SNAPhU
Stellar and Nuclear AstroPhysics Unit

The Turbulent Frontier in Massive Stellar Death

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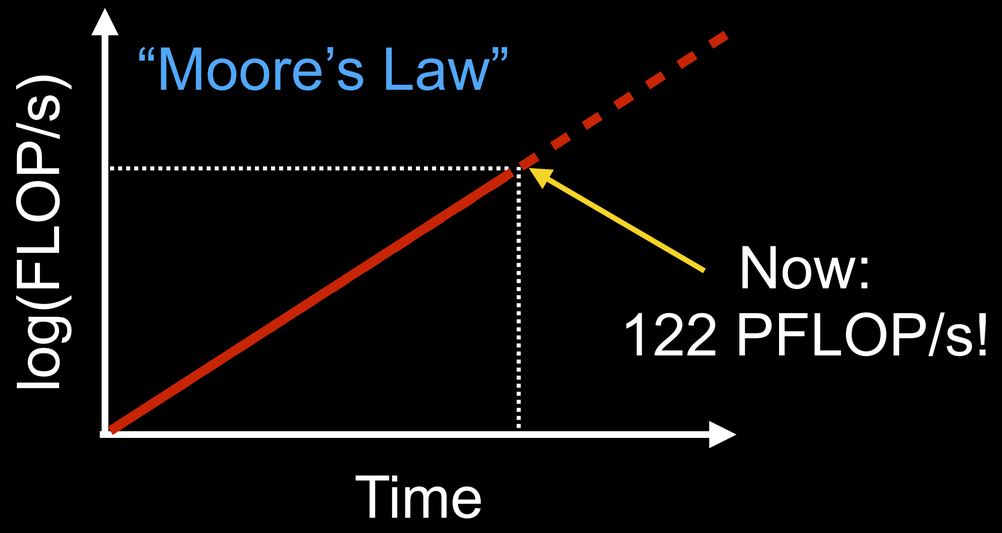
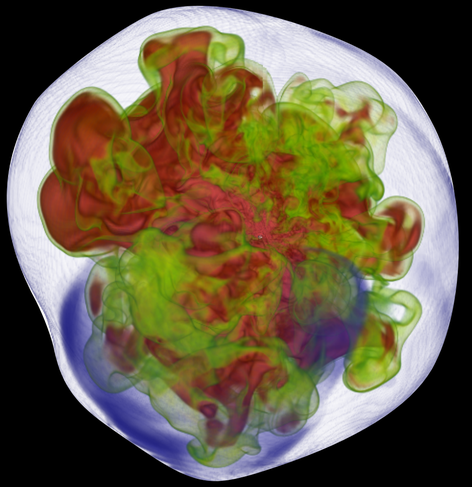
Michigan State University

Midwest Workshop on Supernovae and Transients
UChicago - 26 February 2019

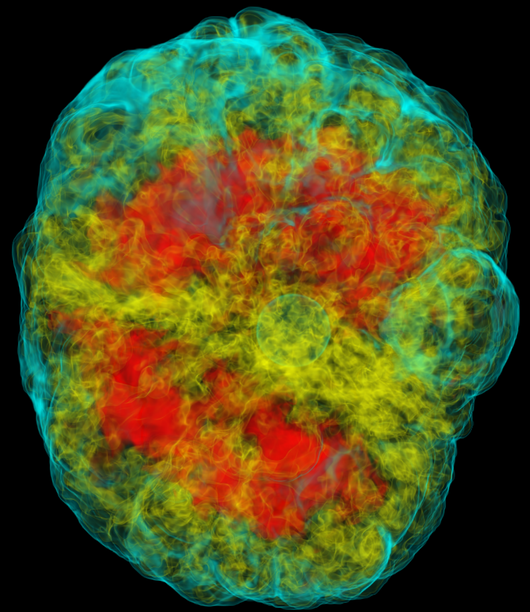
Era of 3D CCSN *Explosions*

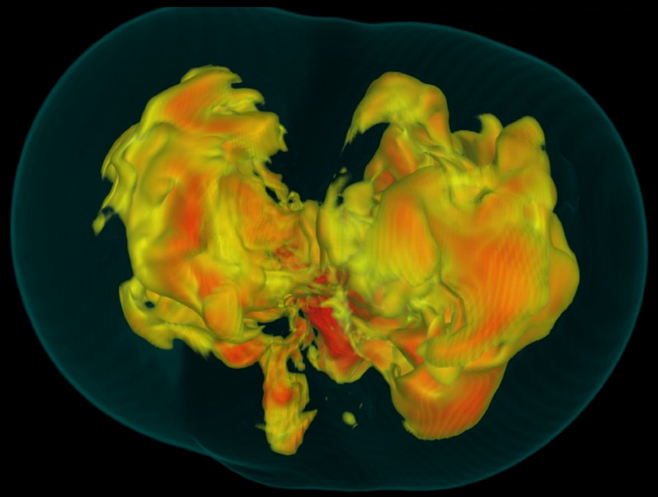


Burrows et al. (2019)



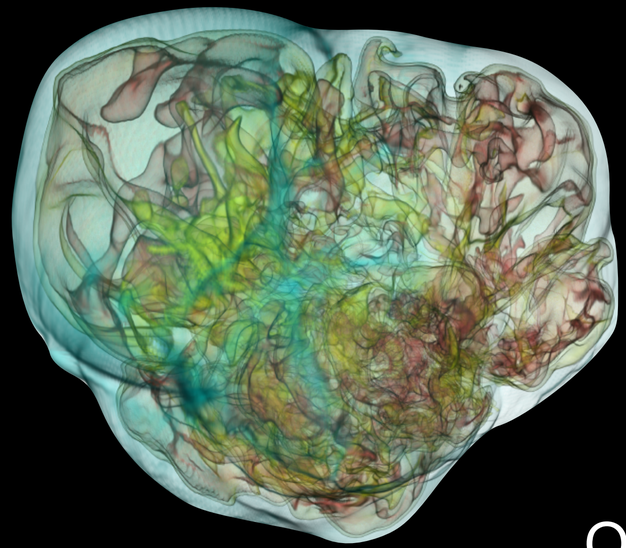
Roberts et al. (2016)

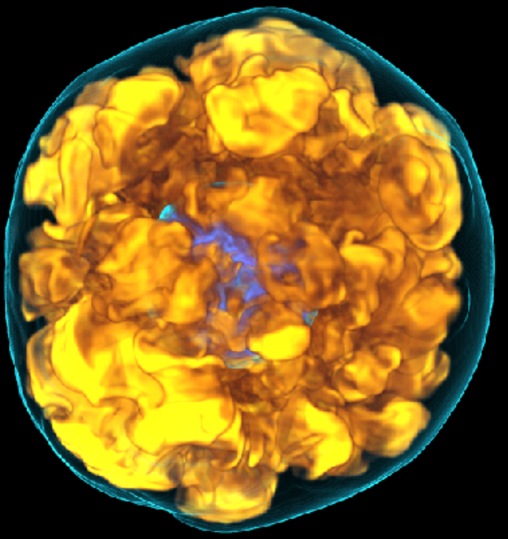




Janka et al. (2016)

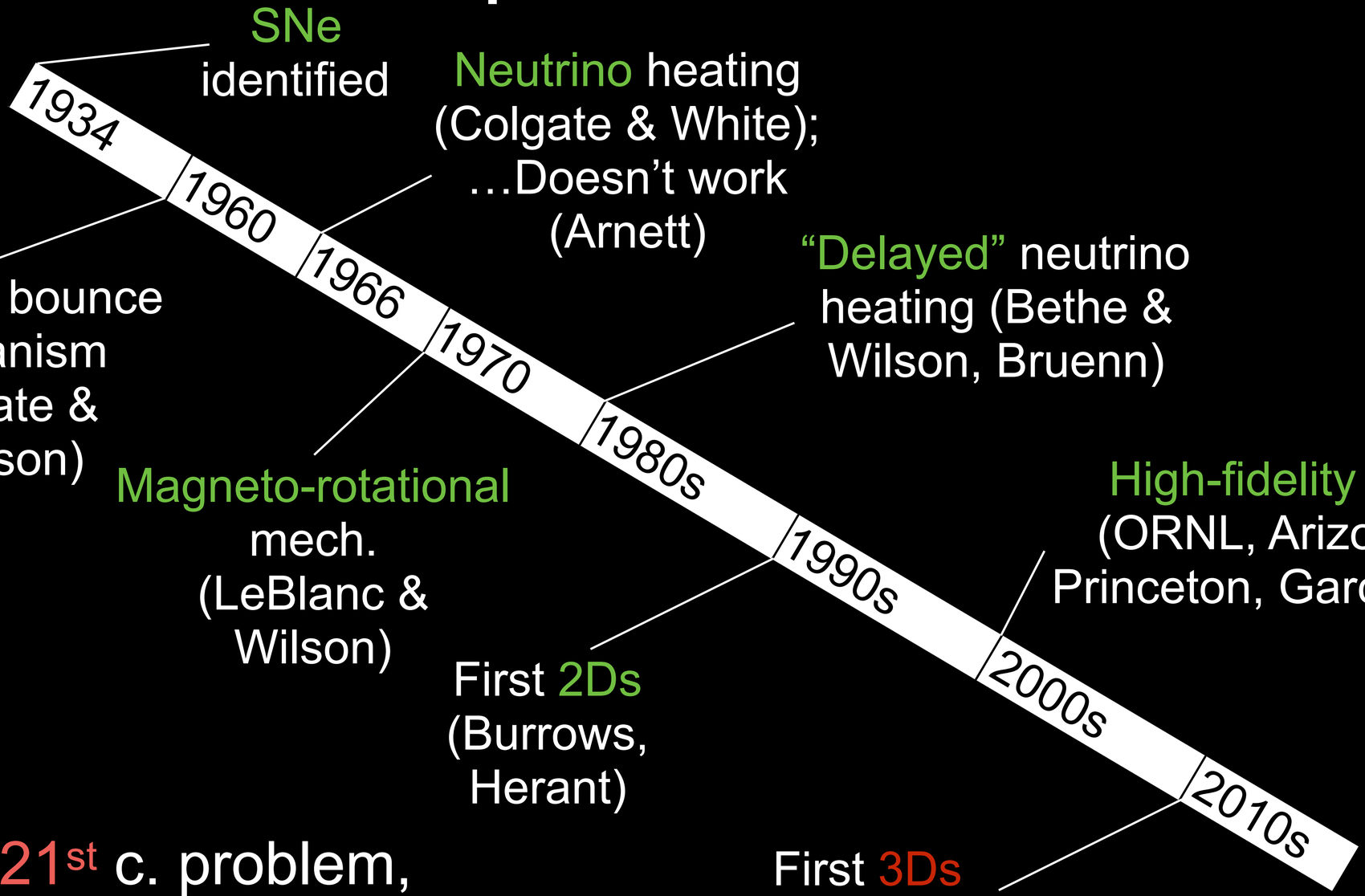
Lentz et al. (2016)





O'Connor & SMC (2018b)

Quest for Explosion Mechanism



A 21st c. problem, uncovered in the 20th c.

Multiphysics Challenges

Fully-coupled!

3D Magnetohydrodynamics

General Relativity

Boltzmann ν-transport

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

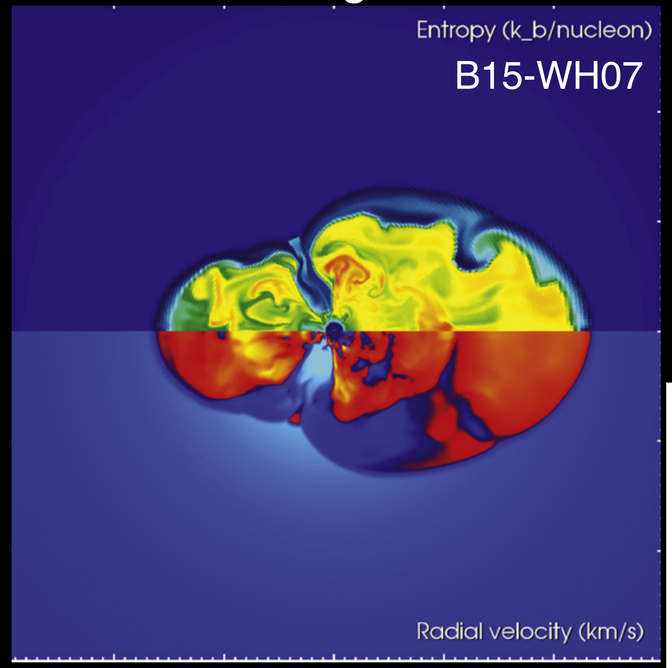
All four Forces:
Gravity
EM
Weak
Strong

Need 21st c. tools:

- Modern microphysics
- Cutting-edge numerical algorithms
- Petascale computers (exascale?)
- Sophisticated software infrastructure (and open-source!)

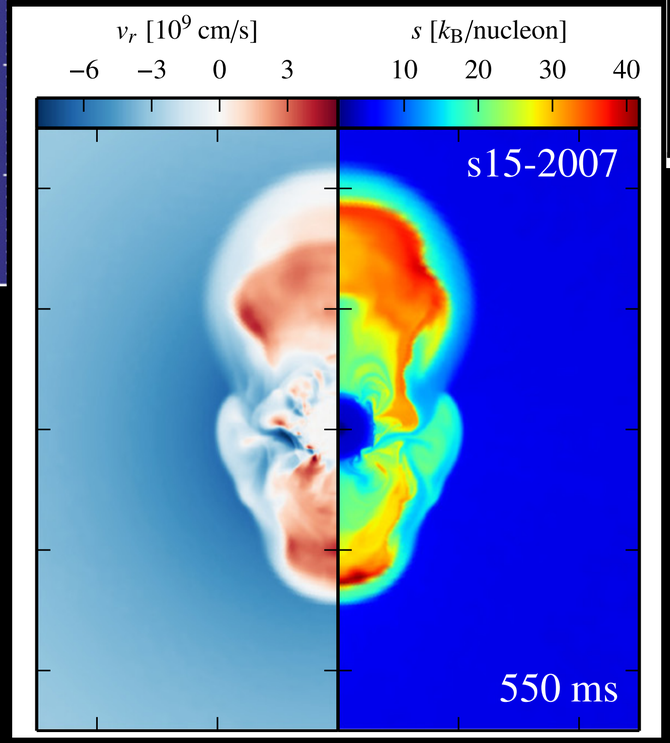
High-Fidelity Explosions in 2D

Oak Ridge-FAU



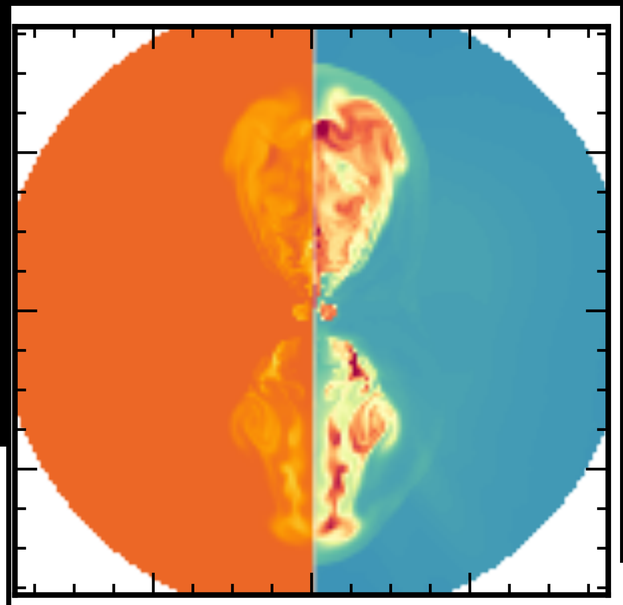
Bruenn et al. (2016)

Garching-Monash



Summa et al. (2016)

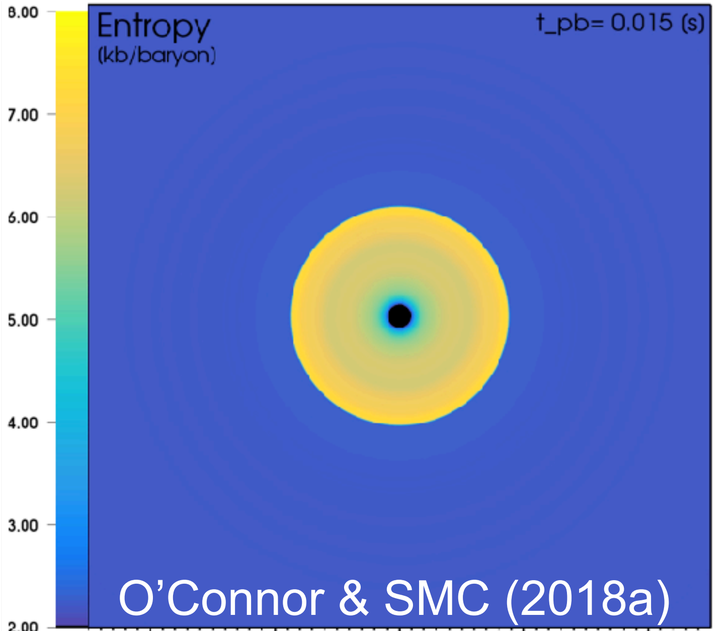
Princeton-LANL



Vartanyan et al. (2018)

Emerging agreement in *quantitative* results

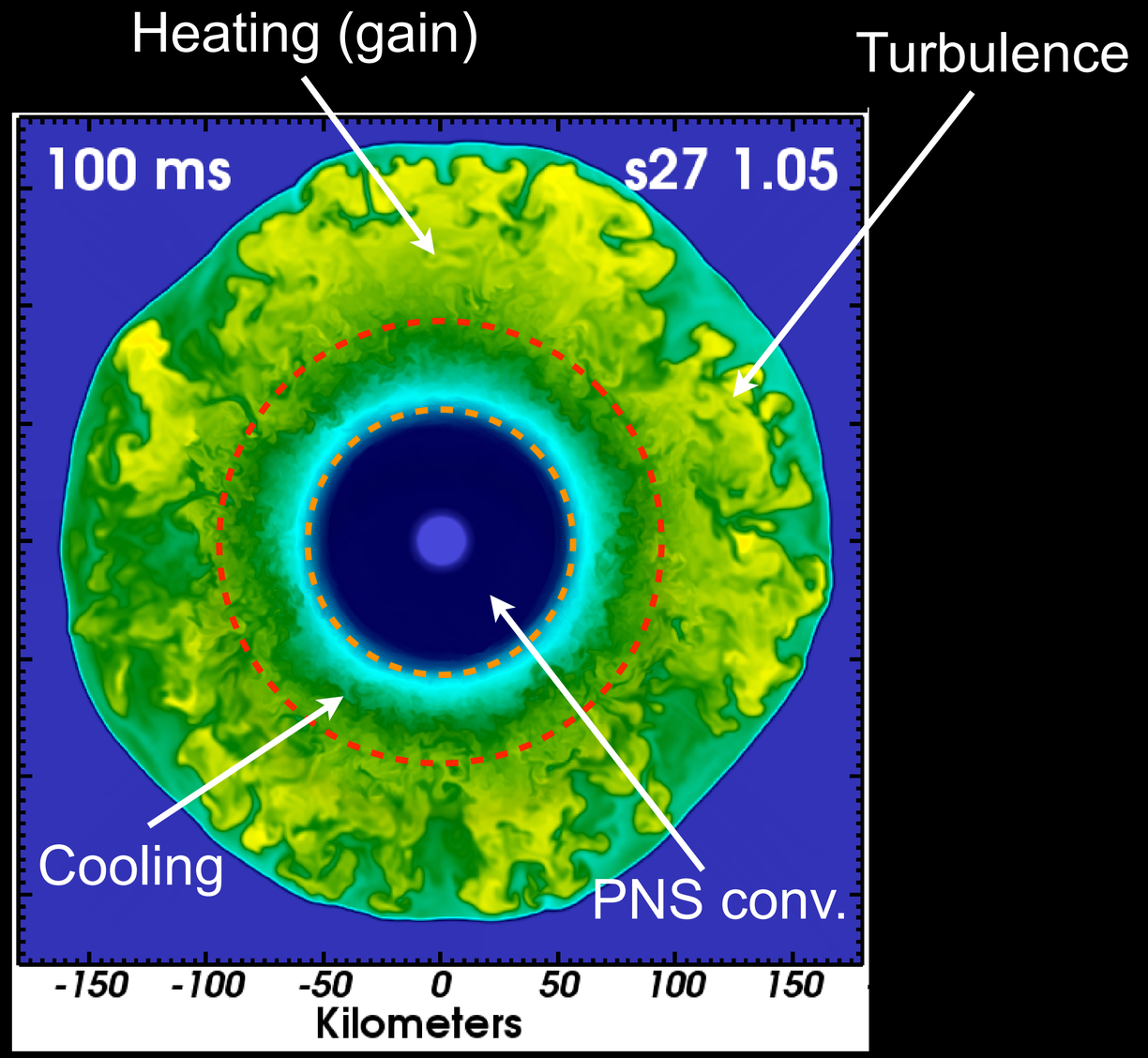
MSU-Stockholm



O'Connor & SMC (2018a)

Why Do 2D & 3D Explode?

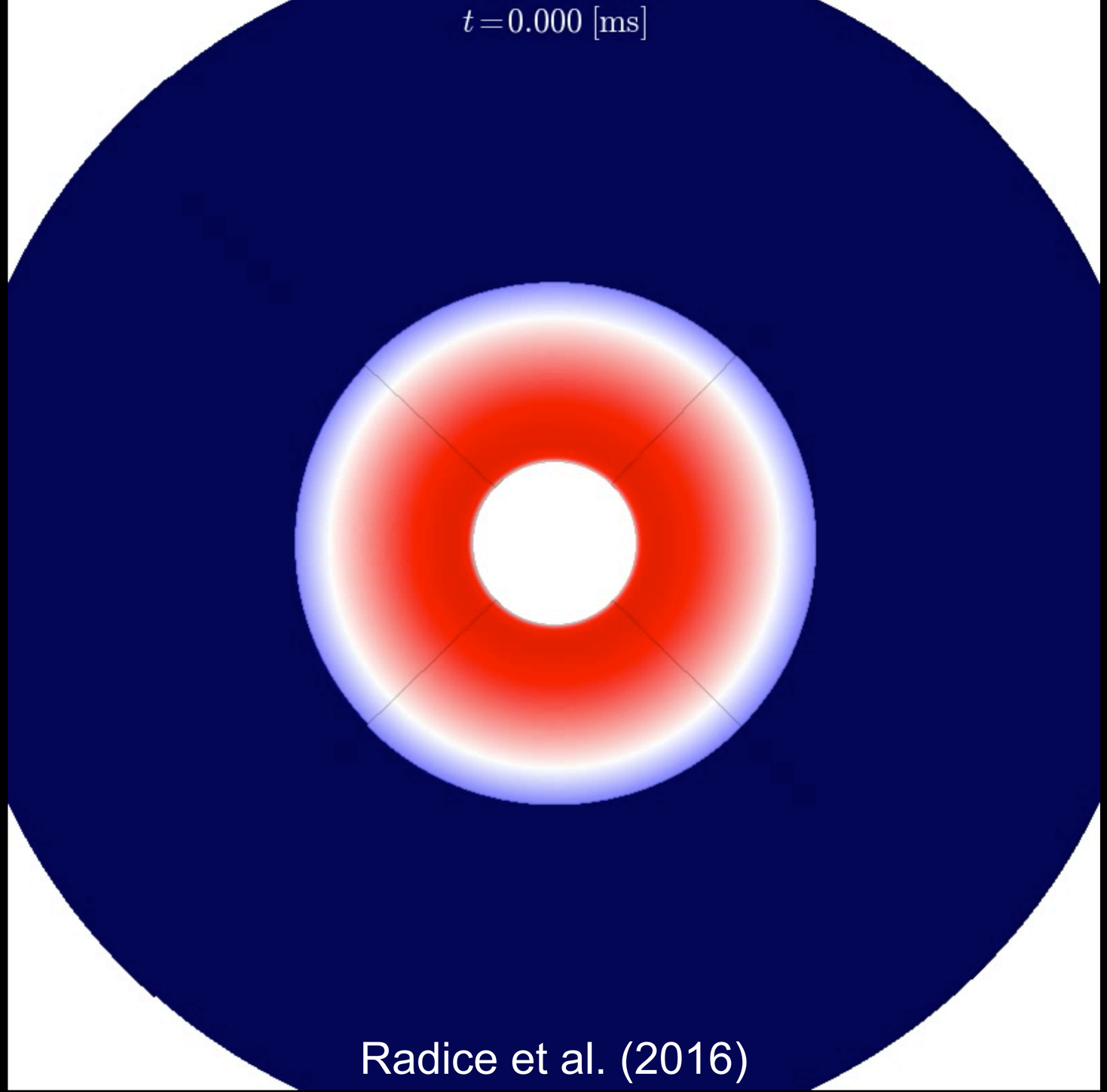
- Proto-neutron star convection => enhances neutrino luminosities
- Gain layer convection => increases matter dwell times
- Standing Accretion Shock Instability => expands gain region
- Strong turbulence => pushes shock out/heats gain region



Turbulence in CCSNe

Murphy et al. (2013);
SMC & C. Ott (2015)

- Neutrino heating => buoyant convection
- Convective plumes “stir” the post-shock region
- Turbulence exerts significant stress (i.e., pressure)
- Turbulent energy dissipates to thermal (Mabanta & Murphy 2018)

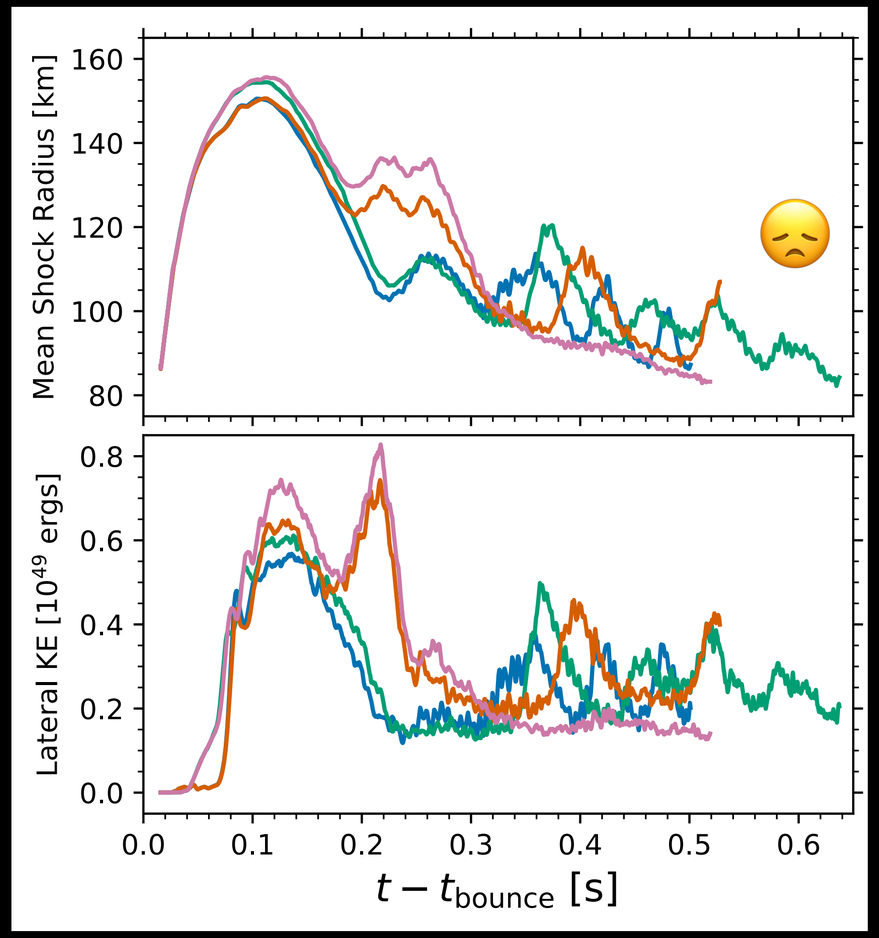


Radice et al. (2016)

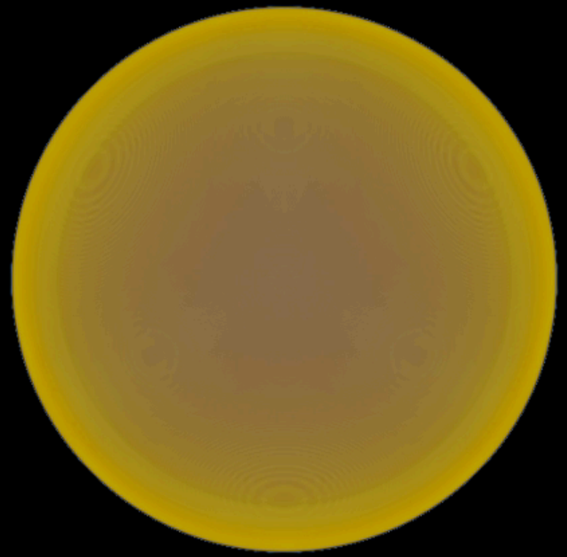
Does the neutrino mechanism work in 3D?

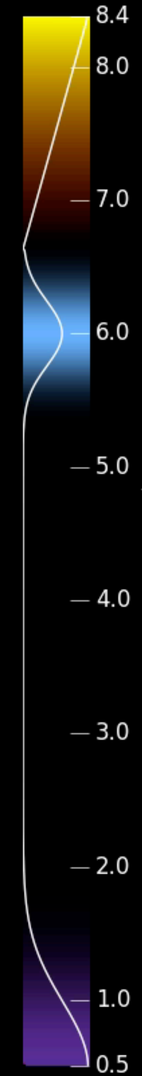
3D FLASH-M1 Sims

O’Connor & SMC (2018b)



Time = 16.8 (ms)

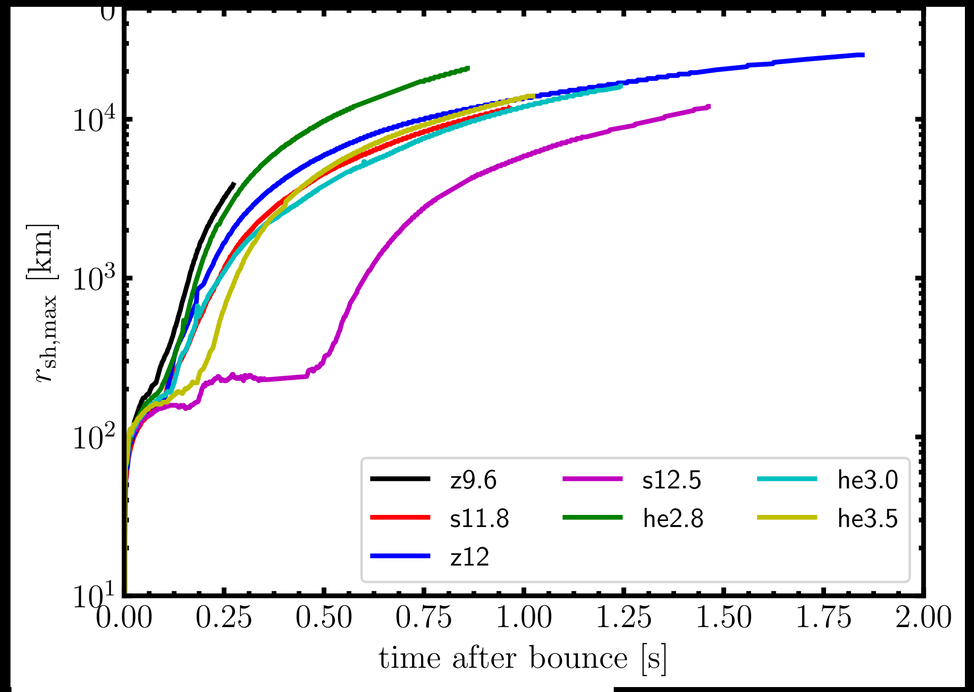


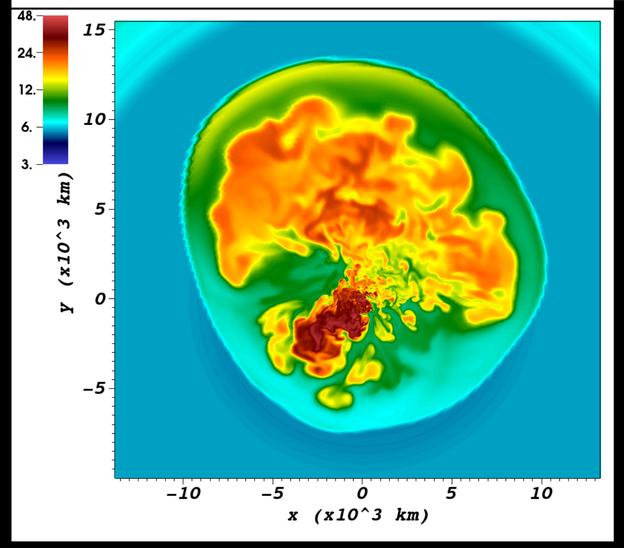


U.S. DEPARTMENT OF ENERGY
INCITE
LEADERSHIP COMPUTING

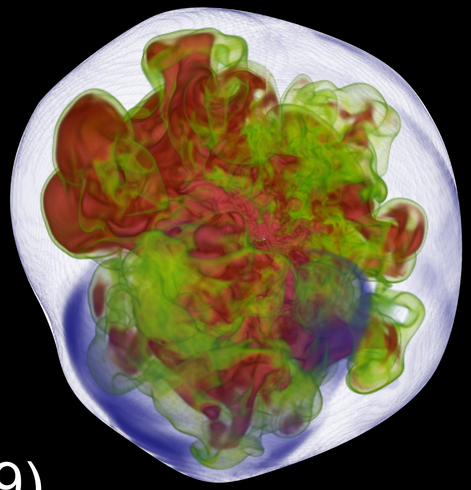
Choice of progenitor model!

“Low-mass” Stars Explode

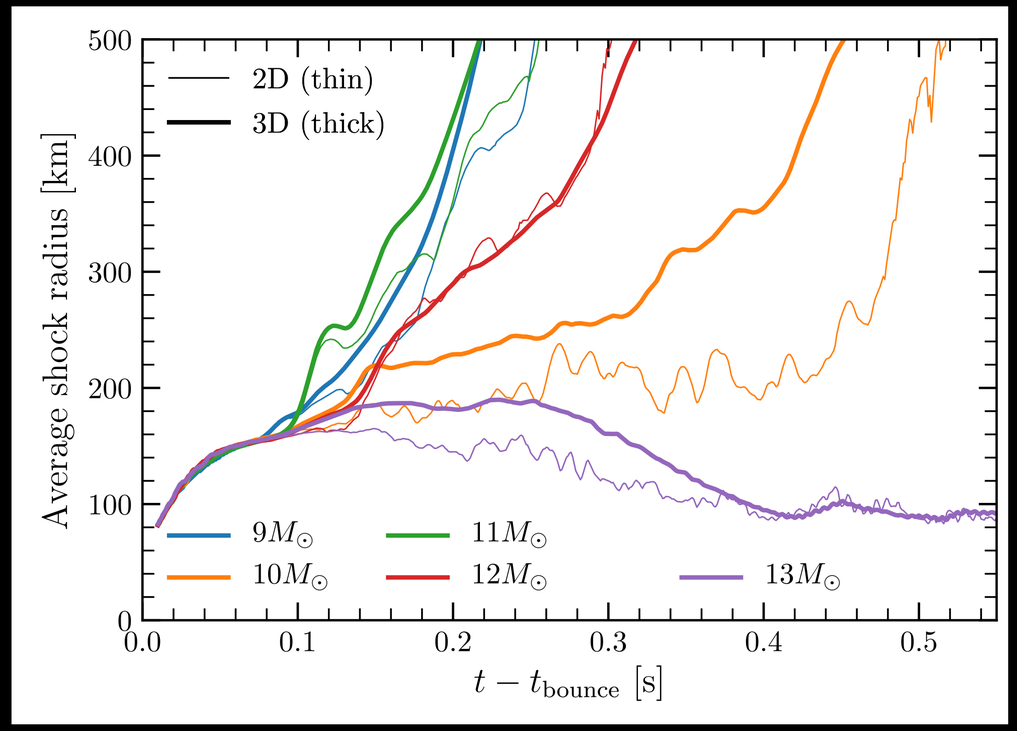




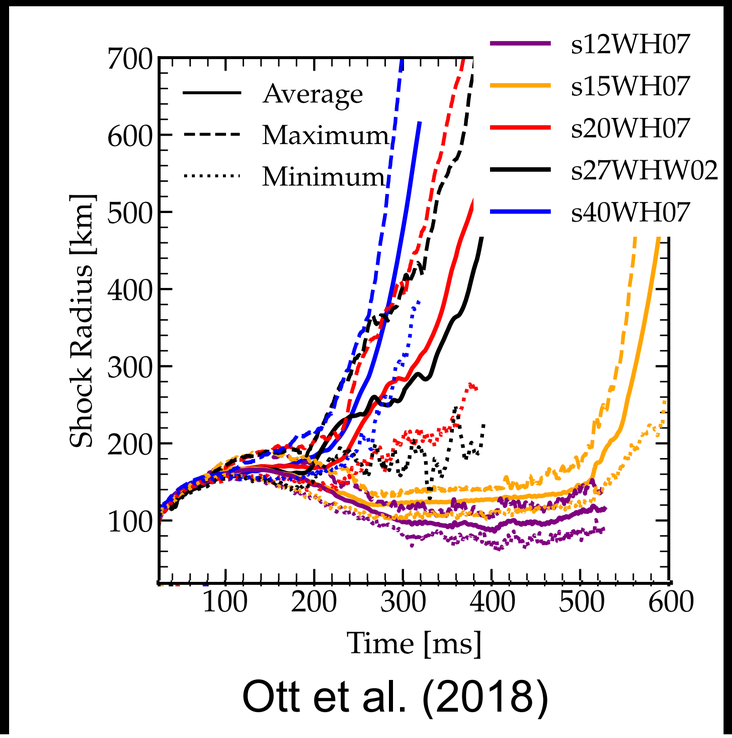
Mueller et al. (2019)



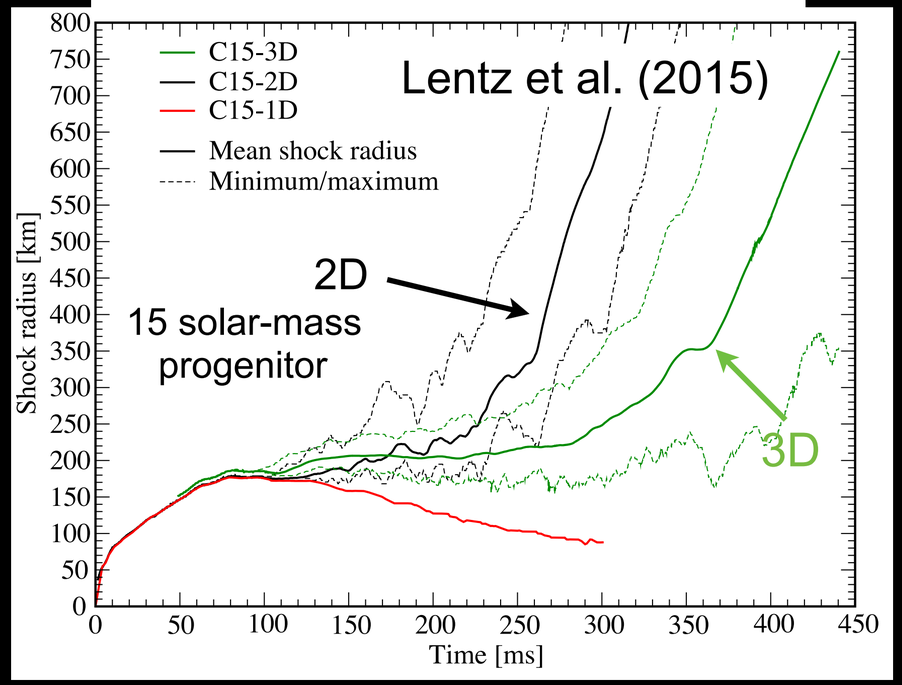
Burrows et al. (2019)



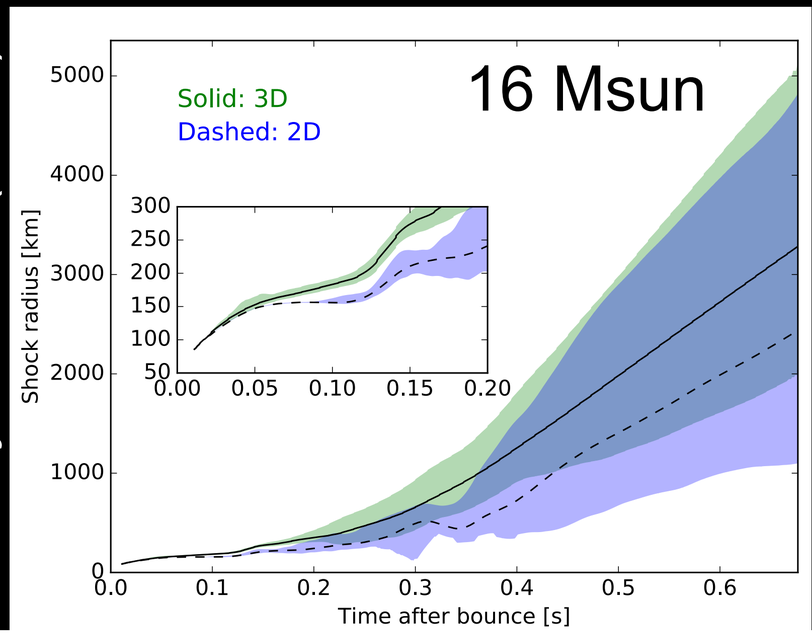
High-mass Explosions

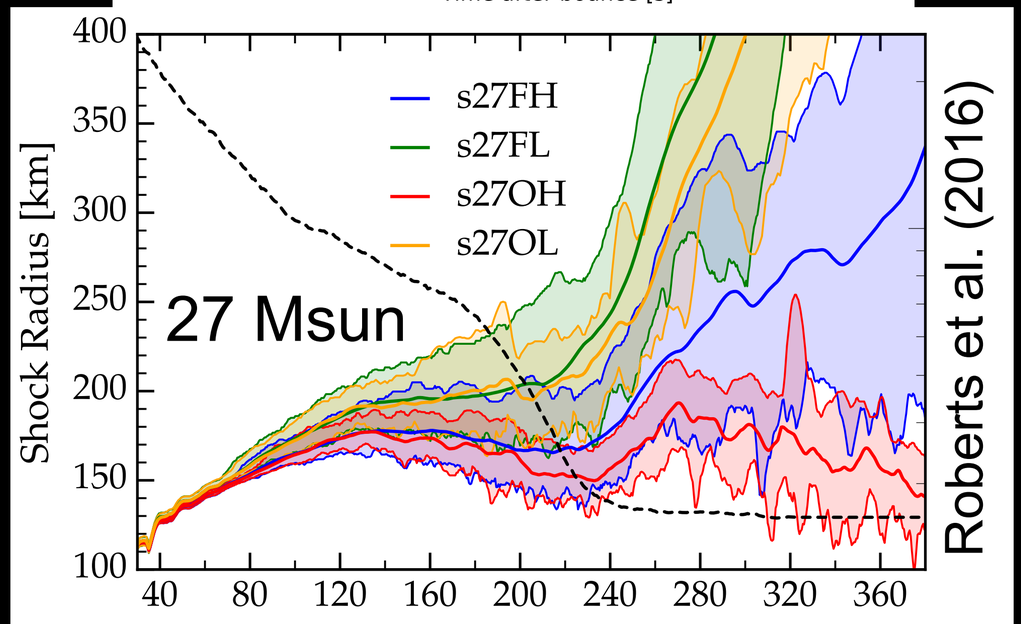


Ott et al. (2018)



Vartanyan et al. (2019)





Roberts et al. (2016)

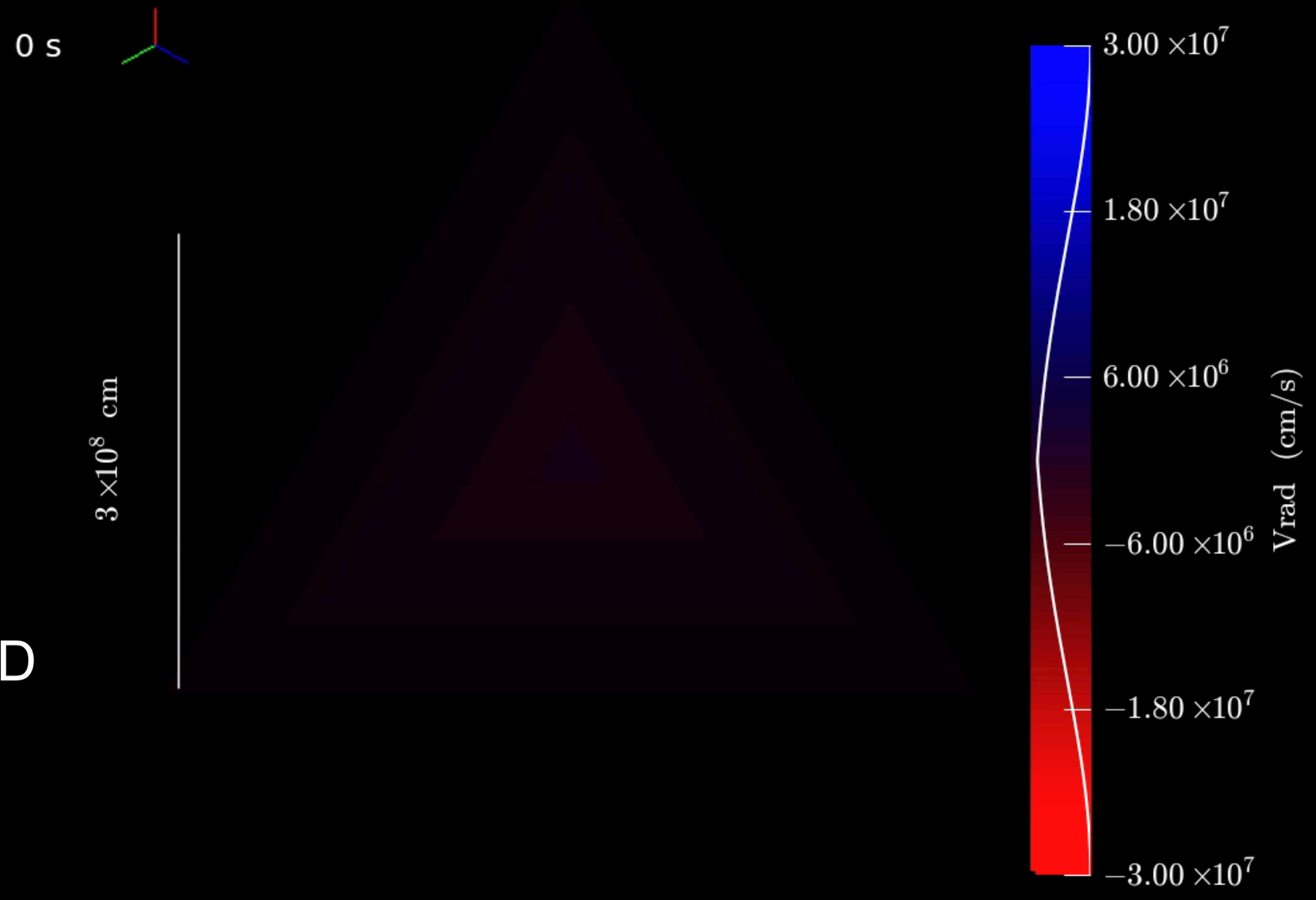
Does the neutrino mechanism work in 3D?

Yes!

Stars aren’t spherical…

3D CCSNe Progenitors

SMC, Chatzopoulos, Arnett, & Timmes (2015, ApJL, 808, L21)

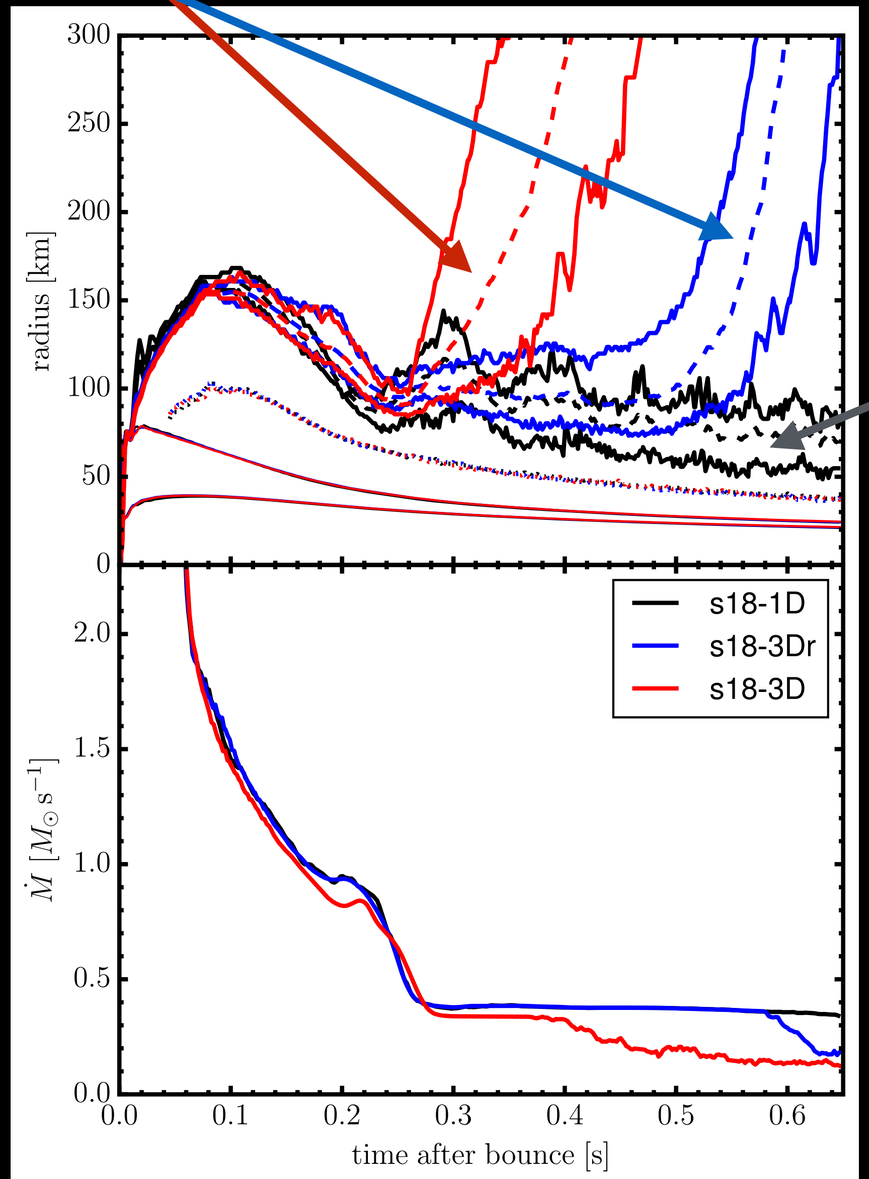


- Nuclear shell burning drives strong convection
- Included in 1D stellar evolution (via MLT)
- Previously neglected in 2D/3D CCSN sims…

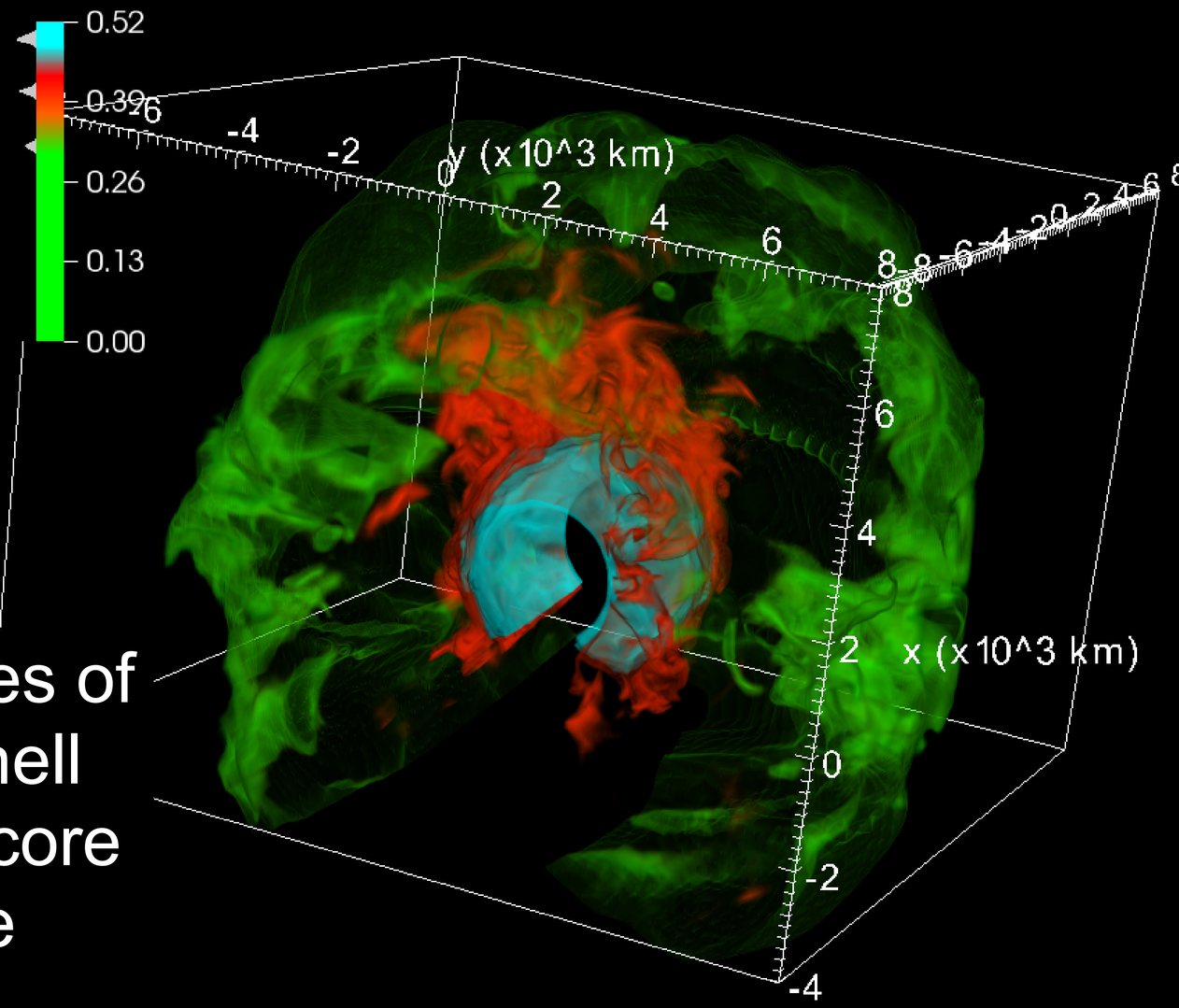
3D Progenitor Sims

B. Mueller, Viallet, Heger, & Janka (2016, arXiv:1605.01393)

3D progenitors



1D progenitors

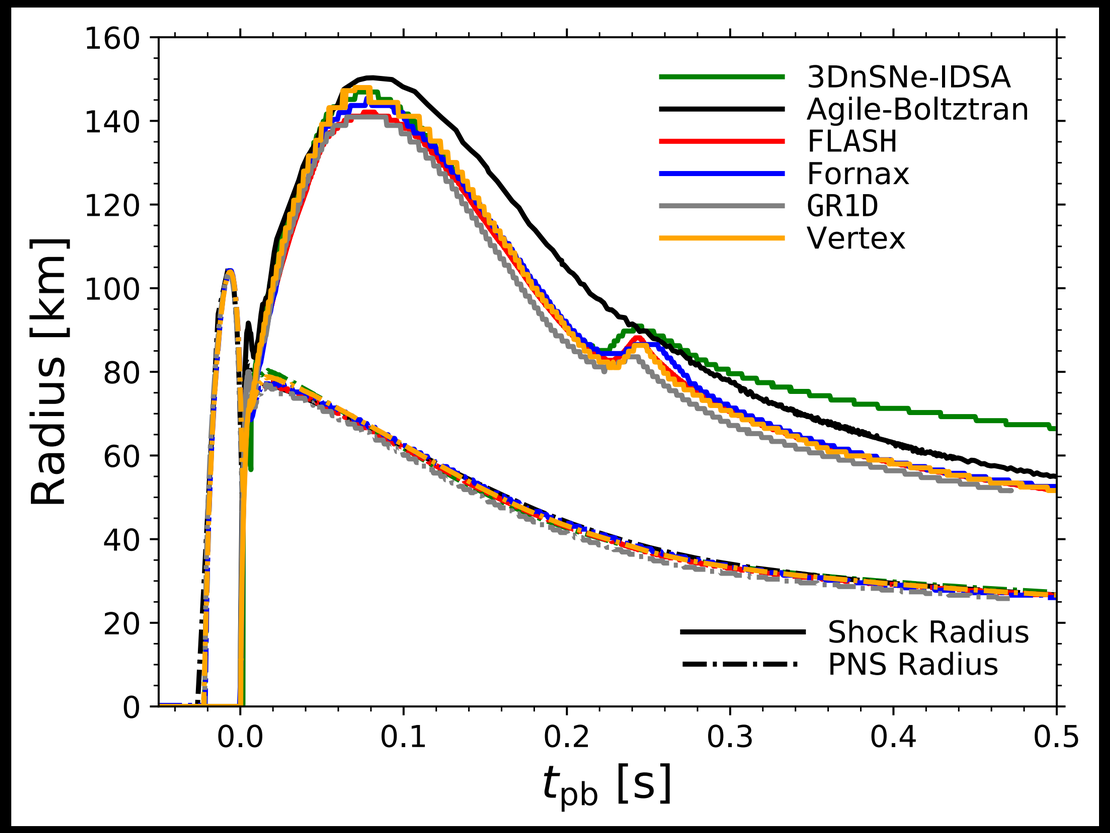


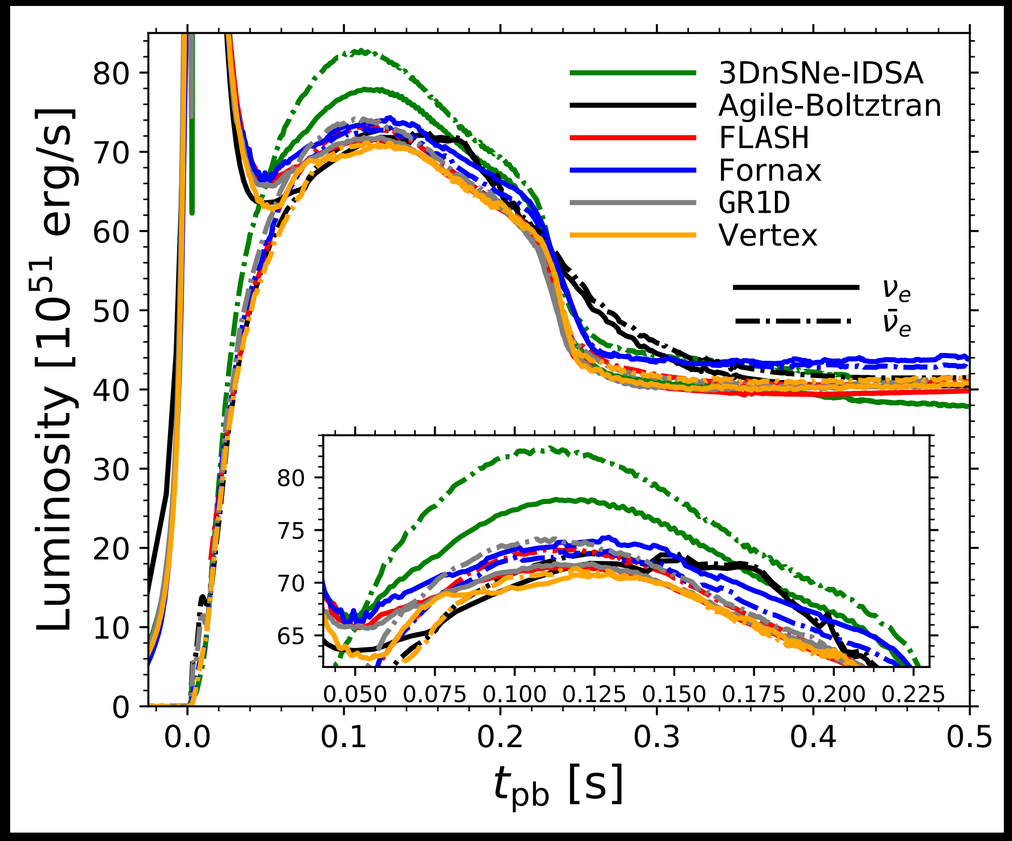
Final minutes of oxygen shell burning to core collapse

Outstanding Issue: Agreement in Results

Global 1D CCSN Comparison

E. O'Connor, Bollig, Burrows, SMC, Fischer, Janka, Kotake, Lentz, Liebendorfer, Messer, Mezzacappa, Takiwaki, Vartanyan (2018)





Toward **E**xascale **A**strophysics of **M**ergers and **S**upernovae **TEAMS**

- In-depth study of r-process sites
- “Clearing” house for data/results
- Code comparisons
- 3D CCSN progenitors (MSU/SBU)
- 3D MHD CCSNe (MSU postdoc C. Harris)

W. Raphael Hix, Oak Ridge National Laboratory
Ann Almgren, Lawrence Berkeley National Laboratory
Adam Burrows, Princeton University
Alan C. Calder, Stony Brook University
Sean M. Couch, Michigan State University
Anshu Dubey, Argonne National Laboratory
Christopher L. Fryer, Los Alamos National Laboratory
George M. Fuller, University of California, San Diego
Daniel Kasen, University of California, Berkeley
O. E. Bronson Messer, Oak Ridge National Laboratory
Anthony Mezzacappa, University of Tennessee
Sanjay Reddy, University of Washington
Luke F. Roberts, Michigan State University
Rebecca Surman, Notre Dame University
Andrew W. Steiner, University of Tennessee
Michael Zingale, Stony Brook University
John Bell, Lawrence Berkeley National Laboratory
Stephen W. Bruenn, Florida Atlantic University
Christian Cardall, Oak Ridge National Laboratory
Andrew Christlieb, Michigan State University
Joshua C. Dolence, Los Alamos National Laboratory
Eirik Endeve, Oak Ridge National Laboratory
Wesley P. Even, Los Alamos National Laboratory
Wick Haxton, University of California, Berkeley
Aimee L. Hungerford, Los Alamos National Laboratory
James Lattimer, Stony Brook University
Eric J. Lentz, University of Tennessee
Christopher M. Malone, Los Alamos National Laboratory
Eliot Quataert, University of California, Berkeley
David Radice, Princeton University
Ryan T. Wollaeger, Los Alamos National Laboratory
Stanford E. Woosley, University of California, Santa Cruz

SciDAC
Scientific Discovery through Advanced Computing

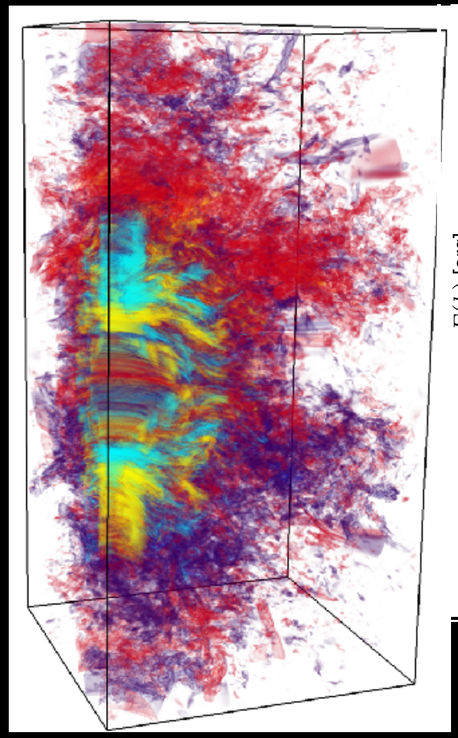
Outstanding Issue: Rotation and B-fields

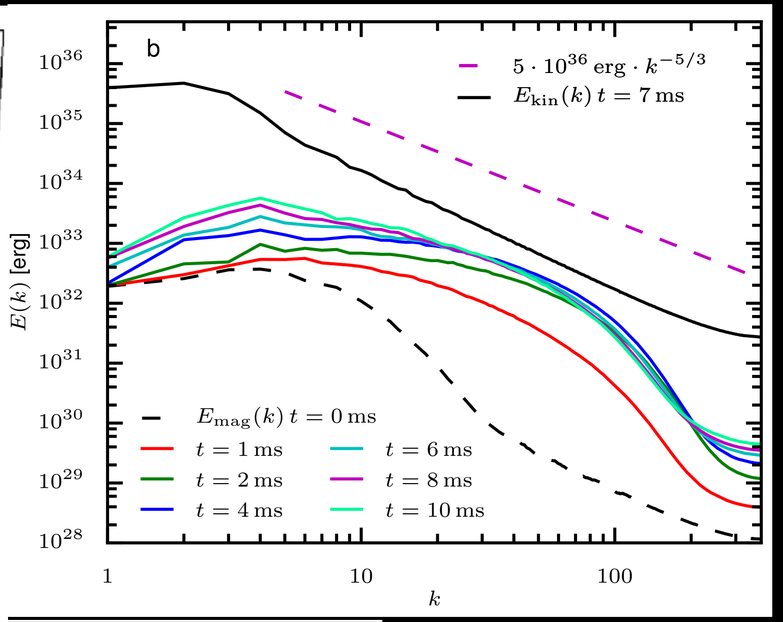
Magnetorotational Effects

"The last refuge of the astrophysical scoundrel."

IGRBs
~10^{-4} CCSN rate

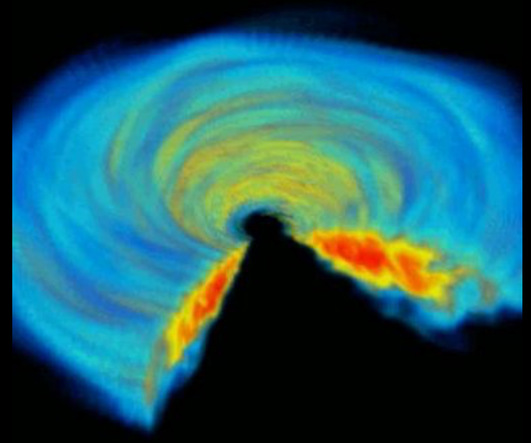
Moesta et al. 2015





inverse turbulent cascade

α-ω Dynamo



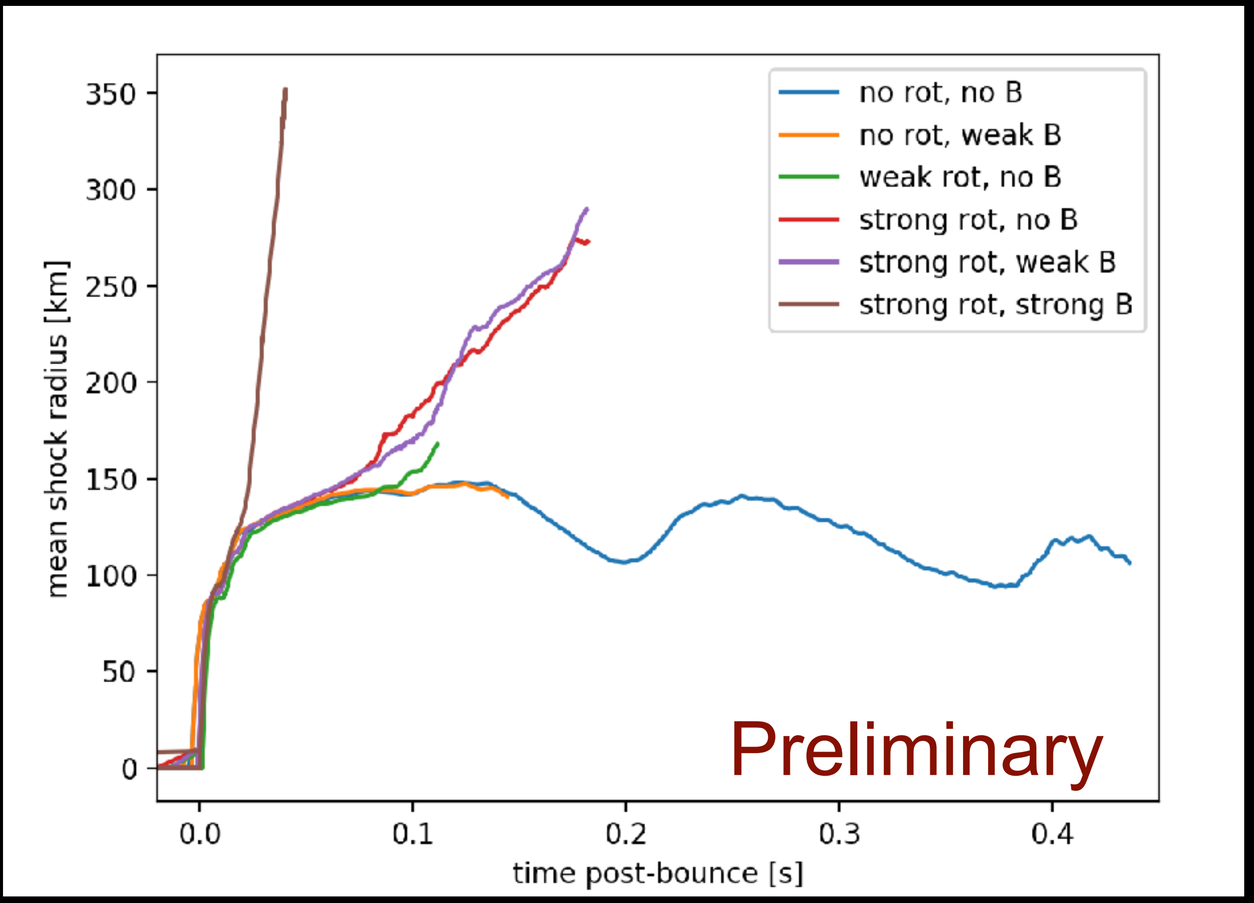
MRI

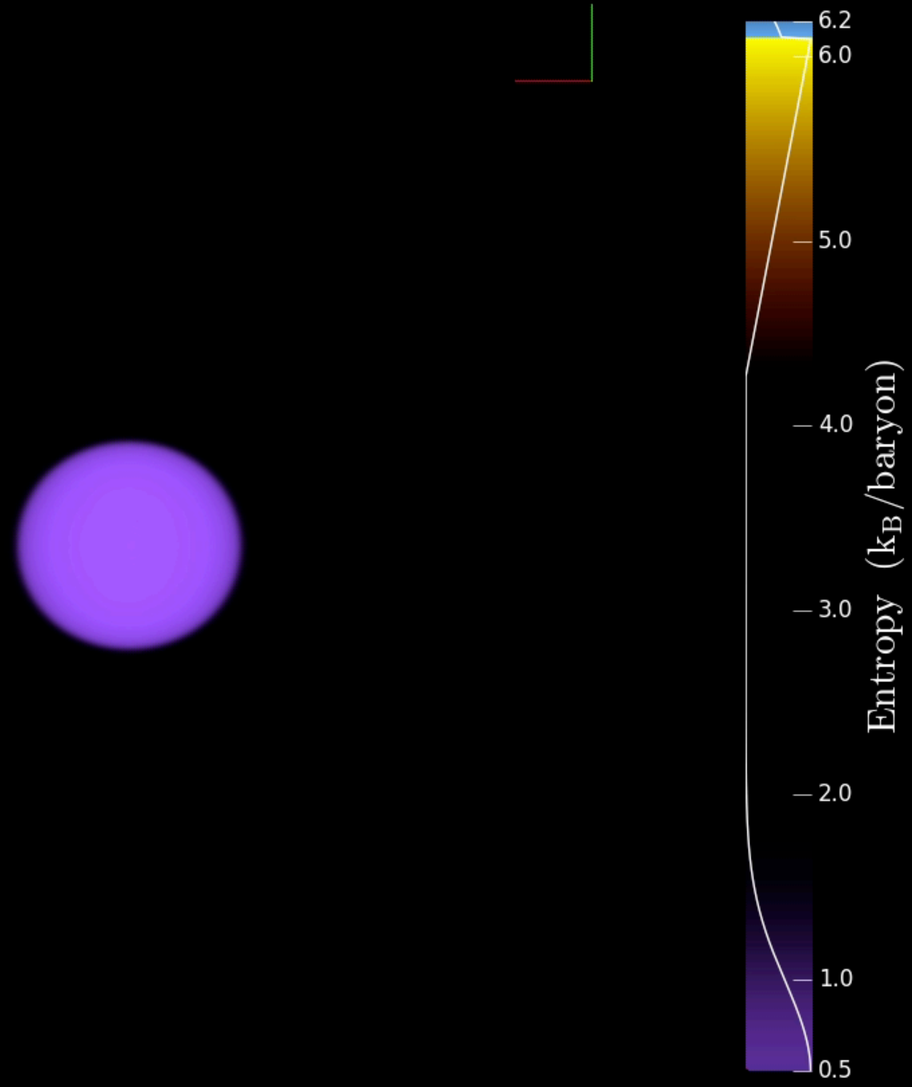
$\tau \sim \omega^{-1}$

$\lambda\!\!\!^{-} \sim \omega^{-1} \sim 10$ m

Magnetorotational Explosions

SMC et al., in prep.



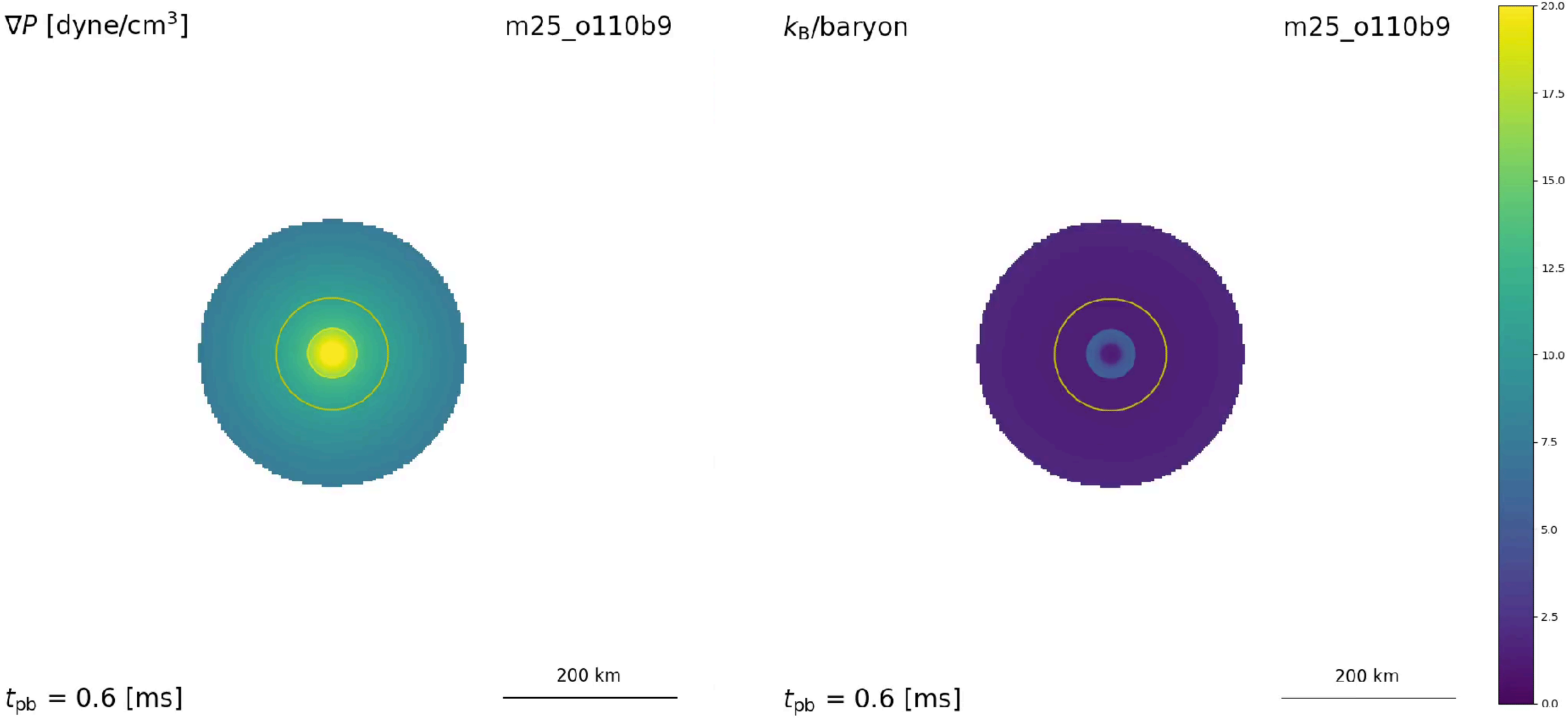


See also Summa et al. 2018

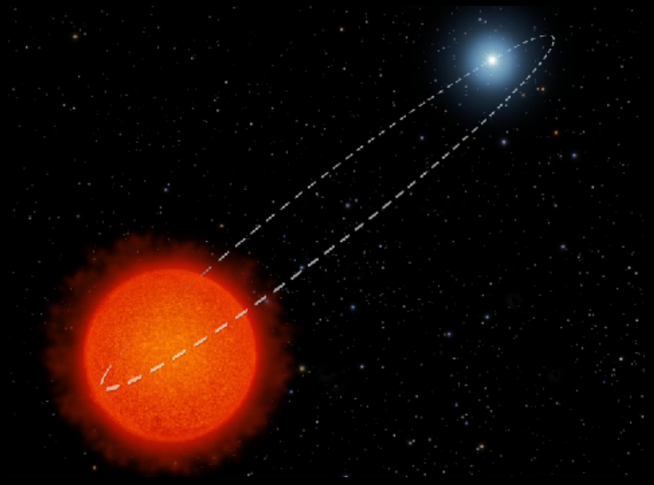
Compare to Moesta et al. (2014)

Magnetorotational Explosions

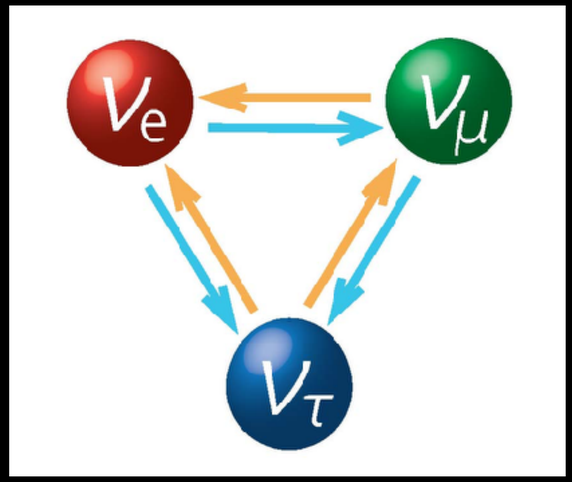
SMC et al., in prep.



Other outstanding issues



- Binarity
- Resolution in 3D
- Neutrino oscillations
- Complex neutrino interactions
- Uncertain nuclear equation of state
- Later time simulations
- unknown unknowns



Turbulent Frontiers

- The neutrino mechanism *works* - time to compare observation
- Turbulence aids neutrinos in explosions
- (3D) Progenitor structure crucial
- Emerging agreement in results (code comparisons!)
- Magnetorotational effects may matter!
- Time to make rigorous comparison to observations