Physics 224
The Interstellar Medium

Lecture #18

Molecular Clouds

Observed Characteristics

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

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Virial Theorem

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

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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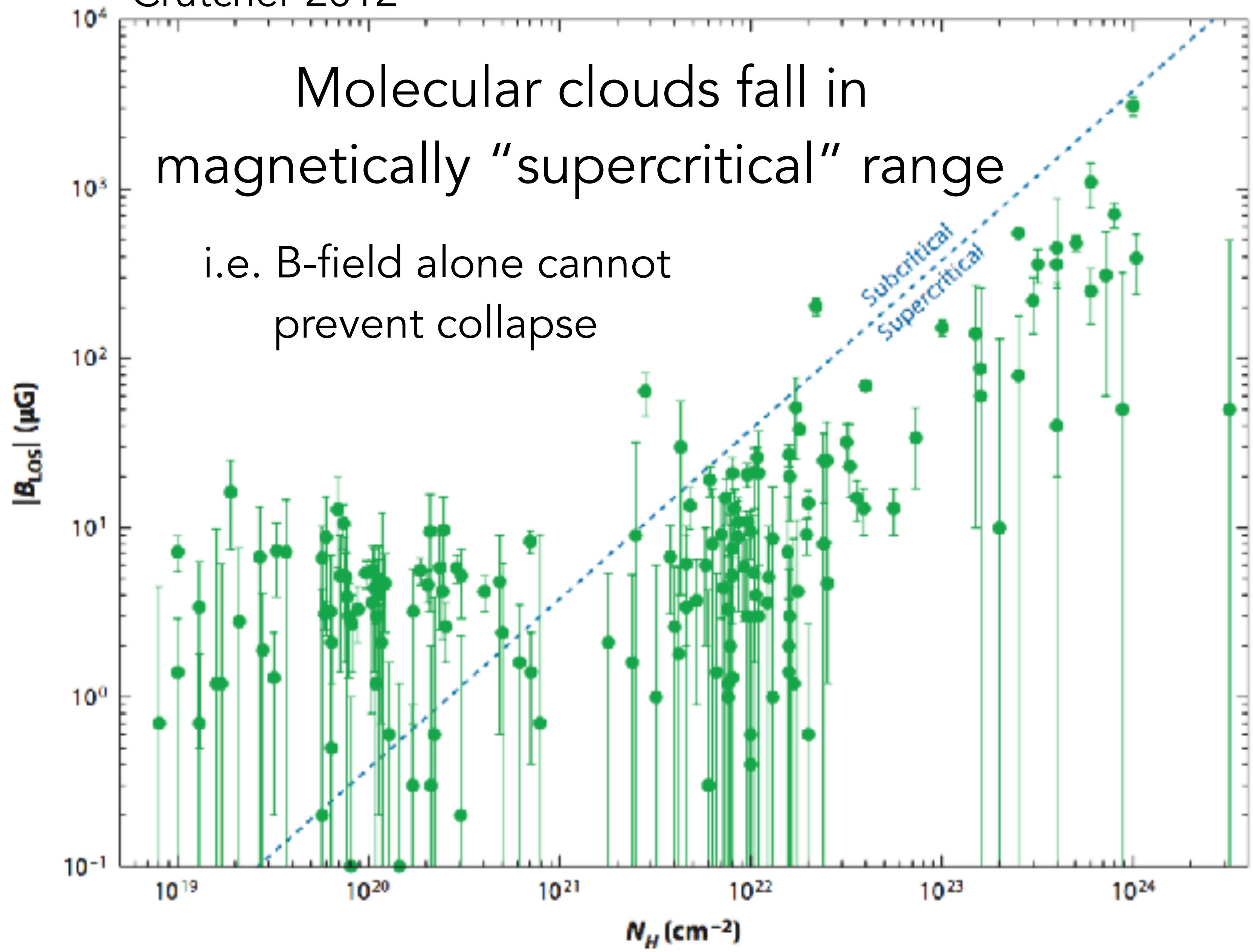
Crutcher 2012



Molecular clouds fall in magnetically “supercritical” range

i.e. B-field alone cannot prevent collapse

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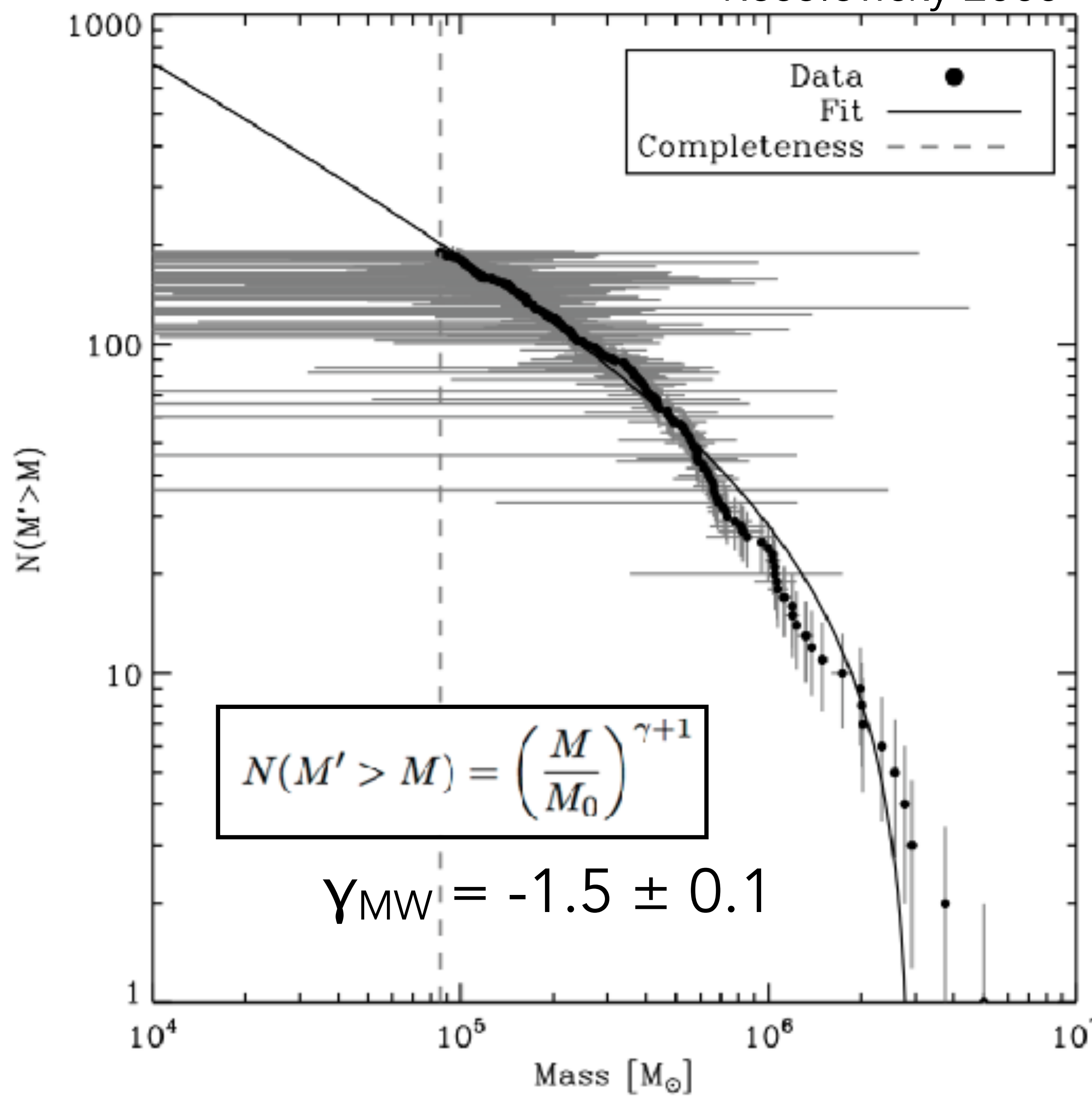
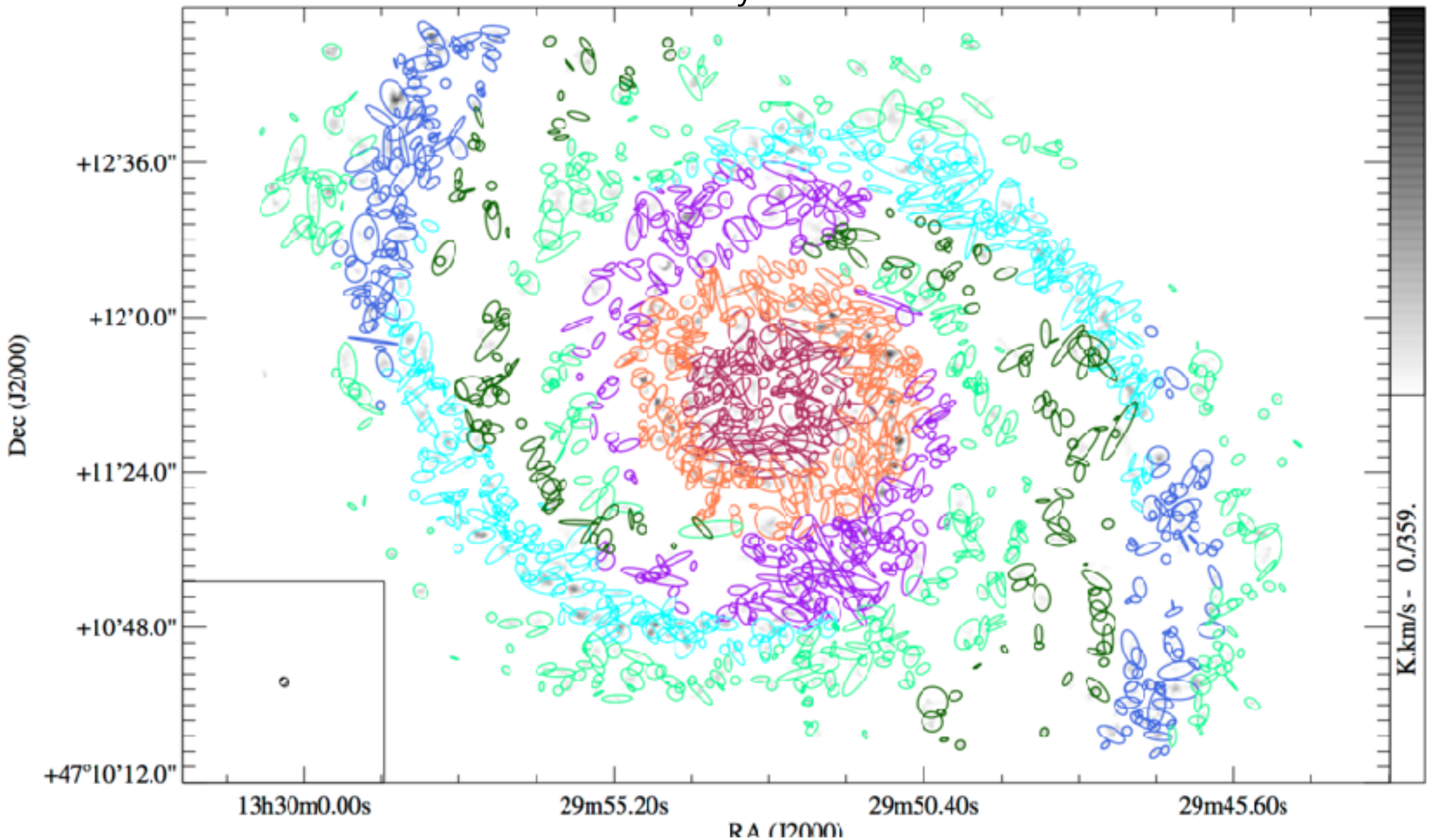
Rosolowsky 2005



Molecular Clouds

Colombo et al. 2014 - PAWS survey of M51



Molecular Clouds

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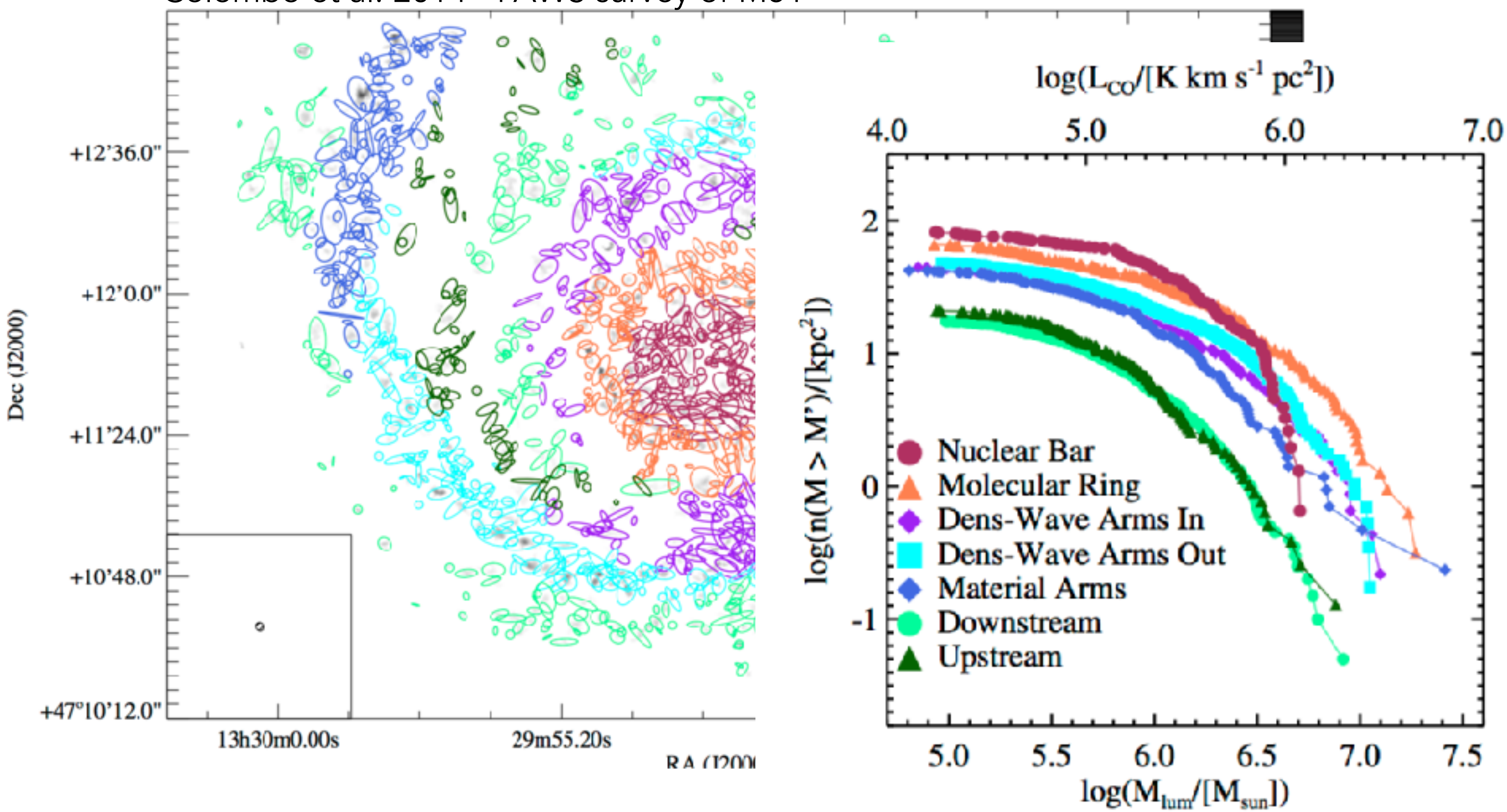

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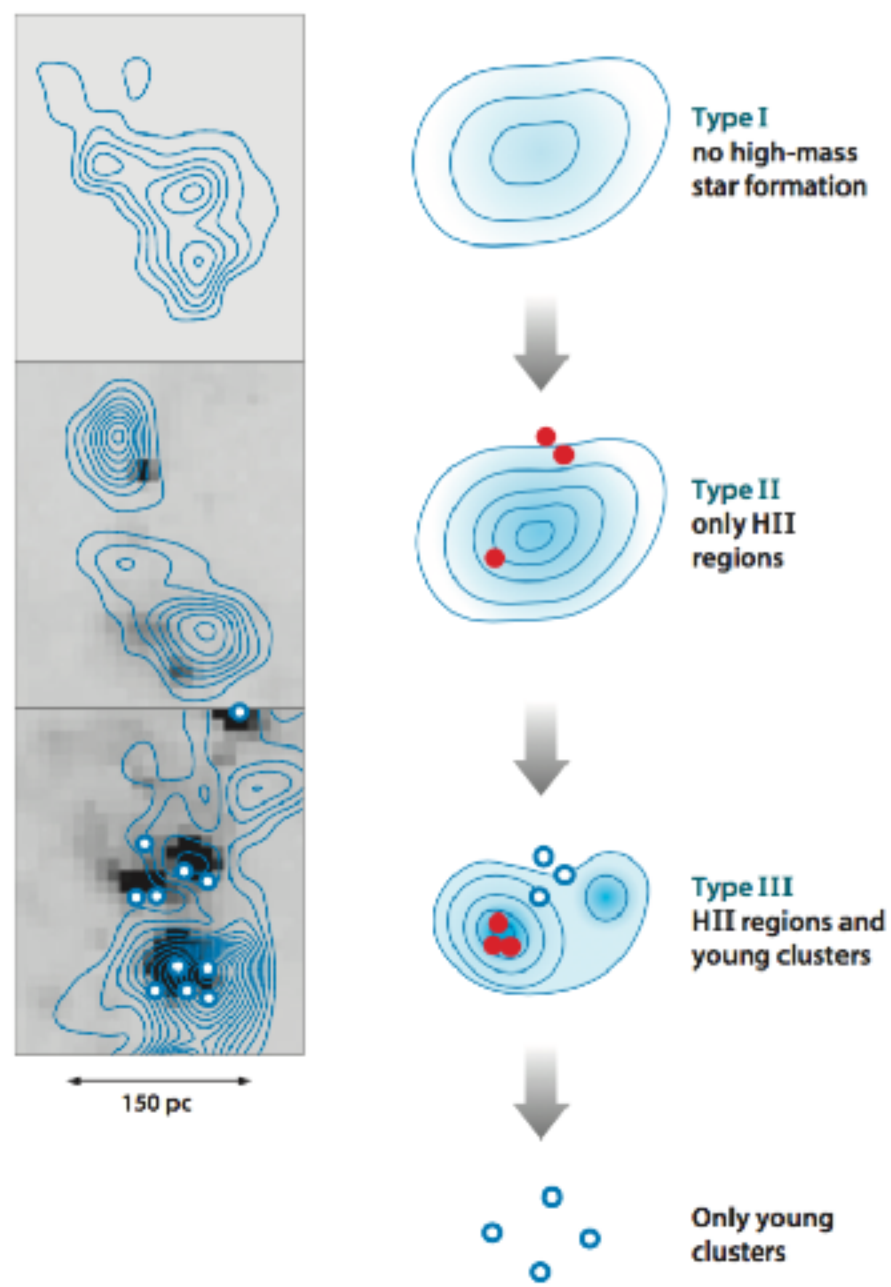
Kawamura et al. 2009



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

Star Formation

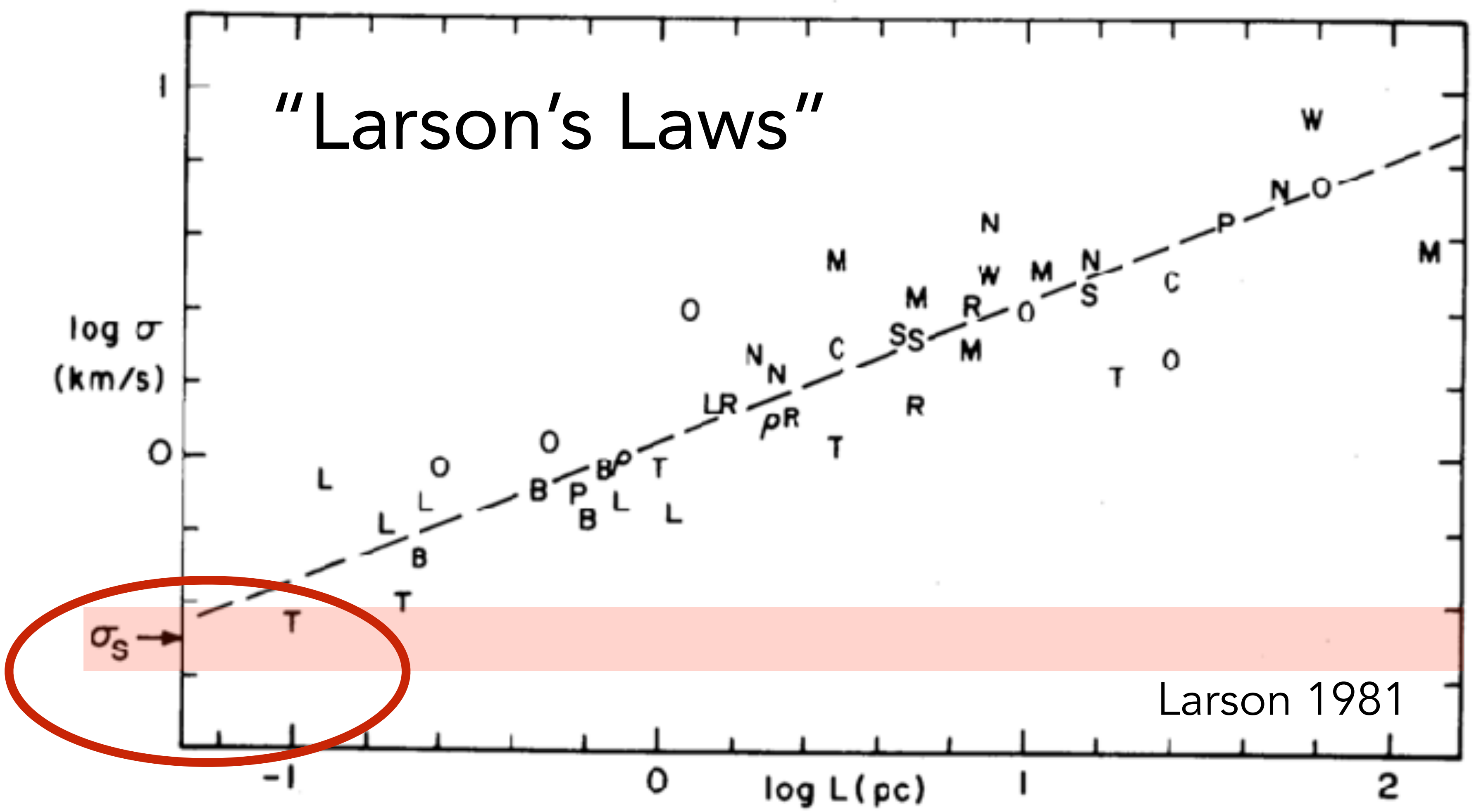
Table 1 Properties of dark clouds, clumps, and cores

	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^+.

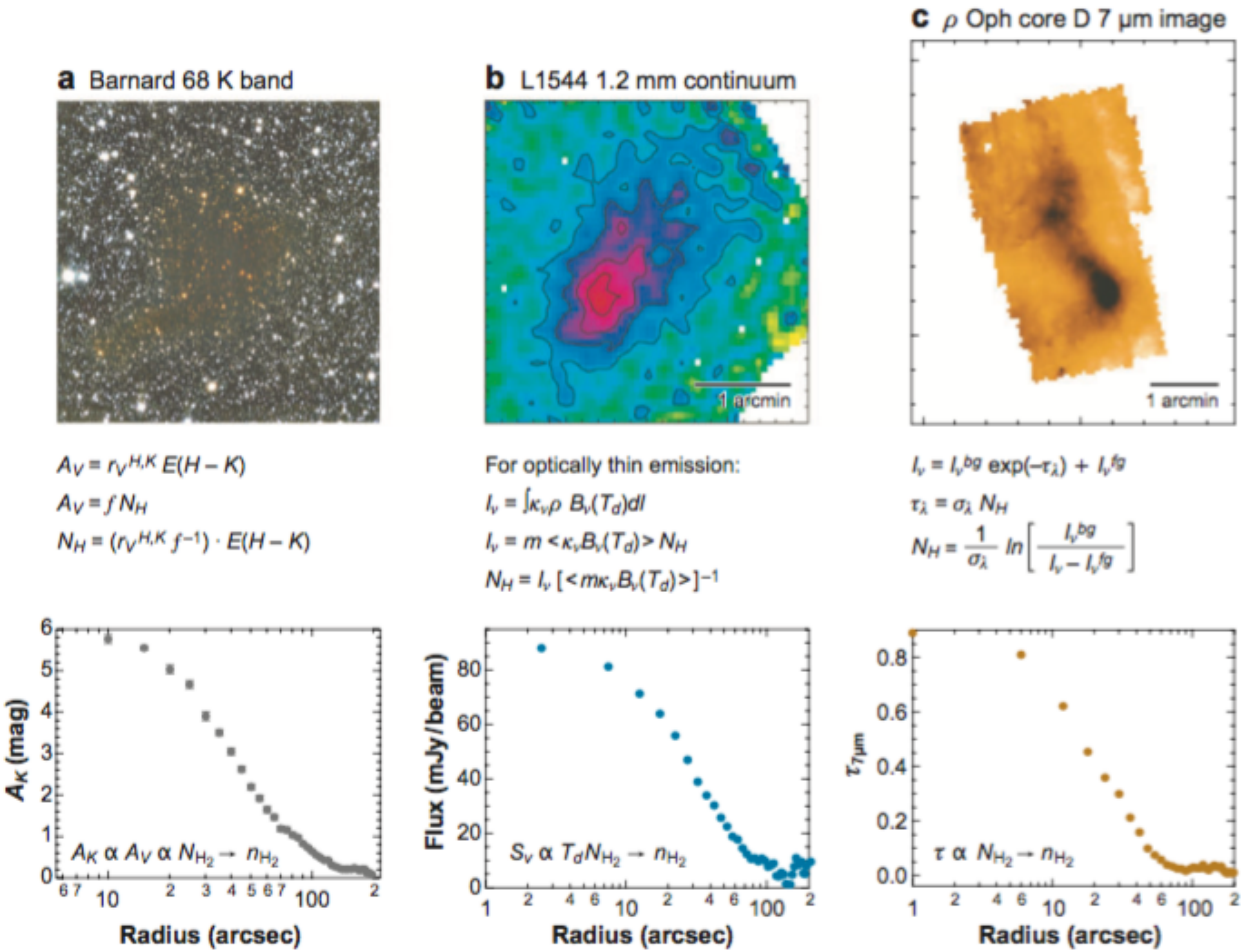
Bergin & Tafalla 2007

Star Formation



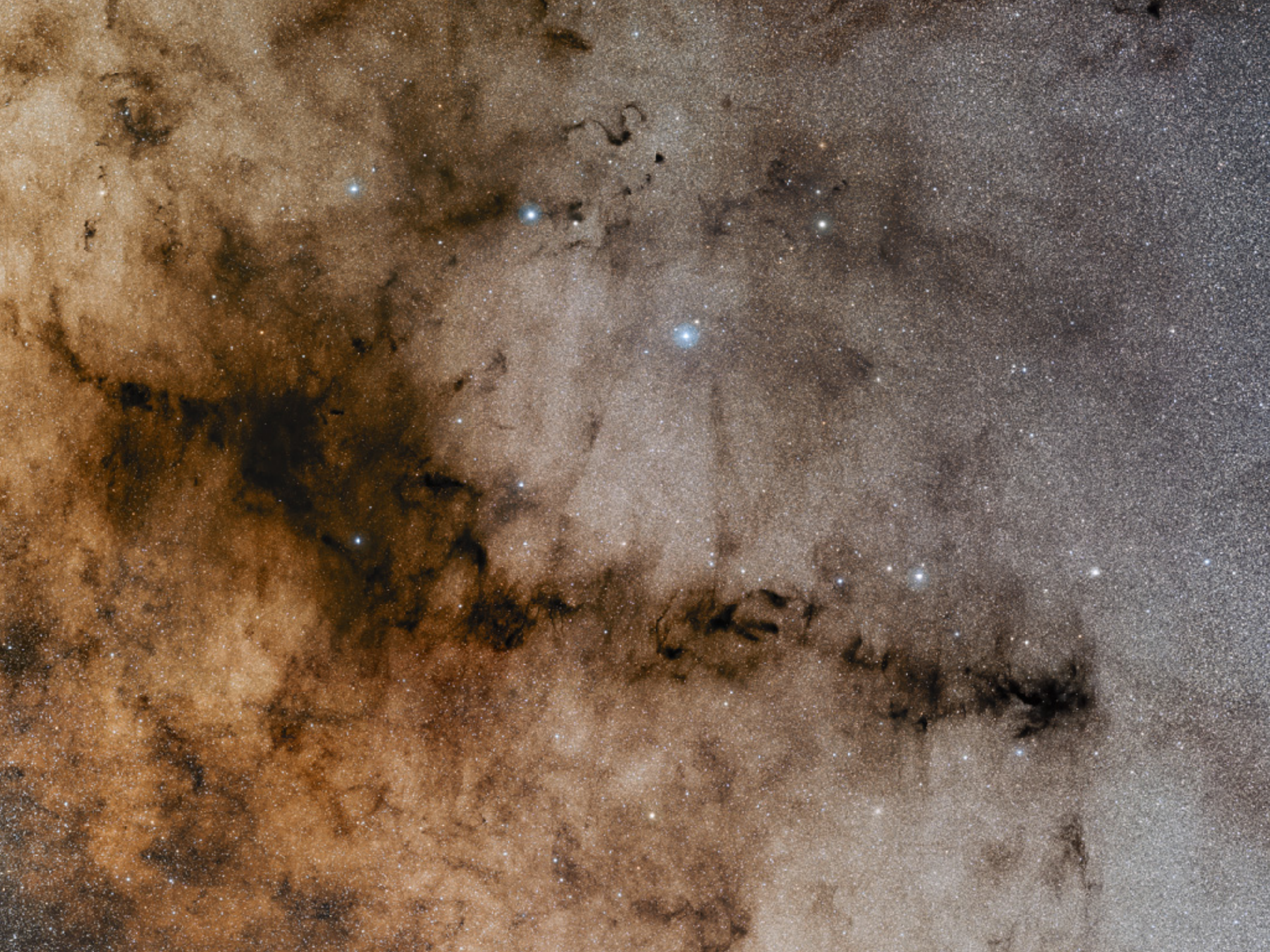
At small scales in clouds, thermal pressure support takes over from turbulence.

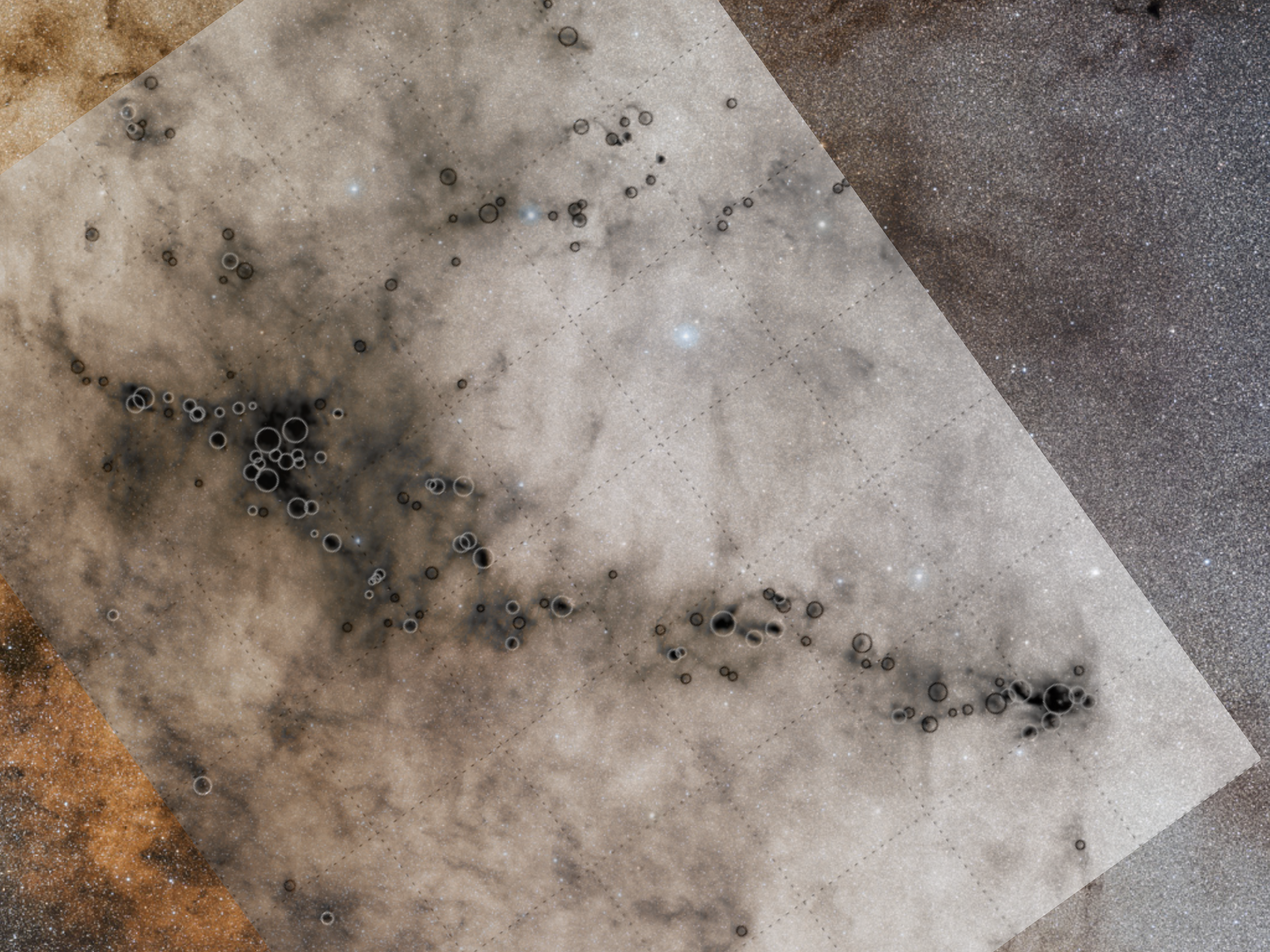
Cores in Molecular Clouds

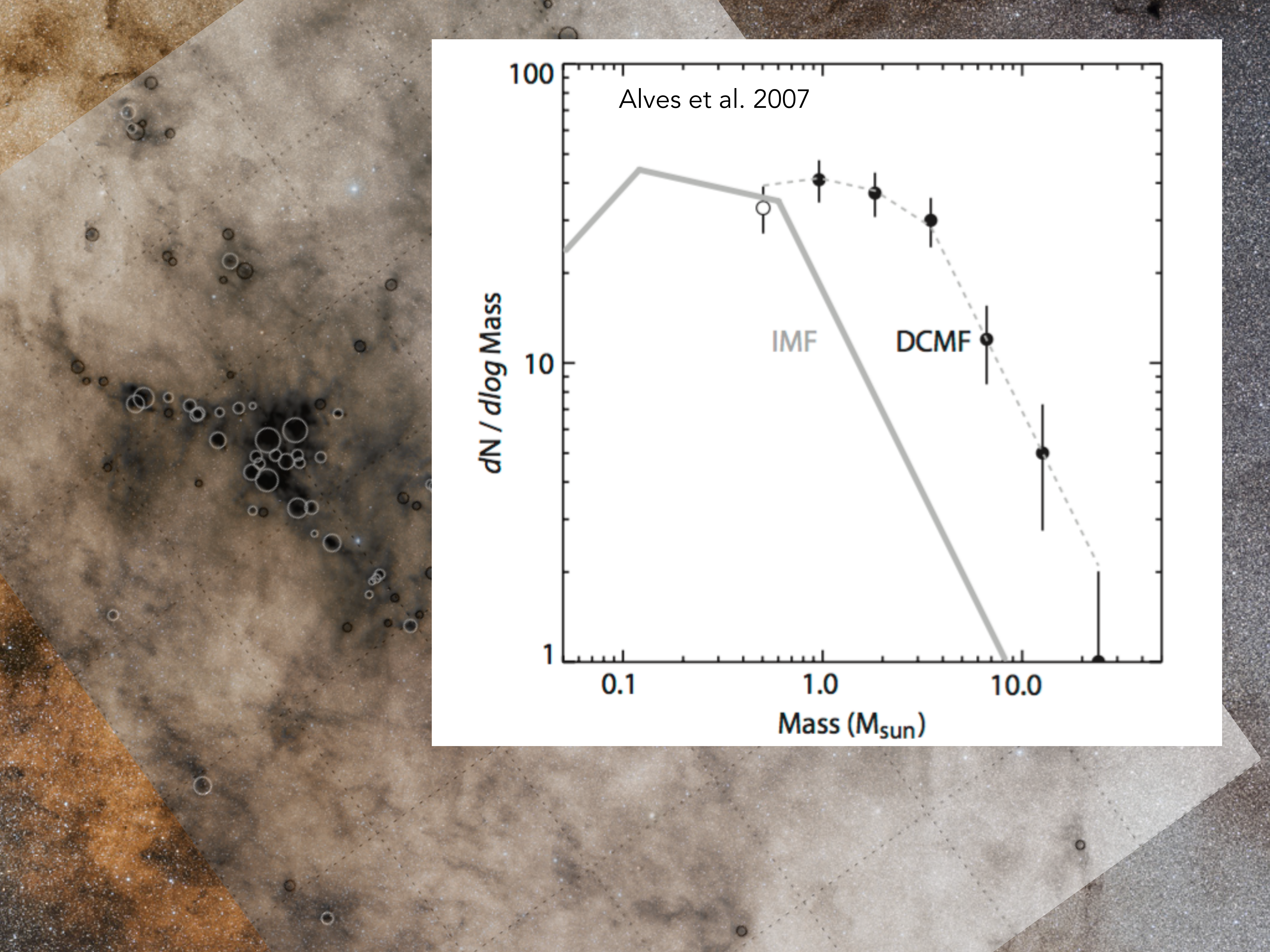


Column density profiles of dense cores are similar to Bonnor-Ebert profile (isothermal, marginally stable spherical cloud, supported against collapse by pressure)

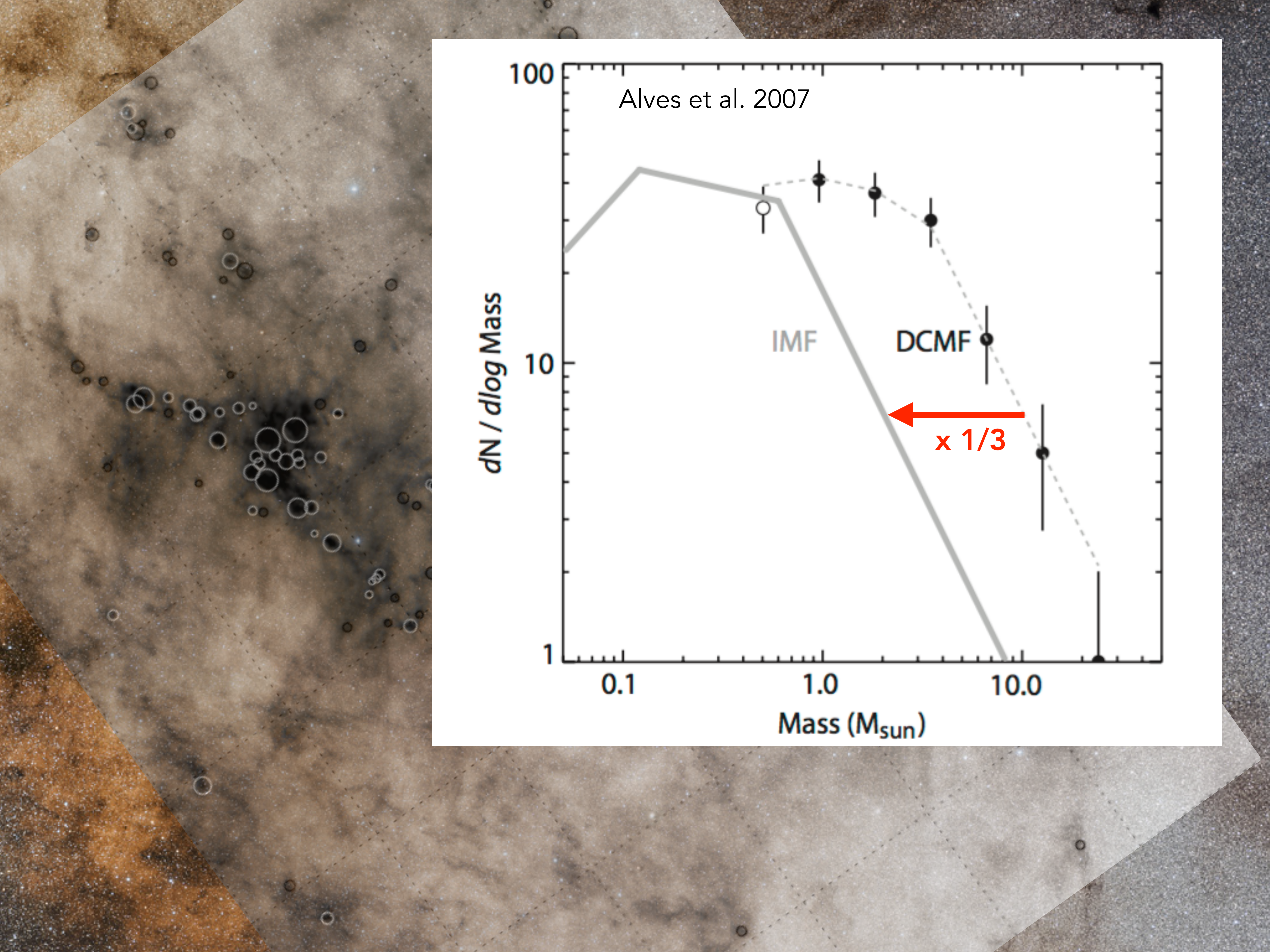
Bergin & Tafalla 2007







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



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

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

Controversy persists over whether it is the same everywhere.

Offner et al. 2014

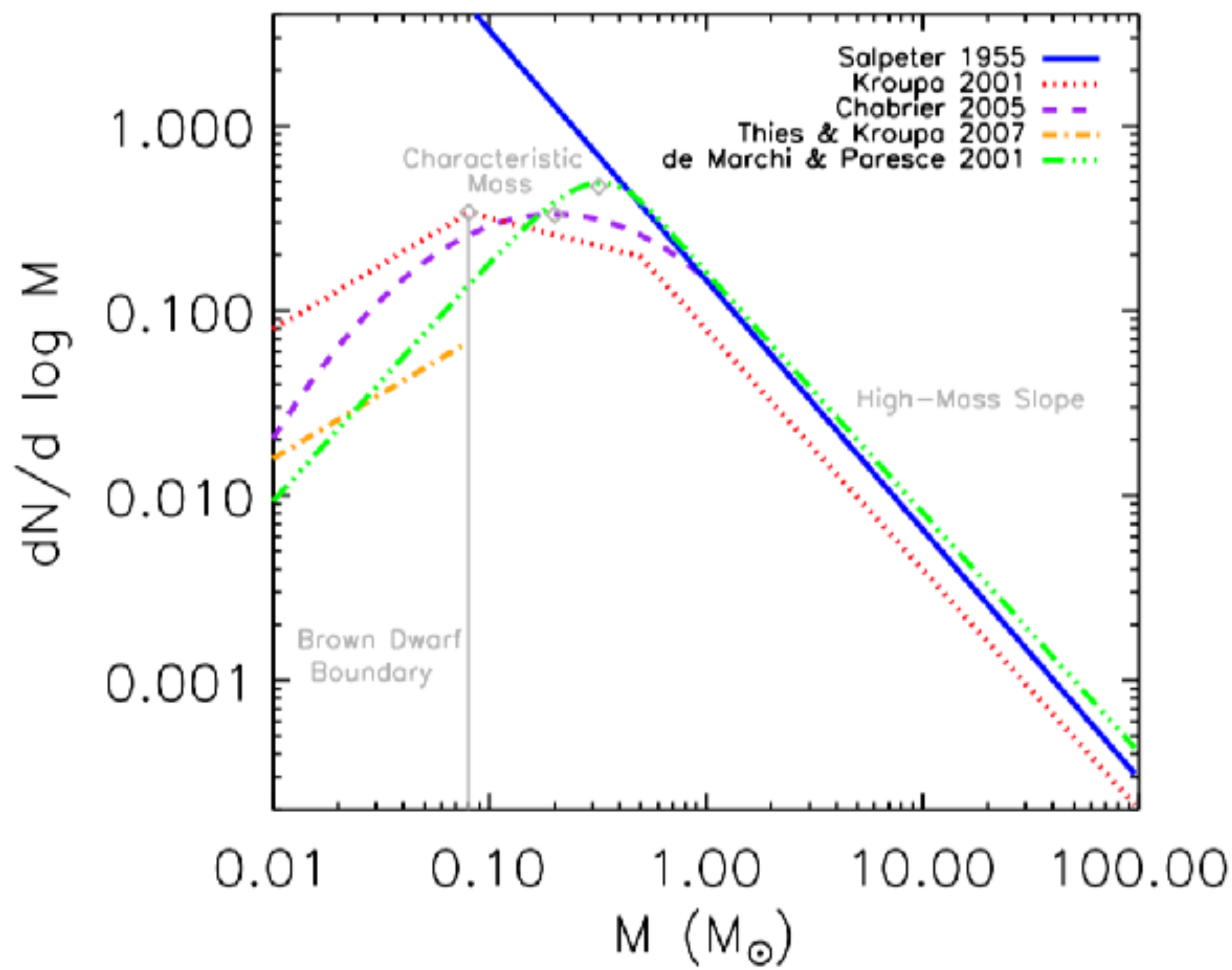
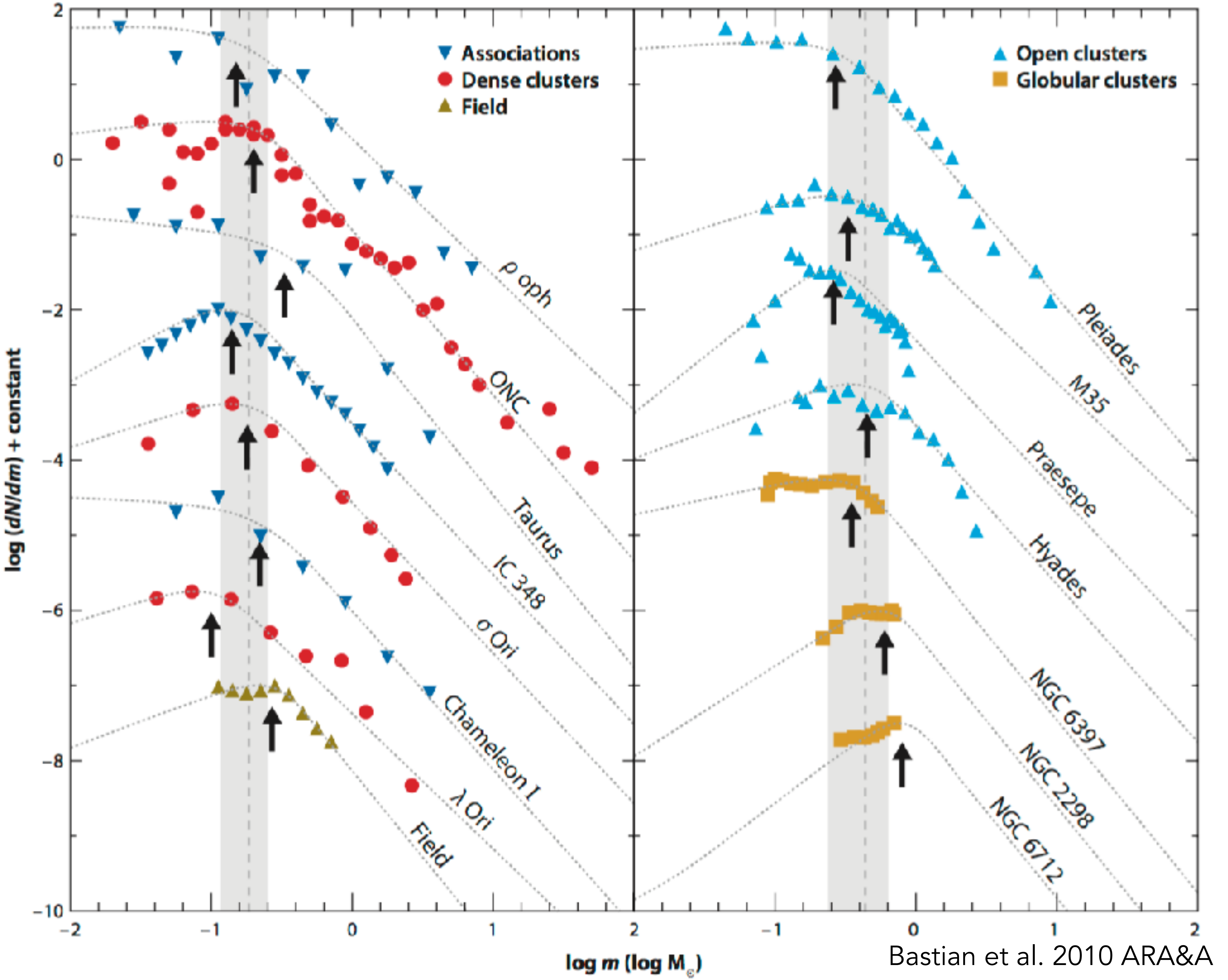
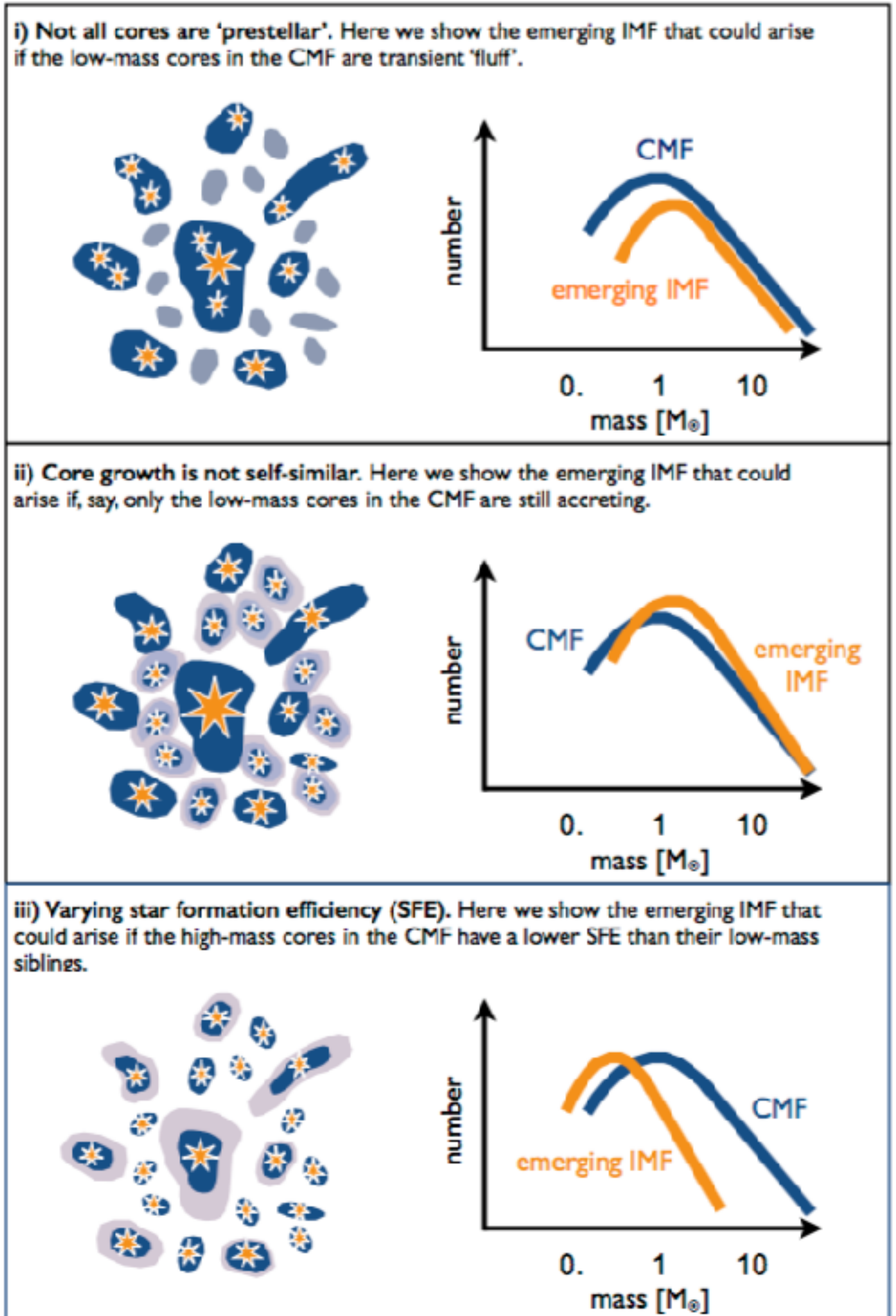


Fig. 1.— IMF functional forms proposed by various authors from fits to Galactic stellar data. With the exception of the Salpeter slope, the curves are normalized such that the integral over mass is unity. When comparing with observational data, the normalization is set by the total number of objects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

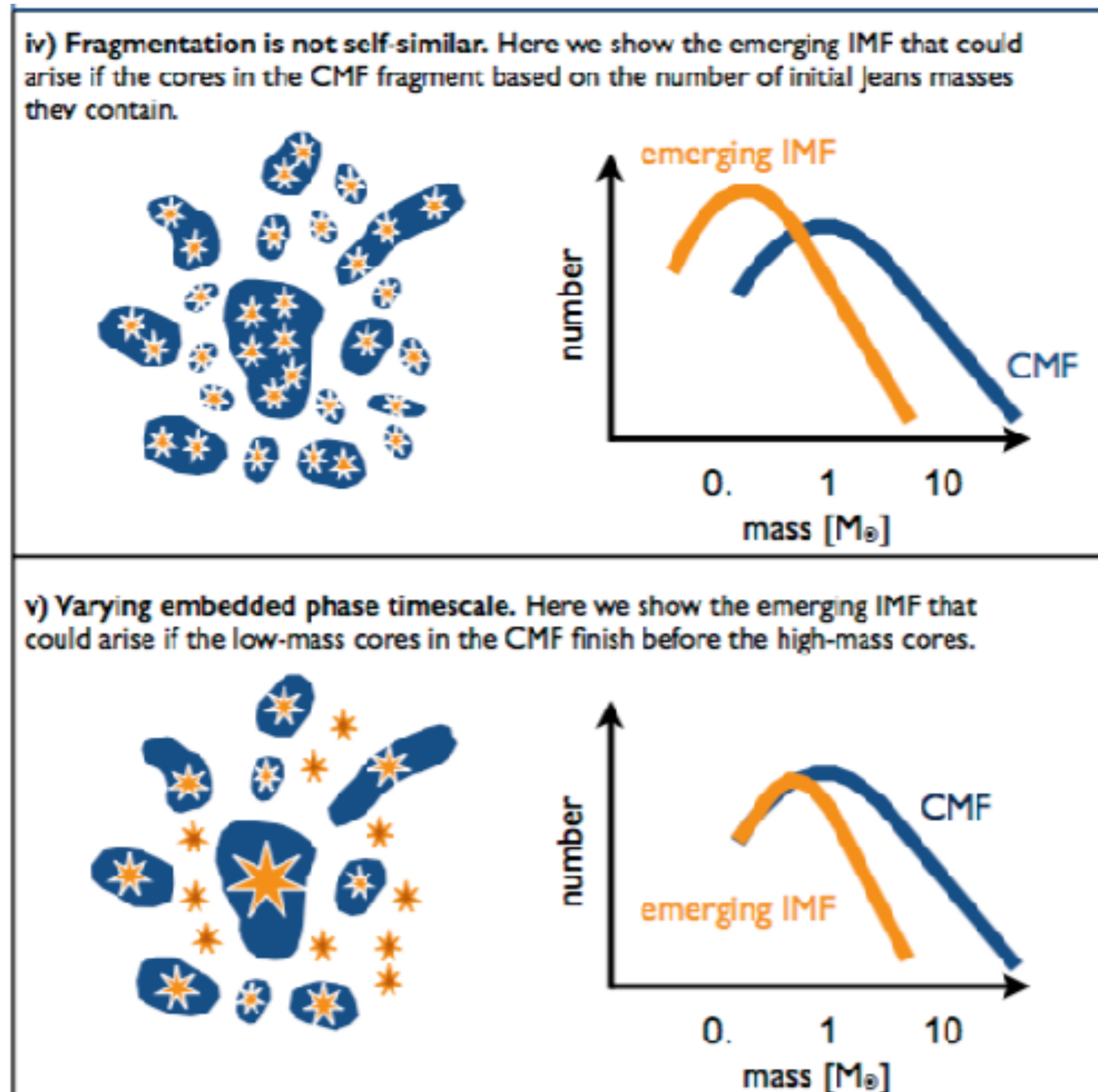


Bastian et al. 2010 ARA&A

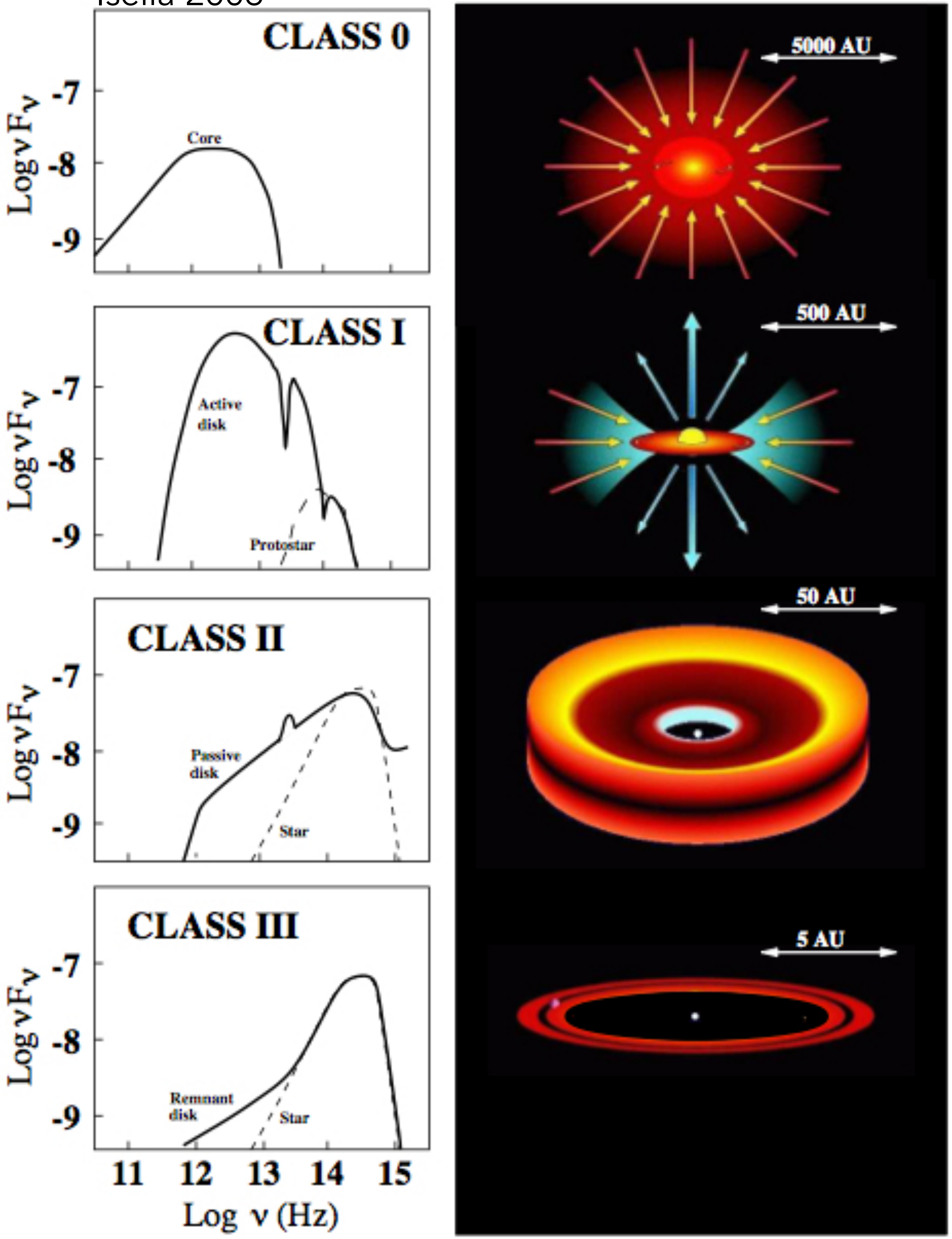
When does the CMF map to the IMF?



Offner et al. 2014



Isella 2006



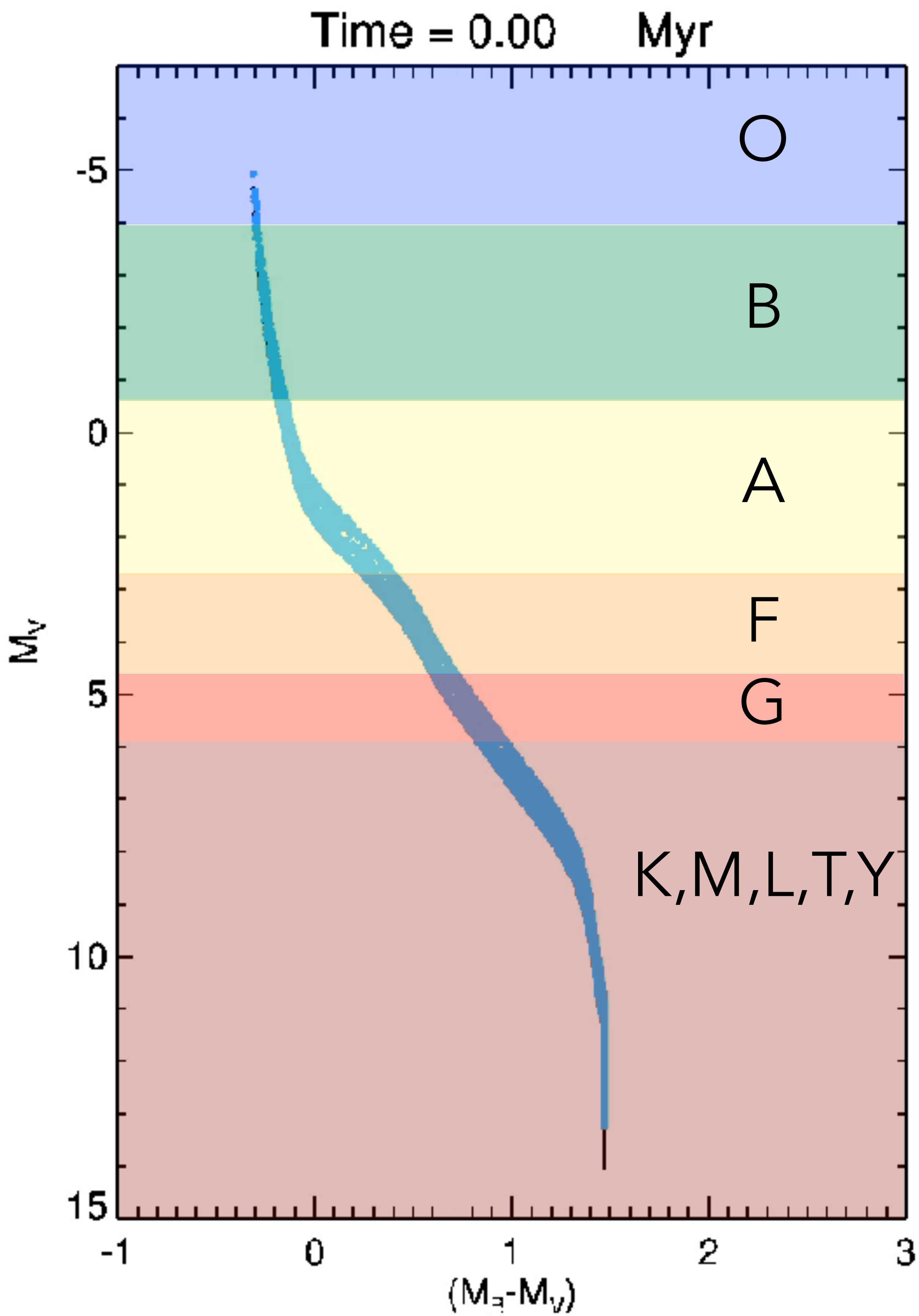
Protostars

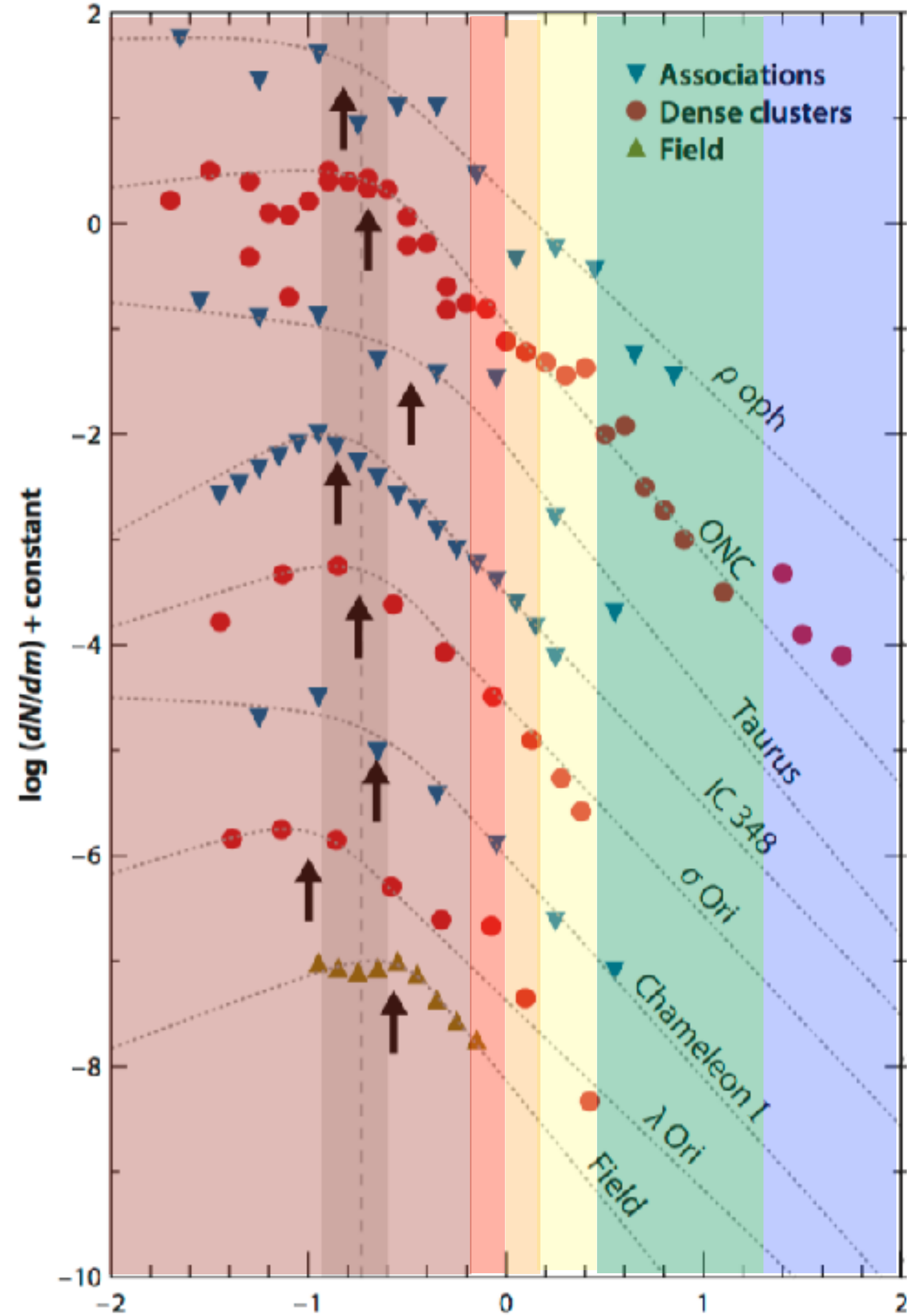
Gravitational collapse

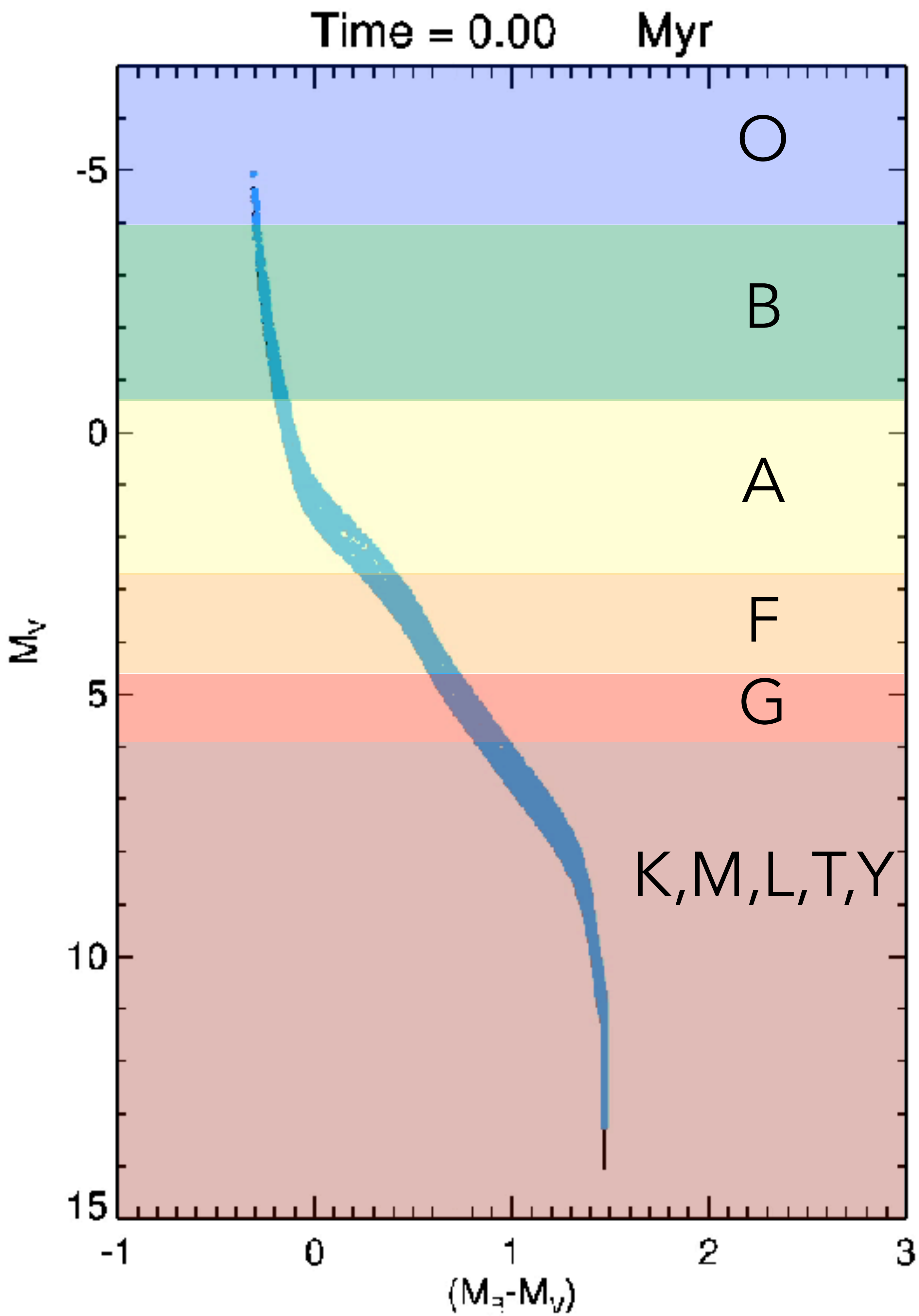
Angular momentum
-> disk formation
-> outflows & jets

Most material is in a disk, accretion onto protostar through disk.

Most material accreted, remnant disk.


Time = 0.00 Myr
O
B
A
F
G
K,M,L,T,Y
M_V
(M_B-M_V)


Associations
Dense clusters
Field
ρ oph
ONC
Taurus
IC 348
σ Ori
Chameleon I
λ Ori
Field
log (dN/dm) + constant


Time = 0.00 Myr
O
B
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M_V
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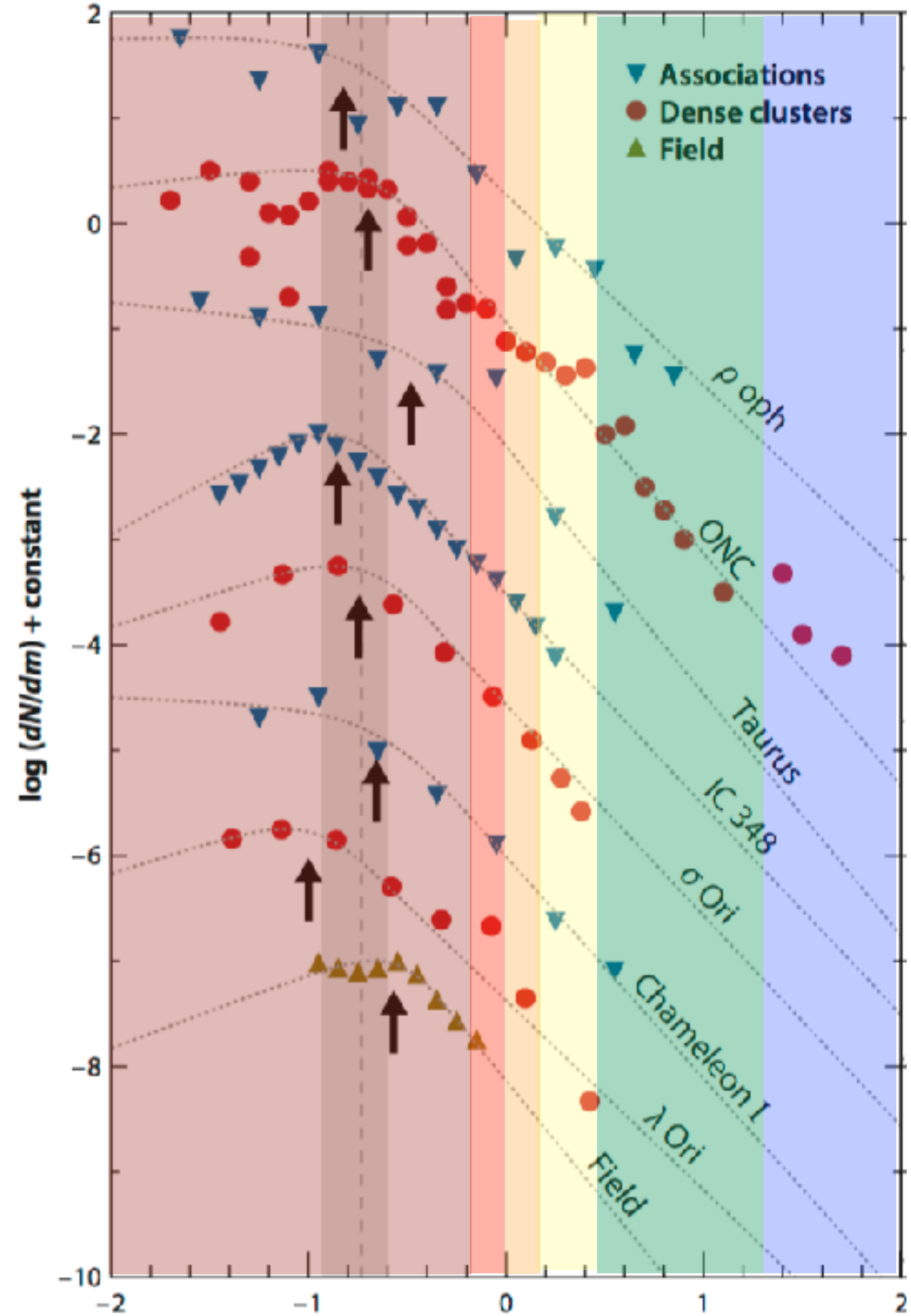
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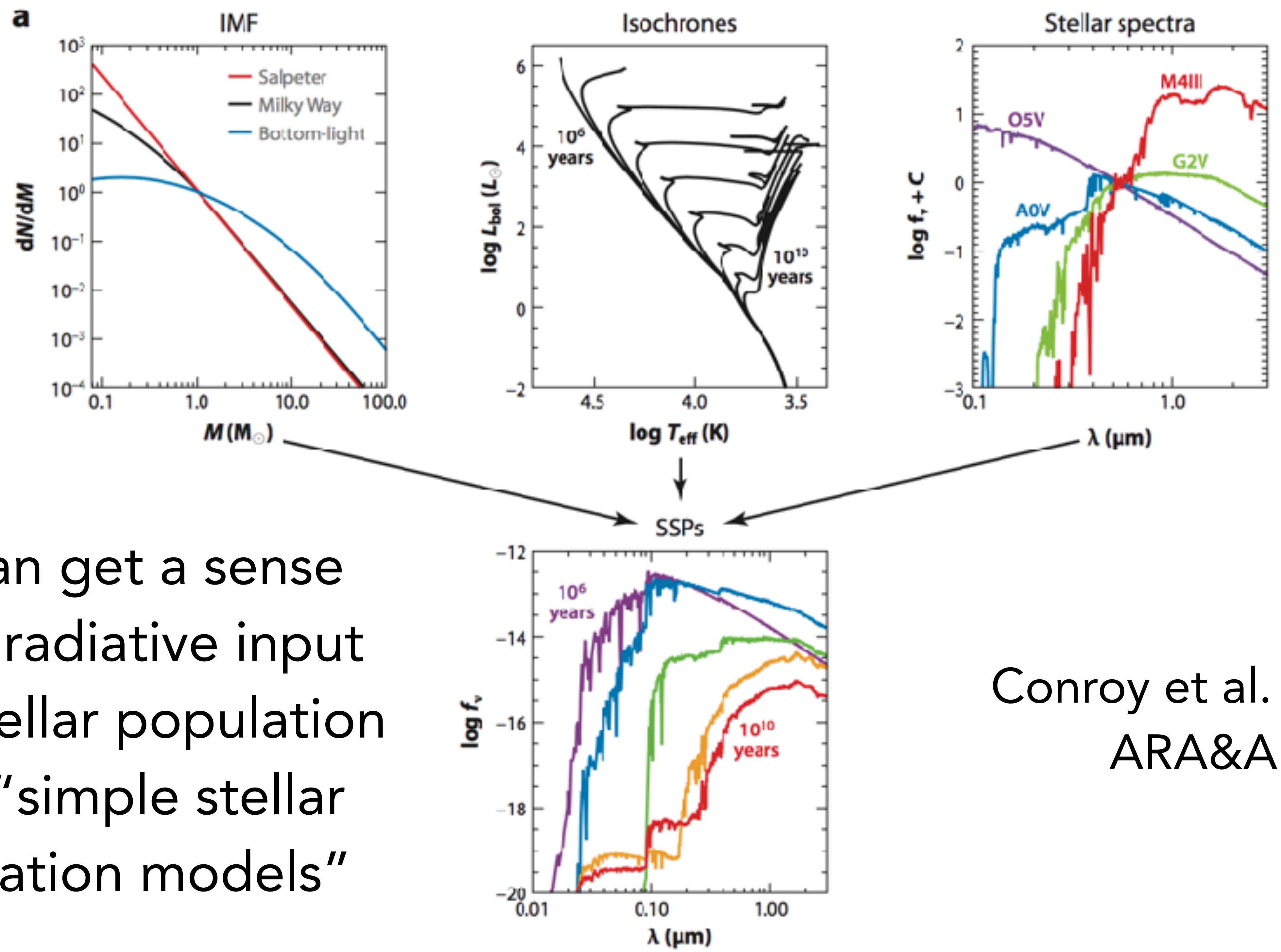
Radiative Feedback



We can get a sense of the radiative input from stellar population from "simple stellar population models"

Conroy et al. 2013 ARA&A

Radiative Feedback

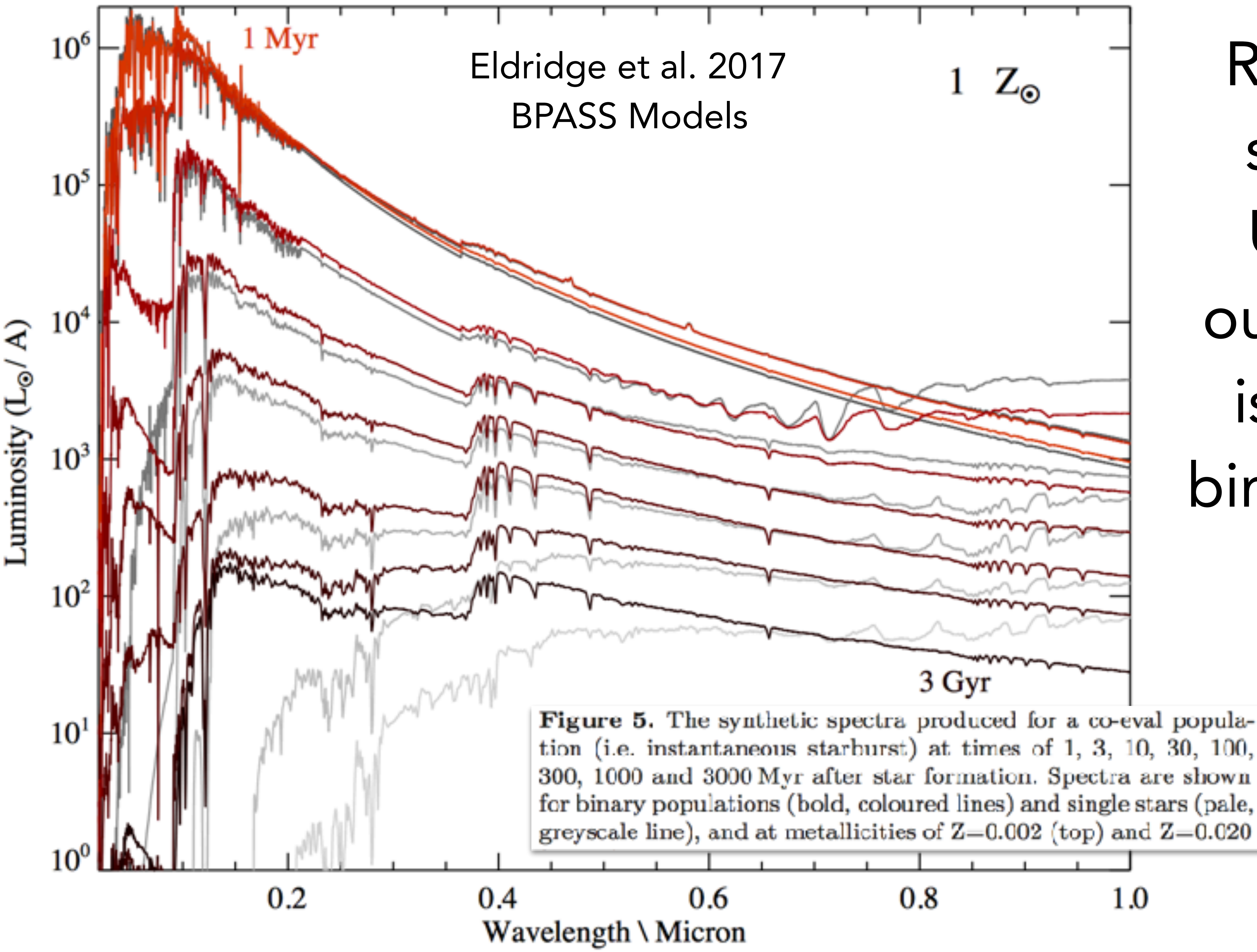
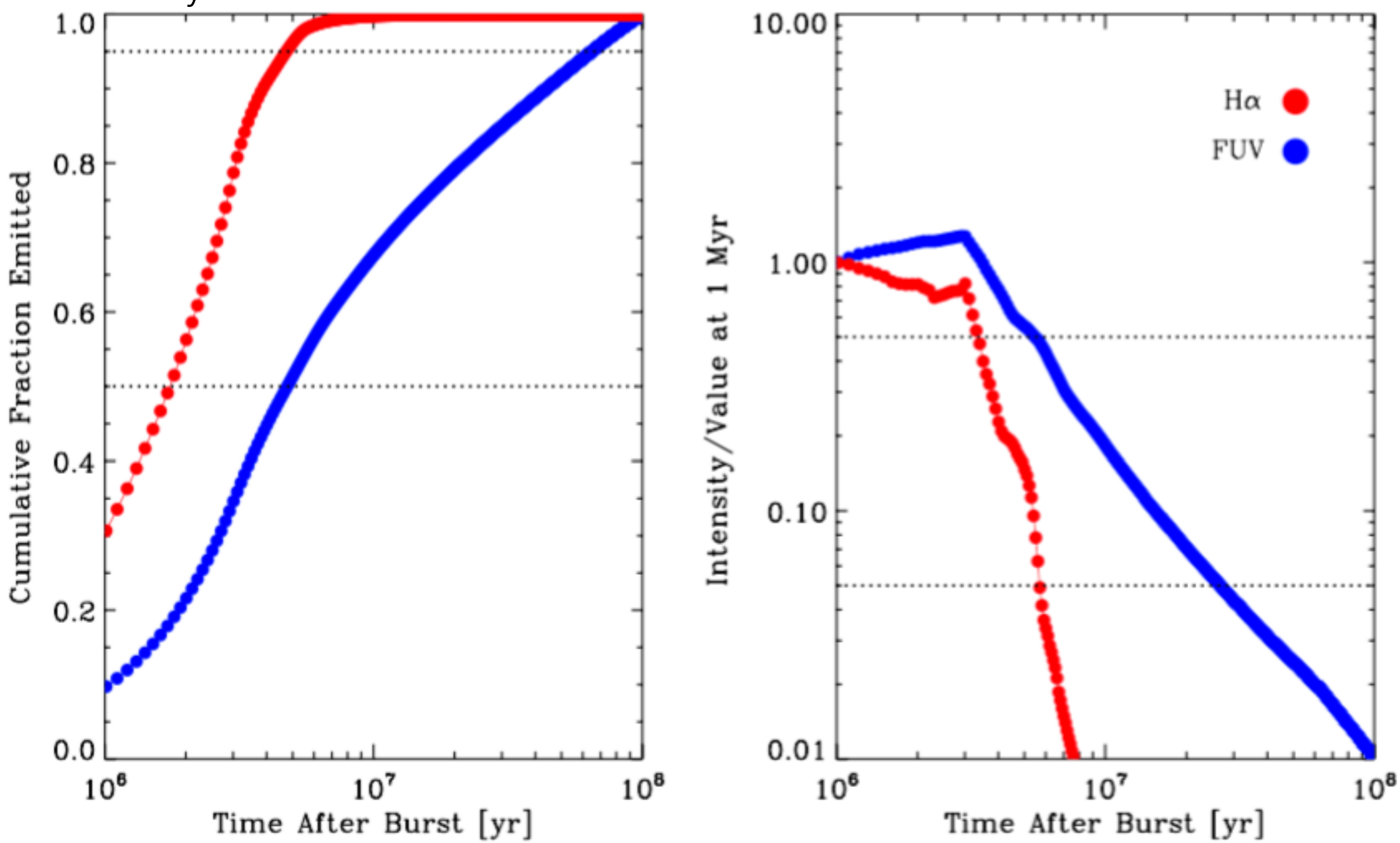


Figure 5. The synthetic spectra produced for a co-eval population (i.e. instantaneous starburst) at times of 1, 3, 10, 30, 100, 300, 1000 and 3000 Myr after star formation. Spectra are shown for binary populations (bold, coloured lines) and single stars (pale, greyscale line), and at metallicities of Z=0.002 (top) and Z=0.020

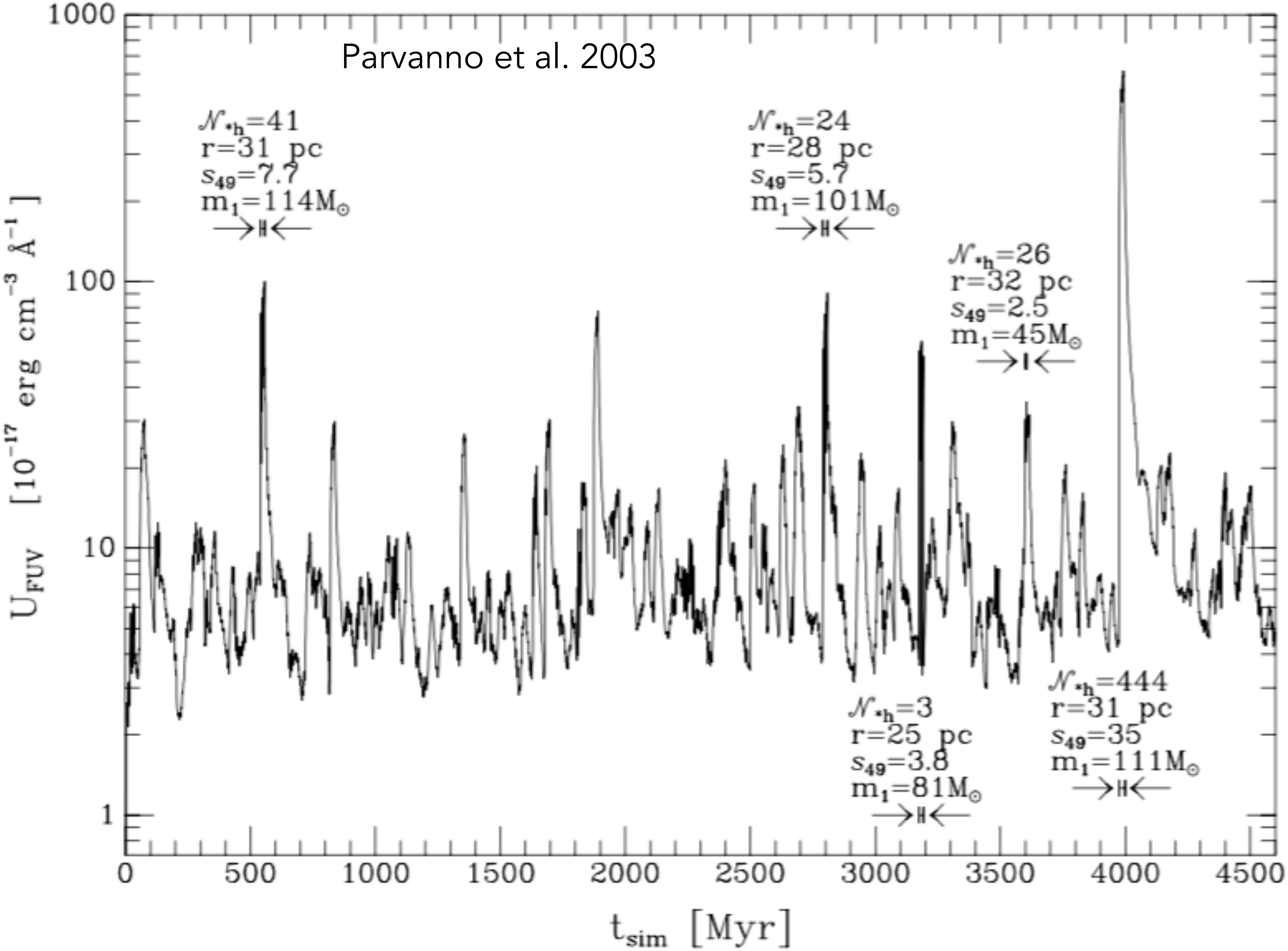
Recent results suggest that UV radiation output of a SSP is sensitive to binary evolution.

Radiative Feedback

Leroy et al. 2012

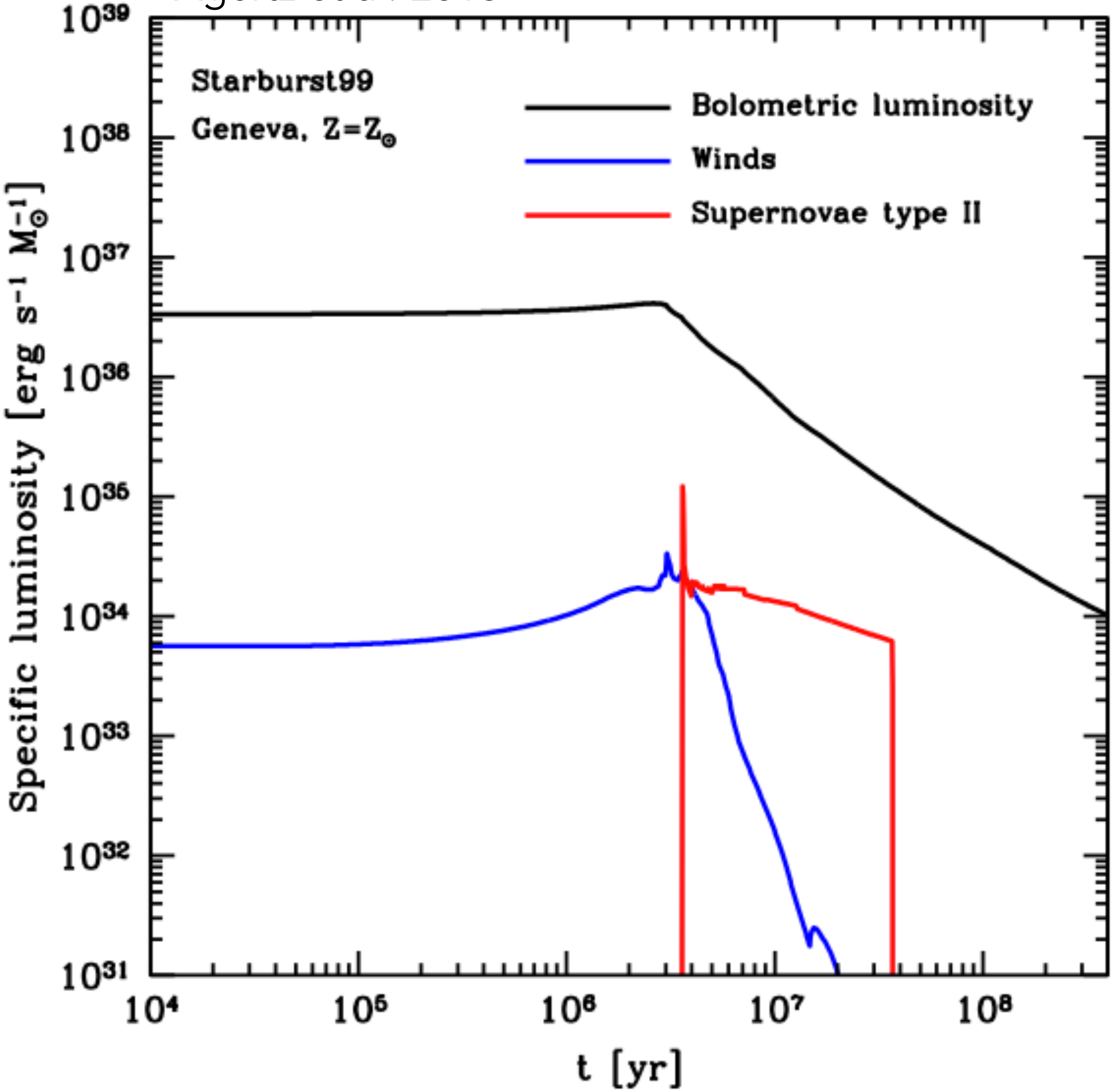


Radiative Feedback



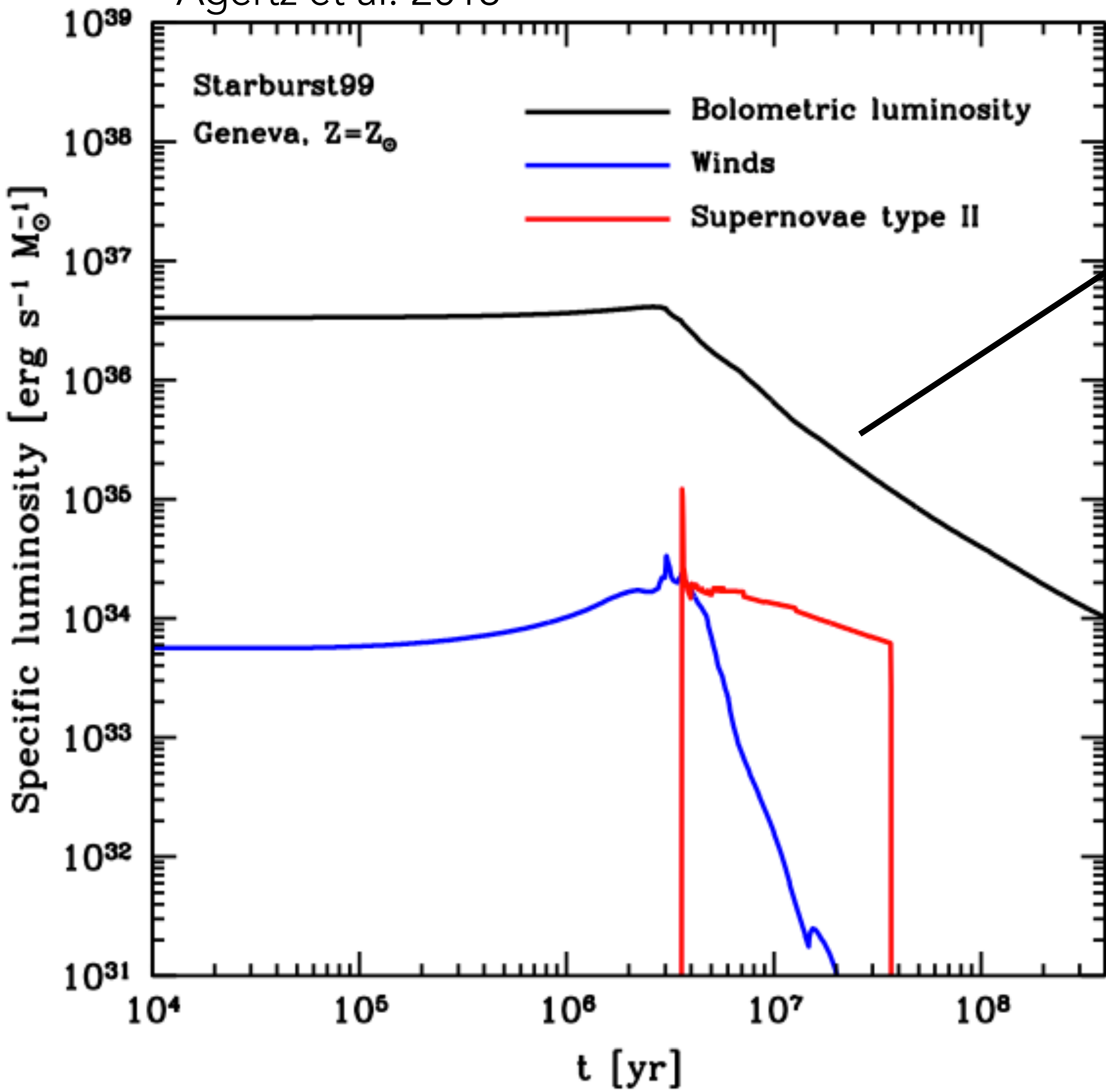
Mechanical Feedback

Agertz et al. 2013



Mechanical Feedback

Agertz et al. 2013

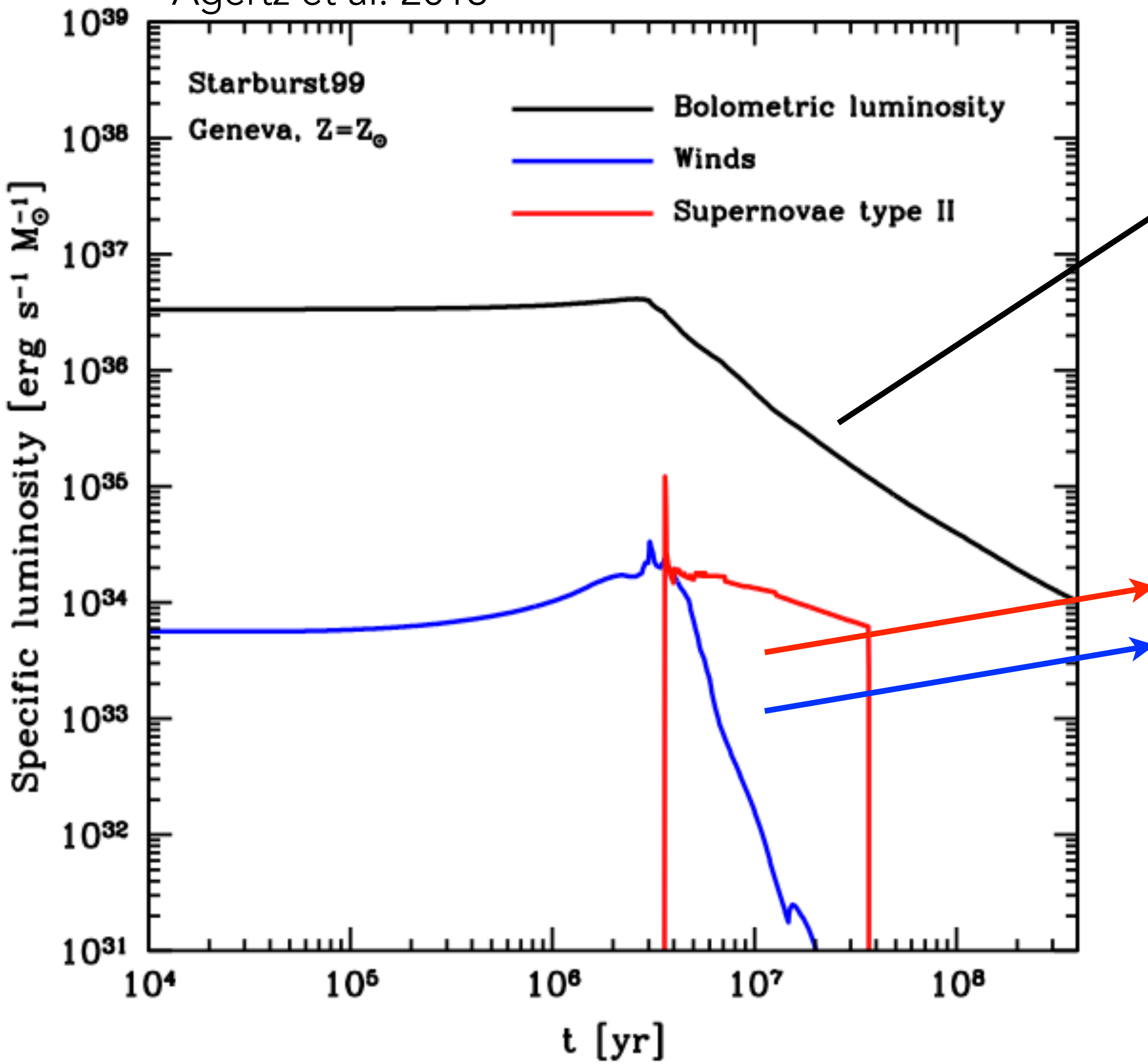


fraction into ionization, photoelectric heating, dust heating?

deposited where?

Mechanical Feedback

Agertz et al. 2013



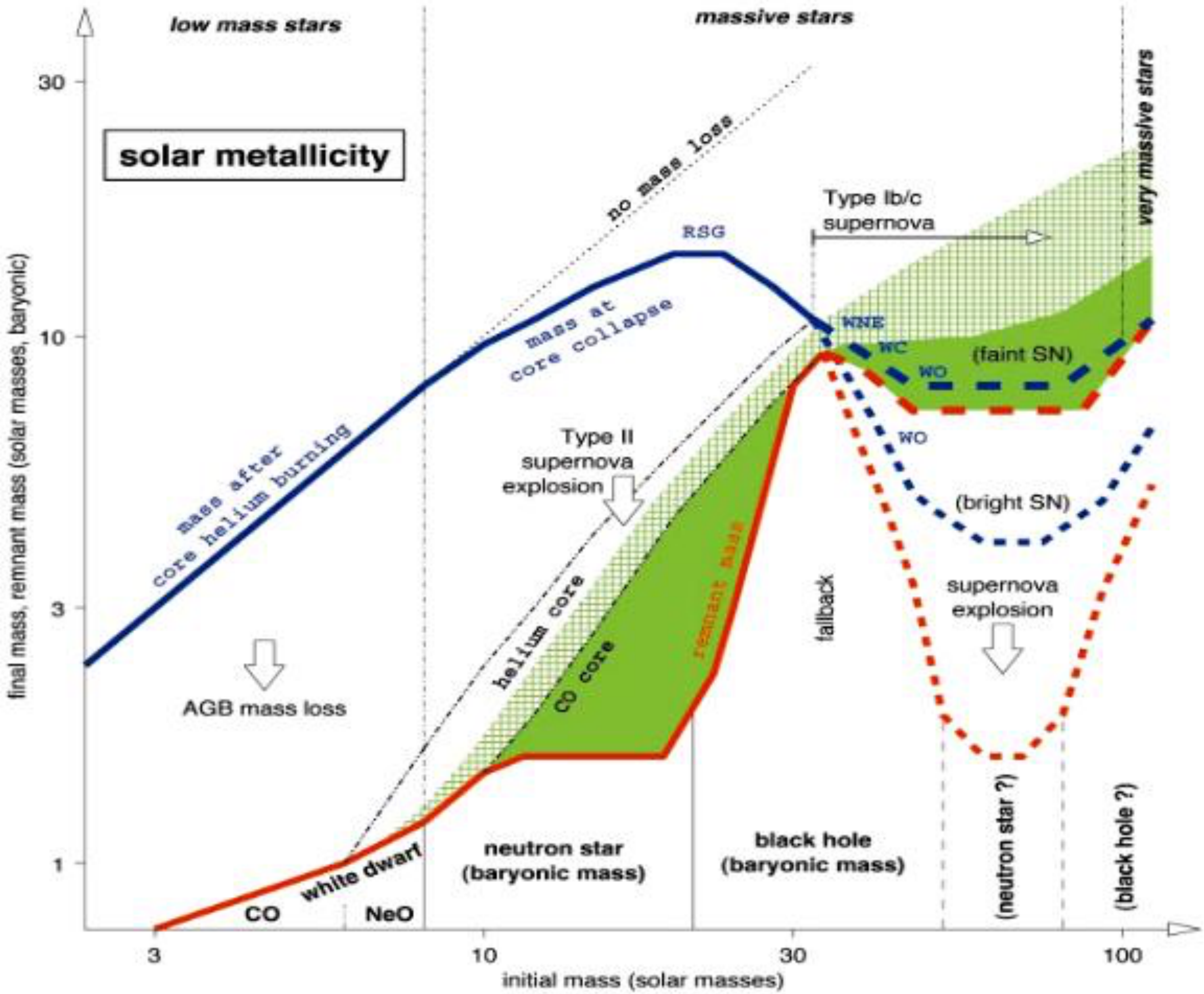
fraction into ionization, photoelectric heating, dust heating?

deposited where?

which phases is this deposited into, at what distances from stars?

Supernovae

Woosley et al. 2002



Stars with masses > 8 $M_\odot$ explode.

Supernovae produce $\sim 10^{53}$ ergs in neutrinos $\sim 10^{51}$ ergs in kinetic energy

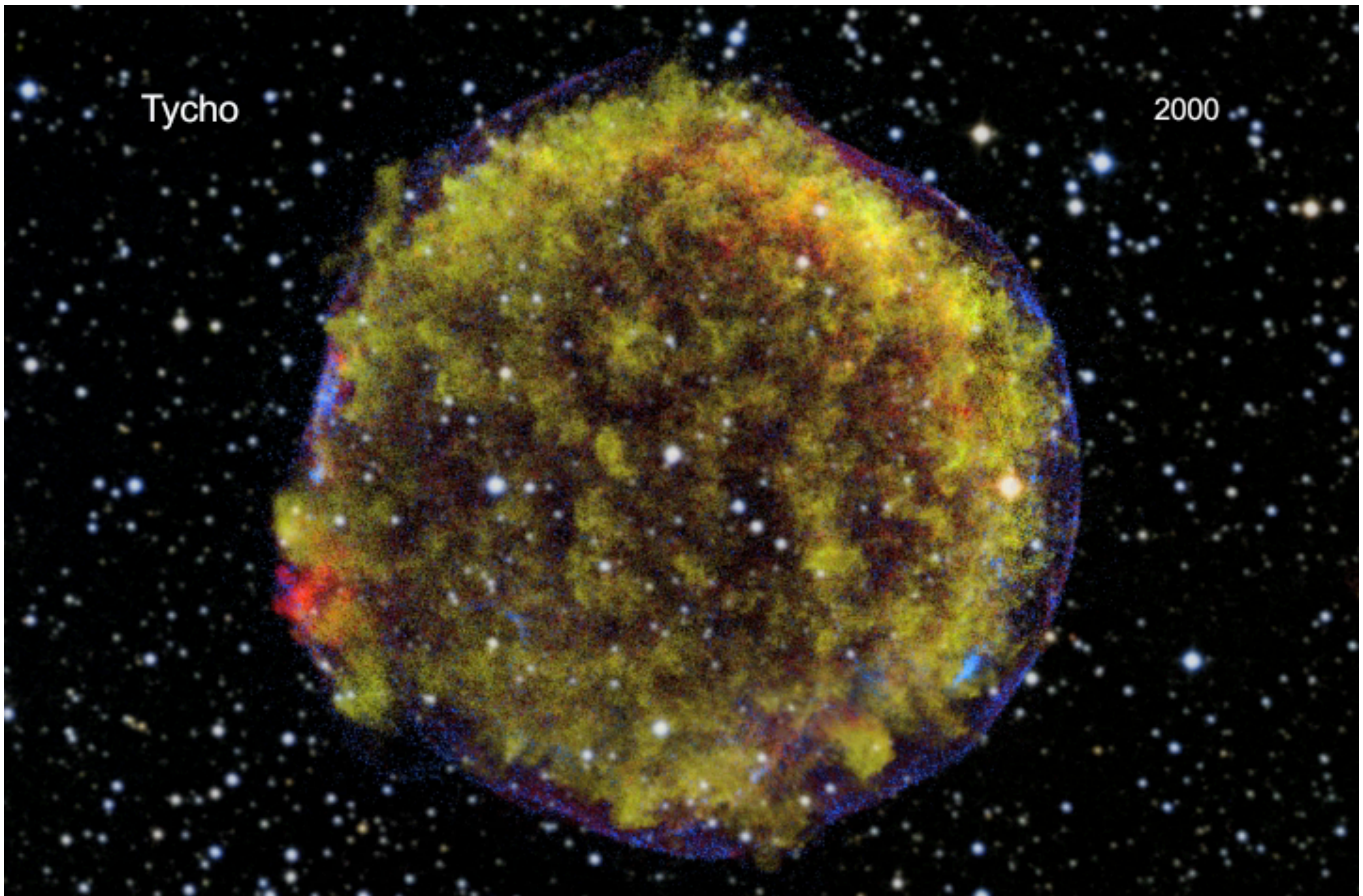
Supernovae

Initially: M_{ejecta} ~ few $M_{\odot}$, v_{ejecta} ~10^4 km/s

Phase	**Characteristics**	**Ends when…**	**Radius & time dependence**
Free Expansion	ballistic expansion, shock wave into ISM/CSM, ejecta cools due to adiabatic expansion, reverse shock when $P_{shocked\ ISM} > P_{ej}$	$M_{swept} > M_{ej}$	$R \sim t$
Sedov-Taylor	ejecta is very hot, $P_{ej} > P_{ISM}$ expansion driven by hot gas, radiation losses are unimportant	radiative losses become important	$R \sim t^{2/5}$
Snow Plow	pressure driven expansion with radiative loss, then momentum driven	shock becomes subsonic	$R \sim t^{2/7}$ $R \sim t^{1/4}$
Fadeaway	turbulence dissipates remnant structure and merges with ISM	-	-

Supernovae

Tycho SN Remnant in x-rays from Chandra



(Credit: NASA/CXC/GSFC/B.Williams et al;)

Supernovae

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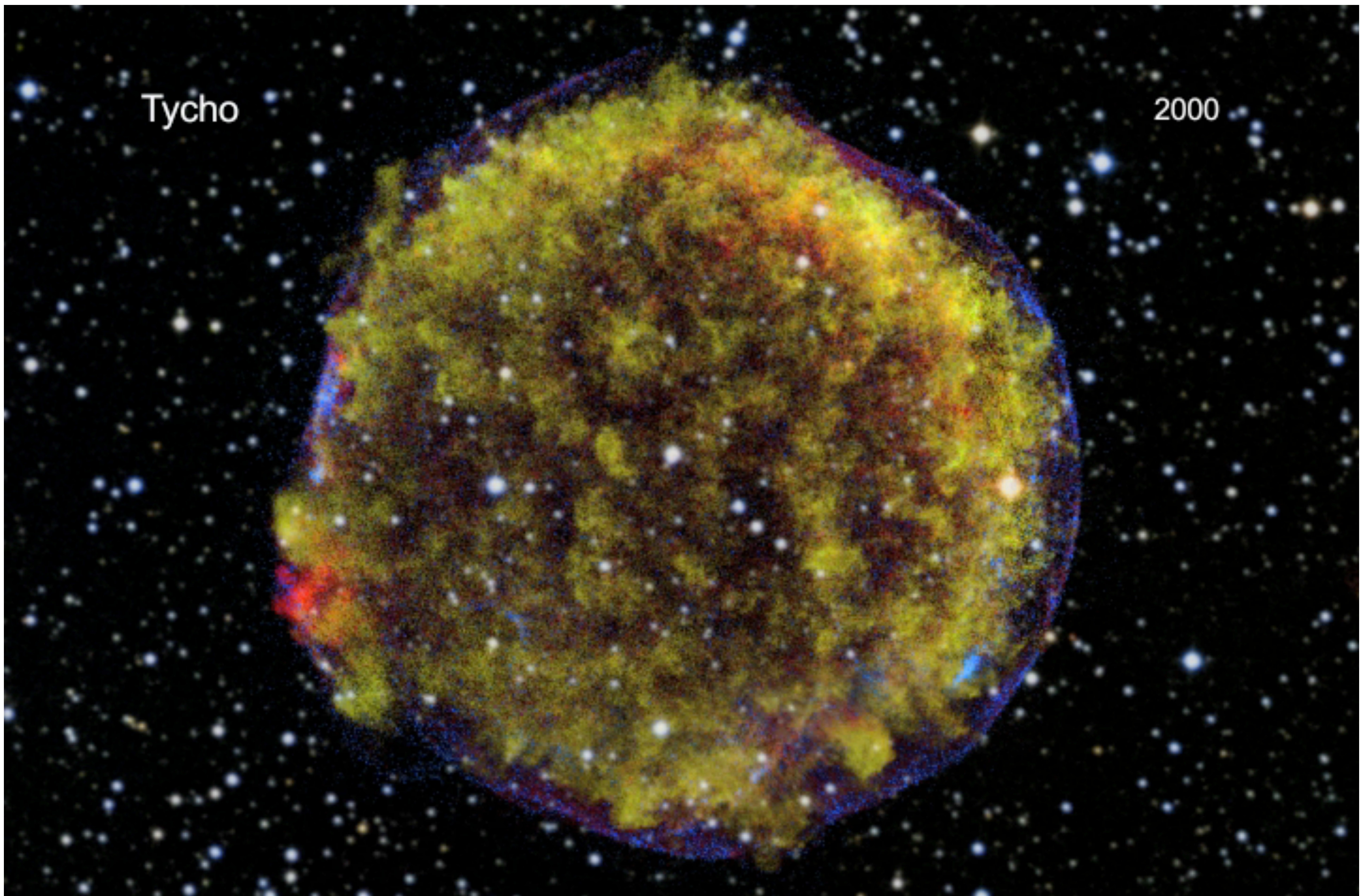

(Credit: NASA/CXC/GSFC/B.Williams et al;)