Prestellar Cores

- formation and structure

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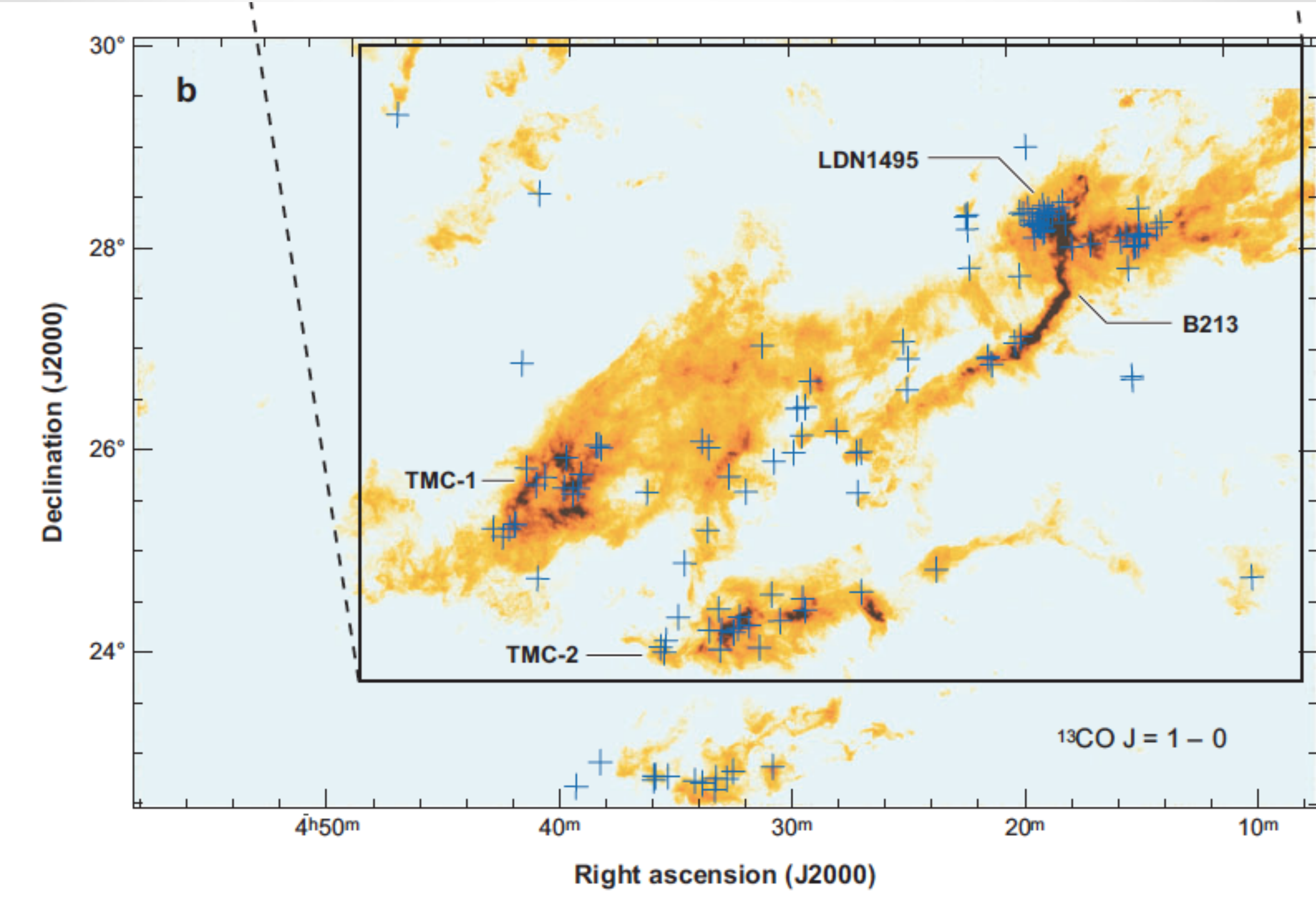
Princeton, Oct 2012

Outline

- Observation
- Definition and classification
- Typical core
- Size distribution
- Physics in Play
- Gravity and magnetic fields: Important mass scales (M_J, M_{BE}, M_{cr})
- Turbulence
- Formation models
- Initial formation and evolution
- Summary



Taurus Molecular Cloud Bergin & Tafalla (2007)

Observation & Classification

- Cores - High density peaks in GMC:

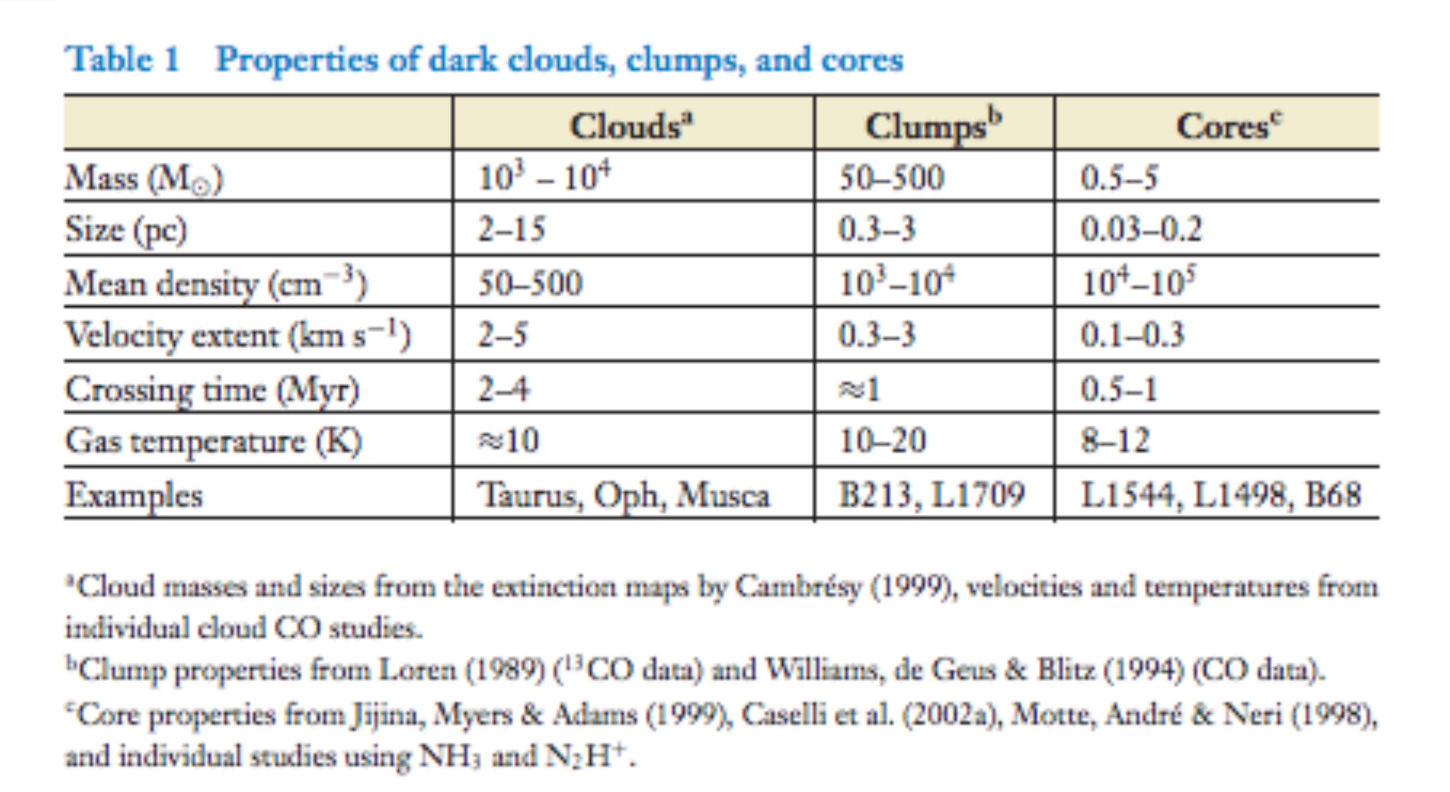


Table 1 Properties of dark clouds, clumps, and cores

	Clouds[a]	Clumps[b]	Cores[c]
Mass ($M_\odot$)	$10^3 - 10^4$	50–500	0.5–5
Size (pc)	2–15	0.3–3	0.03–0.2
Mean density (cm^{-3})	50–500	10^3–10^4	10^4–10^5
Velocity extent (km s^{-1})	2–5	0.3–3	0.1–0.3
Crossing time (Myr)	2–4	≈1	0.5–1
Gas temperature (K)	≈10	10–20	8–12
Examples	Taurus, Oph, Musca	B213, L1709	L1544, L1498, B68

[a] Cloud masses and sizes from the extinction maps by Cambrésy (1999), velocities and temperatures from individual cloud CO studies.

[b] Clump properties from Loren (1989) (^{13}CO data) and Williams, de Geus & Blitz (1994) (CO data).

[c] Core properties from Jijina, Myers & Adams (1999), Caselli et al. (2002a), Motte, André & Neri (1998), and individual studies using NH$_3$ and N$_2$H$^+$.

Bergin & Tafalla (2007)

Observation & Classification

Before collapse:

- Starless cores ($C^{18}O$, NH_3, dust extinction)
- Prestellar cores (starless but self-gravitating, dust continuum emission, NH_3, N_2H^+)

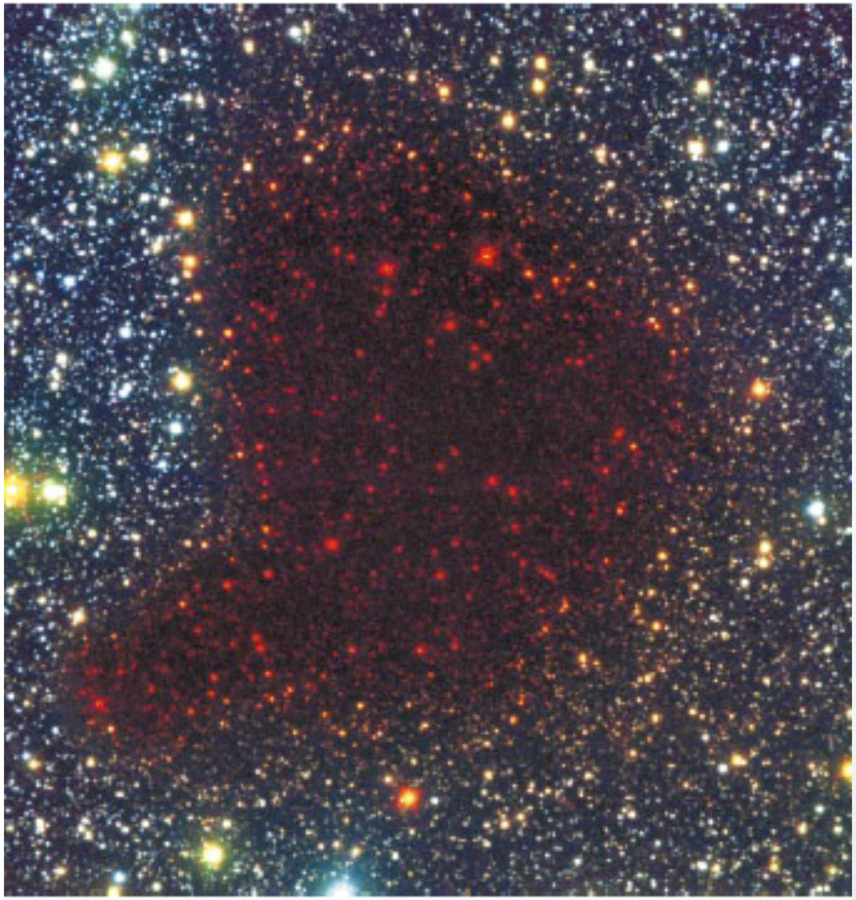
After collapse (More in Andrea's talk) :

- Class 0 protostellar cores(result from gravitational collapse: $M_{star} << M_{env}$)
- Class I, II, III protostars and YSOs

Barnard 68

Visible

Near infrared



Alves et. Al. (2001)

Summary of core properties I

- (Median?) Size: 2 $M_{\odot}$, 0.1pc
- Density: (10^4-10^7 cm^{-3})

dust emission (absorption) => N(dust)=>N(gas)

Molecular lines

- Temperature: (dust: 15-20K ; gas: 10-12 K)

Well coupled by collision

Bergin & Tafalla (2007)

Summary of c

- Velocity structure:

External: supersonic (Sash

Internal: subsonic

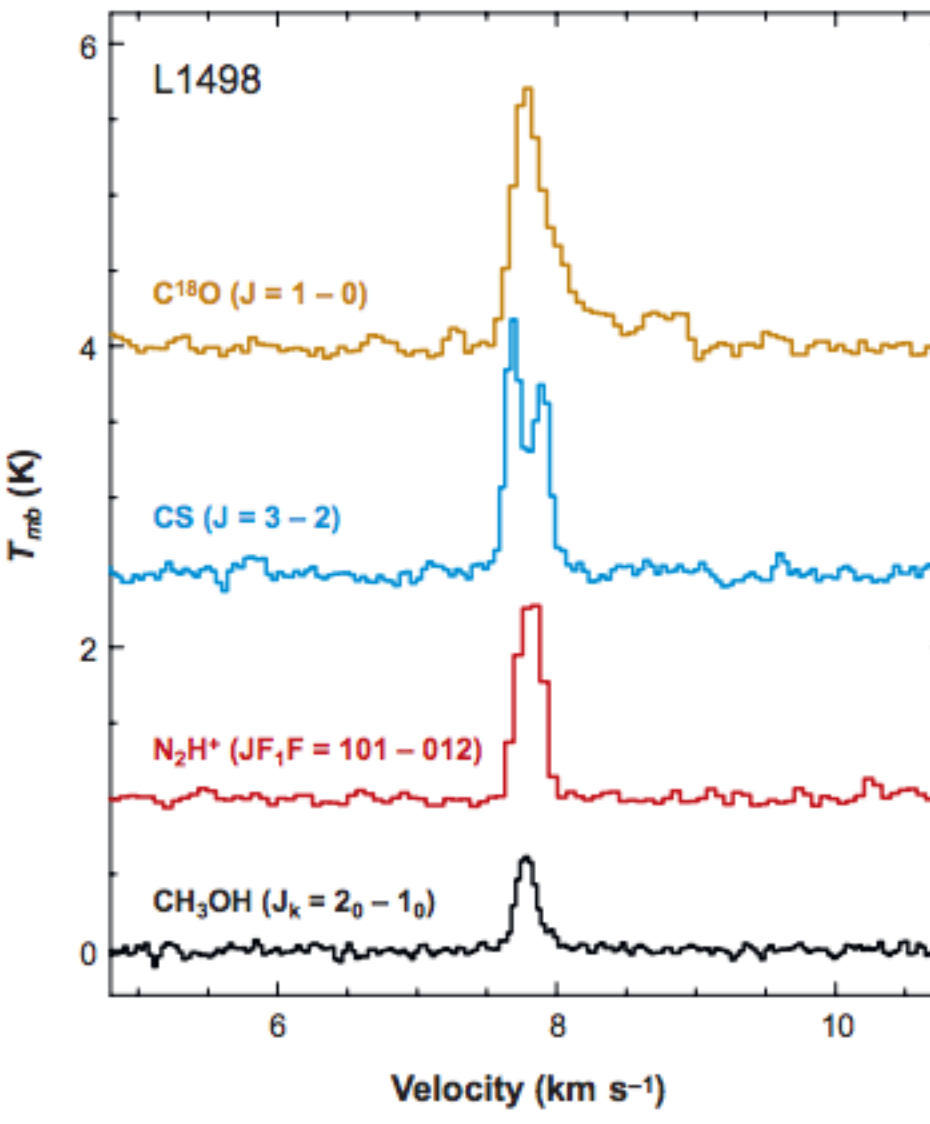
Cs~ 0.2, 0.66, 2 km/s for

T~ 10, 100, 1000 K

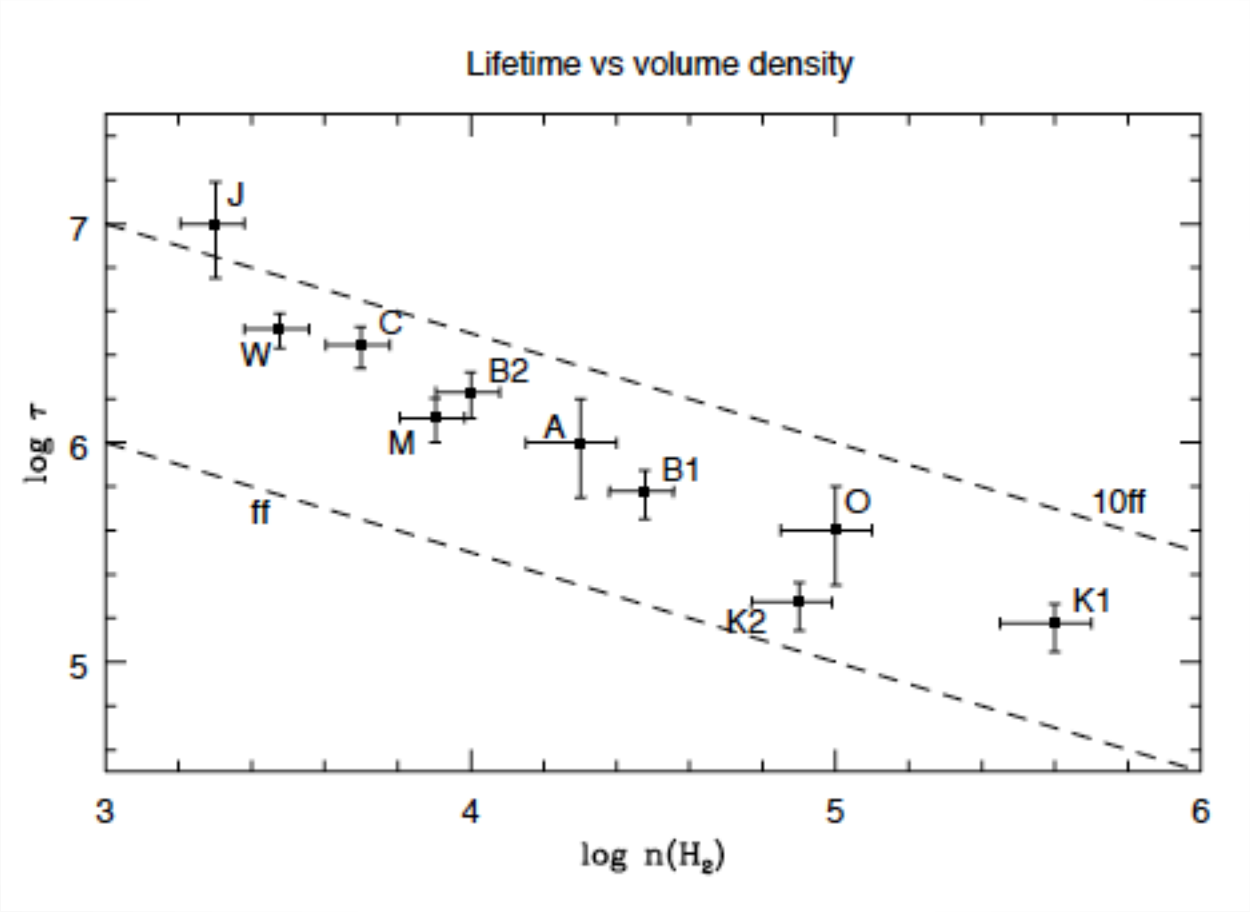
- Magnetic field:

Zeeman splitting and pola

(>5-10 μ G)



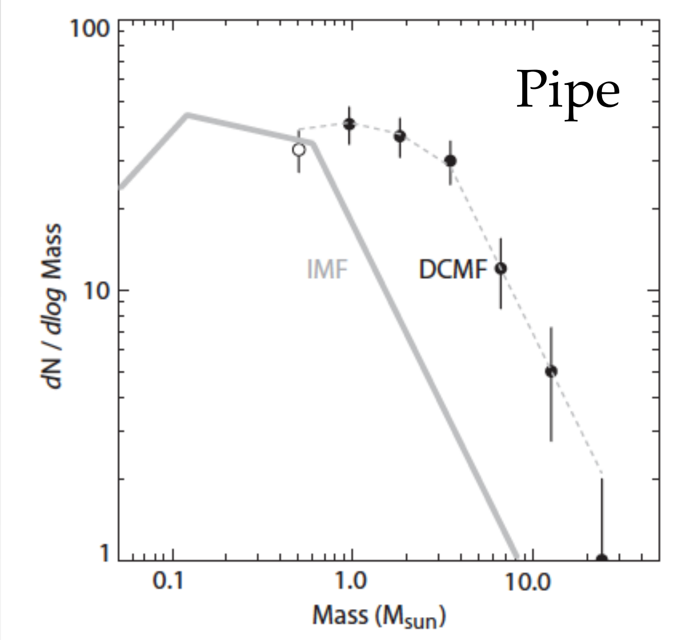
Core life time



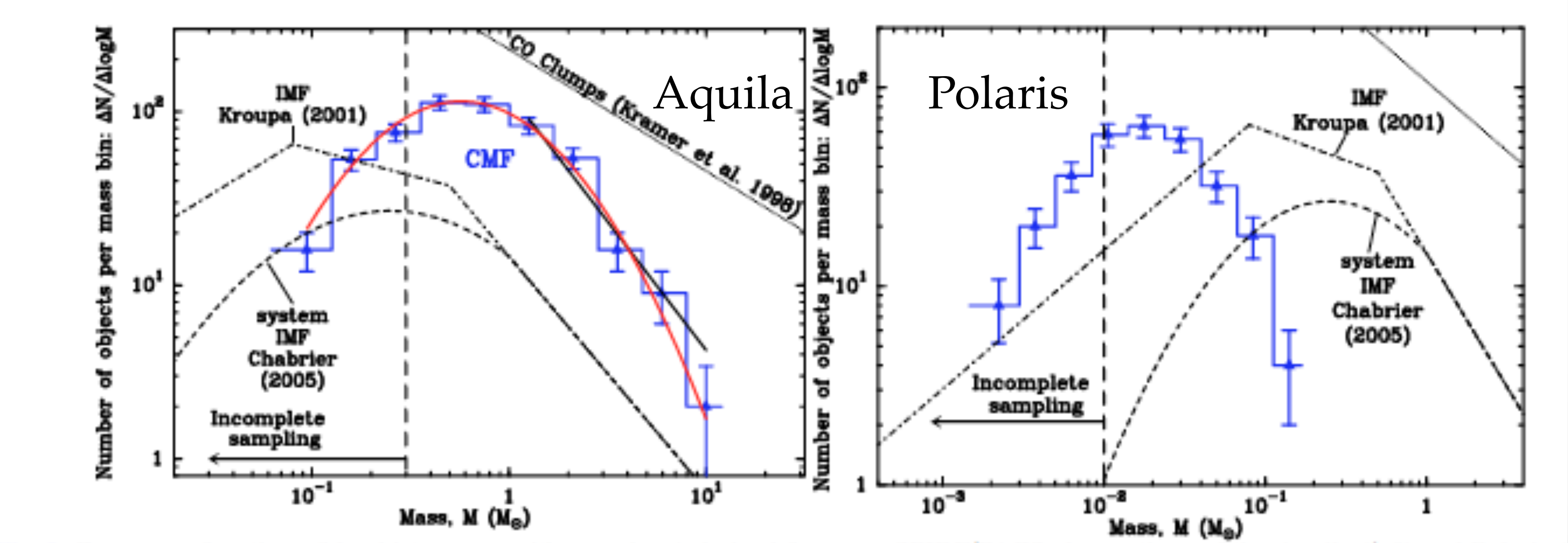
Andre et.al. (2008)

Core Mass Function CMF

More in Elisa's talk



Alves (2007)



Andre et. al. (2010)

Physics in play:

…

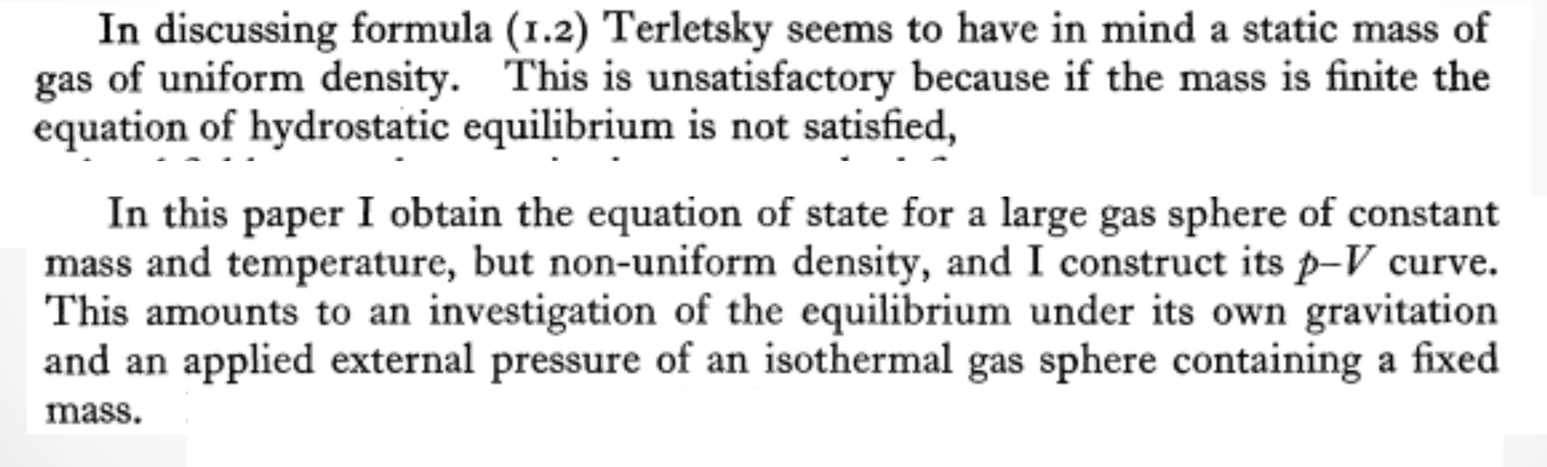
Gravity, Magnetic field, Turbulence, and more …

Self Gravity

- Jeans Mass vs Boner-Ebert Mass

Jeans Mass: an infinite homogeneous gravitating system: $t_{\rm ff} < t_{sound}$.

$$M_J = \left(\frac{4\pi}{3}\right)\rho R_J^3 = \left(\frac{\pi}{6}\right)\frac{c_s^3}{G^{3/2}\rho^{1/2}} \simeq (2\ \mathrm{M}_\odot)\left(\frac{c_s}{0.2\ \mathrm{km\ s^{-1}}}\right)^3\left(\frac{n}{10^3\ \mathrm{cm^{-3}}}\right)^{-1/2}.$$



In discussing formula (1.2) Terletsky seems to have in mind a static mass of gas of uniform density. This is unsatisfactory because if the mass is finite the equation of hydrostatic equilibrium is not satisfied,

In this paper I obtain the equation of state for a large gas sphere of constant mass and temperature, but non-uniform density, and I construct its *p*–*V* curve. This amounts to an investigation of the equilibrium under its own gravitation and an applied external pressure of an isothermal gas sphere containing a fixed mass.

Bonnor 1956

Bonnor-Ebert Mass

- For a pressure bound isothermal sphere:

The virial theorem gives:

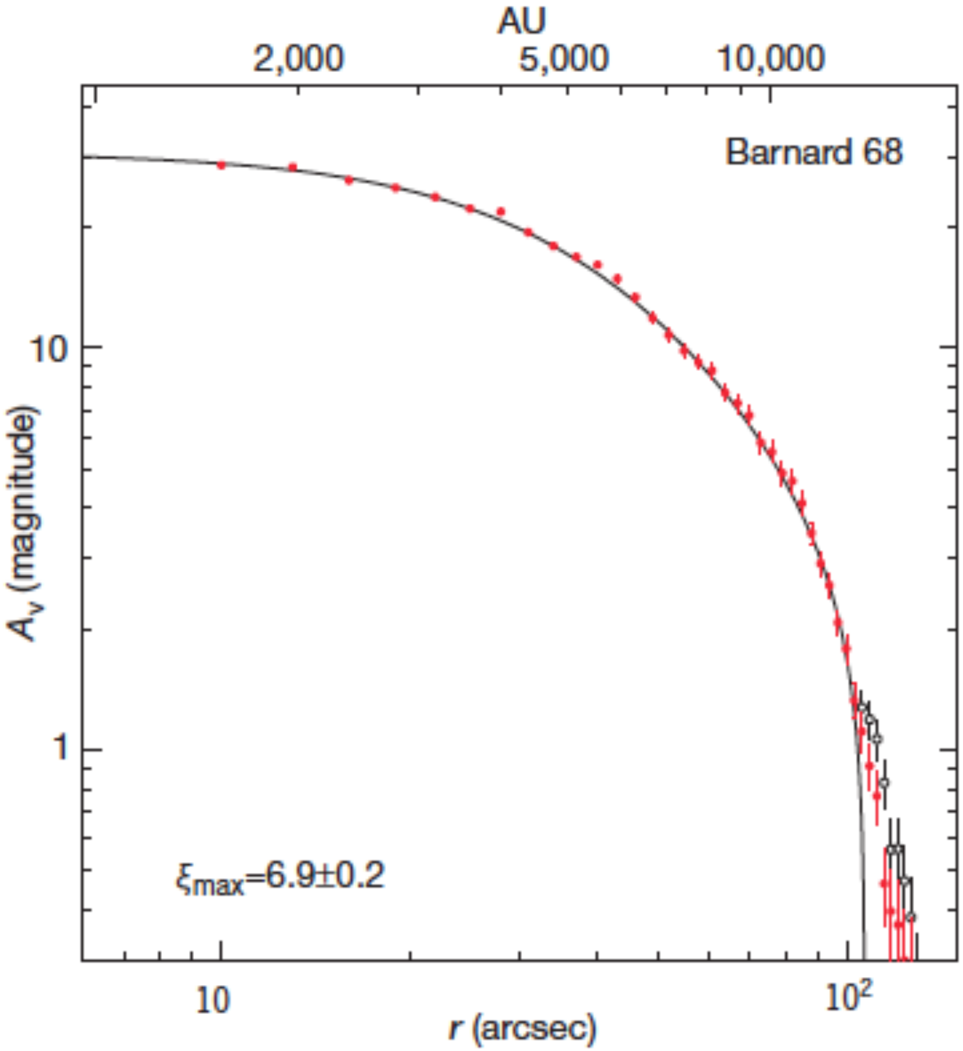
$$0 = \frac{3}{2} M\sigma^2 - 4\pi R^3 P_S - a\frac{GM^2}{R},$$

The maximum allowed external pressure =>
the maximum allowed enclosure mass

$$P_S = \frac{3^7\sigma^8}{2^{14}\pi a^3 G^3 M^2}.$$

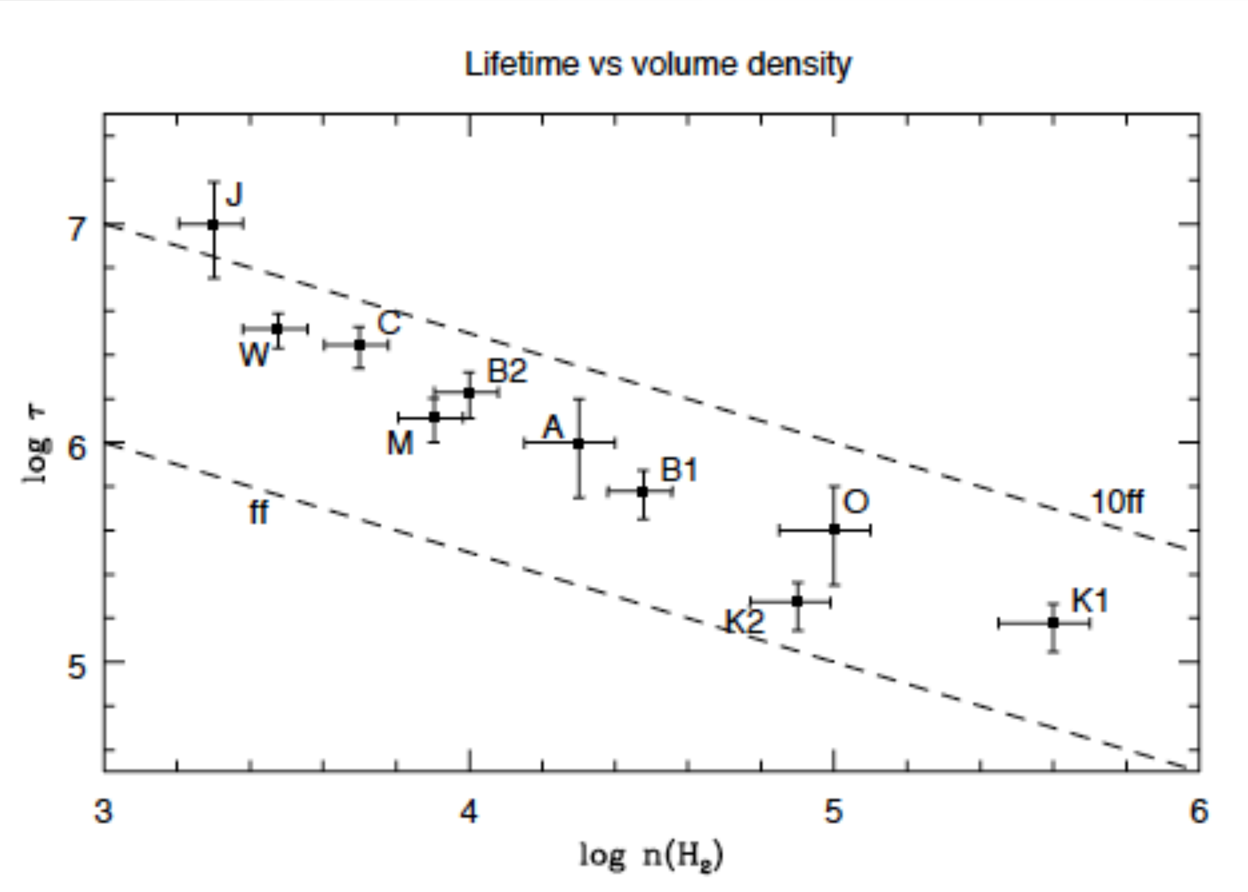
$$M_{BE} \approx 1.18\frac{\sigma^4}{G^{3/2}P_S^{1/2}} = 0.47 M_\odot \left(\frac{\sigma}{0.2\ \mathrm{km\ s^{-1}}}\right)^4 \left(\frac{P_S/k_B}{10^6\ \mathrm{K\ cm^{-3}}}\right)^{-1/2}.$$

For typical prestellar cores: $M_{BE} \approx 1.18 M_J$



A self-gravitating, pressure confined isothermal sphere

Alves et. al. (2001)



$t_{\text{core}} > t_{\text{ff}}$

Andre et.al. (2008)

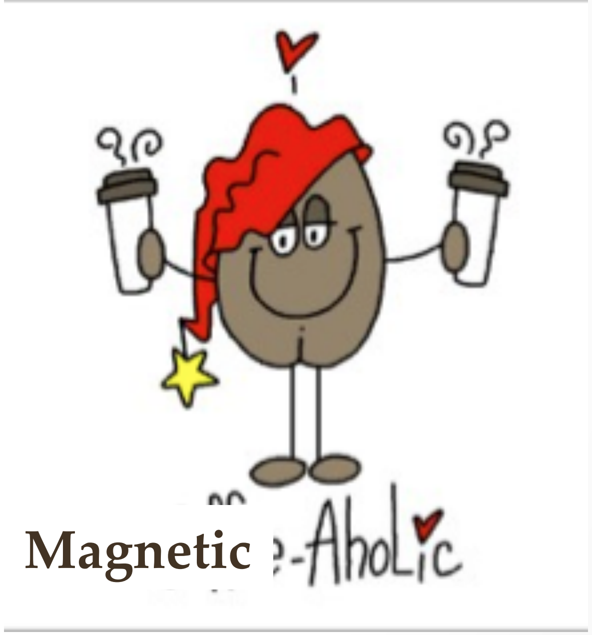
Ways to support the cores against self-gravity:

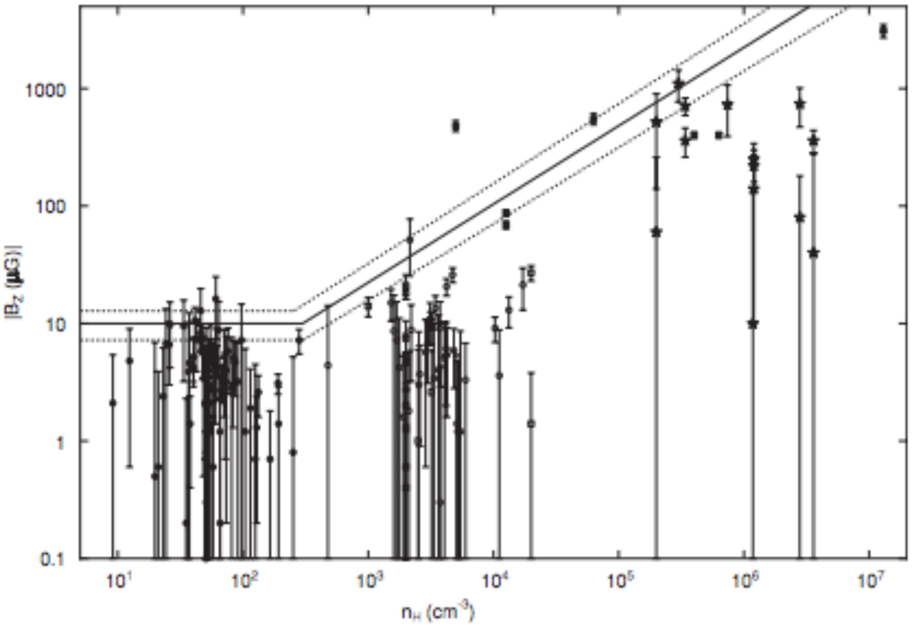
Magnetic field

Role of Magnetic Fields?

Magneticphobic

.vs.



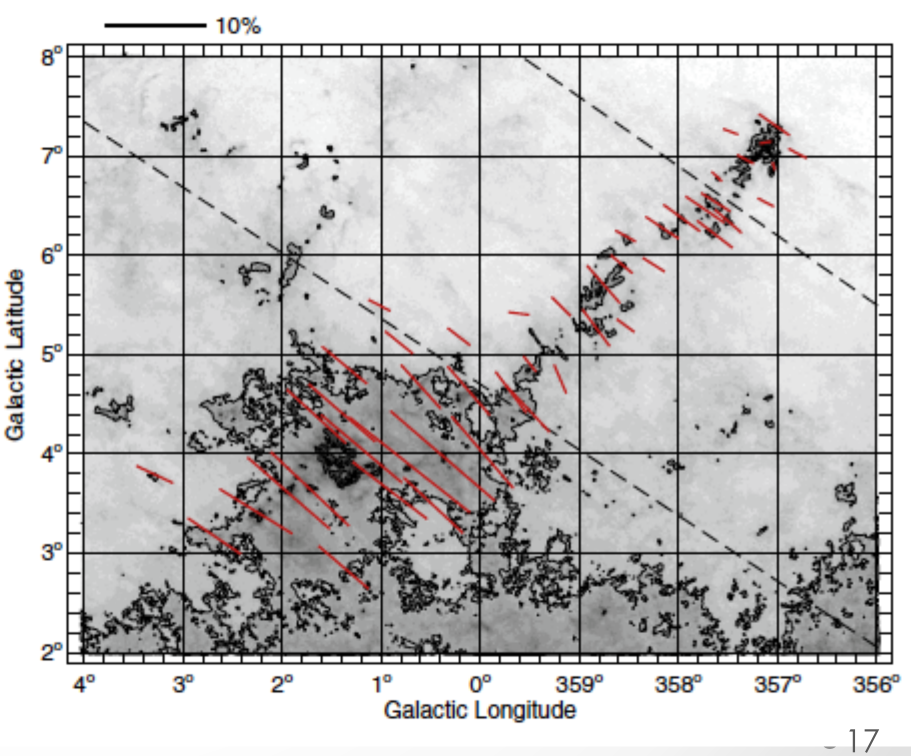


Alves (2008)

Polarization measurement in Pipe

Magnetic fields in interstellar clouds

Crutcher (2010)



Magnetic Critical mass

- Let's look at the virial theorem including the magnetic term:

$$\frac{1}{2}\ddot{I} = 2(\mathcal{T} - \mathcal{T}_S) + \mathcal{M} + \mathcal{W}$$

$$\mathcal{T}_S = \int_S r P dS$$

$$\mathcal{M} = \frac{1}{8\pi}\int_V \left(B^2 - B_0^2\right) dV.$$

Spherical cloud and uniform magnetic field:

$$\mathcal{M} \approx \frac{B^2R^3}{6} - \frac{B_0^2R_0^3}{6} = \frac{1}{6\pi^2}\left(\frac{\Phi_B^2}{R} - \frac{\Phi_B^2}{R_0}\right) \approx \frac{\Phi_B^2}{6\pi^2 R}.$$

$$\mathcal{M} + \mathcal{W} = \frac{\Phi_B^2}{6\pi^2 R} - \frac{3}{5}\frac{GM^2}{R} \equiv \frac{3}{5}\frac{G}{R}\left(M_\Phi^2 - M^2\right)$$

<0 supercritical
>0 subcritical

$$M_\Phi \equiv \sqrt{\frac{5}{2}}\left(\frac{\Phi_B}{3\pi G^{1/2}}\right)$$

$$M_{cr} = 0.13\frac{\Phi}{G^{1/2}} \approx 10^3\ M_\odot\left(\frac{B}{30\ \mu\mathrm{G}}\right)\left(\frac{R}{2\ \mathrm{pc}}\right)^2.$$

Standard Model

(Shu, Adams & Lizano 1987)

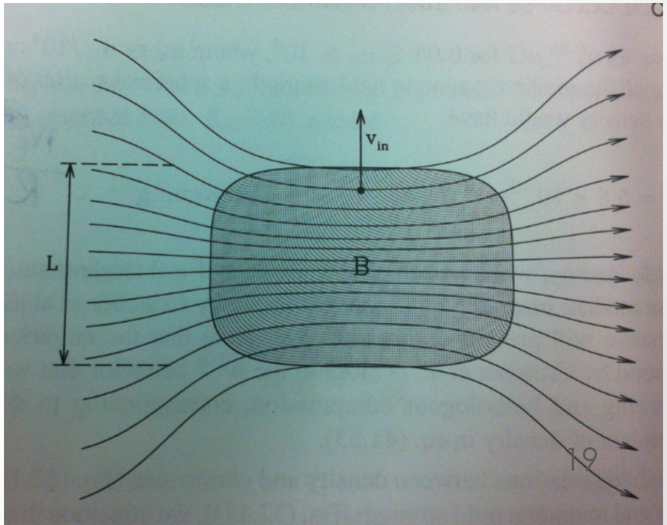
- **Supercritical**-Magnetically diluted fragmentation

High mass star formation or high star formation efficiency

- **Subcritical**-dominated by the time scale of ambipolar diffusion

Low mass star formation and low star formation efficiency.

$$\tau_{slip} = \frac{L/2}{|v_i - v_n|} \approx 7\times10^7 n_4^{-1.42} yr.$$



(Drain 2011)

Turbulence

Transient (decaying) Turbulence

- Supersonic in the gas and cores;
- Core-to-Core dispersion higher than gas dispersion

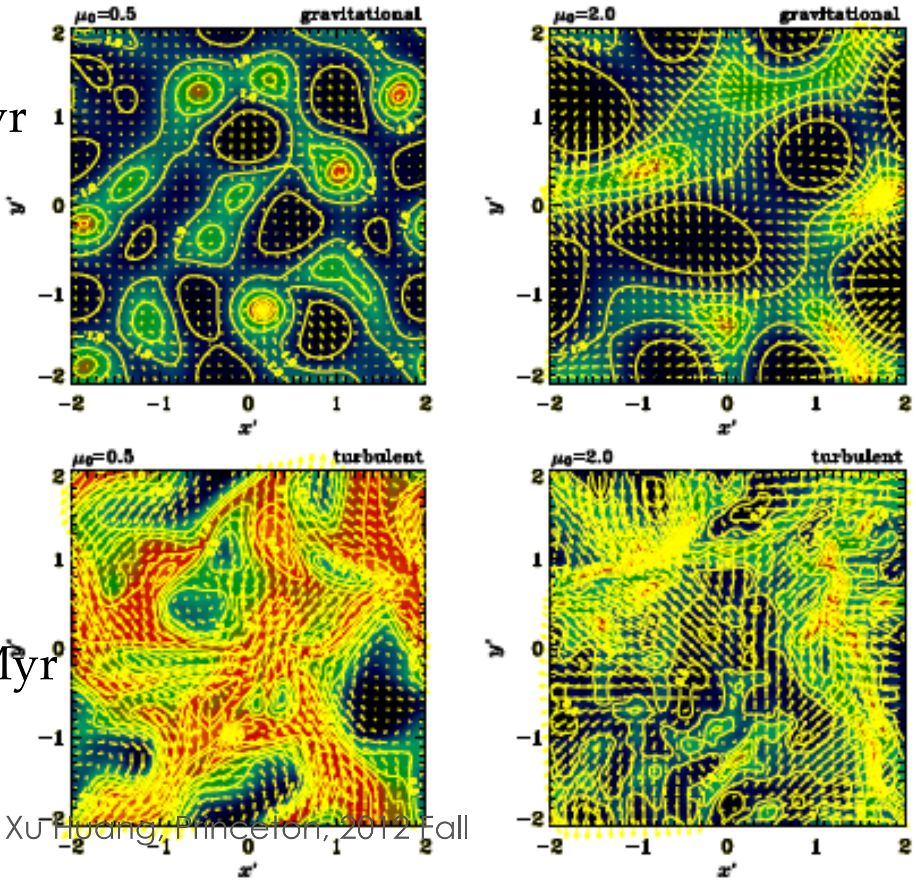
Regenerated (driven) Turbulence

- Supersonic outside cores, transsonic inside cores;
- Core-to-Core dispersion similar to that of gas;

Offner (2008)

Formation Scenarios (I)
Initial CMF

- Gravitational Fragmentation (linear perturbations)
- Turbulent Fragmentation (non-linear perturbations)



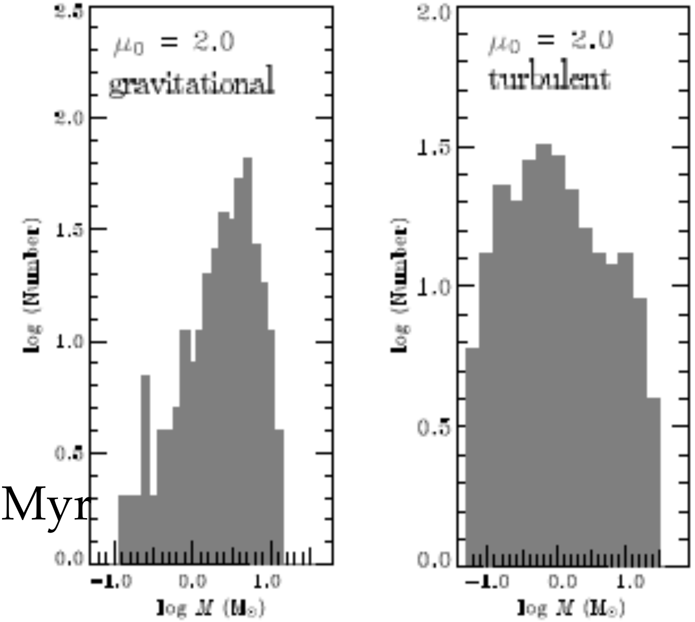
7.4Myr

0.83Myr

1.2Myr

0.04Myr

Andre et.al. (2008)



Formation Scenarios (II) Evolution

- Relevant Time Scales:

Freefall: $t_{ff} \approx \sqrt{\frac{3\pi}{32G\rho}} \approx 0.9Myr\left(\frac{2\times10^{3}cm^{-3}}{n_{H_2}}\right)^{1/2}$

Sound crossing time: $t_{cs} = \frac{2R_c}{C_s} \approx 1Myr\frac{R_c}{0.1pc}\frac{0.2km/s}{C_s}$

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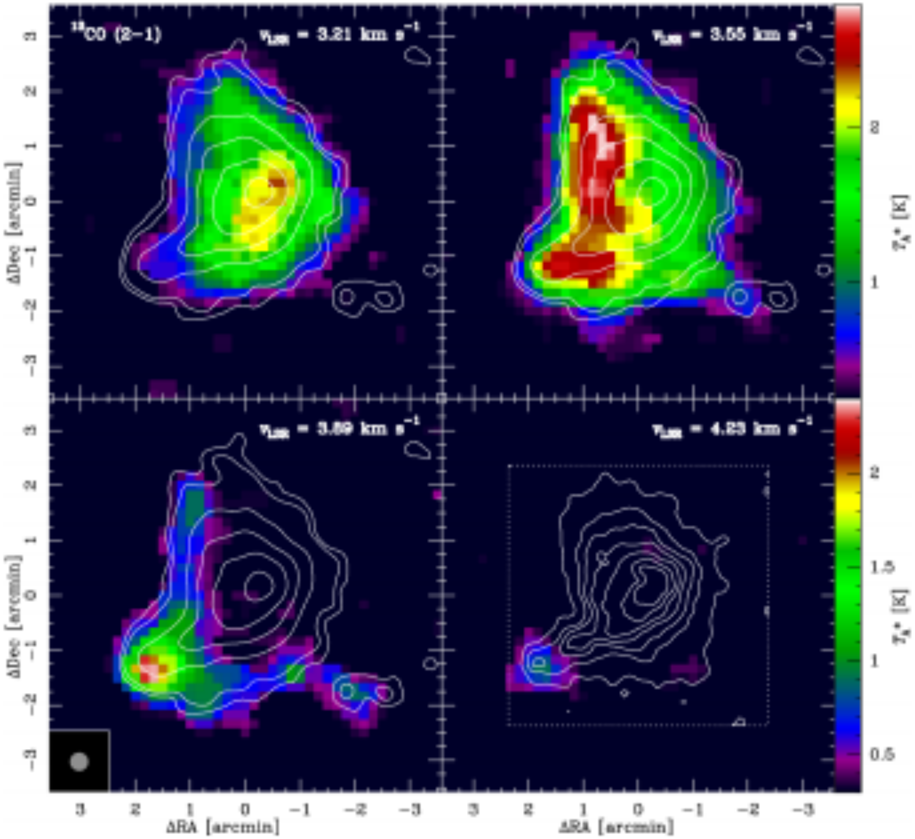
Collision:

$$\tau_{\rm coag} \sim \frac{1}{2\pi R_c^2 n_c \sigma} = 1\ {\rm Myr} \left(\frac{R_c}{0.1\ {\rm pc}} \right) \left(\frac{f_f}{0.1} \right)^{-1} \left(\frac{\sigma}{2\ {\rm km\,s^{-1}}} \right)^{-1} .$$

Evidence for core collision



Barnard 68

Nielbock et. al. 2012

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Mass loss:

for example, Kelvin-Helmholtz instability (unbound cores)

$$\tau_{\mathrm{KH}} = \left(\frac{\sigma}{R_c(m)D_\rho^{\frac{1}{2}}}\right)^{-1} = 1\ \mathrm{Myr}\left(\frac{\sigma}{\mathrm{kms^{-1}}}\right)^{-1}\left(\frac{R_c(m)}{0.1\ \mathrm{pc}}\right)\left(\frac{D_\rho}{100}\right)^{1/2}$$

KH instability for a core in the wind

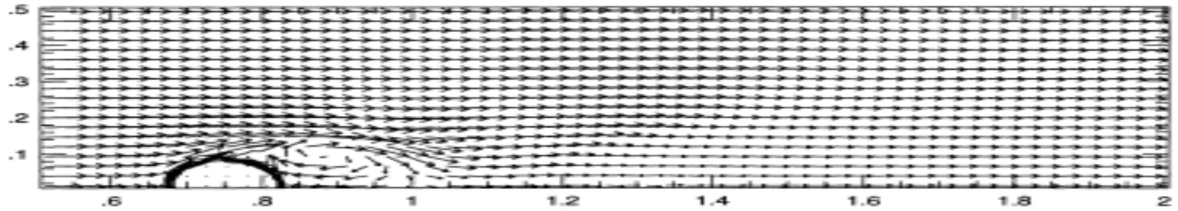


FIG. 1a

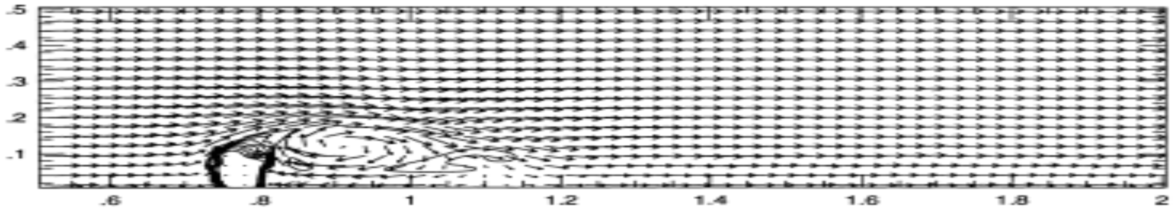


FIG. 1b

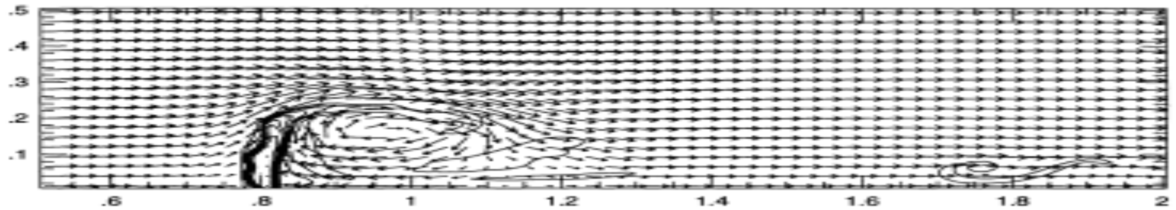


FIG. 1c

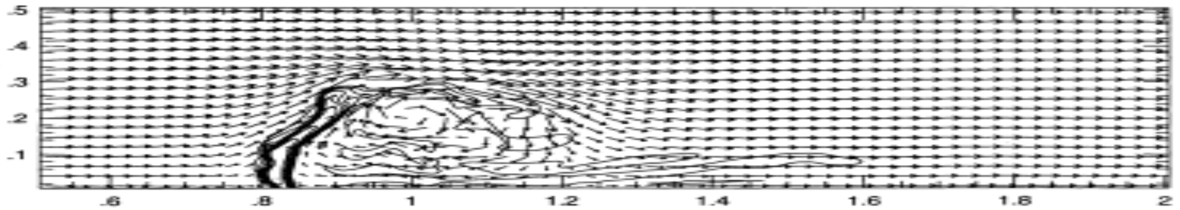
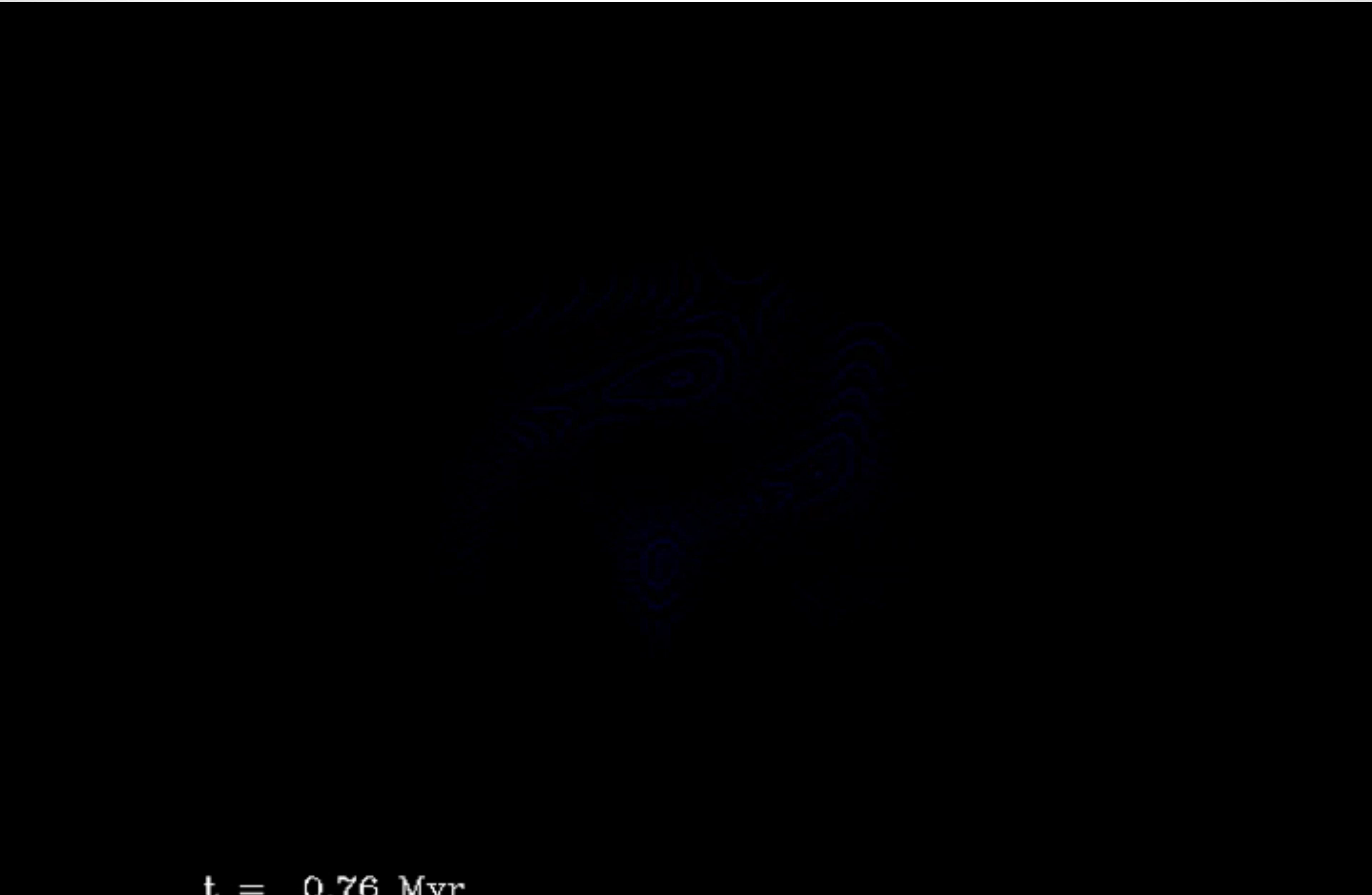


FIG. 1d

Murray et.al 1993

Fabian & Hartmann (2008)



Summary

- Cores are density peaks in GMCs.
- The core mass distribution may resemble IMF
- Magnetic fields and turbulence are important in the formation of cores.
- Other physics processes such as accretion may also be important in the evolution of cores.
- Need more data to constrain the models

$t \sim 1\mathrm{Myr}$ $M \sim 1M_\odot$

Reference

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- Andre,P. et. al.(2010) From filamentary clouds to prestellar cores to stellar IMF: Initial highlights from the Herschel Gould Belt Survey
- Bergin & Tafalla (2007) Cold dark clouds: the initial conditions for star formation
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- Drain (2011) Physics of the interstellar and intergalactic medium; Chapter 32,41
- Shu, Lizano and Adams (1987) Star formation in molecular cloud

Thanks for listening…

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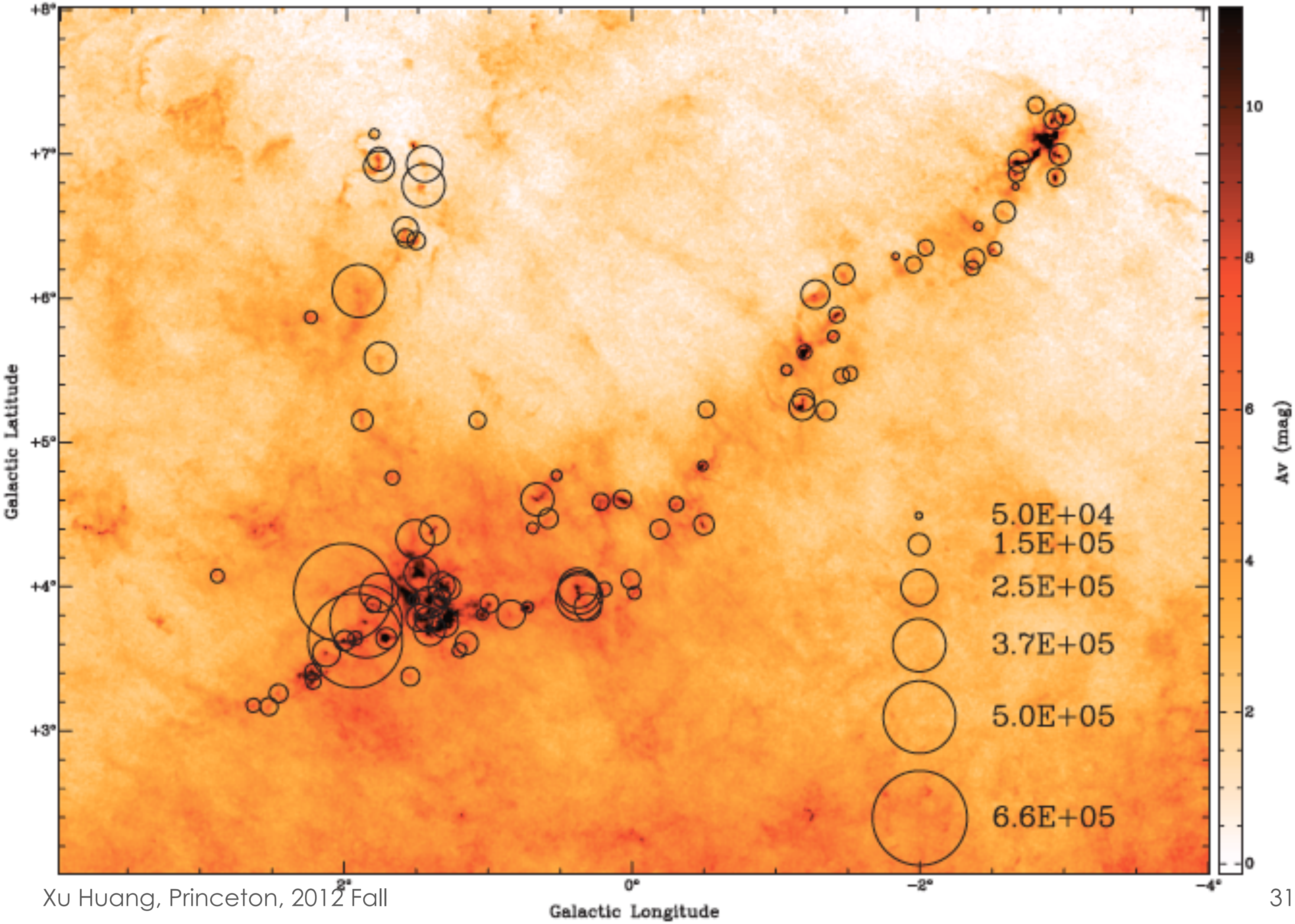
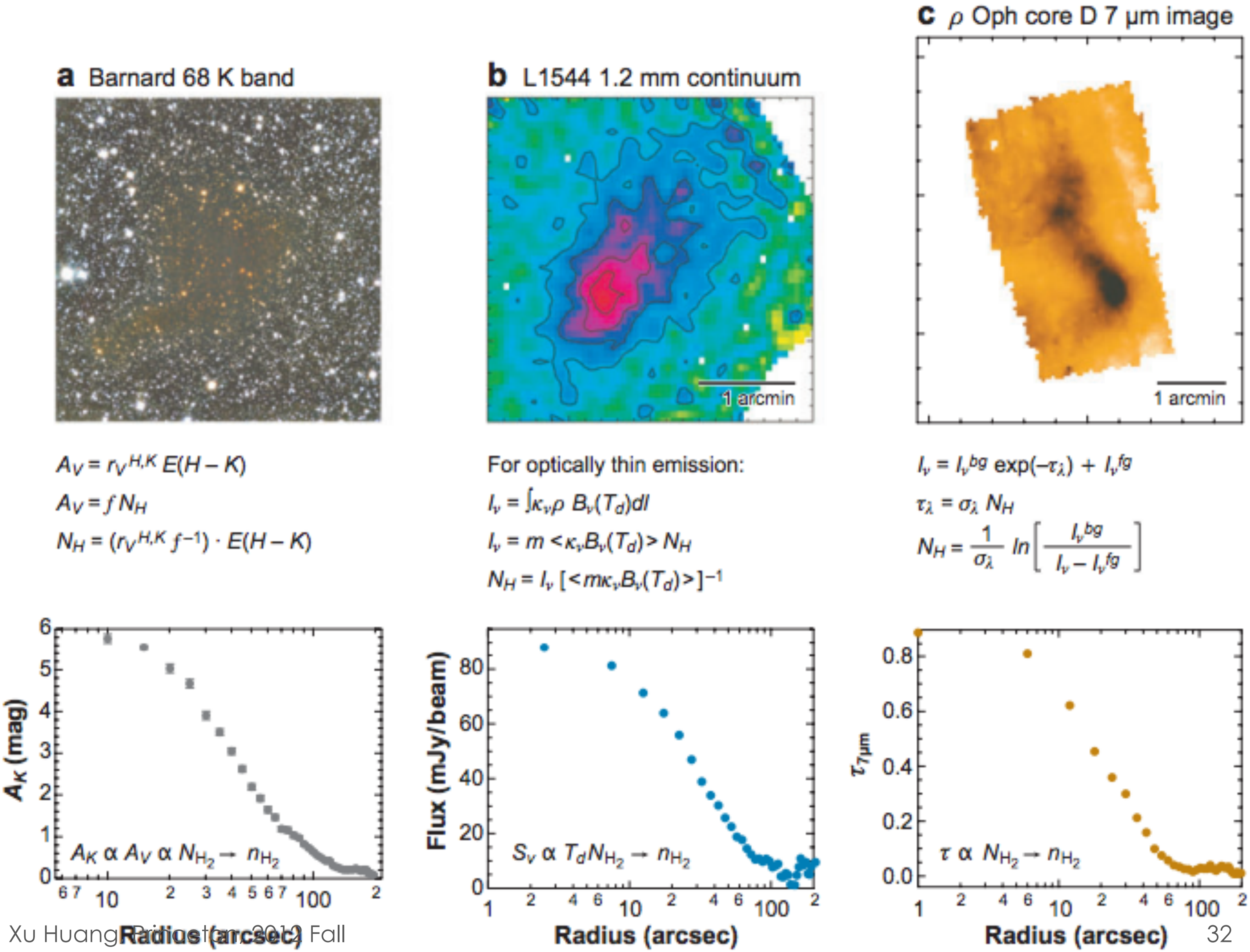
Pipe Nebula (Lada 2008)





a Barnard 68 K band

$A_V = r_V^{H,K}\, E(H-K)$

$A_V = f\, N_H$

$N_H = (r_V^{H,K} f^{-1}) \cdot E(H-K)$

b L1544 1.2 mm continuum

For optically thin emission:

$I_\nu = \int \kappa_\nu \rho\, B_\nu(T_d)\, dl$

$I_\nu = m <\kappa_\nu B_\nu(T_d)> N_H$

$N_H = I_\nu\, [<m\kappa_\nu B_\nu(T_d)>]^{-1}$

c ρ Oph core D 7 μm image

$I_\nu = I_\nu^{bg} \exp(-\tau_\lambda) + I_\nu^{fg}$

$\tau_\lambda = \sigma_\lambda N_H$

$N_H = \frac{1}{\sigma_\lambda} \ln\left[\frac{I_\nu^{bg}}{I_\nu - I_\nu^{fg}}\right]$

Formation of cores in Simulation
Offner (2008)