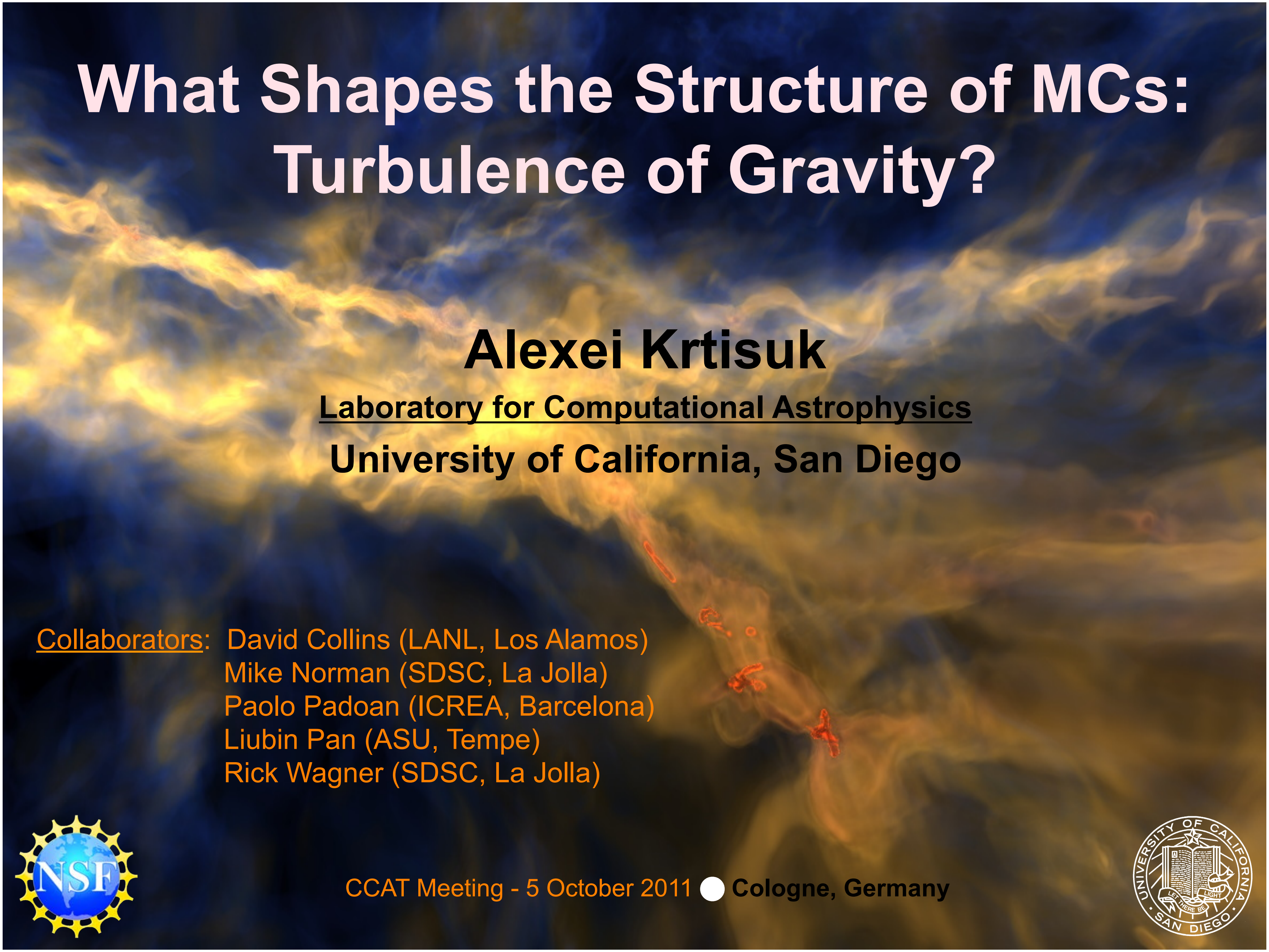

What Shapes the Structure of MCs: Turbulence of Gravity?

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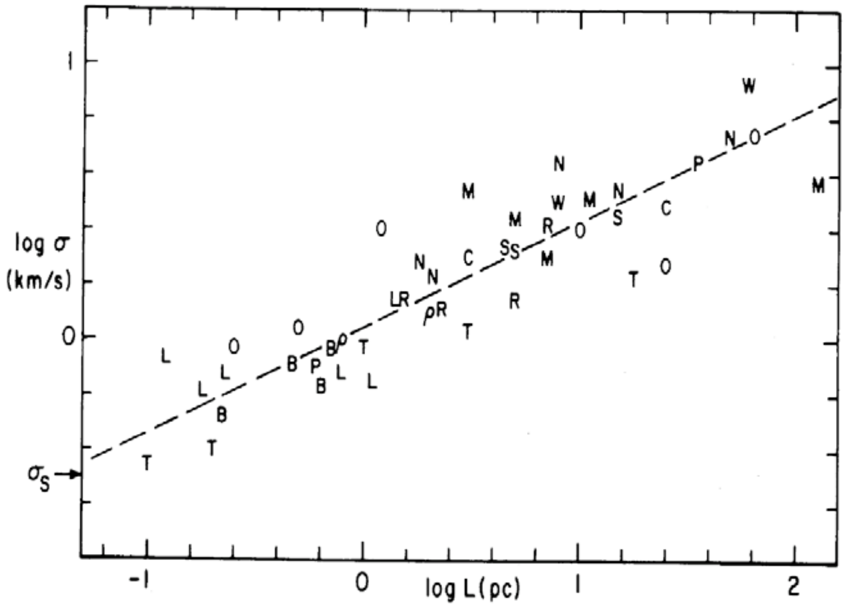
CCAT Meeting - 5 October 2011 ● **Cologne, Germany**

Motivation: Interpretations differ

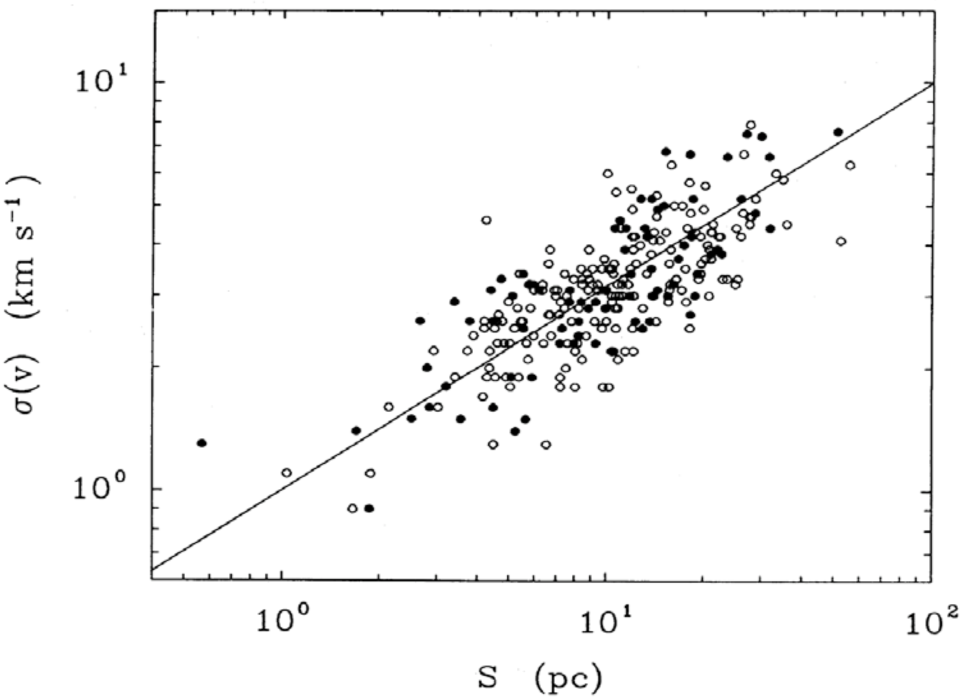
Larson (1981)

$$\sigma_u = 1.10 L^{0.38} km/s$$



Solomon et al. (1987)

$$\sigma_u = (1.0 \pm 0.1) S^{0.5 \pm 0.05} km/s$$



- Power index is similar to the Kolmogorov law of incompressible **turbulence**.
- Observed nonthermal linewidths originate from a common hierarchy of interstellar turbulent motions.
- Structures cannot have formed by simple gravitational collapse.

- The Kolmogorov turbulent spectrum is ruled out by the new data.
- The size-linewidth relation arises from **virial equilibrium**.
- MCs are in or near virial equilibrium since their mass determined dynamically agrees with other independent measurements.
- MCs are not in pressure equilibrium with warm/hot ISM.

What’s the nature of this MC conspiracy?

Let’s see what we know about turbulence and gravity…

> “I soon understood that there was little hope of developing a pure, closed theory, and because of the absence of such theory the investigation must be based on hypotheses obtained in processing experimental data.”
>
> *A. N. Kolmogorov*
>
> Selected Works, 1985

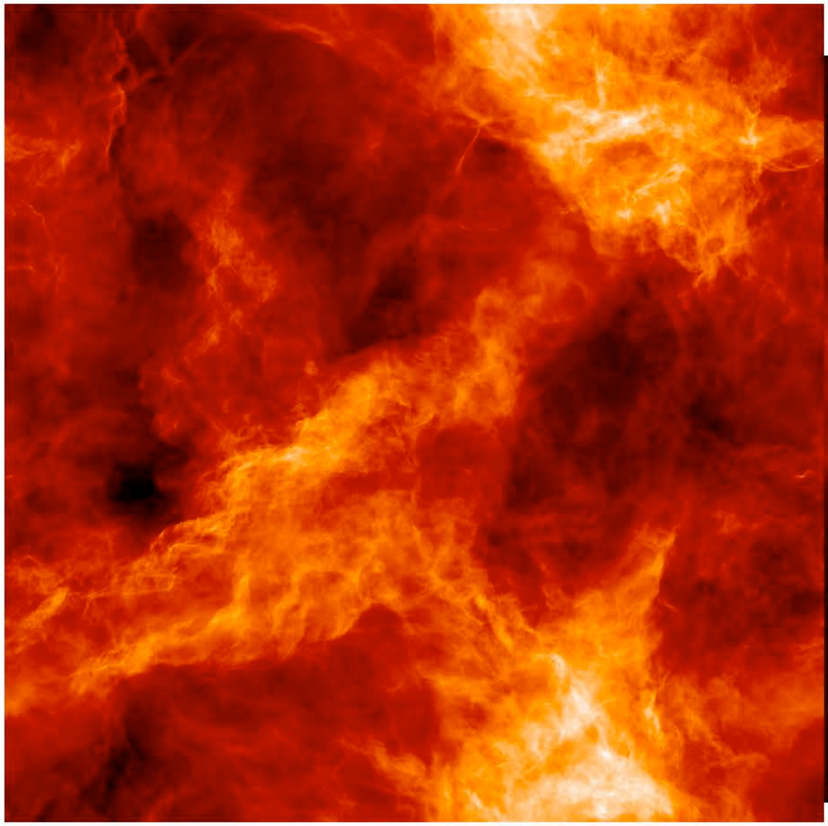
Disclaimer:

Both turbulence and self-gravity are important in GMCs.

Column density maps

SIMULATION ↓

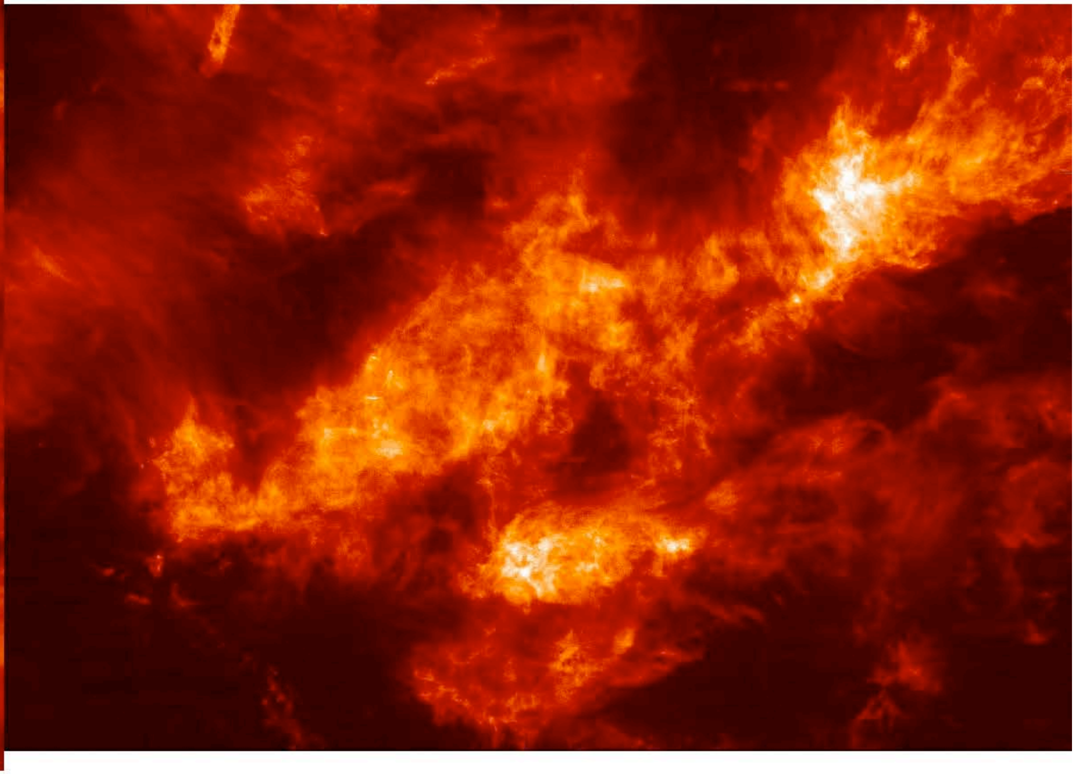
2048^3 isothermal HD turbulence, Mach 6



[Kritsuk et al. 2009]

OBSERVATION ↓

Taurus MC: ^{12}CO

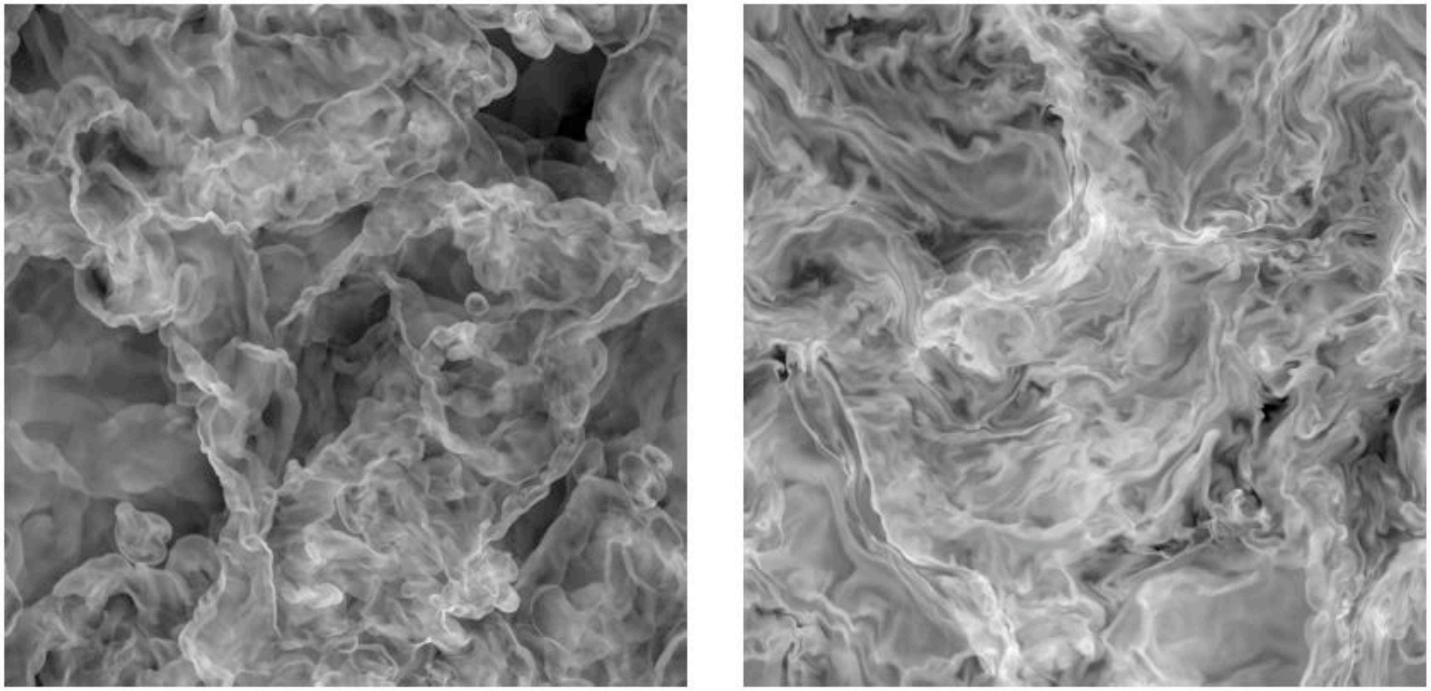


[Goldsmith et al. 2008]

Density structures are morphologically similar overall, but…

A note of caution…

Density slices from two simulations with resolution 1024^3 points



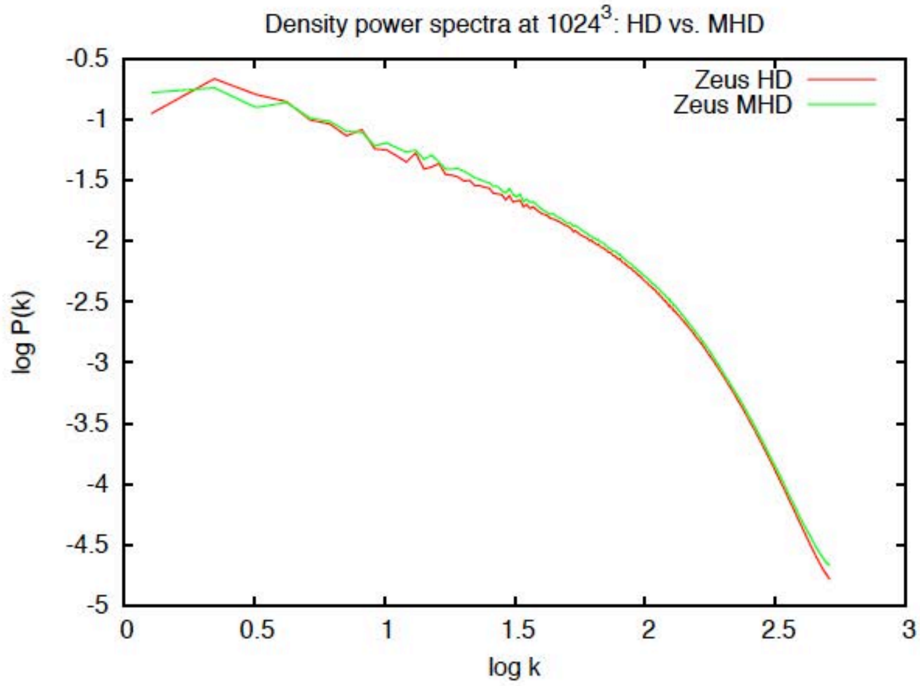
Zeus HD

Zeus MHD

Structures are different due to suppression of K-H instability by B-fields

A note of caution…

Density power spectra for two snapshots with resolution 1024^3 points



While structures are different, power spectra appear identical.

See also Padoan et al. (2007) and 512^3 MHD by Kowal & Lazarian (2007)

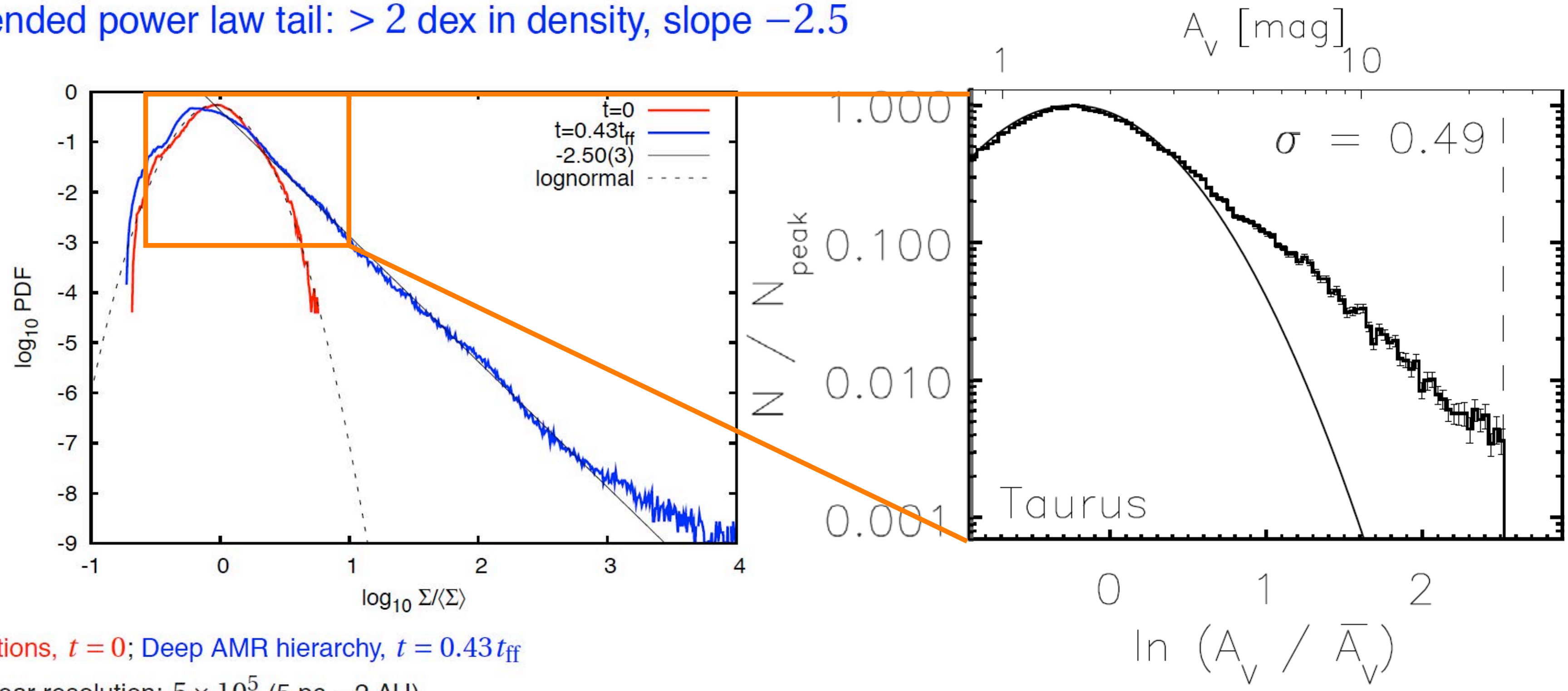
Column density PDFs

SIMULATION ➜ OBSERVATION ➜

512^3+L5x4 self-gravitating isothermal HD turbulence, Mach 6

Taurus: Dust extinction map

Extended power law tail: > 2 dex in density, slope -2.5



- Initial conditions, $t = 0$; Deep AMR hierarchy, $t = 0.43\,t_{\rm ff}$
- Effective linear resolution: 5×10^5 (5 pc – 2 AU)

[Kritsuk et al., ApJL, 2011]

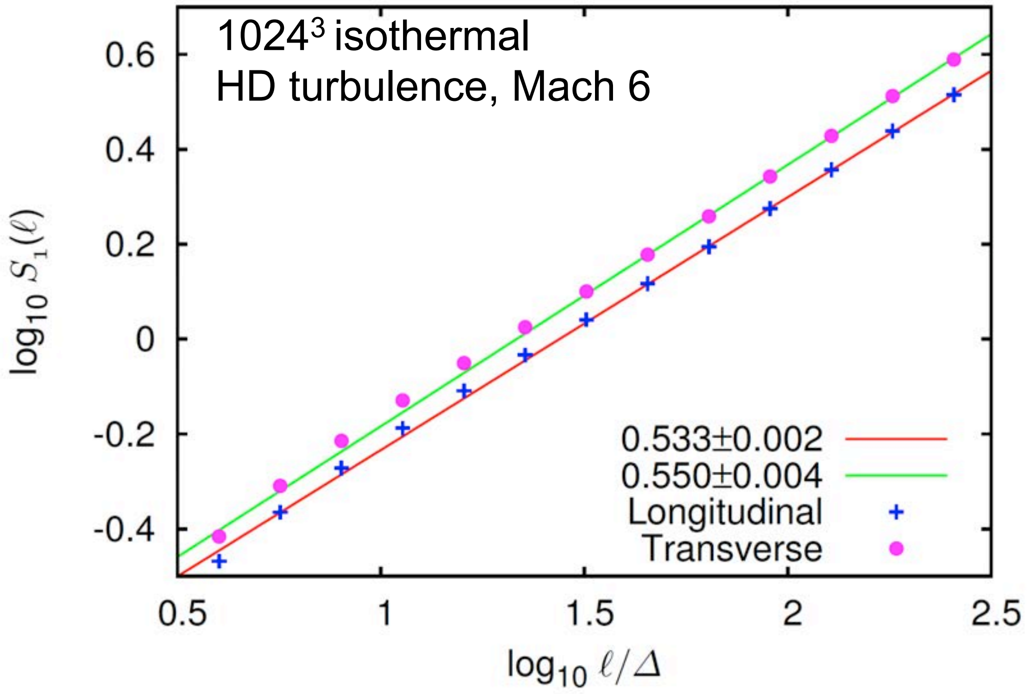
[Kainulainen et al. 2009]

Column density PDFs are similar

Velocity structure functions

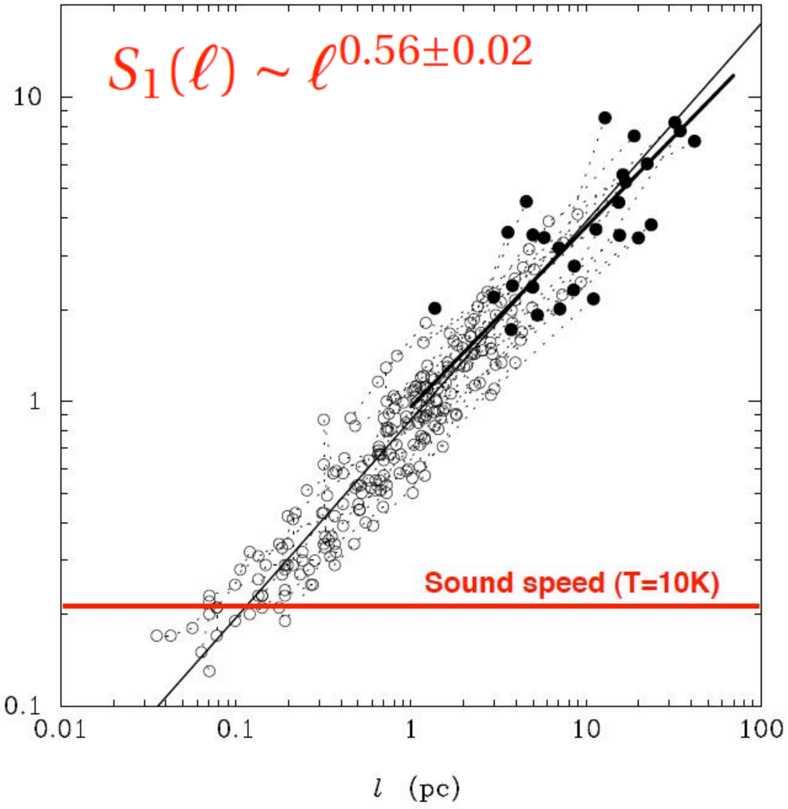
SIMULATION ➔

$$S_1(\boldsymbol{u},\ell) \equiv \langle|\boldsymbol{u}(\boldsymbol{r}+\boldsymbol{\ell})-\boldsymbol{u}(\boldsymbol{r})|\rangle \sim \ell^{0.54\pm0.01}$$



[Kritsuk et al., ApJ, 2007]

OBSERVATION ➔



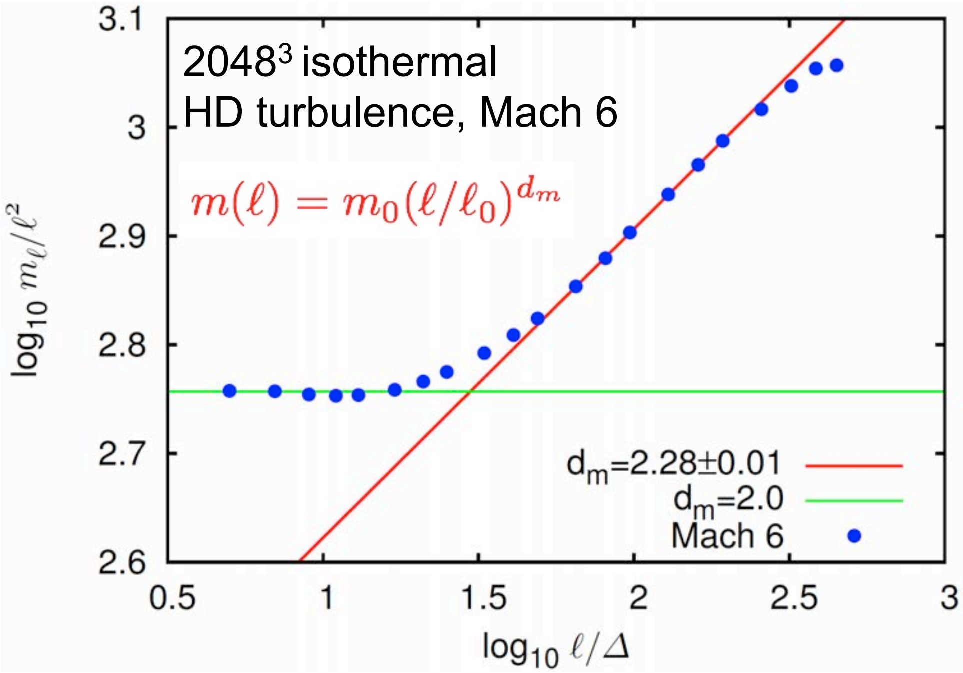
[Heyer & Brunt, 2004]

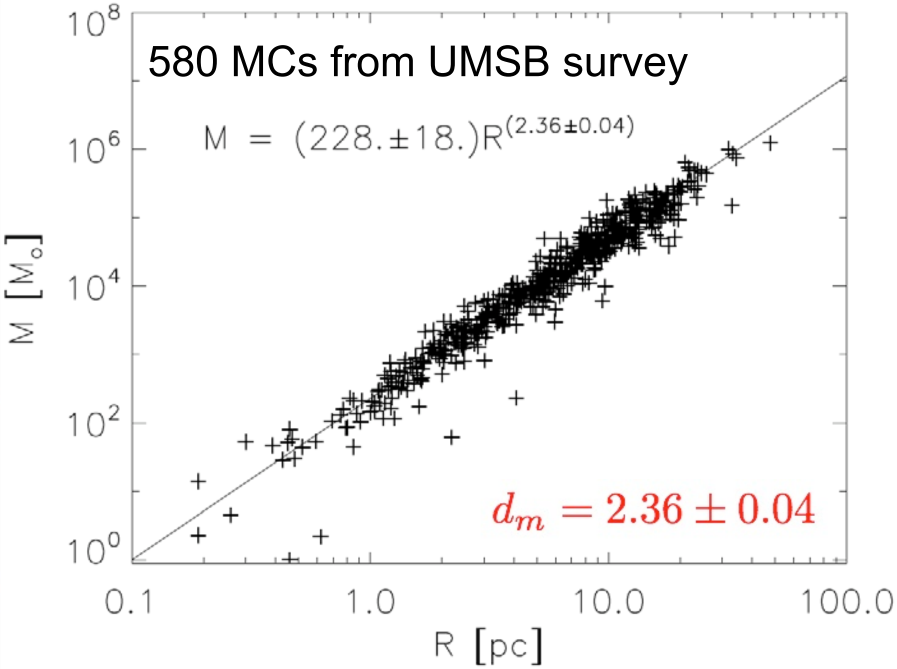
First-order velocity SFs have similar slopes

Mass dimension

SIMULATION ↓

OBSERVATION ↓





[Kritsuk et al., ASPC, 2009]

[Roman-Duval et al., 2010]

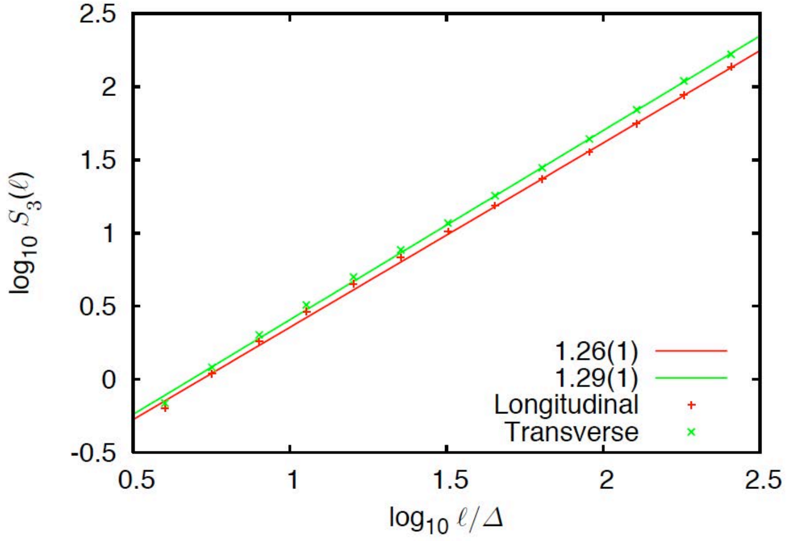
Mass dimensions are similar

What’s universal & what’s not

Is supersonic turbulence Kolmogorov or not?

$$v \equiv \rho^{1/3} u \qquad S_3(v, \ell) \propto \ell$$

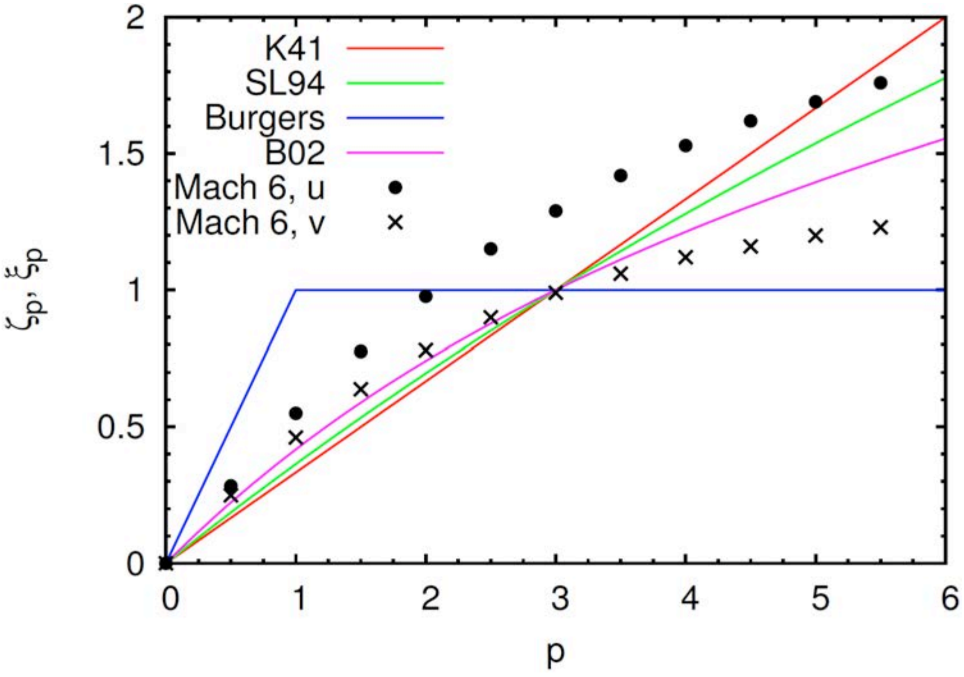
$$S_3(\boldsymbol{u}, \ell) \equiv \langle |\boldsymbol{u}(\boldsymbol{r} + \boldsymbol{\ell}) - \boldsymbol{u}(\boldsymbol{r})|^3 \rangle \sim \ell^{1.27 \pm 0.02}$$



$S_3^{\parallel}(\boldsymbol{u}, \ell)$ does not scale linearly with ℓ at $M_s = 6$

[Kritsuk et al., ApJ, 2007]

No, but…



[Kritsuk et al., AIPCP, 2007]

Yes!

Column density–size relation

$E = \langle \rho u^2/2 + c_{\rm s} \rho \ln(\rho/\rho_0) \rangle$ ← Total energy is conserved

$\upsilon \equiv \rho^{1/3} u$ $\qquad S_3(\upsilon, \ell) \equiv \langle |\delta \upsilon_\ell|^3 \rangle = \langle \epsilon \rangle \ell$

$$\rho_\ell \left(\delta u_\ell\right)^3 \ell^{-1} \sim \Sigma_\ell \left(\delta u_\ell\right)^3 \ell^{-2} \sim \Sigma_\ell \ell^{3\zeta_1 - 2} \sim const$$

Assume ➔ $\zeta_1 = 0.56 \pm 0.02 \quad (\zeta_1 : S_1(u, \ell) \propto \ell^{\zeta_1})$

Then ➔ $\Sigma_\ell \sim \ell^{2 - 3\zeta_1} \sim \ell^{0.32 \pm 0.06}$

Assume ➔ $d_{\rm m} = 2.36 \pm 0.04$

Then ➔ $\Sigma_\ell \sim m_\ell \ell^{-2} \sim \ell^{d_{\rm m} - 2} \sim \ell^{0.36 \pm 0.04}$

Overall: $\boxed{\Sigma_\ell \propto \ell^{1/3}}$

“Math” (cont’d)

$\langle|\delta v_\ell|\rangle \sim \langle\epsilon_\ell^{1/3}\rangle\ell^{1/3}$ Intermittency ➔ $\langle\epsilon_\ell^{1/3}\rangle \propto \ell^{\tau_{1/3}}$

$$\delta u_\ell \ell^{-1/2} \propto \rho_\ell^{-1/3}\ell^{-1/6+\tau_{1/3}} \sim \Sigma_\ell^{-1/3}\ell^{1/6+\tau_{1/3}}$$

We know that ➔ $\Sigma_\ell \propto \ell^{1/3}$

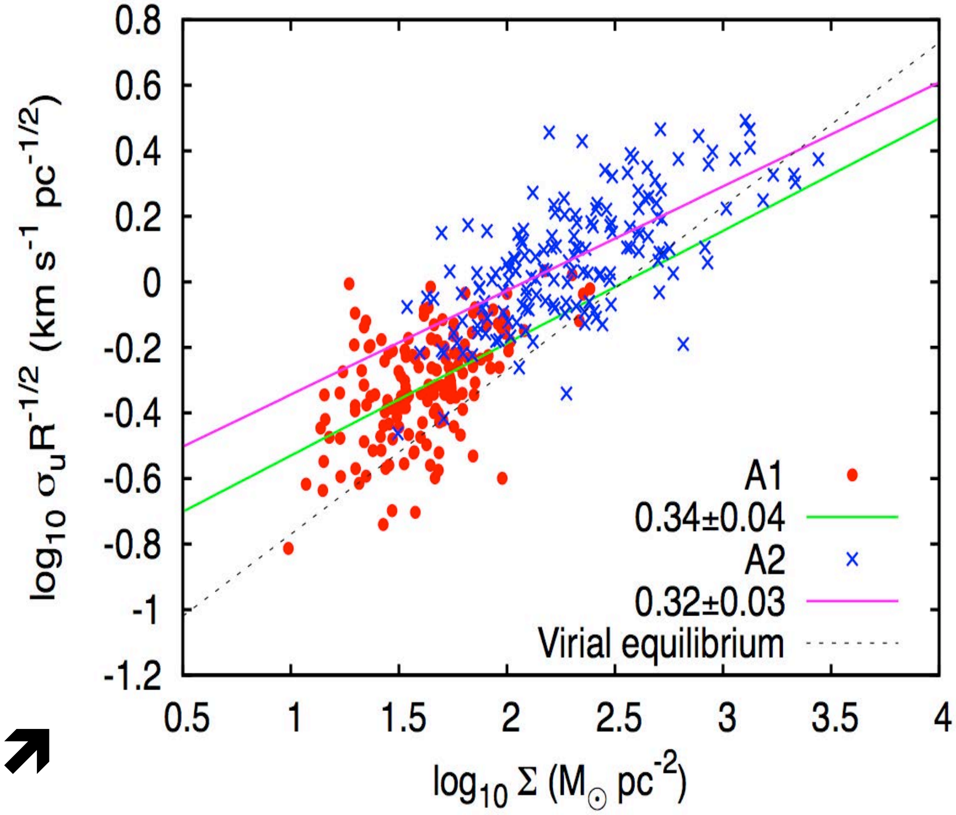
Therefore ➘

$$\delta u_\ell \ell^{-1/2} \propto \Sigma^{1/6+3\tau_{1/3}}$$

Pan et al. (2009) ➘

$$\tau_{1/3} \approx 0.055$$

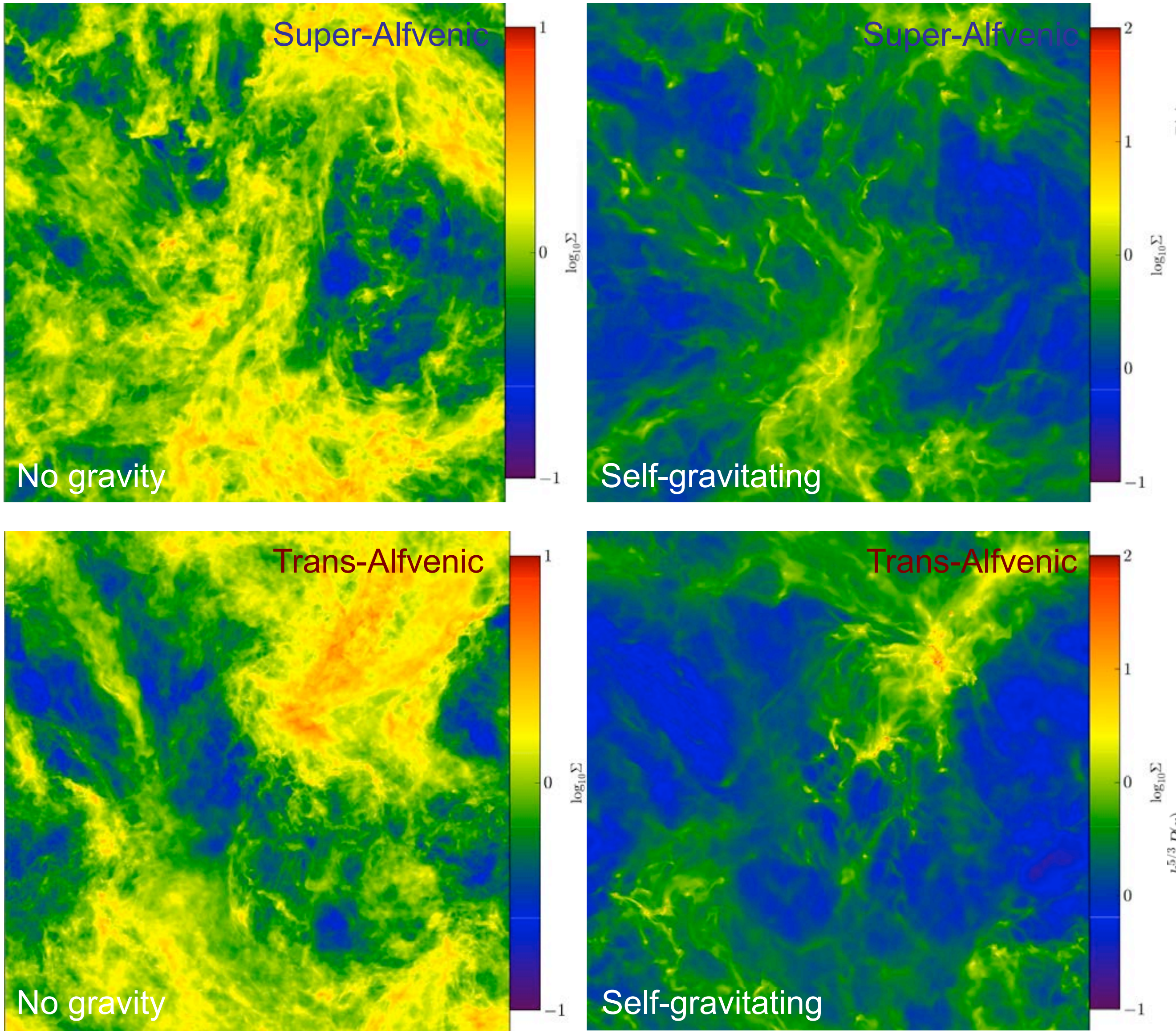
$$\boxed{\delta u_\ell \ell^{-1/2} \propto \Sigma^{0.33}}$$

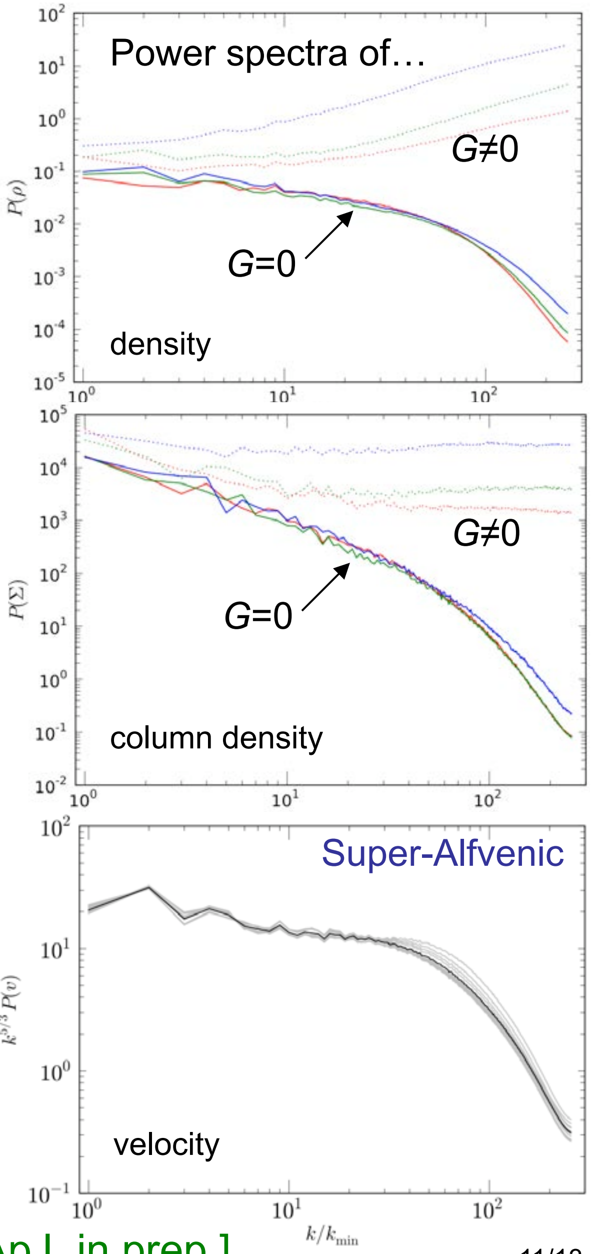


Data from Heyer et al. (2009) ➚

Where is gravity?

Projected (column) density for Mach 10 MHD-AMR turbulence simulations





[Collins et al. (2011), ApJ, in prep.]

Summary

- Supersonic turbulence alone is sufficient to explain the observed slopes of the linewidth−size and mass−size relations.
- Gravity may be important on large scales and is important on small scales.
- On small scales, formation of self-gravitating filaments and collapse of dense cores do not seem to leave detectable signature in pure velocity statistics (e.g., velocity power spectra). Why?
- Turbulence simulations predict the following approximate scaling relations for $\ell \geq 0.5$ pc, assuming weak magnetic field:

$$\boxed{S_1(u,\ell) \propto \ell^{0.55}} \qquad \boxed{\Sigma_\ell \propto \ell^{0.33}}$$

$$\boxed{m_\ell \propto \ell^{2.35}} \qquad \boxed{\delta u_\ell \ell^{-1/2} \propto \Sigma^{0.33}}$$

CCAT potential

- Large-area, high-resolution surveys tracing the substructure and kinematics of MCs on scales down to and below the sonic scale (~0.1pc).
- Spectral line observations are essential as they help to probe gas dynamics at scales of interest, not just the column density.
- Observations of nearby galaxies would help to examine the integral scale of MC turbulence and constrain the major energy injection mechanisms.
- Zeeman measurements of $B_{||}$ combined with linear polarization measurements of $B_{\perp}$ would be extremely useful for constraining magnetic field properties in star formation models.