

Astrophysical Gas Dynamics

ASTR4012 / ASTR8002

ANU – 2nd semester 2022

Christoph Federrath

Tuesdays and Thursdays 12:00-14:00
(lecture: 12:15-13:30, drop-in session: 13:30-14:00)
Woolley Seminar Room (RSAA) and Online Live (Zoom)

Course Webpage:

https://www.mso.anu.edu.au/~chfeder/teaching/astr_4012_8002/astr_4012_8002.html

Astrophysical Gas Dynamics

Topics:

- **Motivation** (most of astrophysics is gas dynamics: stars, accretion discs, galaxies)
- **Hydrodynamical Equations** (derivation, Eulerian, Lagrangian, conservation laws)
- **Gas Equation of State**
- **Fluid Instabilities** (Jeans, Kelvin-Helmholtz, Parker, etc.)
- **Wind/Outflows and Accretion**
- **Waves and Shocks** (Supernova explosion)
- **Magnetohydrodynamics**
- **Turbulence**
- **Computational Fluid dynamics** (numerical solution of hydro equations, advection)
 -> get computer account at RSAA
- **Guest lectures and some programming**

Resources:

Lecture notes by Bai, Ogilvie, Sijaki, Sormani, Zaroubi, Zingale (search the internet)

Fluid Mechanics Films:

<http://web.mit.edu/hml/ncfmf.html>

Astrophysical Gas Dynamics

Student representatives:

- Need at least **two student representatives**
- Student rep communicates with students and course convener
- Student rep name and email address published on Course website
- Please nominate yourself or someone else, if you are interested!

Astrophysical Gas Dynamics

Assignments:

- assessment based on **4 assignments in total**
- **4th assignment counts double as final exam**
- one assignment per about every 2 weeks
- assignments published on webpage and on Wattle
- submission via Turnitin
- feedback within about 2 weeks after submission

The Gas Dynamics in Star Formation and Turbulence

Christoph Federrath

ANU – 28 July 2022



Australian Government

Australian Research Council



Australian
National
University



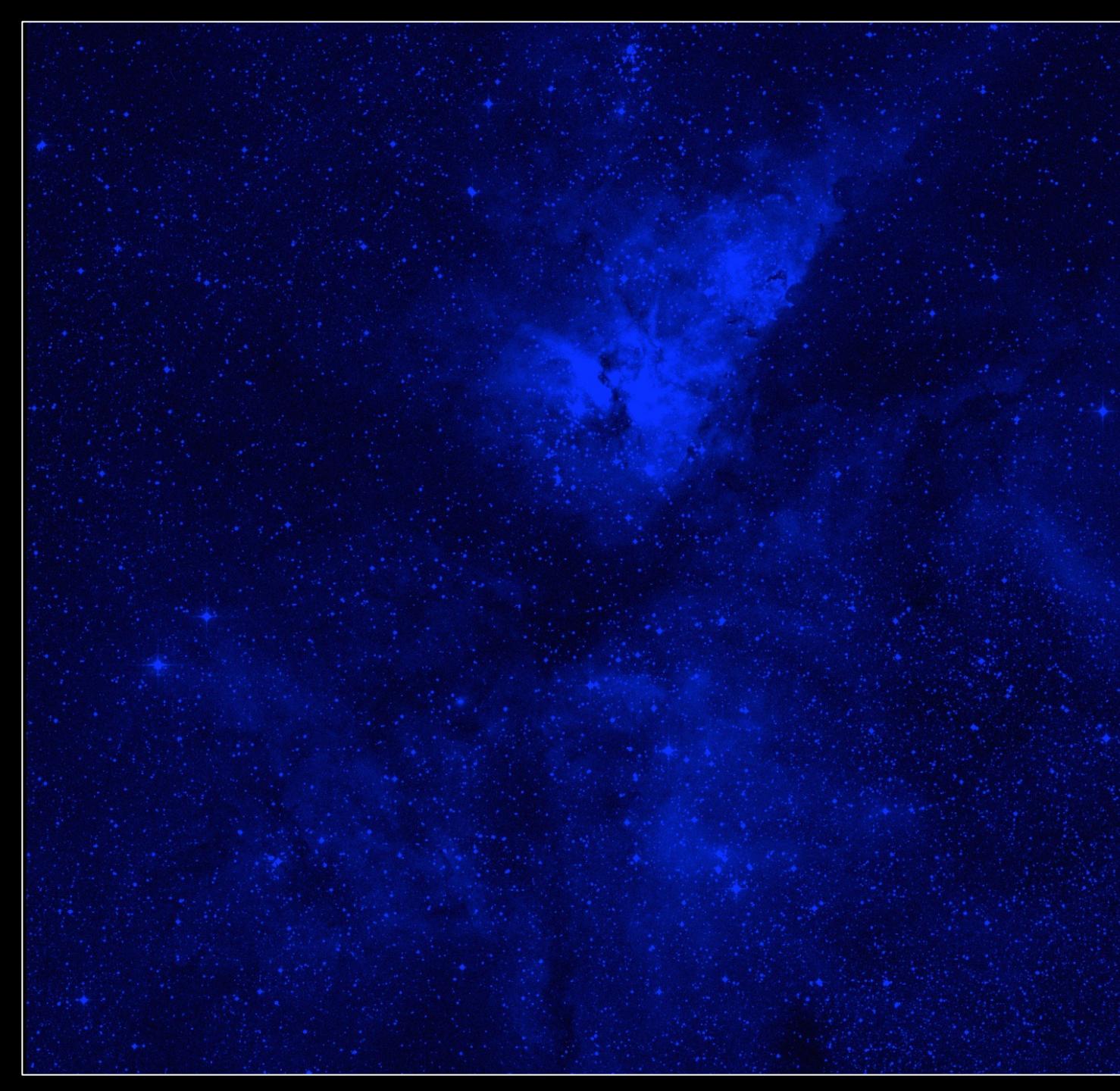
M51: The Whirlpool Galaxy

Optical

Infrared



Image credit: M. S. Povich

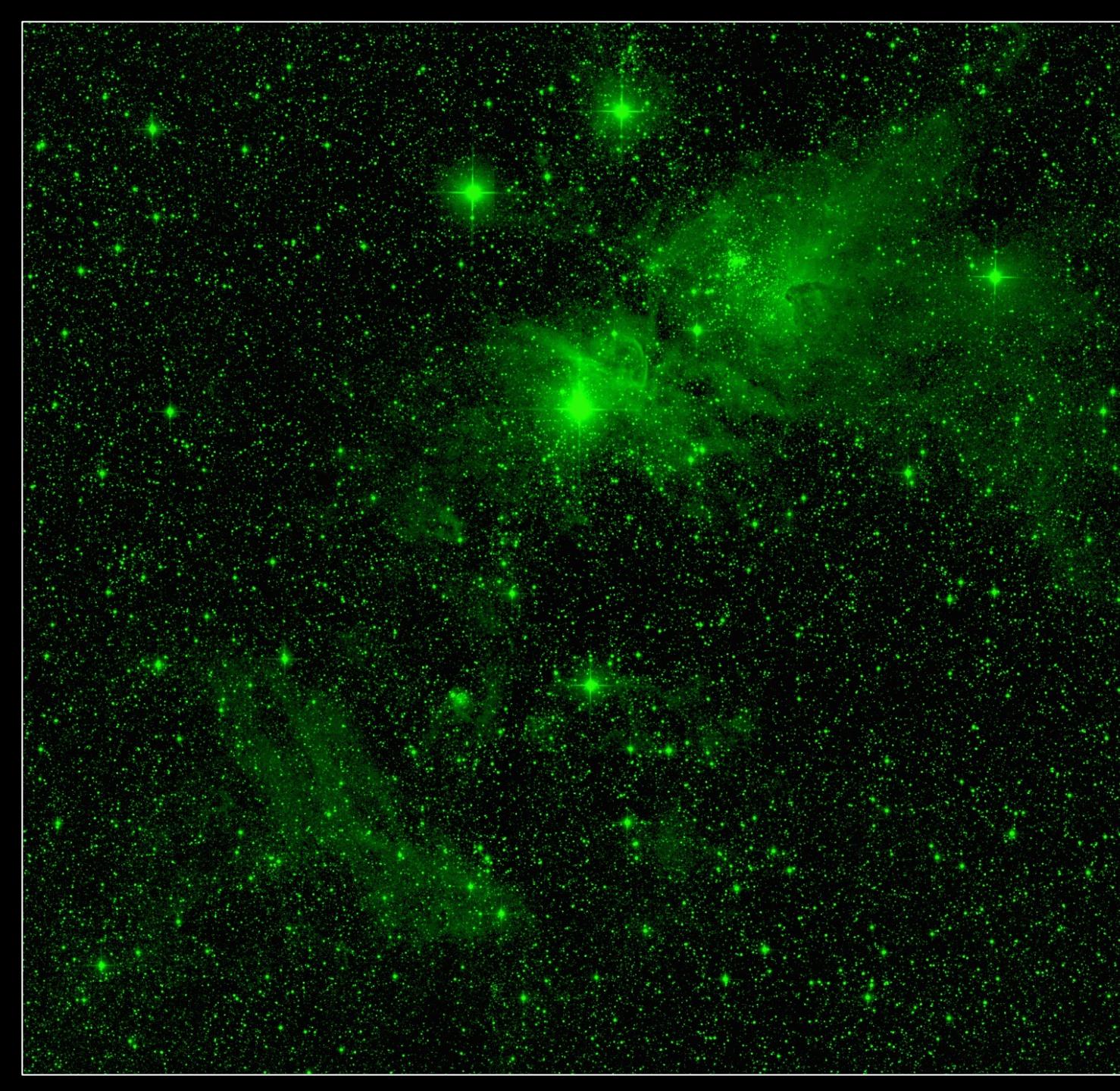


The Great Nebula in Carina

Visible Light
Digitized Sky Survey

Dark regions within
the [Visible nebula](#)
are obscured by
dust.

New Massive Stars
Found Hiding in
Famous Nebula
M. S. Povich



The Great Nebula in Carina

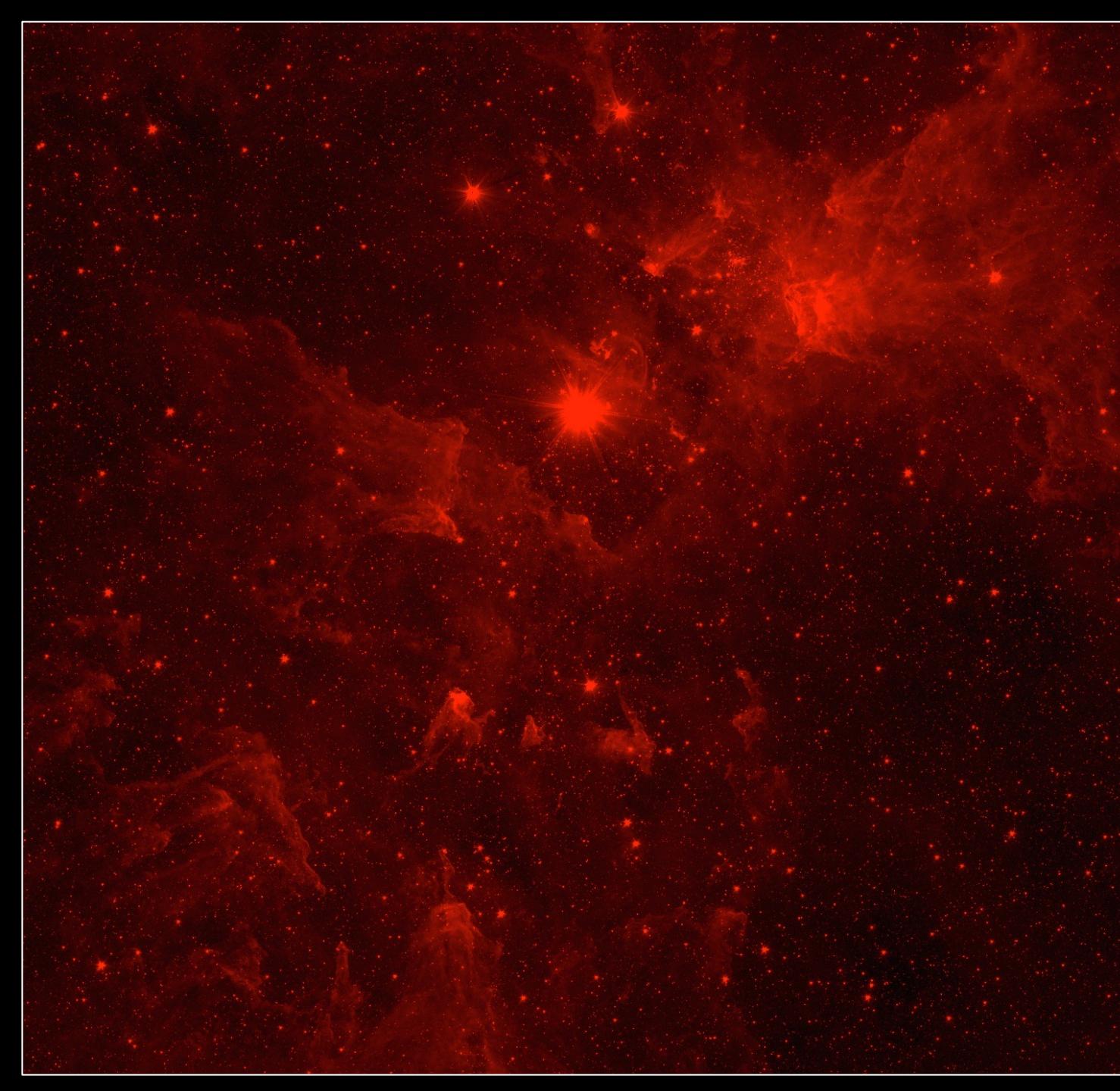
Near-Infrared

Two-Micron All-Sky Survey

Near-infrared light passes through the dust, revealing more stars.

New Massive Stars Found Hiding in Famous Nebula

M. S. Povich

A deep space photograph showing the Great Nebula in Carina. The nebula is a vast cloud of interstellar dust and gas, appearing as a dark, reddish-brown glow against the blackness of space. Numerous bright, star-like points of light are scattered throughout the field, with several prominent stars visible in the upper left and center. The nebula's structure is complex, with various filaments and regions of different densities.

**The Great Nebula
in Carina**

Mid-Infrared
Spitzer Space Telescope

The dust clouds
themselves glow in
mid-infrared light.

New Massive Stars
Found Hiding in
Famous Nebula
M. S. Povich

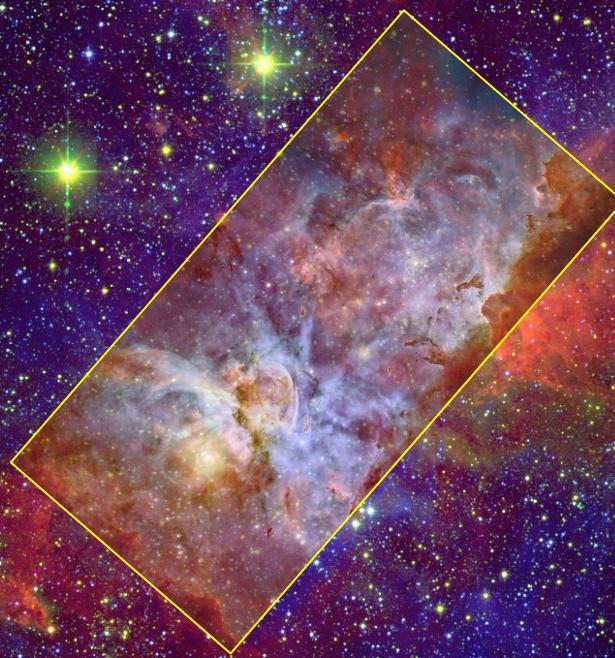
The Great Nebula in Carina

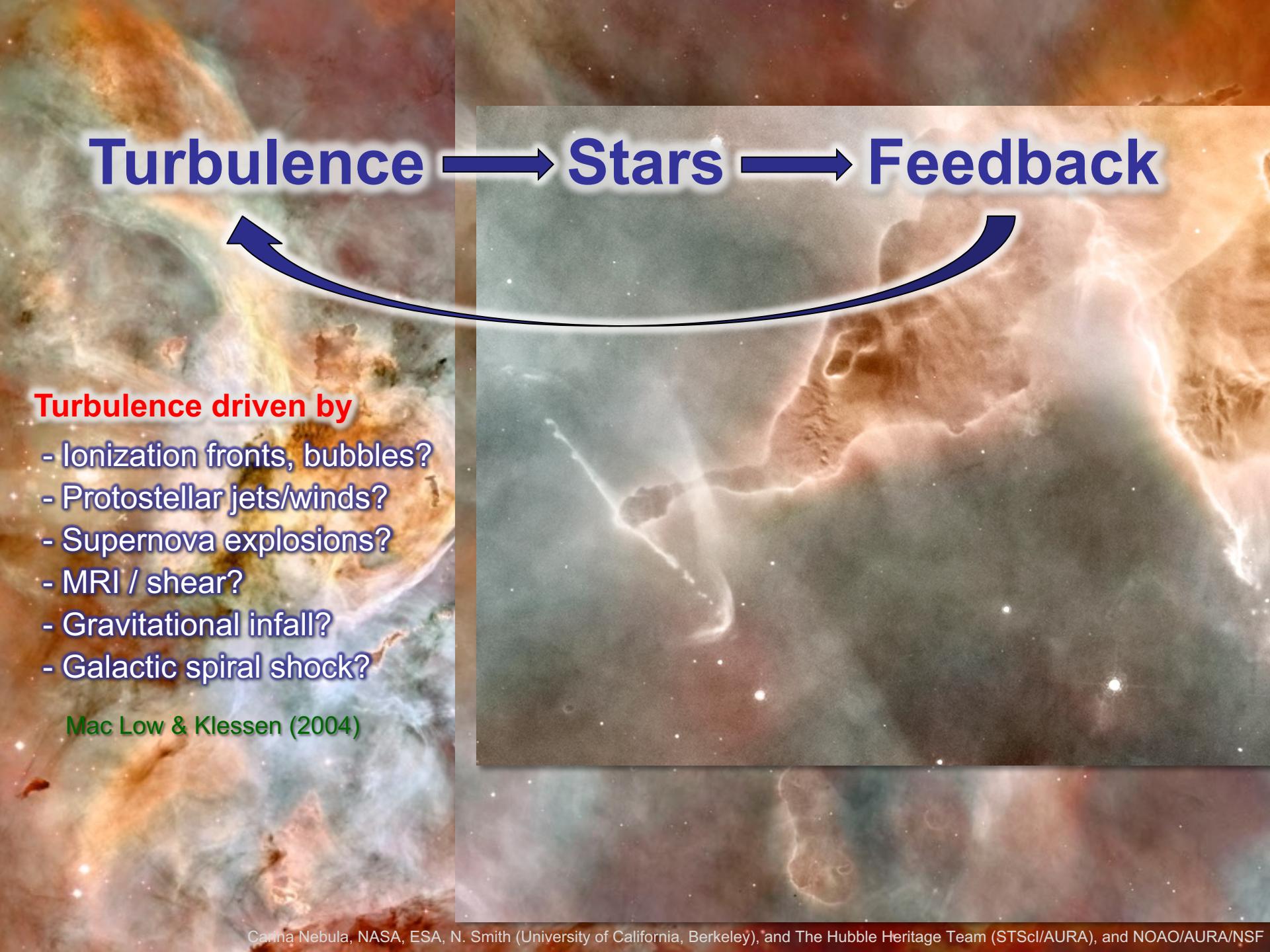
Visible Light
Digitized Sky Survey

Near-Infrared
Two-Micron All-Sky Survey

Mid-Infrared
Spitzer Space Telescope

New Massive Stars
Found Hiding in
Famous Nebula
M. S. Povich





Turbulence → Stars → Feedback

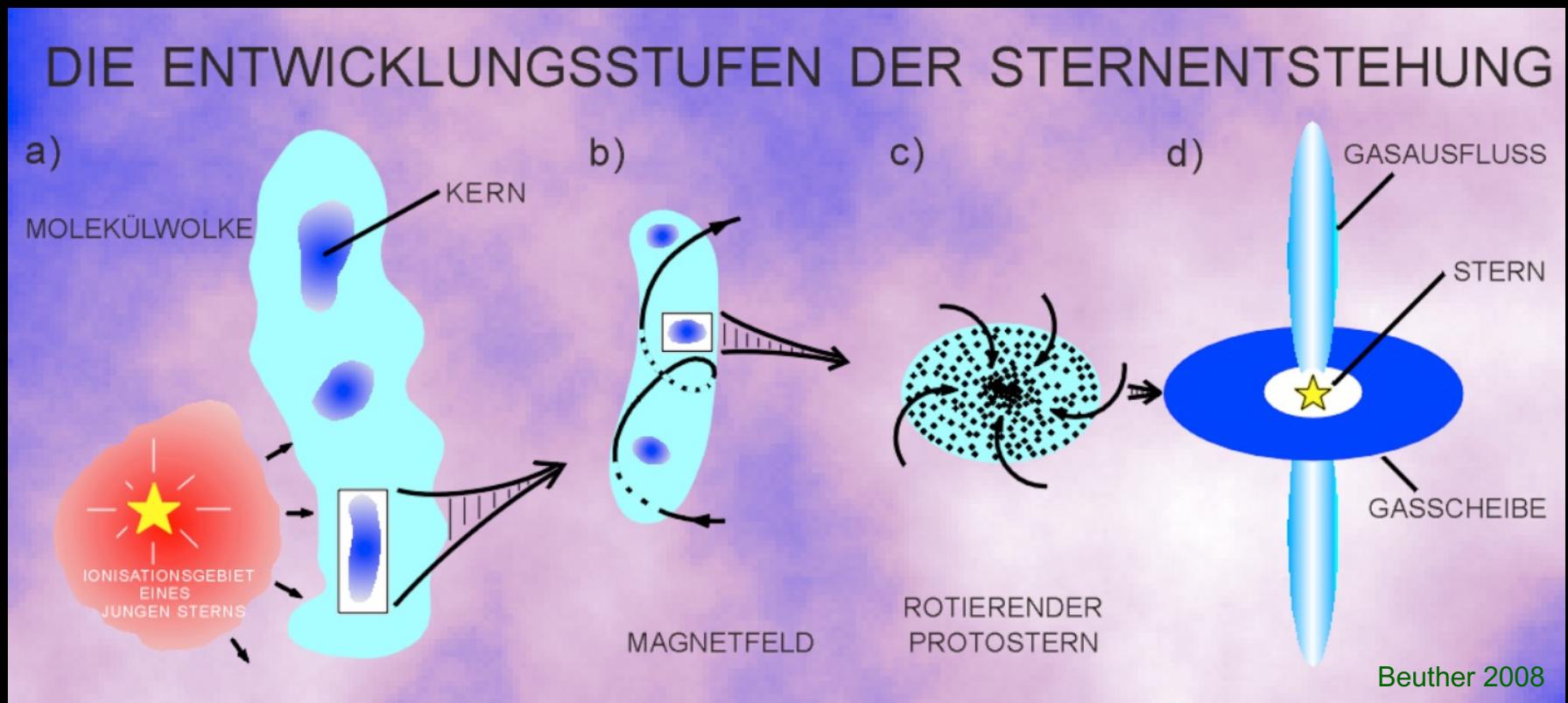
Turbulence driven by

- Ionization fronts, bubbles?
- Protostellar jets/winds?
- Supernova explosions?
- MRI / shear?
- Gravitational infall?
- Galactic spiral shock?

Mac Low & Klessen (2004)

The Star Formation Paradigm

Clouds → Cores → Disk + Star + Jet / Outflow



Star Formation Rate



S. Guisard ESO

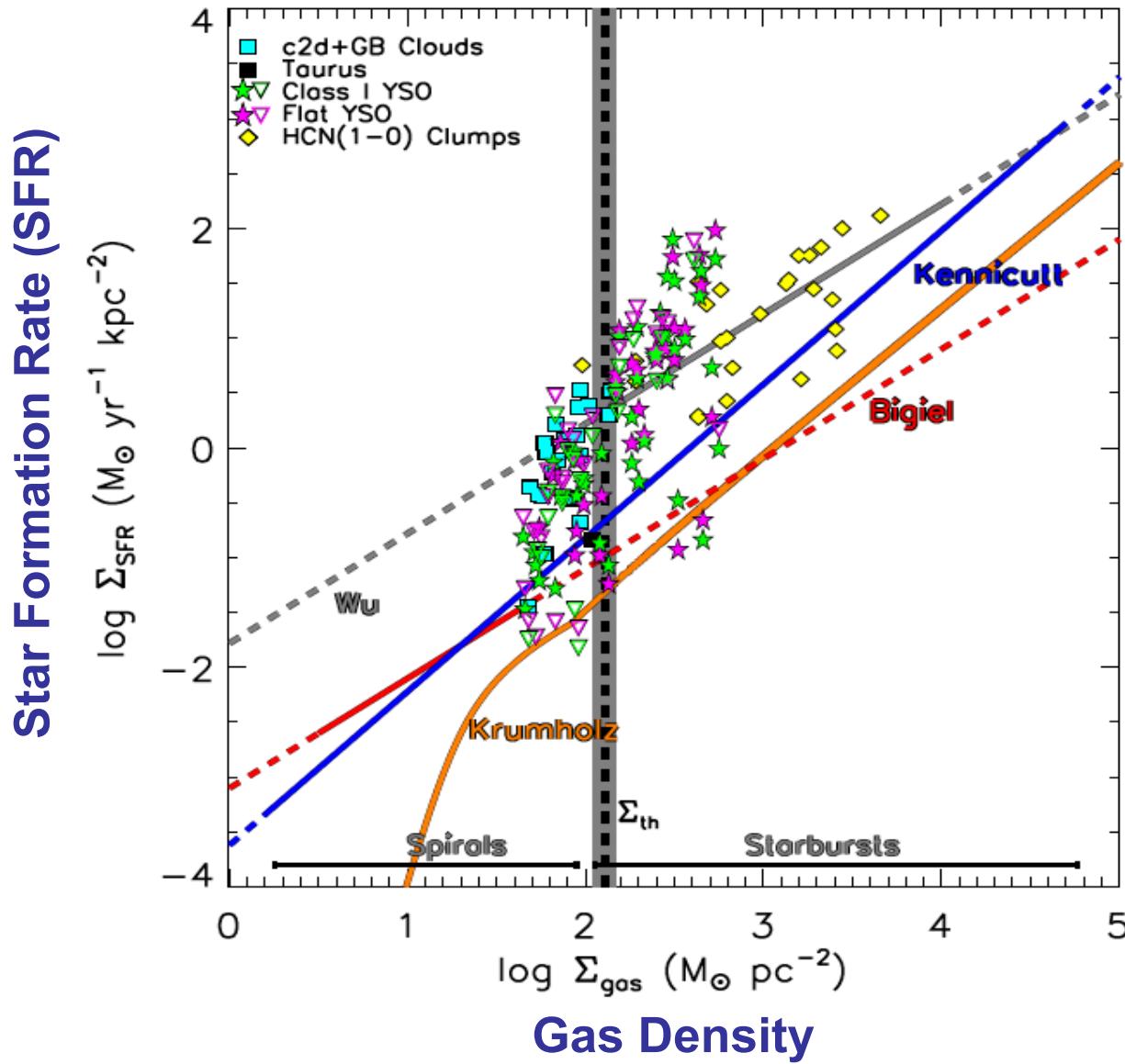
Pipe Nebula

Rho Ophiuchi Cloud

$$\text{SFR}_{\text{Oph}} = 15 \times \text{SFR}_{\text{Pipe}}$$

(Lada et al. 2010)

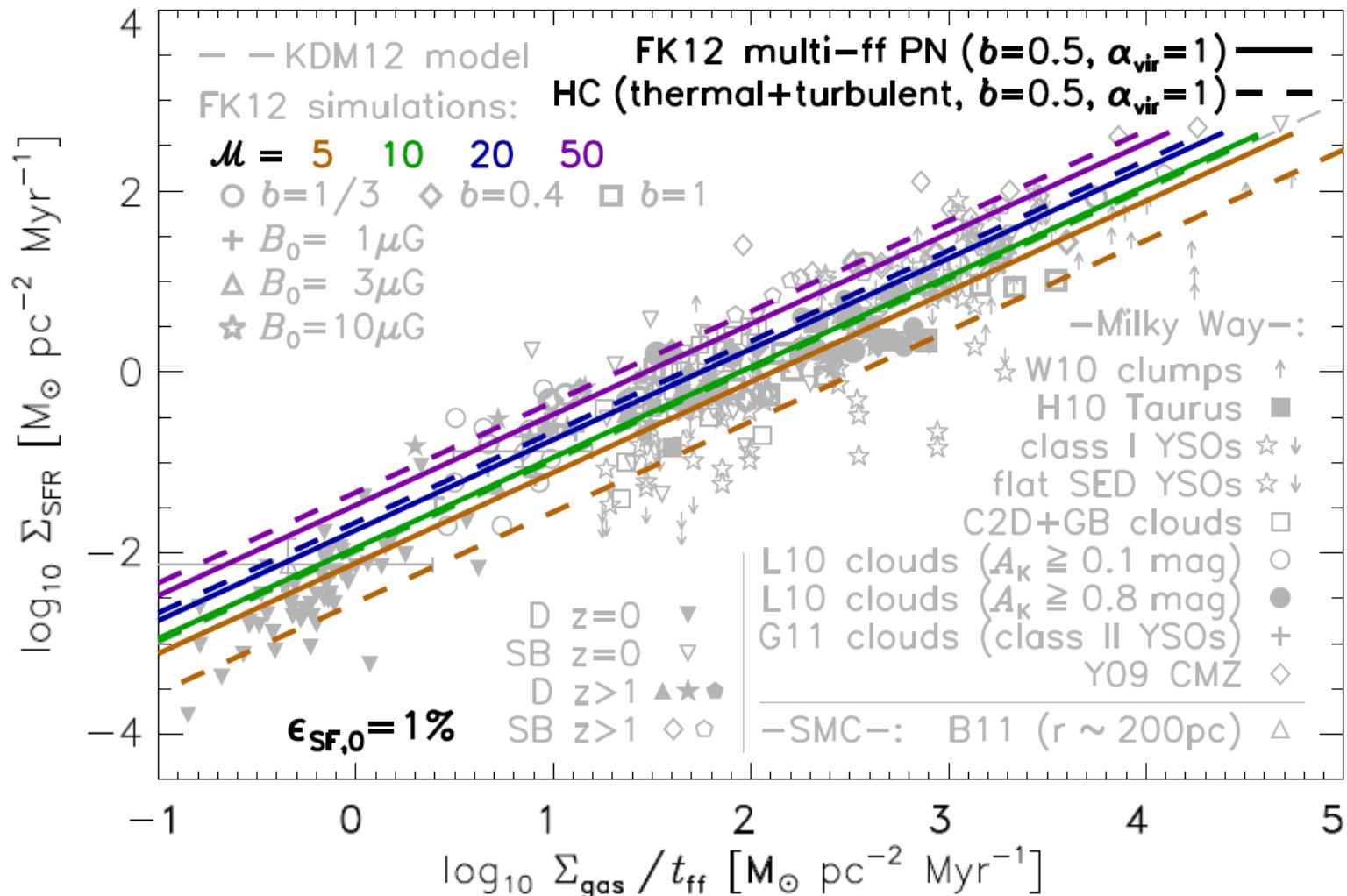
Universal star formation “law”?



Scatter?

Observational scatter
and physical variations
caused by
Turbulence

Physical Variations in the Universal Star Formation Law



→ Scatter caused by variations in the TURBULENCE
(Mach number, driving, etc.)

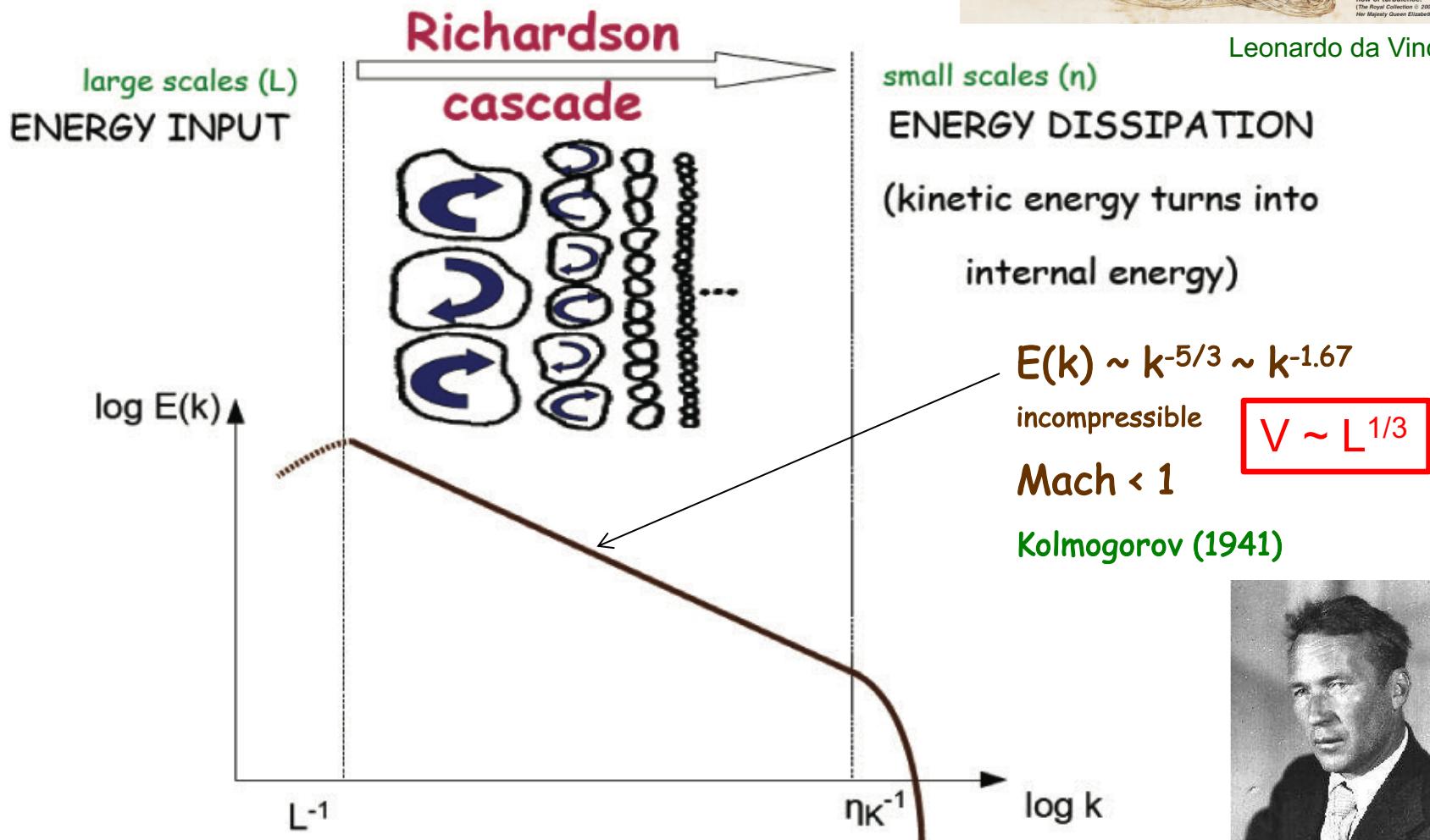
Federrath (2013, MNRAS 436, 3167);
see also Salim, Federrath, Kewley (2015, ApJ 806, L36)

Turbulence

- Reynolds numbers > 1000
- Kinetic energy cascade



Leonardo da Vinci

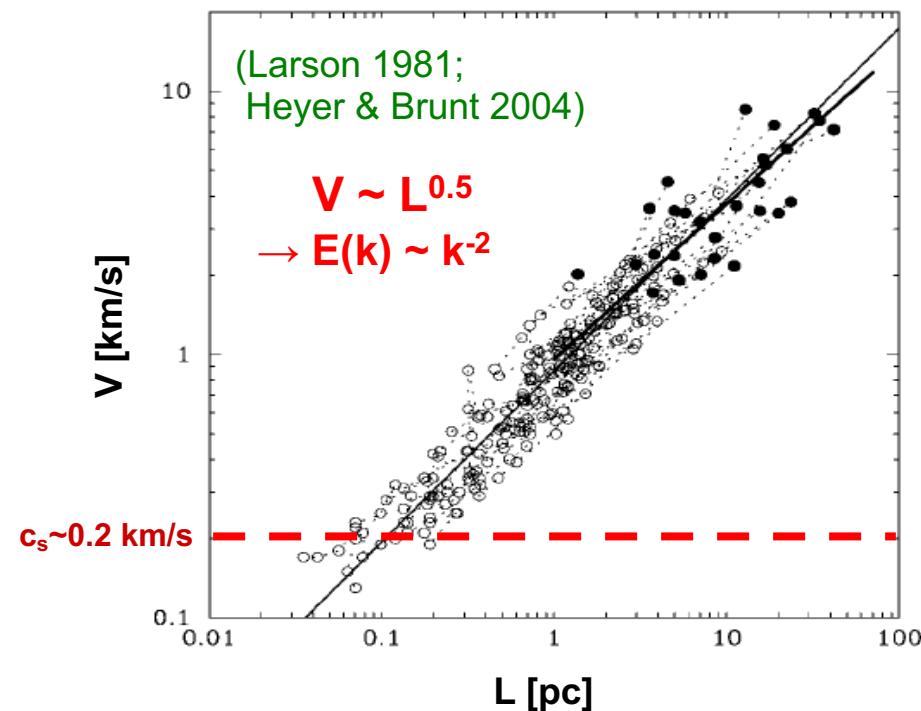


Interstellar Turbulence – scaling

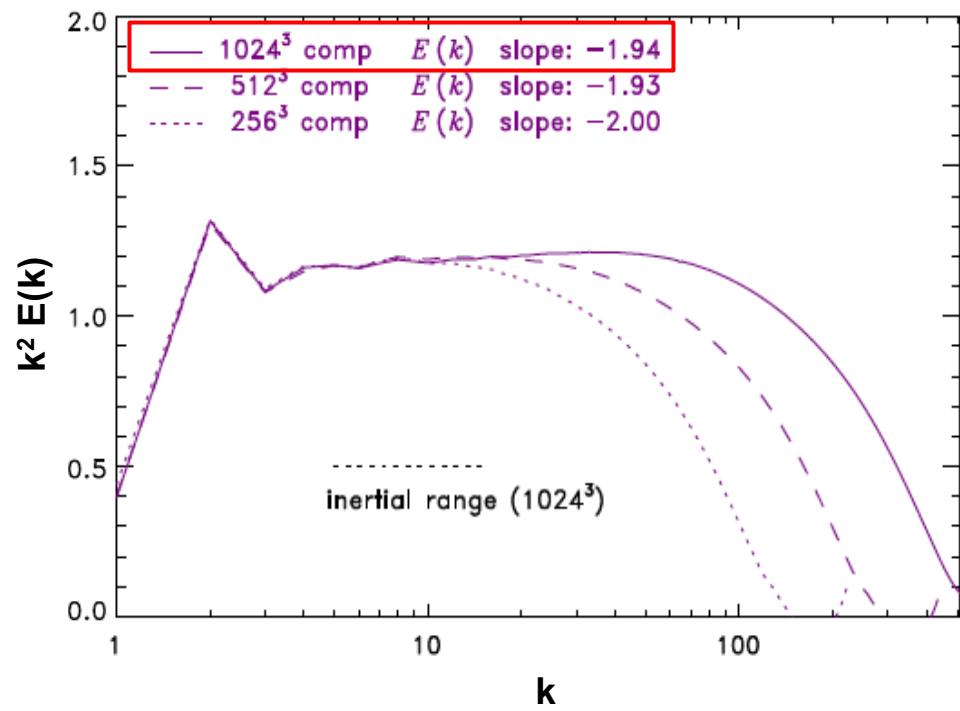
BUT: Larson (1981) relation: $E(k) \sim k^{-1.8-2.0}$

(see also Heyer & Brunt 2004; Roman-Duval et al. 2011)

Observation



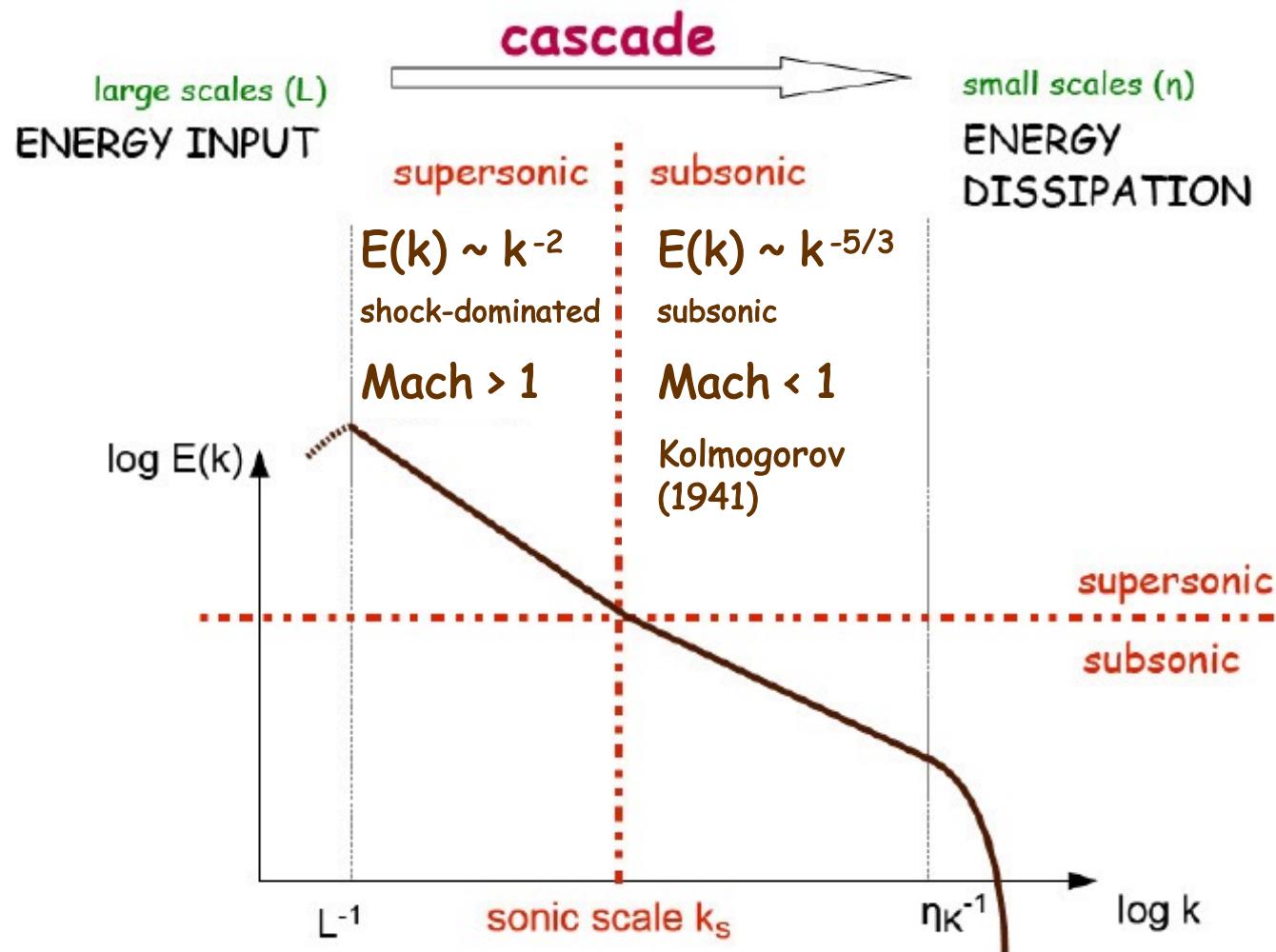
Simulation



Supersonic, compressible turbulence has steeper $E(k) \sim k^{-1.9}$ than Kolmogorov ($E \sim k^{-5/3}$)

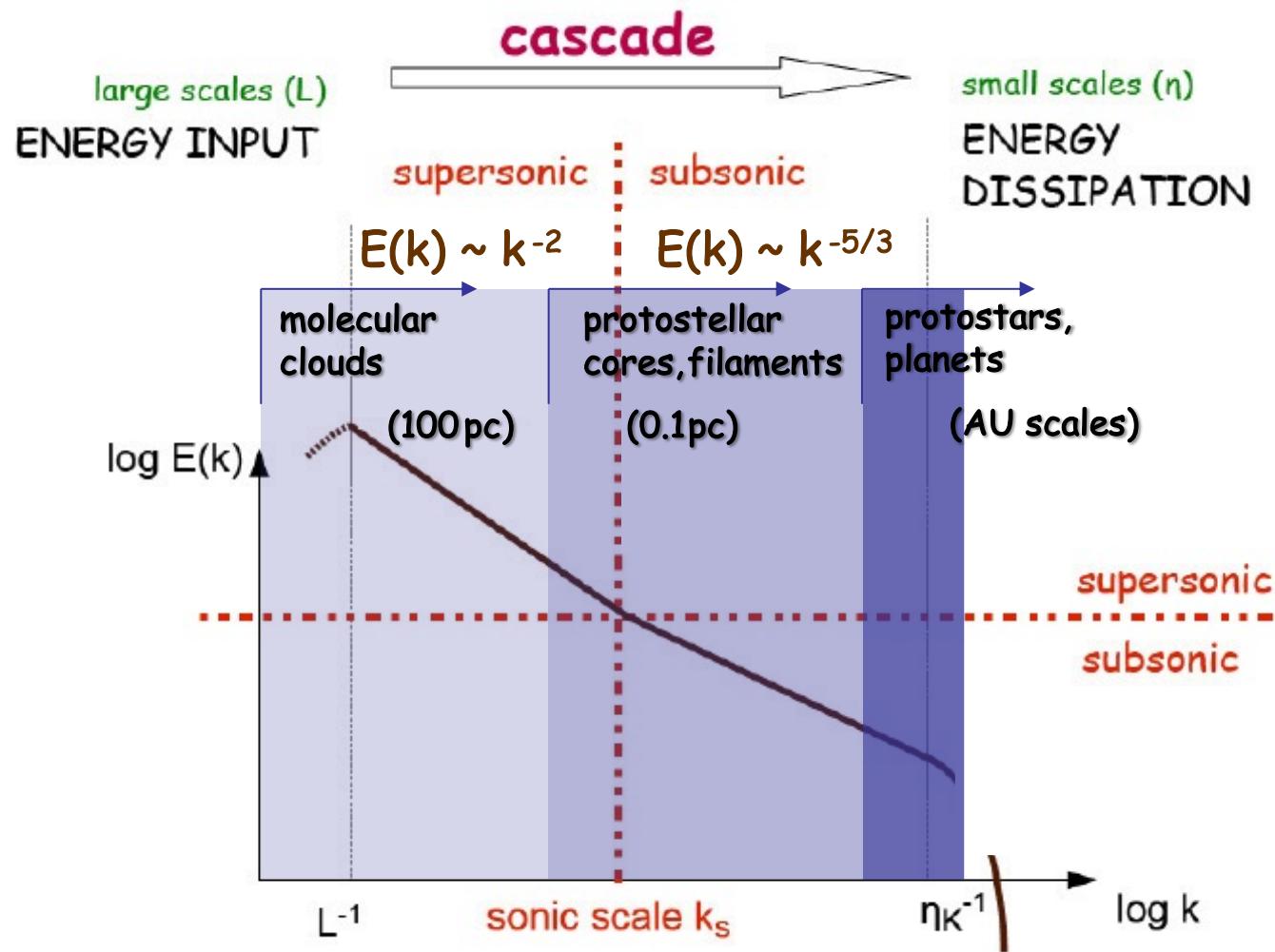
Interstellar Turbulence

- Reynolds numbers > 1000
- Kinetic energy cascade



Interstellar Turbulence

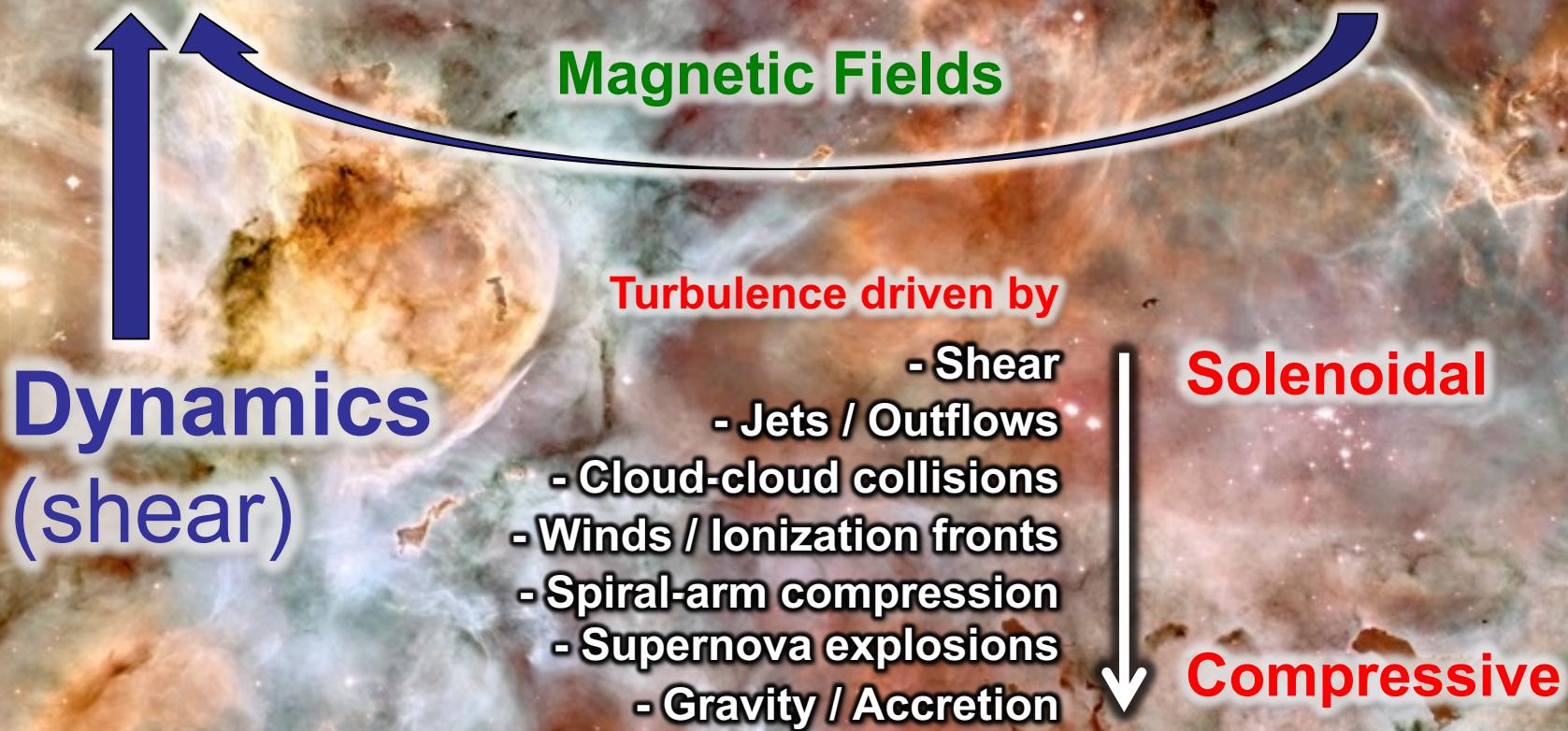
- Reynolds numbers > 1000
- Kinetic energy cascade



Turbulence is key for Star Formation

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

Turbulence → Stars → Feedback

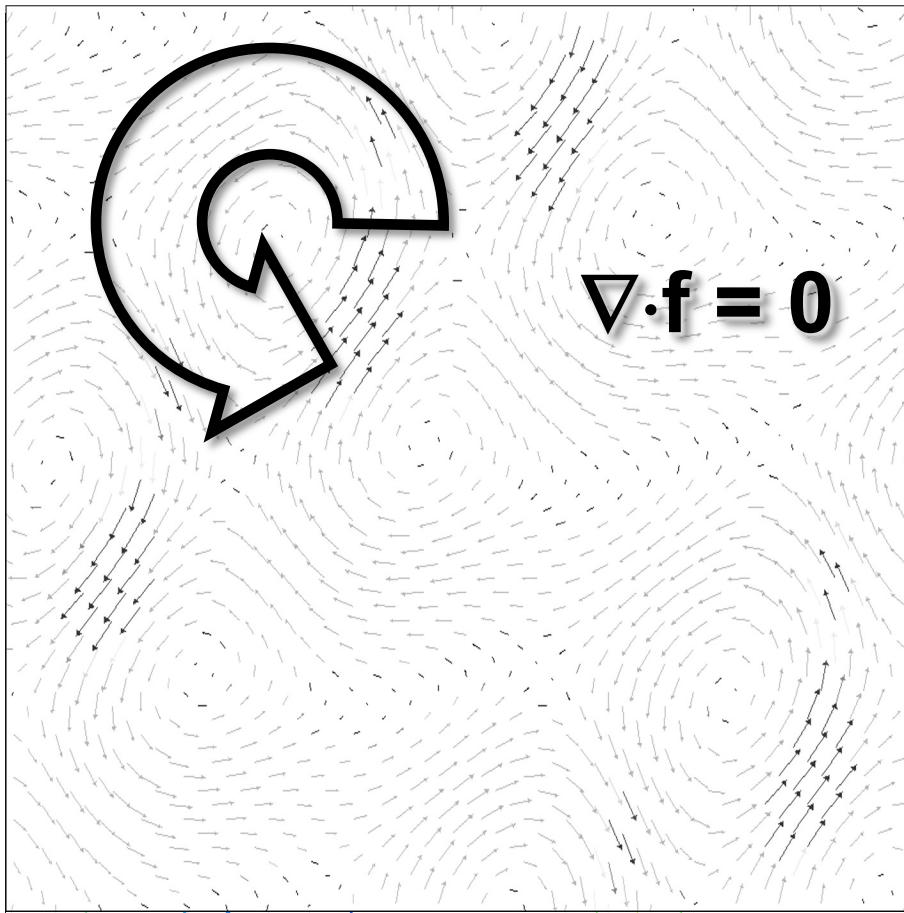


Turbulence driving – solenoidal versus compressive

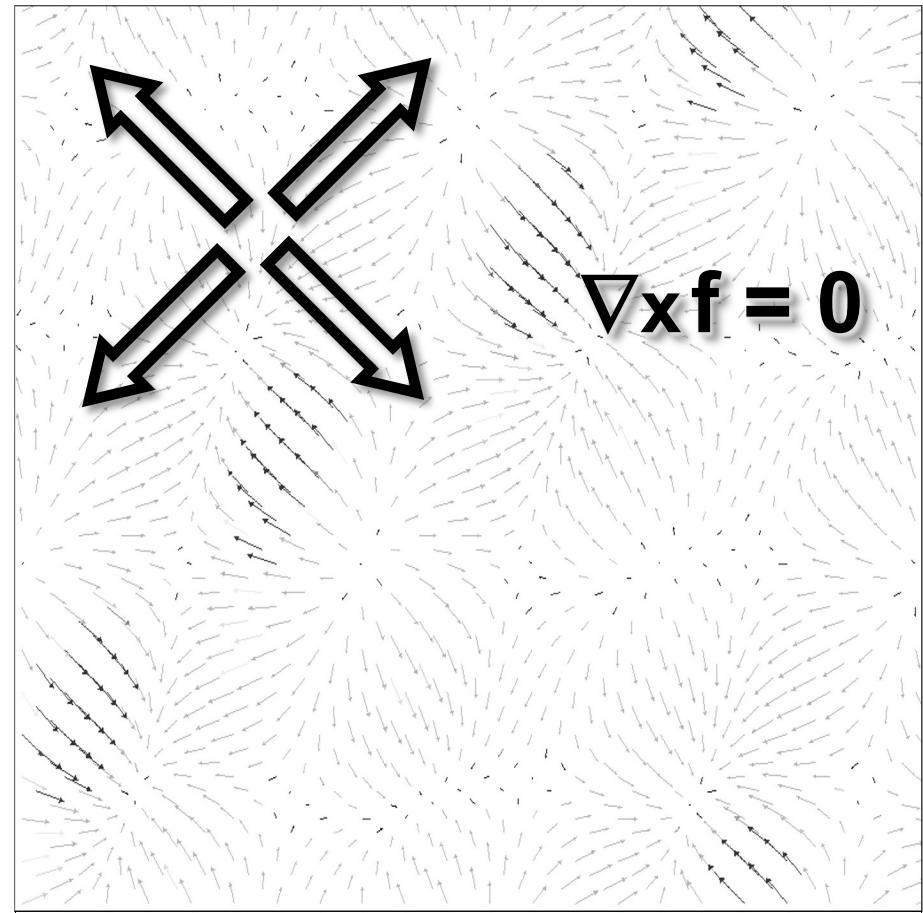
Ornstein-Uhlenbeck process (stochastic process with autocorrelation time)

→ **forcing varies smoothly in space and time,**
following a well-defined random process

Solenoidal forcing



Compressive forcing



Turbulence driving – solenoidal versus compressive

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

solenoidal driving

compressive driving

solenoidal driving

$$D_f \sim 2.6$$

compressive driving

$$D_f \sim 2.3$$

(see Federrath et al. 2009;
Roman-Duval et al. 2010;
Donovan-Meyer et al. 2013)

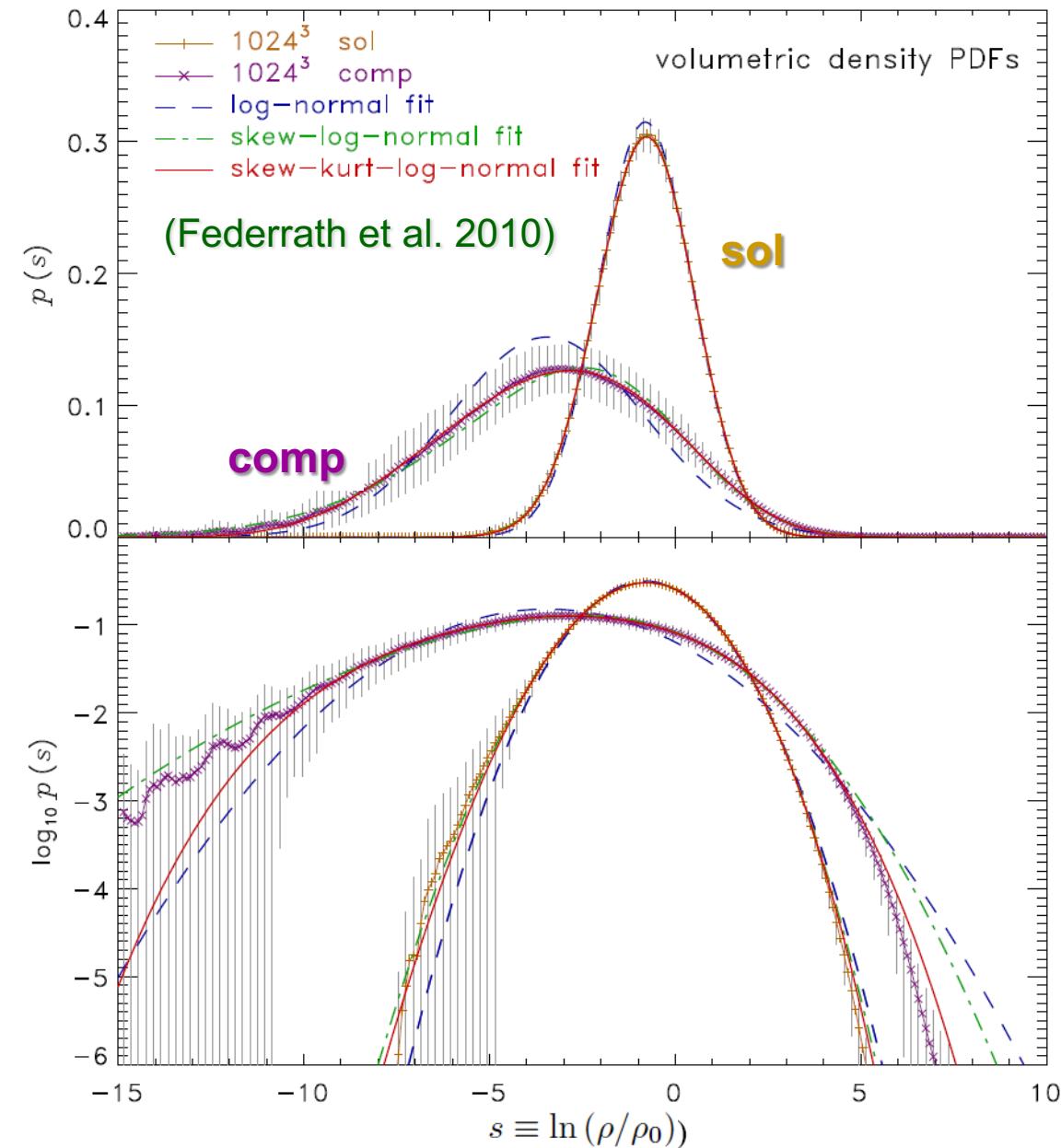
Federrath 2013

Federrath 2013

Compressive driving produces much stronger density enhancements

(Federrath 2013, MNRAS 436, 1245: Supersonic turbulence @ 4096^3 grid cells)

The density PDF



Density PDF

log-normal:

$$p_s ds = \frac{1}{\sqrt{2\pi\sigma_s^2}} \exp\left[-\frac{(s - \langle s \rangle)^2}{2\sigma_s^2}\right] ds$$

$$s \equiv \ln(\rho/\rho_0)$$

Vazquez-Semadeni (1994); Padoan et al. (1997); Ostriker et al. (2001); Hopkins (2013)

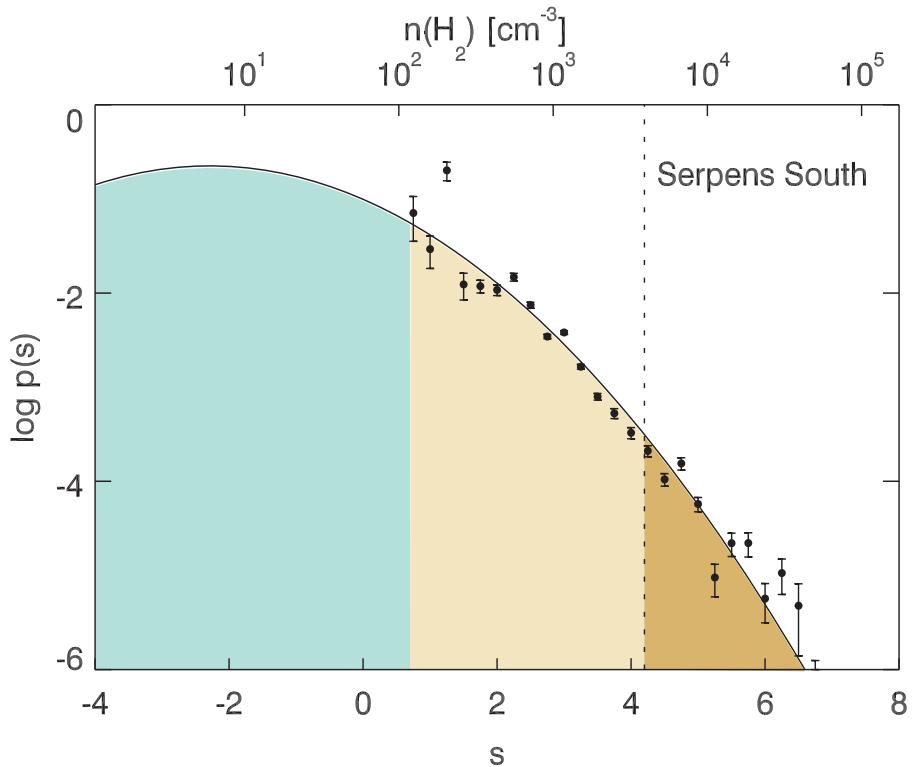
$$\sigma_s^2 = \ln(1 + b^2 \mathcal{M}^2)$$

→ **$b = 1/3$ (sol)**
 $b = 1$ (comp)

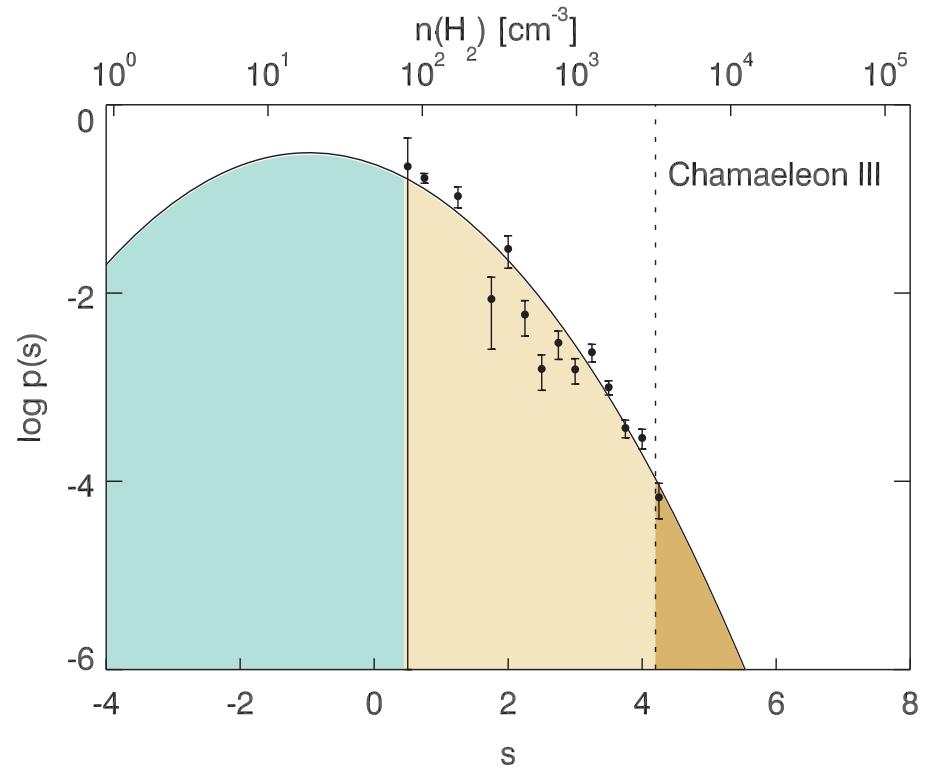
Federrath et al. (2008, 2010);
 Price et al. (2011); Konstandin et al. (2012);
 Molina et al. (2012); Federrath & Banerjee
 (2014); Nolan et al. (2015)

PDF → The dense gas fraction

Active star formation



No star formation



Kainulainen, Federrath, Henning (2014, *Science* 344, 183)

Power-law tails →
gravitational collapse

Schneider et al. 2012–2015; Federrath & Klessen 2013;
Girichidis et al. 2014; Sadavoy et al. 2014; Myers 2015; Cunningham et al., in prep.

2D → 3D
conversion

(Brunt et al. 2010a,b)

Turbulence → Density PDF

Density PDF → Star Formation Rate

Why is star formation so inefficient?

Density PDF → Star Formation Rate

Density PDF is key for star formation theories:

- **Initial Mass Function** (Padoan & Nordlund 02, Hennebelle & Chabrier 08,09,
- **Star Formation Efficiency** (Elmegreen 08, Federrath & Klessen 13)
- **Kennicutt-Schmidt relation** (Elmegreen 02, Krumholz & McKee 05, Tassis 07, Ostriker+10, Elmegreen 11, Veltchev+11, Hopkins 12, Federrath 13, Salim+15)
- **Star Formation Rate** (Krumholz & McKee 05, Padoan & Nordlund 11, Renaud+12, Federrath & Klessen 2012)

All based on integrals over the turbulent density PDF

$$\text{SFR}_{\text{ff}} = \frac{\epsilon_{\text{core}}}{\phi_t} \int_{x_{\text{crit}}}^{\infty} xp(x) dx$$

Krumholz & McKee (2005), Padoan & Nordlund (2011); Hennebelle & Chabrier (2011,2013)

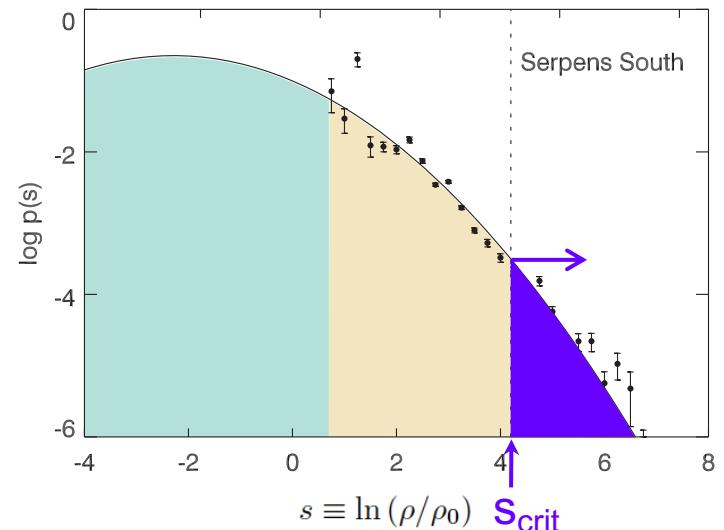
The Star Formation Rate

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



Hennebelle & Chabrier (2011) : “multi-freefall model”

The Star Formation Rate

Statistical Theory for the Star Formation Rate:

SFR ~ Mass/time

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

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

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

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

Hennebelle & Chabrier (2011) : “multi-freefall model”

The Star Formation Rate

Statistical Theory for the Star Formation Rate:

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freefall time mass fraction

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

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

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

From sonic and Jeans scales:

$$s_{\text{crit}} \propto \ln(\alpha_{\text{vir}} \mathcal{M}^2)$$

(Krumholz & McKee 2005, Padoan & Nordlund 2011)

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

→ ↑ ←
 2 $E_{\text{kin}}/E_{\text{grav}}$ forcing Mach number

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

(e.g., Federrath et al. 2008)

Federrath & Klessen (2012)

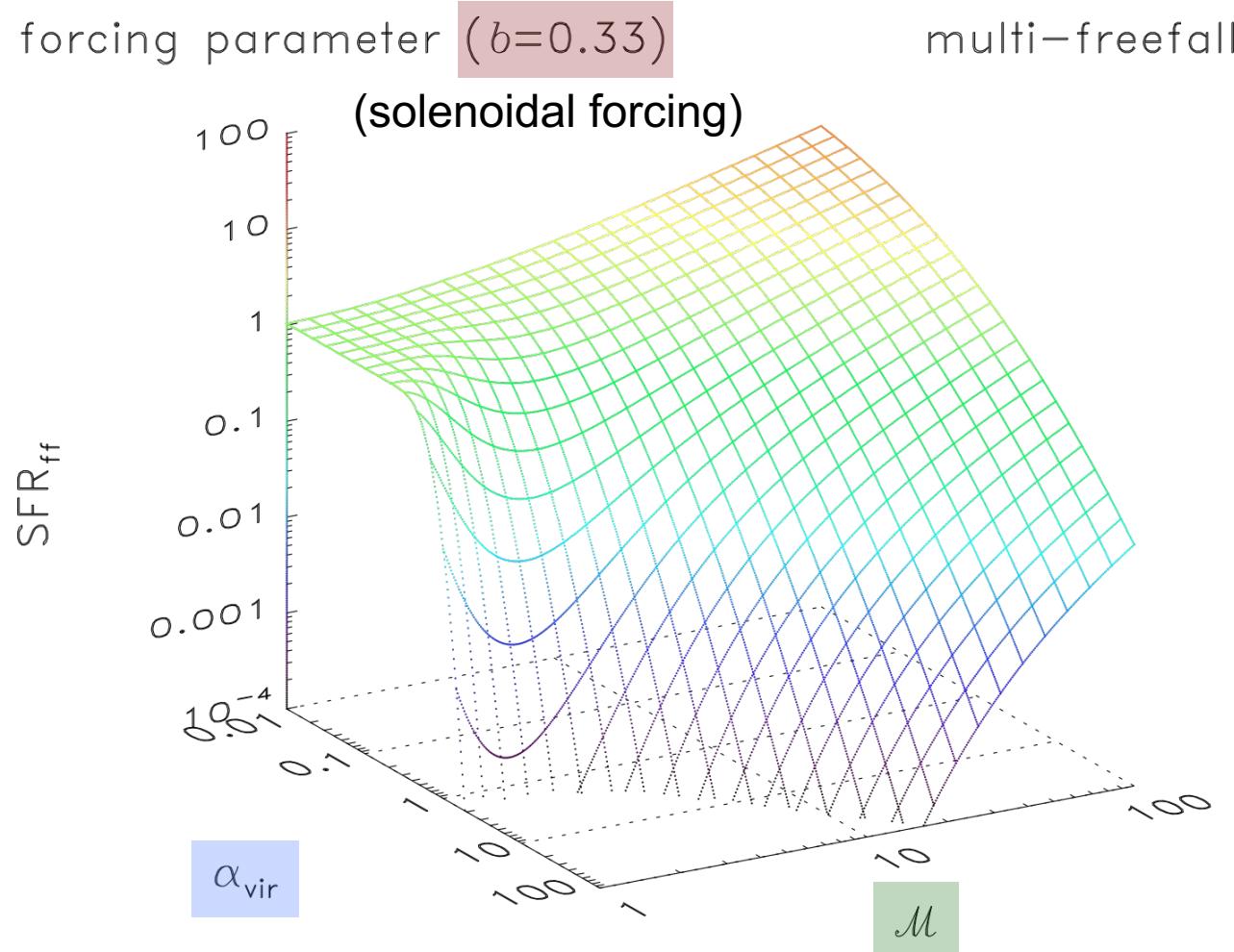
Density PDF → Star Formation Rate

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

$$2E_{\text{kin}}/E_{\text{grav}}$$

forcing

Mach number



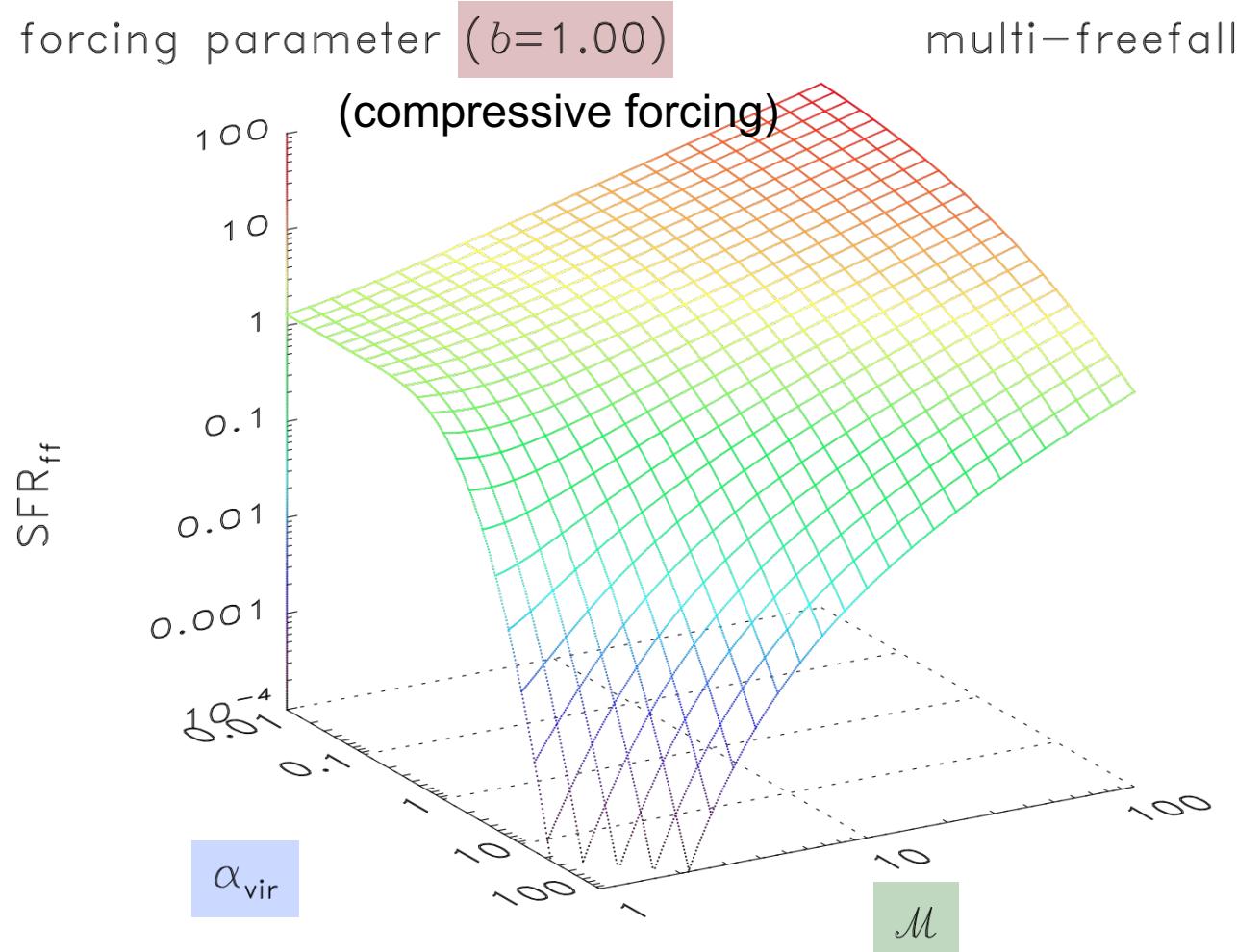
Density PDF → Star Formation Rate

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

$$2E_{\text{kin}}/E_{\text{grav}}$$

forcing

Mach number

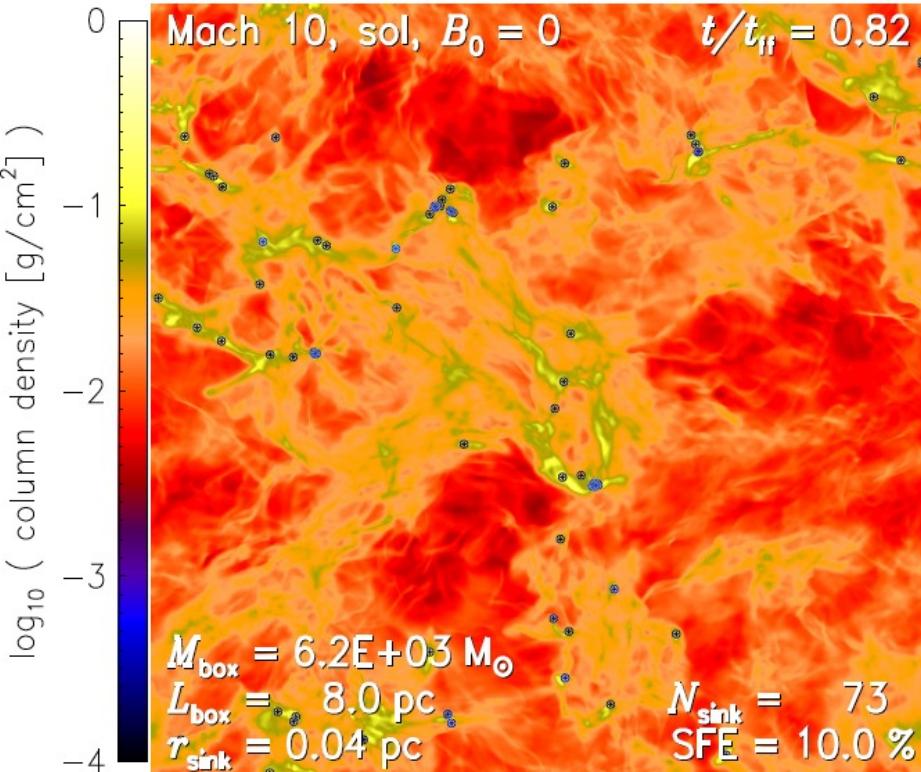


Density Distribution → Star Formation Rate

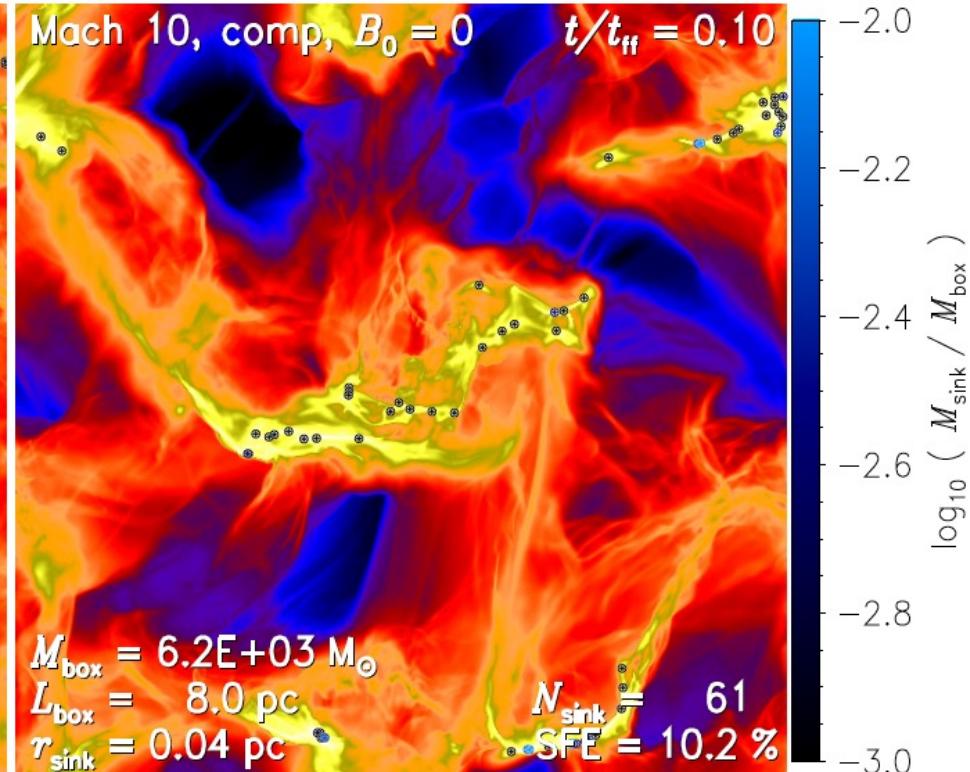
Numerical experiment for Mach 10

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

Solenoidal Driving ($b=1/3$)



Compressive Driving ($b=1$)



$$\text{SFR}_{\text{ff}} \text{ (simulation)} = 0.14$$

$$\text{SFR}_{\text{ff}} \text{ (theory)} = 0.15$$

$$\times 20$$

$$\times 15$$

$$\text{SFR}_{\text{ff}} \text{ (simulation)} = 2.8$$

$$\text{SFR}_{\text{ff}} \text{ (theory)} = 2.3$$

Turbulence driving is a key parameter for star formation!

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 $\beta = P_{\text{th}}/P_{\text{mag}}$

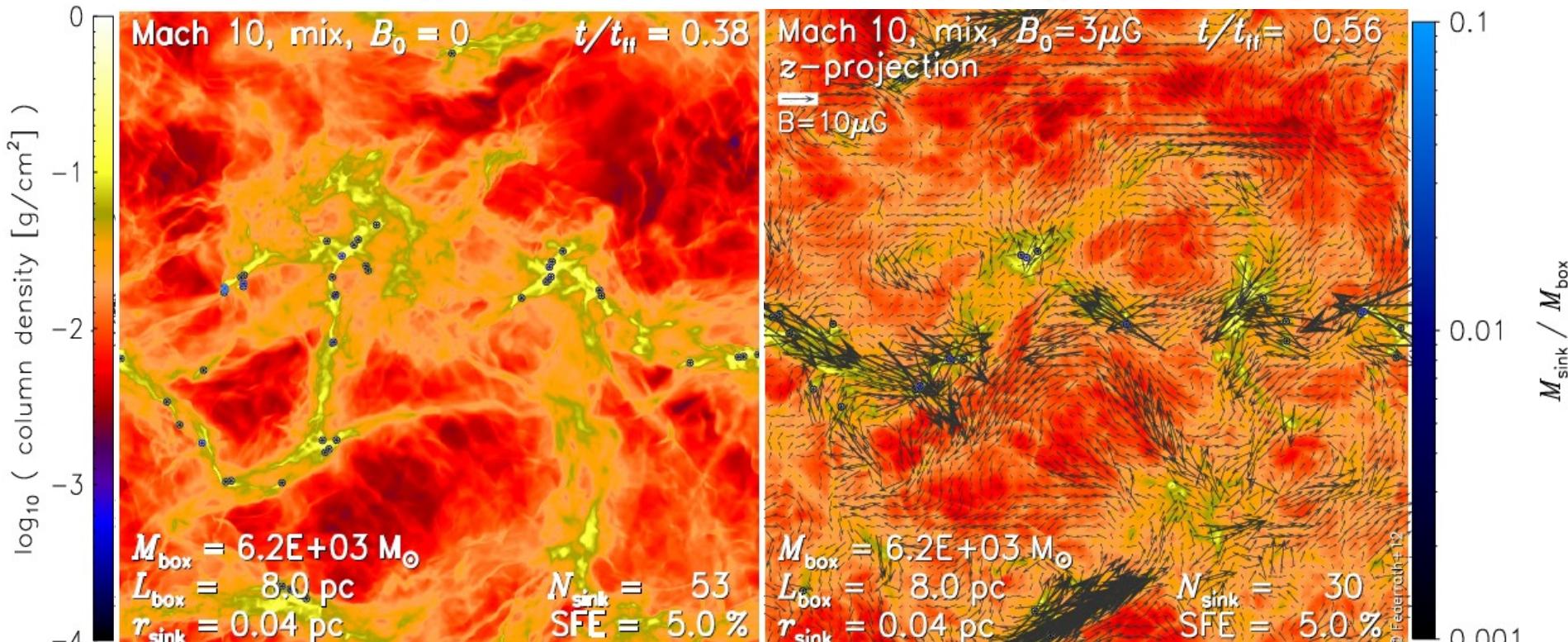
The Star Formation Rate – Magnetic fields

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

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

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

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



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

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

$$\times 0.63$$

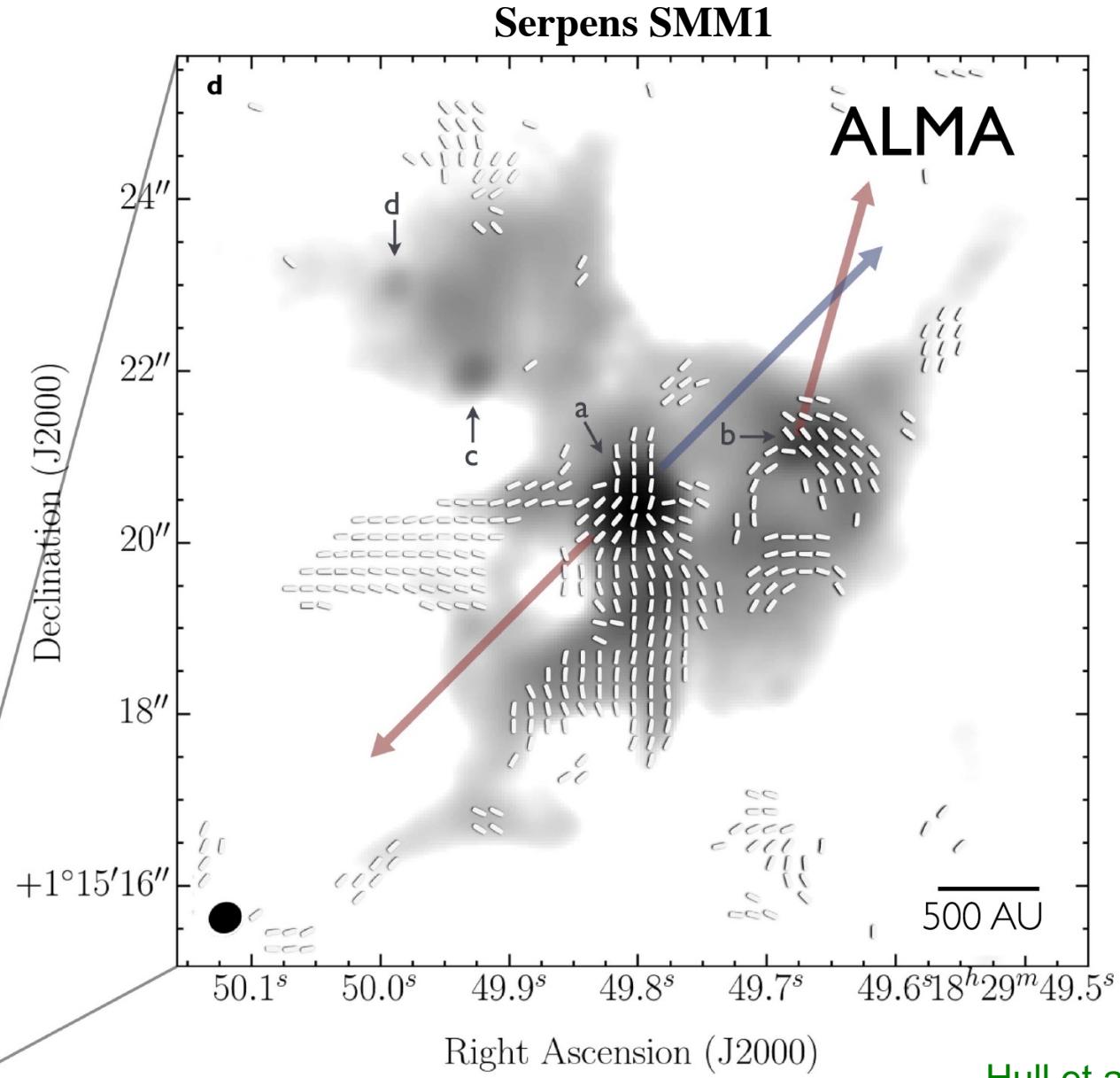
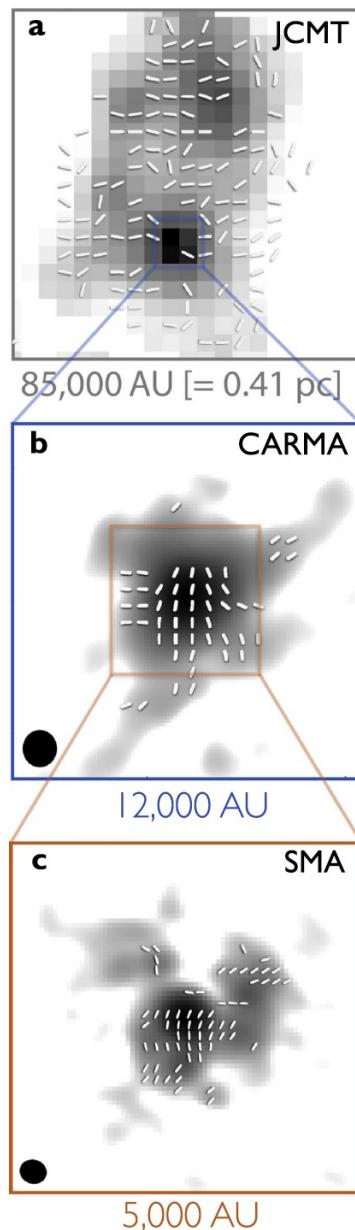
$$\times 0.40$$

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

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

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

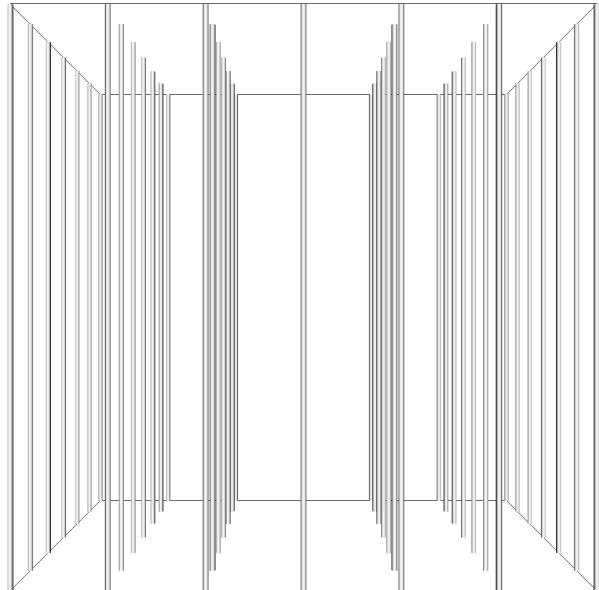
The role of magnetic field structure



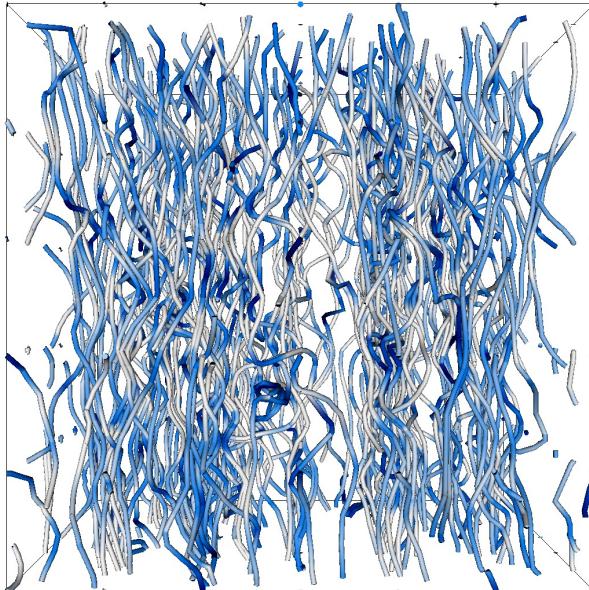
Hull et al. (2017)

The role of magnetic field structure

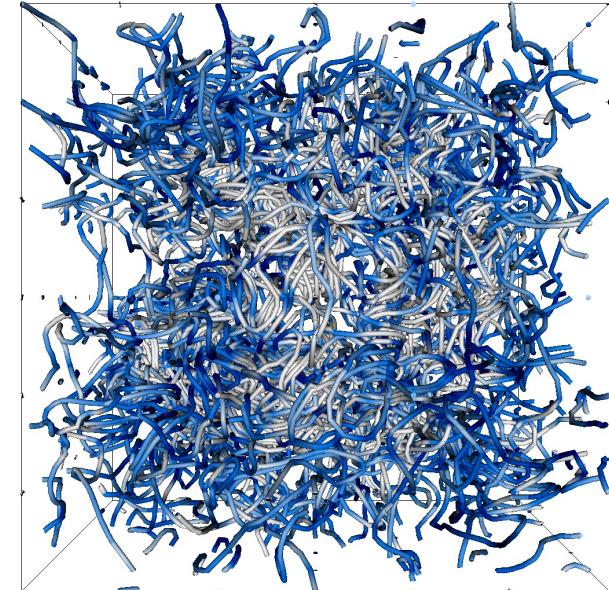
Uniform Magnetic Field



Partially Turbulent Field



Fully Turbulent Field

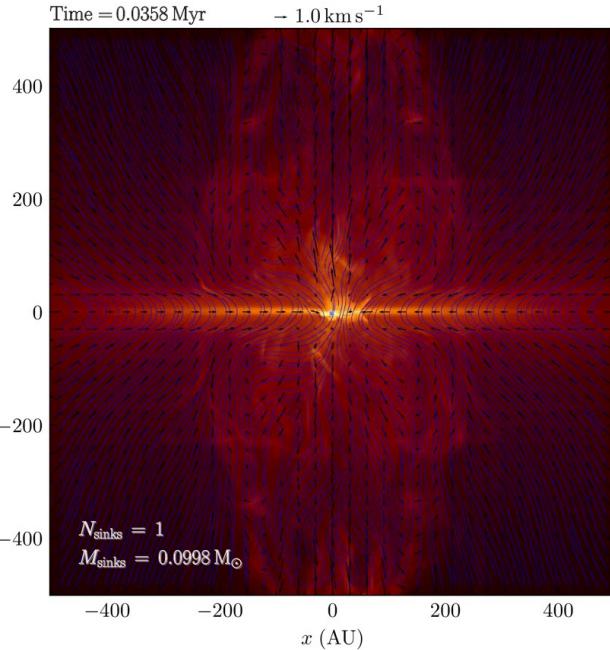


Gerrard et al. (2019)

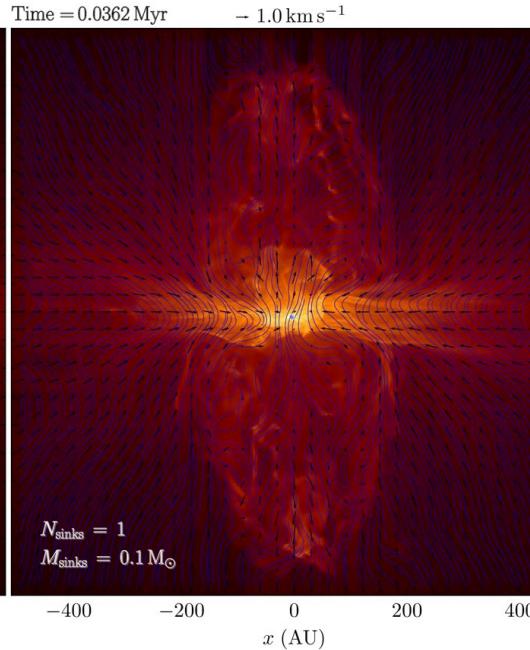
The role of magnetic field structure for jet launching

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

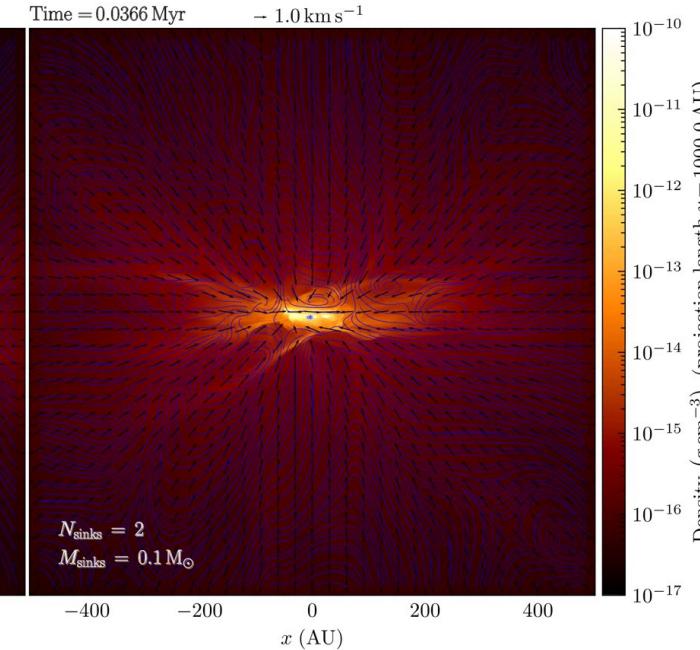
Uniform Magnetic Field



Partially Turbulent Field



Fully Turbulent Field



Density (g cm^{-3}) (projection length $y = 1000.0 \text{ AU}$)

10^{-10}
 10^{-11}
 10^{-12}
 10^{-13}
 10^{-14}
 10^{-15}
 10^{-16}
 10^{-17}

Gerrard et al. (2019)

→ Need ordered magnetic field component for jet launching

(Blandford & Payne 1982)

Turbulence → Density PDF

Density PDF → Star Formation Rate

Why is star formation so inefficient?