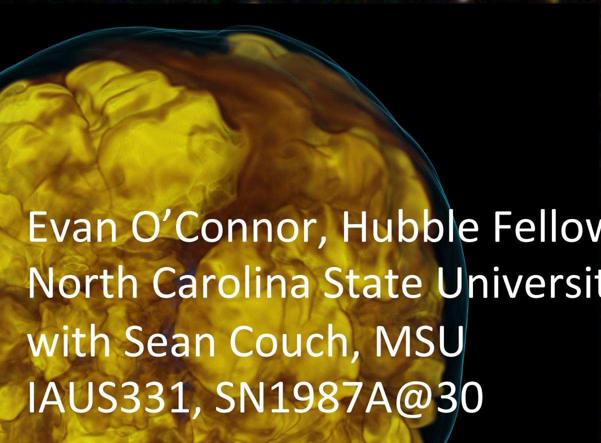
Multidimensional neutrino-transport simulations of the core-collapse supernova central engine



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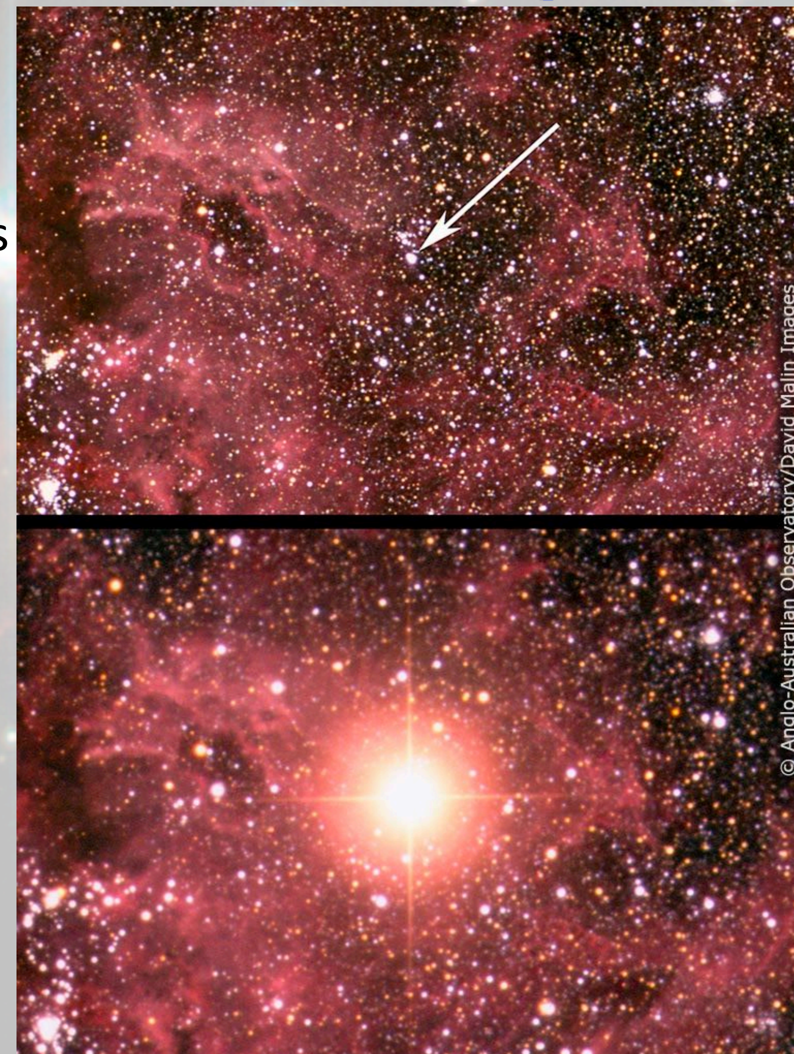
Outline

- Core-Collapse Supernovae Theory
- Simulation Code
- Results: 2D Simulations looking at:
  - Progenitors variations
  - Neutrino opacity improvements
- Results: 3D Simulations looking at:
  - Influence of perturbations
  - Influence of symmetries

Core-Collapse Supernovae

- CCSNe are one of the brightest astrophysical phenomena in the modern universe and mark the end of a massive star's life
- CCSNe are an important site for nucleosynthesis and the mechanism for unbinding elemental products of stellar evolution and spreading them throughout the galaxy. They help trigger local star formation, and are the source of both neutron stars and black holes.
- The central engine provides an unique and fantastic laboratory for studying extreme densities and temperatures, and neutron rich conditions where all four forces play a role. Requires us being able to observe the central engine: Neutrinos and GWs!

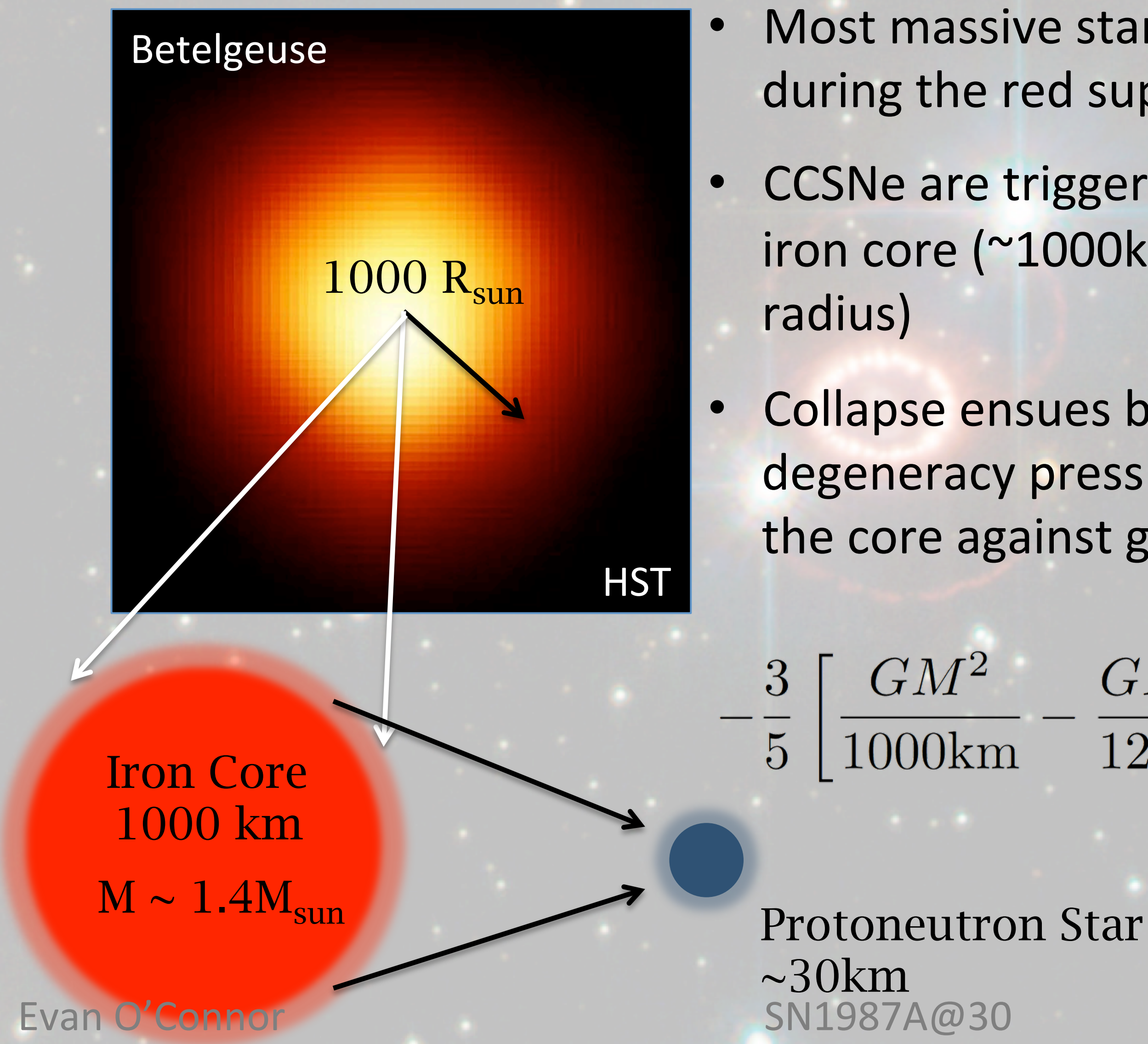


AAO

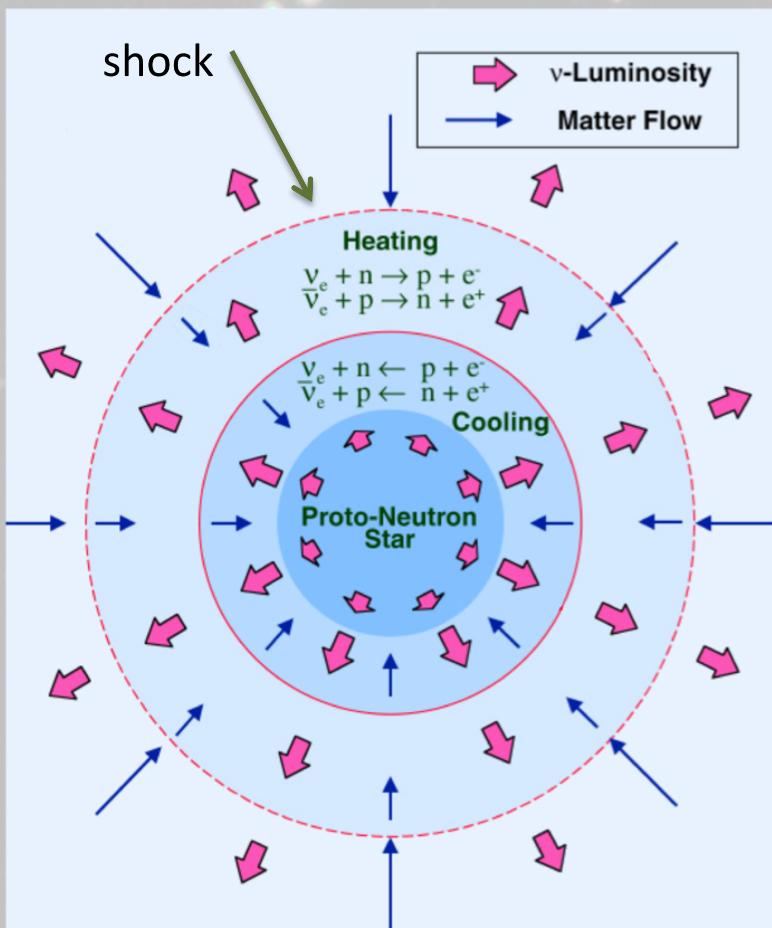
Core-Collapse

- Most massive stars undergo core collapse during the red supergiant phase
- CCSNe are triggered by the collapse of the iron core (~1000km, or $1/10^6$ of of the star's radius)
- Collapse ensues because electron degeneracy pressure can no longer support the core against gravity.

$$-\frac{3}{5}\left[\frac{GM^2}{1000\mathrm{km}} - \frac{GM^2}{12\mathrm{km}}\right] \sim 300 \times 10^{51}\mathrm{ergs}$$



Core-Collapse Explosions



Adapted from H-T. Janka

- Matter will continue to accrete onto the protoneutron star at rates ~1 M_{sun} / s; $P_{in} < P_{ram}$ and the shock stalls.
- In order for a successful supernova to occur, the shock must reenergized and sent through the outer layers of the star.
- Neutrino mechanism relies on a small fraction (~10%) of emitted neutrinos capturing on free neutron and protons at lower densities, giving net *heating*.

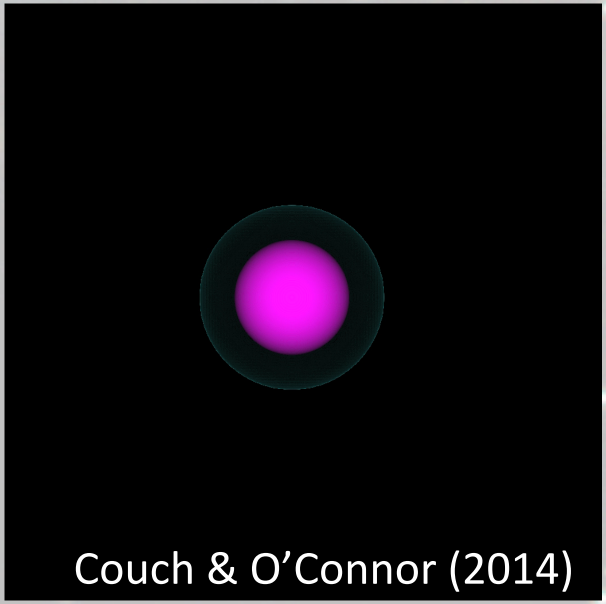
FLASH

FLASH is a multiphysics simulation framework

1. Unsplit hydrodynamics, adaptive mesh refinement, Cartesian grid
2. Multidimensional M1 ν-transport scheme (Shibata et al. 2011; O'Connor 2015)
3. Open-source nuclear equation of state and neutrino interactions
4. Effective General Relativistic Gravity (Marek et al. 2006; Case A)

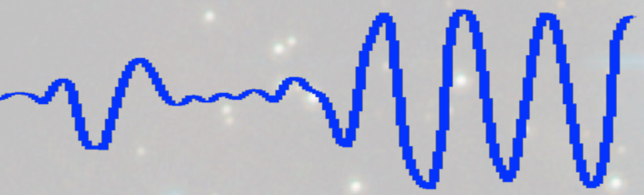
M1 gif

O'Connor & Couch (2015)


Couch & O'Connor (2014)

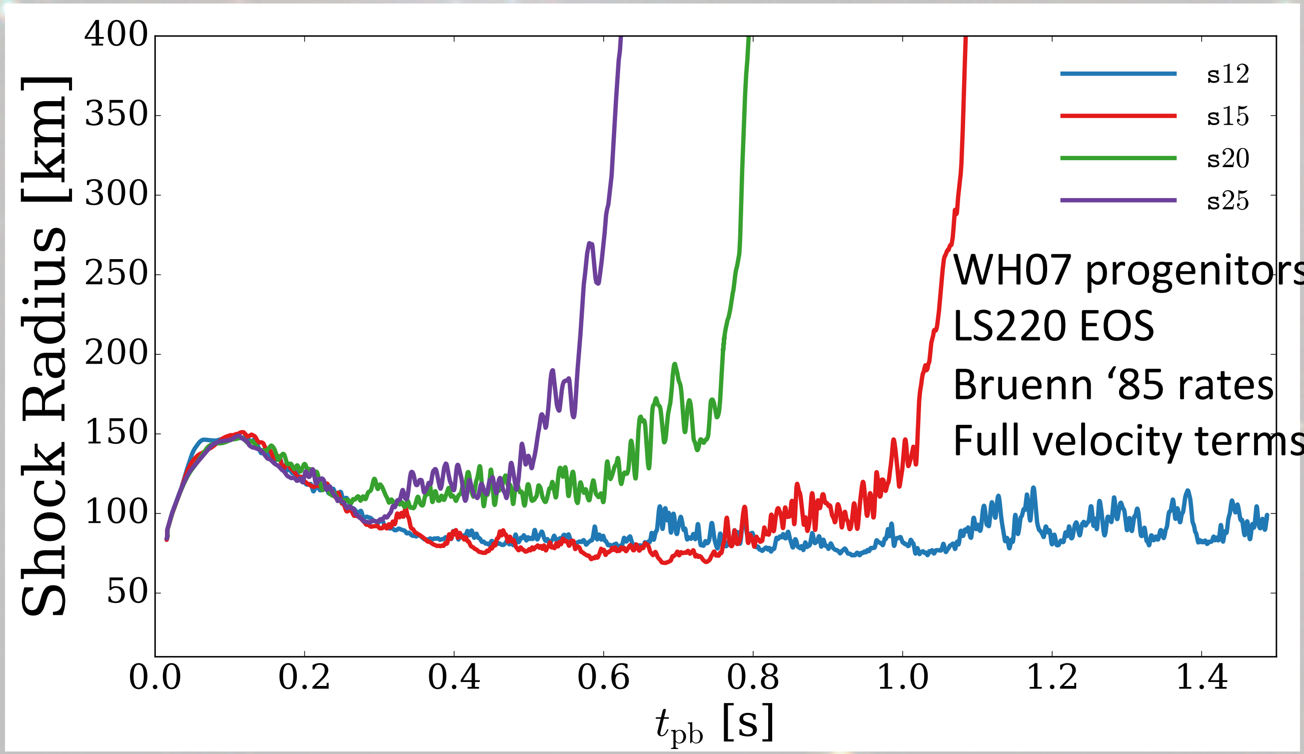
ν-leakage

2D Simulations



- Simulate four progenitors in 2D: $12M_{sun}$, $15M_{sun}$, $20M_{sun}$, and $25M_{sun}$
- Attempt to match other studies:
  Bruenn et al. (2016); Summa et al. (2016); Burrows et al. (2016)
- Find explosions in 3 of 4 models, qualitative agreement, but systematically later than all others

The main difference between this work and most others are the neutrino interaction rates



2D Simulations

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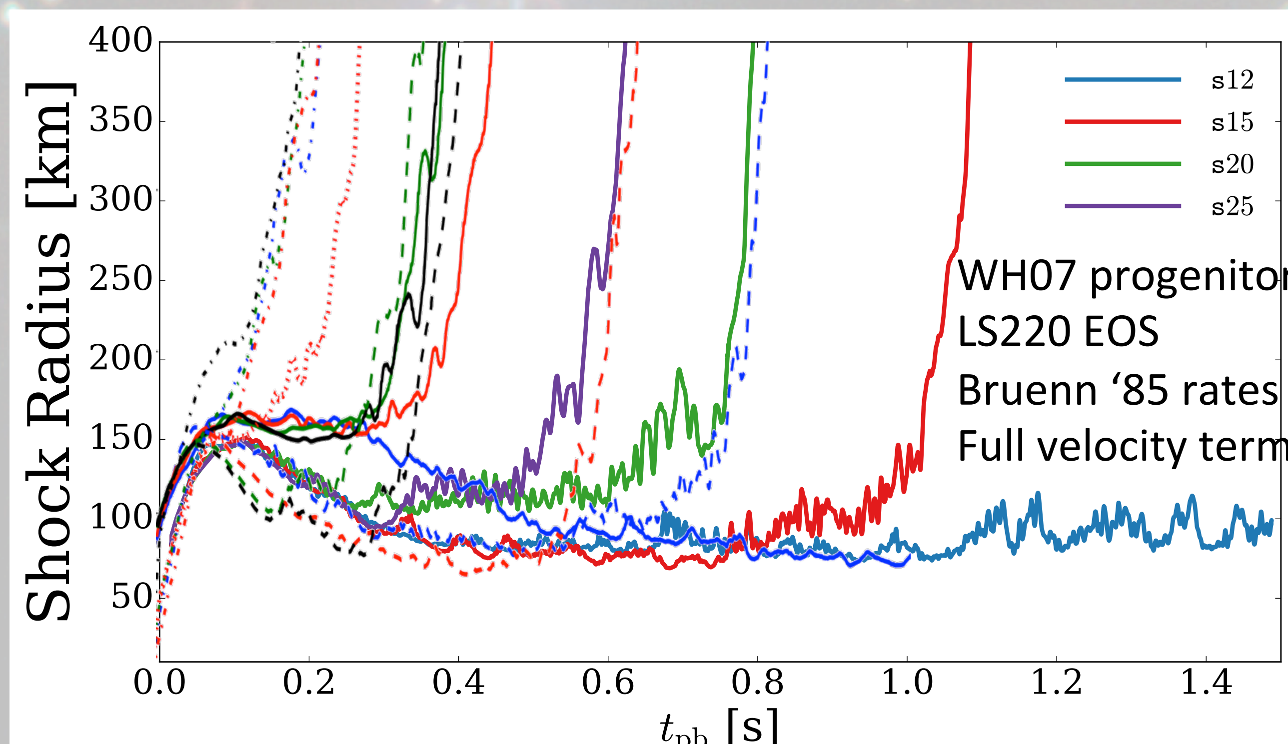
overlay: Burrows et al. (2016)
Summa et al. (2016)
Bruenn et al. (2016)



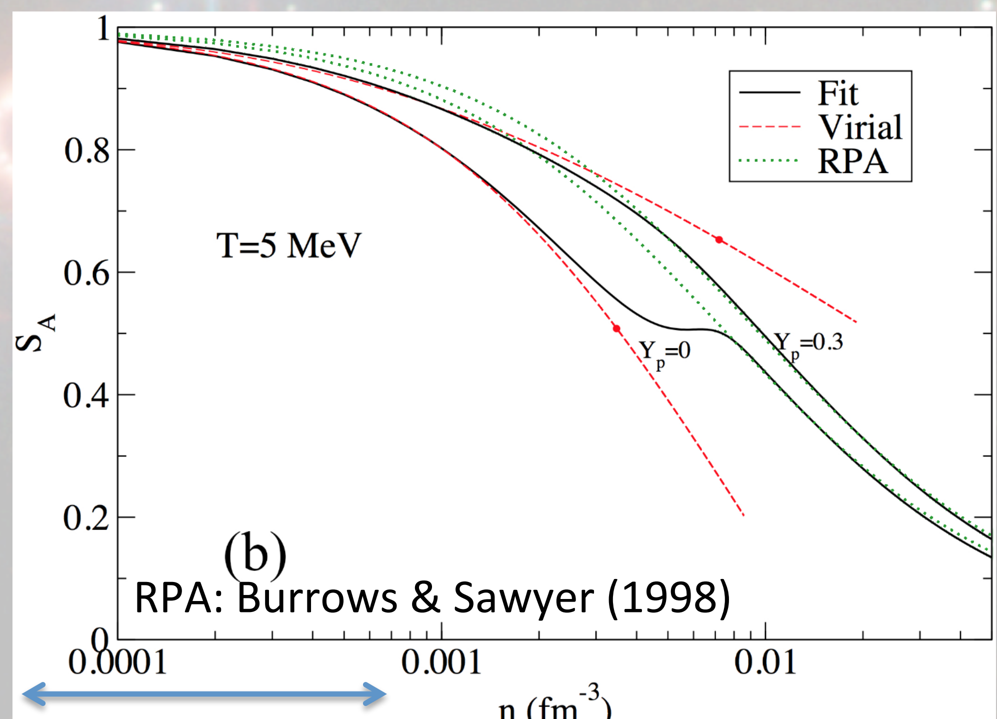
2D Simulations

- In Horowitz et al. (2017) we explored corrections to the standard neutral current neutrino scattering (NC) cross section.
- Using the Virial EOS, we derive *model independent* expressions for the low density vector and axial responses (S_V and S_A)
- Combine with RPA at high densities where Virial EOS fails

$$\frac{1}{V}\frac{d\sigma}{d\Omega} = \frac{G_F^2 E_\nu^2}{16\pi^2}\Big(g_a^2(3-\cos\theta)(n_n+n_p)S_A + (1+\cos\theta)n_n S_V\Big).$$

$$S_A \approx 1 + \lambda^3 \frac{(n_n^2+n_p^2)b_a - 2n_n n_p b_{pn}^a}{n_p+n_n}.$$

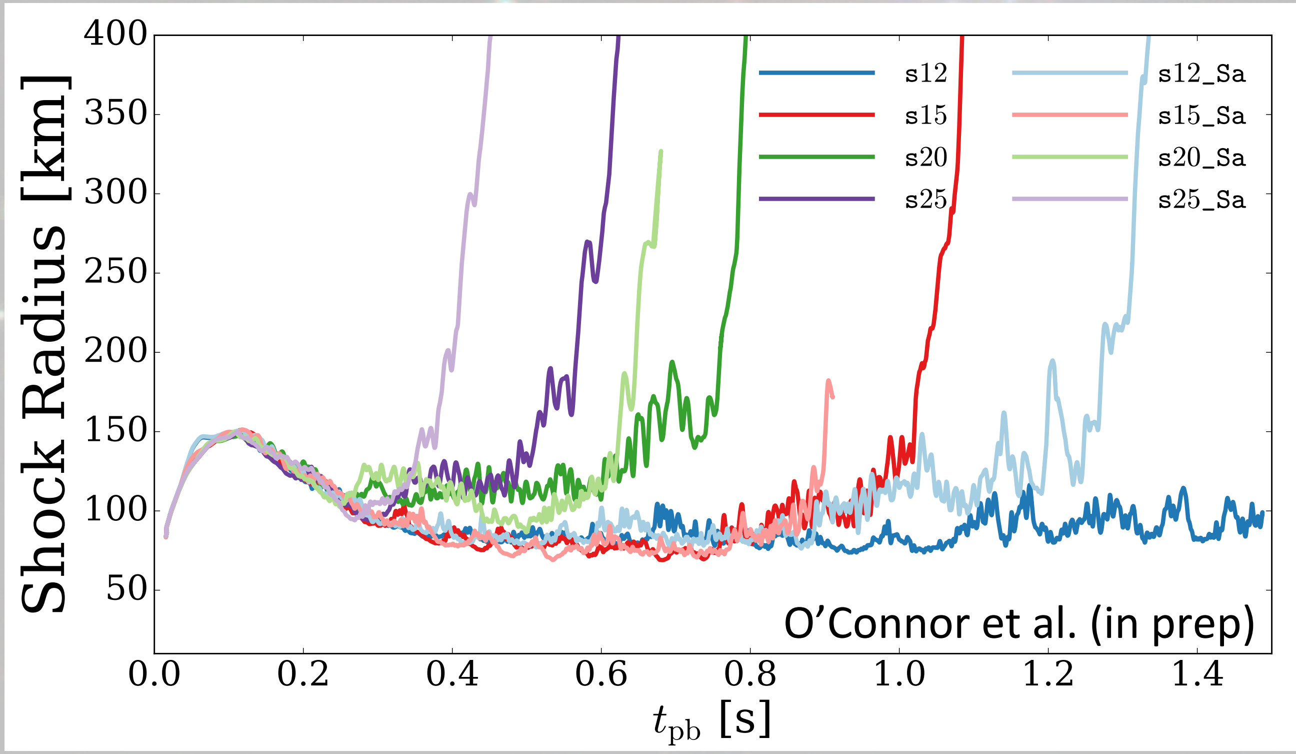
At neutrinosphere densities (10^{11} -> 10^{12} g cm^{-3}), the Virial EOS predicts reductions in NC cross section upwards of ~10-20% over the free rates, and ~50-100% more reduction than current RPA rates



10^{11} g cm^{-3} 10^{12} g cm^{-3}

2D Simulations

- Including many-body corrections (both Virial and RPA) to the NC scattering rates enhances cooling via ν_x and ultimately drives more neutrino heating and earlier explosions in the four cases studied.
- Still to determine overall roll of Virial vs. RPA and role of stochasticity.



Essentially same effect as seen in Melson et al. 2015

3D Simulations

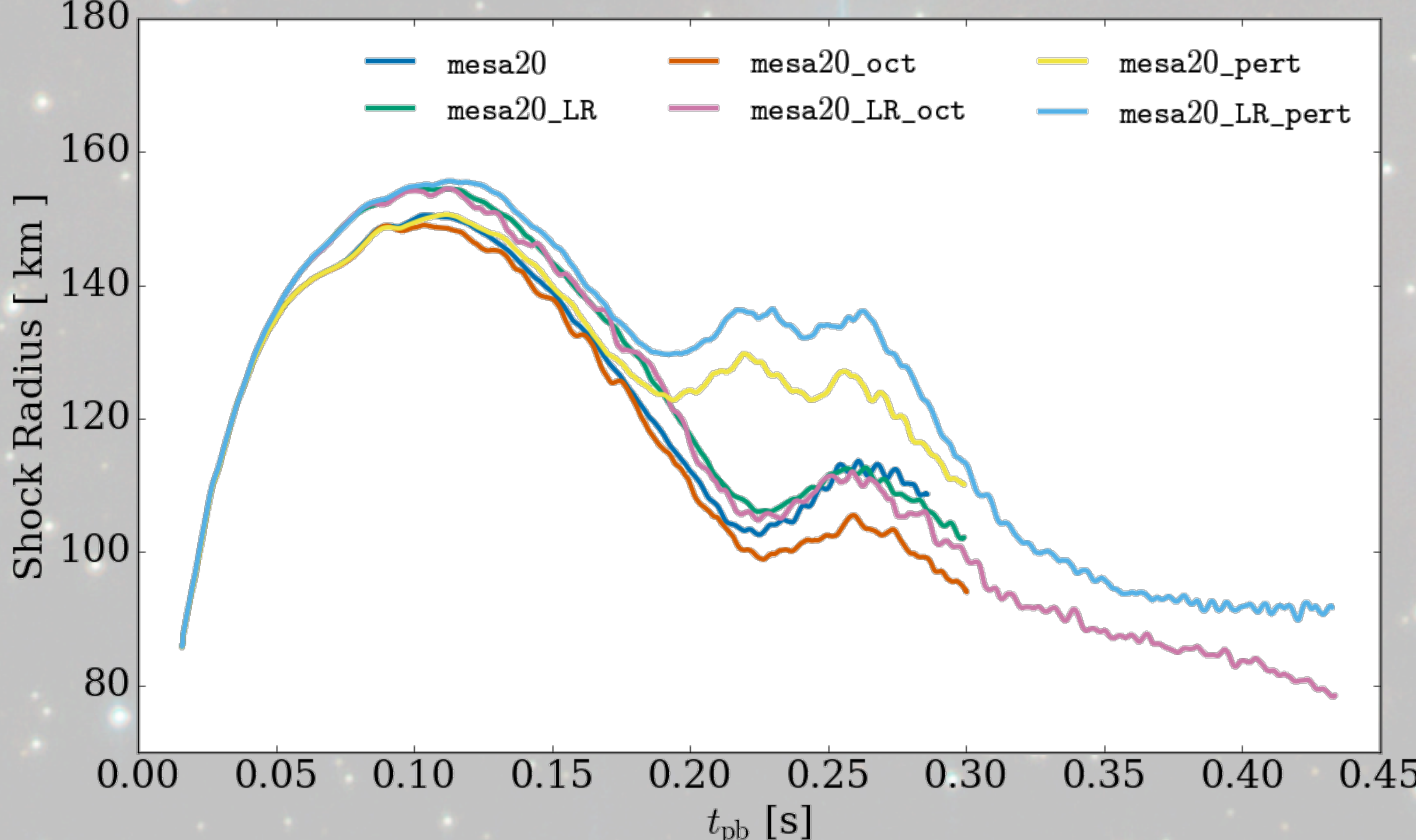
20 M_{sun} progenitor model from MESA (Paxton et al.)
GR effective gravity, 2-moment neutrino transport, SFHo EOS
8 simulations using MIRA, ANL supercomputer

- `LR`: ~1 degree resolution (compared to 0.5 degree)
- `pert`: convective-like motions in both Si and O shells
- `oct`: restricting simulation with octant symmetry
- `v`: including full velocity dependence, including advection

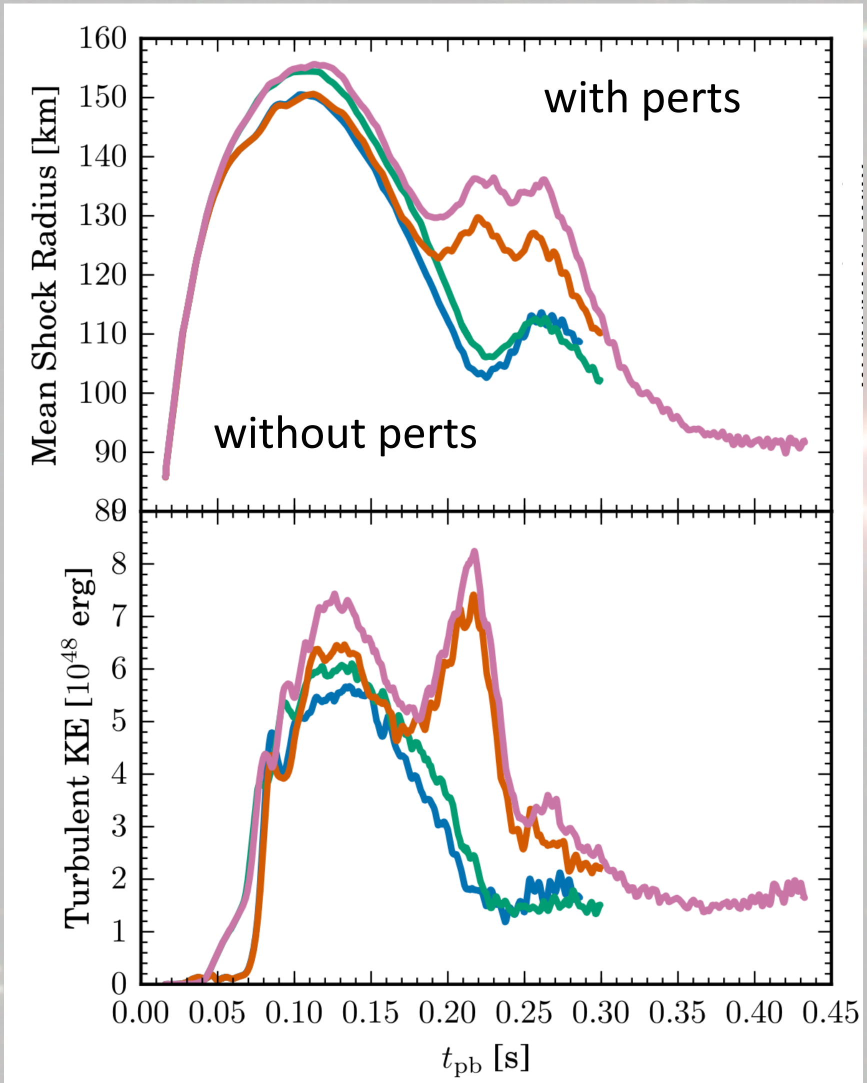
mesa20	**mesa20_pert**	**mesa20_oct**	**mesa20_v_LR**
mesa20_LR	**mesa20_pert_LR**	**mesa20_oct_LR**	**mesa20_v_LR_oct**

Total MIRA time, 105 MSU

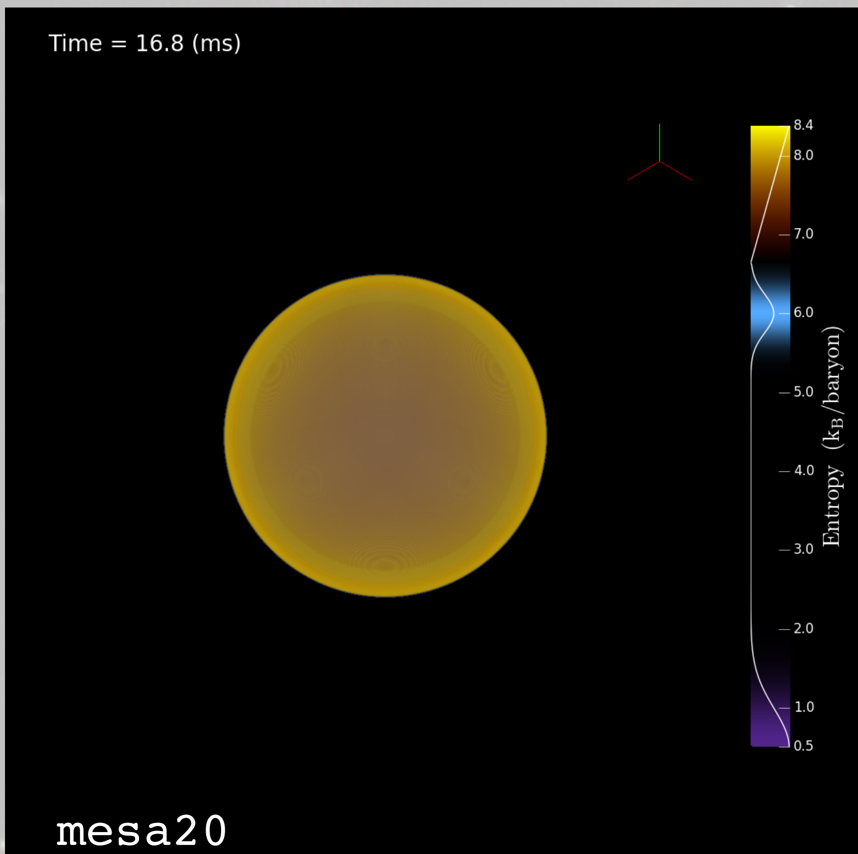
Results: No explosions :(

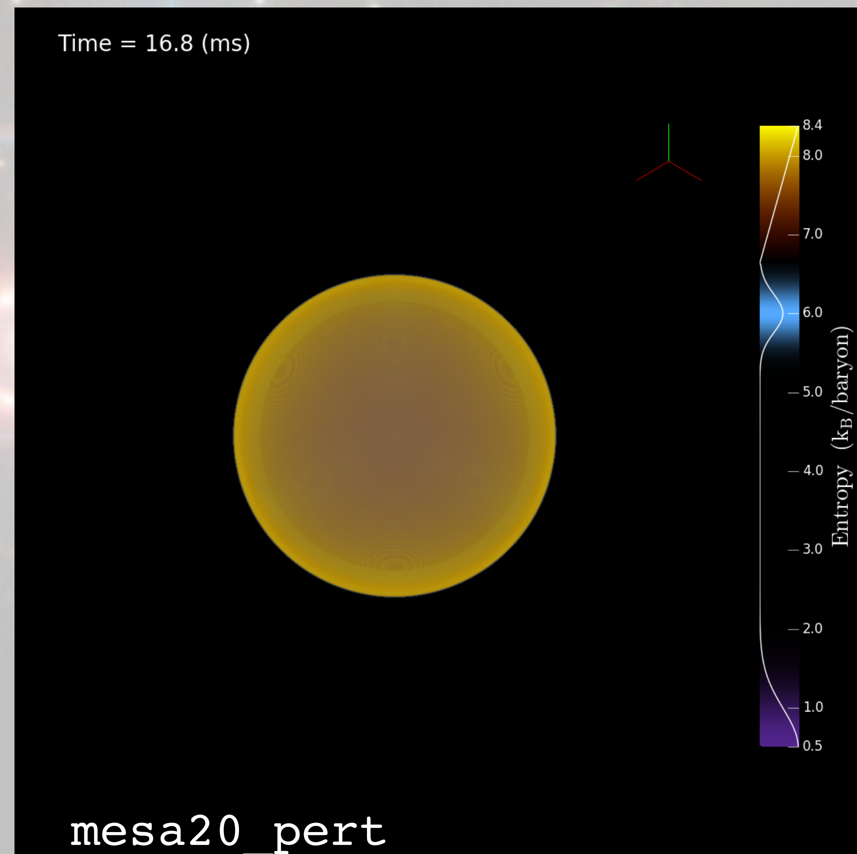


Impact of Perturbations



- CCSNe progenitors are not spherically symmetric – we expect convective motions in oxygen and perhaps silicon shell.
- Velocity perturbations based on Mueller & Janka (2015), extended to 3D, and placed in both silicon and oxygen shell.
- We find that convective motions at the top of the silicon shell result in strong turbulent motions in the gain region.
- This provides turbulent pressure support, inhibits shock recession, and increases efficacy of neutrino heating.





Thanks to Kuo-Chuan Pan for generating the movie renders

Impact of Symmetries

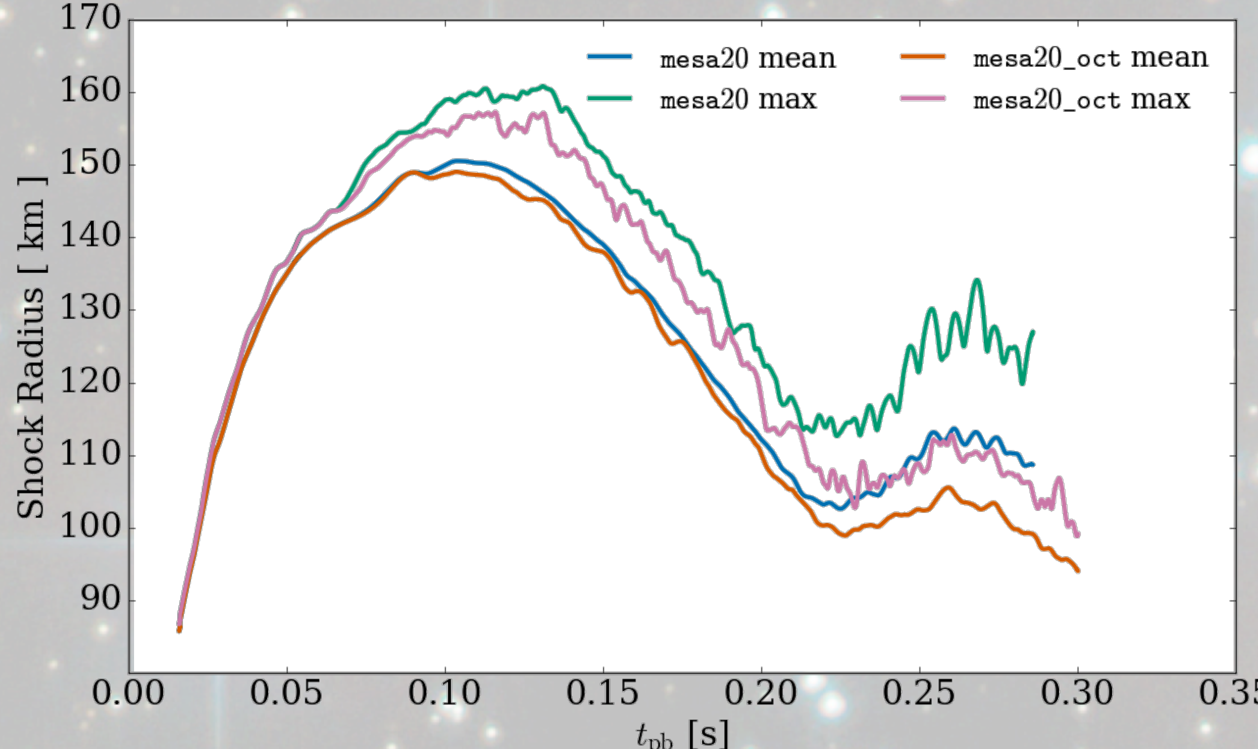
---- 0.2

gifs

'normal' to SASI plane

gifs

'parallel' to SASI plane



- Octant simulations suppress the development of global modes, like the standing accretion shock instability, which otherwise aid shock revival via increased neutrino heating and turbulent support

Summary

- With FLASH we now have high resolution simulations of the core-collapse supernovae central engine.
  - Explosions in 2D – broadly consistent with community
  - No Explosions in 3D model explored here

- Many –body correlations that reduce NC scattering cross section improve explosion outcomes in our 2D models
- We see a modest impact of progenitor perturbations on the post-bounce dynamics. Leads to increased turbulent pressure and bring simulations quantitatively closer to explosion
- We see the growth of the SASI throughout the entire simulation. Impacts mechanism and neutrino signal.