THE LIFE CYCLE OF DUST: DUST AS A TRACER OF STAR FORMATION

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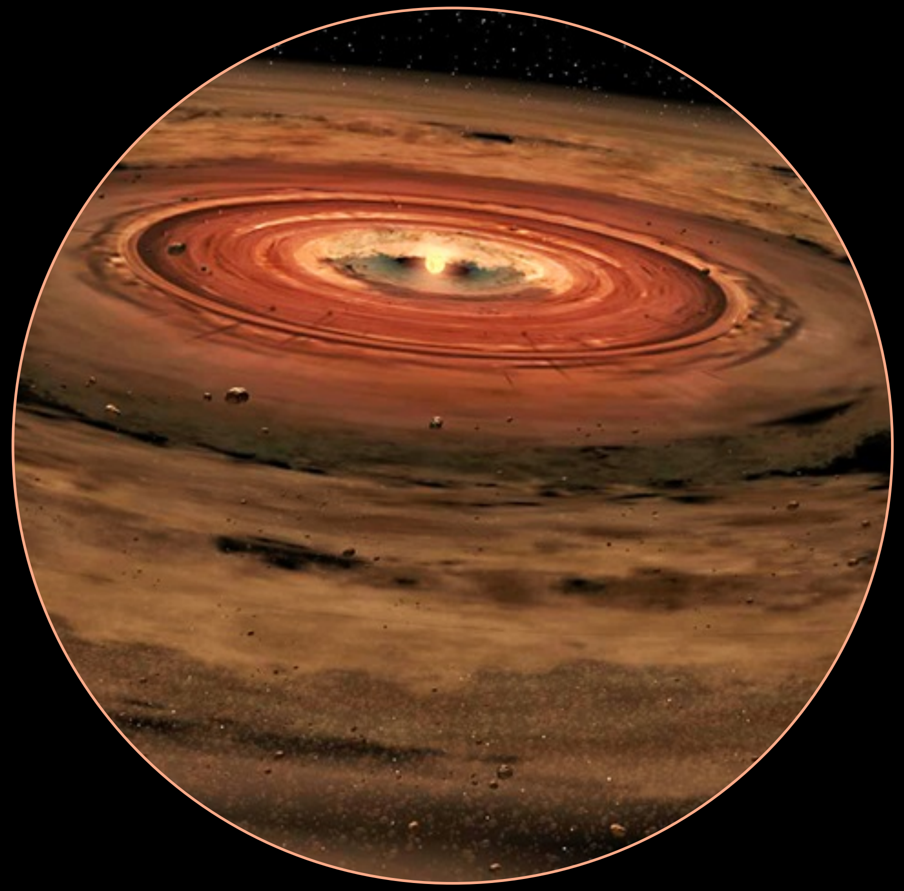

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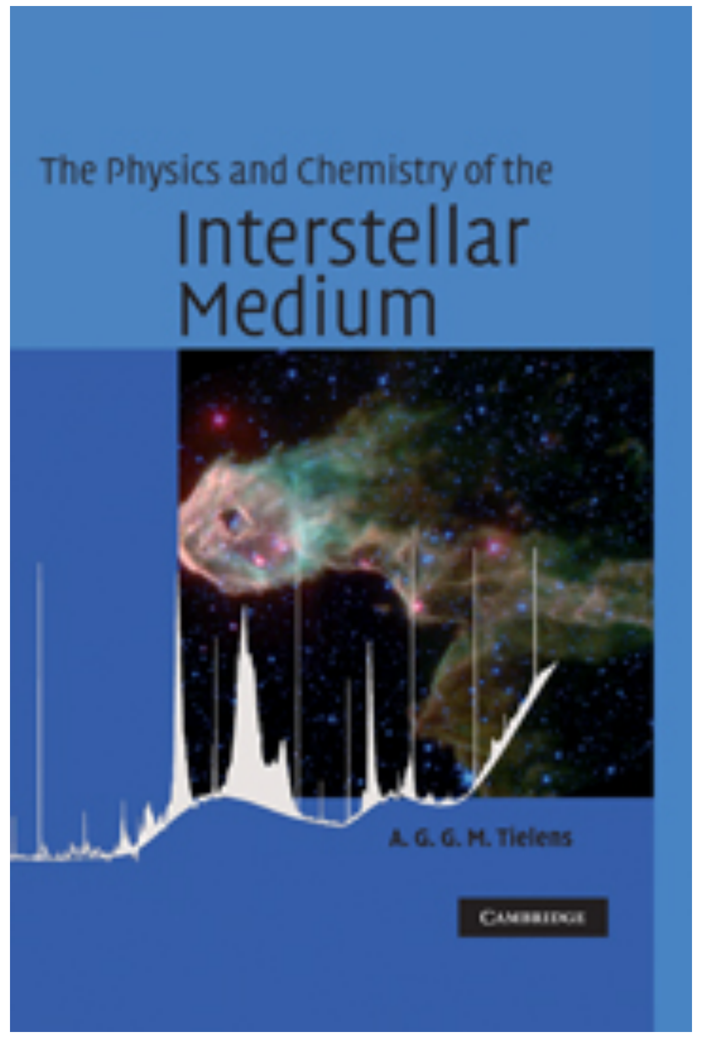
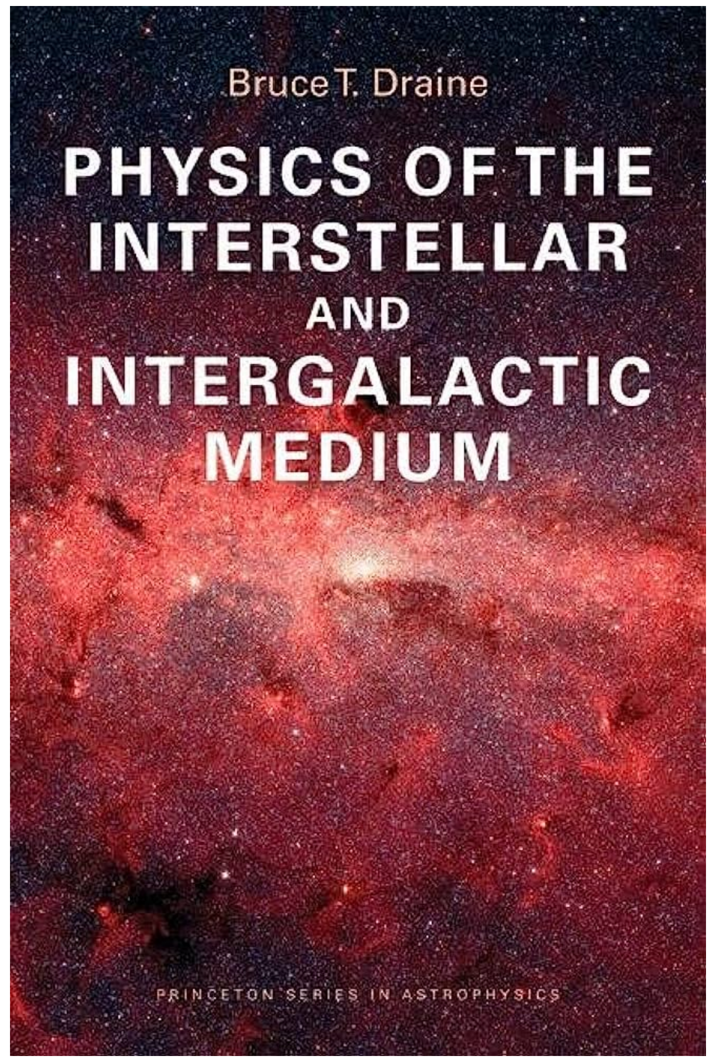
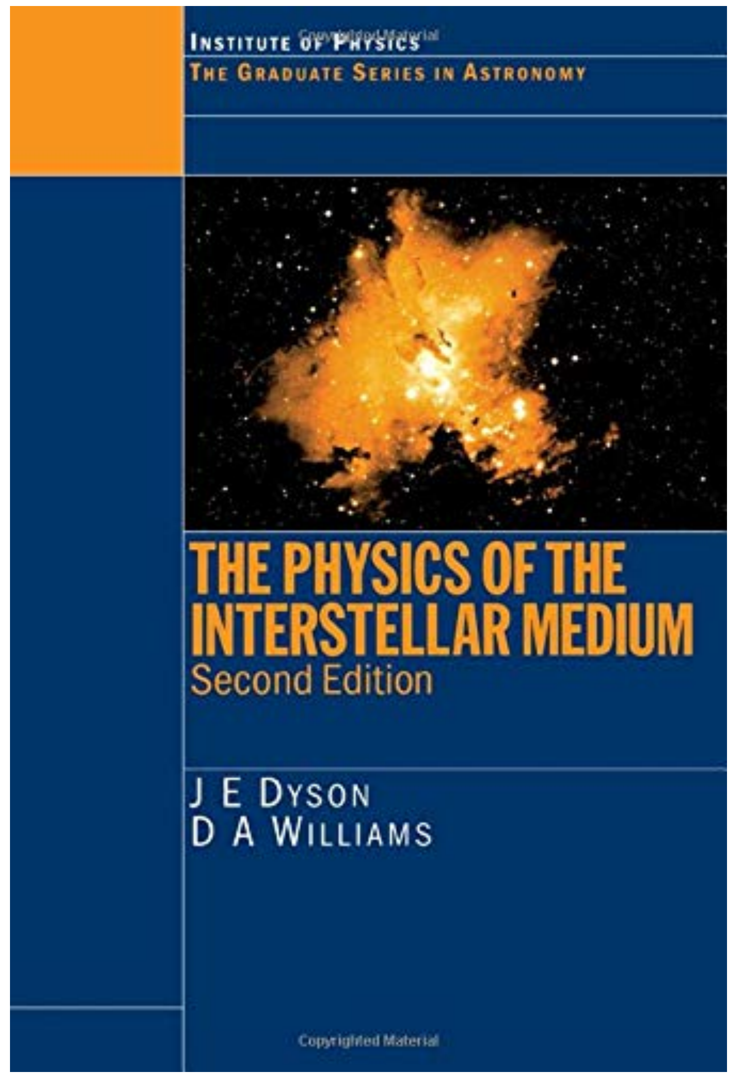
LITERATURE SUGGESTIONS

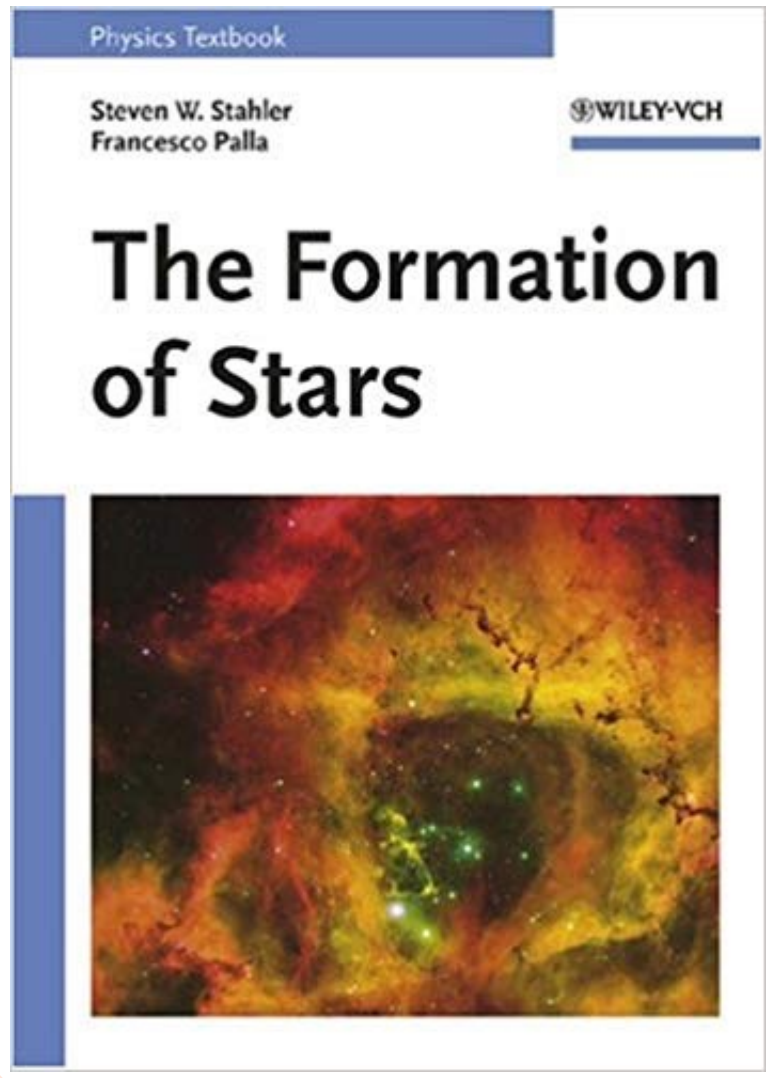
INTERSTELLAR MEDIUM

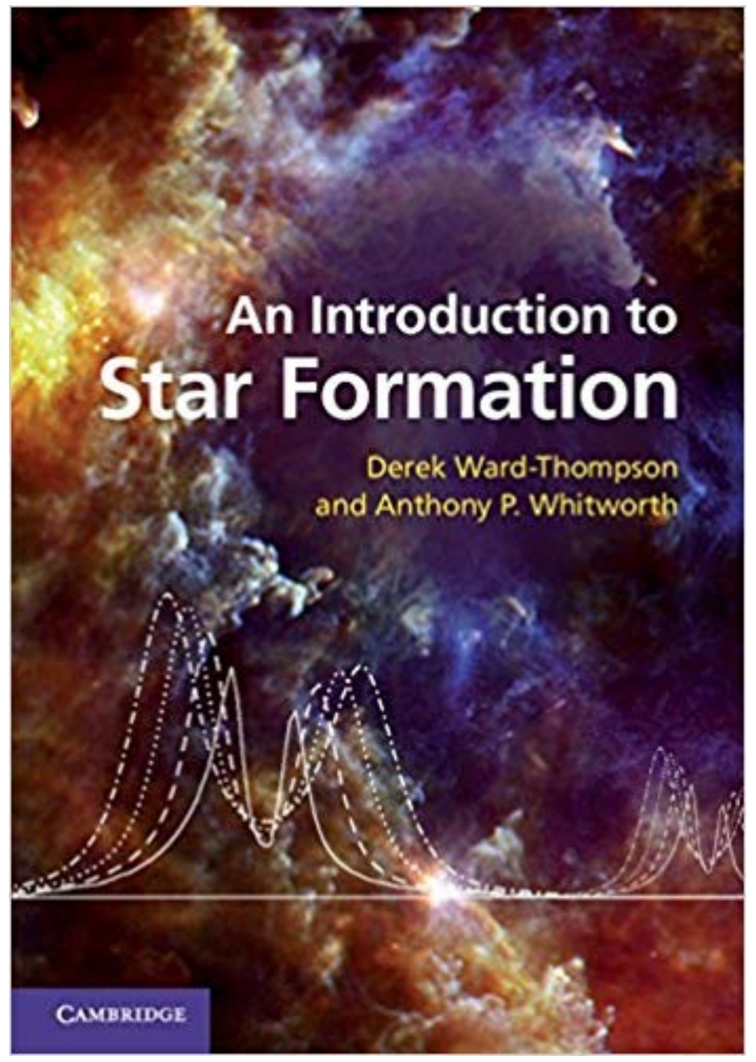


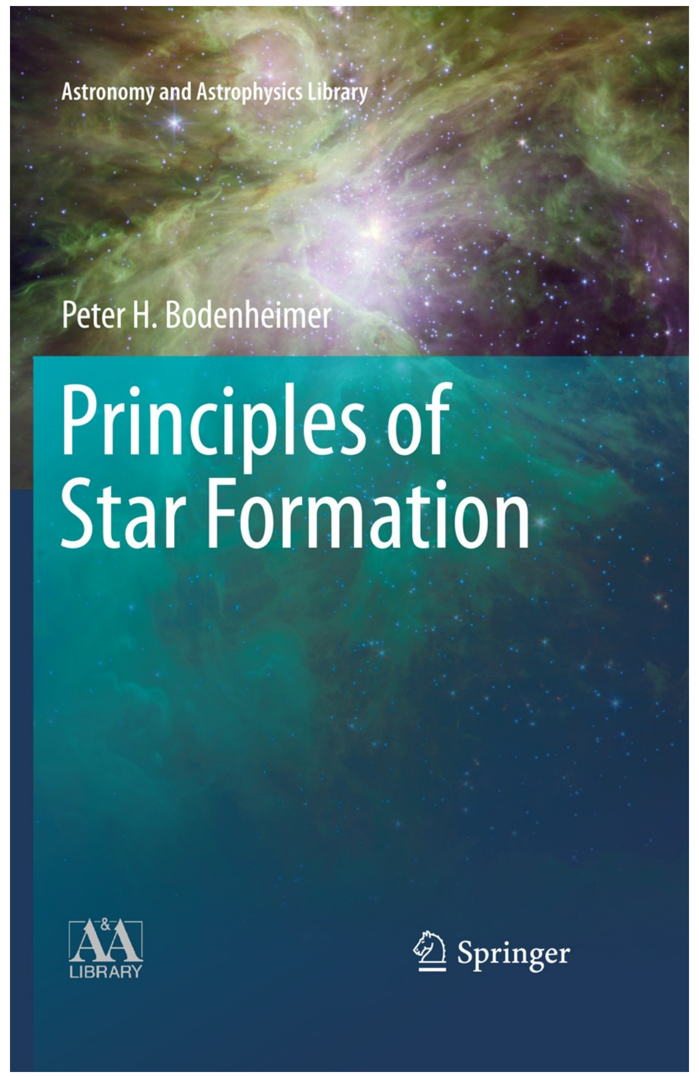




STAR FORMATION

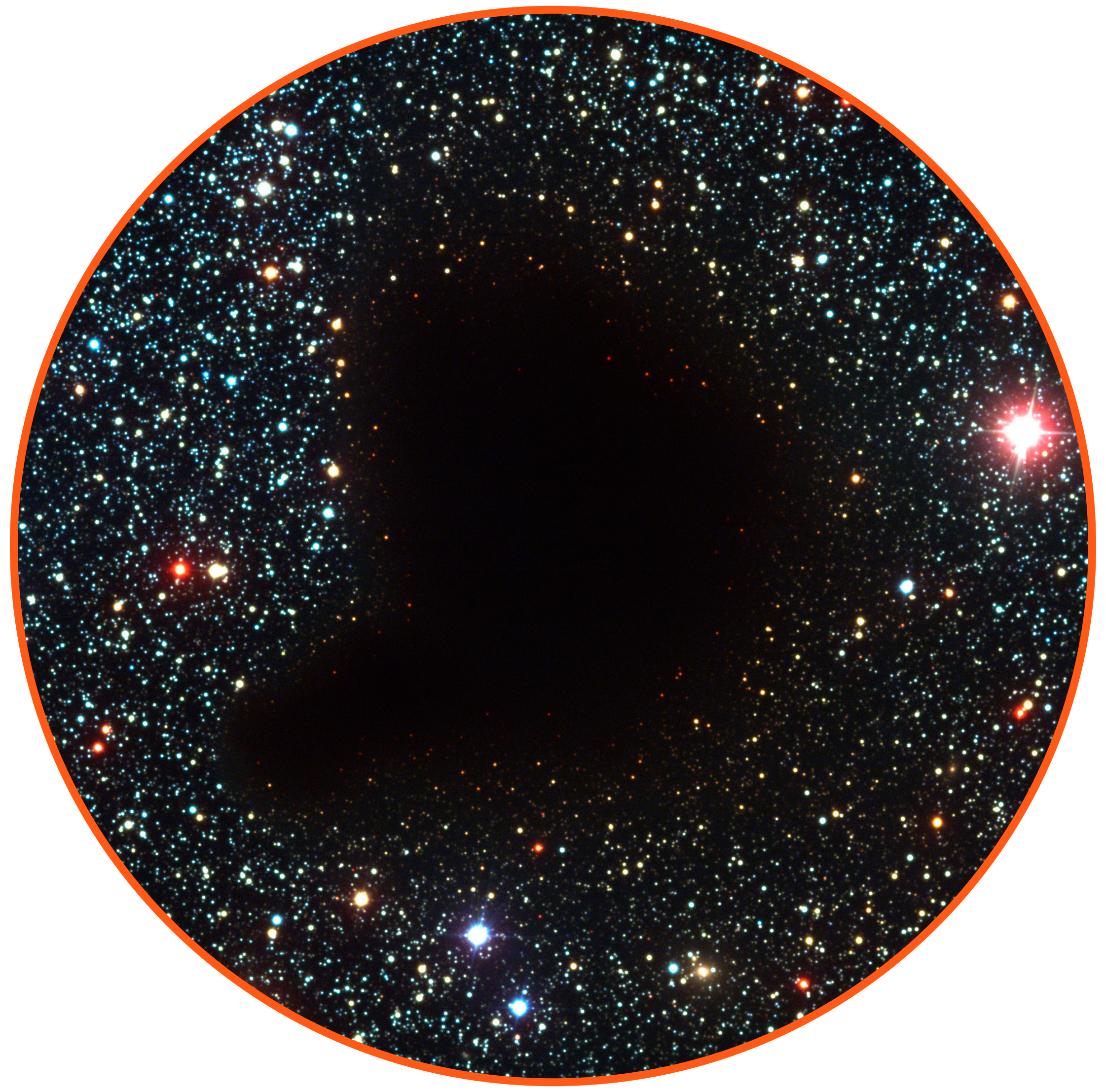






OUTLINE

THE INTERSTELLAR MEDIUM

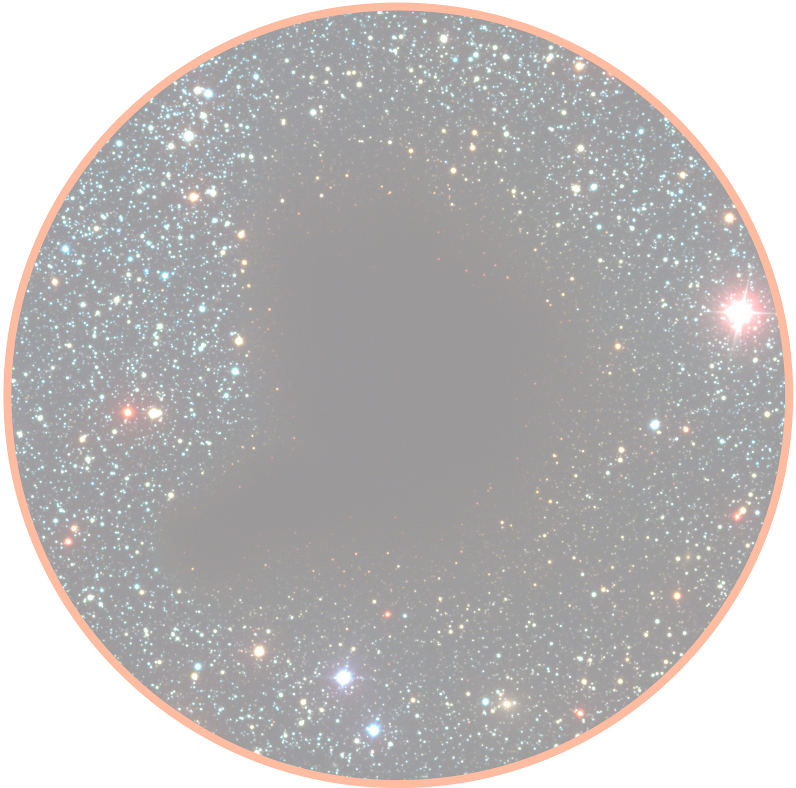


MOLECULAR CLOUDS: THE STELLAR NURSERIES

CLOUD FRAGMENTATION AND CLUSTER FORMATION

OUTLINE

THE INTERSTELLAR MEDIUM



MOLECULAR CLOUDS: THE STELLAR NURSERIES

CLOUD FRAGMENTATION AND CLUSTER FORMATION

THE MILKY WAY SEEN BY GAIA: 1.7 BILLIONS STARS

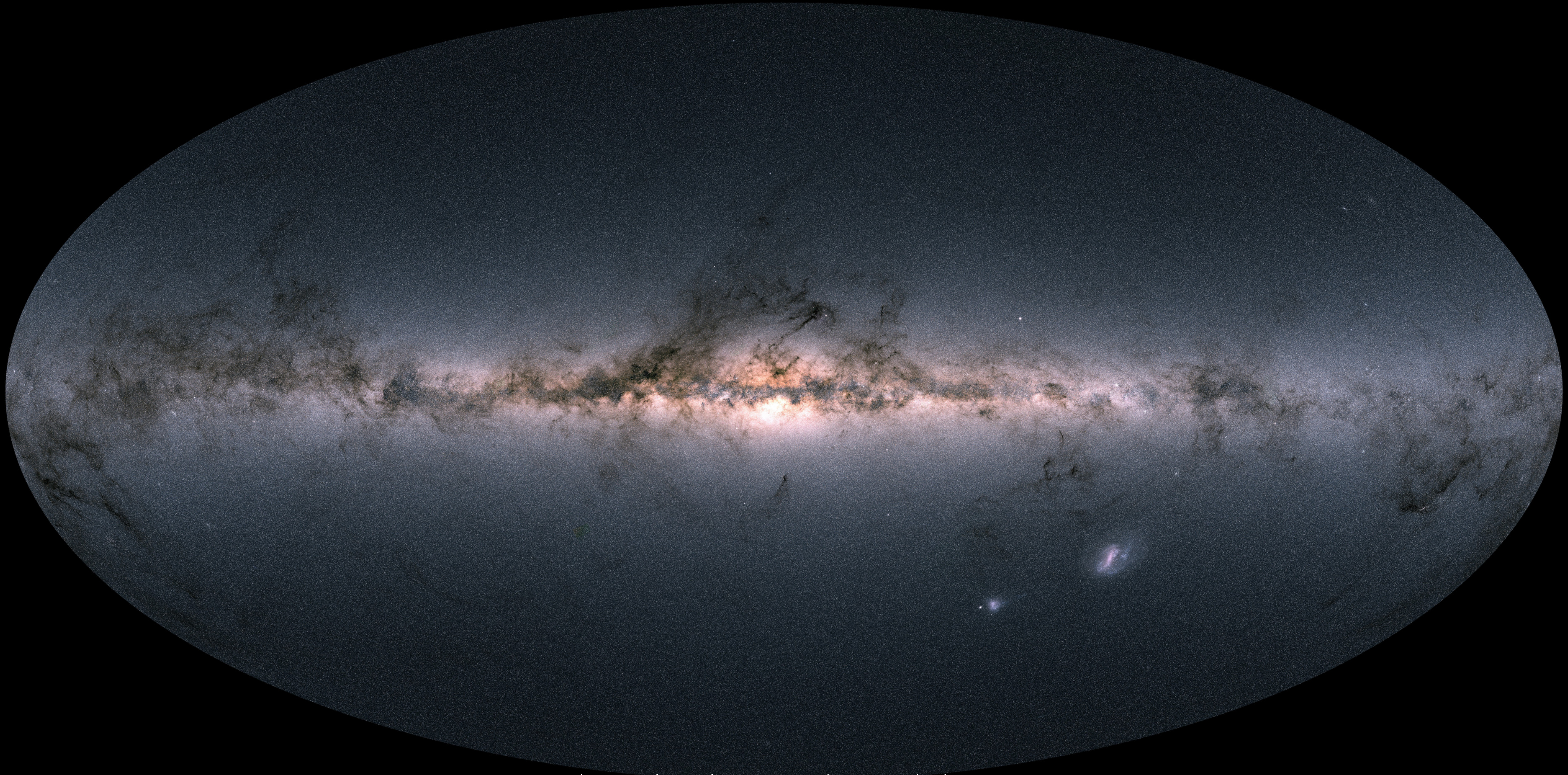


Image Credit: ESA/Gaia/DPAC; Credit Herschel images: ESA

THE MILKY WAY SEEN BY GAIA: 1.7 BILLIONS STARS

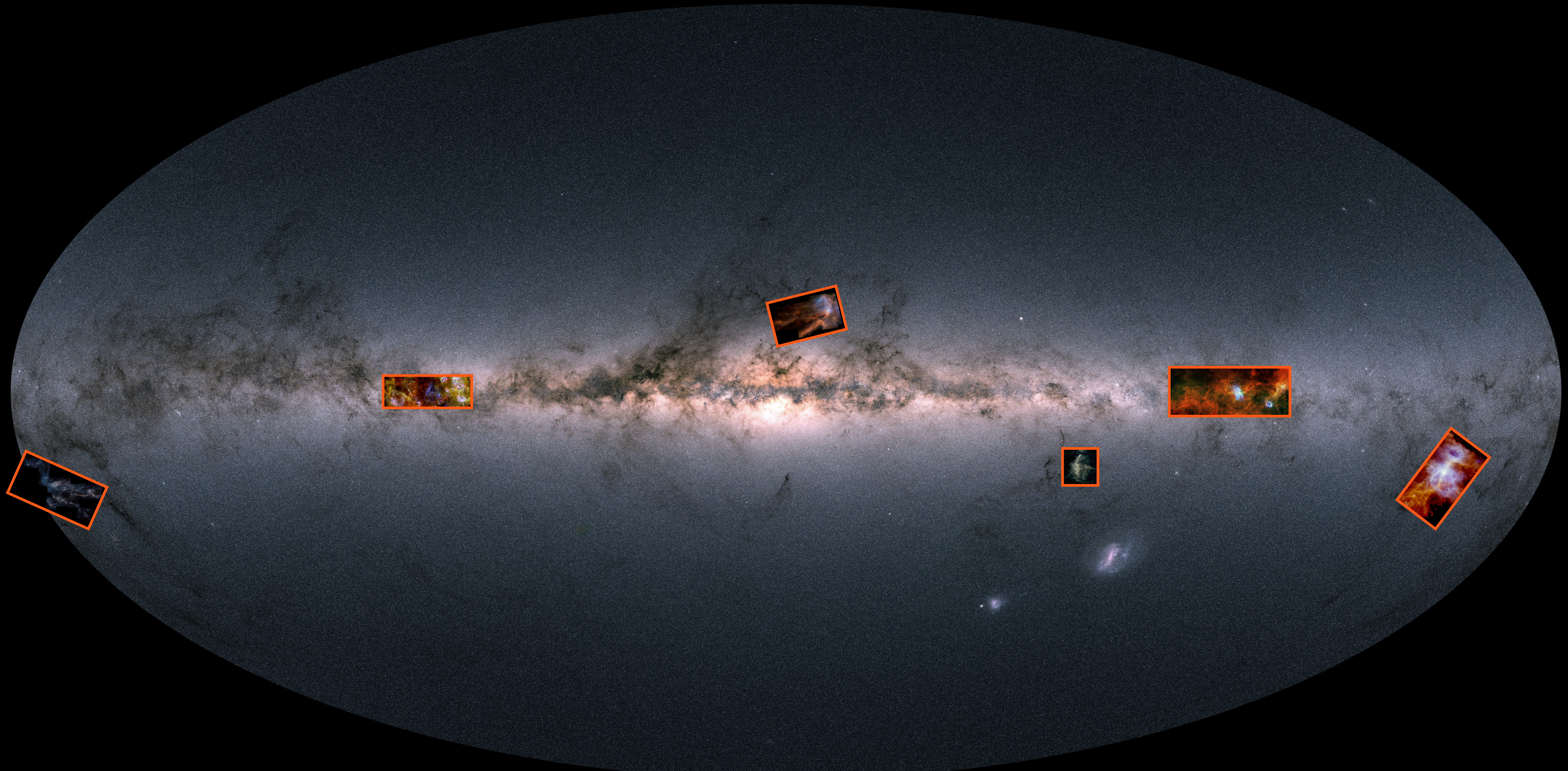


Image Credit: ESA/Gaia/DPAC; Credit Herschel images: ESA

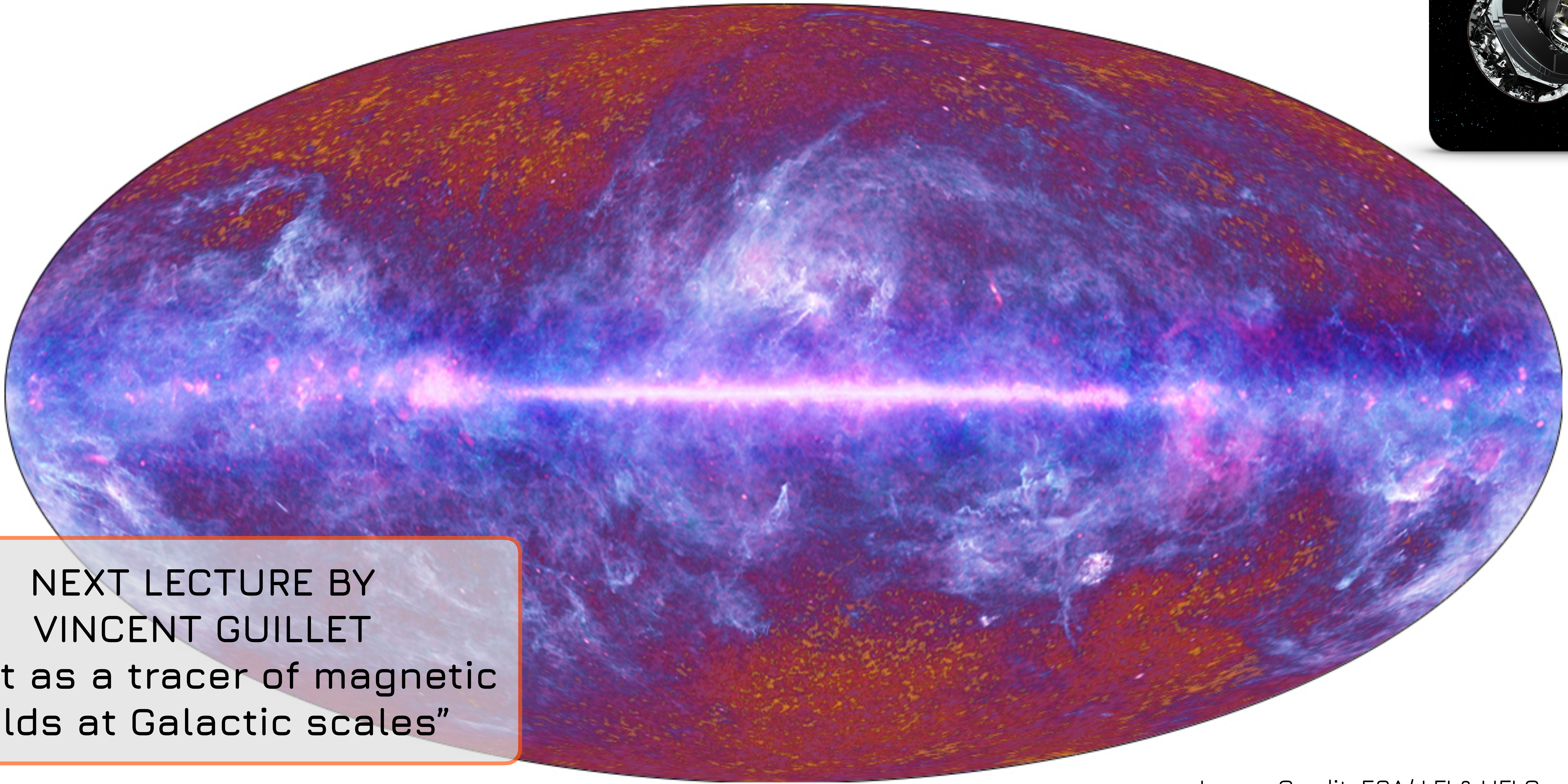
THE MILKY WAY SEEN BY GAIA: 1.7 BILLIONS STARS

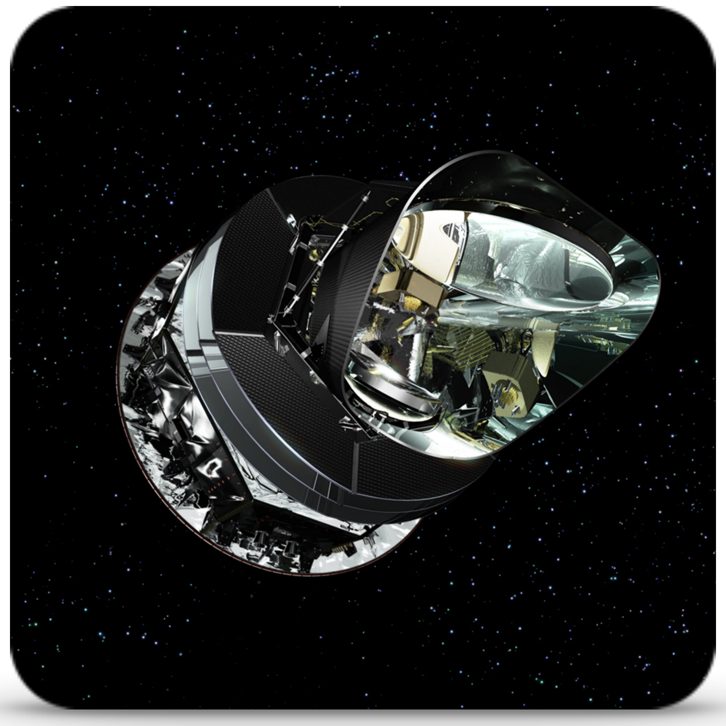
Image Credit: ESA/Gaia/DPAC; Credit Herschel images: ESA

GALACTIC DUST EMISSION MAP

PLANCK

30 GHz 40 GHz 70 GHz 100 GHz 143 GHz 217 GHz 353 GHz 545 GHz 857 GHz





NEXT LECTURE BY
VINCENT GUILLET
“Dust as a tracer of magnetic fields at Galactic scales”

Image Credit: ESA/ LFI & HFI Consortia

THE INTERSTELLAR MEDIUM: DUST

Very low density ~1 cm^{-3} (compared to Earth's atmosphere ~10^{19} cm^{-3})

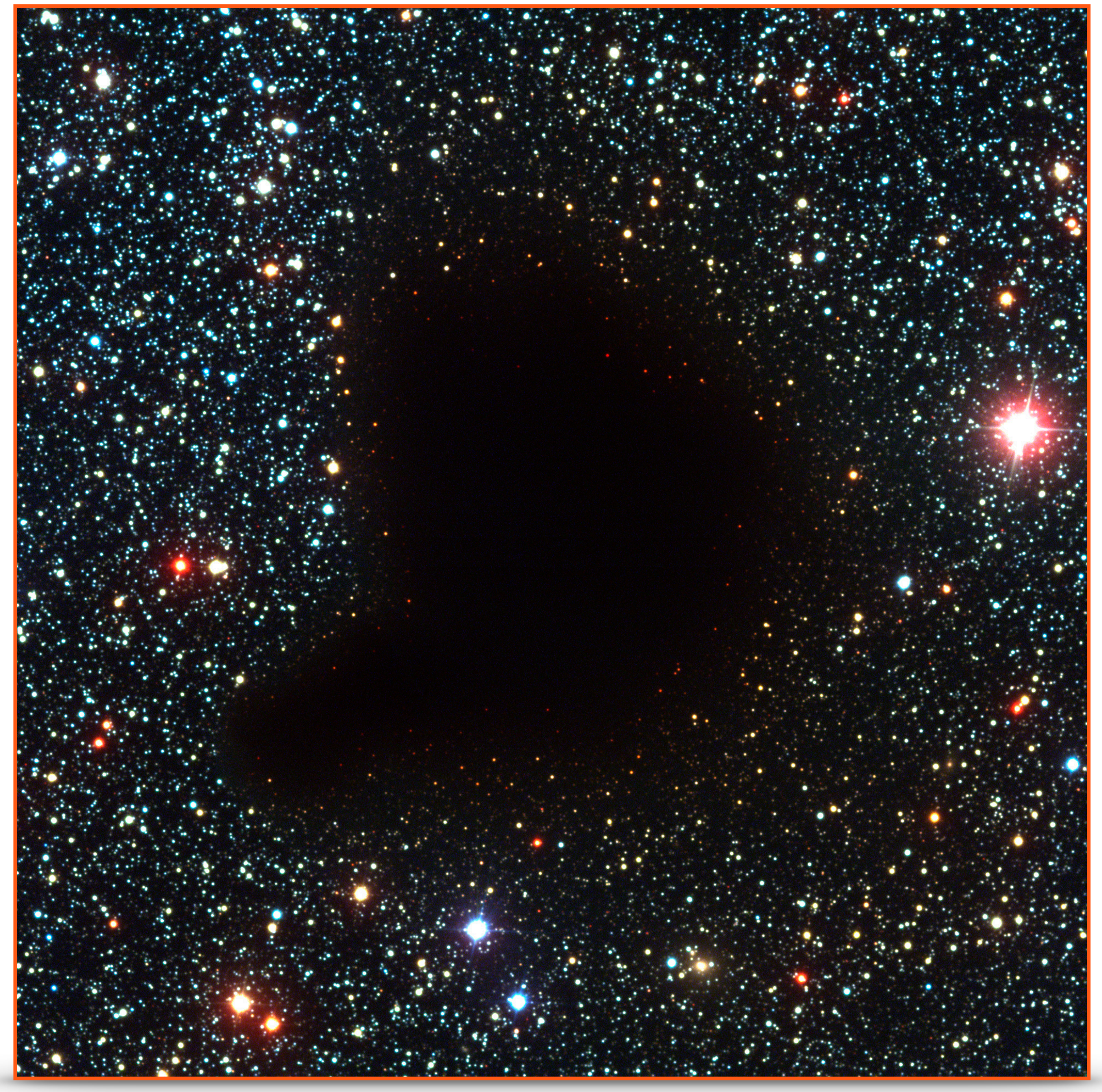
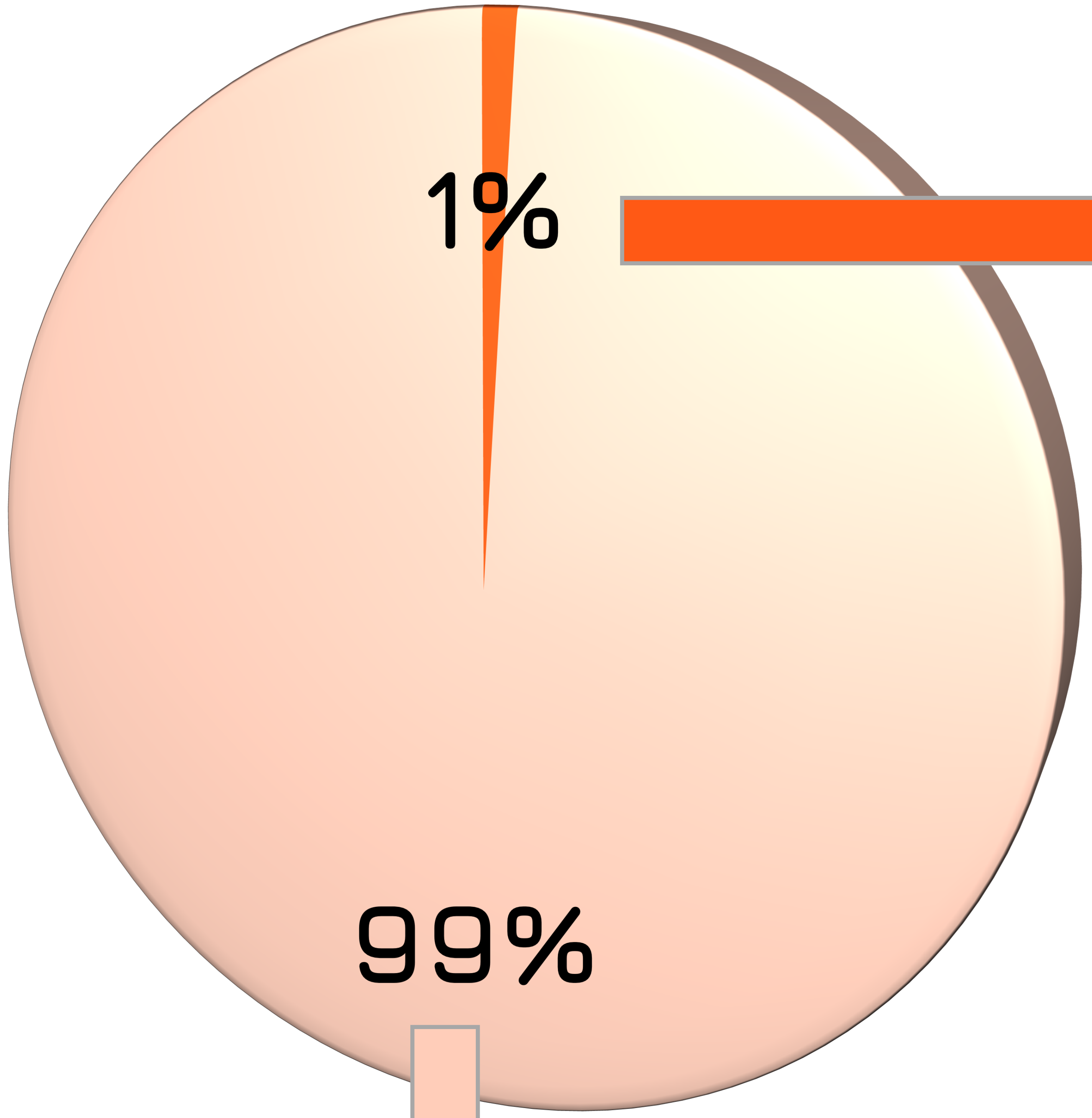


Image Credit: ESO



DUST

Small solid particles (<1 μm)

Composition

Amorphous silicates and carbonaceous grains (in molecular clouds covered by icy mantles)

GAS: ions, atoms and molecules

91% H, 8.9% He, 0.1% heavier elements

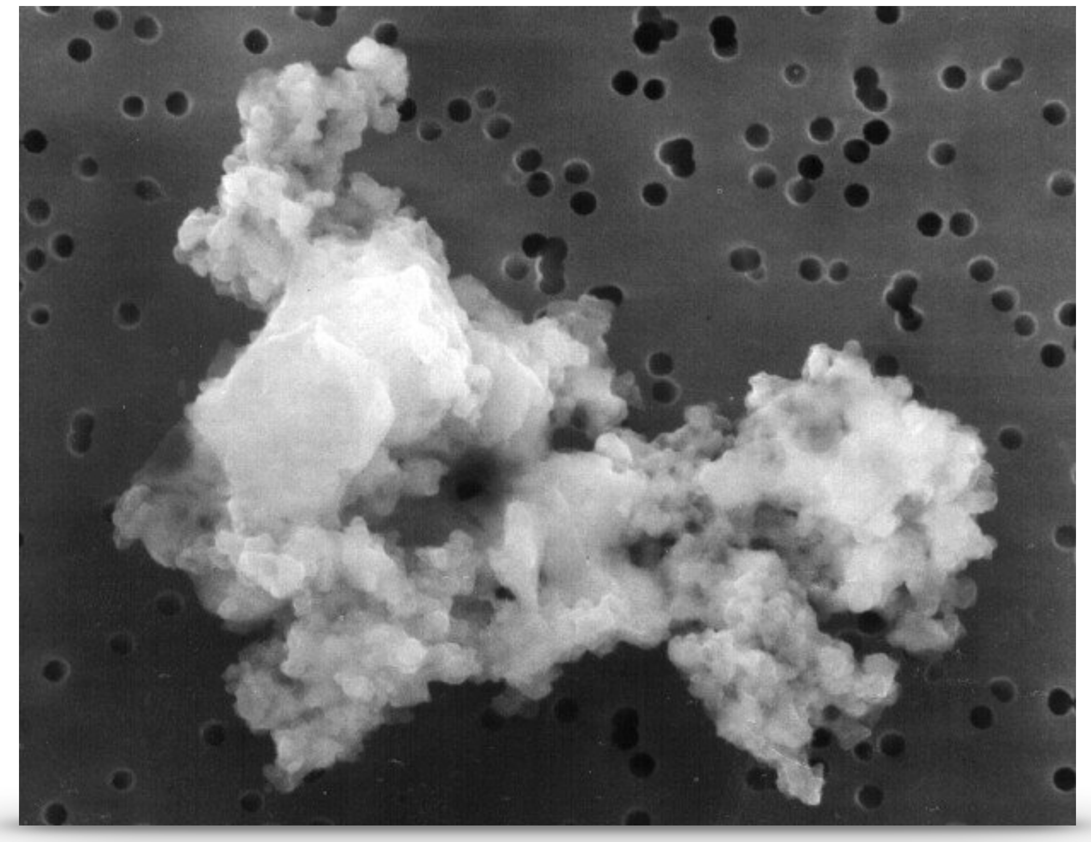


Image Credit: NASA

THE INTERSTELLAR MEDIUM: DUST

OPTICAL

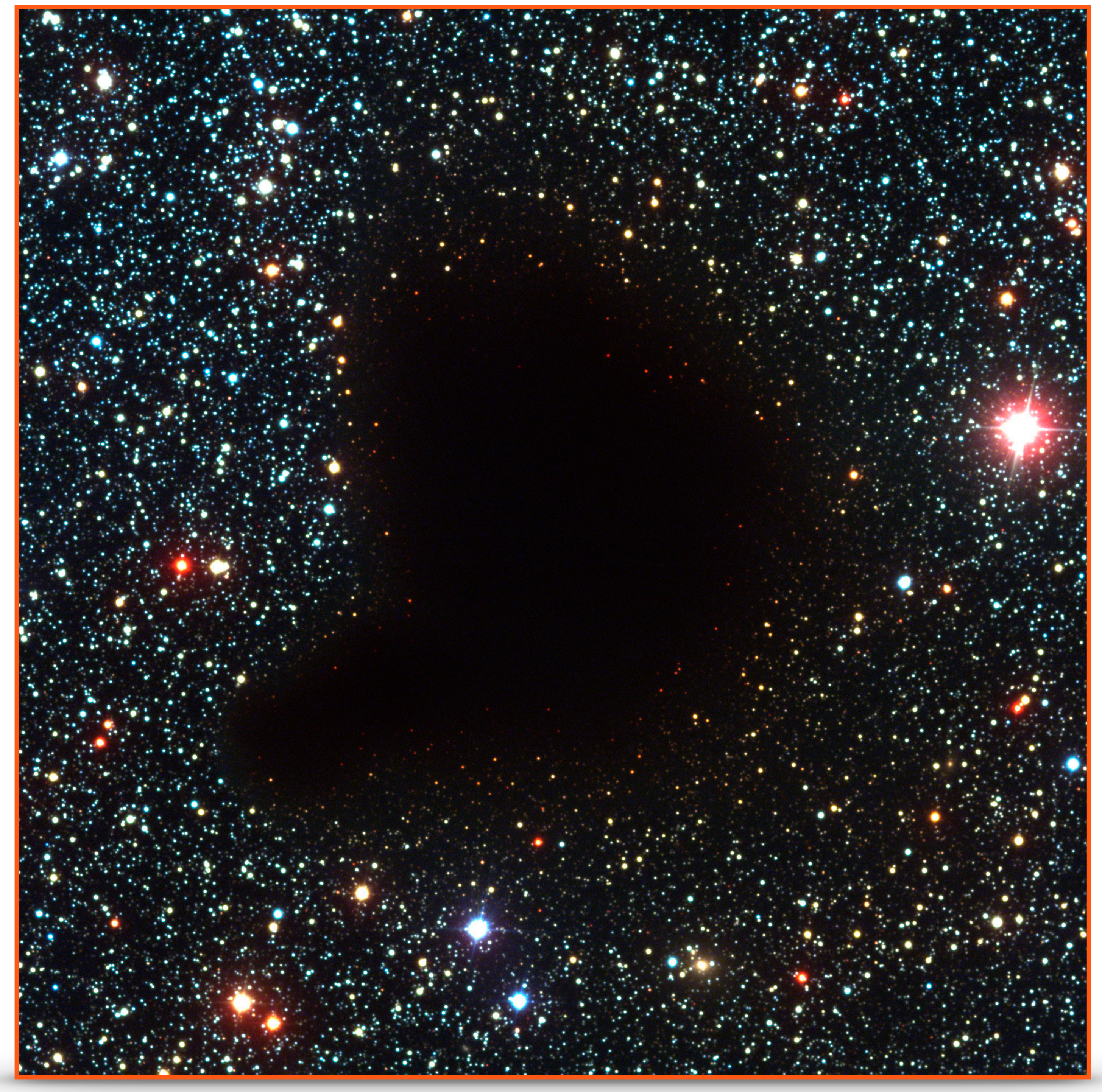
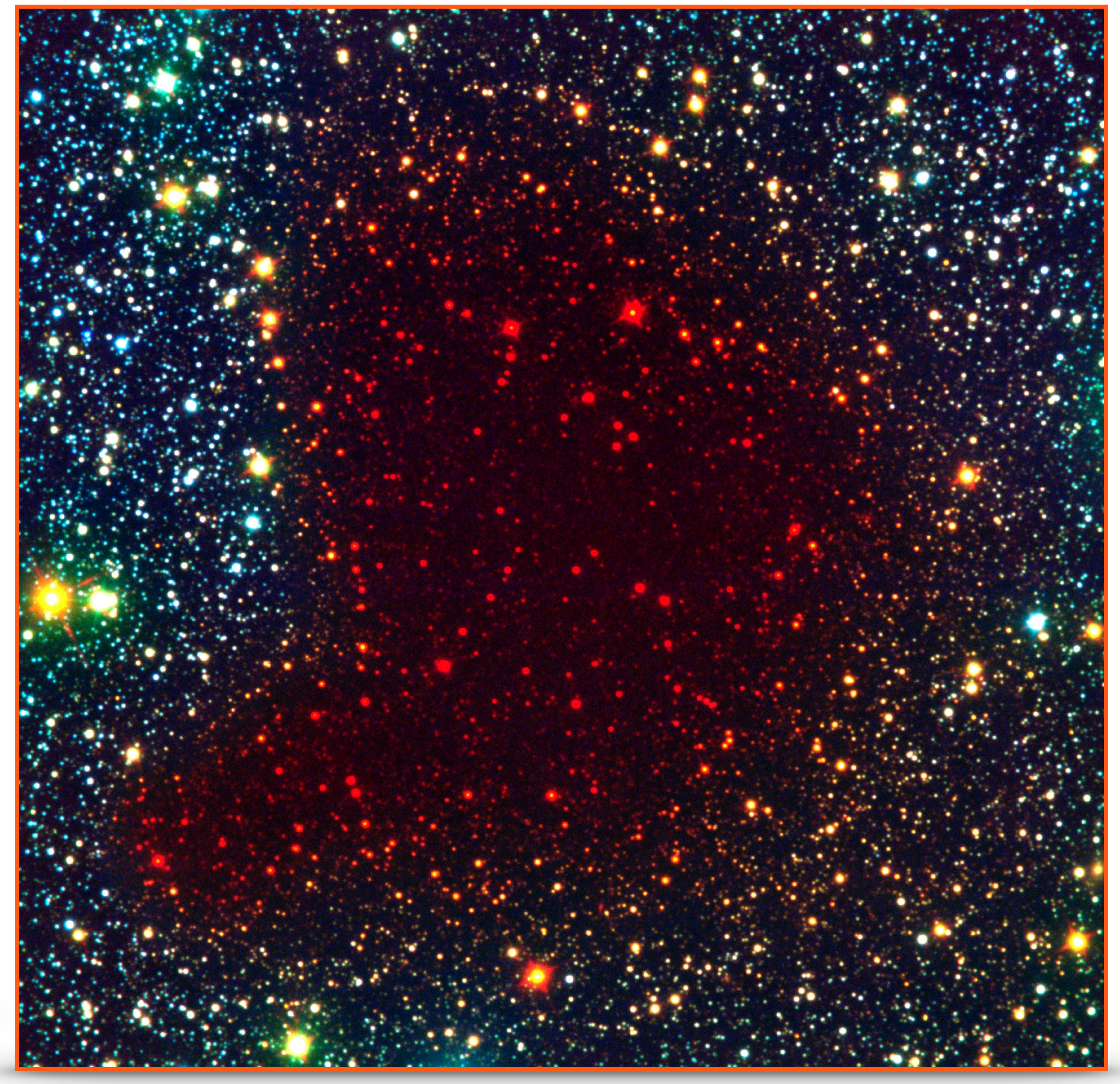
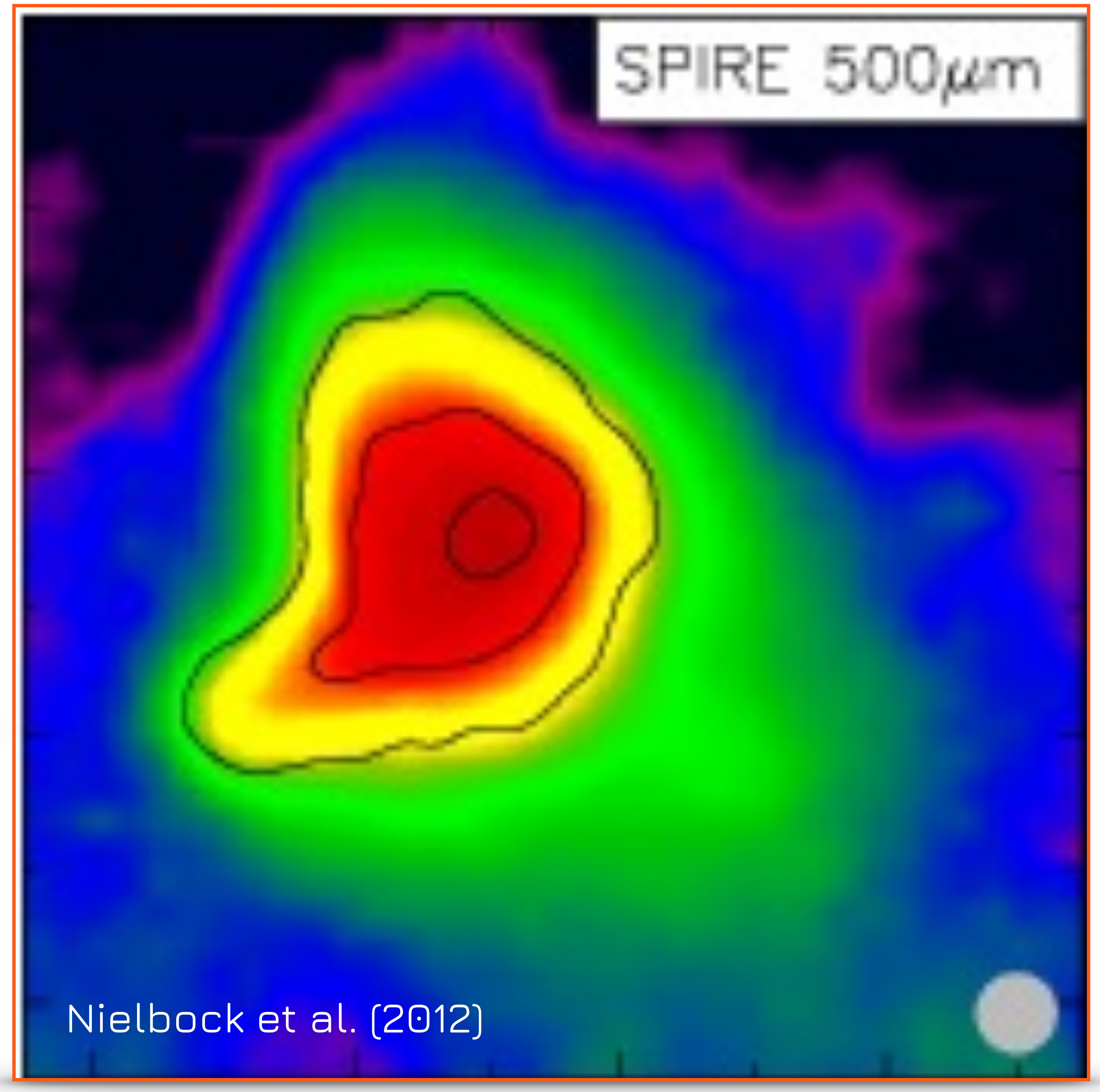


Image Credit: ESO

INFRARED



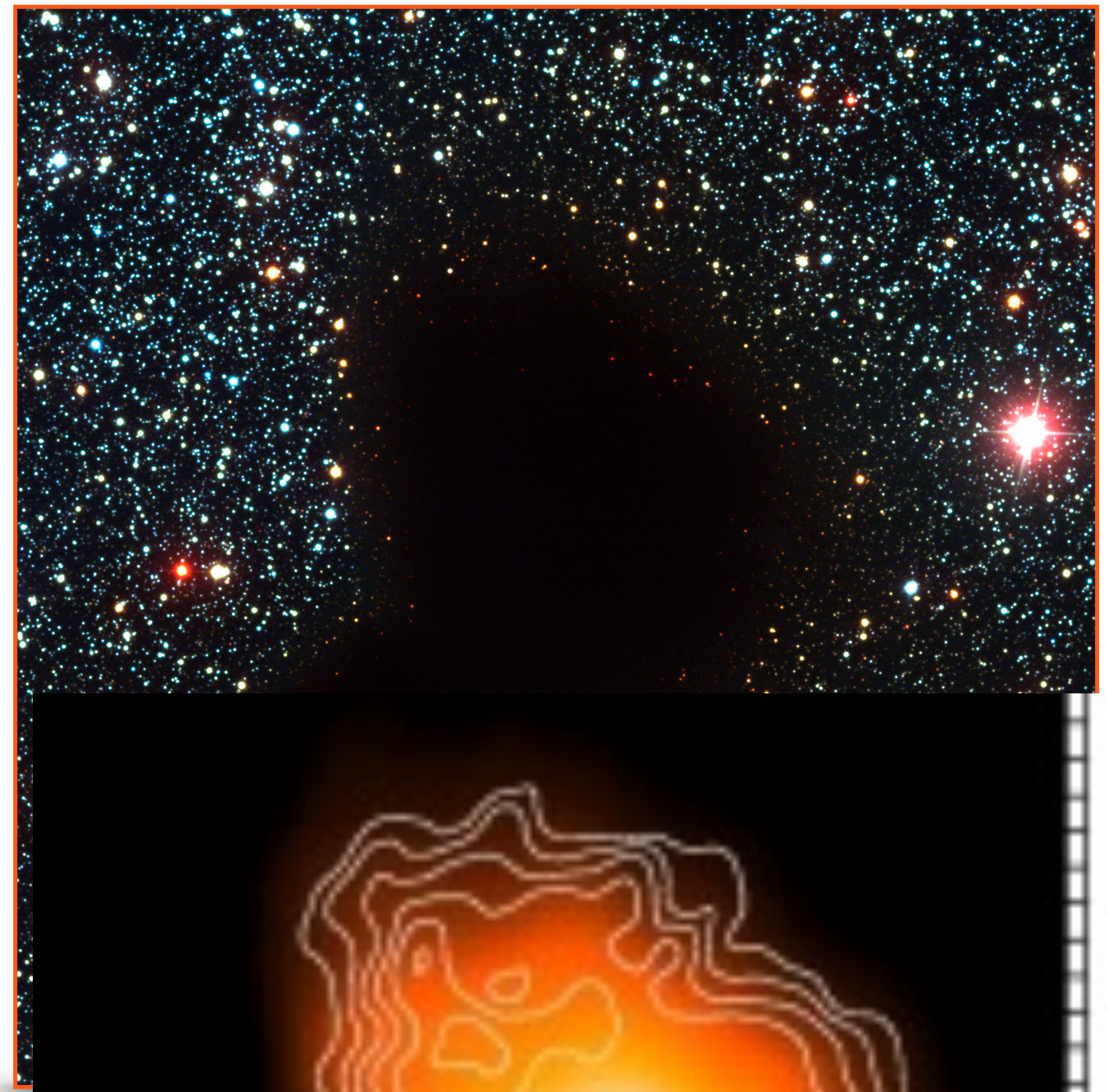
FAR-INFRARED/SUBMM



THE INTERSTELLAR MEDIUM: DUST

Image Credit: ESO

OPTICAL



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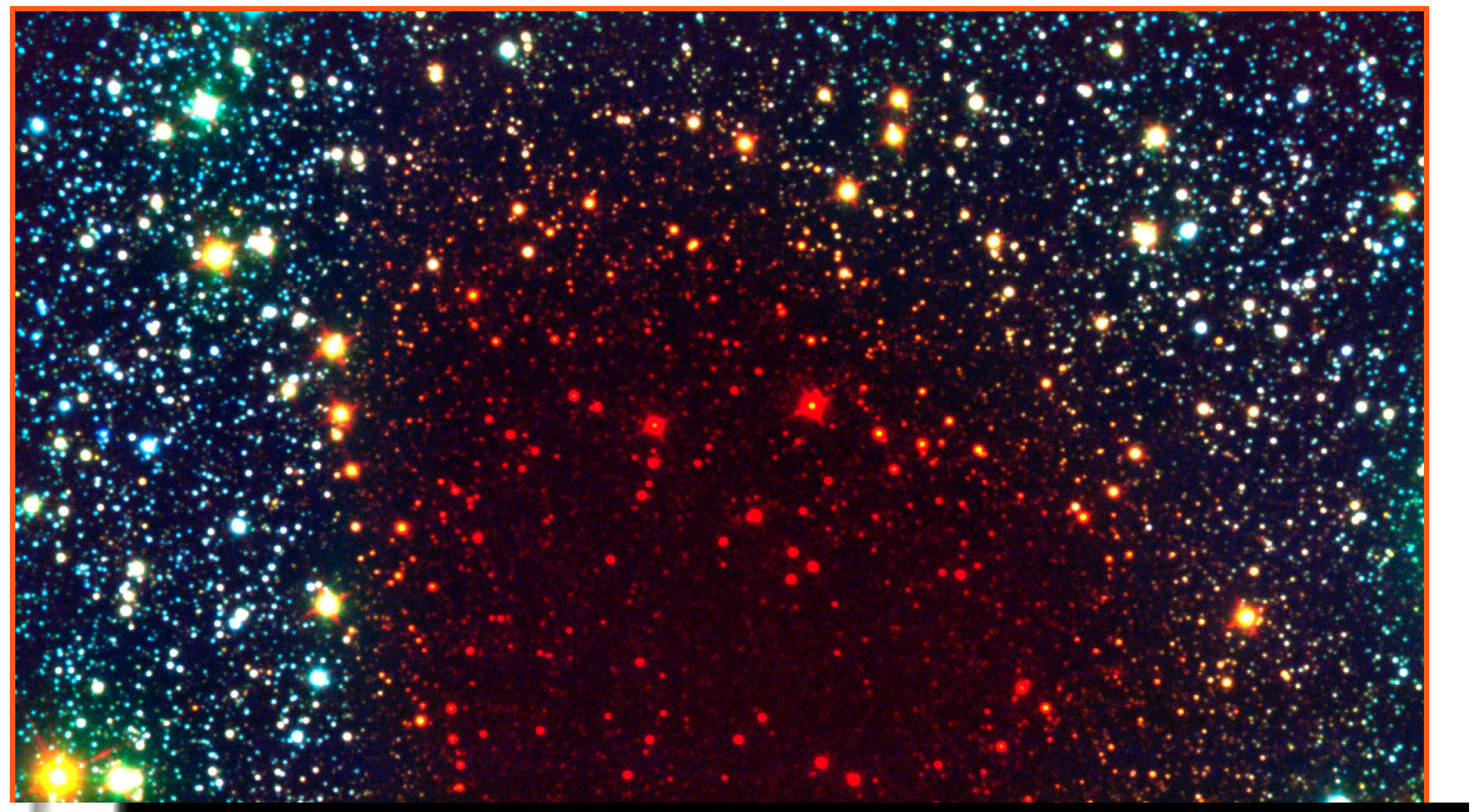

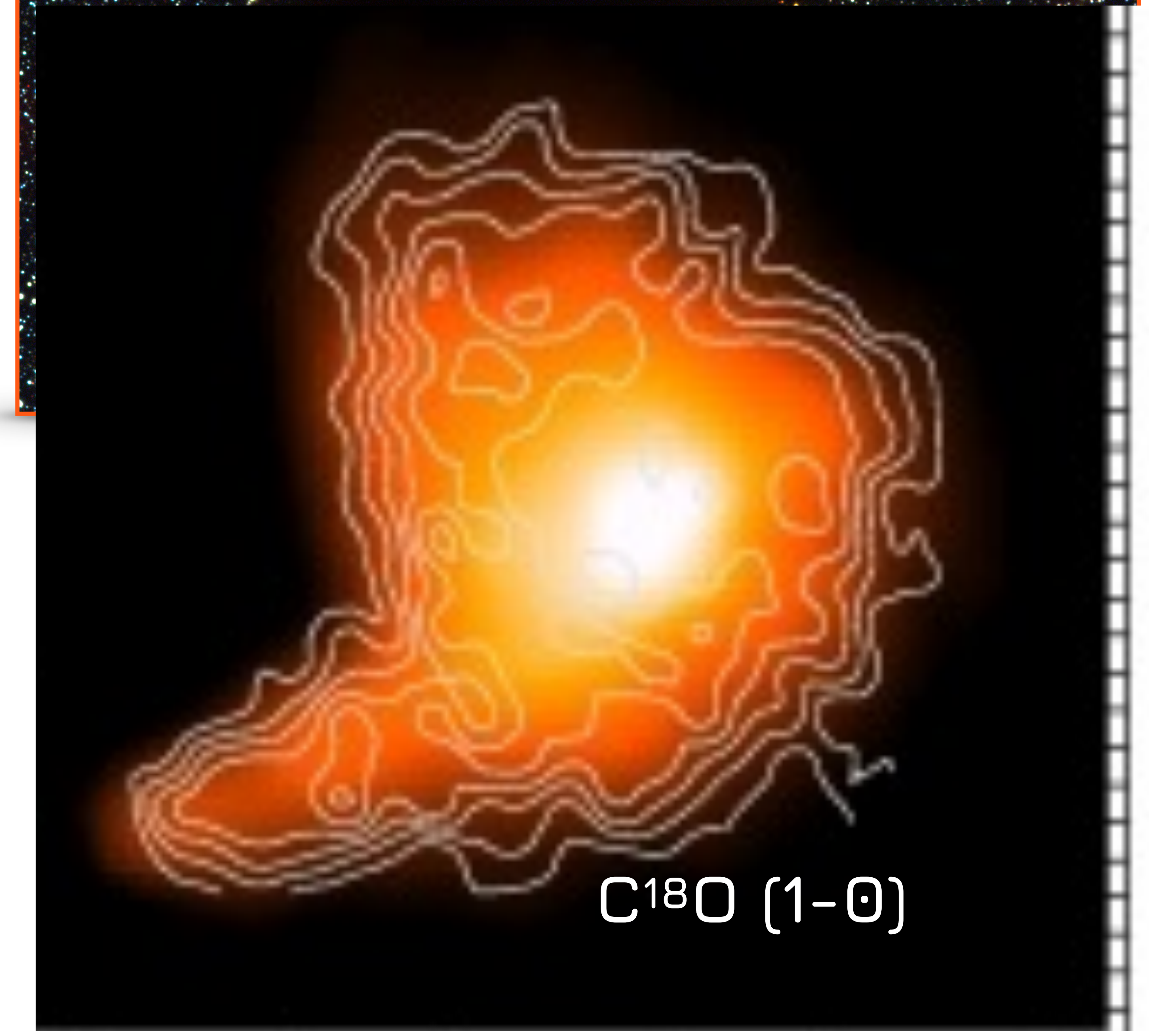

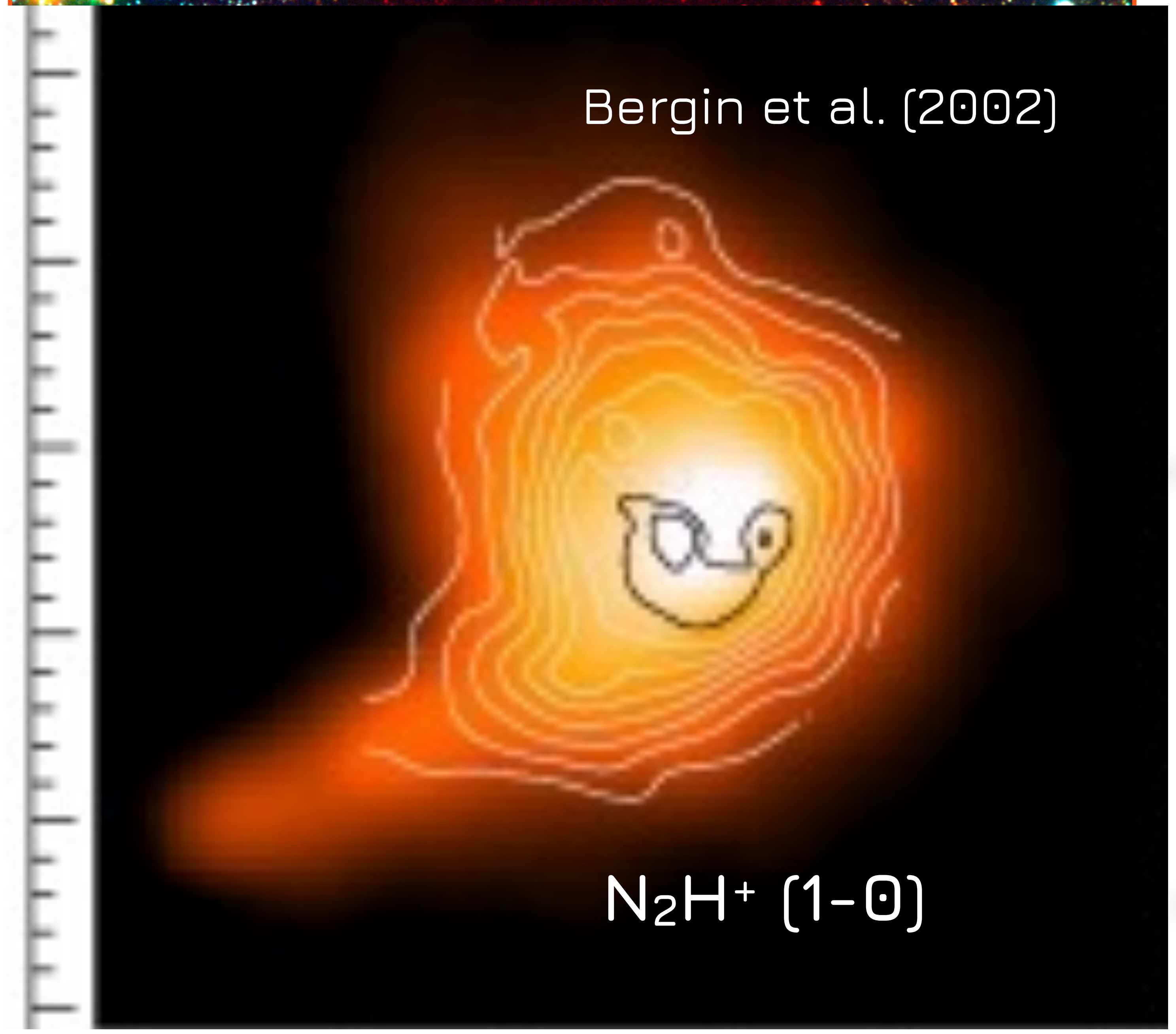

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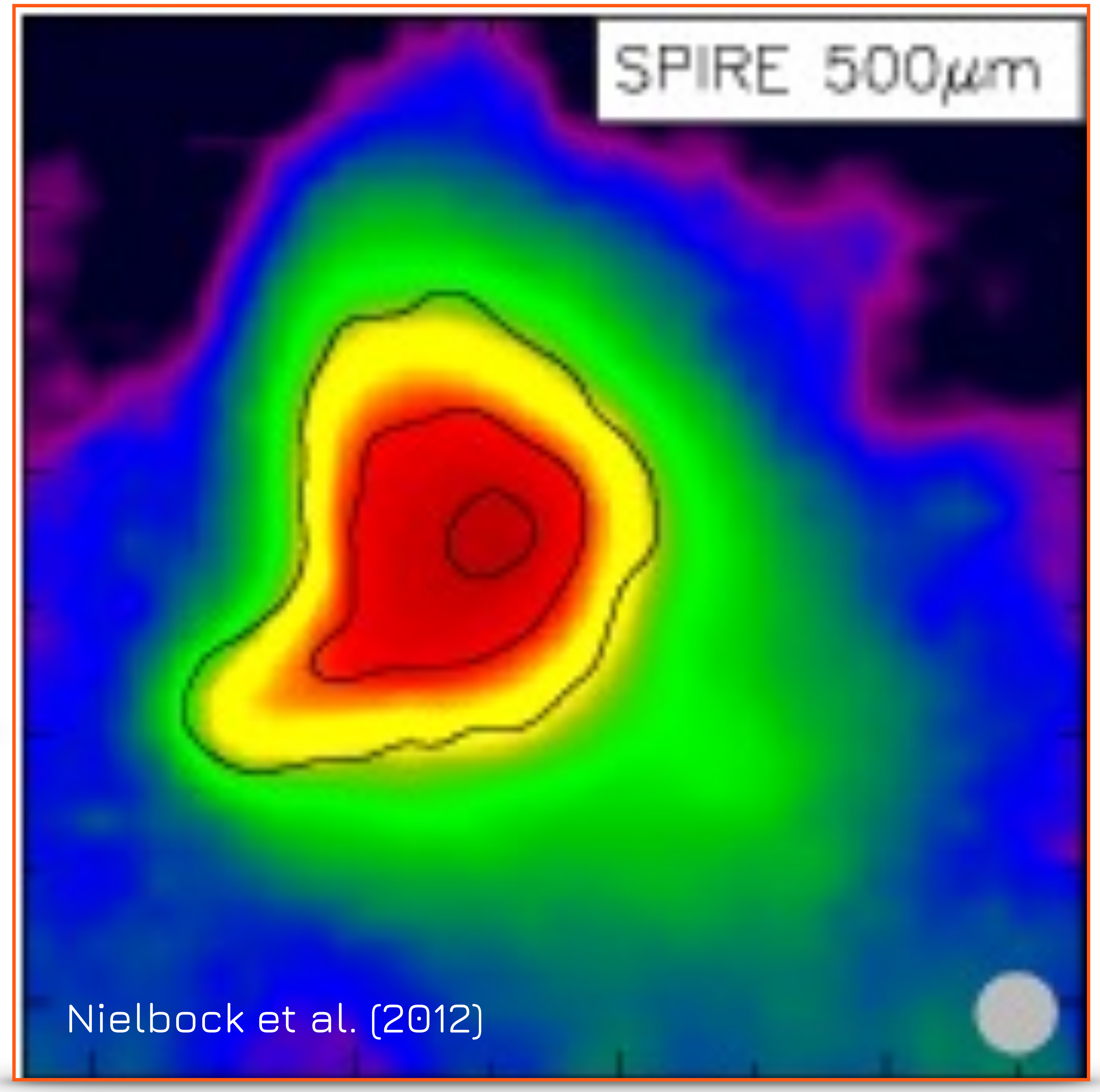
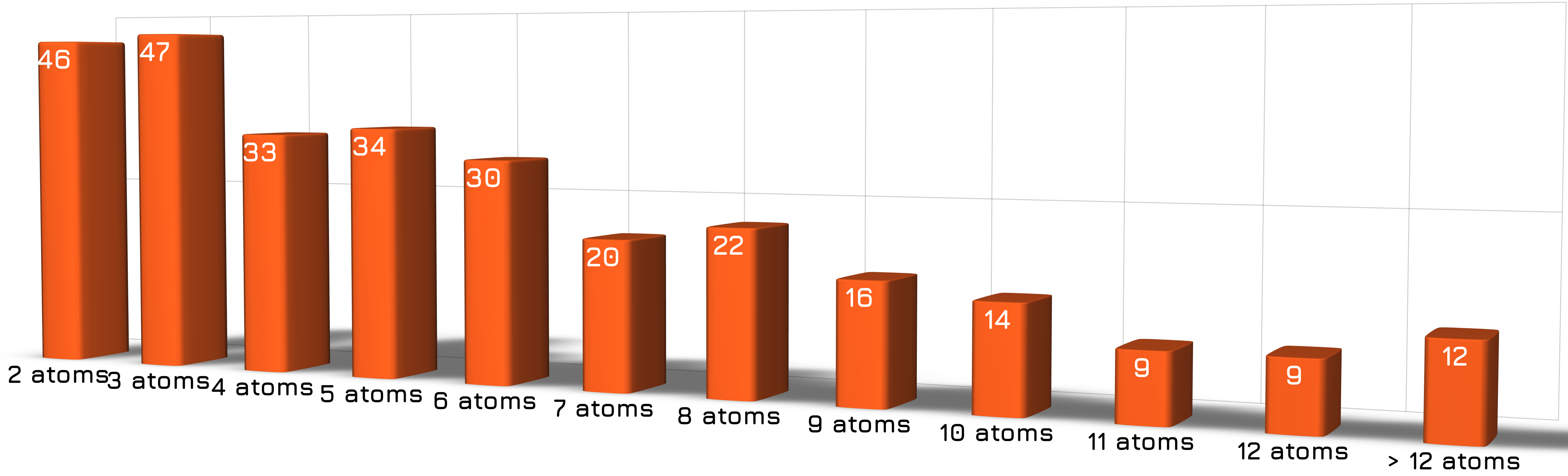


MOLECULES IN SPACE



From Cologne Database for Molecular Spectroscopy (CDMS):
https://cdms.astro.uni-koeln.de

About 300 molecules have been detected in the ISM including > 60 complex (6 or more atoms)

➡ First interstellar Complex Organic Molecule (iCOM)* detected in the interstellar medium: Methanol (CH_3OH) in 1970

* iCOMs are carbon-based compounds with > 6 atoms (Herbst & van Dishoeck 2009)

THE ROLE OF DUST IN THE ISM

Extinction $m_\lambda = M_\lambda + 5\log\left(\frac{r}{10\,\mathrm{pc}}\right) + A_\lambda$

Reddening $(m_{\lambda_1} - m_{\lambda_2}) = (M_{\lambda_1} - M_{\lambda_2}) + (A_{\lambda_1} - A_{\lambda_2})$

$$E_{12} = A_{\lambda_1} - A_{\lambda_2}$$

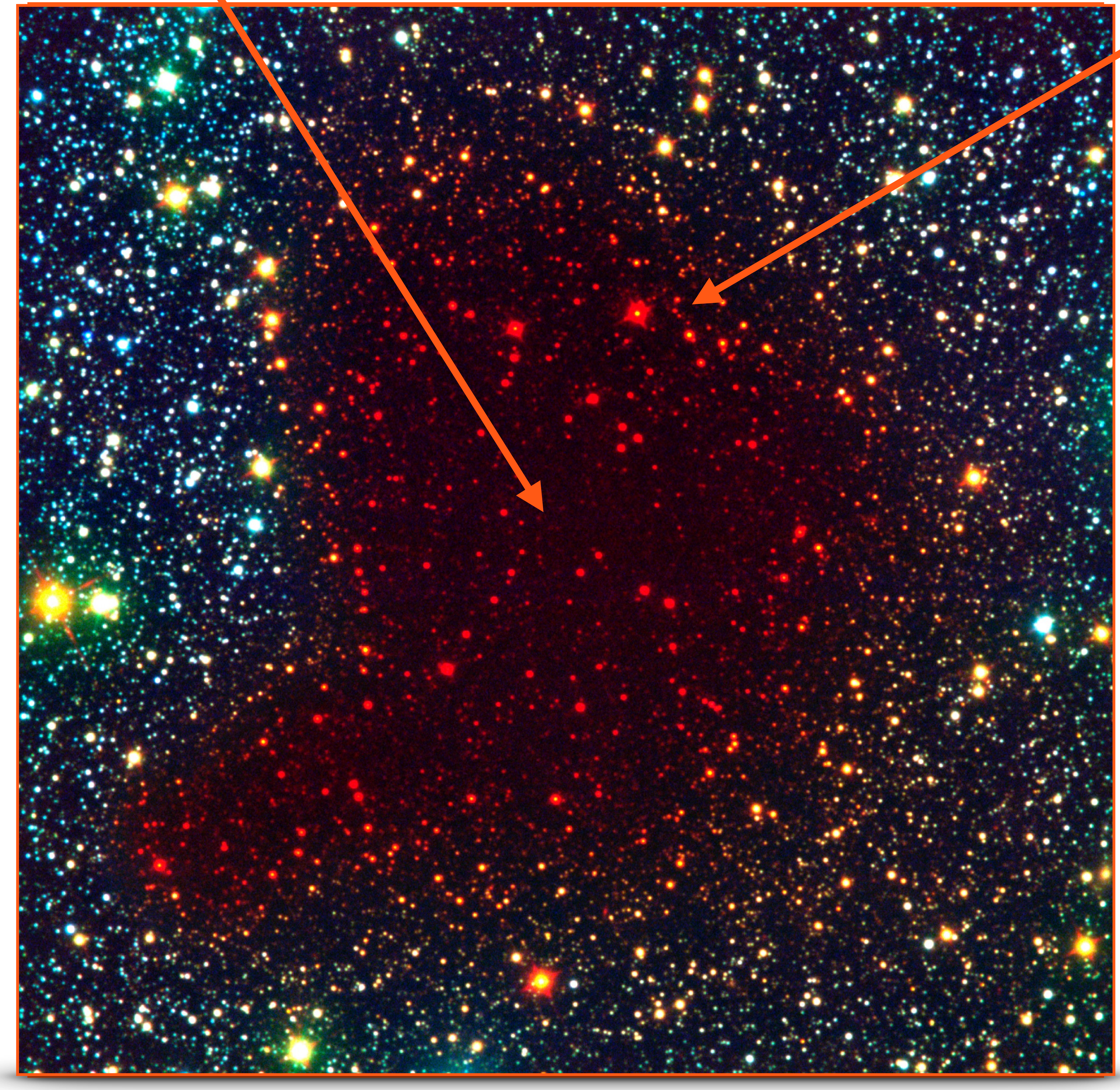


Image Credit: ESO

➡ Extinction and color excess are proportional to the column density of dust grains along the line of sight

$$A_V/N_H = 5.3 \times 10^{-22}\,\mathrm{mag\,cm^2}$$

➡ Reflect light from nearby stars (Reflection Nebula)

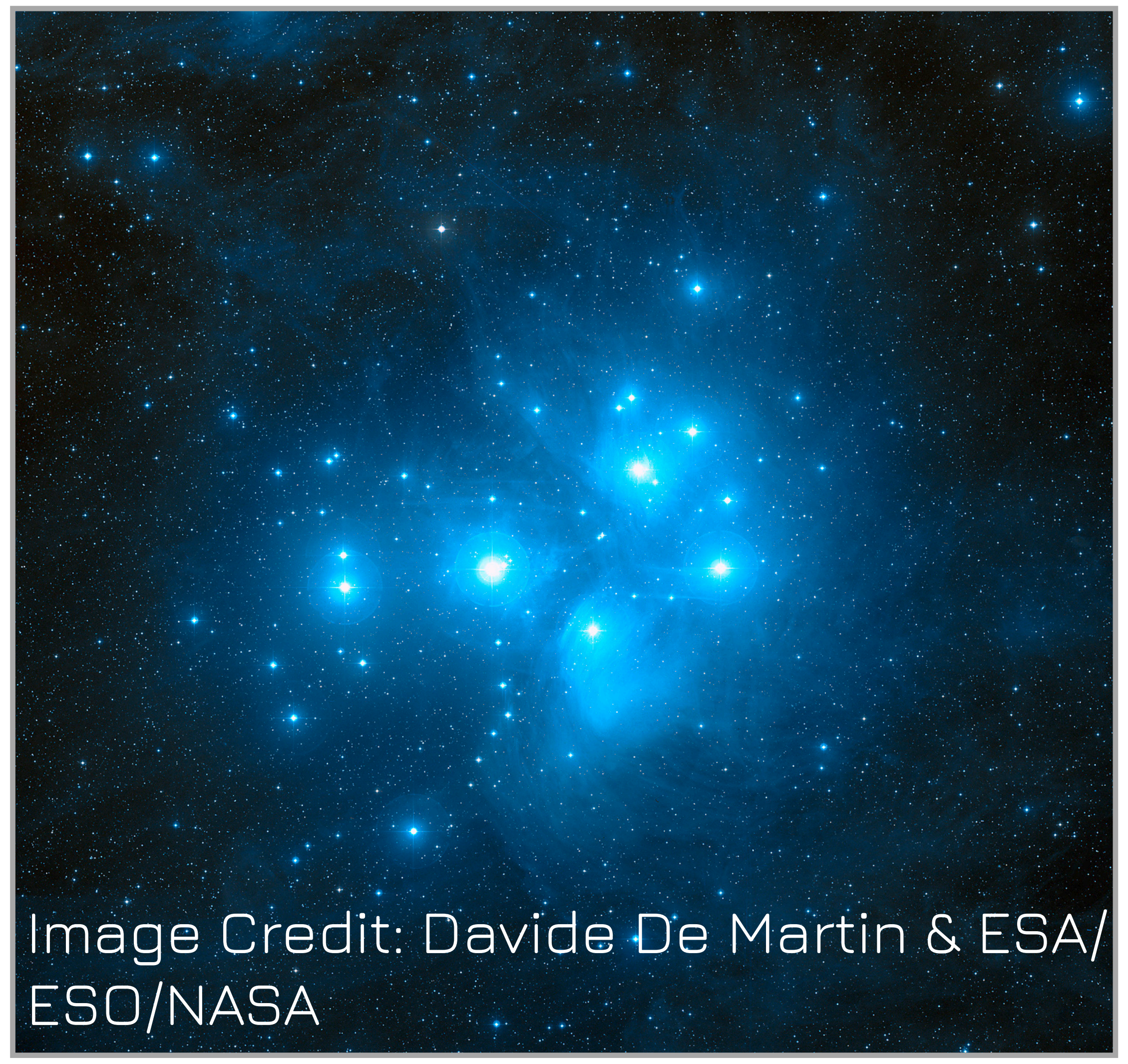
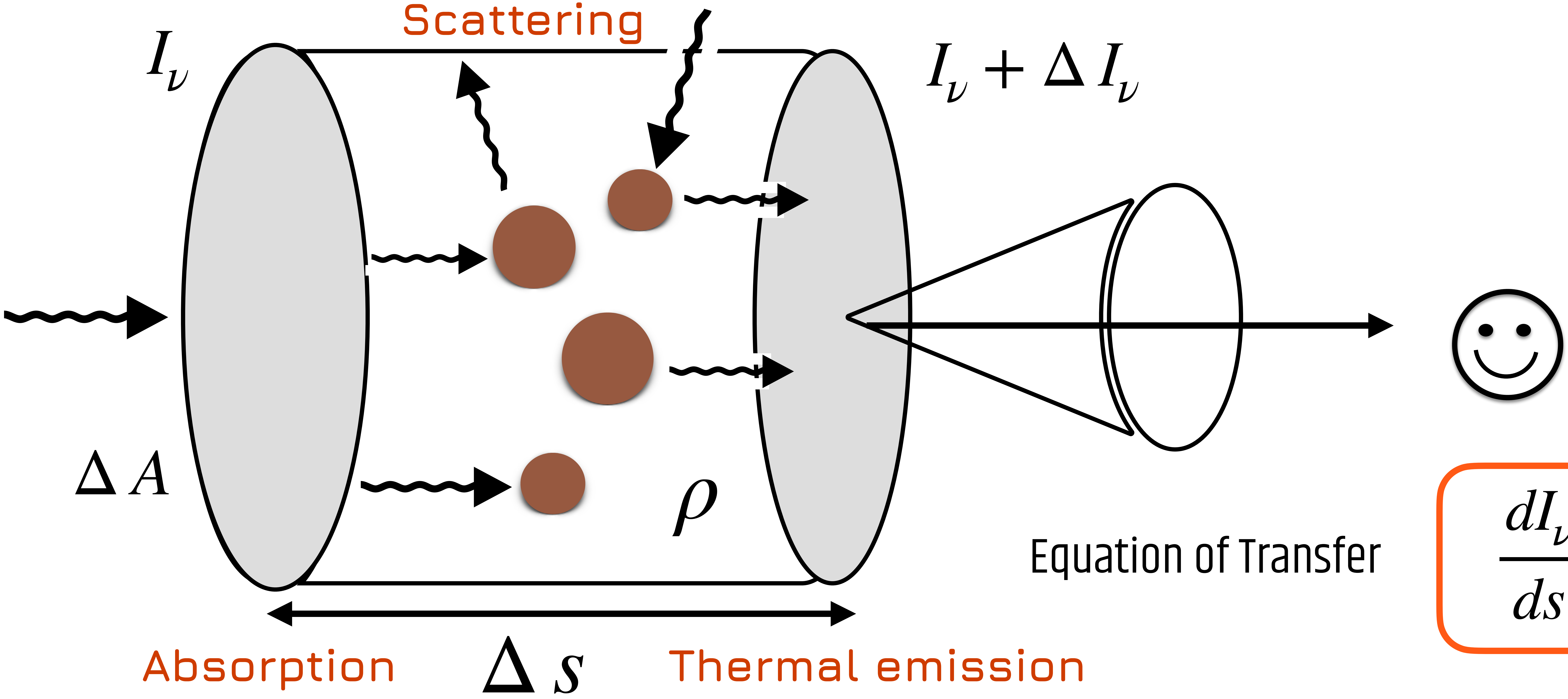


Image Credit: Davide De Martin & ESA/ESO/NASA

THE ROLE OF DUST IN THE ISM



Equation of Transfer

$$\frac{dI_\nu}{ds} = -\rho\,\kappa_\nu I_\nu + j_\nu$$

Optical depth

$$\rho\,\kappa_\nu\,\Delta s = \Delta\,\tau_\nu$$

Optically-thick medium: $\Delta\,\tau_\nu >> 1$

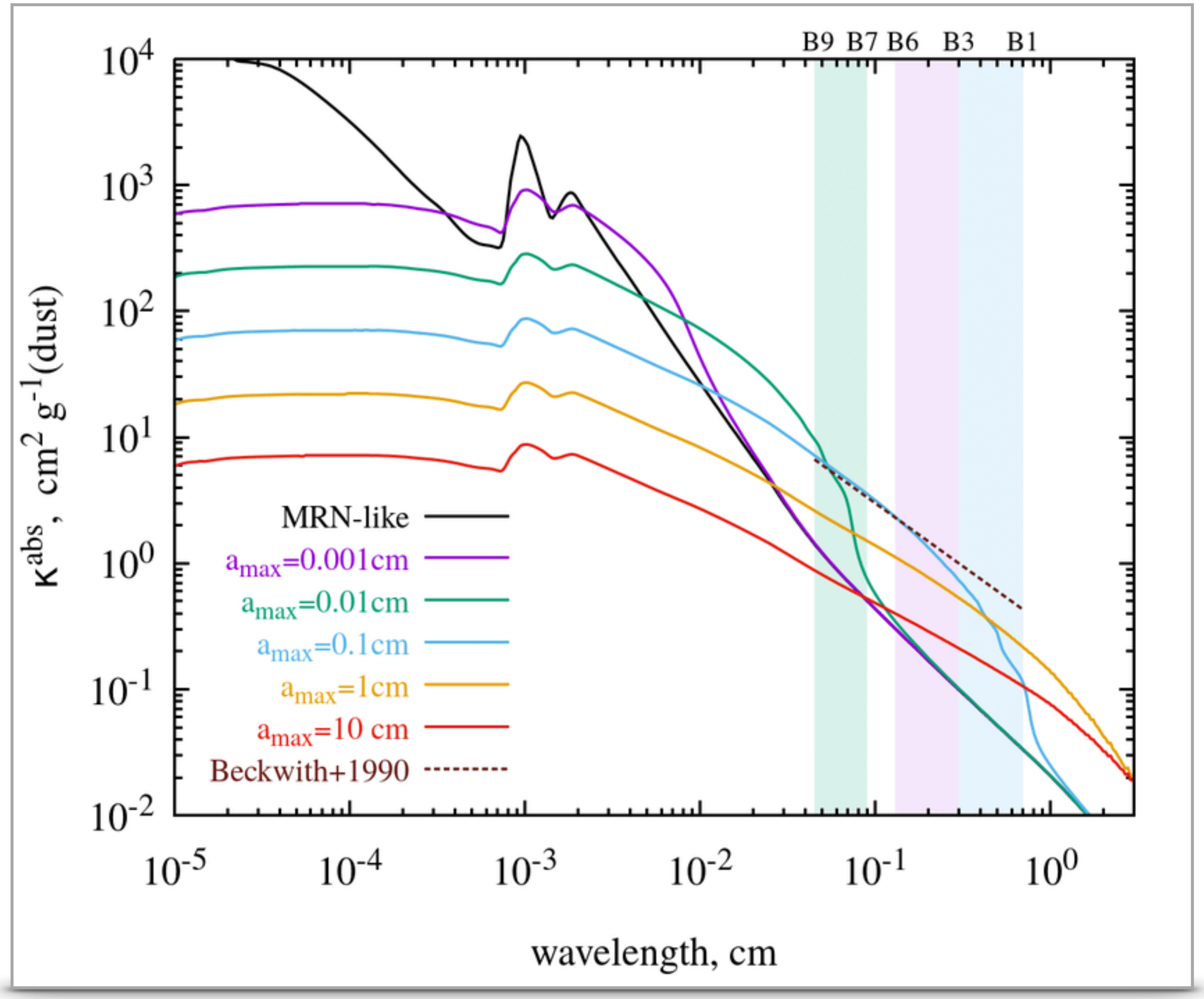
Optically-thin medium: $\Delta\,\tau_\nu << 1$

THE ROLE OF DUST IN THE ISM

➡ Polarization: starlight is, in general, partially linearly polarized by a few per cent (proportional to the amount of extinction)

➡ Dust absorption coefficient (opacity): $\kappa_\nu \propto \nu^\beta$ with dust emissivity index $\beta \sim 1 - 2$ (~1.6 for the diffuse ISM) but it can be < 1 in the envelopes of Young Stellar Objects (YSOs) and in Protoplanetary disks

Pavlyuchenkov et al. (2019)



Tomorrow's Lectures
Anaëlle Maury, Carlos Carrasco-González & François Ménard

Opacity:

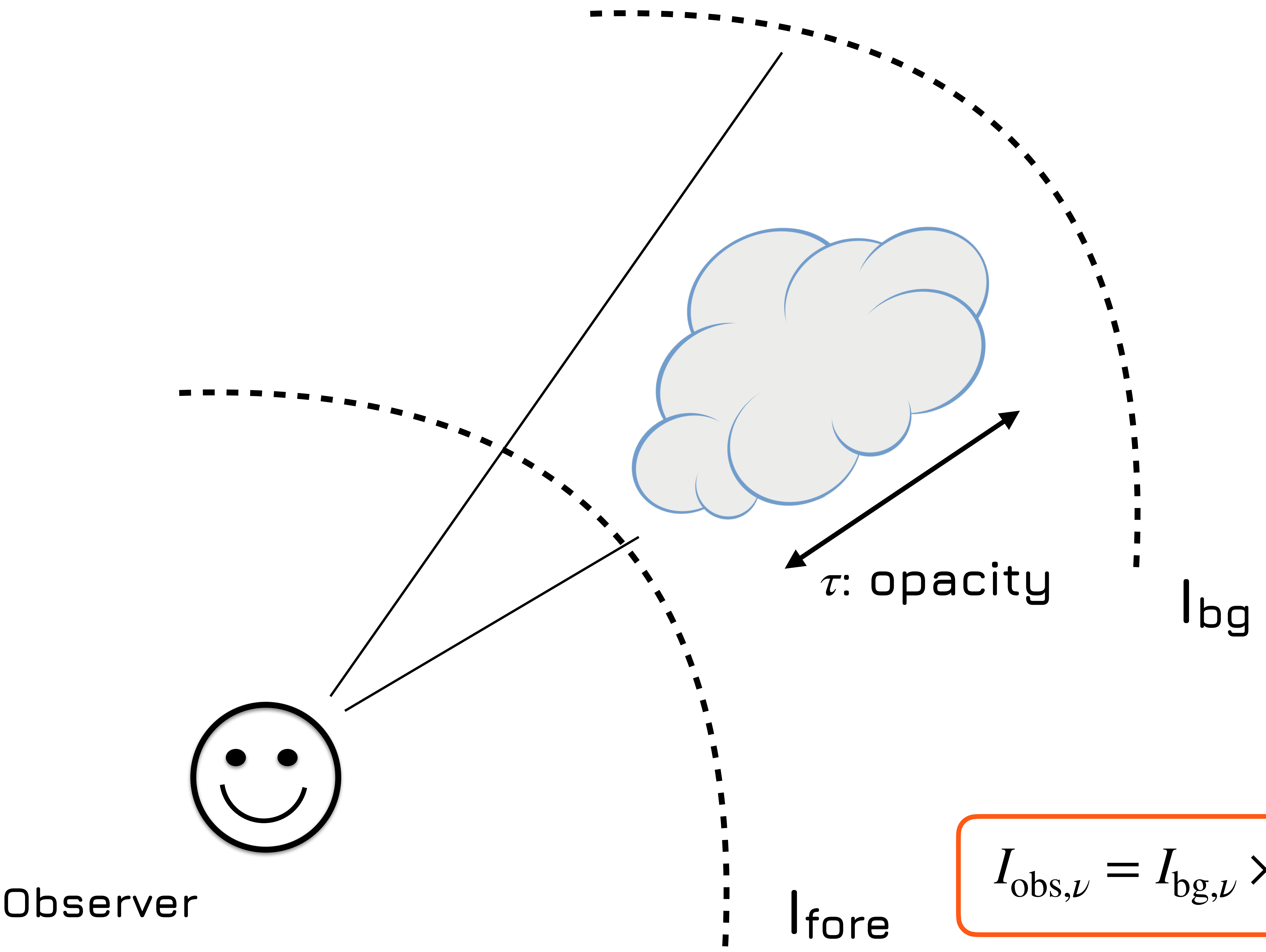
Measurement of the dust absorption cross sections.

Depends on the frequency and physical properties of dust grains (composition, mass and size)

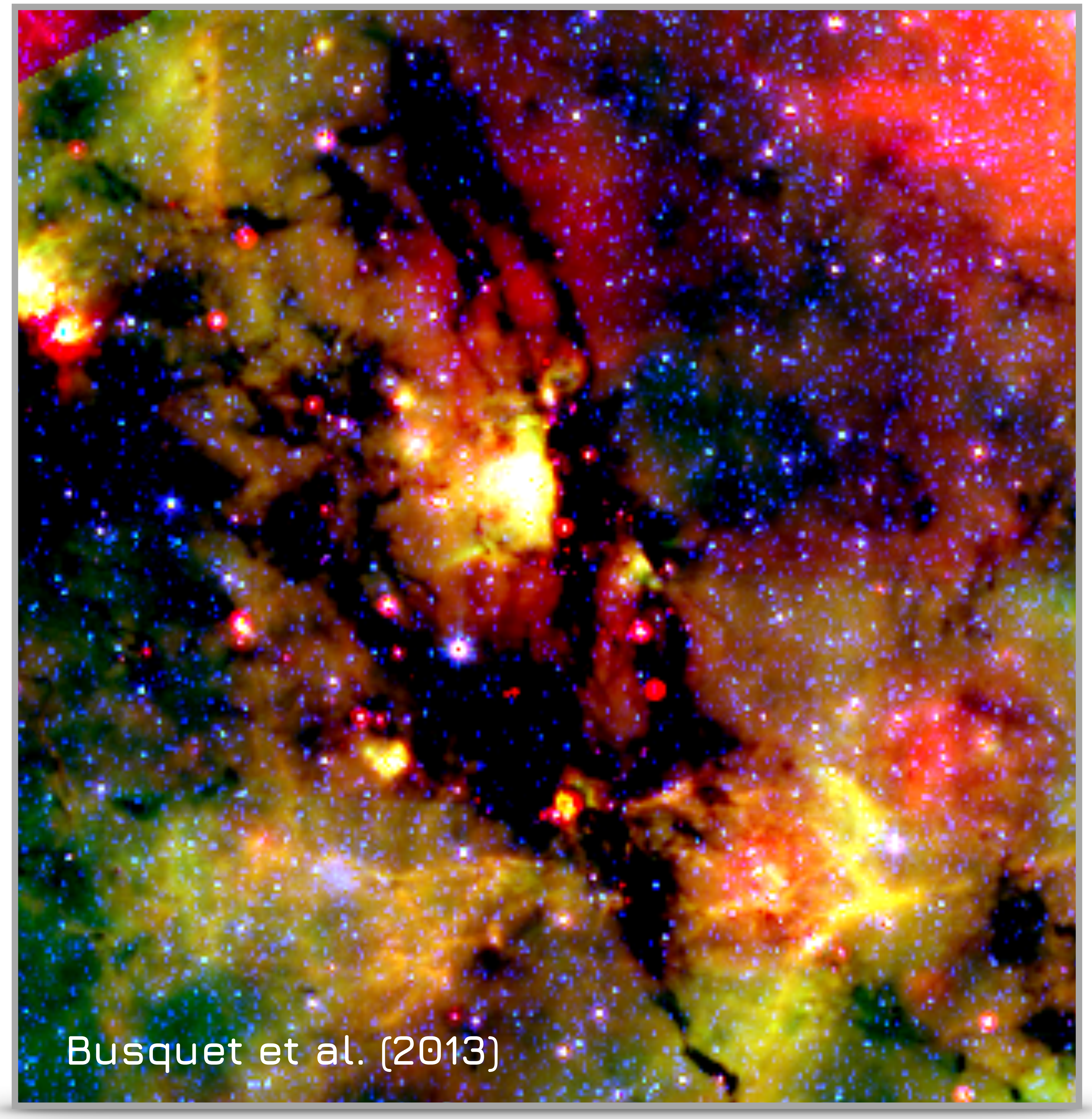
$$\kappa_\nu = 10\left(\frac{\nu}{10^{12}\,\mathrm{Hz}}\right)^\beta \mathrm{cm^2\,g^{-1}} \text{ with } \beta = 1$$

Beckwith et al. (1990)

THE ROLE OF DUST IN THE ISM



IRDC G14.225-0.506: Spitzer composite image



$$I_{obs,\nu} = I_{bg,\nu} \times exp(-\tau_\nu) + I_{fore,\nu}$$

$$\tau_\nu = N_{H_2} \kappa_\nu$$

THE ROLE OF DUST IN THE ISM

➡ Thermal emission: Energy from starlight absorbed by dust heats the grains and is then re-emitted thermally at the temperature of dust (continuum emission). Emitting dust is described as a blackbody x opacity term (modified blackbody or grey-body)

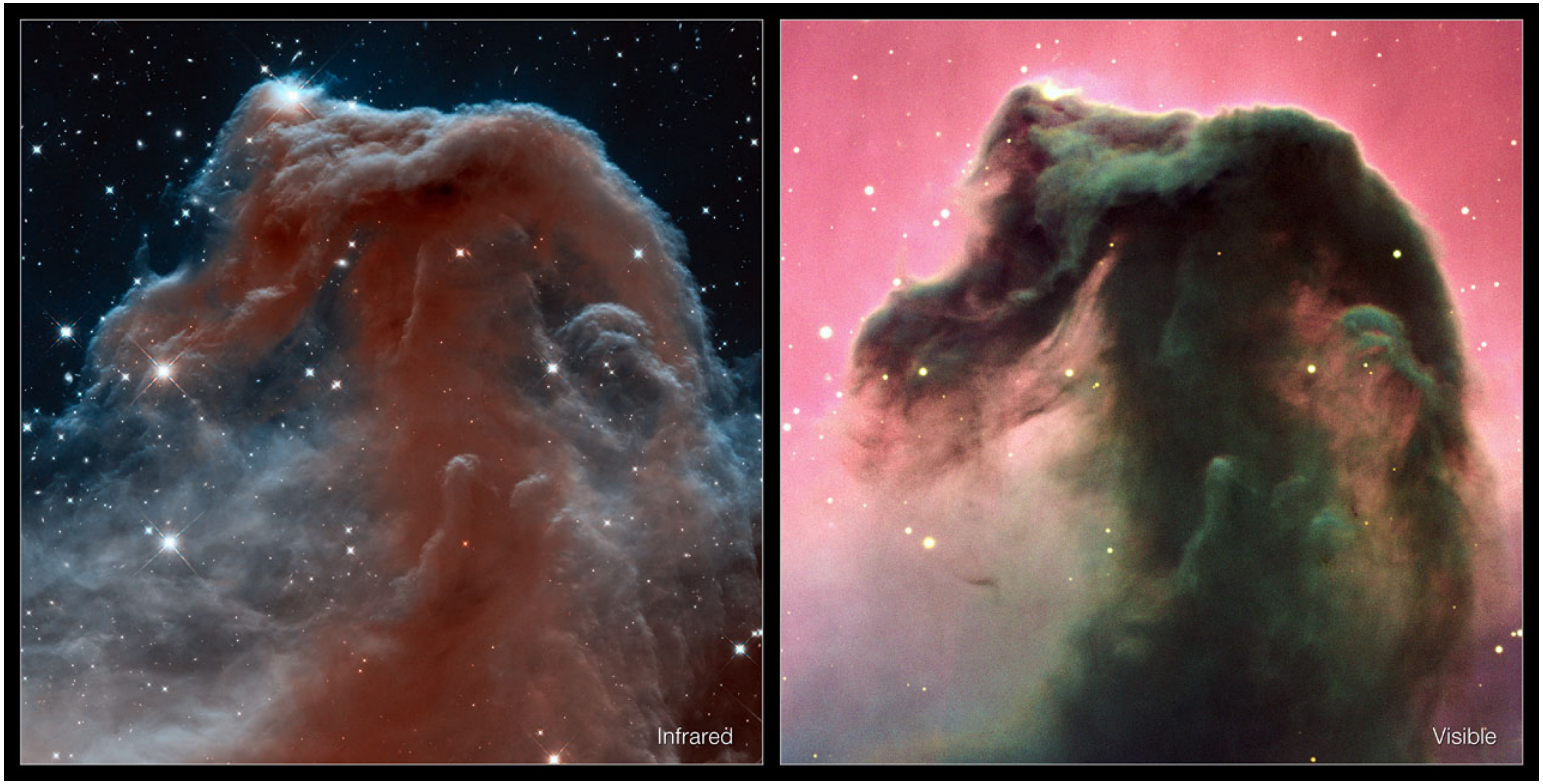


Image Credit: NASA, ESA, and the Hubble Heritage Team (AURA/STScI); ESO

$$I_\nu = B_\nu(T)(1 - e^{-\tau_\nu})$$

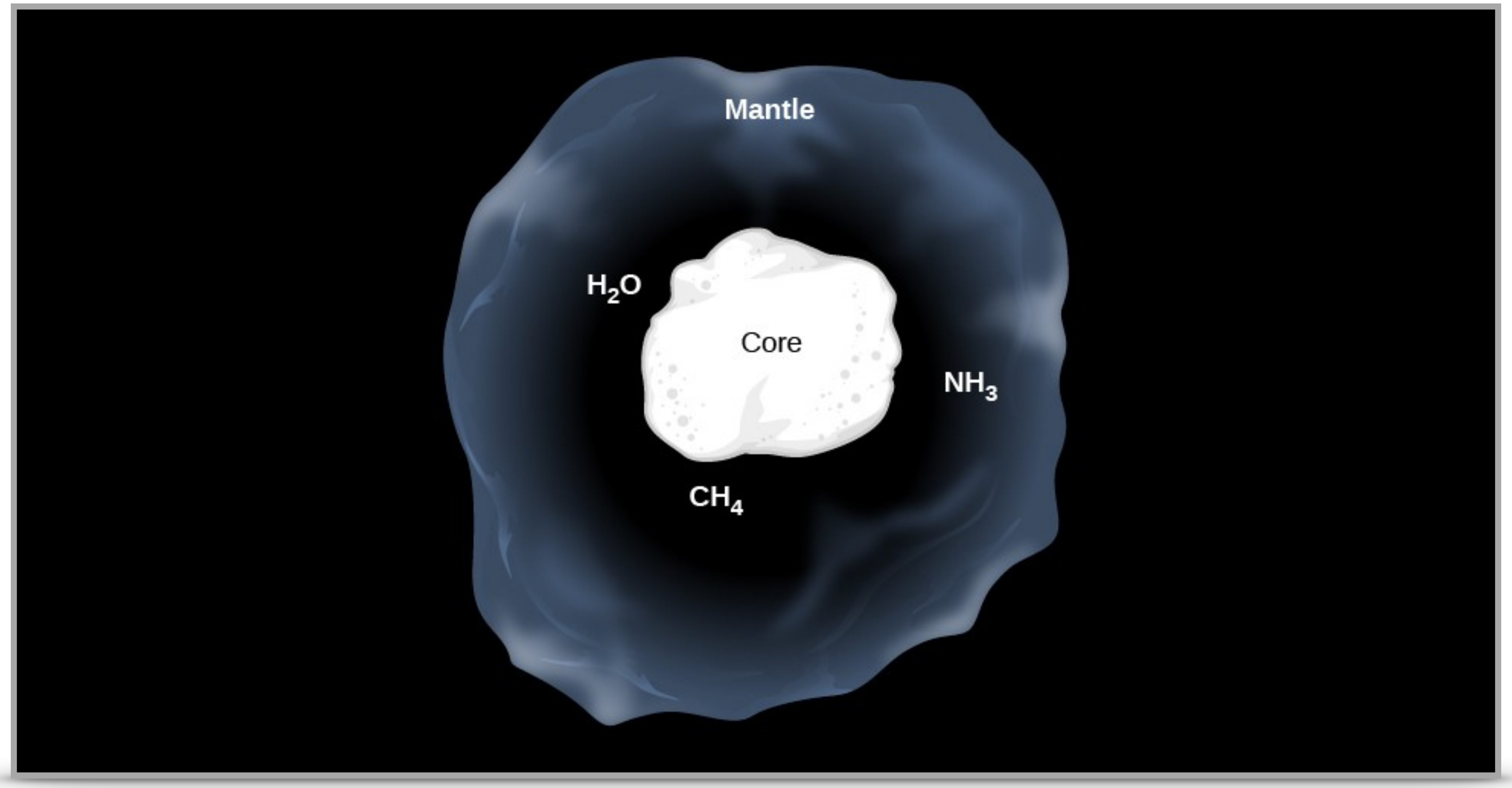
$$I_\nu \approx B_\nu(T)\,\tau_\nu$$

Planck's law:

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT} - 1}$$

THE ROLE OF DUST IN THE ISM

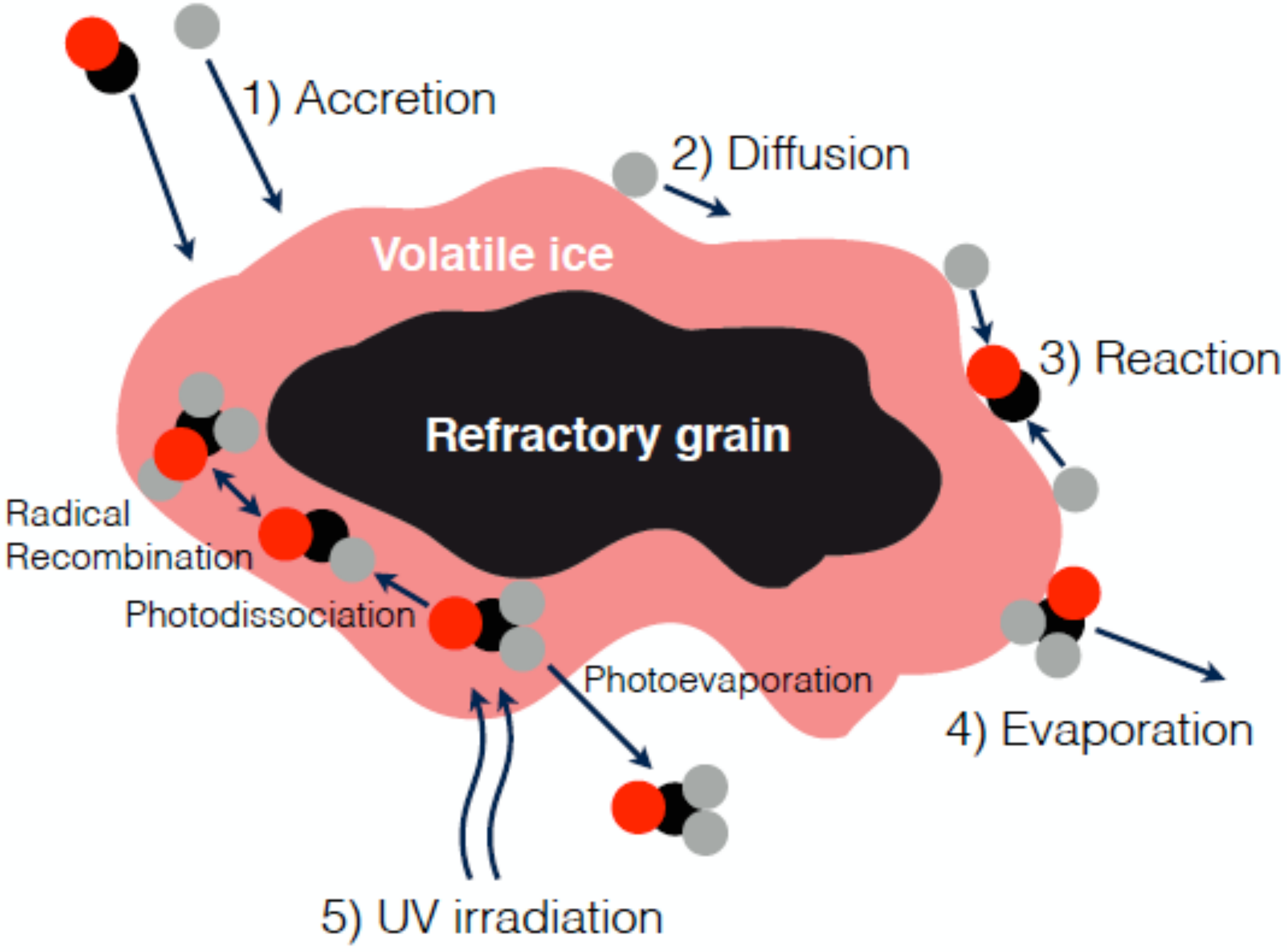
➡ Dust plays a crucial role in cooling down the interstellar material and is at the center of molecule formation process such as H_2 (grain surface chemistry) and in the preservation of molecules once they are formed (prevents the destruction from UV radiation)



Dominant ice species:

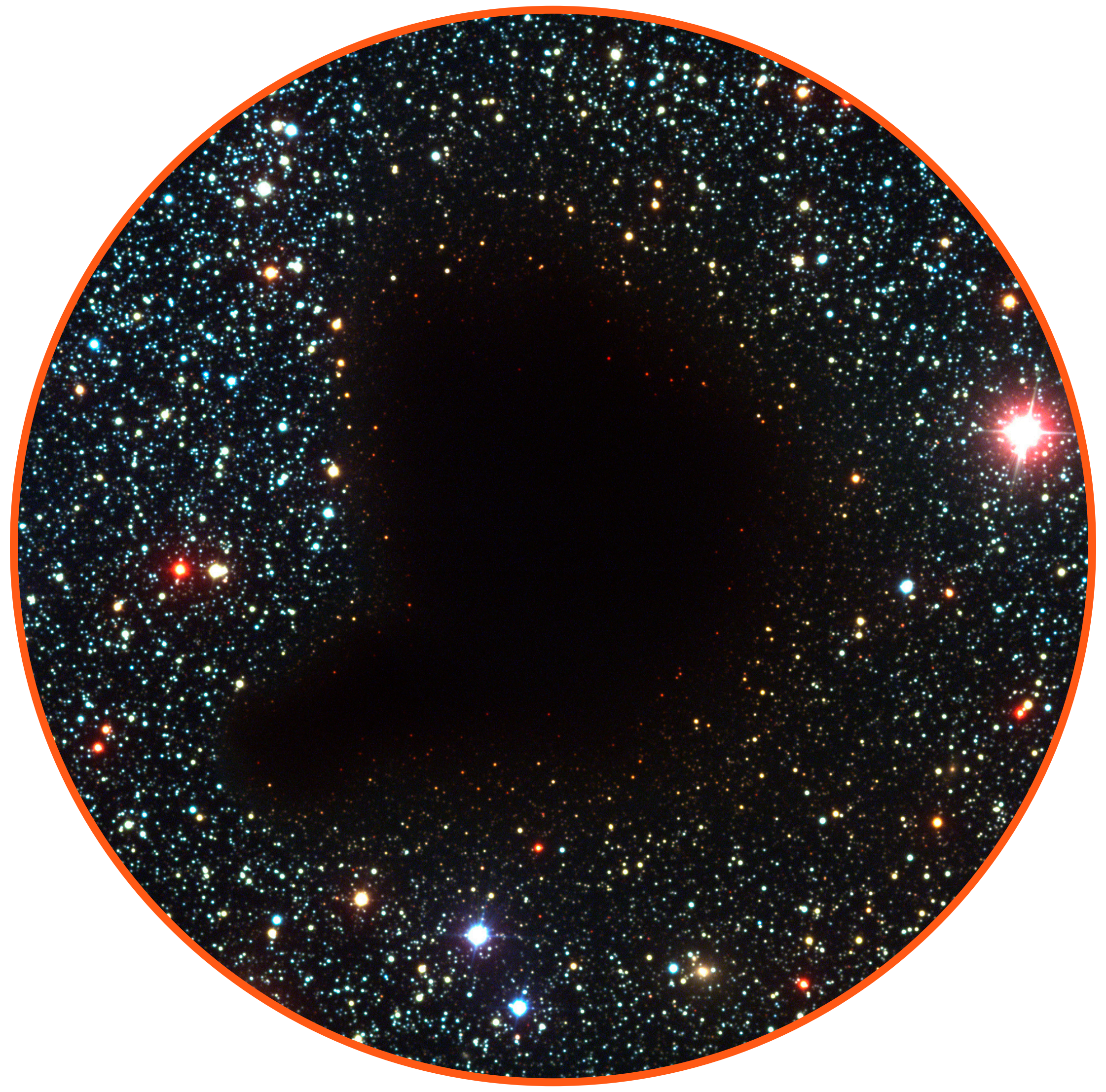
H_2O, CO, CO_2, CH_4, NH_3 and CH_3OH

Wednesday Lecture by Albert Rimola
“Chemistry on dust surfaces: H_2 formation and molecular diversity”



OUTLINE

THE INTERSTELLAR MEDIUM

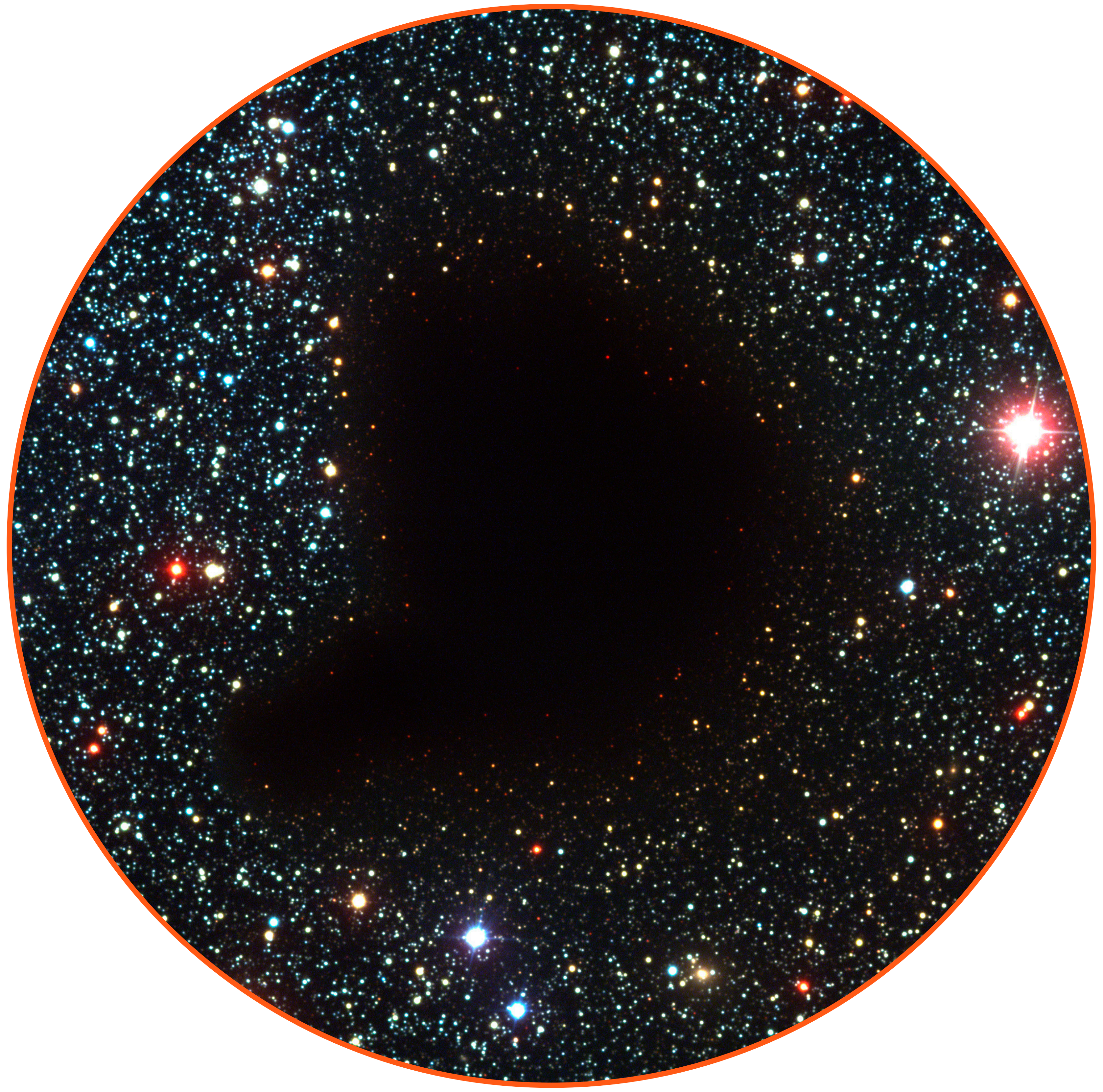


MOLECULAR CLOUDS: THE STELLAR NURSERIES

CLOUD FRAGMENTATION AND CLUSTER FORMATION

OUTLINE

THE INTERSTELLAR MEDIUM



MOLECULAR CLOUDS: THE STELLAR NURSERIES

CLOUD FRAGMENTATION AND CLUSTER FORMATION

THE STAR FORMATION CICLE

- **GMC:** 10^5-10^6 $M_\odot$, T~10 K, $n(H_2)$~10^2 cm^{-3}
- **Pre-stellar cores** [0.01-0.1 pc] onset of future star formation
- **Protostar** (0.1-1 $M_\odot$) **+ disk system:** powerful jets + a natal disk (0.01-0.1 $M_\odot$) + large scale envelope [0.1 pc in size]
- **Protoplanetary disk:** envelope is dissipated. A young star (or stars) and a disk (1-10% $M_\star$) remain
- **Main sequence phase:** cessation of accretion on the star and dispersal of the molecular gas

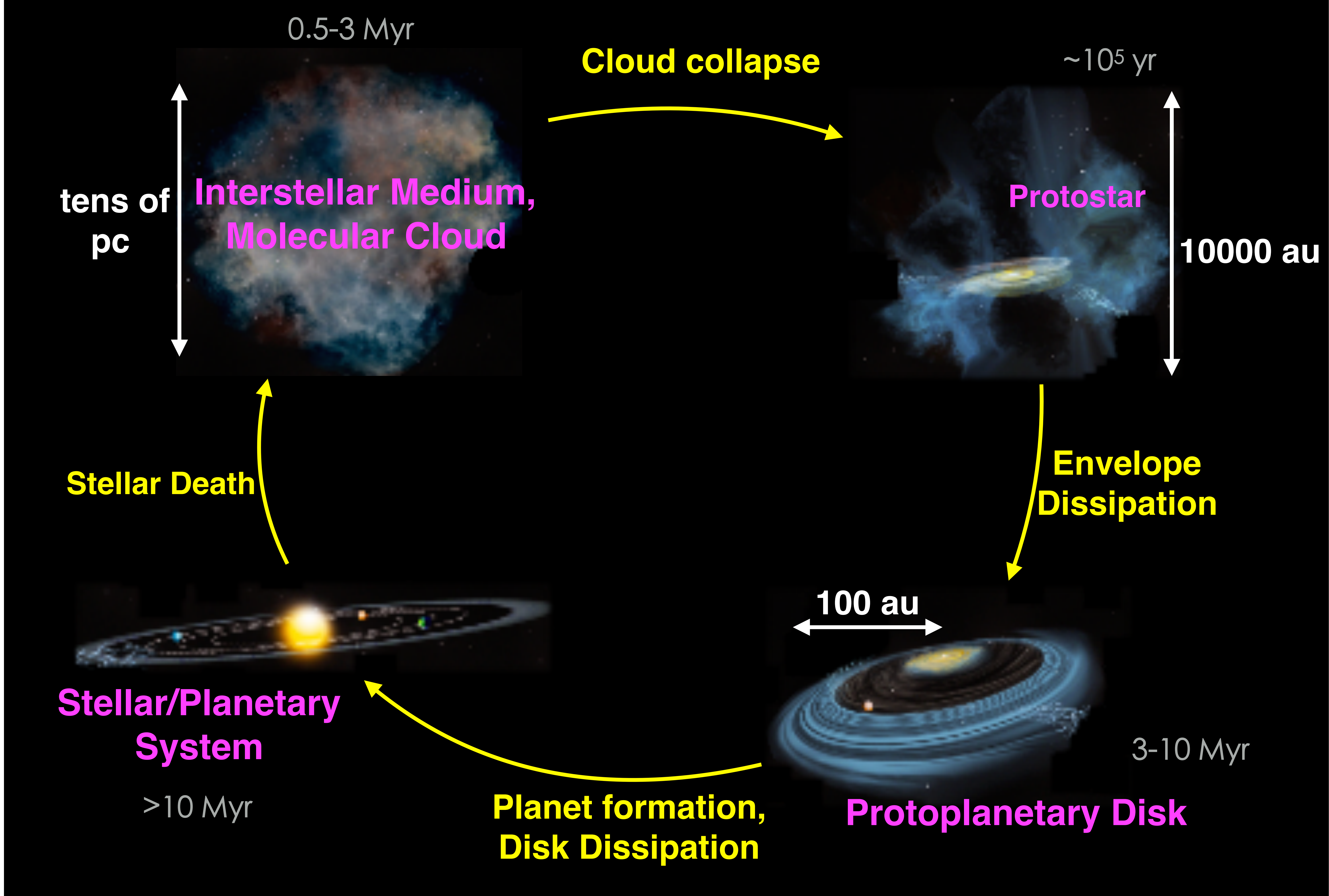
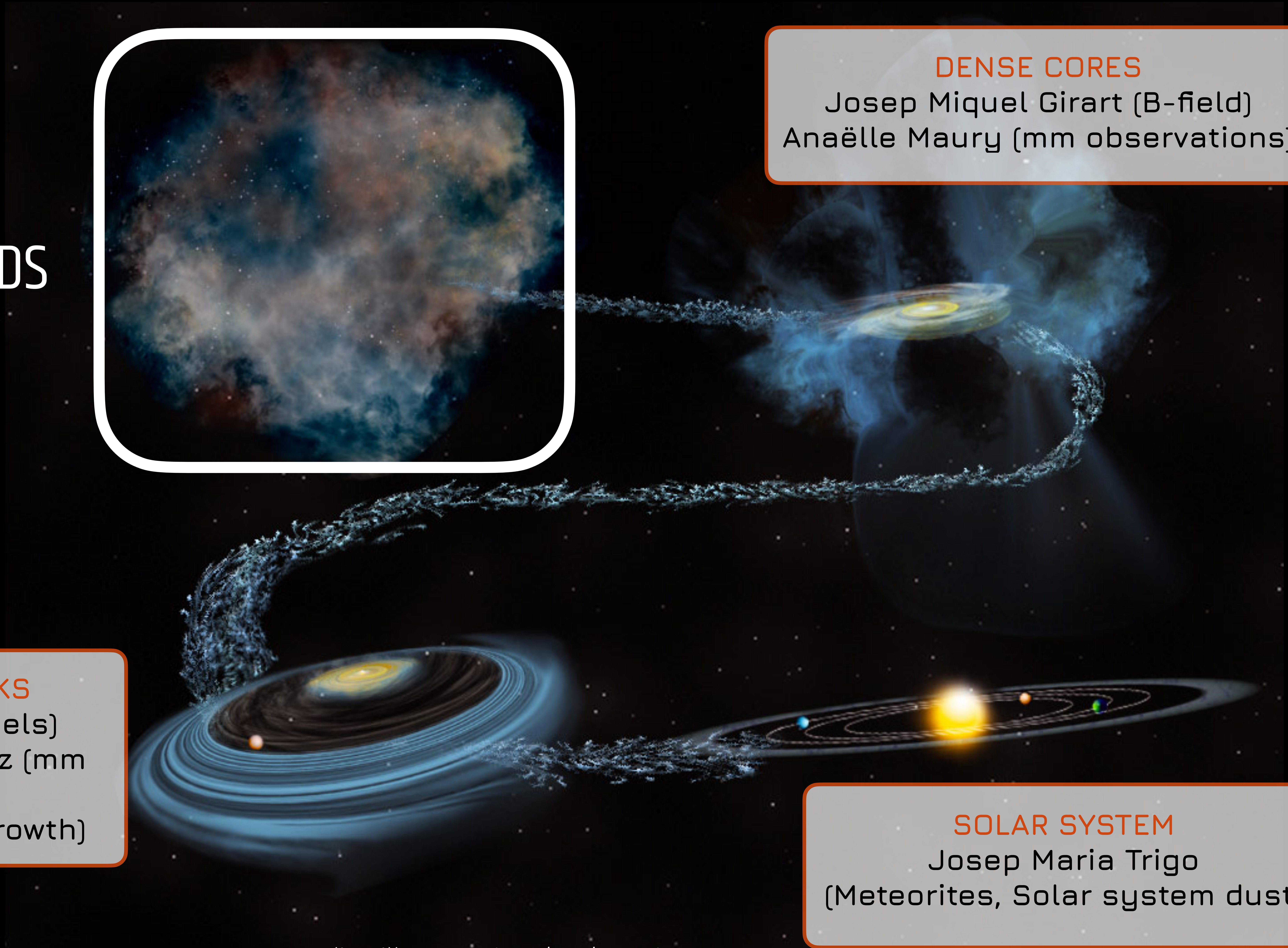


Image Credit: L. I. Cleeves, PhD Thesis (adapted from Bill Saxton (NSF/AUI/NRAO))

MOLECULAR CLOUDS



DENSE CORES
Josep Miquel Girart (B-field)
Anaëlle Maury (mm observations)

PROTOPLANETARY DISKS
Mayra Osorio (disk models)
Carlos Carrasco-González (mm observations)
François Menard (grain growth)

SOLAR SYSTEM
Josep Maria Trigo
(Meteorites, Solar system dust)

Image Credit: Bill Saxton (NSF/AUI/NRAO)

THE STELLAR NURSERIES

Molecular clouds are the densest phase of the ISM.

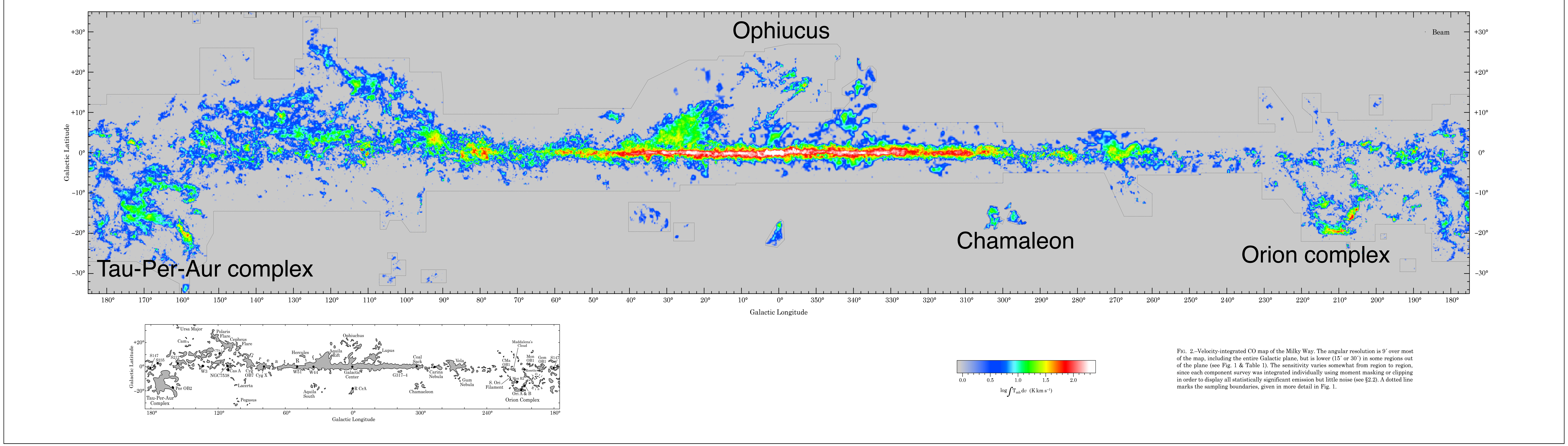
★FUV photons are absorbed at the surface in a region of Av~1: PDR

★H_2 can survive after it has formed on dust grains thanks to the PDR-shield

★Dust effectively shields the interiors of a dense cloud from the UV radiation, which destroys molecules

★Chemistry is initiated as other molecules form together with H_2

Dame, Hartmann, & Thaddeus (2001)



T_{kin}=10 K, $n(H_2)>10^3$ cm^{-3}, size~50 pc

THE STELLAR NURSERIES

The Physics at High Angular resolution in Nearby GalavieS (PHANGS) ALMA Survey

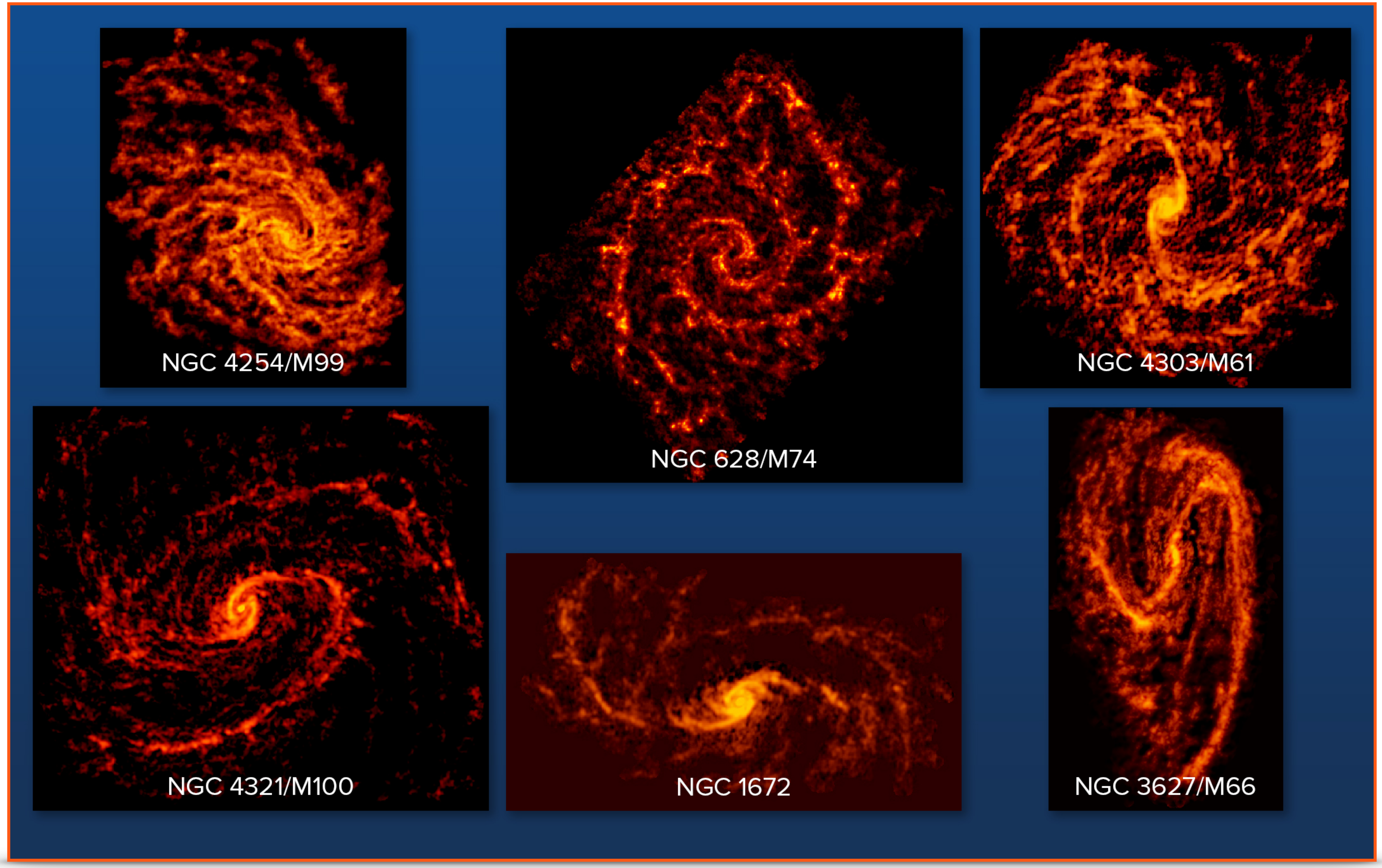


Image Credit: ALMA (ESO/NAOJ/NRAO); NRAO/AUI/NSF, B. Saxton

SETTING THE CHEMICAL TRAJECTORY FOR STAR AND PLANET FORMATION

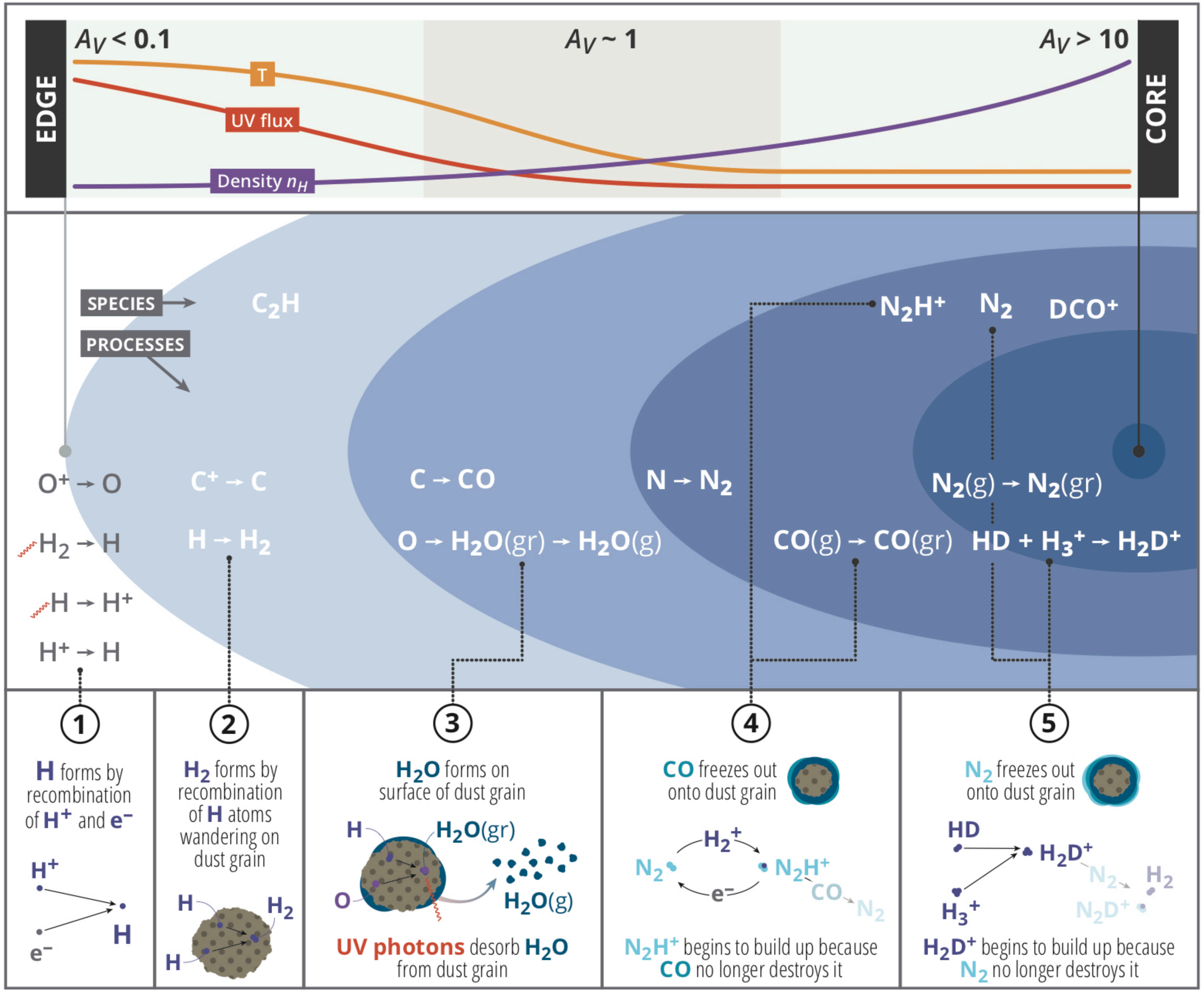


Image Credit: K. Peek (Öberg & Bergin 2021)

- ➡ In Molecular Clouds: major volatile carriers of oxygen, carbon and nitrogen form: H_2O, CO, N_2
- ➡ Formation sites of most abundant volatile organics (CH_4, CH_3OH, NH_3): Building blocks of any organic chemistry

(3) Inner surface layer: C is rapidly converted into CO, effectively locking in most of the volatile carbon budget. Remaining O is incorporated into the much less volatile H_2O.

(4) (5) Deepest molecular cloud region: all molecules except for H_2, H_3^+ rapidly freeze-out onto grains (efficient deuterium fractionation)

SETTING THE CHEMICAL TRAJECTORY FOR STAR AND PLANET FORMATION

➡ Initial icy grain mantles are composed mainly of H_2O and CO_2. Main host of CH_4 and NH_3.

➡ At Low Extinction where temperatures are warmer (T>10 K) and UV radiation is diluted but present.

➡ At High Extinction the gas and dust are cold with UV radiation extinguished. Elevated densities result in a CO freeze-out rate that is too high for H-atoms activated grain-surface reaction: CO containing outer ice mantle.

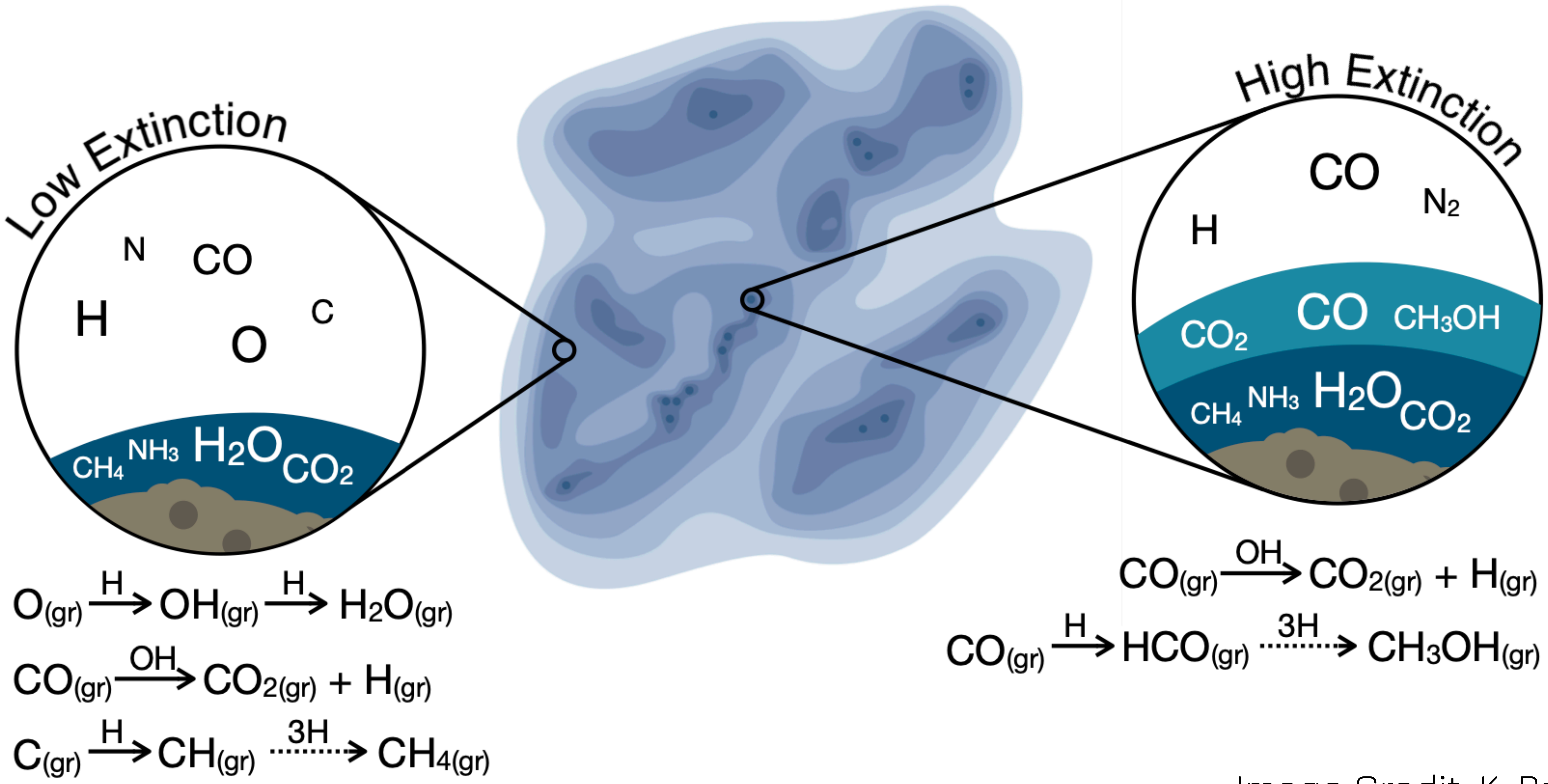


Image Credit: K. Peek (Öberg & Bergin 2021)

PHYSICAL PROPERTIES OF MOLECULAR CLOUDS

➡ Solution of the radiative transfer equation for a medium with optical depth τ_ν and for a source function constituted by the Planck blackbody B_ν at temperature T is:

$$I_\nu = B_\nu(T)(1 - e^{-\tau_\nu}) \quad \text{where} \quad B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/k_BT} - 1}$$

➡ Assuming I_ν being uniform over the solid angle Ω, the corresponding flux is:

$$F_\nu = \Omega(1 - e^{-\tau_\nu})\, B_\nu(T)$$

➡ Empirical behaviour of τ_ν as a function of ν for large interstellar dust grains is modelled as a power law: $\tau_\nu = \left(\frac{\nu}{\nu_0}\right)^\beta$ where the cut-off frequency $\nu_0 = c/\lambda_0$ is such that $\tau_{\nu_0} = 1$

➡ In the limit of $\nu << \nu_0$: $(1 - e^{-\tau_\nu}) = \tau_\nu$ ➡ $I_\nu \approx \left(\frac{\nu}{\nu_0}\right)^\beta B_\nu(T)$

Observations at three or more wavelengths this simple model can be used to determine both **T** and **β**

PHYSICAL PROPERTIES OF MOLECULAR CLOUDS

➡ Assumptions:

1) Single temperature for all dust particles within the beam.
2) Spectral index **β** is constant within the beam and over the observed wavelengths.
3) Emission is assumed to be optically thin, making the determination of temperature and spectral index independent of the column density.

➡ Obtain Mass/Column density: $I_\nu \approx \left(\frac{\nu}{\nu_0}\right)^\beta B_\nu(T)$ Definition of optical depth: $\tau_\nu \equiv \kappa_\nu \int \rho \, ds$

$$\tau_\nu \approx \kappa_{ref} \left(\frac{\nu}{\nu_{ref}}\right)^\beta \Sigma$$

Surface/column density: $\Sigma = M/A$

PHYSICAL PROPERTIES OF MOLECULAR CLOUDS

➡ For a source located at a distance d: $A = \Omega\, d^2$

$$\Omega = M/(\Sigma\, d^2) = M\kappa_{ref}/\tau\, d^2$$

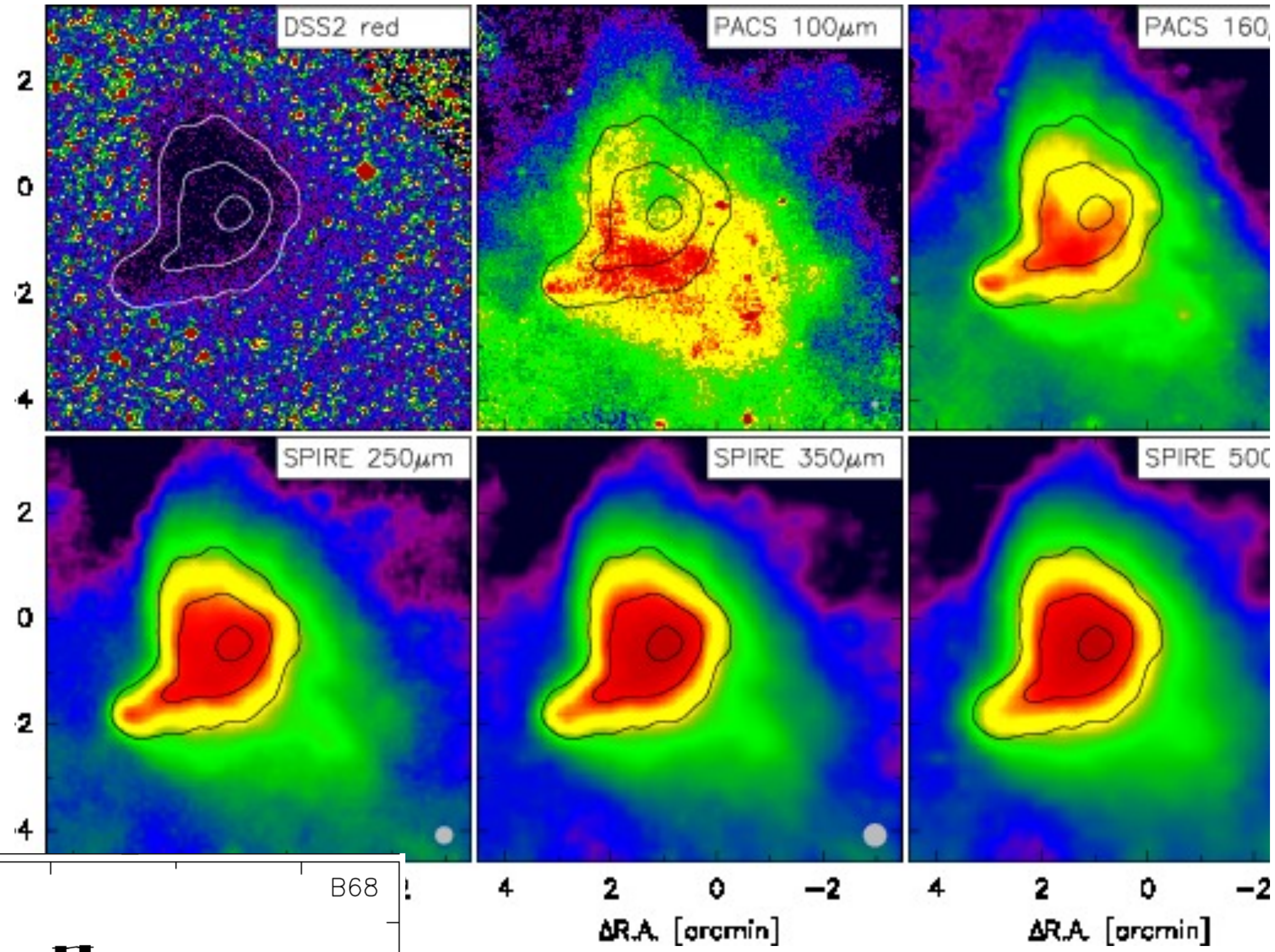
$$F_\nu = \Omega(1 - e^{-\tau_\nu})\, B_\nu(T) = \frac{M\,\kappa_{ref}}{d^2}\left(\frac{\nu}{\nu_{ref}}\right) B_\nu(T)$$

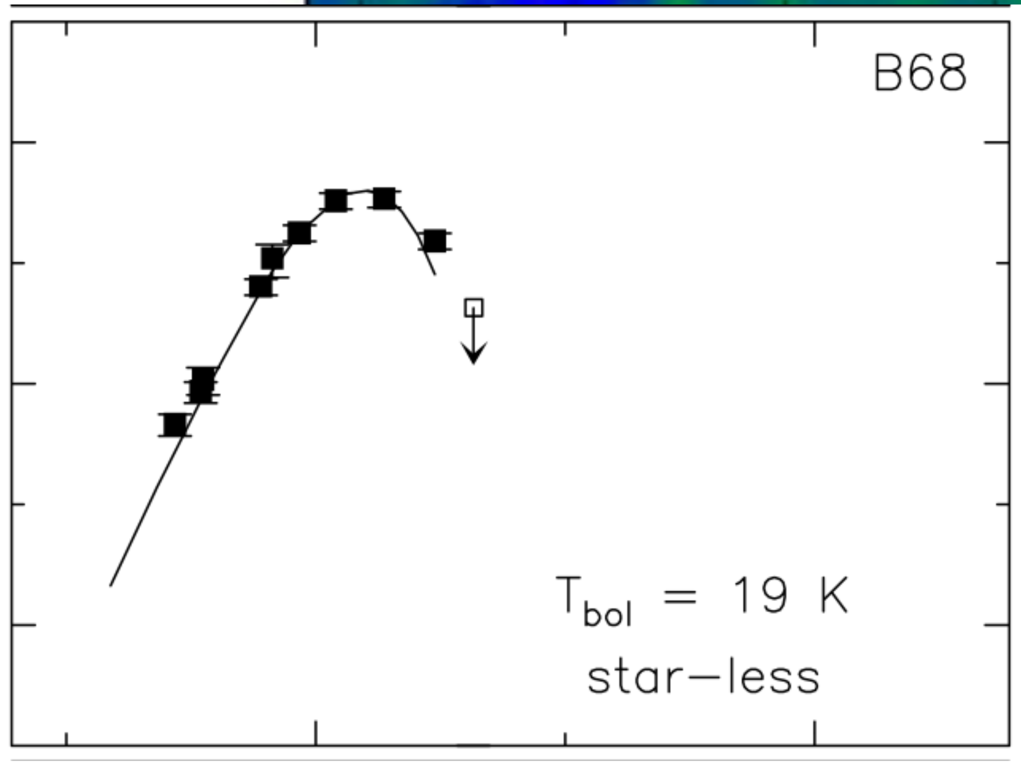
➡ Under the assumption that the emission at (sub)millimeter wavelengths is fully optically thin and in the Rayleigh-Jeans regime:

$$\left[\frac{M}{M_\odot}\right] = 1.6 \times 10^{-6}\left[\frac{\nu}{1000\,\mathrm{GHz}}\right]^{-(2+\beta)}\left[\frac{S_\nu}{\mathrm{Jy}}\right]\left[\frac{T_d}{\mathrm{K}}\right]^{-1}\left[\frac{d}{\mathrm{pc}}\right]^2$$

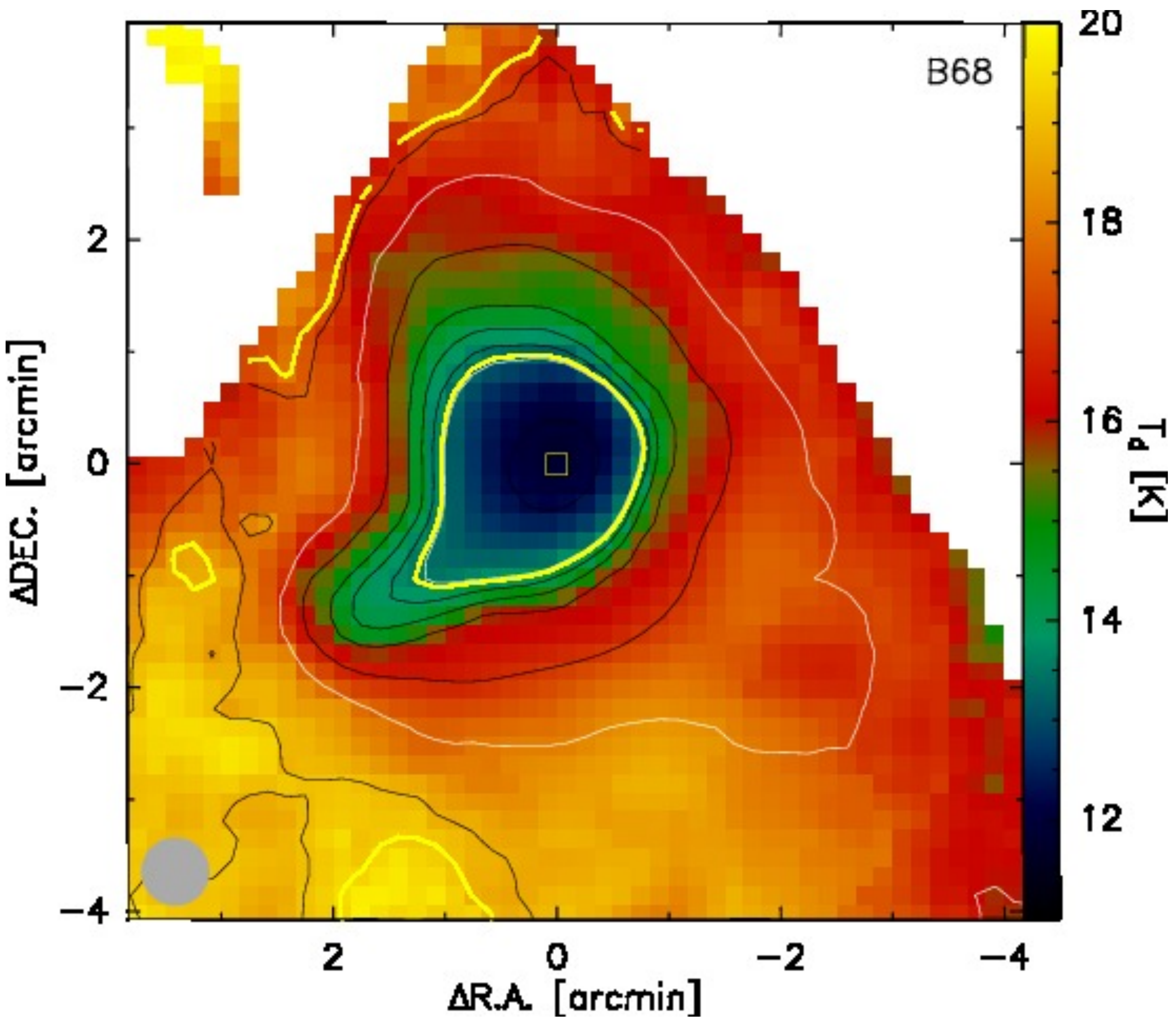
SED FITTING

Nielbock et al. (2012)



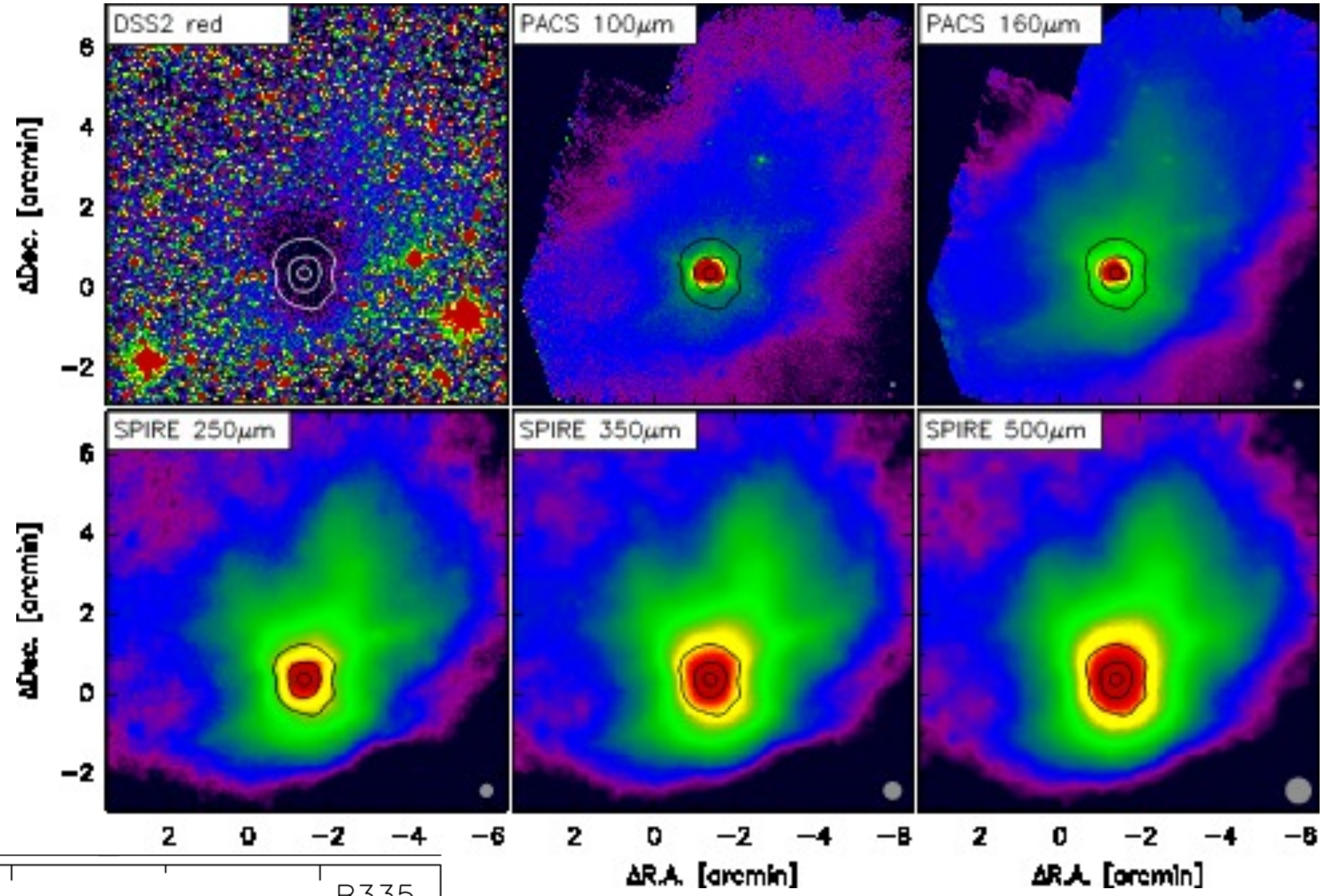


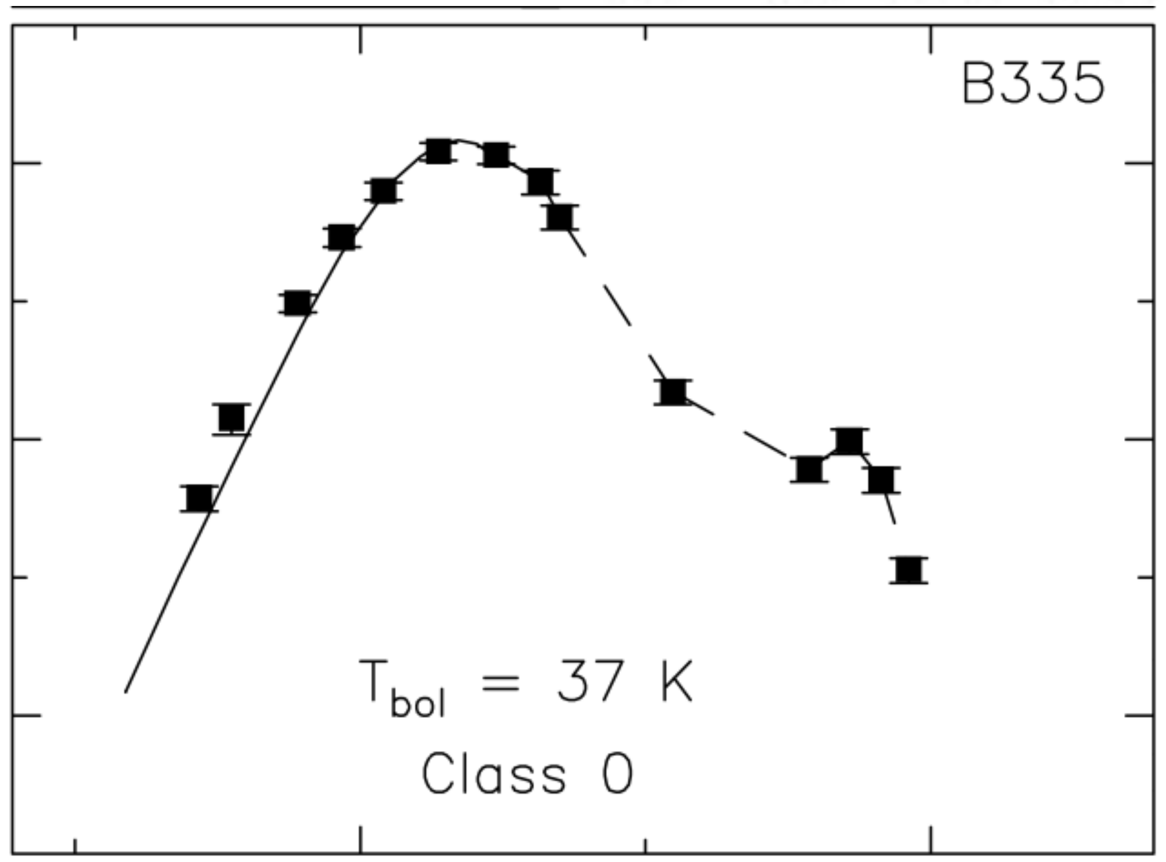
B68 TEMPERATURE MAP



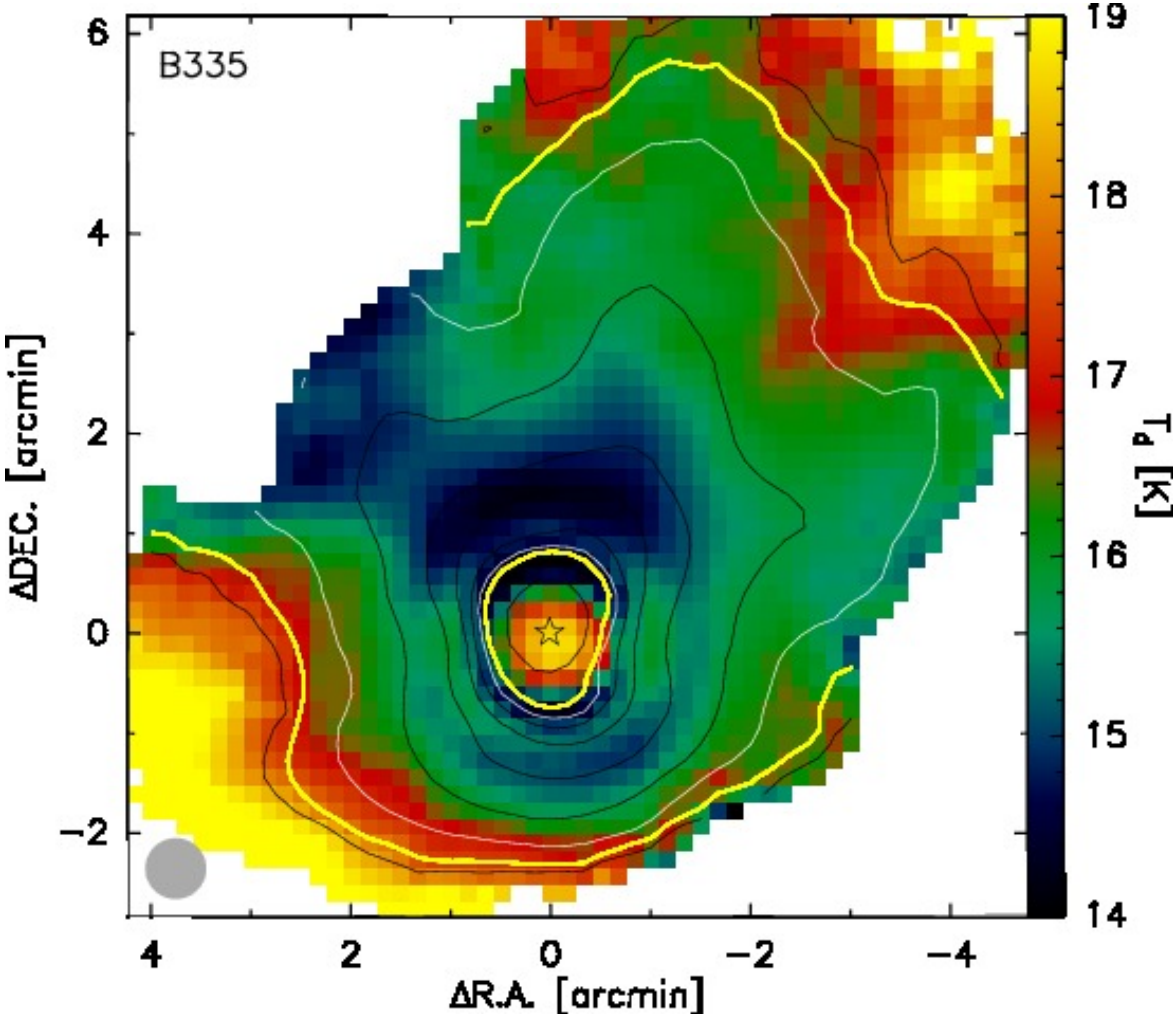
SED FITTING

Launhardt et al. (2013)





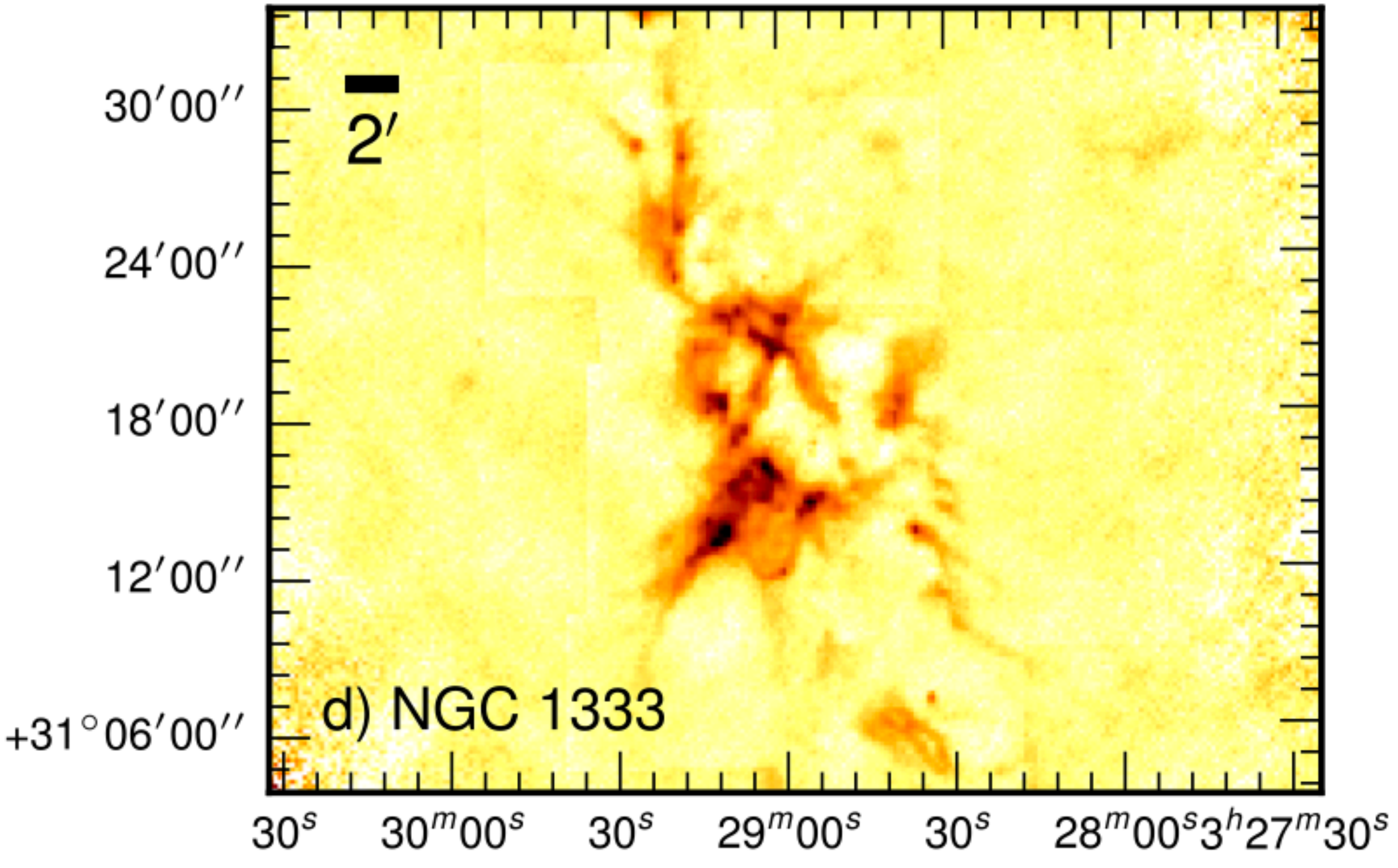
B335 TEMPERATURE MAP



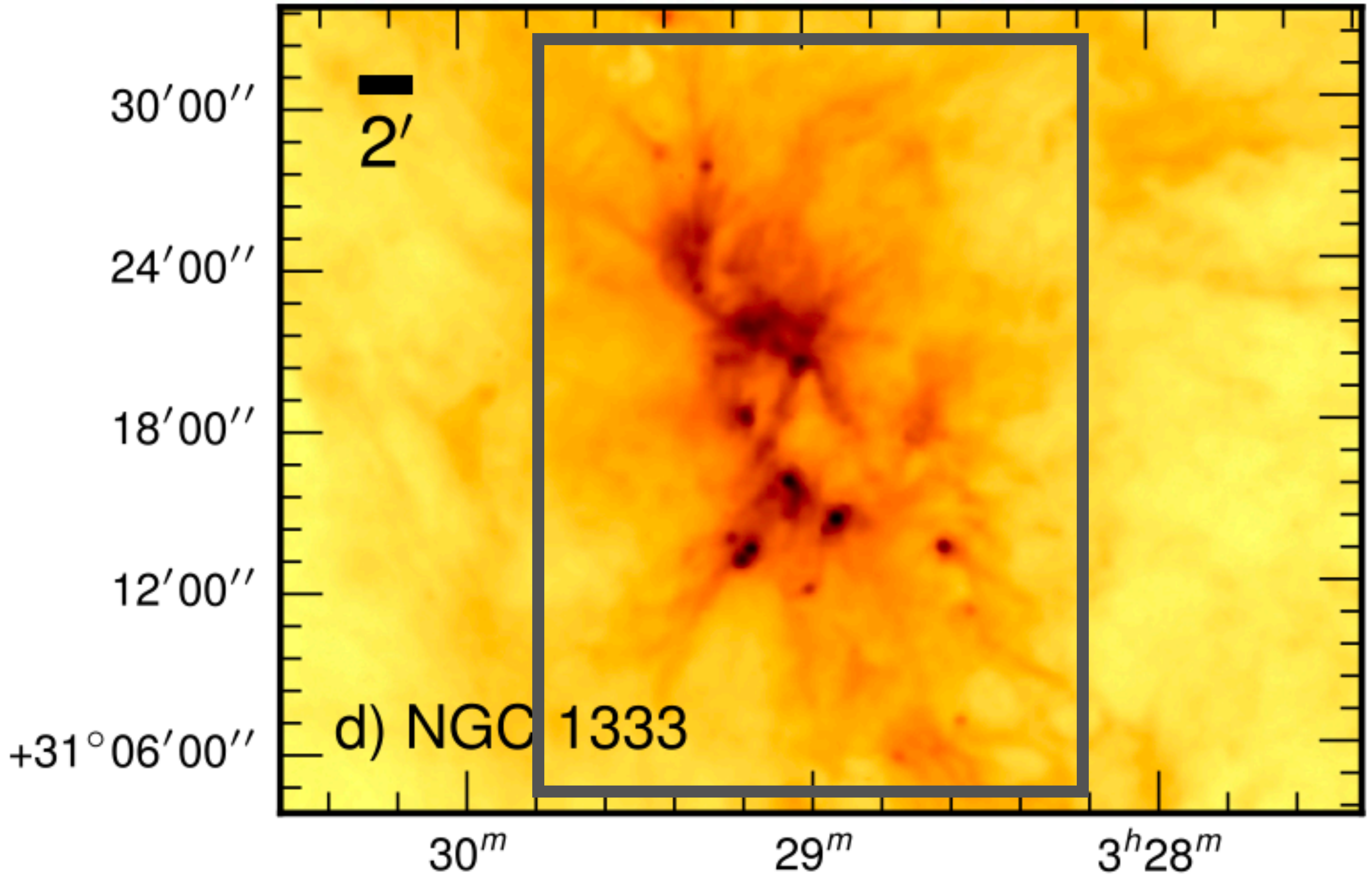
SED FITTING

NGC1333 star-forming region in Perseus cloud

JCMT SCUBA-2 map at 850 μm



Herschel SPIRE map at 250 μm



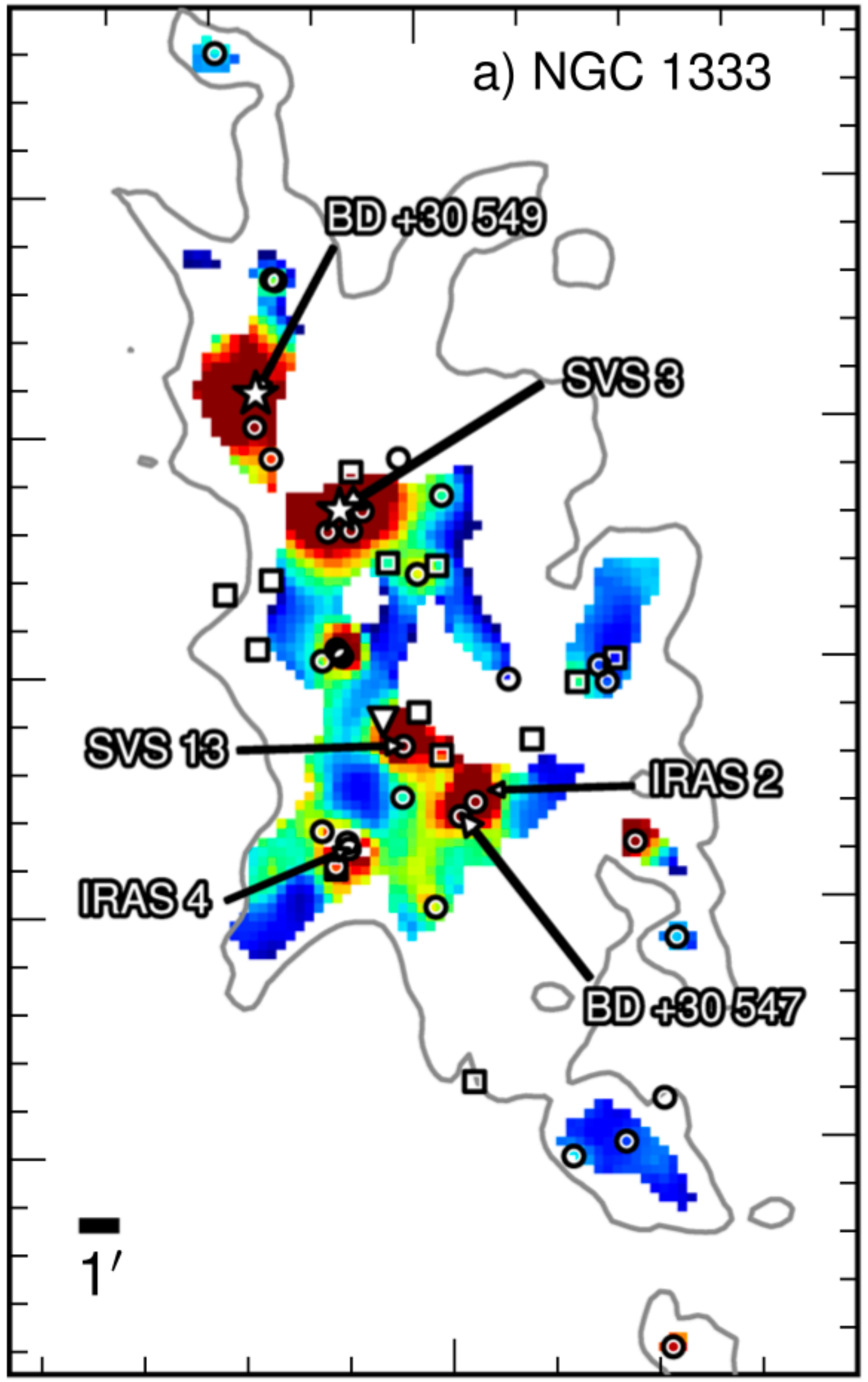
Chen et al. (2016)

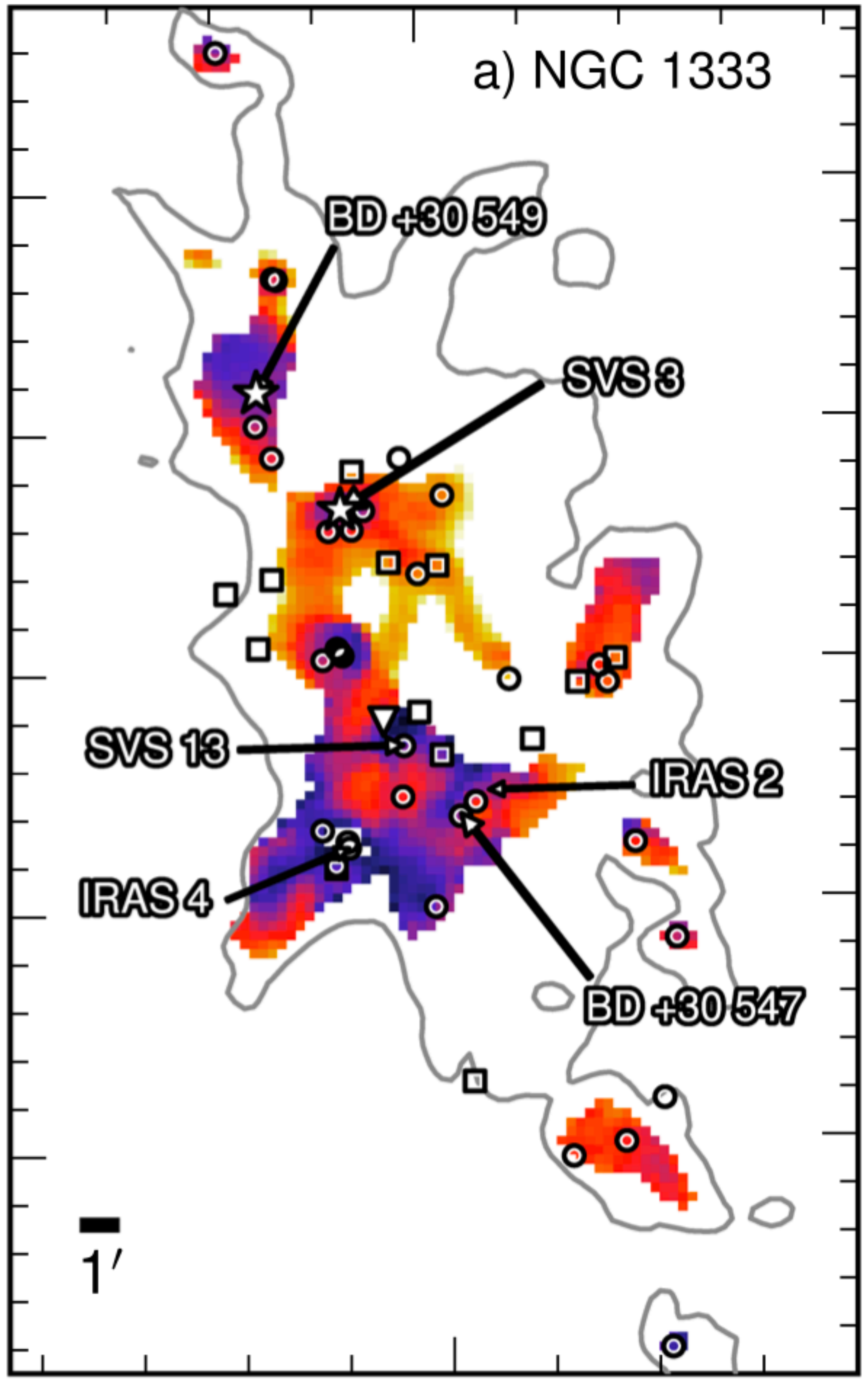
SED FITTING

NGC1333 star-forming region in Perseus cloud

Temperature map:

[9-18 K]





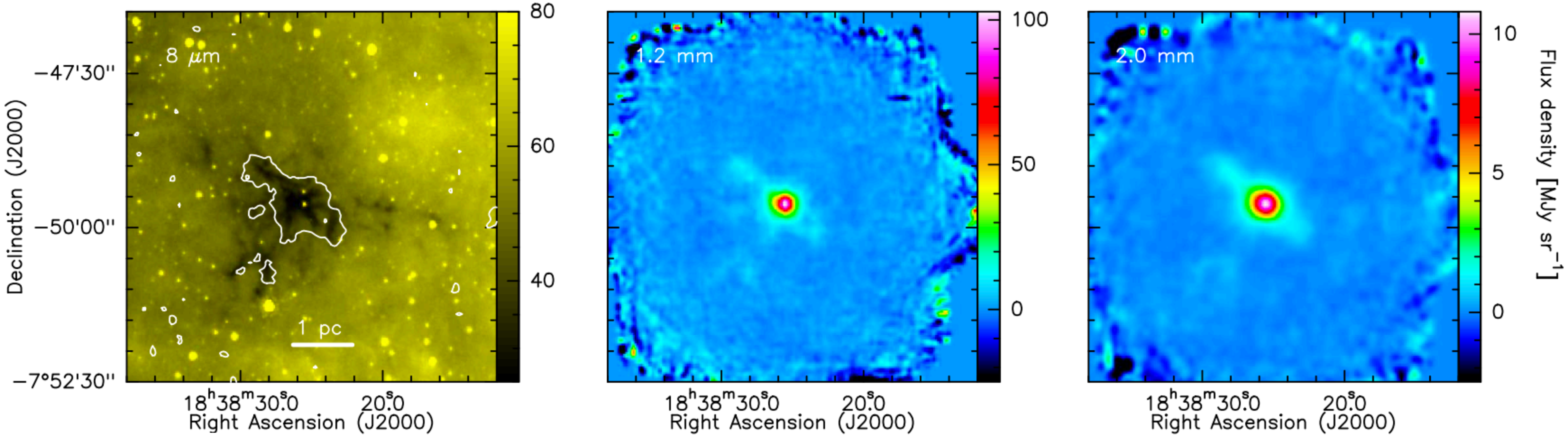
β map: ranges from 1 to 3

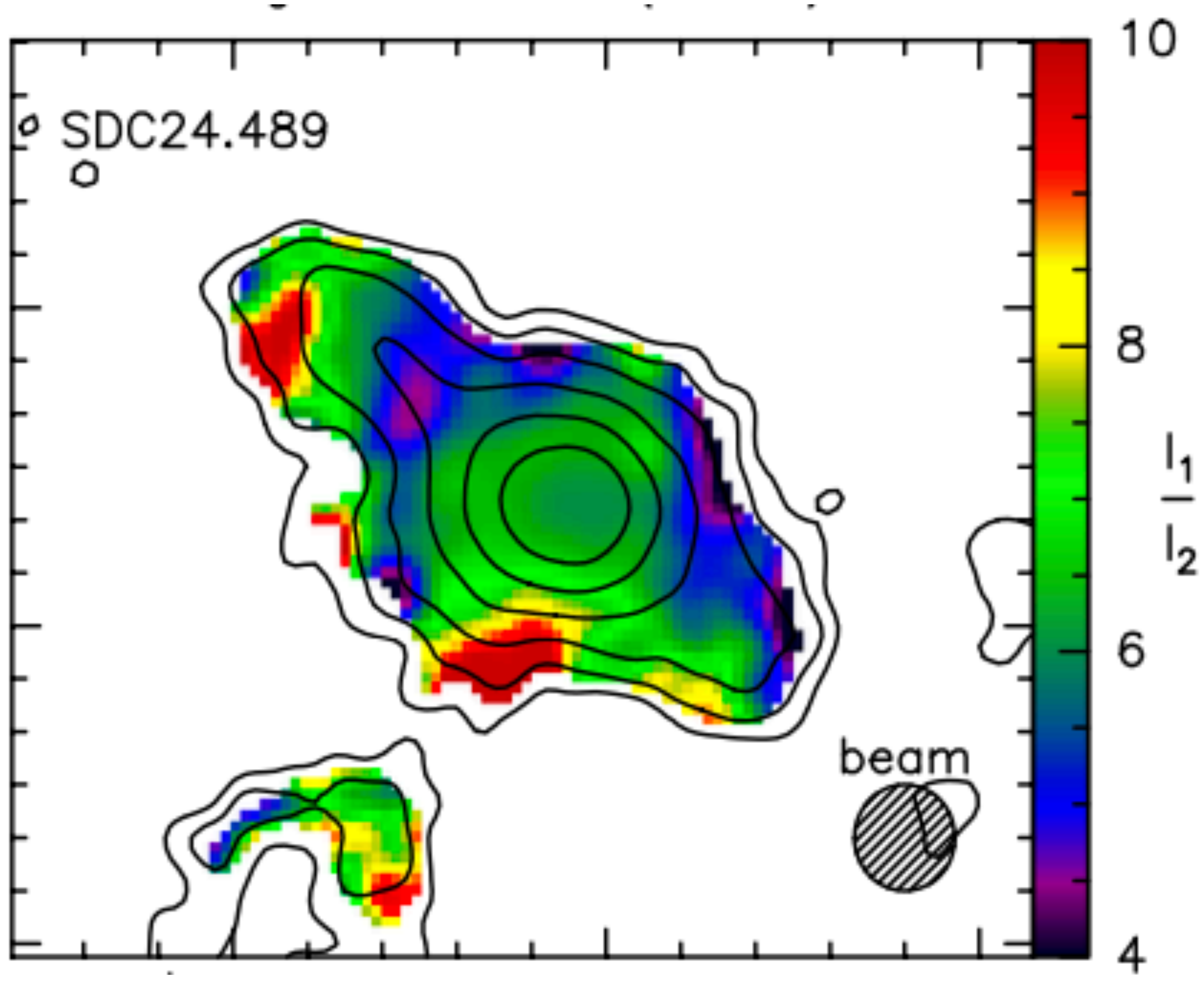
- ➡ Low values tend to correlate with T_d peaks
- ➡ β values can be intrinsically temperature dependent (Boudet et al. 2005)
- ➡ Grain growth can cause β values to decrease significantly

Chen et al. (2016)

SED FITTING

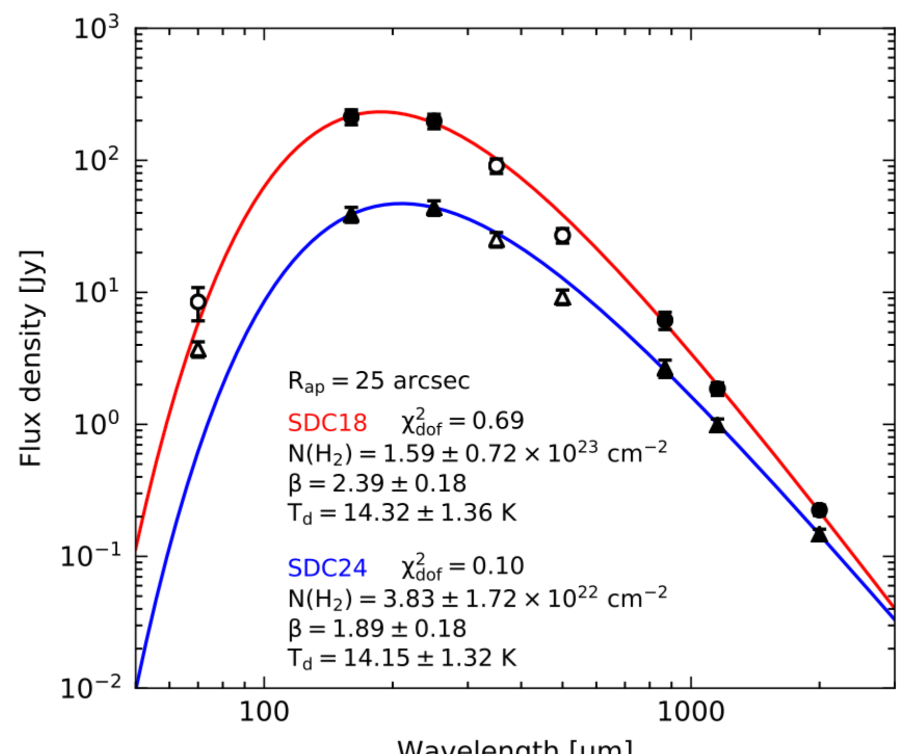
The Infrared Dark Cloud
SDC24-489-0.689





I_1=1.2 mm
I_2=2 mm

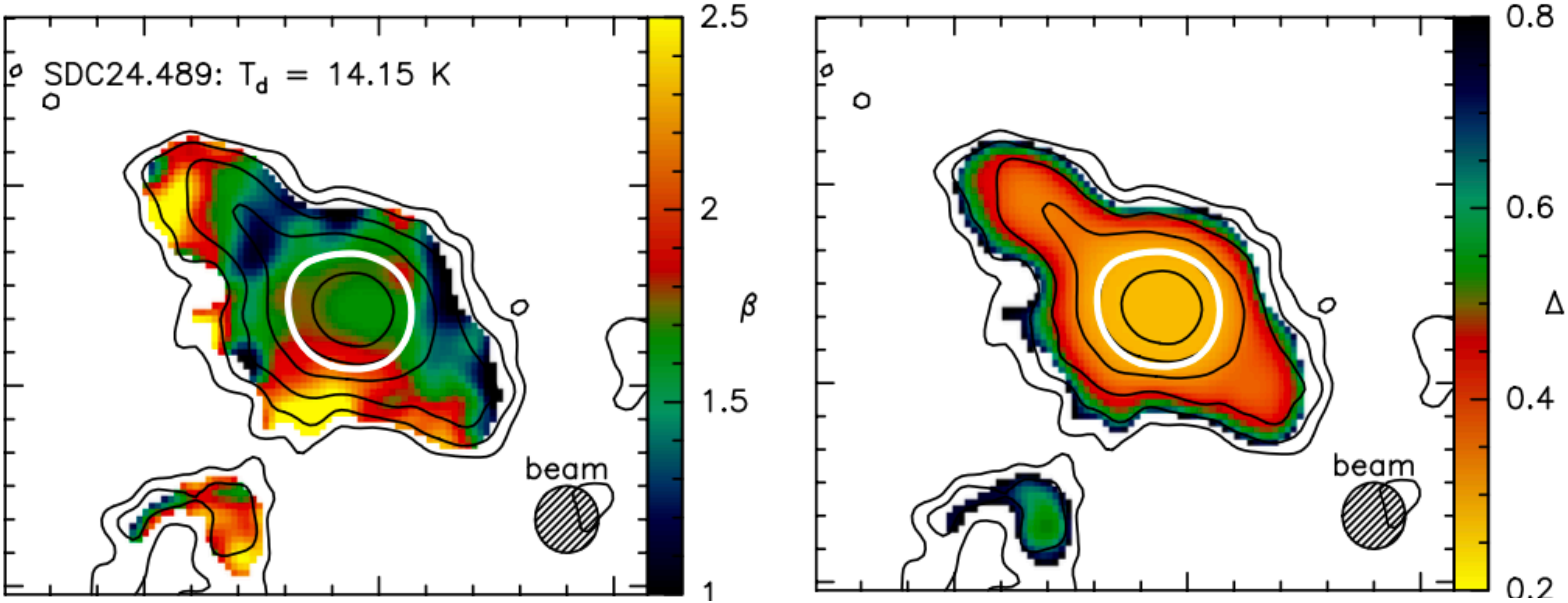
$$\beta = ln\left(\frac{I_1}{I_2}\frac{B_2(T_d)}{B_1(T_d)}\right) \times \left[ln\frac{\nu_1}{\nu_2}\right]^{-1}$$



Rigby et al. (2018)

SED FITTING

The Infrared Dark Cloud SDC24-489-0.689



Rigby et al. (2018)

SUMMARY

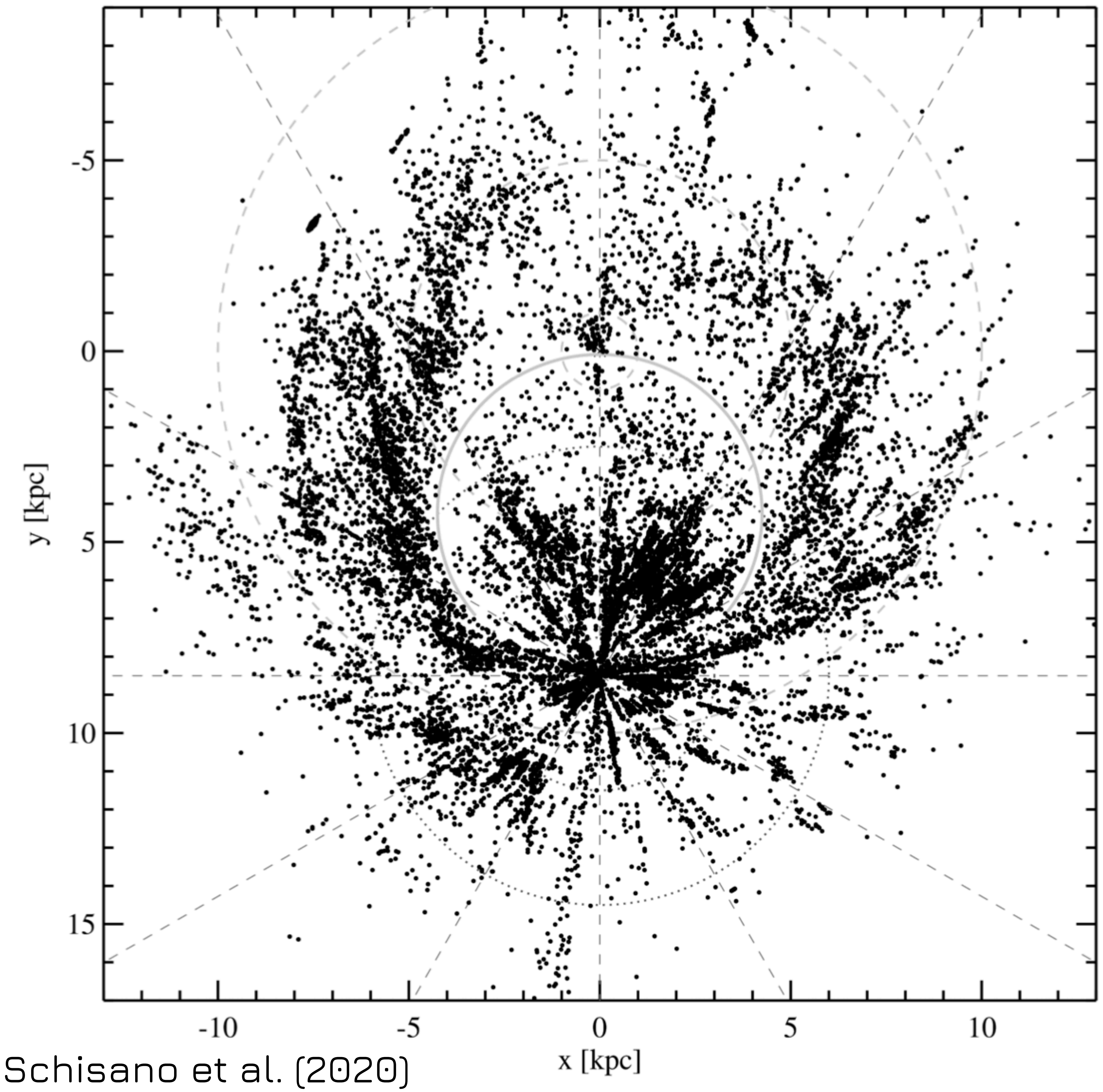
- ➡ Dust emissivity spectral index (β) is a critical parameter to obtain Mass and dust Temperature (T_d) of star forming regions ➡ Gravitational stability
- ➡ β depends on various grain properties: size, porosity, and surface composition
- ➡ Expected to vary as dust grains evolve
- ➡ Difficult to measure β (requires the SED)
- ➡ Wide range of β values (β ~1-3) have been reported in star-forming regions (Friesen et al. 2005, Shirley et al. 2005, 2011, Chen et al. 2016, Rigby et al. 2018 and many many more!)

FILAMENTS AND CLUMPS: THE HERSCHEL REVOLUTION

Image Credit: ESA/PACS/SPIRE/Marting Hennemann & Frederique Motte, Laboratoire AIM Paris-Saclay, CEA/Irfu - CNRS/INSU- Univ. Paris Diderot

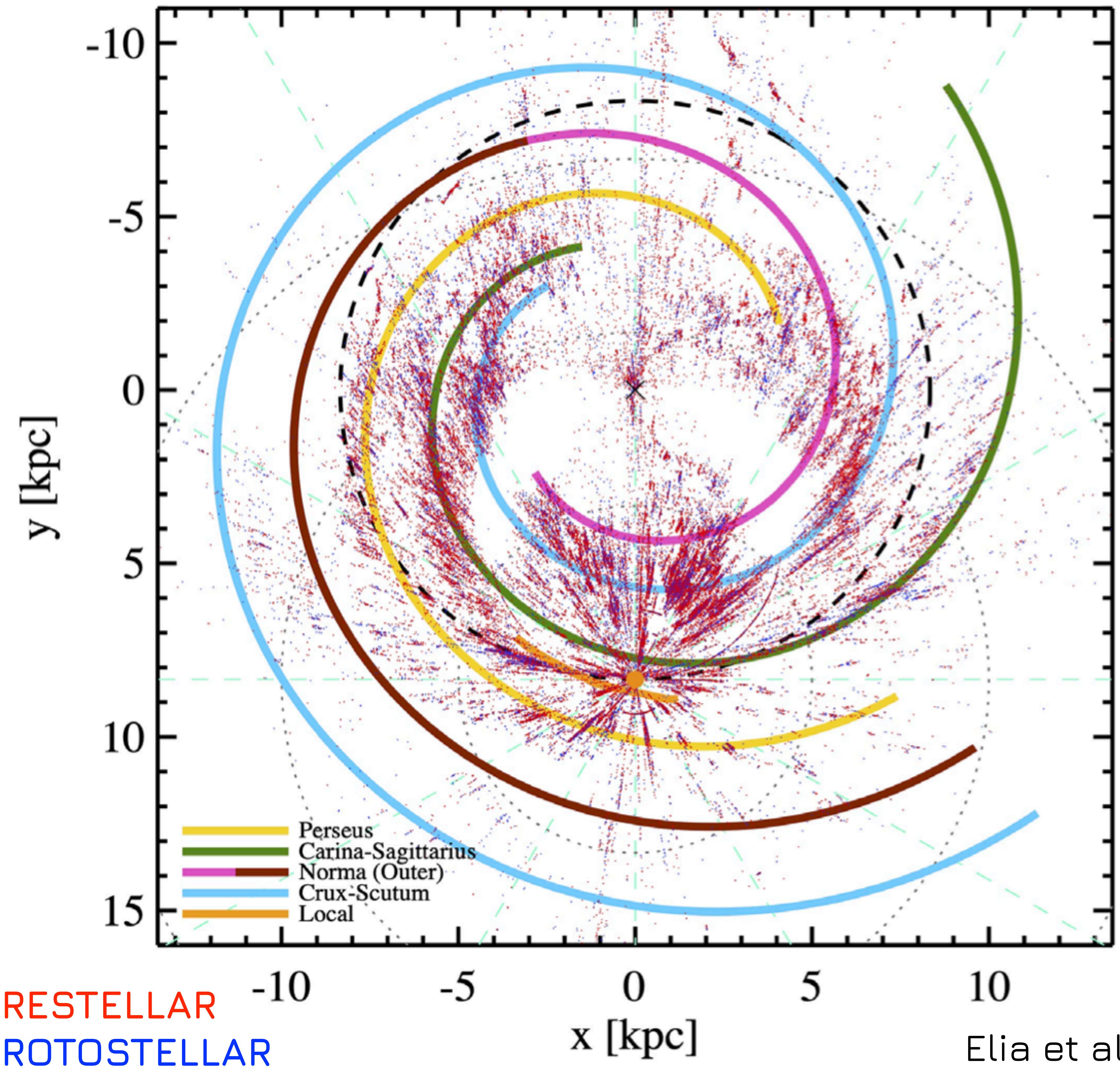
FILAMENTS AND CLUMPS

Location of 16.861 candidate filaments from Hi-GAL survey



Schisano et al. (2020)

Location of Galactic plane Hi-GAL objects

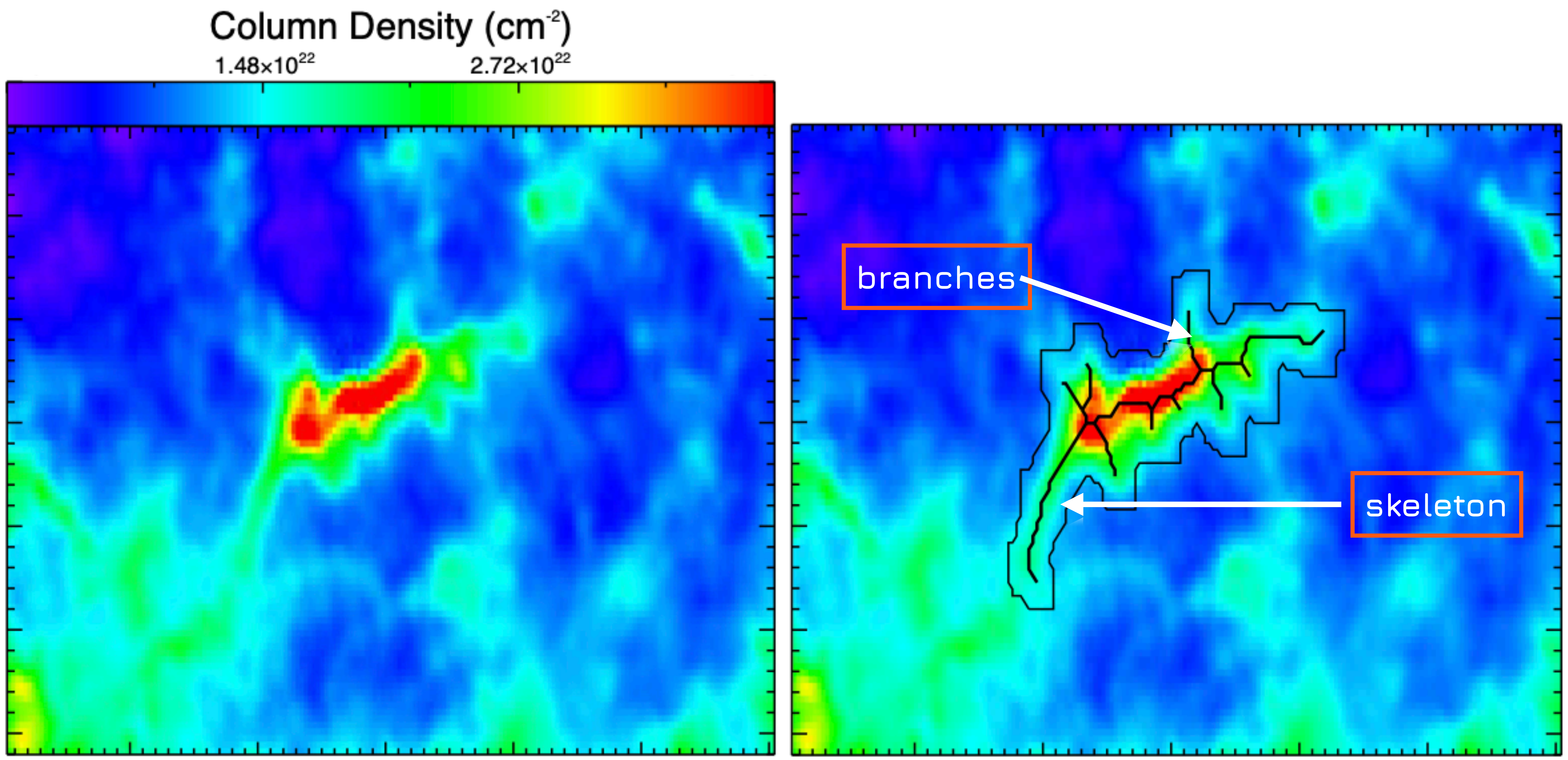


PRESTELLAR
PROTOSTELLAR

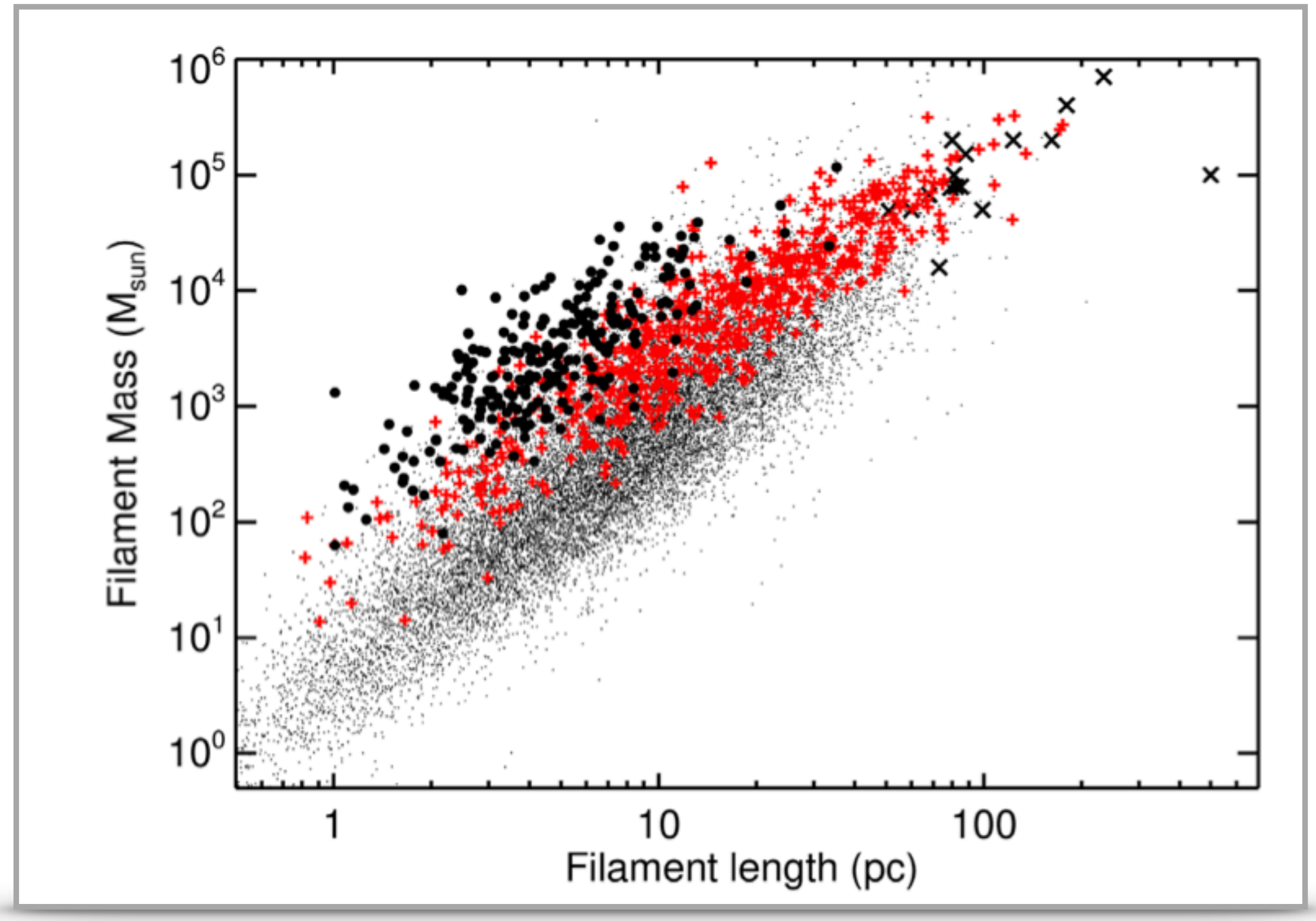
Elia et al. (2021)

FILAMENTS

Schisano et al. (2020)



Hi-GAL (small dots and crosses)
ATLASGAL (large filled dots)
Red crosses: Hi-GAL objects that match ATLASGAL

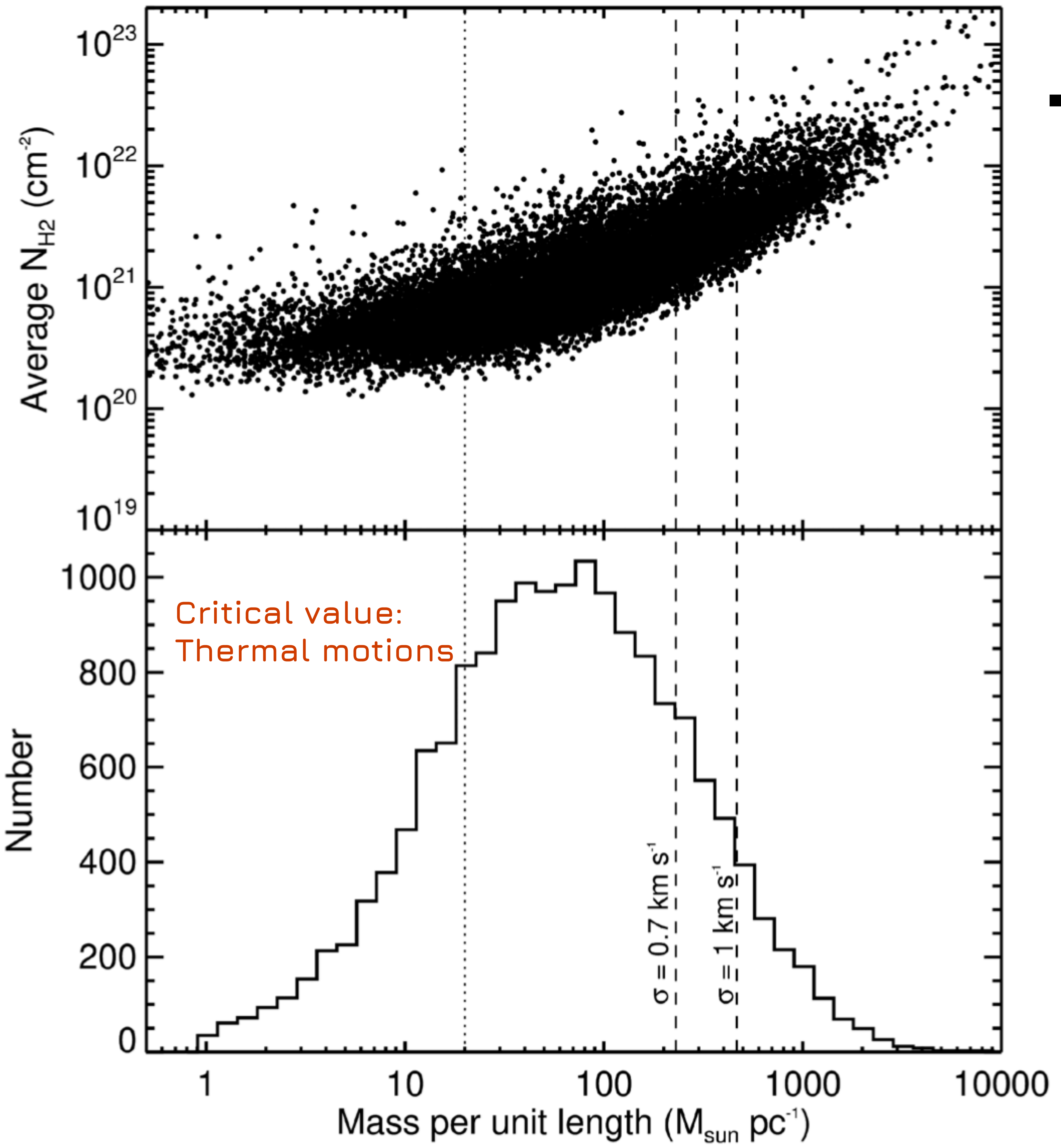


$$M^{\rm fil} = \mu_{\rm H_2} m_{\rm H} (\theta d)^2 \sum_{i,j}^{\rm mask} N^{\rm fil}_{\rm H_2}(i, j),$$

θ: angular pixel size

μ_{H2}: mean molecular weight of the ISM with respect to hydrogen molecules (2.8)

FILAMENTS



➡ Critical line mass (mass per unit length) of a filament: hydrostatic, isothermal cylinder model (Stodólkiewicz 1963, Ostriker 1964, see Hacar et al. 2022 for a review)

$$m_{\rm crit}(T) = \frac{2\,c_s^2}{G} \sim 16.6\left(\frac{T}{10\ K}\right)\ {\rm M_\odot\,pc^{-1}}$$

$m_{\rm lin} \lesssim m_{\rm lin}^{\rm crit}$ → Subcritical filament: hydrostatic equilibrium

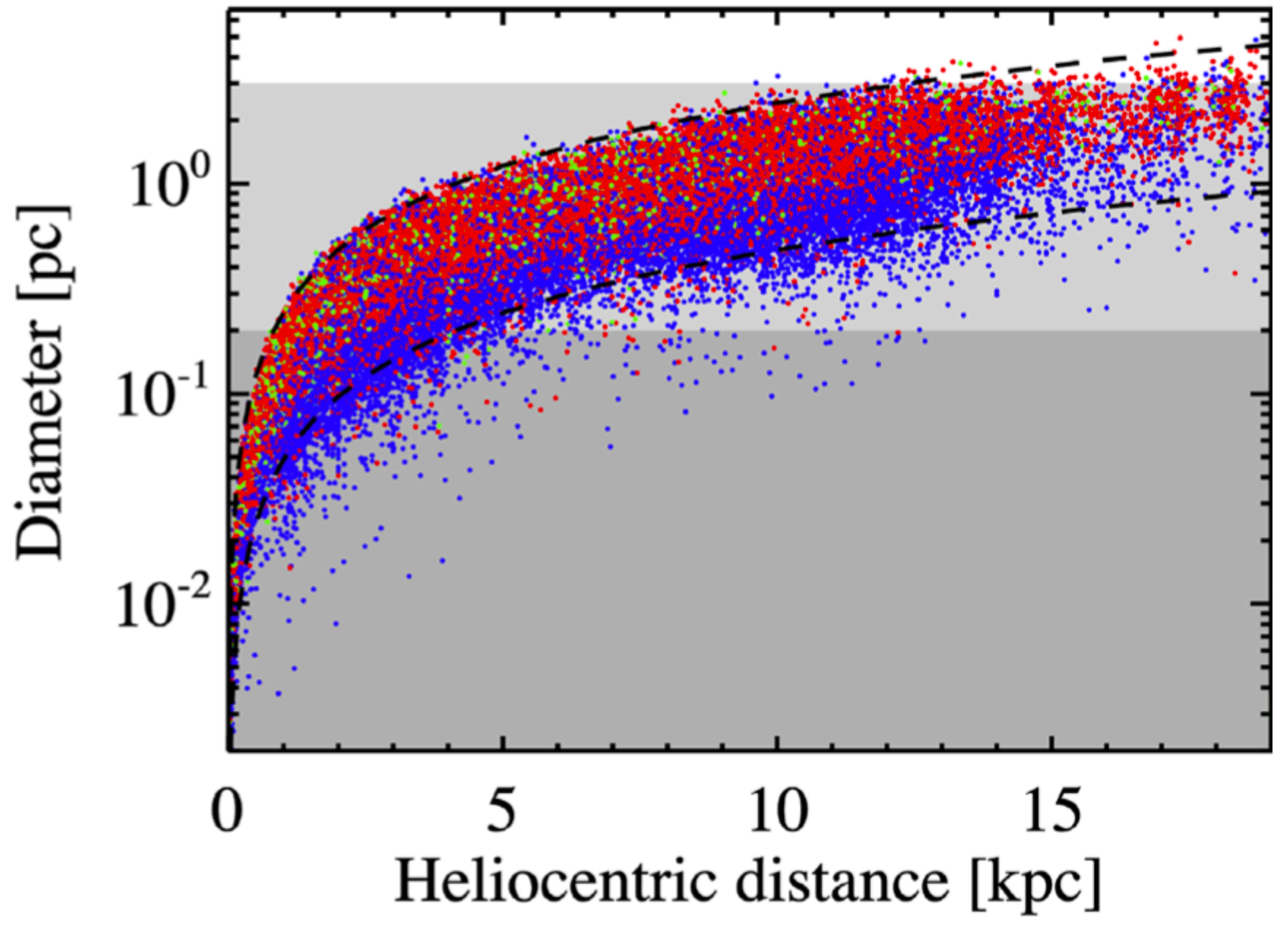
$m_{\rm lin} \gtrsim m_{\rm lin}^{\rm crit}$ → Supercritical filament: unstable and must collapse under their own gravity

Schisano et al. (2020)

STAR FORMATION RATE IN THE MILKY WAY

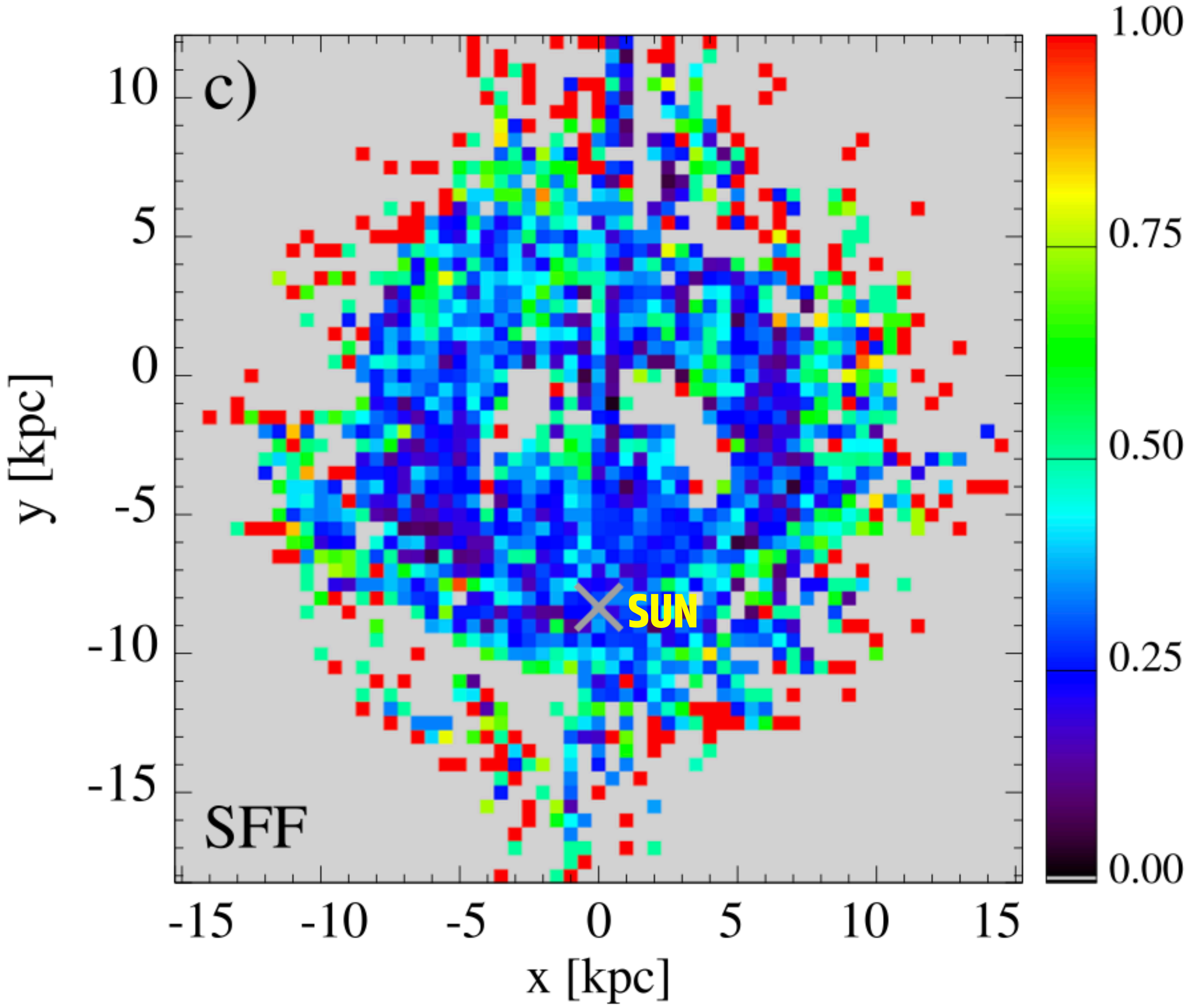
Hi-GAL compact sources catalog

Elia et al. (2021)



CLUMPS: diameter (0.3 < D < 3 pc)
Bergin & Tafalla (2007)

$$SFR_{\rm cl} = (5.6 \pm 1.4) \times 10^{-7} (M_{cl}/M_{\odot})^{0.74 \pm 0.03}\ \mathrm{M_{\odot}\,yr^{-1}}$$



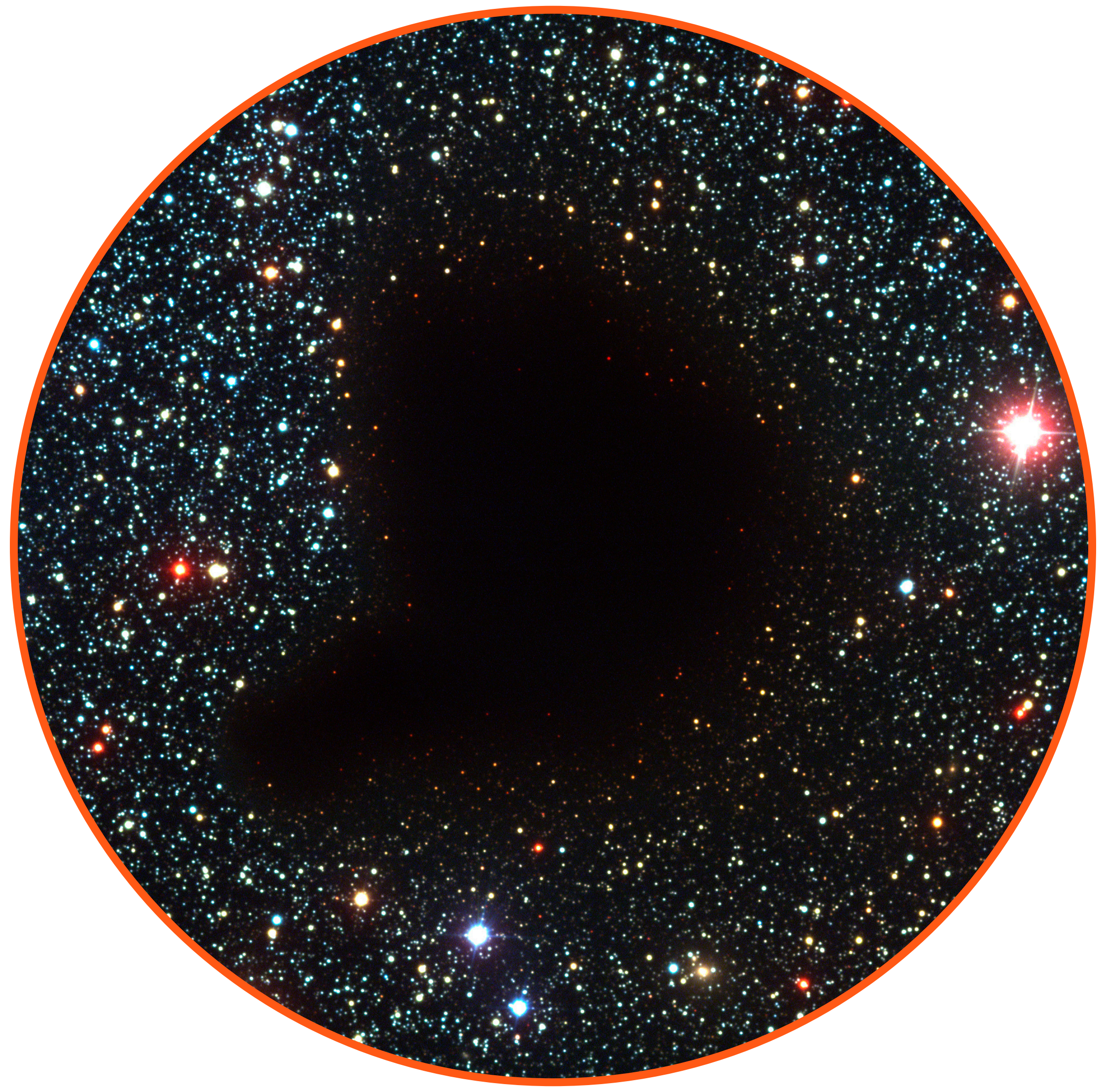
➡ Considering all clumps classified as protostellar and provided with heliocentric distance:

$$SFR = (1.7 \pm 0.6)\ \mathrm{M_{\odot}\,yr^{-1}}$$

References: Veneziani et al. (2013, 2017), Molinari et al. (2008), Elia et al. (2021, 2022), Kennicutt & Evans 2012, McKee & Ostriker 2007, Krumholz 2014, Chomiuk & Povich (2011)

OUTLINE

THE INTERSTELLAR MEDIUM

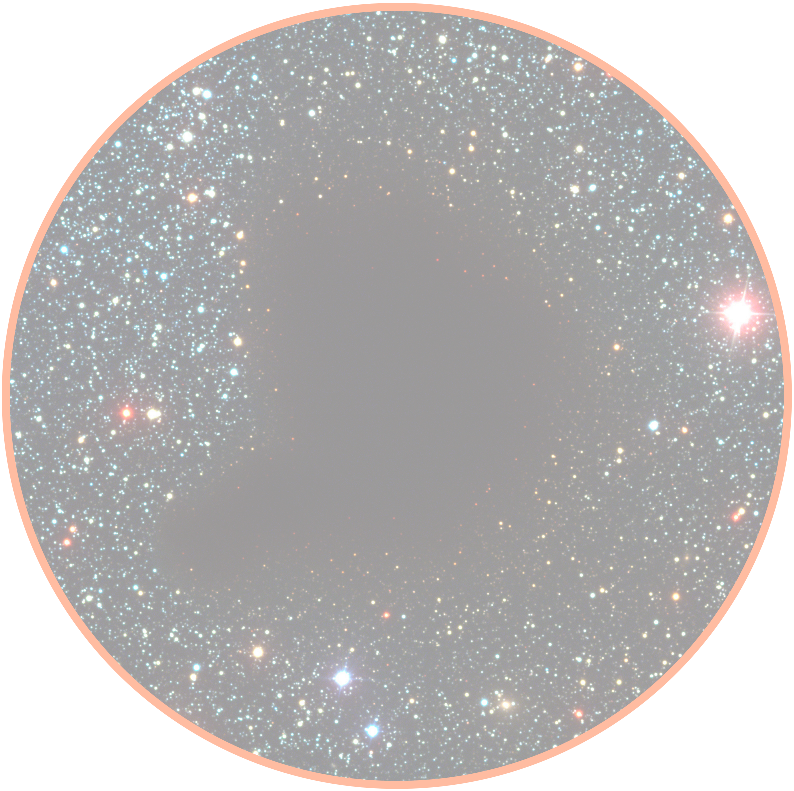


MOLECULAR CLOUDS: THE STELLAR NURSERIES

CLOUD FRAGMENTATION AND CLUSTER FORMATION

OUTLINE

THE INTERSTELLAR MEDIUM



MOLECULAR CLOUDS: THE STELLAR NURSERIES

CLOUD FRAGMENTATION AND CLUSTER FORMATION

WHY STAR CLUSTER FORMATION?

- ★ Most stars in the Galaxy form in clusters or in groups of at least a few tens of stars (e.g., Lada & Lada 2003)
- ★ Our Sun was born in a cluster environment (Adams 2010)

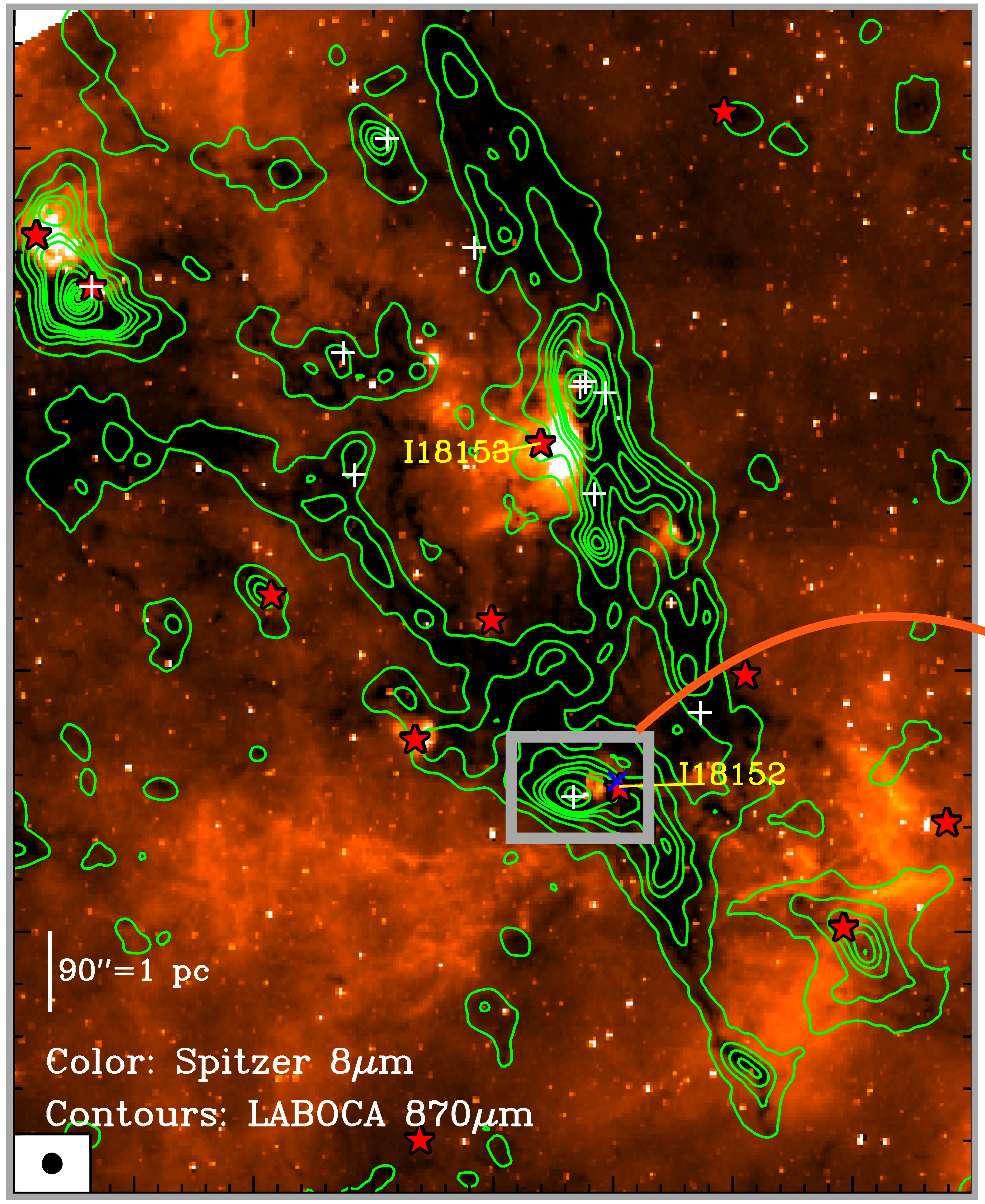
Image credit: ESO/H. Drass et al.

THE ORION NEBULA CLUSTER

CLUMPS: PROGENITORS OF STAR CLUSTERS

Cloud

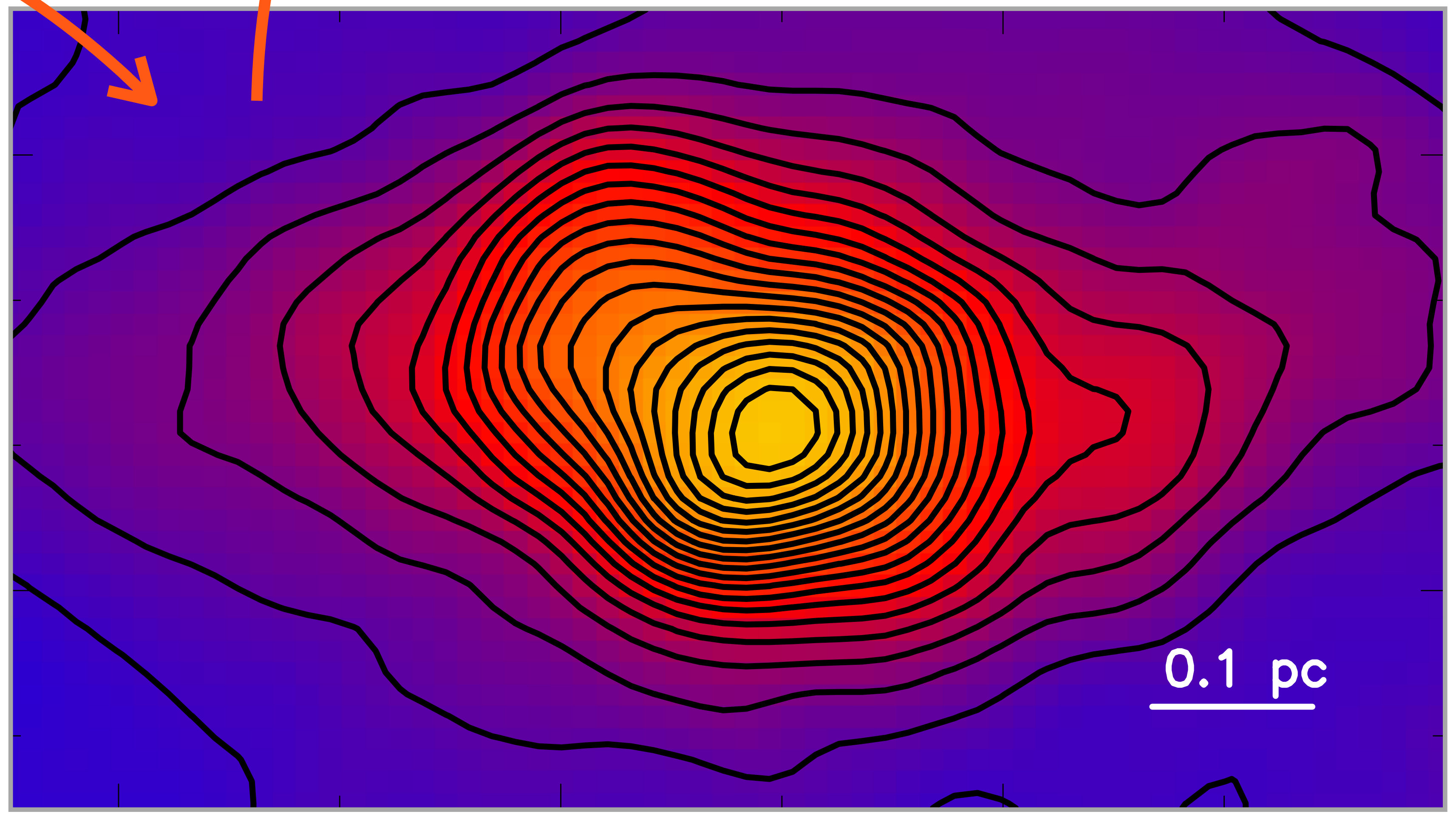
~15 pc



Busquet (2010) PhD Thesis

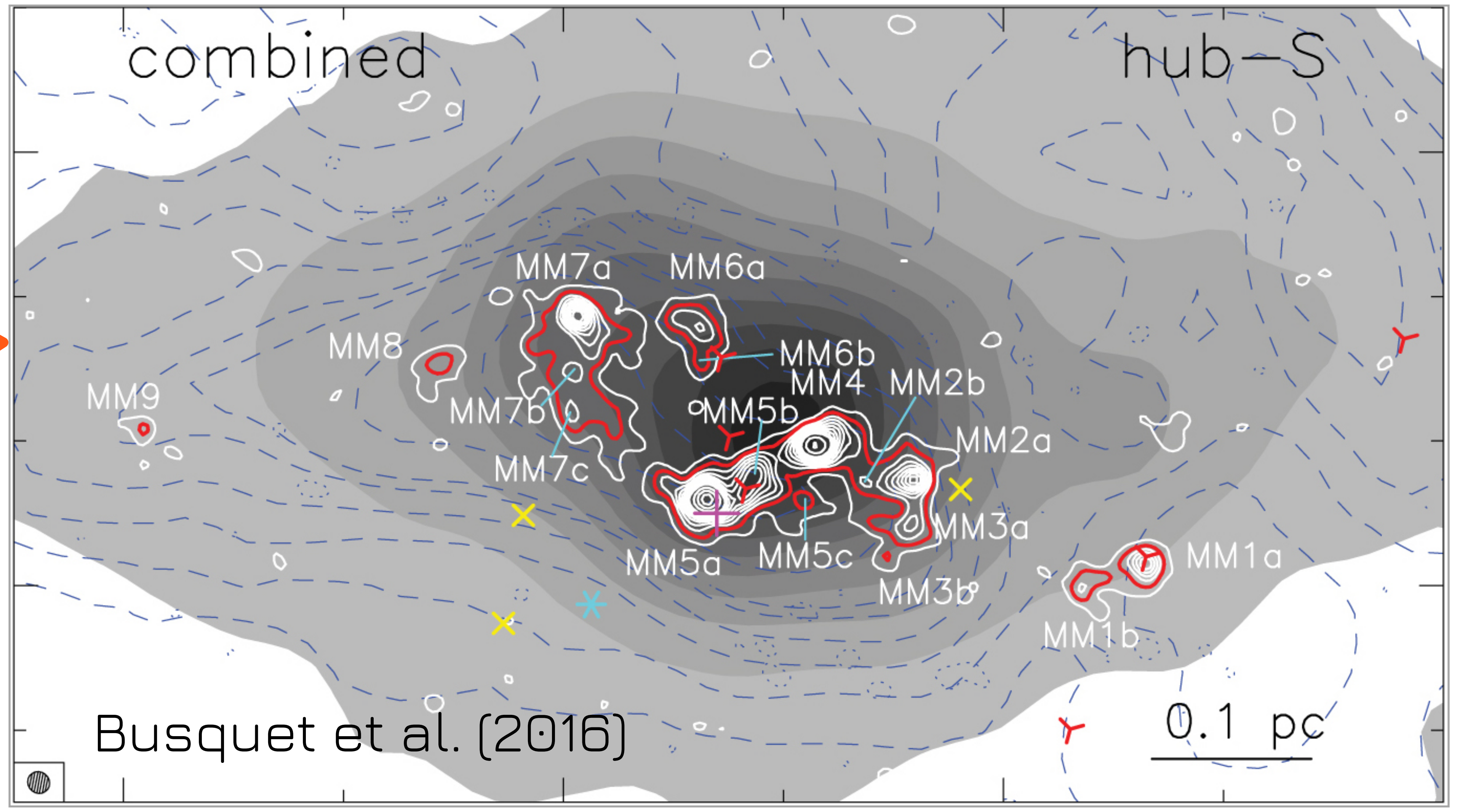
High degree of Fragmentation

Hub/Clump



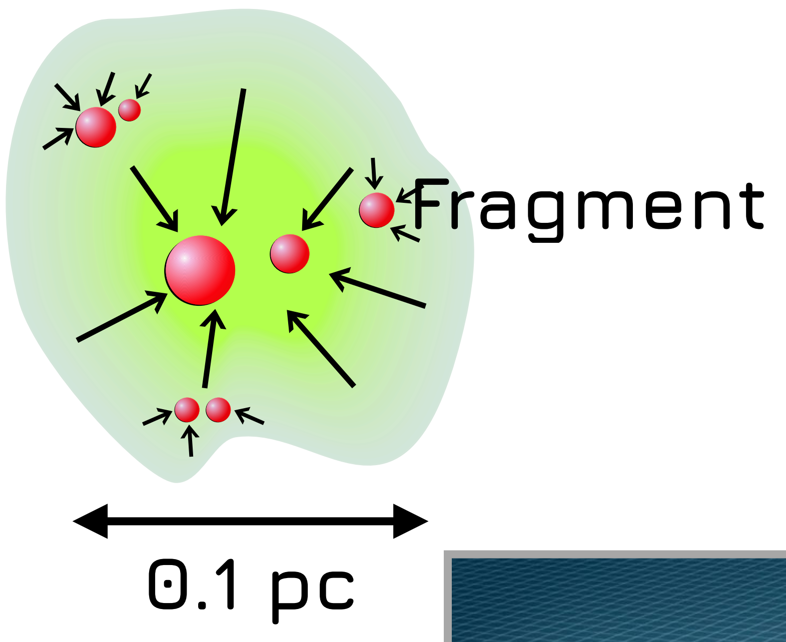
~1 pc

Protocluster



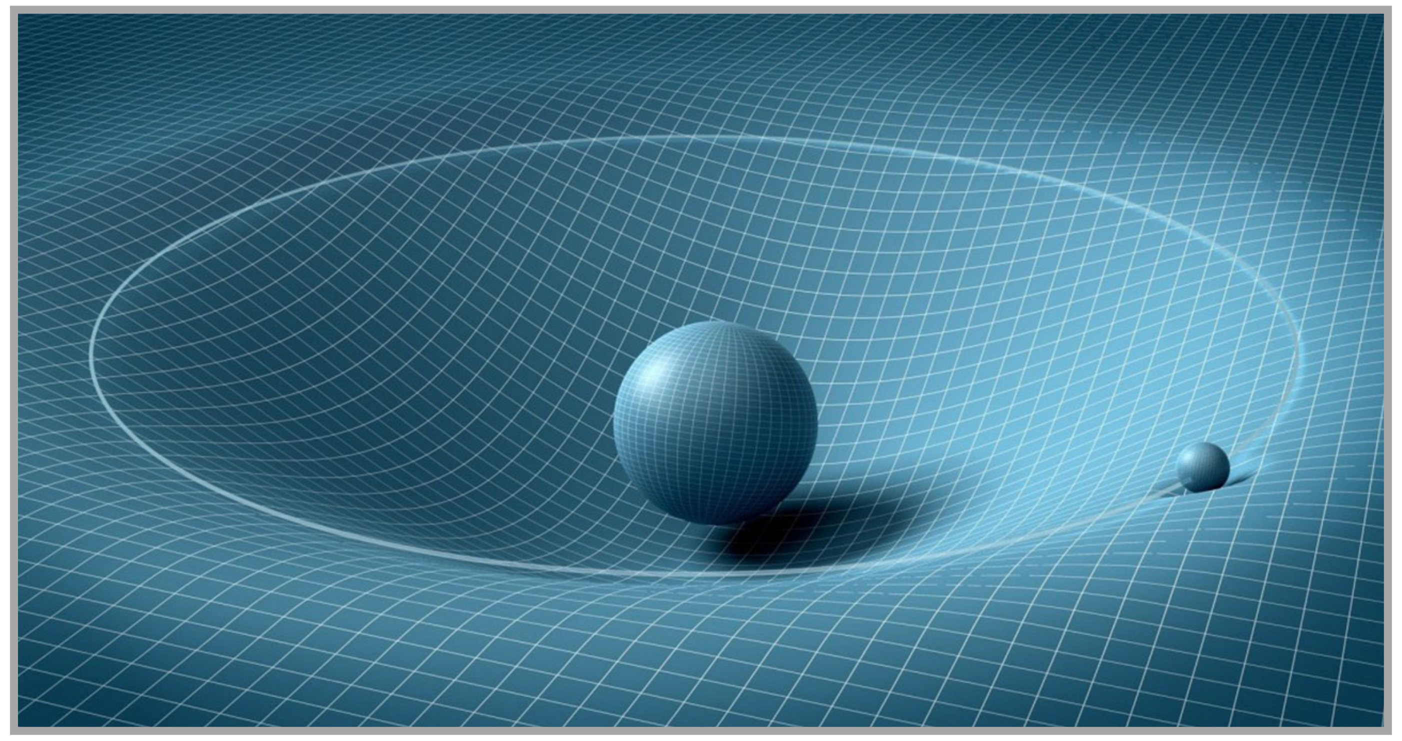
Stellar cluster

Massive Dense Core
M~50-1000 M$_\odot$



THE MAIN PLAYERS

Gravity



Turbulence

B-fields

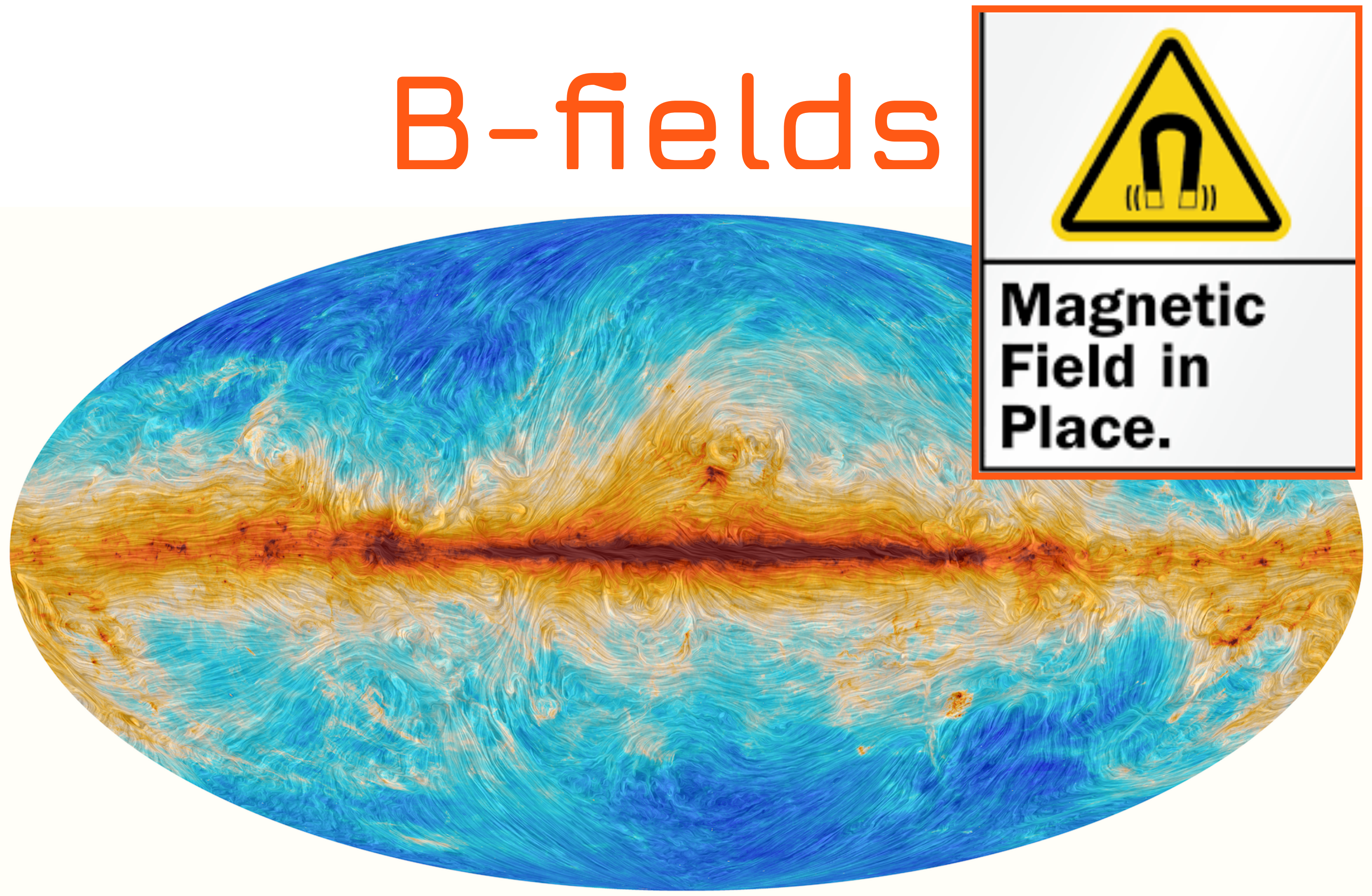


Image Credit: Planck/ESA

Angular momentum

Stellar feedback

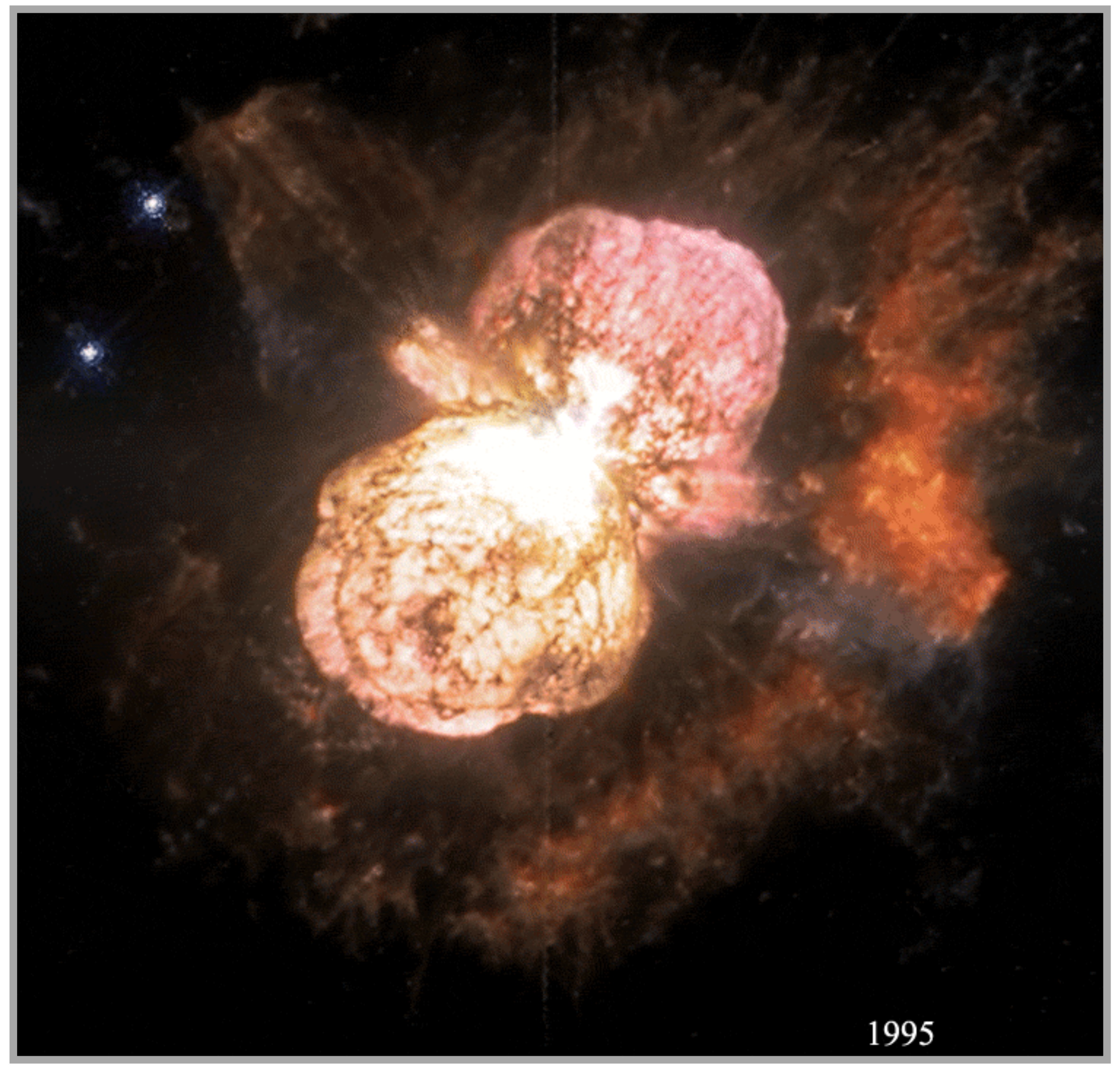
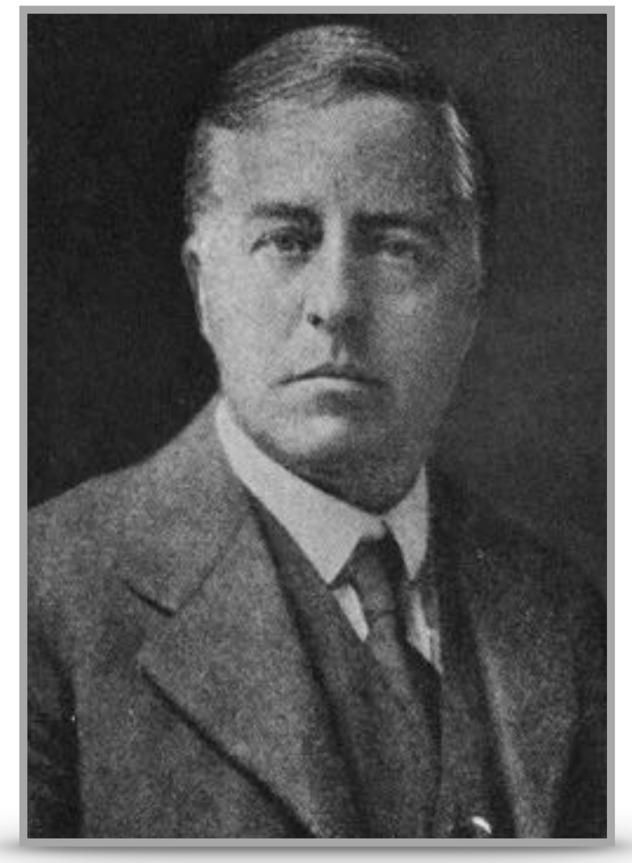


Image Credit: Hubble/NASA/ESA

COLLAPSE AND FRAGMENTATION



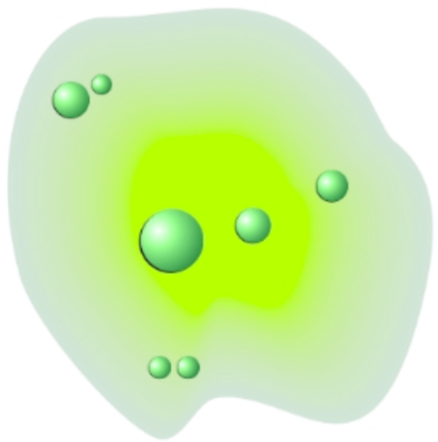
James Jeans
(1877-1946)

- ➡ Consider an infinite static 3D medium with initial uniform density ρ and uniform isothermal sound speed c_s.
- ➡ Due to a random fluctuation a portion of this medium become slightly more dense.

Will the spherical portion become denser and condenses out due to its self-gravity?

Will the internal pressure make it to expand back to the same density as the surrounding medium?

Core: T, n



Fragment ~0.01 pc

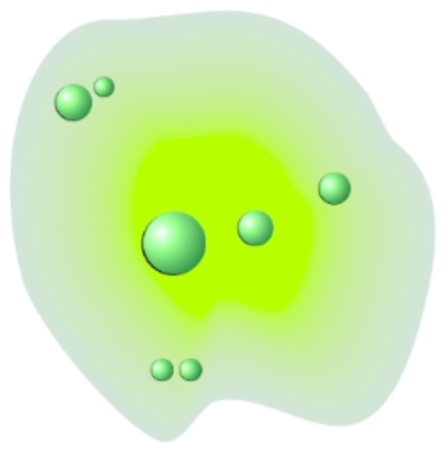
$$\left[\frac{M^{th}_{Jeans}}{M_{\odot}}\right] = 0.6285\left[\frac{T}{10K}\right]^{3/2}\left[\frac{n_{H_2}}{10^5 cm^{-3}}\right]^{-1/2}$$

Efficient at producing low-mass fragments

CRITERION FOR FRAGMENTATION

Jeans (1902): A fragment will collapse if its gravitational energy overcome its thermal energy

Core: T, n



Fragment ~0.01 pc

$$\left[\frac{M^{th}_{Jeans}}{M_\odot}\right] = 0.6285\left[\frac{T}{10K}\right]^{3/2}\left[\frac{n_{H_2}}{10^5 cm^{-3}}\right]^{-1/2}$$

Efficient at producing low-mass fragments

"Generalized"Jeans criterion: include other forms of support

TURBULENCE:

Chandrasekhar 53

$$\left[\frac{M^{nth}_{Jeans}}{M_\odot}\right] = 0.8225\left[\frac{\sigma_{1D,nth}}{0.188 km\, s^{-1}}\right]^{3}\left[\frac{n_{H_2}}{10^5 cm^{-3}}\right]^{-1/2}$$

M_J~120 Msun (σ~1km/s)
naturally produces massive fragments
(but only a few)

MAGNETIC FIELD:

Bertoldi & McKee 92,
McKee & Ostriker 07

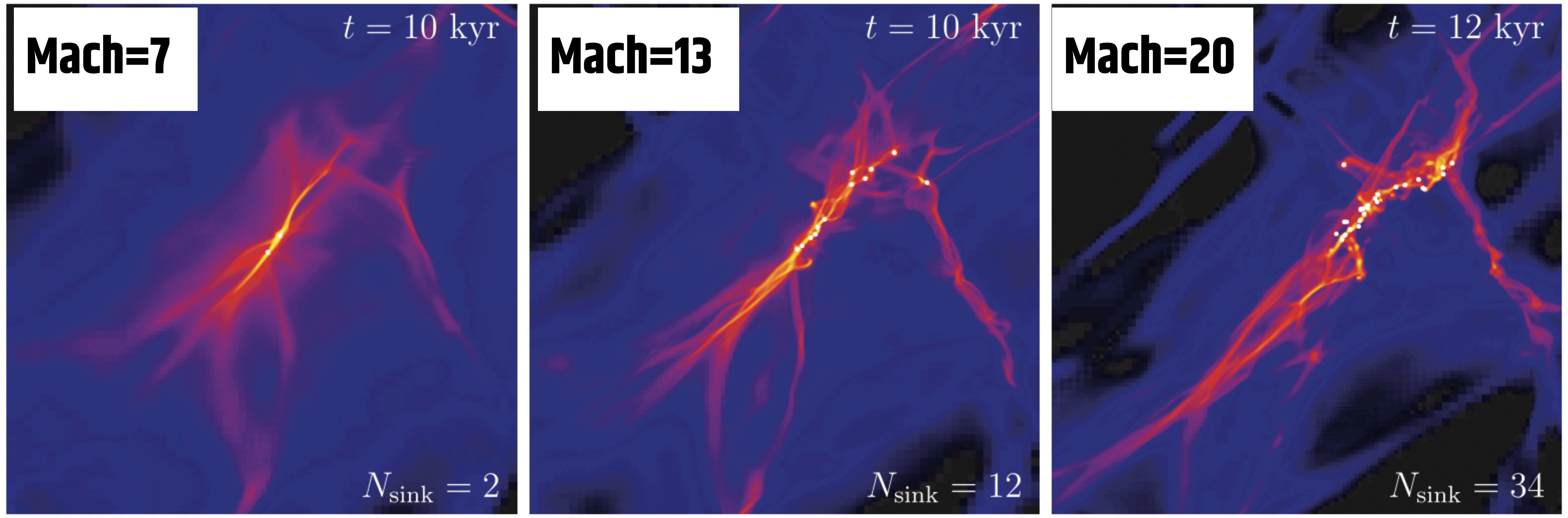
$$\left[\frac{M_{crit}}{M_\odot}\right] = 1020\left[\frac{R}{Z}\right]^{2}\left[\frac{B}{30\,\mu\, G}\right]^{3}\left[\frac{n_{H_2}}{10^3 cm^{-3}}\right]^{-2}$$

M_{crit}~150 Msun
(0.1x0.5 pc, 1 mG, 10^5 cm^{-3})
massive fragments (but only a few)

NUMERICAL SIMULATIONS

TURBULENCE: initial kinetic energy

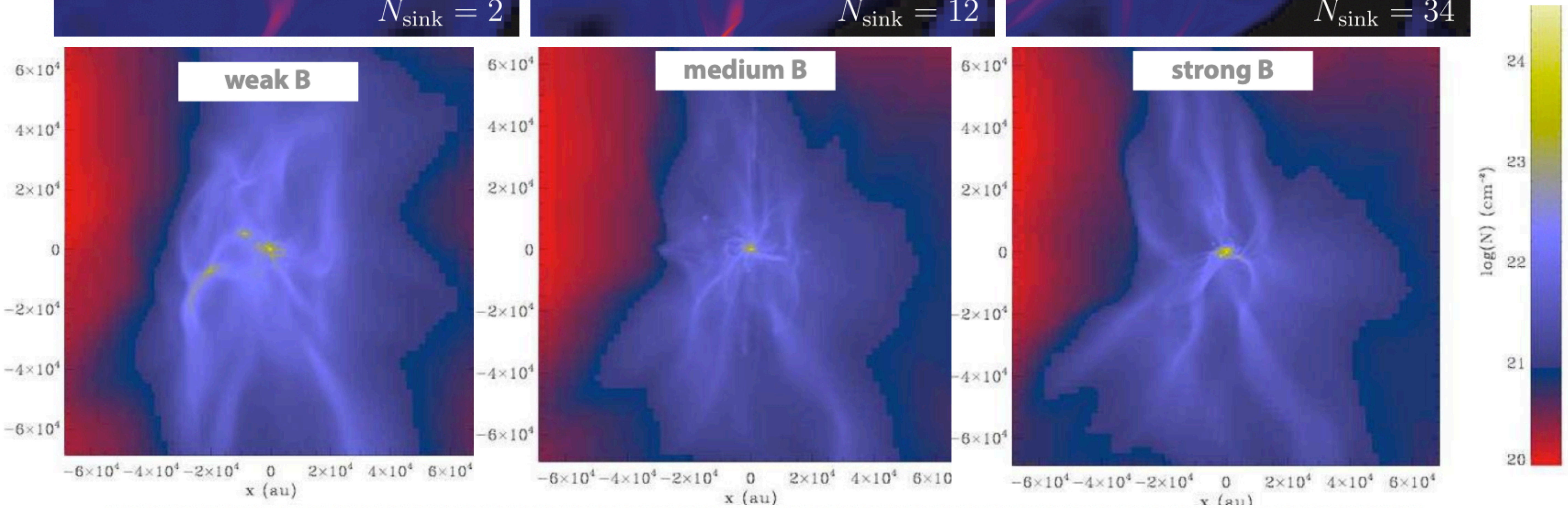
Mach number $= \sigma_{3D,nth}/c_s$



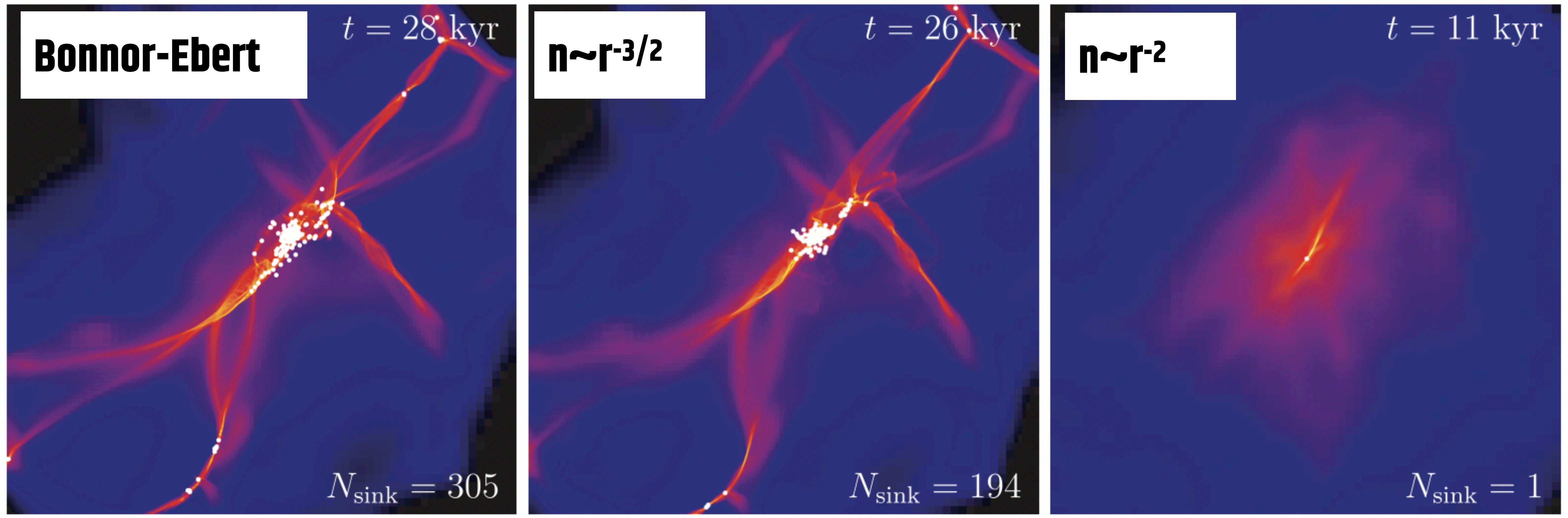
Girichidis et al. 2011; also Vázquez-Semadeni et al. 1996, Padoan & Norlund 2002, Schema & Klessen 2004, Federrath et al. 2008…

MAGNETIC FIELD: higher B-field suppress fragmentation

Hennebelle et al. 2011, Commerçon et al. 2011; also Vàzquez-Semadeni et al. 2005, 2011, Banerjee & Pudritz 2006, Price & Bate 2007, Myers et al. 2013…

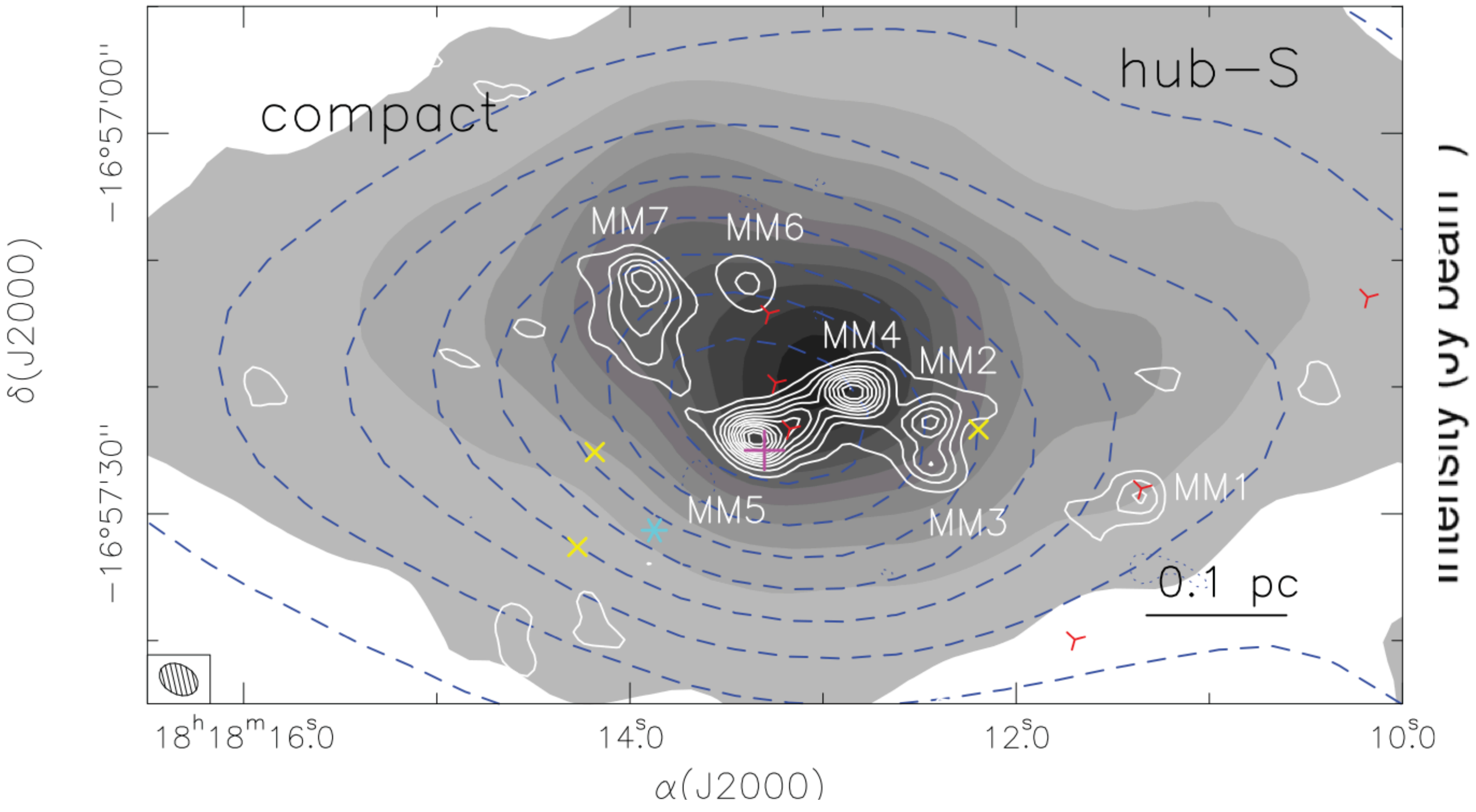


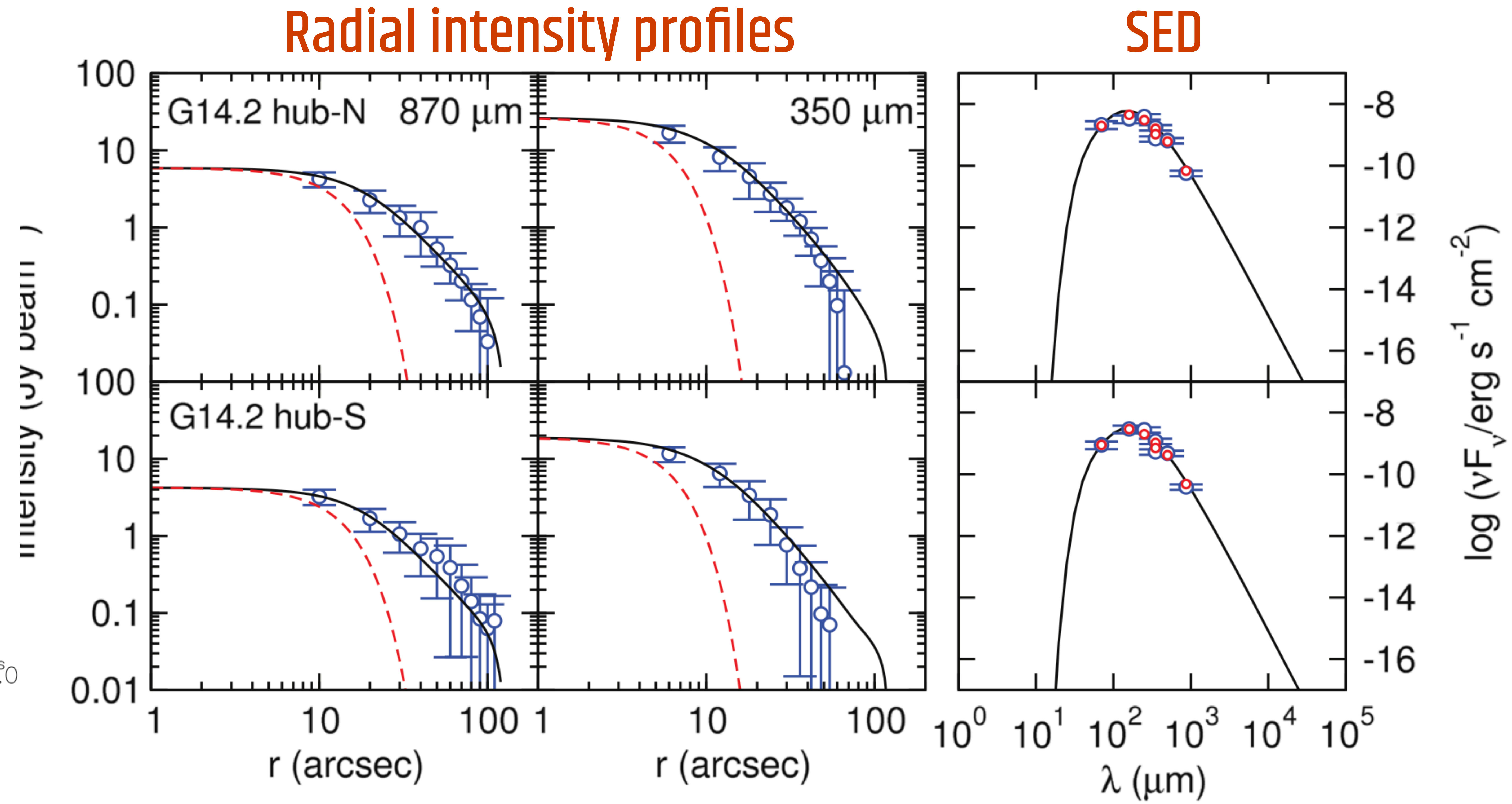
DENSITY STRUCTURE: higher fragmentation for flatter density profiles ($n \sim r^{-1}$)



Girichidis et al. 2011; also Myhill & Kaula 1992, Burkert et al. 1997…

DENSITY STRUCTURE OF MASSIVE CLUMPS





➡ Density structure: Plummer-like function or a power law

$$\rho(r) = \rho_c \left[1 + \left(\frac{r}{r_c} \right)^2 \right]^{-p/2}$$

$$\rho_c(r) = \rho_0 (r/r_0)^{-p}$$

➡ Temperature structure: power law function

$$T(r) = T_0 (r/r_0)^{-q} \qquad q = 2/(4+\beta)$$

➡ Dust opacity law: $\kappa_\nu = \kappa_0 (\nu/\nu_0)^\beta$

$\kappa_0 = 0.008991\ \mathrm{cm^2\,g^{-1}}$ at $\nu_0 = 230$ GHz Ossenkopf & Henning (1994)

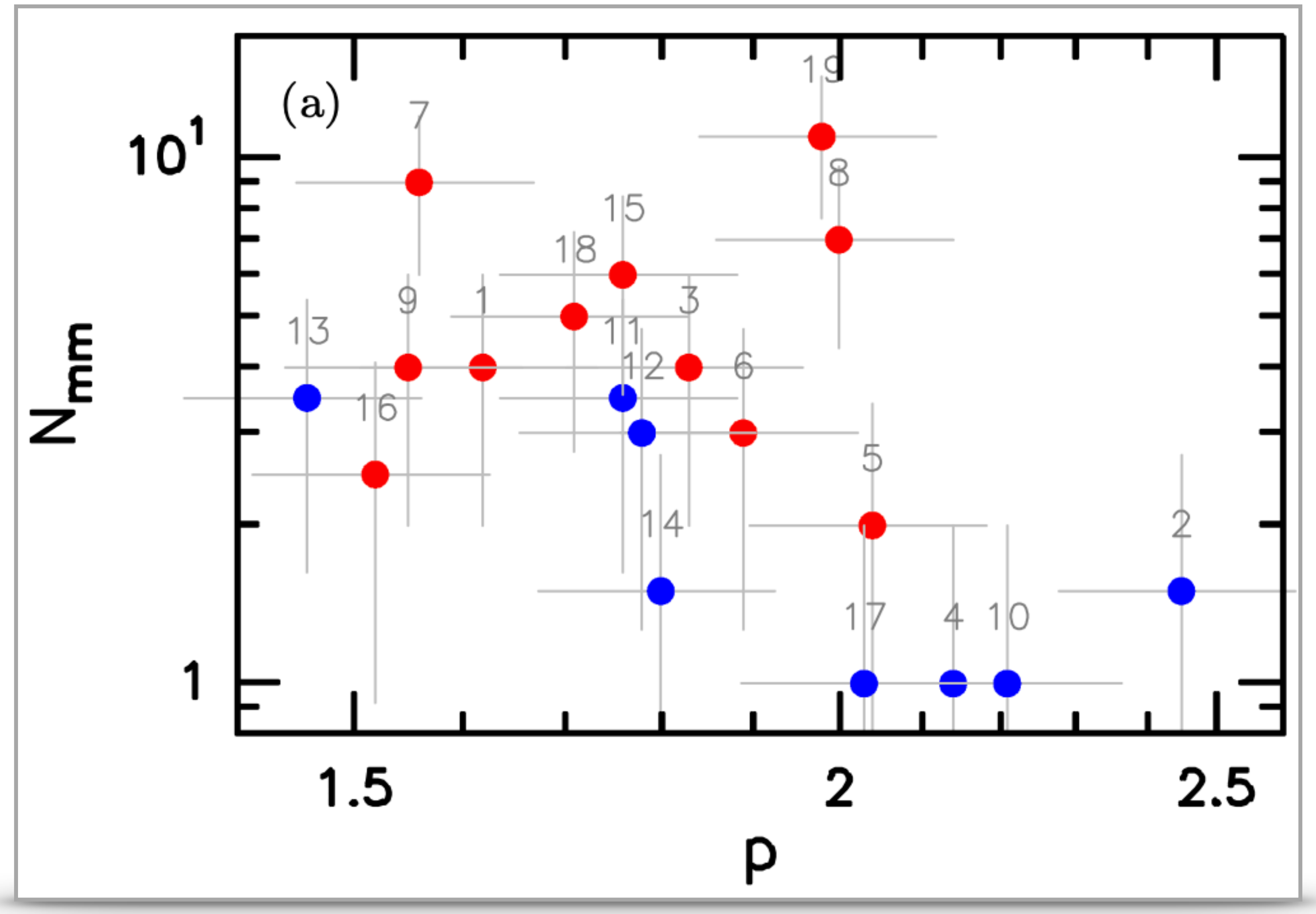
Busquet et al. (2016)

DENSITY STRUCTURE OF MASSIVE CLUMPS

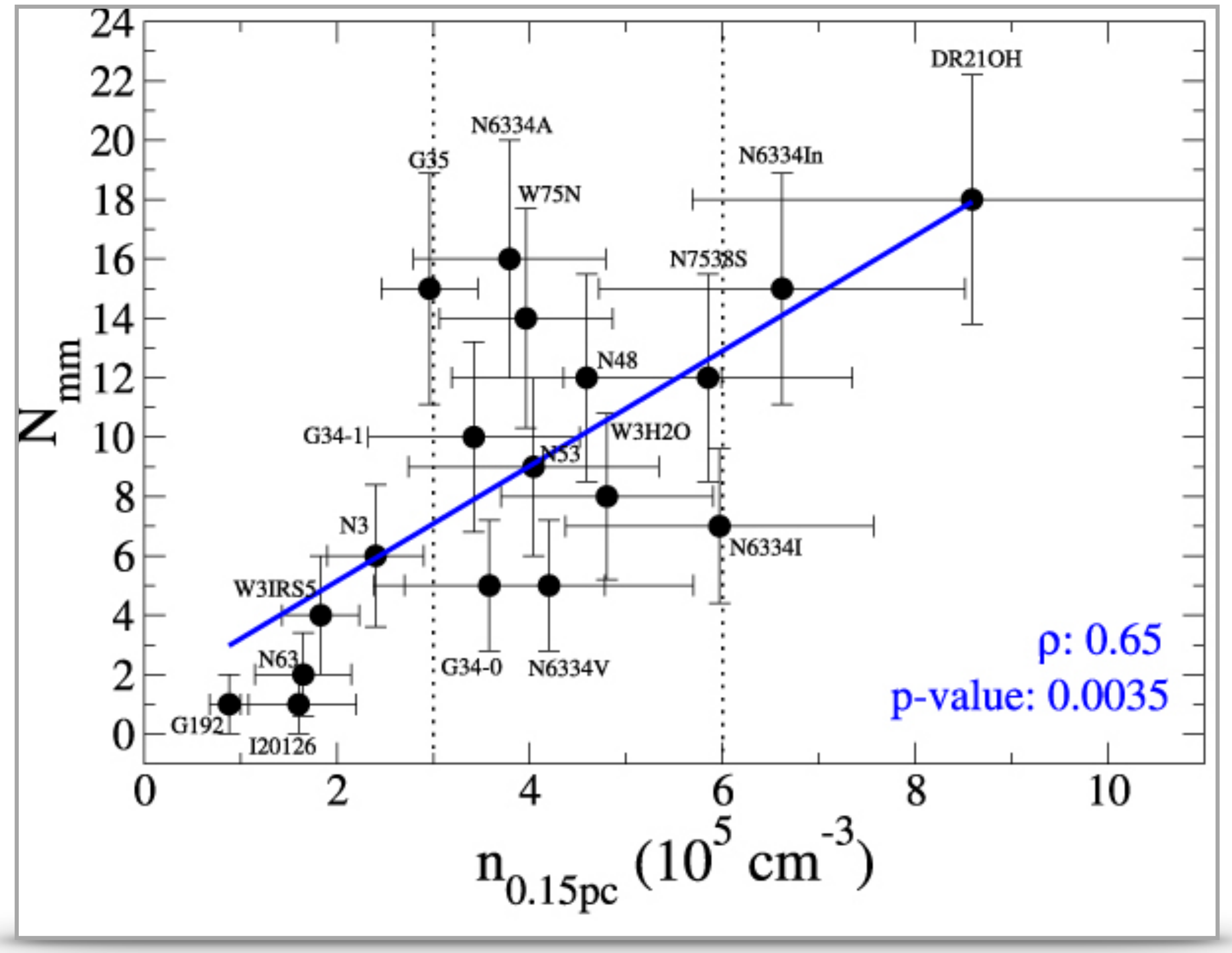
Free parameters fitted by the model

Source	β^a	$T_0{}^a$ (K)	$\rho_0{}^a$ (g cm^{-3})	$r_c/r_0{}^a$	p^a	$\chi_r{}^a$	$\rho_c{}^b$ (g cm^{-3})	q^b
hub-N	1.81 ± 0.08	51 ± 2	$(1.3 \pm 0.2) \times 10^{-15}$	21 ± 4	2.24 ± 0.04	0.69	$(1.4 \pm 0.6) \times 10^{-18}$	0.34
hub-S	1.89 ± 0.08	45 ± 2	$(1.0 \pm 0.2) \times 10^{-15}$	20 ± 3	2.24 ± 0.04	0.76	$(1.2 \pm 0.5) \times 10^{-18}$	0.34

➡ Low fragmentation levels in clumps with steeper density profiles.



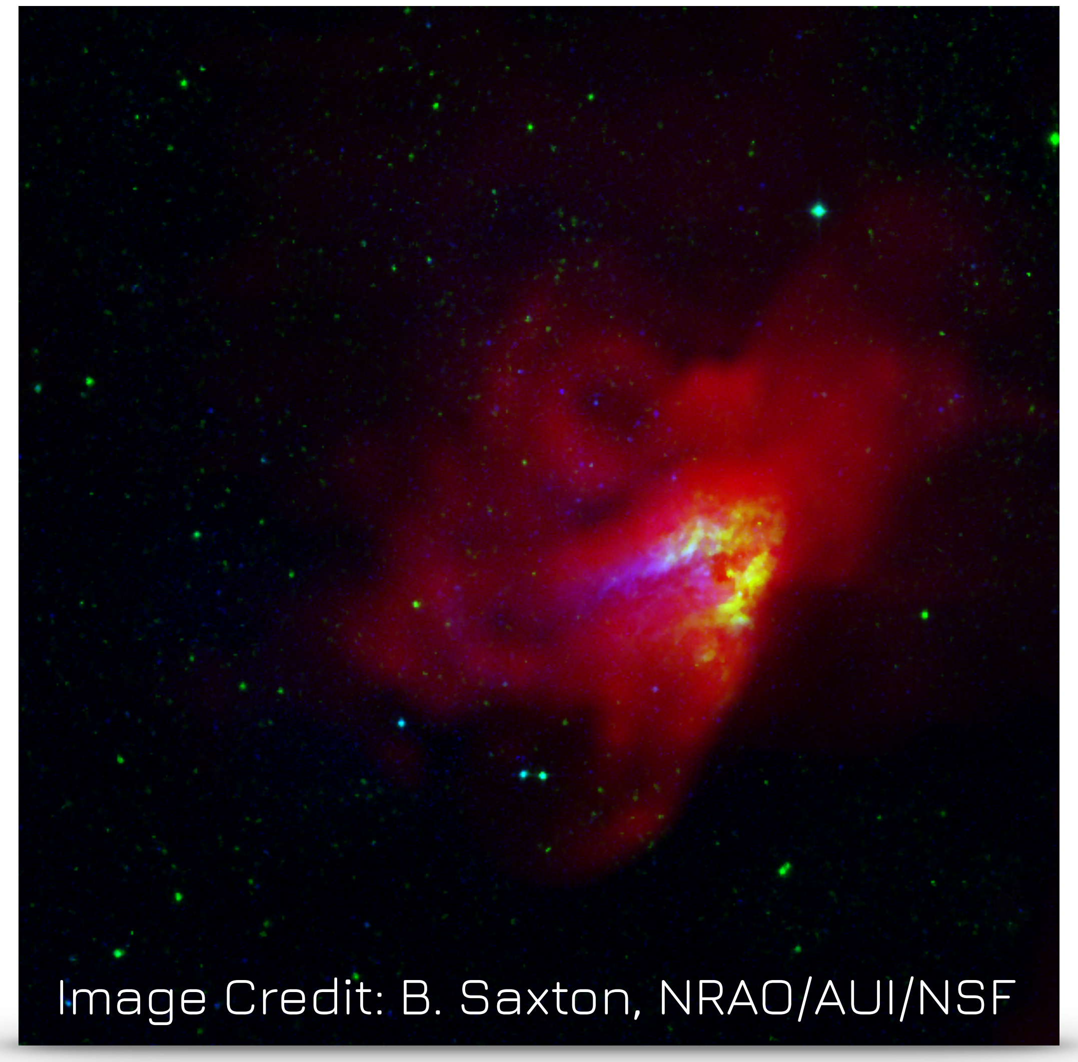
➡ High fragmentation levels in clumps with higher density



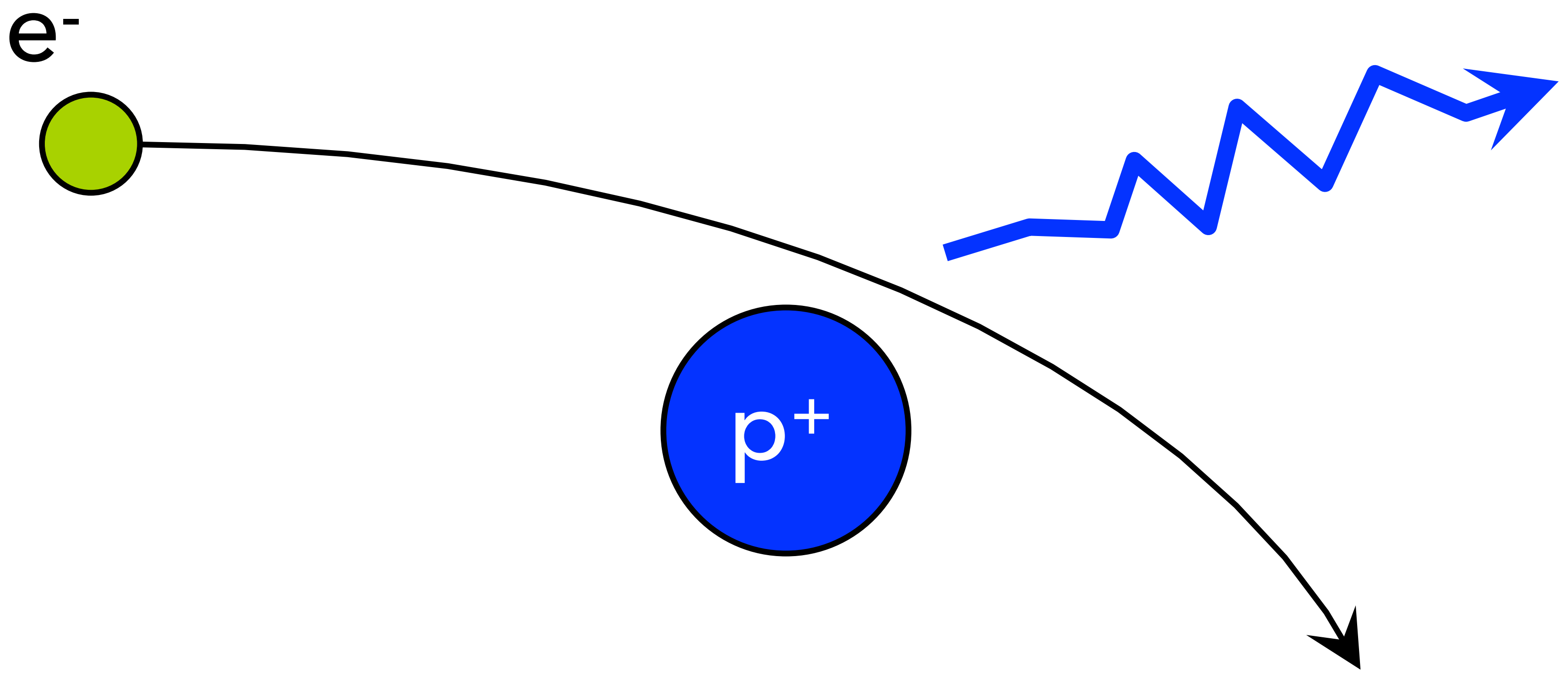
See: Palau et al. (2014), Busquet et al. (2016), Palau et al. (2021)

FREE-FREE CONTAMINATION

➡ HII REGIONS: radiation produced by the acceleration of protons and electrons in an ionised medium



$$e^{-} + p^{+} \longrightarrow e^{-} + p^{+} + \text{photon}$$



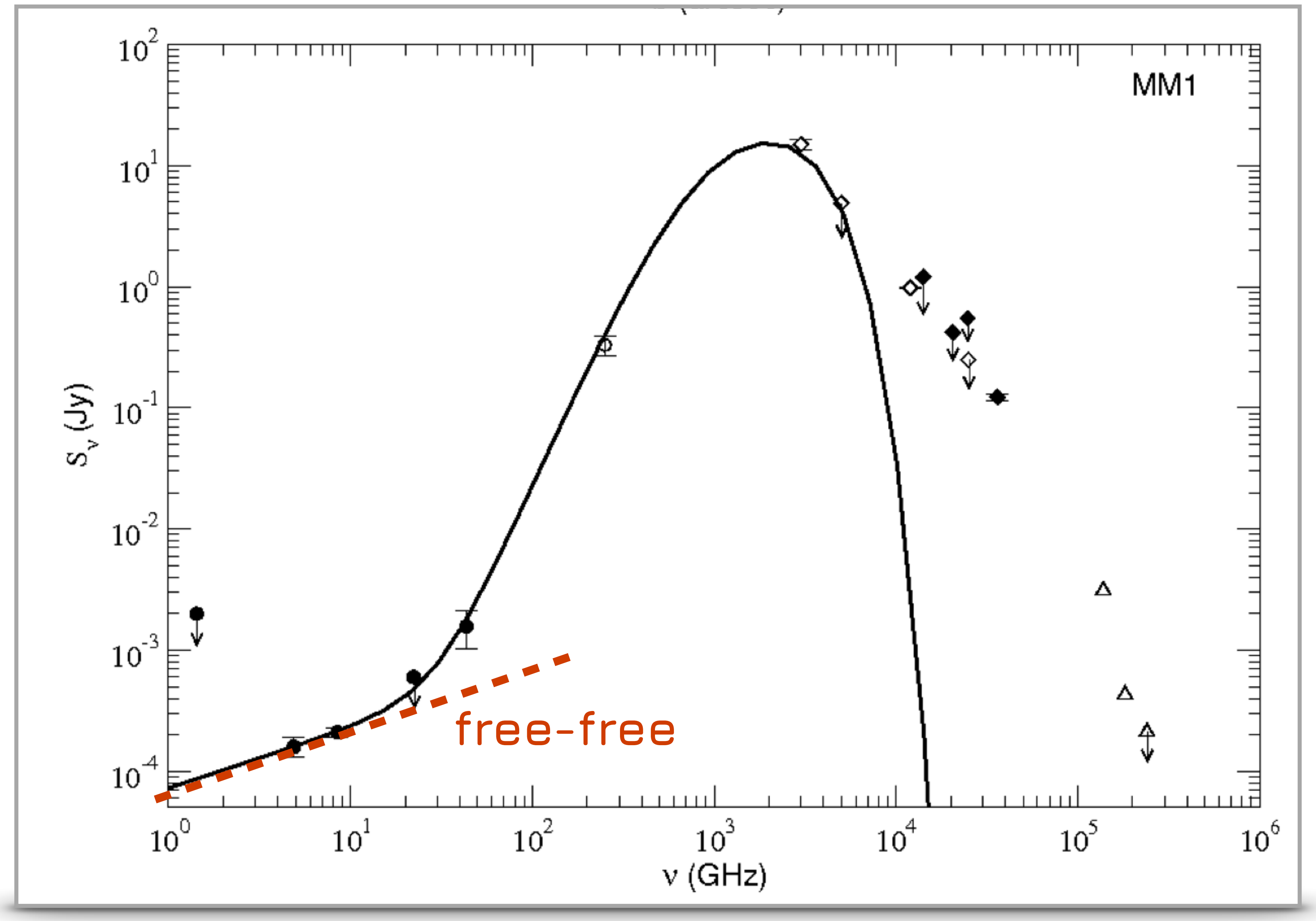
Infrared radiation: dust clouds

Optical light and Radio emission:

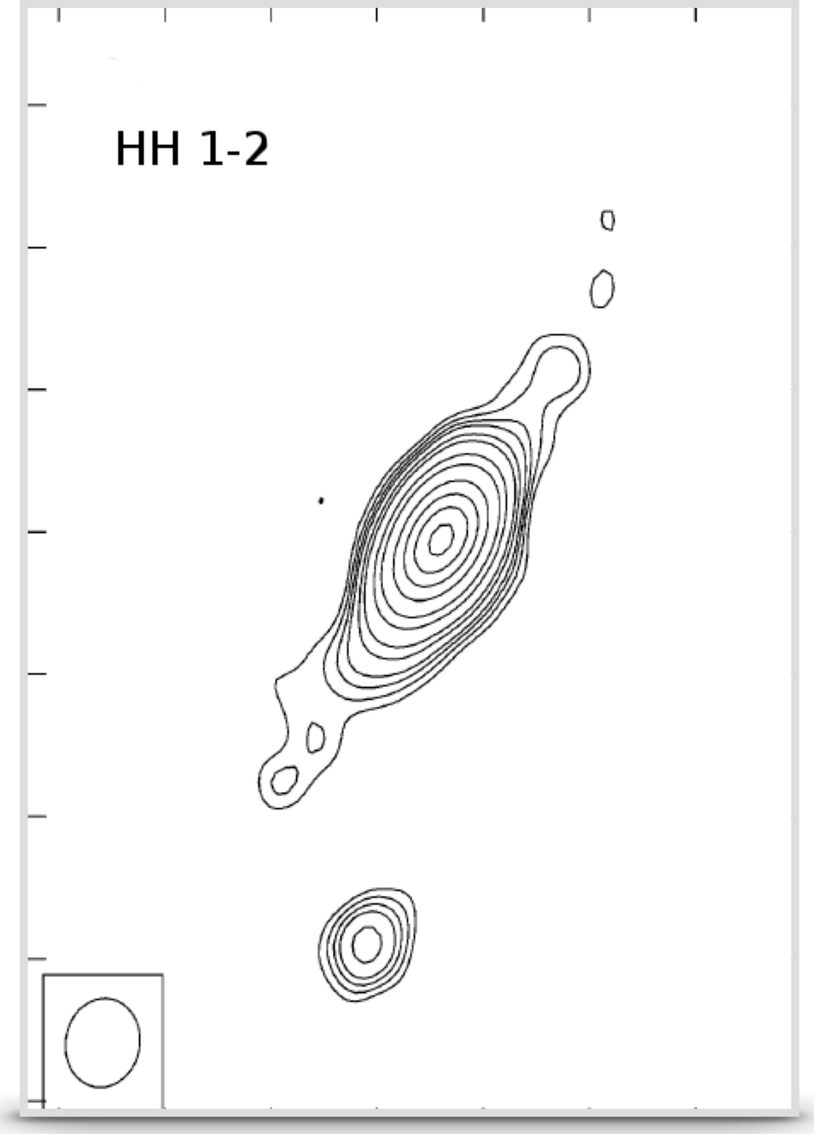
hot, young stars ionise the gas

➡ THERMAL RADIO JETS: ionised by shocks (see Anglada, Rodríguez, Carrasco-González (2018) for a review

$$S_{\nu} \propto \nu^{0.6}$$



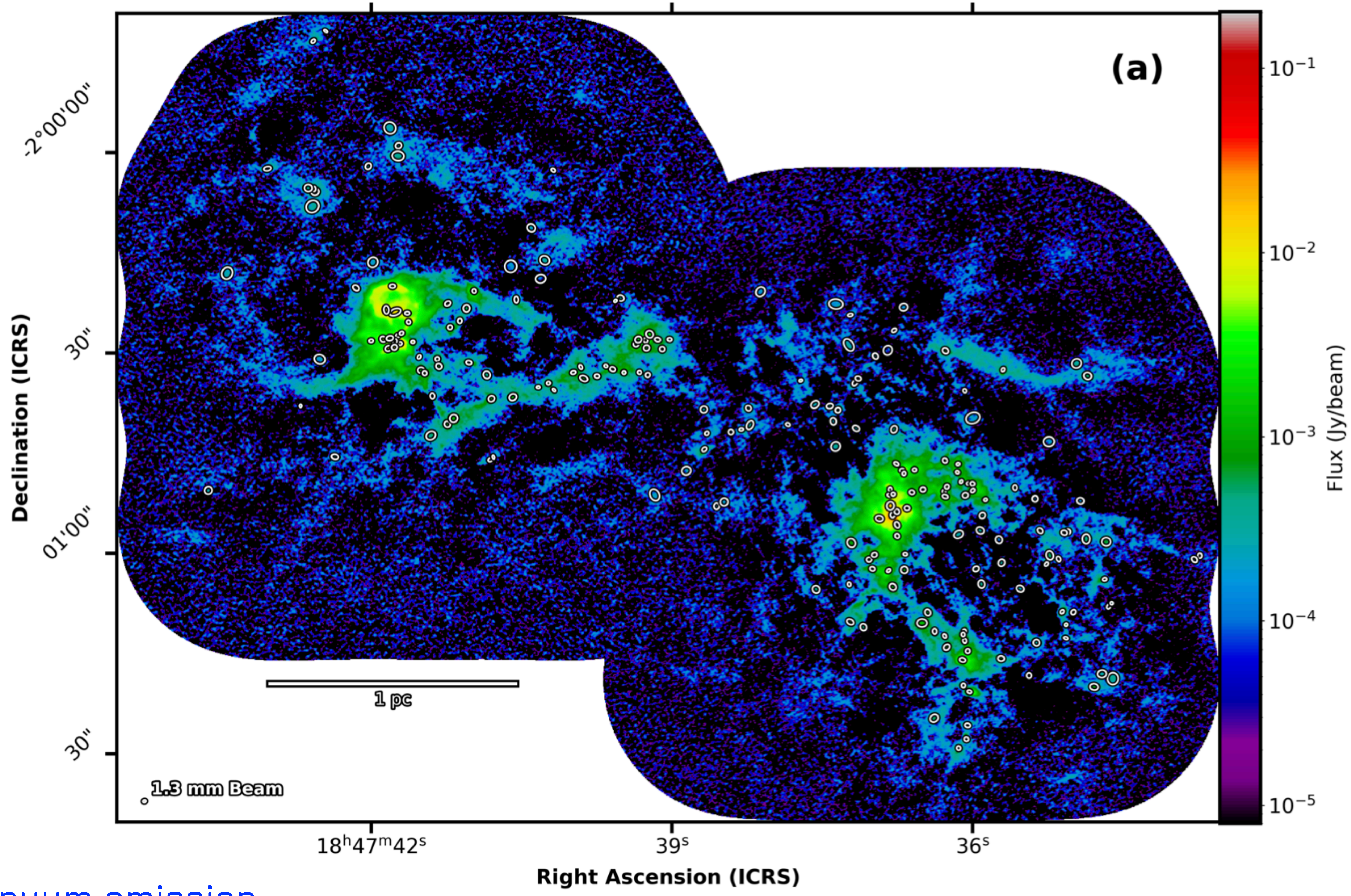
Busquet et al. (2009)



Rodriguez et al. (2000)

FREE-FREE CONTAMINATION

ALMA 1.3 mm continuum image of the W43-MM2&MM3 protocluster cloud

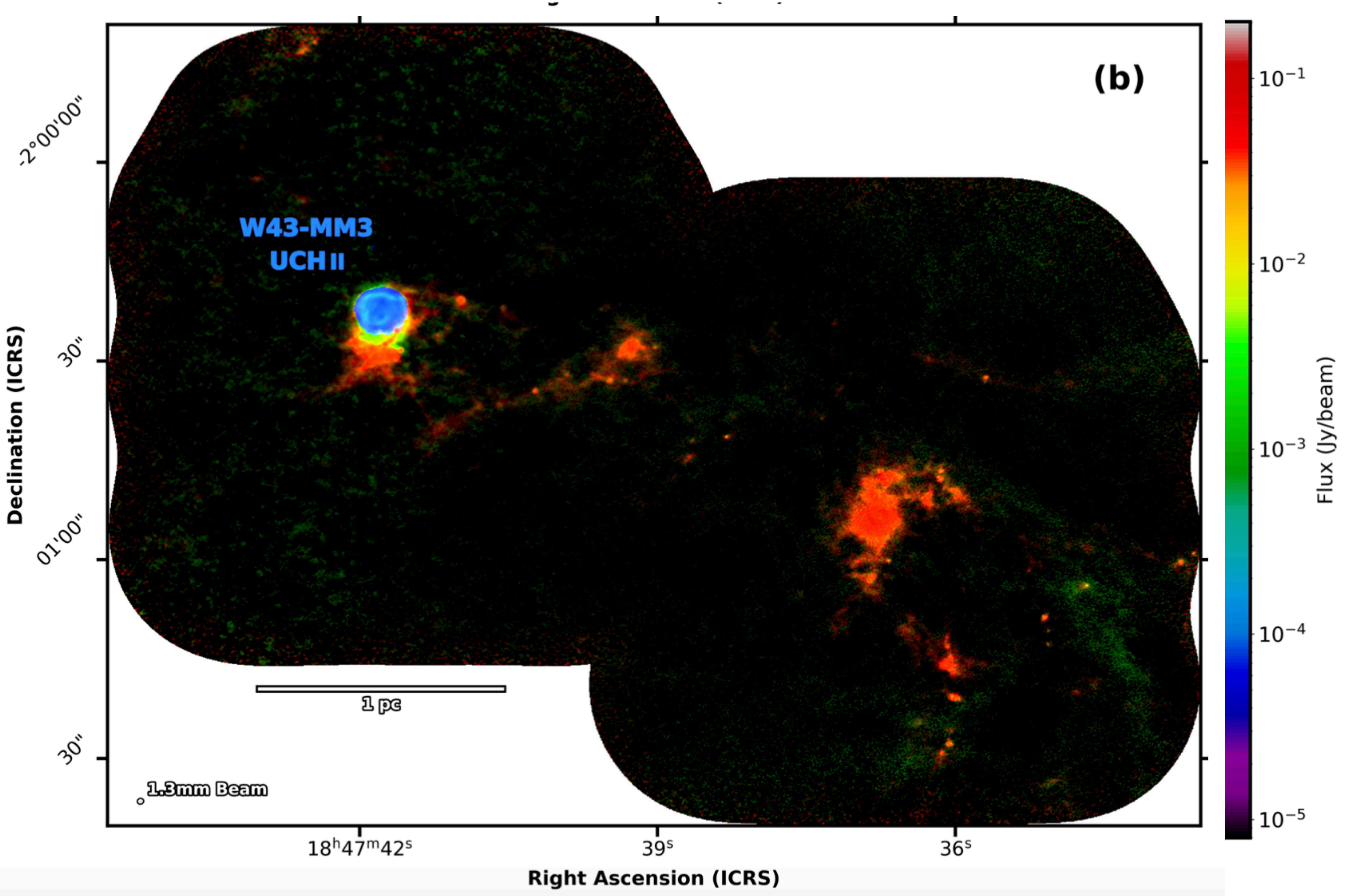


1.3mm
3 mm
H41α: free-free continuum emission

Pouteau et al. (2021)

FREE-FREE CONTAMINATION

ALMA 1.3 mm continuum image of the W43-MM2&MM3 protocluster cloud



1.3mm
3 mm
H41α: free-free continuum emission

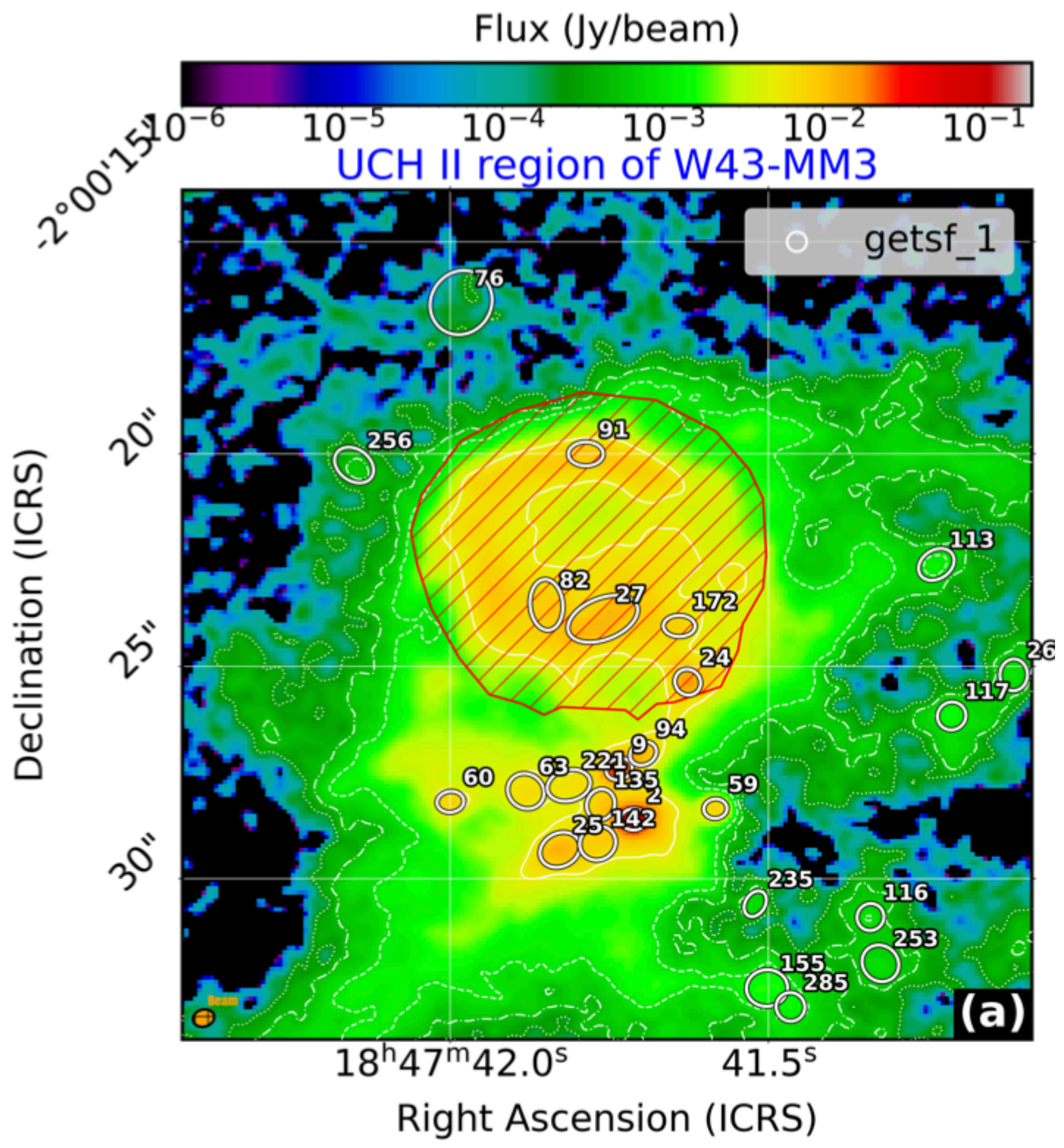
Pouteau et al. (2021)

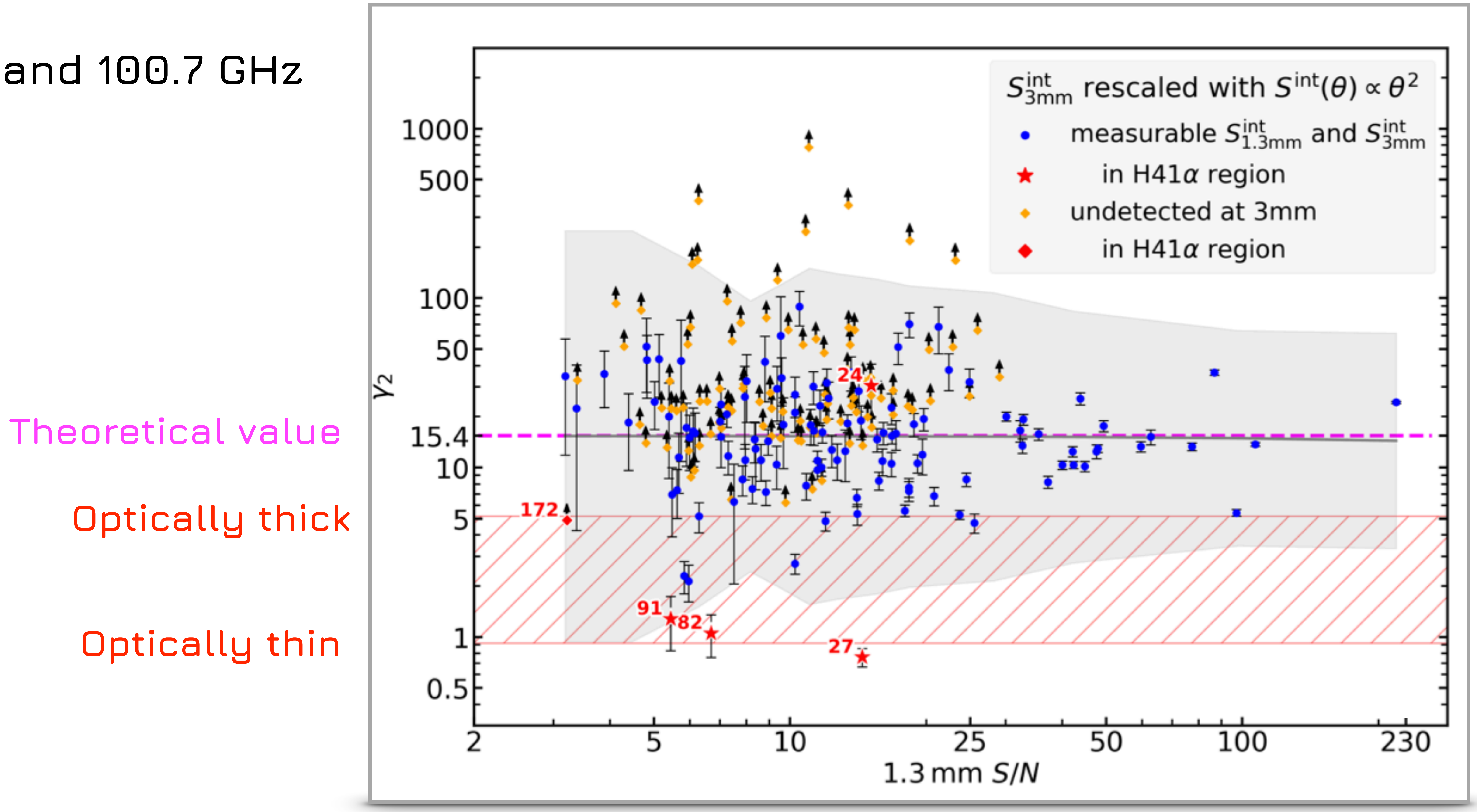
FREE-FREE CONTAMINATION

➡ Theoretical flux ratio of thermal dust emission assuming optically thin emission

$$\gamma = \frac{S^{\text{int}}_{1.3\text{mm}}}{S^{\text{int}}_{3\text{mm}}} = \frac{\kappa_{1.3\text{mm}}}{\kappa_{3\text{mm}}} \frac{B_{1.3\text{mm}}(T)}{B_{3\text{mm}}(T)} = \frac{\kappa_{1.3\text{mm}}}{\kappa_{3\text{mm}}} \frac{\nu^3_{1.3\text{mm}}}{\nu^3_{\nu_{3\text{mm}}}} \frac{e^{h\nu_{1.3\text{mm}}/\kappa_B T_d} - 1}{e^{h\nu_{1.3\text{mm}}/\kappa_B T_d} - 1} \simeq 15.4$$

➡ T_{dust}=23 K, frequencies: 228.9 GHz and 100.7 GHz





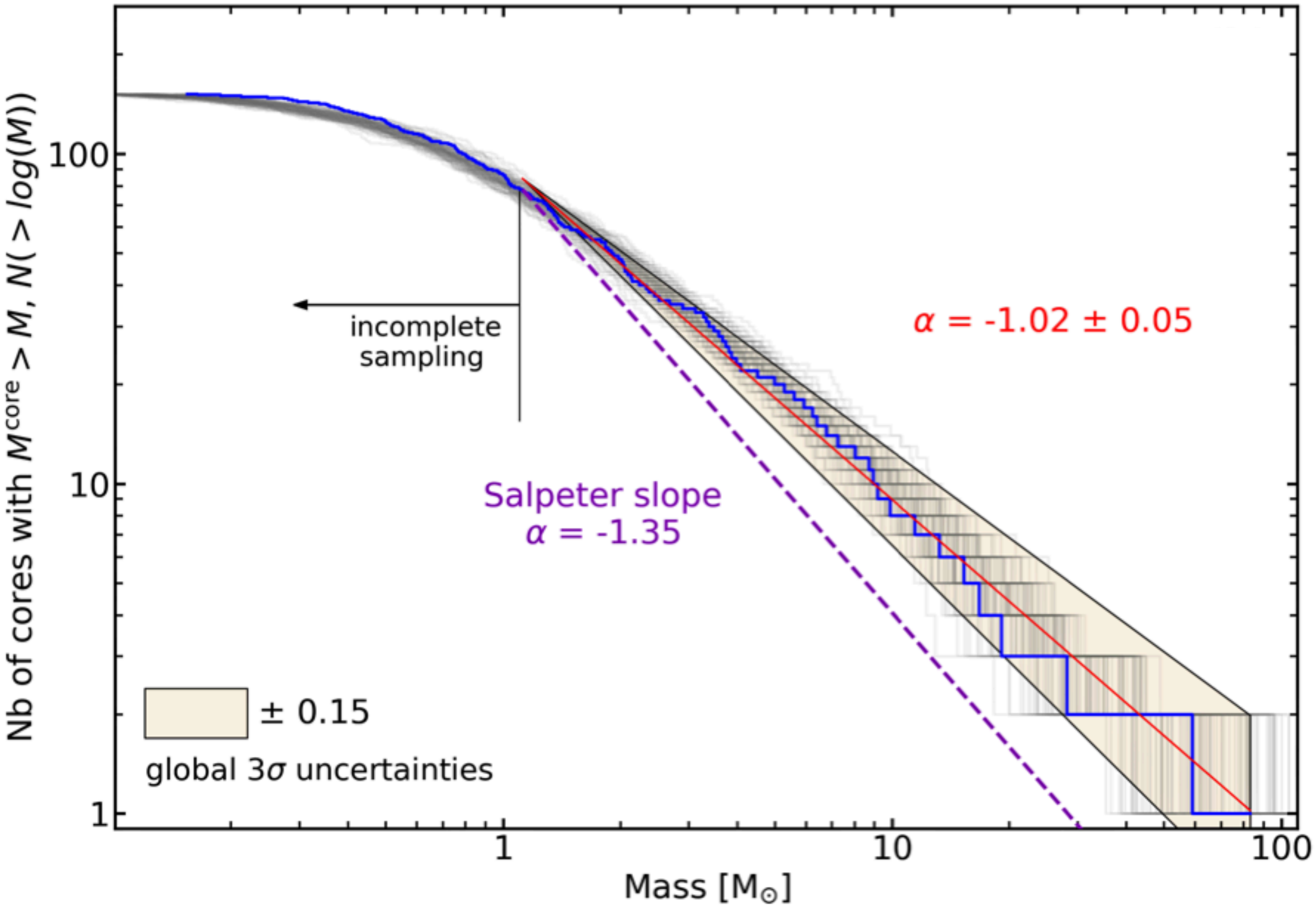
Pouteau et al. (2021)

THE STELLAR INITIAL MASS FUNCTION

➡ IMF: characterizes the mass distribution of stars above 0.01 M_{Sun}.

➡ Found to display a universal (Saltpeter 1955, Scalo 1986, see also Chabrier 2005, Bastian et al. 2010, Hopkins 2012, Kroupa et al. 2013)

$$\frac{dN}{d\log M} \propto M^{-1.35}$$



Pouteau et al. (2021)