

# Astrophysical Gas Dynamics

TODAY:

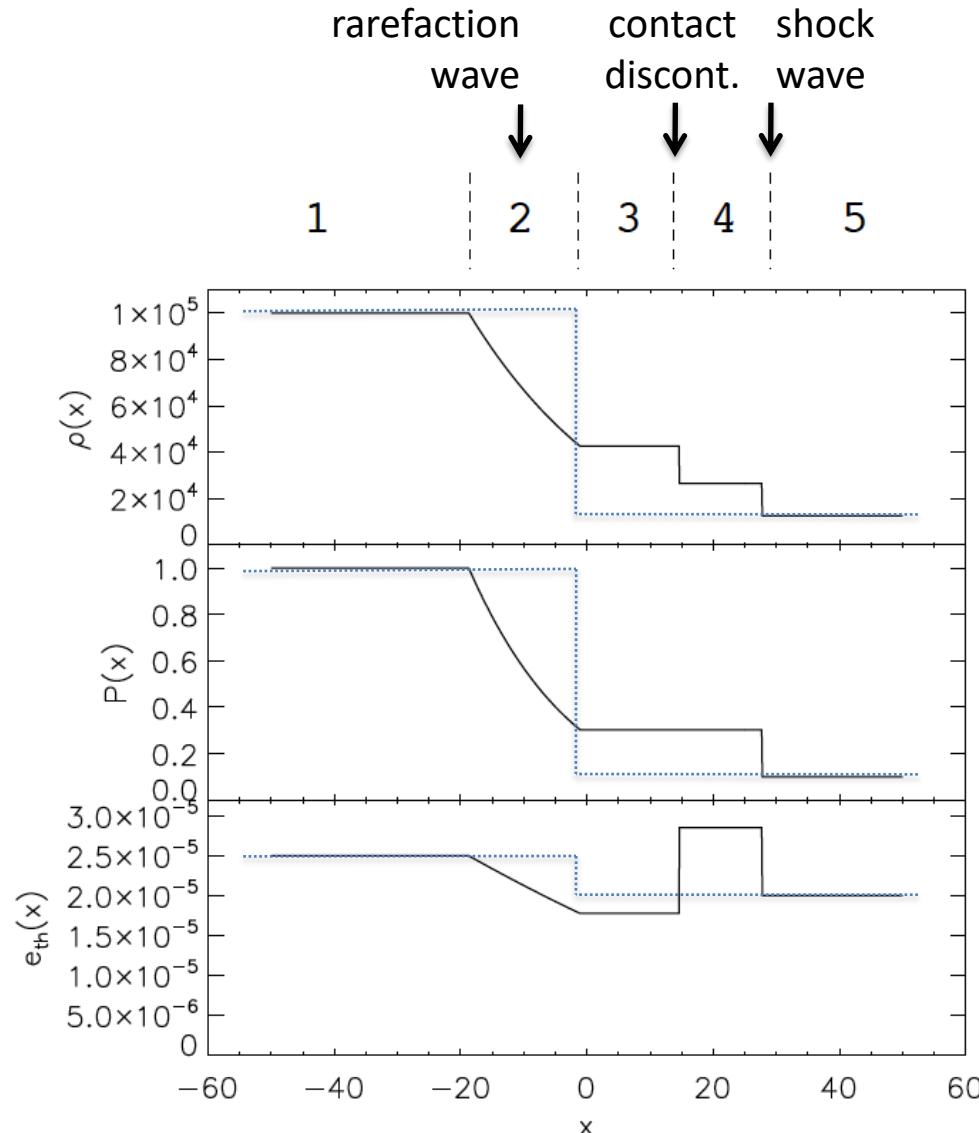
- *RH shock jump conditions and shock speed ( $\rightarrow$  recap)*
- *Supernova explosions (scalings, start Sedov solution)*

# Astrophysical Gas Dynamics

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- *RH shock jump conditions and shock speed ( $\rightarrow$  recap)*
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Sod shocktube test:  $\rho_l = 10^5$ ,  $P_l = 1$        $\rho_r = 1.25 \times 10^4$  and  $P_r = 0.1$   
(Sod 1978)



# Using the Rankine-Hugoniot shock jump conditions

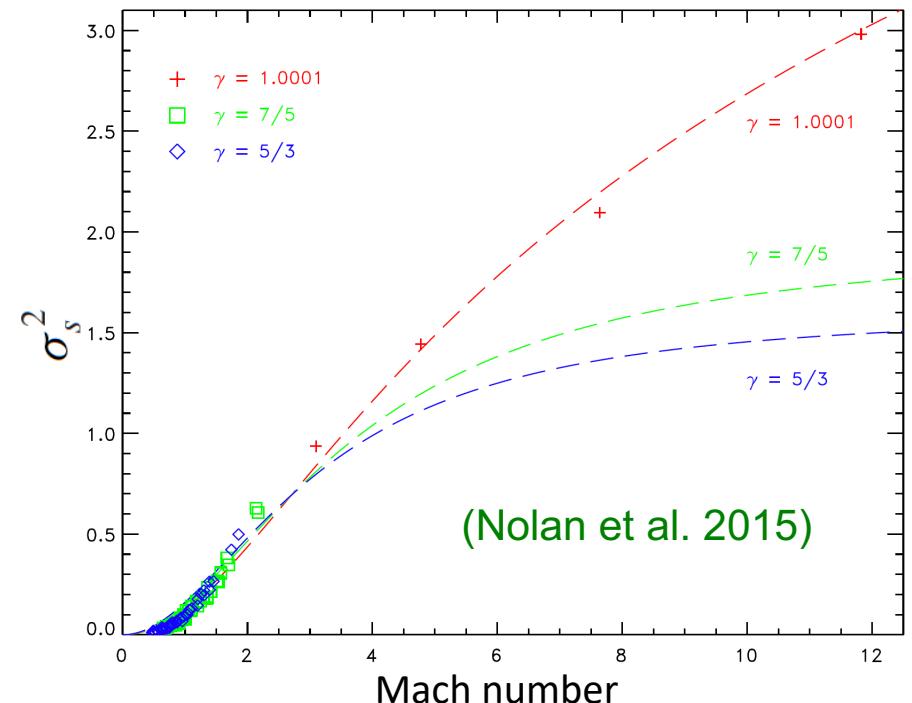
Using the Rankine-Hugoniot shock jump conditions to derive  
the density variance – Mach number relation of supersonic turbulence

$$\frac{\rho}{\rho_0} = \frac{v_0}{v} = \frac{(\gamma + 1)b^2 \mathcal{M}^2}{(\gamma - 1)b^2 \mathcal{M}^2 + 2} \quad (\text{Nolan et al. 2015})$$

with  $\sigma_{\rho/\rho_0}^2 = \frac{1}{V} \int_V \left( \frac{\rho}{\rho_0} - 1 \right)^2 dV$  (Padoan & Nordlund 2011)

gives  $\sigma_s^2 = \ln \left( 1 + \frac{(\gamma + 1)b^2 \mathcal{M}^2}{(\gamma - 1)b^2 \mathcal{M}^2 + 2} \right)$

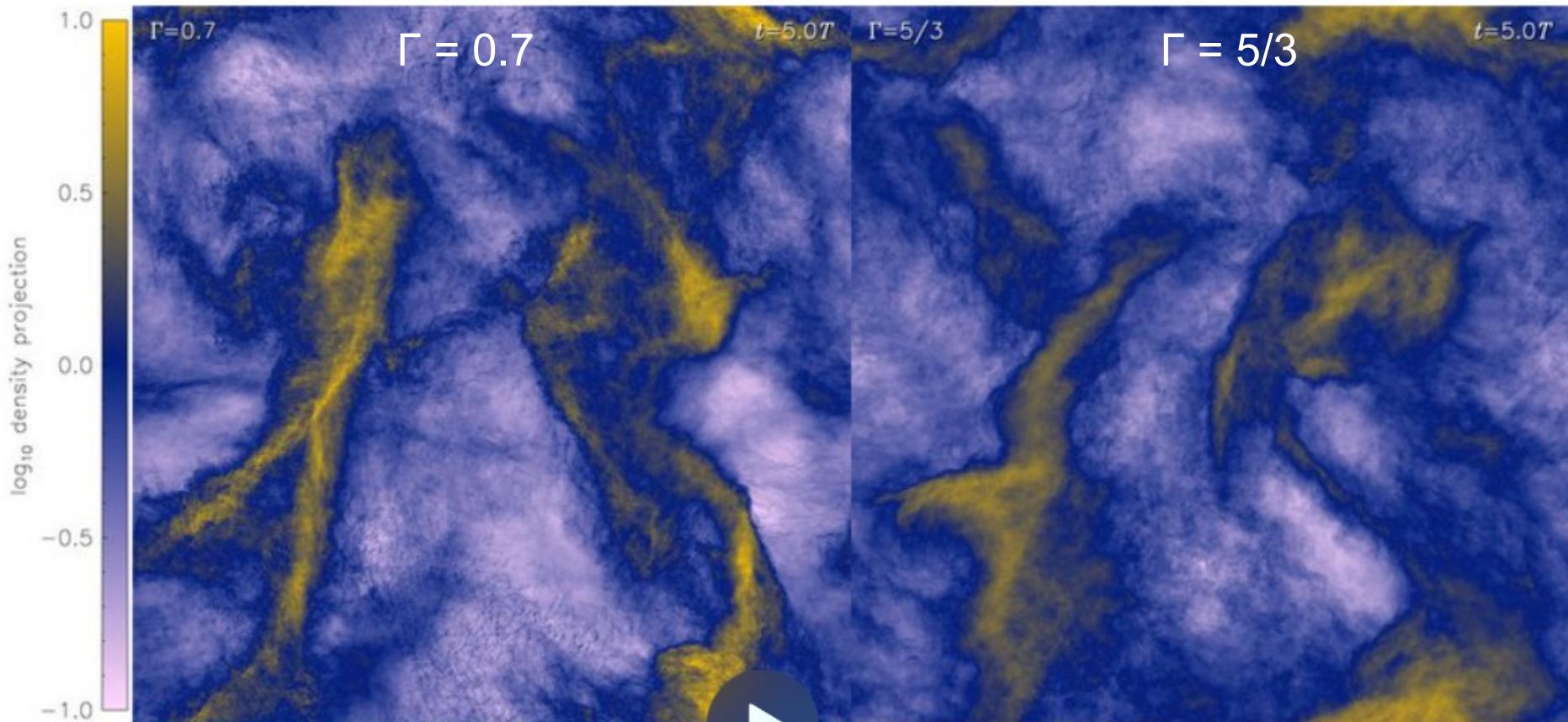
Density variance – Mach number relation  
for supersonic adiabatic turbulence



# Equation of State – Polytropic EOS

$$P_{\text{th}} = K \rho^{\Gamma}$$

Using the Rankine-Hugoniot shock jump conditions to derive  
the density variance – Mach number relation of supersonic turbulence



For supersonic polytropic turbulence (Federrath & Banerjee 2015)

Movies available: <http://www.mso.anu.edu.au/~chfeder/pubs/polytropic/polytropic.html>

# Using the Rankine-Hugoniot shock jump conditions

Using the **Rankine-Hugoniot shock jump conditions** to derive  
the **density variance – Mach number relation** of **supersonic turbulence**

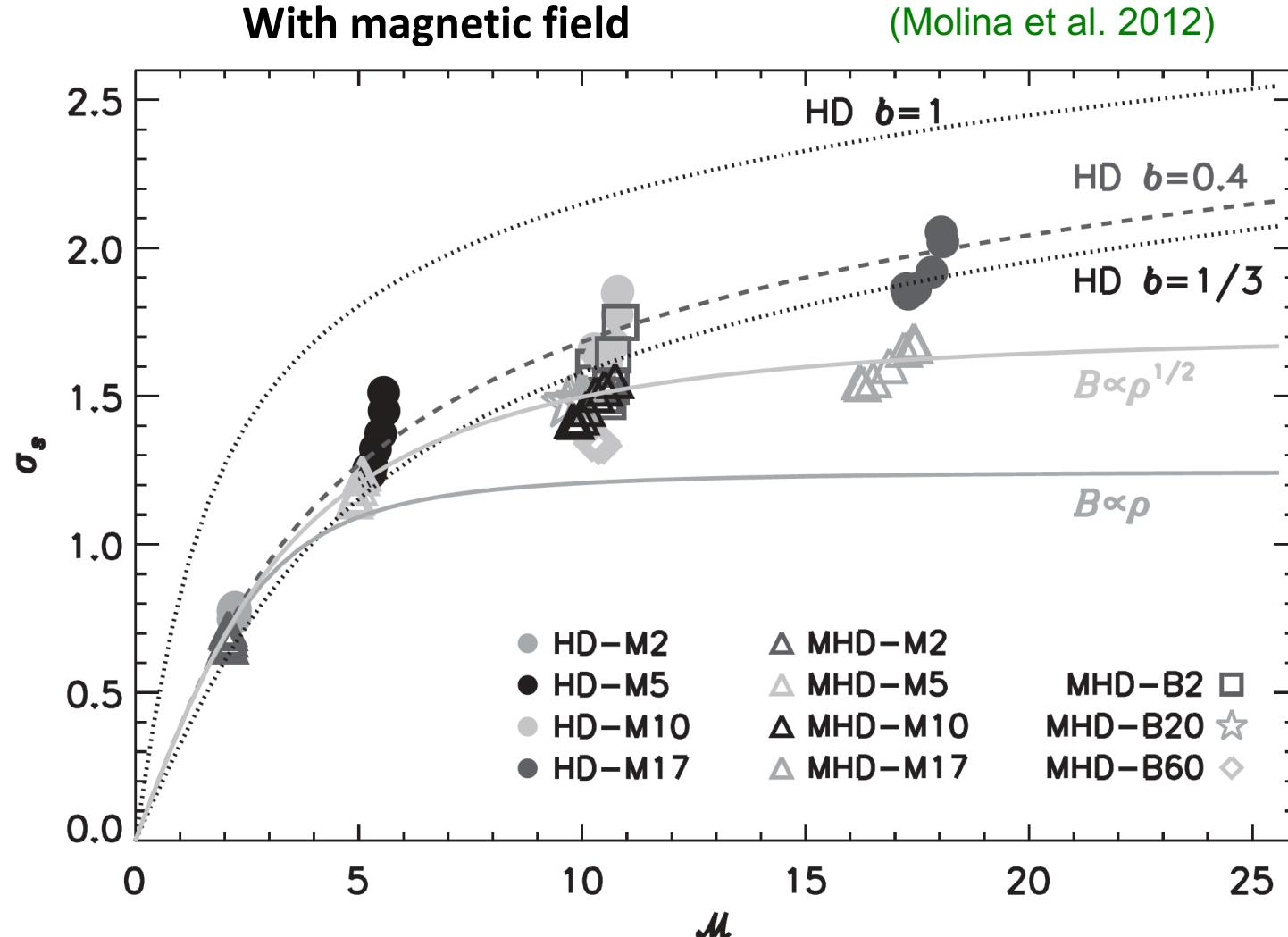
**With magnetic field**

(Molina et al. 2012)

$$\rho_1 \left( v_{\parallel,1}^2 + \frac{c_{s,1}^2}{\gamma_1} + \frac{v_{A\perp,1}^2}{2} \right) = \rho_2 \left( v_{\parallel,2}^2 + \frac{c_{s,2}^2}{\gamma_2} + \frac{v_{A\perp,2}^2}{2} \right)$$

# Using the Rankine-Hugoniot shock jump conditions

Using the Rankine-Hugoniot shock jump conditions to derive  
the density variance – Mach number relation of supersonic turbulence



# The Star Formation Rate – Magnetic fields

## Statistical Theory for the Star Formation Rate:

**SFR ~ Mass/time**

$$\text{SFR}_{\text{ff}} = \epsilon \int_{s_{\text{crit}}}^{\infty} \frac{t_{\text{ff}}(\rho_0)}{t_{\text{ff}}(\rho)} \frac{\rho}{\rho_0} p(s) ds$$

freefall time  
 mass fraction

$$= \frac{\epsilon}{2} \exp\left(\frac{3}{8}\sigma_s^2\right) \left[ 1 + \operatorname{erf}\left(\frac{\sigma_s^2 - s_{\text{crit}}}{\sqrt{2}\sigma_s^2}\right) \right]$$

### MAGNETIC FIELD:

$$P_{\text{th}} \rightarrow P_{\text{th}} + P_{\text{mag}}$$

$$\mathcal{M} \rightarrow \mathcal{M} (1 + \beta^{-1})^{-1/2}$$

$$\text{SFR}_{\text{ff}} = \text{SFR}_{\text{ff}} (\alpha_{\text{vir}}, b, \mathcal{M}, \beta)$$

$$p(s) = \frac{1}{\sqrt{2\pi\sigma_s^2}} \exp\left(-\frac{(s - s_0)^2}{2\sigma_s^2}\right)$$

$$s = \ln(\rho/\rho_0) \quad t_{\text{ff}}(\rho) = \left(\frac{3\pi}{32G\rho}\right)^{1/2}$$

$$\downarrow \int_{s_{\text{crit}}}^{\infty} \exp\left(\frac{3}{2}s\right) p(s) ds$$

$$s_{\text{crit}} \propto \ln\left(\alpha_{\text{vir}} \mathcal{M}^2 \frac{\beta}{\beta + 1}\right)$$

$$\sigma_s^2 = \ln\left(1 + b^2 \mathcal{M}^2 \frac{\beta}{\beta + 1}\right)$$

(Padoan & Nordlund 2011; Molina et al. 2012)

2  $E_{\text{kin}}/E_{\text{grav}}$  forcing Mach number plasma  $\beta = P_{\text{th}}/P_{\text{mag}}$

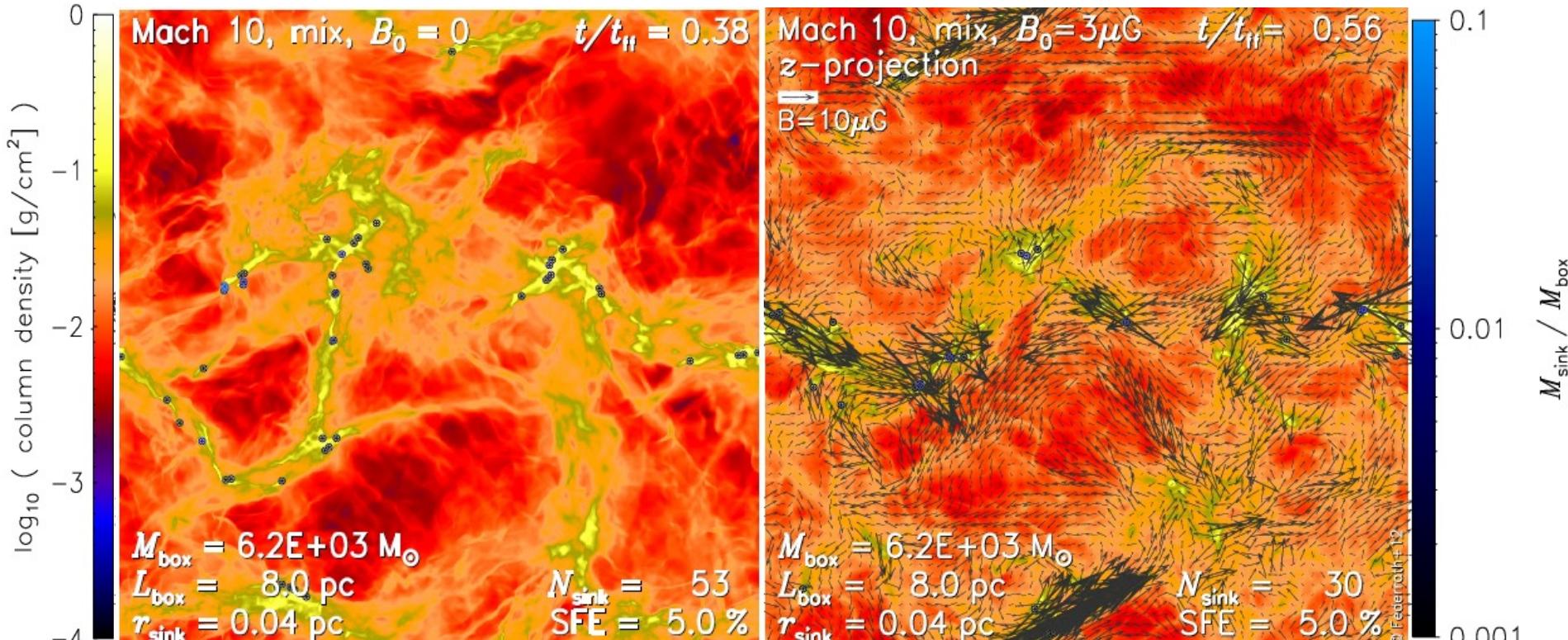
# The Star Formation Rate – Magnetic fields

## Numerical experiment for Mach 10 and $\alpha_{\text{vir}} \sim 1$

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

$B=0$  ( $M_A=\infty$ ,  $\beta = \infty$ )

$B=3\mu\text{G}$  ( $M_A=2.7$ ,  $\beta = 0.2$ )



$$\text{SFR}_{\text{ff}} \text{ (simulation)} = 0.46$$

$$\text{SFR}_{\text{ff}} \text{ (theory)} = 0.45$$

$$\times 0.63$$

$$\times 0.40$$

$$\text{SFR}_{\text{ff}} \text{ (simulation)} = 0.29$$

$$\text{SFR}_{\text{ff}} \text{ (theory)} = 0.18$$

Magnetic field reduces SFR and fragmentation (by factor 2) → IMF

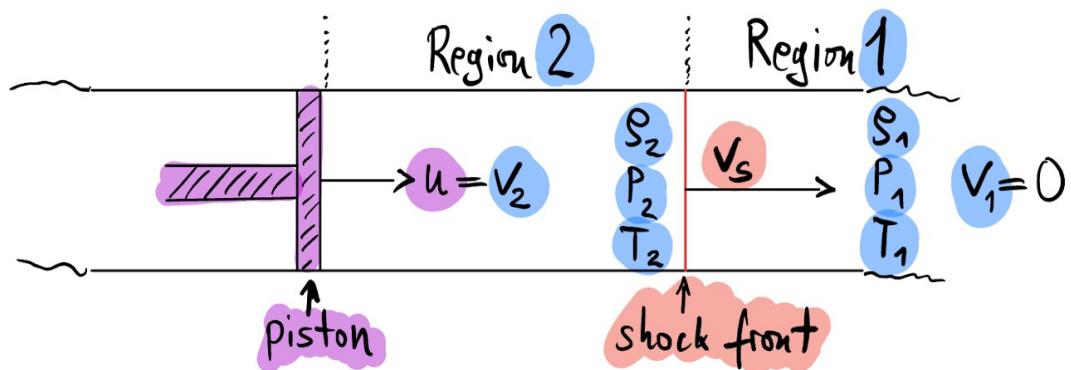
# Astrophysical Gas Dynamics

*Derivation of shock speed*

# Shock waves

- Python program to solve 1D hydro equations: [hydro.py](#)
- `> ./hydro.py -h`
- `> ./hydro.py -sim shockpiston_test`

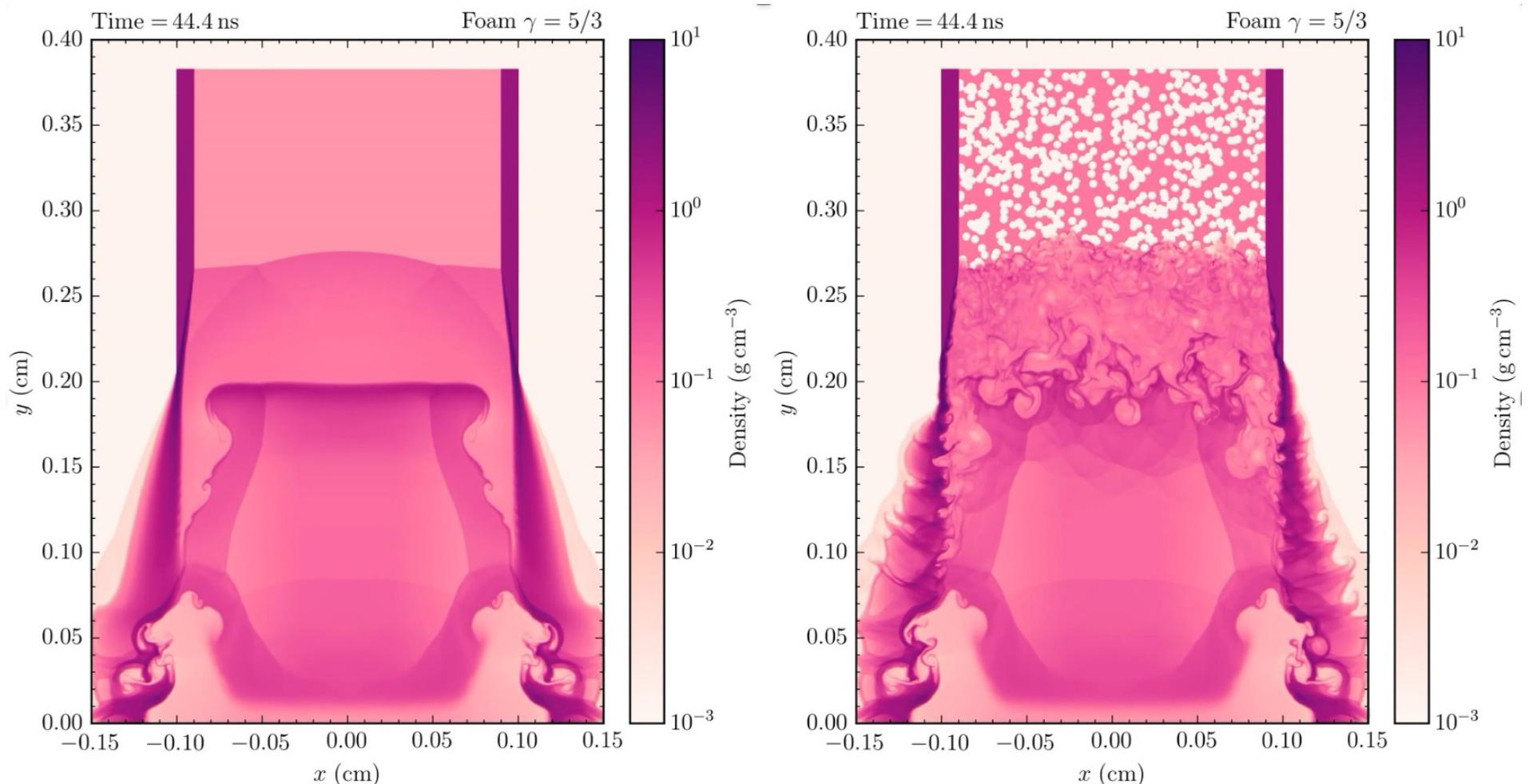
Test the derived  
shock speed  $v_s$   
(try for different gamma)



This code uses cftools:

[https://www.mso.anu.edu.au/~chfeder/teaching/astr\\_4012\\_8002/codes/cftools/](https://www.mso.anu.edu.au/~chfeder/teaching/astr_4012_8002/codes/cftools/)

# Astrophysical Gas Dynamics - Shocks

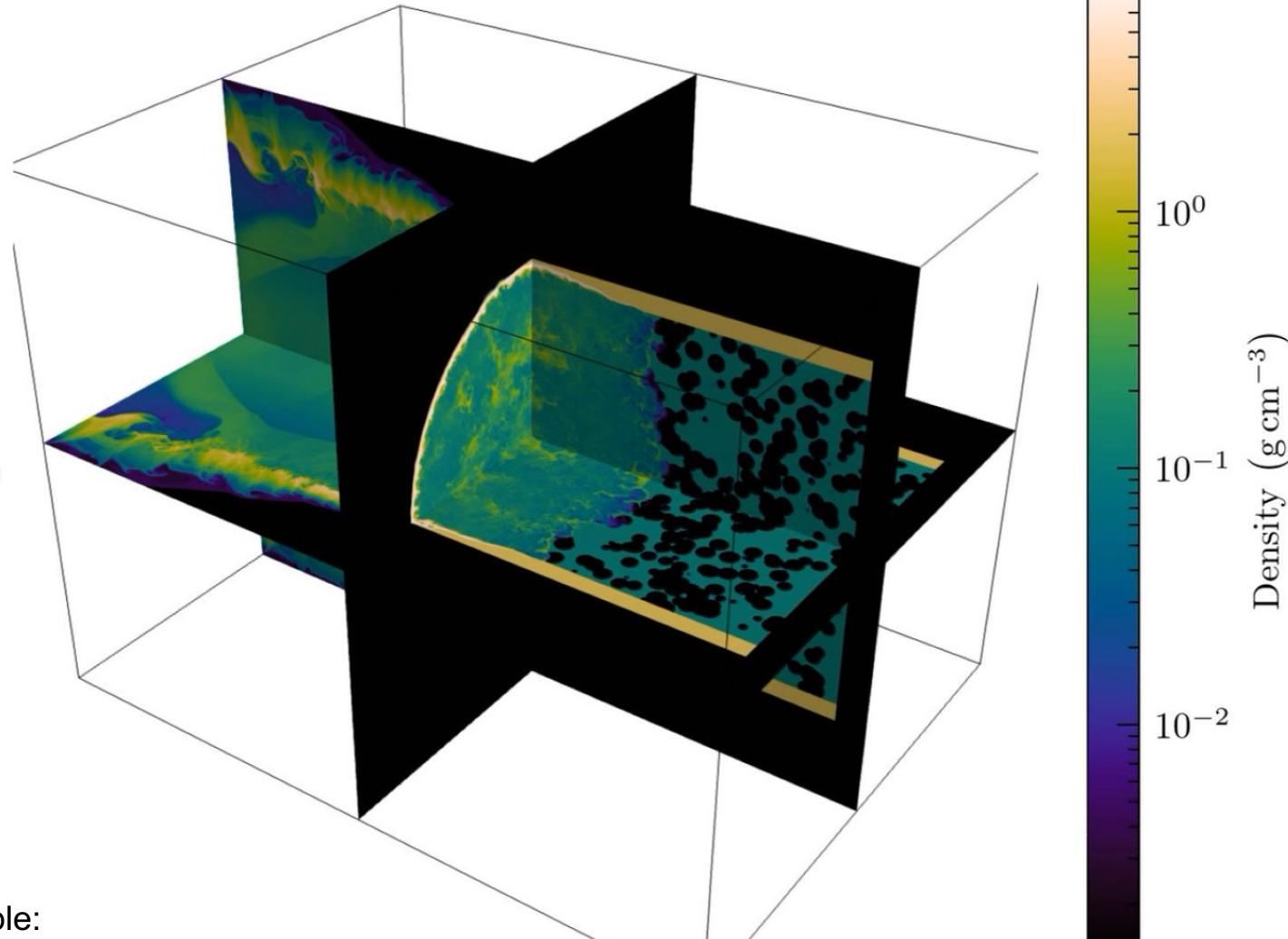


Movies available:

[https://www.mso.anu.edu.au/~chfeder/movies/laser/nif\\_laser.html](https://www.mso.anu.edu.au/~chfeder/movies/laser/nif_laser.html)

# Astrophysical Gas Dynamics - Shocks

Time = 43.8 ns



Movies available:

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Simulation of a laser-induced shock running into foam

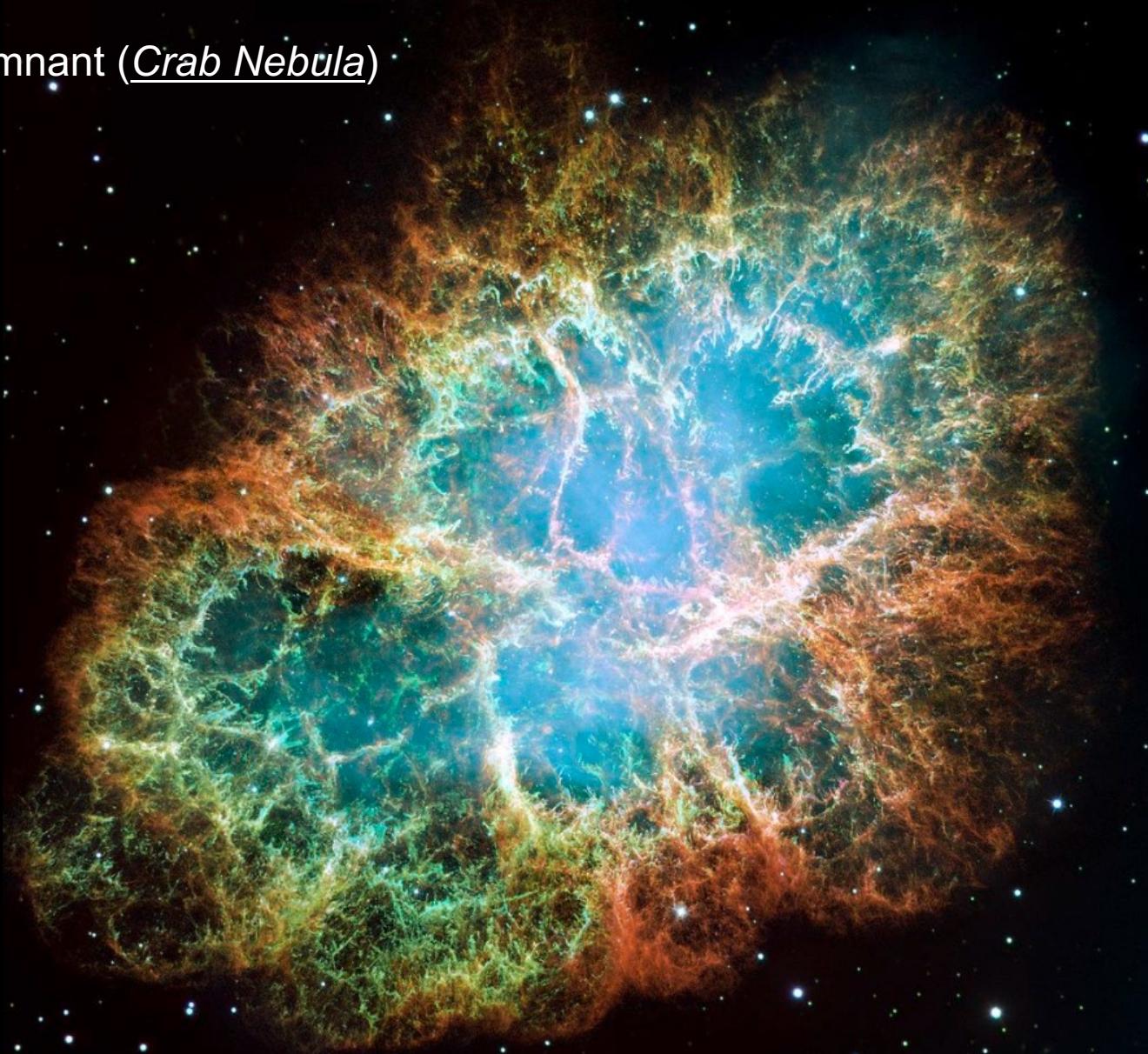
# Astrophysical Gas Dynamics

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- *Supernova explosions (scalings, start Sedov solution)*

# Supernova explosions

SN 1054 remnant (*Crab Nebula*)



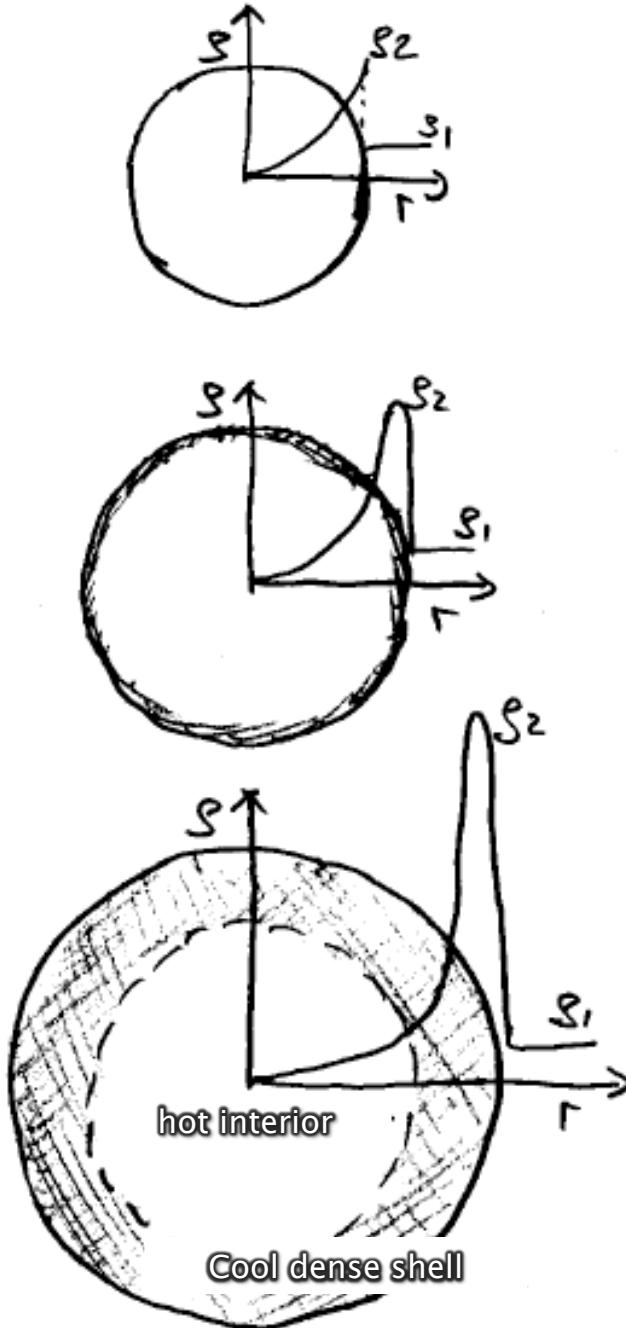
# Supernova explosions

Type Ia versus type II/Ibc

	no H-Balmer lines	H-Balmer lines
Thermonuclear explosion	Si SN Ia	- / -
	no Si	
	He      no He	
Core collapse	SN Ib	SN Ic
		SN II

# Supernova phases

Evolutionary sequence ↓



## Energy-driven expansion

Shock speeds of about 1000 km/s

## “Snow-plow phase”

Cooling  $\rightarrow$  dense, thin shell forms  
and sweeps up more material;  
Thickness of shell  $\sim 1\text{pc}$  with  
density  $n \sim 1\text{-}100 \text{ cm}^{-3}$

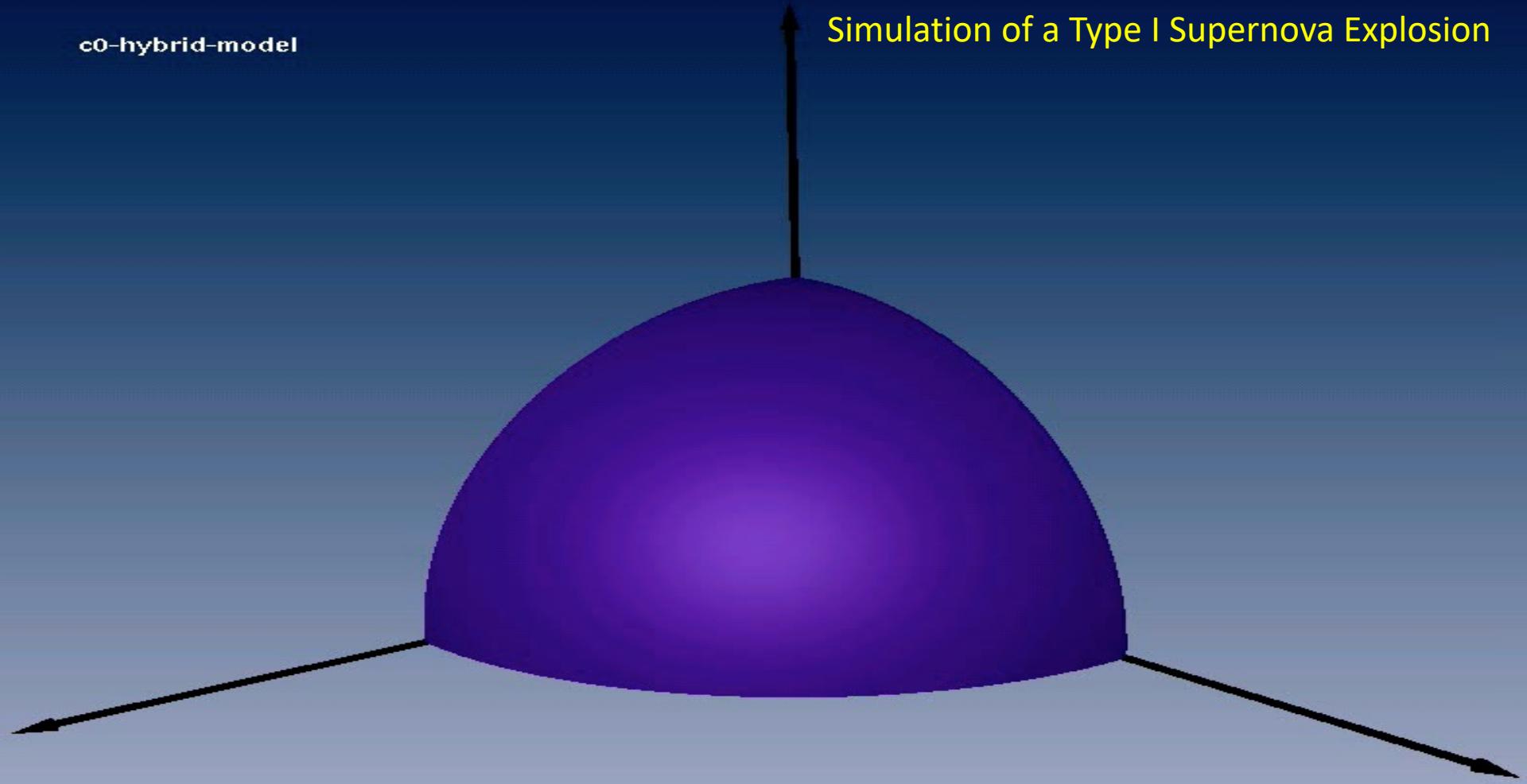
## Momentum-driven phase

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

# Supernova explosions

co-hybrid-model

Simulation of a Type I Supernova Explosion



Movies available: [http://www.mso.anu.edu.au/~chfeder/movies/supernova/supernova\\_movies.html](http://www.mso.anu.edu.au/~chfeder/movies/supernova/supernova_movies.html)

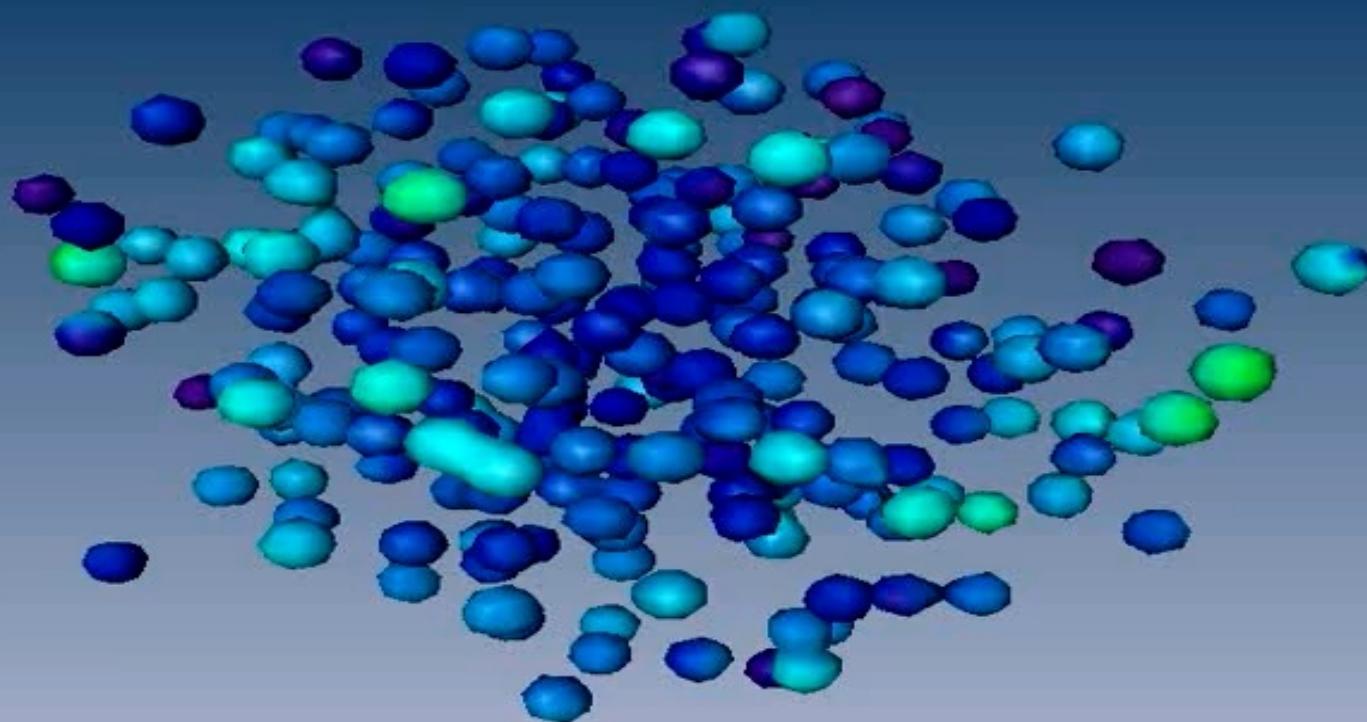
Log [q\_sgs]



# Supernova explosions

popcorn-4pi-model

Simulation of a Type I Supernova Explosion

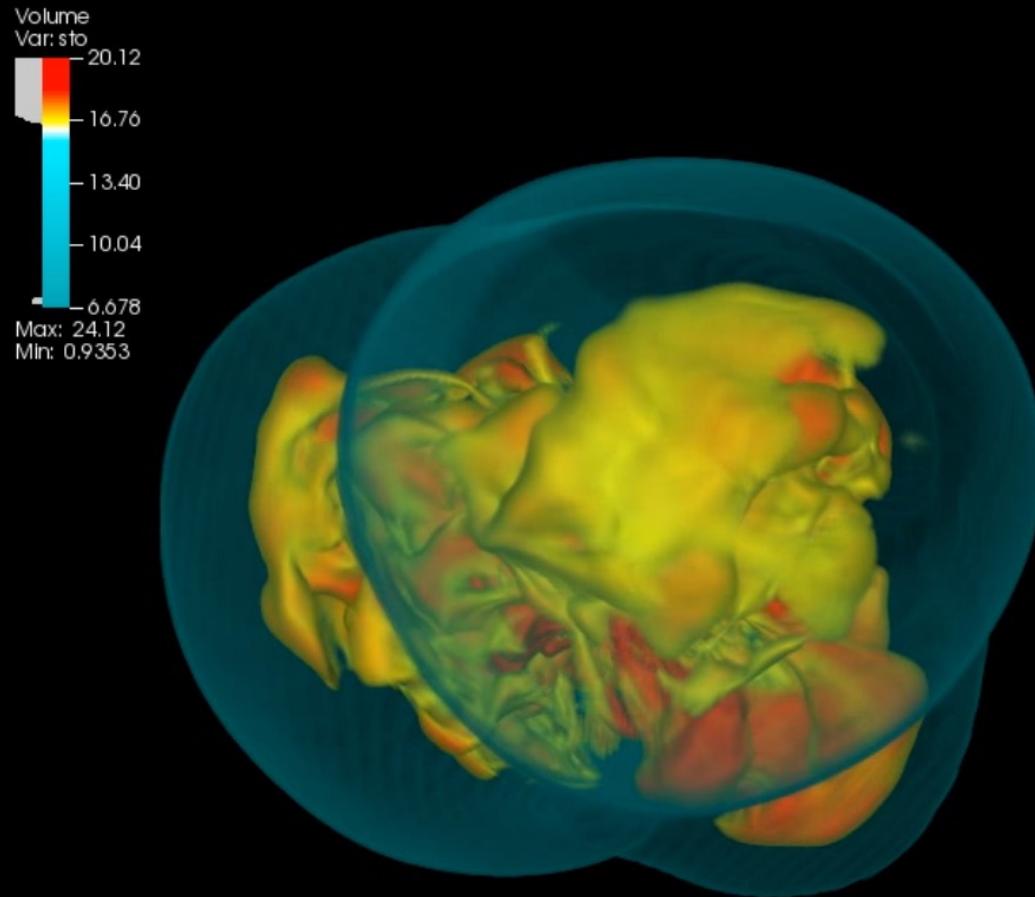


Movies available: [http://www.mso.anu.edu.au/~chfeder/movies/supernova/supernova\\_movies.html](http://www.mso.anu.edu.au/~chfeder/movies/supernova/supernova_movies.html)



# 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)

# Astrophysical Gas Dynamics

*NEXT TIME:*

- *Supernova explosions (Sedov solution finished)*