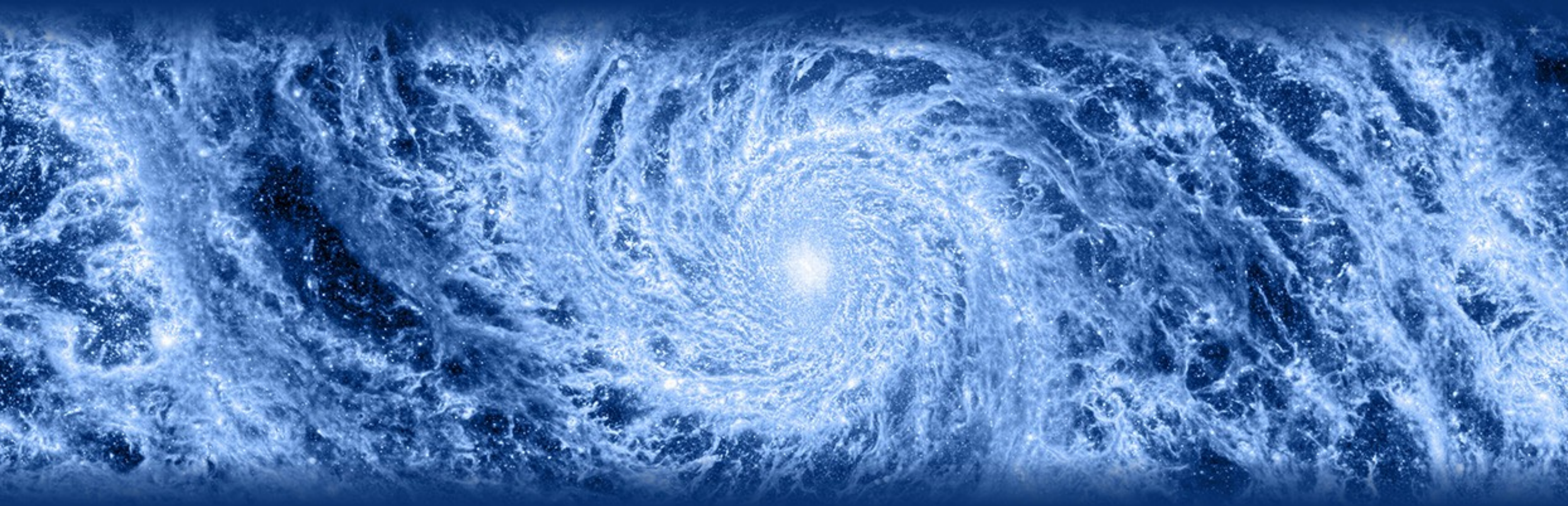
Galaxies

Prof. Benedikt Diemer

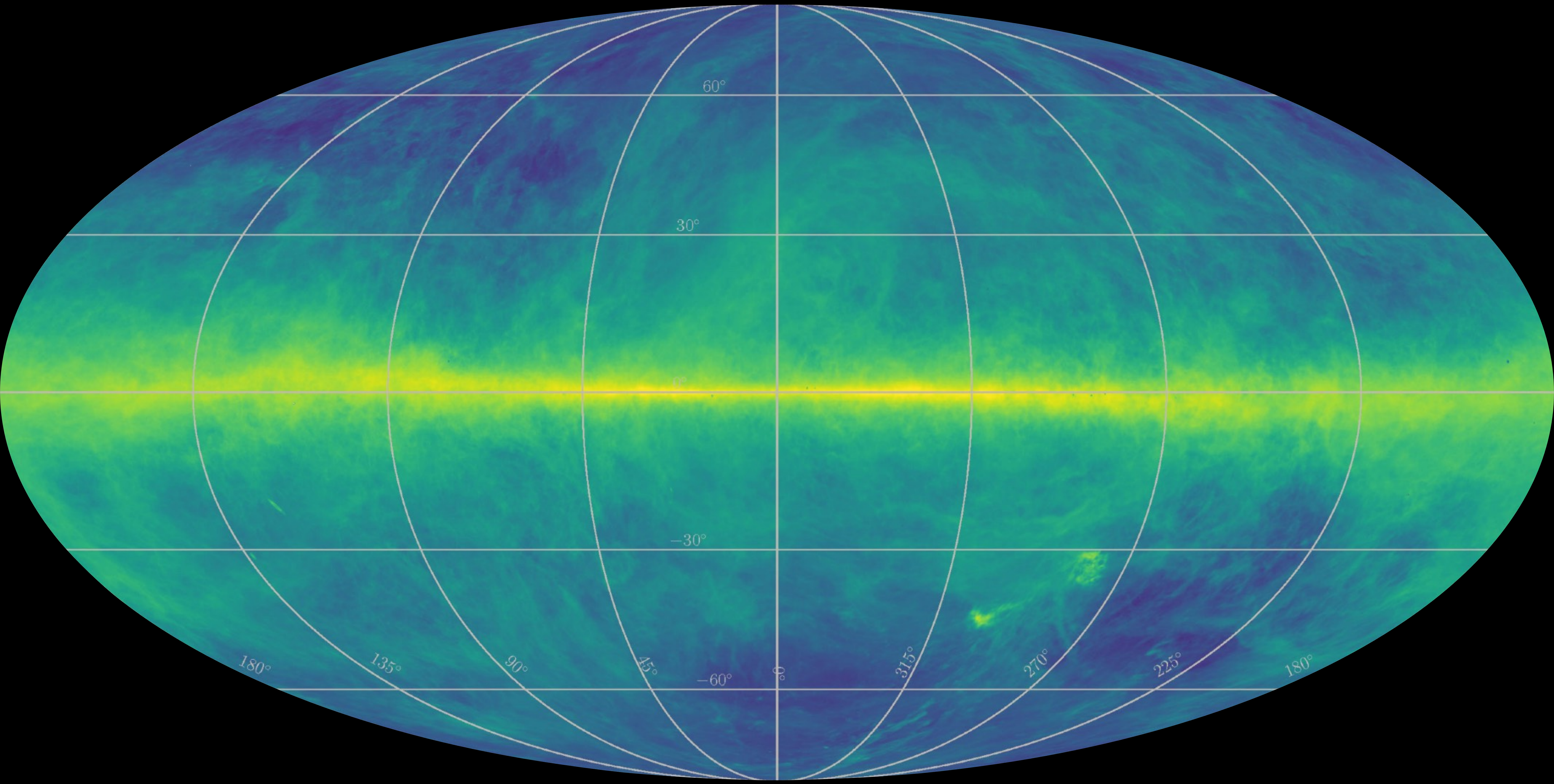


Chapter 7 • Stars and stellar populations

§7.1 • Star formation

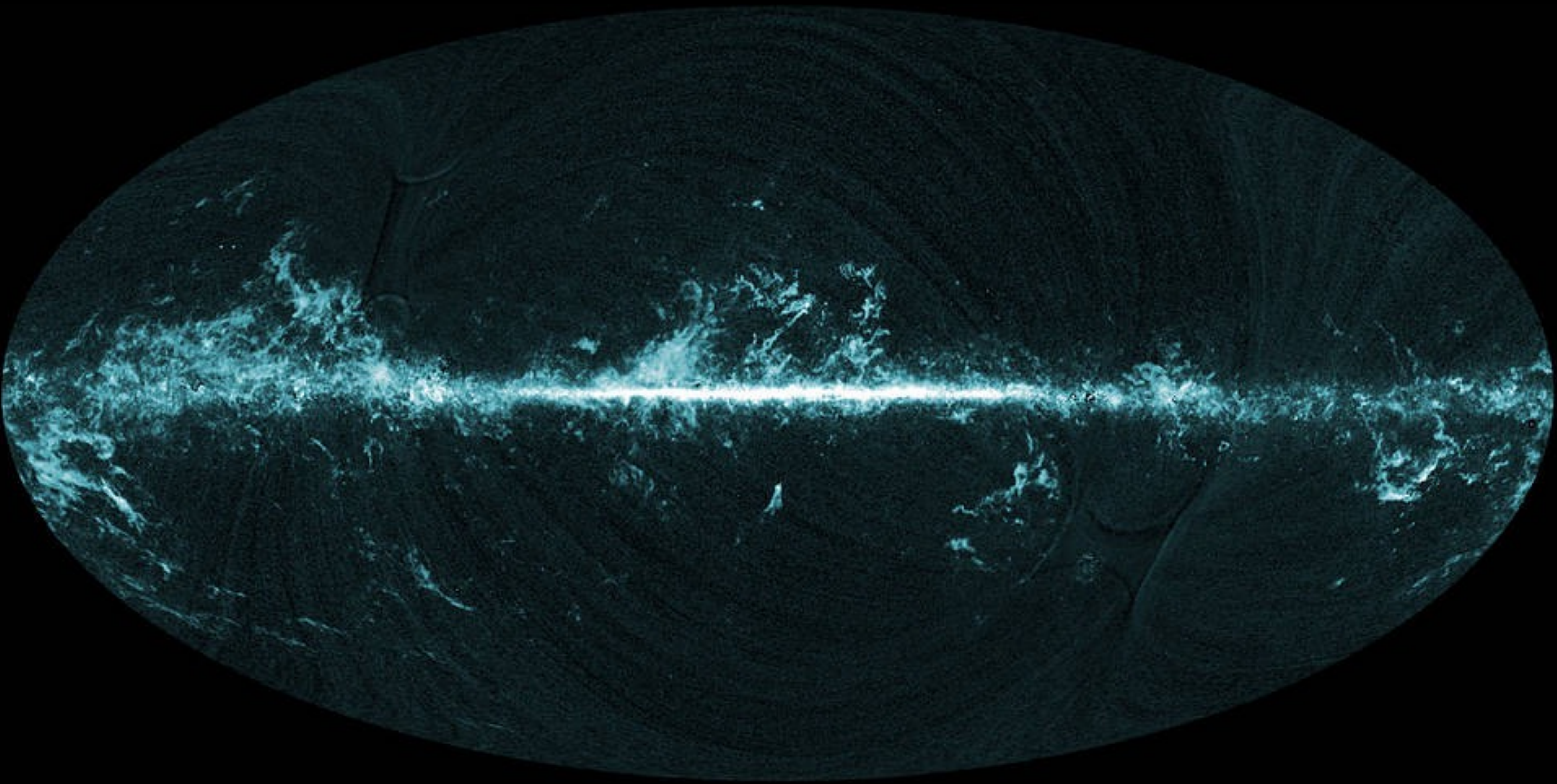
§7.1.1 • The interstellar medium and molecular clouds

21 cm / radio / neutral hydrogen atoms



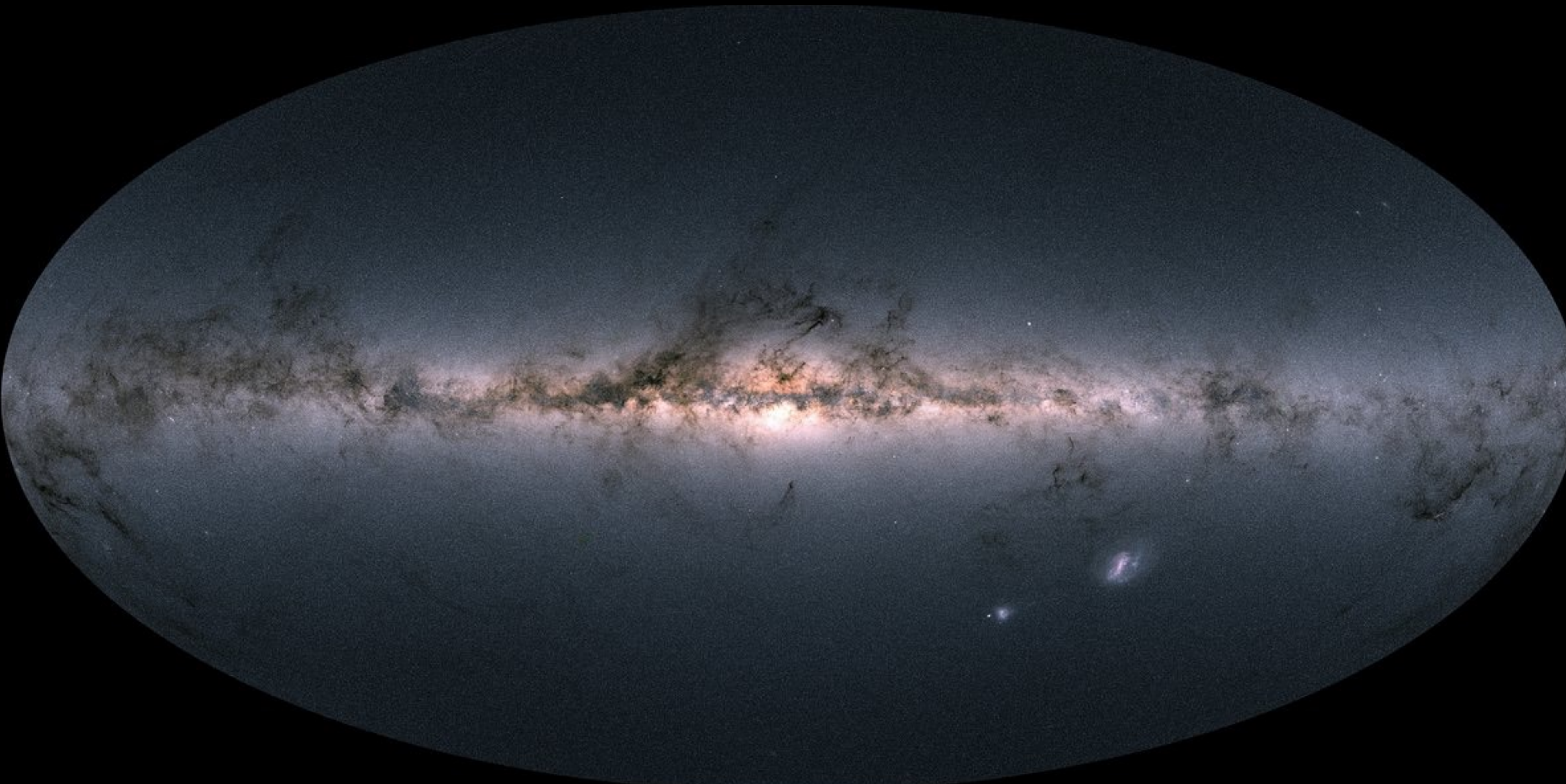
Effelsberg + Parkes surveys

2.6 mm / microwave / carbon monoxide molecules



Planck satellite

300-1000 nm / optical / stars



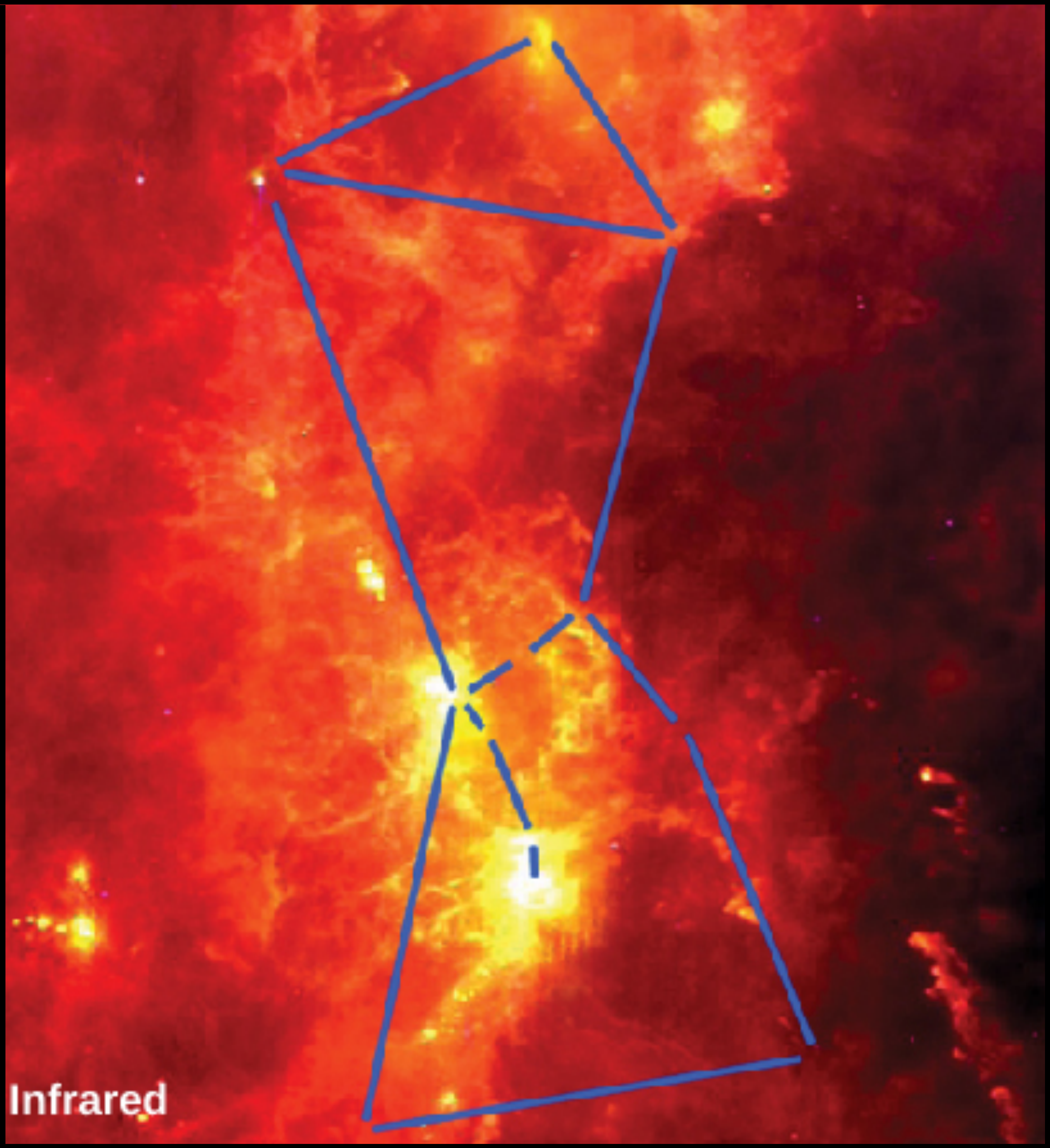
GAIA satellite

Gas phases (in the Milky Way)

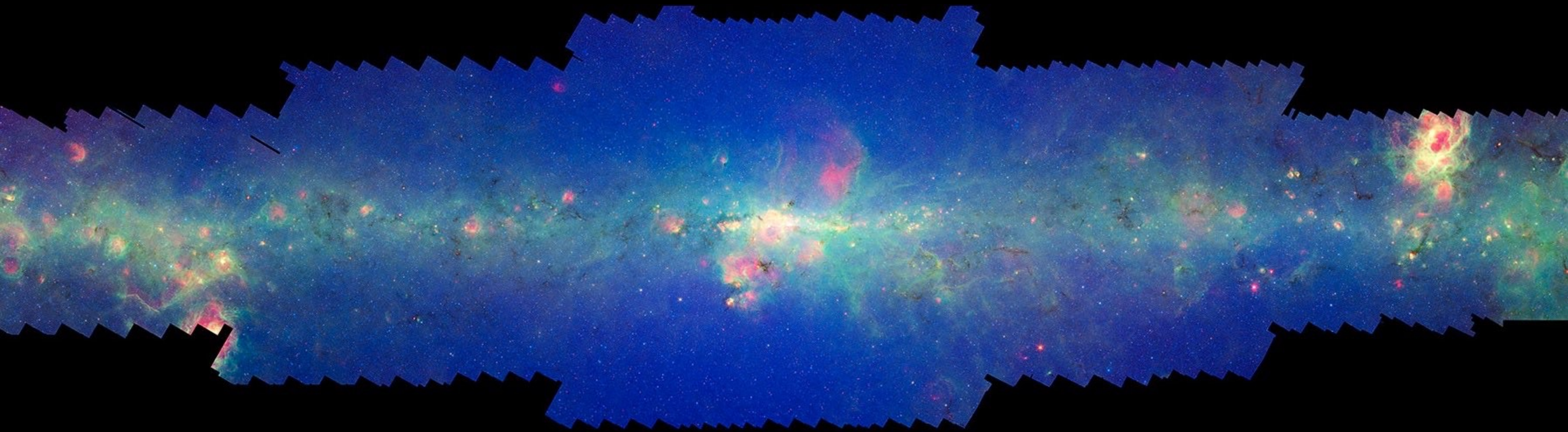
	Phase	T (K)	n_H (cm^{-3})	f_V -	P/k_B (K/cm^3)	Comments
H II 23%	**Hot ionized medium (HIM)**	$10^{5.7}$	0.004	0.5	4400	Collisionally ionized, shock-heated by supernovae and stellar winds
	H II regions	10000	0.1-10^4	0.01	varies	Photo-ionized nebulae around stars; density and pressure vary across these bubbles
	Warm ionized medium (WIM)	8000	0.2	0.1	4400	Diffuse photo-ionized gas, large scatter in temperature and density
H I 60%	**Warm neutral medium (WNM)**	8000	0.5	0.4	4400	About 60% of HI by mass; in pressure equilibrium witn CNM
	Cool neutral medium (CNM)	100	40	0.01	4400	Significant fraction of the mass despite small volume filling fraction
H_2 17%	**Diffuse molecular gas**	50	150	0.001	4400	Self-shielded against dissociation, but not dense enough to form stars
	Molecular clouds	10-50	10^3-10^6	0.0001	>10000	The site of star formation; more or less gravitationally bound

§7.1.2 • The (in)efficiency of star formation

Star-forming regions

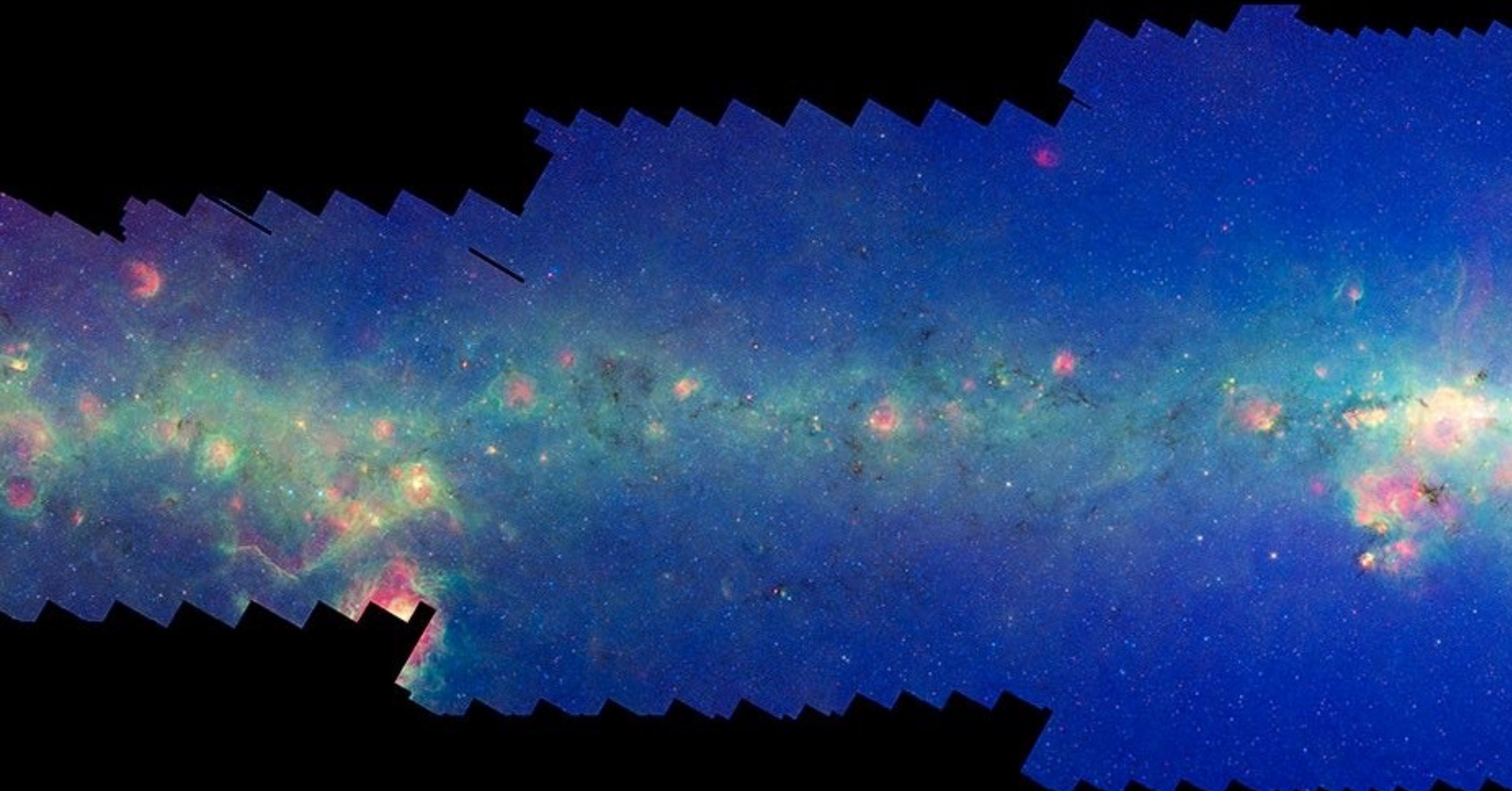


The Milky Way from our position (gas)

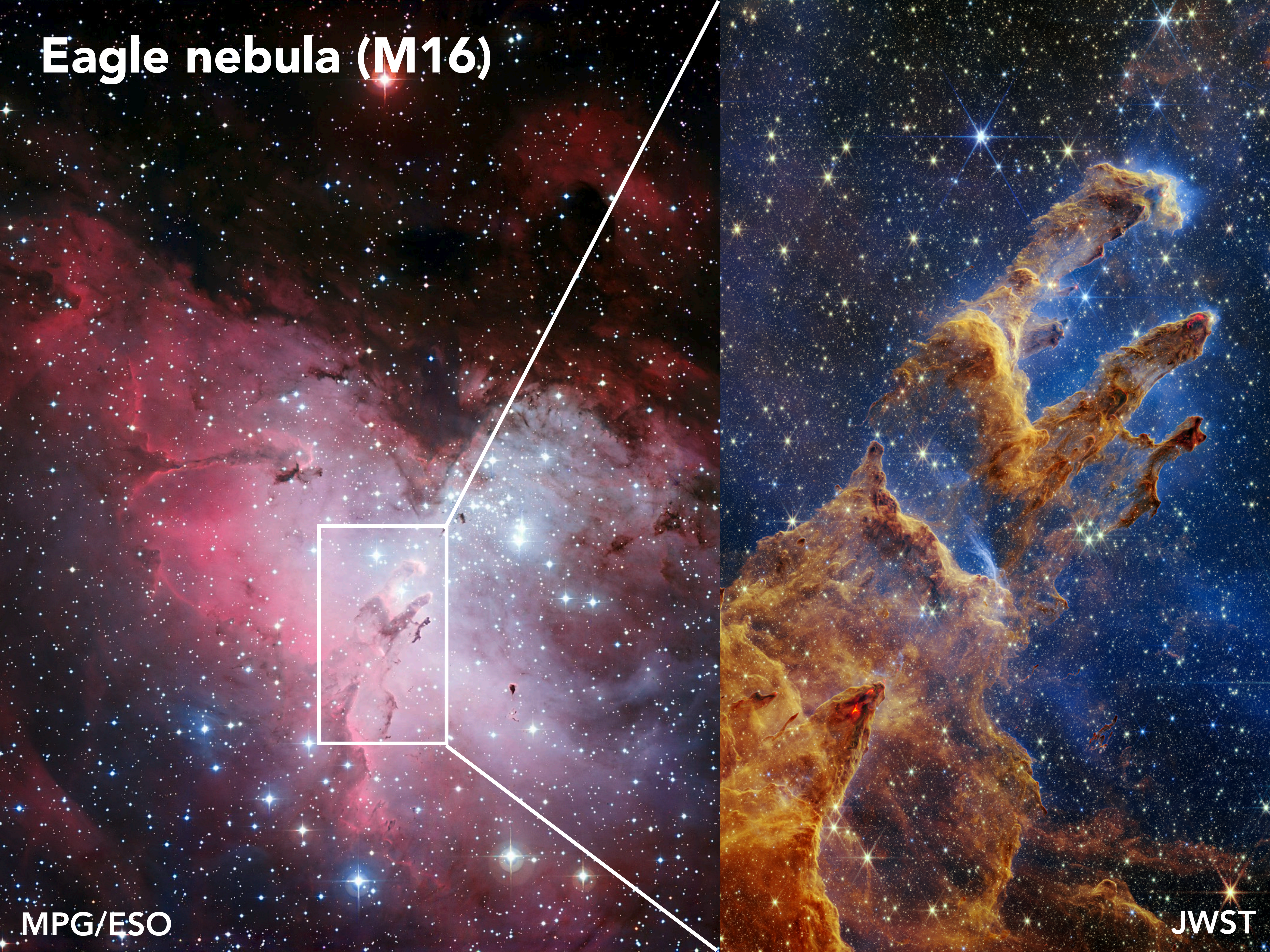


Spitzer Space Telescope

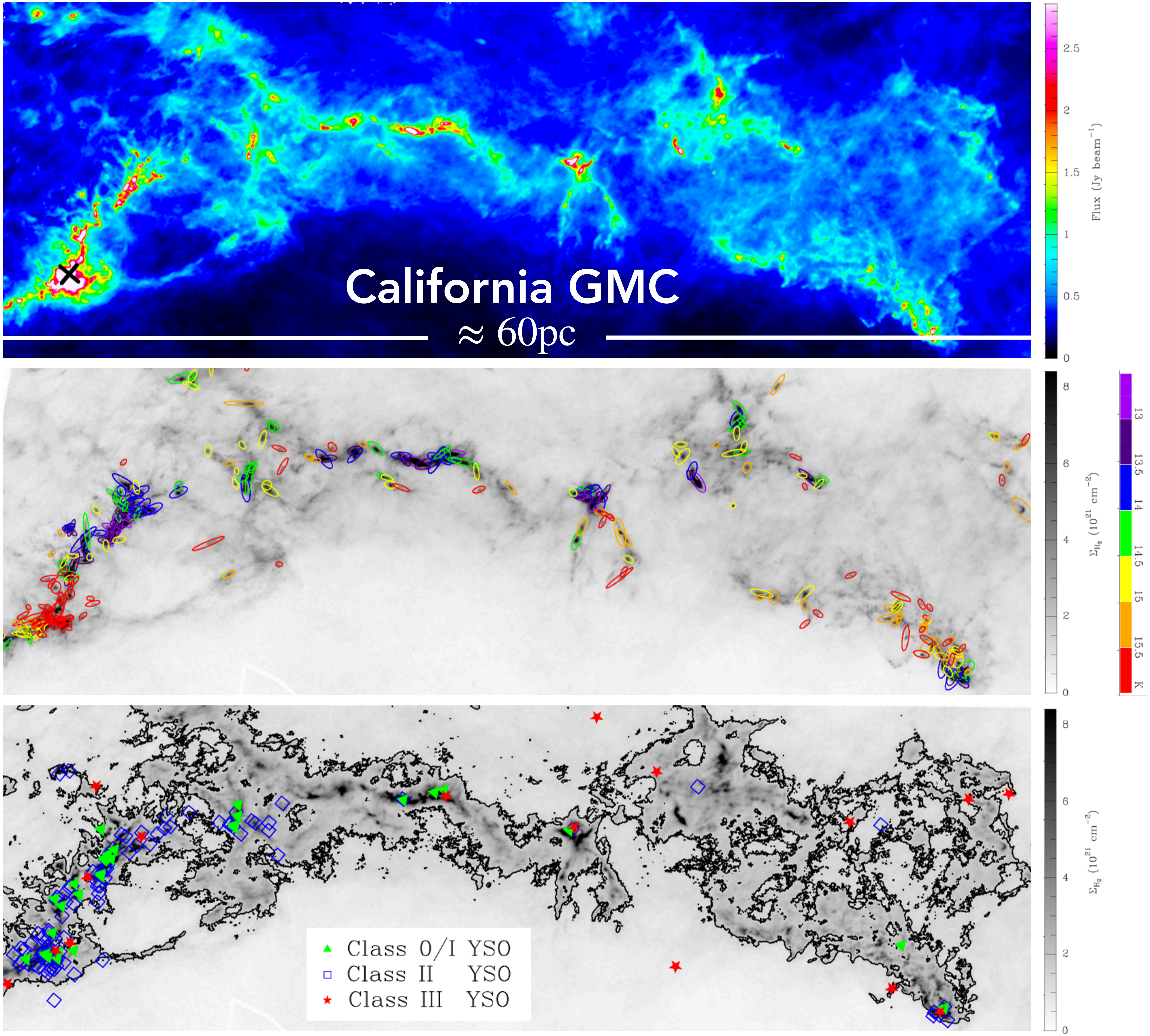
The Milky Way from our position (gas)



Spitzer Space Telescope


Eagle nebula (M16)
MPG/ESO
JWST

JWST



Dust surface density

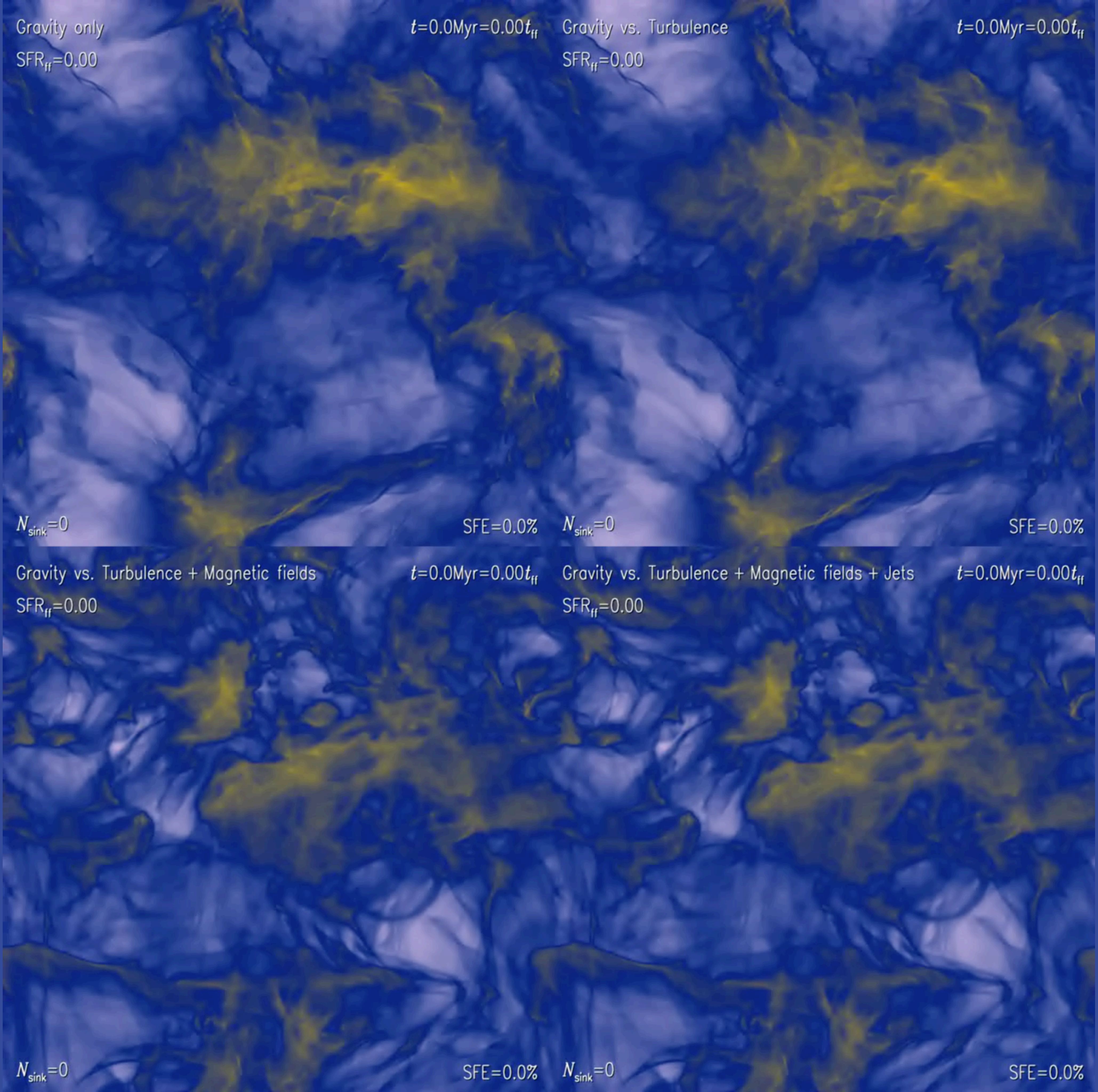
Cold molecular cores

Young stellar objects

Zhang et al. 2019

Gravity only

Gravity + turbulence

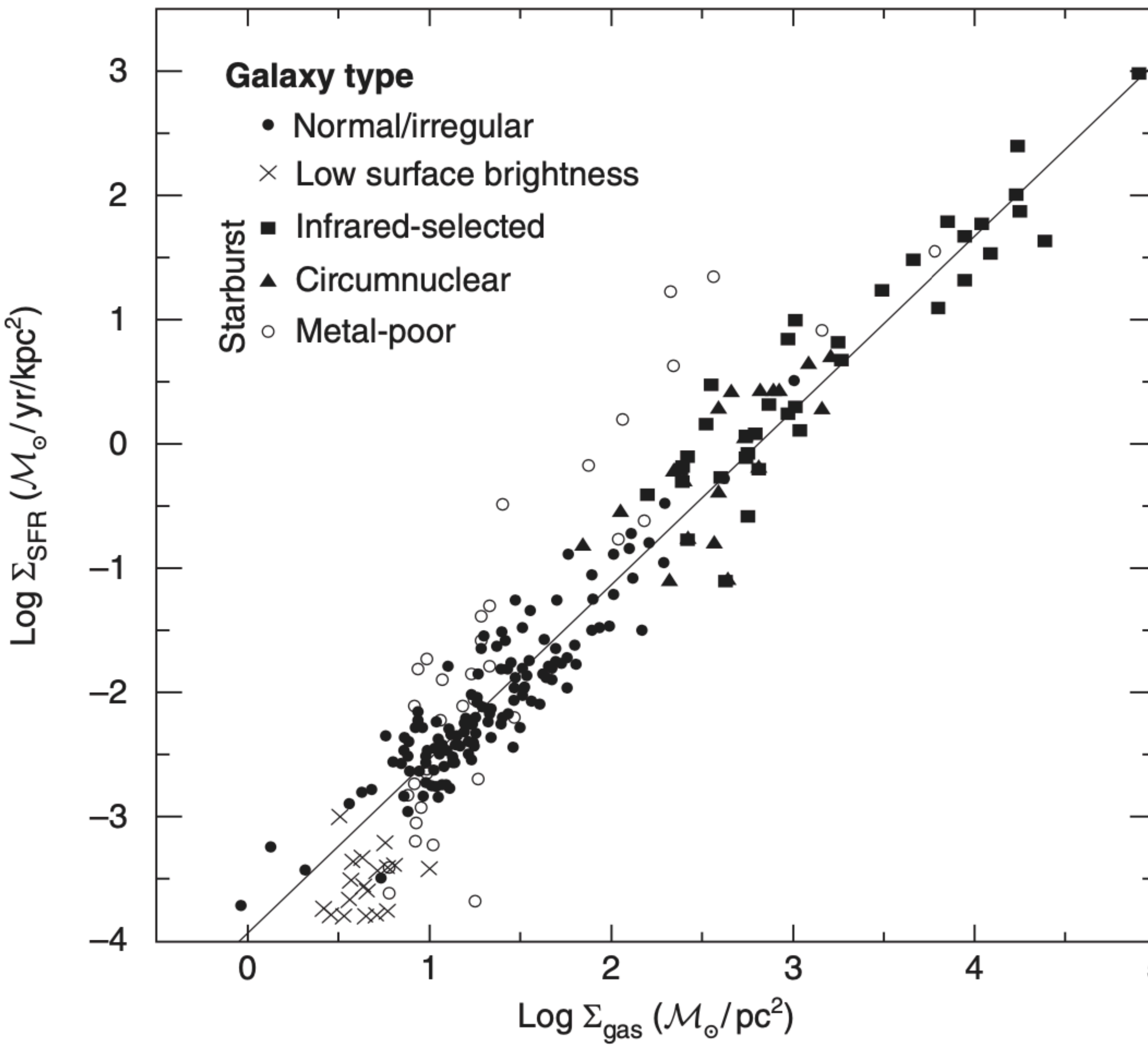


Gravity + turbulence + B

Gravity + turb. + B + jets

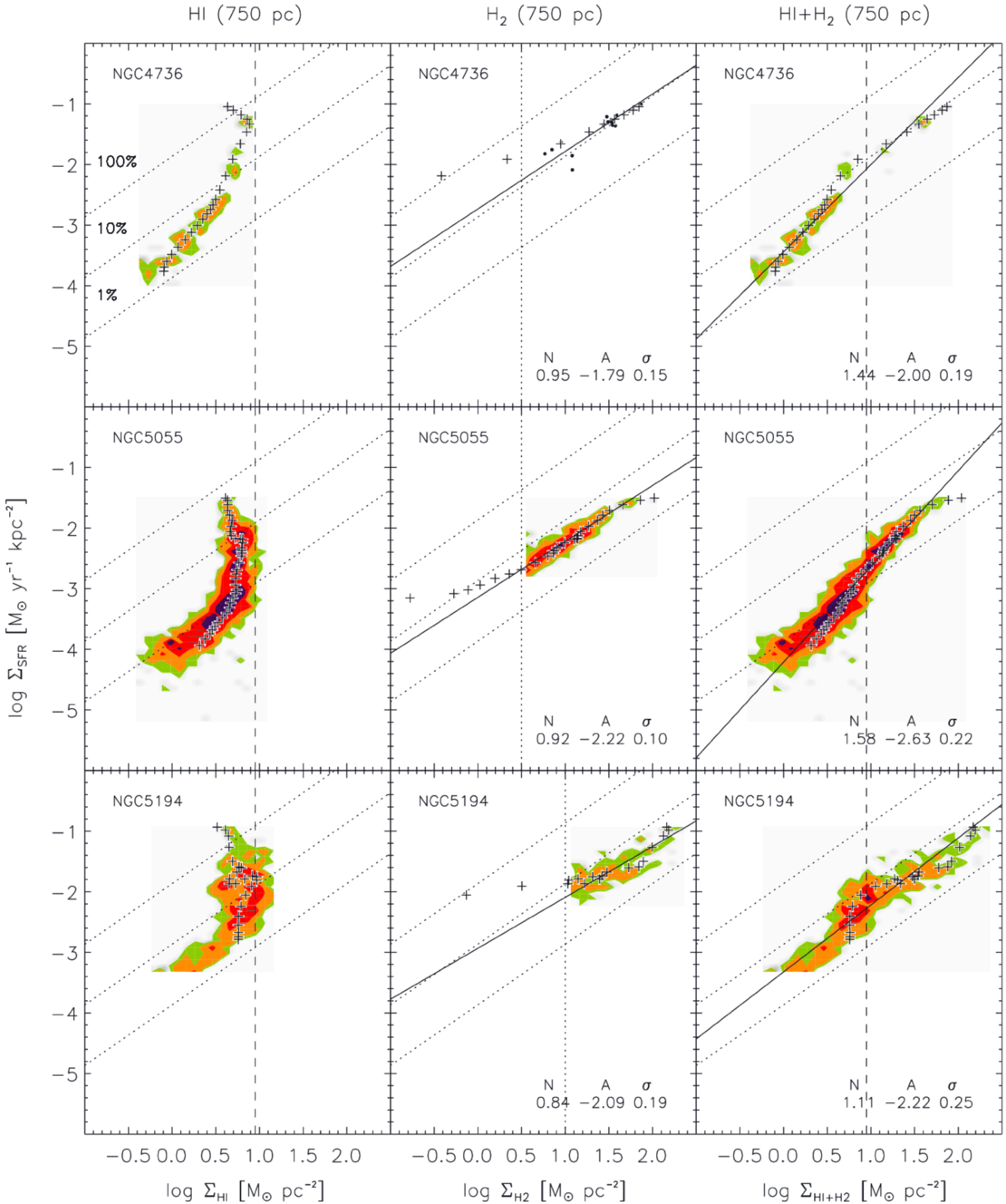
Federrath et al. 2015 (movie page)

The Kennicutt-Schmidt relation of stars



Kennicutt 1998

The Kennicutt-Schmidt relation

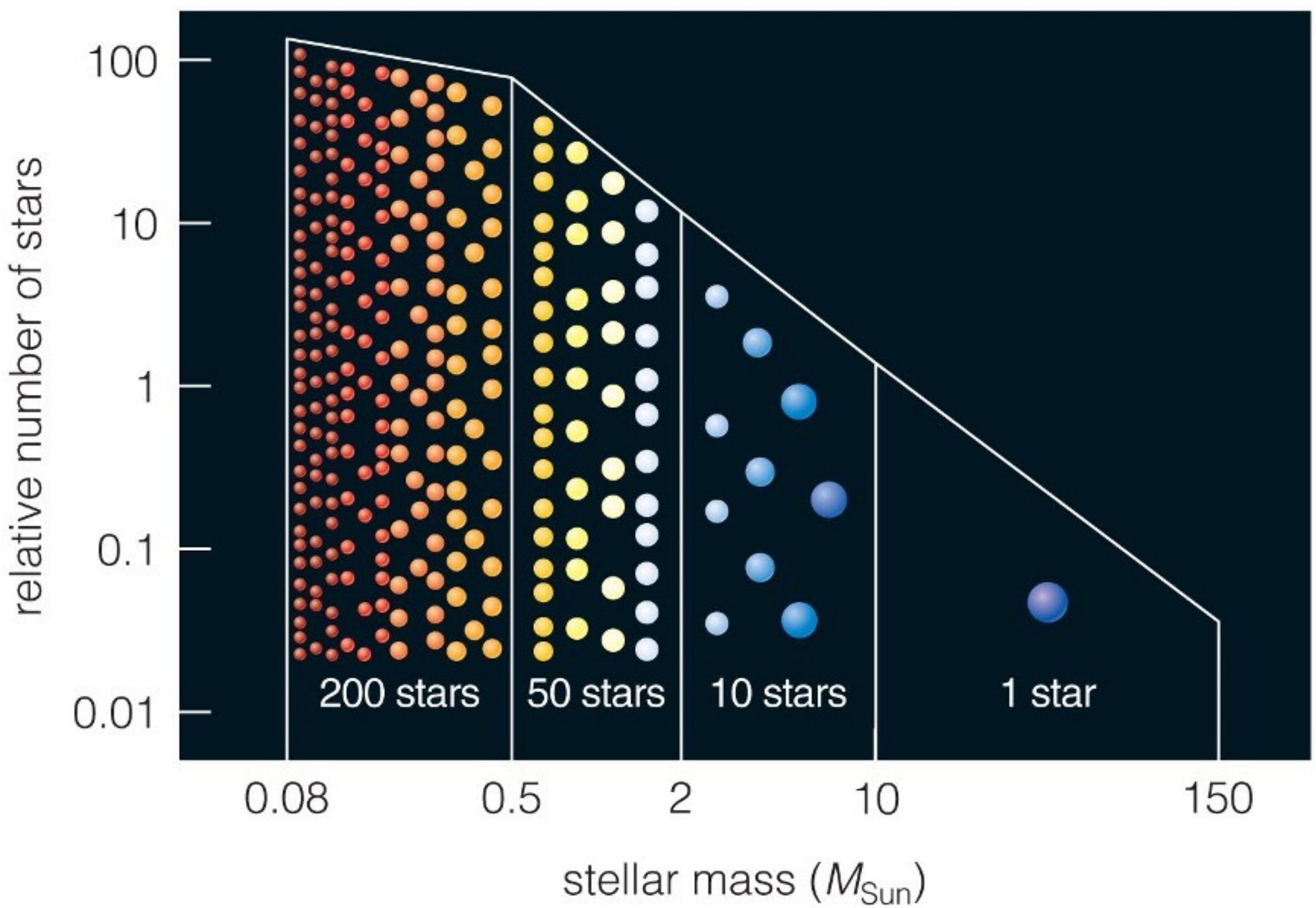


Bigiel et al. 2008

§7.1.3 • The initial mass function

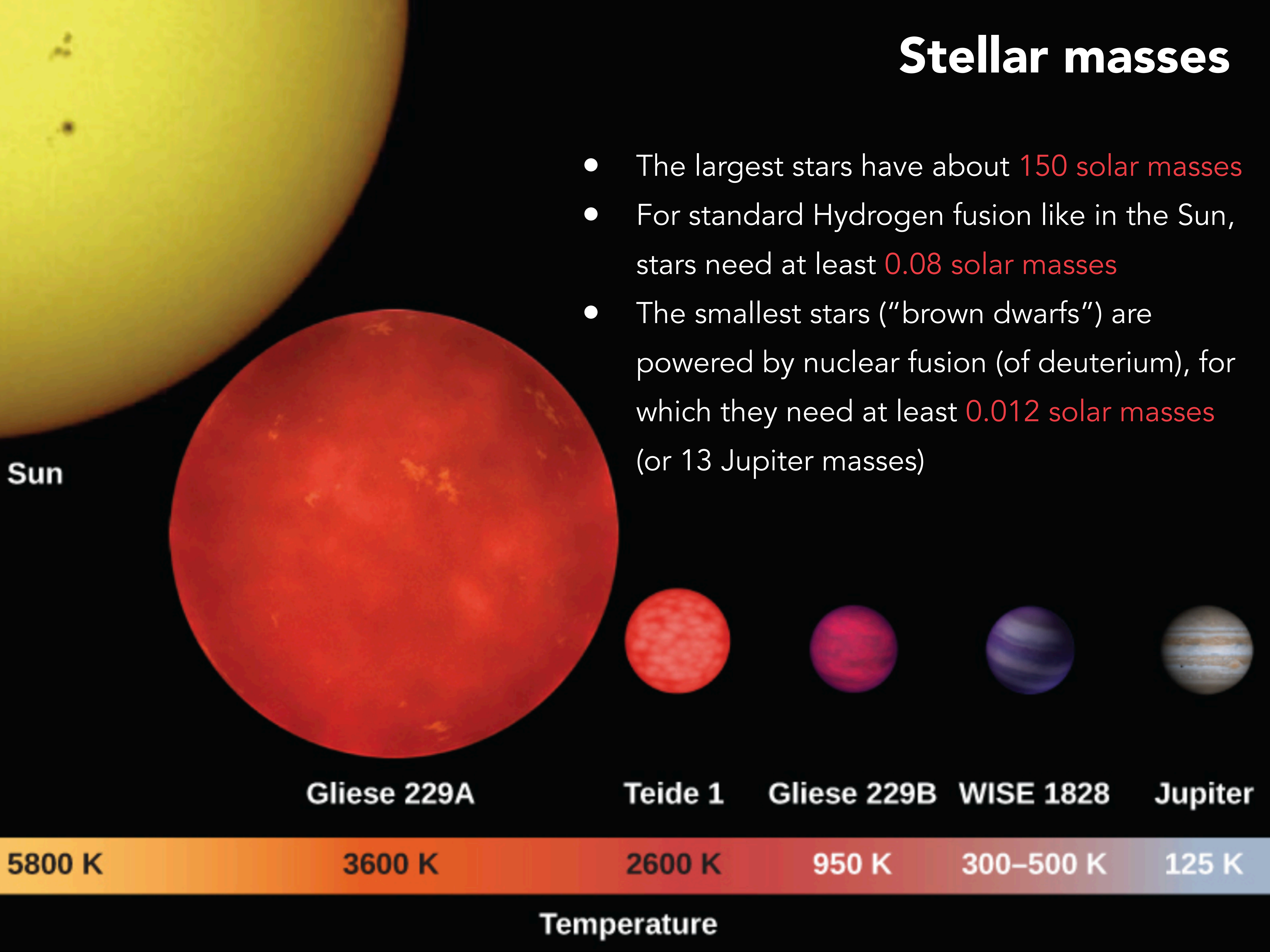
The abundance of stars

- Big stars are rare for two reasons:
  - The star formation process makes fewer of them
  - They exhaust their fuel and die more quickly

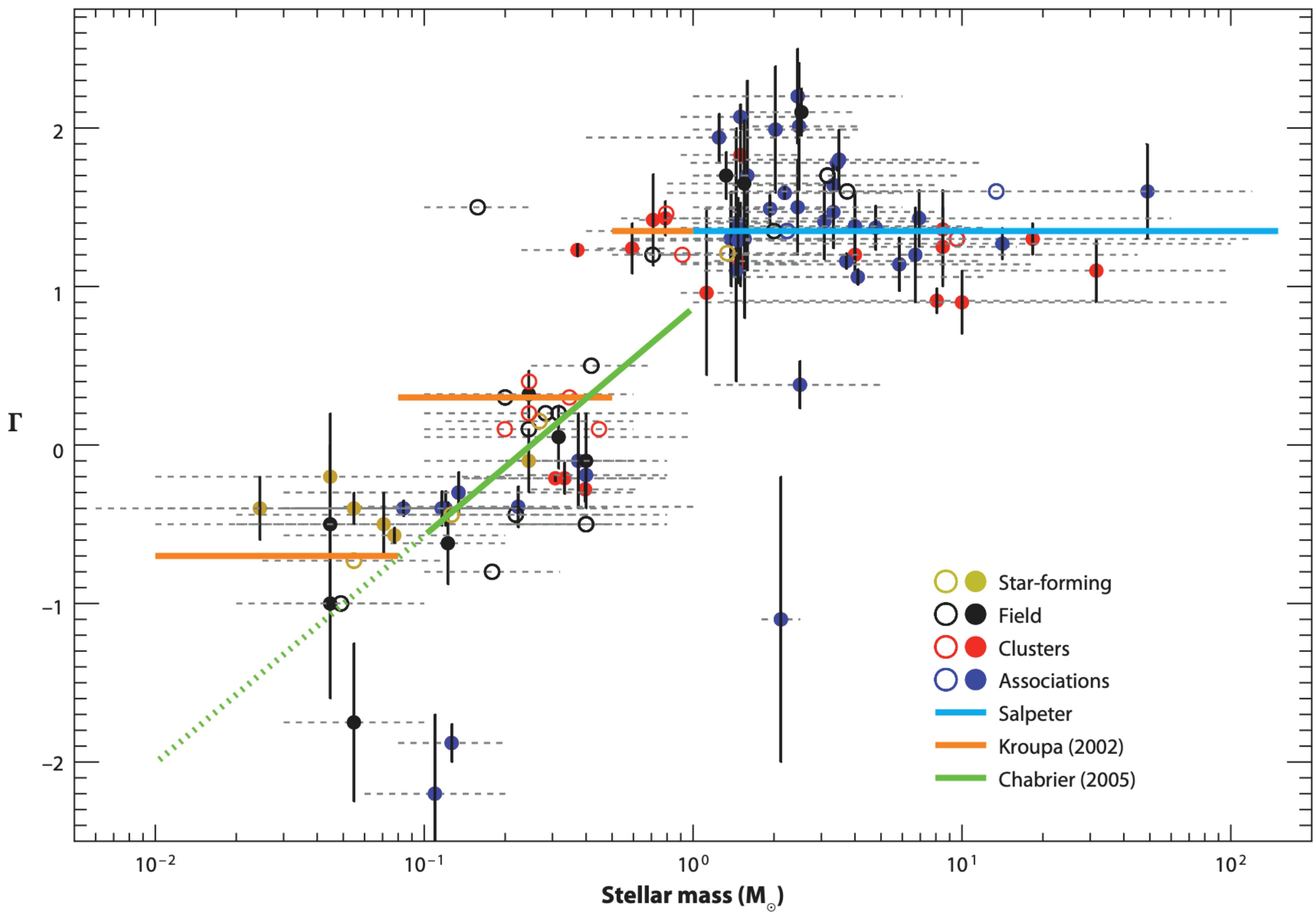


Stellar masses

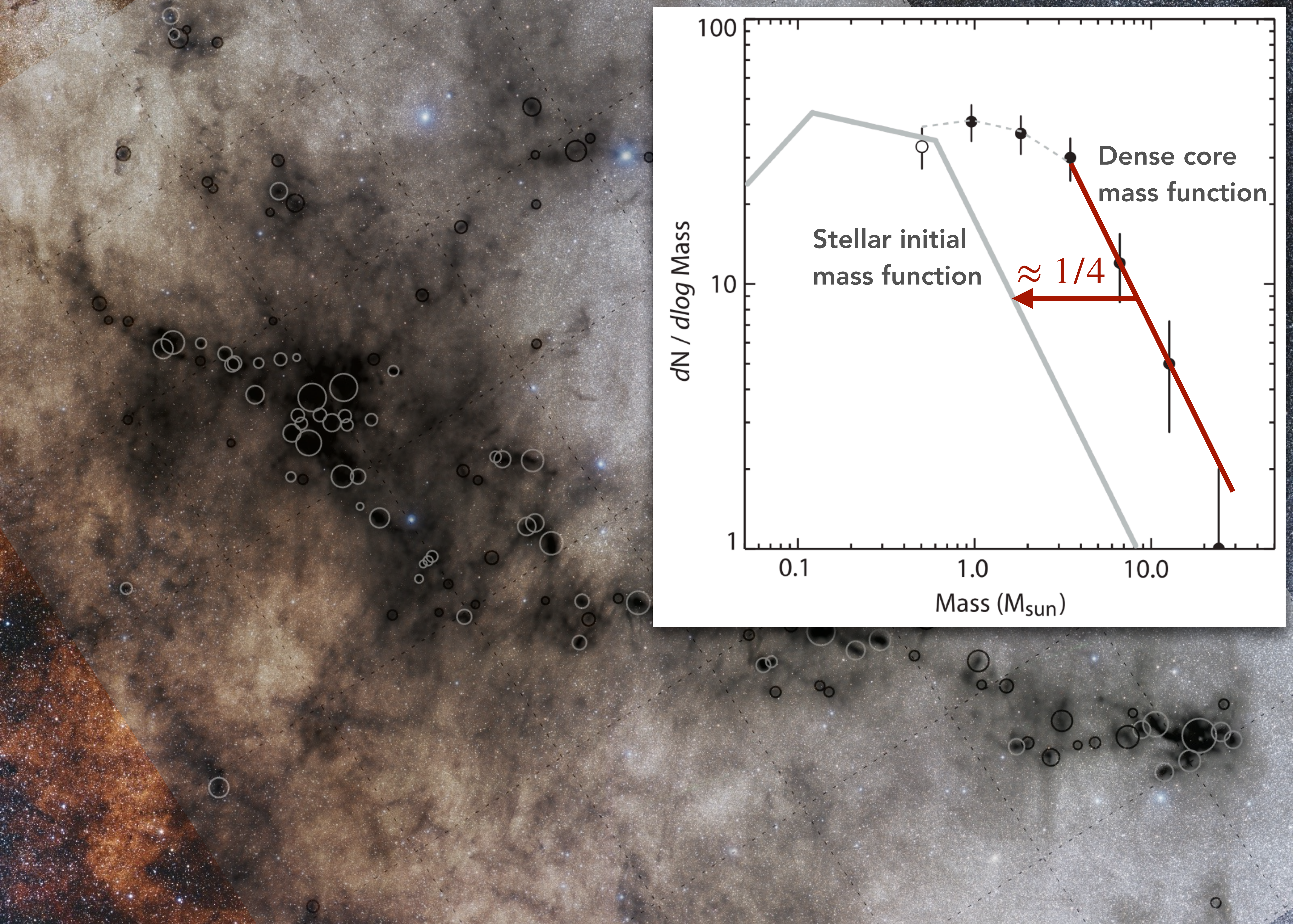
- The largest stars have about 150 solar masses
- For standard Hydrogen fusion like in the Sun, stars need at least 0.08 solar masses
- The smallest stars (“brown dwarfs”) are powered by nuclear fusion (of deuterium), for which they need at least 0.012 solar masses (or 13 Jupiter masses)



Stellar initial mass function (IMF)



Bastian et al. 2010

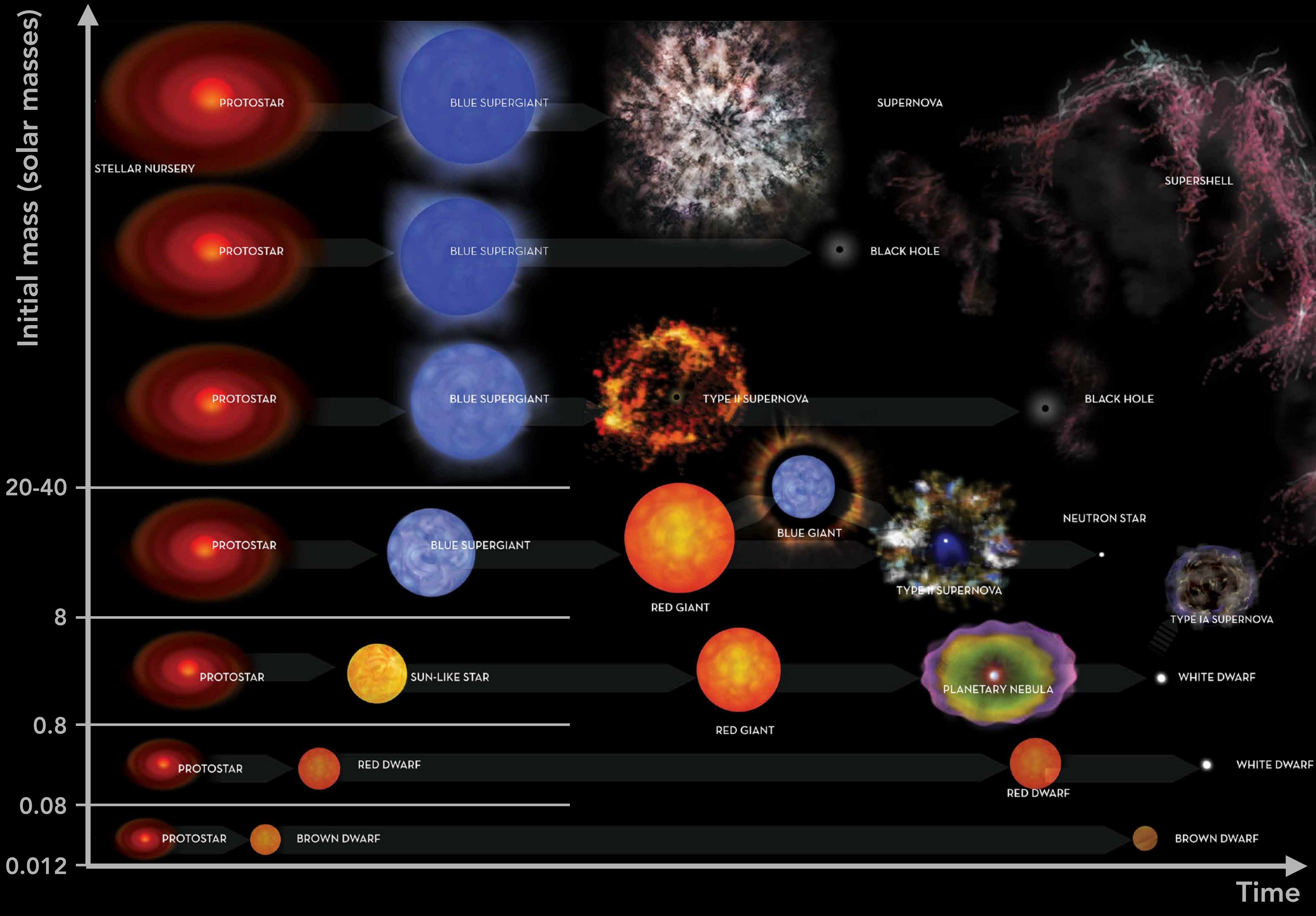


Pipe Nebula • Yuri Beletsky/Las Campanas • Alves et al. 2007 • Slide inspired by Karen Sandstrom

§7.2 • Stellar feedback

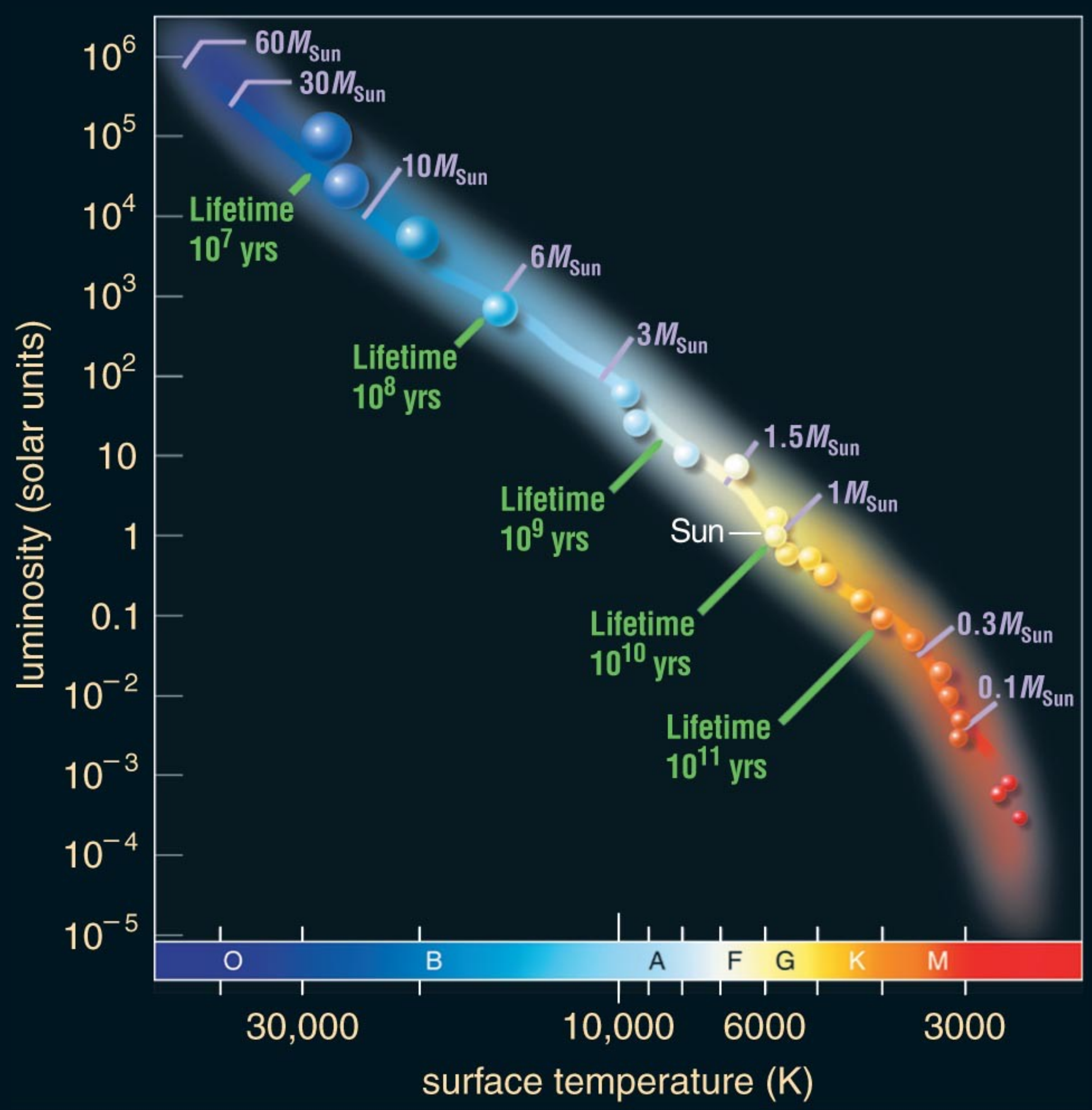
§7.2.1 • Supernovae

Summary of stellar evolution

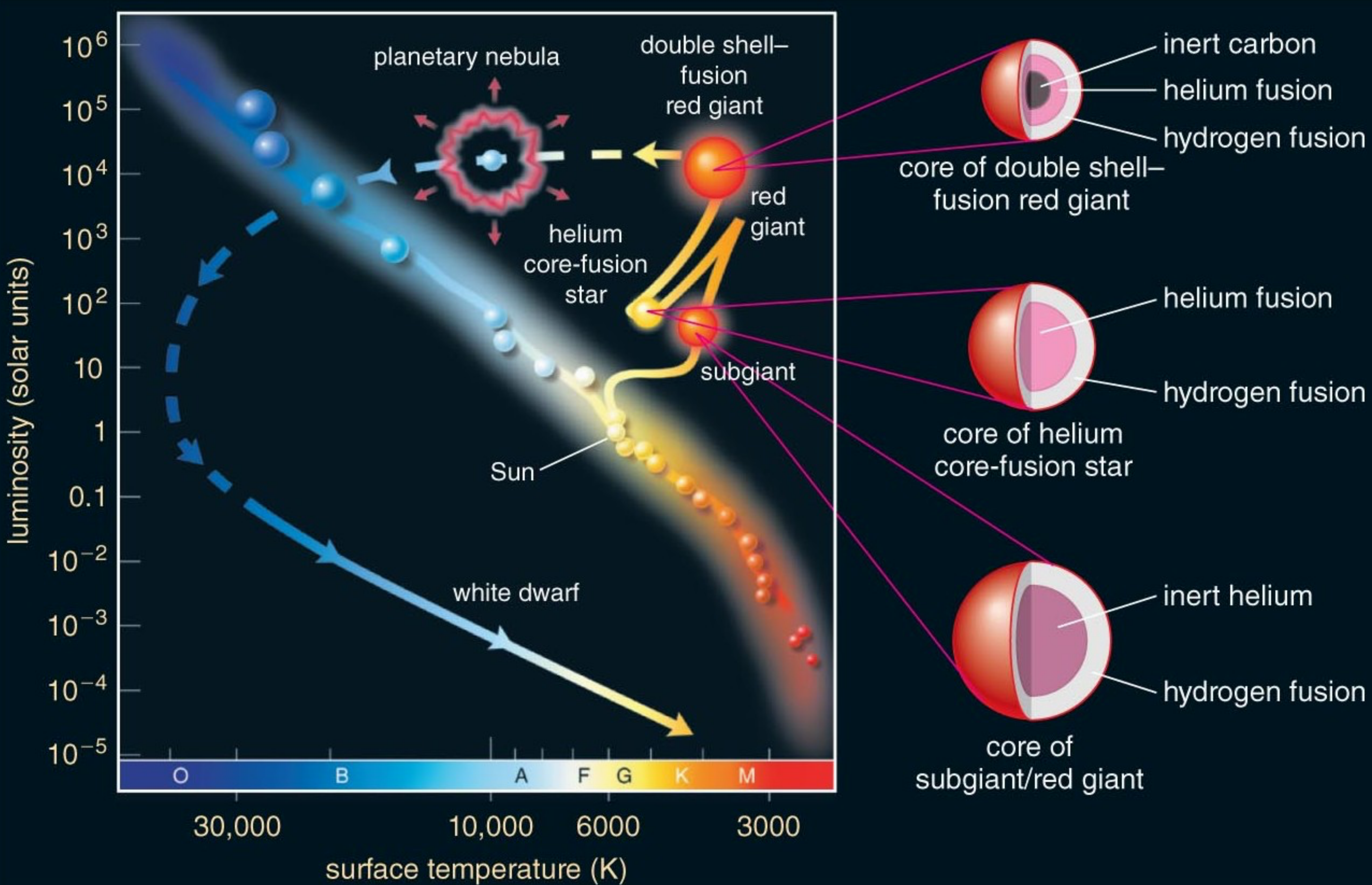


Stellar lifetimes on the main sequence

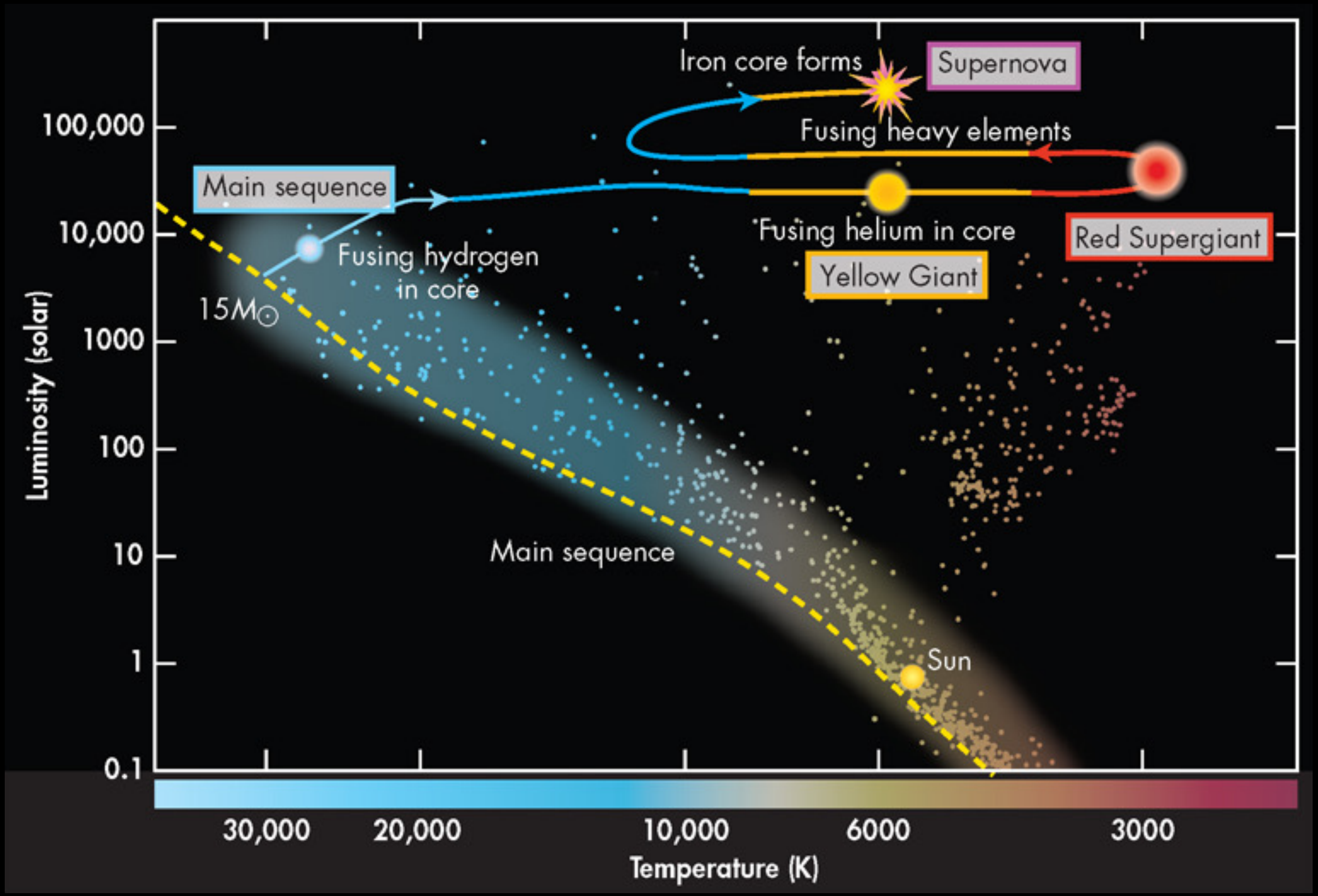
- High-mass stars ($> 8\ M_\odot$)
  Lifetime <100 million years
- Intermediate mass stars (2-8 $M_\odot$)
  Lifetime 100 million to 1 billion yrs
- Low-mass stars (<2 $M_\odot$)
  Lifetime of 1 to 1000 billion yrs



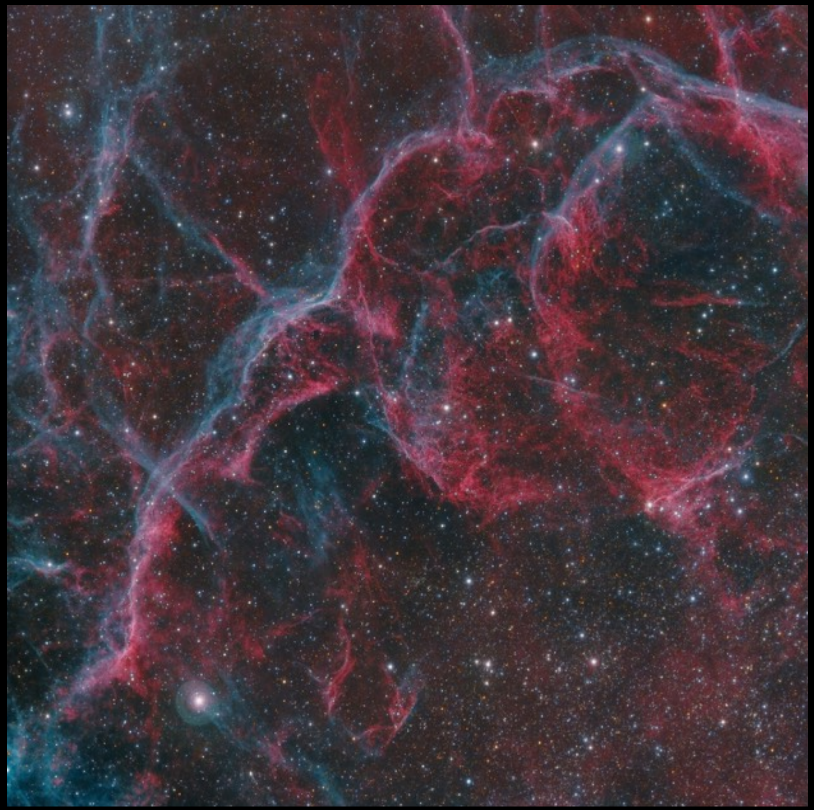
Post-main sequence life (low-mass stars)



The life of massive stars on the HR diagram



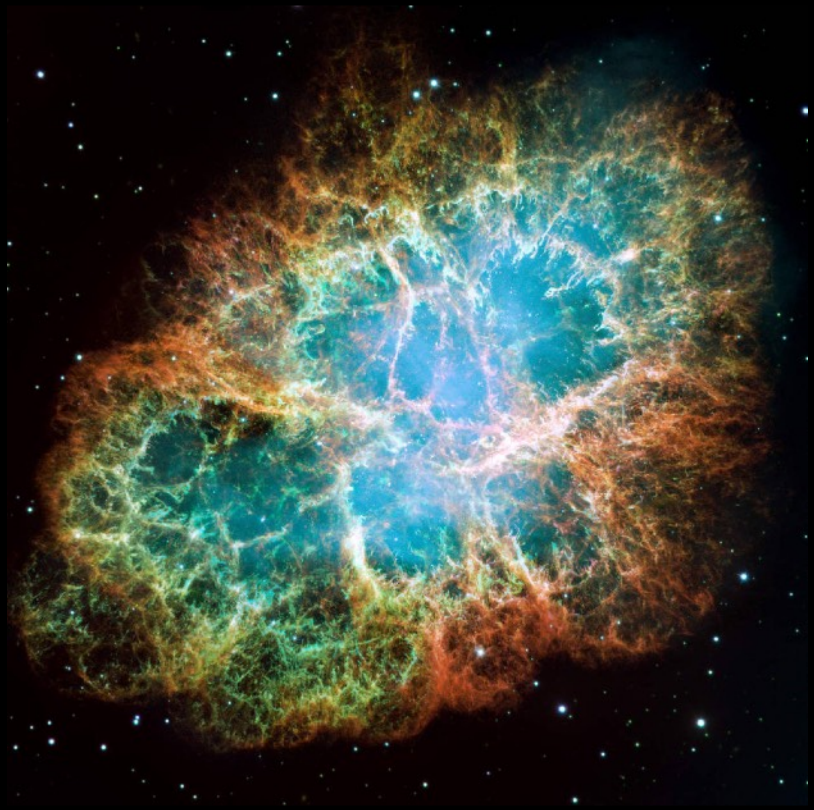
Galactic supernova remnants



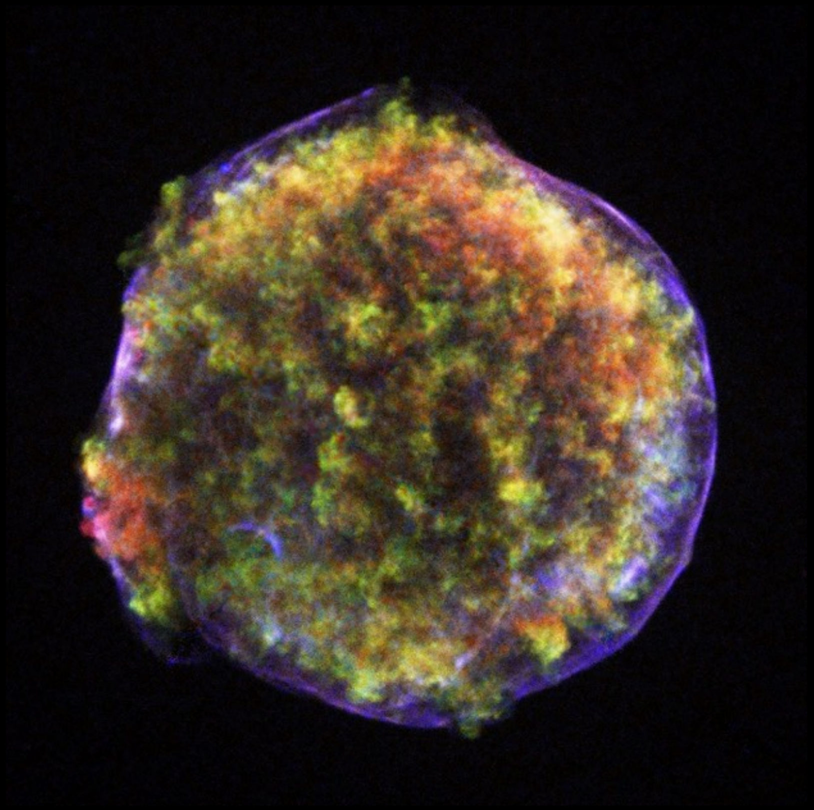
Vela SNR (~12000 yr old)

Abell 85 / Cannonball pulsar

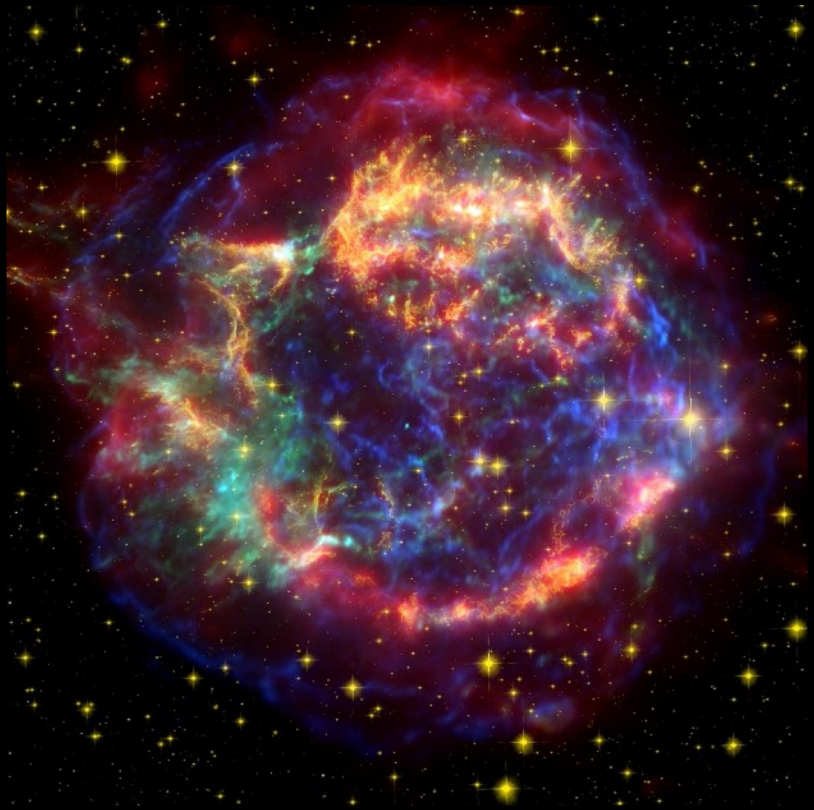
SN 1006 (Type Ia)



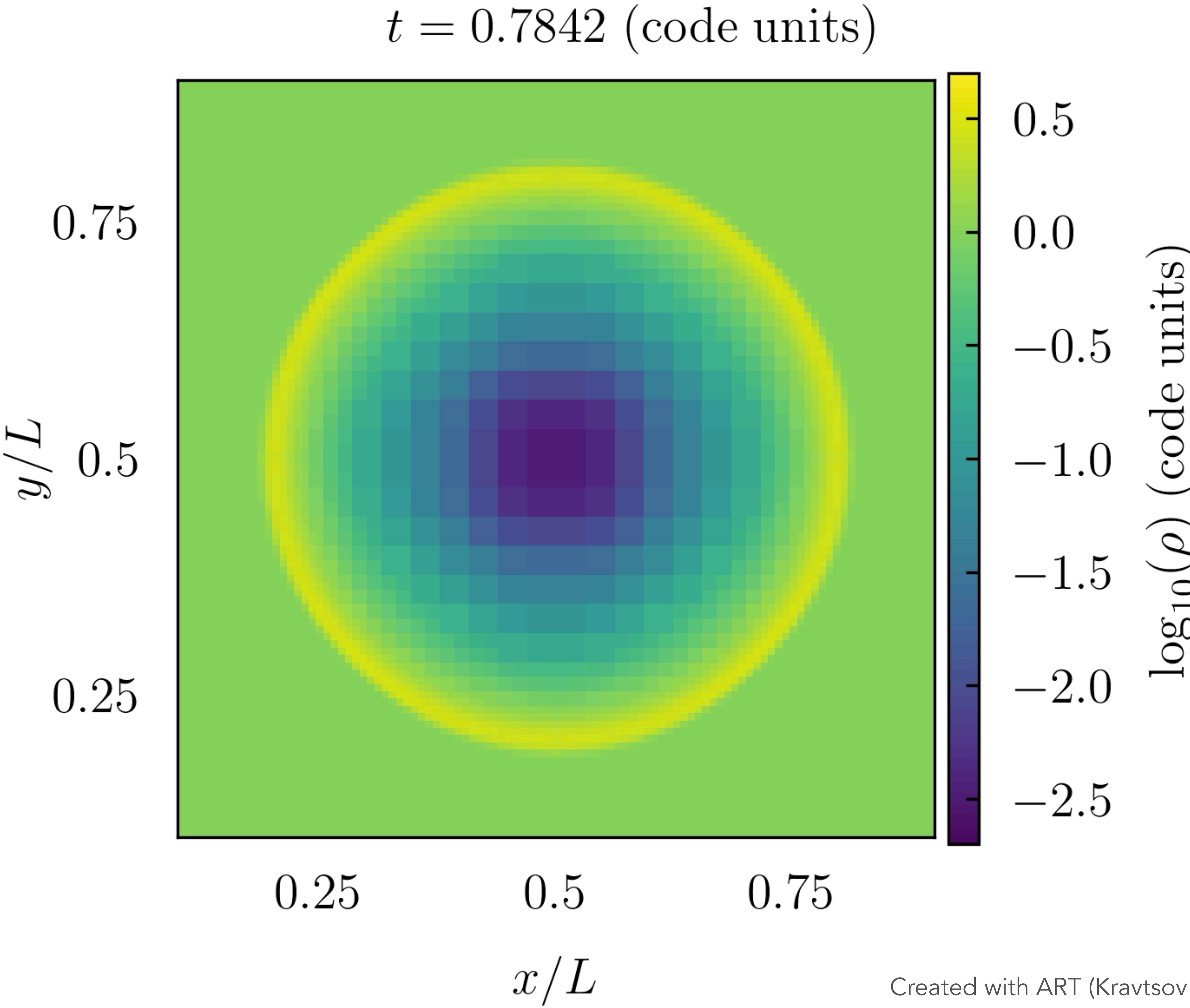
SN 1054 / Crab nebula



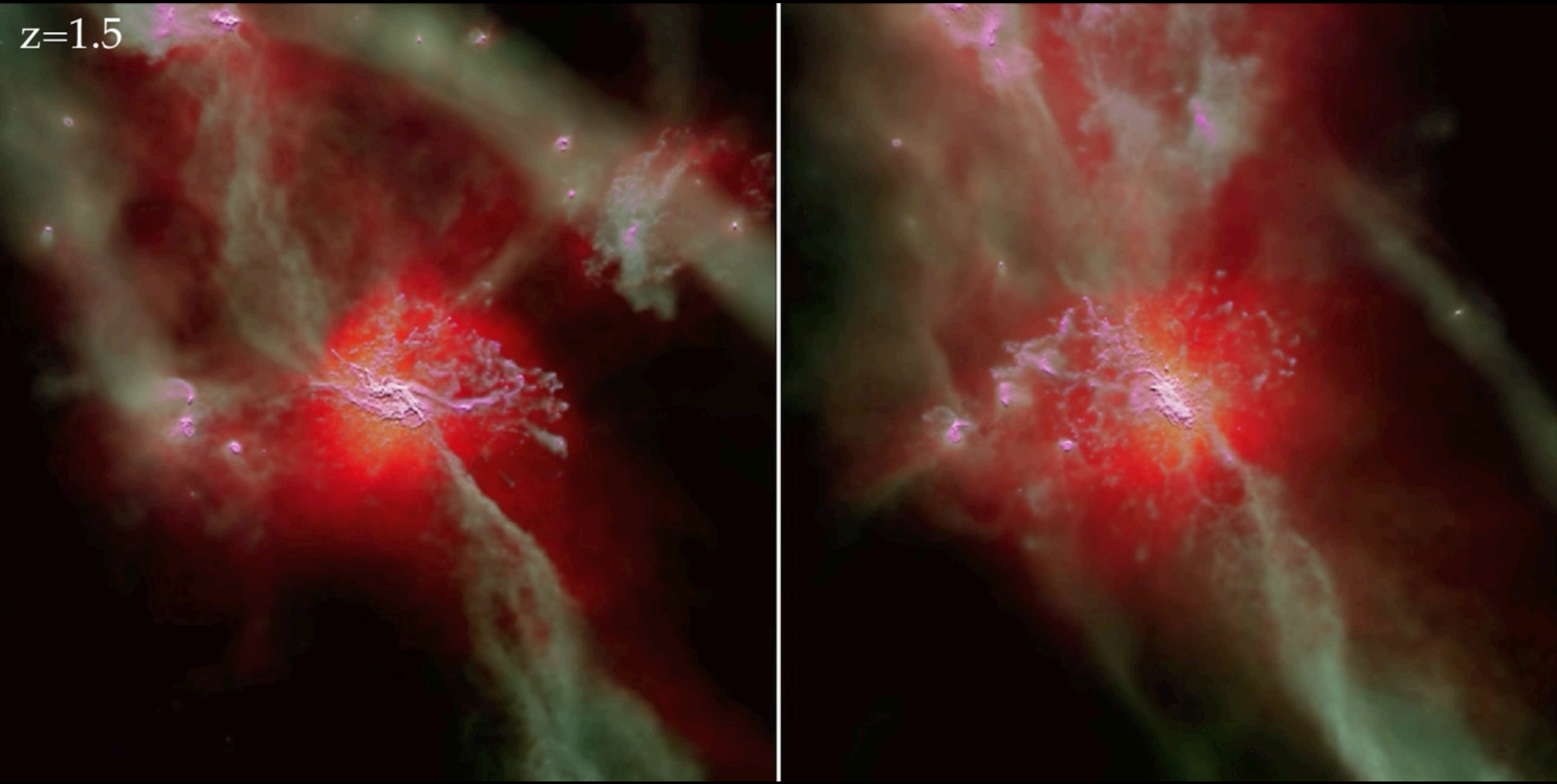
SN 1752 (Tycho's SN, Type Ia)



Cassiopeia A (~1690?)



Created with ART (Kravtsov et al. 1997)



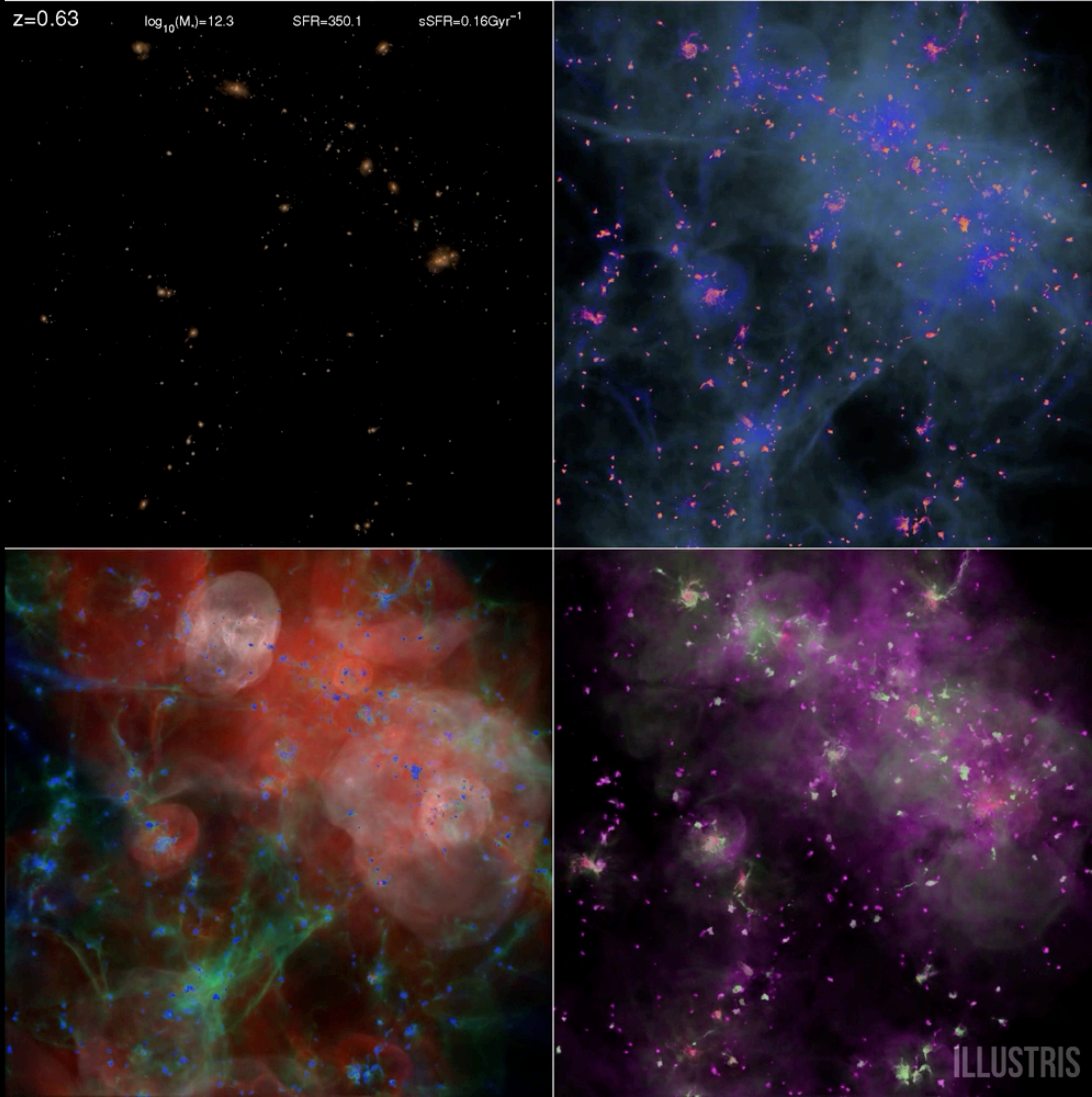
FIRE Collaboration (movie page)

Star light

Gas density

Gas temperature

Heavy elements in gas



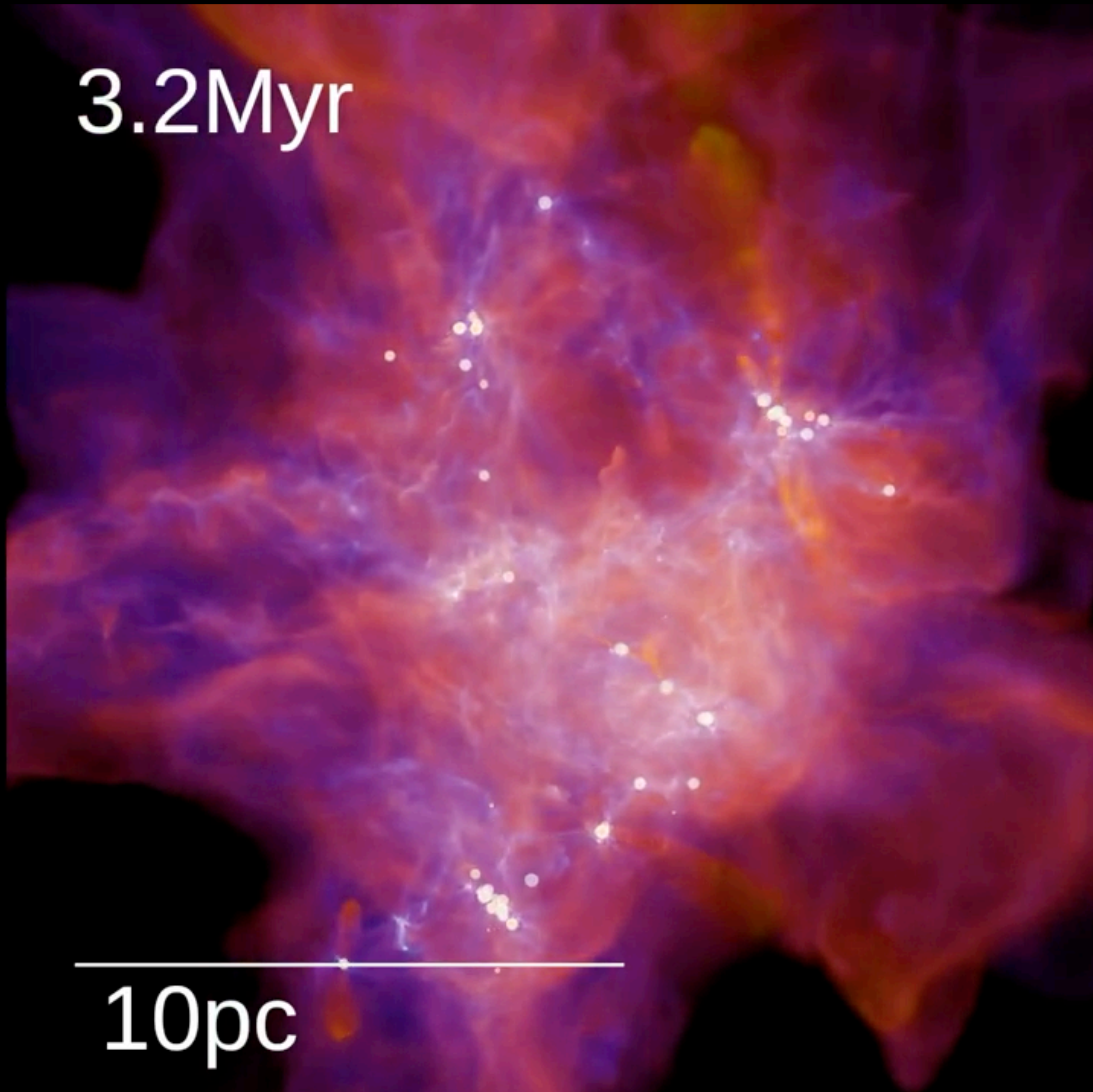
Illustris simulation: Vogelsberger et al. 2013, 2014ab (movie page)
See also **EAGLE** (Schaye et al. 2015 • **SIMBA** (Dave et al. 2019)

§7.2.2 • Stellar winds

Stellar winds

NGC 602

Star formation simulation

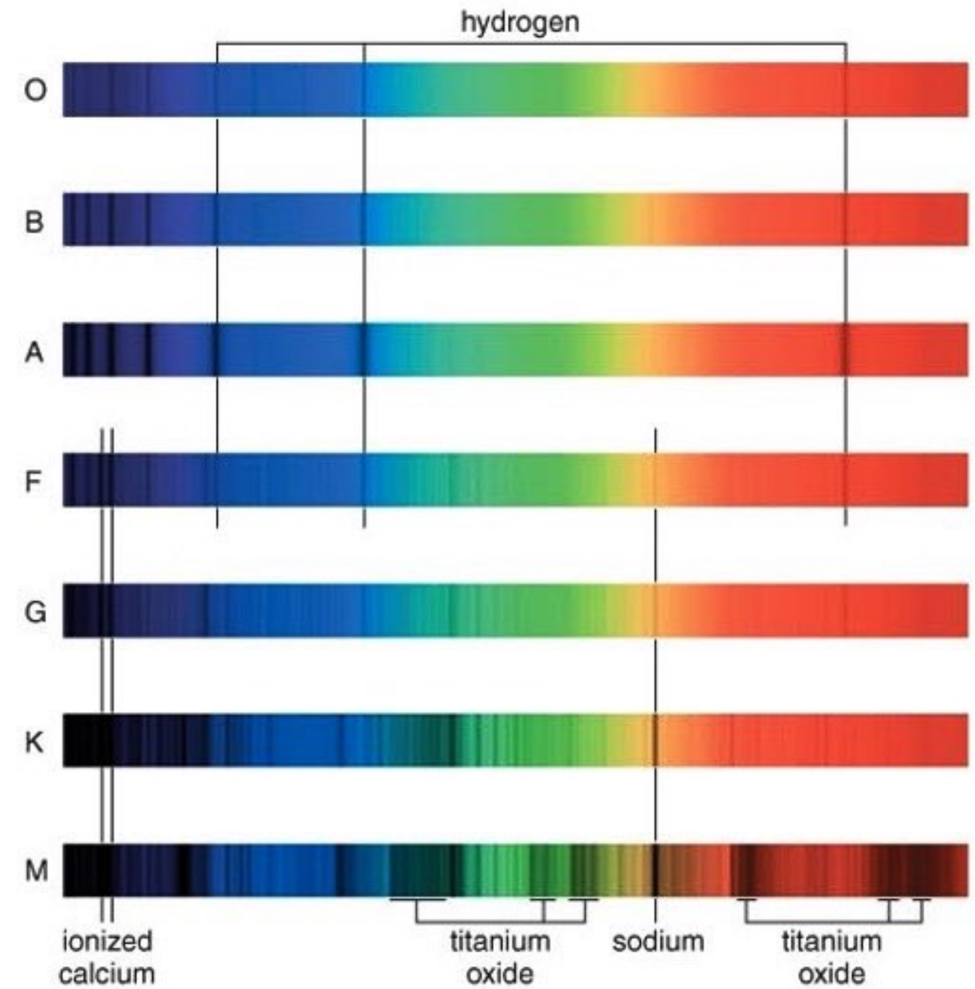


STARFORGE Collaboration (movie page)

§7.3 • Galactic spectra from stellar population synthesis

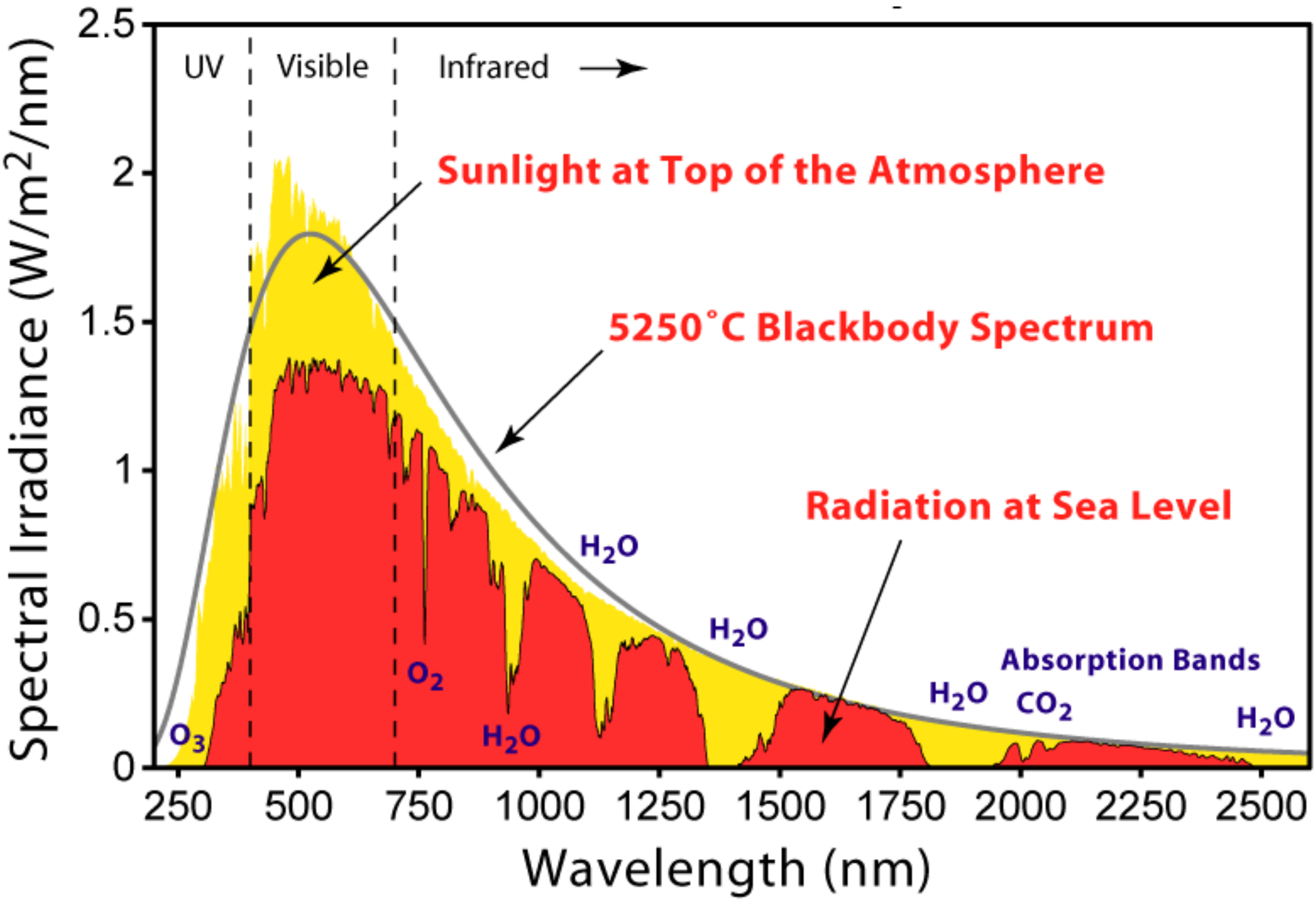
Spectral types

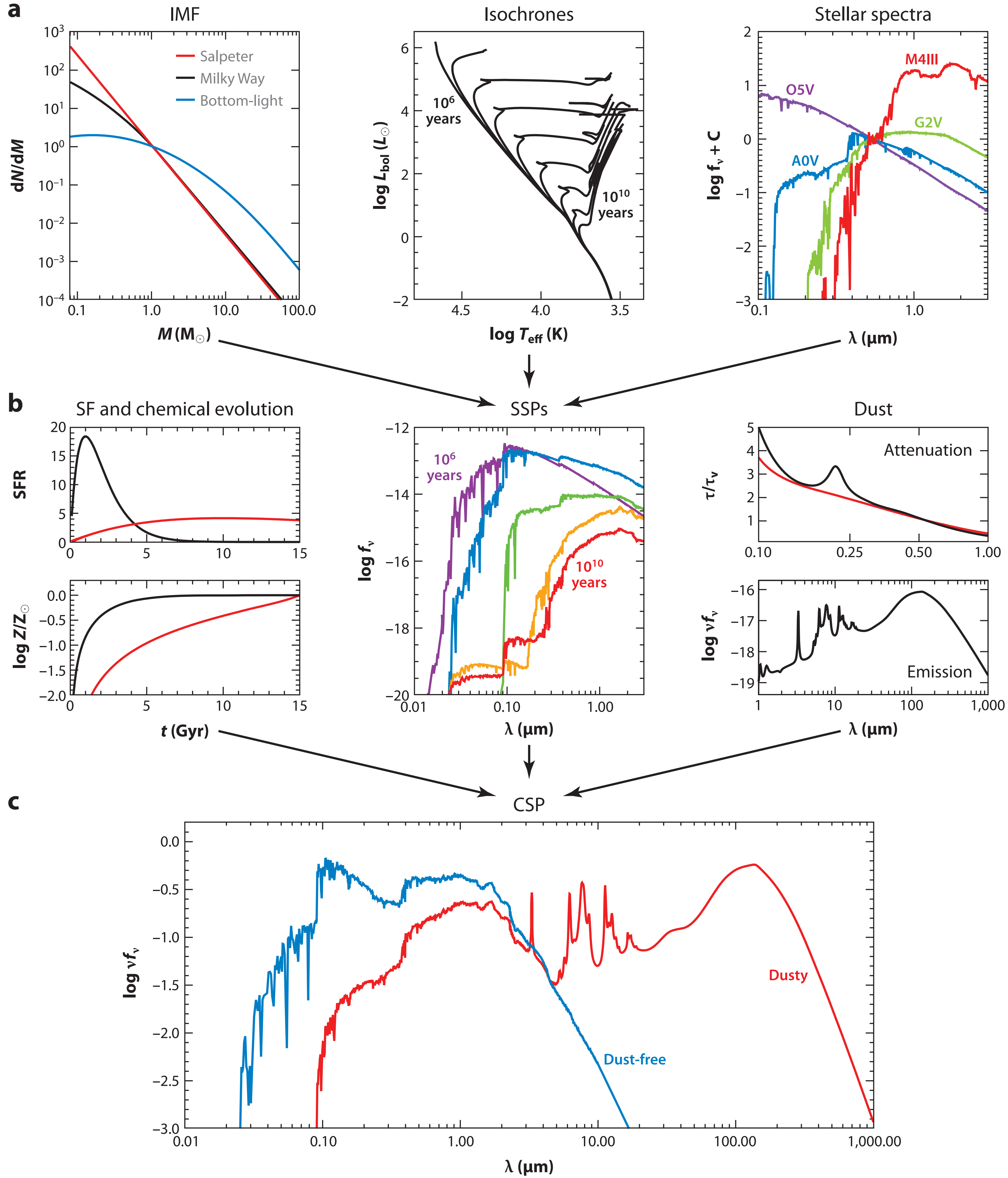
Spectral Type	Example(s)	Temperature Range	Key Absorption Line Features	Brightest Wavelength (Color)	Typical Spectrum
O	Stars of Orion's Belt	>30,000 K	Lines of ionized helium, weak hydrogen lines	<97 nm (ultraviolet)*	
B	Rigel	30,000 K–10,000 K	Lines of neutral helium, moderate hydrogen lines	97–290 nm (ultraviolet)*	
A	Sirius	10,000 K–7500 K	Very strong hydrogen lines	290–390 nm (violet)*	
F	Polaris	7500 K–6000 K	Moderate hydrogen lines, moderate lines of ionized calcium	390–480 nm (blue)*	
G	Sun, Alpha Centauri A	6000 K–5000 K	Weak hydrogen lines, strong lines of ionized calcium	480–580 nm (yellow)	
K	Arcturus	5000 K–3500 K	Lines of neutral and singly ionized metals, some molecules	580–830 nm (red)	
M	Betelgeuse, Proxima Centauri	<3500 K	Strong molecular lines	>830 nm (infrared)	



- Stellar spectra have absorption lines due to material above the photosphere
- Both the overall color and the spectral lines change with temperature
- Color changes are caused by different blackbody temperature
- Line changes are due to which atoms are ionized, excited, and so on

Spectrum of the Sun





a
IMF
Salpeter
Milky Way
Bottom-light
dN/dM
M (M☉)
Isochrones
10^6 years
10^10 years
log L_bol (L☉)
log T_eff (K)
Stellar spectra
M4III
O5V
G2V
A0V
log f_ν + C
λ (μm)
b
SF and chemical evolution
SFR
log Z/Z☉
t (Gyr)
SSPs
10^6 years
10^10 years
log f_ν
λ (μm)
Dust
Attenuation
τ/τ_V
Emission
log νf_ν
λ (μm)
c
CSP
log νf_ν
Dusty
Dust-free
λ (μm)

Conroy 2013

§7.4 • Observable indicators of stellar mass and SFR

Galaxies in different wavelengths

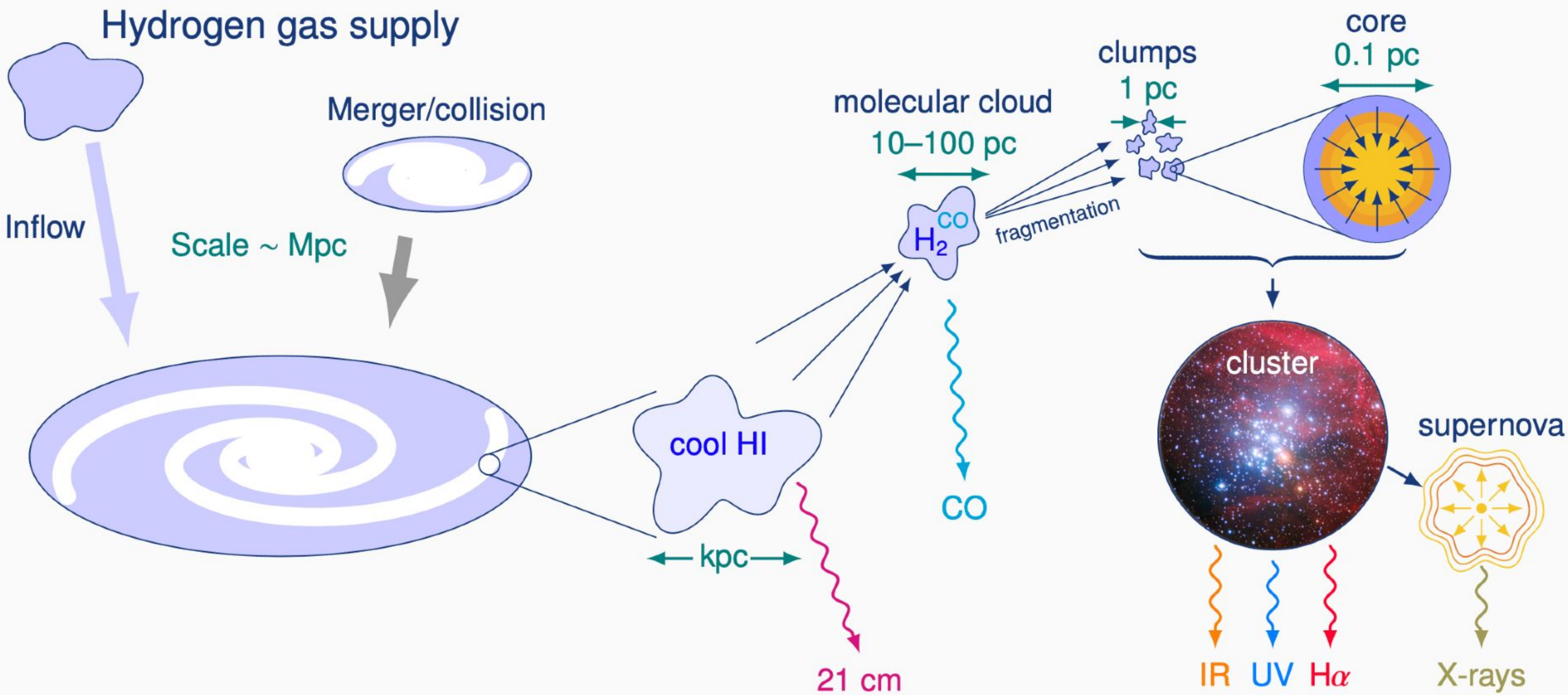


Image by Markus Pössel

SFR indicators

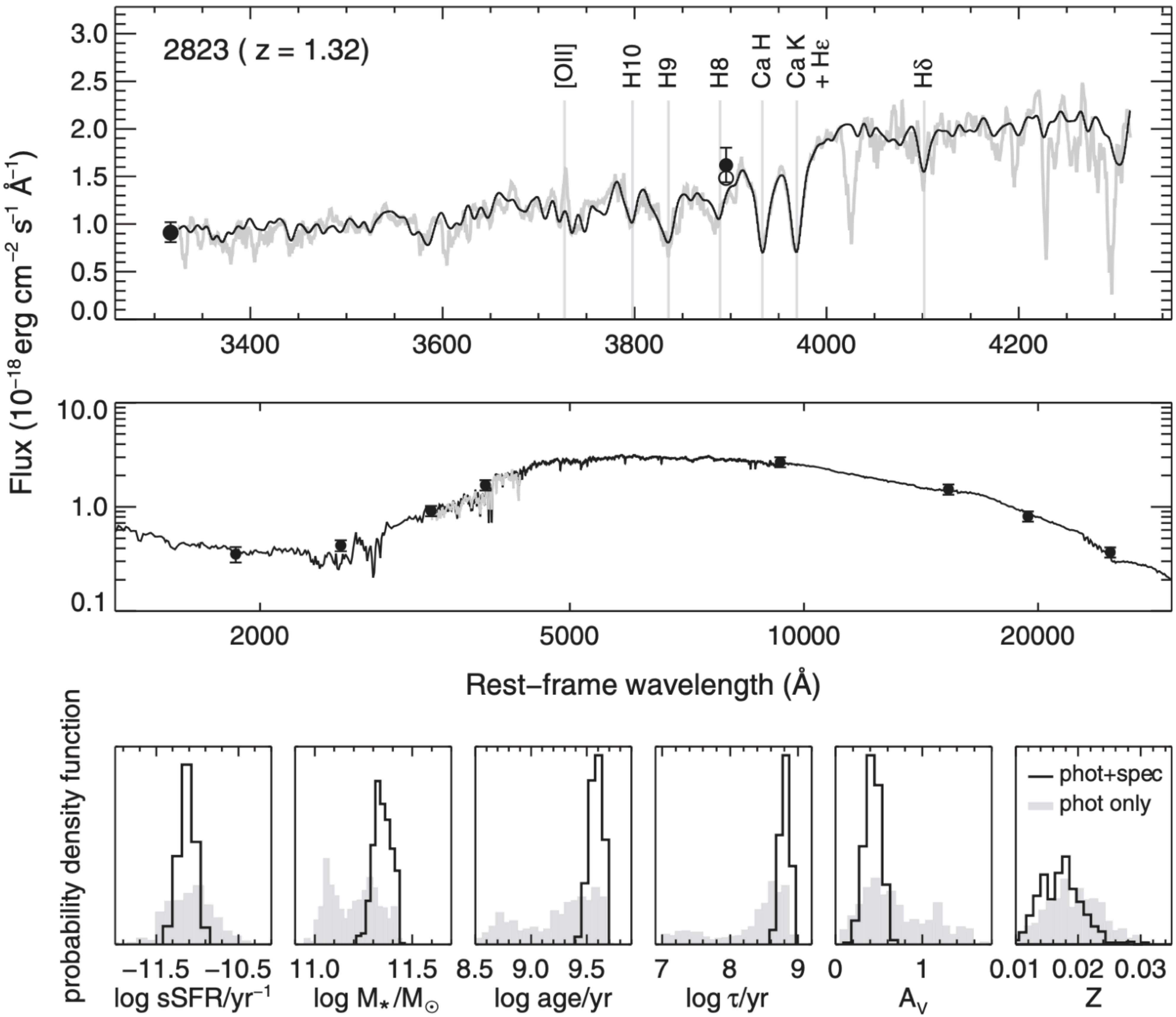
Band	Age range (Myr)[a]	L_x units	log C_x[b]	$\dot{M}_* / \dot{M}_*$(K98)[c]	Reference(s)
FUV	0-10-100	ergs s^{-1} (νL_ν)	43.35	0.63	Hao et al. (2011), Murphy et al. (2011)
NUV	0-10-200	ergs s^{-1} (νL_ν)	43.17	0.64	Hao et al. (2011), Murphy et al. (2011)
Hα	0-3-10	ergs s^{-1}	41.27	0.68	Hao et al. (2011), Murphy et al. (2011)
TIR	0-5-100[d]	ergs s^{-1} (3–1100 μm)	43.41	0.86	Hao et al. (2011), Murphy et al. (2011)
24 μm	0-5-100[d]	ergs s^{-1} (νL_ν)	42.69		Rieke et al. (2009)
70 μm	0-5-100[d]	ergs s^{-1} (νL_ν)	43.23		Calzetti et al. (2010b)
1.4 GHz	0-100	ergs s^{-1} Hz^{-1}	28.20		Murphy et al. (2011)
2–10 keV	0-100	ergs s^{-1}	39.77	0.86	Ranalli et al. (2003)

[a]Second number gives mean age of stellar population contributing to emission; third number gives age below which 90% of emission is contributed.

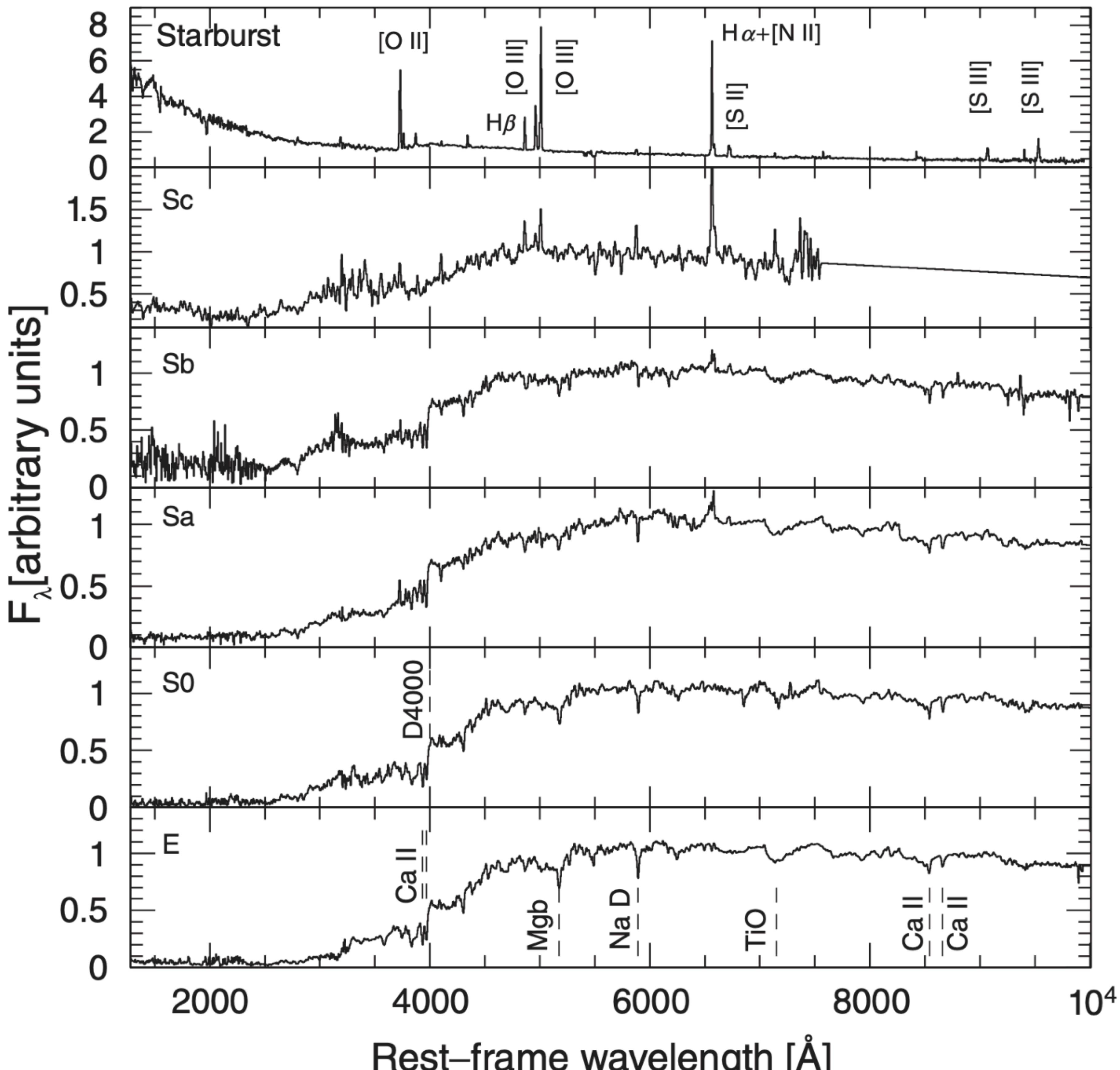
$$\log \dot{M}_*(\mathrm{M}_\odot\ \mathrm{year}^{-1}) = \log L_x - \log C_x$$

Kennicutt & Evans 2012

Spectral fitting



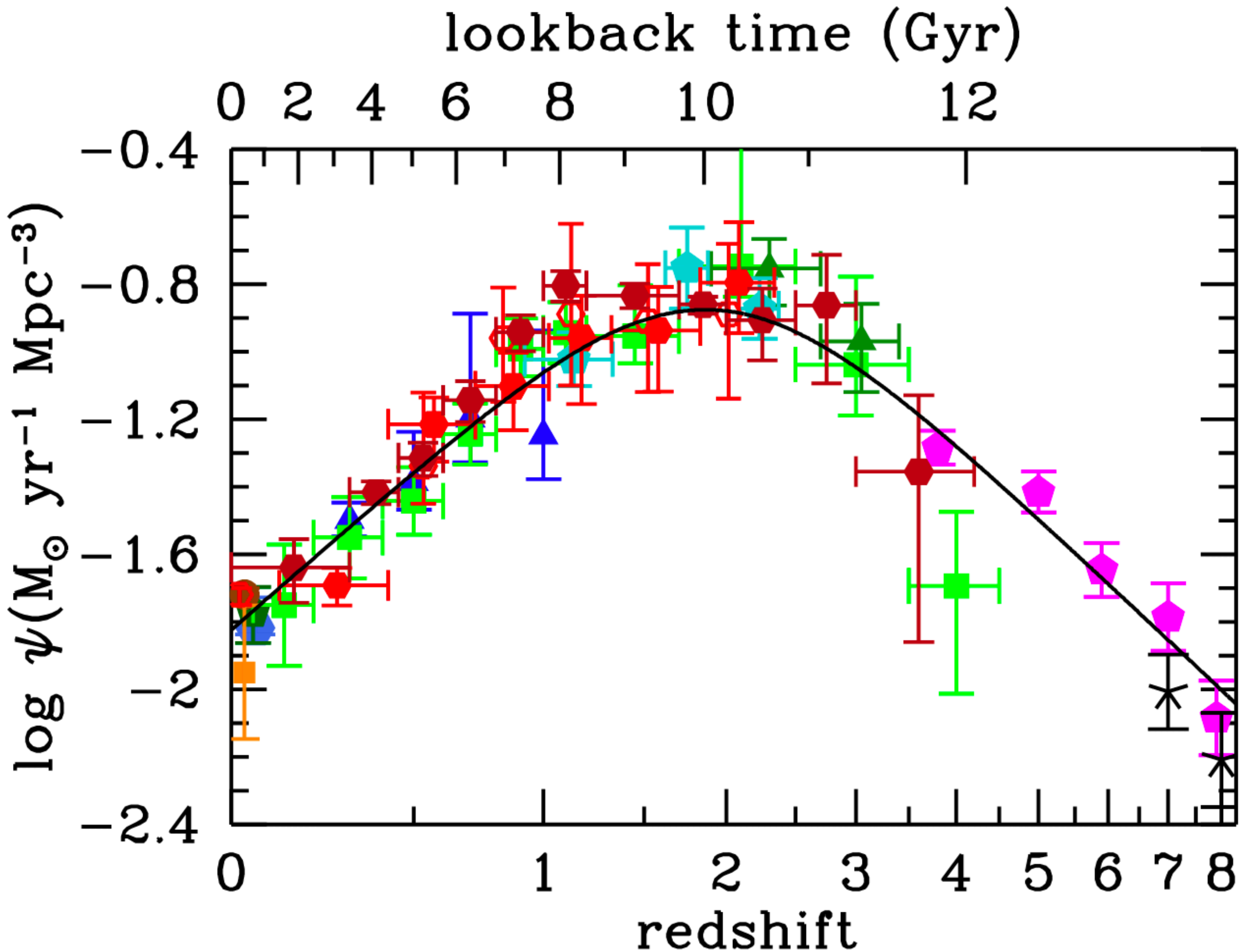
Observed galaxy spectra



CFN §3.4.1

§7.5 • Observed correlations

Global star formation rate density (SFRD)



Madau & Dickinson 2014

Reading

- CFN
    - 7.1: §4.2.9, §8.3
    - 7.2: §8.7.1-8.7.2
    - 7.3: §8.6
    - 7.4: §3.4.0, §11.1.2-11.1.3
    - 7.5: §3.4.1, §4.4.4, §11.3.4-11.3.5
- MvdBW
    - 7.1: §9
    - 7.2: §8.6, §10.5
    - 7.3: §10.3