Astrophysical Gas Dynamics

TODAY:

- *Supernova explosions (scalings → recap)*
- *Sedov solution*

Image credit: M. S. Povich

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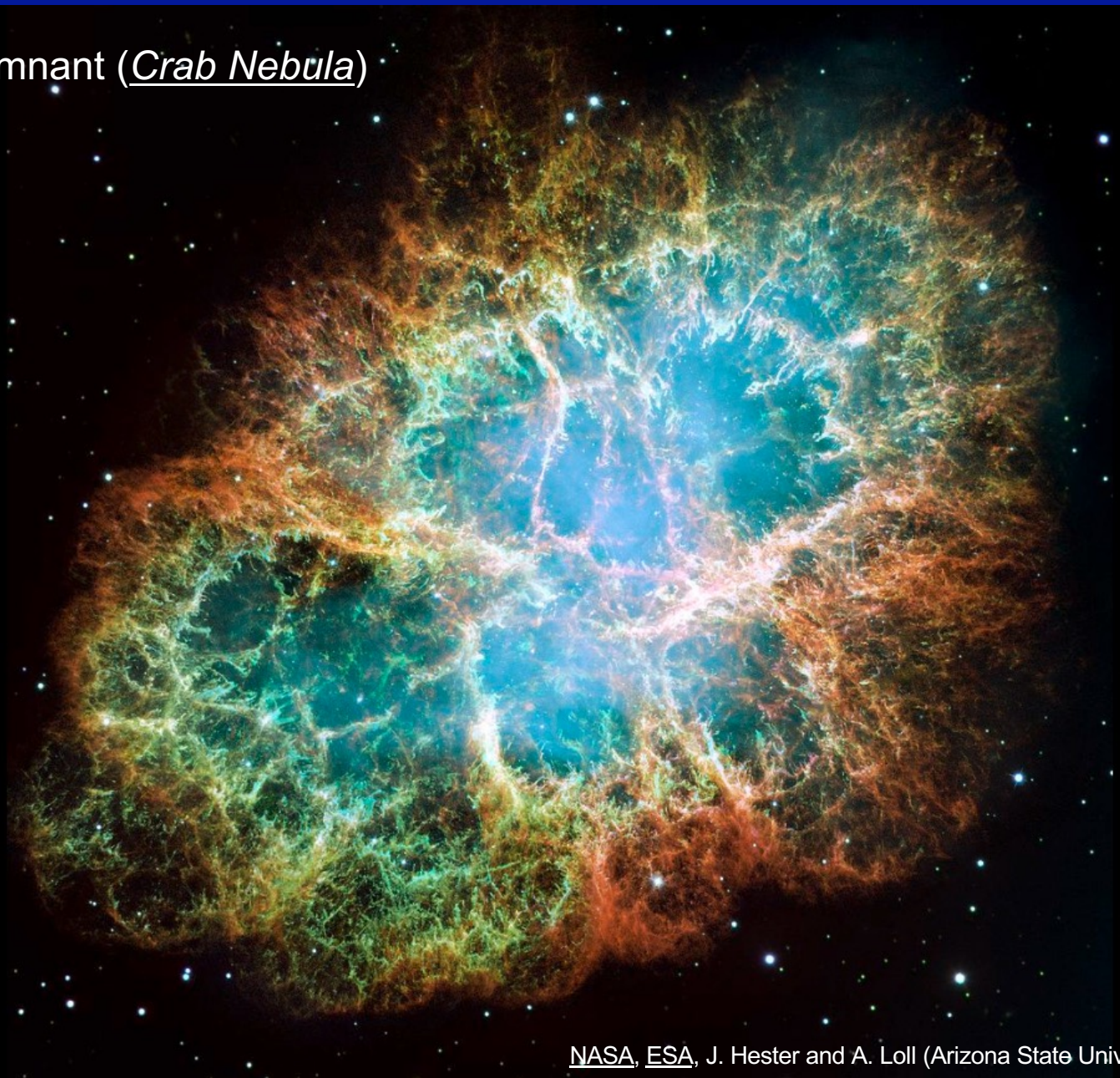
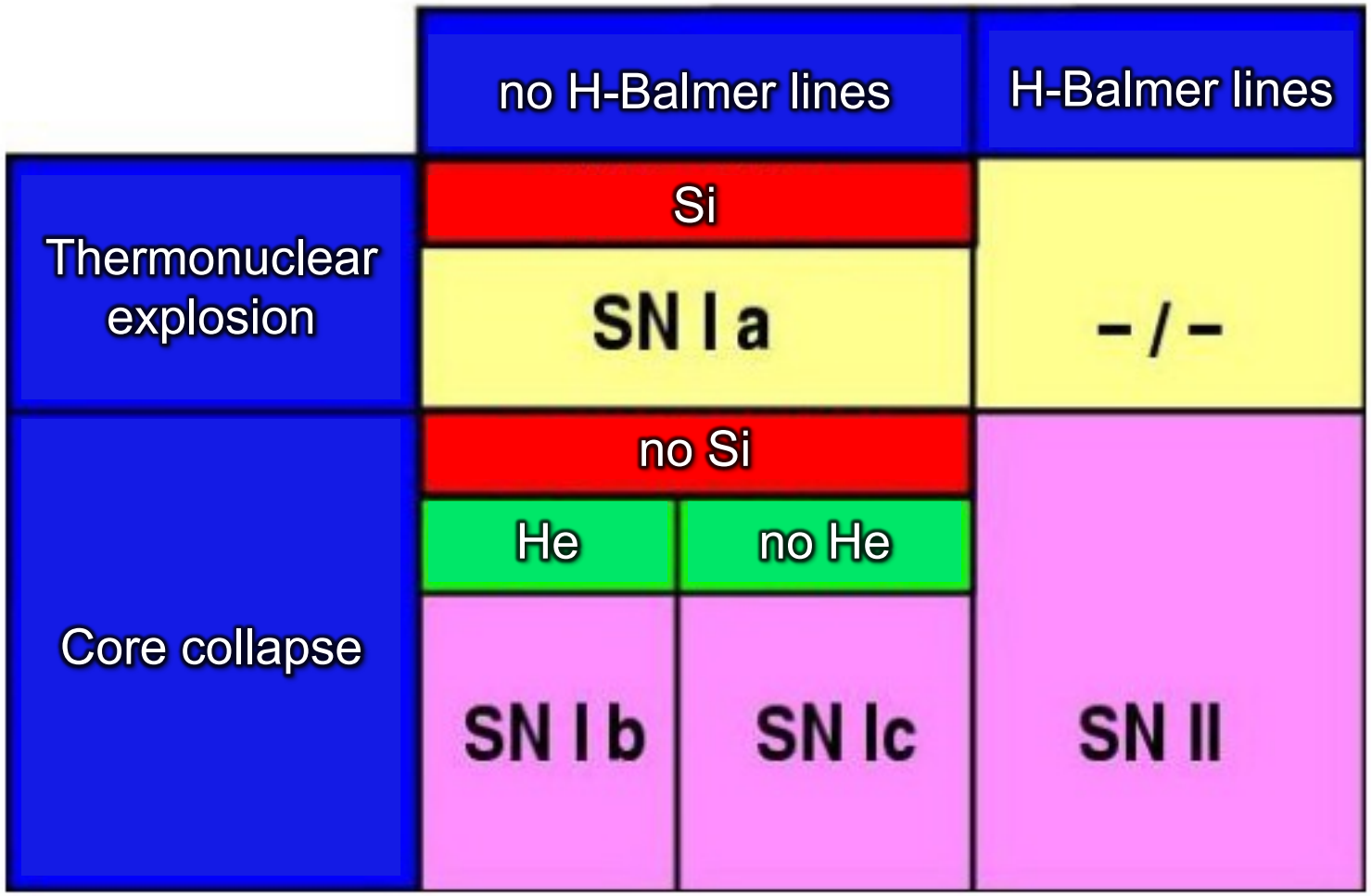
Supernova explosions

SN 1054 remnant (*Crab Nebula*)

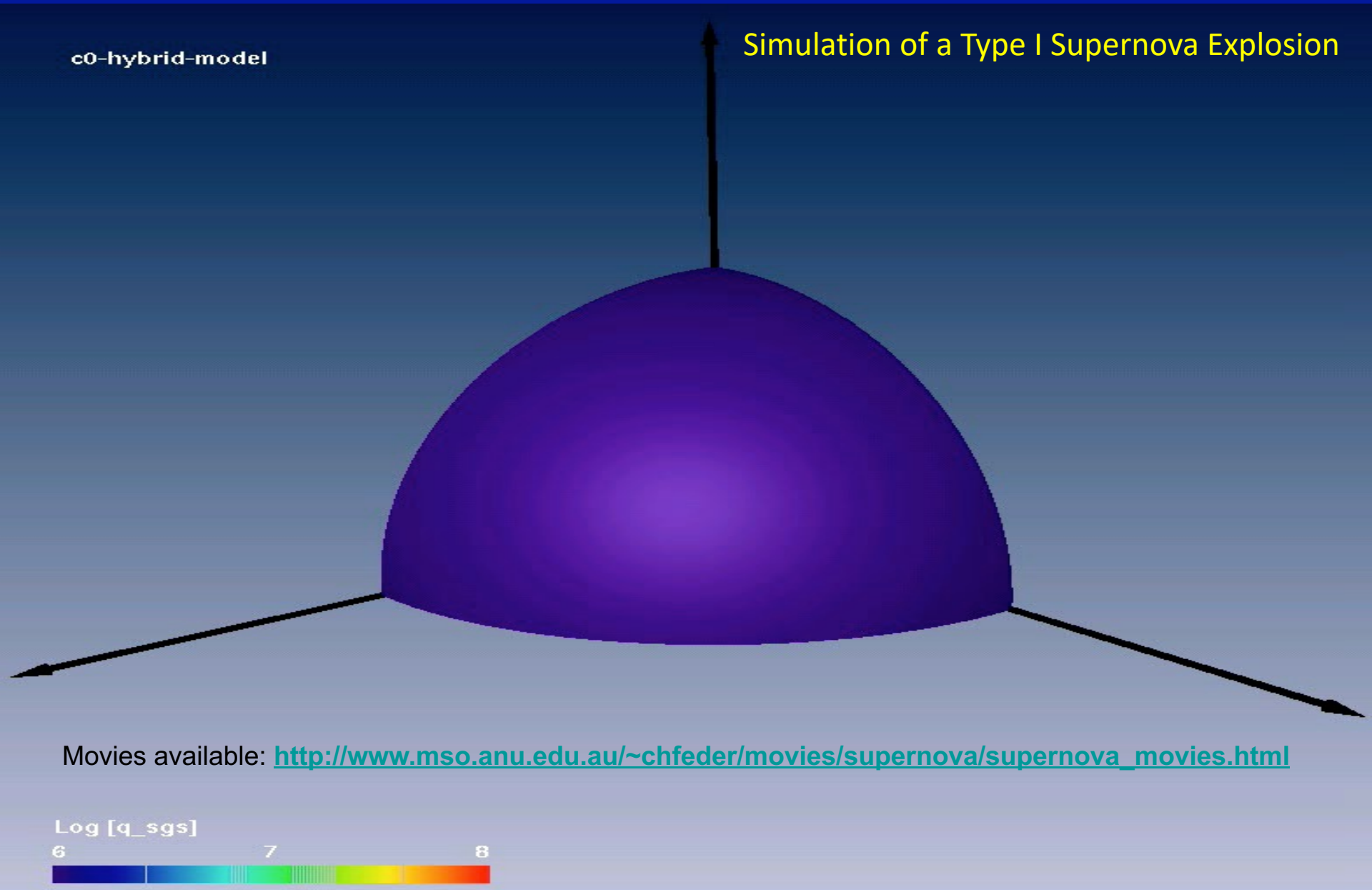


NASA, ESA, J. Hester and A. Loll (Arizona State University) - HubbleSite

Type Ia versus type II/Ibc



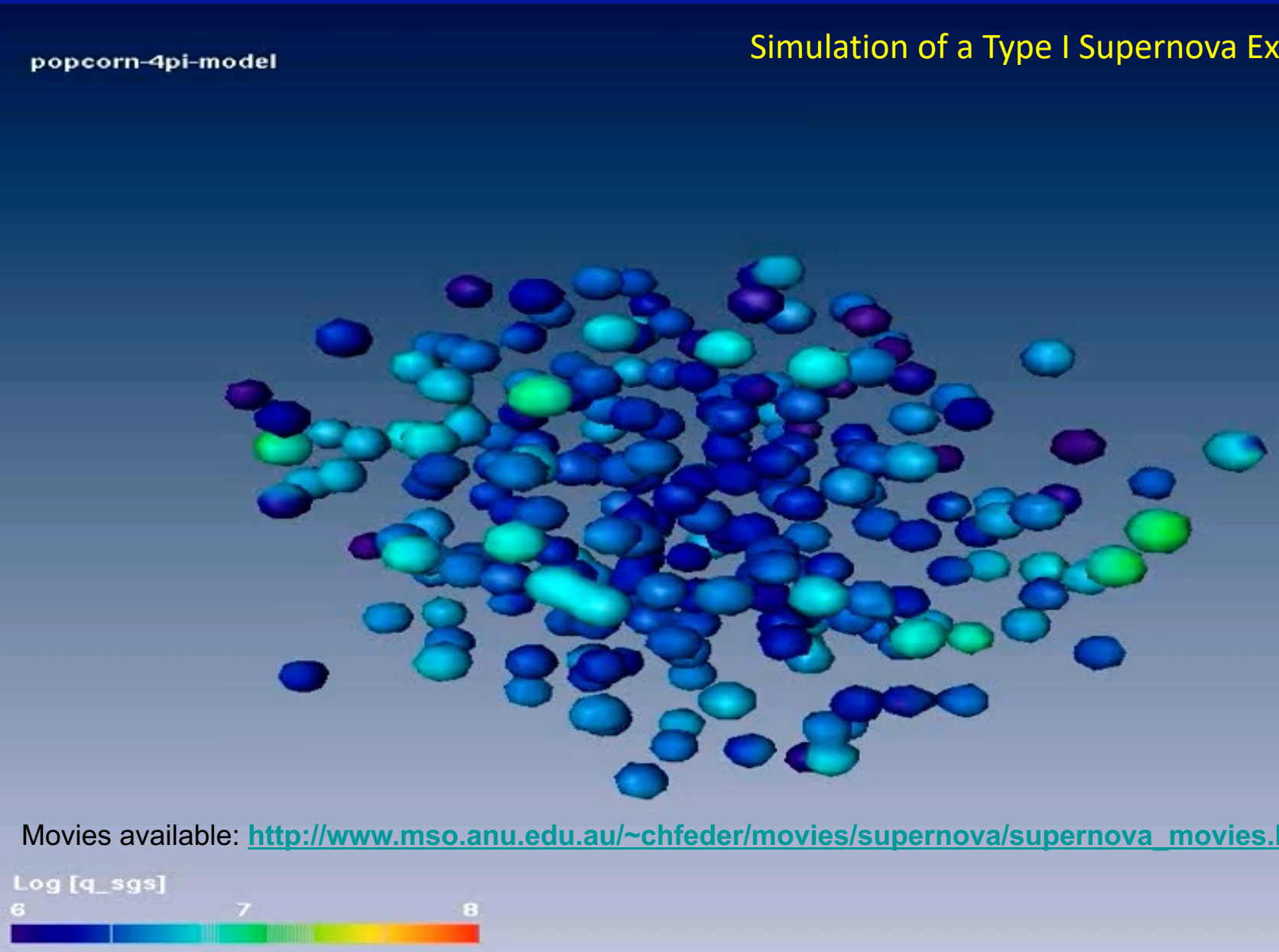
Supernova explosions



Movies available: http://www.mso.anu.edu.au/~chfeder/movies/supernova/supernova_movies.html

Supernova explosions

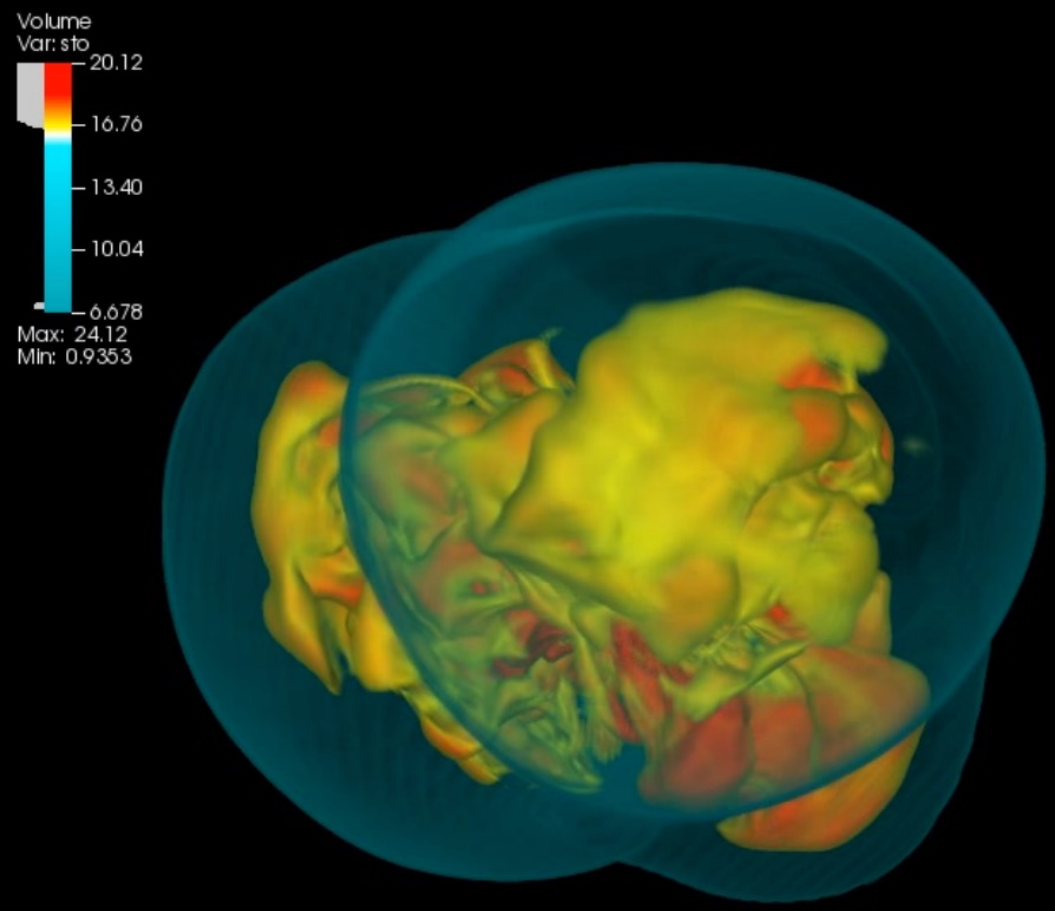
Simulation of a Type I Supernova Explosion



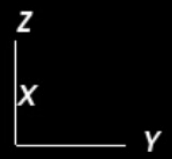
Movies available: http://www.mso.anu.edu.au/~chfeder/movies/supernova/supernova_movies.html

Astrophysical Gas Dynamics

Simulation of a Type II Supernova Explosion



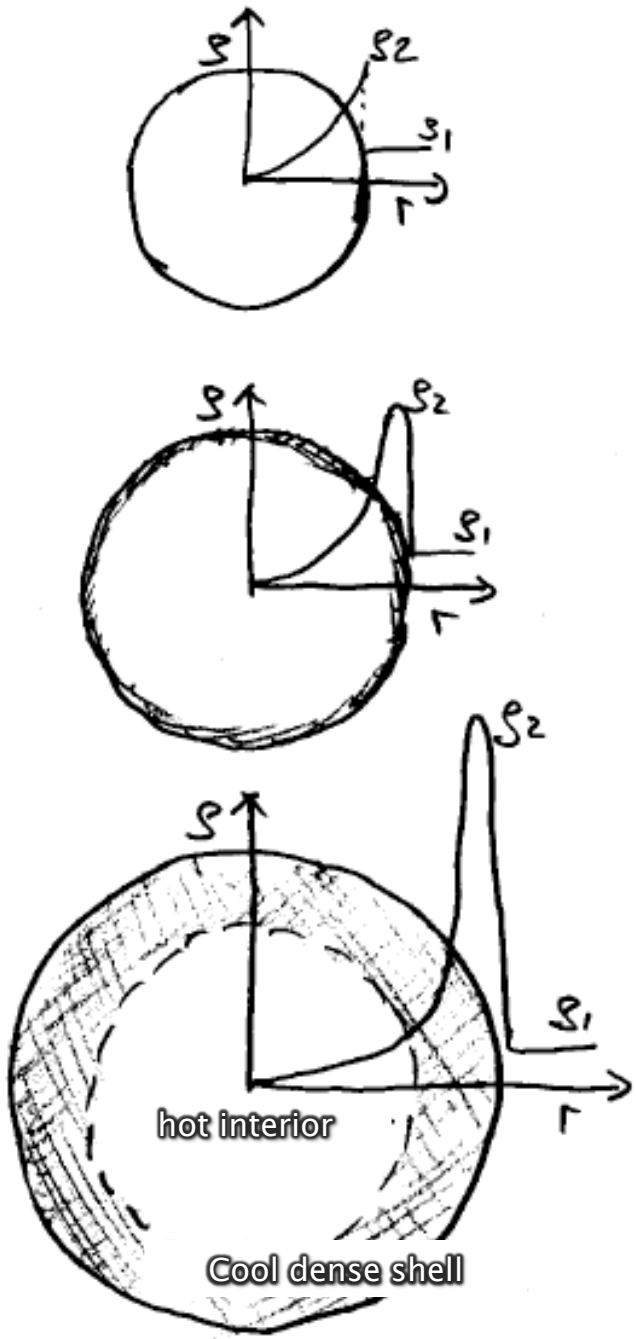
Movies available:
https://wwwmpa.mpa-garching.mpg.de/ccsnarchive/movies/



(Summa, Janka et al. 2018)

Supernova phases

Evolutionary sequence



Energy-driven expansion
Shock speeds of about 1000 km/s

"Snow-plow phase"
Cooling -> dense, thin shell forms and sweeps up more material; Thickness of shell ~ 1pc with density n ~ 1-100 cm^{-3}

Momentum-driven phase
Expansion eventually comes to a halt after about 30,000 yr, when momentum of swept-up material equals the initial momentum of the shell

(Klessen script on Theoretical Astrophysics)

Astrophysical Gas Dynamics

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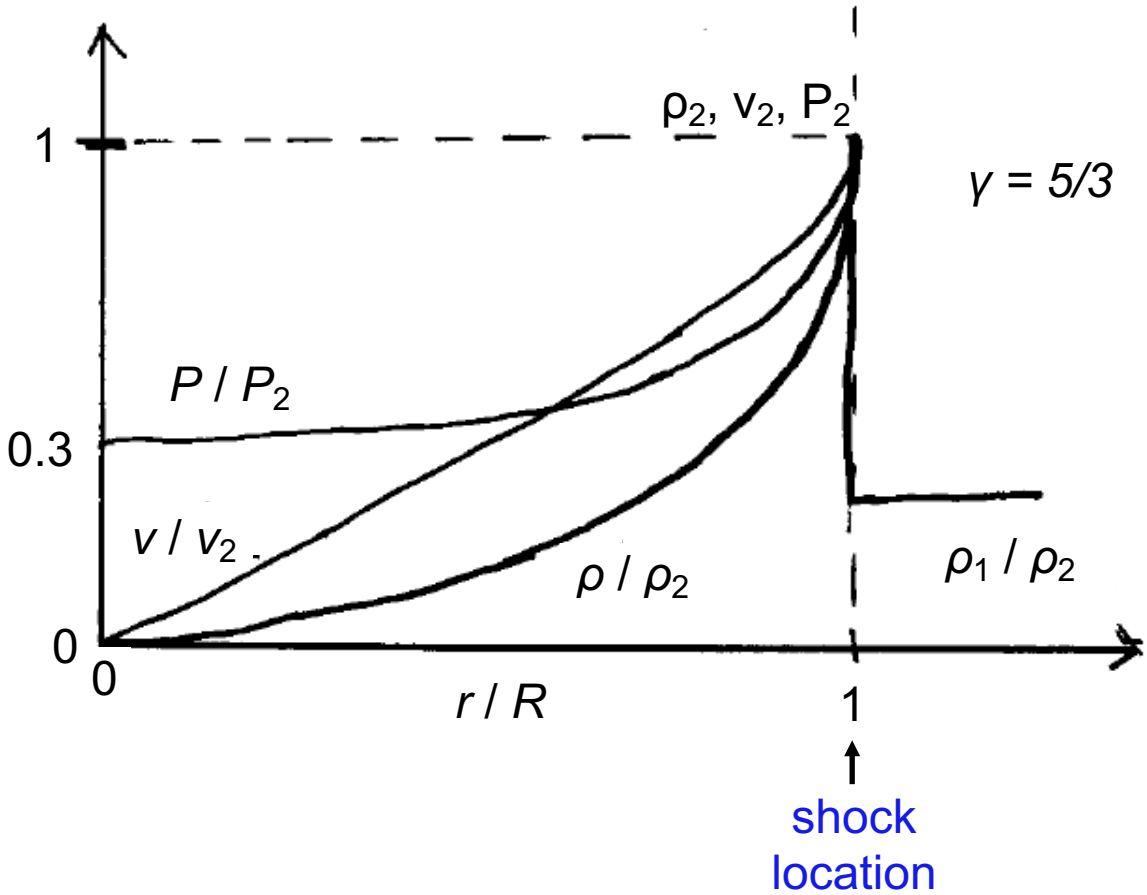
- *Sedov solution*

Image credit: M. S. Povich

Sedov solution

Self-similar Sedov solution for density, velocity, and pressure

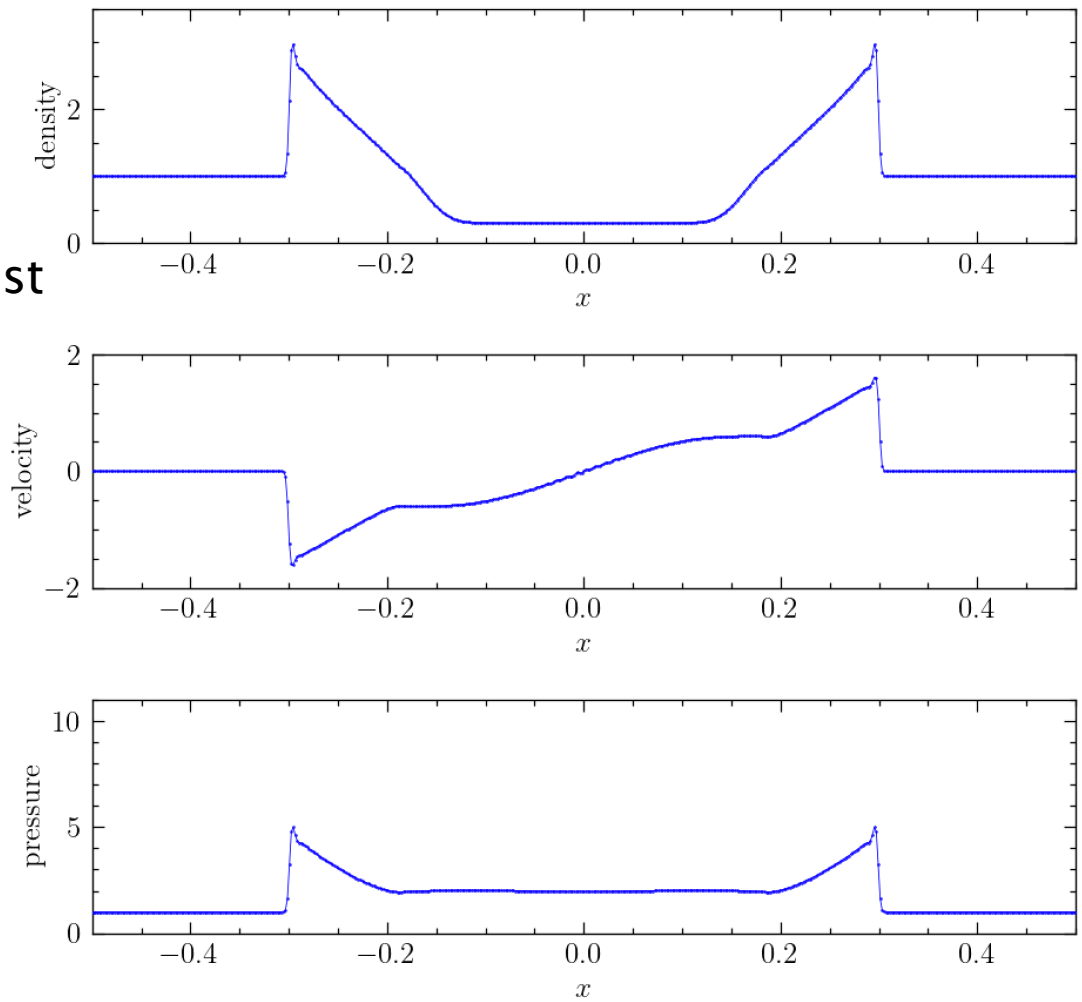
(shock wave expanding into uniform medium of density ρ_1)



(Klessen script on Theoretical Astrophysics)

Sedov explosion

- Python program to solve 1D/2D hydro equations: hydro.py
- > ./hydro.py -h
- > ./hydro.py -sim sedov_test



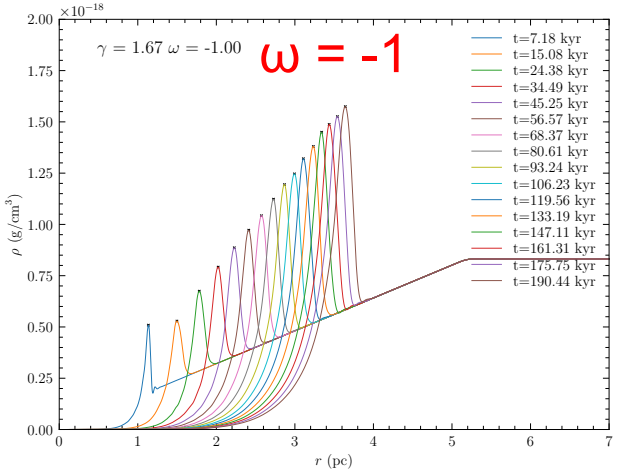
Suggested: Modify the code to change the initial conditions, e.g., energy injection zone, grid resolution, etc.; compare to analytic solution

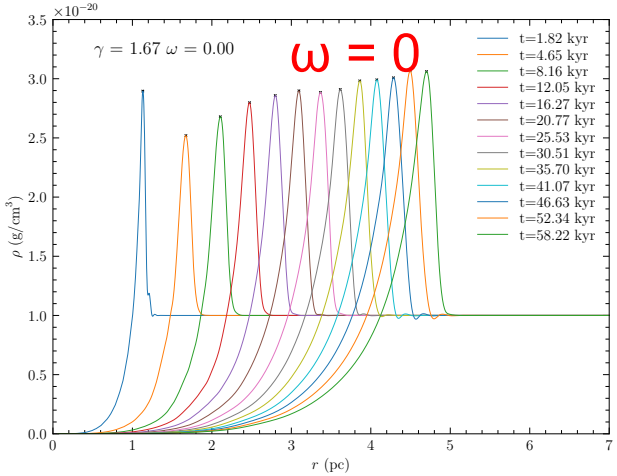
This code uses cftools:
https://www.mso.anu.edu.au/~chfeder/teaching/astr_4012_8002/codes/cftools/

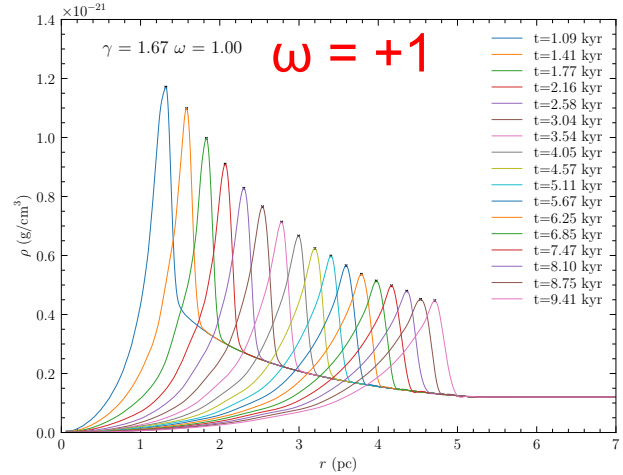
Sedov solution for non-uniform medium with $\rho_{amb}(r) \sim r^{-\omega}$

(see Book 1994, for a summary and discussion of the analytic solutions)

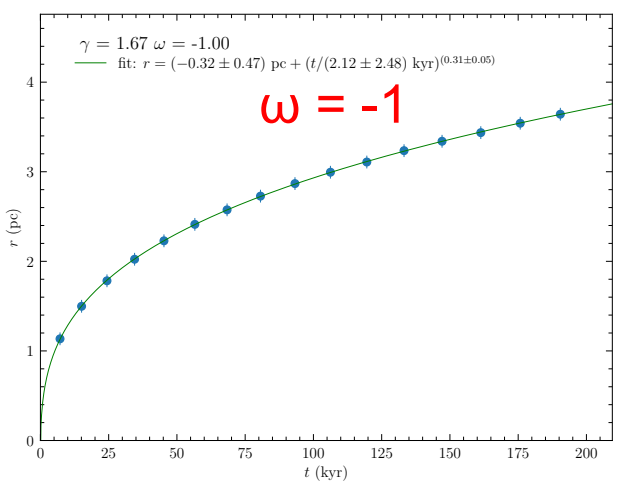
Density profiles ρ(r)

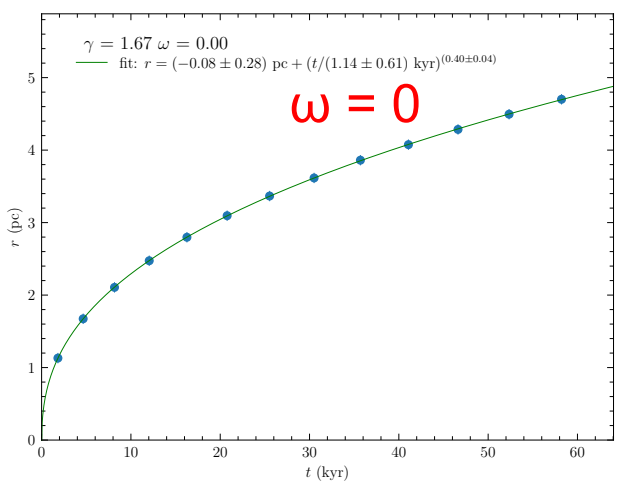


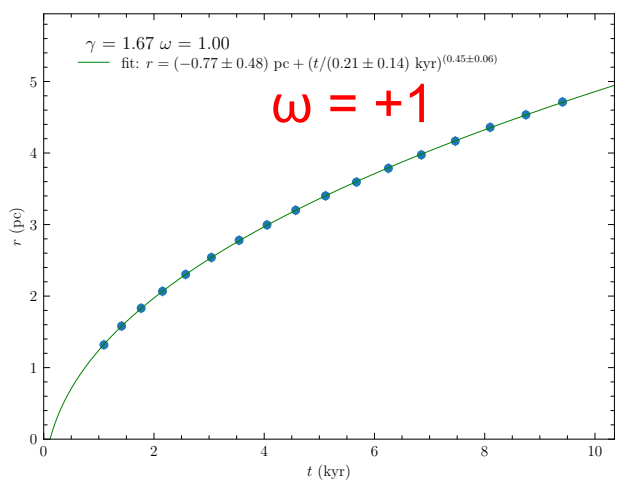




Evolution of shell expansion radius r(t)



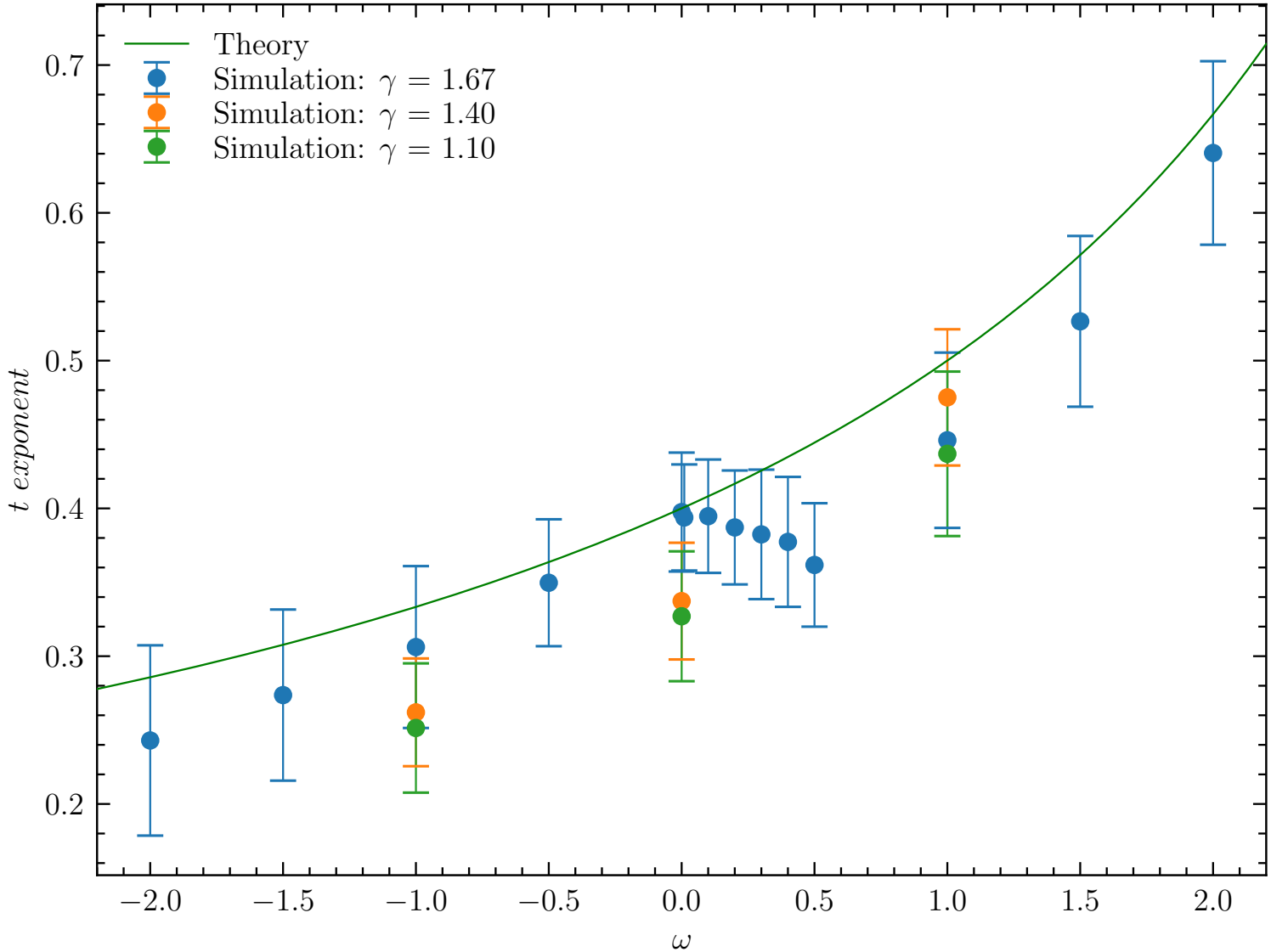




(Monica Bapna et al., in prep.)

Sedov solution for non-uniform medium with $\rho_{amb}(r) \sim r^{-\omega}$

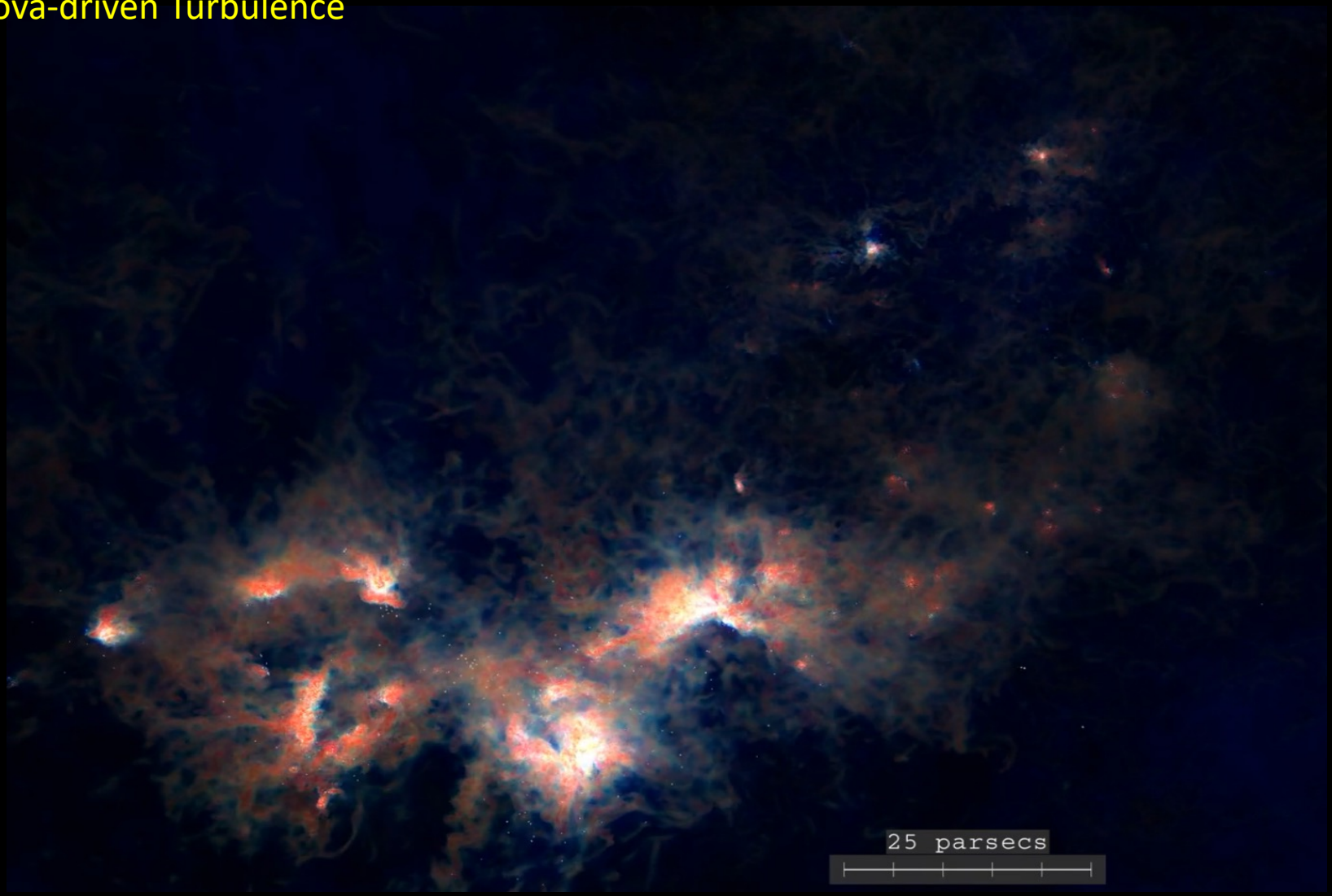
(see Book 1994, for a summary and discussion of the analytic solutions)



(Monica Bapna et al., in prep.)

Supernova-driving of turbulence

Supernova-driven Turbulence



(Padoan et al. 2016, 2017)

Driving of turbulence by supernova explosions

Comparison of Milky Way turbulence dissipation and SN injection rates

Turbulence energy dissipation rate:

$$\dot{e} \simeq -(1/2)\rho v_{\rm rms}^3/L_{\rm d} = -(3\times10^{-27}\,{\rm erg\,cm^{-3}\,s^{-1}})\left(\frac{n}{1\,{\rm cm^{-3}}}\right)\left(\frac{v_{\rm rms}}{10\,{\rm km\,s^{-1}}}\right)^3\left(\frac{L_{\rm d}}{100\,{\rm pc}}\right)^{-1}$$

Supernova energy injection rate:

$$\begin{aligned}\dot{e} &= \frac{\sigma_{SN}\eta_{SN}E_{SN}}{\pi R_{sf}^2 H_c}\\ &= (3\times10^{-26}\ {\rm erg\ s^{-1}\ cm^{-3}})\left(\frac{\eta_{SN}}{0.1}\right)\left(\frac{\sigma_{SN}}{1\ {\rm SNu}}\right)\left(\frac{H_c}{100\ {\rm pc}}\right)^{-1}\left(\frac{R_{sf}}{15\ {\rm kpc}}\right)^{-2}\left(\frac{E_{SN}}{10^{51}\ {\rm erg}}\right)\end{aligned}$$

(η_{SN} is the fraction of kinetic energy per SN)
(1 SNu is about 1 SN per 50 years for the Milky Way)

(Mac Low & Klessen 2004)

Turbulence is key for Star Formation

(Federrath & Klessen 2012; Federrath et al. 2016)

Turbulence → Stars → Feedback

Magnetic Fields

Dynamics (shear)

Turbulence driven by

- Shear
- Jets / Outflows
- Cloud-cloud collisions
- Winds / Ionization fronts
- Spiral-arm compression
- Supernova explosions
- Gravity / Accretion

Solenoidal

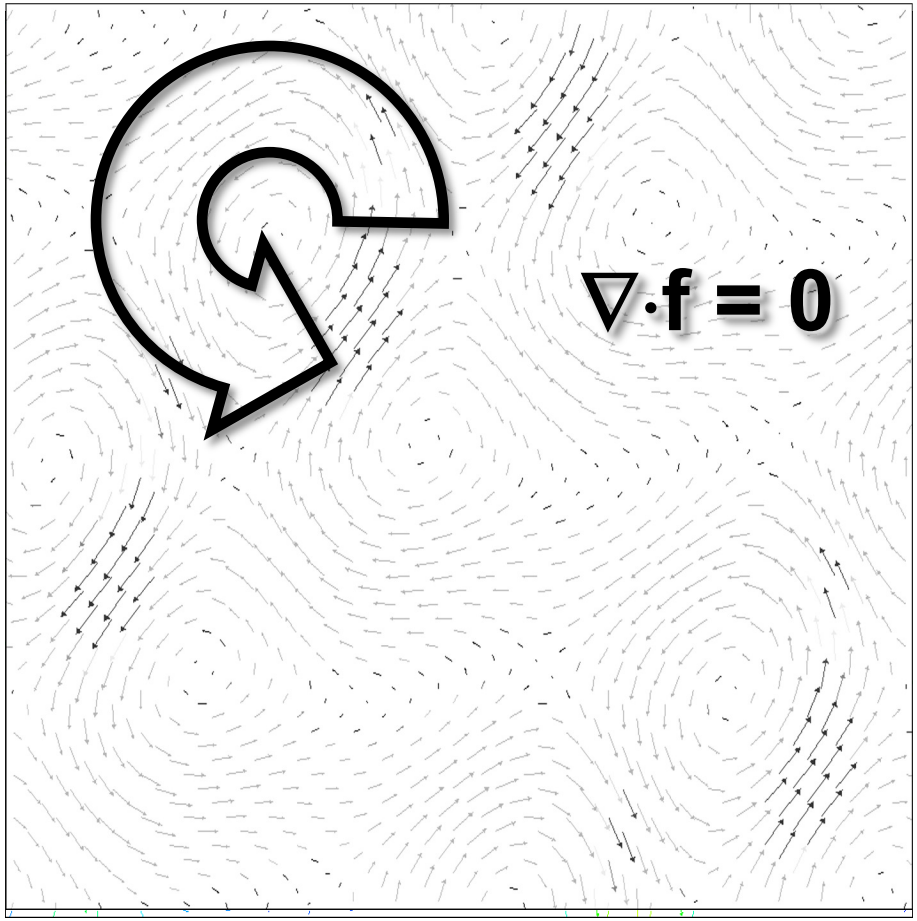
Compressive

Carina Nebula, NASA, ESA, N. Smith (University of California, Berkeley), and The Hubble Heritage Team (STScI/AURA), and NOAO/AURA/NSF

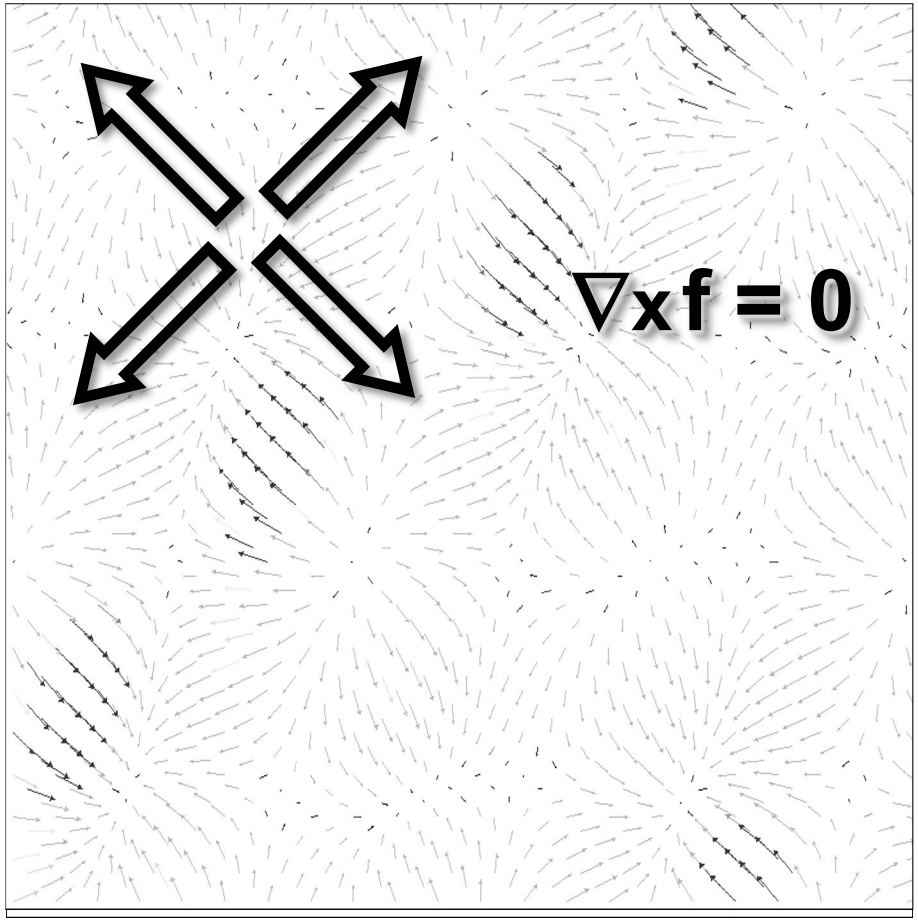
Turbulence driving – solenoidal versus compressive

Ornstein-Uhlenbeck process (stochastic process with autocorrelation time)
→ **forcing varies smoothly in space and time,**
following a well-defined random process

Solenoidal forcing



Compressive forcing

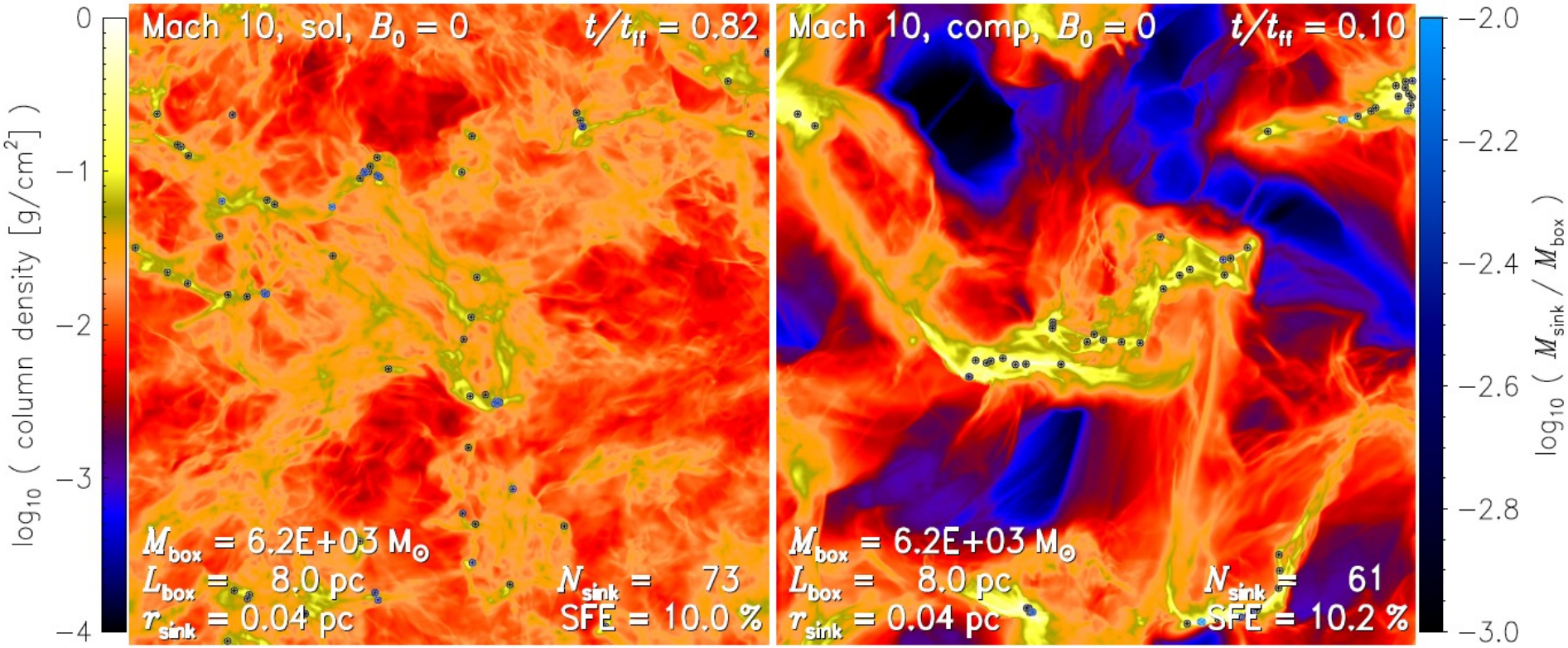


Density Distribution → Star Formation Rate

Numerical experiment for Mach 10

Movies available: http://www.mso.anu.edu.au/~chfeder/pubs/sfr/sfr.html

Solenoidal Driving (b=1/3) | Compressive Driving (b=1)



SFR_{ff} (simulation) = **0.14**	x **20**	SFR_{ff} (simulation) = **2.8**
SFR_{ff} (theory) = **0.15**	x **15**	SFR_{ff} (theory) = **2.3**

Turbulence driving is a key parameter for star formation!

Federrath & Klessen (2012)

Astrophysical Gas Dynamics

NEXT TIME:

- *Teaching Break ☺*
- *Then: Magnetohydrodynamics (MHD)*

Image credit: M. S. Povich