Magnetic Fields in Molecular Clouds

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- Small-scale (~5-20pc) *isothermal* turbulence simulations

Question 3: Are weak fields in GMCs consistent with observations?

Comparison of simulations with Zeeman measurements:
- Energy ratios
- Core versus envelope

Question 1:

How strong is the <u>mean</u> magnetic field of GMCs?

Two different views on the magnetic field strength in clouds

1) The "traditional" view of molecular clouds

Strong mean magnetic field: Molecular clouds are magnetically supported

$E_{\mathrm{G}} \sim E_{\mathrm{K}} \sim E_{\mathrm{M}} \gg E_{\mathrm{TH}}$ → Star formation is controlled by **ambipolar drift**

(see review by *Shu, Adams & Lizano 1987*)

2) The super-Alfvénic model of molecular clouds

Padoan and Nordlund (1997-1999): **The mean magnetic field is weaker**

$E_{\mathrm{G}} \sim E_{\mathrm{K}} > E_{\mathrm{M}} > E_{\mathrm{TH}}$ → Super-Alfvénic turbulence:

- Molecular clouds are not magnetically supported
- The B field detected in dense cores is much larger than the mean B field
- ***Prestellar cores are formed by turbulent shocks, not by ambipolar drift***

Why are GMCs born super-Alfvénic?

GMCs are formed by large-scale compressions in the warm ISM (SN remnants).

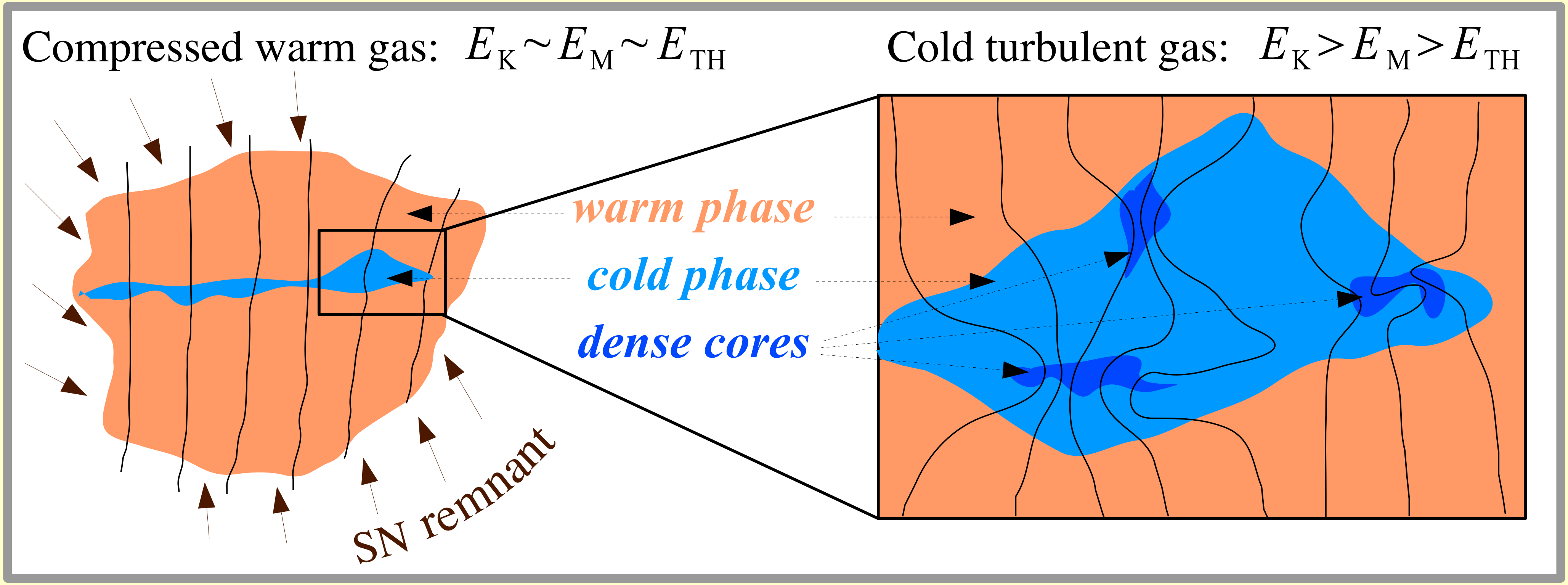
– Before the compression, the turbulence is trans-Alfvénic, or mildly super-Alfvénic.

– After the compression: $\rho_{\rm cold} \sim 100\, \rho_{\rm warm} \longrightarrow E_{\rm K,cold} = \rho_{\rm cold}\, u^2/2 \sim 100\, E_{\rm K,warm}$

The magnetic energy per unit volume initially does not change much

→ the turbulence becomes highly super-Alfvénic and supersonic.

→ B is *locally* stretched and compressed so $\langle B^2 \rangle$ grows, with $\langle B \rangle \sim$ const.



Large-scale multiphase MHD turbulence (PPML – 512^3)

Previous works with SN driving (*Korpi et al. 1999; Mac Low et al. 2005; De Avillez and Breitschwerdt 2005, 2007; Joung and Mac Low 2006, 2009)* have stressed the important role of dynamic pressure:

- Large gas mass fraction out of thermal equilibrium
- Densities and temperatures of GMCs are reached without gravity
- GMCs could be transient (though their cold gas may be longer-lived)
- Effective driving scale ~ 75 pc
- $\delta B/B_0 \sim 1$, not very large

Kritsuk et al. 2010: Idealized turbulent box:

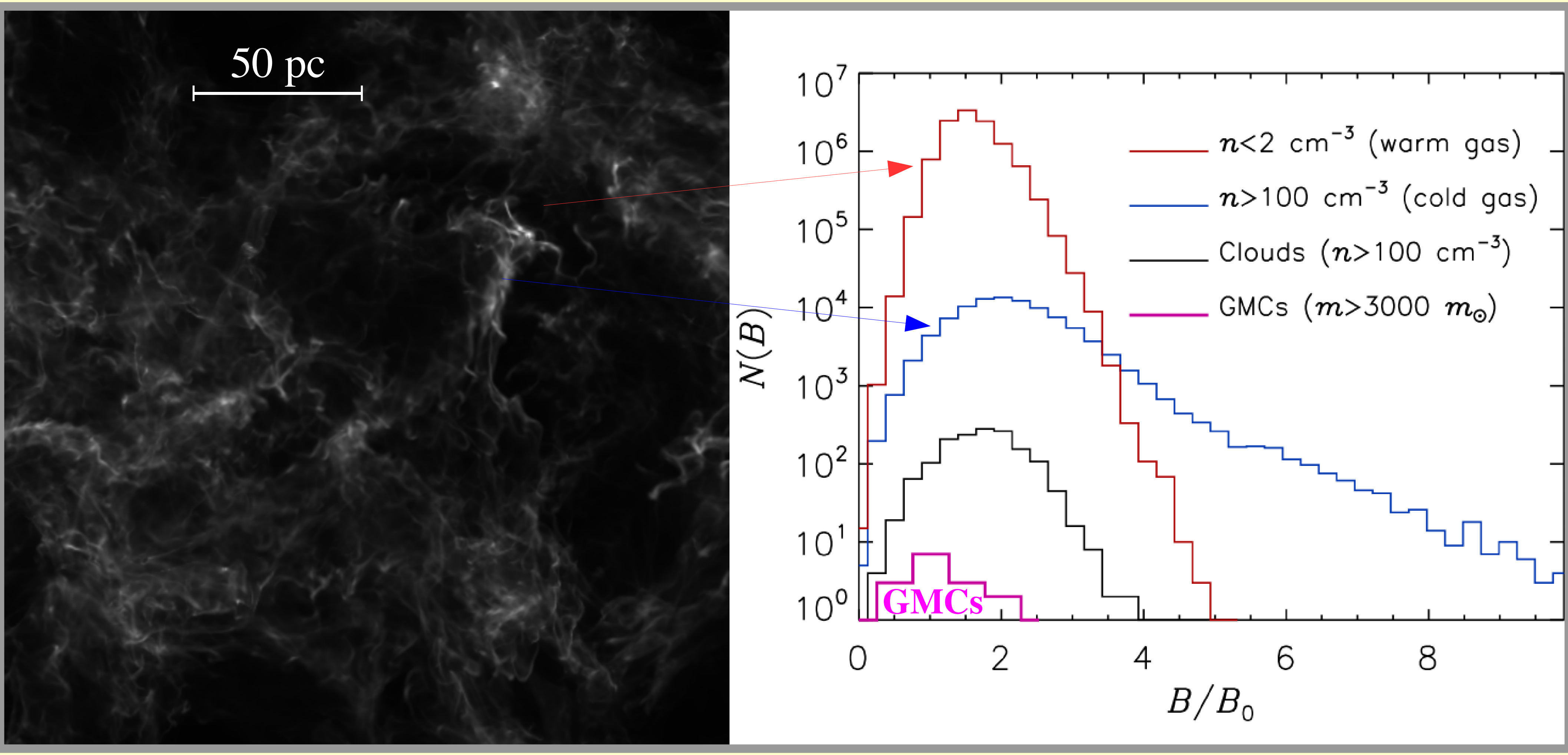
- $L = 200$ pc, random solenoidal forcing $1 < k < 2$, no SN, no gravity
- Periodic domain, 512^3 zones, $L = 200$ pc → **Δx = 0.39 pc**
- **$\mathcal{M}$s ≈ 4, $\mathcal{M}$a ≈ 2** (using mean gas pressure and B_0)
- $\langle n \rangle = 5$ cm^{-3}, **$n_{max} \approx$ 5,000 cm^{-3}**, $T_{min} = 18$ K
- Analytical cooling and heating rate approximations from *Wolfire et al. 2003*

<u>Result:</u> *GMCs have $\langle B \rangle \sim B_0$ (large-scale mean magnetic field), even if they are ~100 times denser than the mean.*

Cold clouds: $\langle B_{\mathrm{MC}}\rangle \approx 2\, B_0$, $\langle B_{\mathrm{GMC}}\rangle \approx B_0$

→ Clouds are born with a weak mean magnetic field

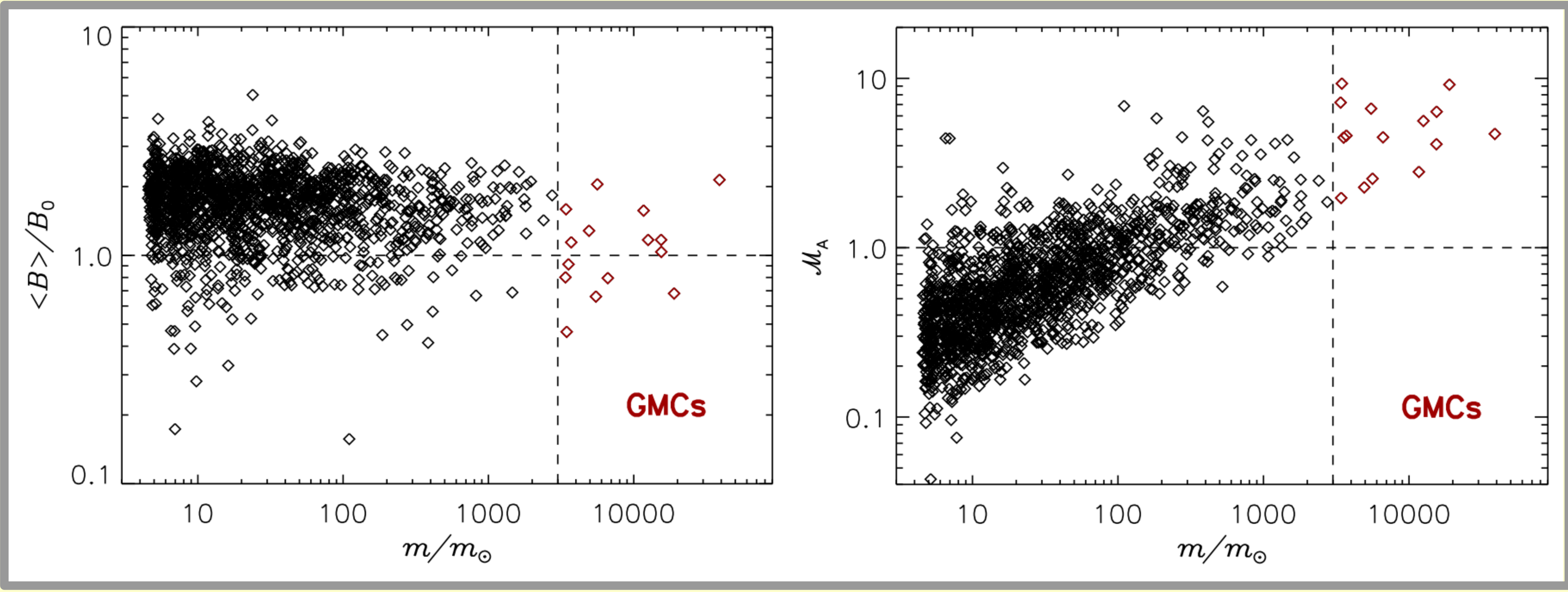
→ Almost no *B* compression going from warm gas to cold clouds!



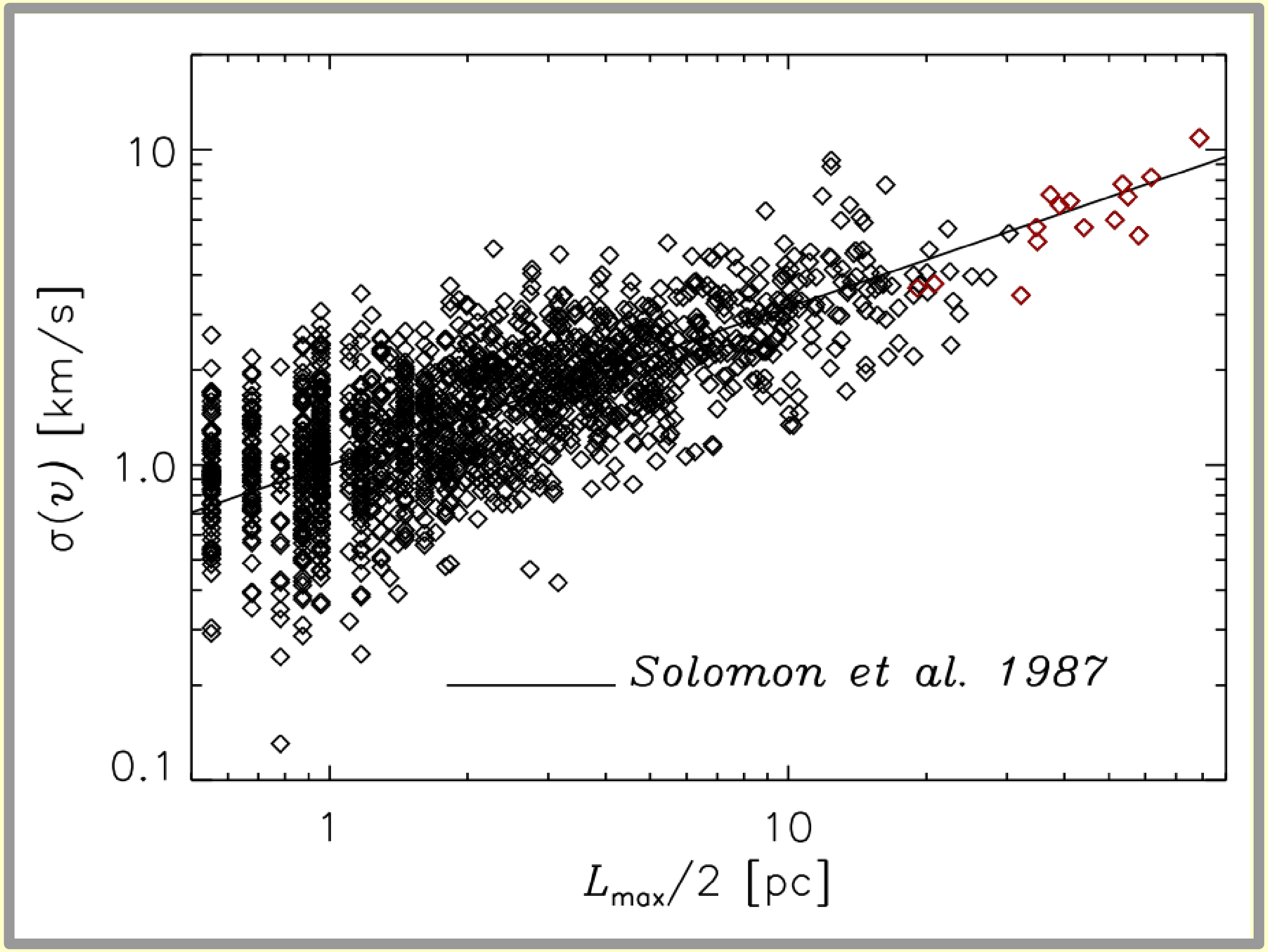
As a result of the weak mean magnetic field, GMCs are super-Alfvénic with respect to their own <*B*>: $\mathbf{2 < \mathcal{M}_{A,GMC} < 10}$

Only smaller clouds can be in equipartition, or sub-Alfvénic (but notice that all clouds were selected with the same density threshold, ~100 cm^{-3}).

$\mathbf{<B_{GMC}> \approx B_0}$ $\mathbf{<\mathcal{M}_{A,GMC}> \approx 5}$



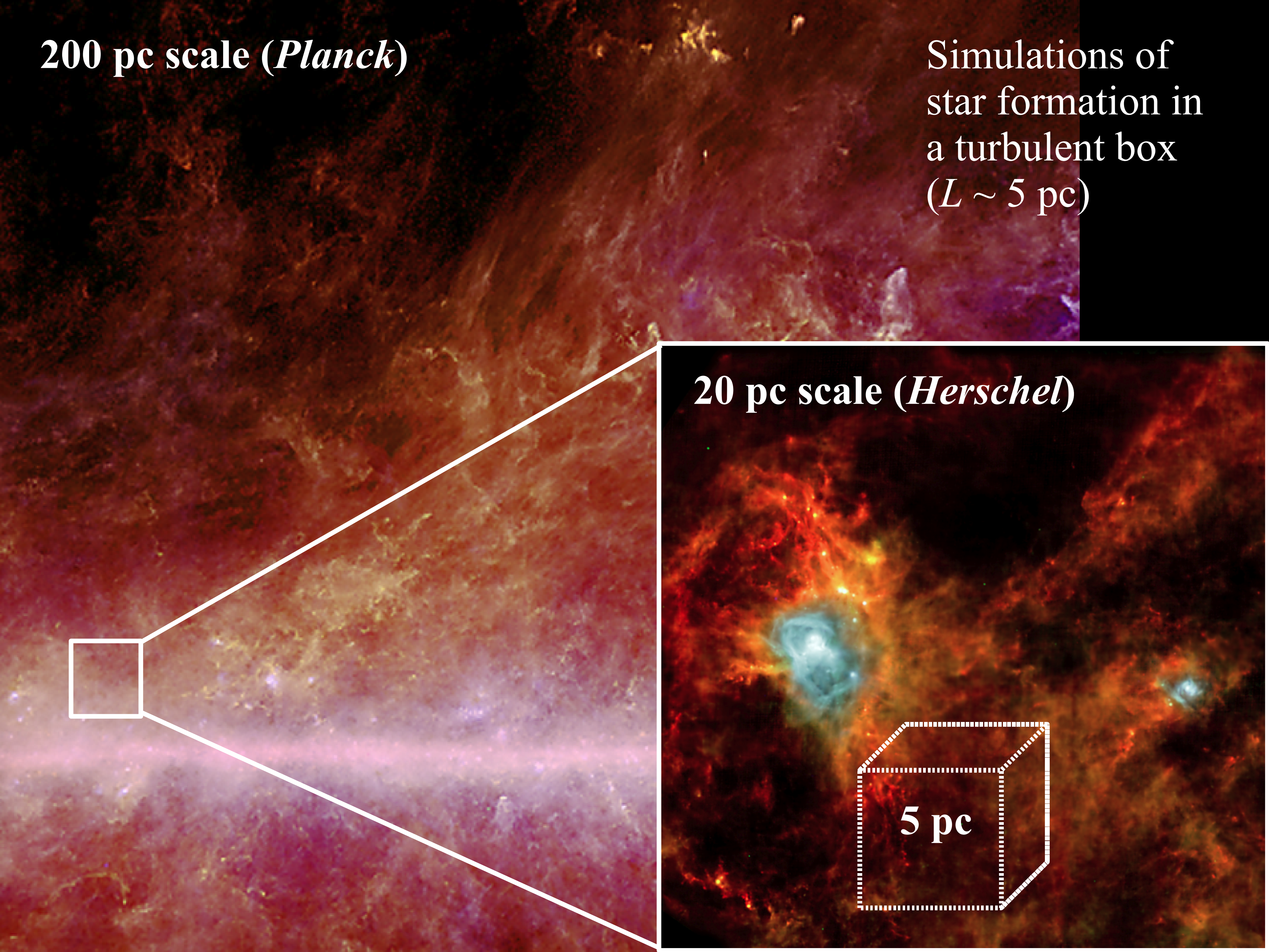
Velocity-size relation: Large clouds have large velocity dispersion, but $\langle B \rangle \sim B_0$ (flat *B*-*n* relation), hence they are very super-Alfvénic.



Question 2:

How strong is the rms magnetic field of GMCs?

From large-scale (200 pc) multiphase MHD turbulence
to small-scale (5 pc) isothermal MHD turbulence



Simulations of
star formation in
a turbulent box
($L \sim 5$ pc)

Numerical simulations of MHD turbulence (PPML – 1024^3)

(*Ustyugov et al. 2009; Kritsuk et al. 2009a,b, 2010*)

- Uniform initial magnetic and density fields
- Large scale ($1 < k < 2$), random, solenoidal initial velocity and forcing
- Forcing for several crossing times → steady state
- No gravity, no ambipolar drift, isothermal equation of state

$$\beta_0 = 2\, c_S^2 / v_{A,0}^2 = 2\, (\mathcal{M}_{A,0} / \mathcal{M}_S)^2$$

<u>Based on mean *B* and *n*:</u>

$\mathcal{M}_S$	$\mathcal{M}_{A,0}$	β_0
10	31.6	20.0
10	10.0	2.0
10	3.2	0.2

→

<u>Based on rms v_A:</u>

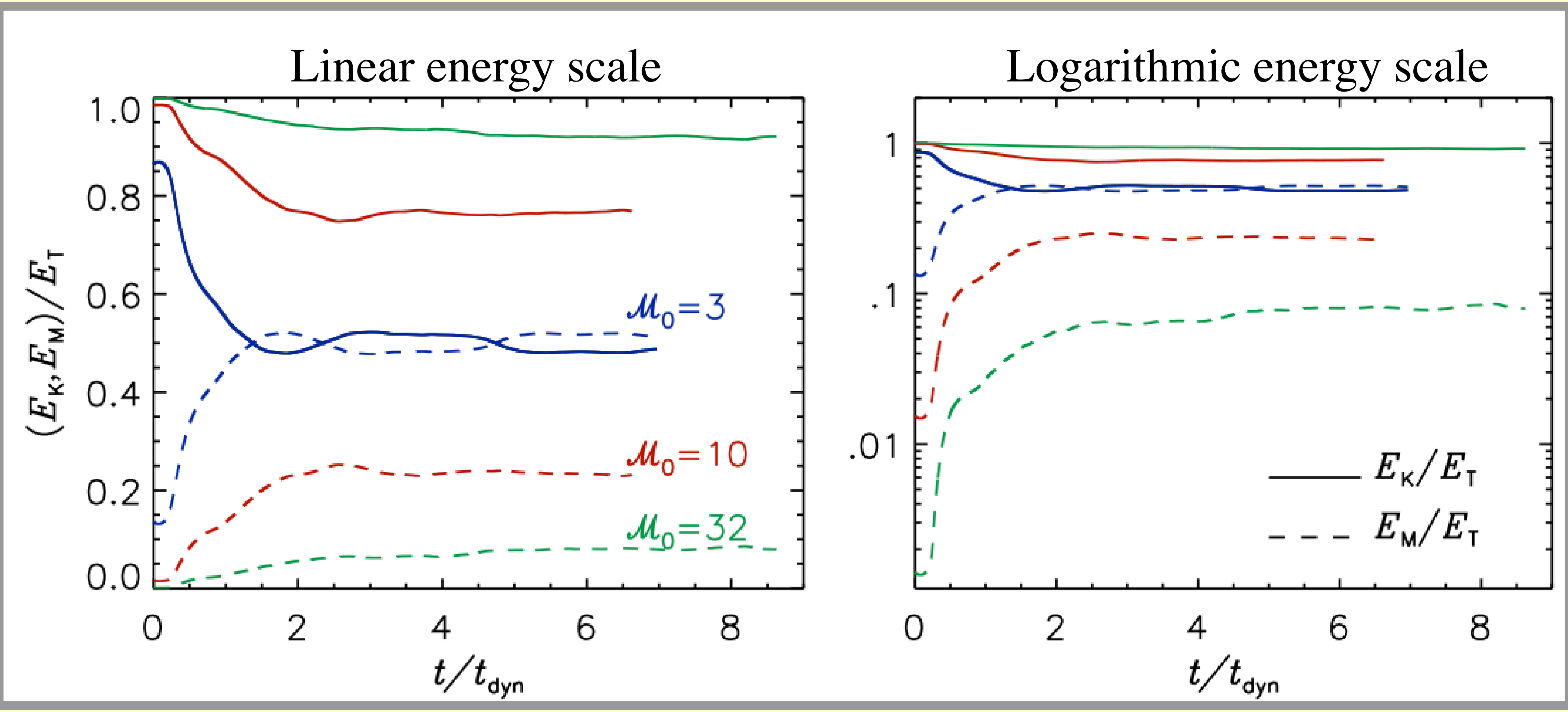
β
0.11
0.03
0.01

All these models are *super-Alfvénic* with respect to the *mean* magnetic field (lower mean magnetic field than in the “standard” model).

Is $<B^2>$ amplified to equipartition by a turbulent dynamo?

Time evolution of magnetic energy

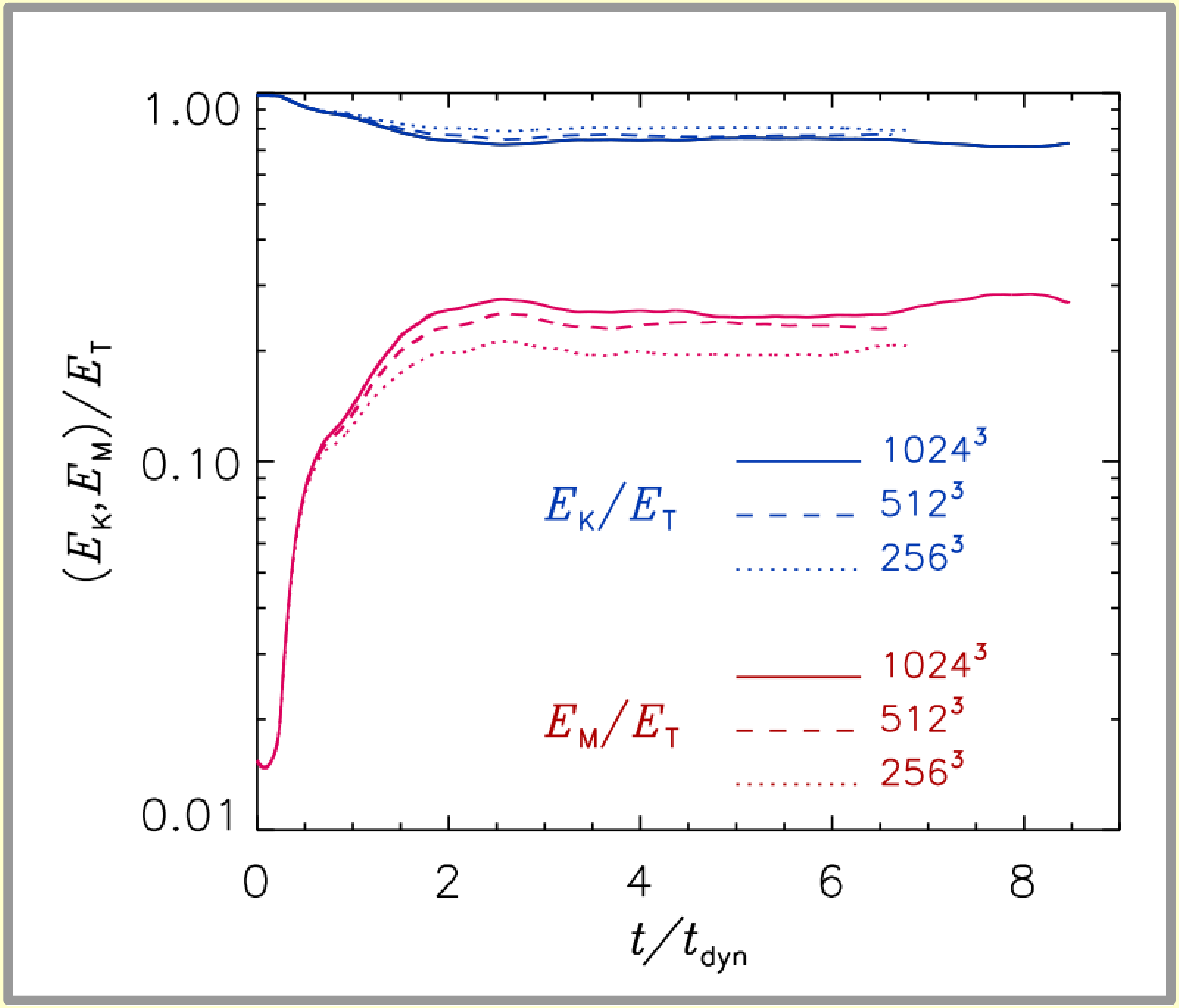
Rapid saturation of E_m to a level *below equipartition* for $\mathcal{M}_{\mathrm{A},0}=10$ and 30
→ The turbulent dynamo is inefficient in supersonic turbulence.


Linear energy scale

Logarithmic energy scale

Haugen et al. 2004: At Pr_M~1 and $\mathcal{M}_\mathrm{S}$~2.5 the critical magnetic Reynolds number for dynamo action is $Re_\mathrm{M,cr}=80$, and depends weakly on $\mathcal{M}_\mathrm{S}$.
But they find some evidence of growth rate decreasing with increasing $\mathcal{M}_\mathrm{S}$.

Numerical convergence for $\mathcal{M}_{A,0}$=10

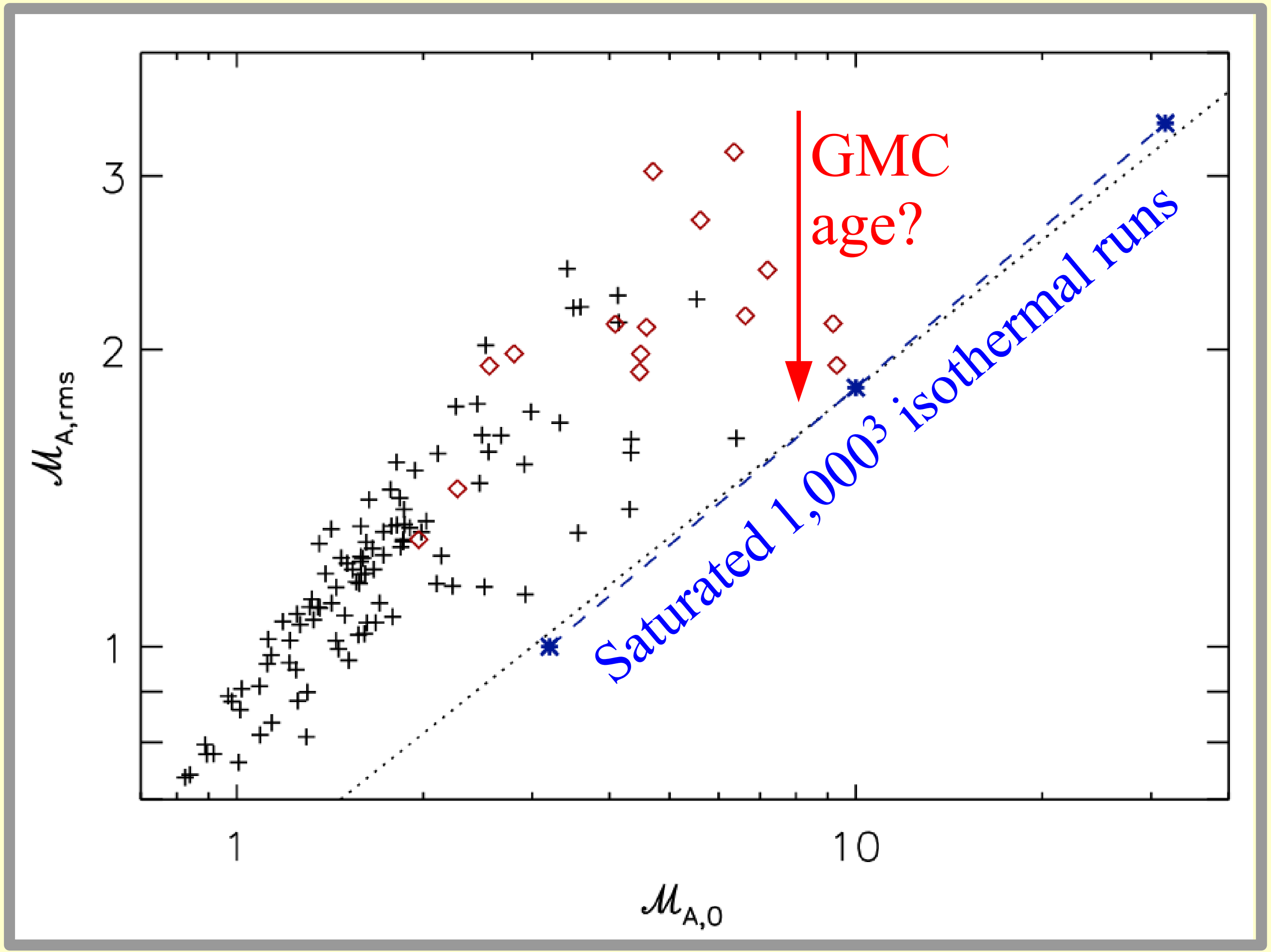


The “GMCs” selected from the multiphase runs have $\mathcal{M}_{\rm A,0}$ in the range 2 – 10.

According to the isothermal runs, approximately half of these GMCs should reach equipartition with respect to the rms B, *in 2 – 3 dynamical times*.

Indeed, their $\mathcal{M}_{\rm A,rms}$ values are scattered within a factor of two above the saturated values of the 1,000^3 isothermal runs ⟶ Age of transient GMCs in the turbulent flow?

$$\mathcal{M}_{\rm A,rms} \equiv \frac{\sigma_{\rm v,3D}}{\langle B(x)^2/4\pi\rho(x)\rangle^{1/2}} \qquad \mathcal{M}_{\rm A,0} \equiv \frac{\sigma_{\rm v,3D}}{B_0/(4\pi\rho_0)^{1/2}}$$



GMC age?

Saturated 1,000^3 isothermal runs

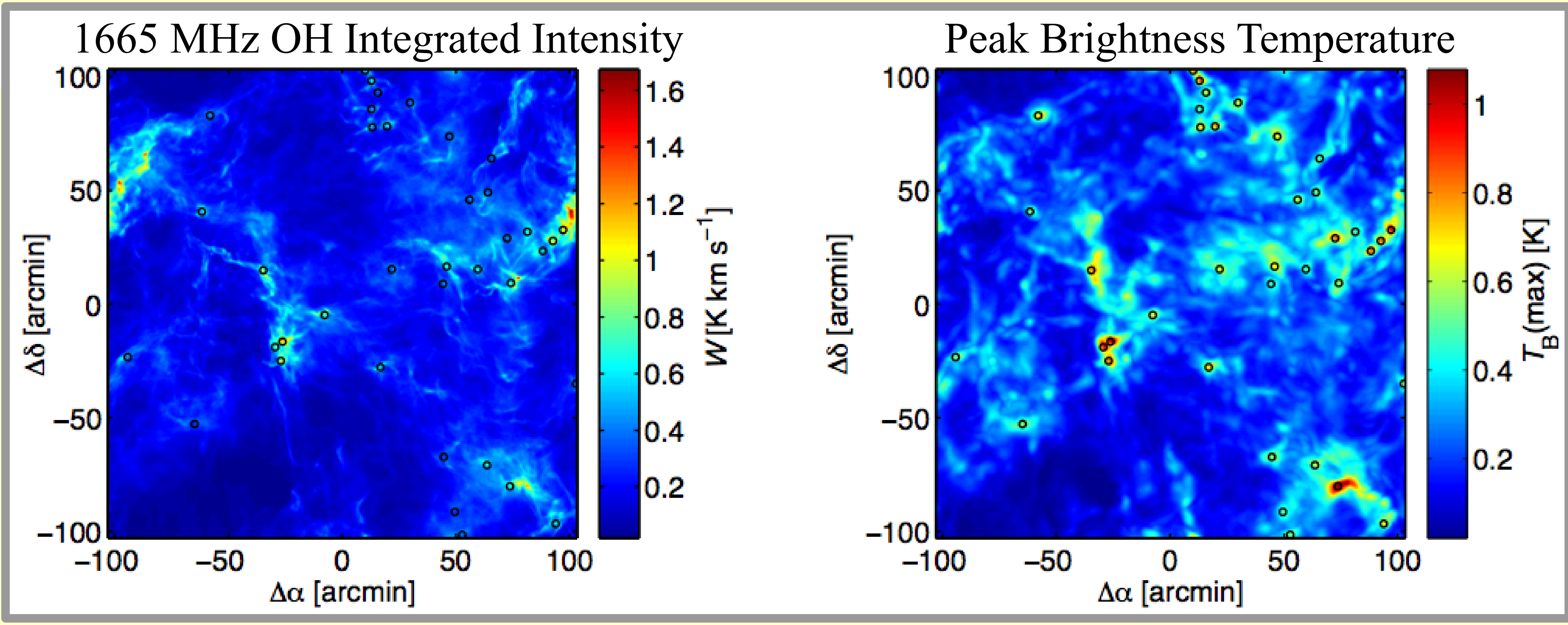
Question 3:

Are weak fields in GMCs consistent with observations?

Synthetic Zeeman Measurements from MHD Simulations

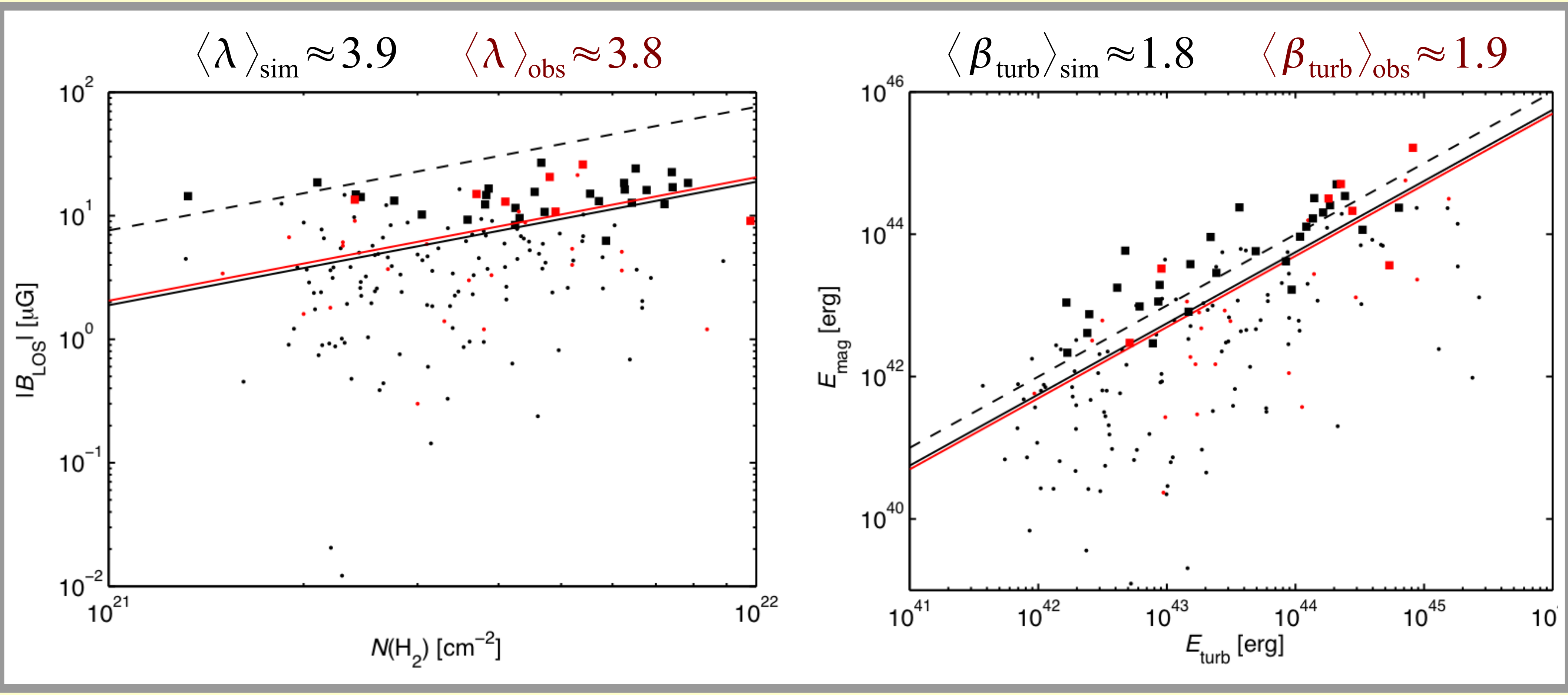
Lunttila et al. 2009: Solution of the coupled radiative transfer equations for the four Stokes parameters (1665 and 1667 MHz OH lines)

Very low mean field, $\langle B \rangle = 0.34\ \mu\mathrm{G}$ (but $\langle B^2 \rangle^{1/2} = 3.05\ \mu\mathrm{G}$)



Core selection in the 1665 MHz OH maps (3' beam) with P-P-V clumpfind algorithm (*Williams et al. 1995*): *Cores correspond to brightness temperature peaks (not so much to projected density structures).*

Comparison with Observations (*Troland and Crutcher 2008*)



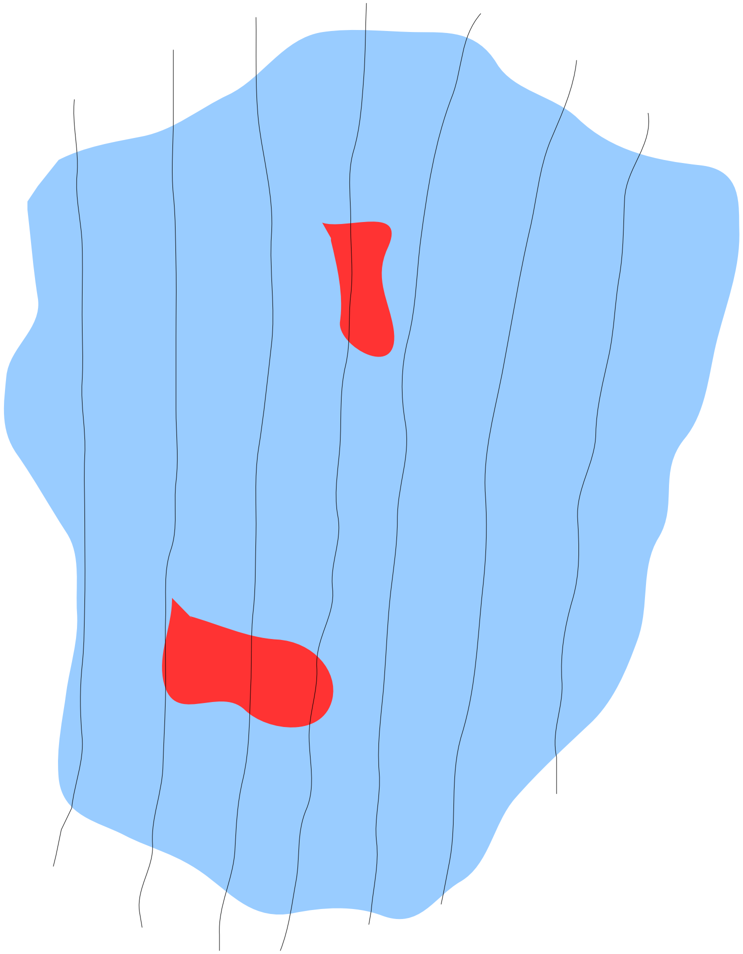
Using only detections:

$\langle \lambda \rangle_{sim} \approx 2.5 \pm 0.4$, $\langle \lambda \rangle_{obs} \approx 2.5 \pm 0.6$ $\langle \beta_{turb} \rangle_{sim} \approx 0.6 \pm 0.4$, $\langle \beta_{turb} \rangle_{obs} \approx 0.9 \pm 0.6$

The mass-to-flux ratio and the magnetic-to-kinetic energy ratio in the cores are consistent with the observations, despite the very low mean magnetic field.

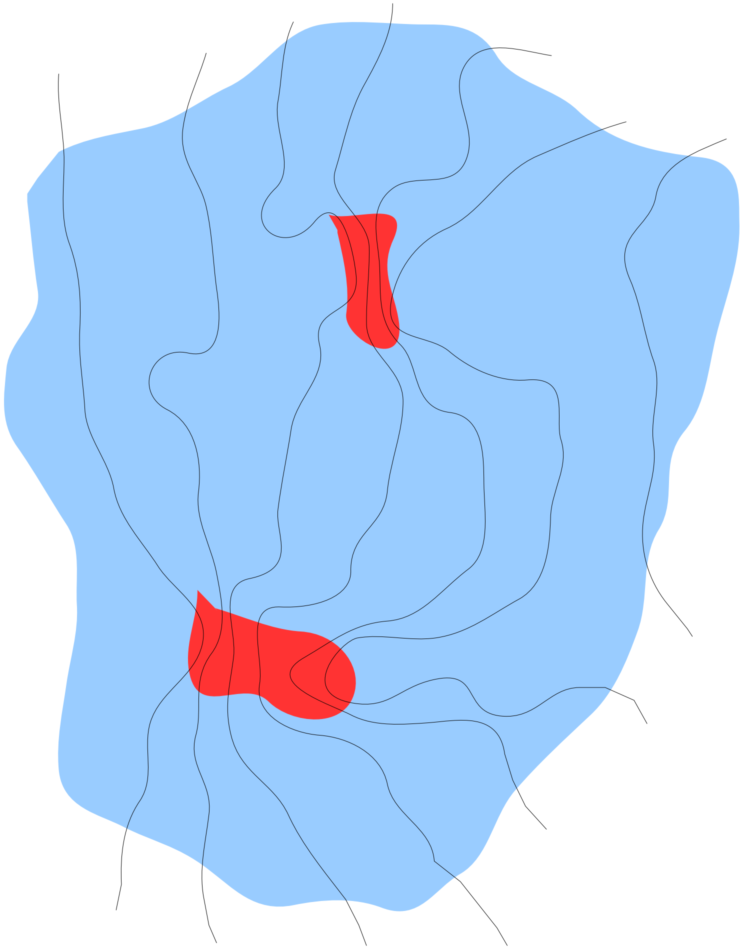
Is the mean B in the envelope as strong as inside the dense core?

Strong Mean Field: $E_G \sim E_K \sim E_M$



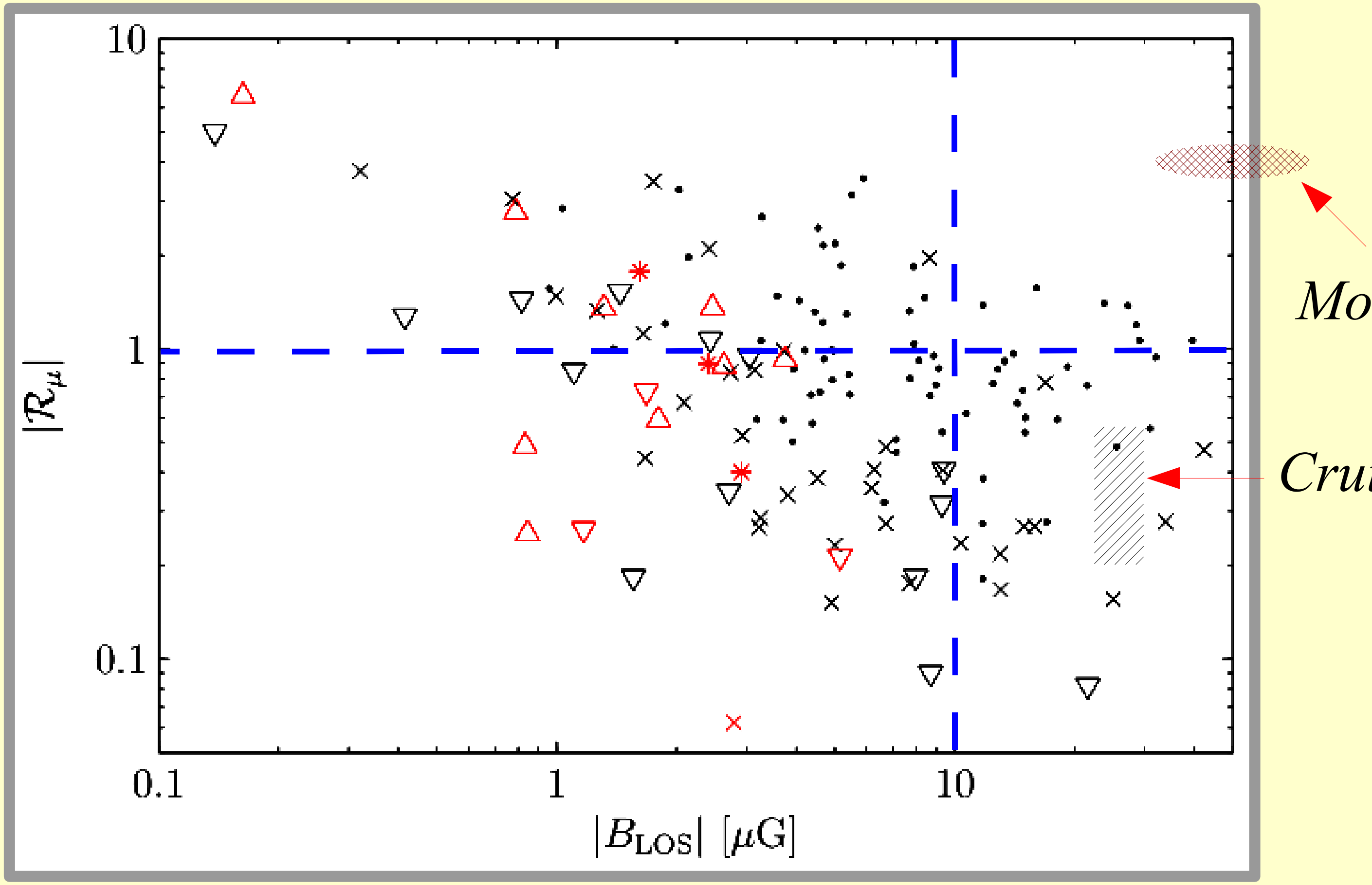
Cores formed by ambipolar drift

Weak Mean Field: $E_G \sim E_K > E_M$



Cores formed by turbulent shocks

Ratio between mass-to-flux in the core and in the envelope



Ciolek & Mouschovias 1994

Crutcher et al. 2009

Prediction of super-Alfvénic turbulence (*Lunttila et al. 2008*): Large scatter in R_μ , **R_μ < 1** for B >10 μG

Prediction of ambipolar-drift model of core formation (*Ciolek & Mouschovias 1994*): **R_μ > 1** (~ 4)

Crutcher et al. 2008: **R_μ = 0.41±0.2** (for the core B1)

Conclusions

Giant Molecular Clouds are super-Alfvénic with respect to their $<B>$.

In most GMCs the turbulence may remain super-Alfvénic also with respect to $<B^2>^{1/2}$, unless $\mathcal{M}_{A,0} \leq 3$ and the cloud is older than ~ 2 dynamical times.

Super-Alfvénic simulations yield magnetic field strength and energy ratios in dense cores consistent with the observed values based on Zeeman measurements.

The predicted relative mass-to-flux ratio (core to envelope) is consistent with Zeeman measurements of molecular cores.