# Magnetic Fields in Molecular Clouds

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**Question 2: How strong is the <u>rms</u> magnetic field of GMCs?**

Magnetic field amplification in supersonic MHD turbulence:
- 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

$E_G \sim E_K \sim E_M \gg E_{TH}$ $\rightarrow$ 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**

$E_G \sim E_K > E_M > E_{TH}$ $\rightarrow$ 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).

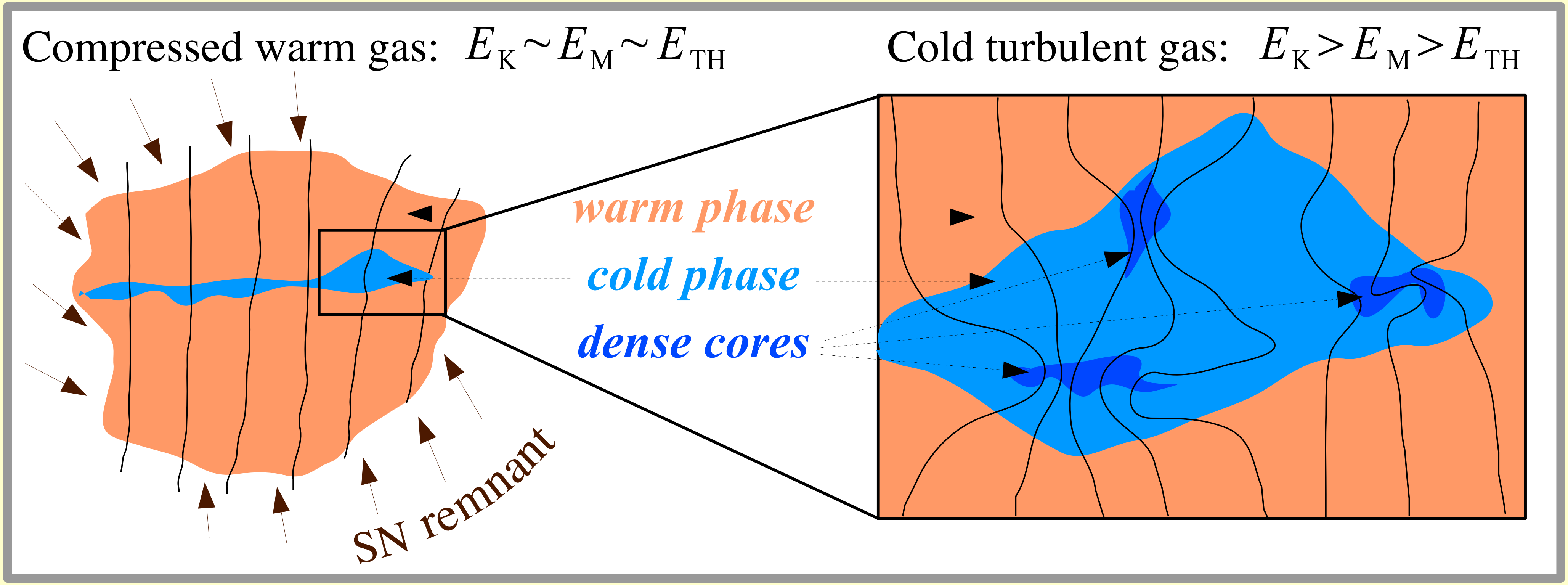
– Before the compression, the turbulence is trans-Alfvénic, or mildly super-Alfvénic.

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

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

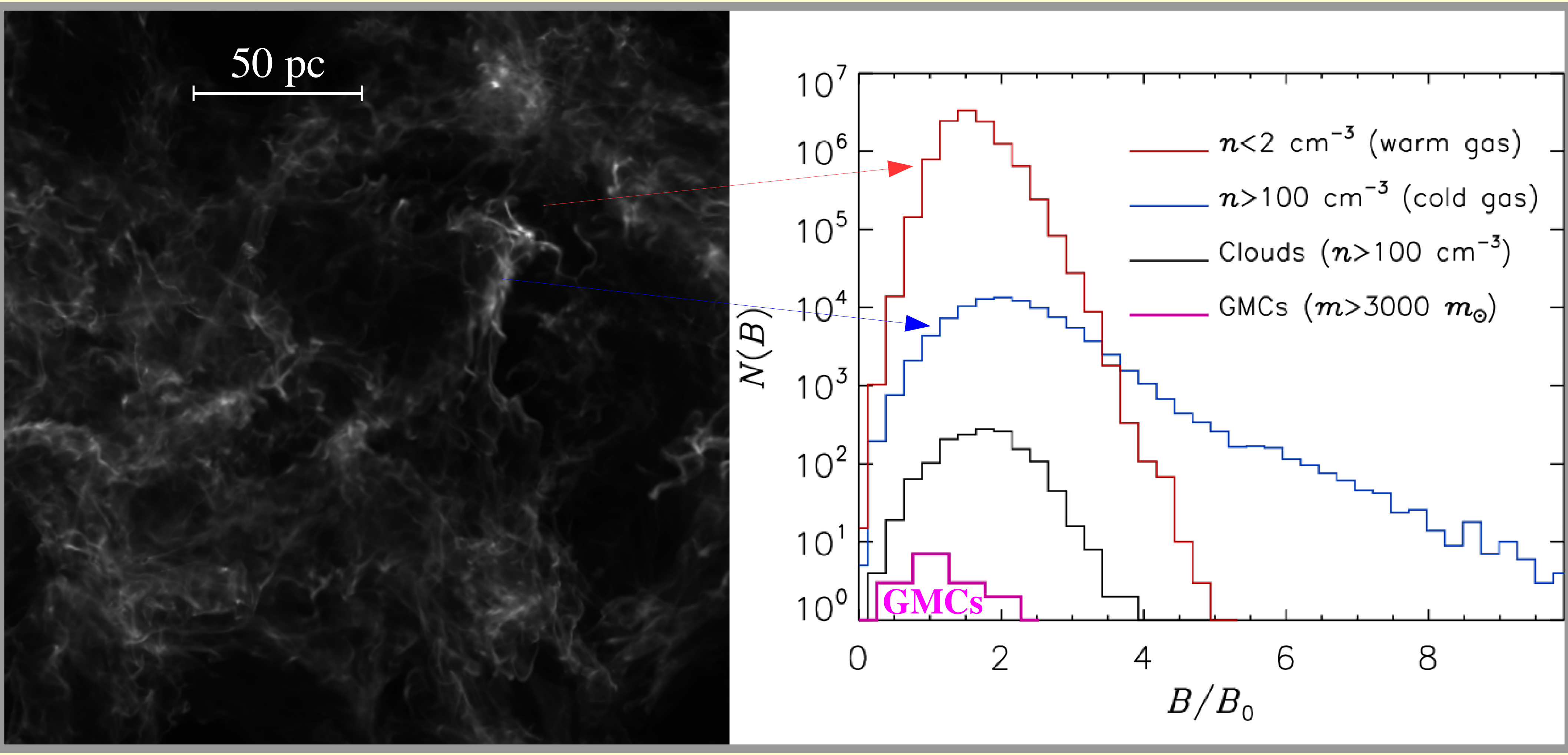
*Kritsuk et al. 2010*: Idealized turbulent box:

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

Result: *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: $\langle B_{MC} \rangle \approx 2\, B_0$ , $\langle B_{GMC} \rangle \approx B_0$

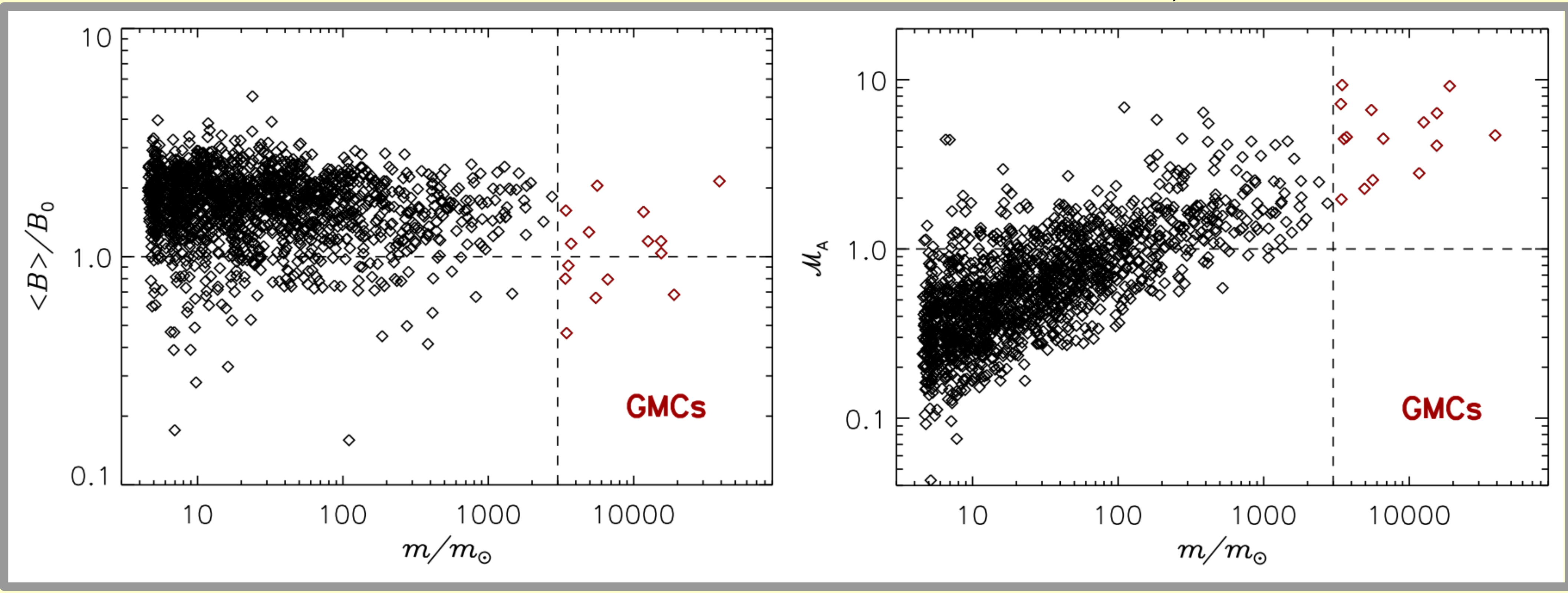
→ Clouds are born with a weak mean magnetic field
→ Almost no $B$ compression going from warm gas to cold clouds!



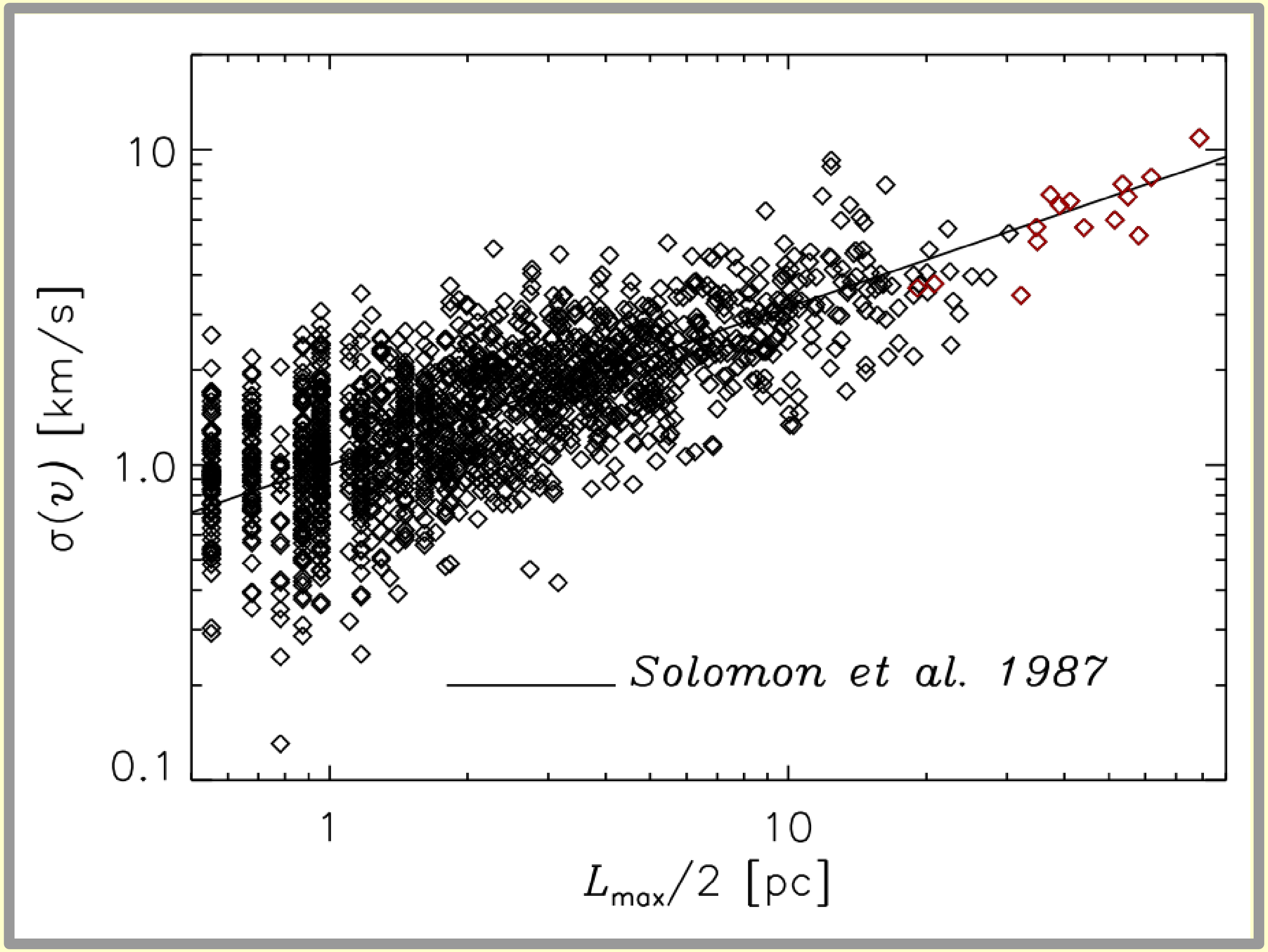
As a result of the weak mean magnetic field, GMCs are super-Alfvénic with respect to their own <*B*>.

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

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



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



## Question 2:

## How strong is the rms magnetic field of GMCs?

## 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

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

Based on mean $B$ and $n$:

| $\mathcal{M}_S$ | $\mathcal{M}_{A,0}$ | $\beta_0$ |
|---|---|---|
| 10 | 31.6 | 20.0 |
| 10 | 10.0 | 2.0 |
| 10 | 3.2 | 0.2 |

→

Based on rms $v_A$:

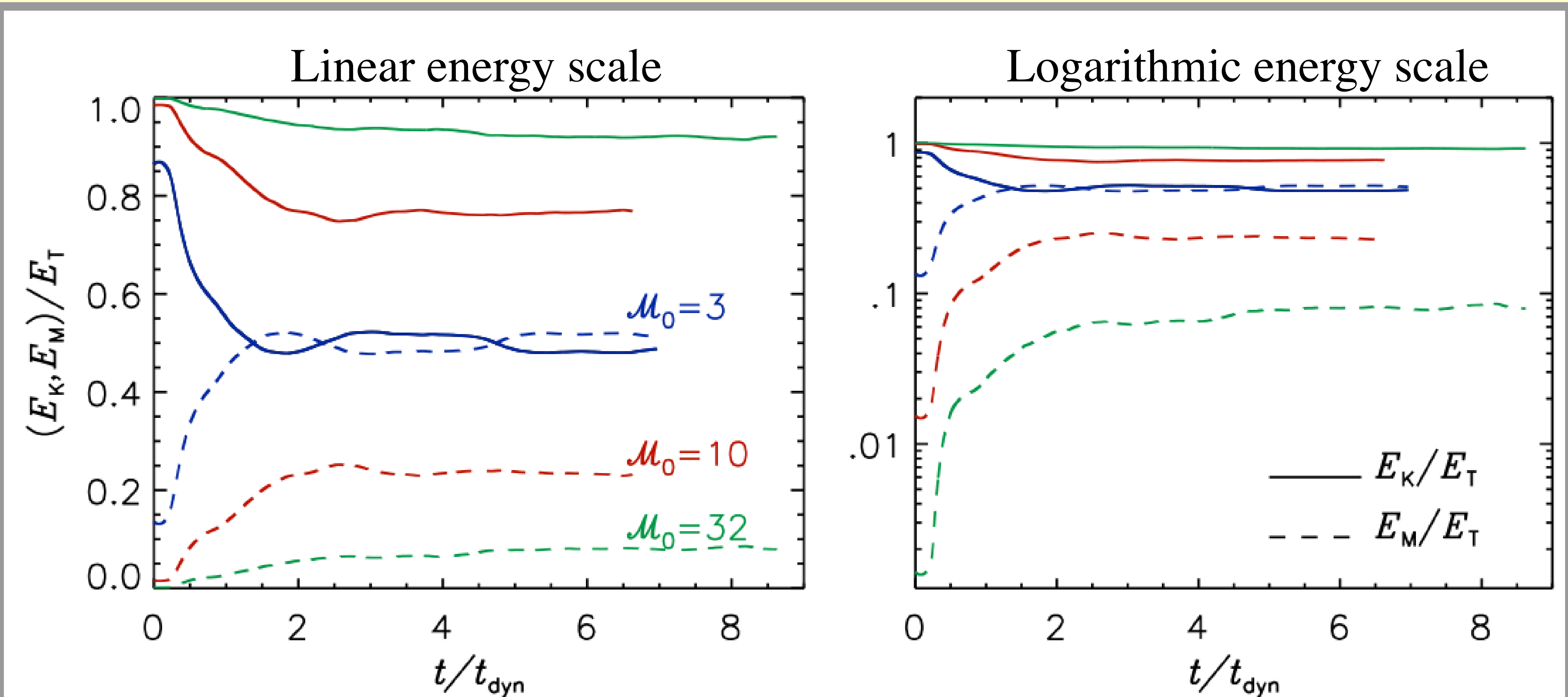
| $\beta$ |
|---|
| 0.11 |
| 0.03 |
| 0.01 |

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

*Is* $\langle B^2 \rangle$ *amplified to equipartition by a turbulent dynamo*?

# Time evolution of magnetic energy

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

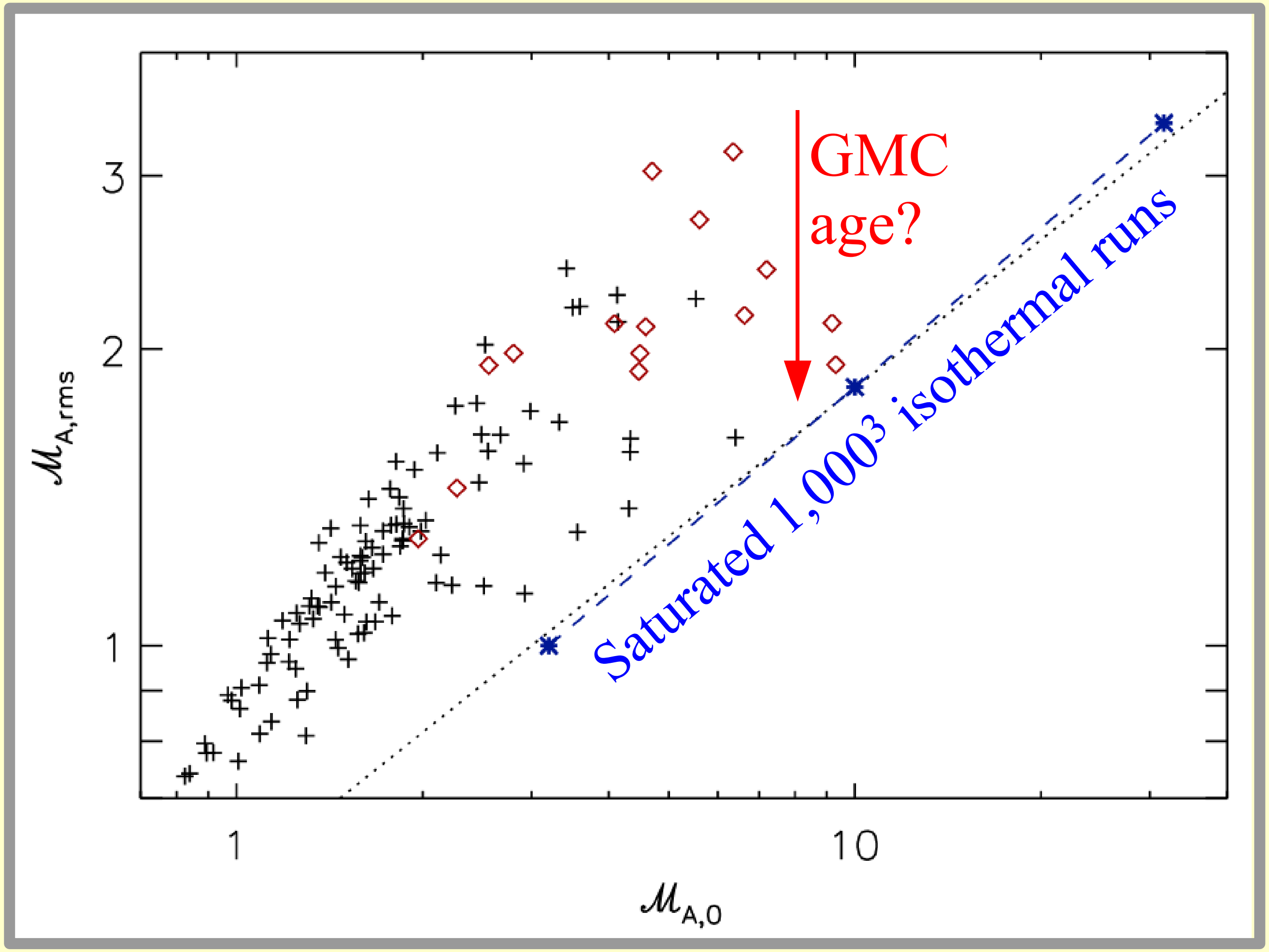



*Haugen et al. 2004*: At $Pr_{\mathrm{M}}$~1 and $\mathcal{M}_{\mathrm{S}}$~2.5 the critical magnetic Reynolds number for dynamo action is $Re_{\mathrm{M,cr}}$=80, and depends weakly on $\mathcal{M}_{\mathrm{S}}$.
But they find some evidence of growth rate decreasing with increasing $\mathcal{M}_{\mathrm{S}}$.

The “GMCs” selected from the multiphase runs have $\mathcal{M}_{A,0}$ 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 $\mathcal{M}_{A,rms}$ 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?



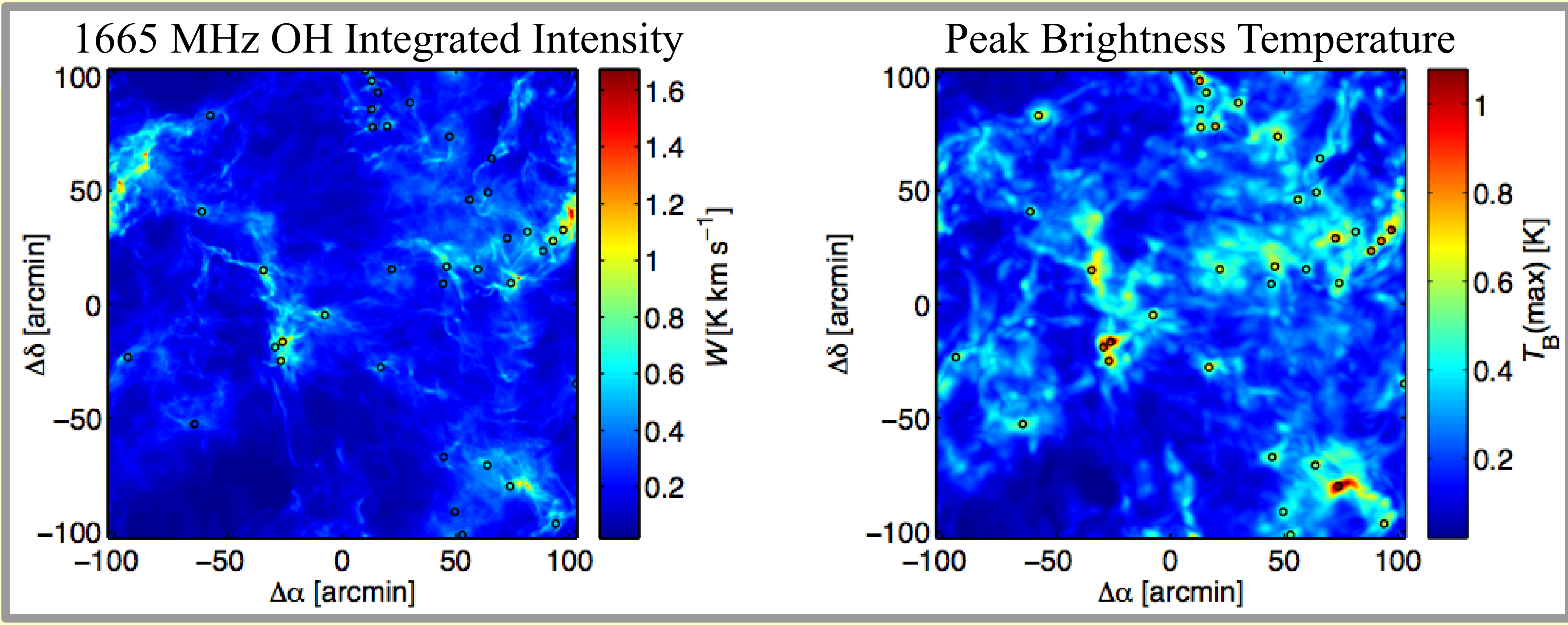
## Question 3:

## Are weak fields in GMCs consistent with observations?

# Synthetic Zeeman Measurements from MHD Simulations

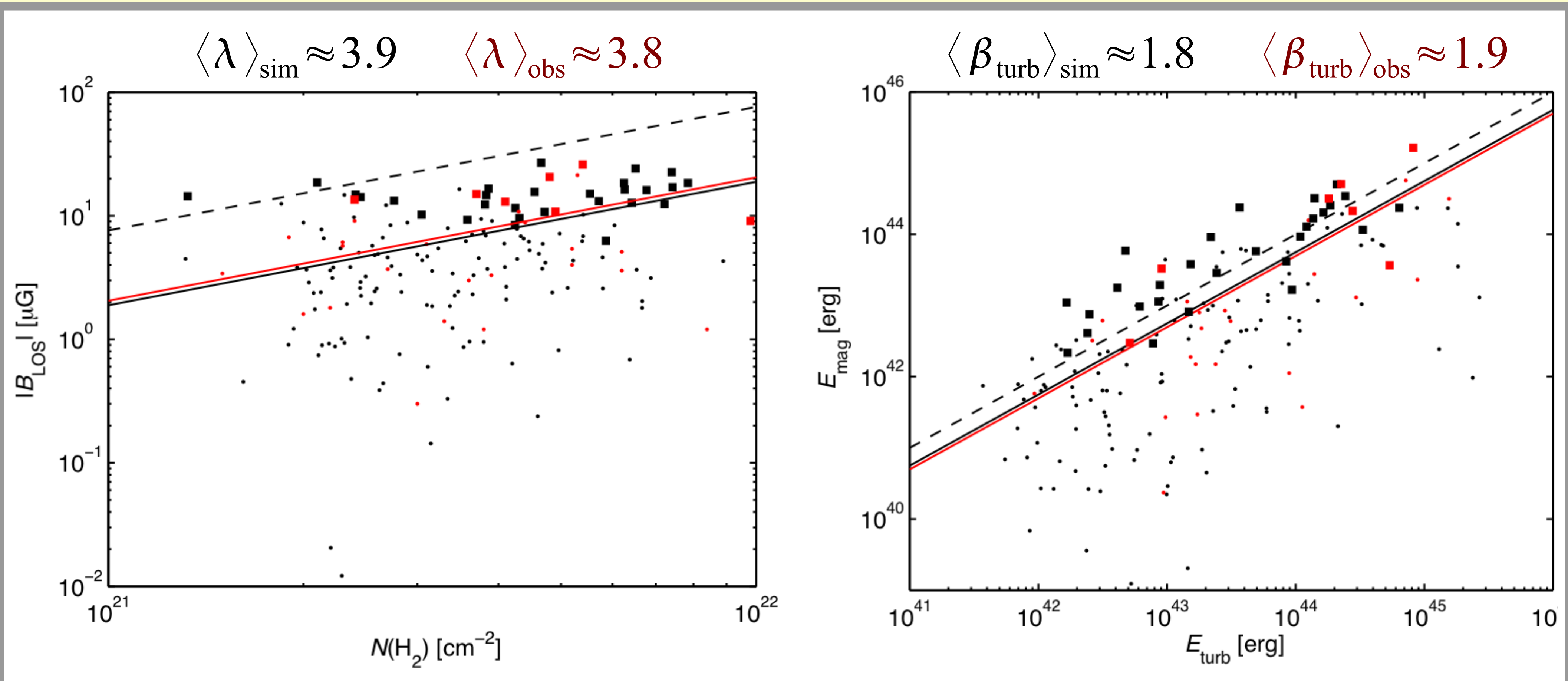
*Lunttila et al. 2009*: Solution of the coupled radiative transfer equations for the four Stokes parameters (1665 and 1667 MHz OH lines)

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




**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*)



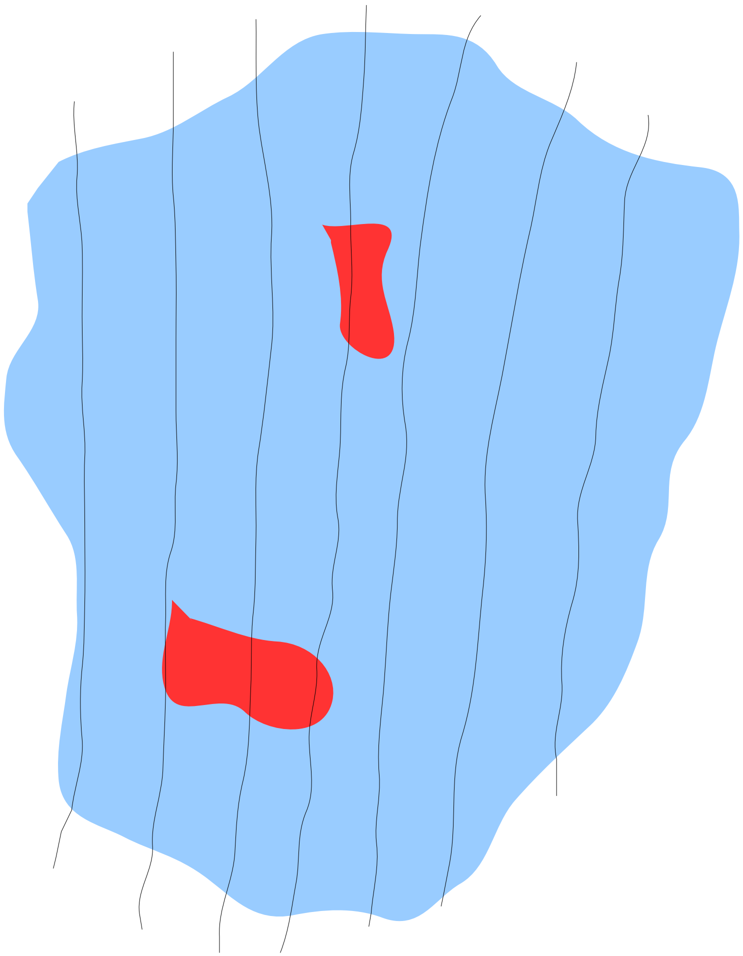

Using only detections:

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

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.

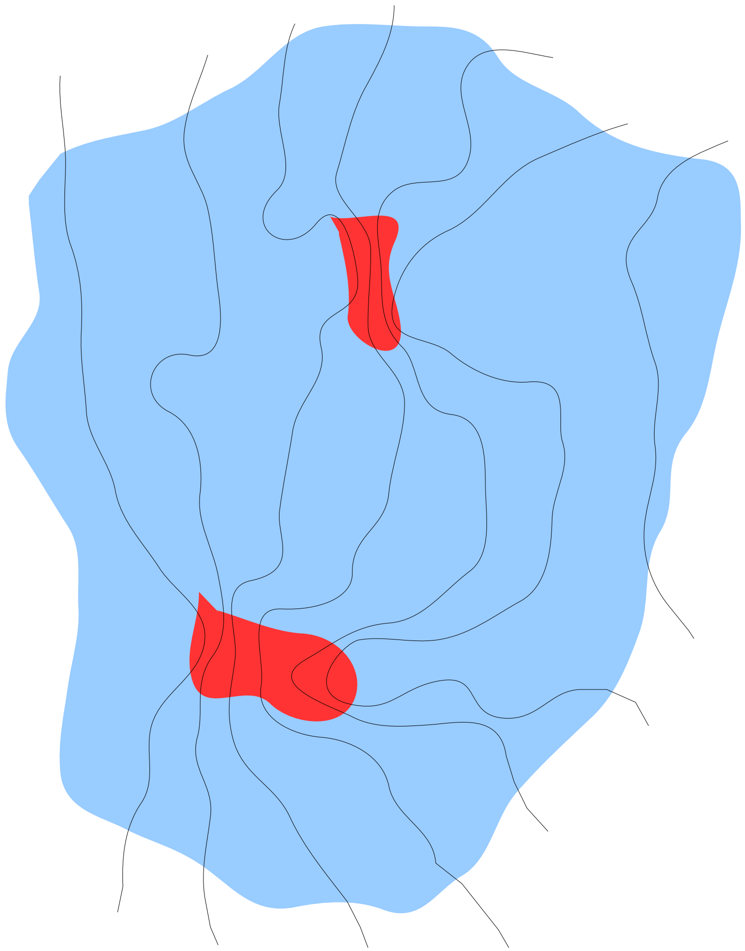
## *Is the mean B in the envelope as strong as inside the dense core?*

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



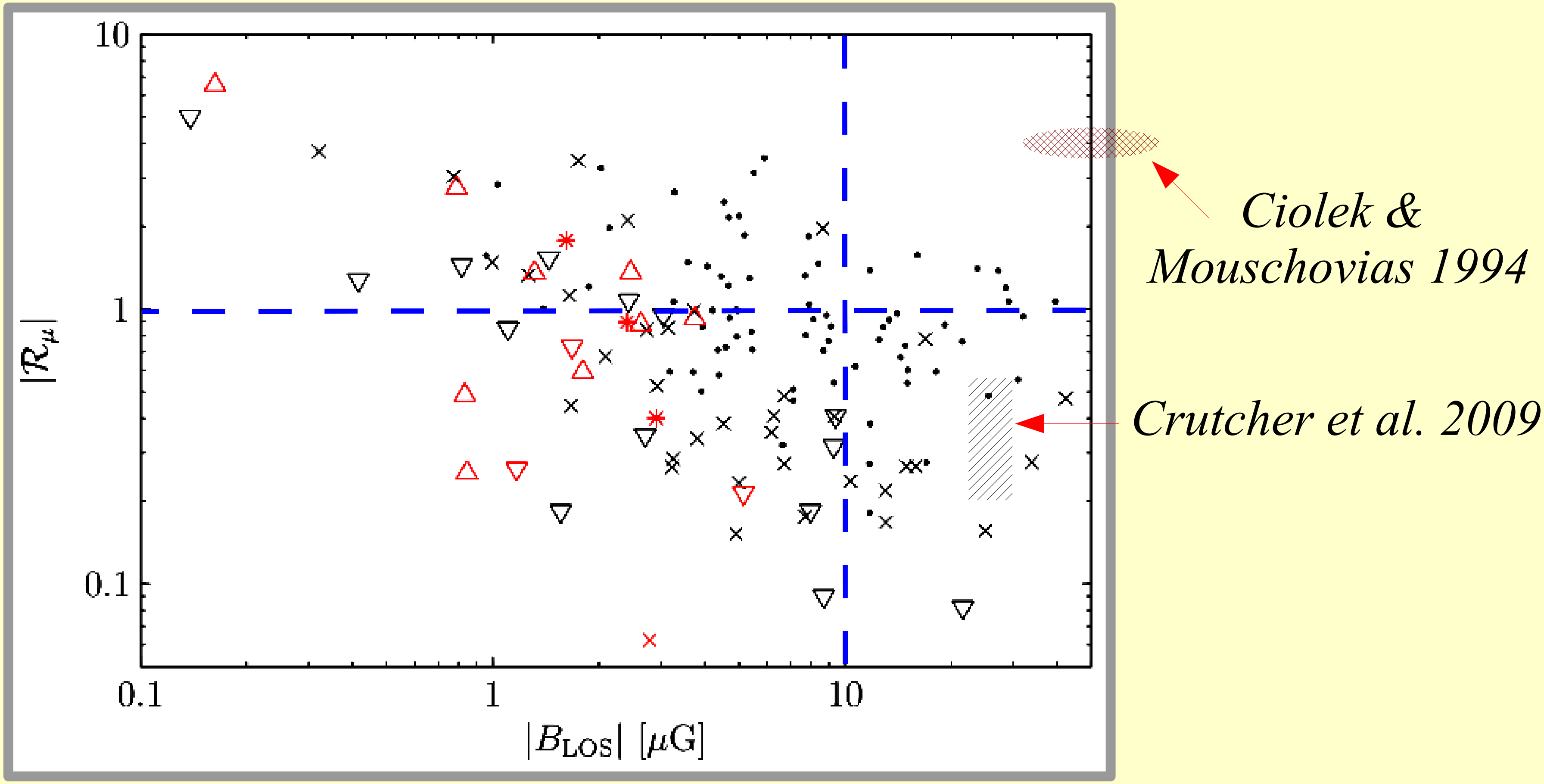
Cores formed by ambipolar drift

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



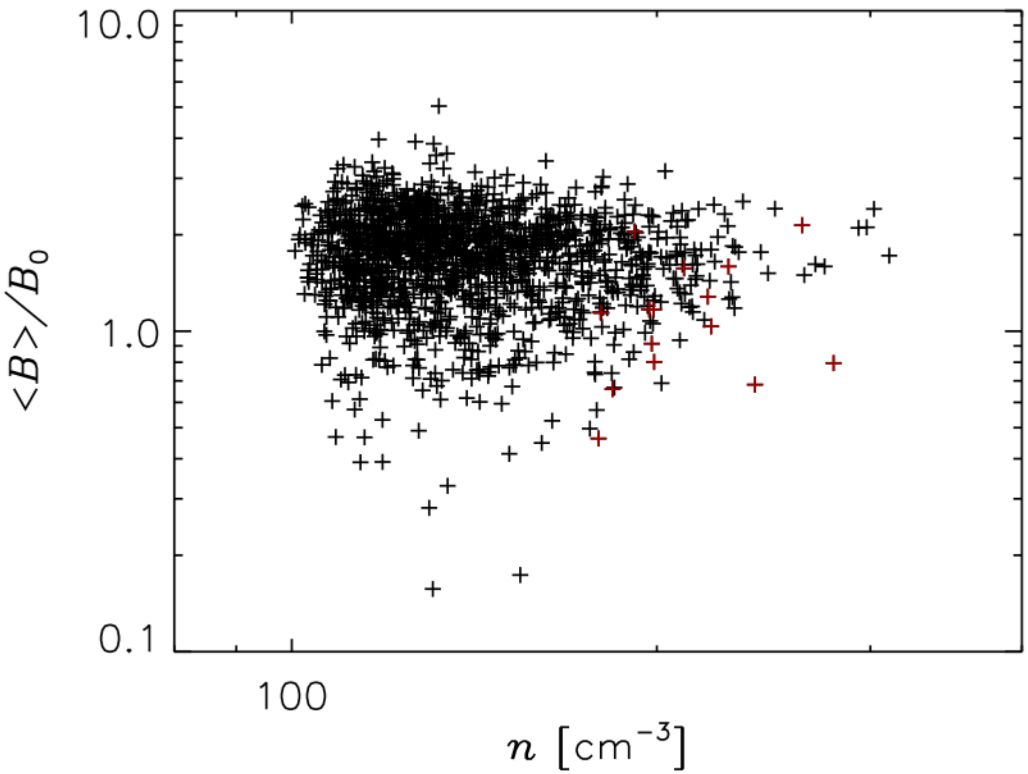

Prediction of super-Alfvénic turbulence (*Lunttila et al. 2008*):
Large scatter in $R_\mu$ , $\boldsymbol{R_\mu < 1}$ for $B$ >10 μG

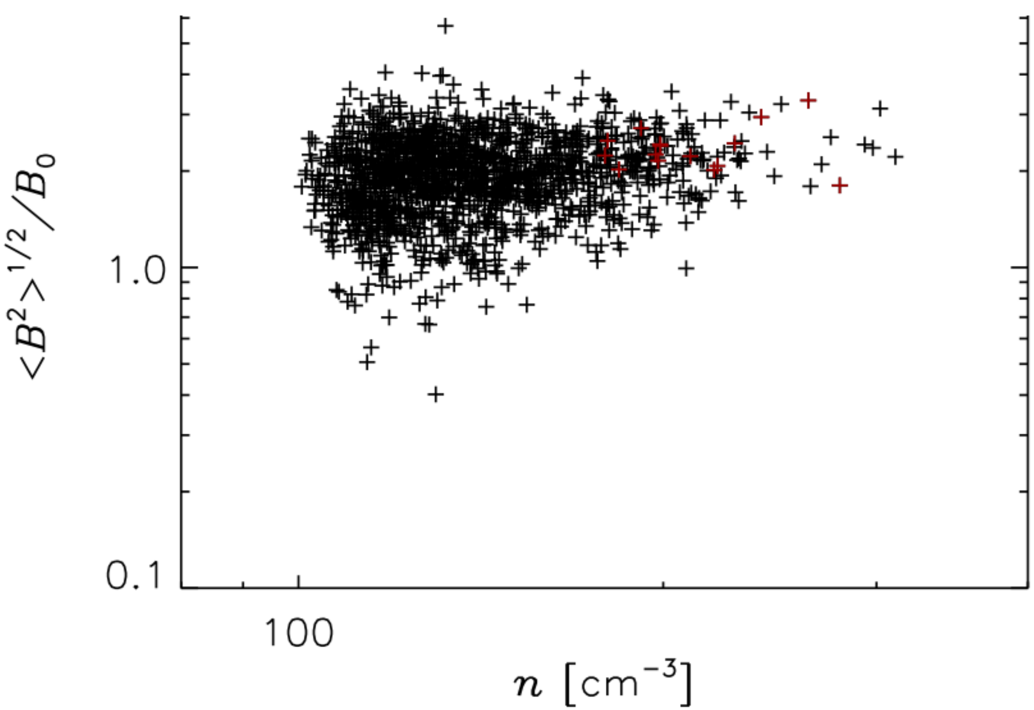
Prediction of ambipolar-drift model of core formation (*Ciolek & Mouschovias 1994*): $\boldsymbol{R_\mu > 1}$ (~ 4)

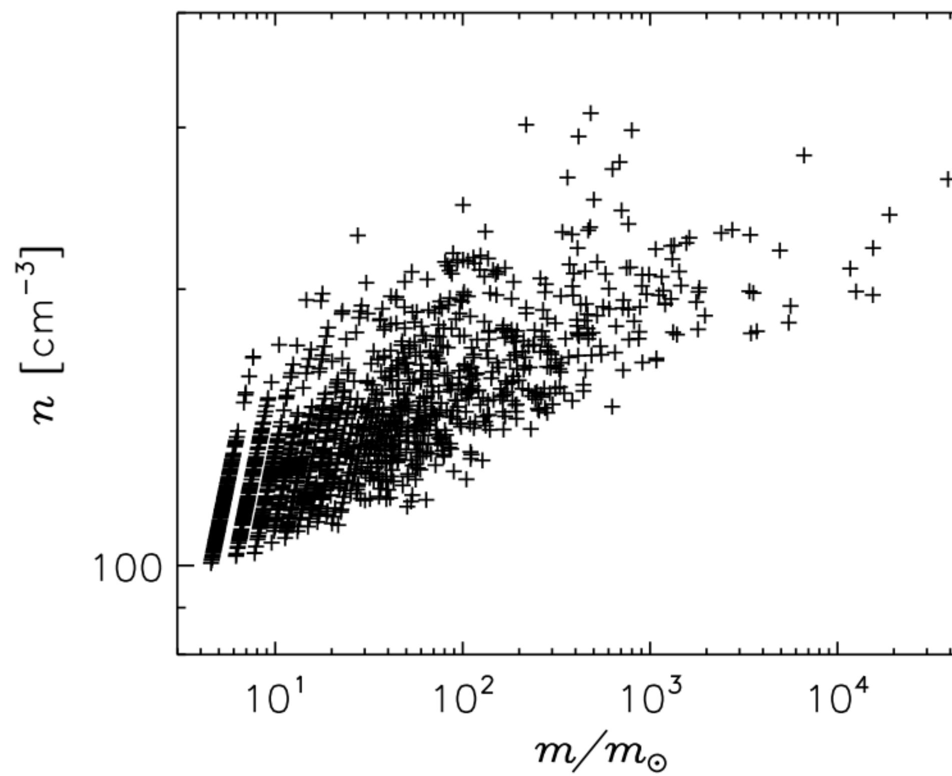
*Crutcher et al. 2008*: $\boldsymbol{R_\mu = 0.41 \pm 0.2}$ (for the core B1)

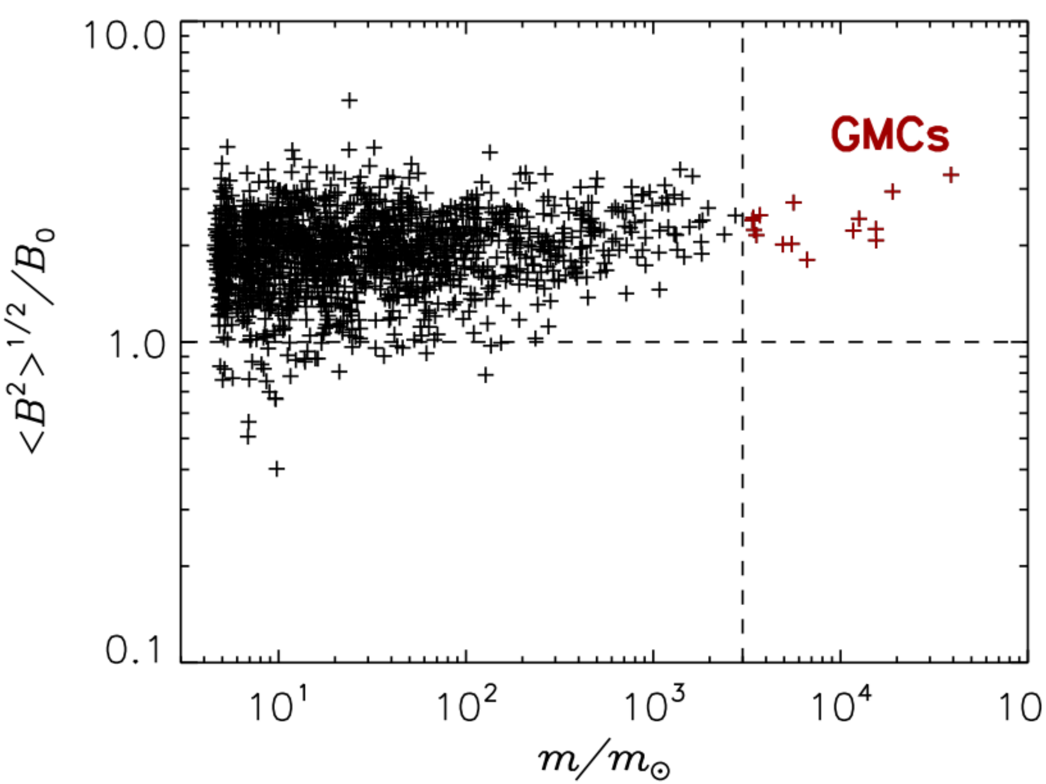
# Conclusions

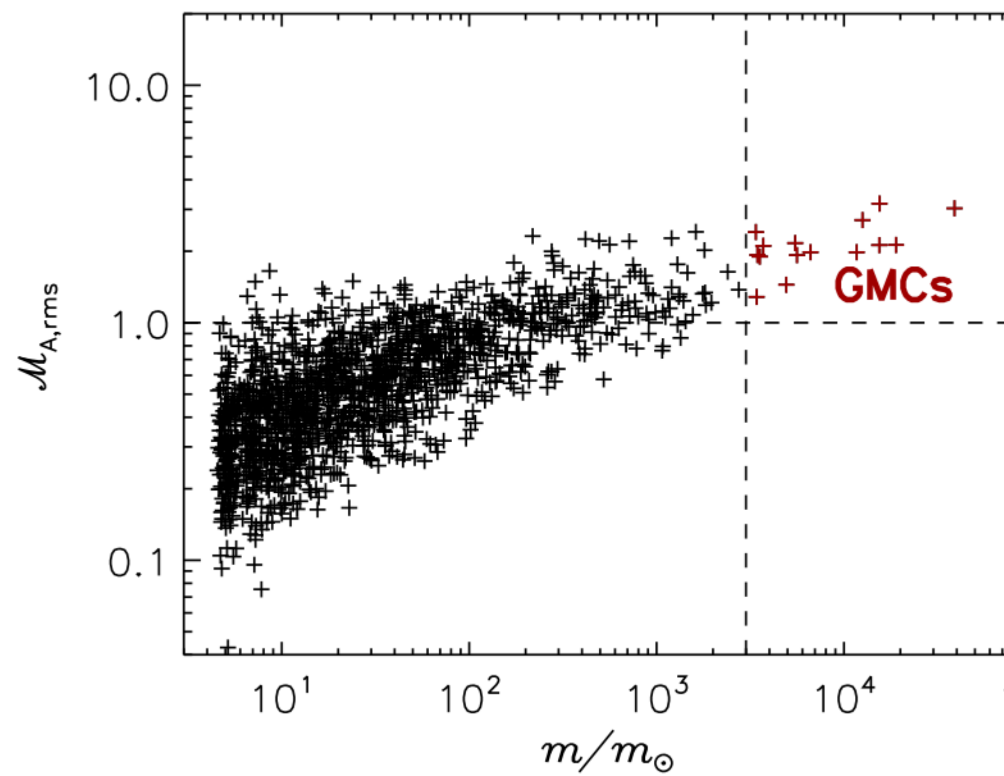
- Giant Molecular Clouds are super-Alfvénic with respect to their $\langle B \rangle$.
- In most GMCs the turbulence may remain super-Alfvénic also with respect to $\langle B^2 \rangle^{1/2}$, unless $\mathcal{M}_{\mathrm{A},0} \leq 3$ and the cloud is older than ~ 2 dynamical times.
- Super-Alfvénic 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.


10.0
1.0
0.1
100
$<B>/B_0$
$n$ [cm$^{-3}$]


1.0
0.1
100
$<B^2>^{1/2}/B_0$
$n$ [cm$^{-3}$]

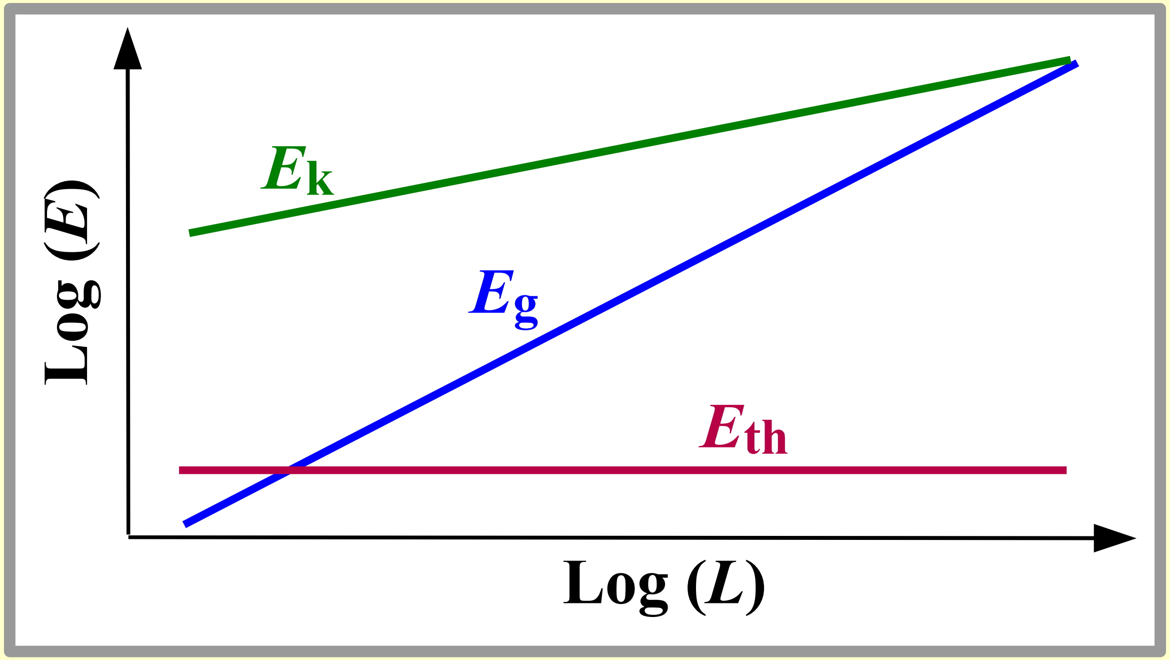

100
$10^1$
$10^2$
$10^3$
$10^4$
$n$ [cm$^{-3}$]
$m/m_\odot$


GMCs
10.0
1.0
0.1
$<B^2>^{1/2}/B_0$
$10^1$
$10^2$
$10^3$
$10^4$
10
$m/m_\odot$


GMCs
10.0
1.0
0.1
$\mathcal{M}_{A,\mathrm{rms}}$
$10^1$
$10^2$
$10^3$
$10^4$
$m/m_\odot$

# The turbulence controls the dynamics within GMCs

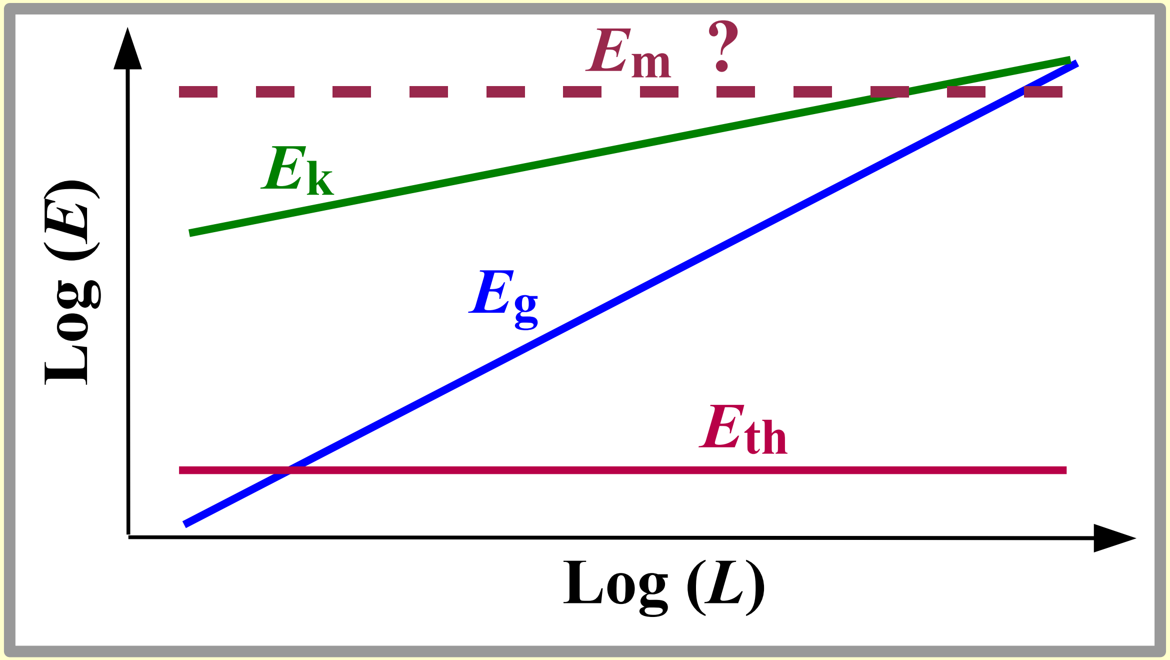
$$\frac{E_k}{E_g} \sim \frac{u^2}{G\rho_0 L^2}, \quad u \sim L^{0.4}, \quad \frac{E_{k,0}}{E_{g,0}} \sim 1 \quad \Rightarrow \quad \frac{E_k(L)}{E_g(L)} = \left(\frac{L}{L_0}\right)^{-1.2}$$




→ The turbulence can prevent locally the gravitational collapse
(star formation occurs only in the densest regions)

# The turbulence controls the dynamics within GMCs

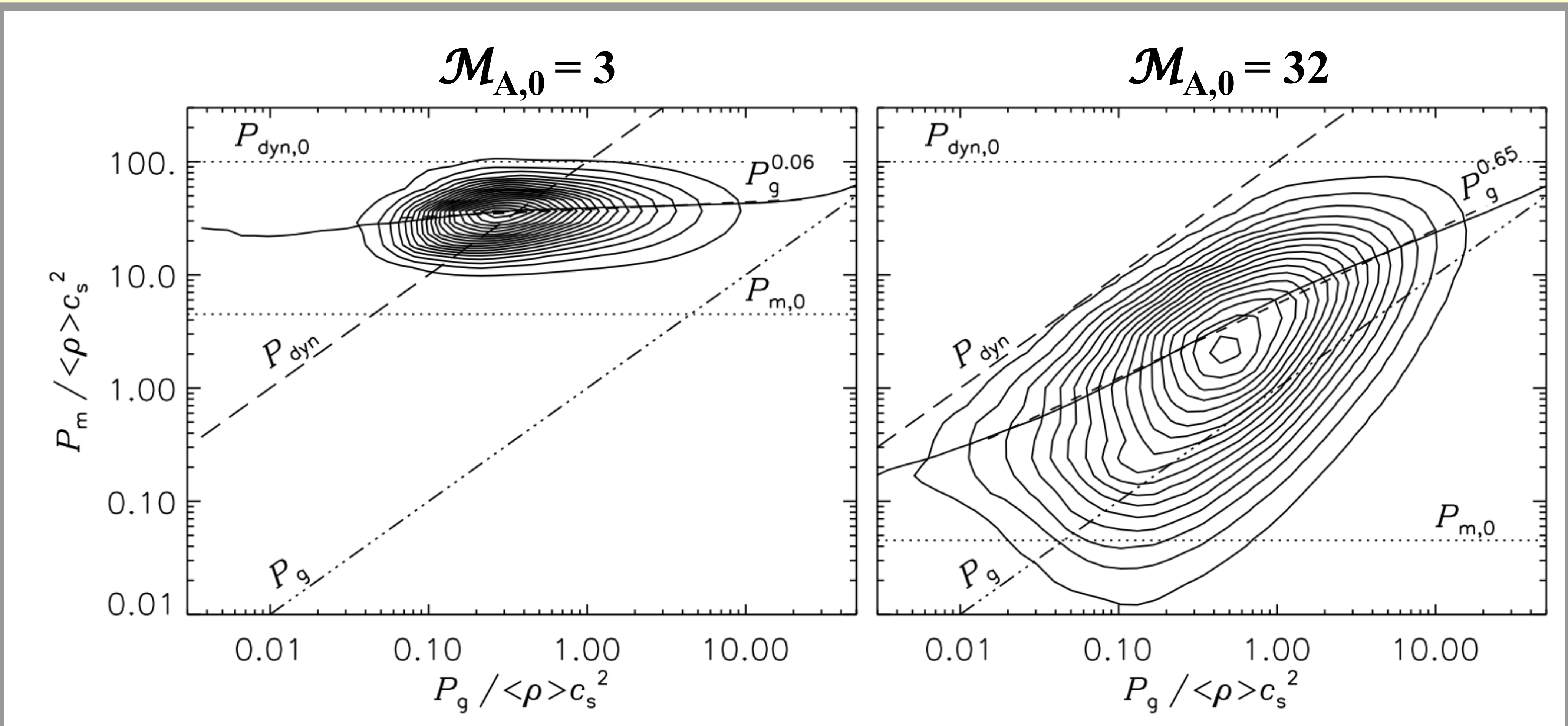
$$\frac{E_{\mathrm{k}}}{E_{\mathrm{g}}} \sim \frac{u^2}{G\rho_0 L^2}, \quad u \sim L^{0.4}, \quad \frac{E_{\mathrm{k,0}}}{E_{\mathrm{g,0}}} \sim 1 \quad \Rightarrow \quad \frac{E_{\mathrm{k}}(L)}{E_{\mathrm{g}}(L)} = \left(\frac{L}{L_0}\right)^{-1.2}$$




→ The turbulence can prevent locally the gravitational collapse
(star formation occurs only in the densest regions)

*How strong is the magnetic field?*

# $\boldsymbol{B}$-$\boldsymbol{n}$ relation ($N$=$1024^3$)

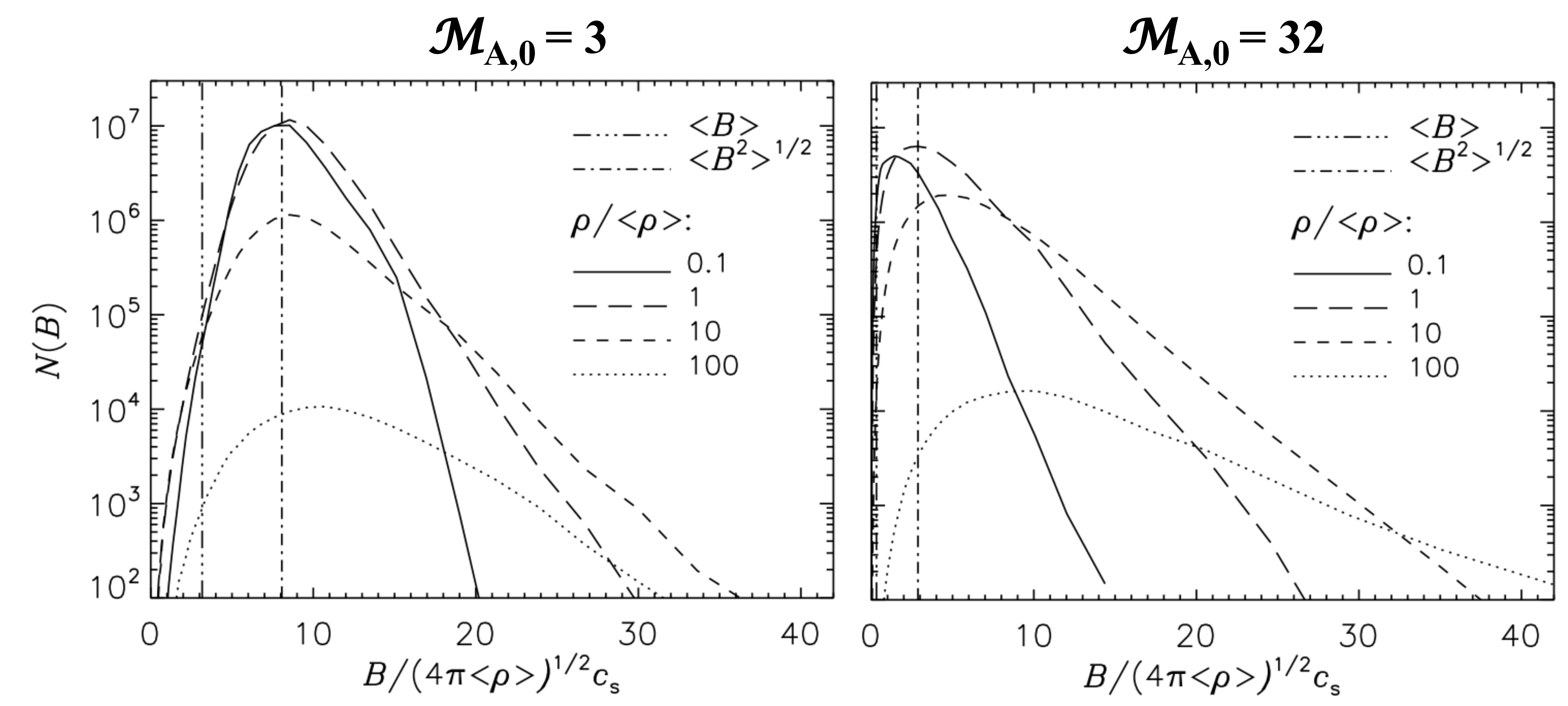



Weaker Magnetic field → Steeper *B-n* relation and larger scatter

– $\mathcal{M}_{A,0} = 32$**:** The upper envelope shows local equipartition of magnetic and dynamic pressure (passive role of B)

– $\mathcal{M}_{A,0} = 3$**:** Magnetic pressure often in excess of dynamic pressure

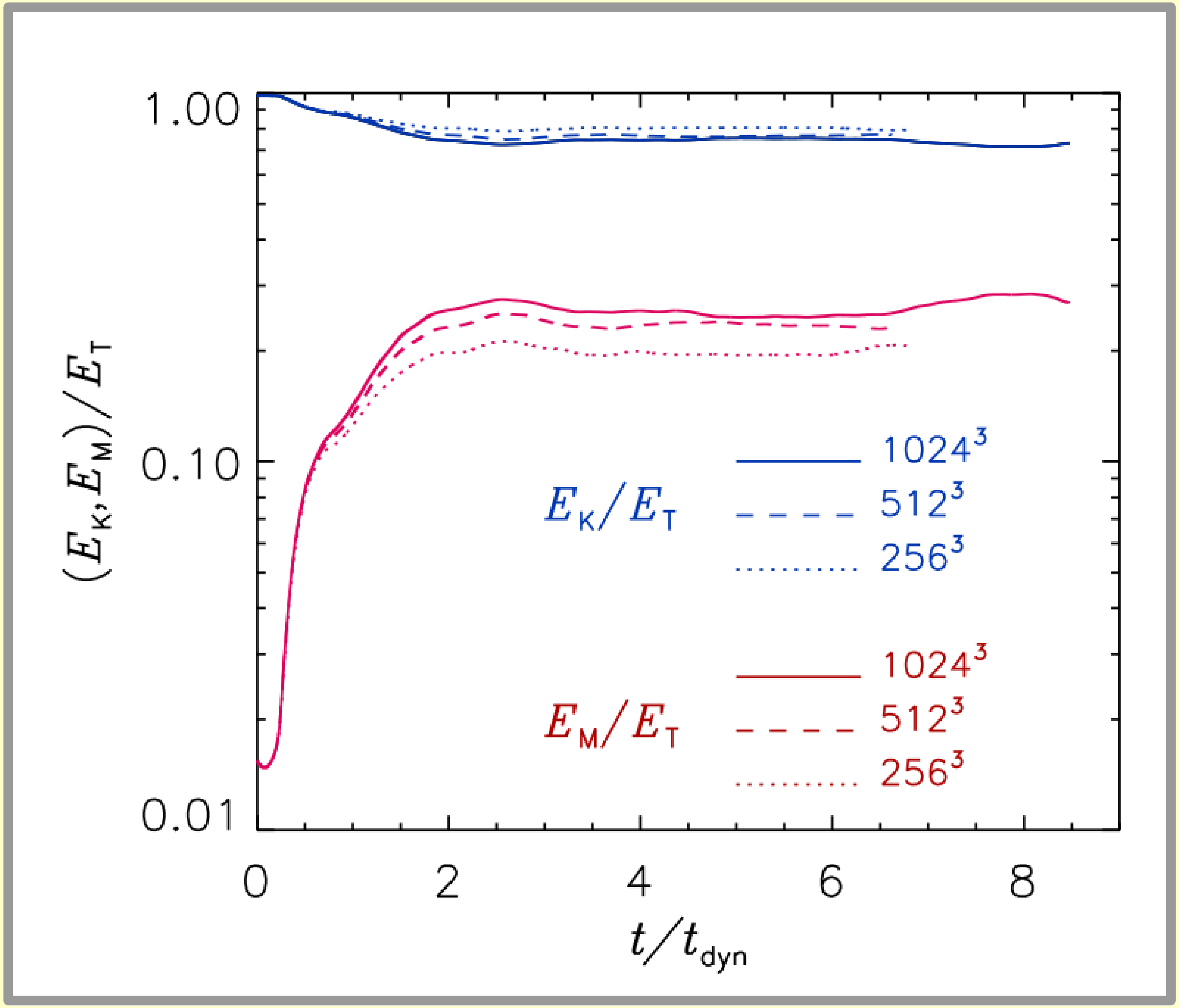
# PDFs of *B* conditioned to *n* ($N$=$1024^3$)




Extended exponential PDF tails, especially for the weaker mean B case:
Field stretching, not just compressions (the gas density PDF is Log-Normal).

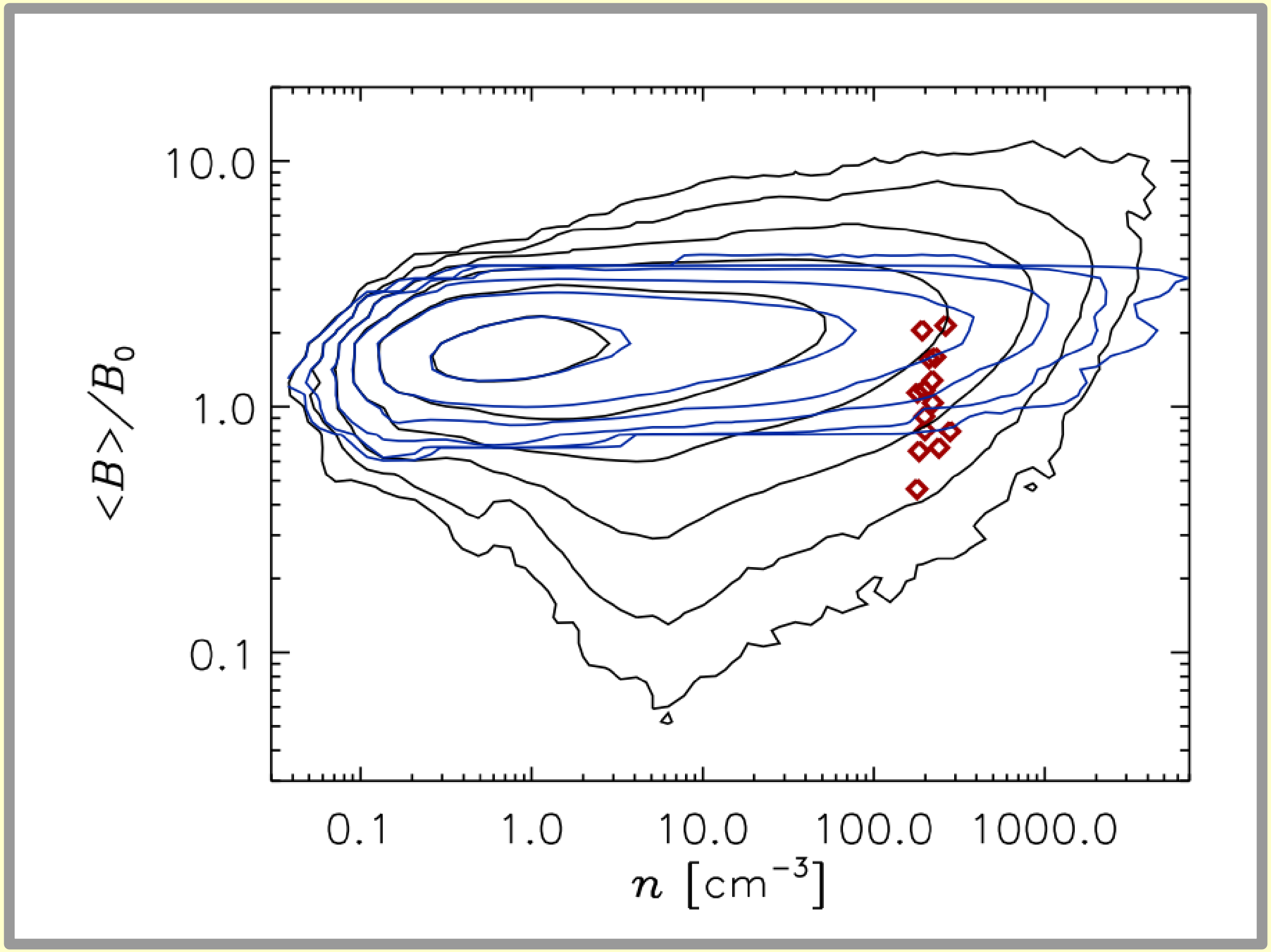
Typical Zeeman detections yield $B \gg \langle B\rangle$, and even $\gg \langle B^2\rangle^{1/2}$.
(even worse due to Zeeman bias towards large density – see below.....)

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



We can further illustrate this result from the point of view of steady-state turbulence correlations: *B*-*n* and velocity-size relations.

*B*-*n* relation:




The *B*-*n* relation is very flat, especially if *B* is averaged over a region of 20 pc (blue contours).