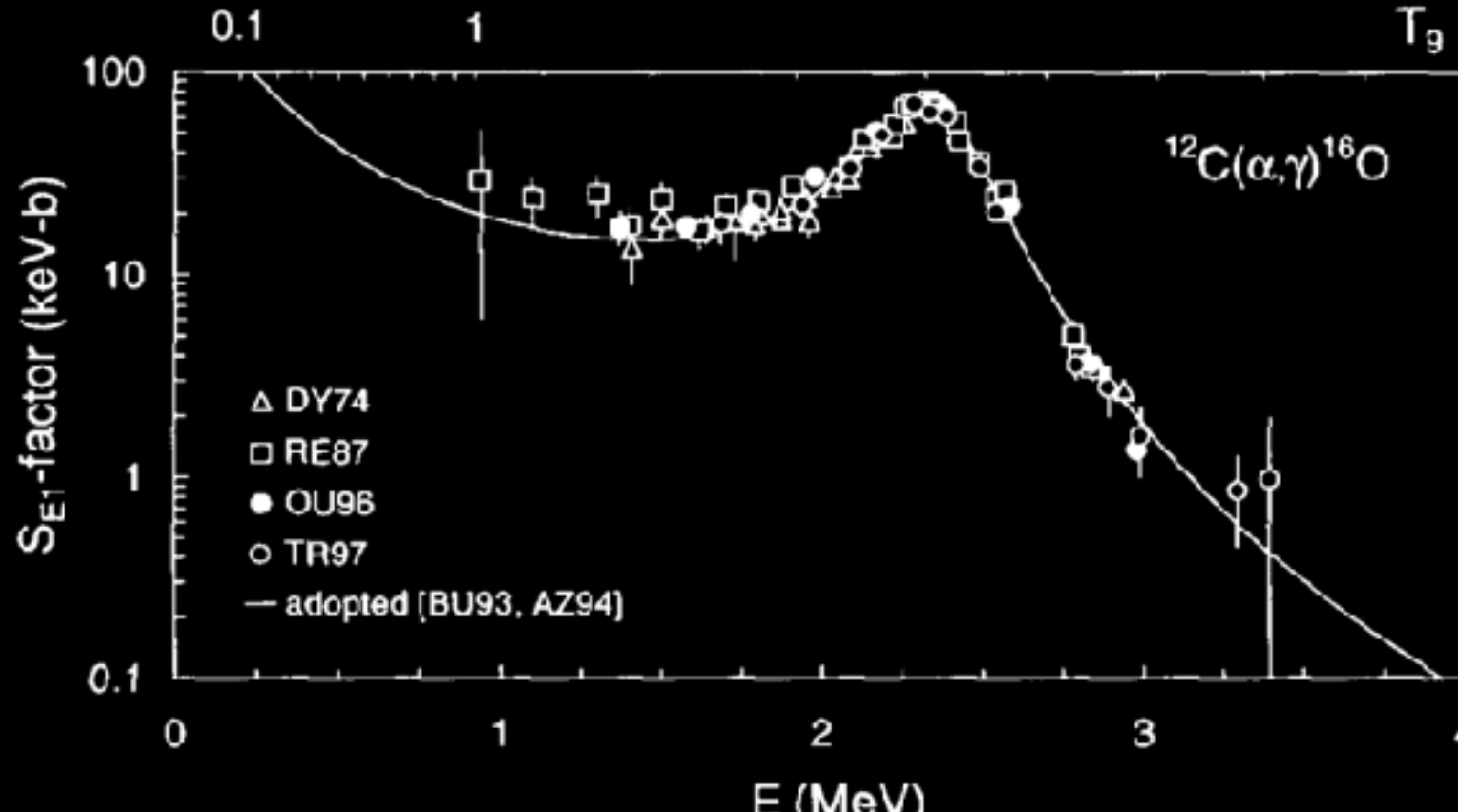
Empirical Calibrations

- Nuclear physics experiments
- Astrophysical observations
- Direct numerical simulations

STELLAR MODELS IN 1D

Connecting models to nuclear experiments

- **Nuclear reaction rates** regulate burning in stellar models.
- Rates governed by experimental cross sections.
- Extrapolation introduces uncertainties.



(Angulo + 1999)

Astrophysical S-factor of the $^{12}C(\alpha,\gamma)^{16}O$ reaction rate.

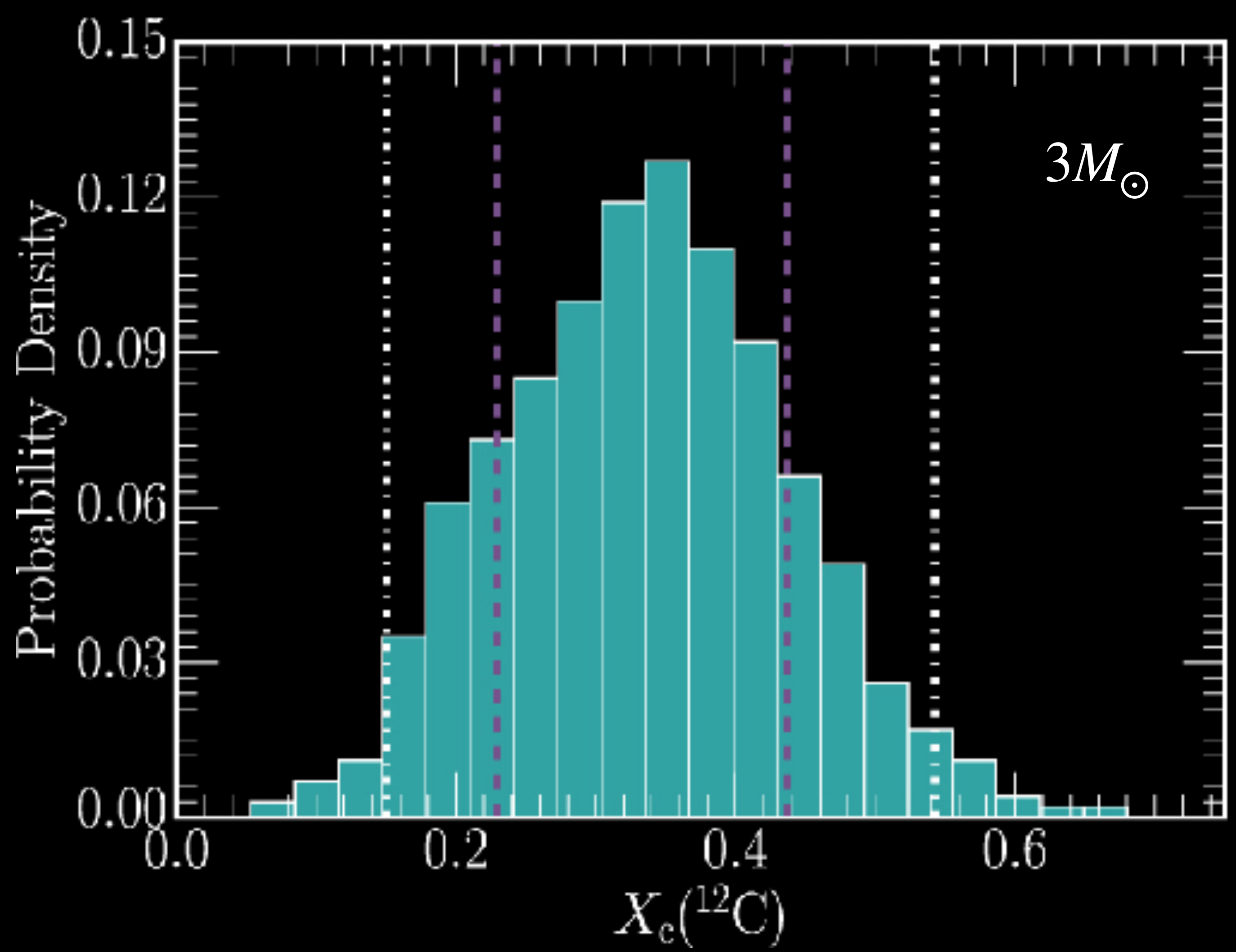
STELLAR MODELS IN 1D

Measuring distribution of stellar properties

MESA 1D Stellar Models

- Measure stellar properties varying rate uncertainties.
- Set limits on key properties: relevant to white dwarfs.
- Identify key reaction rates.

$^{12}C(\alpha,\gamma)^{16}O \,|\, r_S = -0.95$



Resources required: laptop, small cluster

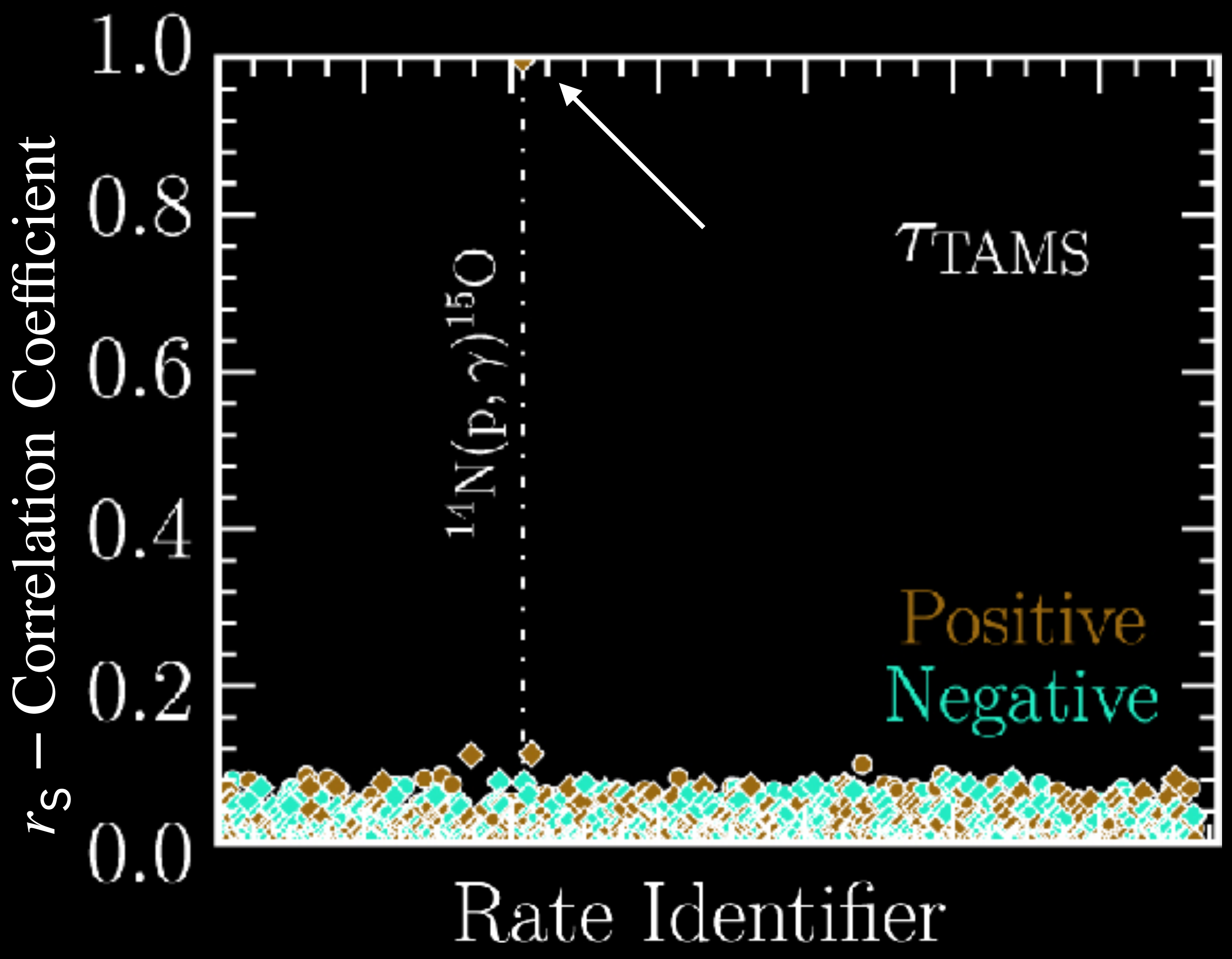
(Fields + ApJ, 2016)

STELLAR MODELS IN 1D

Identifying key reaction rates

MESA 1D Stellar Models

- Extend study to massive stars.
- Set limits on key properties: *main-sequence lifetimes.*
- Sample > 600 rates simultaneously.



Resources required: laptop, small cluster

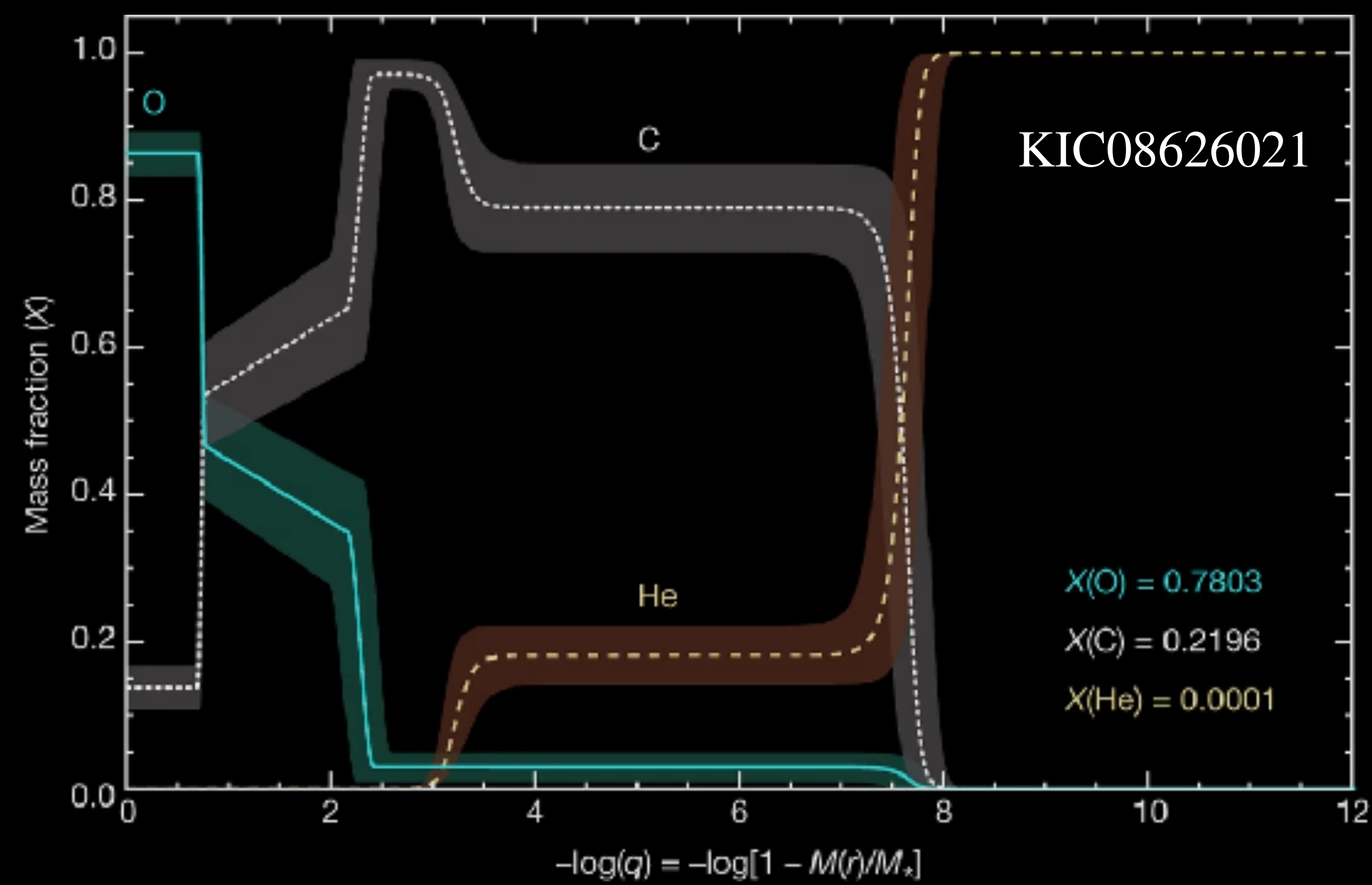
(Fields + ApJS, 2018)

STELLAR MODELS IN 1D

***Future Efforts**: Connecting asteroseismology, stellar models, and nuclear physics*

- pulsating DB white dwarf star
- Forward modeling approach to fit pulsation period to grid of stellar models.
- Stellar models have N free parameters which alter the period spectrum.

Best Fit Model - *Kepler* data

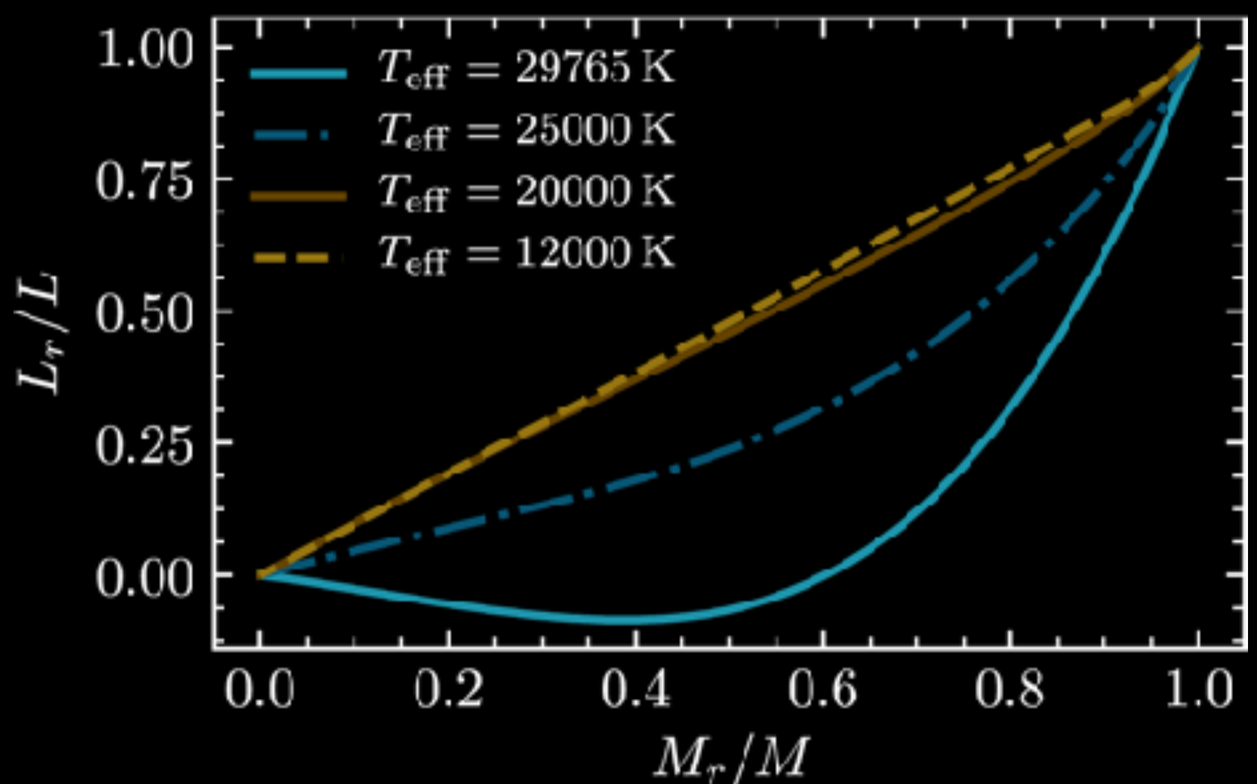


(Giammichele + Nature, 2018)

STELLAR MODELS IN 1D

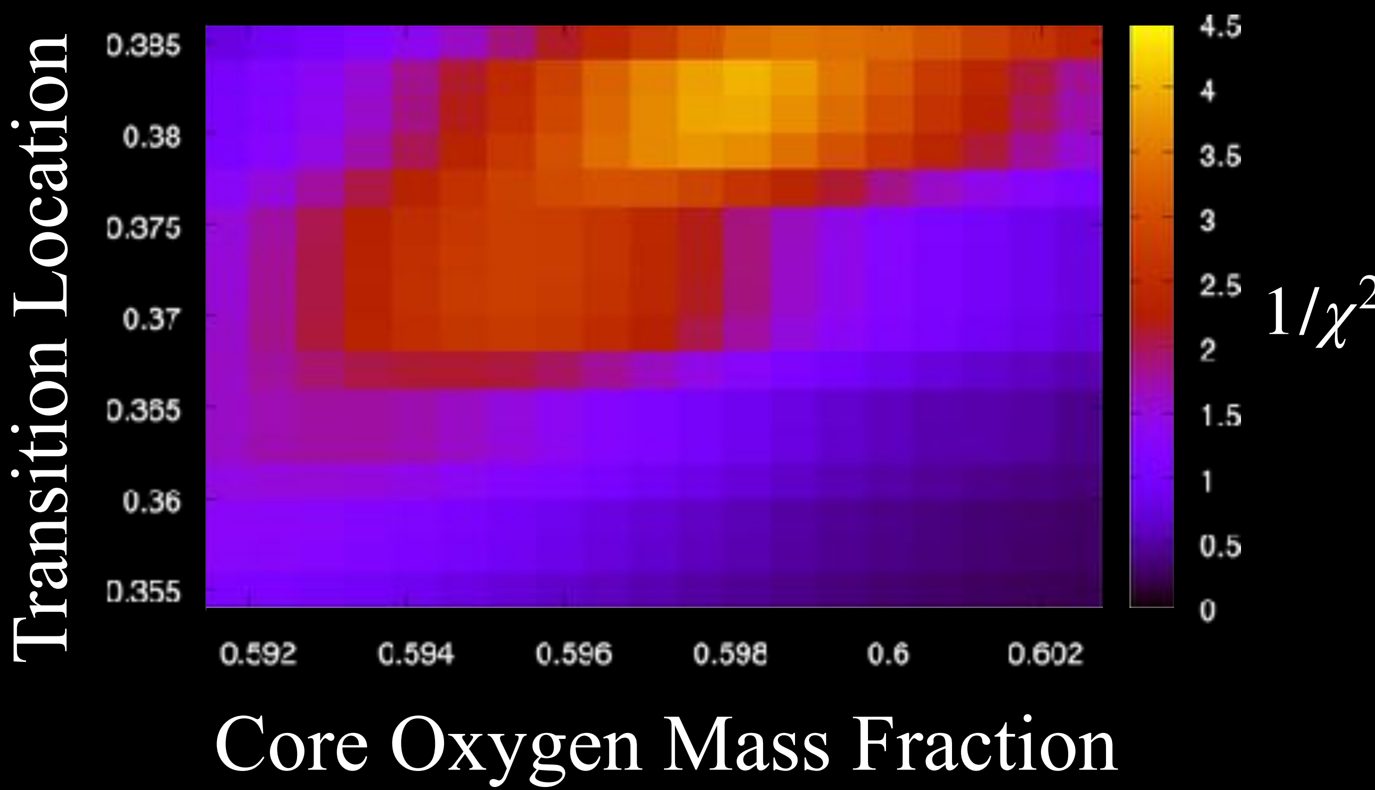
***Future Efforts**: Building new WD models*

Neutrino cooling



(Timmes + inc. Fields ApJL, 2018)

Beyond ab initio models



(Guifang + ApJ, 2021)

STELLAR MODELS IN 1D

Current and Future Directions

White Dwarfs

- A closer look at Ab Initio Models *(in collab. w/ Chidester, Timmes @ ASU)*
- Updated Nuclear Cross-Sections
- WD Age Estimates *(in collab. w/ Heintz, Hermes @ BU)*
- Larger sample of observational data

Progenitors of Stellar Transients

- Neutron Capture Rates *(in collab. w/ Spyrou @ MSU/FRIB)*
- Angular momentum transport in massive progenitors
- Updated Nuclear Cross-Sections
- 3D stellar convection to 1D models *(in collab. w/ Cantiello, Goldberg @ CCA)*
- Mixing constraints informed by observations

FOUNDATIONS

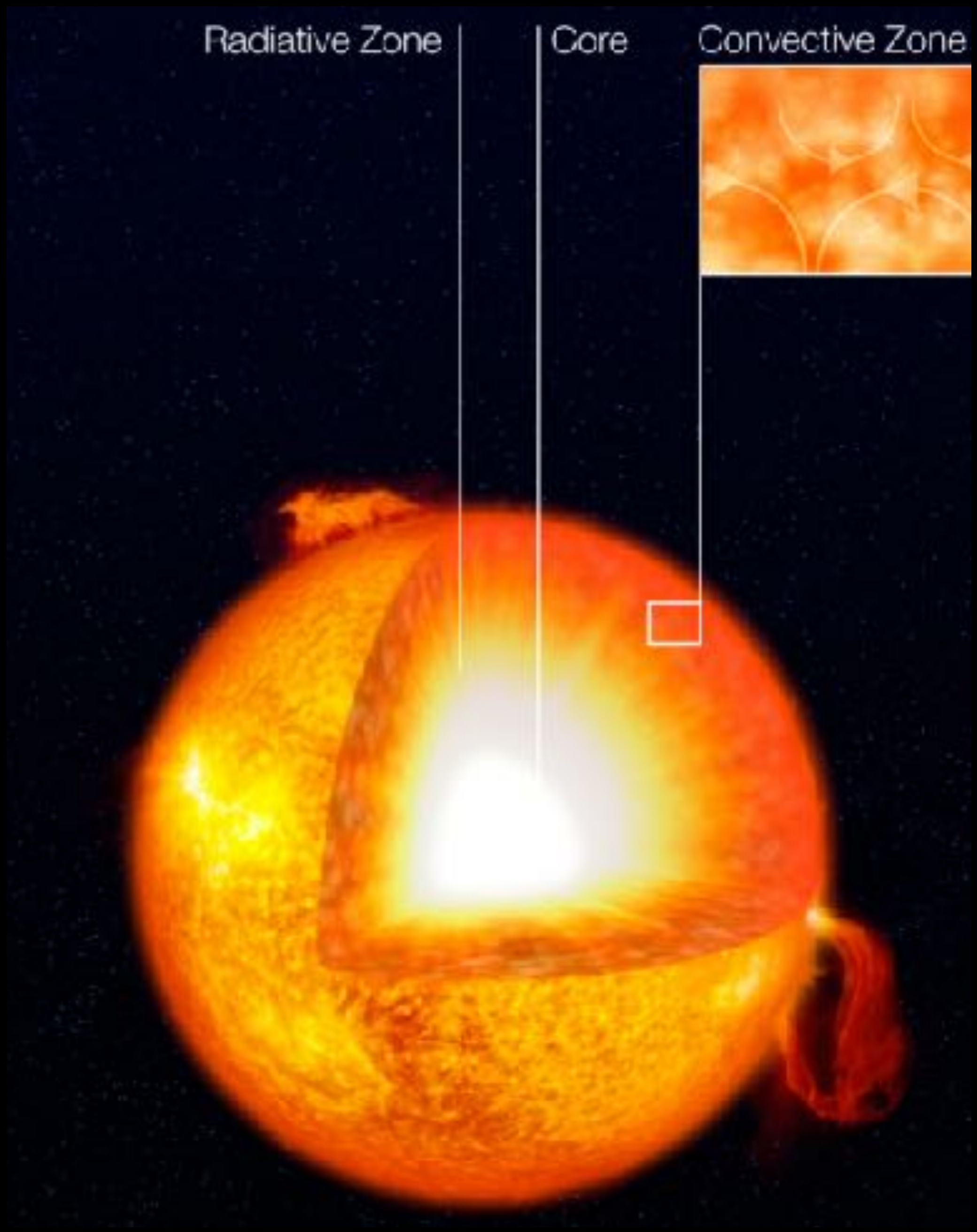
Stellar models are powerful and necessary tools

FOUNDATIONS

Stellar convection is a critical part of stellar models

STELLAR CONVECTION

- **Convection** refers to the transport of energy via mass motions.
- When radiation inefficient, fluids move, convect.
- Convection inherently 3D, **approximated** in 1D.
- Works well for the Sun.



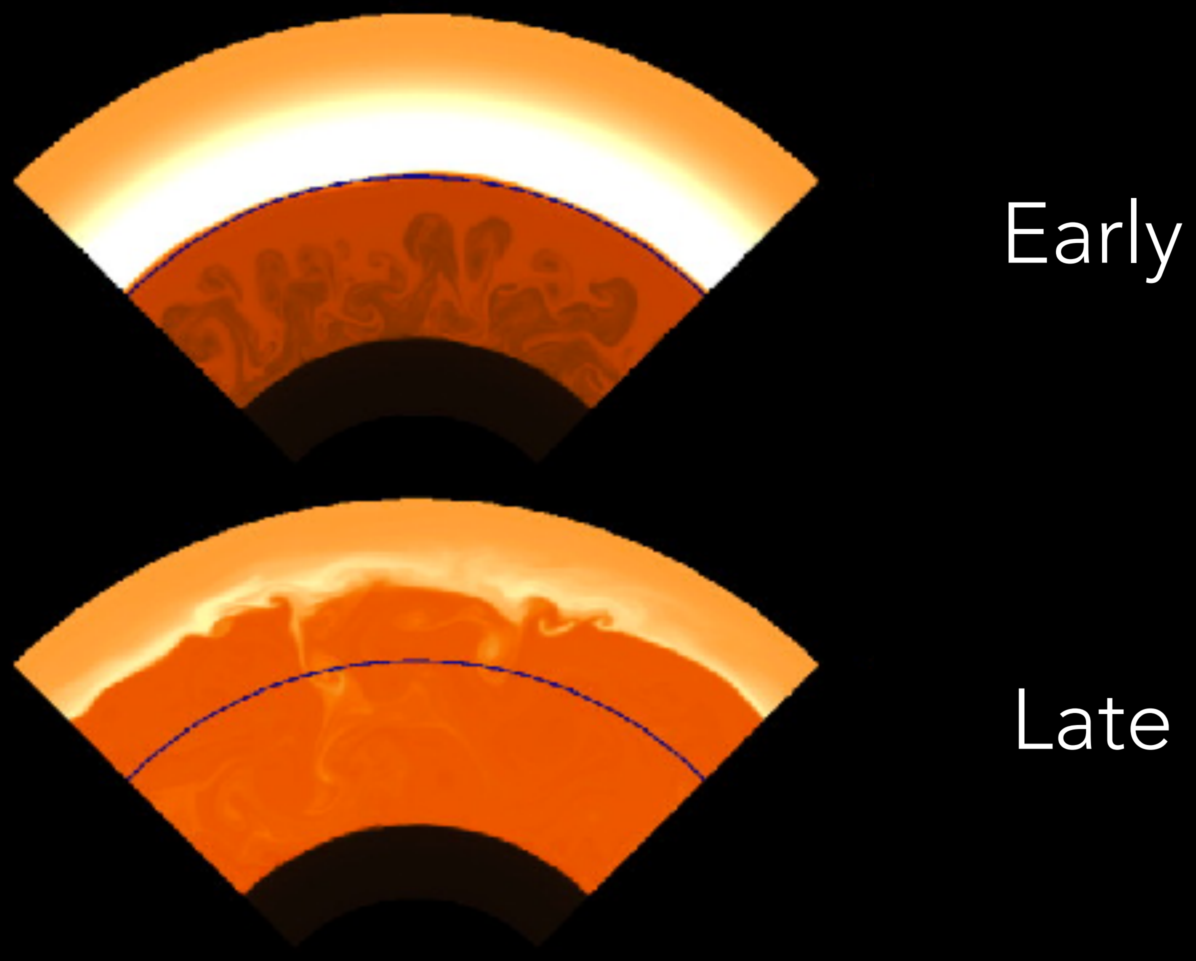
Artist's impression of convection in a low mass star - like the Sun.
Credit: ESO

STELLAR CONVECTION

multi-D convection models developed over decades

- Start from 1D and evolve for for $\mathcal{O}(10)$ turnover timescales.
- Mixing beyond previously stable boundaries.
- Properties diverge from 1D stellar models.

O-shell burning $23 M_{\odot}$



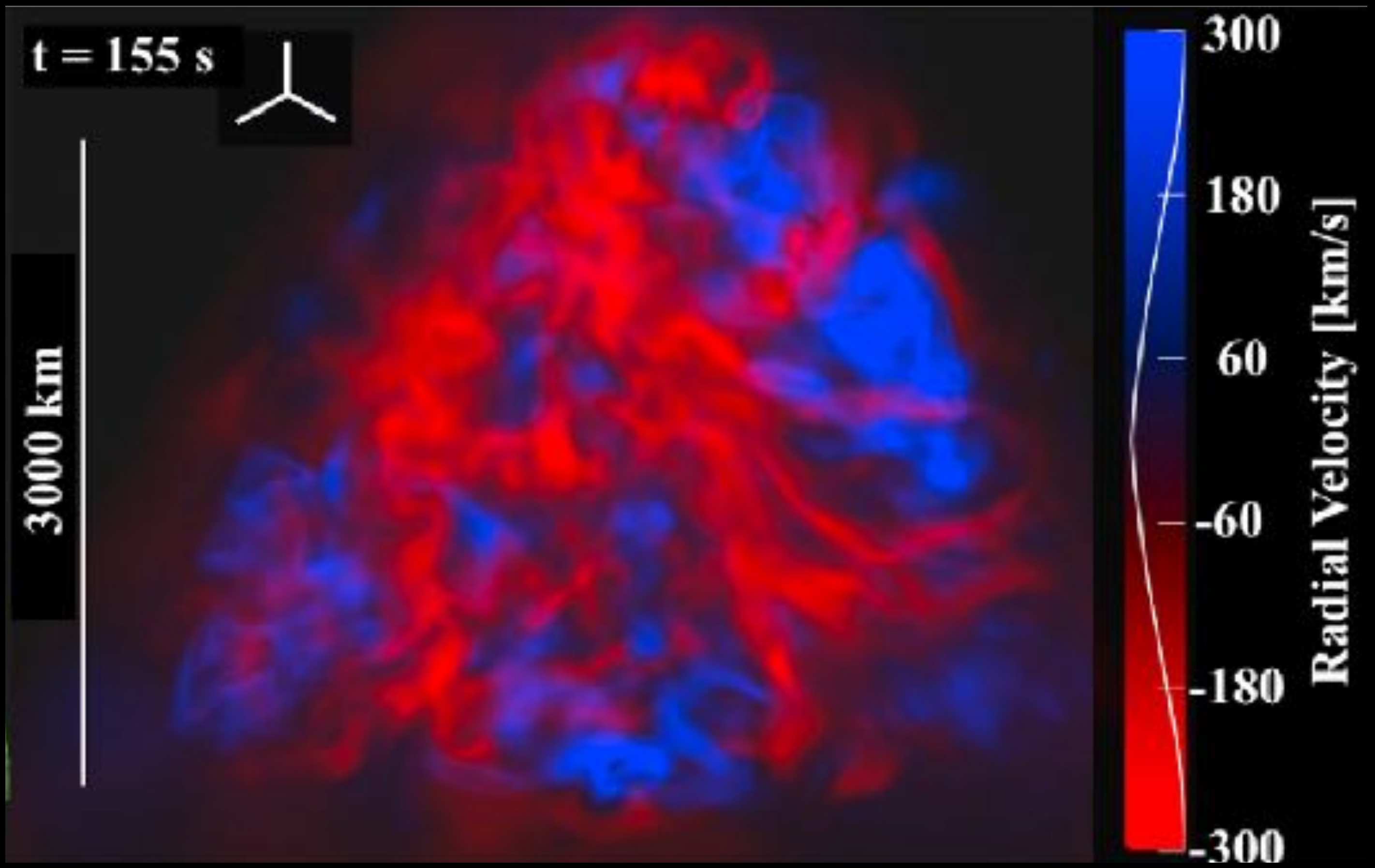
(Meakin & Arnett ApJ, 2007)

STELLAR CONVECTION

3D models of stellar convection near collapse

3D Stellar Convection $15M_\odot$

- Start closer to collapse and evolve for few turnovers.
- Advanced shell burning in 3D provides new insight.
- Properties again diverge from 1D stellar models.



(Couch + ApJL, 2015)

STELLAR CONVECTION

Advancing our understanding of stellar convection

Open Challenges

- Calibrating to 1D stellar models
- Rotation distribution of massive stars
- 3D stellar structure at collapse
- Magnetic field generation, amplification, and transport
- Pre-supernova nucleosynthesis

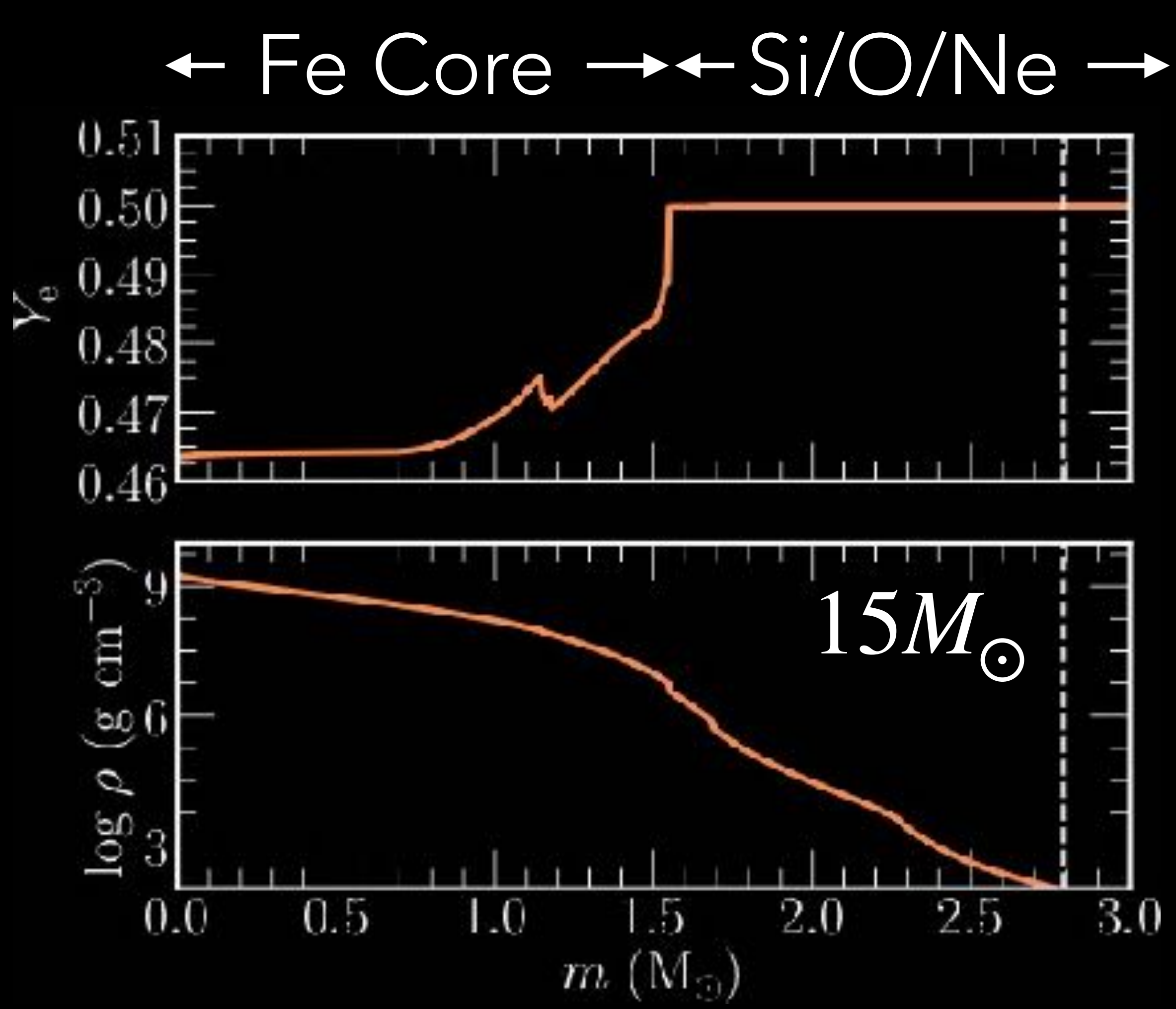
Paths Forward

- Hybrid approach - 1D initial conditions from stellar models.
- Multi-dimensional (2D/3D) simulations using FLASH toolkit.
- Leverage new techniques, advancements in hardware to move us forward.

STELLAR CONVECTION

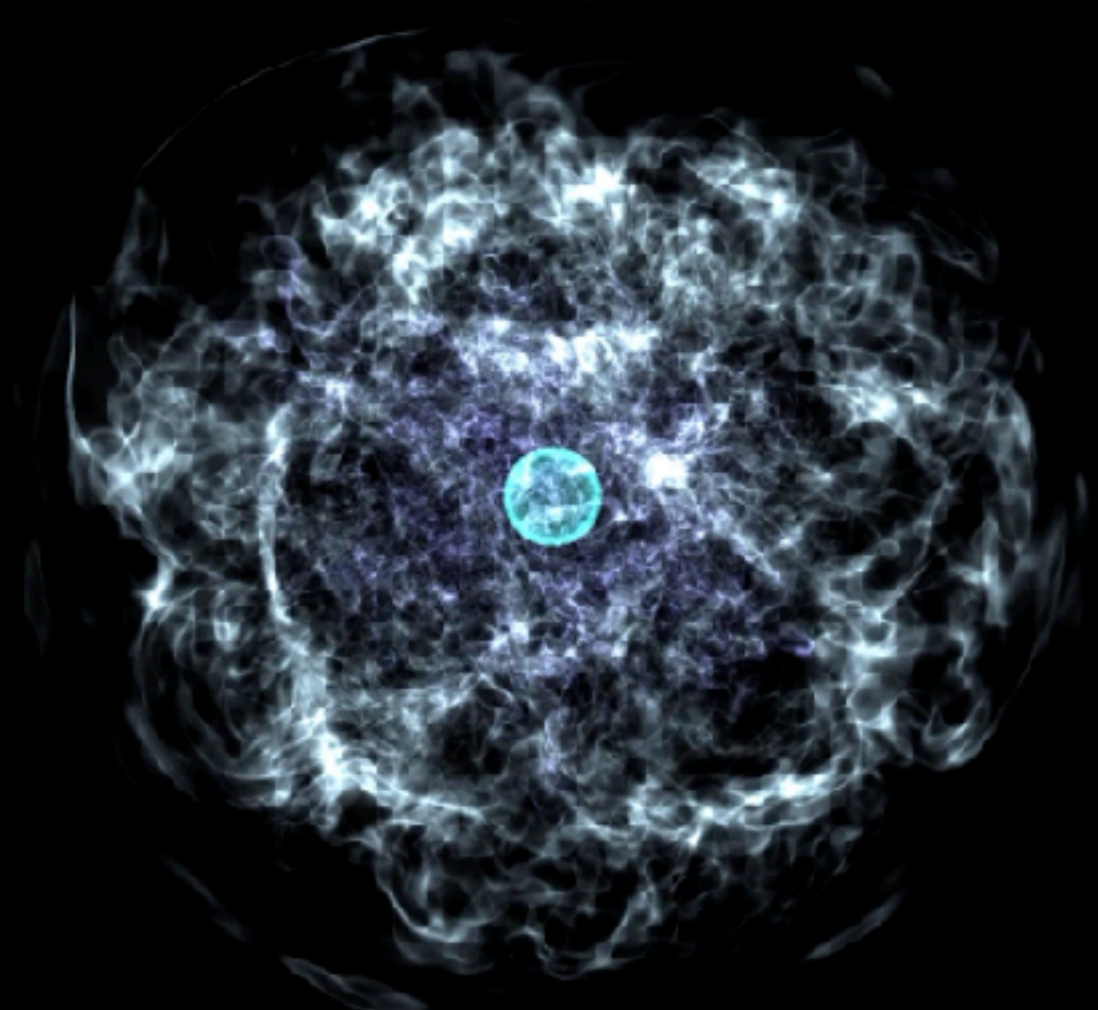
Our approach in modeling 3D stellar convection

3D Convection in FLASH



(Fields & Couch ApJ, 2020)

Velocity



Resources required: small/medium cluster

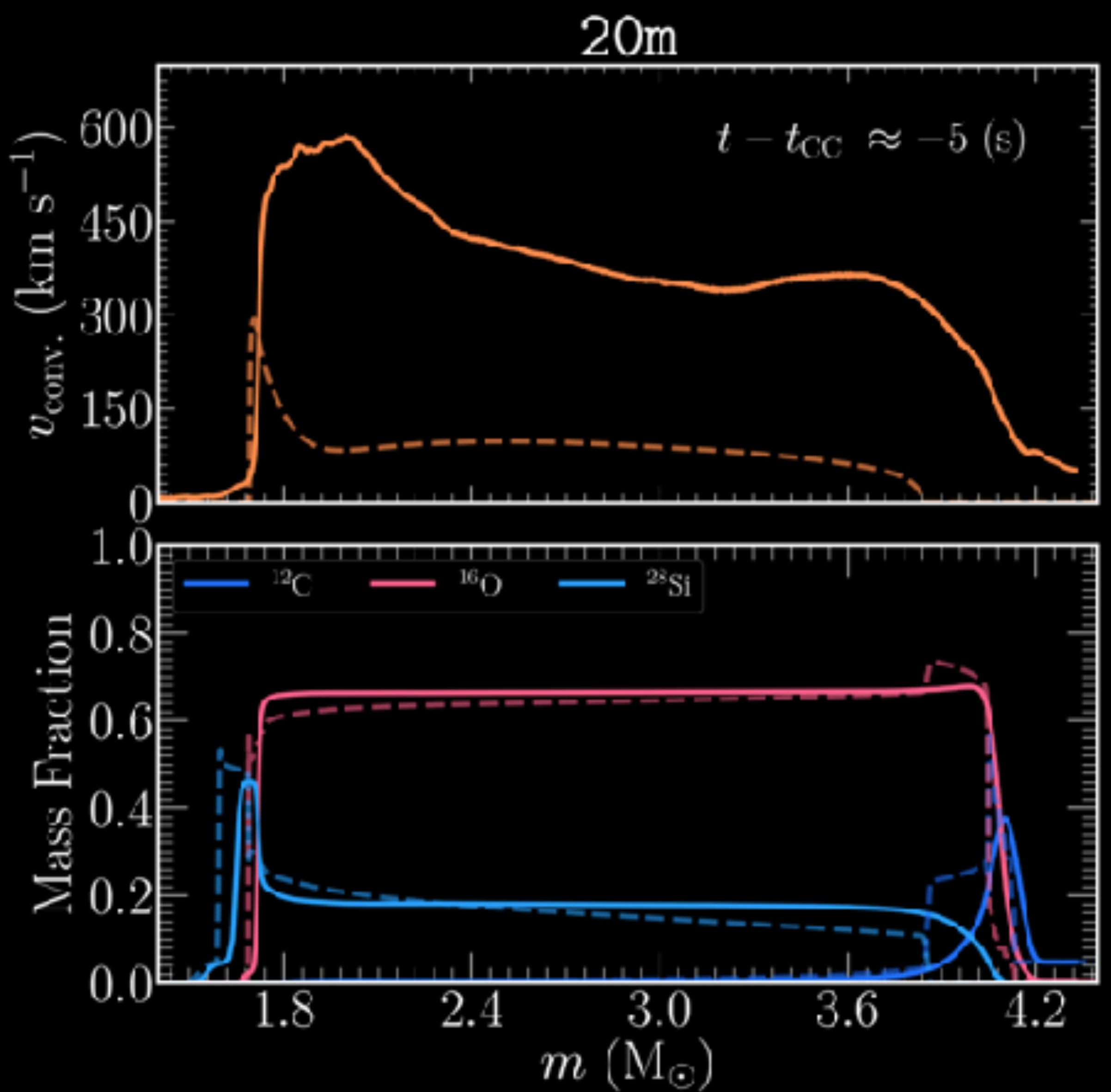
STELLAR CONVECTION

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.

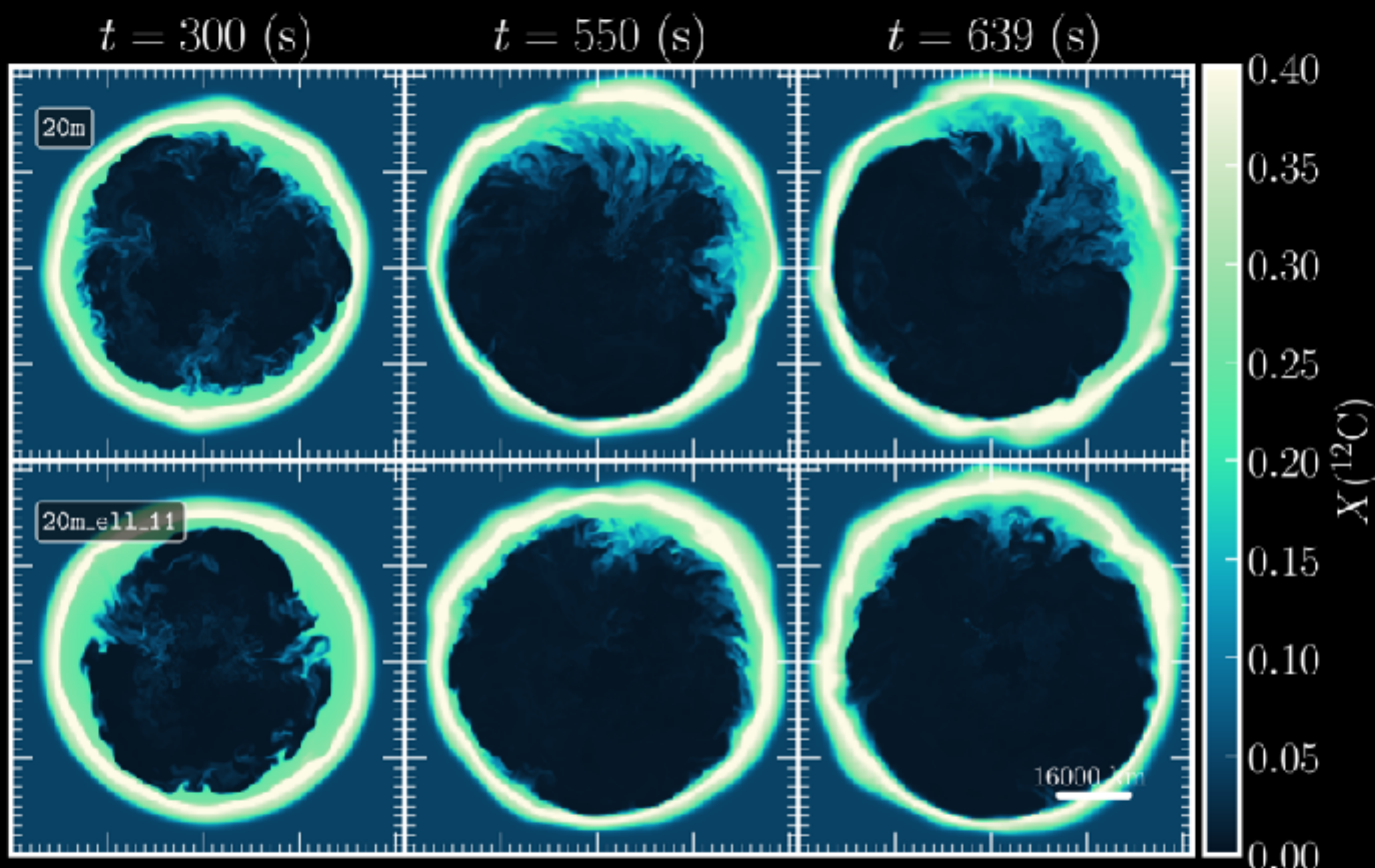
Resources: small/medium cluster (UA HPC)



(Fields & Couch ApJ, 2021)

STELLAR CONVECTION

Measuring 3D mixing and chemical enrichment



(Fields & Couch ApJ, 2021)

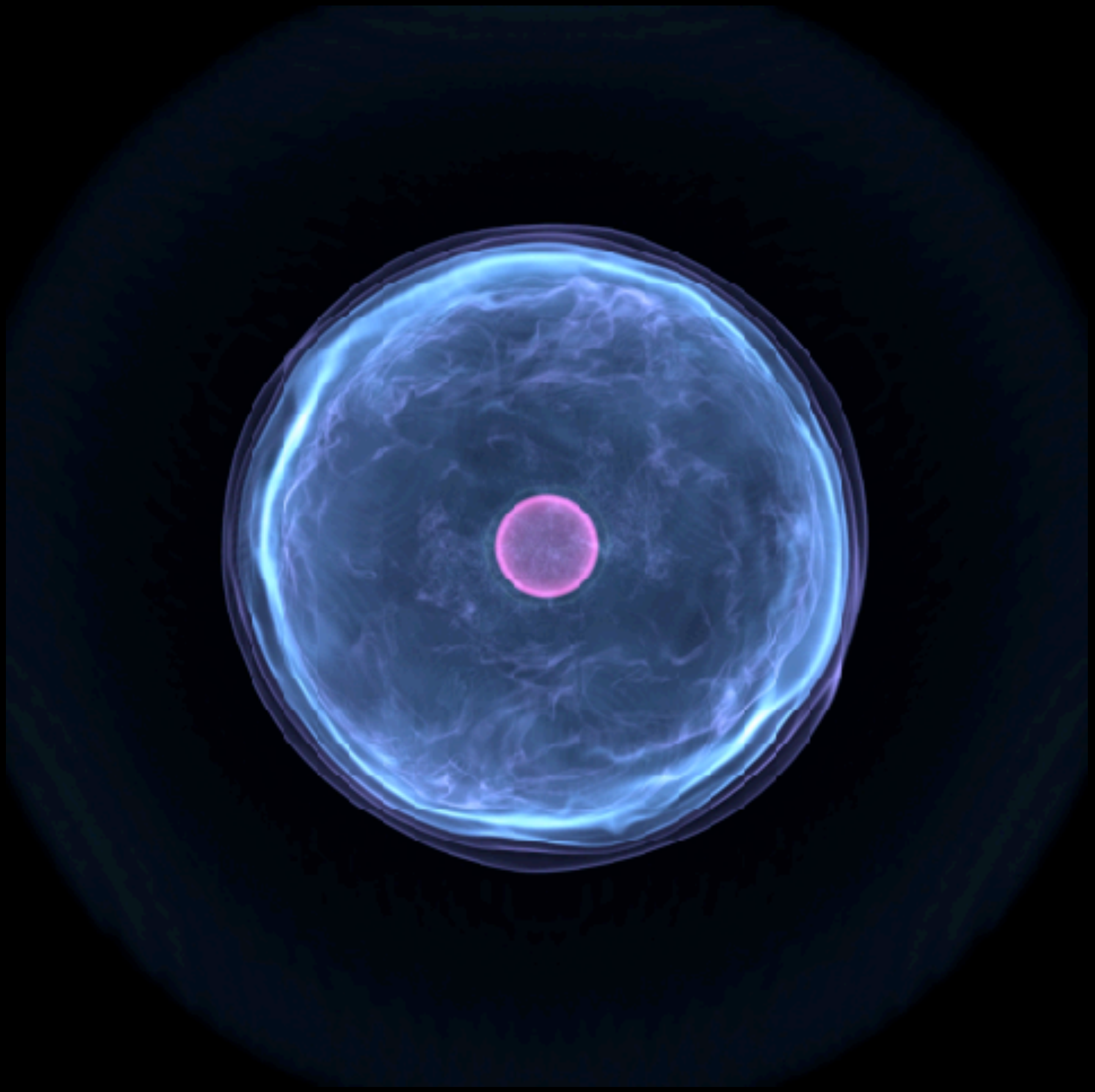
Entrainment can affect galactic **chemical evolution** models.

STELLAR CONVECTION

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.



Resources: small/medium (UA HPC)

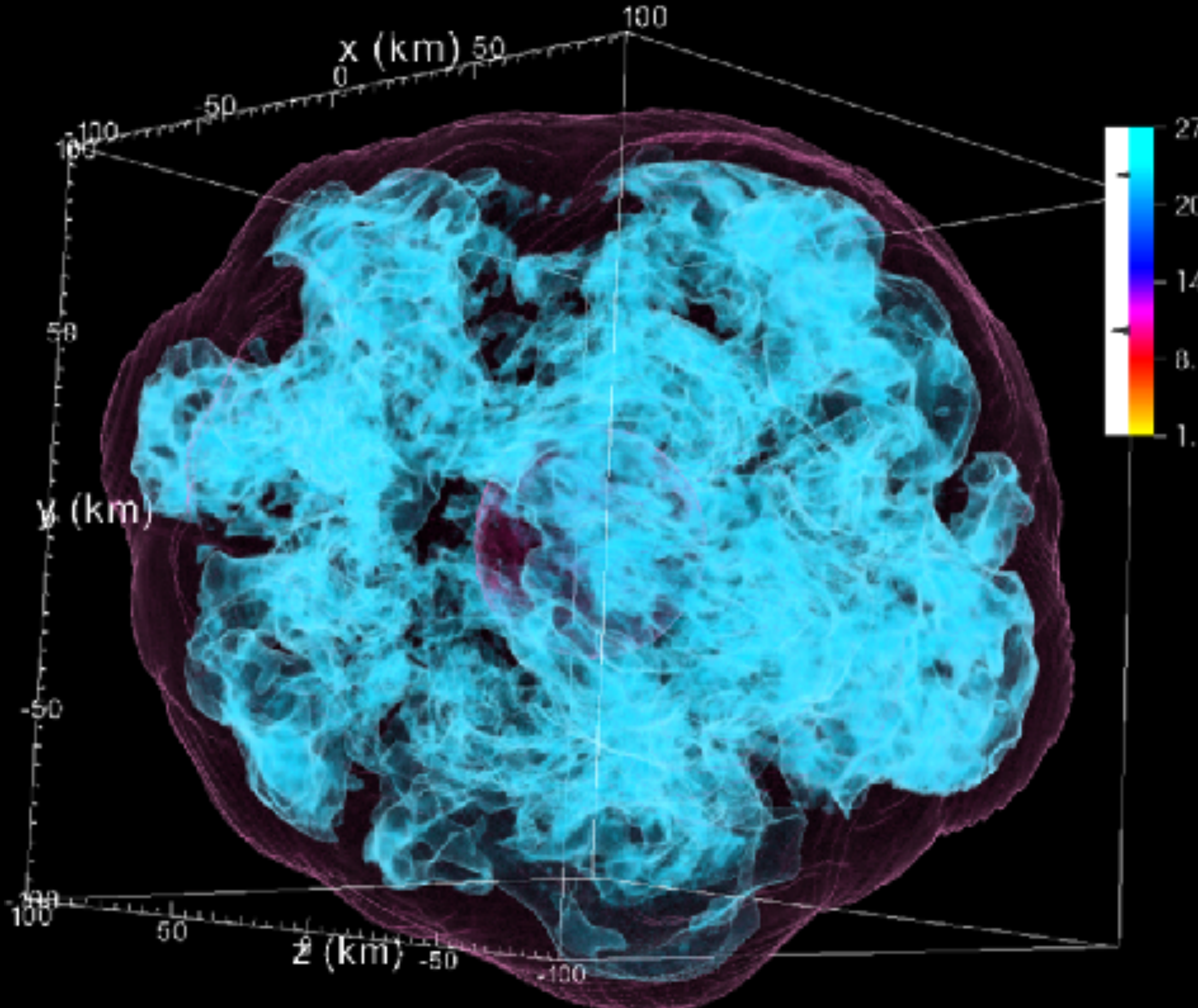
(Fields ApJL, 2022)

STELLAR CONVECTION

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

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

3D MHD CCSN Explosion



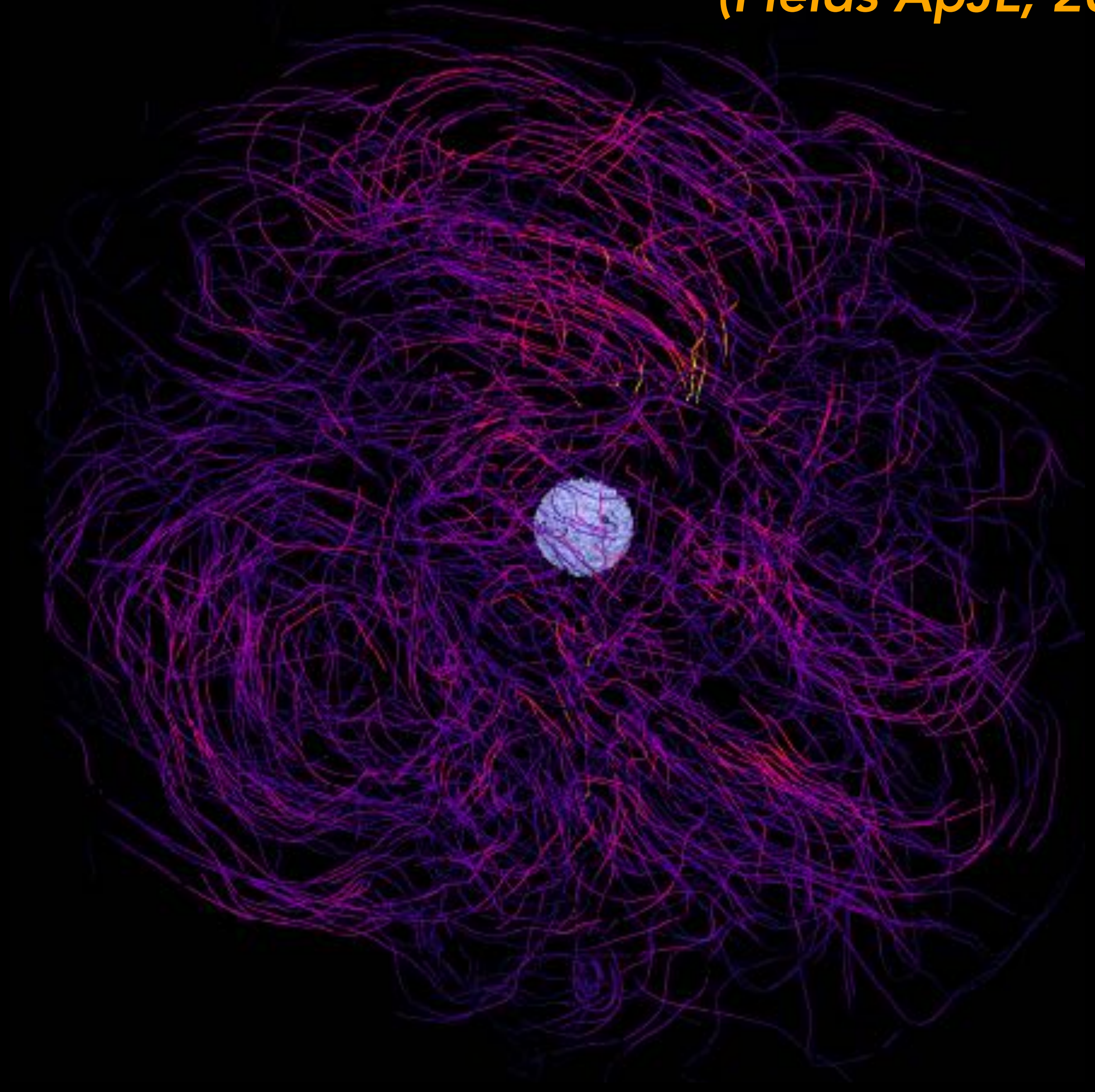
(Muller + ApJL, 2021)

STELLAR CONVECTION

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

(Fields ApJL, 2022)

3D MHD Progenitors in FLASH



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

Resources: small/medium (UA HPC)

STELLAR CONVECTION

Current and Future Directions

Pre-Supernova Stellar Convection

- Deeper look into rotation and AM transport *(in collab. w/ Goldberg @ CCA)*
- Magnetic field strength and topology *(in collab. w/ Couch, O'Connor @ MSU/OKC)*
- Progenitors of GRBs *(in collab. w/ Fryer @ LANL)*
- Internal Gravity Waves, Stellar Variability *(in collab. w/ Edelmann @ LANL)*
- Mass entrainment and implications for nucleosynthesis
- Enable core neutronization via large networks *(in collab. w/ Timmes @ ASU)*

Connecting to 1D Stellar Models

- Angular momentum transport calibration
- Earlier stage burning epochs with MAESTRO
- Inform Mixing Length Theory

Successful Computing Proposal:
12M SU 2022-2023 - STARS

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

FOUNDATIONS

Stellar convection is a critical part of stellar models

FOUNDATIONS

Stellar explosions require next-generation simulations

STELLAR EXPLOSIONS

The death of a massive star

Stellar Transients

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

Compact Object Formation

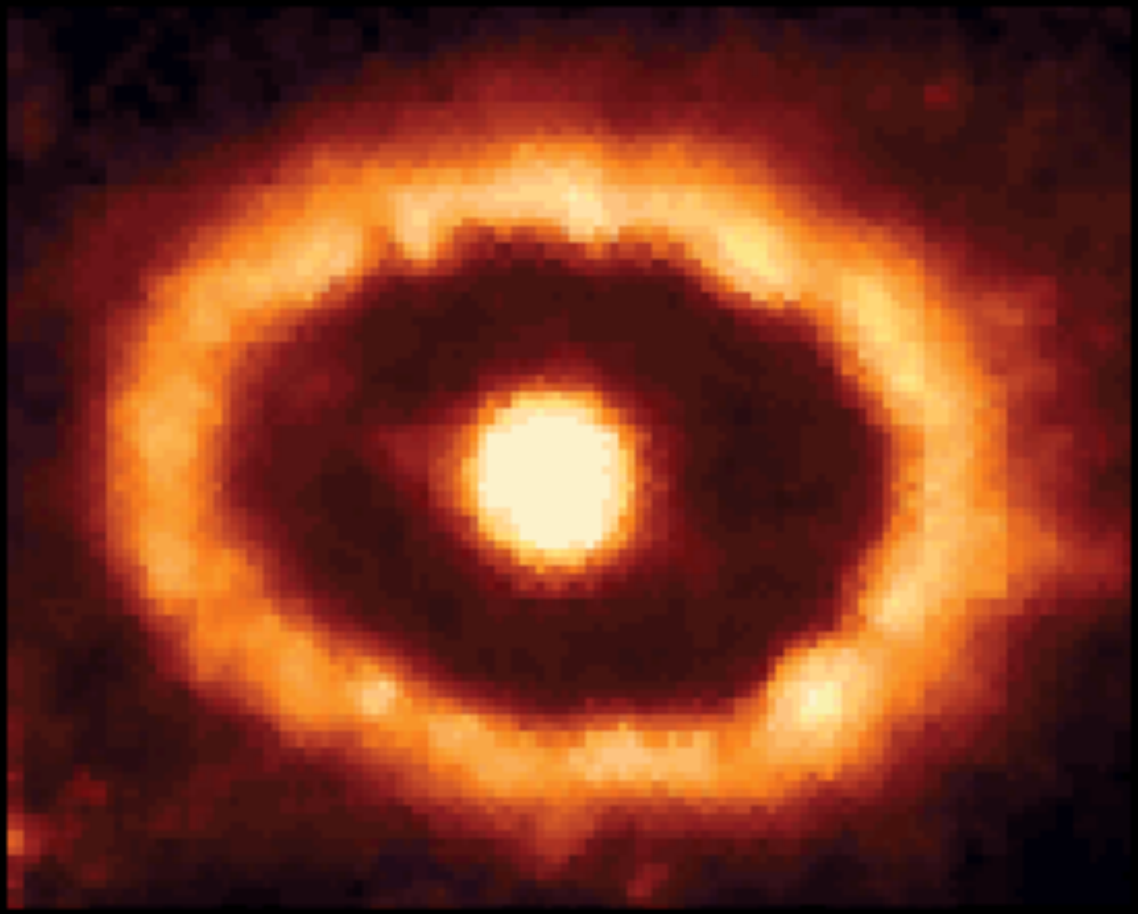
- Produce NS / stellar mass BHs

Galactic Chemical Evolution

- Nucleosynthesis
- Stellar Feedback

Multi-Messenger Astronomy

- Gravitational Waves
- Neutrinos
- Electromagnetic



(Larsson + 2011)

09/1994

STELLAR EXPLOSIONS

***Open Challenges**: Connecting models of stellar explosion to observations*

Explosion Energy

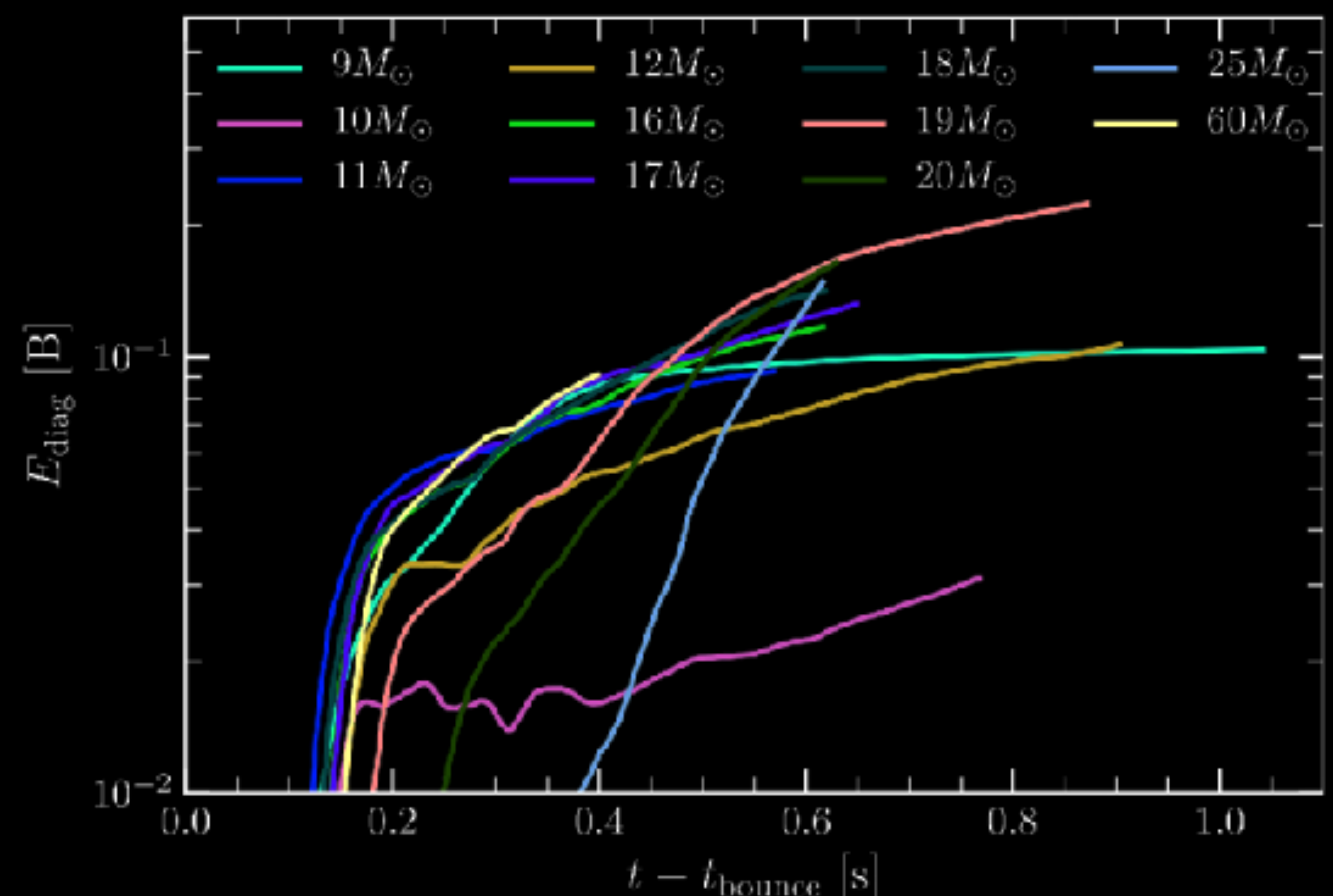
- Struggle to match range of Type IIP explosion energies of ~0.5-4B.

Shock Revival

- Models fail to explode in some cases.

Fate of Compact Remnants

- Require long term simulations



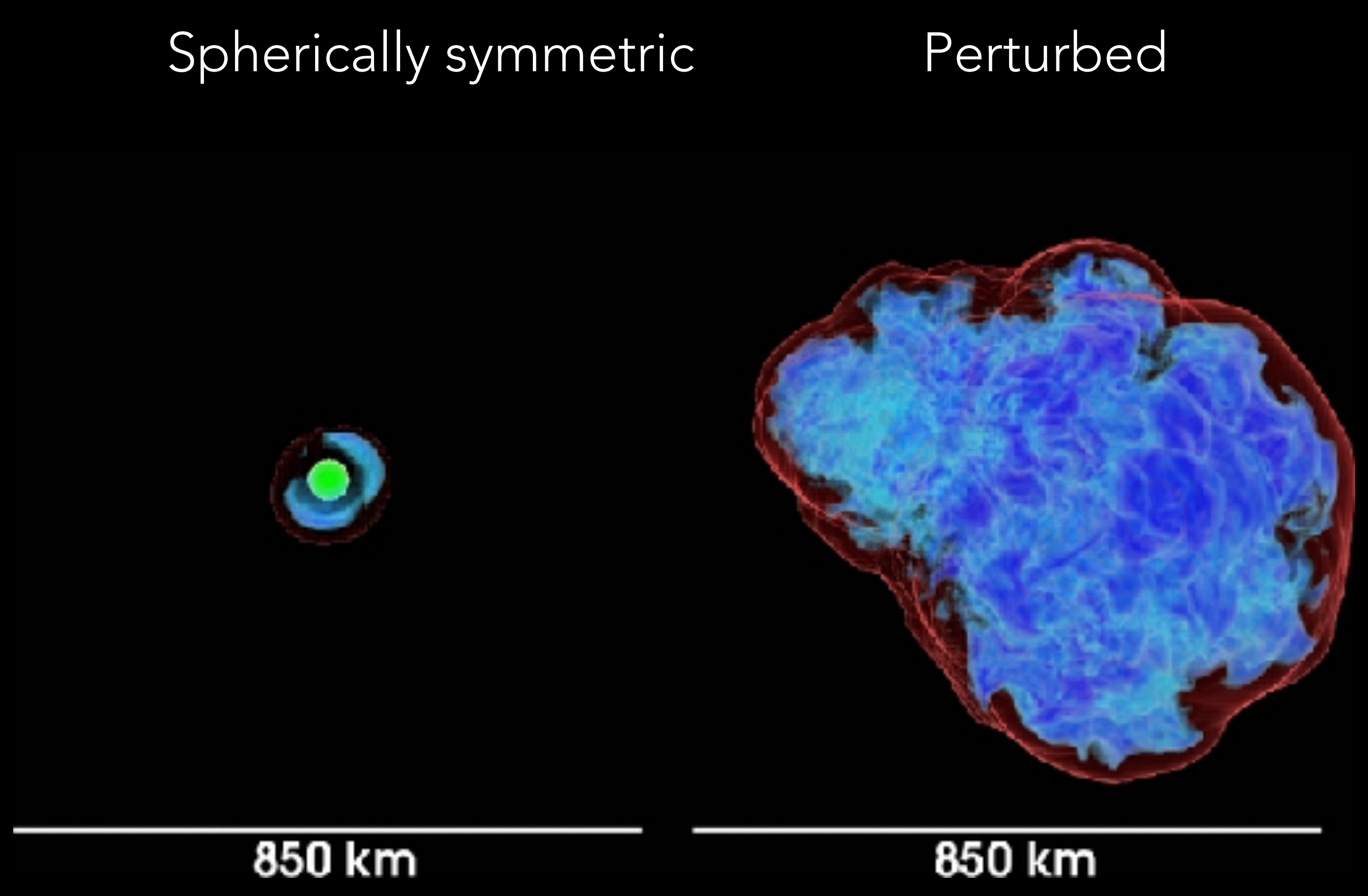
(Burrows +, MNRAS, 2019)

STELLAR EXPLOSIONS

Path Forward: *CCSN from Multi-Dimensional Pre-Supernova Models*

- Pre-supernova convection can help **revive stalled shock**.
- Successful explosions are more energetic.

CCSN from 3D initial conditions



(Couch + ApJ, 2013)

STELLAR EXPLOSIONS

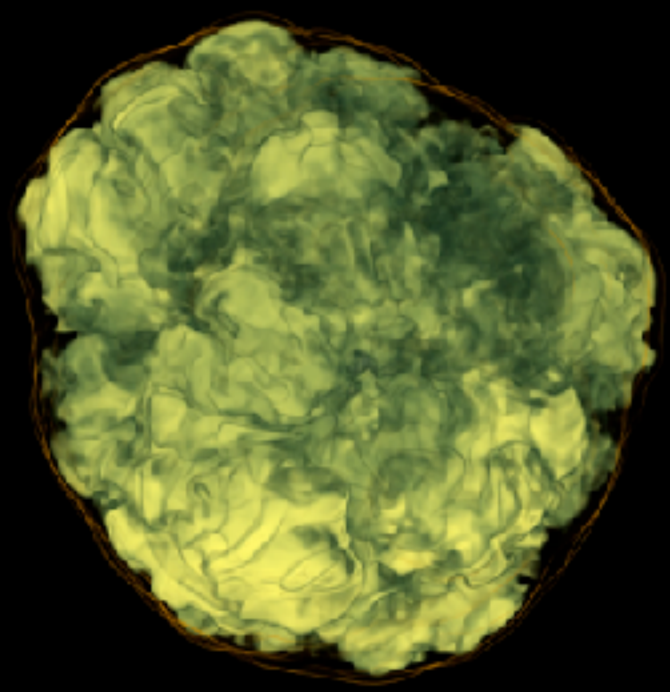
Future Efforts: *CCSN explosion models from realistic conditions*

FLASH 2D/3D CCSN Models

- Start from realistic multi-D initial conditions.
- Observe asymmetric shock runaway.
- Impact on MM signals.

Resources: medium (UA HPC) & leadership (INCITE/ALCC)

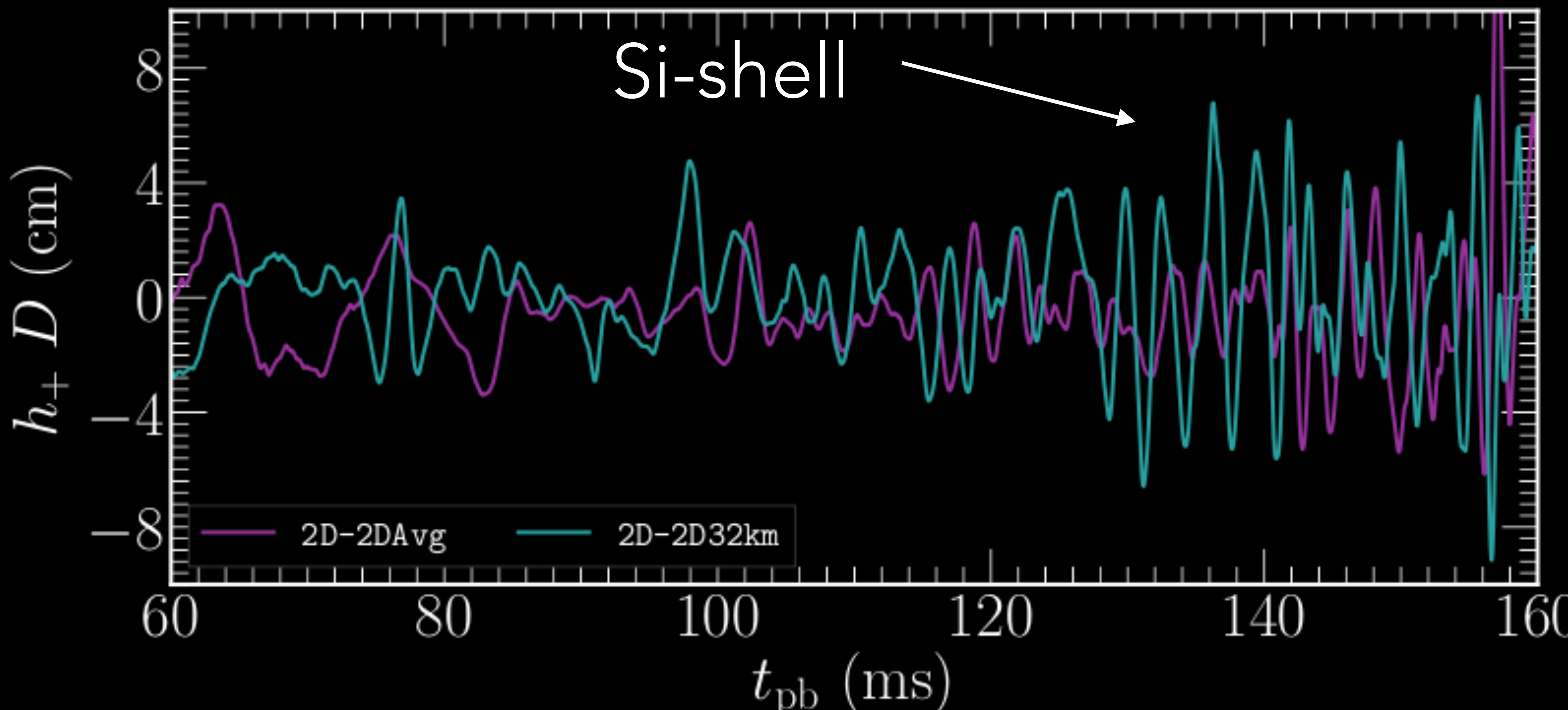
3D CCSN from 3D progenitor



(Fields 2021, PhD Thesis).

STELLAR EXPLOSIONS

Future Efforts: *Measuring the impact on new explosion models on GWs*



(Fields 2021, PhD Thesis)

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

STELLAR EXPLOSIONS

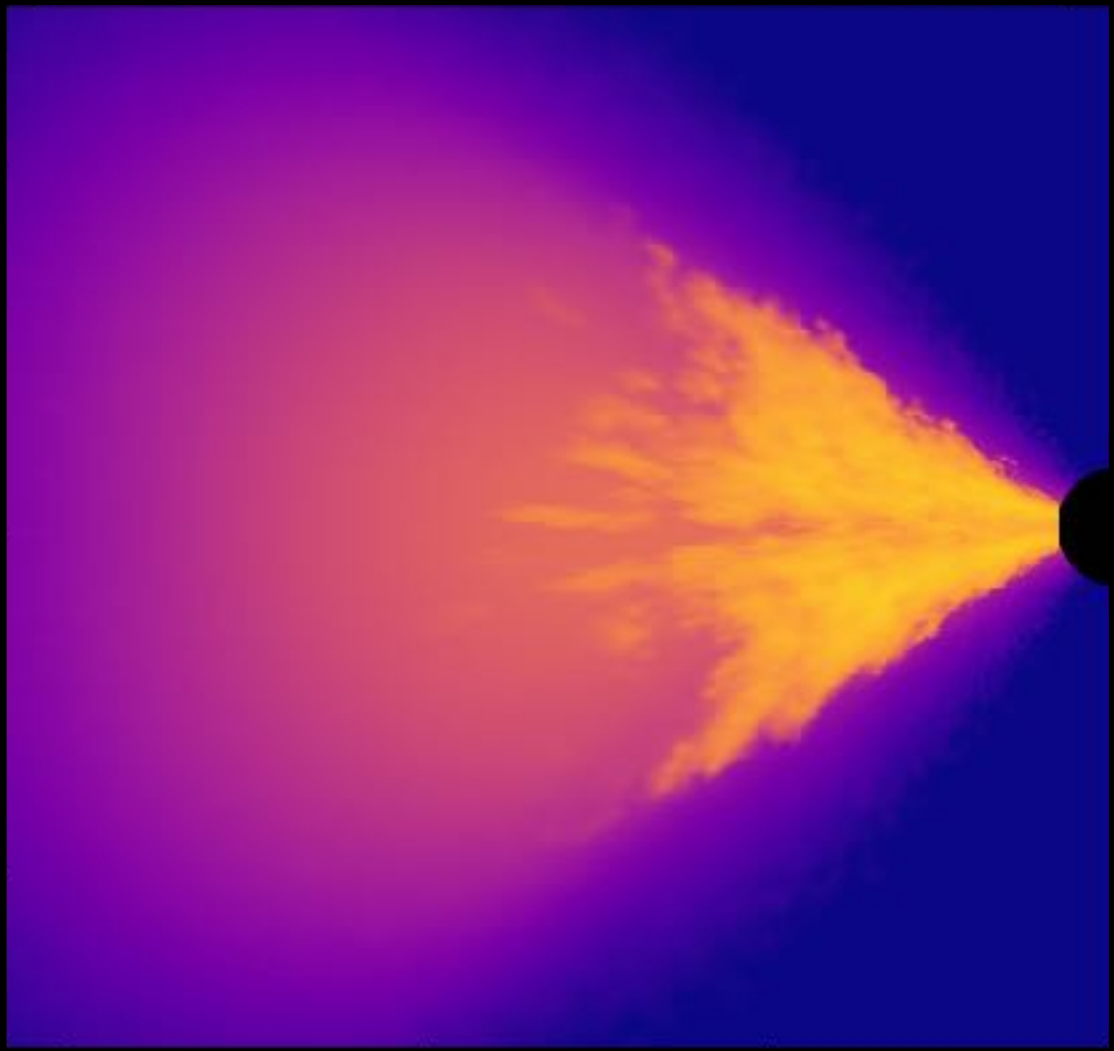
Future Efforts: Late-time simulations of compact remnant and nucleosynthesis

3D GRMHD Accretion onto Compact Object

- Inform nucleosynthesis yields
- Compare 3D structures to 1D approximations
- Necessary for capturing the complete story of stellar collapse.

Resources: medium (UA HPC/ALCC) & leadership (INCITE)

Accretion onto $3M_{\odot}$ black hole



(Miller + ApJ, 2020)

STELLAR EXPLOSIONS

Current and Future Directions

Multi-Dimensional Models of Stellar Explosions

- Impact of rotation and perturbations on MM signals (*in collab. w/ Pajkos @ CalTech*)
- Magnetic field strength and topology *(in collab. w/ Couch, O'Connor @ MSU/OKC)*
- Progenitors of GRBs *(in collab. w/ Fryer @ LANL)*
- Shock Breakout / Nucleosynthesis
- Neutrino-Radiation GRMHD Explosions *(in collab. w/ Dolence, Miller, Ryan @ LANL)*

Late-Time Compact Remnants

- Long term evolution of merger remnants *(in collab. w/ Miller, Dolence @ LANL)*
- Hyper massive NS late-time accretion *(in collab. w/ Miller, Dolence @ LANL)*

FOUNDATIONS

Stellar explosions require next-generation simulations

FOUNDATIONS

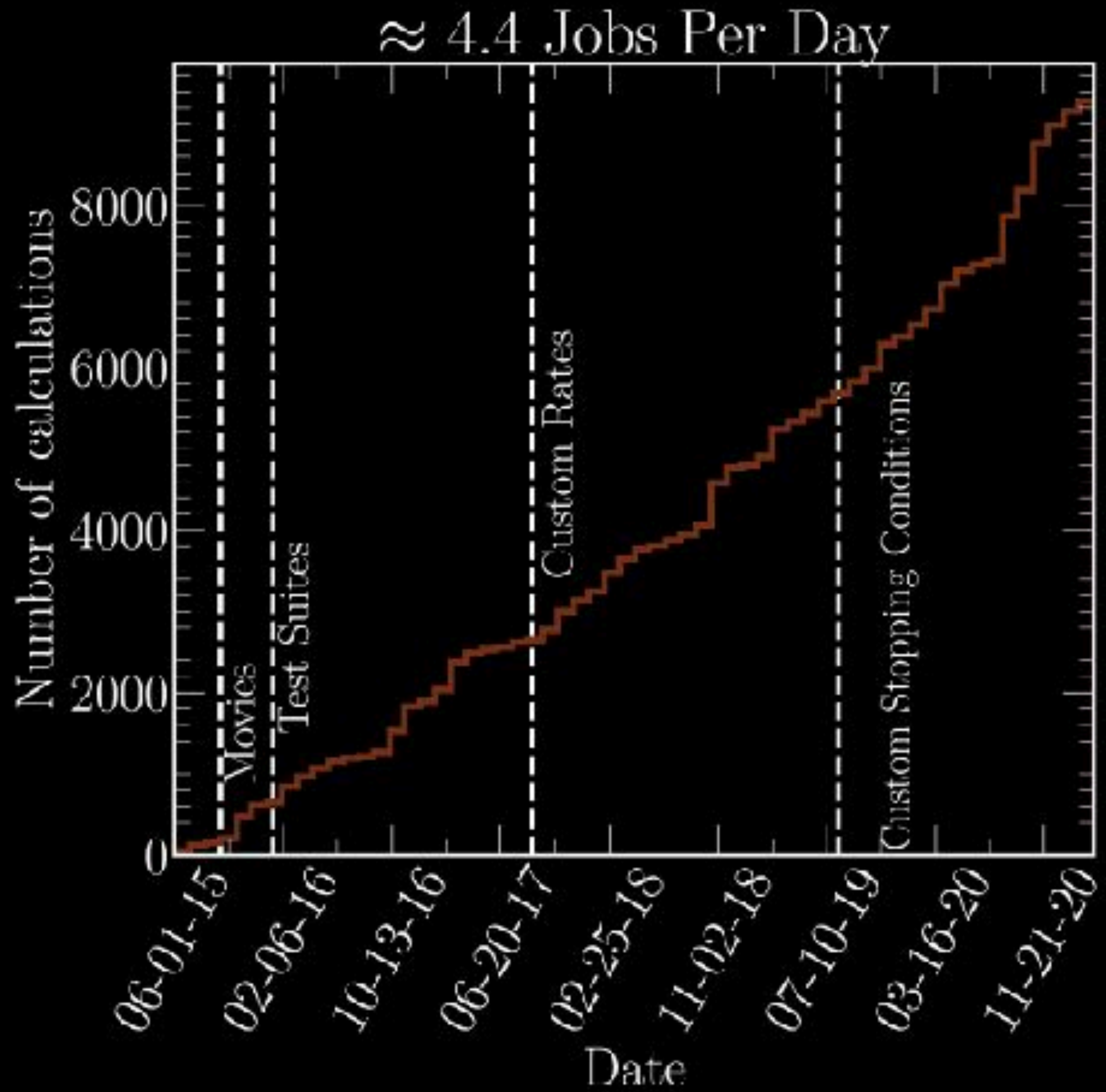
A vision for collaborative, reproducible, and open-source science

COLLABORATIVE FUTURE

Stellar models in the classroom

MESA-Web Online Tool

- Create and lead development of **MESA-Web**.
- Over 1400 unique users, incorporated in classrooms across the world.



In collaboration with Frank Timmes (ASU), Rich Townsend (UW), Aaron Dotter (Dartmouth)

(Fields + 2023 AEJ, under review)

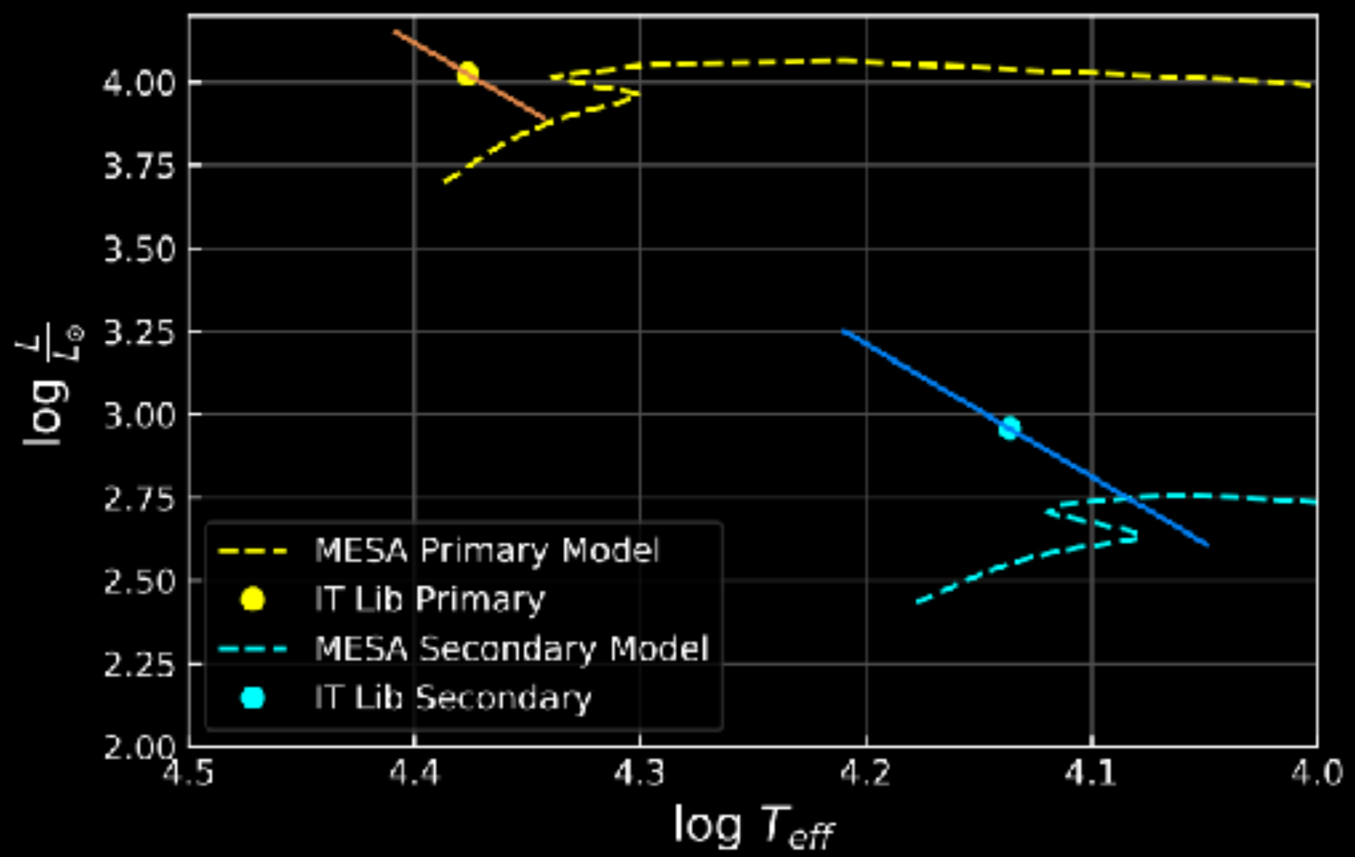
COLLABORATIVE FUTURE

Increasing accessibility to stellar models

MESA-Web used for research

- A tool for researchers
- Ability to input new reaction rates, range of physical parameters.
- More capabilities in the future!

Stellar tracks using MESA-Web



(Wysocki + 2022, arXiv:2202.08337)

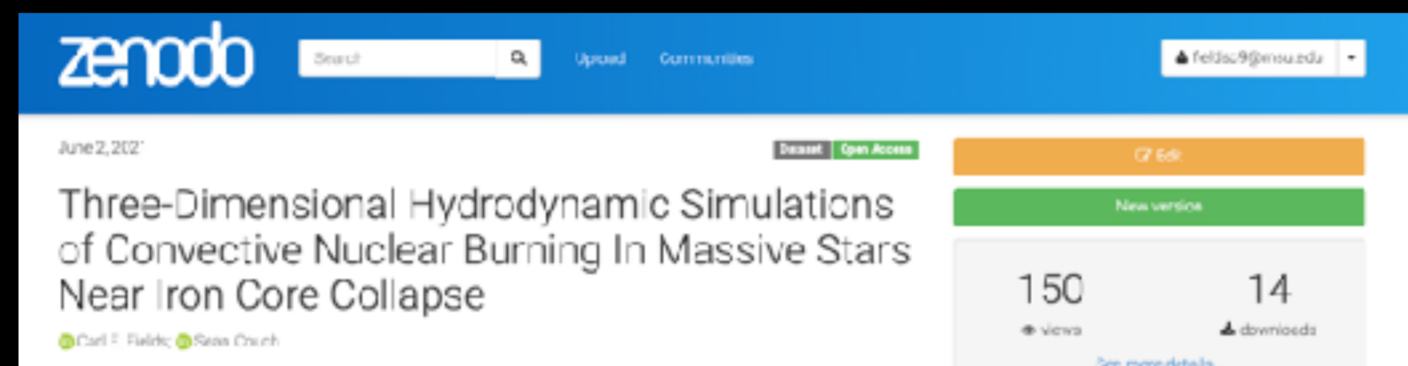
In collaboration with Frank Timmes (ASU),
Rich Townsend (UW), Aaron Dotter (Dartmouth)

COLLABORATIVE FUTURE

Reproducible and collaborative science

Scientific Vision

- Data transparency and reproducibility
- Open-source tools
- Collaborative support
- Current and upcoming support for exascale development applications



FLASH CENTER

MAESTROeX

MESA

FOUNDATIONS

A vision for collaborative, reproducible, and open-source science

CONCLUSIONS

Stellar models are powerful and necessary tools

- Measure stellar parameters
- Place constraints using nuclear physics data
- Connect to astrophysical observations

Stellar convection is a critical part of stellar models

- Inform 1D stellar models: convection/mixing
- Nucleosynthesis and AM transport in late phases
- Progenitors can address long-standing problems in CCSNe

Stellar explosions require next-generation simulations

- Explosions from 3D progenitors can agree with observations
- New predictions for multi-messenger astronomy
- Late-time remnant efforts direct connect to observables

Collaborative, reproducible, and open-source science

THANK YOU

Stellar models are powerful and necessary tools

Stellar convection is a critical part of stellar models

Stellar explosions require next-generation simulations

Collaborative, reproducible, and open-source science

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

Los Alamos NATIONAL LABORATORY

@carlnotsagan

FOUNDATIONS

The Next Generation of Stellar Astrophysics Has Begun

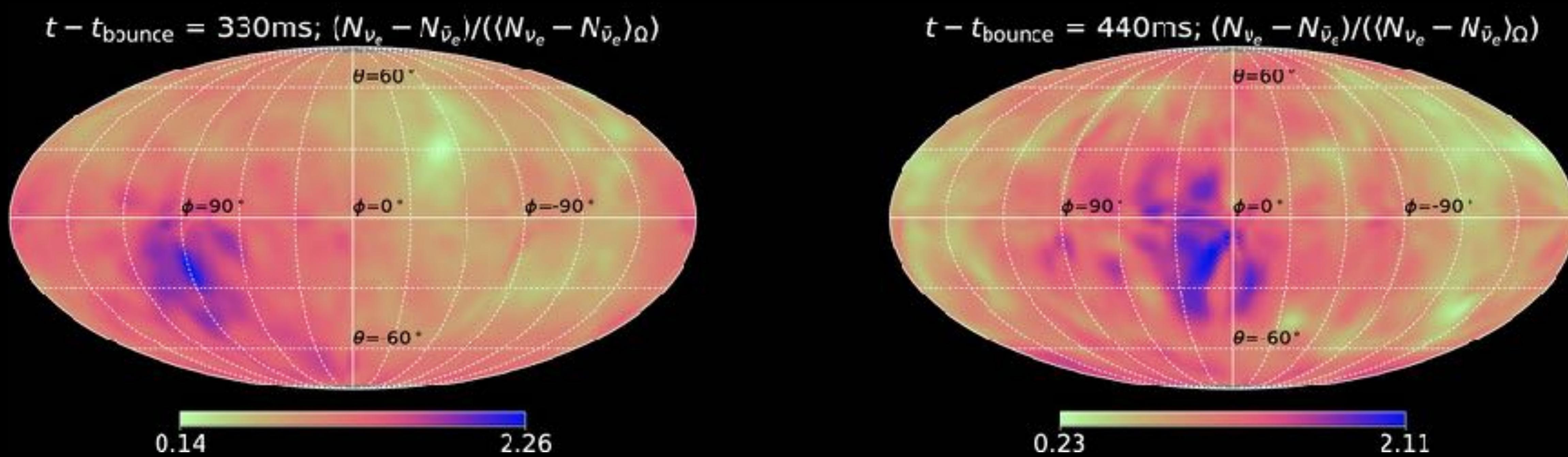
MAESTROeX

CENTER

MESA

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.

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, 2022 arXiv:2112.12800)

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

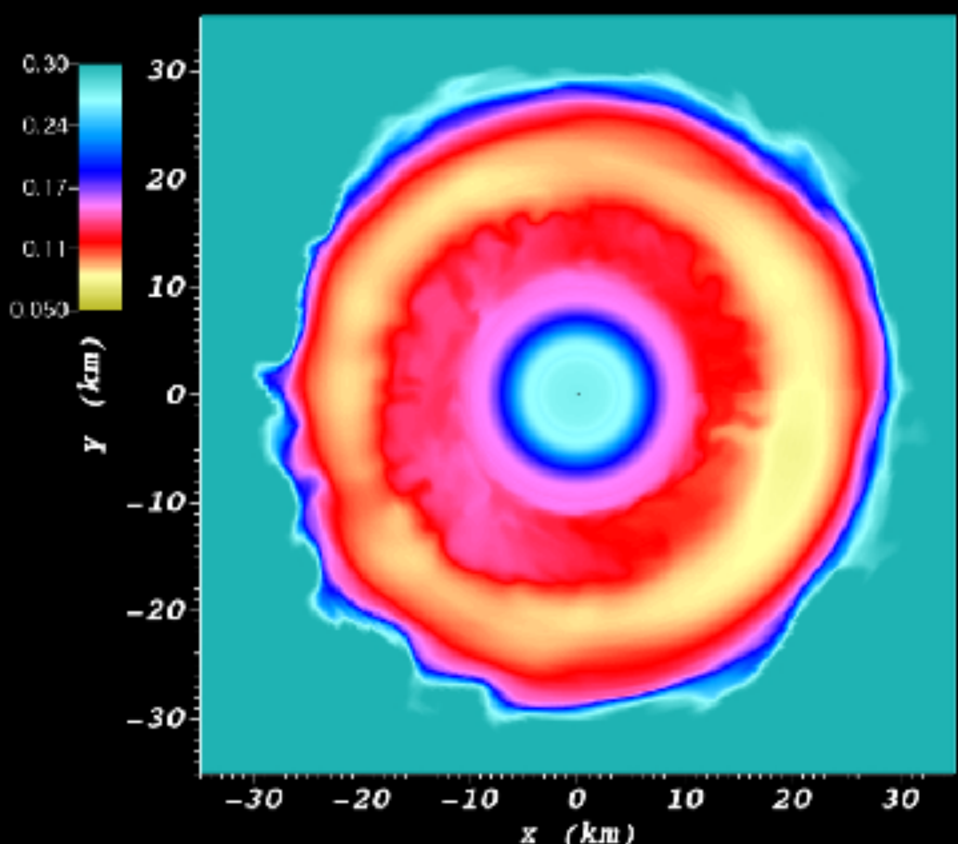
Multi-D models can provide input for successful CCSN models

(Fields, 2022b, in prep.)

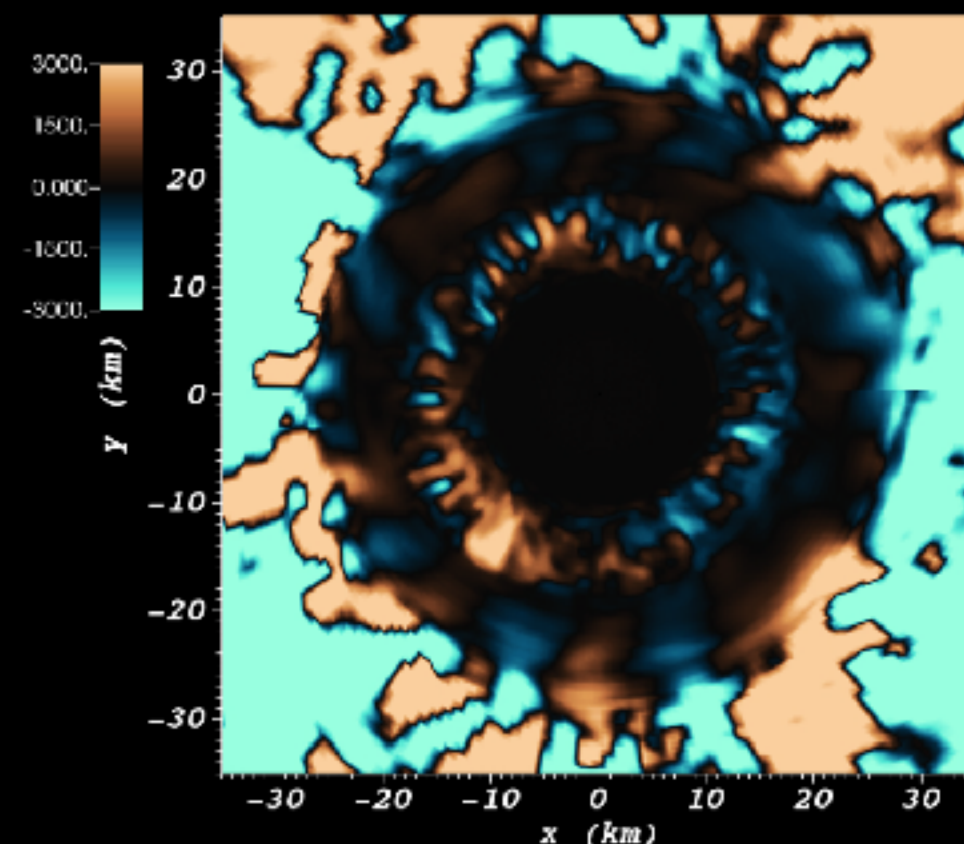
- Larger non-radial kinetic energy when using multi-D progenitor input
- 3D CCSN model showed prompt convection, asymmetric shock runaway
- Explosion properties suggest robust impact on multi-messenger signals

IMPACT ON MULTI-MESSENGER ASTRONOMY

Y_e



v_{radial}



(Muller+, 2020)

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

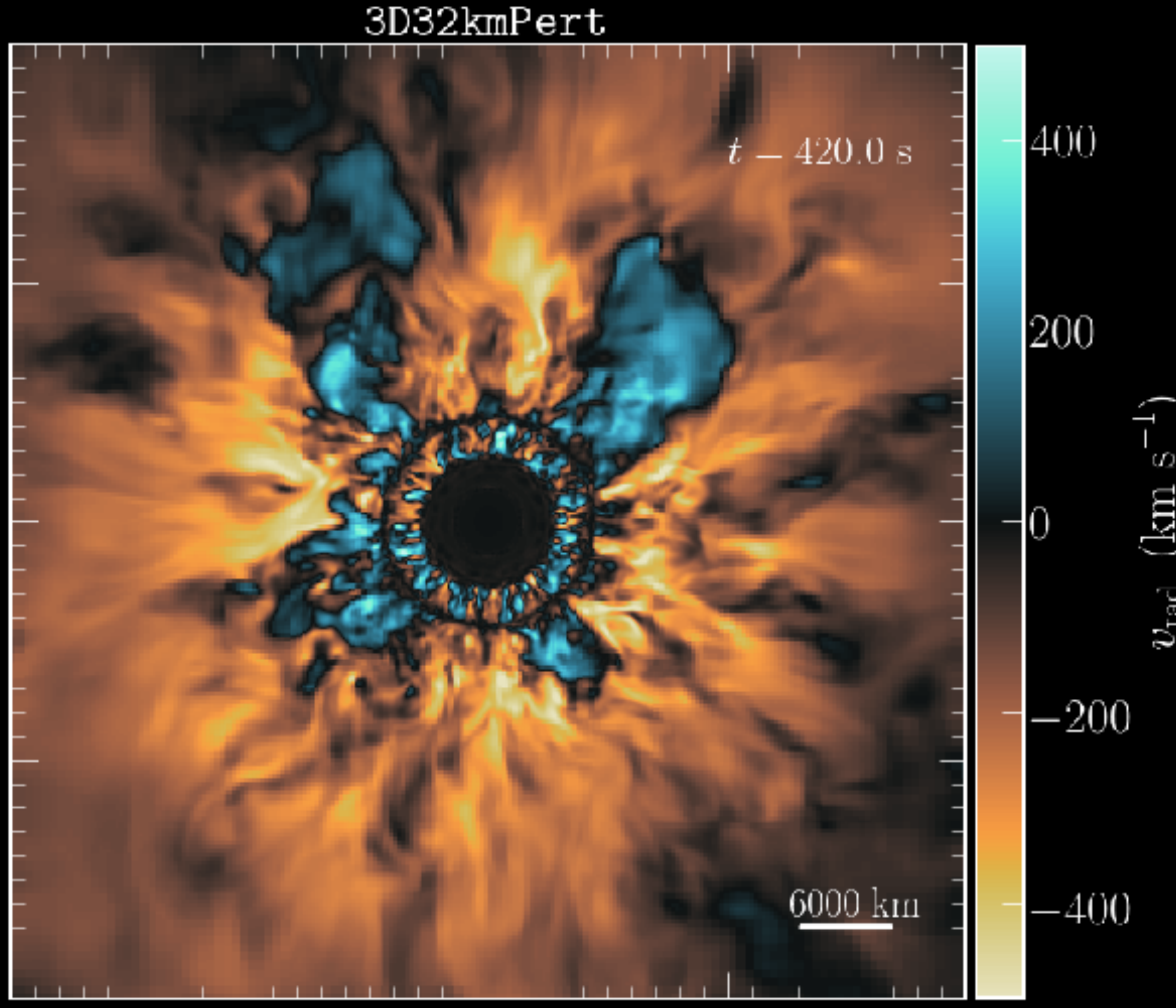
David Vartanyan[1*], Matthew S. B. Coleman[2], Adam Burrows[2]
[1] *Department of Physics and Astronomy, University of California, Berkeley, CA 94720, USA*
[2] *Department of Astrophysical Sciences, 4 Ivy Lane, Princeton University, Princeton, NJ 08544, USA*

(arxiv.org/abs/2109.10920)

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

MULTI-DIMENSIONAL SIMULATIONS OF MASSIVE STARS

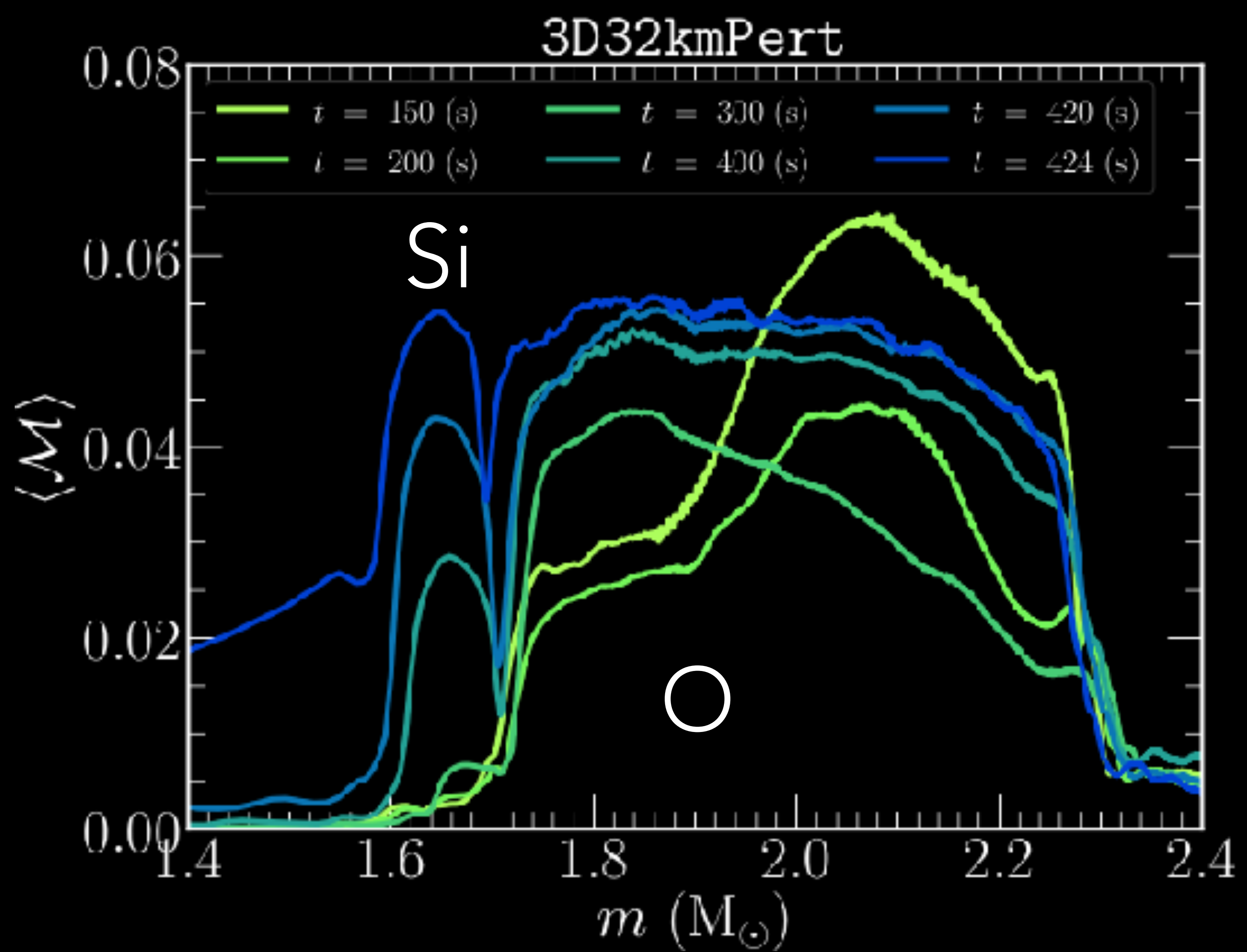
- 4 pi 3D model shows large scale plumes.
- Strong Si-shell convection.
- Convective speeds of several hundred km/s.



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).***

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

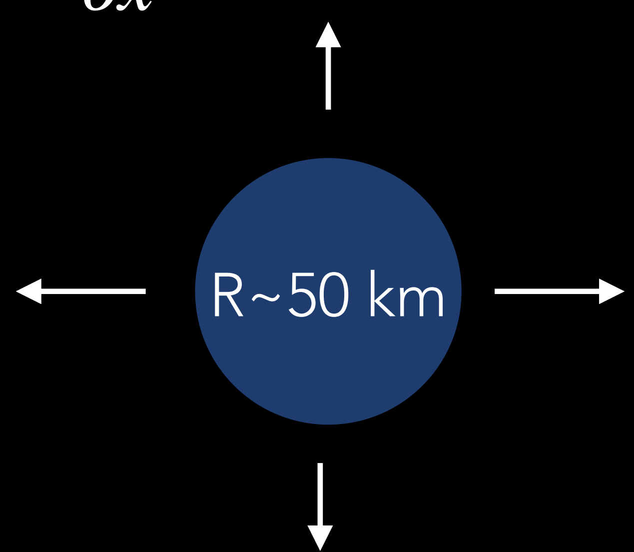
$Y_e \sim 0.27$

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

PHYSICS OF STELLAR CORE-COLLAPSE

"Bounce"
Stiffening of Core
Launch Shock

$$\frac{\partial}{\partial x}(P, v, \rho) \neq 0$$

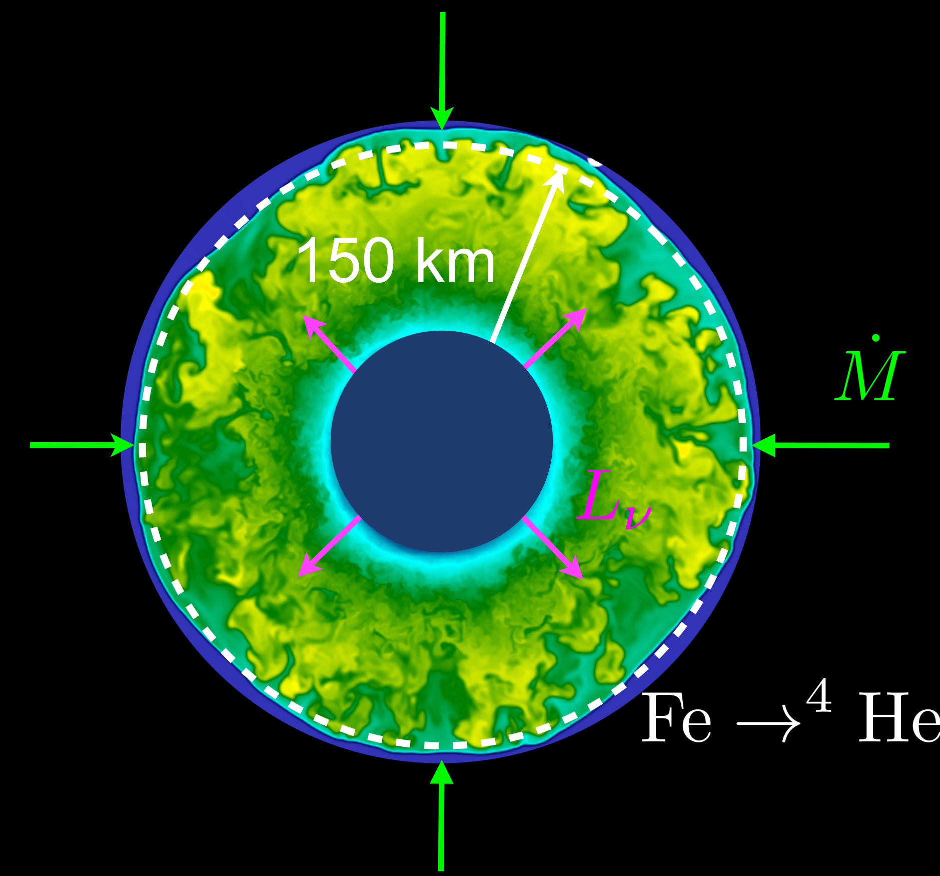


Not enough energy to promptly explode star.

"Bounce" to
Stalled Shock

$$t \sim 100 \text{ ms}$$

Stalled Shock



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

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).

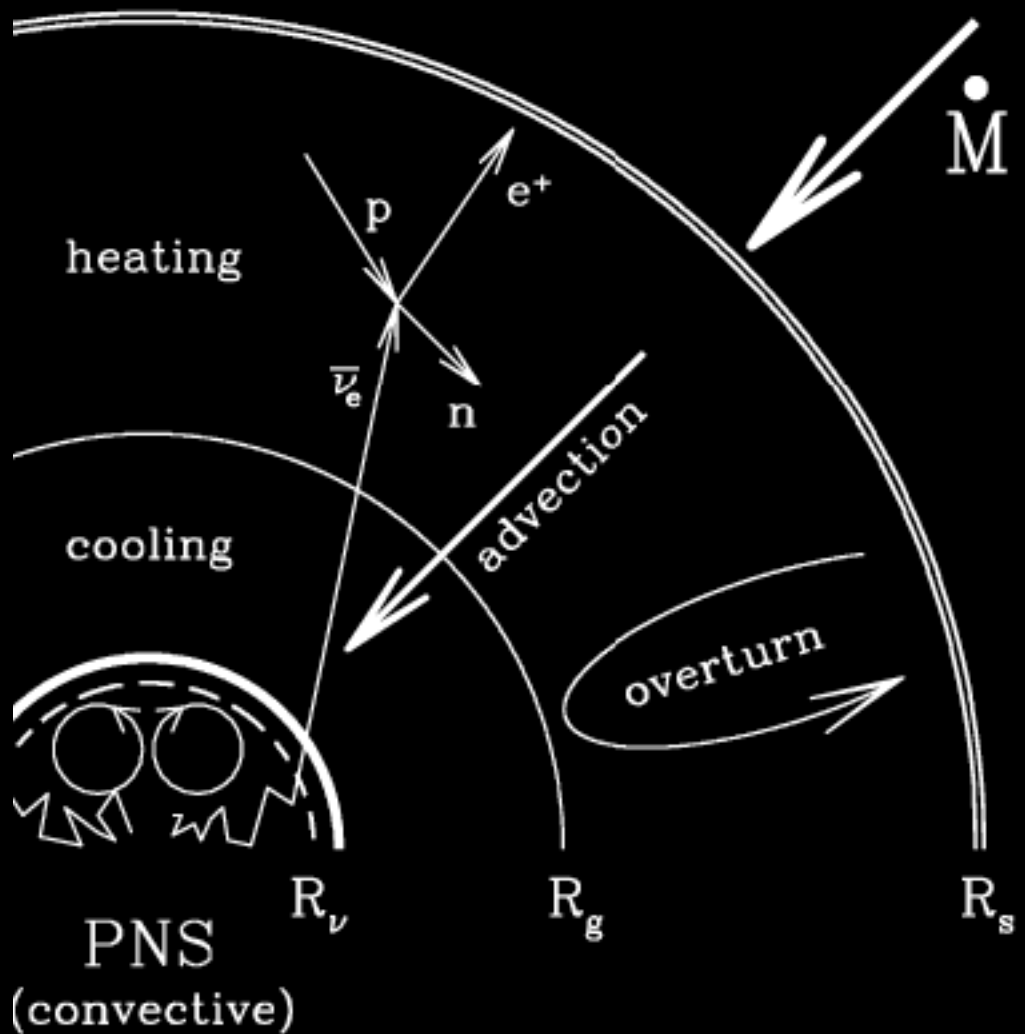
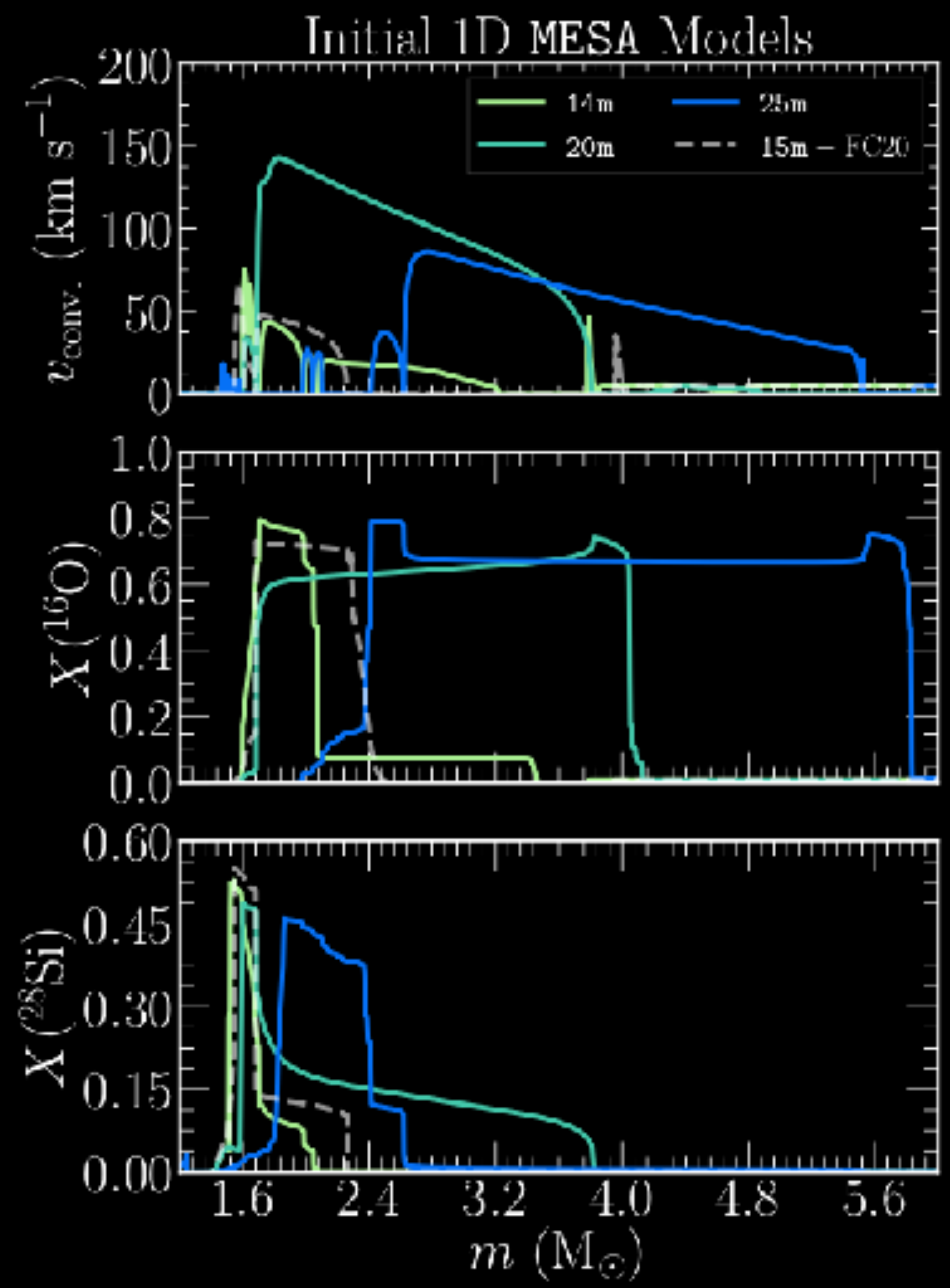


Diagram showing revival of stalled shock.
Credit: Janka (2011).

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 2021)

SIMULATIONS OF MASSIVE STAR CONVECTION IN MULTIPLE PROGENITORS

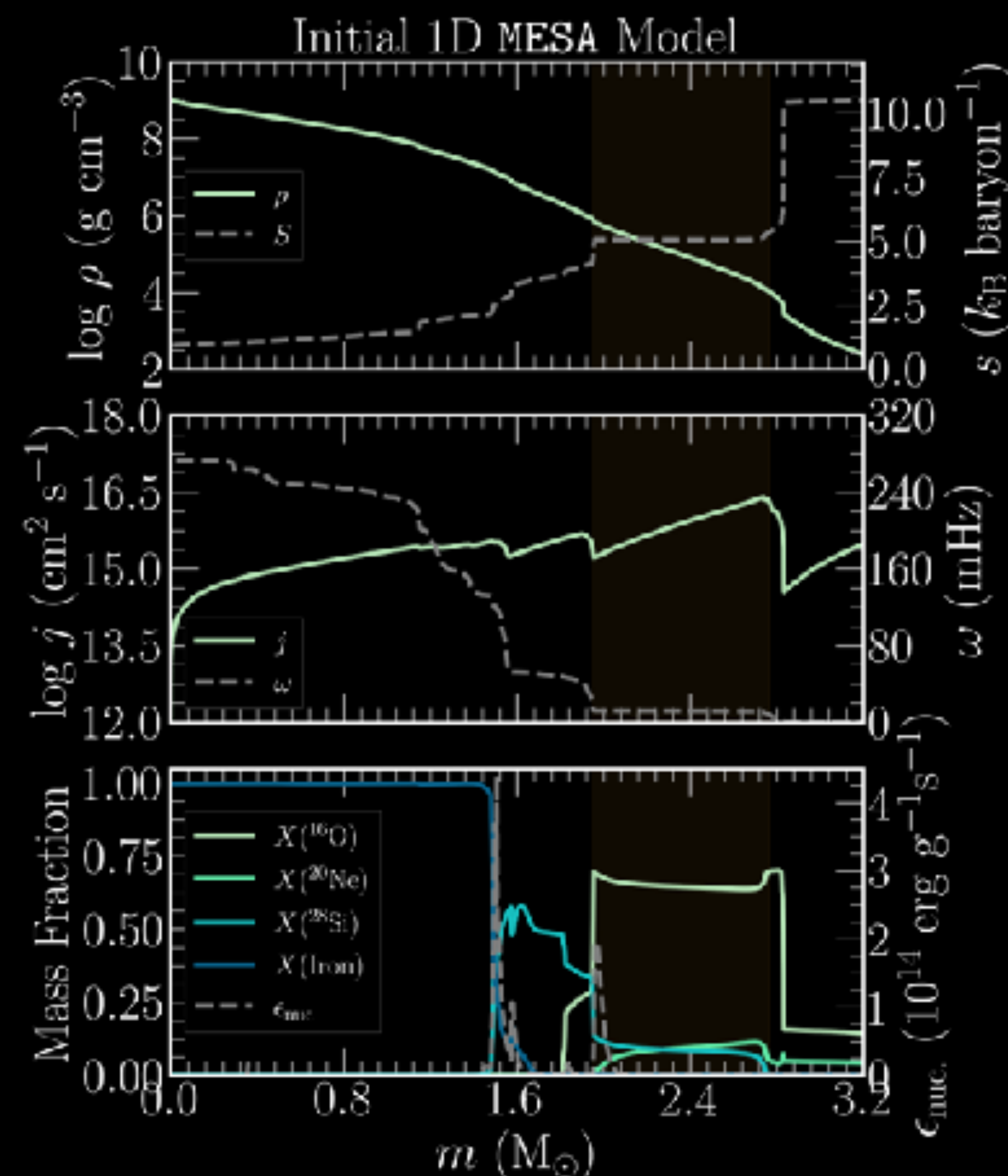
- Smaller O-shell Region, smaller mach numbers,~0.04!
- Convection occurring at broad range of scales.

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

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

CONVECTION IN RAPIDLY ROTATING PROGENITORS

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

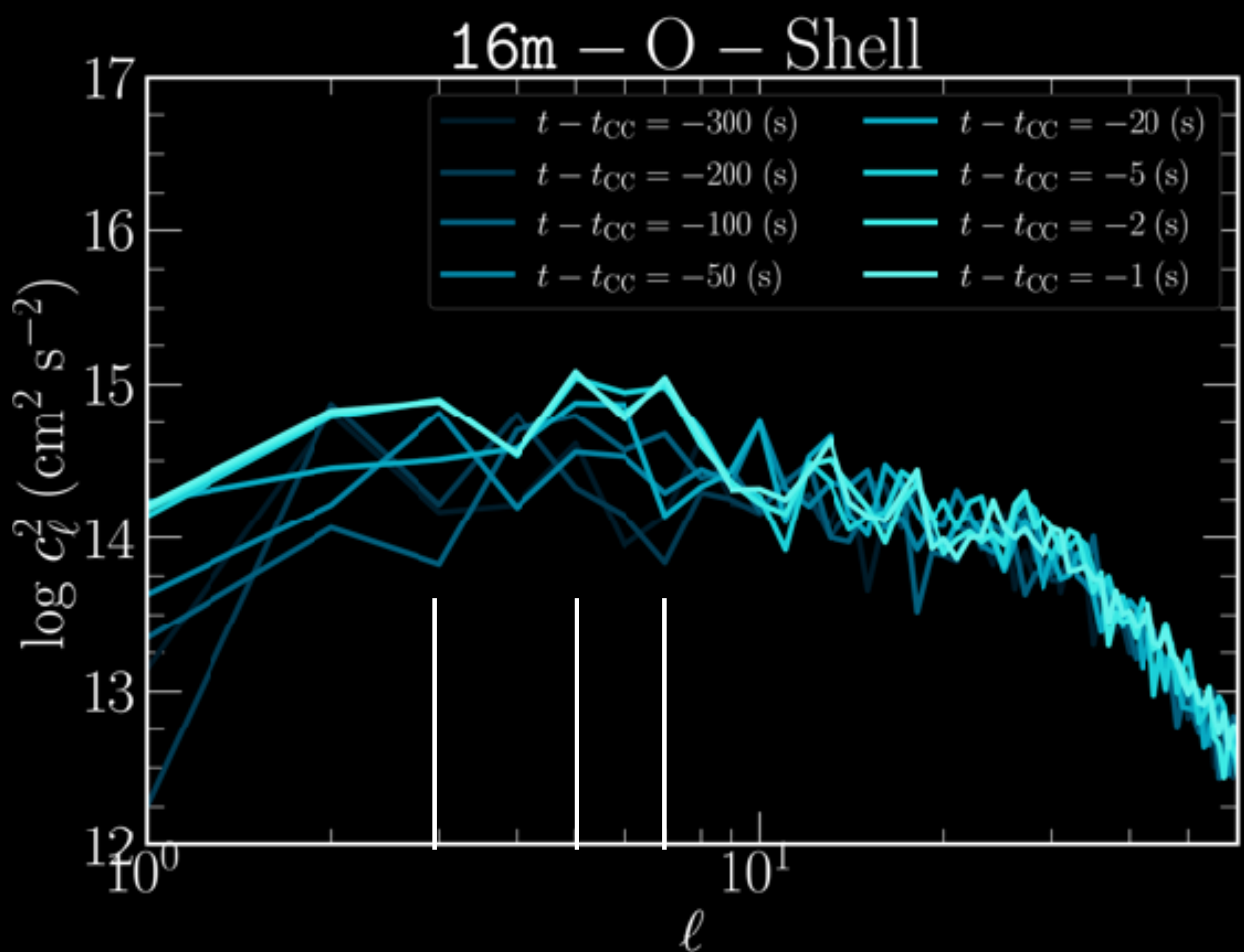


Initial 1D profile structure for 3D model.

(Fields, 2022)

MASSIVE STAR CONVECTION IN ROTATING PROGENITORS

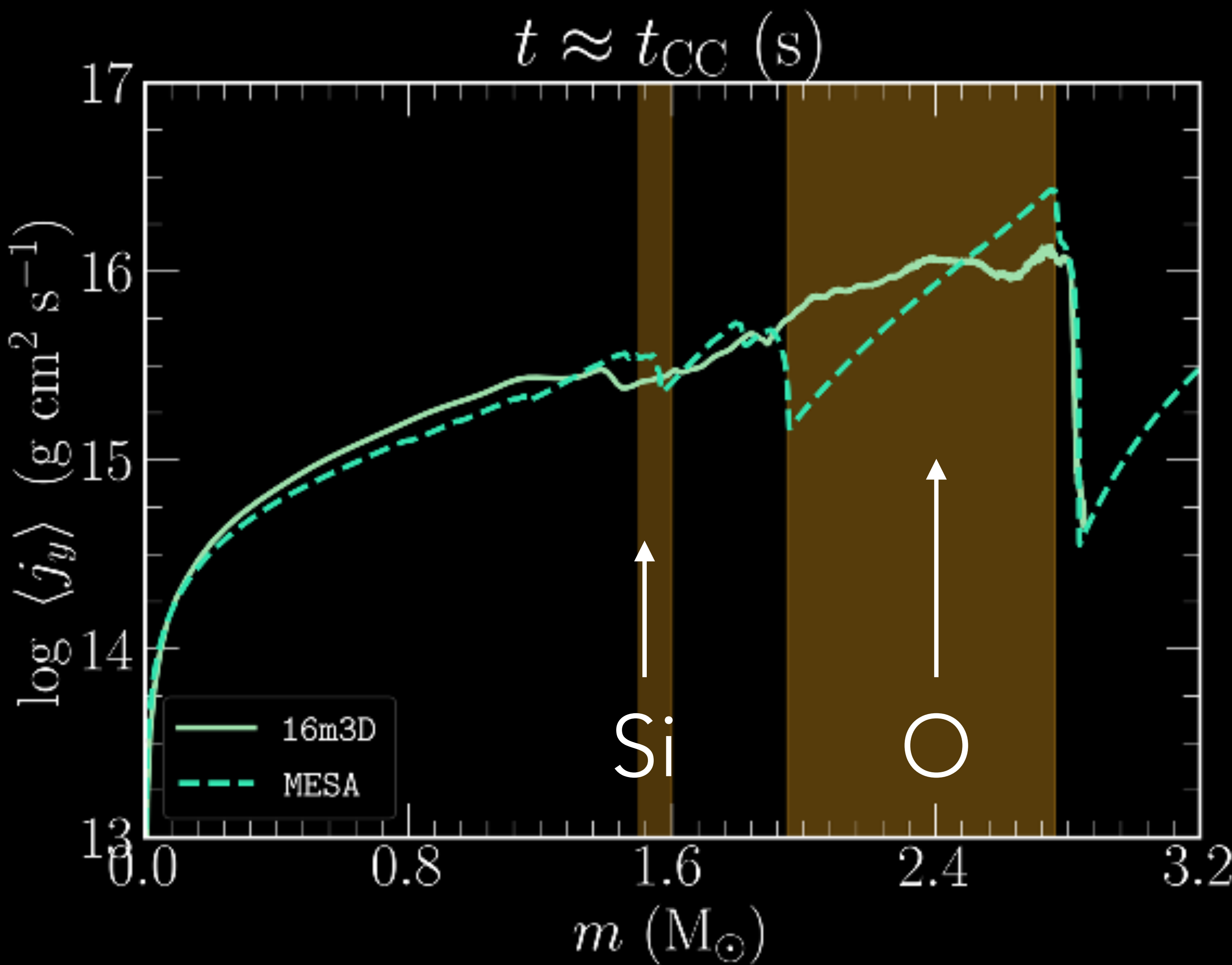
- Convection across a range of scales.
- Flow tends towards large scales at late times ($\ell = 3,5,7$).



Spectrum of radial velocity field for 3D rotating progenitor.
***(Fields 2022*)**

MASSIVE STAR CONVECTION IN ROTATING PROGENITORS

- 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).

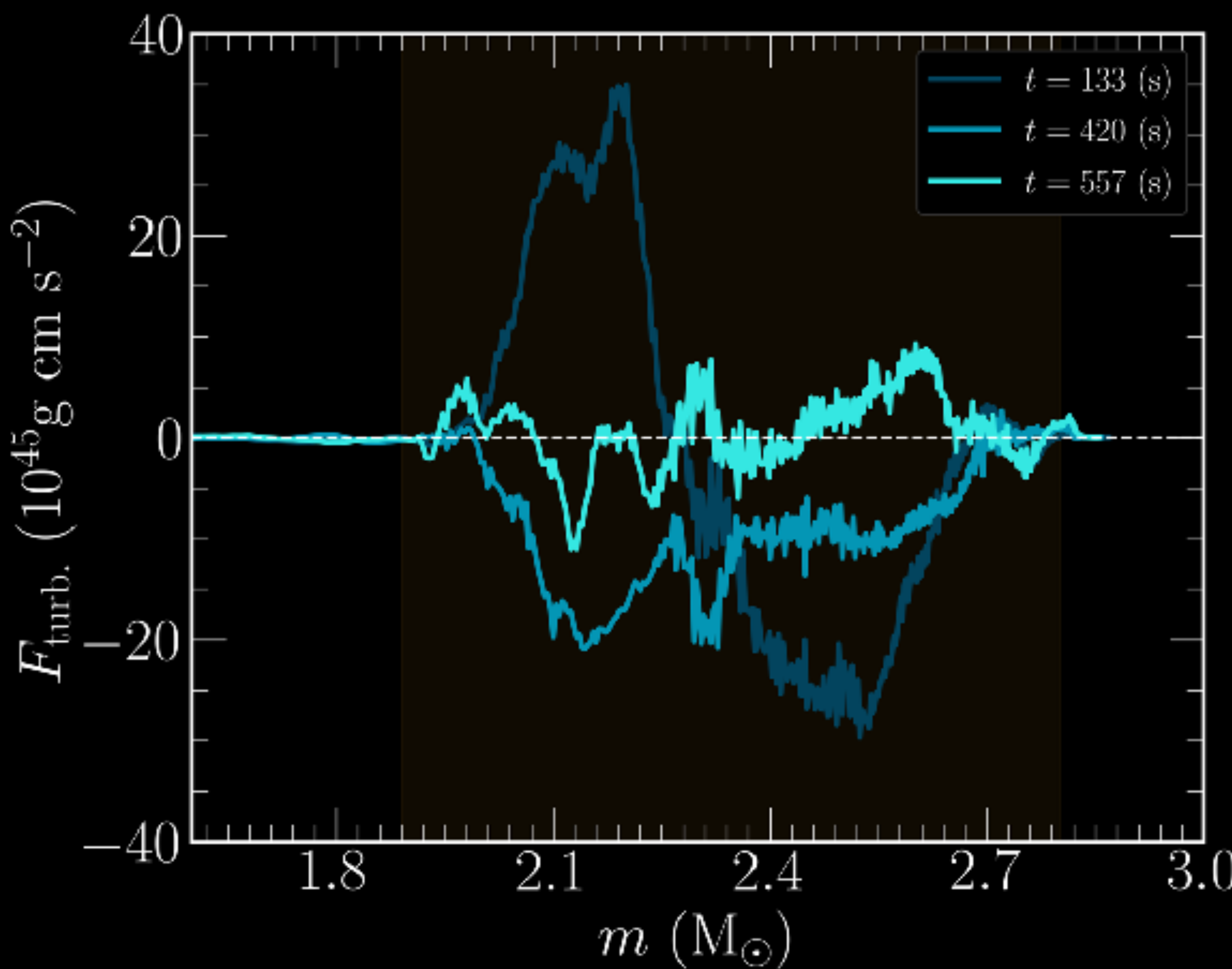


Angular momentum profiles for rotating 3D progenitor.
(Fields 2022)

MASSIVE STAR CONVECTION IN ROTATING PROGENITORS

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

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



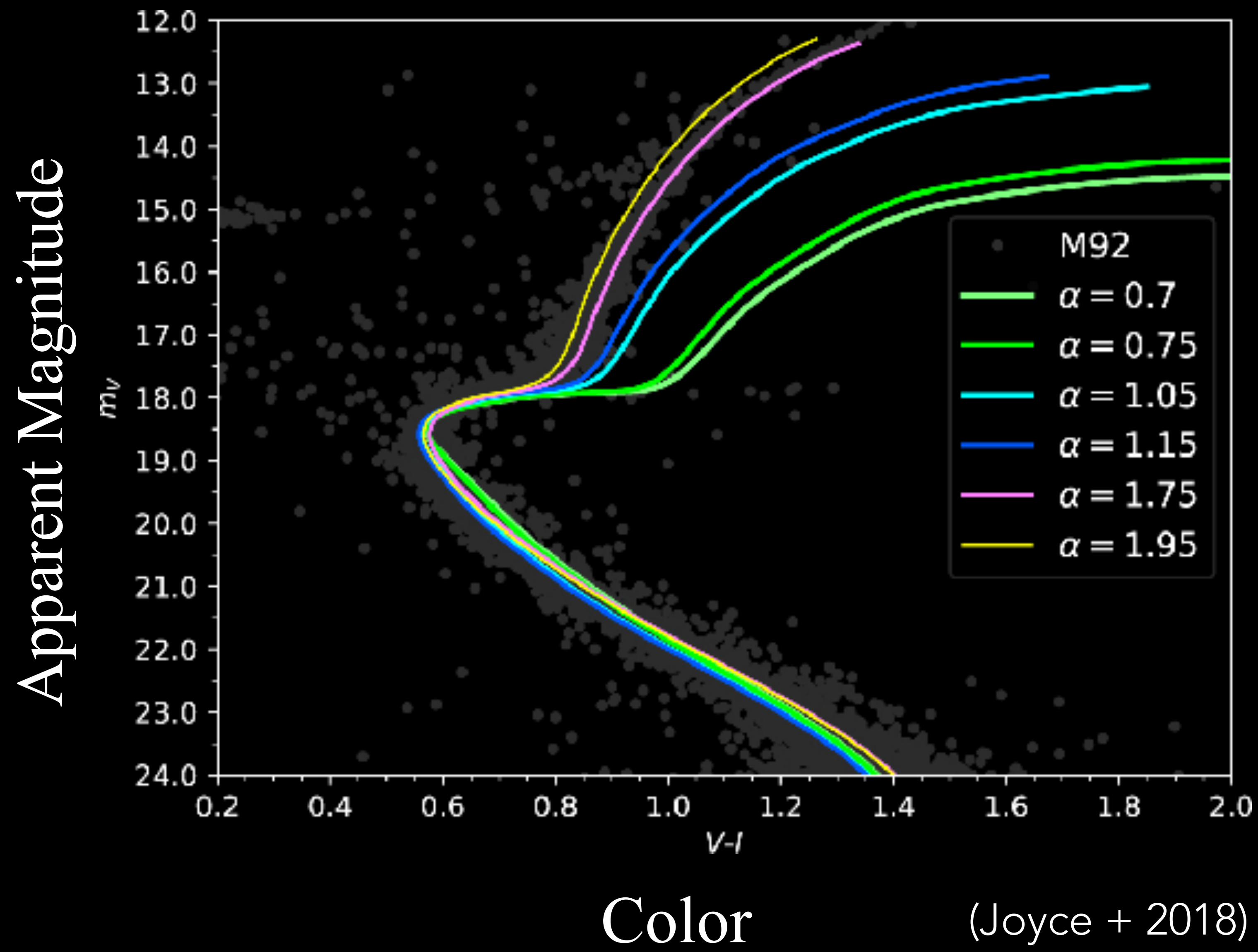
Angular momentum flux profiles.

(Fields 2022)

STELLAR MODELS

Input Physics

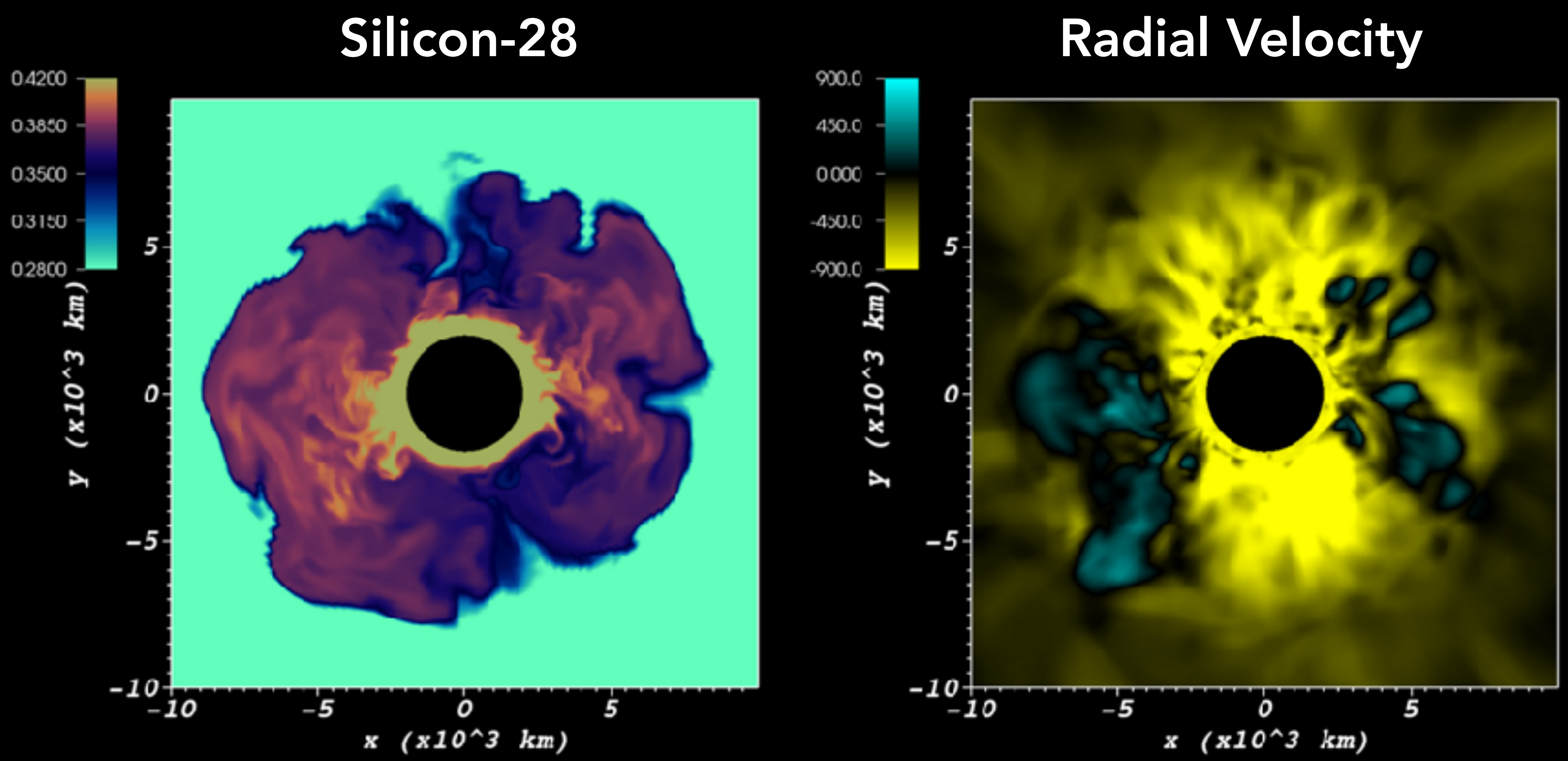
- Mass loss
- Mixing length (convection)
- Nuclear reaction rates
- Opacities
- Angular momentum transport
- Magnetic fields



(Joyce + 2018)

CMD showing effect of different mixing length values effect on the duration of the sub giant branch.

STELLAR EXPLOSIONS



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

STELLAR EXPLOSIONS

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.

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

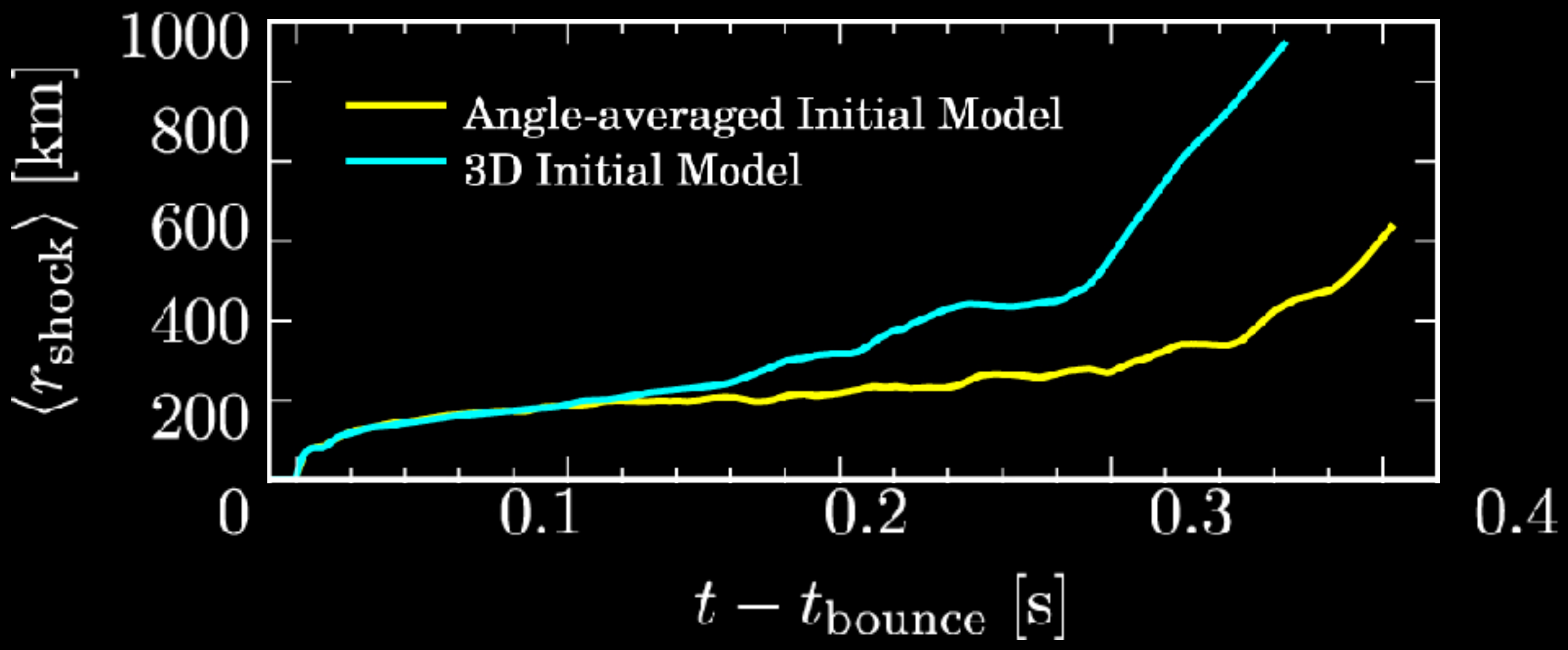
(Muller + 2017)

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

(Couch + 2014, 2015)

STELLAR EXPLOSIONS

3D Initial model leads to faster, stronger explosion.

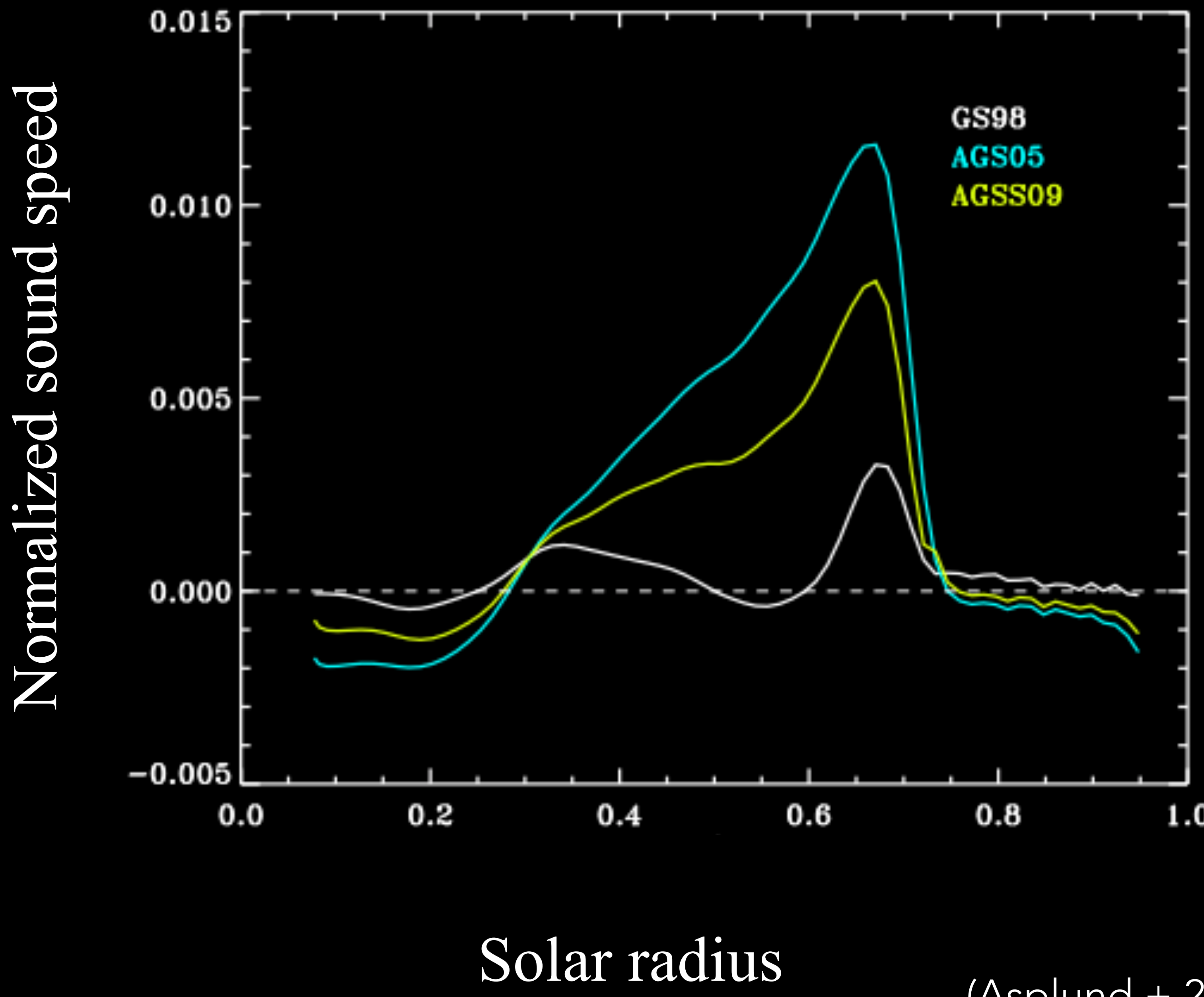


- Multi-D progenitors provide a solution to the core-collapse problem.

STELLAR MODELS

- Stellar models leveraged in Solar calibration.
- Uncertainties in **opacities, convection** can affect.

The Sun

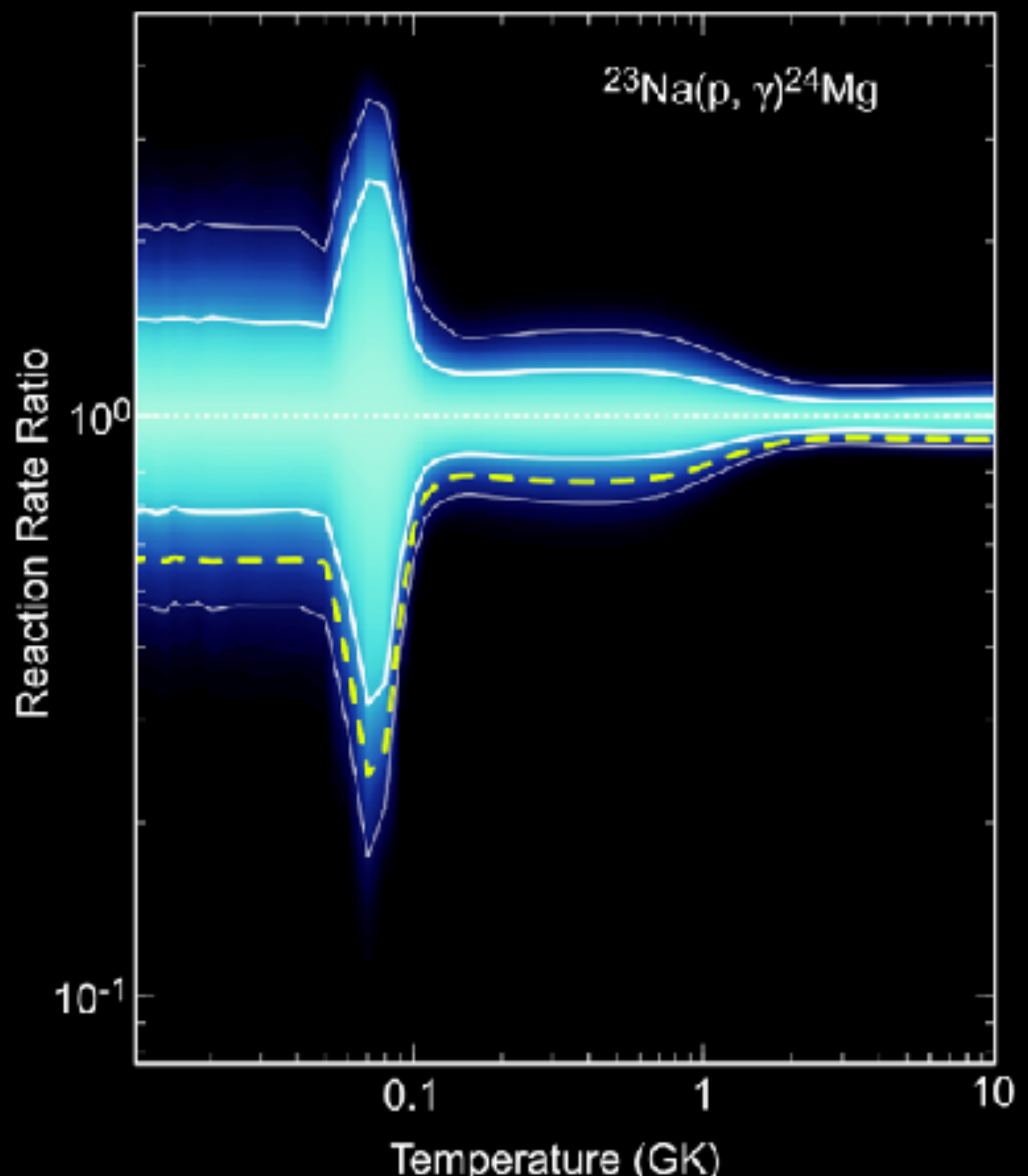


(Asplund + 2009)

STELLAR MODELS IN 1D

Impact of reaction rate uncertainties

- Grid of 3 $M_\odot$ models using 1D MESA Stellar Evolution Code.
- Each model sampled 26 key nuclear reactions.
- Evolved from pre-MS to first thermal pulse.



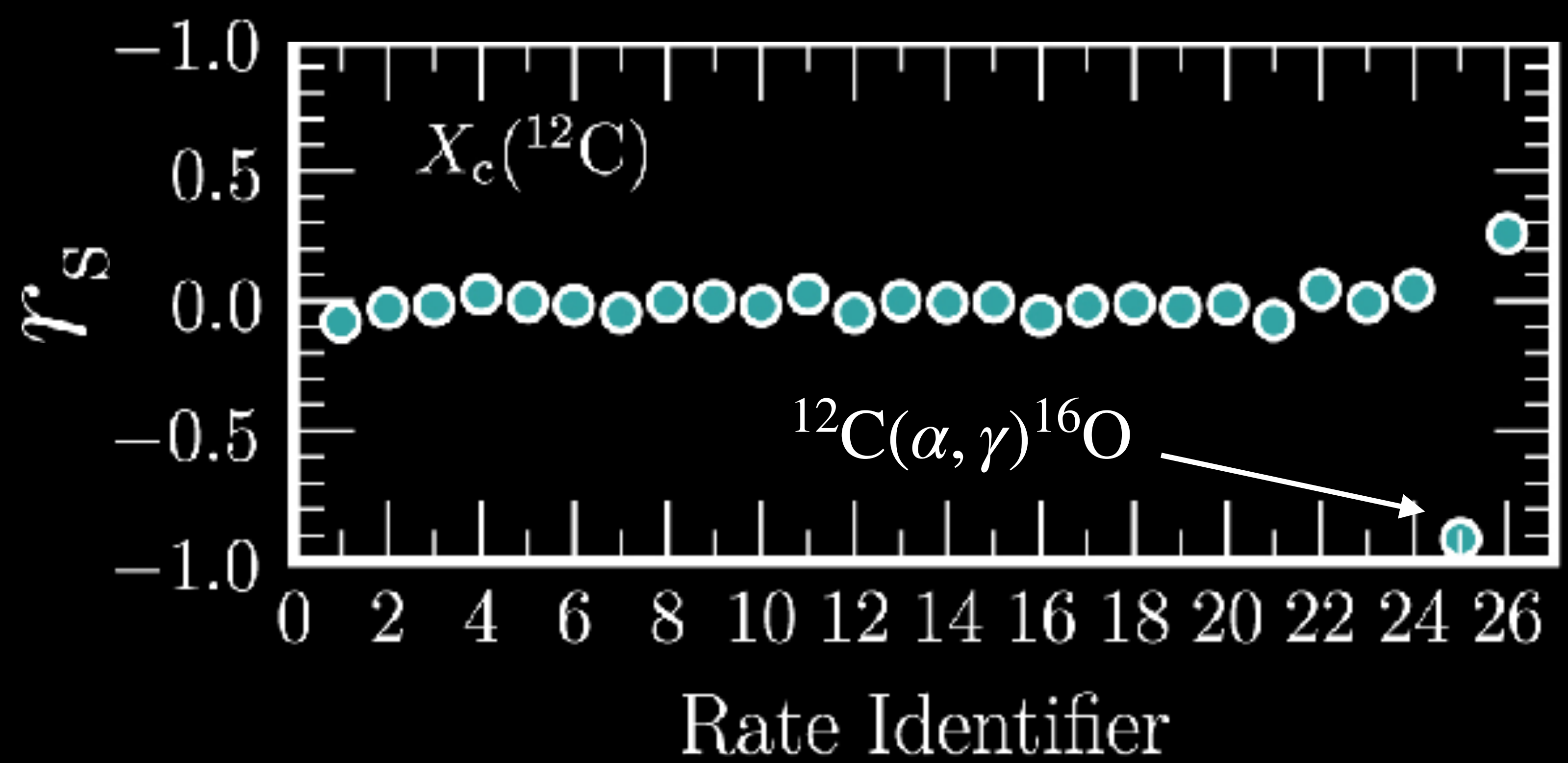
Sampled nuclear reaction rate. (Iliadis + JPhG, 2015)

STELLAR MODELS IN 1D

Identifying key reaction rates

- Correlations between physical quantities and reaction rates.
- We can identify the strongest correlations.
- Results motivates efforts to constrain the reaction cross section.

Central ^{12}C abundance

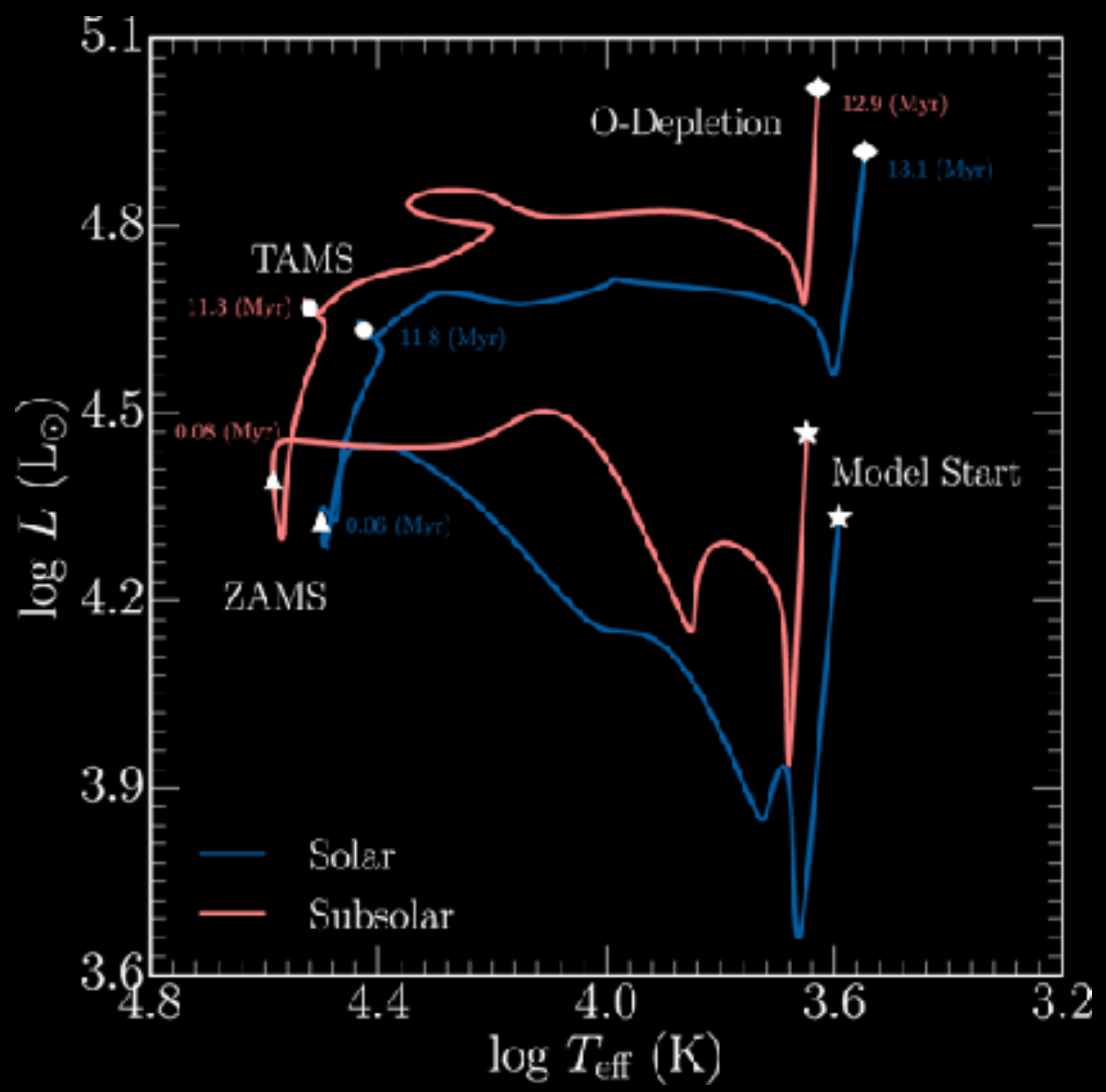


(Fields + ApJ, 2016)

STELLAR MODELS IN 1D

Extending to massive stars

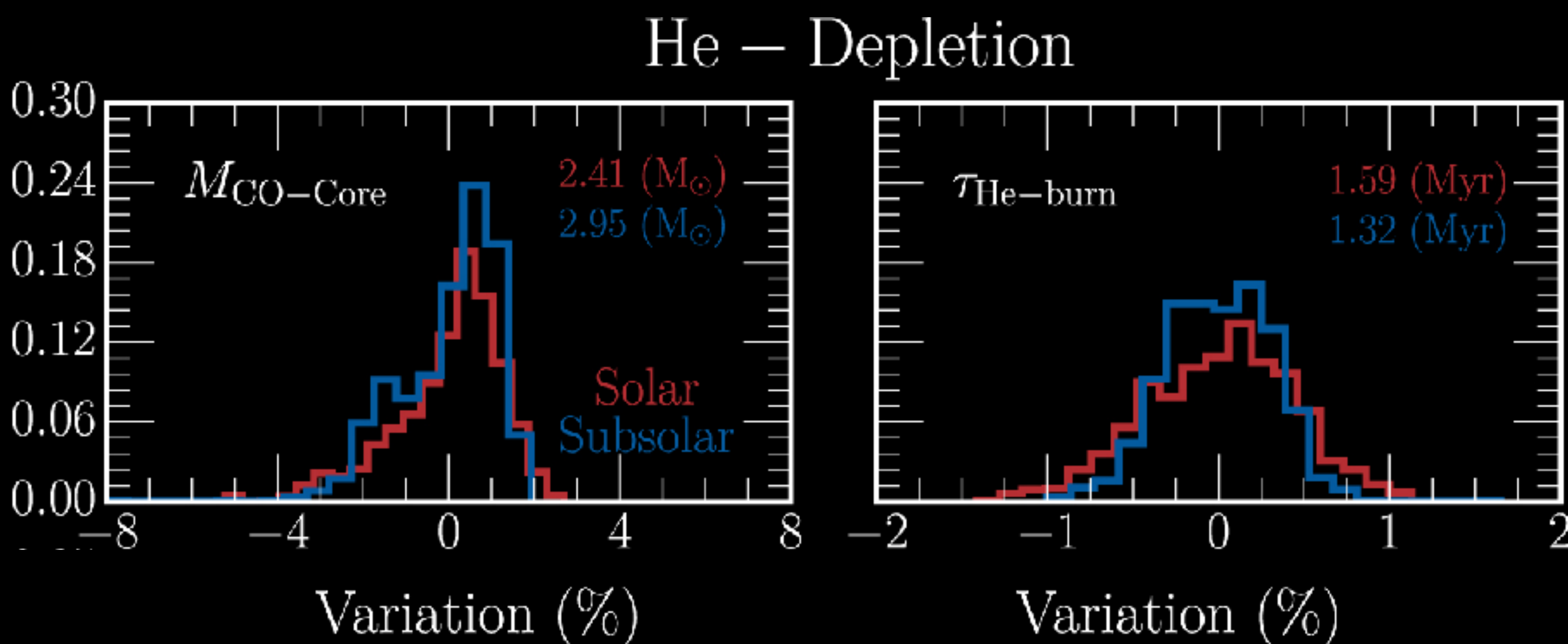
- Grid of 2000 15 $M_\odot$ models.
- Sampled **665** nuclear reactions.
- Evolved to O-depletion.



(Fields + ApJS, 2018)

STELLAR MODELS IN 1D

Measuring distributions of stellar properties



(Fields + ApJS, 2018)

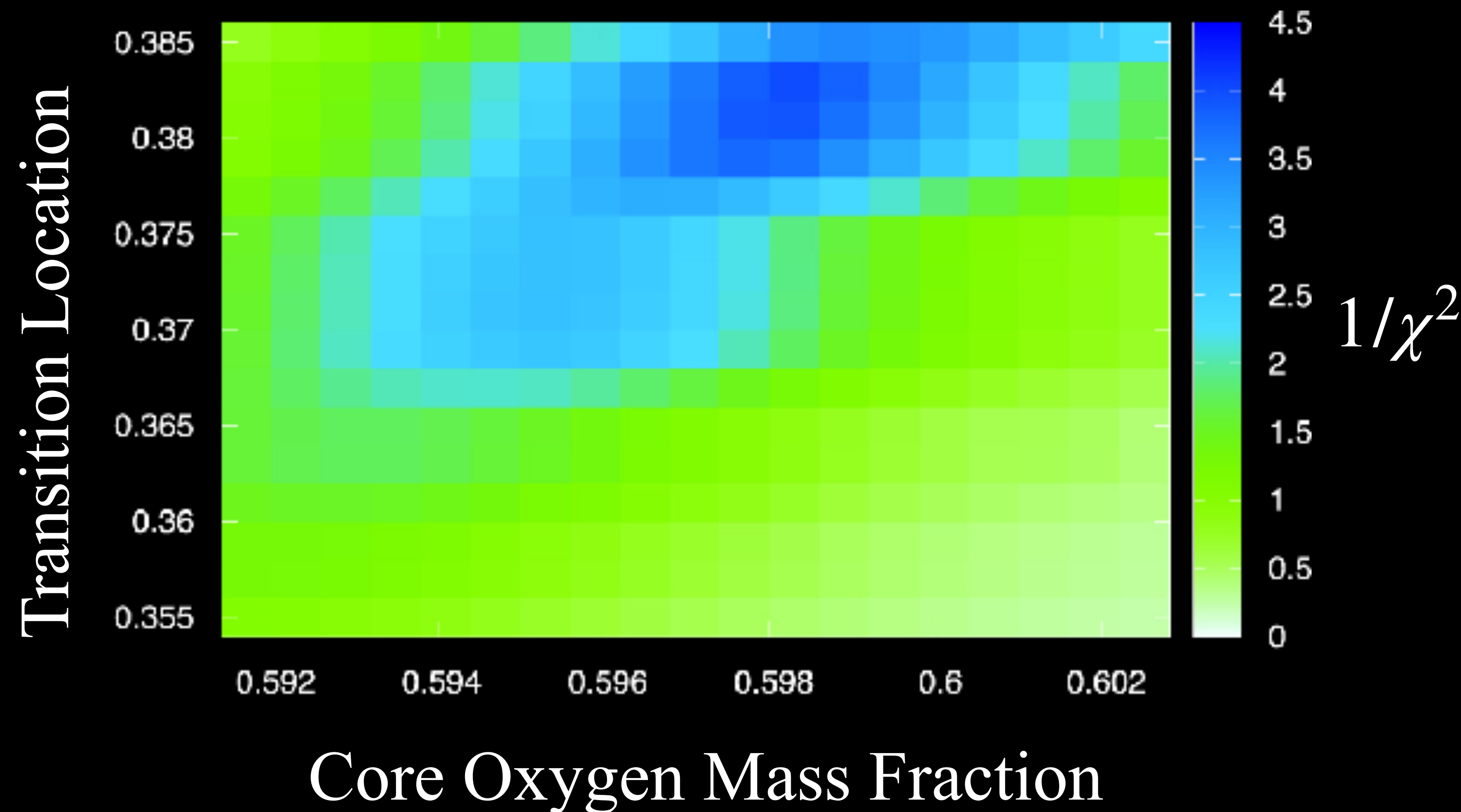
- In general, ***most*** properties show variations **comparable** to uncertainties in mass and network resolution (Farmer + 2016).

STELLAR MODELS IN 1D

Moving beyond parameterized models

- Evolve a grid of stellar evolution models.
- Choose evolutionary model that most closely matches observed periods.
- Ab initio models show larger O mass fractions as well.

HS 0507+0434B

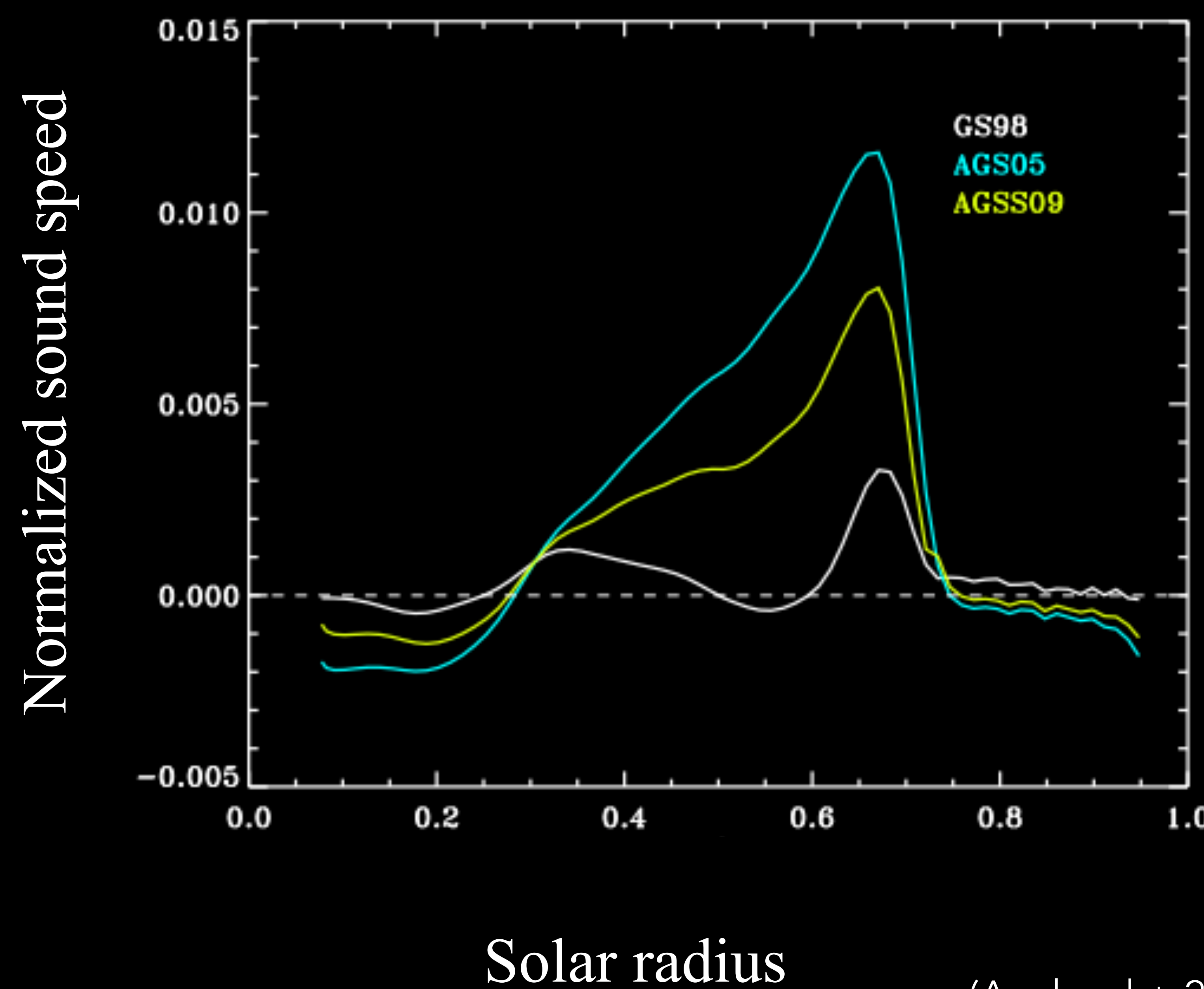


(Guifang + ApJ, 2021)

STELLAR CONVECTION

- Stellar models leveraged in Solar calibration.
- Sensitive to properties of **convection** at the surface.
- Requires 3D radiation transport simulations of the surface: Trampedach +2014.

Profile in the Sun

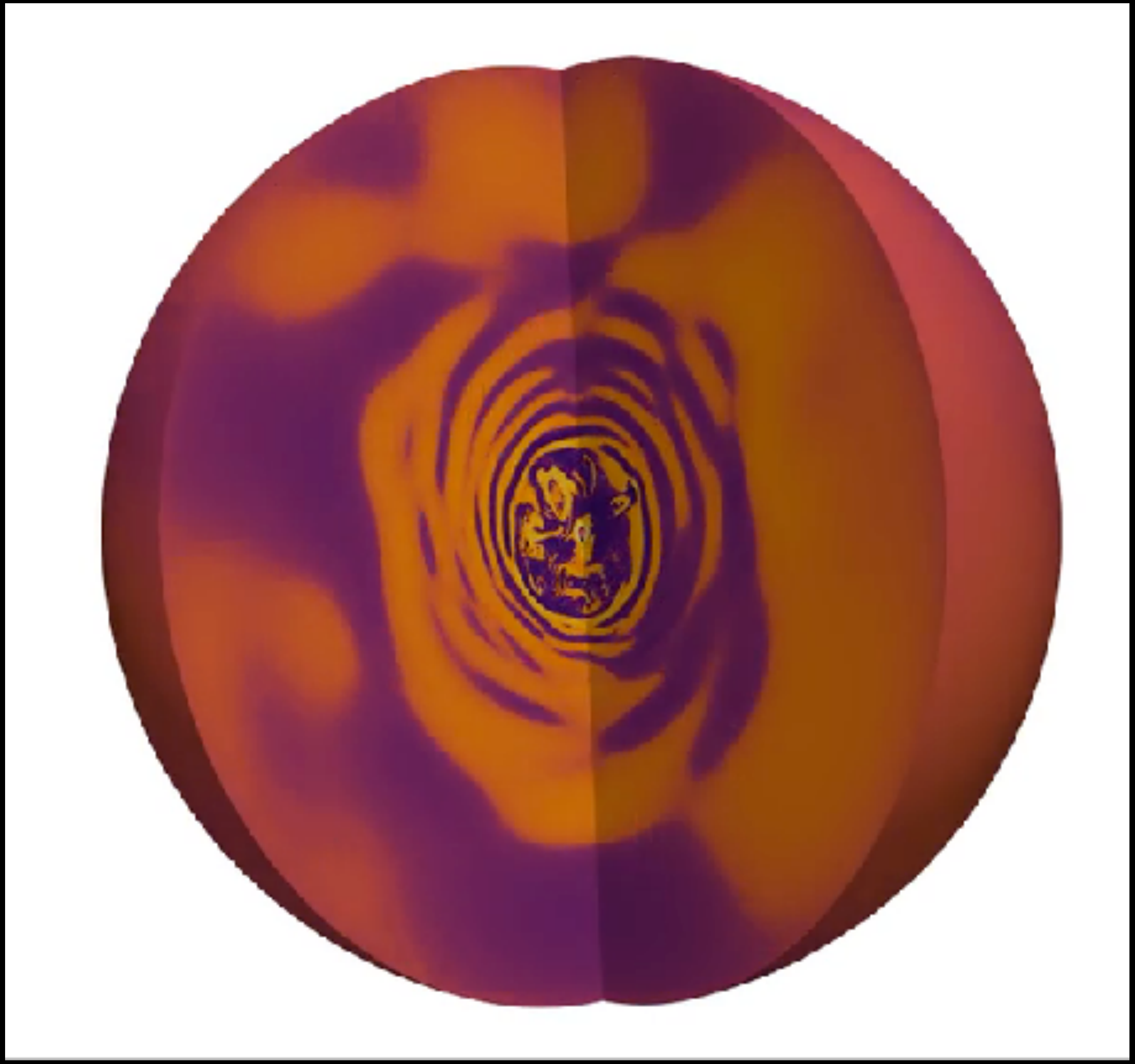


(Asplund + 2009)

STELLAR CONVECTION

- 3D hydrodynamical models possible.
- Convective core generates internal gravity waves (IGWs).
- IGWs can transport angular momentum, possibly explain episodic mass loss, and many more!

$M = 3M_\odot$

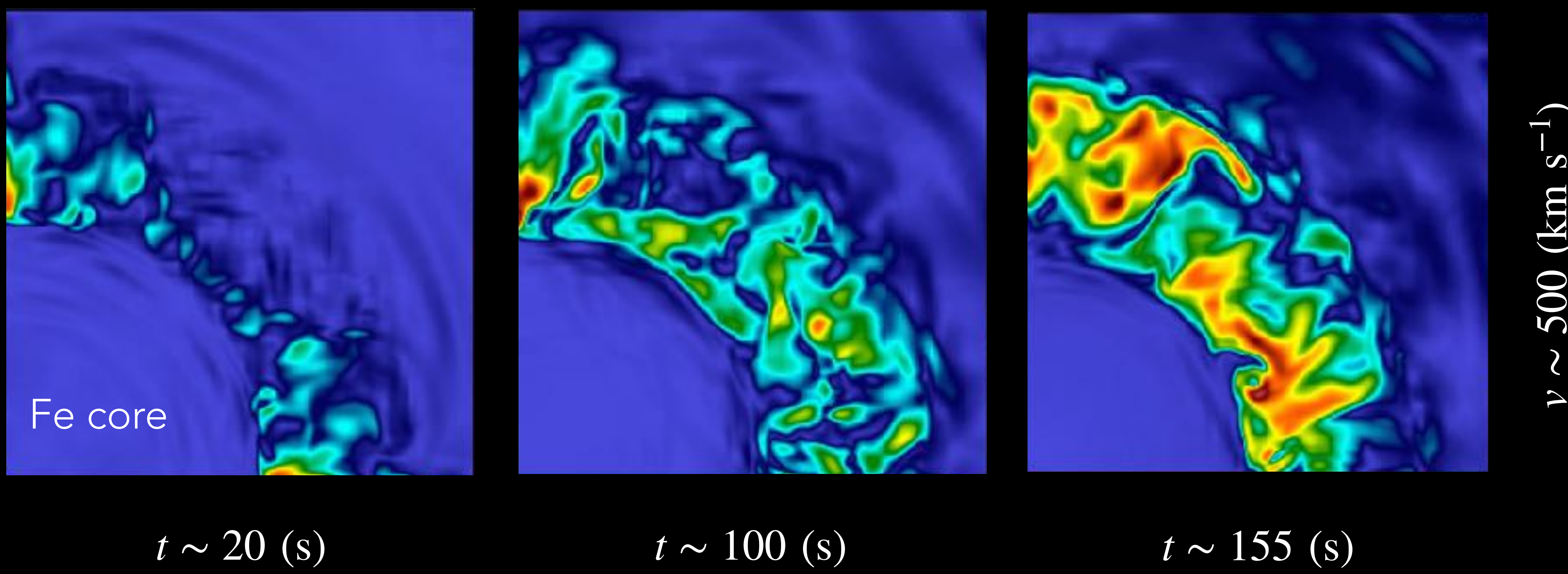


$T - T_{\mathrm{background}}$

(Edelmann + 2019)

STELLAR CONVECTION

Convection in pre-supernova massive stars

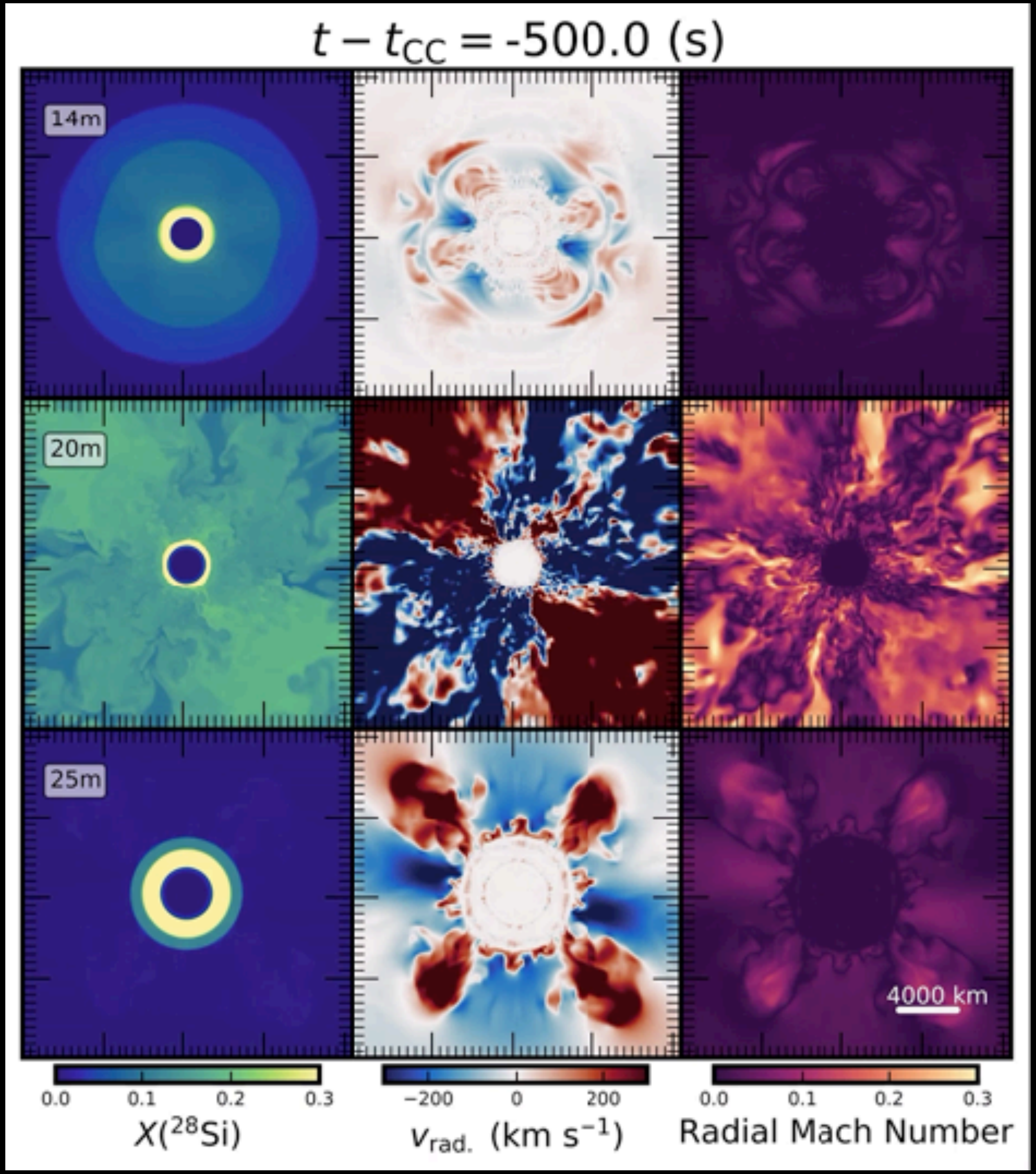


(Couch + ApJL, 2015)

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

STELLAR CONVECTION

- 3D simulations using FLASH for 14-,20-, and 25 $M_\odot$ models.
- Surveying different initial conditions.
- Significant non-radial flow with large Mach numbers.



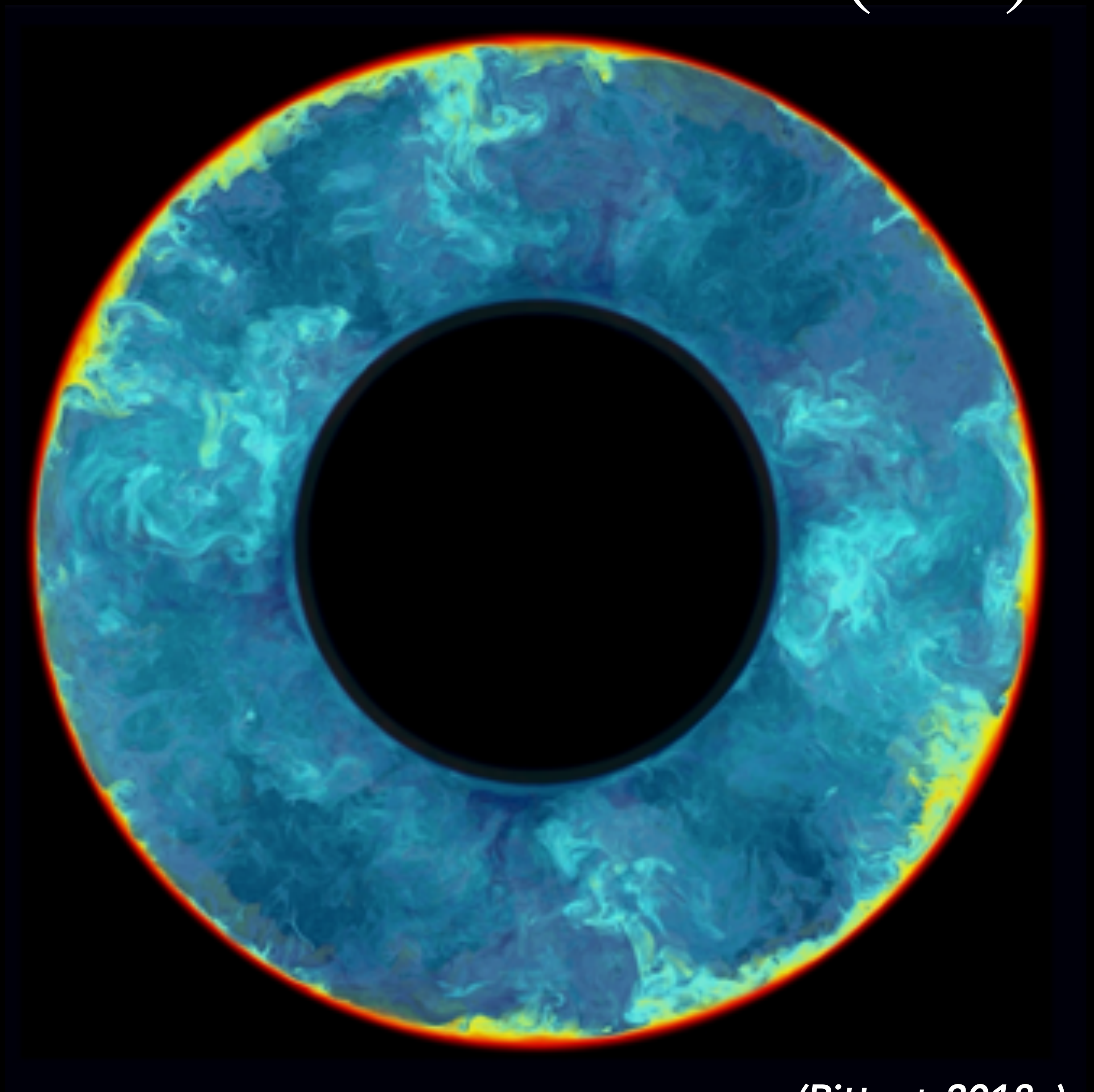
(Fields & Couch 2021)

STELLAR CONVECTION

3D convection and stellar nucleosynthesis

- Significant mass entrainment can lead to overproduction of odd-Z elements.
- Entrainment rate of $10^{-3} M_{\odot}\ \mathrm{yr}^{-1}$ can give OP of 7.
- Explain deficiency of these elements in galactic chemical evolution models (Nomoto + 2013).

$FV(^{12}\mathrm{C})$

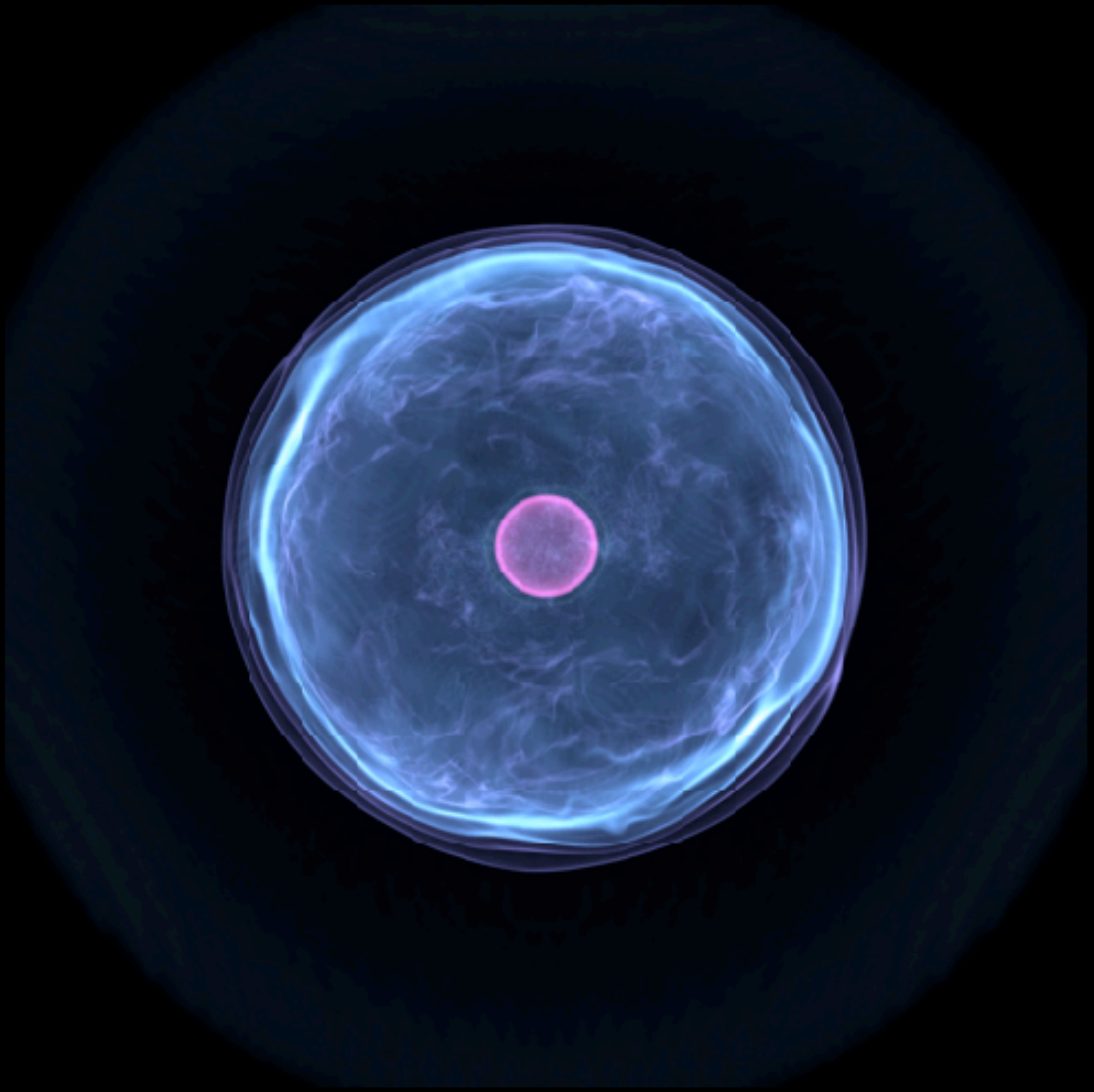


(Ritter+ 2018a)

STELLAR CONVECTION

Impact of rotation on 3D stellar convection

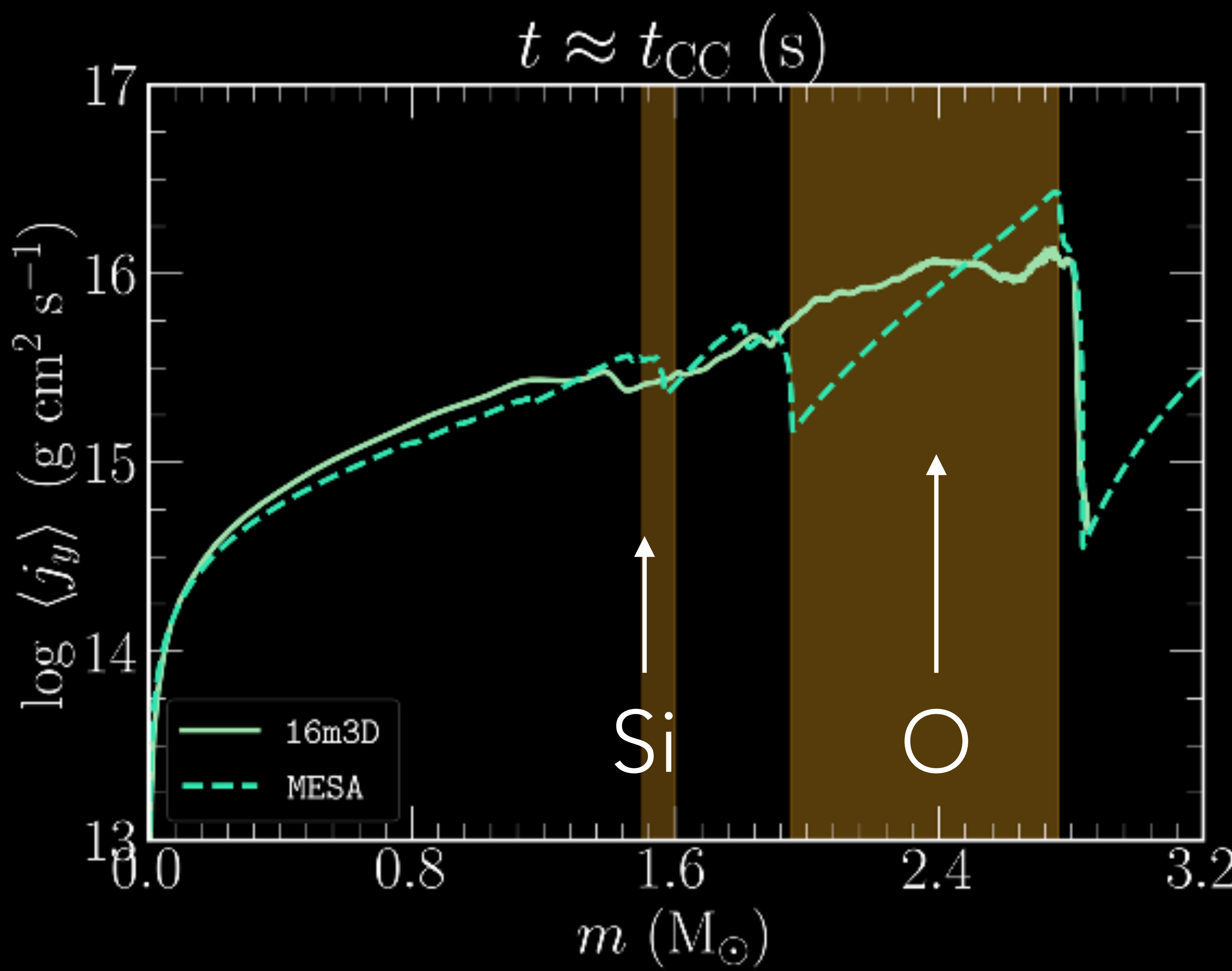
- 3D simulations using FLASH for $16M_{\odot}$ model.
- Rotation initialized to 350 km s^{-1} at ZAMS.
- Includes complete iron core.



STELLAR CONVECTION

Transport of Angular Momentum (AM)

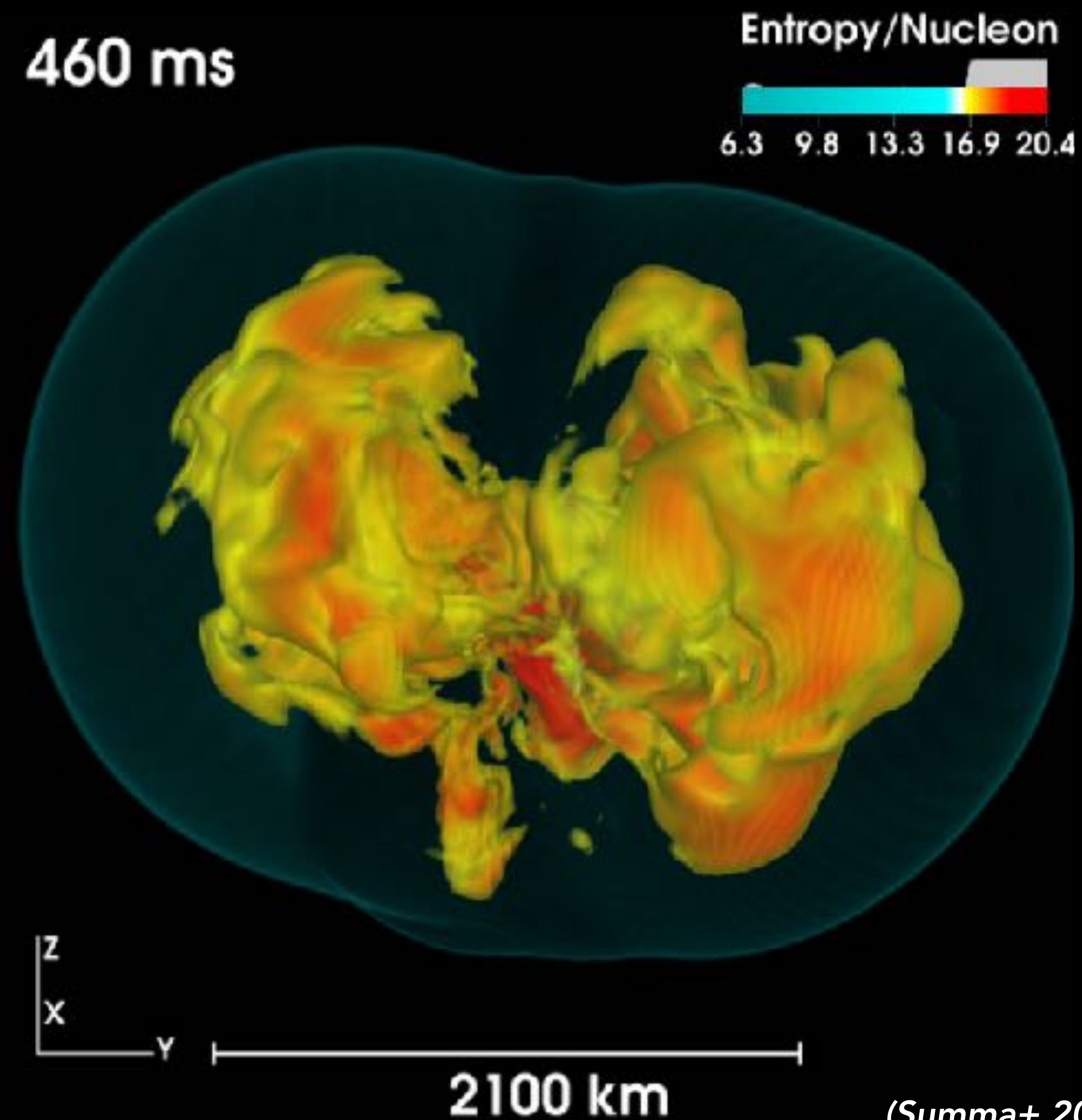
- AM profile diverges from MESA in convective regions.
- Observe differences in remnant spin period.



Angular momentum profiles for rotating 3D progenitor.
(Fields 2022)

STELLAR CONVECTION

- Spin periods of NS rely on AM profile (Ma+ 2019).
- AM profile can **qualitatively alter** explosion outcome.



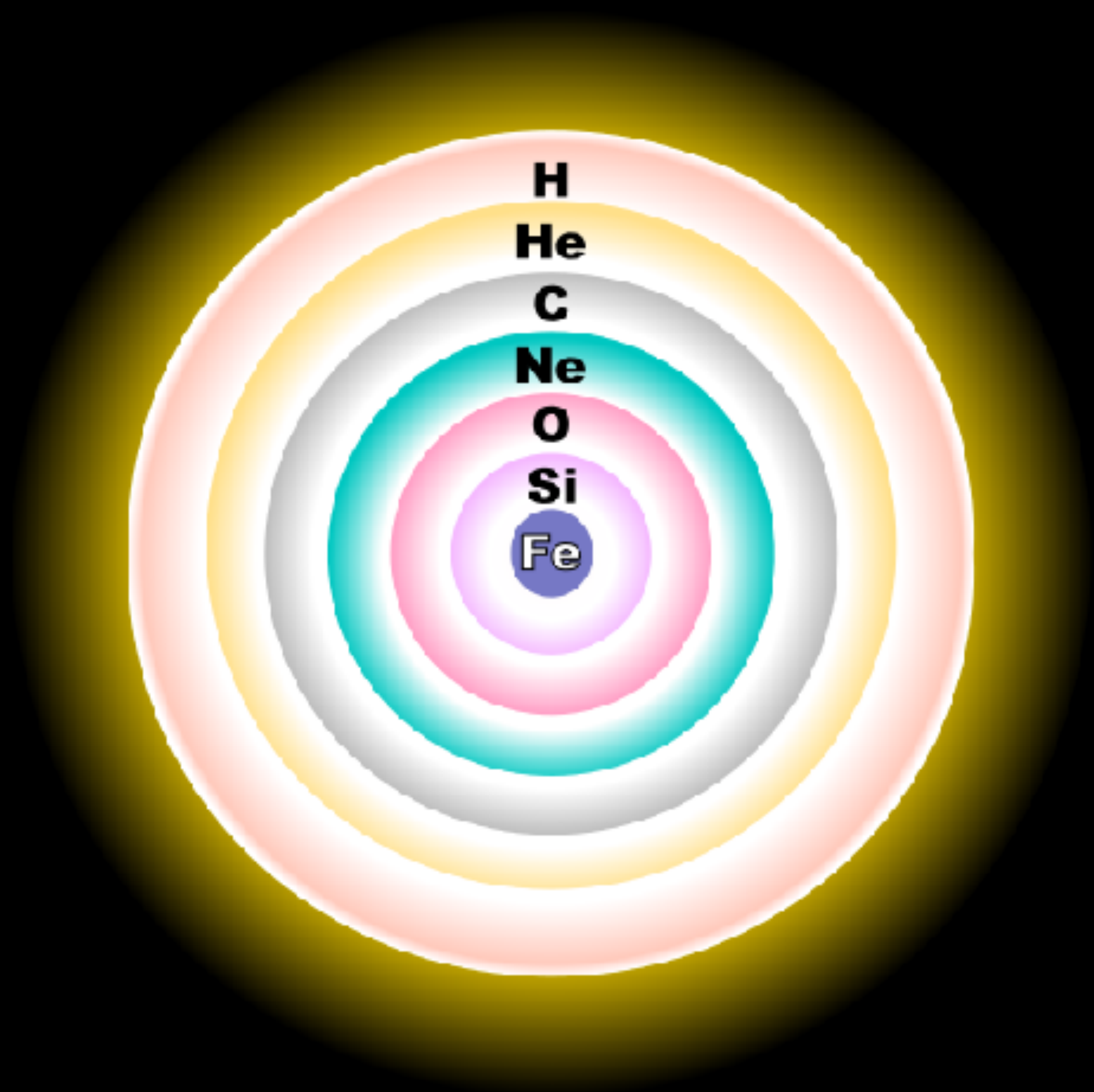
(Summa+ 2018a)

Explosion of rotating progenitor with enhanced AM profile.

STELLAR EXPLOSIONS

Evolution to Core-Collapse

- 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 !

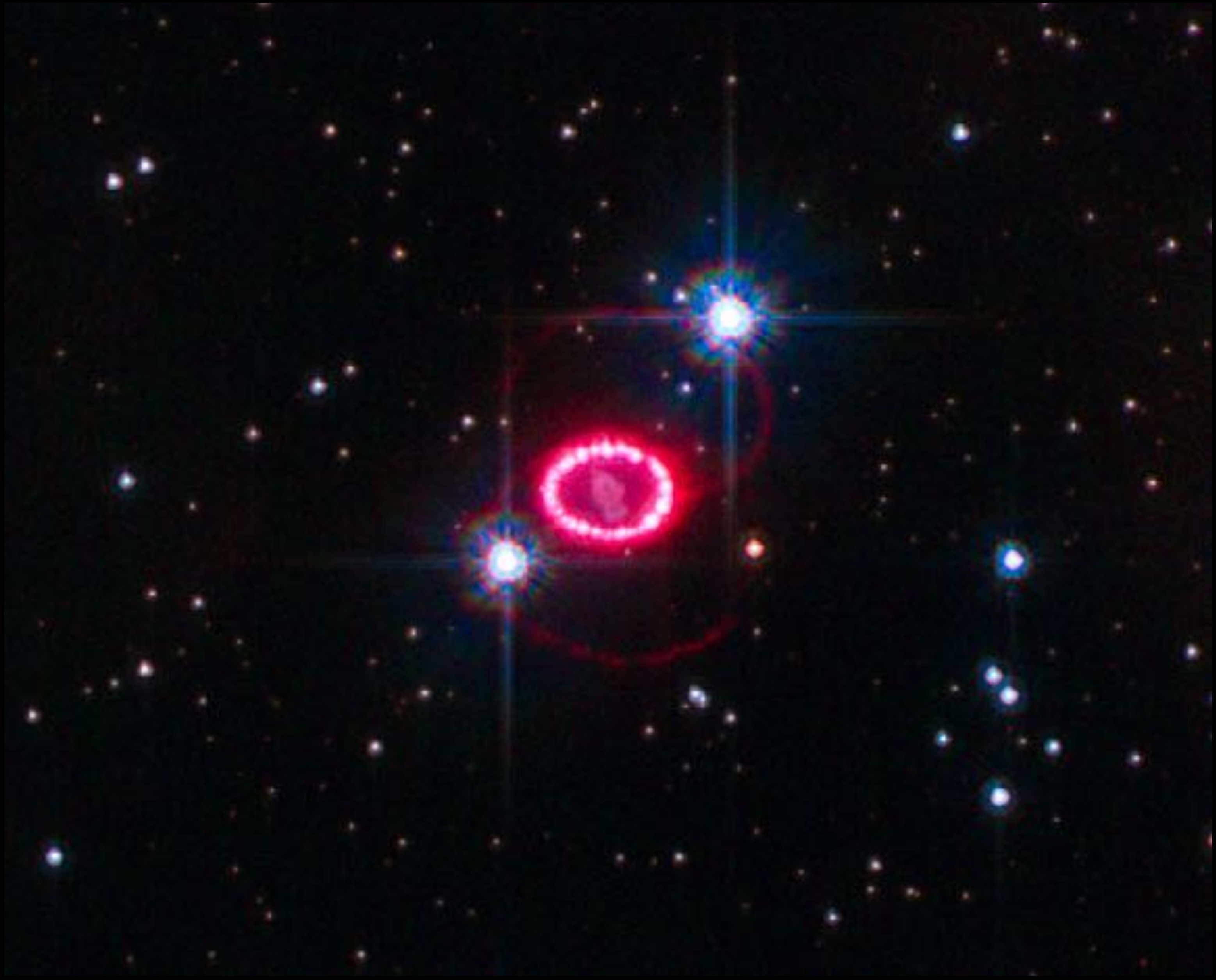


CREDIT: R. J. HALL

STELLAR EXPLOSIONS

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**.

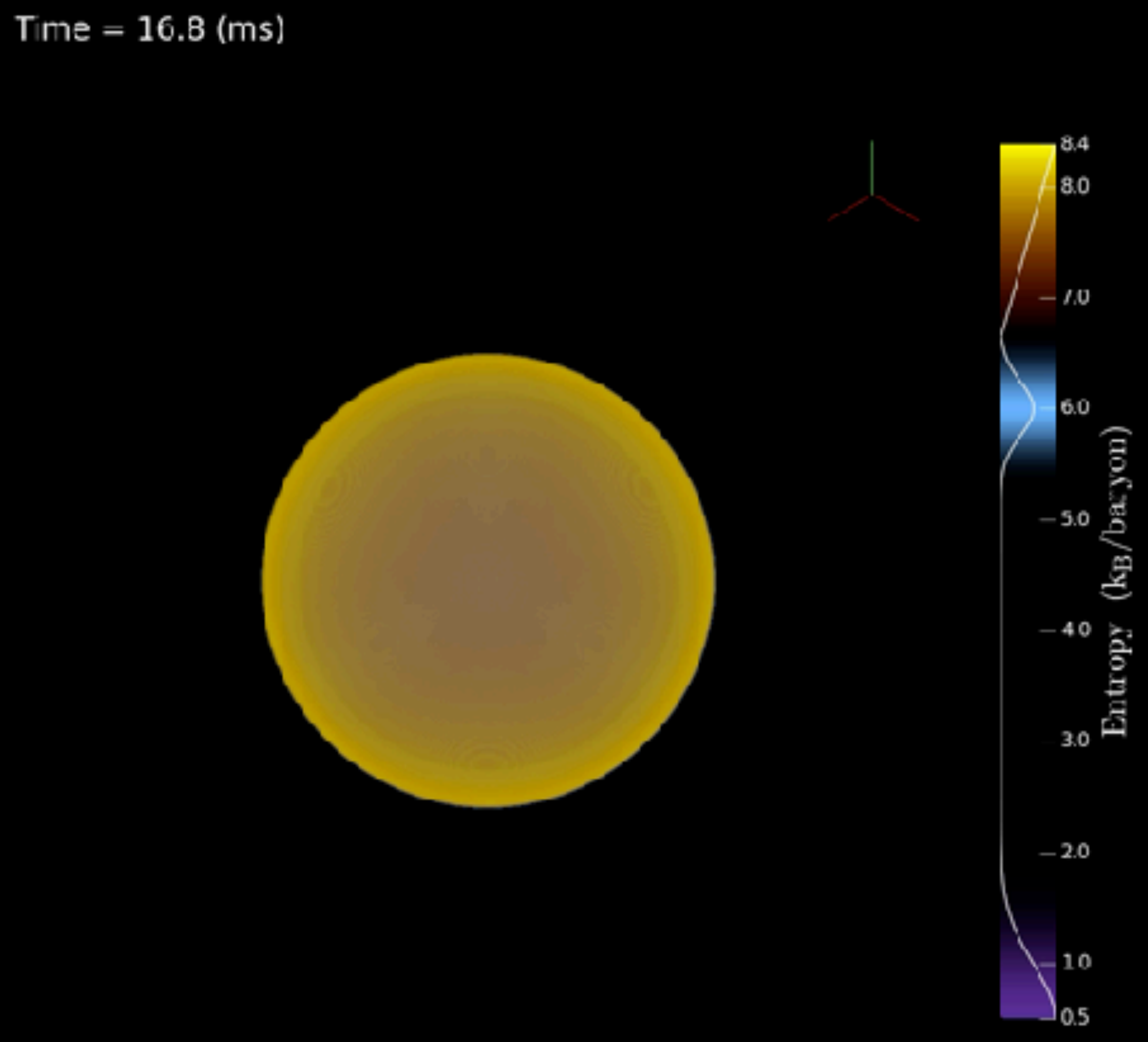


THE REMNANT OF SN 1987A. SOURCE: NASA GSFC.

STELLAR EXPLOSIONS

How do we model stellar explosions?

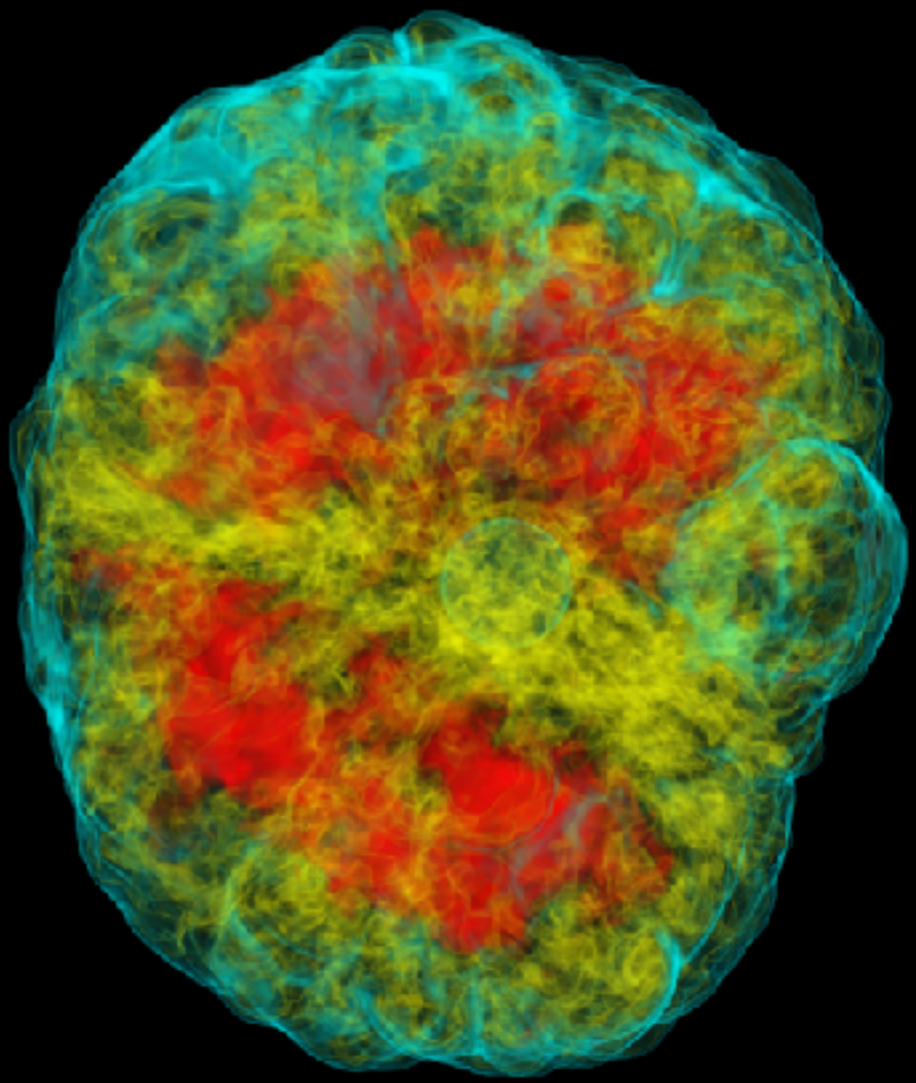
- 1D Stellar Evolution Codes for pre-supernova evolution.
- Evolve explosion in 2/3D using multi-D hydro codes.
- Shock failed to be revived in some models.



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

STELLAR EXPLOSIONS

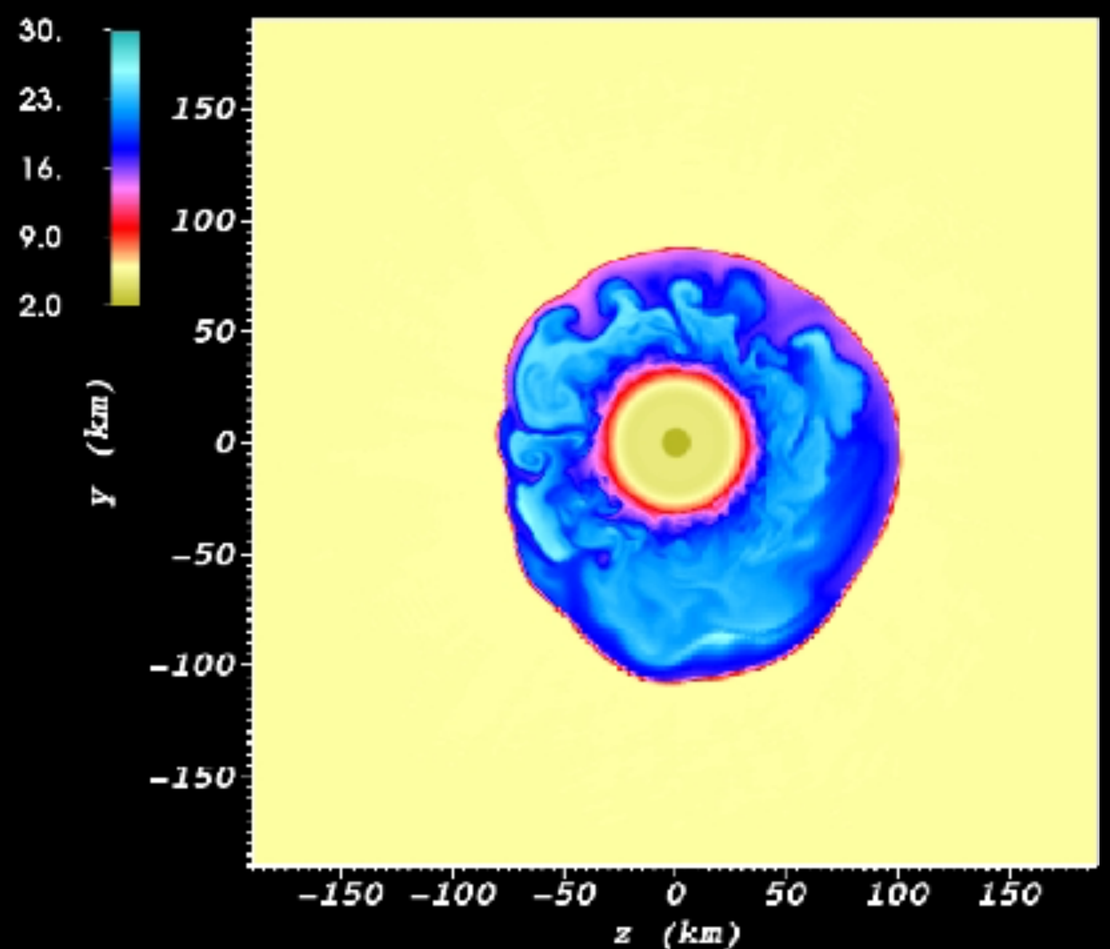
- General Relativistic Gravity - More compact PNs lead to larger neutrino luminosities.
- Sophisticated Neutrino Transport - Full Transport + GR can result in explosion.
- **Initial models/Perturbations** - Pre-SN models are **not** spherical and can vary.



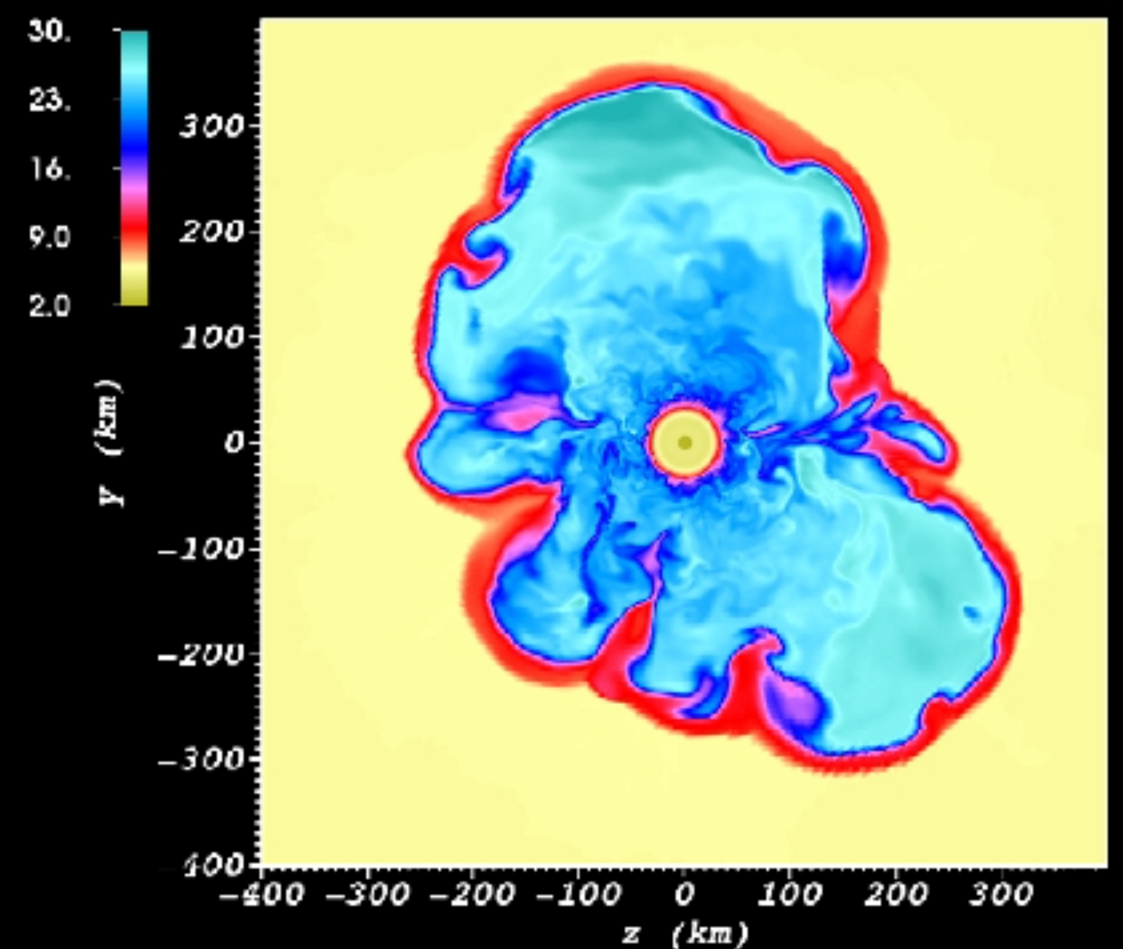
Volume rendering of the entropy distribution from *Roberts + 2016.*

STELLAR EXPLOSIONS

Convective perturbations from 3D massive stars



1D initial progenitor



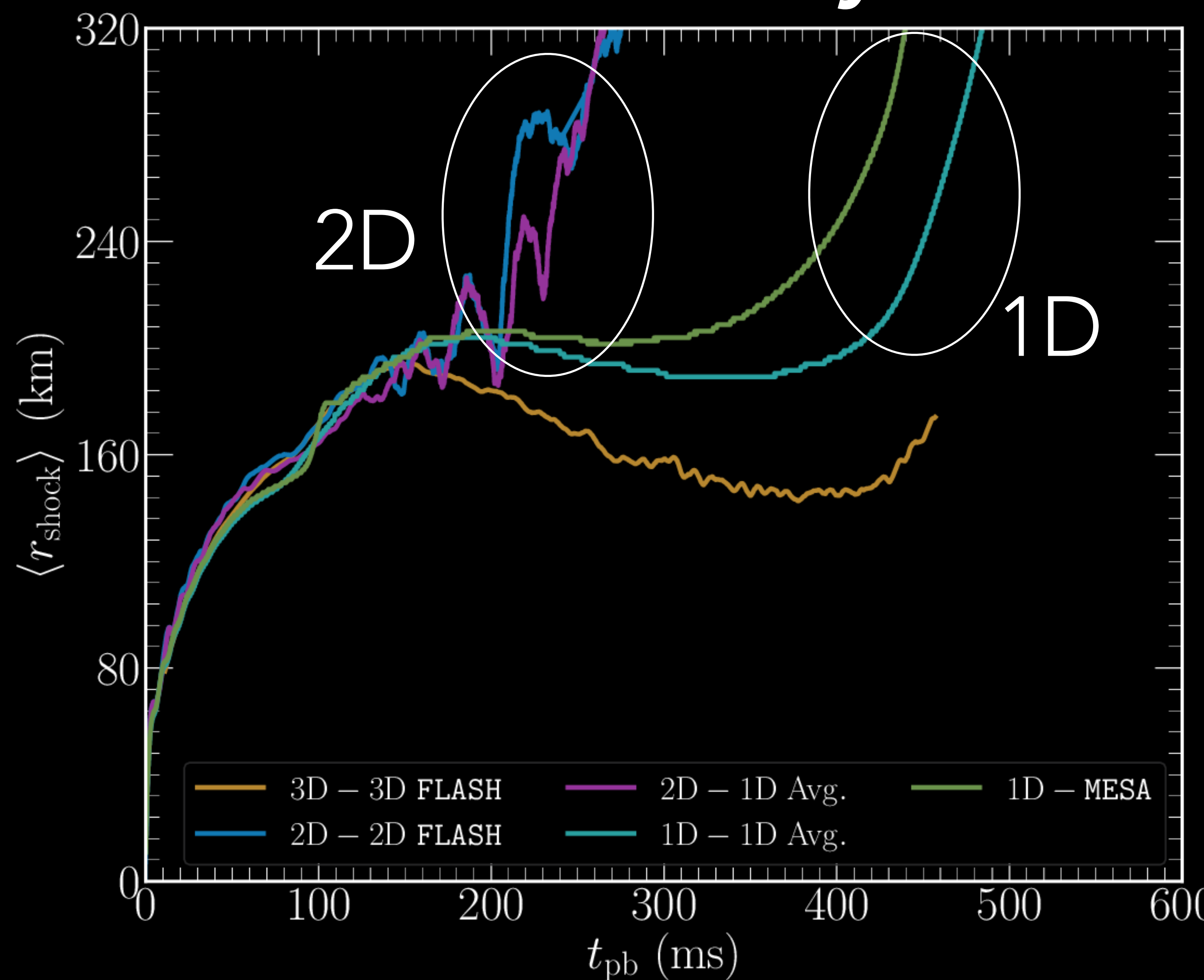
3D initial progenitor

(Muller + 2017)

STELLAR EXPLOSIONS

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

Preliminary



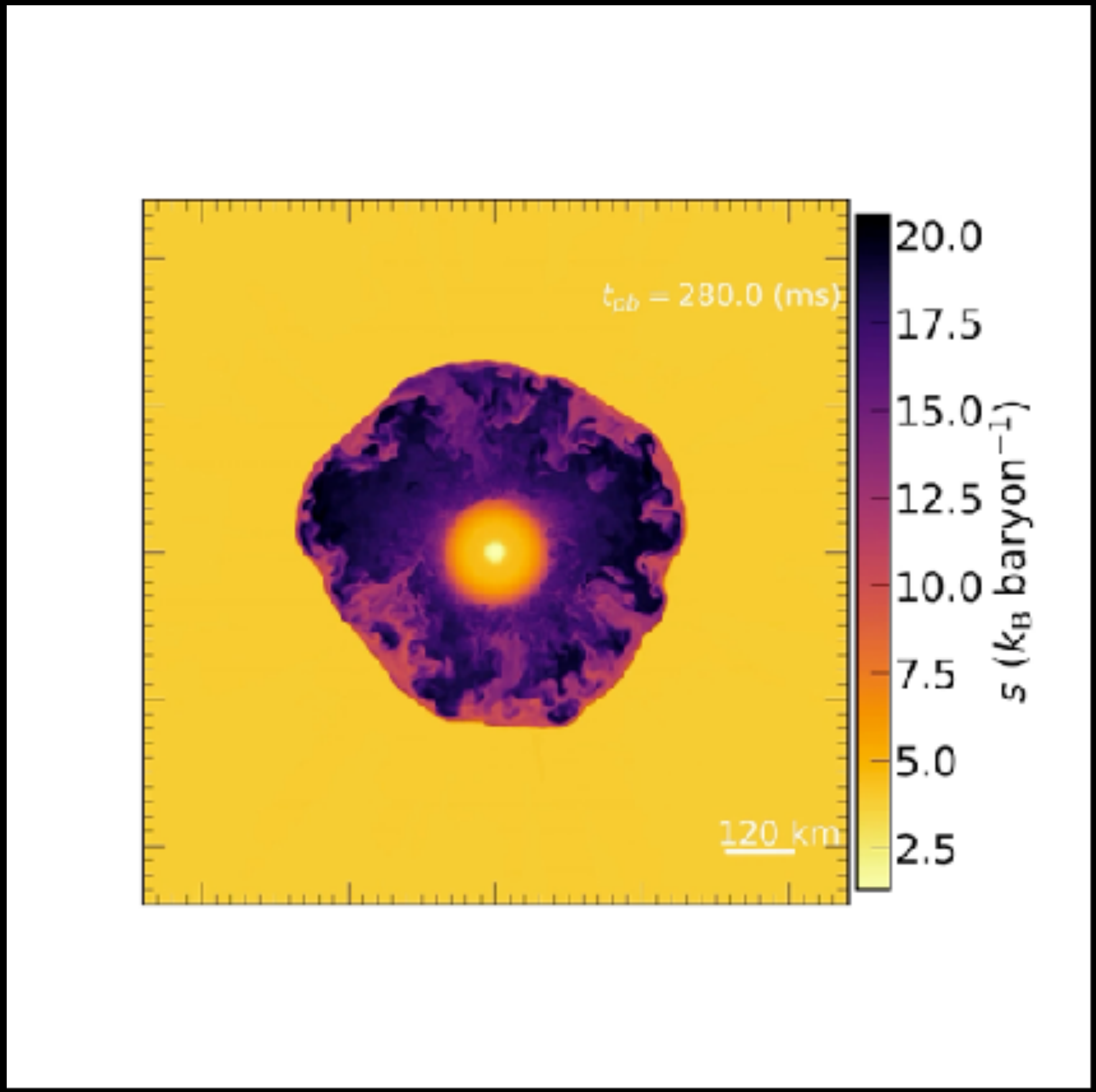
Mean shock radius evolution for multi-D CCSN models

(Fields + 2022b, in prep.).

STELLAR EXPLOSIONS

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

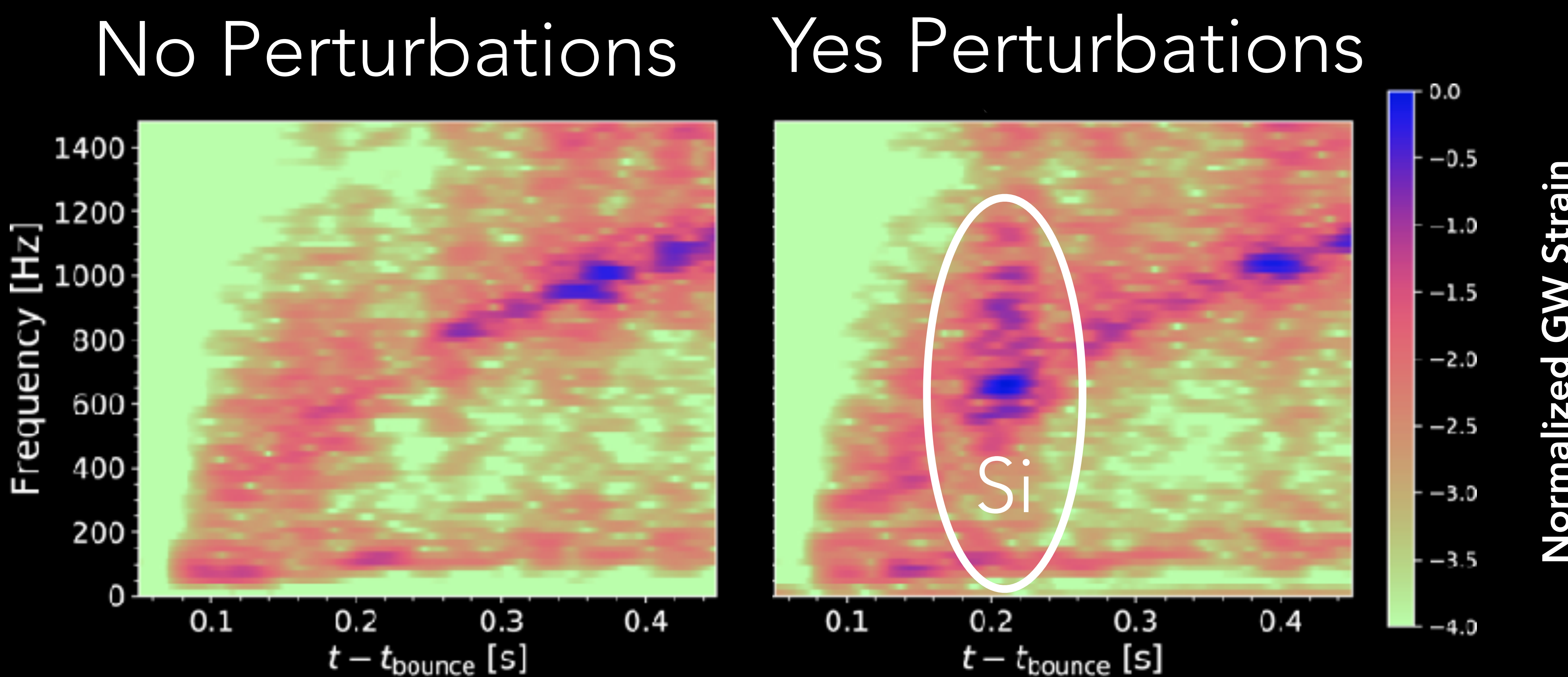
Preliminary



Slice of entropy in the x-y plane for 3D CCSN model ***(Fields + 2022b, in prep.).***

STELLAR EXPLOSIONS

Impact of 3D progenitor on GW emission?

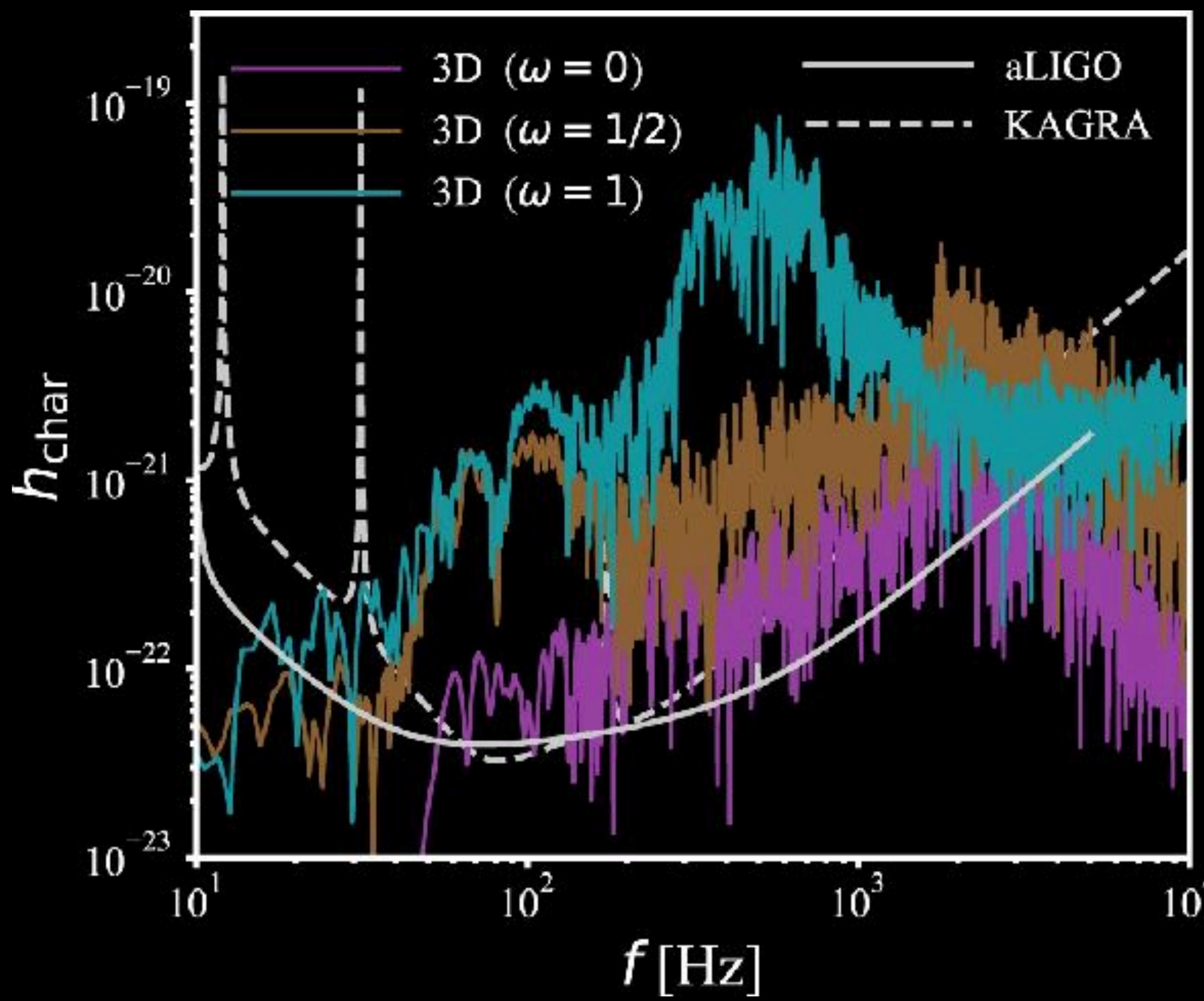


(O'Connor & Couch, 2018)

Si-shell perturbations shown in GW emission.

STELLAR EXPLOSIONS

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



(Pan+ 2021, ApJ).