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Alpha Ori imaging science

Radiation hydrodynamics simulations
of the convective envelope of a red supergiant

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Outline

- Introduction: stellar convection
- Numerical simulations of solar-type granulation
- Radiation hydrodynamics code CO^{5}BOLD
- Numerical models of Betelgeuse
- Observations
- Conclusions

Convection as physical process

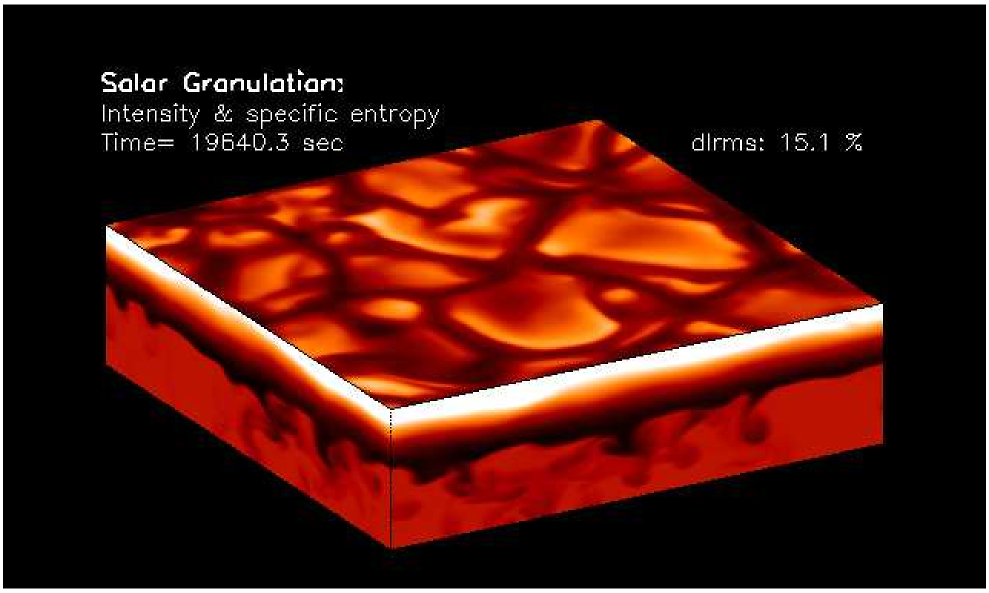
- Simple mechanism:
  heat transport by macroscopic motion of matter
  in a gravitationally stratified environment
- Complex details e.g. on Earth: clouds, weather, climate

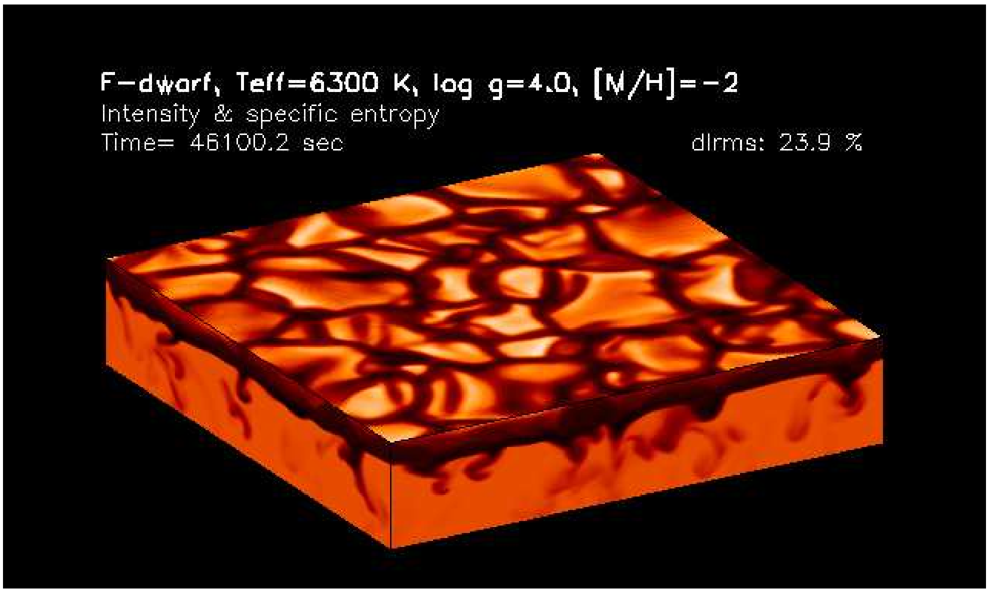
Stellar convection

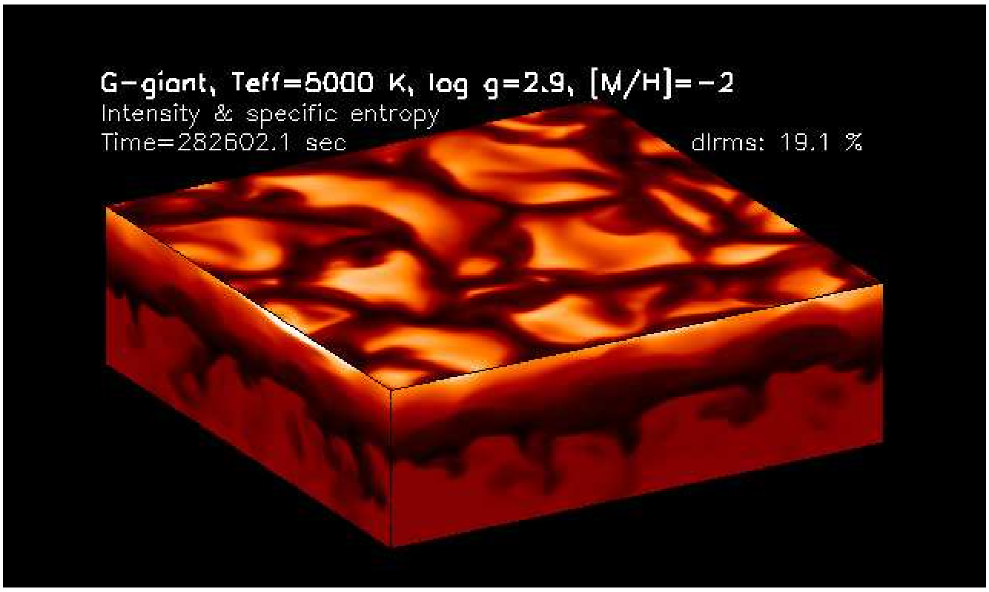
- Heat transport $\rightarrow$ temperature stratification
- Transport of matter $\rightarrow$ mixing, abundances
- Motion $\rightarrow$ broadening and shift of spectral lines,
  pressure stratification
- Heat engine $\rightarrow$ kinetic energy, waves
- Non-linearity $\rightarrow$ structure formation, chaos
- Interaction with magnetic fields $\rightarrow$ dynamo

Local simulations of solar-type granulation

Examples by Matthias Steffen (Potsdam)

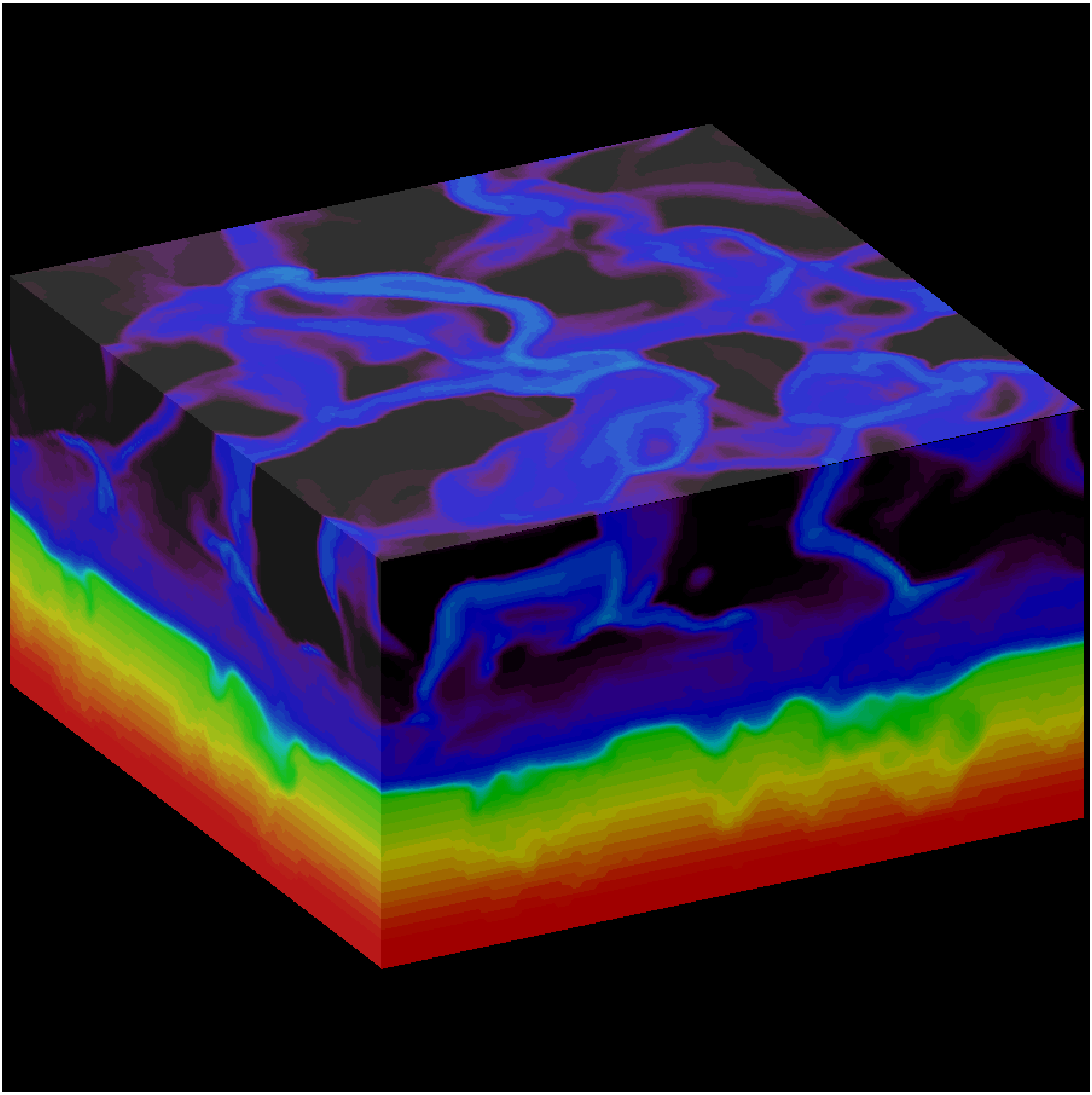






Chromospheric shocks

Example by Sven Wedemeyer (Kiel)



Betelgeuse: Basic parameters

- Betelgeuse: α Orionis, HD39801, HIP27989
- M2 Iab Red Supergiant
- Among the stars with largest apparent diameter
- Θ=42 – 65 mas, R=600 – 1000 $R_\odot$
- Hipparcos-distance =131 $\pm$ 30 pc
- M=5 – 20 $M_\odot$
- T_{eff}=3400 – 3600 K, $\log g$= -0.5 – 0.5

Schwarzschild's suggestion (1975)

- Horizontal size of granules $\propto$ characteristic vertical length
- E.g. $H_p/R_* \propto T_{\mathrm{eff}}/(M_* g)^{1/2}$
- "Surface of red supergiant might be covered by only a handful of granules."

Simulations with CO^{5}BOLD

COnservative
COde for the
COmputation of
COmpressible
COnvection in a
BOx of L Dimensions, l=2,3

Code features

- Hydrodynamics: approximate 1D Riemann solver (Roe-type)
- Hydrodynamics: additional 3D tensor viscosity
- Radiation transport: non-local, strict LTE, long- or short-characteristics scheme
- EOS: tabulated, accounts for ionization effects
- Opacities: tabulated, grey, based on realistic PHOENIX + OPAL tables
- Properties: conservative, parallelized with OpenMP

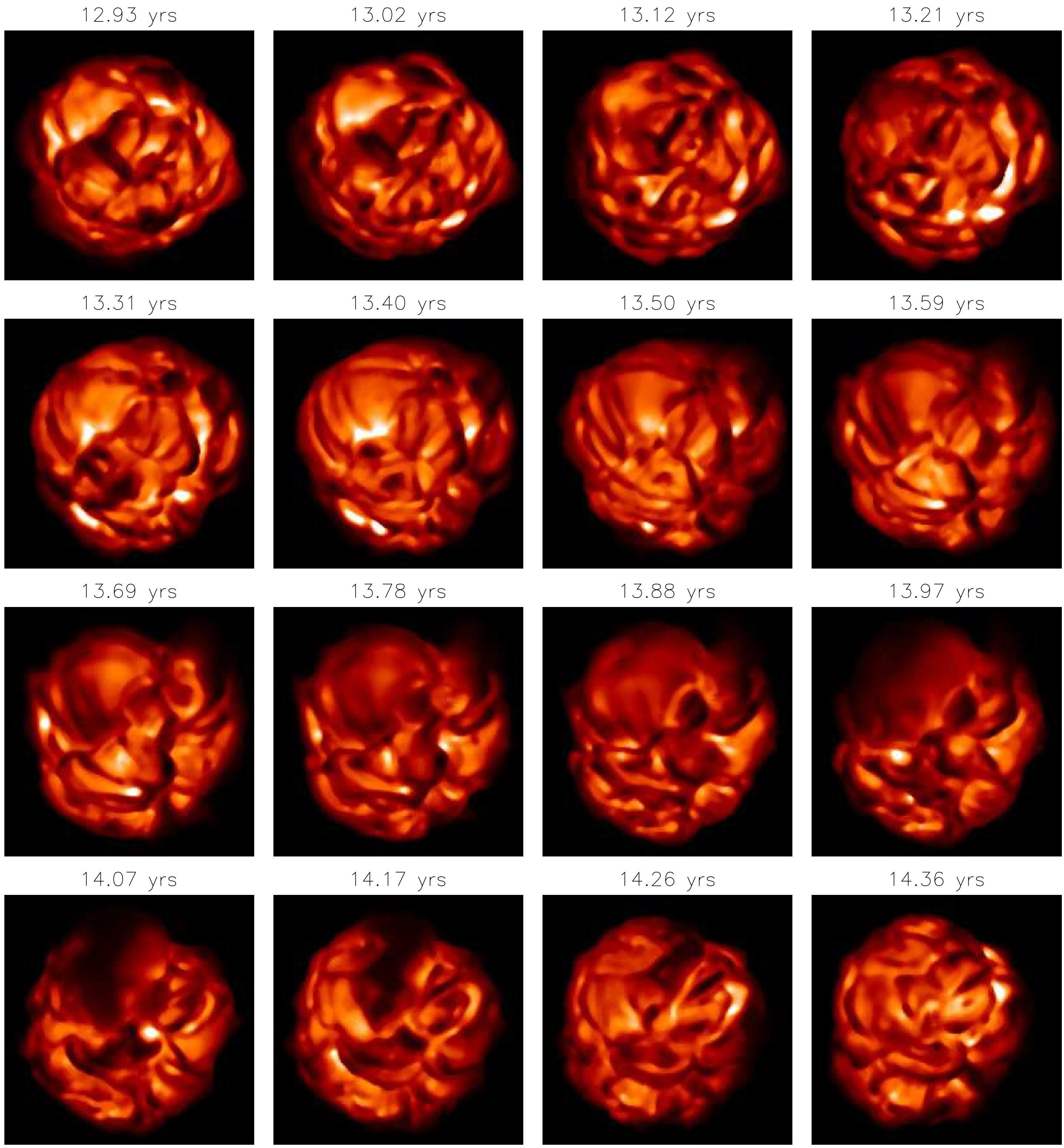
Model setup

- Computational domain: cube,
  edge length 1626 $R_\odot$, 171^3 points
- Gravitation: spherical $1/r$ potential,
  smoothed in the center
- Energy source: within a sphere of radius r_0=135 $R_\odot$
- Outer boundaries: open, transmitting for waves
- Parameters (model st35gm04n06):
  - solar composition
  - $M_\star = 5 M_\odot$
  - $T_{\rm eff} \sim$ 3330 K
  - $\log g \sim$ -0.46 (cgs units)
  - $R_\star \sim$ 630 $R_\odot$
  - $L_\star \sim$ 44 000 $L_\odot$

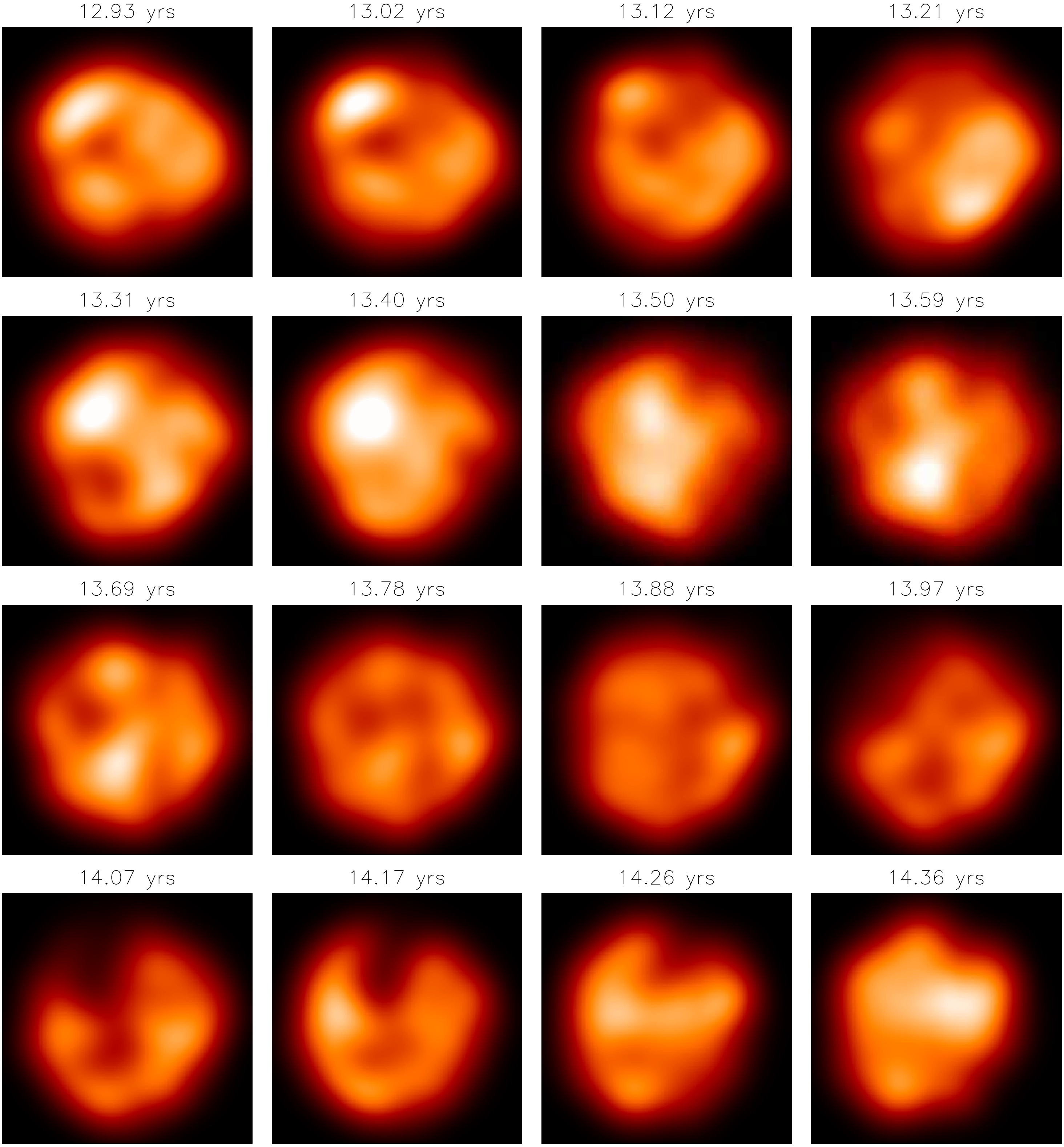
Difficulties

- Small ratio of radiative to hydrodynamical time-step, $\approx 1/100$th of solar value
- Violent convective flows, high Mach-numbers
- Temperature sensitivity of opacity
- Non-local coupling by waves:
  importance of core and outer atmosphere
- Simulations: CPU time consuming,
  relatively poor spatial resolution

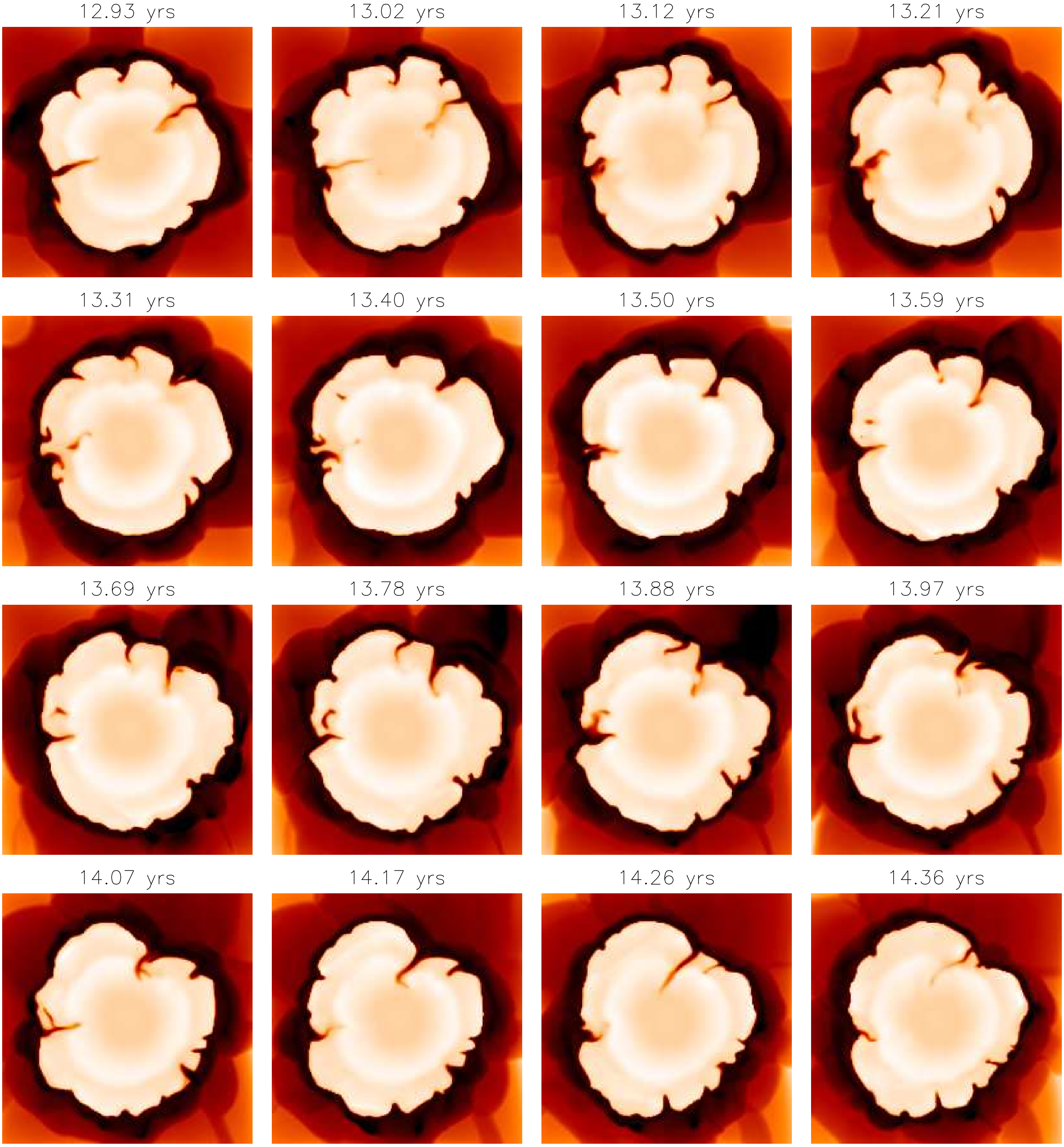
Results: Intensity sequence



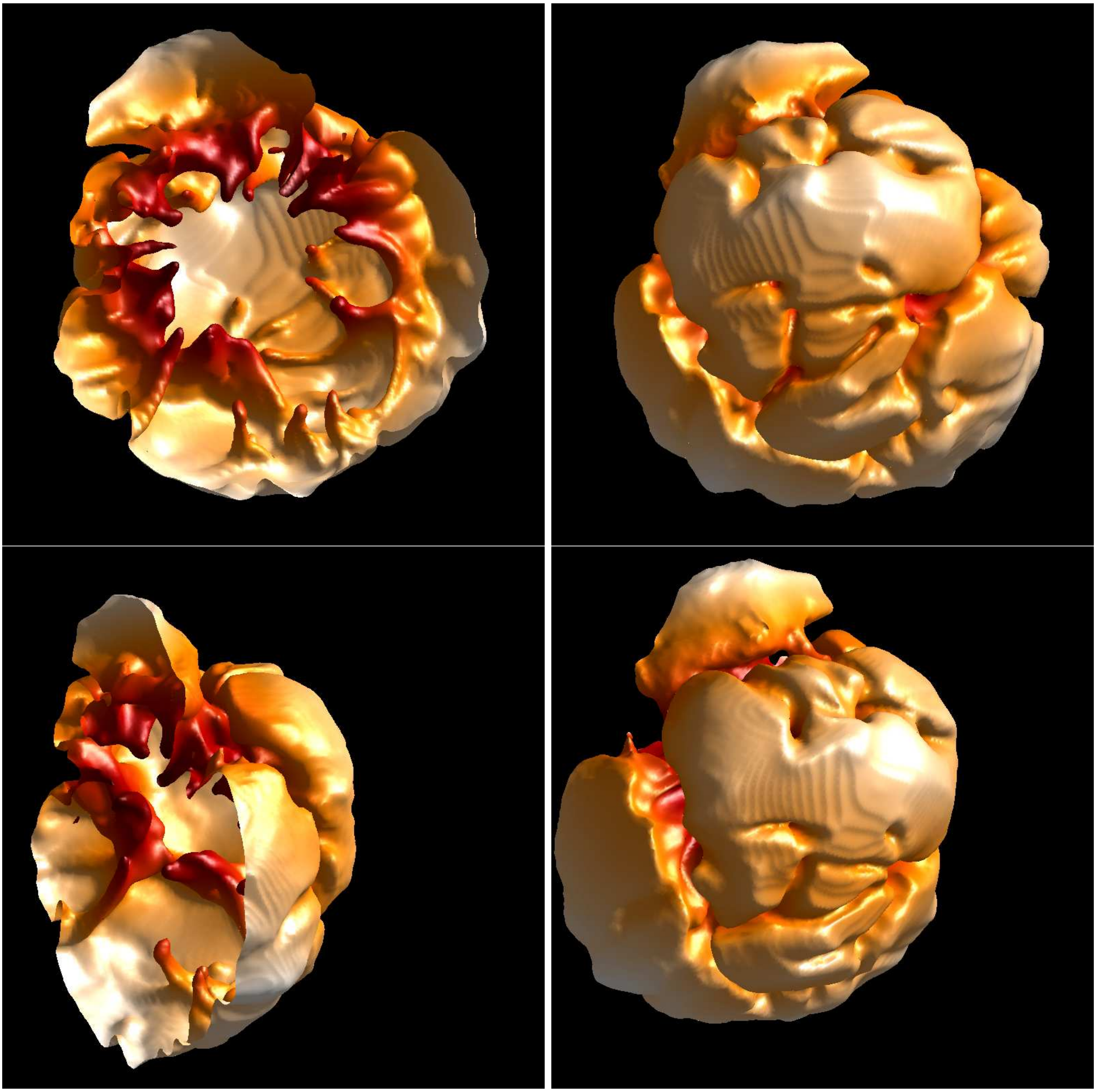
Results: Blurred intensity sequence



Results: Entropy slices

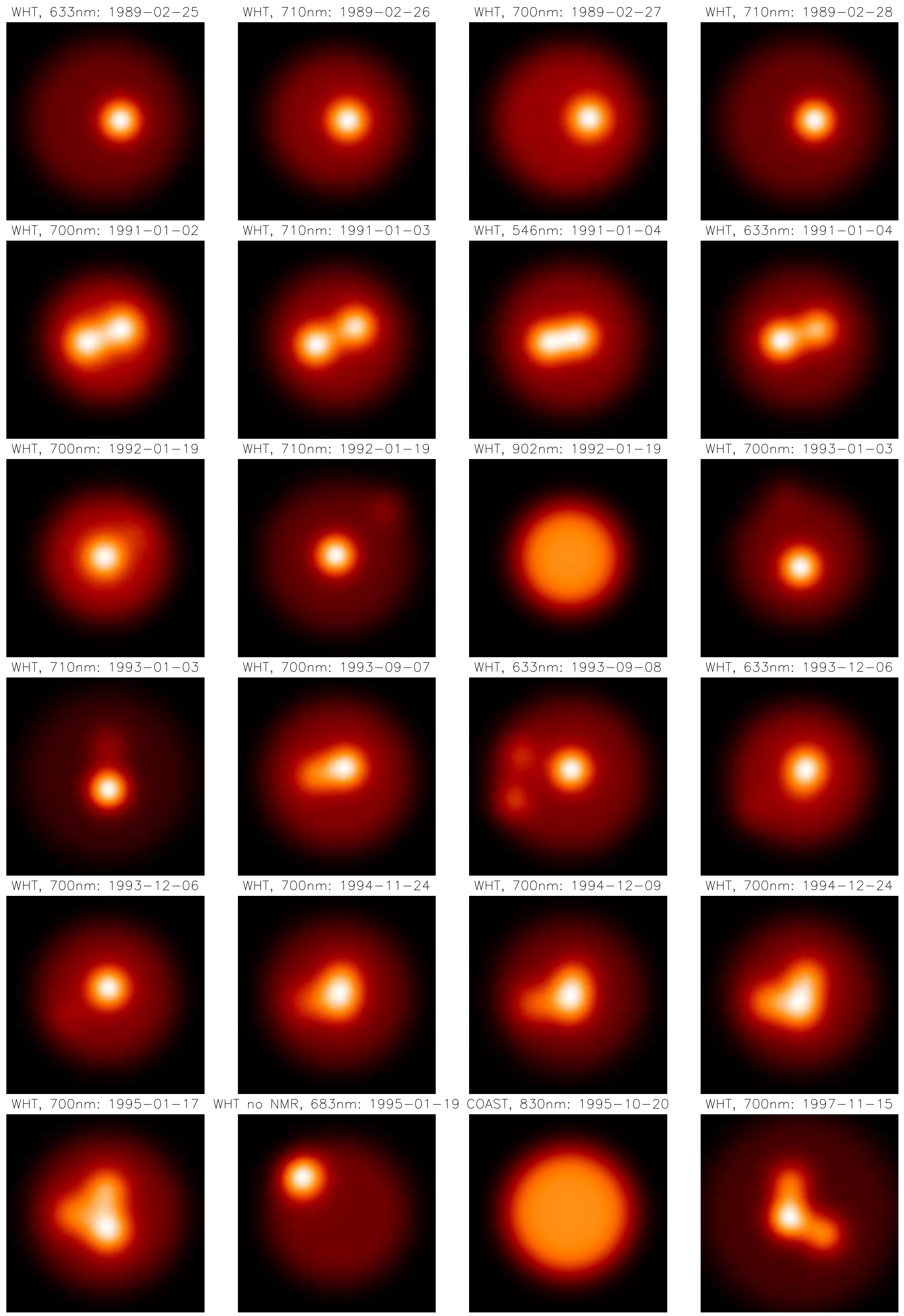


Results: Entropy iso-surfaces

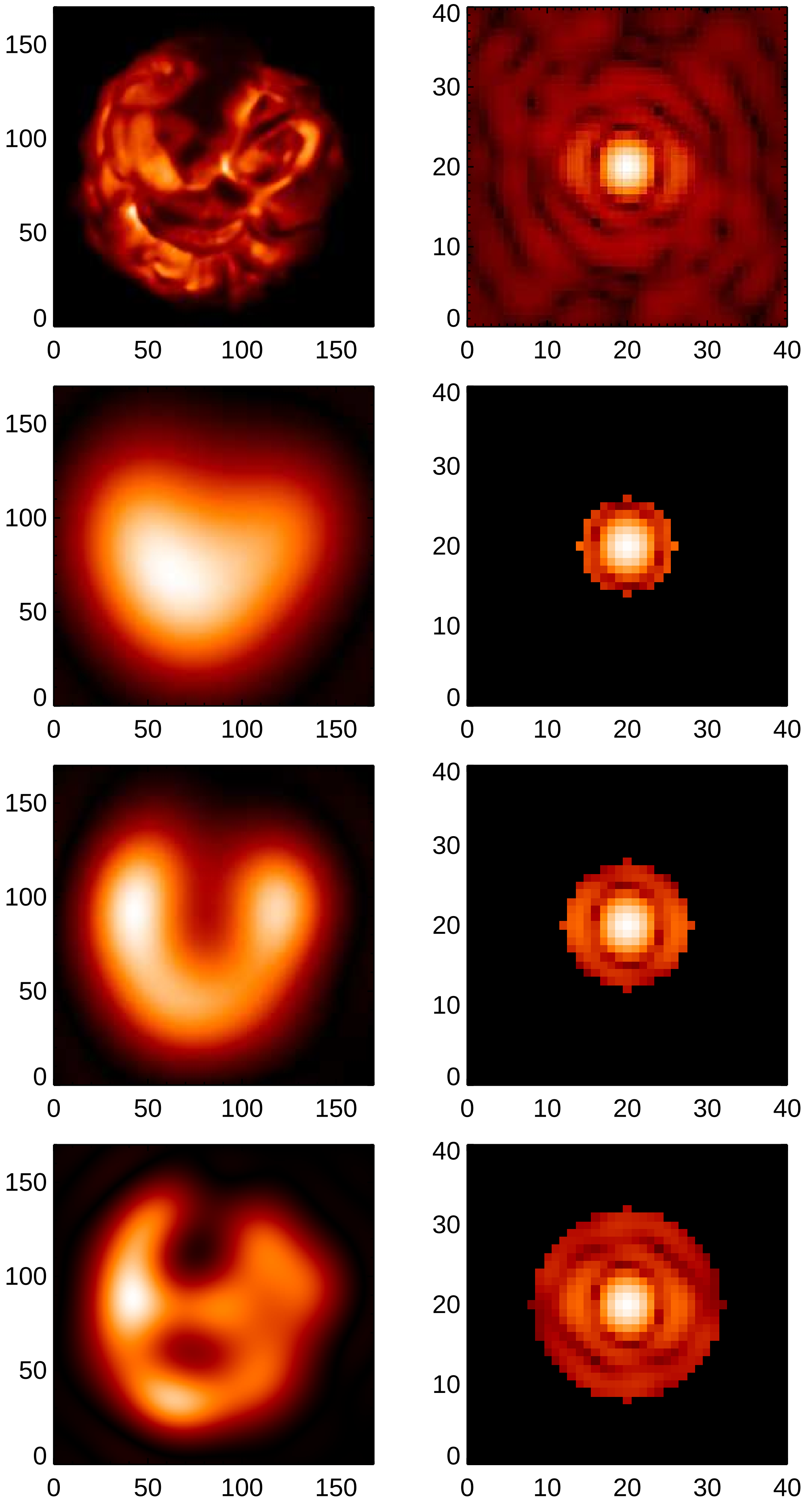


Observations

...from Buscher et al., 1990, MNRAS 245, 7p; Wilson et al., 1992, MNRAS 257, 369; Tuthill et al., 1997, MNRAS 285, 529; Wilson et al., 1997, MNRAS 291, 819; Klueckers et al., 1997, MNRAS 284, 711; Burns et al., 1997, MNRAS 290, L11; Young et al., 2000, MNRAS 315, 635.



Observations: Simulated



Conclusions

Realistic 3D radiation hydrodynamics simulations of the outer convective envelope and atmosphere of Betelgeuse

- Complex surface pattern
  - A handful of giant envelope convection cells
  - More and smaller surface cells
  - Waves/pressure fluctuations

$\Rightarrow$ Large-scale high-contrast brightness fluctuations

- Qualitative agreement between existing observations and models

Improvements

- Simulations: finer numerical grid, more detailed treatment of radiative transfer, spectrum synthesis
- Observations: better spatial resolution, measurements in regular intervals