ISM/Molecular Cloud/Star Formation Simulations

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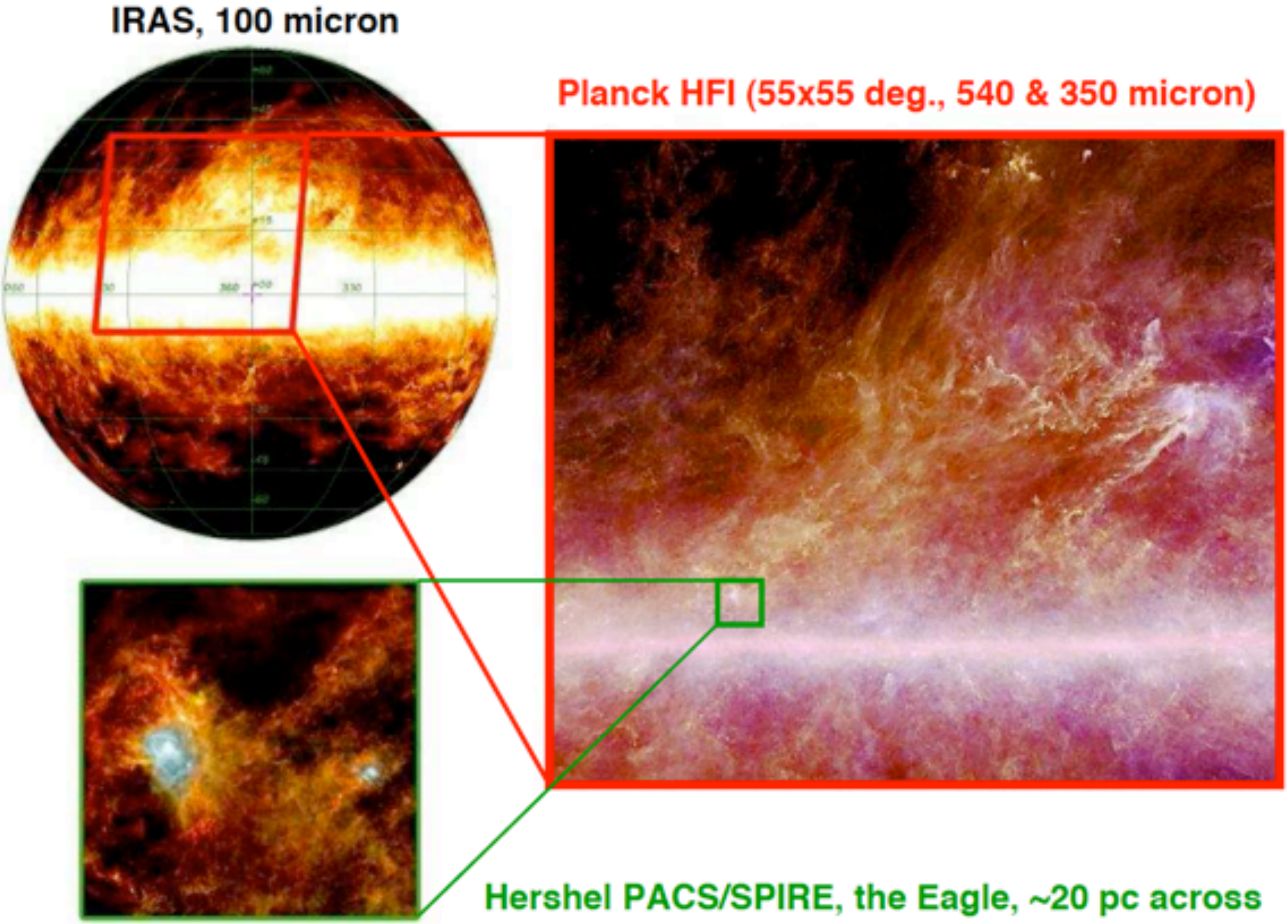
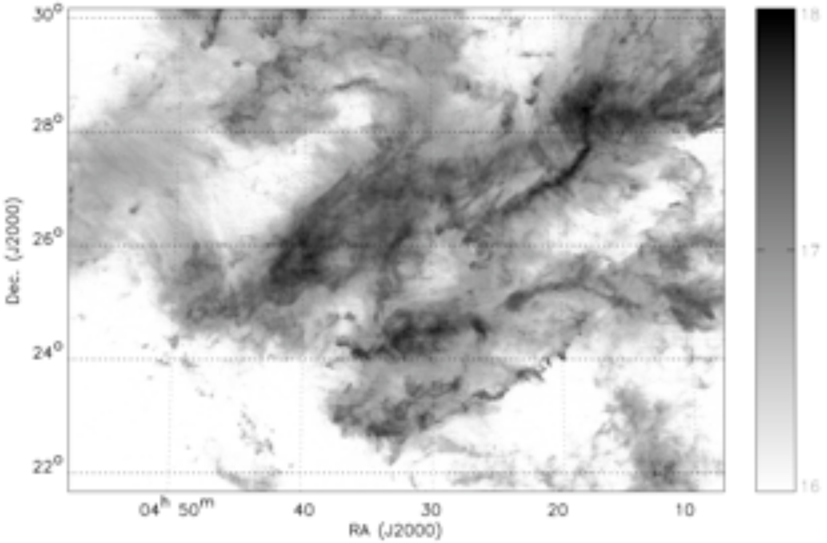
Rick Wagner (SDSC)

The Future of AstroComputing
SDSC, December 17, 2010

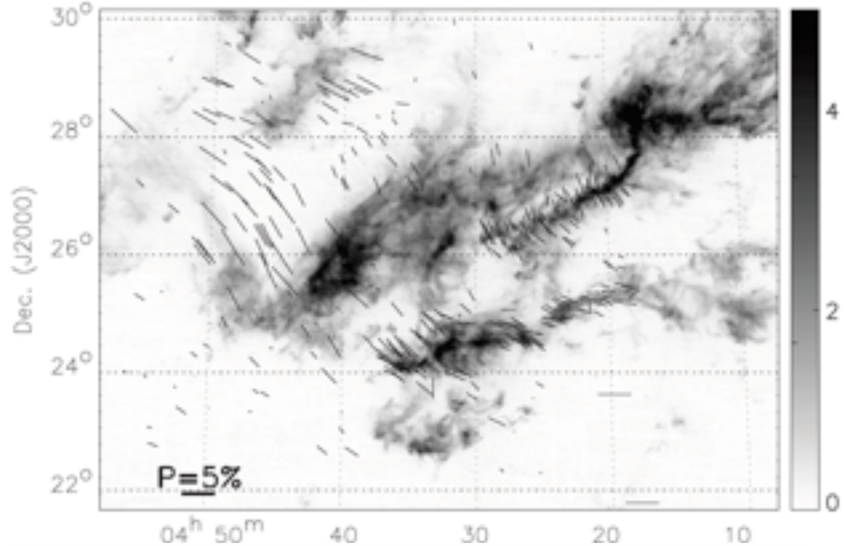
Dust structures within 150 parsecs of the Sun

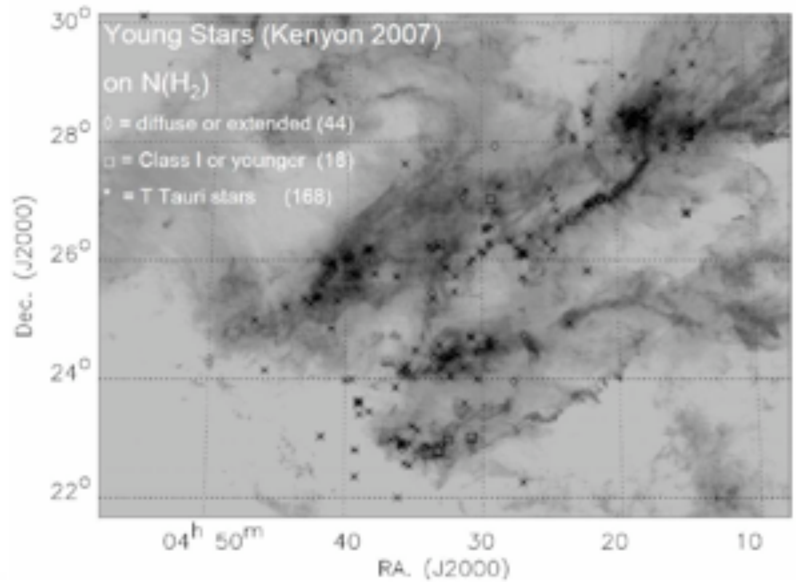


Molecular gas, B-fields & YSO in Taurus



The ^{12}CO column density (cm^{-2}) distribution; 21×26 pc [Goldsmith et al., 2008]





- **Filamentary hierarchical structure of MCs**
- **Magnetic field lines are preferentially ⊥ to the filaments**
- **Stars form in dense cold molecular cores deep within the filaments**

Initial conditions for star formation

Initial conditions for star formation

- **Turbulence**

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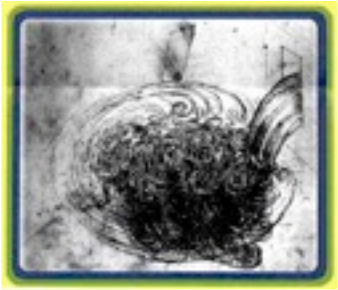
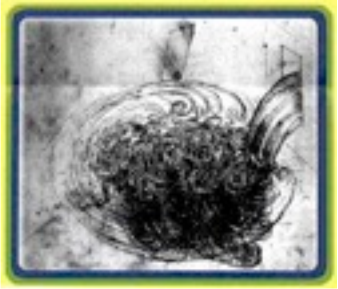
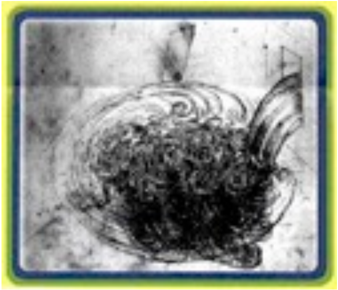


Initial conditions for star formation



- Turbulence
- Gravity

Initial conditions for star formation



- **Turbulence**
- **Gravity**

Initial conditions for star formation

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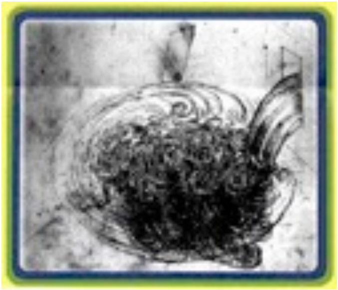
- Magnetic fields



Initial conditions for star formation

- **Turbulence**
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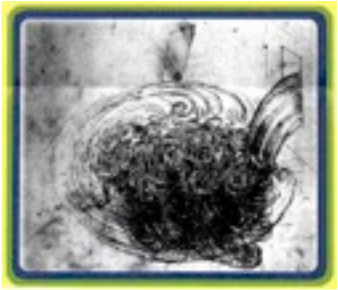
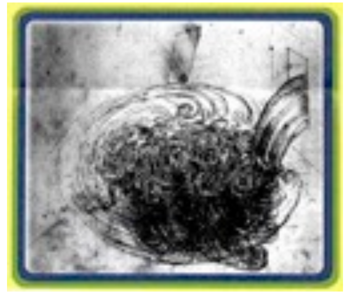


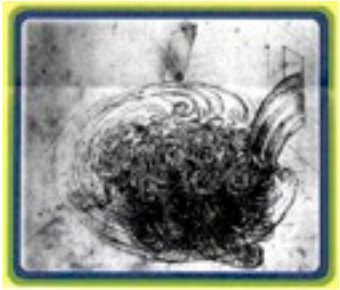
Initial conditions for star formation

- **Turbulence**
- **Gravity**
- **Magnetic fields**
- Thermodynamics



Initial conditions for star formation

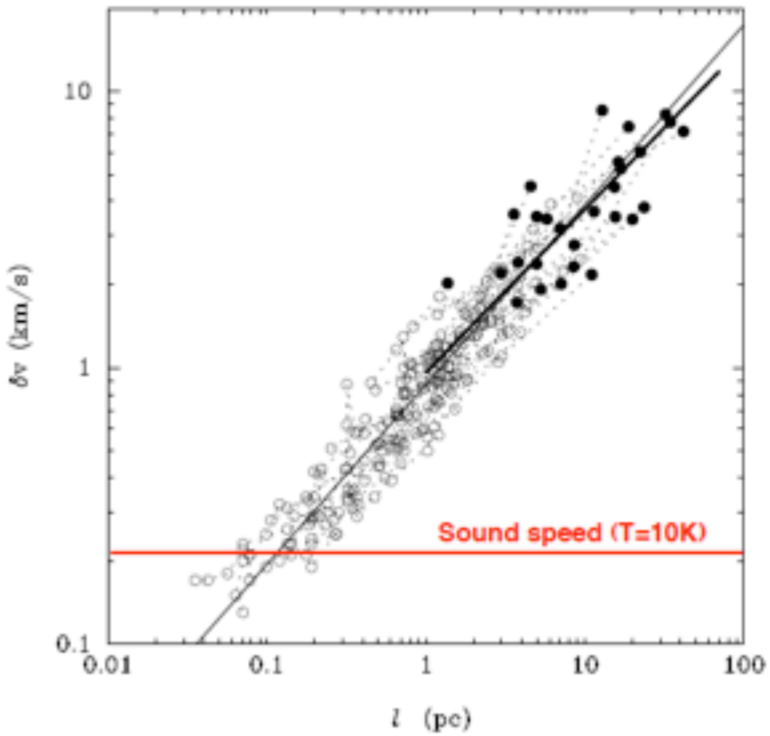
- Turbulence
- Gravity
- Magnetic fields
- Thermodynamics
- Radiative feedback
- Outflows



I. Turbulence

Universal linewidth-size relation

Interstellar turbulence within MCs is invariant over a wide range of scales



Reynolds number: $Re = \frac{u(L)L}{\nu} \sim 10^8$

Outer scale: $L \gtrsim 50$ pc

Mach number: $M_s(L) \equiv \frac{u_{\rm rms}}{c_s} \gg 1$

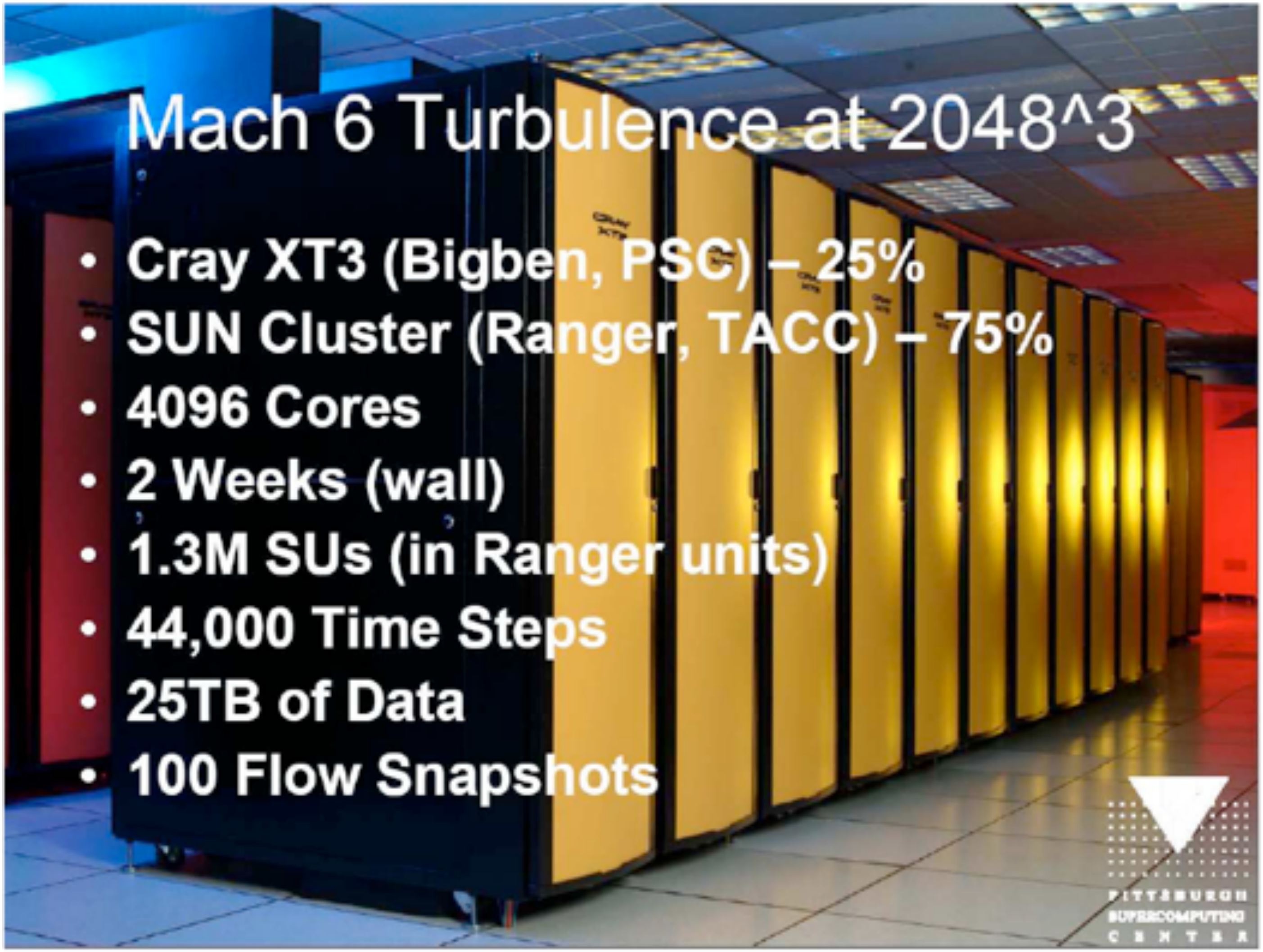
Velocity scaling: $S_1(\ell) \sim \ell^{0.56 \pm 0.02}$

Filled circles – global velocity dispersion and size for each cloud.

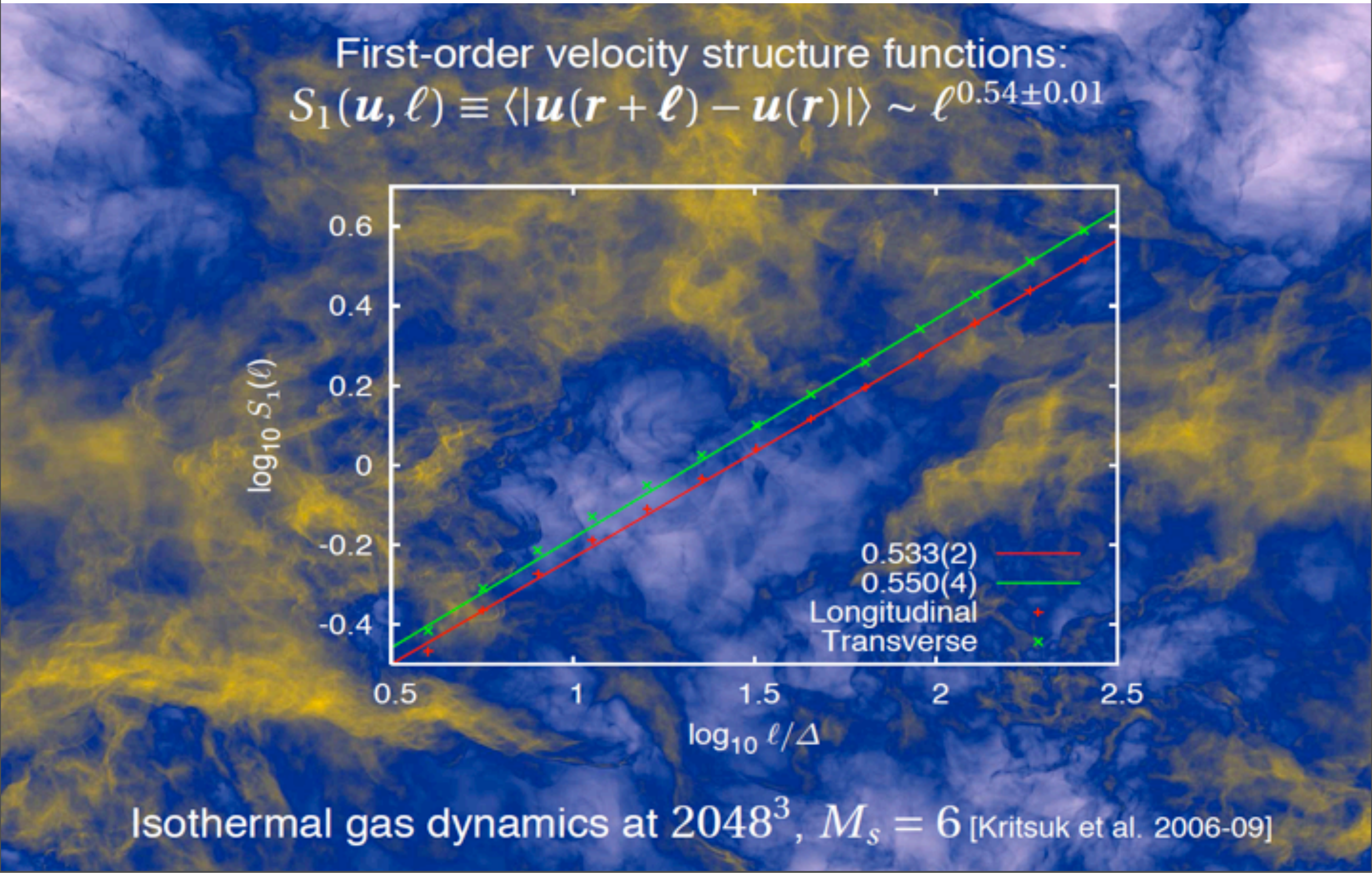
Heavy solid line is equivalent to Larson's (1981) relation.

The composite relation from PCA decompositions of ^{12}CO J=1-0 imaging observations of 27 molecular clouds, $\delta u = (0.87 \pm 0.02)\,\ell^{0.65 \pm 0.01}$, corresponds to a 1st-order structure function scaling: $S_1(\ell) \sim \ell^{0.56 \pm 0.02}$ [Heyer & Brunt, 2003-04].

ENZO simulation 2008



Supersonic turbulence: Scaling - I

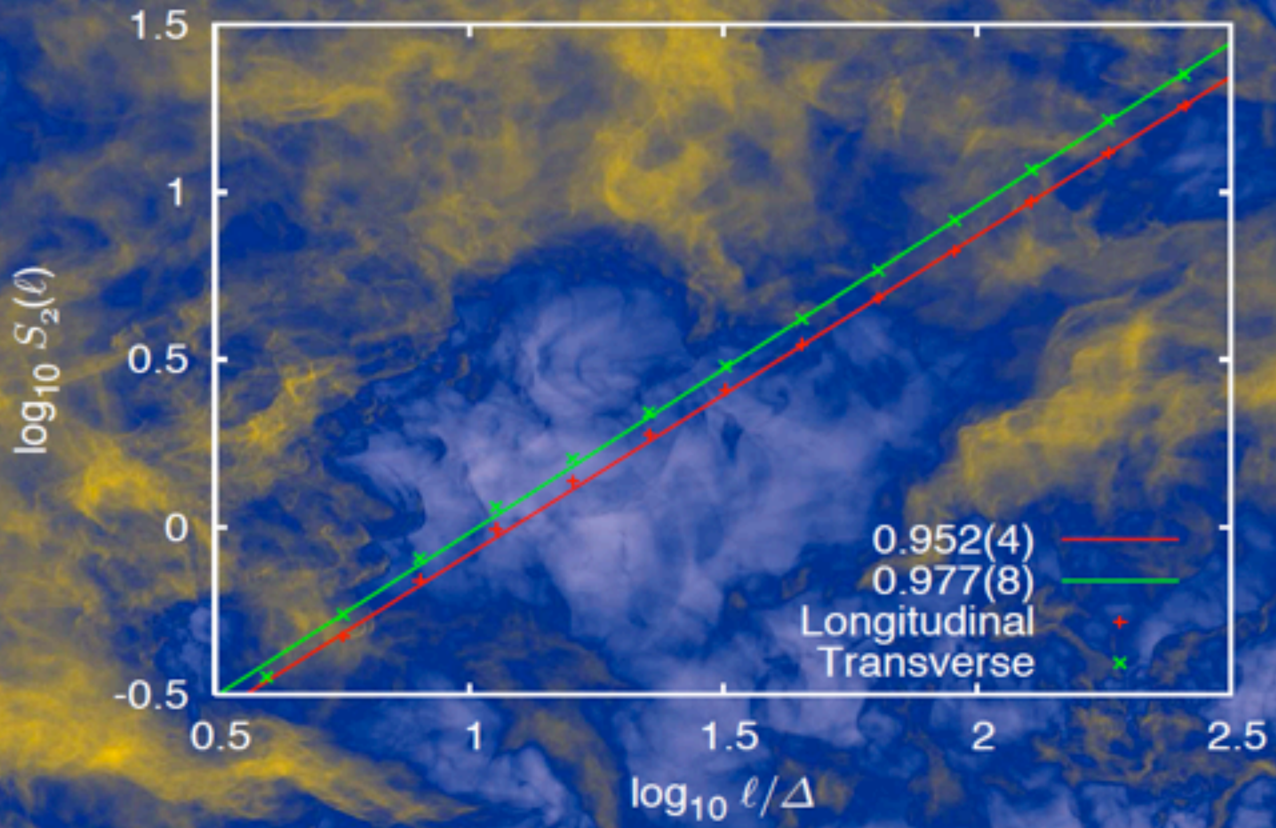


Friday, December 17, 2010

Supersonic turbulence: Scaling - II

Second-order velocity structure functions:

$$S_2(\boldsymbol{u},\ell) \equiv \langle|\boldsymbol{u}(\boldsymbol{r}+\boldsymbol{\ell})-\boldsymbol{u}(\boldsymbol{r})|^2\rangle \sim \ell^{0.96\pm0.01}$$

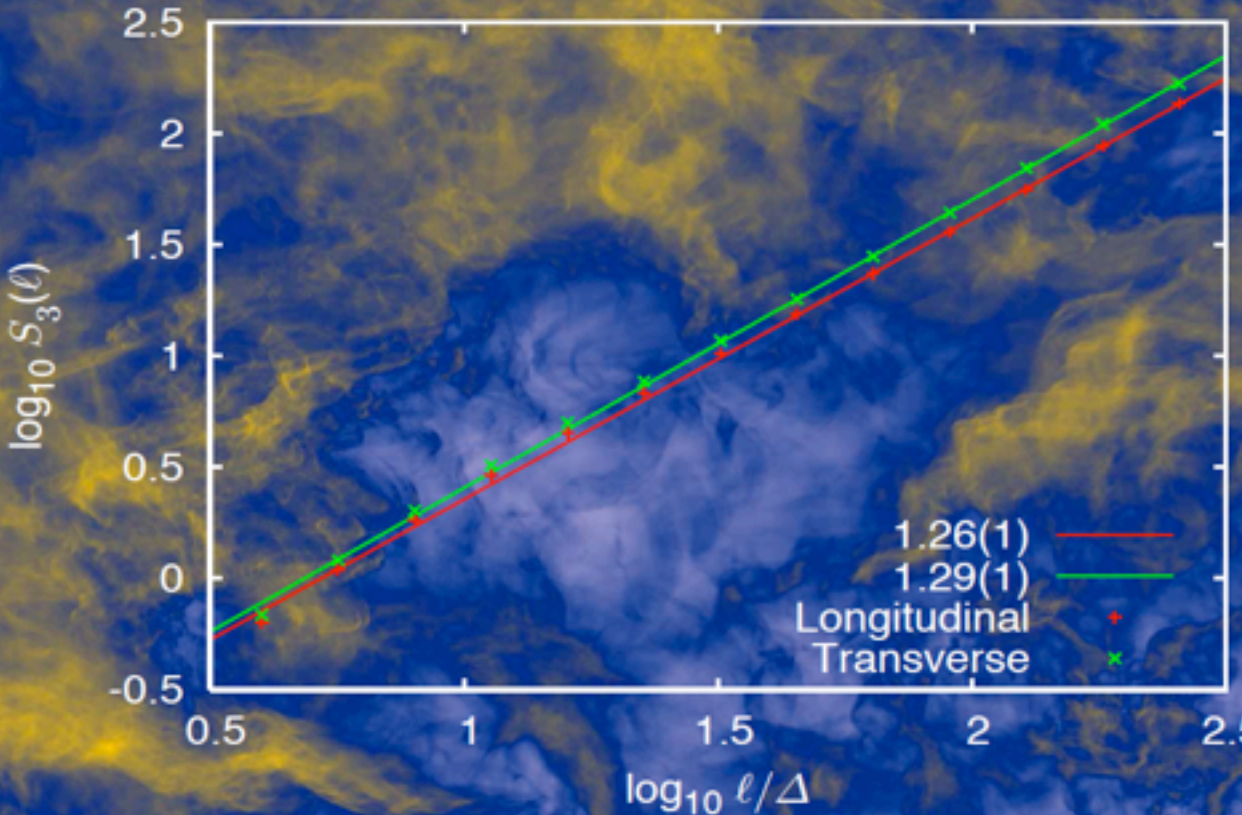


$S_2^{\perp} = \frac{4}{3} S_2^{\parallel}$ converts into $S_2^{\perp} \approx 1.27 S_2^{\parallel}$ at $M_s = 6$ [Kritsuk et al. 2007]

Supersonic turbulence: Scaling - III

Third-order velocity structure functions:

$$S_3(\boldsymbol{u},\ell) \equiv \langle |\boldsymbol{u}(\boldsymbol{r}+\boldsymbol{\ell}) - \boldsymbol{u}(\boldsymbol{r})|^3 \rangle \sim \ell^{1.27\pm0.02}$$

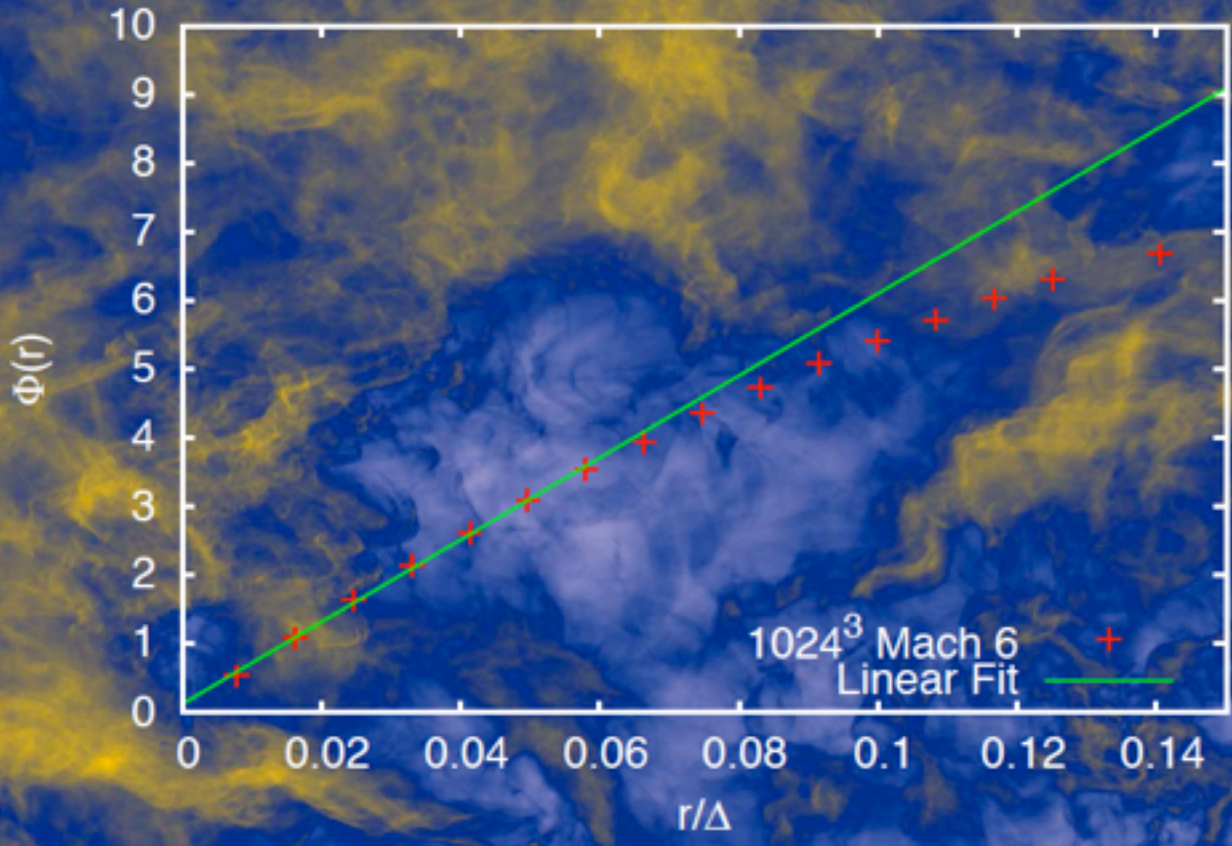


$S_3^{\parallel}(\boldsymbol{u},\ell)$ does not scale linearly with ℓ at $M_s = 6$ [Kritsuk et al. 2007]

Supersonic turbulence: Scaling - IV

Exact current-density correlation function [Falkovich et al. 2010]

$$\Phi(r_i) \equiv \sum_j \langle \rho(0)\, u_i(0) \left[\rho(\mathbf{r})\, u_j(\mathbf{r})\, u_i(\mathbf{r}) + p(\mathbf{r}) \delta_{ij} \right] \rangle = \frac{\epsilon r_i}{3}$$



$\Phi(r)$ does scale linearly with r at $M_s = 6$ [Wagner et al. 2011, in prep.]

Supersonic turbulence: Energy cascade

- Simple dimensional arguments:

Energy cascade in incompressible turbulence:

$$\delta u^2 \left(\frac{\delta u}{\ell}\right) \equiv const \Rightarrow \delta u^3 \sim \ell \Rightarrow \delta u^p \sim \ell^{\frac{p}{3}}$$ [Kolmogorov 1941]

Energy cascade in supersonic turbulence:

$$\rho \delta u^2 \left(\frac{\delta u}{\ell}\right) \equiv const$$ [e.g., Lighthill 1955] $$\Rightarrow \rho \delta u^3 \sim \ell$$

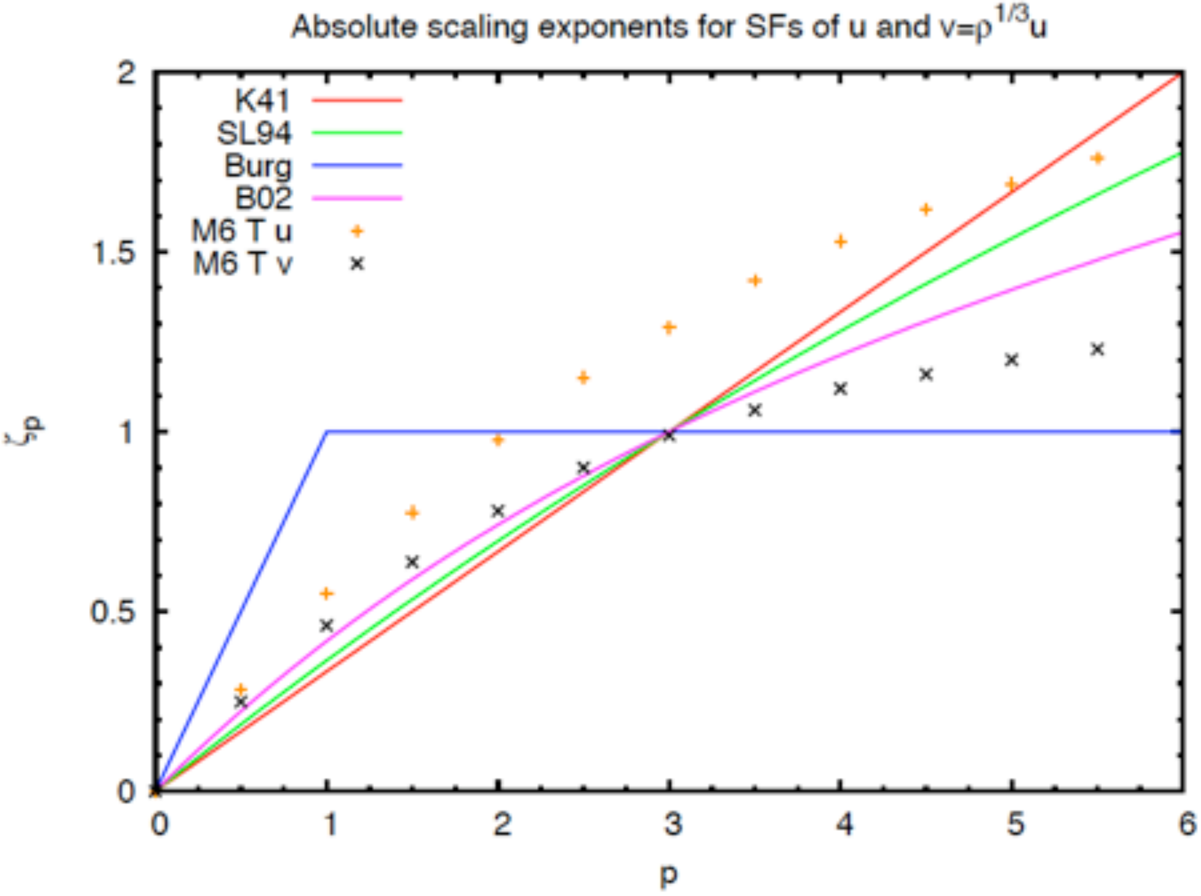
$$\delta v \equiv \rho^{\frac{1}{3}} \delta u \Rightarrow \delta v^p \sim \ell^{\frac{p}{3}}$$

These scaling laws (both incompressible (K41) and compressible) do not include intermittency corrections.

Using v instead of u, one properly accounts for density–velocity correlations in compressible flows.

[Henricksen (1991); Fleck (1996); Kritsuk et al. (2007); . . .]

Supersonic turbulence: Intermittency

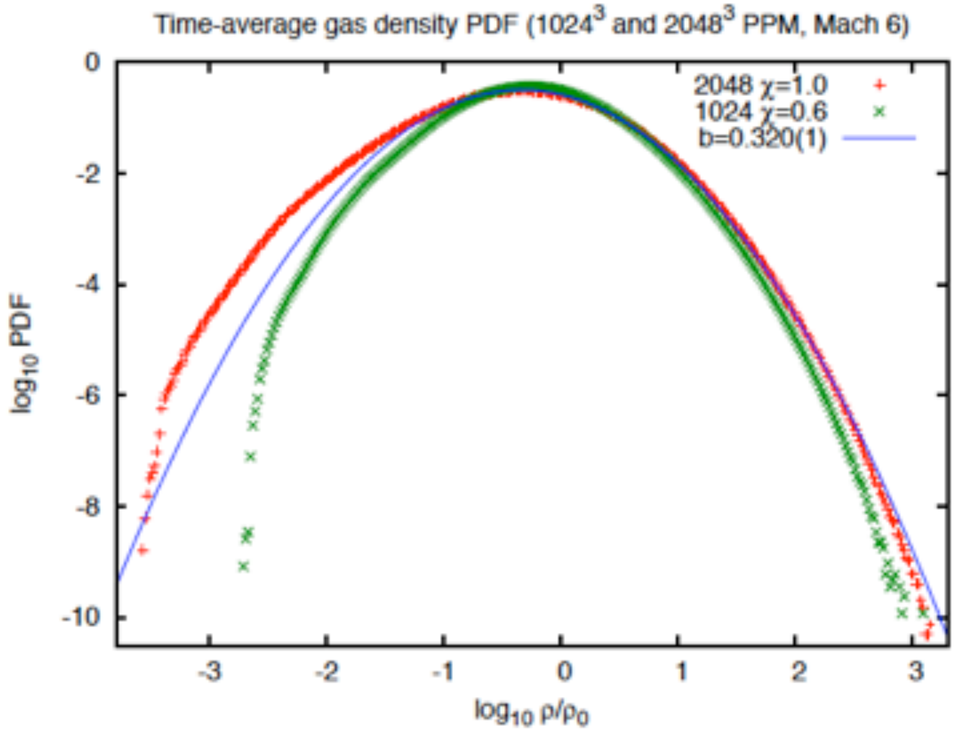


Kritsuk et al. (2006-10); Kowal & Lazarian (2007-10); Schwarz et al. (2010); Price & Federrath (2010); Falkovich et al. (2010); Schmidt et al. (2008-09); Federrath et al. (2010)

II. Gravity

Lognormal density PDF

Theory: Vazquez-Semadeni 1994; Padoan, Nordlund & Jones 1997; Passot & Vázquez-Semadeni 1998; Nordlund & Padoan 1999; Biskamp 2003

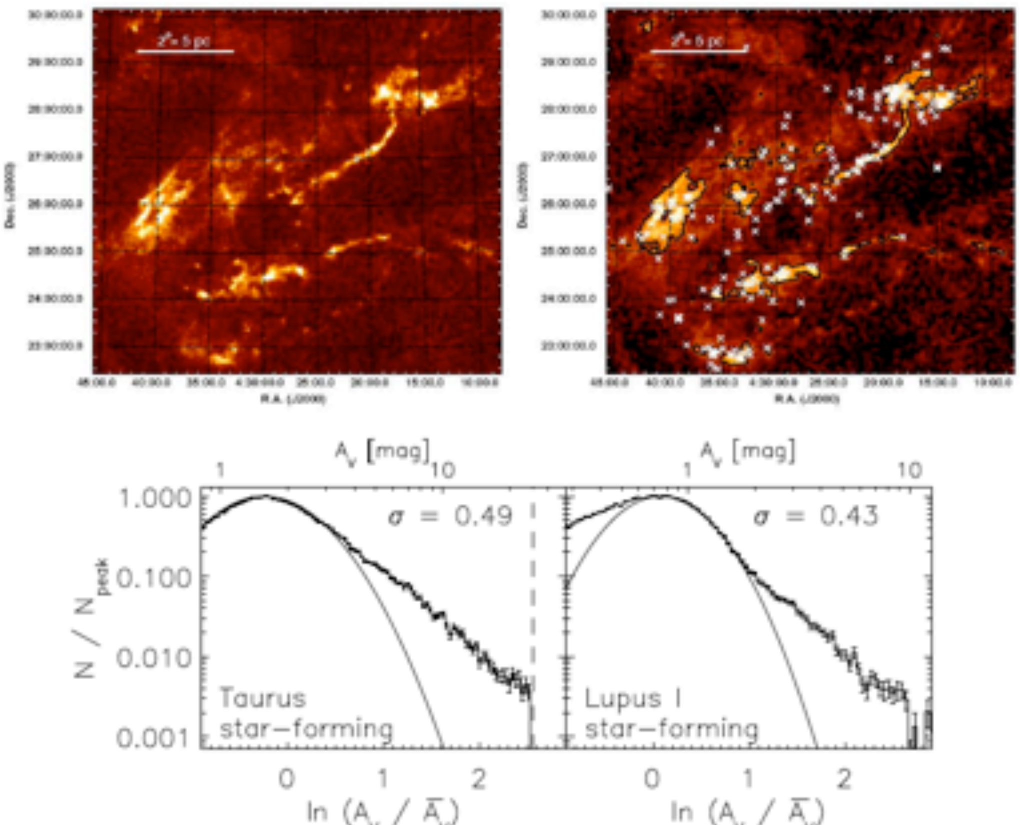


- Good fit quality over 8 decades in probability!
- Sample size 2×10^{11} (1024^3) and 9×10^{11} (2048^3)
- The best-fit values of the width parameter are $b \approx 0.260 \pm 0.001$ and $b \approx 0.320 \pm 0.001$, respectively, for $\log_{10} \rho \in [-2, 2]$

Power-law tails in the density PDF

Wide-field dust extinction map of the Taurus MC complex

18×18 pc; $N(H_2 + H)/A_V = 9.4 \times 10^{20}$ cm^{-2} [Bohlin et al., 1978]



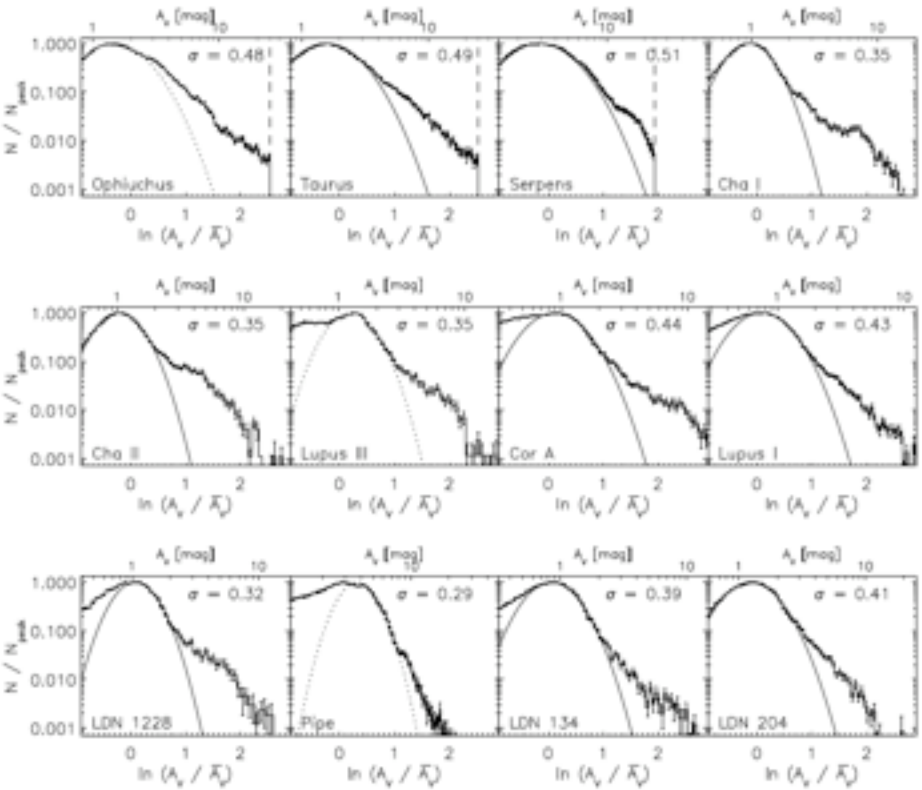
- *Left*: linear A_V; *Right*: logarithmic A_V [Kainulainen et al. 2009]
- The contour at $A_V = 4$ mag shows where the column density PDF deviates from lognormal

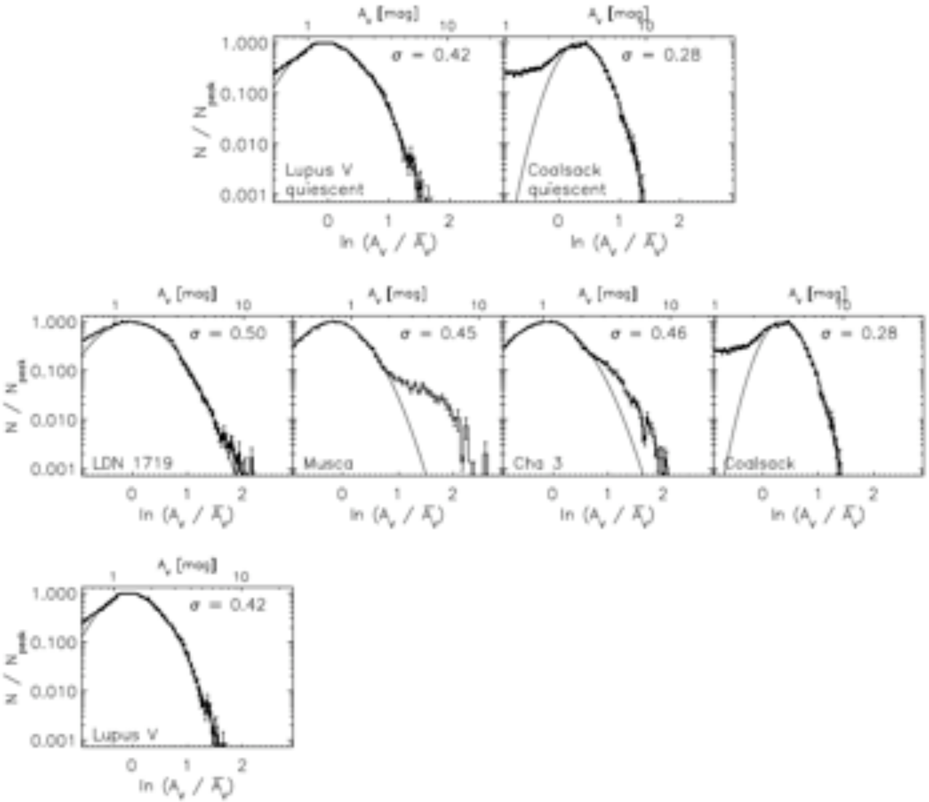
Power-law tails in the density PDF

Star-forming MCs

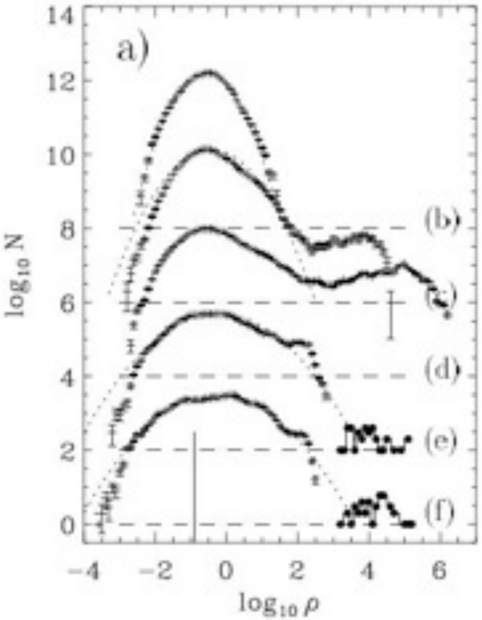
Non-star-forming MCs

Kainulainen et al. (2009)

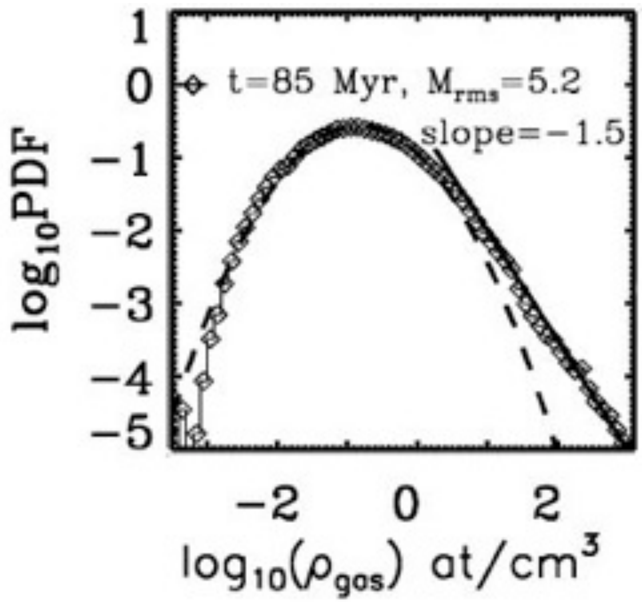




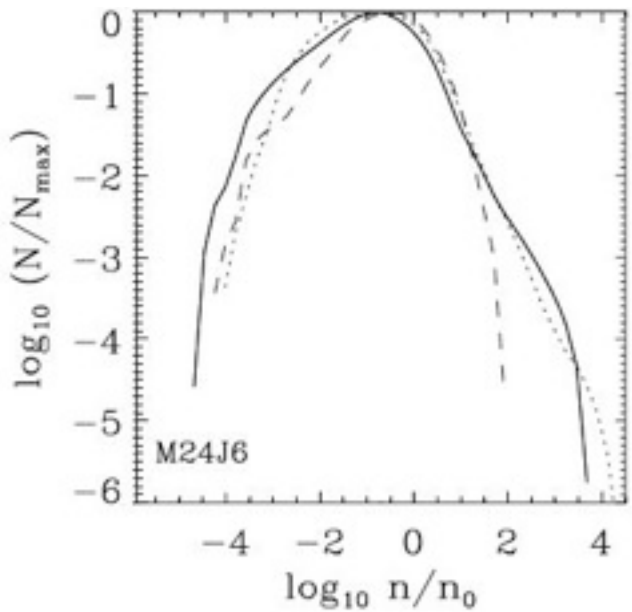
Power-law tails in the density PDF



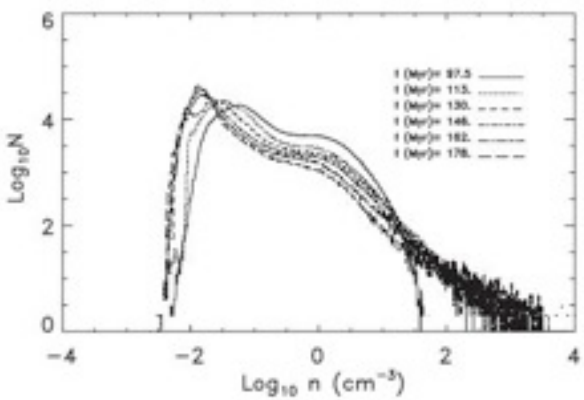
Klessen 2000 (SPH)



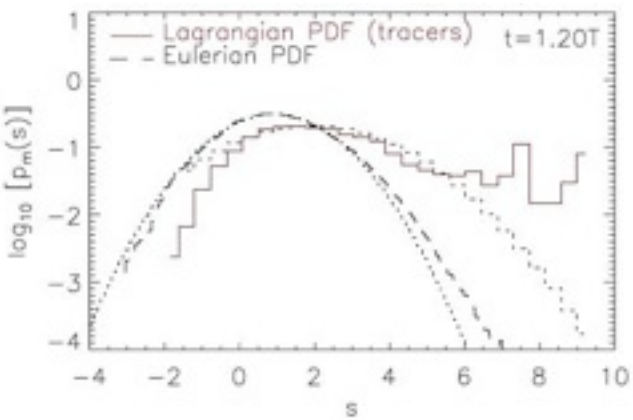
Slyz + 2005 (ENZO)



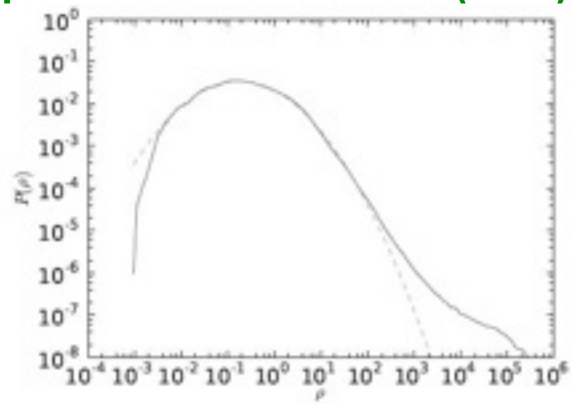
Vazquez-Semadeni + 2008 (TVD)



Dib & Burkert 2005 (ZEUS-MP)



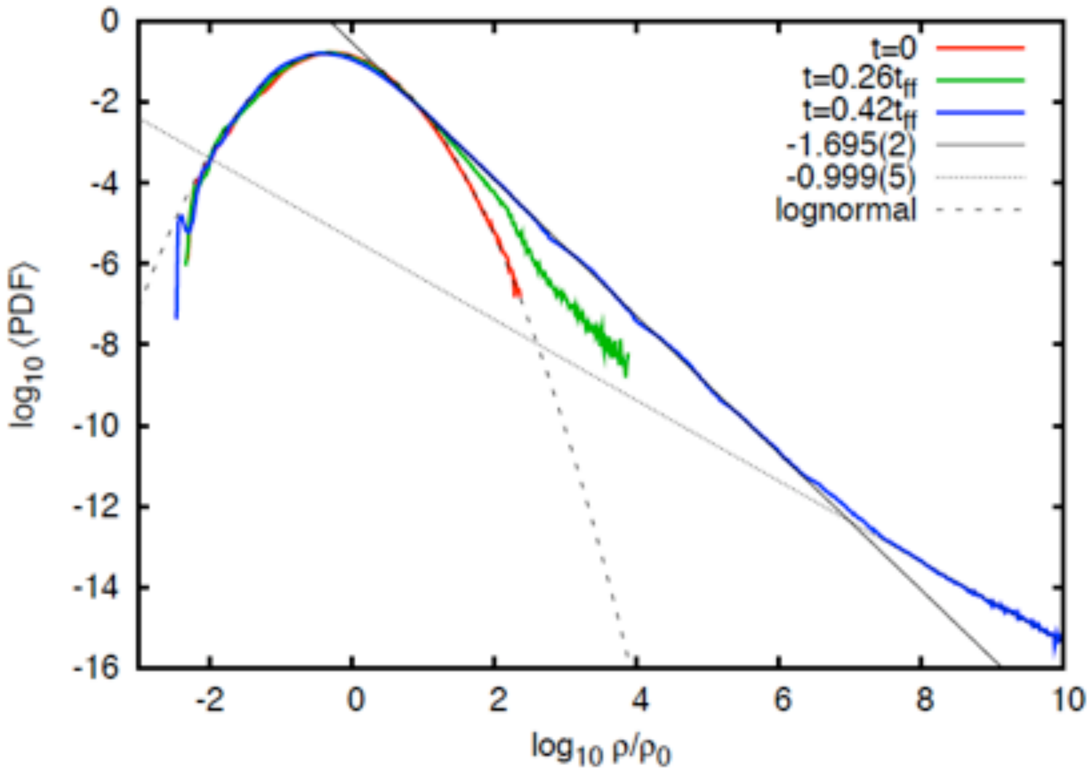
Federrath + 2008 (ENZO)



Collins + 2010 (AMR-MHD)

Power-law tails in the density PDF

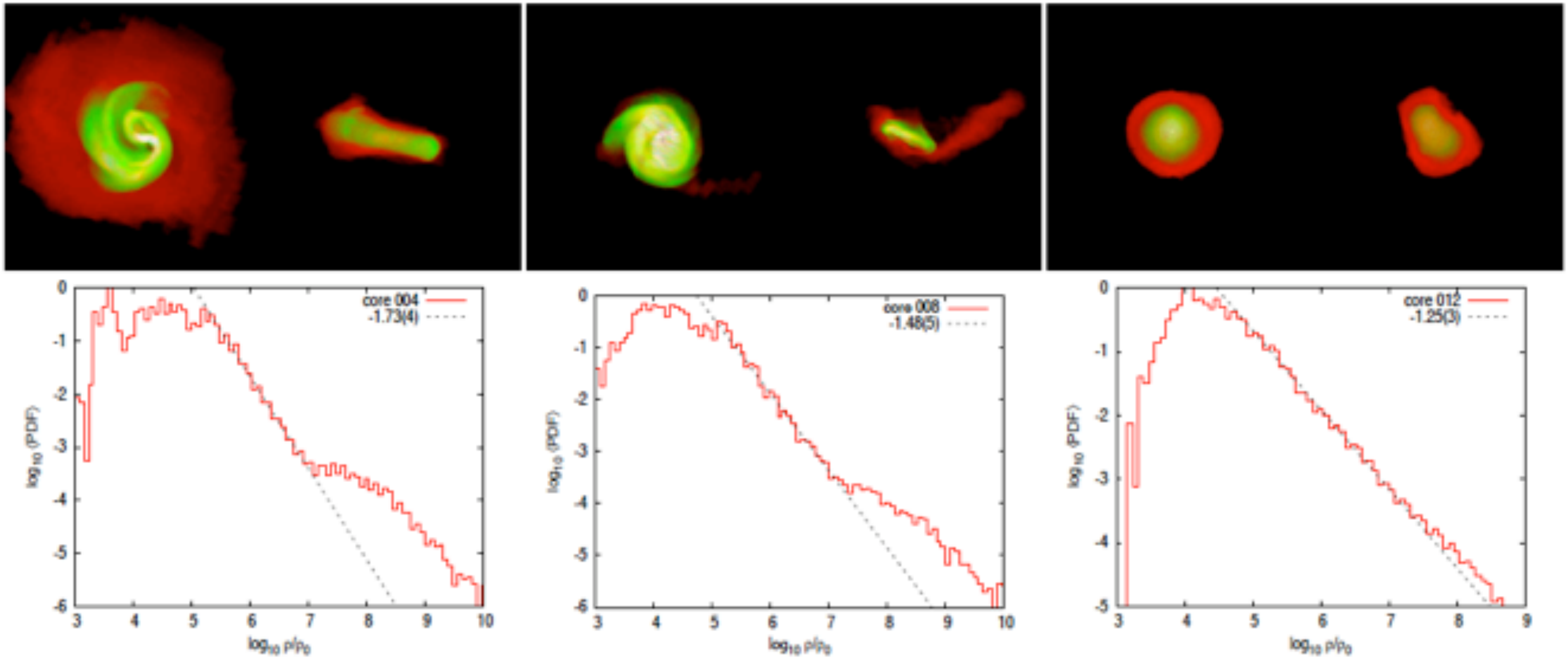
Extended power law tail: > 6 dex in density, slope -1.7



- Initial conditions, $t = 0$; First subgrids created, $t = 0.26\,t_{\rm ff}$; Deep AMR hierarchy, $t = 0.42\,t_{\rm ff}$
- Effective linear resolution: 5×10^5 (5 pc – 2 AU)
- Two breaks in slope: at $\rho \sim 10^{6.2}\rho_0$ (-1.5) and at $10^7\rho_0$ (-1)

Power-law tails in the density PDF

Three selected condensed objects and their PDFs; $\sim (700\ \mathrm{AU})^3$



- Individual slopes vary from -1.2 to -1.8
- Rotation-induced pile-ups at $\rho > 10^7 \rho_0$
- Cores 1 and 2 exhibit strong rotation, core 3 shows only modest flattening

Power-law tails in the density PDF

The PDF for a spherically symmetric configuration with $\rho = \rho_0 (r/r_0)^{-n}$ density profile is a power law

$$dV = \frac{4}{3}\pi r_0^3 \, d\left[\left(\frac{\rho}{\rho_0}\right)^{-3/n}\right] \propto d\left(\rho^{-m}\right).$$

The projected density of an infinite sphere with the $\rho \sim r^{-n}$ density profile,

$$\Sigma(R) = 2\int_0^\infty \rho\left(\sqrt{R^2 + x^2}\right) dx \propto R^{1-n},$$

also has a power-law PDF,

$$dS \propto d\left(\Sigma^{-\frac{2}{n-1}}\right) \propto d\left(\Sigma^{-p}\right).$$

For the LP [Larson-Penston, 1969] , PF [Penston, 1969], and EW [Shu, 1977] similarity solutions: $n = 2, \frac{12}{7}$, and $\frac{3}{2}$; $m = \frac{3}{2}, \frac{7}{4}, 2$; $p = 2, 2.8$, and 4, respectively.

III. B-fields

Self-organization in MHD turbulence

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- **ISM is a turbulent driven dissipative system**

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- **Kinetic energy is injected at large scales**
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- **Usual MHD constraints (conservation laws)**
- **Relaxation through nonlinear interactions**

Self-organization in MHD turbulence

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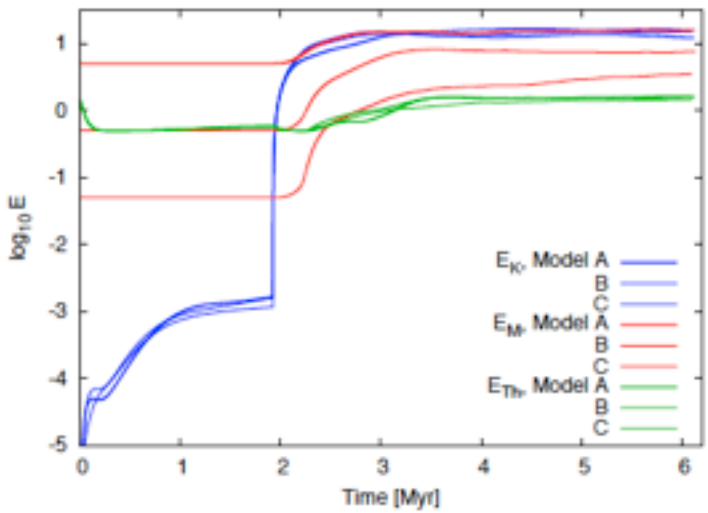
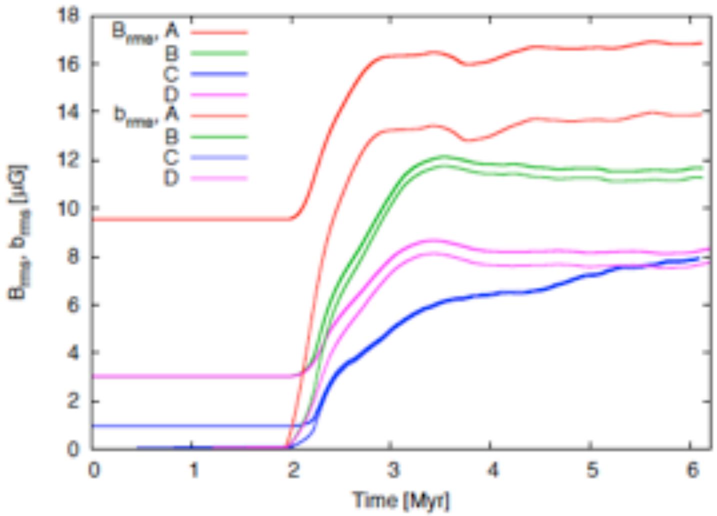
- Thermal energy input, radiative cooling
- Usual MHD constraints (conservation laws)
- Relaxation through nonlinear interactions
- MCs form as dissipative structures (active regions of intermittent turbulent cascade that drain the kinetic energy supplied by forcing)

Global energetics

Kinetic, magnetic, and thermal energy density versus time



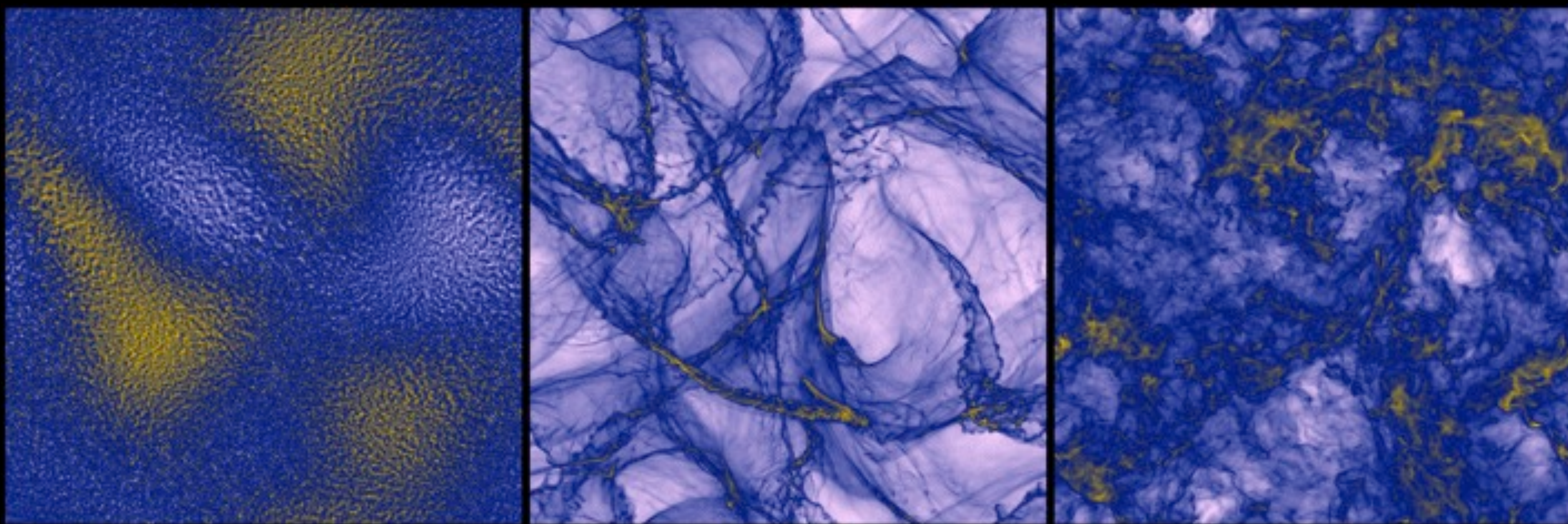


- Models A, B & C have uniform magnetic fields $B_0 = 10$, 3, & 1 μG, respectively
- Model A demonstrates global energy equipartition ($E_K \sim E_M$)
- Models B and C stop short of reaching the equipartition
- Model C: $b_{\rm rms}$ continues to grow linearly after $6t_{\rm dyn}$; no statistical steady state reached
- Dynamical time $t_{\rm dyn} \equiv L/2u_{\rm rms} = 0.65$ Myr

Time-evolution of cloudy structures

Projected gas density for Model A (200 pc box)

Two-phase medium	Turbulence forcing is ON	Developed turbulence



t = 2 Myr	t = 3 Myr	t = 4 Myr

Time-evolution of cloudy structures

Projected gas density for Model A

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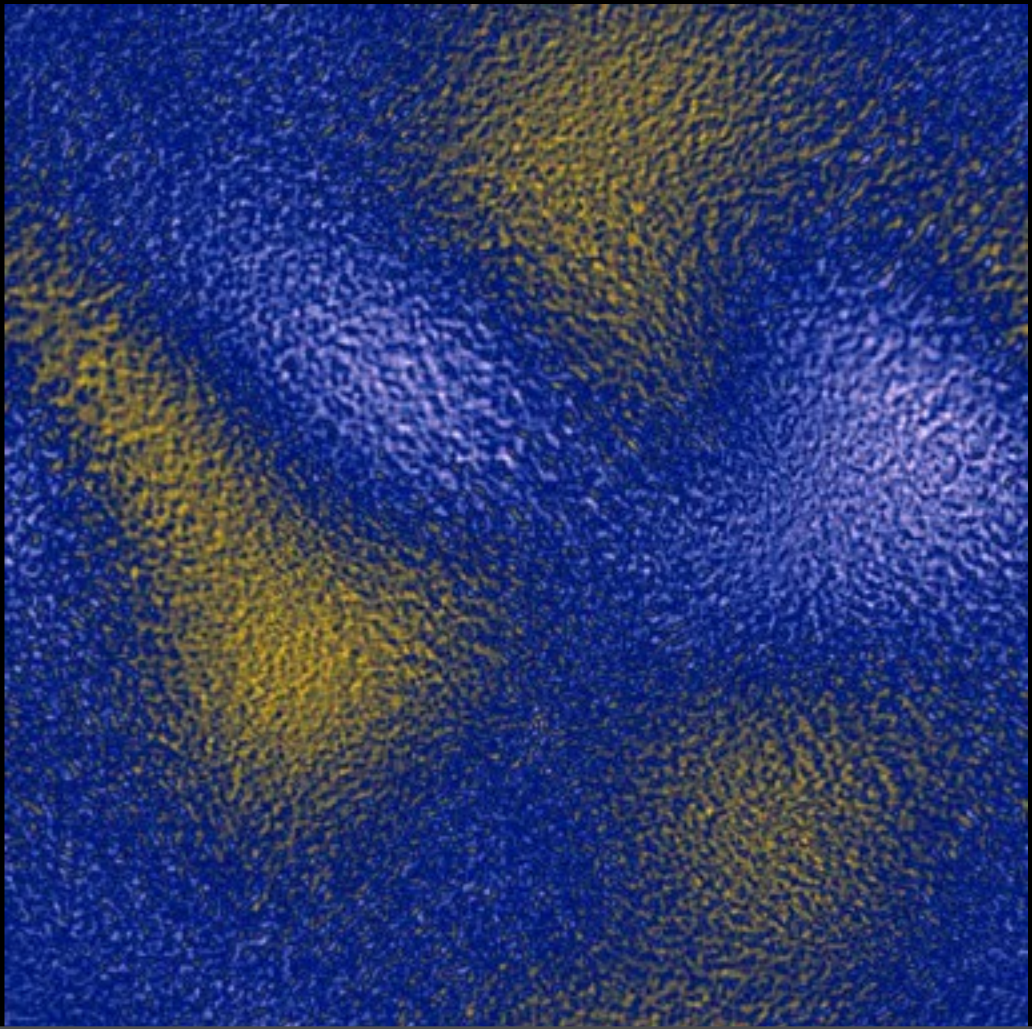
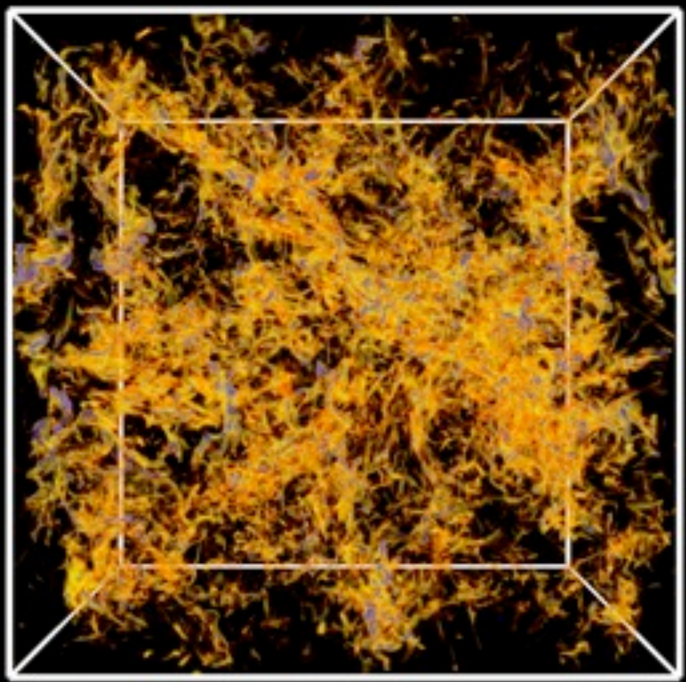
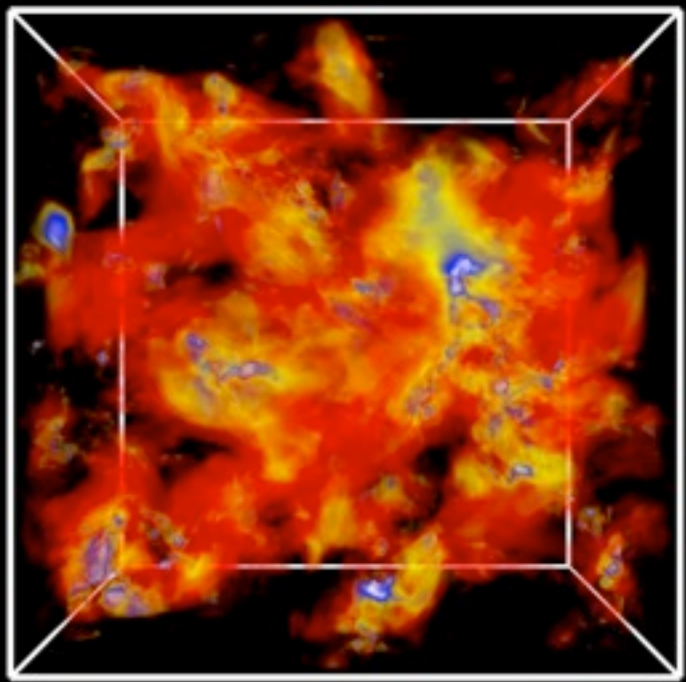
Projected gas density for Model A



Structures in the multiphase ISM

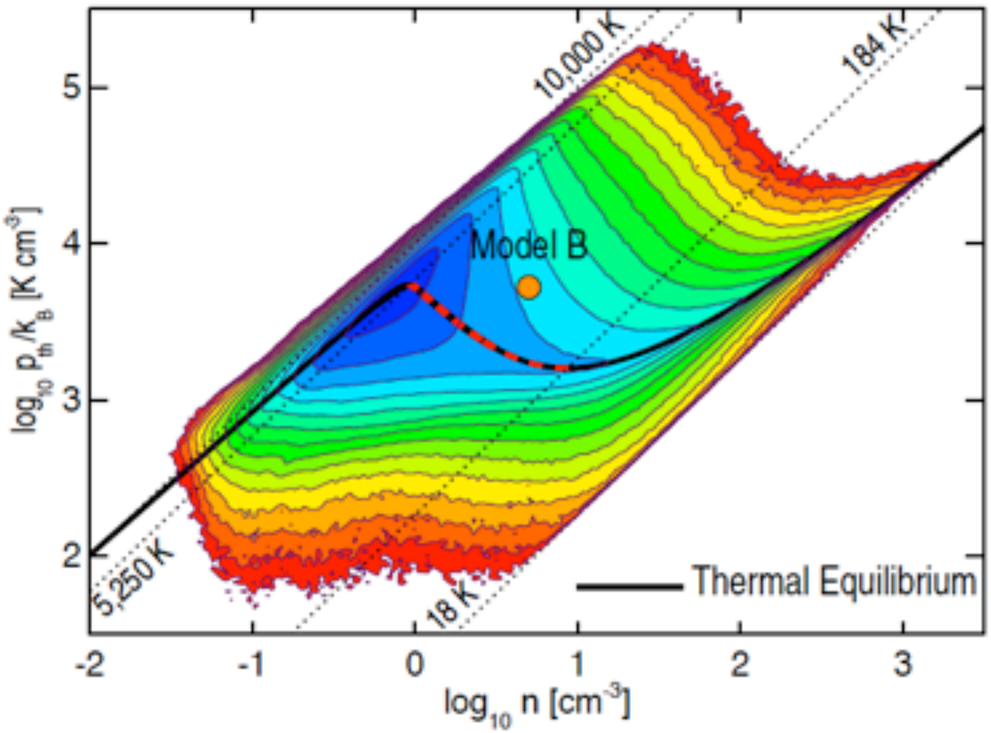




Dense material is assembled in hierarchical filamentary structures
Large molecular complexes contain comparable amounts of HI

"Thermodynamics"

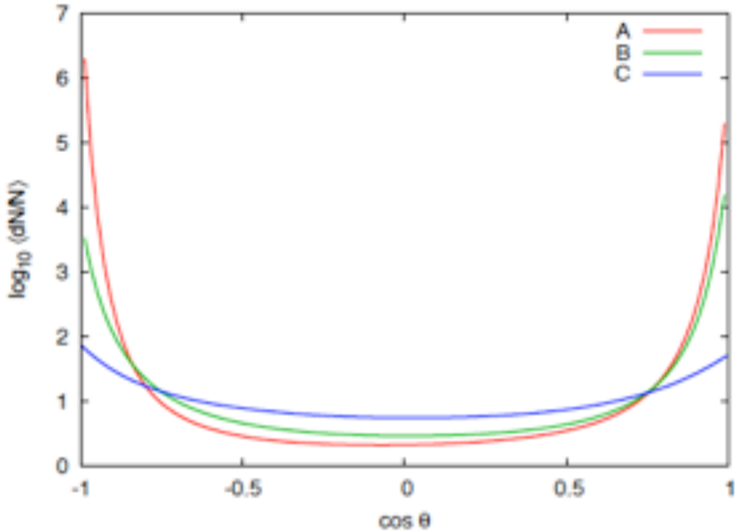
Turbulence supports a wide range of thermal pressures;
$p_{\rm th}$ in molecular gas is higher than that in the diffuse ISM

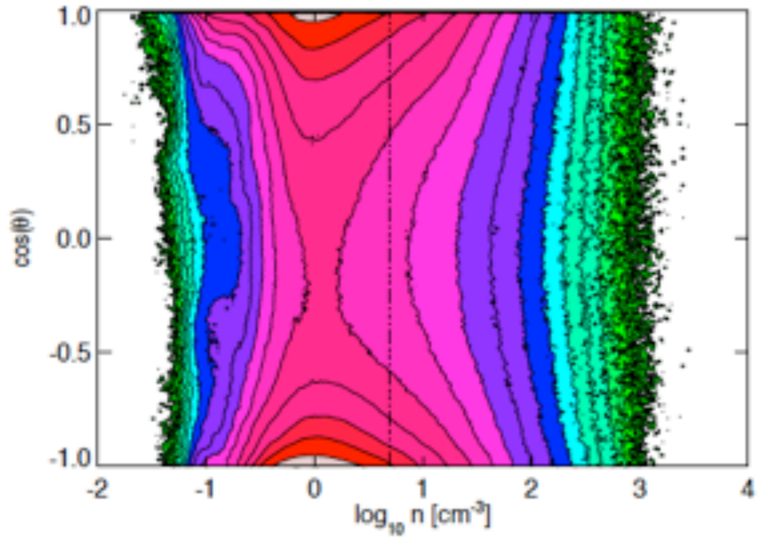


- Heavy line indicates thermal equilibrium: $n\Lambda(T) = \Gamma$
- Orange circle shows the initial conditions for Model B

Dynamic alignment

Distribution of $\cos\theta \equiv \frac{\mathbf{B}\cdot\mathbf{u}}{Bu}$ shows strong alignment of $\mathbf{B}$ and $\mathbf{u}$ at large B_0

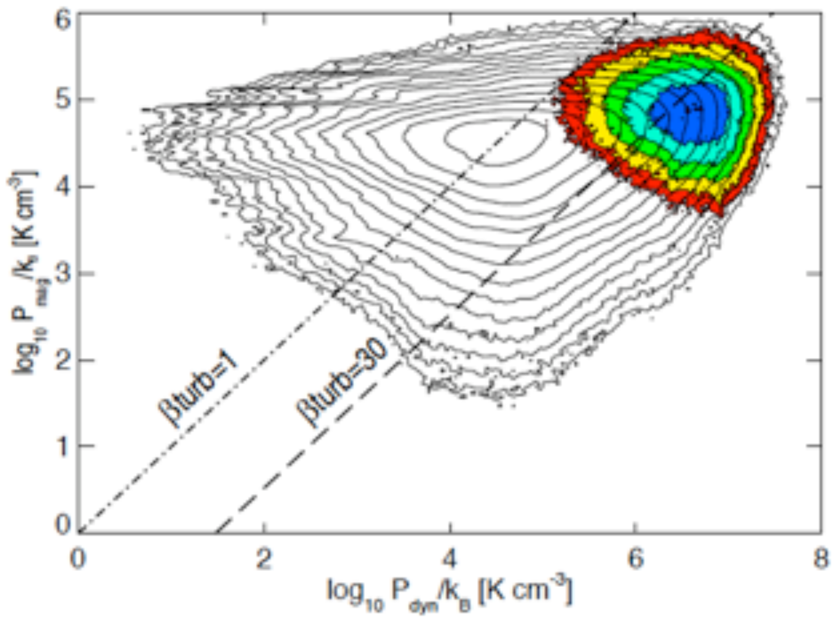




- $\mathbf{B} - \mathbf{u}$ alignment is most pronounced in Model A where $E_K \sim E_M$
- Alignment is strong in the bulk of the volume (trans-Alfvénic turbulence)
- Alignment is weak at low densities and at high densities
- Model C shows no significant alignment because $E_K \gg E_M$

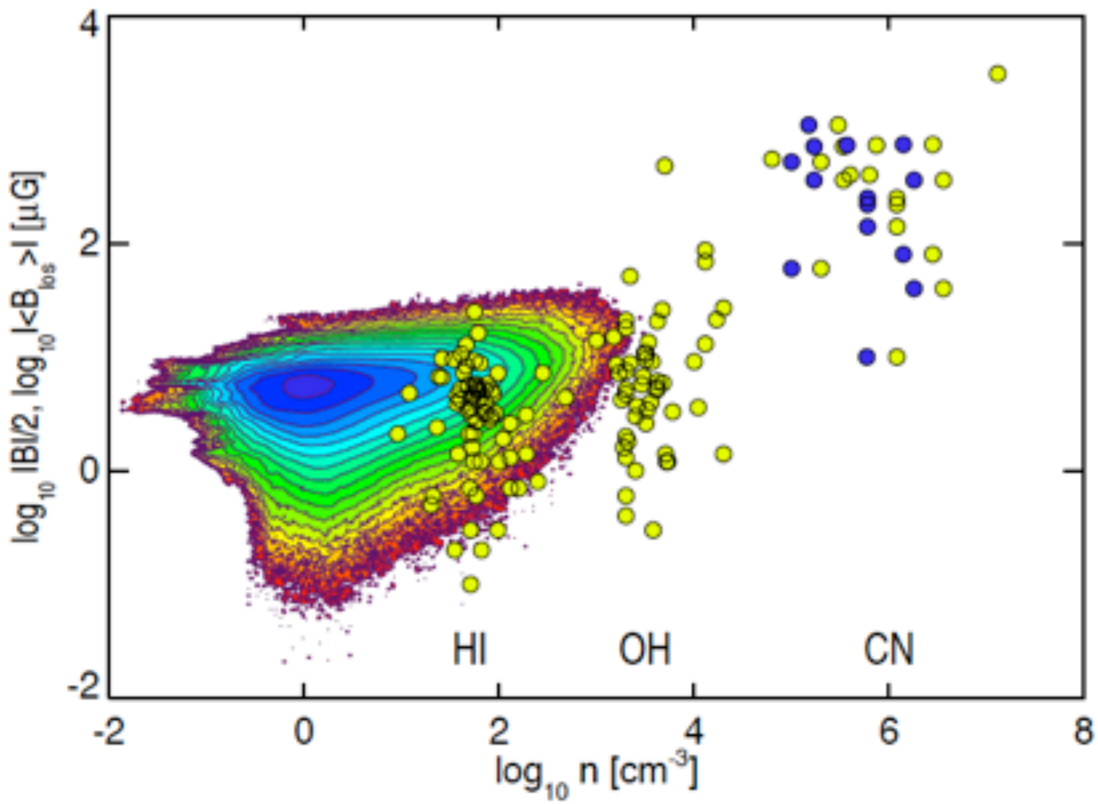
Magnetic vs. dynamic pressure

Molecular clouds are born super-Alfvénic with $\beta_{turb} > 30$



- Isolevels for a subset of cells with the cold ($T < 100$ K) and dense ($n > 100$ cm^{-3}) material representative of the molecular gas are shown in color
- Black isocontours are the same as on previous slide
- Dashed line indicates $\beta_{turb} = 30$, dash-dotted: $\beta_{turb} = 1$

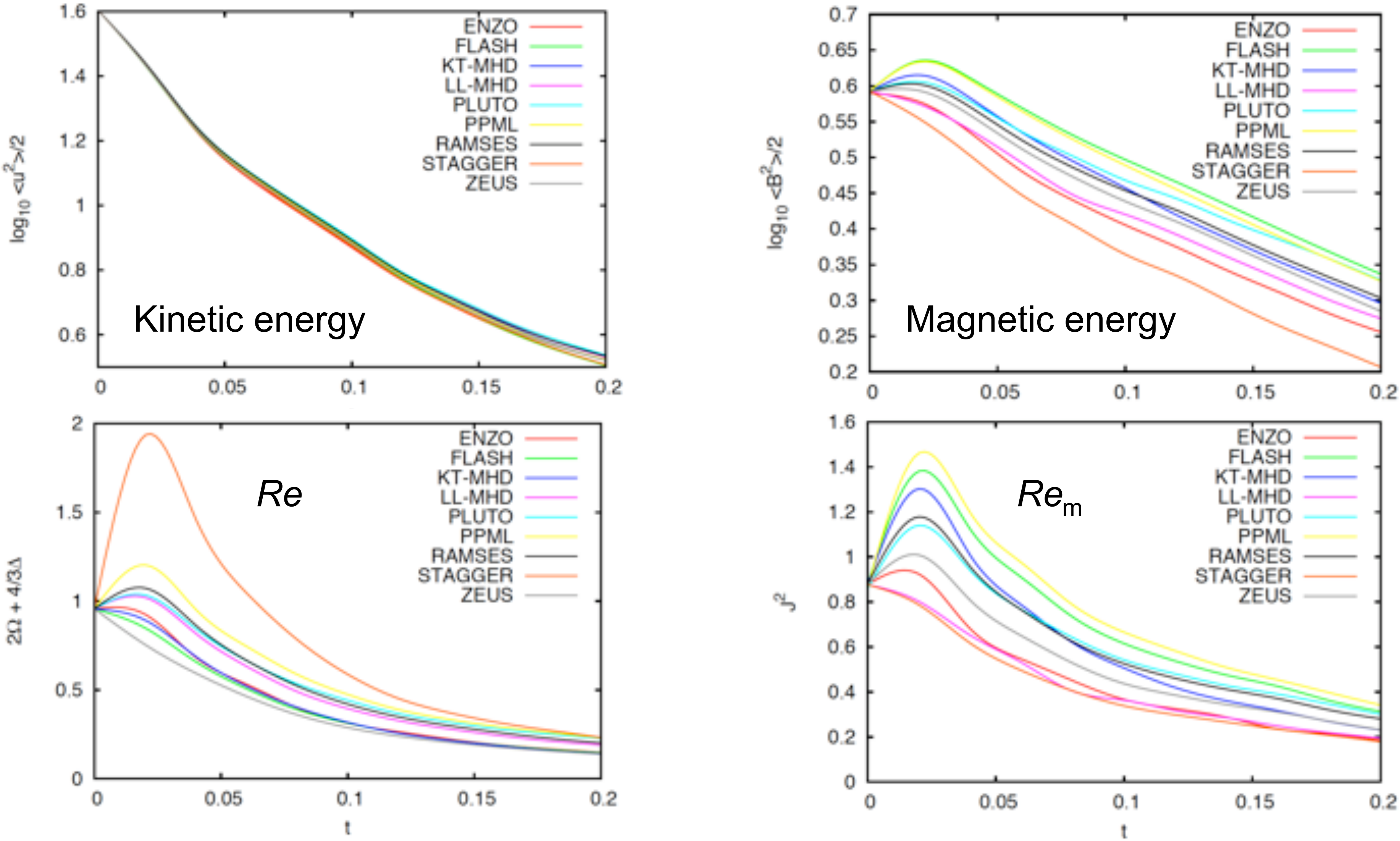
B-n diagram



- Isocontours represent data snapshot from Model B
- Observational data points: • Crutcher et al. (2010), • Falgarone et al. (2008)
- Model B matches the HI Zeeman data from Crutcher et al. (2010)

IV. Numerics

Supersonic MHD turbulence decay test



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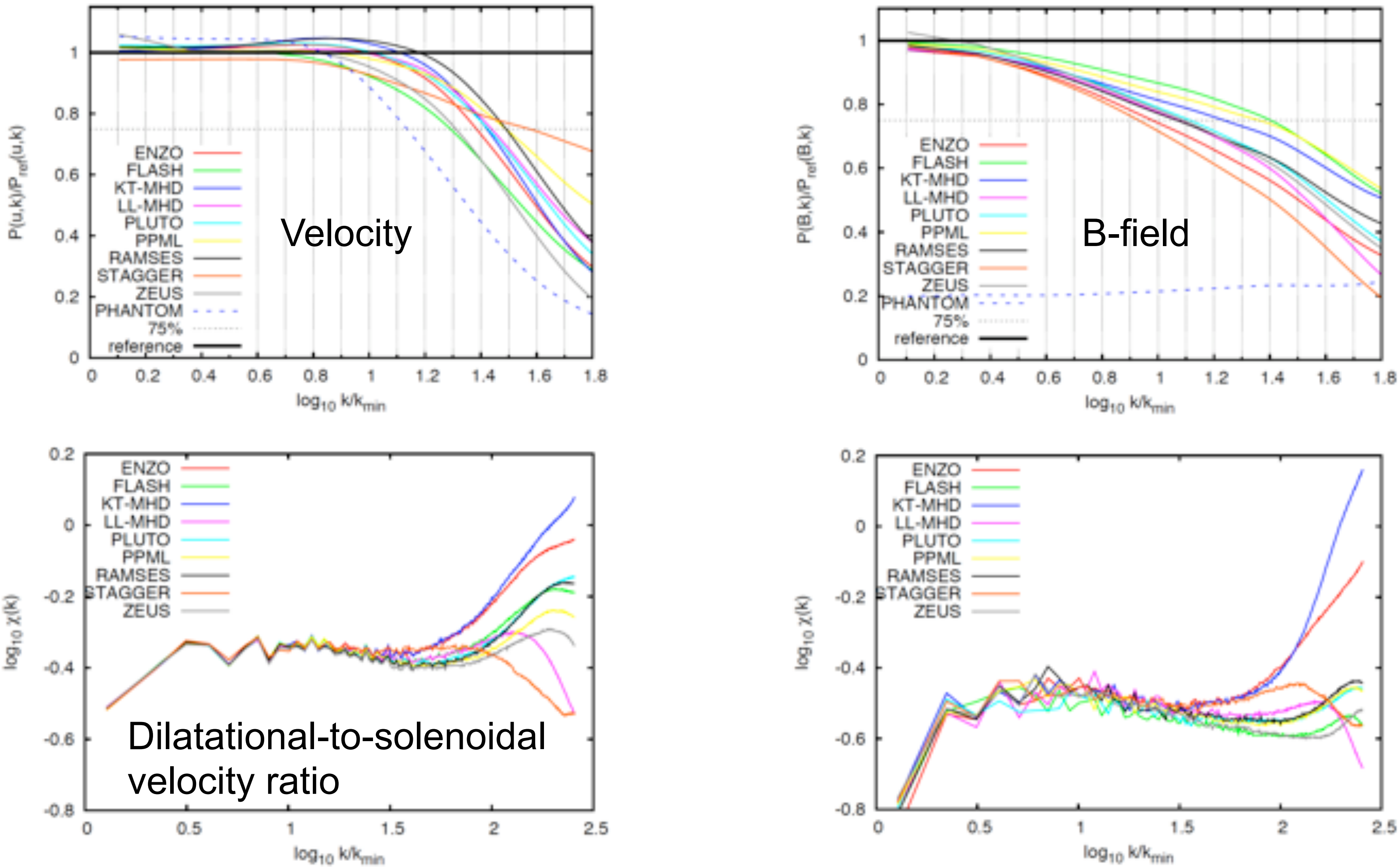

Summary

- **We now understand ISM turbulence “better”**
- **More work ahead on MHD, dynamo, etc.**
- **Large MHD simulations on uniform grids**
- **Better numerical methods (accuracy and stability are crucial)**
- **Deep AMR-MHD star formation simulations**
- **More complex physics (non-ideal effects, chemistry, RT)**