From Clouds to Pre-stellar Cores: Insights from Simulations

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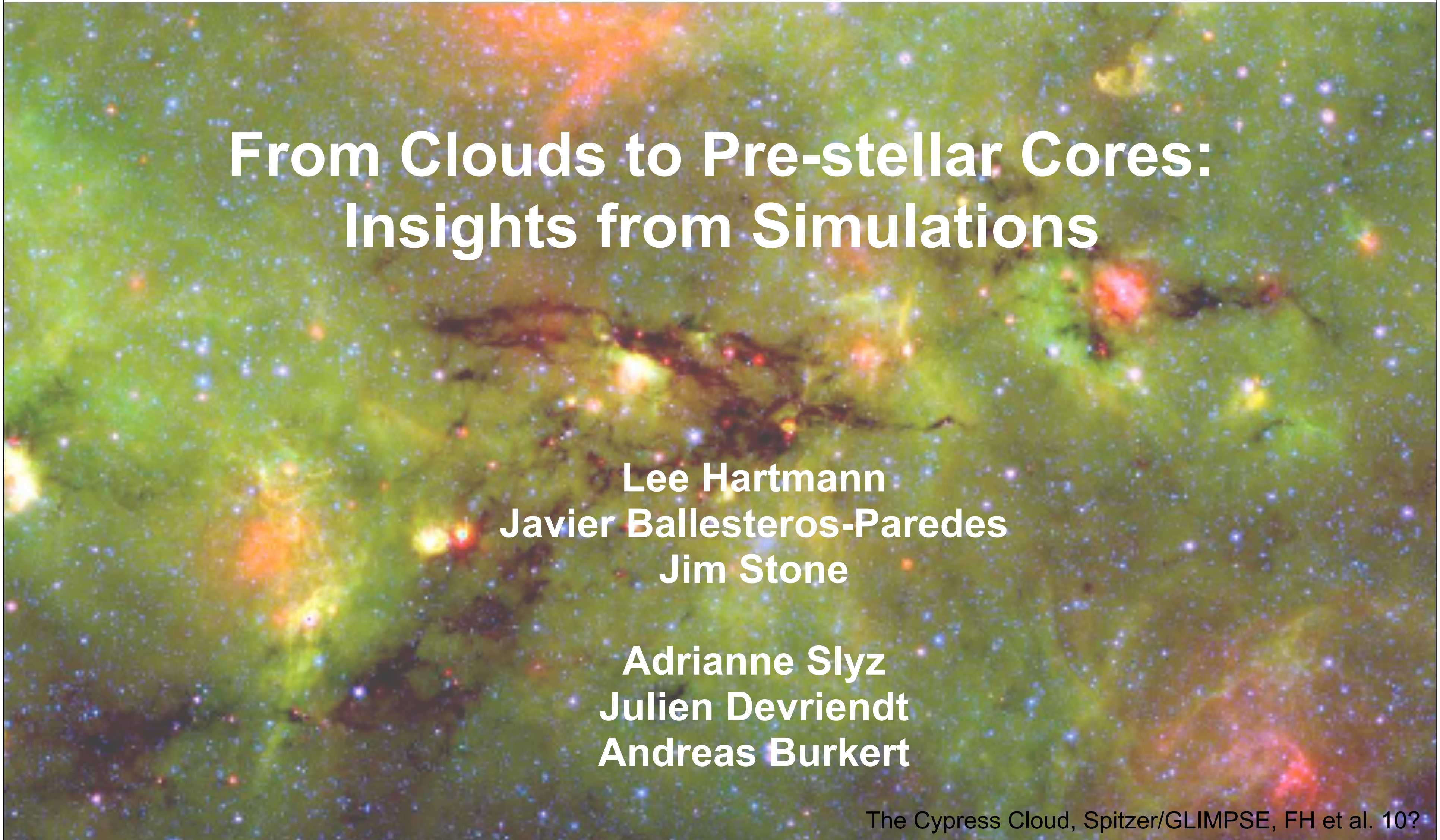

The Cypress Cloud, Spitzer/GLIMPSE, FH et al. 10?

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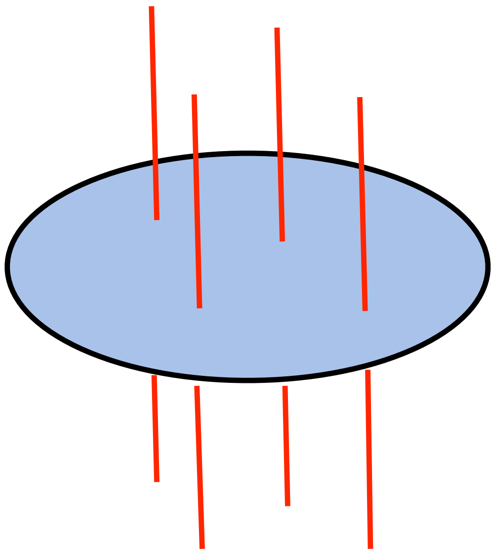
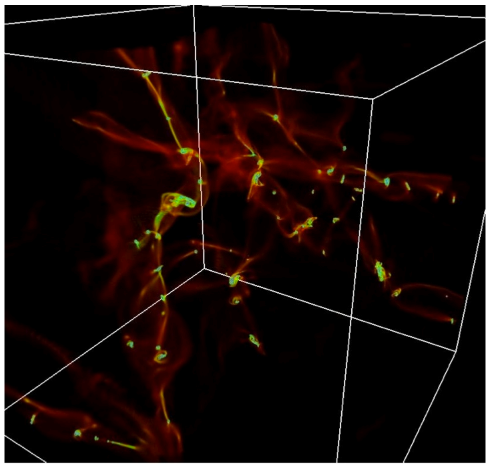
Core Formation: Fragmentation

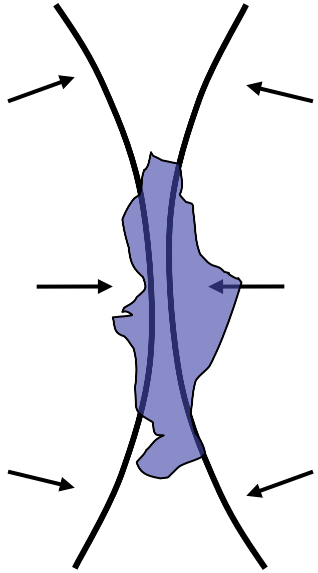
What sets the core formation efficiency in molecular clouds?

Concept 1	Concept 2	Concept 3
magnetically supported sheet	turbulent fragmentation	cloud formation & thermal fragmentation





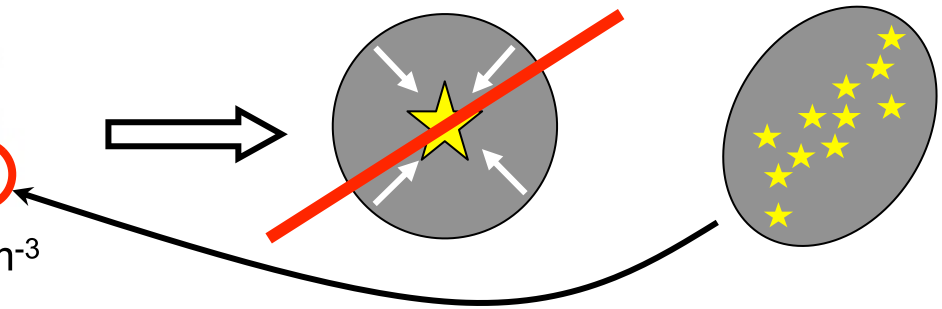
snapshot from P. Padoan



Core Formation: Fragmentation

If all the molecular gas in the Galaxy collapsed on its free-fall time, the star formation rate would be ~20 times higher than observed.

$$\tau_{ff} = \sqrt{\frac{3\pi}{32G\rho}}$$



3Myr @ 100 cm^{-3}

free-fall time independent of radius.

Linear density perturbations will be swept up in global collapse.

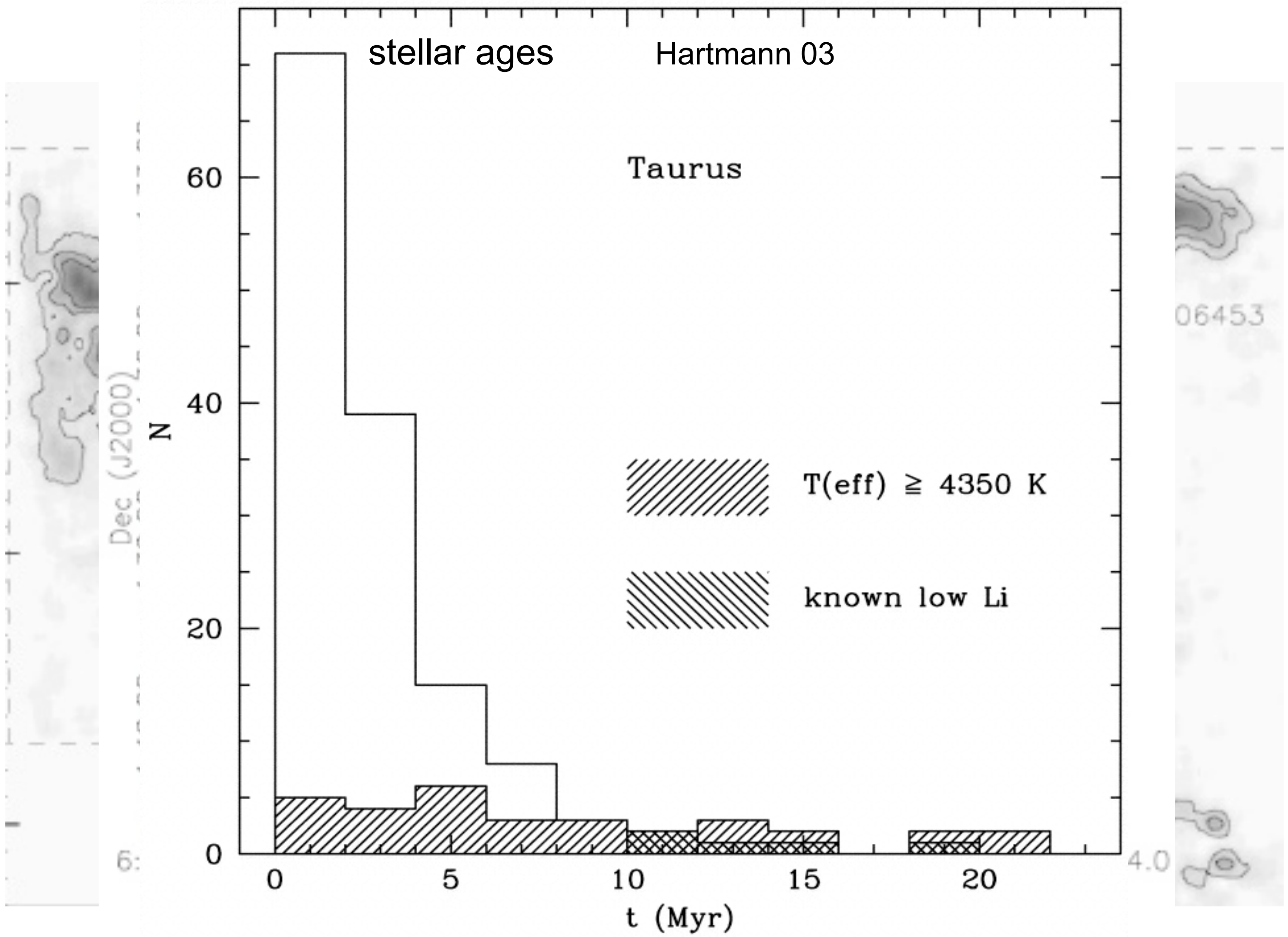
Burkert & Hartmann 04, Pon et al. 10

A Few Constraints

Most clouds form stars.

Stellar age spreads are small (1-3 Myr).

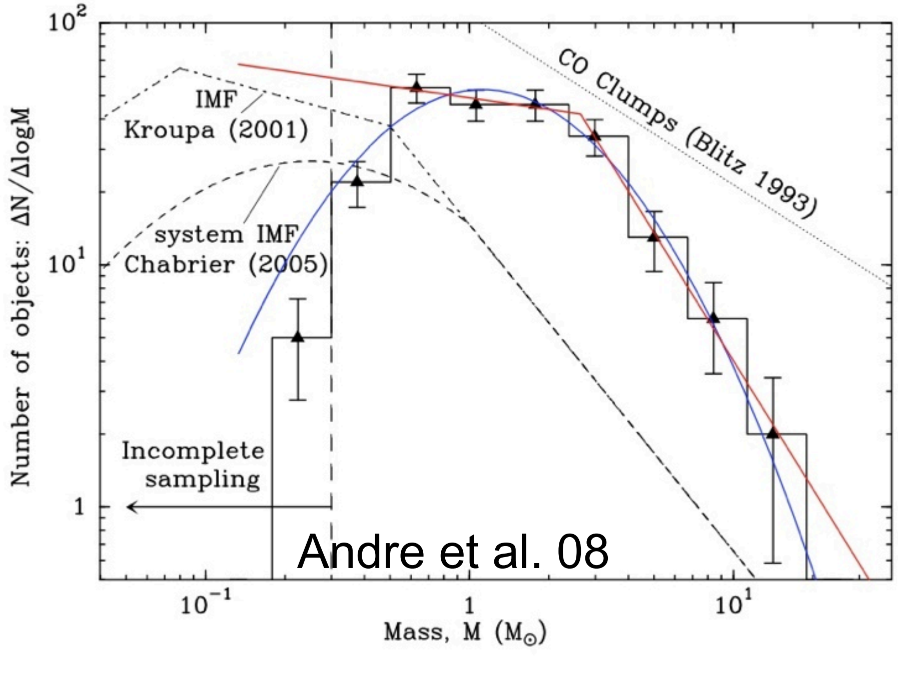
There is (nearly) no delay between cloud and star formation.

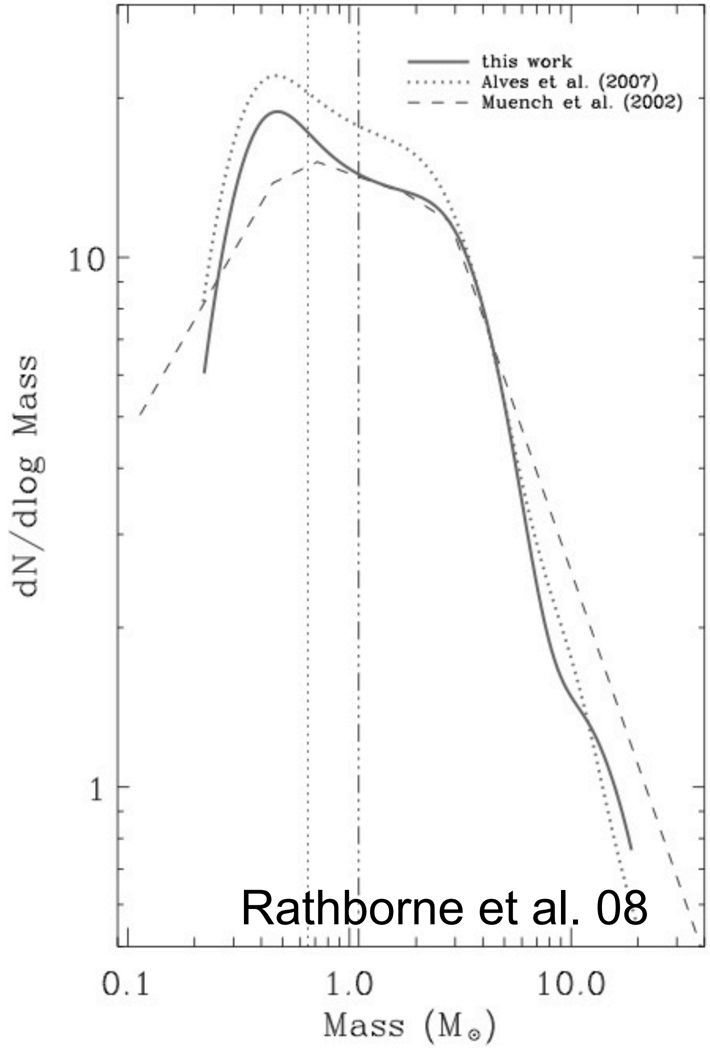


A Few Constraints

Cloud fragmenting into cores sets efficiency and IMF.

- < 10% of mass in dense gas/at high A_V.
  Lada 10, Heidermann et al. 10, Goldsmith et al. 08, Nutter et al. 05, Hatchell et al. 05
- SFE in cores is high.
  Evans 10
- CMF and IMF similar up to “efficiency factor”.
  Andre et al. 08, Rathborne et al. 08

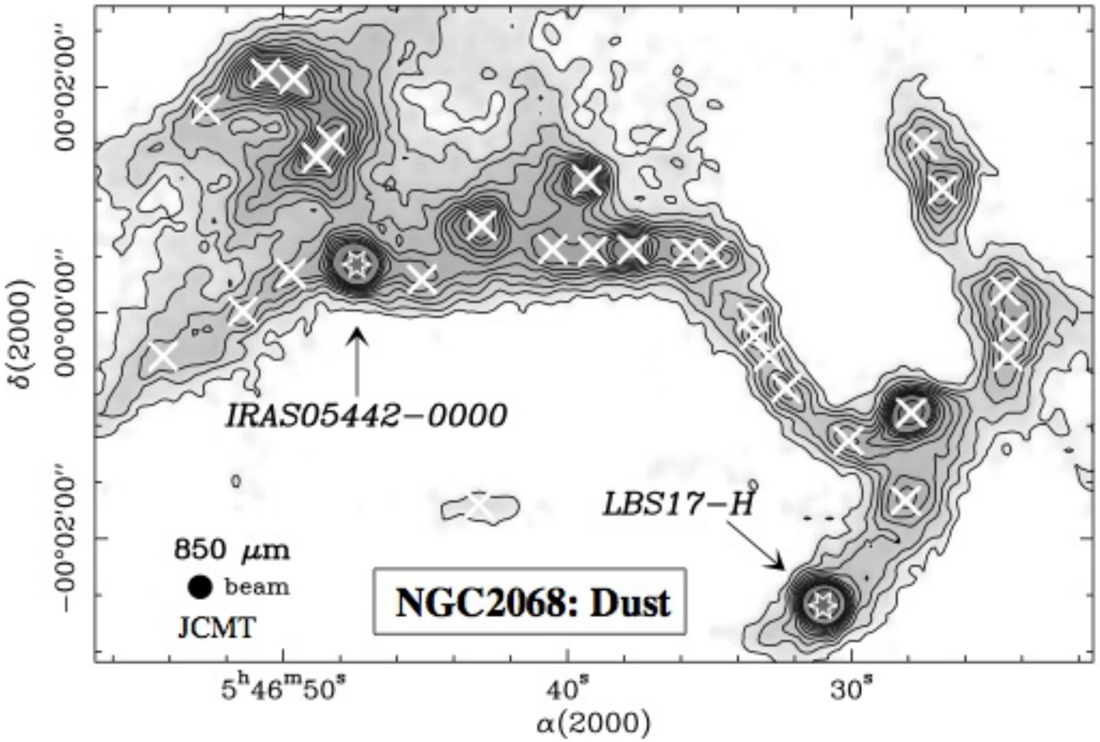




A Few Constraints

Cores (and stars) form in filaments.
Ostriker 64, Larson 85, Burkert & Hartmann 04

Preferred scale for fragmentation (and mass).



Andre et al. 08, Motte et al. 01

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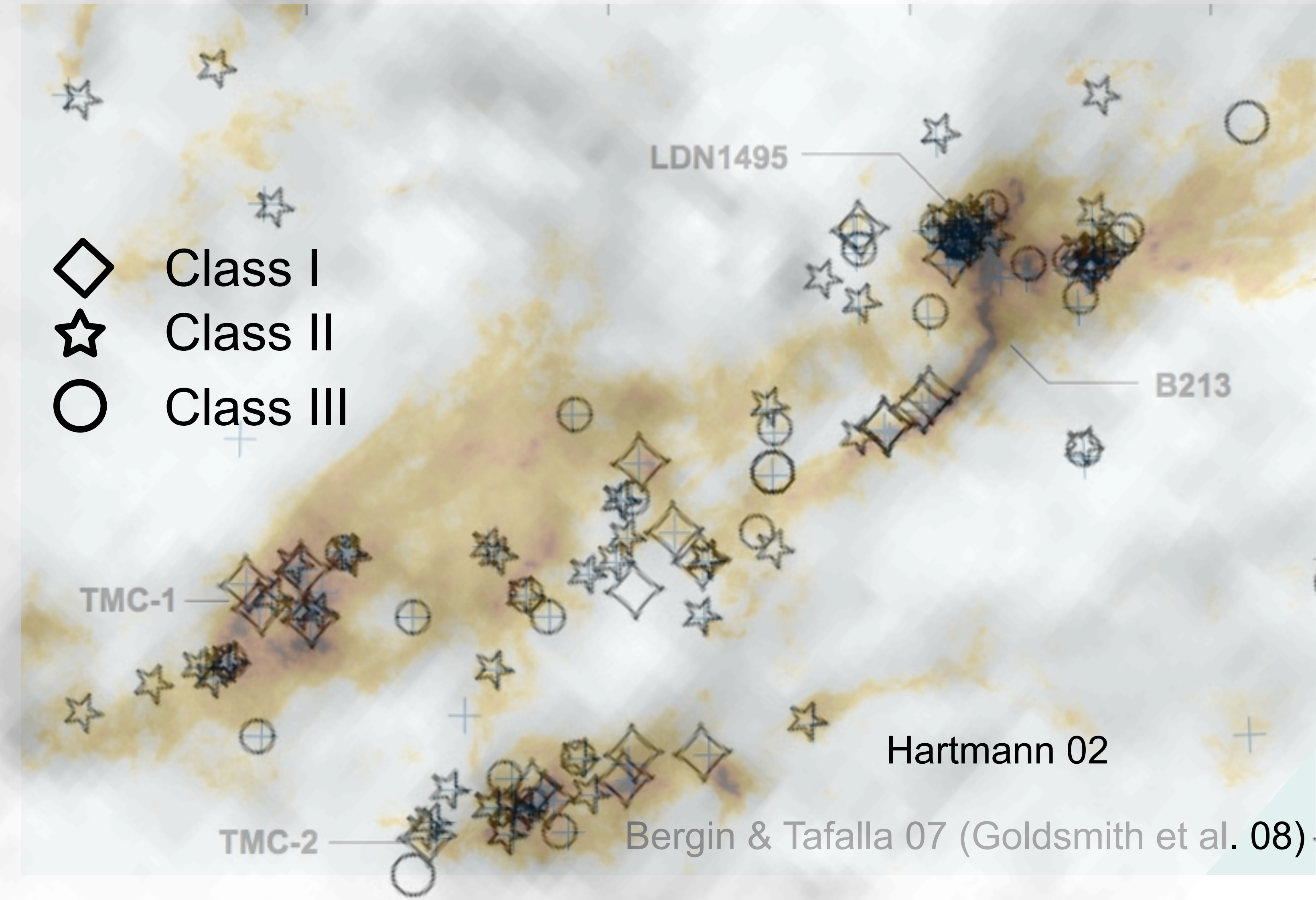


Bergin & Tafalla 07 (Goldsmith et al. 08)

A Few Constraints: Summary

(1) Star formation occurs directly after or during molecular cloud formation.

Star formation is rapid (but inefficient). No support of dense gas.

Ha

(2) Co

Ne ... n.

FH

(3) Co

Tu

Ba

Definitions:

Star Formation **Rate**:

resolved : M_{star} / t_{dyn}: average over timescale

unresolved: based on luminosity (instantaneous)

Star Formation **Efficiency**:

resolved : M_{star} / M_{cloud} (instantaneous)

unresolved: average over population

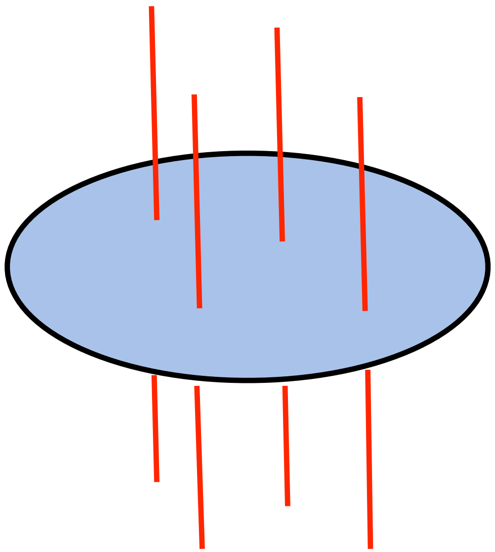
"Gravity makes things round." is only true if there is an isotropic pressure to counter it.

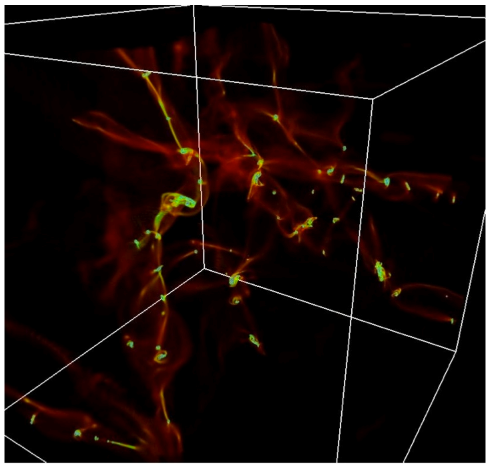
Fragmentation Mechanisms

What sets the core formation efficiency in molecular clouds?

Since most of the mass is in low-density gas, it must be a **rapid** fragmentation mechanism.

Concept 1	Concept 2	Concept 3
magnetically supported sheet	turbulent fragmentation	cloud formation & thermal fragmentation





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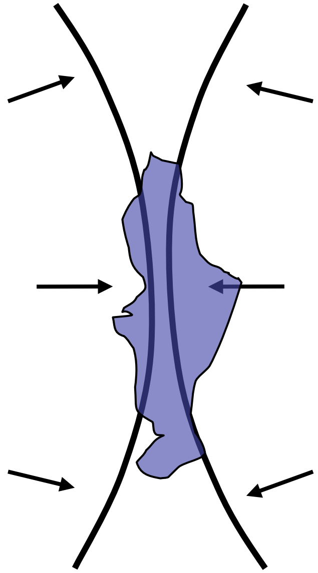
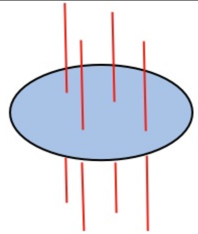


(1) Fragmentation Mechanisms: Magnetically Supported Sheet



Mechanisms:

(1) Flux-freezing leads to support if Crutcher 1999

$$\lambda \equiv (M/\Phi)_{observed}/(M/\Phi)_{critical} < 1$$

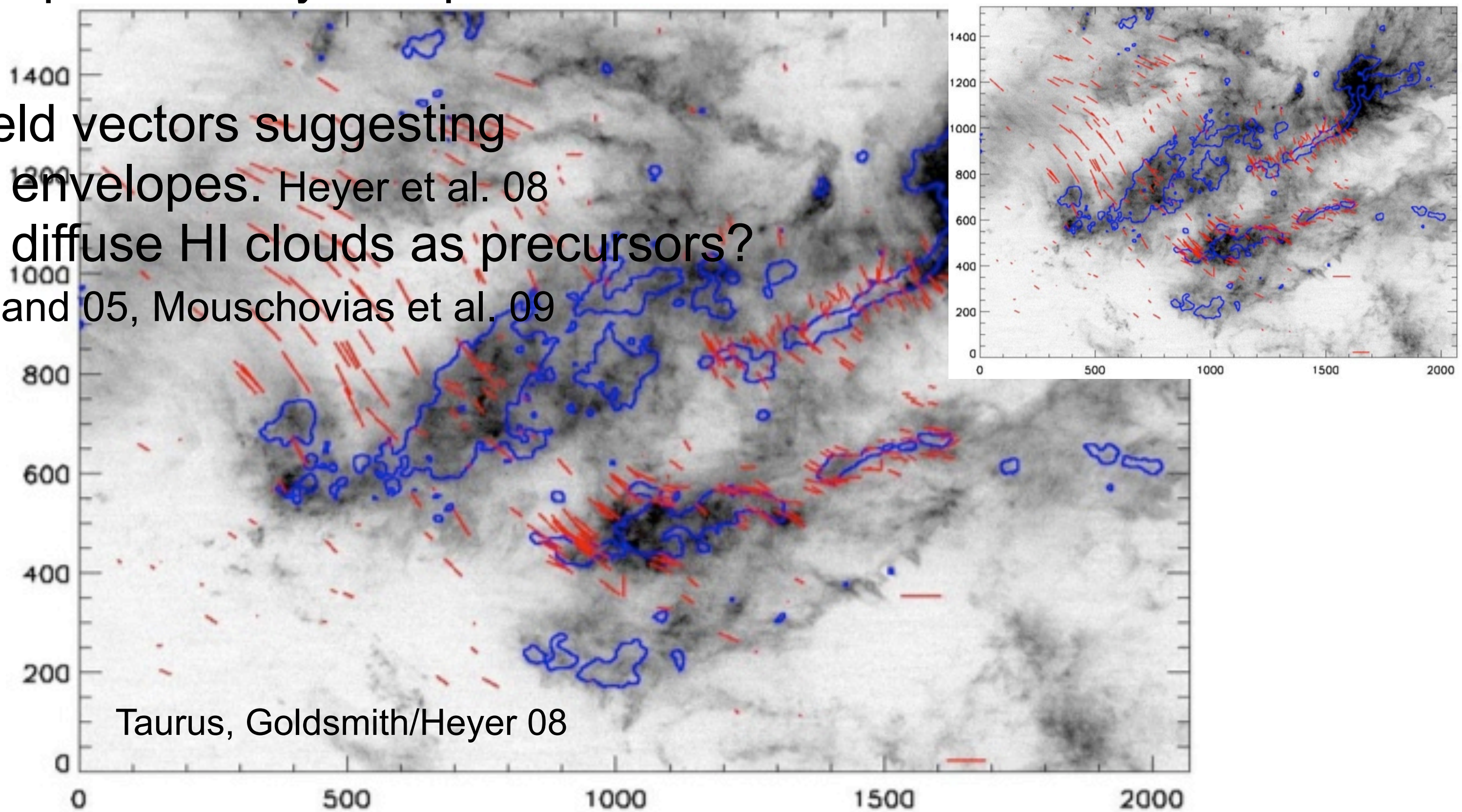
$$\lambda = 7.6 \times 10^{-21} N(H_2)/B_{los}$$

(2) Decoupling of ions and neutrals leads to drift and quasi-steady collapse. Shu et al. 87, Ciolek & Mouschovias 94

Motivation:

(1) Ordered field vectors suggesting subcritical envelopes. Heyer et al. 08

(2) Subcritical diffuse HI clouds as precursors? Heiles & Troland 05, Mouschovias et al. 09



Taurus, Goldsmith/Heyer 08

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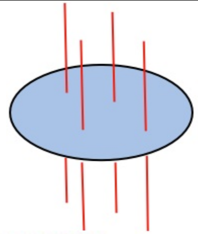

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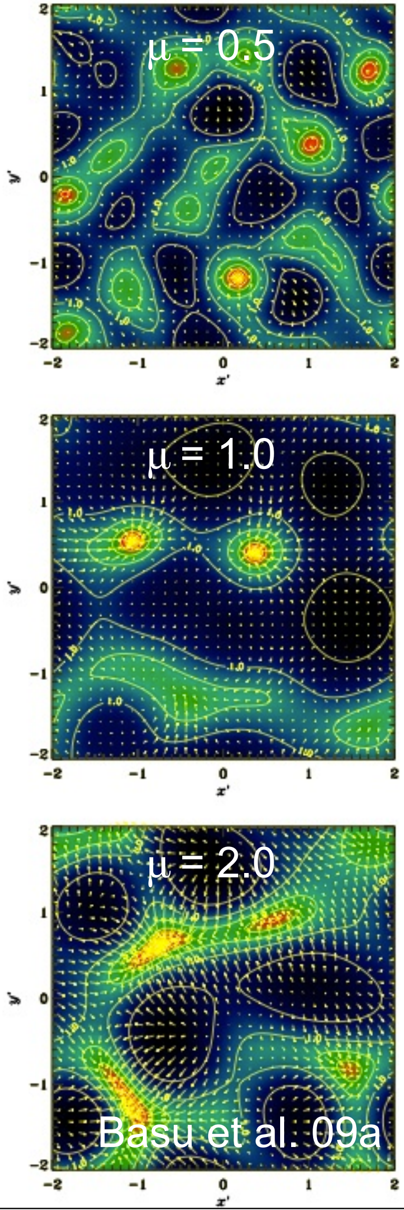
Predictions (Basu et al. 2009a,b):

(1) Preferred fragmentation scale.

(2) “Coreless clouds” depending on criticality.

(3) Subcritical models: subsonic infall, supersonic models: supersonic infall. Kirk et al. 09

(4) Age spread for subcritical models.



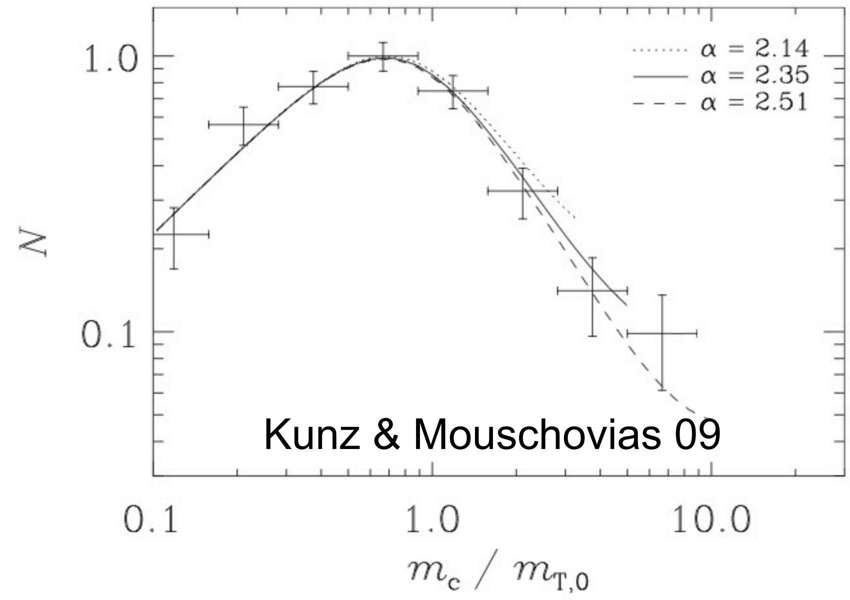
(1) Magnetically Supported Sheet:

Strengths:

(1) Low efficiency

(2) Reproduction of CMF
Kunz & Mouschovias 09

(3) Subsonic infall velocities,
coherent core-to-core velocities
Basu et al. 09a,b



Weaknesses:

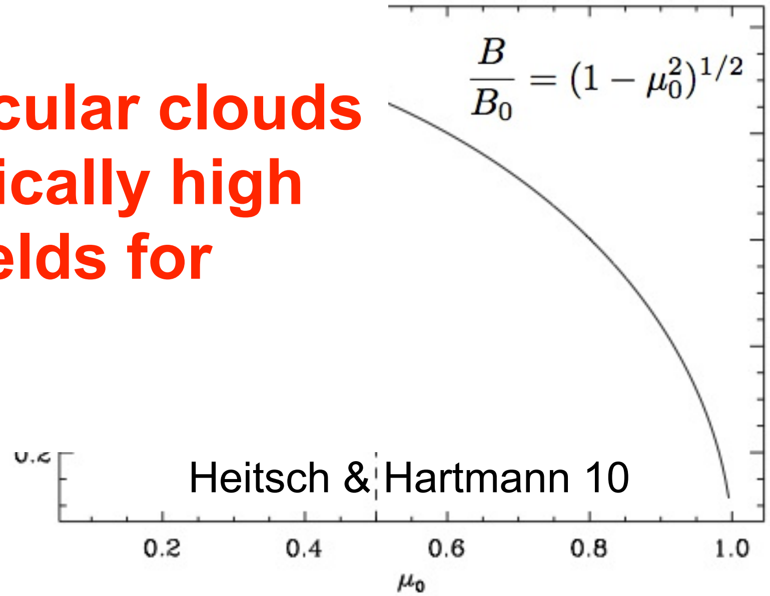
(1) Large age spread in stars predicted
but not c
Ballestero

But: turbul
Zweibel 02

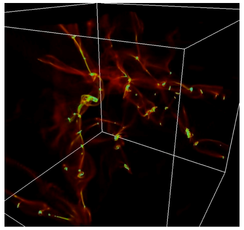
(2) Bounda
subcriti

Globally subcritical molecular clouds would require unrealistically high external magnetic fields for confinement.

for a **finite** 2D sheet:



(2) Fragmentation Mechanisms: Supersonic Turbulence



Mechanisms:

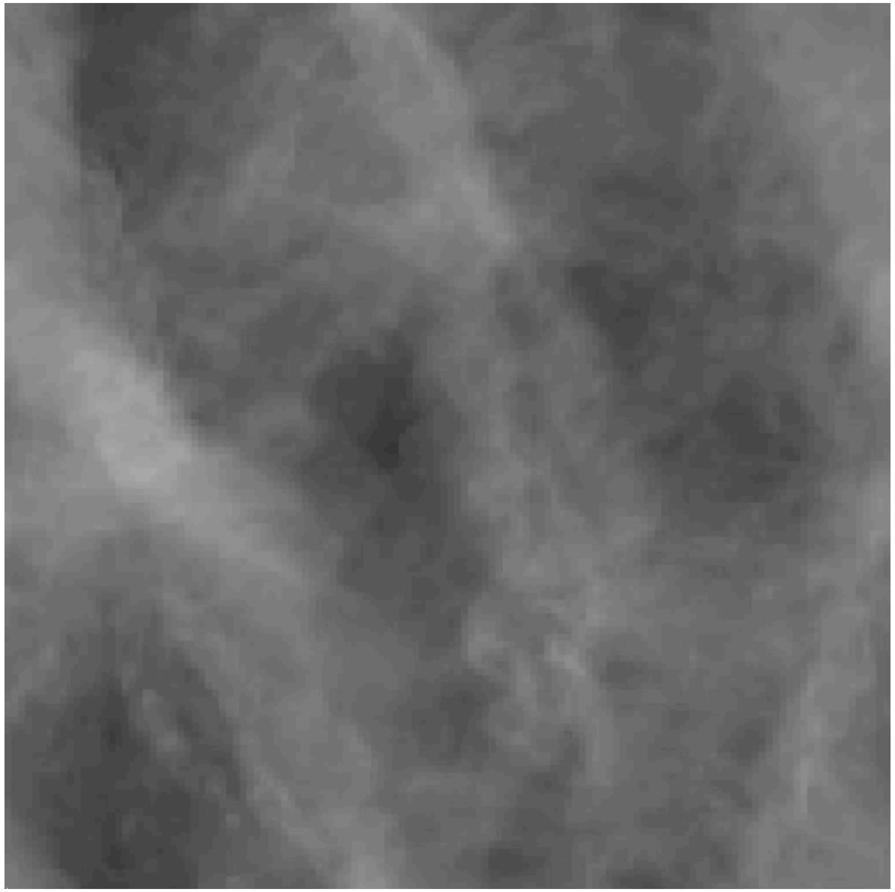
(1) Sweep-up of gas into filaments

(2) Promotion of local collapse due to compression (lower Jeans length)

Padoan et al. 99, Klessen et al. 01, Padoan & Nordlund 02

$$\lambda_J \equiv \sqrt{\frac{\pi}{G\rho}} c_s \qquad \rho_s = \rho_0 \mathcal{M}^2 \qquad \lambda_J \propto \mathcal{M}^{-1}$$

Movie by P. Padoan



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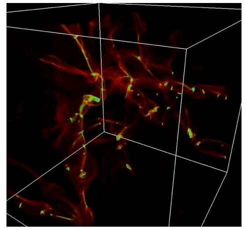

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Pa

λ_J

Definitions:

Supersonic turbulence:
Supersonic (shock-producing) (random?) motions of gas.
In models usually driven to keep Mach numbers high.

Supersonic turbulence (hydro & MHD) decays within
a dynamical (crossing) time.
Mac Low et al 98, Padoan et al. 98, Stone et al. 98

Motiv

(1) Br
Fa

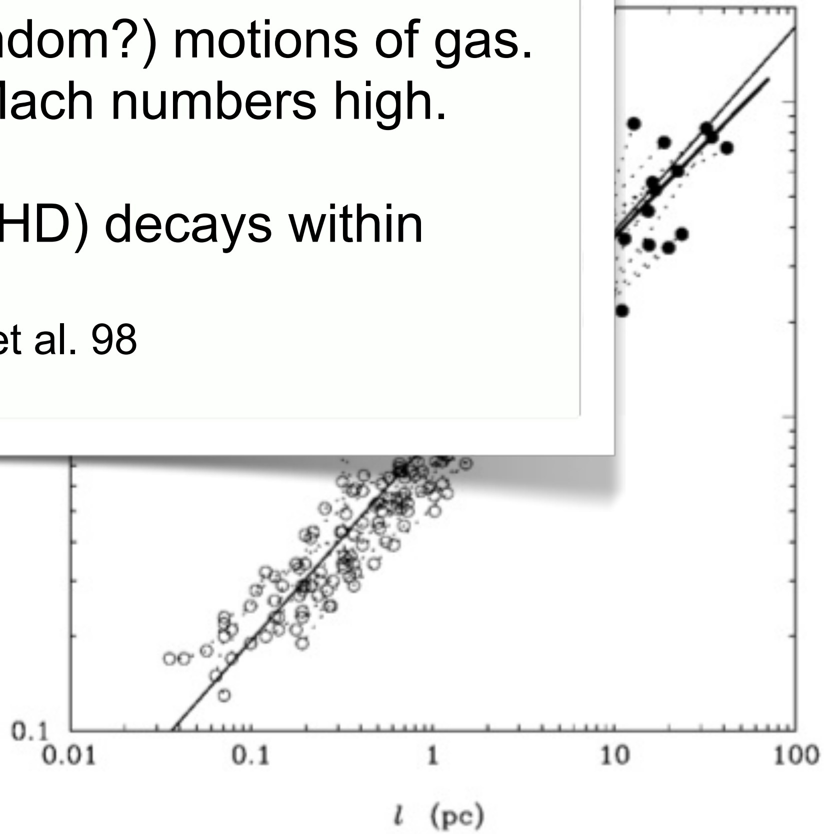
(2) "T
La

Predi

(1) Rapid core formation.
Klessen et al. 00, Bate et al. 02, 03

(2) Core mass functions (?)
Klessen 00, Jappsen et al. 05

(3) Hydrostatic cores in disguise.
Ballesteros-Paredes et al. 03



(2) Supersonic Turbulence:

Strengths:

(1) Rapid fragmentation
Padoan et al. 99, Klessen et al. 00, Bate & Bonnell 02, 03

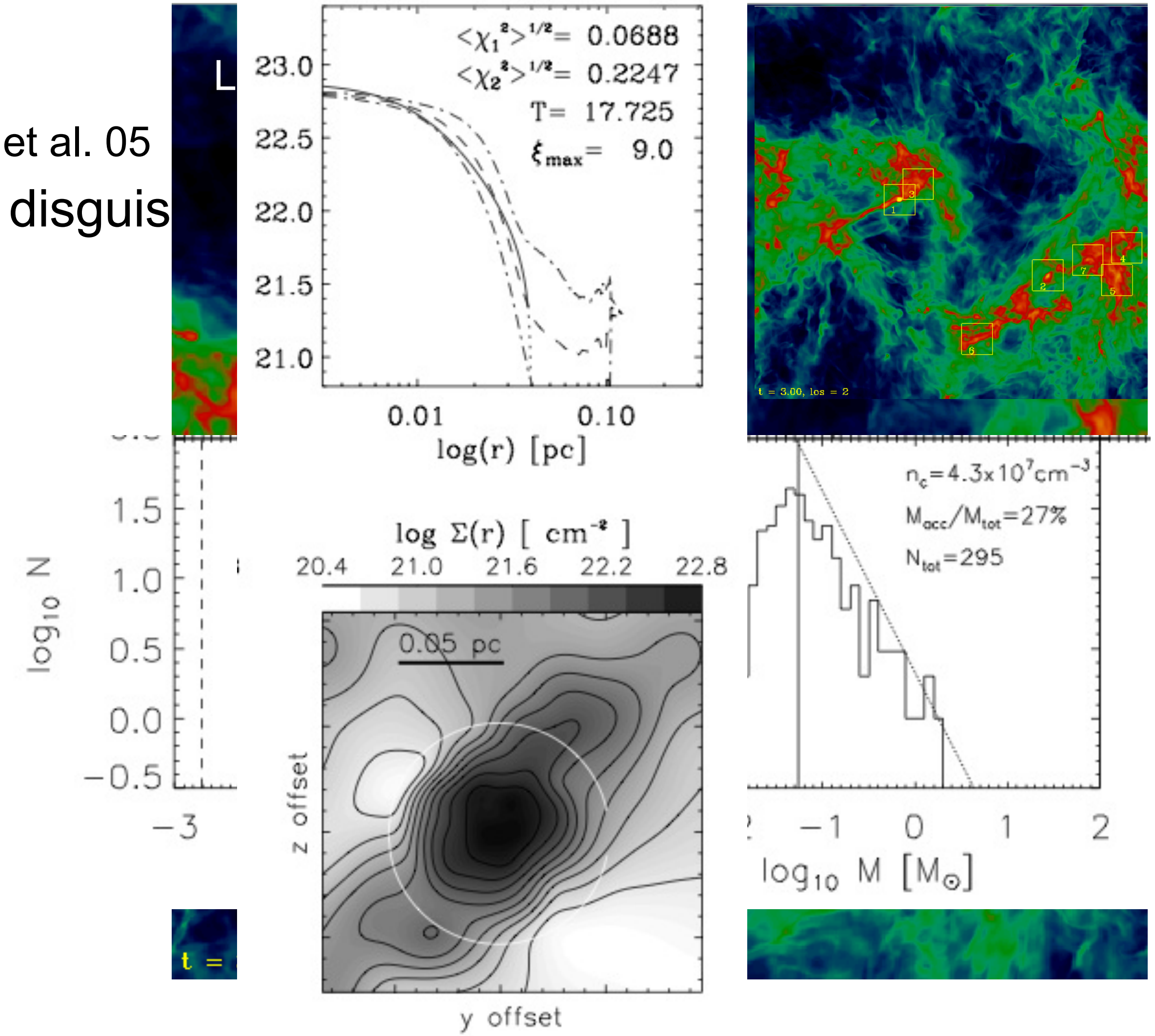
(2) Filamentary structure

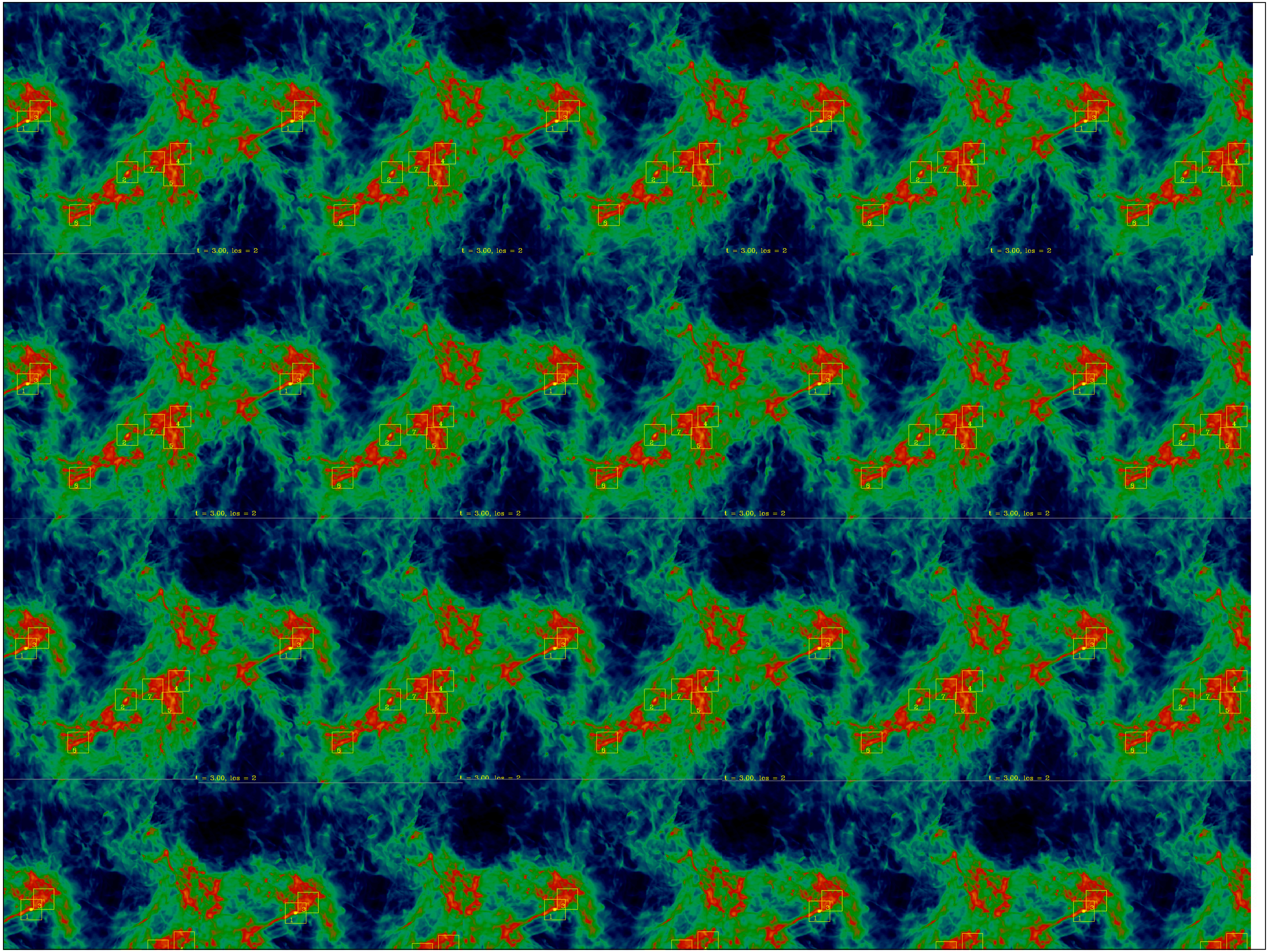
(3) Reproduction of CMF?
Klessen & Burkert 02, Jappsen et al. 05

(4) Cores are “hydrostatic in disguis

Ballesteros-Paredes et al. 03

Weaknesses:

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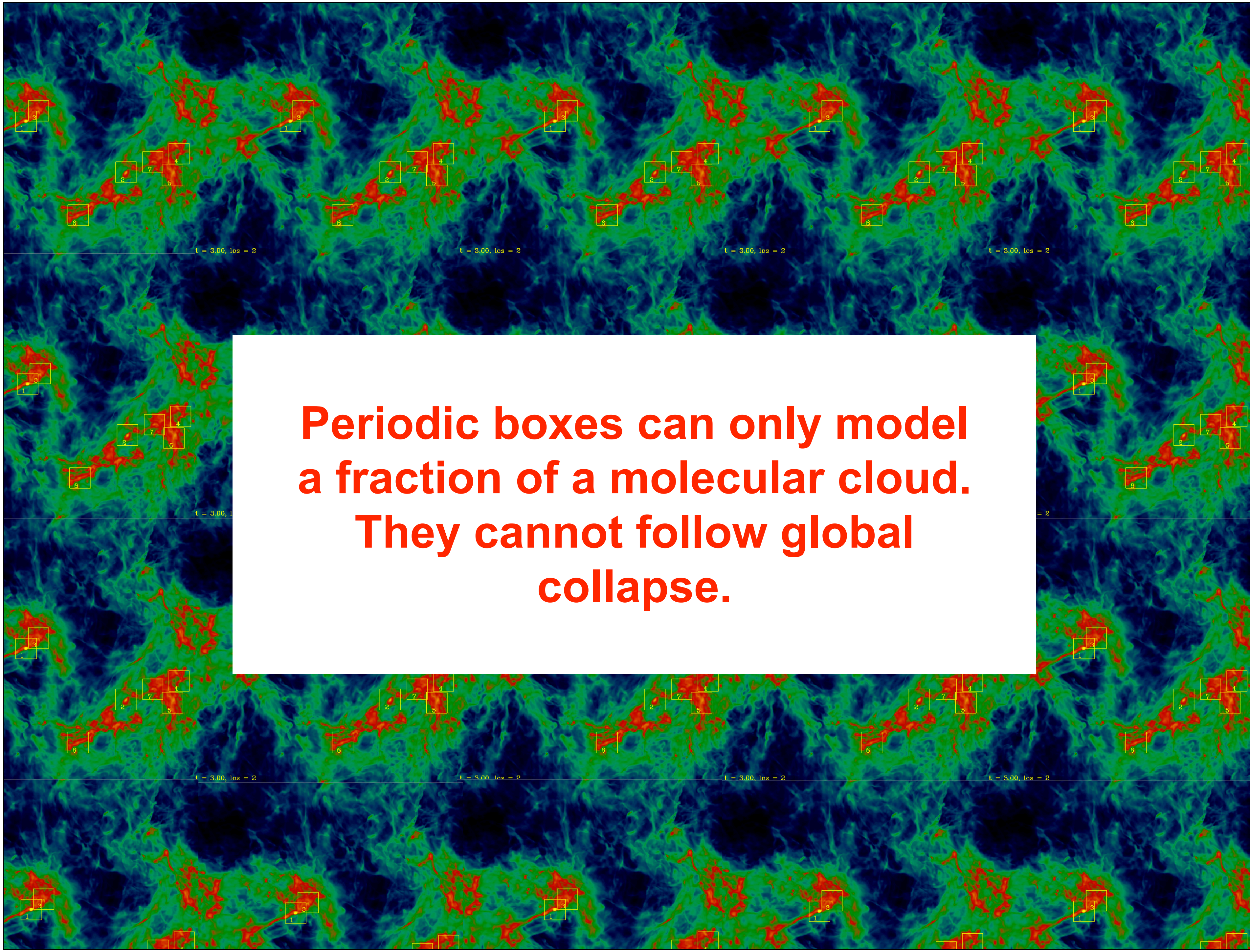
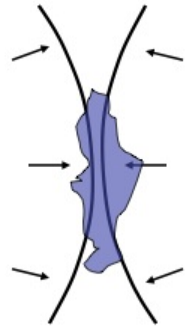


Periodic boxes can only model a fraction of a molecular cloud. They cannot follow global global collapse.

(3) Fragmentation Mechanisms: Cloud Formation & Fragmentation

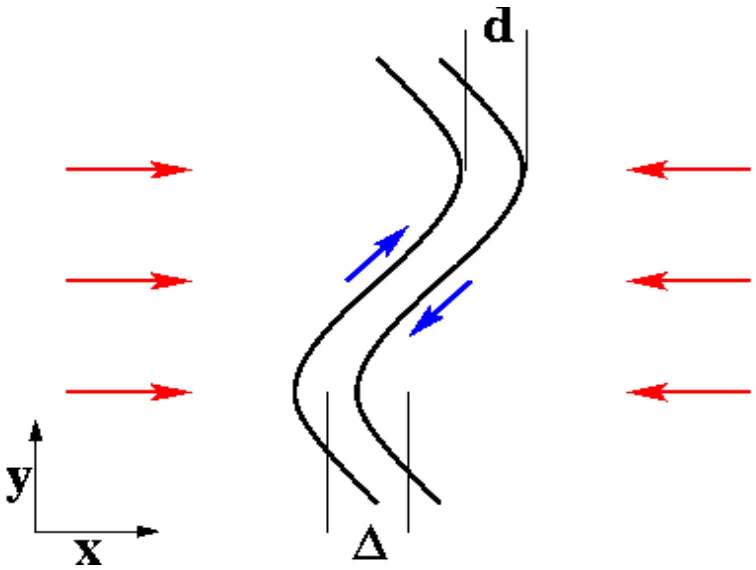


Mechanisms:

(1) Shocks & shearflows: turbulence, fragmentation
Vishniac 94, Hueckstaedt 03, FH et al. 05, 06

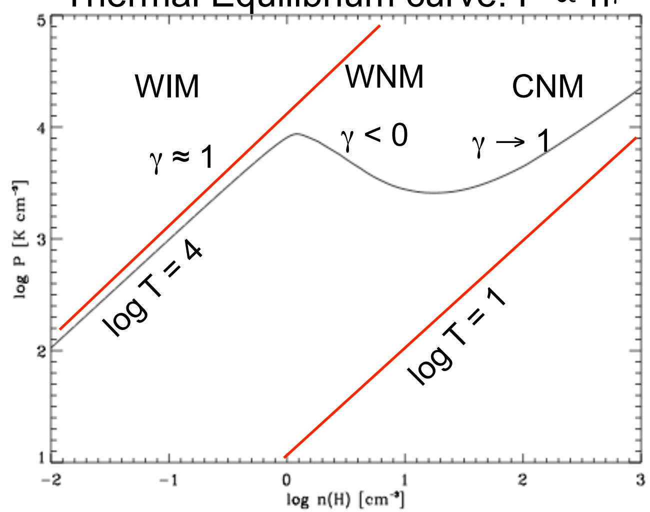
(2) radiative losses: highly compressible fragmentation
Field 65, Koyama & Inutsuka 00, 02, 04

(3) Gravity: fragmentation, collapse
Field et al. 08, 10



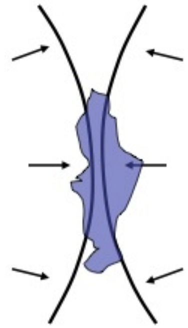
Fragmentation of shock-bounded slab

$$\mathcal{L}(n,T) \equiv n\Gamma - n^2\Lambda(T) \quad [\mathrm{erg\ s^{-1}\ cm^{-3}}]$$



Fragmentation due to thermal instability

(3) Fragmentation Mechanisms: Cloud Formation & Fragmentation



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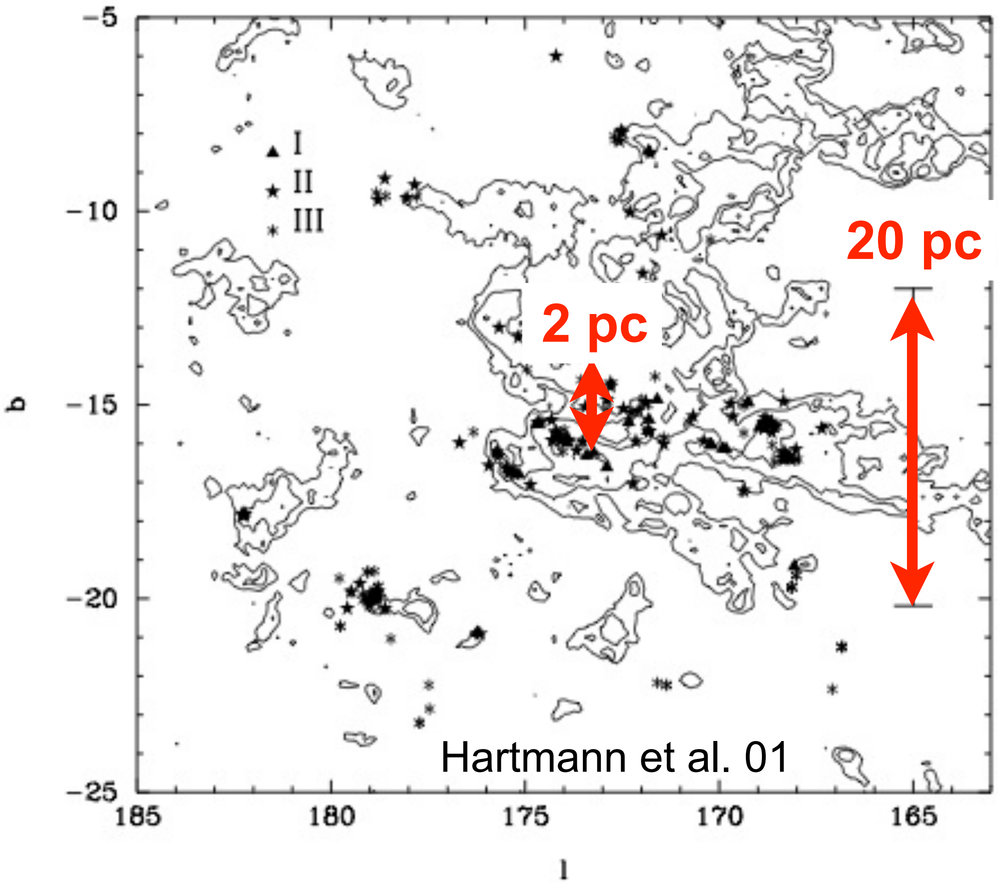
Motivation:

(1) Crossing-time problem
Elmegreen 00, Hartmann et al. 01



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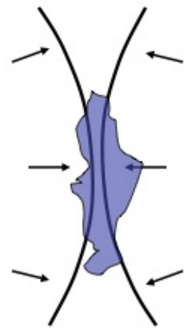

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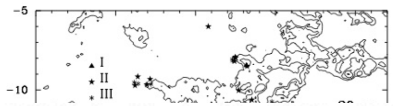

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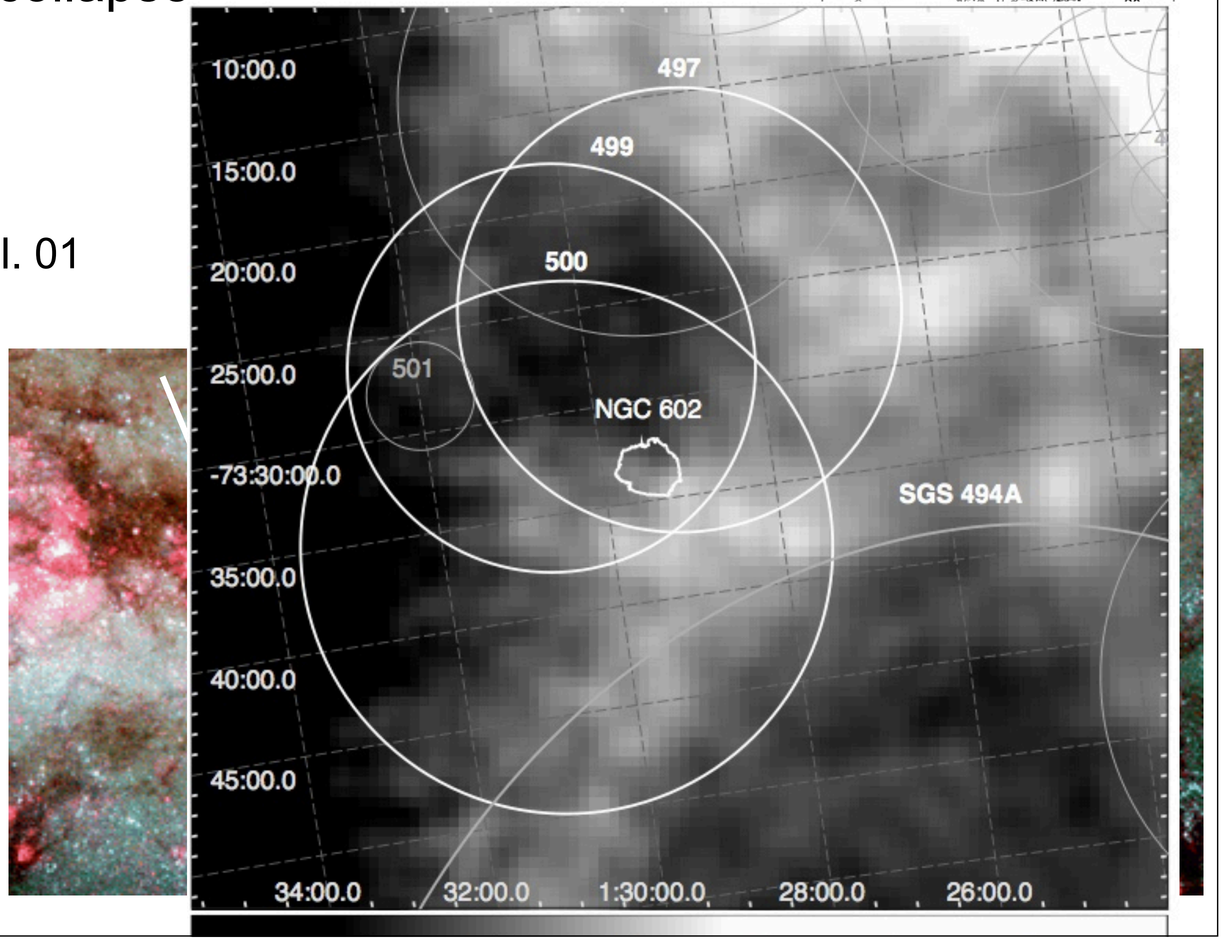
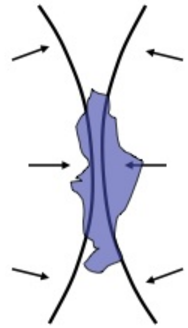
Elmegreen 00, Hartmann et al. 01

(2) Large-scale gas flows
Elmegreen 07, Nigra et al. 08



(3) Fragmentation Mechanisms: Cloud Formation & Fragmentation



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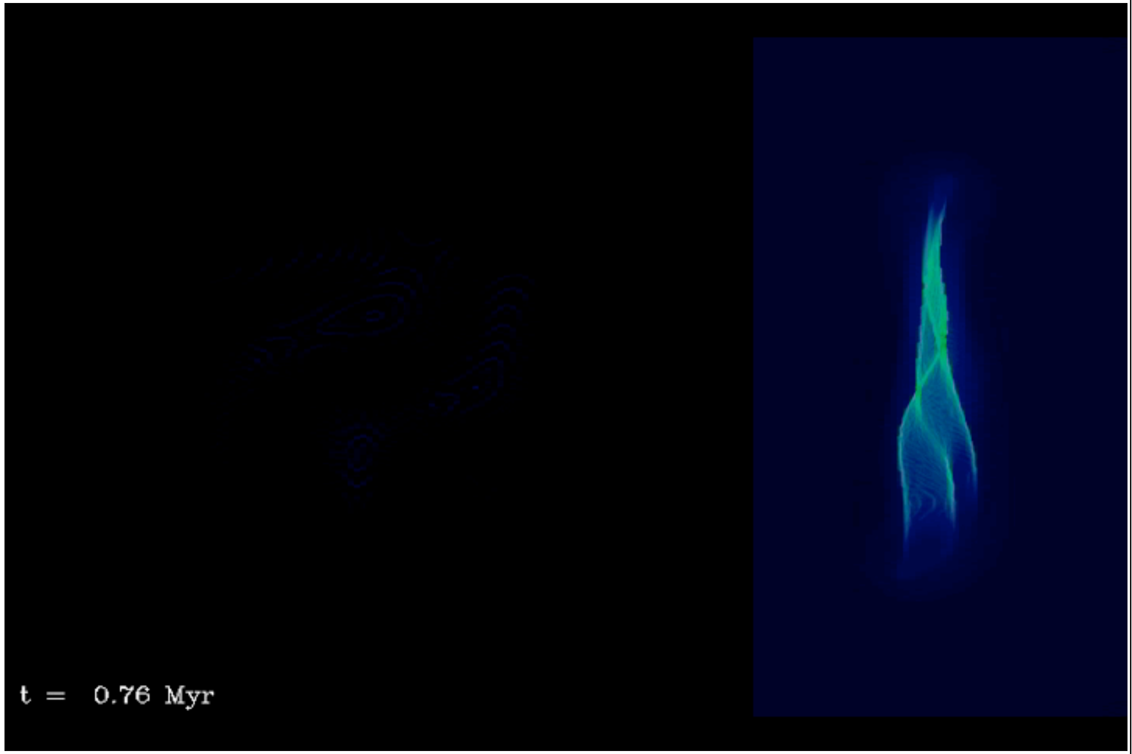
Elmegreen 07, Nigra et al. 08

Predictions:

(1) Turbulence generation
Audit & Hennebelle 05, FH 05

(2) Rapid fragmentation and core formation.
Vazquez-Semadeni et al. 07, FH et al. 08

(3) Small core-to-core dispersion
FH et al. 08, 09



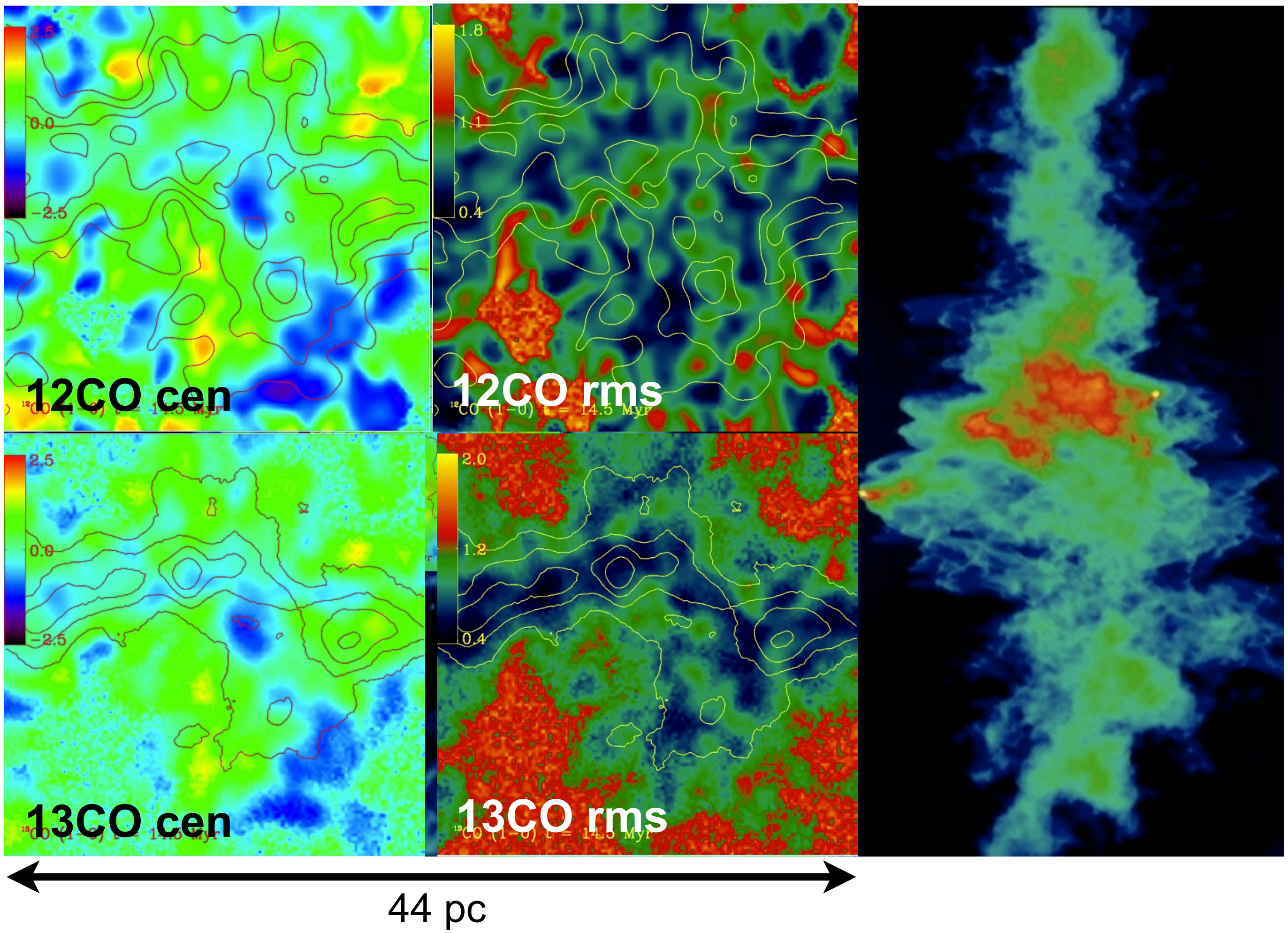
blue/**green** : thermal fragmentation;
red/**yellow** : local collapse;
filament : global collapse

(3) Flow-Driven Cloud Formation :

Strengths:

(1) Filamentary structure, including coherent velocity structure.

Burkert & Hartmann 04, Vazquez-Semadeni et al. 07, FH et al. 08,09



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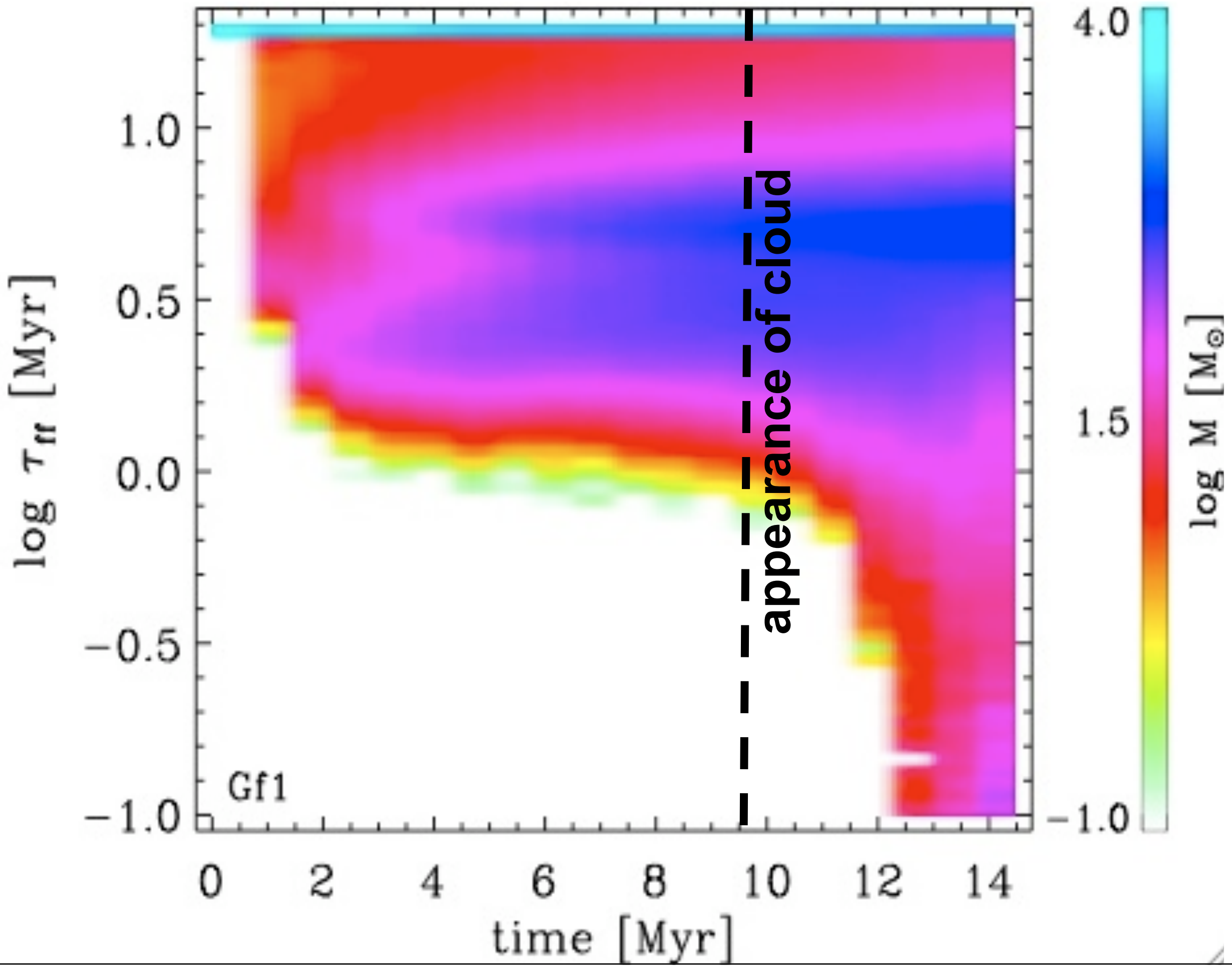
(2) Rapid fragmentation (and “star formation”).
FH & Hartmann 08



Densest regions form stars, while the envelope (“blue”) is not participating. The envelope gas need not be spatially coherent.

see also Vazquez-Semadeni et al. 09, 10, Banerjee et al. 09

$$\tau_{ff} = \sqrt{\frac{3\pi}{32G\rho}}$$

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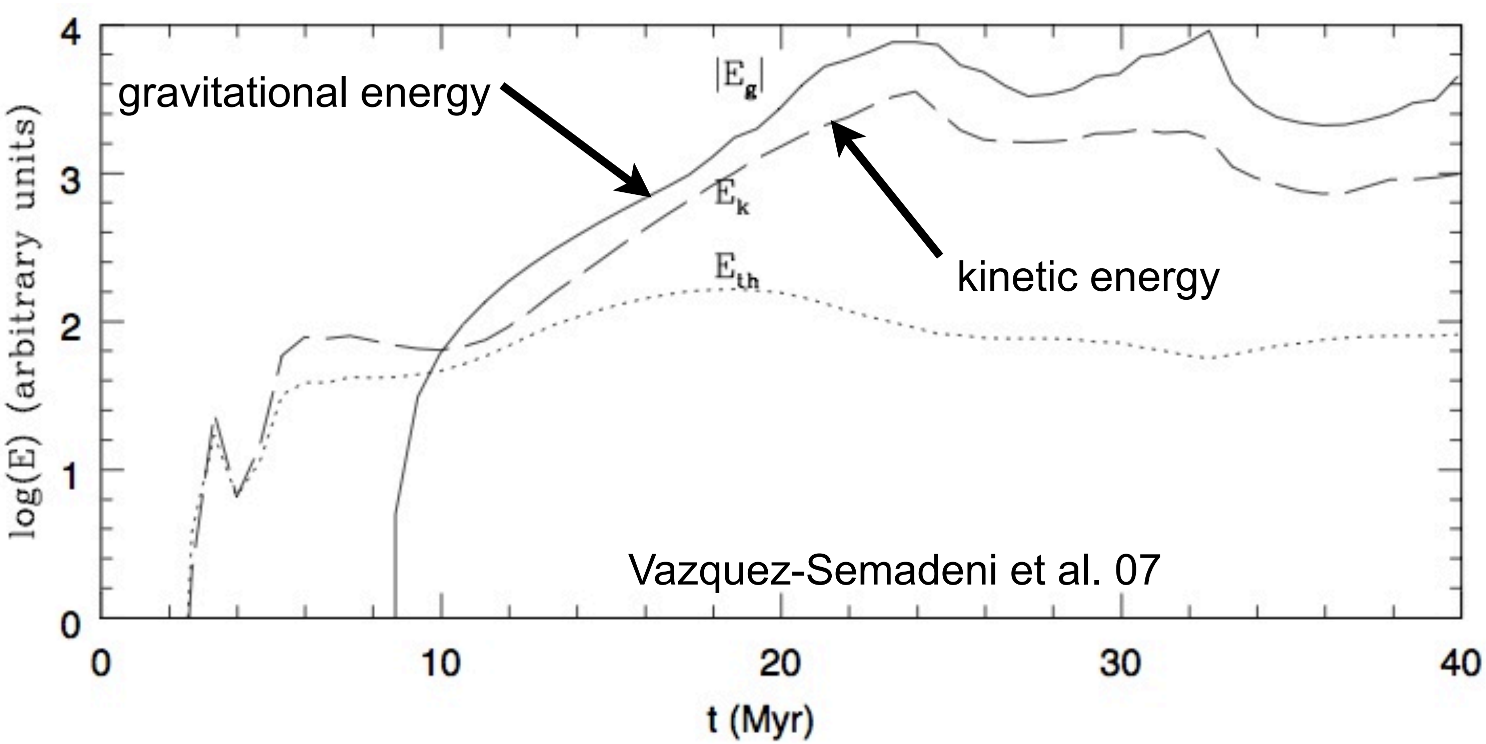
(3) Turbulence as a consequence of formation and collapse.
Audit & Hennebelle 05, VS et al. 07, FH et al. 08 etc



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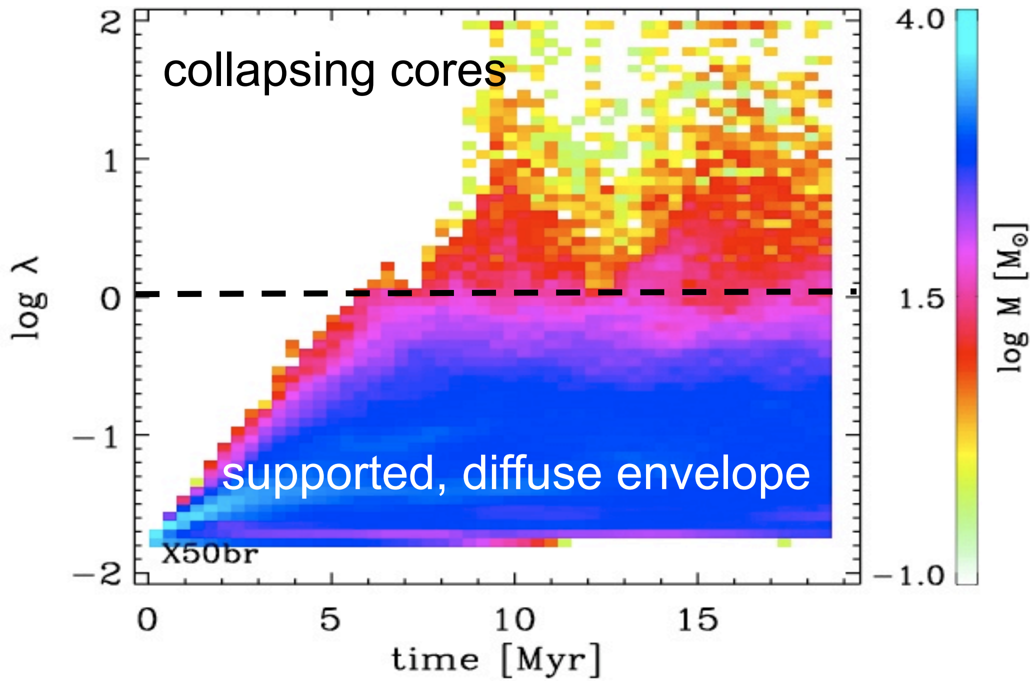
(4) Support of diffuse envelope by magnetic field.
FH et al. 10, see Elmegreen 07, Heyer et al. 08



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Audit & Hennebelle 05, VS et al. 07, FH et al. 08 etc

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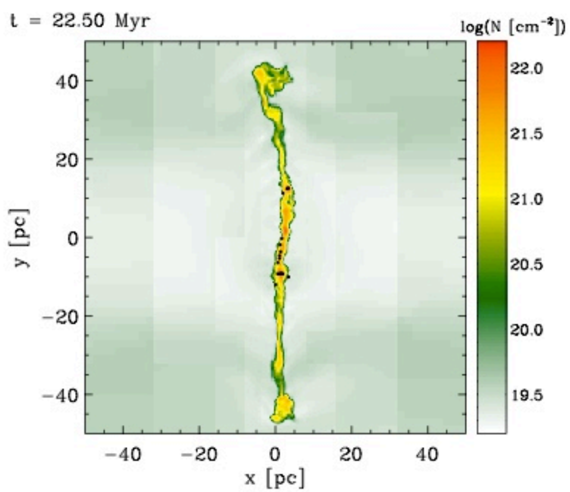
FH et al. 10, see Elmegreen 07, Heyer et al. 08

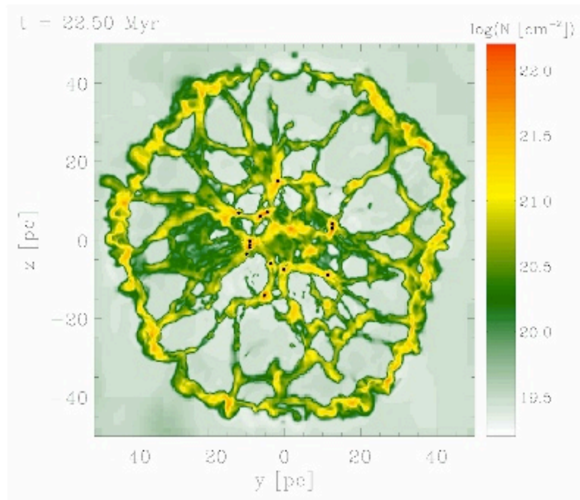
Weaknesses:

(1) Inclusion of reasonable magnetic fields leads to “flat” clouds.
Banerjee et al. 09, FH et al. 09

(2) Flows only inferred from idealized in models.

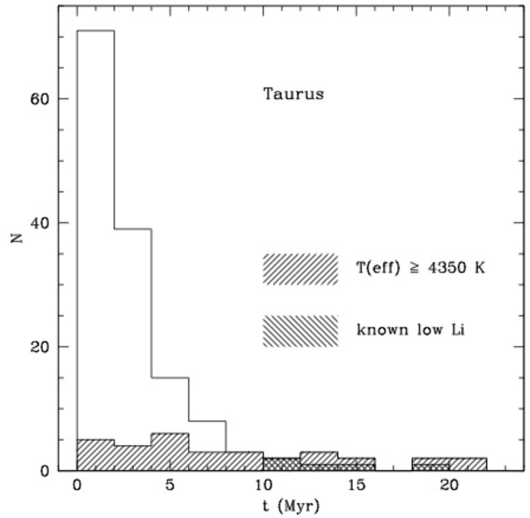
(3) Still need a dispersal me
keep SFE low.
VS et al. 07,10; FH et al. 08



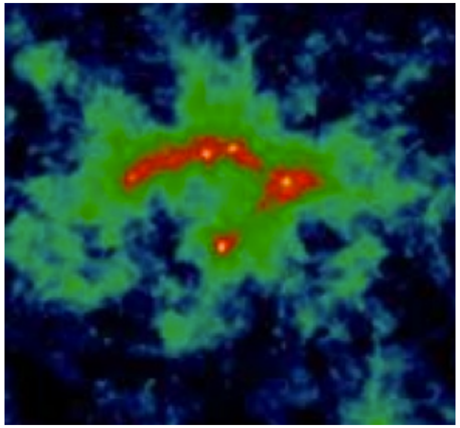


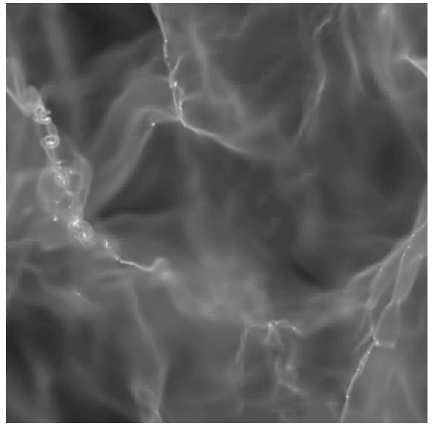
Summary: Morphology

(1) Core formation is rapid
(stellar age spreads, most clouds form stars).
⇒ *No cloud support, no equilibrium of cloud.*

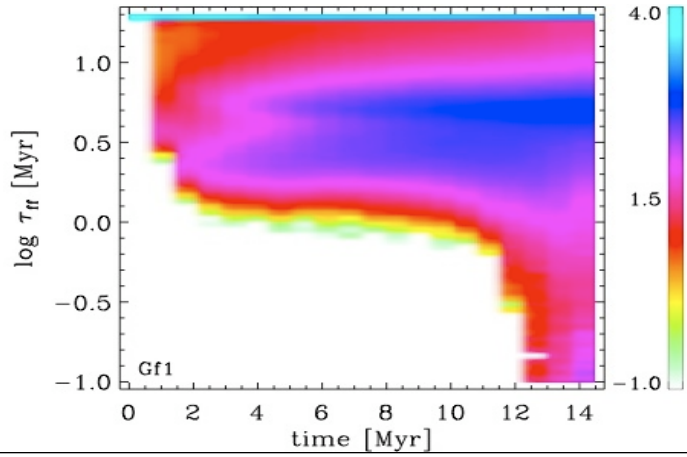


(2) Core formation occurs in filaments.
⇒ global gravity and/or
⇒ (supersonic) turbulence.



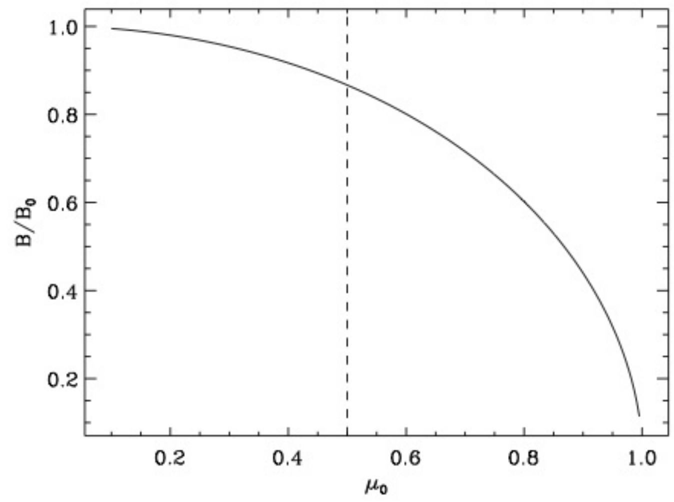


(3) Most of the mass is in diffuse "envelope"
⇒ Low core formation efficiency.
⇒ Global free-fall time is meaningless.

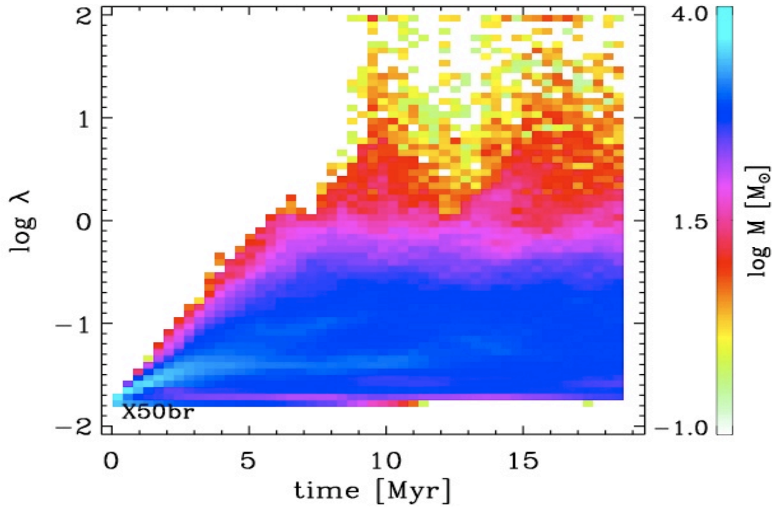


Summary: Magnetic Fields

(1) Molecular clouds cannot be subcritical globally, unless they are infinite.



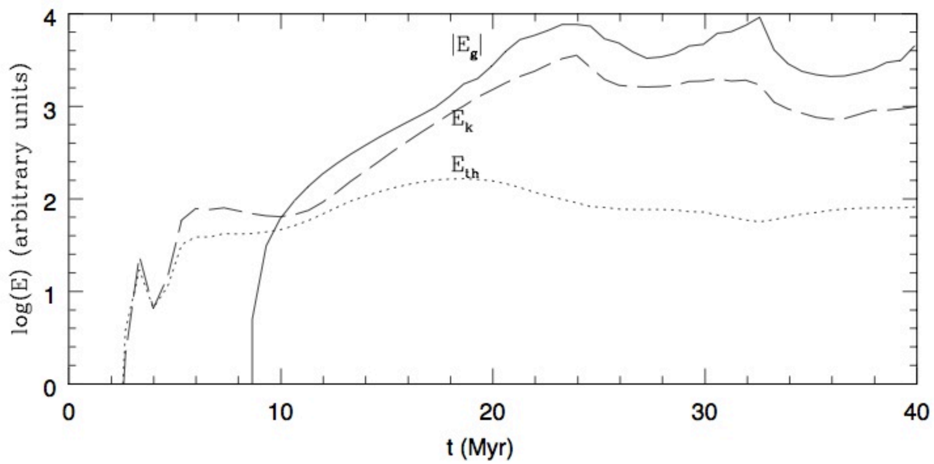
(2) Envelopes are most likely subcritical, thus do not contribute to SF.
Heyer et al. 08



(3) Ion-neutral drift happens, and is accelerated by turbulence. This leads to the necessary rapid flux loss during the assembly of cloud.
FH et al. 04, Li & Nakamura 04, Inoue et al. 06, 08

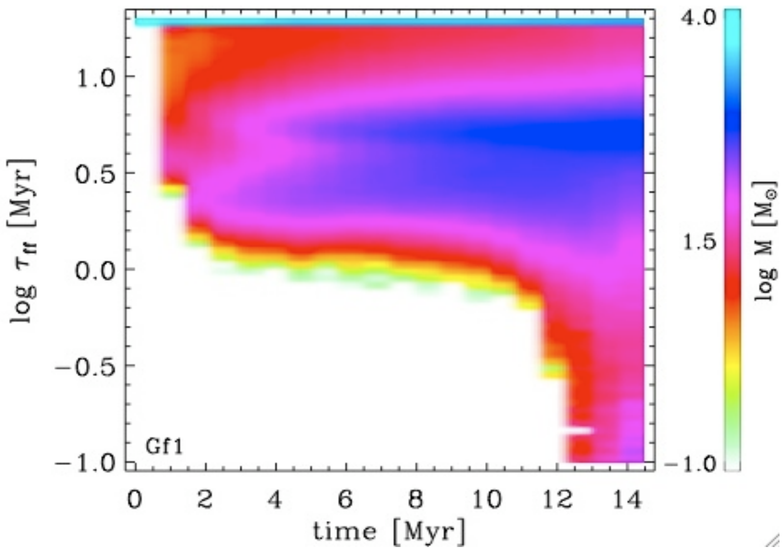
Summary: Flow Fragmentation & Turbulence

(1) Turbulence in molecular clouds is first a consequence of cloud assembly and gravit. collapse.



(2) Local core formation seeded by fragmentation due to thermal & dynamical instabilities during cloud formation.

Warmer, diffuse and subcritical envelope does not participate in SF.
Avoidance of Zuckerman-Evans problem.



(3) Subsonic cores and subsonic infall can both be reproduced by magnetized models and cloud formation models.

END

Summary: Turbulence

(1) Turbulence is a consequence of the cloud formation process and of global collapse.
Supersonic turbulence cannot support a molecular cloud.
(2) Turbulence leads to acceleration of ion-neutral drift.
(3) Turbulence may not be supersonic hydrodynamically.

The Points to be Made:

(1) Molecular clouds are *finite*.
And gravity is a long-range force.
Thus, global gravity rules.
Filaments are a natural consequence.

(2) Molecular clouds are dynamic (= not in equilibrium).
They are collapsing and accreting mass (see Pipe/Ophiuchus).

(3) “Turbulence” in molecular clouds is driven by global gravity.
Turbulent support does not exist.

(4) Magnetic fields support diffuse envelope, but seem irrelevant in high-density filaments.

---

(5) The SFE is set by rapid fragmentation during the cloud’s formation (thermal/dynamical/gravitational).
The diffuse cloud “envelope” is not contributing to the SF budget (magnetic field, rotation).
Need for an exit strategy (feedback, dissociation, tidal disruption)?

Turbulence-Controlled Star Formation:

Remedies:

(1) decaying turbulence

(2) finite clouds/cylinders (Bonnell, Bate, but then issues

Strengths:

(1) Rapid fragmentation

Padoan et al. 99, Klessen et al. 00, Bate & Bonnell 02, 03

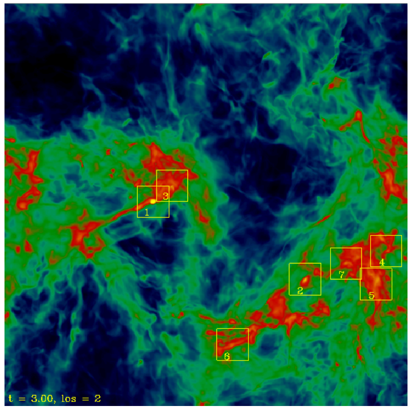
(2) Filamentary structure

(3) Reproduction of CMF?

Klessen & Burkert 02, Jappsen et al. 05

(4) Cores are “hydrostatic in disguise”

Ballesteros-Paredes et al. 03



Weaknesses:

(1) Small core-to-core dispersions only in some models, depending on boundary conditions.

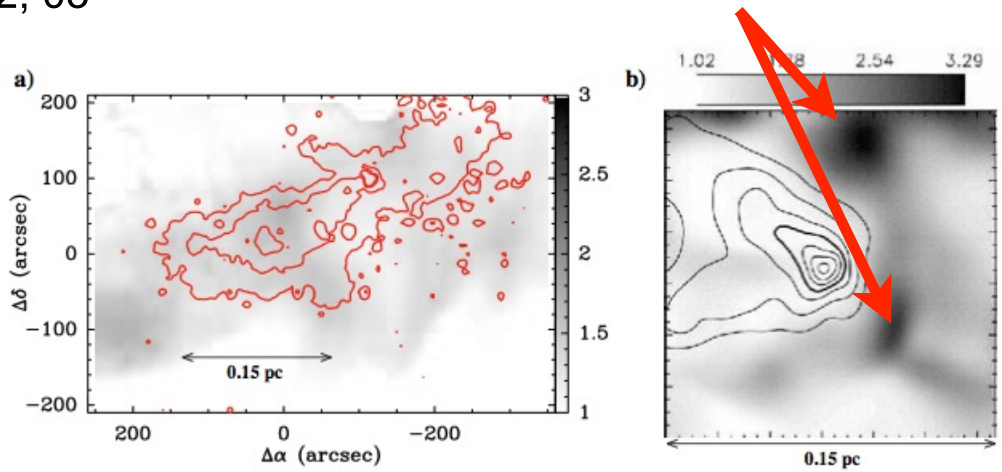
Offner et al. 08 vs e.g. Bate & Bonnell 02, 03

(2) Velocity structure around cores

Andre et al. 08

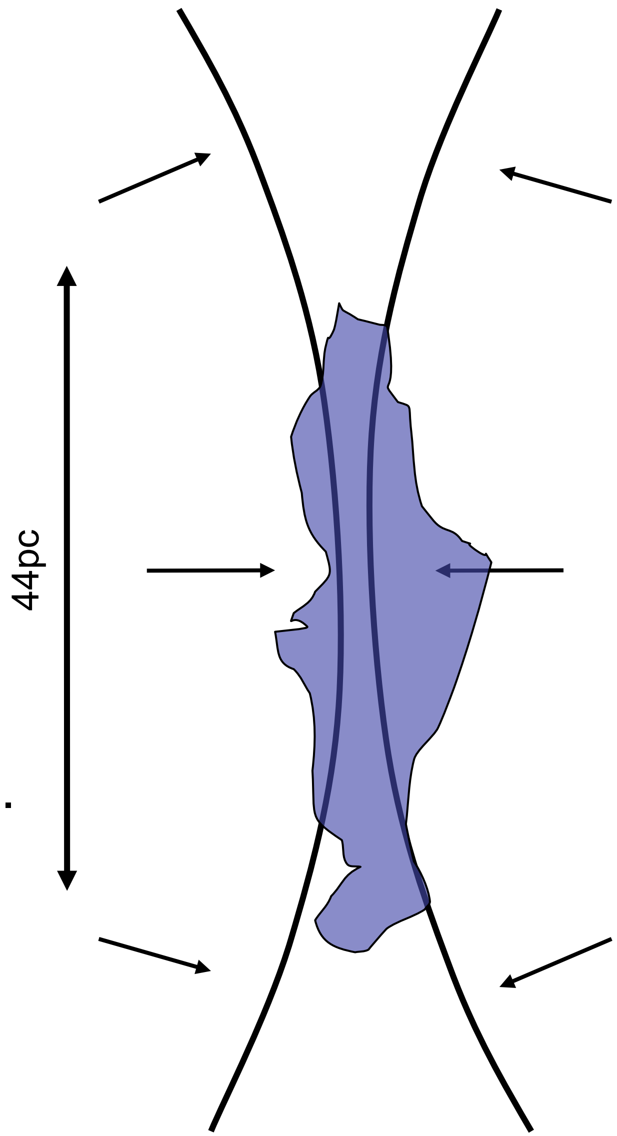
(3) Periodic boxes do not allow for g

(4) meaning of “driven turbulence” u



A Numerical Experiment of Cloud Formation:

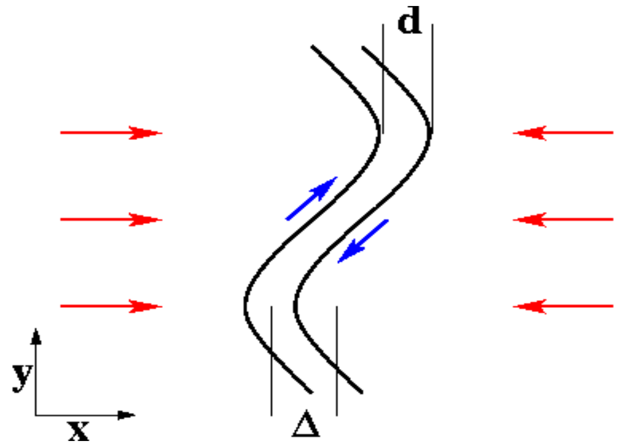
Two uniform, identical flows
no assumption about turbulence
colliding head-on at interface
expanding shells, spiral arms
with large-scale geometric perturbation
mimicking unavoidable shear
in non-periodic domain.
allowing global gravitational modes
Burkert & Hartmann 04, Li 01



Heating and cooling to model WNM → CNM.
No stellar feedback.
Hydro and MHD models.
Fixed-grid simulations.

Methods: Proteus FH et al. 04, 07, 08
Athena Stone et al. 08

Fluid Dynamics of Cloud Formation

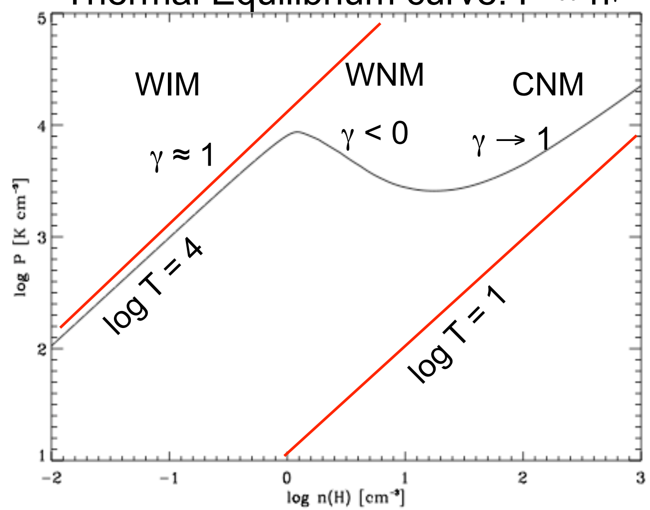


Large-scale flows assembling gas:

- spiral arms
- gravitational instability
- expanding/colliding shells
- galaxy mergers

$$\mathcal{L}(n,T) \equiv n\Gamma - n^2\Lambda(T) \quad [\mathrm{erg\ s^{-1}\ cm^{-3}}]$$

Thermal Equilibrium curve: $P \propto n^{\gamma}$



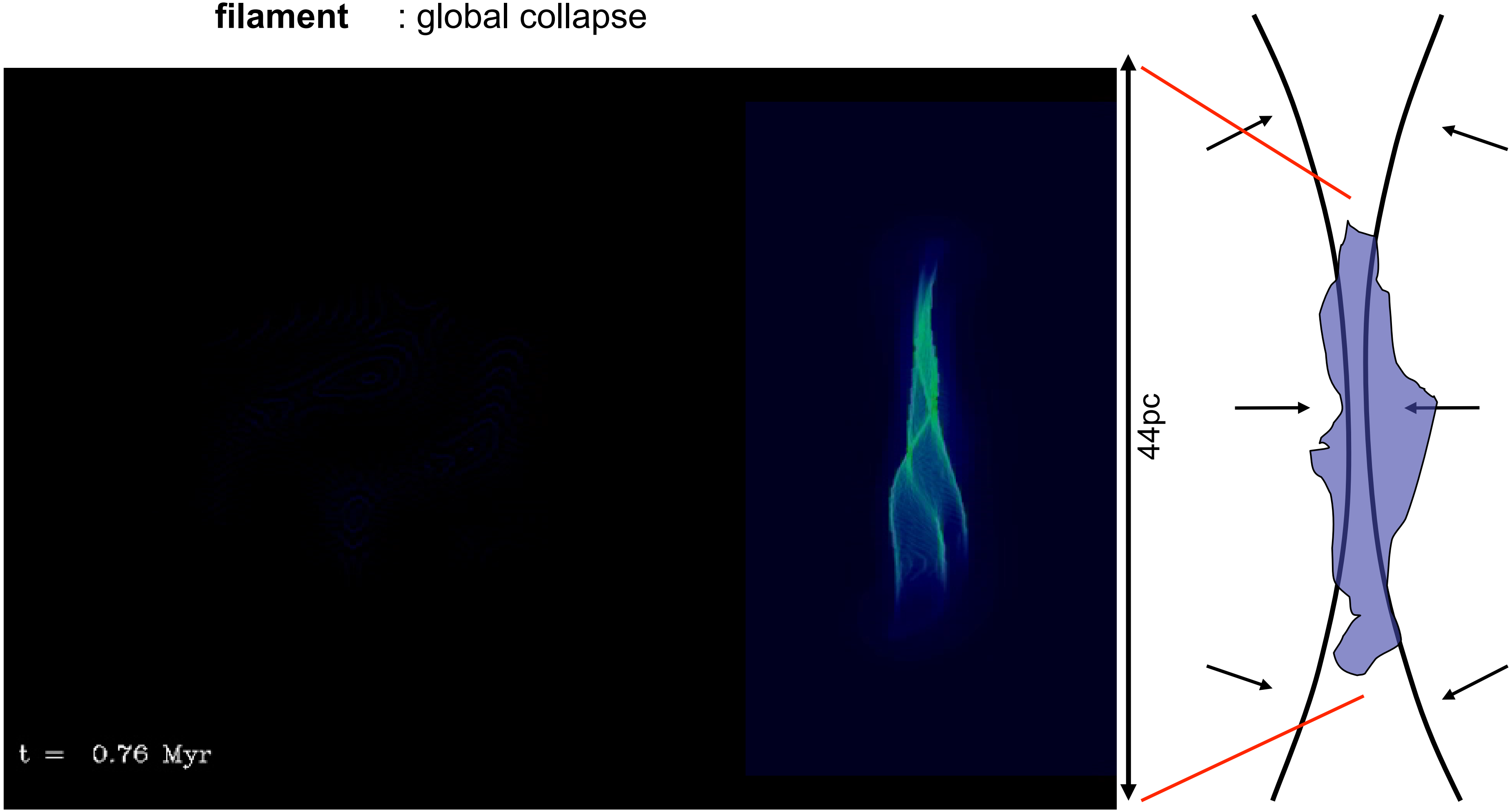
Processes & Agents:

- shocks & shear flows
  fragmentation, turbulence
- radiative losses/thermal instability
  fragmentation, strong compression
- gravity
  fragmentation, collapse
- magnetic fields
  we'll get them later

$$M_J \approx 5.0 \left(\frac{T}{10\ \mathrm{K}}\right)^2 \left(\frac{P}{10^4\ \mathrm{K\ cm^{-3}}}\right)^{-1/2} \mathrm{M}_{\odot}$$

Cooling, Gravity & Geometry

blue/**green** : thermal fragmentation;
red/**yellow** : local collapse;
filament : global collapse



3D at 256 x 512 x 512
$19 < \log N$ [cm^{-2}] < 23

$n = 3$ cm^{-3}
$v = 9$ km s^{-1}

FH et al. 08a

The “rapid” formation of molecular clouds and stars

Global gravity increases CO formation.

without self-gravity | with self-gravity

$$\langle N_H \rangle = 2 \times 7.9 \text{ km s}^{-1} \times 3 \text{ cm}^{-3} t$$
$$= 1.5 \times 10^{20} \text{ cm}^{-2} (t/\text{Myr}) \,,$$

but

N(filament) @ 10 Myr ~ $10^{22.5}$ cm^{-2}

22 pc

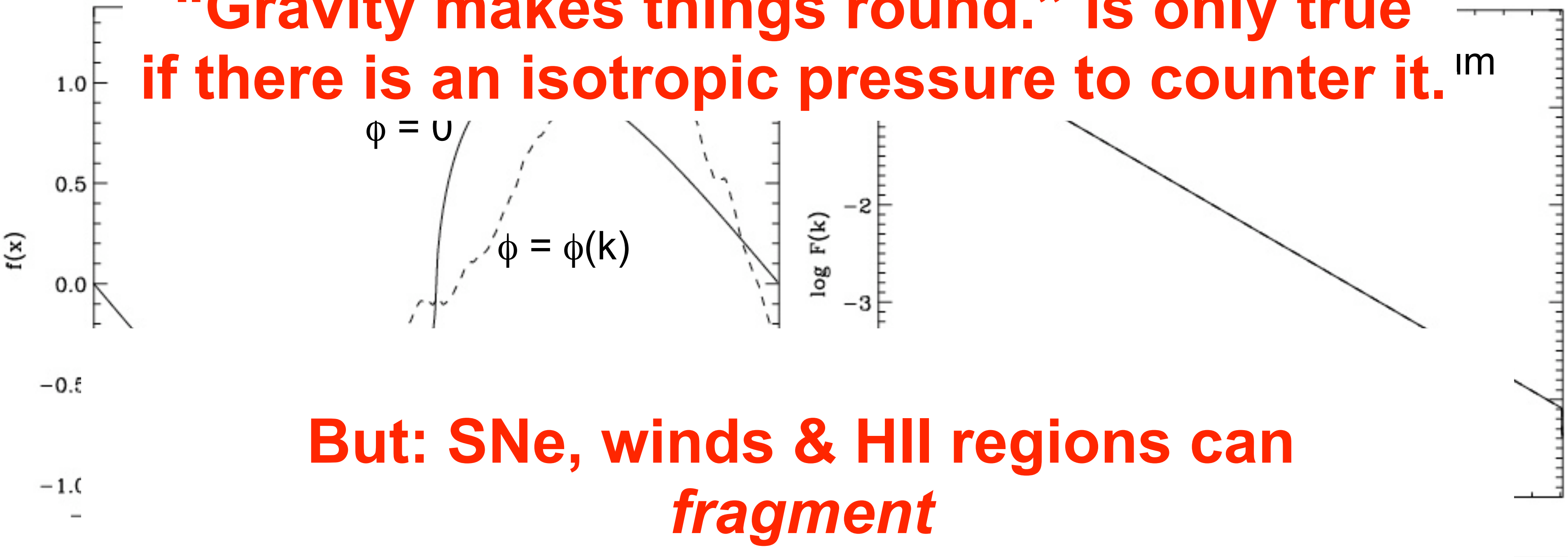
Hf1,

FH & Hartmann 08

contours: HI
color : CO

The Role of Turbulence:

Since turbulence is a **consequence**
of the cloud's formation and collapse,
it **can not** support the cloud.
The bulk of the energy is on the largest scales.
There is no scale-separation (no "micro-turbulence").



"Gravity makes things round." is only true
if there is an isotropic pressure to counter it.

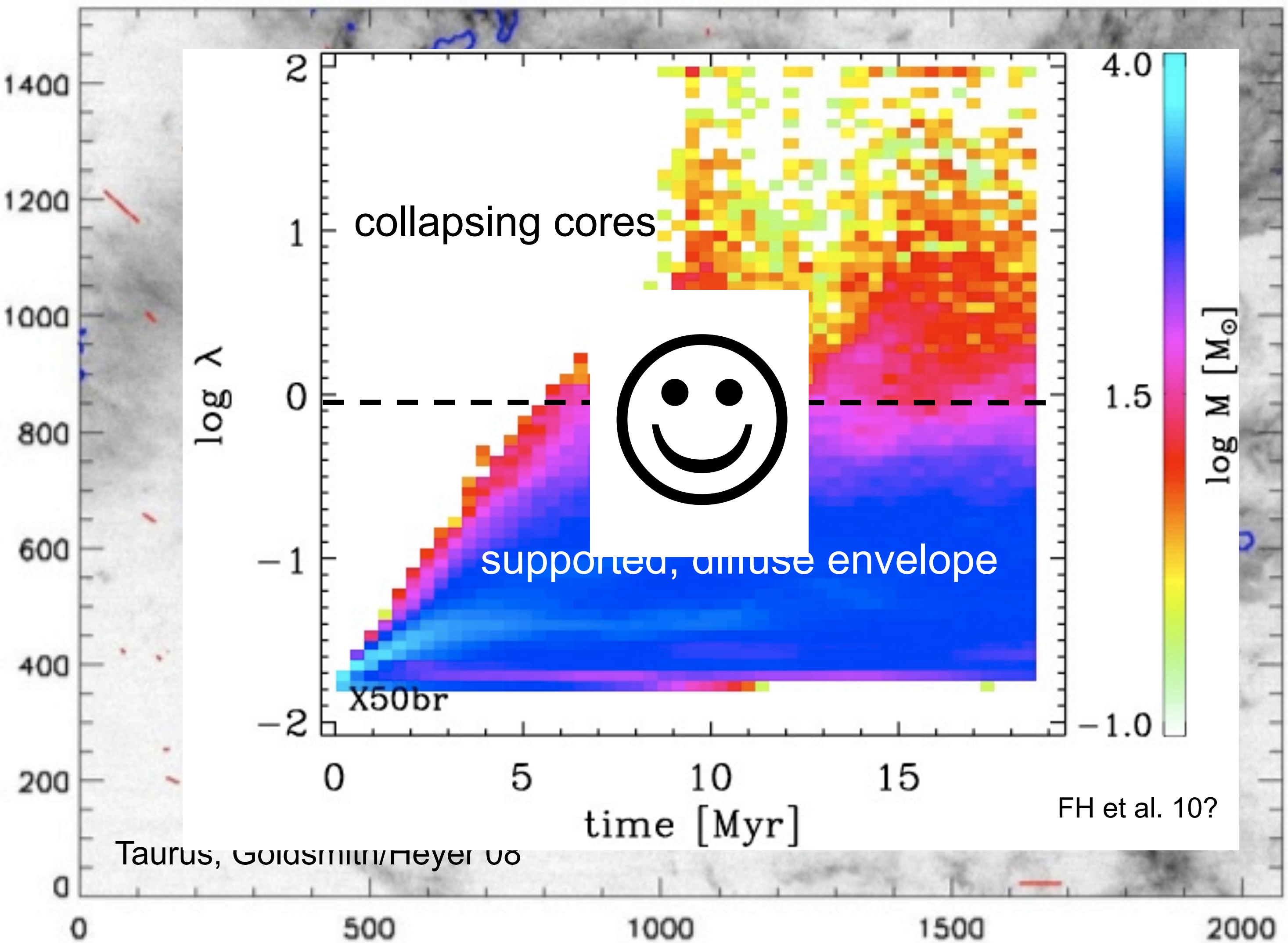
But: SNe, winds & HII regions can
fragment
the surrounding cloud.

("Turbulent fragmentation", PP et al., M-MML et al, RK et al, FH et al., VS et al. etcpp)

$$f(x) = \sum_{k=1} \left(\frac{}{k}\right) \sin(kx + \varphi(k))$$

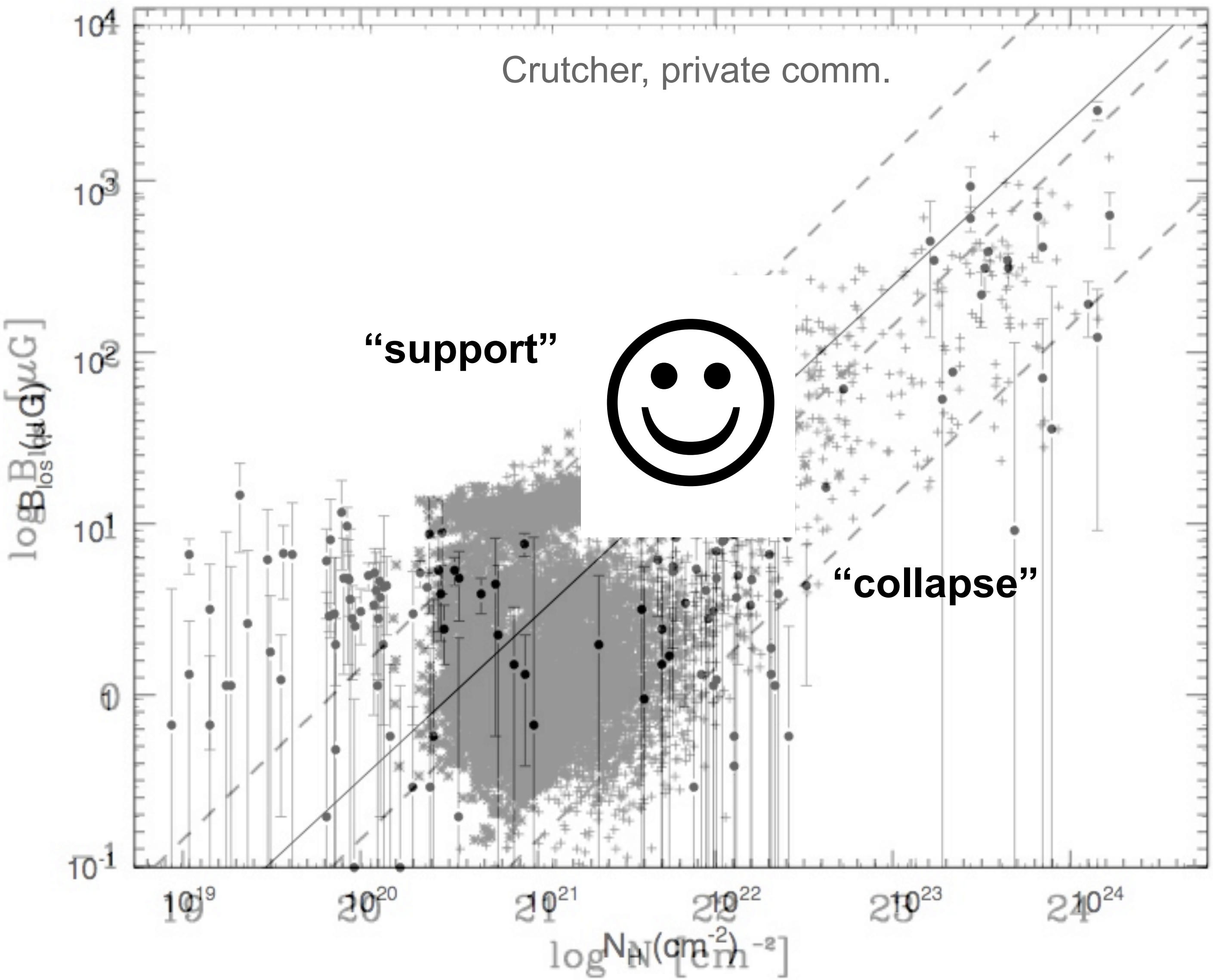
Magnetic Fields: Models

Collapse of dense regions, support of diffuse envelope.

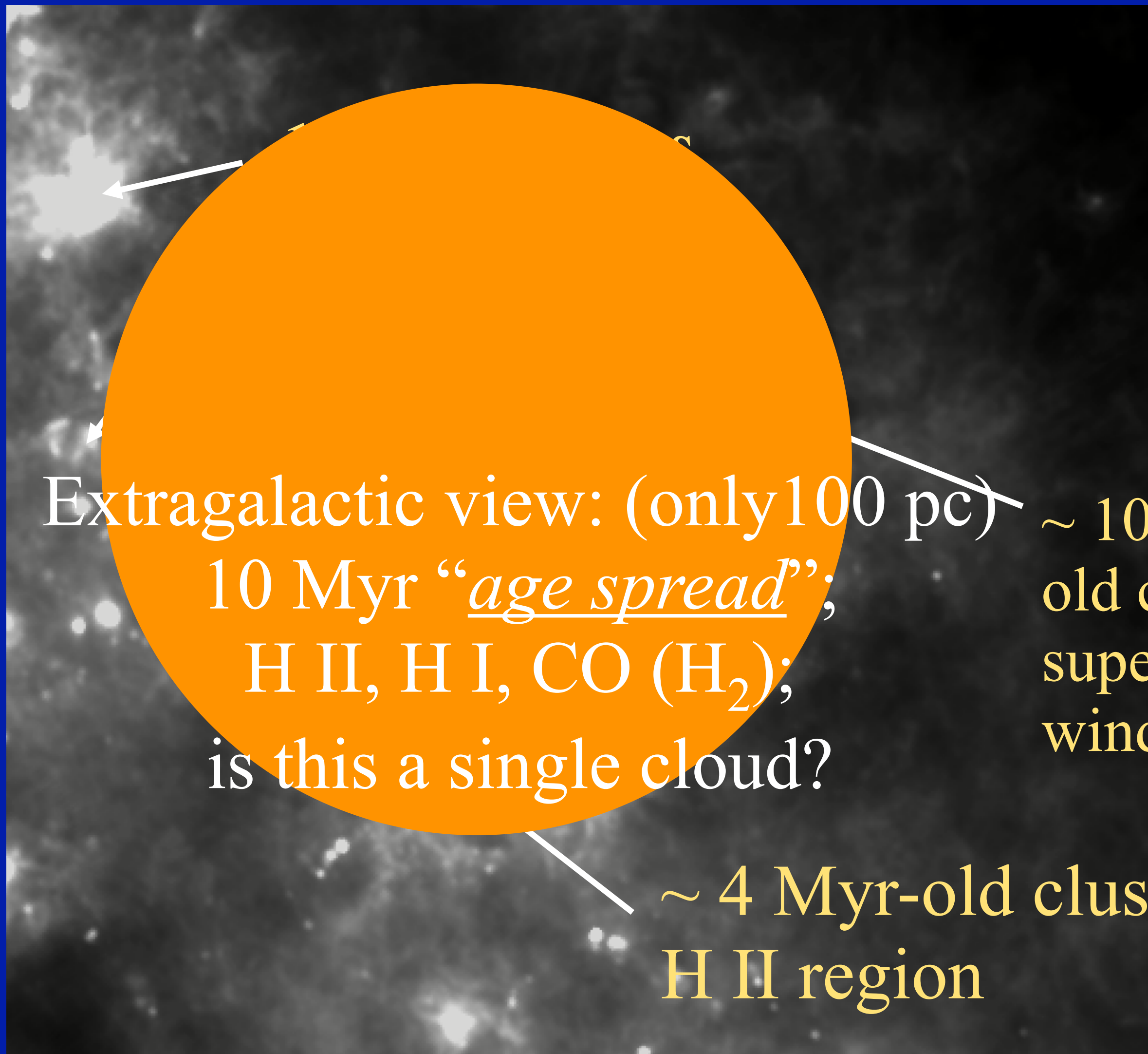


Magnetic Fields: Observations

Field-Density Relation (from HI and OH Zeeman measurements// ~500 model cores):



Cep OB2: supernova, H II region-driven bubbles



50 pc

100 µm IRAS
dust emission

The “unstable” ISM in the density-temperature plane

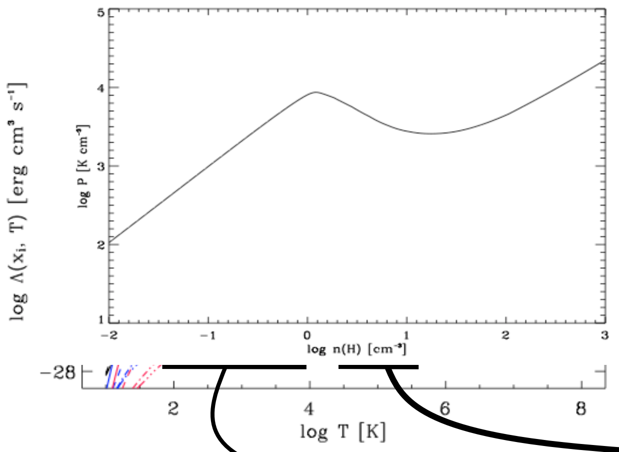
Thermal instability provides “shortcut” to sm… …lapse.
Since it is local, the condensation mode leads…

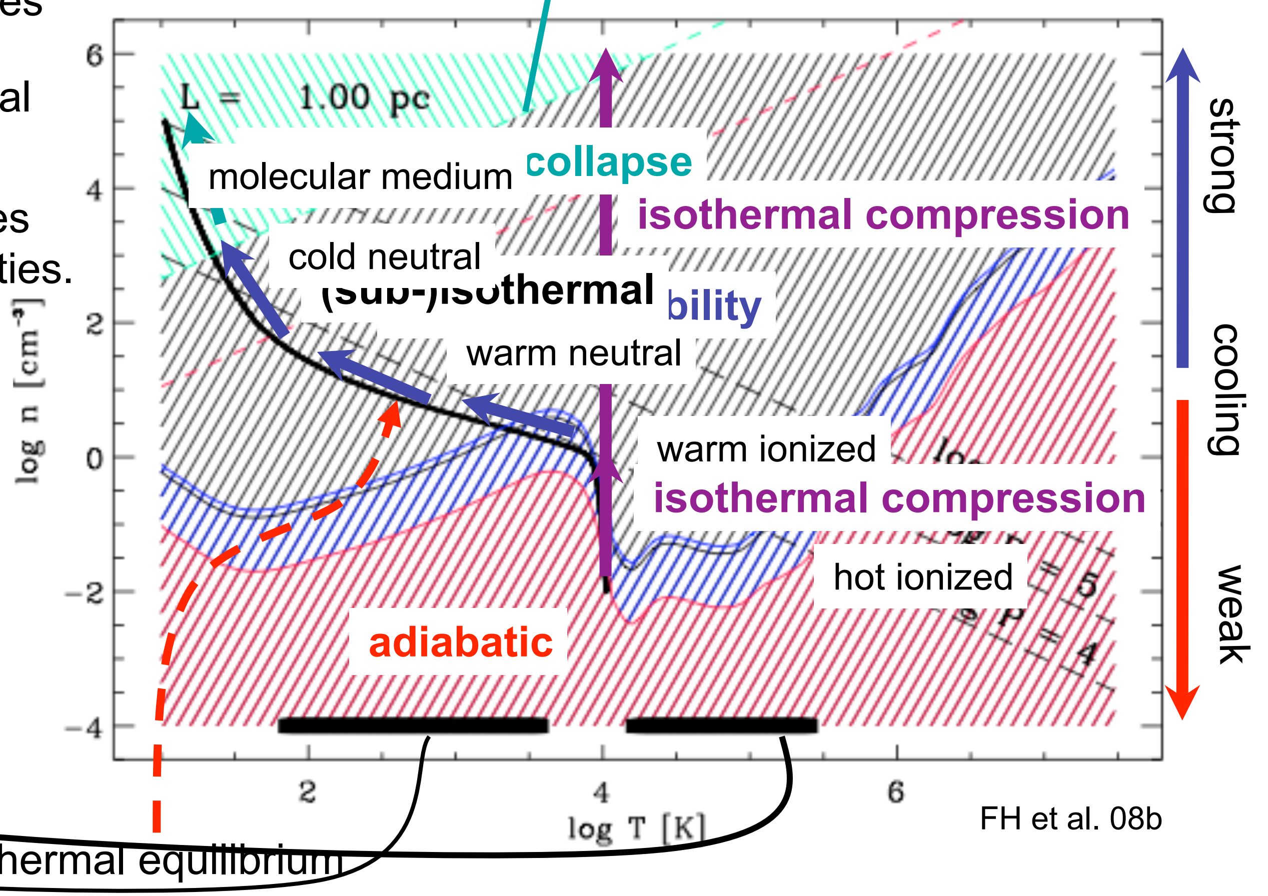
$$M_J = \frac{4}{3}\pi^{5/2}\left(\frac{k_B T}{\mu m_H G}\right)^{3/2}\rho_0^{-1/2}$$

red : dynamical instabilities
blue : thermal instability
black : dynamical/isothermal
green : gravity/isothermal

At fixed scale. For smaller scales all regimes shift to higher densities.

regimes of thermal instability





FH et al. 08b