Physics 224
The Interstellar Medium

Lecture #17: Observations of Molecular Gas

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Magnetic Fields in the ISM

Observational Tracers:

- Synchrotron emission - from charged particles interacting with the magnetic field.
- Faraday Rotation - different phase velocities of right & left circularly polarized light in the presence of B-field leads to rotation of polarization angle
- Polarization - of starlight due to dust grains aligned along B-field or of dust emission from aligned grains
- Zeeman splitting - splitting of fine structure levels in atoms/ molecules due to interaction of electron magnetic moment and B-field

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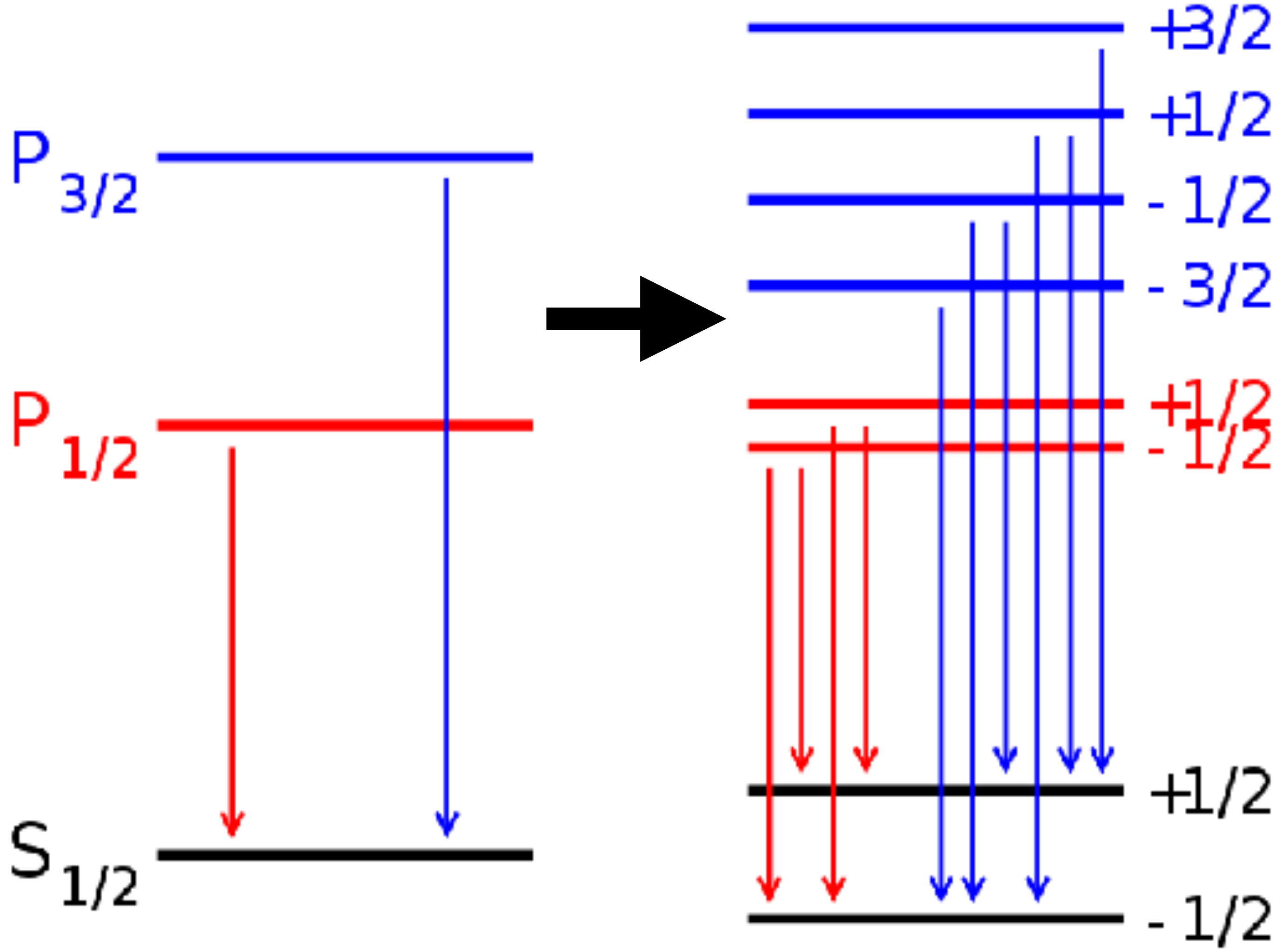
Magnetic Fields in the ISM

Zeeman Effect



Zeeman splitting is largest when there is an unpaired electron in outer shell: e.g. HI, OH, CN, CH, CCS, SO, and O_2

Even then, energy shift is small.

But, shifted levels produce different circular polarizations.

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Magnetic Fields in the ISM

Quick review of polarization:

$$E_x(z,t) = E_{0x} e^{i(kz - 2\pi\nu t + \delta_x)} ,$$
$$E_y(z,t) = E_{0y} e^{i(kz - 2\pi\nu t + \delta_y)} .$$

Electric field of plane wave traveling in +z direction with +x north and +y east.

$$I \equiv \langle E_x E_x^* \rangle + \langle E_y E_y^* \rangle ,$$
$$Q \equiv \langle E_x E_x^* \rangle - \langle E_y E_y^* \rangle ,$$
$$U \equiv \langle E_x E_y^* \rangle + \langle E_x^* E_y \rangle ,$$
$$V \equiv i \left(\langle E_x E_y^* \rangle - \langle E_x^* E_y \rangle \right) ,$$

Stokes vectors: completely quantify the propagation of polarized radiation.

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Magnetic Fields in the ISM

Normalized Jones and Stokes Vectors for Simple Polarization States

Polarization State (1)	α (2)	δ (3)	$\mathbf{E}_0$ (4)	$\mathbf{E}_0$(CP) (5)	S (6)
Linear Horizontal	0°	...	$\begin{bmatrix}1\\0\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$	$\begin{bmatrix}1\\1\\0\\0\end{bmatrix}$
Linear Vertical	90°	...	$\begin{bmatrix}0\\1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}i\\-i\end{bmatrix}$	$\begin{bmatrix}1\\-1\\0\\0\end{bmatrix}$
Linear at $\alpha = +45°$	+45°	0°	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1+i\\1-i\end{bmatrix}$	$\begin{bmatrix}1\\0\\1\\0\end{bmatrix}$
Right-Handed Circular (RCP) ...	...	+90°	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\i\end{bmatrix}$	$\begin{bmatrix}1\\0\end{bmatrix}$	$\begin{bmatrix}1\\0\\0\\1\end{bmatrix}$
Left-Handed Circular (LCP)	...	−90°	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-i\end{bmatrix}$	$\begin{bmatrix}0\\1\end{bmatrix}$	$\begin{bmatrix}1\\0\\0\\-1\end{bmatrix}$

My favorite reference on polarization & Zeeman splitting:

T. Robishaw Ph.D. Thesis, 2008, Berkeley

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Magnetic Fields in the ISM

Stokes Parameters for Classical Derivation of the Zeeman Effect

$$S = \frac{1}{4}\left(I(\nu - \nu_-) \begin{bmatrix} 1+\cos^2\theta \\ -\sin^2\theta \\ 0 \\ -2\cos\theta \end{bmatrix} + I(\nu - \nu_0) \begin{bmatrix} 2\sin^2\theta \\ 2\sin^2\theta \\ 0 \\ 0 \end{bmatrix} + I(\nu - \nu_+) \begin{bmatrix} 1+\cos^2\theta \\ -\sin^2\theta \\ 0 \\ 2\cos\theta \end{bmatrix} \right)$$

for unpolarized spectral line: $S = I(\nu - \nu_0) \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}$

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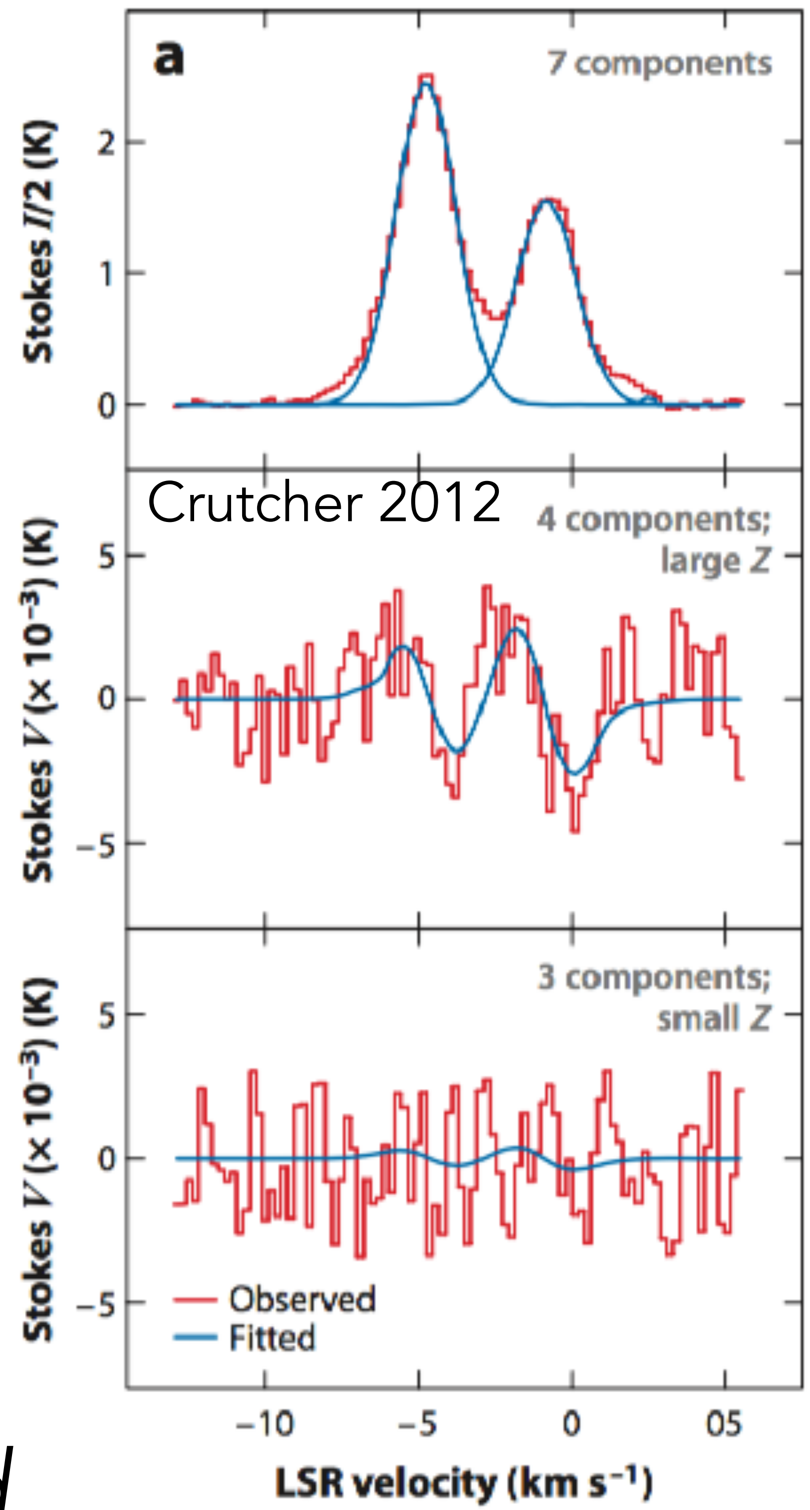
Magnetic Fields in the ISM

Total intensity
7 hyperfine components for mm rotational lines of CN
two velocity components along line of sight.

Circularly polarized emission:
4 components with large Zeeman splitting

Circularly polarized emission:
3 components with small Zeeman splitting

line-of-sight B-field



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e.g. HI, OH, **CN**, CH, CCS, SO, and O_2

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Molecular Clouds

Observed Characteristics

- Self-Gravity
- Turbulence
- Substructure
- **Magnetic Fields**
- Mass Spectrum
- Lifetimes
- Star Formation

Virial Theorem

$$\frac{1}{2}\ddot{I} = 2(\mathcal{T} - \mathcal{T}_S) + \mathcal{B} + \mathcal{W} - \frac{1}{2}\frac{d}{dt}\int_S (\rho \mathbf{v} r^2) \cdot d\mathbf{S}$$

2nd derivative of moment of Inertia of cloud

$$I = \int_V \rho r^2 \, dV$$

see Krumholz “Notes on Star Formation” for a very clear derivation

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total kinetic plus thermal energy of the cloud

$$\mathcal{T} = \int_V \left(\frac{1}{2}\rho v^2 + \frac{3}{2}P\right) dV$$

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confining pressure on the cloud's surface

$$\mathcal{T}_S = \int_S \mathbf{r} \cdot \mathbf{\Pi} \cdot d\mathbf{S}$$

fluid pressure tensor $\mathbf{\Pi} \equiv \rho \mathbf{v}\mathbf{v} + P\mathbf{I}$

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difference in magnetic pressure in cloud interior vs magnetic pressure plus tension at cloud surface

$$\mathcal{B} = \frac{1}{8\pi}\int_V B^2\, dV + \int_S \mathbf{r} \cdot \mathbf{T}_M \cdot d\mathbf{S}$$

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gravitational energy of the cloud

$$\mathcal{W} = -\int_V \rho \mathbf{r} \cdot \nabla \phi \, dV$$

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rate of change of momentum flux across cloud surface

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for cloud in equilibrium between gravitational force and magnetic field

$$0 = \mathcal{B} + \mathcal{W} = \frac{\Phi_B^2}{6\pi^2 R} - \frac{3}{5}\frac{GM^2}{R} \equiv \frac{3}{5}\frac{G}{R}\left(M_\Phi^2 - M^2\right)$$

where $\Phi_B = \pi B R^2$

magnetic flux through cloud

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and $M_\Phi = \sqrt{\frac{5}{2}}\left(\frac{\Phi_B}{3\pi G^{1/2}}\right)$ "magnetic critical mass"

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"magnetic critical mass"

if $M > M_\Phi$

then $\mathcal{B} + \mathcal{W} < 0$

and the cloud will collapse

"magnetically super-critical"
means B-field is not strong enough
to support cloud against gravitational collapse

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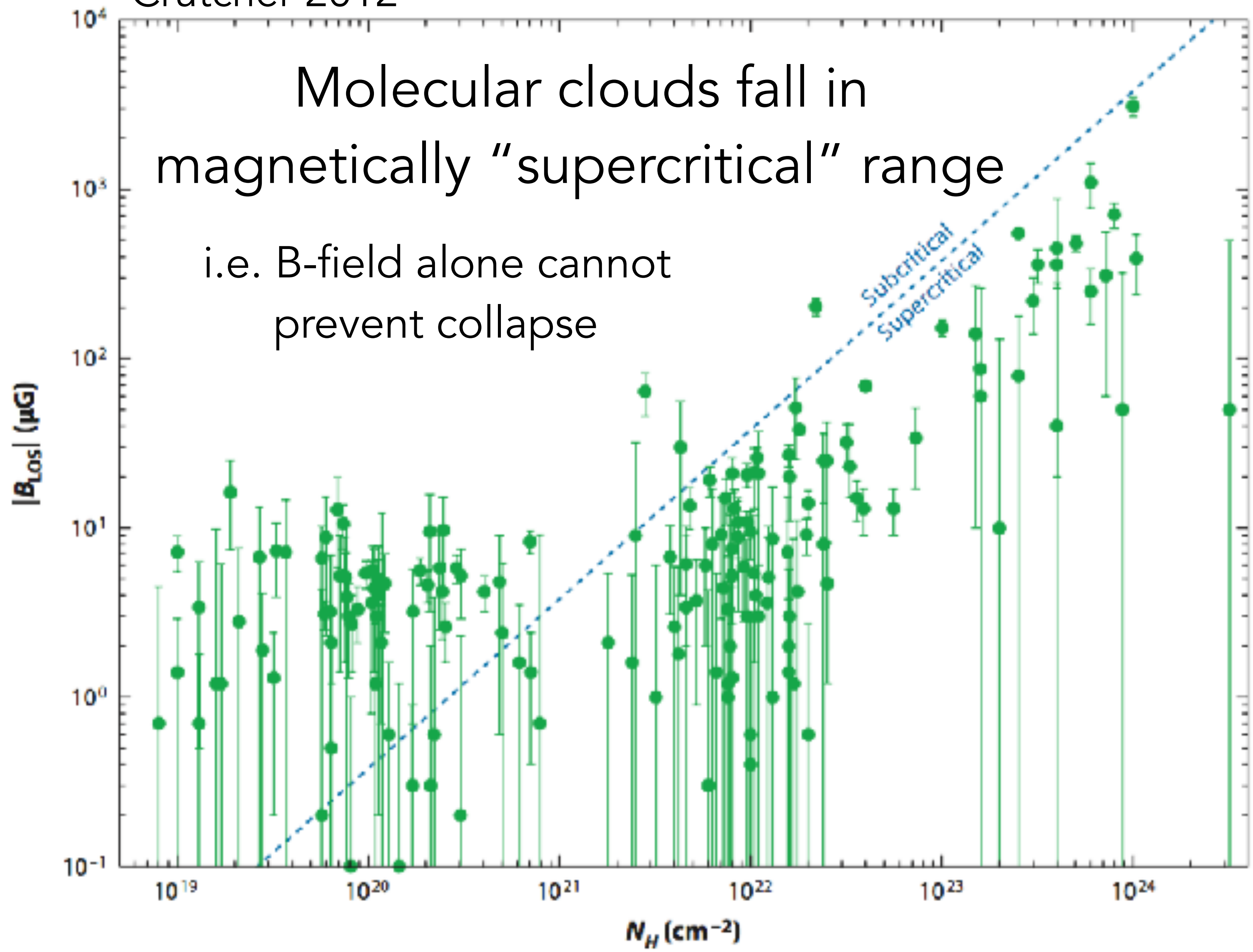
Crutcher 2012



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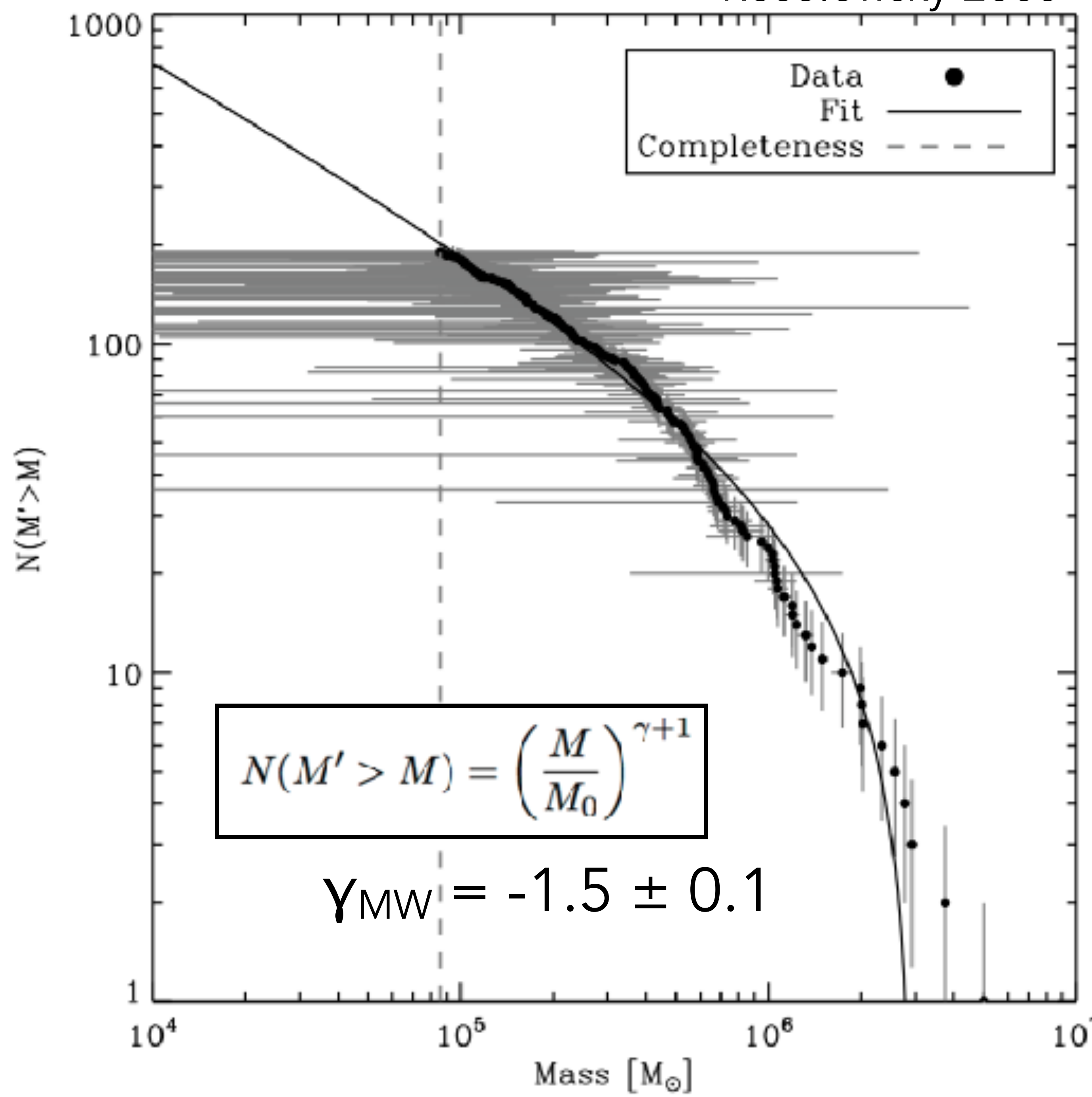
Rosolowsky 2005



$$N(M' > M) = \left(\frac{M}{M_0}\right)^{\gamma+1}$$

$\gamma_{MW} = -1.5 \pm 0.1$

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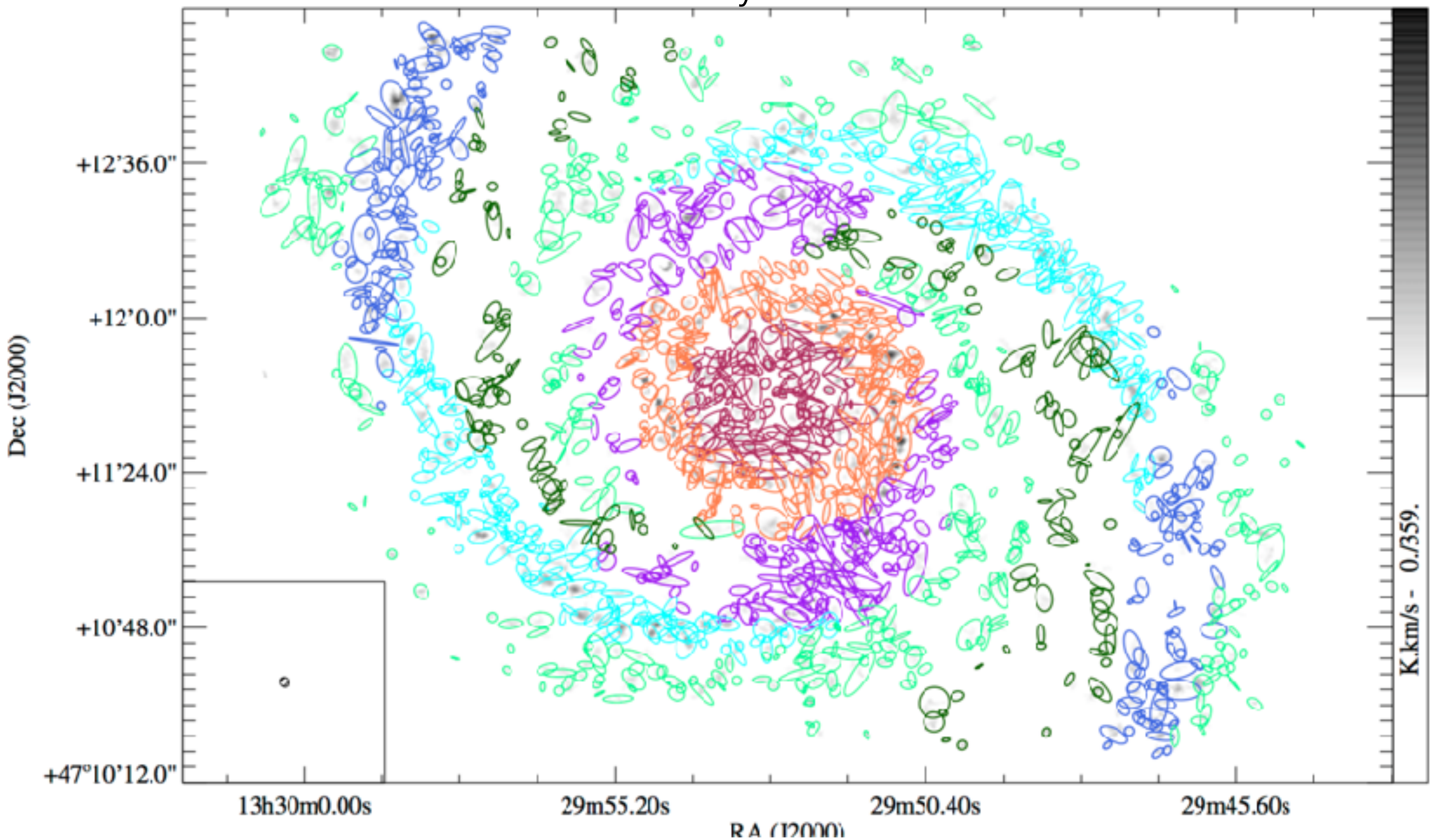
Molecular Clouds

Colombo et al. 2014 - PAWS survey of M51



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Molecular Clouds

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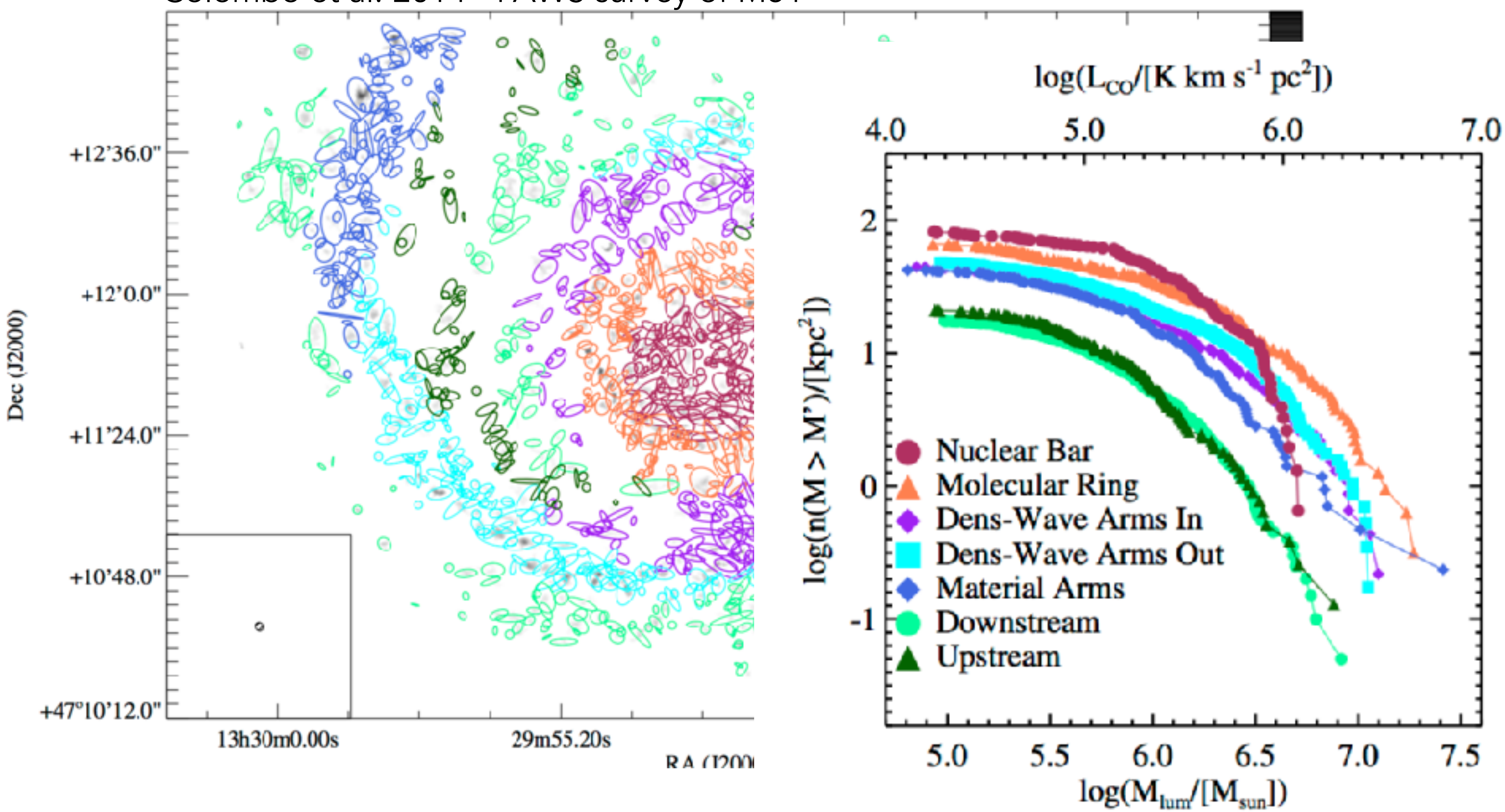

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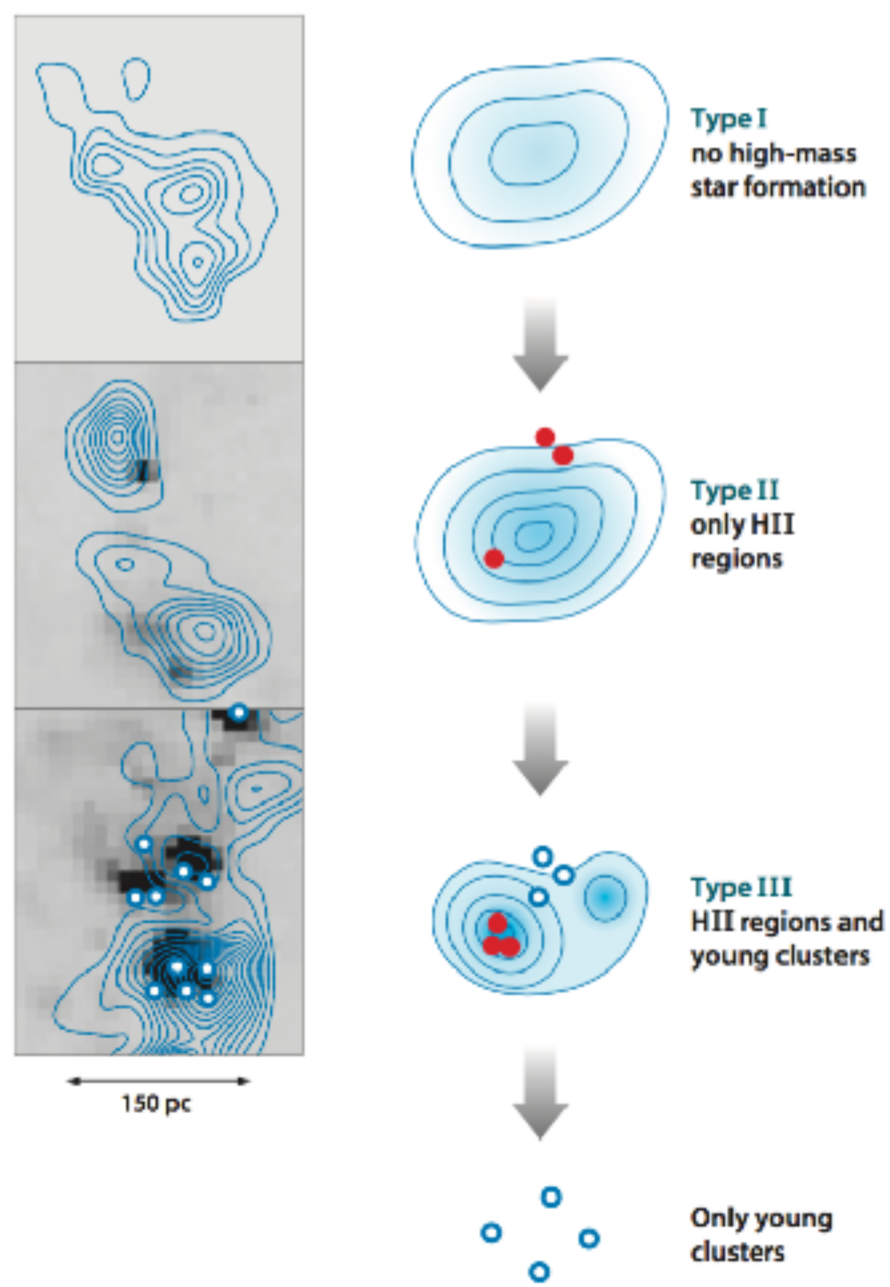
Kawamura et al. 2009



If star formation rate is constant, relative numbers of clouds in each evolutionary state, plus ages of clusters when no molecular gas is around gives you cloud lifetimes.

~20-30 Myr

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Star Formation

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_2H^+.

Bergin & Tafalla 2007

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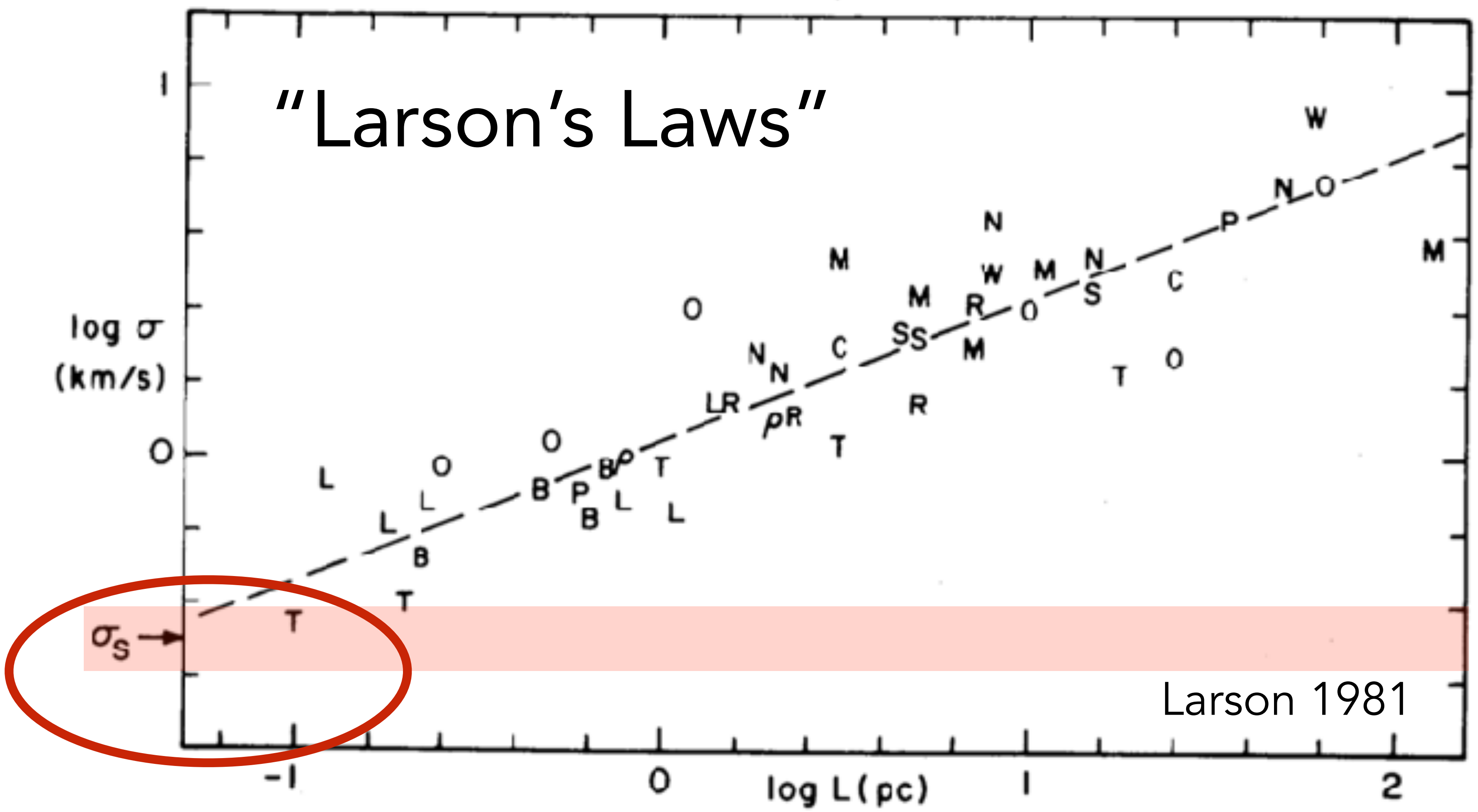
Star Formation



At small scales in clouds, thermal pressure support takes over from turbulence.

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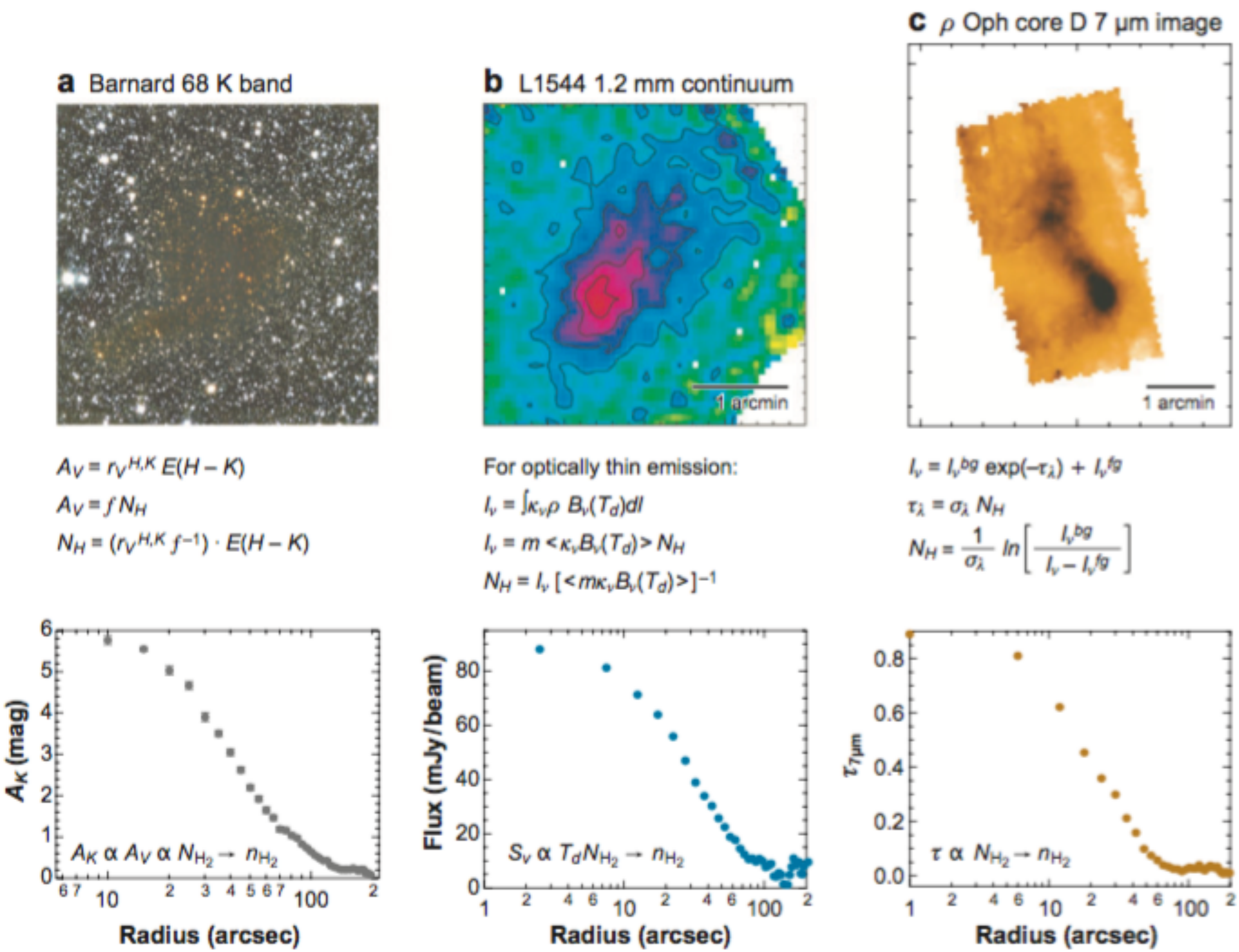
Cores in Molecular Clouds



Column density profiles of dense cores are similar to Bonnor-Ebert profile (isothermal, marginally stable spherical cloud, supported against collapse by pressure)

Bergin & Tafalla 2007

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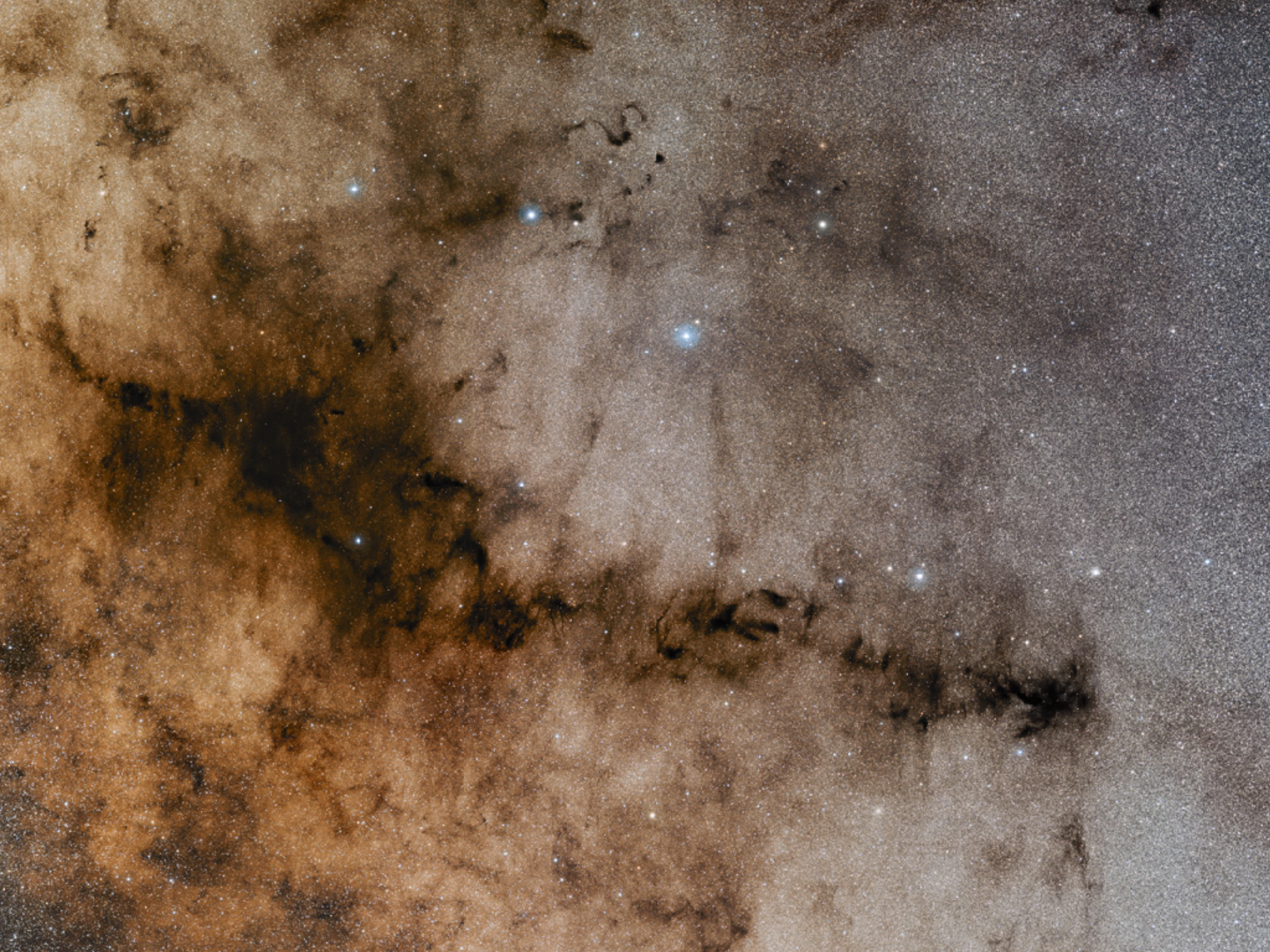
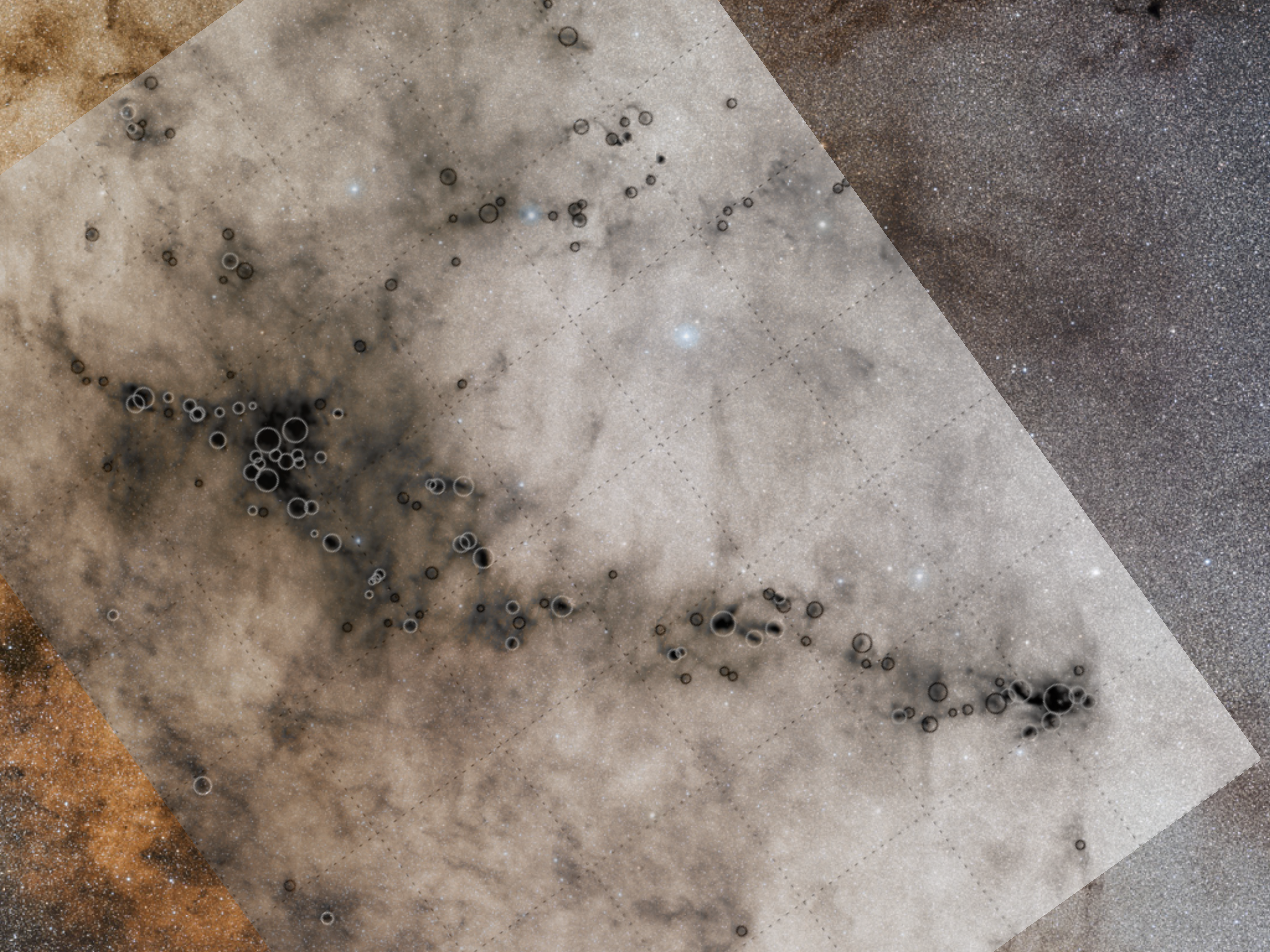
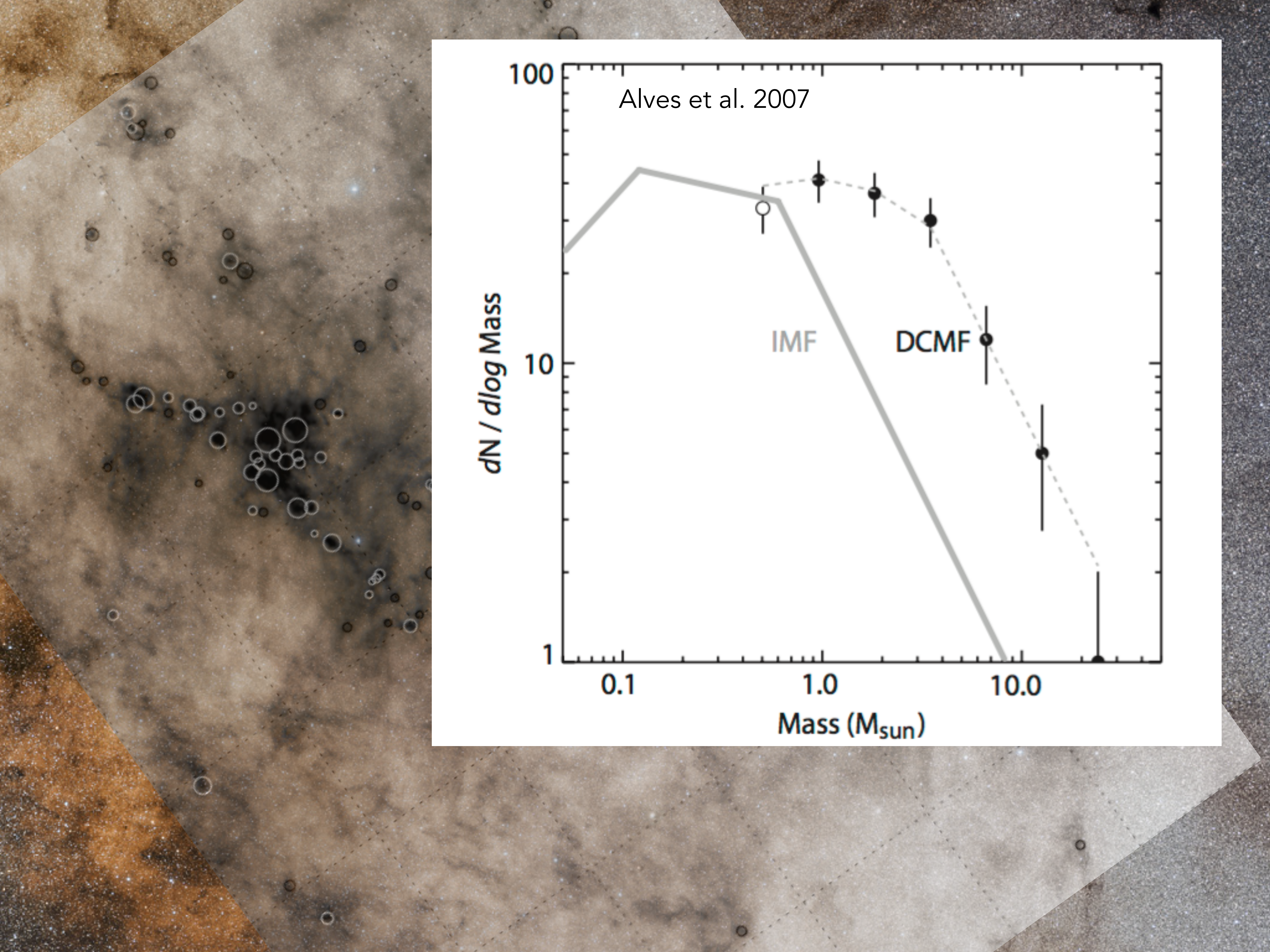
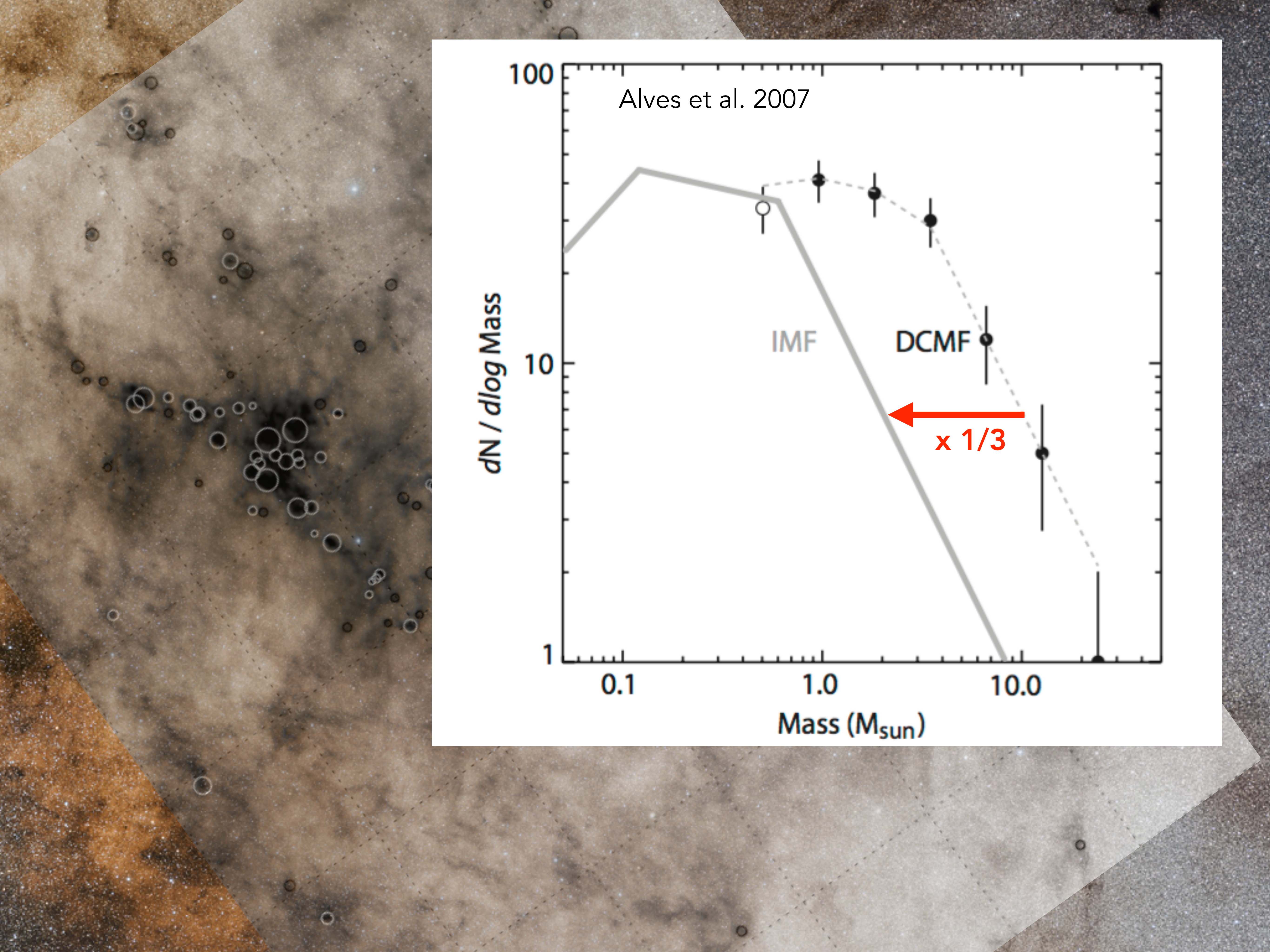






Alves et al. 2007
100
10
1
dN / dlog Mass
IMF
DCMF
0.1
1.0
10.0
Mass (Msun)


Alves et al. 2007
100
10
1
dN / dlog Mass
IMF
DCMF
x 1/3
0.1
1.0
10.0
Mass (Msun)

The Initial Mass Function

Offner et al. 2014

Number of stars per unit log(M) that are formed.

Controversy persists over whether it is the same everywhere.

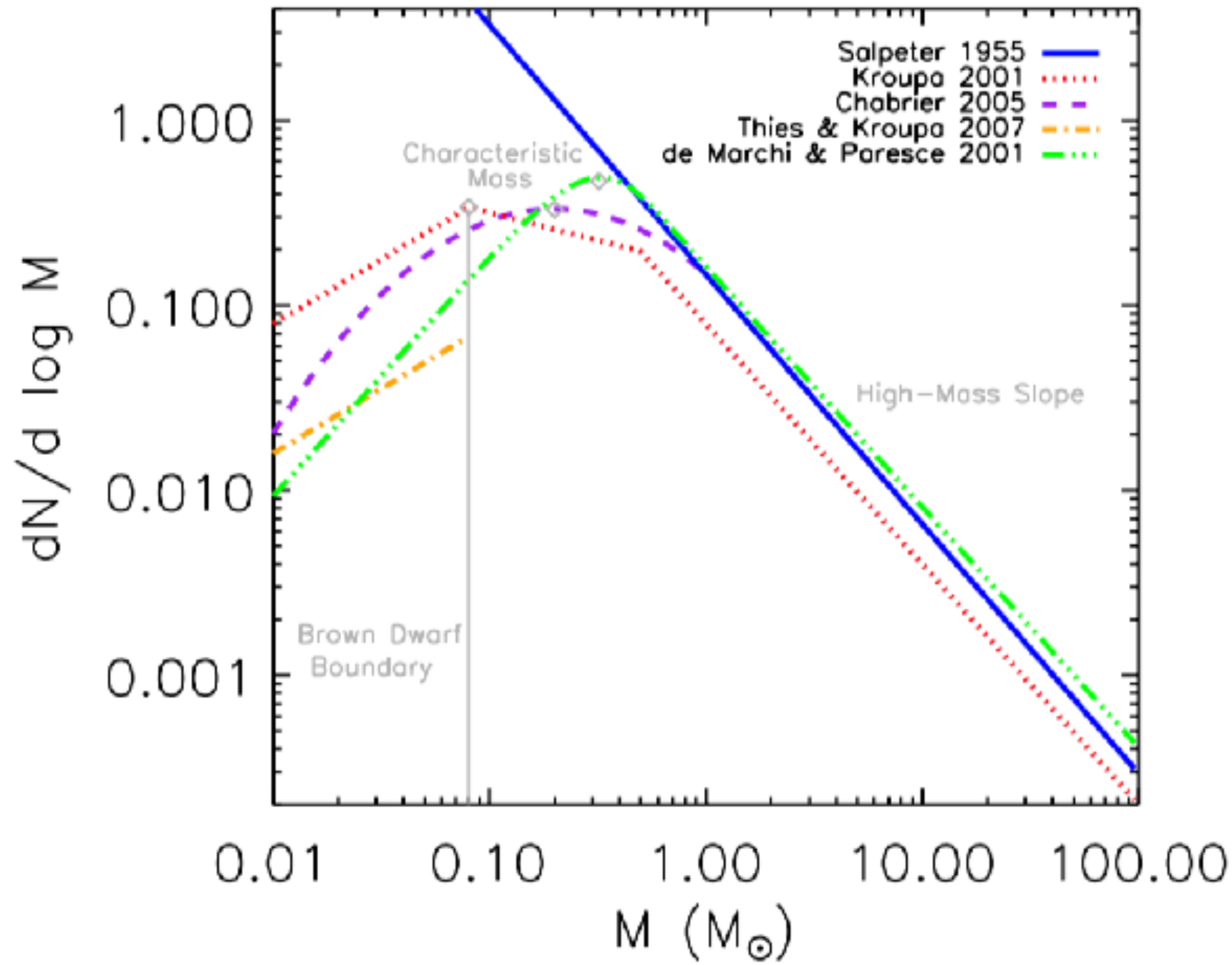


Fig. 1.— IMF functional forms proposed by various authors from fits to Galactic stellar data. With the exception of the Salpeter slope, the curves are normalized such that the integral over mass is unity. When comparing with observational data, the normalization is set by the total number of objects as shown in Figure 2.

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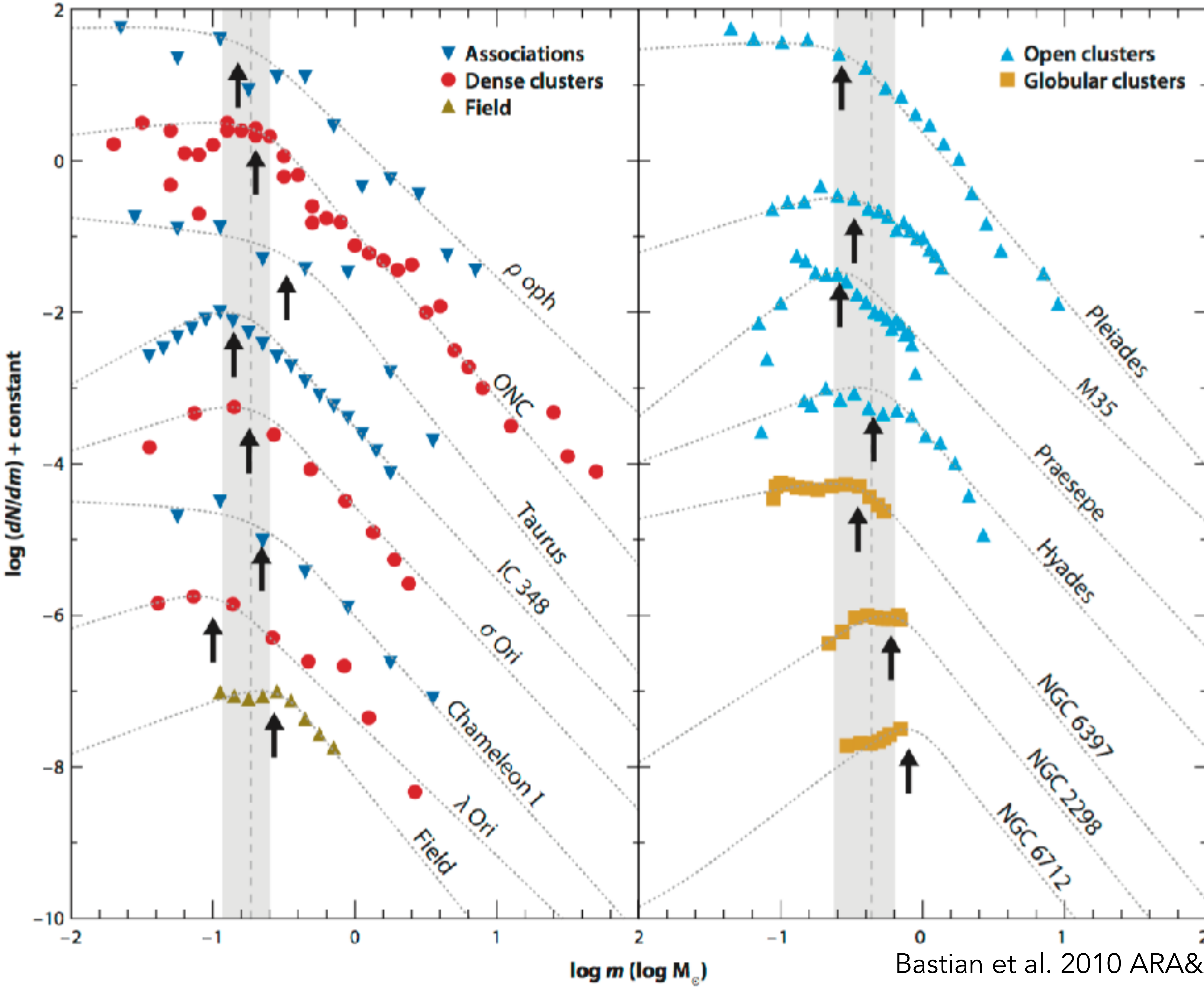
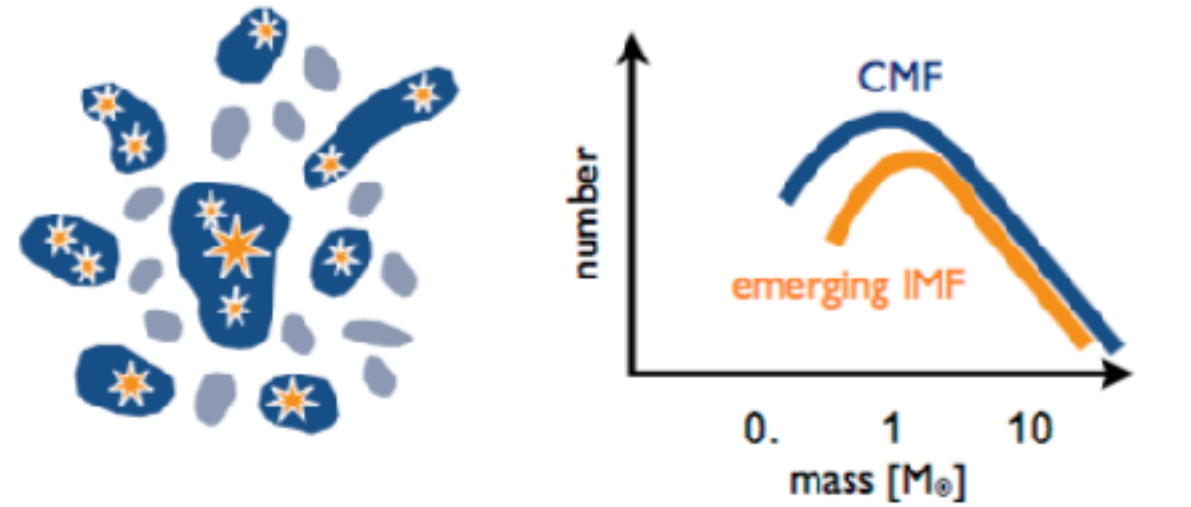


Bastian et al. 2010 ARA&A

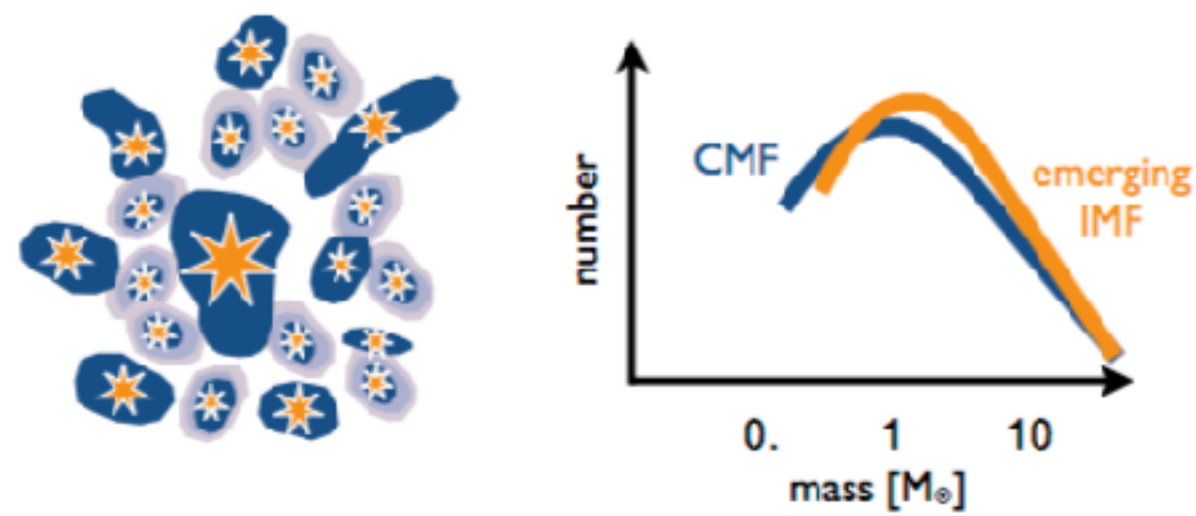
When does the CMF map to the IMF?

Offner et al. 2014

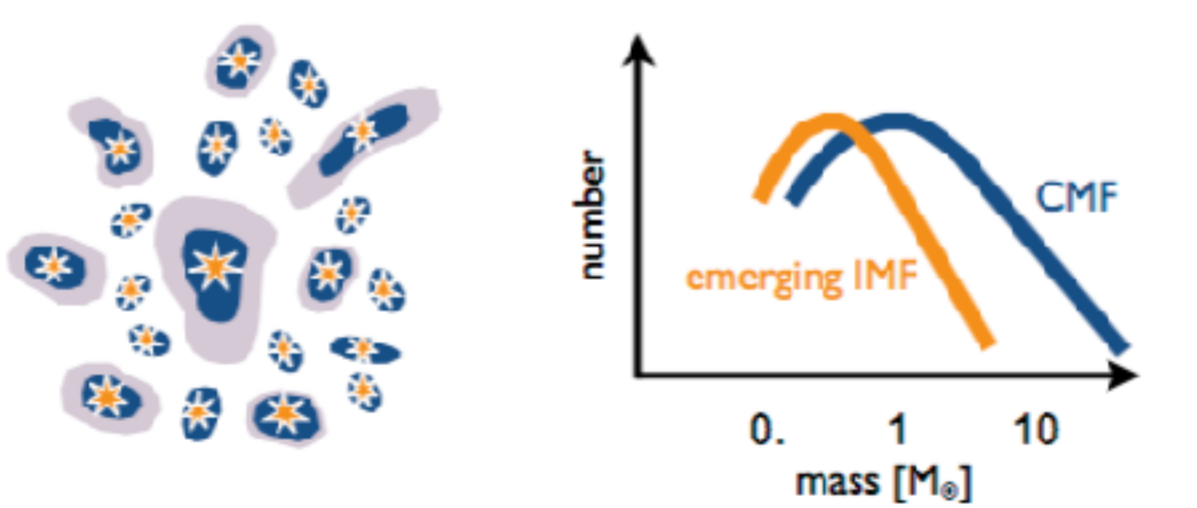
i) Not all cores are 'prestellar'. Here we show the emerging IMF that could arise if the low-mass cores in the CMF are transient 'fluff'.



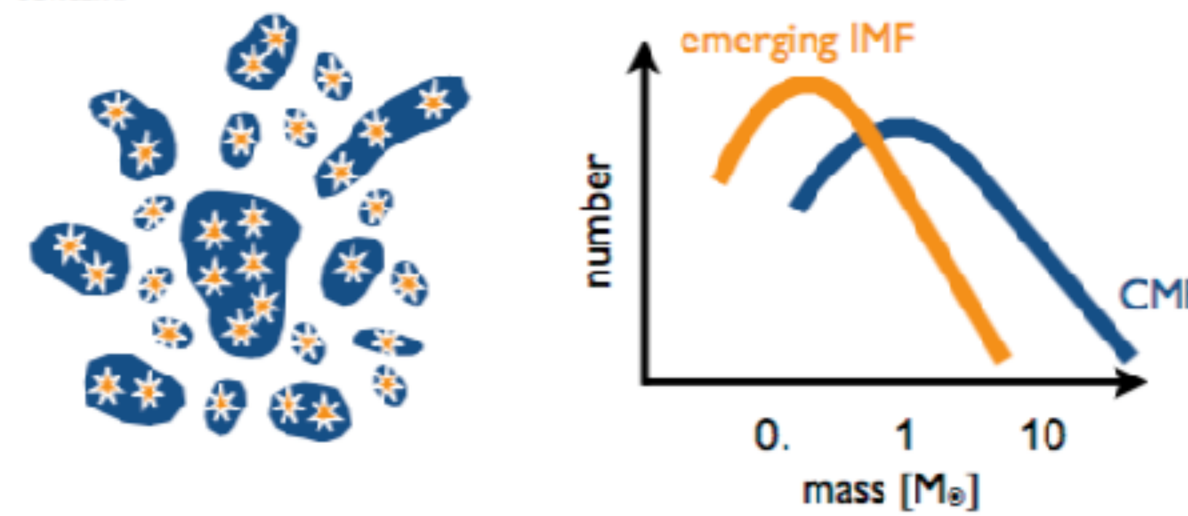
ii) Core growth is not self-similar. Here we show the emerging IMF that could arise if, say, only the low-mass cores in the CMF are still accreting.



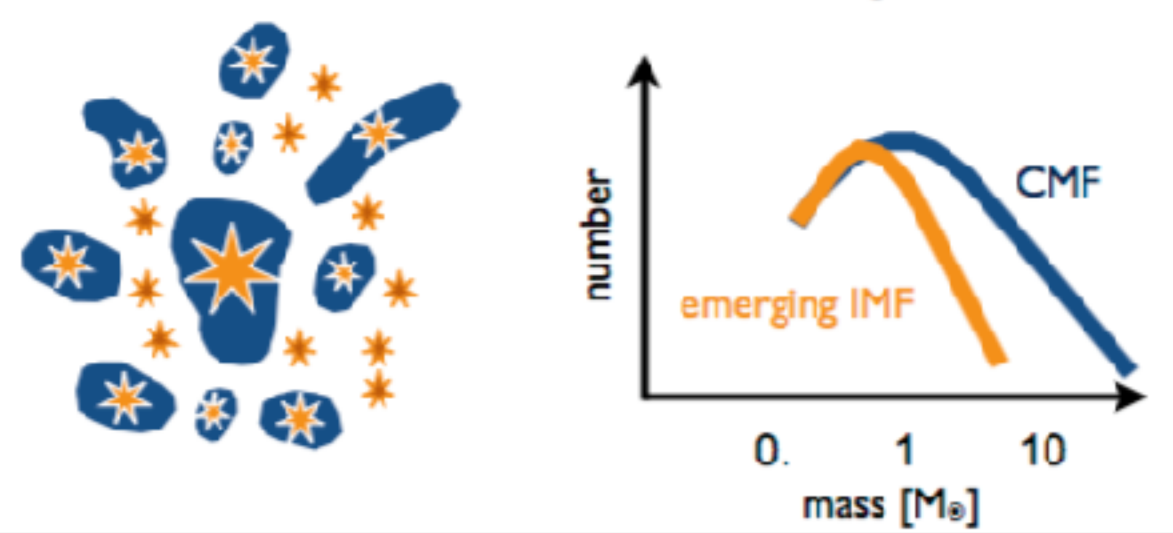
iii) Varying star formation efficiency (SFE). Here we show the emerging IMF that could arise if the high-mass cores in the CMF have a lower SFE than their low-mass siblings.



iv) Fragmentation is not self-similar. Here we show the emerging IMF that could arise if the cores in the CMF fragment based on the number of initial Jeans masses they contain.



v) Varying embedded phase timescale. Here we show the emerging IMF that could arise if the low-mass cores in the CMF finish before the high-mass cores.



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