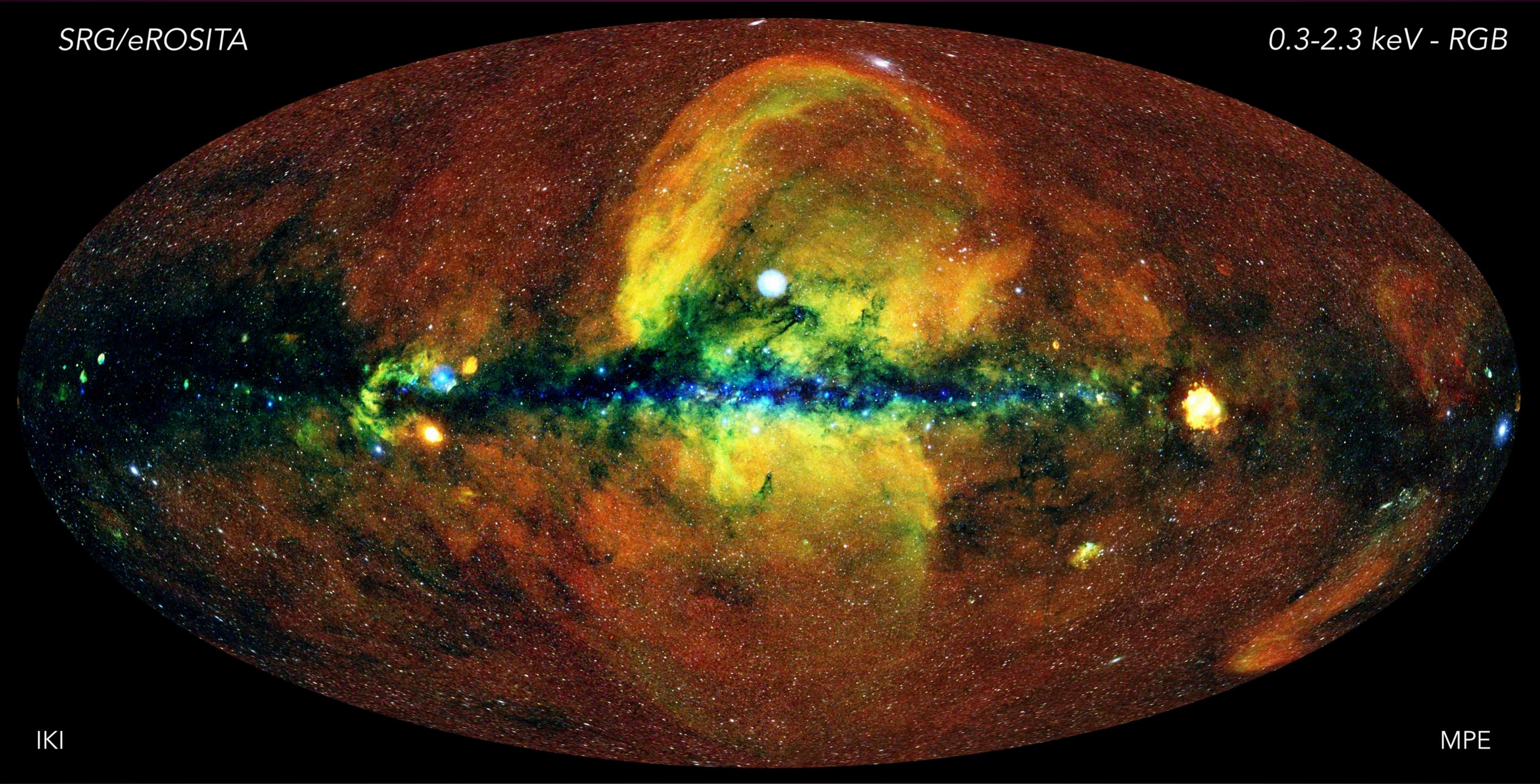
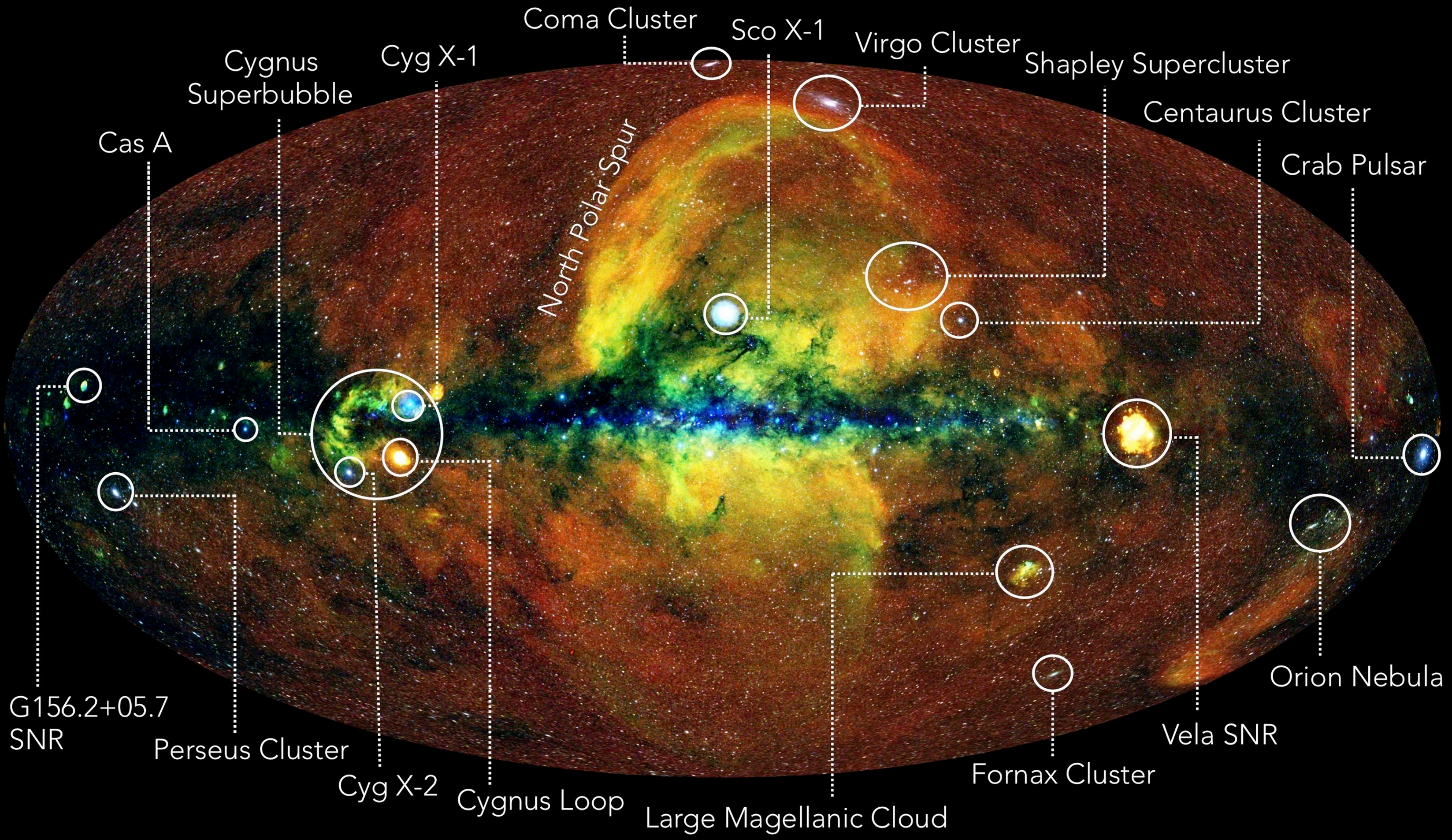
Overview of the diffuse phases and radiative transfer primer

ASTR 605
Joe Burchett
8/22/2021


SRG/eROSITA
0.3-2.3 keV - RGB
IKI
MPE

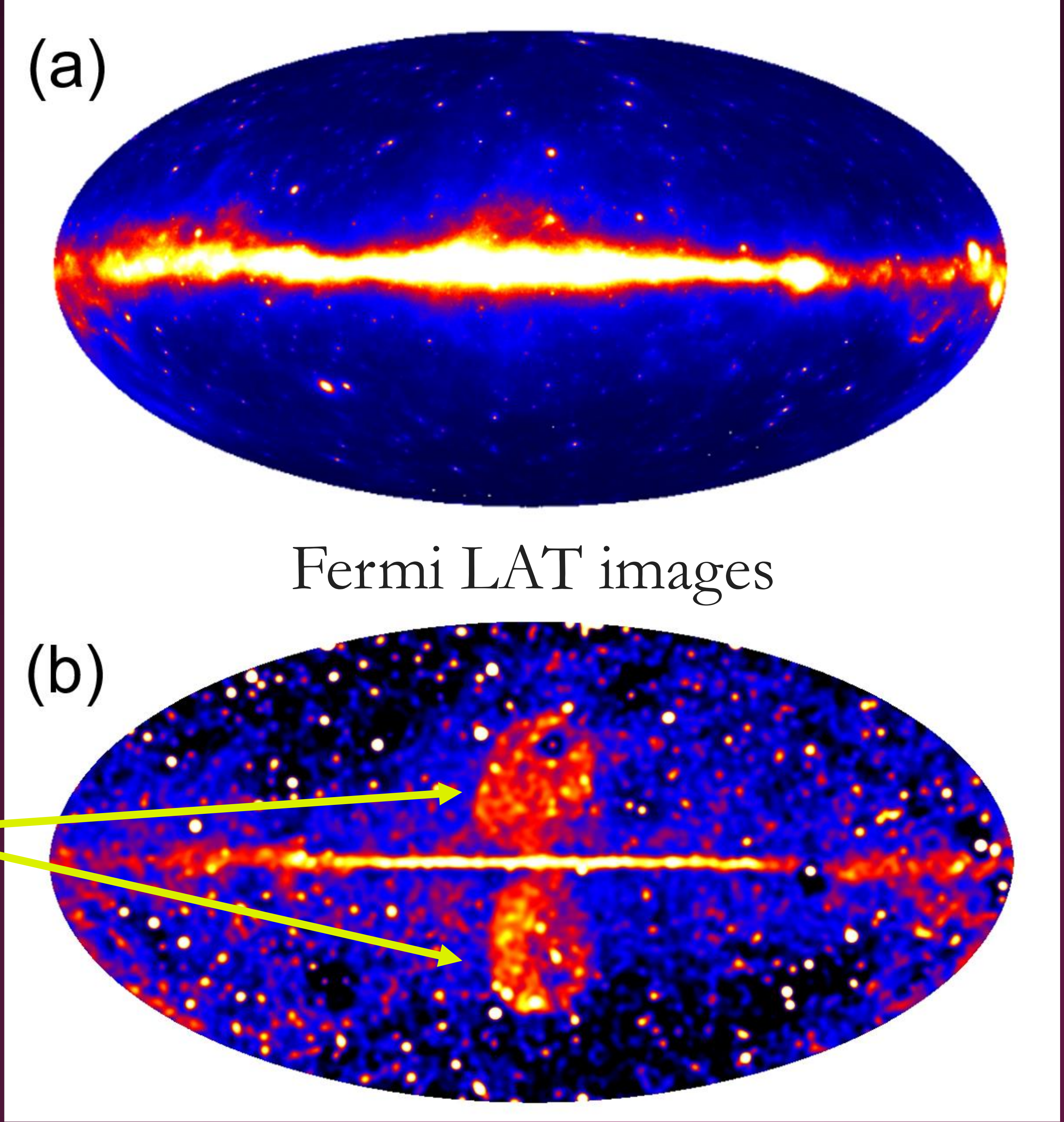
Navigating the eROSITA X-ray sky



IKI

SRG/eROSITA 0.3-2.3 keV - RGB Map

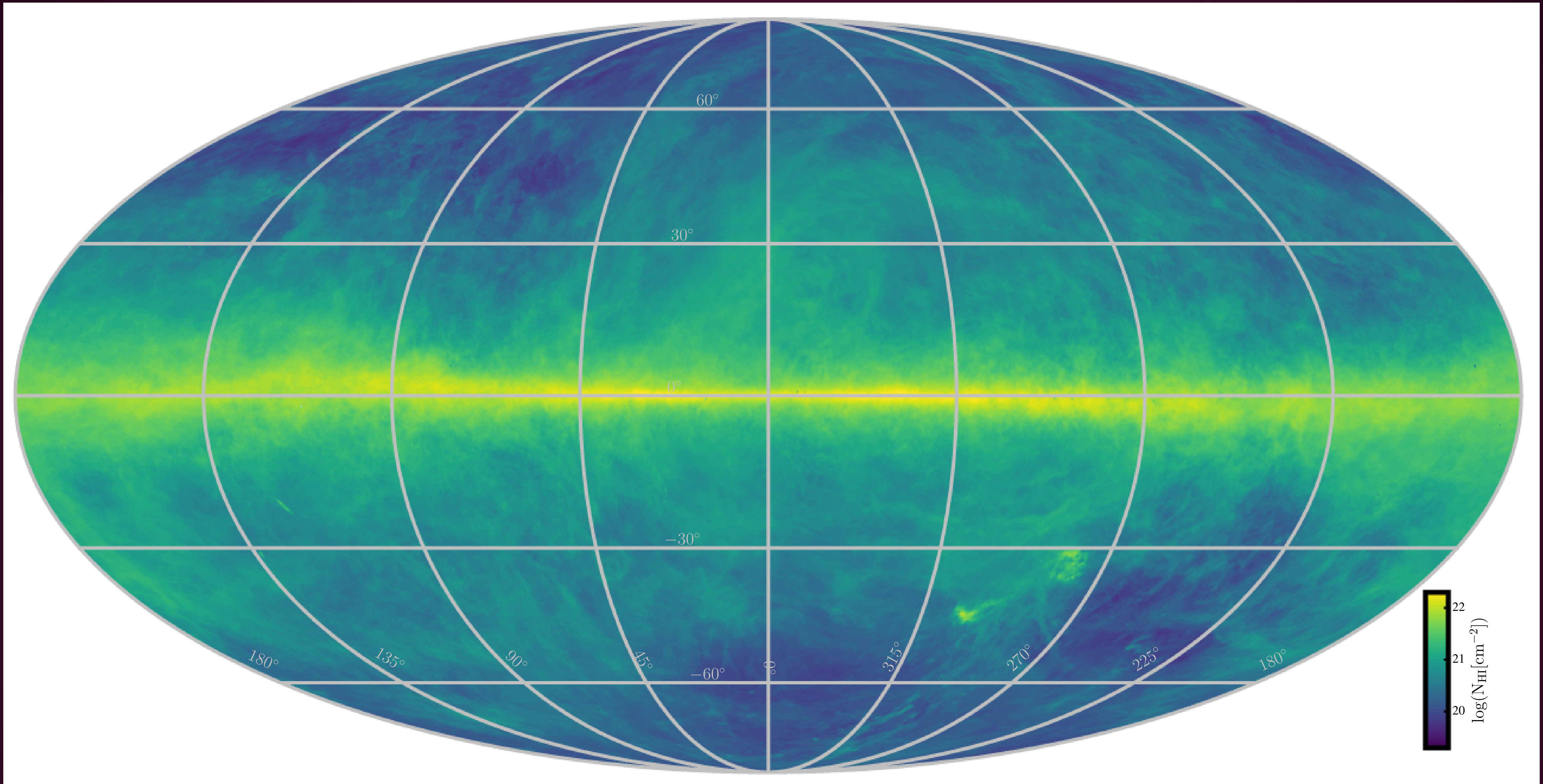
MPE



‘Fermi bubbles’

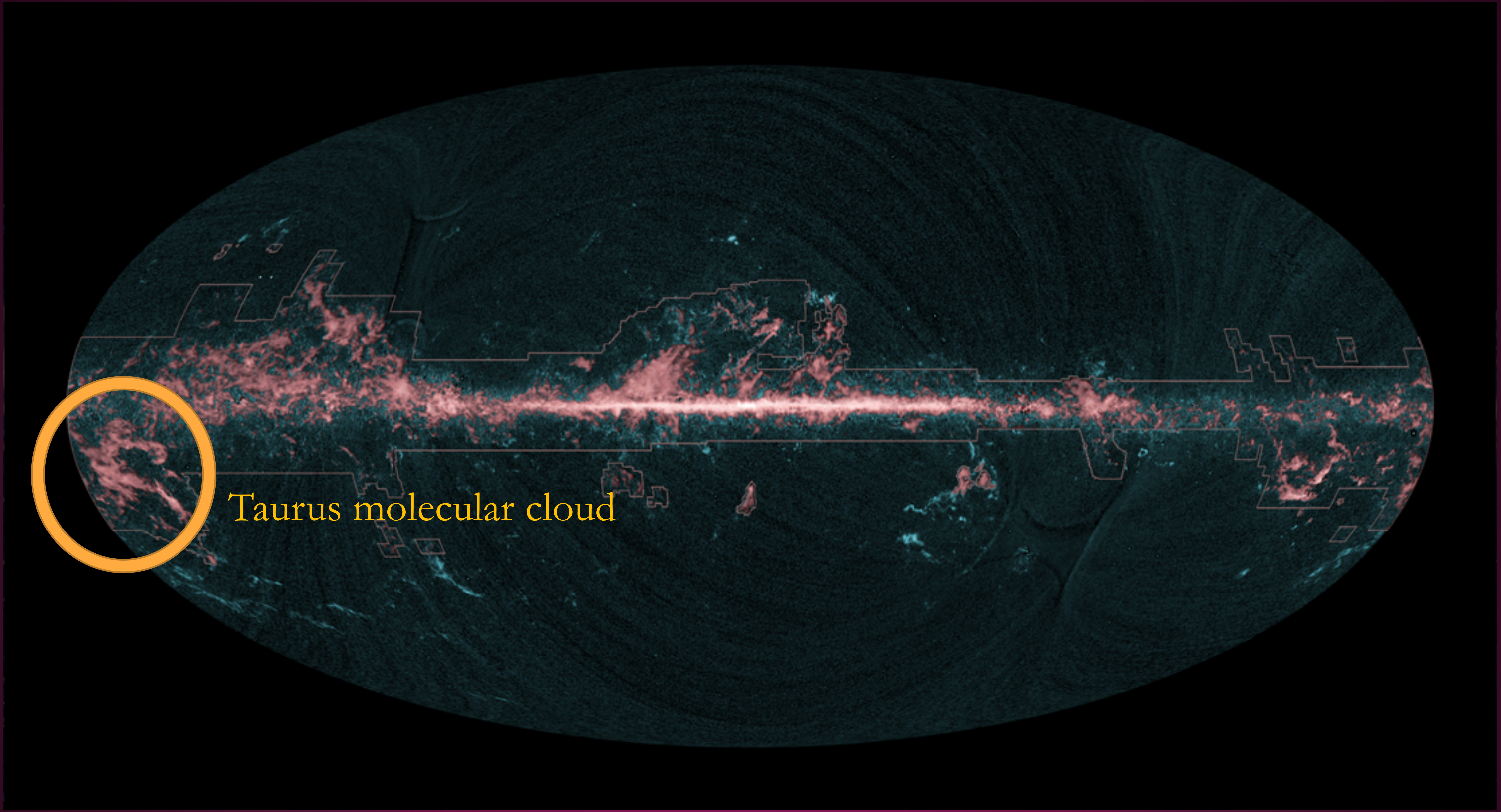
Kataoka et al. 2018

21cm neutral hydrogen column density map



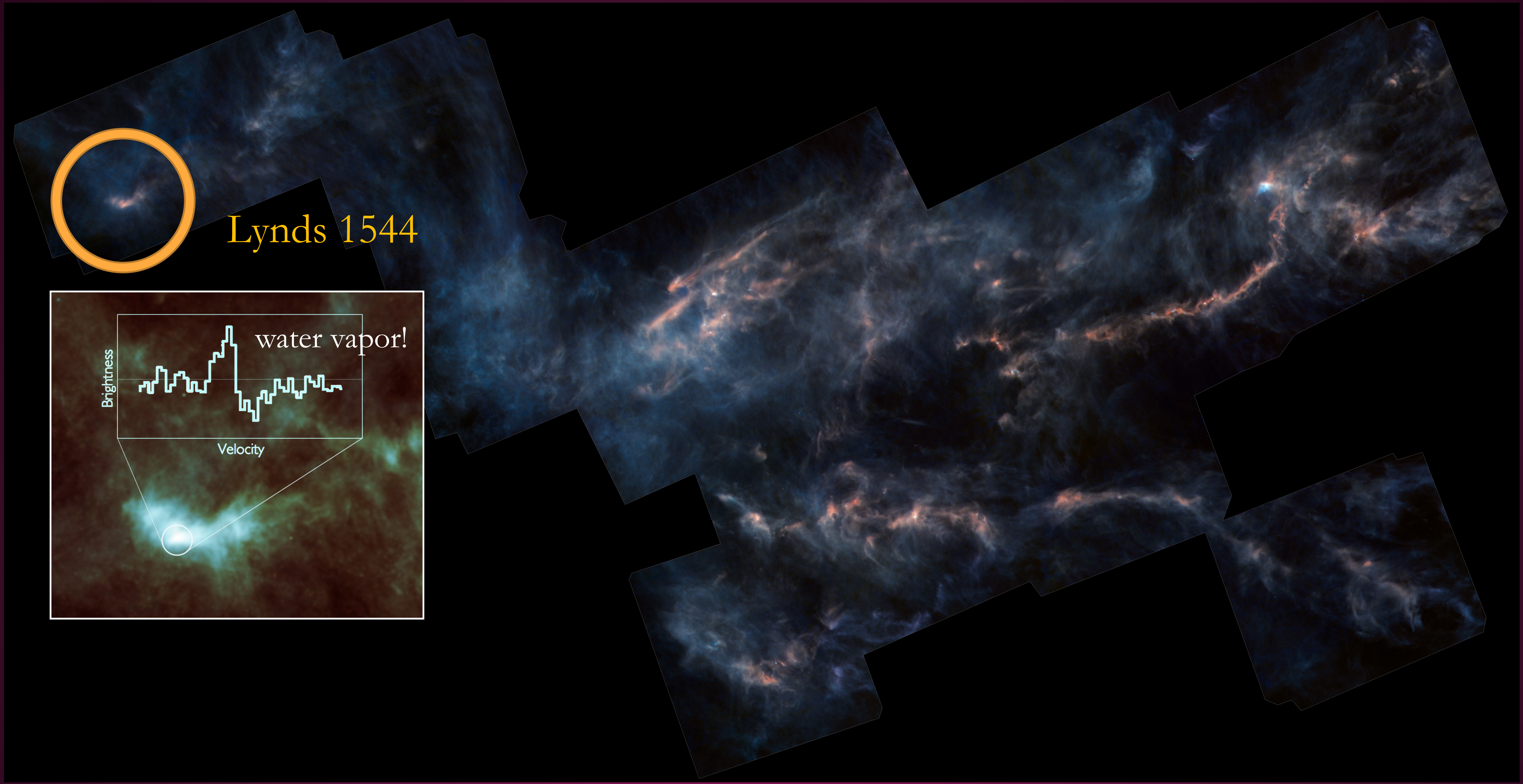
HI4PI collaboration et al. 2016

Molecular gas (H_2 traced by CO)



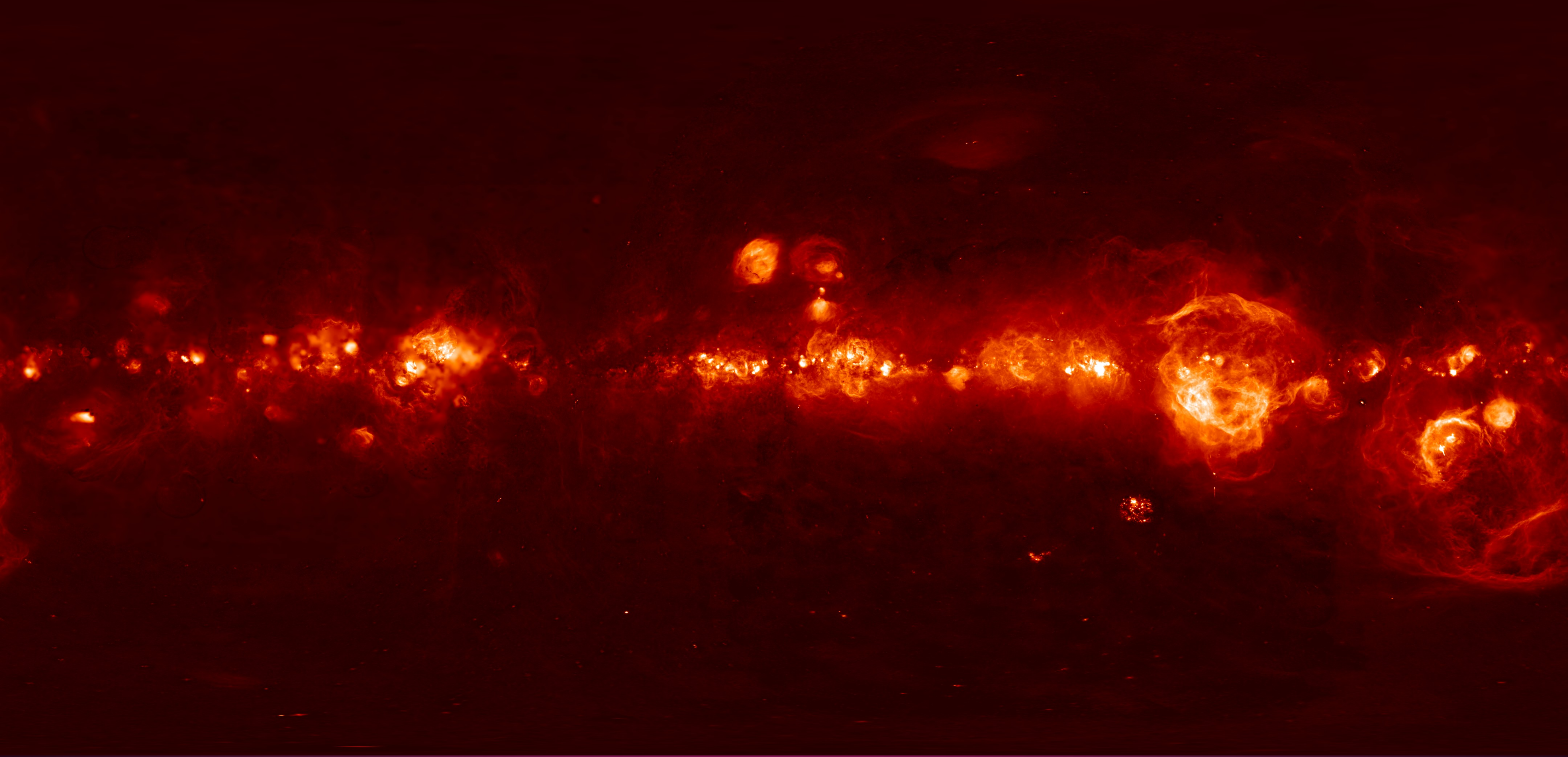
ESA/Planck Collaboration; T. Dame et al., 2001

Taurus Molecular Cloud – Far-IR (Herschel)



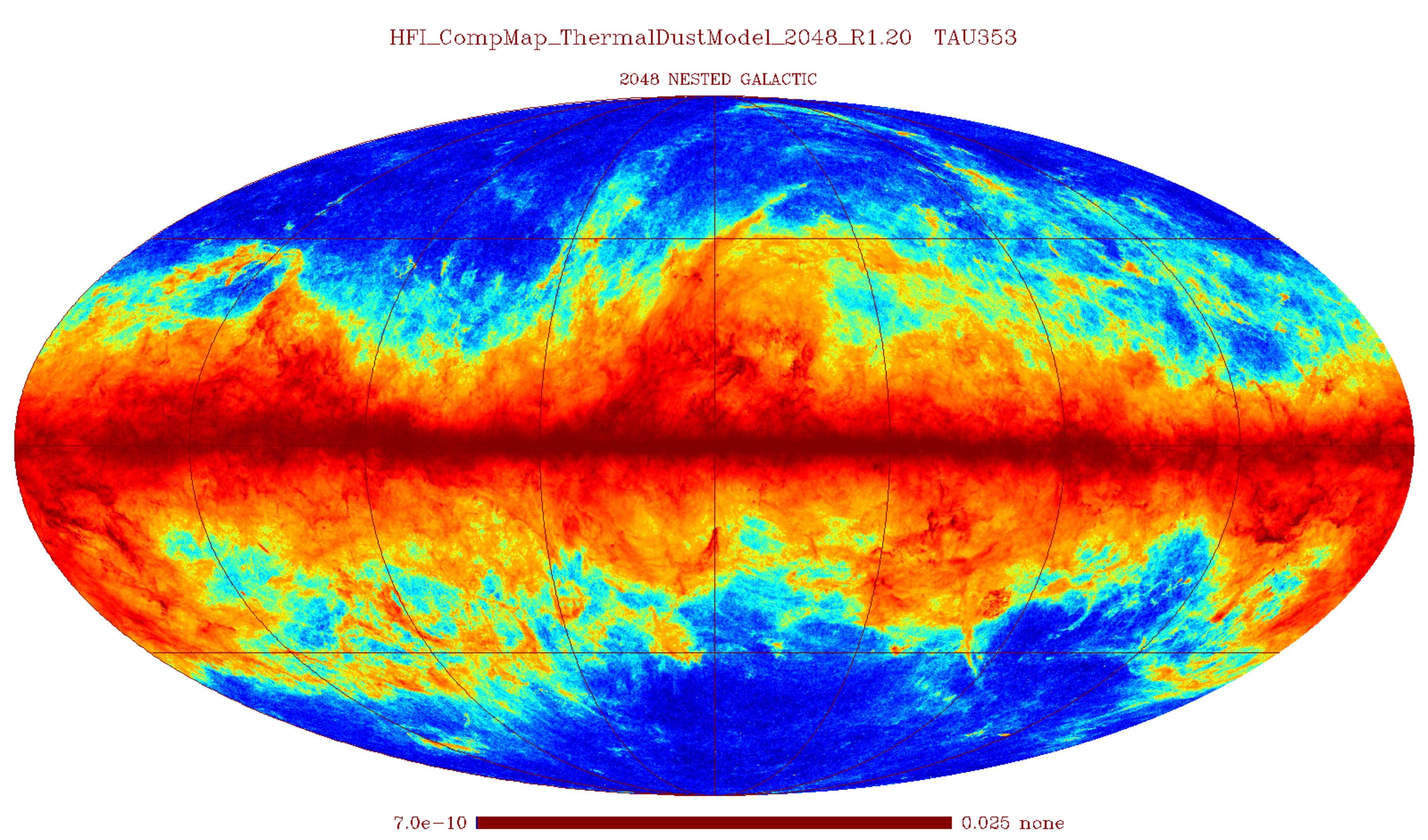
ESA/Herschel/NASA/JPL-Caltech, CC BY-SA 3.0 IGO;
Acknowledgement: R. Hurt (JPL-Caltech)

Ionized gas – Hα



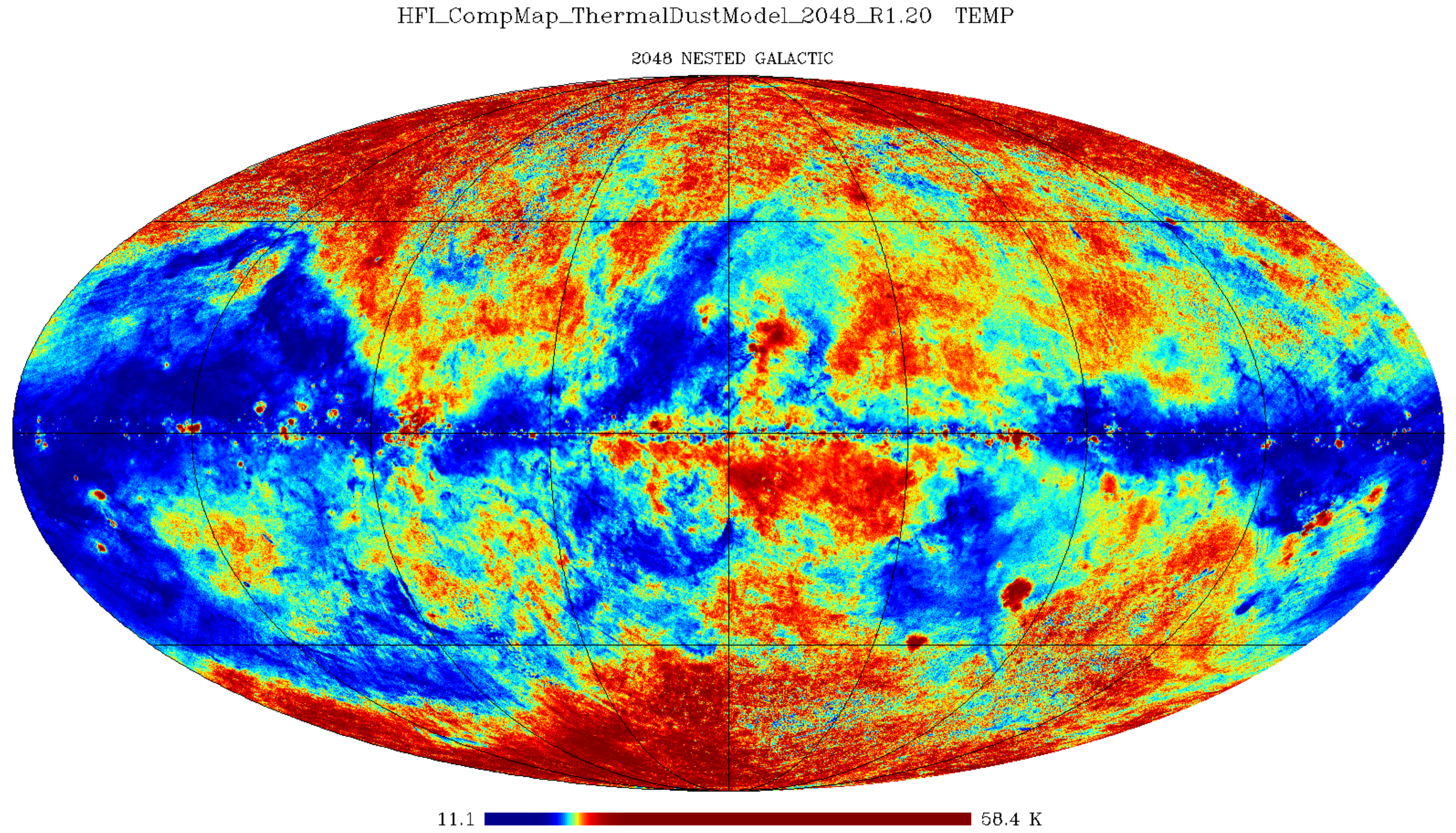
Finkbeiner 2003

Dust emission – Millimeter wave (Planck)



ESA/Planck Collaboration; T. Dame et al., 2001

Dust emission – Millimeter wave (Planck)



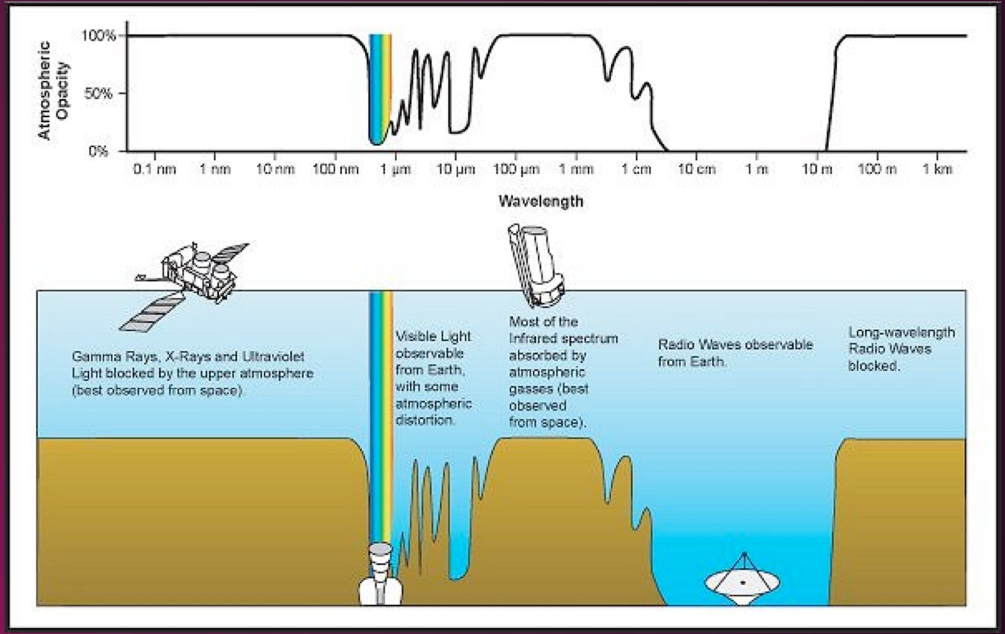
ESA/Planck Collaboration; T. Dame et al., 2001

B68 – dust extinction at optical wavelengths

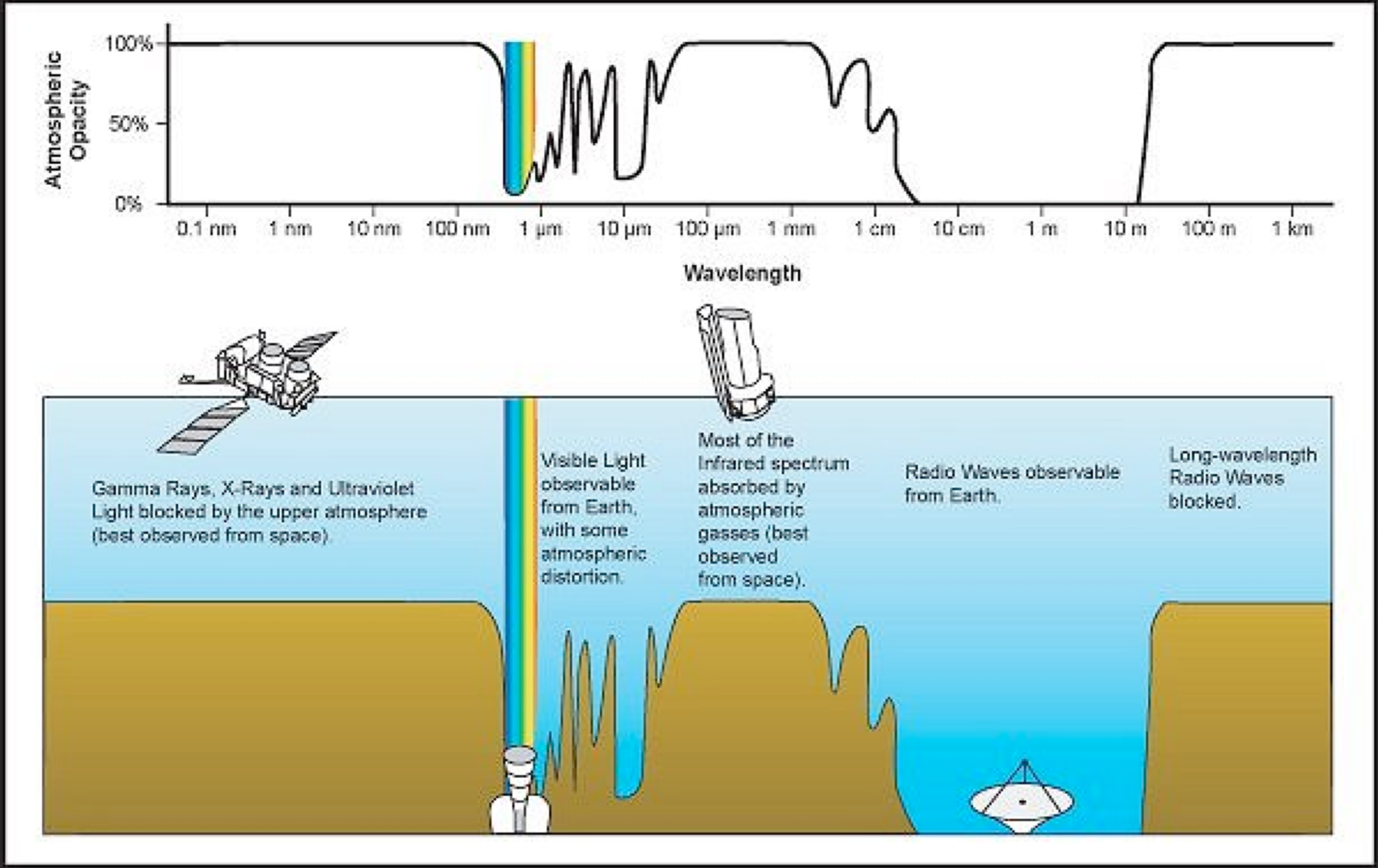
ESO

Primary observational regimes

- Gamma rays - $\lambda < 10^{-11}$ m = 0.1 Å
- X-rays - 0.1 Å ≤ λ ≤ 100 Å
- UV - 100 Å ≤ λ ≤3200 Å
- Visible (optical) - 3200 Å ≤ λ ≤ 10,000 Å = 1 μm
- Near-IR - 1 μm ≤ λ ≤ 3 μm (J, H, K bands)
- Mid-IR - 3 μm ≤ λ ≤ 40 μm
- Far-IR - 40 μm ≤ λ ≤ 300 μm
- Sub-mm - 300 μm ≤ λ ≤ 1 mm
- mm - 1 mm ≤ λ ≤ 5 mm
- Radio - > 5 mm



Atmospheric Transmission



Components of the ISM

- Dust
  - Distribution of grain sizes and varying composition
  - Attenuates light in optical/UV
  - Emits light at far-IR and mm wavelengths
  - Often associated with cold, dense media but can survive in hotter environments
  - Few x 10^8 $M_\odot$ in MW disk
- Gas
  - 99% hydrogen and helium; the rest ($Z > 2$) 'metals'
  - Emits and absorbs light across electromagnetic spectrum
  - 7 x 10^9 $M_\odot$ in disk of Galaxy (compare to 5 x 10^{10} $M_\odot$ in stars)
  - Wide range in temperatures: few K to $>10^7$ K

Components of the ISM

- Radiation
  - Very long wavelengths (e.g., Cosmic Microwave Background) to very high energies (e.g., emission from active galactic nuclei)
  - Important role in heating and cooling of medium
  - Photoionization ubiquitous
- Cosmic rays
  - Relativistic particles from shocks and AGN
  - Can heat and ionize gas as well as dissociate molecules
  - Possibly very important driver of galactic winds
  - Comparable or greater in energy density than thermal energy and radiation

Components of the ISM

- Magnetic fields
  - Because ISM is ionized, flows of plasma produce magnetic fields
  - Important for cloud stability to collapse and cosmic ray transport
  - Observed by polarization of dust grains and, e.g., Zeeman effect in spectral lines
  - Typical strength of a microgauss

Phases of ISM

Particle number density

- Molecular clouds
  - Typical T = 10-100 K and n = 10^2-10^6 cm^{-3}
- Cold neutral medium
  - T = 100 K; n = 10-1000 cm^{-3}
- Warm neutral medium
  - T = 5000 K; n = 0.6 cm^{-3}
- Warm ionized medium
  - T = 10^4 K; n = 0.3 cm^{-3}
- H II regions
  - T = 10^4 K; n = 0.1-10^4 cm^{-3}
- Hot, ionized medium
  - T > 3 x 10^5 K; n = 10^{-2}-10^{-3} cm^{-3}

Notice: rough pressure equilibrium:
nT = 3000 K cm^{-3}

Exercise: Mass of the circumgalactic medium

Thus far, we've focused on components of the ISM roughly located in the Galaxy disk. Let us now turn our attention to the gas in the halo. We need two ingredients: a density profile shape and CGM gas density measurements. First, assume the gas follows the dark matter and adopt a Navarro-Frenk-White profile. Adopt a fiducial density of 10^{-3} cm^{-3} for ρ_0 and 8.1 for R_s (Lin & Li 2019):

$$\rho(r) = \frac{\rho_0}{\frac{r}{R_S}\left(1+\frac{r}{R_S}\right)^2}$$

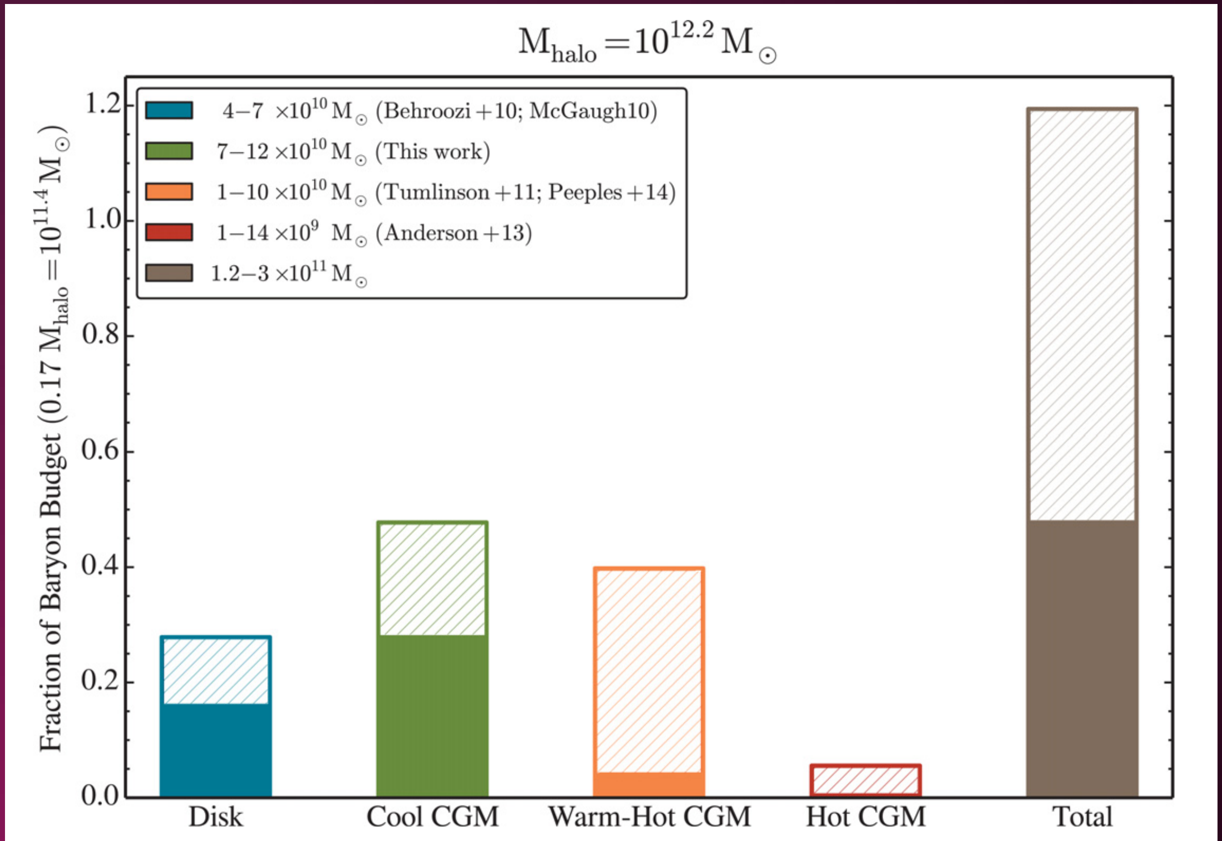
Now, assume the profile inferred by Werk et al. 2014:

$$\rho(r) = 10^{-4.2} cm^{-3} \left(\frac{r}{Rvir}\right)^{-0.8}$$

Under these two density profiles, what is the CGM mass in the measured phase? Assume the extent of the CGM is the virial radius, approximately 250 kpc for the MW.

The CGM is a major component of a galaxy's baryonic mass!

- $10^9 – 10^{11}$ $M_\odot$ in 'cool' phase (10^4 K) alone
- However, the CGM is multiphase!
- 'Warm-hot' ($10^{5\text{-}6}$ K) and 'hot' (>10^6 K) phases also significant
  - Both in mass contribution and function
- Densities $n = 10^{-5}$ - 10^{-2} cm^{-3}
  - Very diffuse gas
  - Primarily observed in absorption



Major heating and cooling processes

Heating

- Shocks
  - supernovae, supermassive black hole feedback, accretion shocks
- Photoelectrons
  - H/He atoms or dust grains are photoionized – excess energy goes to kinetic energy of free electrons
- Cosmic rays

Cooling

- Adiabatic expansion
  - Gas loses internal (thermal energy) by 'doing' p-V work
- Line emission
  - X-ray - UV - optical - IR – radio
- Continuum emission
  - Thermal continuum, synchrotron, free-free (*bremstrahllung*)

Tying it all together (sort of)

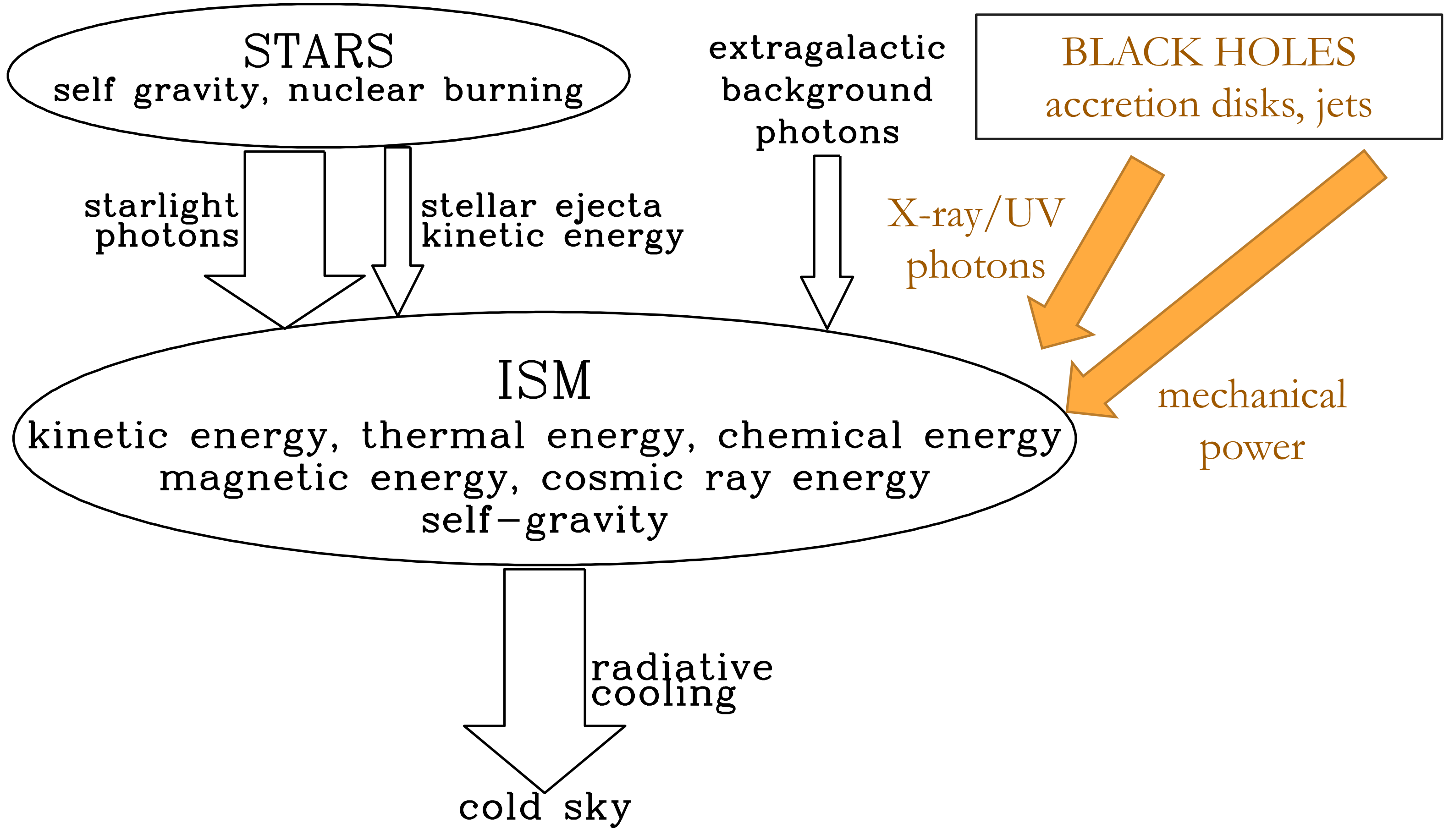
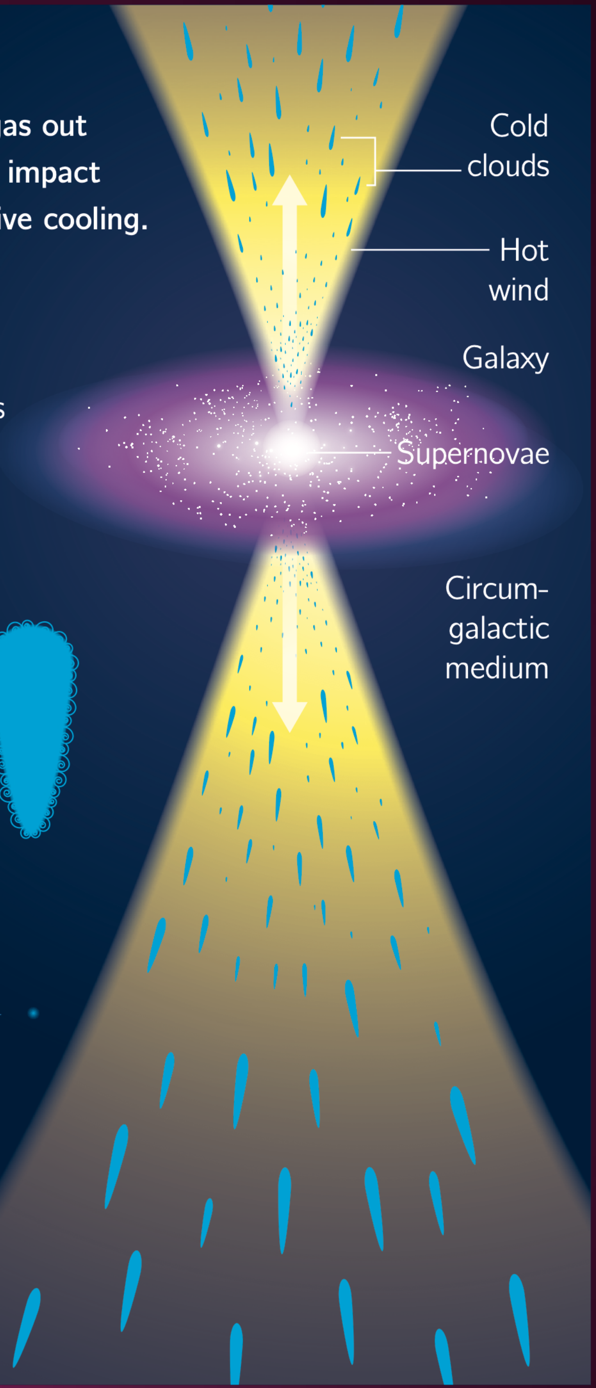


Figure 1.3 Flow of energy in the Milky Way.

A more nuanced view of matter and energy transfer

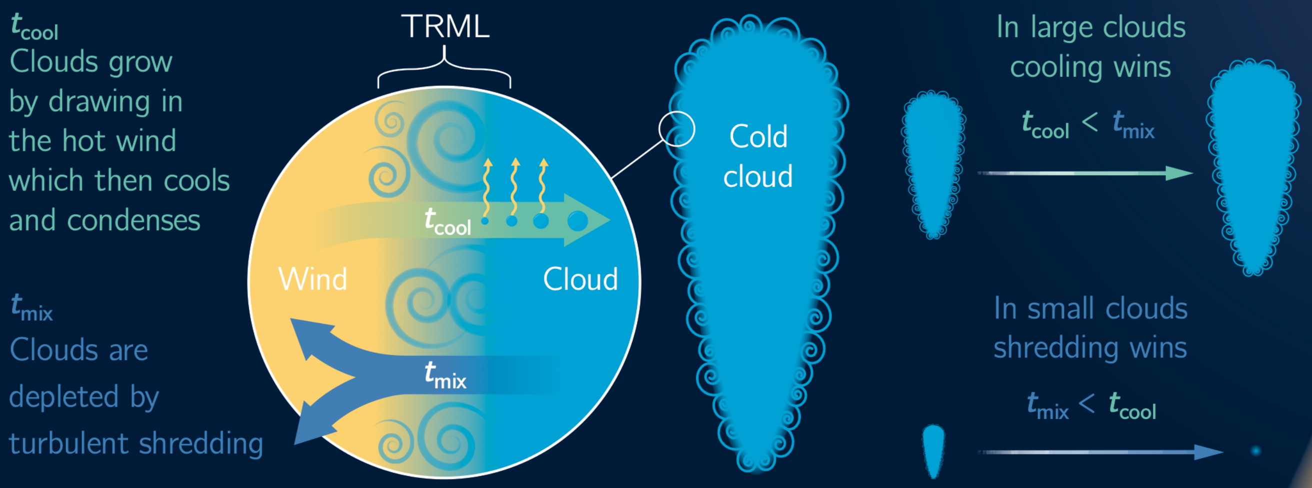
Multiphase Galactic Winds

Supernovae drive hot (>10^6 K) winds that are peppered with pockets of cold (~10^4 K) gas out into the surrounding circumgalactic medium. The fate of these cold clouds — and their impact on the hot wind — depends on the competition between turbulent shredding and radiative cooling.



The Impact of the Hot Wind on the Cold Clouds

The relative motion of the hot wind and a cold cloud gives rise to a *turbulent radiative mixing layer* (TRML) at their interface. The cloud's fate is set by the relative timescales for cooling (t_{cool}; primarily set by the pressure and metallicity) and mixing ($t_{mix}=r_{cl}/v_{turb}$; where r_{cl} is the cloud's size and v_{turb} is the turbulent velocity).



The Impact of the Cold Clouds on the Hot Wind

The clouds back react causing the wind to:

- **Decelerate** as momentum transfers to the clouds
- **Heat up** from thermalization of relative kinetic energy
- **Cool down** as it mixes with the cold material
- **Gain/lose mass** from/to the clouds

[simulation movies]