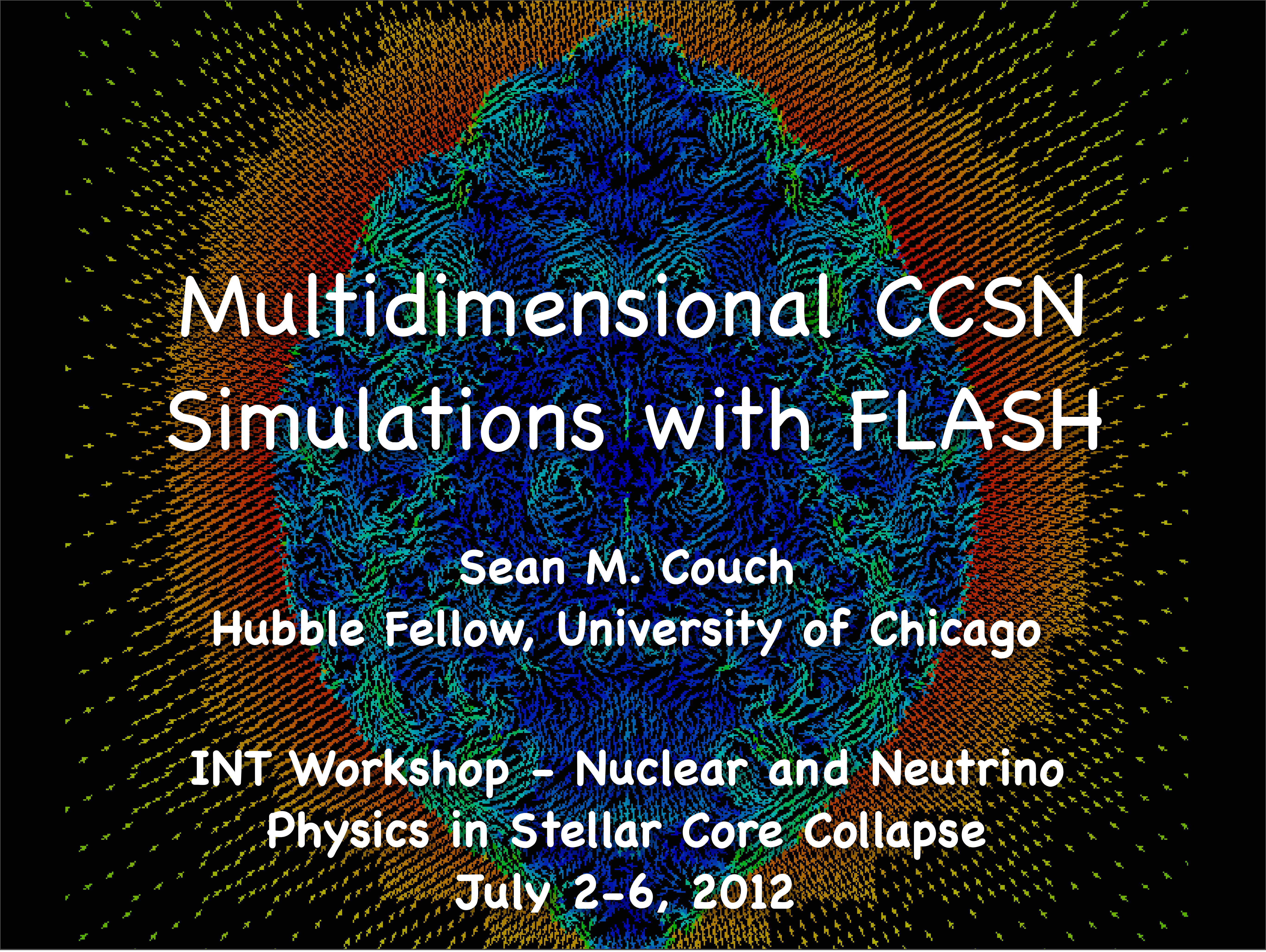


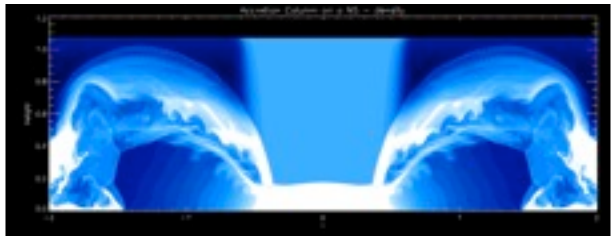
Multidimensional CCSN Simulations with FLASH

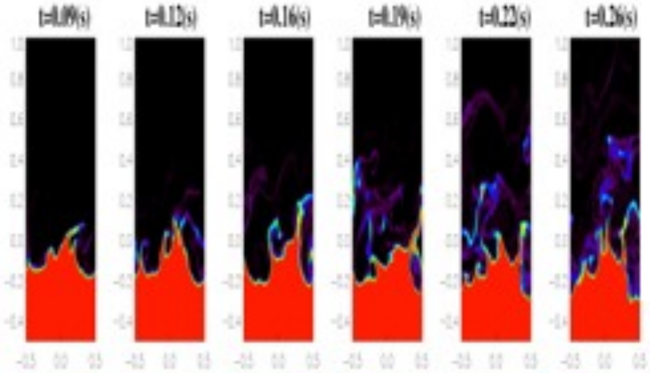
Sean M. Couch
Hubble Fellow, University of Chicago

INT Workshop - Nuclear and Neutrino Physics in Stellar Core Collapse
July 2-6, 2012

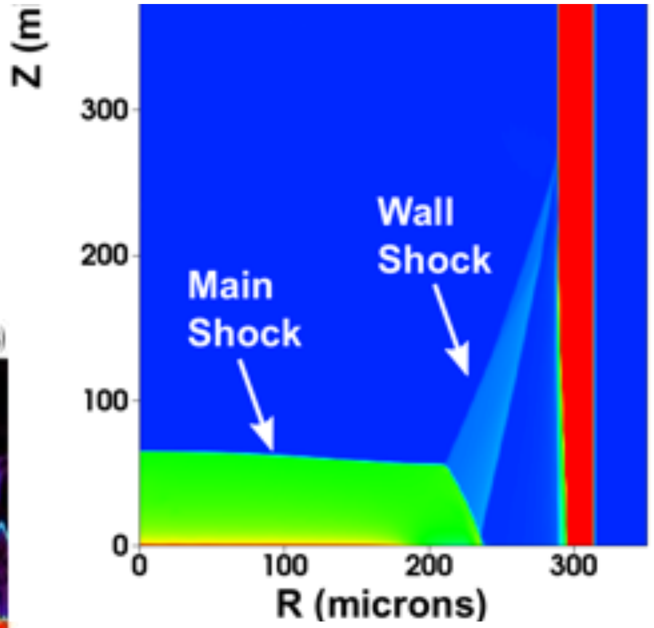
- FLASH as a tool for studying CCSNe
- EOS effects in simulations with parametric neutrino heating in 1D and 2D
- Beyond 2D
- Magnetorotational CCSN

FLASH Capabilities Span a Broad Range…

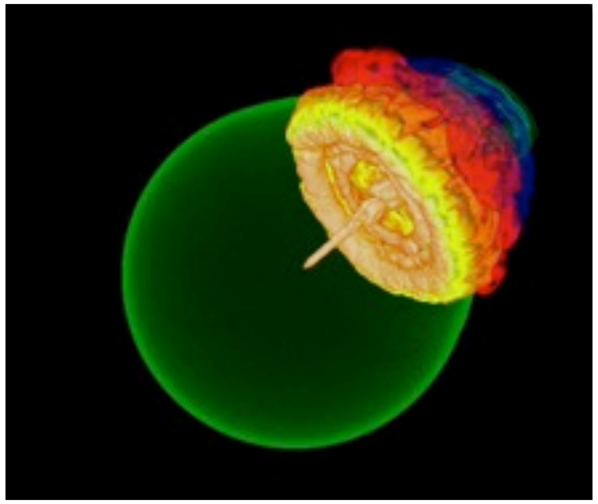

Shortly: Relativistic accretion onto NS

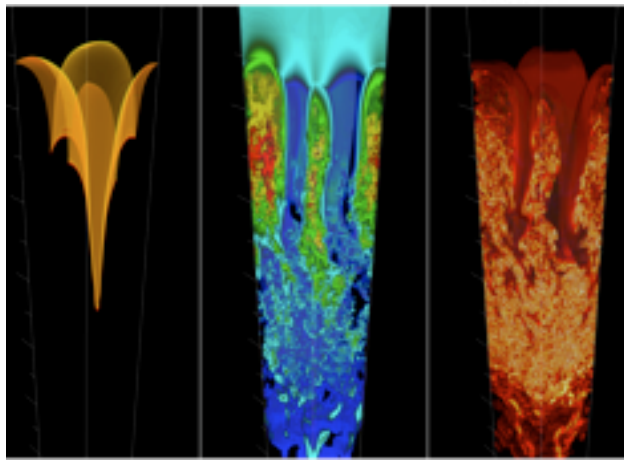


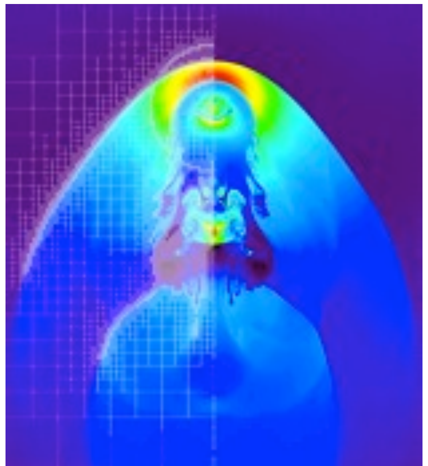
Wave breaking on white dwarfs

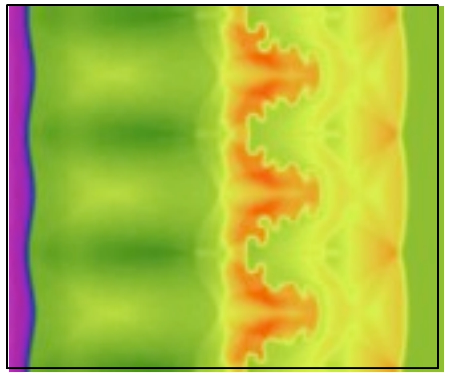


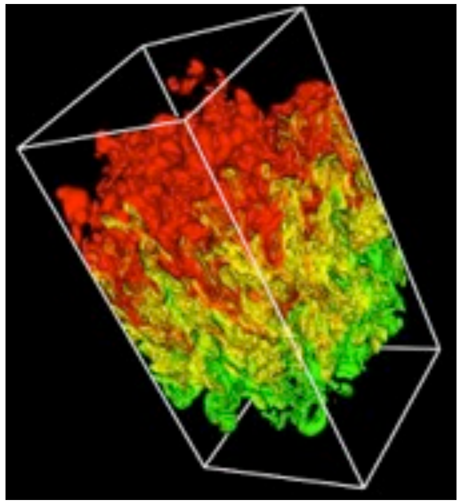
radiative shock
experiment

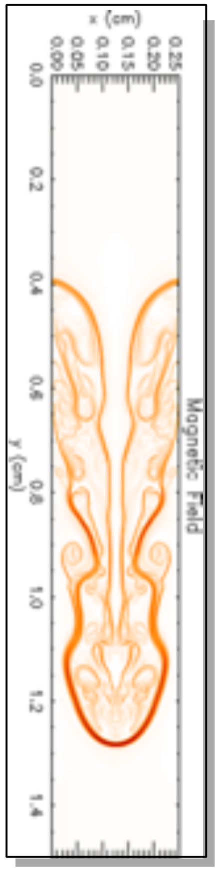

Gravitationally confined
detonation


Turbulent Nuclear Burning

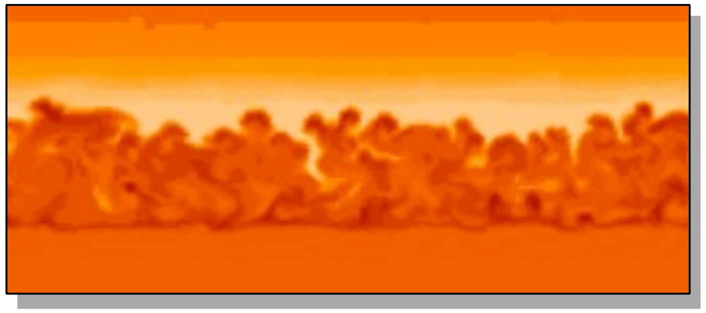

Intracluster interactions

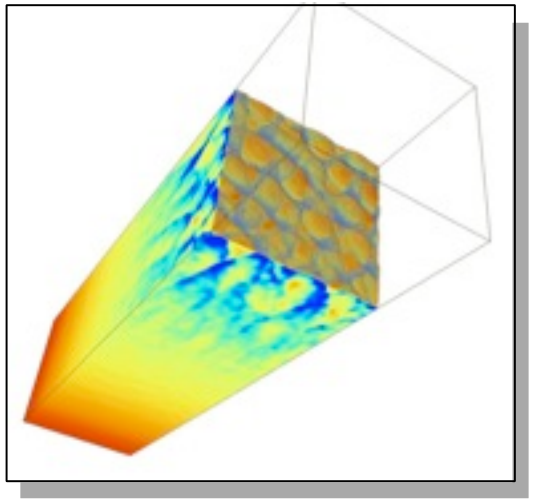

Laser-driven shock instabilities

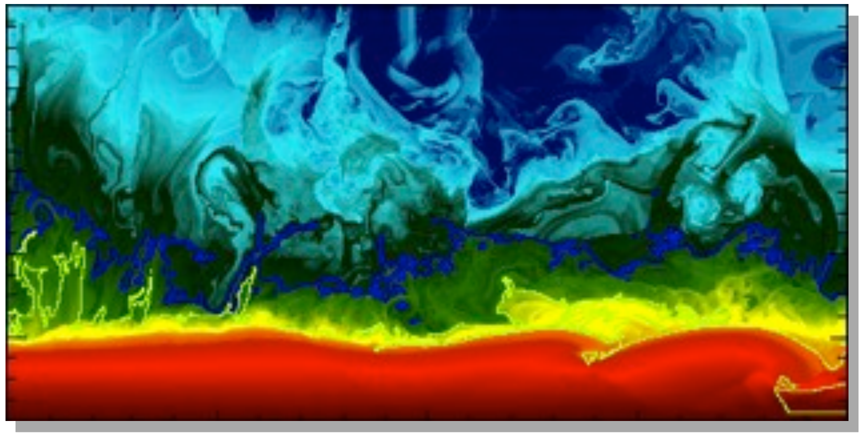

Rayleigh-Taylor instability

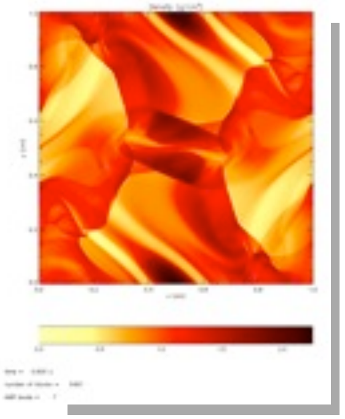


Magnetic
Rayleigh-Taylor


Nova outbursts on white dwarfs


Cellular detonation


Helium burning on neutron stars


Orzag/Tang MHD
vortex


Richtmyer-Meshkov instability

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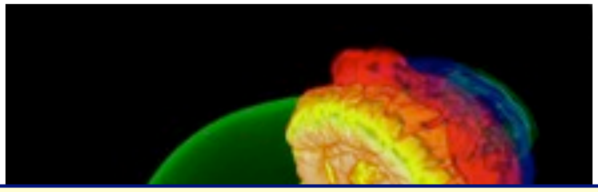
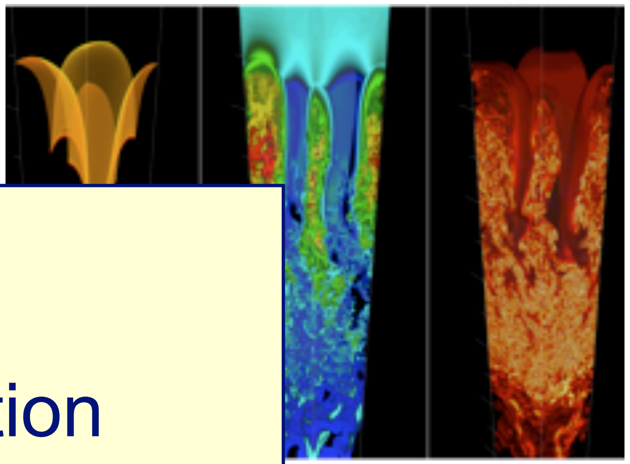
The University of Chicago

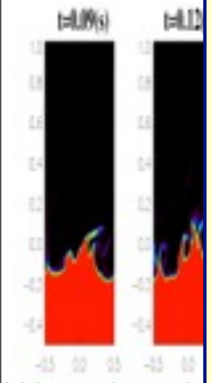
FLASH Capabilities Span a Broad Range…

Shortly: Rel

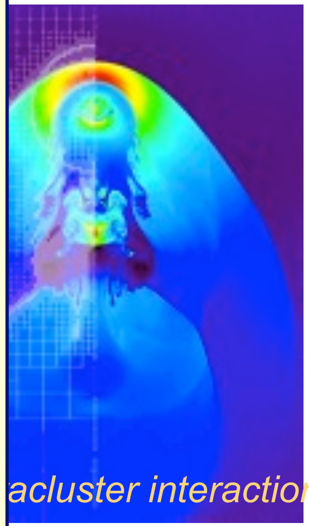




urning



Wave break

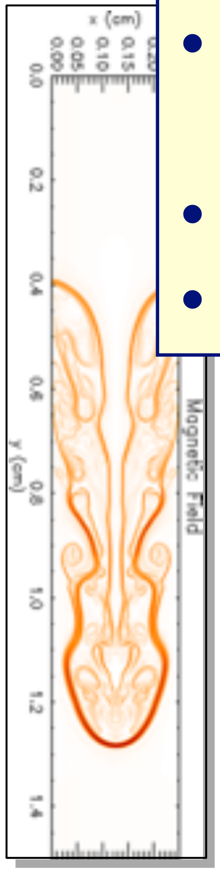


acluster interactions

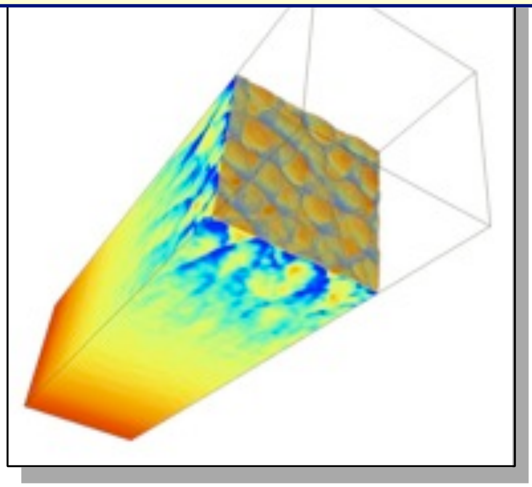
The FLASH code

1. Parallel, adaptive-mesh refinement (AMR) code
2. Block structured AMR; a block is the unit of computation

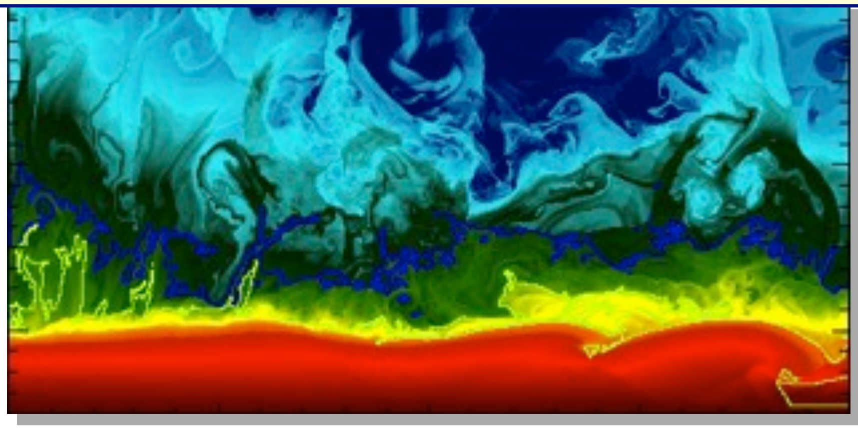
- Originally designed for compressible reactive flows
- Can solve a broad range of (astro)physical problems
- Portable: runs on many massively-parallel systems
- Scales and performs well
- Fully modular and extensible: components can be combined to create many different applications
- Well defined auditing process
- Extensive user base



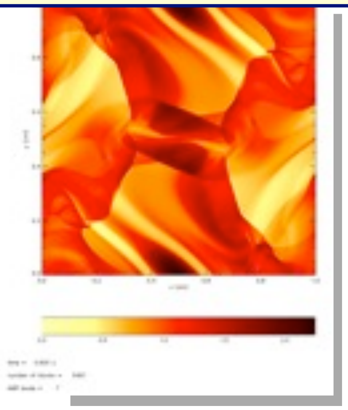
Magnetic Rayleigh-Taylor



Cellular detonation



Helium burning on neutron stars



Orzag/Tang MHD vortex

Richtmyer-Meshkov instability

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FLASH v4.0

- Fryxell et al. (2000) - My FLASH CCSN application shares no lines of code in common with F00.
- We are preparing a new ‘FLASH’ paper: Lee, SMC, et al. (in prep). See also A. Dubey et al. (2009).
- Open-source. Get it at: flash.uchicago.edu
- User contributions accepted!

FLASH v4.0

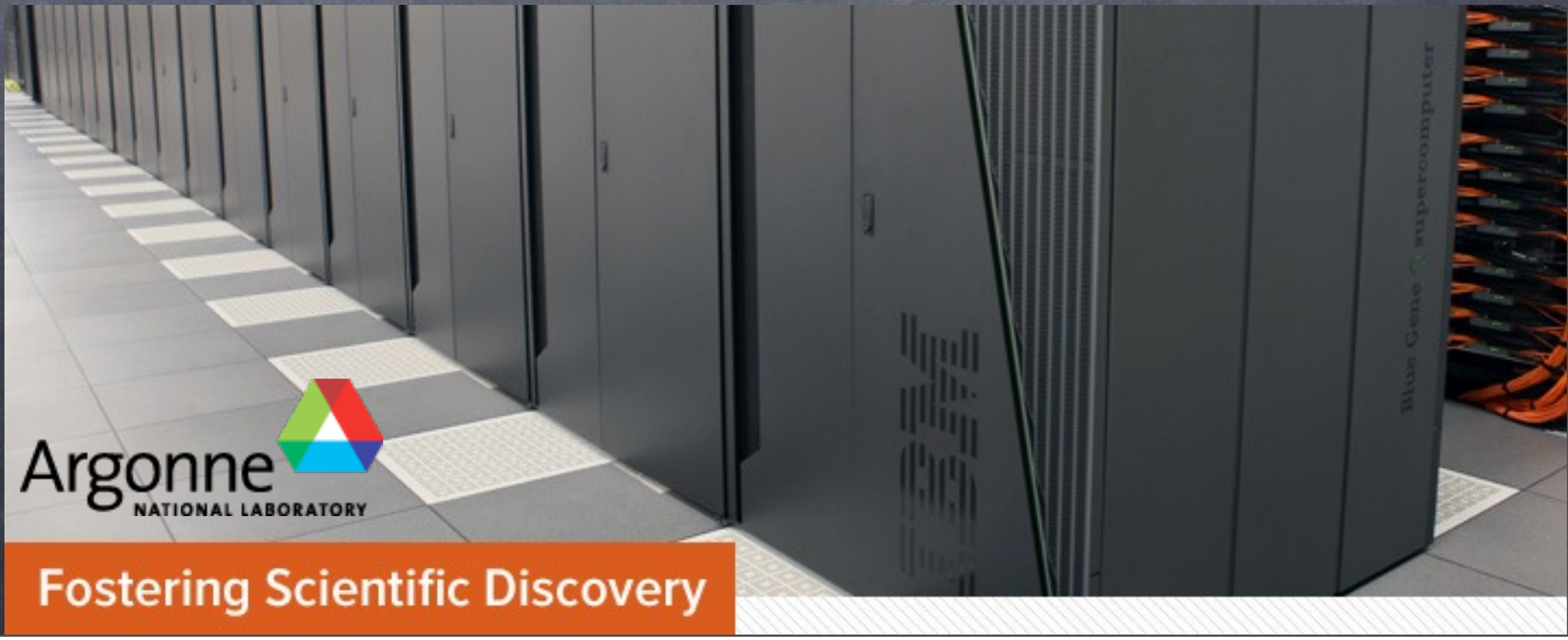
- Directionally-unsplit staggered mesh MHD solver with constrained transport
- Ideal and non-ideal MHD
- Reconstruction orders: 1 (Godunov), 2 (MUSCL-Hancock), 3 (PPM), 5 (WENO)
- Multiple slope limiters and Riemann solvers (HLL, HLLC, HLLD, Roe, Lax-Friedrichs,...)
- New multipole Poisson solver. Significantly faster, more accurate and efficient.
- Multigroup FLD with HYPRE linear algebra

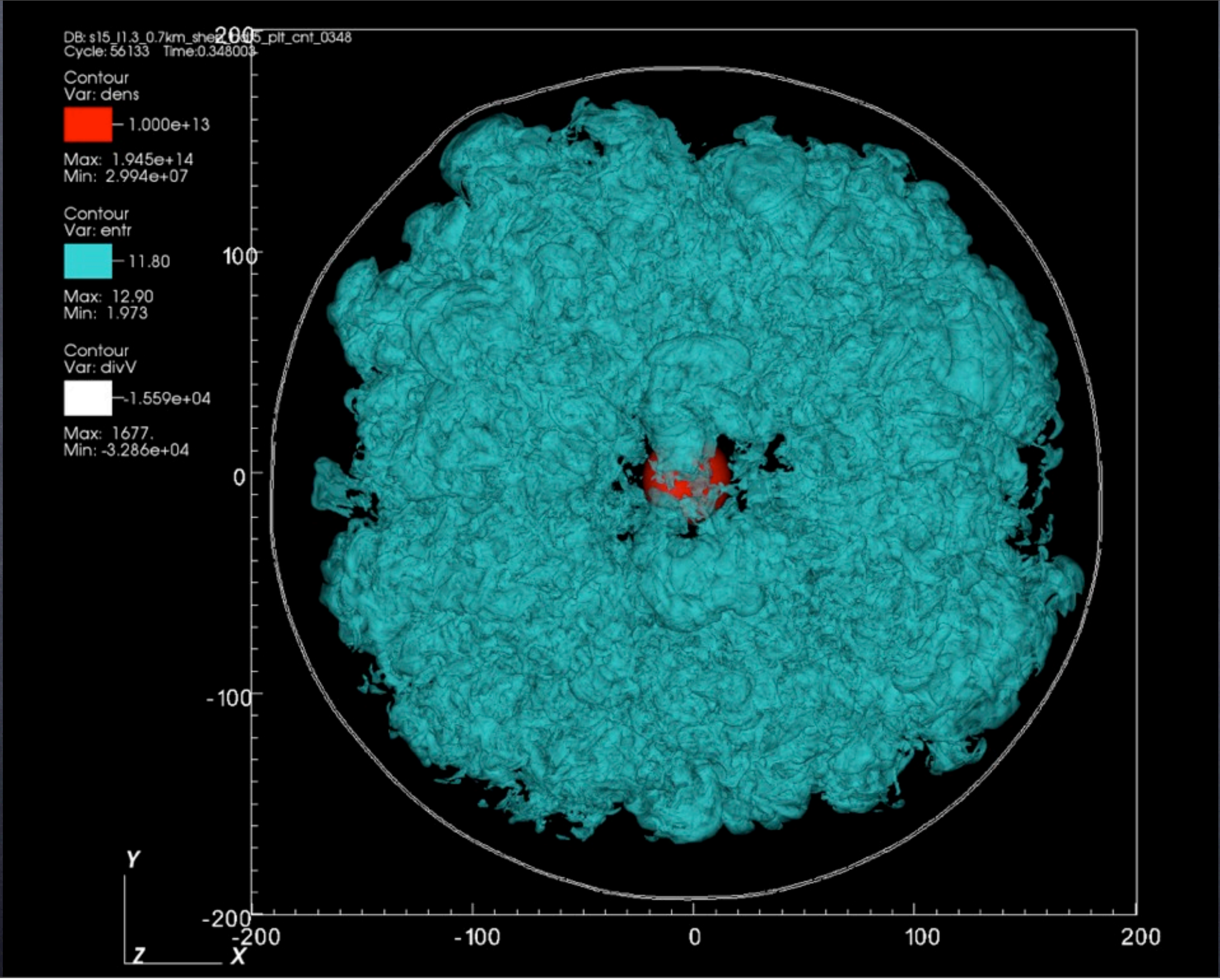
FLASH v4.0 for CCSNe

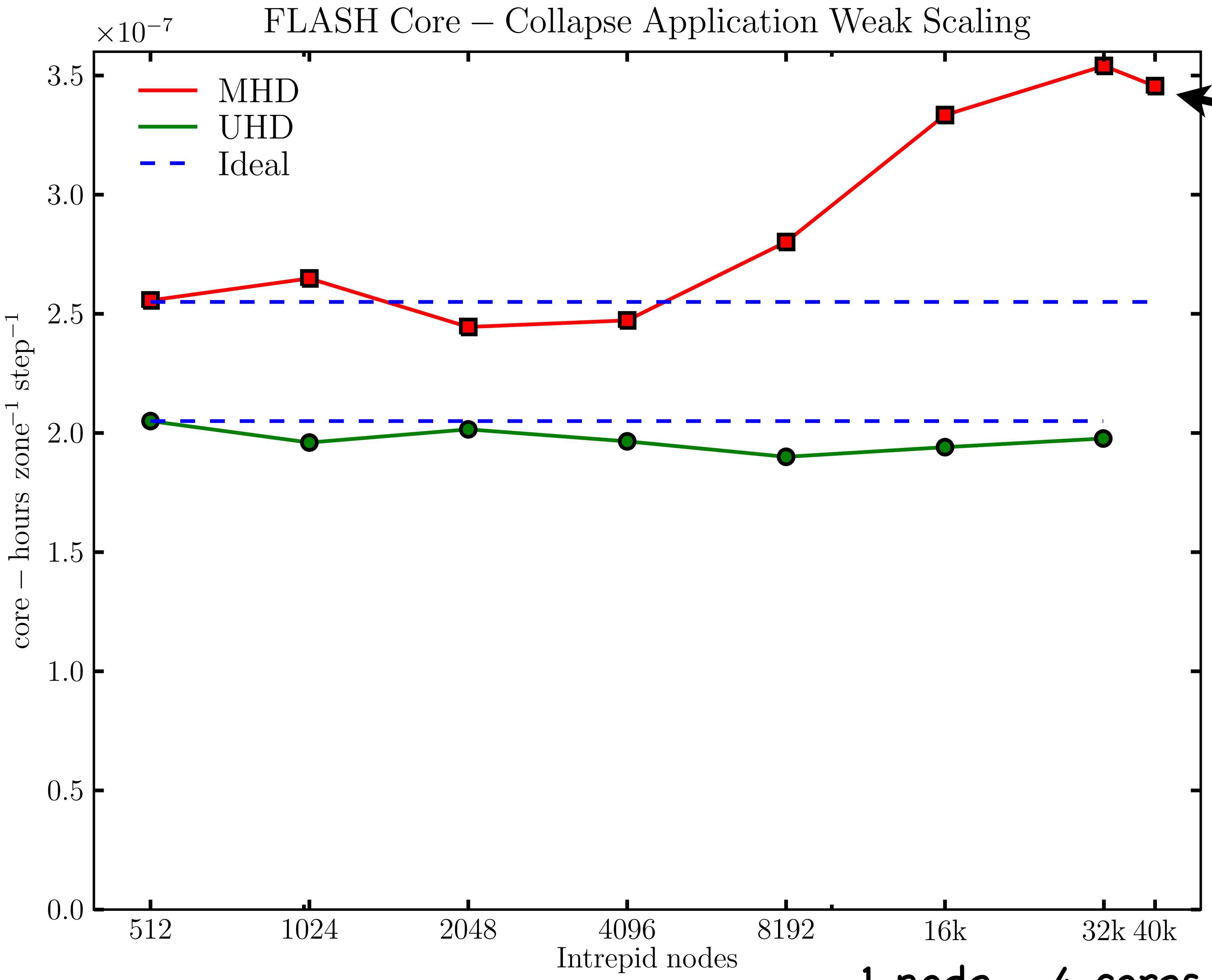
- Extension of unsplit solvers to spherical and cylindrical geometries
- Addition of 1.5D and 2.5D rotation
- Finite temperature EOS (via E. O'Connor, stellarcollapse.org)
- Neutrino 'lightbulb' heating/cooling
- Deleptonization a la Liebendorfer (2005)
- And new this week: Ray-by-Ray Neutrino Leakage (from GR1D, E. O'Connor)

3D CCSNe Simulations Require Petascale Computing!

- About 70 million zones in 3D (1% angular/radial resolution)
- Argonne Leadership Computing Facility: Intrepid (557 Tera-FLOP BG/P) and next year, Mira (10 Peta-FLOP BG/Q)




DB: s15_l1.3_0.7km_she
5_plt_cnt_0348
Cycle: 56133 Time:0.348003
Contour
Var: dens
1.000e+13
Max: 1.945e+14
Min: 2.994e+07
Contour
Var: entr
11.80
Max: 12.90
Min: 1.973
Contour
Var: divV
-1.559e+04
Max: 1677.
Min: -3.286e+04
200
100
0
-100
-200
-200
-100
0
100
200
Y
Z
X



160k cores!

1 node = 4 cores

*MHD perfect scaling achieved with bigger AMR blocks

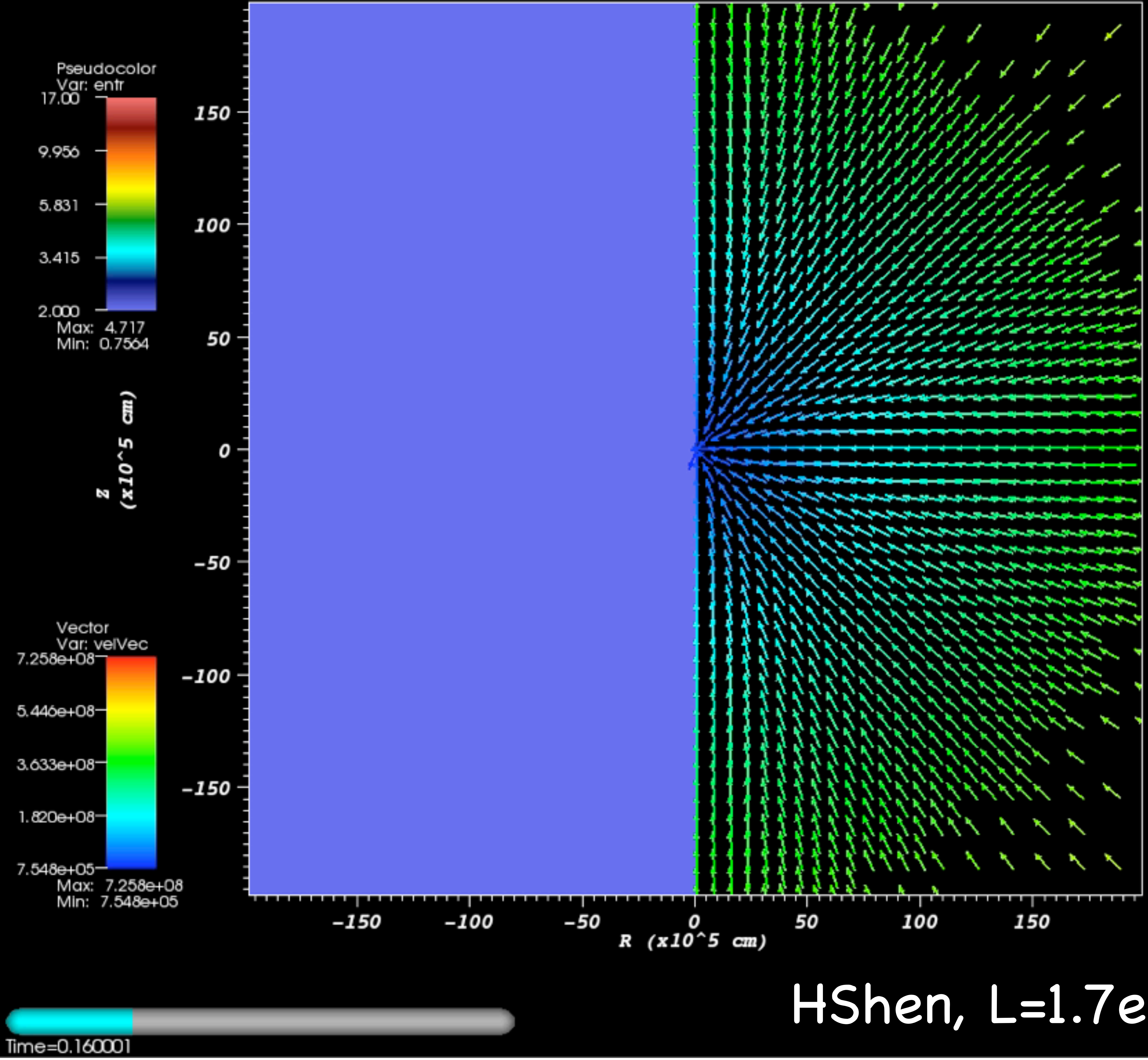
First Steps: The influence of EOS in parameterized simulations (Couch 2012)

$$\mathcal{H} = 1.544 \times 10^{20} \left(\frac{L_{\nu_e}}{10^{52}\ \mathrm{erg\ s^{-1}}} \right) \left(\frac{T_{\nu_e}}{4\ \mathrm{MeV}} \right)^2 \times \left(\frac{100\ \mathrm{km}}{r} \right)^2 (Y_p + Y_n) e^{-\tau_{\nu_e}}$$

$$\mathcal{C} = 1.399 \times 10^{20} \left(\frac{T}{2\ \mathrm{MeV}} \right)^6 (Y_p + Y_n) e^{-\tau_{\nu_e}}$$

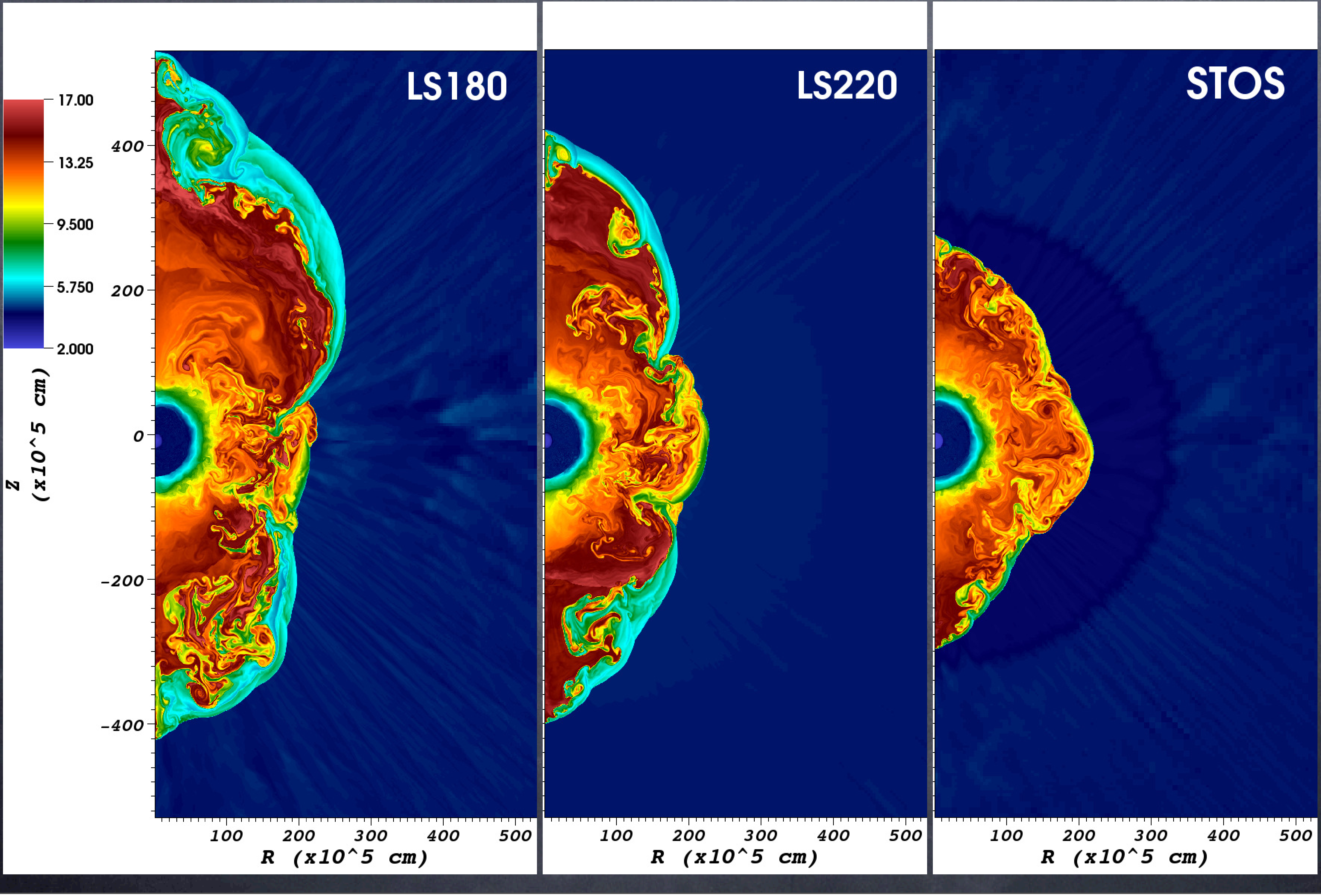
3 EOS in 1D and 2D with s15s7b2:
HShen and Lattimer & Swesty (K=180,220 MeV)

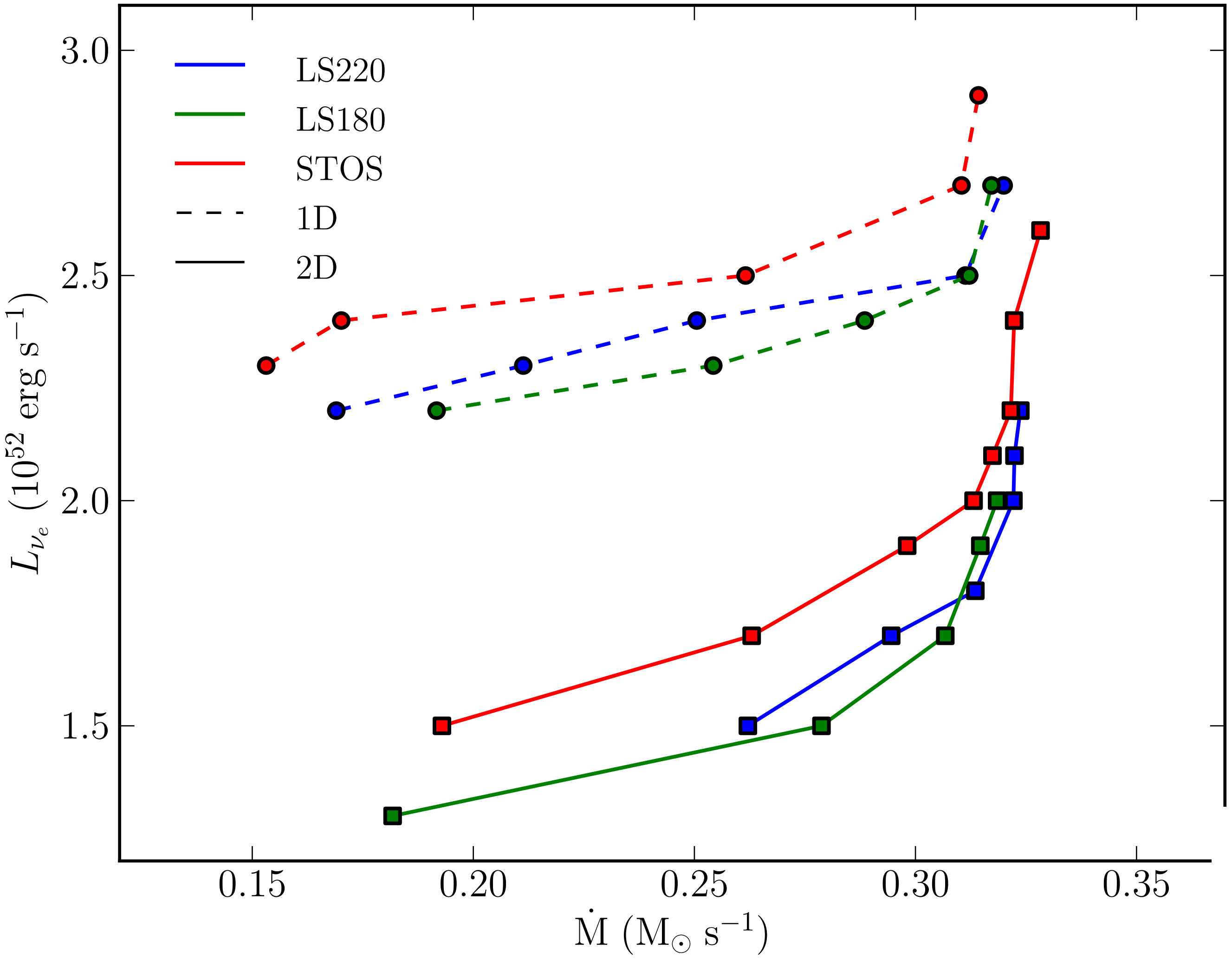
HShen, L=1.7e52



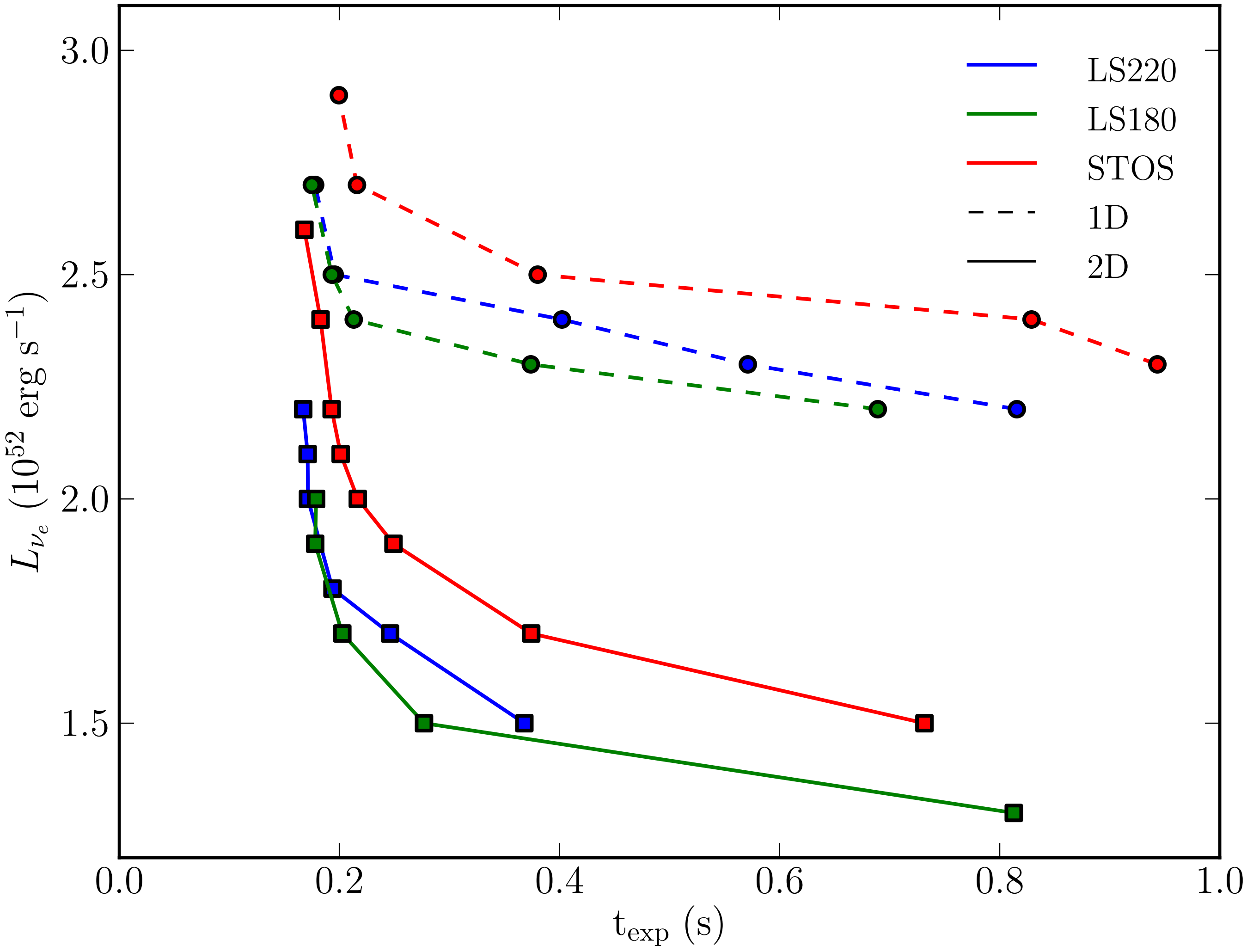
HShen, L=1.7e52

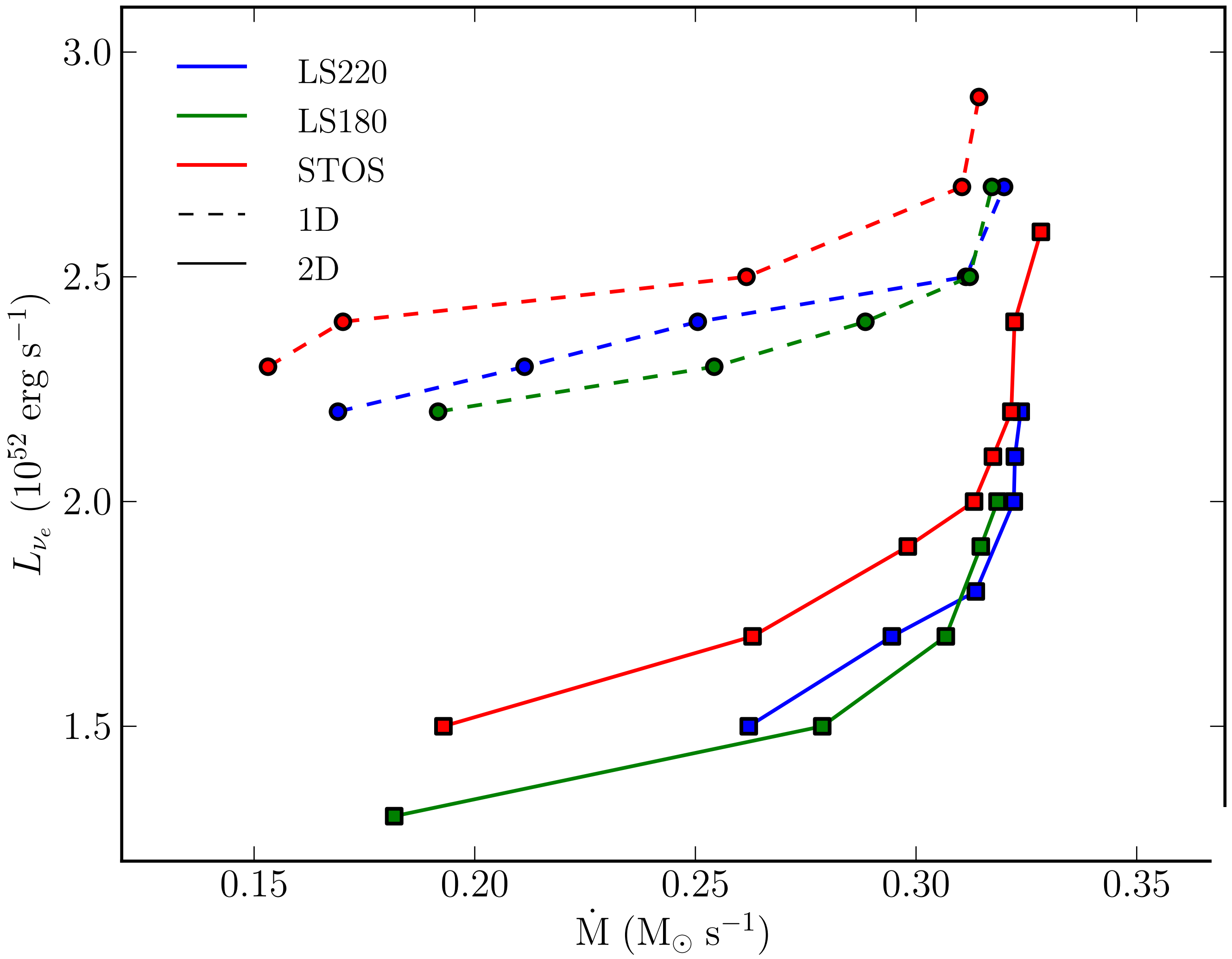
L=1.3e52, 600 ms post-bounce:





- 2D is significantly easier than 1D
- LS curves are lower than STOS
- LS180 is lower than LS220





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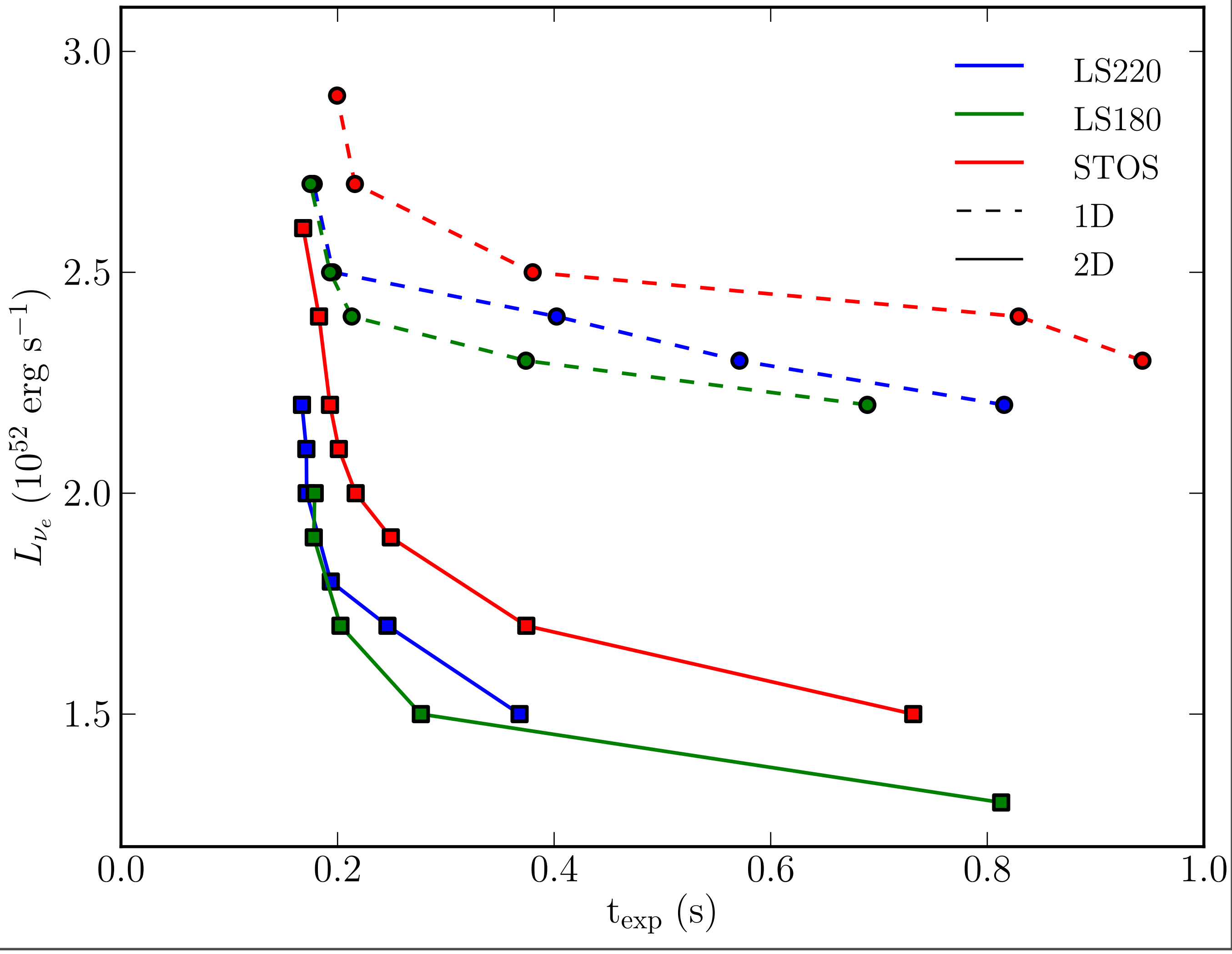
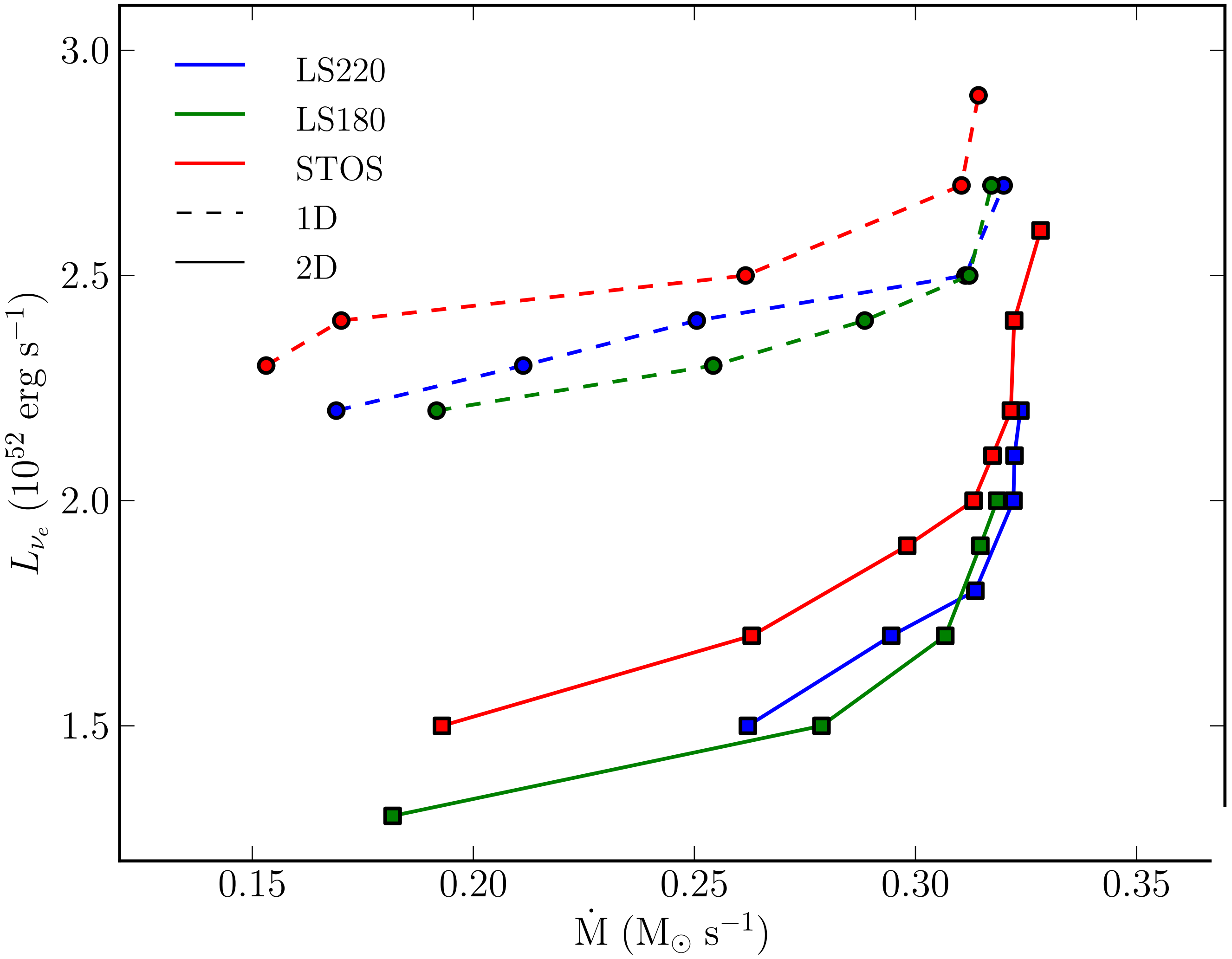
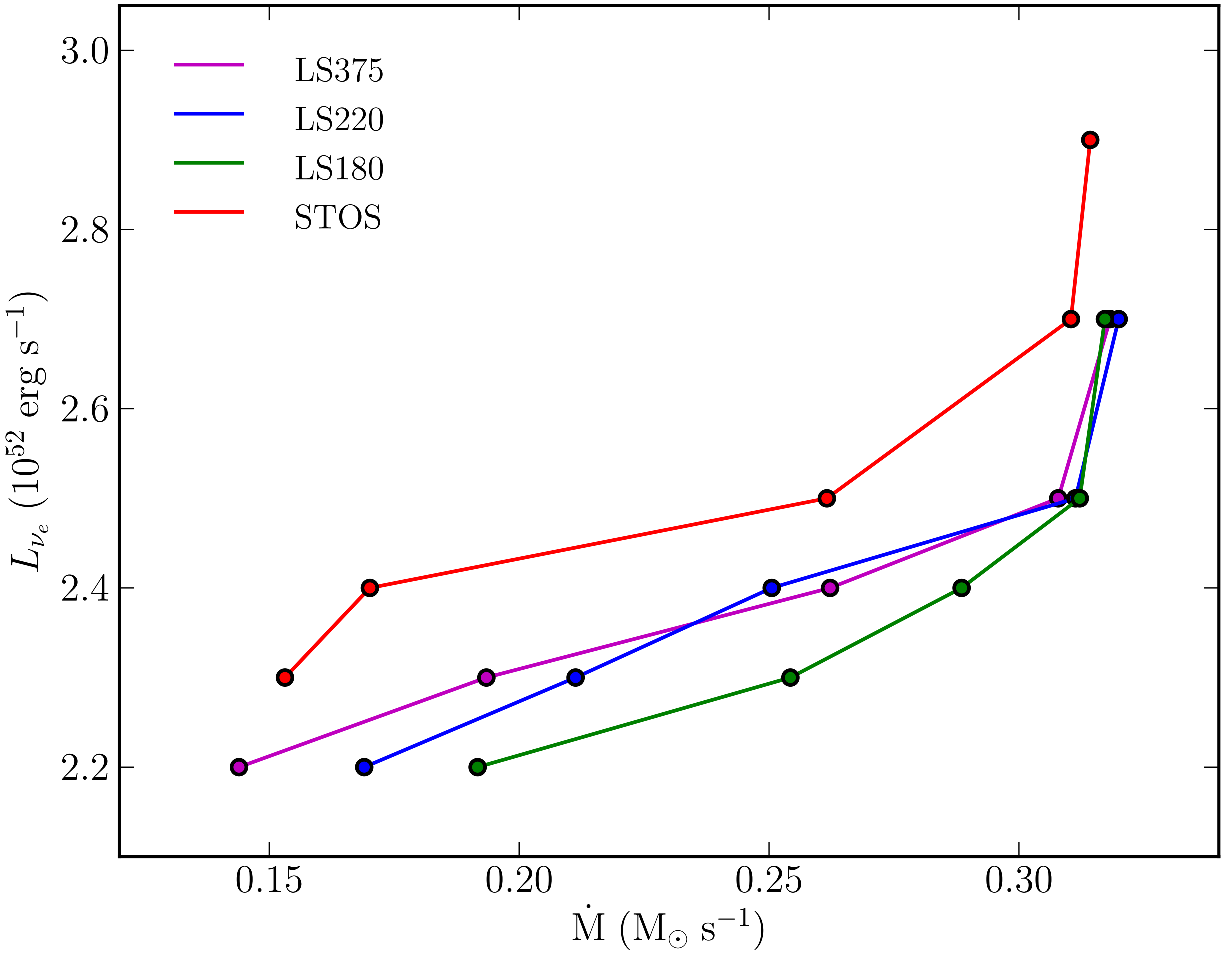
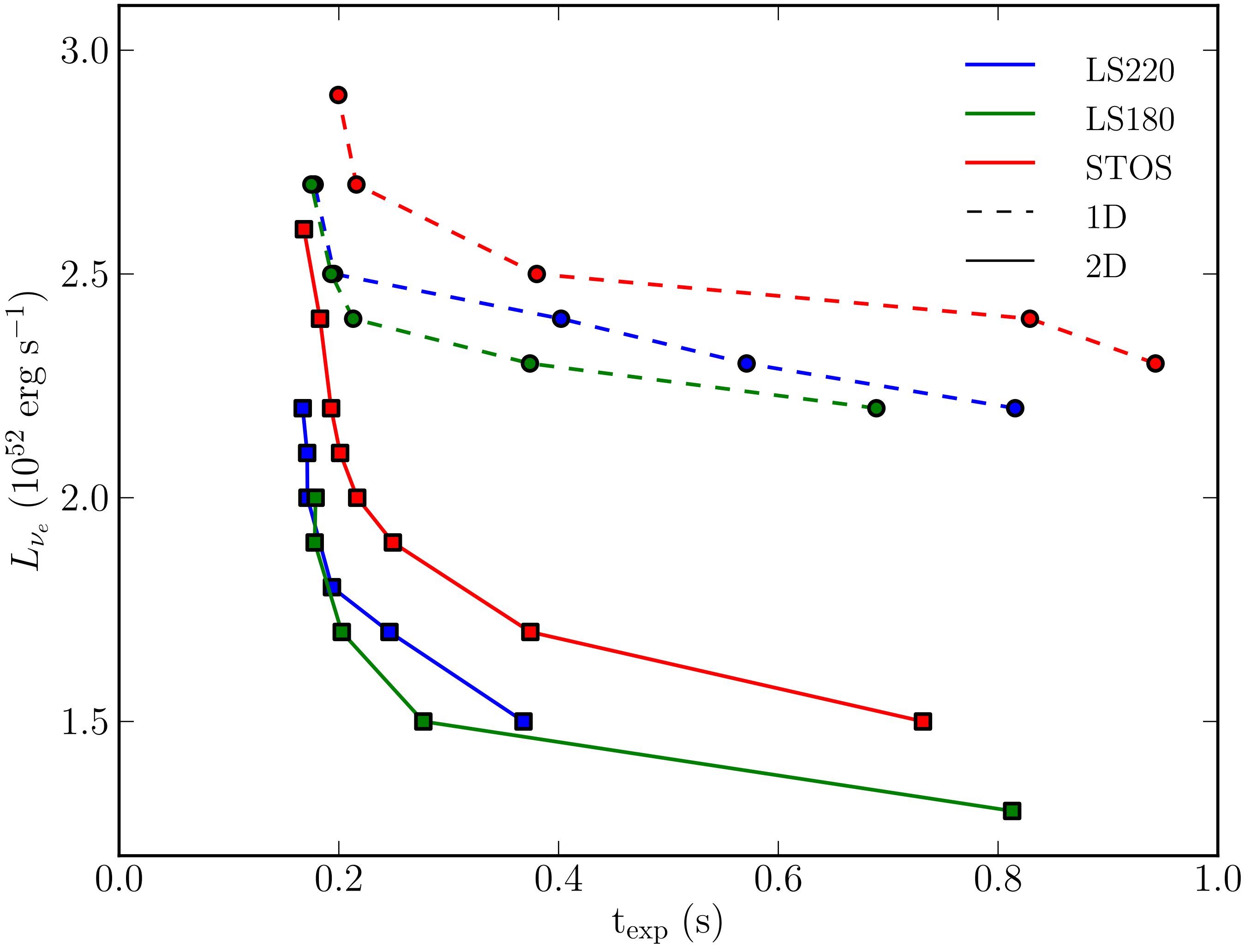
Ordering with compressibility K?: Not quite.







Ordering with compressibility K?: Not quite.



Why do the explosion times depend on EOS?

- Difference in alpha-particle abundance causing difference in (Y_p+Y_n)? Tried $(1.-Y_H)^2$ in heating/cooling terms. No qualitative change.

- Difference in buoyant convection/turbulence? Look at optical depth through gain region (Murphy, Burrows, & Dolence 2012): $E_k \sim L_{\nu_e}\tau$

Why do the explosion times depend on EOS?

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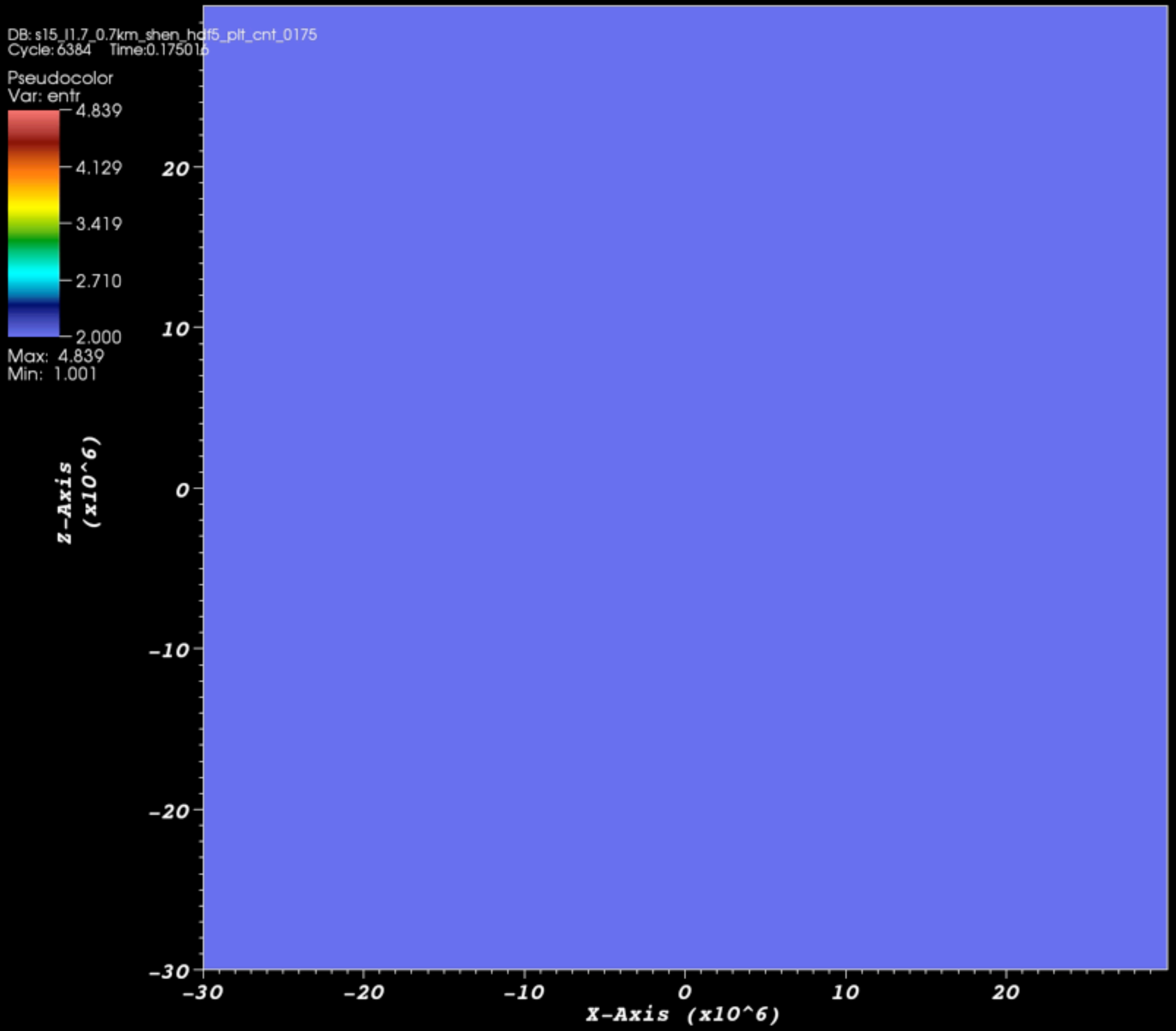
- Difference in buoyant convection/turbulence? Look at optical depth through gain region (Murphy, Burrows, & Dolence 2012): $E_k \sim L_{\nu_e}\tau$
- Could be due to different development of the SASI. The softer LS EOS produce more compact, denser PNS and advective deceleration regions. Thus, acoustic wave generation is more efficient. Denser PNS are better sonic transducers.

Looking into 3D

- Simulations not done, so sorry, no conclusions yet.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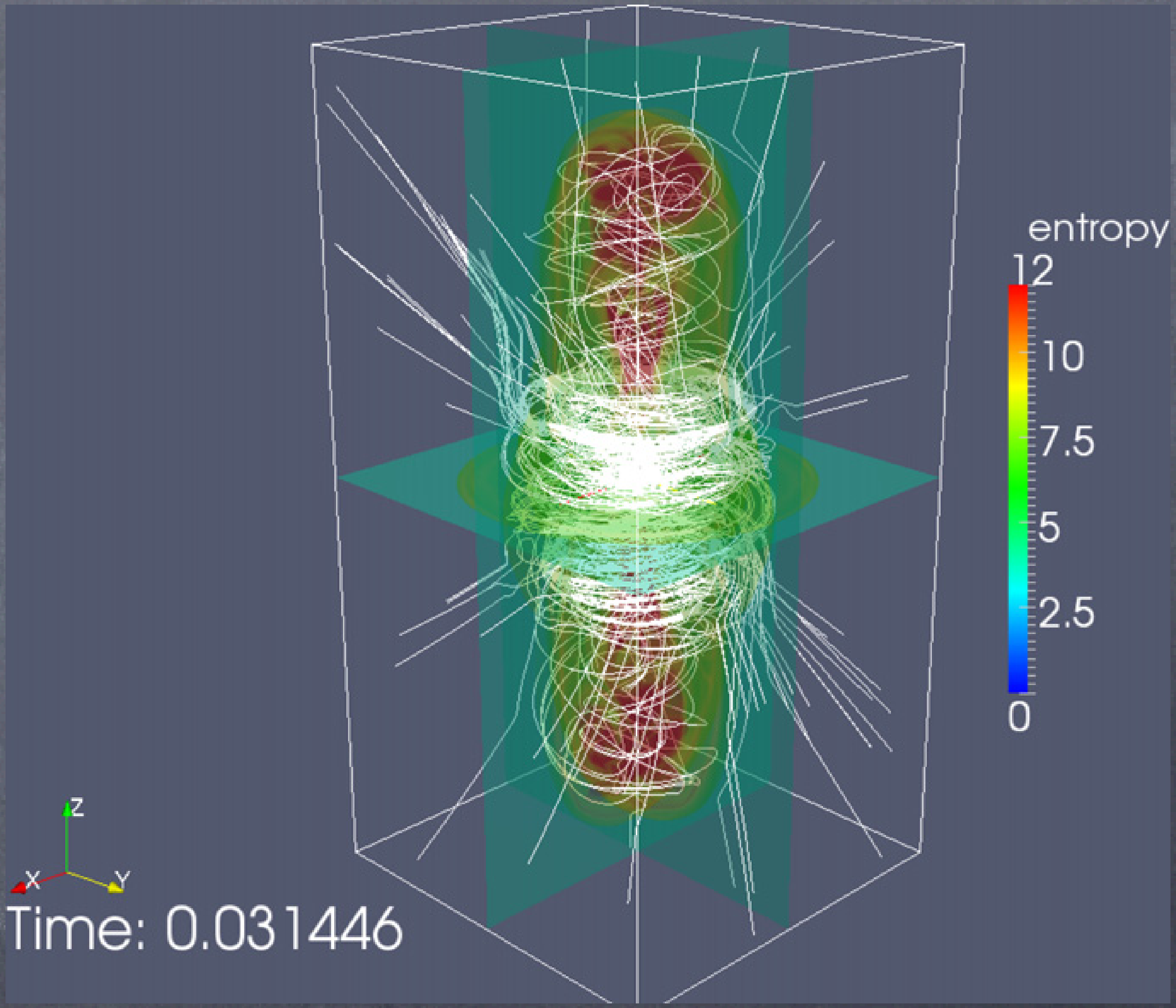
Cycle: 6384 Time:0.175016
Pseudocolor
Var: entr
4.839
4.129
3.419
2.710
2.000
Max: 4.839
Min: 1.001
Z-Axis (x10^6)
X-Axis (x10^6)
20
10
0
-10
-20
-30
-30
-20
-10
0
10
20

What I'd like to do next...

- Magnetic, rotating progenitors!
- How important could MR be for normal supernovae? Aiding neutrinos, shaping explosions, driving explosions?
- How does MR affect the SASI, convection, and turbulence in a range of progenitors?
- What is the threshold in initial P/B above which MR is important?
- Can we better capture the important dynamics of unresolved amplification mechanisms?

Rotation and Magnetic Fields Are Important!

- Important implications for initial spin and B-field of neutron stars
- Possible r-process site (e.g. Winteler et al. 2012)
- Connection to GRBs
- Possible explanation for observational evidence of bipolar SNe (but see, e.g., Hammer et al. 2010)



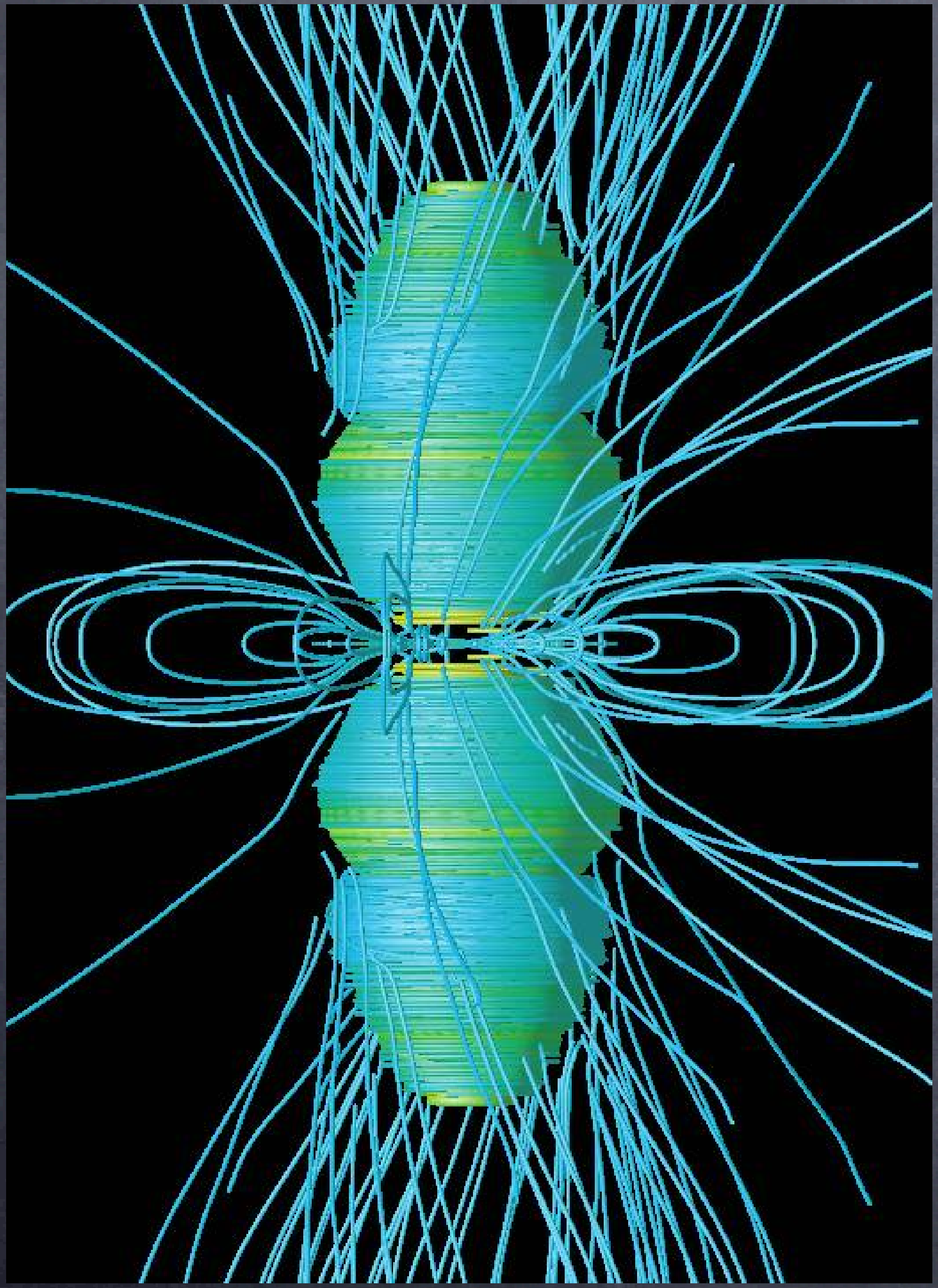
Winteler et al. 2012

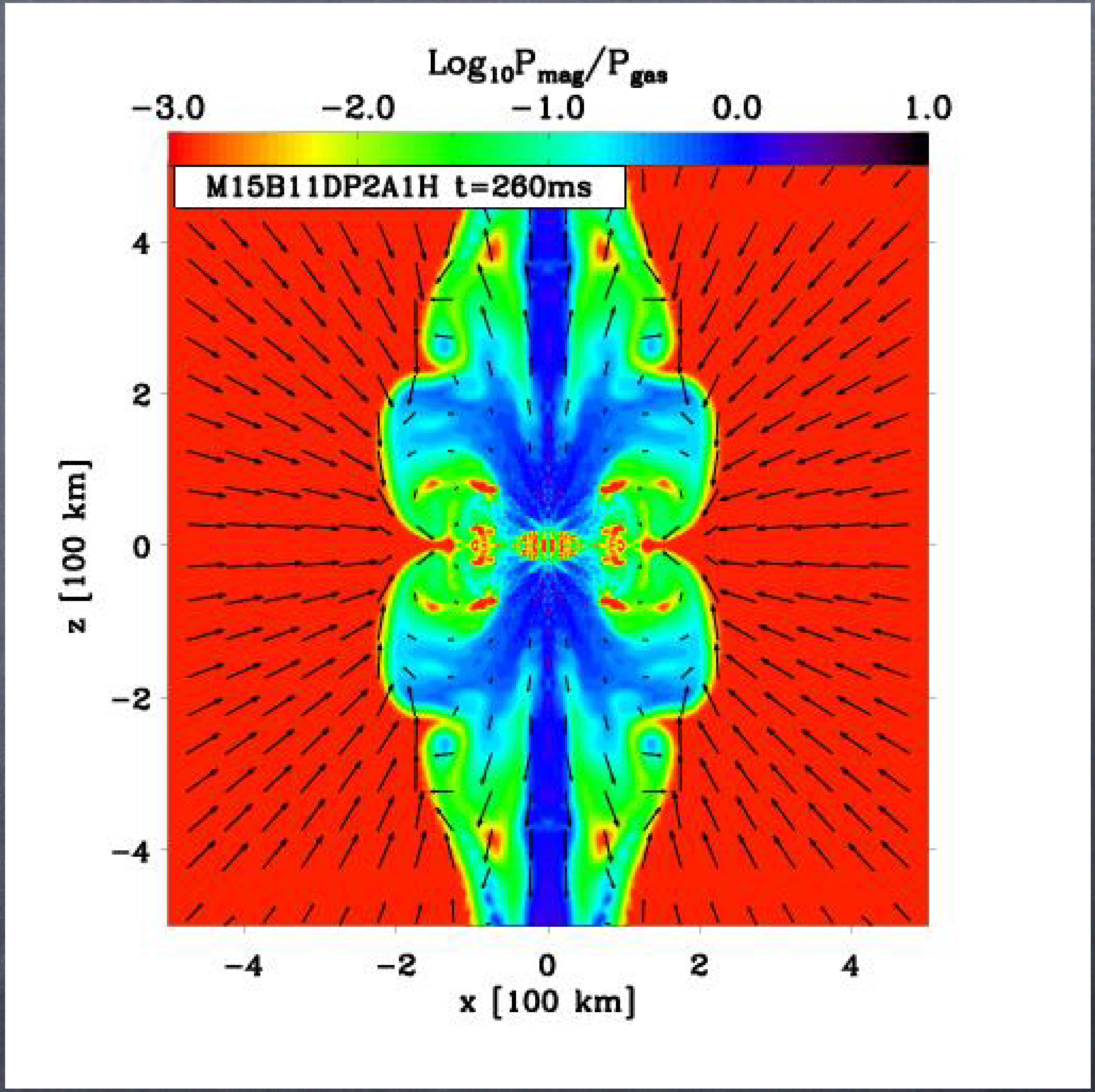
Magnetorotational CCSNe

$$E_{\rm rot,PNS} \approx \frac{1}{2} I_{\rm PNS} \Omega_{\rm PNS}^2$$
$$\approx 9 \times 10^{50} {\rm ergs} \left(\frac{M_{\rm PNS}}{1.5\ M_\odot}\right) \left(\frac{\Omega_{\rm PNS}}{250\ {\rm s}^{-1}}\right)^2 \left(\frac{R_{\rm PNS}}{50\ {\rm km}}\right)^2$$

- Explosions by MHD jets first suggested by LeBlanc & Wilson (1970). Explored further in Meier et al. (1976)
- Possible importance revisited by Wheeler et al. (2000,2002).
- Recent work by Burrows et al. (2007) and Takiwaki et al. (2009) in 2D, Winteler et al (2012) in 3D.

Magnetorotational SNe





Burrows et al. 2007

B-field Amplification in CCSNe

See, e.g., Endeve et al. (2010,2012), Obergaulinger & Janka (2011)

- Field compression: field carried along with collapsing plasma: "flux-freezing"
- Field winding: linear process, wraps up field lines. $B_\phi \approx 2\pi n_\phi B_p$
- Possible (small-scale) dynamo
- Magnetorotational Instability (MRI): exponential growth of initial field. Saturation field strengths as high as 10^{15} - 10^{16} G. Akiyama et al. (2003).

MRI in the Linear Regime

E.g., Balbus & Hawley (1992), Obergaulinger et al. (2009)

Considering only radial gradients, instability criterion:

$$C_r = \left[\frac{1}{\rho}\frac{\partial P}{\partial r}\left(\frac{1}{\rho}\frac{\partial \rho}{\partial r} - \frac{1}{\Gamma_1 P}\frac{\partial P}{\partial r}\right) + r\frac{\partial \Omega^2}{\partial r}\right] / \Omega^2 < 0$$

gravity buoyancy rotation

$$k_{\mathrm{FGM}} \approx [-C_r(C_r+8)]^{1/2}\Omega/4v_A \qquad \omega_{\mathrm{FGM}} \approx (-C_r^2)^{1/2}\Omega/4$$

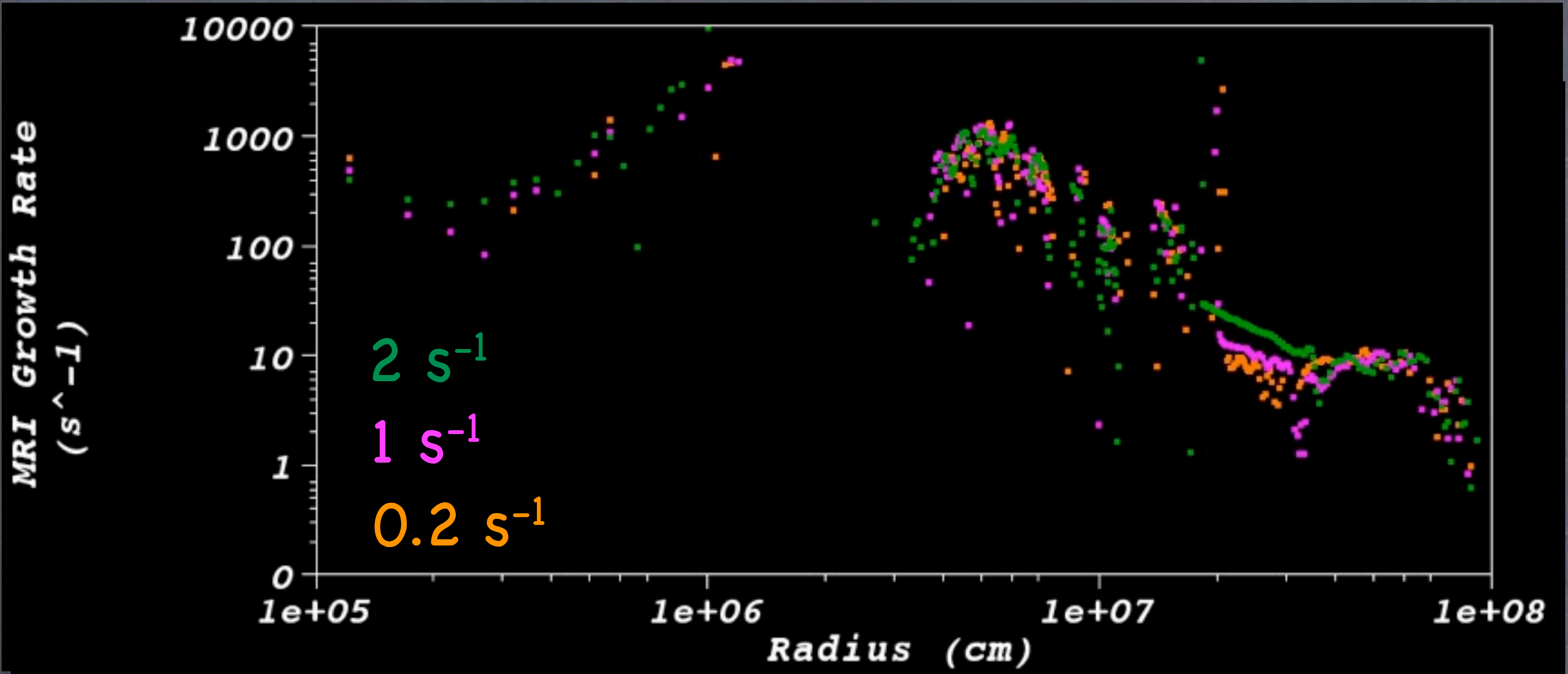
$$B_f \sim B_0 e^{i\omega_{\mathrm{FGM}}t} \qquad t_{\mathrm{MRI}} \sim \ln(B_f/B_0)/i\omega_{\mathrm{FGM}}$$

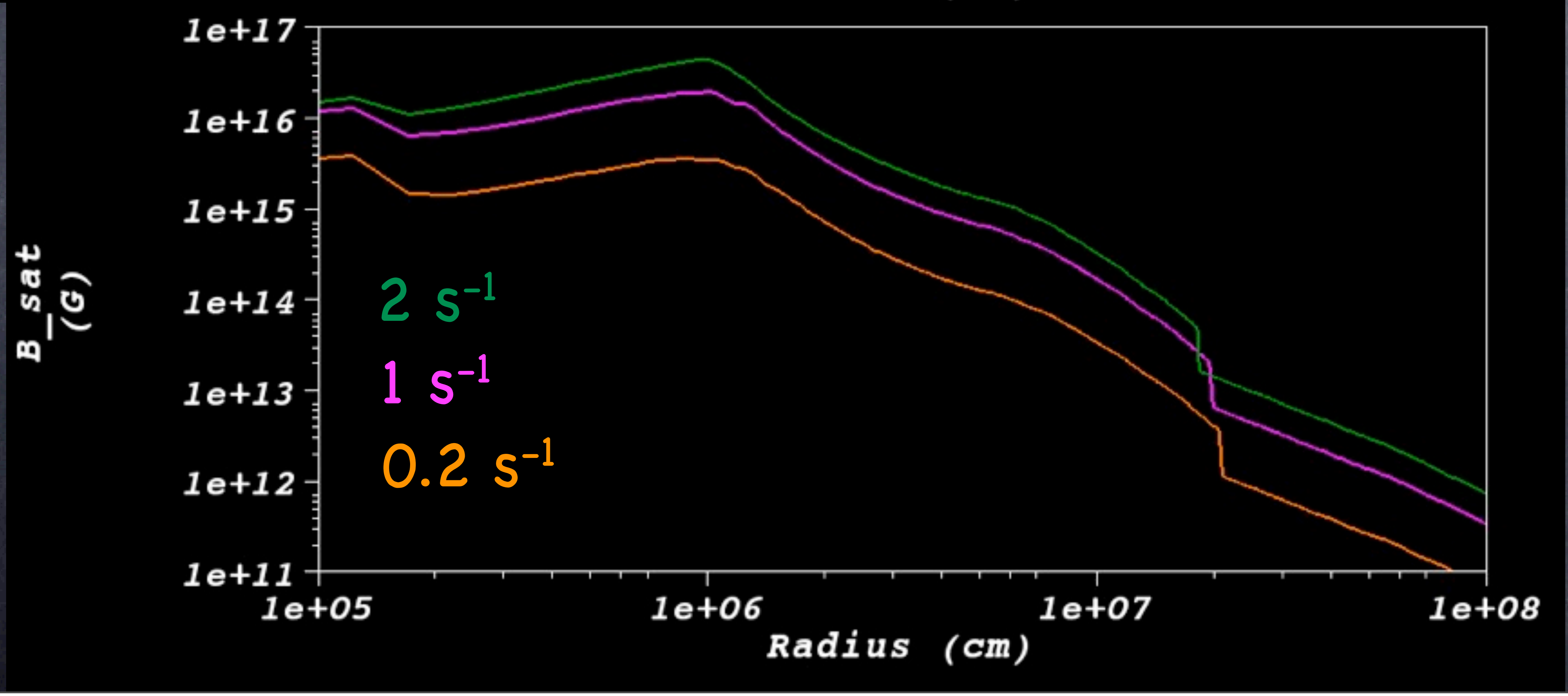
$$B_{\mathrm{sat}} \approx \alpha r \Omega (4\pi\rho)^{1/2},\ \alpha < 1$$

Magnetic, Rotating Progenitors

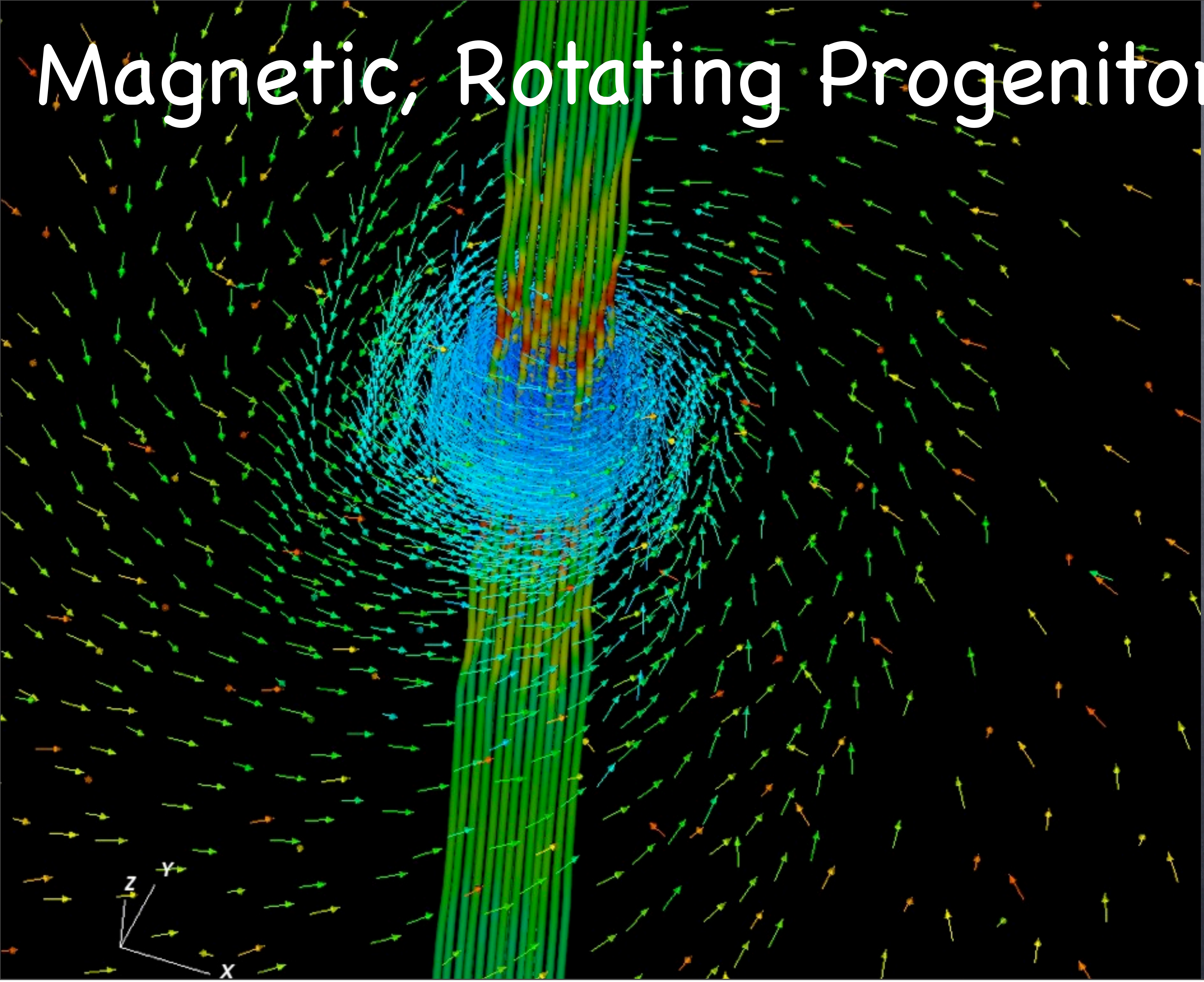
Heger, Woosley, & Spruit (2005)

- Magnetic torques slow rotation of cores by a factor of 30-50 relative to non-magnetic progenitors
- standard 15 M_{sun} model: 0.2 s^{-1} (v. 8.0 s^{-1})
- 1.5D collapse simulations for 0.2, 1.0, 2.0 s^{-1}

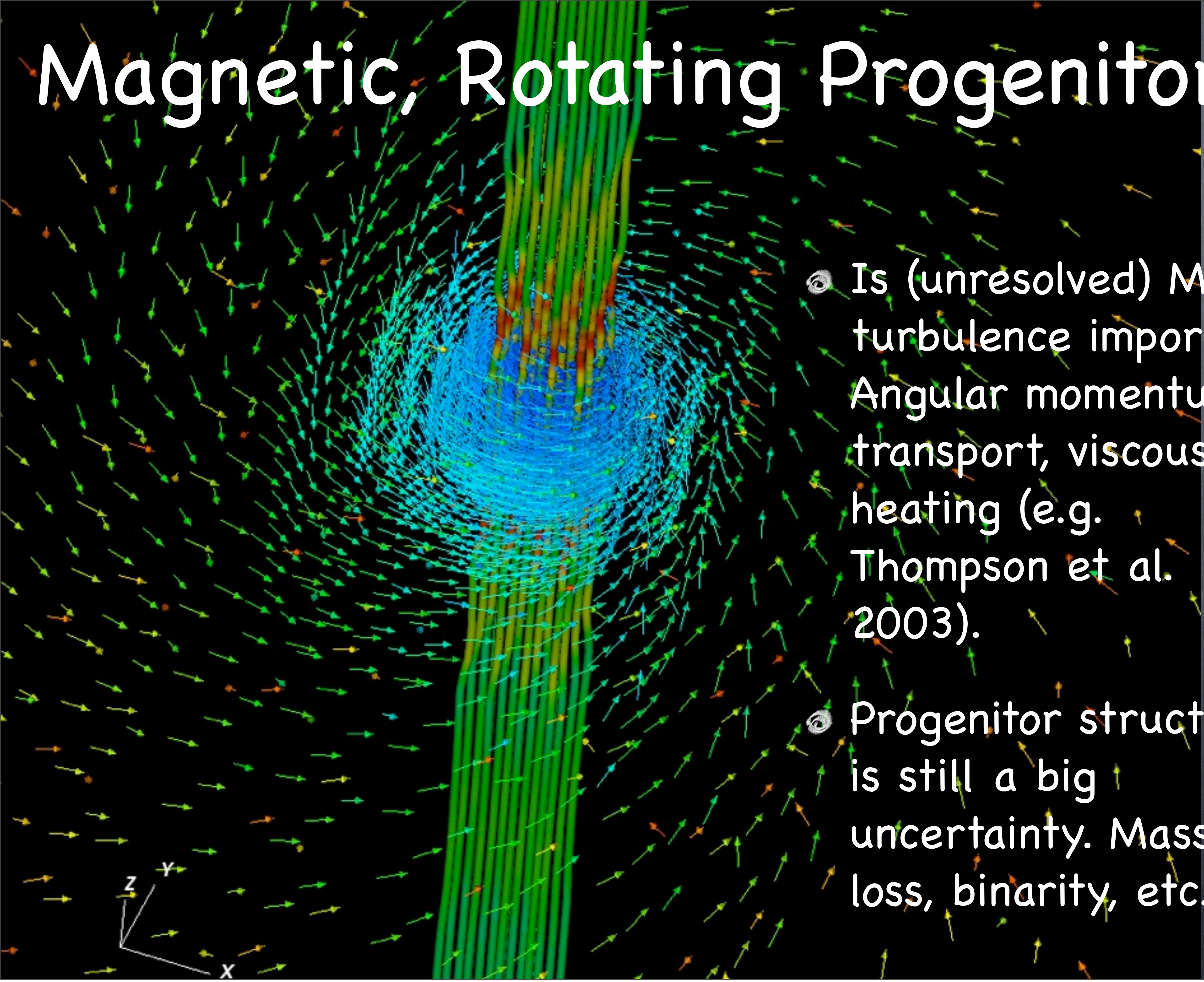

MRI Growth Rate
(s^-1)
10000
1000
100
10
1
0
1e+05
1e+06
1e+07
1e+08
Radius (cm)
2 s^{-1}
1 s^{-1}
0.2 s^{-1}


B_sat
(G)
1e+17
1e+16
1e+15
1e+14
1e+13
1e+12
1e+11
1e+05
1e+06
1e+07
1e+08
Radius (cm)
2 s^{-1}
1 s^{-1}
0.2 s^{-1}

Magnetic, Rotating Progenitors



Magnetic, Rotating Progenitors

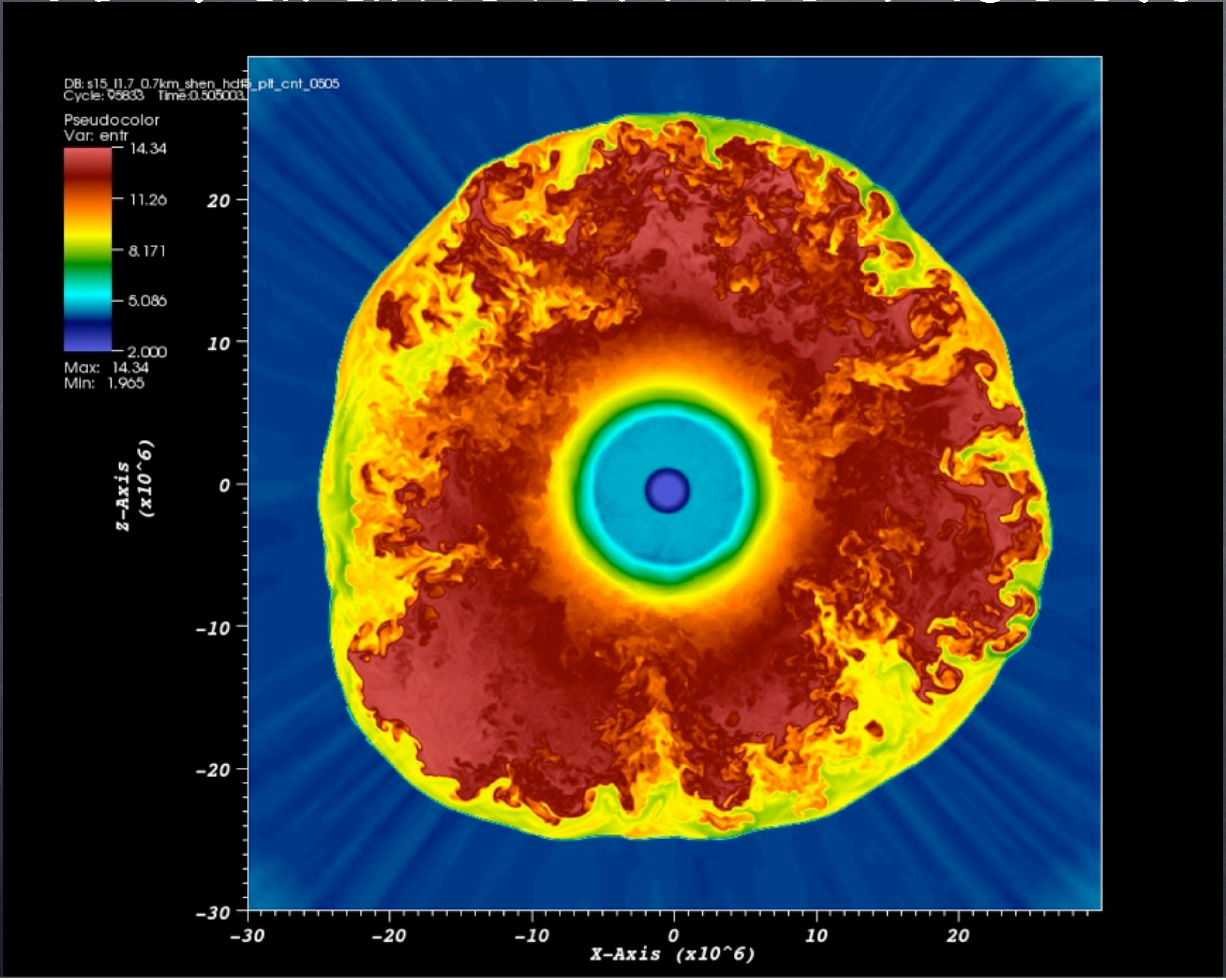


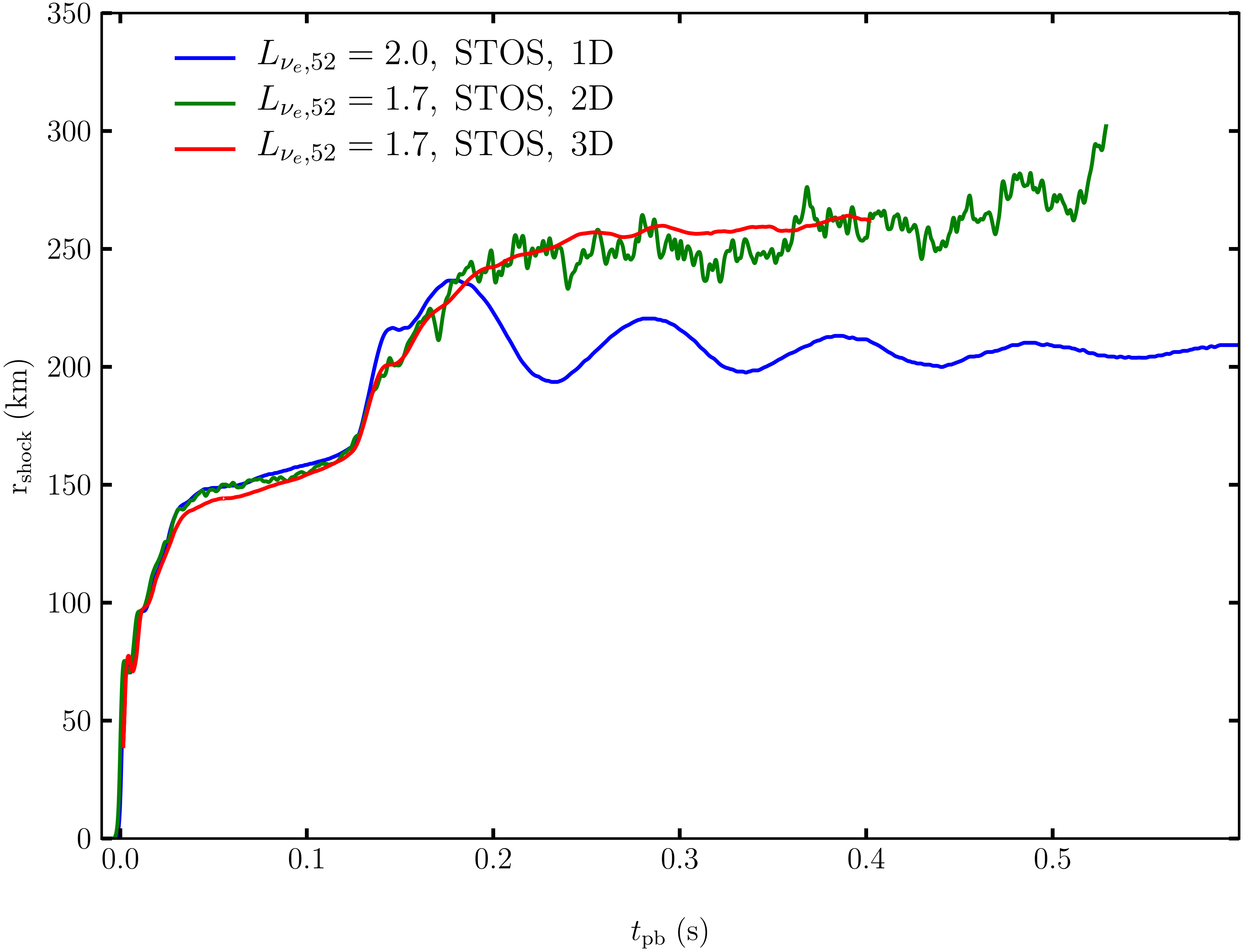
- Is (unresolved) MRI turbulence important? Angular momentum transport, viscous heating (e.g. Thompson et al. 2003).
- Progenitor structure is still a big uncertainty. Mass loss, binarity, etc.

Conclusions

- FLASH is a great tool for astrophysical simulation, and now CCSNe as well
- In parametric-neutrino simulations, the time-to-explosion depends on EOS
- Possibly due to enhanced acoustic flux from PNS accelerating SASI growth
- FLASH 3D parametric simulations on the way!
- Magnetorotational effects need further study. Could be very important for certain progenitors

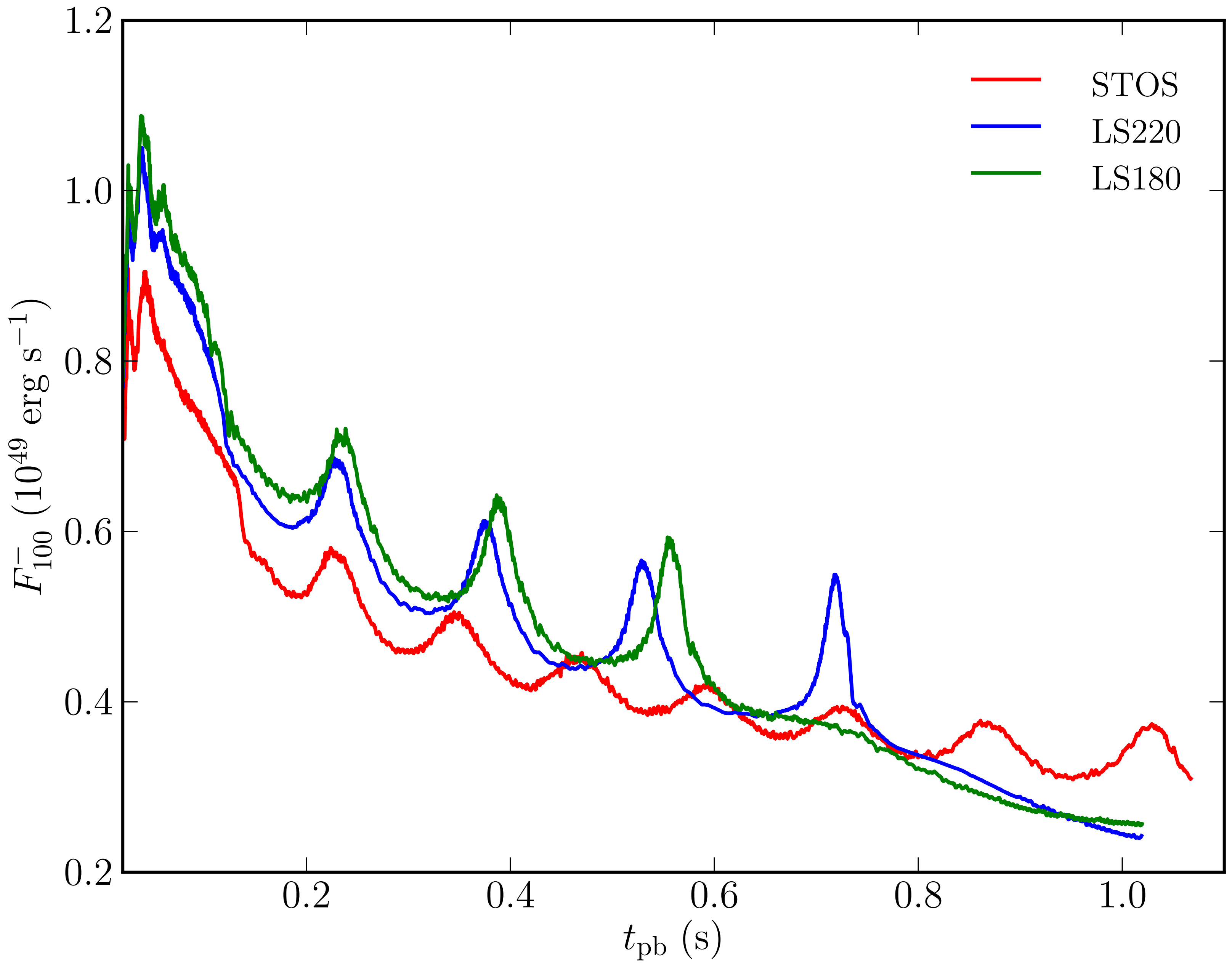
3D Parameterized Models



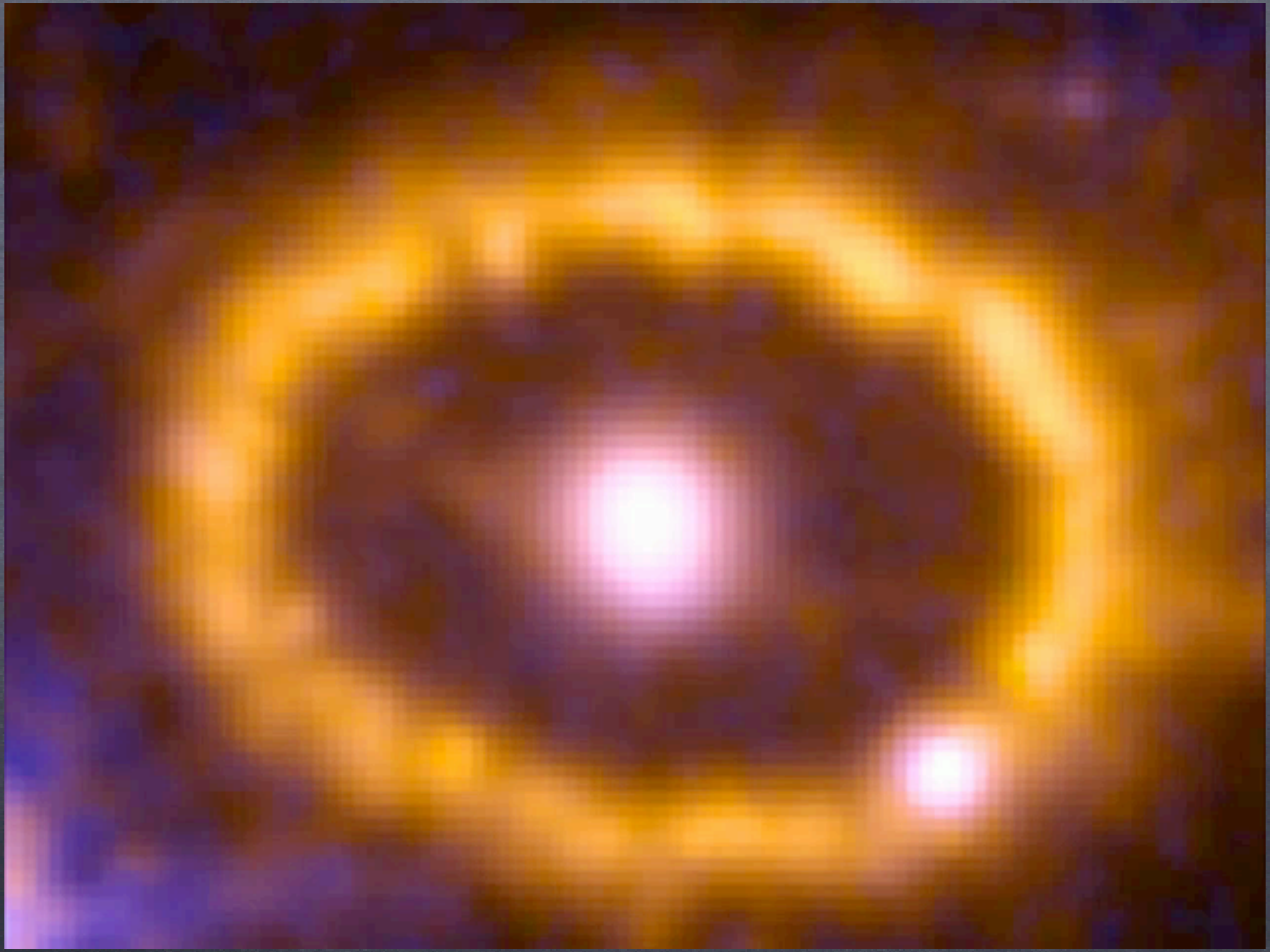


$L_{\nu_e,52} = 2.0,\ \mathrm{STOS},\ \mathrm{1D}$
$L_{\nu_e,52} = 1.7,\ \mathrm{STOS},\ \mathrm{2D}$
$L_{\nu_e,52} = 1.7,\ \mathrm{STOS},\ \mathrm{3D}$
$r_{\rm shock}$ (km)
350
300
250
200
150
100
50
0
0.0
0.1
0.2
0.3
0.4
0.5
$t_{\rm pb}$ (s)

$$F_{100}^{-} = \dot{M} c_S^2 \frac{1-\mathcal{M}}{\mathcal{M}} \left(\frac{\delta P}{\Gamma_1 P} \right).$$

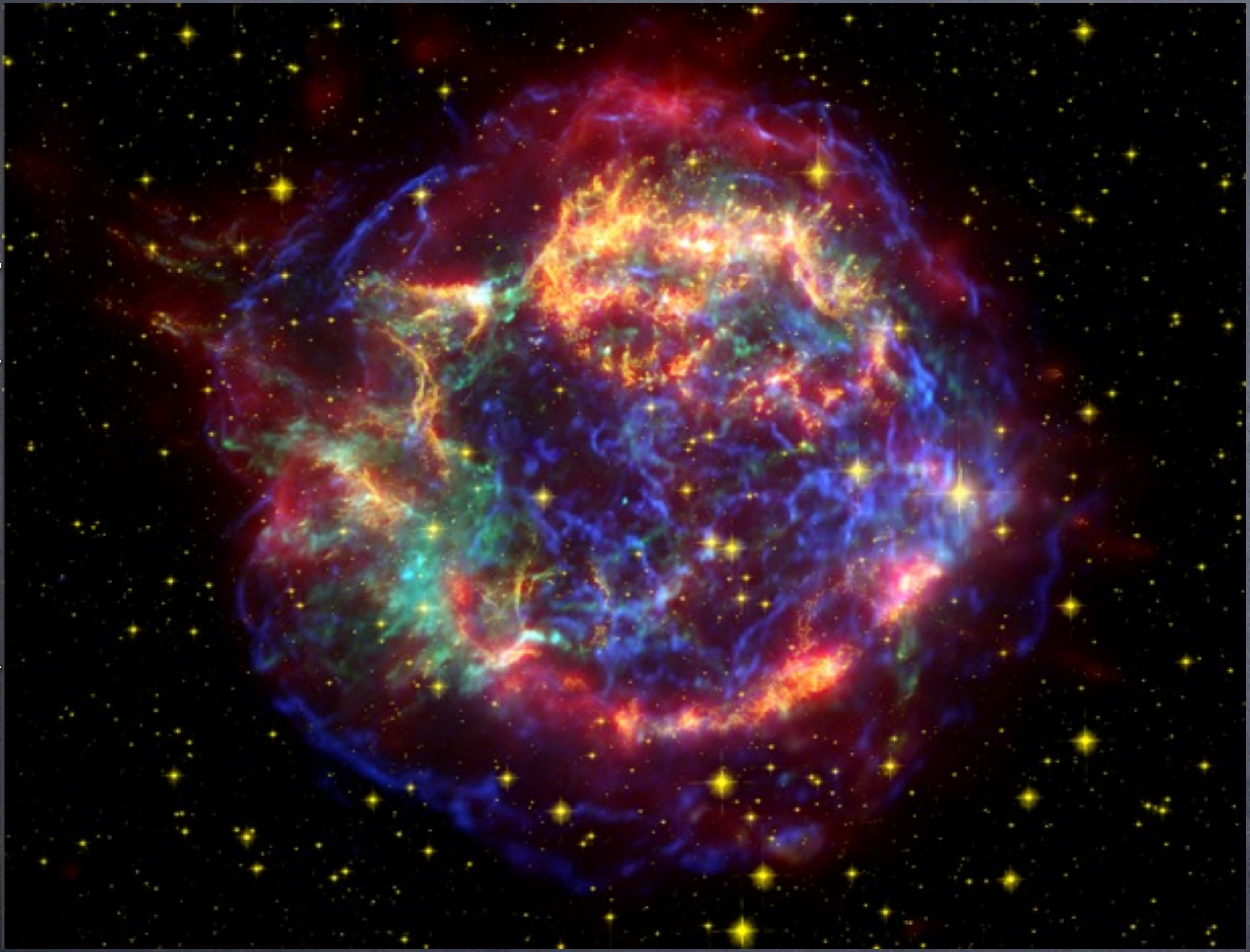


SN 1987A



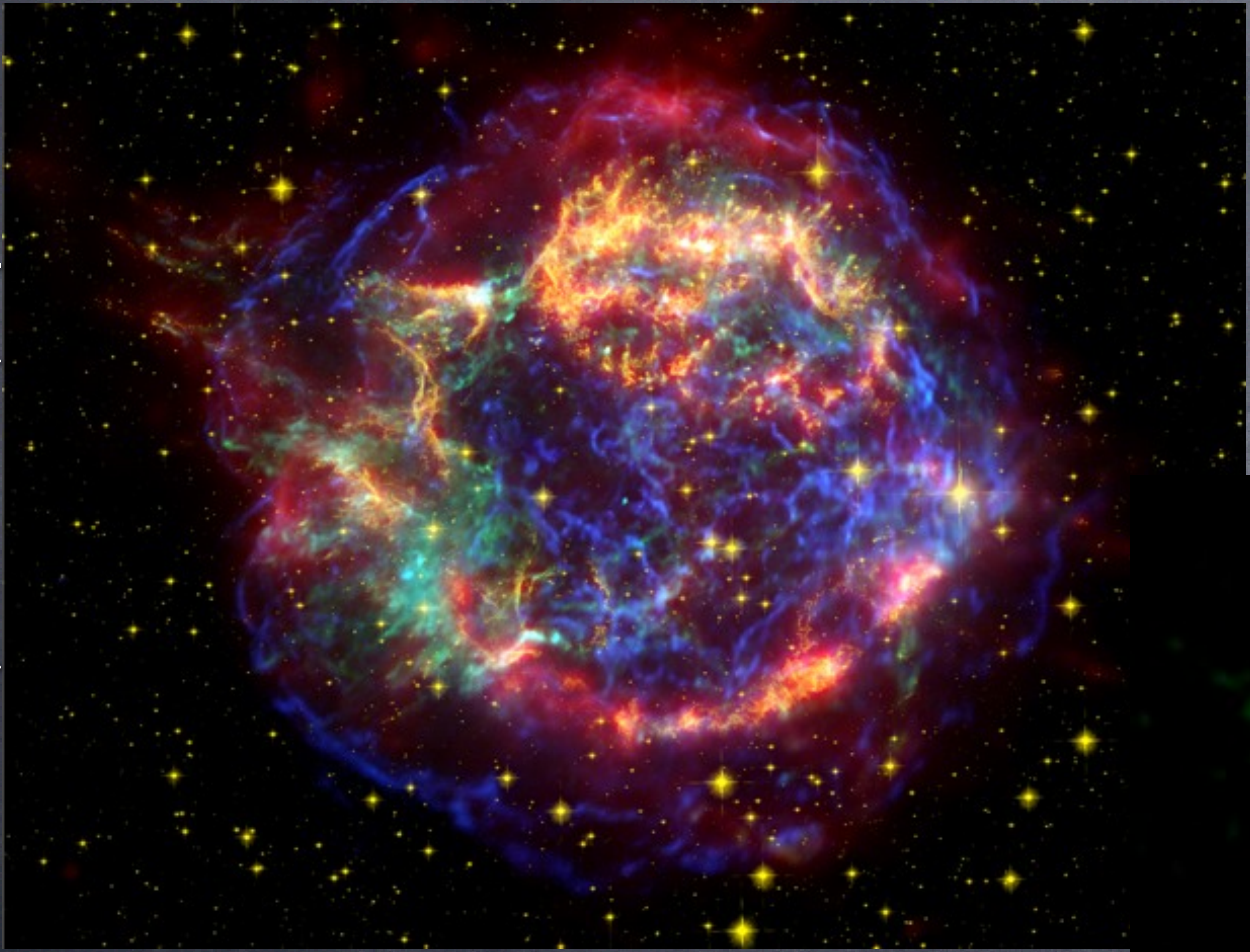
Hubble

Cas A

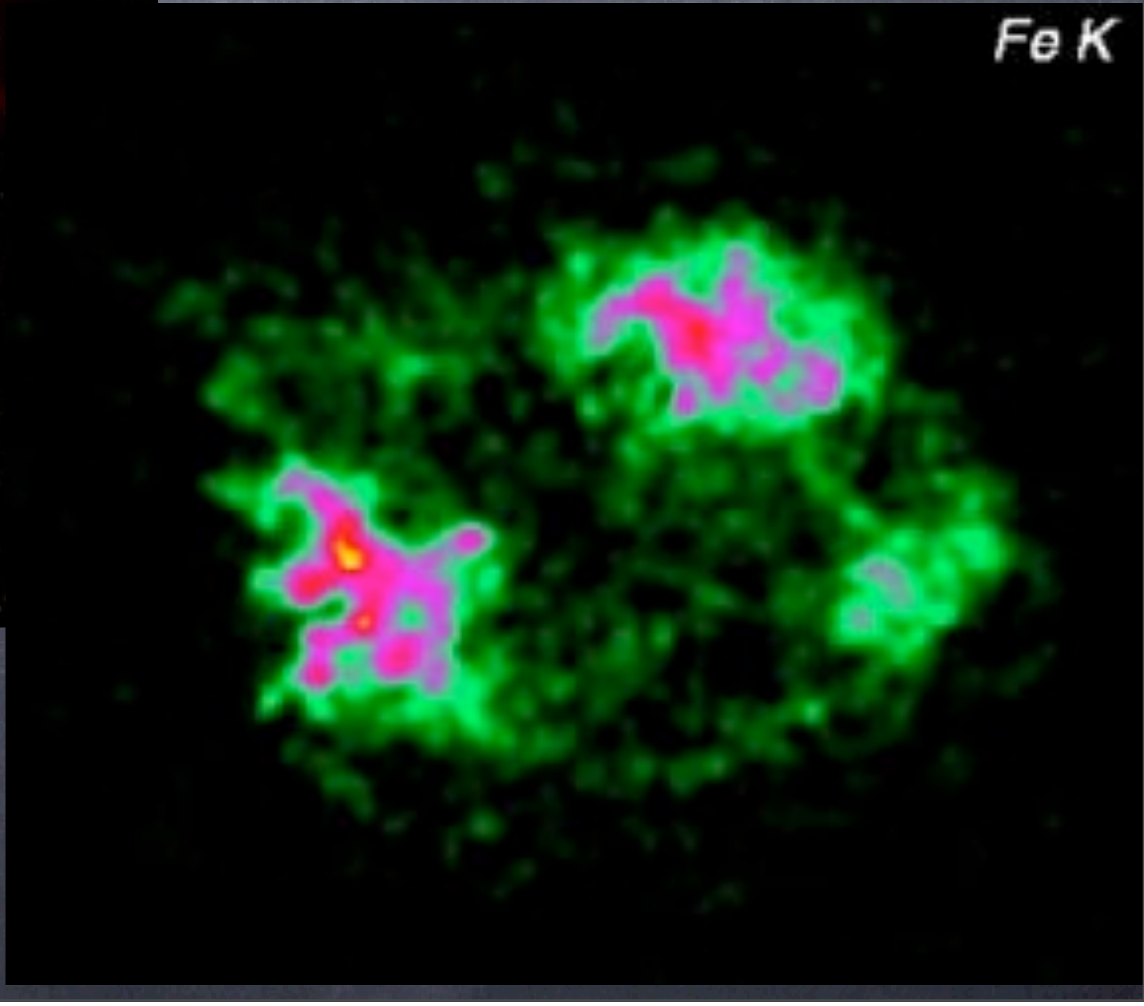


Hubble, Chandra, Spitzer

Cas A


Hubble, Chandra, Spitzer

Chandra



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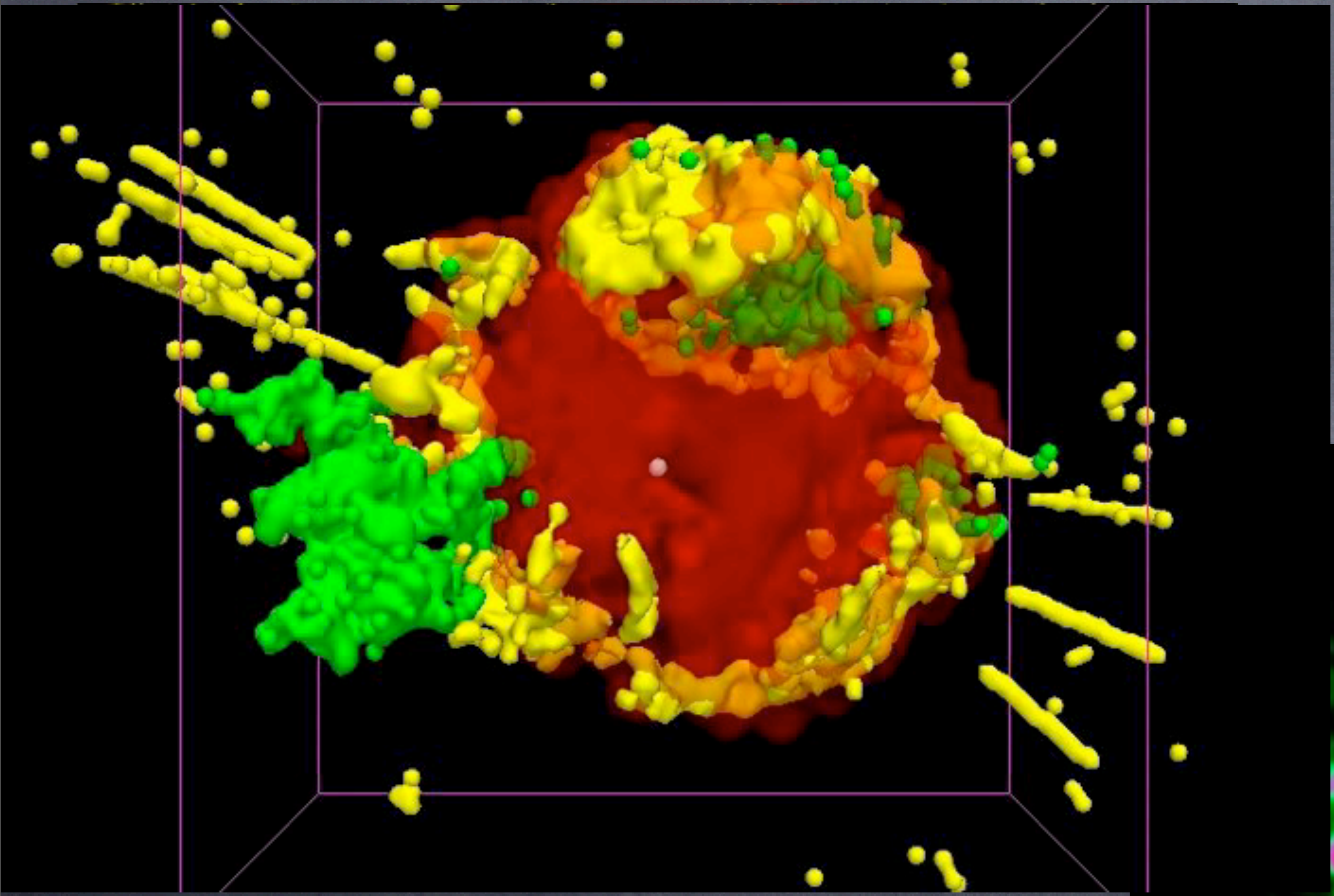
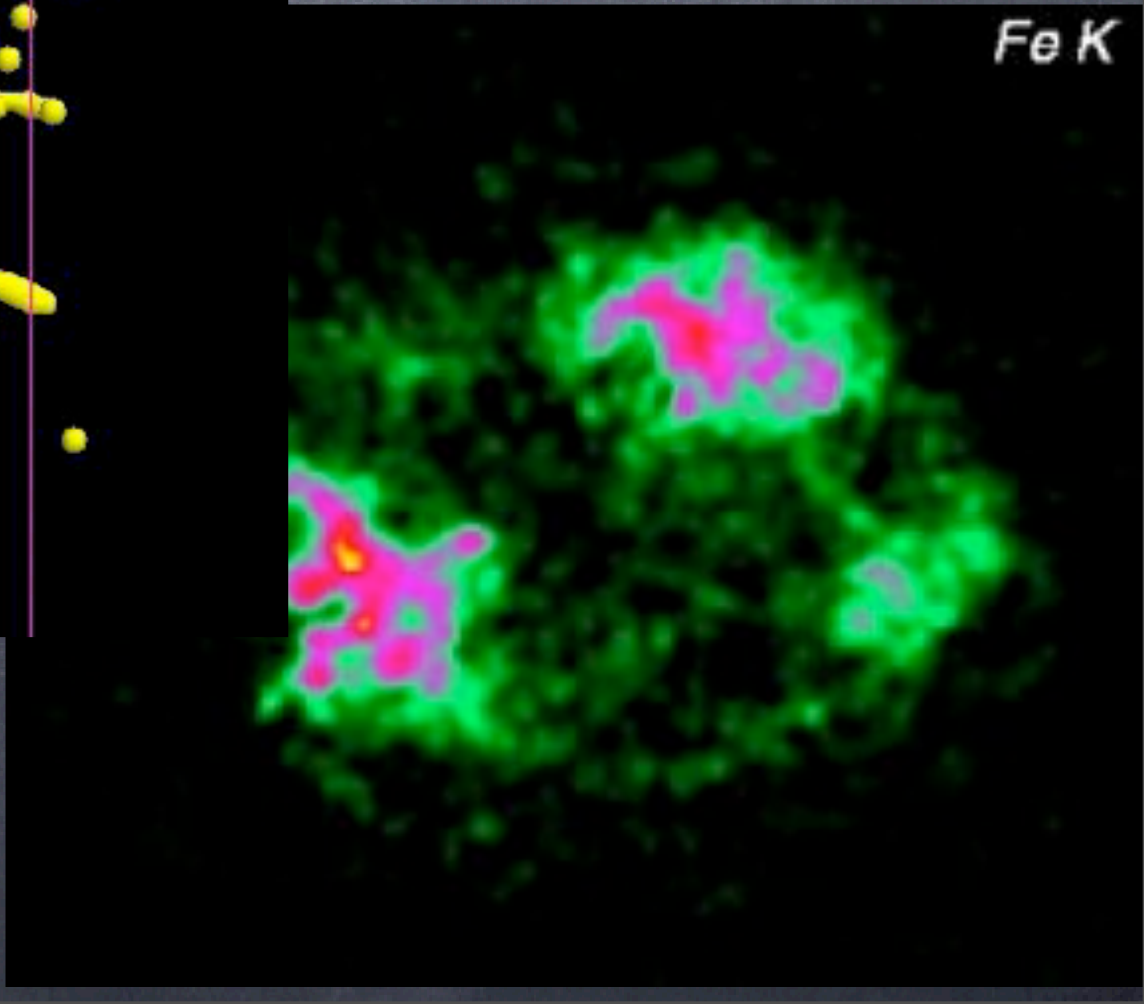


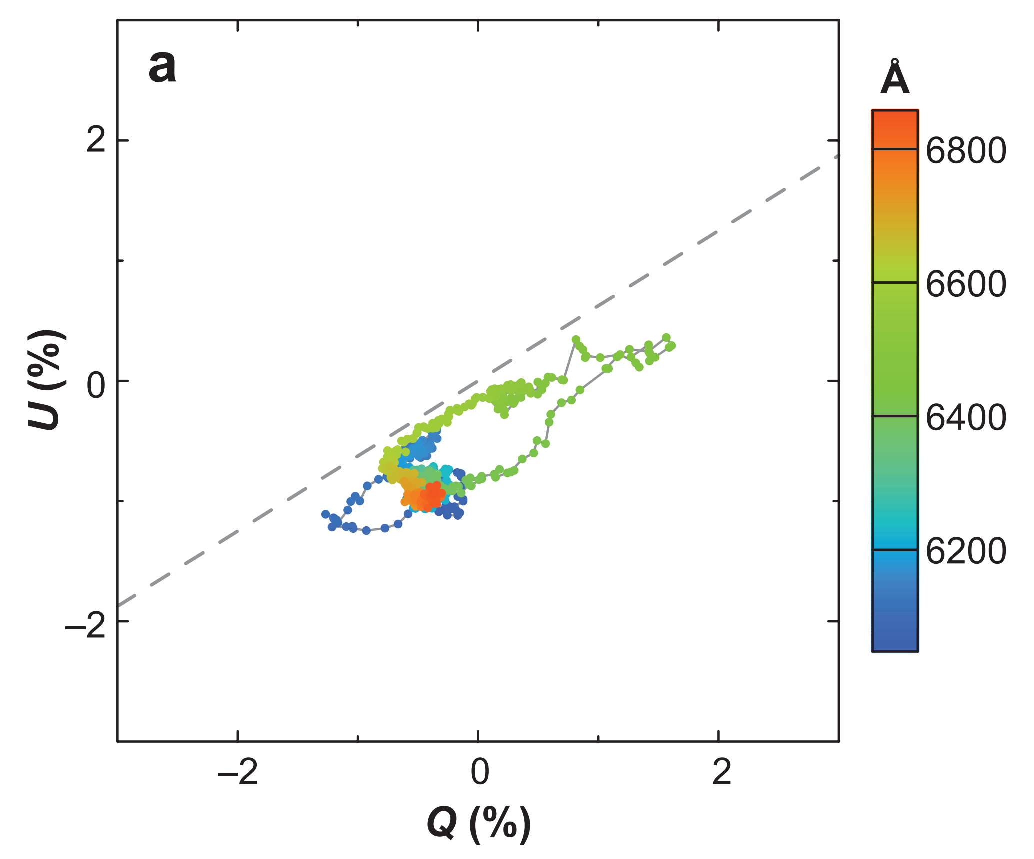
Delaney et al.

Chandra



SN Polarization

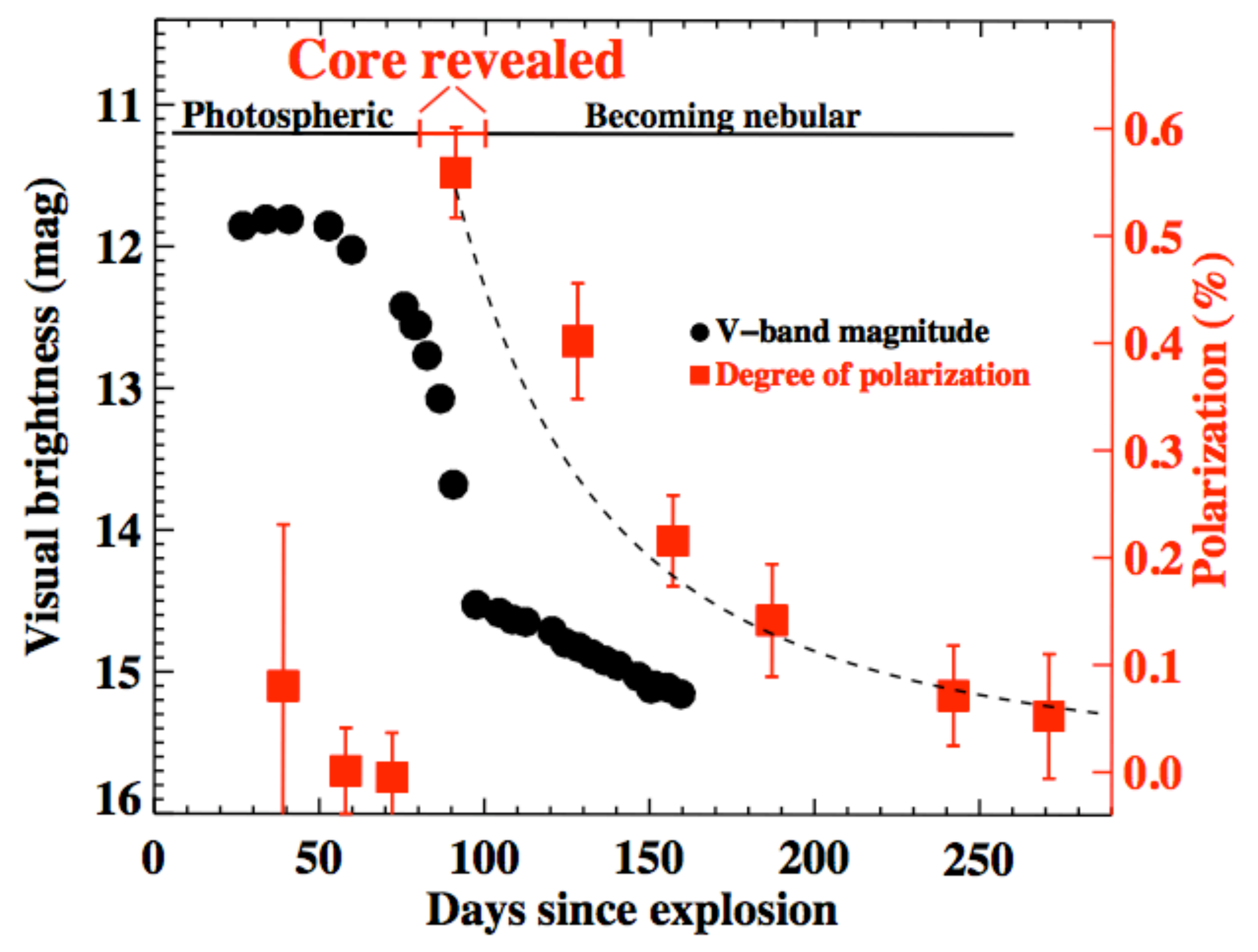
- ALL core-collapse SNe are polarized
- Higher asymmetries in the cores of explosions
- Often show a "dominant axis" in Q/U plane – indicates an elongated explosion
- Loops in Q/U plane indicate non-axisymmetry



Wang & Wheeler 2008

Type IIP Polarization

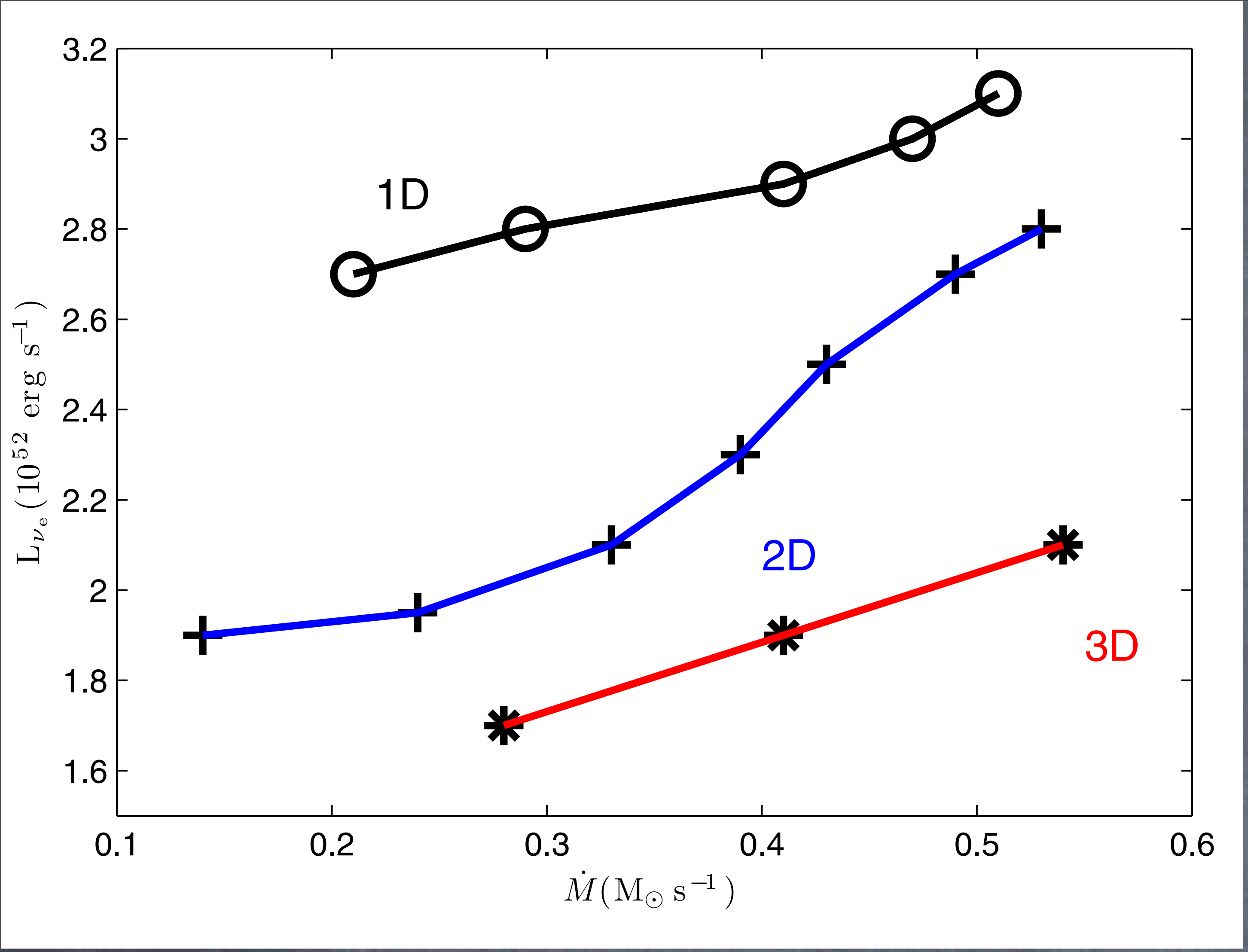
SN 2004dj

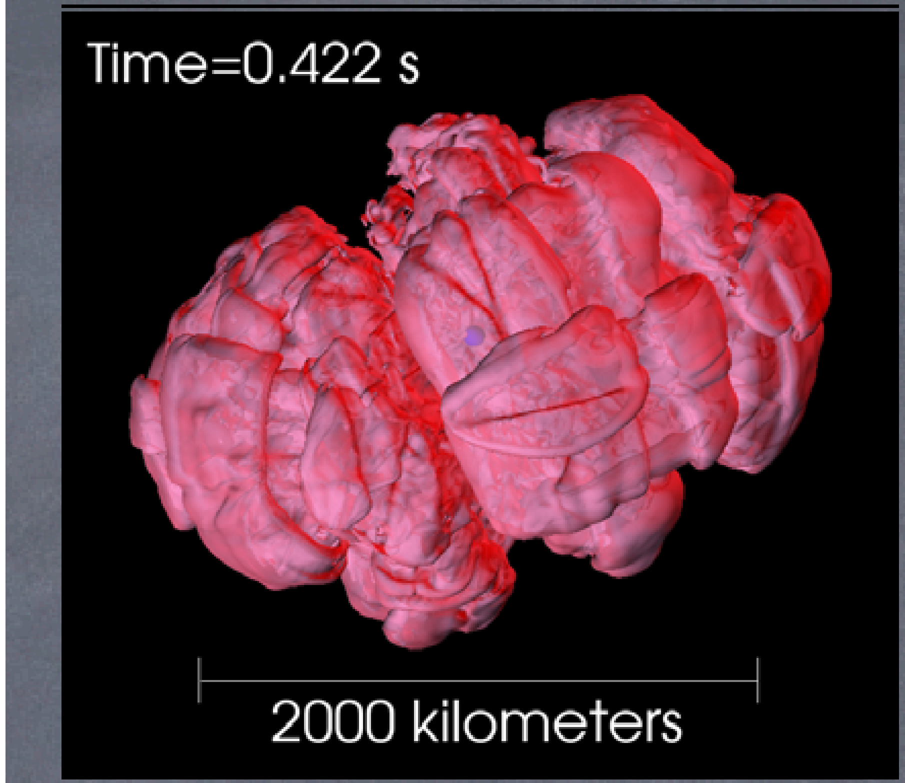


Leonard et al. 2006

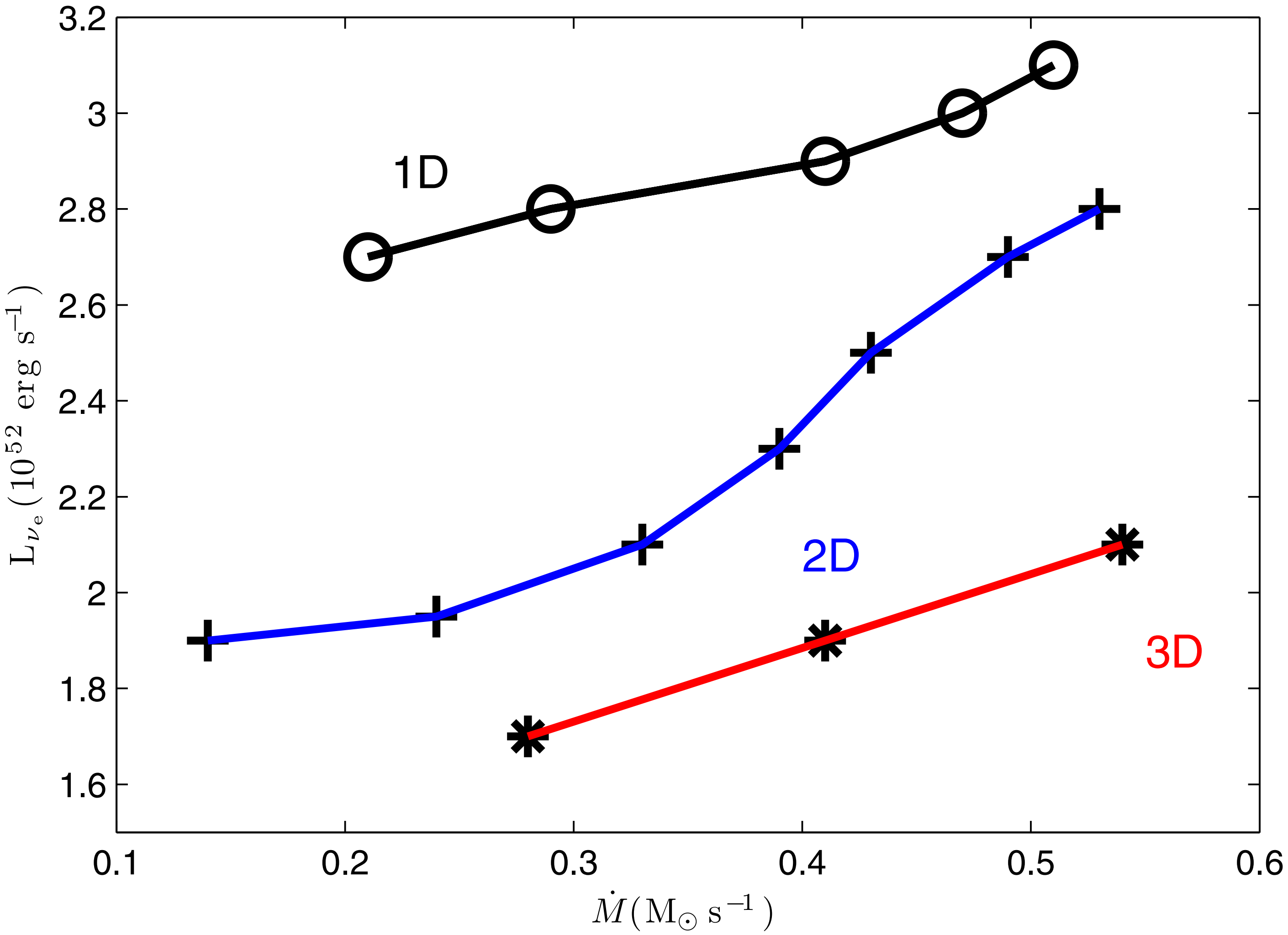
What Do the Observations Tell Us?

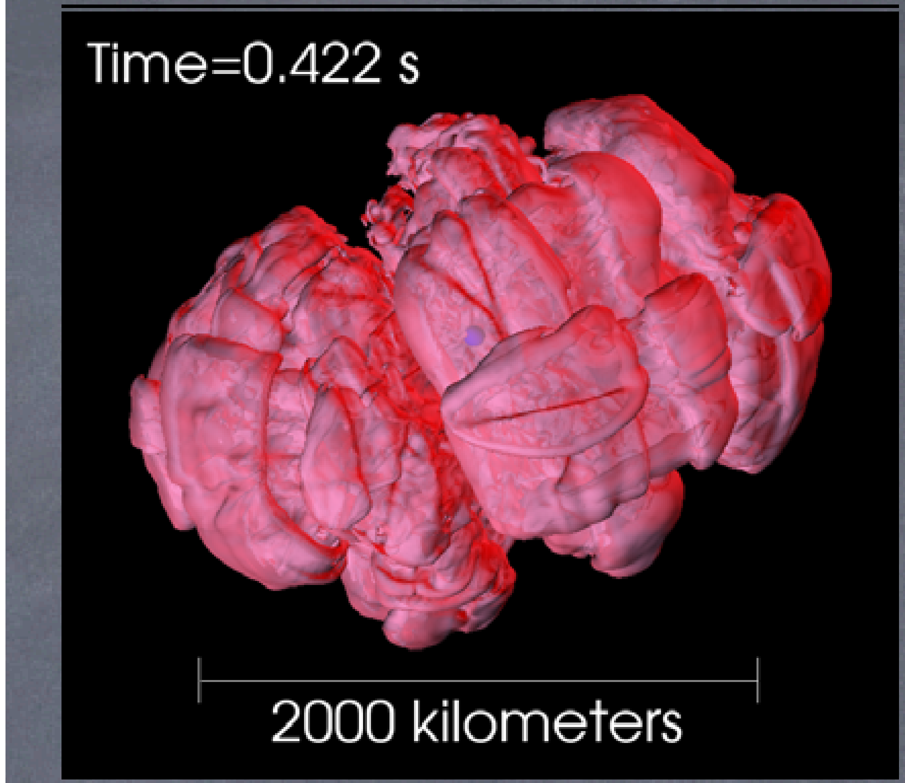
- Massive stars explode all the time, with energies around 10^{51} erg!
- They are NOT spherically-symmetric
- They often show general 'bi-polarity' with significant non-axisymmetry and time-dependent polarization.
- They leave remnants that often have high kick velocities and strong magnetic fields.
- Some CCSNe are associated with GRBs.
- Mixing & overturn commonly indicated.





Nordhaus et al. 2010





Nordhaus et al. 2010

Hanke et al. 2011