The Role of Magnetic Fields, Ambipolar Diffusion, and Turbulence in Fragmentation

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Through Cosmic Time
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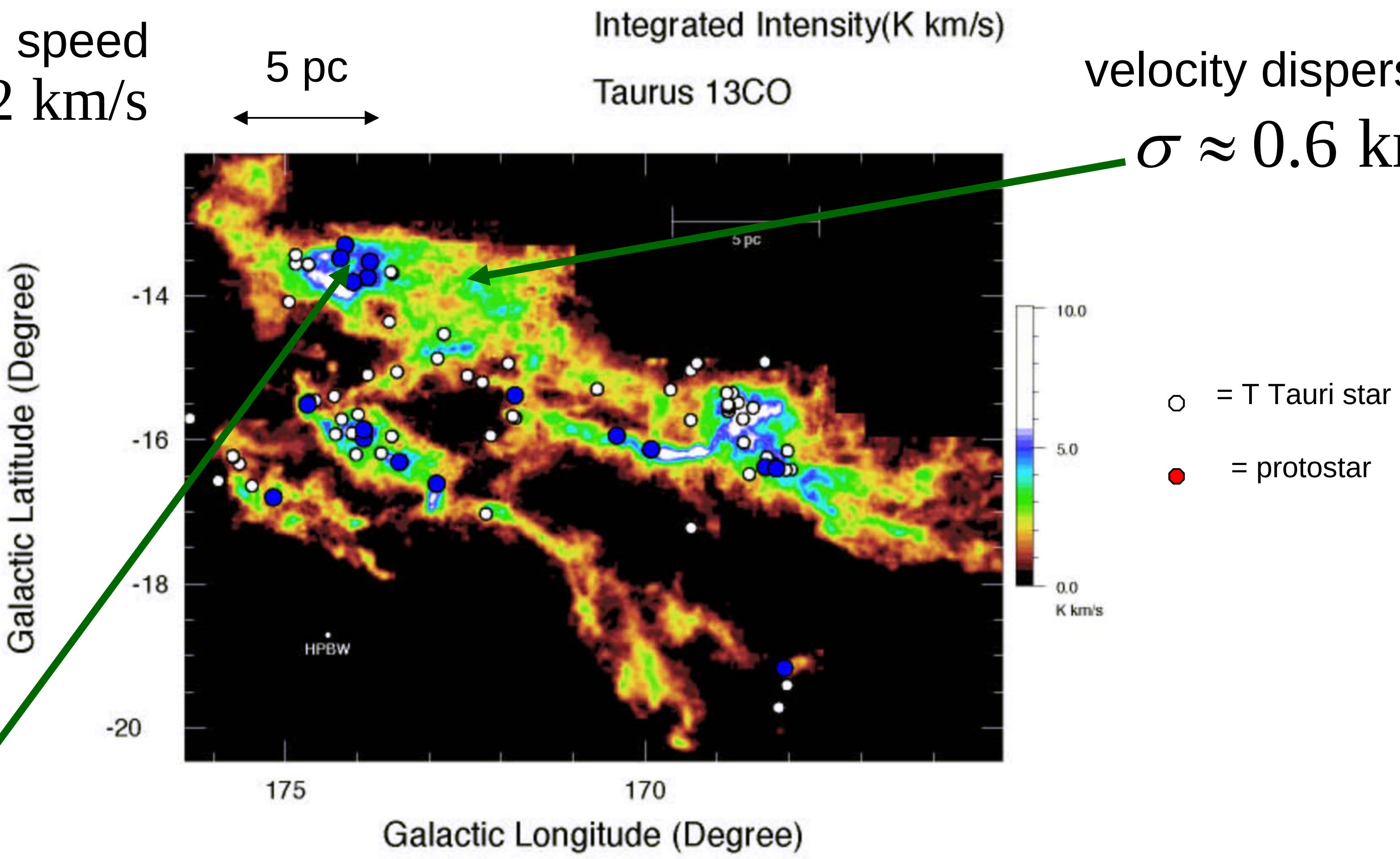
Taurus Molecular Cloud

distance = 140 pc

sound speed

$c_s \approx 0.2$ km/s

5 pc



velocity dispersion

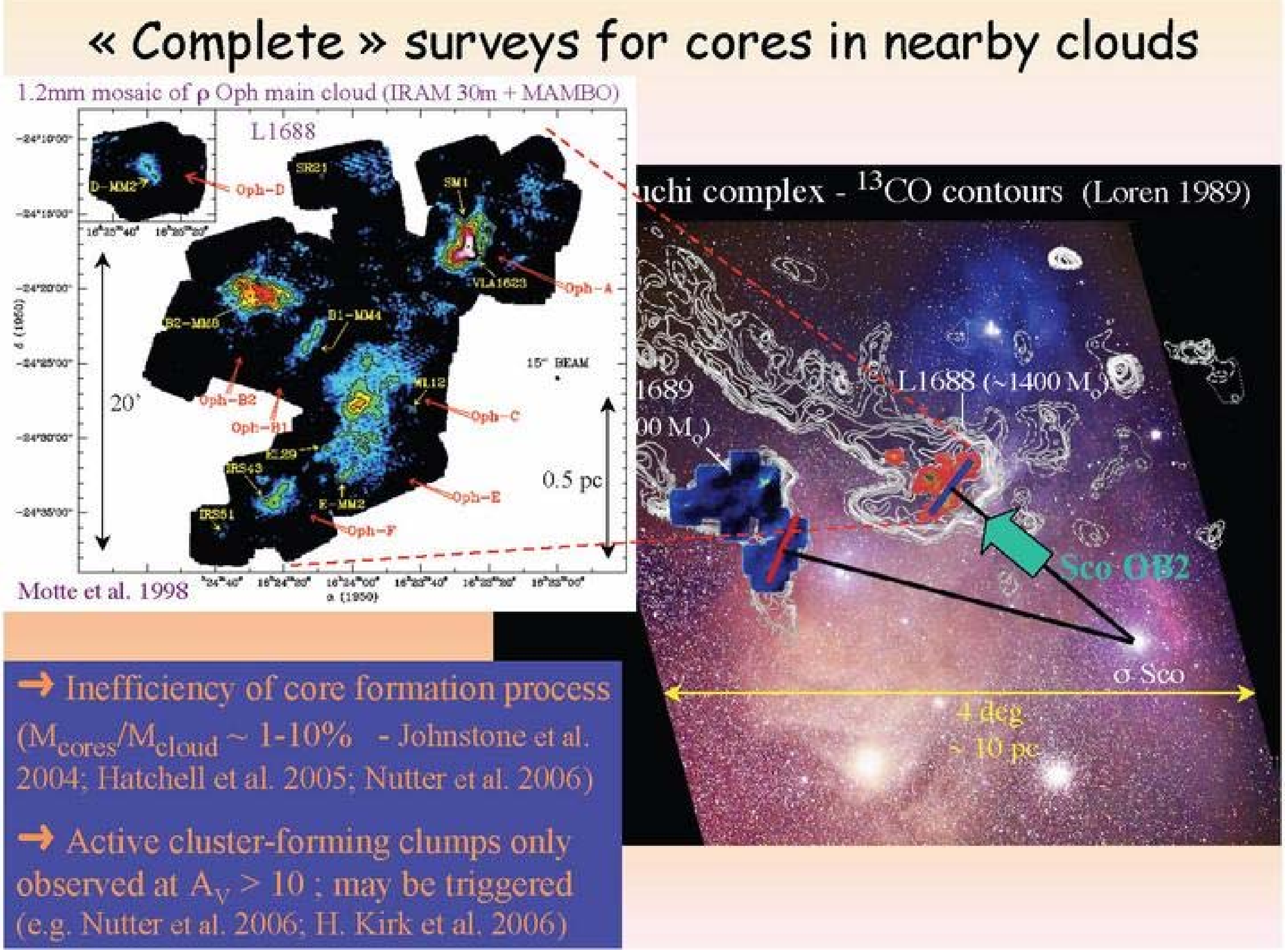
$\sigma \approx 0.6$ km/s

$\sigma \approx 0.25$ km/s

Onishi et al. (2002)

Rho Ophiuchus

Slide courtesy P. Andre



« Complete » surveys for cores in nearby clouds

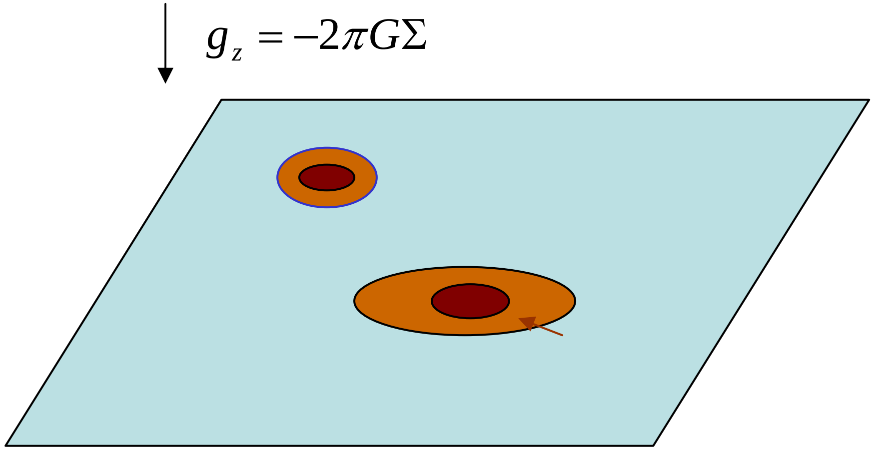
1.2mm mosaic of ρ Oph main cloud (IRAM 30m + MAMBO)

Motte et al. 1998

uchi complex - ^{13}CO contours (Loren 1989)

- Inefficiency of core formation process (M_{cores}/M_{cloud} ~ 1-10% - Johnstone et al. 2004; Hatchell et al. 2005; Nutter et al. 2006)
- Active cluster-forming clumps only observed at $A_V > 10$; may be triggered (e.g. Nutter et al. 2006; H. Kirk et al. 2006)

Layer Instability



Consider a layer of surface density Σ.

Linear perturbation analysis yields dispersion relation

$$\omega^2 = c_s^2 k^2 - 2\pi G\Sigma |k|.$$

Gravitational instability if

$$\lambda > \lambda_{crit} = \pi H = \frac{c_s^2}{G\Sigma}.$$

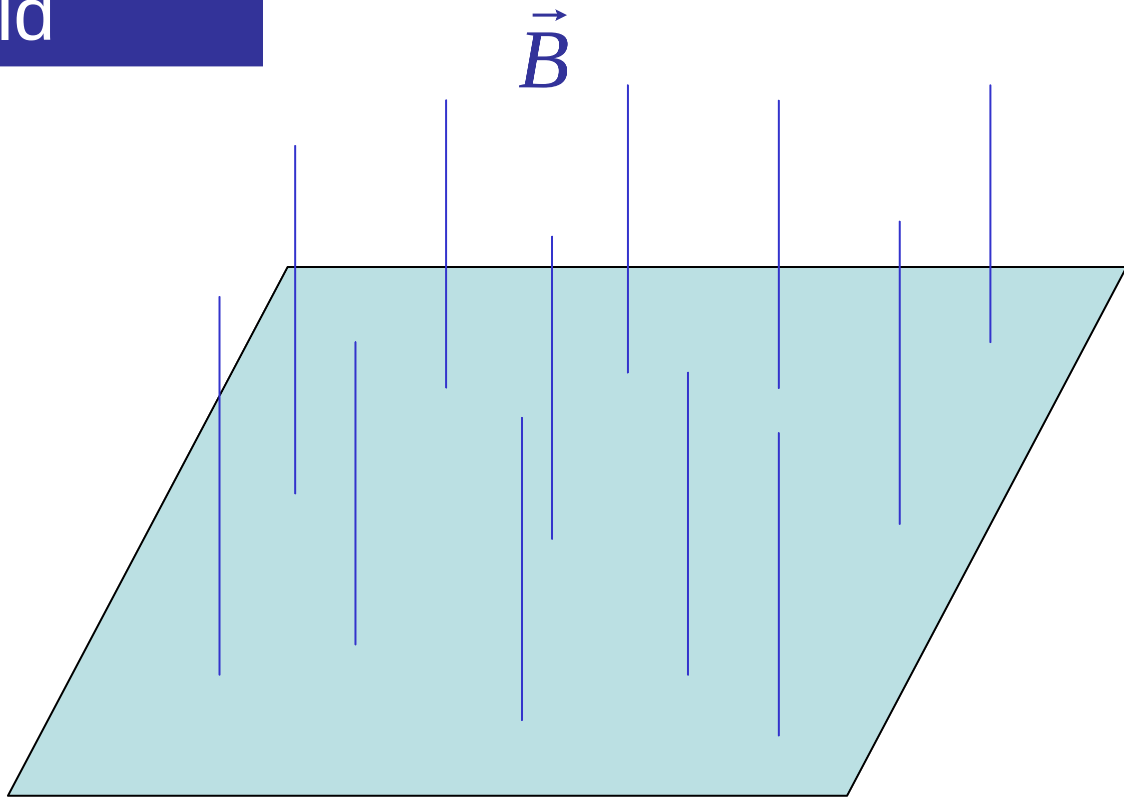
H is the vertical scale height of the layer.

Moreover, there is a **preferred** fragmentation scale.

$$\lambda = \lambda_{\max} = 2\pi H = \frac{2c_s^2}{G\Sigma}$$

at which the growth time is a *minimum*.

Effect of Magnetic Field



Critical magnetic field if

$$\frac{B^2}{8\pi} = \frac{\pi}{2} G\Sigma^2$$

magnetic pressure

self-gravitational pressure

Where magnetic flux-freezing applies:

Subcritical cloud $\mu = \frac{\Sigma}{B} 2\pi G^{1/2} < 1$ No fragmentation occurs

Supercritical cloud $\mu = \frac{\Sigma}{B} 2\pi G^{1/2} > 1$ Fragmentation occurs

Ambipolar Diffusion

In a weakly ionized gas, the mean velocity of neutral atoms or molecules will not generally equal the mean velocity of ions and electrons.

Neutrals do not feel the Lorentz force directly, but only through collisions arising from a drift relative to ions.

$$\mathbf{v}_{i,p} = \mathbf{v}_{n,p} + \frac{\tau_{ni}}{\sigma_n} F_{\mathrm{Lorentz}}$$

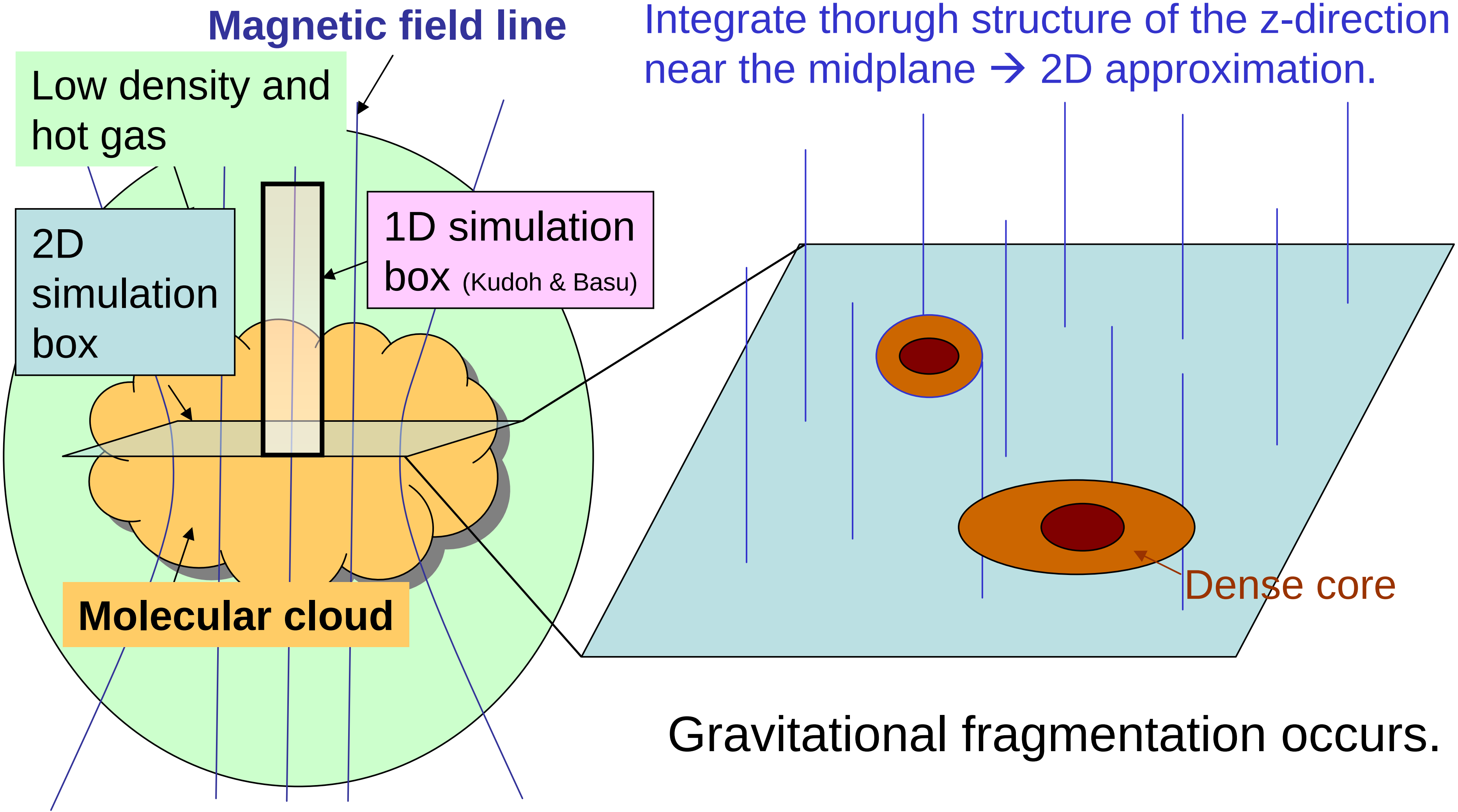
$$\tau_{ni} = 1.4 \frac{m_i + m_n}{\rho_i \langle \sigma w \rangle_{in}}, \quad n_i = K n_n^{1/2}$$

neutral-ion collision time

ion density vs. neutral density relation, primarily due to cosmic ray ionization

Even SUBCRITICAL clouds can undergo fragmentation instability due to ambipolar diffusion, i.e. ion-neutral slip.

MHD simulation: 2-dimensional



Integrate thorugh structure of the z-direction near the midplane → 2D approximation.

Gravitational fragmentation occurs.

Kudoh & Basu (2003,2006) – dense midplane of stratified turbulent cloud has transonic/subsonic motions.

Modes of Fragmentation

- Gravitational Fragmentation (Linear perturbations)
  - **dynamic (supercritical mass-to-flux ratio)**
  - **quasistatic ambipolar-diffusion (subcritical mass-to-flux ratio)**
- Turbulent Fragmentation (Highly nonlinear perturbations)
  - **supercritical**
  - **subcritical**

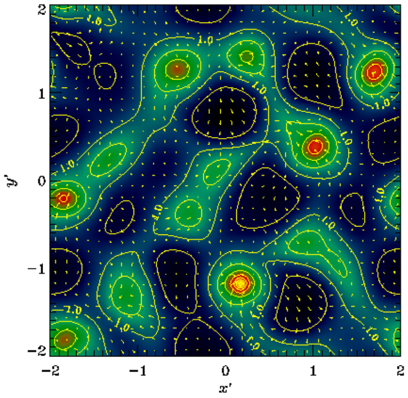
We can test all of these scenarios including the effects of magnetic fields and ambipolar diffusion.

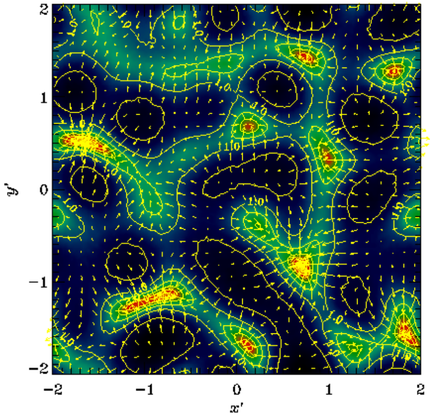
MHD Model of Gravitational Fragmentation

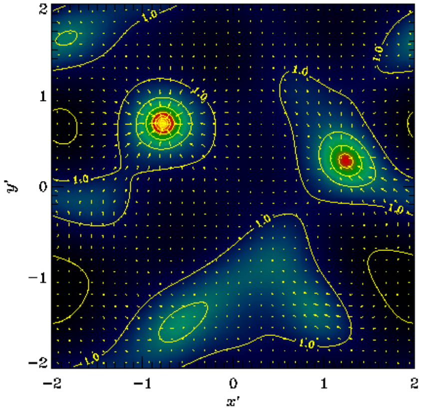
Added small (few %) initial random white noise perturbations to column density, magnetic field.

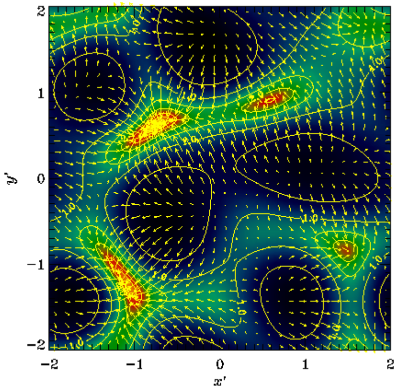
$$\Sigma_{n,\max}/\Sigma_{n,0} = 10$$

In all images, but magnetic field strength varies.









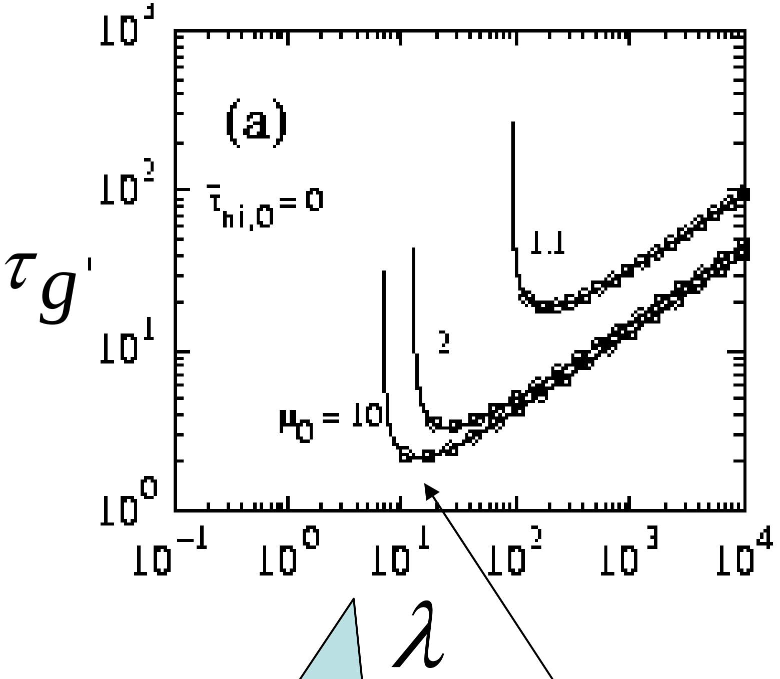
Thin disk approximation

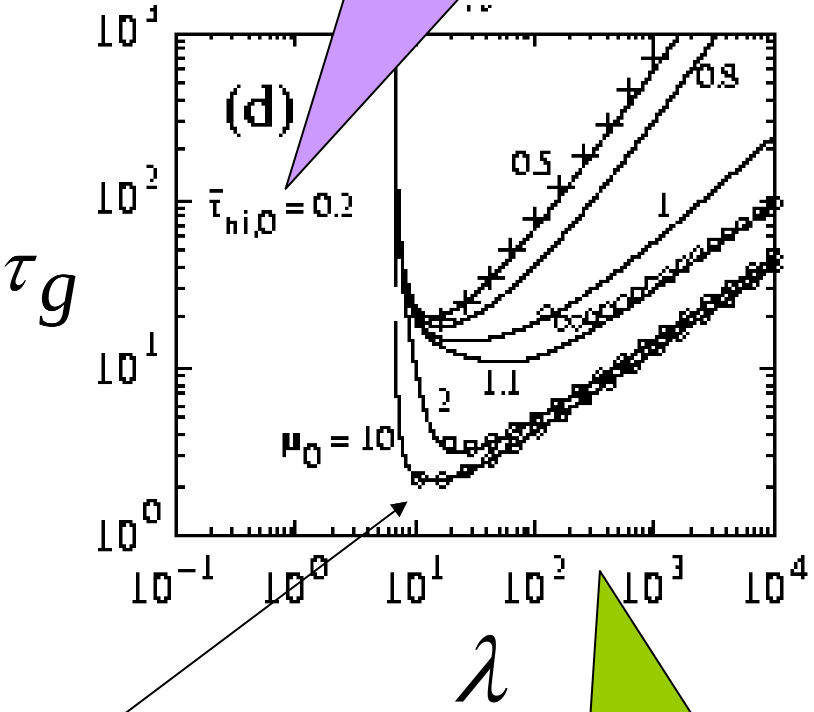
Linear Perturbation Analysis for Magnetic Disk with AD

Ciolek & Basu (2006)

CR ionization

$\chi_i = 10^{-7}$ at $n = 10^4$ cm^{-3}





flux freezing

imperfect coupling

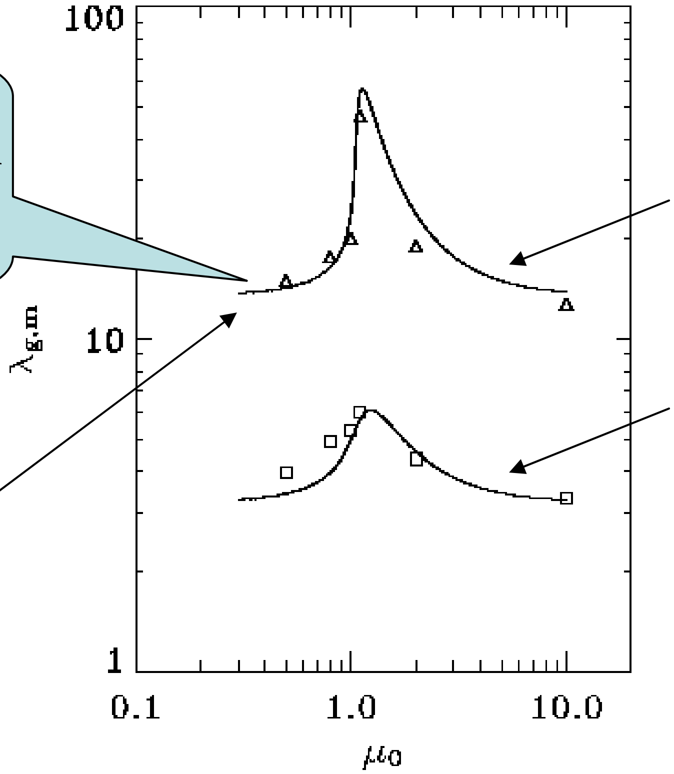
$$\lambda = 2\pi H,\ \tau_g = H/c_s$$

Fragmentation Scales

$\lambda_{g,m}$ = wavelength with maximum growth rate.

Solid lines = linear fragmentation theory. Symbols = result of 2D numerical simulations

Converges to $\lambda_{g,m} = 2\pi H$ for both μ □ 1 and μ □ 1.



Case of low external pressure on disk

High external pressure case

This curve first derived by Morton & Mouschovias (1991)

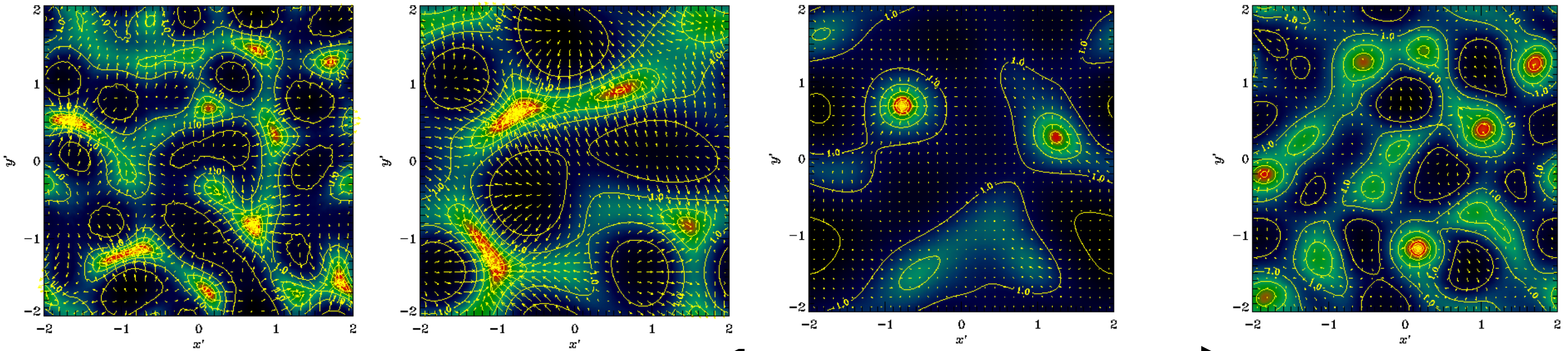
Ciolek & Basu (2006); Basu, Ciolek, & Wurster (2007)

MHD Model of Gravitational Instability

Basu, Ciolek & Wurster (2007)

$\Sigma_{n,\max}/\Sigma_{n,0} = 10$ in all images

128^2 cells in each model



Very weak $\vec{B}$

Highly supercritical

$\mu_0 = 10$

- t = 10
- $|v|_{\max}$=1.2 c_s
- most elongated

Weak $\vec{B}$

Supercritical

$\mu_0 = 2$

- t = 20
- $|v|_{\max}$=1.1 c_s
- moderate elongation
- large spacing

Critical $\vec{B}$

$\mu_0 = 1$

- t = 100
- $|v|_{\max}$=0.7 c_s
- largest spacing

Strong $\vec{B}$

Subcritical

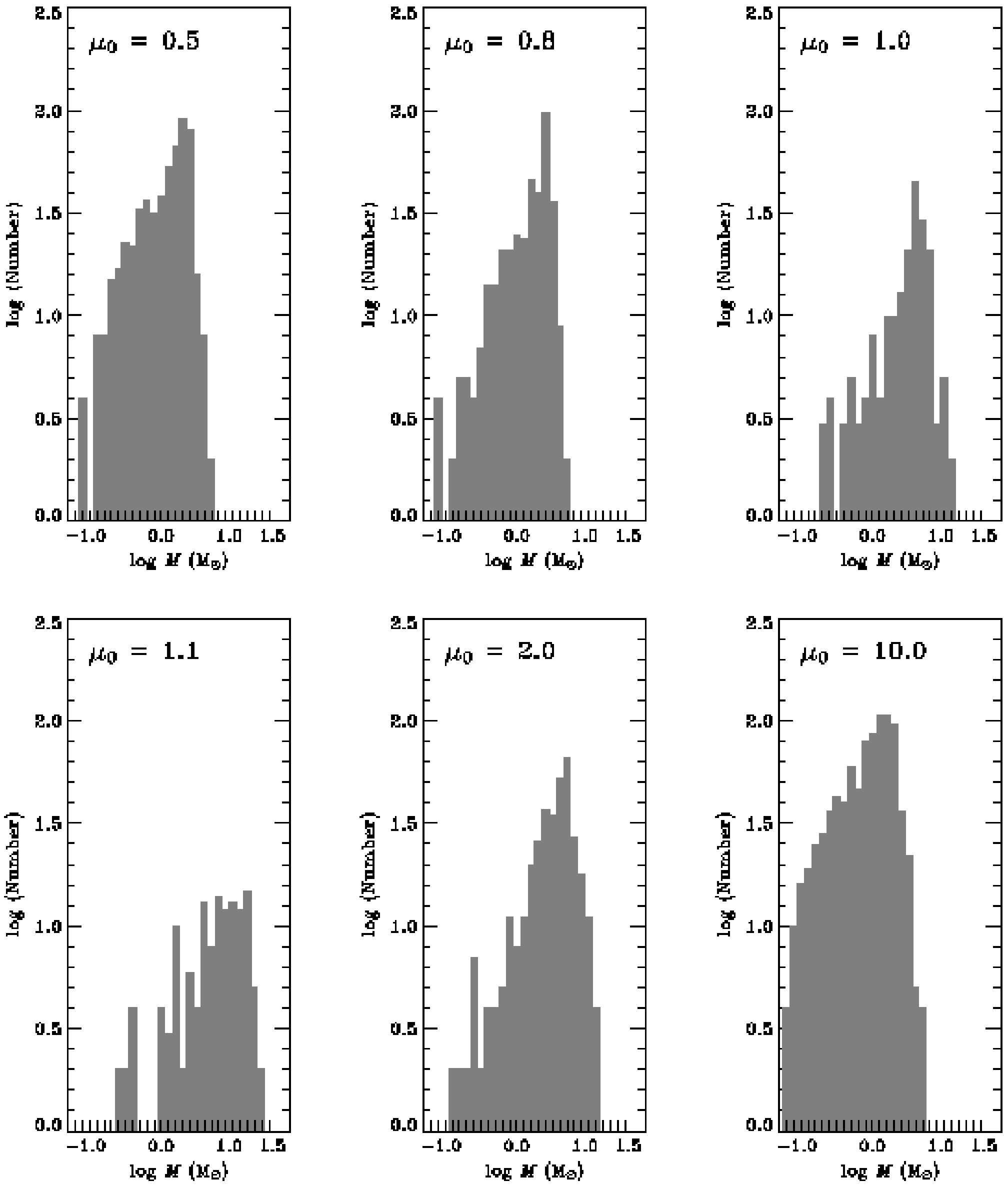
$\mu_0 = 0.5$

- t = 200
- $|v|_{\max}$=0.4 c_s
-mildest core elongation

box size ~ 2 pc, time unit ~ 2 x 10^5 yr if $n_{n,0}$= 3 x 10^{-3} cm^{-3}, scales as $n_{n,0}^{-1/2}$.

INITIAL Core Mass Function (Grav. Fragmentation)

Narrow lognormal-like. High-mass slope much steeper than observed CMF/IMF.

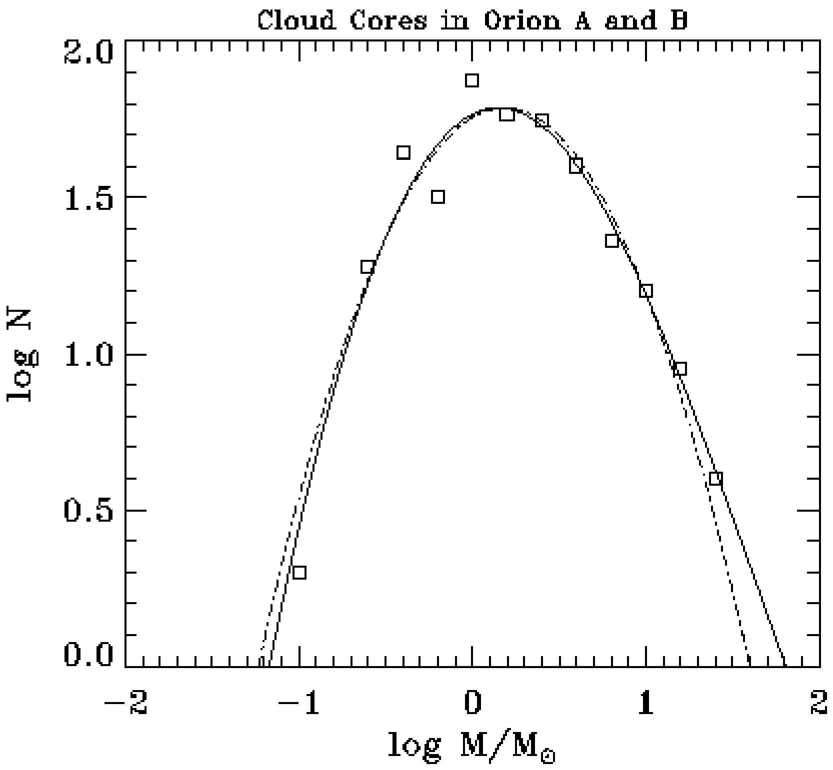


“Core” = enclosed region with

$$\Sigma_n/\Sigma_{n,0} \geq 2.$$

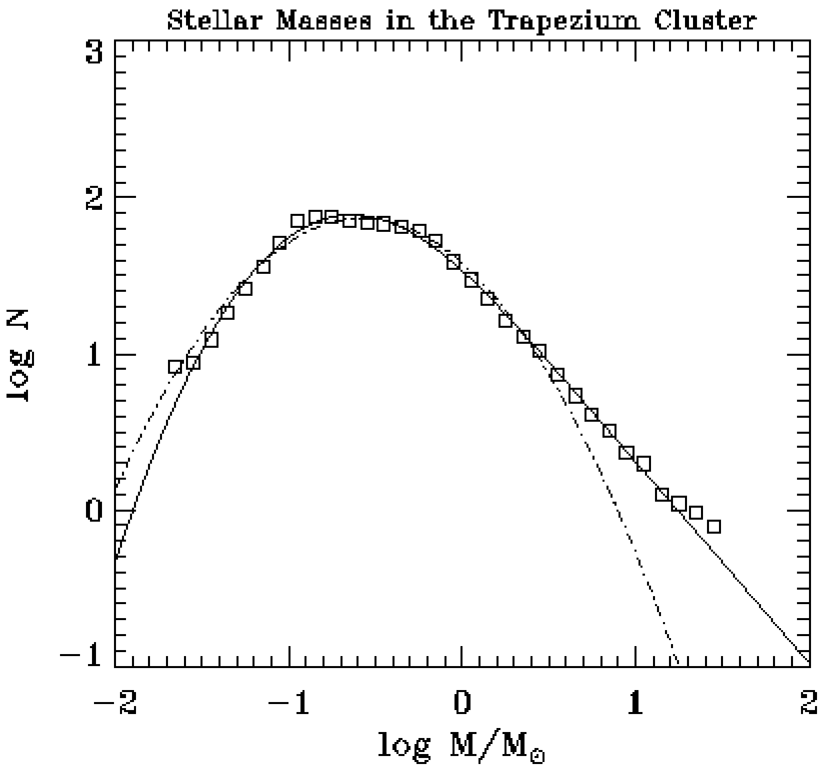
Observed Core Mass Fcn and Initial Mass Fcn

Lognormal



Data from Nutter & Ward-Thompson (2007)

Lognormal/power-law



Data from Muench, Lada, & Lada (2002)

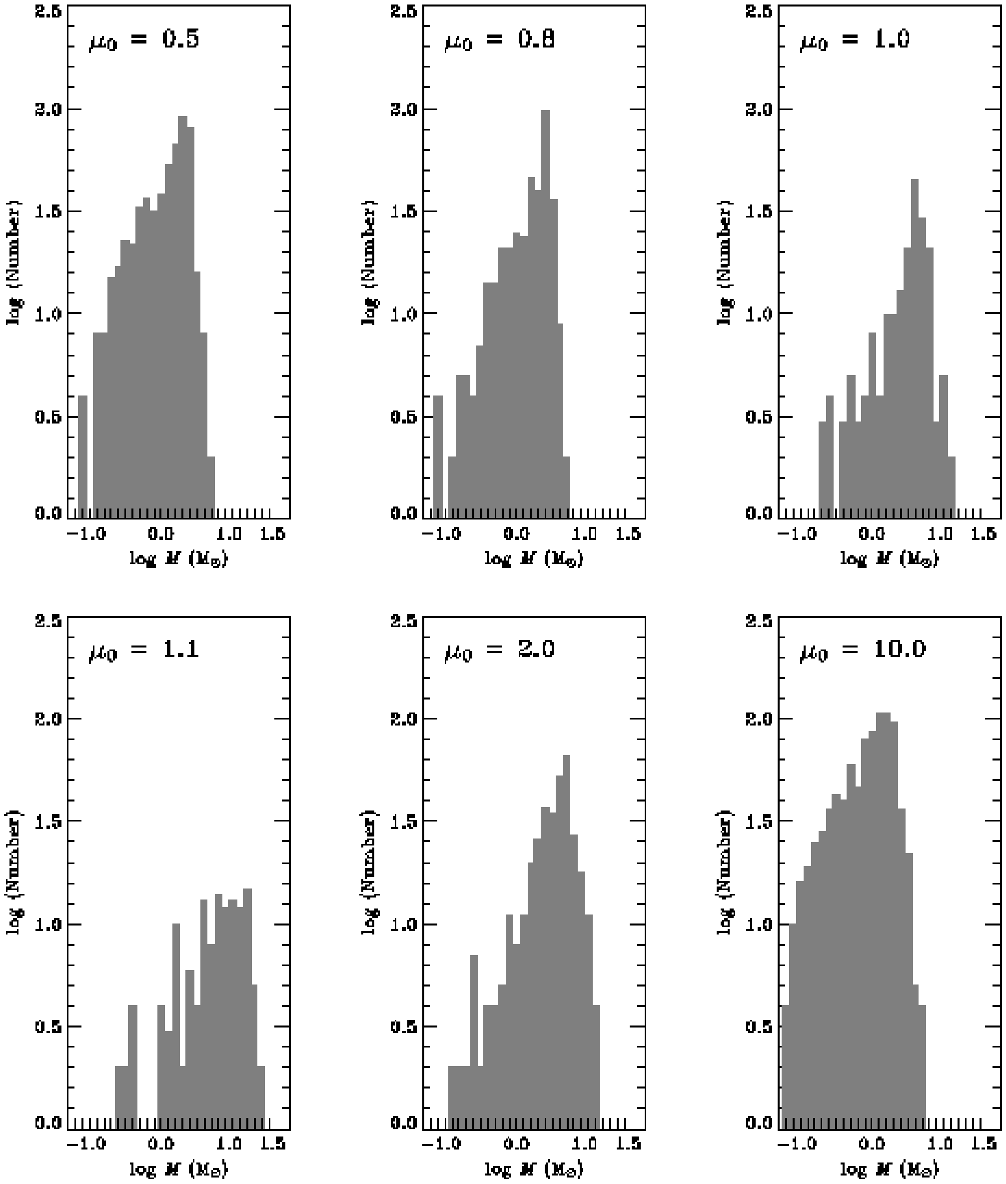
INITIAL Core Mass Function (Grav. Fragmentation)

Narrow lognormal-like. High-mass slope much steeper than observed CMF/IMF.

Must be more to the story.

“Core” = enclosed region with

$$\Sigma_n/\Sigma_{n,0} \geq 2.$$



Possible ways to get broader final CMF/IMF:

1. Continuing core accretion: Zinnecker, Bate & Bonnell, Myers, Basu & Jones,…

OR

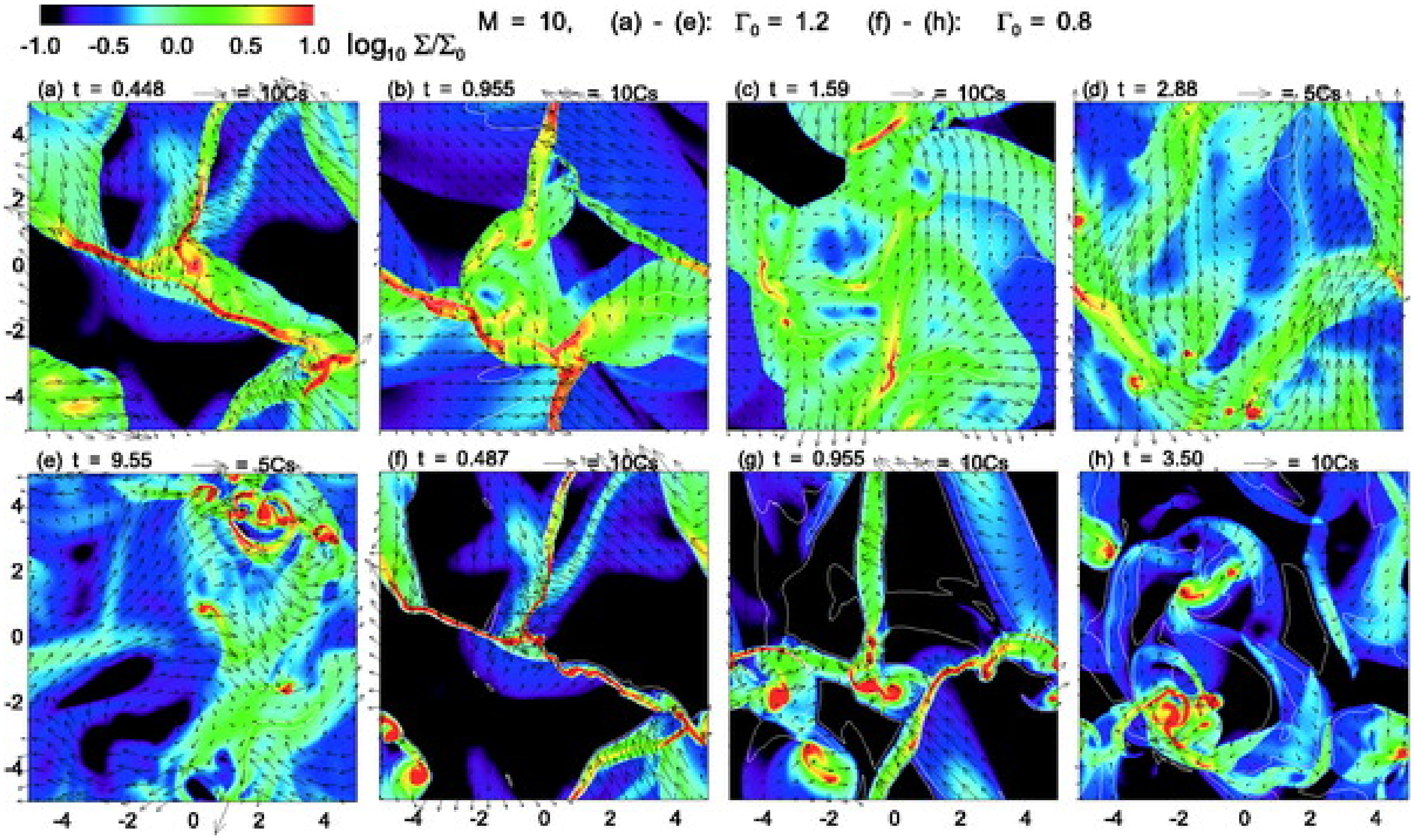
2. Turbulence ➔ broad CMF: Padoan & Nordlund, Klessen, MacLow,…

Turbulent Fragmentation with *B* and Ambipolar Diffusion

Thin disk approximation

But will this work in 3D?

Li & Nakamura (2004)



time unit = 2 Myr; box width = 3.7 pc

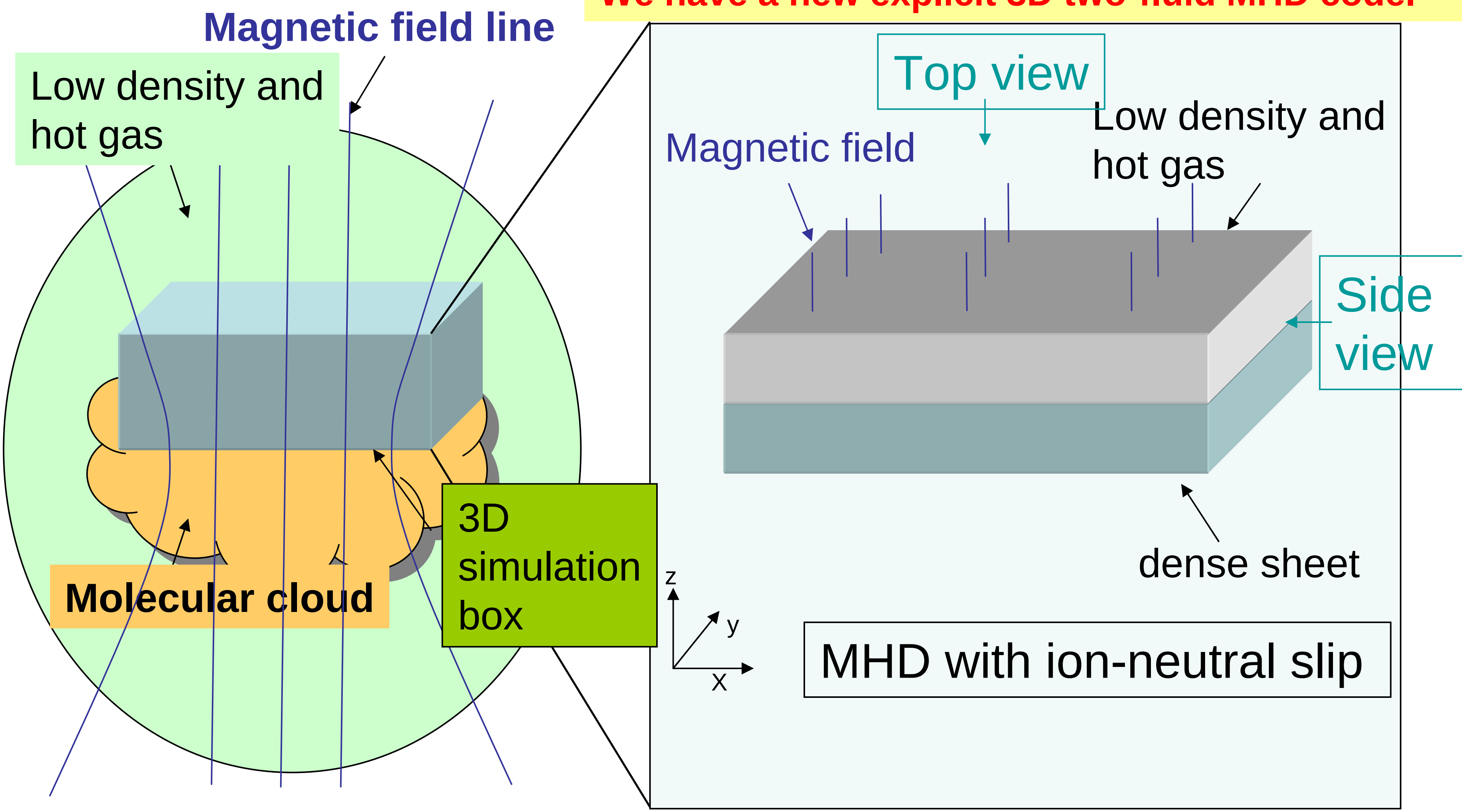
(a)-(e) subcritical ($\mu_0 = 0.83$) model,
(f)-(h) supercritical ($\mu_0 = 1.25$) model.

$v_k^2 \sim k^{-4}$ spectrum – really a large-scale flow

note filamentarity and velocity vectors

MHD simulation: (1+2 =) 3-dimensional

We have a new explicit 3D two-fluid MHD code.



Magnetic field line

Low density and hot gas

Molecular cloud

3D simulation box

Top view

Magnetic field

Low density and hot gas

Side view

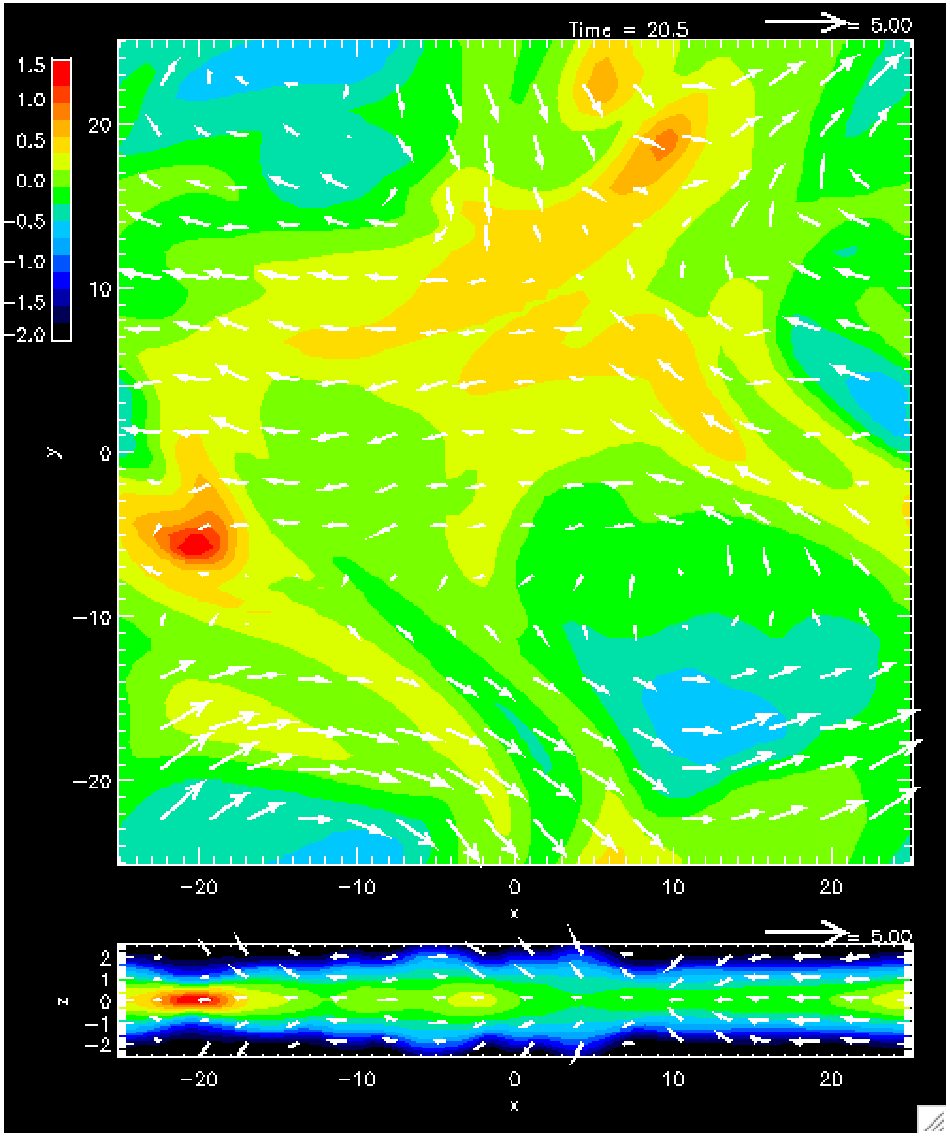
dense sheet

MHD with ion-neutral slip

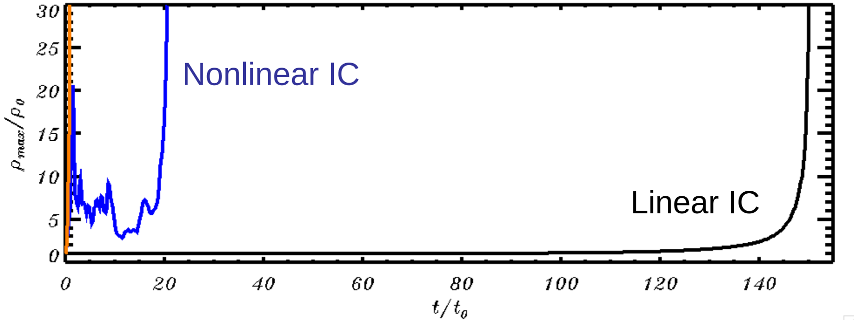
Kudoh, Basu, Ogata, & Yabe (2007),
Kudoh & Basu (2007)

Input large perturbation perpendicular to magnetic field at *t=0*

3D Turbulent Fragmentation with *B* and AD



box width = 2.5 pc



$t_0 \approx 2\times10^5\,\mathrm{yr}$

Nonlinear initial velocity field

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

Velocity rms amplitude = 3 c_s

$\mu_0 = 0.5$

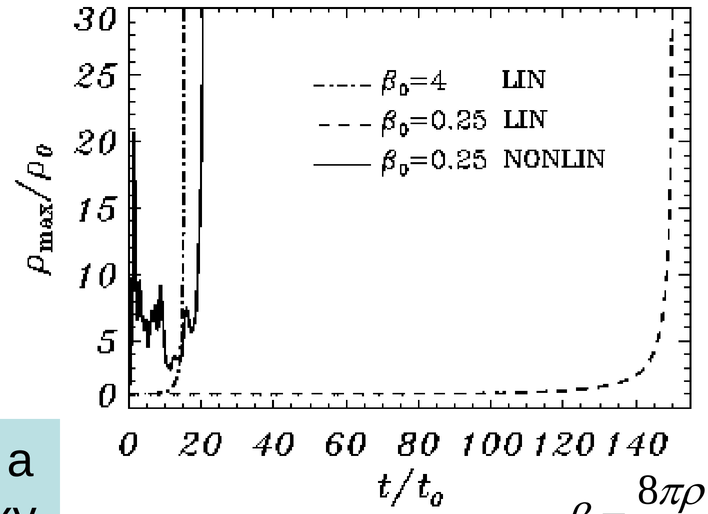
Gas density in midplane (*z*=0)

A vertical slice of gas density

Kudoh & Basu (2007)
using 64 x 64 x 40 cells

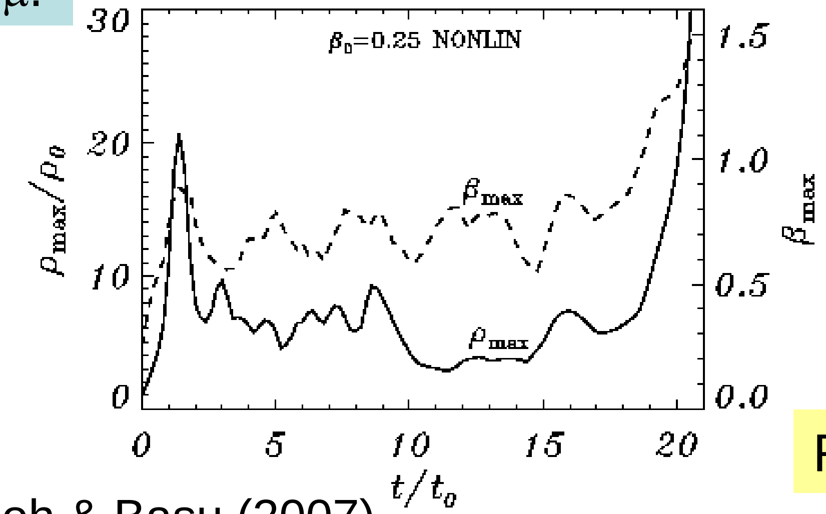
3D Turbulent Fragmentation with *B* and AD

What's really happening?



β is a proxy for μ.

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



Kudoh & Basu (2007)

$$\frac{\partial B}{\partial t} - \nabla \times (v_n \times B)$$

$$= \nabla \times \left\{ \frac{\tau_{ni}}{4\pi\rho_n} \left[(\nabla \times B) \times B \right] \times B \right\}.$$

$$\tau_{AD} \propto \frac{\rho_n L^2}{B^2 \tau_{ni}} \propto \frac{\rho_n \rho_i L^2}{B^2} \propto \frac{\rho_n^{3/2} L^2}{B^2}$$

Early turbulent compression

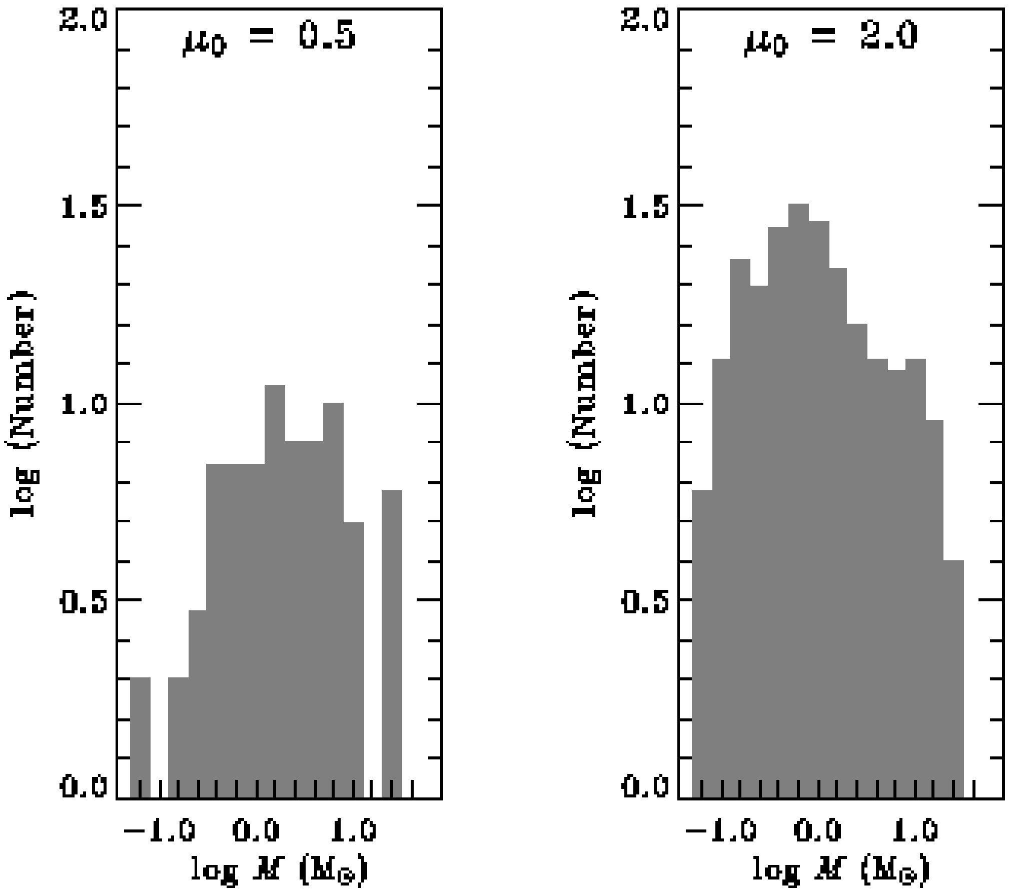
$$\tau_{AD} \propto L^{5/2} \Rightarrow \beta \uparrow \text{ quickly as } L \downarrow$$

Then, higher density region evolves with near vertical force balance

$$\tau_{AD} \propto \rho^{-1/2} \Rightarrow \beta \uparrow \text{ more slowly}$$

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

Core Mass Spectrum for 2D Turbulent Model



BROAD tail, ROUGHLY consistent with IMF.

But, final fate still undetermined.

Basu, Ciolek, & Wurster (2007)

Conclusions

- Transcritical gravitational fragmentation has a maximum (>> Jeans) fragment scale. Subcritical and supercritical fragmentation both occur at ~ Jeans scale
- Nonlinear gravitational fragmentation yields expected fragment spacings and observationally testable kinematics for different μ's. *Supercritical fragmentation may be good enough for some cluster-forming regions*
- Turbulent fragmentation – new 3D two-fluid MHD simulation reveals that Turbulence Accelerated Magnetically Regulated Fragmentation *works within a specific region of parameter space. Also, non-magnetic parameter space is problematic*
- Core Mass Functions can be derived from large numbers of (2D) simulations. Narrow initial distribution for gravitational fragmentation and broad one for turbulent fragmentation. *However, final outcome is far from settled*