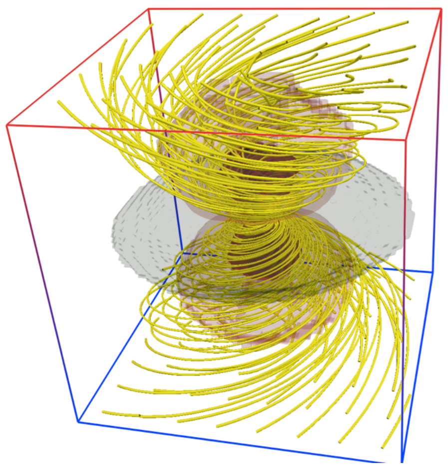
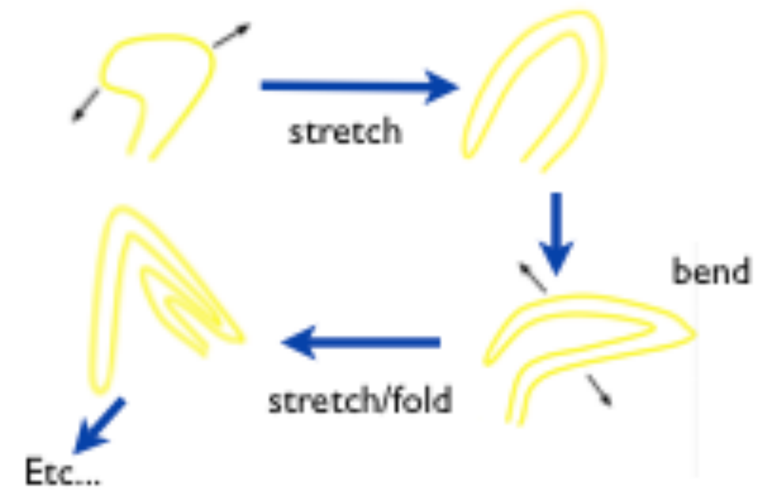
Star formation now and then: The role of magnetic fields



Dominik Schleicher

Institut für Astrophysik,
University of Göttingen

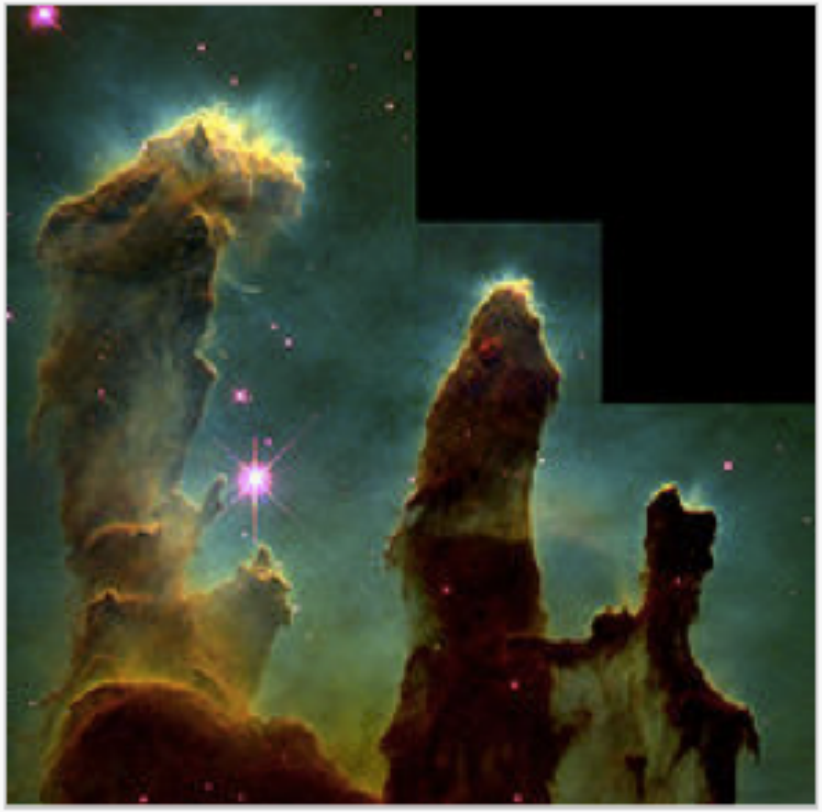


Collaborators:
T. Arshakian (Bonn), R. Banerjee (Heidelberg), R. Beck (Bonn), C. Federrath (Lyon), D. Galli (Florence), S. Glover (Heidelberg), R. Klessen (Heidelberg), M.A. Latif (Groningen), F. Palla (Florence), F. Miniati (Zürich), T. Peters (Heidelberg), R. Schneider (Florence), J. Schober (Heidelberg), S. Sur (Heidelberg)

Contents

- Star formation now:
  - The initial conditions.
  - Implications of magnetic fields for gravitational collapse.
  - Implications for fragmention and jets.
- Star formation then:
  - The initial conditions.
  - The amplifying of the magnetic field.
  - Implications and uncertainties.

Star formation Now:
The initial conditions



Hubble telescope image known as *Pillars of Creation*, where stars are forming in the Eagle Nebula.

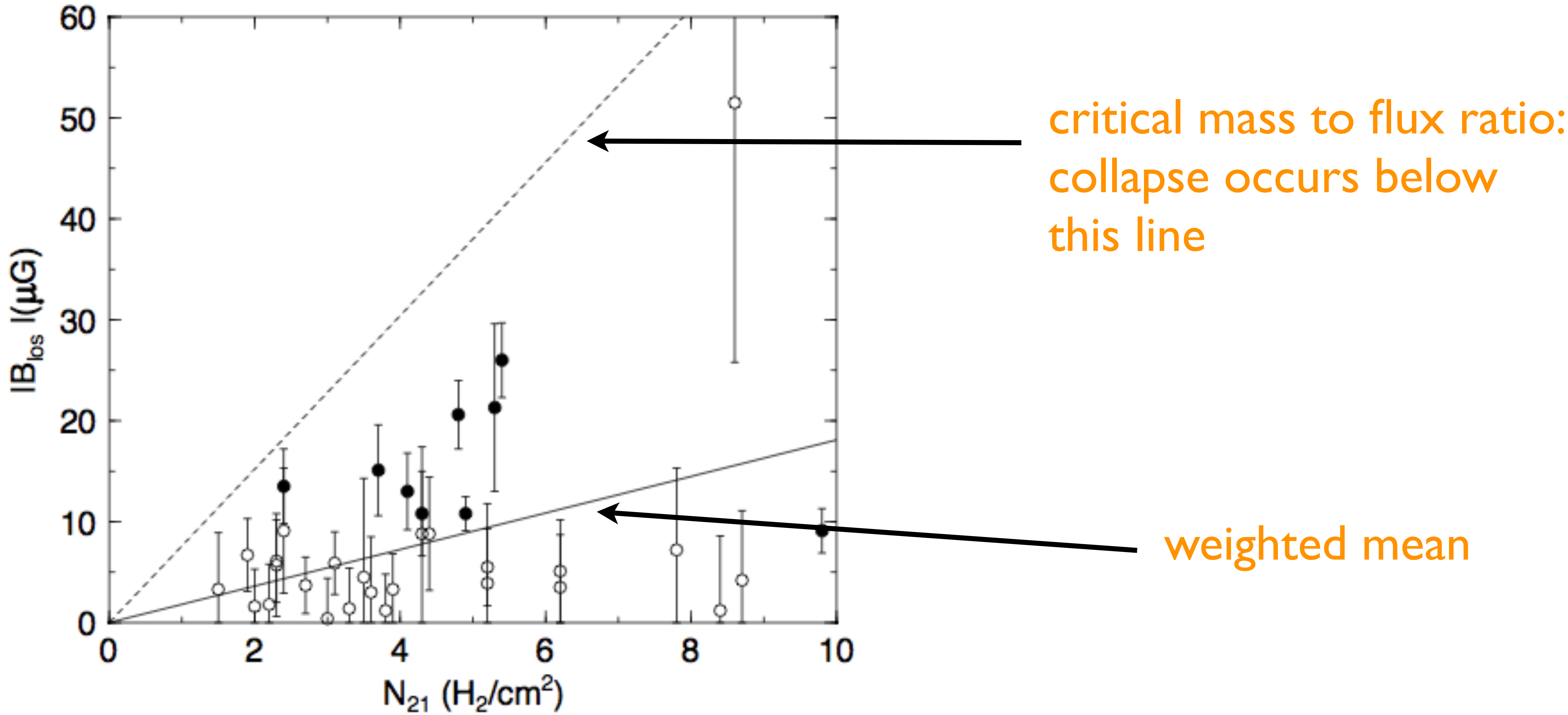
Stellar cluster and star-forming region M 17.

LH 95 stellar nursery in Large Magellanic Cloud.

Today:
Stars form in clouds of molecular gas.
Highly complex, turbulent initial conditions.
Initial conditions and ambient radiation field vary in different star forming regions.

Star formation Now:

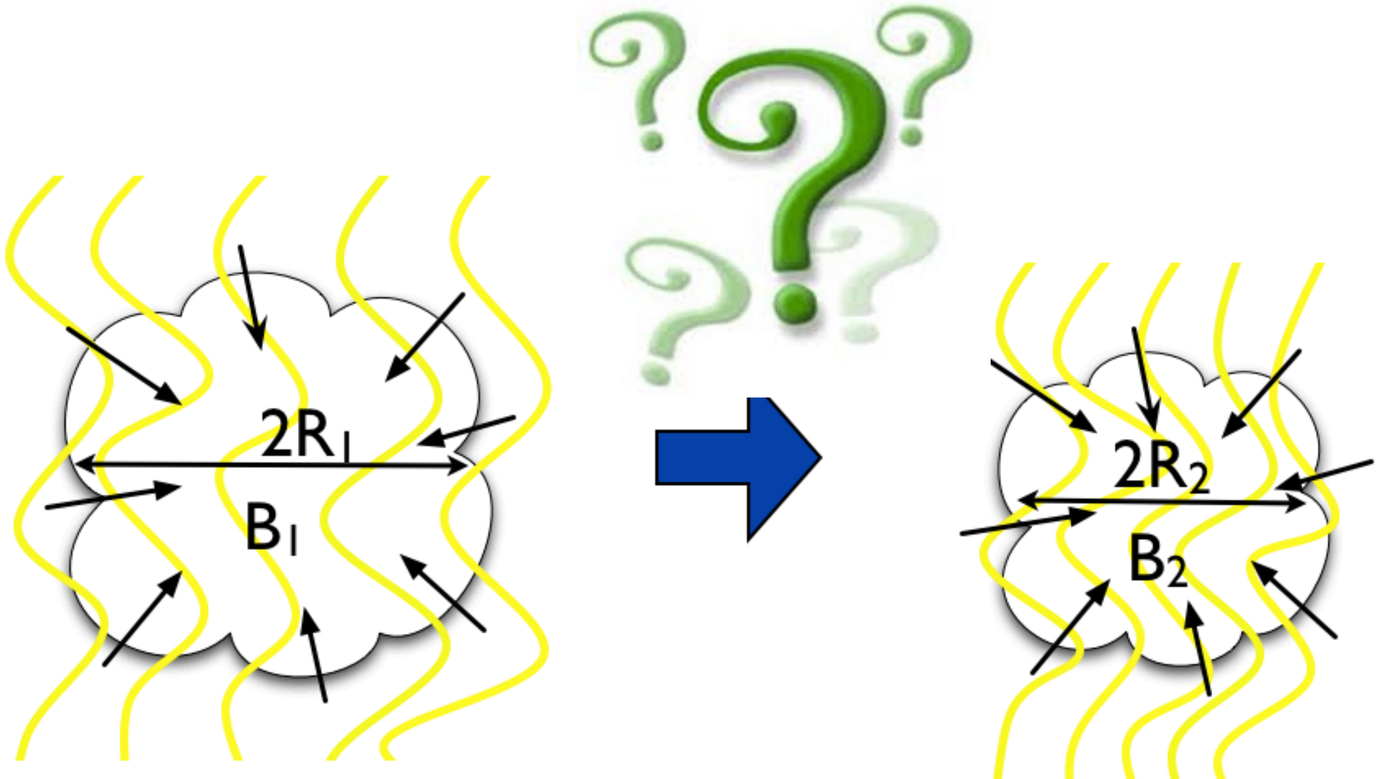
The initial conditions



Troland & Crutcher (2008):
OH Zeeman observations of 34 dark clouds (9 detections, 25 upper limits)

Star formation Now:

Can clouds collapse in the presence of magnetic fields?



Compression:
$B \sim R^2$
rho $\sim R^3$
=> $B \sim$ rho$^{2/3}$

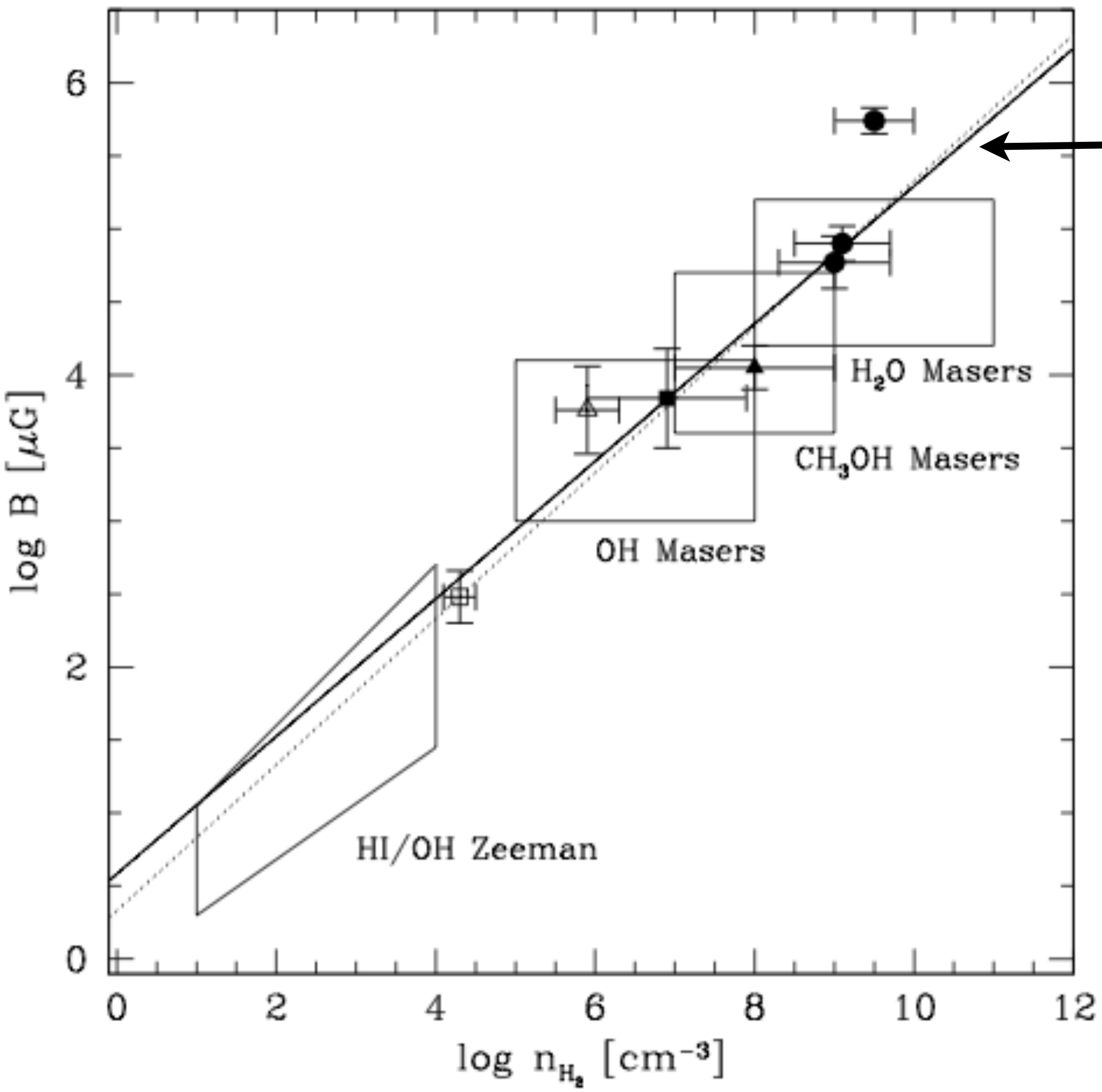
Nakano & Nakamura (1978):
Magnetic pressure may balance the gravitational pull.
Collapse occurs for supercritical clouds, following the condition:

$$\frac{M}{\pi R^2 B_0} > \left(\frac{12}{5}\pi^2 G\right)^{-1/2}$$

Analog: thermal Jeans mass
critical mass to overcome thermal pressure

Star formation Now:

Magnetic field evolution during collapse



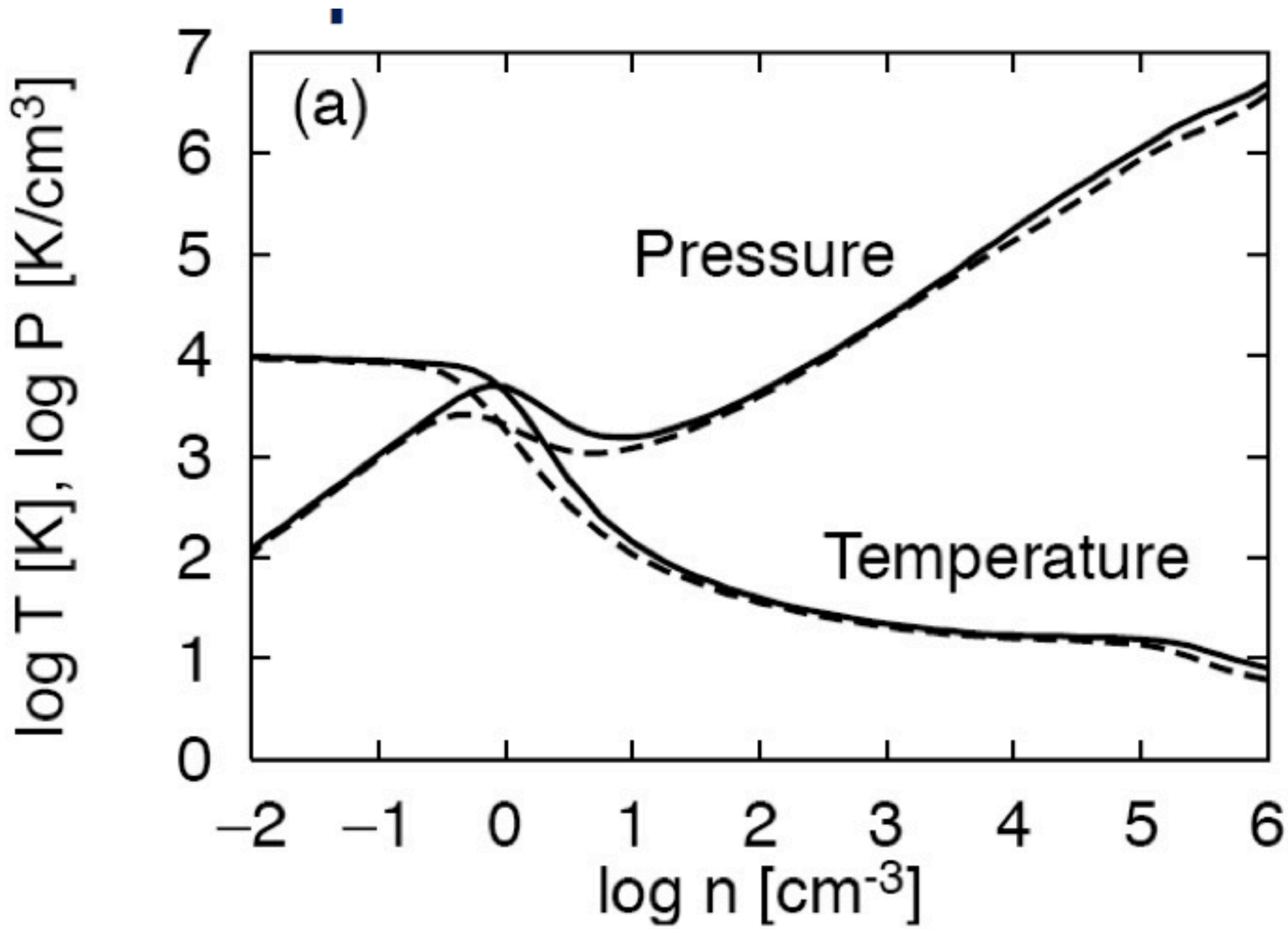
approximate scaling with square root of density

Magnetic field vs neutral gas density in Cepheus A: Zeeman splitting observations

Vlemmings (2008)

Star formation Now:

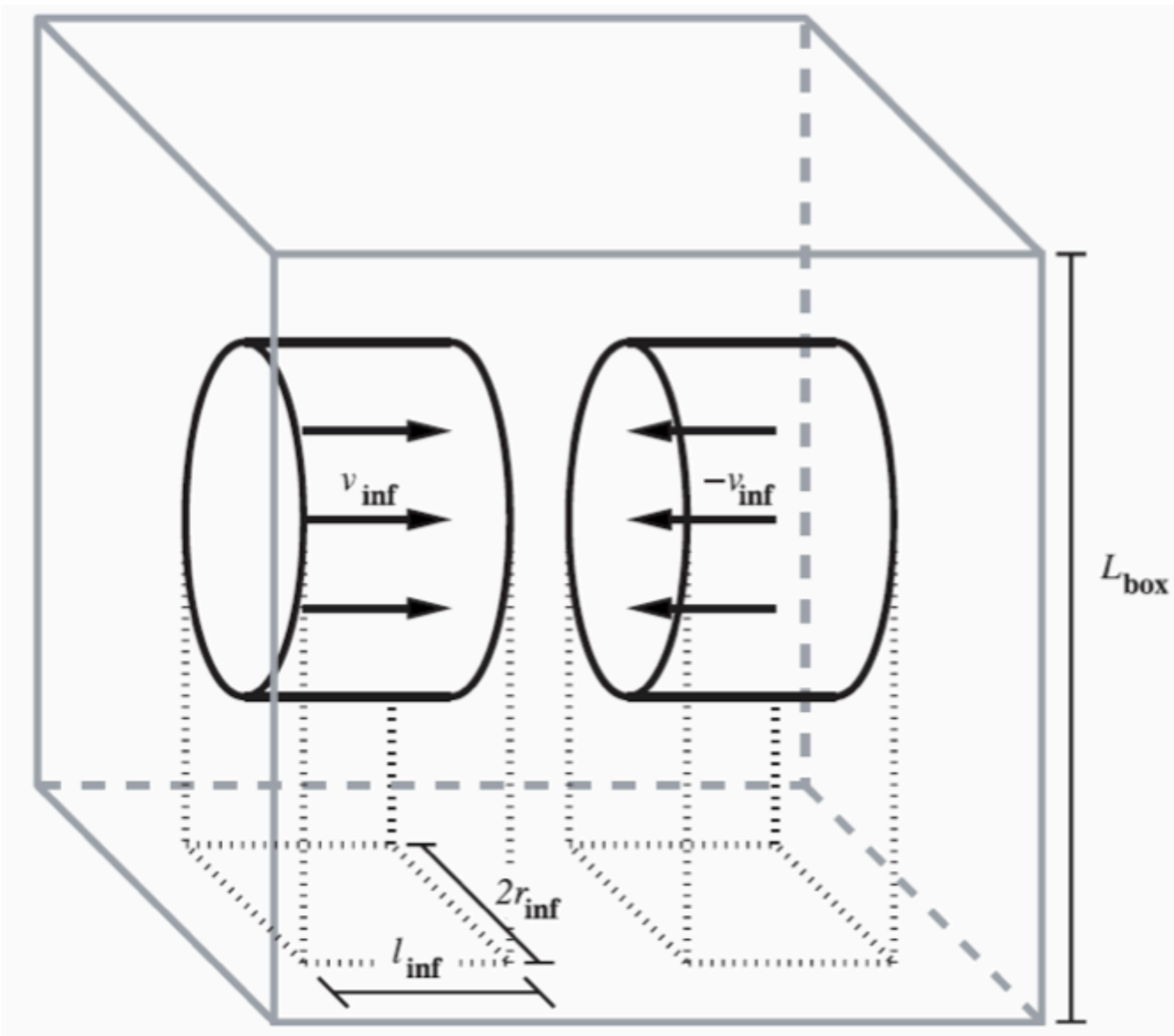
Formation of molecular clouds



Koyama & Inutsuka (2000): Pressure decreases with increasing density at ~1 cm^{-3}
=> thermal instability

Star formation Now:

Cloud formation in colliding flows

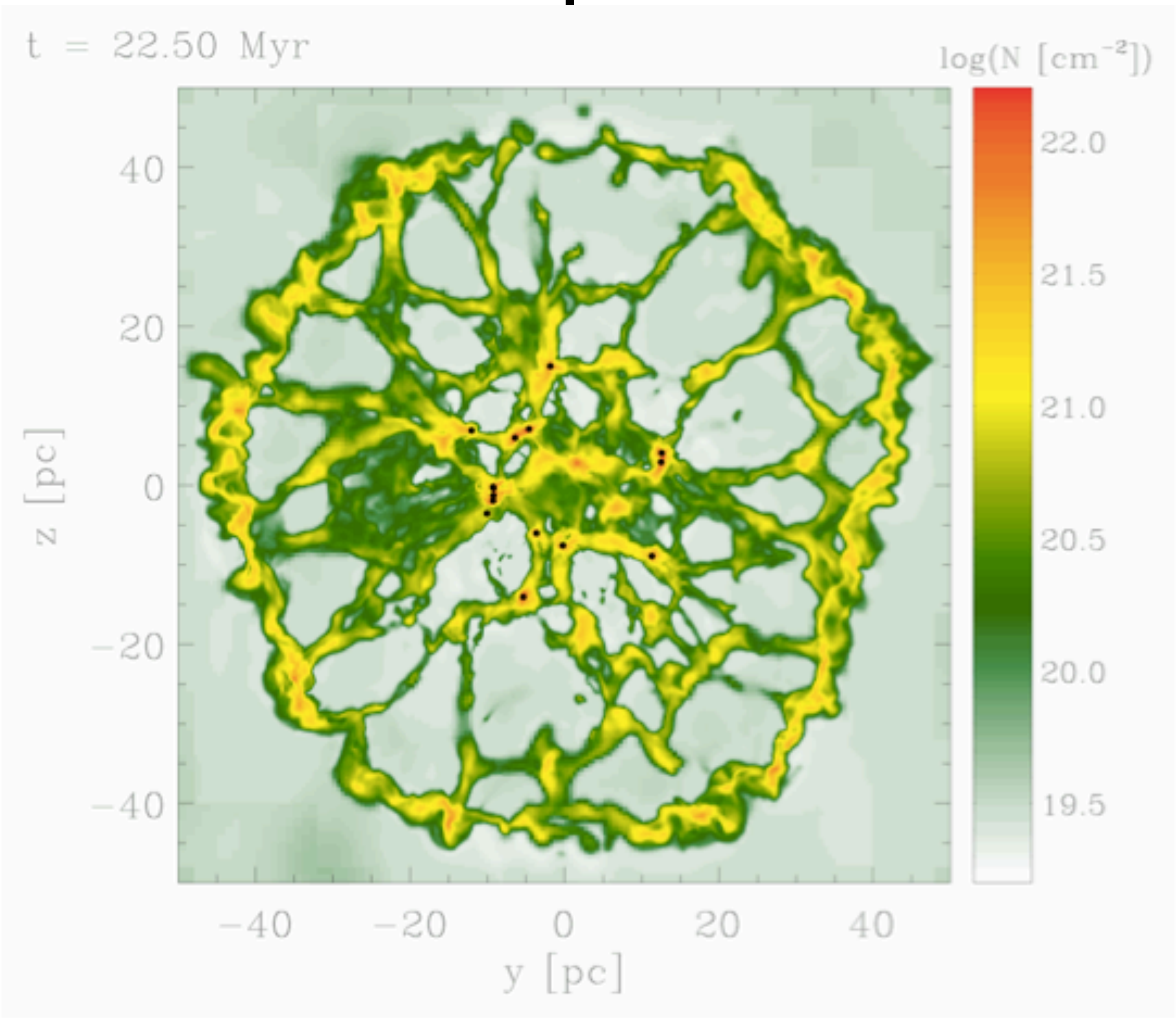


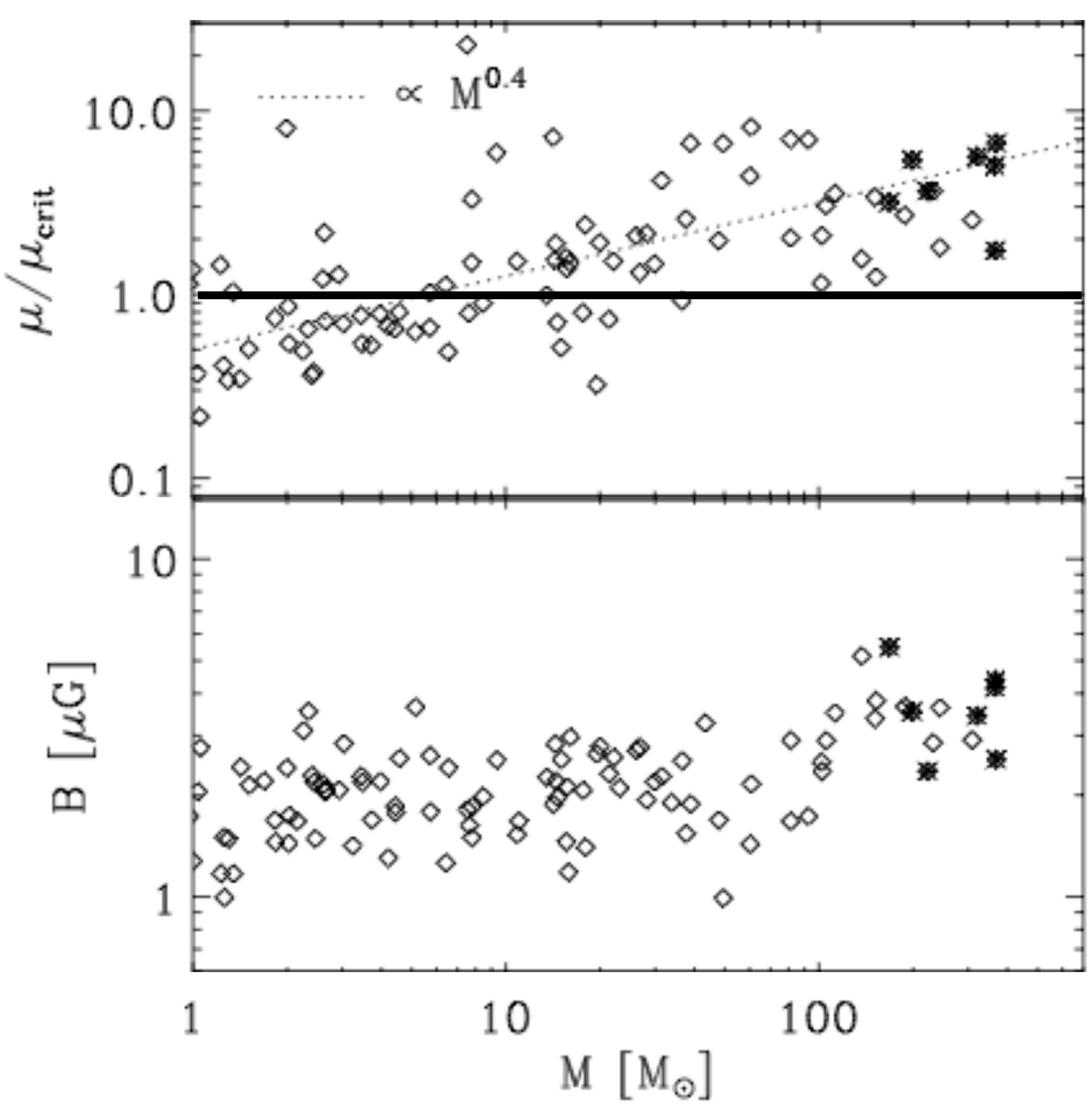
Vazquez-Semadeni et al. 2007

- MHD simulation with FLASH code
- Box size 256 pc, max res. 0.3 pc
- Initial field strength 1 microG
- v_{inf} ~7 km/s
- Number density 1 cm^{-3}

Star formation Now:

Formation of super- and subcritical clouds



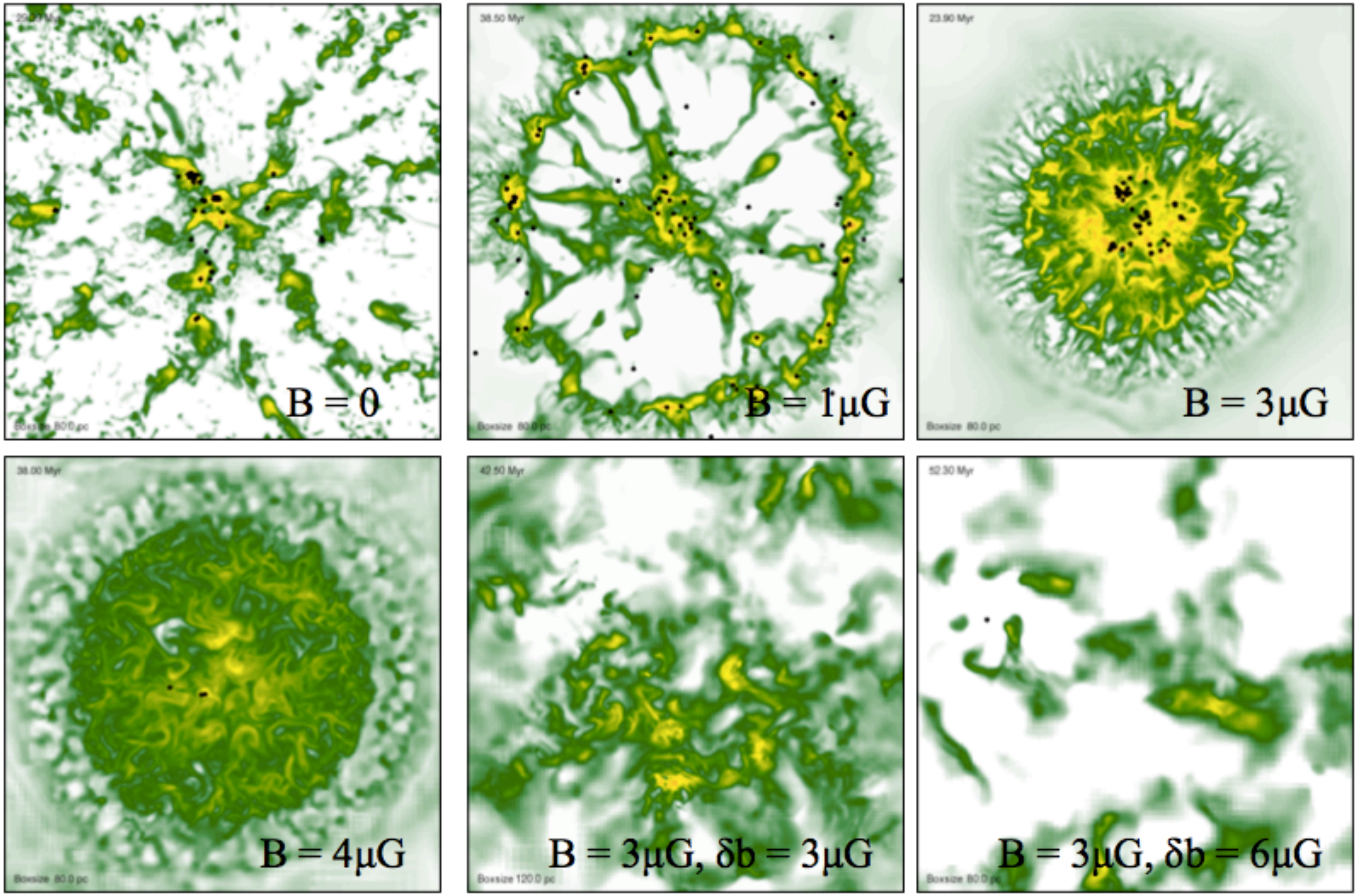


$$\mu_{crit} = \frac{1}{2\pi\sqrt{G}} \approx 0.16/\sqrt{G}$$

Banerjee et al. (2009): Formation of molecular clouds in colliding flows.
Analysis reveals the co-existence of supercritical and sub-critical cores.

Star formation Now:

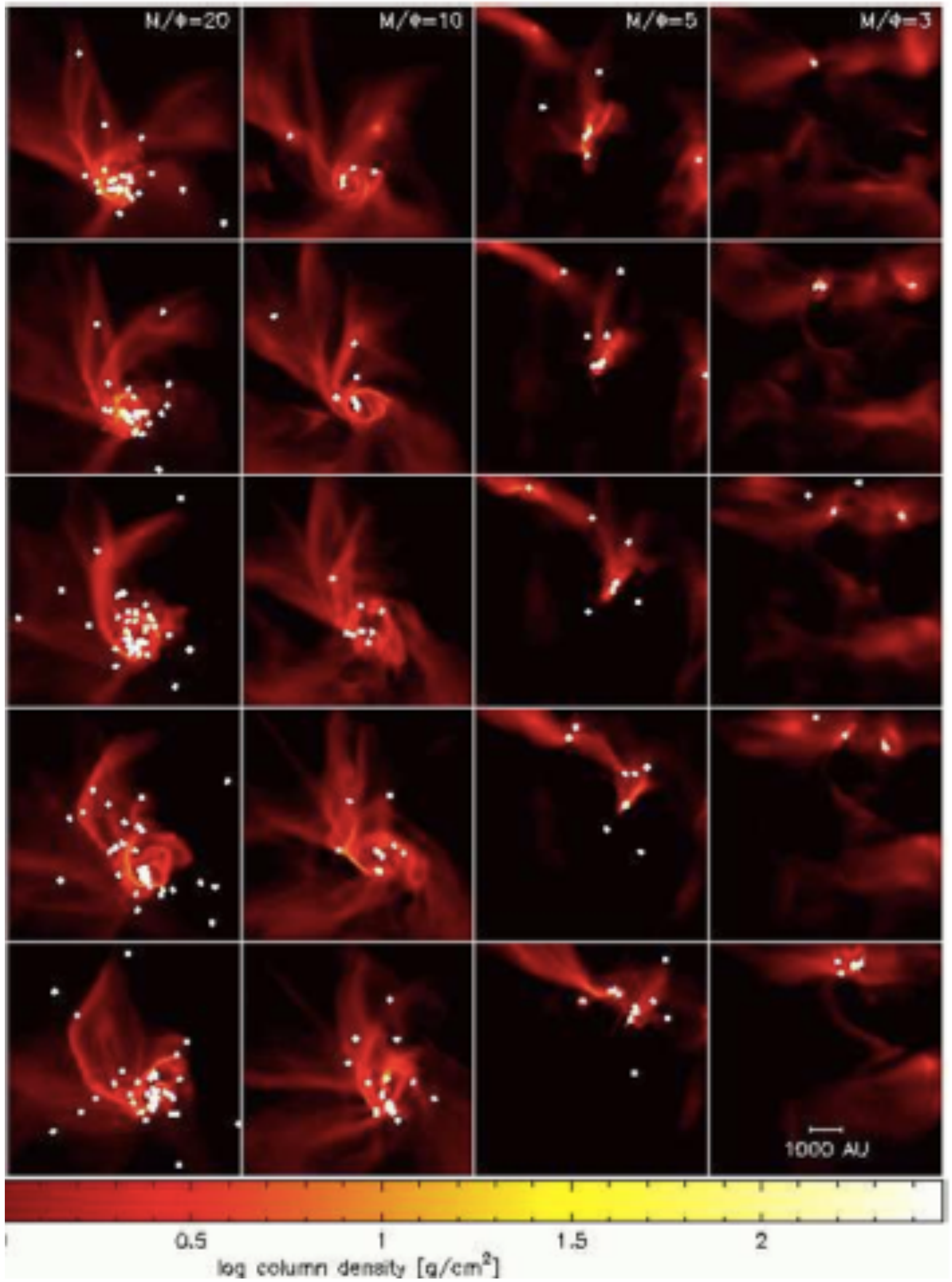
Formation of super- and subcritical clouds



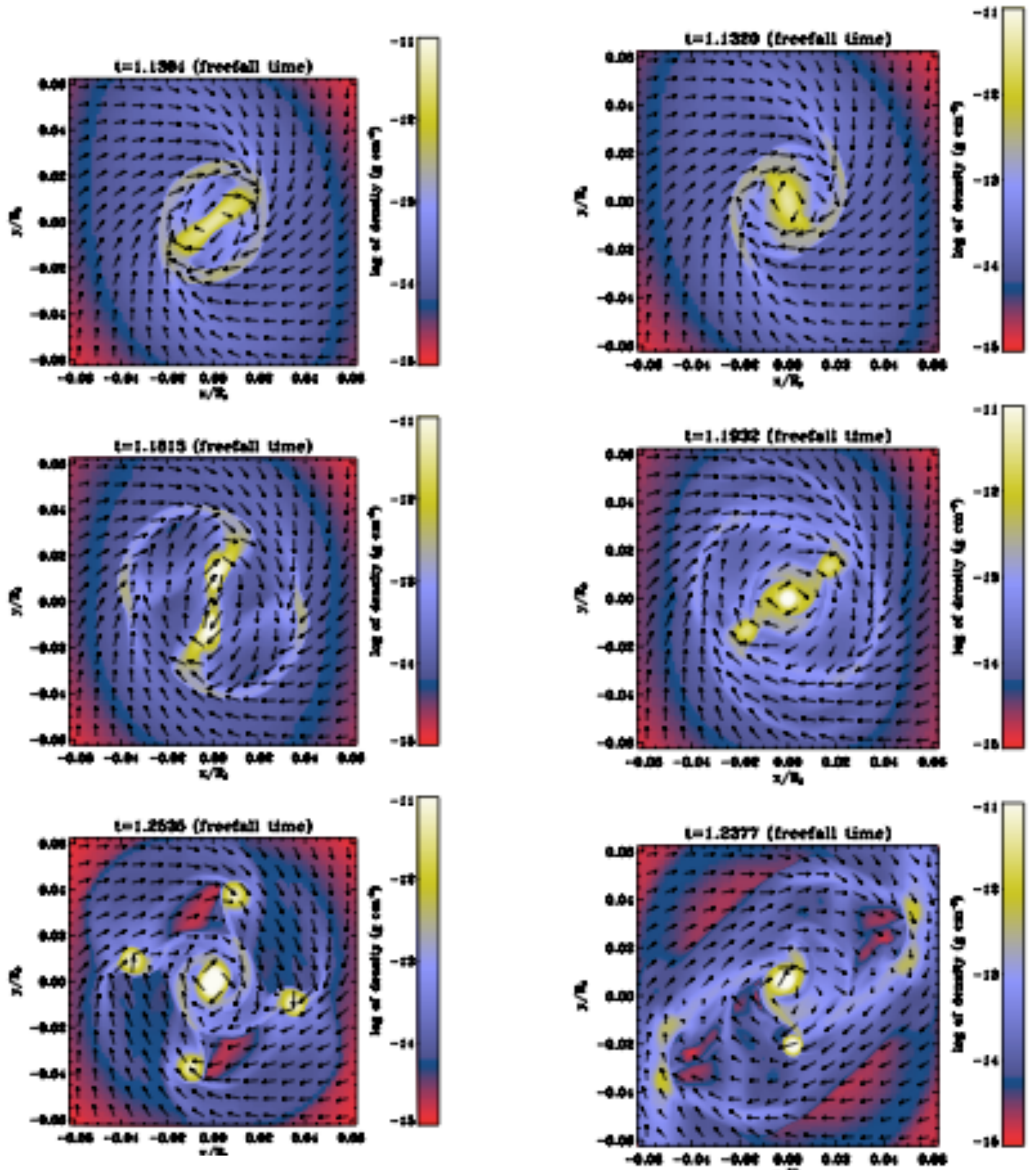
Banerjee et al. (2009): Implications of field strength for the formation of clouds.

Star formation Now:

Implications for fragmentation / binary formation



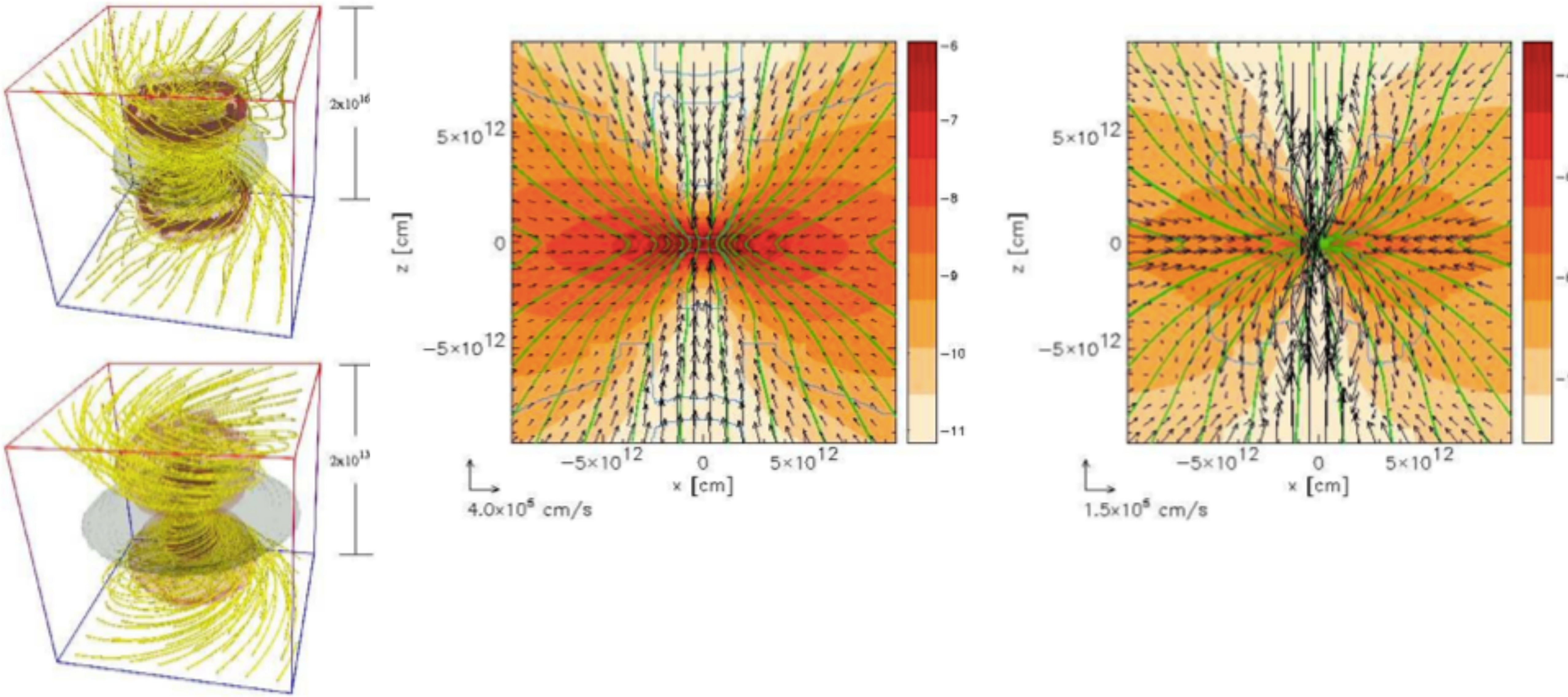
Price & Bate (2008)



Left: high mass-to-flux,
right: low-mass-to flux ratio
Hennebelle & Teyssier (2008)

Star formation Now:

Jet formation



Banerjee & Pudritz (2006): Centrifugally driven jet after the formation of a disk.

Star formation Now:

Evolution of supercritical cores

- Collapse controlled by gravity, turbulence and radiative cooling.
- Typically occurs on free-fall timescale (short):

$$t_{\rm ff} = \sqrt{3\pi/32G\rho}$$

$$\tau_{\rm ff} = (0.34\ {\rm Myr})\left(\frac{n}{10^4\ {\rm cm}^{-3}}\right)^{-1/2}$$

- Magnetic fields regulate fragmentation & jet formation.
- Binaries are common.

Star formation Now:

Evolution of subcritical cores

- No collapse possible in framework of ideal MHD.
- Non-ideal MHD: Only ions couple directly to the magnetic field, indirect coupling of the neutrals via collisions -> diffusion.
- Collapse may proceed on ambipolar diffusion timescale:

$$\tau_{\rm AD} = \left(\frac{L}{v}\right) Re_M = 2.2 \times 10^9 \left(\frac{n}{10\ {\rm cm}^{-3}}\right)^2 \times \left(\frac{L}{\rm pc}\right)^2 \left(\frac{B}{\mu{\rm G}}\right)^{-2} \left(\frac{x_e}{10^{-3}}\right) {\rm yr}$$

- No fragmentation expected.
- Mass-to-flux ratio decreases due to ambipolar diffusion.

Star formation Now:
Summary

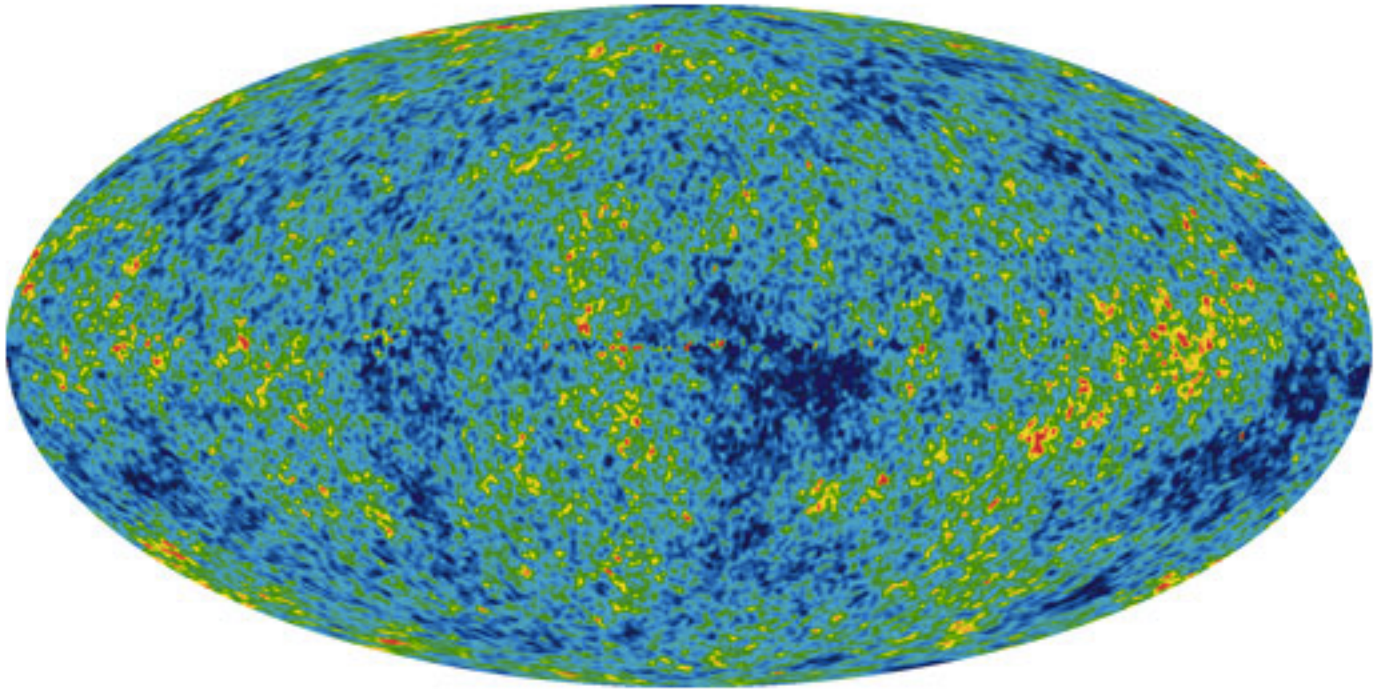
- Initial conditions can be probed from observations and vary in different star-forming regions.
- Supercritical clouds collapse under their own weight, in sub-critical clouds collapse is balanced by magnetic pressure.
- Observed molecular clouds tend to be supercritical, but we need larger samples.
- Simulations suggest the co-existence of sub- and supercritical clouds.
- Dynamical implications:
  Formation of jets, suppression of fragmentation / binary formation.

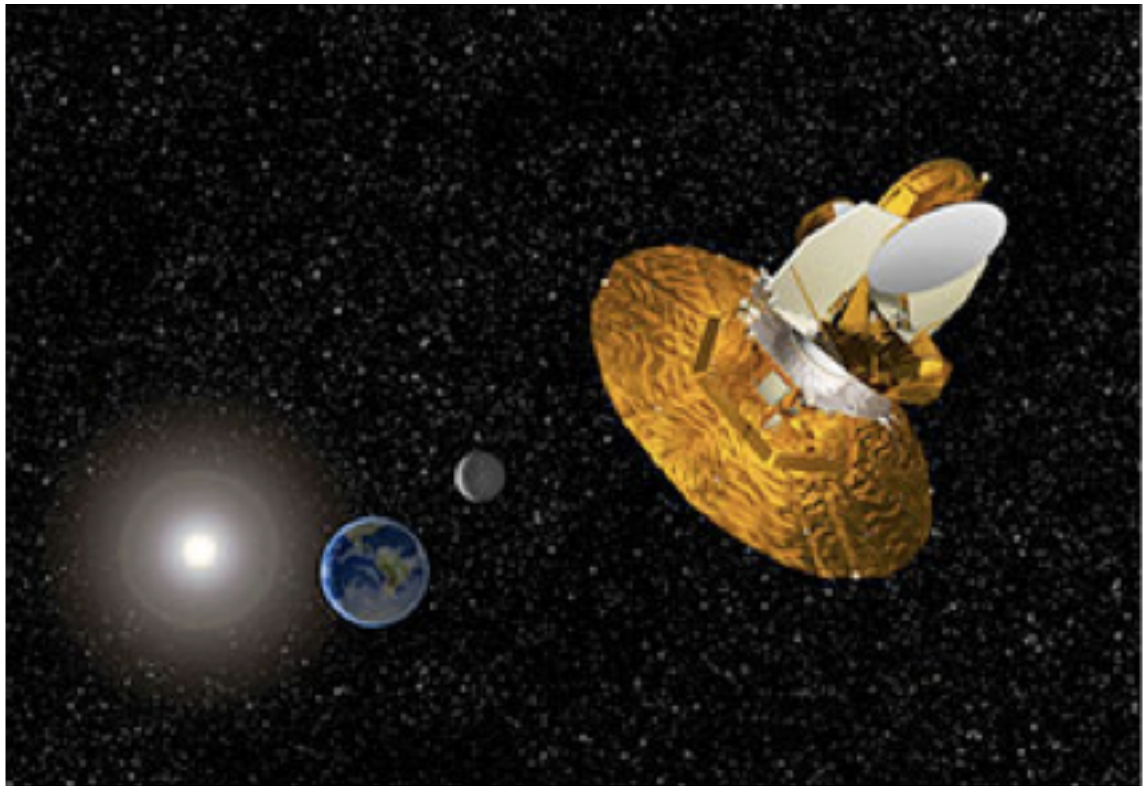
Contents

- Star formation now:
  - The initial conditions.
  - Implications for gravitational collapse.
  - Implications in the disk.
- Star formation then:
  - The initial conditions.
  - Maintaining and amplifying the magnetic field.
  - Implications and uncertainties.

Star formation Then:

The initial conditions

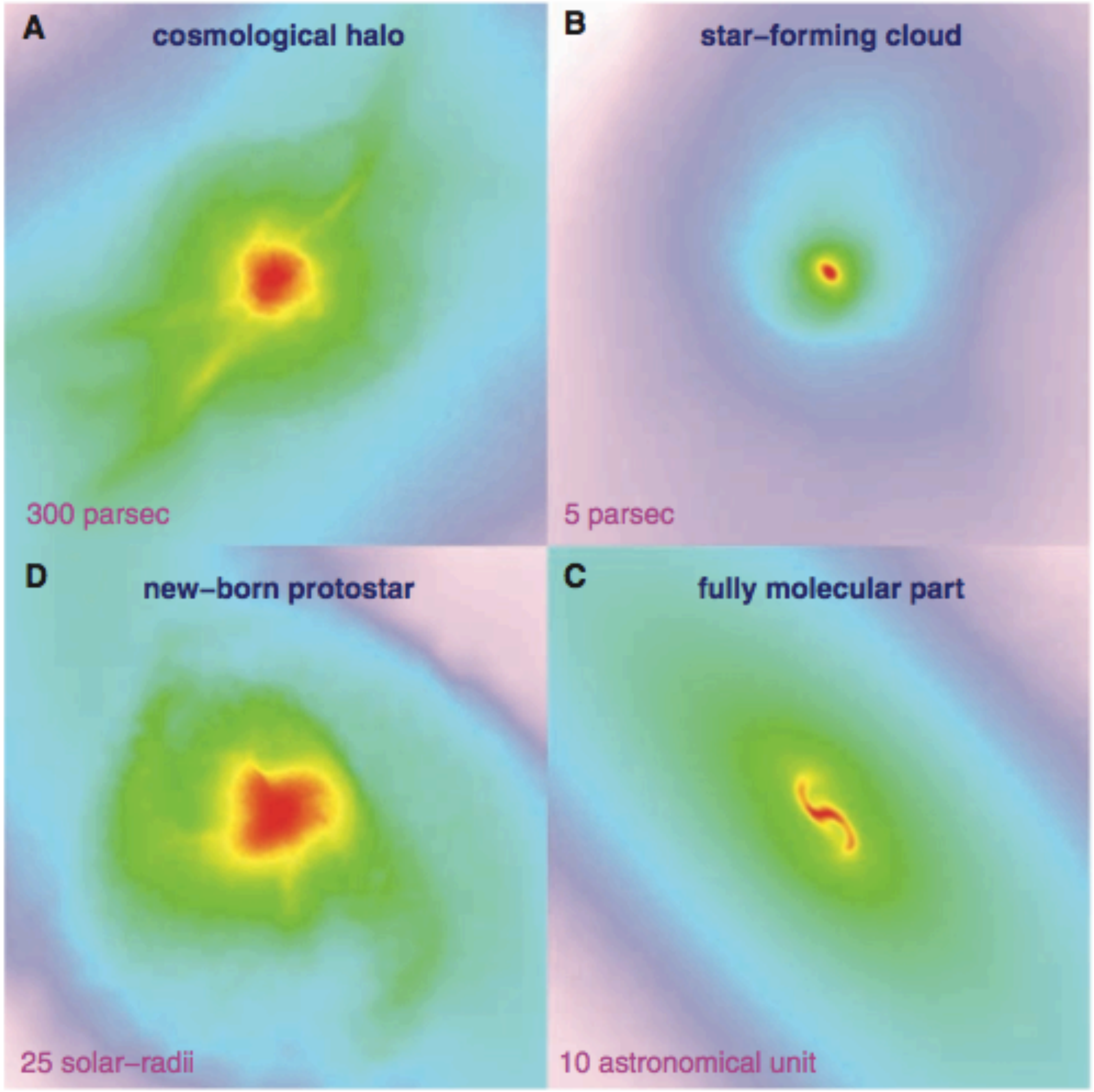




- Initial conditions at z~1100 measured by WMAP satellite!
- Linear theory: Growth until z~100.
- Cosmological simulations: Nonlinear structure formation, first objects at z~20-30.

Star formation Then:

The initial conditions



Yoshida et al. (2008)

- Big Bang nucleosynthesis: The first stars form out of primordial gas (H, He, tiny fractions of D and Li).
- Chemical initial conditions: Neutral atomic gas, small abundances of molecules, non-zero ionization degree.
- Dynamical evolution followed with hydrodynamical simulations until the formation of a disk.

Star formation Then:

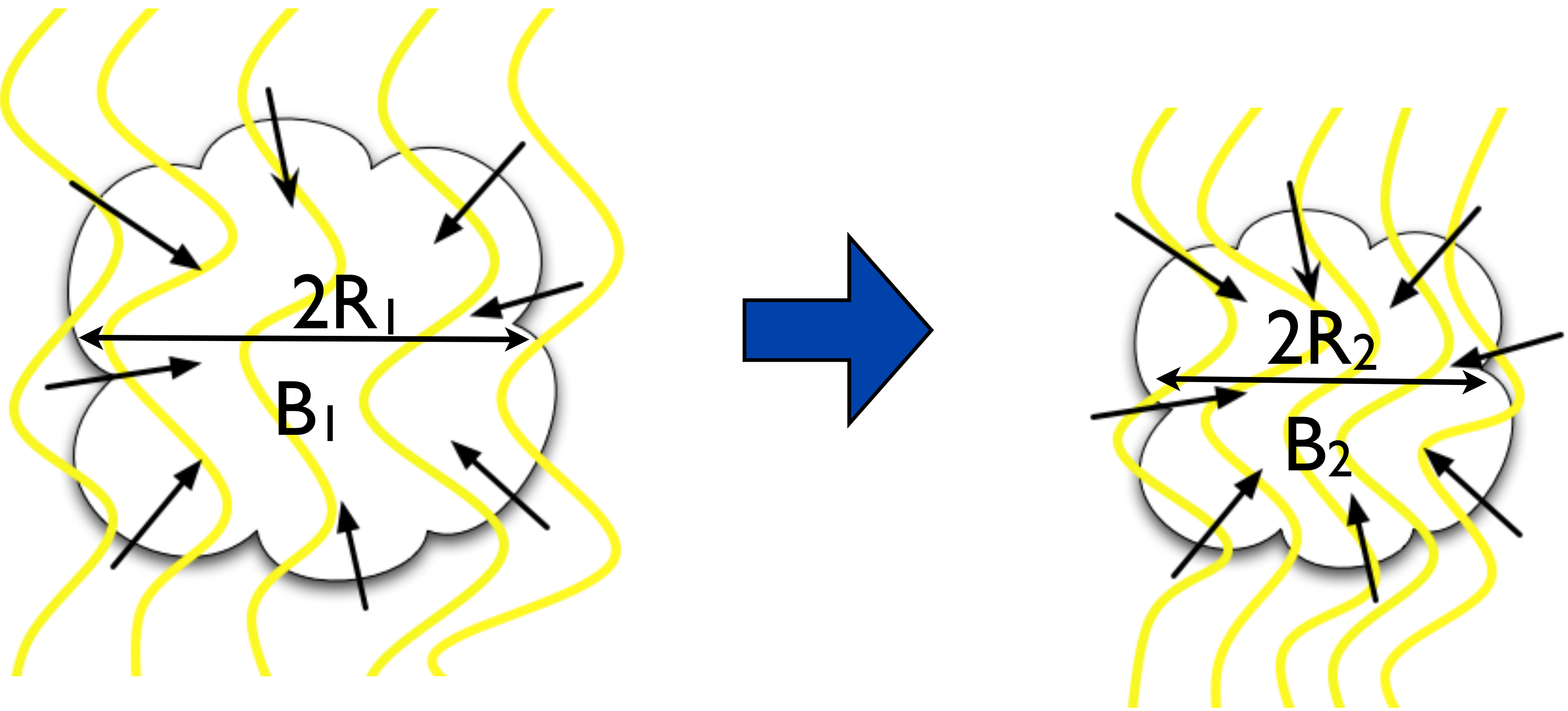
The initial field strength

- Upper limit from CMB: ~3 nG.
- Upper limit from reionization: ~4-5 nG (see tomorrow).
- Lower limit from FERMI data: $\sim 10^{-15}$ G (see tomorrow).
- Magnetic fields from QCD epoch: 0.01-3 nG (Banerjee & Jedamzik 2004).
- Biermann battery: $\sim 10^{-15}$ G (Xu et al. 2008).

Uncertainties are significant - Can we amplify it?

Star formation Then:

Magnetic field amplification during collapse



flux conservation:

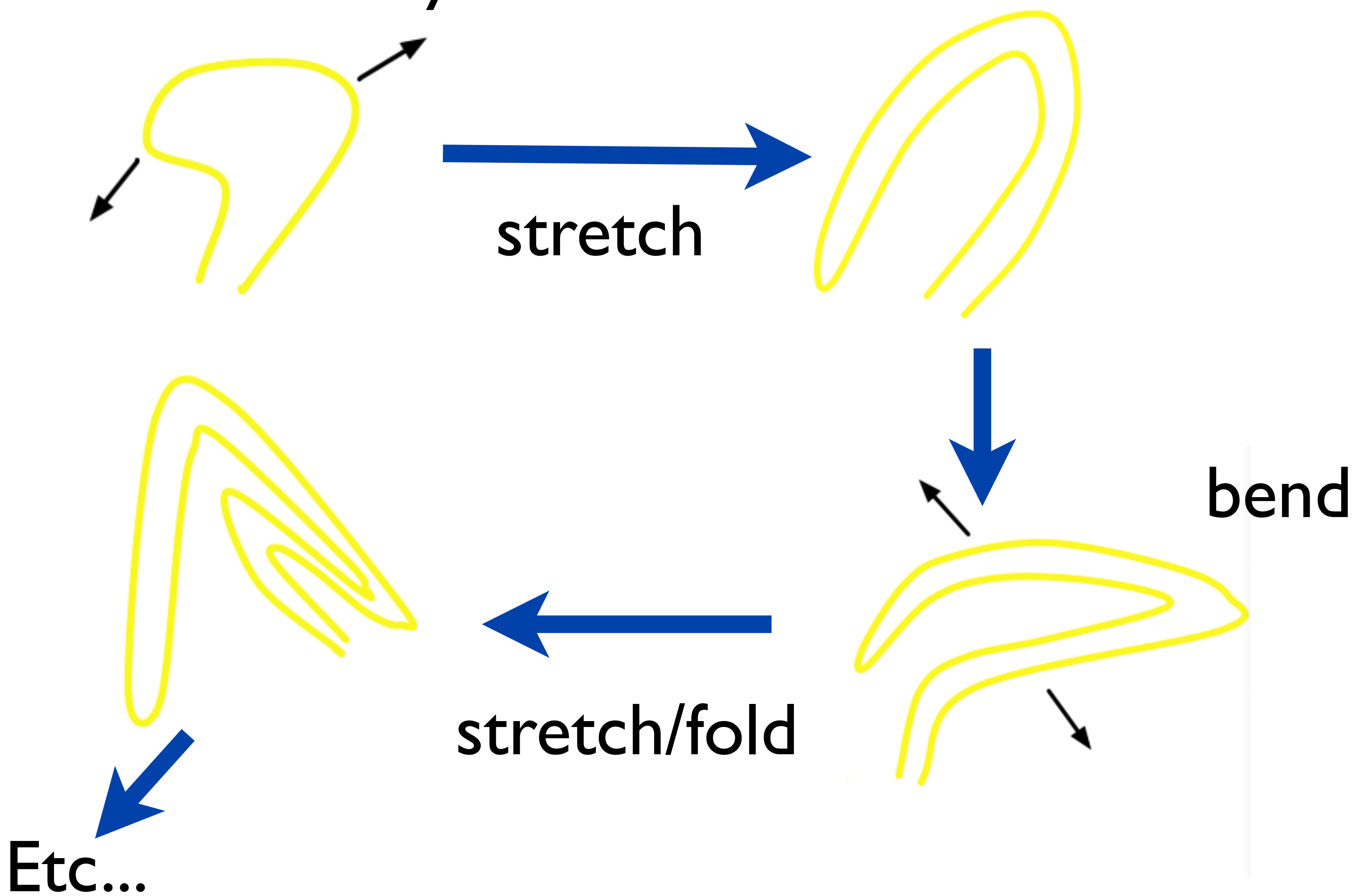
$R_1^2 B_1 = R_2^2 B_2$

density ~ R^{-3}

-> B ~ density$^{2/3}$

Star formation Then:

The small-scale dynamo

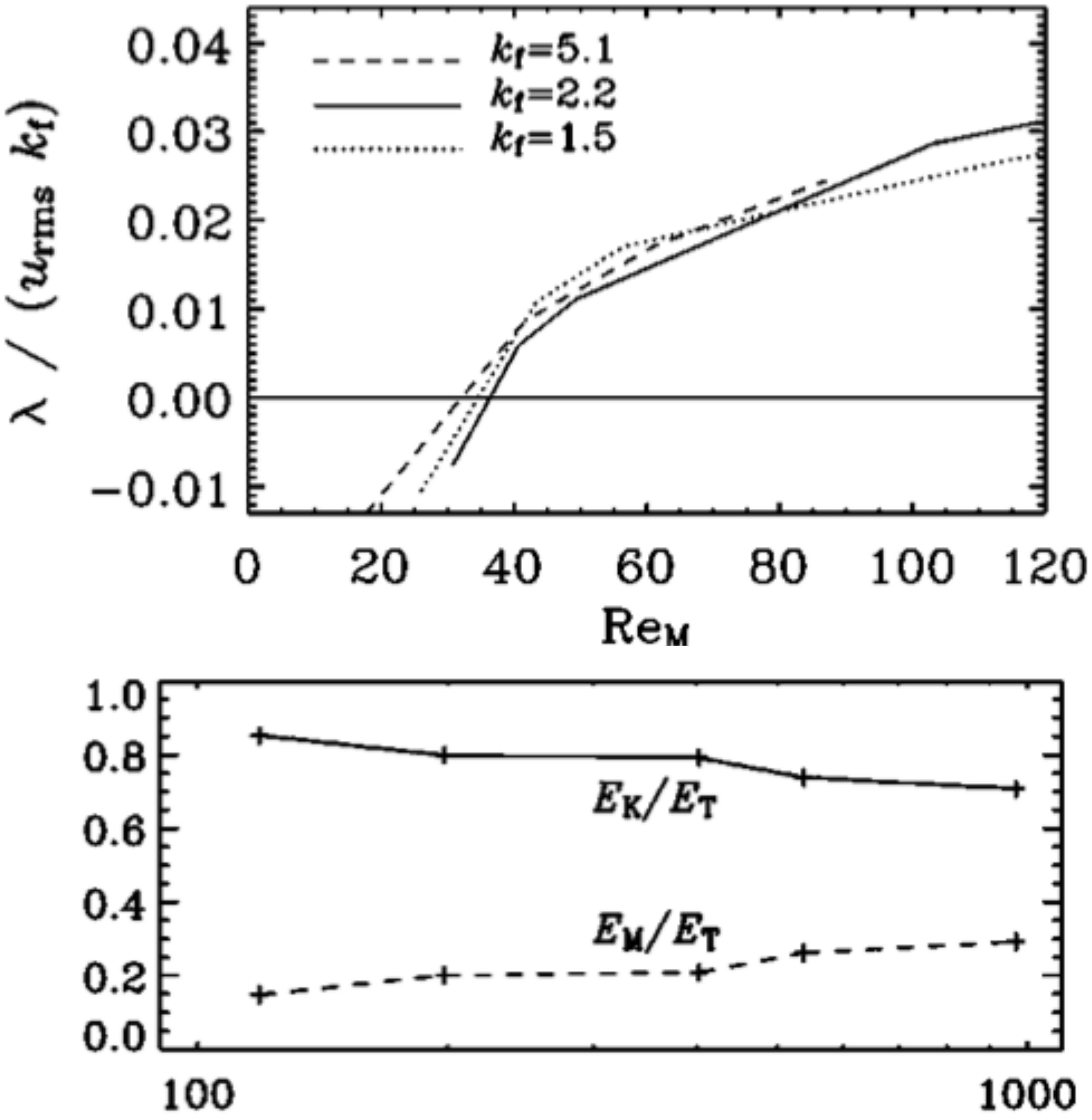


Amplification via stretch-and-fold

Schleicher, Banerjee, Sur, Arshakian, Klessen, Beck & Spaans (2010)

Star formation Then:

The small-scale dynamo



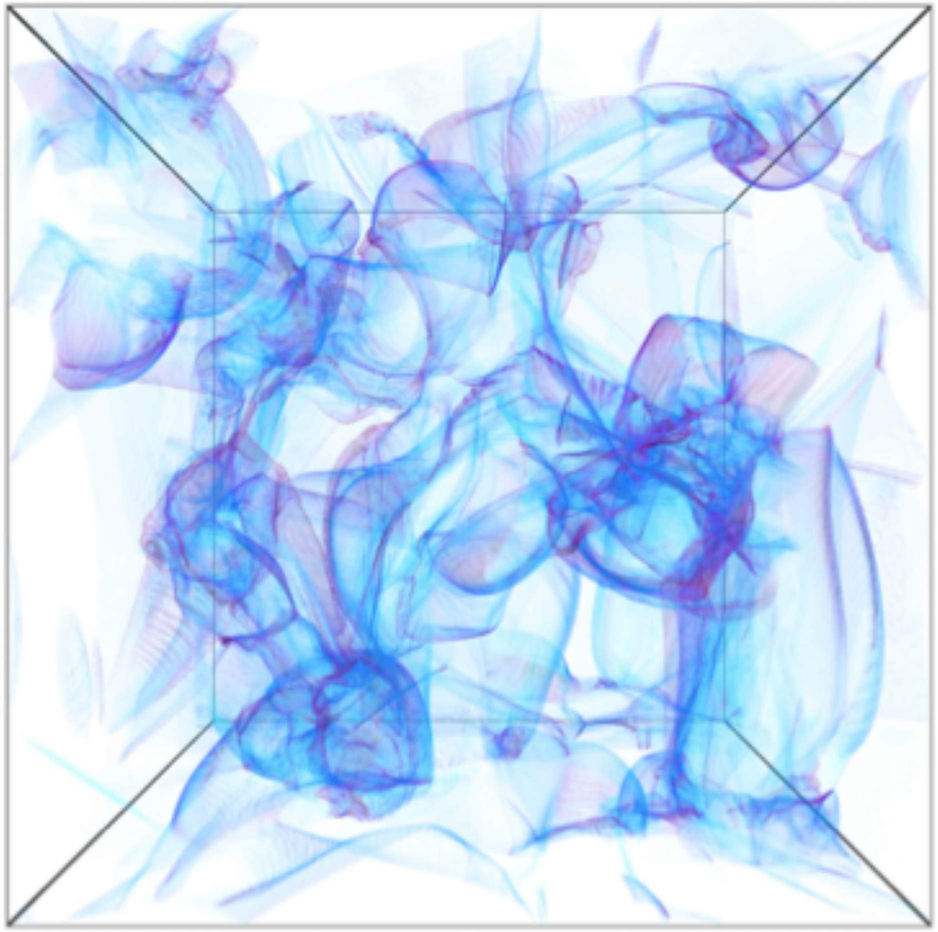
Haugen et al. (2004)

- Magnetic Reynolds number: U L / eta
- Top: Magnetic field amplification depends strongly on the magnetic Reynolds number.
- Bottom: Weak dependence of the saturation value.

Star formation Then:

Small-scale dynamo - theory

Turbulent scaling laws:
$v \sim l^{1/3}$ (Kolmogorov)
$v \sim l^{1/2}$ (Burgers)
Realistic turbulence often inbetween, with comparable amounts of rotation and compression



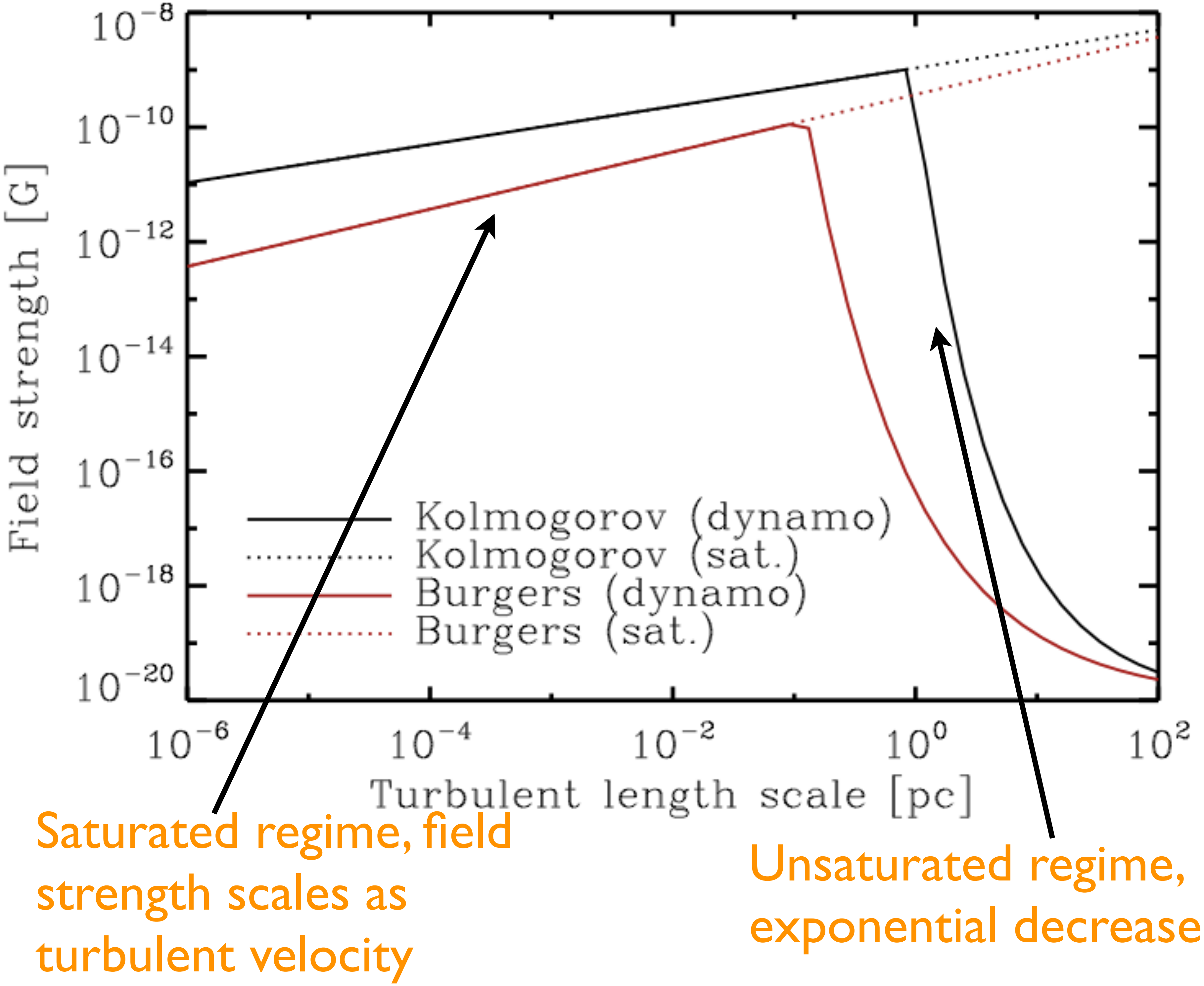
Schmidt et al. (2009)

Variation of growth rate with Reynolds-number:
$\text{Gamma} \sim \text{Re}^{1/2}$ (Kolmogorov)
$\text{Gamma} \sim \text{Re}^{1/3}$ (Burgers)

Schober et al., in prep.
See also Subramanian (1998) for Kolmogorov turbulence.

Star formation Then:

The small-scale dynamo

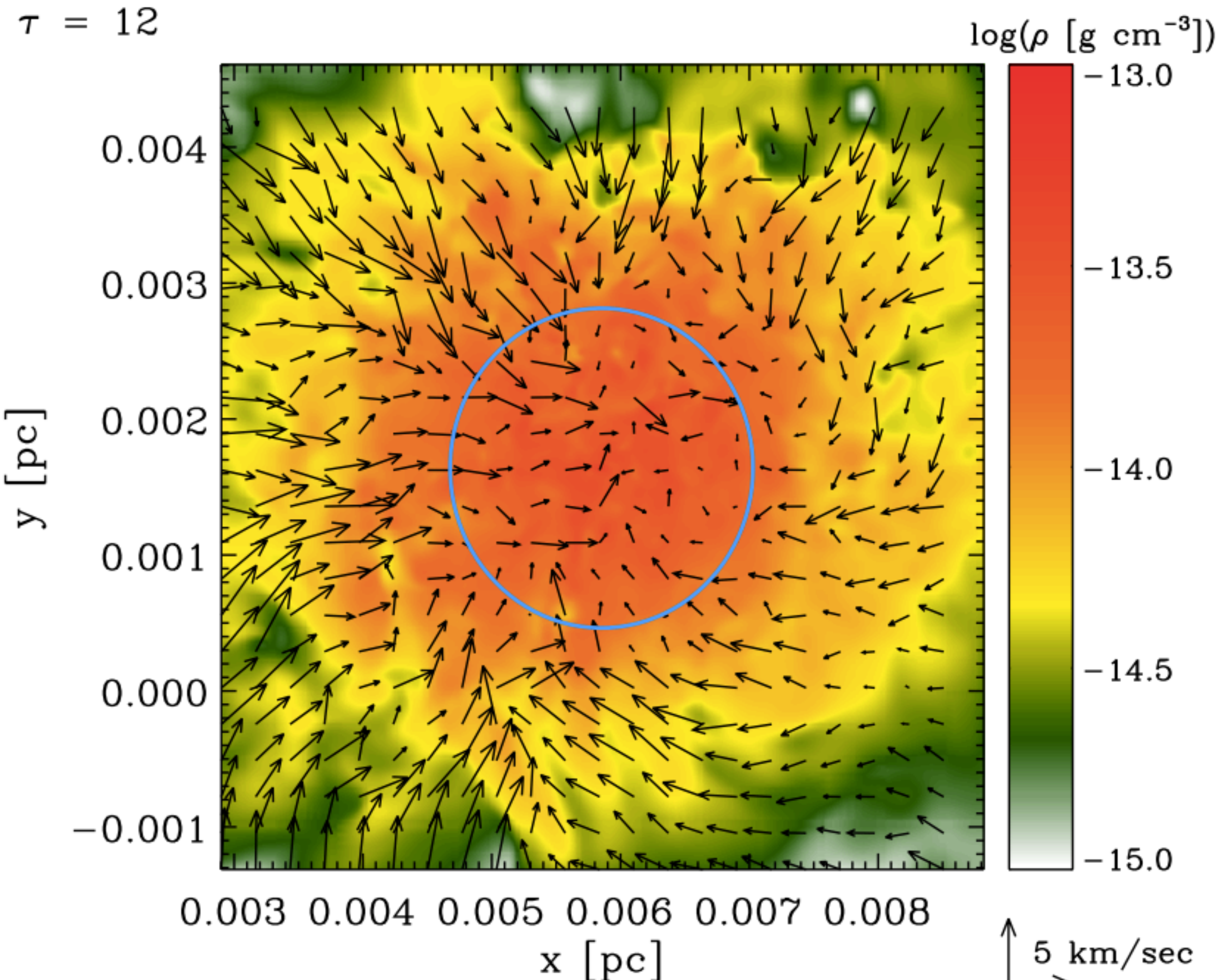


- Collapse timescale: $t_{ff} = 1/\sqrt{\rho G}$
- Eddy timescale $t_{\mathrm{ed}} = l/v$
- Amplification ~exp(t_{ff} / t_{ed})

Schleicher, Banerjee, Sur, Arshakian, Klessen, Beck & Spaans (2010)

Star formation Then:

The small-scale dynamo in collapse simulations

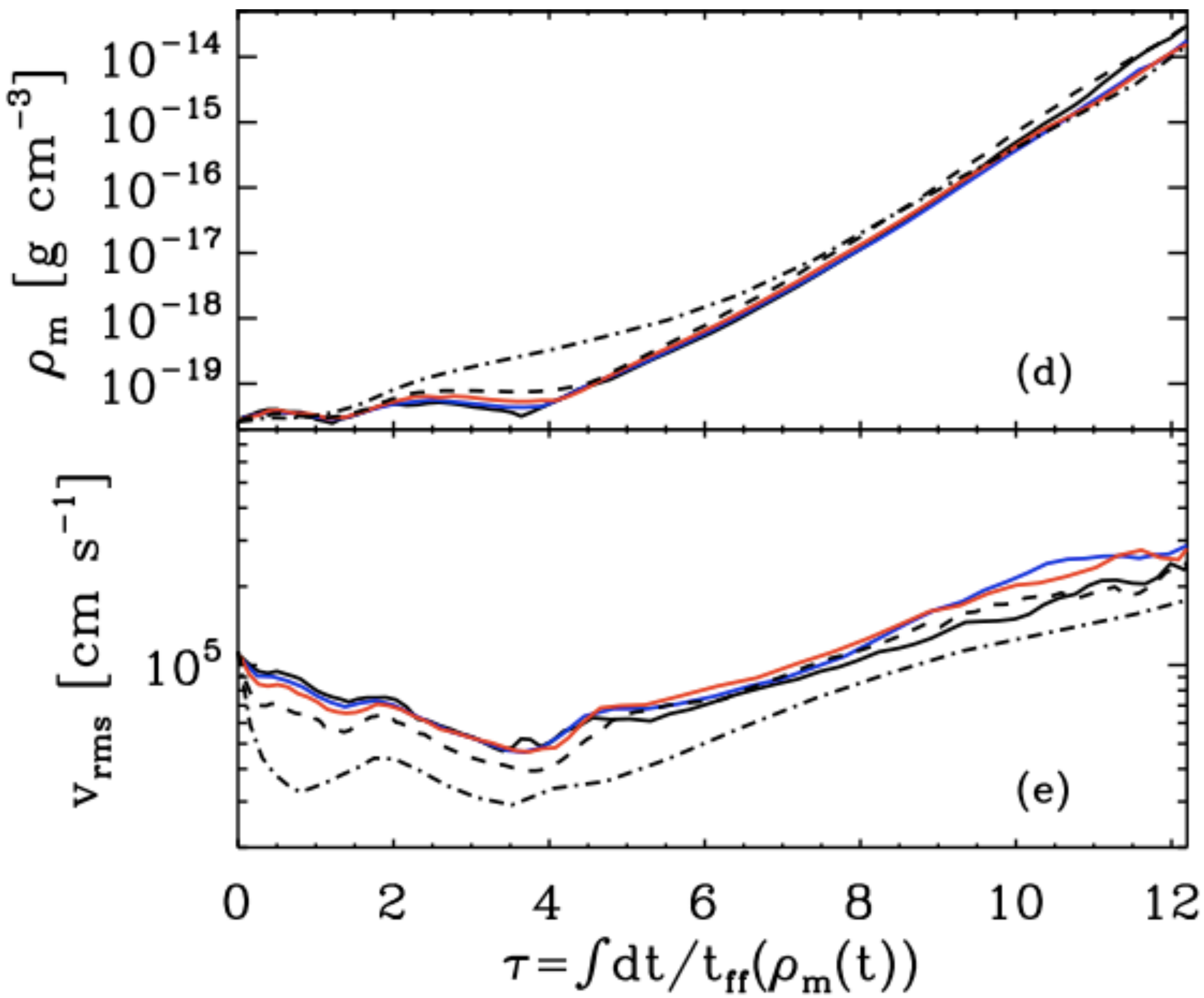


Sur, DS, Banerjee, Federrath & Klessen (2010)

- Motions dominated by infall on large scales.
- Formation of a turbulent core in the center.
- Core size comparable to Jeans length.

Star formation Then:

Evolution of dynamical quantities

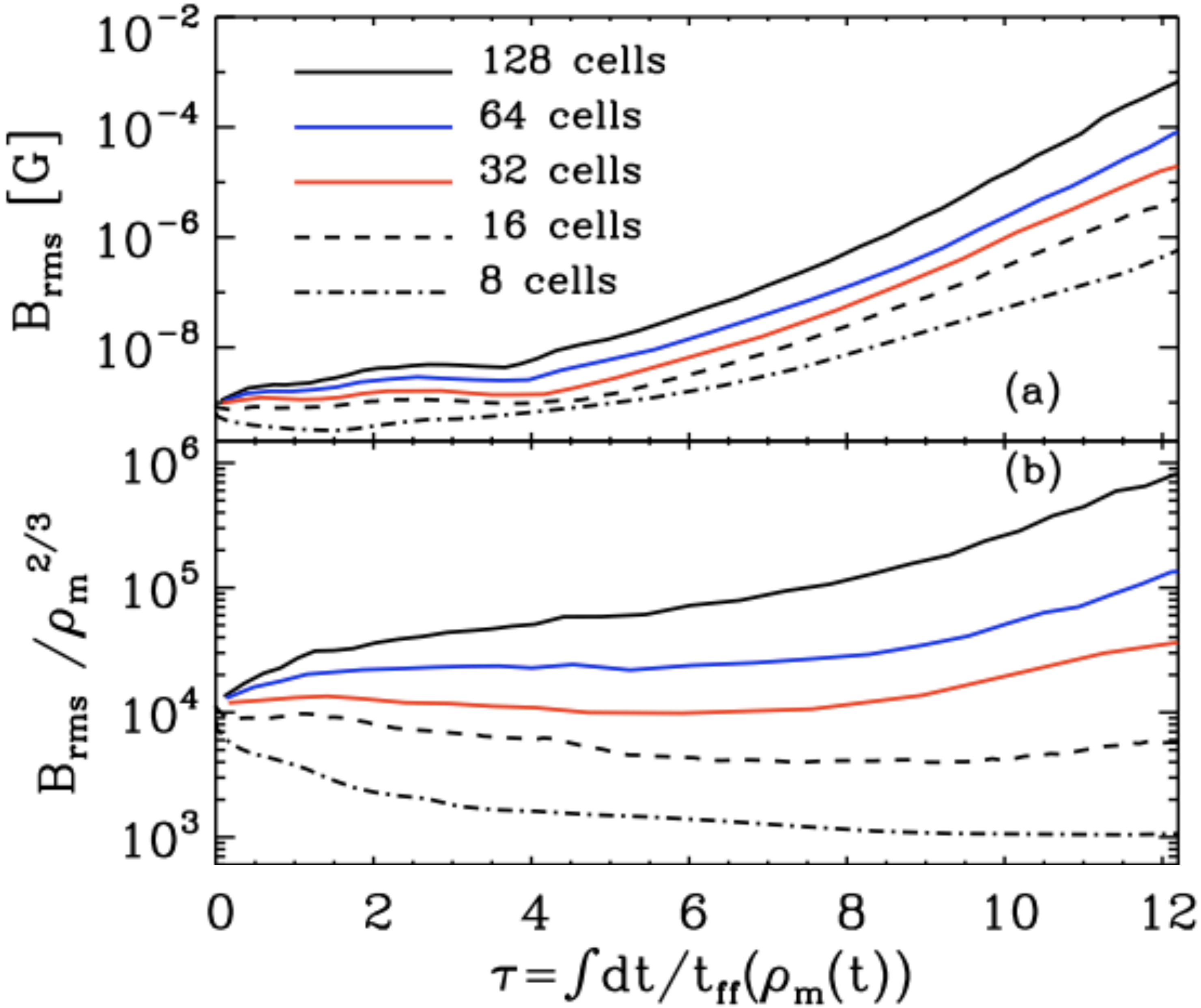


Evolution of density and rms velocity.

Sur, DS, Banerjee, Federrath & Klessen (2010)

Star formation Then:

Evolution of the magnetic field

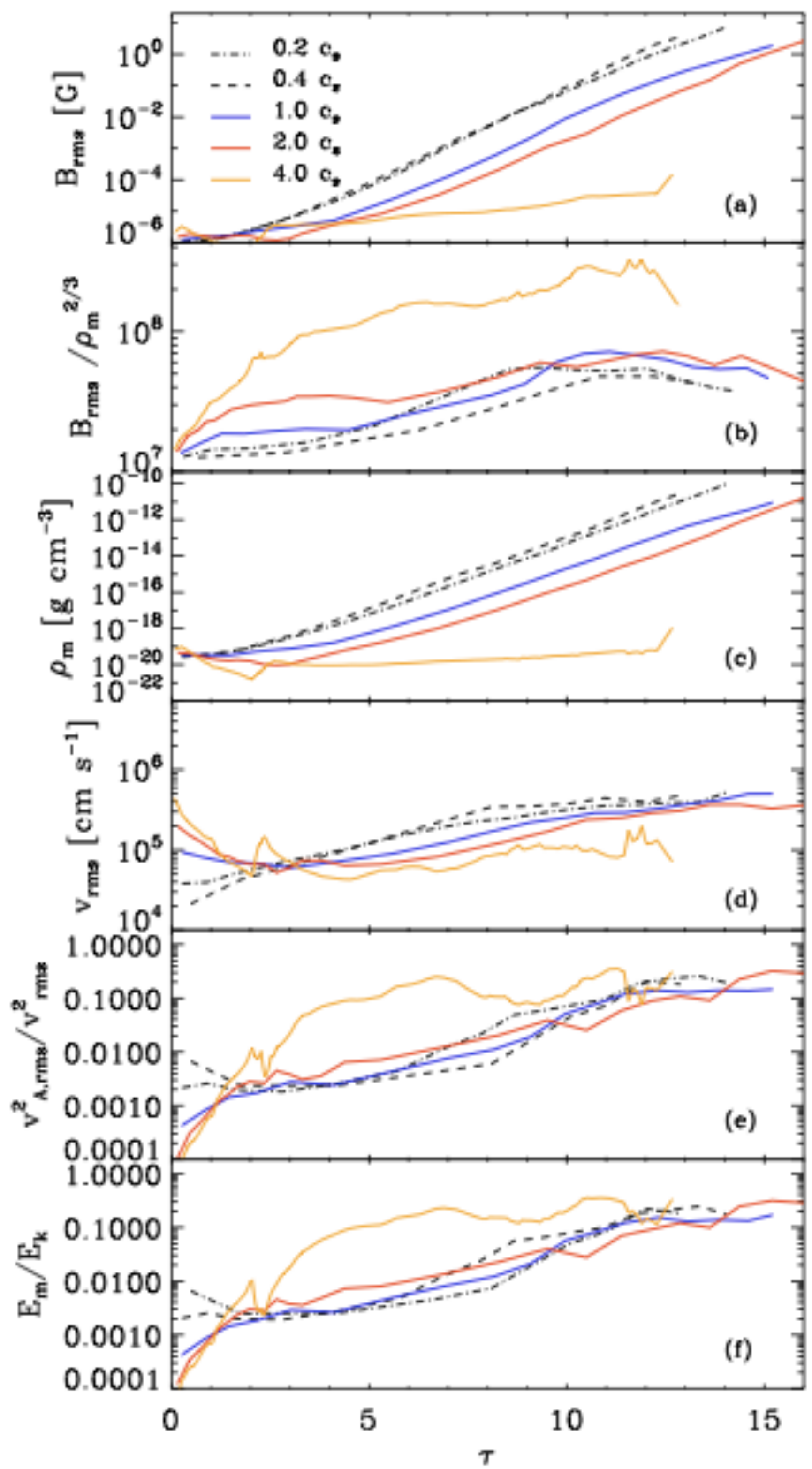


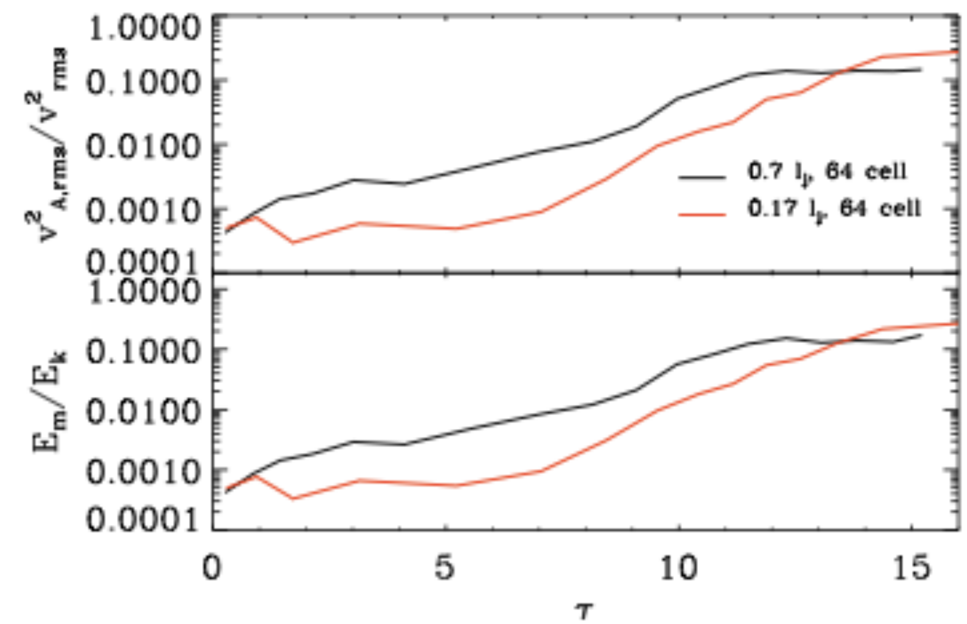
More efficient magnetic field amplification at higher resolution
-> dependence on Reynolds number and numerical diffusivity
(see Brandenburg & Subramanian 2005)

Sur, DS, Banerjee, Federrath & Klessen (2010)

Star formation Then:

Dependence on turbulent properties



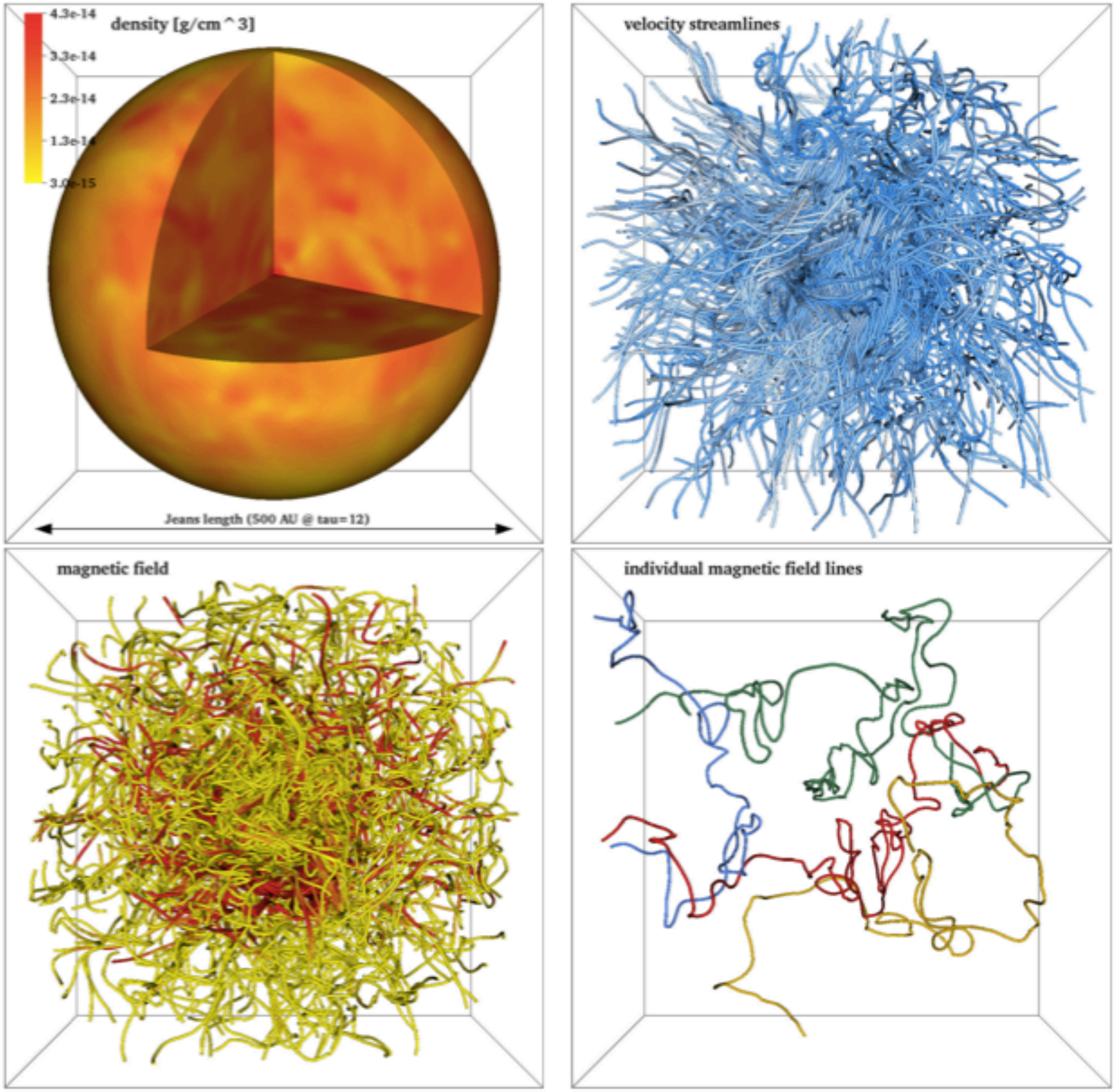


Left: Variation of the turbulent Mach number.
Right: Variation of the injection scale.

Sur et al., in prep.

Star formation Then:

Turbulence and magnetic field structure

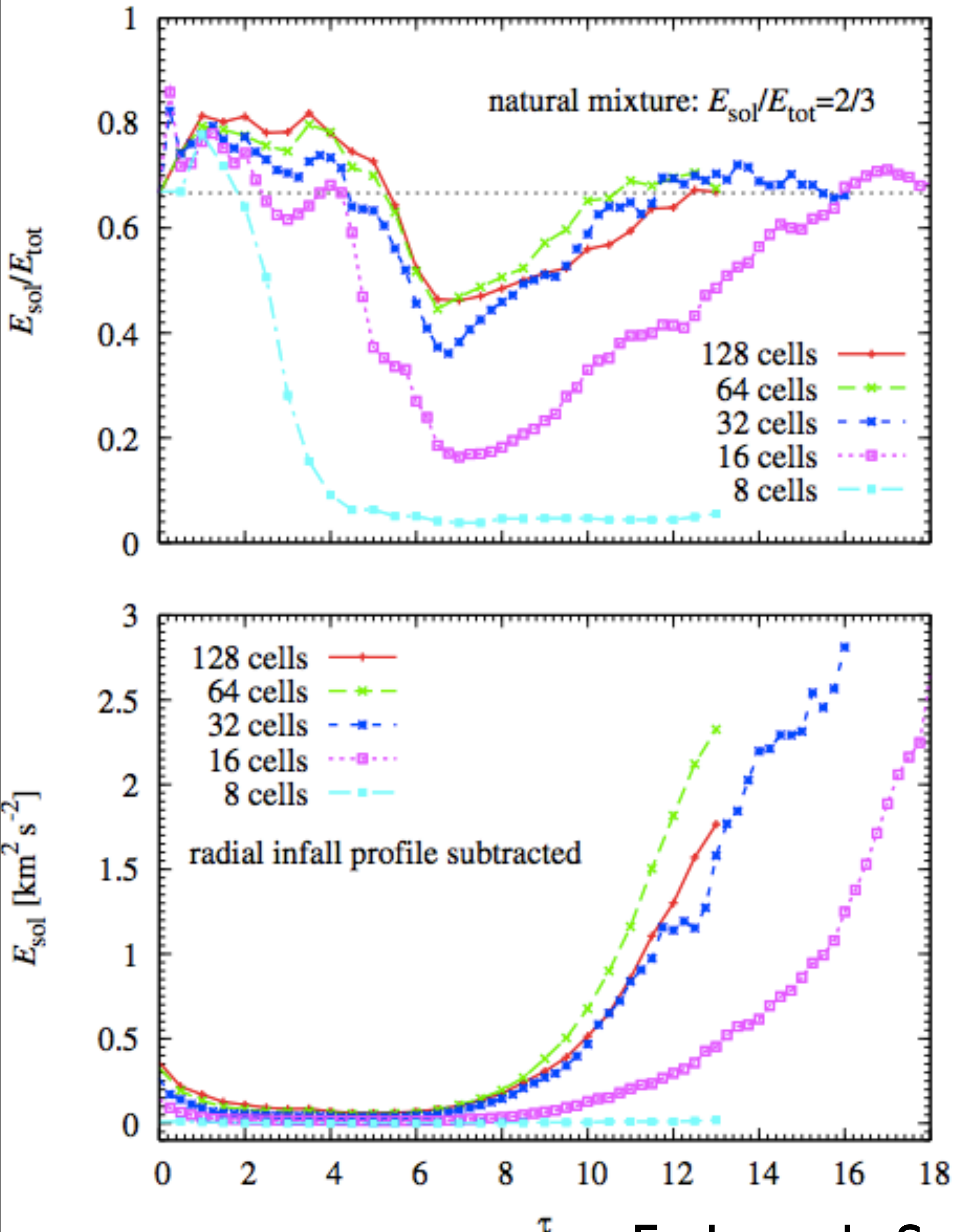


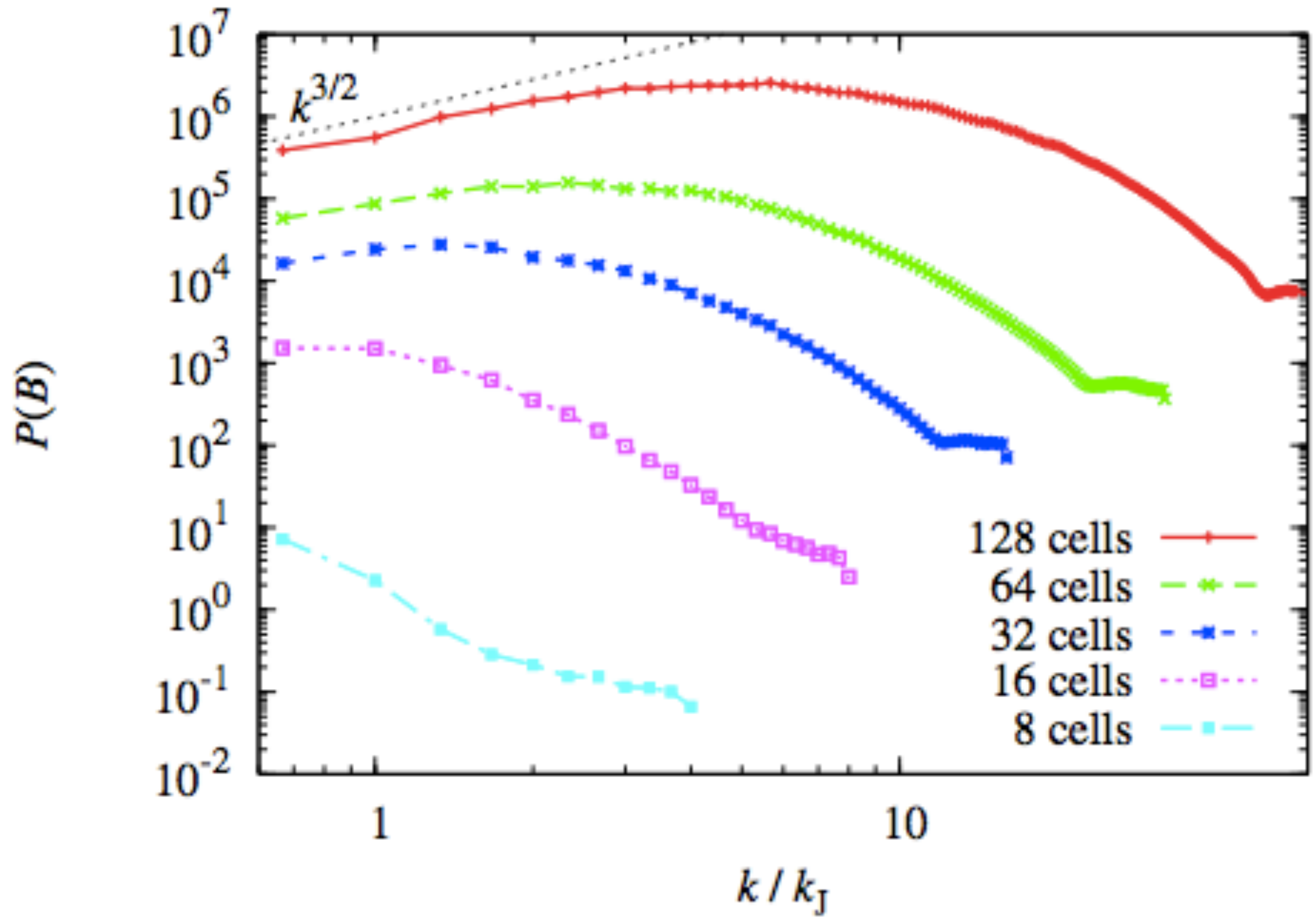
Federrath, Sur, Schleicher & Klessen (2011)

- Magnetic field enhanced by turbulence and compression
- Highly tangled magnetic field structure
- Still reflecting density distribution due to compression

Star formation & magnetic fields:

Turbulent properties and a critical resolution



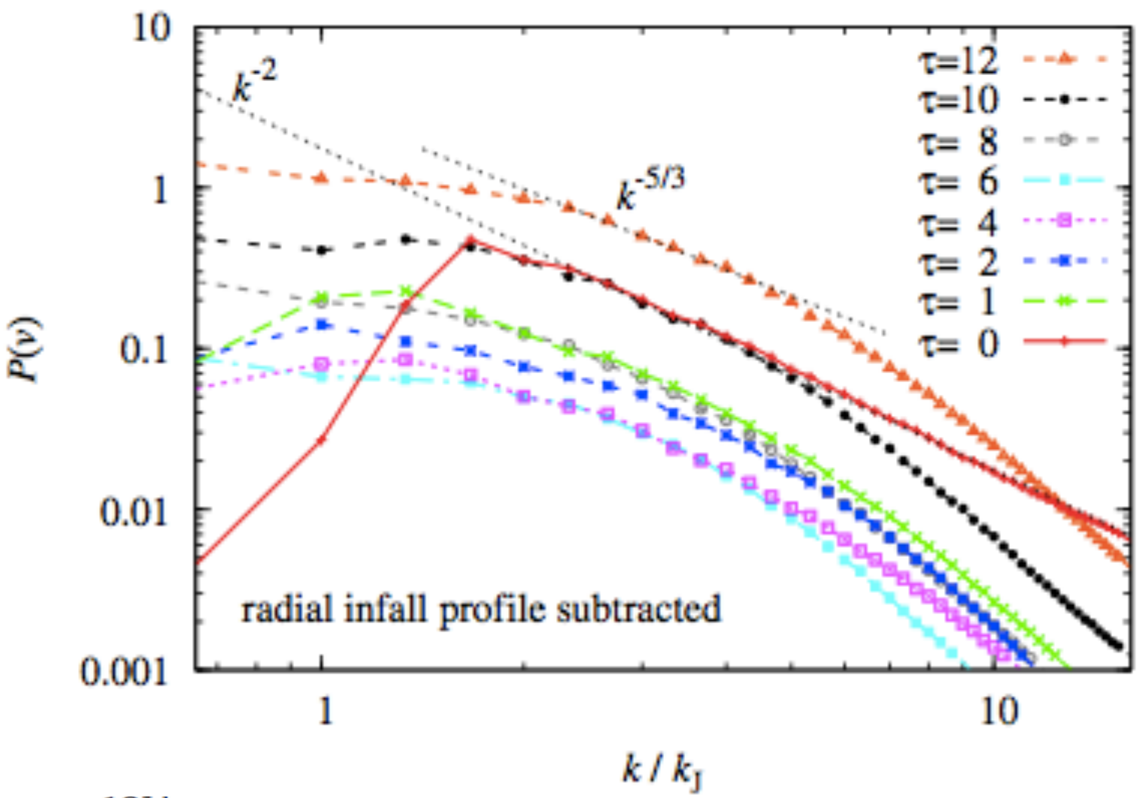


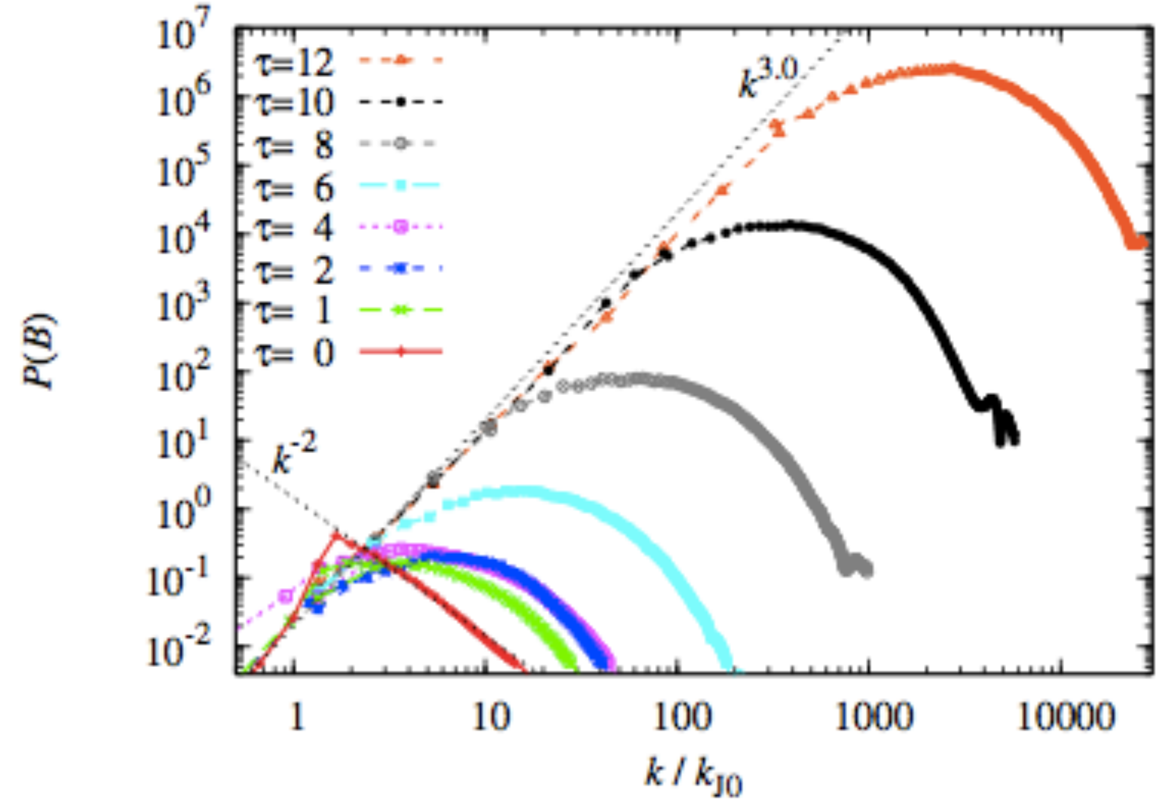
At least 32 cells per Jeans length to model turbulence and dynamos

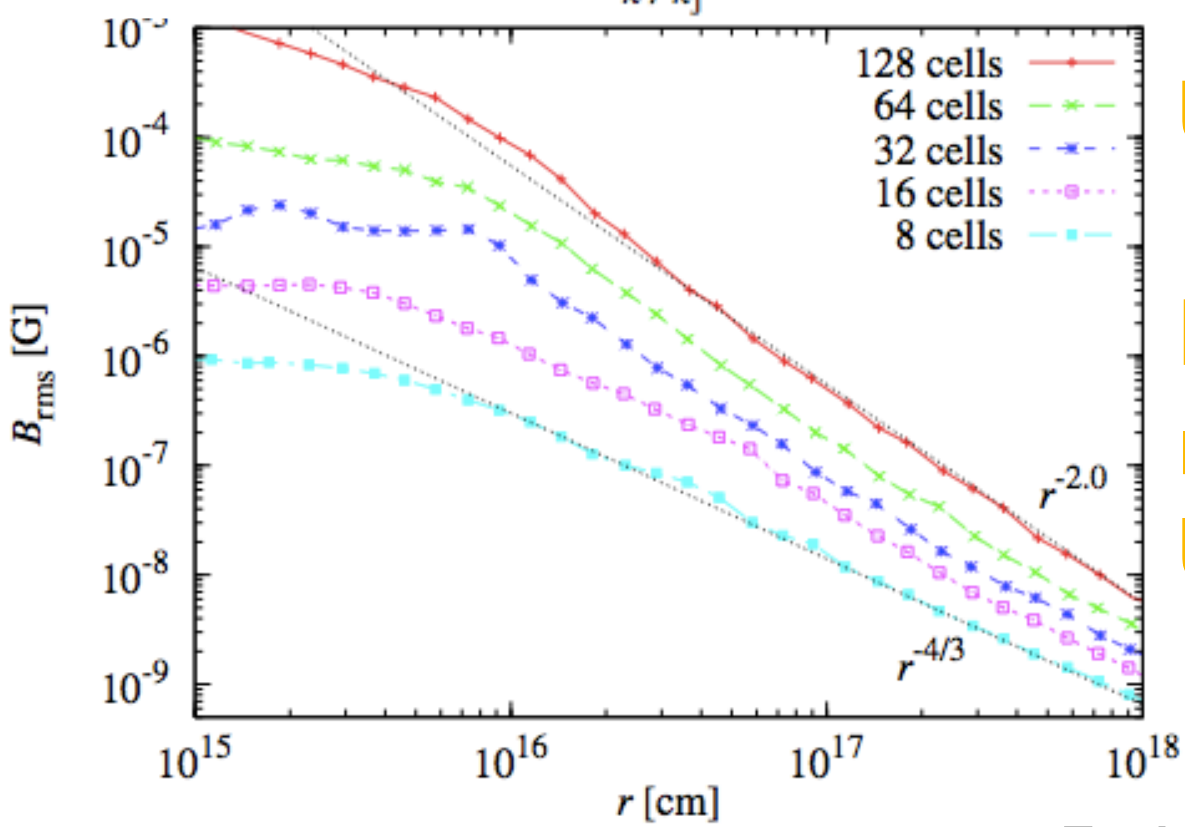
Federrath, Sur, Schleicher & Klessen (2011)

Star formation & magnetic fields:

Spectra and analysis







Upper left: Injection of turbulence at Jeans scale

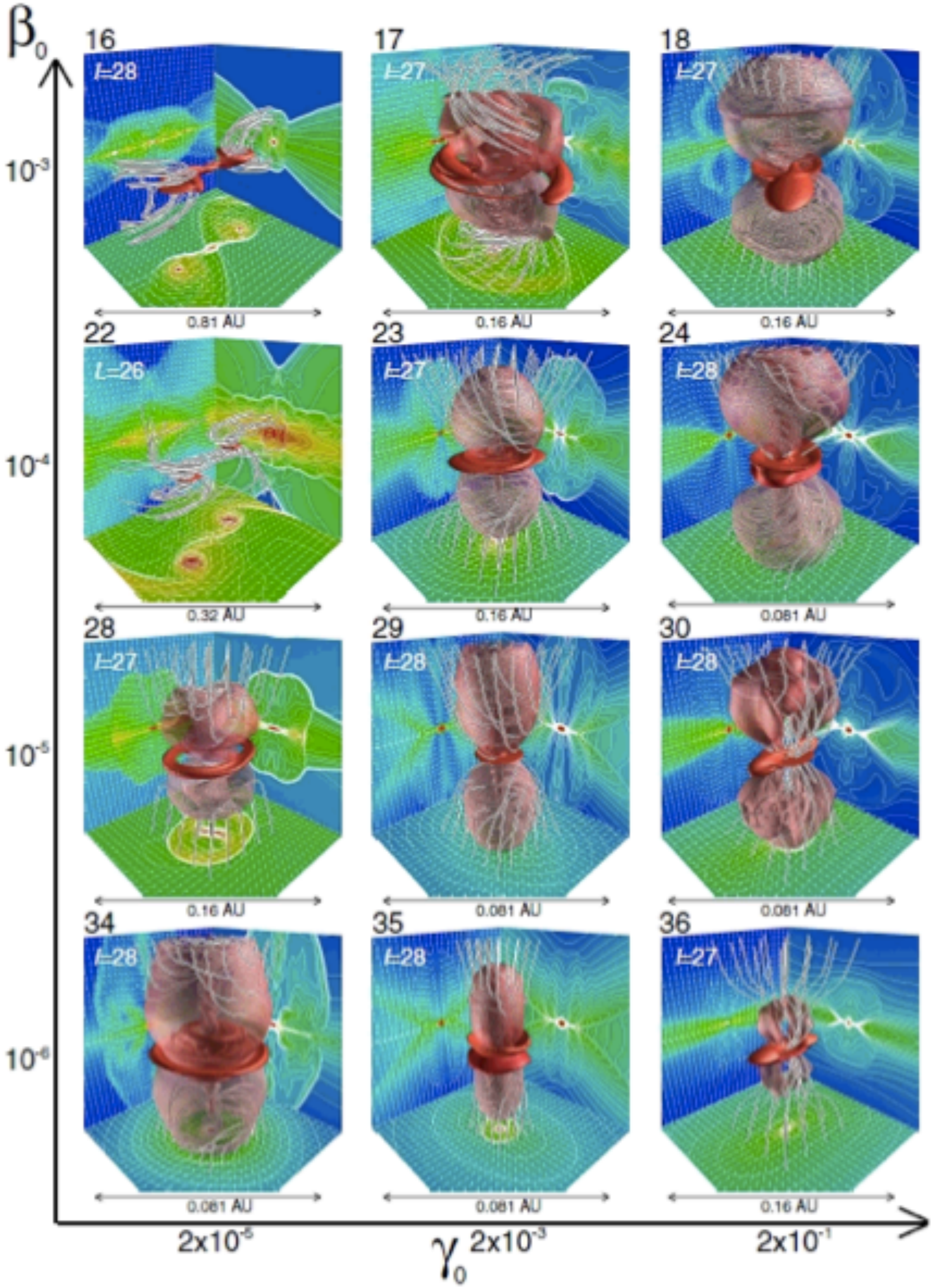
Lower left: Radial profile at different resolutions

Upper right: Evolution of field spectra

Federrath et al. (2011)

Star formation Then:

Is jet formation possible?



- beta$_0$: rotational over grav. energy
- gamma$_0$: magnetic over grav. energy
- gamma$_0$ > beta$_0$: jet
- gamma$_0$ < beta$_0$: fragmentation
- Magnetic fields may thus suppress fragmentation and lead to the formation of jets

Machida et al. (2008)

Star formation Then:

Summary and future work

- Initial field strength highly uncertain, potentially provided by the Biermann battery.
- Rapid amplification by the small-scale dynamo, strong dependence on the Reynolds number.
- Critical resolution of 32 cells per Jeans length for dynamo amplification and converged turbulent properties.
- Magnetic field structure highly tangled and non-trivial.
- Future work: Implications of global rotation -> more coherent fields in the disk?
- Future work: Implications for fragmentation -> larger clumps? See also talk Klessen.