

Astrophysical Gas Dynamics

TODAY:

- *Magnetohydrodynamics (→ recap)*
- *Turbulence*
- *MHD dynamos*

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Magnetohydrodynamics (MHD)

Most gases in the Universe are electrically conductive.

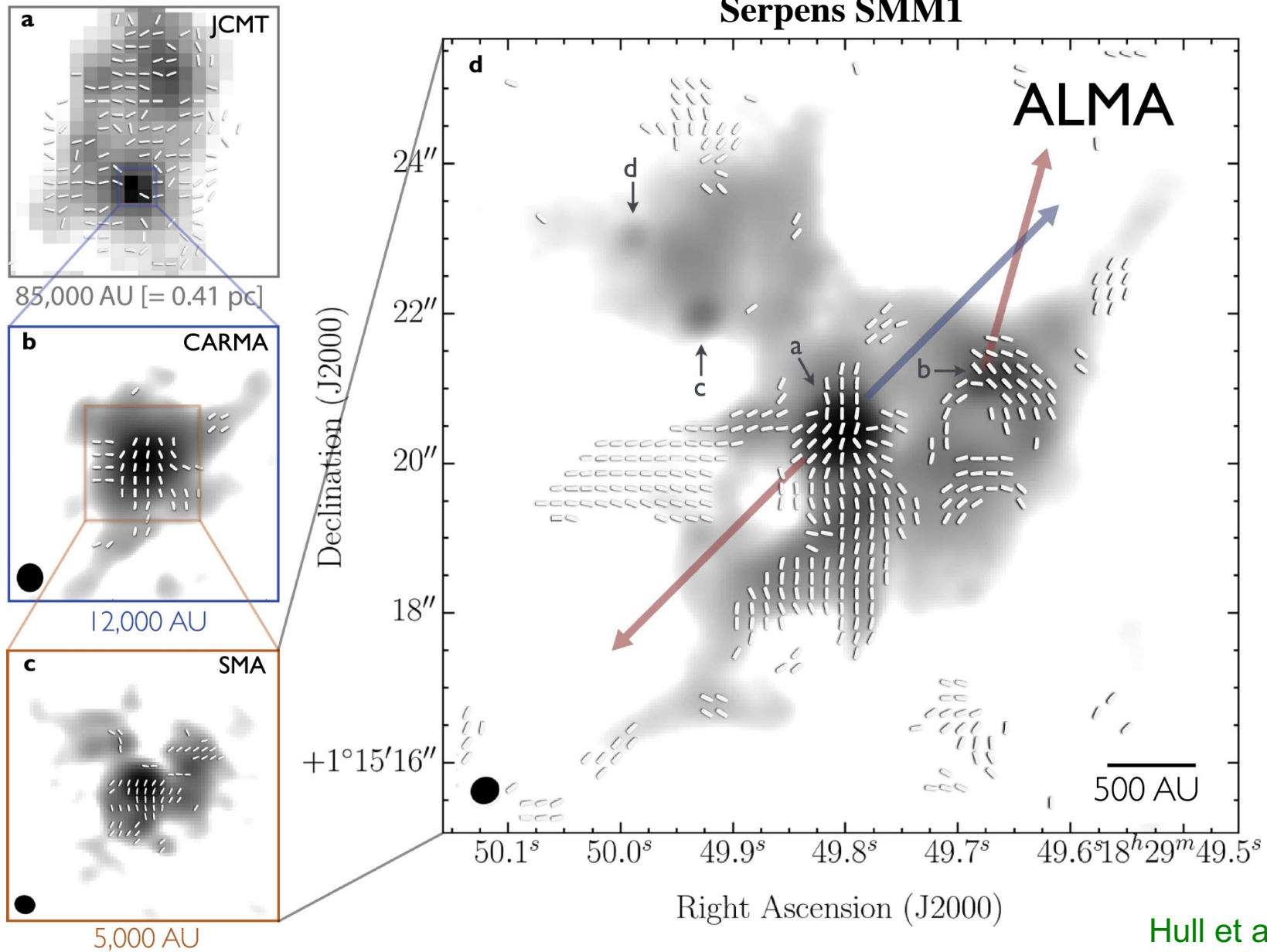
For example:

- 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.

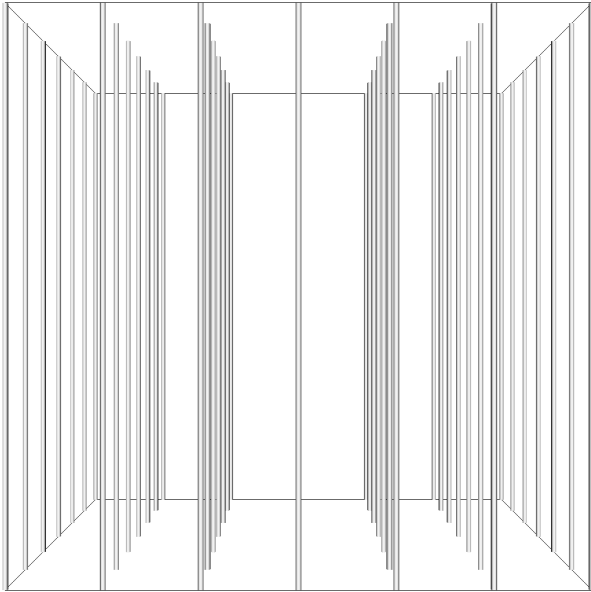
This theory is called MAGNETOHYDRODYNAMICS (MHD).

The role of magnetic field structure

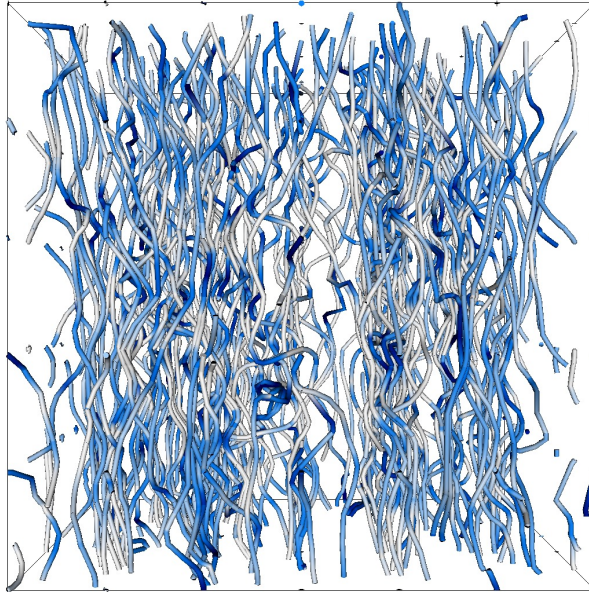


The role of magnetic field structure

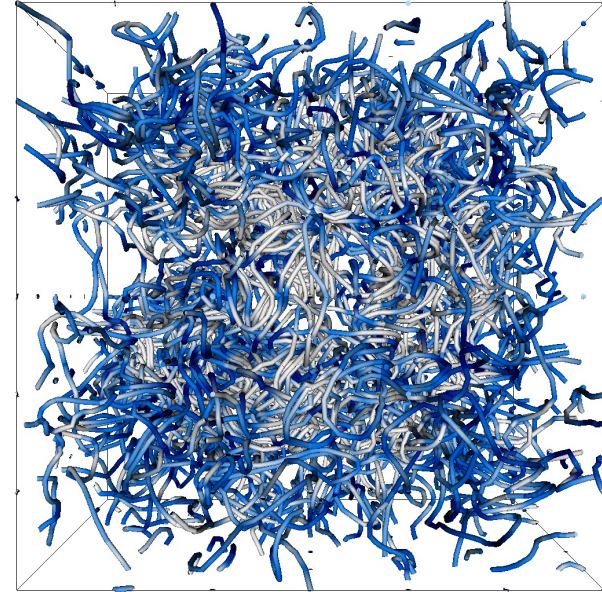
Uniform Magnetic Field



Partially Turbulent Field



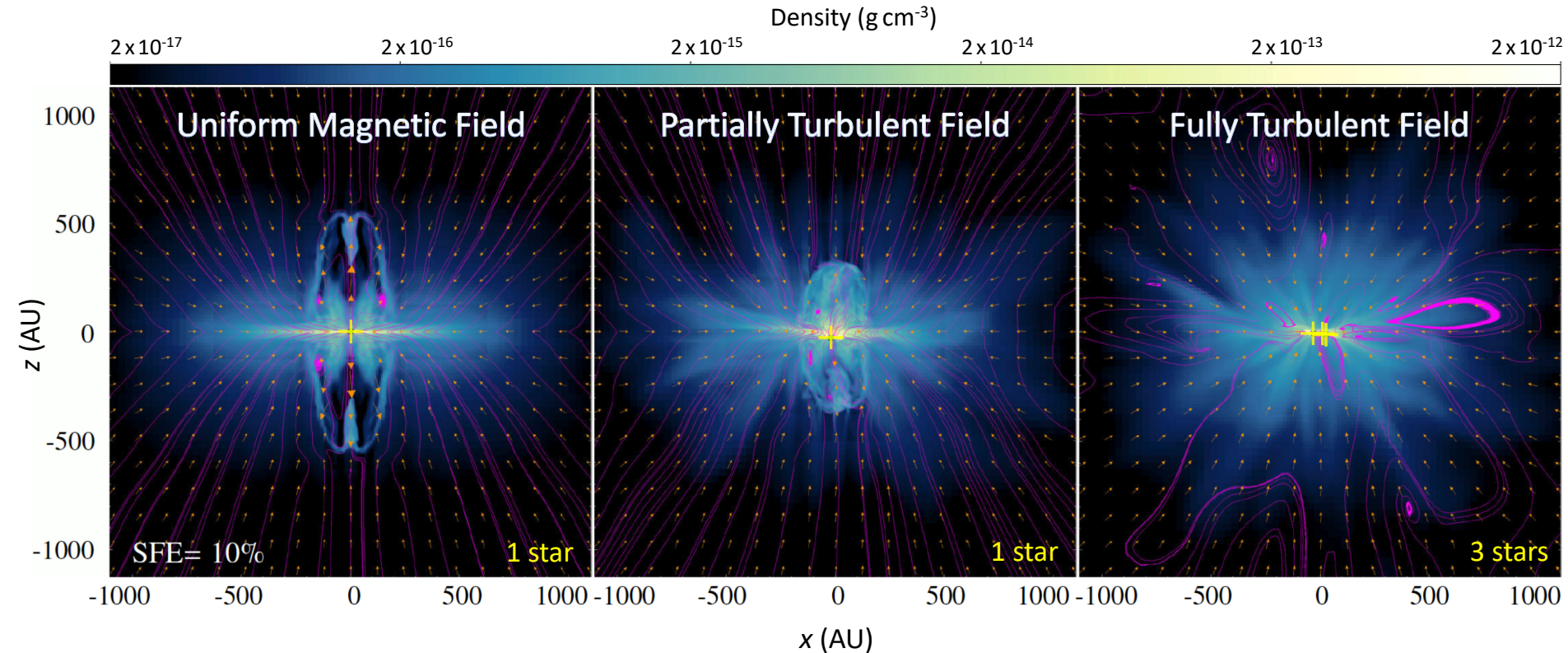
Fully Turbulent Field



Gerrard et al. (2019)

The role of magnetic field structure

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



Gerrard et al. (2019)

See also Hodapp & Chini (2018) on dual jet/outflow components launched in Serpens South

→ Need ordered magnetic field component for jet launching (Blandford & Payne 1982)

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Turbulence is key for Star Formation

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

Turbulence → **Stars** → **Feedback**

Magnetic Fields

**Dynamics
(shear)**

Turbulence driven by

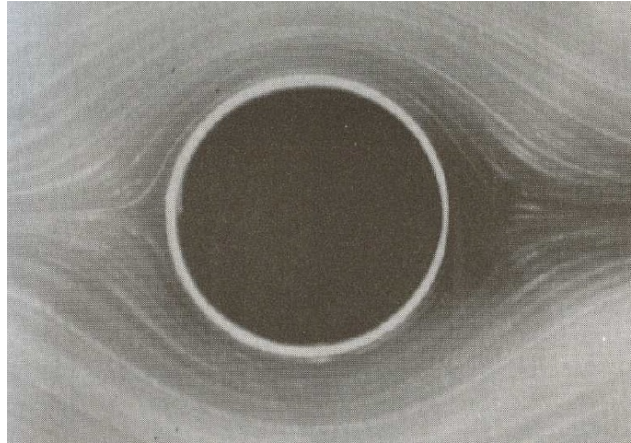
- Shear
- Jets / Outflows
- Cloud-cloud collisions
- Winds / Ionization fronts
- Spiral-arm compression
- Supernova explosions
- Gravity / Accretion

Solenoidal

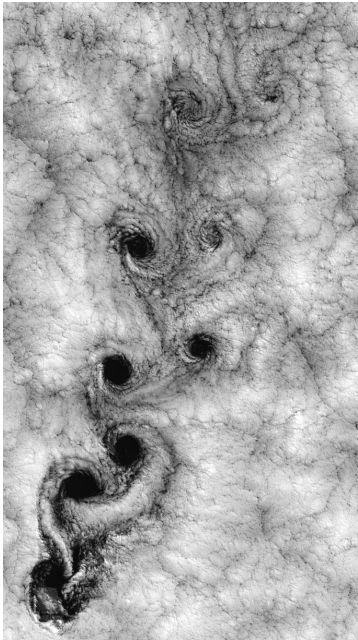
Compressive

Turbulence

- Reynolds number ($Re = LV/\nu$)



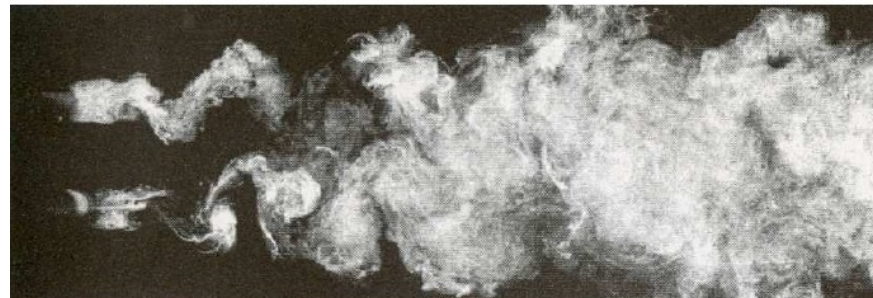
Laminar flow around cylinder ($Re \sim 0.1$)



Kármán vortex street caused by wind flowing around the [Juan Fernández Islands](#) off the Chilean coast (wikipedia)



Karman vortex street ($Re \sim 240$)



Turbulence ($Re \sim 1800$)

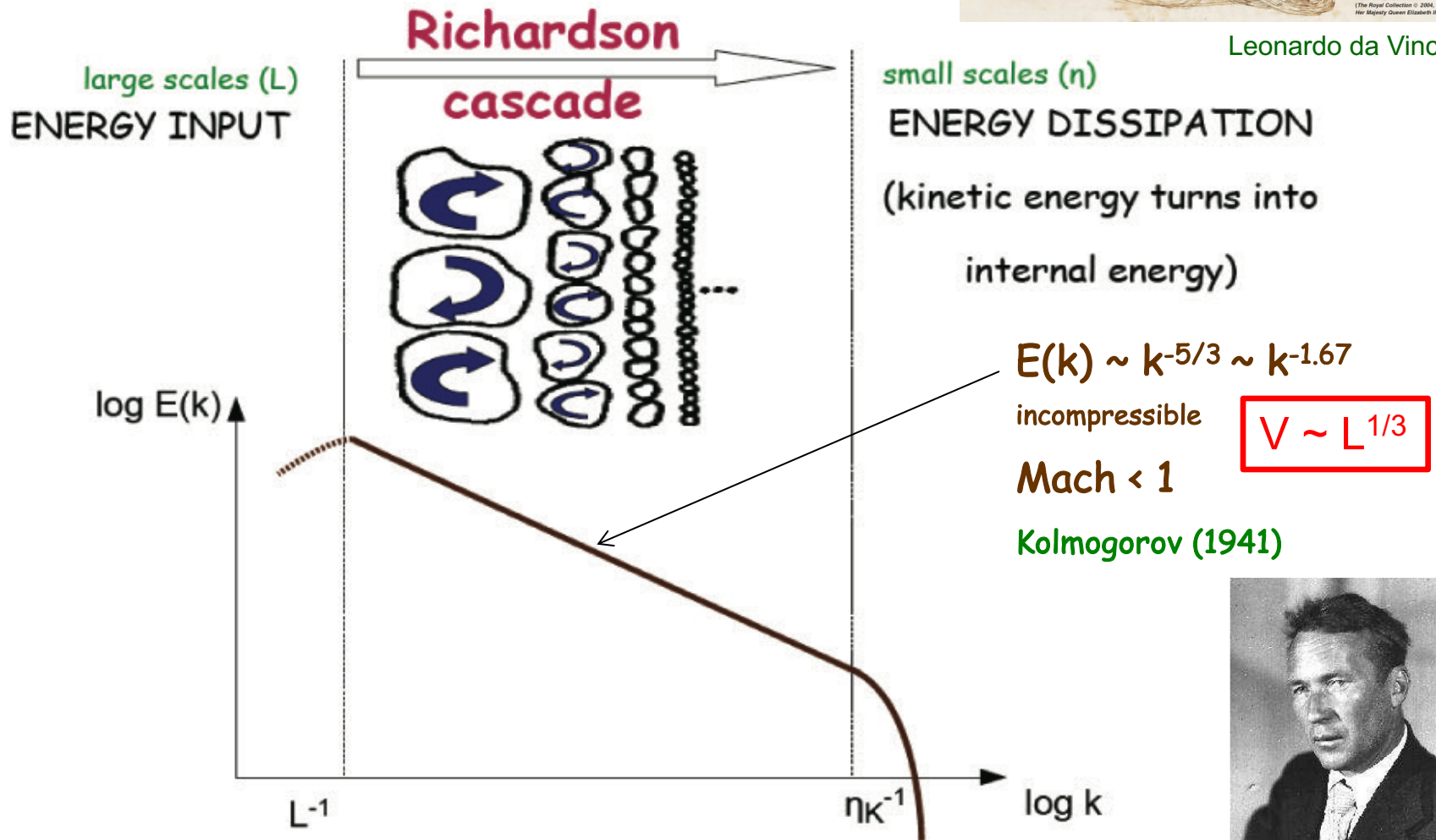
Frisch (1995)

Turbulence

- Reynolds numbers > 1000
- Kinetic energy cascade



Leonardo da Vinci

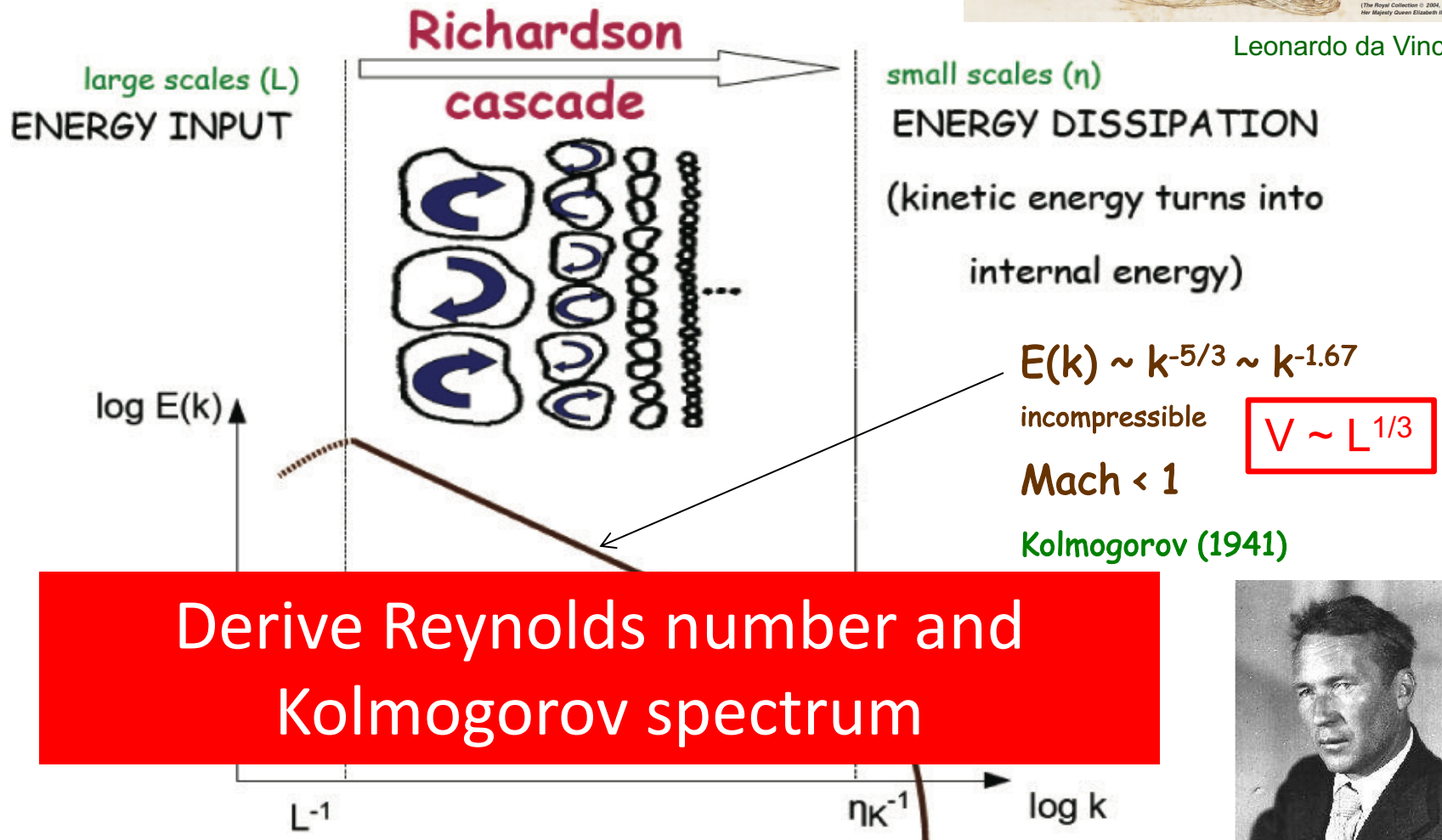


Turbulence

- Reynolds numbers > 1000
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Leonardo da Vinci

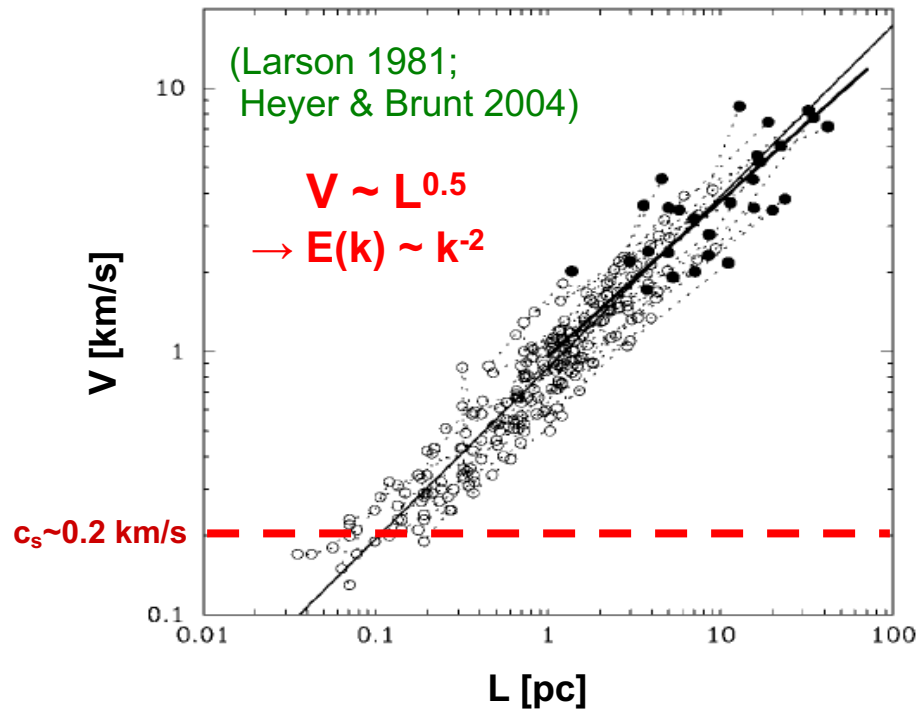


Interstellar Turbulence – scaling

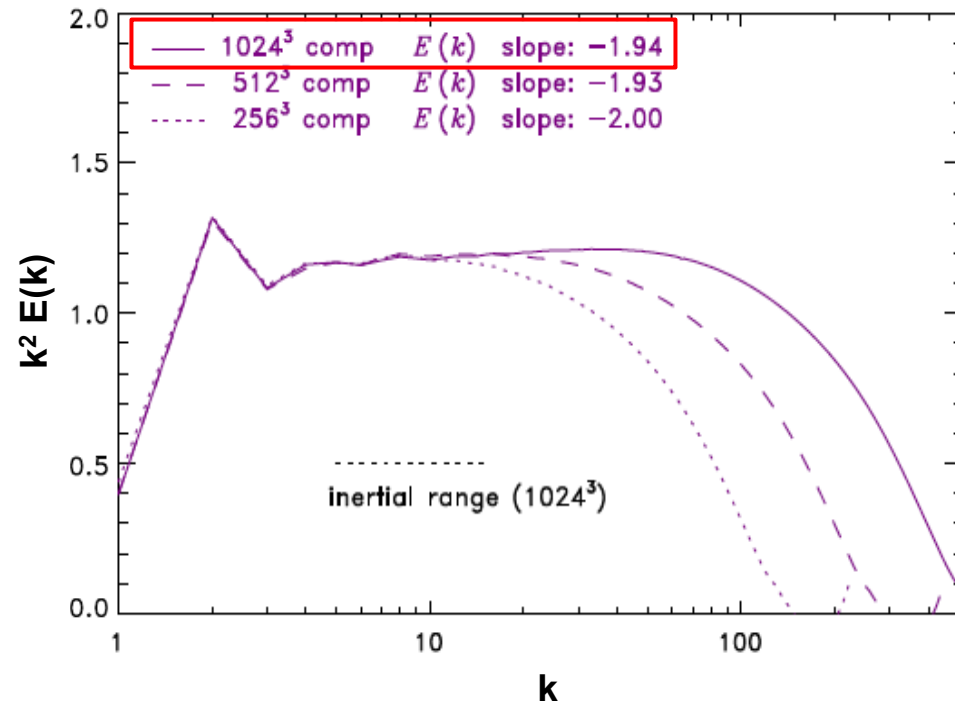
BUT: Larson (1981) relation: $E(k) \sim k^{-1.8-2.0}$

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

Observation



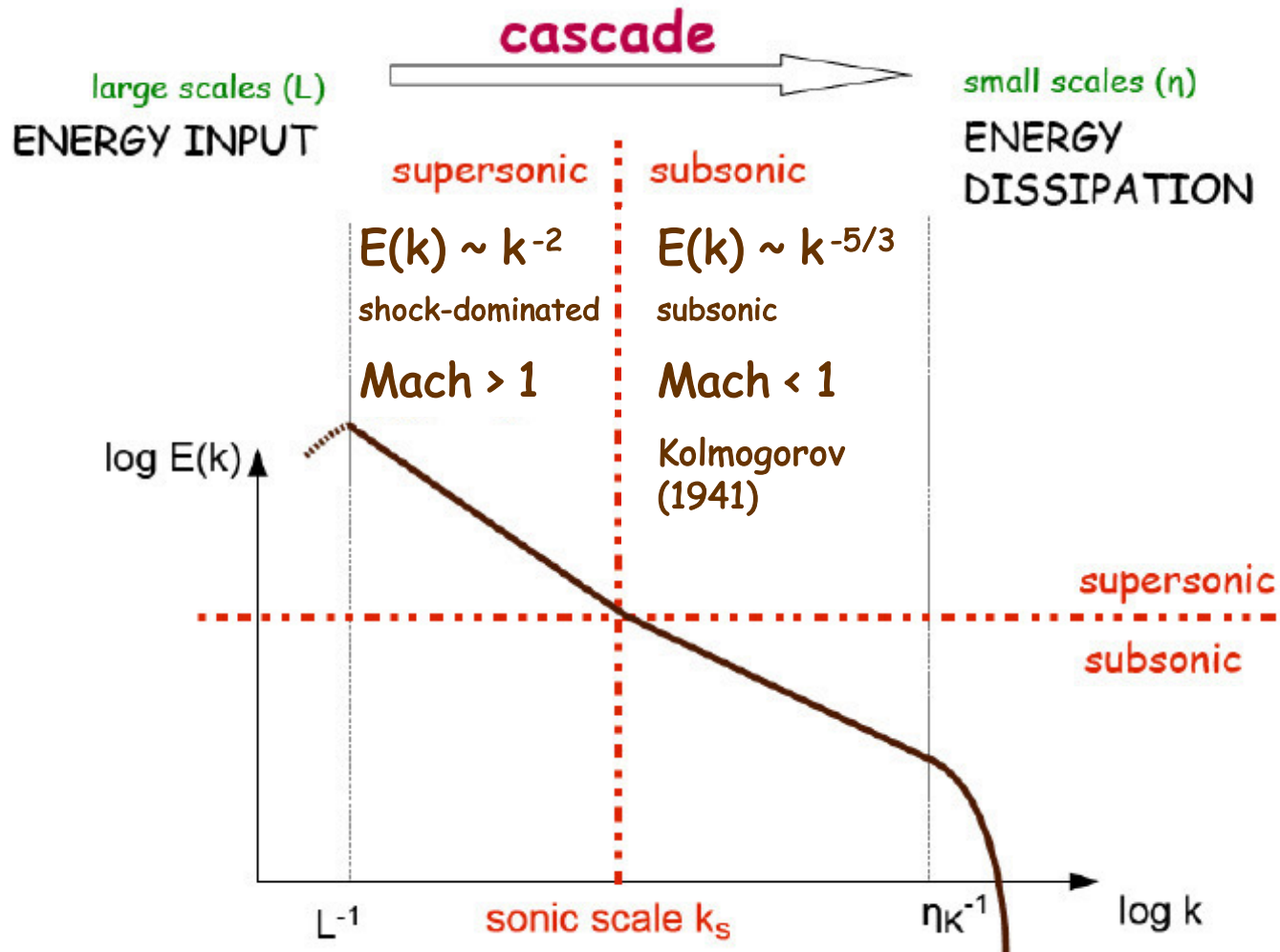
Simulation



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

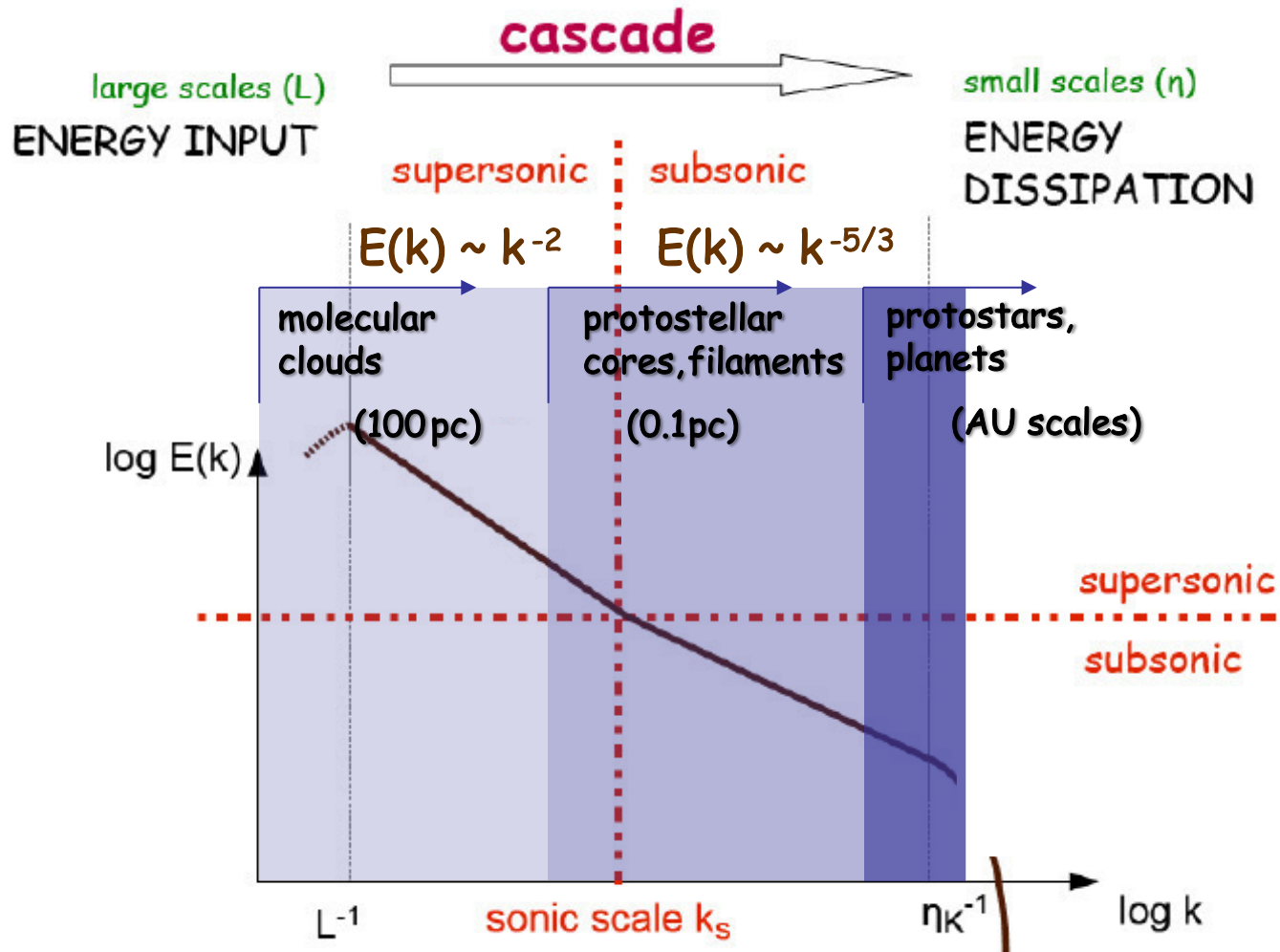
Interstellar Turbulence

- Reynolds numbers > 1000
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Interstellar Turbulence

- Reynolds numbers > 1000
- Kinetic energy cascade

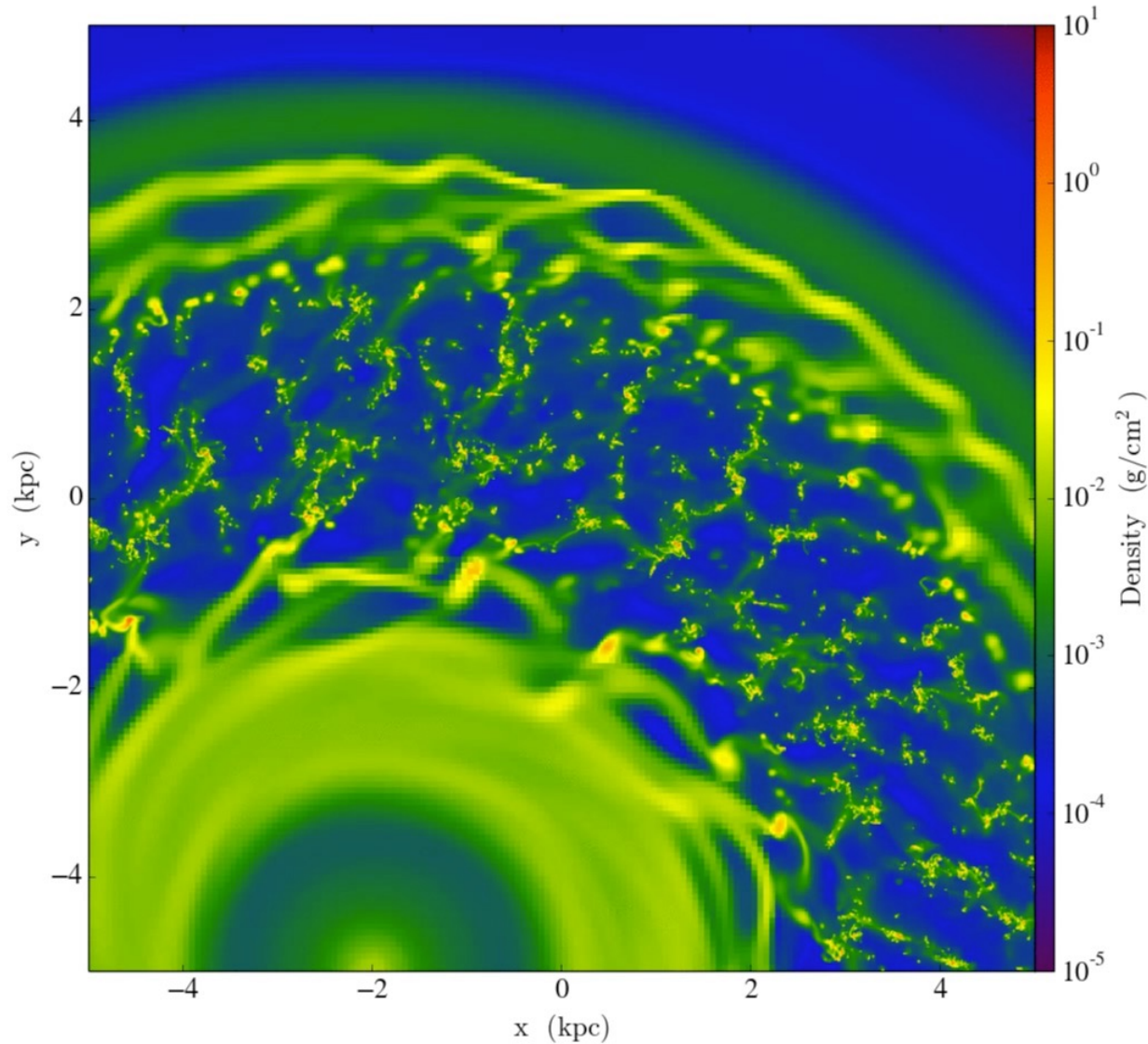




Turbulence in galaxies

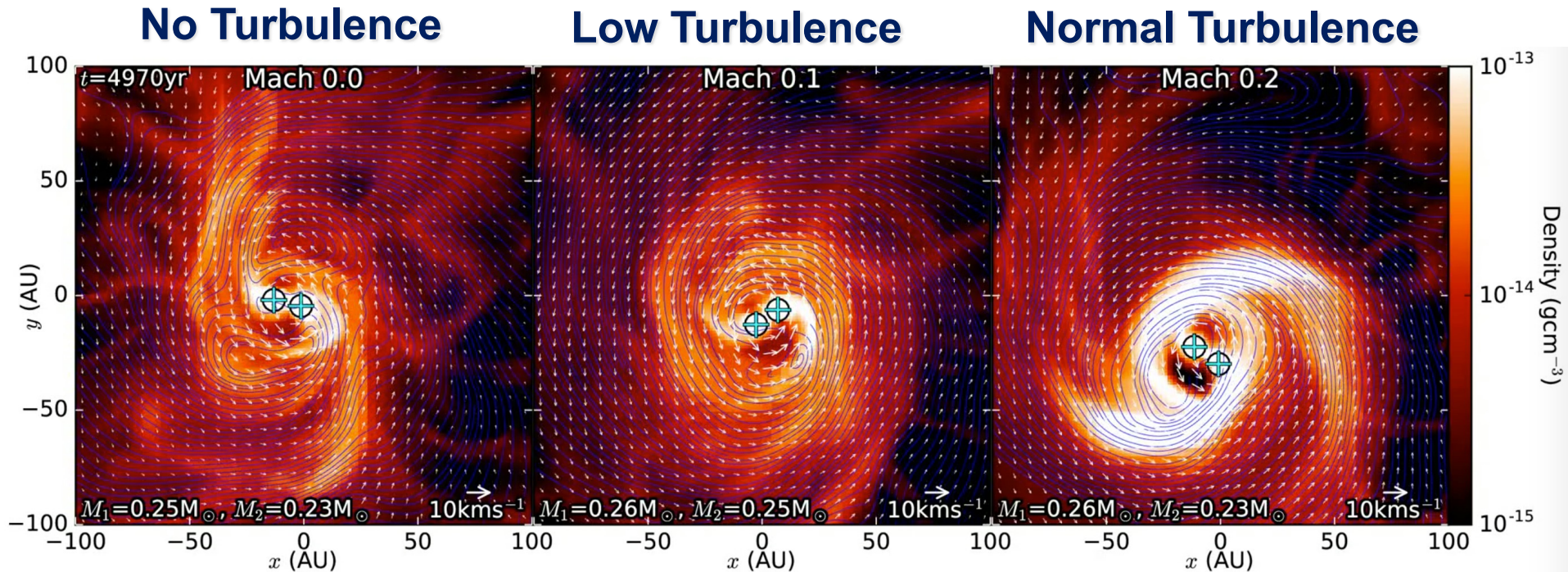
Movies available: https://www.mso.anu.edu.au/~chfeder/pubs/turb_driv_gal/turb_driv_gal.html

Simulations of a disc galaxy:



(Jin et al. 2017)

Build-up of circum-binary disks



Movies available: http://www.mso.anu.edu.au/~chfeder/pubs/binary_discs/binary_discs_xy.mp4

Turbulence makes bigger discs → relevant for planet formation

Magnetic field structure is key for outflow/jet launching

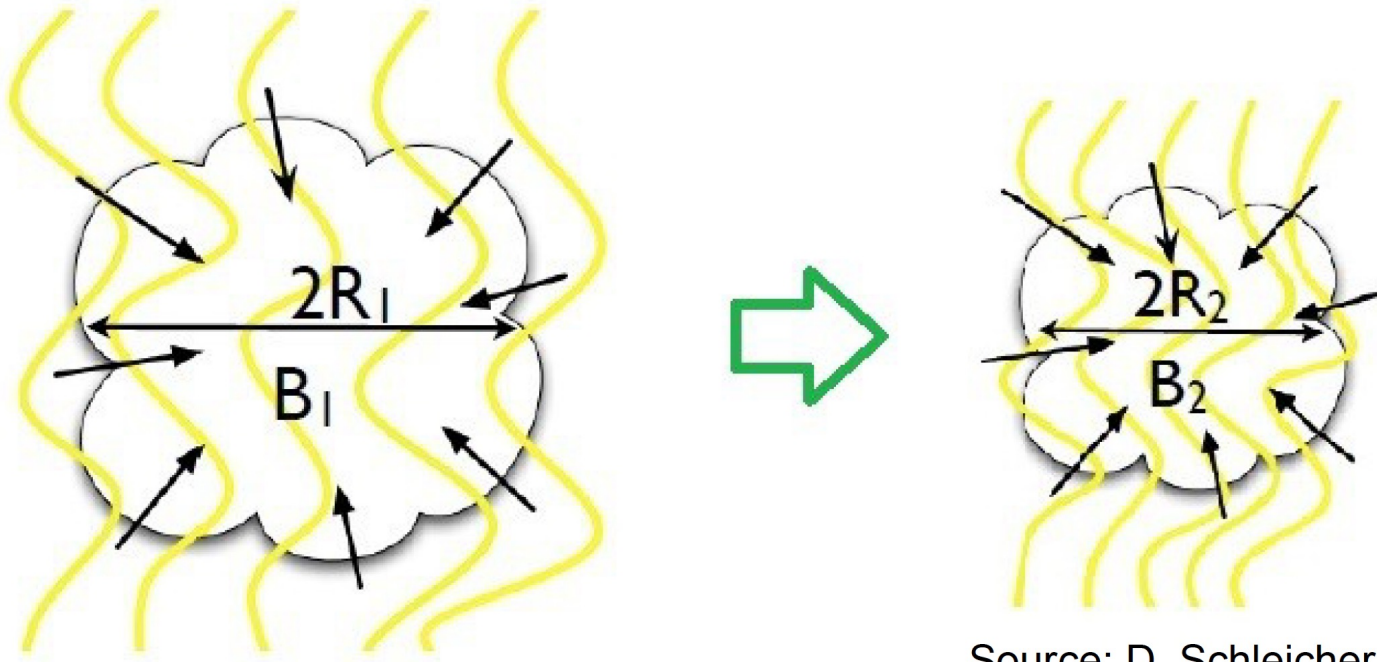
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Turbulent dynamo in compressible gases

Compression of field lines during collapse (flux-freezing):



Source: D. Schleicher 2010

conservation of magnetic flux:

$$R_1^2 \cdot B_1 = R_2^2 \cdot B_2$$

$$\longrightarrow B \propto \rho^{2/3}$$

Dynamo:

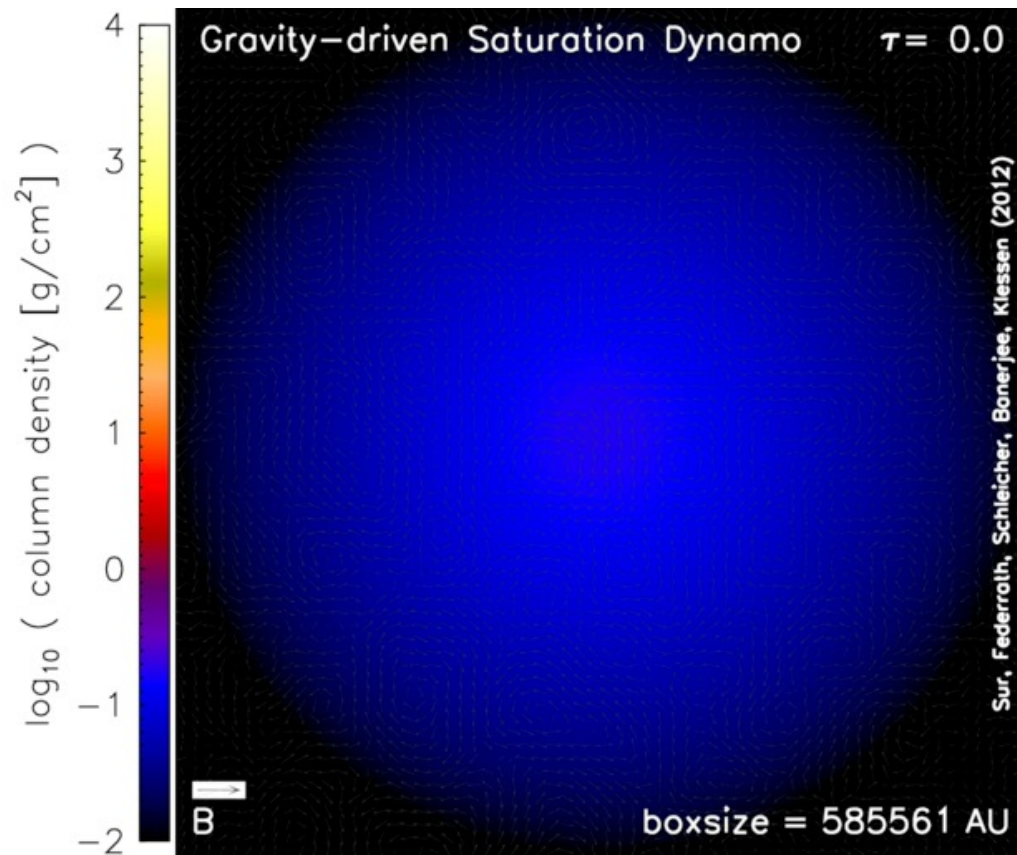
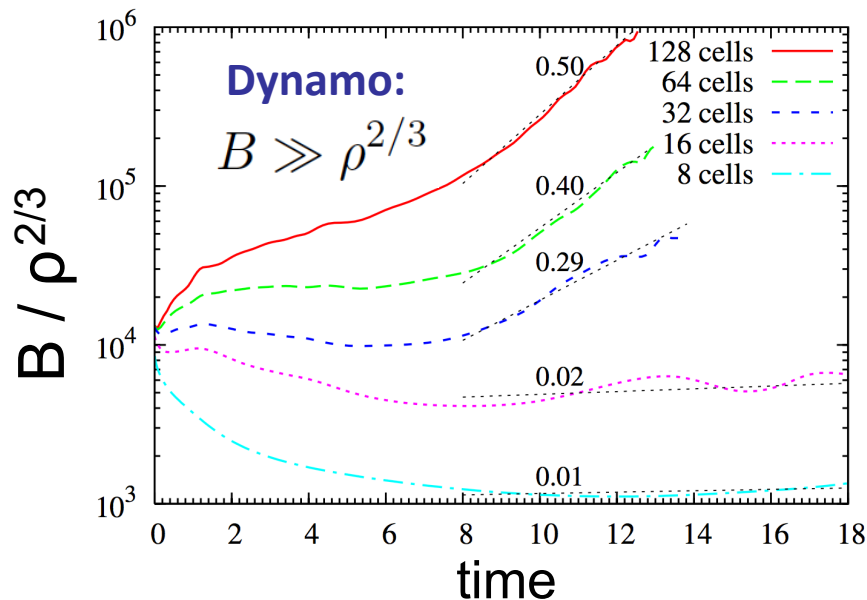
$$B \gg \rho^{2/3}$$

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

Can dynamo work in a collapsing cloud?

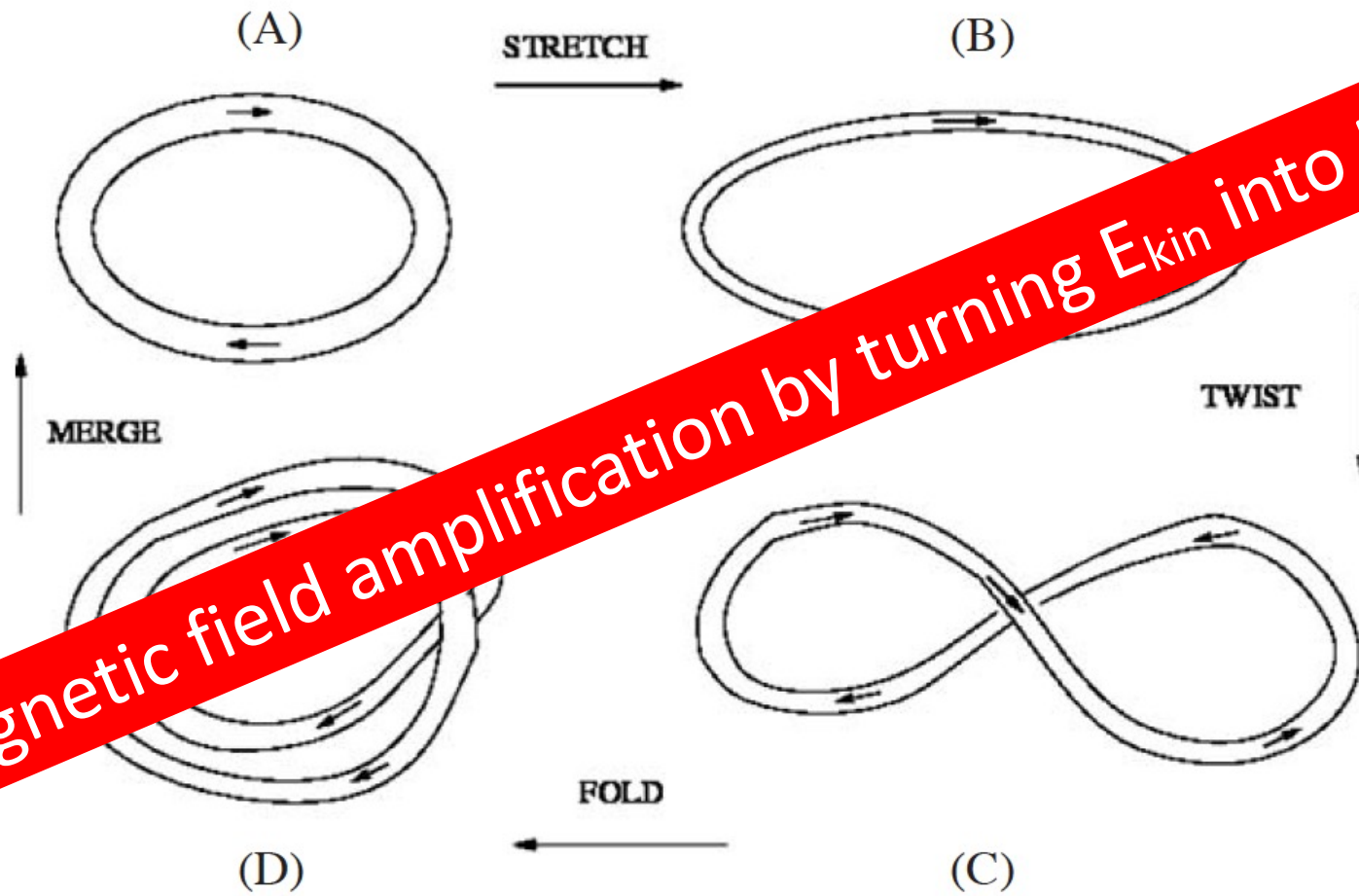
Magnetohydrodynamic simulations by
Sur et al. (2010, 2012); Federrath et al. (2011):

- Gravitationally unstable Bonnor-Ebert sphere
- Initial large-scale turbulence
- Weak initial $B = 1$ nano Gauss
- Adaptive Mesh Refinement (AMR)



Turbulent dynamo in compressible gases

Stretch-Twist-Fold Dynamo („turbulent dynamo“):



Magnetic field amplification by turning E_{kin} into E_B

Turbulent dynamo in compressible gases

Induction equation:
$$\frac{\partial \mathbf{B}}{\partial t} = \underbrace{\nabla \times (\mathbf{v} \times \mathbf{B})}_{\text{non-linear}} + \underbrace{\eta \nabla^2 \mathbf{B}}_{\text{diffusive}}$$

Exponential amplification of B :

Saturation

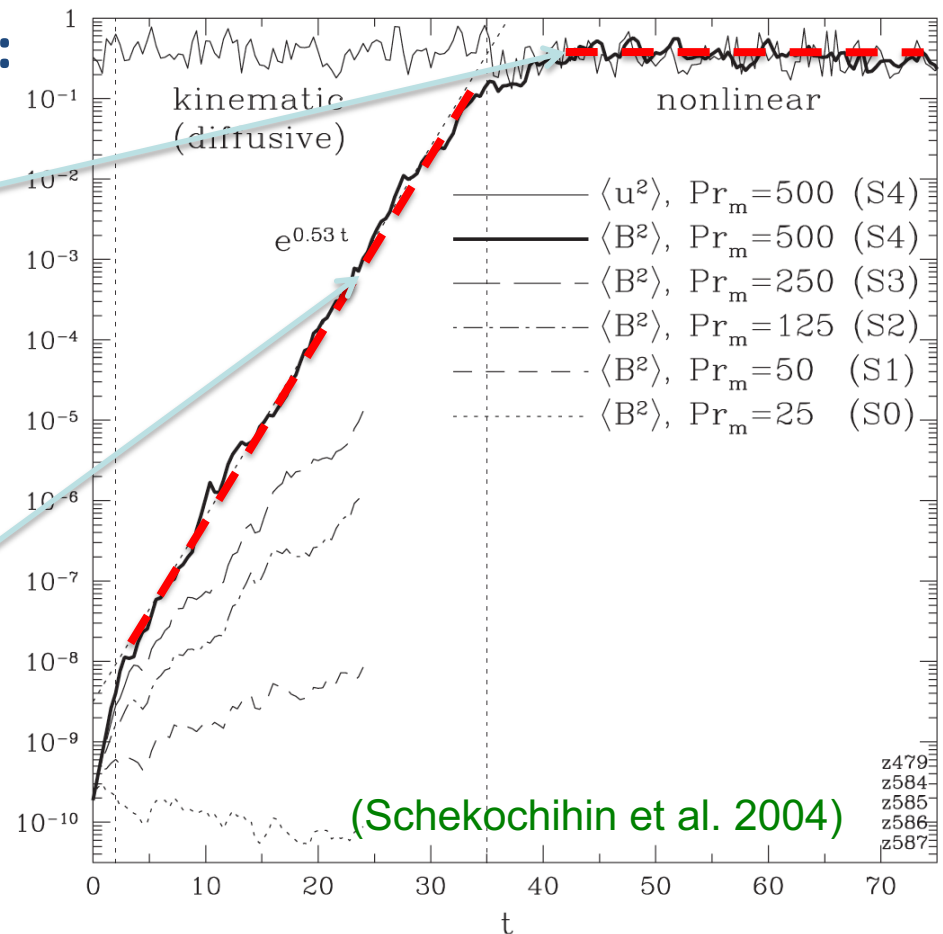
$$E_B \approx E_{\text{kin}}$$

(Schober et al. 2011)

Exponential growth with

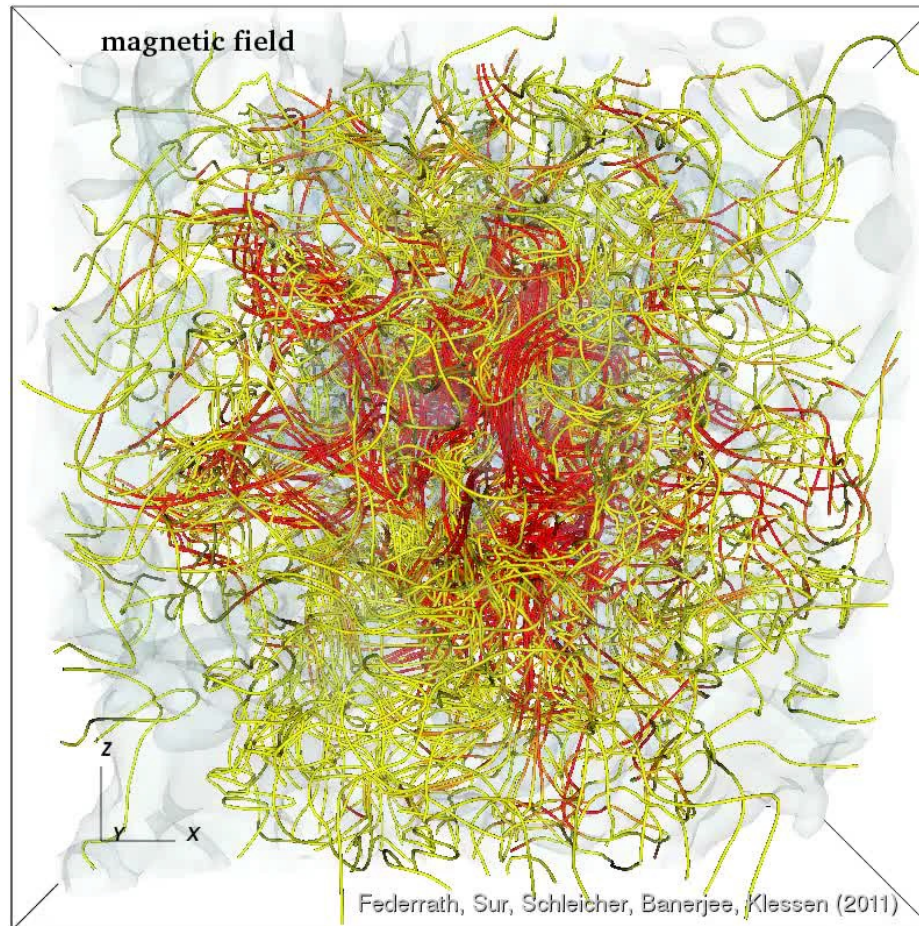
$$B \propto \exp \left(\sqrt{\text{Re}} \frac{t}{t_{\text{eddy}}} \right)$$

(see also Seta & Federrath 2020; Kriel et al. 2022; Achikanath Chirakkara et al. 2021; Beattie et al. 2022; for recent work on the dynamo)



Gravity-driven dynamo

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

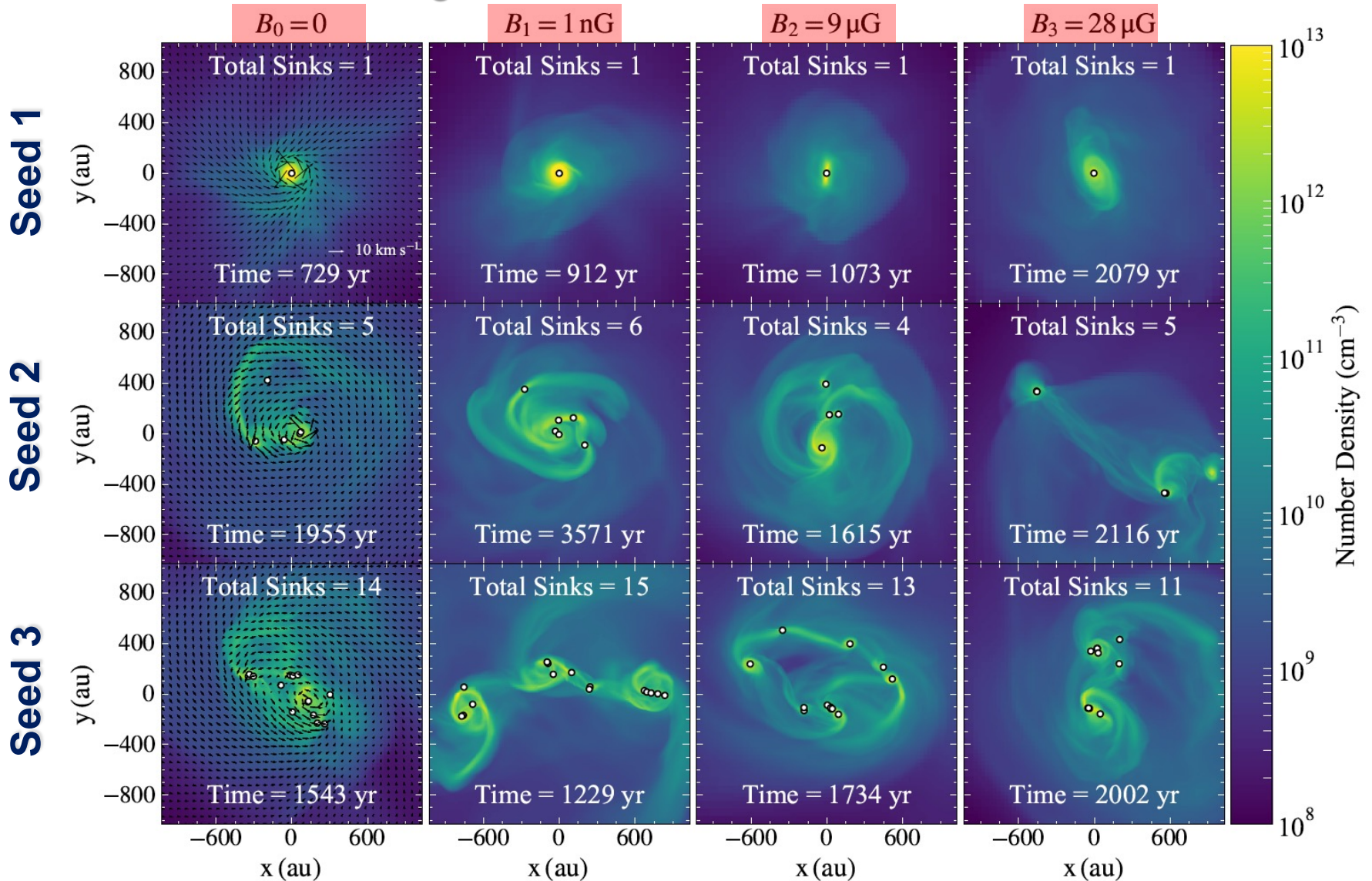


Main conclusion:

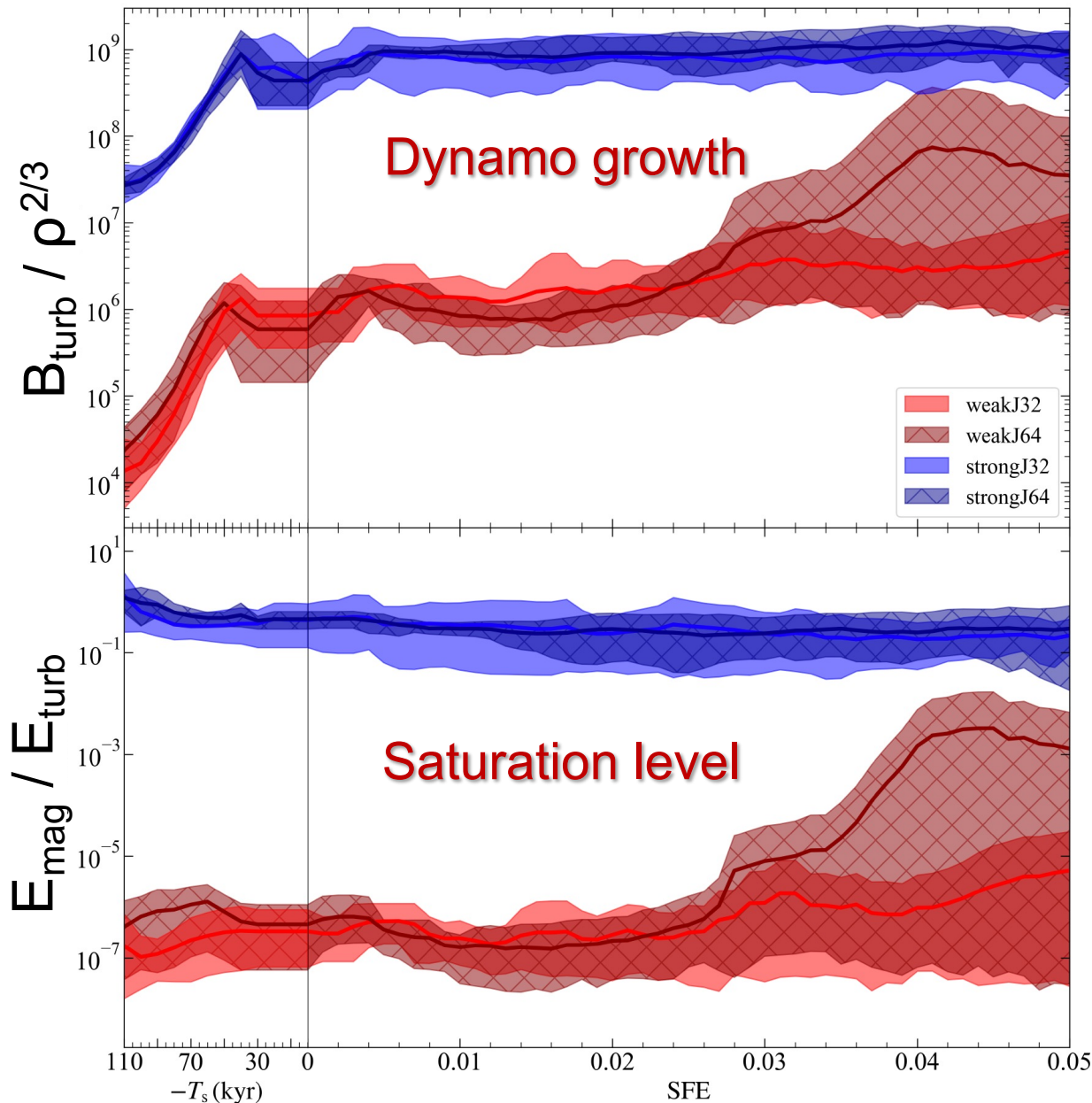
Dynamo works; Magnetic Field important even in Early Universe!

Primordial Star Formation (First Stars)

The role of magnetic fields for the formation of the First Stars



Dynamo – First Stars

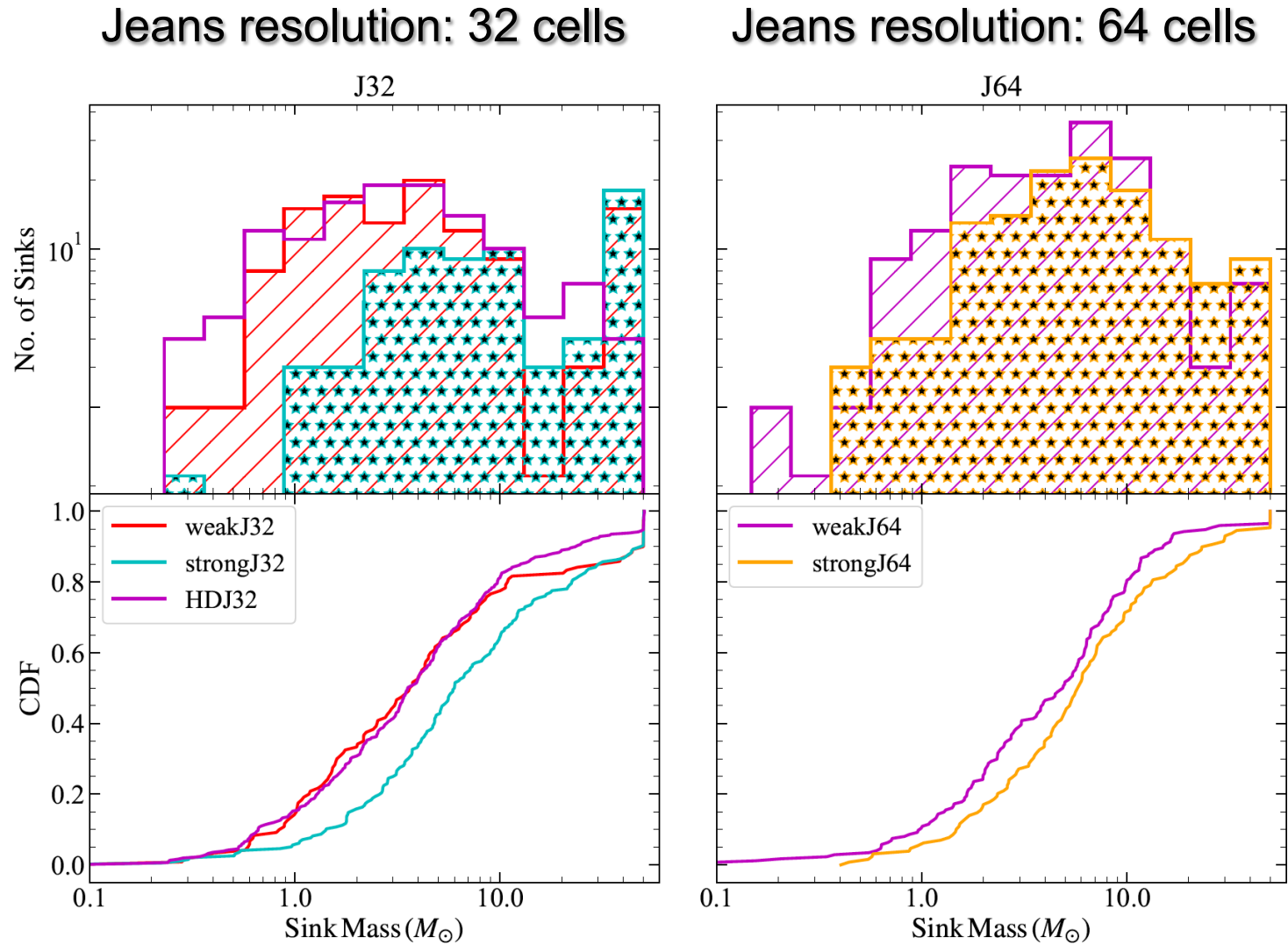


Sufficient
Jeans resolution



Dynamo growth
in primordial discs

Dynamo – First Stars

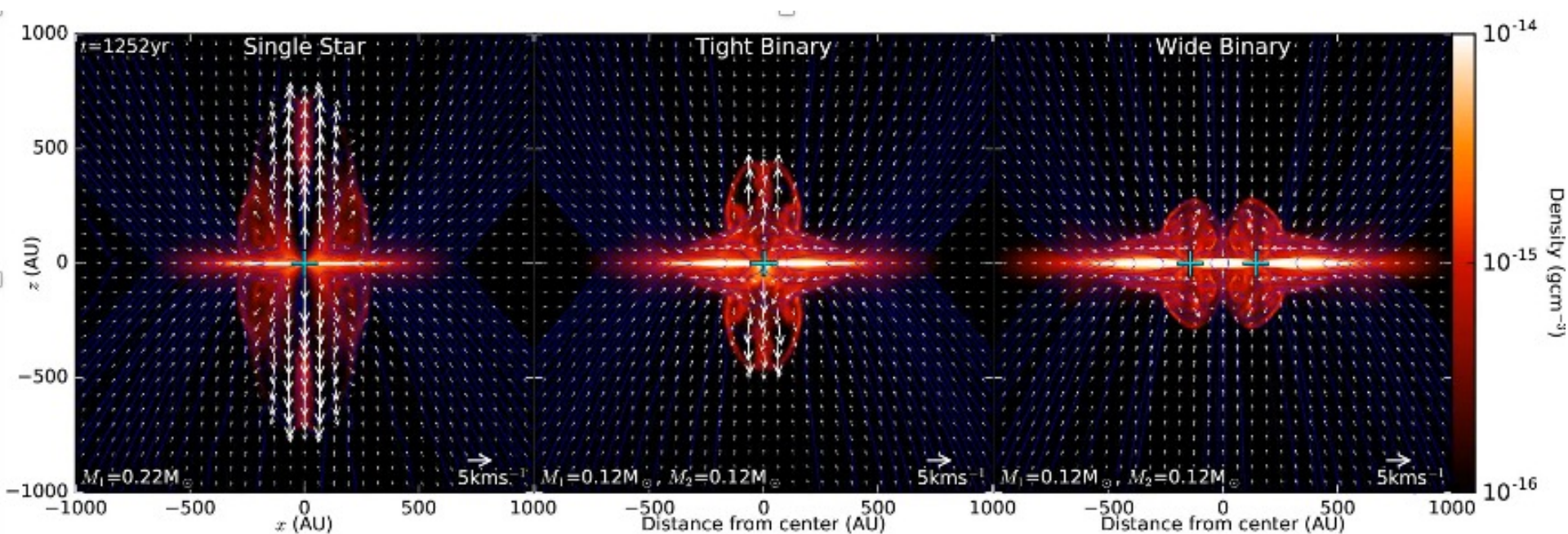


→ Even initially weak fields grow to influence the IMF of the First Stars

Jet Feedback in Star Formation

Magnetic Fields → Jet Feedback important even in Formation of First Stars?

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



For present-day star formation: Kuruwita et al. (2017)

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NEXT TIMES:

- *Guest Lectures*