Multi-dimensional Progenitors of Core Collapse Supernovae

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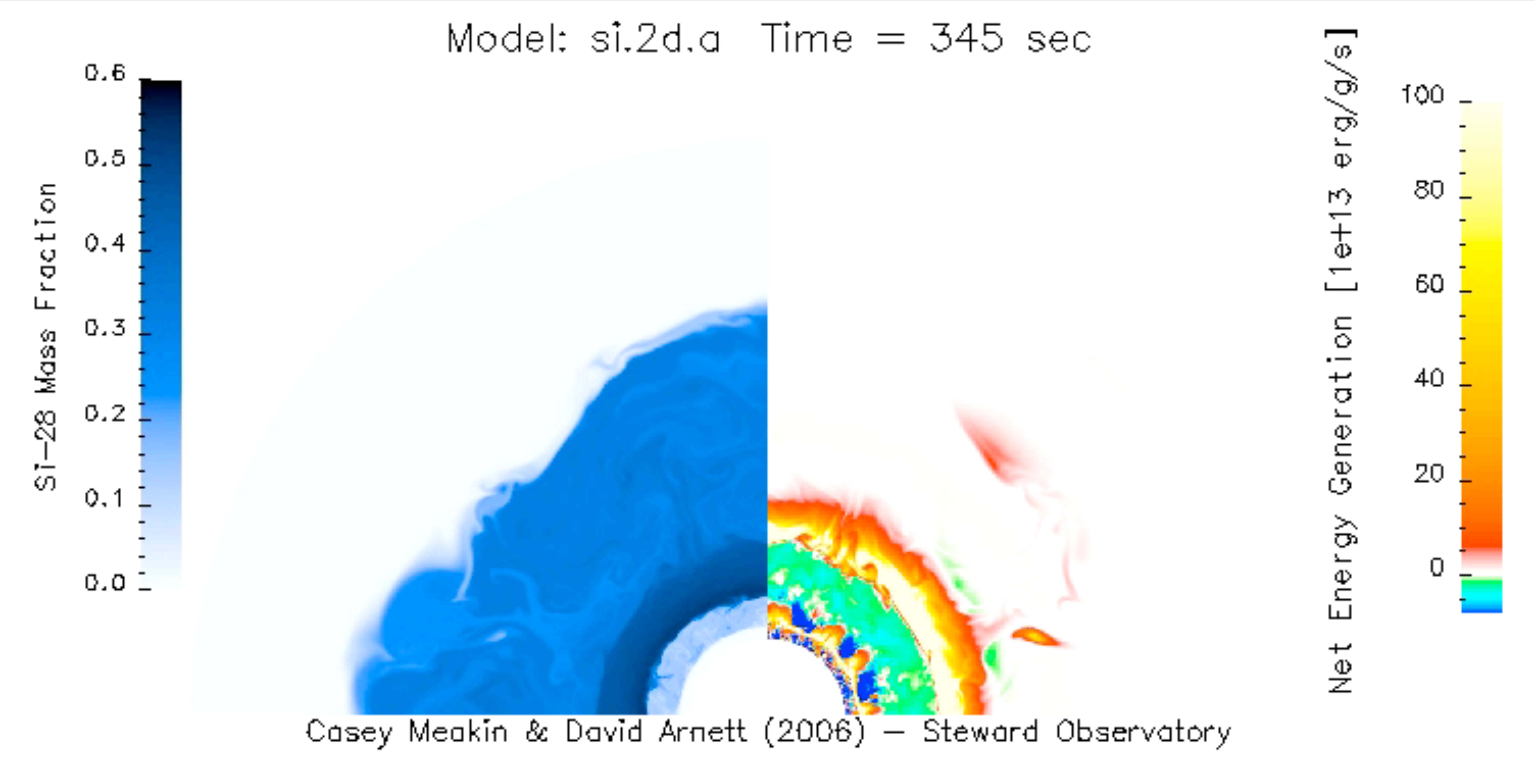
Topics:

- Pre-collapse dynamics: O+O and Si shell interaction (a major issue!)
- A Turbulence Model to replace mixing-length theory (MLT) for evolutionary time scales
- Rotation and convection: a bifurcation in progenitor evolution (first results)

C, Ne and O burning
versus
C, Ne, O and Si burning

- Map same1D model onto a 2D grid
- Use the same microphysics
- Allow time derivatives to be nonzero
- What happens? Are 1D models OK?


Model: ob.2d.e (entire domain) Time = 164 sec
Net Energy Generation [1e+13 erg/g/s]
25
20
15
10
5
0


Model: si.2d.a Time = 345 sec
Si-28 Mass Fraction
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Net Energy Generation [1e+13 erg/g/s]
100
80
60
40
20
0
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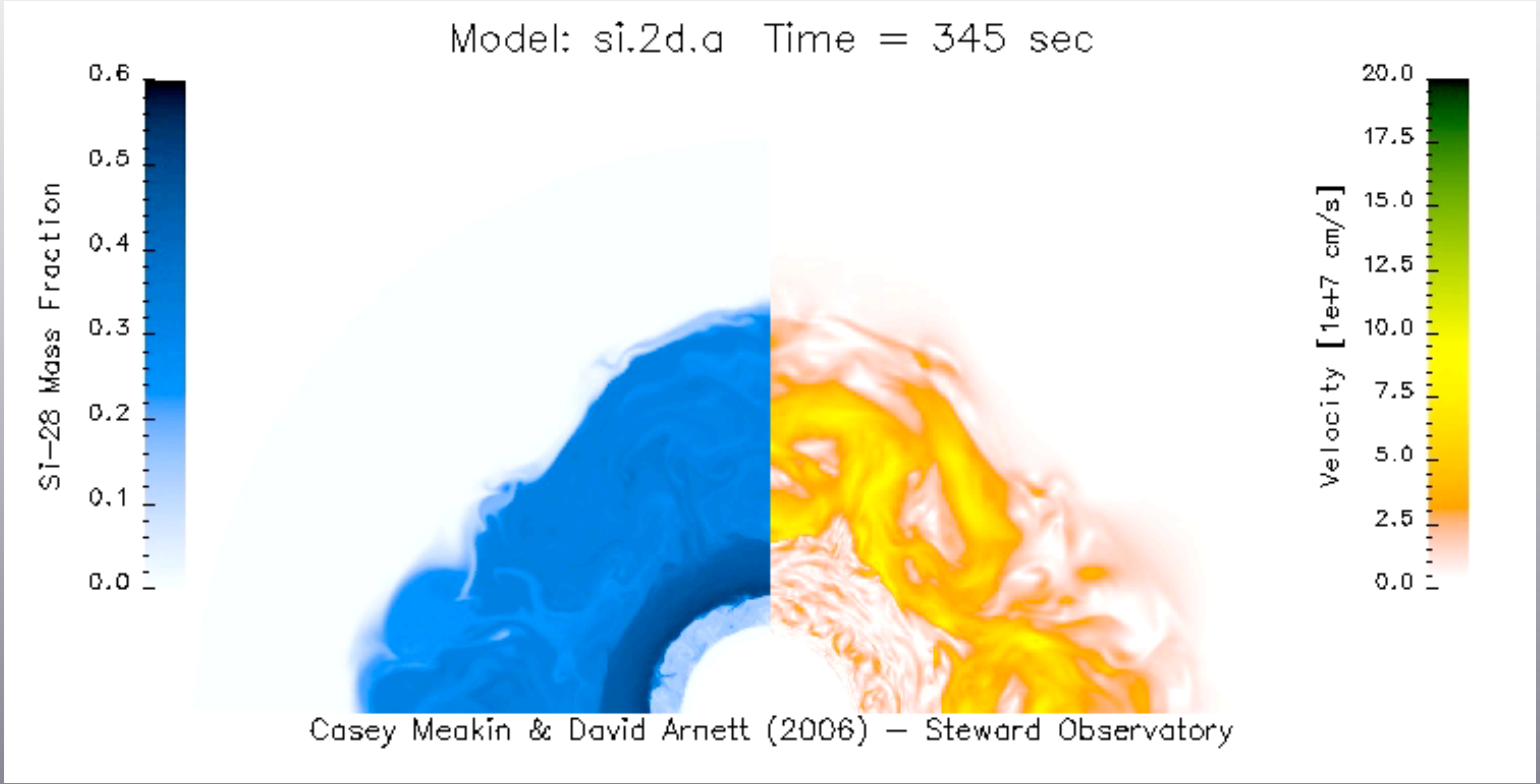

Model: si.2d.a Time = 345 sec
Si−28 Mass Fraction
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Velocity [1e+7 cm/s]
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
Casey Meakin & David Arnett (2006) − Steward Observatory

- We need 3D simulations to confirm these 2D results (a major computational challenge; Meakin and Arnett, in progress)

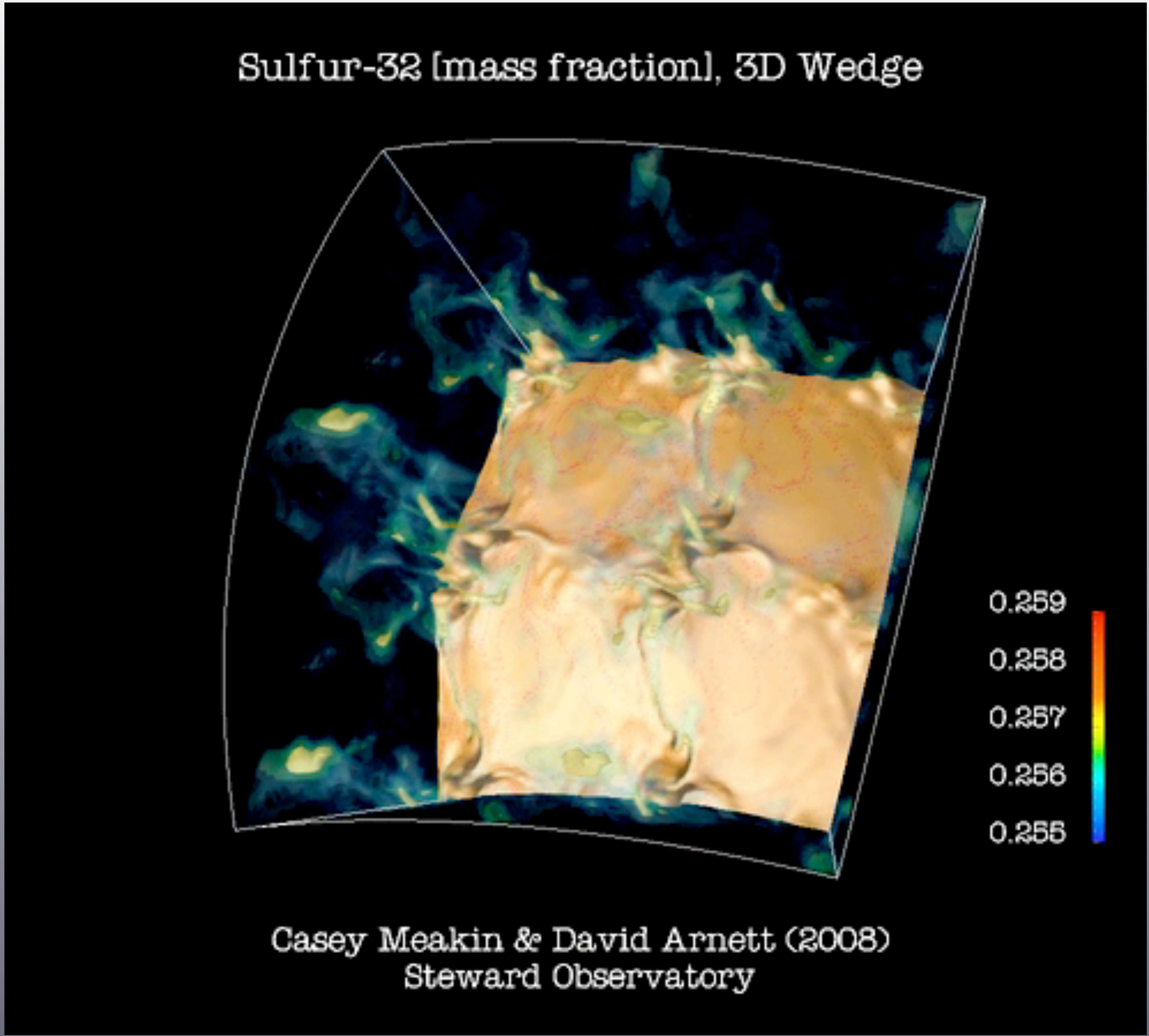
- We need full 4 pi steradian geometry to get the lowest order modes

- Contrary to conventional wisdom, progenitor models are a MAJOR uncertainty for core collapse! (e.g., the compactness parameter of O’Conner & Ott 2012; see also Ugliano et al 2012)

Toward a 3D Turbulence theory:

- numerically simulate turbulent convection in a realistic stellar model (O burning shell in a collapse progenitor)
- theoretically analyze the numerical data
- synthesize a theory which is useable in a stellar evolution code (replaces MLT) for long term evolution

- anelastic and low-mach solvers give an increase in time step of only 10-100 for realistic progenitors due to accuracy limitations (good but not big enough for evolution)
- implicit solvers (Viallet) are also limited
- evolutionary time steps require reformulation to “step over” turbulent variations (Lorenz attractor)

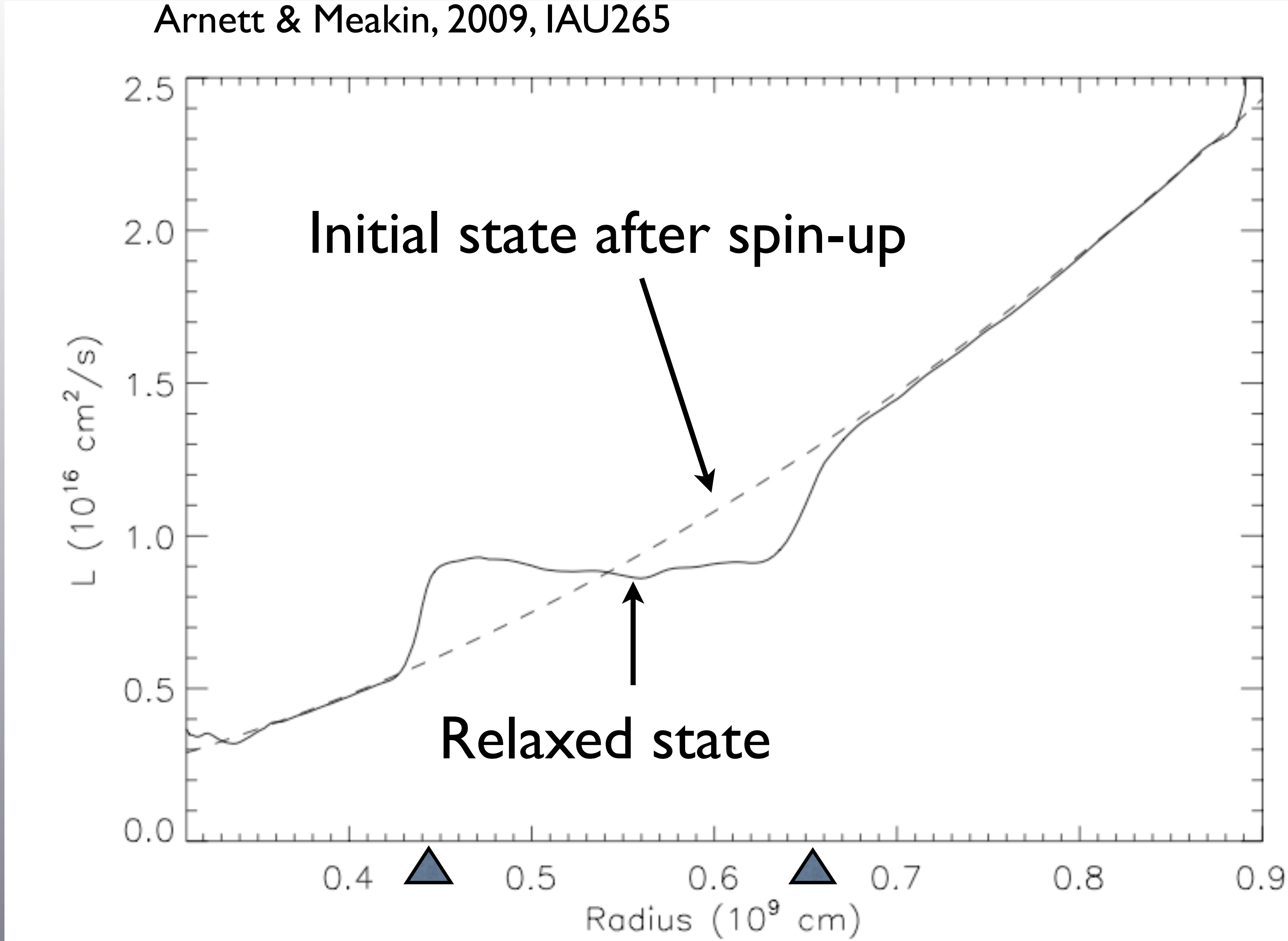

Sulfur-32 [mass fraction], 3D Wedge
0.259
0.258
0.257
0.256
0.255
Casey Meakin & David Arnett (2008)
Steward Observatory

New results:

- Kolmogorov damping balances buoyancy (to fix velocity scale and remove adjustable alpha parameter)
- turbulent braking layers enclose Schwarzschild convection zones (overshoot)
- Fluctuations, cells and Lorenz strange attractor (dynamic systems theory)
- Turbulent heating (thermodynamic consistency)

Rotation and Convection:
a beginning

Case 1: Deep interior



triangles denote top and bottom convective boundary (and shear layer)

Case 2: Surface

Schou, et al., 1998, ApJ

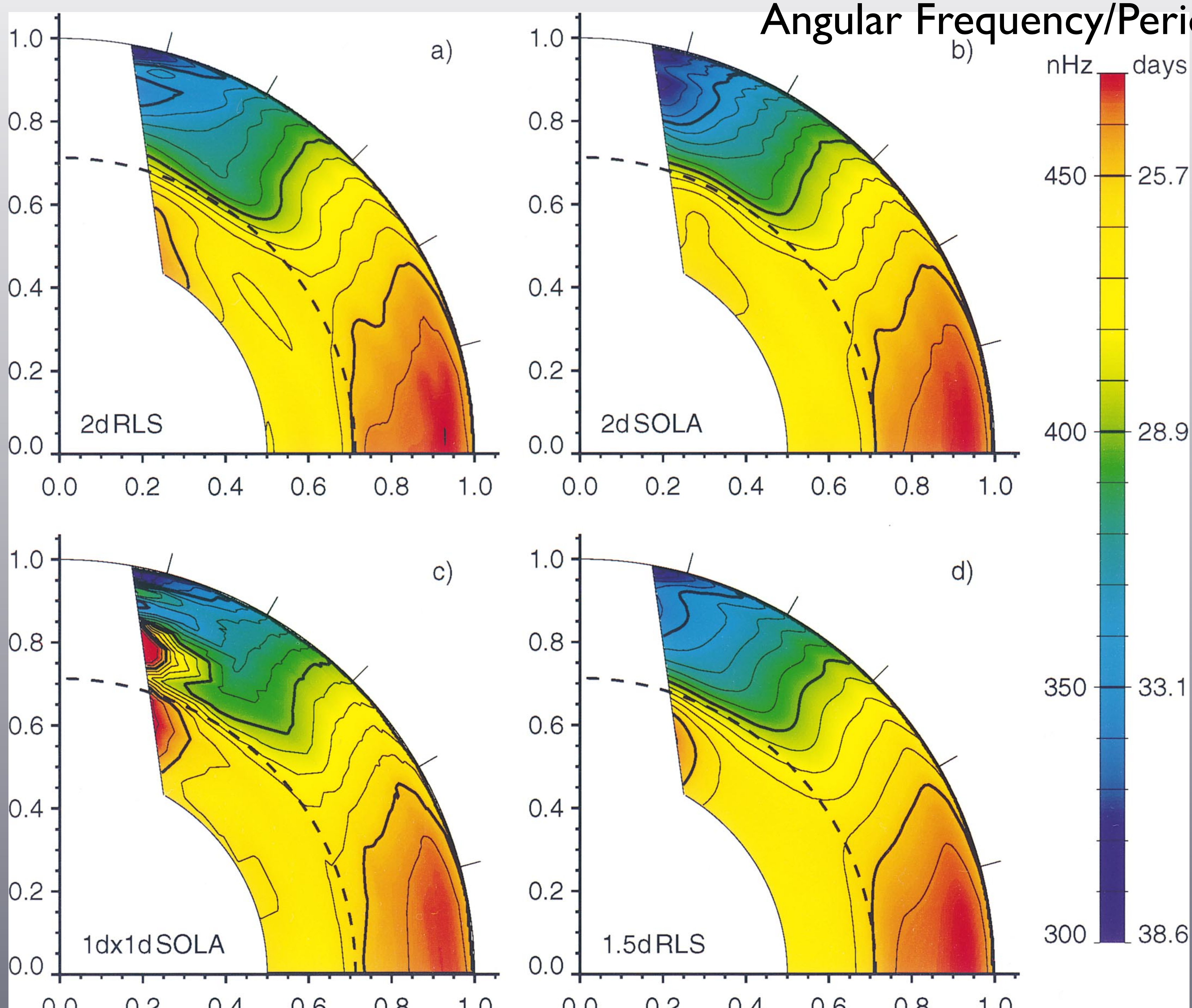


FIG. 5.—As a companion to Fig. 3, inversions for rotation rate $\Omega/2\pi$ with radius and latitude for four inversion methods: (*a*) 2dRLS; (*b*) 2dSOLA; (*c*) 1d × 1dSOLA; (*d*) 1.5dRLS.

- Balbus & Weiss (2009, MNRAS) show that this behavior does NOT require a magnetic field, but may be a result of purely hydrodynamic, turbulent flow.

Case 3: Red Giant

Red Giant: Brun & Palacios, 2009, ApJ, 702, 1078

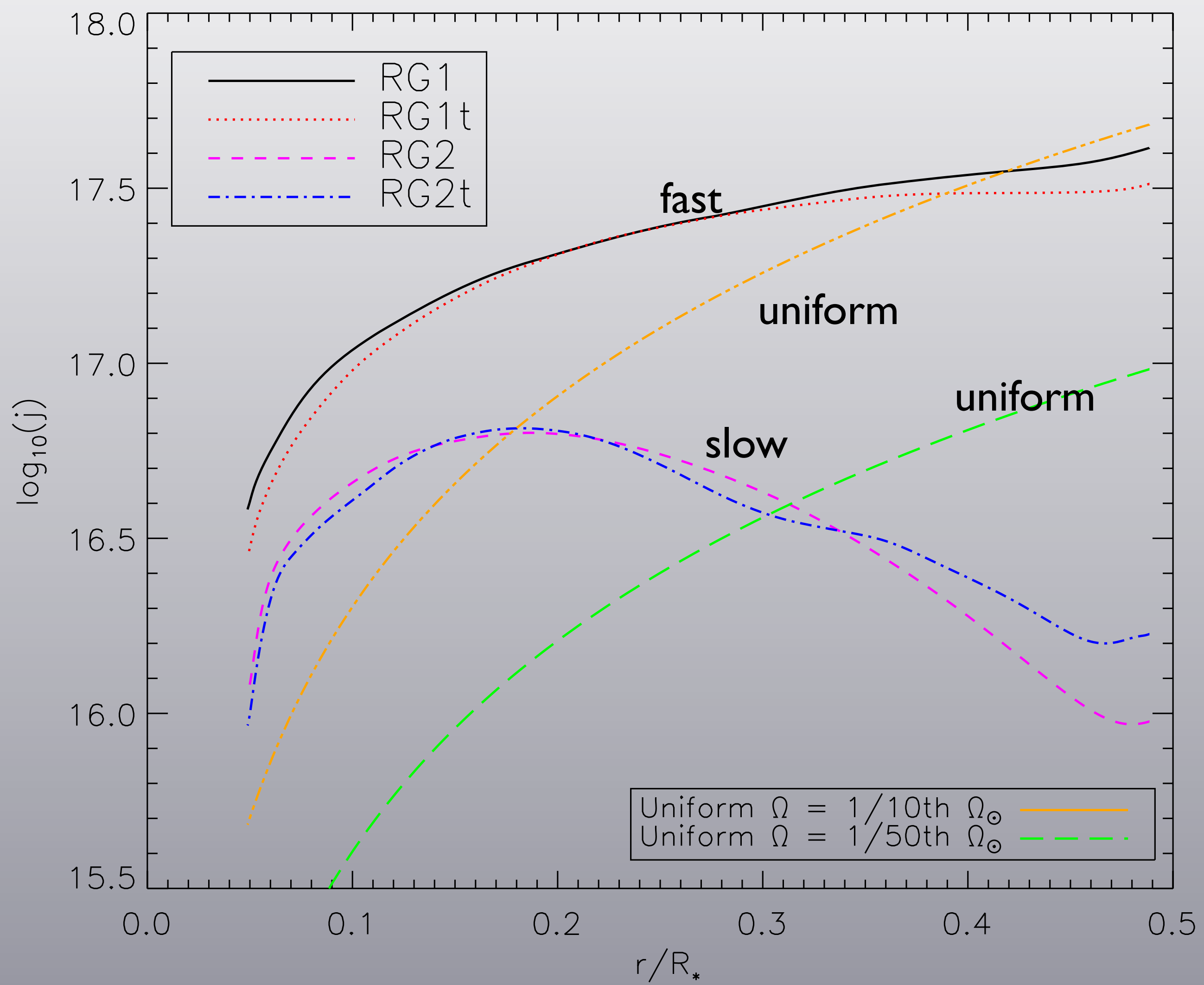


Figure 12. Specific angular momentum profiles throughout the computational domain for the four simulations. These profiles are obtained by averaging the v_ϕ component of the velocity field over latitude, longitudes, and time. The averages are computed over the last rotation period for cases *RG1* and *RG1t*, and over two-thirds of a rotation for case *RG2t*. Overplotted are the profiles that would be obtained if the angular velocity profiles were uniform over the convective shell with values of 1/10th and 1/50th of the solar value.

(A color version of this figure is available in the online journal.)

It is unclear how the ASH energy non-conservation in stratified environments affects this result (Brown et al, 2012).

- We see a variety of behavior!
- It seems to depend upon Rossby number (ratio of inertial to Coriolis force), and perhaps stratification
- above $j \sim 10^{14}$ cm^2/sec, rotation will dominate convective mixing, giving a bifurcation in behavior (and a new class of progenitors)
- The insights from 3D simulations should be applied to calculations of stellar evolution
- We must regard our understanding of the evolution to core collapse as incomplete at best