# Physics 224
# The Interstellar Medium

## Lecture #19: B-fields, Star Formation, Feedback, Cosmic Rays

# Outline

- Part I: Magnetic Fields
- Part II: Star Formation
- Part III: Feedback
- Part IV: Cosmic Rays

# Magnetic Fields in the ISM

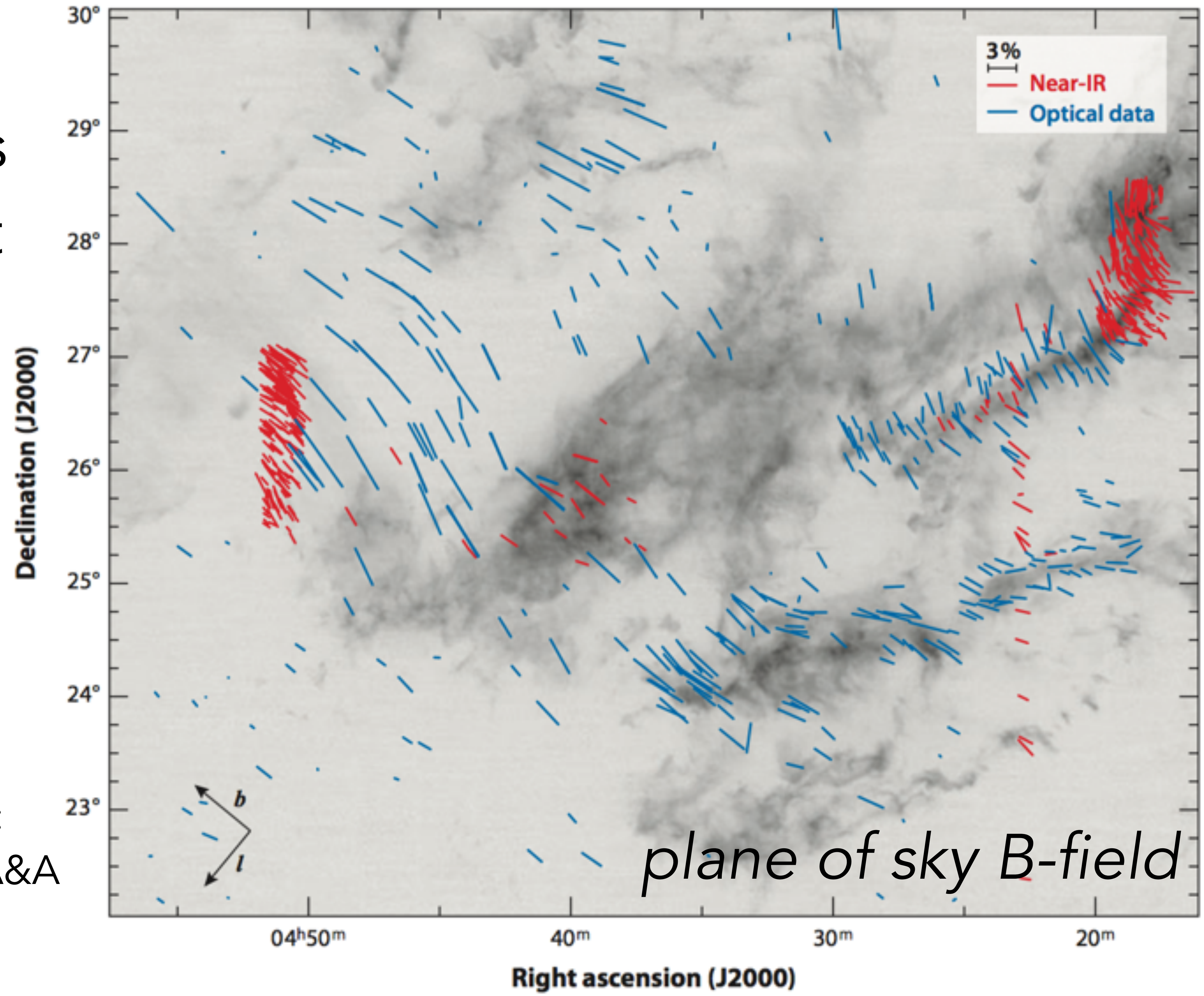
## Observational Tracers:

- 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

# Magnetic Fields in the ISM

Crutcher 2012

Polarization of starlight in Taurus due to alignment of dust grains with the B-field.

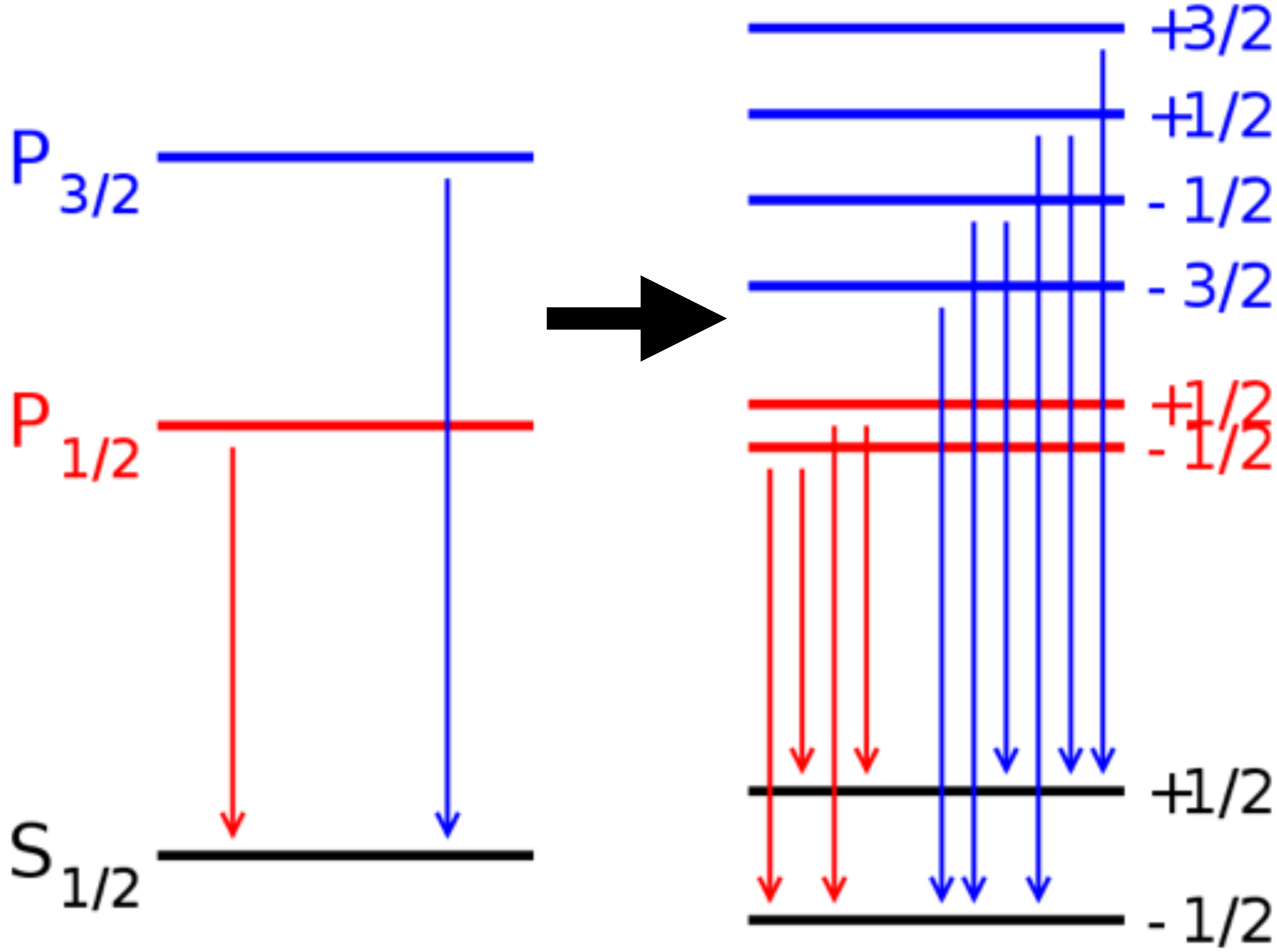



Magnetic fields review:
Crutcher 2012 ARA&A

Grain alignment review:
Andersson et al. 2015 ARA&A

# 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.

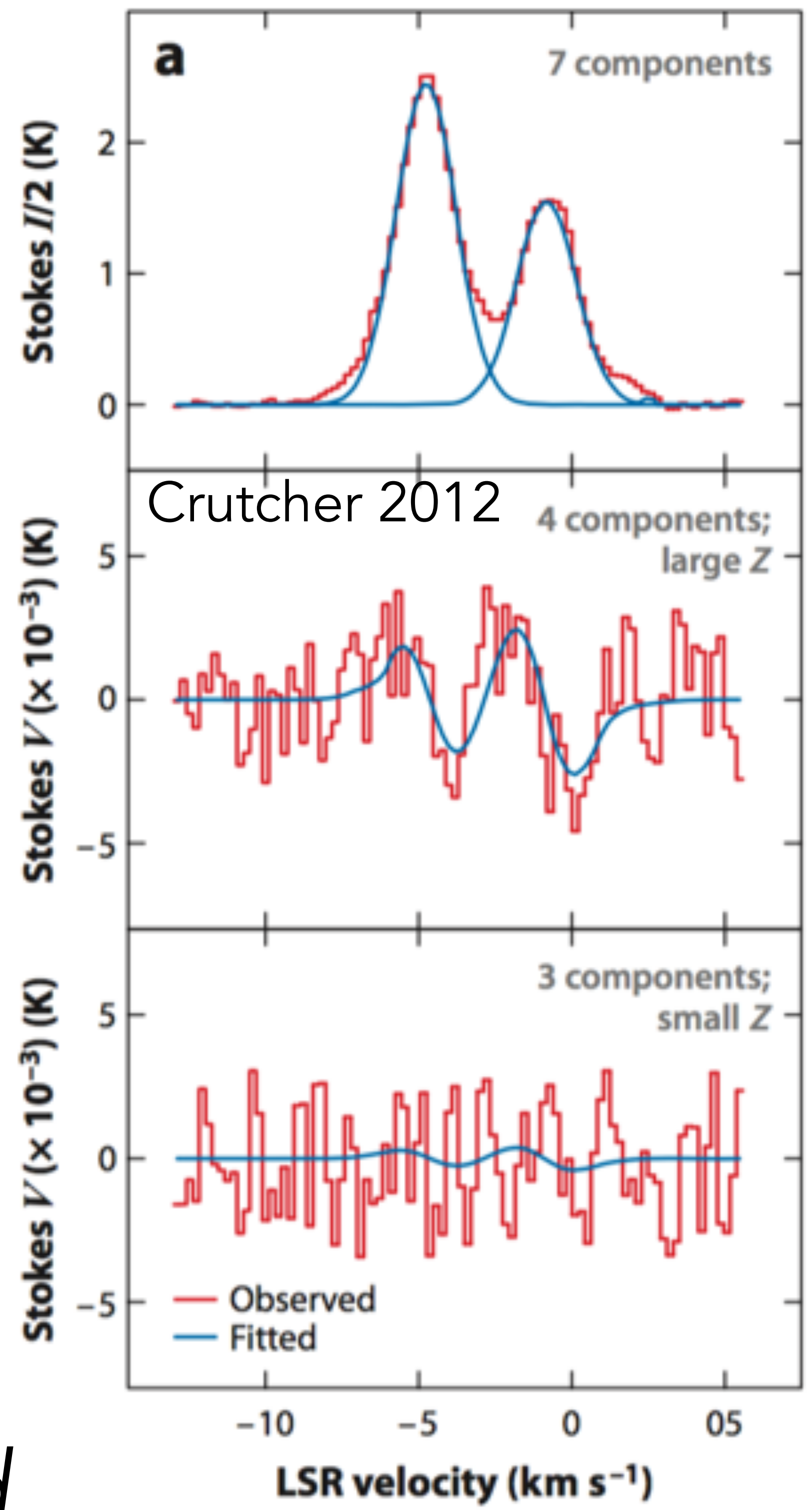
# Magnetic Fields in the ISM

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*




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.

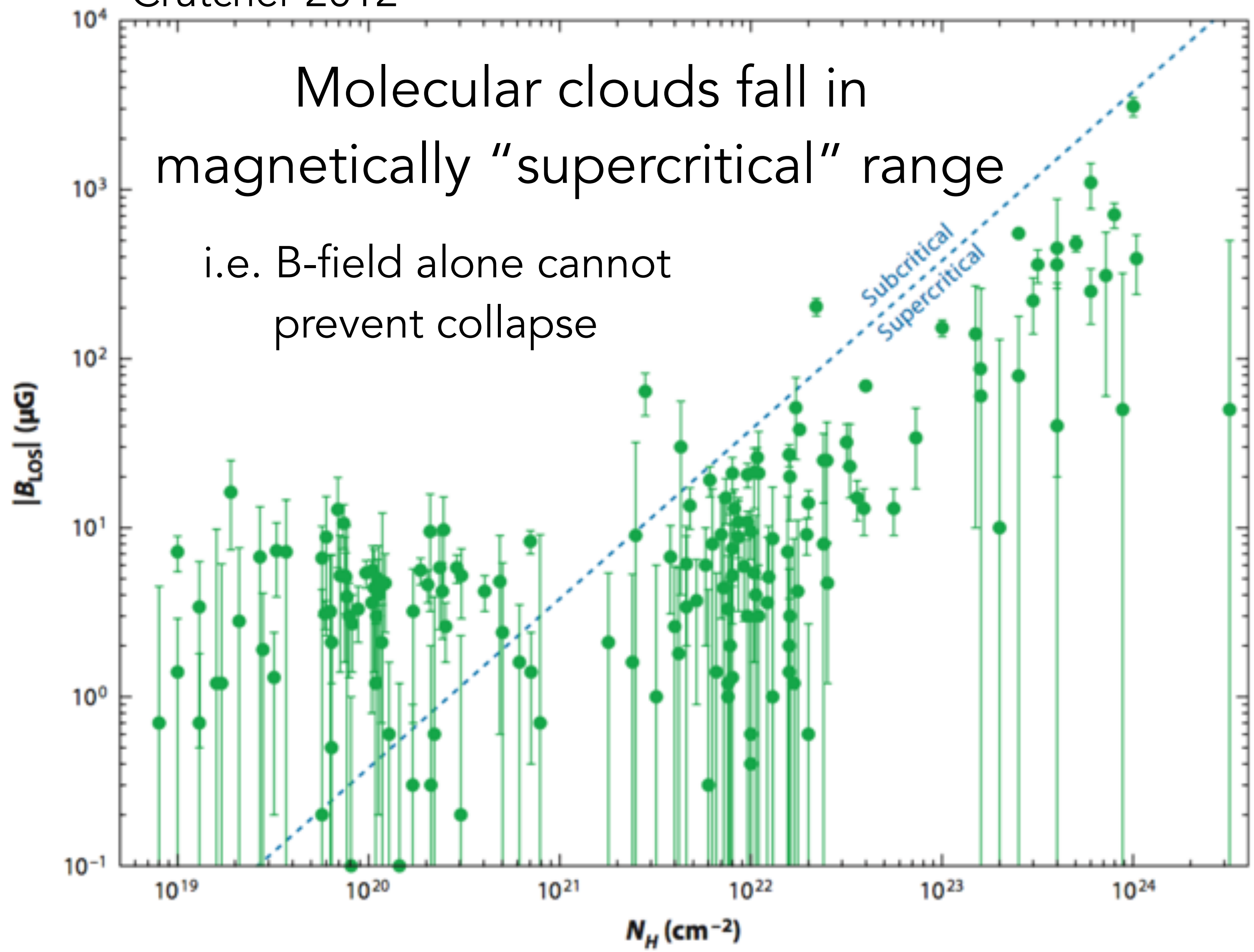
But, shifted levels produce different circular polarizations.

# Molecular Clouds

## Observed Characteristics

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

Crutcher 2012

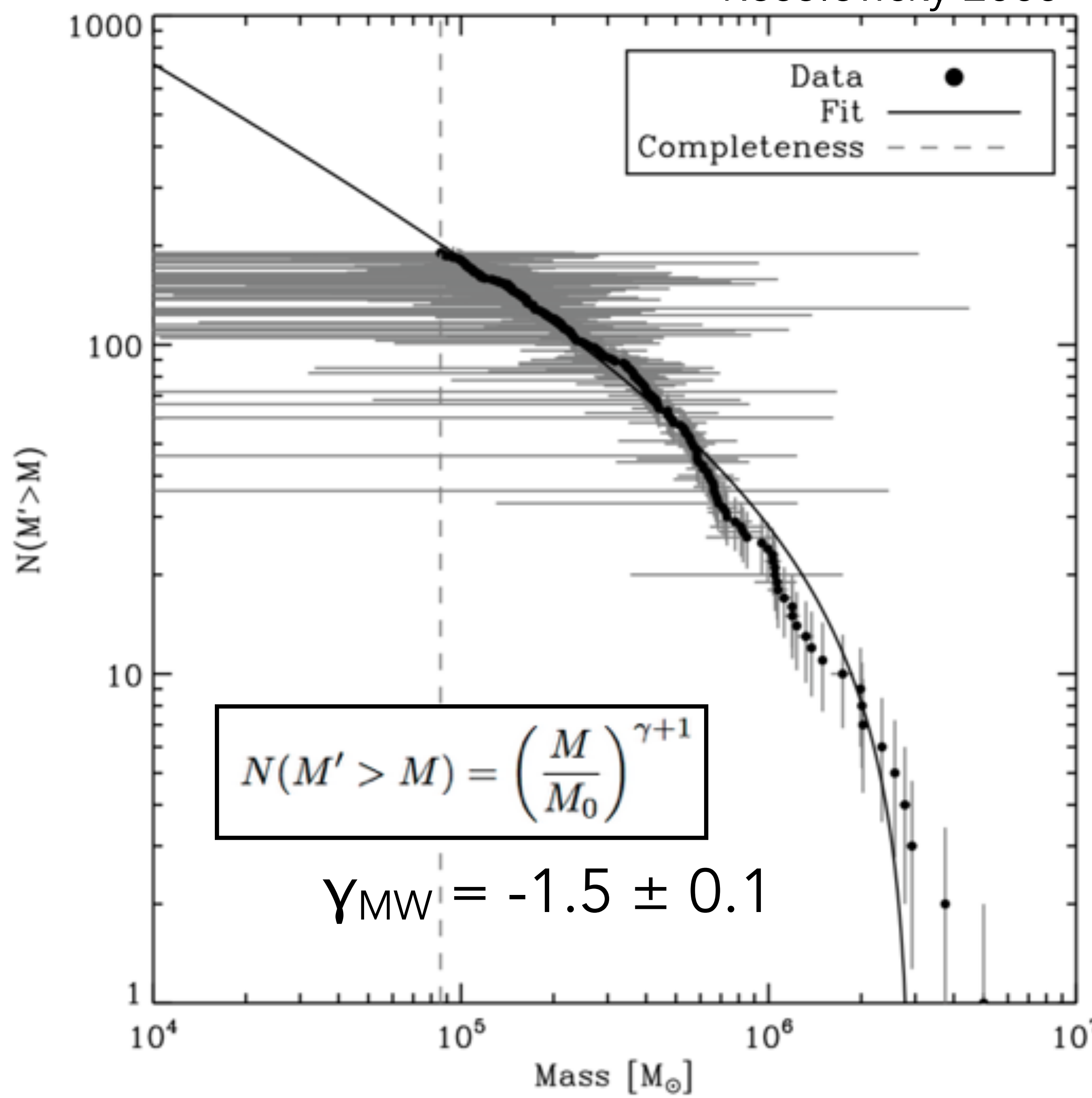


# Molecular Clouds

## Observed Characteristics

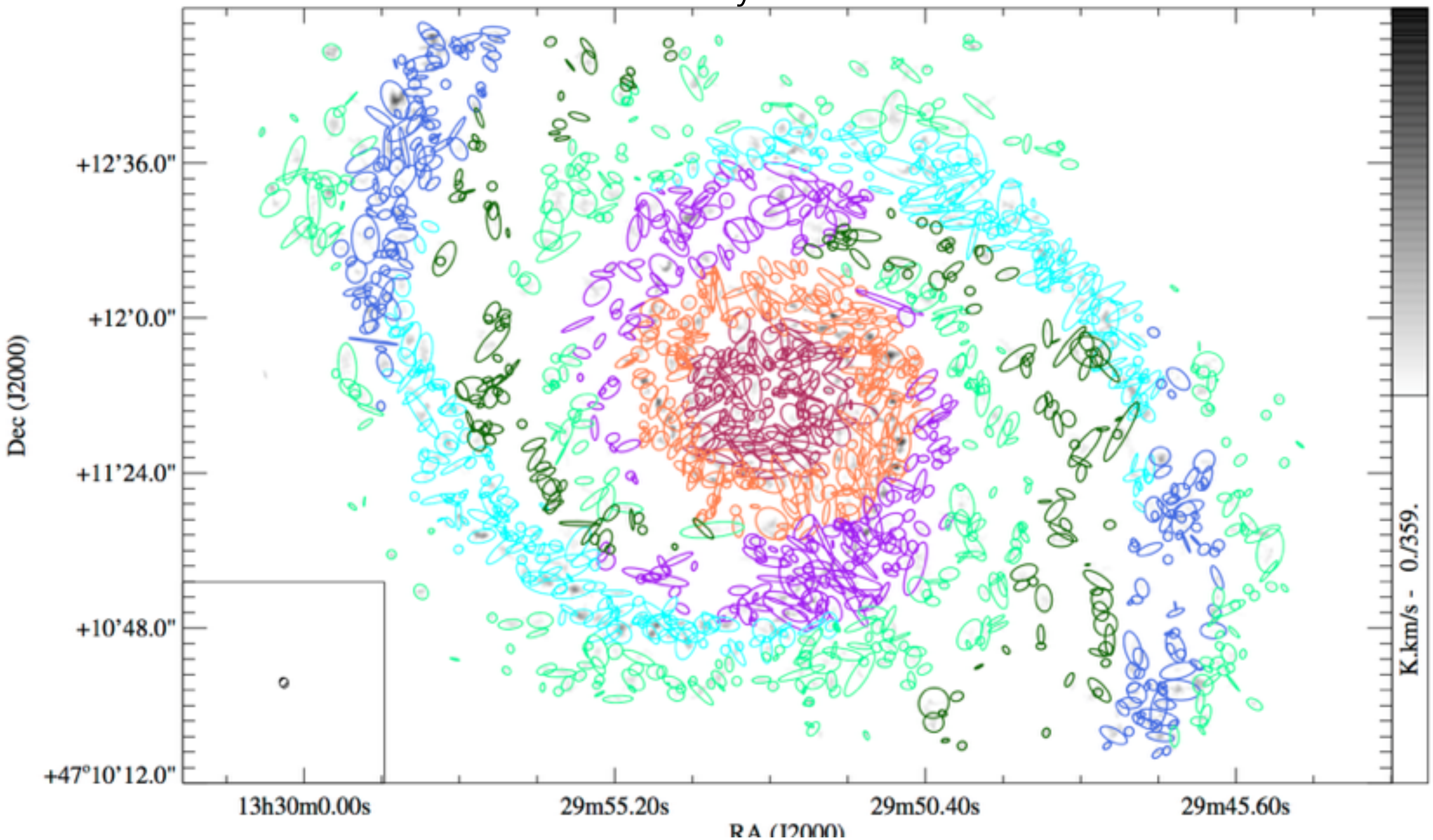
- Self-Gravity
- Turbulence
- Substructure
- Magnetic Fields
- **Mass Spectrum**
- Lifetimes
- Star Formation

Rosolowsky 2005



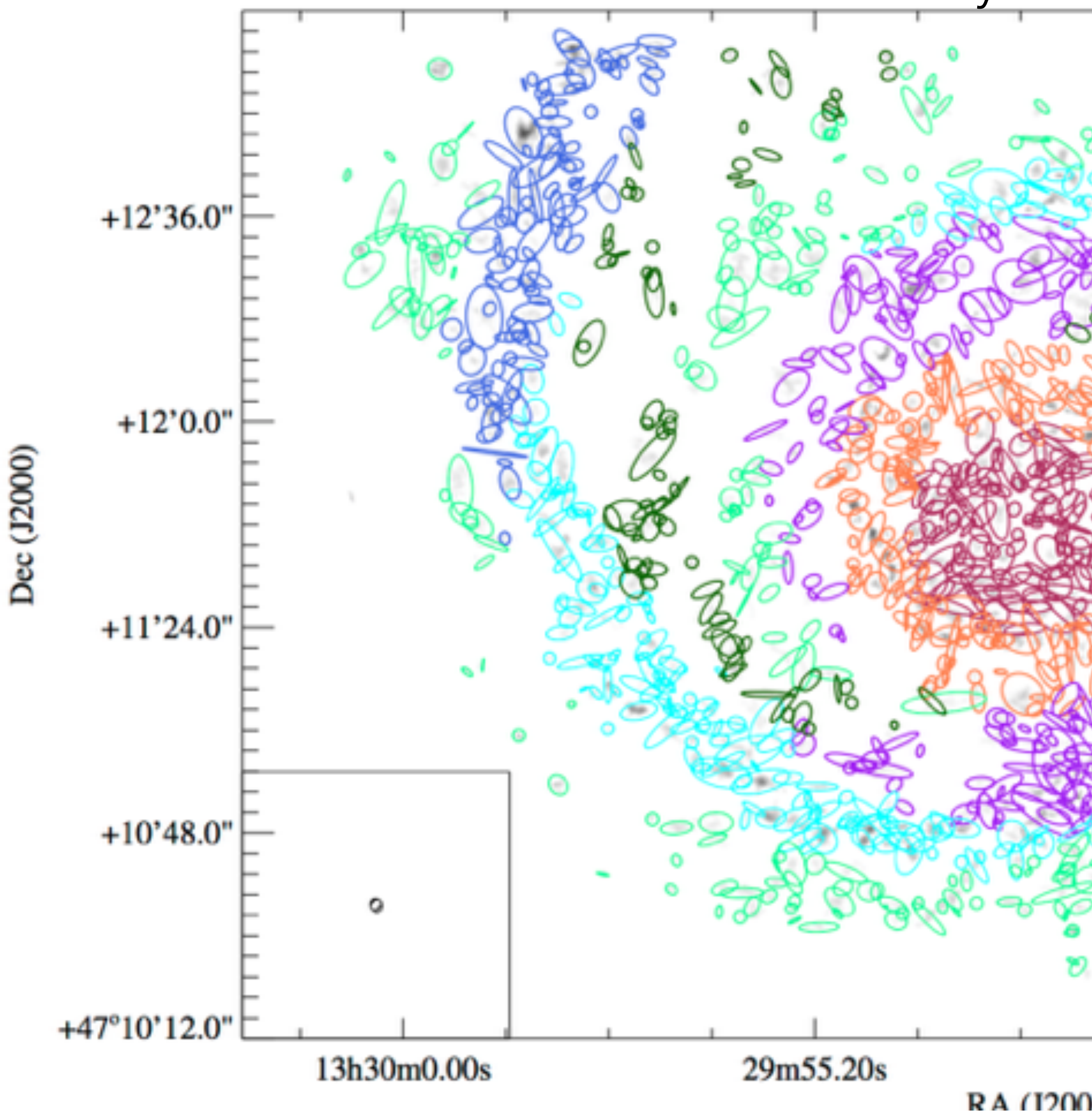
# Molecular Clouds

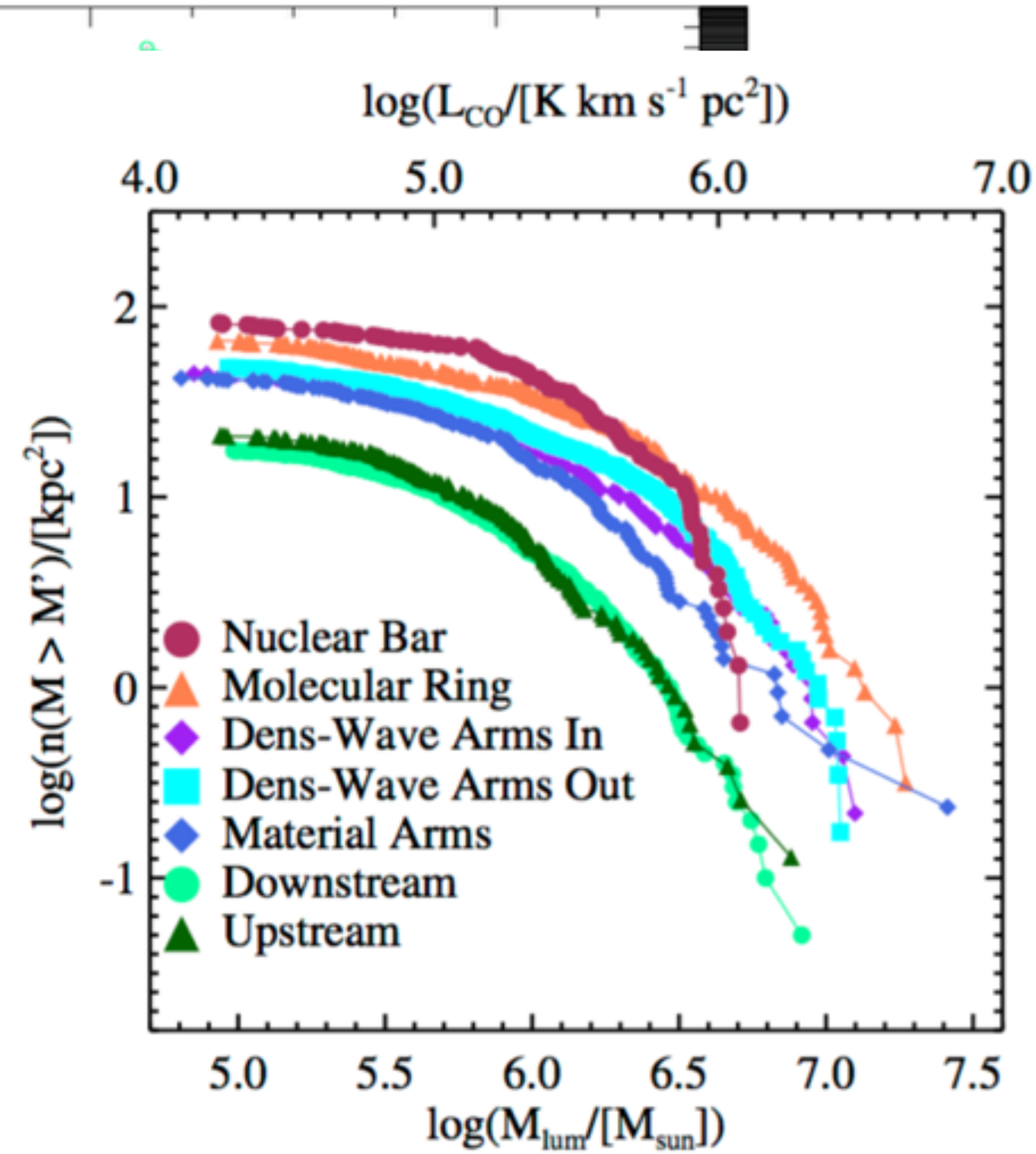
Colombo et al. 2014 - PAWS survey of M51



# Molecular Clouds

Colombo et al. 2014 - PAWS survey of M51



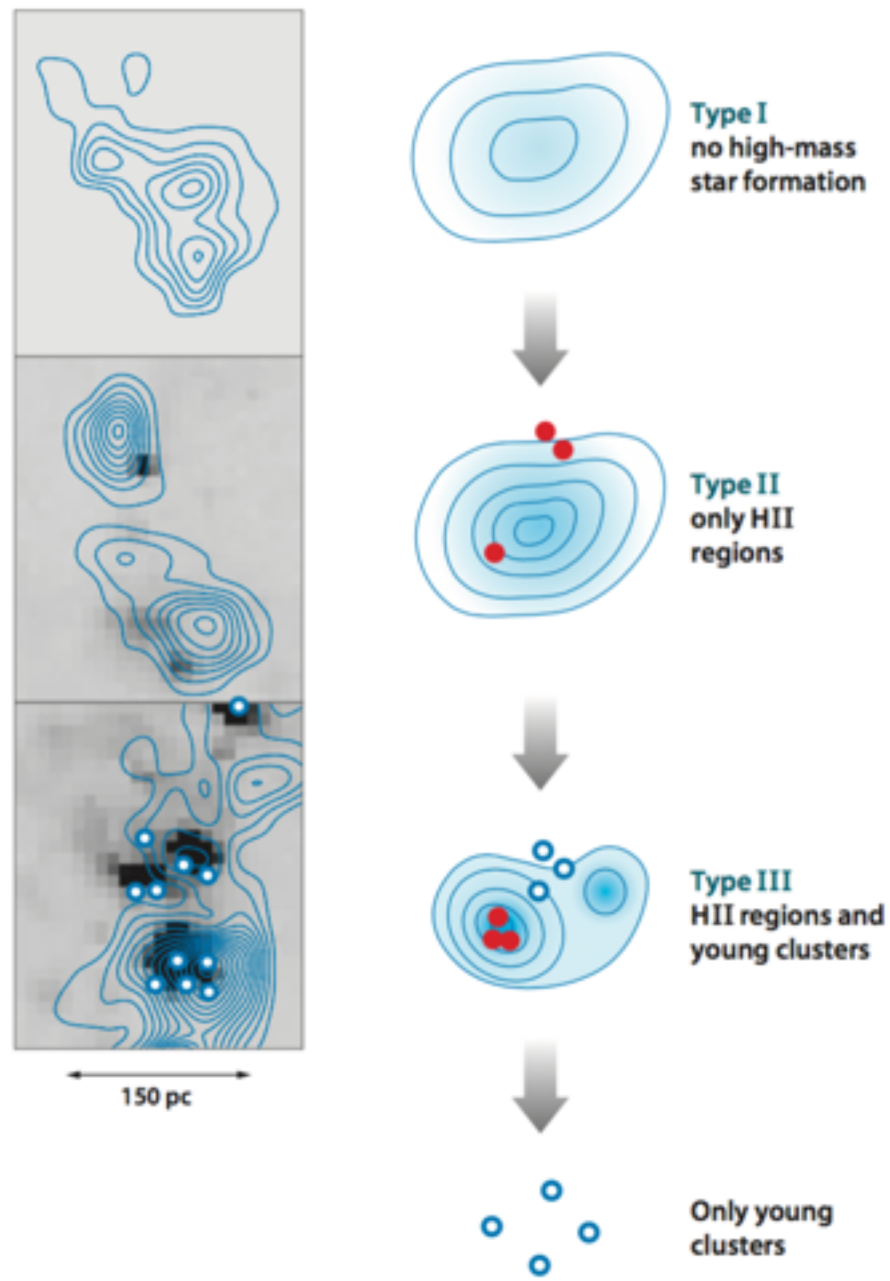



# Molecular Clouds

## Observed Characteristics

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

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

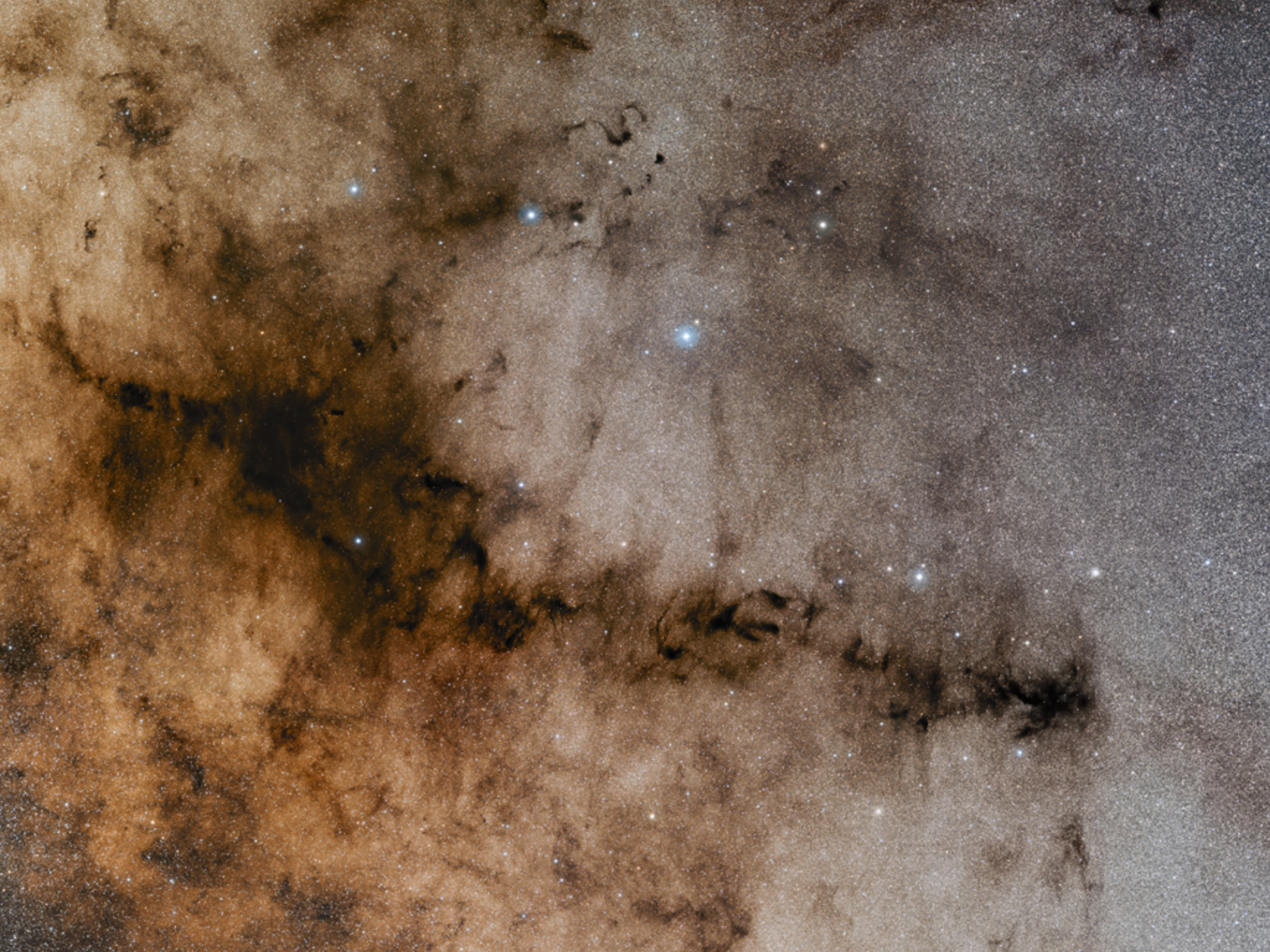
# Star Formation

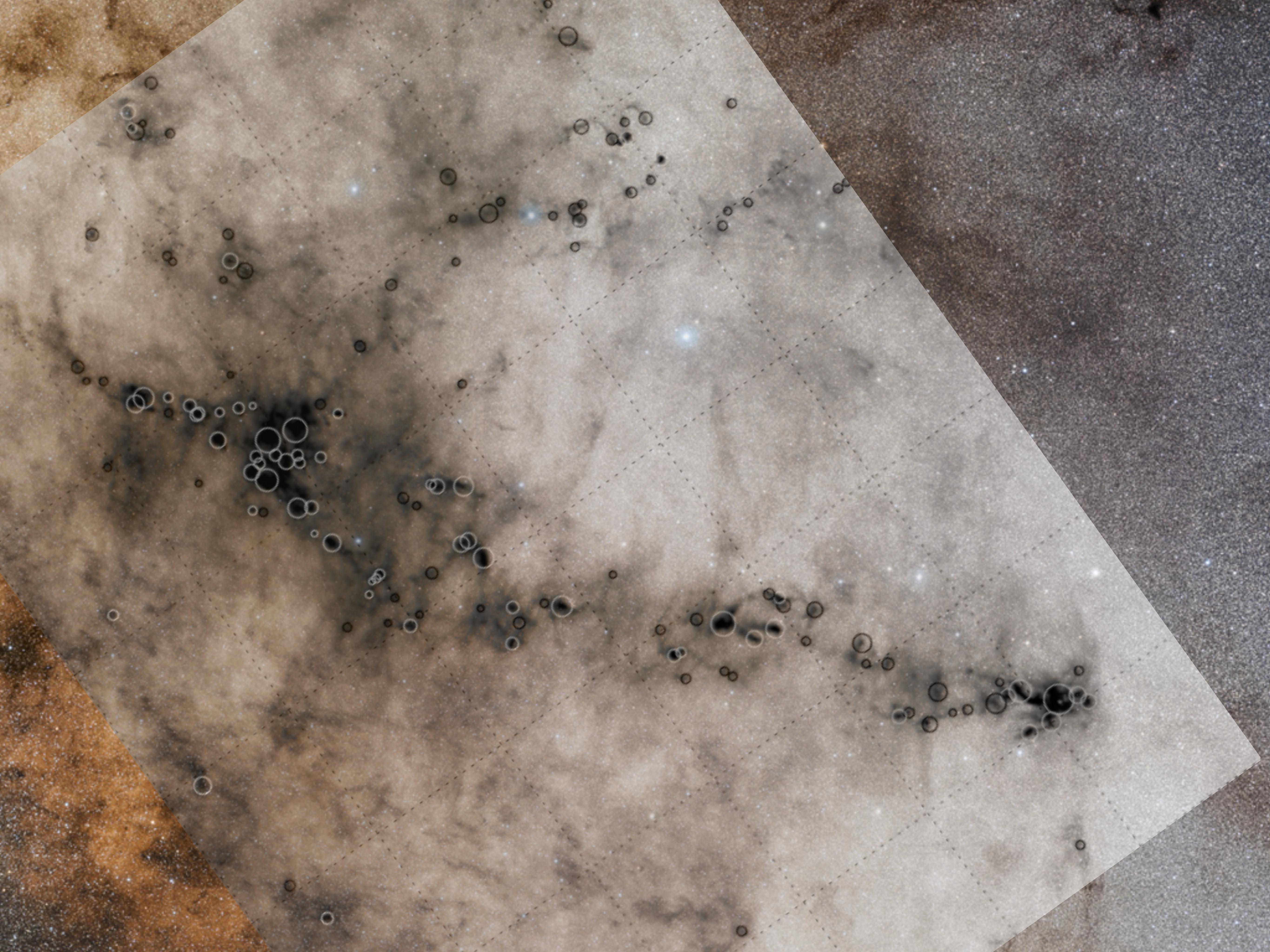
**Table 1 Properties of dark clouds, clumps, and cores**

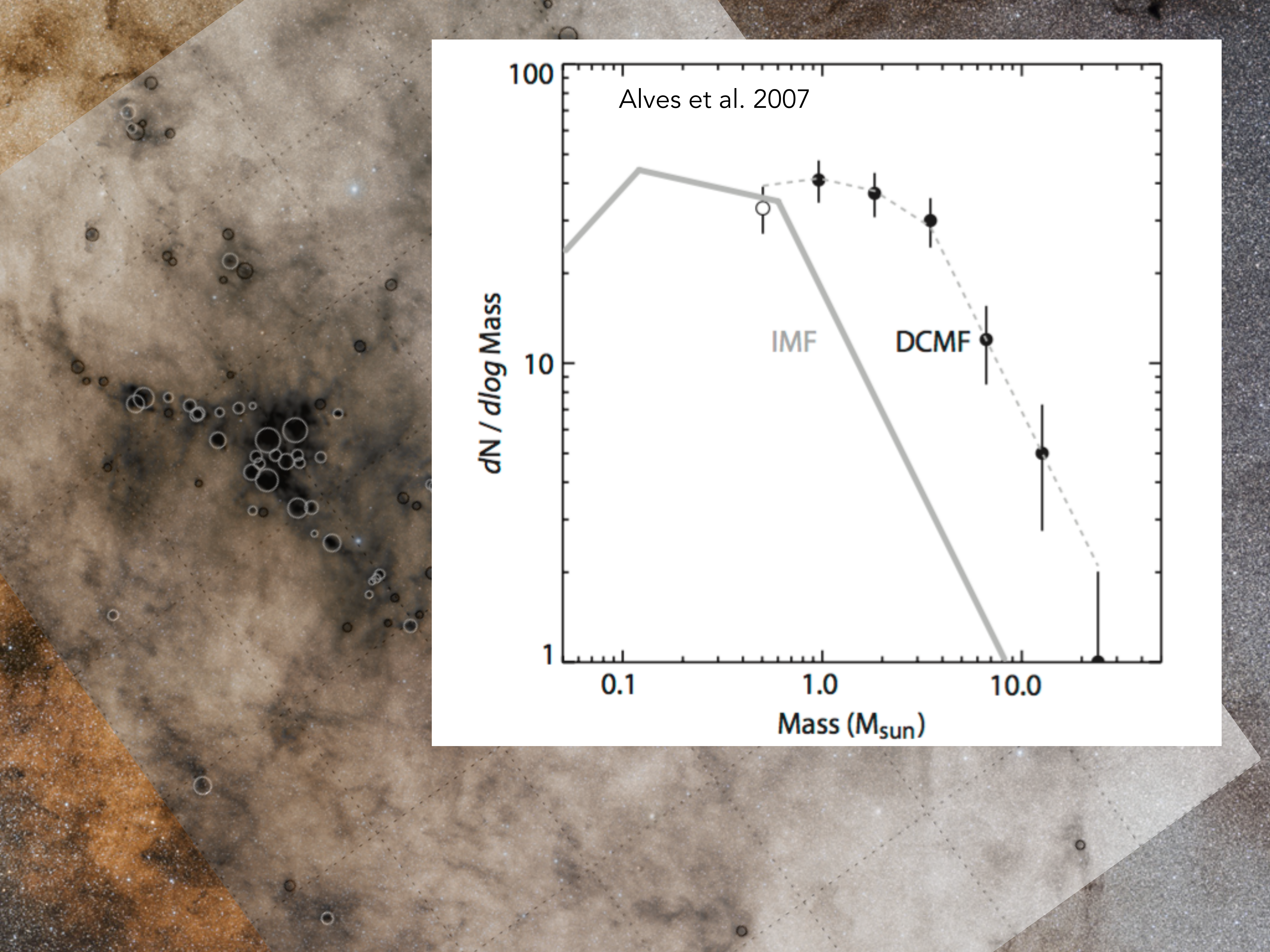
| | Clouds[a] | Clumps[b] | Cores[c] |
|---|---|---|---|
| Mass ($M_\odot$) | $10^3 - 10^4$ | 50–500 | 0.5–5 |
| Size (pc) | 2–15 | 0.3–3 | 0.03–0.2 |
| Mean density ($cm^{-3}$) | 50–500 | $10^3$–$10^4$ | $10^4$–$10^5$ |
| Velocity extent ($km\ s^{-1}$) | 2–5 | 0.3–3 | 0.1–0.3 |
| Crossing time (Myr) | 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 $N_2H^+$.

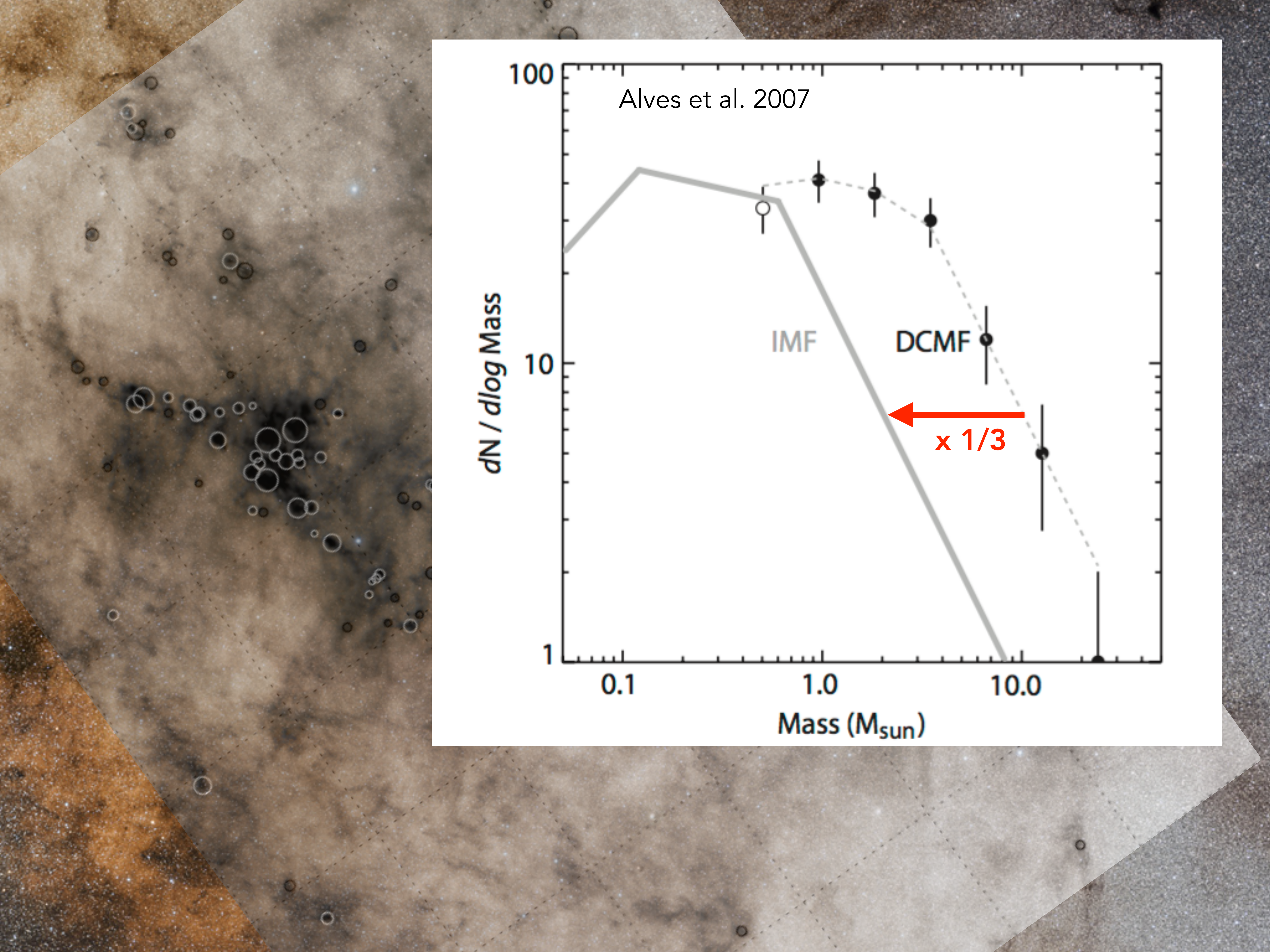
Bergin & Tafalla 2007







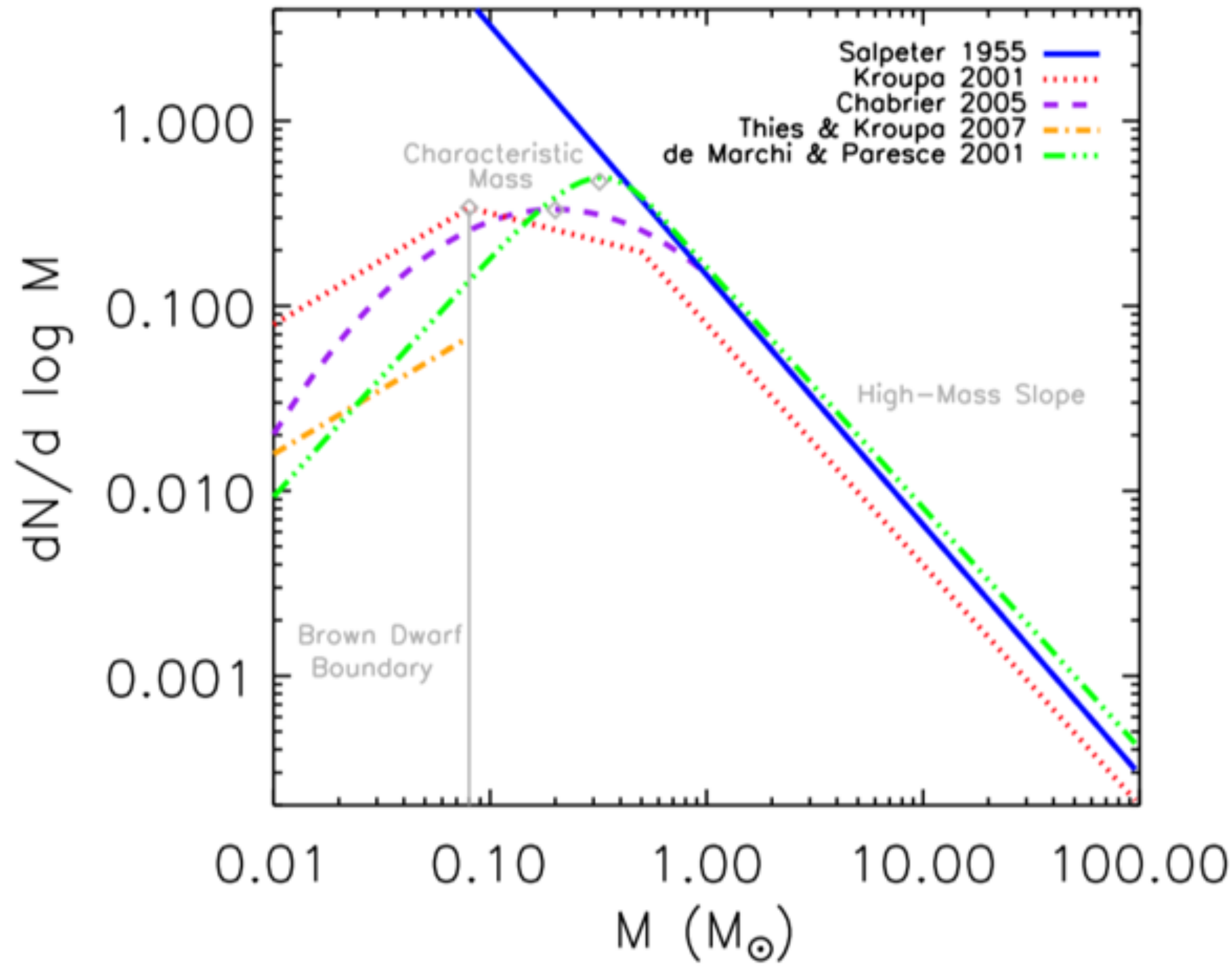
Alves et al. 2007
100
10
1
0.1
1.0
10.0
IMF
DCMF
dN / dlog Mass
Mass (Msun)



Alves et al. 2007
100
10
1
dN / dlog Mass
IMF
DCMF
x 1/3
0.1
1.0
10.0
Mass ($M_{sun}$)

# The Initial Mass Function

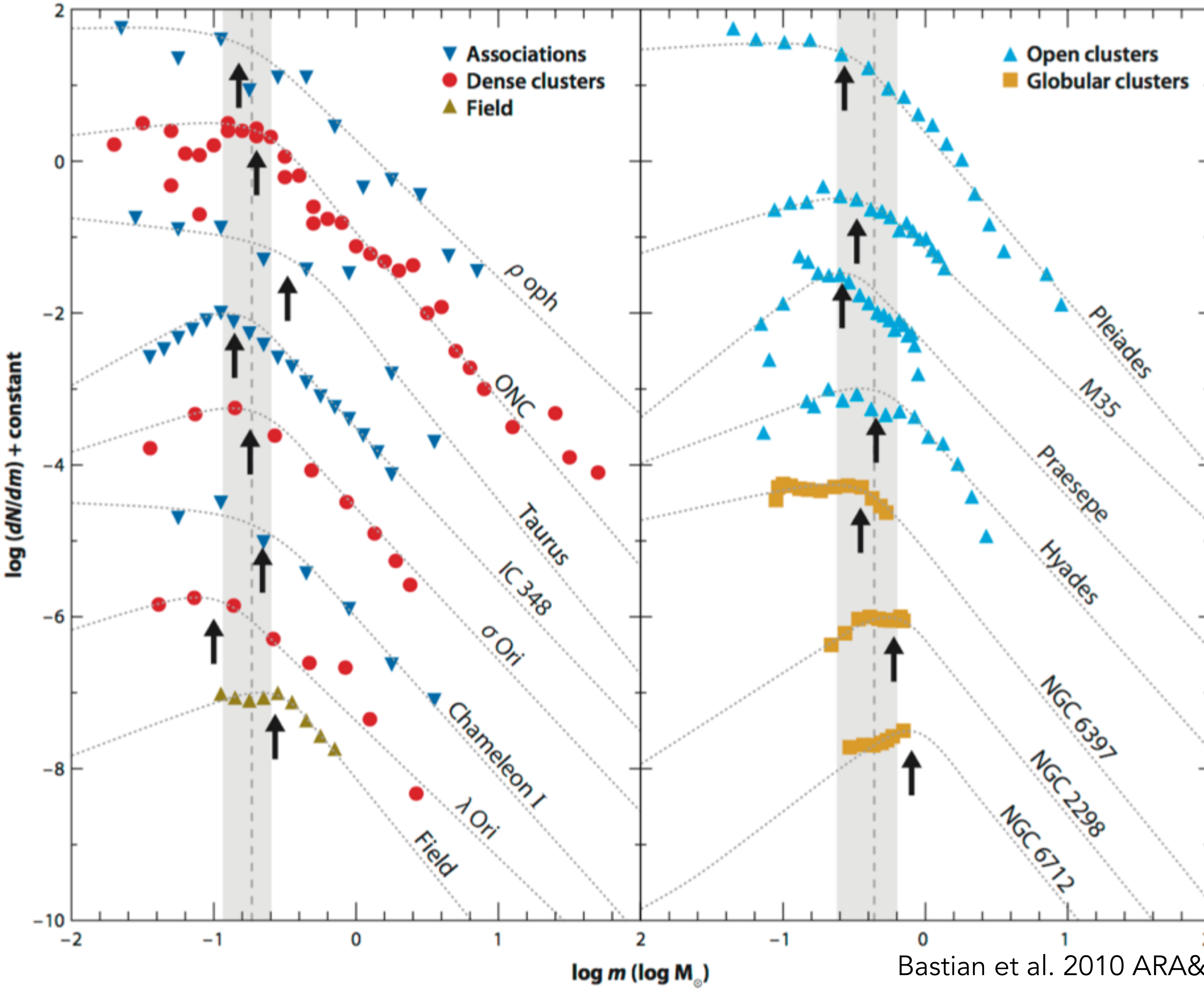
Offner et al. 2014




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

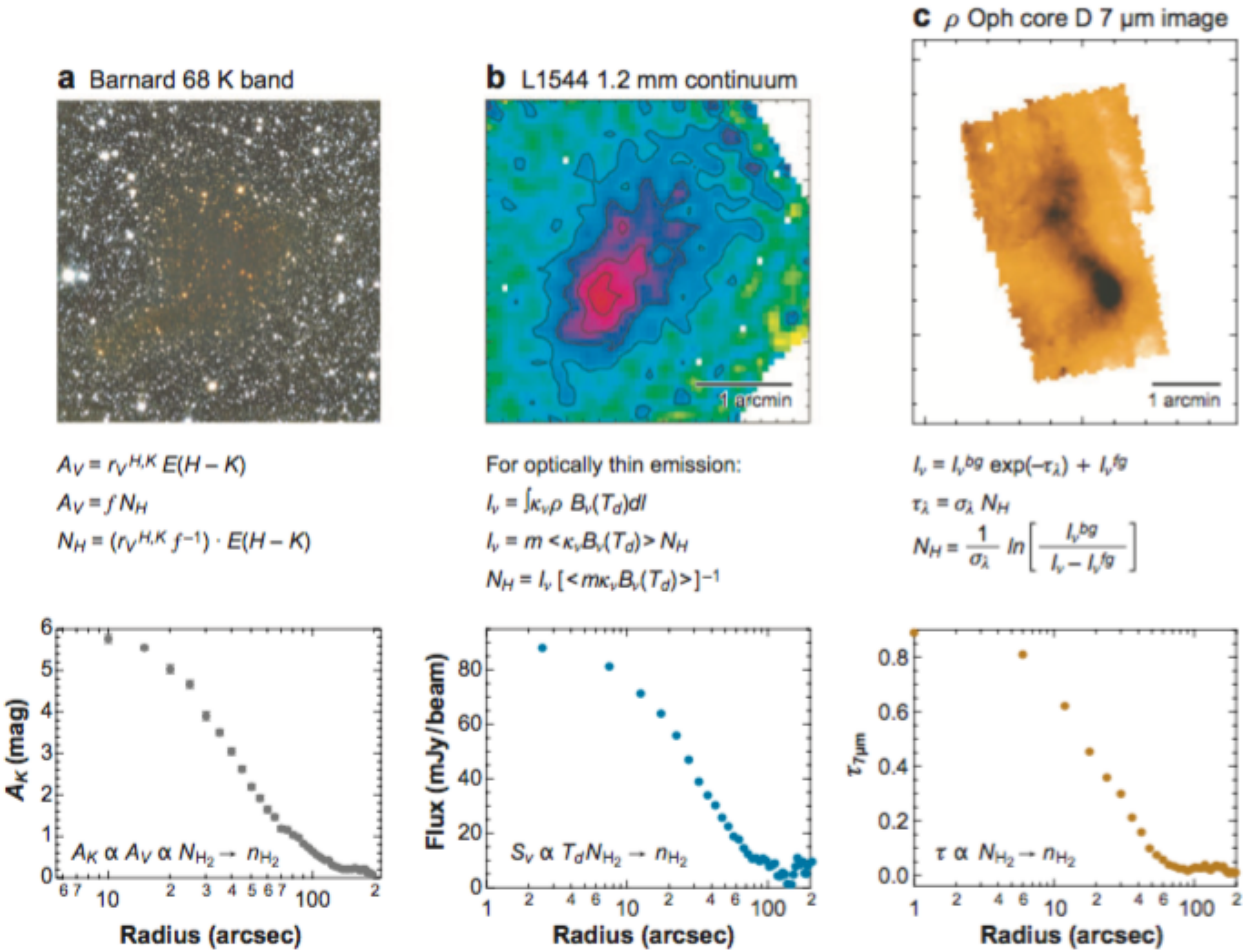
Controversy persists over whether it is the same everywhere.

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.




Bastian et al. 2010 ARA&A

# Cores in Molecular Clouds

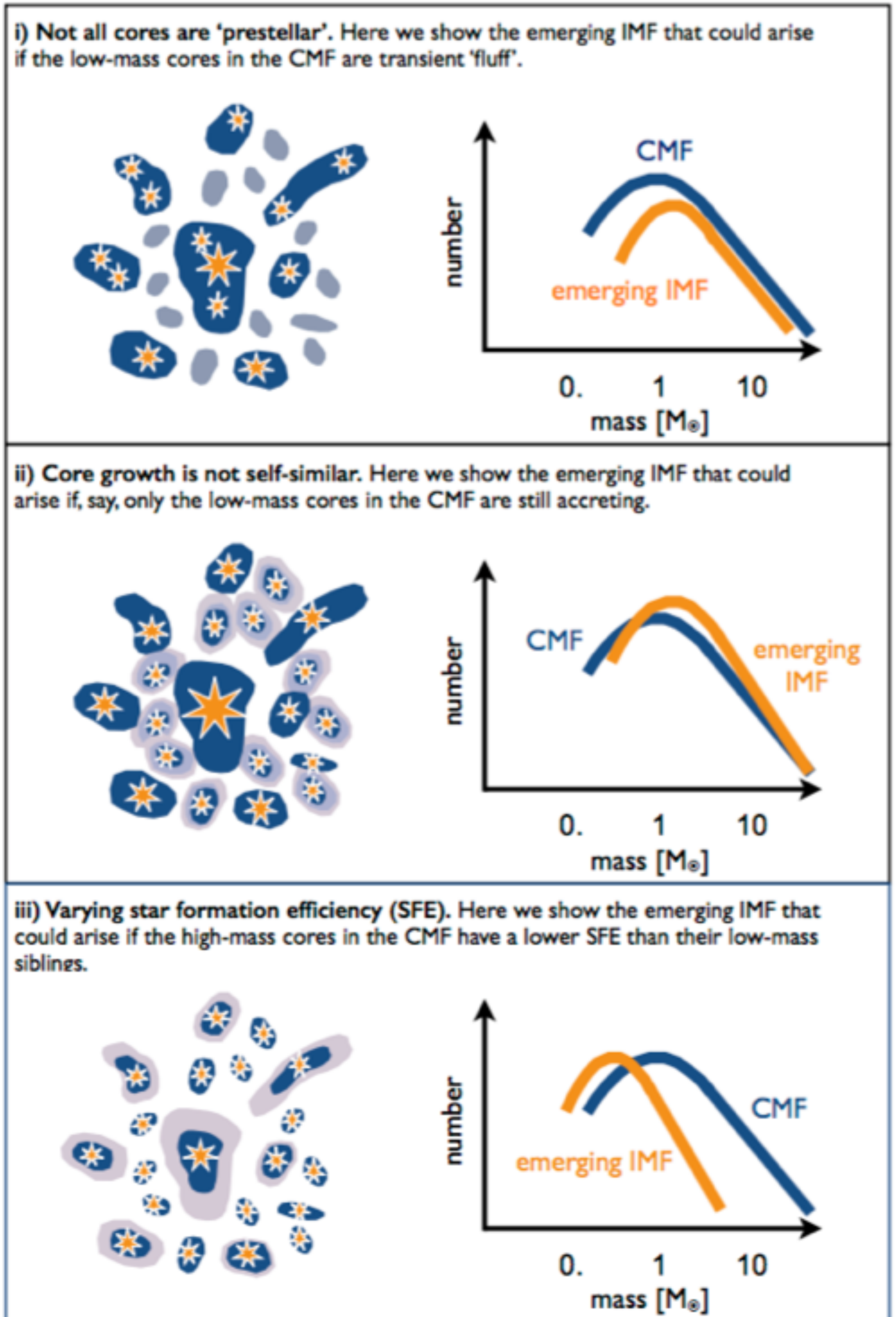


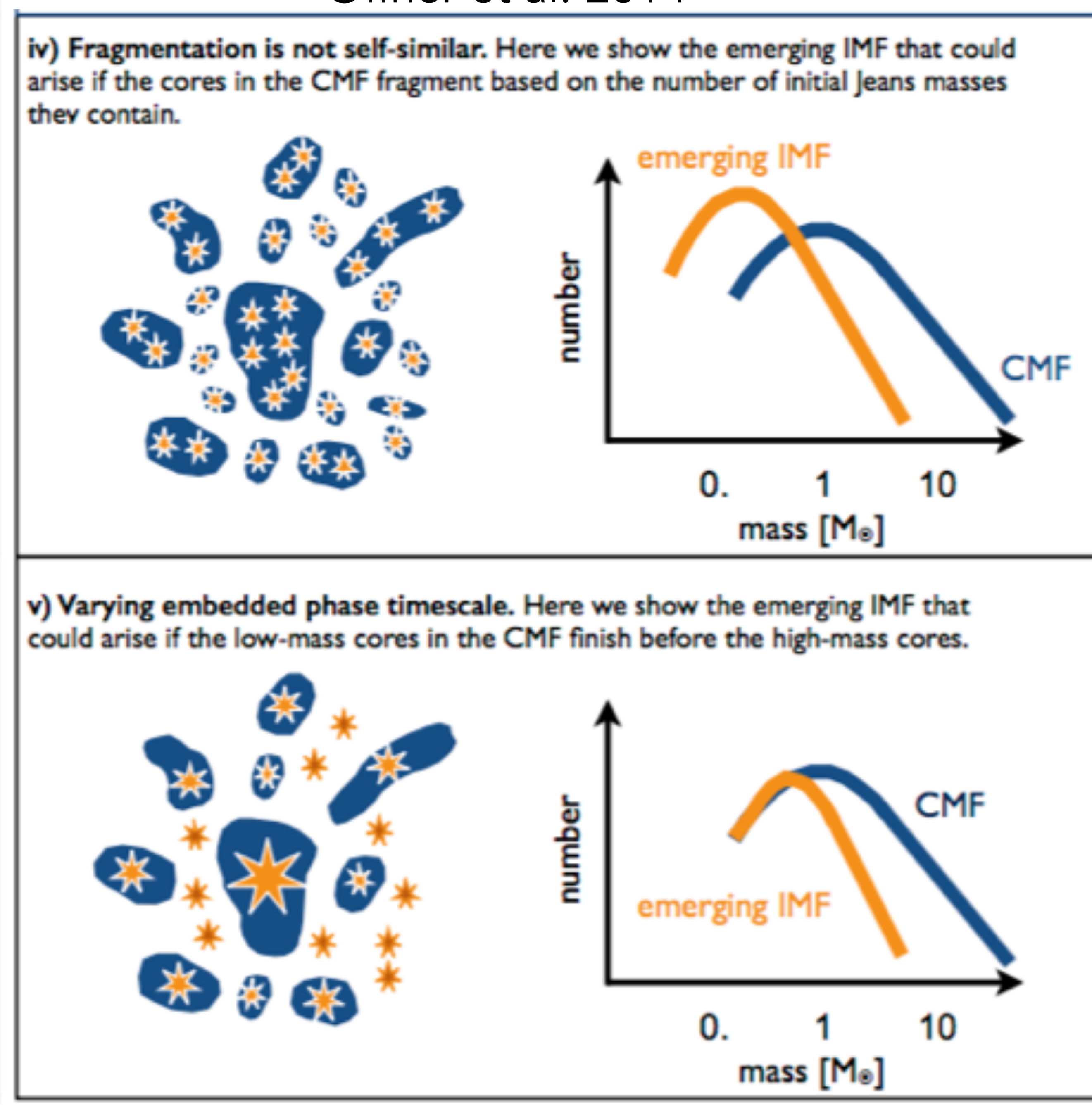

Bergin & Tafalla 2007

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

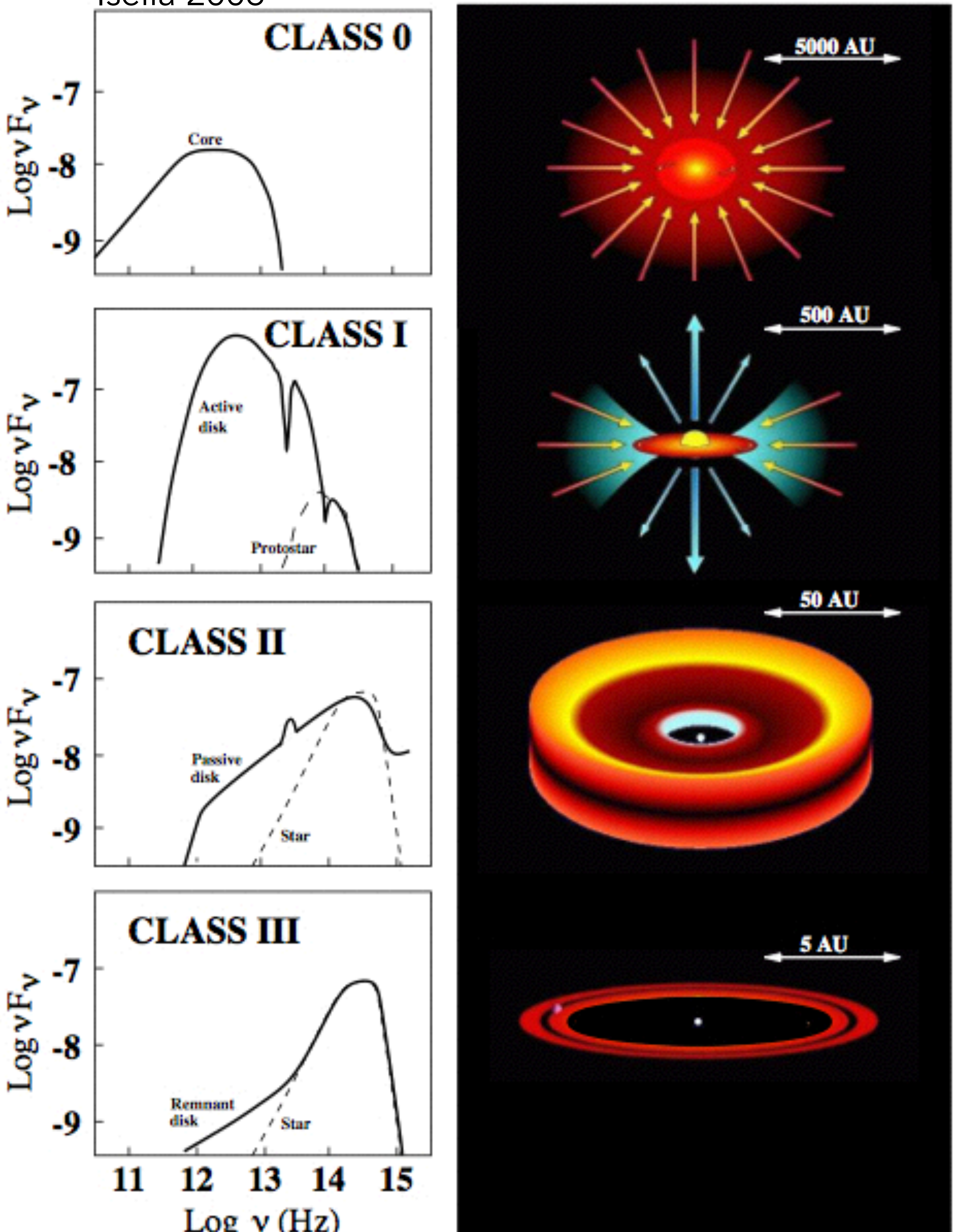
# When does the CMF map to the IMF?

Offner et al. 2014



Isella 2006

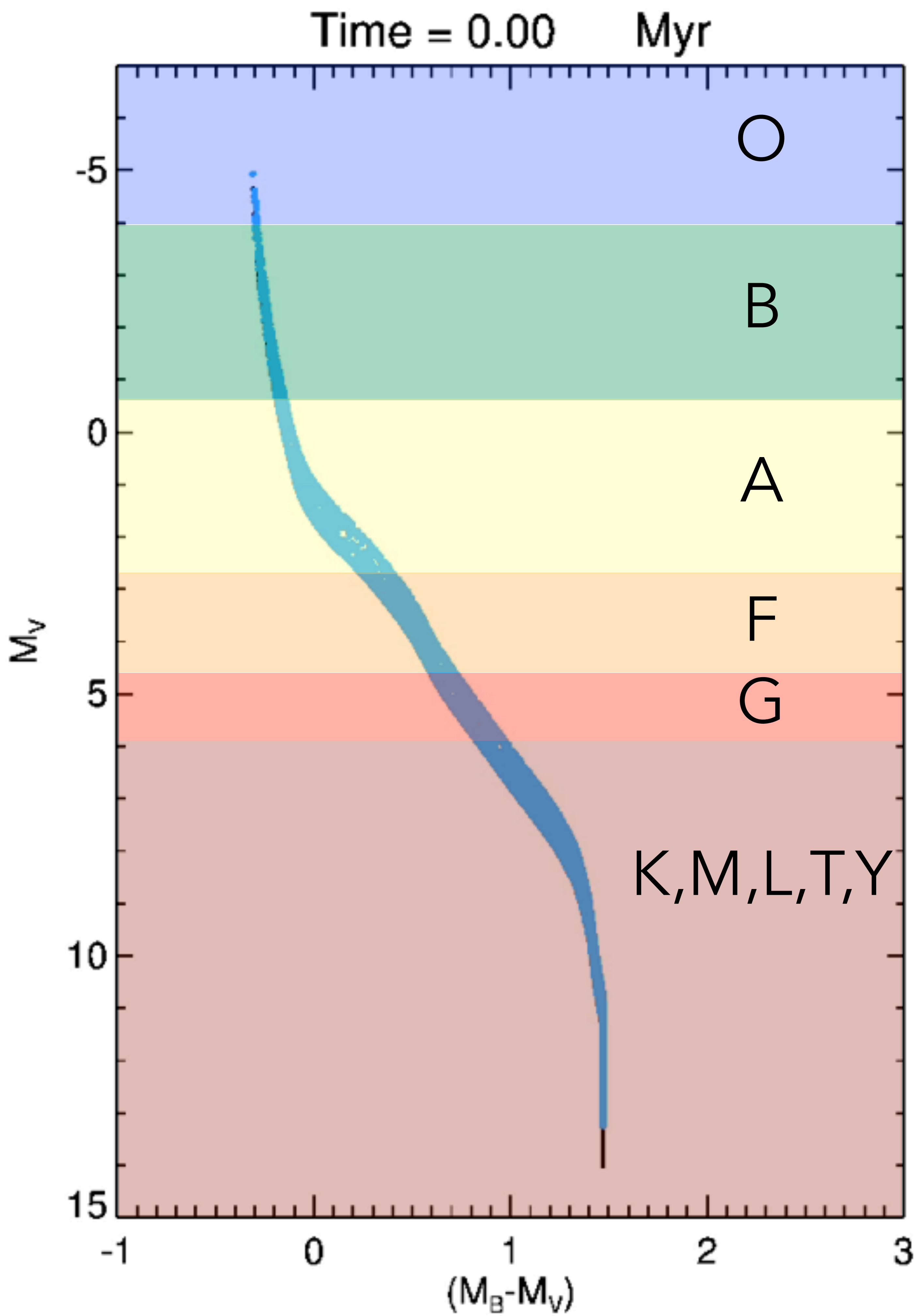


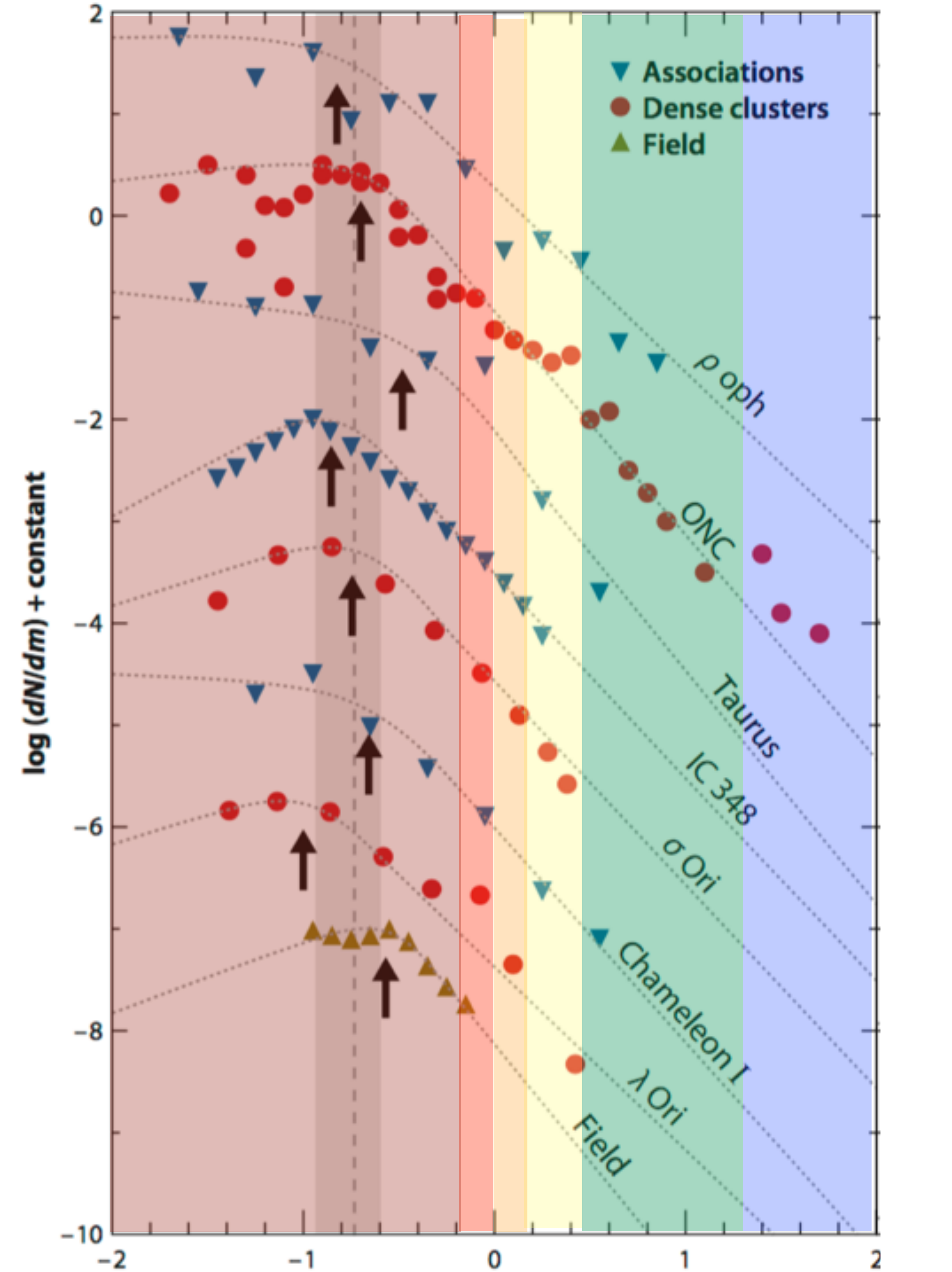

Gravitational collapse

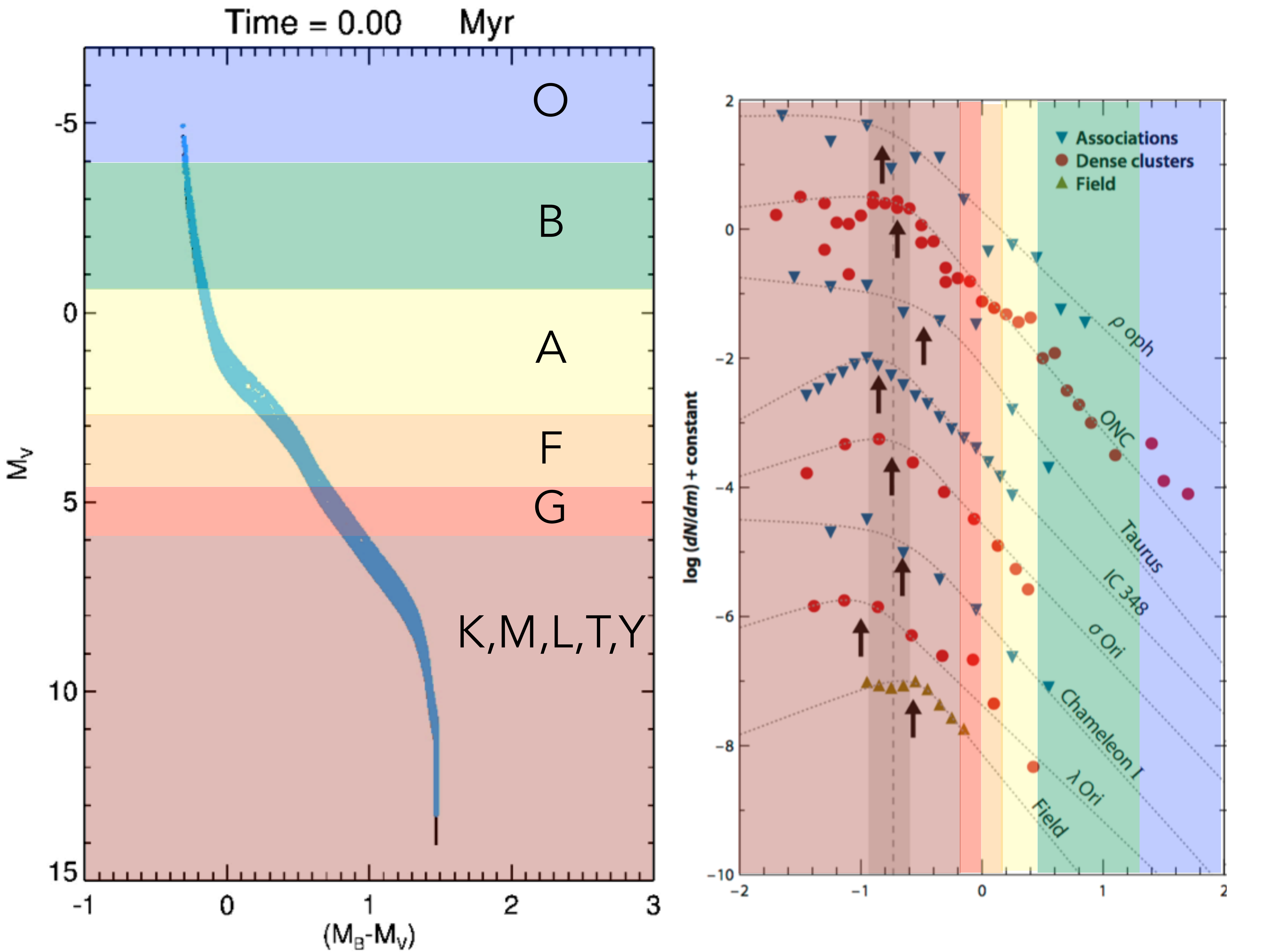
Angular momentum
-> disk formation
-> outflows & jets

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
$M_V$
-5
0
5
10
15
-1
0
1
2
3
$(M_B-M_V)$

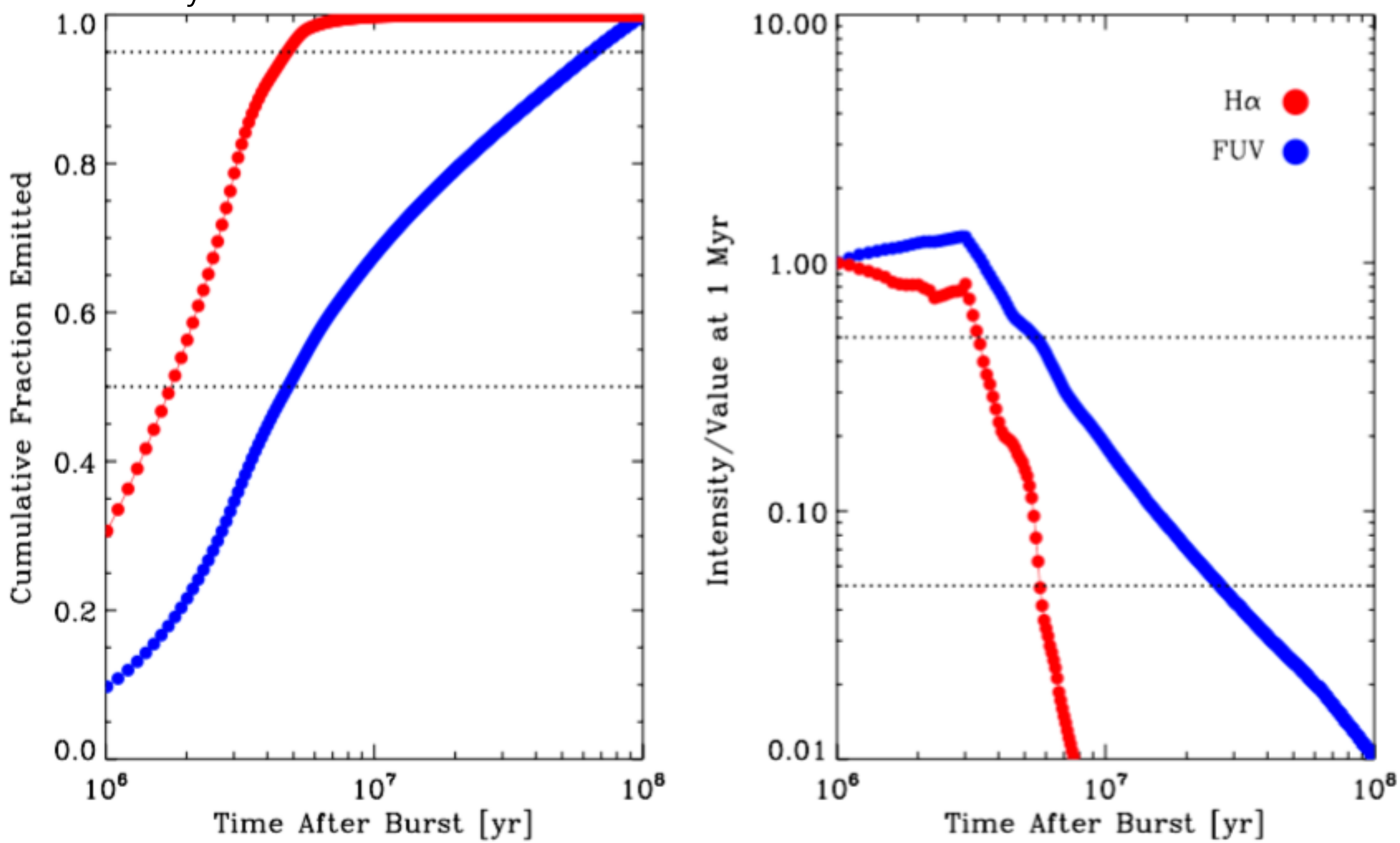

Associations
Dense clusters
Field
ρ oph
ONC
Taurus
IC 348
σ Ori
Chameleon I
λ Ori
Field
log (dN/dm) + constant
2
0
−2
−4
−6
−8
−10
−2
−1
0
1
2



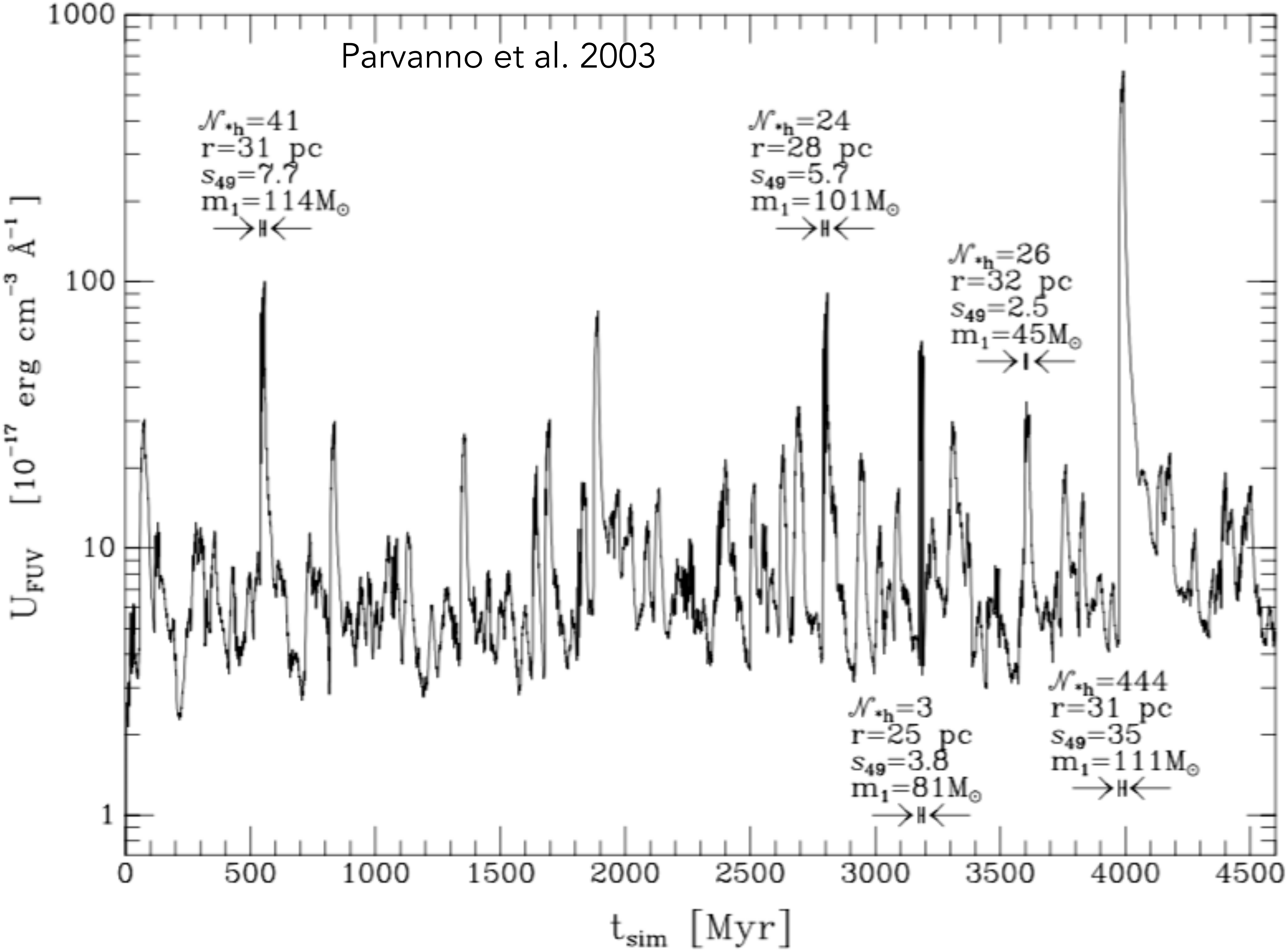
Time = 0.00 Myr
O
B
A
F
G
K,M,L,T,Y
$M_V$
$(M_B-M_V)$
Associations
Dense clusters
Field
ρ oph
ONC
Taurus
IC 348
σ Ori
Chameleon I
λ Ori
Field
log (dN/dm) + constant

# Radiative Feedback

Leroy et al. 2012

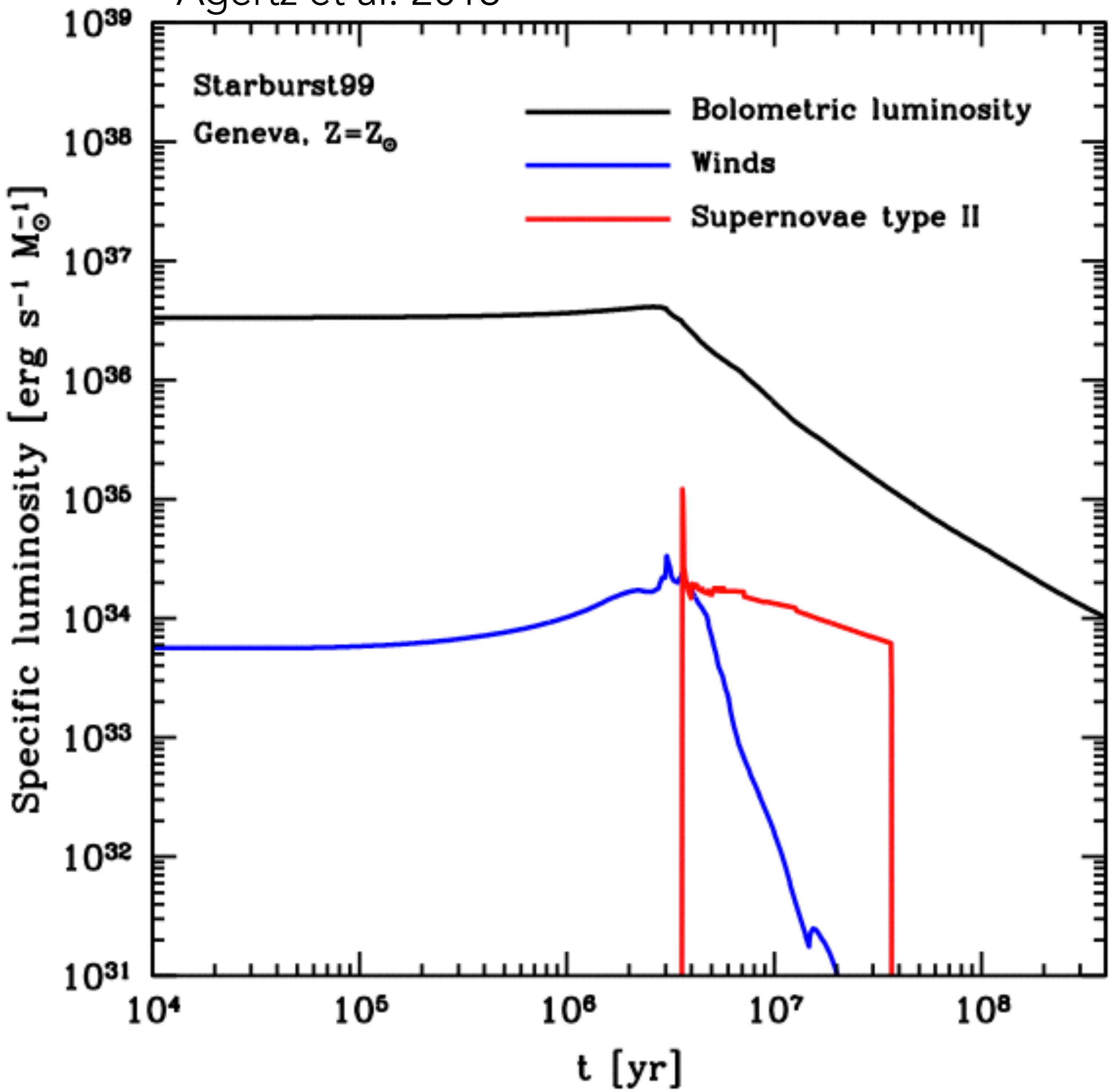


# Radiative Feedback



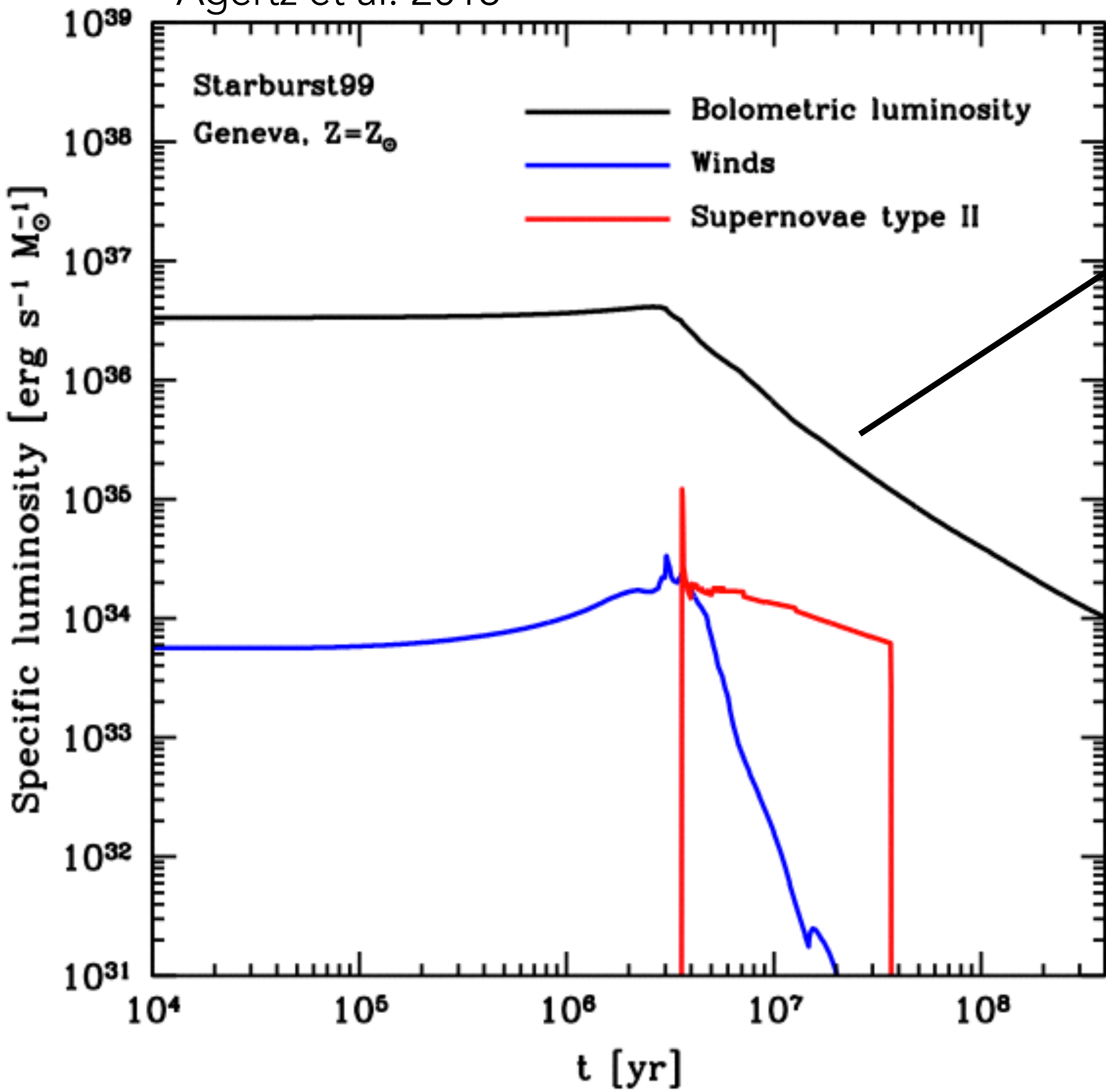
# Mechanical Feedback

Agertz et al. 2013



# Mechanical Feedback

Agertz et al. 2013

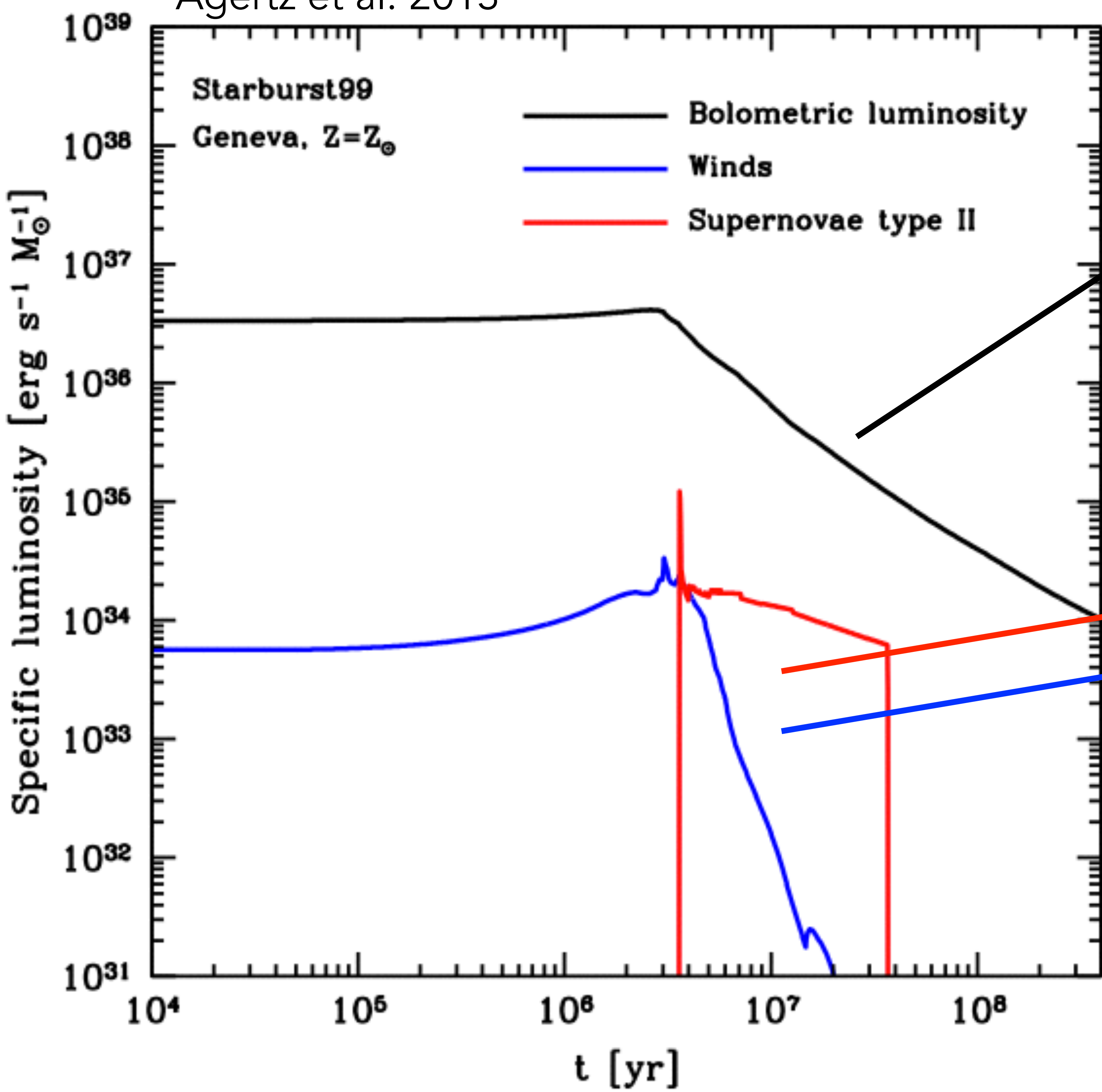



fraction into ionization, photoelectric heating, dust heating?

deposited where?

# Mechanical Feedback

Agertz et al. 2013



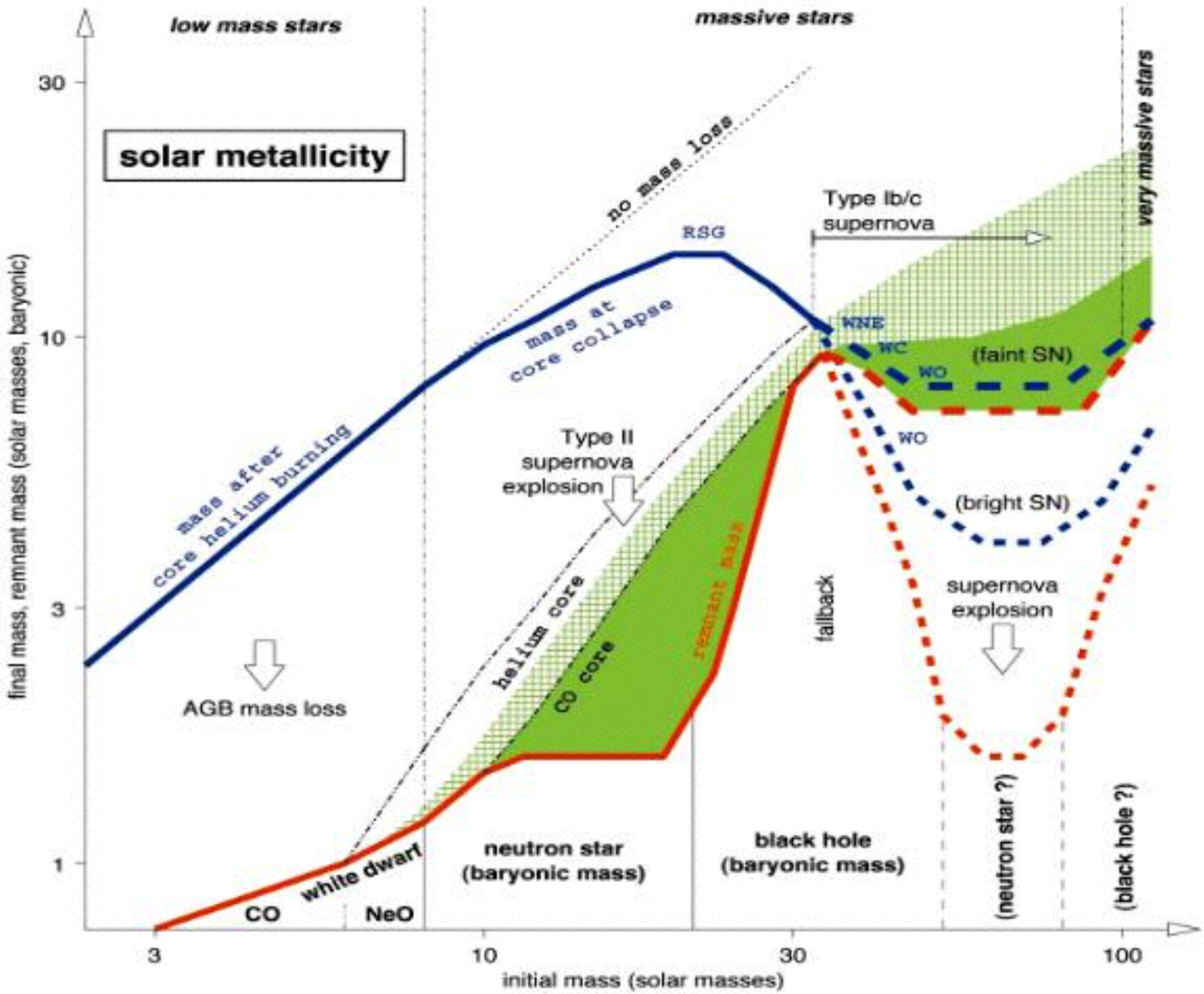

fraction into ionization, photoelectric heating, dust heating?

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 at end |
|---|---|---|---|
| **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 | $R \sim t^{2/7}$<br>$R \sim t^{1/4}$ |
| **Fadeaway** | turbulence dissipates remnant structure and merges with ISM | - | - |

# SILCC: **SI**mulating the **L**ife**C**ycle of molecular **C**louds

Stefanie Walch
Philipp Girichidis
Thorsten Naab
Andrea Gatto
Simon C. O. Glover
Richard Wünsch
Ralf S. Klessen
Paul C. Clark
Thomas Peters
Dominik Derigs
Christian Baczynski

Walch et al., MNRAS 454, 238 (2015)
Girichidis et al., arXiv:1508.06646

**KS SN rate, mixed driving**

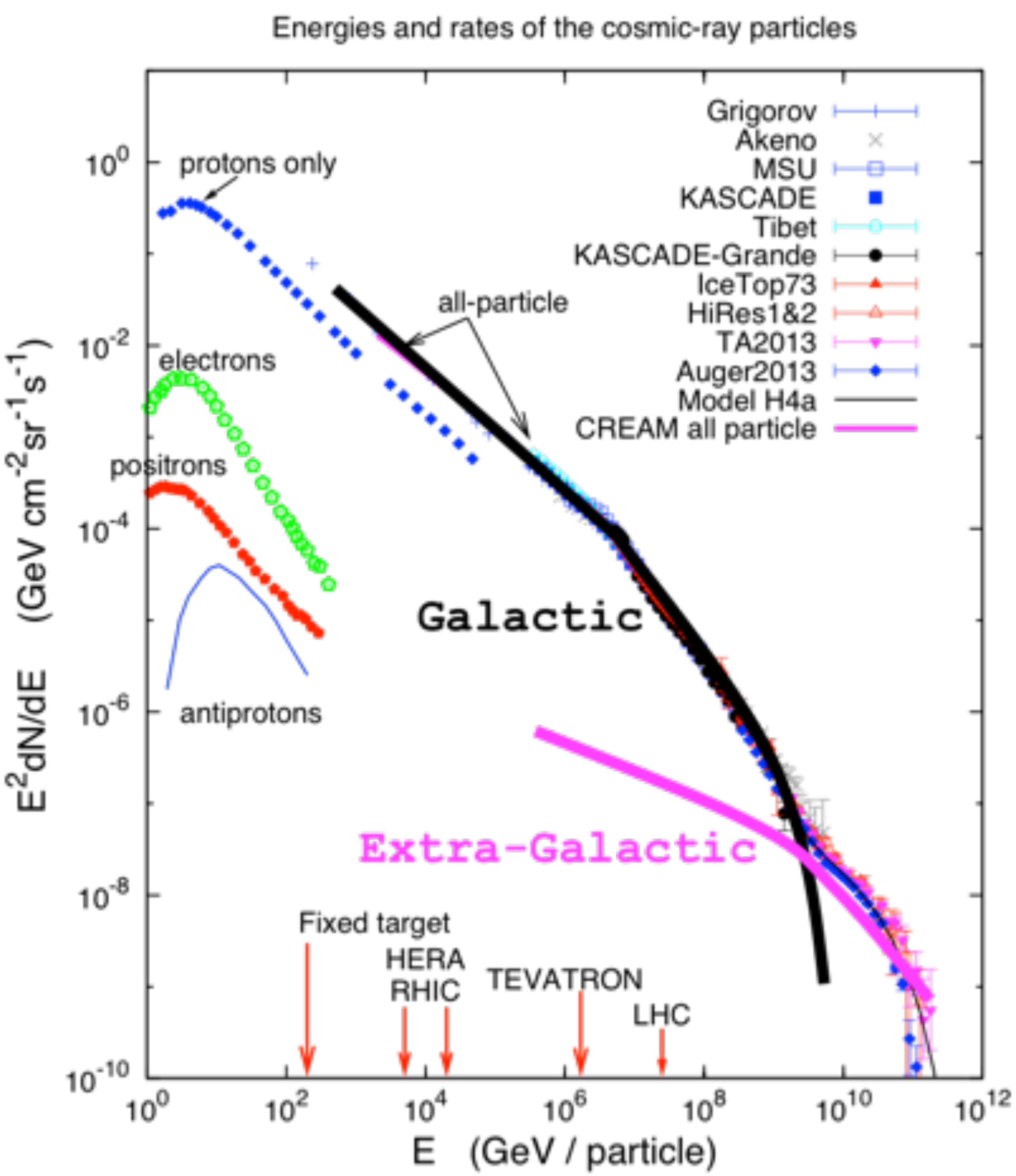
# SILCC: **SI**mulating the **L**ife**C**ycle of molecular **C**louds


**Stefanie Walch**
**Philipp Girichidis**
**Thorsten Naab**
**Andrea Gatto**
**Simon C. O. Glover**
**Richard Wünsch**
**Ralf S. Klessen**
**Paul C. Clark**
**Thomas Peters**
**Dominik Derigs**
**Christian Baczynski**

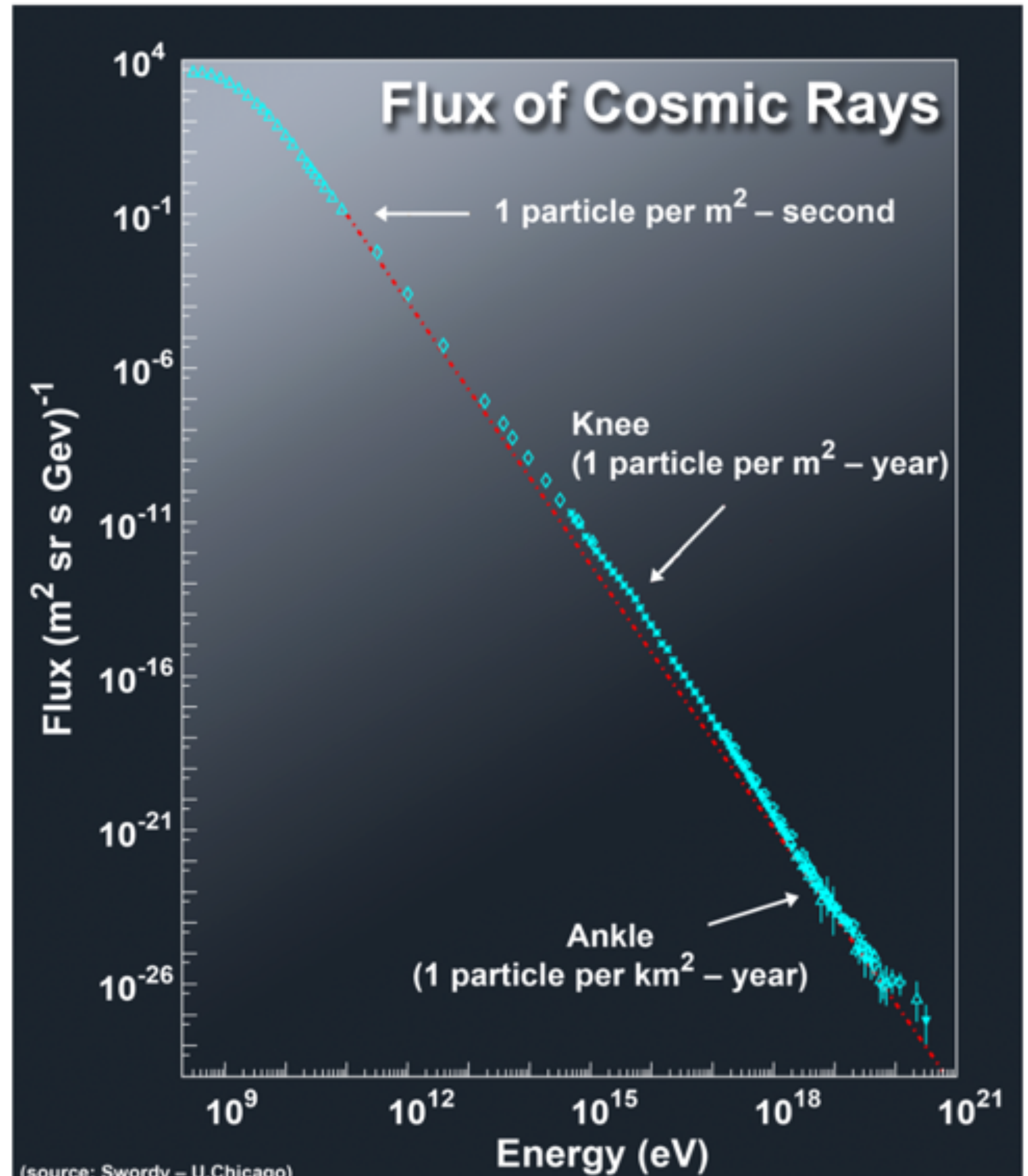

**Walch et al., MNRAS 454, 238 (2015)**
**Girichidis et al., arXiv:1508.06646**

**KS SN rate, mixed driving**

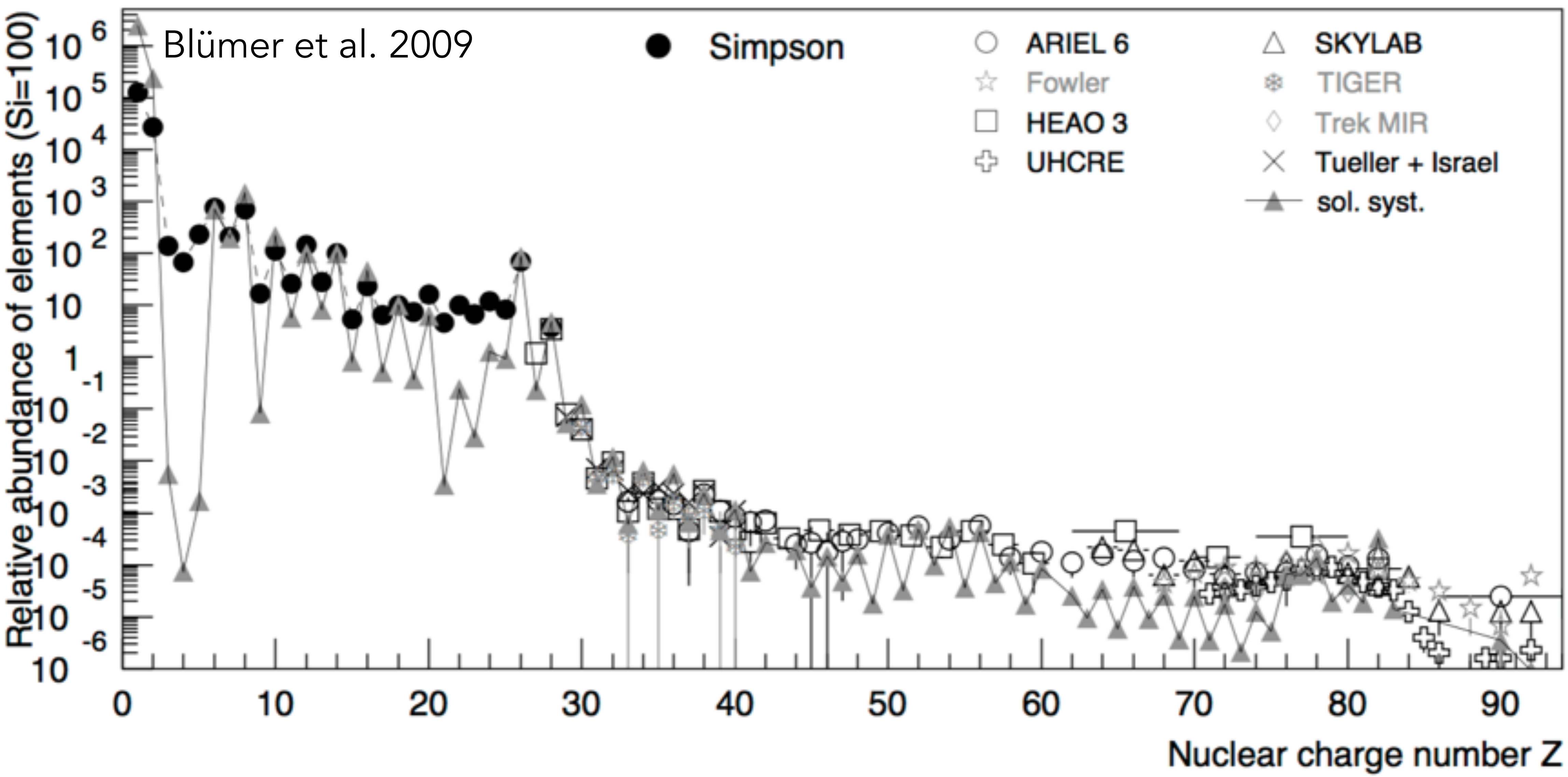
# Cosmic Rays




https://masterclass.icecube.wisc.edu/en/analyses/cosmic-ray-energy-spectrum

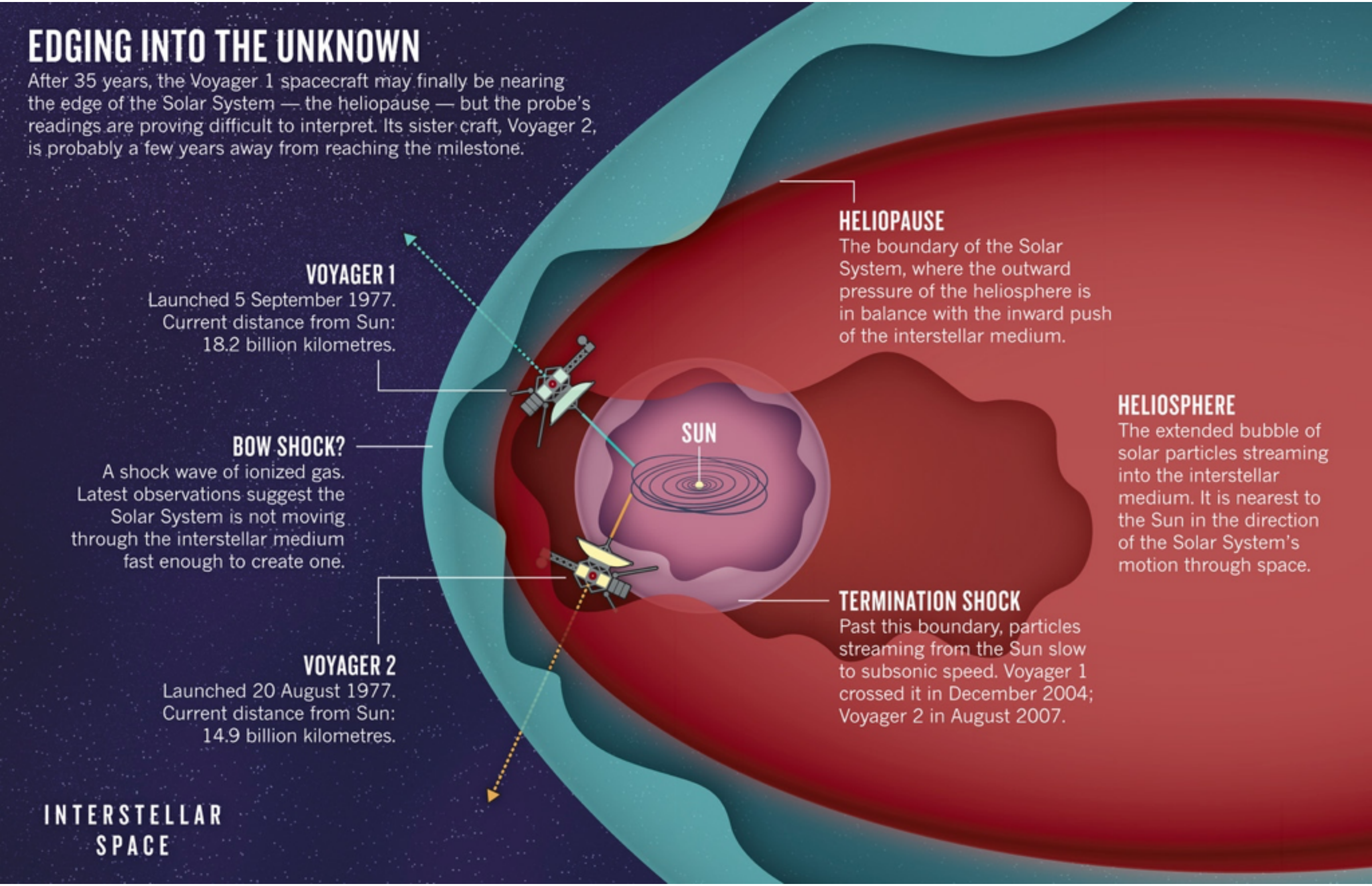


# Cosmic Rays

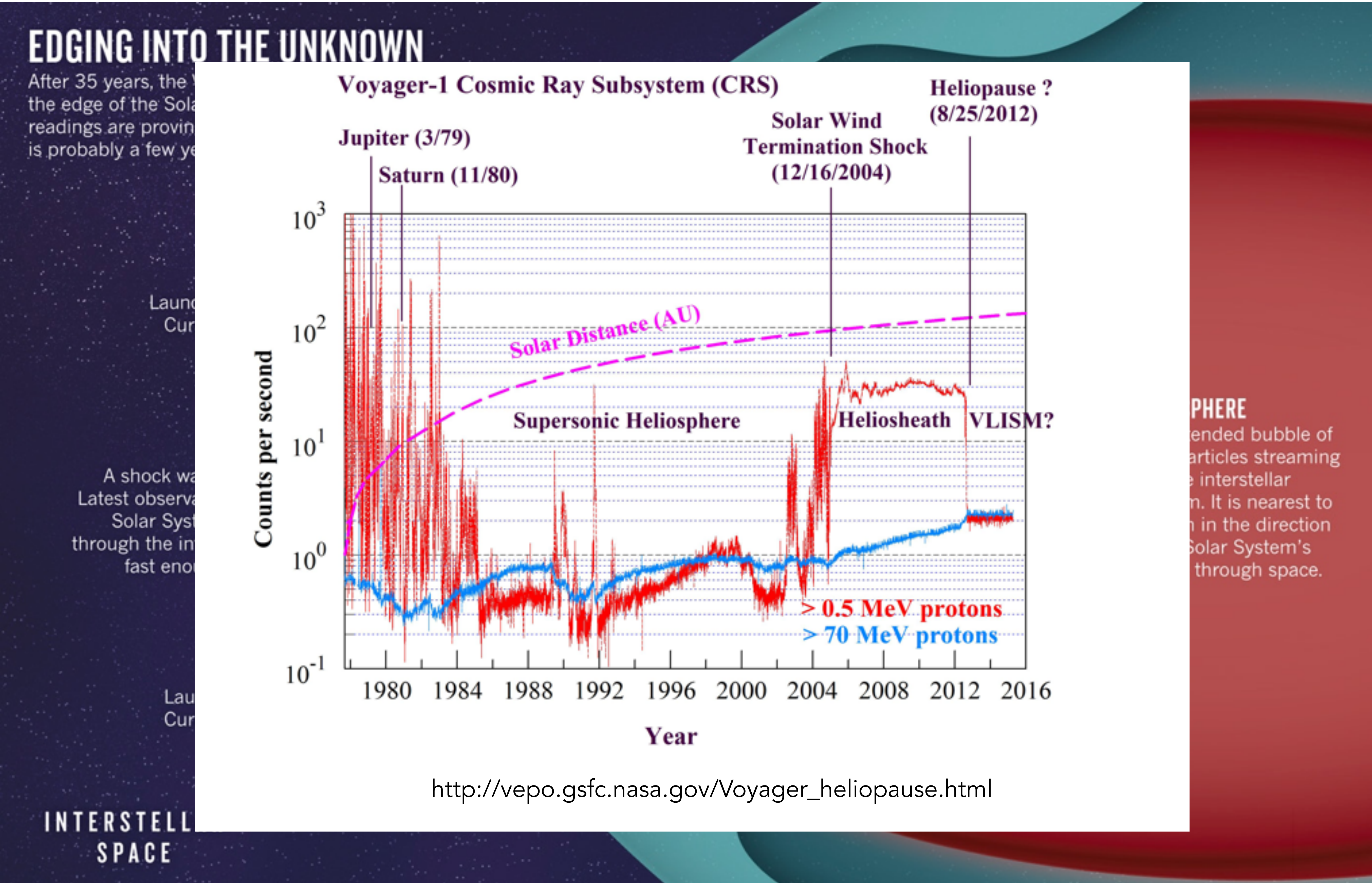



Protons are most abundant, He next.

$^6$Li, $^9$Be, $^{10}$B, $^{11}$B from "spallation".



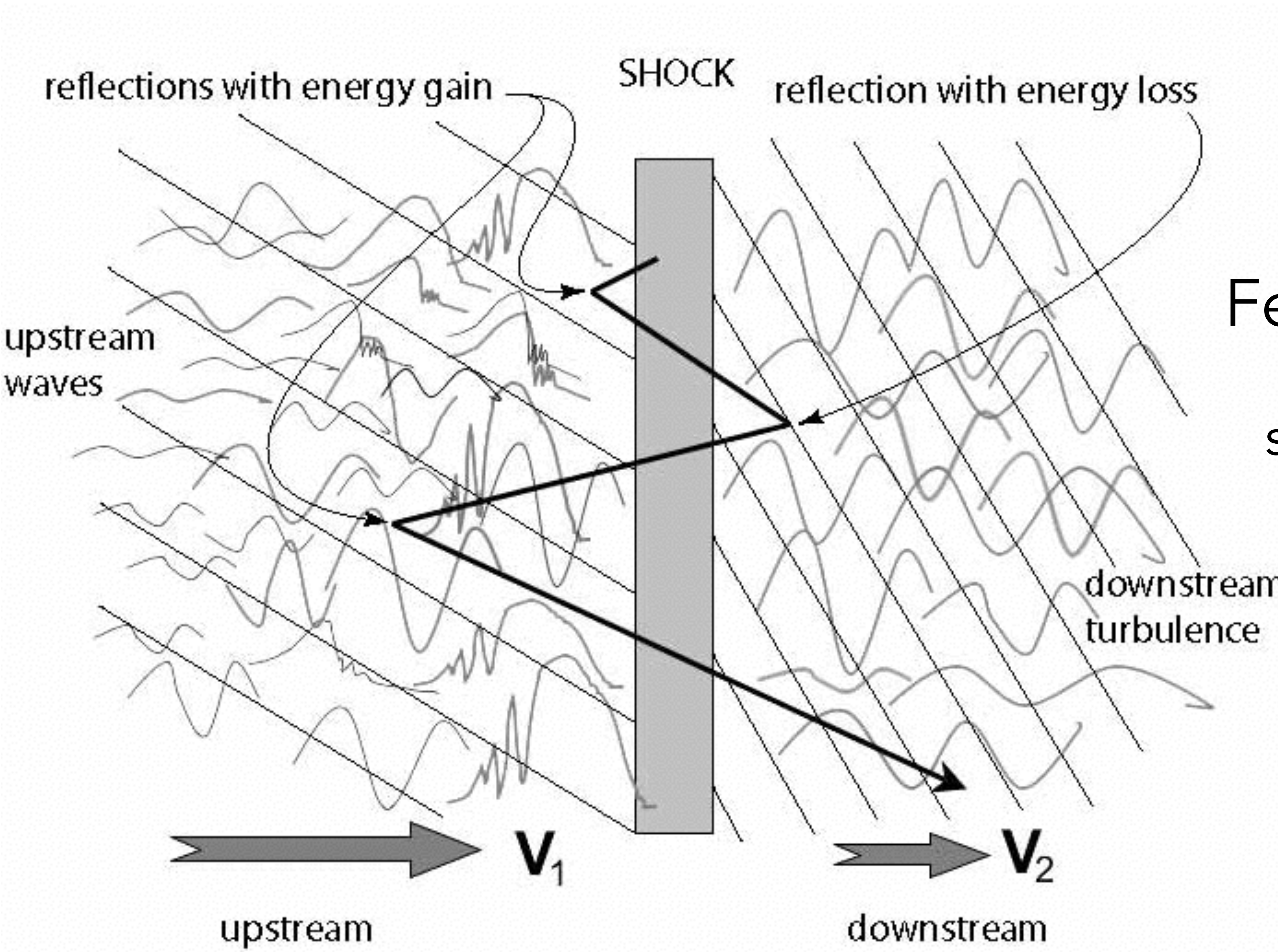

Cowen, *Nature*, 2012




http://vepo.gsfc.nasa.gov/Voyager_heliopause.html

Cowen, *Nature*, 2012

# Acceleration of Cosmic Rays




Treumann, R.A. et al. arXiv:0806.4046

Diffusive shock acceleration (first order Fermi acceleration)

scattering off B-field fluctuations

analogy to particle bouncing between converging walls

# Acceleration of Cosmic Rays

Maximum energy attainable by diffusive shock acceleration is set by when B-fields can no longer confine CR.

gyroradius > scale of system

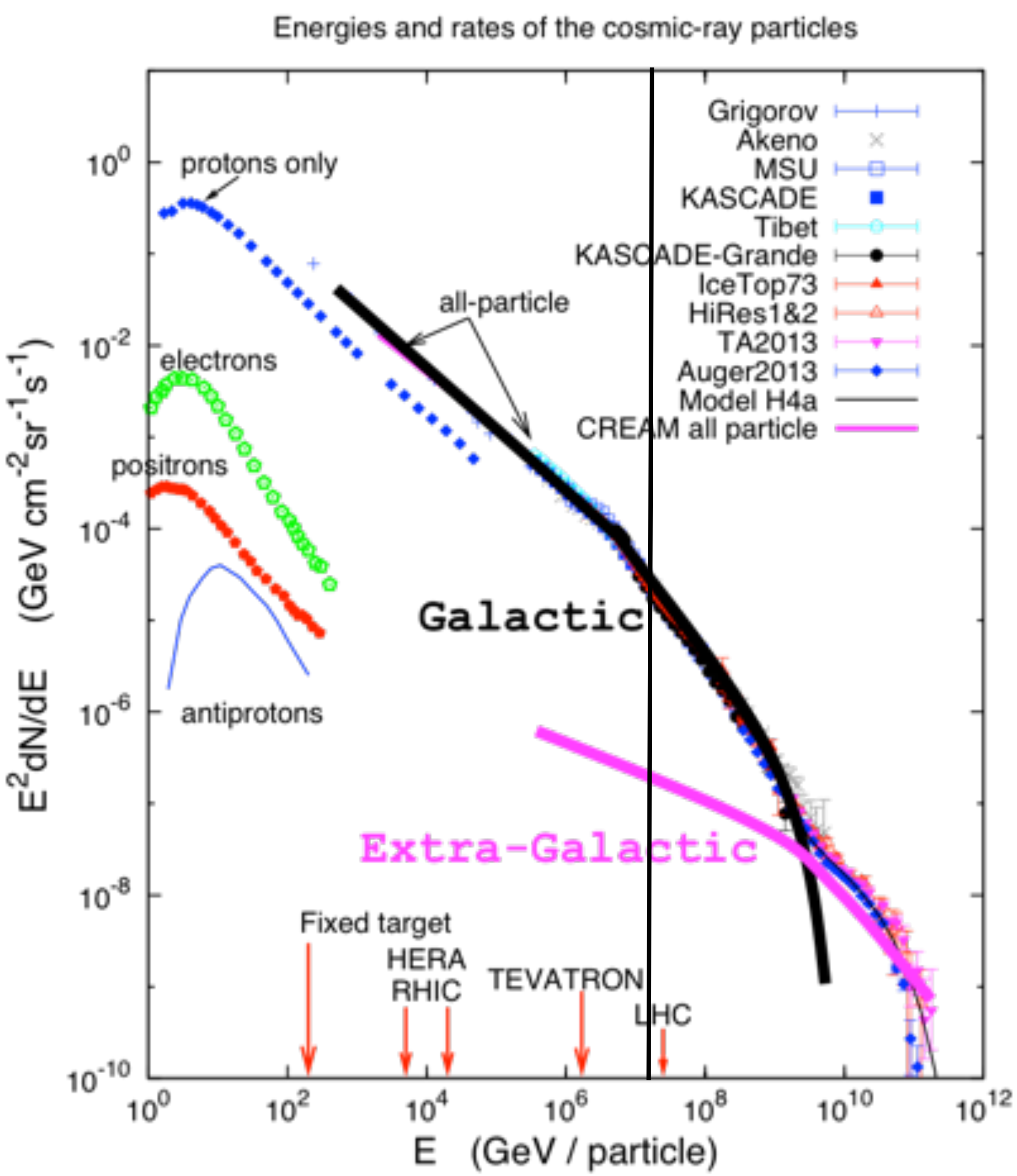
$$R_{\rm gyro} = \frac{pc}{eB_{\perp}}$$

p = momentum

$$E_{\rm max} = eB_{\rm SNR}L$$

$$E_{\rm max} \approx 10^{7.0}{\rm GeV}\left(\frac{L}{23{\rm pc}}\right)\left(\frac{B_{\rm SNR}}{10\mu{\rm G}}\right)$$

# Acceleration of Cosmic Rays

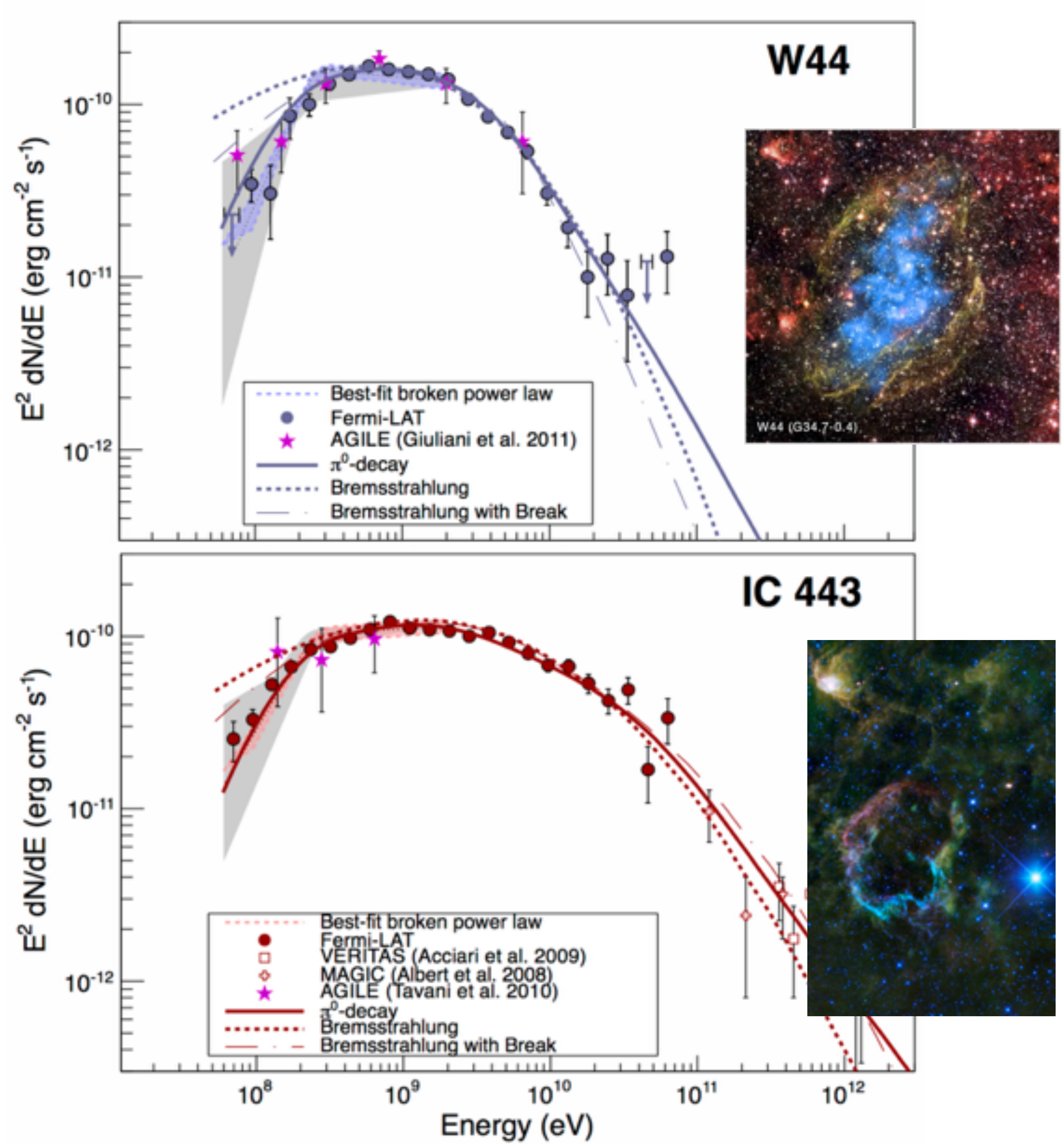



$$E_{\rm max} \approx 10^{7.0}{\rm GeV} \left(\frac{L}{23{\rm pc}}\right)\left(\frac{B_{\rm SNR}}{10\mu{\rm G}}\right)$$

Supernova shocks have long been thought to be the best candidate for CR acceleration.

Recently, first direct evidence…

# Acceleration of Cosmic Rays




Accelerated protons create pions when they run into the surrounding ISM. Pions decay and produce gamma rays.

Fermi confirmation of gamma-ray spectrum following pion decay prediction for some SNRs in the MW. (Ackermann et al. 2013)