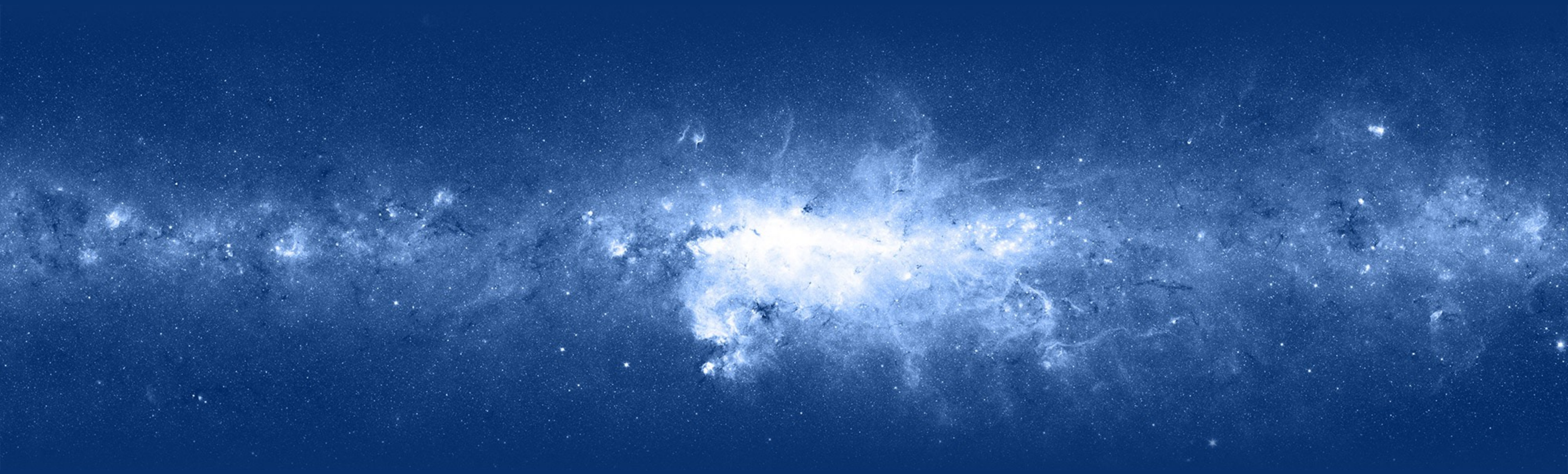
ASTR 670: Interstellar medium and gas dynamics

Prof. Benedikt Diemer



Chapter 1 • Introduction: What is the ISM?

Semester projects

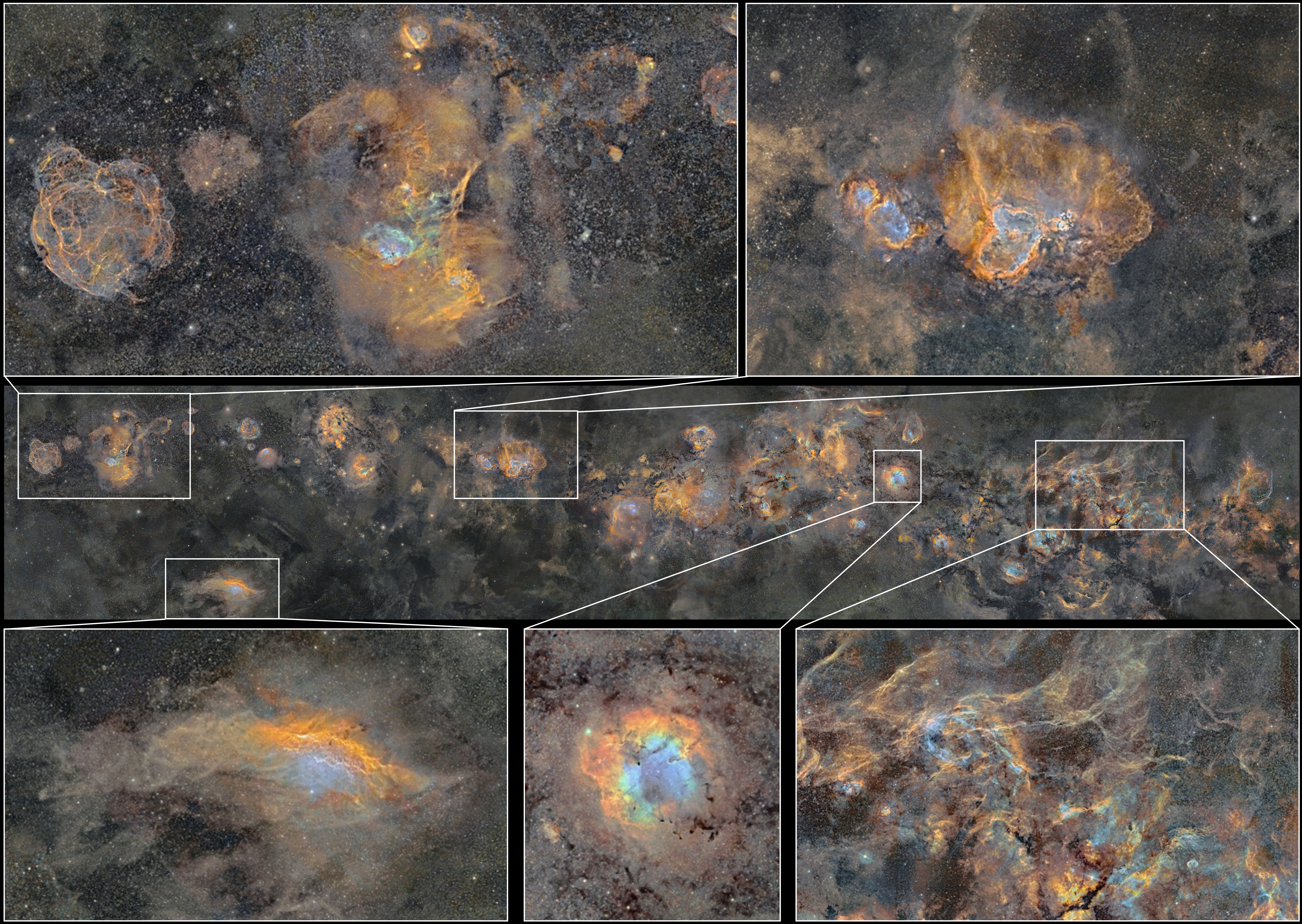
1	Spherically symmetric hydrodynamics	Brendan, Lacey
2	Smoothed particle hydrodynamics	Matt, Sophie
5	AI hydrodynamics	Keyi, Cole
6	Exploring viscosity	Yash, Kylie
7	Supernova bubbles redux	Zuzanna, Mark
8	The thermal instability	Marshall, Enrico
9	Photo-dissociation regions	Shaniya, Keaton
10	Spherical accretion and stellar winds	Brooke, Charles

Mike Grudić
@MikeGrudic

ISM physics is dumb. it's just like yeah this ion you never heard of does a somersault into a dust grain every Tuesday with Mercury in retrograde and this is why life can exist in the universe

12:39 PM · Oct 21, 2022 · Twitter Web App

What is the ISM?

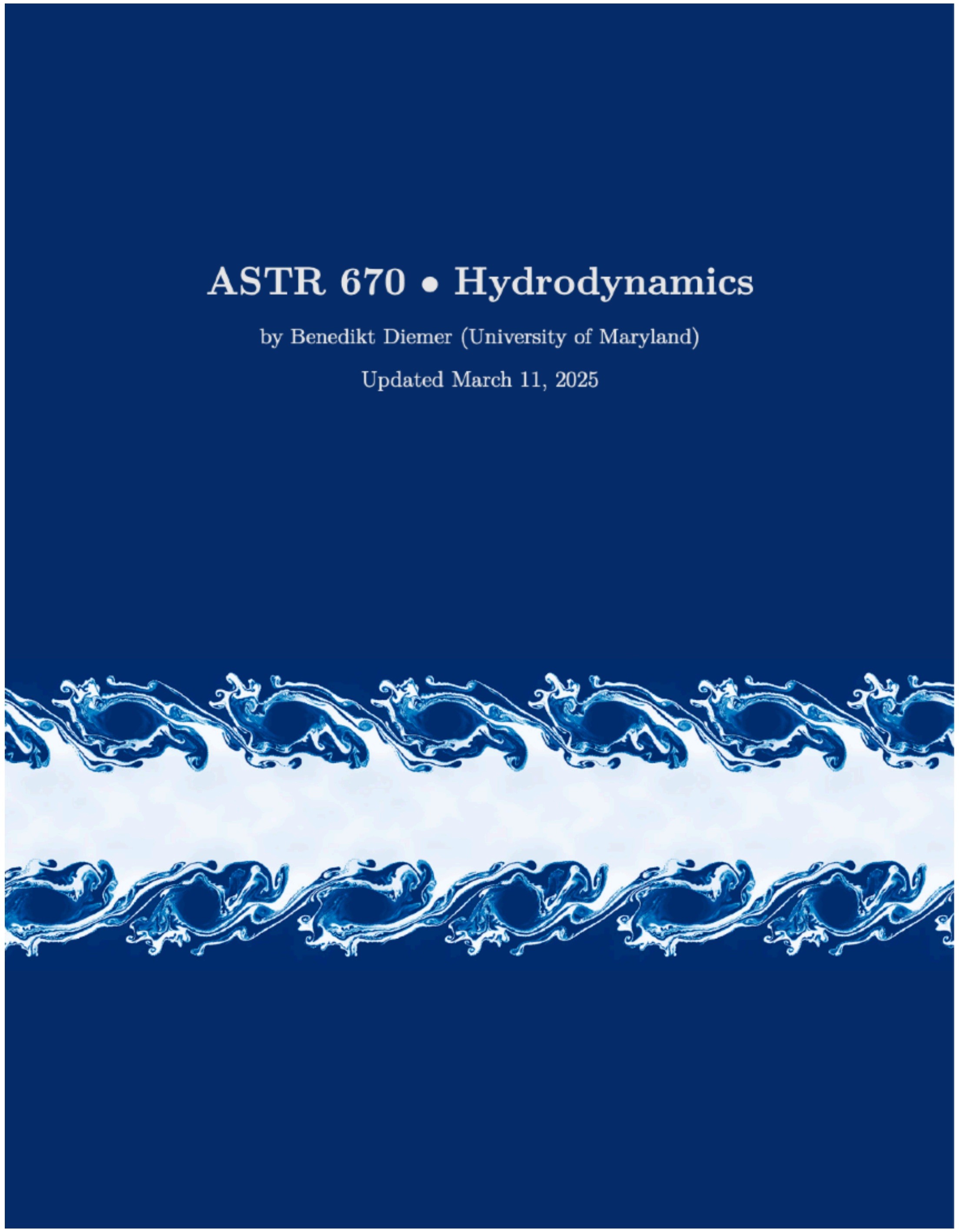


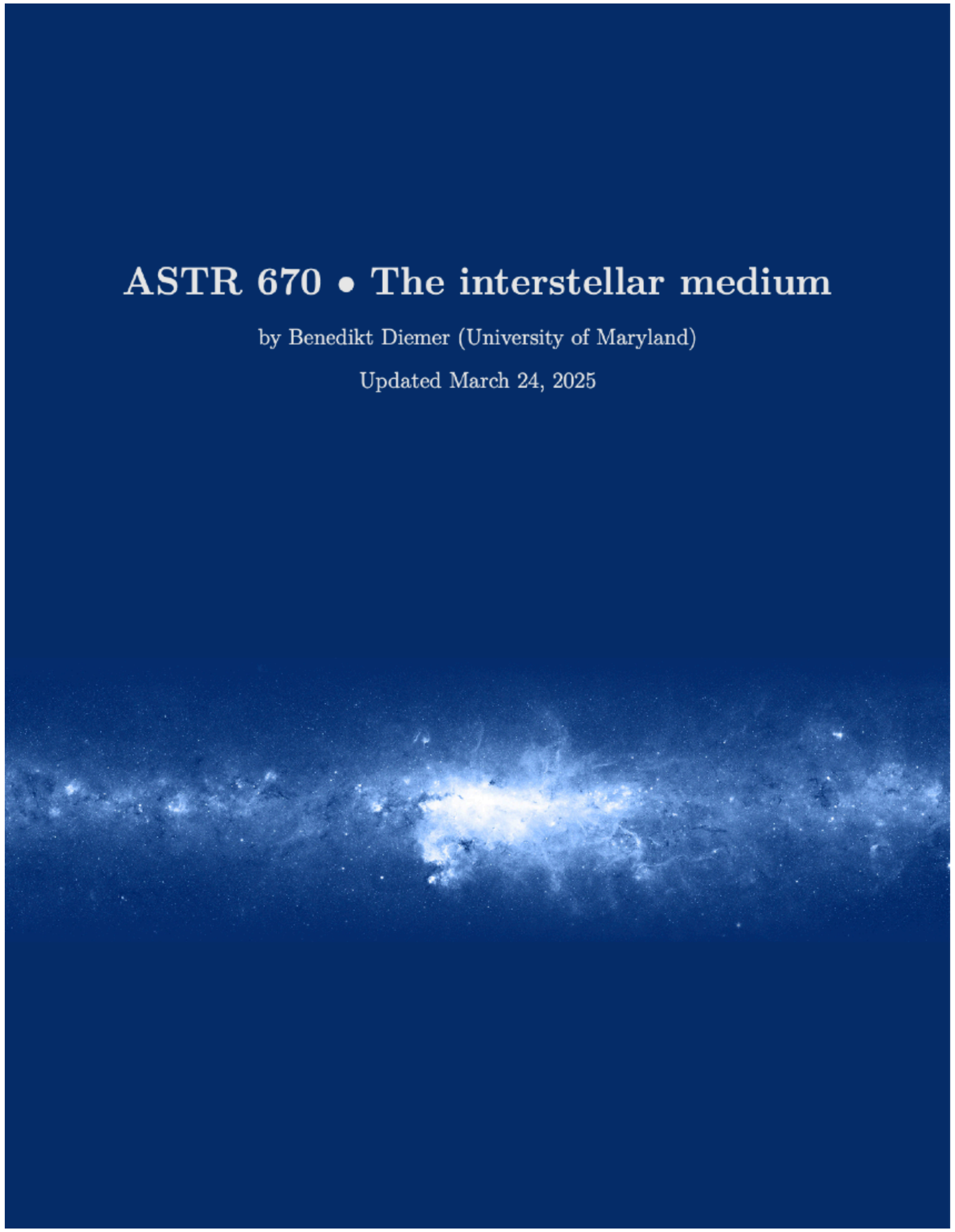
J-P Metsavaino (amateur photography)

What are we going to study?

- Interstellar gas and dust
- Important processes & physics
  - Energy sources
  - Radiation
  - Non-thermal components
    (cosmic rays, magnetic fields, turbulence)
- Emphasis on galactic ISM
- Connection to galactic structure, star formation, feedback
- Big picture & examples of important physics
  (atomic physics, radiative processes, etc.)

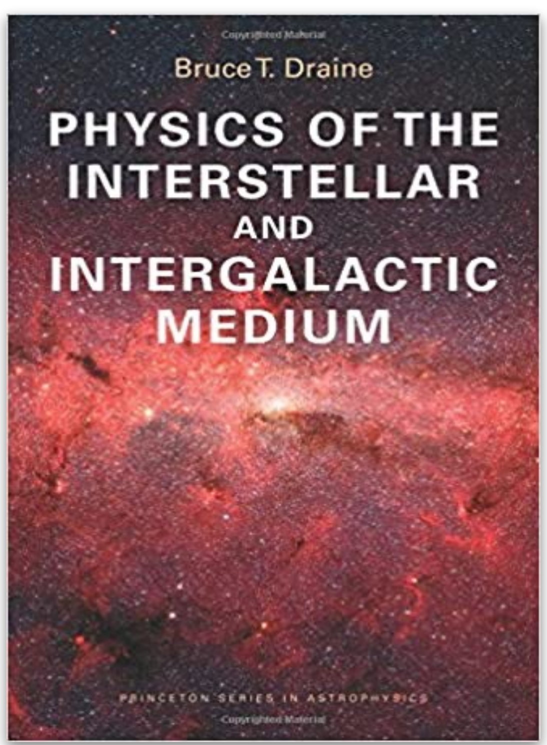
Lecture notes

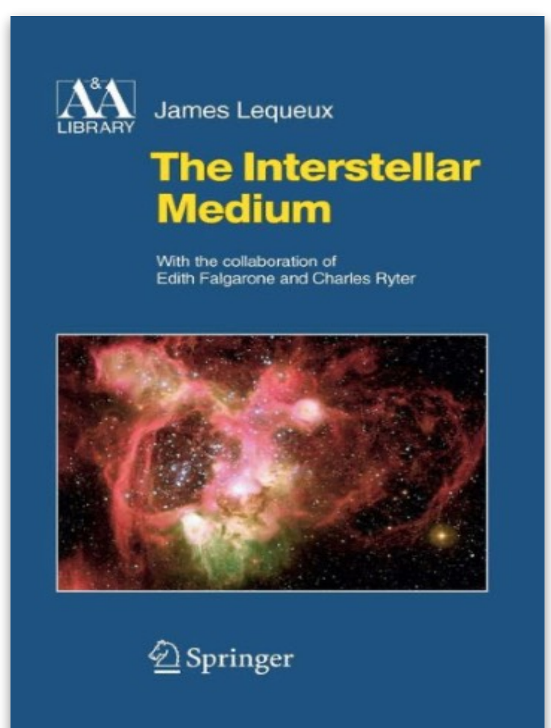


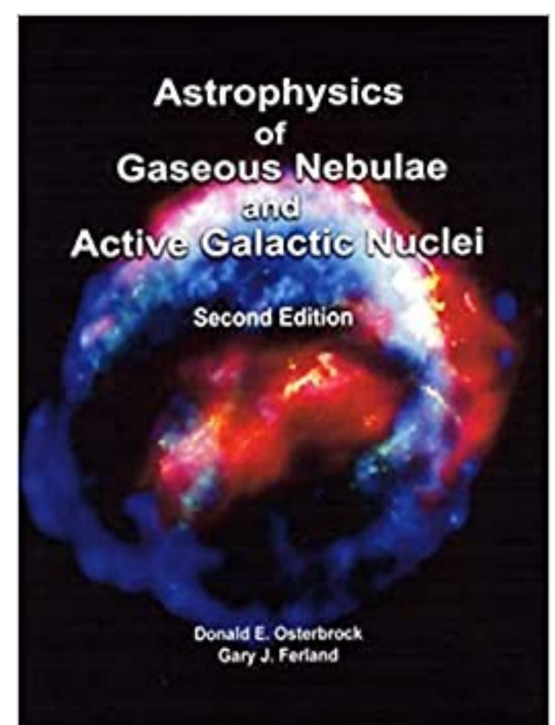


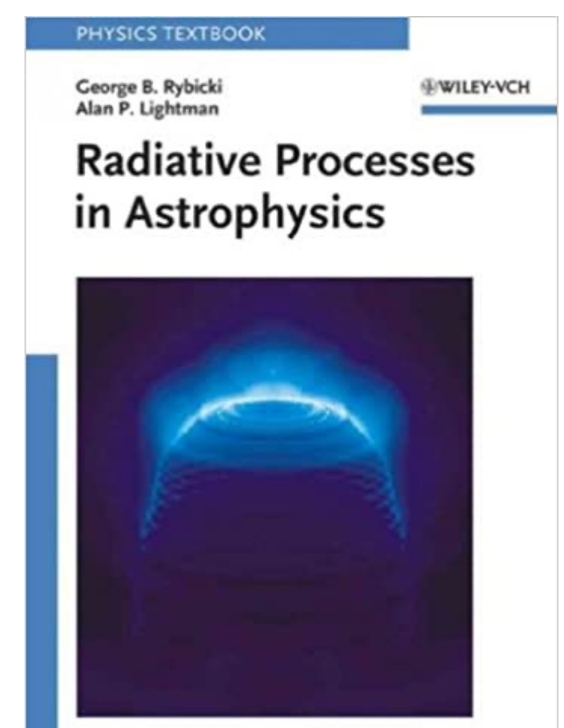
Books

- Most important book:
  - **Draine**
- Other relevant books
  - Lequeux
  - Osterbrock & Ferland
  - Rybicki & Lightman









EM spectrum in astronomy

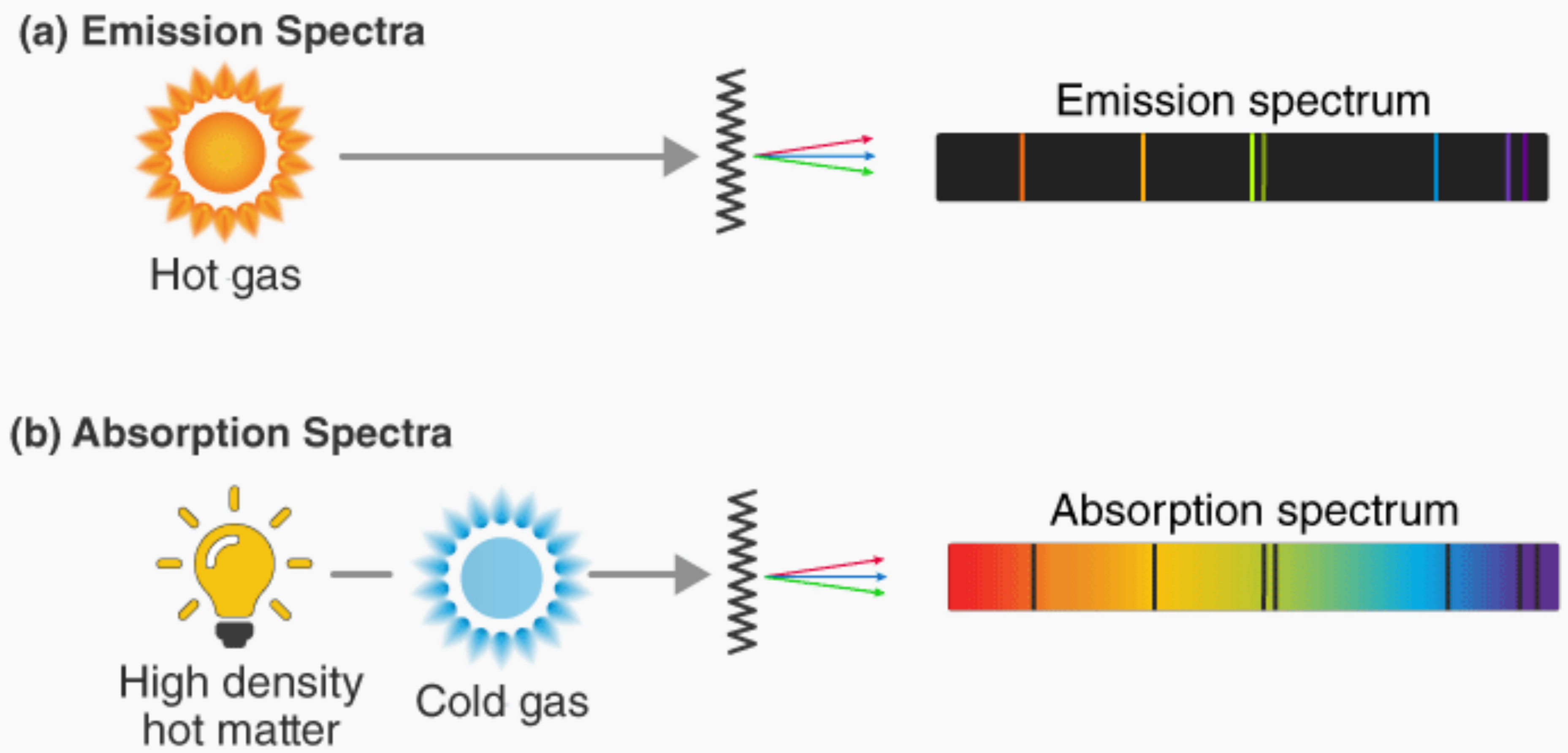
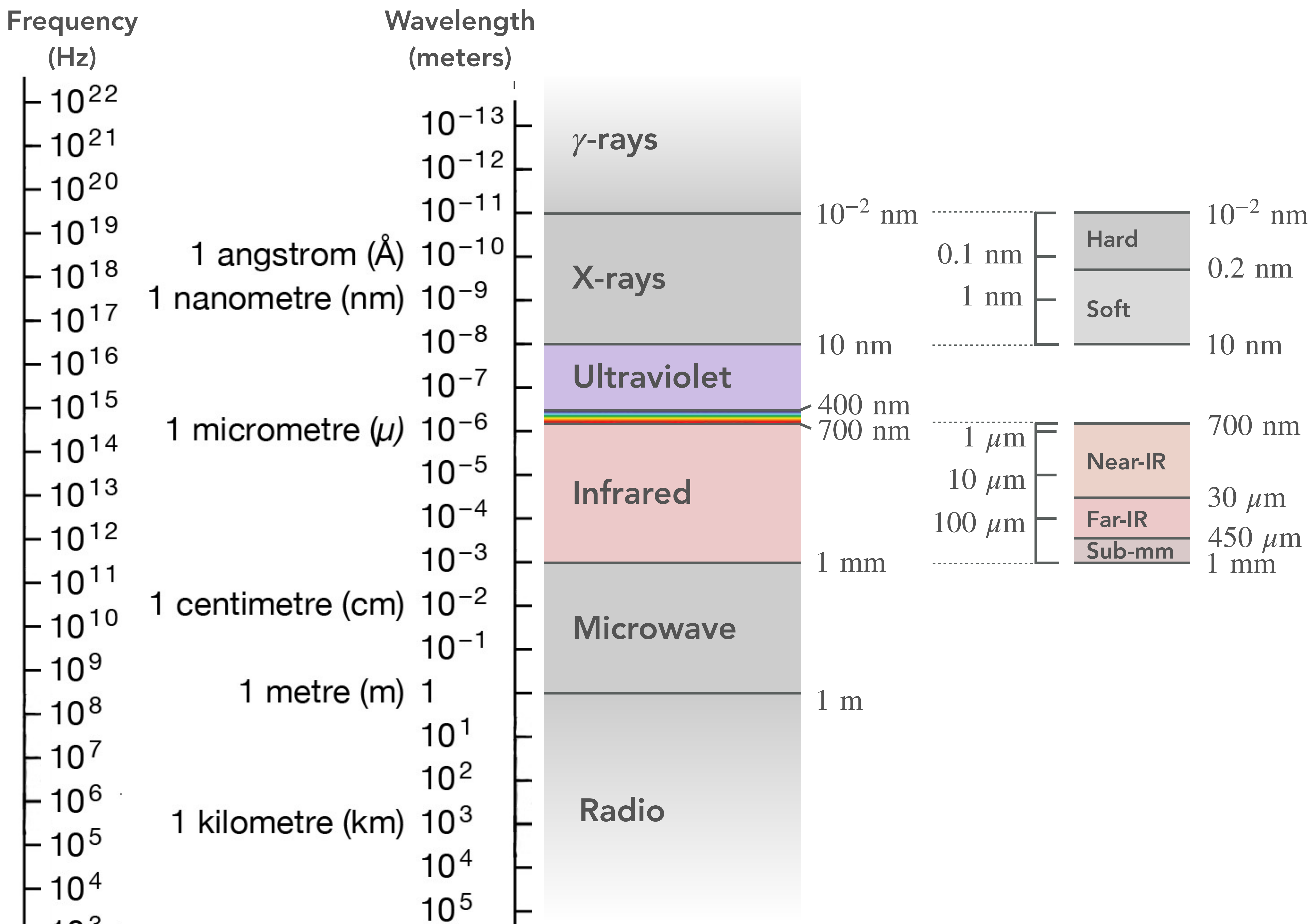


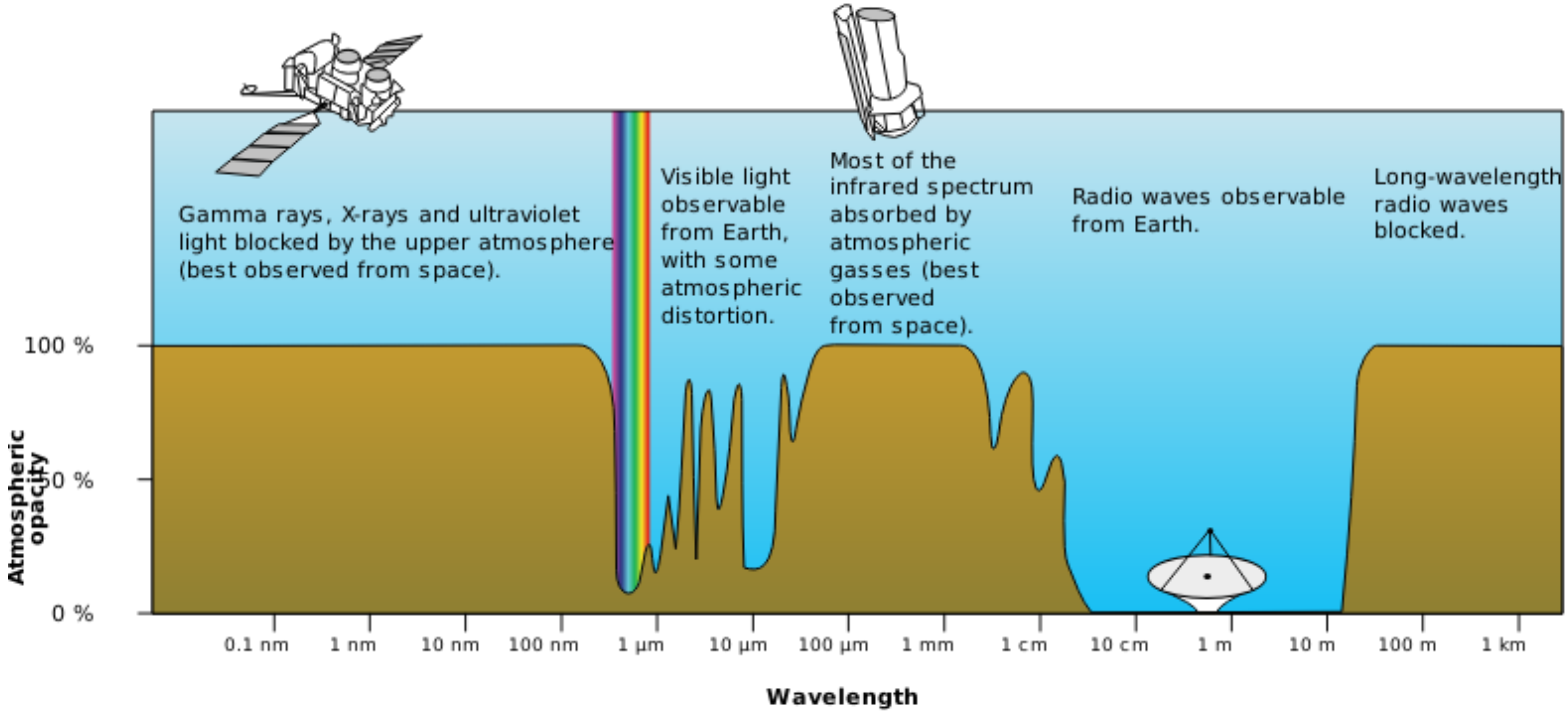
Image: BYJUS

EM spectrum in astronomy



History of ISM Science

Atmospheric windows & History of ISM science

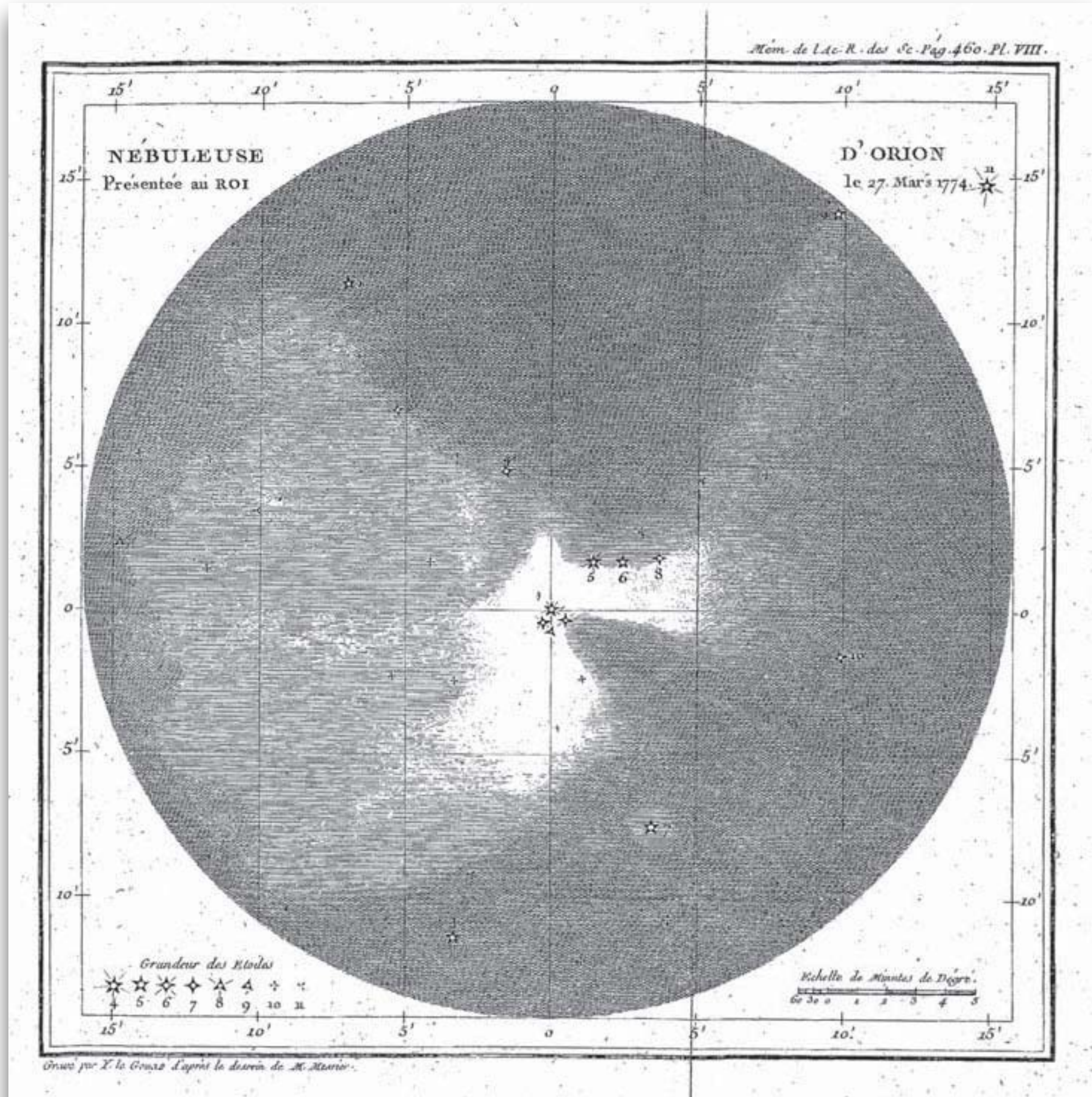


Time

- Optical - Naked Eye
- Optical - Photographic Plates & Imaging
- Optical - Spectroscopy
- Radio
- UV/X-ray/Infrared
- mm

Slide by Karin Sandstrom

1656: Orion Nebula (M42)

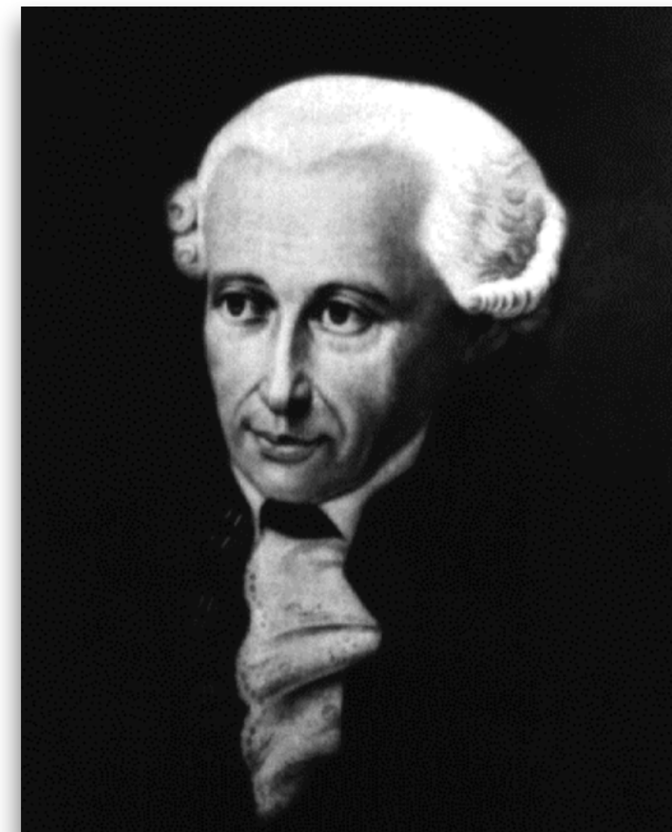


- Discovered by Christiaan Huygens
- Drawing by Messier
- Other nebulae were discovered soon thereafter

Images: ESO / Wikipedia

Immanuel Kant and the Island Universe

- **Philosopher** but also interested in astronomy
- Heard about the “nebulae” and postulated that they are separate “worlds” similar to Milky Way
- Called them “**Island Universes**” (1775)
- Views did not take hold becaues there was no direct evidence yet of other galaxies



Charles Messier (1730 - 1817)

- Identified many **nebulae** (fuzzy patches of light)
- Published **Messier Catalogue** in 1780
- Intended as aids to **comet hunters** to reject “uninteresting” objects
- Catalog contains galaxies, star-forming clouds, star clusters…

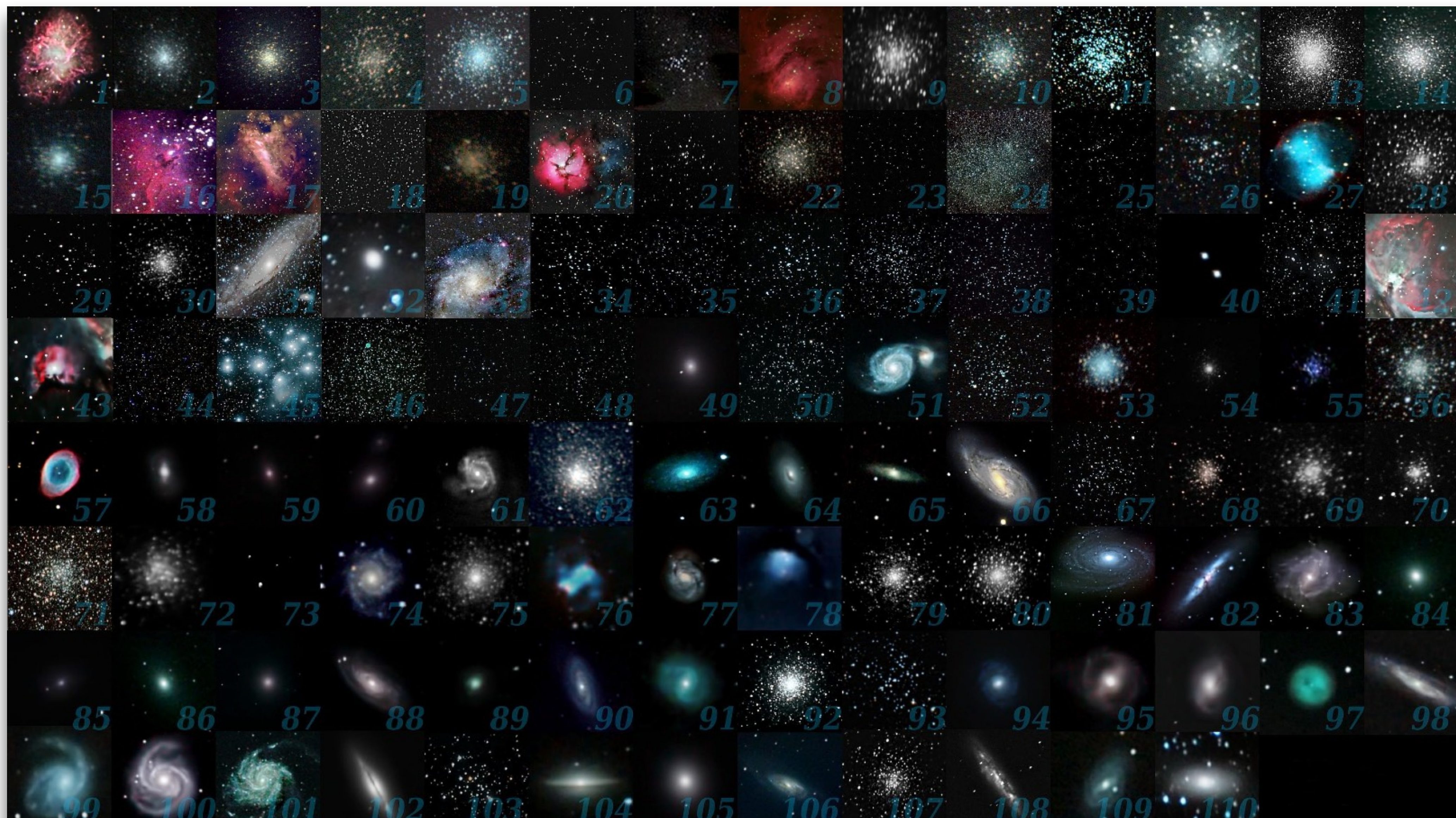


Image: NASA / HST / Wikipedia

Charles Messier (1730 - 1817)

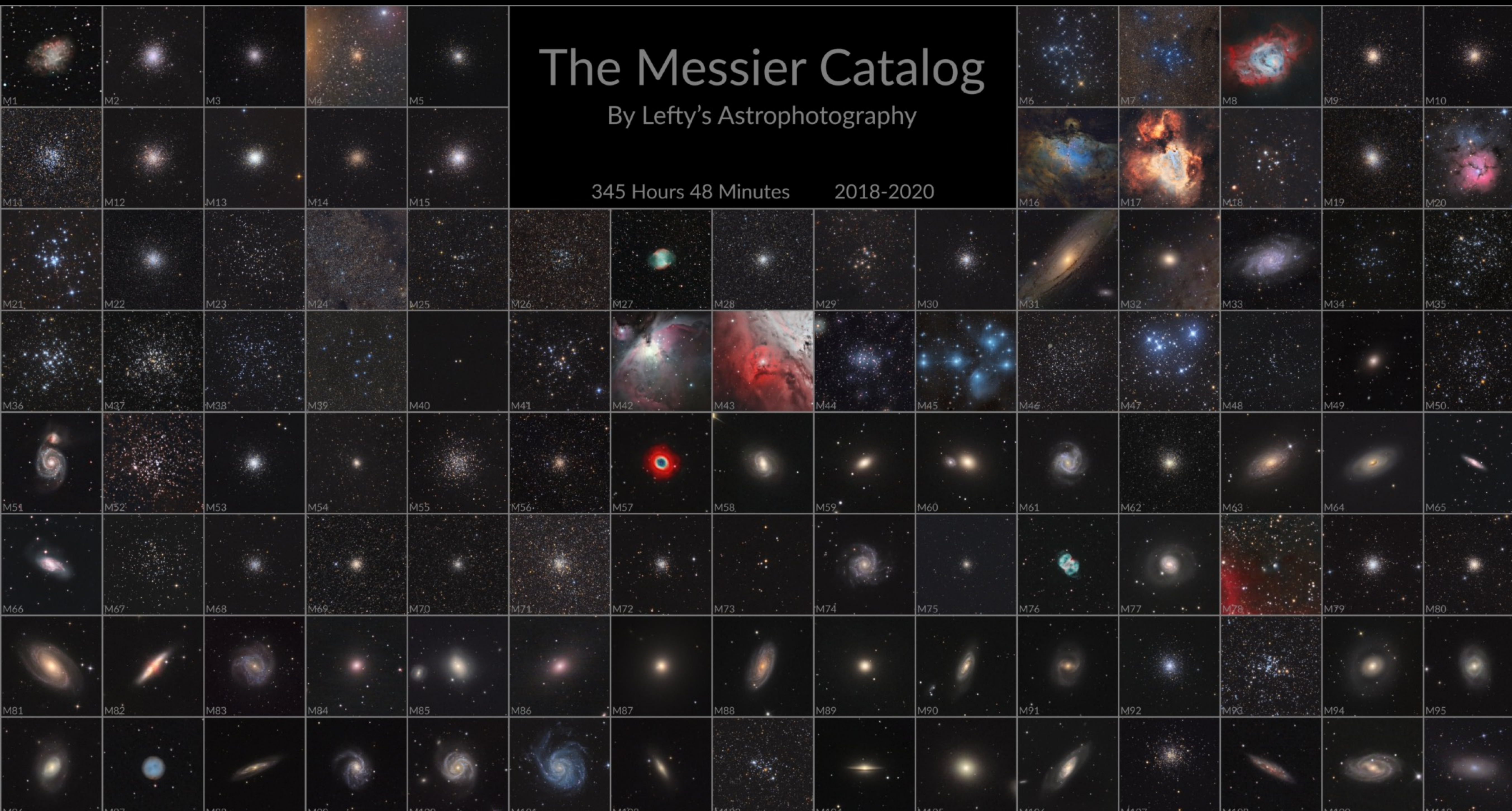


Image: NASA / HST / Wikipedia

Globular clusters (29)

Open clusters (26)

Lefty's Astrophotography

Gas clouds (7)

Lefty's Astrophotography

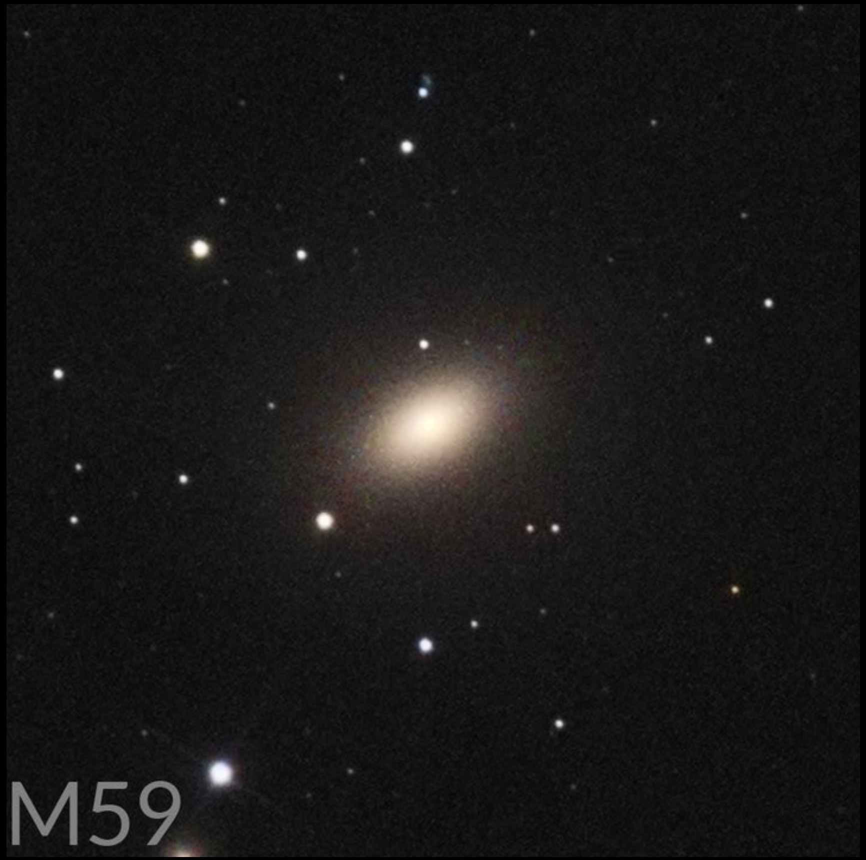
Planetary nebulae (4)

Lefty's Astrophotography

Supernova remnant (1)

Double star (1)

Galaxies (40)



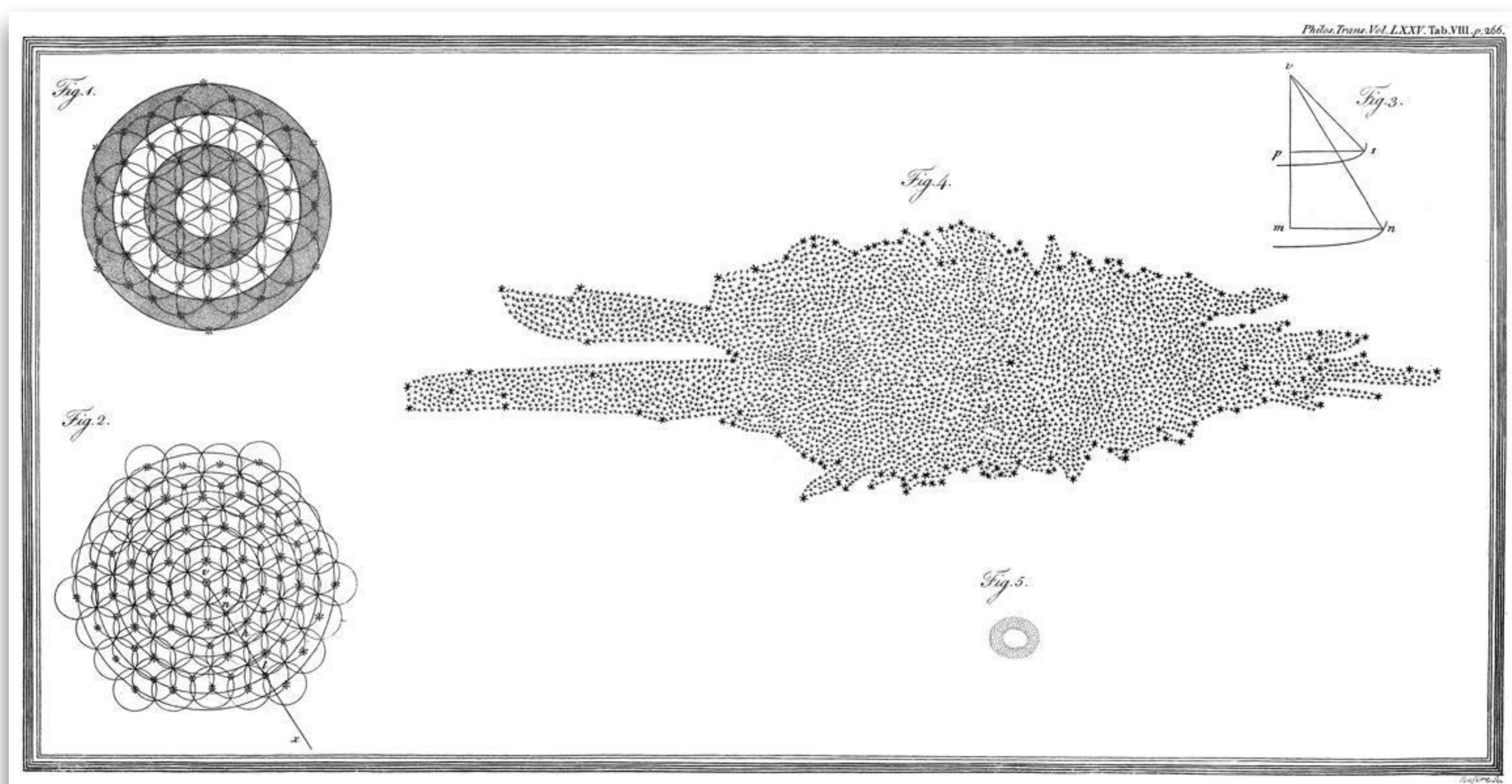
Modern, scientific categories

- Globular cluster (round, compact star cluster)
- Open cluster (less compact cluster of stars)
- Gas cloud (diffuse nebula)
- Planetary nebula (gas cloud around single star)
- Supernova remnant (leftovers of stellar explosion)
- Double star (two stars that happen to appear close)
- Galaxy (the only objects not in MW)

In the Milky Way

William & Caroline Herschel

- Discovered about thousands of new nebulae
- Thought they could be star collections like MW
- Concluded Milky Way was a disk with the Sun at the center (map from 1785)
- First to find dark clouds



Images: Wikipedia

William & Caroline Herschel

40 *Vacant places*

Many places &c: S. 54. F. 472.
It appeared &c: S. 75: . F. 484
S. 78. 78.
The most vacant &c: S. 131.
S. 156. 157. 158. 166. 166.
Scattered large &c: 167.
Very few &c: 170. 174. 177. 179. 182. 182
Many fields without stars S. 182.
Very few stars S. 187. 187.
Some fields without stars 187. 188.
Very few stars S. 188. 188. 188.
Several fields without stars S. 188. 188. 188.
189. 189. 189. 189.
Very few stars S. 189.
Many fields without st. S. 189. 191. 205.
By the gages it appears as if there was a hole &c: S. 222.
The border of the hole pointed out by the gage S. 224.
Many vacant fields, and upon Nebulous ground S. 224.

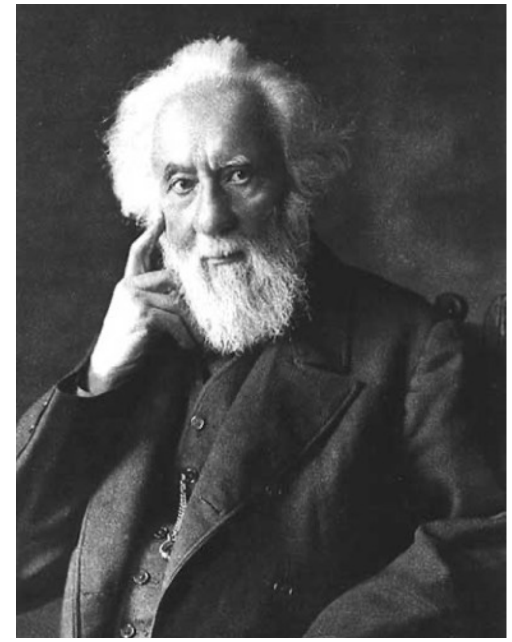
VACANT PLACES

[*Extracted from the Sweeps. Places for the Year of Observation.*]

Sweep.	R.A.			P.D.		Stars.	
383 Mar. 10 1785	16	5	22	109	25	0	
	16	6	22	109	20	0	
	16	6	32	109	31	0	
	16	7	22	109	49	0	
	16	7	42	109	12	0	
	16	11	52	110	17	0	
	16	12	22	109	11	0	
	16	12	40	110	25	0	
	16	13	0	111	29	2	
485 Dec. 7 1785	4	17	37	65	29		Upper border of a vacancy, but it is a very irregular one.
	4	18	30	65	27		Do.
	4	19	17	65	29		Do.
	4	21	35	64	31	0	
	4	22	26	64	22	0	
	4	23	53	64	4	0	and many such in the neighbourhood.
	4	25	17	..			There is a vacancy between the bright row of stars in the direction of Orion's belt and the Bull's head, Perseus' body and the Milky Way, and I am now in that vacancy.
	4	27	26	65	4	0	
	4	28	6	64	10	0	
	4	28	42	65	11	0	Intermixed with places that have many stars.
	4	29	24	65	15	0	
	4	30	54	65	16	0	
	4	37	51	65	16	0	
	4	39	16	..			The straggling stars of the Milky Way seem now to come on gradually, most small.
	4	43	20	..			They begin now to be intermixed with some larger ones.
516 Jan. 30 1786	5	32	16	98	30	0	
	5	32	42	100	21	0	Vacant spaces picked out, between stars sparingly and irregularly scattered.
	5	33	5	99	33	0	
	5	34	40	100	39	0	
566 May 26 1786	16	8	52	113	18		Vacant between these two places.*
	16	9	12	112	25		
	16	11	56	112	53		From this place to the bottom of sweep [113° 20′] vacant.

"Hier ist wahrhaftig ein Loch im Himmel."

Spectroscopy: William & Lindsay Huggins



- Cannot say much more about gaseous objects without spectra
- Huggins took spectra of celestial objects (about 1860 - 1900)
- First to distinguish star-like spectra of Andromeda galaxy from emission line spectra of clouds

Spectroscopy: William & Lindsay Huggins

XVII. *Further Observations on the Spectra of some of the Nebulæ, with a Mode of determining the Brightness of these Bodies.* By William Huggins, *F.R.S.*

Received January 30,—Read February 15, 1866.

§ I. *Introduction.*

In my former papers, "On the Spectra of some of the Nebulæ" *, and "On the Spectrum of the Great Nebula in Orion" †, I described the results of a prismatic examination of the light of some of the objects in the heavens which have been classed together under the common denomination of Nebulæ. The present paper contains the results of the application of the same method of research, with the same apparatus, to the light of others of the same class of bodies. To these observations with the prism are appended the results of an attempt to determine the intrinsic intensity of the light emitted by some of the nebulæ which give a spectrum indicating gaseity.

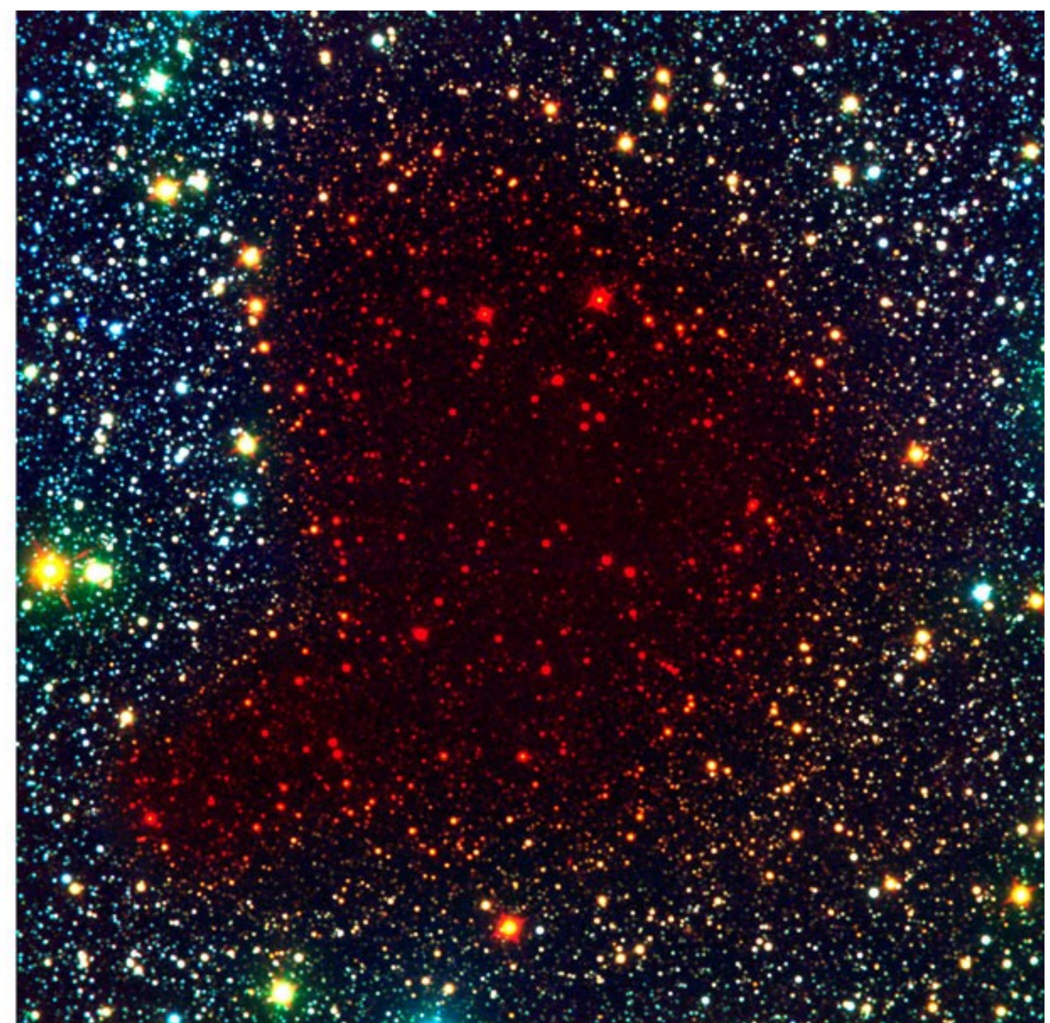
Spectroscopy

- **Hartmann 1904**: stationary (zero-velocity) Ca II lines
  - In binary system δ Orioni
  - Could be of circumstellar or interstellar origin; shown to be interstellar in 1930s
- **Slipher 1909**: some nebulae have stellar spectrum
  - Light must be reflected off small particles
  - Systems like Pleiades might consist of stars that illuminate the gas around them

Dust absorption

- **Struve 1847:** number of stars decreases in all directions
  - makes sense only if we are at center of spherical distribution
- **Barnard 1910s / 1920s:** catalog of dark clouds
  - Revisited Herschel's "holes in the sky"
  - Realized something seemed to absorb starlight

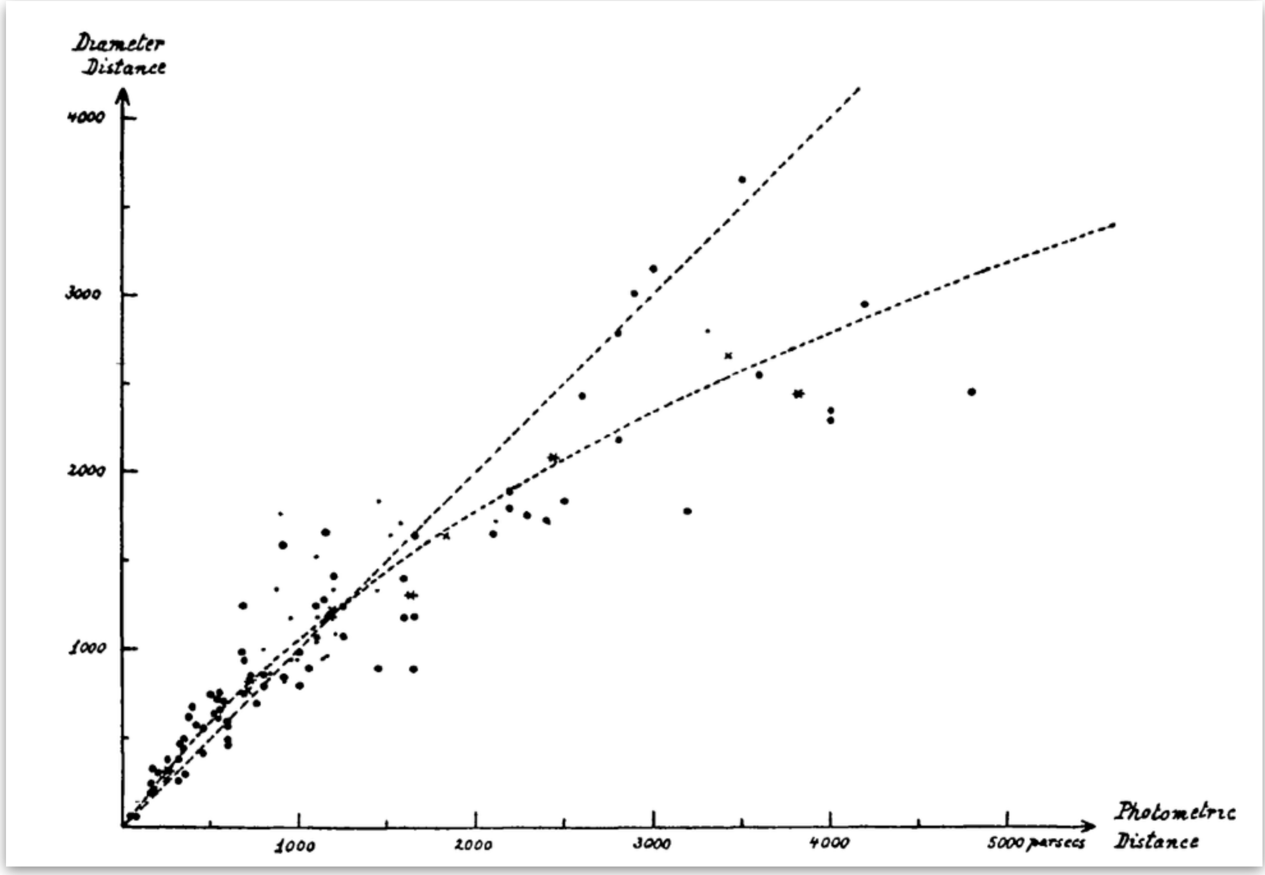
B, V, I

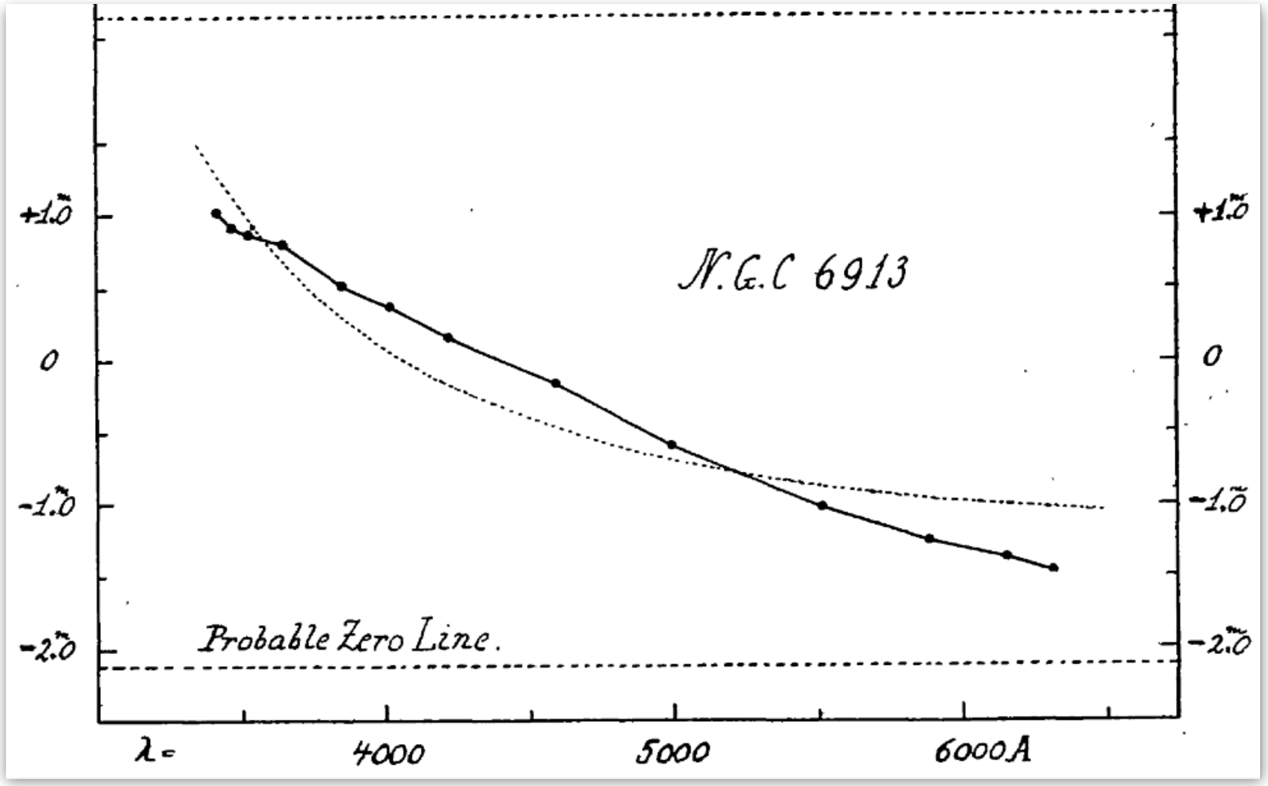


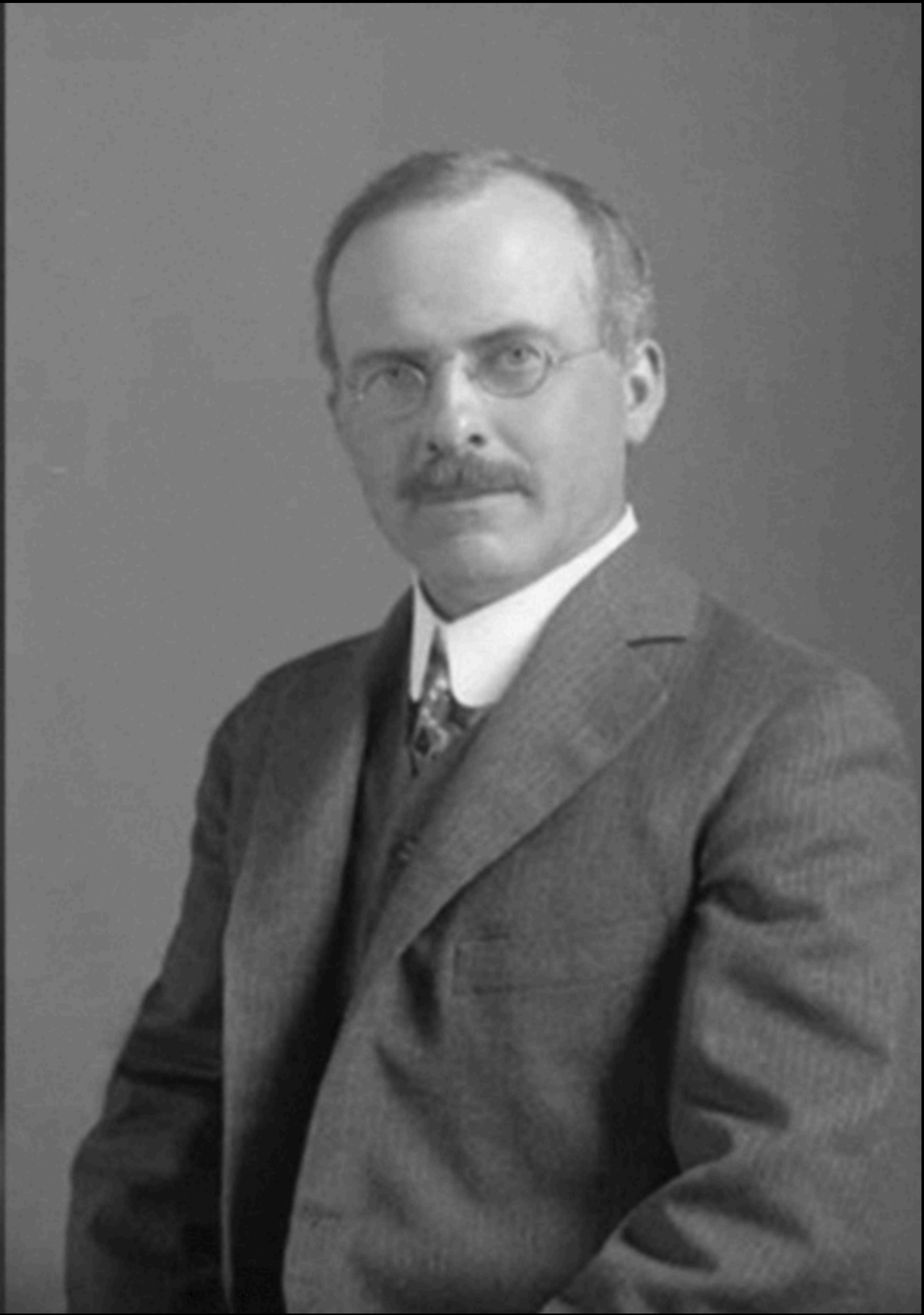
B, I, K

Dust absorption

- **Trumpler 1930**
  - Measured distance to star clusters from their size and brightness
  - General dimming of stars with distance
  - Brightness falls off with distance!
  - Extinction depends on wavelength ("reddening")
  - "…interstellar light absorption may be a consequence of light scattering by small particles, fine cosmic dust, thinly spread through the vast spaces occupied by our Milky Way system."





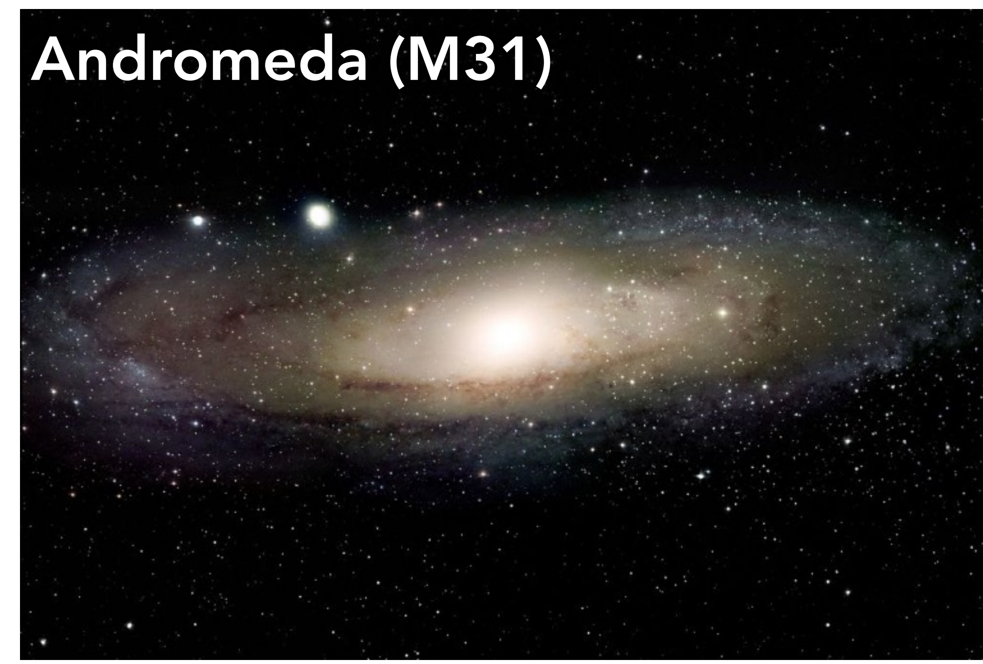


Harlow Shapley

Heber Curtis

The Great Debate

- **Shapley**
  - If Andromeda not in the MW, must be extremely far away
  - Pinwheel galaxy seen to be rotating (wrong)
- **Curtis**
  - More novae in Andromeda than in MW
  - Novae appear faint in Andromeda (and other nebulae)
- **Resolved** a few years later
  - There are multiple types of nebulae!
  - Hubble: galactic "nebulae" are far away



Molecules in space

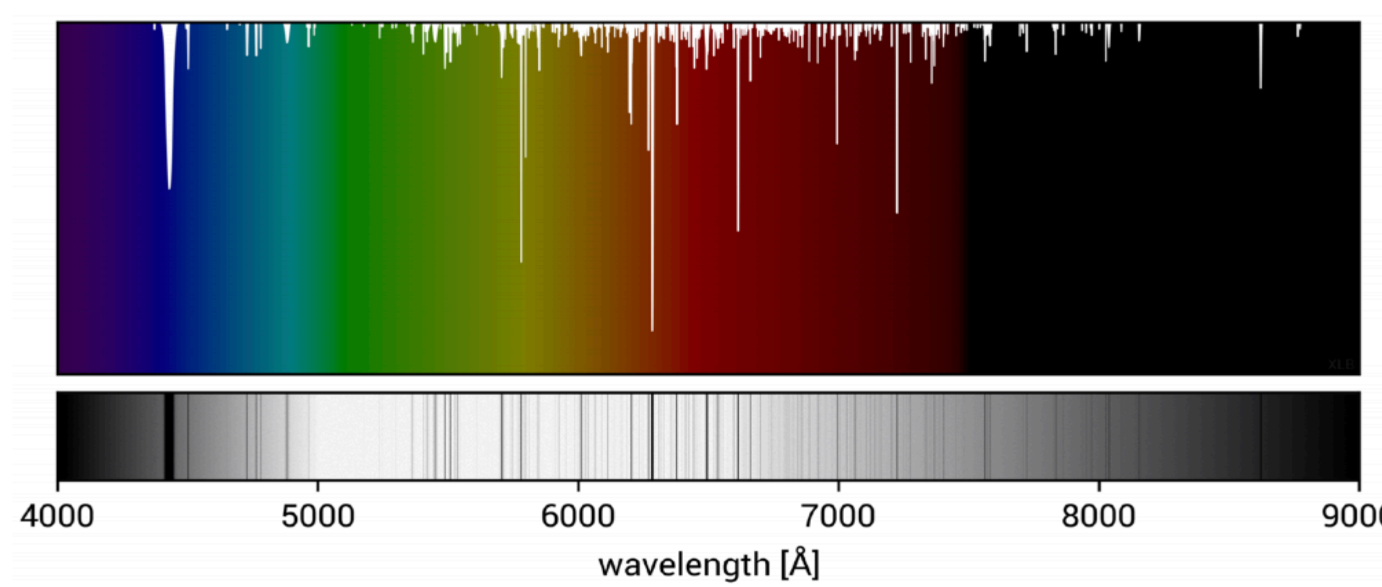
- **Eddington 1926:** Prediction of H_2
- **Merrill 1934:** Discovery of Diffuse Interstellar Bands (DIBs)
  - Wide absorption regions
  - Origin of almost all still unknown!
  - A few identified as caused by C_{60}^+!
- **Swings et al. 1937-40:**
  - First interstellar molecules
  - CN (cyanide), CH (carbyne)
- **1960s:** First polyatomic molecules
  - NH_3 (ammonia), H_20
- **Wilson et al. 1970:** Detection of CO 1-0 emission (2.6 mm, present even at low temperature)

BAKERIAN LECTURE.—*Diffuse Matter in Interstellar Space.*

By A. S. EDDINGTON, F.R.S.

(Received May 21, 1926.)

1. The title of this lecture naturally provokes the question, Is there any appreciable quantity of matter in ordinary regions of space between the stars ?

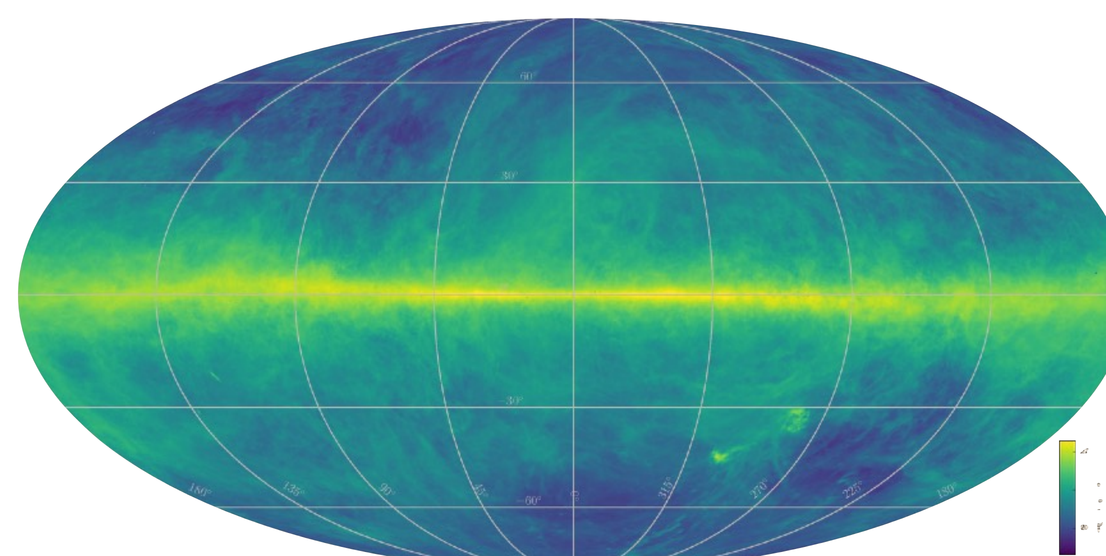


Bacalla 2019

Radio & The 21cm line

- **Jansky 1932:**
  - Discovery of radio emission from the Milky Way
- **van de Hulst 1944:**
  - Prediction of 21cm line: 1.42 GHz radiation due to hyperfine spin-flip transition in atomic hydrogen (HI)
  - Allows us to detect HI
- **Ewen/Purcell & Muller/Oort 1951:**
  - Detection of 21cm radiation from the MW
- **1950s/60s:**
  - First 21cm maps of the MW
  - The bulk of the ISM mass is in atomic H!

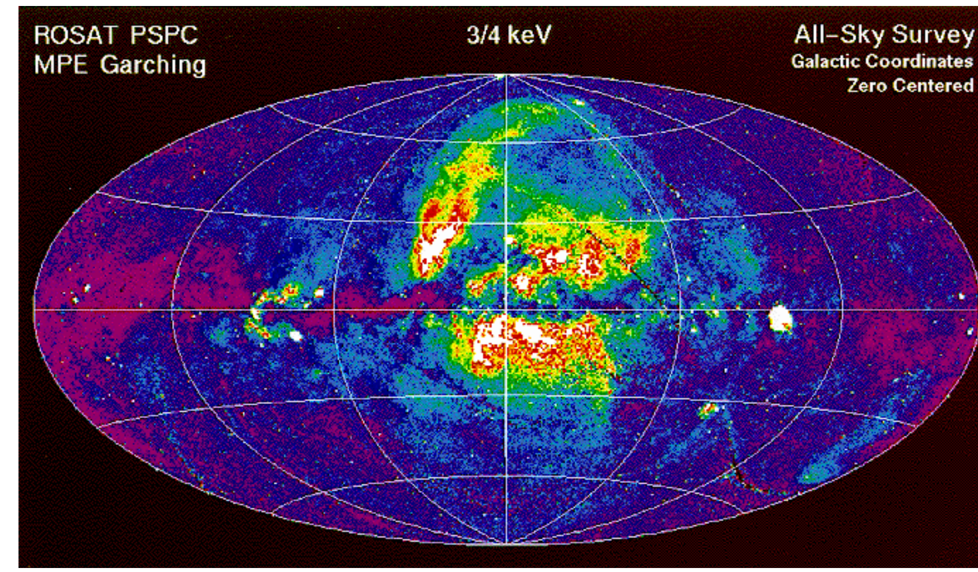
Ewen & Purcell's horn



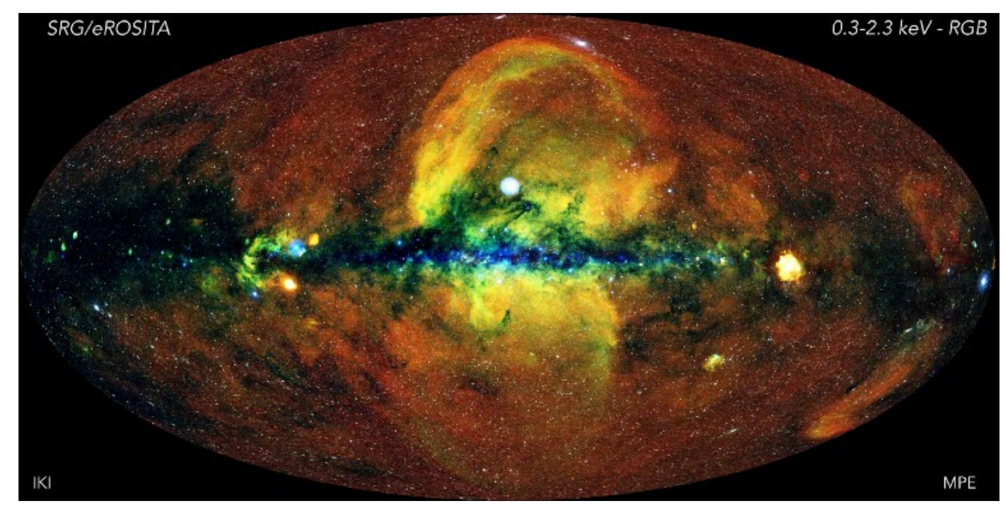
HI all-sky map

X-rays

- **1960s:**
  - Soft X-ray background discovered
  - Caused by local 10^6K gas
- **1990s:** ROSAT satellite produces all-sky X-ray survey
- **Since 1999:** Chandra X-ray observatory
- **Since 2019:** eROSITA



ROSAT all-sky survey



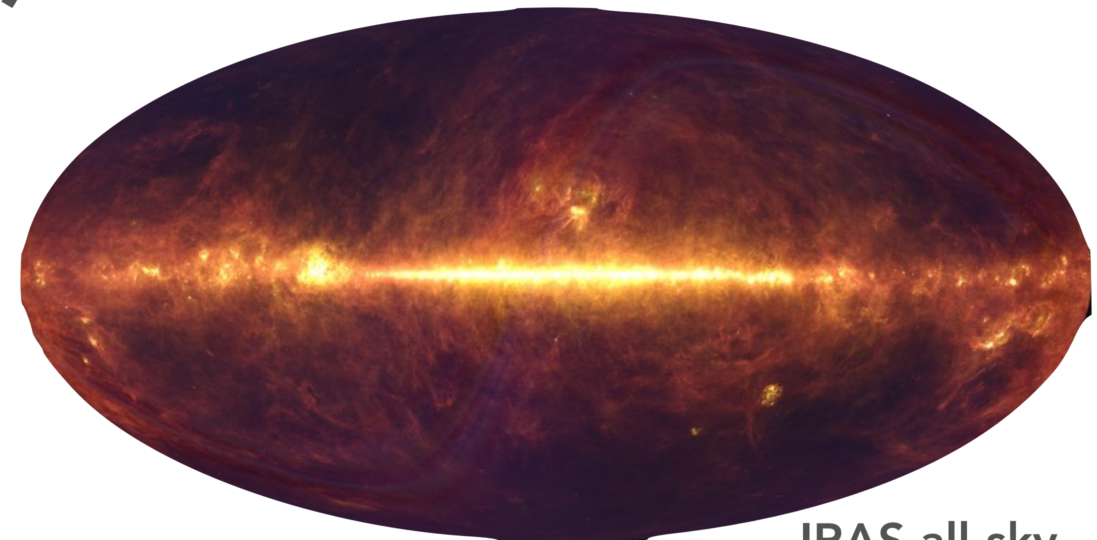
eROSITA all-sky survey

Ultraviolet (UV)

- **Carruthers ~1970:**
  - Detection of interstellar H_2 with rocket-borne UV instrument
- **1973-80: Copernicus satellite**
  - Detection of H_2 in many sightlines
  - Detection of highly ionized atoms such as O IV (indicating very high temperature)
- **2000: FUSE satellite** (Far-UV space explorer)

Infrared (IR)

- **1970s/80s: Infrared**
  - H_2 infrared lines, small dust particles, large molecules
- **1983: IRAS**
  - First all-sky survey at 12, 25, 60, 100 μm
  - Warm dust is everywhere!
- **1990s: more satellites**
  - COBE (galactic distribution of C+, N+)
  - ISO
  - SWAS (Sub-mm wave astronomy sat.)
- **2003-2020: Spitzer**
  - Satellite for near/far IR
- **2009-2013: Herschel**
  - Satellite for far-IR / sub-mm



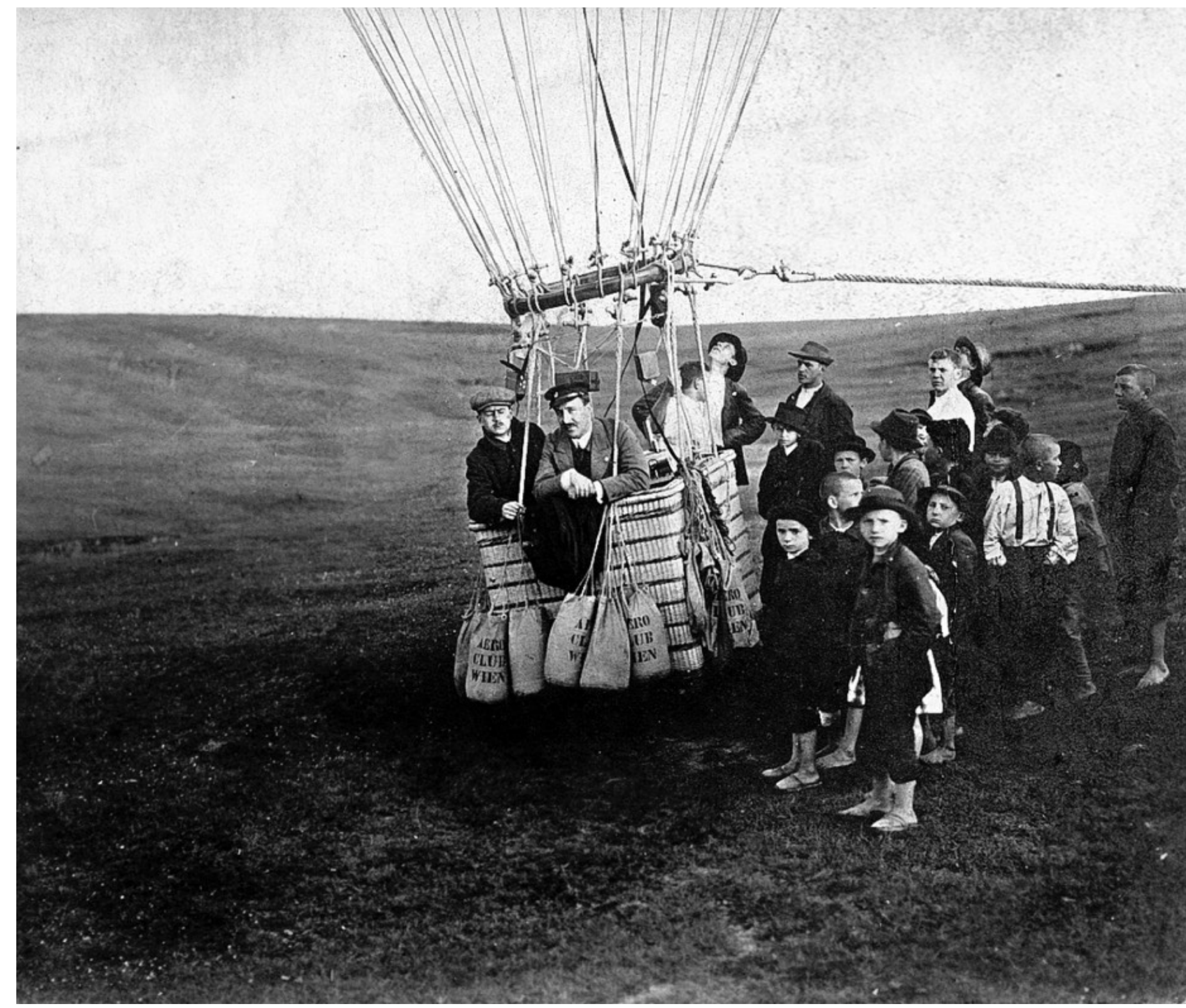
IRAS all-sky

Spitzer mosaic

Herschel + SPIRE: galactic plane

Cosmic Rays

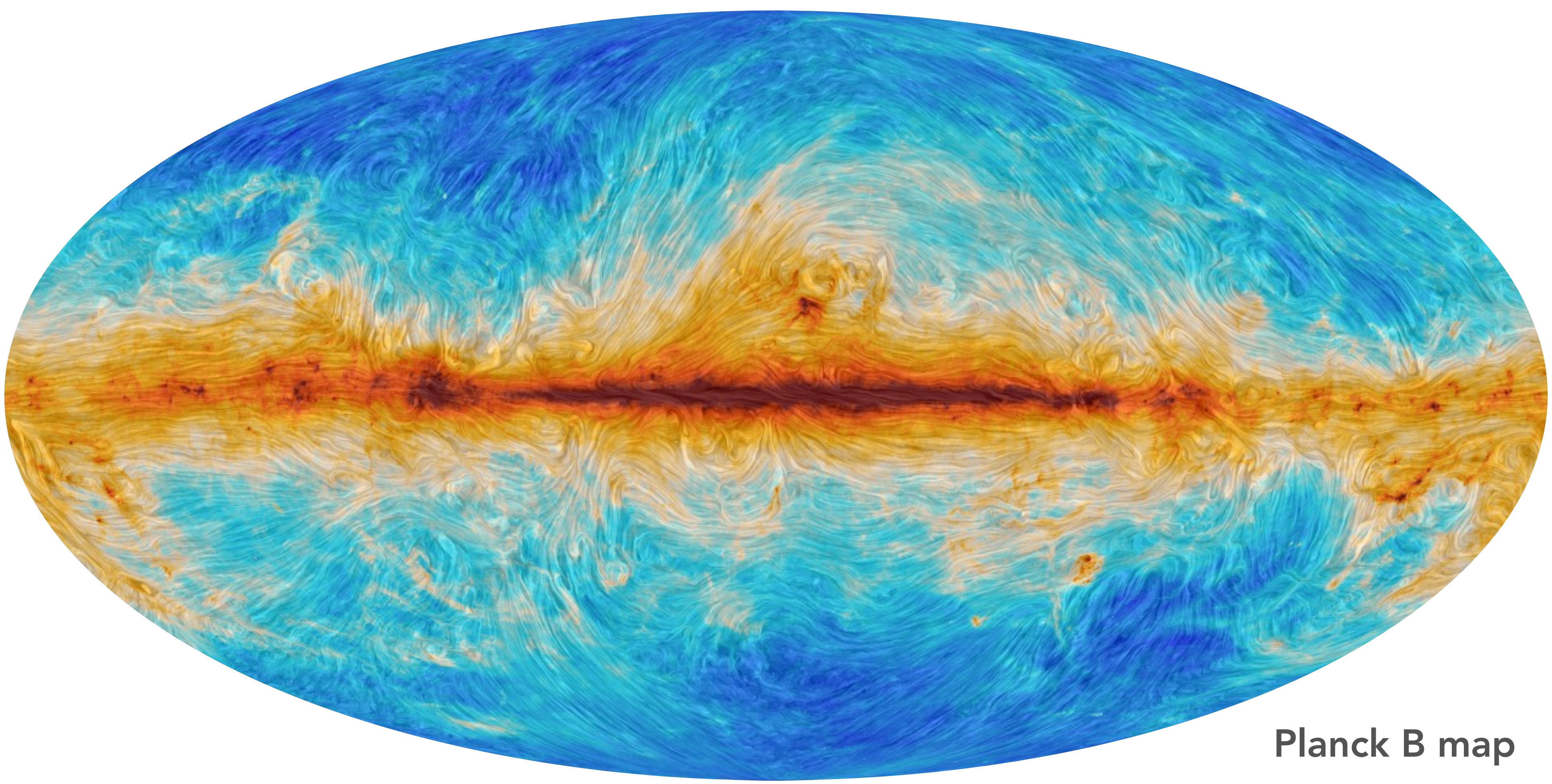
- **Hess 1912:** Discovery of ionizing rays at high altitudes, "Höhenstrahlung"
- **1927-34:** cosmic rays are charged particles, not photons
- **1950s:** cosmic rays are heavy particles such as protons and Helium nuclei (α's)



Hess' balloon expecition

Magnetic Fields

- **Hall & Hiltner 1949:**
  - Polarization of starlight is correlated with reddening
  - Reason: dust grains are aligned with magnetic field, which rotates light due to the Faraday effect

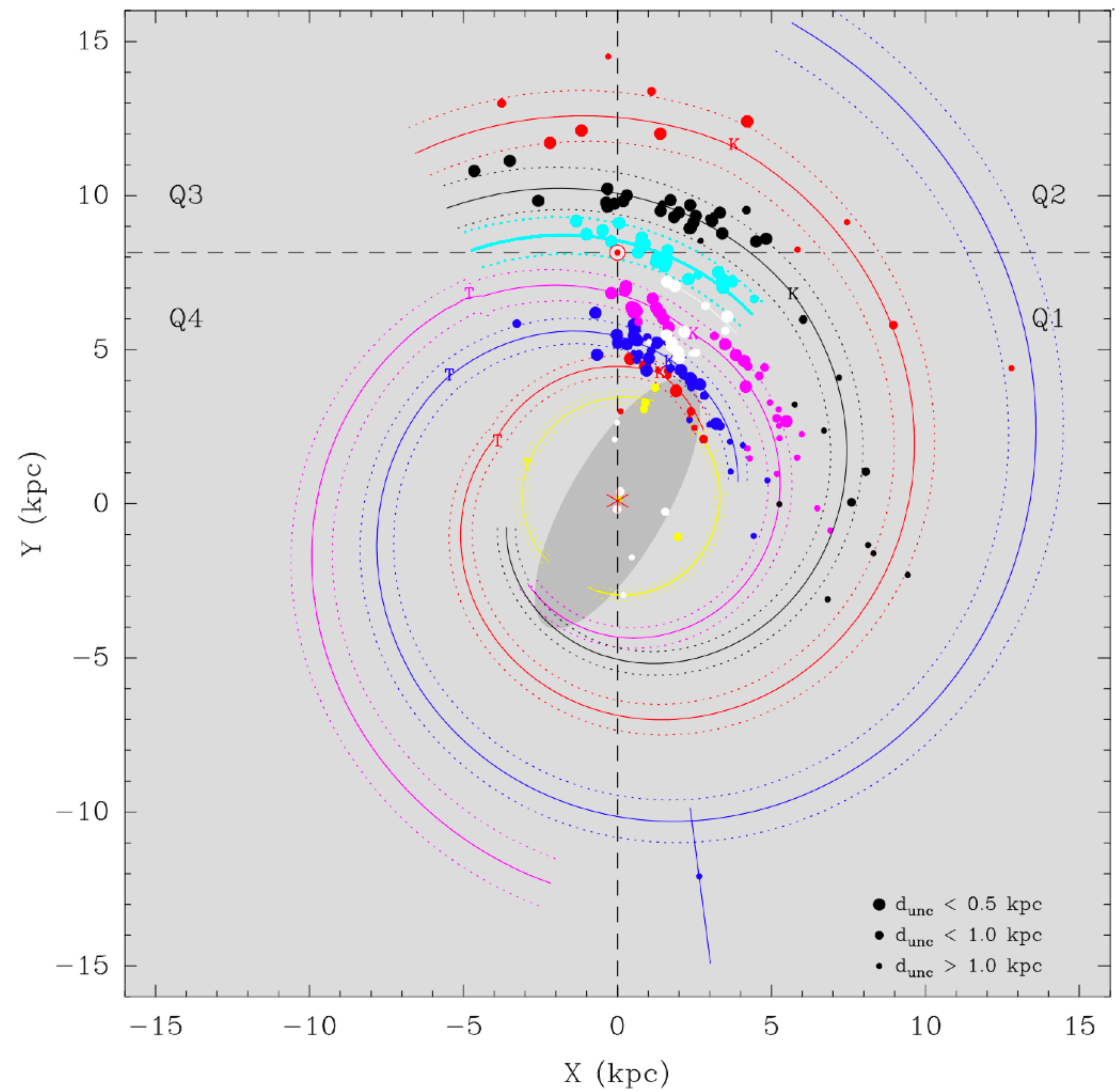


Planck B map

The Galactic ISM

Basic properties of MW

- MW disk is thin, symmetric, blurry boundary
- Half-density thickness about 250 pc
- Sun ~8.5 kpc from center
- Rotation velocity ~230 km/s
- Spiral arms



Reid et al. 2019 • Numbers from Draine

Masses of MW components

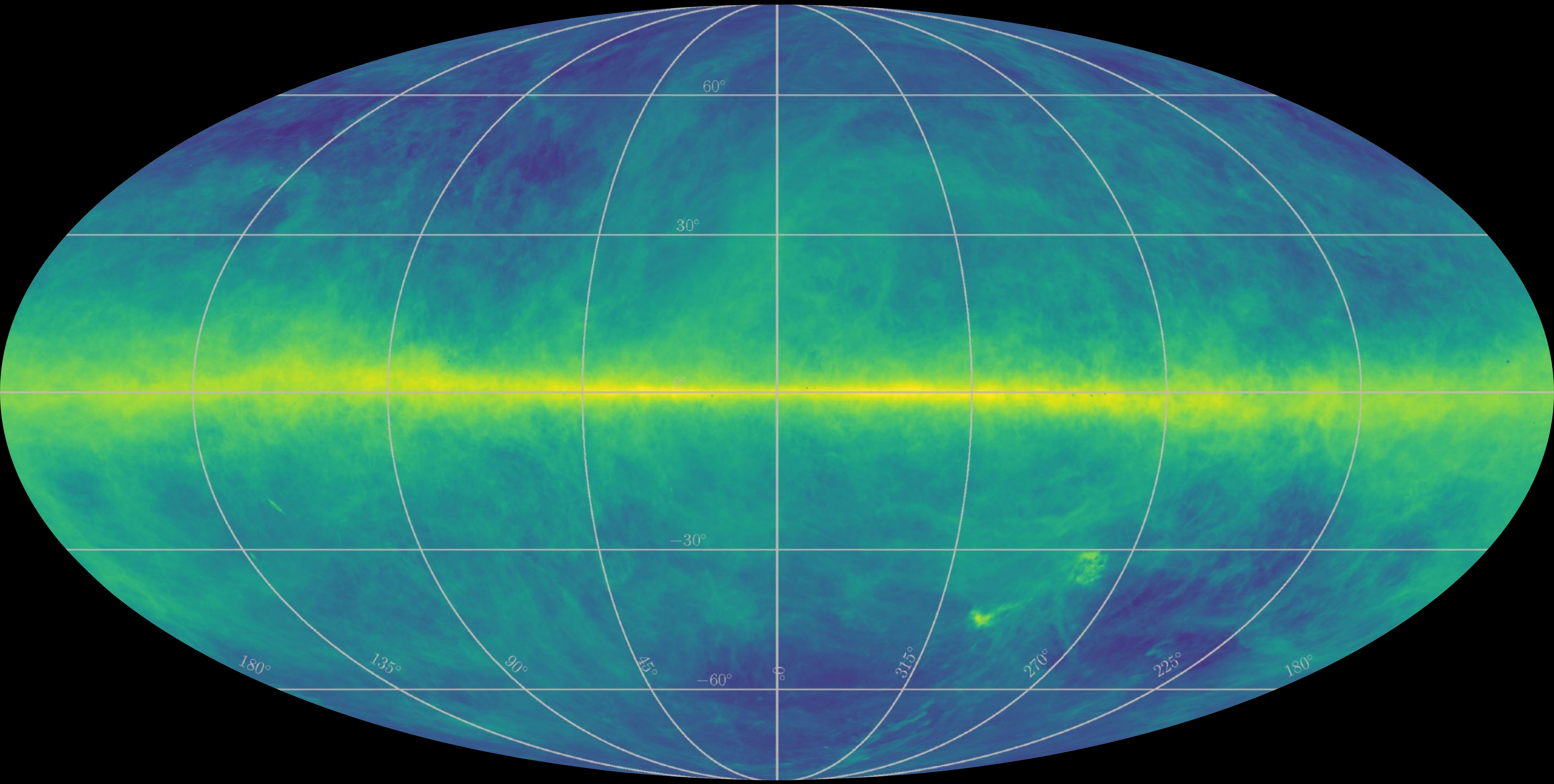
- Within 15 kpc of the center of the MW:
  - About $10^{11} M_\odot$ total
  - $5 \times 10^{10} M_\odot$ stars
  - $5 \times 10^{10} M_\odot$ dark matter
  - $7 \times 10^{9} M_\odot$ gas
    - this includes Helium
    - $5 \times 10^{9} M_\odot$ hydrogen
- Out of hydrogen:
  - 20% ionized
  - 60% HI
  - 20% H_2

Numbers from Draine

EM Spectrum

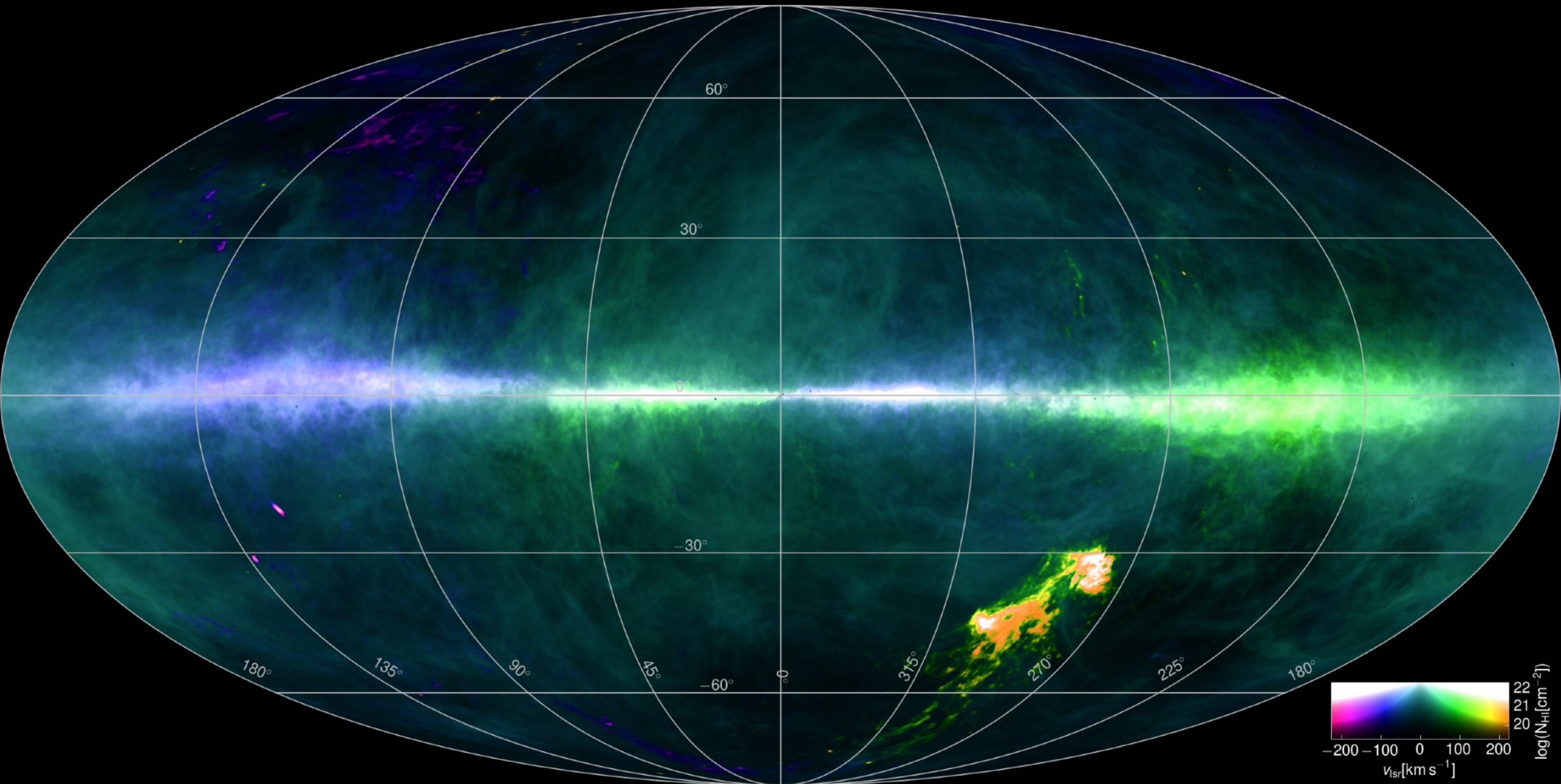
eCUIP / UChicago

21 cm / radio / neutral hydrogen atoms



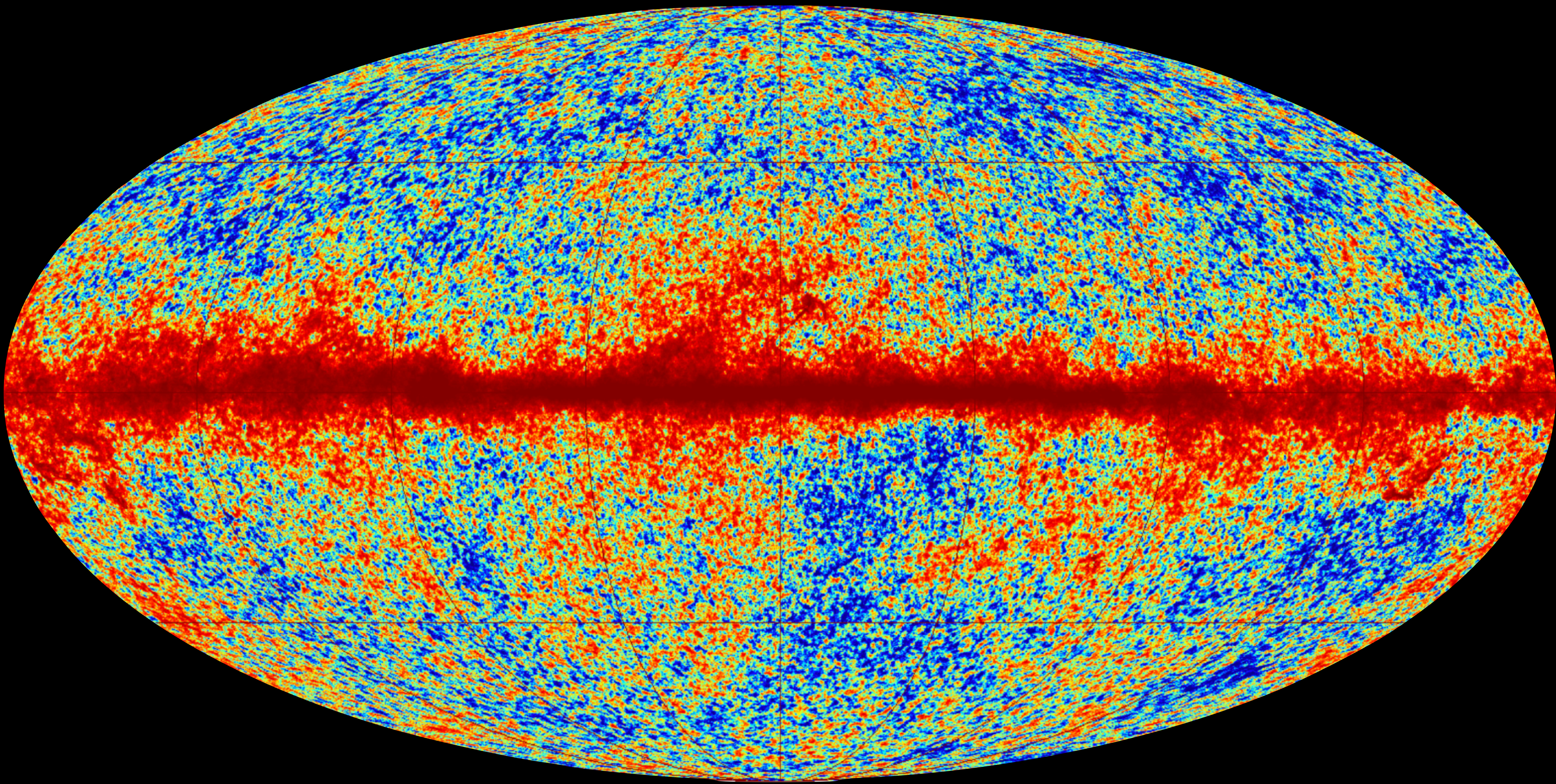
Effelsberg + Parkes surveys

HI velocity



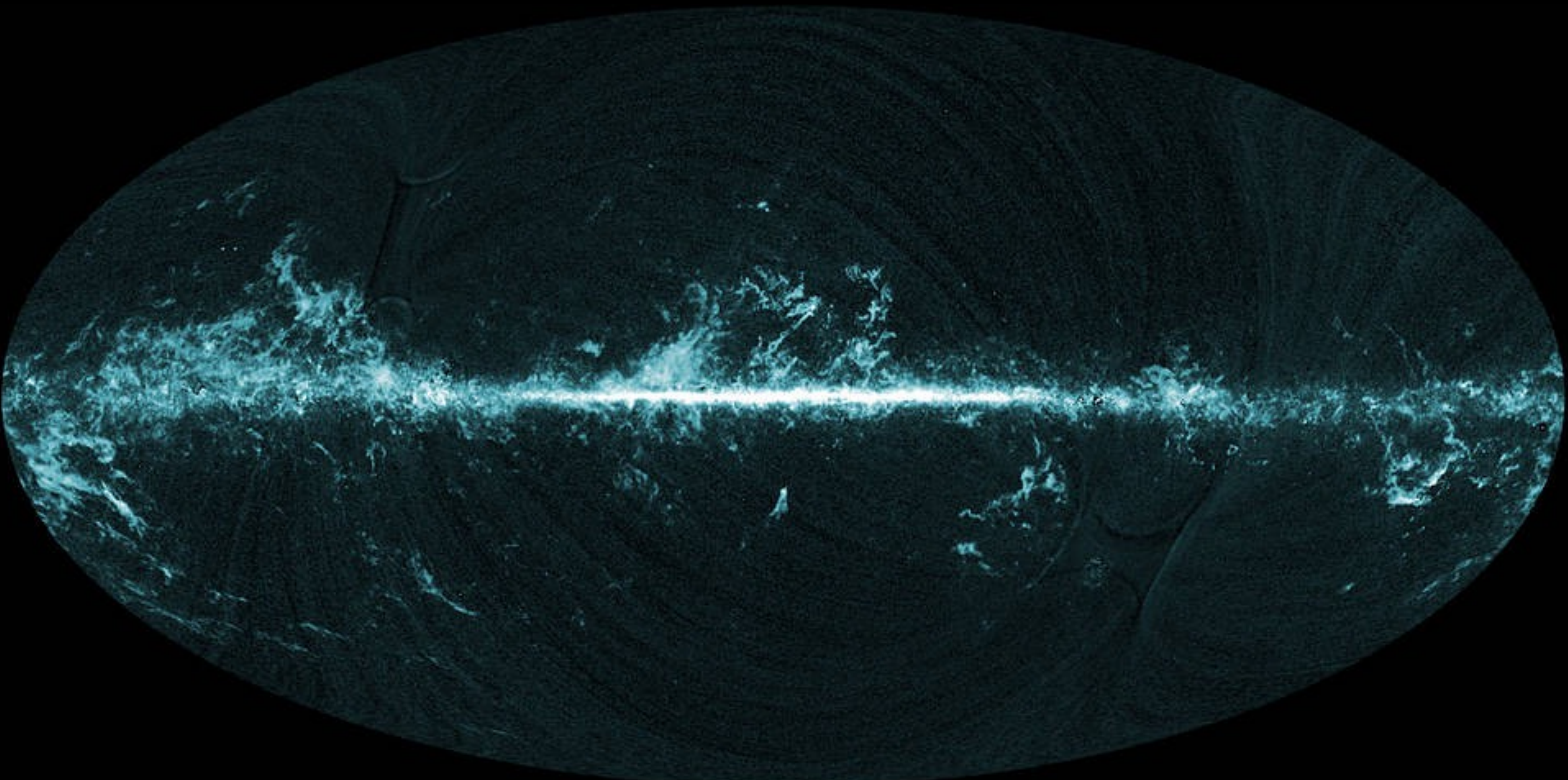
Effelsberg + Parkes surveys

6.8 mm / microwave / CMB + dust in Galaxy



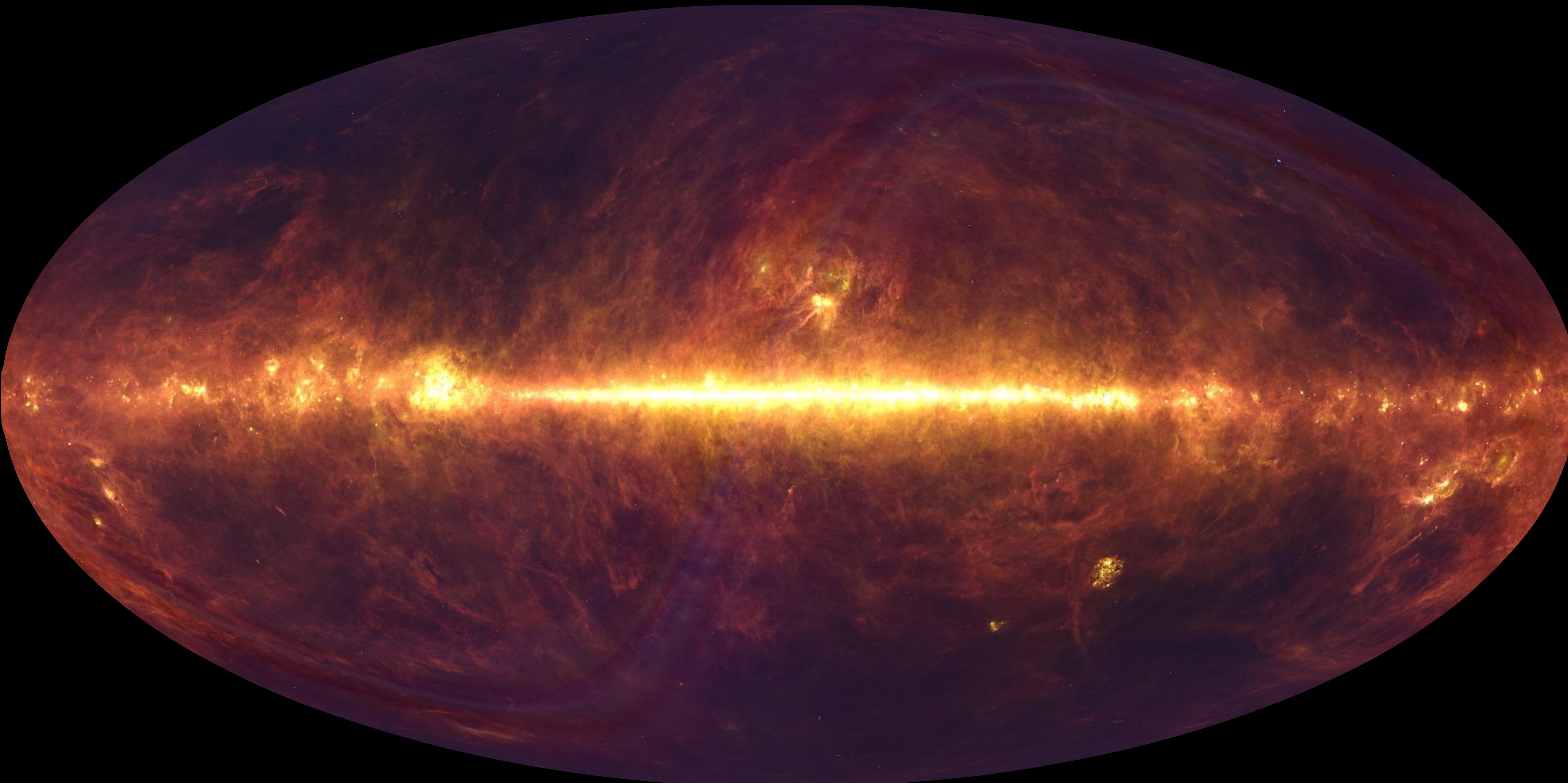
Planck satellite

2.6 mm / microwave / carbon monoxide molecules



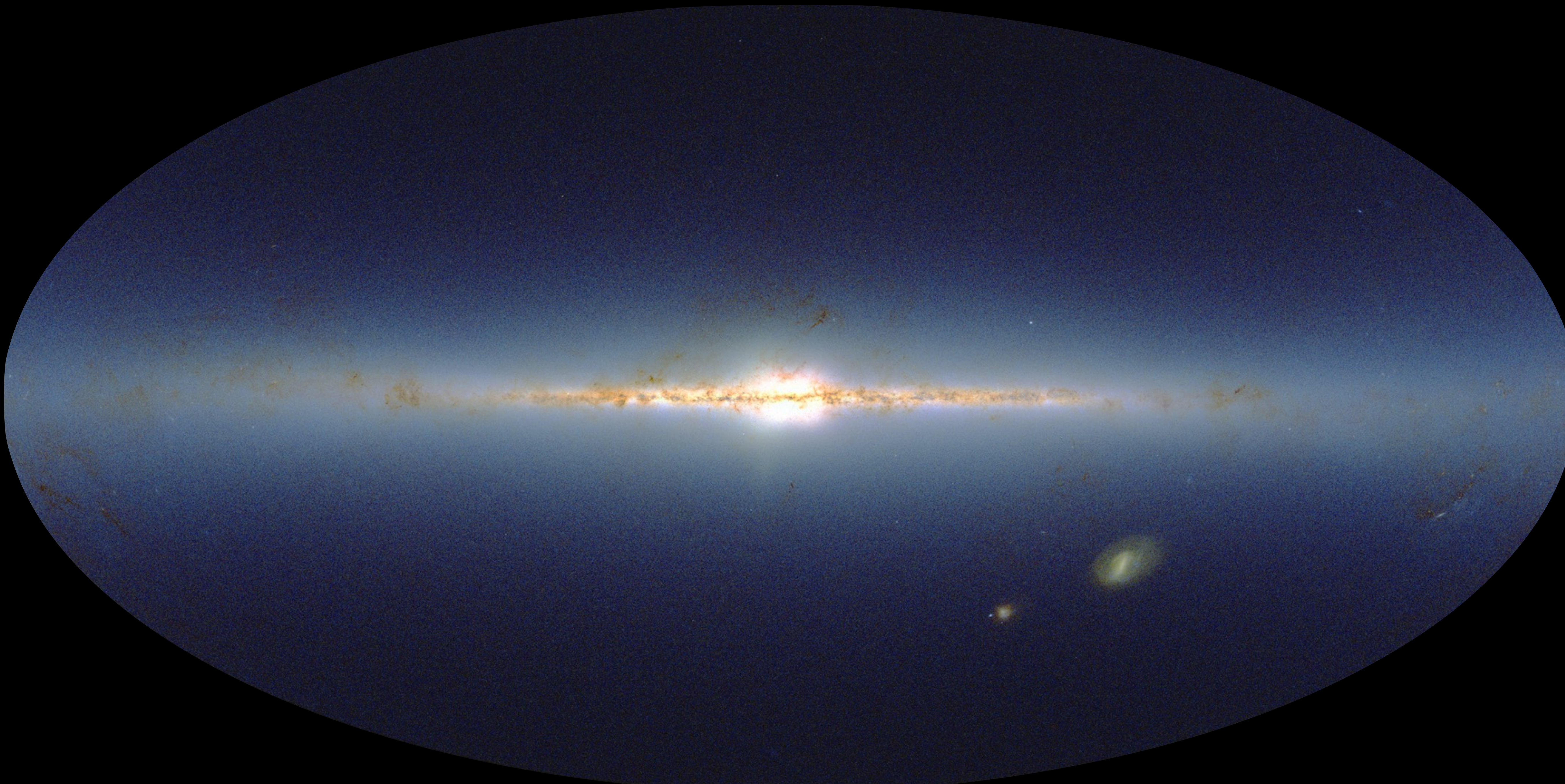
Planck satellite

25-100 μm / infrared / warm dust



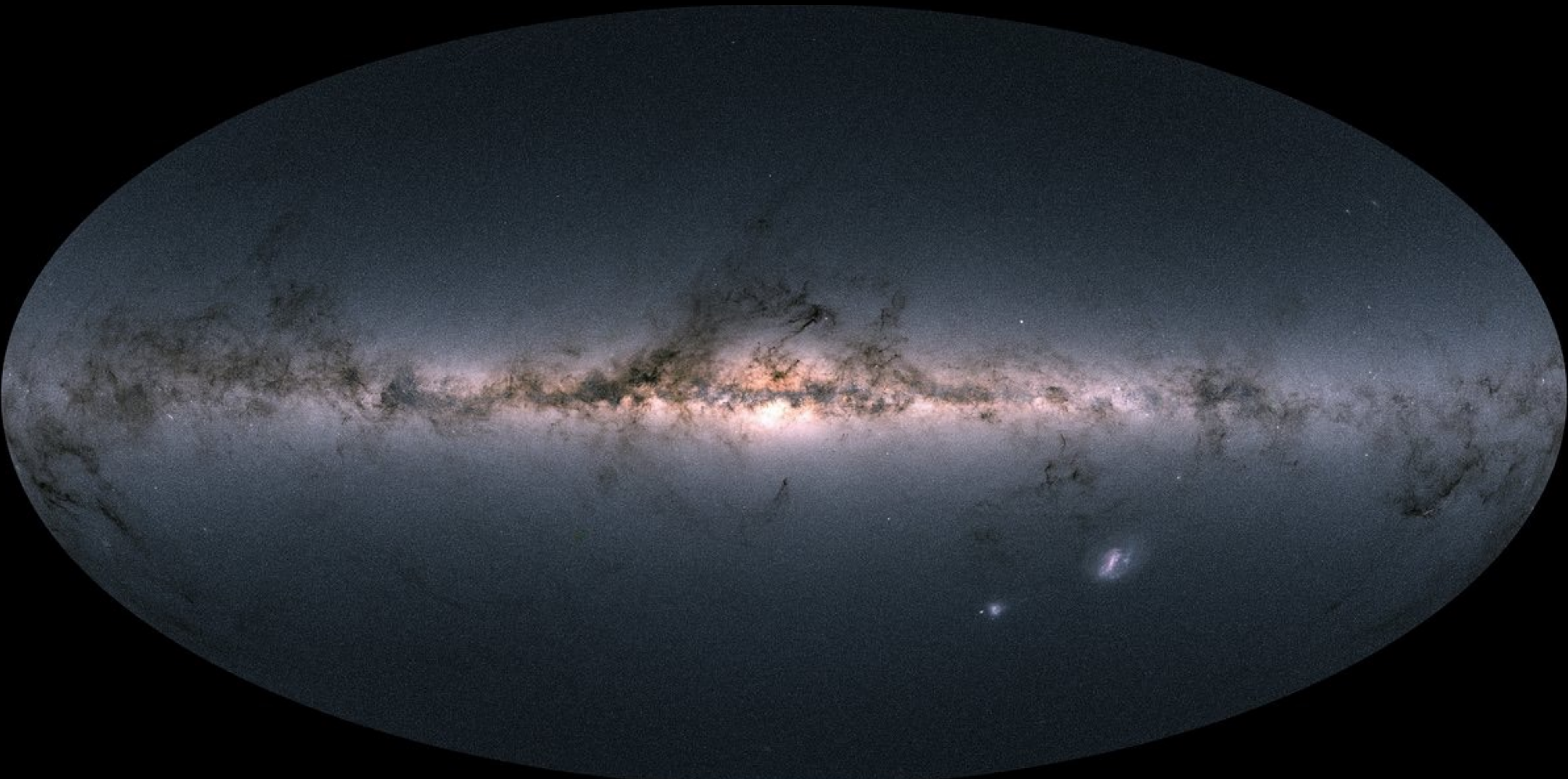
IRAS satellite

2 μm / infrared / stars



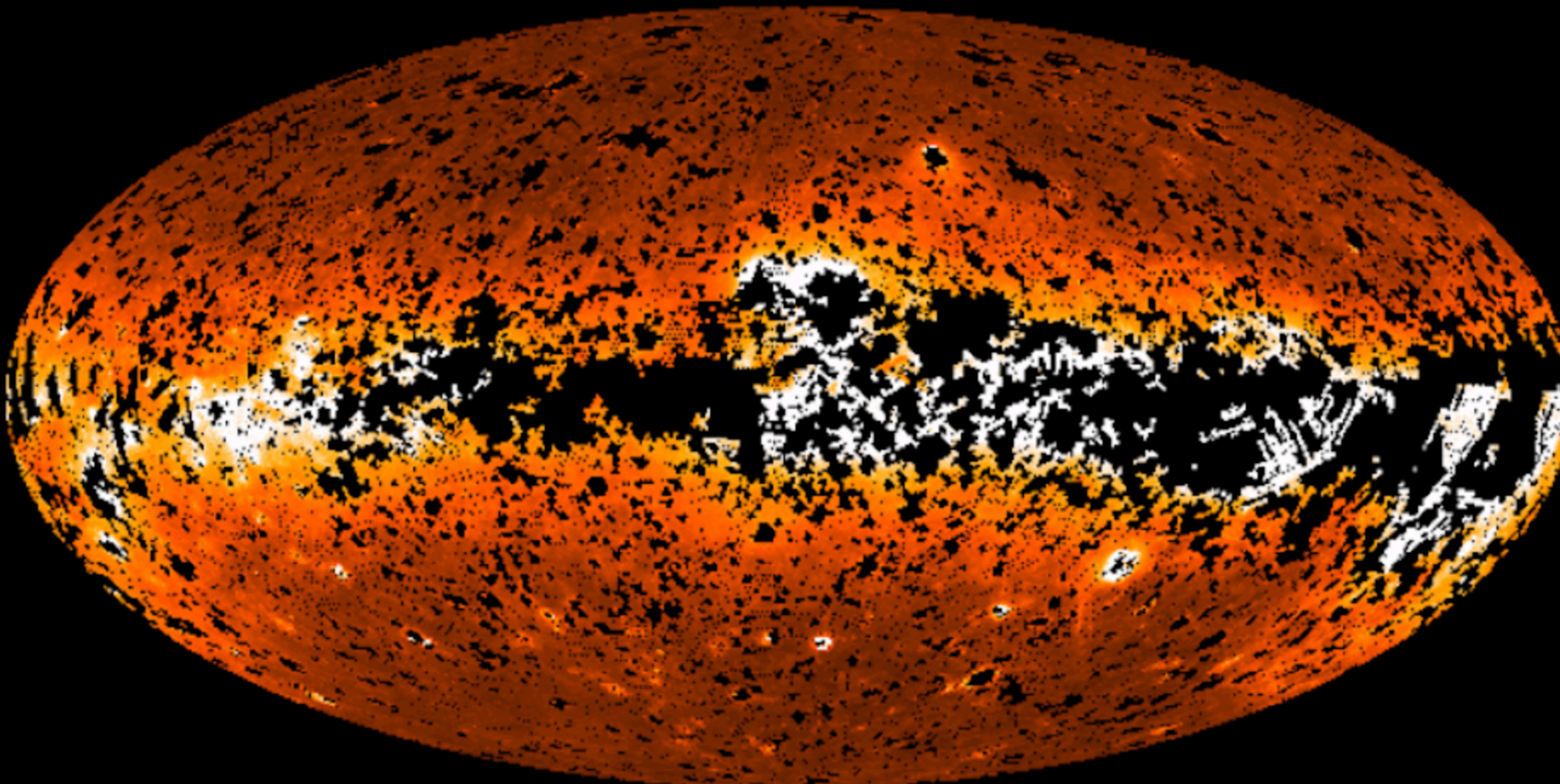
2MASS survey

300-1000 nm / optical / stars



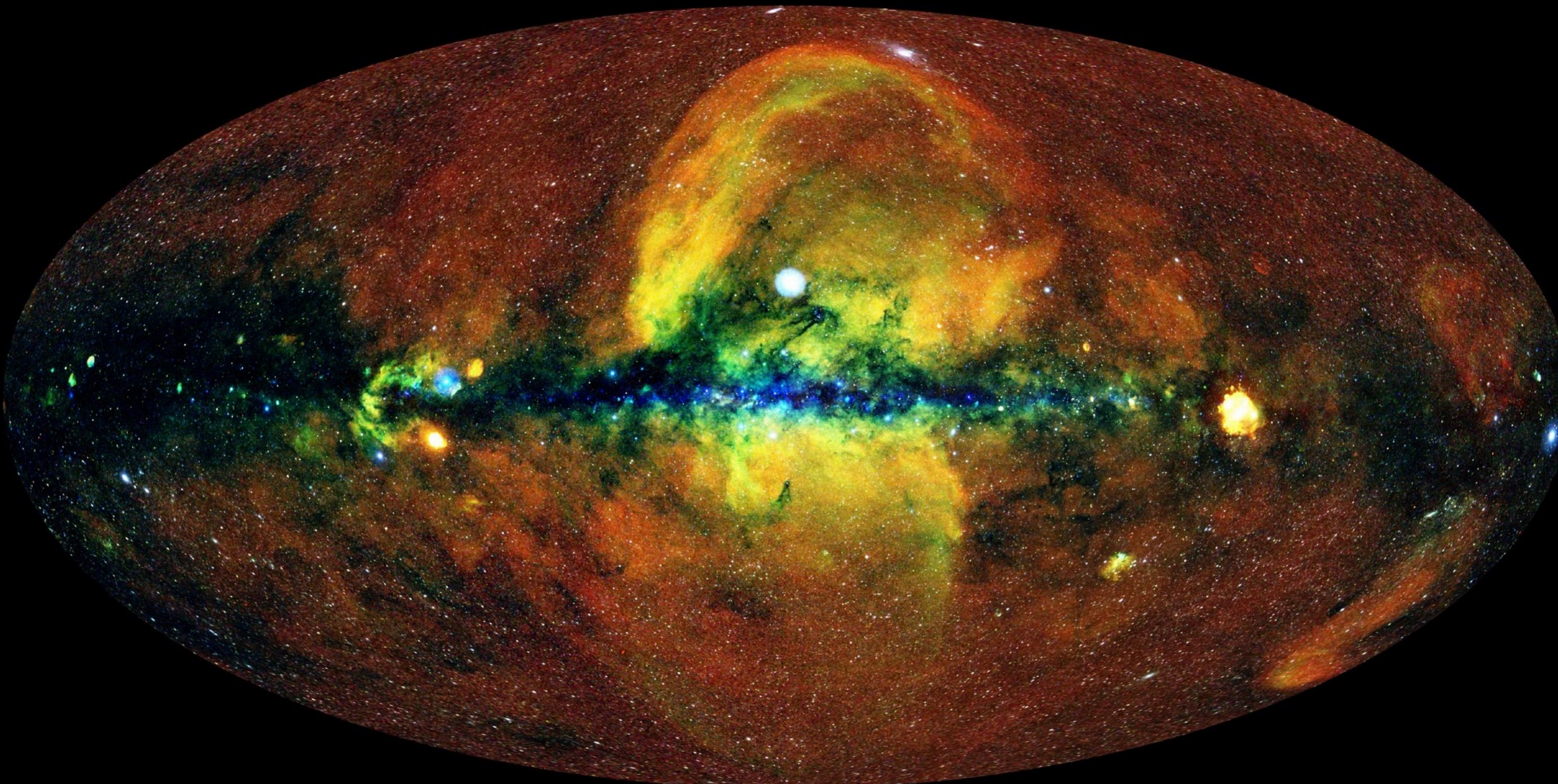
GAIA satellite

175-280 nm / UV / hot stars



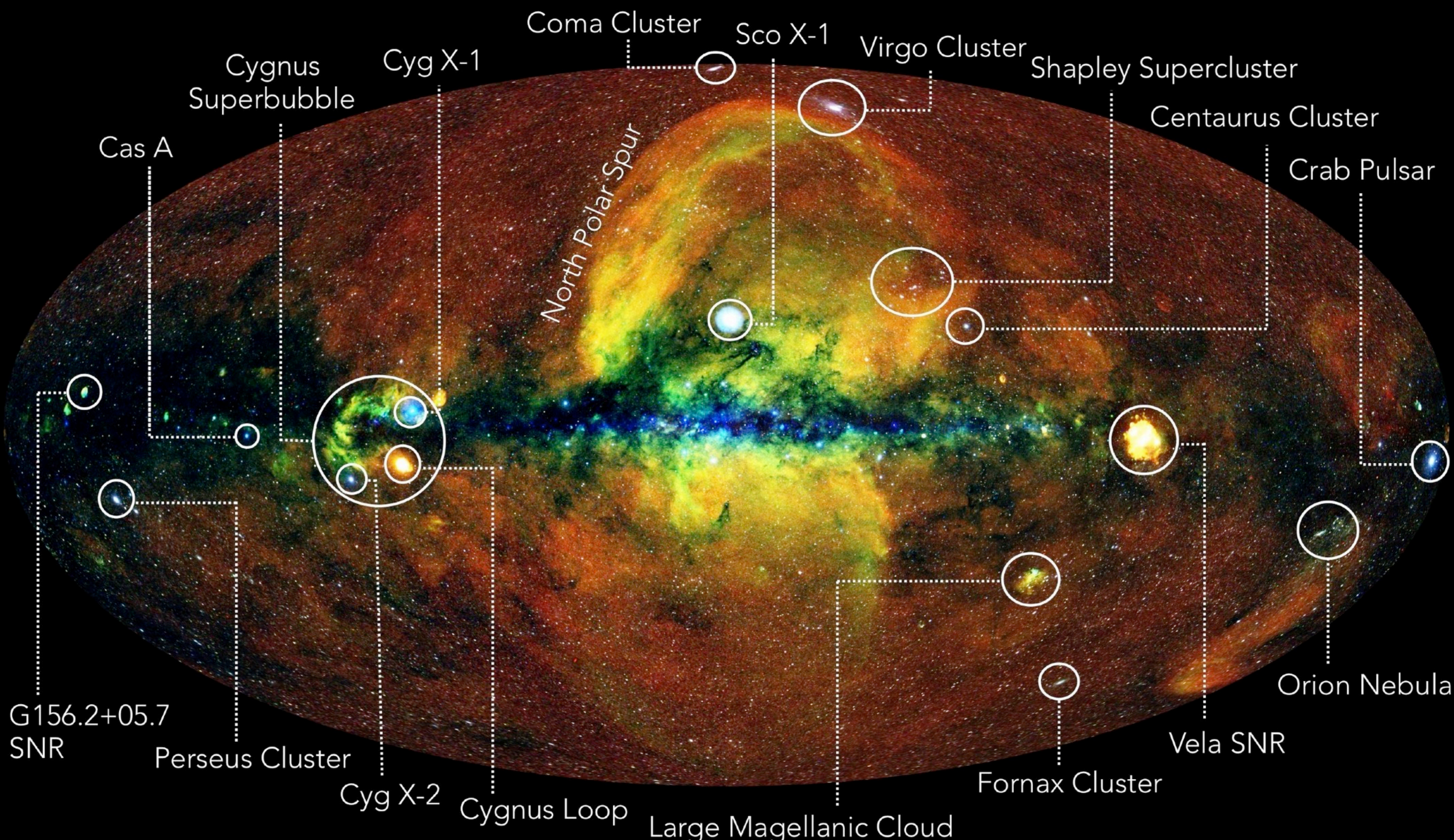
GALEX satellite

0.5-4 nm / X-rays / very hot gas



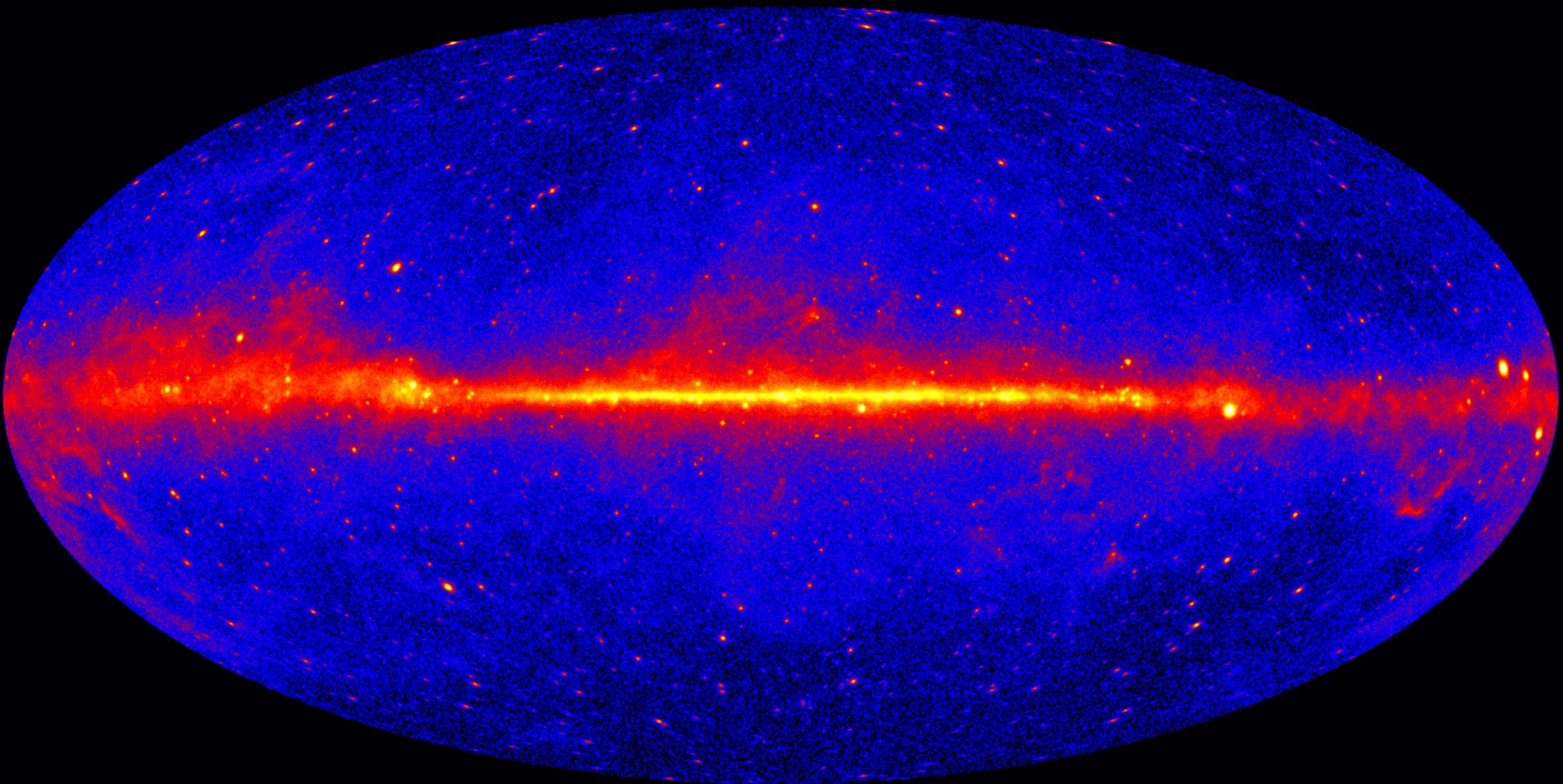
XRG satellite / eROSITA / MPE

0.5-4 nm / X-rays / very hot gas



XRG satellite / eROSITA / MPE

below 10^{-15} m / γ-rays / energetic point sources



Fermi satellite

Backgrounds

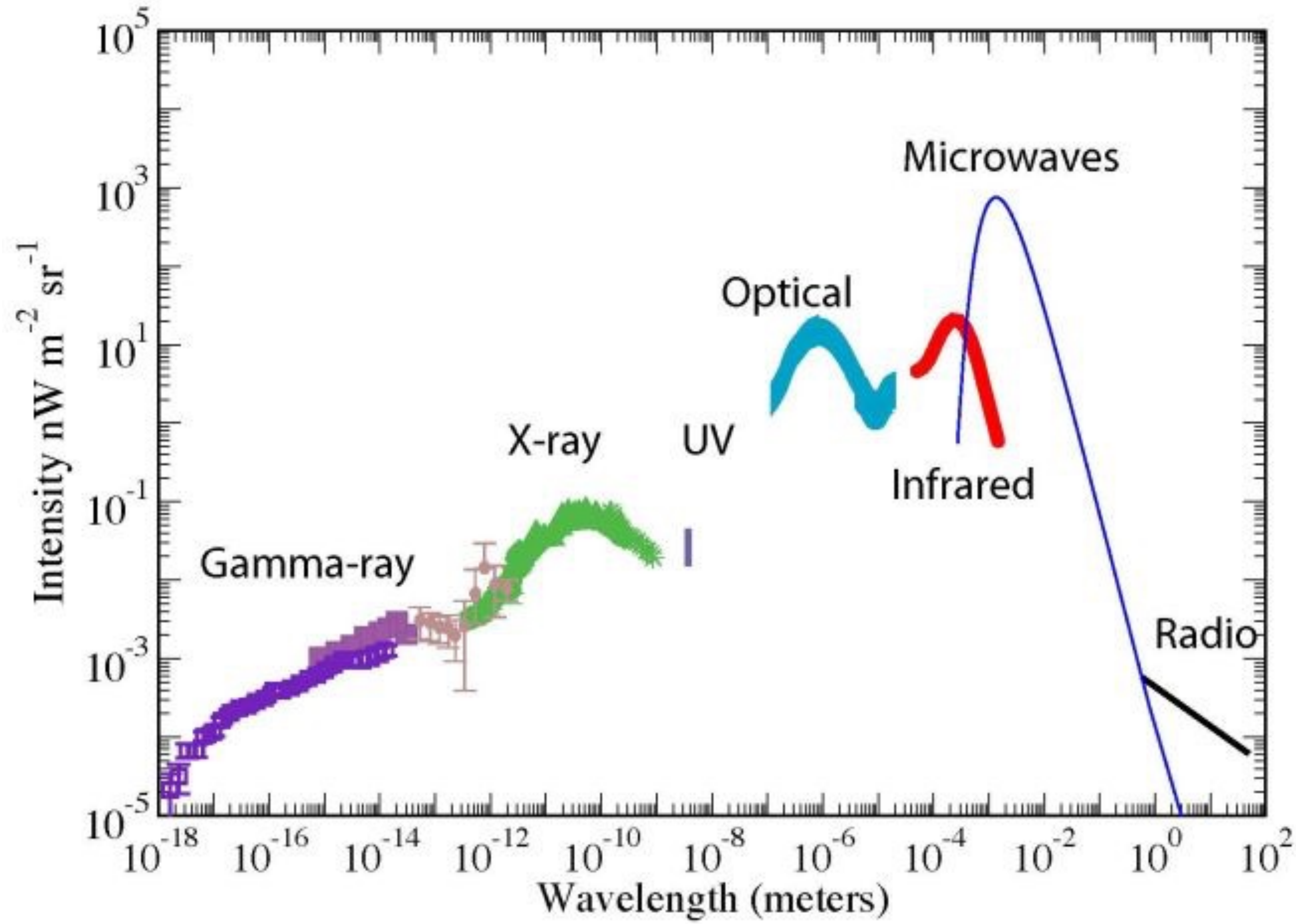


Figure by A. Cooray

The local ISM

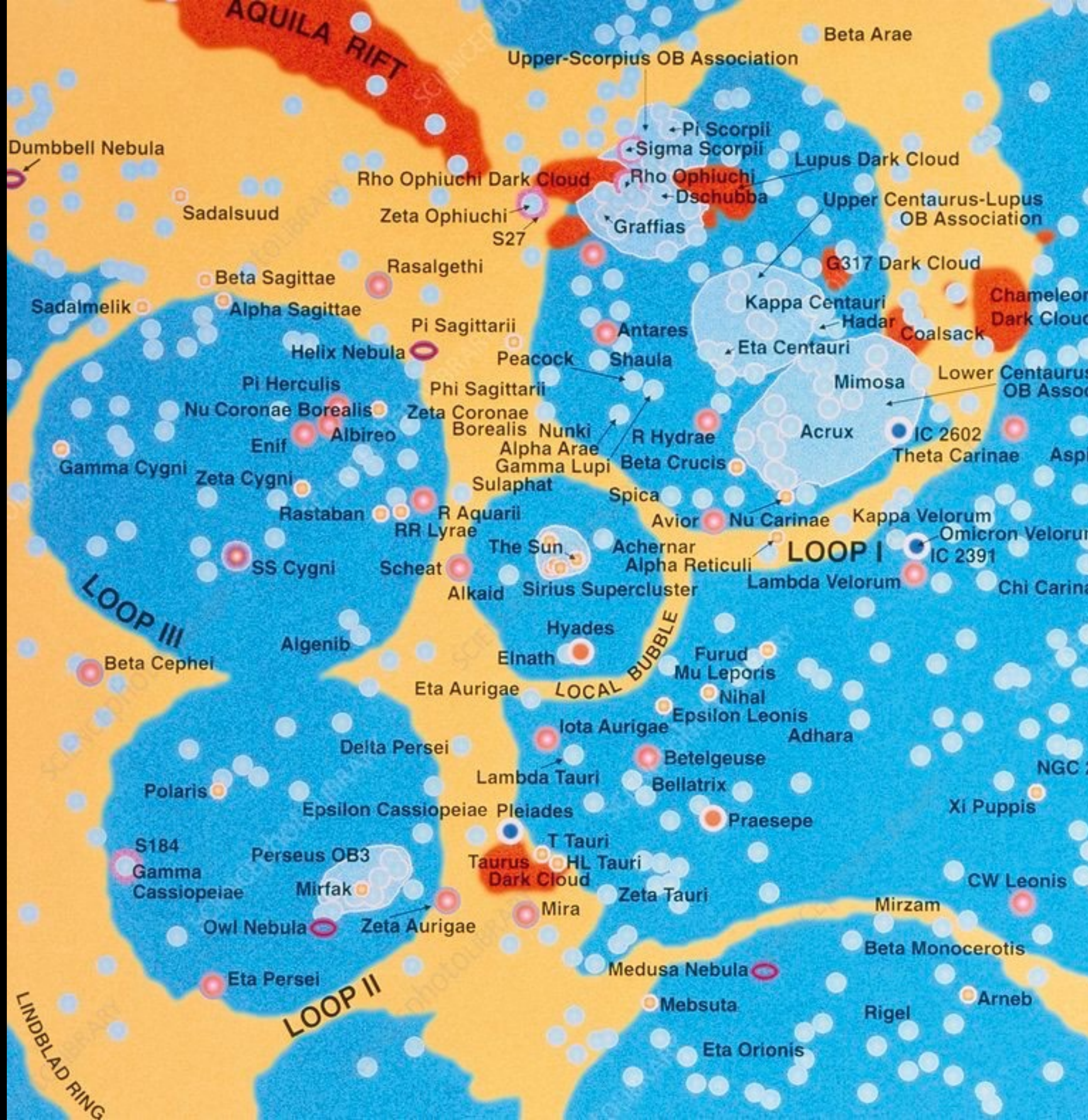
Local ISM (120 pc)

- Galactic center towards upper edge
- Blue = OB stars
  Yellow = AFG
  Orange = KM
- 3D shells of denser, warm gas (~5000K), enclosing hot gas bubbles (~10^6K)
- In local bubble, $n \approx 0.06/\mathrm{cm}^3$
- Local Fluff is a denser region ($n \approx 0.1/\mathrm{cm}^3$) recently encountered by the Sun
- Sun is going left through local fluff at ~20 km/s

Henbest & Couper / Guide to the Galaxy

ISM (500 pc)

- Sun at center
- Redder portions are denser



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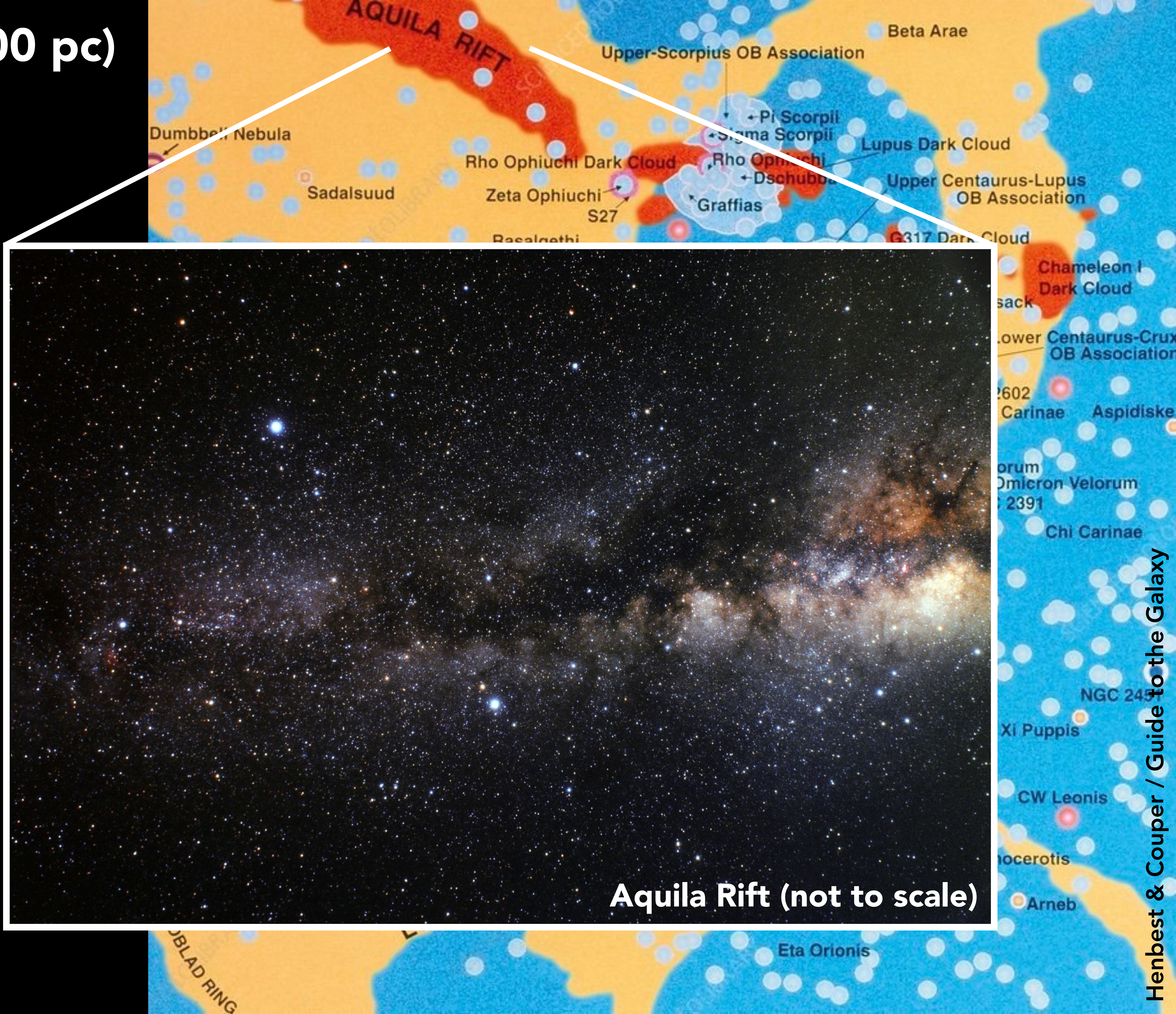
ISM (500 pc)



Aquila Rift (not to scale)

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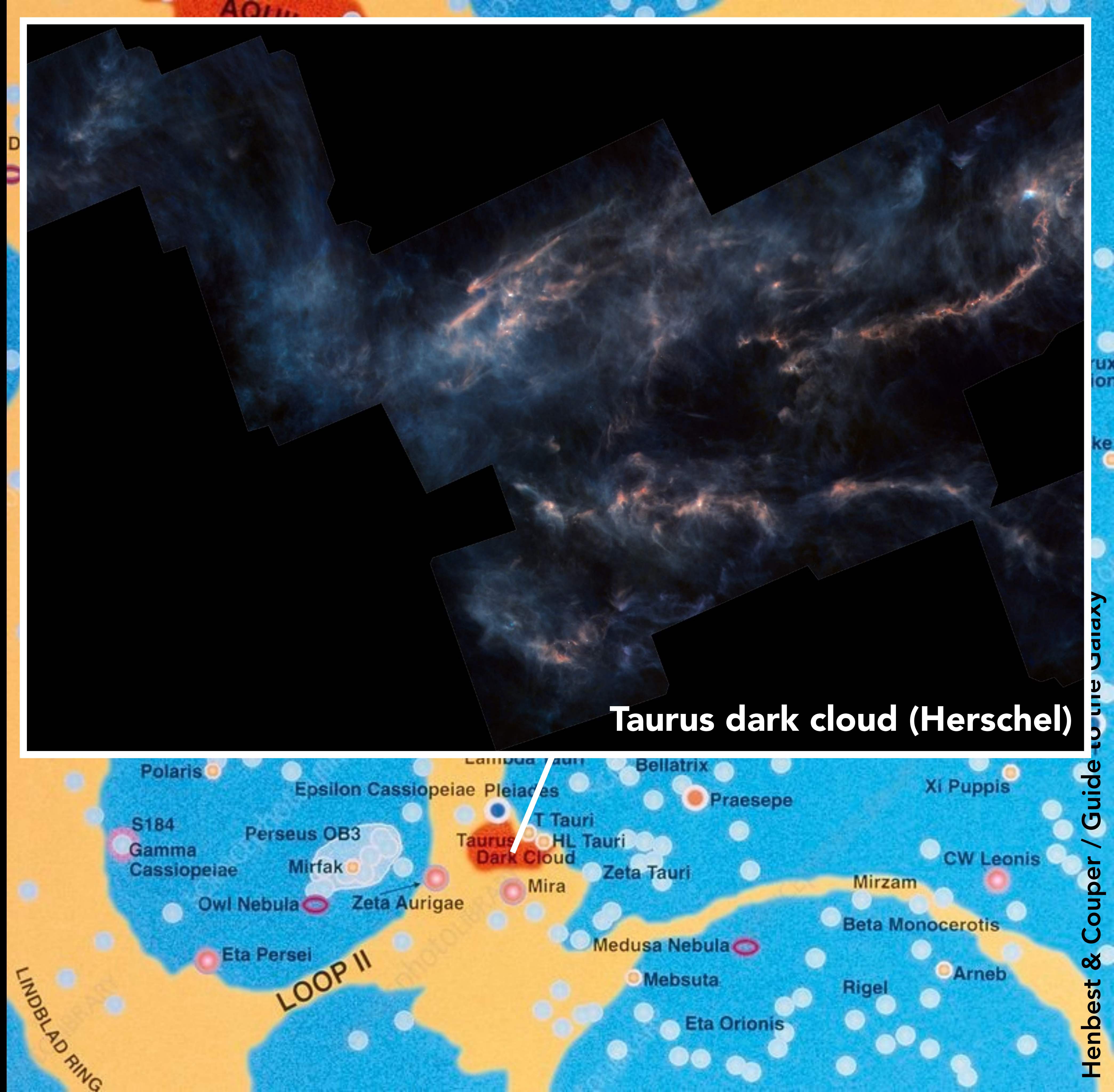
ISM (500 pc)



Taurus dark cloud (Herschel)

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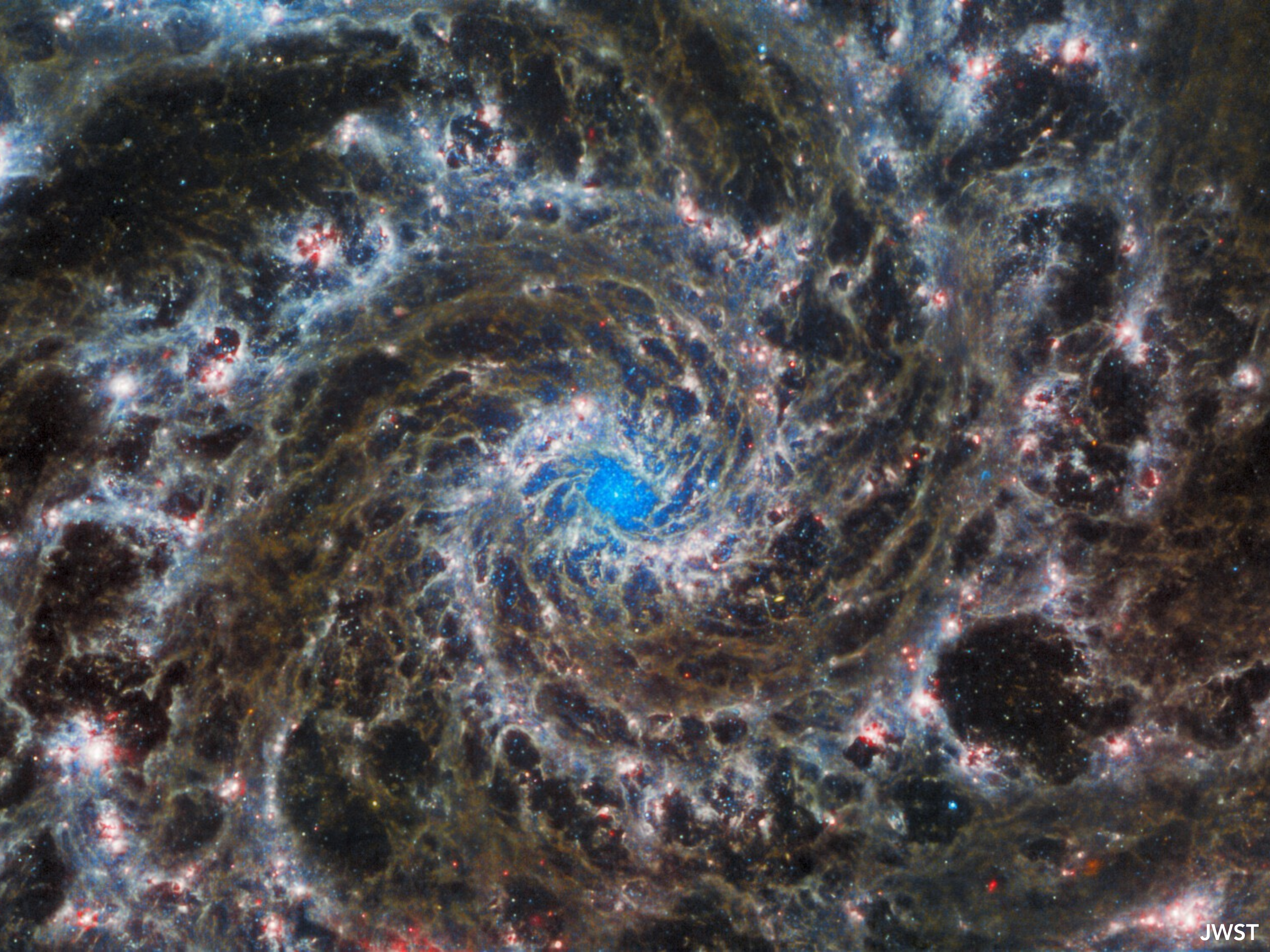
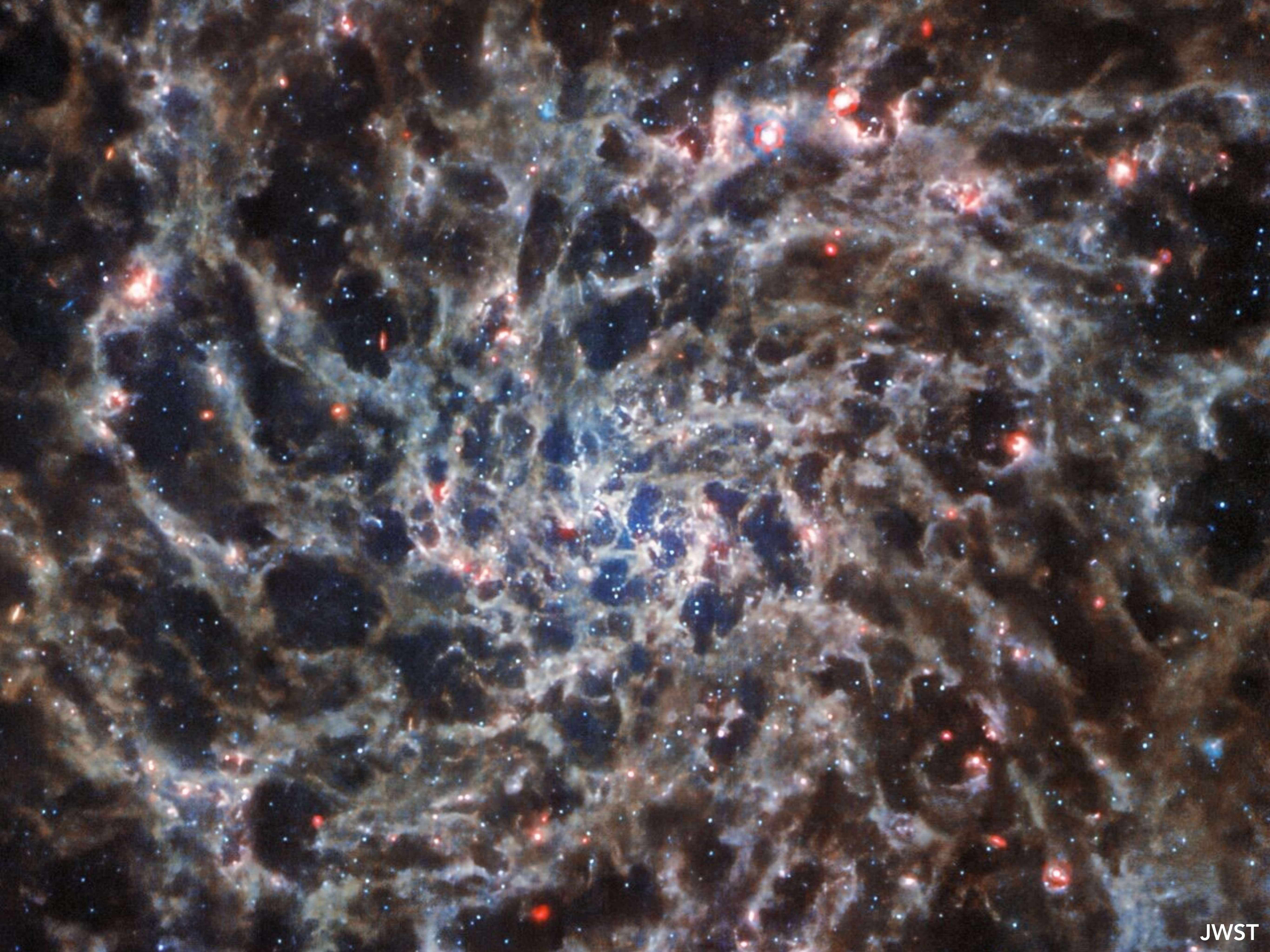
Big Questions

- How are baryons transformed into stars?
- What determines the initial mass function of stars?
- Why do stars form in binaries / multiples?
- How does feedback work?


JWST


JWST

ISM Basics

Composition

- Not known exactly, but the Sun should tell us about the ISM about 5 billion years ago
- About 1-2% elements other than H/He

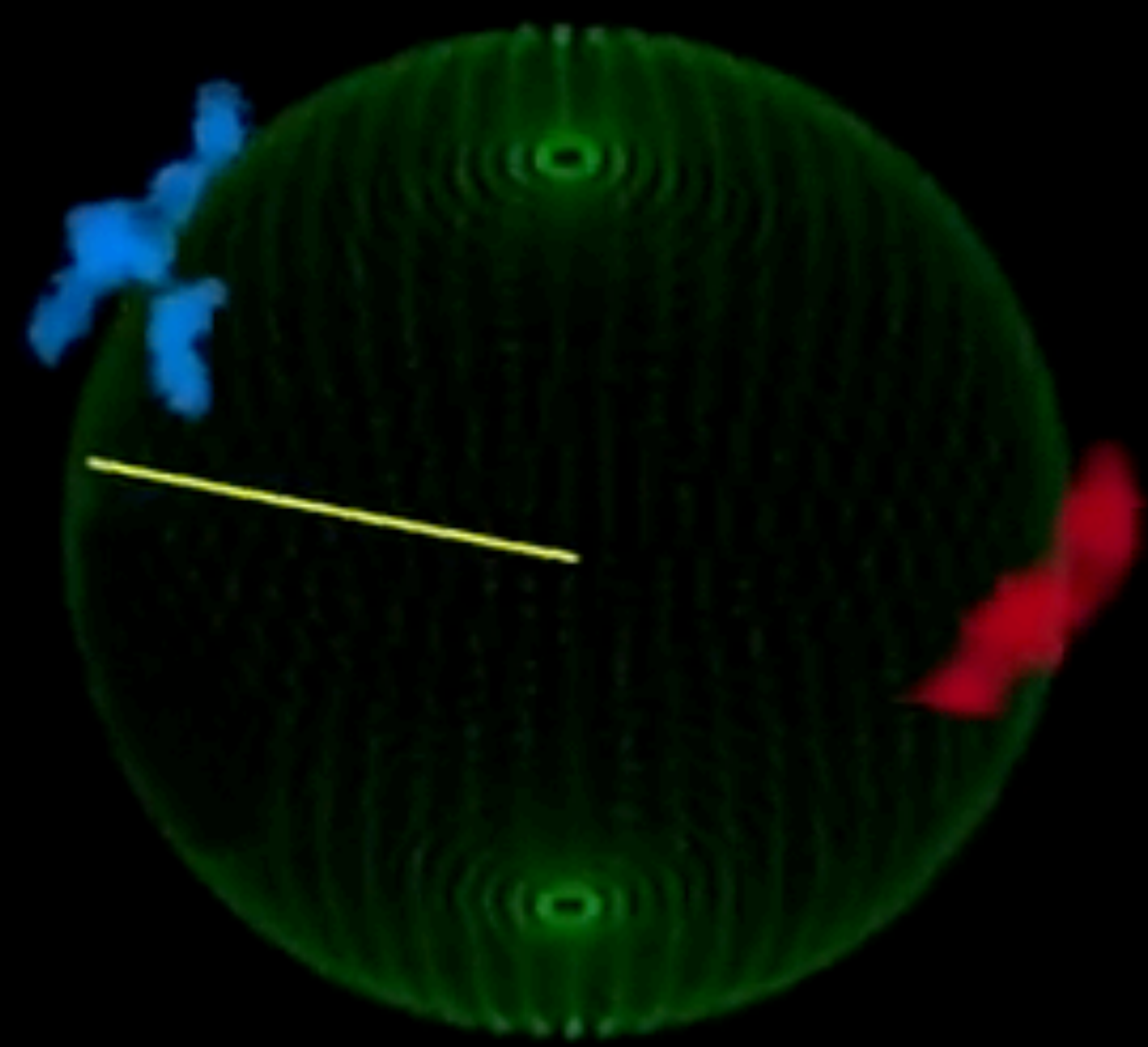
Element	Abundance/H	Mass/H
H	1	1
He	0.10	0.38
Li	$2.0 \cdot 10^{-9}$	$1.4 \cdot 10^{-8}$
C	$3.0 \cdot 10^{-4}$	$3.5 \cdot 10^{-3}$
N	$7.4 \cdot 10^{-5}$	$1.0 \cdot 10^{-3}$
O	$5.4 \cdot 10^{-4}$	$8.6 \cdot 10^{-3}$
Na	$2.0 \cdot 10^{-6}$	$4.7 \cdot 10^{-5}$
Mg	$4.4 \cdot 10^{-5}$	$1.1 \cdot 10^{-3}$
Si	$3.6 \cdot 10^{-5}$	$9.1 \cdot 10^{-4}$
Ca	$2.1 \cdot 10^{-6}$	$8.6 \cdot 10^{-5}$
Fe	$3.5 \cdot 10^{-5}$	$1.9 \cdot 10^{-3}$

Data from Draine

Gas phases

- Gas comes at all kinds of temperatures and densities, but some common properties emerge
- We categorize them by the **state of hydrogen**
  - **Ionized** atomic hydrogen (H^+ or H II)
  - **Neutral** atomic hydrogen (H^0 or H I)
  - **Molecular** hydrogen (H_2)
- Most regions in the ISM are dominated by one of those phases, with thin transition zones

The Perseus-Taurus shell



yellow line from sphere's center points back toward Earth

Alyssa Goodman / Catherine Zucker / Shmuel Bialy / Carter Emmart / Michael Foley / Jasen Chambers (youtube)

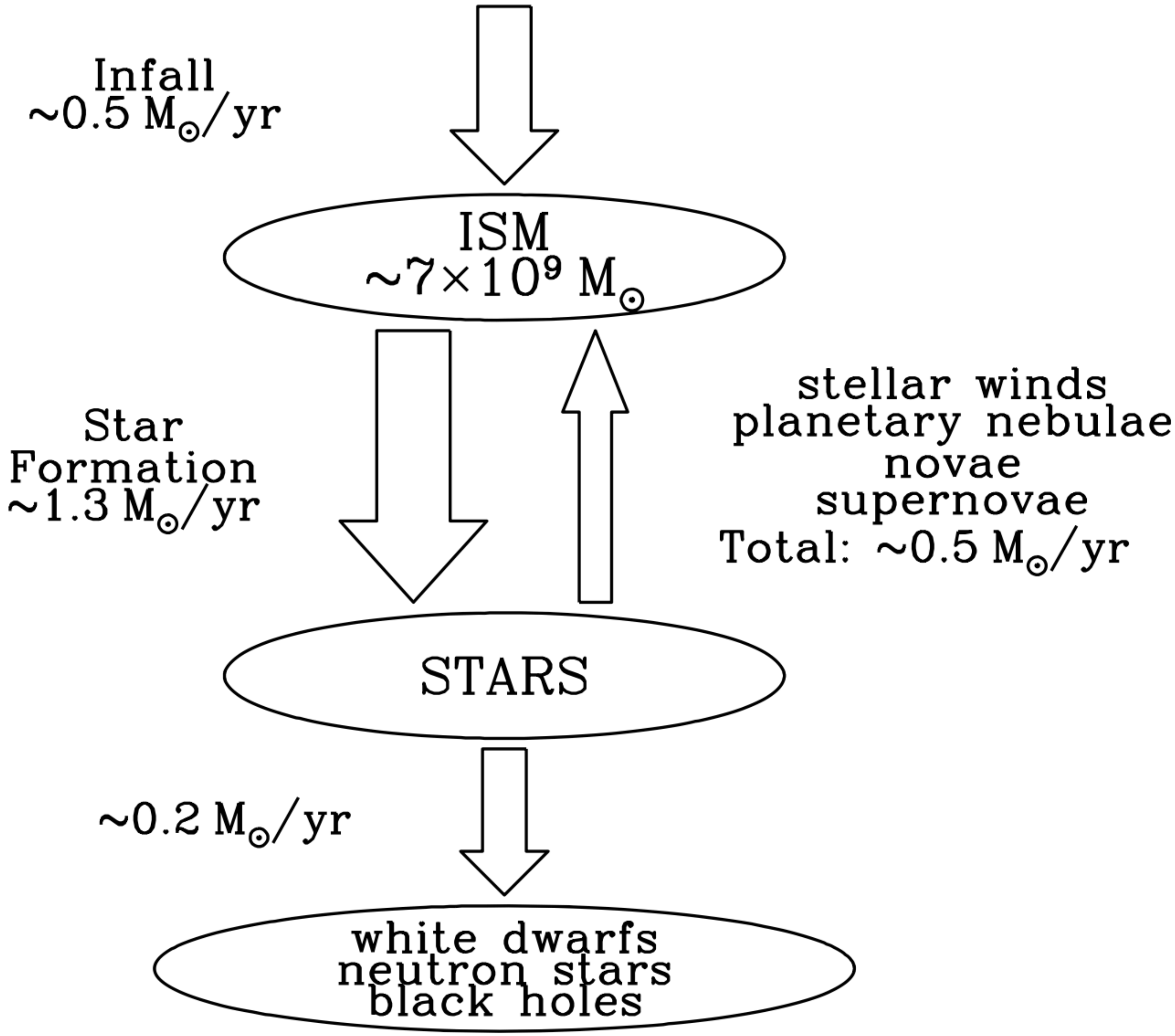
Gas phases (in the Milky Way)

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

Gas phases

- Mostly confined to the disk, some gas in the hot halo
- Large range in temperature
- Even dense regions are “ultra-high vacuum”
  - Laboratory UHV is $n \approx 4 \times 10^6/\mathrm{cm}^3$
- In approximate thermodynamic equilibrium
  - Turbulent, CR, magnetic pressures play a role

Flow of baryons in the MW



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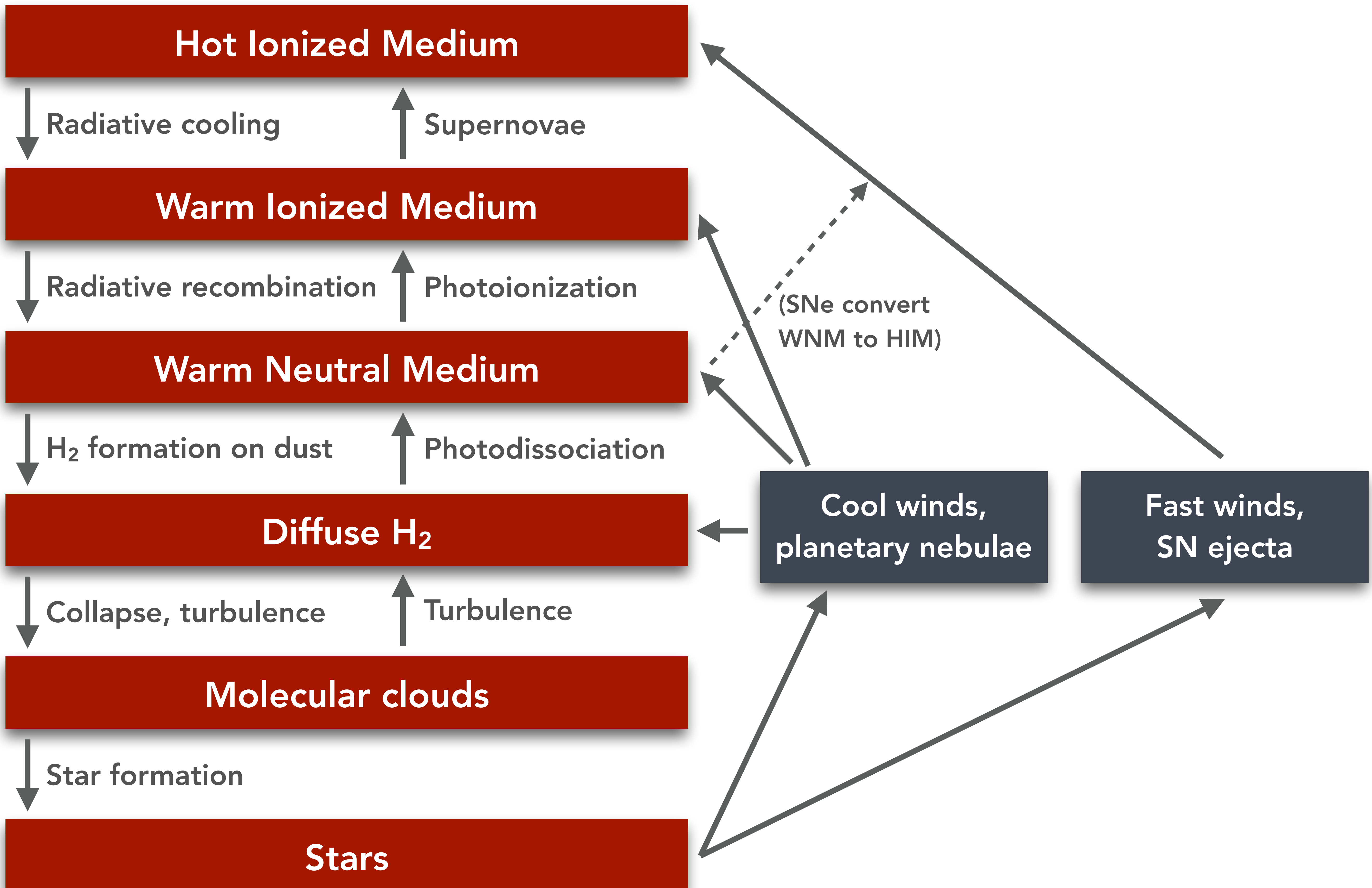
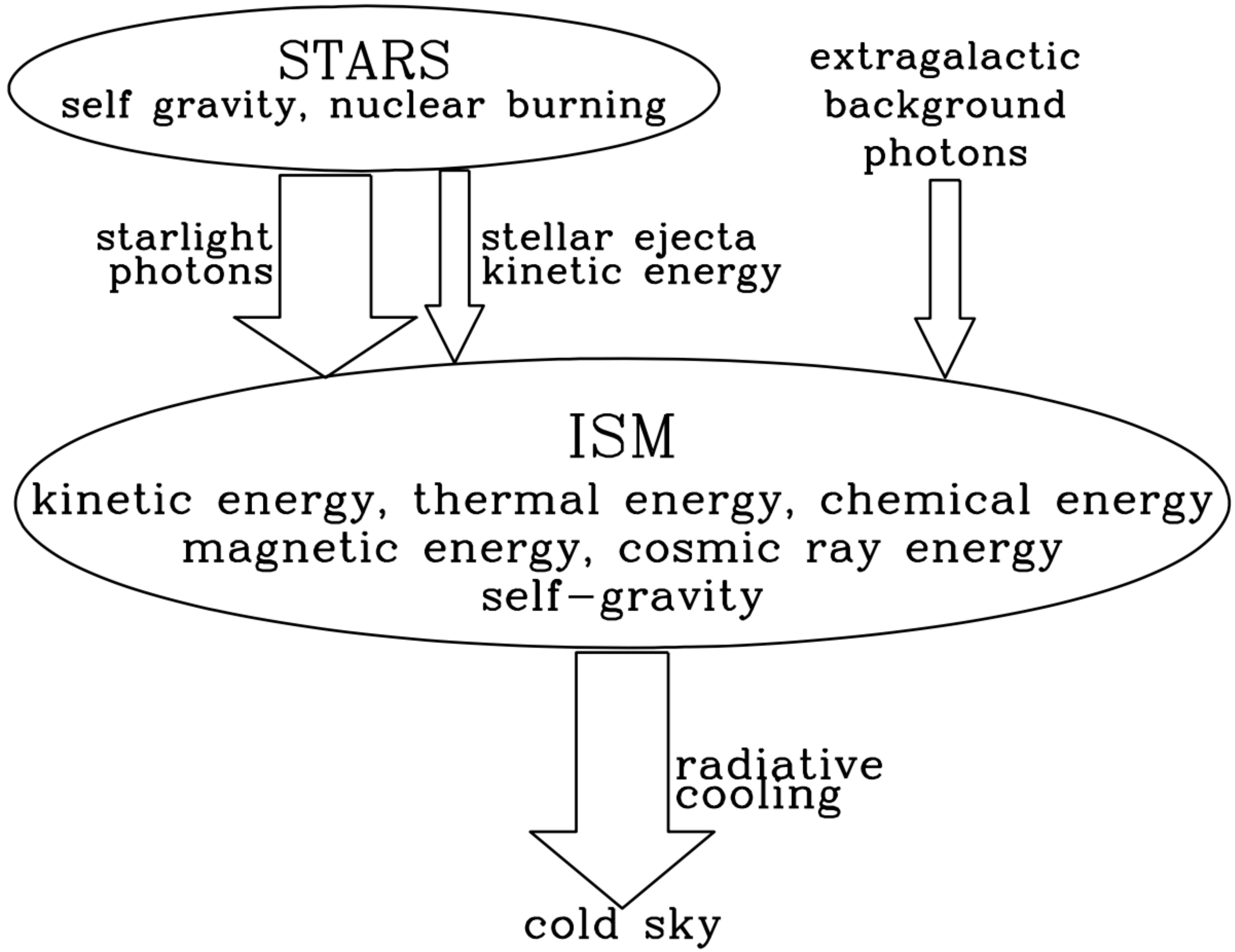
Transformation between phases



Other components

- Dark matter
- Interstellar dust
  - ≈ 0.1 μm size, silicates or carbonaceous material
  - ≈ 1% by mass of ISM
- Light (EM radiation)
  - CMB
  - Star light
  - X-rays from hot gas
- Magnetic field
- Cosmic rays

Flow of energy



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Energy densities

$$E_{\mathrm{th}} = \frac{3}{2} n k_{\mathrm{B}} T$$

$$E_{\mathrm{kin}} = \frac{1}{2} \rho u^2$$

$$E_{\mathrm{B}} = \frac{B^2}{2} = \frac{B_{\mathrm{cgs}}^2}{8\pi}$$

$$E_\gamma = \int_0^\infty h\nu \; n_\nu \; d\nu$$

$$E_{\mathrm{tot}} = E_{\mathrm{th}} + E_{\mathrm{kin}} + E_{\mathrm{B}} + E_{\mathrm{CR}} + E_\gamma$$

- All energies per unit volume
- CR energy is the kinetic energy of CR particles
- Kinetic energy largely from turbulent motion

Energy densities

Component	E (eV/cm^3)	**Comments**
Cosmic microwave background (CMB)	0.27	
Far-IR radiation from dust	0.31	
Starlight	0.54	For energies $h\nu < 13.6$ eV
Thermal energy	0.49	
Kinetic energy	0.22	Largely from turbulence
Magnetic energy	0.89	For a median $B \approx 0.6\mu G$
Cosmic ray energy	1.39	

Reading

Draine

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