Galactic foreground science : multi-wavelength approach to constrain the ISM

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Outline

- Foregrounds : what is on the line of sight ?
- Structure formation - the subgrid physics of EoR

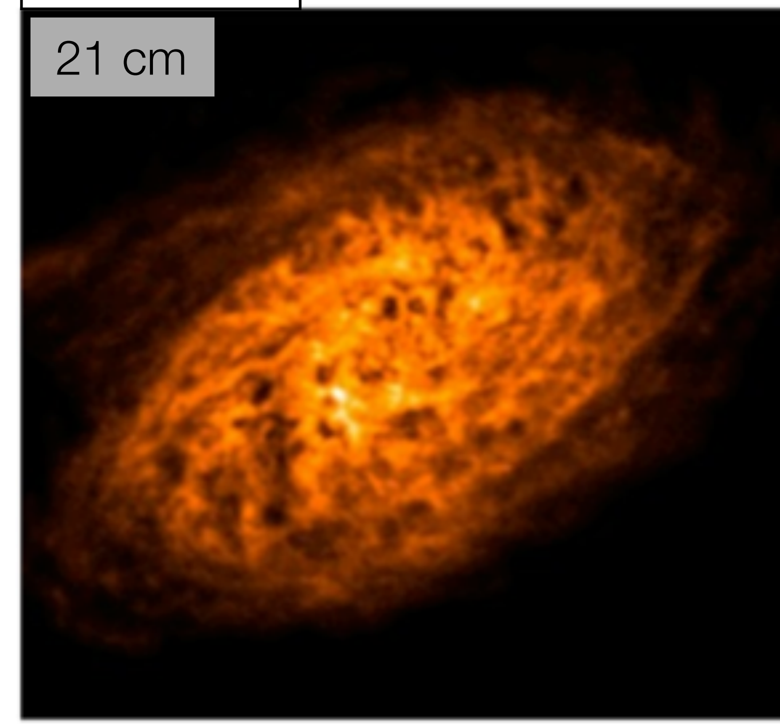
Context

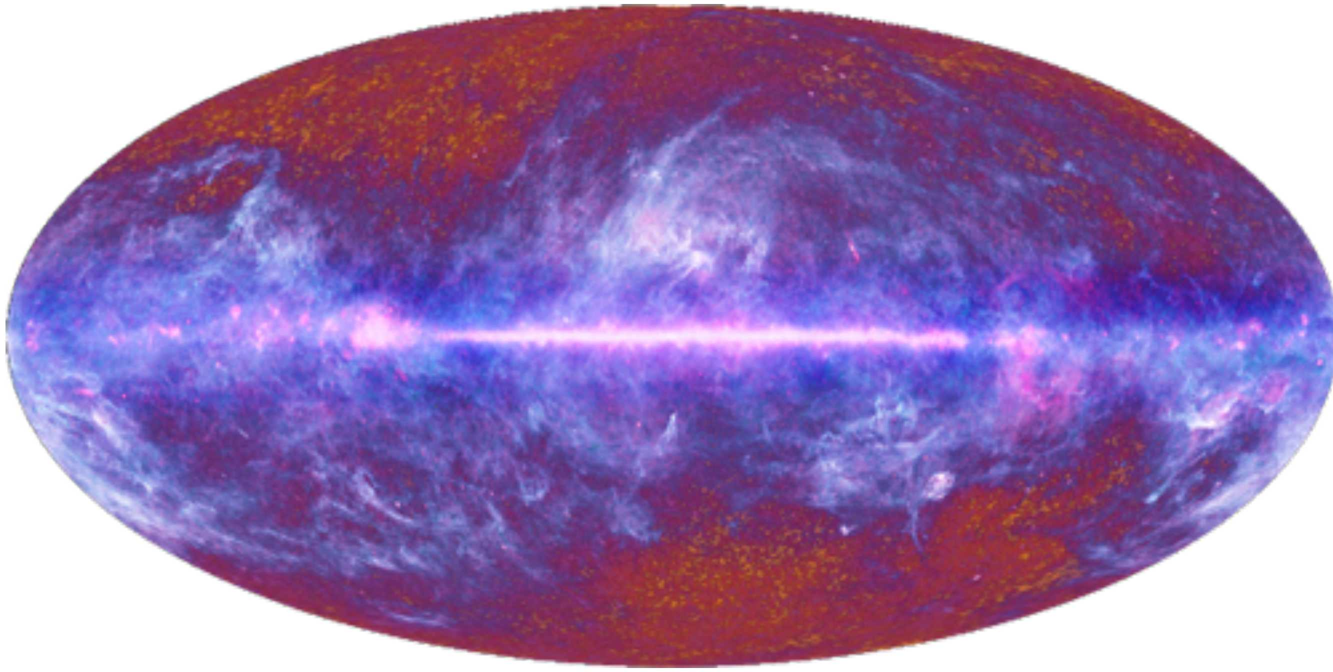
- **<u>The main question : how structures form in the Universe ?</u>**
  - Star and galaxy formation is 10 times less efficient than what is estimated from first principles.

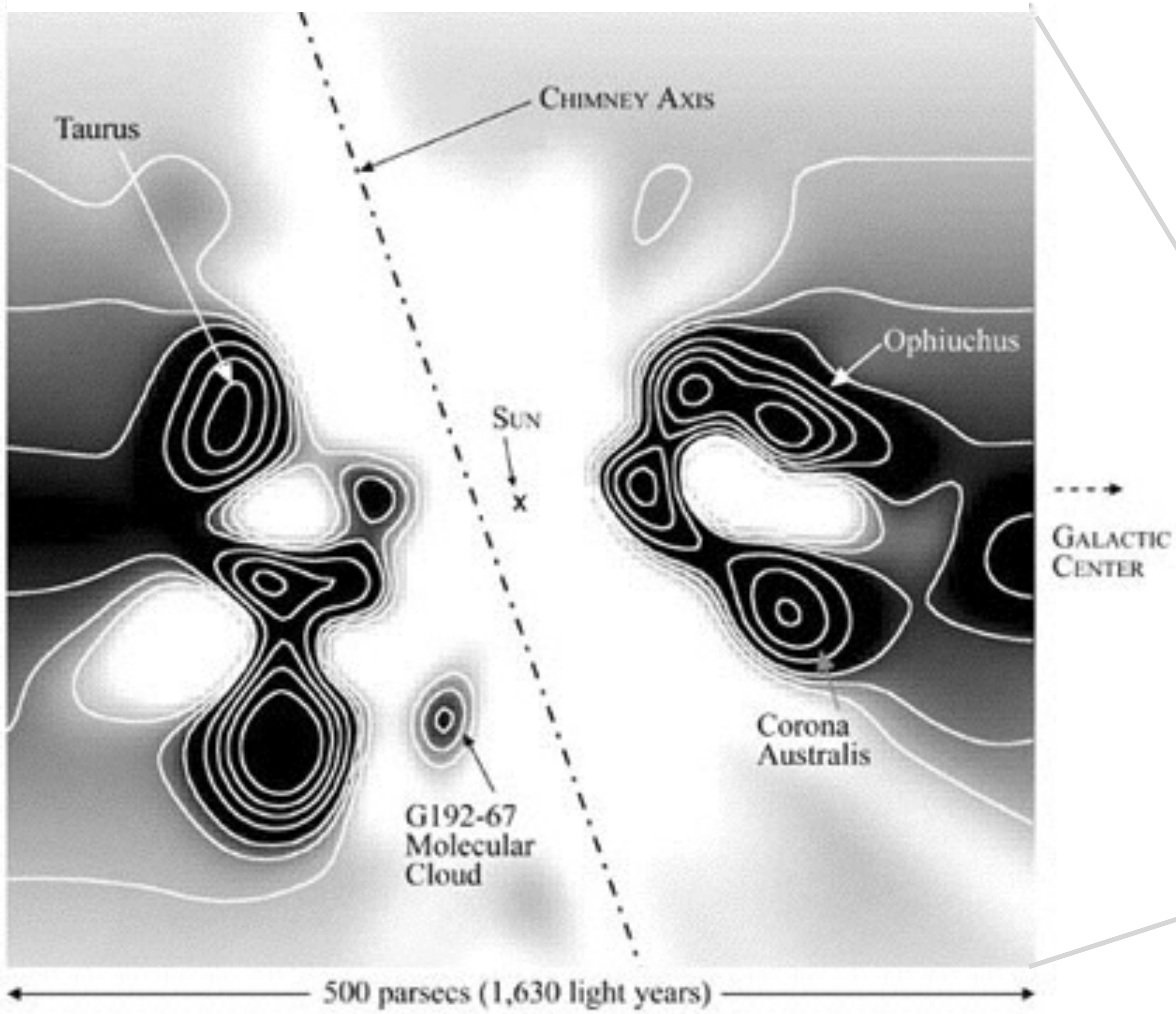
- **<u>Main scientific context</u>**
  - Physical processes involved in the formation of cold structures, stars and planets
  - Complex multi-scale physics :
    - Phase transitions : heating and cooling
    - MHD dynamics, including B amplification and dissipation
    - Gravity
    - Chemistry and dust
    - Feedback from stellar activity
    - Radiation-matter and CR-matter interactions

- **<u>One of the keys : characterize the energy cascade</u>**
  - involves observing scales from kpc (injection) to 10 x mpc (dissipation).
  - The Milky Way is our laboratory

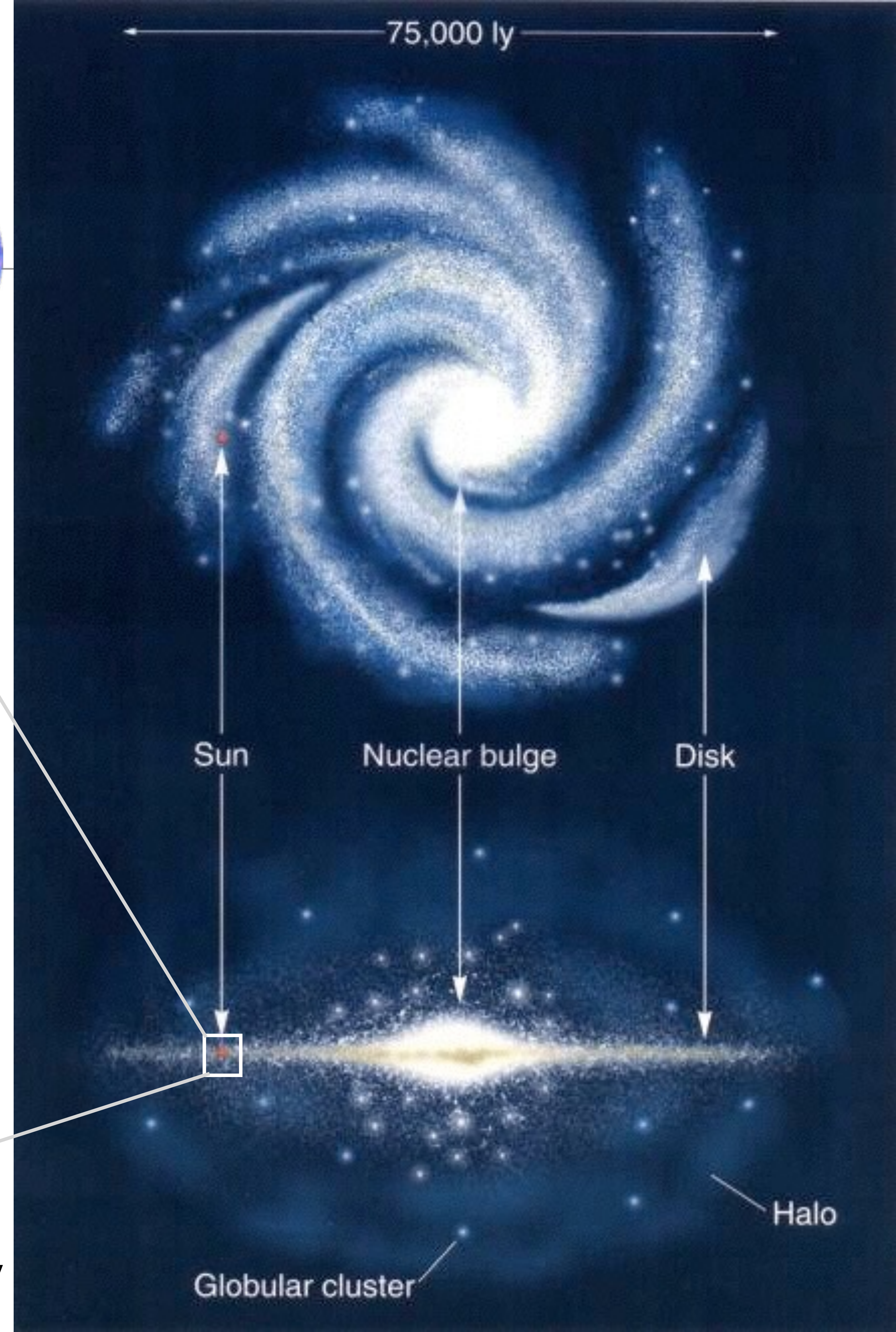
NGC 2403





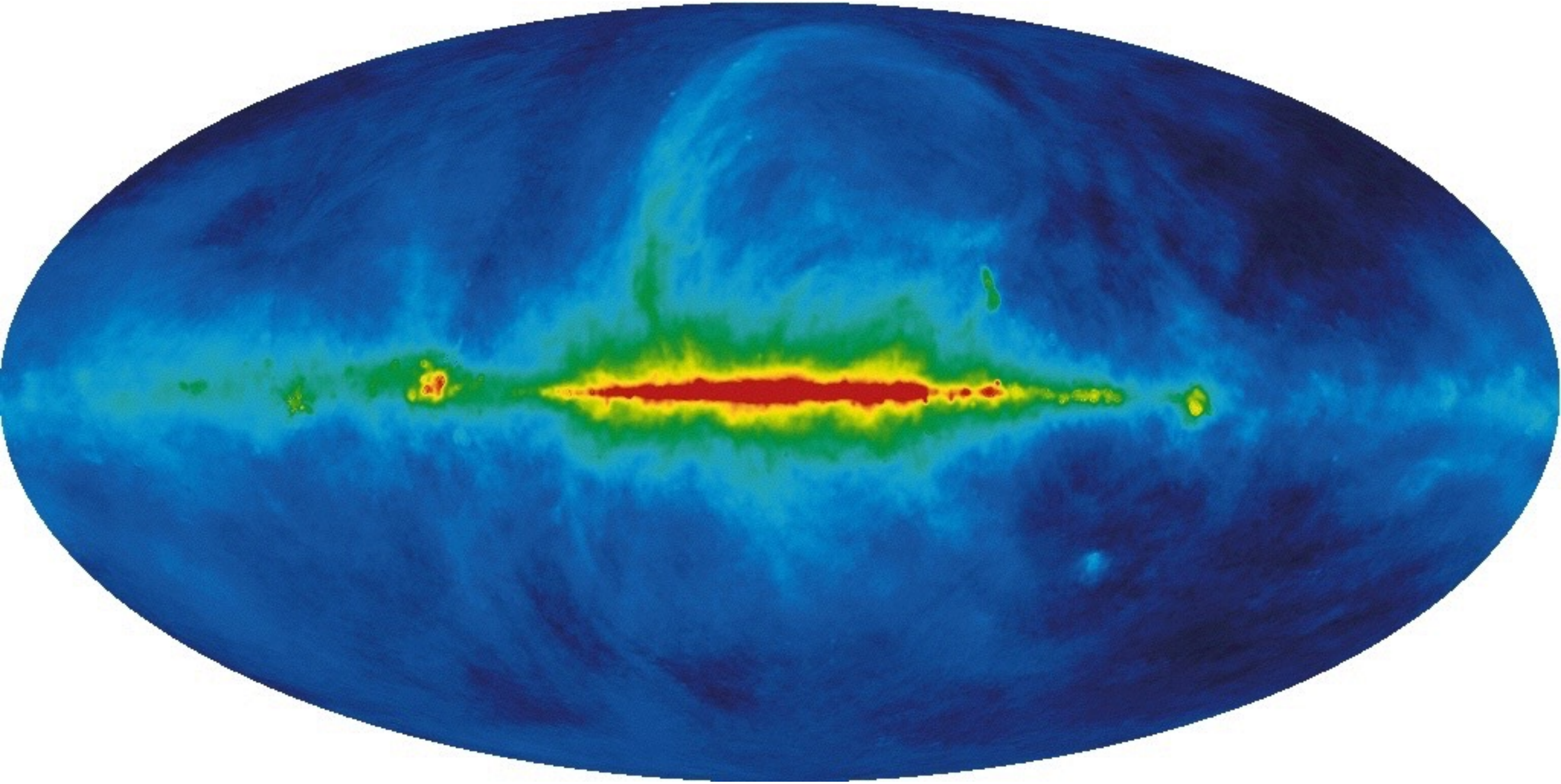


The Milky Way is our laboratory



The magneto-ionic interstellar medium

408 MHz

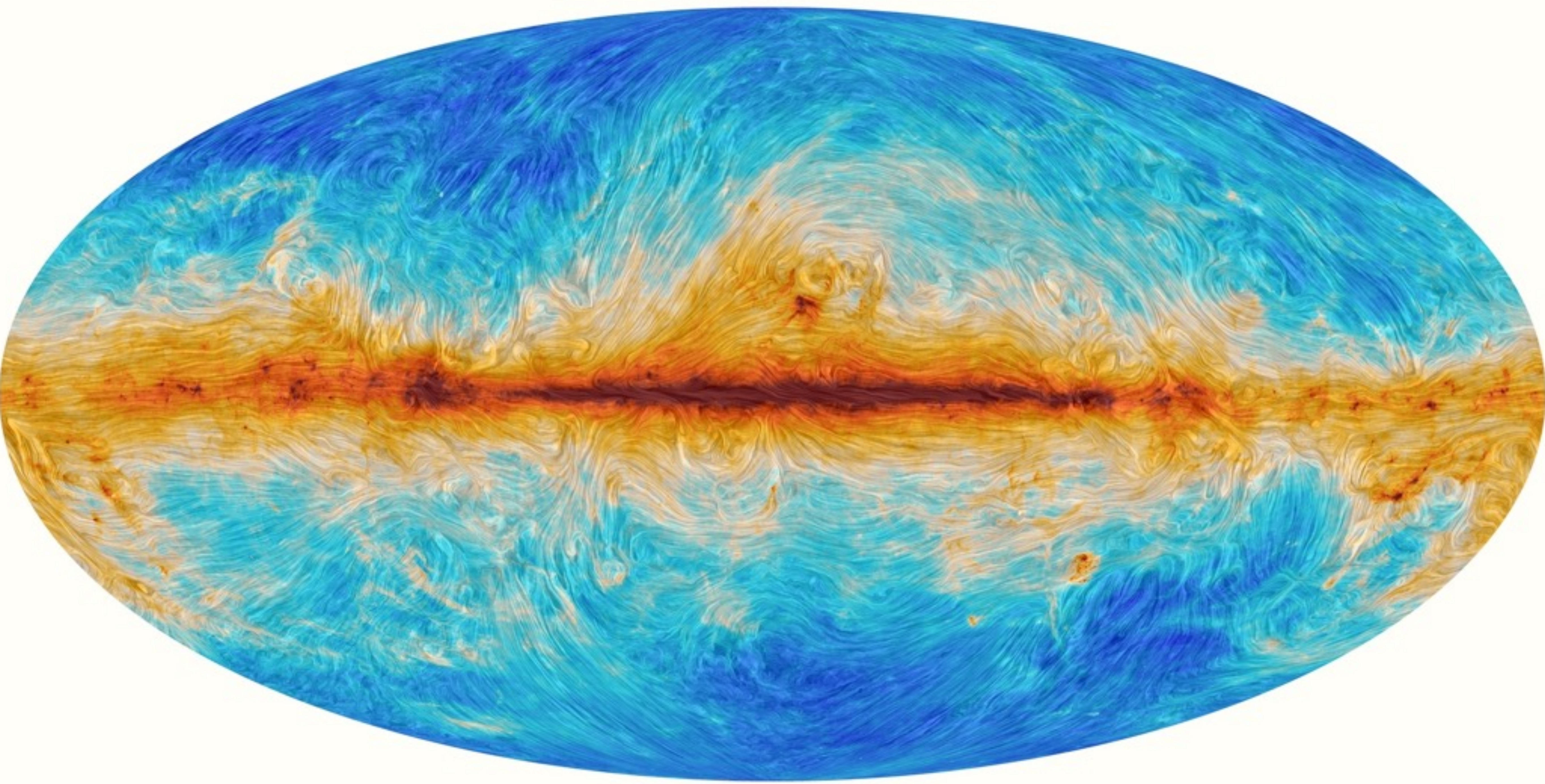


$$S(\nu) = \epsilon_s(\nu) \int_z n_e B_\perp^{(1+s)/2} \, dz$$

Haslam et al. (1982)

The neutral interstellar medium

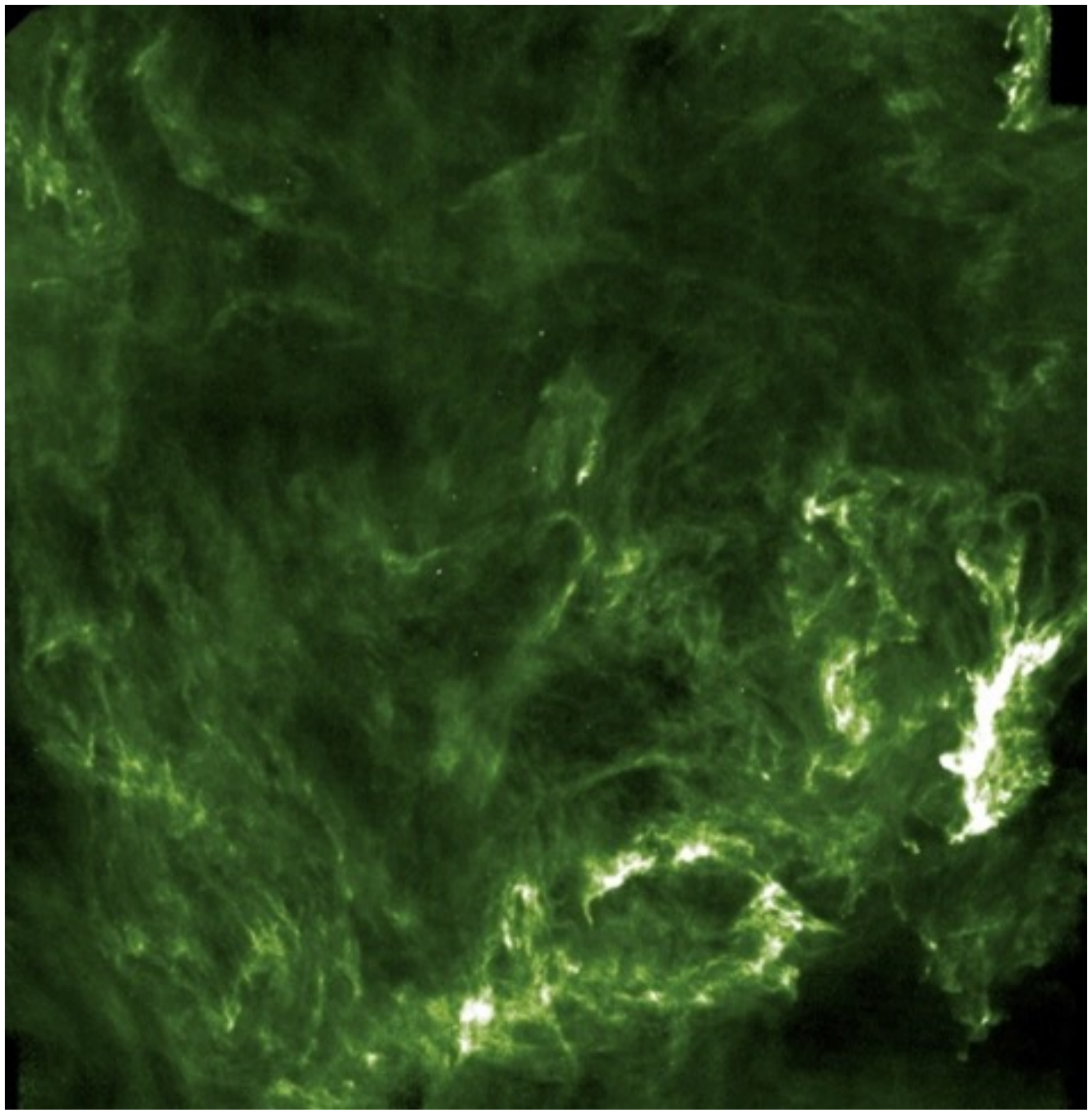
Planck dust column density



$$I_\nu = \tau_{\nu_0} \, B_\nu(T_{\rm obs}) \left(\frac{\nu}{\nu_0}\right)^{\beta_{\rm obs}}$$

Planck collaboration 2013 results. XI (2014)

P(k) of diffuse dust emission



Herschel Polaris
Miville-Deschenes+ 2010

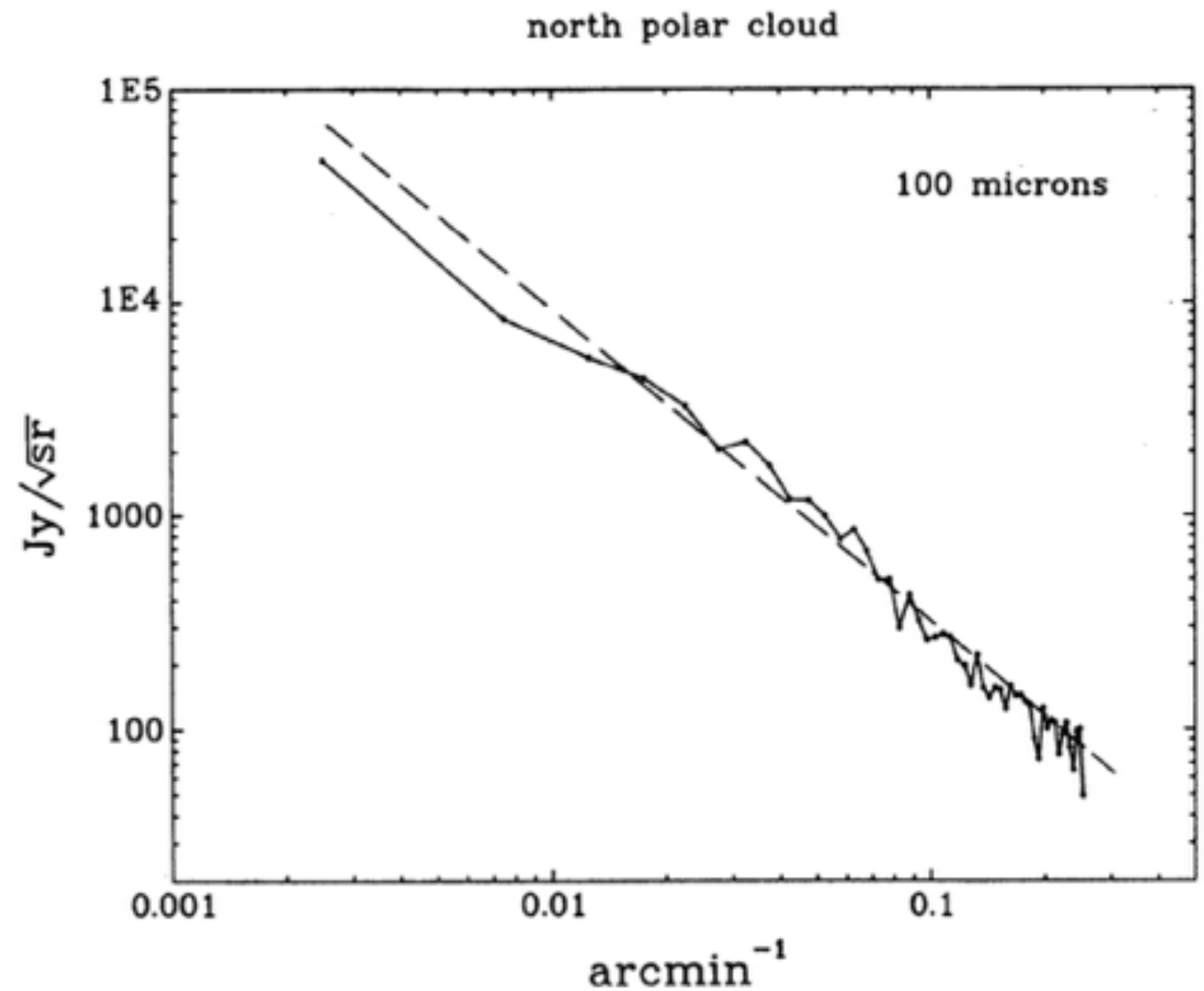


FIG. 2. The square root of the two-dimensional power spectrum at a wavelength of 100 μm of the bright cirrus cloud near the north equatorial pole (the first entry in Table 1) averaged over position angle and plotted against the modulus of frequency. The dotted line has a slope of − 1.45 corresponding to a slope of − 2.9 in the power spectrum.

Gautier et al. 1992

Going to smaller scales ?

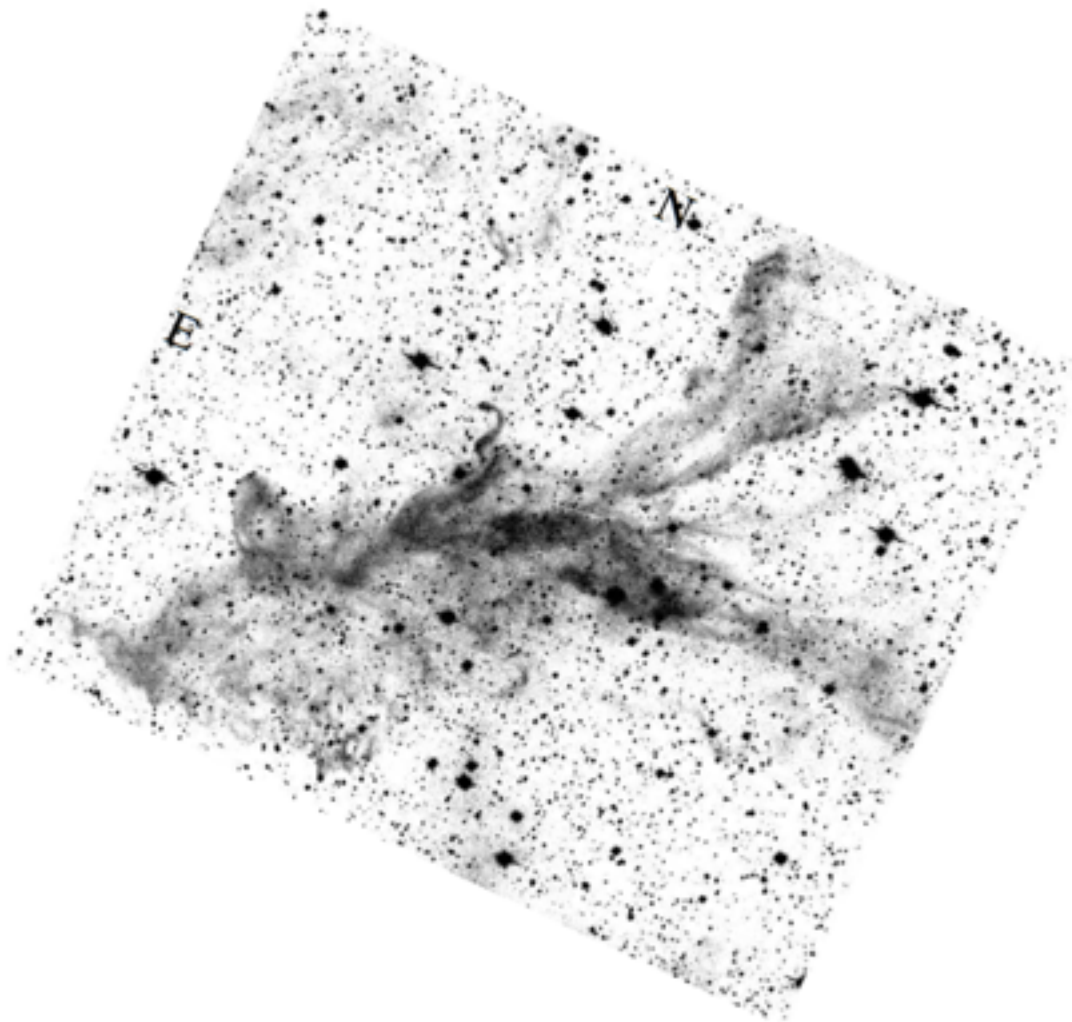
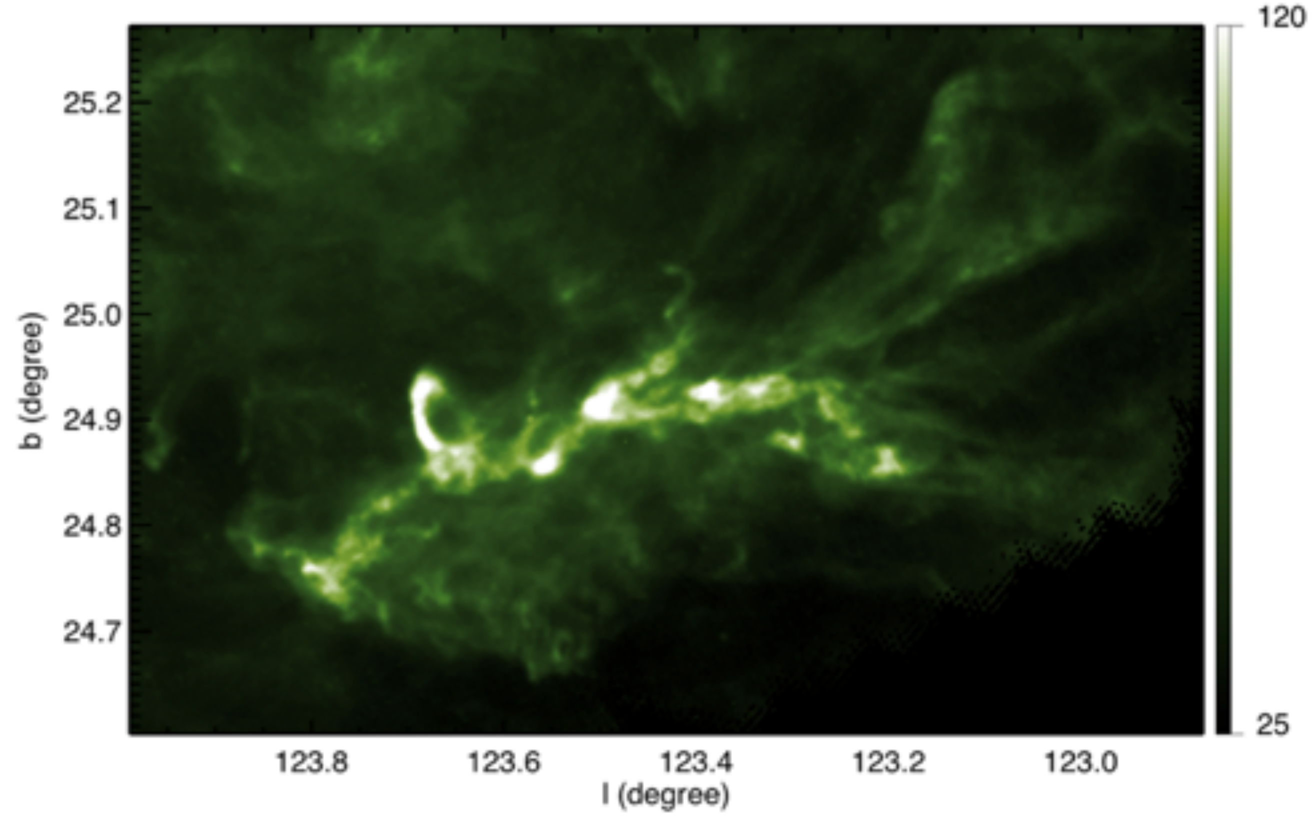


Image en bande I - Kitt Peak.
Zagury et al. (1999)



Herschel SPIRE - 250 micron
Miville-Deschênes et al. (2010)

Dust in the visible

extinction = absorption + scattering

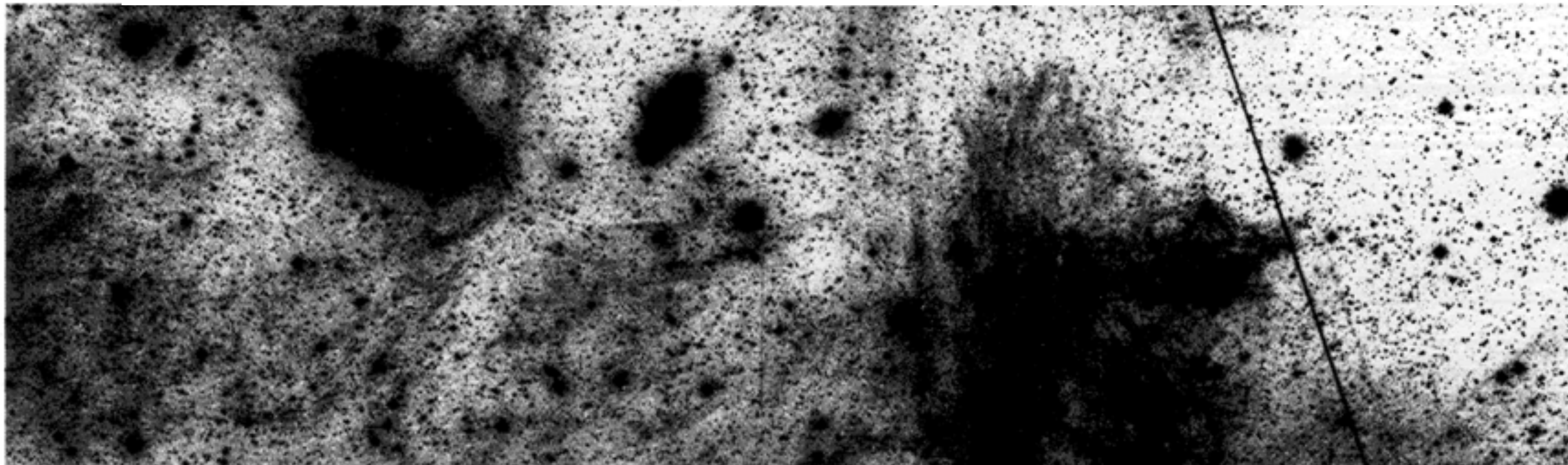
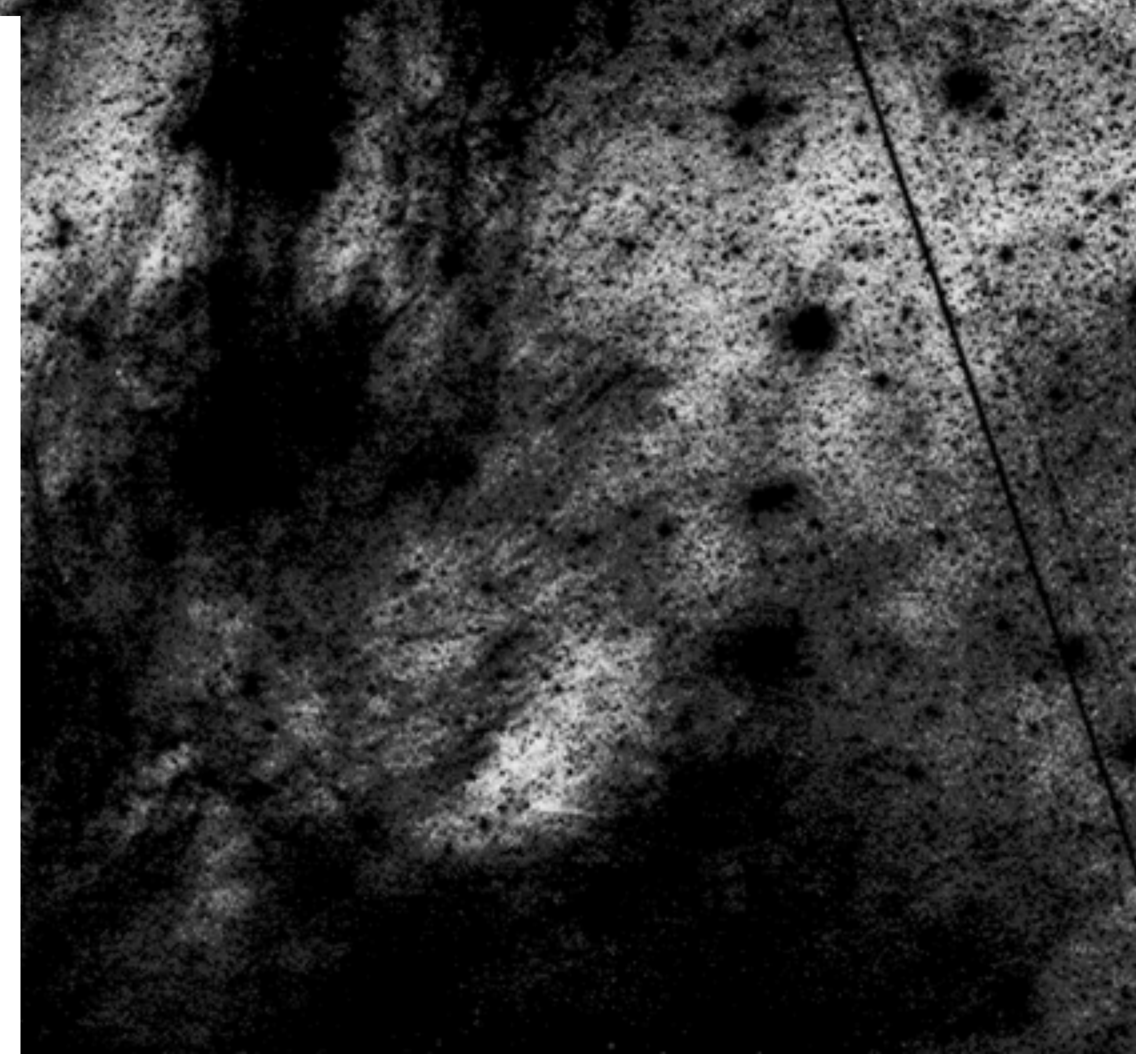
THE ASTRONOMICAL JOURNAL VOLUME 81, NUMBER 11 NOVEMBER 1976

High-latitude reflection nebulosities illuminated by the galactic plane

Allan Sandage

Hale Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California 91101

(Received 28 June 1976)

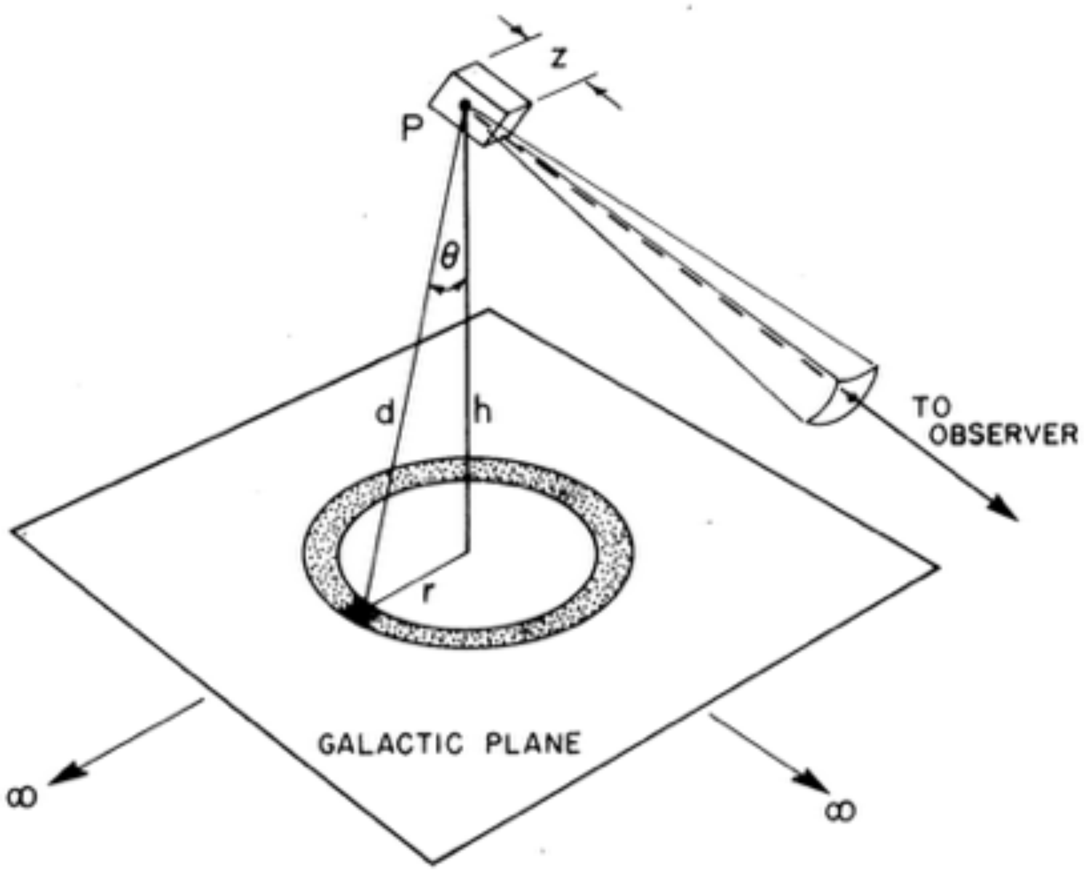
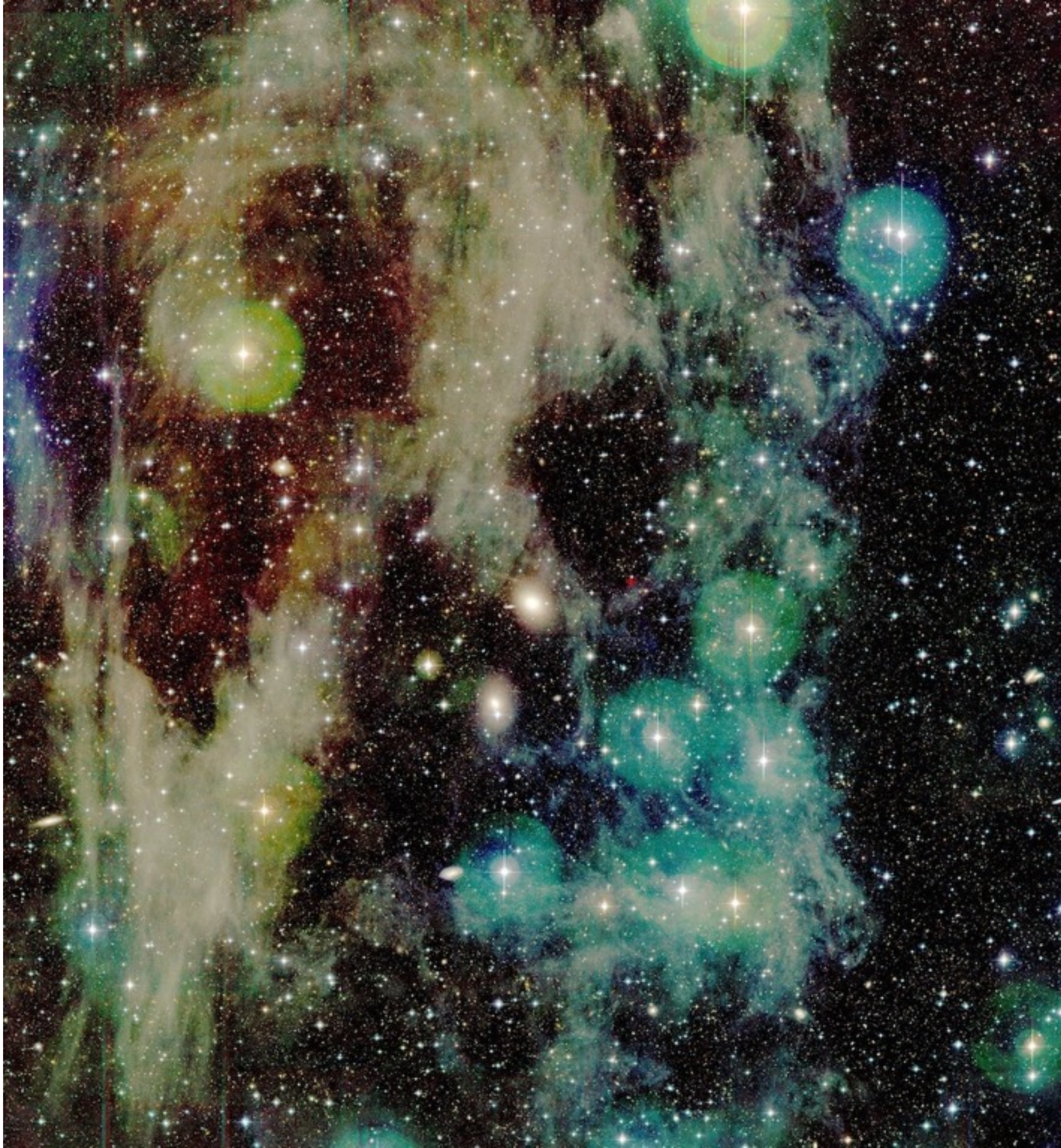


FIG. 1 Geometry of the illumination of point P by the galactic plane, and the subsequent scattering of the incident flux toward the observer.

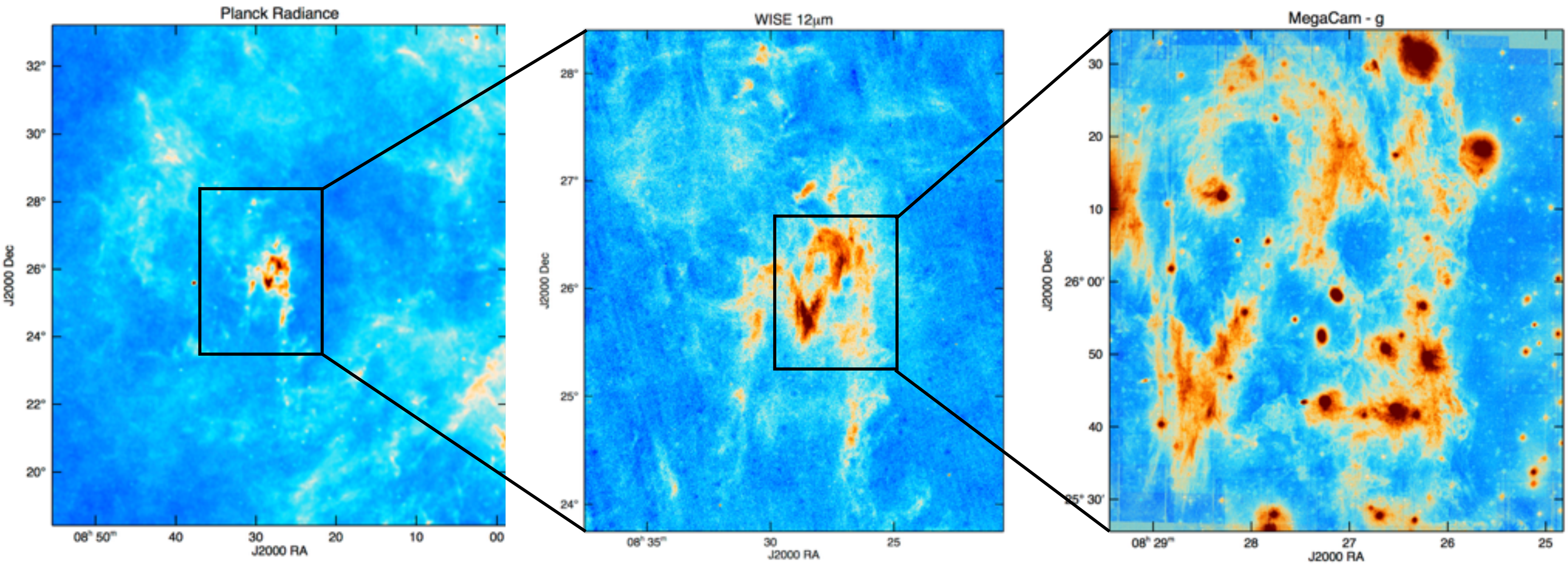
Cirrus in the visible ?

CFHTLS : high Galactic latitude field

- **The MATLAS project** Duc et al. (2015)
- CHFT - MegaCam
- Band g and r
- ~0.5-1 arcsec resolution = 50 AU for clouds at 100 pc
- Field of view : 1 deg^2
- Dithering method to recover large scale emission
- Diffuse cirrus emission found in many of the 250 fields
- Very good correlation with Planck 857 GHz

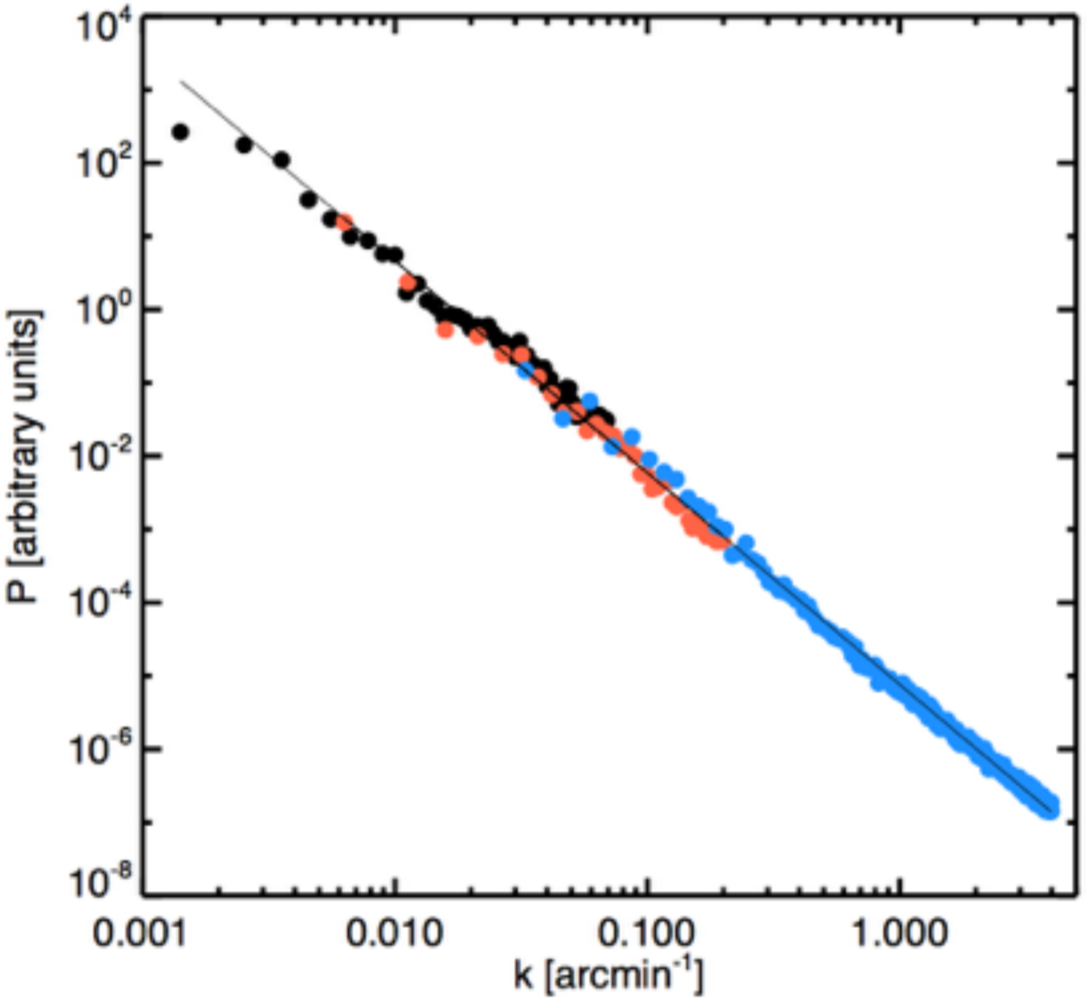


Planck - 5 arcmin | WISE - 15 arcsec | MegaCam - 0.6 arcsec

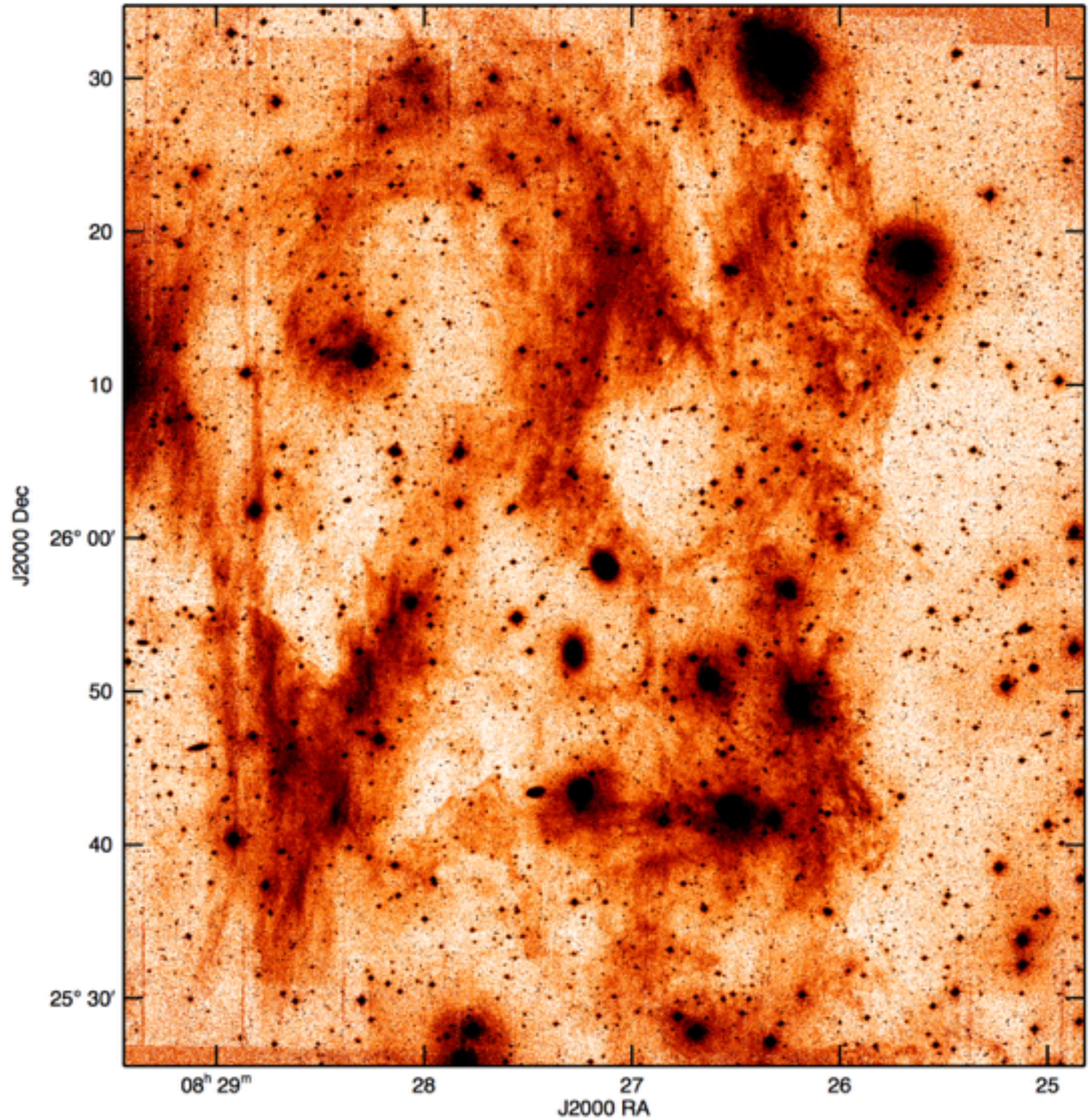


resolution increased by a factor 500

Miville-Deschênes et al. (2016)



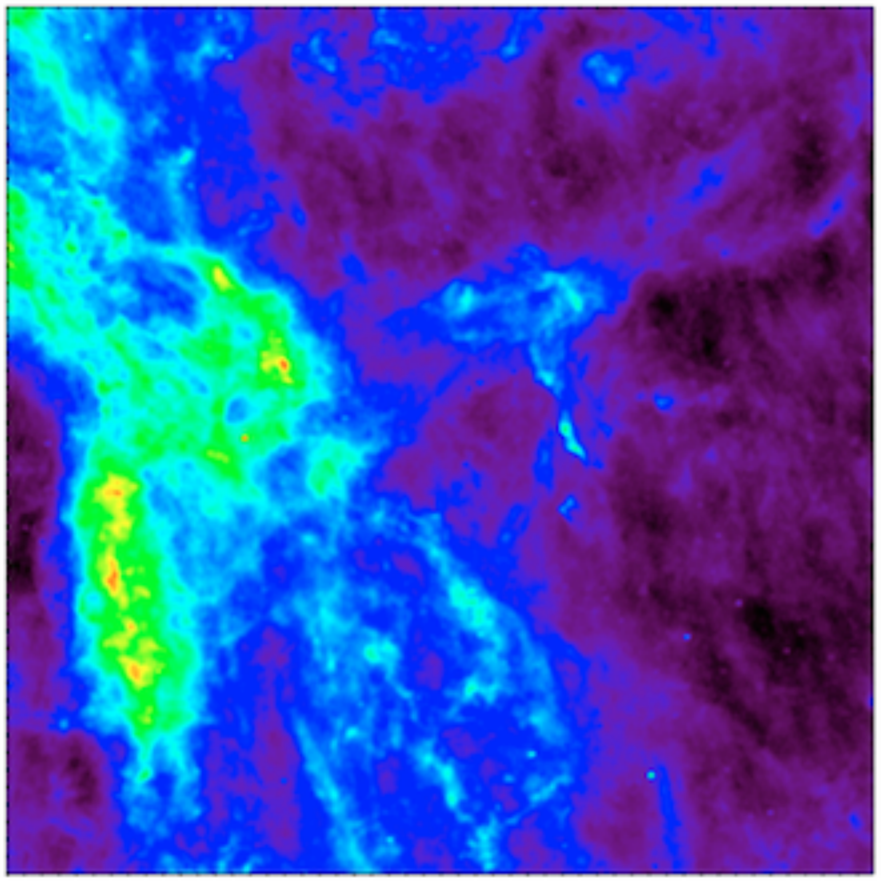
CFHT Megacam g band - 1.5”



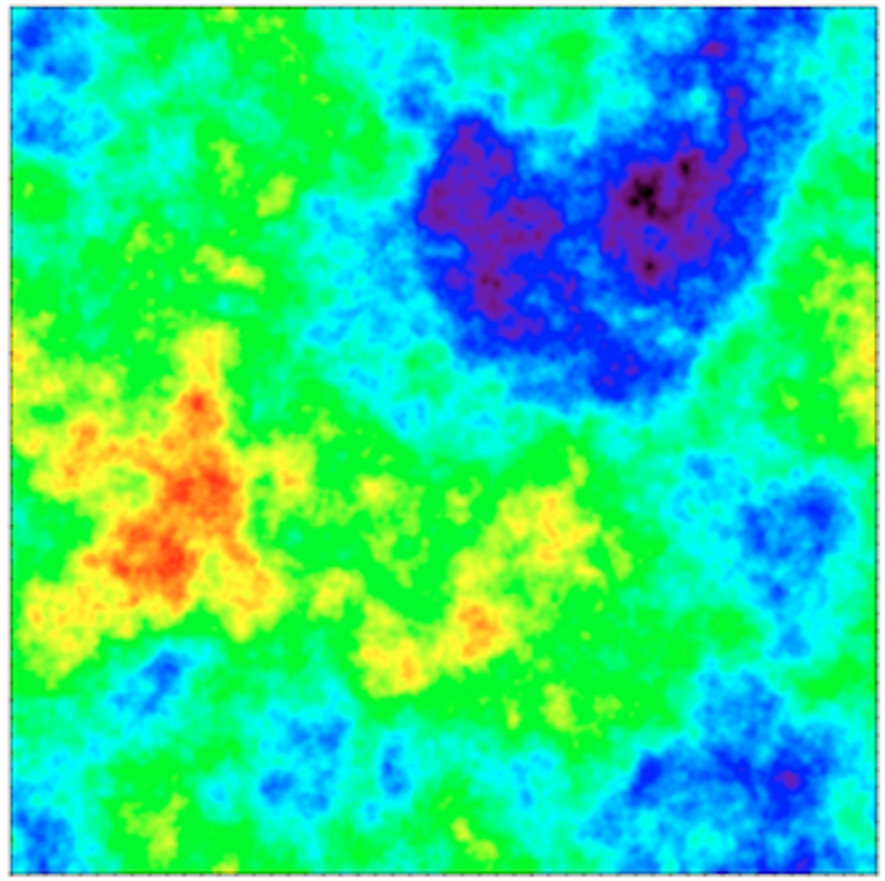
- P(k) ~ k-2.9 +- 0.1
- This is not Kolmogorov turbulence
  - Supersonic turbulence ?
  - Thermal instability ?
- No damping at small scales…
  - smallest scale probed : 0.01 pc, comparable to the ambipolar diffusion scale of the CNM

Miville-Deschênes et al. 2016

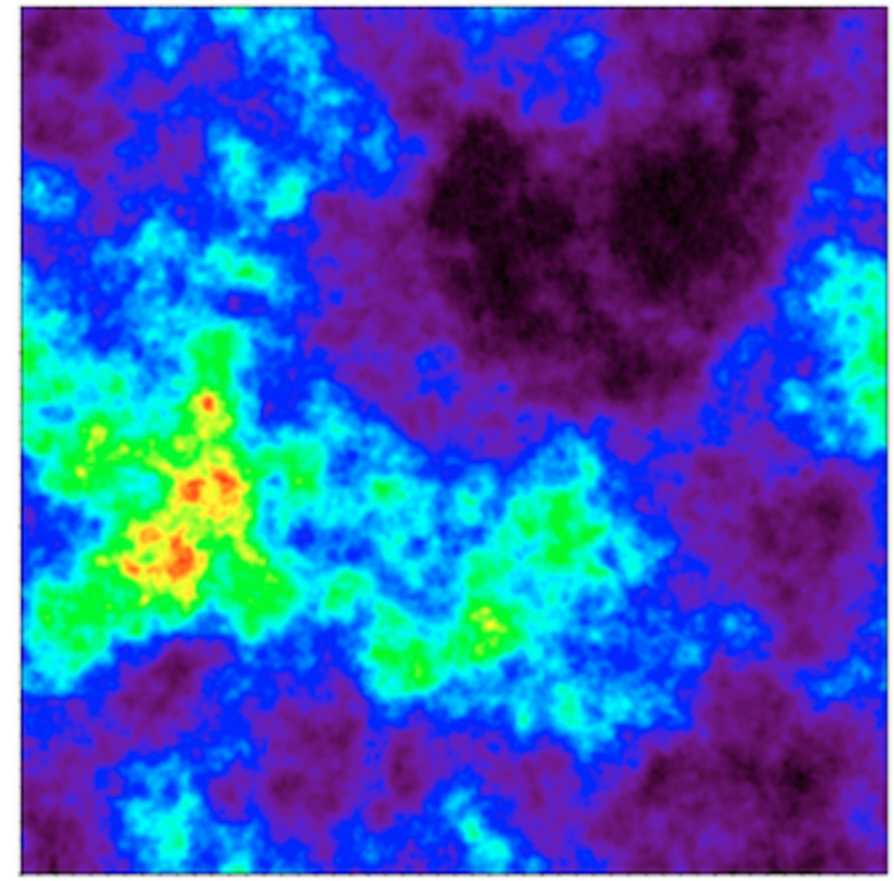
non-stationarity of the foreground emission



Dust emission



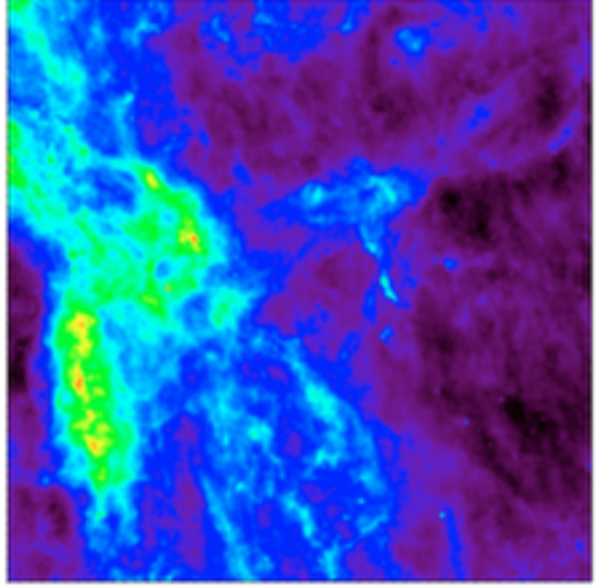
Gaussian field

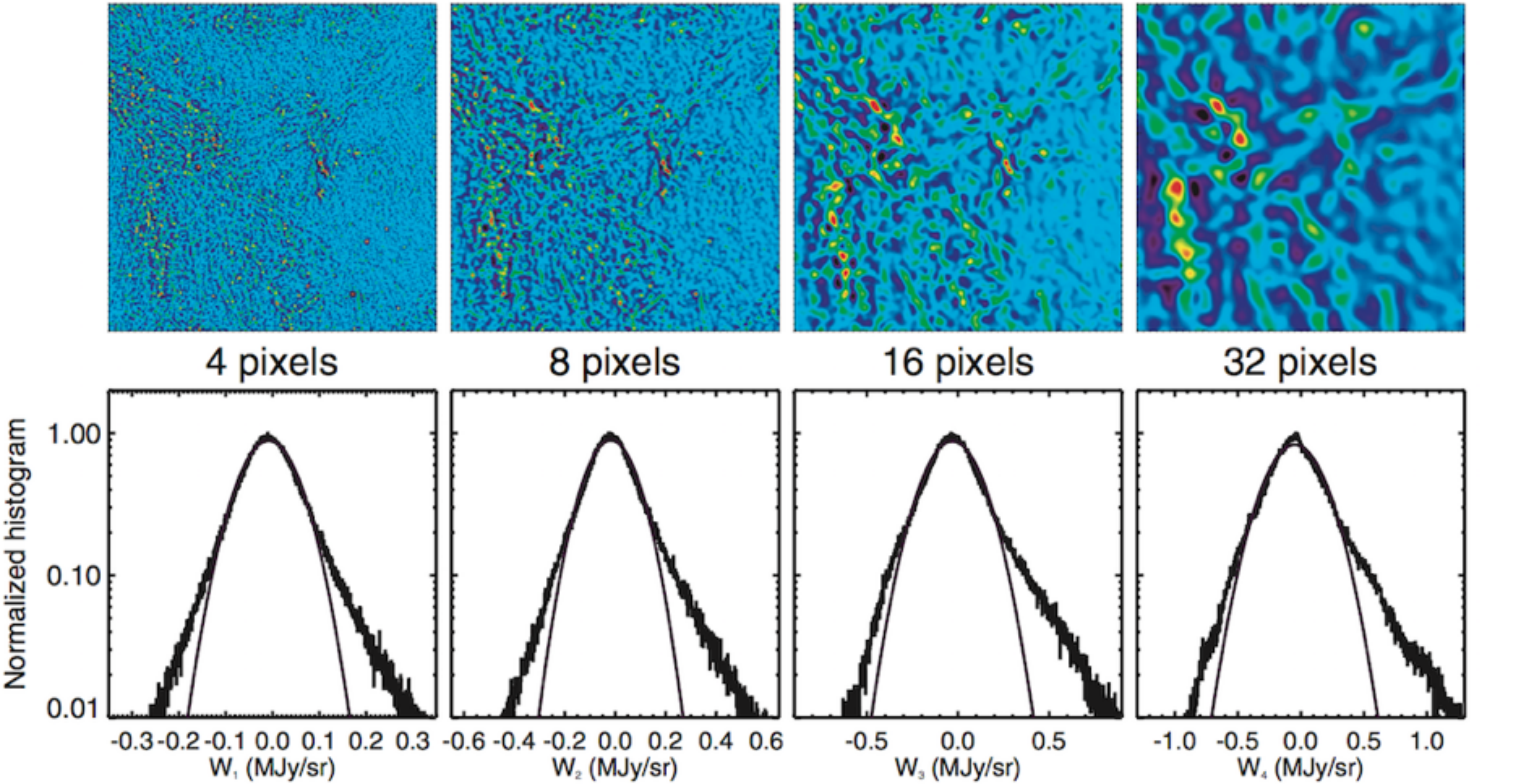


log-normal field

Miville-Deschênes+ 2007

Scale-related fluctuations



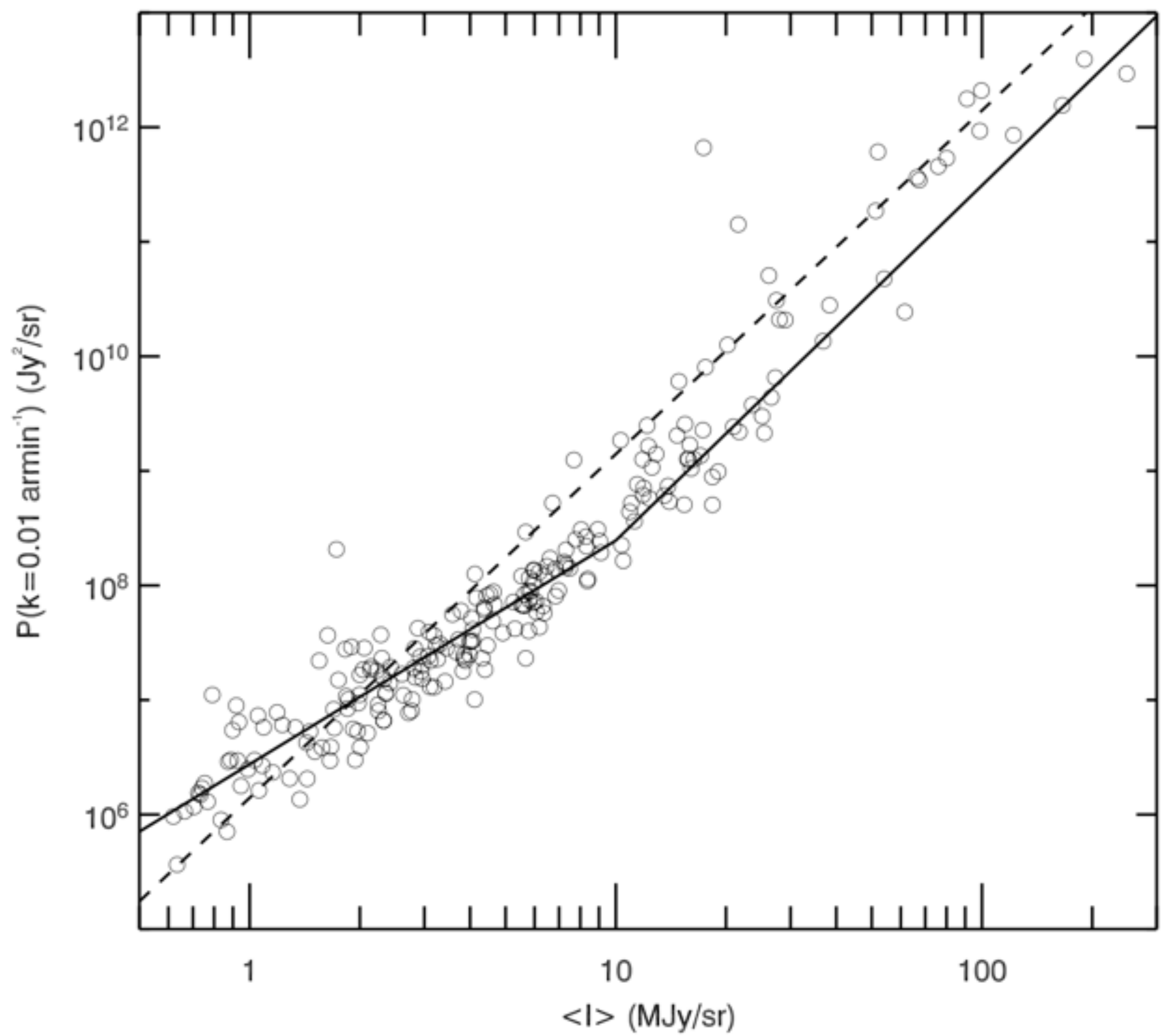


Miville-Deschênes+ 2007

Implications on the P(k) normalisation

- The P(k) normalisation varies locally. It depends on the local average brightness

- But what anisotropy ?



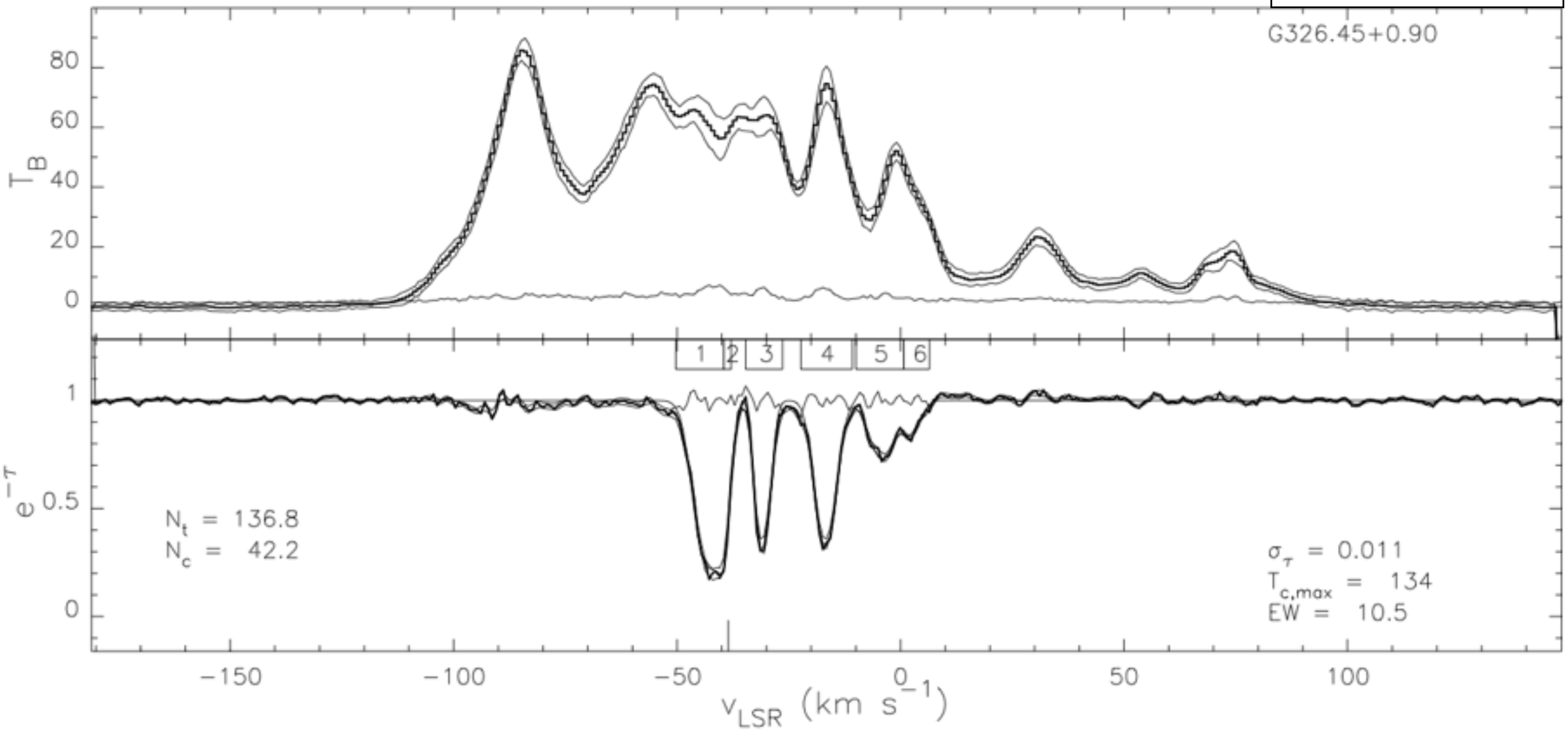
Miville-Deschênes+ 2007

Messages

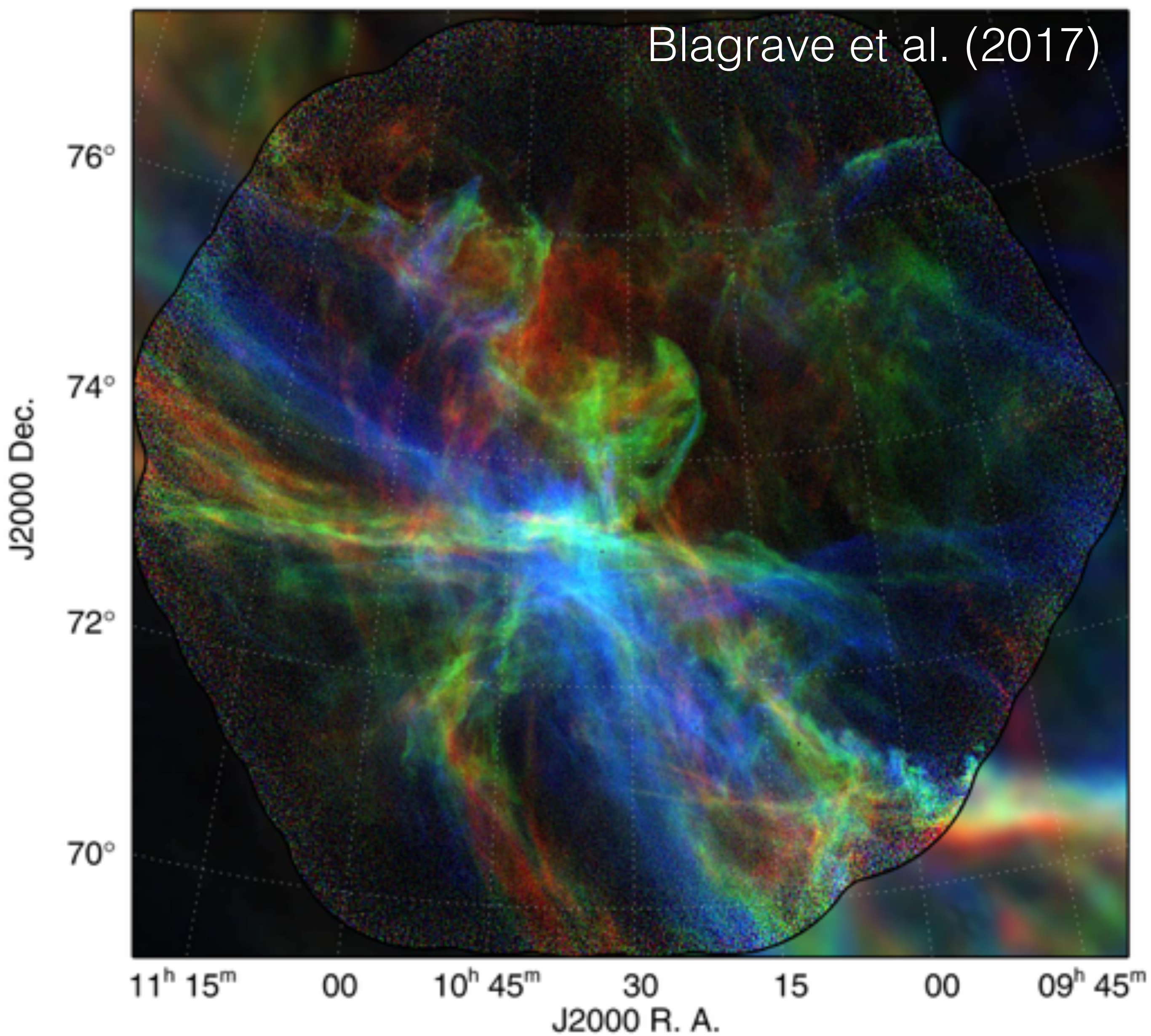
- Galactic emission is well described by a power law, down to arcsec scales, but that is not enough. It is also non-stationary and anisotropic.

The HI is multi-phase

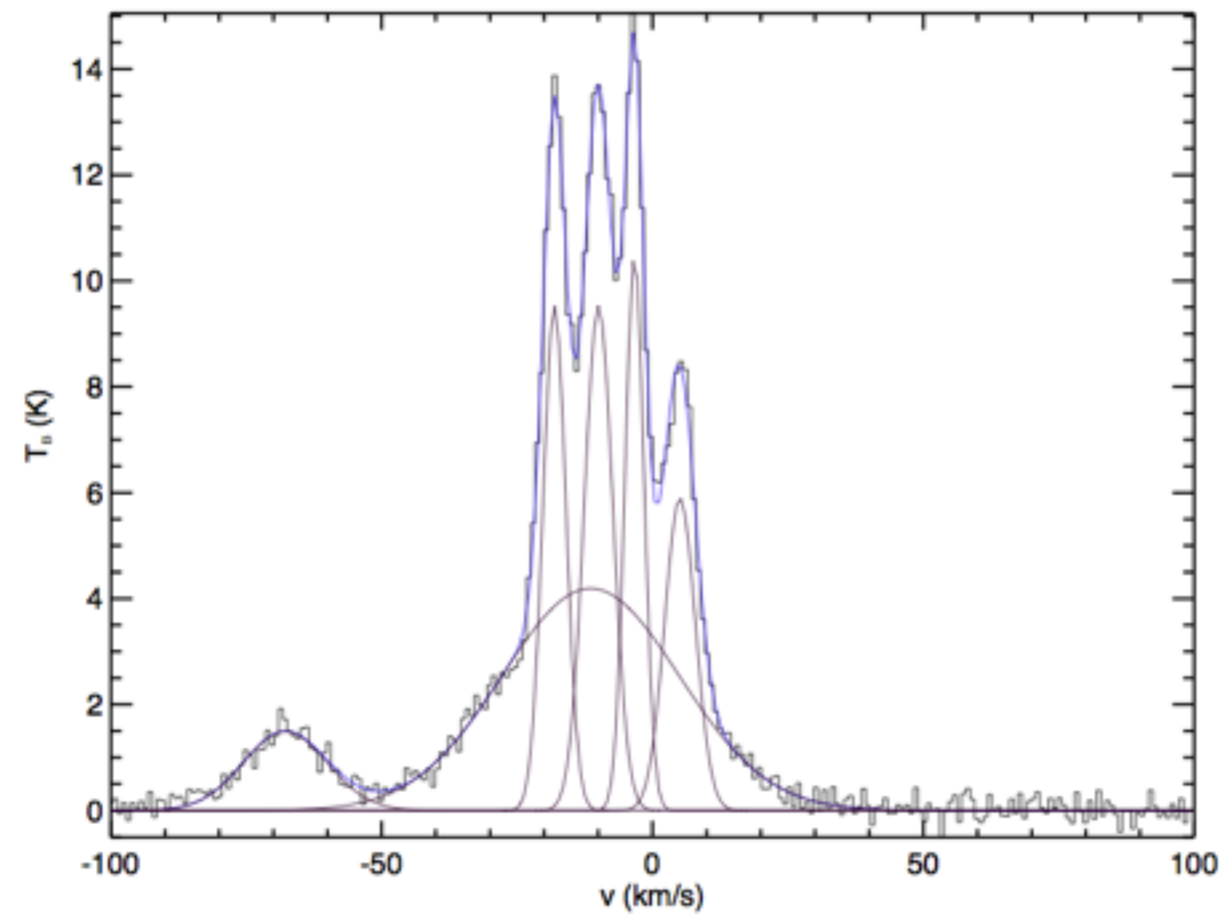
Dickey+ (2003)



- 21 cm transition : emission and absorption are different.
- Only the narrow (cold) features appear in absorption.

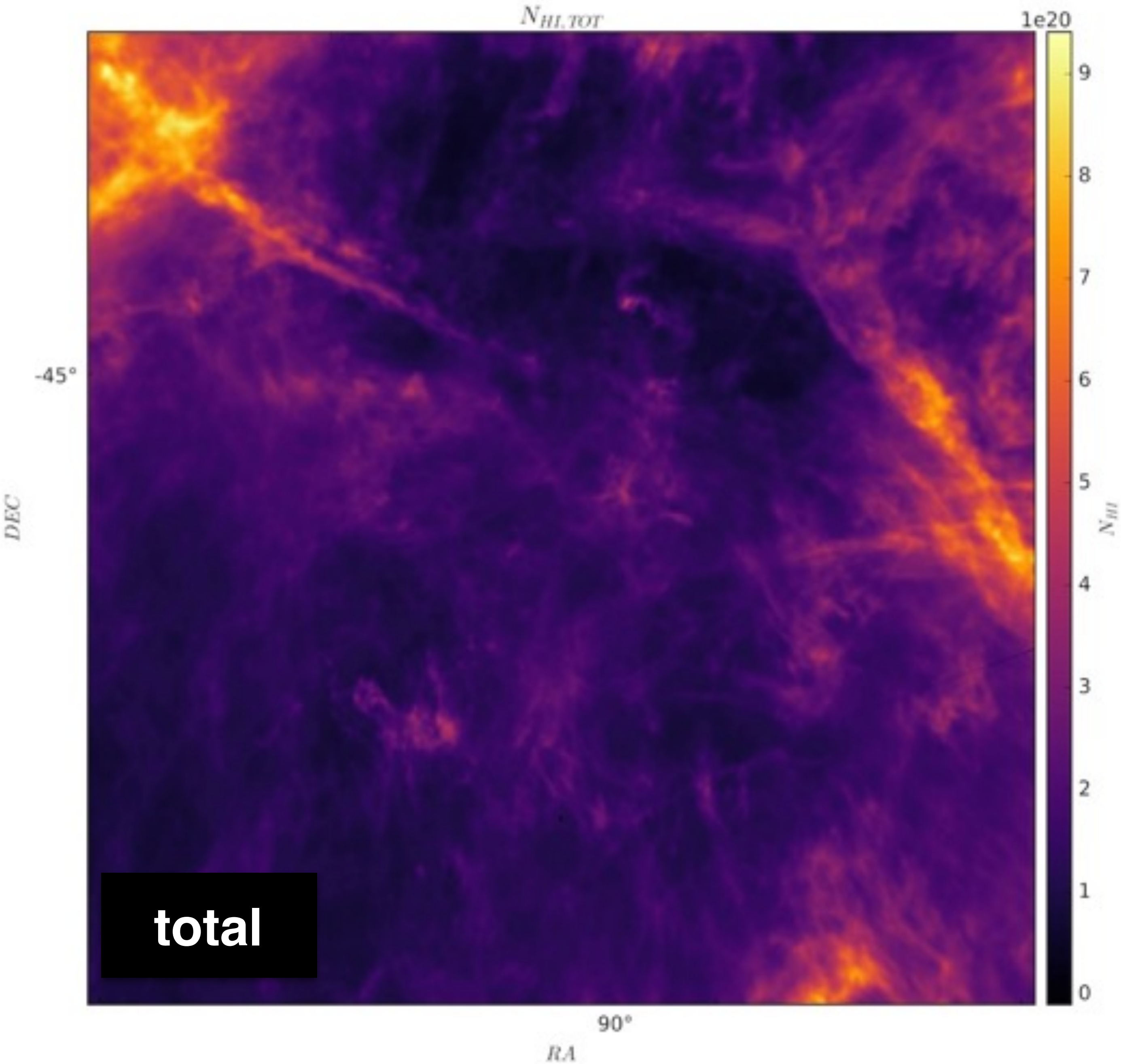


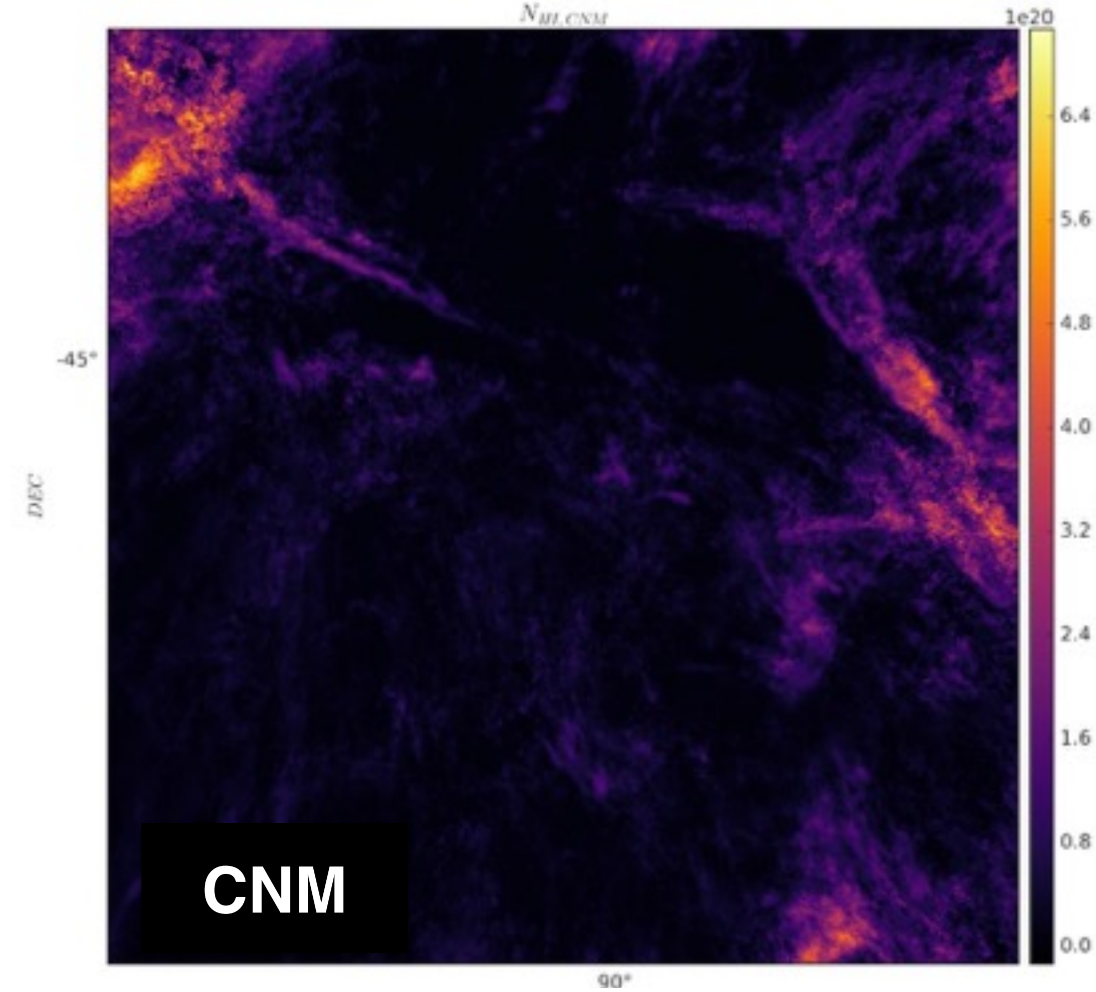
Multi-phase turbulence

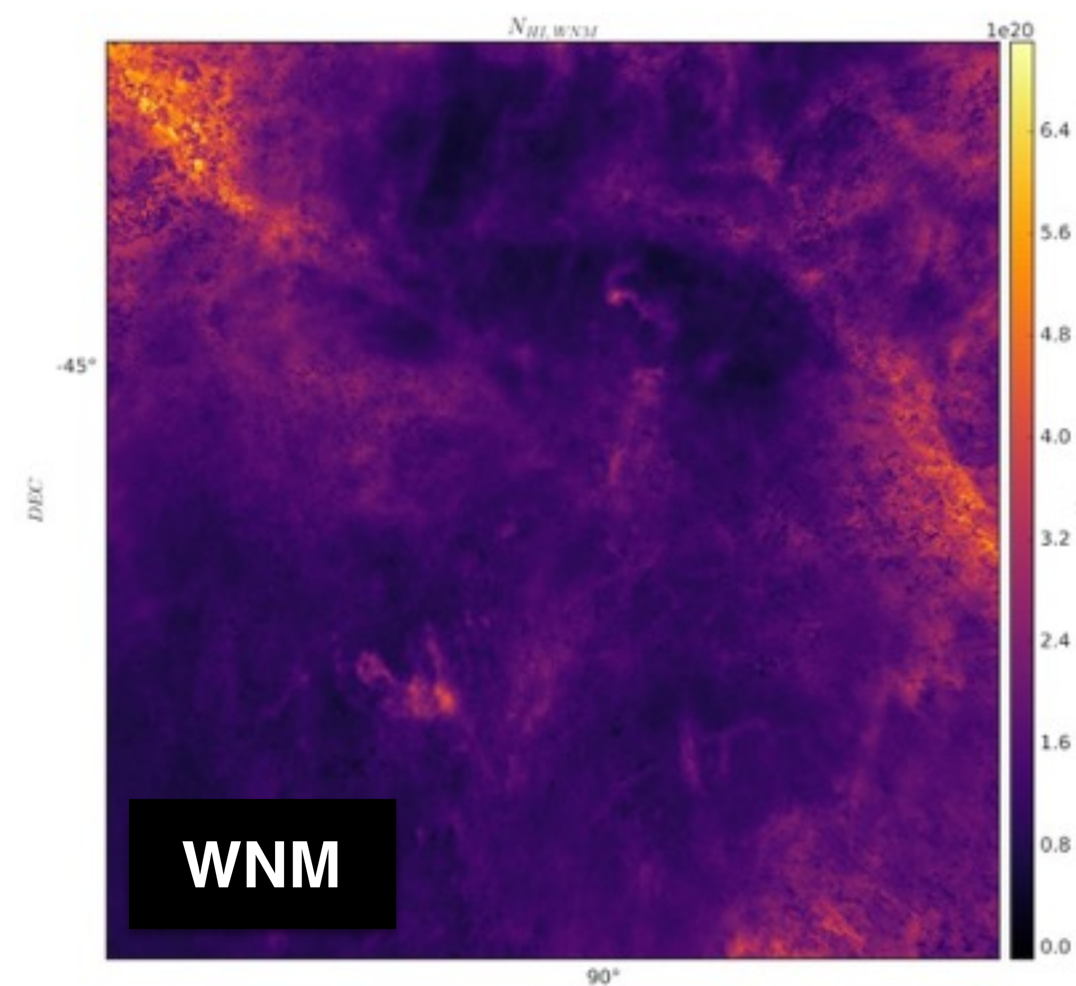


- The diffuse ISM seems to consist of cold-dense structures with a low volume filling factor, immersed in a warm and diffuse phase.

Identifying cold and warm HI

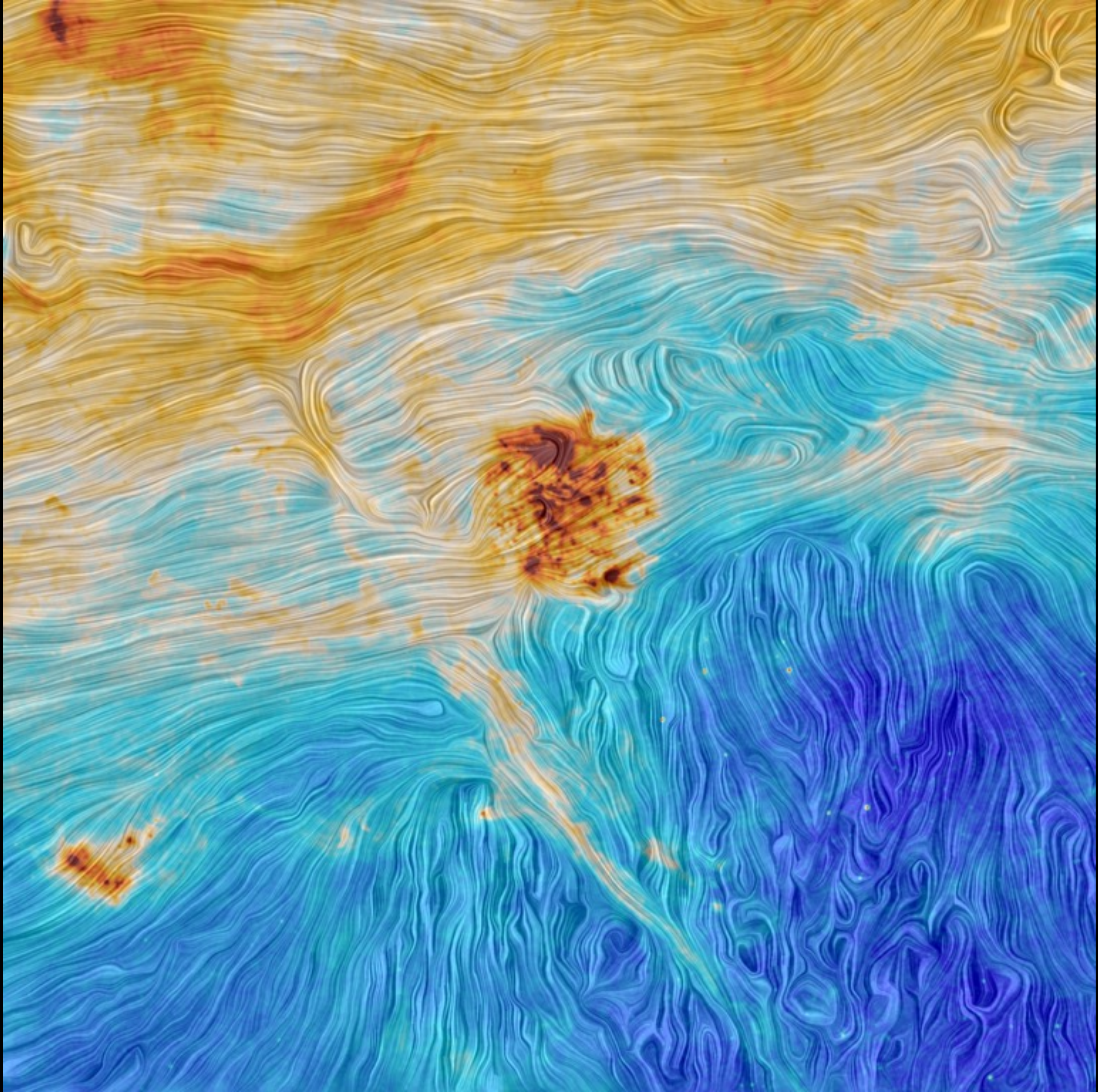




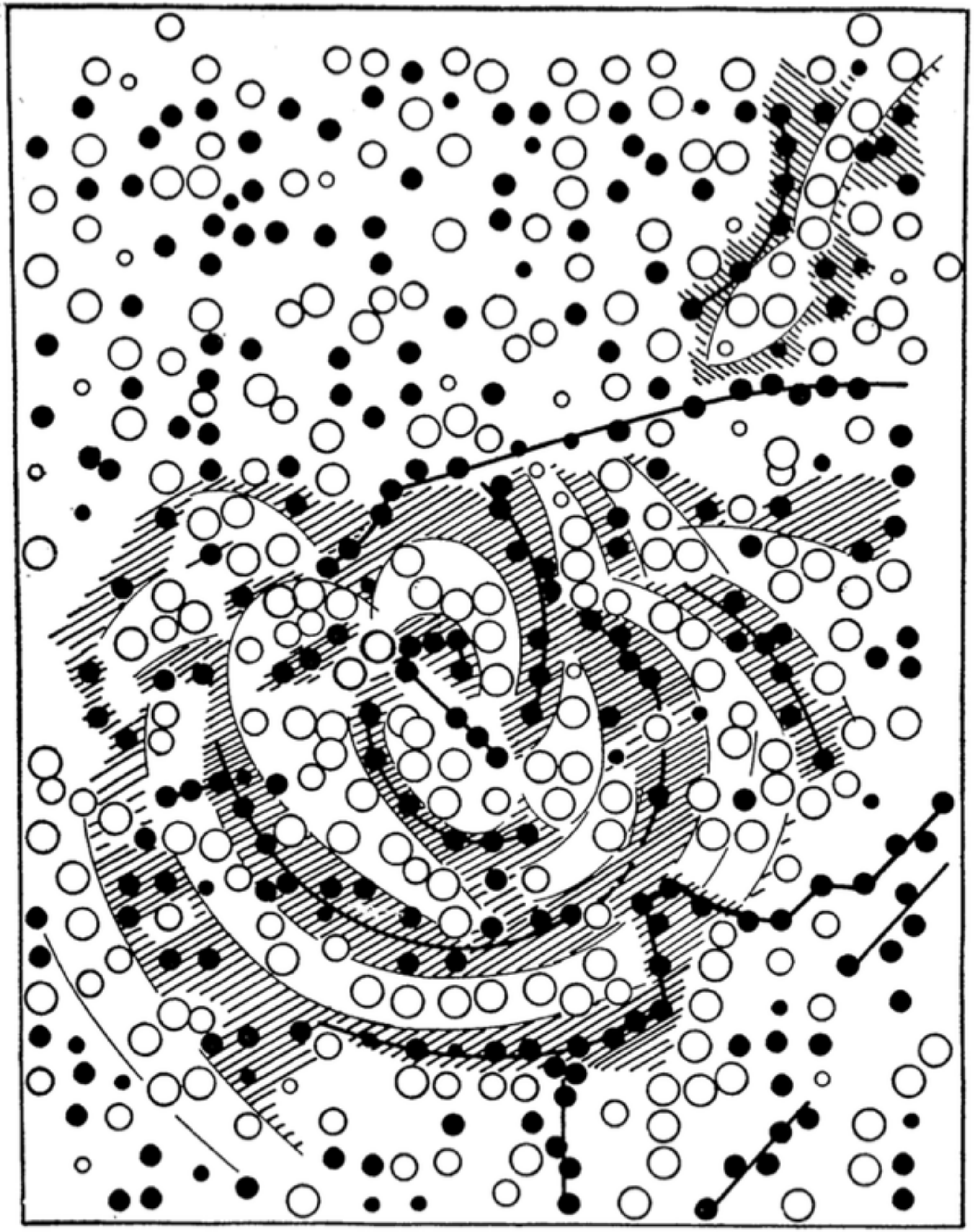


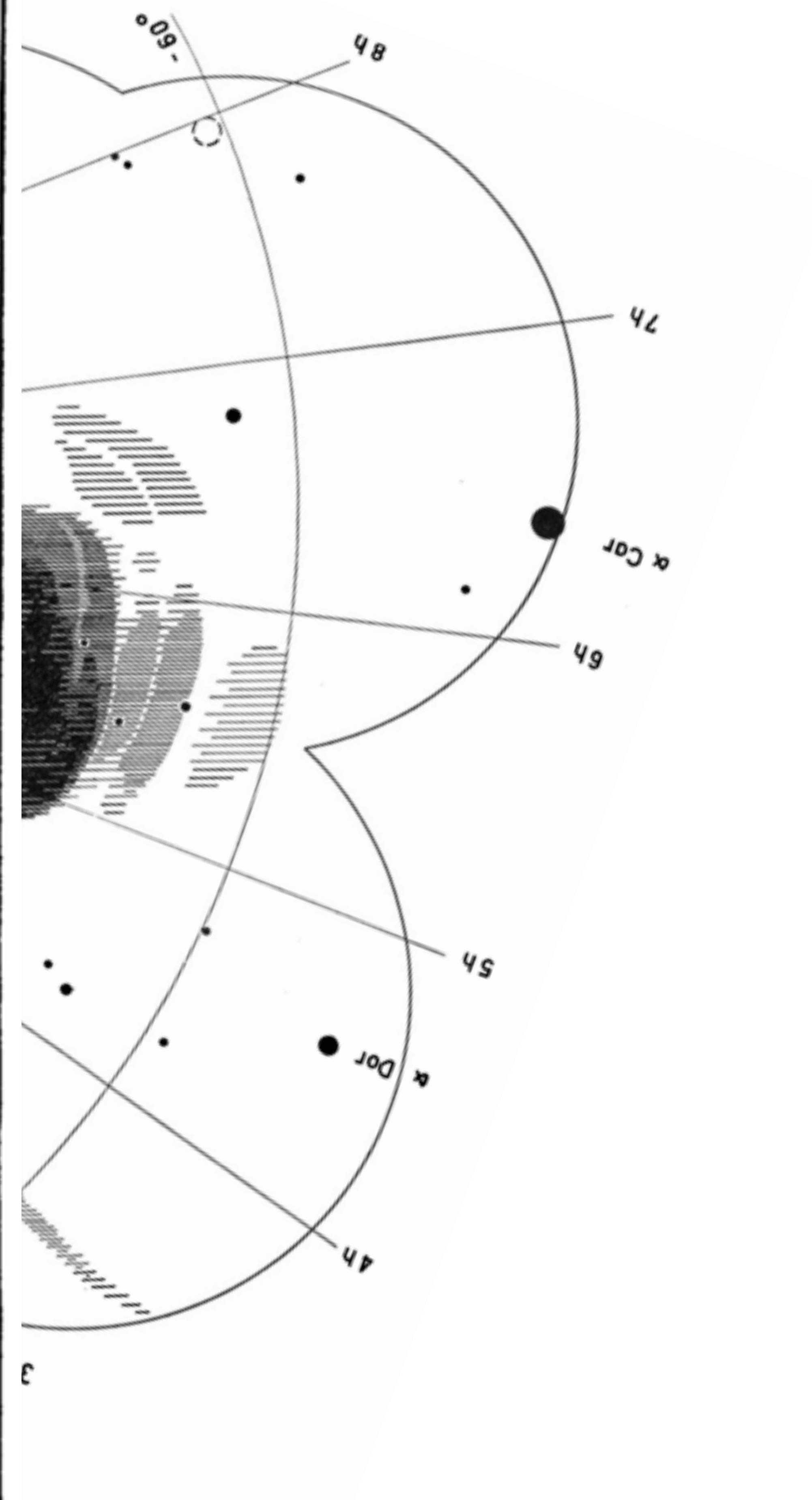
21 cm data from HI4Pi
75x75 deg; 16.2 arcmin resolution

Marchal & M-D (in prep)



de Vaucouleur (1955)





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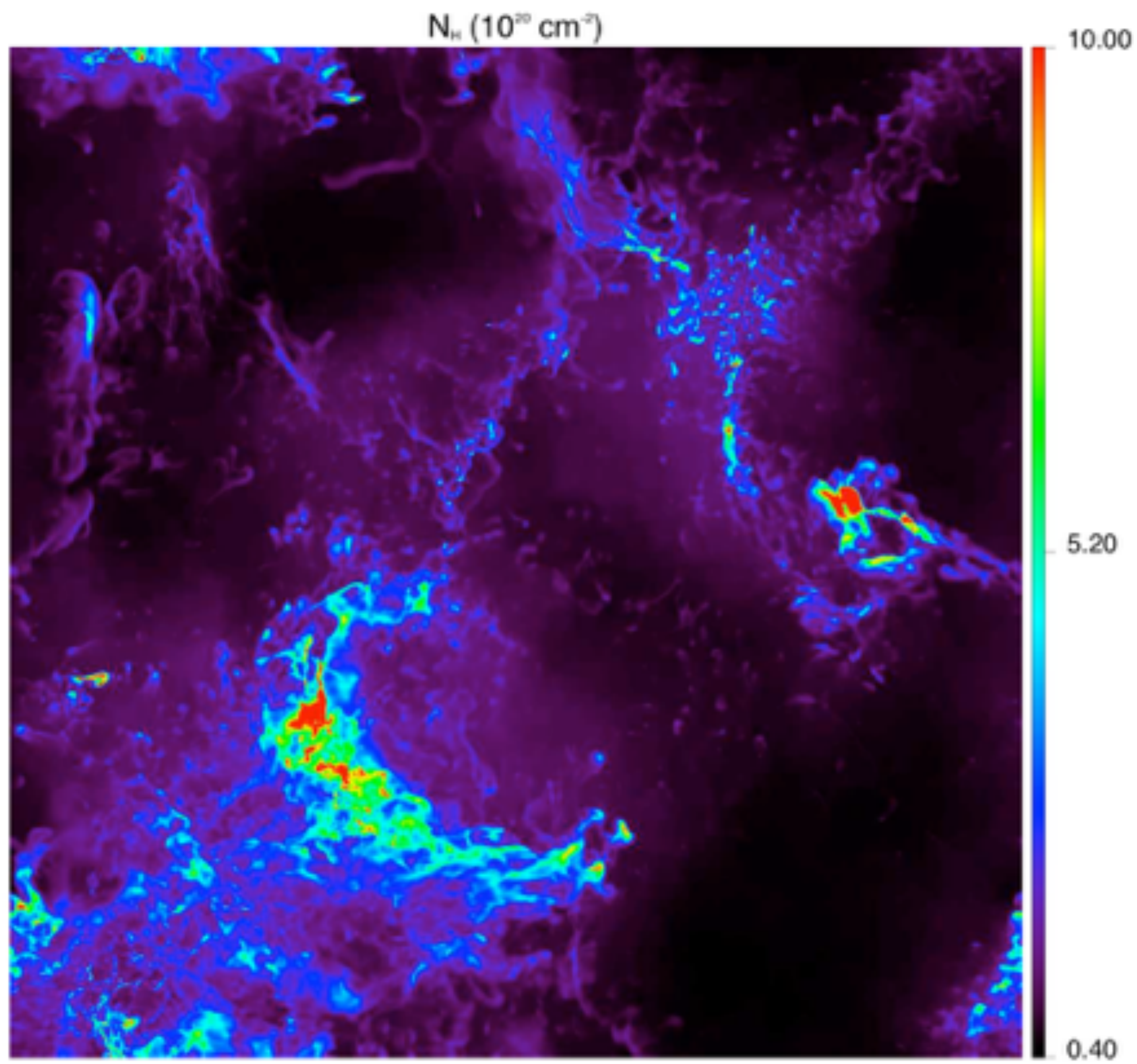
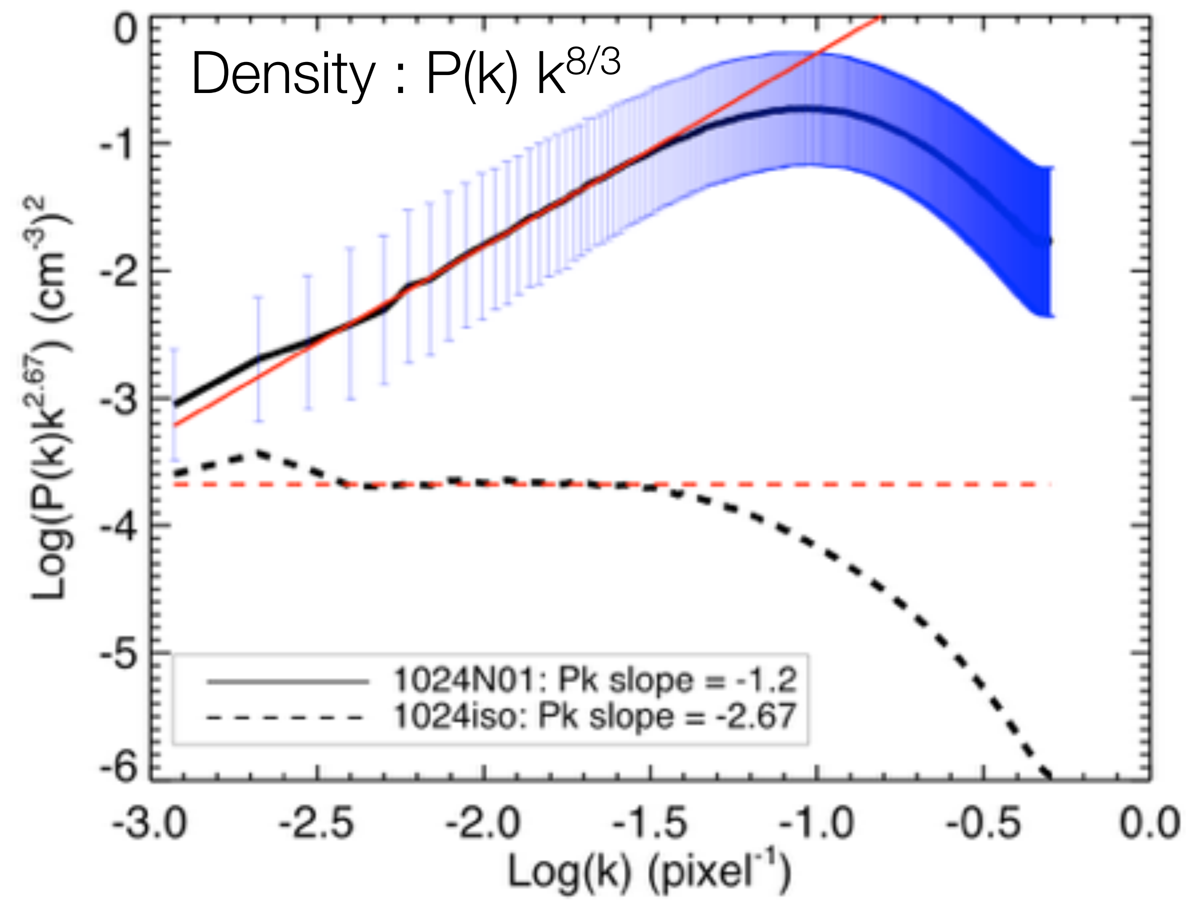
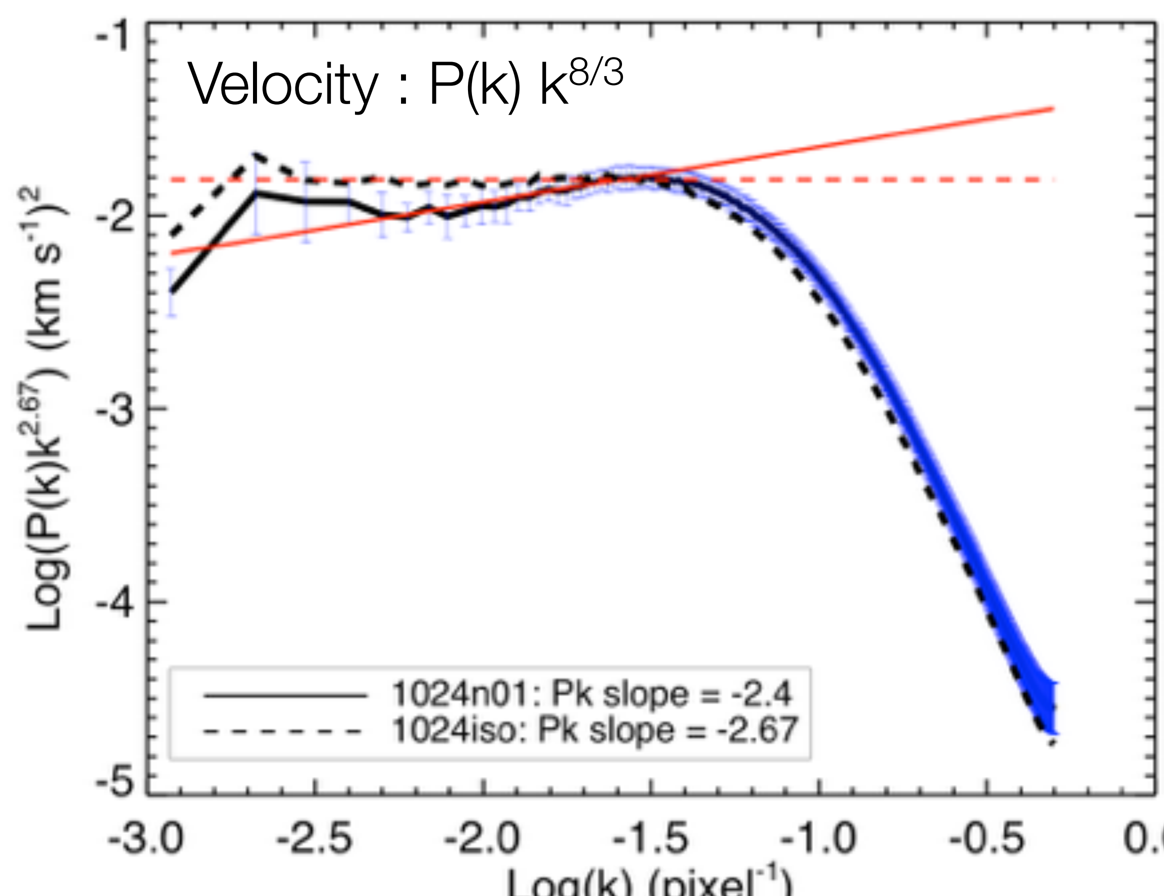
numerical simulation of thermally bi-stable turbulence

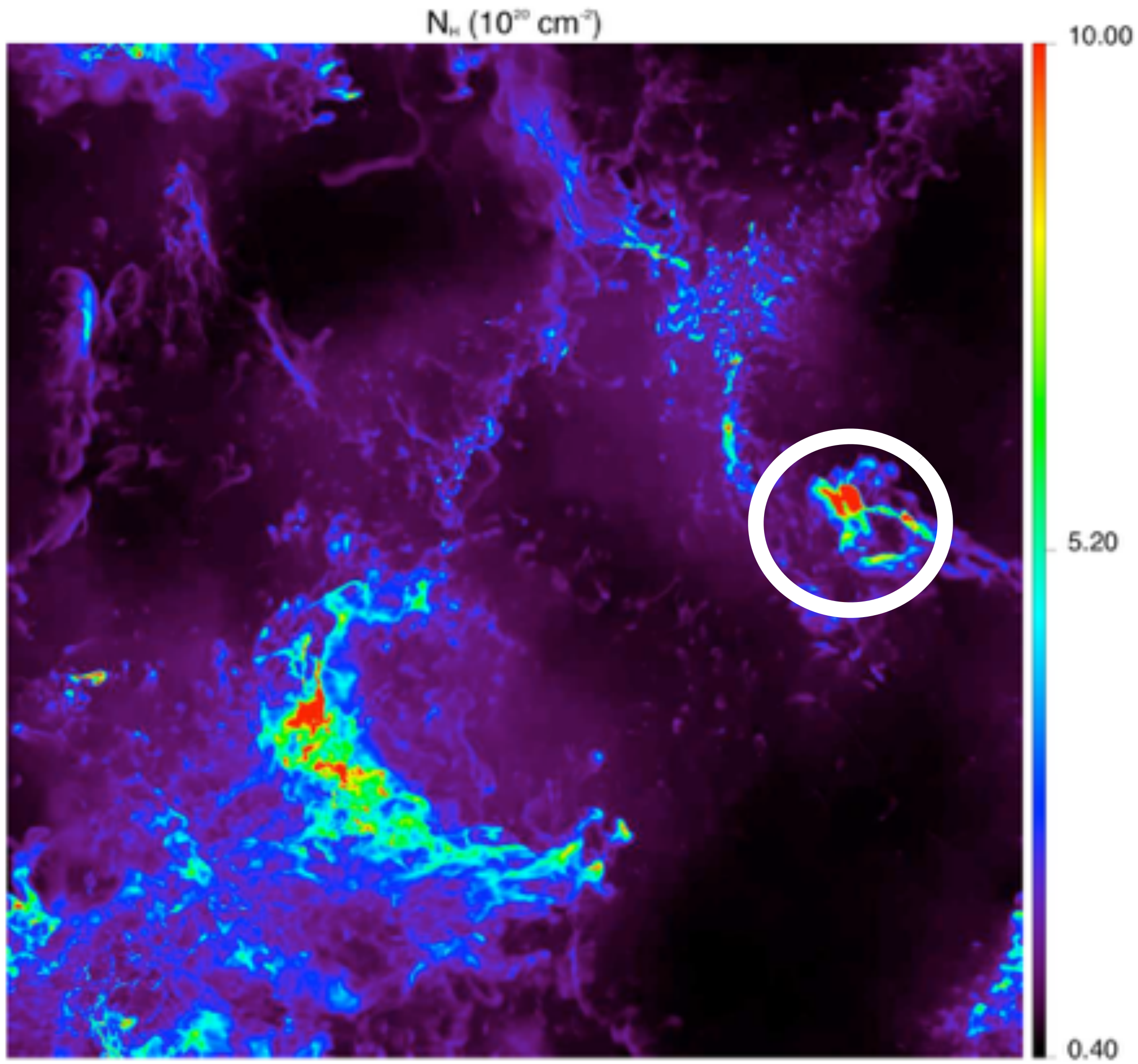


Saury et al. (2014)





what is on the line of sight ?



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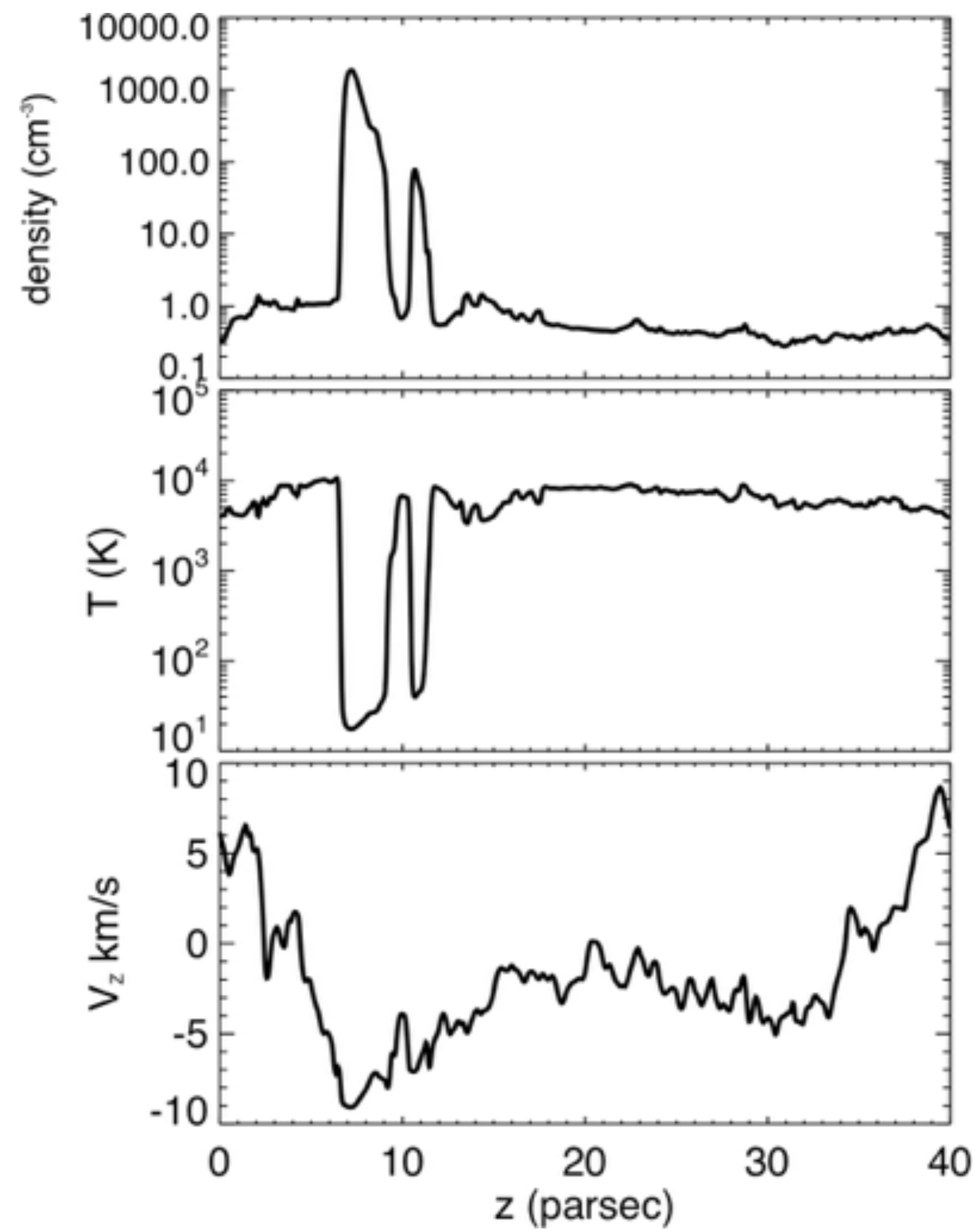
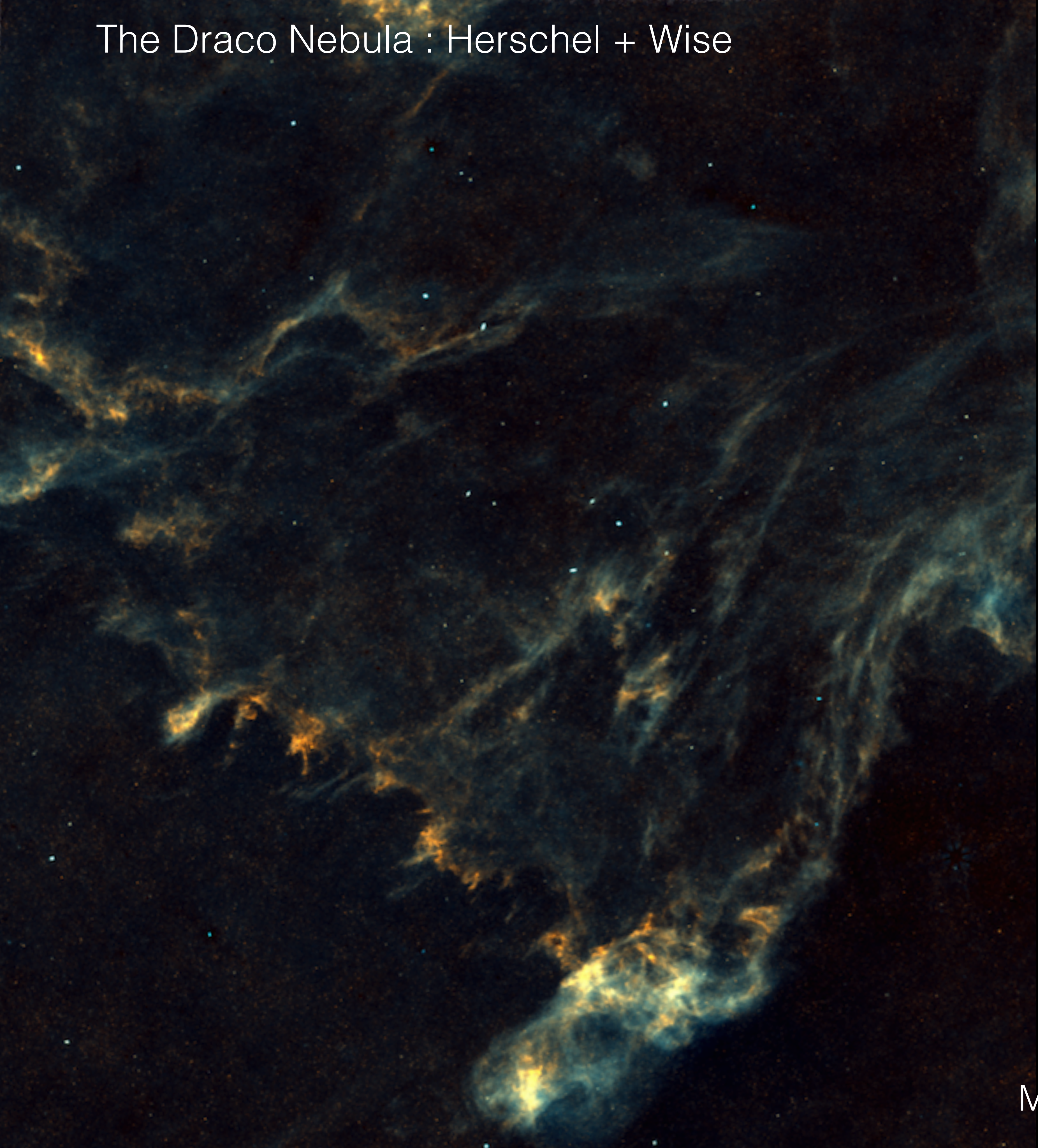


The Draco Nebula : Herschel + Wise

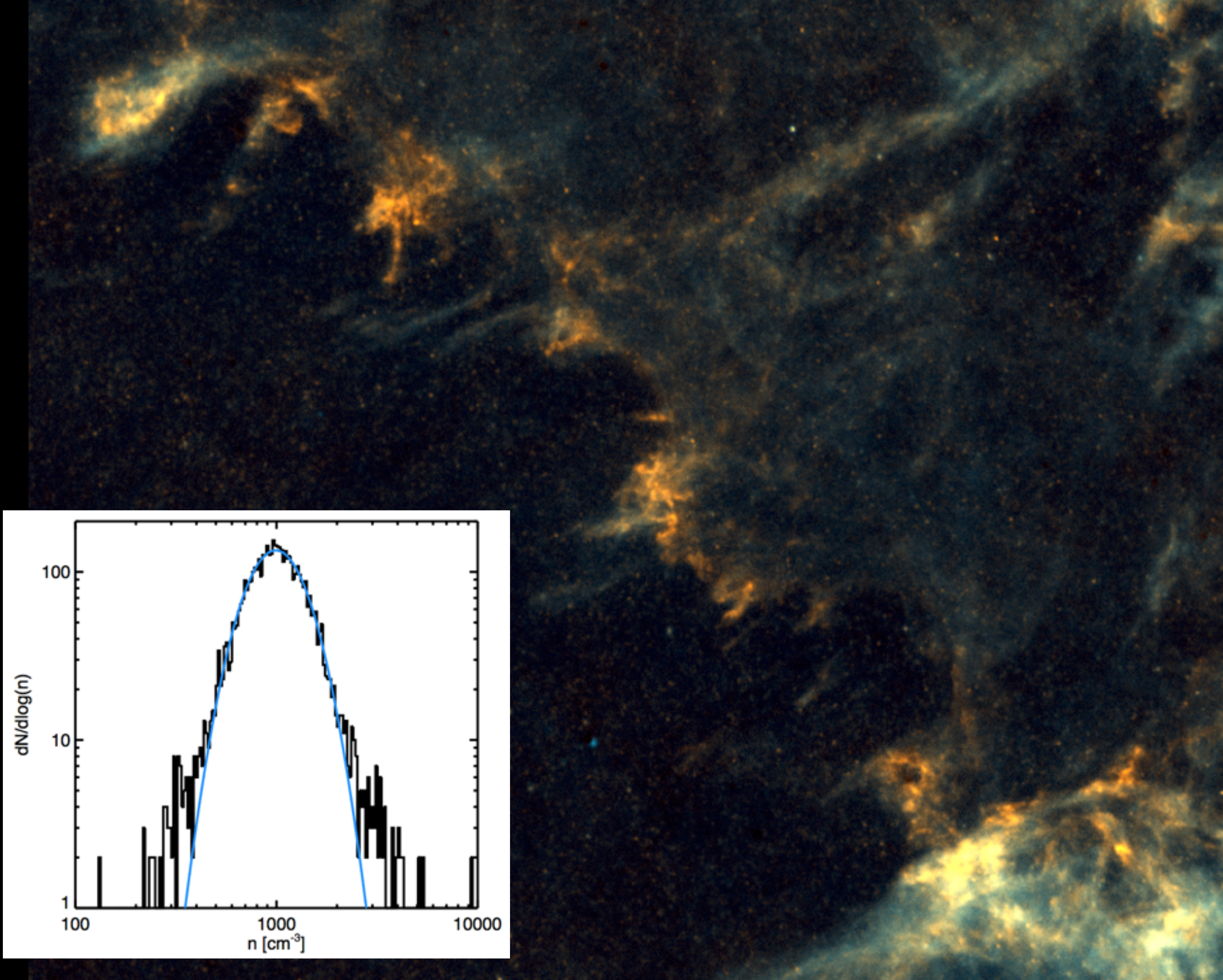


Perfect example of structure formation in a colliding flow of warm gas.

Infall of warm gas from the Galactic halo.

The increase of pressure in the shock puts the gas in the thermally unstable regime leading to efficient formation of cold gas

Miville-Deschênes et al. 2017

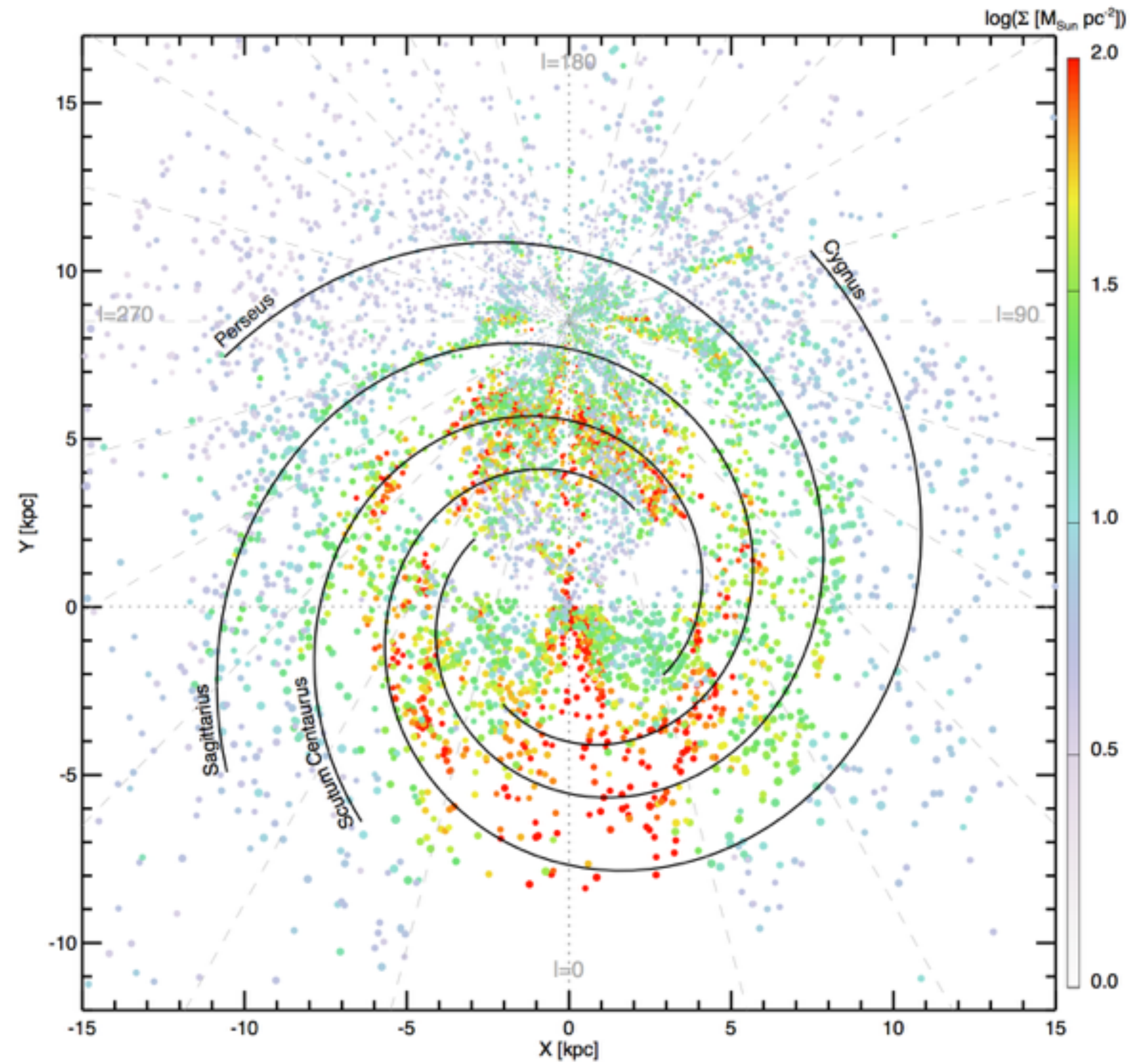

dN/dlog(n)
100
10
1
100
1000
10000
n [cm-3]

Messages

- Galactic emission is well described by a power law, down to arcsec scales, but that is not enough. It is also non-stationary and anisotropic.
- The high latitude sky is composed of a small number of dense, cold and anisotropic structures (1% of the volume) embedded in a warm medium. Mass is about 50-50%.
- Structure formation in the diffuse ISM starts in the non-self gravitating phase by a combination of turbulence and thermal instability

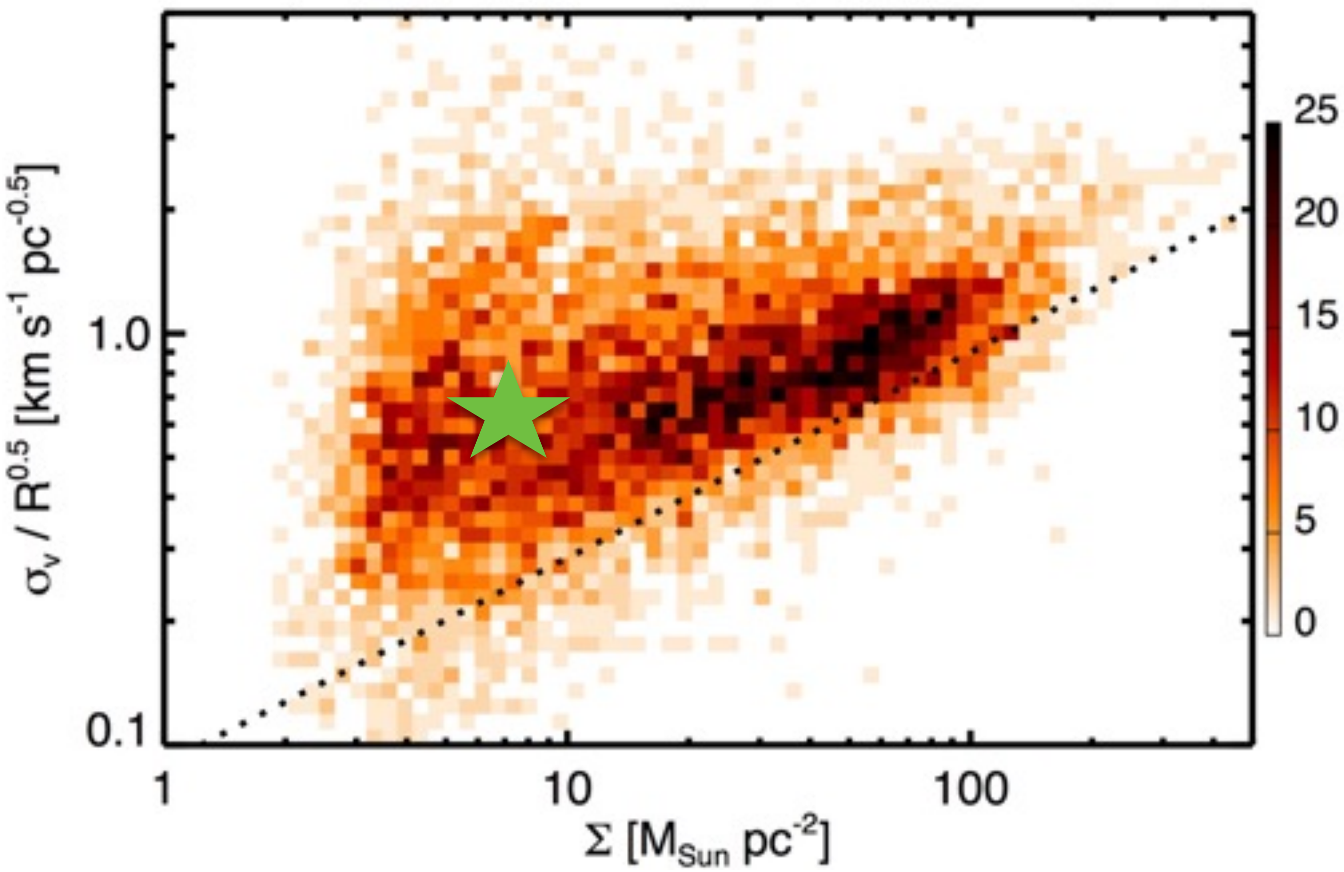
What about star formation ?

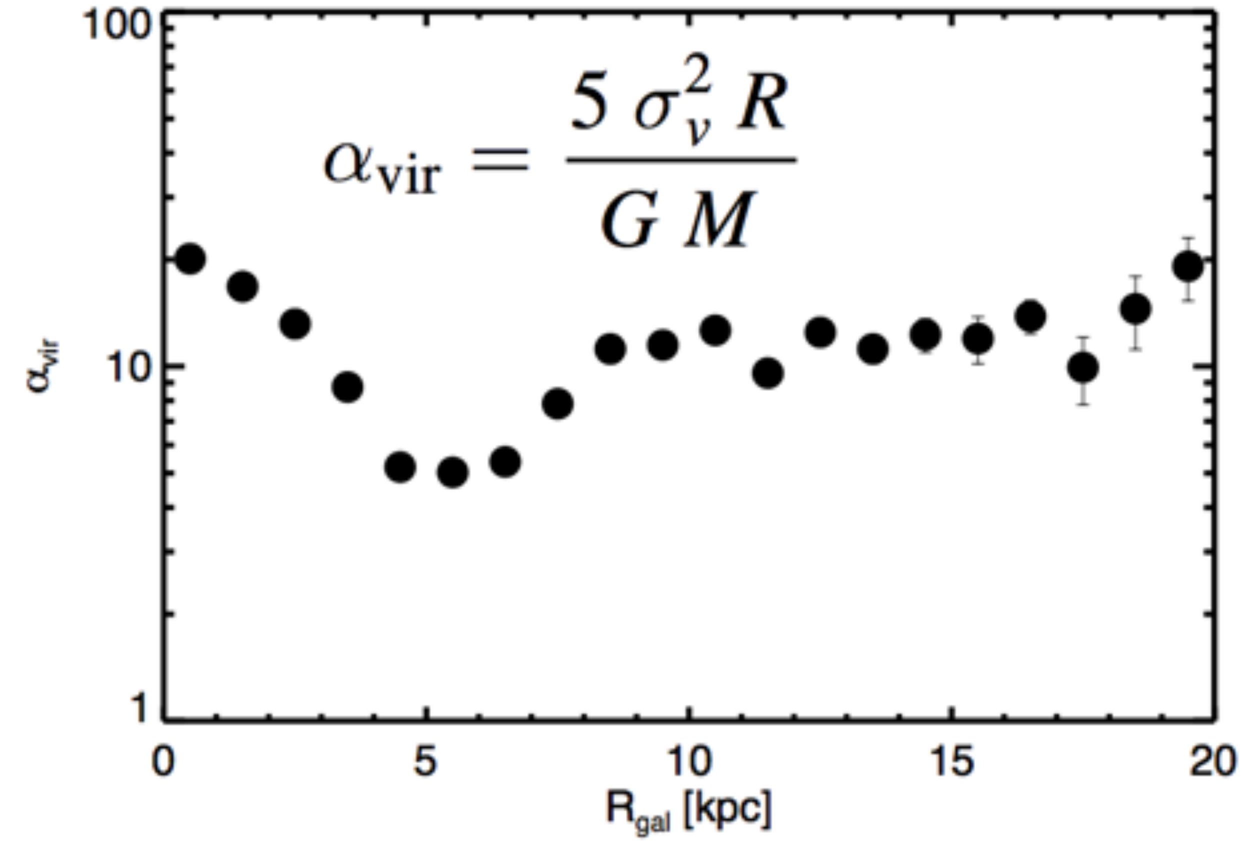
- Decomposition of the Dame et al. (2001) 12CO survey
- Identification of 8107 molecular clouds
- Outer Galaxy : large number of small clouds explained by the accretion of matter in large scale converging flows (Klessen & Hennebelle 2010)



Miville-Deschênes, Murray & Lee, 2017, ApJ, 834, 57

Most molecular clouds are not gravitationally bound





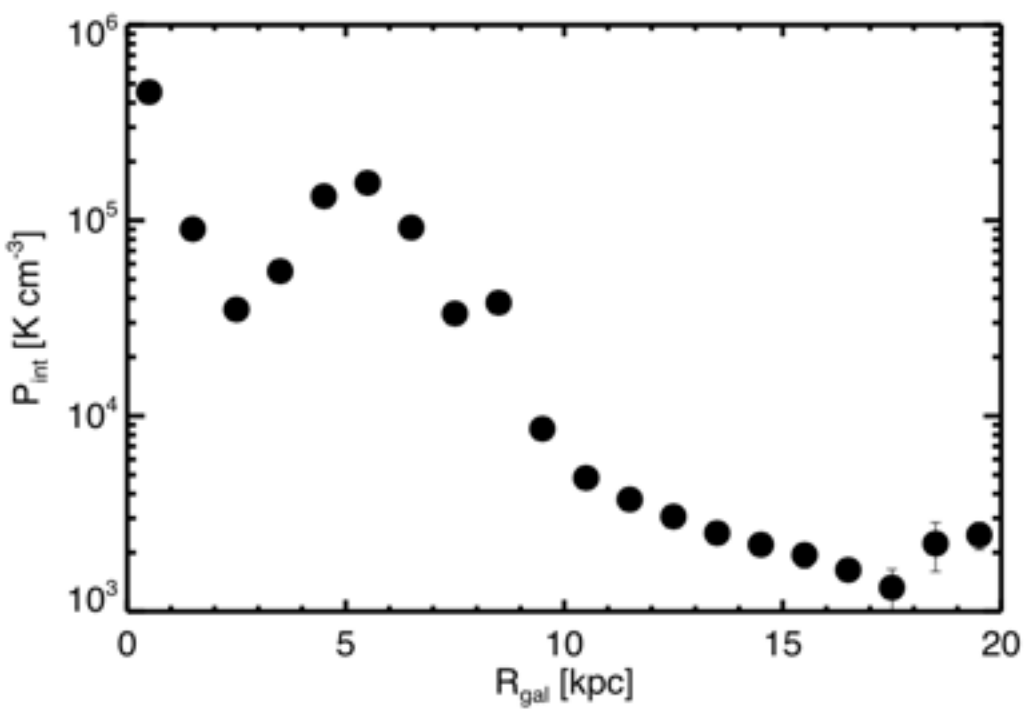
- Only 15% of clouds are bound by gravity (but they represent 40% of the mass)
- Smaller structures in clouds are bound by gravity.
- Molecular clouds evolve rapidly : stars form from small scale clumps inside big puffy clouds.
- Virial parameter is lower in the star forming part of the MW disk.
- In general there is a good correspondance between gravitational and kinetic energy

★ **WNM & CNM**

Miville-Deschênes, Murray & Lee, 2017, ApJ, 834, 57

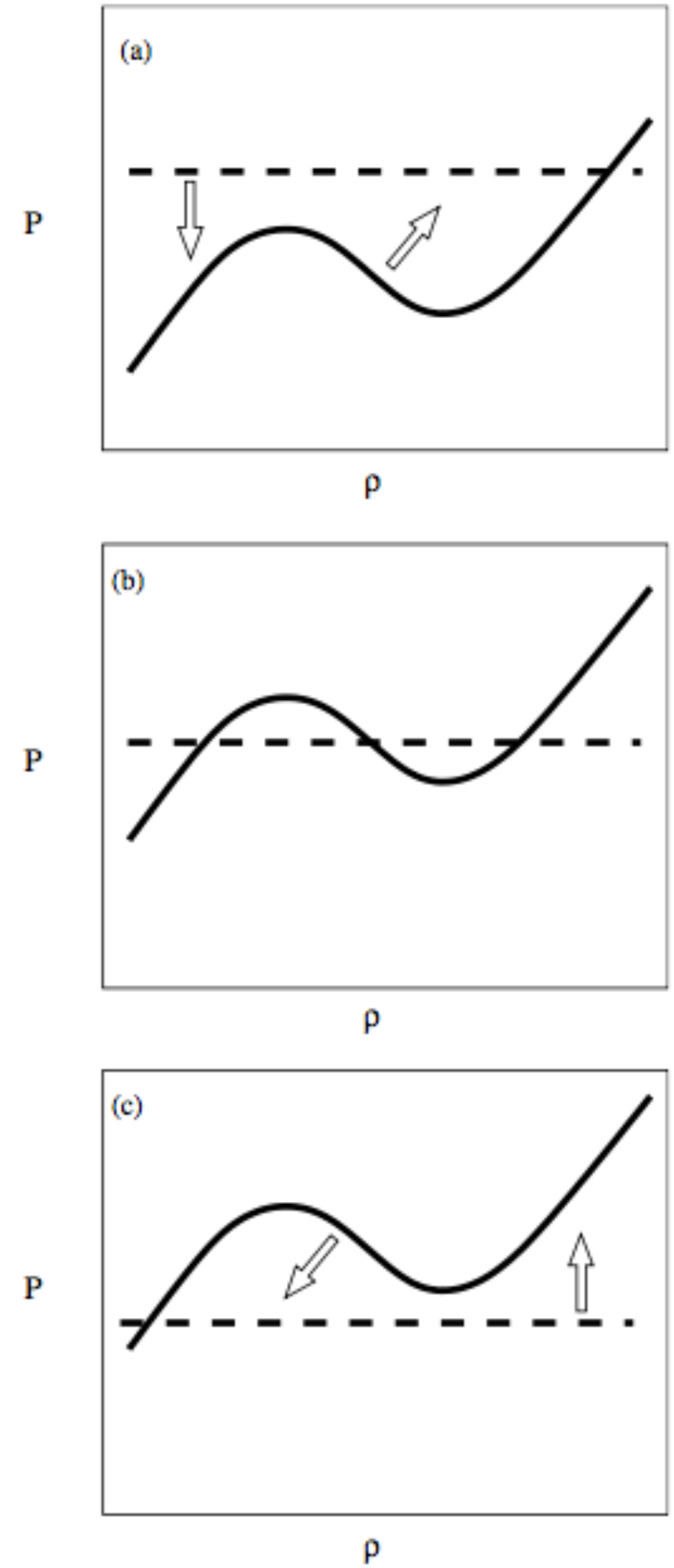
CNM formation and star formation

- Compatible with models of Ostriker+ (2010) showing that pressure sets the formation of cold structure and then the star formation rate



Miville-Deschenes+ (2017)

Ostriker et al. 2010



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France SKA White Book almost ready

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Thanks to instrumental teams :
your building the future of astrophysics/cosmology

Conclusion

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- Every time a new instrument increases the resolution, we have been surprised by the complexity and variety of what was revealed.