The Interstellar Medium: Research Methods

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COURSE STRUCTURE

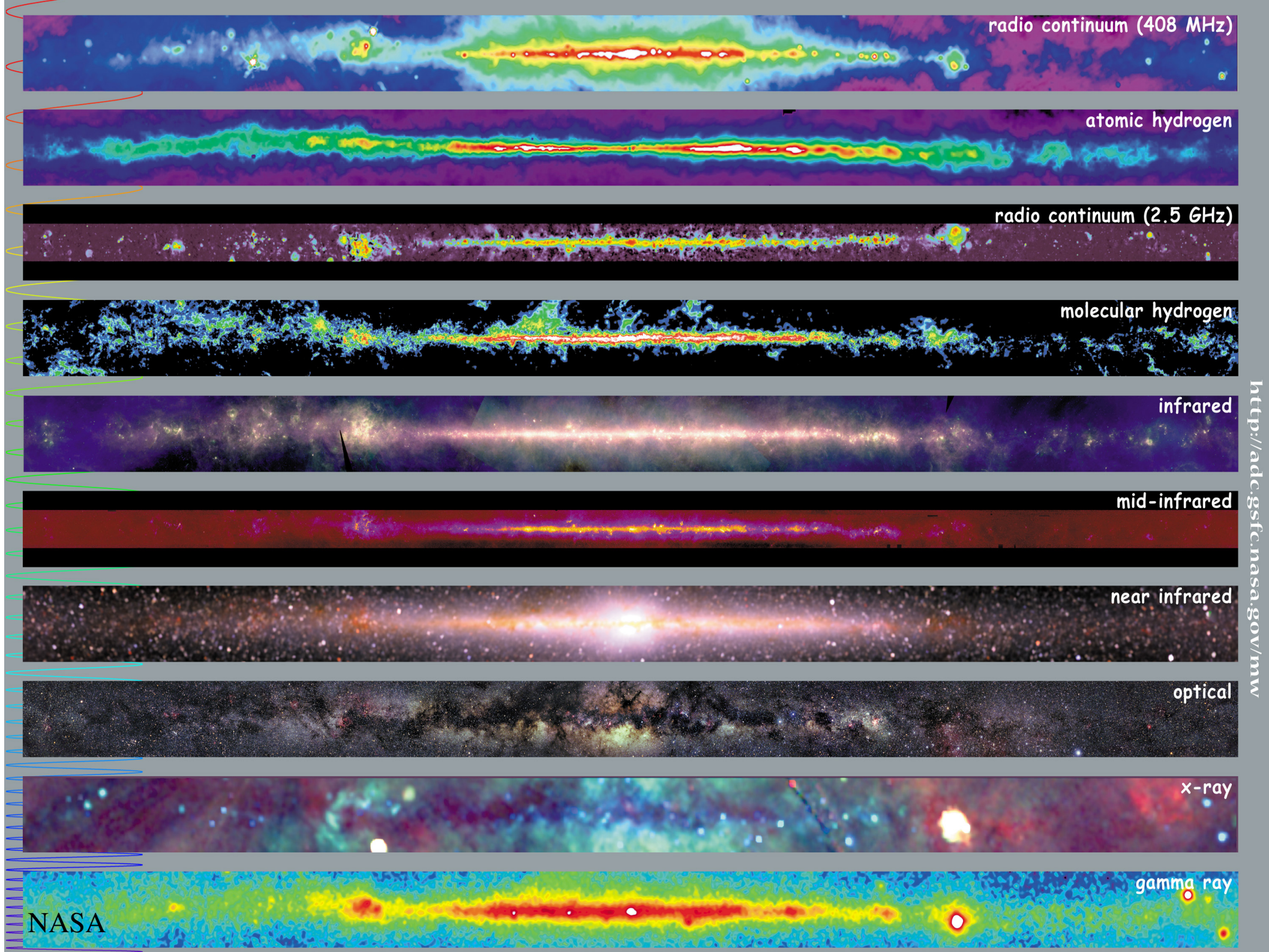
- (1) Overview (I) : Phases, conditions, mass budget.
- (2) Overview (II): Equilibrium issues and spectral lines.
- (3–5) Diffuse clouds.
- (6–8) Molecular gas.
- (9–11) Interstellar dust.
- (12) The Warm Ionized Medium
- (13) The Hot Ionized Medium
- (14) Multi-phase models of the ISM.

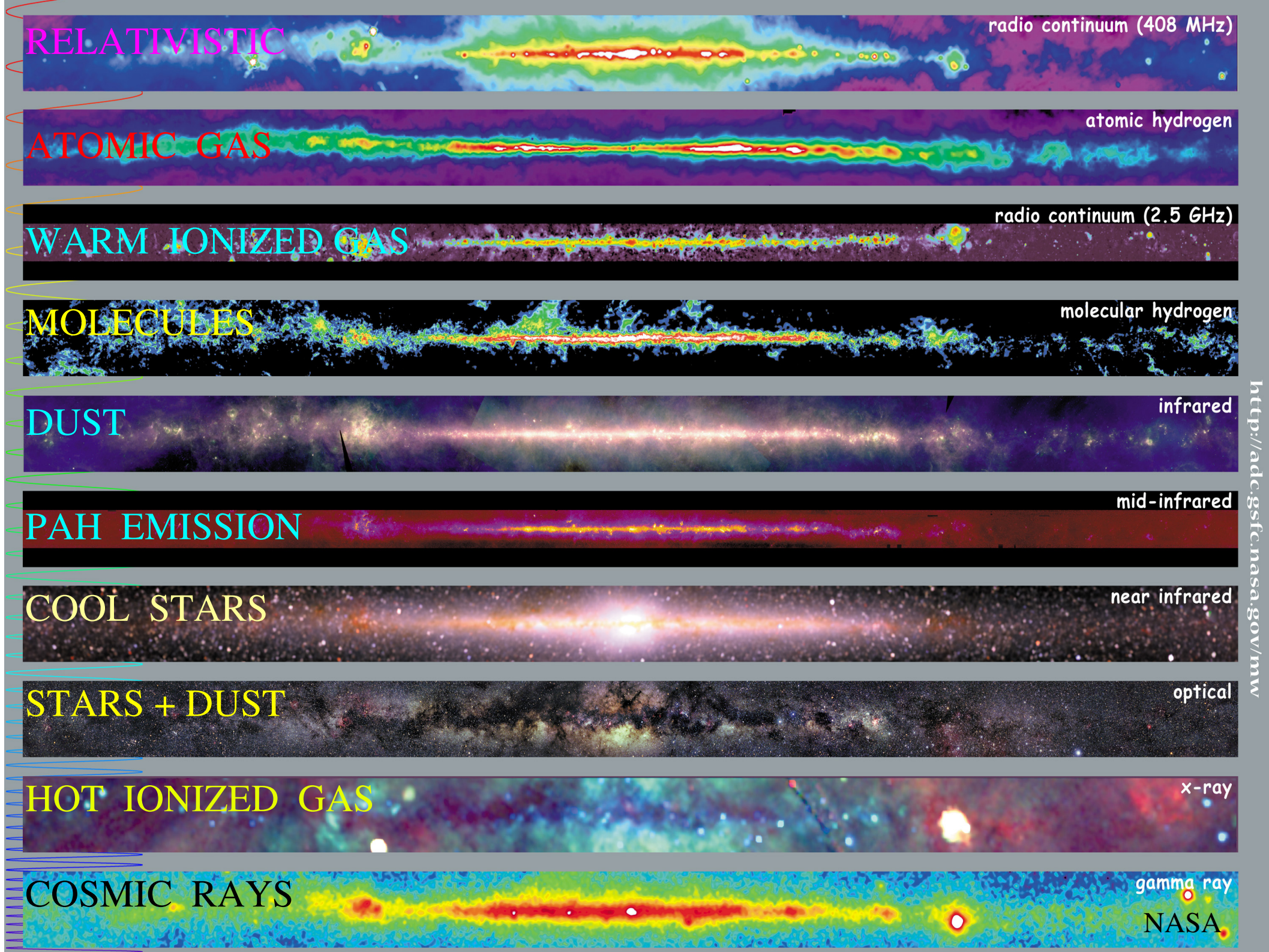
REFERENCES

- Draine: *Physics of the Interstellar and Intergalactic Medium.*
- Tielens: *The Physics and Chemistry of the Interstellar Medium.*
- Lequeux: *The Interstellar Medium.*
- Leiden ISM courses: van der Werf, van der Tak, Hogerheijde.
- Bevington/Robinson: *Data Reduction and Error Analysis...*

GRADING

- Two assignments, midway and at the end ? 50% for each ?
- Assignments will involve using spectra or continuum measurements to derive physical conditions. No questions will be asked.


radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
NASA
http://adc.gsfc.nasa.gov/mw


RELATIVISTIC
radio continuum (408 MHz)
ATOMIC GAS
atomic hydrogen
WARM IONIZED GAS
radio continuum (2.5 GHz)
MOLECULES
molecular hydrogen
DUST
infrared
PAH EMISSION
mid-infrared
COOL STARS
near infrared
STARS + DUST
optical
HOT IONIZED GAS
x-ray
COSMIC RAYS
gamma ray
NASA
http://adc.gsfc.nasa.gov/mw

INTRODUCTION

- The ISM dominates the *volume* of a galaxy. E.g. the distance between Galactic stars is ~ 1 pc, while the size of the heliosphere is ~ 235 AU ⇨ 99.9999997% of the Galactic volume is the ISM!

- Predominantly gas (mostly H, some He, trace metals), a little solid material (dust), cosmic rays, radiation & magnetic fields.

- A galaxy's life cycle: interplay between ISM & stars. Stars form from the ISM, and then heat and ionize the ISM. Also exude metals into the ISM, causing cooling, and further star formation.

- Note: the emission of many galaxies is dominated by their ISM (e.g. high-z sub-mm galaxies).

- The ISM is critical for understanding galaxies! E.g. dynamics, local physical conditions, chemical evolution, detecting high-z galaxies...

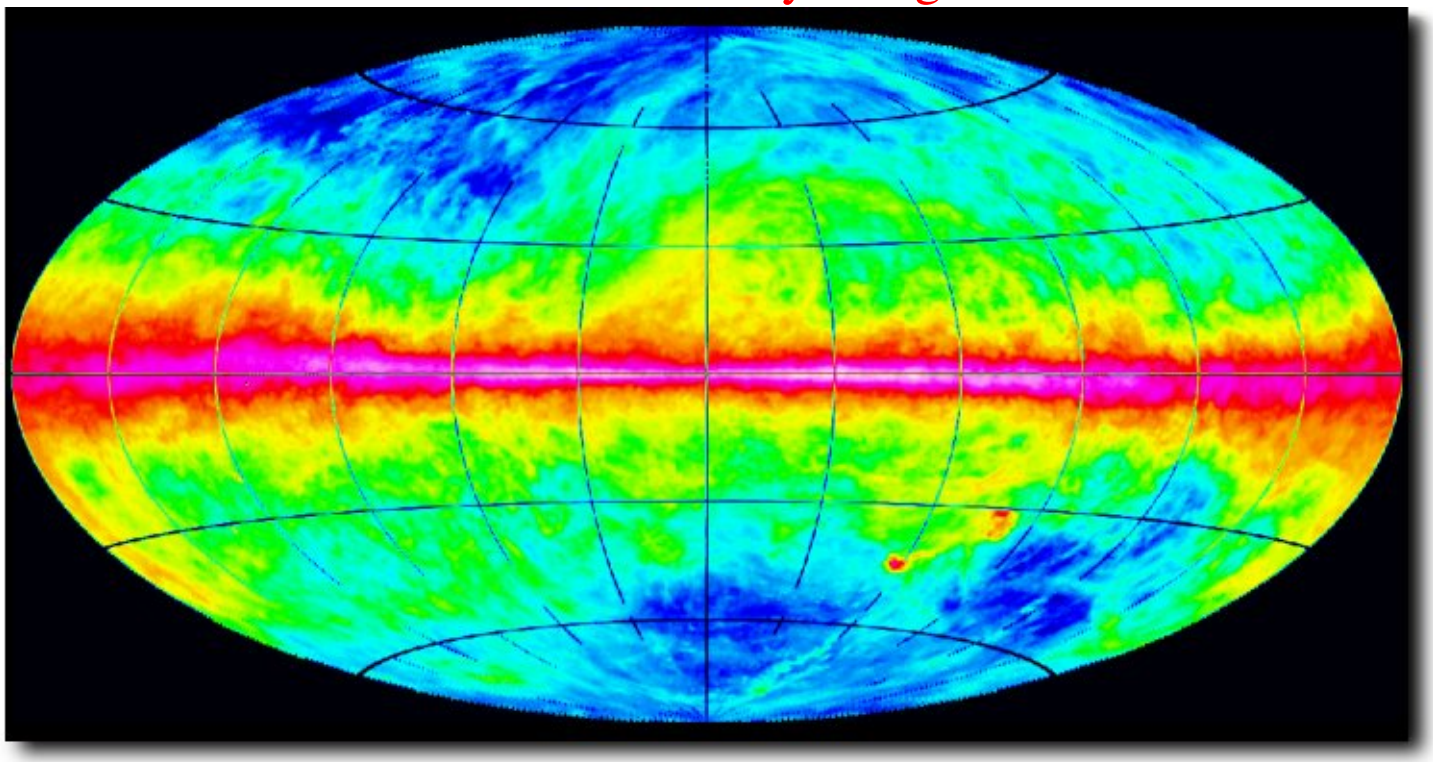
ISM PHASES (of hydrogen)

- Atomic gas clouds (mostly neutral hydrogen, HI).
- Molecular gas clouds (mostly molecular hydrogen, H_2).
- Warm ionized gas (both diffuse gas and HII regions).
- Hot, highly-ionized "coronal" gas.
- Dust.
- Polycyclic Aromatic Hydrocarbons (PAHs).
- Cosmic rays.

ATOMIC GAS CLOUDS (Mostly HI)

- Traced by the HI-21cm line, and by the Lyman-α and metal lines.

HI-21cm all-sky image



Leiden-Argentine-Bonn survey (Kalberla et al. 2005, A&A)

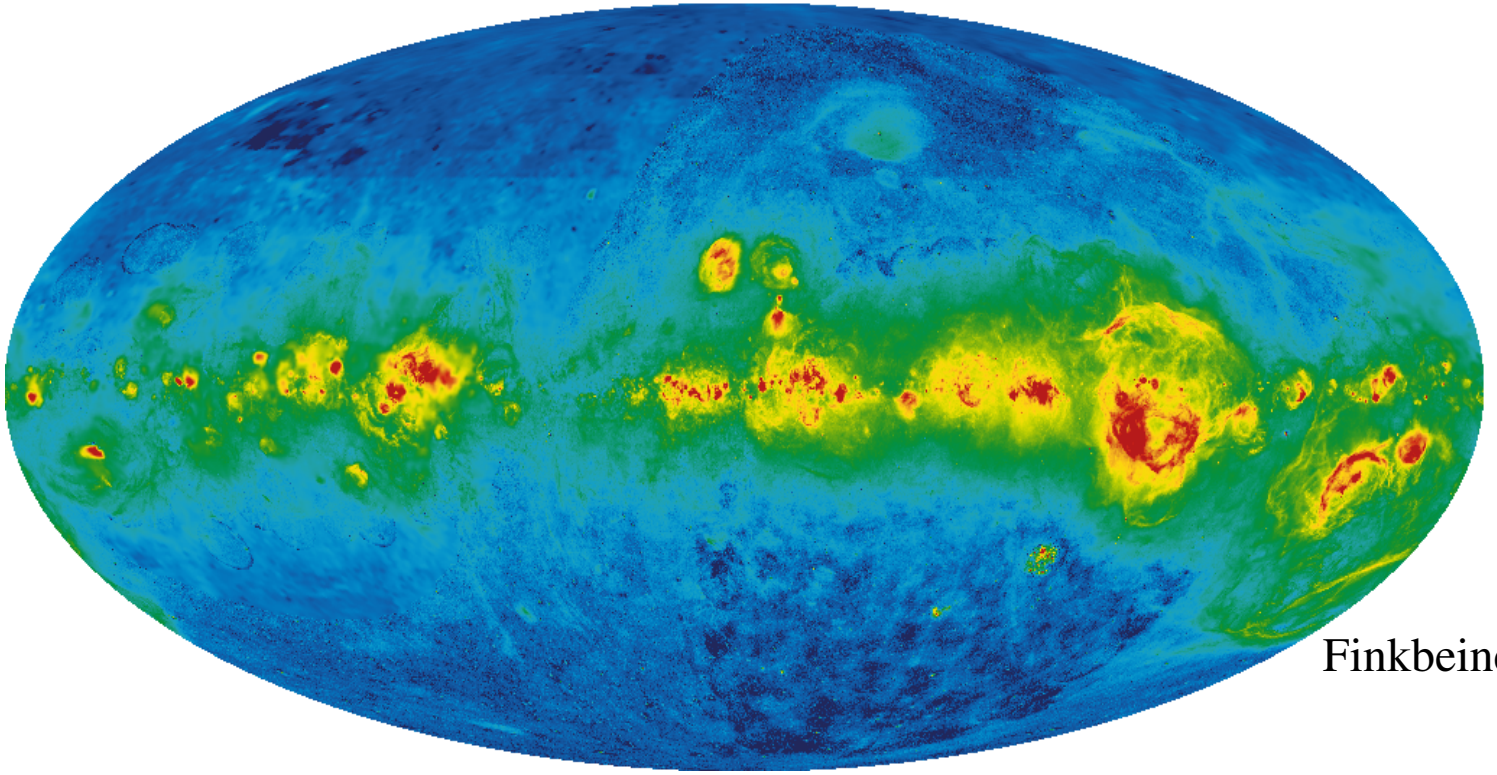
- HI far more extended than the stars in most galaxies (factor >~ 2).

- Cold & Warm phases: "clouds" and "inter-cloud" medium.
  Temperature, density: (~ 80 K, 30 cm^{-3}) or (~ 8000 K, 0.3 cm^{-3}).

WARM IONIZED GAS (Mostly HII)

- Diffuse widespread ionized gas or compact HII regions.
- Produces Hα emission, free-free radio emission, pulsar dispersion...

Hα all-sky image



(LAMBDA; Finkbeiner 2003, ApJS)

- Diffuse WIM: T ~ 8000 K, n ~ 0.3 cm^{-3}.
  Dominates ionized gas mass, ~ 10^9 $M_\odot$.

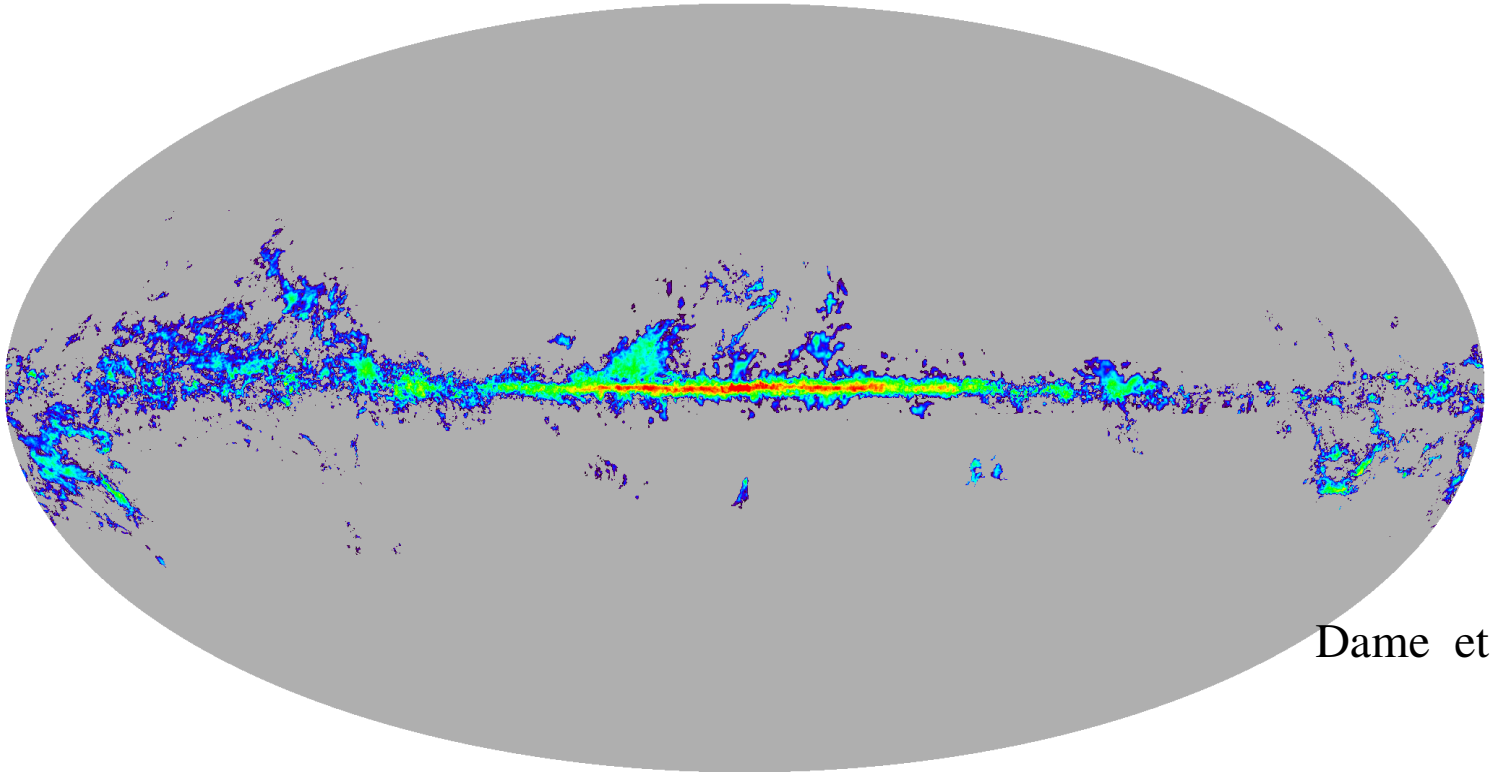
HII REGIONS

- Ionized gas clouds around massive O/B stars (with emission below 13.6 eV).
- Sizes ~ 0.5 – 500 pc.
- Densities ~ $10 - 10^4$ cm^{-3}.
- Temperatures ~ 10^4 K.
- Arise in dusty, molecular clouds with massive star formation.
- Strong optical Hα, OIII, NII, …, lines.
- Strong free-free radio emission.
- Far-IR emission from associated dust.

MOLECULAR CLOUDS (Mostly H_2)

- Difficult to detect H_2 ⇨ Mm-wave CO lines used as "tracers".

CO 1-0 all-sky map



(LAMBDA;
Dame et al. 2001, ApJ)

- Two broad types: "Diffuse" and "Dense".

- Giant Molecular Clouds: T ~ 10 K, n >~ 10^3 cm^{-3}, size ~ 40 pc, mass ~ 10^5 $M_\odot$.

- More than 200 molecular species detected in the ISM!

Dark Clouds

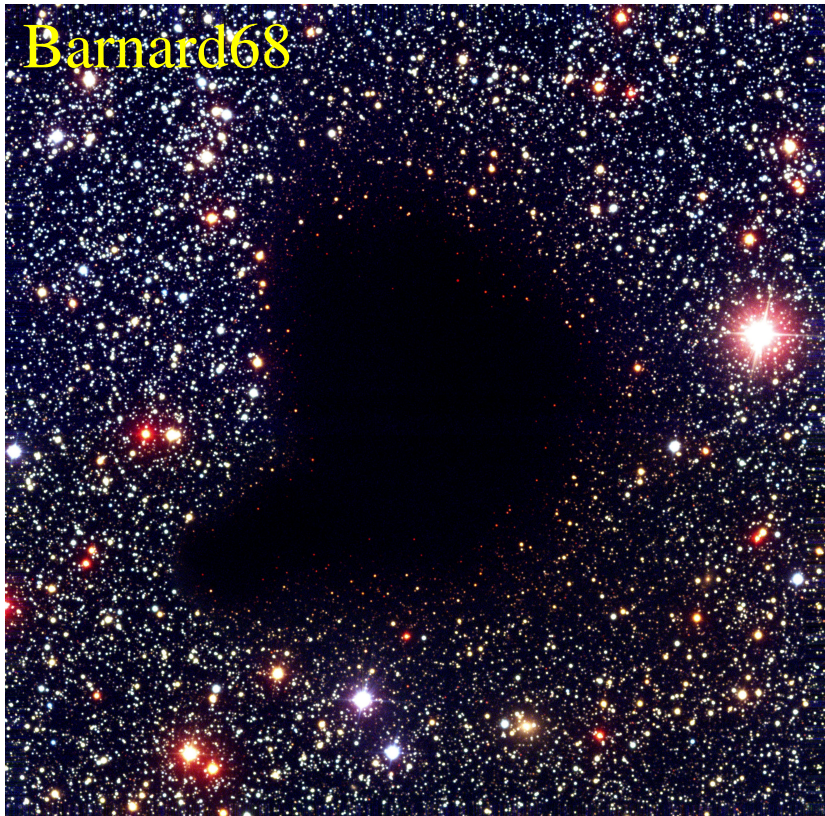
- Shadows absorbing background light.
  No associated stars.

- Range in properties and extinction:
  Some dark at mid-IR wavelengths!
  Others reflect visible light.

- Very bright at far-IR wavelengths.

- Sizes ~ 0.01 – 30 pc.

VLT/FORS team Russell Croman



PHOTODISSOCIATION REGIONS (PDRs)

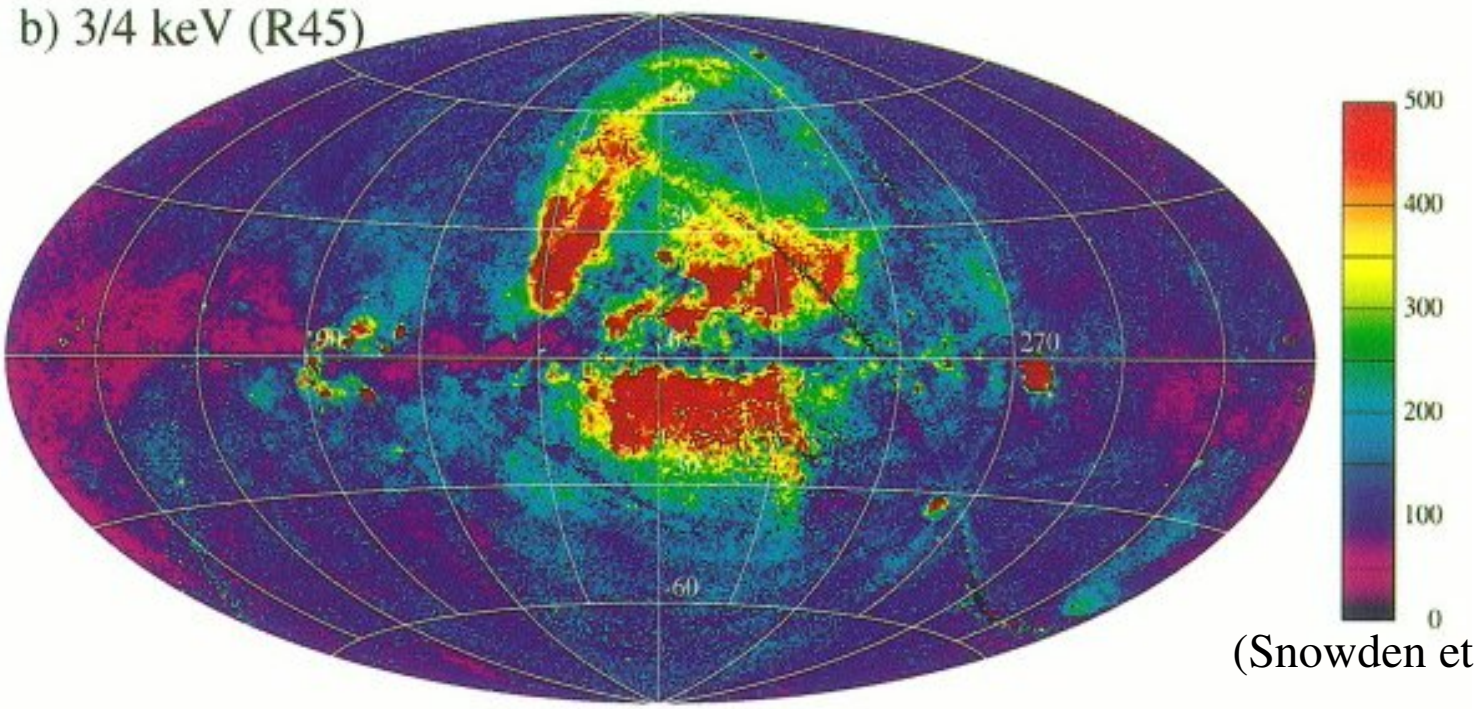
- Transition zones between ionized and molecular gas around O/B stars. Dominated by far-UV photons.
- Far-UV photons dissociate or ionize molecular gas
- Photo-electric effect: T ~ 300 K.
- Strong fine-structure cooling lines.
- Strong molecular lines.
- Far-IR emission from associated dust.
- Today, PDRs = Photon-dominated regions.

HOT IONIZED GAS

- Highly ionized gas; e.g. CIV, SVI, NV, OVI. Extended emission fills the Galactic halo. Also present in compact supernova remnants.

- Detectable in thermal X-ray emission and UV absorption against stars/quasars.

ROSAT 0.75 keV all-sky image



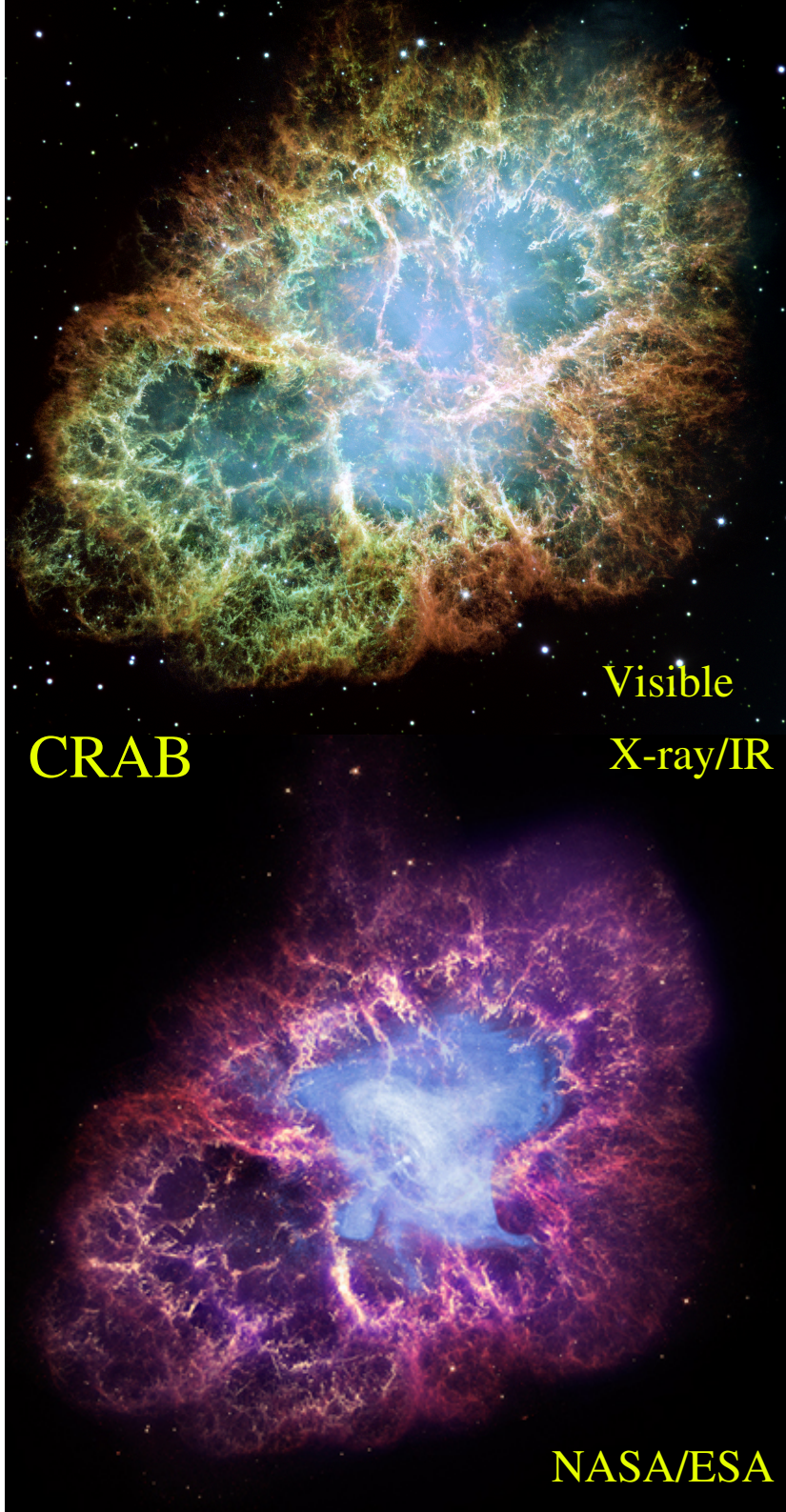
(Snowden et al. 1997, ApJ)

- Heated & ionized by SN shocks; Sun in a local bubble (~ 100 pc).

- Temperature ~ 10^6 K; density ~ 0.003 cm^{-3}.

SUPERNOVA REMNANTS

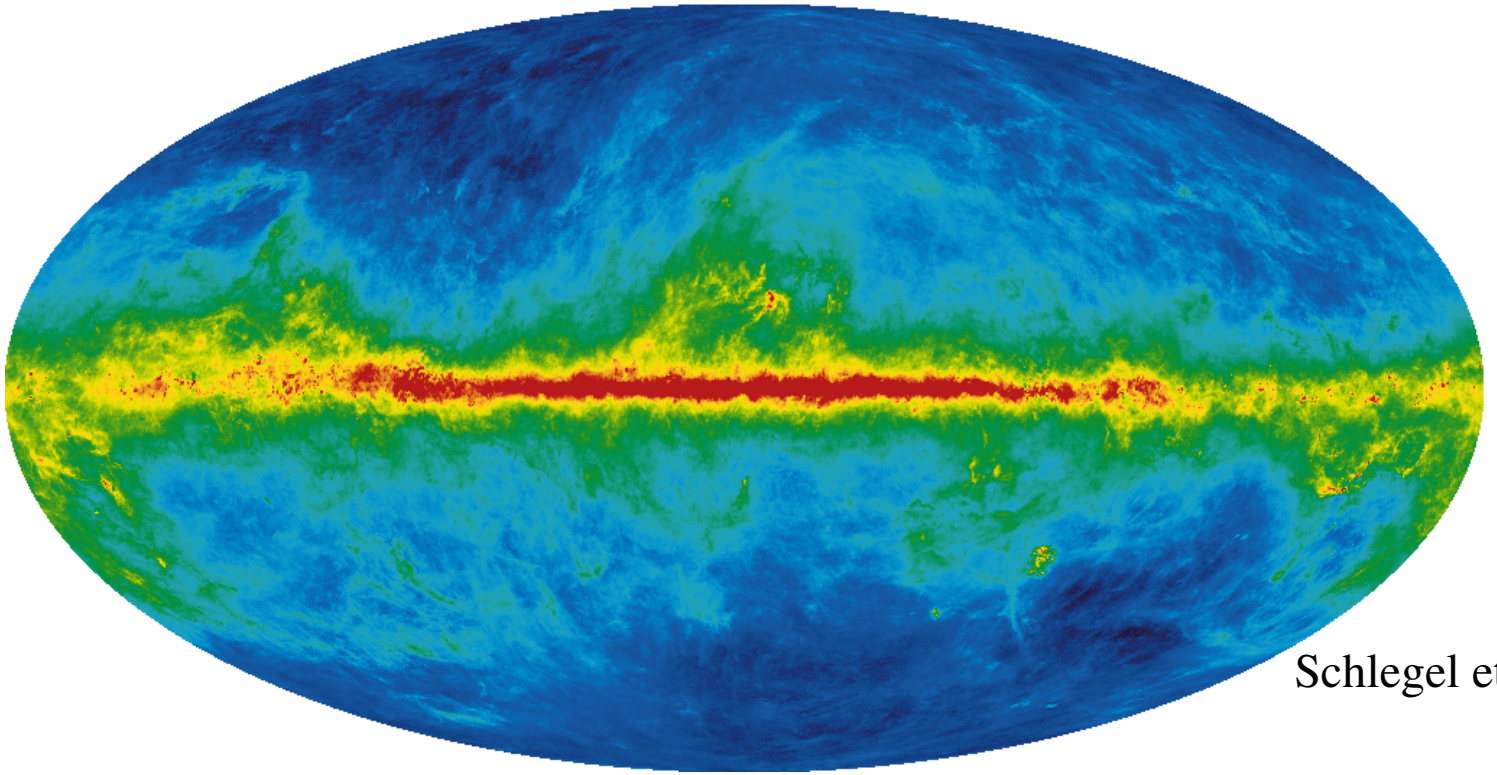
- Origin: Supernova ejecta ram into the surrounding ISM, producing a shock.
- Complex filamentary structures; some compact shells.
- ~ 200 known in the Milky Way.
- High temperatures ~ 10^6 K.
- Strong optical Hα, OIII, SII, …, lines.
- Strong synchrotron radio emission.
- Bright X-ray emission.



INTERSTELLAR DUST

- Extinction/reddening of starlight, strong far-IR emission...
- Main sites for molecule formation via grain chemistry!

IRAS/COBE dust image

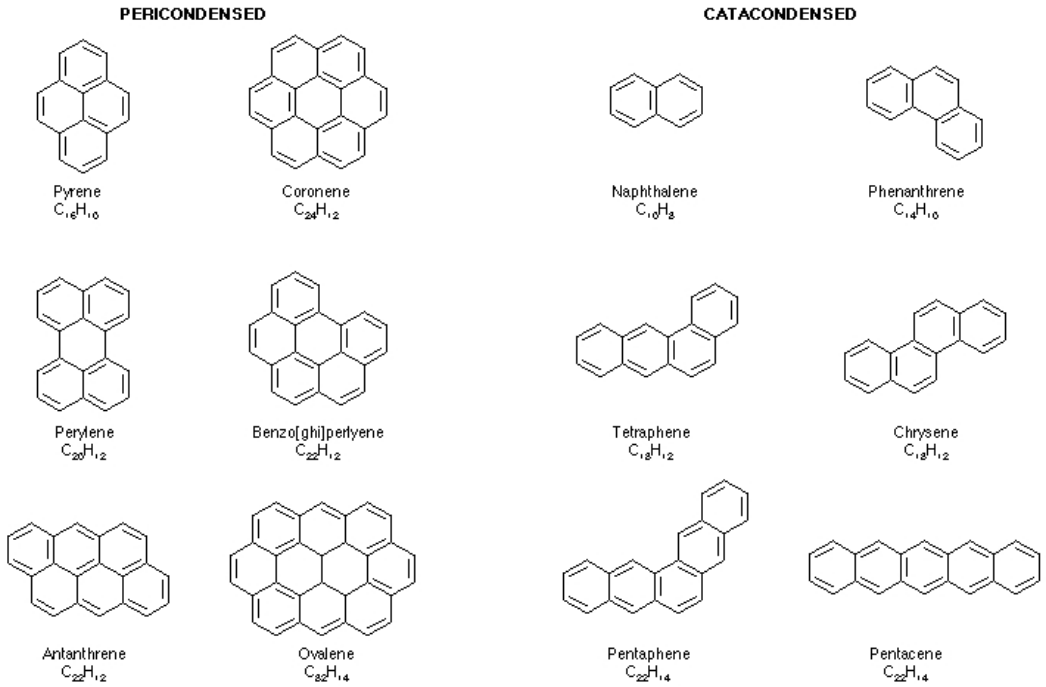


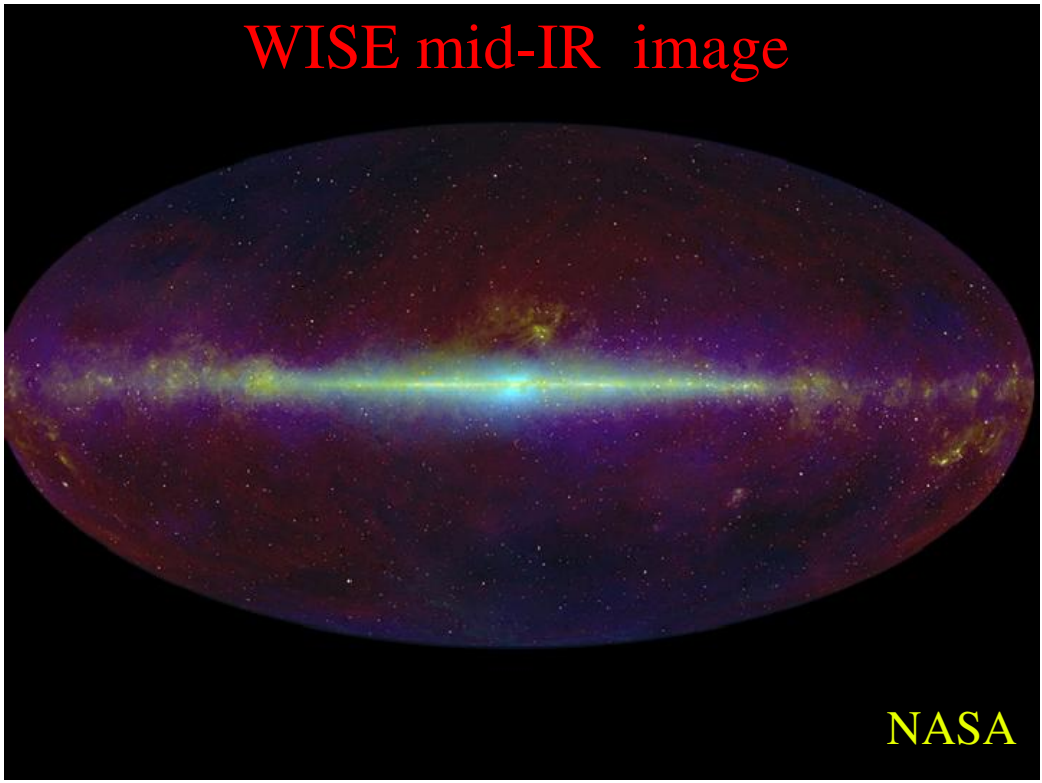
(LAMBDA;
Schlegel et al. 1998, ApJ)

- Reddening wavelength dependence: $n(a) \propto a^{-3.5}$ (5 – 3000 Å).
- Elements like C, Si, Ca, Fe locked in grains: 1% of gas mass.

Polycyclic Aromatic Hydrocarbons (PAHs)

- Large organic molecules (e.g. napthalene, fullerenes).
- Strong mid-IR (~ 5–20 μm) lines; vibrational relaxation modes.

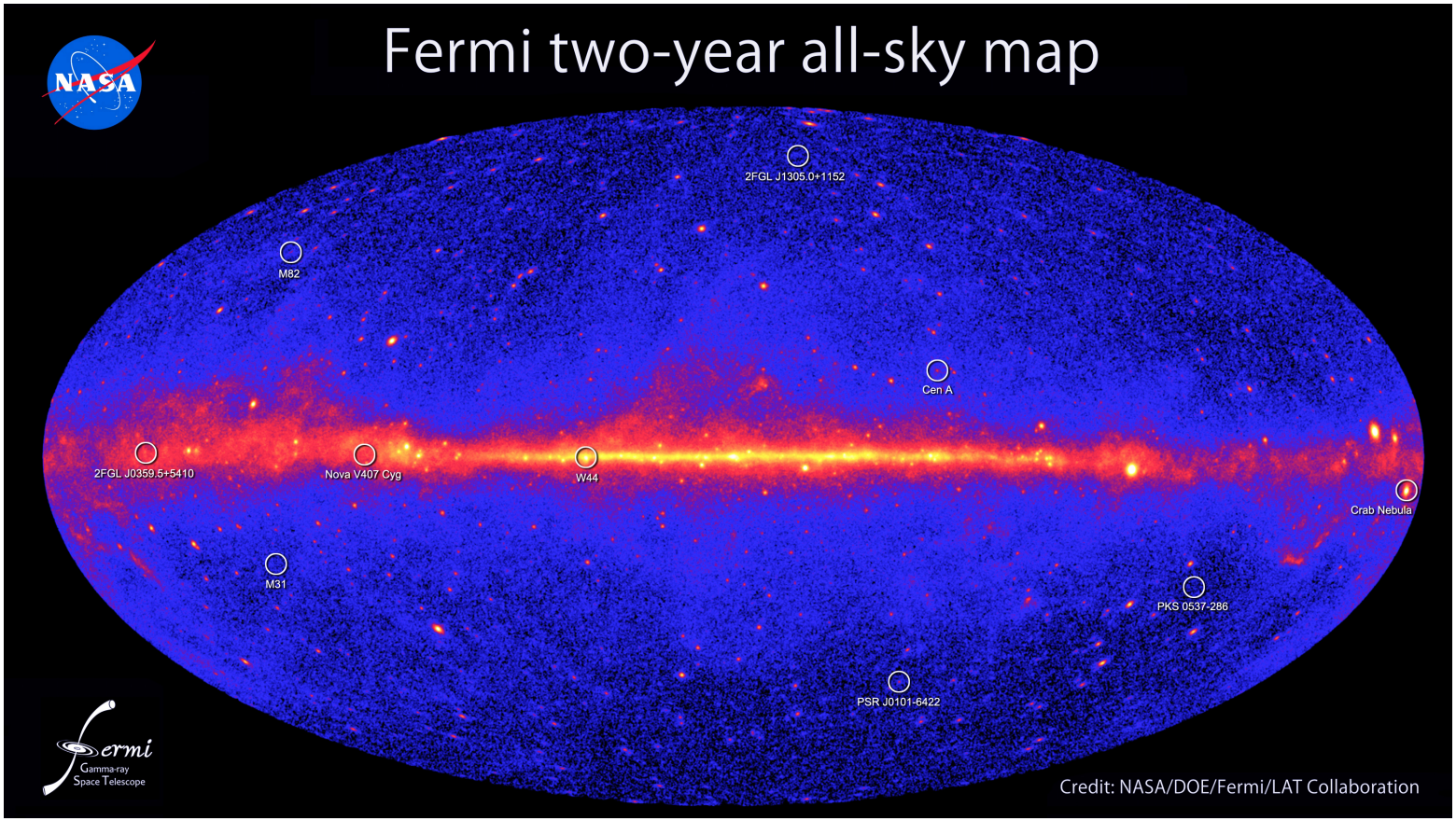




- Contain ~10% of Galactic C; some PAHs have 60 C atoms!
- Most important source of gas heating in the Galaxy!

Cosmic Rays

- Relativistic protons and alpha particles, with energies ~ 1 – 10 GeV.
- Interaction with the ISM produces strong gamma rays.



(NASA/DOE/FERMI-LAT)

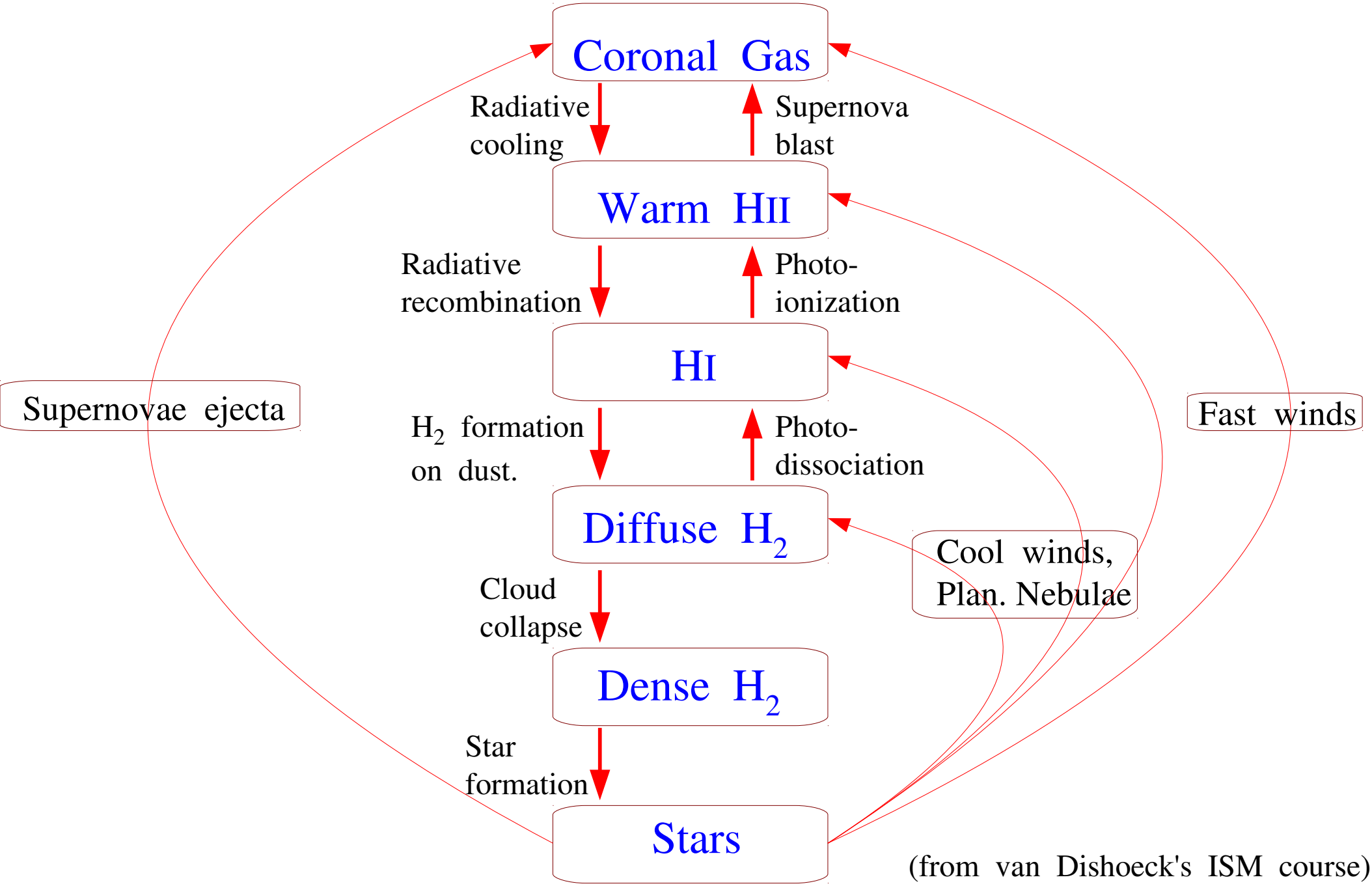
- Important for heating and ionization of the ISM.
- Origin in supernovae recently confirmed!

(Ackermann et al. 2013, Science)

Species	Density cm^{-3}	Temperature K	Pressure P/k $cm^{-3}K$	Mass 10^9 $M_\odot$
HI (CNM)	30	80	~2500	2.8
HI (WNM)	0.3	8000	~2500	2.2
HII (WIM)	0.3	8000	~2500	1.0
H_2	>1000	10	$>10^4$	1.3
HII (HIM)	0.003	10^6	~3000	< 1 ?
DUST	-	-	-	0.1
PAHs	-	-	-	0.01

(e.g. Draine 2011)

THE ISM



(from van Dishoeck's ISM course)