Magnetic Fields and Asymmetric Core Collapse Supernovae

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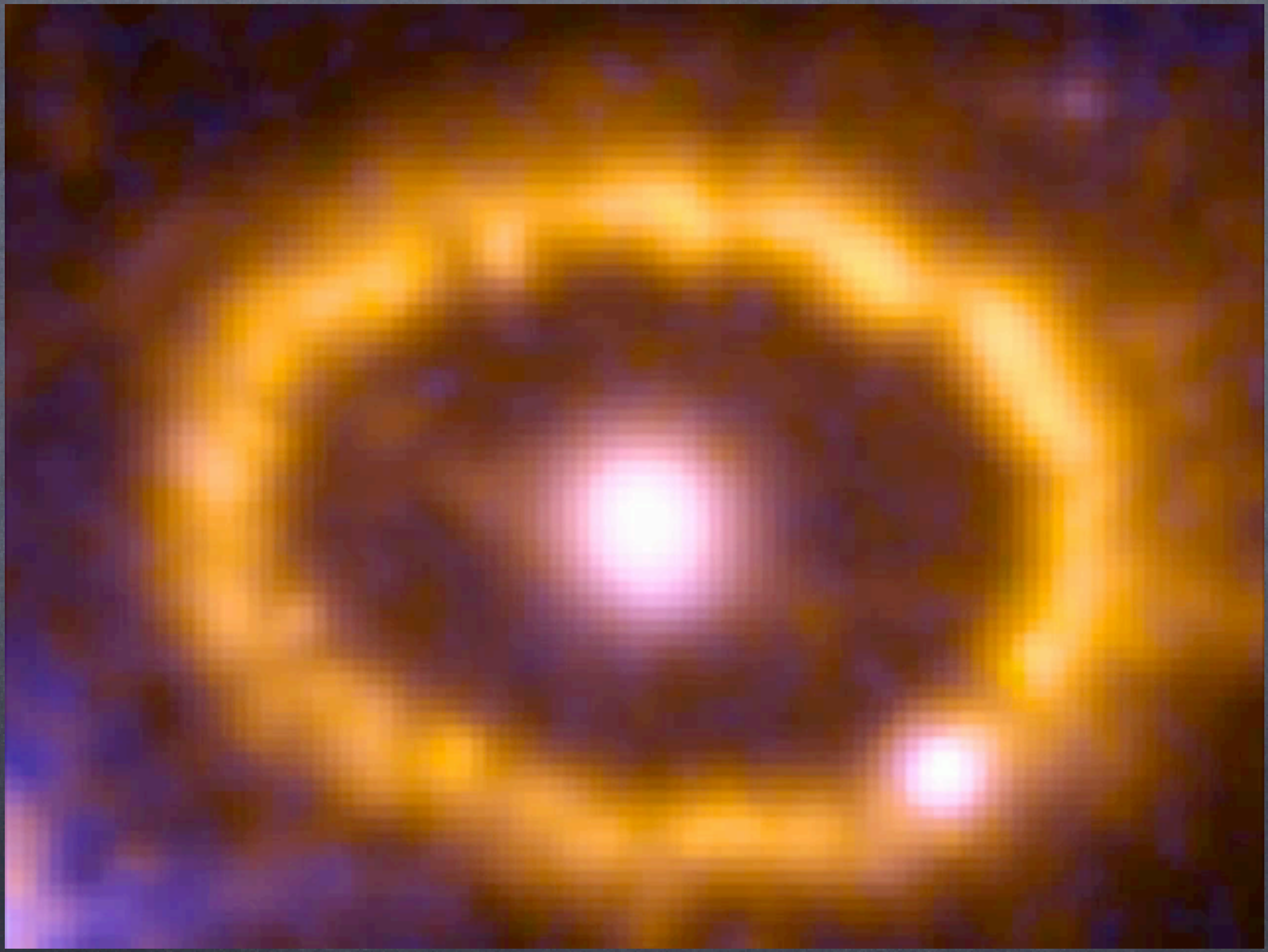
- CCSN Observations indicate asymmetry
- Basic Physics of CCSN & the Neutrino Mechanism
- 1D, 2D, & 3D simulations
- Magnetorotational CCSN
- Can MR-CCSN fit the observations?
- Basics of Magnetohydrodynamics
- MHD in CCSN

So, Who cares?

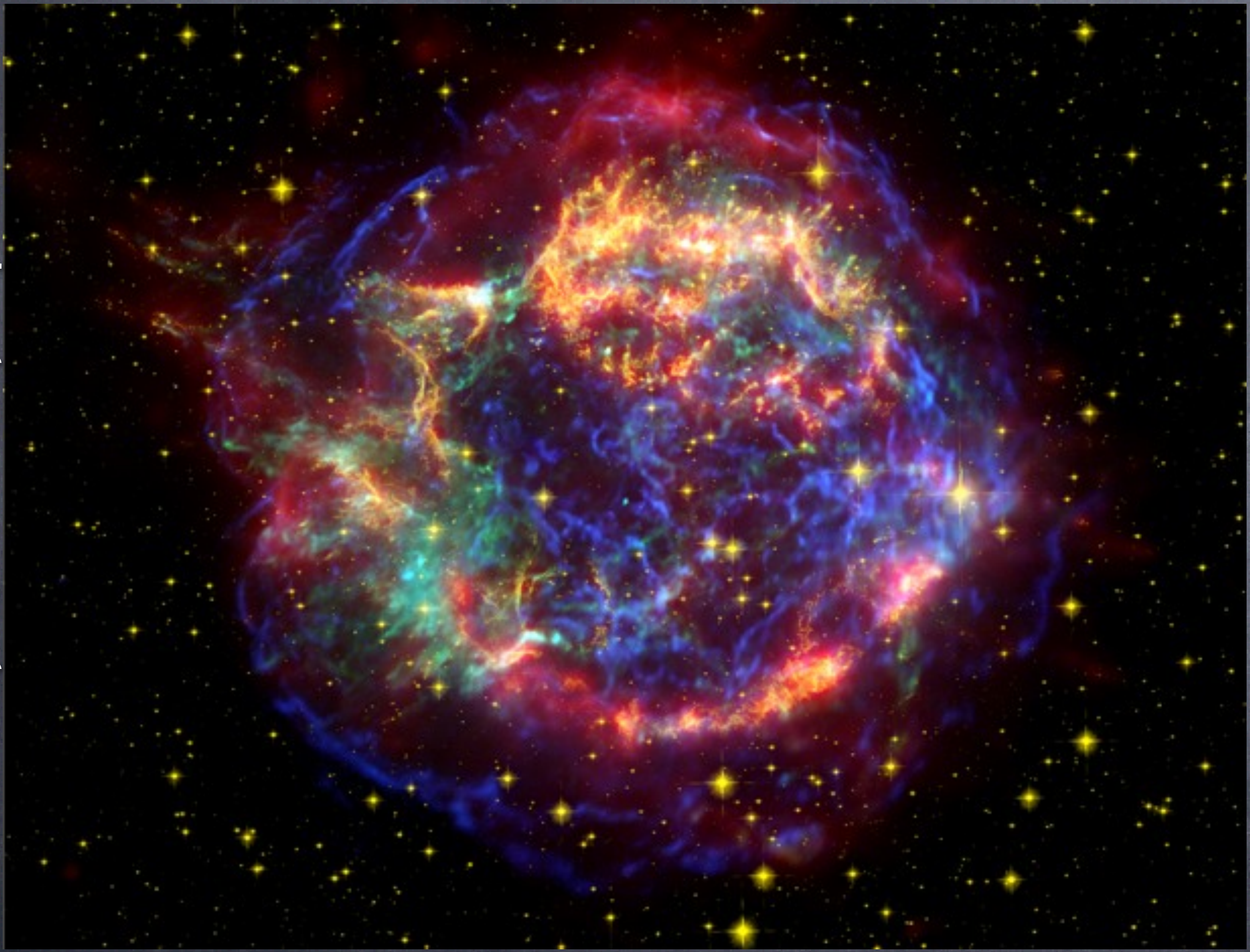
- Real stars rotate and are magnetic!
- The initial conditions are still uncertain...
- Could have dramatic effect on explosion dynamics
- May be critical to explaining observations
- Magnetars, Pulsars, GRBs, oh My!

SN 1987A



Hubble

Cas A



Hubble, Chandra, Spitzer

Cas A

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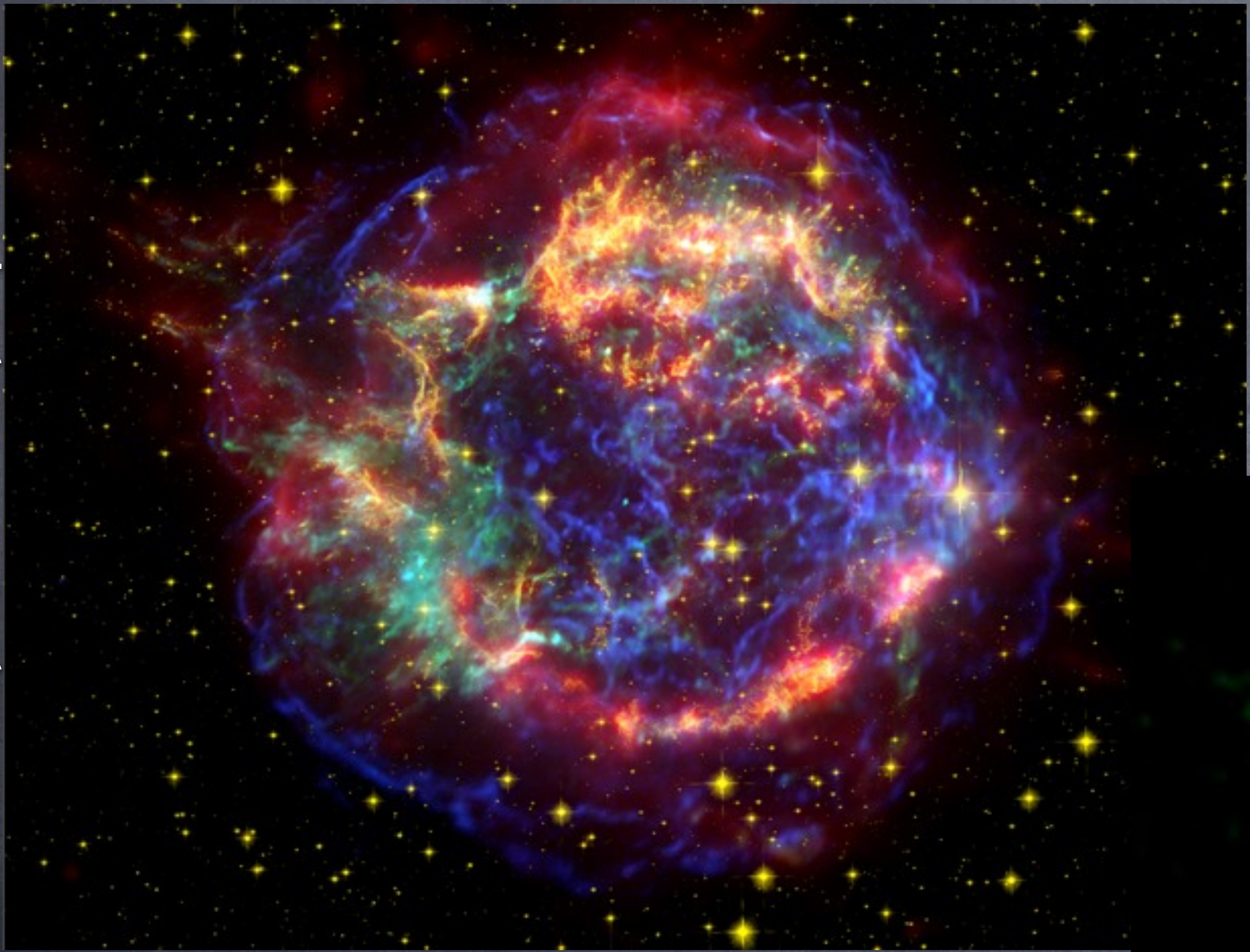
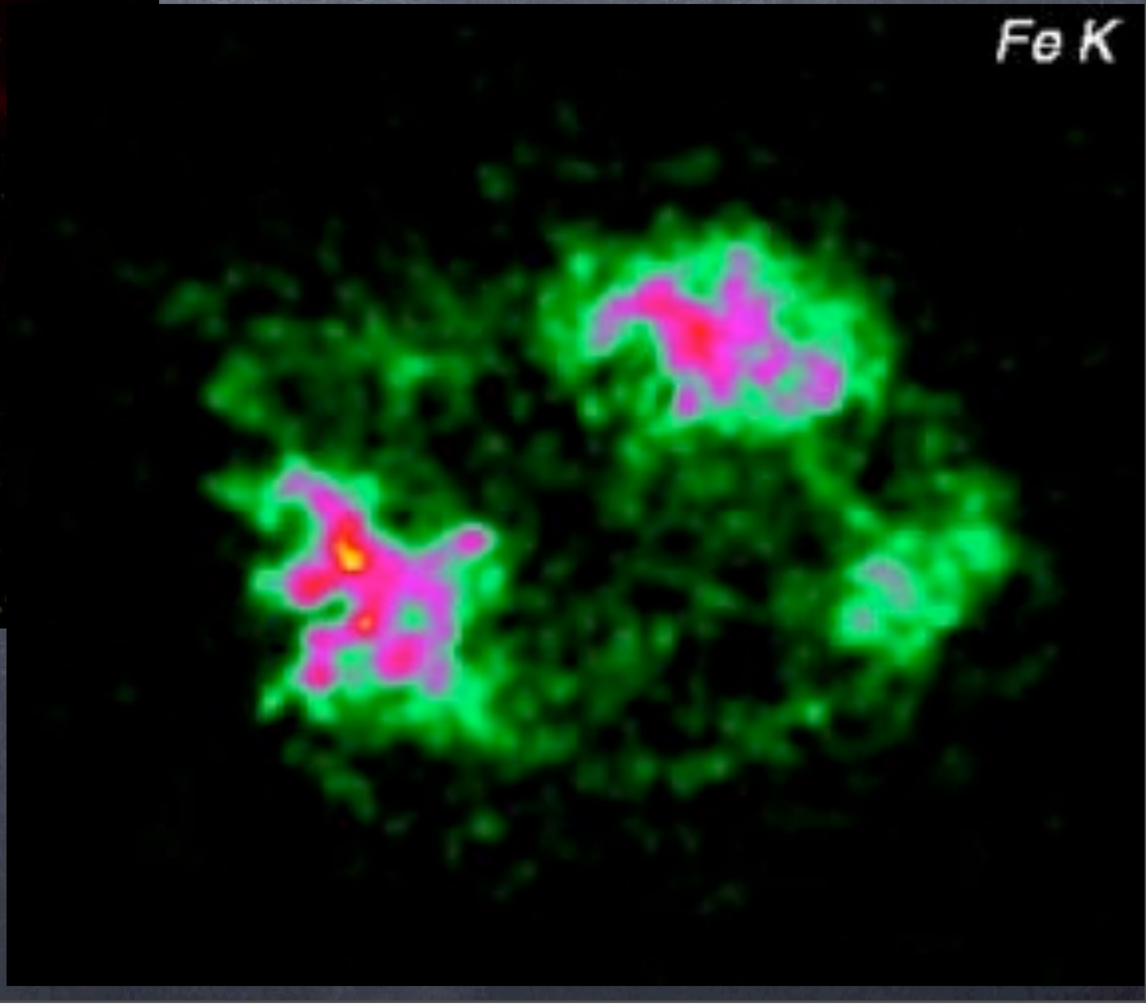
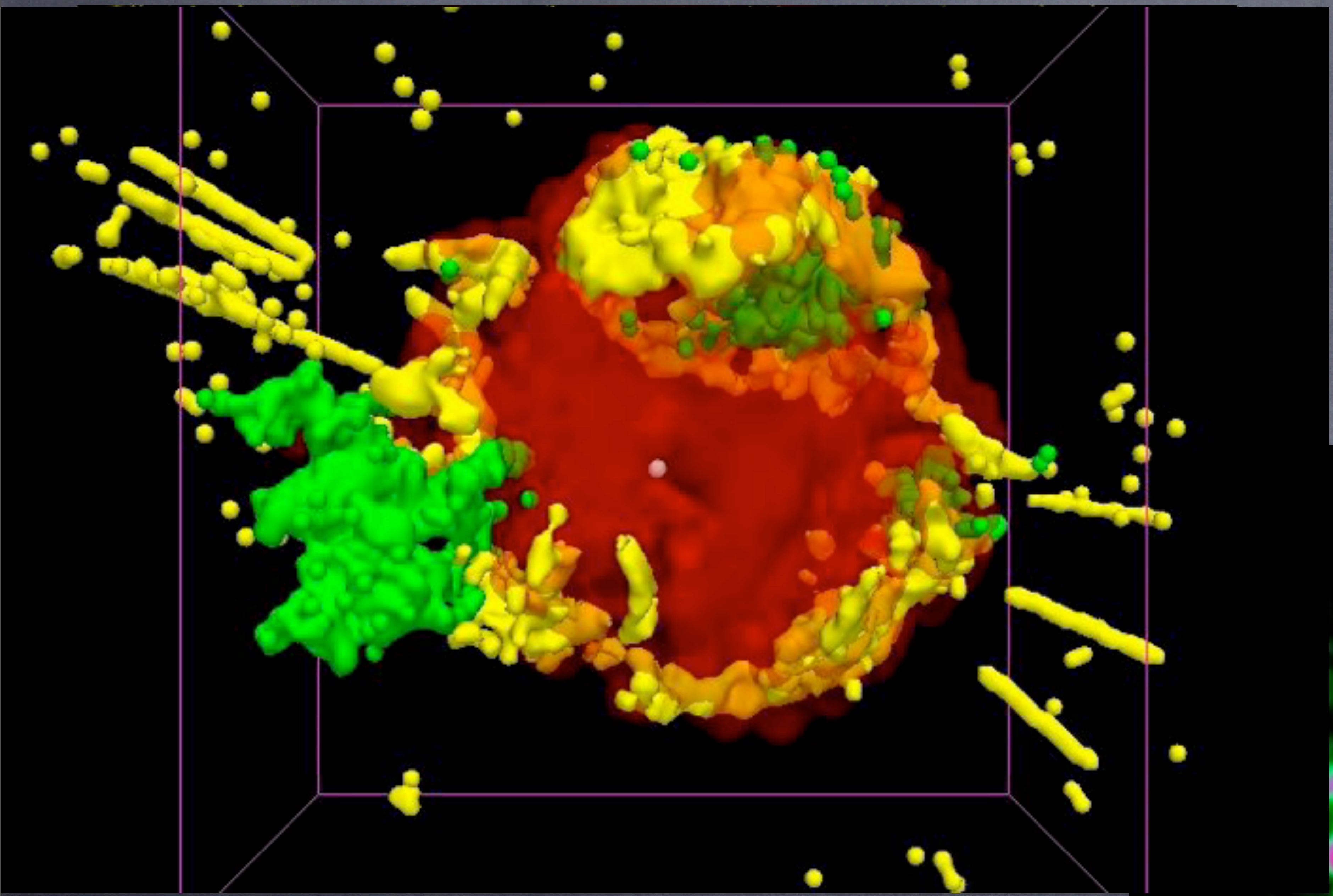


Chandra

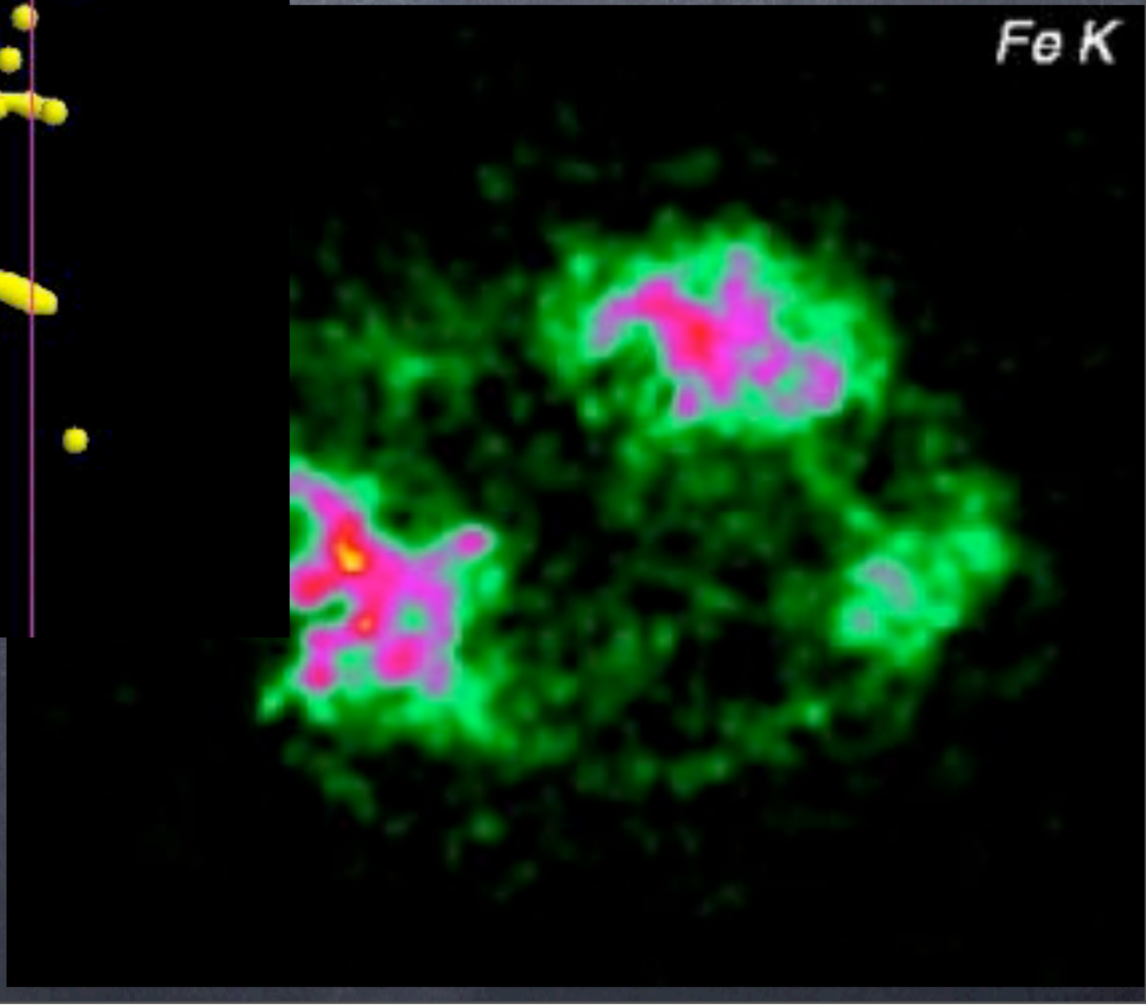


Cas A



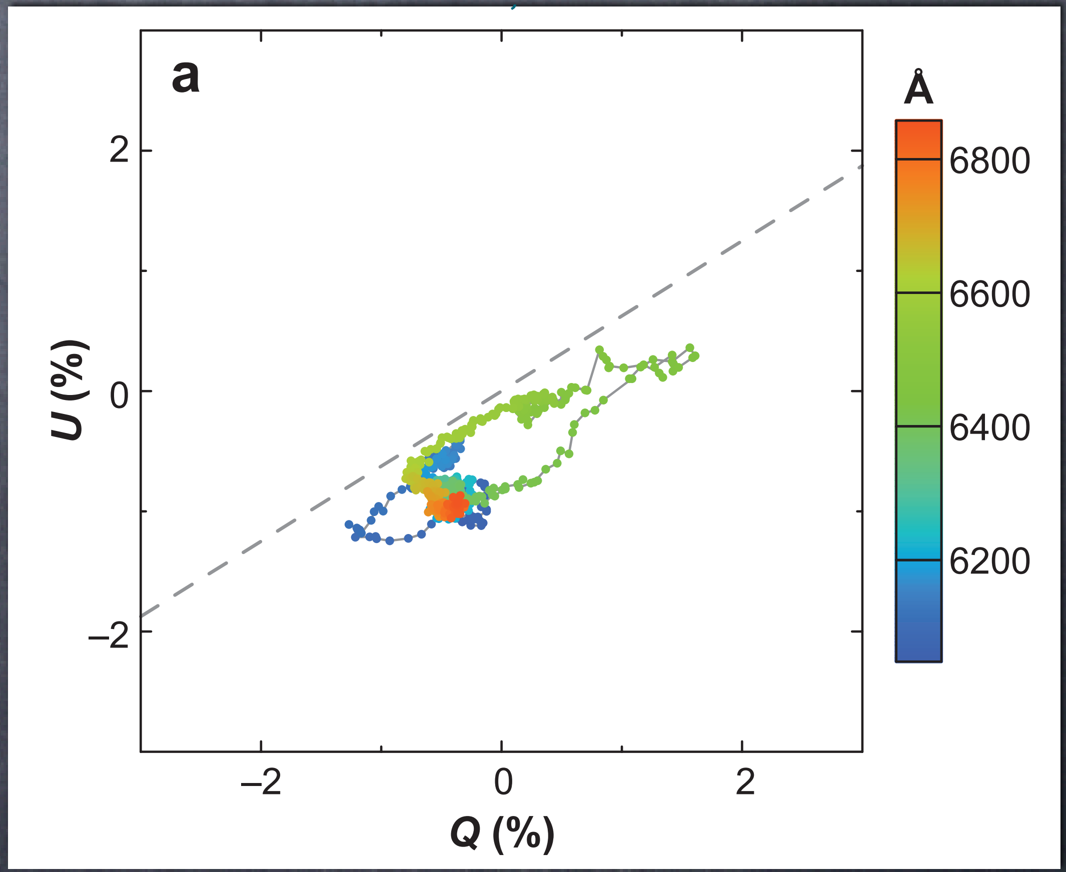
Delaney et al.

Chandra



SN Polarization

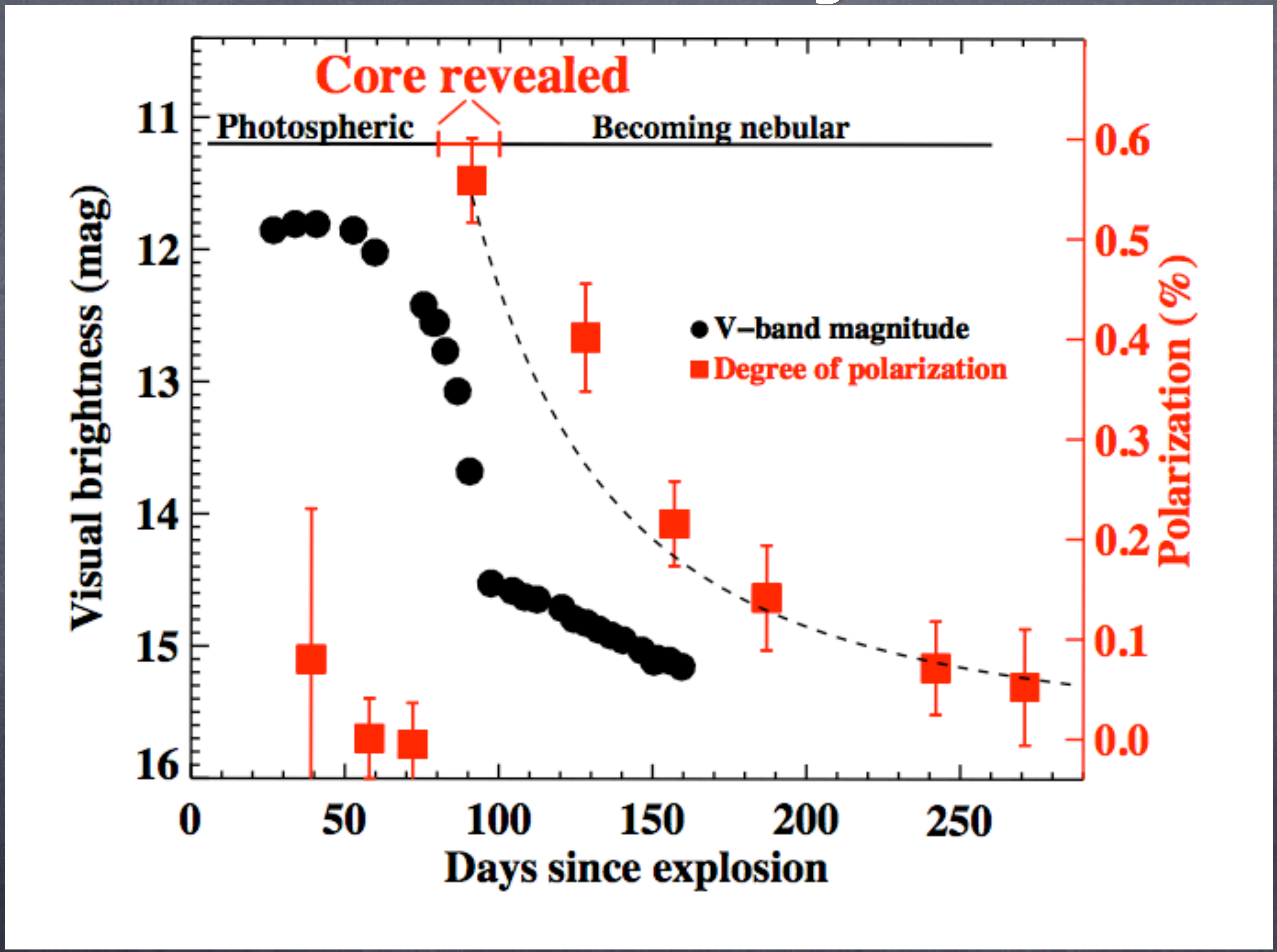
- ALL core-collapse SNe are polarized
- Higher asymmetries in the cores of explosions
- Often show a "dominant axis" in Q/U plane - indicates an elongated explosion
- Loops in Q/U plane indicate non-axisymmetry



Wang & Wheeler 2008

Type IIP Polarization

SN 2004dj



Leonard et al. 2006

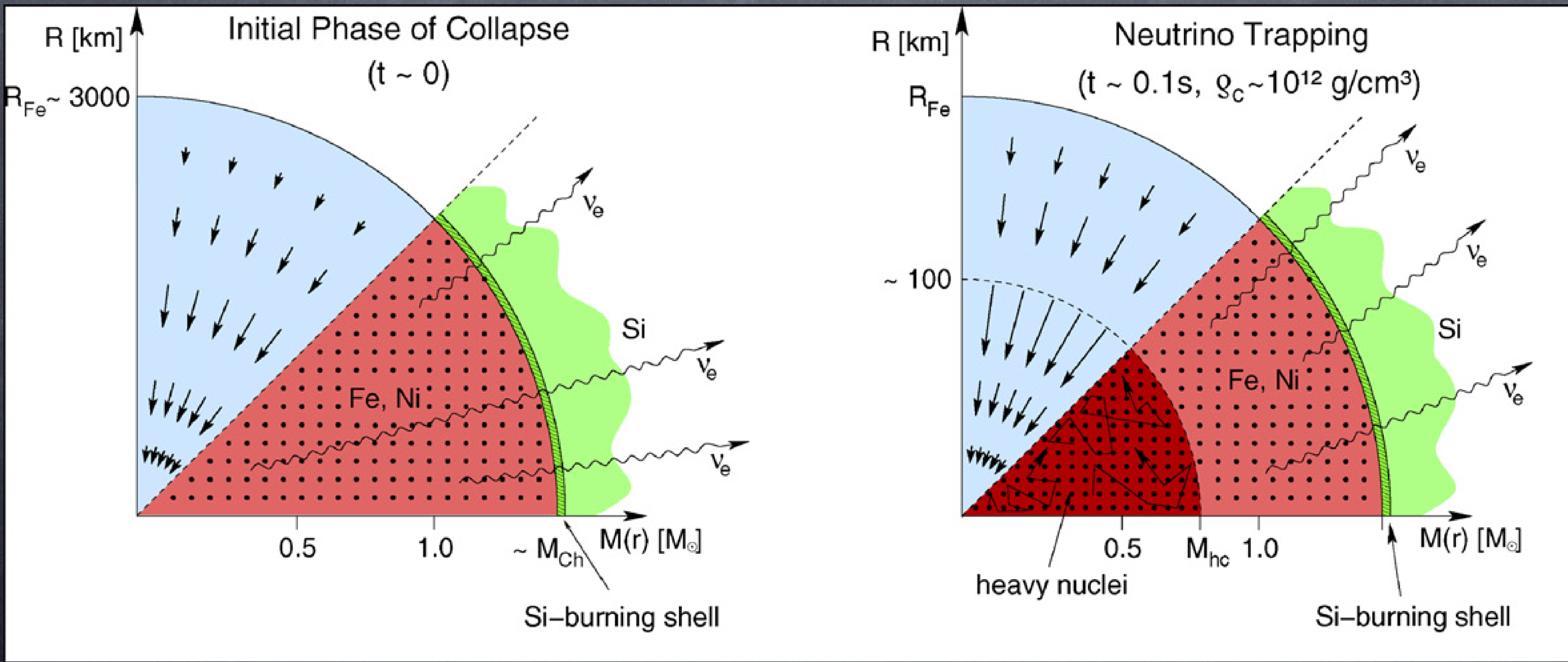
What Do the Observations Tell Us?

- 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.

Core Collapse Basics

$$e^- + p^+ \rightarrow n + \nu_e$$

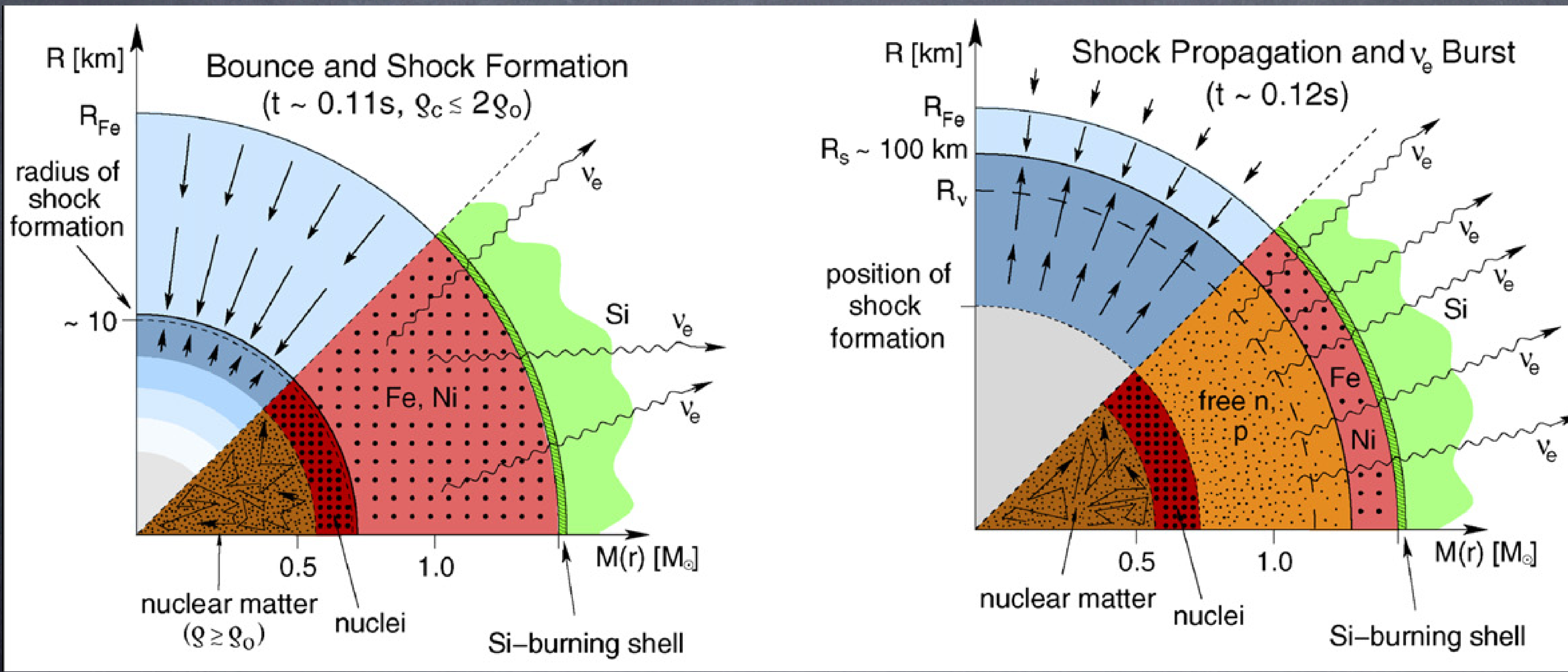
e^- degeneracy pressure fails



Janka (2007)

Core Collapse Basics

$$\rho_0 \sim 10^{14}\ \mathrm{g\ cm^{-3}}$$



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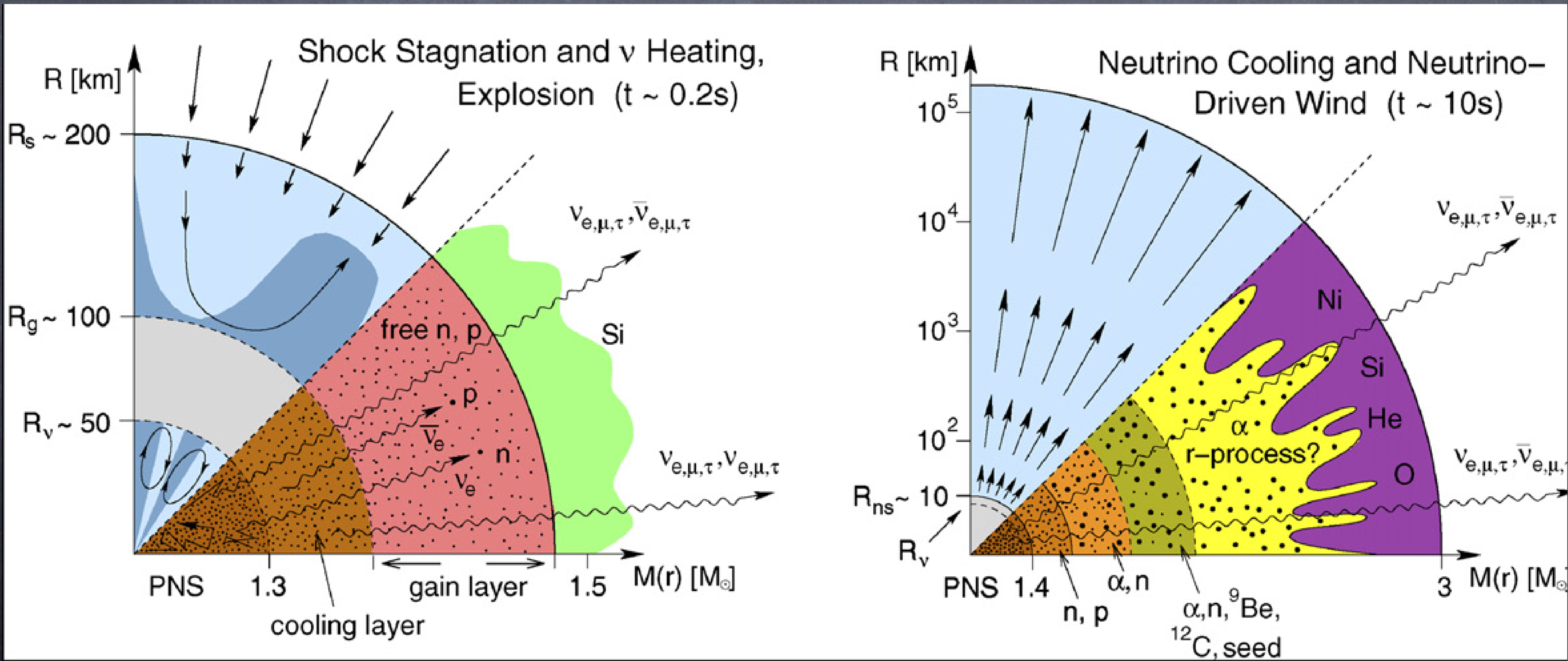
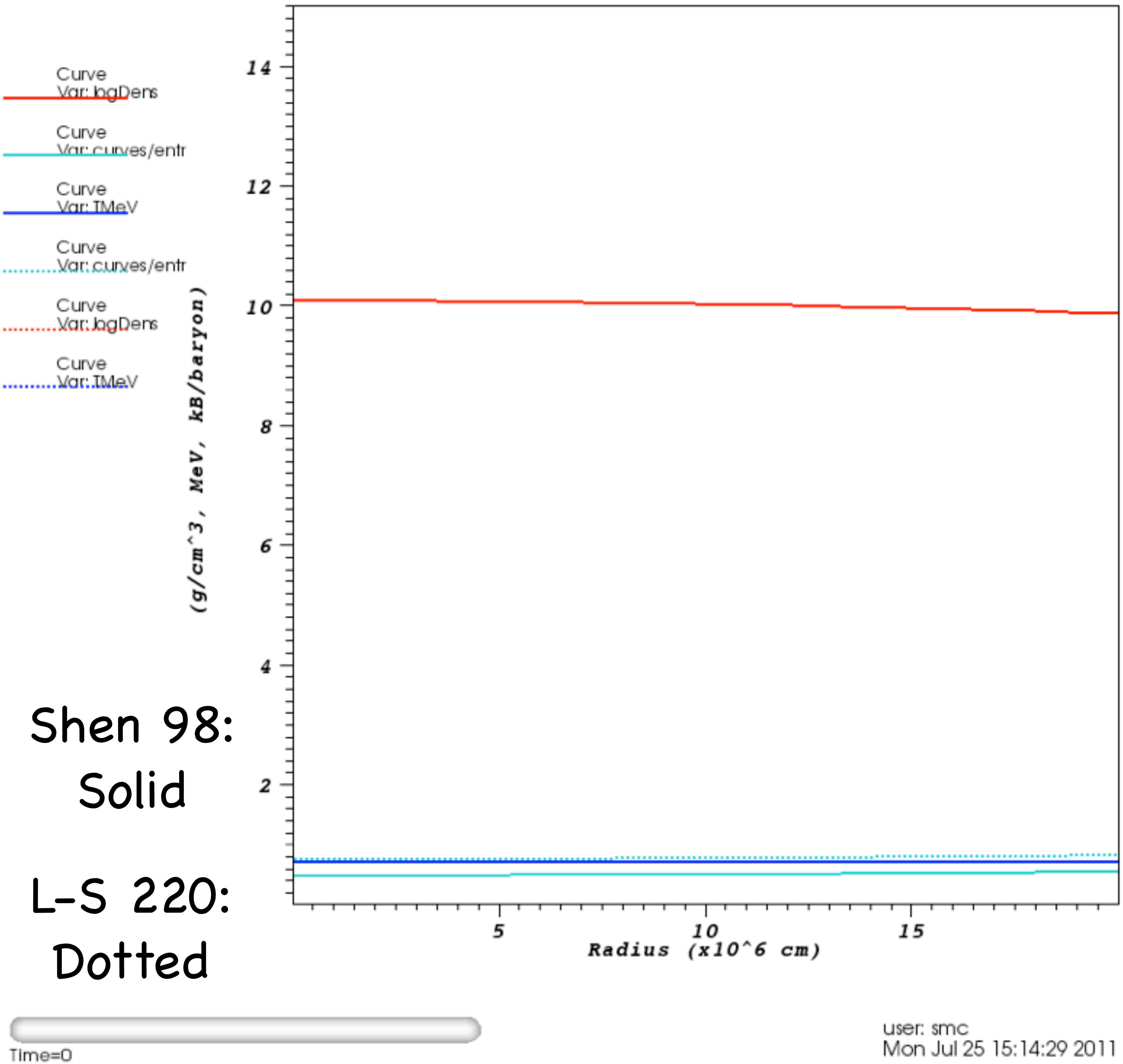


Janka (2007)

Shen 98:
Solid

L-S 220:
Dotted



Shen 98: Solid

L-S 220: Dotted

What's the big deal?

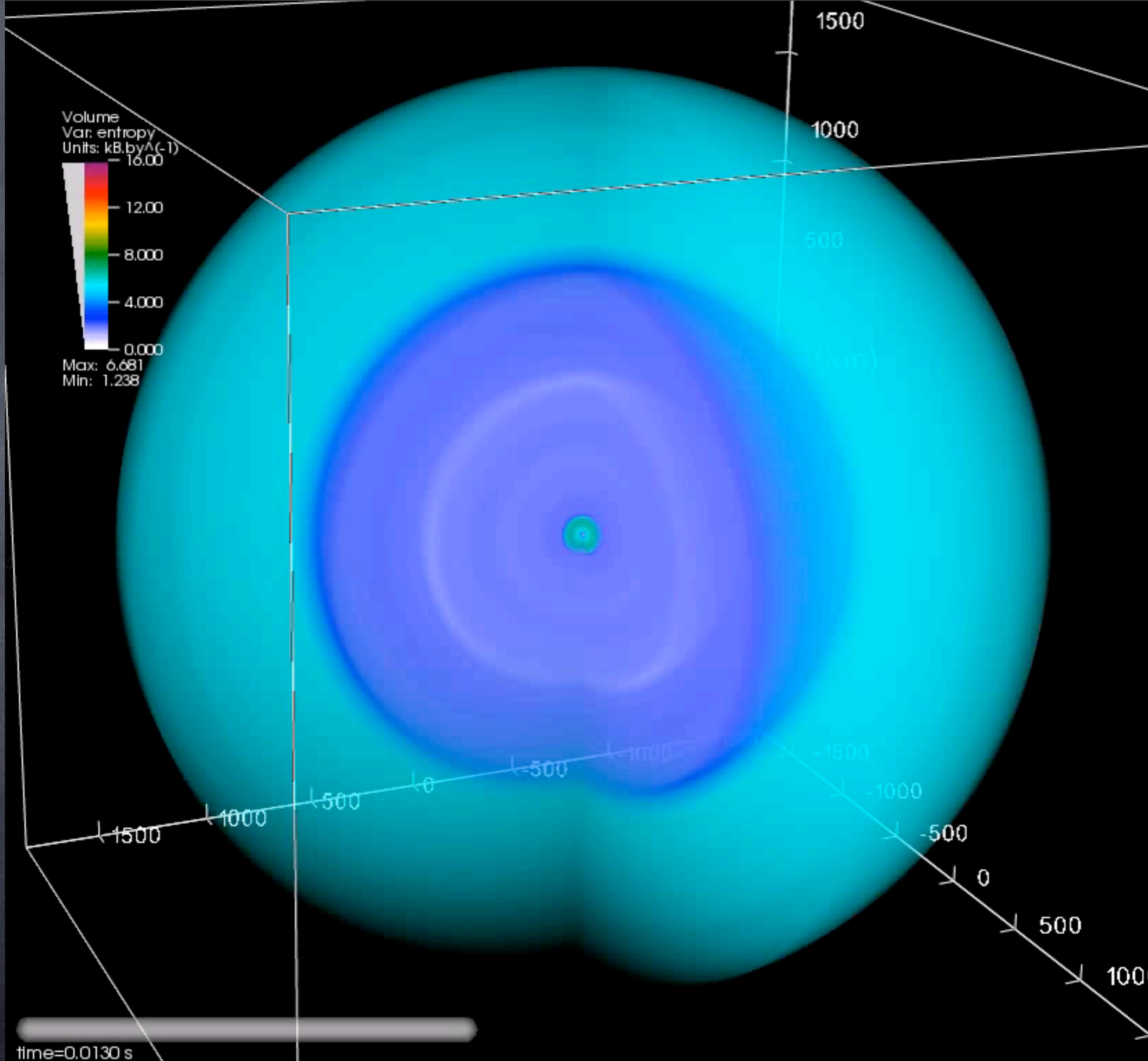
- Neutrino radiation hydrodynamics is hard!
- Highly non-local problem.
- Must have closure scheme for radiation transport (or Boltzmann) moment equations.
- Common closure schemes: Flux-limited diffusion, Ray-by-ray spectral transport, full multi-angle spectral transport, etc.

An Explosion in 2D:

- "Ray-by-ray plus" method (Buras et al. 2006)
- variable Eddington factor technique
- rather under-energetic explosion only for 11.2 M_{sun} star.

Buras, Marek, Janka, Rammp

Buras, Marek, Janka, Rammp



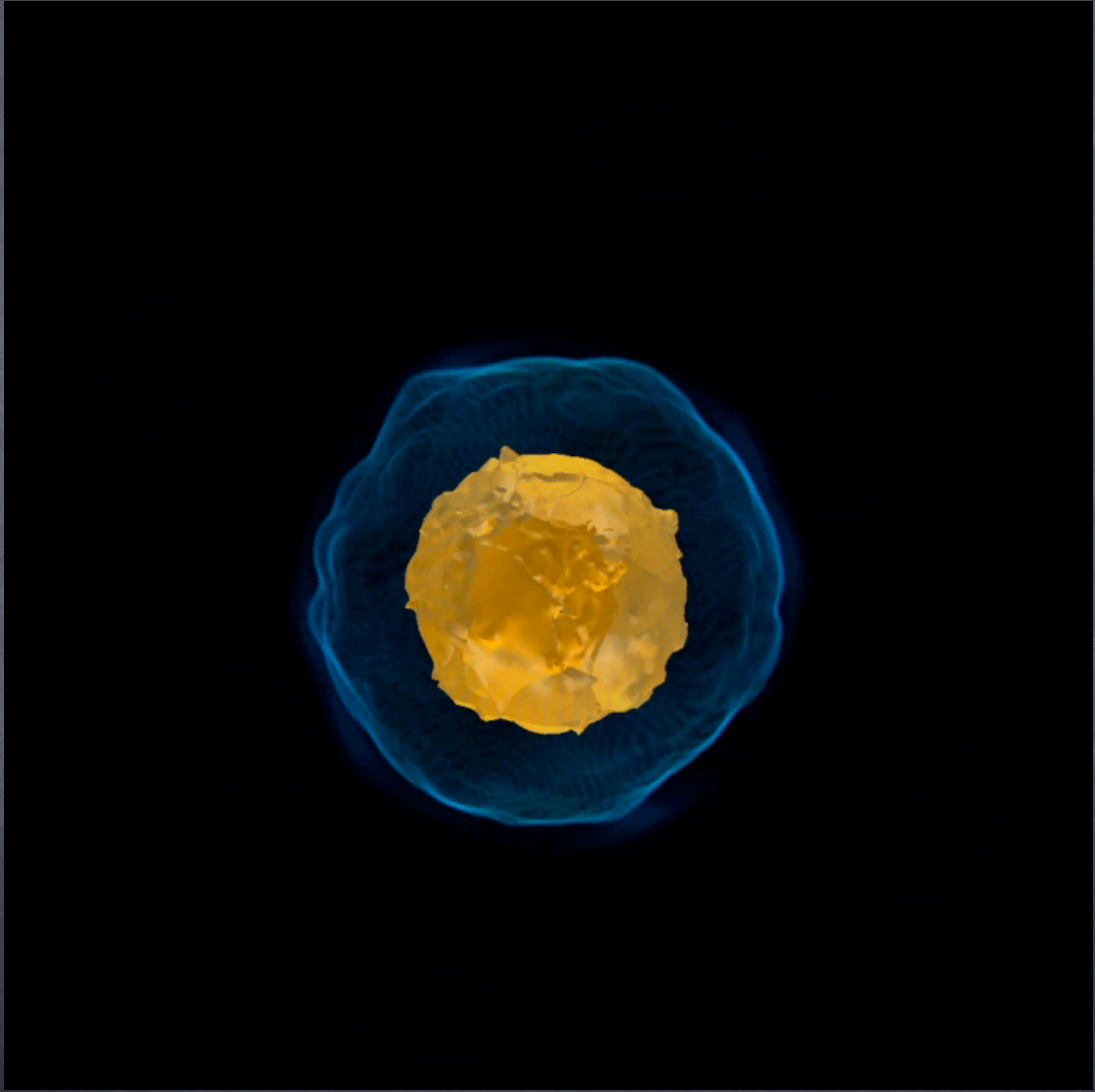
Nature isn't two dimensional...

- Murphy & Burrows (2008) and Nordhaus et al. (2010) found that explosions are more easily obtained in higher dimension.
- Parameterized neutrino heating & cooling with approximate deleptonization scheme.

Entropy

Nordhaus, Burrows, Bell, Almgren, Chupa

Entropy



Nordhaus, Burrows, Bell, Almgren, Chupa

Some Salient Features of the Neutrino Mechanism

- 10^{53} erg released in neutrinos!
- Sophisticated 1D simulations don't give explosions for progenitors bigger than about 10 M_{sun}.
- 2D simulations only give explosions for 11.2 M_{sun} progenitors.
- Multidimensional effects (convection, SASI) critical to success.
- Easier to get explosion in 3D!

Neutrino Mechanism Report Card

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Magnetorotational SNe

- All stars rotate and have magnetic fields!
- Magnetic fields can tap the energy in differential rotation to power outflows
- Some progenitors may rotate fast enough to power a magnetorotational explosion
- See Wheeler et al. 2000, 2002

$$E_{\mathrm{rot,PNS}} \approx \frac{1}{2} I_{\mathrm{PNS}} \Omega_{\mathrm{PNS}}^2$$

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

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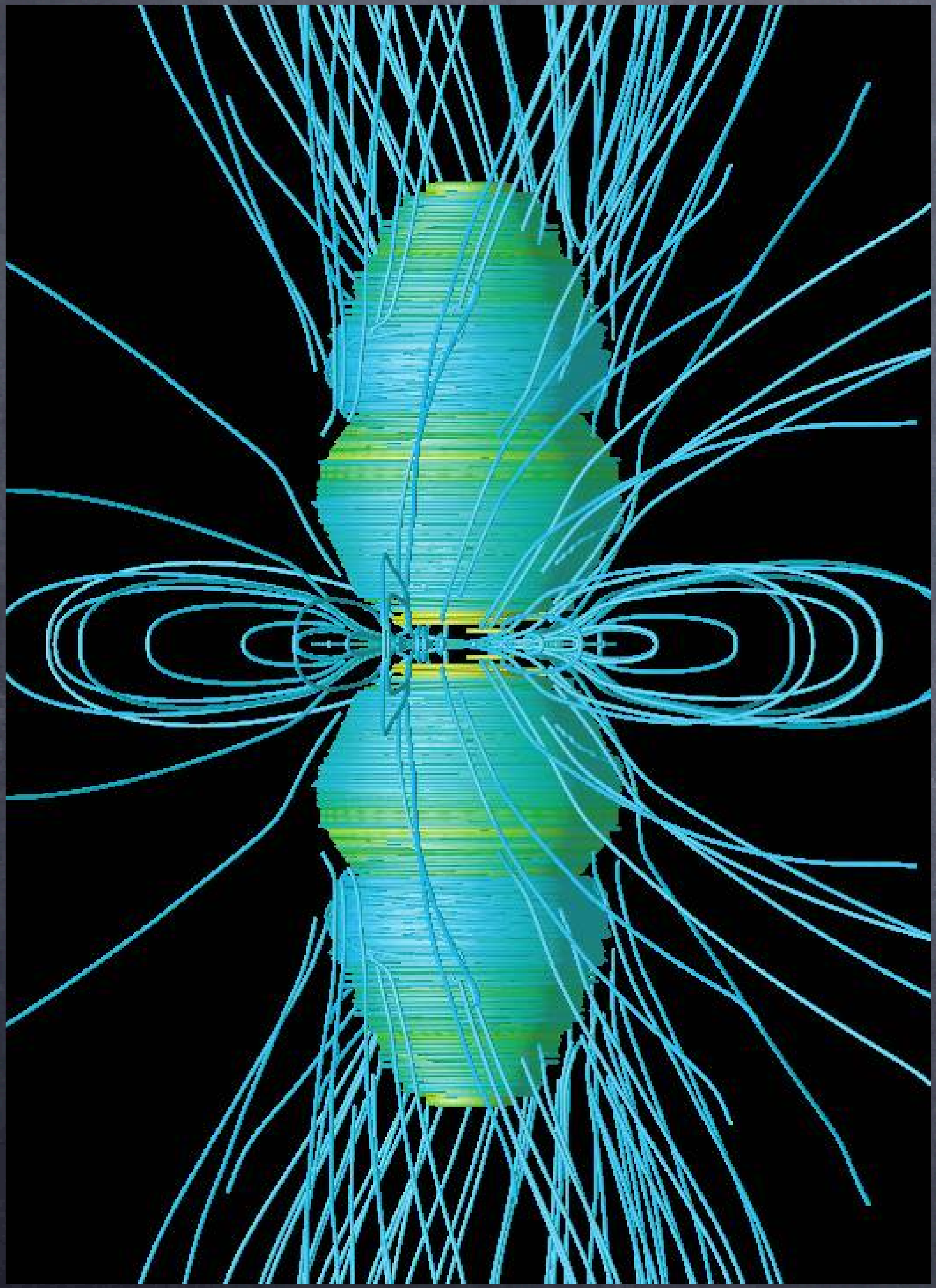
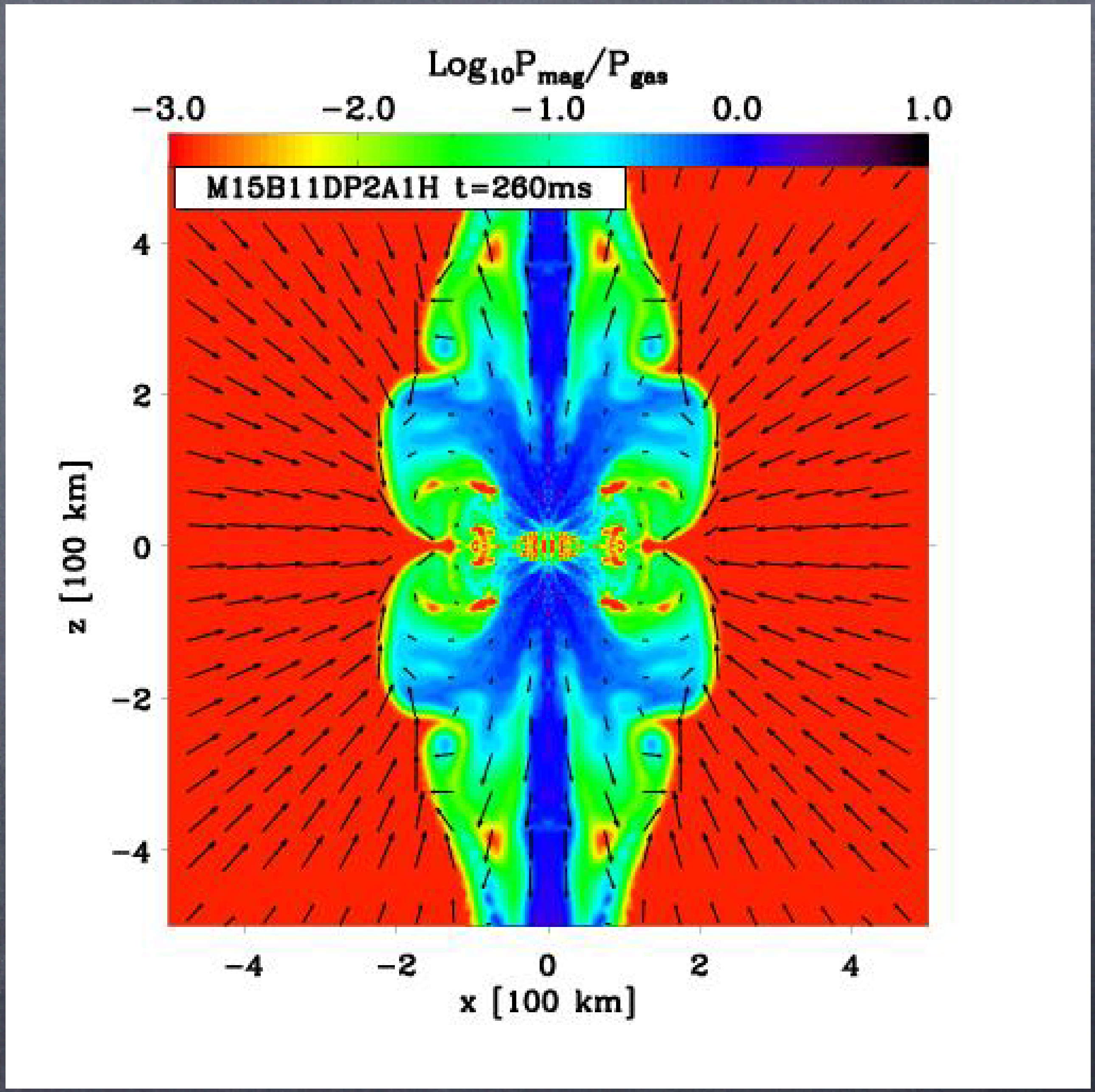
Rapid rotation, but in line with PNS rotation speeds from Burrows et al. (2007).

Not all of this energy will be available to drive an explosion!

Magnetorotational SNe





Burrows et al. 2007

Magnetorotational SNe

- Rapid rotation required for MHD jet-driven explosion
- MHD & rotation may still be important in slower rotators
- SN progenitor core rotation and B-field not well defined
- MRI not resolved in simulations

Magnetorotational SNe

- Elongated explosions
- Non-axisymmetries via instabilities
- High-velocity nickel clumps
- Complex, large-scale structures
- Mechanism for pulsar kicks
- Continuum to GRBs with higher rotation

Can Bipolar Explosions Explain Observations?

Jet-driven Type IIP SNe

SMC, Wheeler, Milosavljevič 2009, ApJ, 696, 953

- 15 $M_\odot$ Red Supergiant progenitor star
- FLASH hydrodynamics code
- Jets introduced at inner boundary
- Four physically-motivated jet models
- Evolved to 500,000 seconds

Dynamic Range

- Δ_r ~ 10^6 cm out to 10^{15} cm
- 2D spherical geom.
- 7 refinement levels, re-gridding algorithm

Stage	t_i [s]	t_f [s]	$r_{\rm in}$ [cm]	$r_{\rm out}$ [cm]	$N_{r,0}$	$\Delta r_{\rm min}$ [cm]
0:	0	5	3.82×10^8	3.2×10^{10}	192	2.6×10^6
1:	5	25	3.82×10^8	7.5×10^{10}	192	6.1×10^6
2:	25	100	1.0×10^9	2.5×10^{11}	192	2.0×10^7
3:	100	300	2.0×10^9	9.0×10^{11}	192	7.3×10^7
4:	300	1×10^3	4.0×10^9	3.0×10^{12}	320	1.5×10^8
5:	1×10^3	3×10^3	1.0×10^{10}	6.0×10^{12}	320	2.9×10^8
6:	3×10^3	1×10^4	2.0×10^{10}	2.0×10^{13}	352	8.9×10^8
7:	1×10^4	3×10^4	5.0×10^{10}	6.0×10^{13}	352	2.7×10^9
8:	3×10^4	1×10^5	1.0×10^{11}	2.0×10^{14}	384	8.1×10^9
9:	1×10^5	2×10^5	2.0×10^{11}	4.0×10^{14}	384	1.6×10^{10}
10:	2×10^5	5×10^5	5.0×10^{11}	1.0×10^{15}	384	4.1×10^{10}

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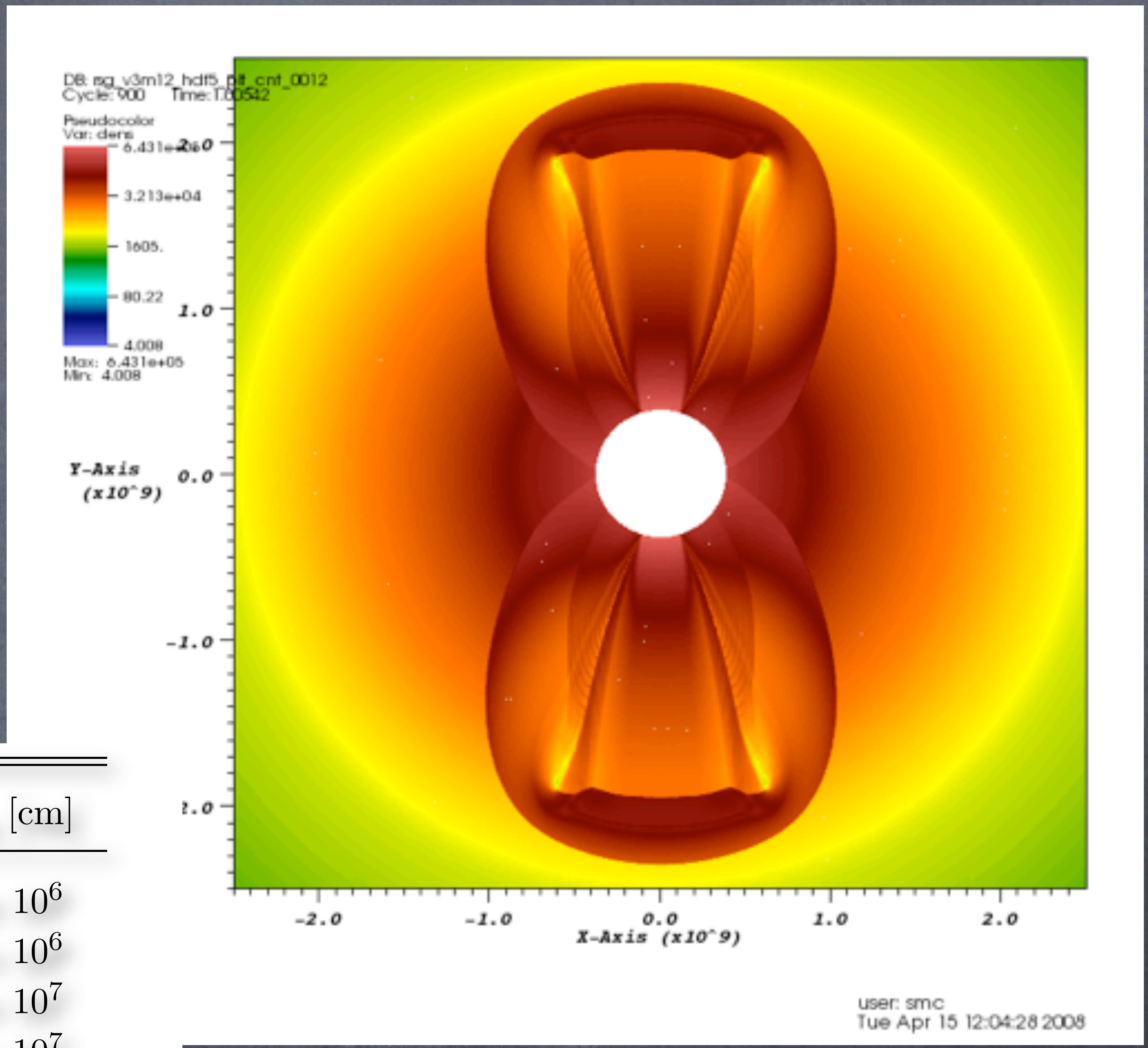

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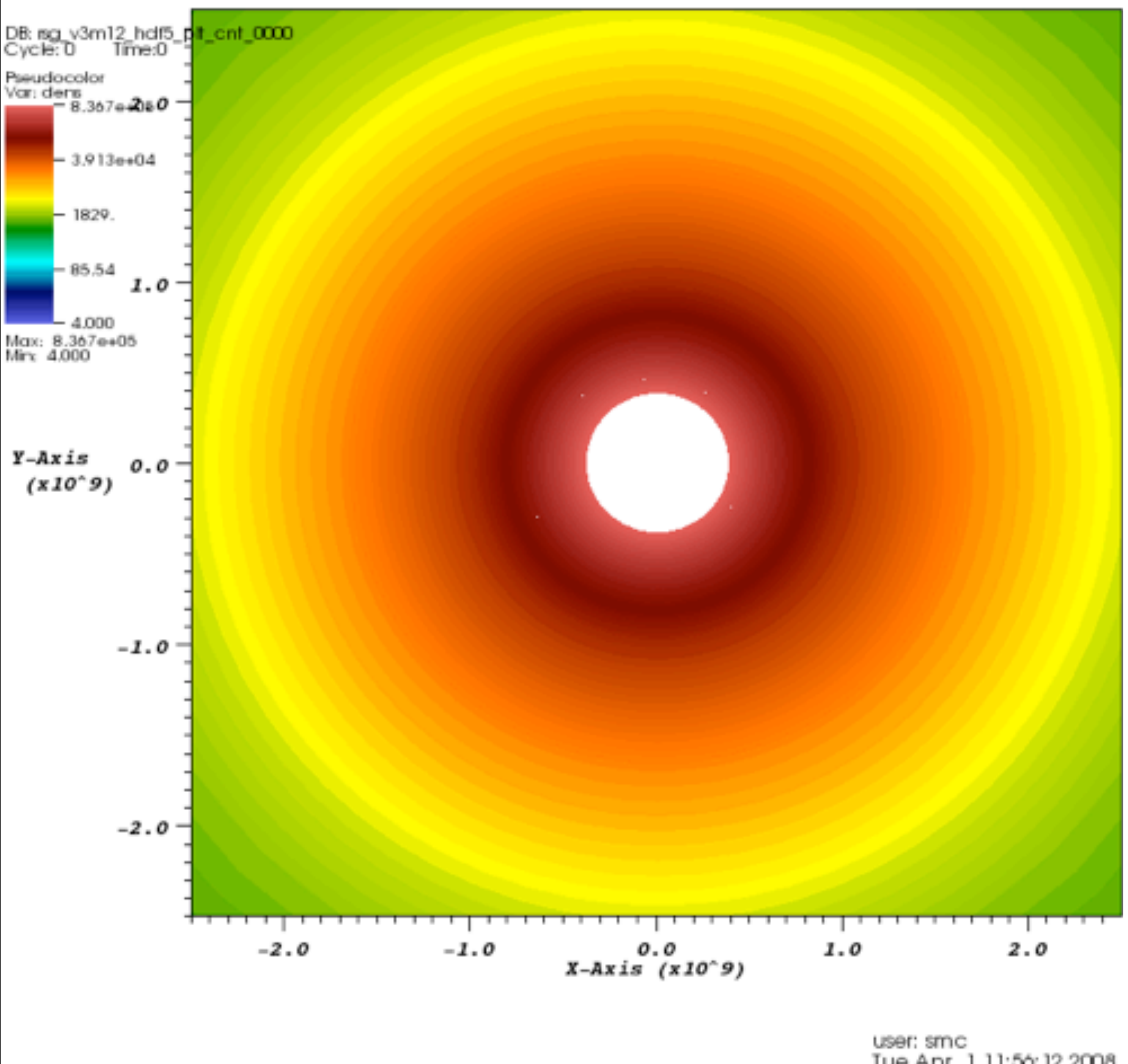
Density

Fast, kinetic

Slow, thermal

Density



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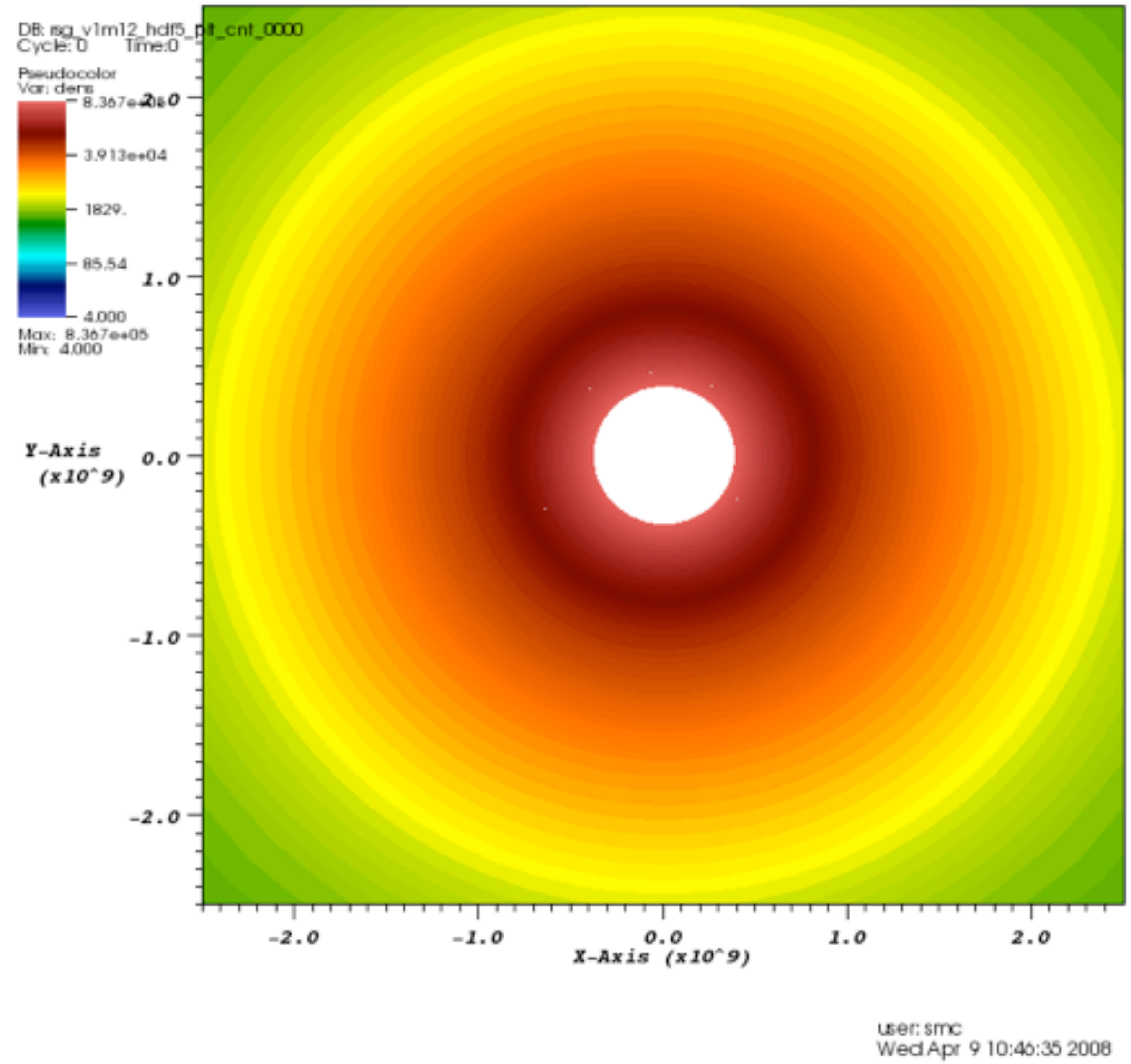


Slow, thermal

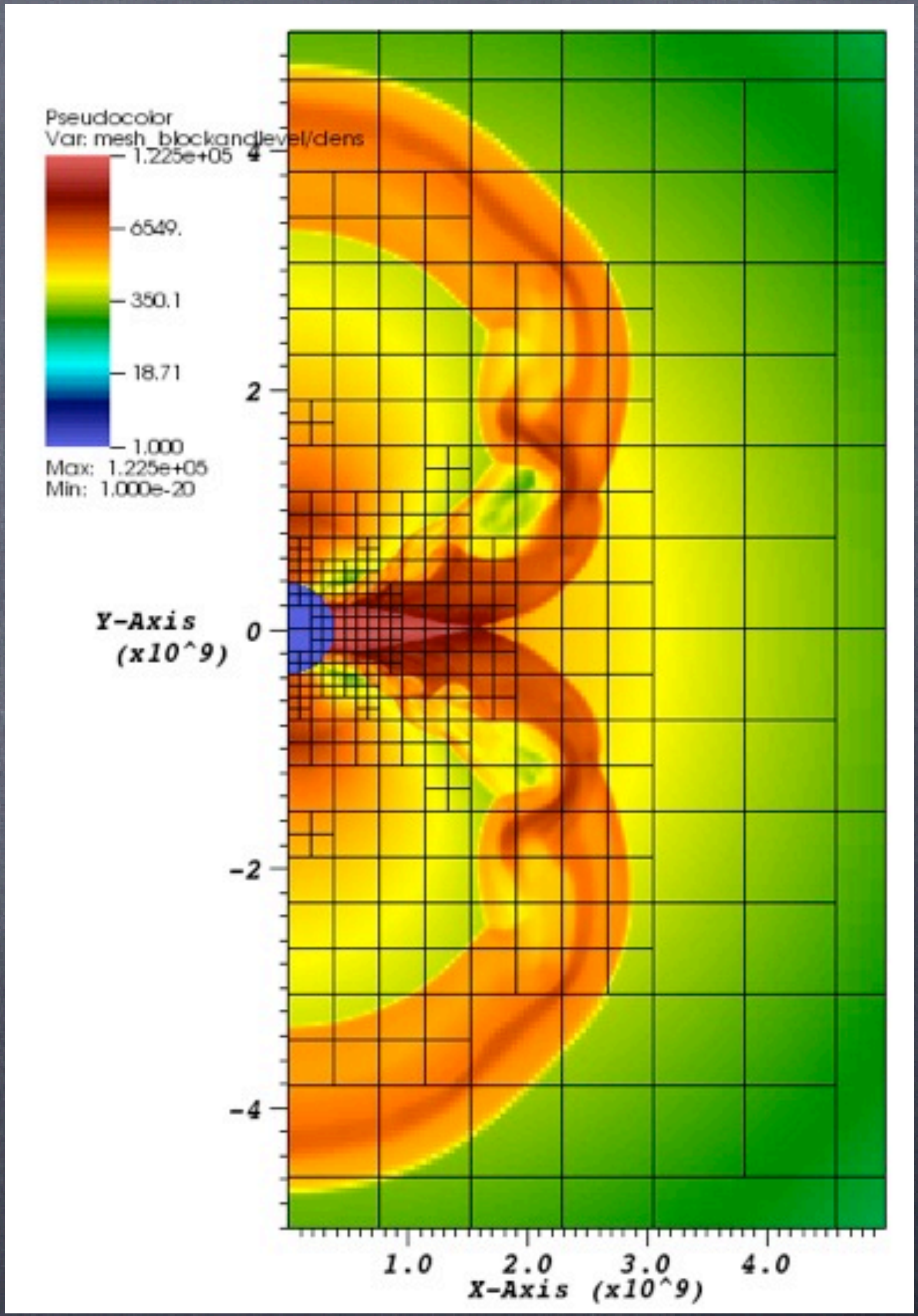
Jet-driven Type Ib SNe

SMC, Pooley, Wheeler, Milosavljevič 2011, ApJ, 727, 104

- 2.5 & 6 $M_\odot$ helium core progenitors
- Thermal & kinetic jet models in each
- FLASH hydro
- Custom post-processing radiation modeling

Dynamic range

- 2D cylindrical geom.
- Radius, time-dependent max. refinement level
- Modified FLASH to excise central hole
- Hole radius expands with time
- No need for regrid; start with 25 refinement levels



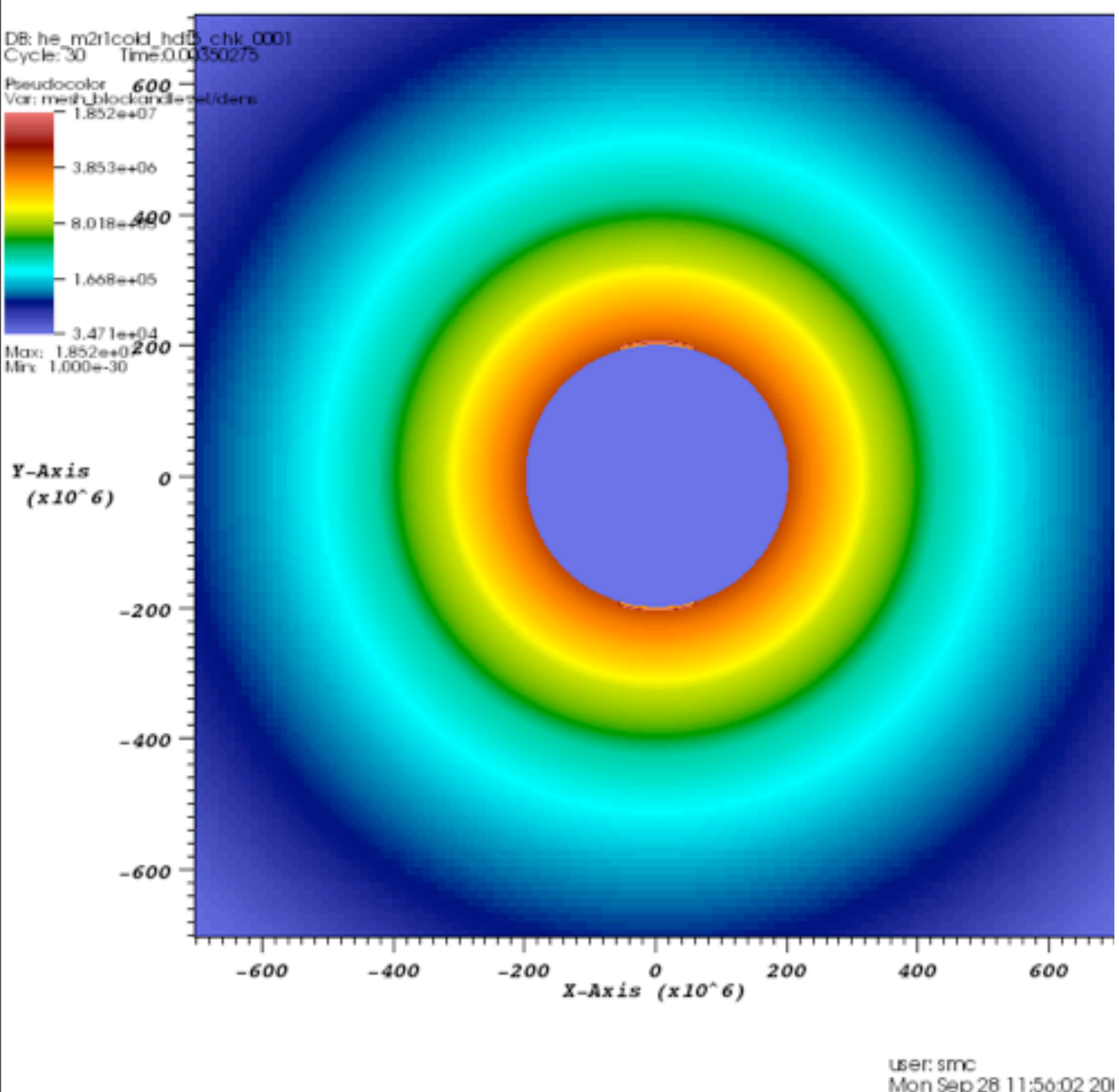
Density

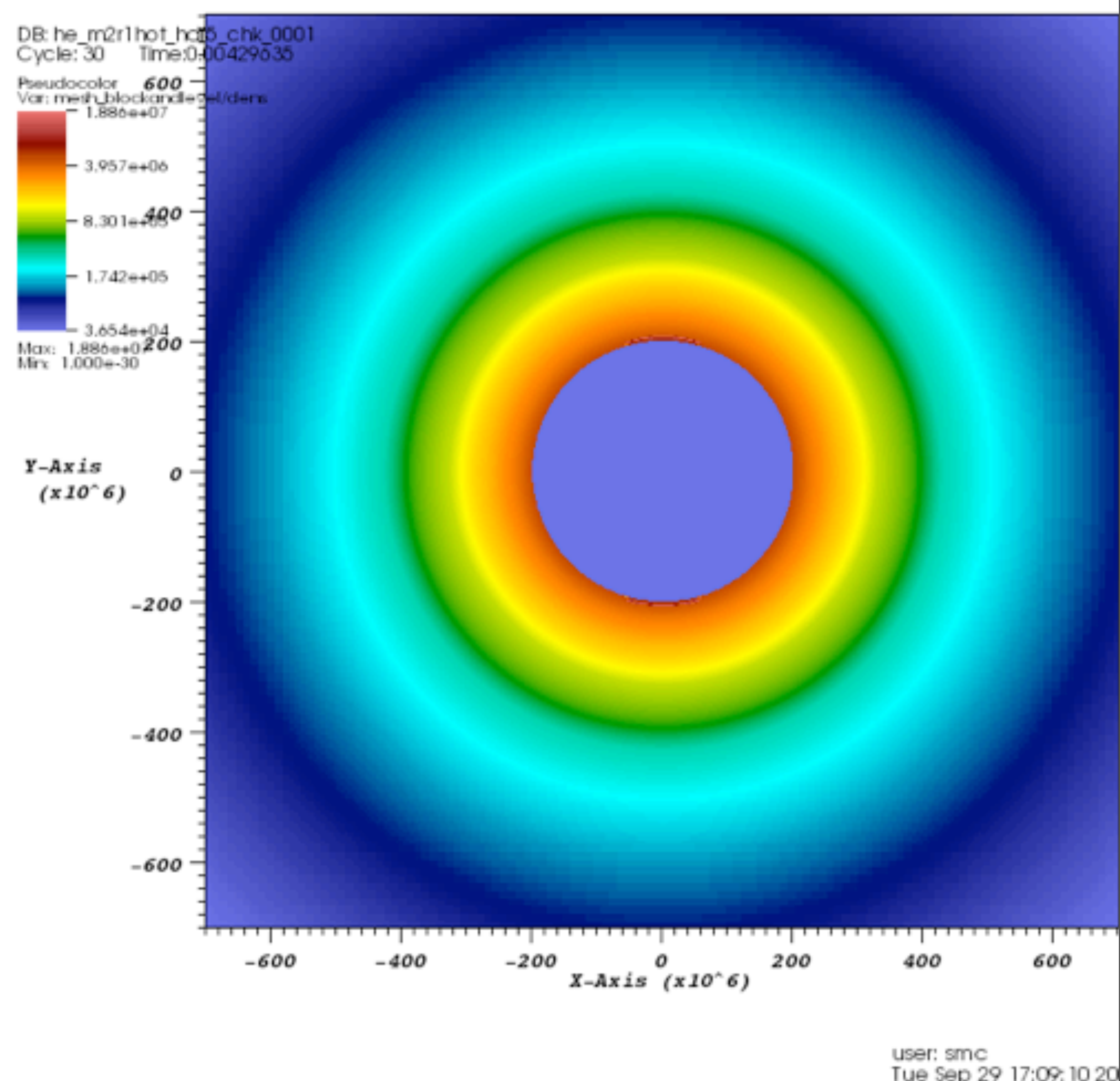
Kinetic

Thermal

Smaller Progenitor

Density



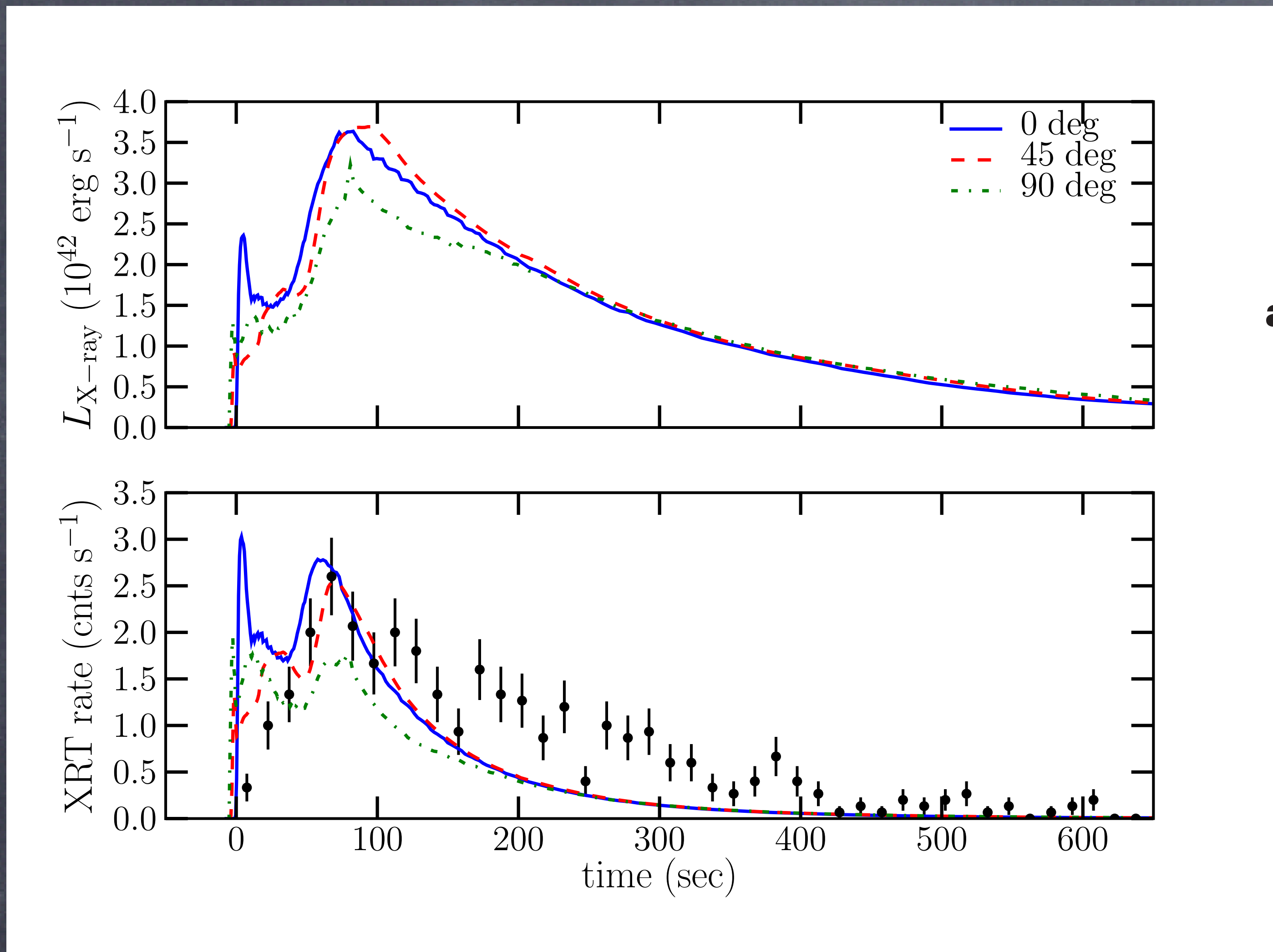


Kinetic

Thermal

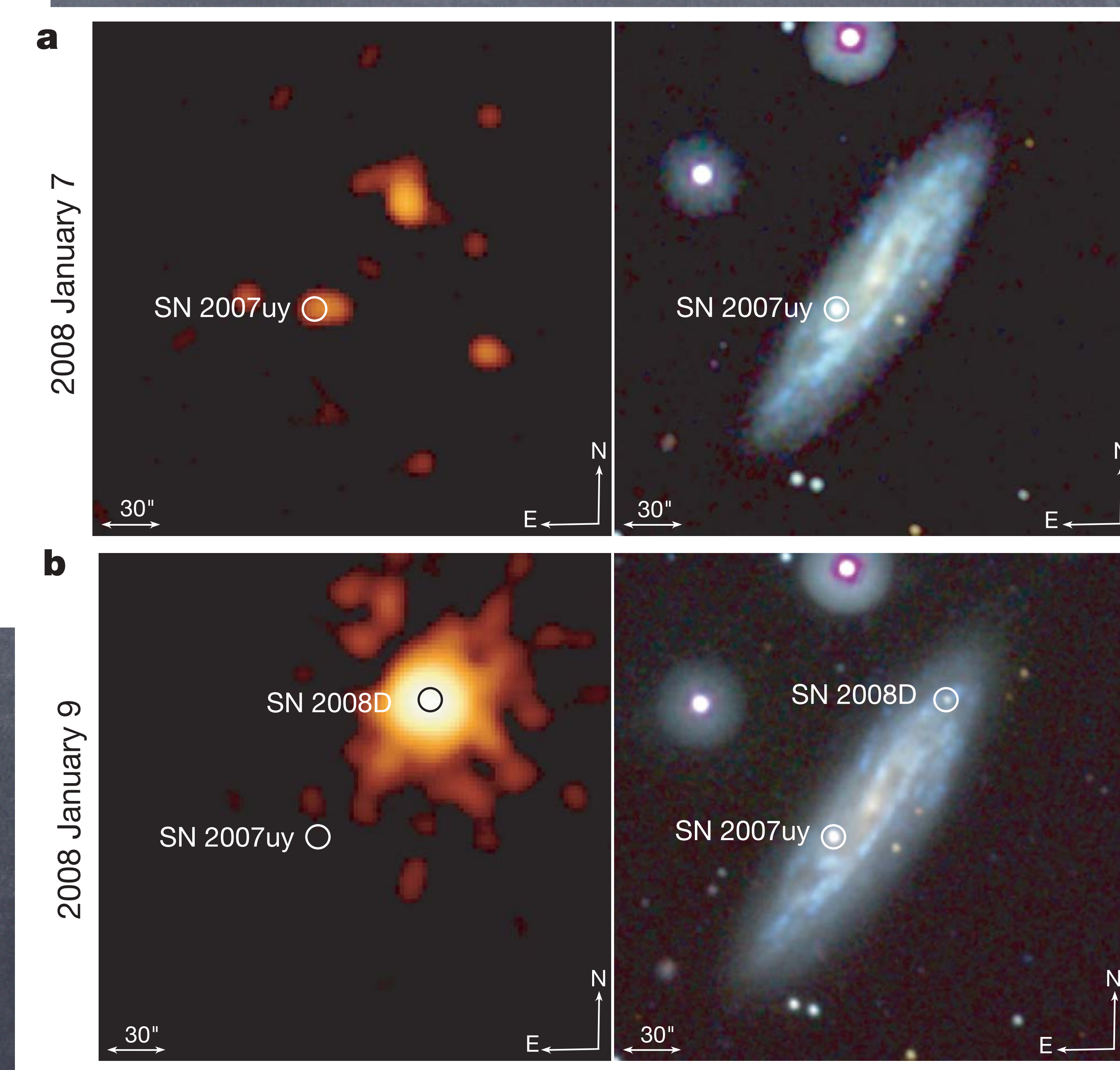
Smaller Progenitor

Small progenitor, kinetic jets



- LC shape and time scales about right

X-ray UV



- Spectra are too soft
- LC time scales right-on!

Soderberg et al. 2008

- Phenomenological, jet-driven explosions can explain many of the observations, but lack crucial physics.
- Need nuclear EOS, neutrinos, and MHD:

Euler Equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$ Mass

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v}) + \nabla P = \rho \mathbf{g}$$ Momentum

$$\frac{\partial \rho E}{\partial t} + \nabla \cdot [(\rho E + P)\mathbf{v}] = \rho \mathbf{v} \cdot \mathbf{g}$$ Energy

$$E = \epsilon + \frac{1}{2}|\mathbf{v}|^2$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

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$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v} - \mathbf{B}\mathbf{B}) + \nabla P_* = \rho \mathbf{g} + \nabla \cdot \tau$$

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$$P_* = P + \frac{B^2}{2}$$

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τ = viscosity tensor

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$$P_* = P + \frac{B^2}{2}$$

$$E_* = \epsilon + \frac{1}{2}v^2 + \frac{1}{2}\frac{B^2}{\rho}$$

τ = viscosity tensor

σ = thermal conductivity

η = resistivity

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

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Induction Equation:

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot (\mathbf{v}\mathbf{B} - \mathbf{B}\mathbf{v}) = -\nabla \times (\eta \nabla \times \mathbf{B})$$

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$$\nabla \cdot \mathbf{B} = 0$$

Solenoidal Constraint

Three Common Methods to Satisfy Constraint:

1. Elliptic projection (Brackbill & Barnes 1980)
2. Constrained transport (Evans & Hawley 1988)
3. Divergence cleansing (Powell et al. 1999)

B-field Amplification in CCSNe

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

MRI

$$\tau_{\rm MRI} \sim 4\pi \left(\frac{\partial \ln r}{\partial \Omega}\right) \sim 2P$$

$$\lambda_{\rm MRI}^{\rm max} \sim \frac{2\pi v_A}{\Omega} \sim (10^4\ {\rm cm})\ P_{10} \frac{B_{12}}{\rho_{11}^{1/2}}$$

- Grows on the rotational time scale.
- Requires restrictive resolution! 100 times that of high-resolution CCSNe sims.
- See, e.g., Akiyama et al. (2003), Obergaulinger et al. (2011).

Conclusions

- Observations show that CCSN are aspherical
- Physics of CCSN & the Neutrino Mechanism
- Robust neutrino-driven explosions are not found in sophisticated calculations
- Rotation and magnetic fields may play an important role in shaping or driving CCSN explosions
- Bipolar explosions may explain observations indicating asymmetry
- MHD effects are important in CCSN

Extra Slides

Basics of Unsplit Staggered-Mesh (USM) Constrained Transport

$$\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{F}}{\partial x} + \frac{\partial \mathbf{G}}{\partial y} = 0$$

$$\mathbf{U} = (\rho, \rho u, \rho v, \rho w, B_x, B_y, B_z, E)^T$$

$$\mathbf{F} = \begin{pmatrix} \rho u \\ \rho u^2 + p_{\text{tot}} - B_x^2 \\ \rho u v - B_y B_x \\ \rho u w - B_z B_x \\ 0 \\ u B_y - v B_x (= -E_z) \\ u B_z - w B_x (= E_y) \\ (E + p_{\text{tot}}) u - B_x (u B_x + v B_y + w B_z) \end{pmatrix}, \quad \mathbf{G} = \begin{pmatrix} \rho v \\ \rho v u - B_x B_y \\ \rho v^2 + p_{\text{tot}} - B_y^2 \\ \rho v w - B_z B_y \\ v B_x - u B_y (= E_z) \\ 0 \\ v B_z - w B_y (= -E_x) \\ (E + p_{\text{tot}}) v - B_y (u B_x + v B_y + w B_z) \end{pmatrix}.$$

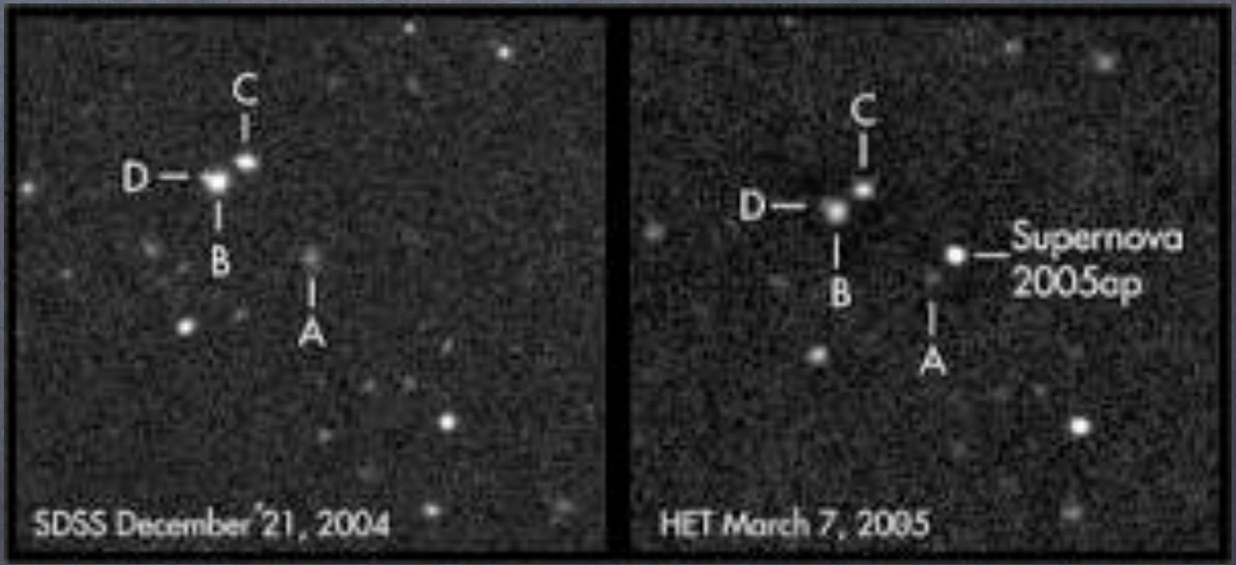
From Lee & Deane (2009)

MHD Waves

- Alfvén waves
-

SN Polarization

- Cannot "see" the shapes of distant SNe
- Can get wavelength-dependent info on the shapes of the photosphere and line-forming regions
- Measure Stokes parameters:



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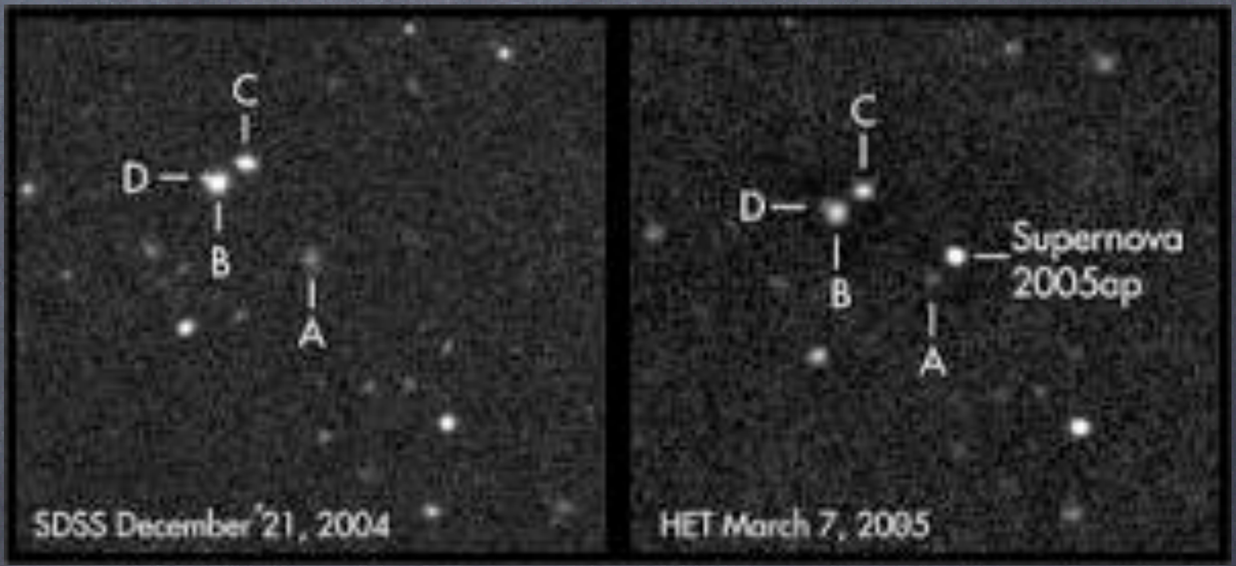
$$I = I_0 + I_{90} \qquad \leftrightarrow + \updownarrow$$
$$Q = I_0 - I_{90} \qquad \leftrightarrow - \updownarrow$$
$$U = I_{45} - I_{-45} \qquad \searrow - \nwarrow$$



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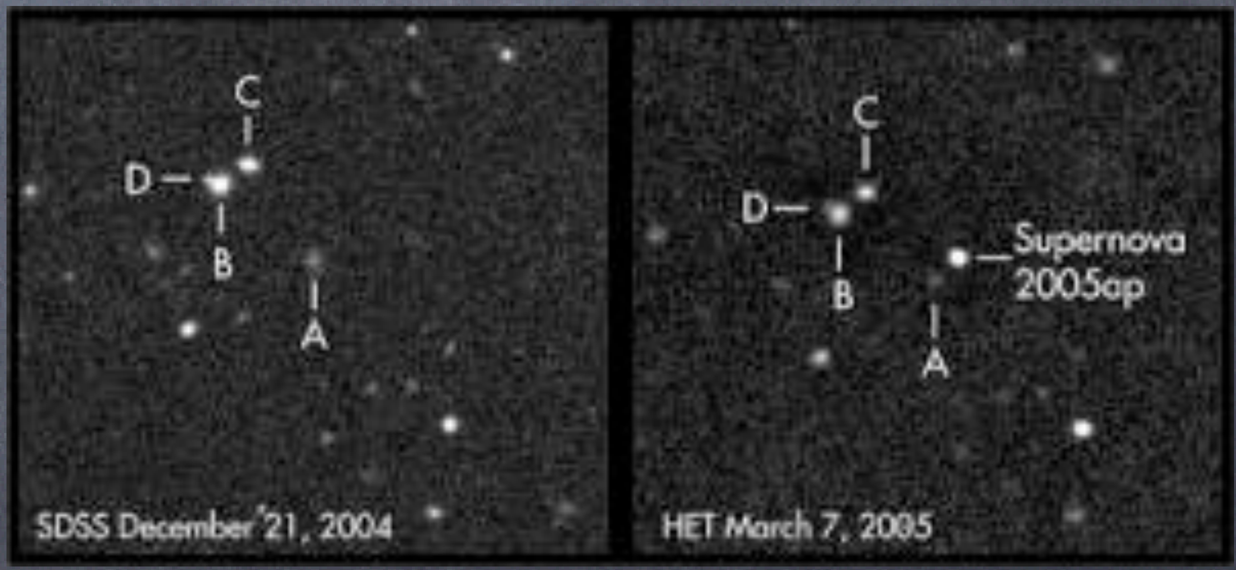

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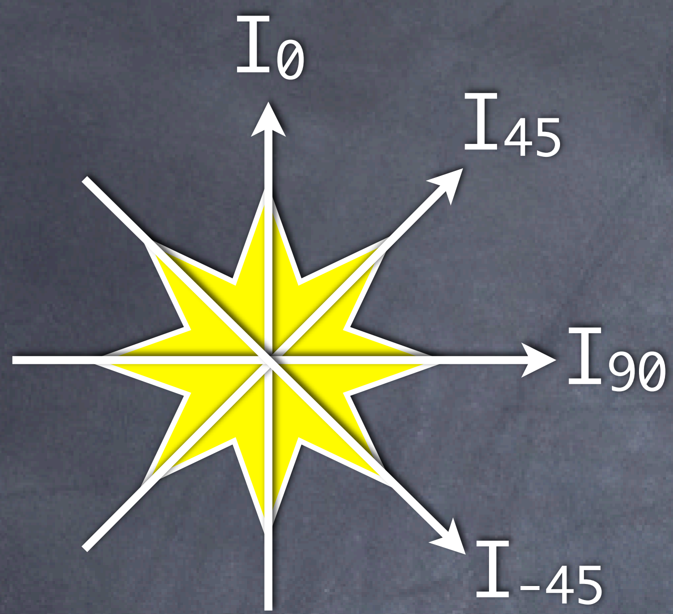
$$U = I_{45} - I_{-45} \qquad \searrow - \nwarrow$$

$$P = \sqrt{Q^2/I^2 + U^2/I^2} = \sqrt{q^2 + u^2} \qquad \chi = \frac{1}{2}\tan^{-1}(u/q)$$

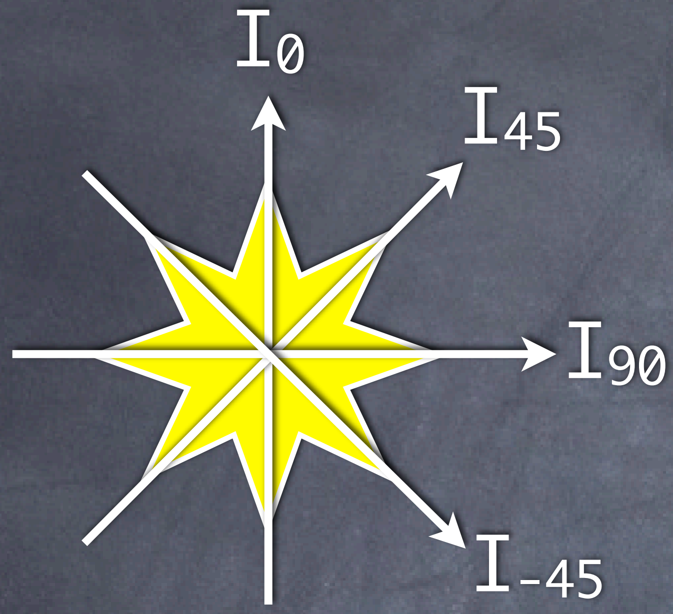
SN Polarization

SN Polarization



- P=Q=U=0: no net polarization, circularly symmetric

SN Polarization



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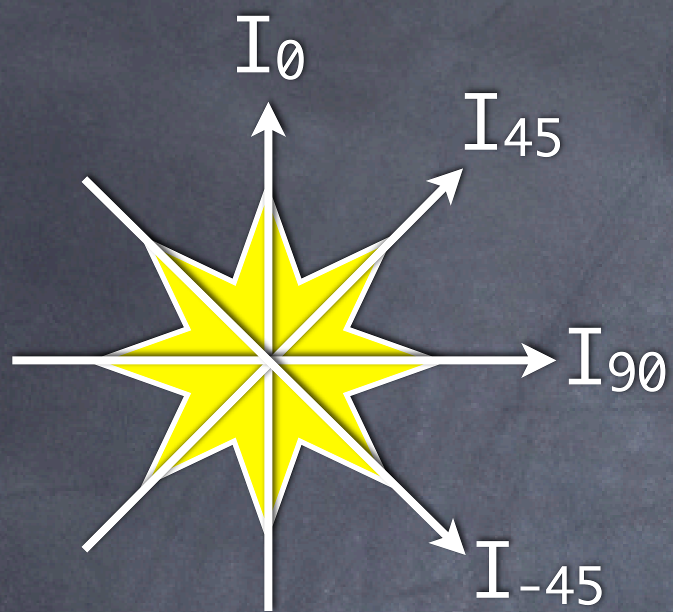

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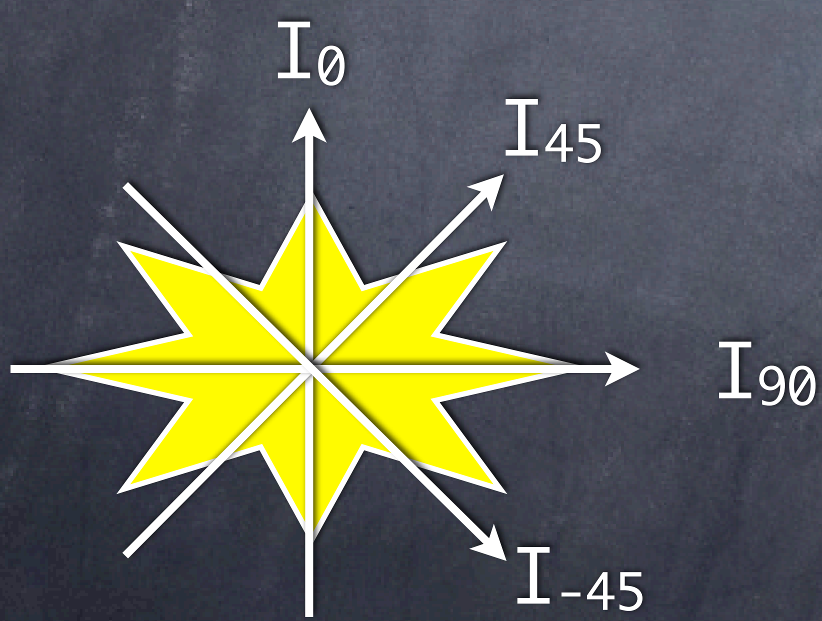
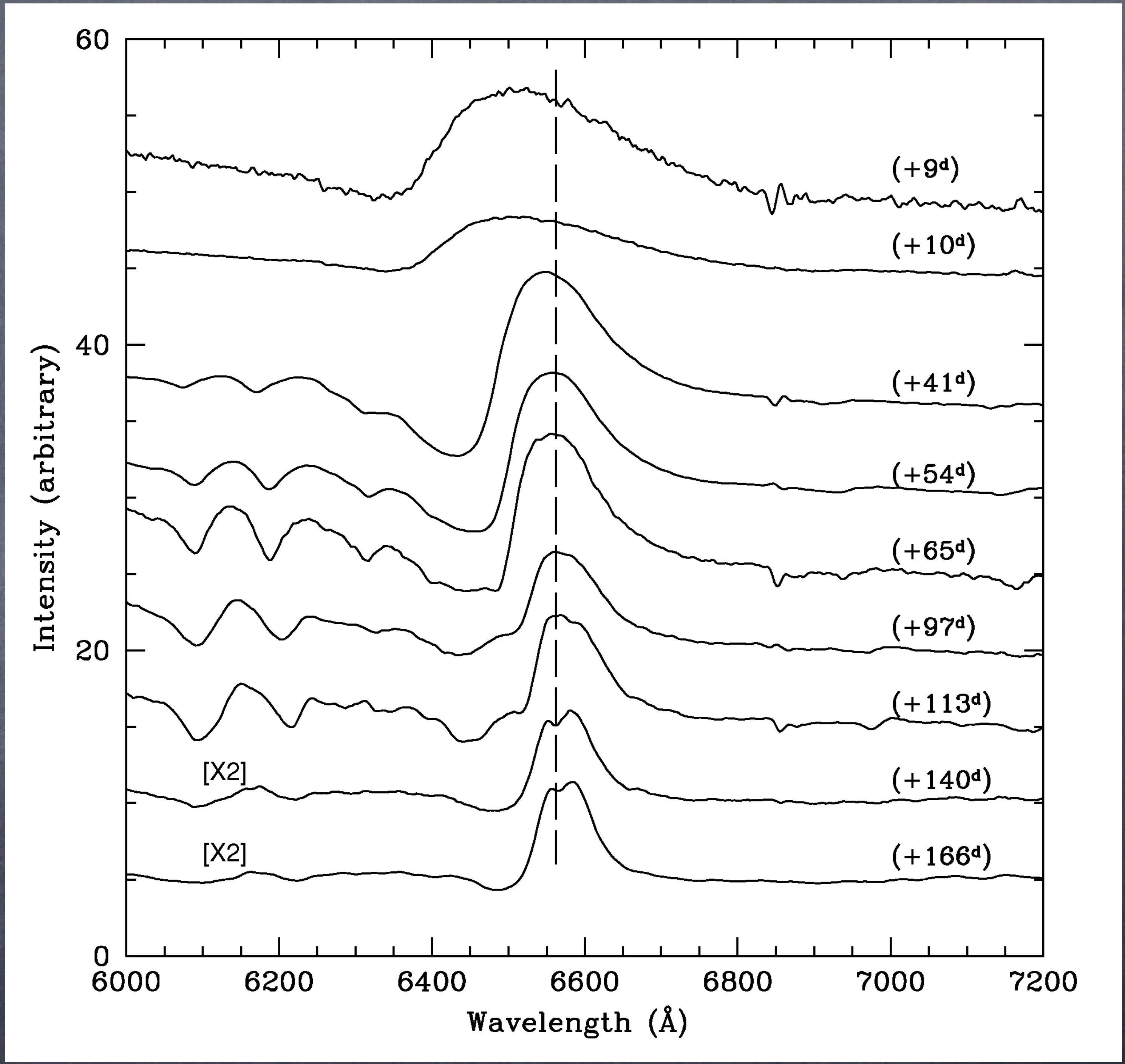


- P,Q,U≠0: net polarization, asymmetric emitting region

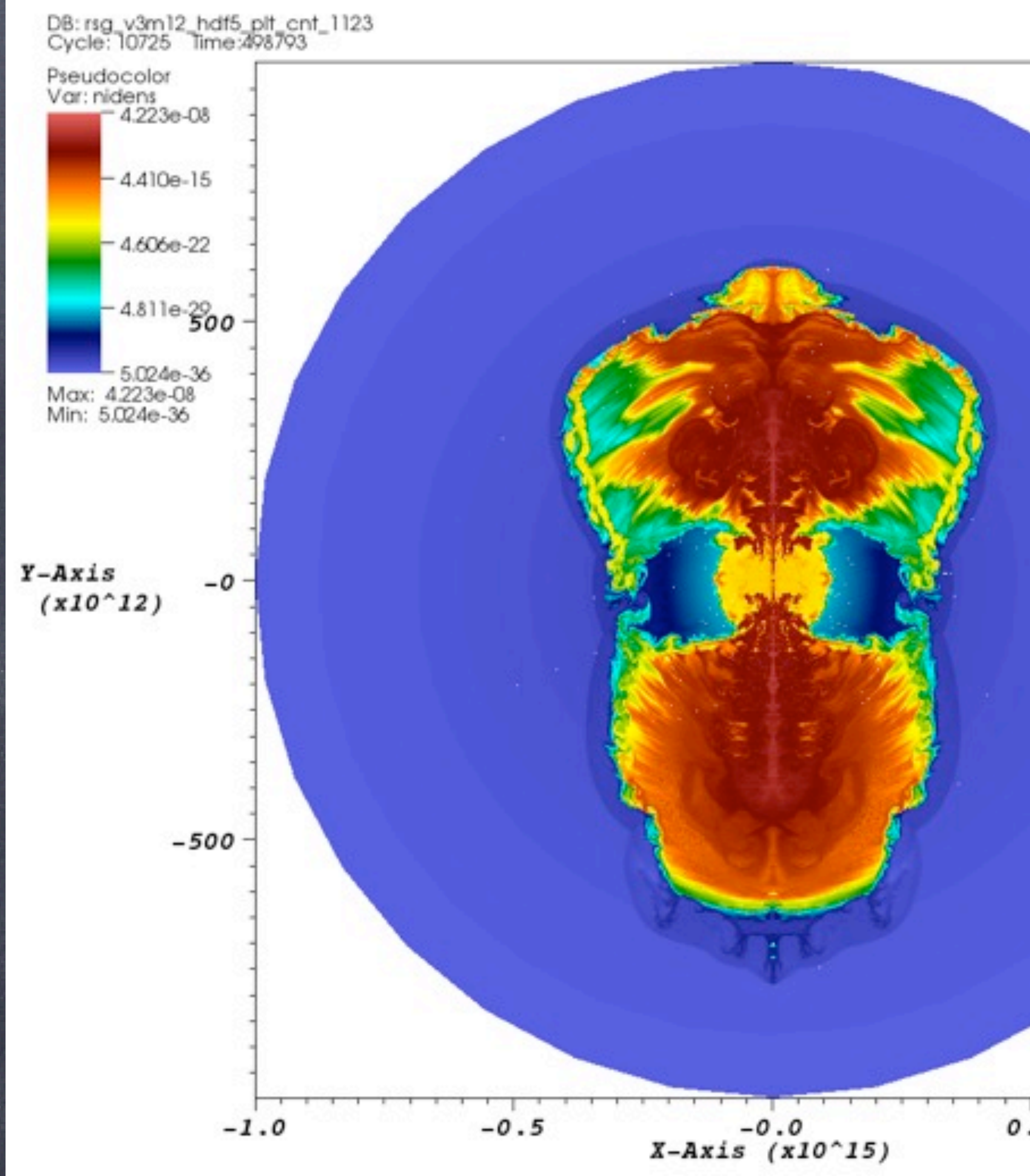
Hα sub-structure

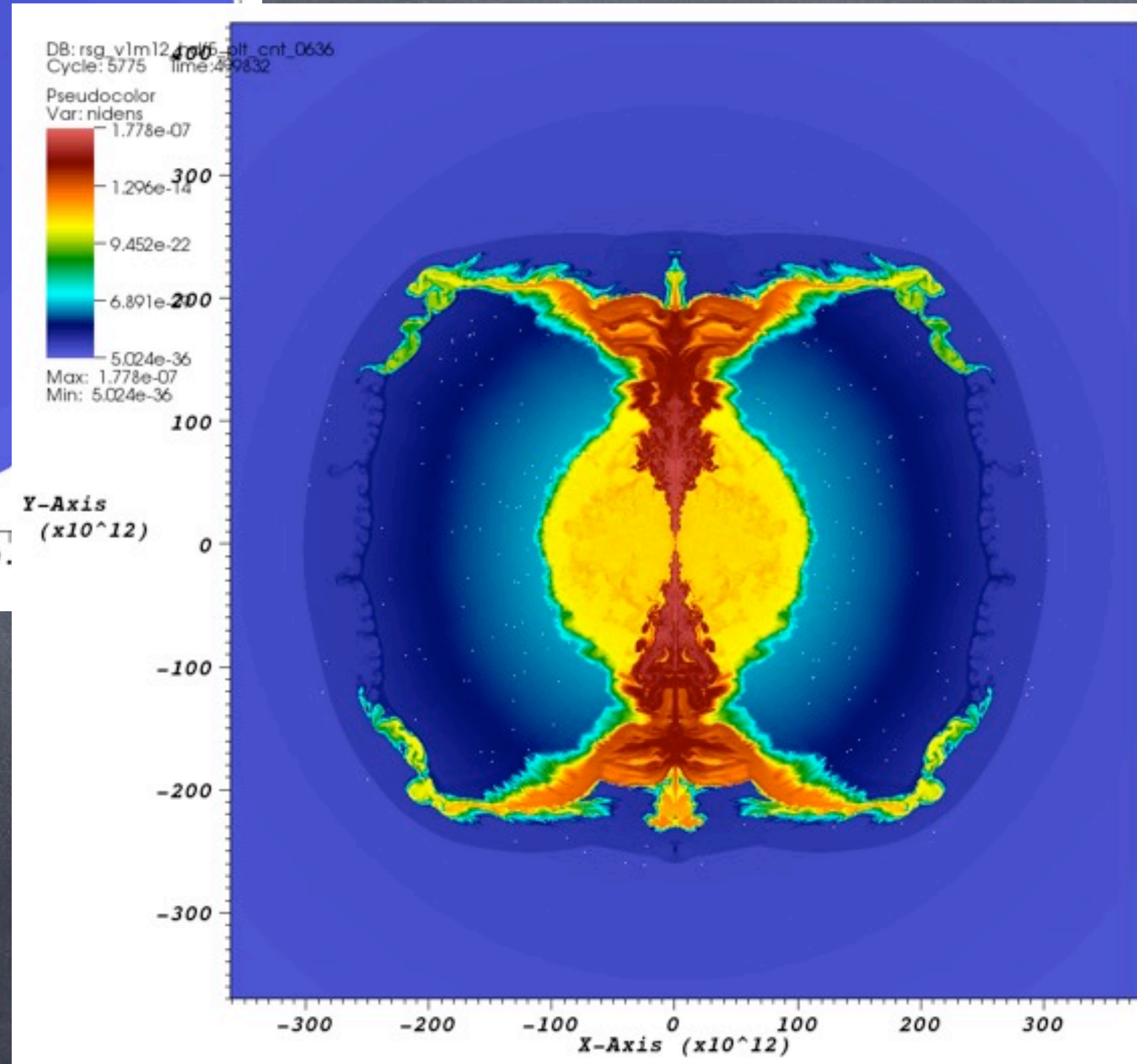
- Appearance of peaks in line require fast nickel clumps



Elmhamdi et al. 2003

Nickel Clumps

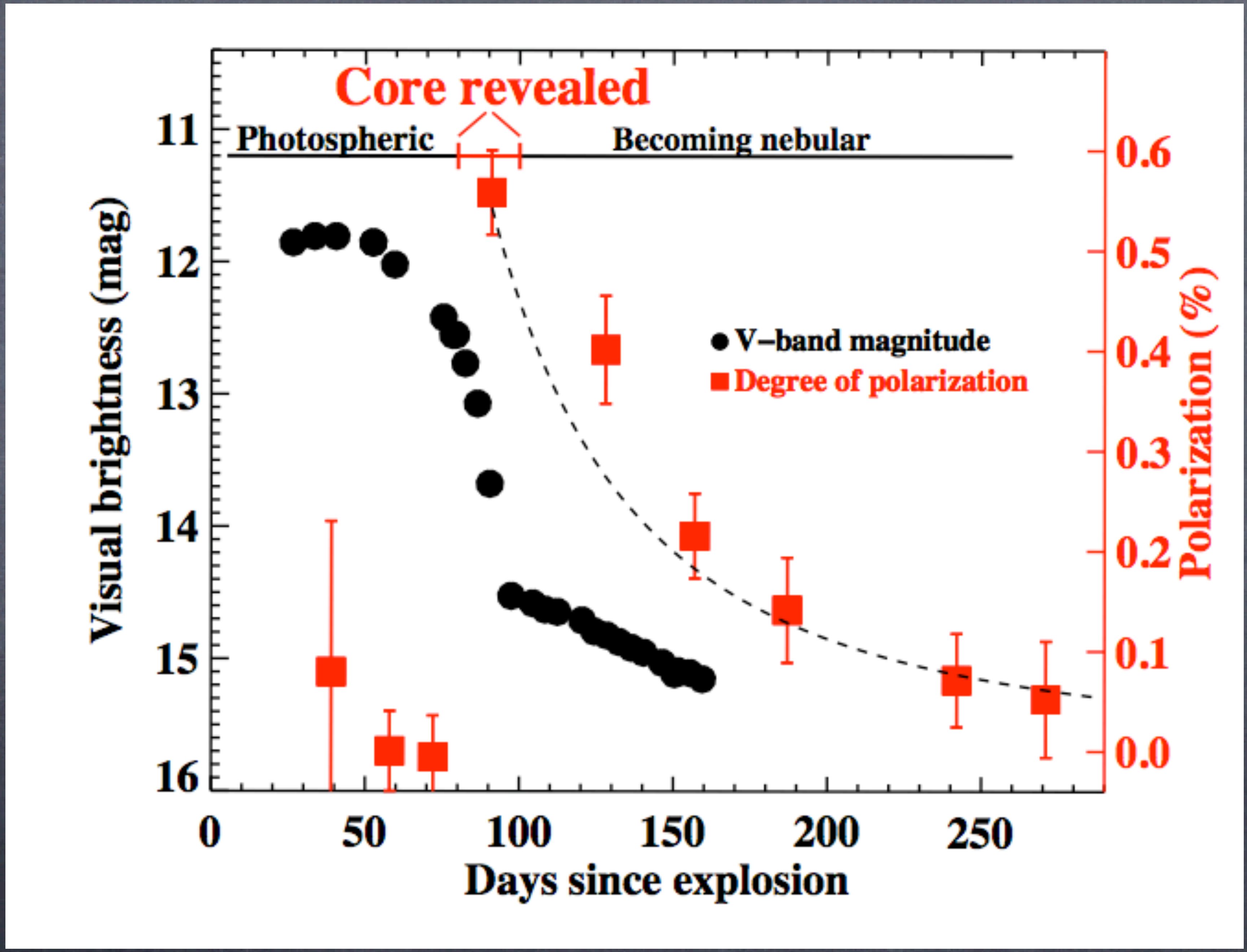




- High-velocity bipolar clumps
- May effect spectral lines

Type IIP Polarization

SN 2004dj

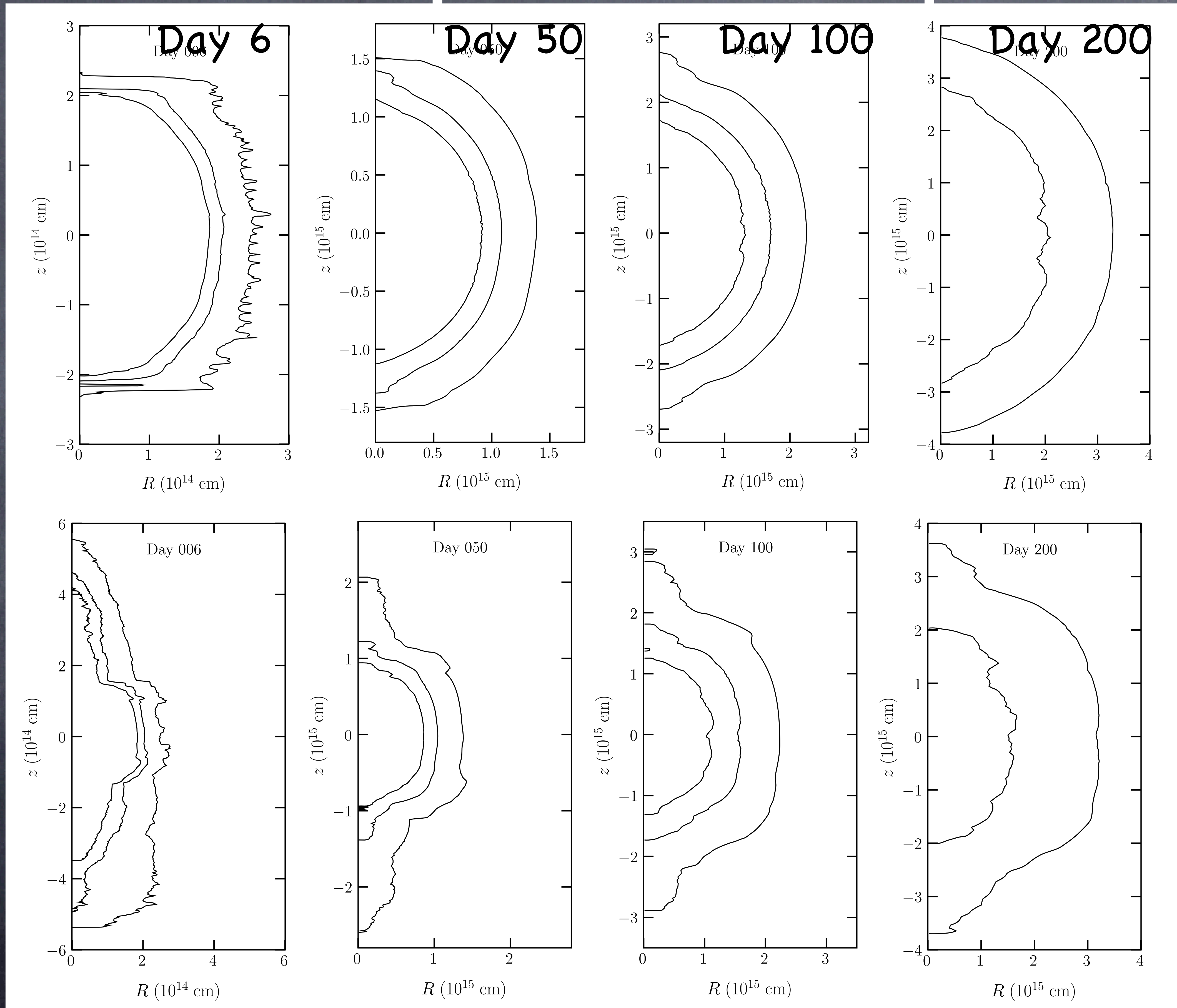


Leonard et al. 2006

Photosphere Shapes

Thermal

Kinetic



τ_{es}= 1, 10, 30