Understanding the Star Formation Rate
(paper appears on arXiv tomorrow)

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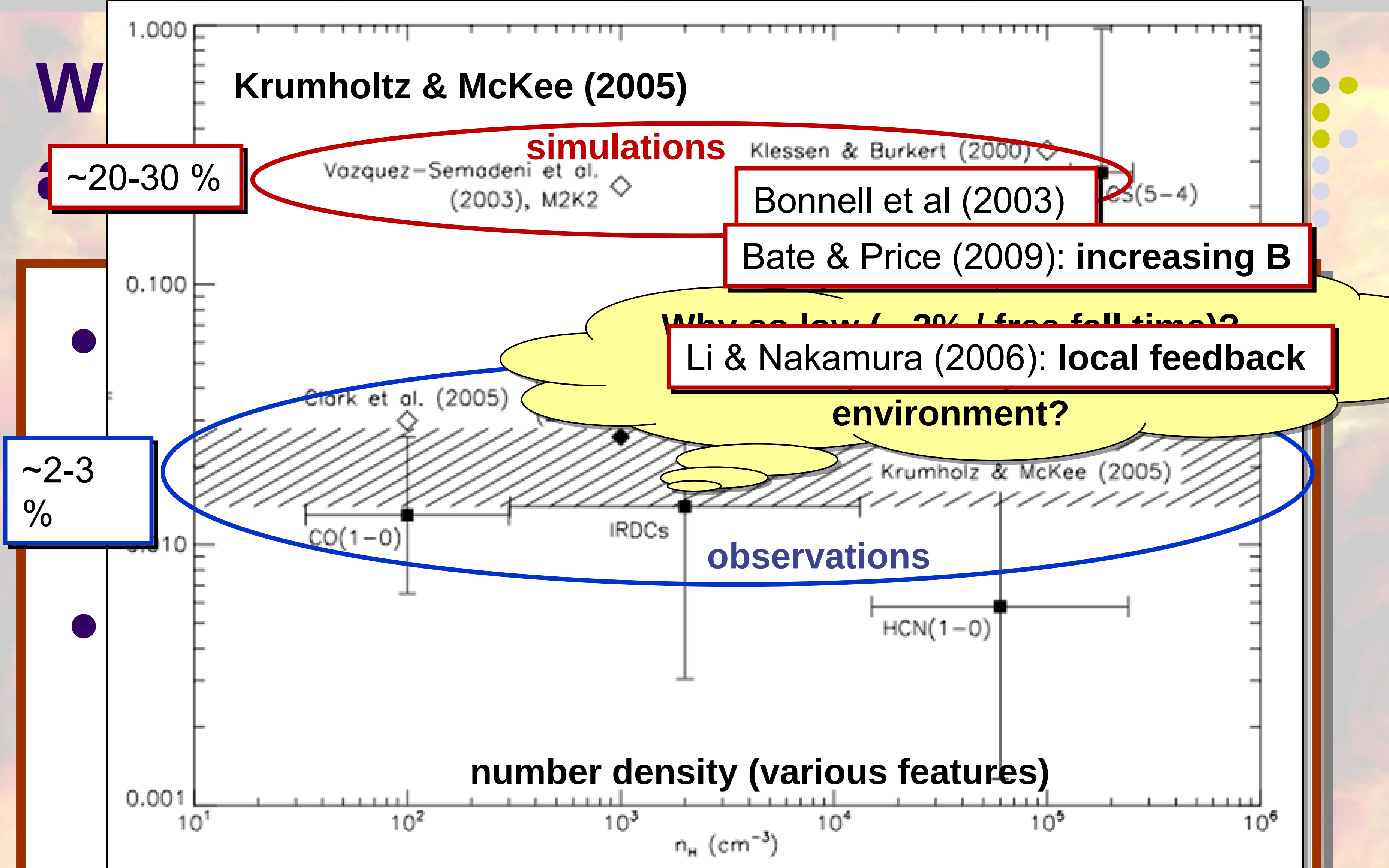
What’s ”Star Formation Rate”, and why-do-you-want-to-know?

- **Quick answer, ”what?”:**
  - The %’ ISM turned into stars ***per free-fall time***
    - *The **local free-fall time** is the ”natural unit”*

- **Quick answers, ”why?”:**
  - This is a key property in models of
    - ***Galaxy formation***
    - ***Star cluster formation***
  - **It isn’t what one would naively guess**
    - **Nor what most models predict!**



- **It isn't what one would naively guess**
  - **Nor what most models predict!**

In this talk (and in astro-ph/0907.0248 – released tomorrow!)

- **We show how to map the SFR dependence on the main parameters**
  - ***Must first understand what the main parameters are***
    - ***Then vary the most important one!***

- **We show why the star formation rate is so low**
  - ***It wouldn’t have to be – the low value reflects a ”servo equilibrium”***

Two ”methods” aspect

- **How were the results obtained?**
  - What methods were used?
  - Why these methods?
- **This can be used in larger scale simulations!**
  - Galaxy formation
  - GMC formation

What’s behind the new results?

- **A large grid of high resolution unigrid (mostly 500^3 and some 1000^3) *supersonic MHD simulations with selfgravity and sink particles***
  - decaying and ***driven***

- **A small number of *AMR (RAMSES & ENZO) simulations* with identical initial conditions and collapse handled *with a barotropic equation-of-state***
  - decaying; for ”sanity checks”

What do we do differently?

- **We lock B to a value consistent with observations**
  - A ”must” (insufficient resources to explore)!
- **We assume isothermal (10 K) conditions**
  - Radiation effects are assumed unimportant
- **We focus on the virial ratio**
  - The kinetic energy is ***by far*** the largest counter-acting one!
  - We highlight what actually sets the virial ratio

First, let's remind ourselves: What's Local Free-Fall Time?

- **Take the law of gravity:**

$$F = m\ddot{r} = -\frac{GMm}{r^2}$$

- **Divide with *mr*:**

Has dimension (1/time)^2

$$\frac{\ddot{r}}{r} = -\frac{GM}{r^3} = -\frac{1}{t_{ff}^2}$$

Local Free Fall

- **So, we have, f**

This time depends on only one physical quantity – the local mass density!

$$t_{ff}^2 = \frac{r^3}{GM} = \frac{3}{4\pi G\rho}$$

But that isn’t the whole story; gravity isn’t the only player:

- There is gas pressure
  - Collapse or not then depends

$$M \geq M_{Jeans} \sim \frac{c_{sound}^{3}}{G^{3/2}\rho^{1/2}}$$

So, now temperature enters

Increases during collapse!

- So if gravity ”wins” her[e] … big”, and the collapse time should indeed be essentially the free fall time!

But there are other, even more important factors:

- **Turbulence!**
  - so the **Mach number** $M=U_{rms}/c_{sound}$ enters **..**
- **Magnetic fields!**
  - so the **Alfvénic Mach number** $M=U_{rms}/c_{A,rms}$ enters **..**

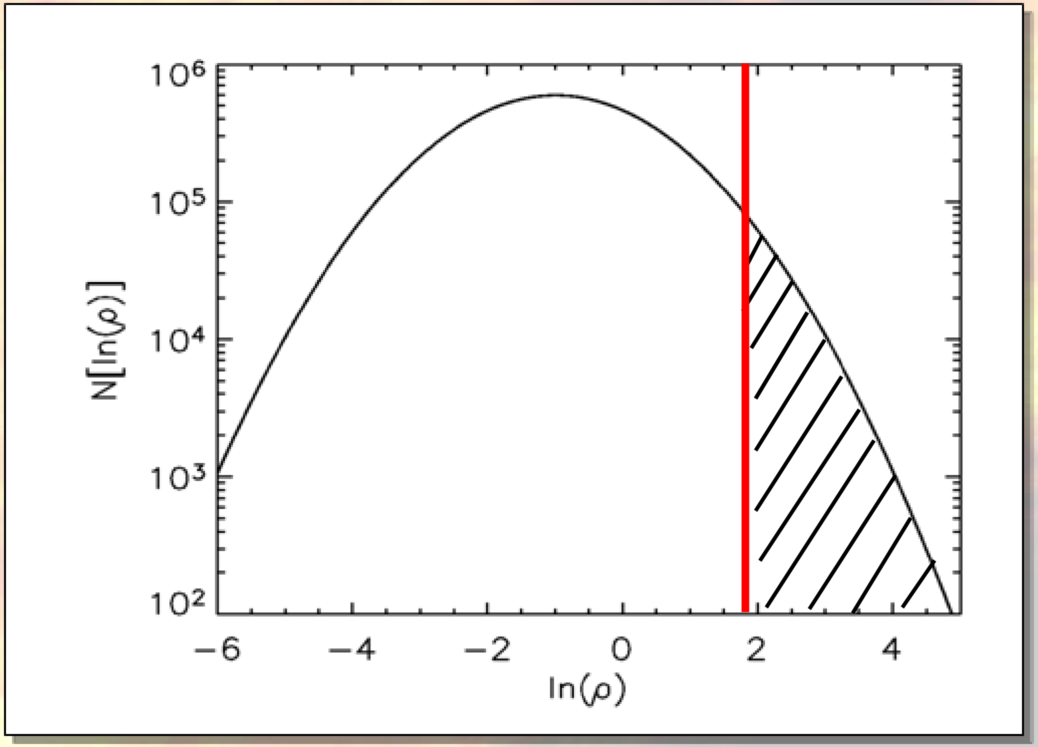
"Three against one"; the energy density play-off

- **Gravitational energy density**
  - The one to fight against!
- **Kinetic energy density**
  - By far the strongest defender!
- **Magnetic energy density**
  - Smaller by the square of $M_{Alfvén}$ ~1/10
- **Thermal energy density**
  - The smallest; by the square of M_{sound} ~1/100

Turbulence and the Star-Formation Rate

Supersonic isothermal turbulence results in large density fluctuations:

Wide density pdf → SFR as the mass fraction above a *critical density,* divided by a characteristic time (e.g. τ_{ff})

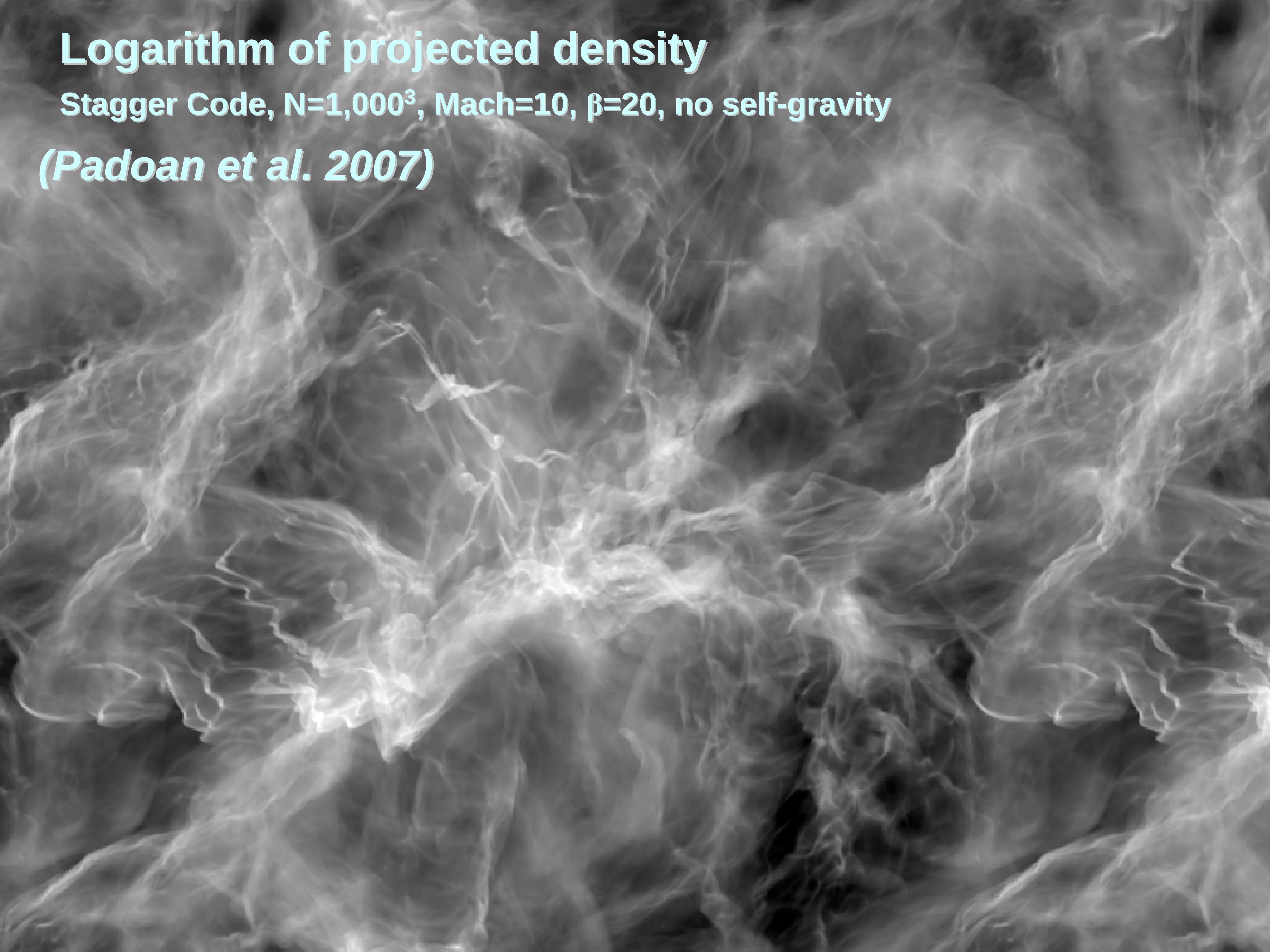


Only a small mass fraction can collapse into stars, hence one reason for the low SFR

Logarithm of projected density

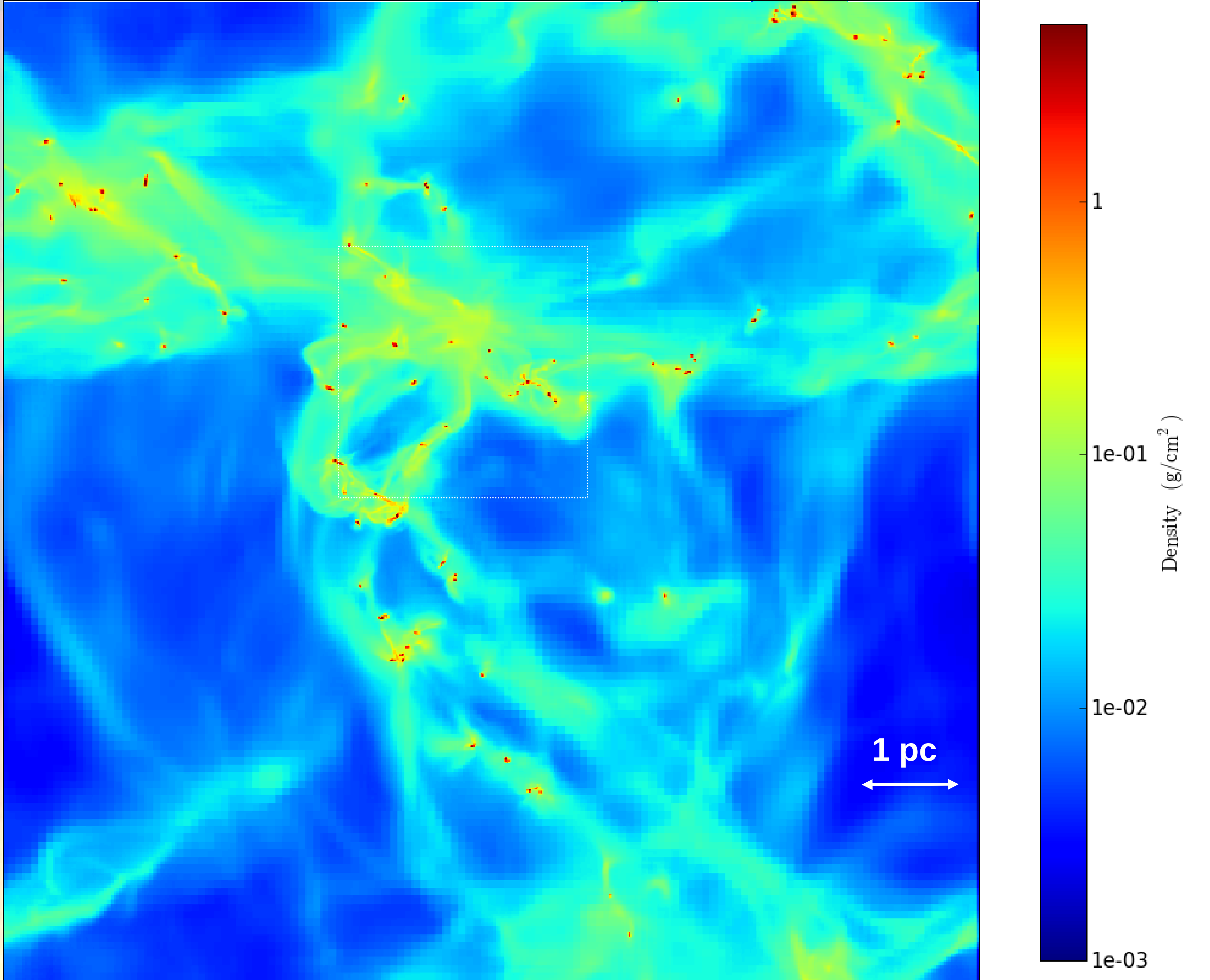
Stagger Code, N=1,000^3, Mach=10, β=20, no self-gravity

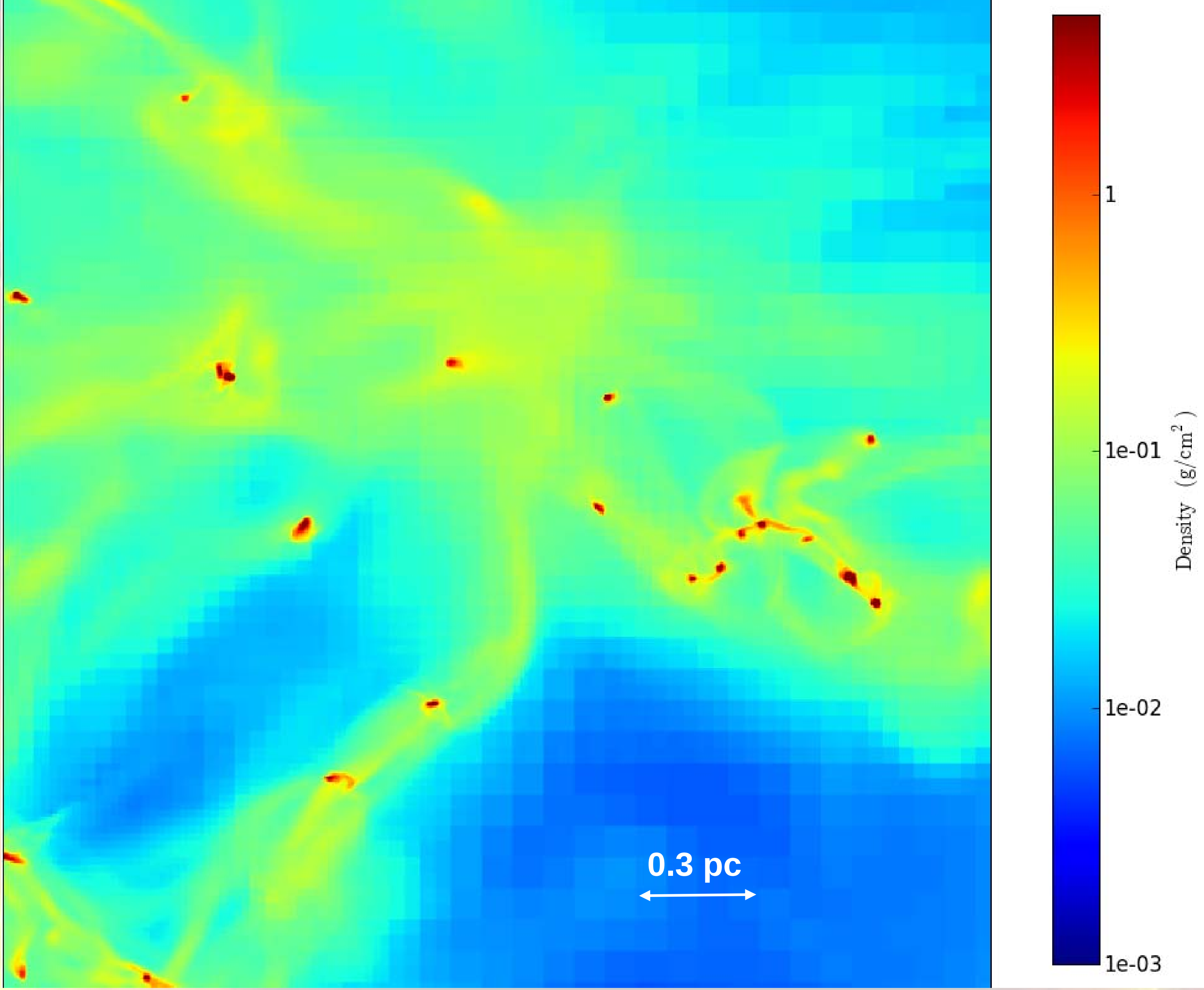
(Padoan et al. 2007)



ENZO AMR/MHD

- ***Collins et al. 2009:***
  - AMR criterion: ¼ Jeans length
  - Refinement: 4 levels, factor of 2
  - Root grid: 128^3
  - Effective Resolution: $2{,}048^3$
  - Li's MHD solver (2nd order in time and space; isothermal HLLD Riemann solver)
  - Gardiner & Stone CT for the induction equation
  - Balsara AMR for interpolation.


1 pc
1
1e-01
1e-02
1e-03
Density (g/cm^2)


0.3 pc
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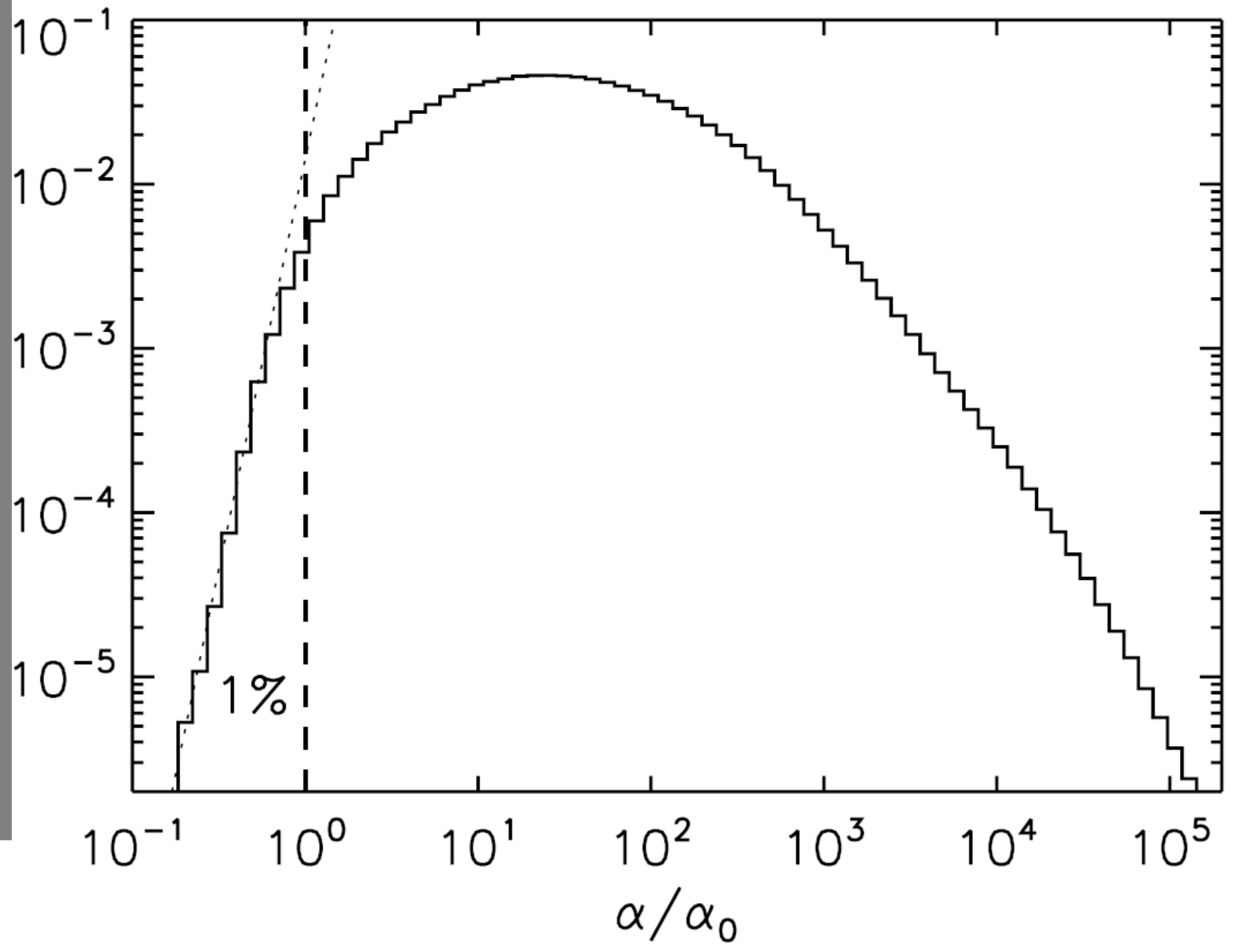
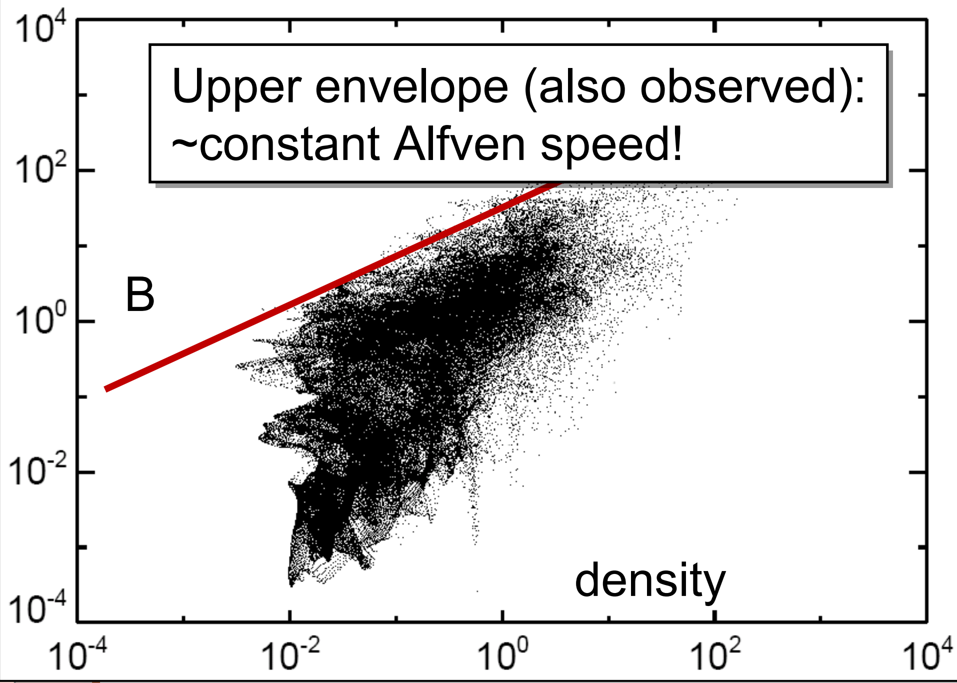
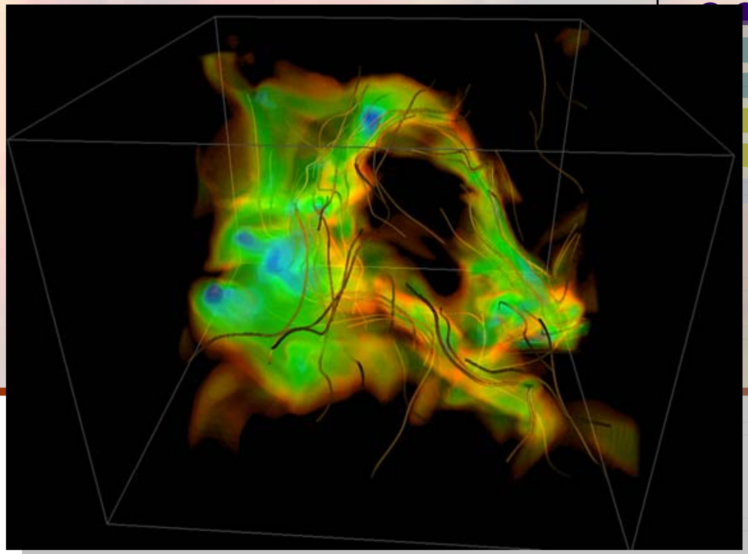
Density (g/cm²)

The PDF of local virial ratios

- **Most local virial ratios are very large!**
- **A small fraction are small enough for collapse!**





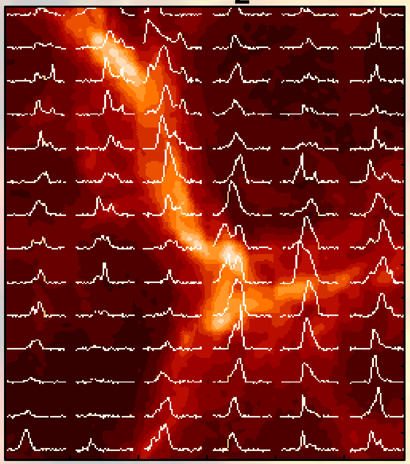


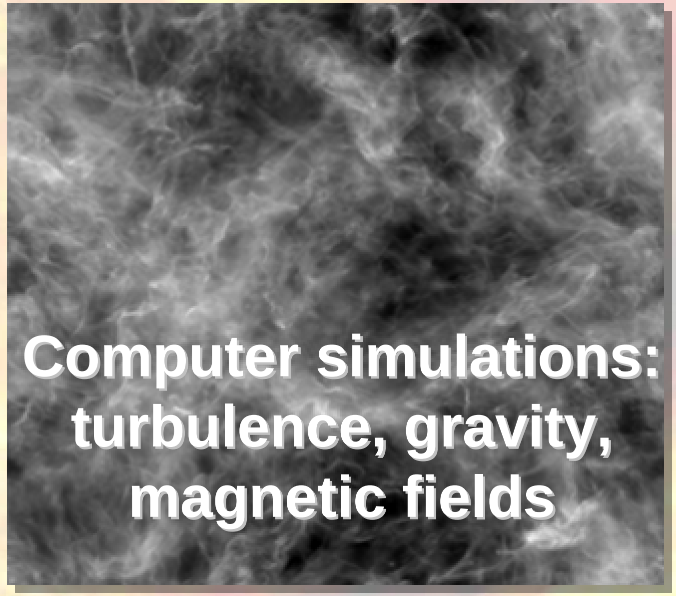
- **What is the distribution of magnetic fields in star forming regions?**
  - **Scatter plot; apparent mess!**
  - **Visualizations; even more apparently a mess!**
- **Why is there a B-n relation?**
  - **Good question – and it has an answer**
  - **Dynamic pressure confinement!**

Comparing synthetic and real observations

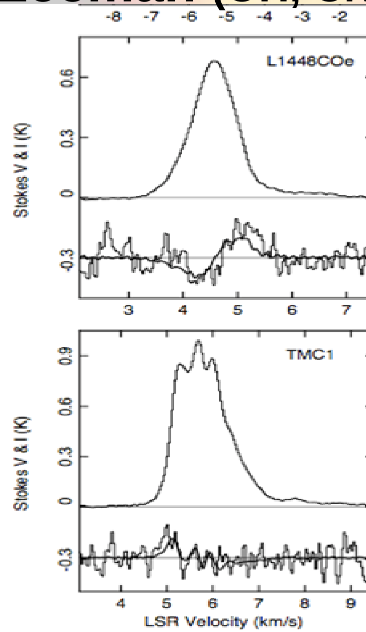
Emission Lines

(CO, CS, N_2H^+, ...)

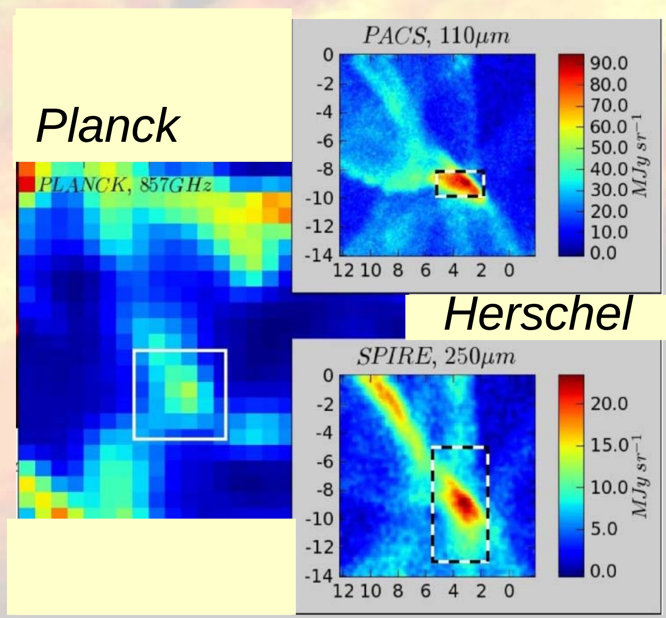




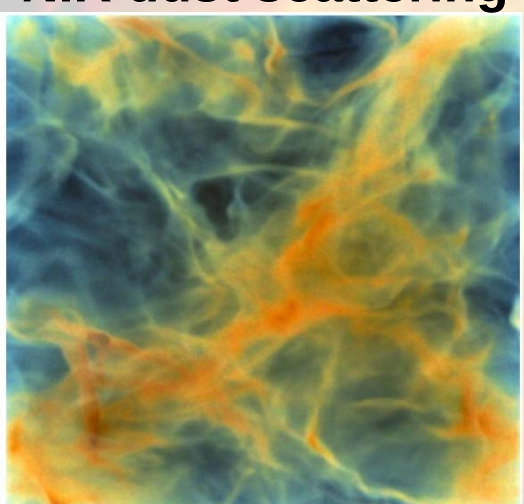
Zeeman (OH, CN)



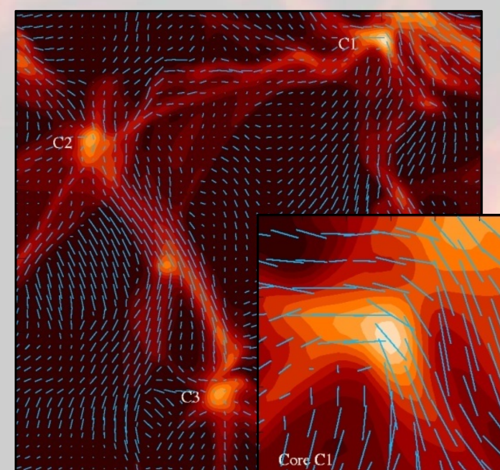
FIR dust emission



NIR dust scattering



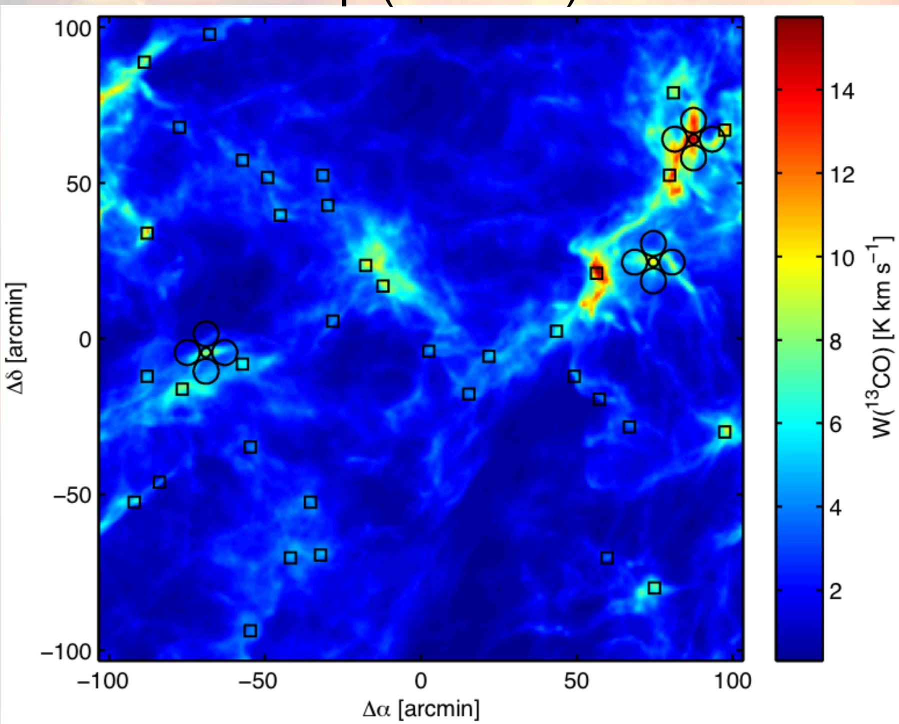
Polarized dust emission



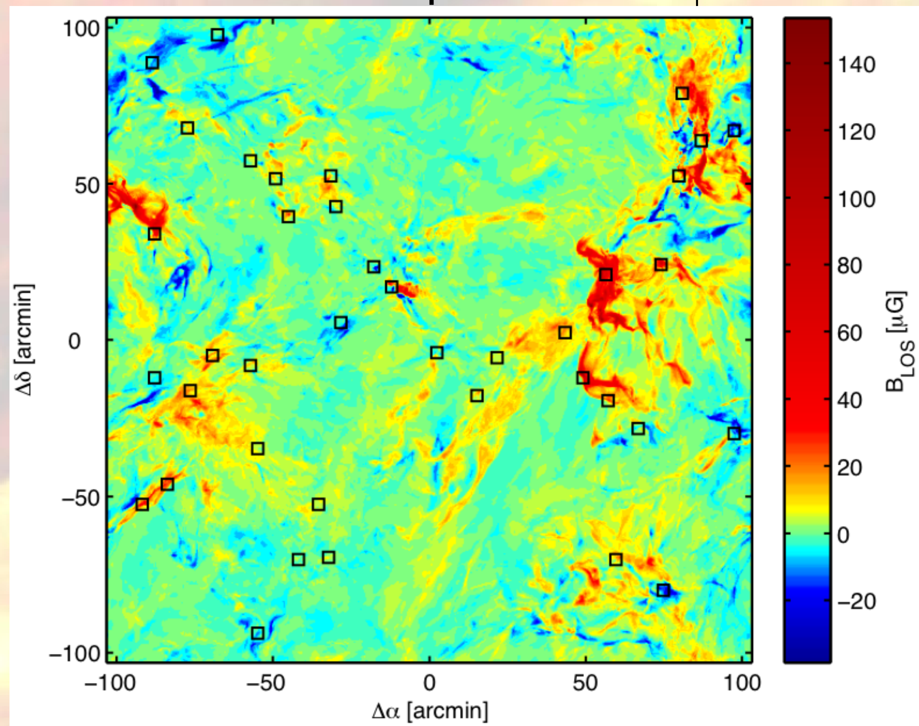
Simulated Zeeman effect in super-Alfvenic turbulence

Lunttila, Padoan et al. 2008:

OH map (3' beam)



Zeeman map



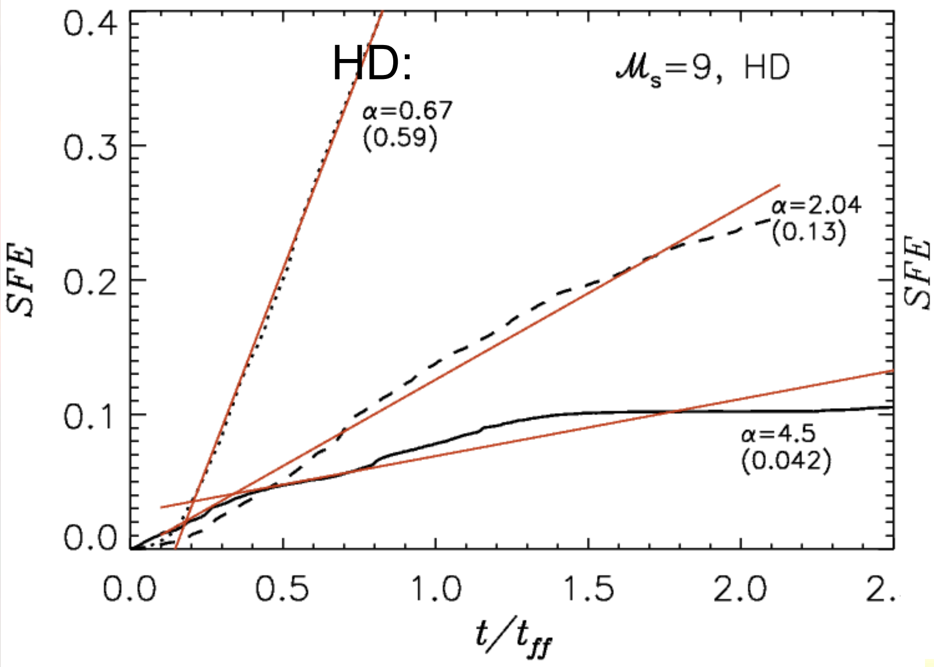
From a $1{,}000^3$ simulation with $<B>$ = 0.69 μG, but rms *B* such that $\beta \approx 0.4$.

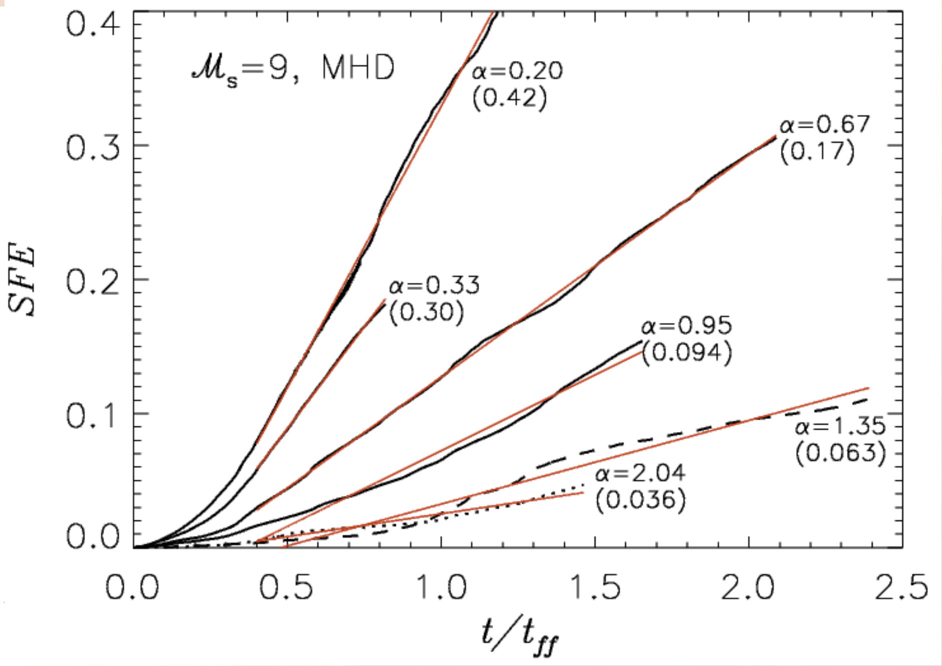
The Zeeman map shows that large B_{los} can be detected in cores, despite the very low value of the mean magnetic field (super-Alfvenic turbulence).

Consistency of our B-field: Synthetic Zeeman splitting

- **Luntilla et al (ApJ 2008)**
  - ***Predicted*** relative mass-to-flux ratio, later observed by Chrutcher (ApJ 2009)
- **Luntillla et al (ApJ 2009)**
  - Showed that a range of properties were consistent with Troland & Crutcher (ApJ 2007)
- **See also Luntilla et al (astro-ph/0907.xx..)**
  - Paper is under refereeing

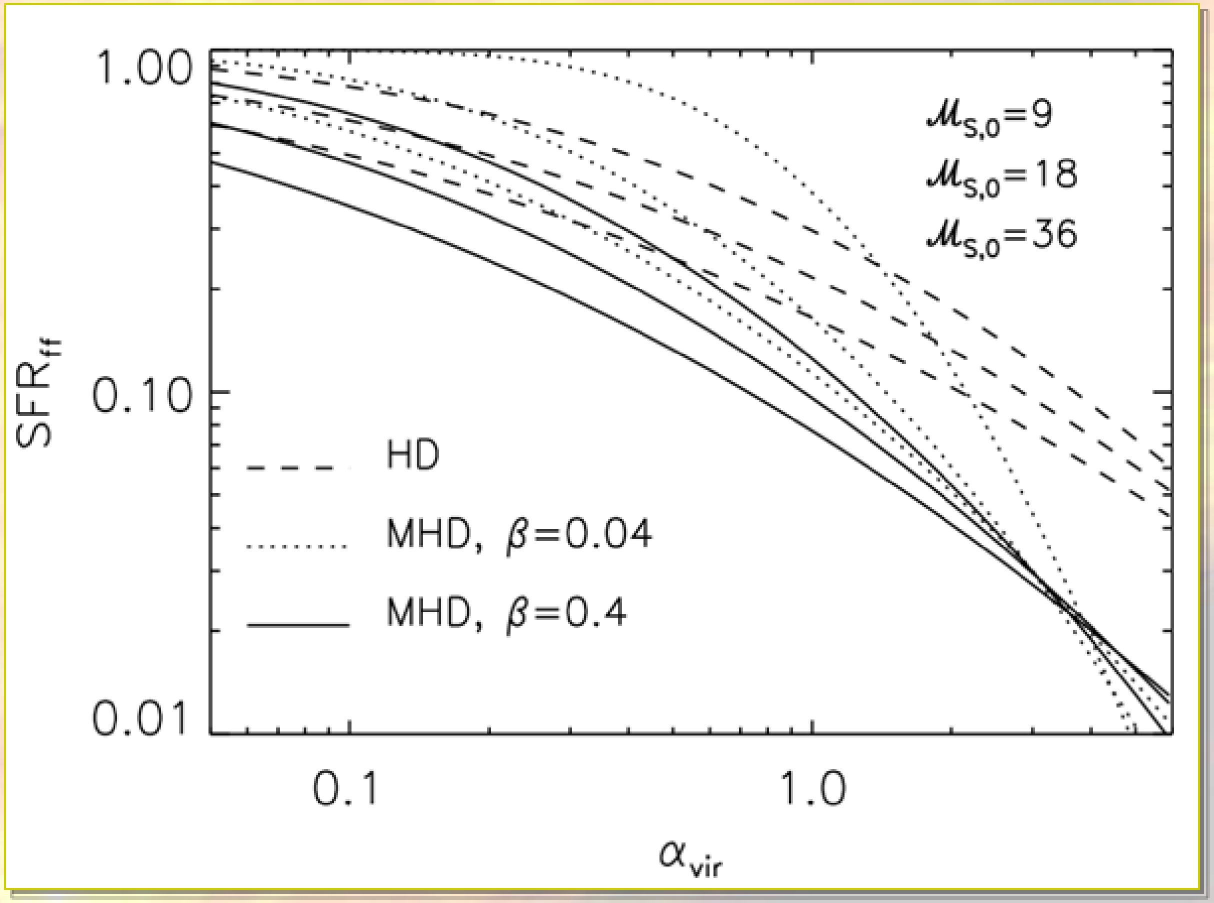
Star-Formation Rate versus Virial Parameter and Magnetic Field



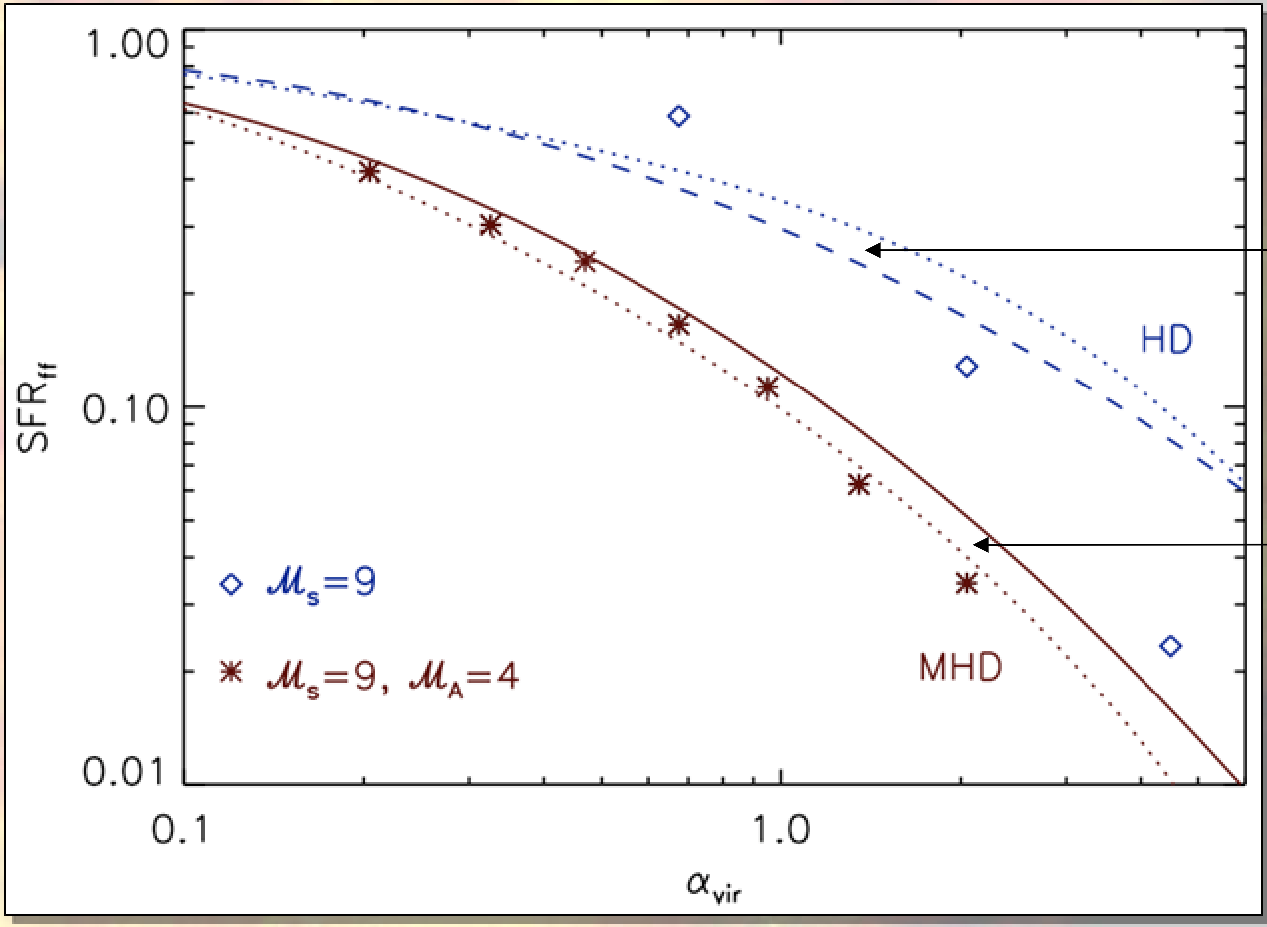


The SFR is low due to both the turbulence and the magnetic field.

Model results



Comparison with theoretical predictions



Excellent agreement between MHD model and the numerical results.

What determines the *actual value* of the virial parameter?

- **Here we have explored the function**

$$SFR = SFR(\alpha_{vir}; M_s; M_A)$$

"what would be the SFR for a given α_{vir}"

- **But there is also the reverse relation!**

$$\alpha_{vir} = \alpha_{vir}(SFR; M_s; M_A)$$

"what α_{vir} would the ISM have, given a certain SFR?"

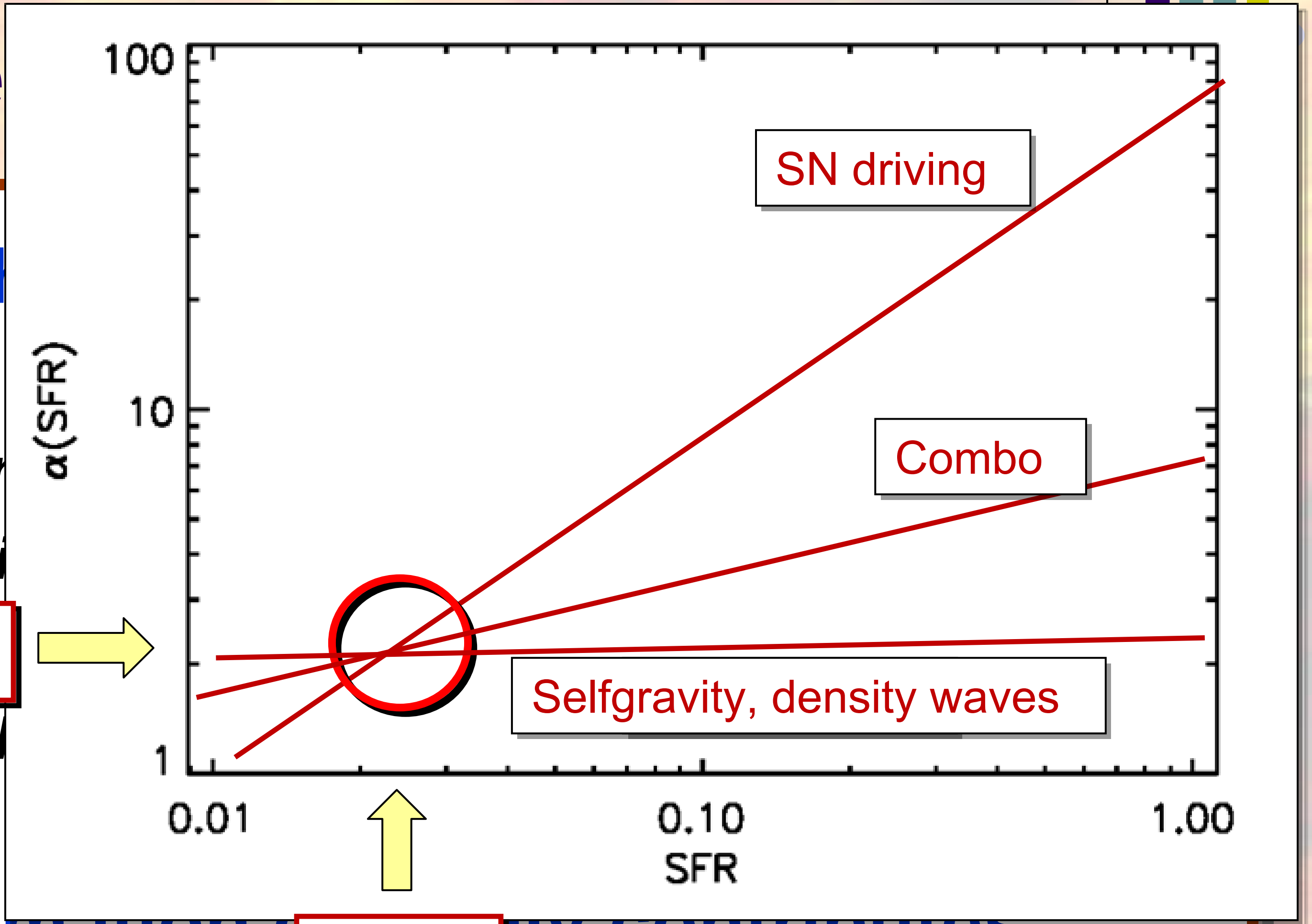
What determines α_{vir} (SFR)?

- **Well, what determines the ISM velocity dispersion? Conflicting views:**
  - ***Supernova driving***
    - ***Korpi et al, MacLow et al, ...***
  - ***Density waves + selfgravity***
    - ***Ostriker et al, Norman& Wada, Agertz et al, ..***

- **Star formation certainly contributes**
  - **So there is a positive slope!**

What de

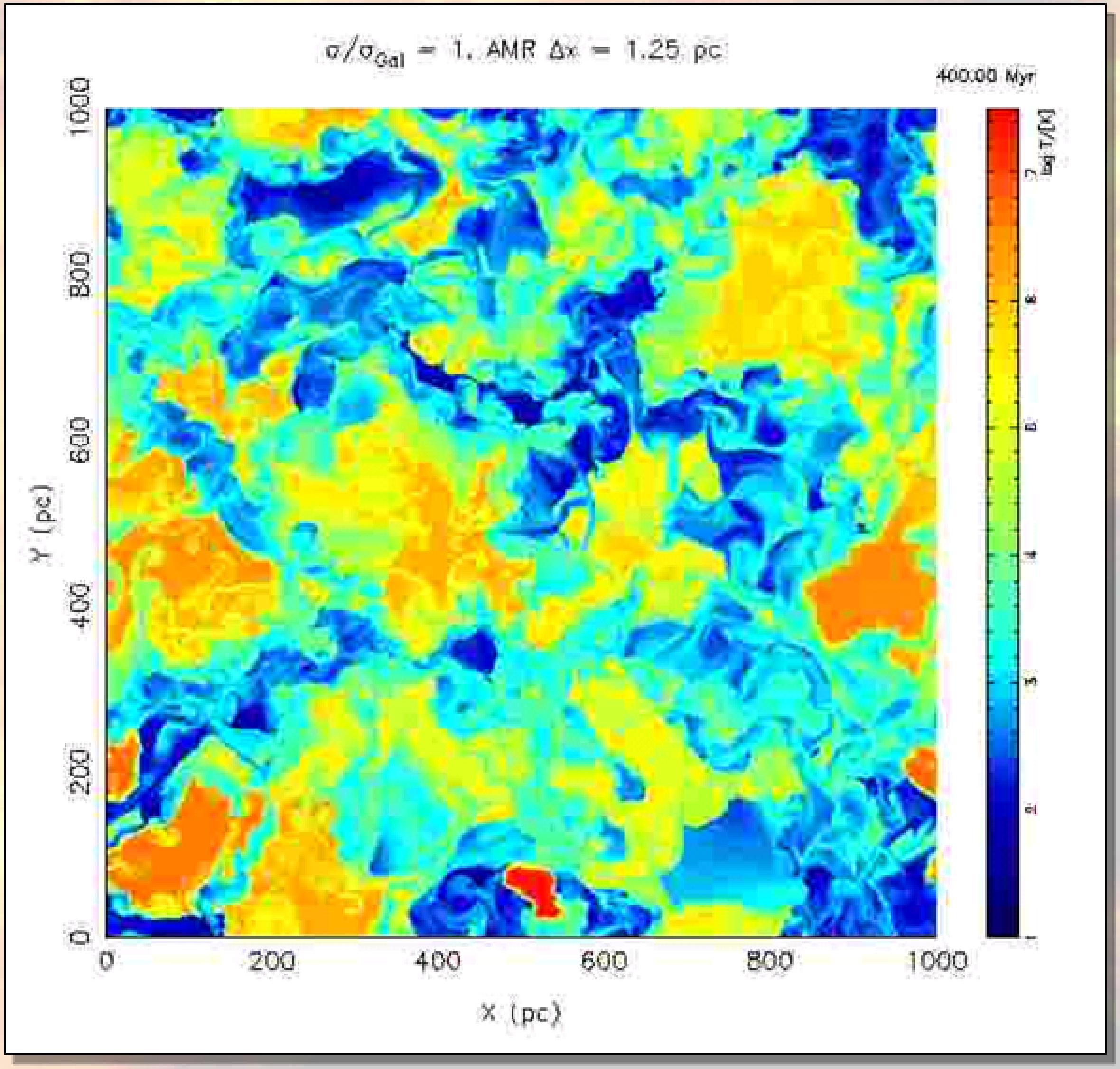
- **Well, wh**
  dispers
  - ***Superr***
    - ***Korpi***
  - ***De*** α~2
    - ***Ostril***



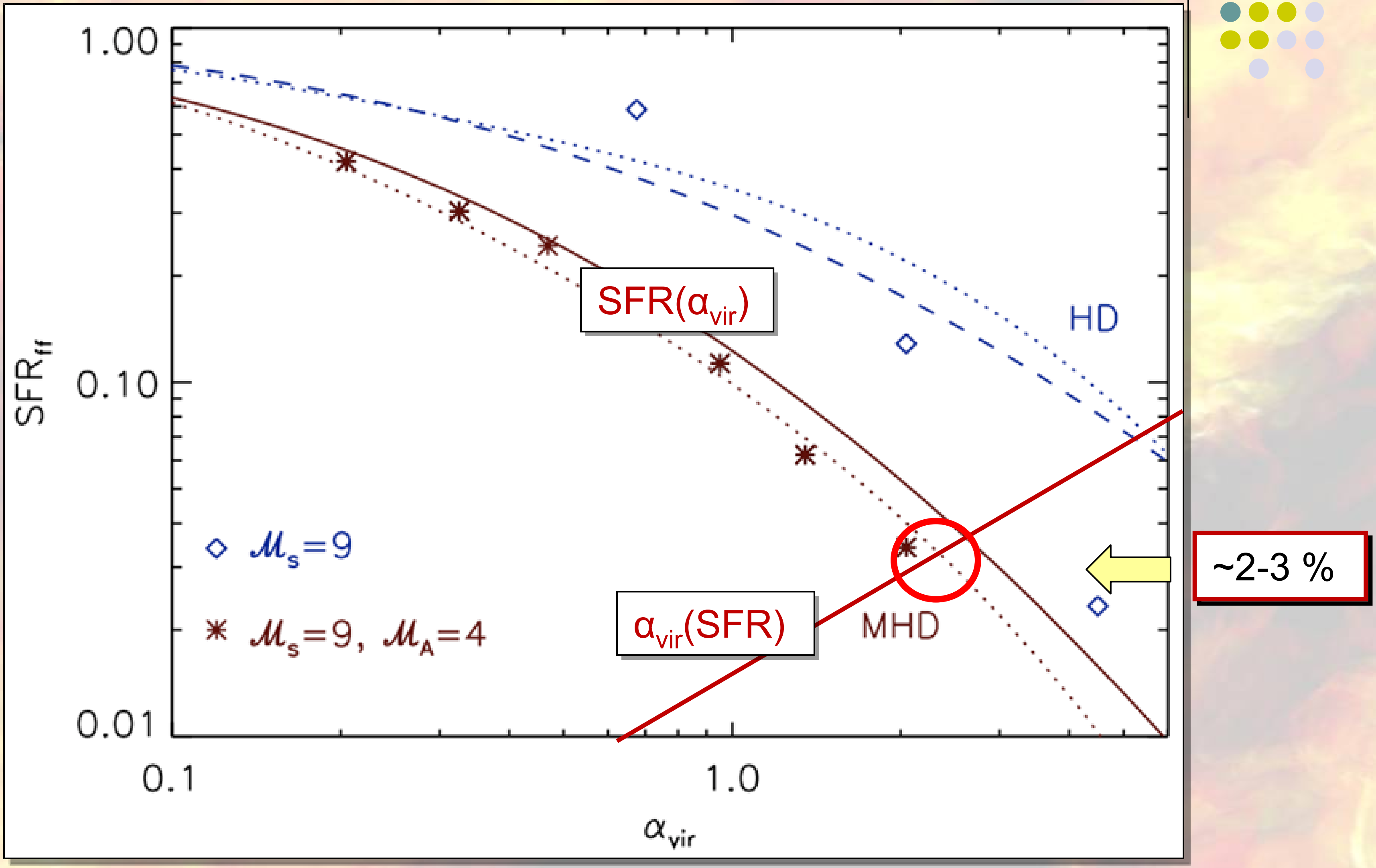
~2-3 %

- **Star formation ... ly contributes**
  - **So there is a positive slope!**

State of the art:
de Avillez & Breitschwerdt 2004, 2005, 2007



Combine the two



Previous SFR-study attempts

- **No-one mentioned, all remembered :-!**
- **Failed to maintain a constant virial ratio**
  - Had neither outer scale nor driving
- **Trying to patch this with B fails**
  - <B^2> decays, so becomes ineffective
  - ***or*** initial B much too large; B is ***not*** a free param!
    - synthetic data should be consistent with observations

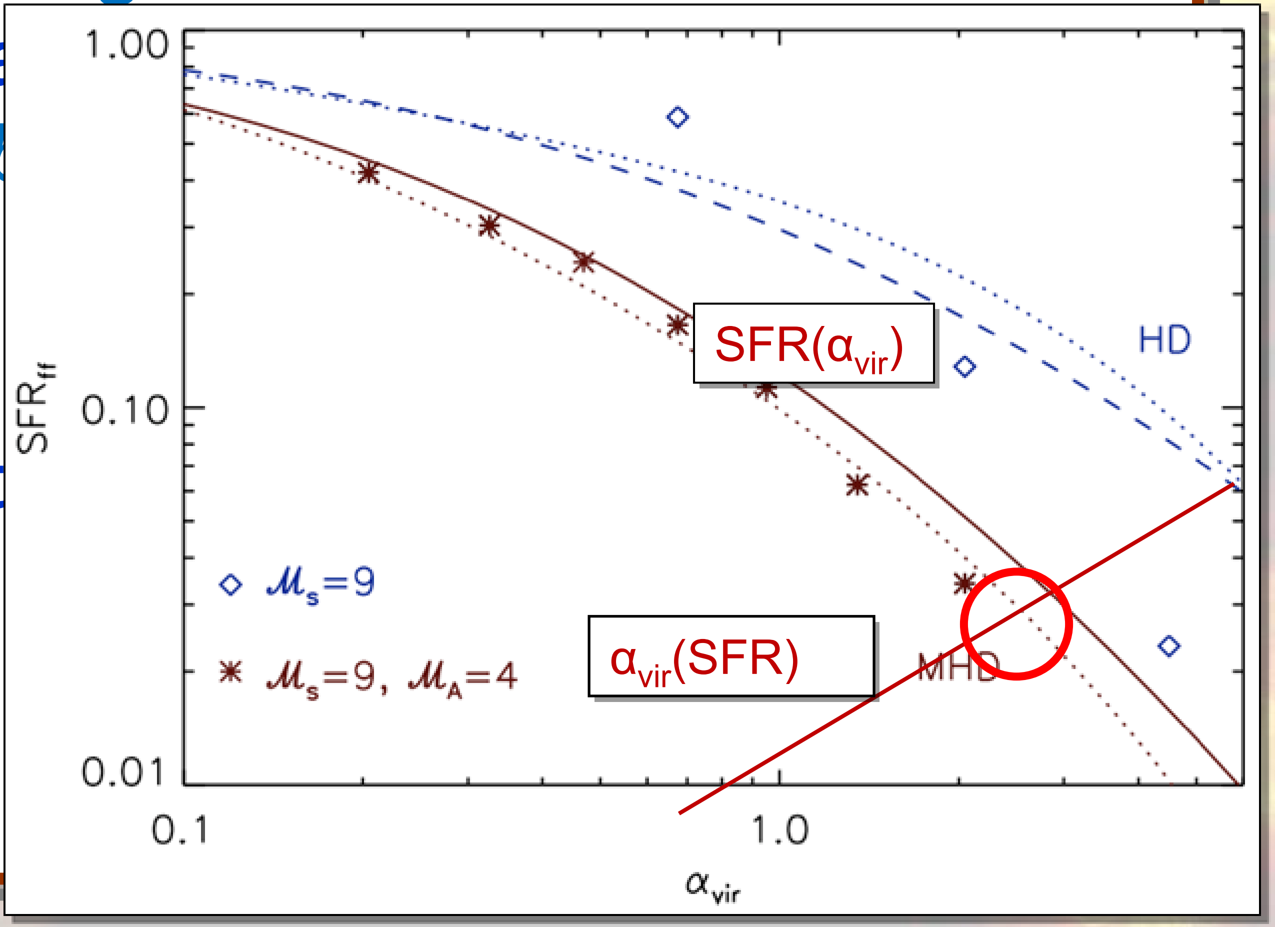
Conclusions

- *Turbulent fragmentation* reduces the Star Formation Rate with increasing *virial number* (at given magnetic energy)

- The actual value of the Star Formation Rate is set by a feedback loop:
  - $\alpha_{vir} \rightarrow \mathrm{SFR} \rightarrow \alpha_{vir}$

Conclusions

- ***Turbulent fragmentation*** **reduces the Star Forma**
  virial numb
- **The actual Rate is set**
  - $\alpha_{vir} \rightarrow$ SFR



Thanks for your attention!

The "velocity law"

- Here is the figure from Larson's 1981 paper:

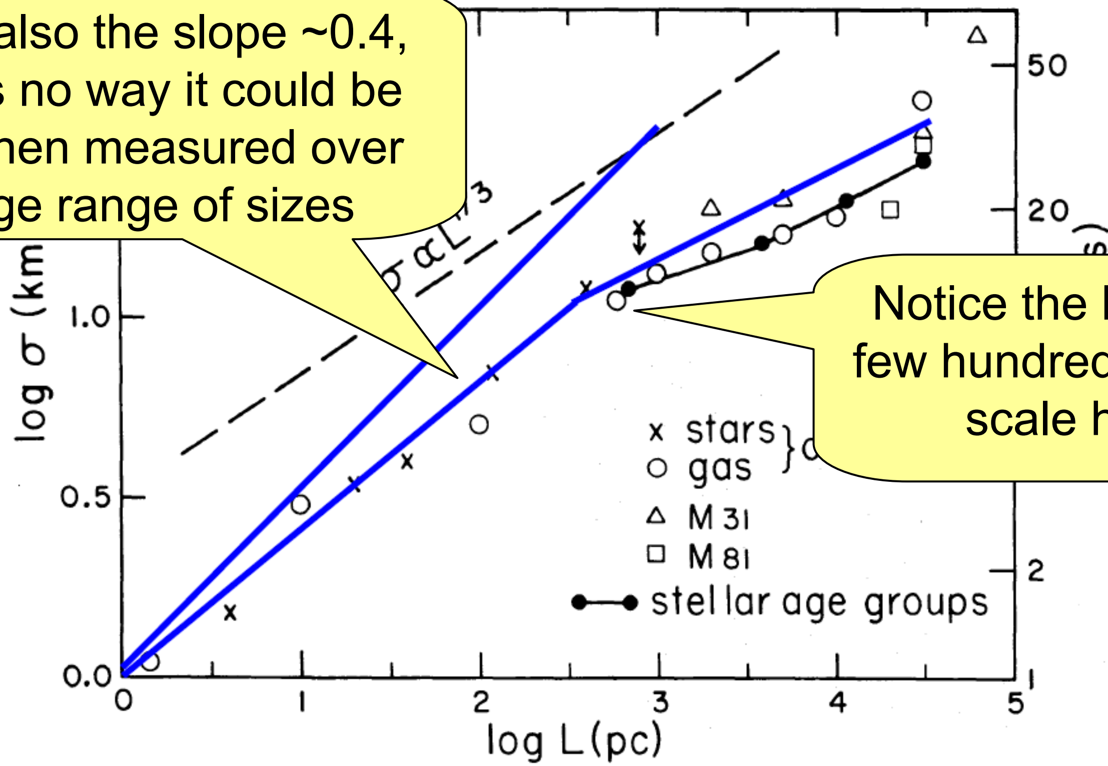


Figure 1. The three-dimensional velocity dispersion σ versus region diameter L from Table 1 for young stars (crosses) and interstellar gas (open circles) in our Galaxy. Also shown are data for the velocity dispersion of the gas in M31 (triangles) and M81 (squares). The dots and solid line give the relation between velocity dispersion and diameter of the region of origin for stars in different age groups from Table 2.

The "velocity law"

coefficient, $v_\circ$, exhibits little variation from cloud to cloud, despite the large range in cloud sizes and star formation activity. Effectively, when the individual structure functions are overlayed onto a single plot, they form a nearly co-linear set of points (see Figure 2).

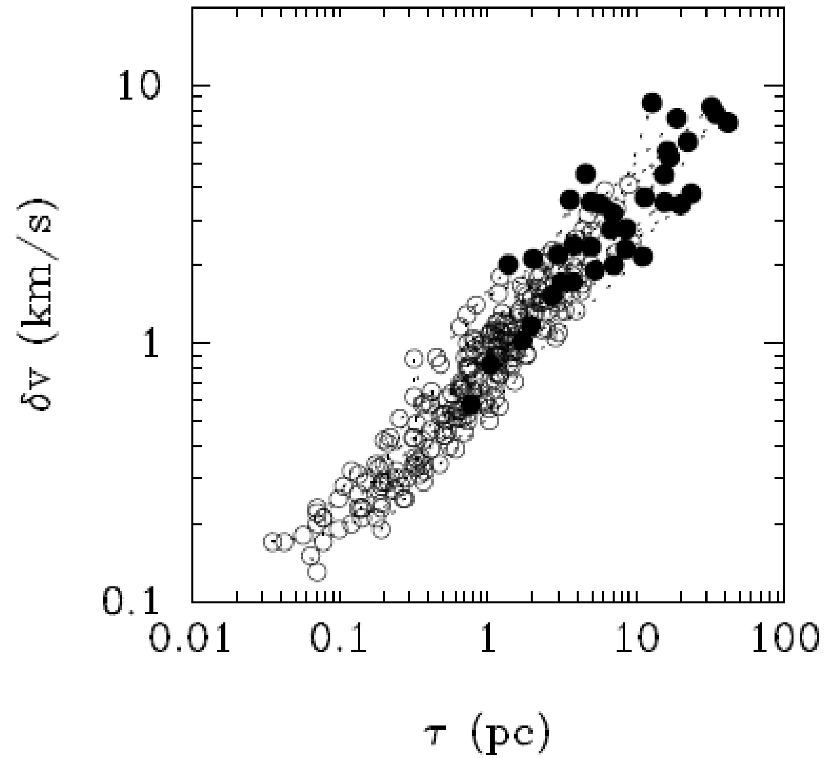
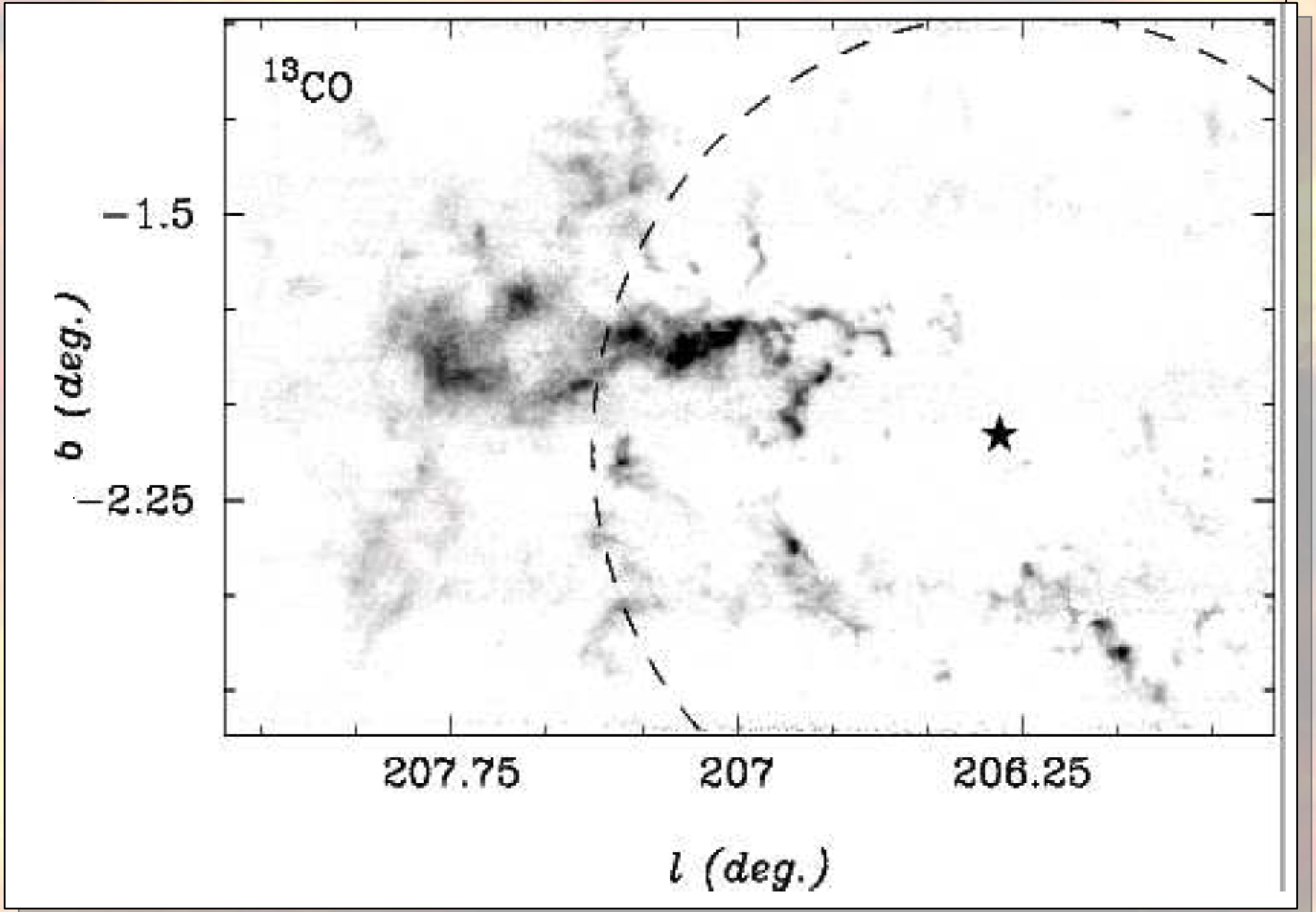
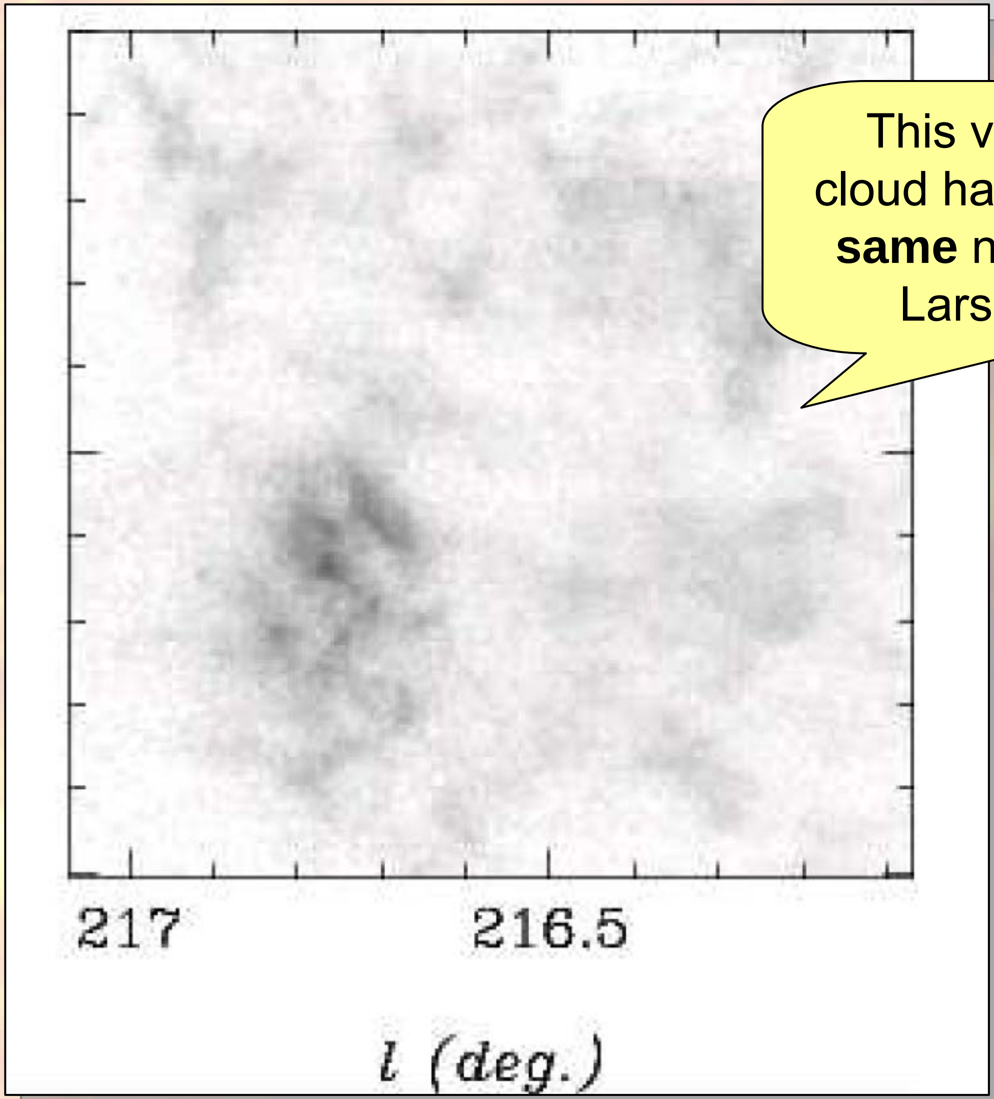


Figure 2. The velocity structure functions for 29 clouds derived from PCA of ^{12}CO J=1-0 data cubes (Heyer & Brunt 2004). The nearly co-linear set of points attest to the near-invariant functional form of structure functions despite the large range in size and star formation activity. The filled circles are the upper endpoints for each structure function and are equivalent to the size and global line-width for each cloud.

Rosetta Cloud, $C_{13}O$ – vigurous star formation



Maddalena Cloud $C_{13}O$ – practically no star formation



This very quiescent cloud has practically **the same** normalization of Larson's v-law !!