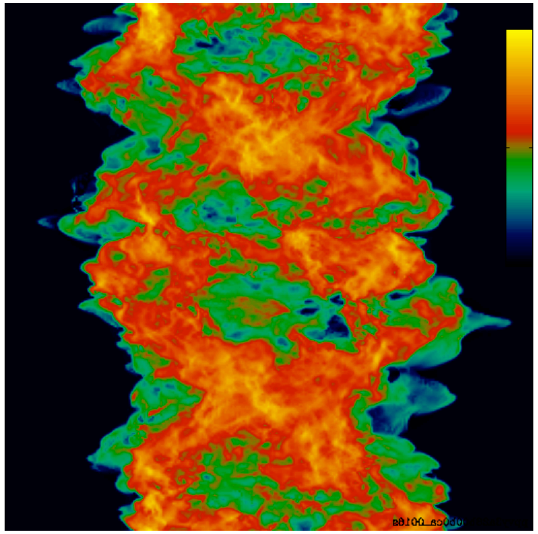
Flows, Filaments and Fragmentation: Formation of Molecular Clouds in Colliding HI-Flows



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Julien E.G. Devriendt *ENS Lyon*
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Tom Bethell *U Michigan*
Ted Bergin *U Michigan*

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In a Nutshell:

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Molecular clouds:

- filamentary, highly structured

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→ **cloud properties must be consequence of formation process**

Colliding flows provide a natural mechanism for formation of structured molecular clouds, including non-linear density seeds for local gravitational collapse.

gas: 10% of baryonic mass in Galaxy

~50% of gas molecular

at solar circle: H_2/HI ~ 0.25 Dame 1998

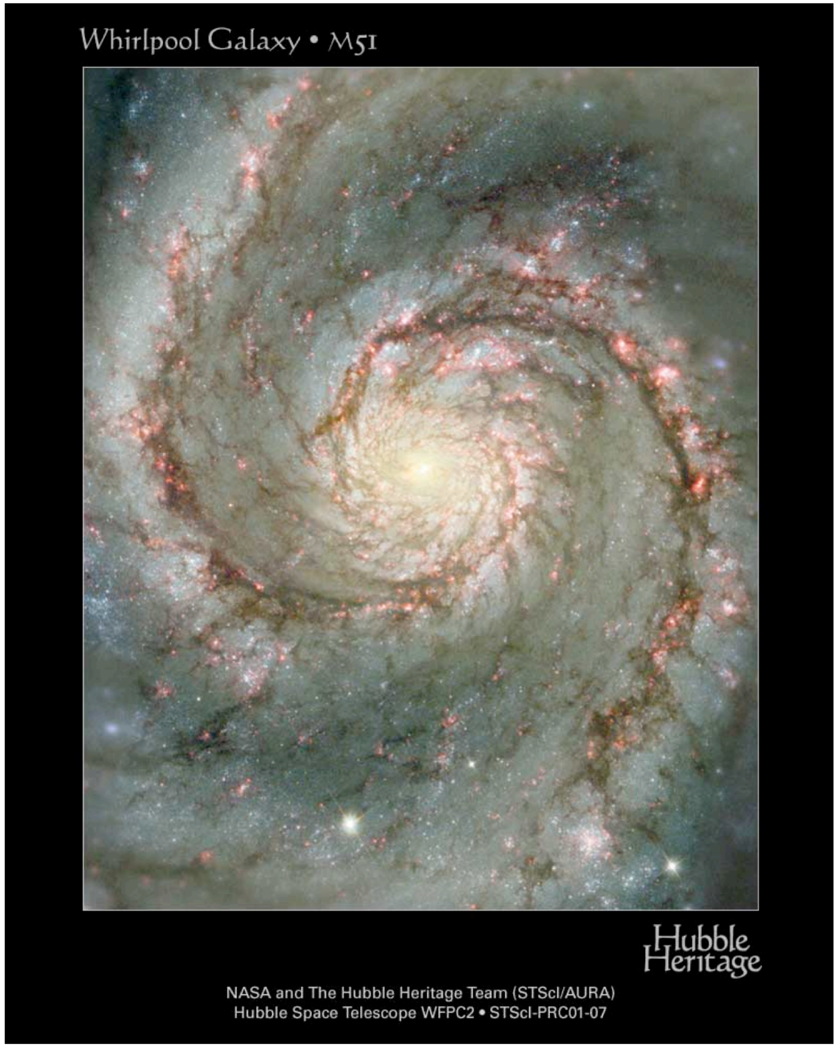
in molecular ring: H_2/HI > 0.5

clouds:

scales: 0.1 ~ few 10 pc

temperatures: 10 ~ 50 K

densities: > 100 cm^{-3}



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see talk by A. Burkert

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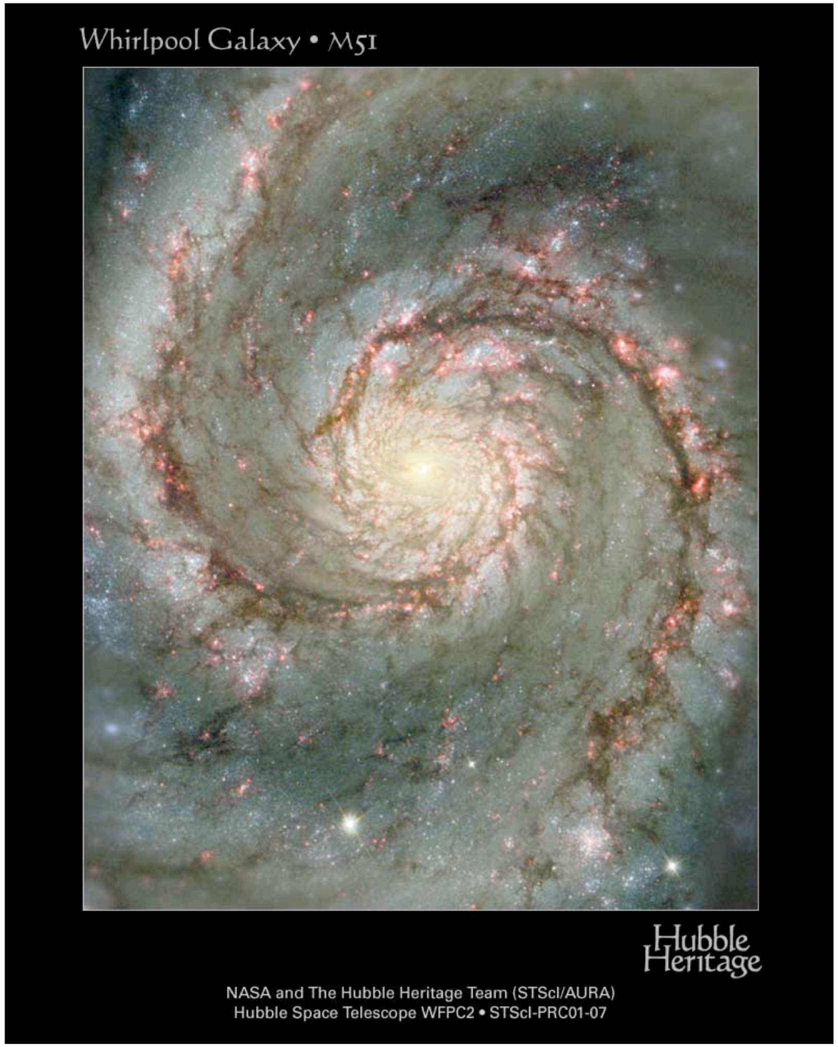
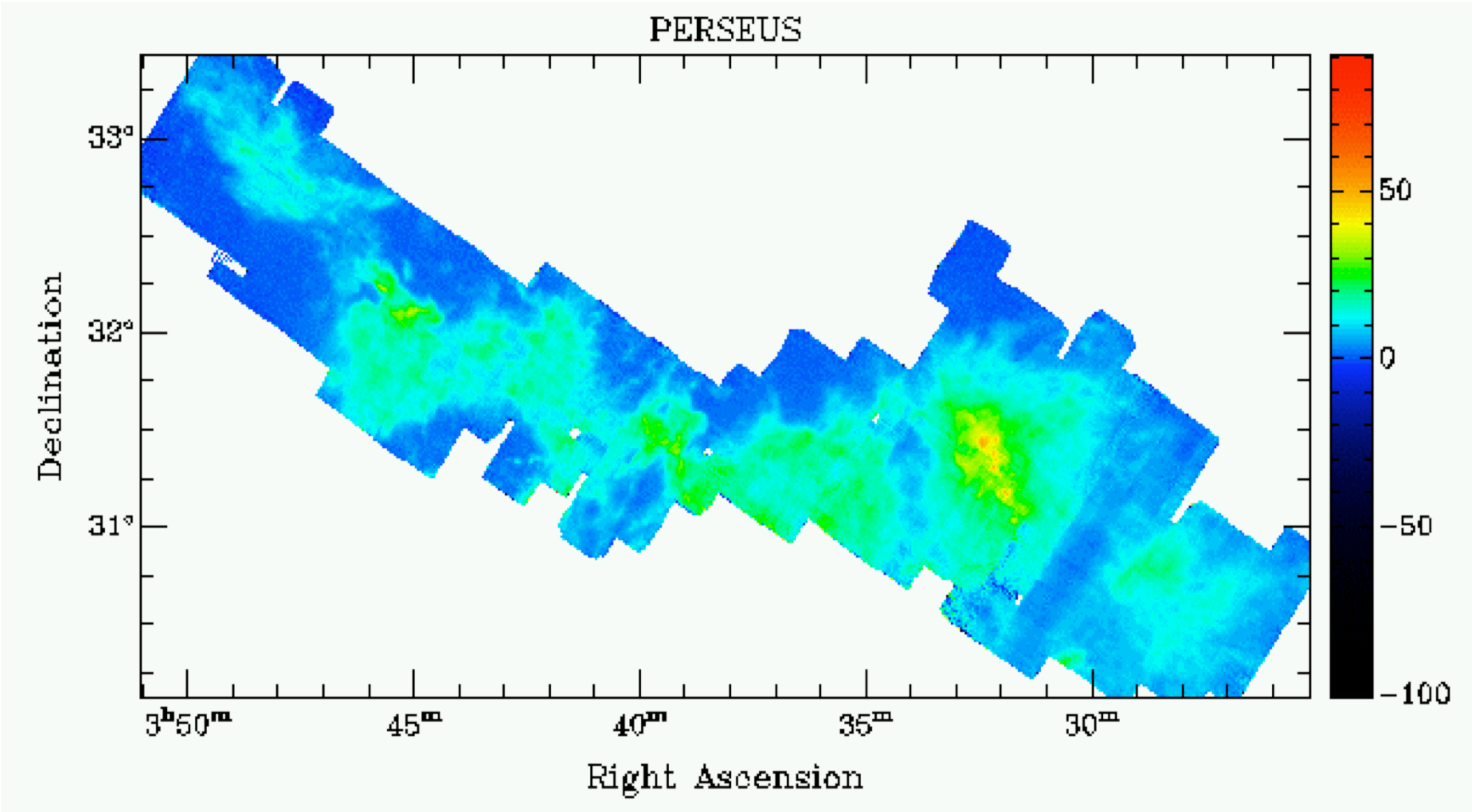
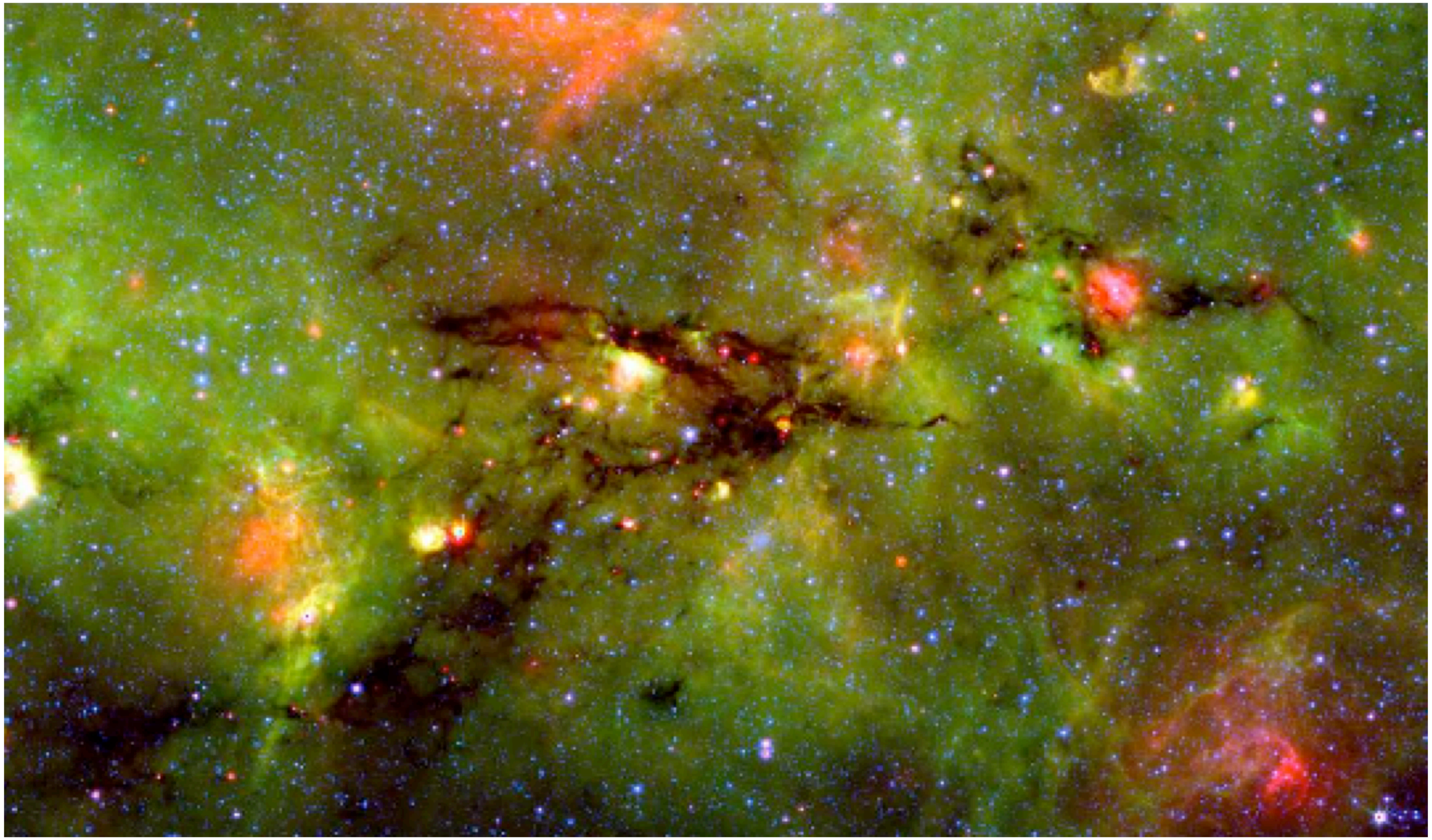




COMPLETE-survey, ^{12}CO
Goodman et al. 2003, Ridge et al. 2006



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red : 2

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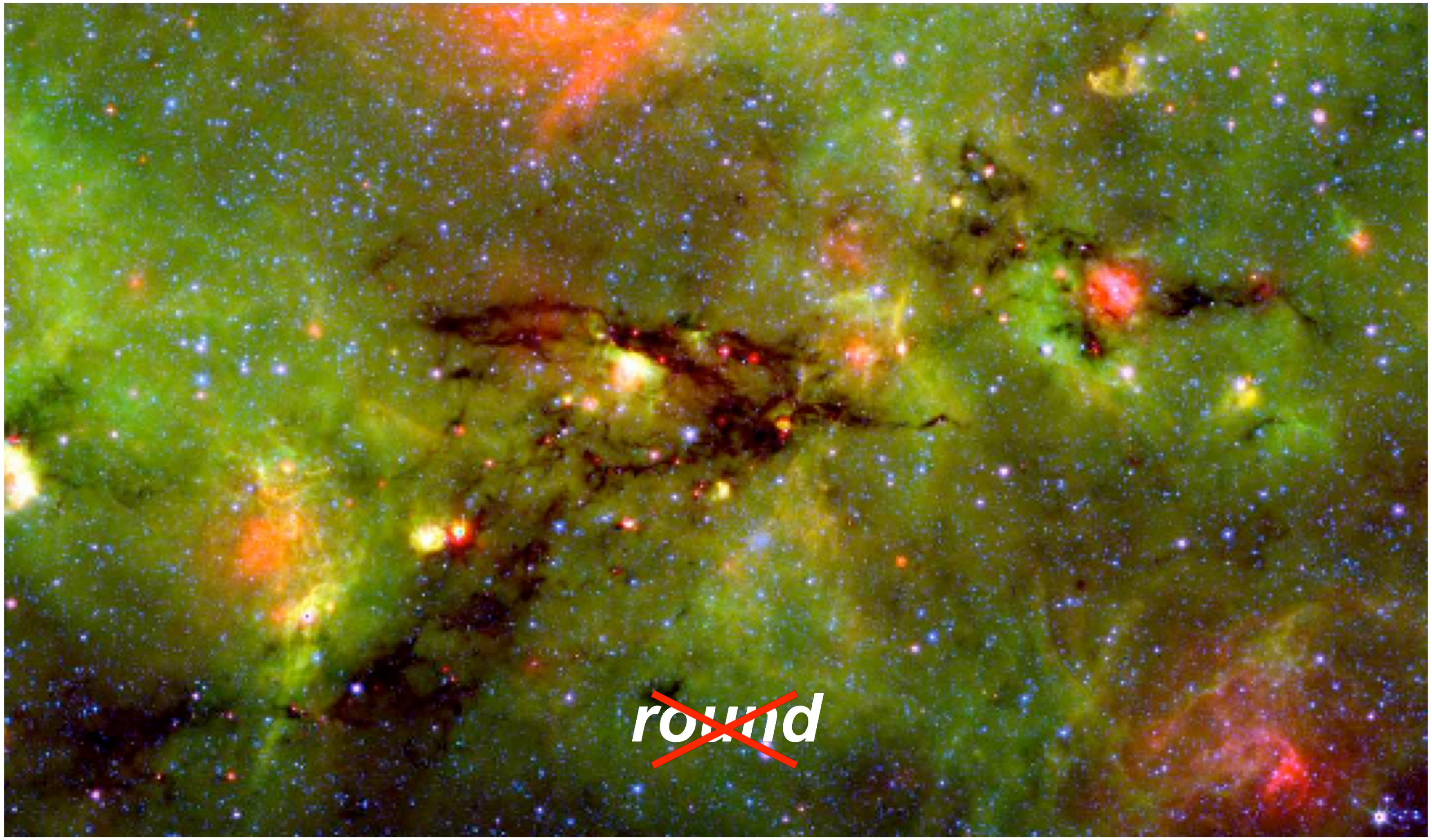
Heitsch, Whitney, Indebetouw et al., in prep.



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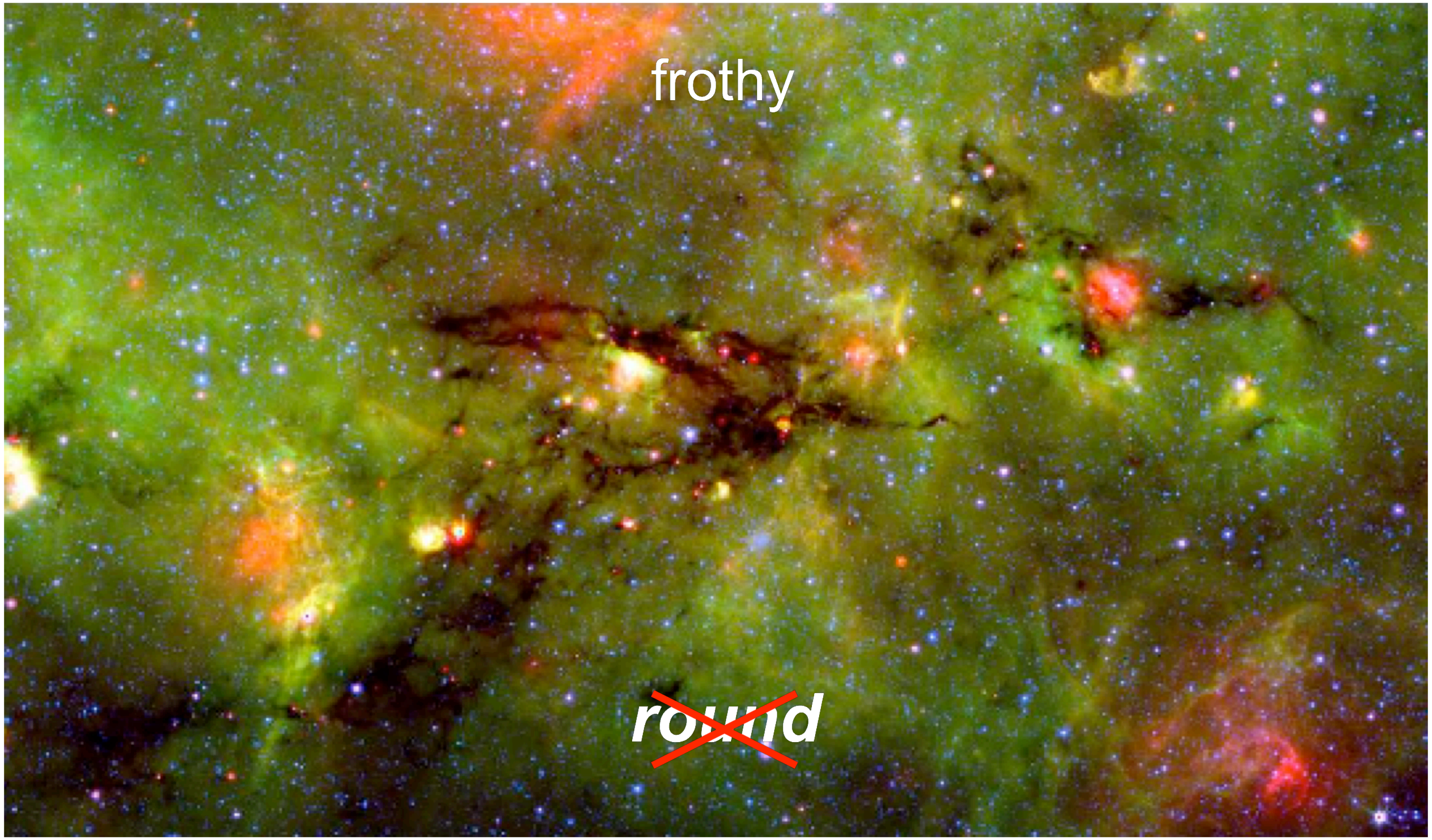

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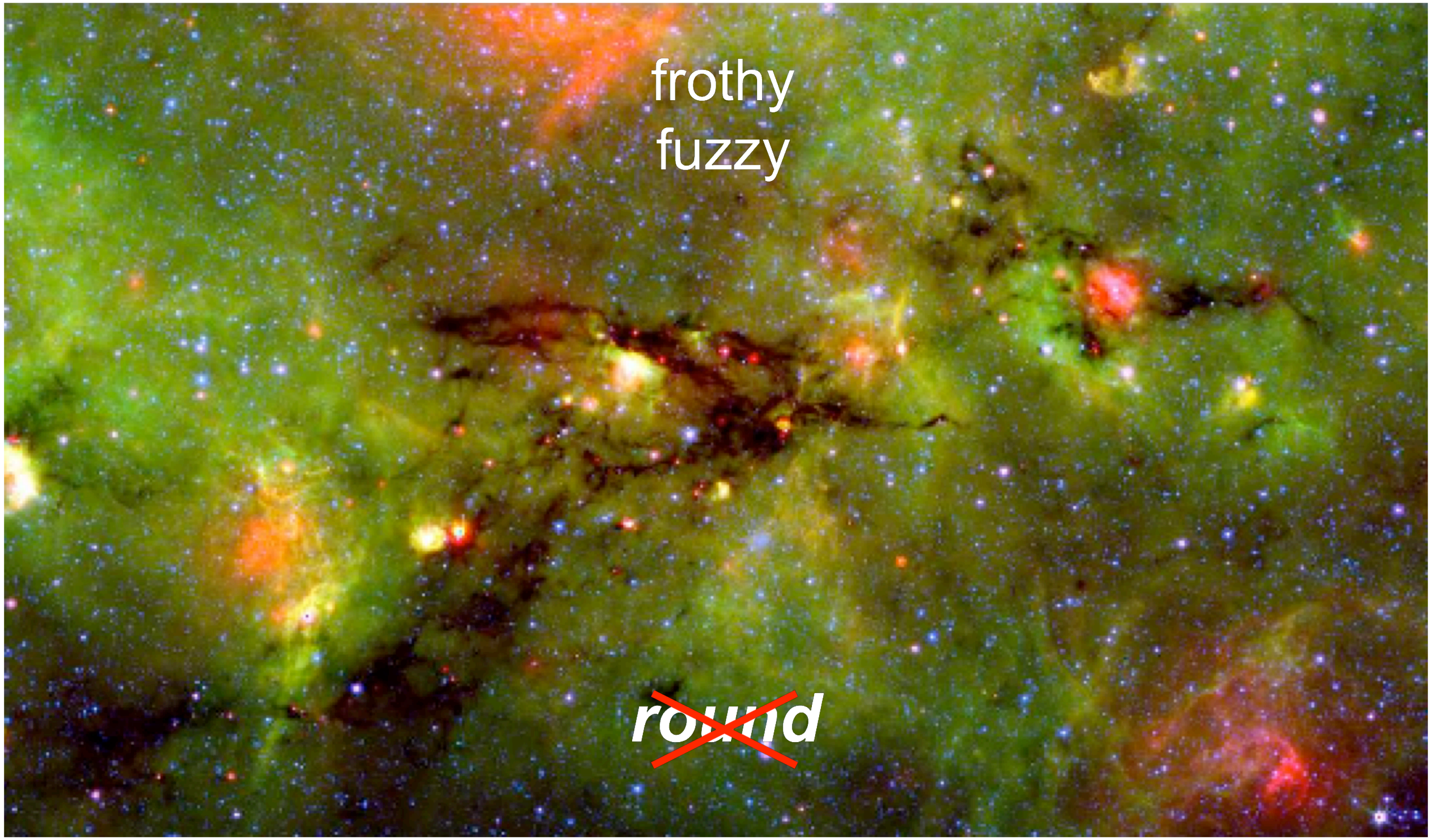

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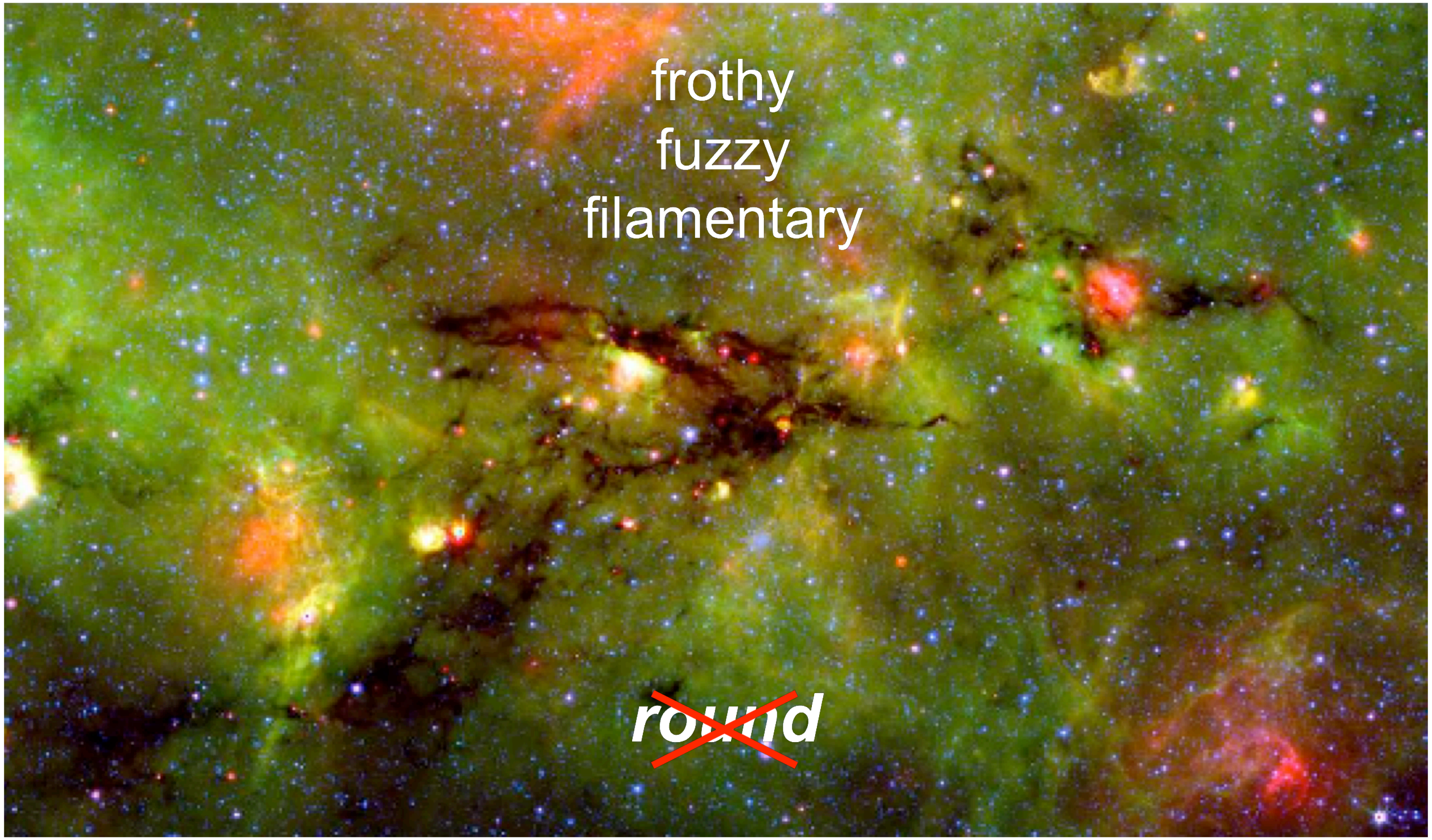

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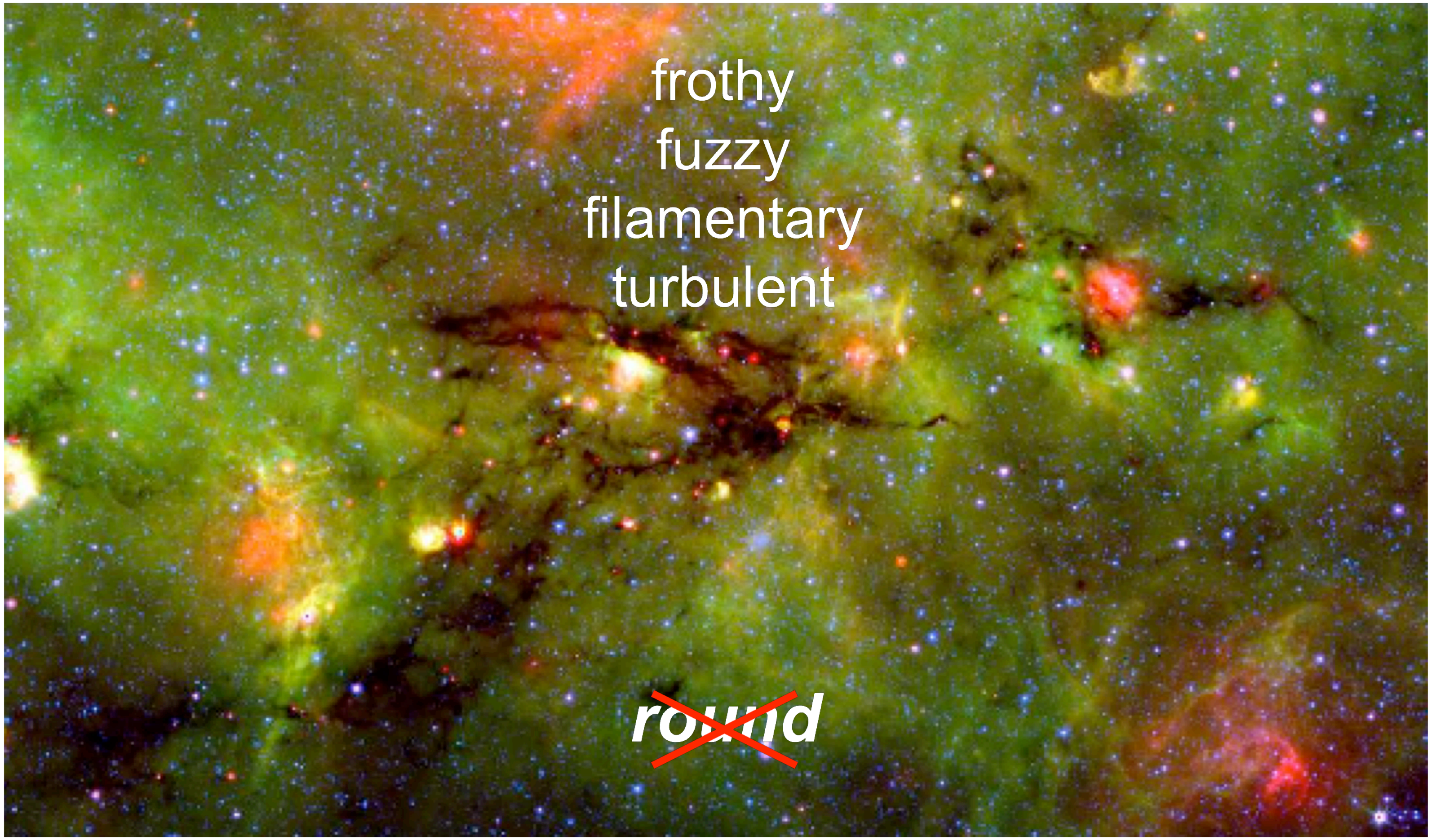

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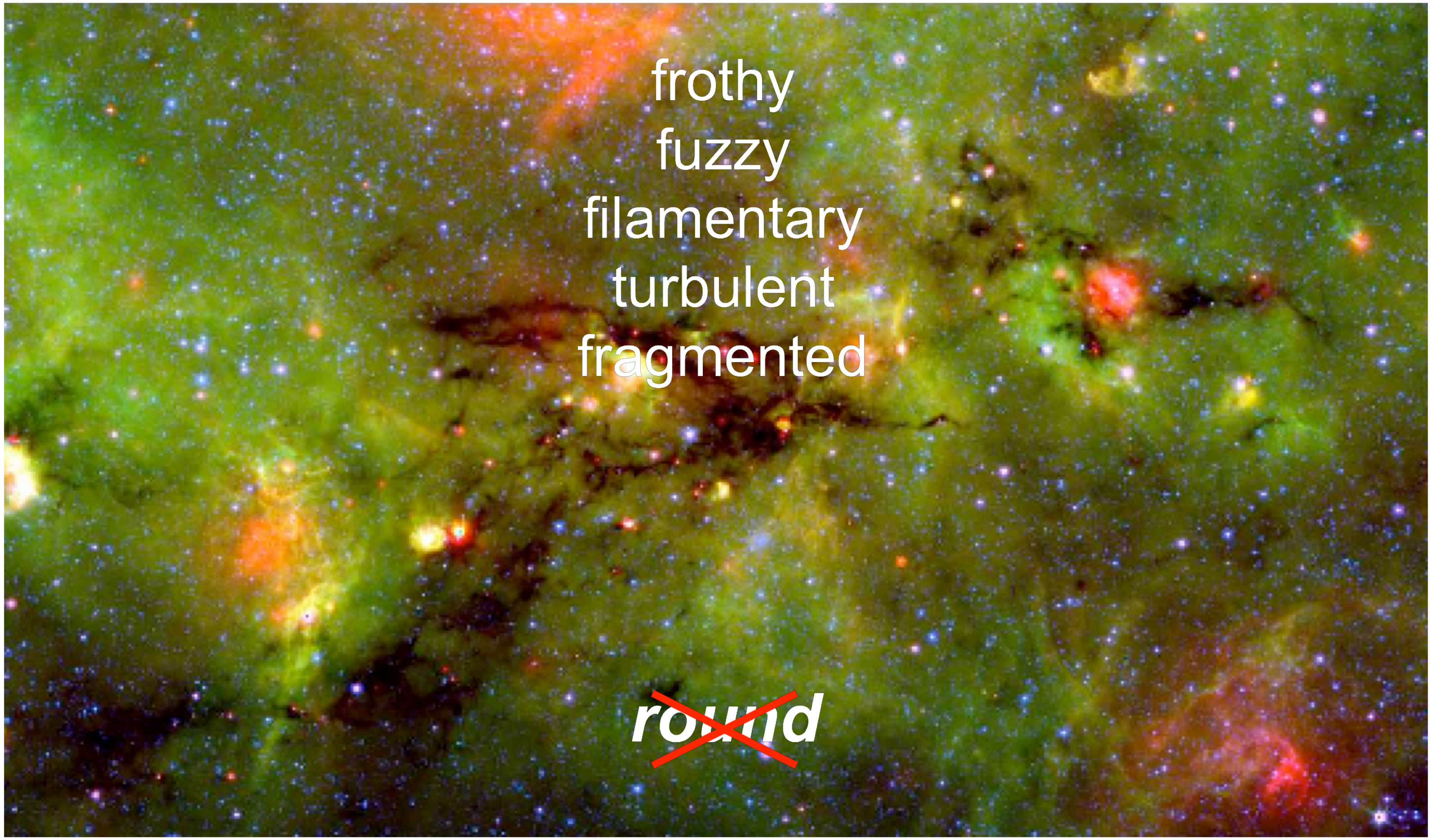

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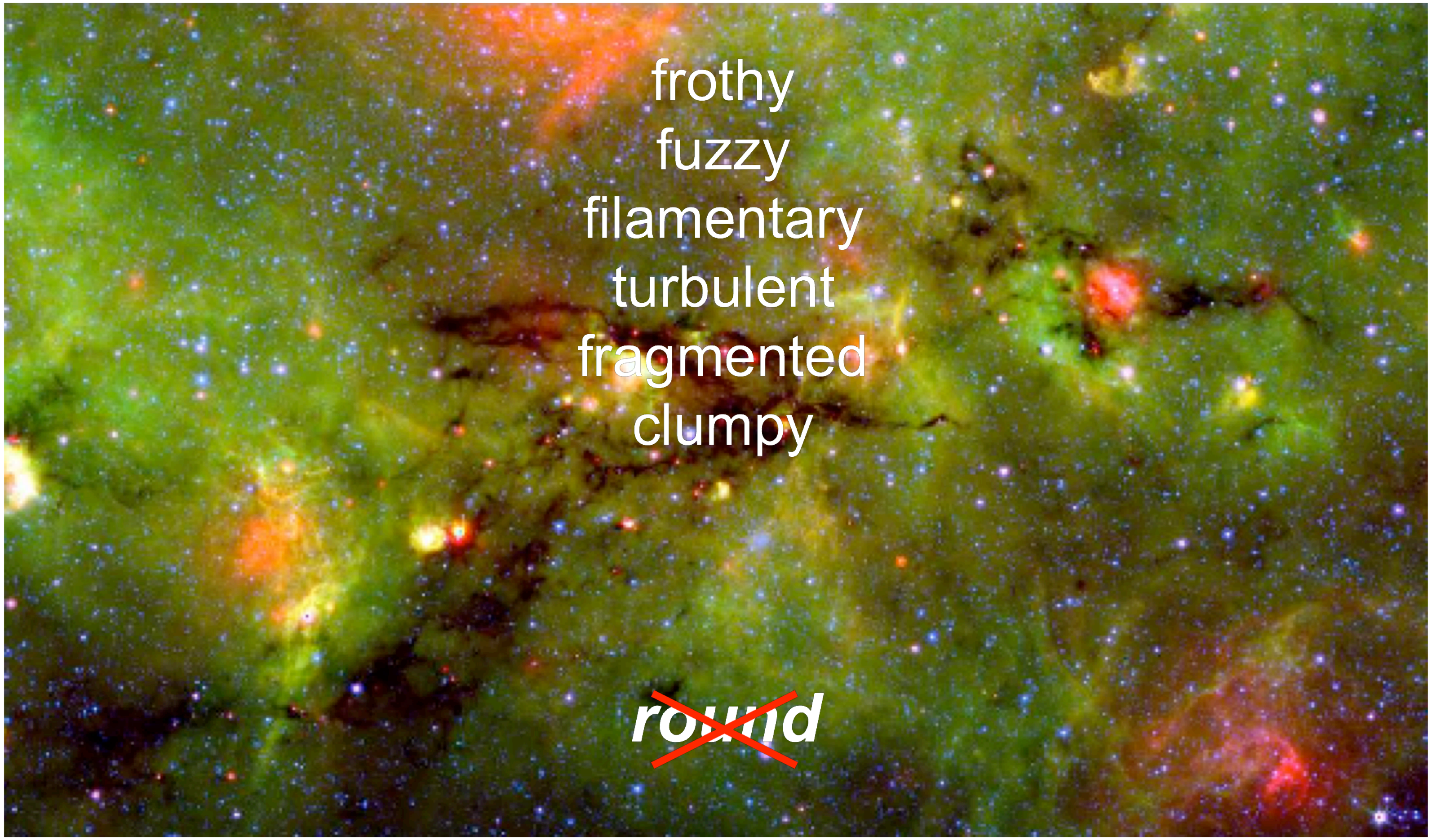

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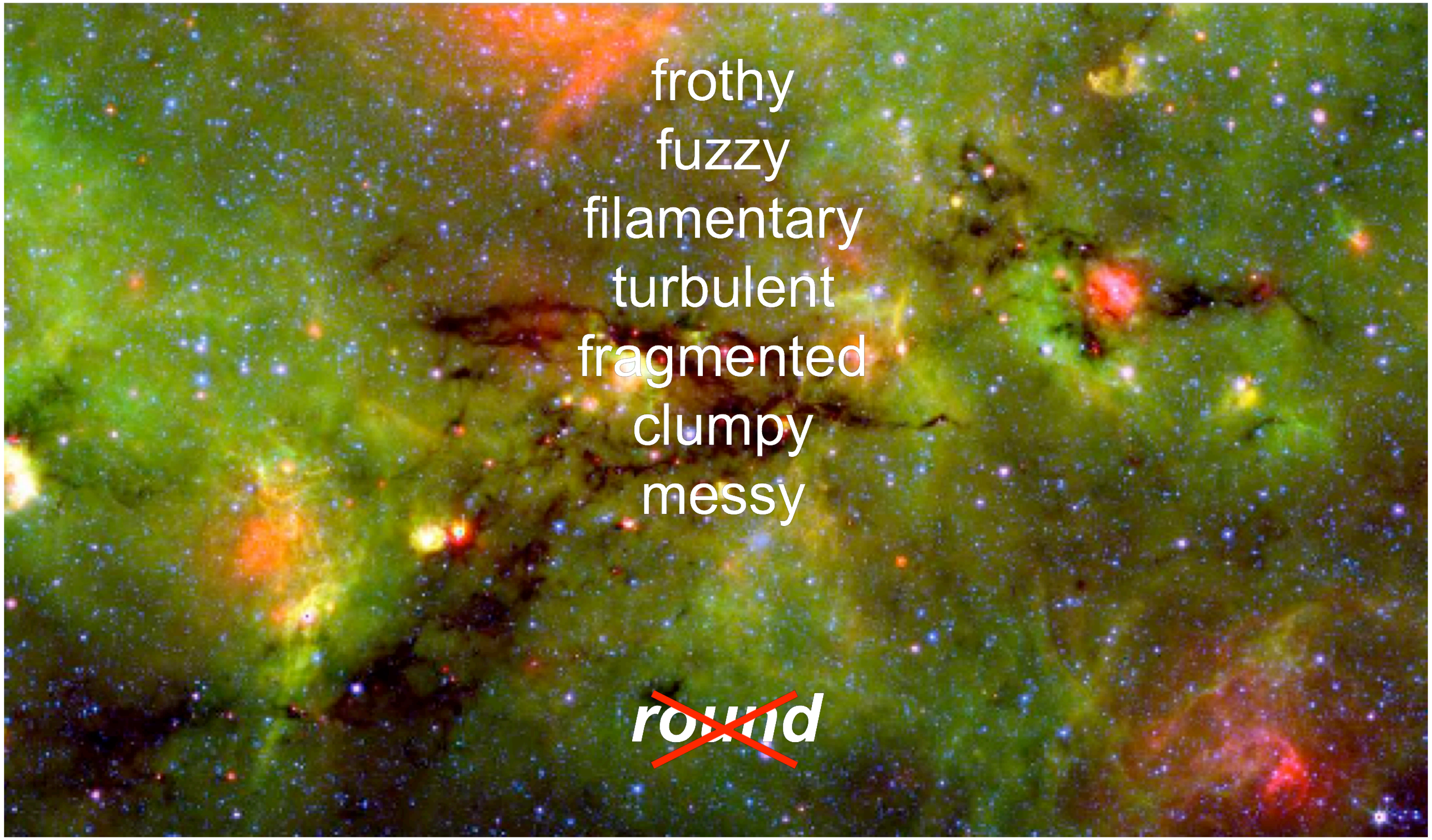

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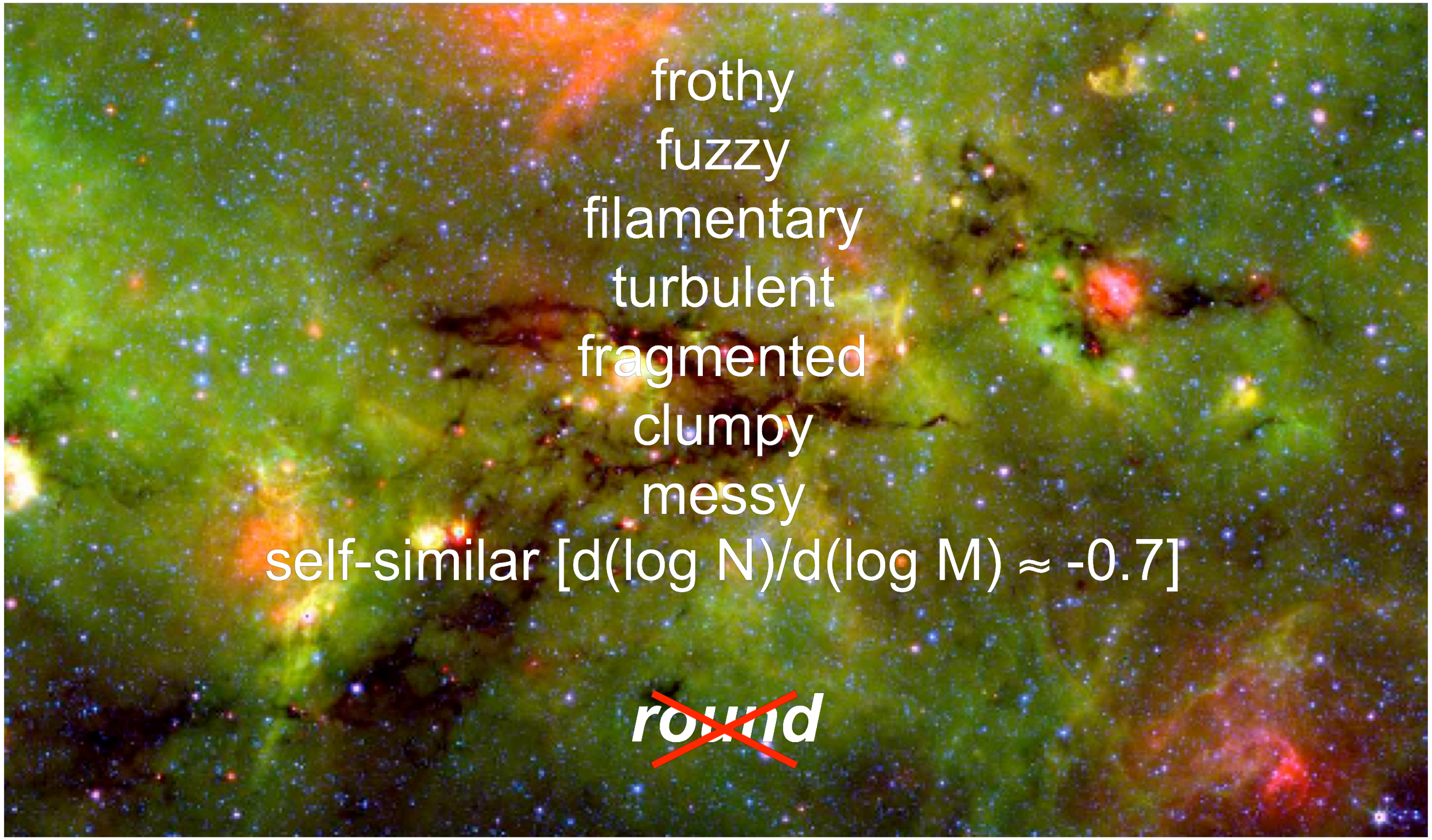

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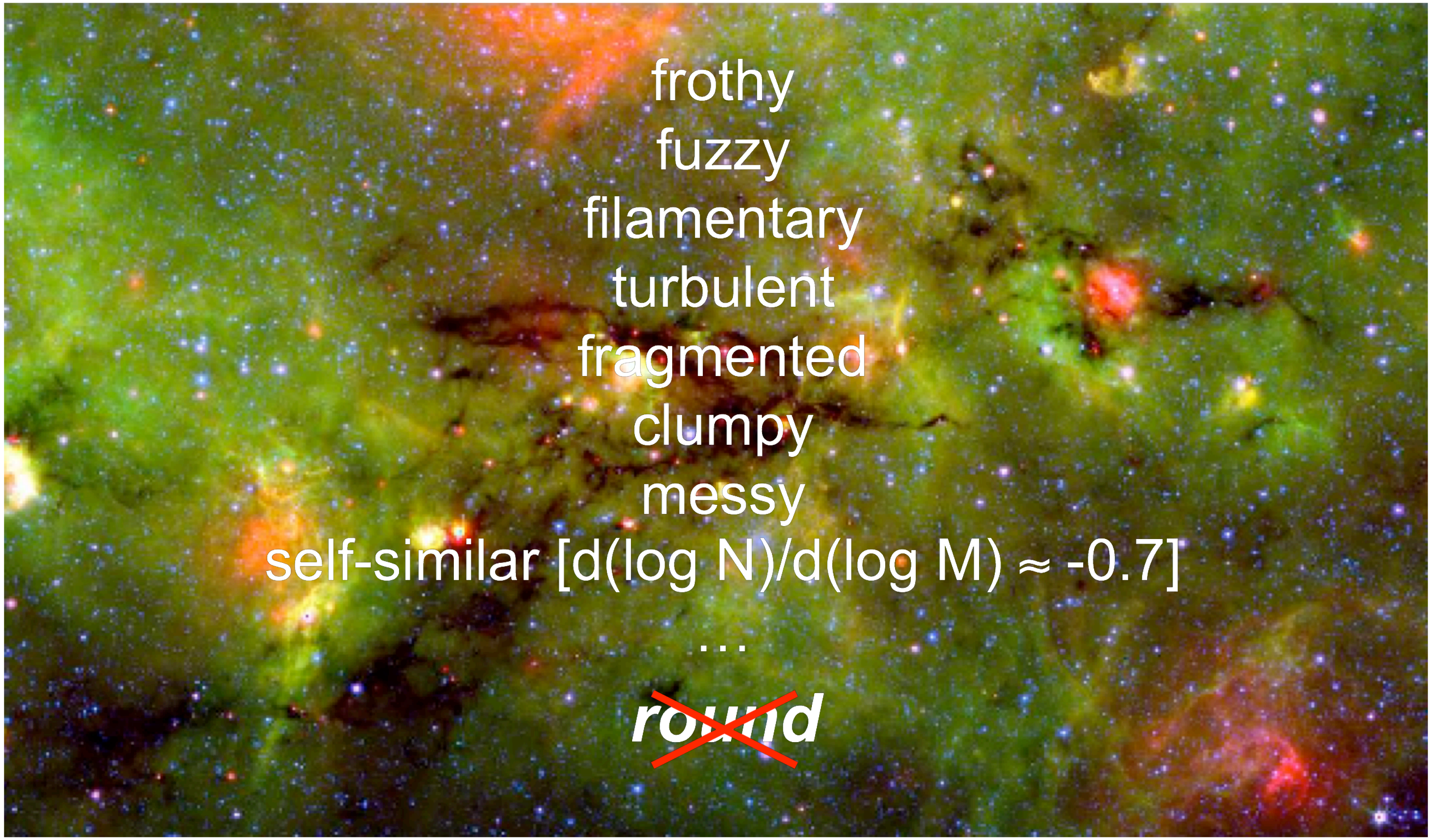

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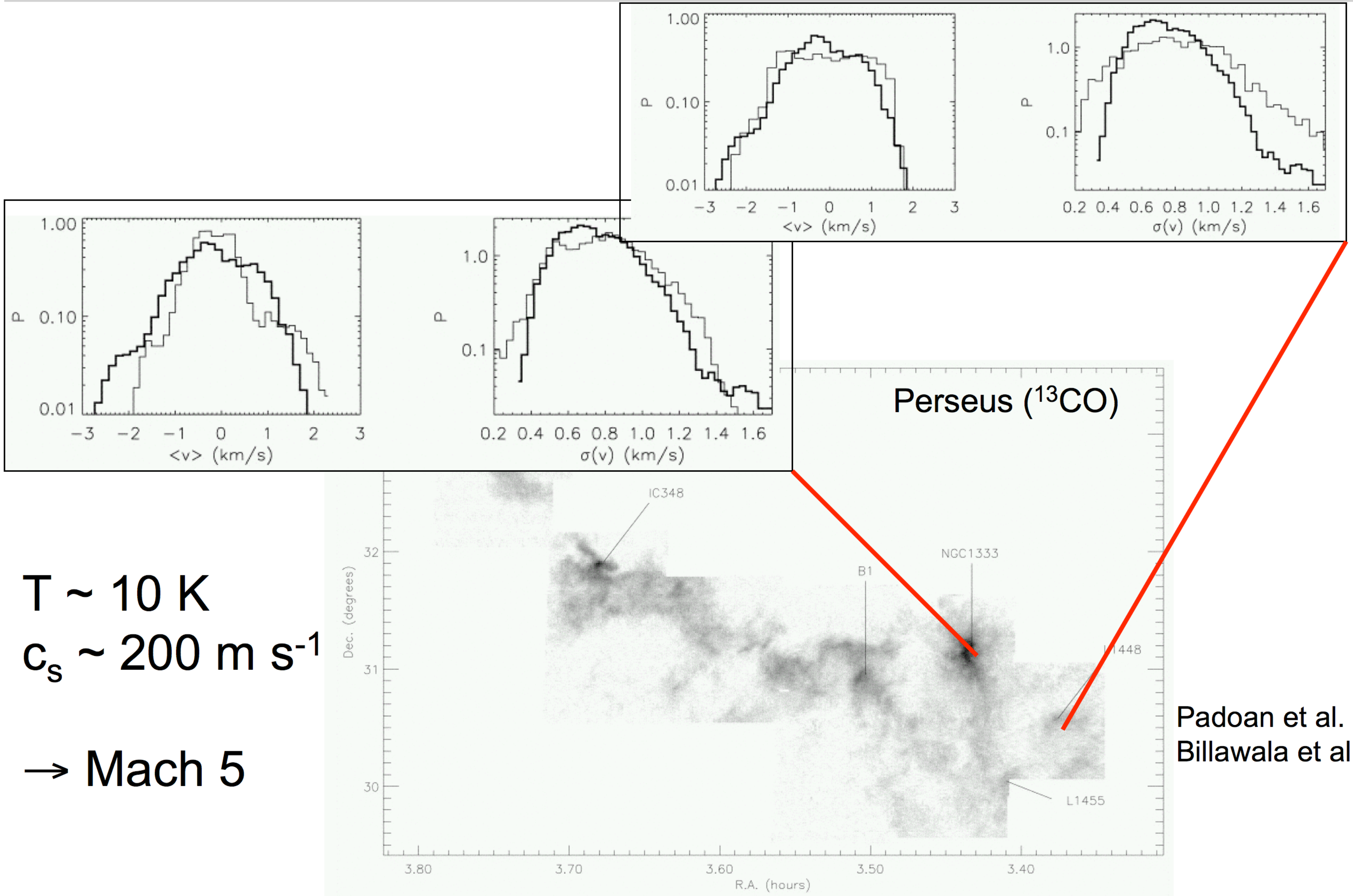

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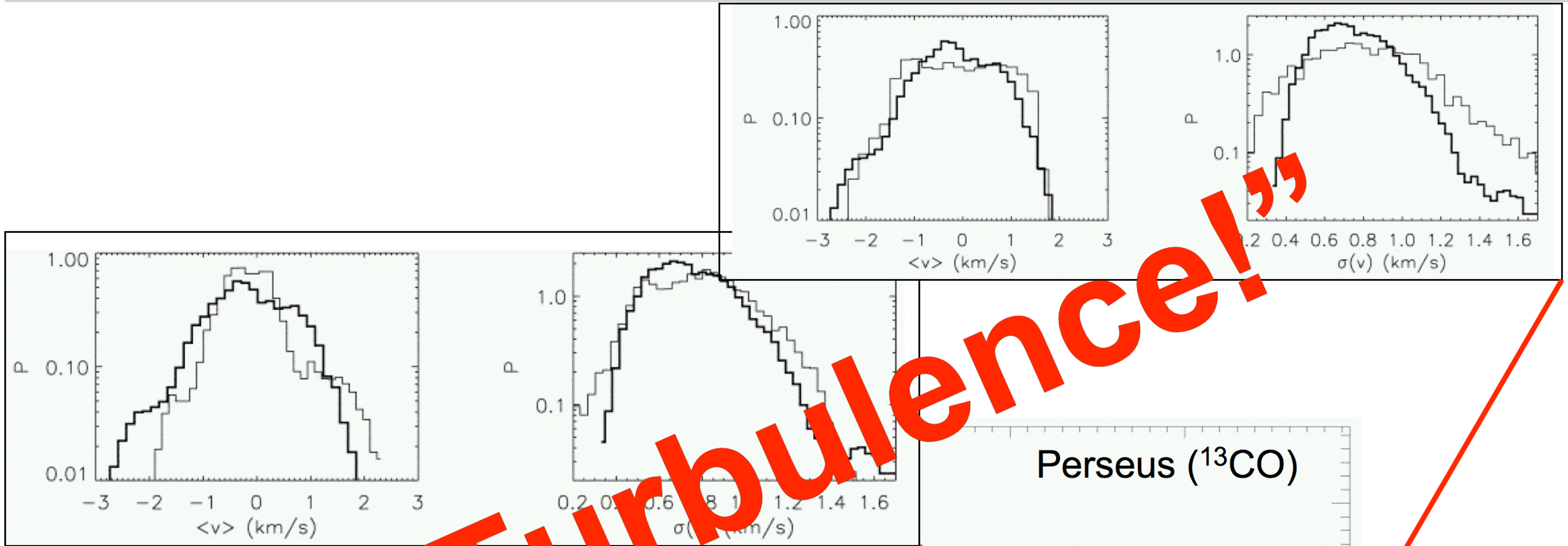
$c_s \sim 200$ m s^{-1}

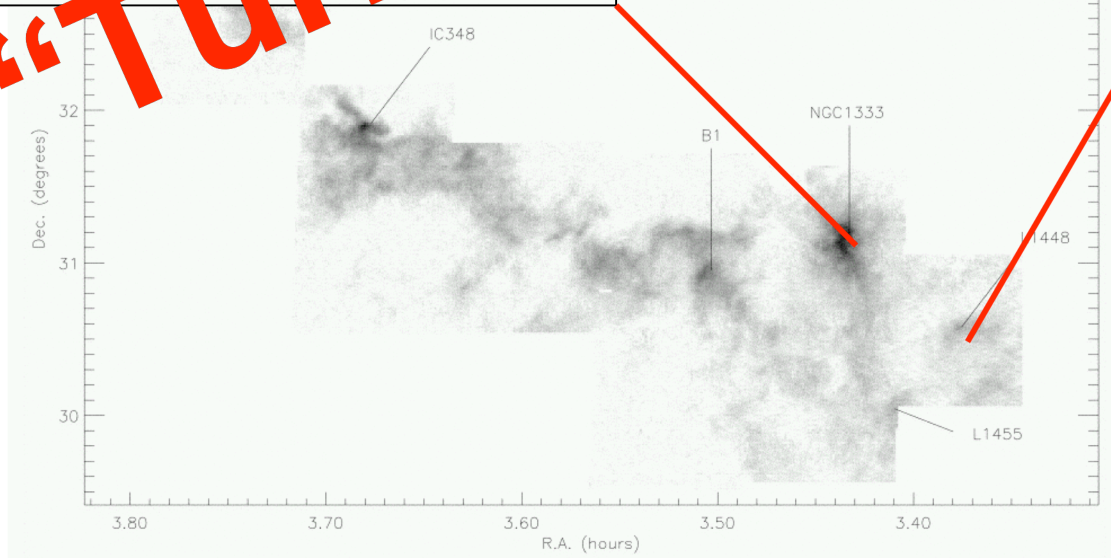
→ Mach 5

Padoan et al. 19

Billawala et al. 1



“Turbulence!”



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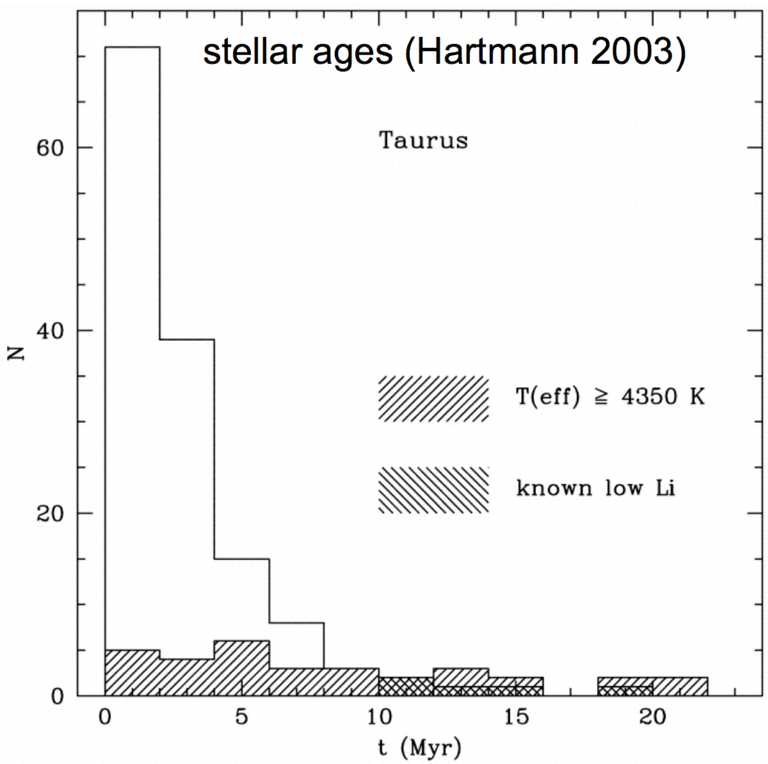
A Clock: stellar ages in star-forming regions in the solar neighborhood

- molecular clouds have young (1-2 Myr) stellar populations
- most molecular clouds form stars

(Spitzer c2d, GLIMPSE, Hartmann et al. 2001, 2003…)



STAR-FORMING REGIONS

Region	$\langle t \rangle$[a] (Myr)	Molecular Gas?	Ref. (age)
Coalsack	…	Yes	…
Orion Nebula	1	Yes	1
Taurus	2	Yes	1, 2, 3
Oph	1	Yes	1
Cha I, II	2	Yes	1
Lupus	2	Yes	1
MBM 12A	2	Yes	4
IC 348	1–3	Yes	1, 4, 5, 6
NGC 2264	3	Yes	1
Upper Sco	2–5	No	1, 6, 7
Sco OB2	5–15	No	8
TWA	~10	No	9
η Cha	~10	No	10

[a] Average age in Myr.

REFERENCES.—(1) Palla & Stahler 2000. (2) Hartmann 2001. (3) White & Ghez 2001. (4) Luhman 2001. (5) Herbig 1998. (6) Preibisch & Zinnecker 1999. (7) Preibisch et al. 2001. (8) de Geus et al. 1989. (9) Webb et al. 1999. (10) Mamajek, Lawson, & Feigelson 1999.

Hartmann et al. 2001

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- star formation epoch is short (1-3 Myr)
- clouds live generally shorter than 10 Myr

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Cloud formation process provides initial conditions for star formatior

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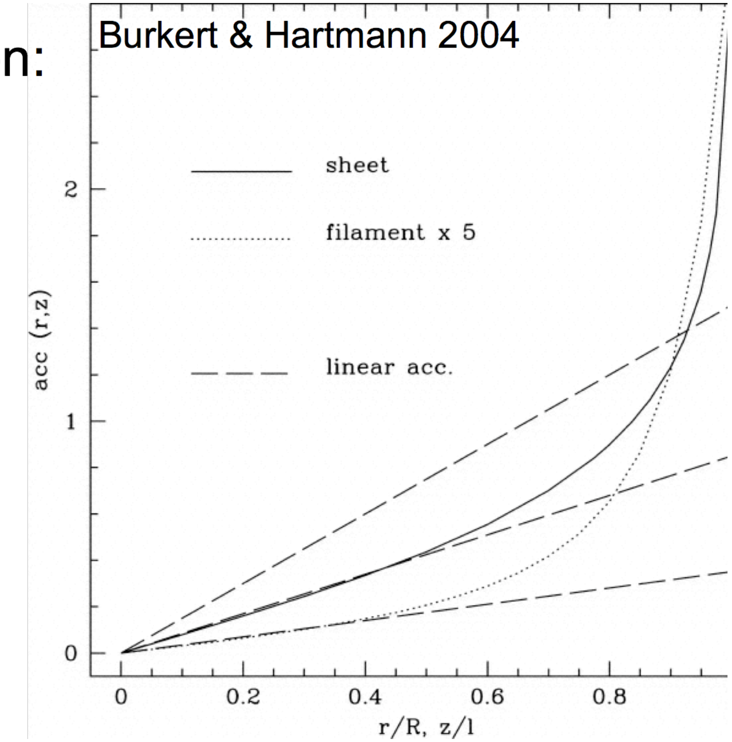
$$a_r = -\frac{\partial \Phi}{\partial r} = 4G\Sigma \frac{R}{r}\left[K\left(\frac{r}{R}\right) - E\left(\frac{r}{R}\right)\right] \xrightarrow[r \to R]{} \infty$$



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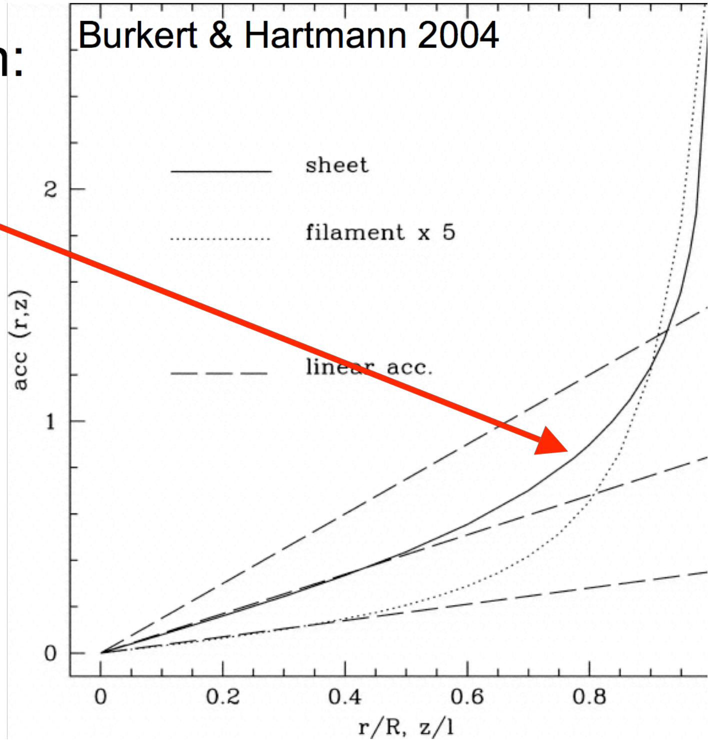
Burkert & Hartmann 2004



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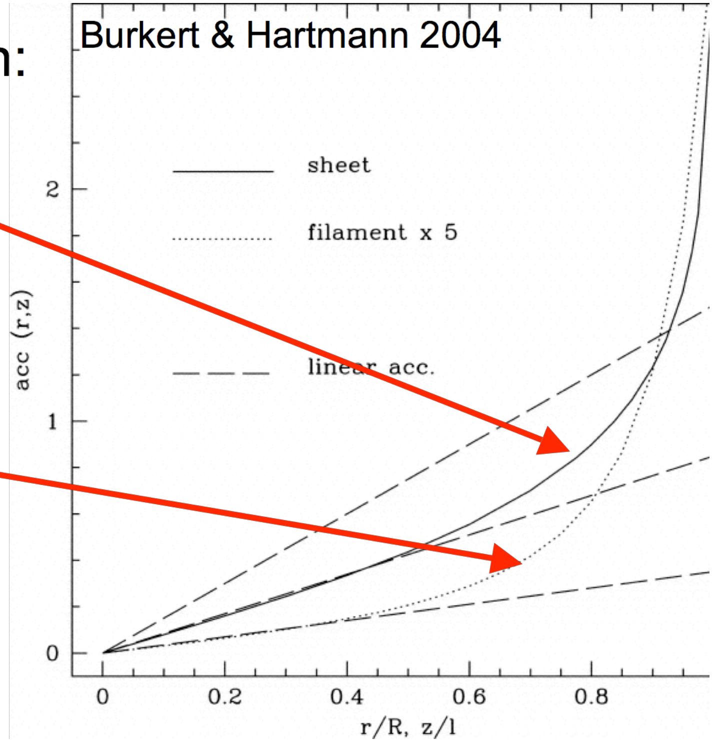
collapse of a thin filament: axial acceleration:

$$a_z \approx -Gm\left(\frac{2z}{l^2 - z^2}\right) \xrightarrow[z \to l]{} \infty$$



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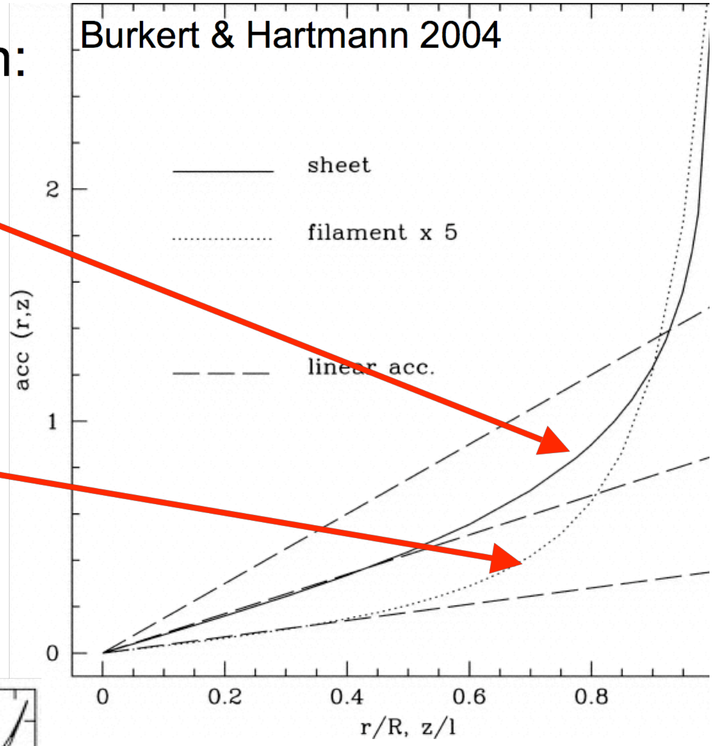
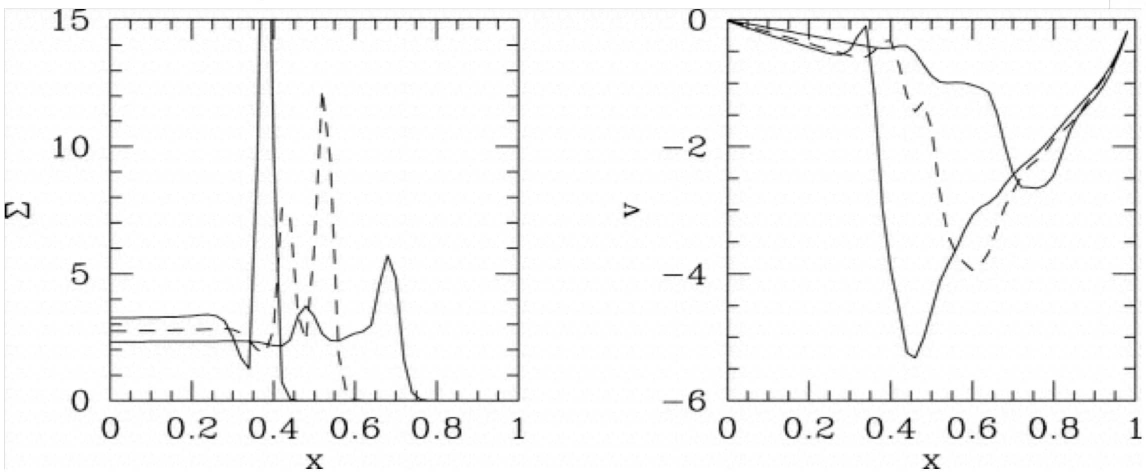


time evolution of radial density and velocity profile:

edge wins over linear perturbation



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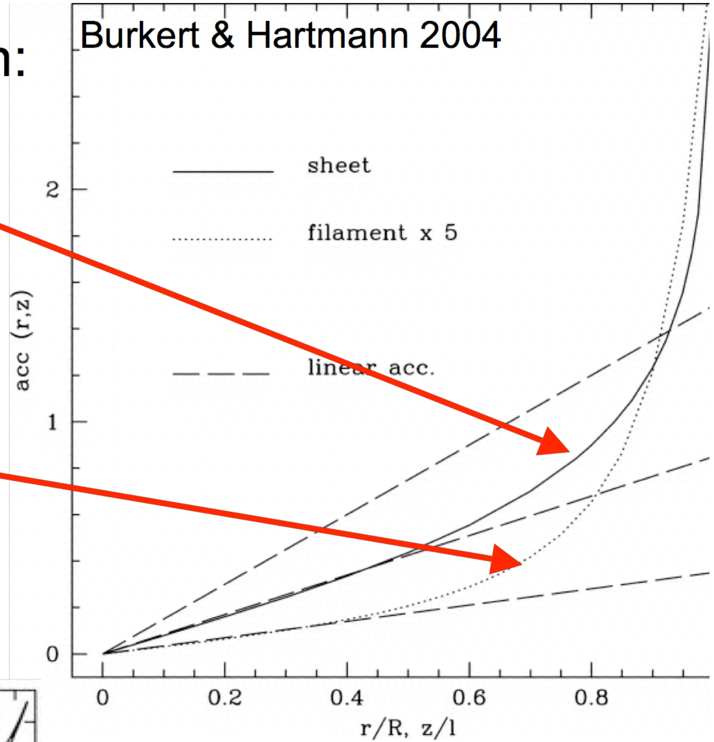

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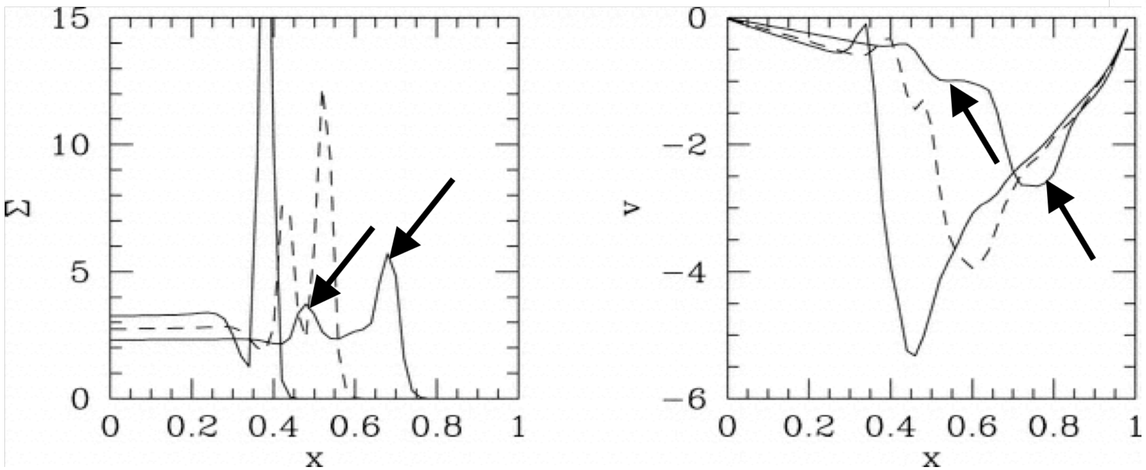

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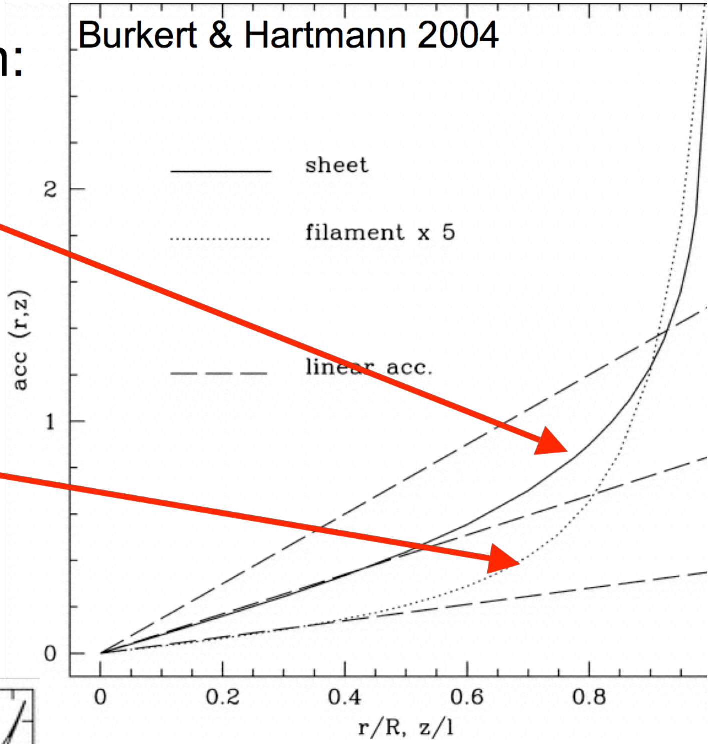

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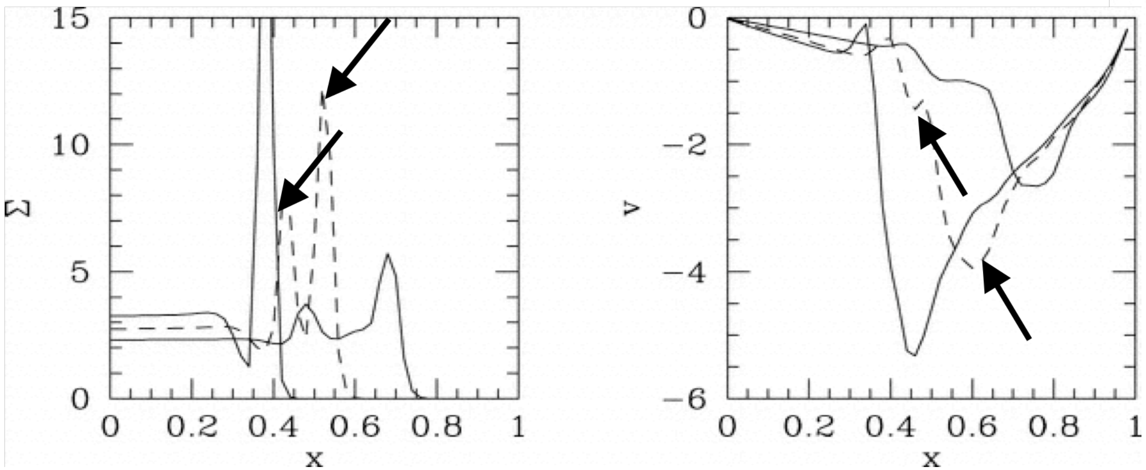

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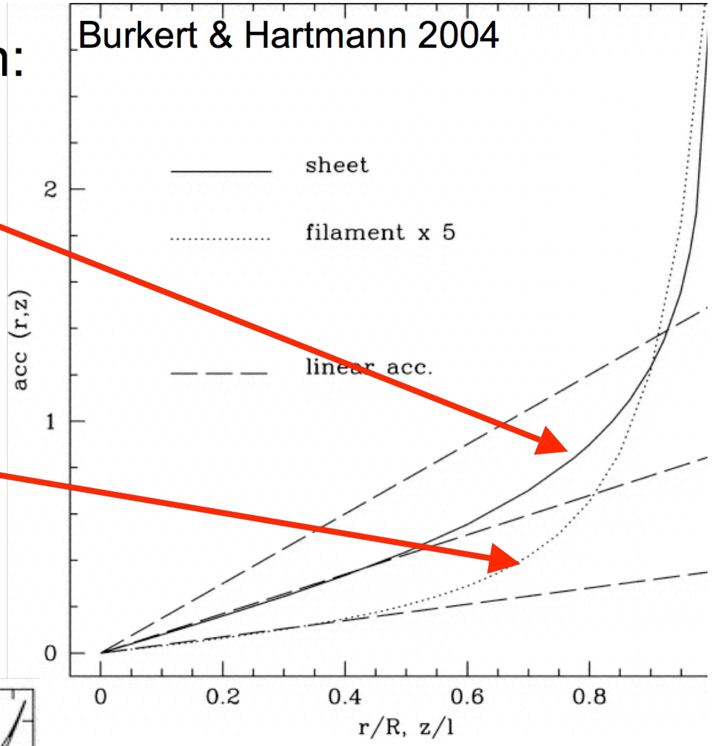

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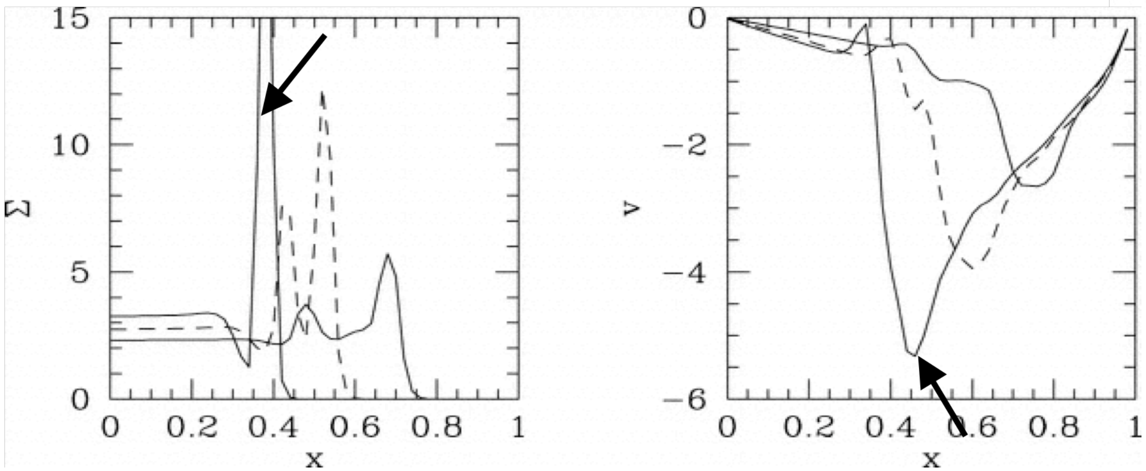

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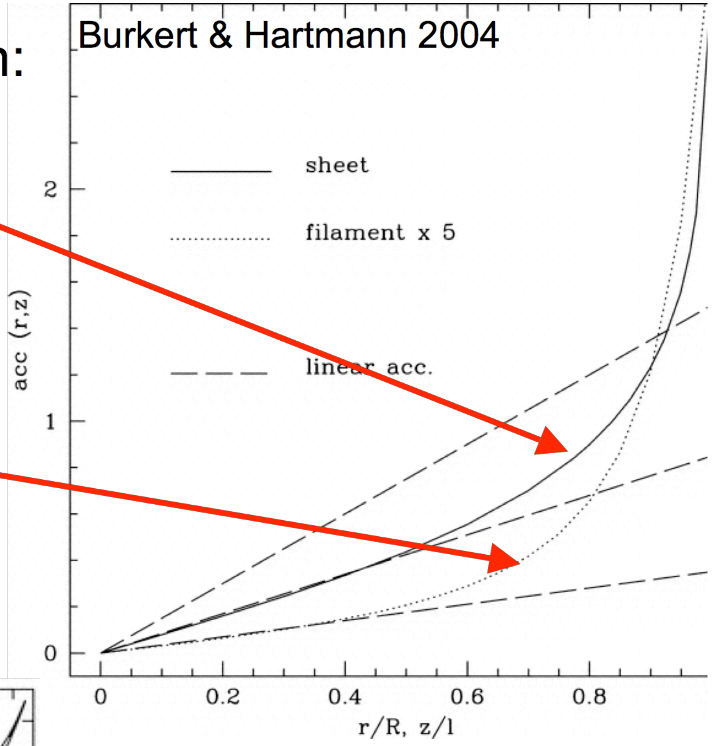

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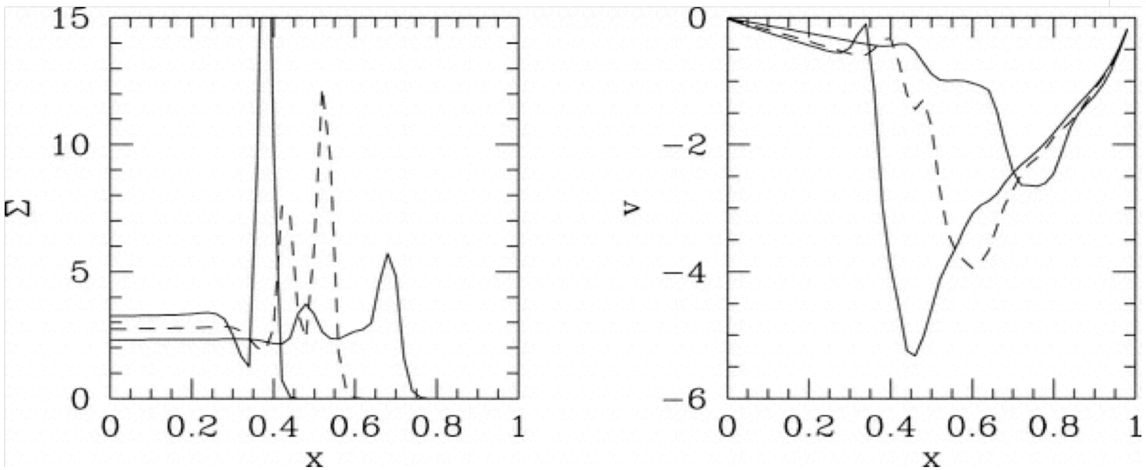


Rapid star formation requires non-linear density seeds during cloud formation.

A possible answer:

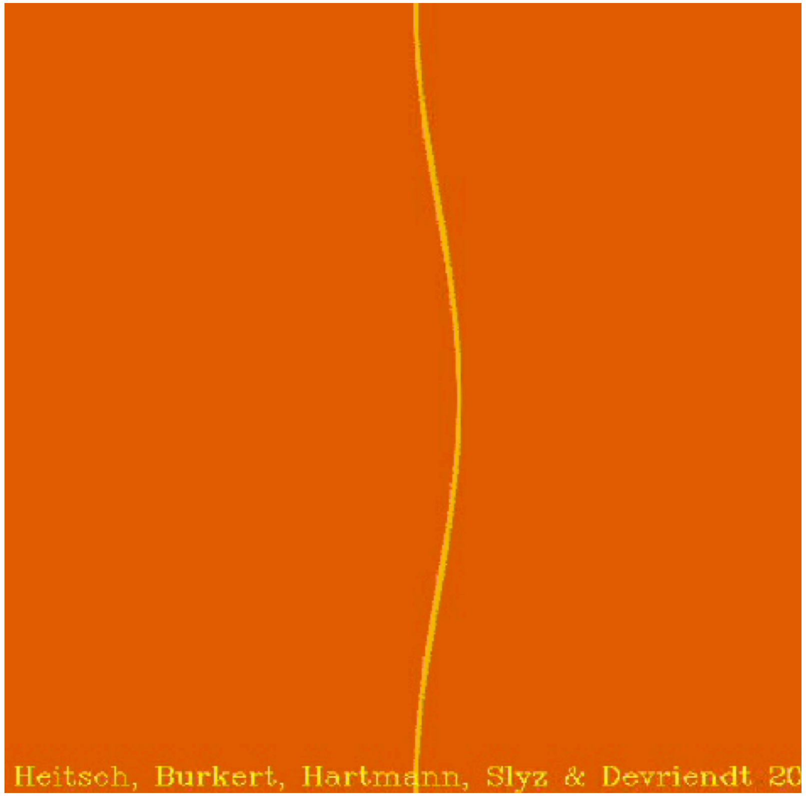
Ballesteros-Paredes et al. 1999, Hartmann et al. 2001

The properties of molecular clouds are a direct consequence of their formation process.

Molecular clouds form in converging flows of atomic hydrogen.

Combination of thermal and dynamical instabilities leads to substructure and non-linear seeds for rapid local action of gravity.
→ *prevention of global collapse.*

Heitsch et al. 05, 06;
see also Audit & Hennebelle 2005;
Vazquez-Semadeni et al. 06, 07
Hennebelle et al. 2007a,b



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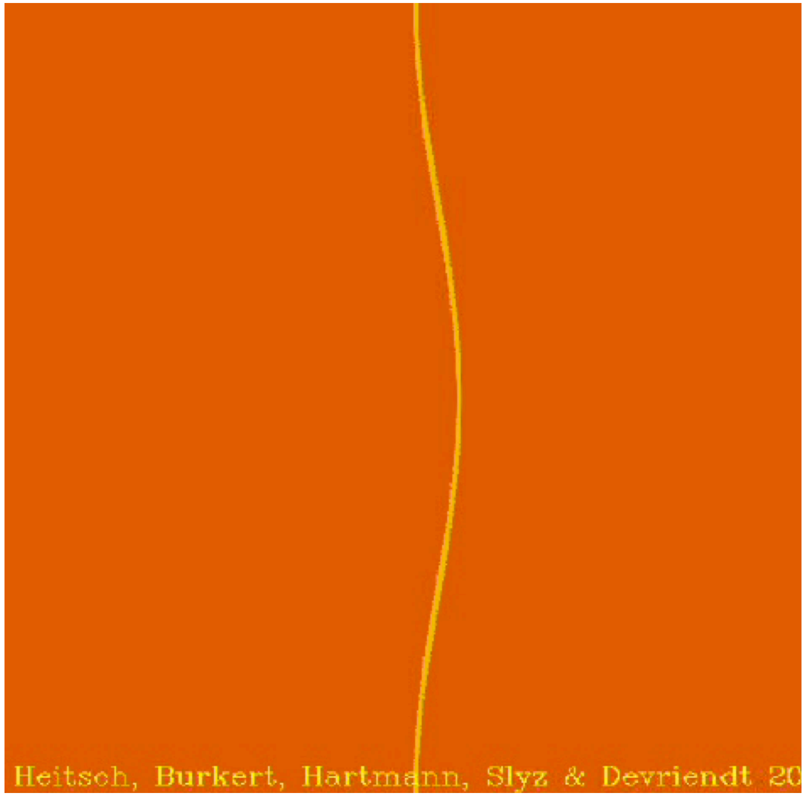


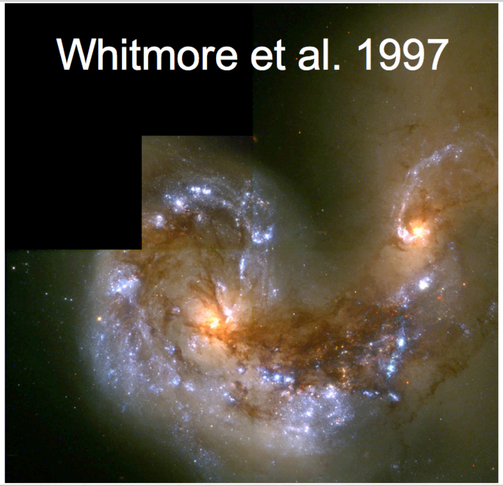
expanding shells (HII, SNe)
Patel et al. 1995, 97, Hartmann et al. 2001

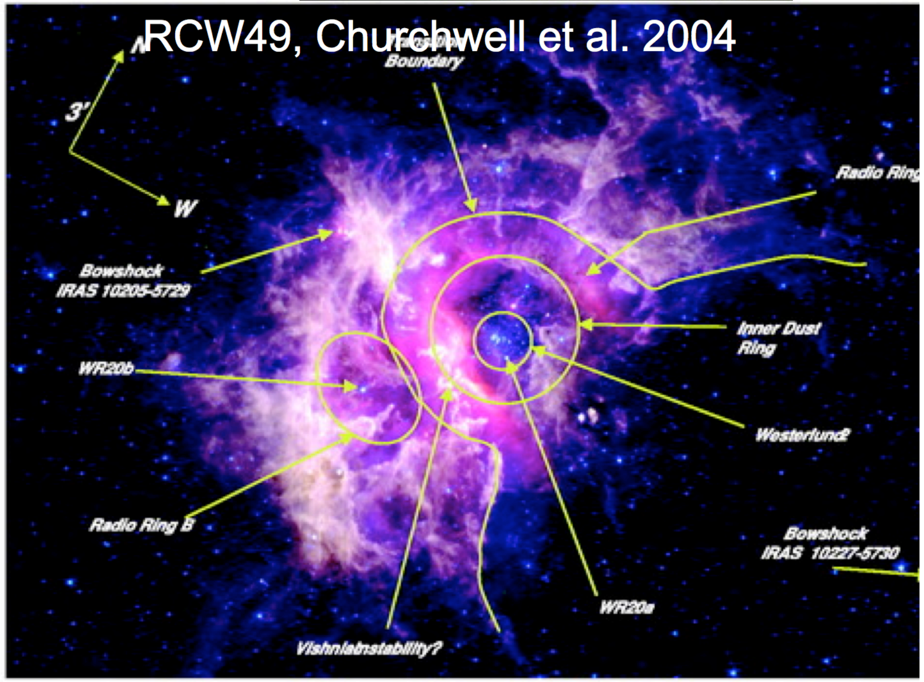
stellar winds
Walder & Folini 1998, 2000; Churchwell et al. 2004

spiral density waves
Tilanus & Allen 1990

large-scale turbulence (MRI-driven?)

galaxy mergers


Whitmore et al. 1997



RCW49, Churchwell et al. 2004

A numerical *experiment*: the extreme view.

Two uniform, identical flows

colliding head-on at interface

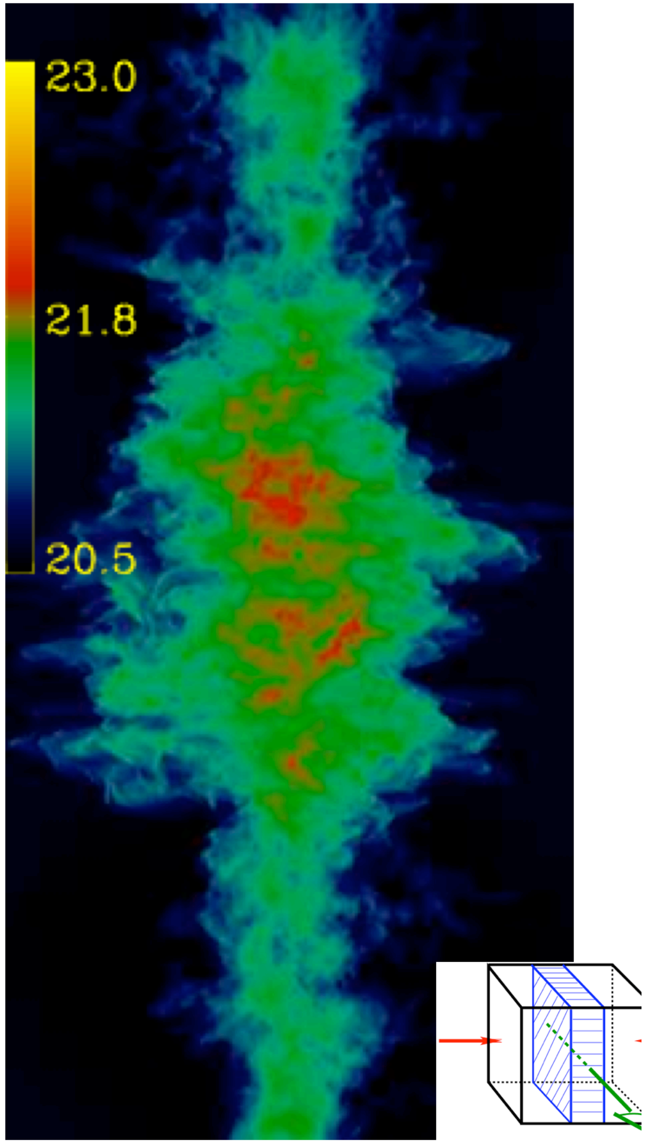
with large-scale geometric perturbation

in non-periodic domain.

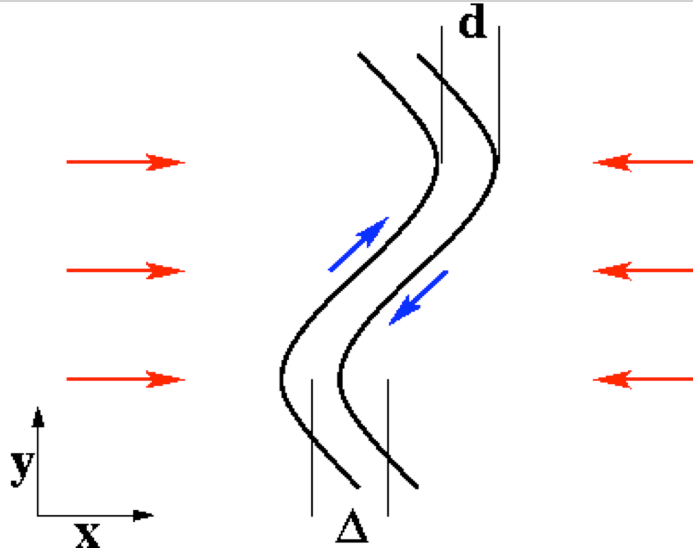
→ *turbulence generation "from scratch"*

→ *avoid Wypiiwygo-problem*

→ *global gravitational effects*



Non-linear Thin Shell Instability Vishniac 1994



- formation of dense slab (weak eq. of state)
- transverse (y) x-momentum transport

  Hunter et al. 1986, Walder & Folini 1998, 2000, Hueckstaedt 2003 (all 2D)

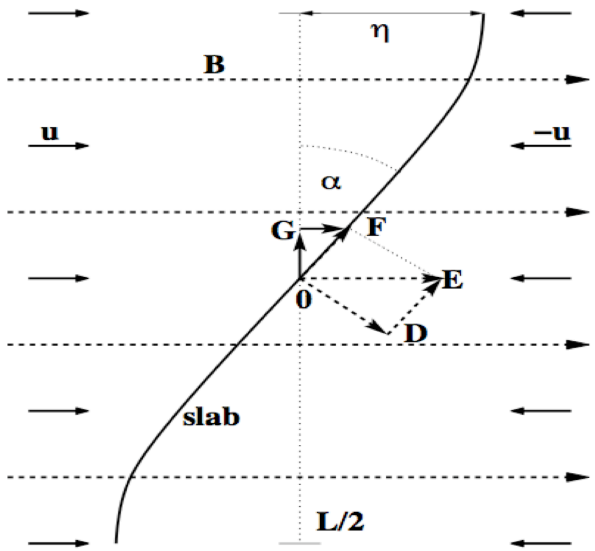
growth rate $\omega \sim c_s\, k\, (k\Delta)^{1/2}$

Fragmentation of a coherent sheet.

- magnetic fields reduce growthrate
- fields can suppress NTSI (in 2D!) if

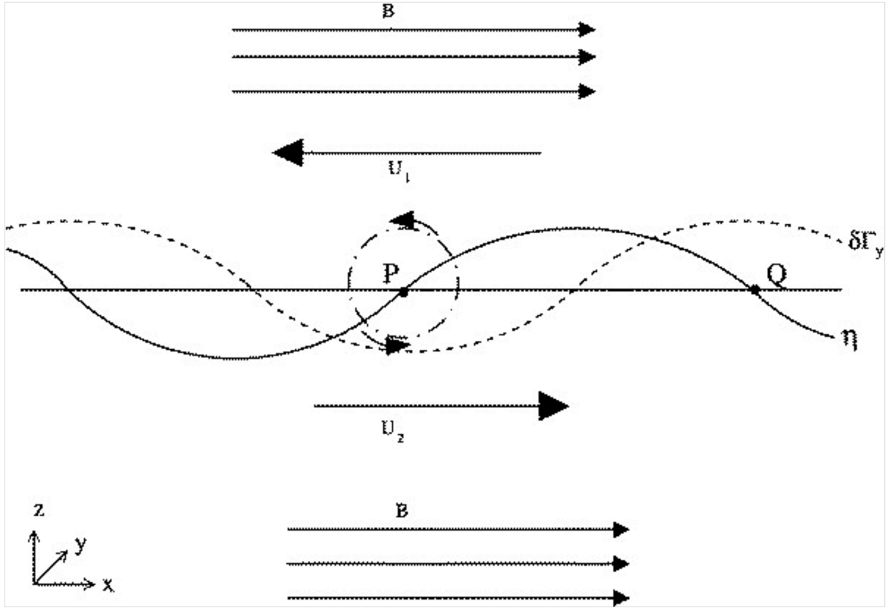
$$\rho\, u^2 \;\sin\alpha \cos\alpha \;\approx\; B^2/2$$

Heitsch et al. 2007



Kelvin-Helmholtz Instability

shear flows result from deflected inflow



incompressible growth rate

$$\omega \sim k\,(U^2 - c_A^2)^{1/2}$$

MHD-KHI
Palotti, Heitsch, Zweibe
& Huang in prep.

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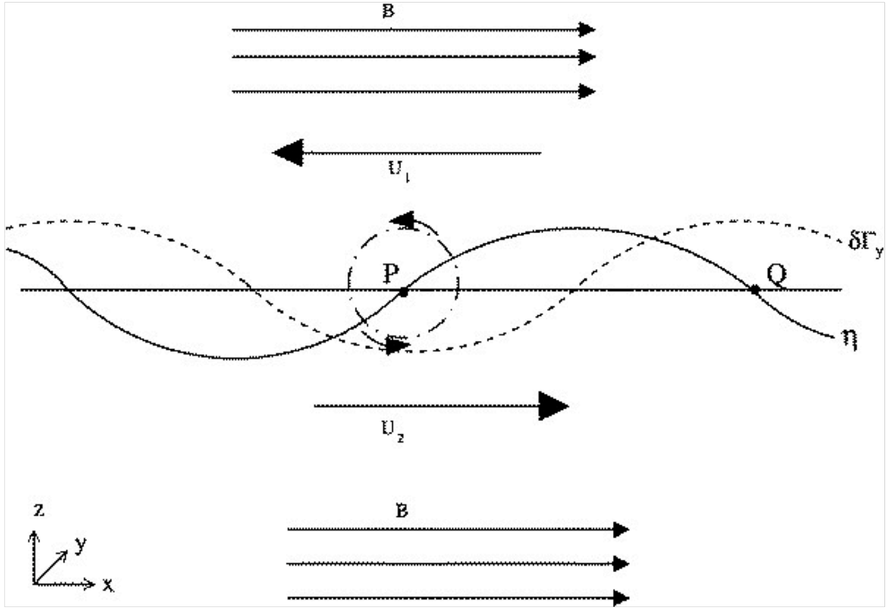
shear flows result from deflected inflow



incompressible growth rate $\omega \sim k\,(U^2 - c_A^2)^{1/2}$

MHD-KHI
Palotti, Heitsch, Zweibe
& Huang in prep.

Regime: transition from

warm ionized medium (WIM) to cold neutral medium (CNM)

$n \approx 1\ cm^{-3}$	warm neutral medium	$n \approx 100\ cm^{-3}$
$T \approx 8500$ K	thermally	$T \approx 40$ K
$c_s \approx 10\ km\ s^{-1}$	unstable	$c_s \approx 2\ km\ s^{-1}$
Mach ≈ 1	regime	Mach ≈ 3
$B \approx 5\ \mu G$		$B \approx 5\text{-}10\ \mu G$

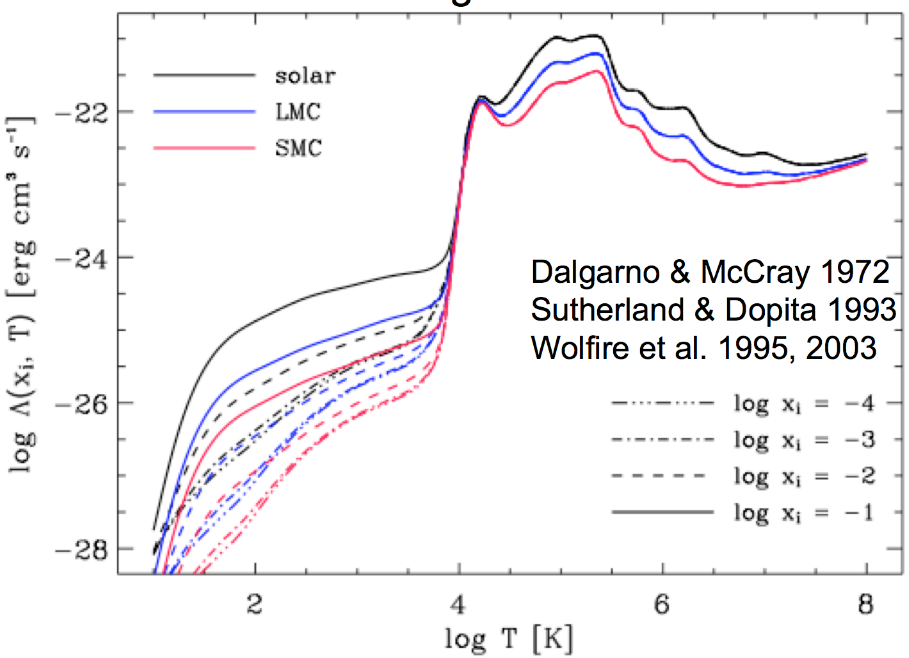
Heiles & Troland 2003, 2005

Thermal Instability Field 1965

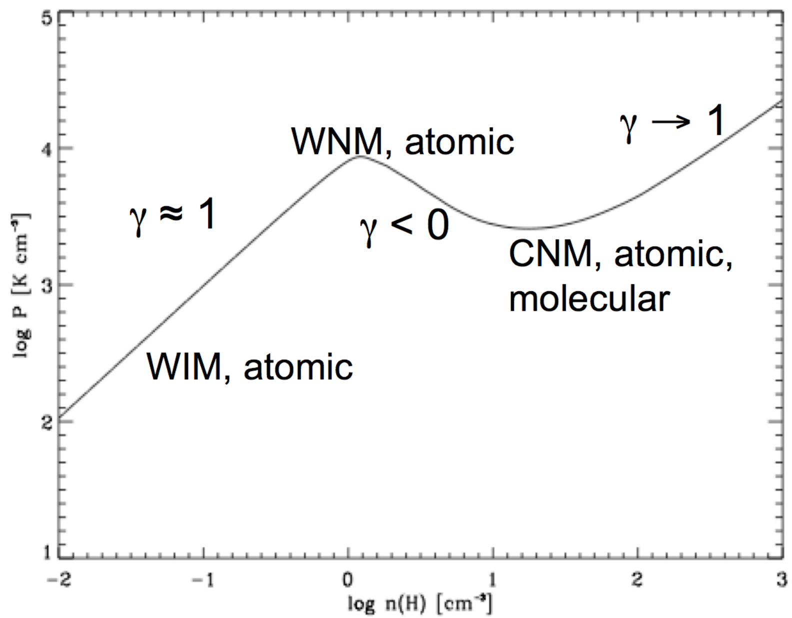
Net cooling rate for collisionally excited, optically thin lines:

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

cooling function



Thermal Equilibrium P(n) curve



Thermal Instability   Field 1965

Net cooling rate for collisionally excited, optically thin lines:

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

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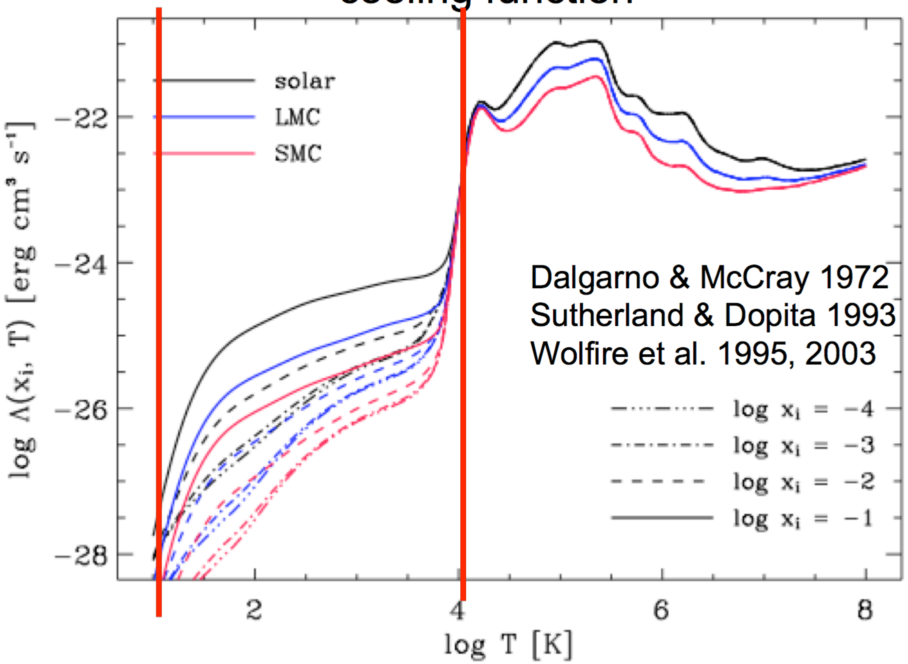

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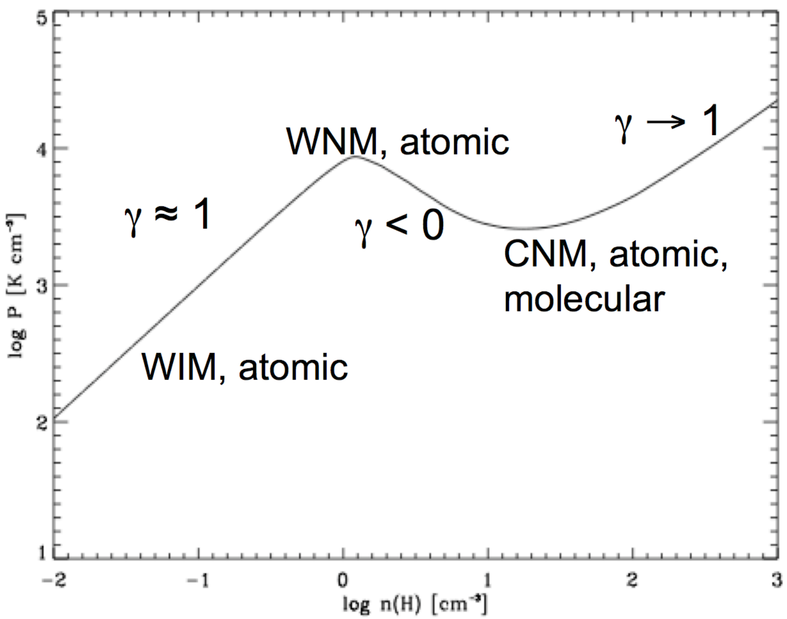

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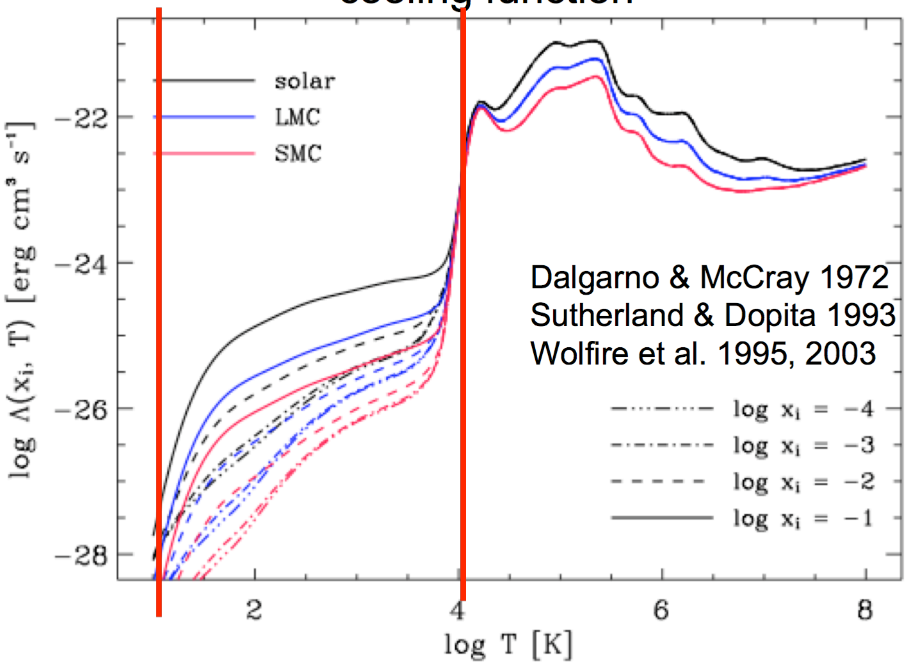

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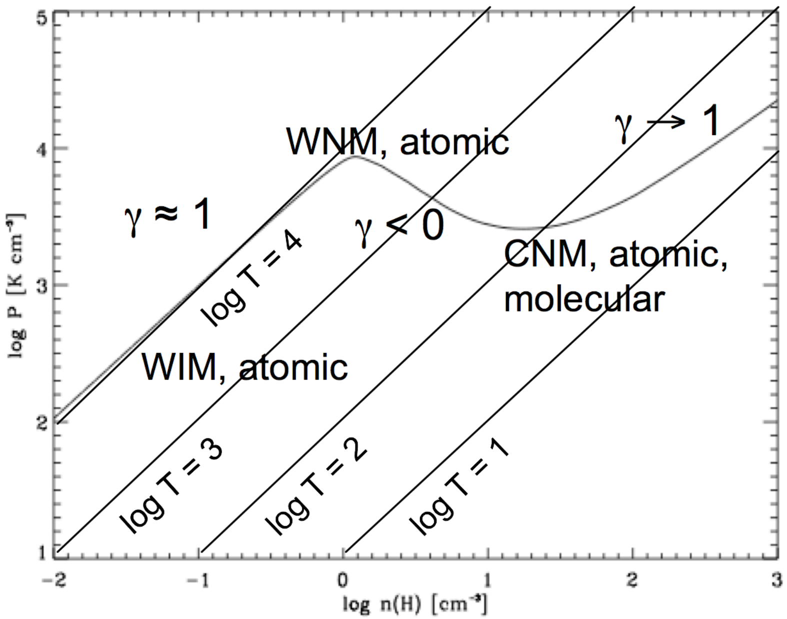
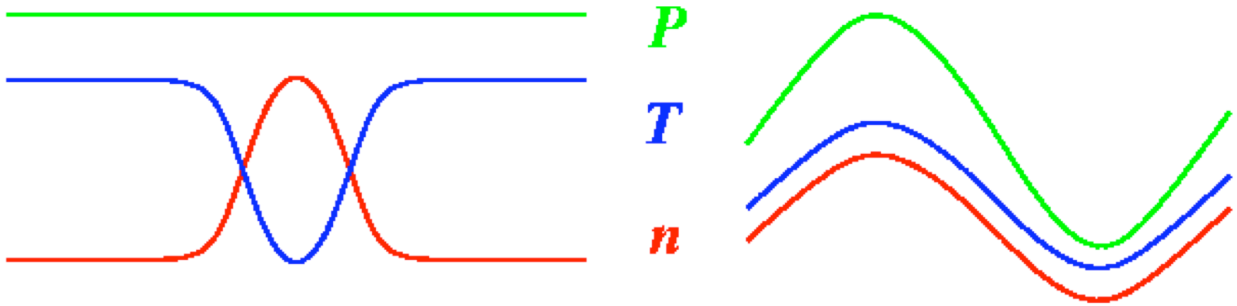


Thermal Instability   Field 1965

modes: condensation mode (isobaric)   acoustic mode (nearly adiabatic)



scales:

lower scale: heat conduction (10^{-3} … 10^{-2} pc): $\lambda_F \equiv \left(\frac{\kappa T}{n^2 \Lambda}\right)^{1/2}$,

needs to be resolved; Koyama & Inutsuka 2004

upper scale: sound crossing scale (10pc): $\lambda_c = \tau_c c_s$, $|\tau_c| \equiv \frac{3}{2} \frac{kT}{|\Gamma - n\Lambda|}$.

grows on **smallest** scales **first** (only limited by heat conduction)

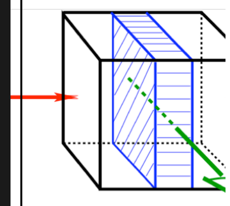
3D
(256x512²)

time evolution of column density

19 < log N < 22

44pc

...
+gravity



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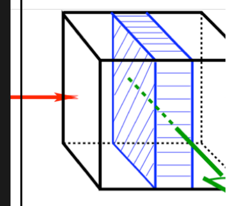


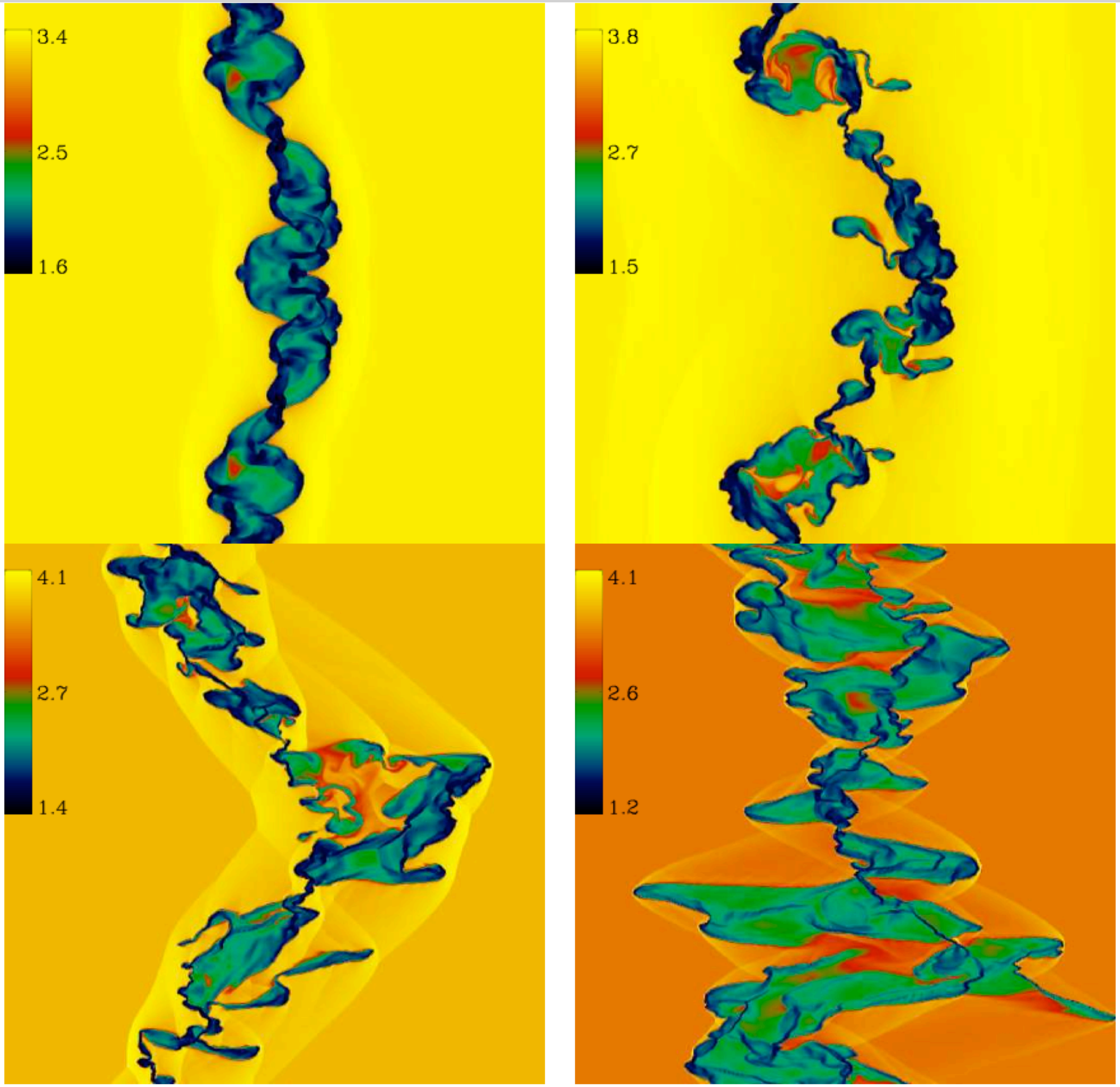
n = 1.0
Mach 1

2D maps
log T [K]

TI

n = 0.5
Mach 1

KHI



n = 0.5
Mach 2

NTSI

n = 0.5
Mach 3

NTSI

Heitsch, Burke
Hartmann, Sly
& Devriendt 2(

n = 1.0
Mach 1

2D maps
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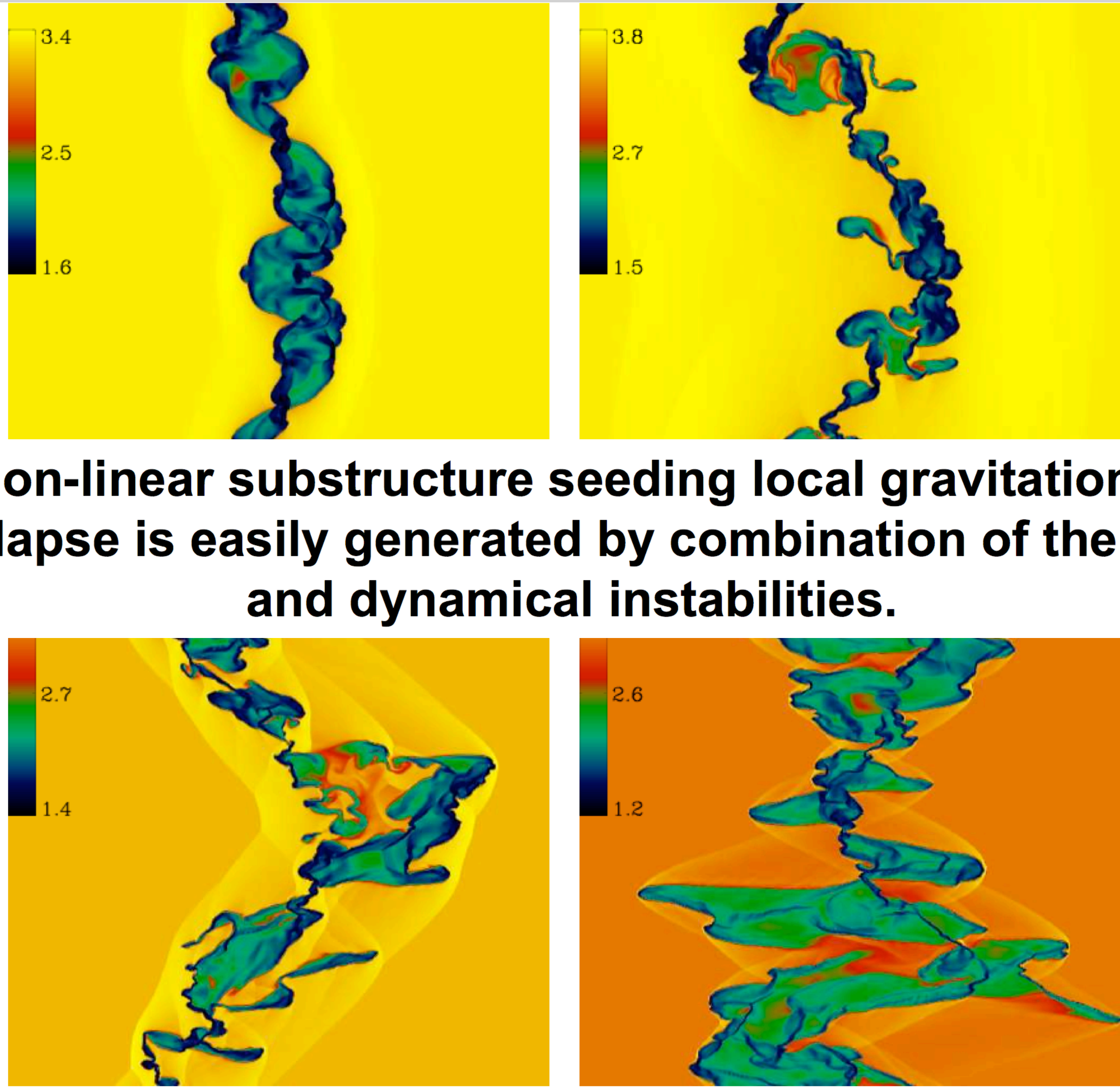


Non-linear substructure seeding local gravitational collapse is easily generated by combination of thermal and dynamical instabilities.

n =
Mach 2

).5
Mach 3

NTSI

NTSI

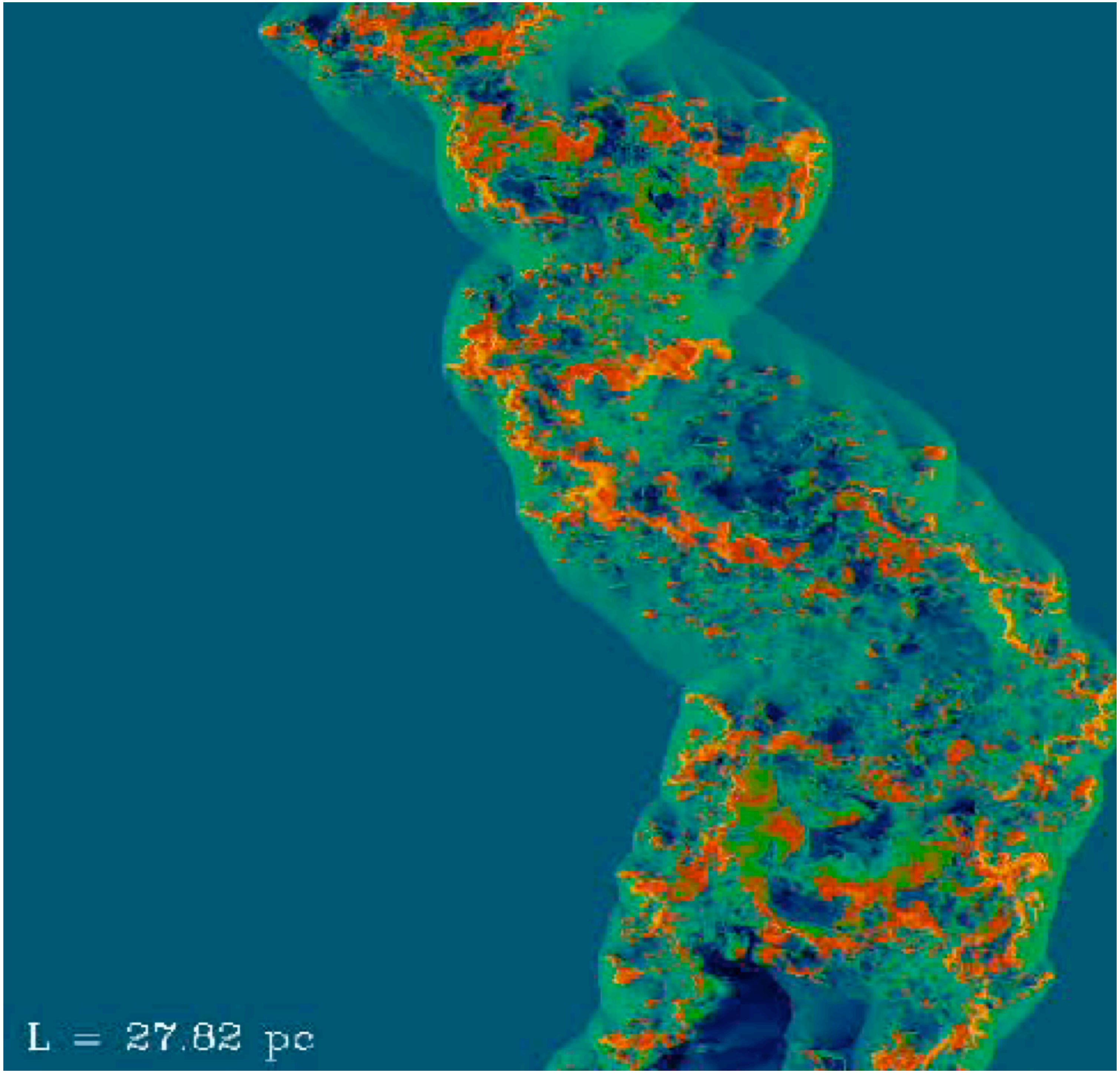
Heitsch, Burke
Hartmann, Sly
& Devriendt 2(

2D at 8192^2

density

10 Myrs

zoom



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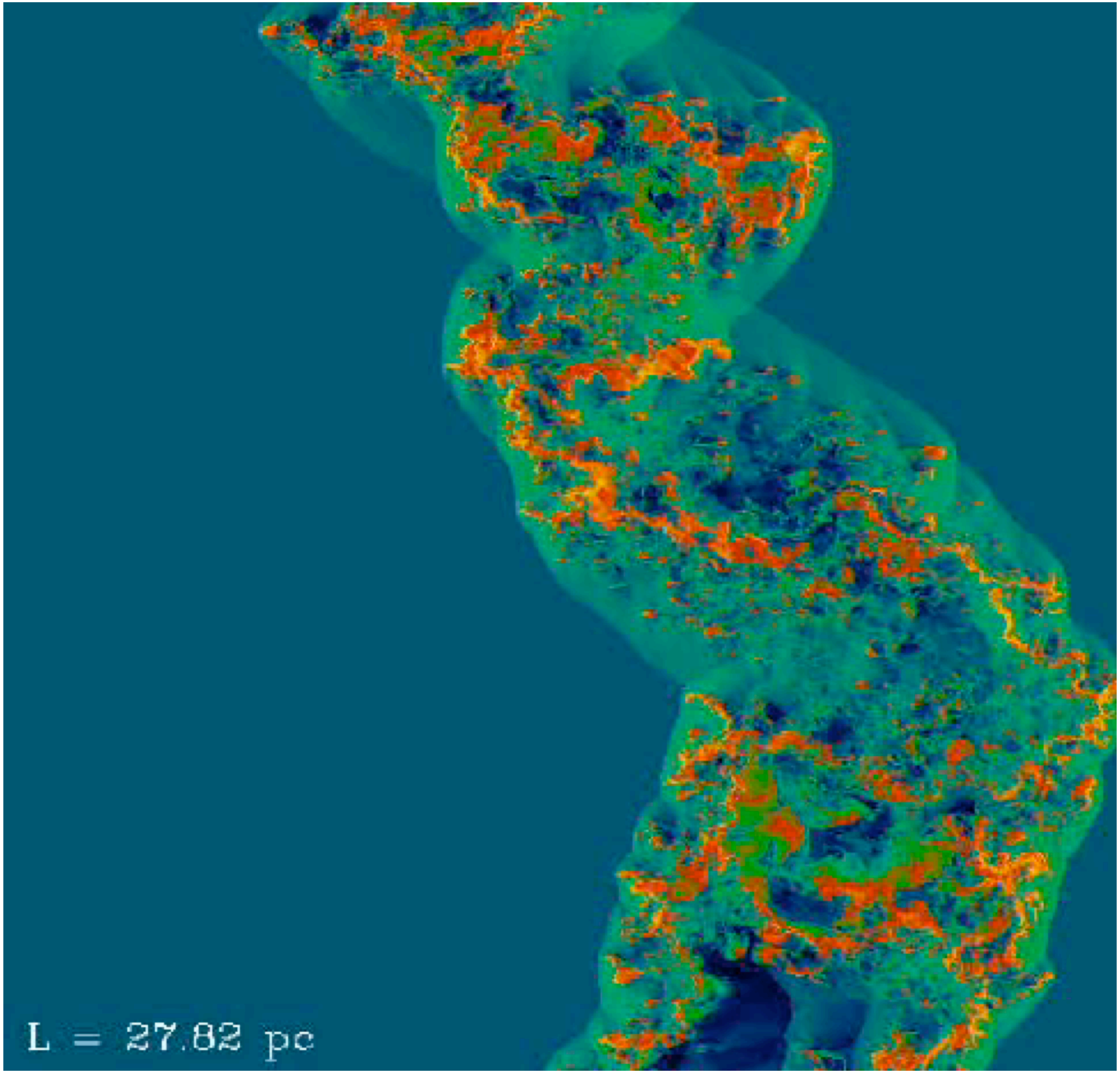
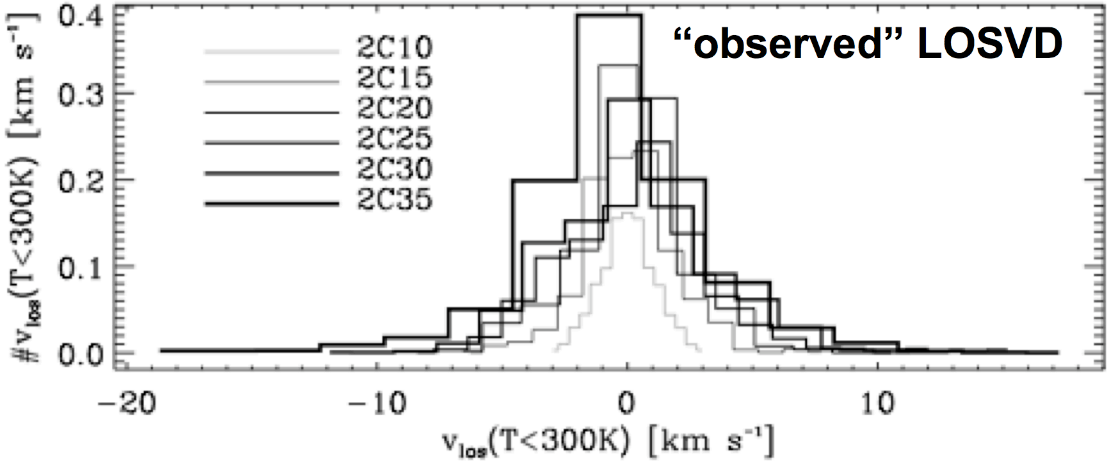
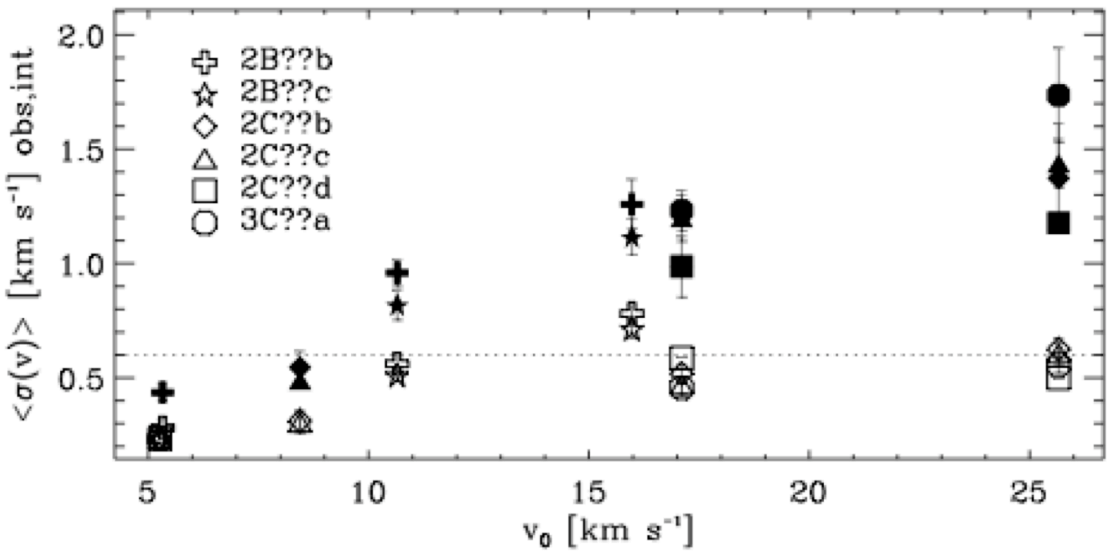


LOSVD for cold gas reproduces observed values



Internal LOSVD is (sub)sonic



Heitsch, Slyz, Devriendt, Hartmann, Burkert 2006

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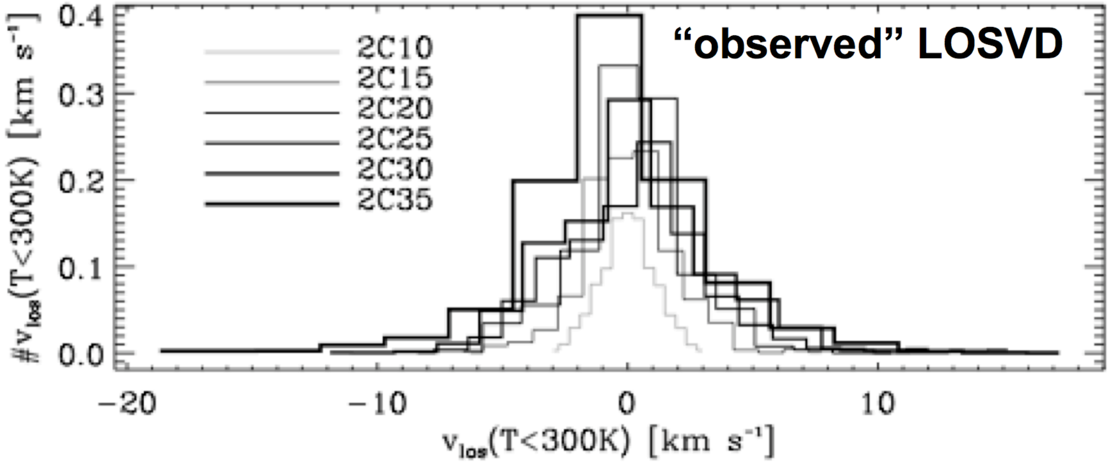

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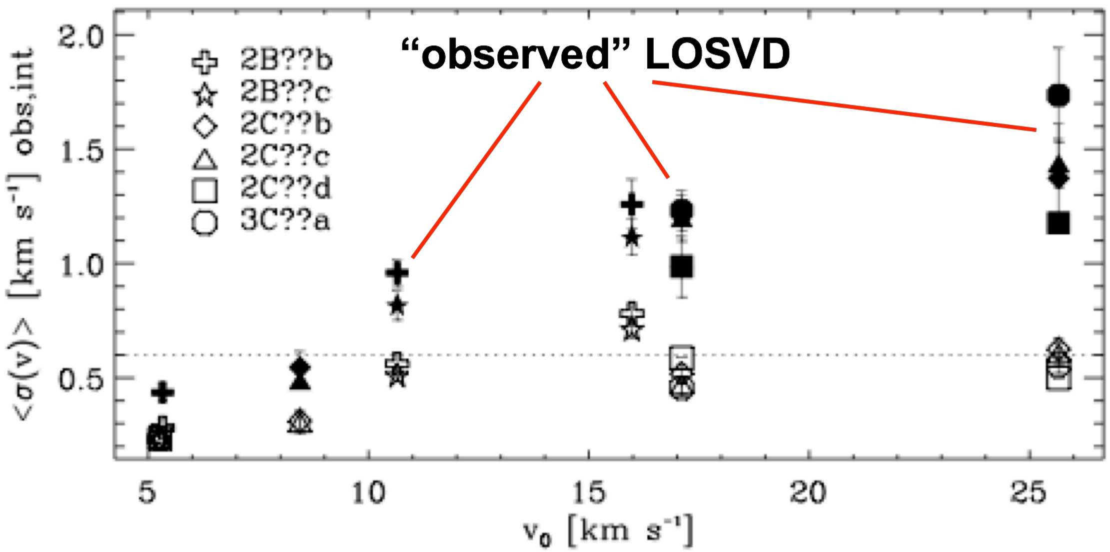

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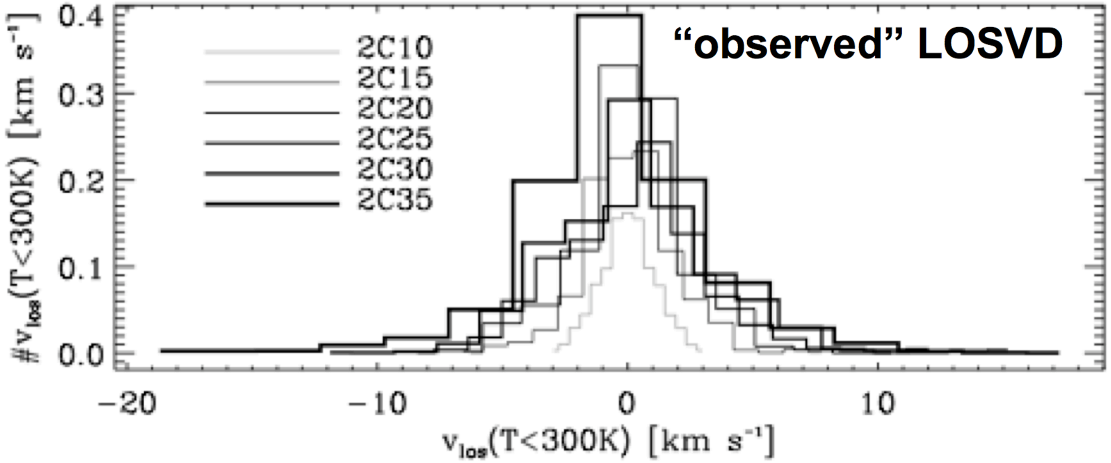

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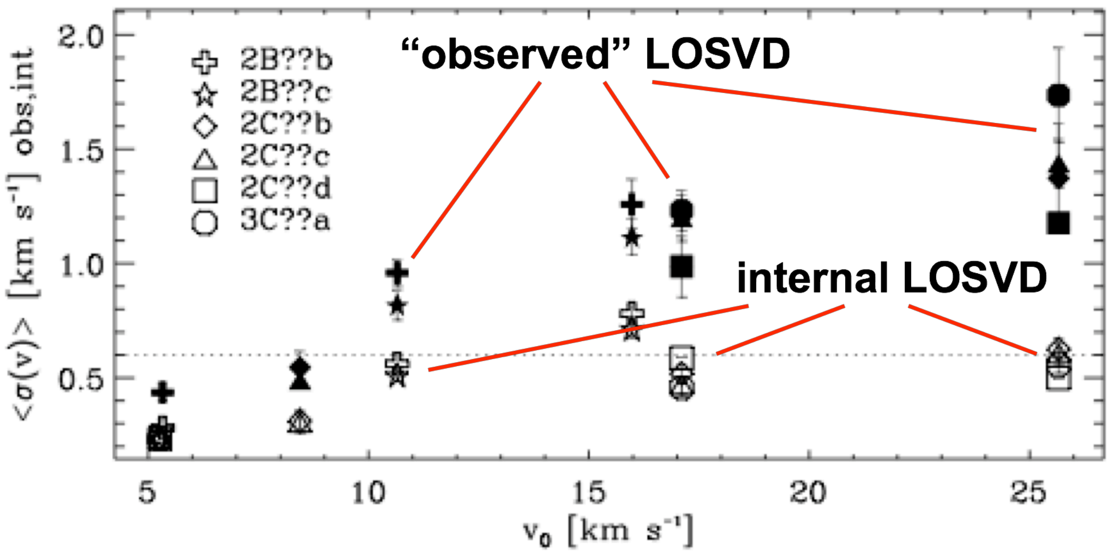

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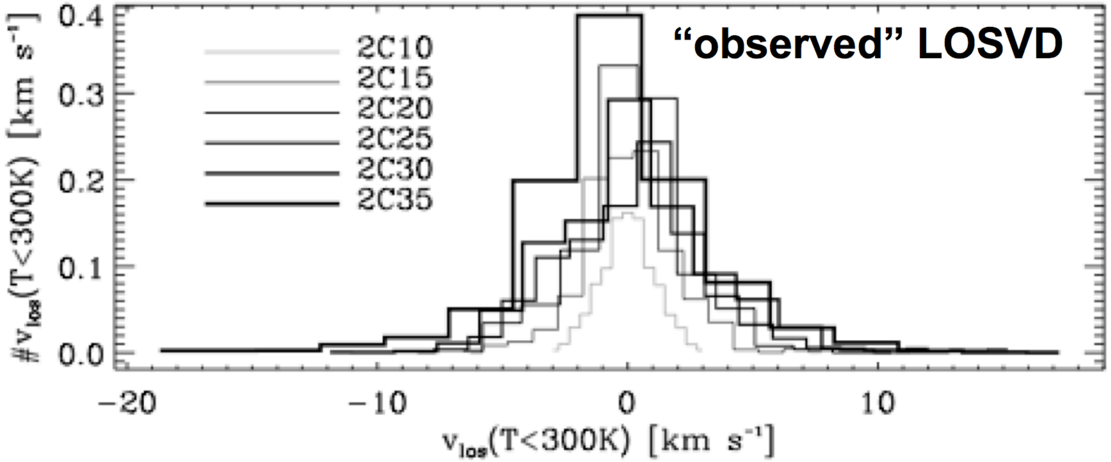

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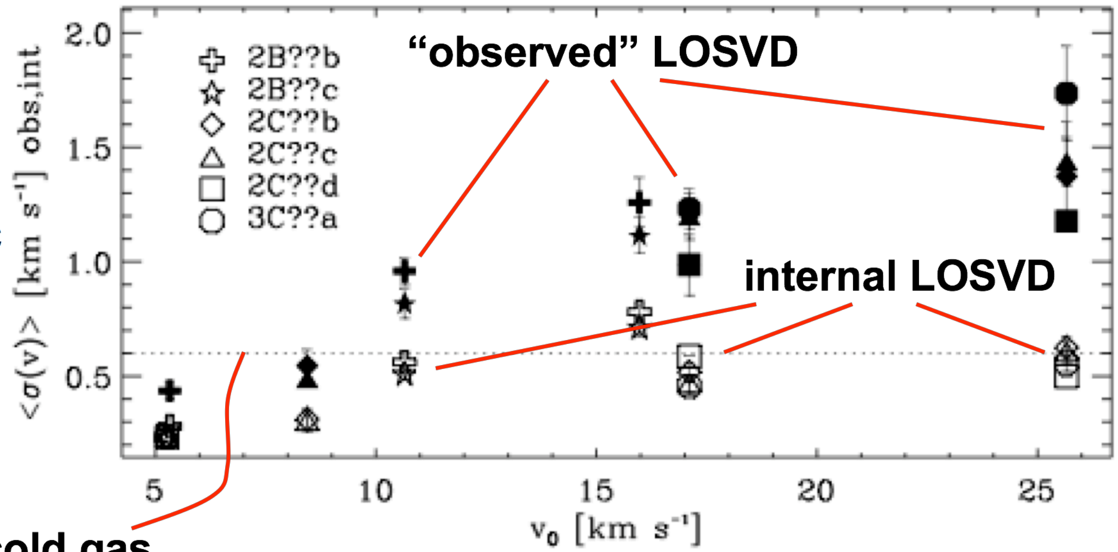
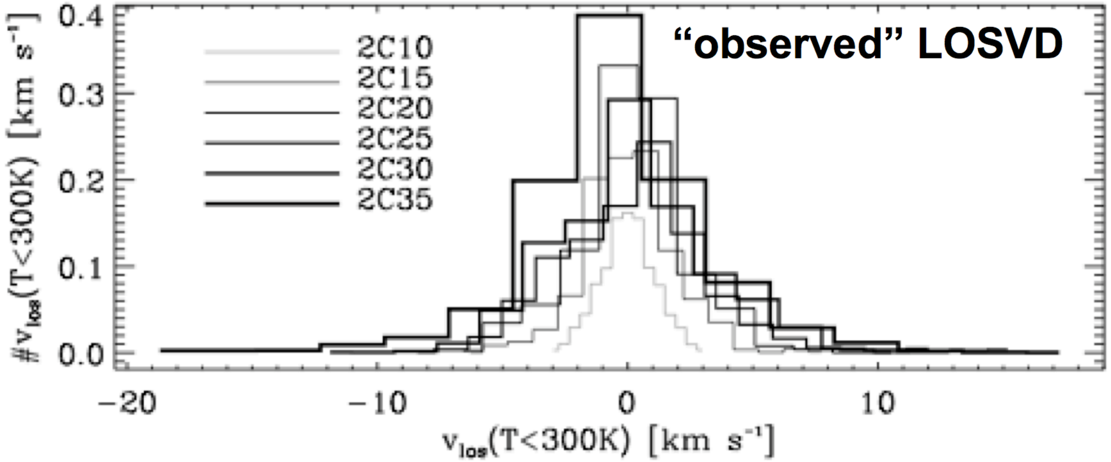


sound speed in cold gas

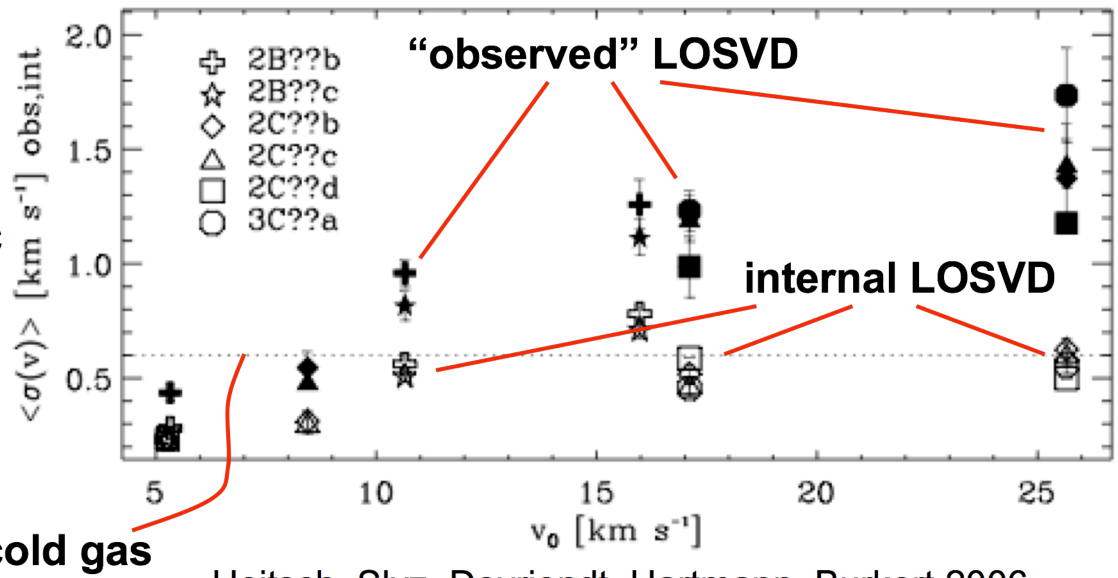
Heitsch, Slyz, Devriendt, Hartmann, Burkert 2006

LOSVD for cold gas reproduces observed values



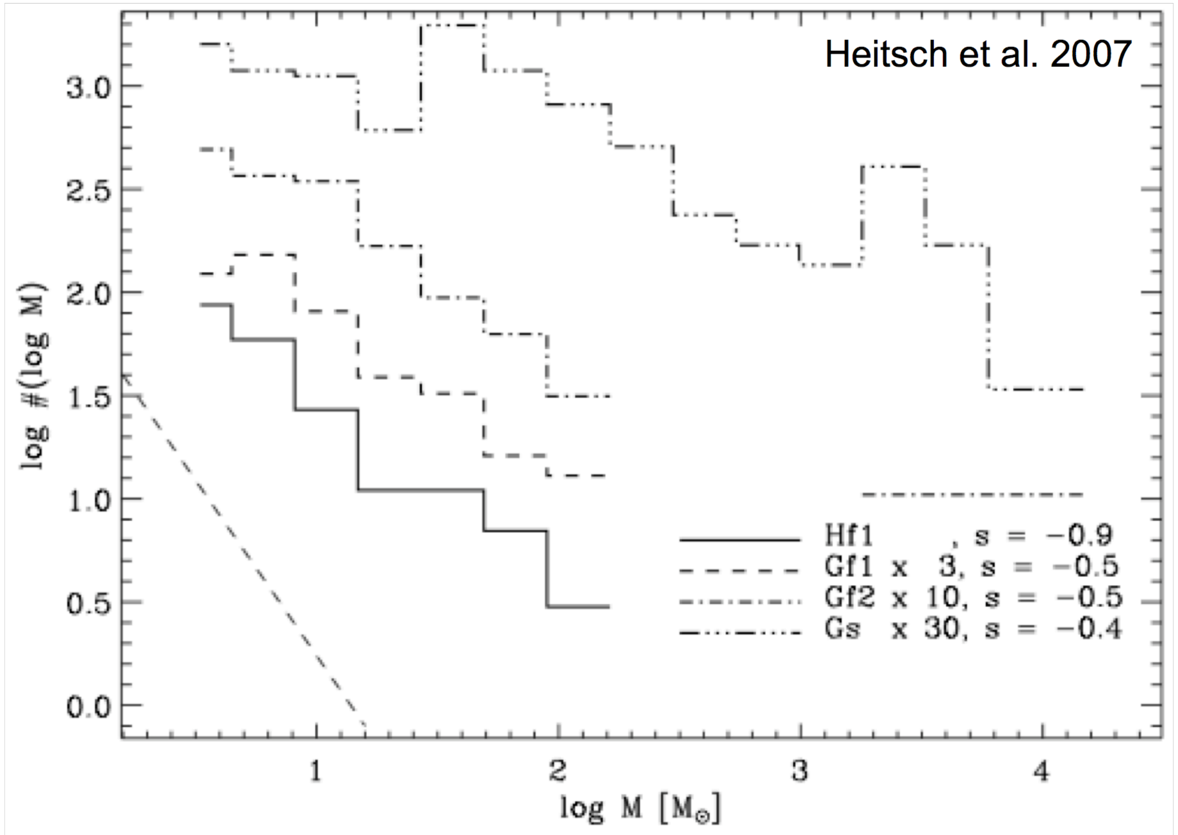
"Supersonic" does not necessarily refer to hydro-dynamical state of gas.

Internal LOSVD is (sub)sonic



Heitsch, Slyz, Devriendt, Hartmann, Burkert 2006

Clump mass distribution (see P. Hennebelle's talk)



Clump mass distribution

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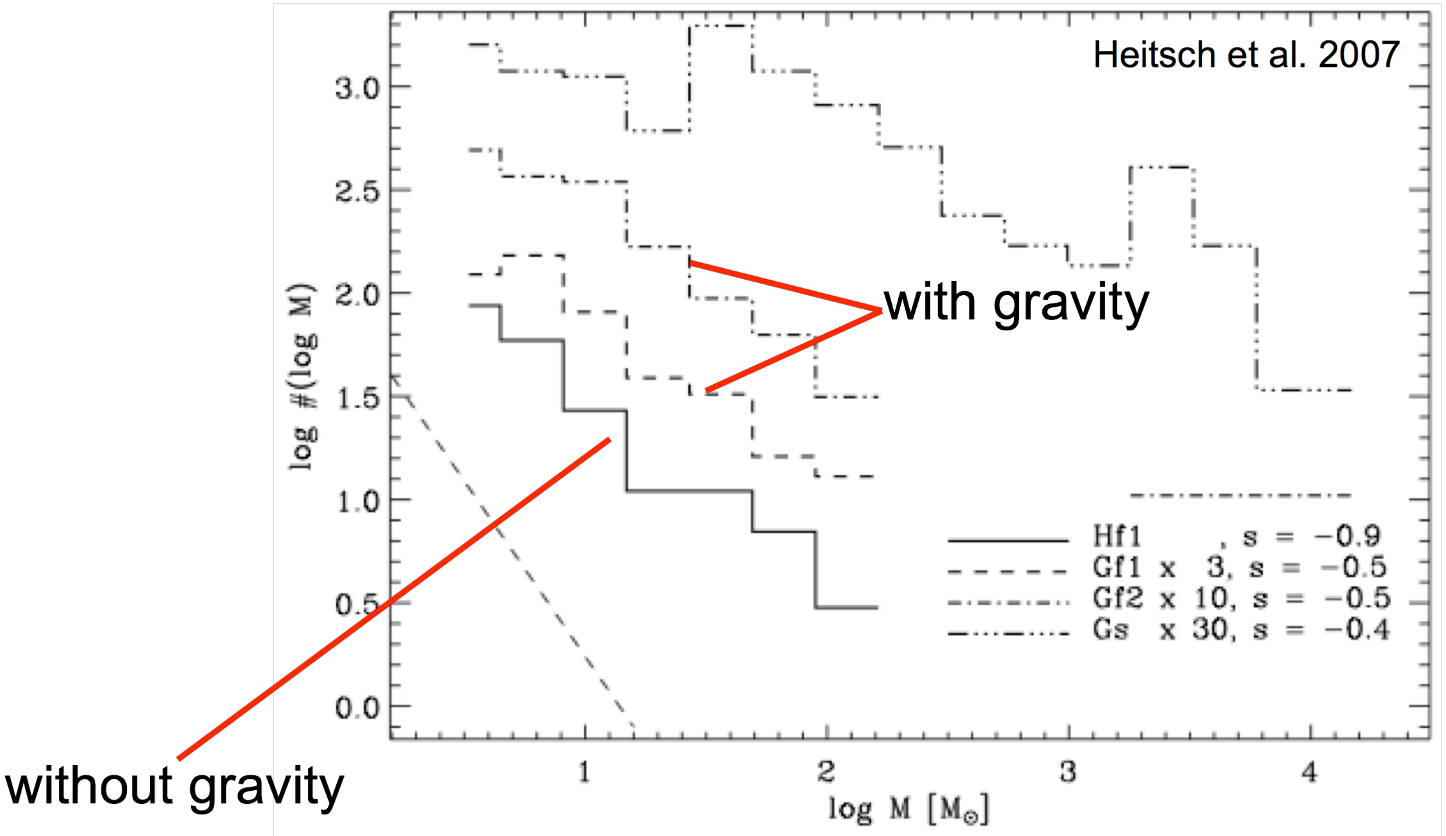

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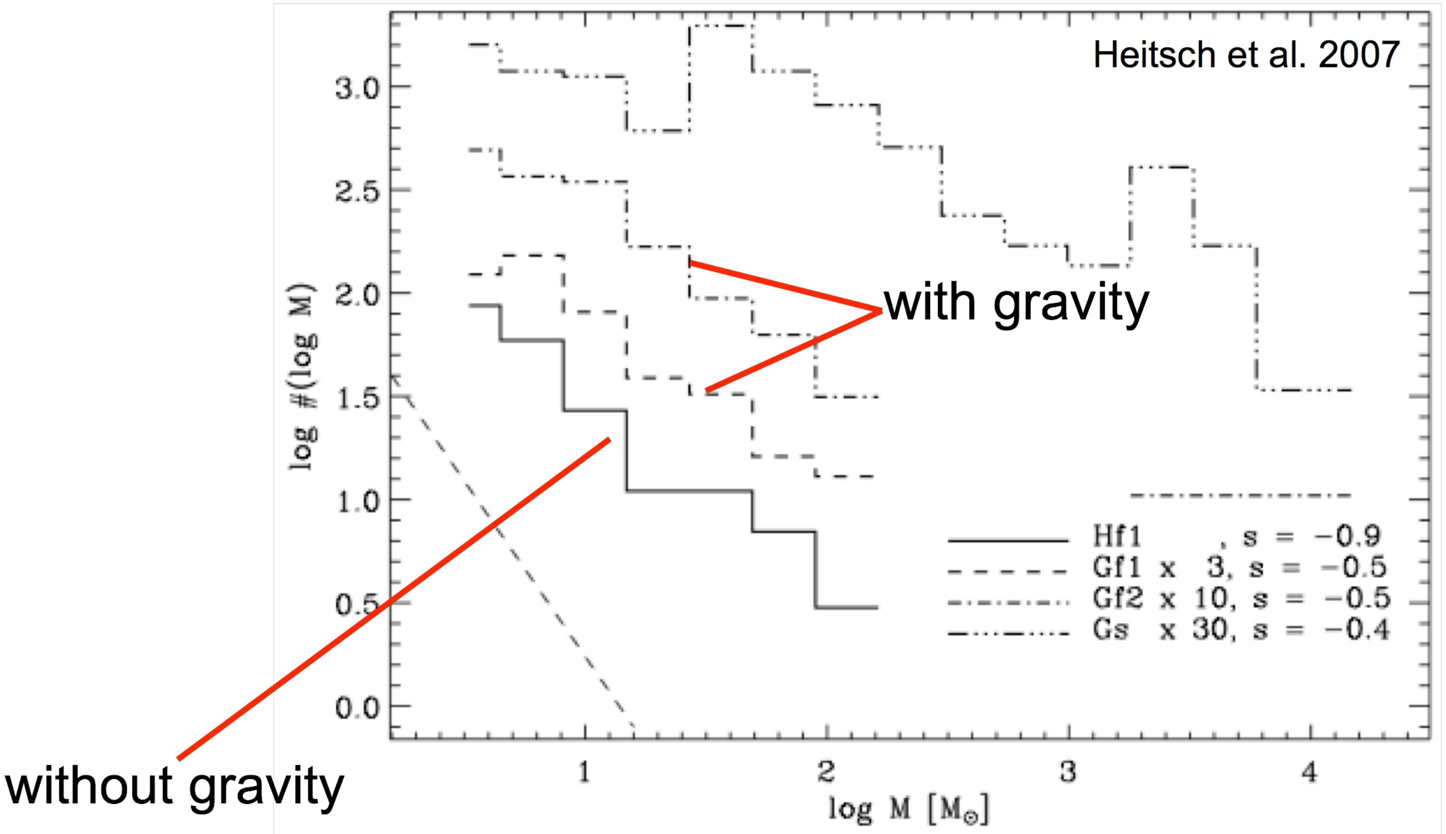

Clump mass distributions: Gravity does not make a significant difference.

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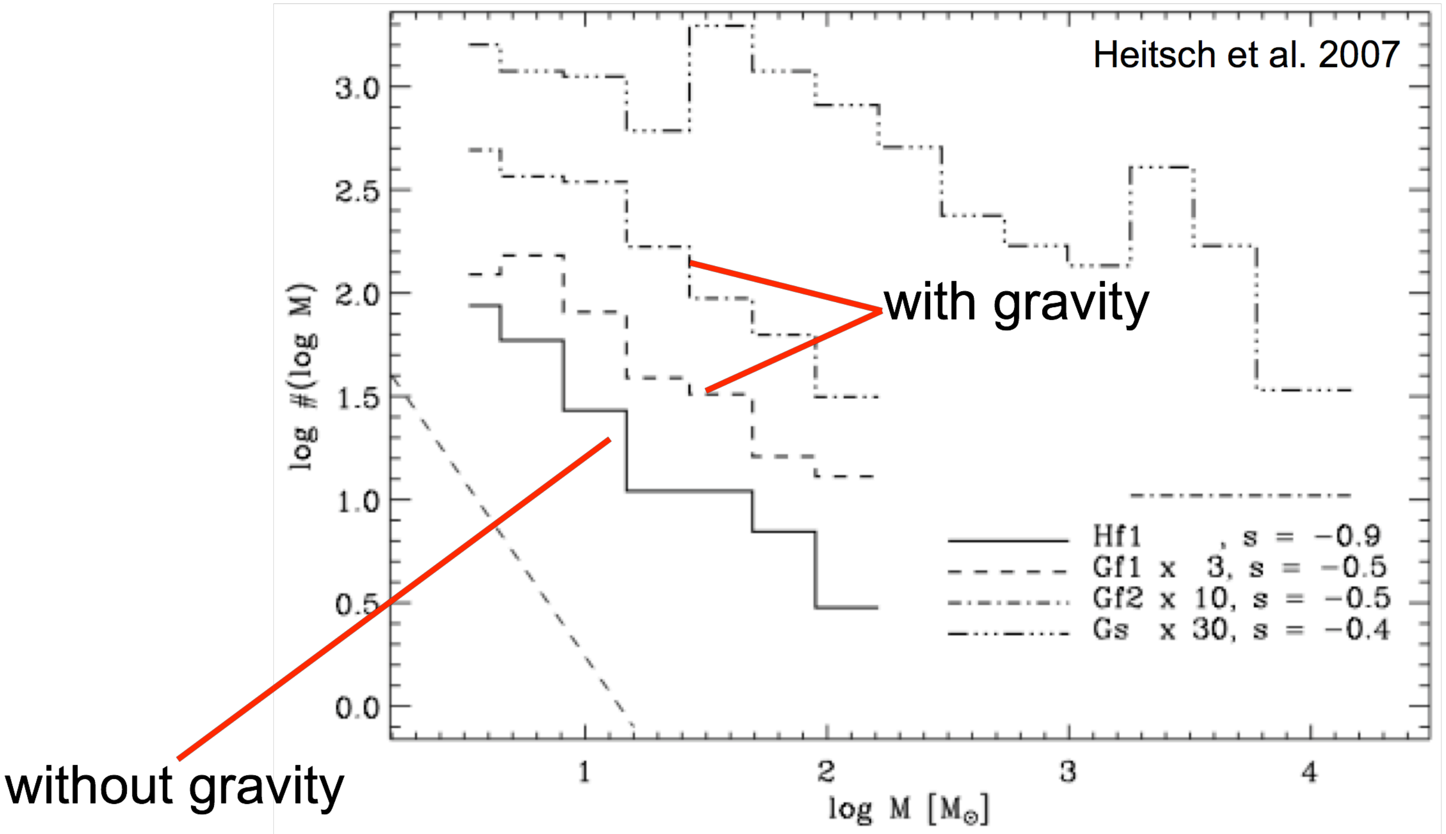
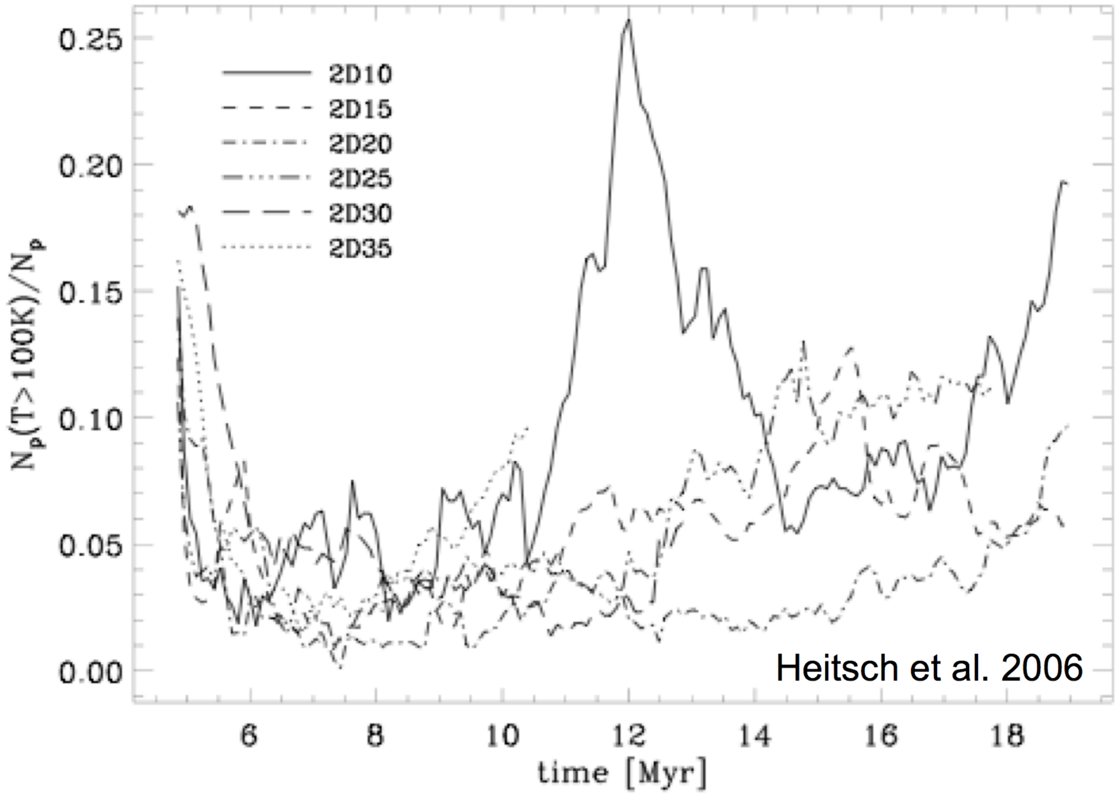


Clump mass distributions: Gravity does not make a significant difference.
Thermal and dynamical fragmentation possibly sets clump mass spectrur

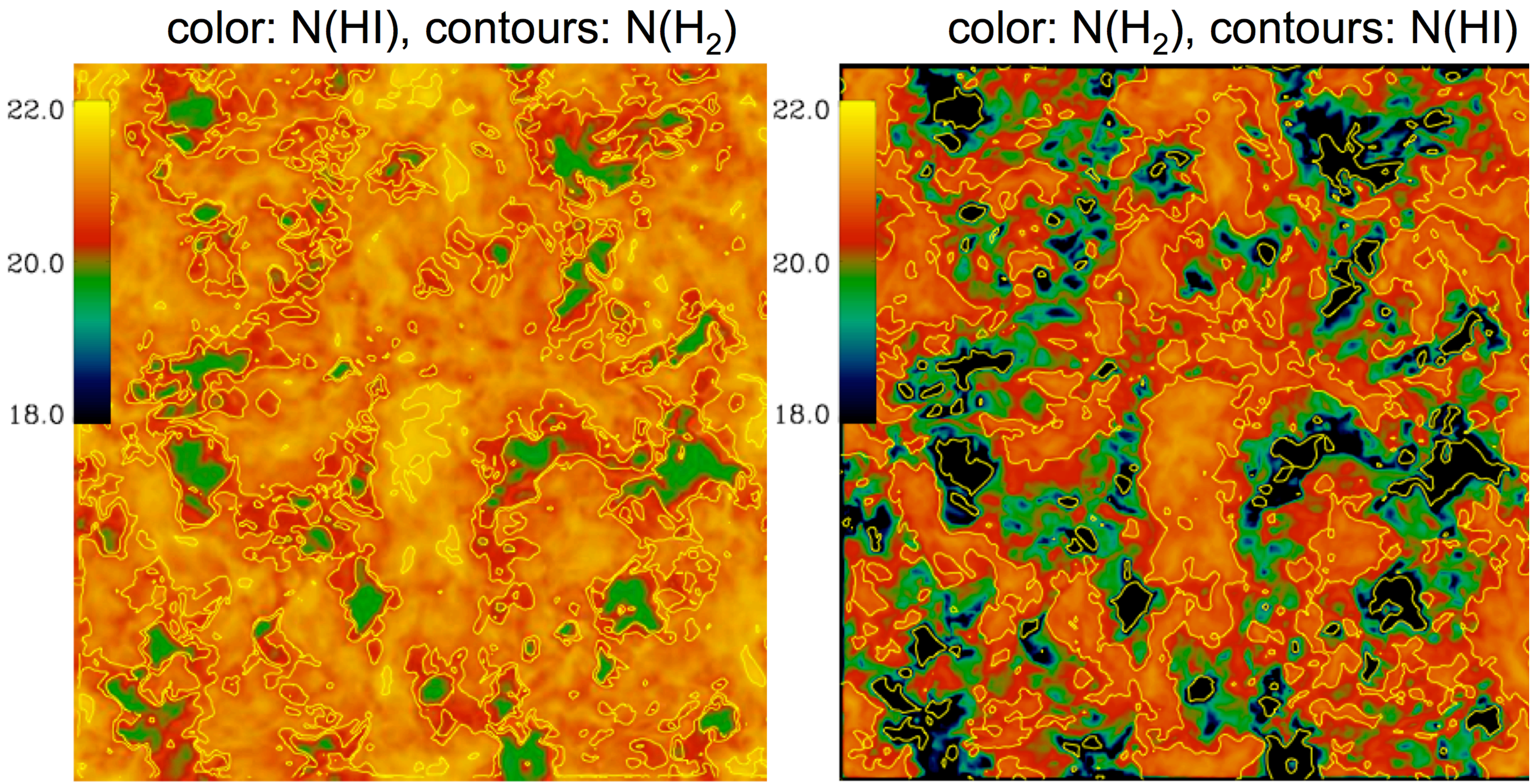
So far, we can only build CNM clouds…

→ implementation of H_2 (and CO) formation Bergin et al. 2004, Glover & Mac Low 2(



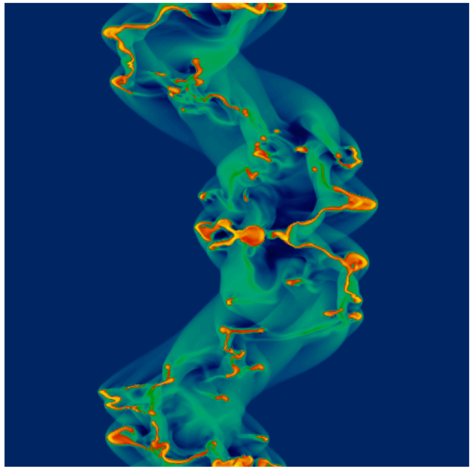
Fraction of (formerly) cold gas that gets reheated.

H_2-formation within dynamical evolution Bergin, Hartmann & Raymond 2004



H_2-abundances via equilibrium chemistry network by T. Bethell

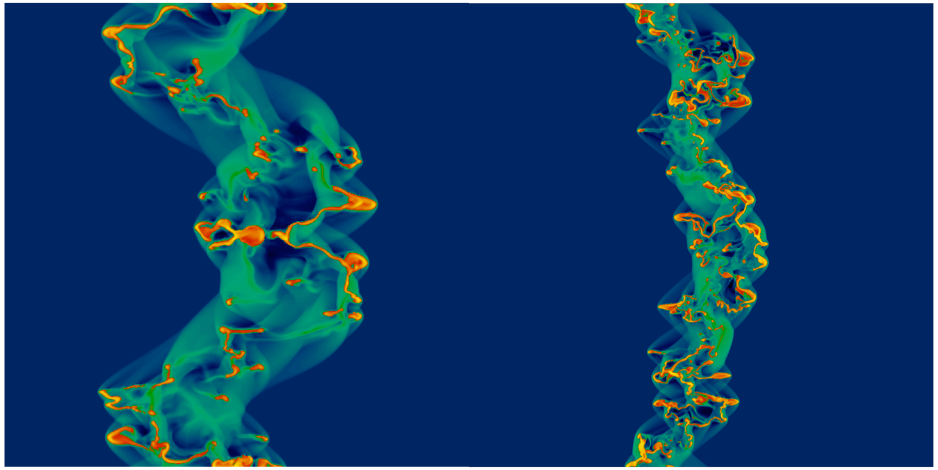
512



NTSI

laminar flow
unresolved cooling length
unresolved Field length

512 1024



NTSI

NTSI suppressed in favor of cooling

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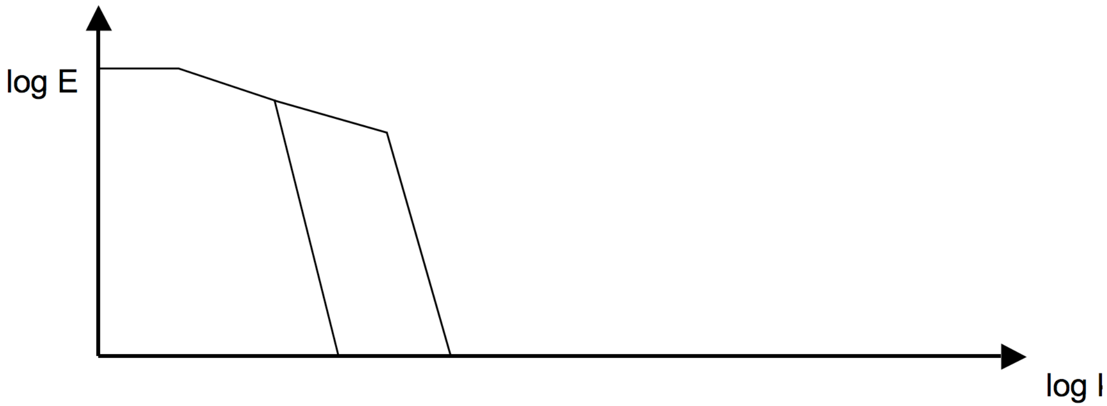
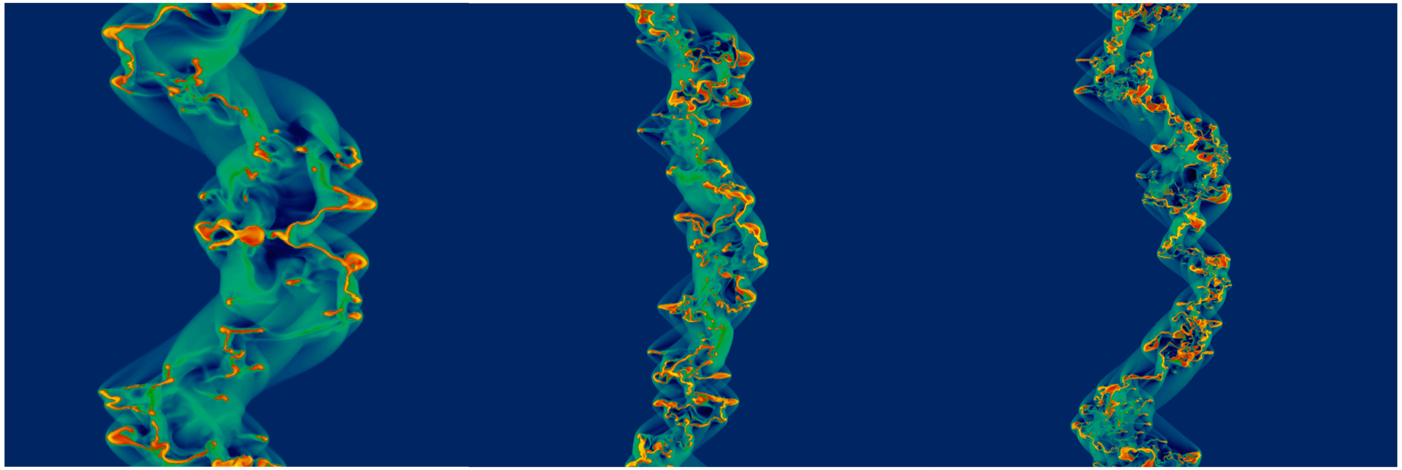


512 1024 2048



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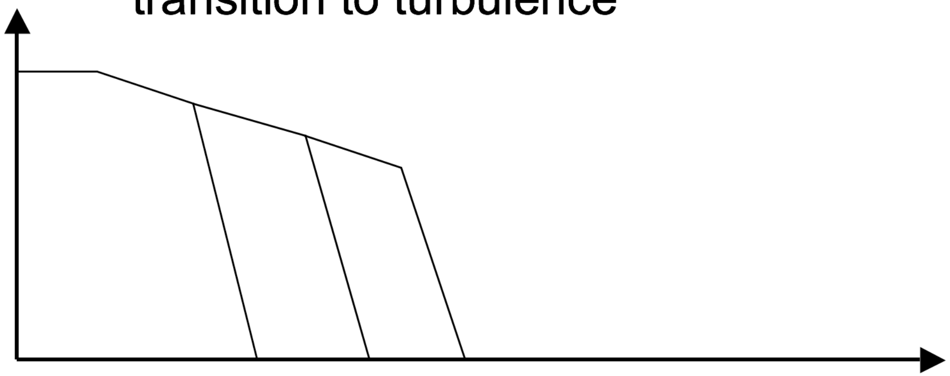
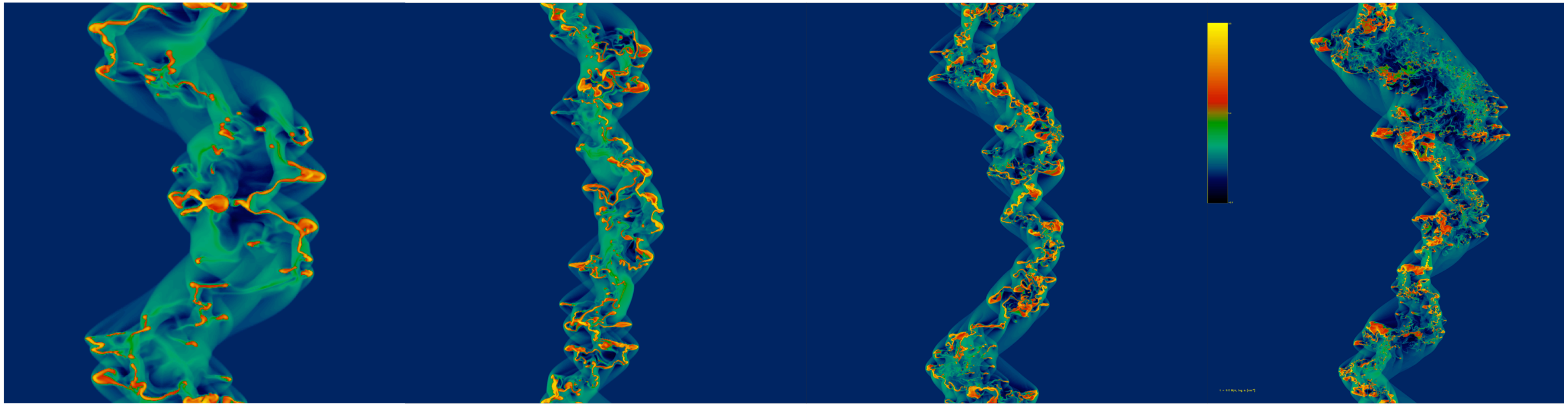
transition to turbulence



512 1024 2048 4096



NTSI

NTSI suppressed in favor of cooling

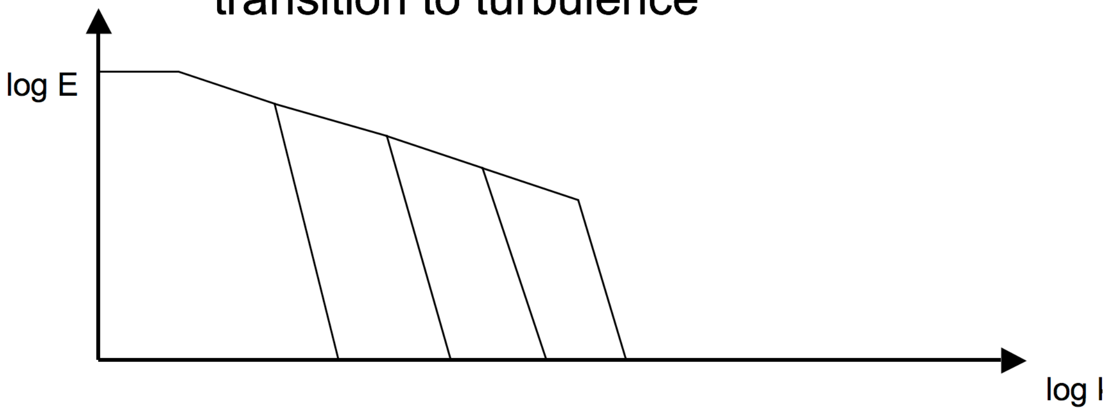
NTSI saturated by turbulence

laminar flow

unresolved cooling length

unresolved Field length

transition to turbulence



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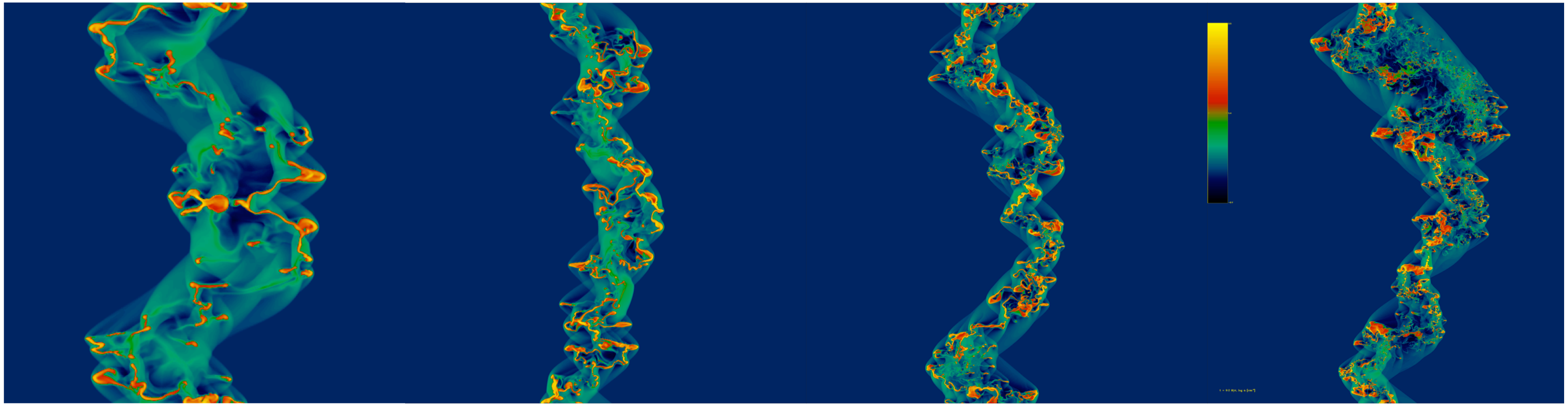

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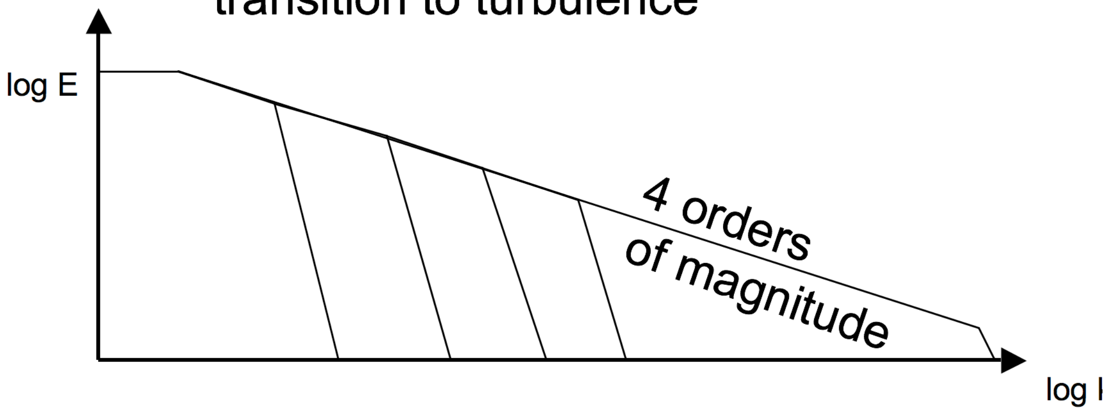

ISM

- Morphologies of molecular clouds
- Turbulence properties

} Cloud properties determined by formation process.

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Initial Conditions

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Colliding flows of atomic hydrogen

- provide natural source of turbulence during cloud formation.
- generate non-linear density perturbations (fragmentation) for immediate gravitational collapse (and star formation) during cloud formation.
- reproduce “supersonic” linewidths, however, the cold gas is (sub)sonic. Mixing between WNM and CNM.
- core mass distribution follows approximately $dN/dM \propto M^{-1.7}$: mass distribution possibly set early during cloud formation (TI!)

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- magnetic fields in 3D? — *suppression of structure, B(n)-relation*
- molecule formation? — *H_2-abundance, time scales*
- feedback? — *cloud dispersal*

END