The Galactic interstellar medium as seen by Planck

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on behalf of the Planck Collaboration

cnes

irap
astrophysique & planétologie

Milky Way's
magnetic fingerprint

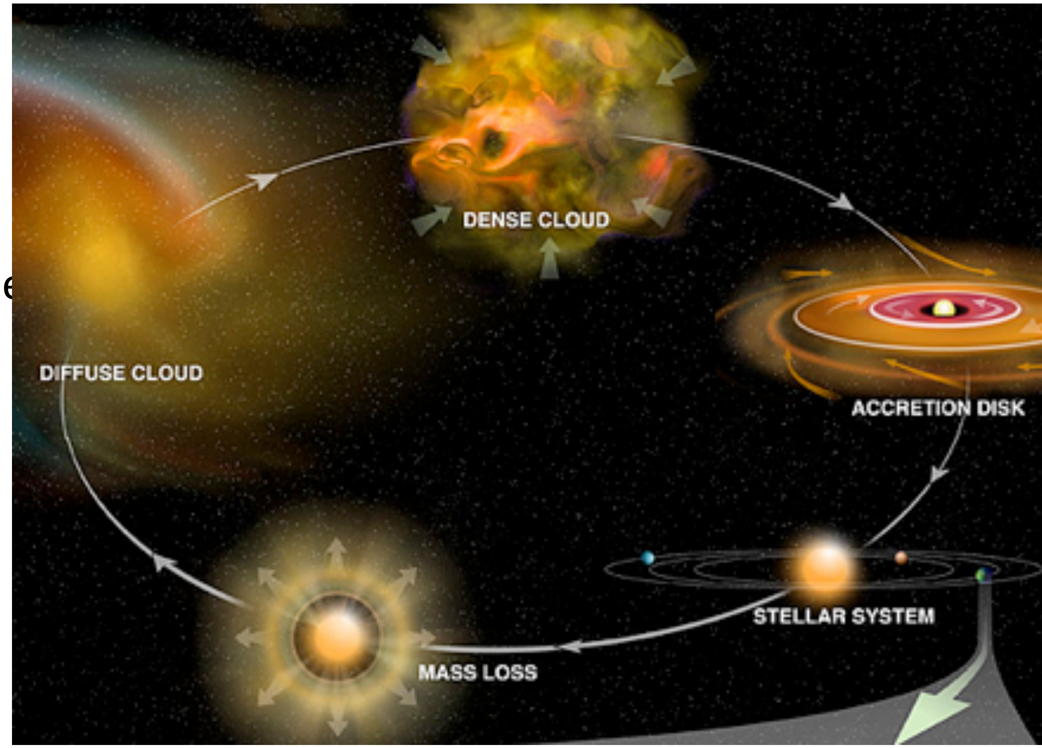
Interstellar Medium (ISM)

★ Interstellar matter (10-15% of the total mass in the Galactic disk):

- gas: electrons, ions, atoms, molecule
- dust: small solid particles mixed with the gas

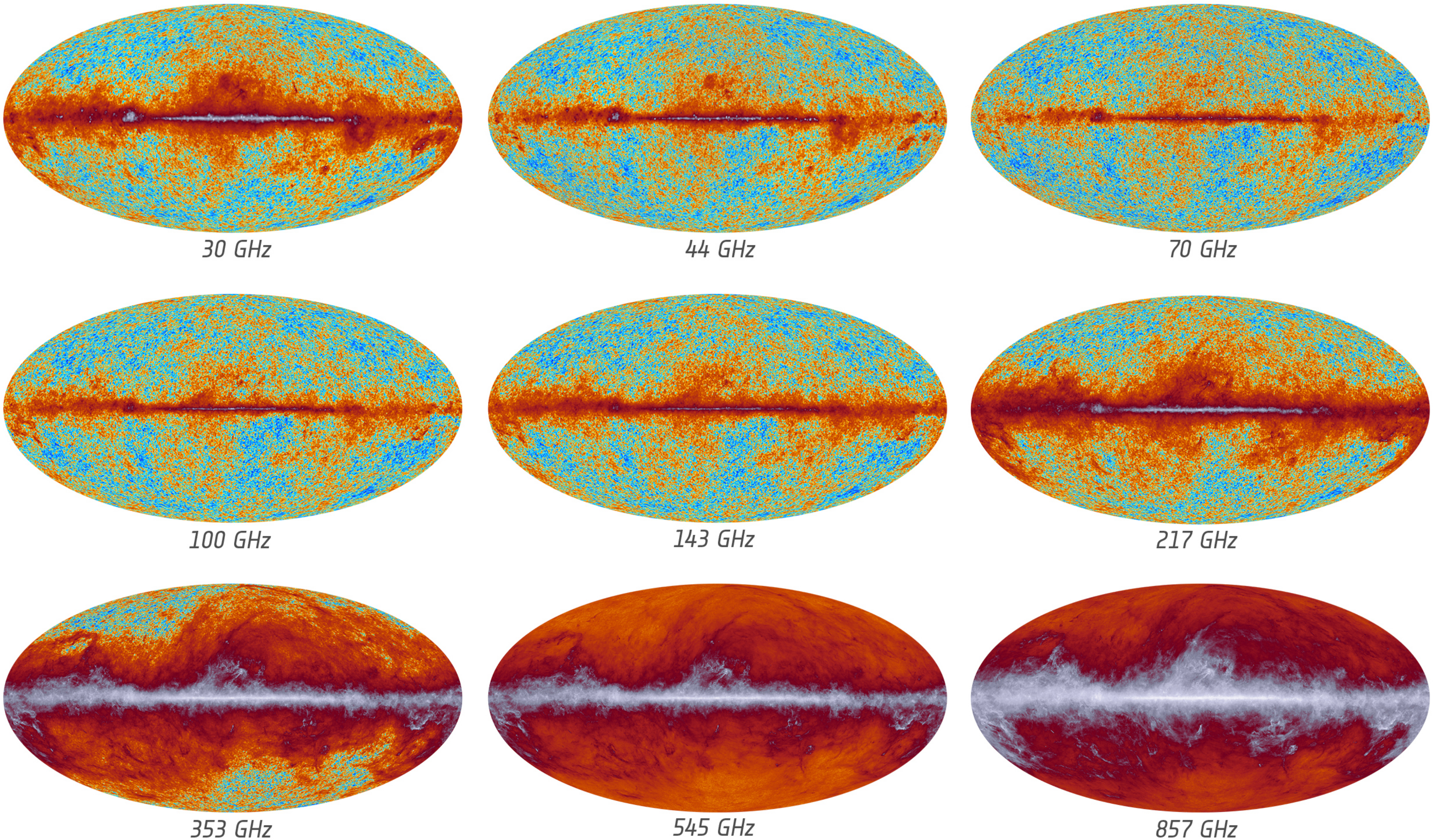
★ Cosmic rays

★ Magnetic fields



Energy in the ISM: thermal, kinetic (turbulent), gravitational, cosmic ray, magnetic and in photons (cosmic microwave background, far-infrared and starlight)
→ in near equipartition

The ISM probed by *Planck*



Planck 2013 results. I. (A&A 2014)

Outline

- Interstellar dust emission
  Tracing the structure of interstellar matter
- Anomalous Microwave Emission
  New perspective on interstellar matter
- Galactic (synchrotron) Haze
  Energetics of the Galactic centre
- Dust polarization
  Structure of the Galactic magnetic field

Dust emission

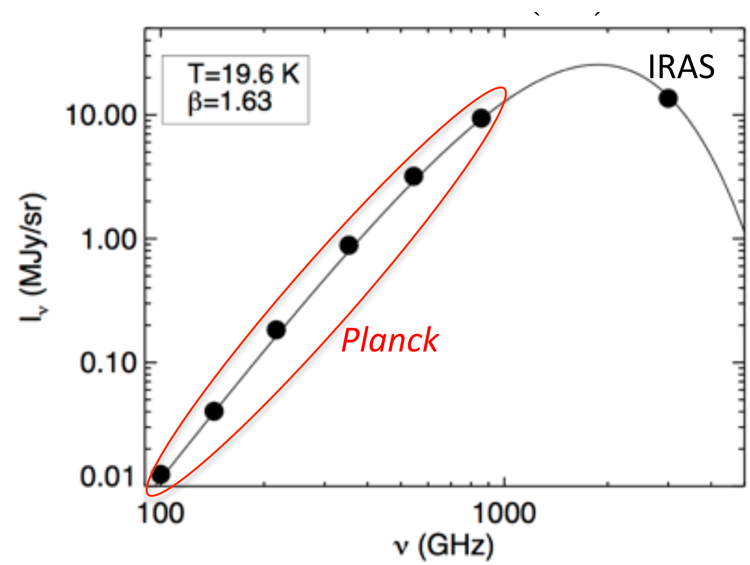
Dust traces the structure of the ISM from all gas phases

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

$$\tau_{353} = \frac{I_{353}}{B_{353}(T_{\rm obs})} = \sigma_{\rm e\,353} \, N_{\rm H}$$

Spectral coverage to derive the opacity accounting for temperature variations:

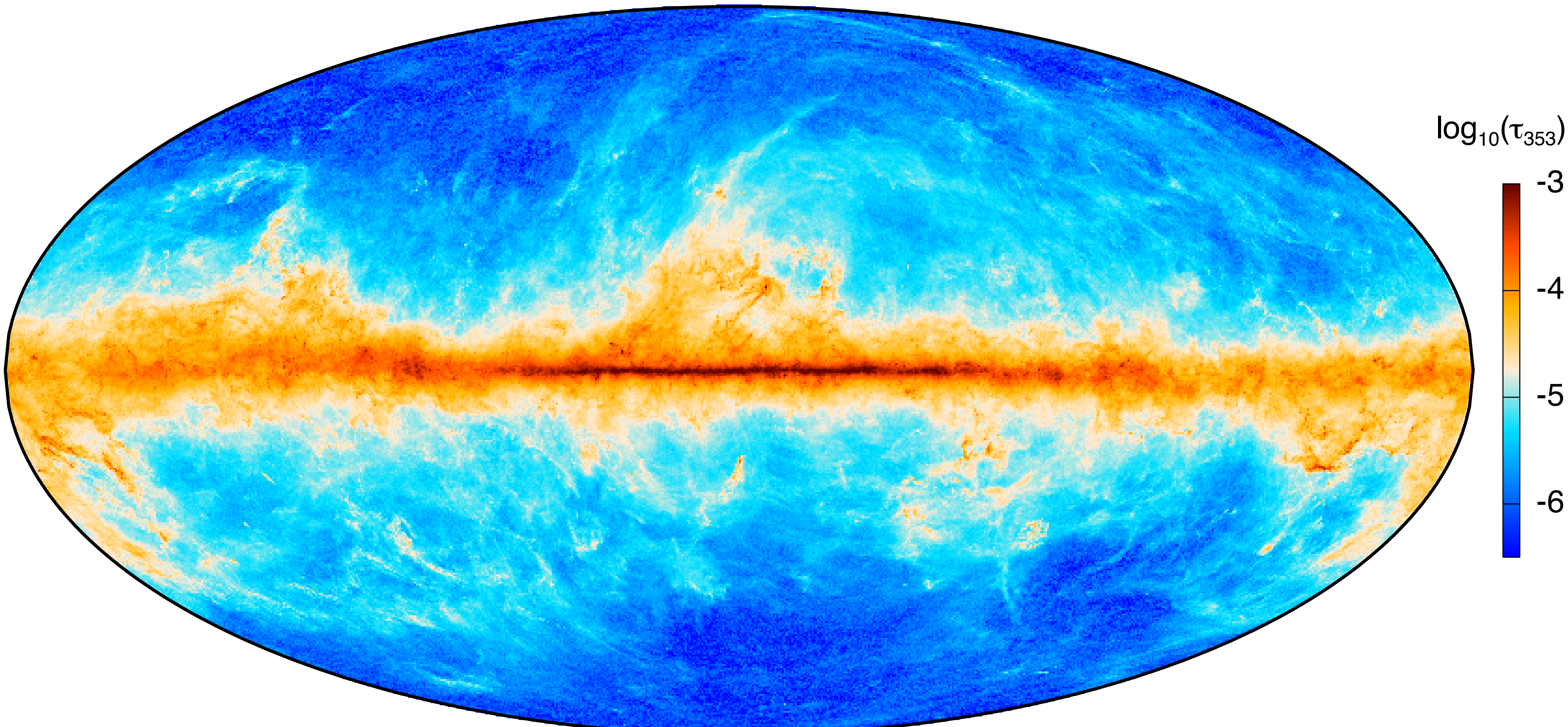
- All-sky map of dust optical depth
- Estimate mass of objects (of known distance)
- All-sky map of dust reddening



Dust optical depth

Tracer of N_H (dust-to-gas ratio, emission opacity)

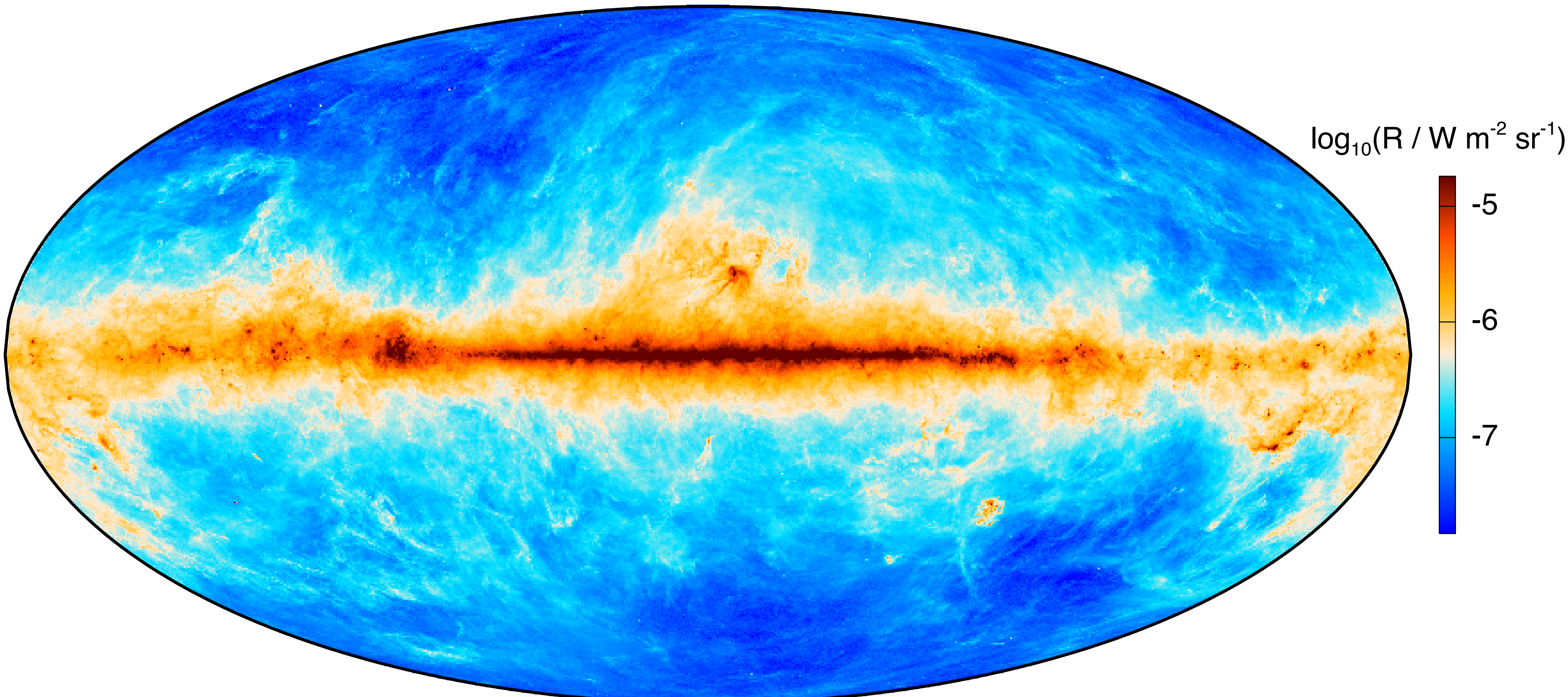
$$\tau_{353} = \frac{I_{353}}{B_{353}(T_{\rm obs})} = \sigma_{\rm e\,353}\, N_{\rm H}$$



Planck 2013 results. XI. (A&A 2014)

Dust radiance

Tracer of N_H (interstellar radiation field, absorption opacity) $\mathcal{R} = \int_\nu I_\nu \, \mathrm{d}\nu \propto U \, \overline{\sigma_\mathrm{a}} \, N_\mathrm{H}$



Planck 2013 results. XI. (A&A 2014)

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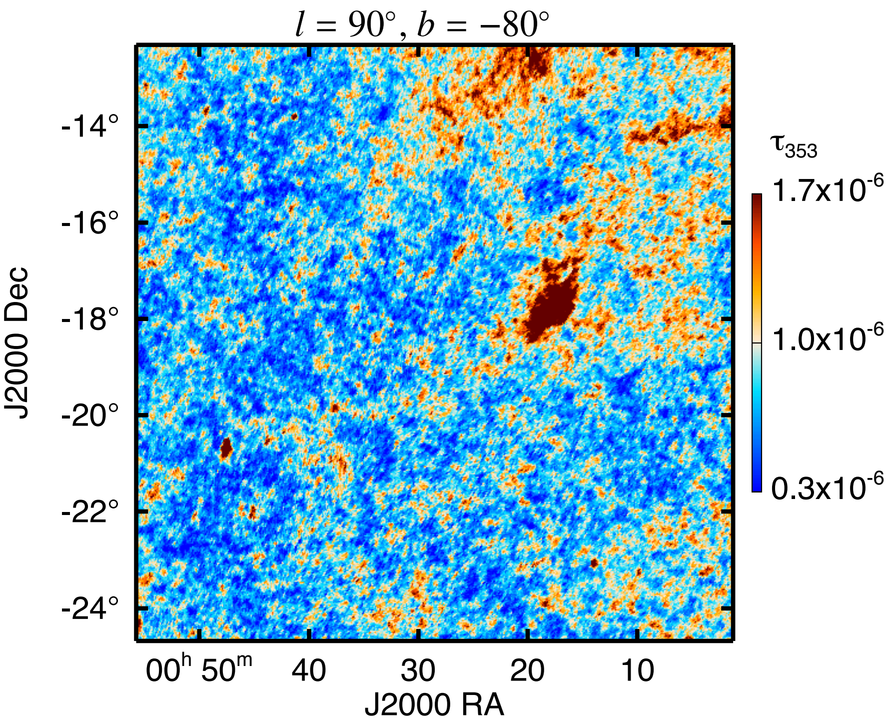
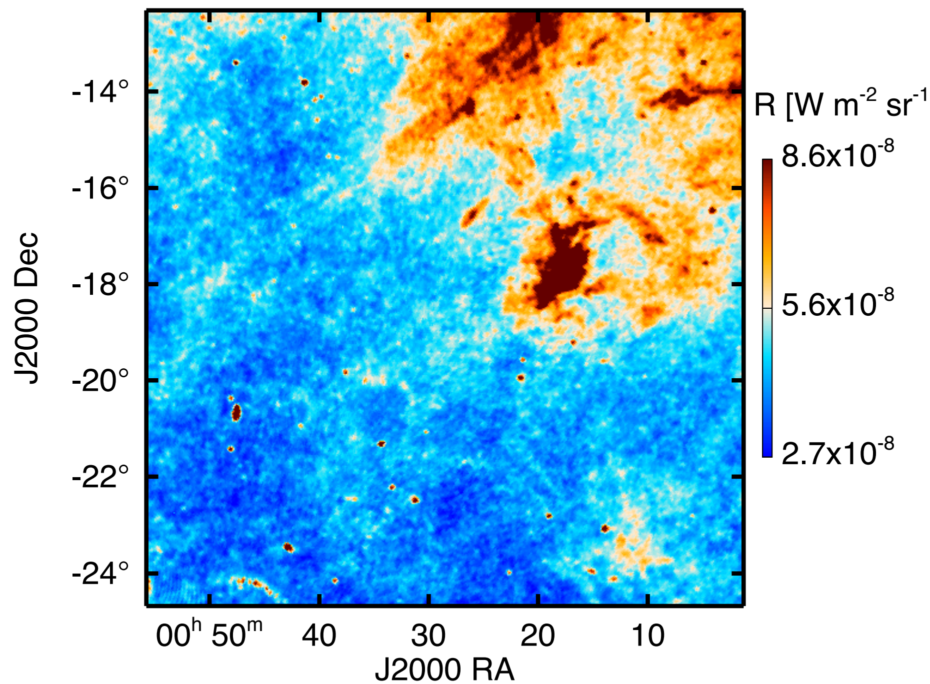
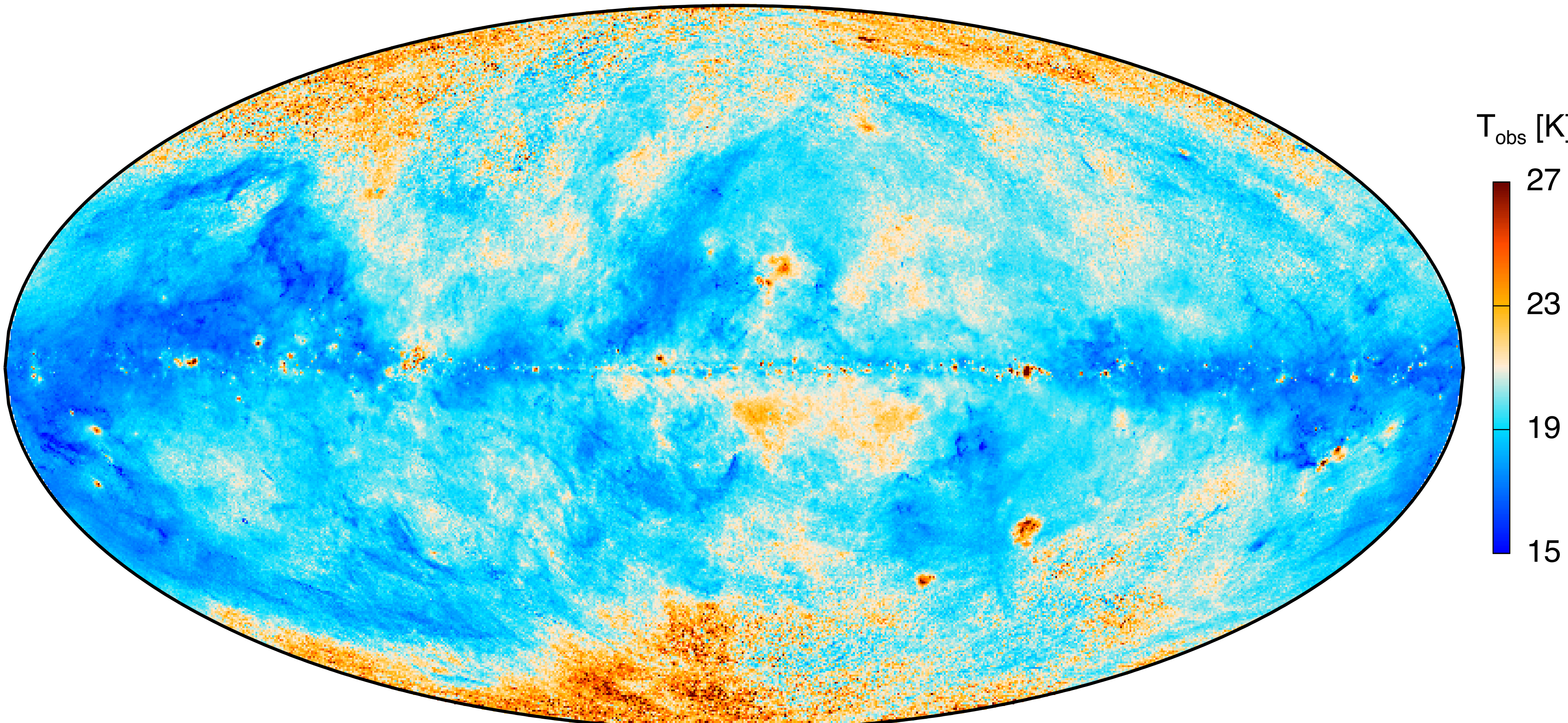




Planck 2013 results. XI. (A&A 2014)

Observed dust temperature



Planck 2013 results. XI. (A&A 2014)

Median 19.7 K
Standard deviation 1.4 K

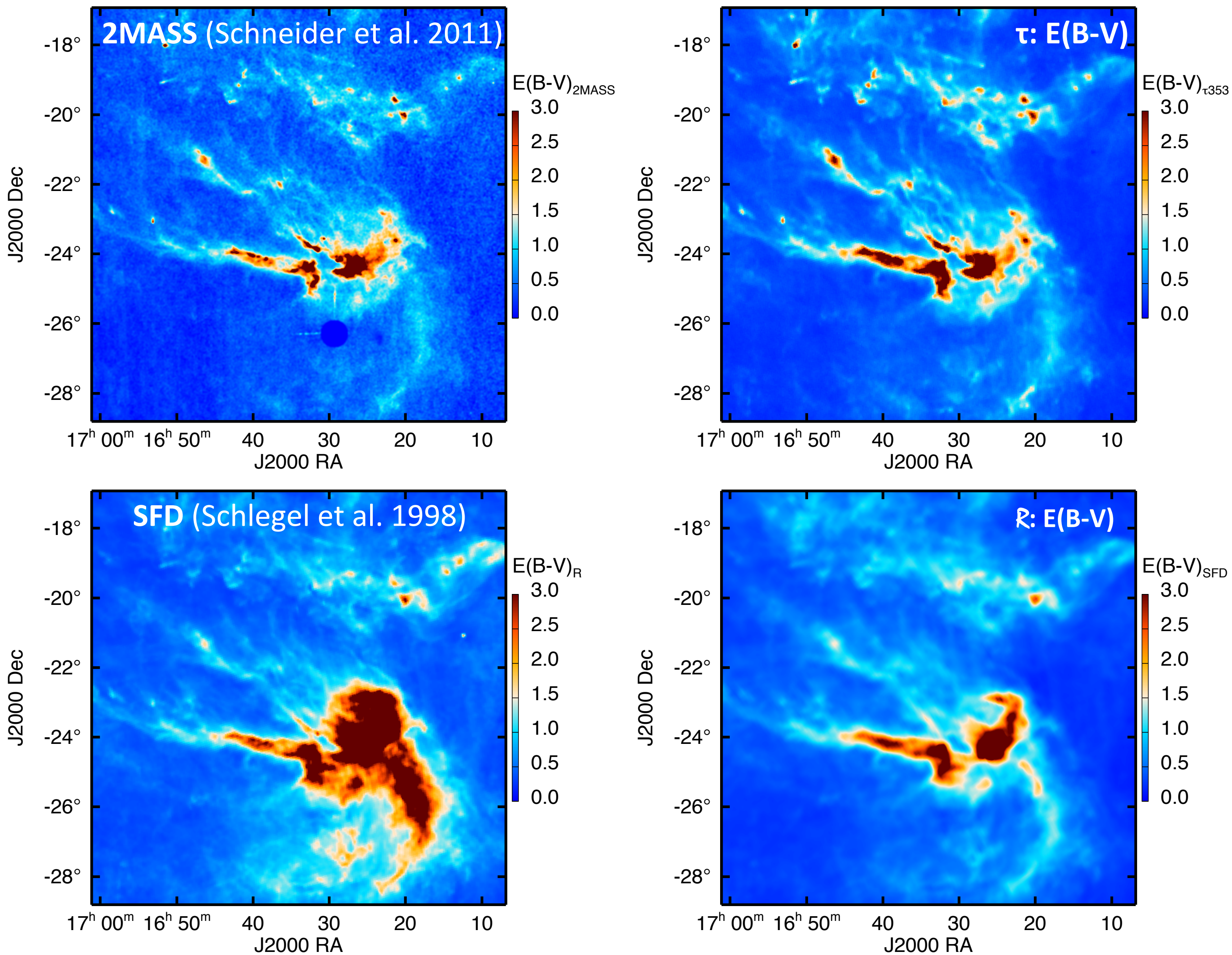
Extinction from *Planck*: E(B-V)

Planck 2013 results. XI. (A&A 2014)

Extinction: obscuration and reddening of starlight as a result of absorption and scattering.

Planck delivered a map of dust reddening for Galactic and extragalactic studies

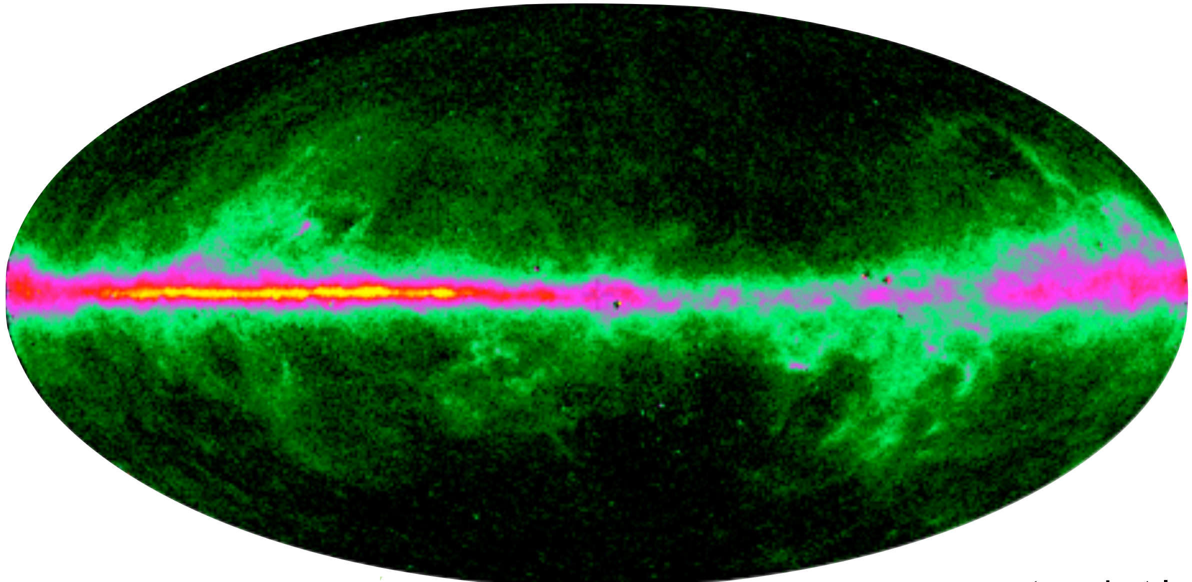
Rho Ophiucus molecular cloud



Synergies with Fermi

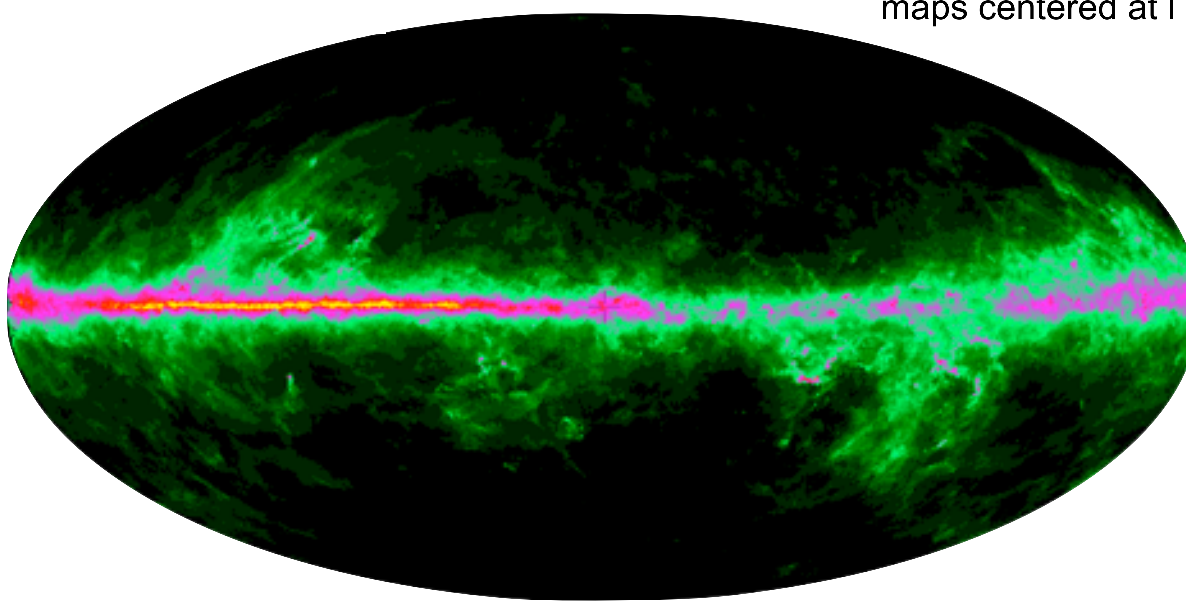
I. Grenier, 47th ESLAB symposium 2013

Fermi: 0.6-7 GeV photons



maps centered at l = 270°

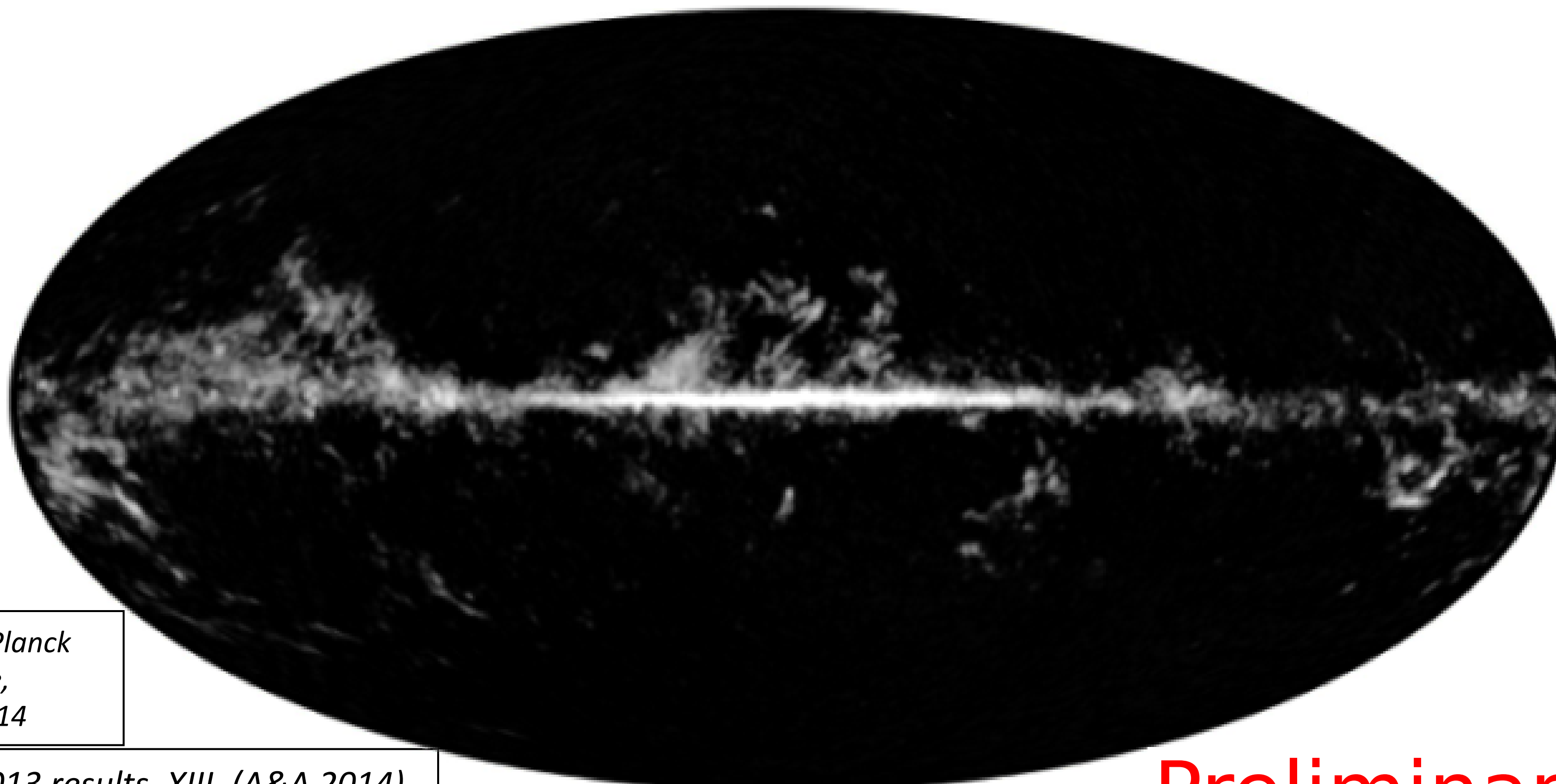
Planck: dust optical depth



Dark neutral medium

Transition between bright-HI and bright-H_2 gas: opaque HI and H_2 gas with little or no CO (predicted theoretically by van Dishoeck & Black 1988)

Discovered as an excess in dust emission above the neutral and molecular gas tracers:
$\tau = a_{HI} N_{HI} + a_{CO} W_{CO} +$ **dark gas** (e.g. Blitz et al. 1990, Grenier et al. 2005, Lee et al. 2012)



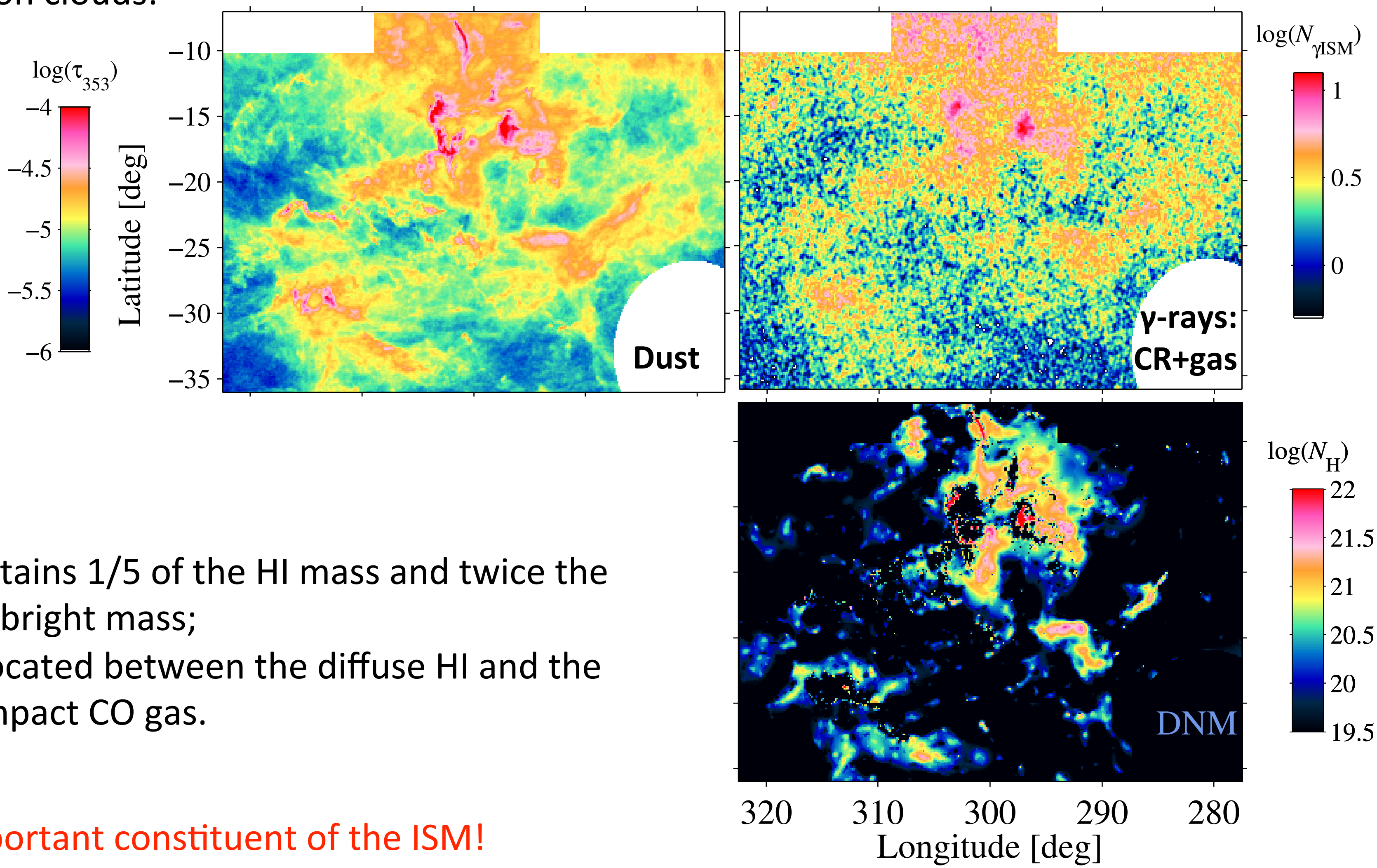
I. Wehus, Planck conference, Ferrara 2014

Planck 2013 results. XIII. (A&A 2014)

Preliminary!

Dark neutral medium – *Planck* and Fermi

Chamaeleon clouds:



DNM:

- contains 1/5 of the HI mass and twice the CO-bright mass;
- is located between the diffuse HI and the compact CO gas.

→ Important constituent of the ISM!

Planck intermediate results. XXVIII. (A&A sub.)

Anomalous Microwave Emission

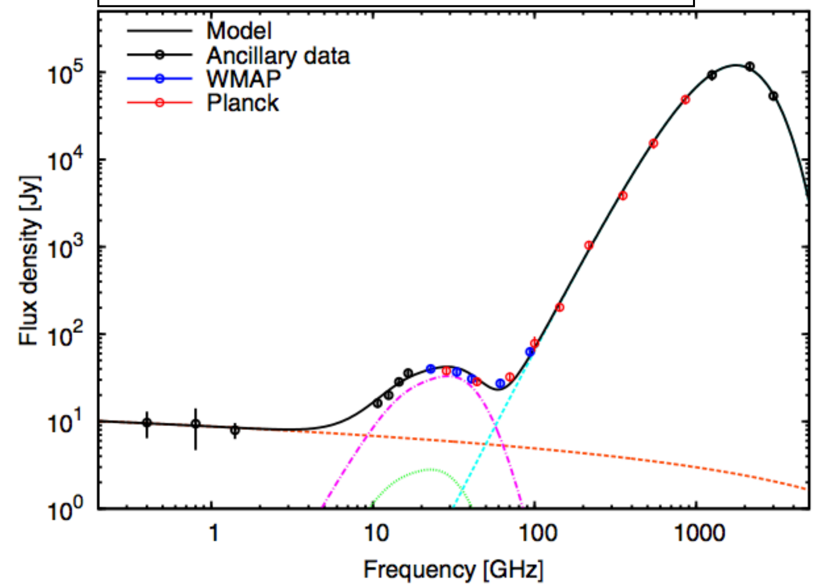
Kogut (1996), Banday et al. (2003), Davies et al. (2006)

- Additional source of diffuse radio emission at frequencies ~ 10-60 GHz
  → Most likely electric dipole radiation from spinning dust grains - First predicted by W.C. Erickson in 1957

- Strongly correlated with far-infrared emission
- Does not appear to be strongly polarized
- Observed in a range of environments
- Before *Planck* only a very few convincing detections in star-forming regions
- Planck intermediate results. XII. (A&A 2013) studies AME in the diffuse ISM
- Planck intermediate results. XV. (A&A 2014) studies AME in individual objects (HII regions, dust clouds)

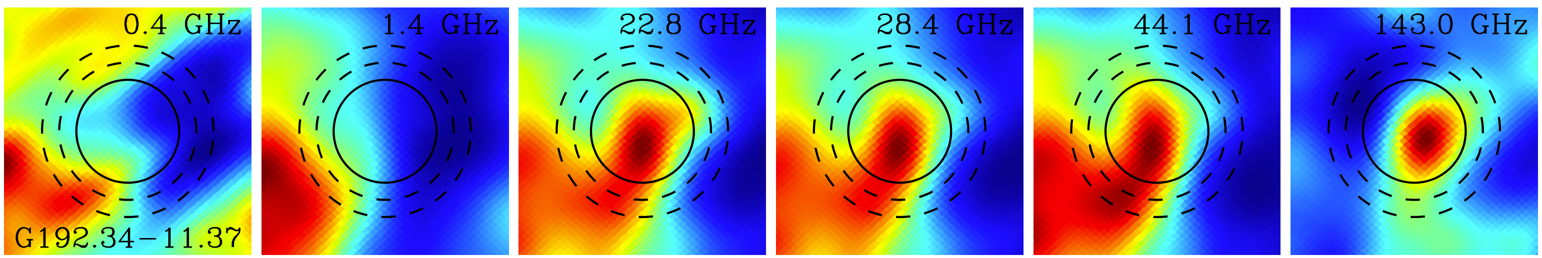
Perseus molecular cloud

Planck early results. XX. (A&A 2011)



AME – individual objects

- Sample of **98 sources** (not a complete sample!) – significant number (27) shows very strong detections of excess emission at 20-60 GHz
- SEDs constructed from aperture photometry, combining Planck with WMAP, IRAS/ DIRBE, low frequency radio data (at 1 degree resolution)
- Fit simple models of optically thin free-free, CMB, thermal dust, synchrotron and spinning dust

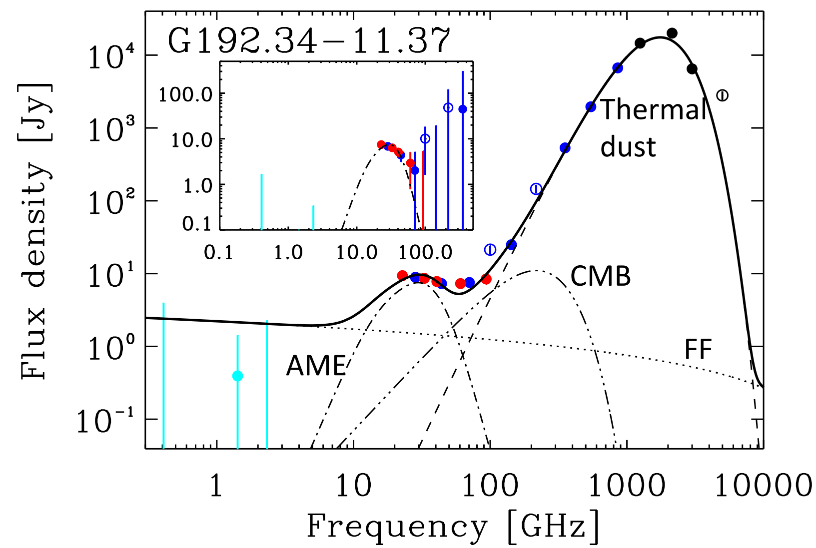


Planck intermediate results. XV. (A&A 2014)

→ Dust in AME regions is colder (14-20 K) than in non-AME objects (20-27 K)

→ AME originates in diffuse rather than more dense regions where PAHs coagulate onto larger grains

→ It arises in the cold neutral ISM phase from radiative and collisional excitation

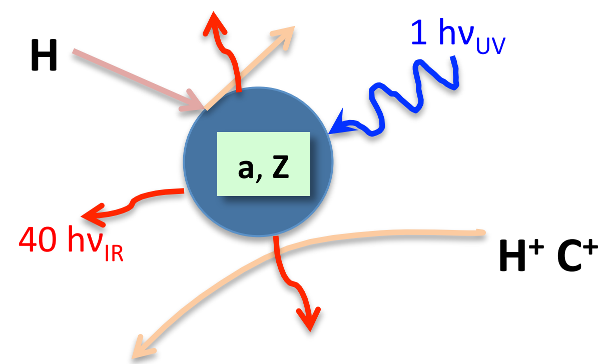


AME – Physical model

- SpDUST (Ali-Haïmoud et al. 2009, Silsbee et al. 2011)
- Hoang et al. (2010,2011)

  Grain properties and dipole moments – still with many simplifications

  Excitation of the particles: collisions, plasma drag, IR photons



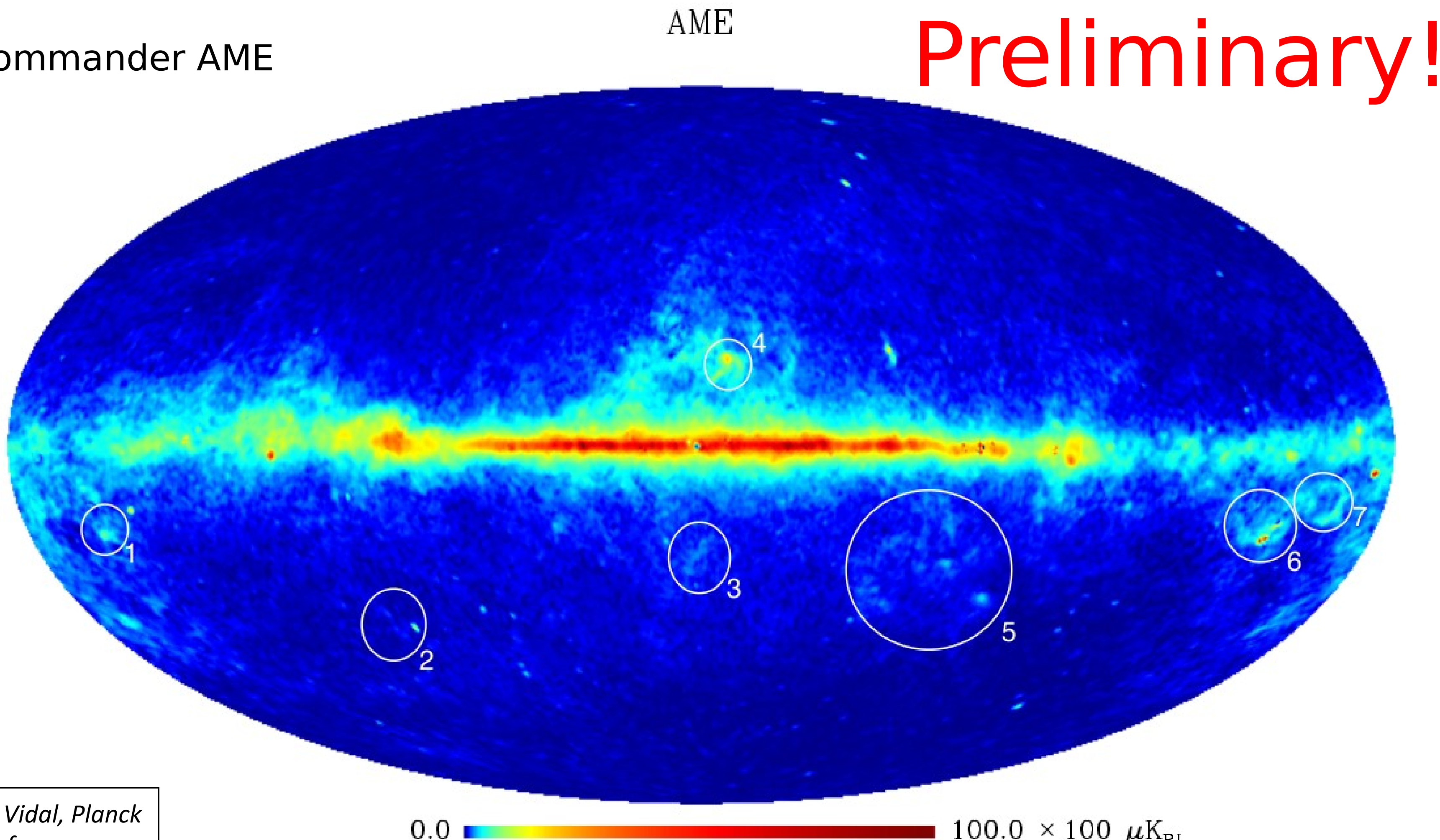
Derived parameters include **density** and **ISRF**, also the dipole moment of PAHs

Spinning dust provides a potential diagnostic for interstellar dust properties – PAH abundance gradients

Small grains are important in the ISM (heating, chemistry, etc)

AME – new detections

Commander AME

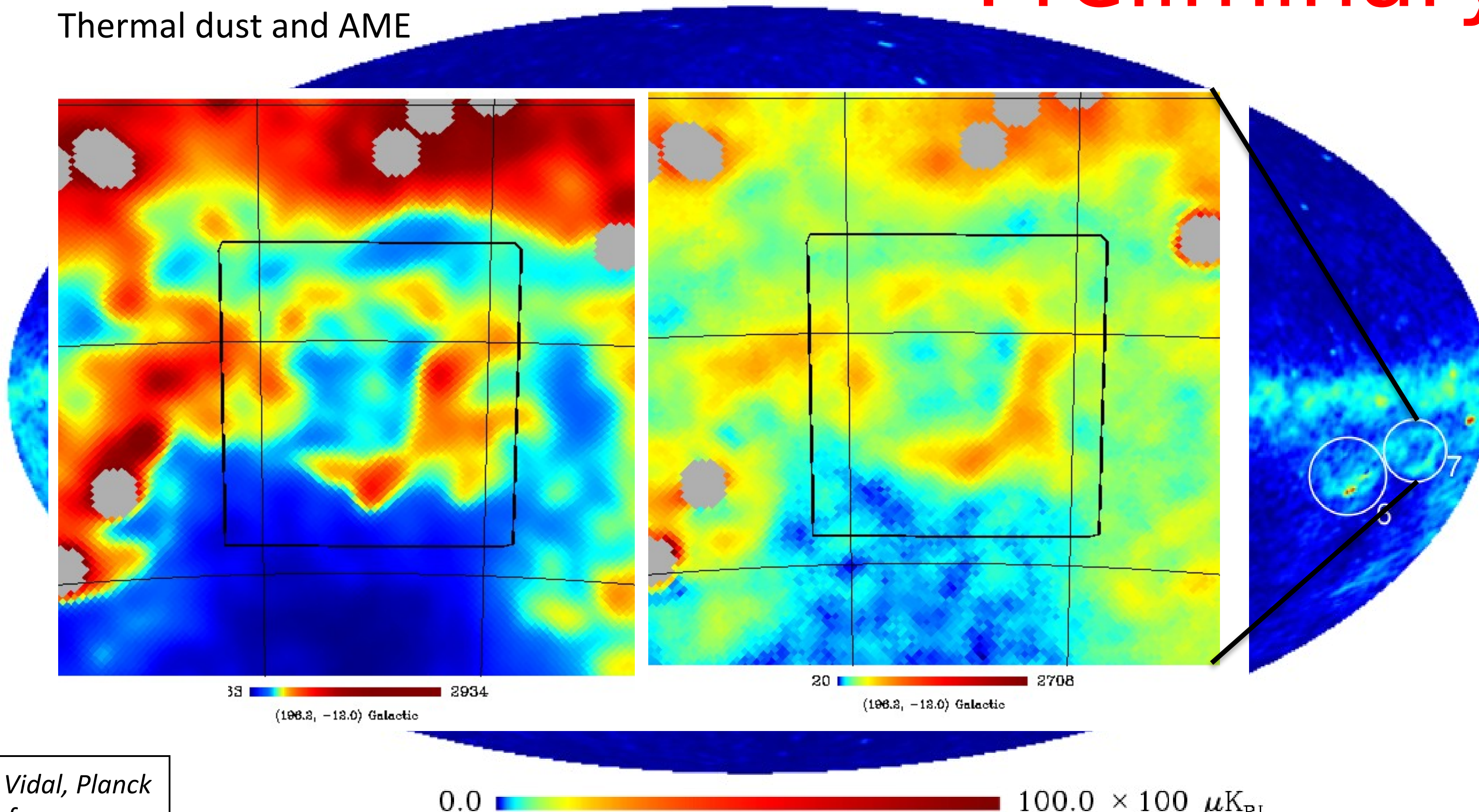


M. Vidal, Planck conference, Ferrara 2014

AME – new detections

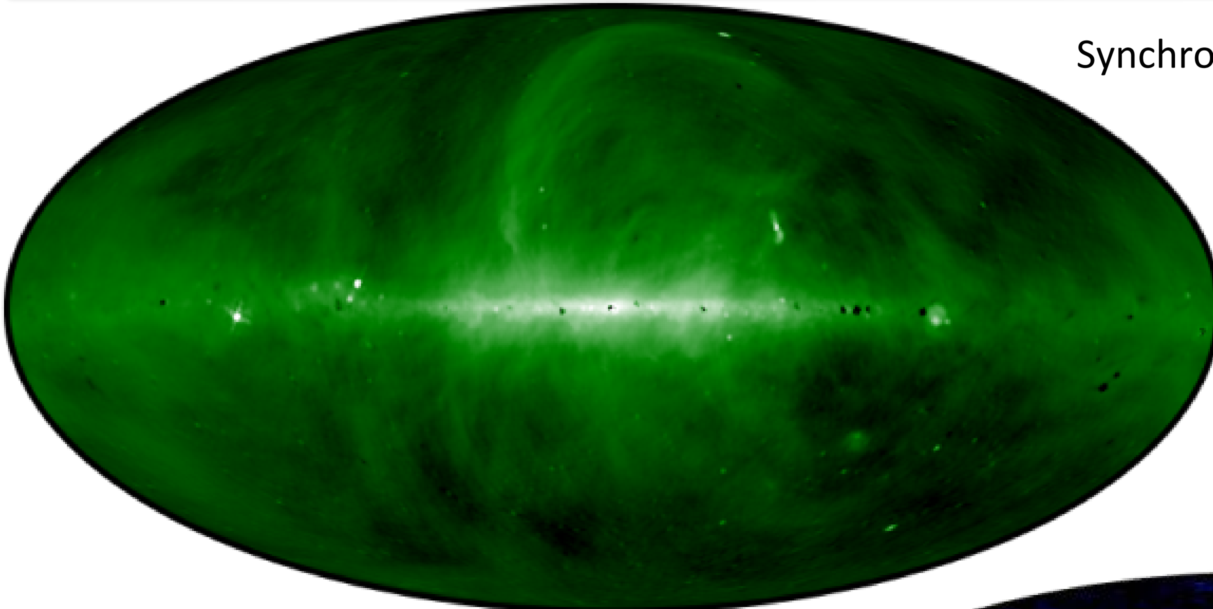
Preliminary!

λ-Orionis
Thermal dust and AME



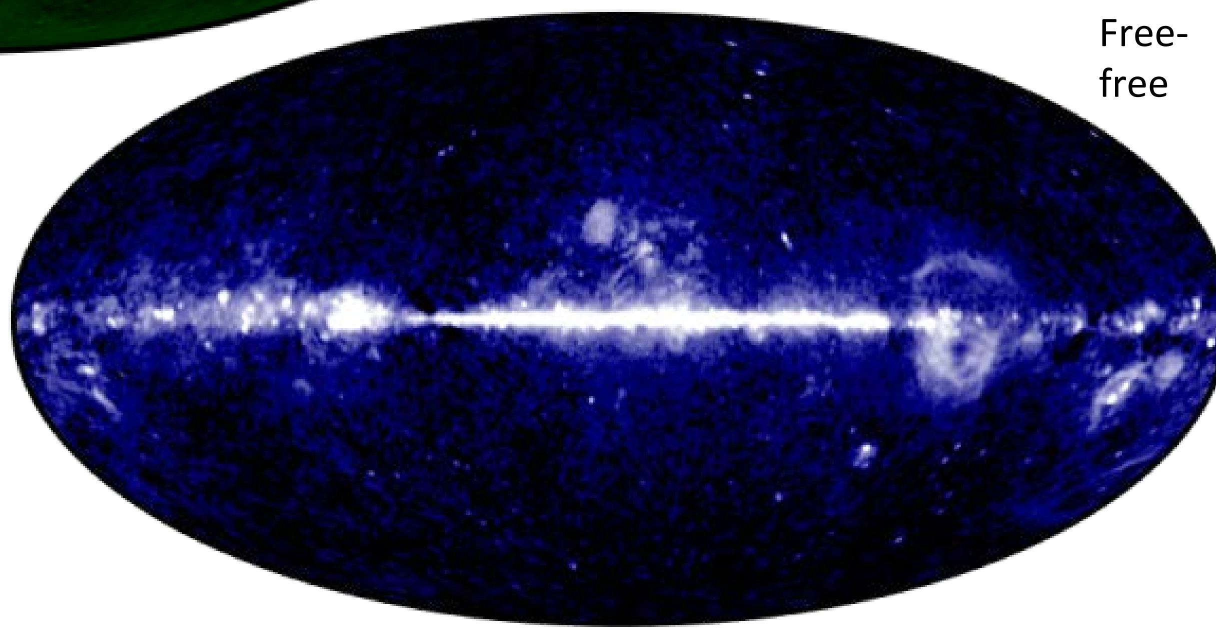
M. Vidal, Planck conference, Ferrara 2014

Galactic emission components



Synchrotron

Preliminary!



Free-
free

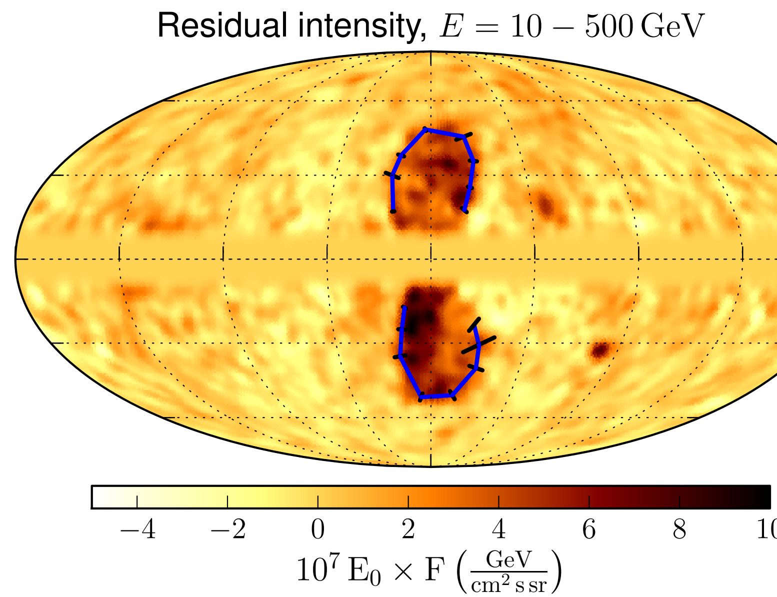
I. Wehus, Planck conference, Ferrara 2014

Microwave haze and Fermi bubbles

- Microwave haze found after subtraction of other (known) Galactic components (Finkbeiner 2004, Dobler & Finkbeiner 2008)

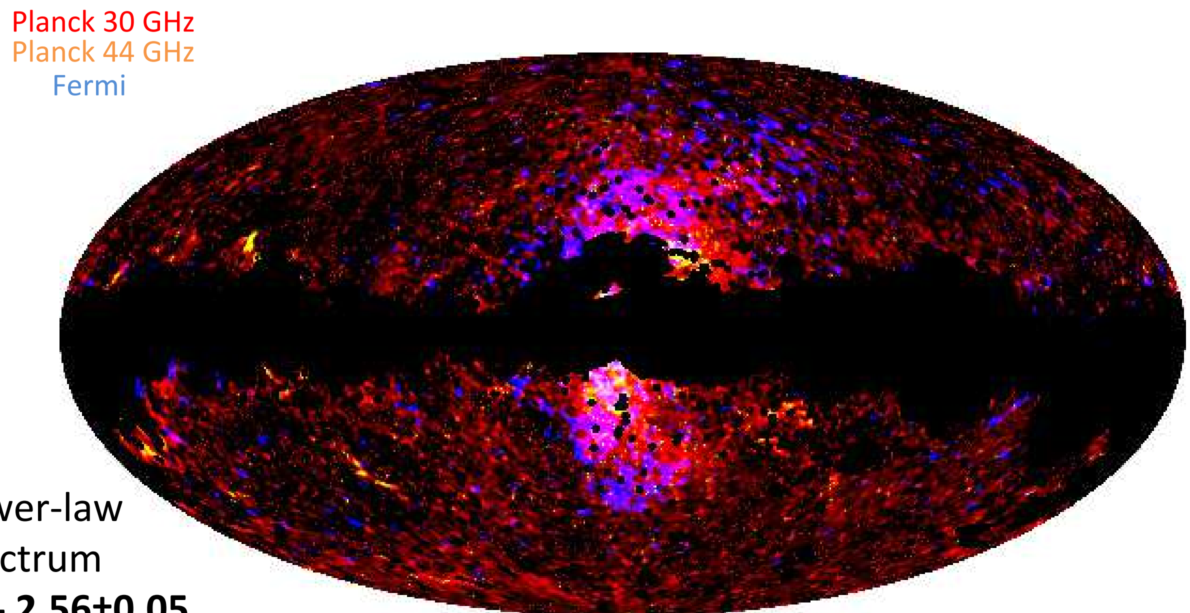
- Fermi bubbles, extend to about 55° above and below the Galactic centre (Dobler et al. 2010, Su et al. 2010, Ackermann et al. 2014)

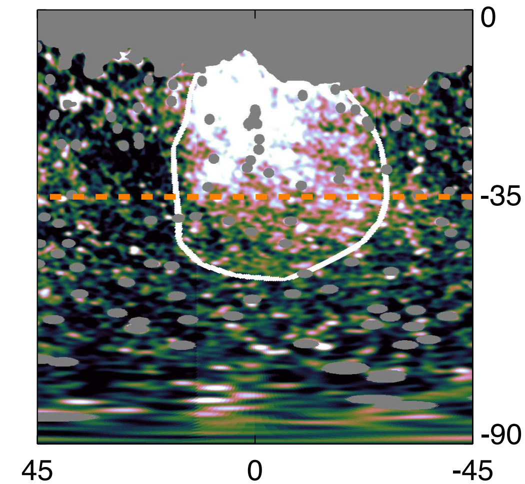
Origin?
Star formation driven (e.g., winds from supernova explosions) or associated to central massive black hole (e.g., outflows or shocks from different accretion events)?



Ackermann et al. (ApJ 2014)

Fermi bubbles in *Planck* data





Power-law spectrum
β= - 2.56±0.05,
(- 3.1 elsewhere)

- Microwave haze consistent with IC from a population of electrons with energy spectrum required to reproduce β=-2.56, dN/dE α $E^{-2.1}$ (so are the Fermi bubbles, Ackermann et al. 2014)
- Strong spatial coincidence between Planck haze and Fermi bubbles at low latitude, |b|<35°

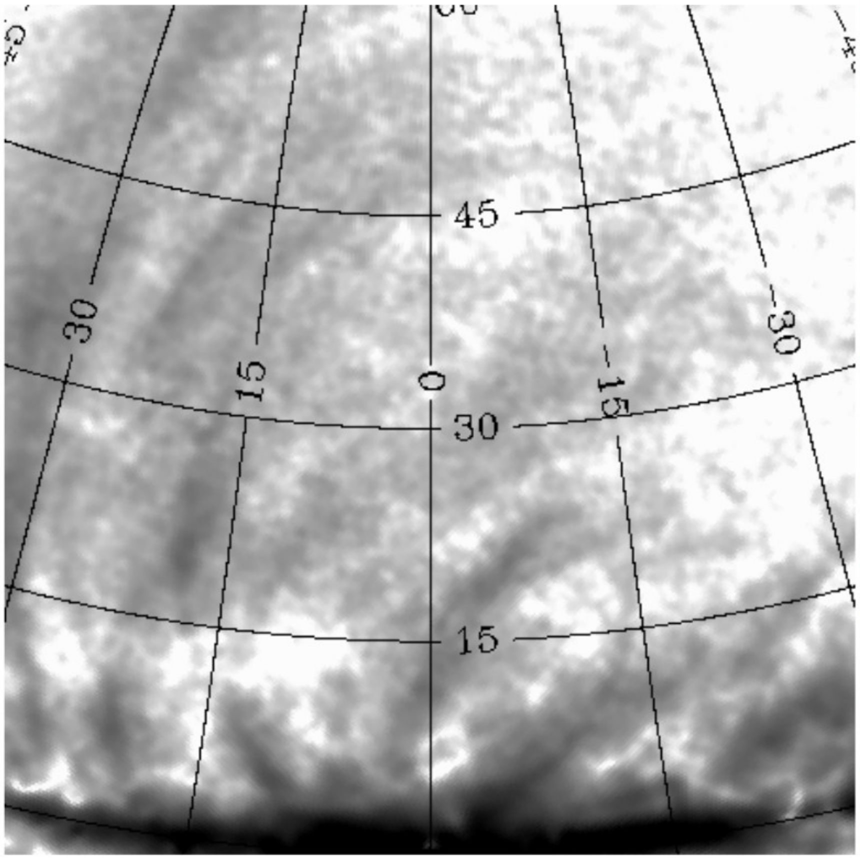
→ The magnetic field within the haze decreases ~5 kpc away from the Galactic plane, whereas the CR distribution extends to ~10 kpc

Planck intermediate results. IX. (A&A 2013)

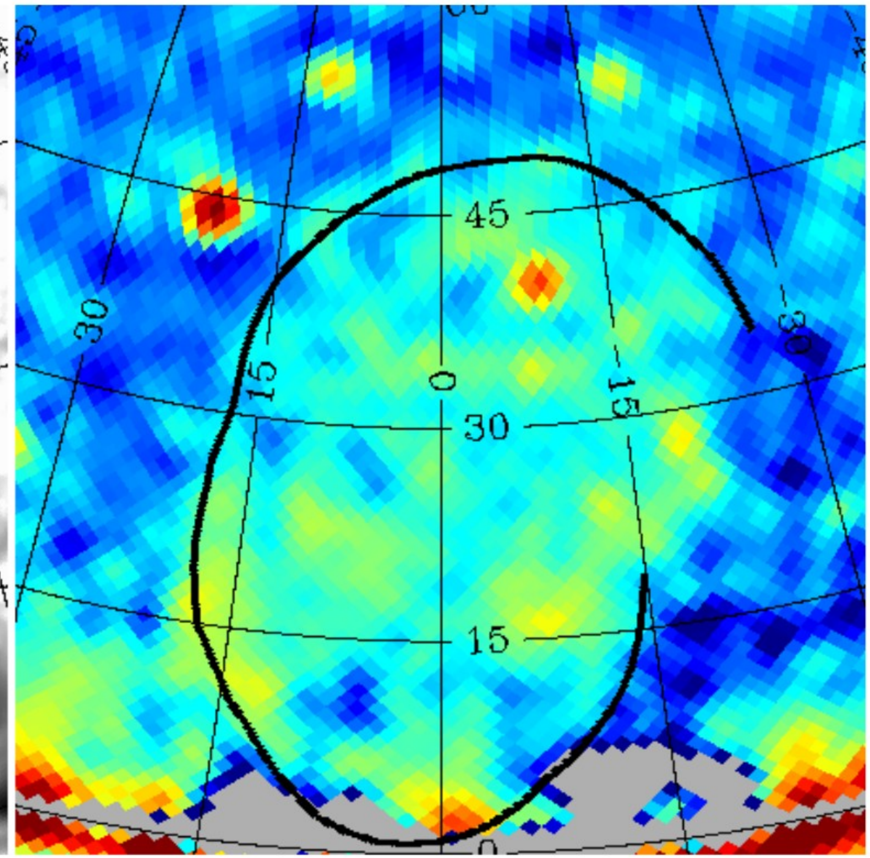
Fermi bubbles in polarization

Preliminary!

Planck Pol. Amplitude



Fermi, E > 10 GeV

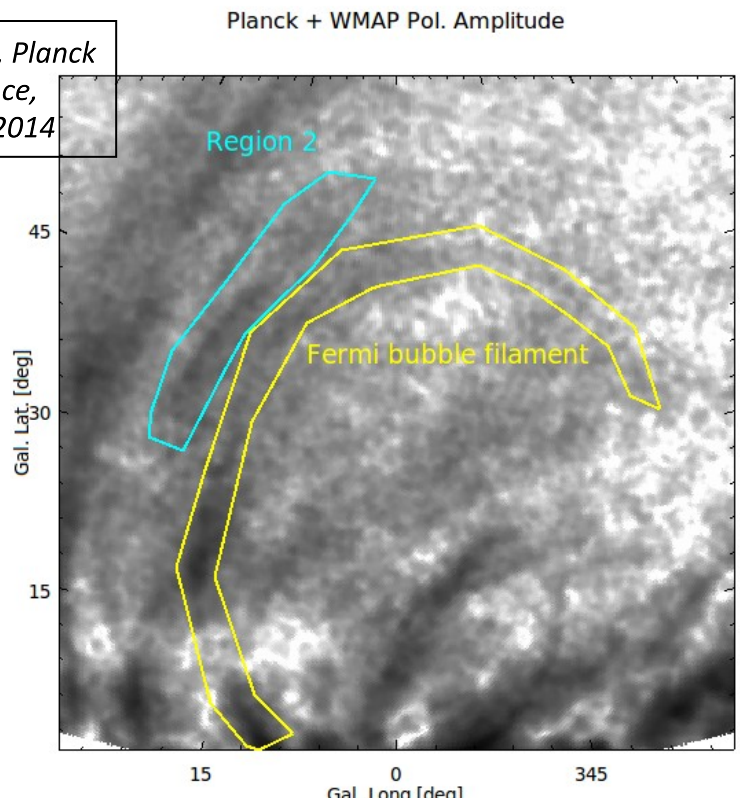


M. Vidal, Planck conference, Ferrara 2014

Fermi bubbles in polarization

Spectral index of *Planck*+WMAP polarized emission (between 23 and 30 GHz):
Bubble β = -2.3±0.1
Control region β = -2.9±0.3

M. Vidal, Planck conference, Ferrara 2014

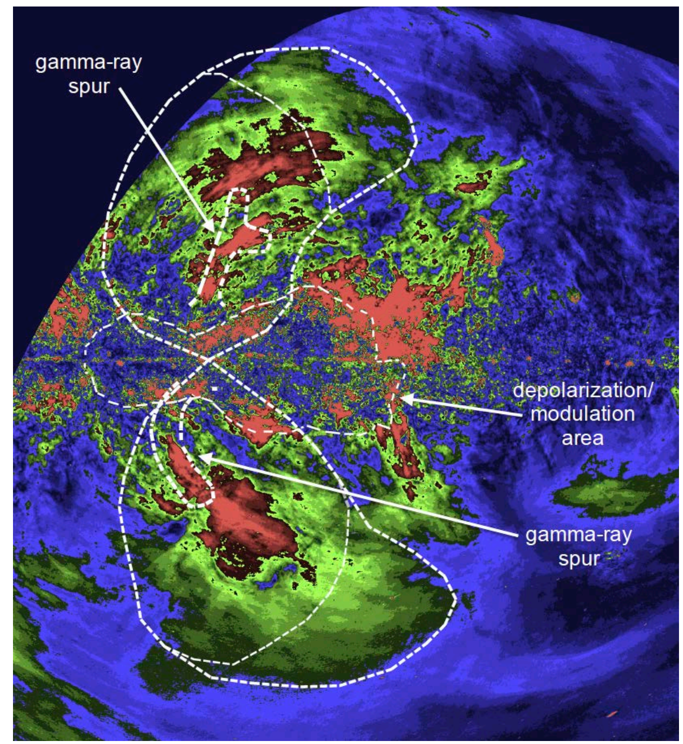


Flatter spectral index

Preliminary!

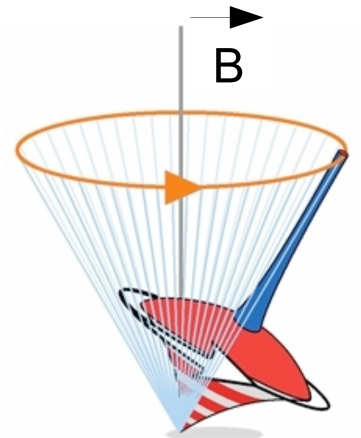
S-PASS (Carretti et al. 2013): survey of the polarized emission at 2.3 GHz

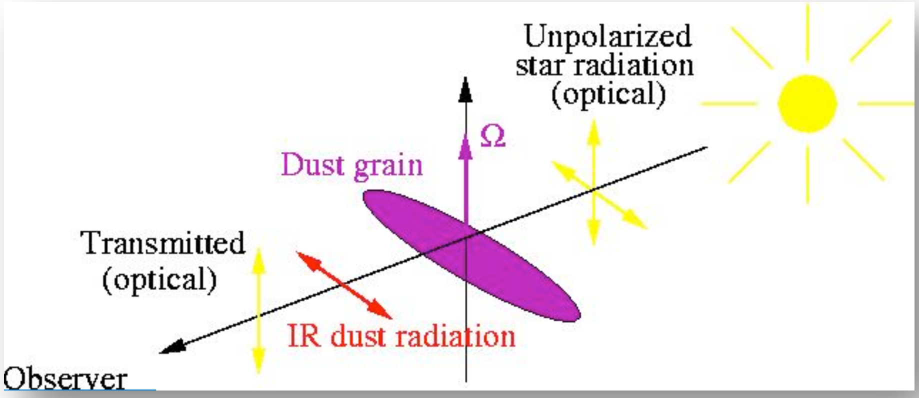
Crocker et al. (2014): star formation powered outflow that drives internal shocks



Dust polarization

Dust polarization holds information on:





- Dust properties & dust alignment efficiency:
- Which dust components contribute to polarization?
- Where in the ISM are grains aligned and with what efficiency?

- Galactic magnetic field:

What is the interplay between the structure of the magnetic field and that of interstellar matter?

Dust polarization

***Planck* gives, for the first time, the possibility to study the Galactic magnetic field through a tracer of the interstellar matter**

- **Synchrotron radiation**: traces the field over the whole volume of the Galaxy including the thick disk and halo. The volume emissivity scales as $n_{cr} \times B_{\perp}^2$; polarized emission gives information on how ordered the field is

- **Faraday Rotation**: traces the amplitude of $B_{//}$ in ionized gas; it scales as $\int n_e \times B_{//}\, ds$

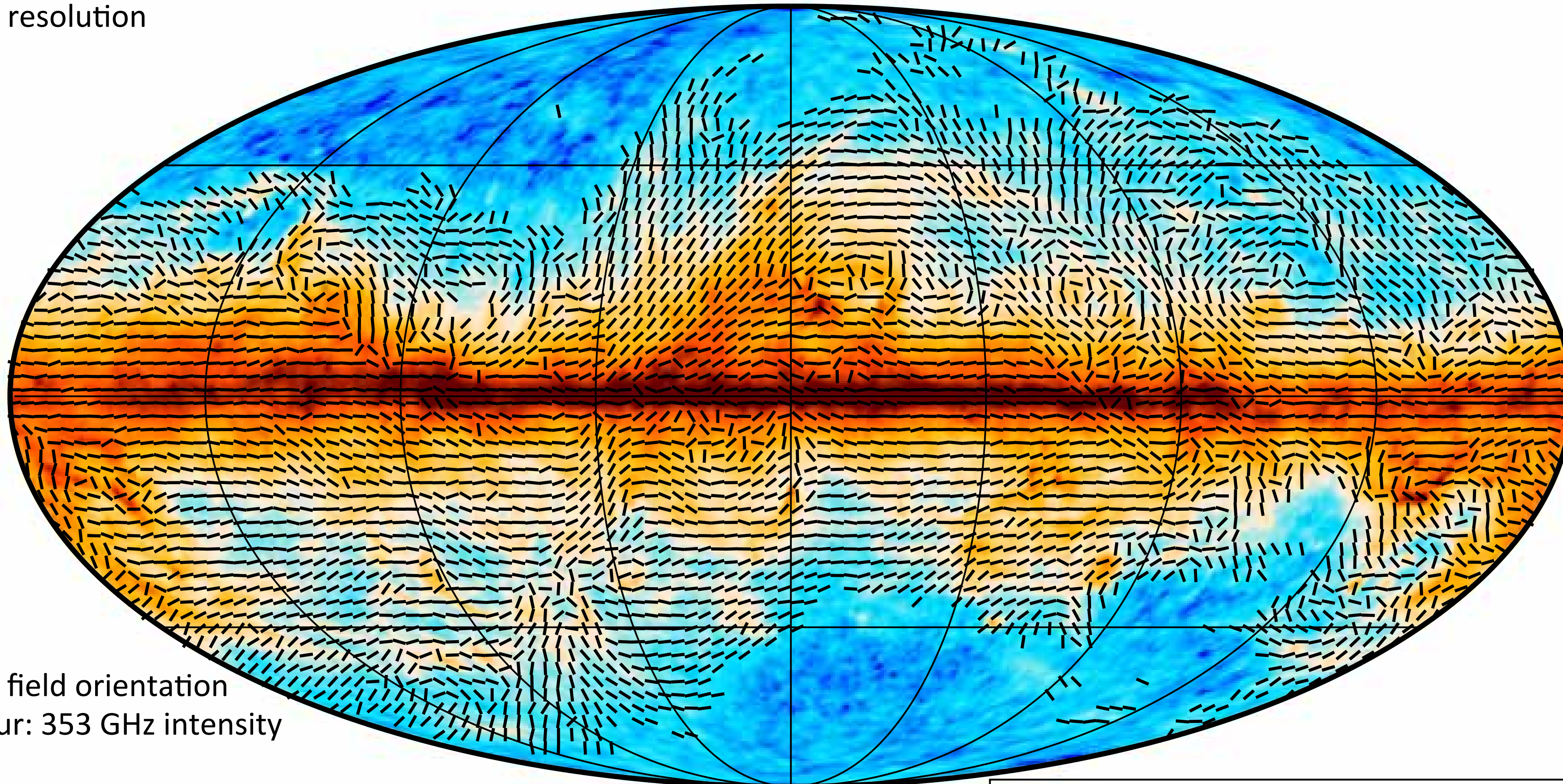
- **Dust polarization**: traces the magnetic field over the thin disk where matter is concentrated. The volume emissivity scales as n_H. The observed polarization is the sum of two contributions:

  - The warm medium (WIM/WNM) with a significant volume filling factor (>20%). This contribution traces the mean direction/structure of the field averaged along the line of sight.
  - The cold medium (CNM) with a small volume filling factor (< 1%). This contribution traces the direction/structure of the field within localized clouds.

Galactic magnetic field

Polarization angle $\psi = 1/2 \tan^{-1}(U,Q) \longrightarrow \psi + 90^\circ$ Magnetic field orientation

1° resolution



||: B field orientation
Colour: 353 GHz intensity

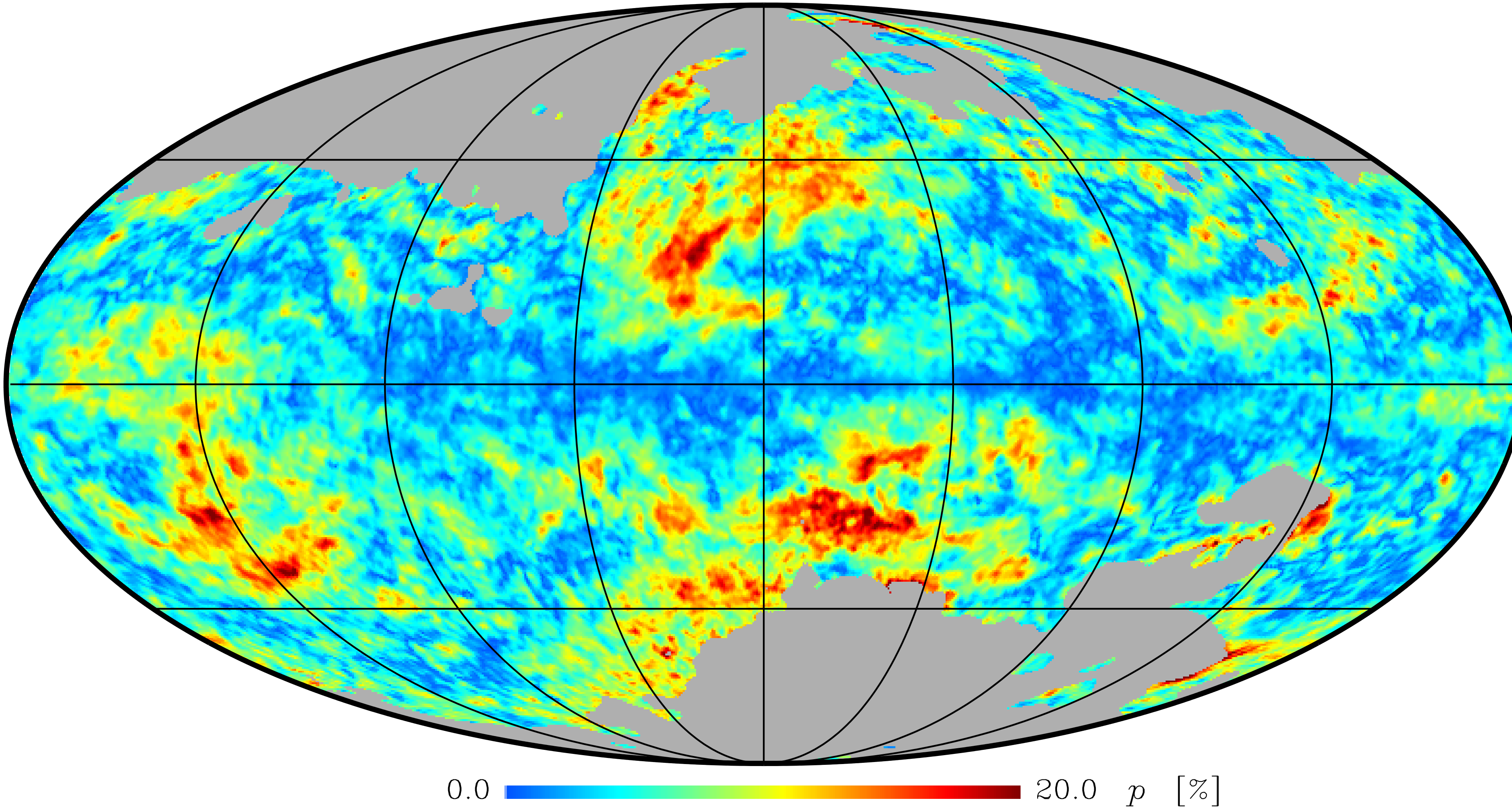
Planck intermediate results. XIX. (A&A sub.)

- Large scale direction consistent with magnetic field in the plane of the Galaxy.
- Field homogeneous over large regions, with strong polarization degree.

Polarization fraction at 353 GHz

Polarization fraction $p = P / I = p_0 \cos^2(\gamma)$

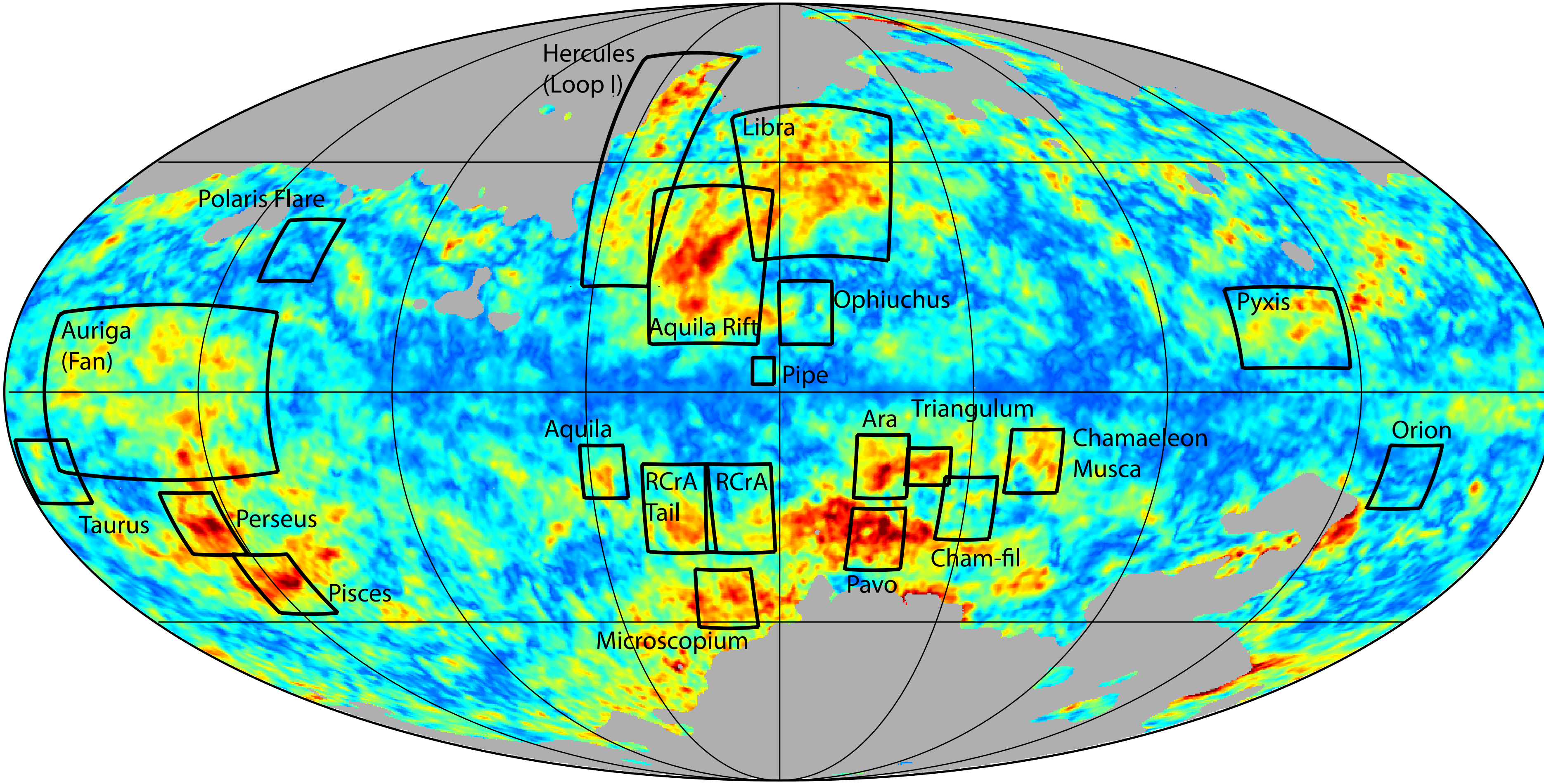
$P = \sqrt{Q^2 + U^2}$



Planck intermediate results. XIX. (A&A sub.)

Polarization fraction at 353 GHz

Polarization fraction: highly polarized regions

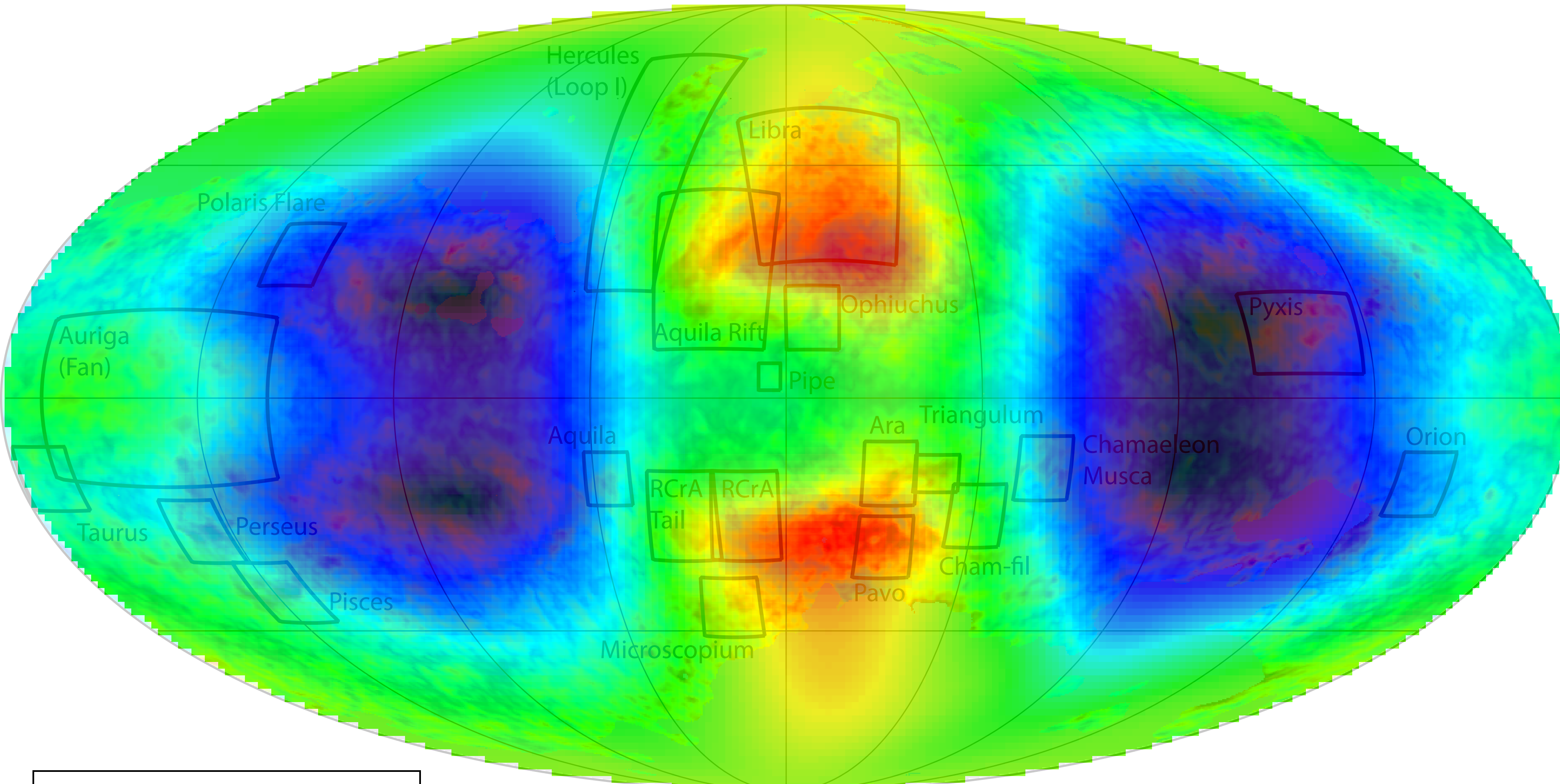


Planck intermediate results. XIX. (A&A sub.)

Polarization fraction at 353 GHz

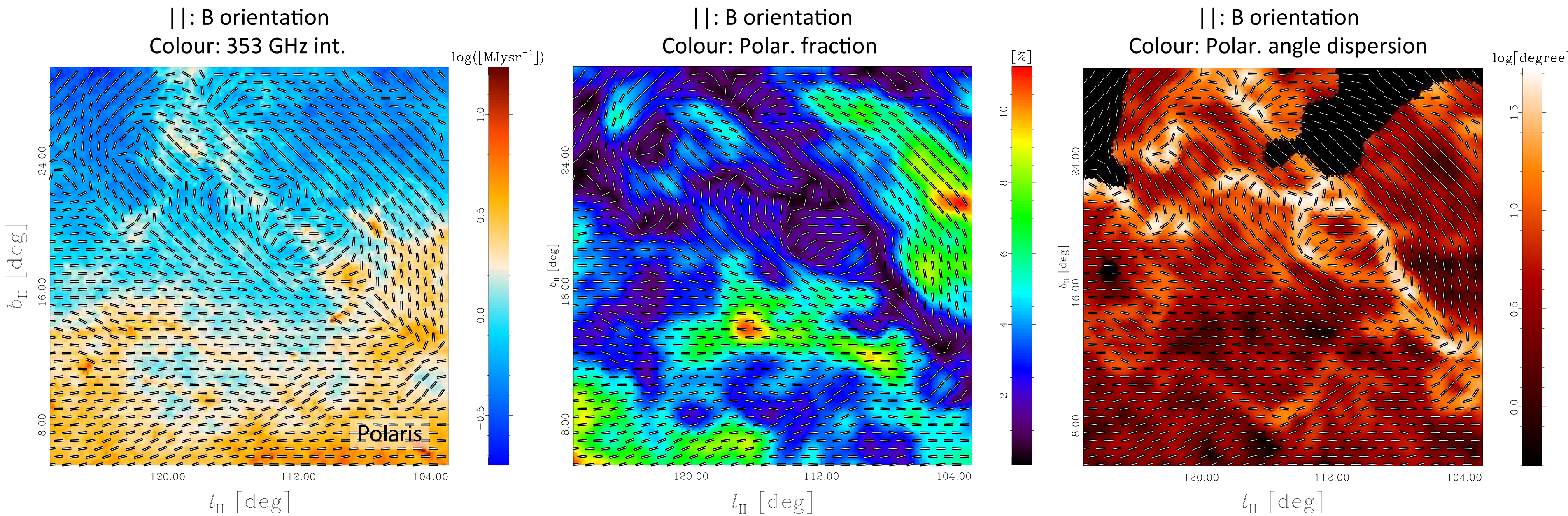
Polarization fraction: large scale depolarization pattern

$$p = P / I = p_0 \cos^2(\gamma)$$



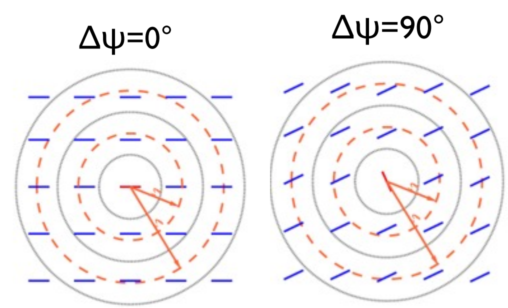
Planck intermediate results. XIX.
Miville-Deschênes et al. (2008)
Delabrouille et al. (2013)

Planck polarization at 353 GHz



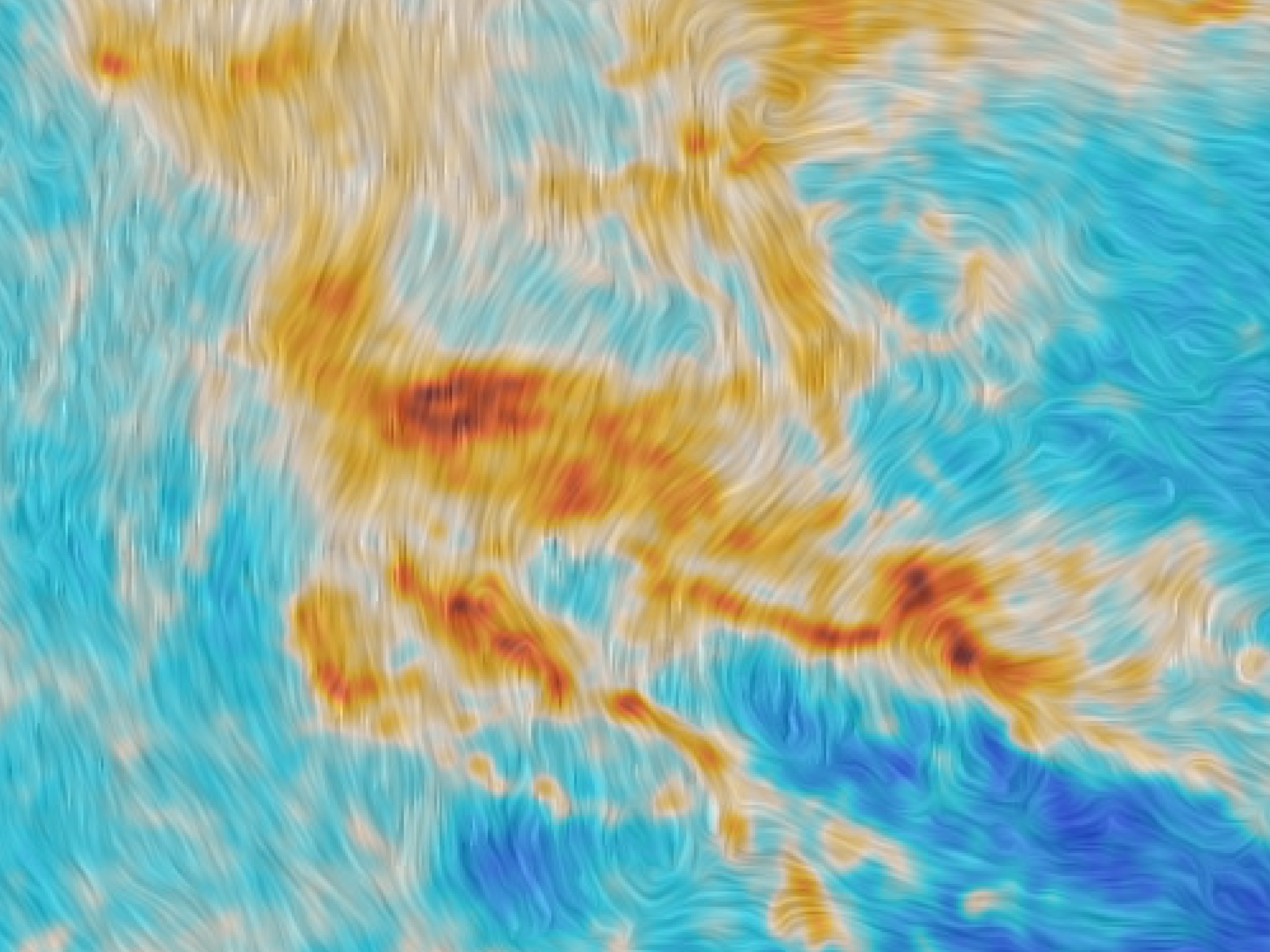
Local dispersion of the polarization angle ψ, within a scale/distance ℓ

$$\Delta\psi^2(\mathbf{r}, l) = \frac{1}{N}\sum_{i=1}^{N}\left[\psi(\mathbf{r}) - \psi(\mathbf{r}+\mathbf{l}_i)\right]^2$$



- The map looks different in polarization!
- Regions of higher polarization fraction have a fairly ordered magnetic field
- The field direction is seen to change within the dense structure – high Δψ

Planck intermediate results. XIX. (A&A sub.)

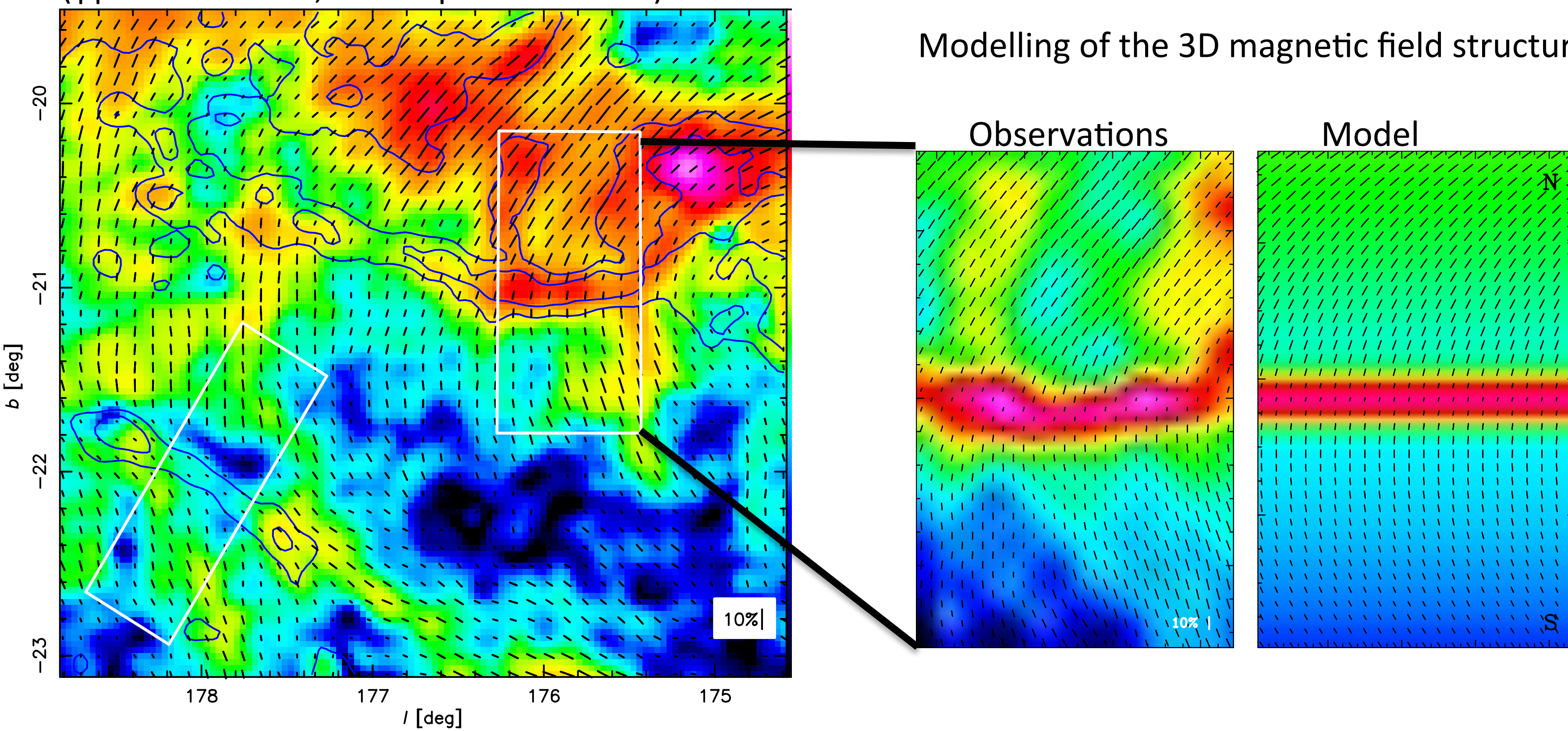


Magnetic field in interstellar filaments

Taurus molecular cloud
(|| B orientaiton; colour polar. fraction)

Planck intermediate results. XXXIII. (A&A sub.)

Modelling of the 3D magnetic field structure

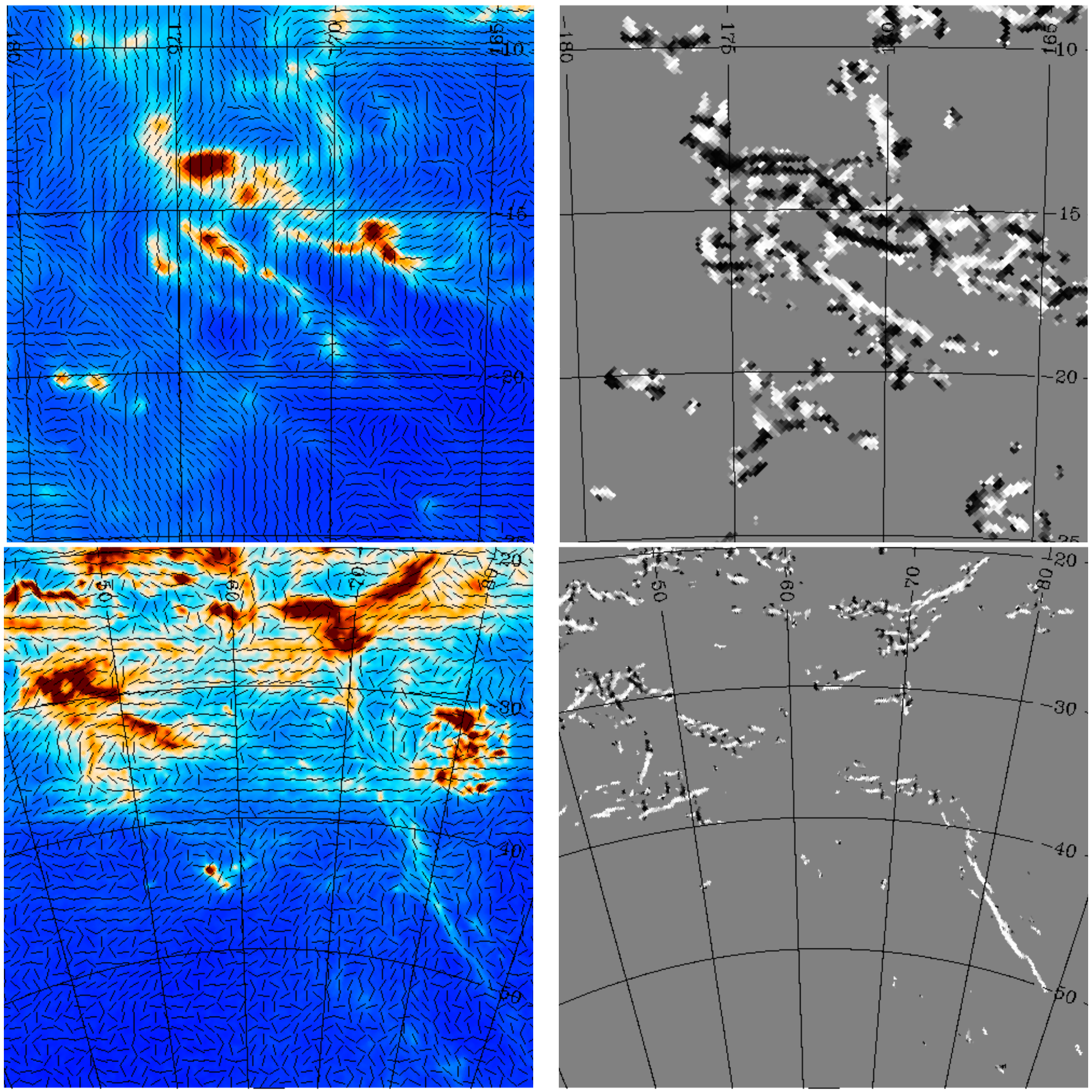


- Magnetic field in molecular cloud is ordered → it is dynamically important
- Comparison with MHD simulations → sub-Alfvénic turbulence: magnetic fields dominate over interstellar turbulence
- Field structure in filaments differs from that in the surrounding cloud → relative motions?

Relative alignment - from diffuse to dense media

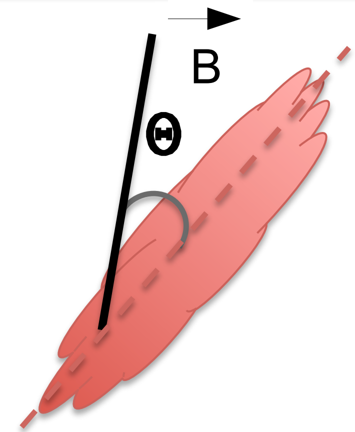
Dust extinction

cos(2Θ)

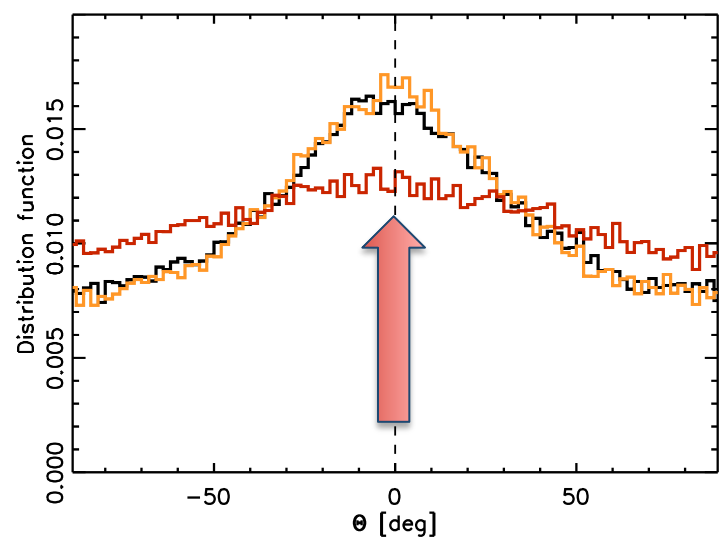


Black:
N_H perp. to **B**

White:
N_H paral. to **B**



Preferential alignment between the magnetic field and density structures



Planck intermediate results. XXXII. (A&A sub.)

Summary

Dust emission

- *Planck*'s optical depth map gives us an image of the Galaxy's reservoir for star formation
- Extinction maps suited for extragalactic studies and diffuse Galactic ISM, as well as for the study of higher density Galactic medium
- There is still much to learn on the physics of dust particles and on the "dark" gas in our Galaxy – along with Fermi

Anomalous Microwave Emission

- New study of many new objects gives definitive evidence for spinning dust
- Improved spinning dust models – take into account the complexity of grain structure and excitation mechanisms
- More data are needed – higher resolution and other frequencies

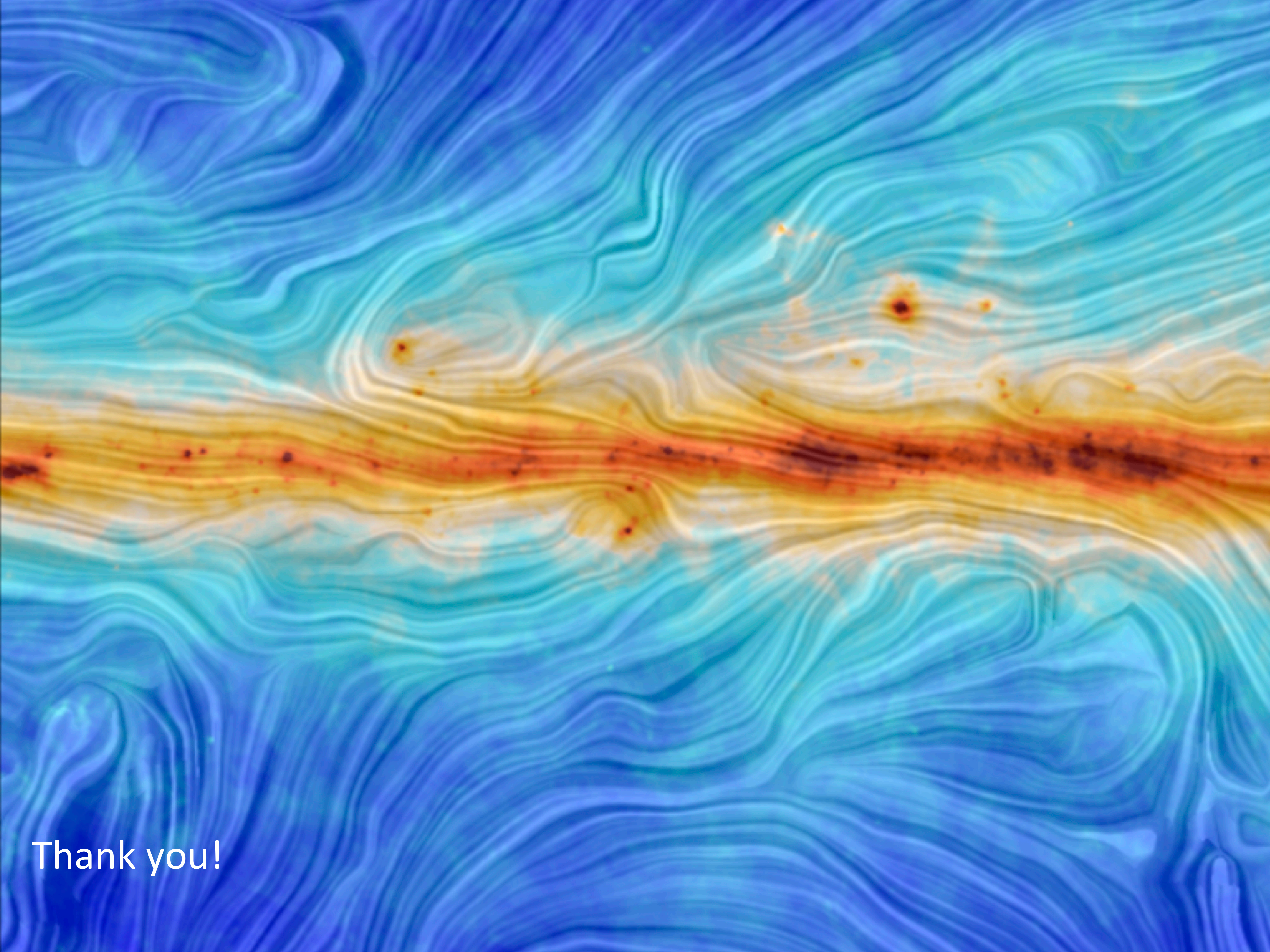
Summary

Galactic Haze

- Detection of the Galactic Haze with *Planck* and improved determination of its spectrum, from a combination with WMAP data, and owing to the improved CMB map from *Planck*
- Spatial correspondence with the Fermi bubbles is rather well settled, and we have now indication that they are also detected in *Planck*+*WMAP* polarization
- Origin is still debated, but models that reconcile multi-frequency observations (including the S-PASS data) suggest energy outflows from star formation in the Galactic centre

Dust polarization

- For the first time we the data needed to characterize the interplay between the structure of the magnetic field and the interstellar matter
- Need to disentangle the various intervening factors: dust properties, dust alignment and structure of the magnetic field
- Complement observations with simulations to understand the role of turbulent energy


Thank you!

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

Herschel – zooming in

Orion B – Gould Belt survey (*André et al. 2010, Schneider et al. 2003*)

Cygnus X - HOBBYS project (*Motte et al. 2010, Henneman et al. 2012*)