Molecular Cloud Fragmentation: Self-Gravity, Magnetic Fields, Ambipolar Diffusion, and Nonlinear Flows

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Star Formation Rate

Regulated (to what extent) by:

$$\Delta \mathbf{v},\ B,\ x_i$$

i.e., nonlinear/nonthermal motions (turbulence, MHD waves)
magnetic field strength (really mass-to-flux ratio $\mu = 2\pi G^{1/2}\Sigma/B$)
ionization fraction (sets neutral-ion coupling)

$\mu \approx 1$ (transcritical) is interesting

For CR ionized sheet, with half thickness Z_0.

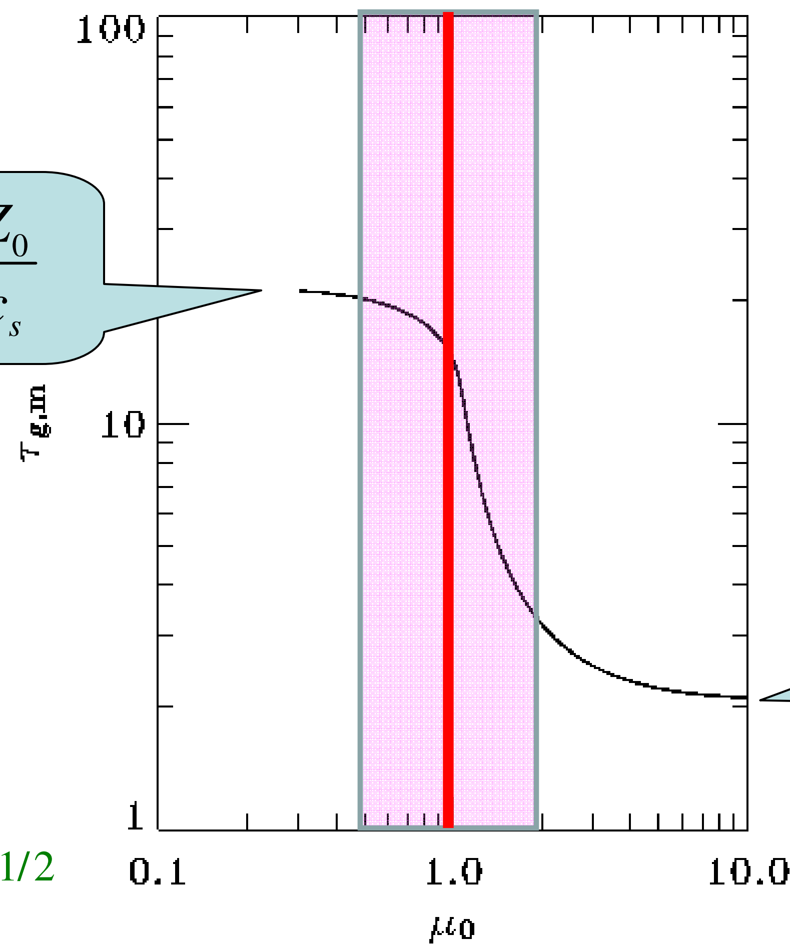
$$x_i = 10^{-7}\left(n_n / 10^4 \text{ cm}^{-3}\right)^{-1/2}$$

e.g. Elmegreen, Nakano (1979)

$$\tau_{g,m} \cong 10 \frac{Z_0}{c_s}$$

τ_{AD}

ambipolar diffusion time

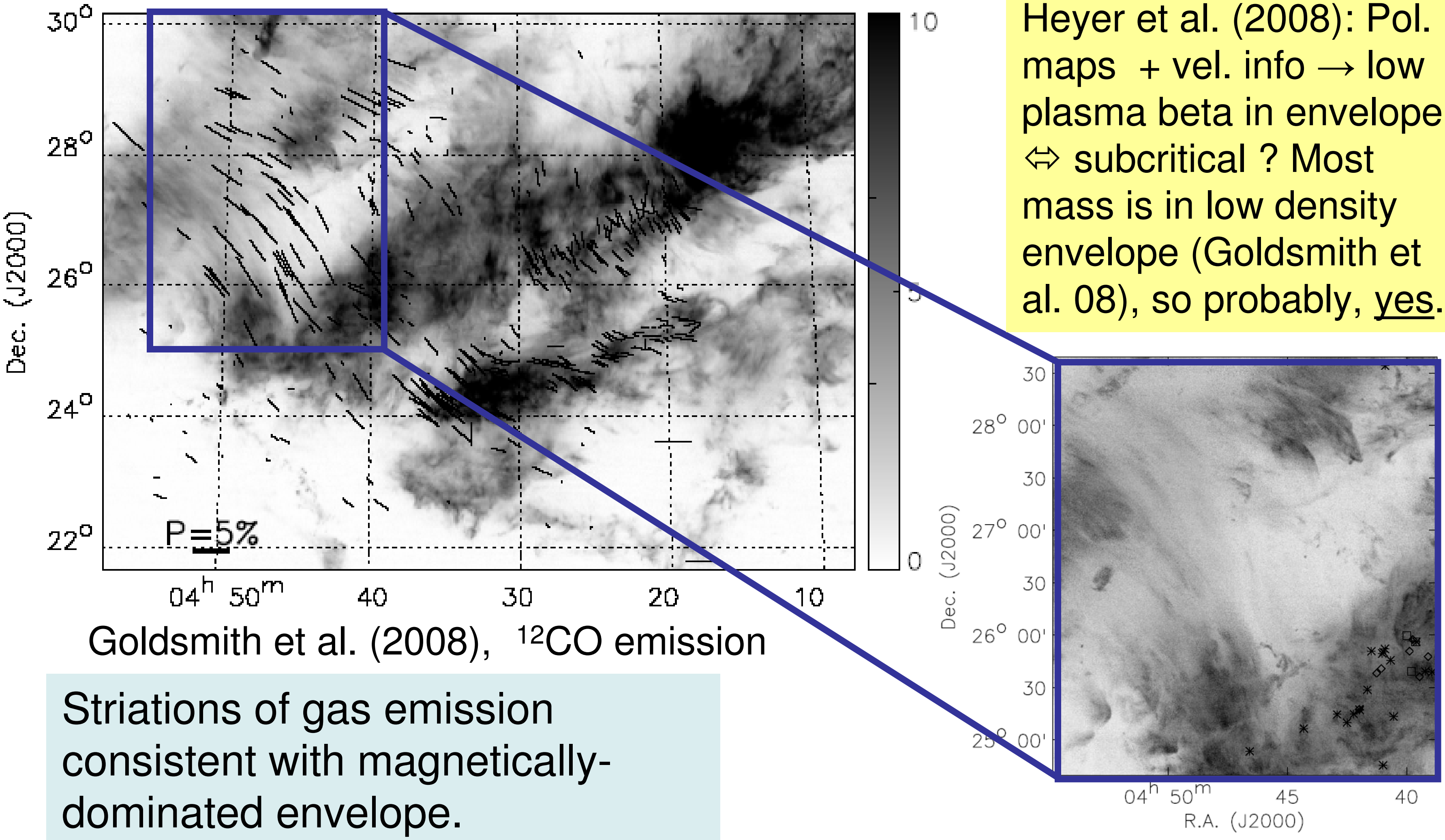


$$\tau_{g,m} = \frac{Z_0}{c_s}$$

$$\mu_0 = \frac{\Sigma}{B} 2\pi G^{1/2}$$

numbers from Ciolek & Basu (2006)

Taurus – B dominated envelope?

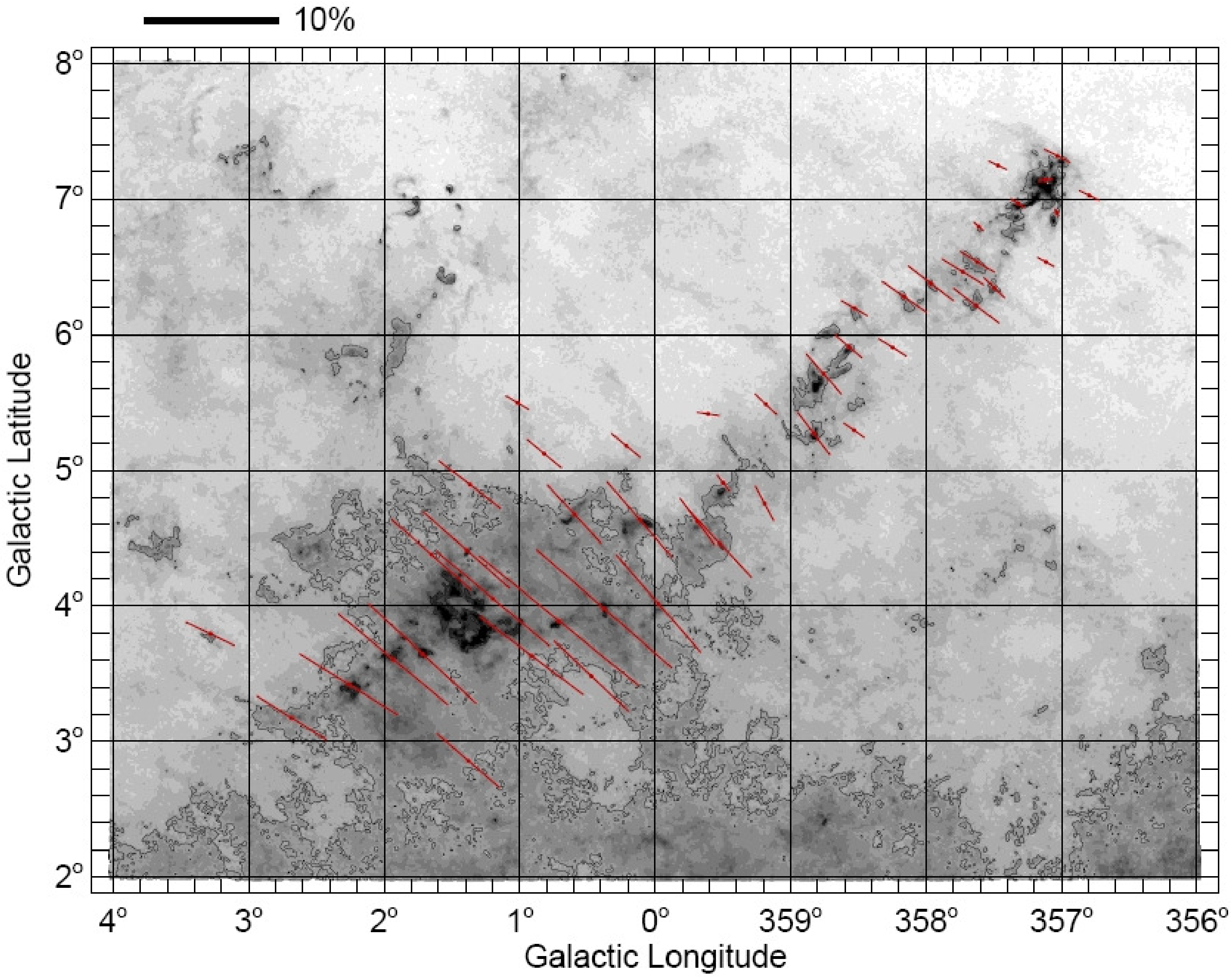


Goldsmith et al. (2008), ^{12}CO emission

Heyer et al. (2008): Pol. maps + vel. info → low plasma beta in envelope ⇔ subcritical ? Most mass is in low density envelope (Goldsmith et al. 08), so probably, yes.

Striations of gas emission consistent with magnetically-dominated envelope.

Pipe Nebula – more B effect?

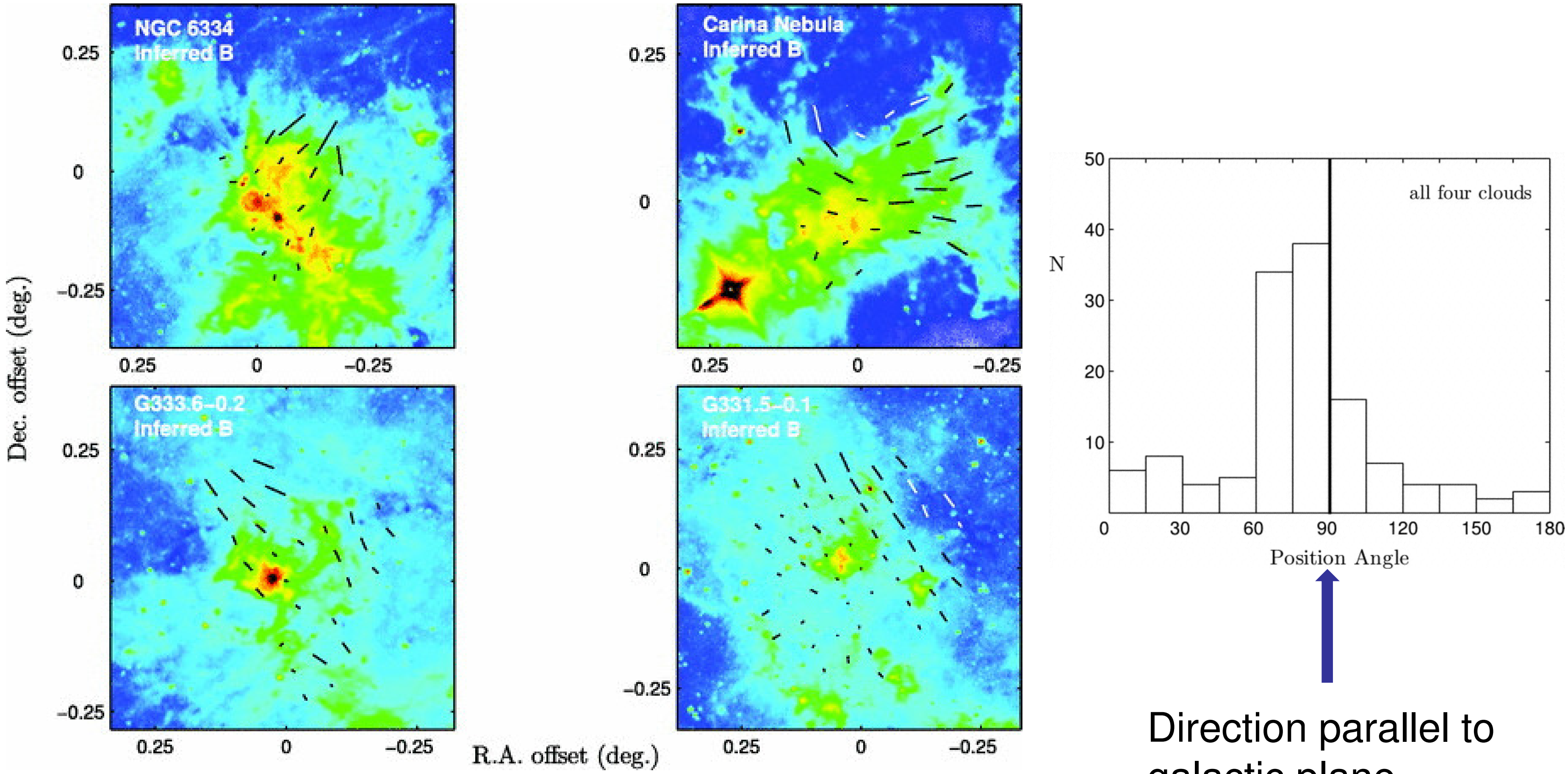


Magnetically regulated cloud formation?

Pipe (and Taurus) ➔ formed by flow or contraction along B?

Alves, Franco, & Girart (2008)

GMC Fields align with Galactic B

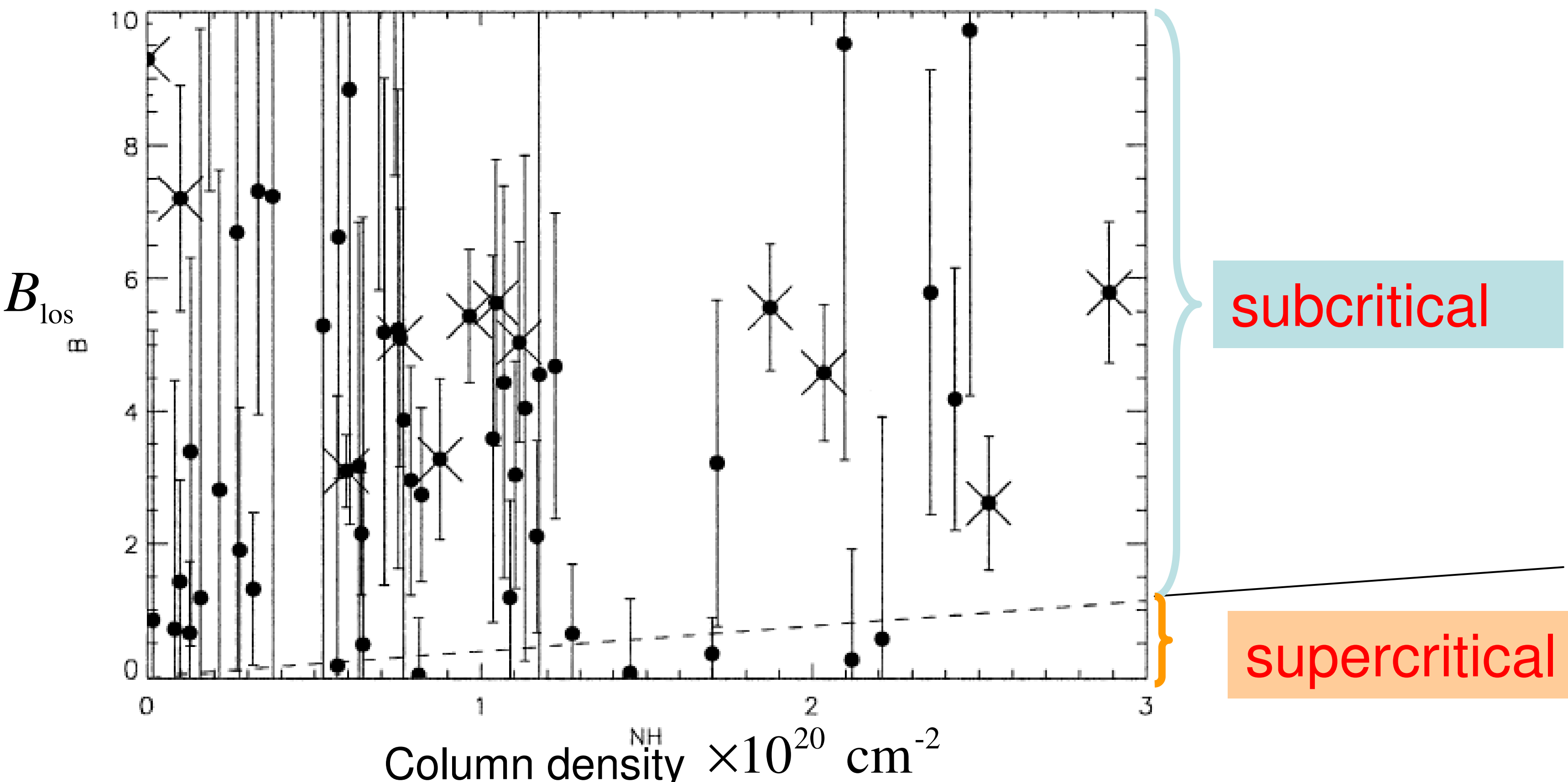


Direction parallel to galactic plane

H. Li et al. (2006)

MC progenitors are H I Clouds

Heiles & Troland (2008)



Flux freezing in HI gas ➔ Critical or supercritical MC formation requires significant accumulation of mass ALONG the magnetic field.

Hard to accumulate supercritical MC rapidly

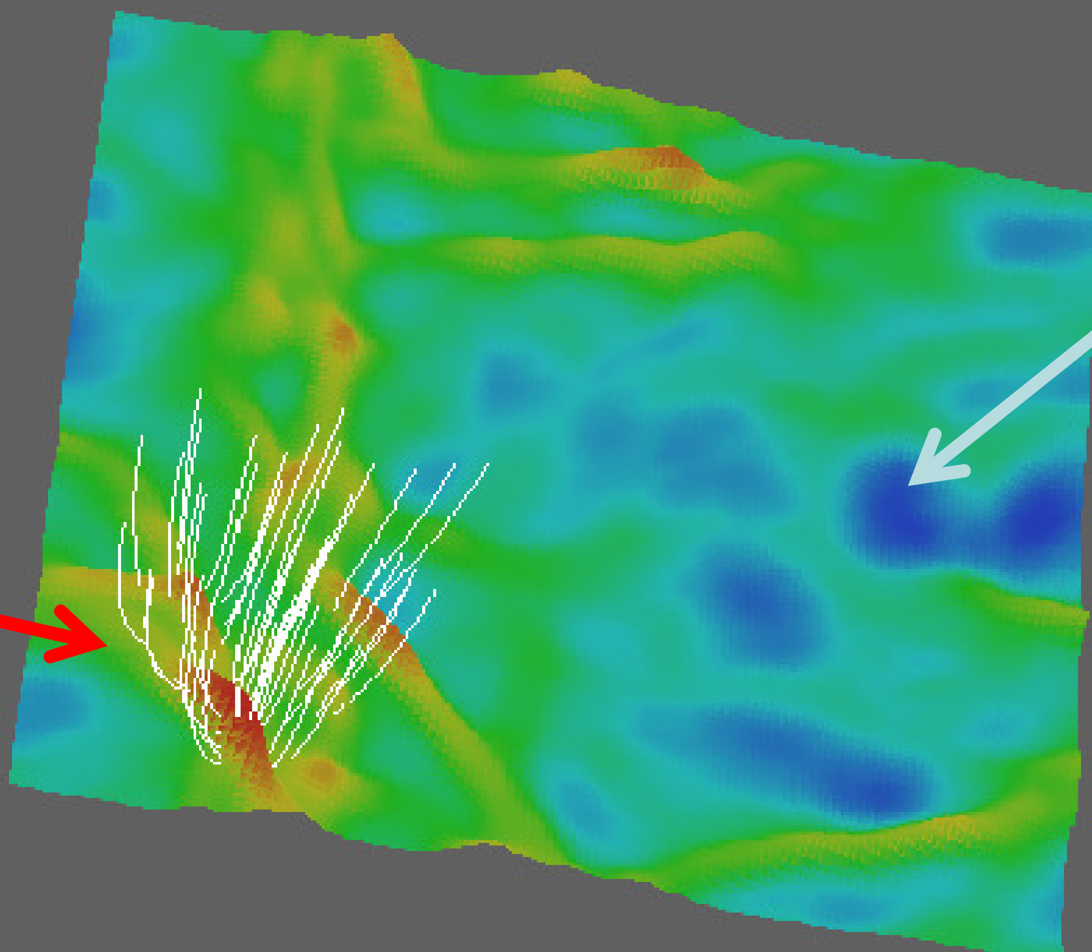
$$L \cong \frac{B}{2\pi G^{1/2}\rho} \cong 150\left(\frac{\mu}{1}\right)\left(\frac{B}{3\times10^{-6}\ \mathrm{G}}\right)\left(\frac{n}{1\ \mathrm{cm}^{-3}}\right)\ \mathrm{pc},$$

$$v \equiv \frac{L}{t} \cong 150\left(\frac{\mu}{1}\right)\left(\frac{B}{3\times10^{-6}\ \mathrm{G}}\right)\left(\frac{n}{1\ \mathrm{cm}^{-3}}\right)\left(\frac{t}{10^{6}\,\mathrm{yr}}\right)^{-1}\ \mathrm{km/s}.$$

Mestel (1999), Stellar Magnetism, and earlier papers quote even larger value, 10^3 above, not 150.

Bottom line: Highly supercritical MC AND rapid formation time t is troublesome!

Scenario

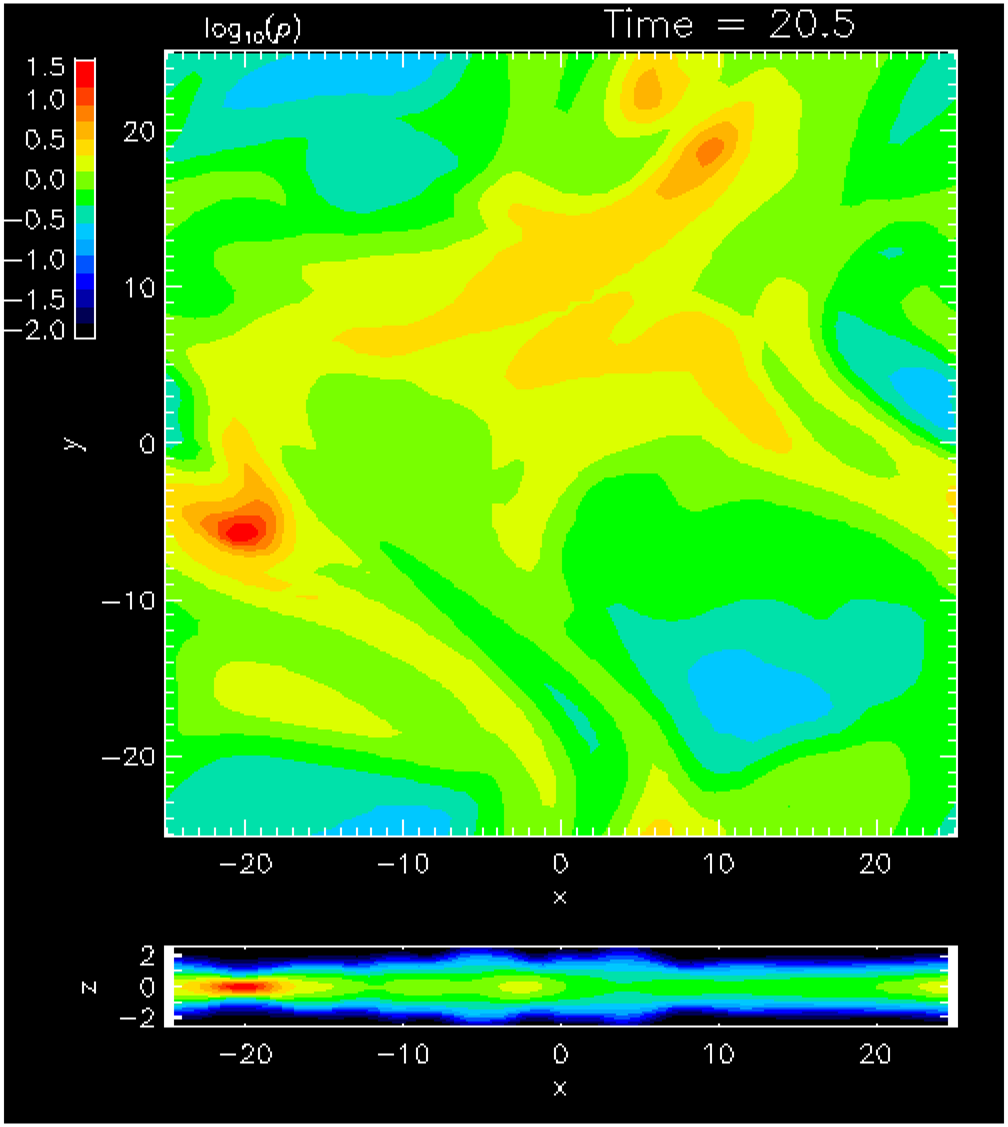


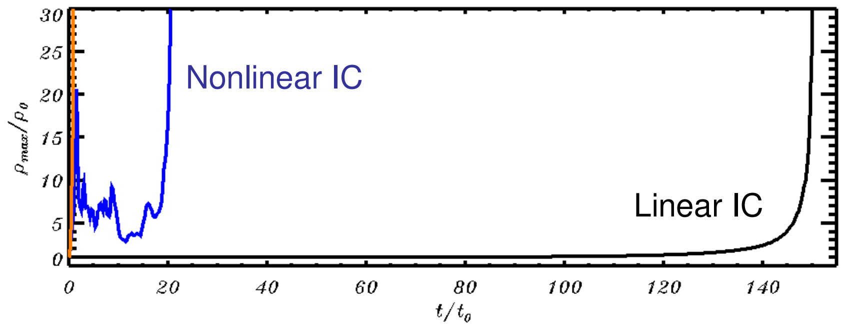
Supercritical high-density regions assembled by turbulent motions

Subcritical common envelope

cf. Nakamura & Li (2005), Elmegreen (2007), Kudoh & Basu (2008), Nakamura & Li (2008), Basu , Ciolek, Dapp, & Wurster (2009; model shown above).

3D Trans-Alfvénic Model → Rapid but Inefficient SF





$t_0 \approx 2\times10^5$ yr

Nonlinear initial velocity field

$v_k^2 \propto k^{-4}$ allowed to decay

rms amplitude $v_a = 3c_s \approx v_{\mathrm{Alf}}$

trans-Alfvénic

$\mu_0 \equiv 2\pi G^{1/2}\,\Sigma_0/B_0 = 0.5$

ionization $x_i = 10^{-7}\left(n_n/10^4\ \mathrm{cm}^{-3}\right)^{-1/2}$

Gas density in midplane (z=0)

A vertical slice of gas density

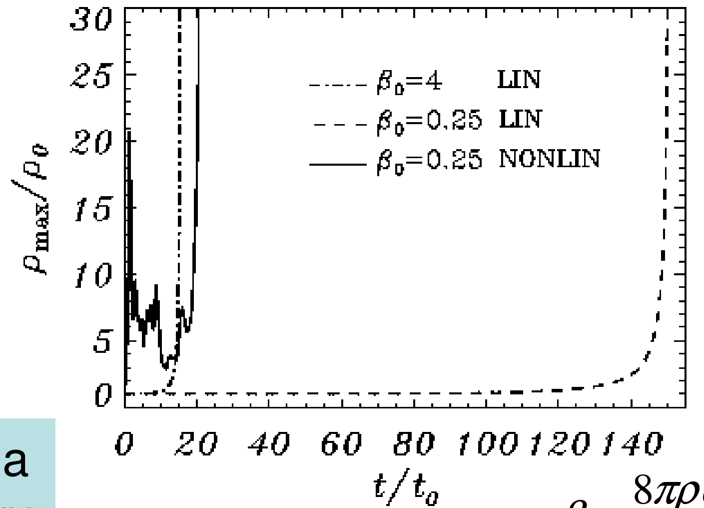
box width = 2.5 pc

Originally 64 x 64 x 40 cells, now 256 x 256 x 40

Kudoh & Basu (2008, ApJ, 679, L79)

How Does Turbulent Ambipolar Diffusion Work?

Runaway collapse of the first core occurs ~ 7 times faster with nonlinear as opposed to small-amplitude IC's.

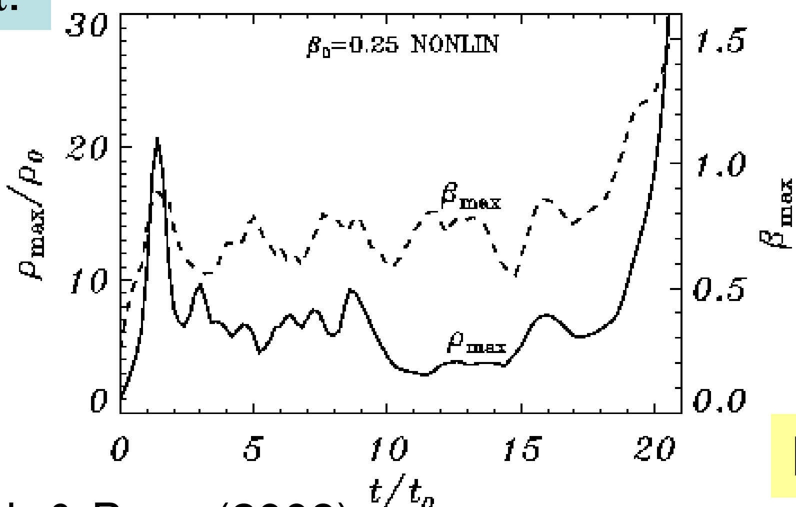


Early turbulent compression

$$\tau_{AD} \propto L^{5/2} \Rightarrow \beta \uparrow \text{ quickly as } L \downarrow$$

β is a proxy for μ.

$$\beta \equiv \frac{8\pi\rho c_s^2}{B} \propto \mu^2$$



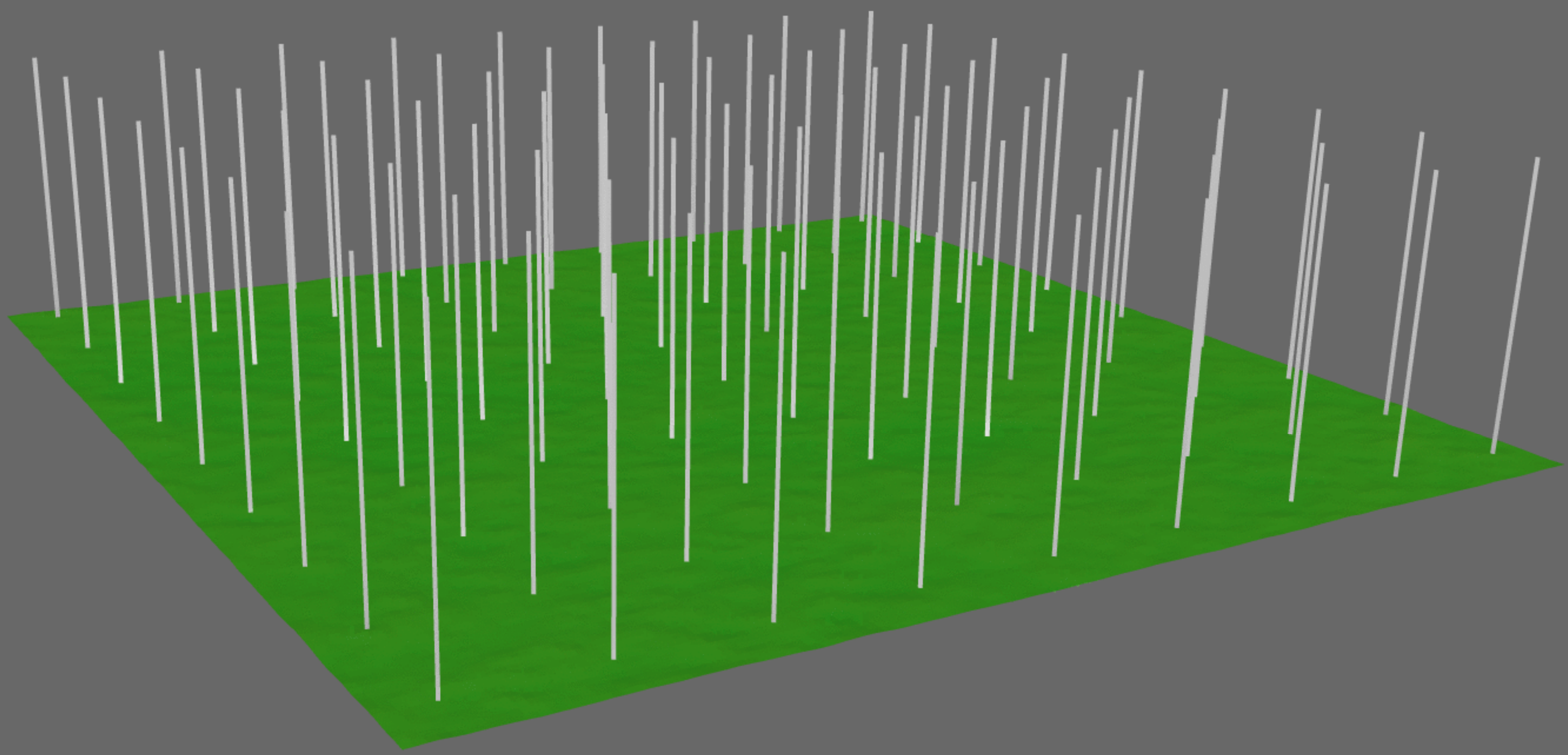
Kudoh & Basu (2008)

Later evolution at higher mean density than in initial state

$$\beta \uparrow \text{ continues more slowly}$$

Rapid contraction when/where $\beta > 1.$

Animation with Field Lines



Thin disk approx. – from models of Basu, Ciolek, Dapp, & Wurster (2009, NewA, 14, 483)

SFR Related to Timescale for Runaway Collapse

Accelerated collapse (some oscillations before collapse)

$$t_{coll} \geq 2\pi Z_0 / c_s$$

$\approx$ system dynamical time

$$v_a < v_{MS,0}$$

initial rms turbulent speed (v_a)

initial magnetosonic speed ($v_{MS,0}$)

Prompt collapse

$$t_{coll} \approx Z_0 / v_a$$

less than dynamical time

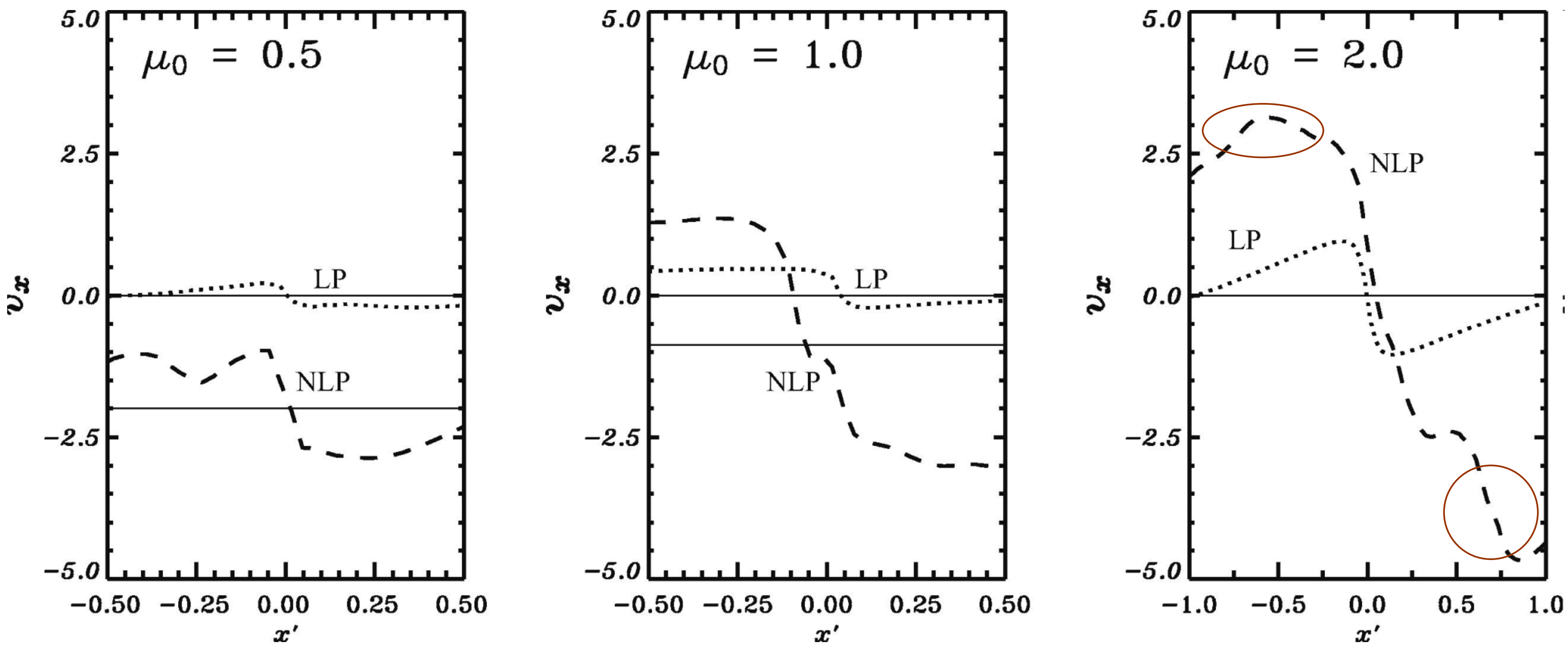
$$v_a > v_{MS,0}$$

for ionization fraction $x_i = 10^{-7} \left(n_n / 10^4 \ \mathrm{cm}^{-3} \right)^{-1/2}$

Expect much greater SFR, especially for driven super-Alfvénic turbulence.

Basu, Ciolek, Dapp, & Wurster (2009)

Super-Alfvénic Model Fails



Velocity cuts through cores

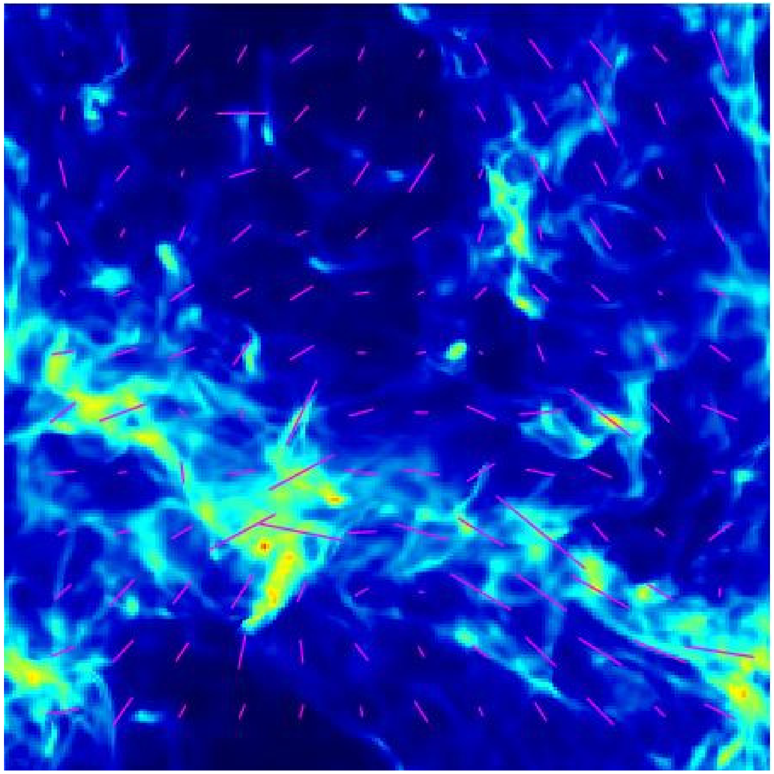
Super Alfvénic → highly supersonic infall and immediate SF.

LP = initial Linear Perturbations

NLP = initial Nonlinear Perturbations $v_a = 2c_s$ → Super-Alfvénic for μ_0= 2.

BCDW09

Turbulent Decay

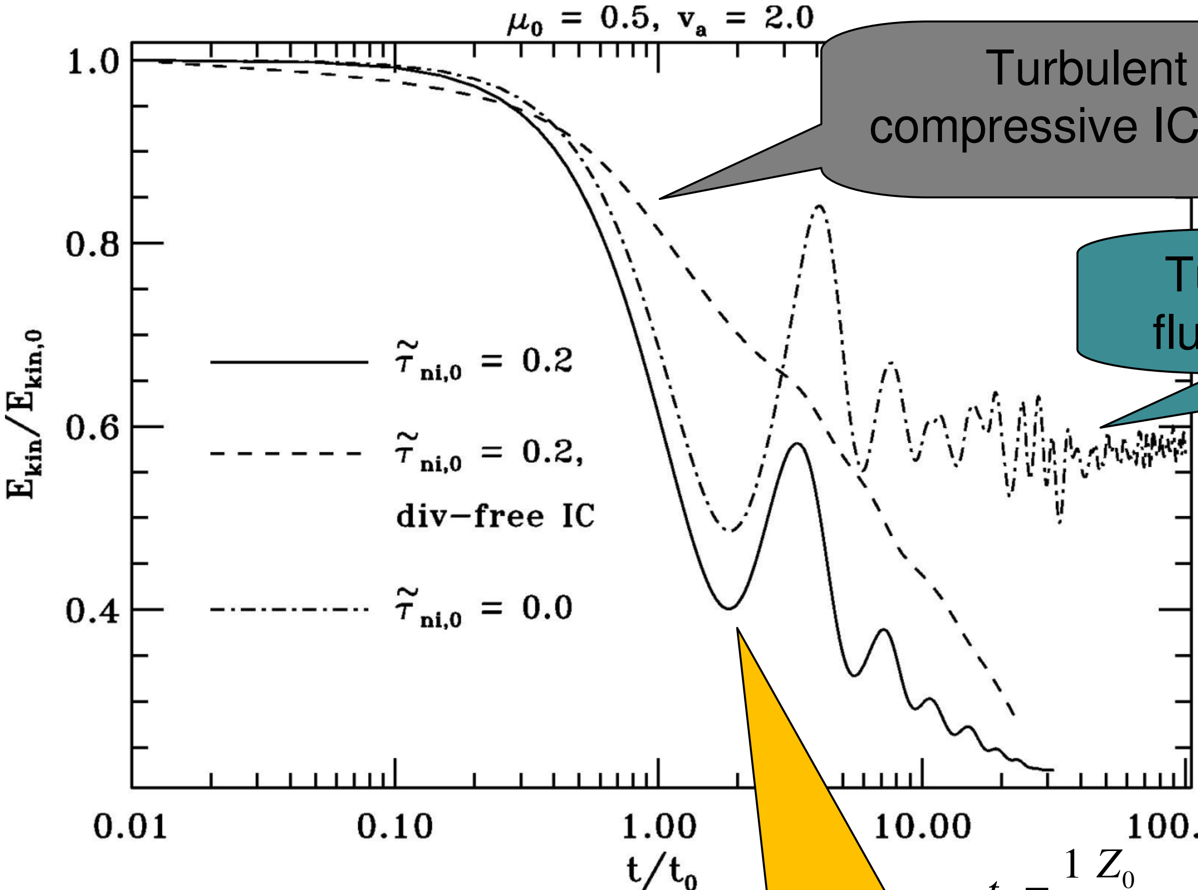


Stone, Ostriker, & Gammie (1998), MacLow et al. (1998), Ostriker, Stone, and Gammie (1999; image above) and many others.

3D local (periodic box) simulations.
Left: integrated column density and simulated polarization maps (Ostriker et al. 1999)

Important result: turbulence decays away on crossing time of characteristic length scale. A robust result for infinite uniform medium.

Turbulent Decay in our models – usually fast, but…

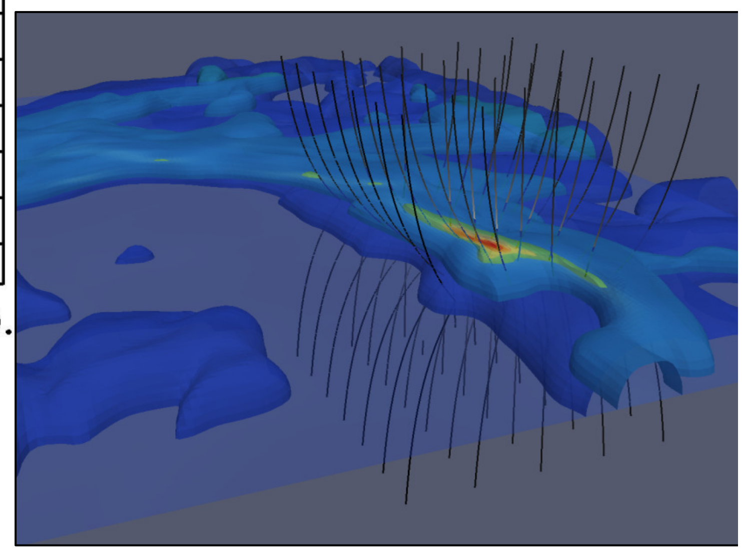


Turbulent non-compressive IC's with AD

Turbulent compressive IC's and flux-freezing; fluctuations persist!

Turbulent compressive IC's with AD

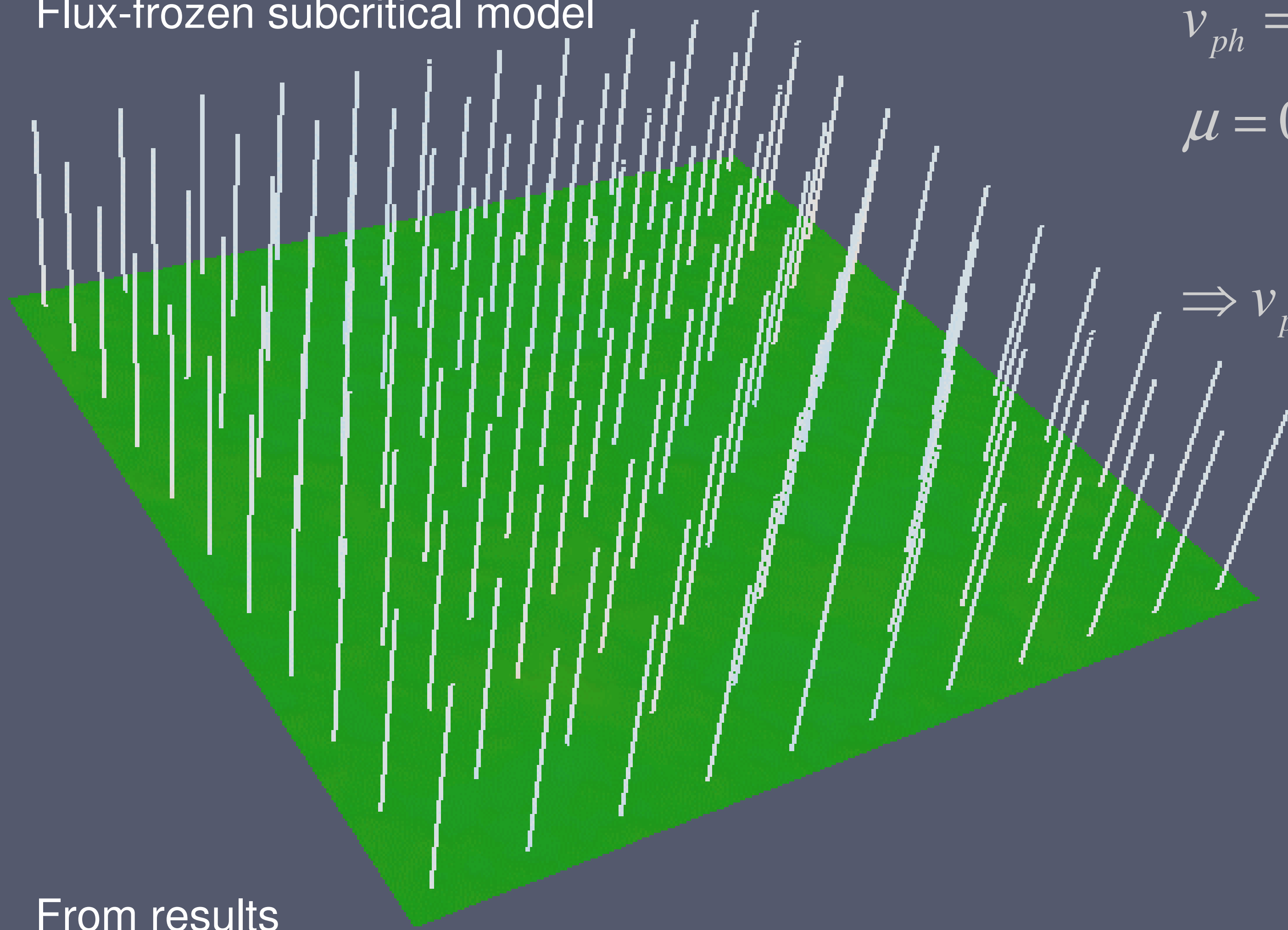
$$t_0 = \frac{1}{2}\frac{Z_0}{c_s}$$



Basu, Ciolek, Dapp, & Wurster (2009)

How can fluctuations persist?

Flux-frozen subcritical model



$$v_{ph} = \sqrt{(\mu^{-2} - 1) G \Sigma \lambda},$$

$$\mu = 0.5, \lambda = 8 c_s^2 / G \Sigma$$

(box size)

$$\Rightarrow v_{ph} \approx 5 c_s.$$

From results of BCDW09

Results and Emerging Scenario

- Thin disk model yields long lived supersonic motions. Effectively flux-frozen (UV ionized, e.g. McKee 1989) cloud envelopes can, if subcritical, maintain indefinite oscillations due to restoring force of externally-anchored *B*. Future…fully global models.
- Meanwhile, 3D models → inner CR ionized regions can undergo turbulence accelerated ambipolar diffusion → rapid core formation.
- SF Rate implications: Trans-Alfvénic turbulence leads to accelerated but low efficiency SF. Super-Alfvénic turbulence leads to prompt SF with very high velocity flows in core vicinity – ruled out generally.

More: see poster by Wolf Dapp