INTERSTELLAR MEDIUM

- Stefano Bovino -

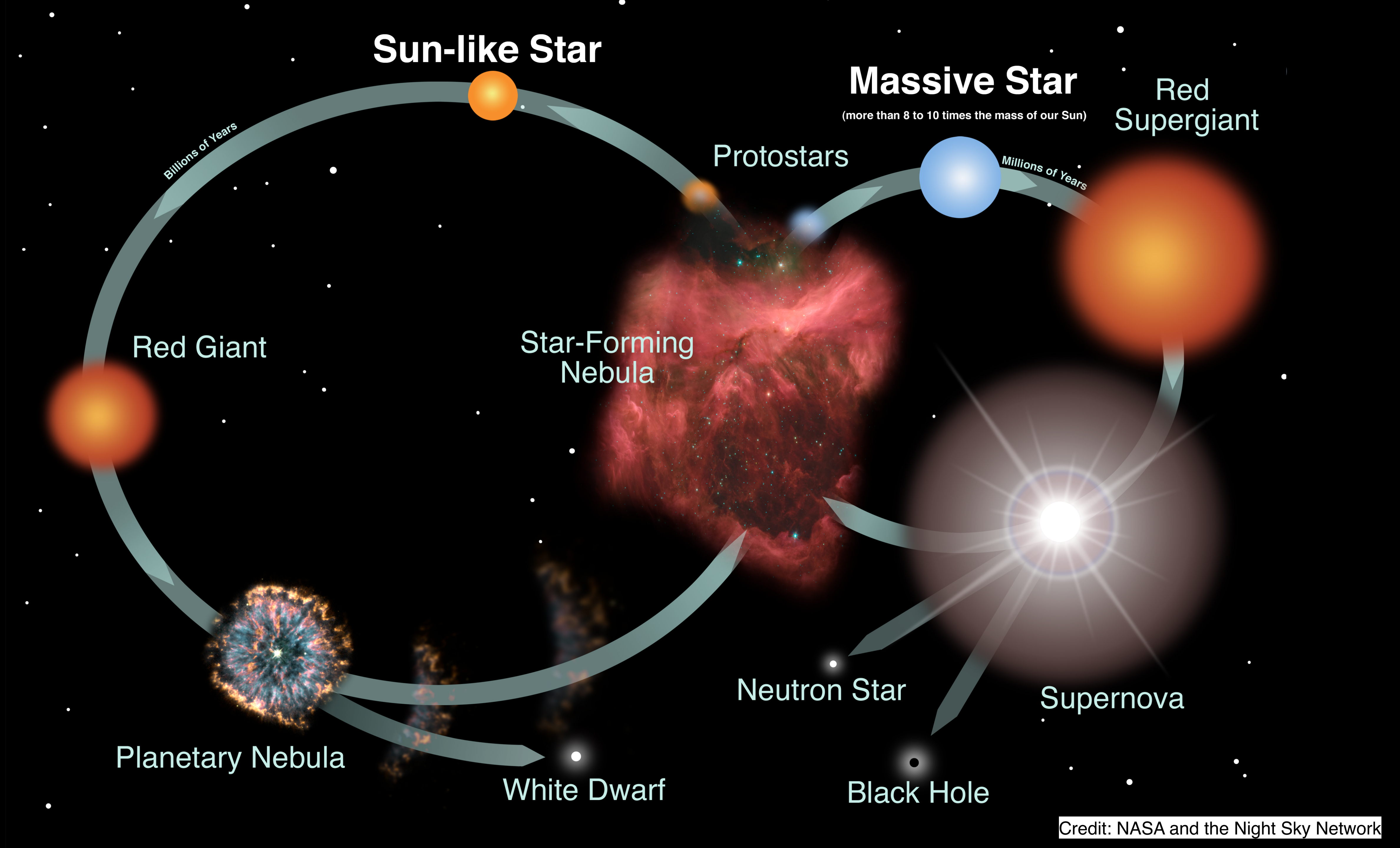
Introduction and MW

What is the Intersteller Medium

- The stuff between the stars in around galaxies
- ISM is the most important part of a galaxy
- ISM is responsible for forming stars (dominant sources of energy)
- Baryons account for 10% of the total mass of the galaxy
- ISM turbulent and out of equilibrium

Why do we study the ISM?

- Stars form from the ISM, and then activate it dynamical and chemically. Gas is the active chemical ingredient of galaxies.
- Understanding the ISM means understanding the physical processes which drive mass, momentum and energy exchange between the stars and the components of the ISM


Sun-like Star
Billions of Years
Massive Star
(more than 8 to 10 times the mass of our Sun)
Red Supergiant
Protostars
Millions of Years
Red Giant
Star-Forming Nebula
Neutron Star
Supernova
Planetary Nebula
White Dwarf
Black Hole
Credit: NASA and the Night Sky Network

What is in between the stars?

- Interstellar gas
- Interstellar dust
- Cosmic rays
- Electromagnetic radiation
- Magnetic field

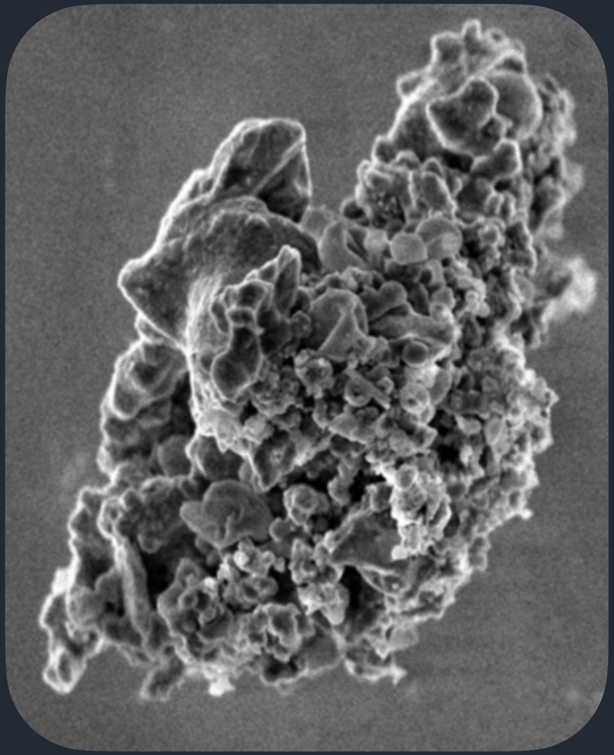
Interstellar gas

- Ions, molecules, atoms in the gas phase, velocity distributions very nearly thermal

Interstellar dust

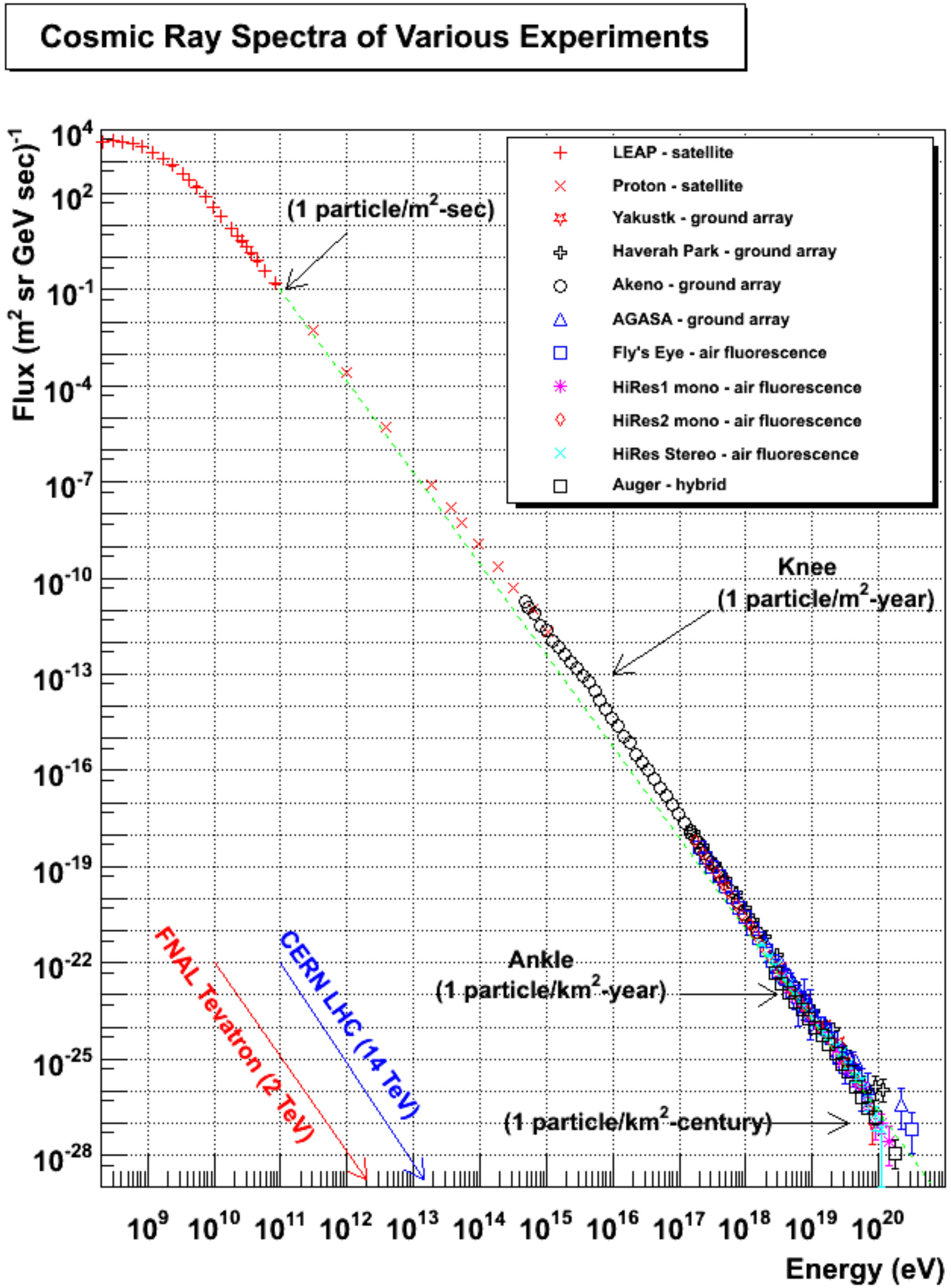
- Small solid particles, mainly less than 1 micron in size, mixed with the interstellar gas

- Dust contains most of the heavy elements
- Are produced in the shells around stars
- Reprocessed in the ISM



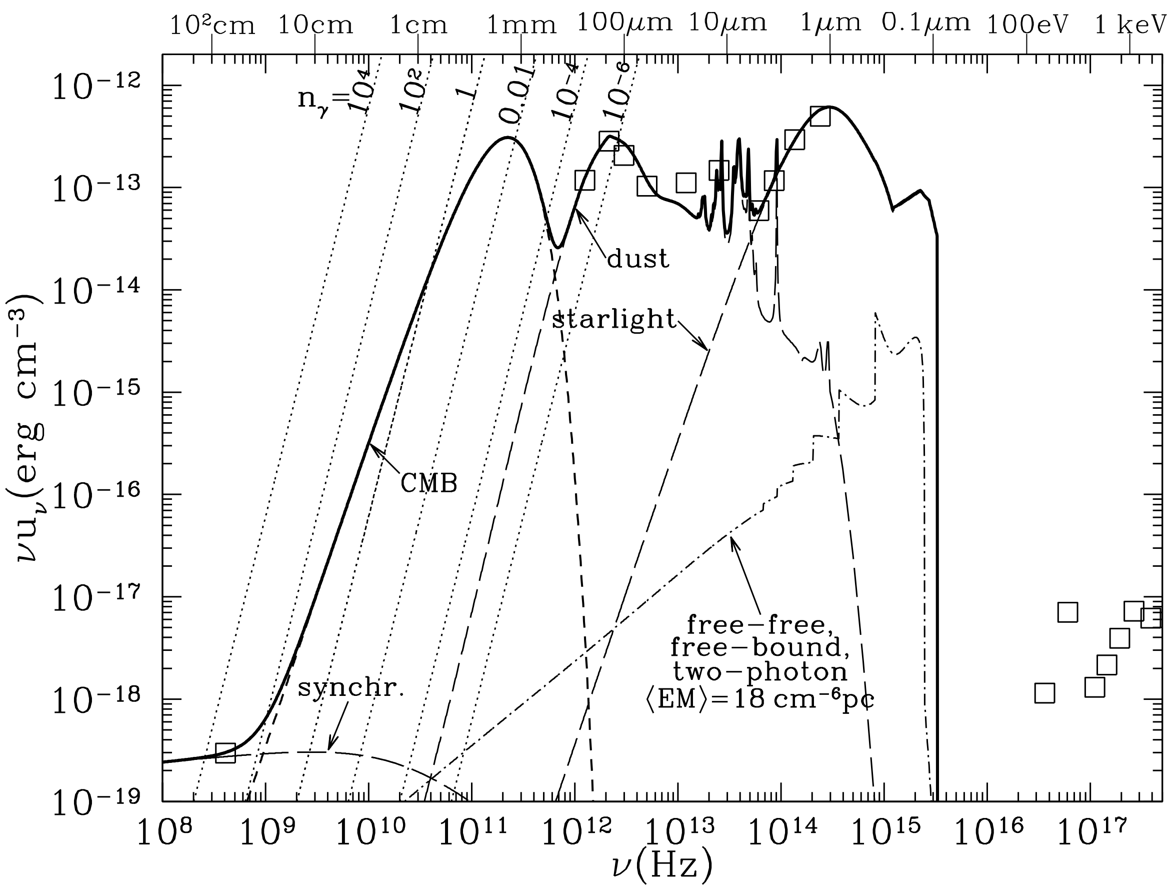
Cosmic rays

- Ions and electrons with high kinetic energies, much larger than thermal, often relativistic



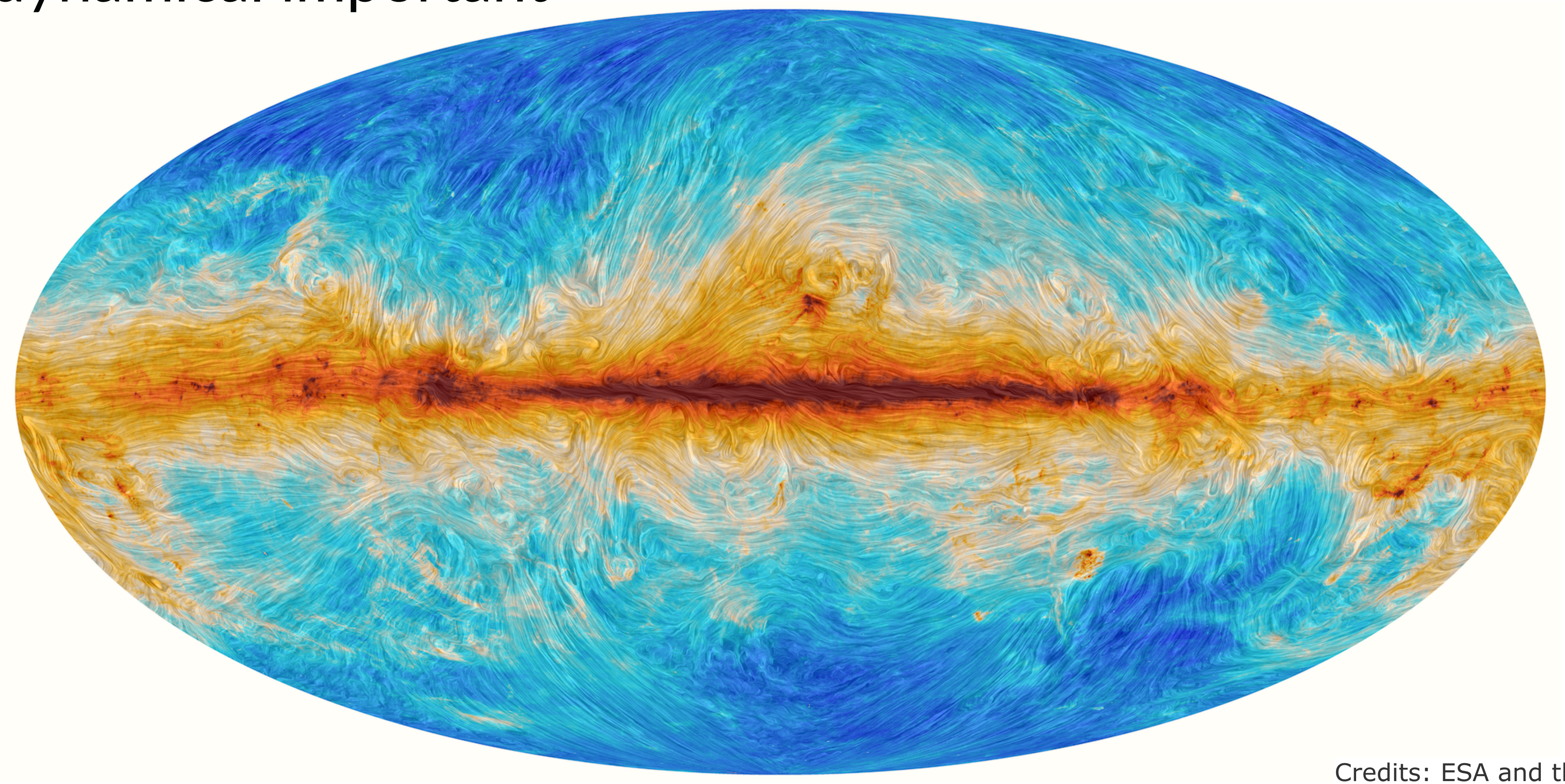
EM radiation

- Photons from many sources, including the CMB; starlight; radiation emitted by ions, atoms and molecules; thermal emission from interstellar grains heated by starlight; bremsstrahlung from plasma; synchrotron radiation from relativistic electrons; gamma rays



Magnetic fields

- Resulting from electric currents in the ISM. Guide the CRs, and they are dynamical important



Credits: ESA and the Planck Collaboration

General properties of the ISM

- Large range in temperature & density

  $T \sim 10\text{-}10^6$ K $n \sim 10^{-3} - 10^6$ cm^{-3}

- Even dense regions are "ultra-high vacuum" difficult to reproduce in Lab

  Lab UHV: 10^{-10} Torr ($n \sim 4 \times 10^6$ cm^{-3})

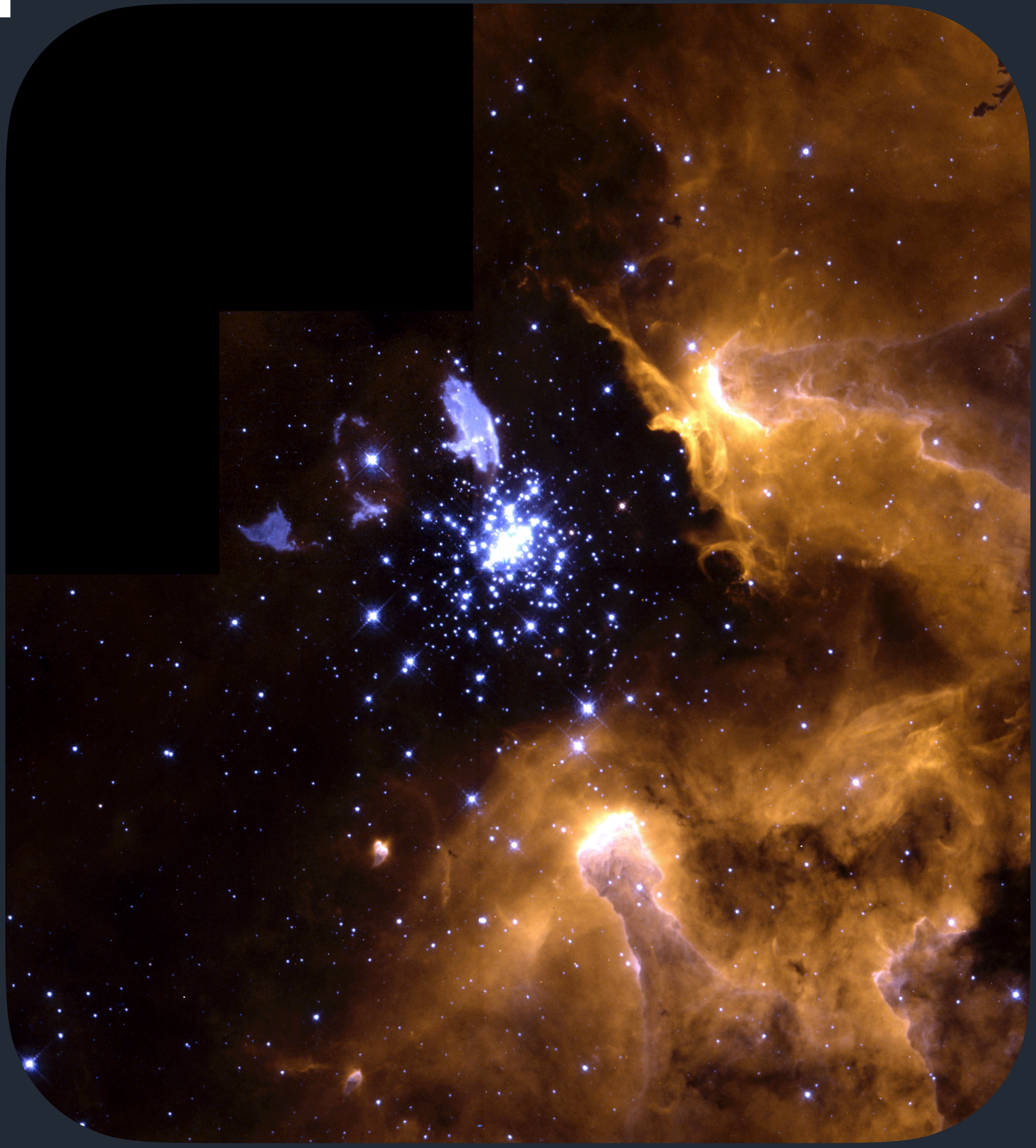
- Multiphase / multicomponent medium (processes interconnected in feedback loops)

- Far from equilibrium and steady state (low density means long timescales to reach equilibrium)

  Complex processes & Challenging physics

General properties of the ISM

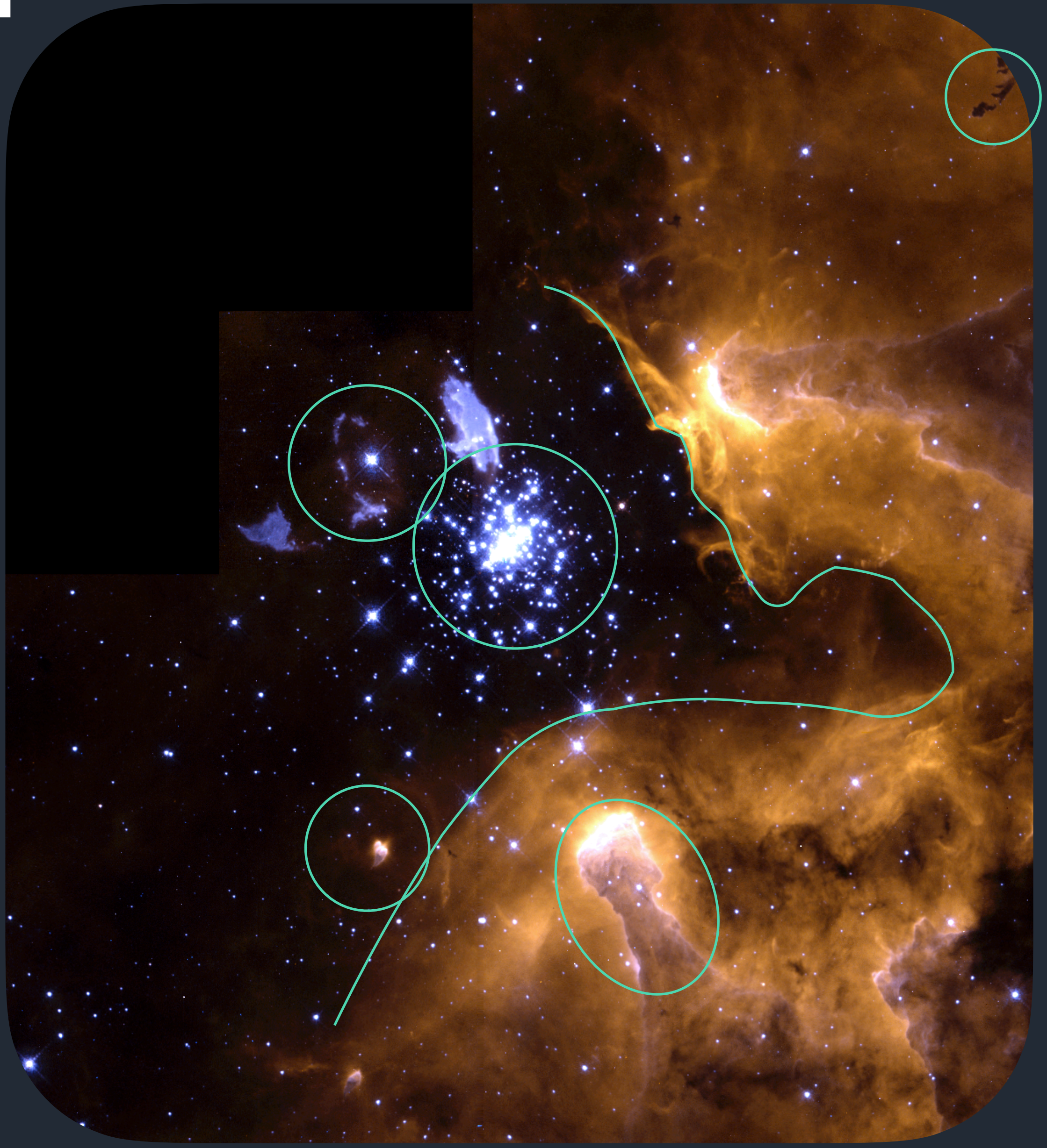
- Most of the ISM space is filled with hot, diffuse (very thin) atomic hydrogen gas.
- Embedded within this we have deep dense clouds of molecular hydrogen
- MCs fills most of the mass but not much of volume



Credit: Wolfgang Brandner (JPL/IPAC), Eva K. Grebel (Univ. Washington), You-Hua Chu (Univ. Illinois Urbana-Champaign), and NASA

General properties of the ISM

- Cluster of bright hot blue stars
- Photodissociation region
- Pillars of glowing hydrogen
- Dark cloud
- Supergiant star Sher 25
- Protoplanetary disc



Credit: Wolfgang Brandner (JPL/IPAC), Eva K. Grebel (Univ. Washington), You-Hua Chu (Univ. Illinois Urbana-Champaign), and NASA

Different phases

- H is the most abundant element (> 90% of nuclei)
- Ionized atomic hydrogen (H^+ or H II) “H-two”

  WIM/HIM/HII   T up to ~ 10^5 K n_e ~ 0.1 - 10^4 cm^{-3}

- Neutral atomic hydrogen (H^0 or H I) “H-one”

  CNM/WNM   T ~ 100-8000 K   n ~ 0.5-40 cm^{-3}

- Molecular hydrogen (H2)

  GMC/DC   T ~ 10-20 K   n ~ 10^2-10^4 cm^{-3}

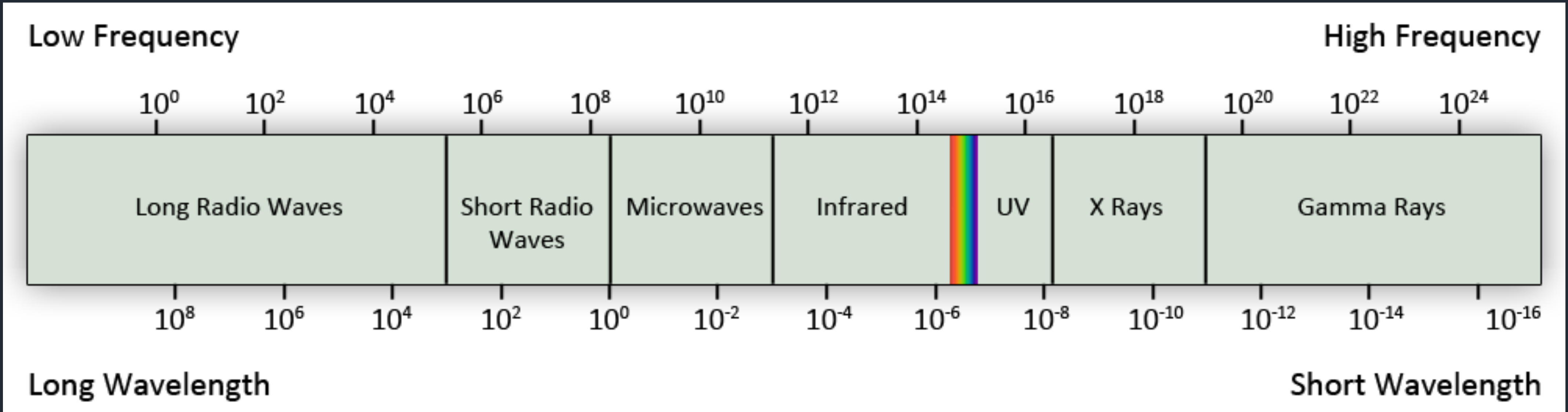
- These regions are usually separated by thin transition zones

Different phases: simple three-phase model

Phase		Density cm^{-3}	Temperature K	Total mass $M_\odot$
Atomic (H I)	Cold	$\simeq$ 25	$\simeq$ 100	1.5×10^9
	Warm	$\simeq$ 0.25	$\simeq$ 8 000	1.5×10^9
Molecular (H_2)		$\geq$ 1 000	$\leq$ 100	10^9?
Ionized	H II regions	$\simeq 1 - 10^4$	$\simeq$ 10 000	5×10^7
	Diffuse	$\simeq$ 0.03	$\simeq$ 8 000	10^9
	Hot	$\simeq 6 \times 10^{-3}$	$\simeq 5 \times 10^5$	10^8?

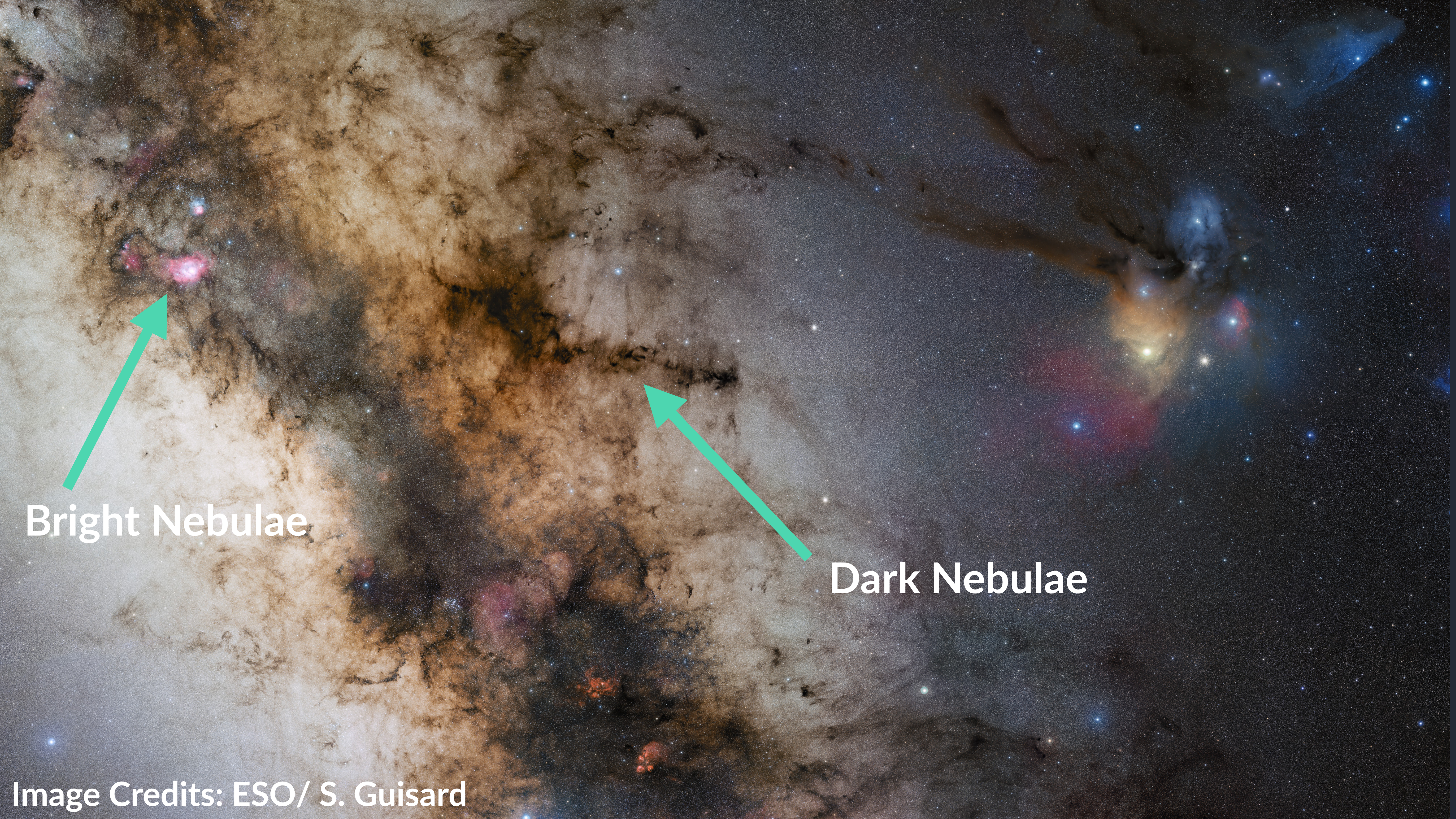
Observing the ISM

- Most of the gas in galaxies is relatively cool and, since a typical wavelength is inversely proportional to temperature it is only observable in *emission* in bands outside of the visible
- Large volume of gas are hot, and require short wavelength observations (UV & X-rays) with satellite observatories.



Past, present, future

- Last half-century the ISM has been intensively studied
- Planck - Herschel provided a multi-wavelength view of the ISM
- ALMA will give fuel for decades
- Wide range of conditions leads to the formation of very different structures
- Different in distribution, volume, morphology, relevant physical processes


Bright Nebulae
Dark Nebulae
Image Credits: ESO/ S. Guisard

The zoo of objects in the ISM

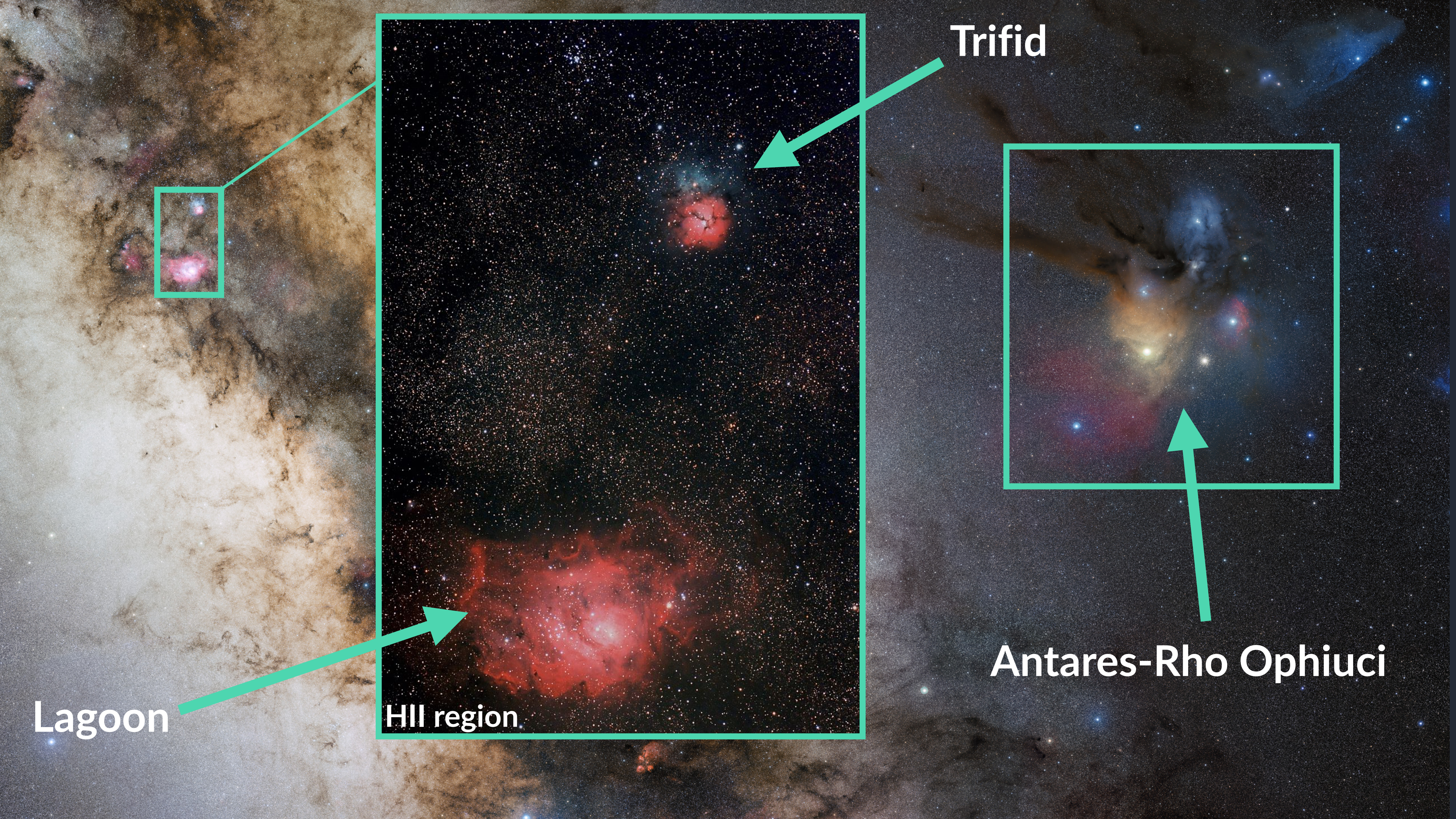
Dark clouds (molecular clouds) - is not associated with bright stars, seen as black patches

Reflection nebula - presence of hot stars (25,000 K) the dust cloud may scatter the stellar radiation

HII region (or emission nebula) - nebula associated with very hot stars (Teff > 25,000 K), gas surrounding is photoionised

Planetary nebula - former atmosphere of a solar mass star death, white dwarf - black dwarf

Supernova remnant - massive stars death, bright gaseous nebula


Trifid
Antares-Rho Ophiuci
Lagoon
HII region

Trifid

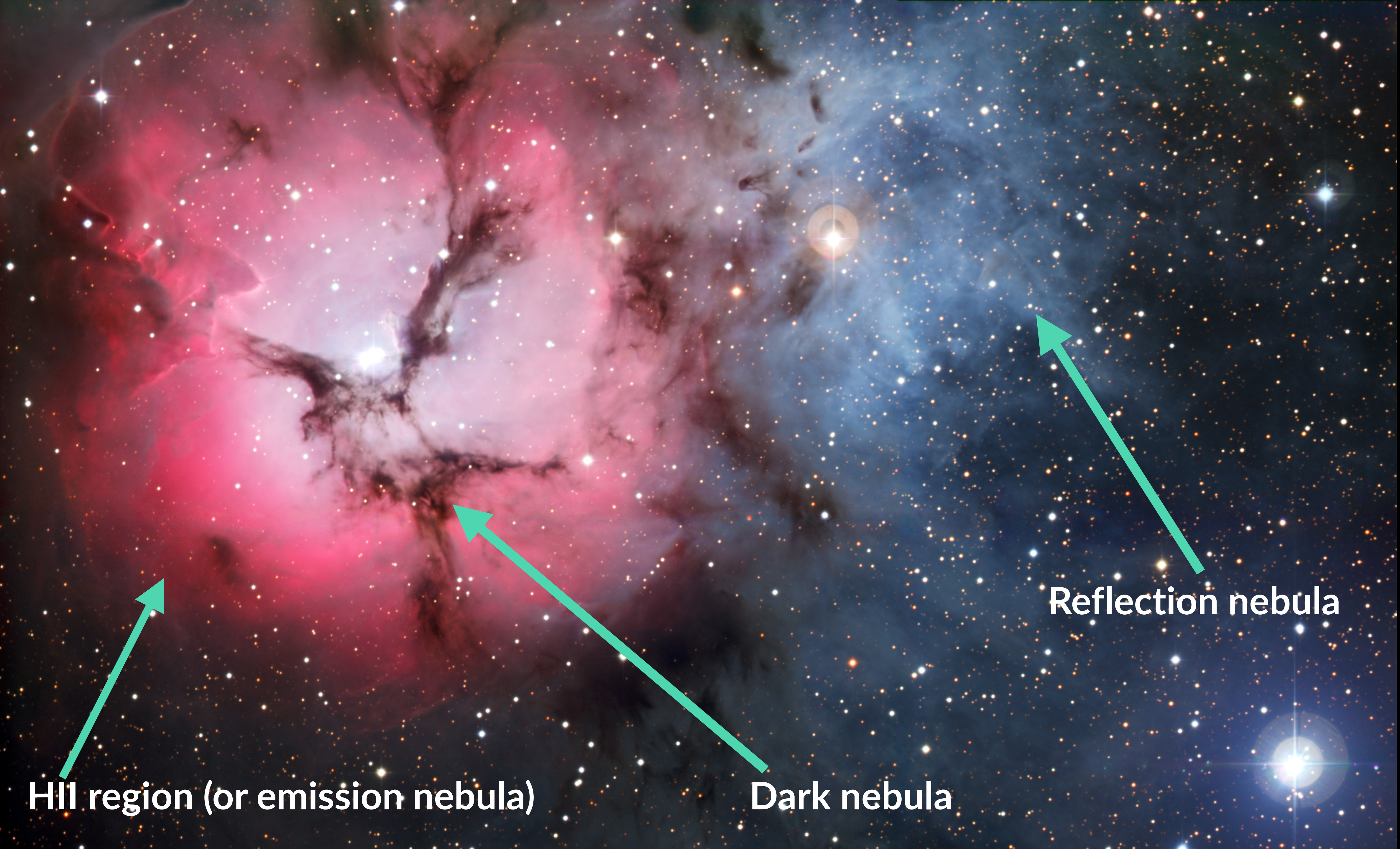


Image Credits: ESO, La Silla

Antares-Rho Ophiuci Complex

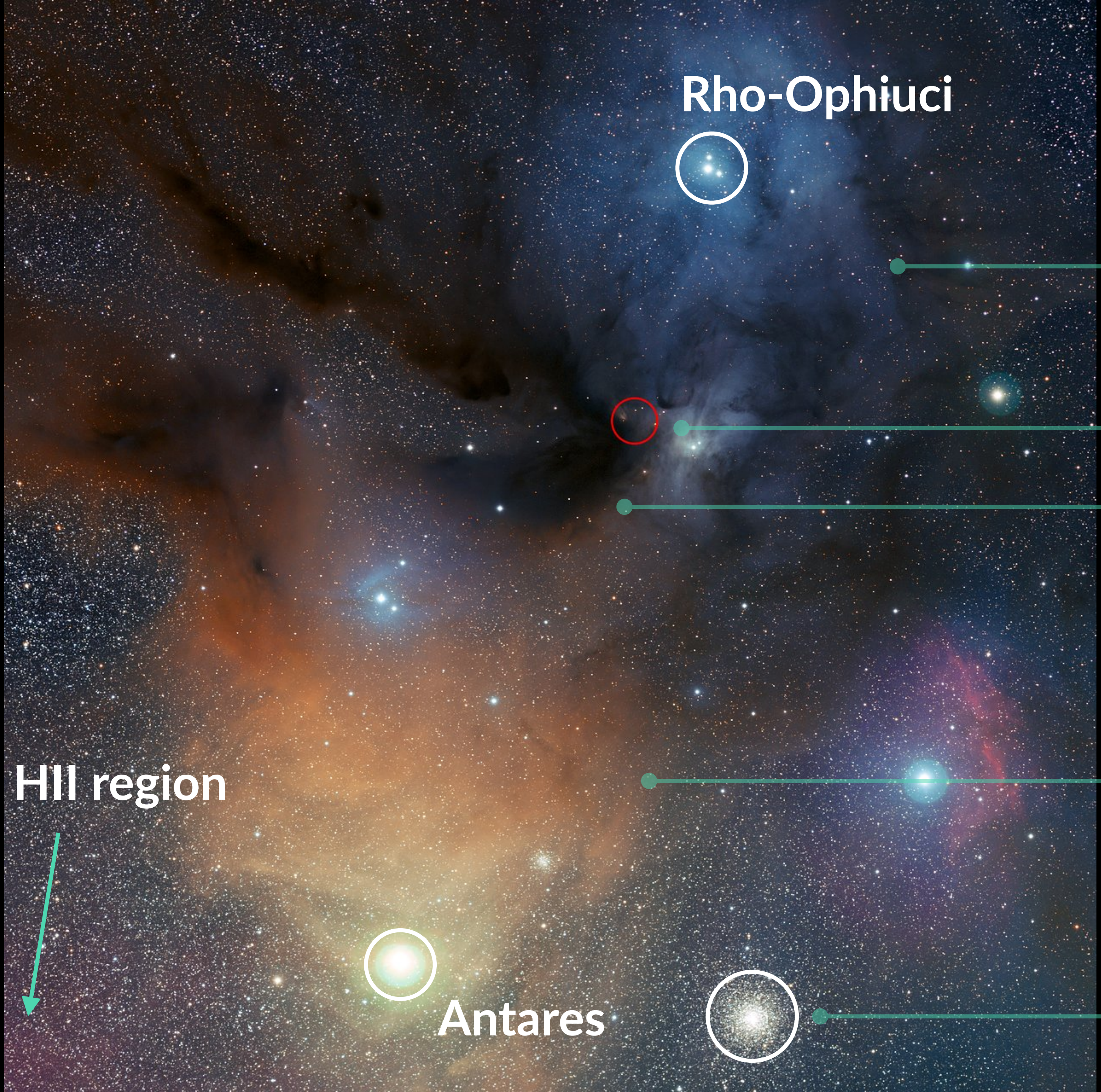
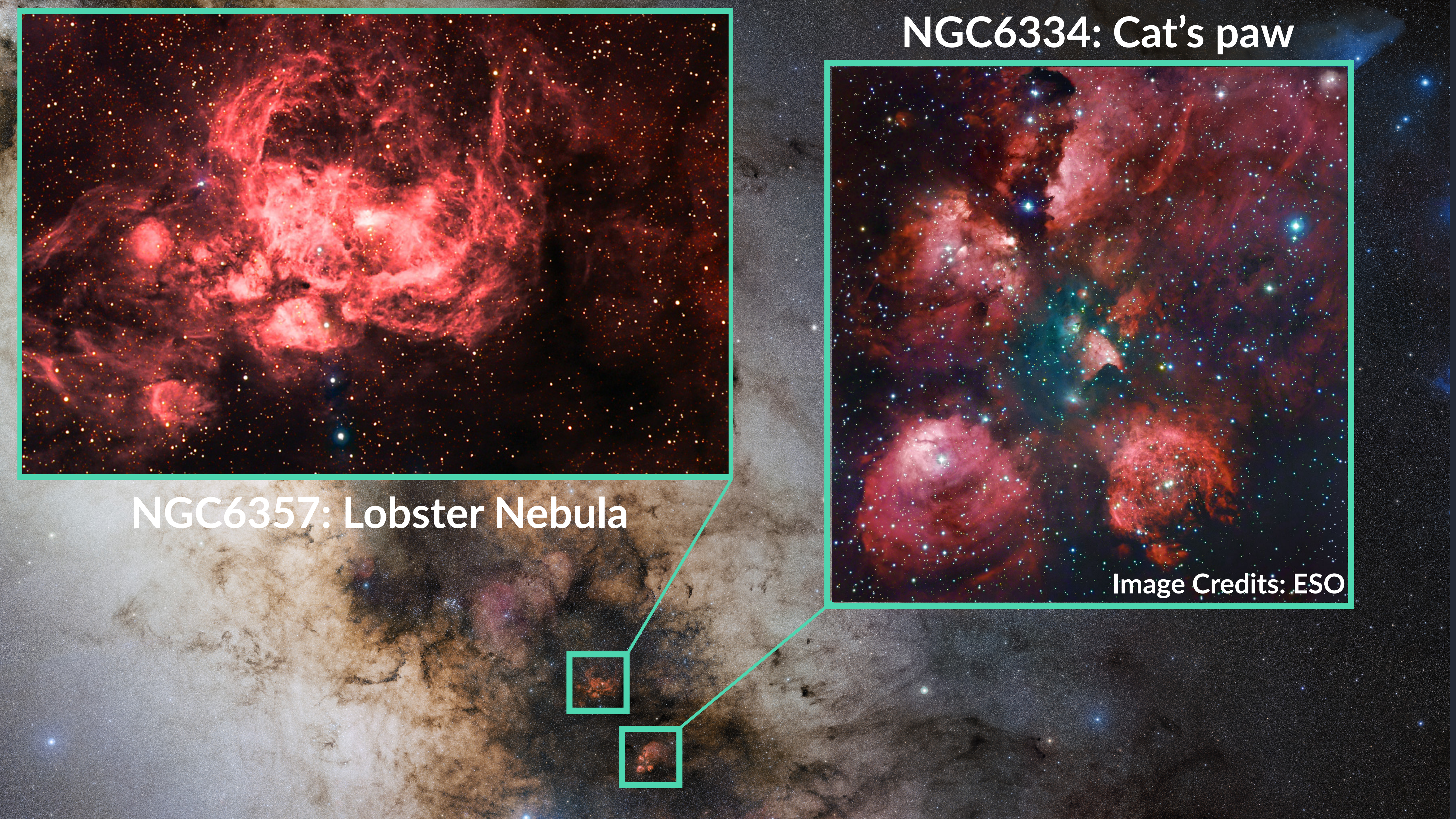
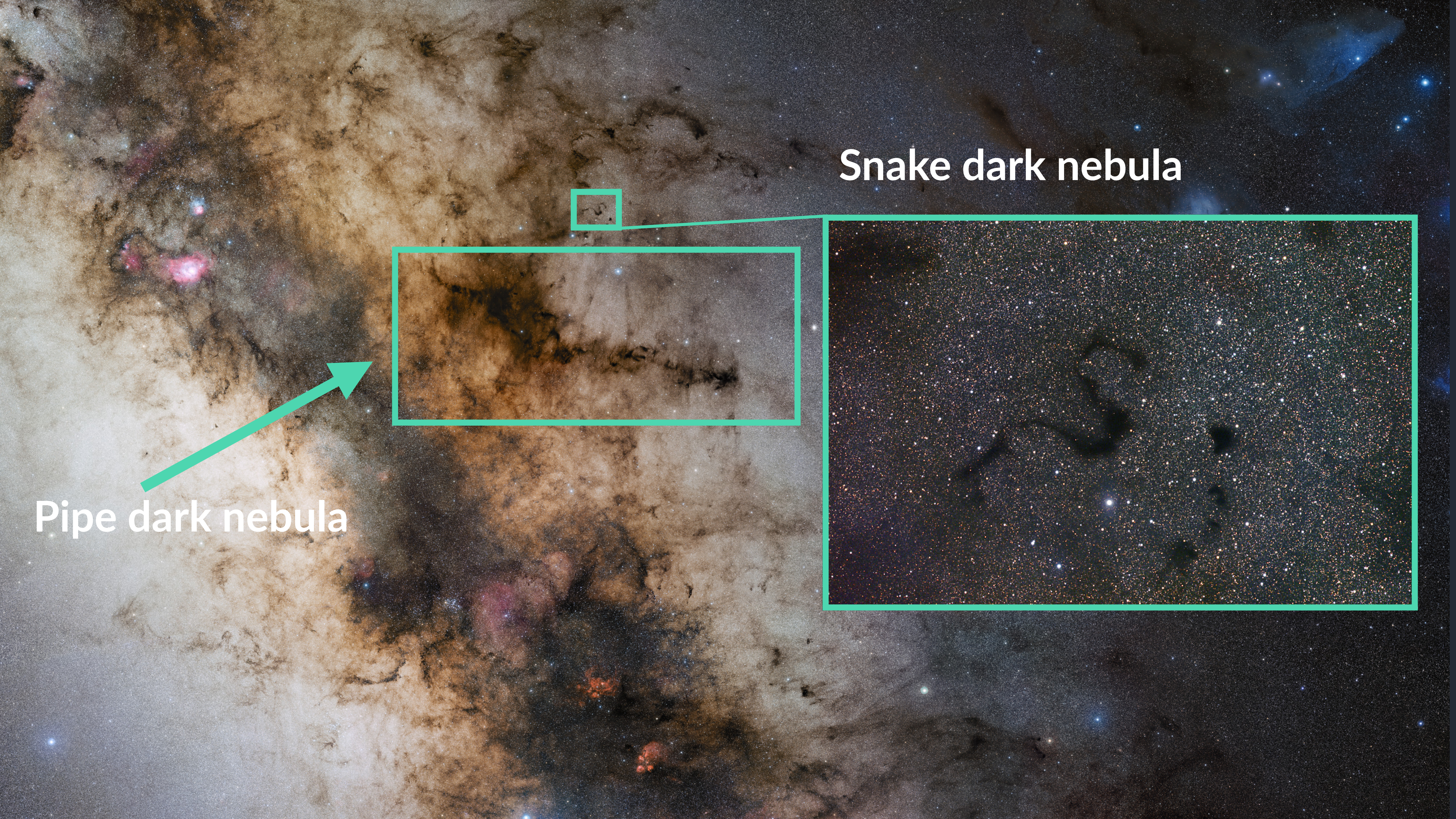


Image Credits: ESO, Paranal


NGC6334: Cat's paw
NGC6357: Lobster Nebula
Image Credits: ESO

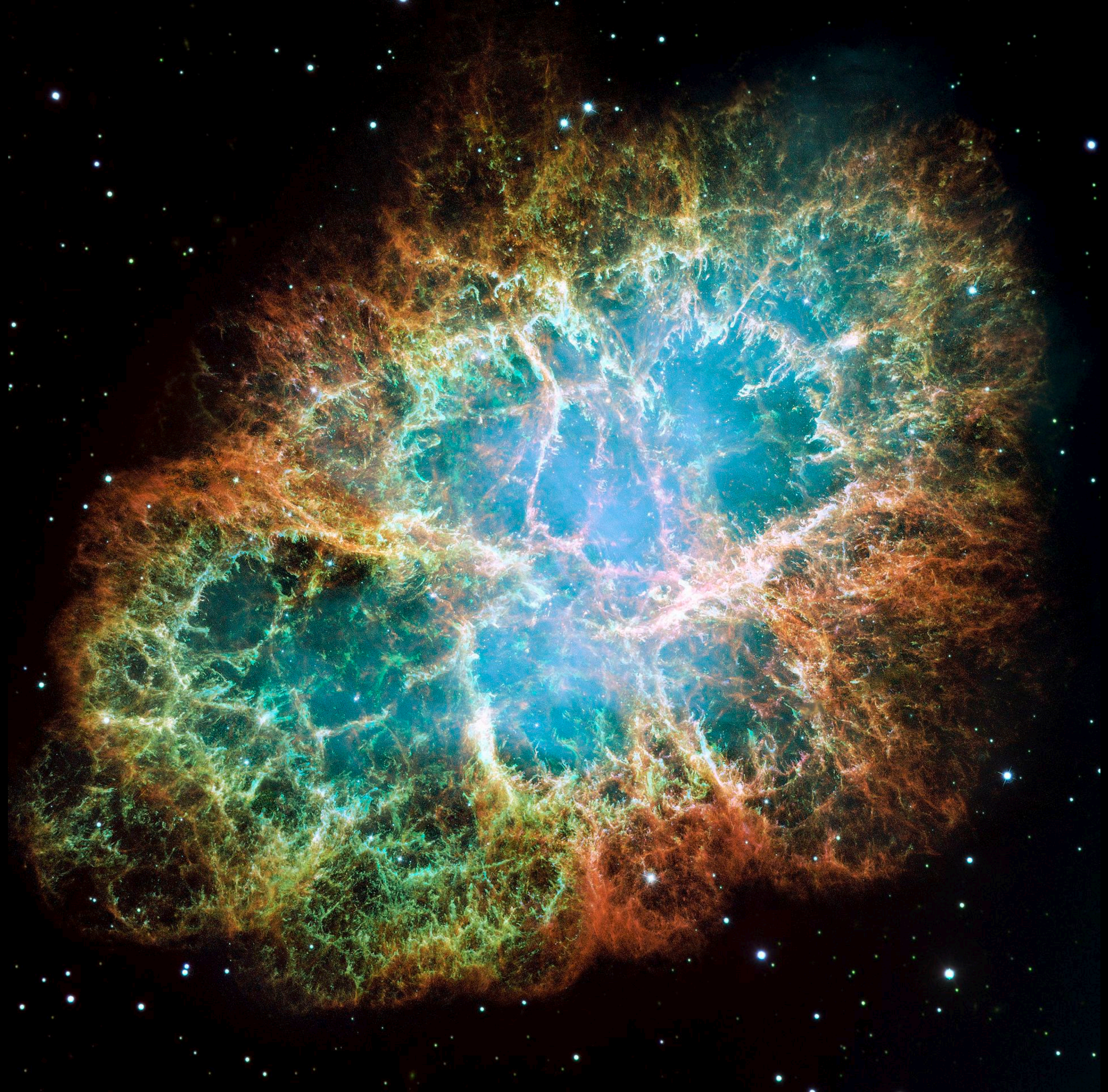
orange - hydrogen
green - oxygen
red - sulfur

Image Credits: ESO


Snake dark nebula
Pipe dark nebula

ESO 378-1

Image Credits: ESO



SNR 1054

Image Credits: NASA, ESA

The Milky Way

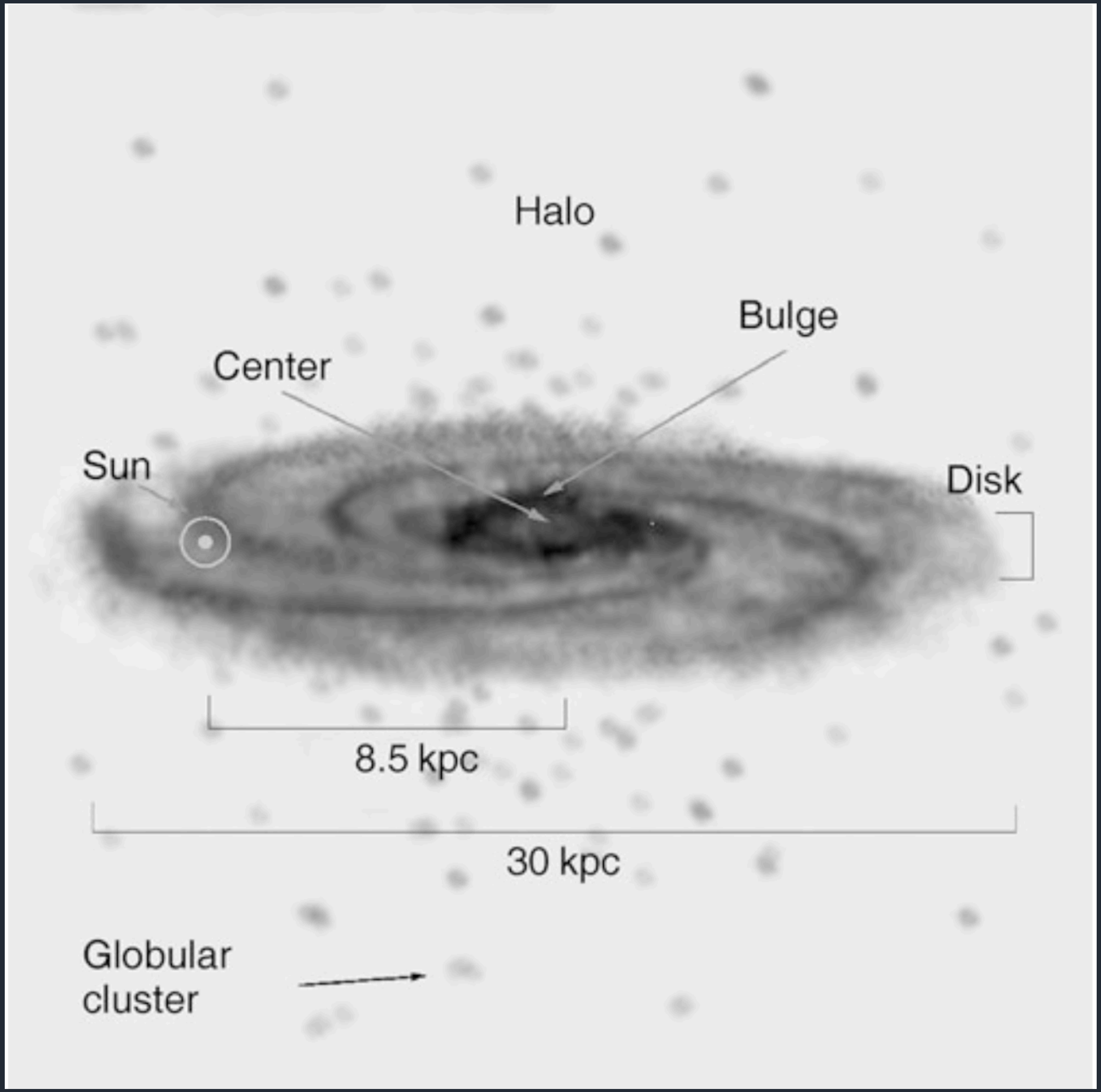
- Complex system of stars, gas and dust particles
- Bathed in a magnetic field, subject to radiation covering the entire EM spectrum
- Exposed to neutral and charged cosmic rays

Our Galaxy: The Milky Way

- Gravitationally bound / isolated system / rotate
  - Self-gravitating
  - Rotating stellar disk
  - Collisionless stellar systems
  - Close system
  - Difficult to describe as a whole (we need sub-systems)

The Milky Way

- Spiral galaxy
- Thin disk of stars/gas w a radius of 20 kpc, height of 300 pc
- 1 kpc thick disk w older stellar population
- Central bulge
- Spherical (nearly) halo w globular cluster



Our Galaxy: The Milky Way

- Total mass ~1.7.x 10^{11} solar masses (within a radius of 20 kpc)
  - Of which ~5 x 10^{10} solar masses in stars
  - ~5 x 10^{10} solar masses in dark matter
  - ~7 x 10^{9} solar masses in gas
- Sun is at 8.5 kpc from the galactic center

Our Galaxy: Chemical composition

- 70% hydrogen, 28% helium, 2% heavy metals
- Metals are distributed differently between gas and dust grains

Table 1.1 Total relative elemental solar abundances (extracted from Asplund *et al.* 2009[5]) for elements X with an abundance greater than one part in 10^7 relative to hydrogen H.

X	[X]/[H]	X	[X]/[H]	X	[X]/[H]
H	1	Mg	4.37×10^{-5}	K	1.32×10^{-7}
He	9.55×10^{-2}	Al	2.95×10^{-6}	Ca	2.14×10^{-6}
C	2.95×10^{-4}	Si	3.55×10^{-5}	Cr	4.79×10^{-7}
N	7.41×10^{-5}	P	3.23×10^{-7}	Mn	3.31×10^{-7}
O	5.37×10^{-4}	S	1.45×10^{-5}	Fe	3.47×10^{-5}
Ne	9.33×10^{-5}	Cl	1.86×10^{-7}	Ni	1.74×10^{-6}
Na	2.04×10^{-6}	A	2.75×10^{-6}	Co	0.98×10^{-7}

Our Galaxy: Energy densities

Component	$u(\mathrm{eV\,cm^{-3}})$	Note
Cosmic microwave background ($T_{\mathrm{CMB}} = 2.725\,\mathrm{K}$)	0.265	*a*
Far-infrared radiation from dust	0.31	*b*
Starlight ($h\nu < 13.6\,\mathrm{eV}$)	0.54	*c*
Thermal kinetic energy $(3/2)nkT$	0.49	*d*
Turbulent kinetic energy $(1/2)\rho v^2$	0.22	*e*
Magnetic energy $B^2/8\pi$	0.89	*f*
Cosmic rays	1.39	*g*

a Fixsen & Mather (2002).

b Chapter 12.

c Chapter 12.

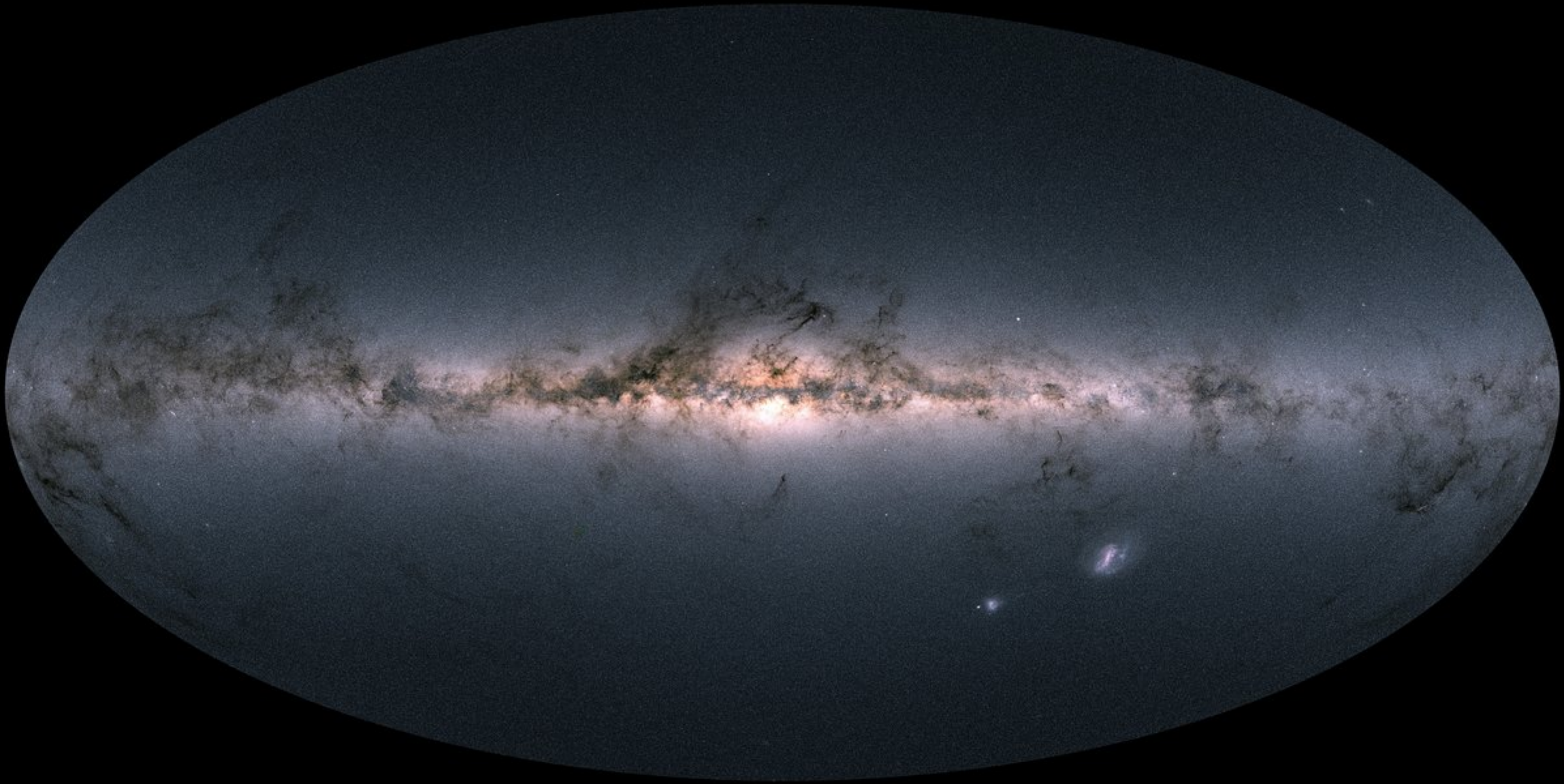
d For $nT = 3800\,\mathrm{cm^{-3}\,K}$ (see §17.7).

e For $n_{\mathrm{H}} = 30\,\mathrm{cm^{-3}}$, $v = 1\,\mathrm{km\,s^{-1}}$, or $\langle n_{\mathrm{H}} \rangle = 1\,\mathrm{cm^{-3}}$, $\langle v^2 \rangle^{1/2} = 5.5\,\mathrm{km\,s^{-1}}$.

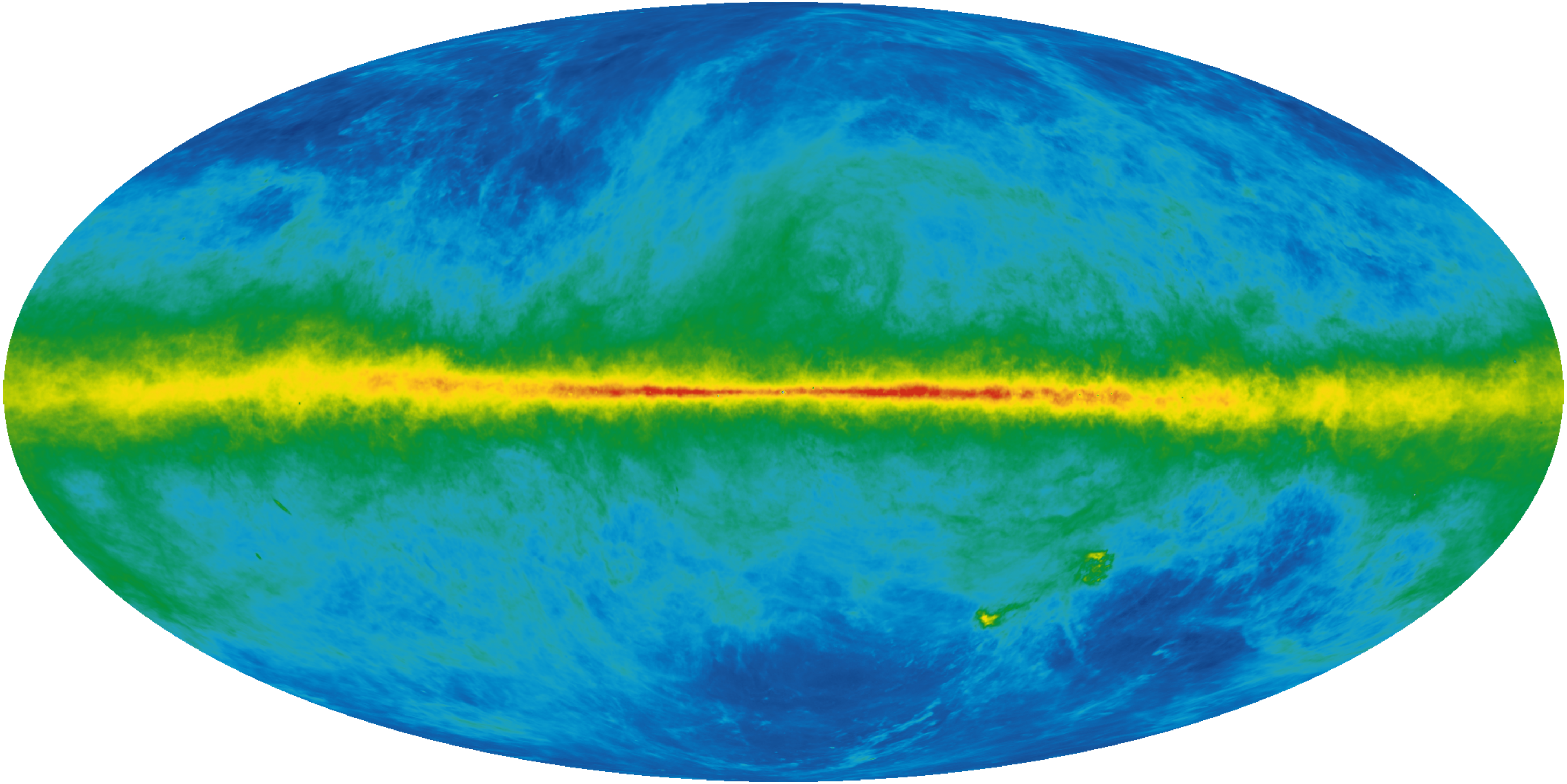
f For median $B_{\mathrm{tot}} \approx 6.0\,\mu\mathrm{G}$ (Heiles & Crutcher 2005).

g For cosmic ray spectrum X3 in Fig. 13.5.

Our Galaxy: in optical light

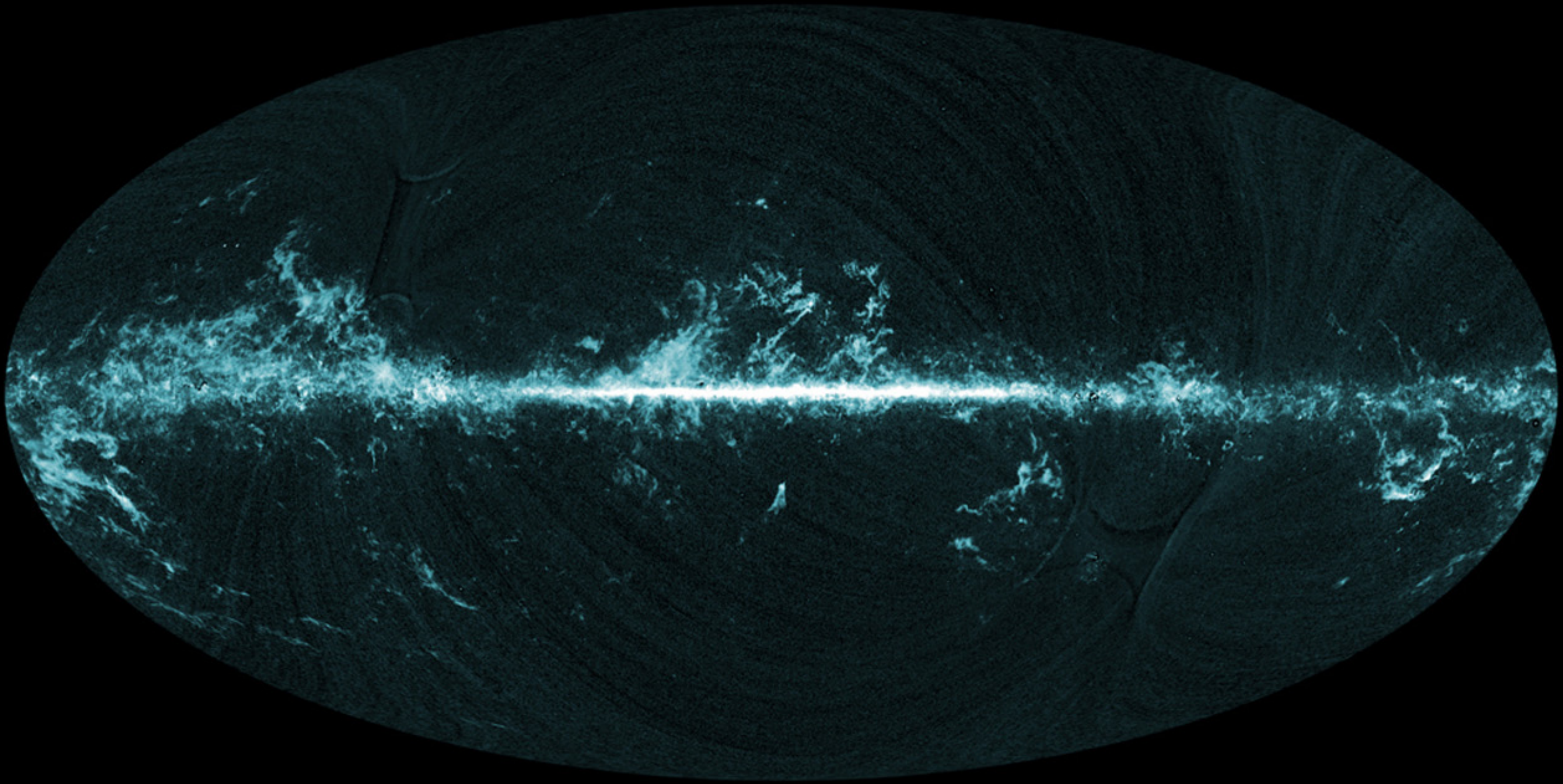


Our Galaxy: in H 21-cm emission



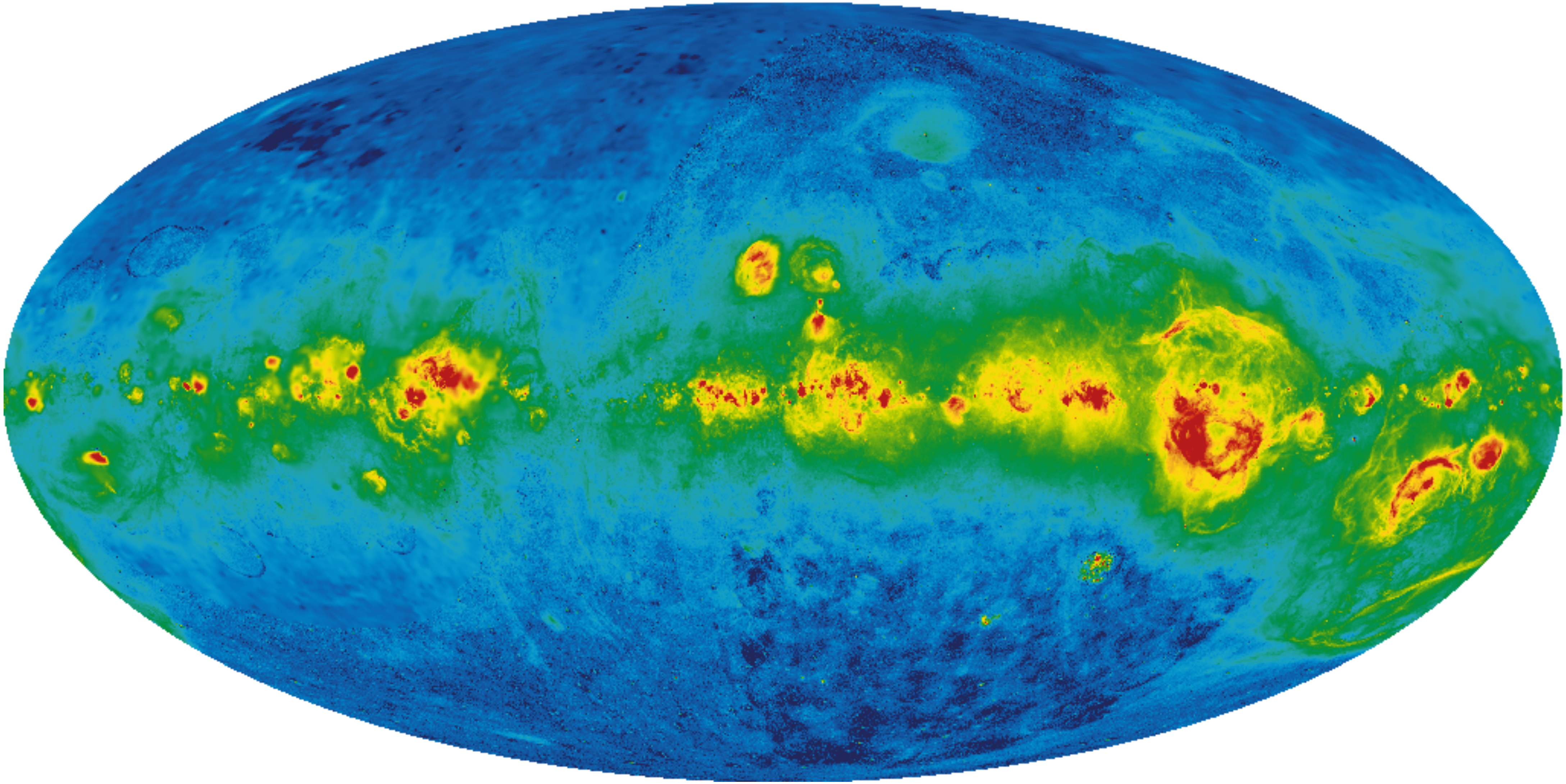
Credits: N(HI) HI4PI Collaboration 2016

Our Galaxy: molecular gas in CO



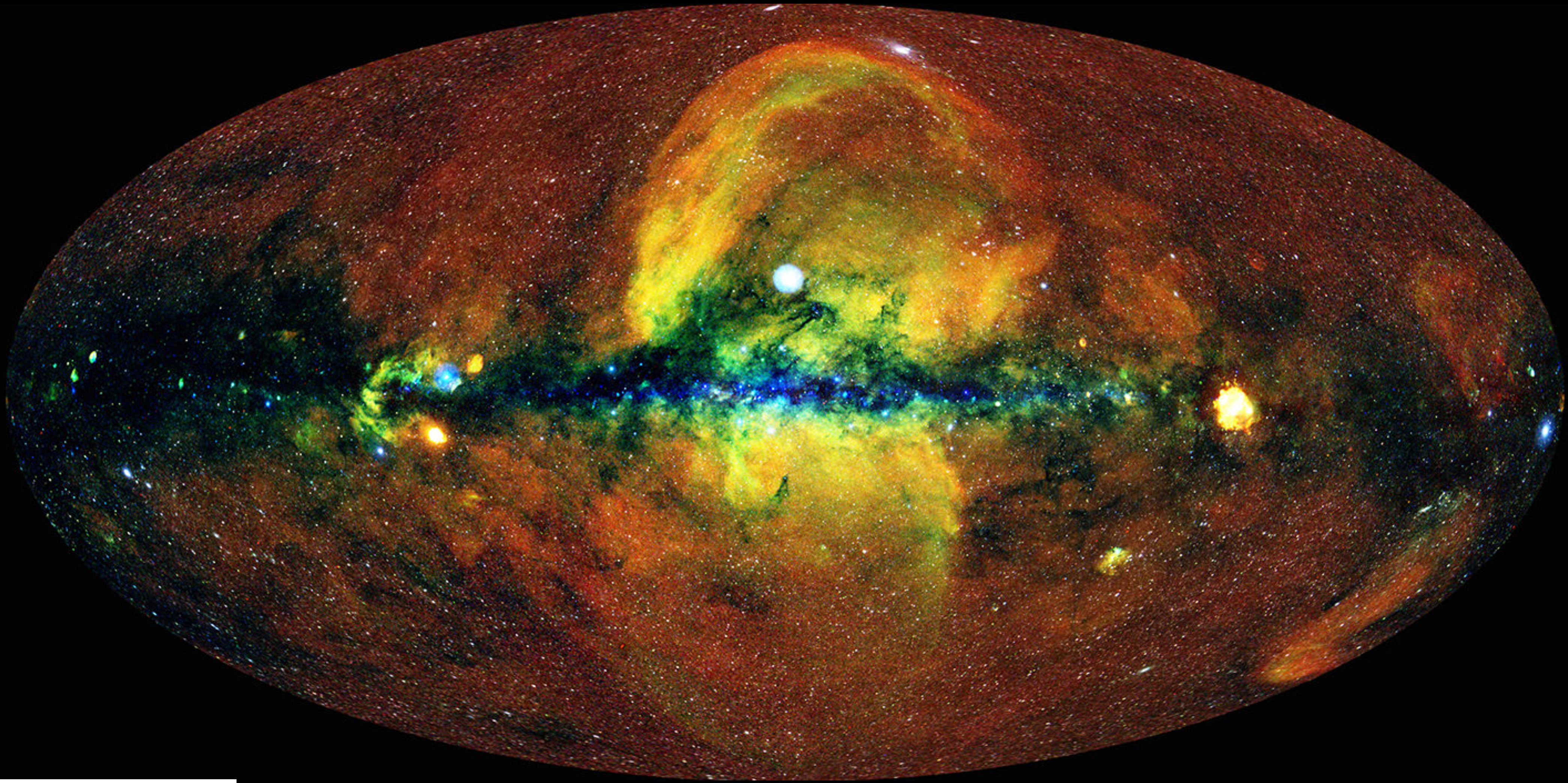
Credit: ESA/NASA/Planck Collaboration

Our Galaxy: hot-gas H-alpha



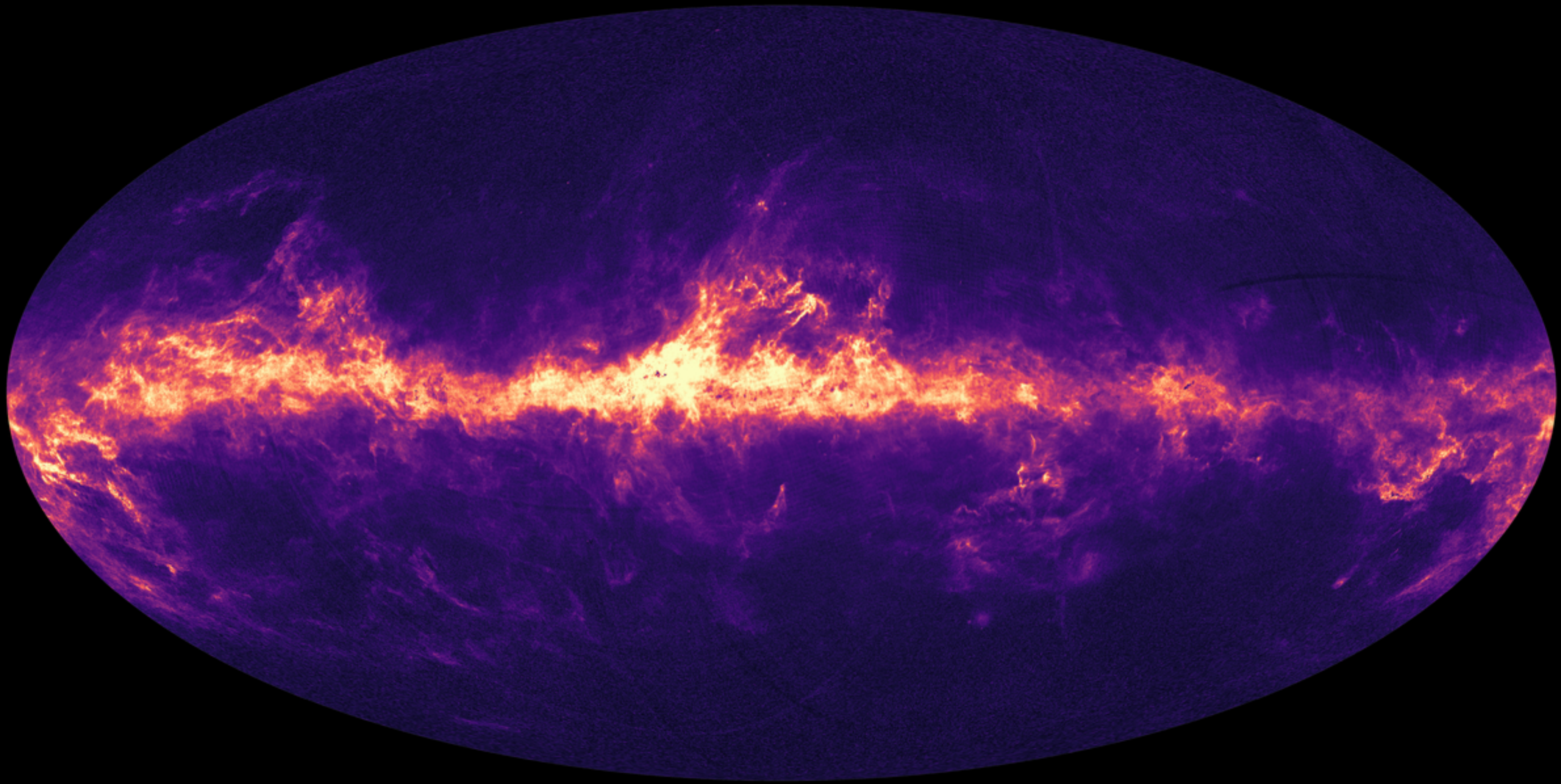
Credit: D. Finkbeiner / LAMBDA

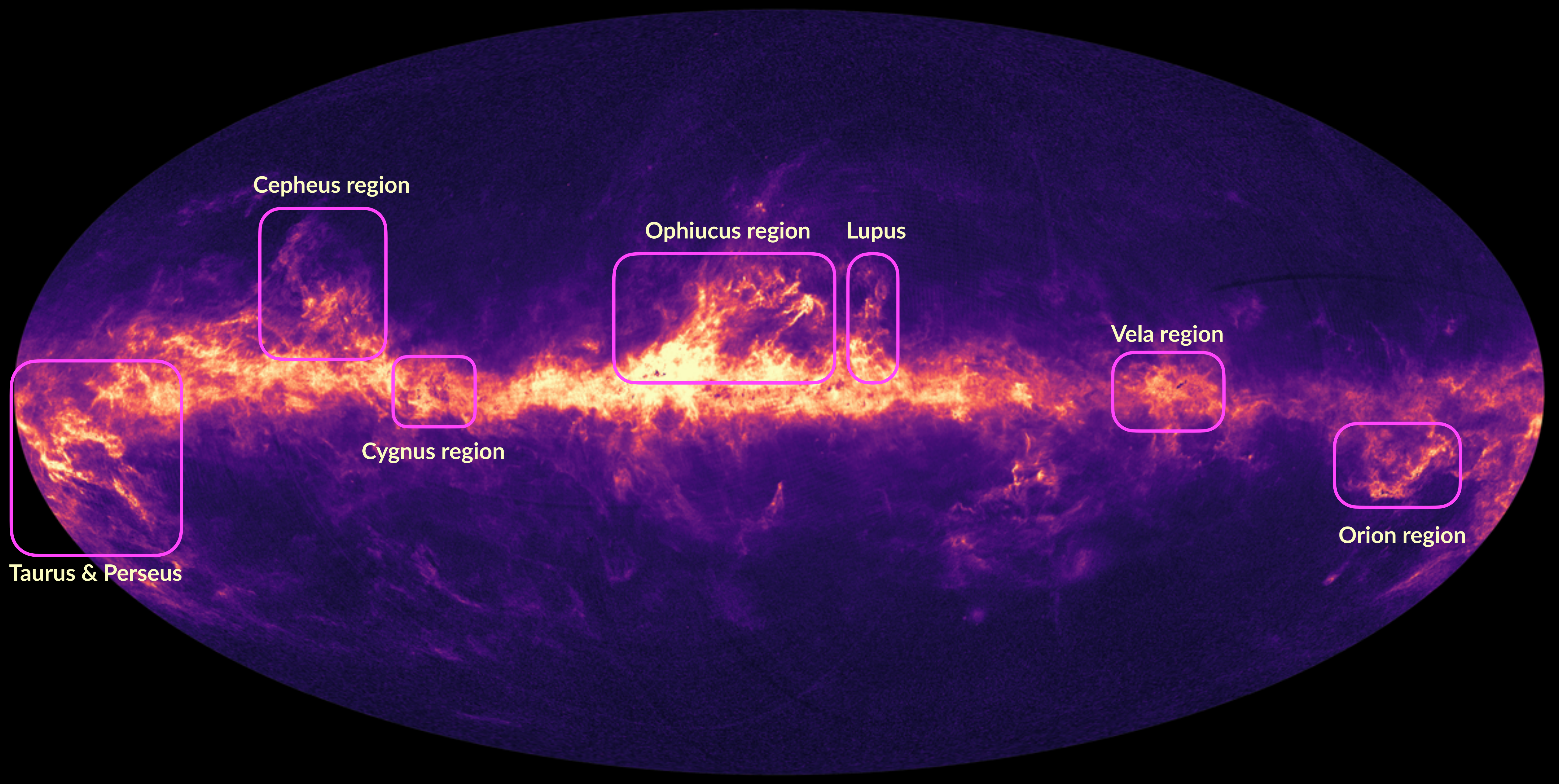
Our Galaxy: X-rays



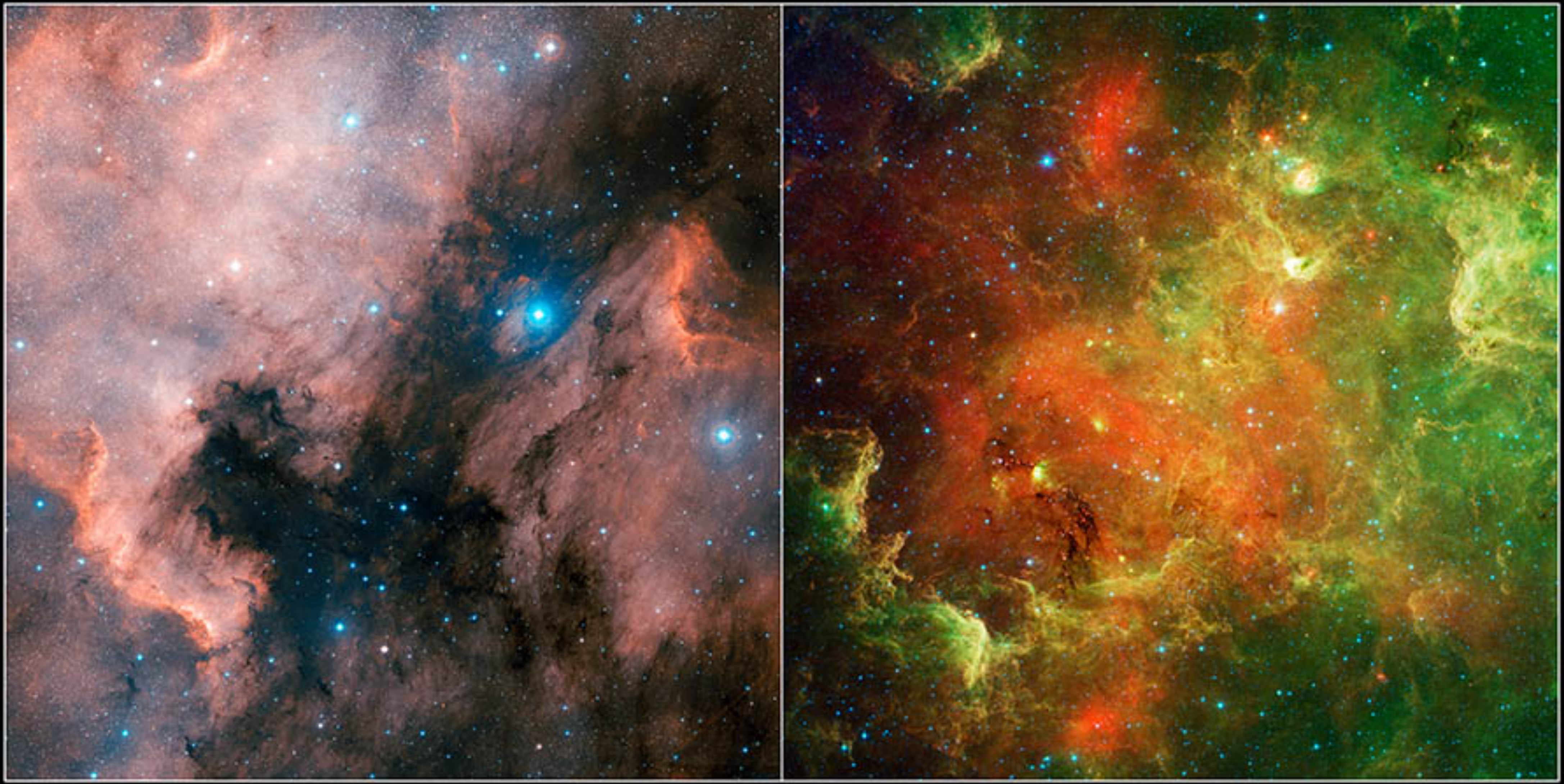
Credit: Jeremy Sanders, Hermann Brunner & the eSASS team / Max Planck Institute for Extraterrestrial Physics / Eugene Churazov & Marat Gilfanov, IKI

Our Galaxy: dust




Cepheus region
Ophiucus region
Lupus
Vela region
Taurus & Perseus
Cygnus region
Orion region

Visible Light (DSS/D. De Martin) | Infrared Light

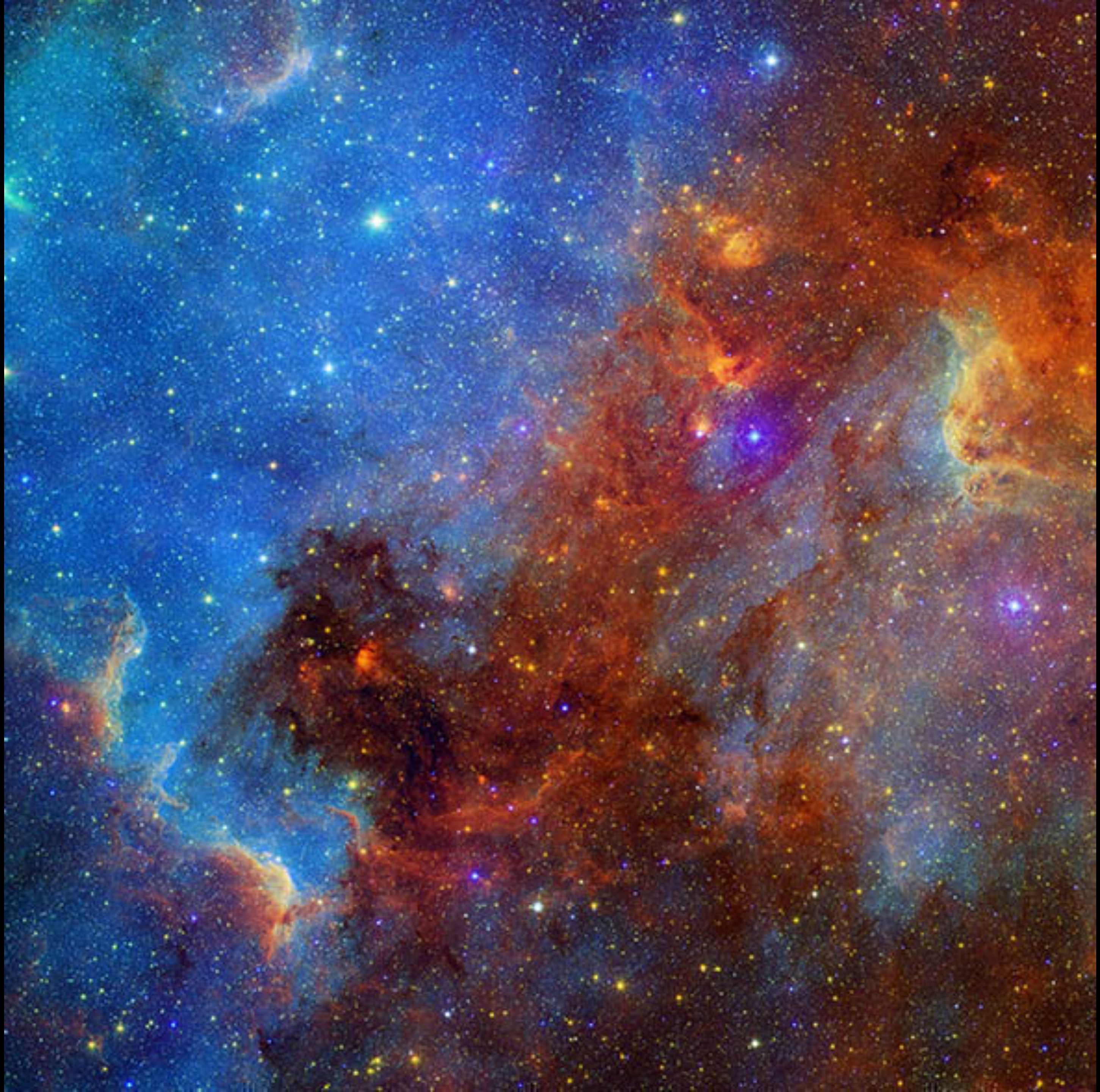


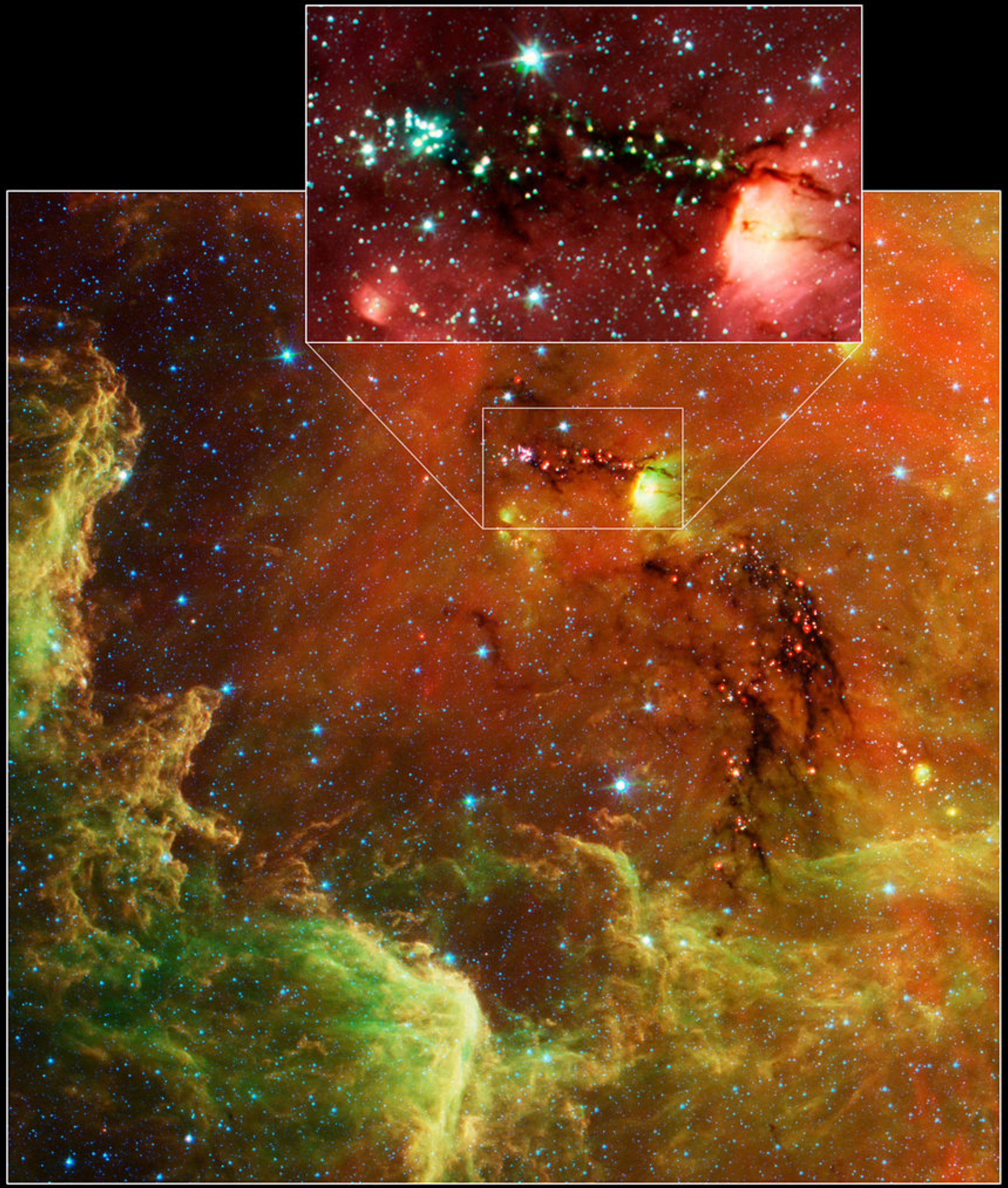
North America Nebula Comparison

NASA / JPL-Caltech / L. Rebull (SSC/Caltech)

Spitzer Space Telescope • IRAC • MIPS

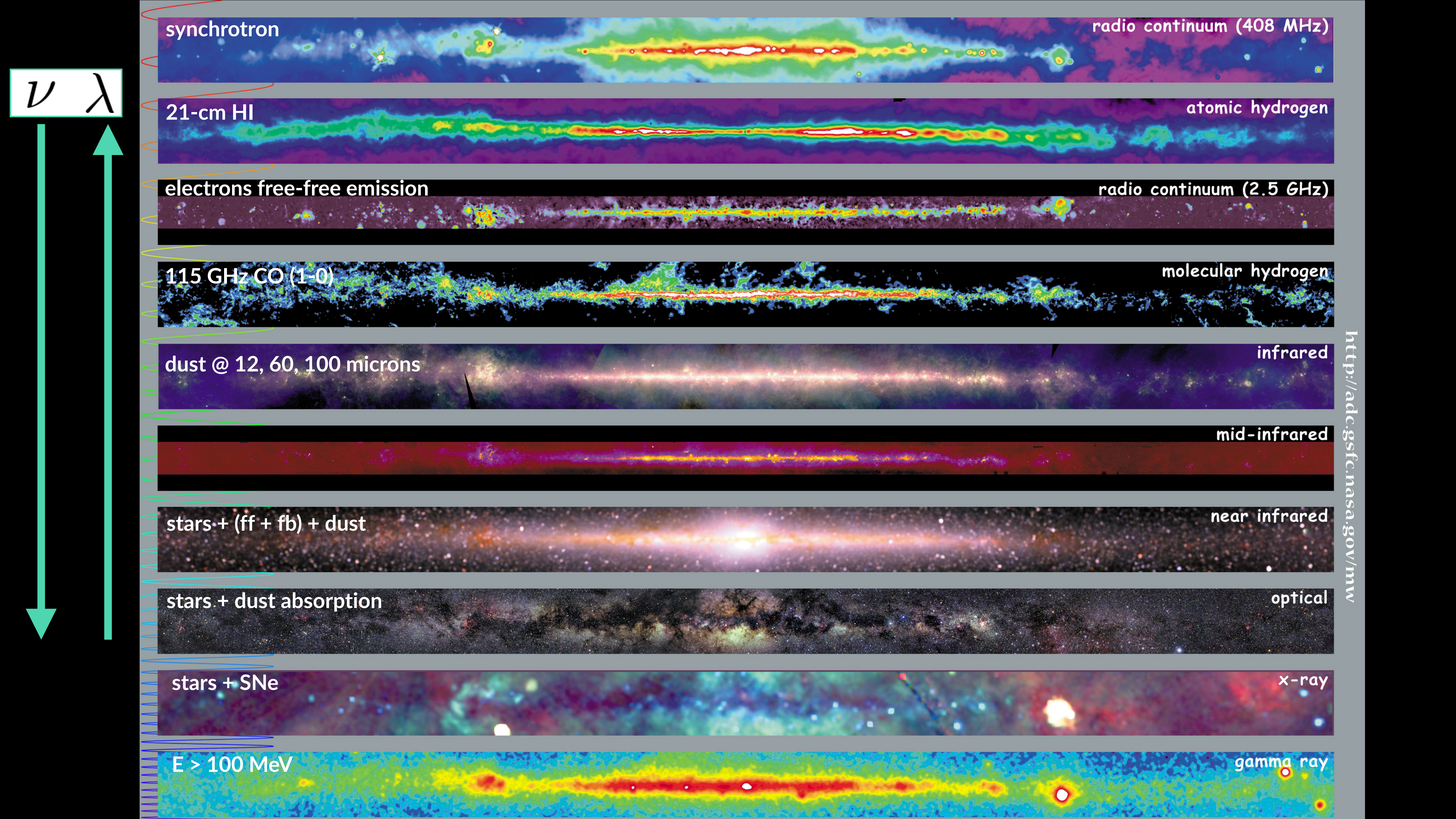
ssc2011-03b





Baby Stars and Jets Near the North America Nebula
Spitzer Space Telescope • IRAC • MIPS

NASA / JPL-Caltech / L. Rebull (SSC/Caltech) ssc2011-03c



ν λ
synchrotron
radio continuum (408 MHz)
21-cm HI
atomic hydrogen
electrons free-free emission
radio continuum (2.5 GHz)
115 GHz CO (1-0)
molecular hydrogen
dust @ 12, 60, 100 microns
infrared
mid-infrared
stars + (ff + fb) + dust
near infrared
stars + dust absorption
optical
stars + SNe
x-ray
E > 100 MeV
gamma ray
http://adc.gsfc.nasa.gov/mw

Units

pc	$= 3.086 \times 10^{18}$ cm	parsec
$M_\odot$	$= 1.989 \times 10^{33}$ g	solar mass
$L_\odot$	$= 3.826 \times 10^{33}$ erg s^{-1}	solar luminosity
yr	$= 3.156 \times 10^{7}$ s	sidereal year
Myr	$\equiv 10^{6}$ yr	megayear
AU	$= 1.496 \times 10^{13}$ cm	astronomical unit
Å	$\equiv 10^{-8}$ cm	Ångstrom
nm	$\equiv 10$ Å $\equiv 10^{-7}$ cm	nanometer
μm	$\equiv 10^{-4}$ cm	micron
km s^{-1}	$\equiv 10^{5}$ cm s^{-1}	km per sec
Jy	$\equiv 10^{-23}$ erg s^{-1} cm^{-2} Hz^{-1}	jansky
R	$\equiv (10^{6}/4\pi)$photons cm^{-2} s^{-1} sr^{-1}	rayleigh
D	$\equiv 10^{-18}$esu cm	debye
eV	$= 1.602 \times 10^{-12}$ erg	electron-volt
G	$= 10^{-4}$ tesla $= 10^{-4}$ weber m^{-2}	gauss