Astrophysical Gas Dynamics

TODAY:

- *Sedov solution (→ recap)*
- *Magnetohydrodyamics (MHD)*

Image credit: M. S. Povich

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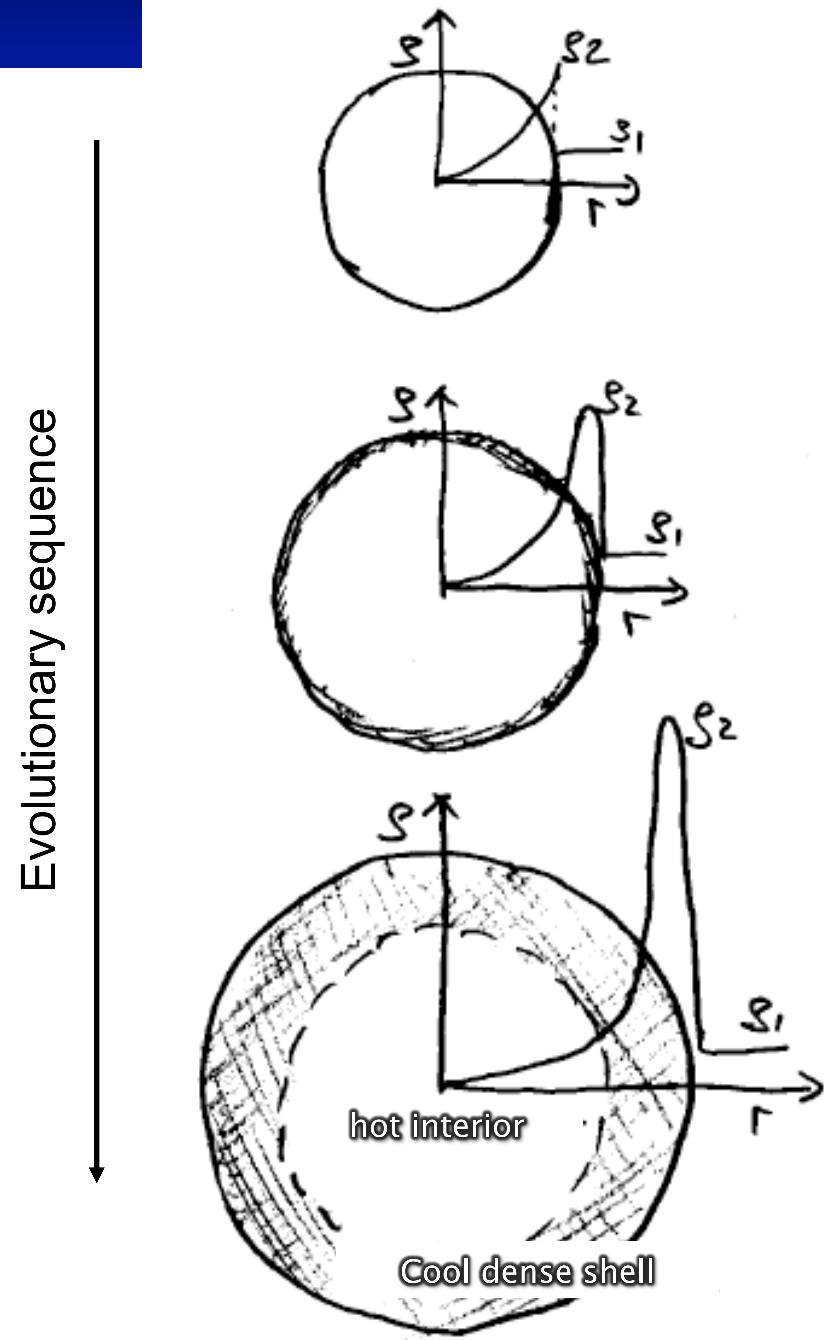
Supernova phases



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

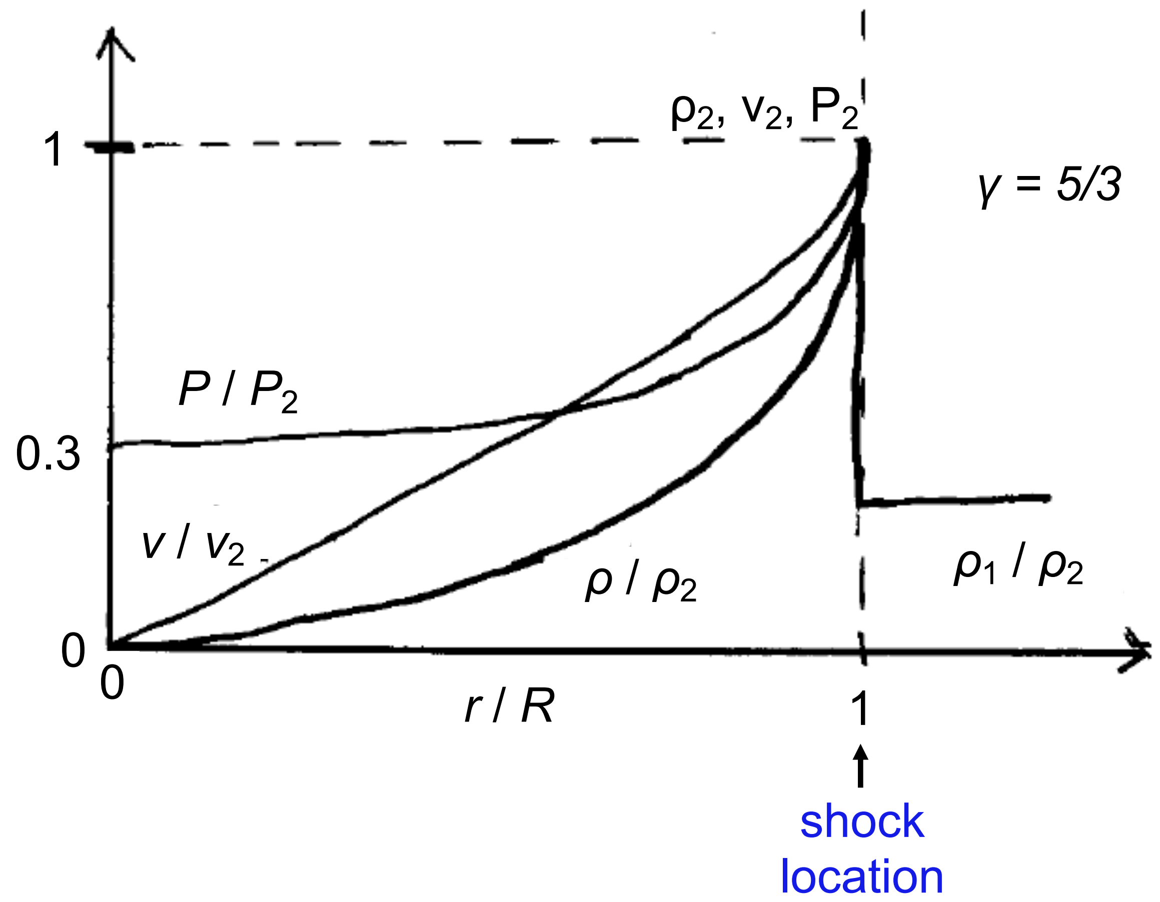
TODAY:

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

Image credit: M. S. Povich

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

(shock wave expanding into uniform medium of density ρ_1)



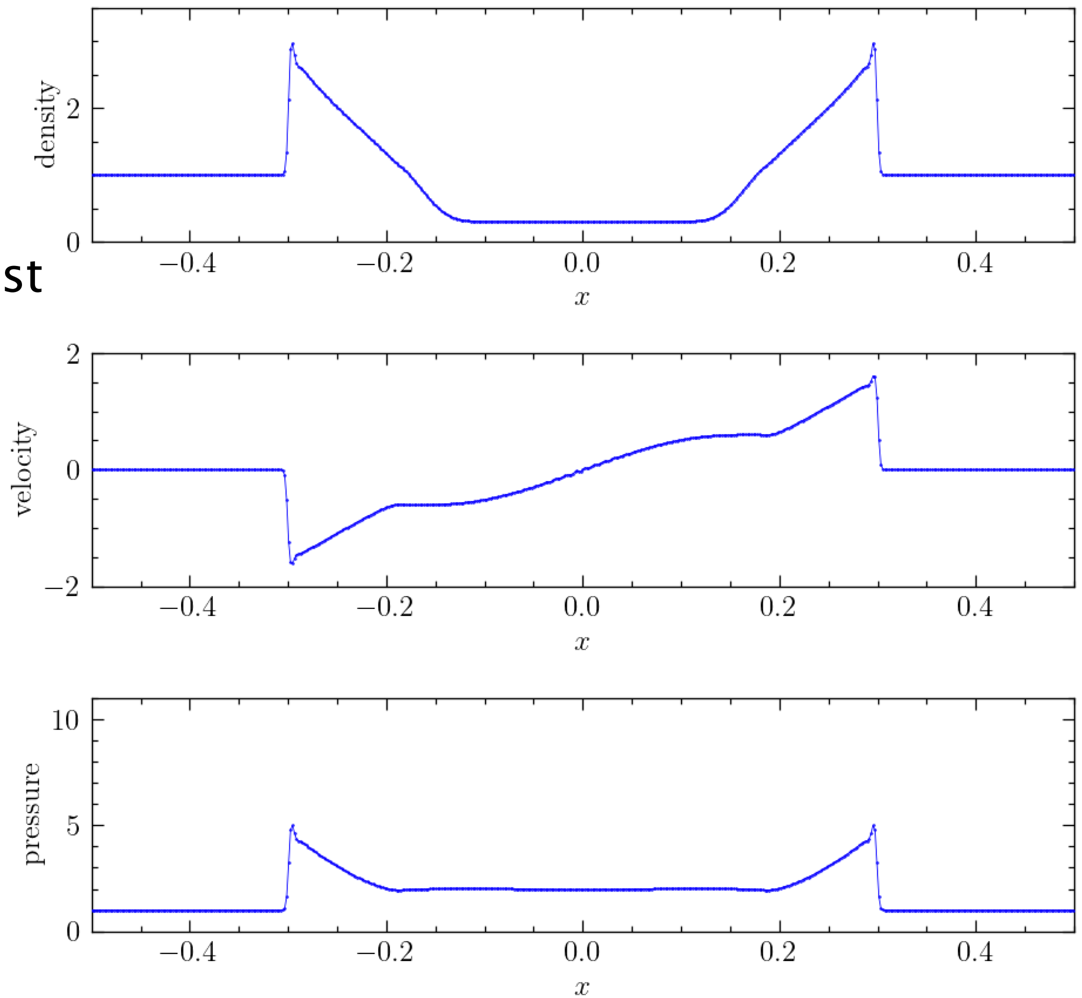
(Klessen script on Theoretical Astrophysics)

Sedov explosion

- Python program to solve 1D/2D hydro equations:

  hydro.py

- > ./hydro.py -h
- > ./hydro.py -sim sedov_test



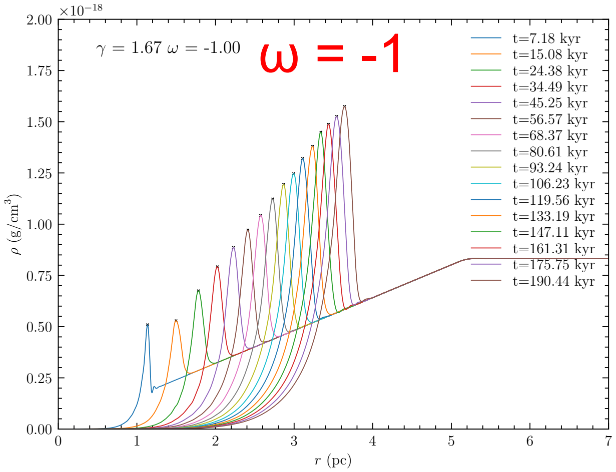
Suggested: Modify the code to change the initial conditions, e.g., energy injection zone, grid resolution, etc.; compare to analytic solution

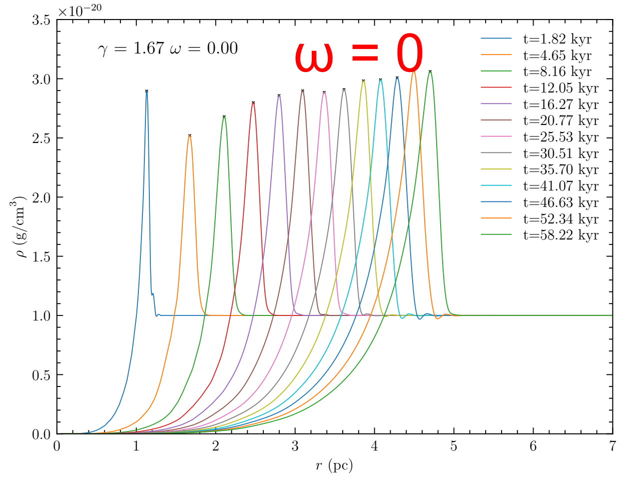
This code uses cfpack; you can simply do “pip install cfpack”

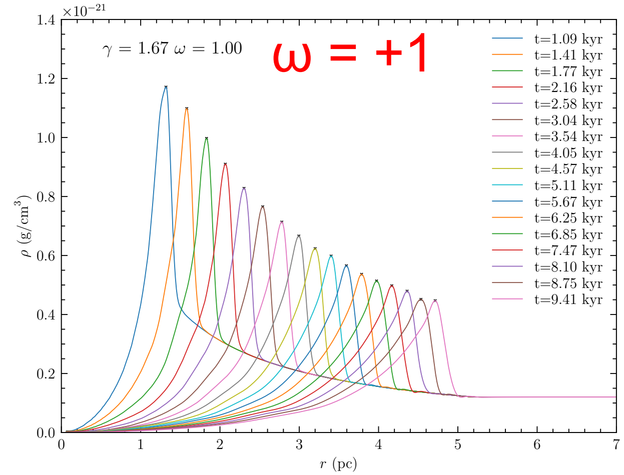
Sedov solution for non-uniform medium with $\rho_{amb}(r) \sim r^{-\omega}$

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

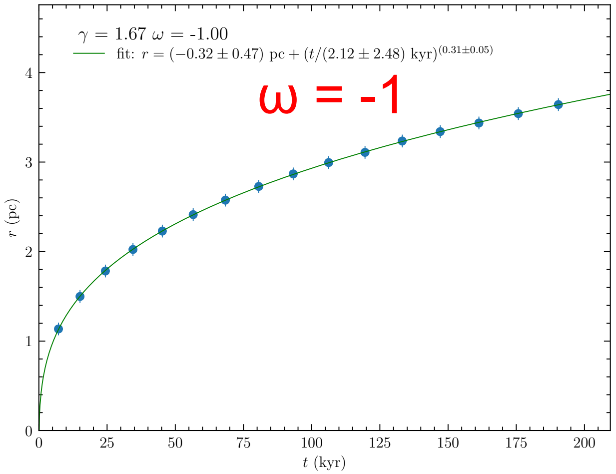
Density profiles ρ(r)

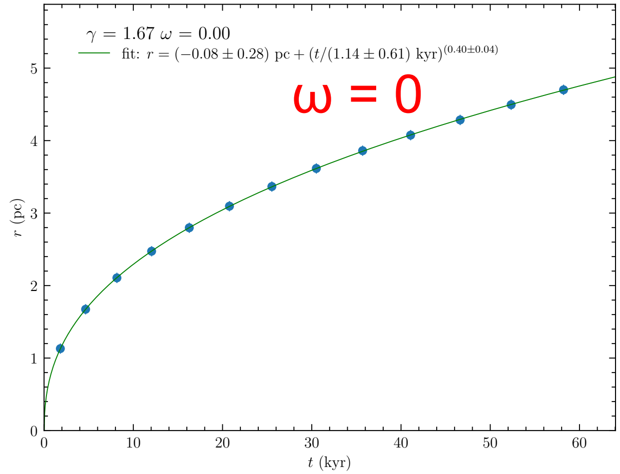


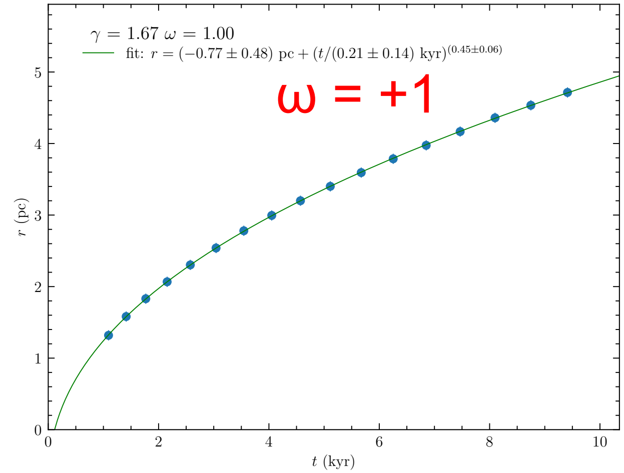




Evolution of shell expansion radius r(t)







(Monica Bapna et al., in prep.)

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

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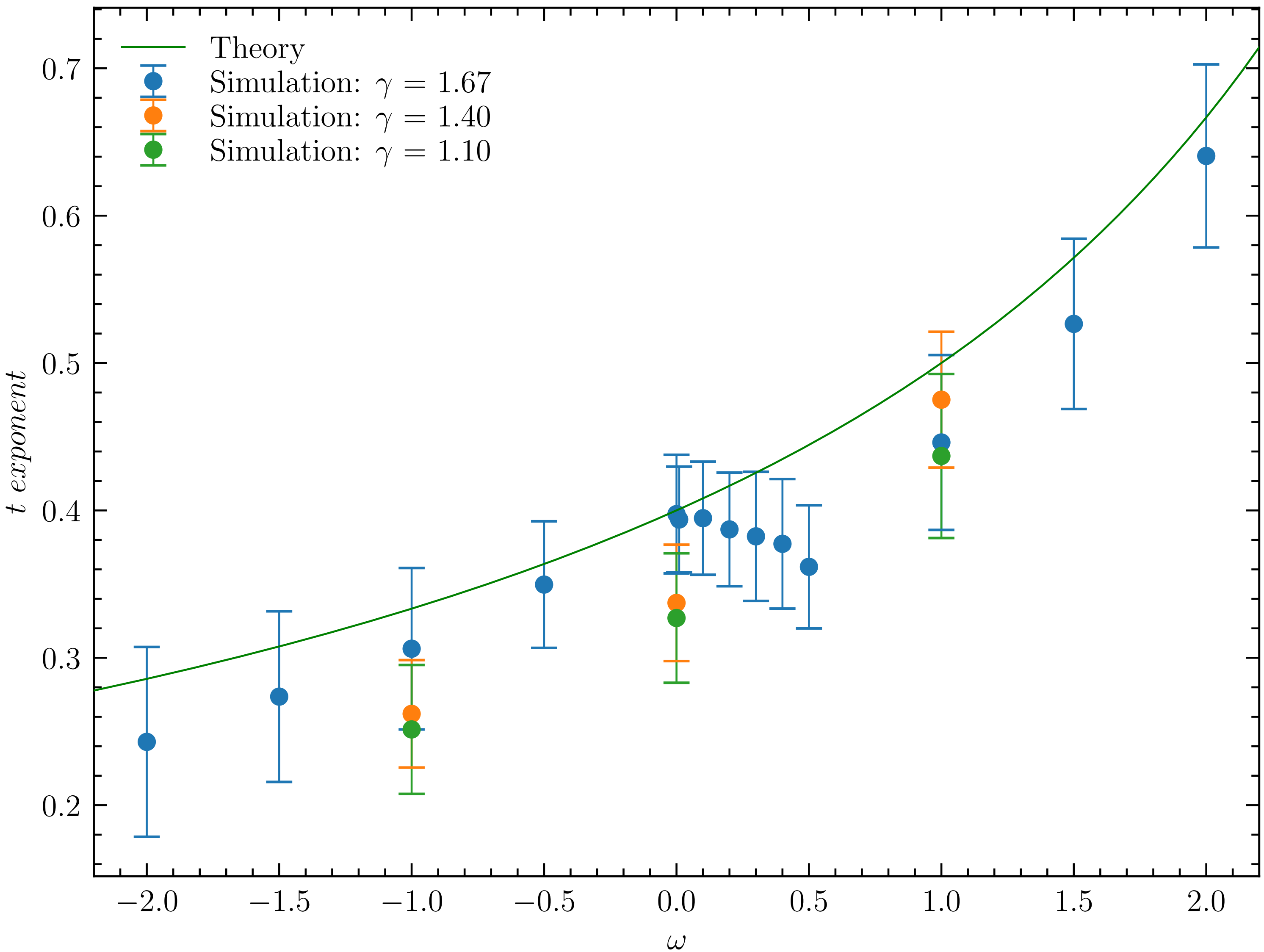
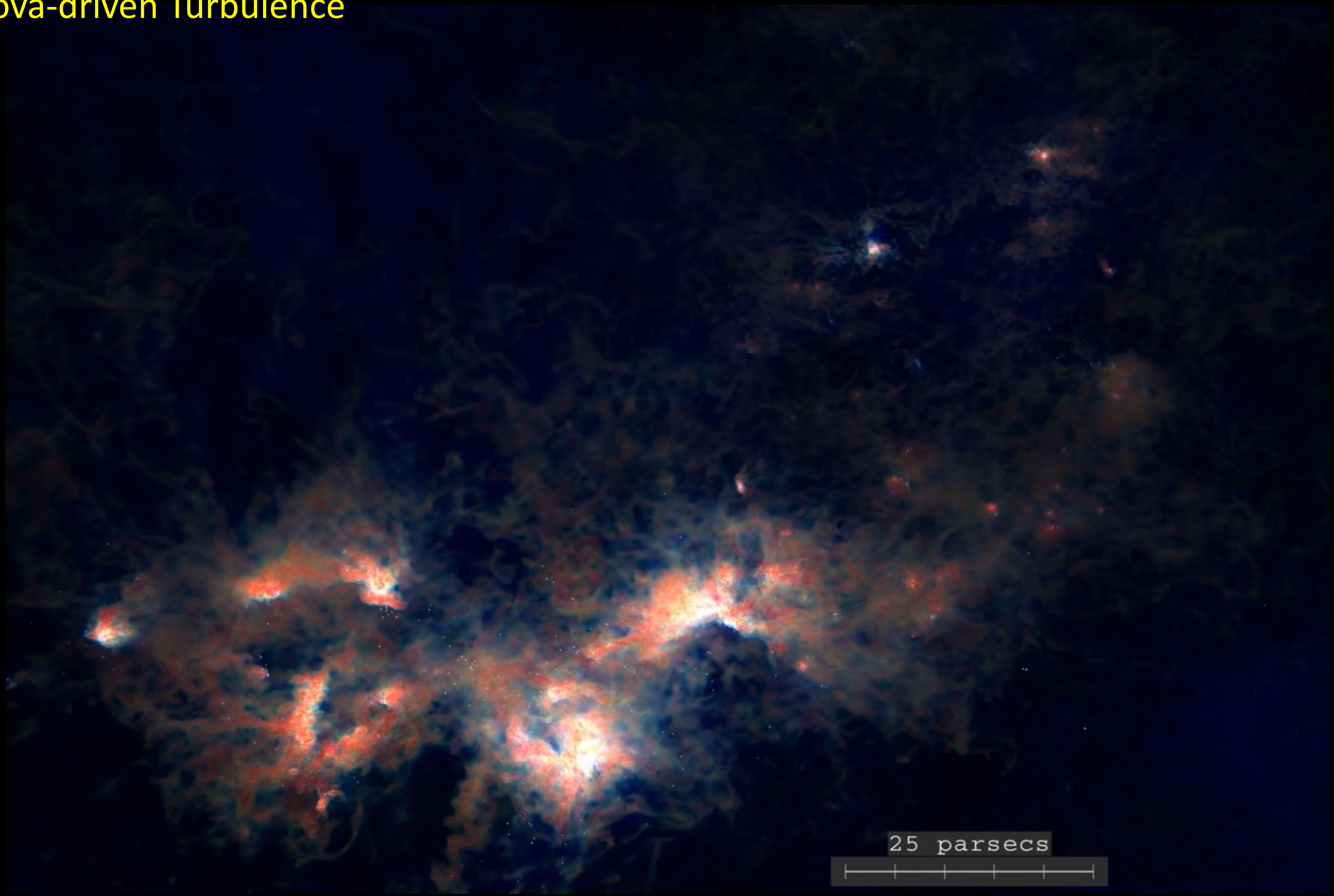


(Monica Bapna et al., in prep.)

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:

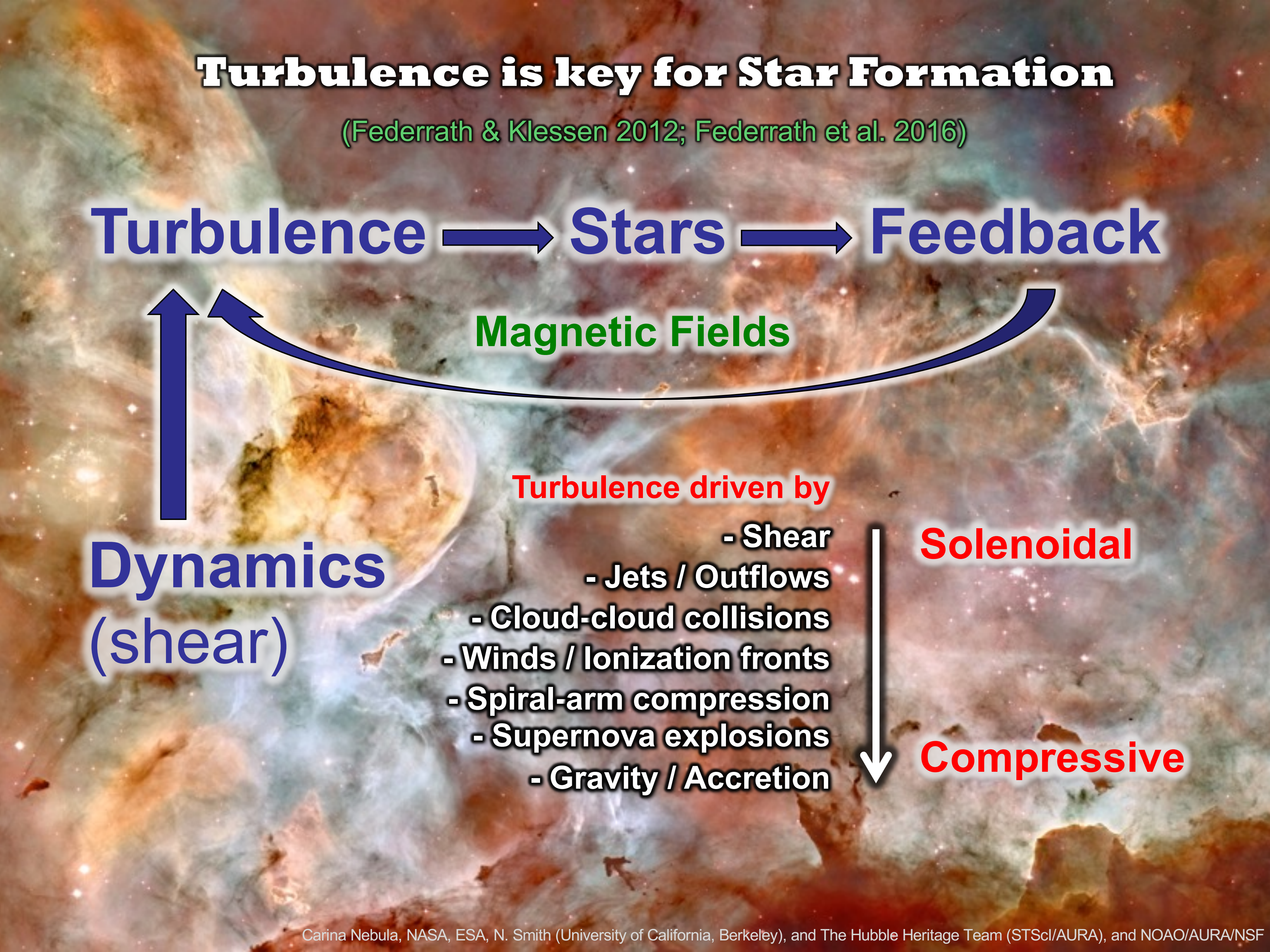
$$\dot{e} = \frac{\sigma_{SN}\eta_{SN}E_{SN}}{\pi R_{sf}^2 H_c}$$

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

(η_{SN} is the fraction of kinetic energy per SN)

(1 SNu is about 1 SN per 50 years for the Milky Way)

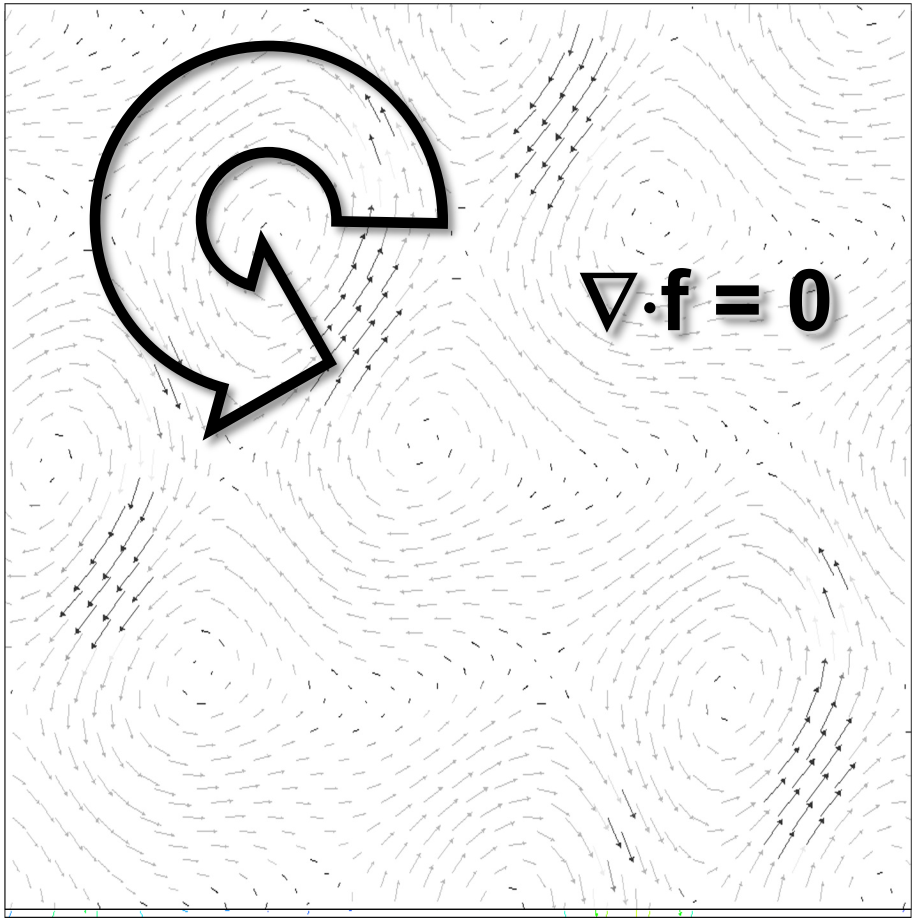
(Mac Low & Klessen 2004)


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

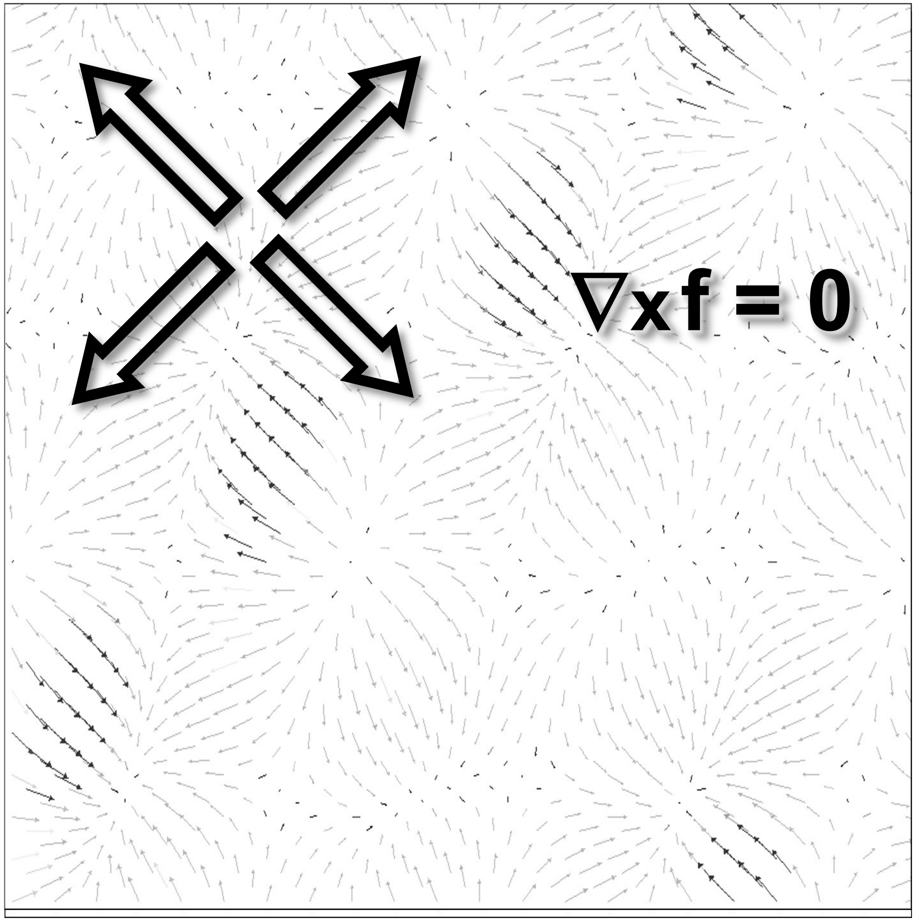
Turbulence driving – solenoidal versus compressive

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

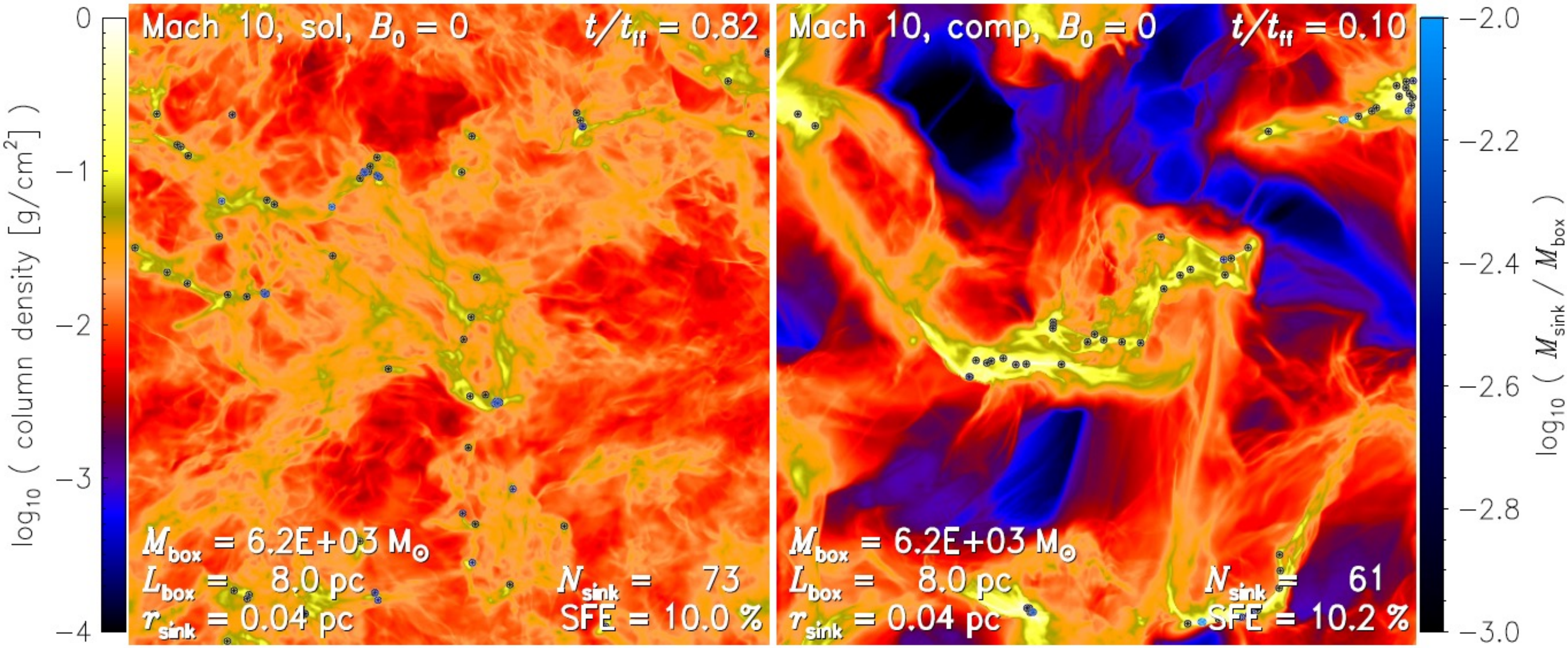


Density Distribution → Star Formation Rate

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)

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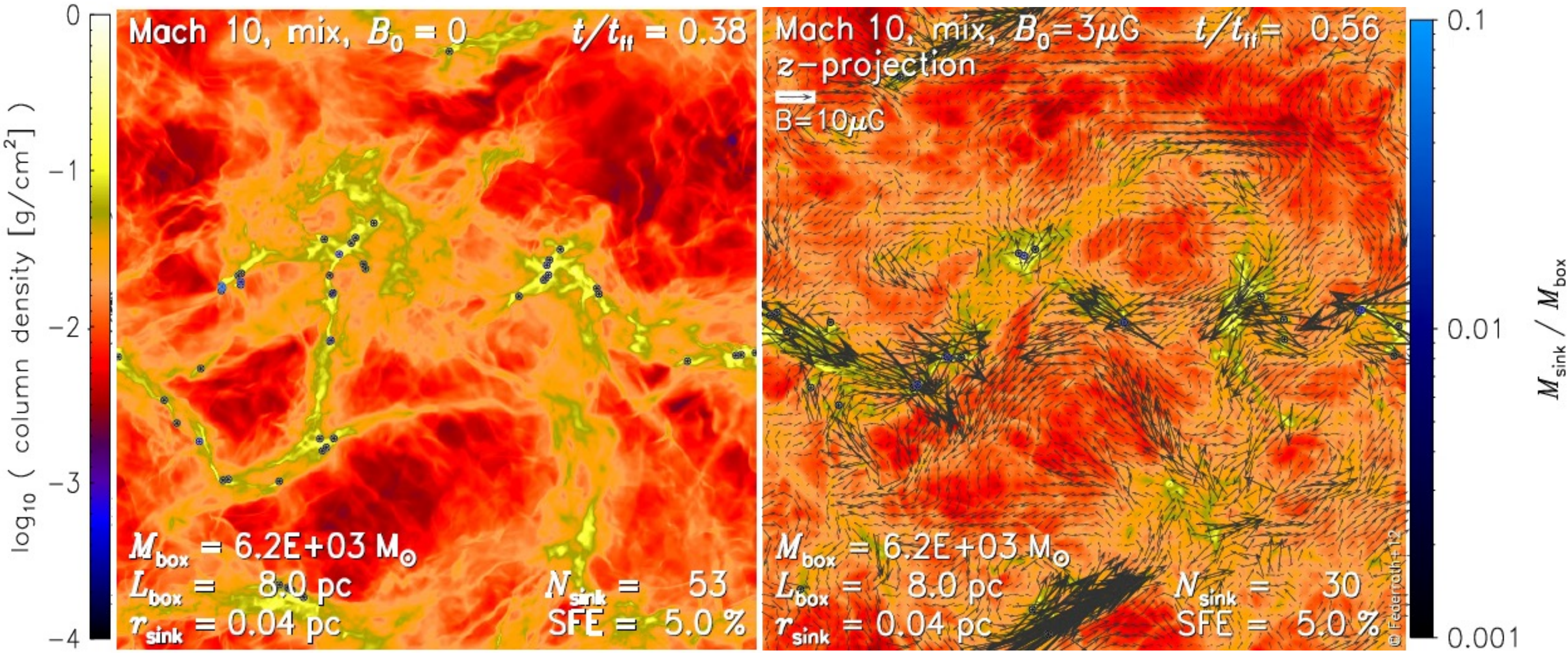
Image credit: M. S. Povich

The Star Formation Rate – Magnetic fields

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

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

B=0 (M_A=∞, β = ∞) B=3μG (M_A=2.7, β = 0.2)

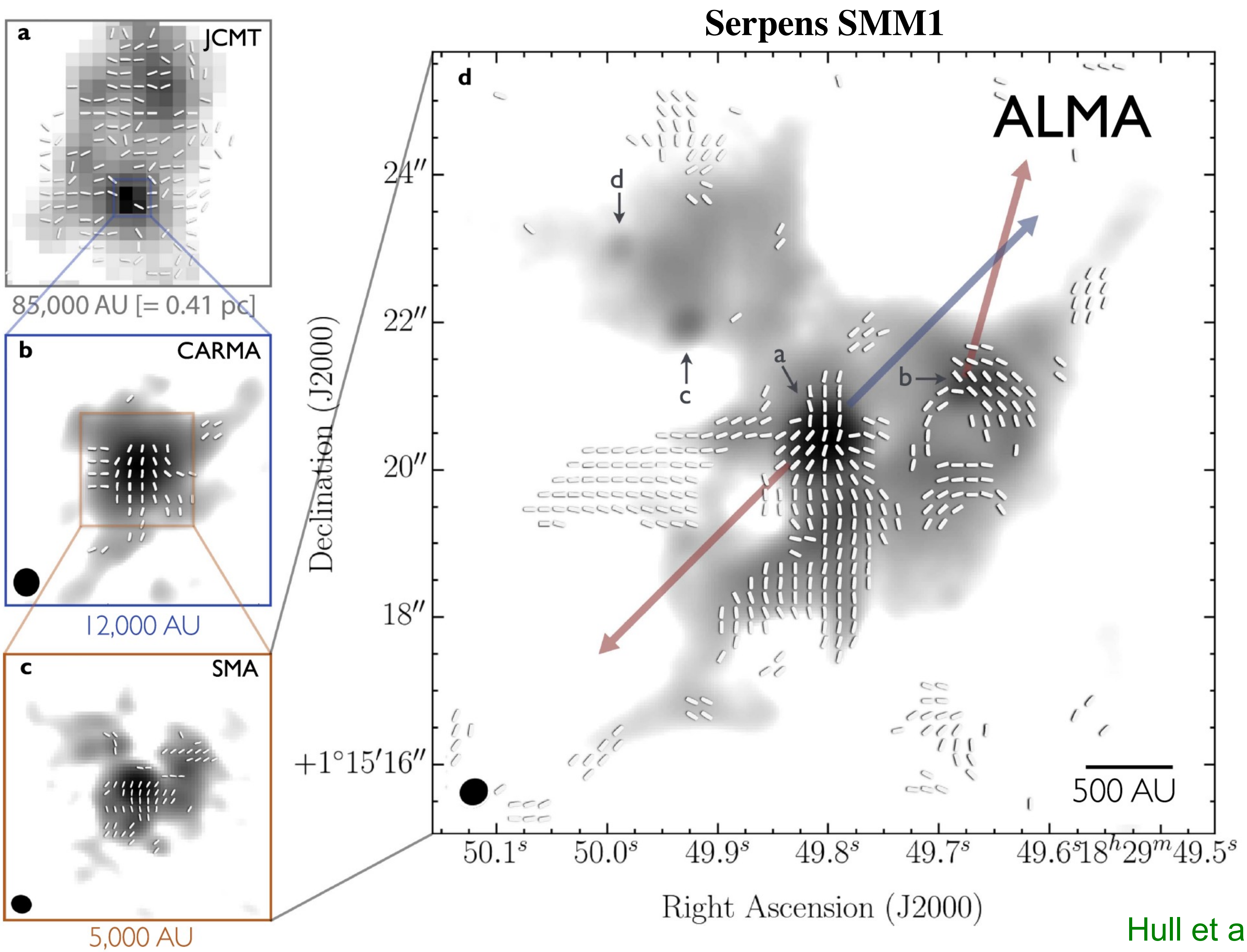


SFR_{ff} (simulation) = **0.46**	x **0.63**	SFR_{ff} (simulation) = **0.29**
SFR_{ff} (theory) = **0.45**	x **0.40**	SFR_{ff} (theory) = **0.18**

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

Federrath & Klessen (2012)

The role of magnetic field structure



Hull et al. (2017)

Magnetohydrodynamics (MHD)

Most gases in the Universe are electrically conductive.

For example:

- Stars are fully ionised.
- The interstellar medium has mostly neutral particles, but even a very small fraction of ions and electrons make the ISM an excellent conductor. What physical processes cause the small ionisation fraction ($\sim 10^{-7}$) in molecular clouds?

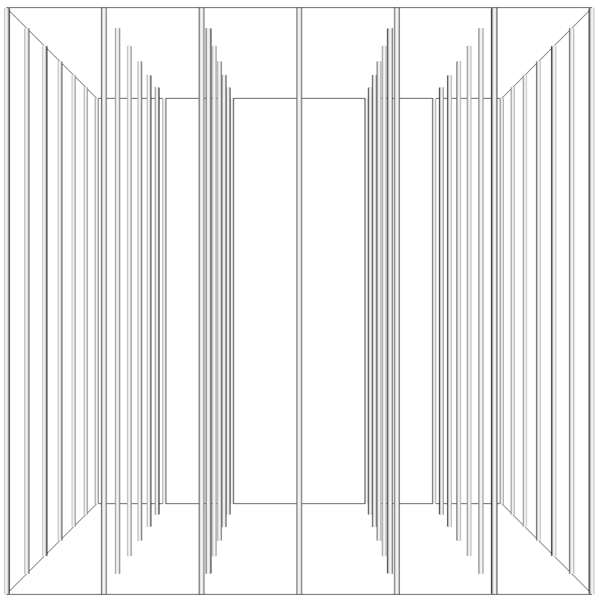
At first it may seem that one needs to treat ions, electrons and neutral particles all separately, because the Lorentz force only acts on the charged particles and depends on the charge. However, in the general approximation of hydrodynamics, namely that the mean free path is small compared to the system size (recall earlier discussion on the validity of the fluid approximation), collisions between neutrals, ions and electrons are so frequent that they can be treated together in a one-component (single fluid) approximation.

This theory is called MAGNETOHYDRODYNAMICS (MHD).

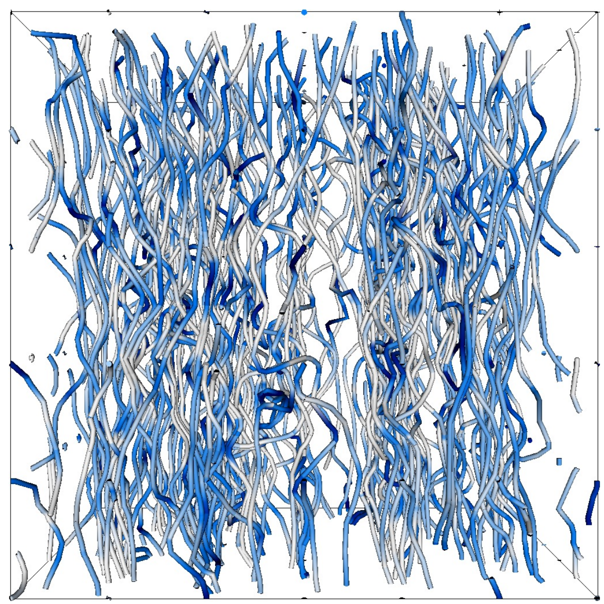
derive in notes...

The role of magnetic field structure

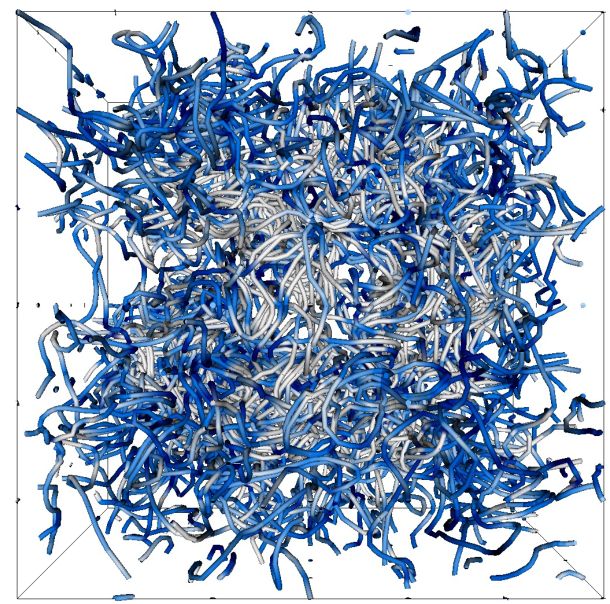
Uniform Magnetic Field



Partially Turbulent Field



Fully Turbulent Field

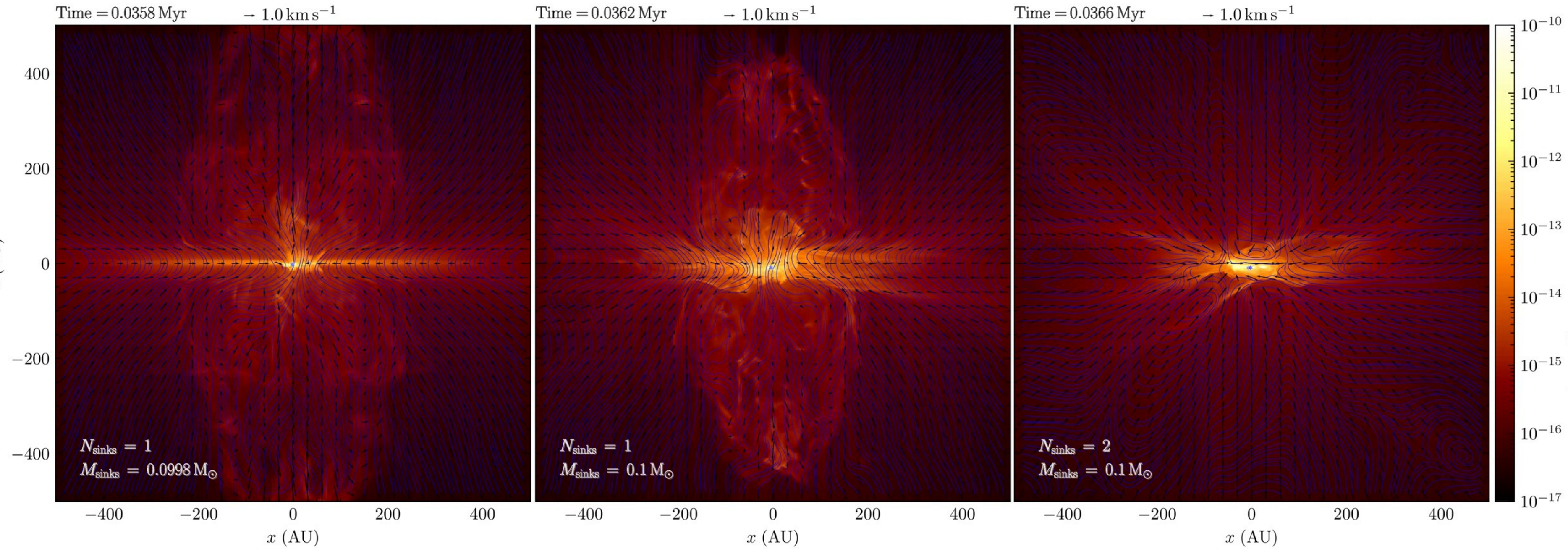


Gerrard et al. (2019)

The role of magnetic field structure for jet launching

Movies available: https://www.mso.anu.edu.au/~chfeder/pubs/turb_b_jets/turb_b_jets.html

Uniform Magnetic Field | Partially Turbulent Field | Fully Turbulent Field



Gerrard et al. (2019)

→ Need ordered magnetic field component for jet launching

(Blandford & Payne 1982)

Astrophysical Gas Dynamics

NEXT TIME:

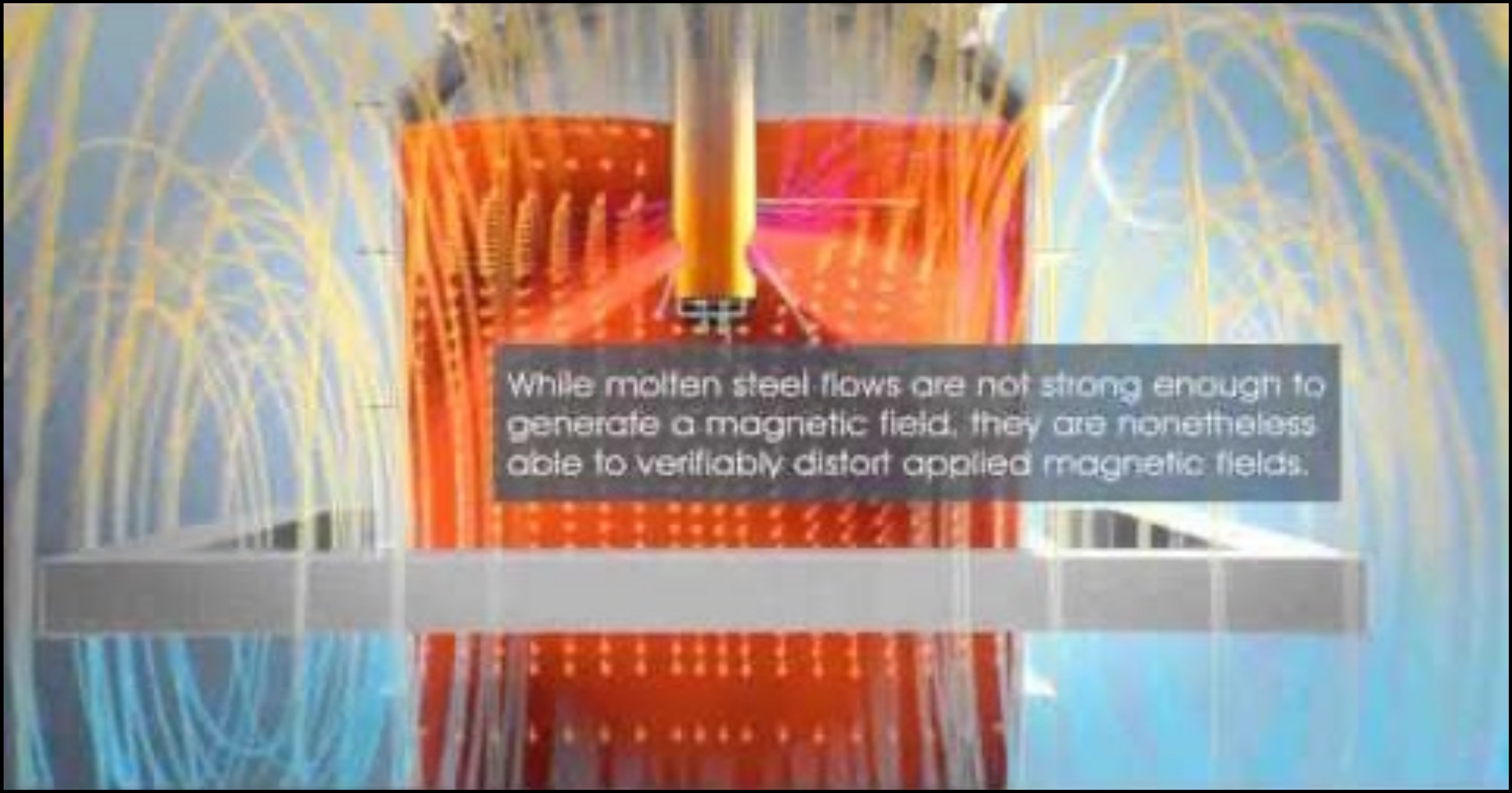
- *no course on Thursday (QEII day)*
- *then: more on MHD (pressure, tension, non-ideal MHD, PIC)*

Image credit: M. S. Povich

Astrophysical Gas Dynamics

Magnetohydrodynamics in the Cosmos and in the Lab

-- Magnetic fields „calm“ turbulent flows :-)



https://youtu.be/i1fuXiBqDqI