(Non-thermal) Radiative processes in Astrophysics

Summer School on Astrophysics and Astroparticles
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Petnica Summer Institute

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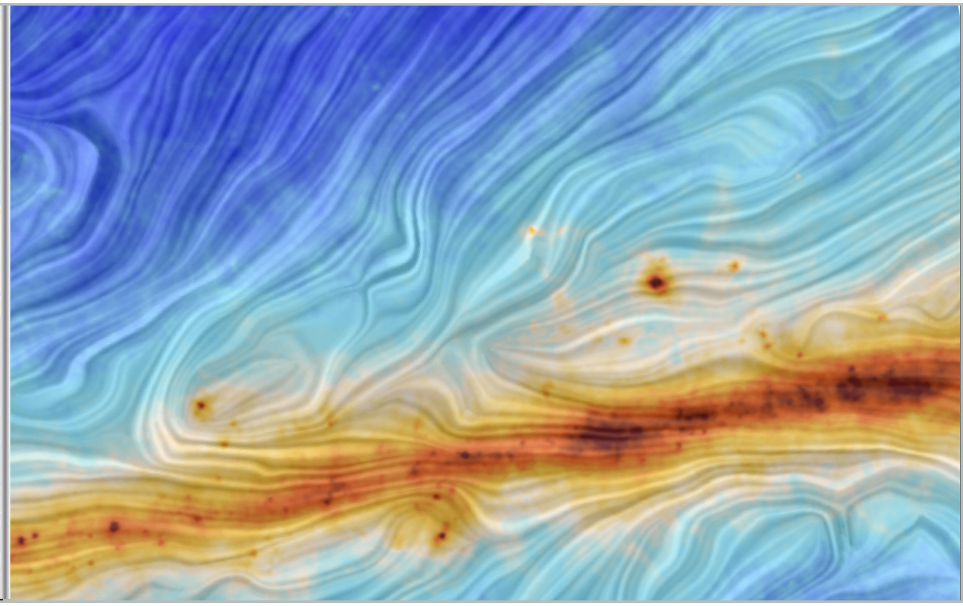
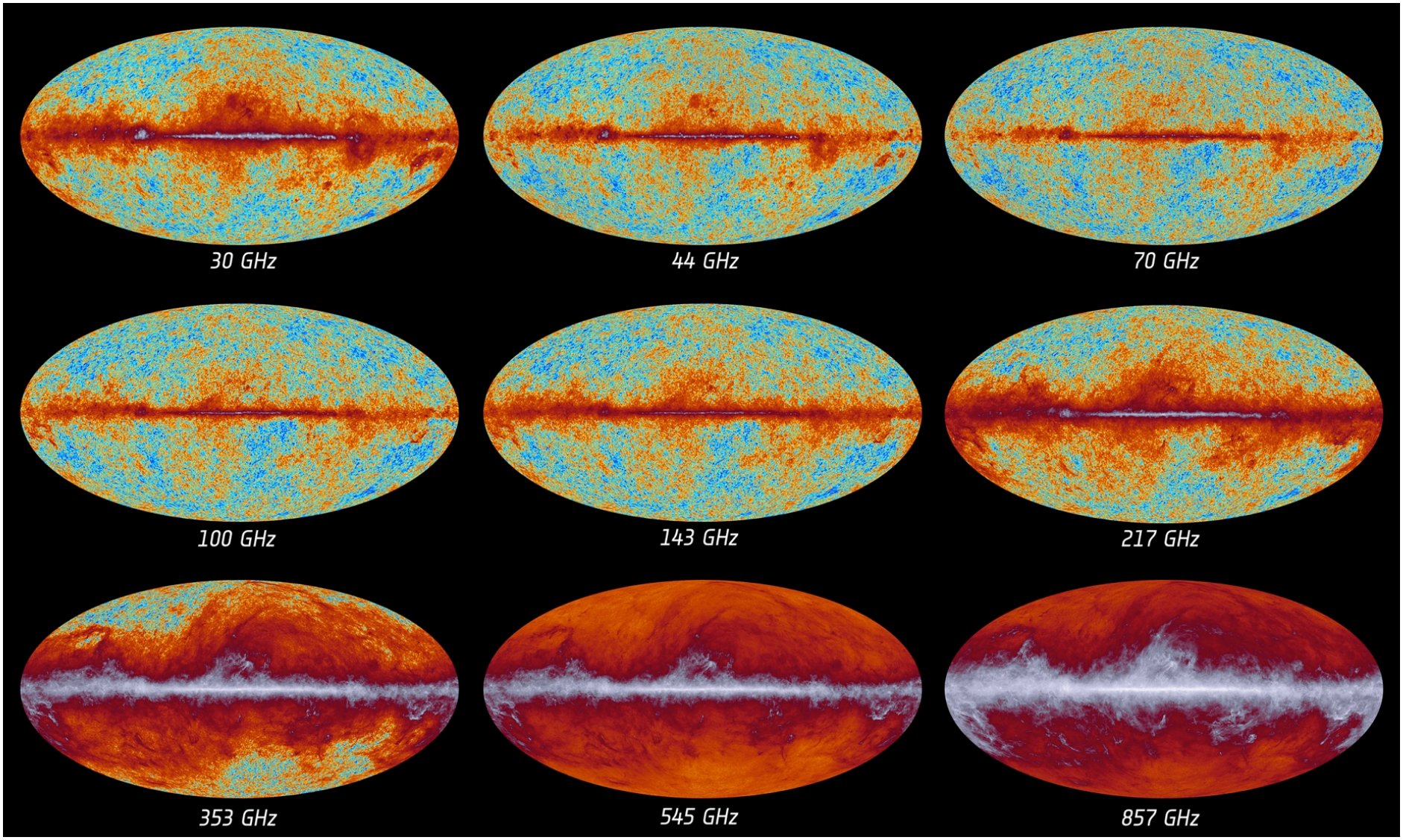


Introduction to the sky – as observed by the Planck satellite



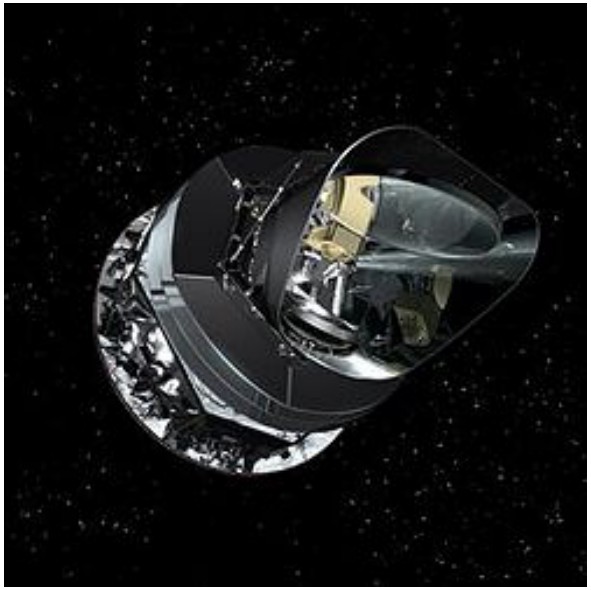
What is Planck? (What is this projection?)
The emission mechanisms of the interstellar medium traced in this frequency range.

The Planck satellite

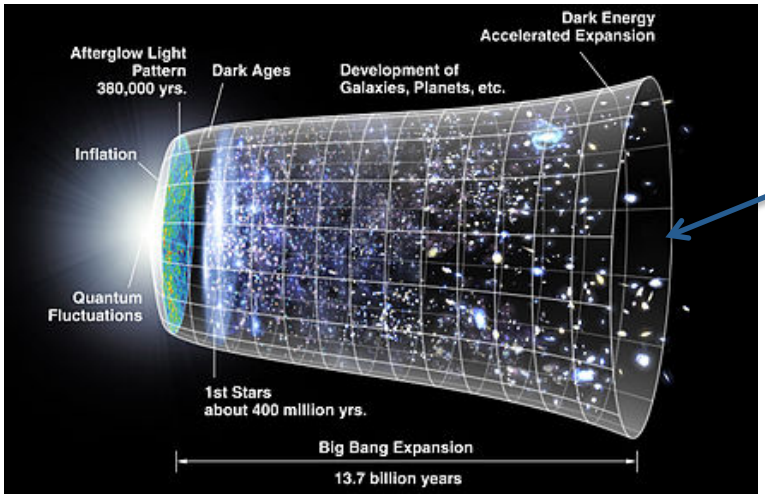
The Planck satellite was launched in April 2009 and observed the sky for 4.5 years (until October 2013):
in **total intensity** and **polarization**.

Planck was designed to observed the anisotropies of the Cosmic Microwave Background (CMB): the primordial radiation from the Universe.

- Frequency coverage: 9 channels from 30 to 857 GHz.
- Spatial resolution: 30’ (size of the Moon) to 5’



ESA Planck



Credits: NASA

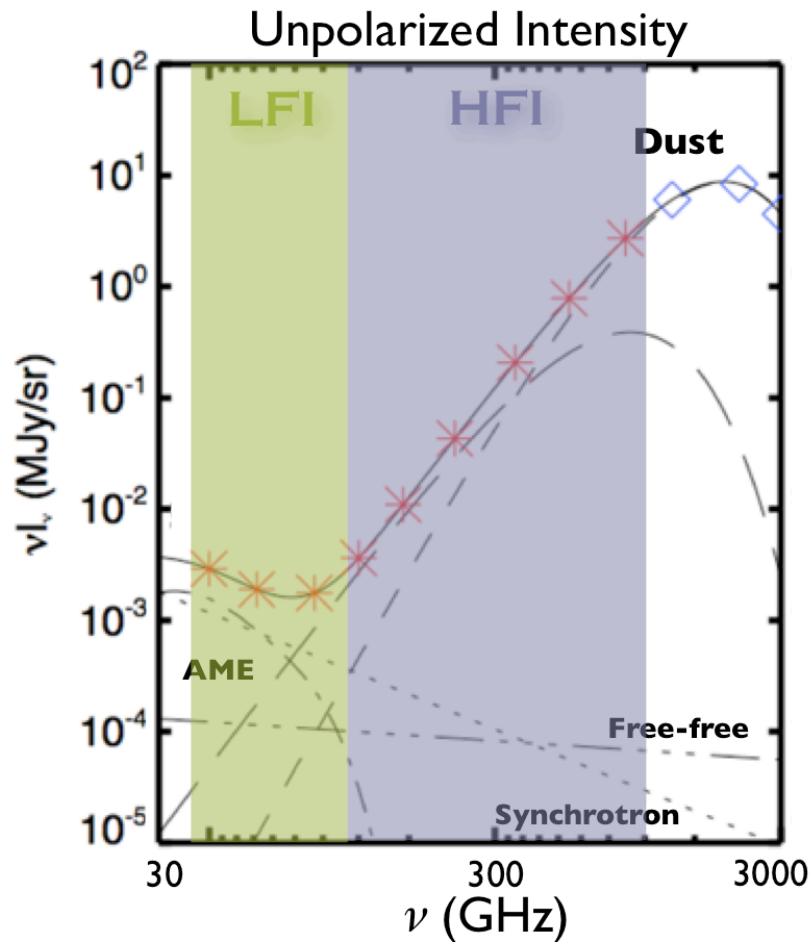
(We are here!)

There is a lot between us the and CMB!

What do these observations show us?

Owing to the frequency coverage of Planck, its sky maps trace the four emission mechanisms (in the continuum) that we known of in the interstellar medium:

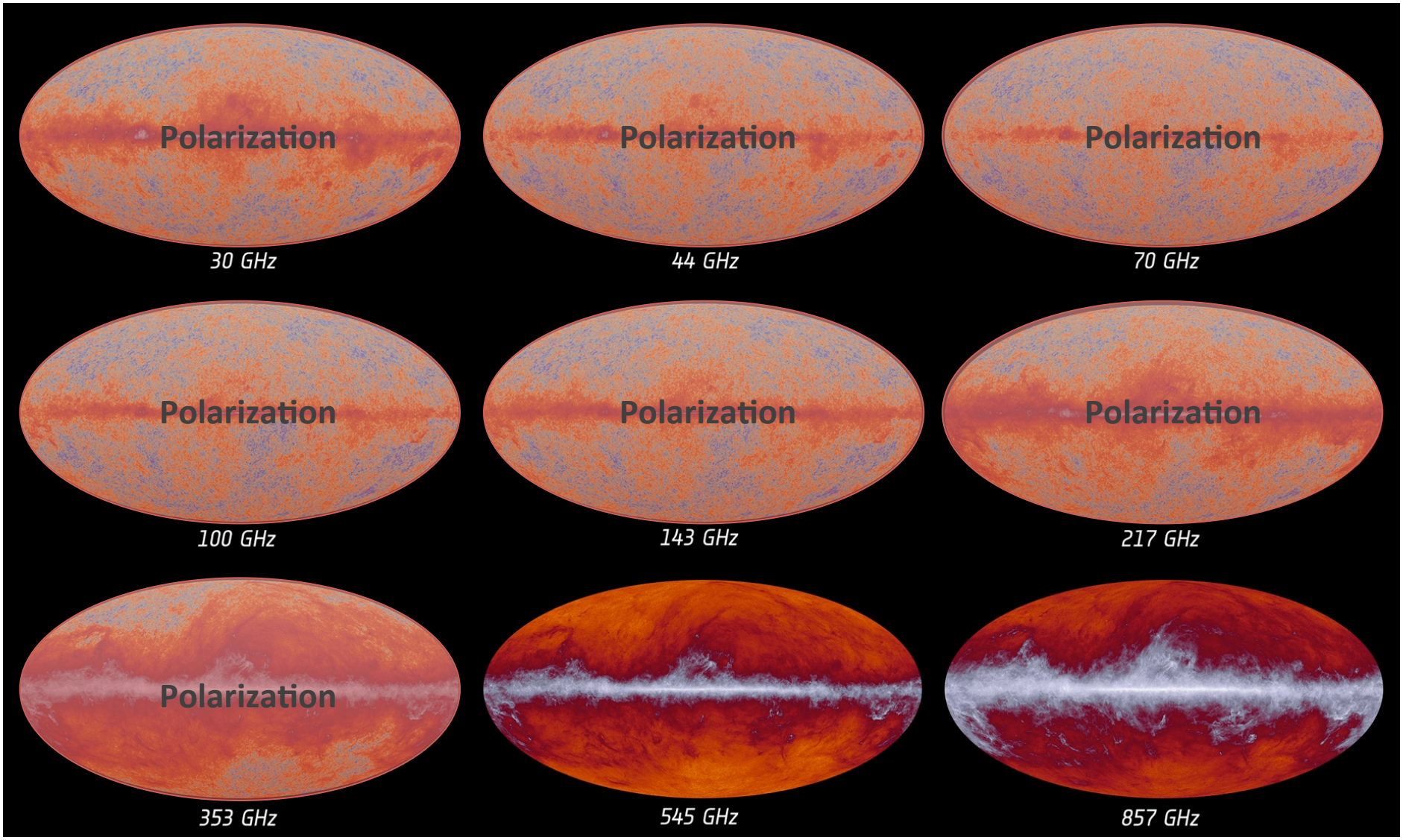
- **Synchrotron emission**
- **Bremsstrahlung (free-free) emission**
- **"Anomalous" microwave emission**
- **Dust emission**



J. Aumont, 2013 ESLAB

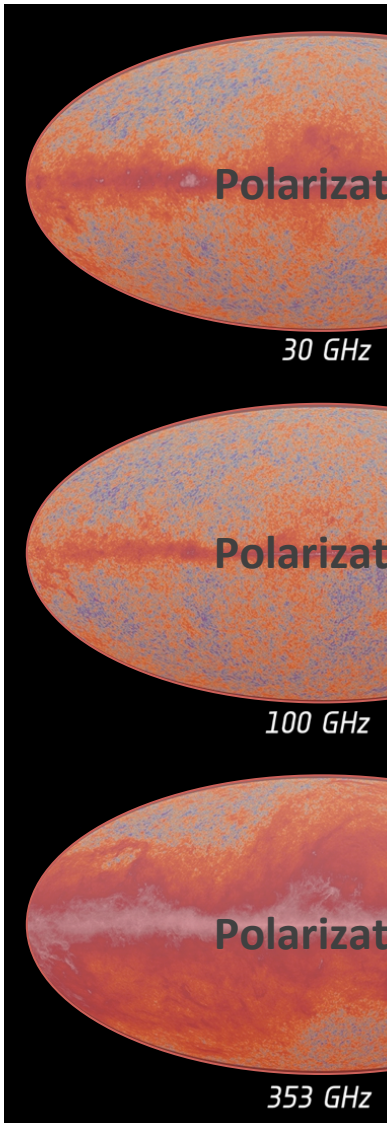
Plus, Planck also mapped the *polarized emission* in 7 of its 9 frequencies → another dimension to our studies of the interstellar medium.

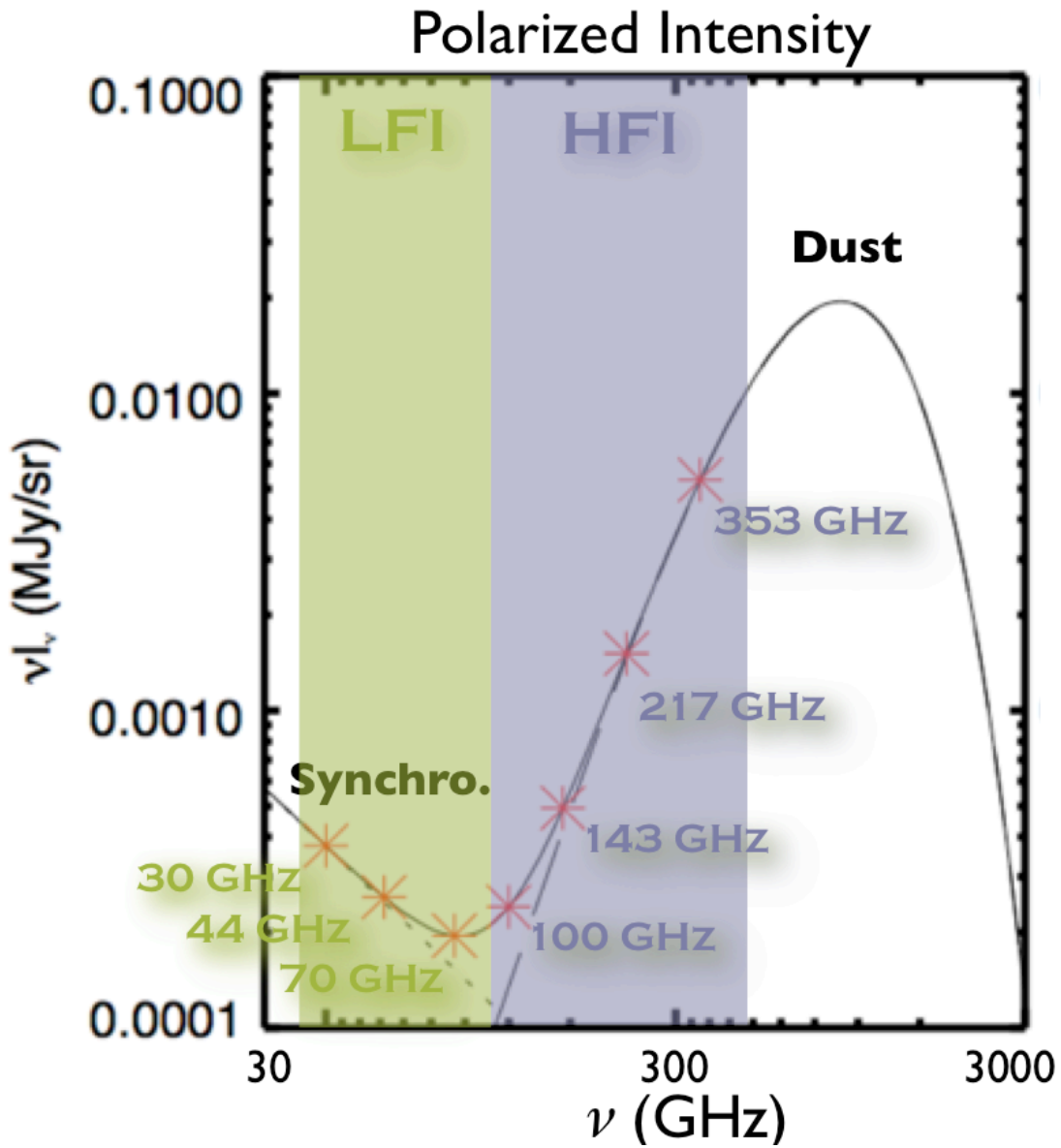
Polarized sky observed by Planck

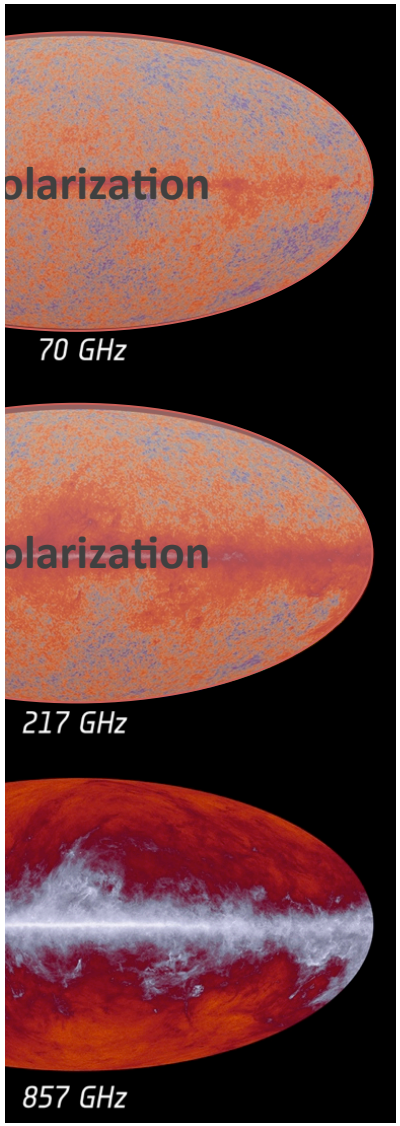


Real maps of the polarized sky to come…

Polarized sky observed by Planck







Real maps of the polarized sky to come…

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Outline

1. The interstellar medium

2. Radiation: thermal vs non-thermal, polarized

3. (Cyclo-) Synchrotron emission

4. Thomson/Compton scattering

5. Bremsstrahlung (free-free) emission

6. Anomalous microwave emission

7. Dust emission

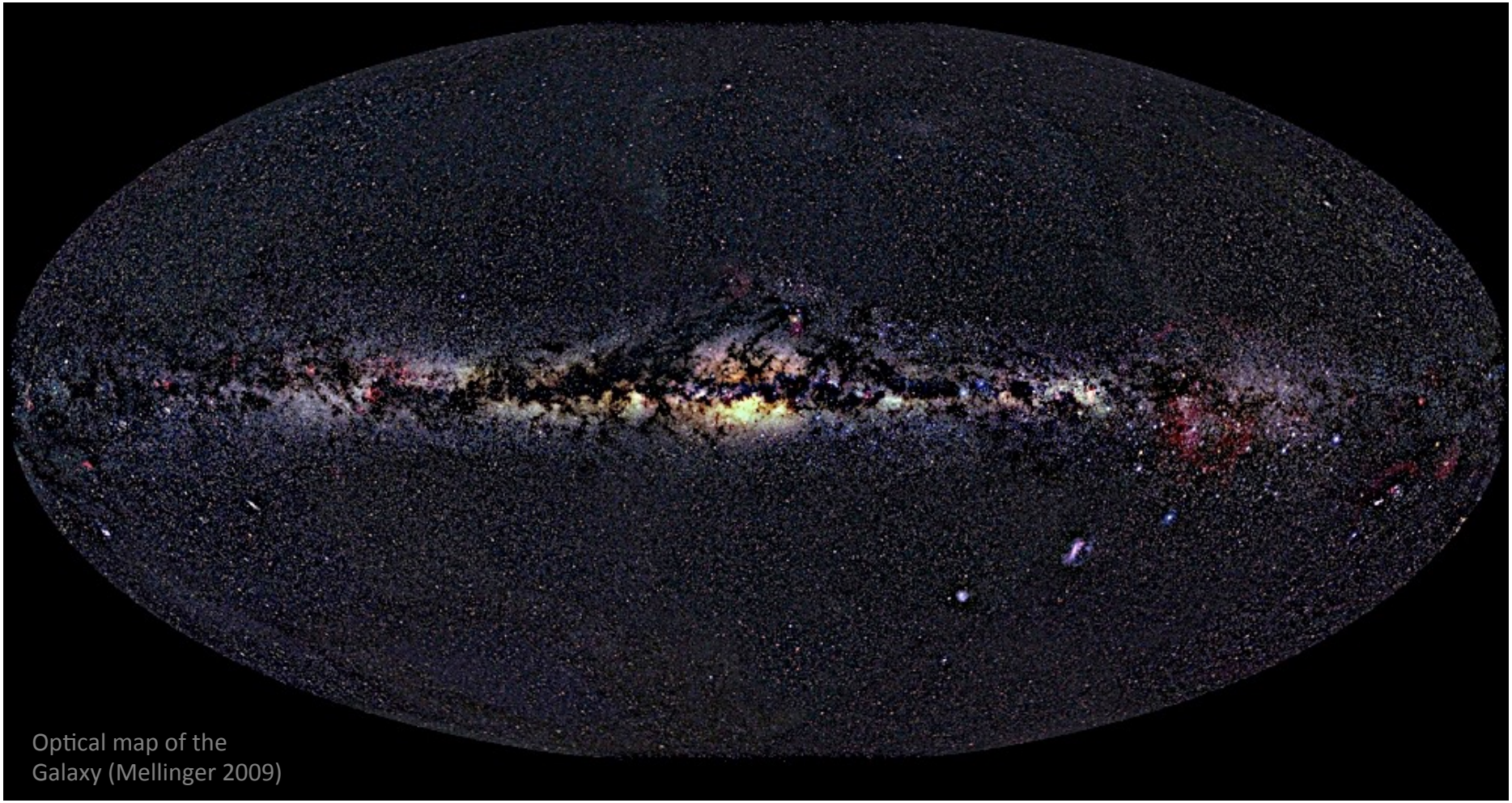
Warning: This course may be slightly biased (my/observer's approach).
Lecture mostly based on:

- series of recent papers on results from Planck
- G. B. Rybicki and A. P. Lightman, *Radiative Processes in Astrophysics*, 1979, NY, Wiley-Interscience
- B. Draine, *Physics of the Interstellar and Intergalactic medium*, 2011, Princeton Univ. Press

1. The interstellar medium

The interstellar medium

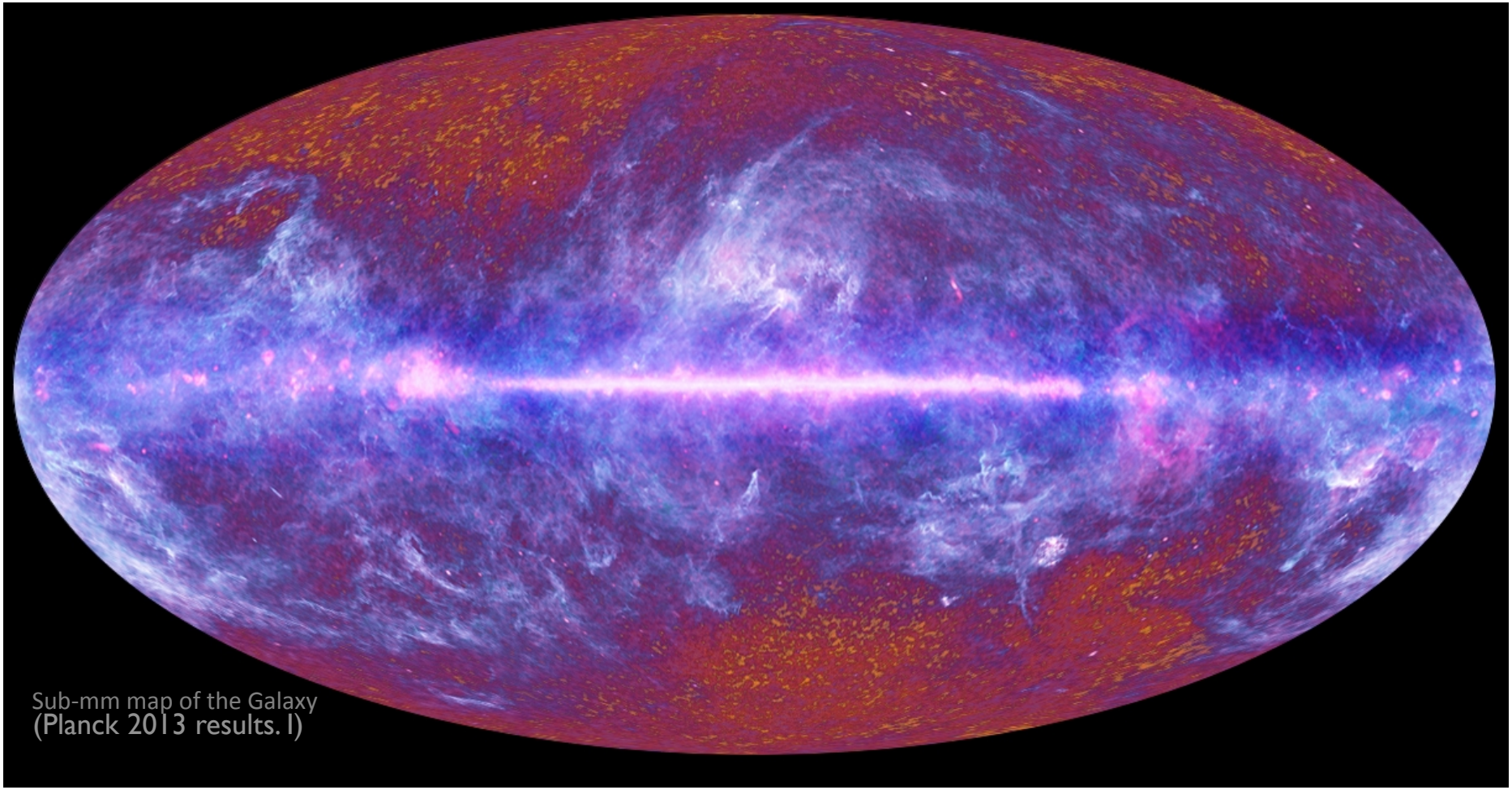
The interstellar medium (ISM) is the tenuous medium in which the stars of our Galaxy are embedded.



Optical map of the Galaxy (Mellinger 2009)

The interstellar medium

The interstellar medium (ISM) is the tenuous medium in which the stars of our Galaxy are embedded.

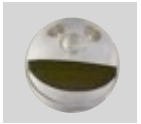


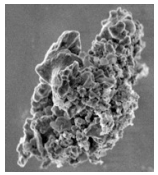
The interstellar medium - composition

The interstellar medium (ISM) is the tenuous medium in which the stars of our Galaxy are embedded:

- *tenuous*, since the density is around 3 x 10^{-24} g/cm^3, which corresponds to about 1 H atom/cm^3;
- most of the mass of our Galaxy is in stars, 10-15% of it is in the ISM.

The ISM is composed of:

- Ordinary matter
  gas (atoms, molecules, ions, and electrons) 

  dust 

- Relativistic charged particles (cosmic rays)

- Magnetic fields

The interstellar medium – life cycle/energetics

Credits: APOD, Ivan Eder

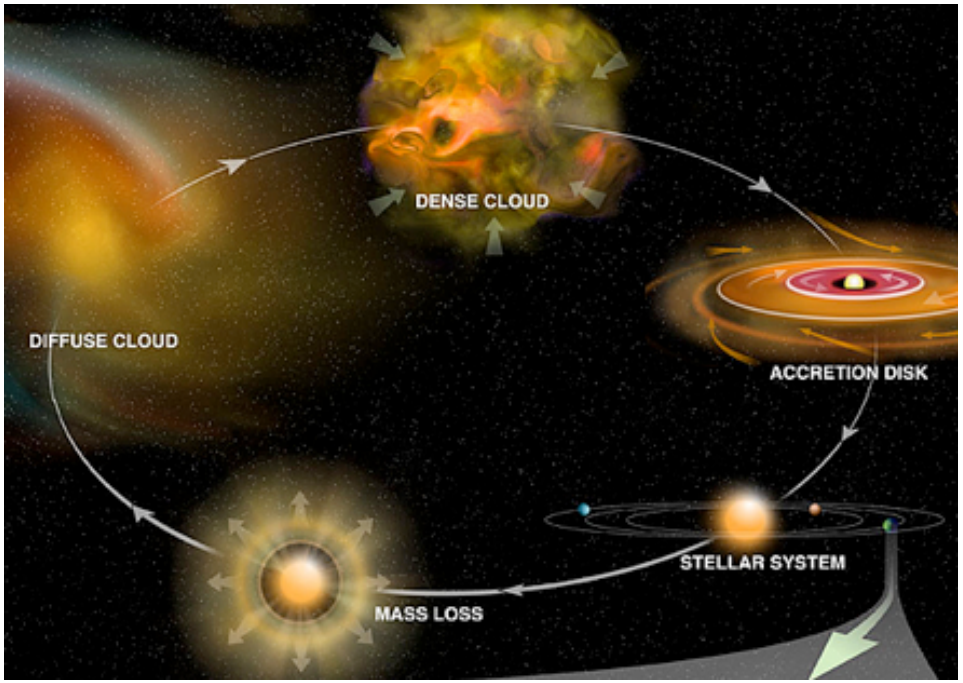
Stars are born (and die) in large clouds of gas and dust, which change (in composition, density, structure, etc.) at each generation.

Star formation is the result of the interplay between the **energy** agents in the ISM:
Thermal, gravitational, kinetic, cosmic ray, magnetic and in photons

The interstellar medium – life cycle/energetics

Different processes and phases of the ISM are related to different emission mechanisms.
Where does each of the ISM emission mechanisms dominate?

Diffuse and dense clouds of hydrogen and dust: **dust and anomalous microwave emission**.



Supernova remnants that inject relativistic particles: **synchrotron emission**.

Massive stars that ionize the surrounding medium: **free-free emission**.

This is a simple picture, since the ISM is much more complex.
To come: maps of the different components where we will see that sometimes they overlap, but there are also well defined regions where one component dominates.

2. Radiation

Radiation - introduction

Electromagnetic radiation can be decomposed into a spectrum covering a large range in energy: 10^{-6} eV in the radio to 10^{6} eV in gamma-rays.

Radiation is represented in terms of: wavelength λ, frequency ν, energy *E* or temperature *T*.

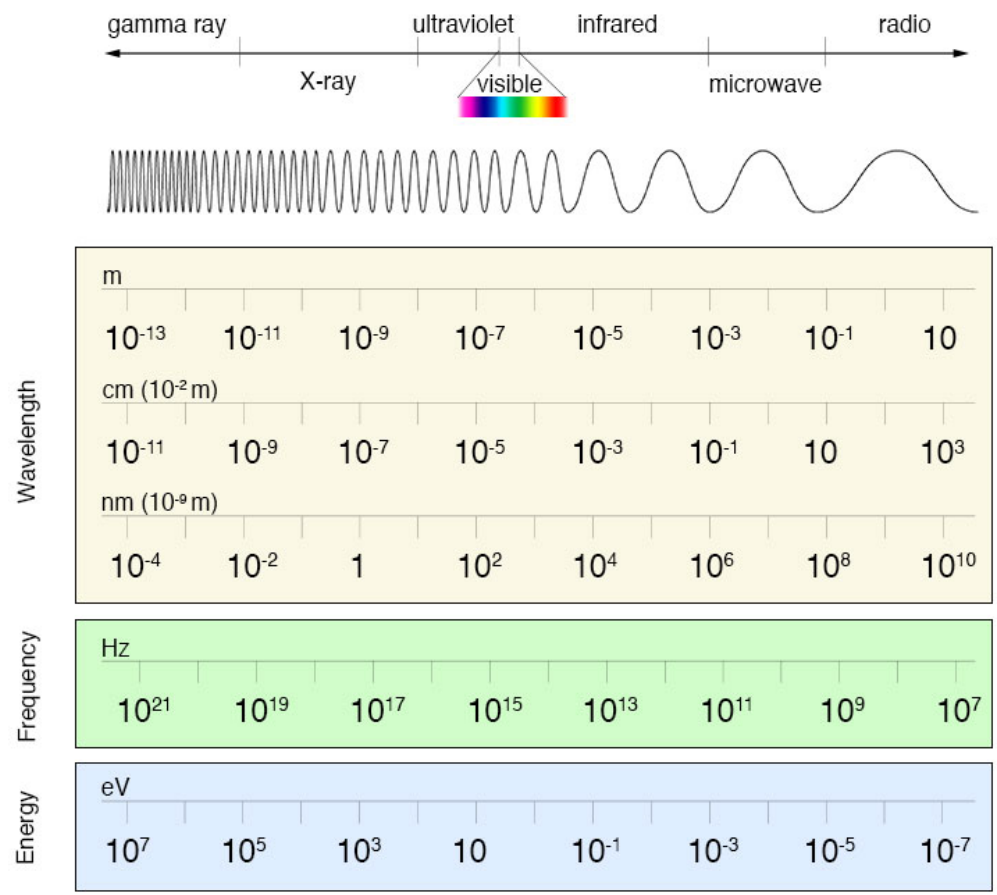
$$\lambda\nu = c$$

Energy of photon of frequency ν

$$E = h\nu$$

Temperature obtained by equating it to an energy using Boltzmann's constant

$$E = kT$$



Credits: NASA's image of the Universe

Radiation – specific intensity

Intensity of a source that radiates in any direction, different amounts of energy at different frequencies:

$$dE = \mathbf{I}_\nu \cdot d\mathbf{A}\, dt\, d\Omega\, d\nu$$

which is equivalent to the amount of energy crossing a surface area *d*A per unit time *d*t per solid angle *d*Ω per frequency *d*ν.

If there is no absorption nor emission along the ray path *d*s, then the specific intensity **is conserved**:

$$\frac{dI_\nu}{ds} = 0$$

However, this is hardly the case in the ISM, thus we need to consider propagation effects: **absorption**, **emission** (and scattering).

Radiation – radiative transfer equation

The radiative transfer equation treats the absorption and emission of light in terms of changes in the specific intensity:

$$\boxed{\frac{dI_\nu}{ds} = j_\nu - \alpha_\nu I_\nu}$$

Emission coefficient: energy emitted by a medium per unit volume, frequency, solid angle and time along a path *ds*:

$$dI_\nu = j_\nu ds$$

Intensity added to a given beam of radiation by spontaneous emission.

Absorption coefficient: rate at which the fraction of total intensity decreases per unit distance along the ray path:

$$dI_\nu = -\alpha\, I_\nu\, ds$$

A positive α corresponds to stimulated emission (maser action, which leads to an increase in the specific intensity).

Radiation – radiative transfer equation

- If there is *only emission*, the intensity increases linearly with distance: $I_\nu(s) = I_\nu(s_0) + \int_{s_0}^{s} j_\nu(s')\, ds'$

- If there is *only absorption*, the intensity decreases exponentially with distance: $I_\nu(s) = I_\nu(s_0) e^{-\tau_\nu(s)}$

where the **optical depth** through an absorbing medium is

$$\tau_\nu(s) = \int_{s_0}^{s} \alpha_\nu(s')\, ds'$$

Medium is ***optically thin*** when most photons escape when $\tau < 1$

When $\tau_\nu > 1$, most photons are absorbed and the medium is ***optically thick***

General solution:

$$\boxed{I_\nu(\tau_\nu) = I_\nu(0) e^{-\tau_\nu} + \int_0^{\tau_\nu} e^{-(\tau_\nu - \tau'_\nu)} S_\nu(\tau'_\nu)\, d\tau'}$$

where S_ν is the source function $S_\nu(s) = \dfrac{j_\nu(s)}{\alpha_\nu(s)}$

Radiation – radiative transfer equation

General solution of the transfer equation:

$$\boxed{I_\nu(\tau_\nu) = I_\nu(0)e^{-\tau_\nu} + \int_0^{\tau_\nu} e^{-(\tau_\nu - \tau'_\nu)} S_\nu(\tau'_\nu)\, d\tau'}$$

If we consider the variation in intensity through an homogeneous medium, $S_\nu = \mathrm{const}$, then:

$$I_\nu(\tau_\nu) = I_\nu(0)e^{-\tau_\nu} + S_\nu \left[1 - e^{-\tau_\nu}\right]$$

In the *optically thin* regime:

$$I_\nu(\tau_\nu) \approx I_\nu(0)[1 - \tau_\nu] + S_\nu \tau_\nu$$

In the *optically thick* regime:

$$I_\nu(\tau_\nu) \approx S_\nu$$

Thermal vs non-thermal radiation

Thermal radiation is emitted by **matter in thermal equilibrium** with its surroundings.

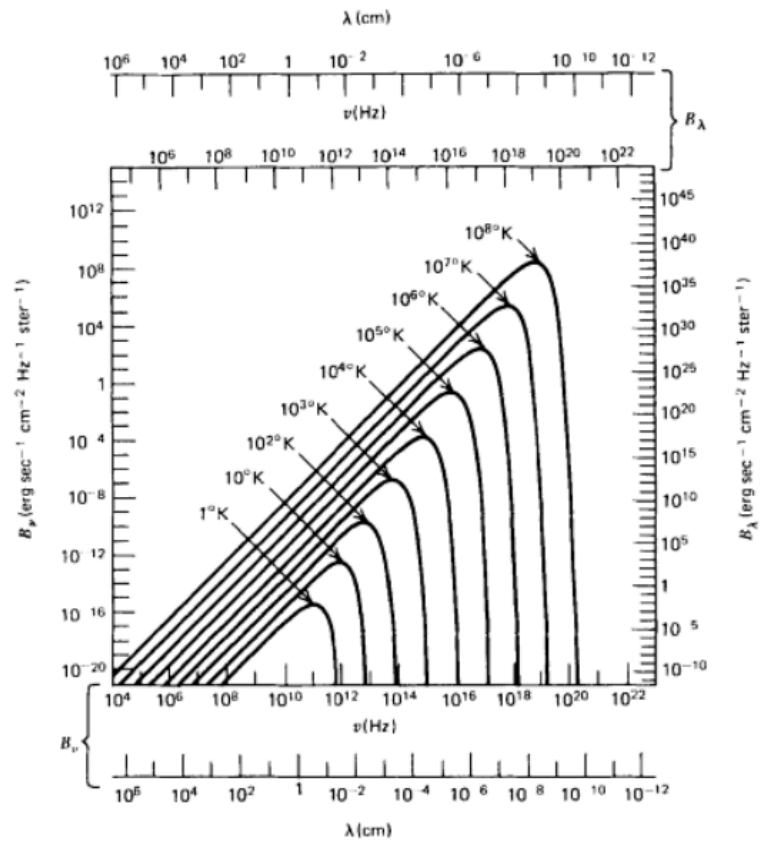
In this case the specific intensity depends only on the local temperature of matter and the source function is given by the Planck function

$$S_\nu = B_\nu(T) \quad = \quad \frac{2h\nu^3/c^2}{\exp(h\nu/kT) - 1}$$

We can then re-write the radiative transfer equation for thermal radiation as follows:

$$\frac{dI_\nu}{d\tau} = \quad B_\nu(T) \; - I_\nu$$

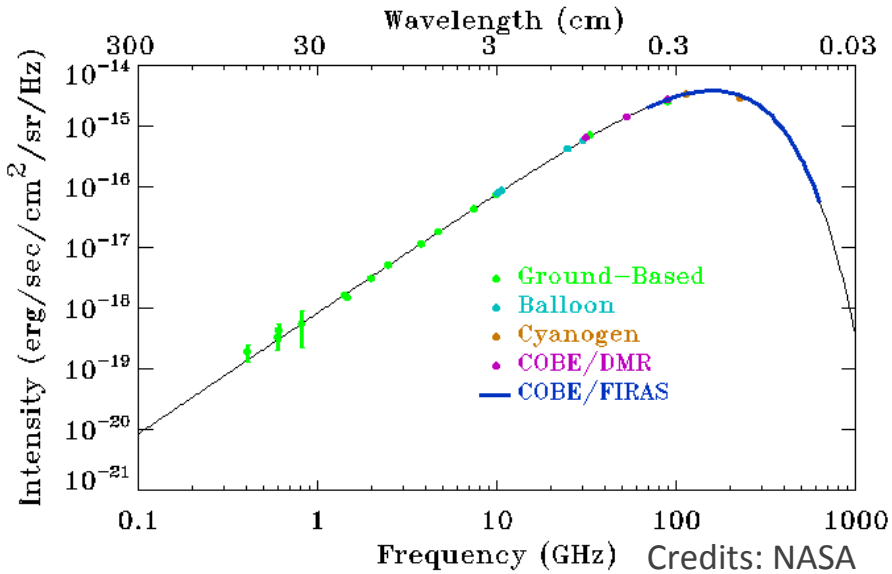
In the optically thick limit, as we saw before, $I_\nu(\tau_\nu) \approx S_\nu$. This means that the specific intensity is equal to the Planck function and we have **blackbody radiation** → radiation which is itself in thermal equilibrium.



Thermal vs non-thermal radiation

Only in *local thermal equilibrium* (LTE) and in the *optically thick limit* can we describe the radiation as blackbody.

The **most perfect blackbody radiation ever observed is the CMB**, with a temperature of about 2.7K (CMB was emitted when matter and radiation were in equilibrium).



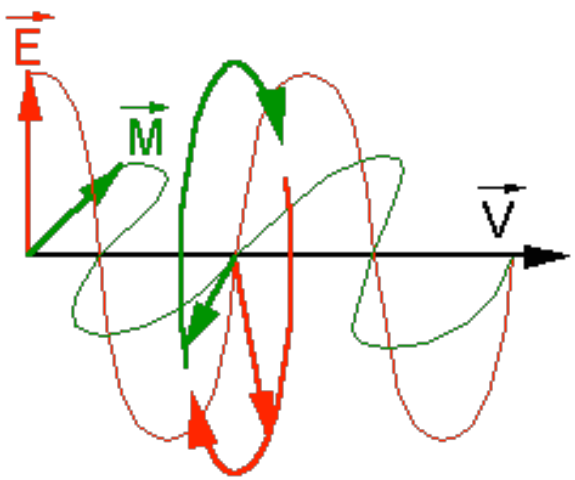
Credits: NASA

Blackbody emission hardly applies in the ISM; although stars and planets are not in LTE nor are they perfect blackbodies, blackbody radiation is still used as a first approximation to the radiation that they emit.
What we do observe in the ISM is greybody (or modified blackbody) emission from the largest dust particles – Part 7 of this course.

The radiation emitted by the non-thermal plasma in the ISM is therefore **non-thermal**.

Polarization of light

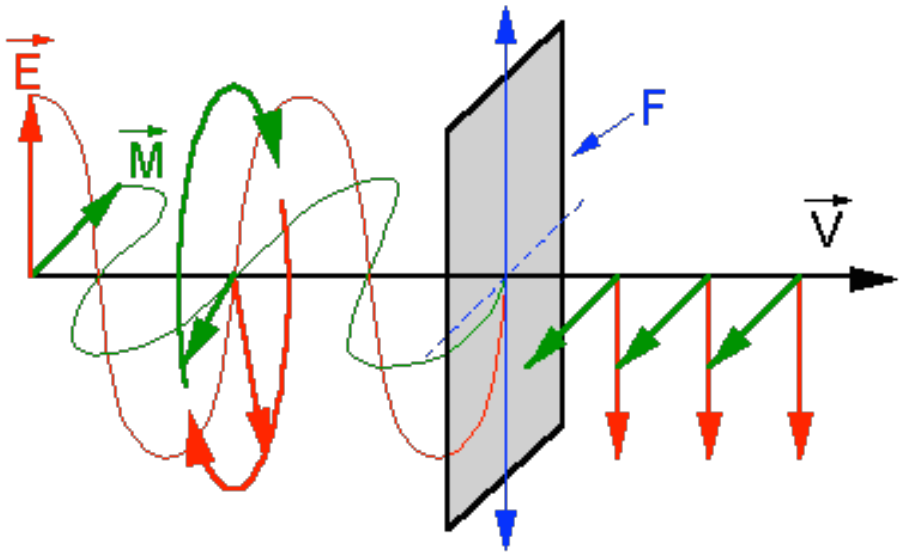
Unpolarized light



The electric and magnetic fields propagate along a given direction, rotating around it.

Unpolarized light

Polarized light

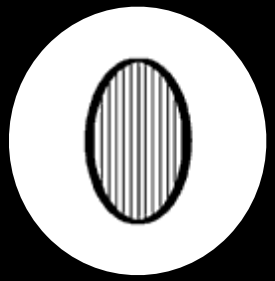


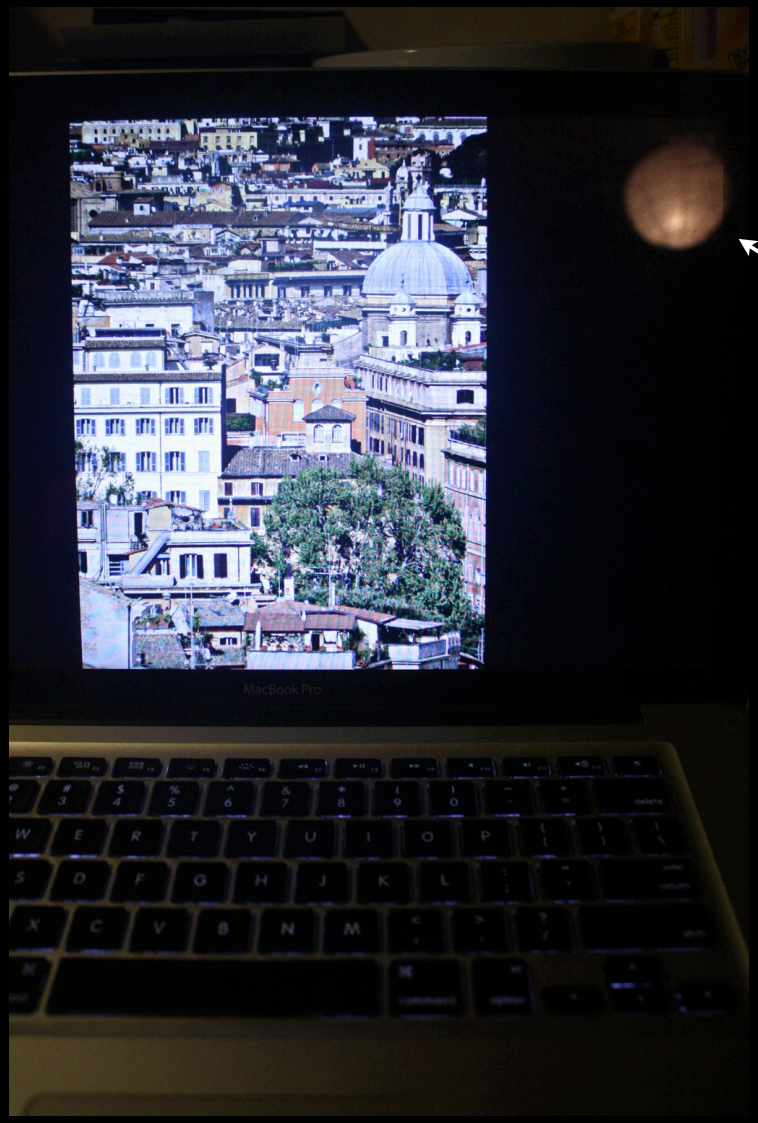
The electric and magnetic fields propagate along a given direction, but with a fixed orientation.

Unpolarized radiation can become polarized (e.g. scattering of starlight by dust grains) or it can be polarized right from its source (e.g. synchrotron emission - Part 3, dust emission – Part 7).

Polarization of light - example

Rotating the polarizer



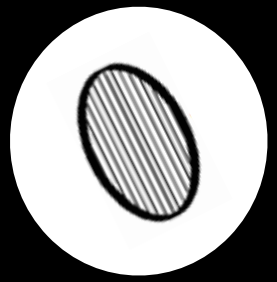


Unpolarized light reflected in the screen

Credits: A. Bracco, CEA

Polarization of light - example

Rotating the polarizer



Unpolarized light
reflected in the screen

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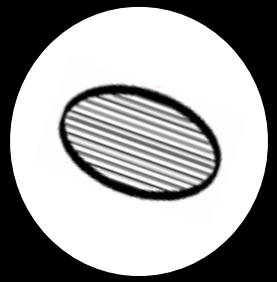
Polarization of light - example

Rotating the polarizer



Unpolarized light reflected in the screen

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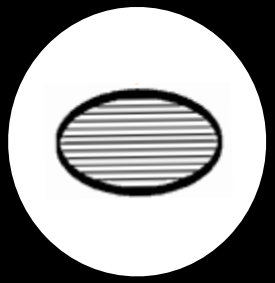
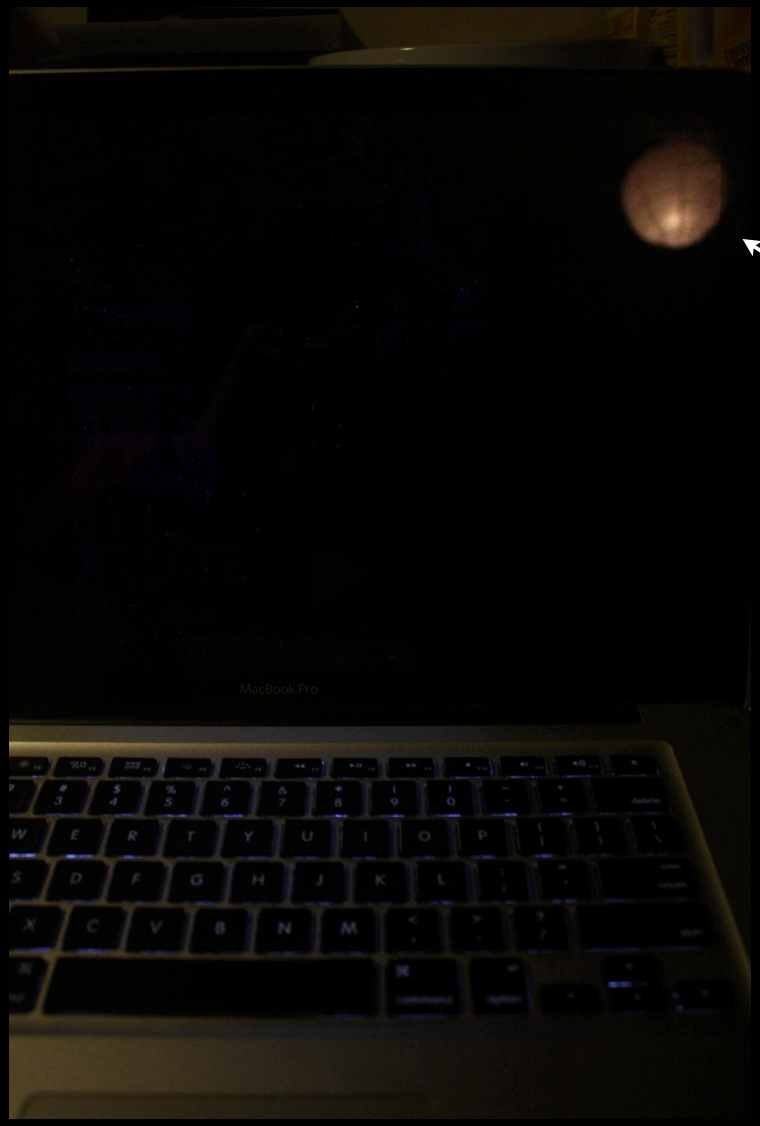
Polarization of light - example

Rotating the polarizer





Unpolarized light reflected in the screen

Credits: A. Bracco, CEA

Polarization of light

The electric field of a monochromatic wave travelling along the **z** direction can be written in terms of its amplitude E, phase ϕ, and frequency ω (from Maxwell's Eqs. → propagation equation for the electric field):

$$\vec{E} = (\vec{e}_x E_1 + \vec{e}_y E_2) e^{-i\omega t}$$

The complex amplitudes E_1 and E_2 are:

$$E_1 = \varepsilon_1 e^{i\phi_1}$$

$$E_2 = \varepsilon_2 e^{i\phi_2}$$

And the real part of the electric field is given by:

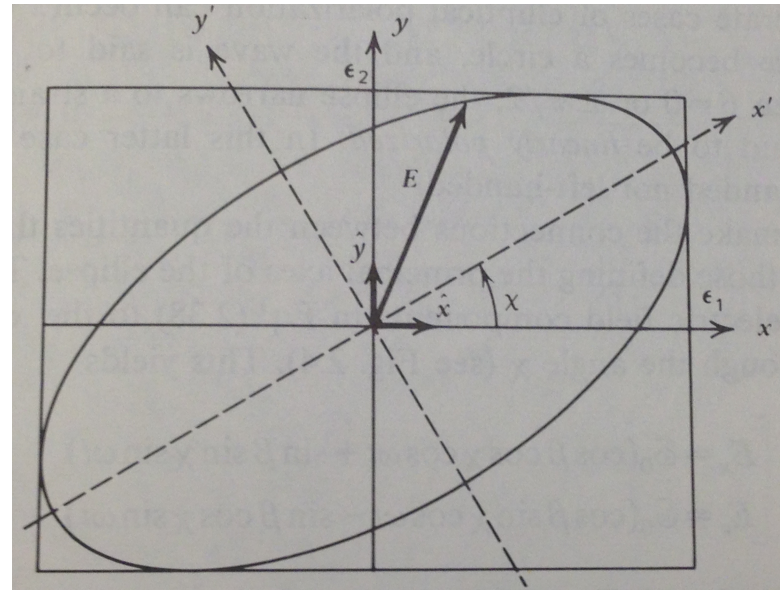
$$E_x = \varepsilon_1 \cos(\omega t - \phi_1)$$

$$E_y = \varepsilon_2 \cos(\omega t - \phi_2)$$

In the general case, the E field traces an ellipse. The equations can be re-written as:

$$E_{x'} = \varepsilon_0 \cos\beta \cos\omega t$$

$$E_{y'} = -\varepsilon_0 \sin\beta \sin\omega t$$



The last equations describe the tip of the electric field vector in the **x' – y'** plane; β is the angle between the electric vector and the long axis of an ellipse that is tilted by an angle χ relative to the **x** axis.

Polarization of light – Stokes parameters

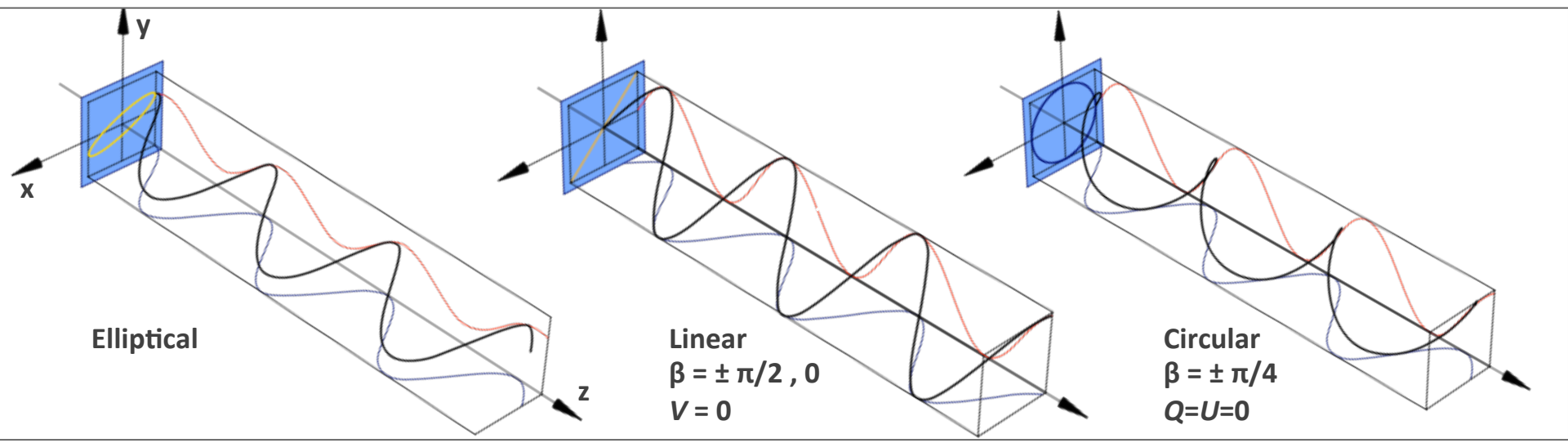
The Stokes parameters *I*, *Q*, *U*, and *V* - which describe the E vector in terms of the ellipse parameters ε, β, and χ - of a monochromatic wave, are defined as follows:

$$
\begin{aligned}
I &= \varepsilon_1^2 + \varepsilon_2^2 = \varepsilon_0^2 \\
Q &= \varepsilon_1^2 - \varepsilon_2^2 = \varepsilon_0^2 \cos 2\beta \cos 2\chi \\
U &= 2\varepsilon_1\varepsilon_2 \cos(\phi_1 - \phi_2) = \varepsilon_0^2 \cos 2\beta \sin 2\chi \\
V &= 2\varepsilon_1\varepsilon_2 \sin(\phi_1 - \phi_2) = \varepsilon_0^2 \sin 2\beta
\end{aligned}
$$

$$I = \varepsilon_0^2$$ Total intensity of the wave

$$V = I \sin 2\beta$$ Circular parameter – measures the product of the ellipse's principal axes

$$U / Q = \tan 2\chi$$ Measure the orientation of the ellipse relative to the **x** axis



Polarization of light – Stokes parameters

The Stokes parameters of a *monochromatic wave* are related as follows:

$$I^2 = Q^2 + U^2 + V^2$$

which means that the wave is **completely polarized**.

What we generally observe is a superposition of many components, each of which with different polarization (quasi-monochromatic wave). In this case, the parameters $\varepsilon_1, \varepsilon_2, \phi_1, \phi_2$ are time dependent and the general equations for the Stokes parameters are the following:

$$\boxed{\begin{aligned} I &= \left\langle \varepsilon_1^2 + \varepsilon_2^2 \right\rangle \\ Q &= \left\langle \varepsilon_1^2 - \varepsilon_2^2 \right\rangle \\ U &= \left\langle 2\varepsilon_1\varepsilon_2 \cos(\phi_1 - \phi_2) \right\rangle \\ V &= \left\langle 2\varepsilon_1\varepsilon_2 \sin(\phi_1 - \phi_2) \right\rangle \end{aligned}}$$

In practice these equations imply that the electric vector traces out an ellipse of fixed shape and fixed orientation, and only its overall size changes slowly with time.

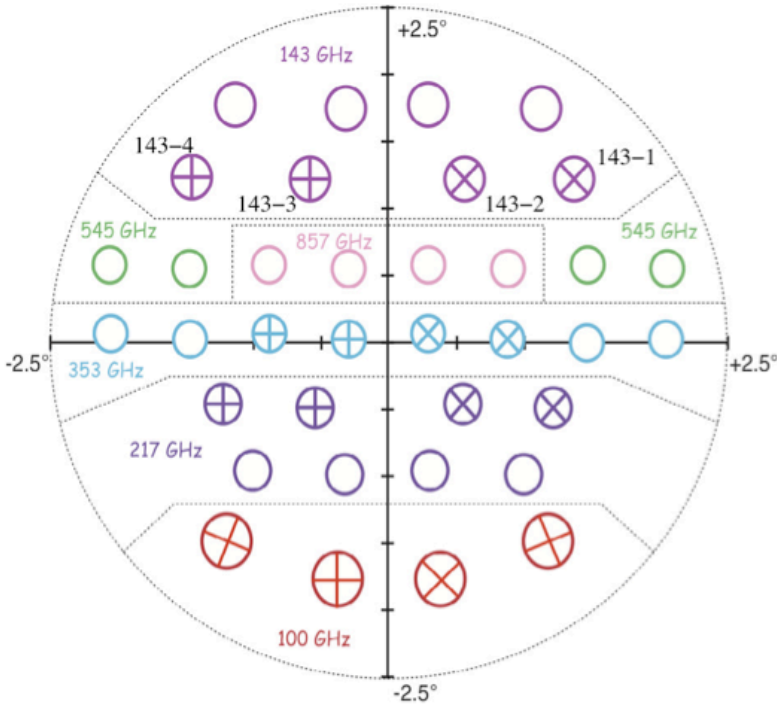
For a *quasi-monochromatic* wave, the polarization intensity:

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

Polarization of light – Stokes parameters – in practice

For the remainder of the lecture, we are interested in *linearly polarized radiation* only.

To measure linear polarization, we need detectors that pick out different (orthogonal) orientations of the electric field. We detect the maximum of *I* when the filter is aligned with the plane of polarization (x' axis), and the minimum along the direction perpendicular to it.



Rosset et al.(2010)

In the focal plane of Planck, there are two pairs of polarization sensitive bolometers, rotated by 45°. (The more pairs/angles we have, the better).

The combination of multiple observations allows us to determine the Stokes parameters, which we then use to study the properties of the radiation.

$$Q = P\cos 2\chi$$

$$U = P\sin 2\chi$$

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

$$p = P / I$$

3. (Cyclo-) Synchrotron emission

In this section

Particles that are accelerated by a magnetic field radiate:

- Non relativistic particles emit **cyclotron radiation**: the frequency of the emission is simply given by the frequency of gyration in the magnetic field

- Relativistic particles can move at many times the gyration frequency; they emit **synchrotron radiation** → of interest for many astrophysical objects.

In the following:
- Emission by relativistic particles
- Synchrotron radiation
- Why is synchrotron emission polarized?

Emission by relativistic particles

Important quantities in relativity:

- Velocity $\beta = v / c$

- Lorentz factor (factor by which time, length and relativistic mass change for a moving object)

$$\gamma = \left(1 - \frac{v^2}{c^2}\right)^{-1/2}$$

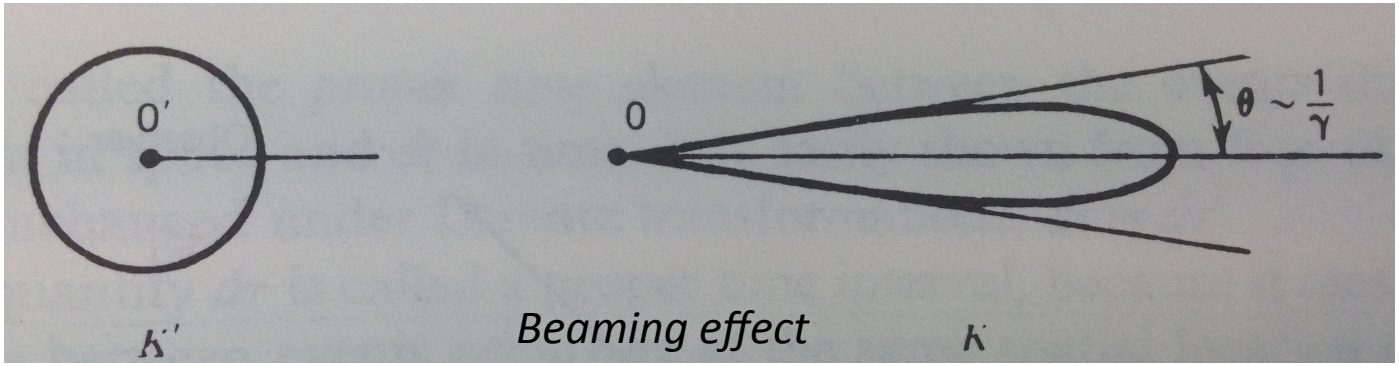
- Energy $E = (\gamma - 1) m_0 c^2$
- Momentum $p = \gamma m_0 v$

Larmor's formula (emission from a single accelerated charge *q*):

$$P = \frac{2q^2}{3c^3} a^2$$

A relativistic particle will be observed in the observer's frame (K) as moving with velocity **v**, whereas the particle is at rest in its rest frame (K').

- In K' all the photons will be emitted isotropically.
- In K the photons are emitted within a cone directed along **v**, which has an angle of the order γ^{-1}



Beaming effect

Synchrotron radiation – particle motion

The Lorentz force – force exerted by an electric field ***E*** and magnetic field ***B*** on a particle of charge *q* moving at velocity ***v*** **-** is given by:

$$\vec{F} = q\left(\vec{E} + \frac{\vec{v}}{c} \times \vec{B}\right)$$

and the rate of work done by the fields on the particle is $\vec{v}.\vec{F} = q\,\vec{v}.\vec{E}$.

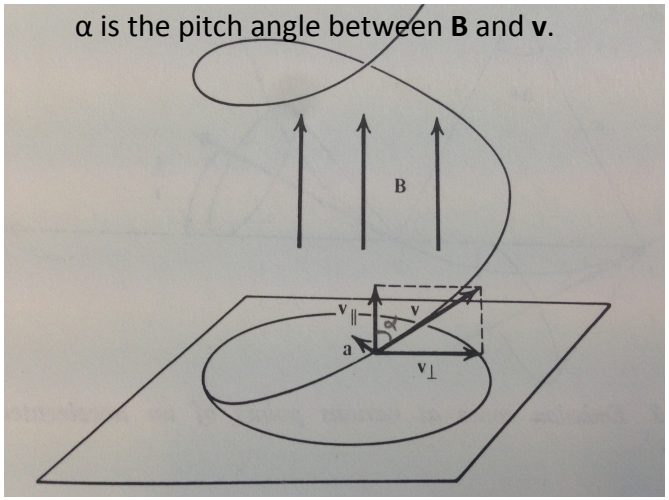
For a relativistic particle under the influence of a magnetic field **B** (**E**=0), this translates into

$$\frac{d}{dt}(\gamma m \vec{v}) = \frac{q}{c}\vec{v} \times \vec{B} \qquad \frac{d}{dt}(\gamma mc^2) = q\,\vec{v}.\vec{E} = 0\,.$$

The above equations imply that |**v**|=cnst and if we separate **v** into parallel and perpendicular components to the **B** field:

$$\frac{dv_{\parallel}}{dt} = 0 \text{ and } \frac{dv_{\perp}}{dt} = \frac{q}{\gamma mc} v_{\perp} \times \vec{B}$$

α is the pitch angle between **B** and **v**.



- Both components of v are constant
- Uniform circular motion on the plane normal to **B** (since the acceleration in this plane is normal to the velocity and of constant magnitude)
- Uniform motion along the **B** field

→ The particle moves in a *helical trajectory*, with a gyration frequency of

$$\omega_B = \frac{qB}{\gamma mc}$$

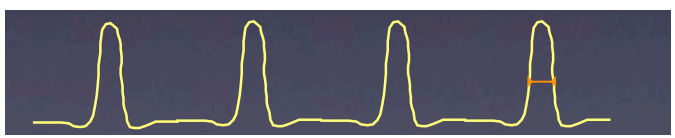
Synchrotron radiation – total emitted power/spectrum

To calculate the **total emitted radiation**, we use *Larmor's formula* – power radiated by a moving particle:

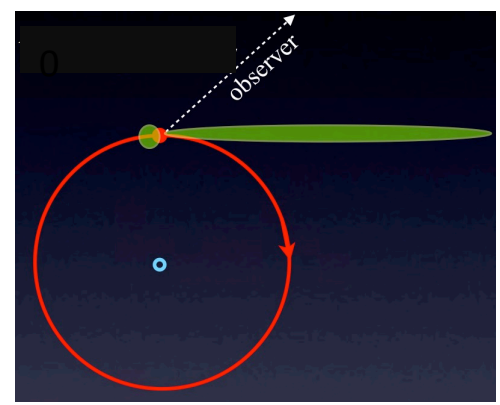
$$P = \frac{2q^2}{3c^3}\gamma^4 a_\perp^2 \qquad \text{with} \quad a_\perp = \omega_B v_\perp$$

from which we obtain $P = \frac{4}{9}\frac{q^4}{m^2c^4}c\beta^2\gamma^2 B^2$

The **spectrum of synchrotron radiation** is related to the detailed variation of the electric field as seen by an observer. Because of the beaming effect, the radiation appears to be concentrated in a narrow set of directions, around the particle's velocity.
The observer will see a pulse of radiation confined to a time interval *much smaller* than the gyration period (by a factor γ^3 – corrections from the rest to the observer's frame):



$$\Delta t \approx (\gamma^3 \omega_B \sin\alpha)^{-1}$$



This means that the synchrotron spectrum will be fairly broad, cutting off at frequencies 1/Δt. We define the critical frequency:

$$\omega_c = \frac{3}{4\pi}\gamma^3 \omega_B \sin\alpha$$

Spectrum of synchrotron radiation

The radiation spectrum - the power emitted as a function of frequency - is obtained from the Fourier transform of the electric field. It corresponds to

$$P(\omega) = \frac{\sqrt{3}}{2\pi}\frac{q^2 B \sin\alpha}{mc^2} F\left(\frac{\omega}{\omega_c}\right)$$ for a single electron, where *F* is a modified Bessel function.

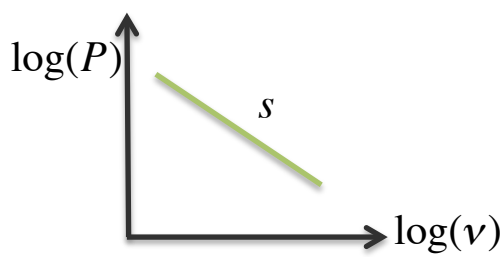
What we observe is the radiation produced by an *ensemble of relativistic electrons*, which has a given distribution of energies. The particle distribution law is usually approximated by a power law of the form:

$$N(E)dE = CE^{-a}dE$$ thus, with a spectral index a.

The resulting total power per unit volume per unit frequency is then: $$\boxed{P_{tot}(\nu) = (cnsts)B^{\frac{a+1}{2}}\nu^{-\frac{a-1}{2}}}$$

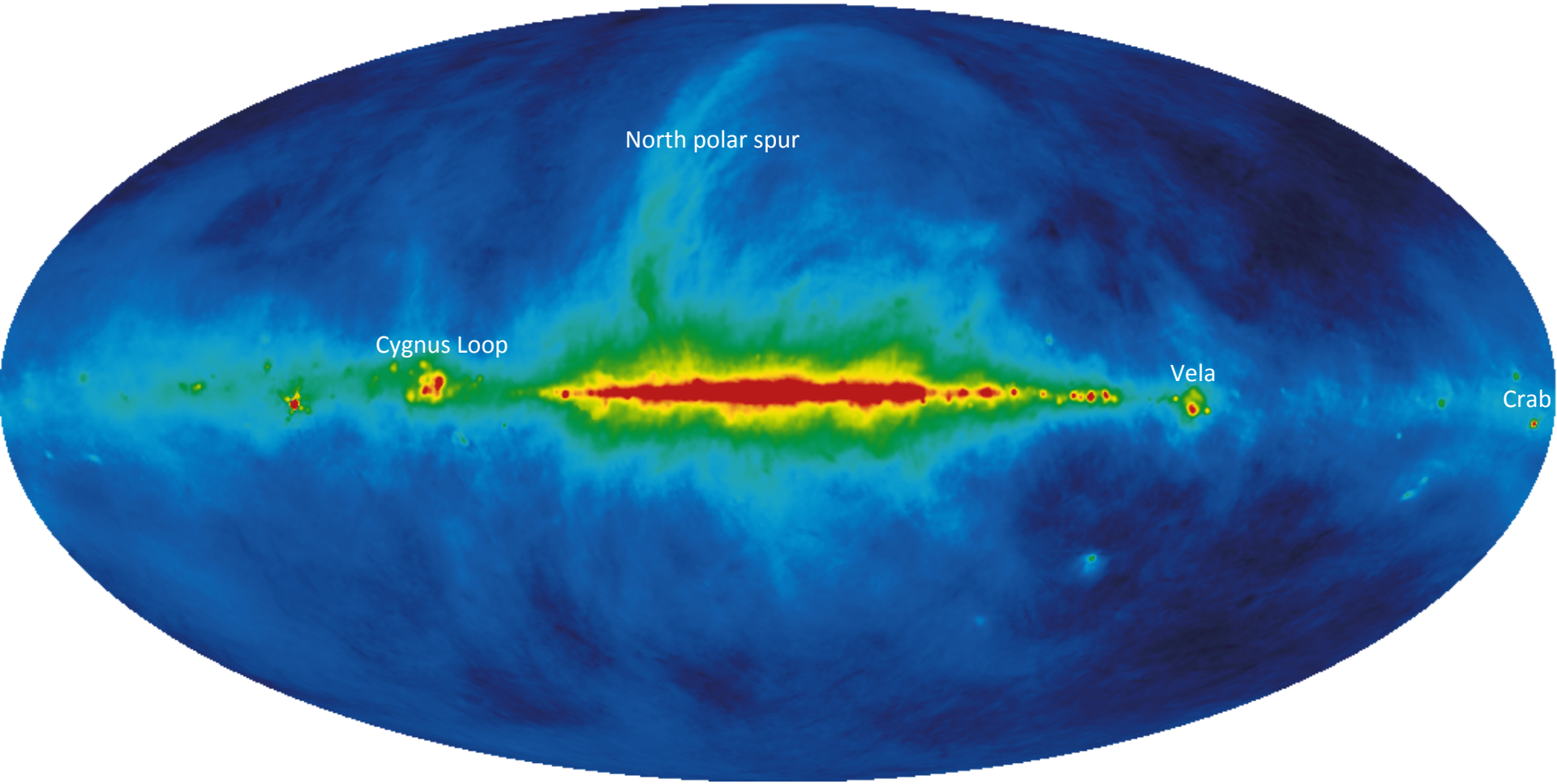
Meaning that we can approximate the frequency spectrum by a power law:

$$P_s \propto \nu^{-s}, s = \frac{a-1}{2}$$



In practice:
The power law slope of relativistic electrons in the energy range relevant to the production of synchrotron emission is $a \approx 2.4$, which implies $s \approx 0.7$, in agreement with the observations.

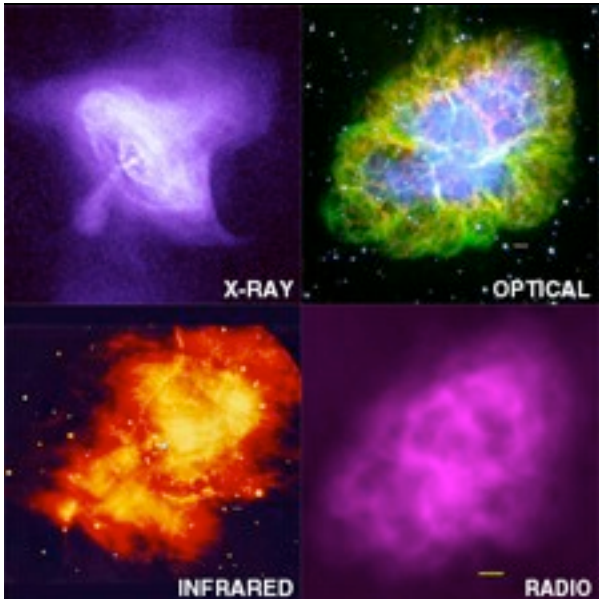
The synchrotron sky



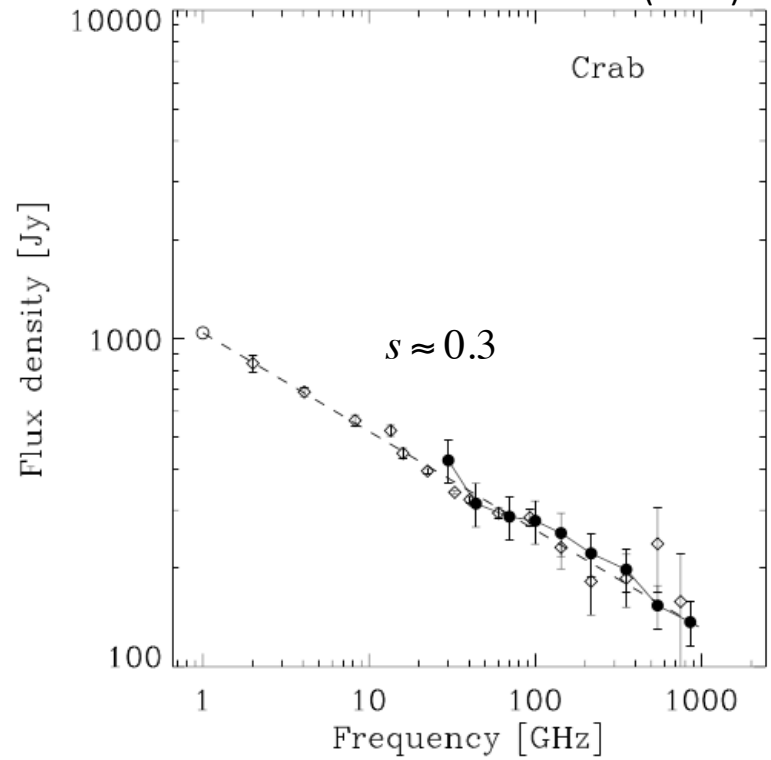
The sky at 408 MHz, observed by four different telescopes (Jodrell Bank MkI, Bonn 100m, Parkes 64m, and Jodrell Bank MkIA, Haslam et al. 1982).

Synchrotron is the dominant emission of radio sources (frequencies 100s MHz – 1 GHz).
There is strong emission in the Galactic plane and also towards isolated objects: supernova remnants.

A synchrotron object – the Crab nebula



Planck Collaboration Int. XXXI (2014)



The Crab is a pulsar wind nebula – the nebula is powered by the winds of the central pulsar, well seen in the X-ray image.

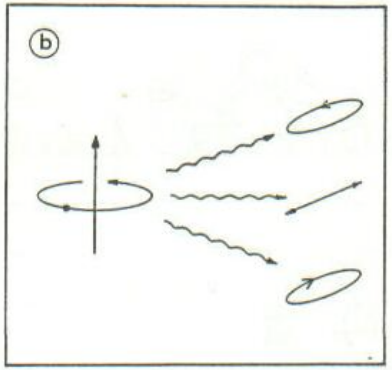
The shallow radio-microwave spectral index (compared to the average 0.7 across the sky) tells us that there are energetic electrons, with a power law index $a \approx 1.6$, which are constantly being injected from the pulsar into the nebula.

Polarization of synchrotron radiation

As we saw before, synchrotron radiation is emitted within a well-defined beam
→ radiation is emitted with a preferred orientation → polarization.

The radiation from a single electron is elliptically polarized.

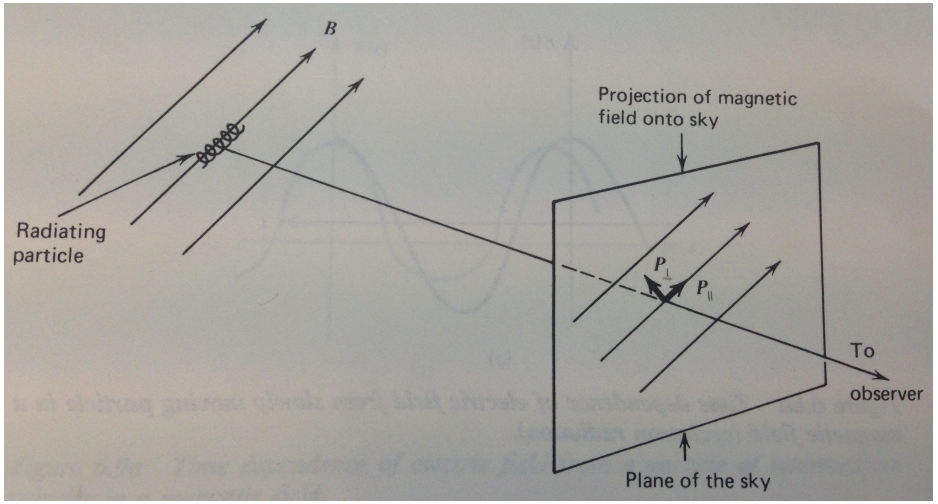
When the emission cones of a distribution of electrons are averaged, the elliptical components cancel out
→ *partial linear polarization*.



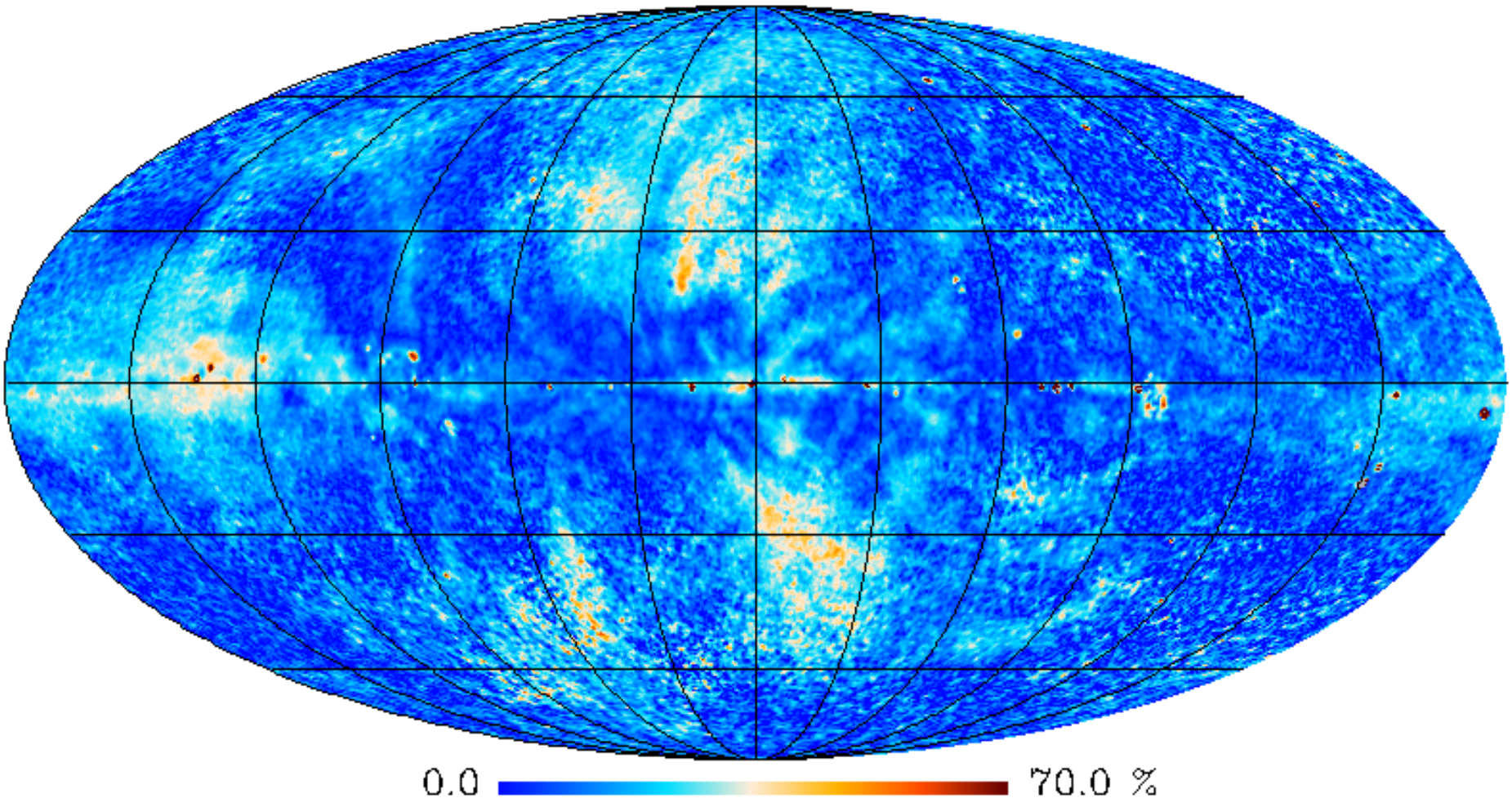
Since the power spectrum of synchrotron emission is well defined, we can estimate the degree of polarization by comparing the power in each component:

$$p = \frac{P_\perp - P_\parallel}{P_\perp + P_\parallel} \quad \text{which can be written as} \quad p = \frac{a+1}{a+7/3}$$

For $a = 2.4$ the intrinsic polarization degree of synchrotron radiation is $p = 72\%$.



The synchrotron polarized sky



The polarized sky, fraction of polarization p, at 23 GHz (Planck Collaboration XXV 2015).

It doesn't really look like the synchrotron sky in total intensity!
And p is hardly close to the intrinsic polarization fraction of 72%... Why?

What can we infer from the polarized emission?

Recall that the Stokes parameters – which are **observed quantities** – allow us to obtain:

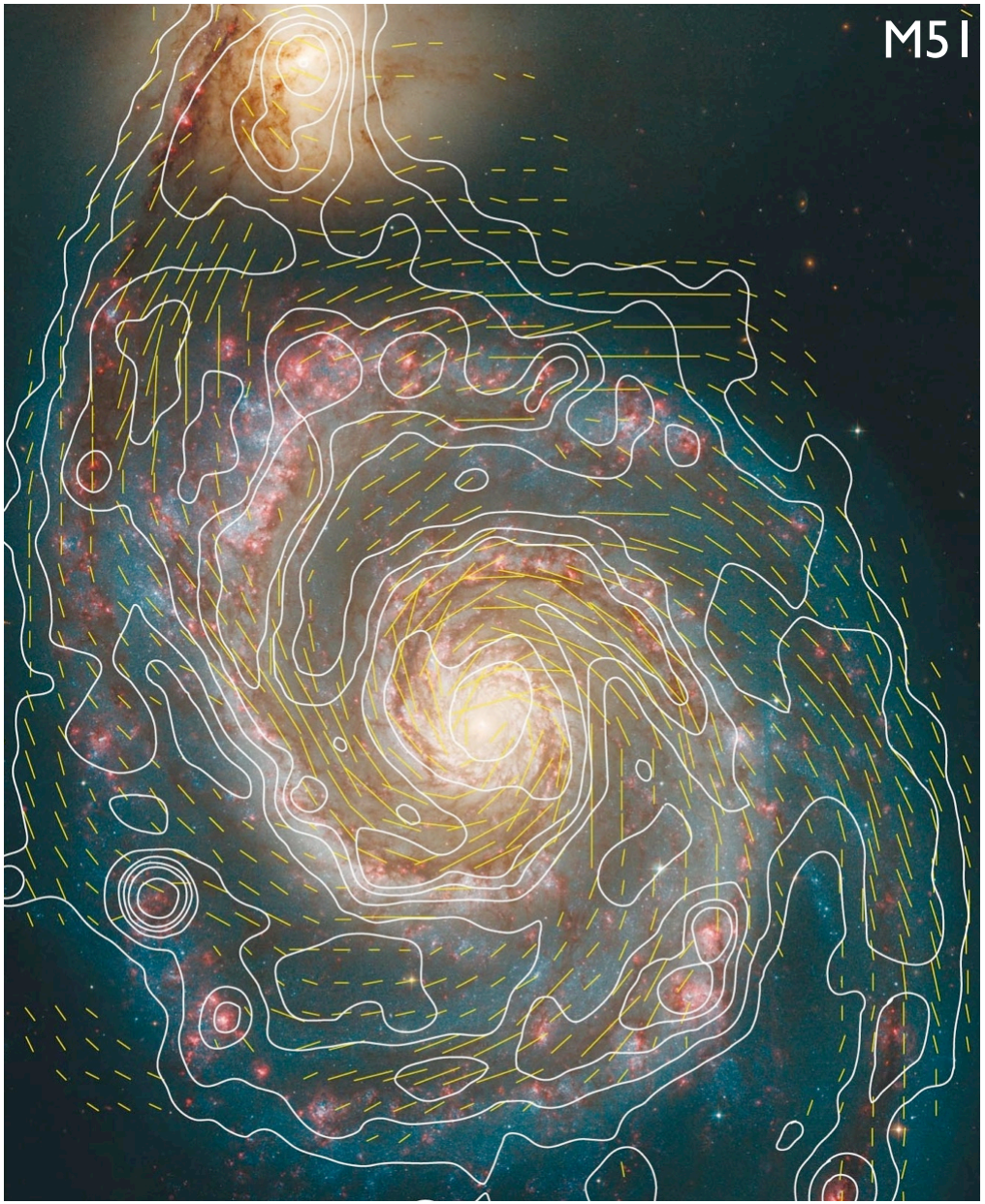
$$Q = I\cos 2\chi$$
$$U = I\sin 2\chi$$
$$P = \sqrt{Q^2 + U^2}$$
$$p = P / I$$

The fraction of polarization – as shown in the previous map – as well as the polarization angle χ.

The polarization angle is **perpendicular** to the magnetic field orientation (for the reasons discussed before; the electron emits radiation perpendicular to the magnetic field).

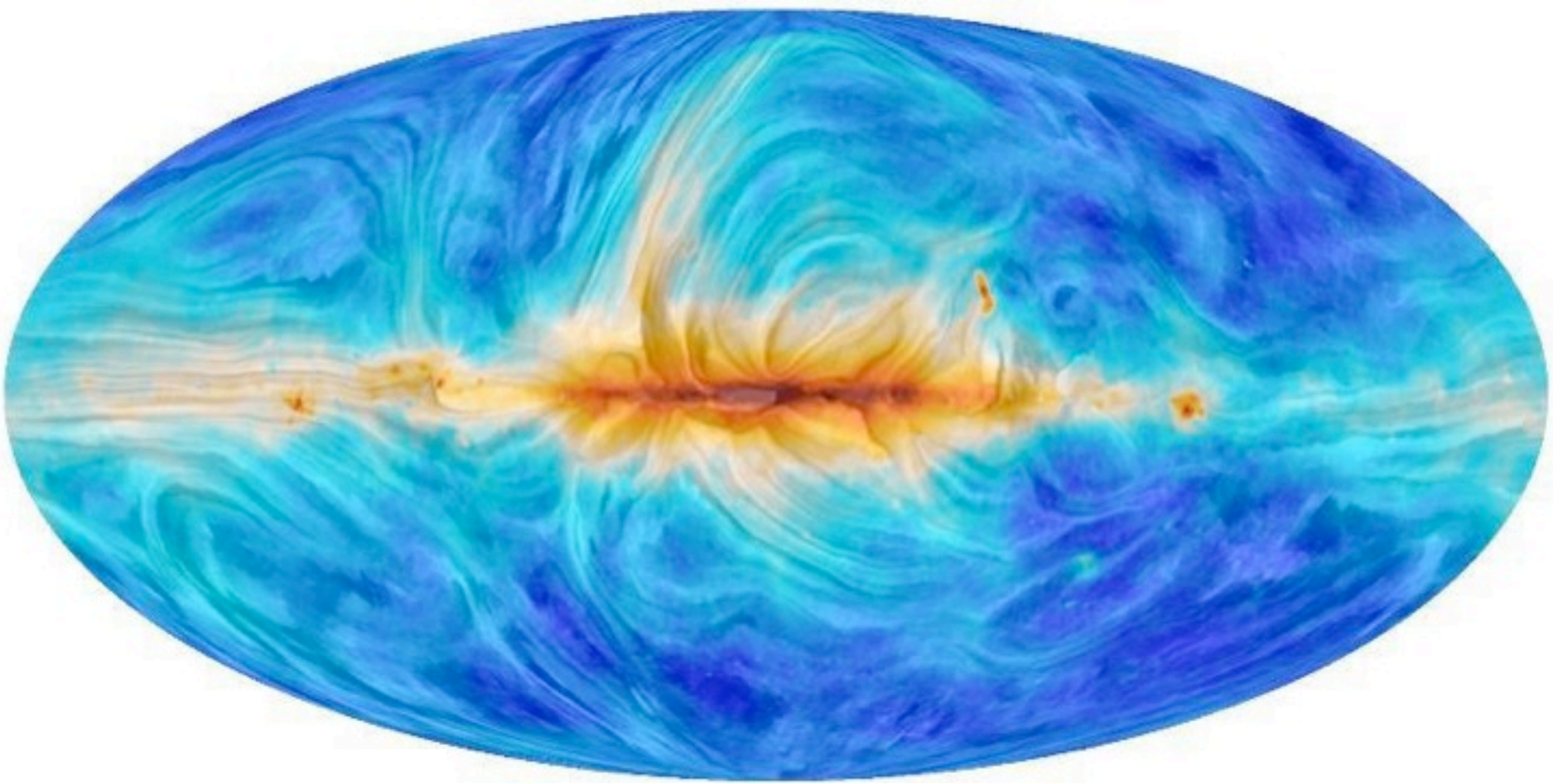
We can infer the orientation of the magnetic field from polarized synchrotron radiation, by rotation the polarization angle by 90°.

The magnetic field of the M51 galaxy



Fletcher et al. 2011

The magnetic field of the Milky Way



Planck collaboration 2015

4. Thomson/Compton scattering

Thomson scattering

Thomson scattering arises when a charged particle radiates in response to an incident electromagnetic wave → **it is accelerated by the electric field of the incident radiation**.

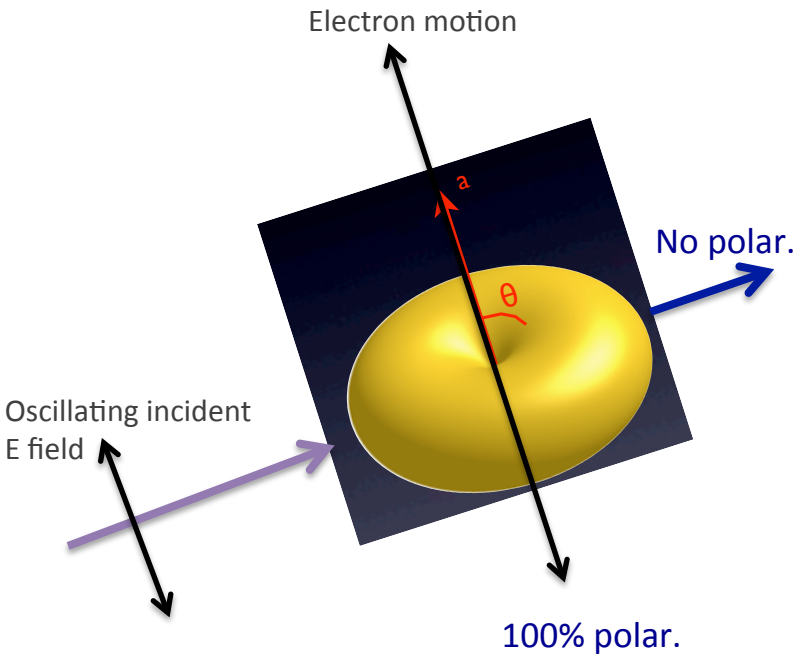
It applies in the non-relativistic regime (v << c → **Compton scattering**) and when the wavelength of the incident radiation is much smaller than the size of the particle (→ **Rayleigh scattering**).

The electron and the photon do not exchange energy, but there is a change in the direction of the radiation, when the particle re-radiates the electromagnetic energy of the photon.

→ The electron will move in the plane of the oscillating electric field – perpendicular to the direction of the incident wave.

→ The electron will emit dipole radiation: there is no radiation in the direction of its motion; on the other hand, the electron radiates most strongly in the perpendicular direction.

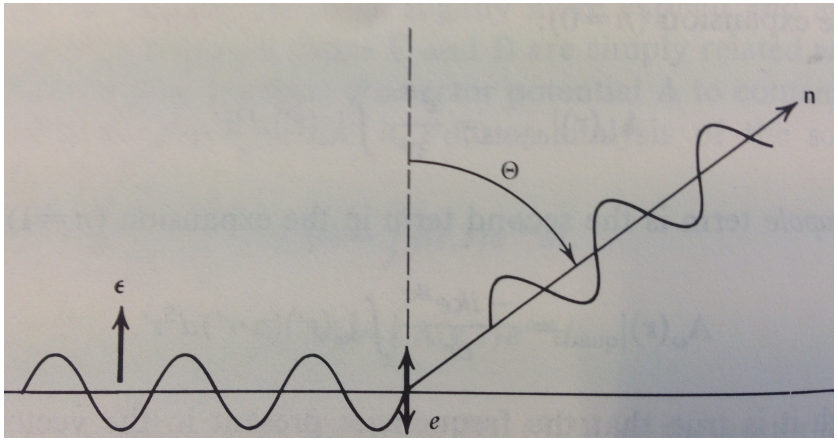
→ The radiation will be polarized along the direction of its motion.



Thomson scattering cross section

The *differential cross section* for Thomson scattering relates the flux from the incident wave <*S*> with the power scattered by solid angle d*P*/d*Ω*:

$$\frac{dP}{d\Omega} = \langle S \rangle \frac{d\sigma}{d\Omega}$$



$$\boxed{\frac{d\sigma}{d\Omega} = \frac{e^4}{m^2c^4}\sin^2\Theta = r_0^2 \sin^2\Theta}$$

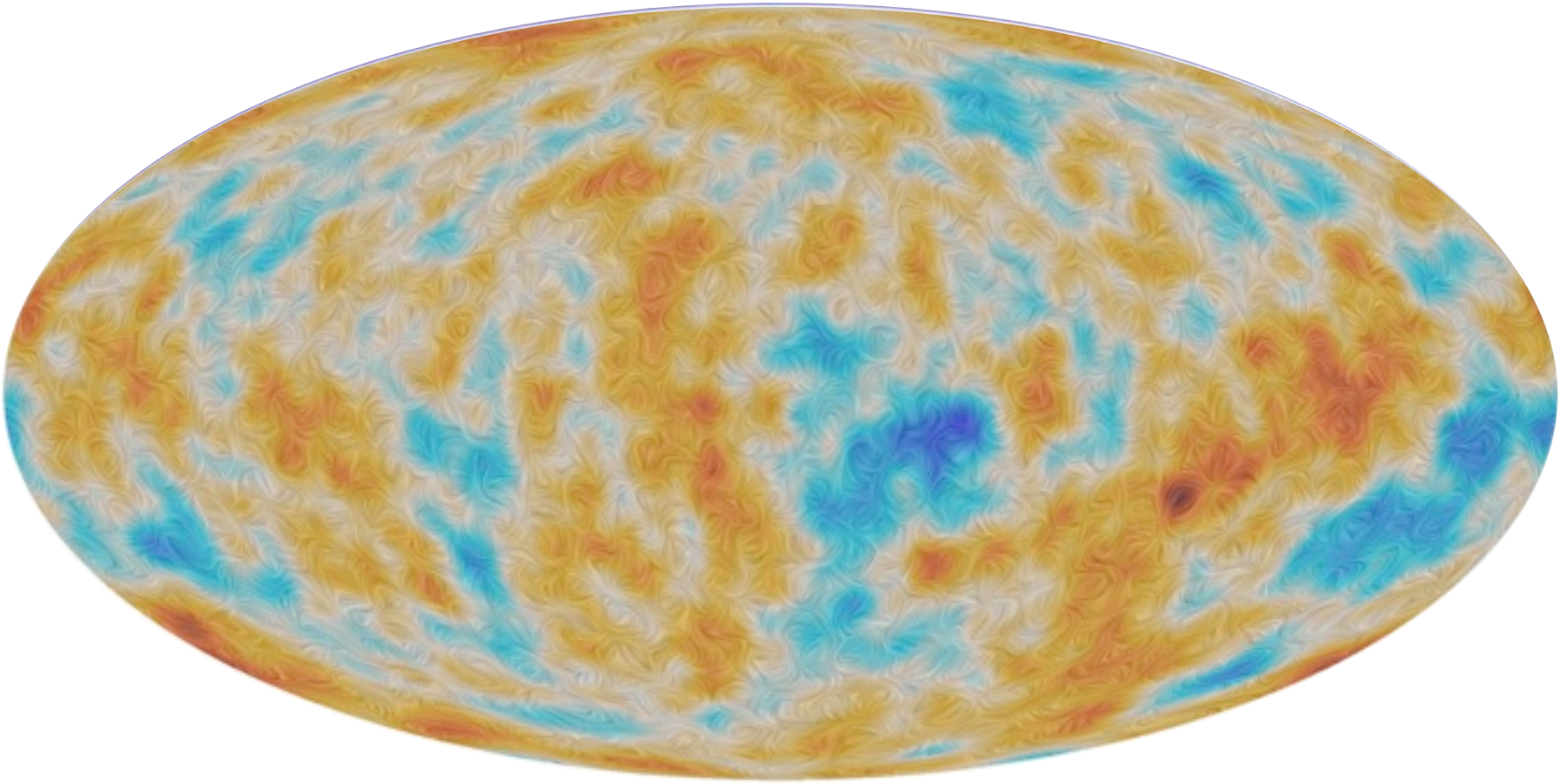
where $r_0 \equiv \dfrac{e^2}{mc^2}$ is called the "classical electron radius".

The total cross section is obtained by integrating over the solid angle: $\sigma = \dfrac{8\pi}{3} r_0^2$

Note: It does not depend on frequency, thus scattering is equally efficient at all frequencies – frequencies at which this approximation applies.

Thomson scattering - example

The cosmic microwave background is **polarized due to Thomson scattering:** electrons that fall in a gravitational/density potential at the time of recombination, scatter the radiation from photons emitted by neighbouring electrons.



Planck Collaboration 2015

Compton scattering

Compton scattering is the inelastic scattering of a photon by an electron.
(Inelastic: because in this regime the electron recoil cannot be neglected.)

Also, the **scattering cross section is reduced** since the energy of the incident photon becomes comparable to, or exceeds, the electron rest mass energy.

The energy ε of the scattered radiation is given by (conservation of four-momentum):

$$\varepsilon_f = \frac{\varepsilon_i}{1 + \frac{\varepsilon_i}{mc^2}(1 - \cos\theta)} \qquad \text{or} \qquad \lambda_f - \lambda_i = \lambda_c(1 - \cos\theta)$$

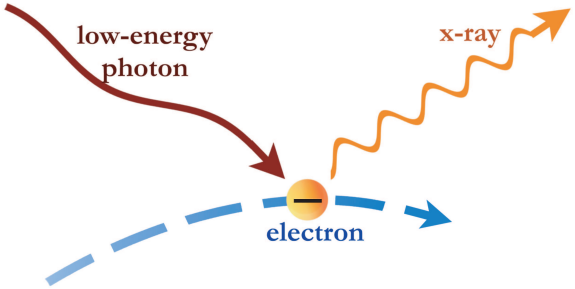
where f and i correspond to the final and incident radiation, and θ is the angle between the incident and scattered wave vectors, and

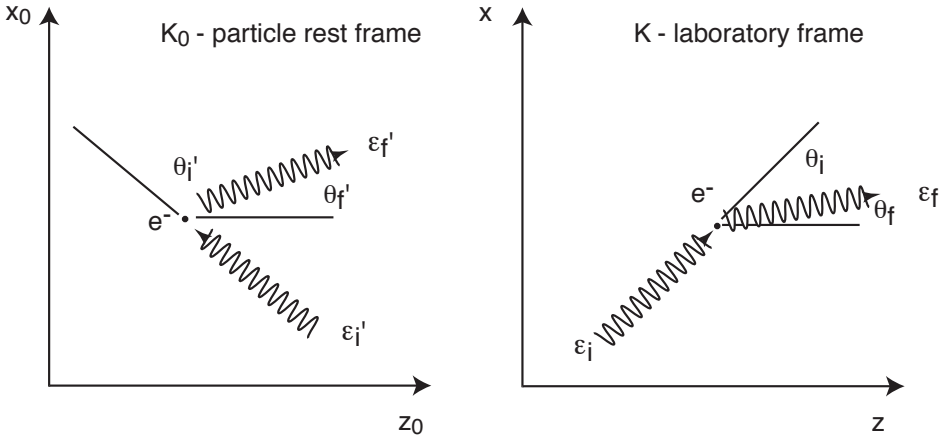
$$\lambda_c = \frac{h}{mc} = 0.024 \text{ Å}$$ is the Compton wavelength (for electrons).

Since 0 < θ < π, the wavelength of the scattered radiation is always larger than that of the incident radiation → loss of energy by the photon.

Inverse Compton scattering

In this case, the opposite happens: the photon gains energy by scattering off a relativistic electron – the electron has sufficient kinetic energy compared to the photon.





θ_i and θ_f are the angles between the incident and scattered radiation relative to the direction of the moving electron – ' corresponds to the rest frame.

(Lorentz transformations): the ratios of the incident energy in the observer's frame, in the rest frame before scattering, and in the observer's frame after scattering are approximately

$$1 : \gamma : \gamma^2$$

thus this process converts a low-energy photon to a high-energy photon by a factor of the order γ^2.

Inverse Compton scattering – cooling time

As a relativistic electron travels through a medium containing low-energy photons, it will lose energy with each Compton scattering – as it loses energy via the emission of synchrotron radiation.

The ratio between the power radiated by an electron in the form of synchrotron radiation and via Inverse Compton scattering is:

$$\frac{P_{synch}}{P_{compt}} = \frac{U_B}{U_{ph}}$$

where U_B and U_{ph} are the energy density of the magnetic field $U_B = B^2 / 8\pi$ and of the photons, respectively.
(Note: the above equation is valid for any value of the electron's velocity, but only when the Thomson scattering limit is valid in the rest frame of the electron.)

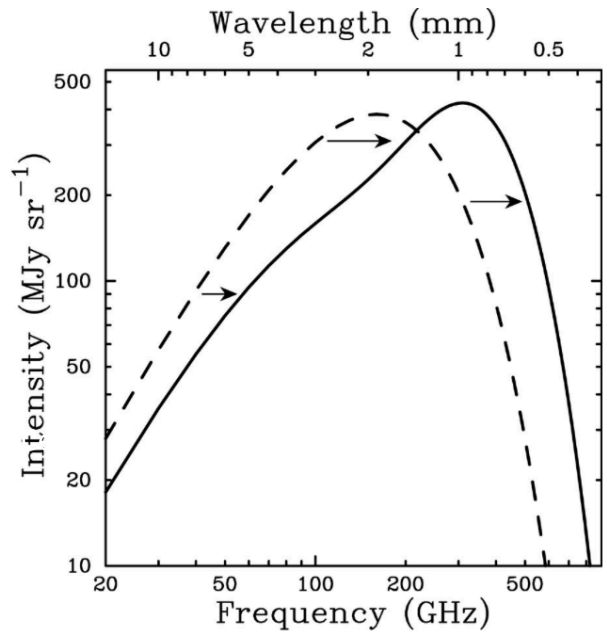
The **cooling time** is proportional to the inverse of the photon energy:

$$t_{compt} \approx U_e / \left(dP / dV \right) \propto 1 / U_{ph}$$

Inverse Compton scattering - examples

Sunyaev-Zel'dovich (SZ) effect: CMB photons gain energy as they scatter from free electrons in the intracluster gas of galaxy clusters.
→ The spectrum of the CMB is shifted towards higher frequencies.

Since the SZ effect is related to the energy (temperature) of the gas, this effect is used to determine the properties of the cluster.



Credits: NED/IPAC

Credits: NASA

γ – ray production: γ – rays are produced by Inverse Compton scattering off high energy electrons in energetic objects e.g. pulsars, active galactic nuclei (AGN), supernova remnants. The electrons are accelerated by these objects and the photons can be provided by, e.g., synchrotron radiation.

5. Bremsstrahlung (free-free) emission

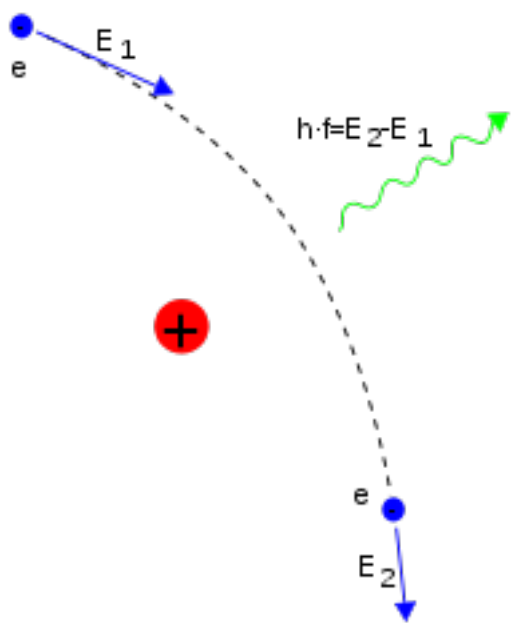
Free-free emission

Radiation due to the acceleration of a charge in the Coulomb field of another charge is called *bremsstrahlung* - which means braking radiation in German - or *free-free* emission - since the particles are unbound before and after the interaction.

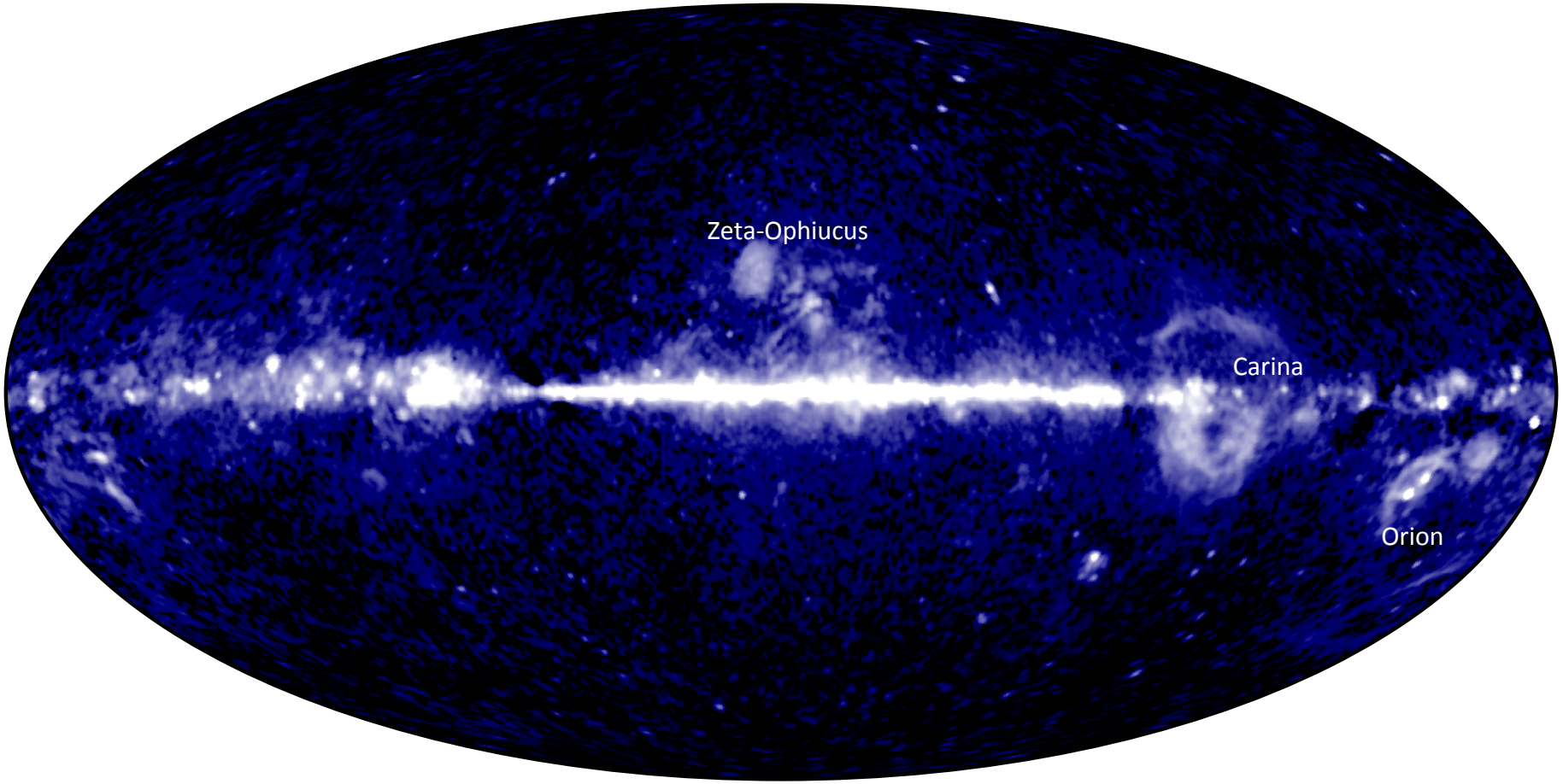
For free-free emission to occur the medium must be relatively **dense**, so that electrons have a higher probability of encountering a charged particle; the medium must also be **ionized**, so that electrons are free from protons, rather than bound to an hydrogen atom.

Free-free emission originates in regions where massive (O/B type) stars are forming, since these are the only stars capable of ionizing hydrogen atoms.

An electron loses energy via free-free radiation by passing close to an ion.



Free-free emission sky



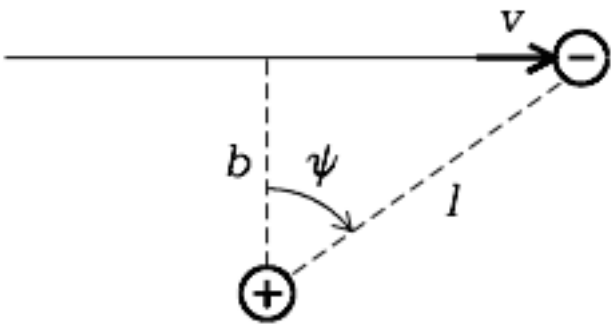
(Planck Collaboration XXV 2015)

All of the bright regions are **ionized (HII) regions**, where massive stars are forming.

Free-free emission – single velocity electrons

A full understanding of the free-free emission process requires a quantum treatment. However, the classical approach, with a correction for the quantum effects, properly describes most of the physical parameters.

The electron is assumed to move past an ion of charge *Ze* rapidly enough so that the deviation from a straight line is negligible.



The two particles interact over a time interval, called the *collision time*, of the order of $\tau = b/v$, where b and v are the impact parameter and velocity of the electron, respectively.

The power radiated in a single collision, from a single velocity electron in a medium of ion density n_i and electron density n_e, is:
(from the Larmor's formula, which gives the power emitted by a moving electron)

$$j_\nu = \frac{16\pi e^6}{3\sqrt{3}c^3 m^2 v} n_e n_i Z^2 g_{ff}(\nu,\omega)$$

Gaunt factor: correction for quantum effects; certain function of the energy of the electron and frequency of emission.

Free-free emission from many electrons

In practice, the particles – electrons – in the ionized gas follow a velocity distribution very close to a Maxwellian distribution, which is determined by the electron temperature *T*. This means that the ionized gas is in thermal equilibrium.

Integrating the power radiated by an electron over all velocities gives:

$$j_\nu^{ff} = 5.4 \times 10^{-41} n_e n_i Z^2 T_4^{-1/2} e^{-h\nu/kT} \bar{g}_{ff}(\nu, T)$$

in erg s^{-1} cm^{-3} Hz^{-1} sr^{-1}

Velocity averaged Gaunt factor:

Quantum effects are important at very low frequencies, close to the plasma frequency $\nu_p = 8.98(n_e / cm^{-3})^{1/2}$, otherwise at radio frequencies – of interest here – we just have a two body Coulomb scattering problem.

The Gaunt factor from quantum mechanical calculations can be approximated by:

$$g_{ff} \approx 6.155(Z\nu)^{-0.118} T_4^{0.177}$$

Free-free emission – spectrum

The previous equations imply that the free-free emissivity is then:

$$j_\nu^{ff} \propto T_4^{-0.32} \nu^{-0.12}$$

therefore the free-free spectrum is *almost flat*, decreasing very slowly with frequency.

Having the gas in thermal equilibrium, we can estimate the free-free absorption coefficient through Kirchhoff's law:

$$\alpha_\nu^{ff} = \frac{j_\nu^{ff}}{B_\nu} \propto \nu^{-3} n_e n_i Z^2 T^{-1/2} (1 - e^{-h\nu/kT}) \bar{g}_{ff}$$

From this we can derive the free-free optical depth, $\tau_\nu(s) = \int_{s_0}^{s} \alpha_\nu(s')\, ds'$, which in the radio limit $h\nu << kT$ corresponds to:

$$\tau_\nu \propto T_4^{-1.32} \nu^{-2.2} EM$$

where the Emission Measure is defined as $EM = \int n_i n_e \, ds$.

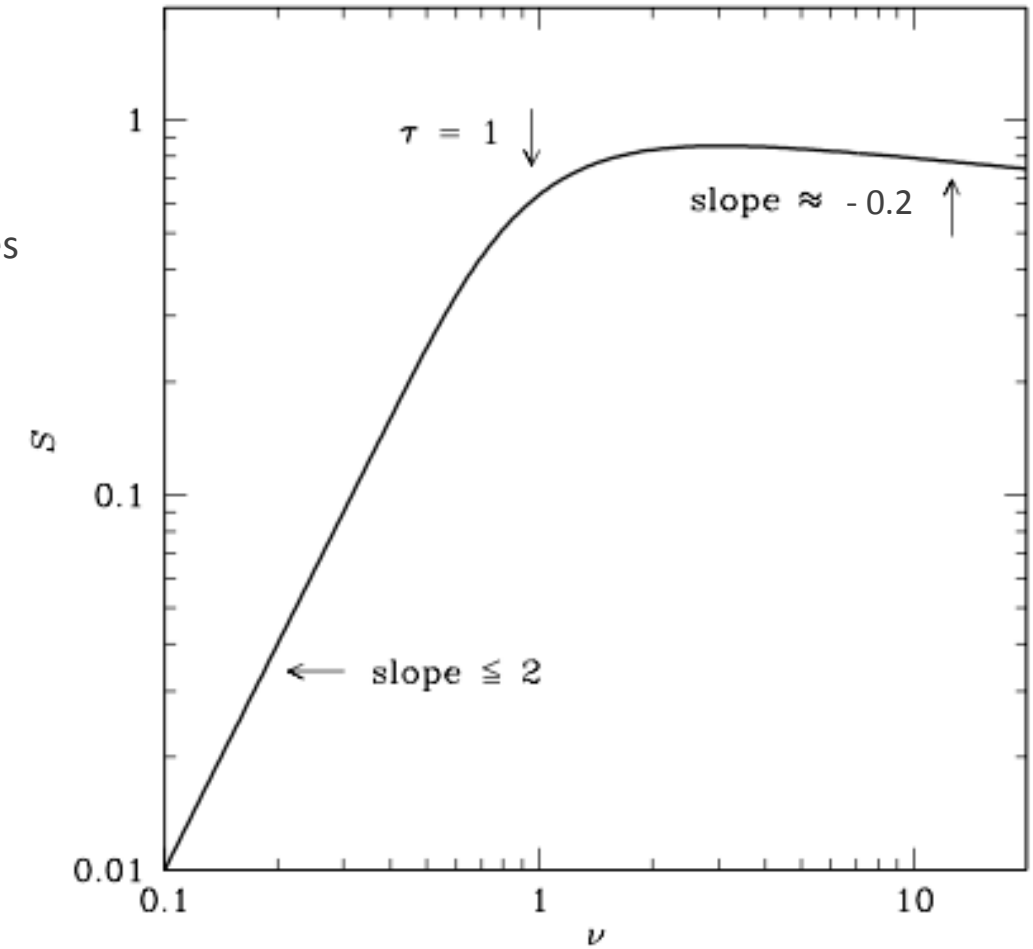
Free-free emission – spectrum

$$\tau_\nu \propto T_4^{-1.32} \nu^{-2.2} EM$$

The optical depth equation tells us that, at low frequencies, free-free emission is optically thick (τ>>1).

In this regime the free-free spectrum behaves like a blackbody with a temperature equal to that of the electrons: $T = T_e$.

→ By measuring the spectrum of an HII region, we can directly infer its **physical properties** (temperature, density, size, etc.).



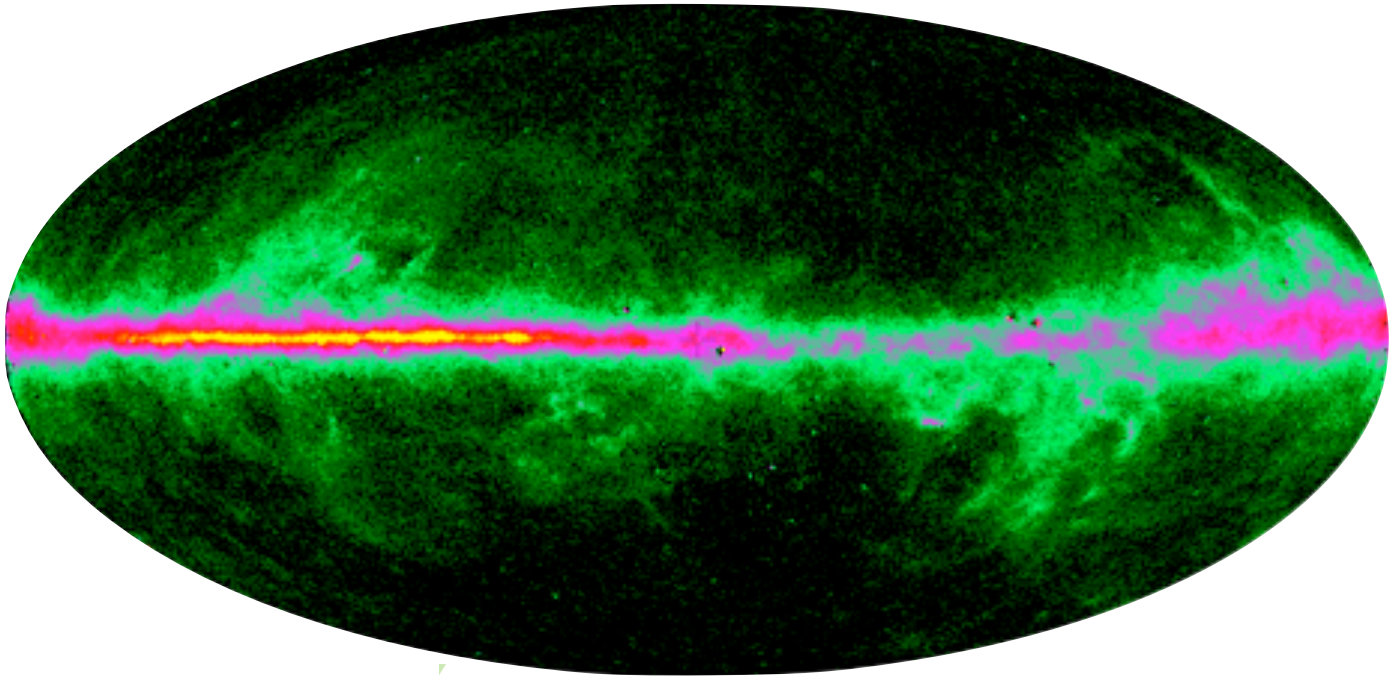
Credits: NRAO

Relativistic Bremsstrahlung radiation

Until now we have discussed the interaction between electrons and ions in a thermal gas of temperature around $T = T_e \approx 10000K$ – typical temperature of HII regions, which give rise to radio photons.

Relativistic bremsstrahlung occurs when a relativistic electron is deflected in the electrostatic potential of an atom, ion, or molecule, giving rise to **X-ray** and **γ-ray photons** of energy

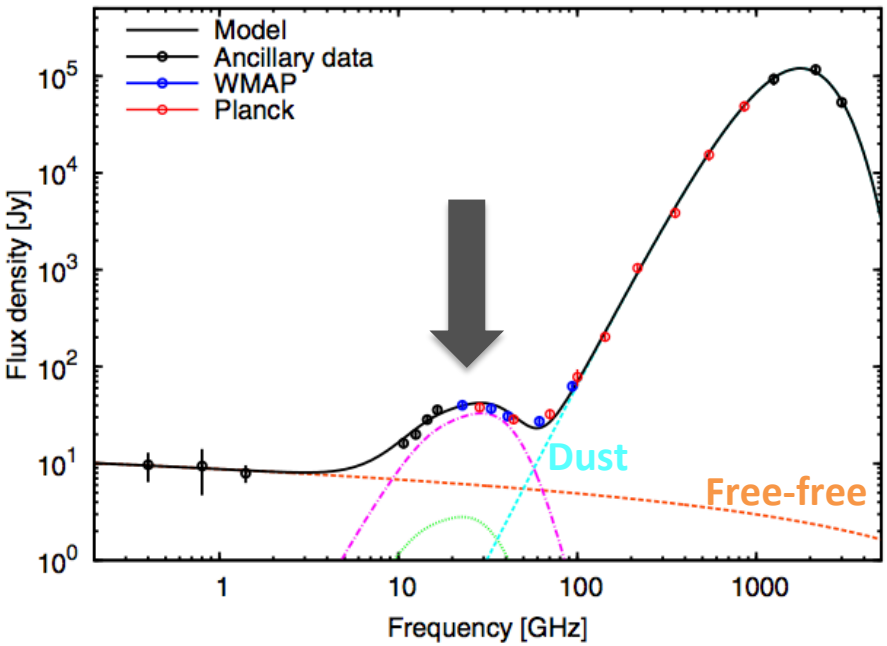
$$E_\gamma \approx E_{ele} / 2 = \gamma mc^2 / 2$$



The sky as seen by the Fermi γ-ray space telescope (Fermi diffuse model, I.Grenier 2013 ESLAB).
(Map centred at l=270°)

6. Anomalous microwave emission

Anomalous ?? microwave emission



Emission spectrum of the Perseus molecular cloud (Planck Early results XX 2012)

Radio to far infrared spectrum: free-free and synchrotron emission dominate at the lowest frequencies; emission from dust grains dominates at the highest frequencies (Part 7).

In the late 90s an *unexpected* "bump" was detected in the microwave spectrum of the Galaxy. *Unexpected* because in this range of frequencies we only expect free-free and synchrotron emission!

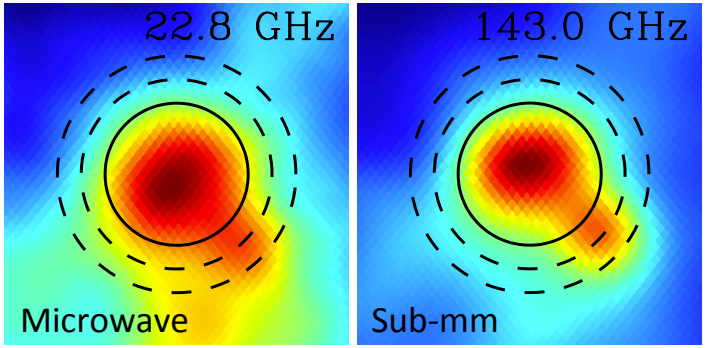
(And this is the reason for name "anomalous microwave emission" or AME.)

AME – where/what?

AME was first detect in 1996 by Kogut et al. at high Galactic latitudes, in the so-called *diffuse medium*.

Soon after, a few *individual objects* – molecular clouds, infra-red dark clouds, HII regions - were studied and the idea that **spinning dust emission** was behind AME arose (in 1998 by Draine & Lazarian; the microwave emission by spinning dust grains had been first predicted by W.C. Erickson in 1957).

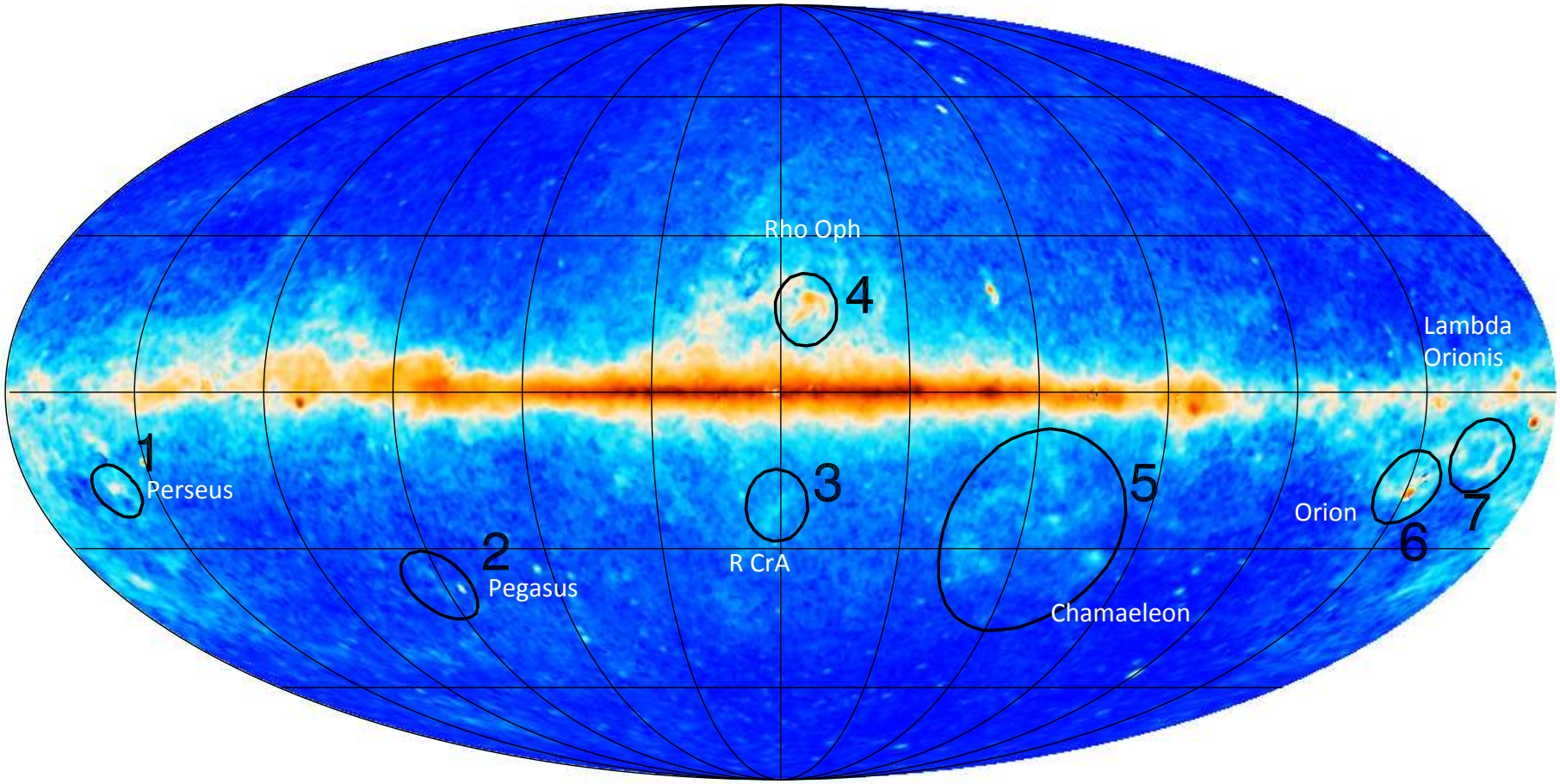
→ This hypothesis was mostly motivated by the fact that the microwave emission was correlated with the far-infrared/sub-mm emission – which traces emission from interstellar dust grains.



Example:
G5.4+36.5; Planck Coll. XV 2014

Before Planck there were only a few convincing examples of AME – spinning dust emission. With the much higher statistics on individual objects and a significant detection of AME in the diffuse medium, it is now well established that small spinning dust grains are responsible for the AME.

AME sky

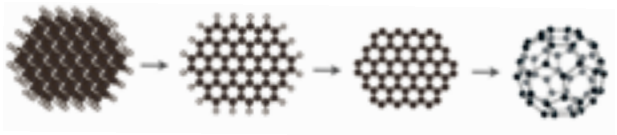


(Planck Collaboration XXV 2015)

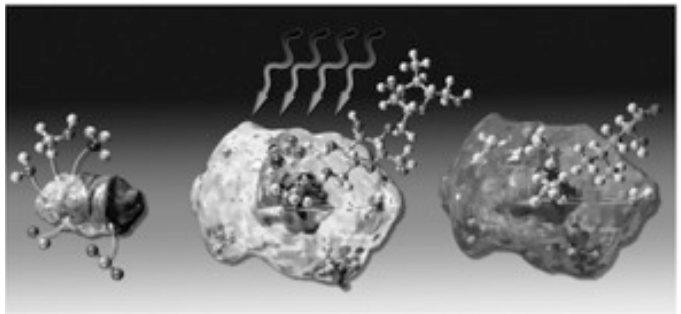
There is AME everywhere in the sky – from individual regions at high latitude, to diffuse emission, to a bright band of emission in the Galactic plane.

AME - dust particles

Dust grains in the interstellar medium have different sizes, compositions, properties, etc.

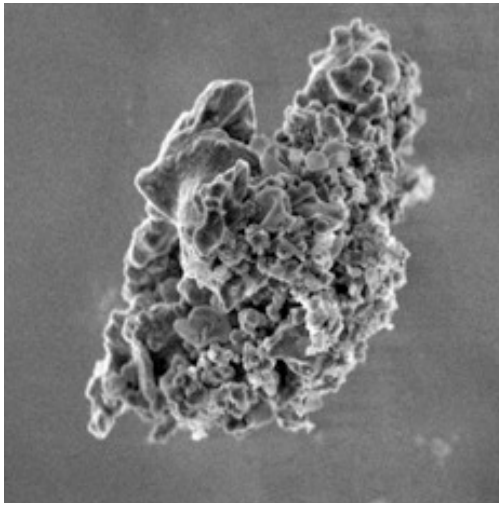


Large molecules: polycyclic aromatic hydrocarbons (PAHs); size ~ 0.6 nm



Small grains: aggregates of large molecules; size ~ 5 nm

Responsible for the AME

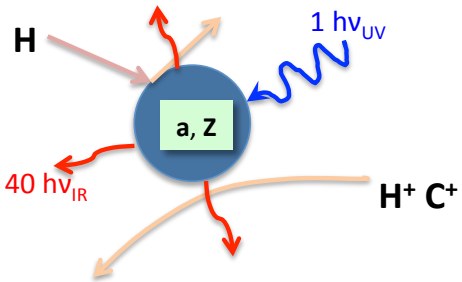


Big grains: carbon/silicate cores and ice mantles; size ~ 10 nm

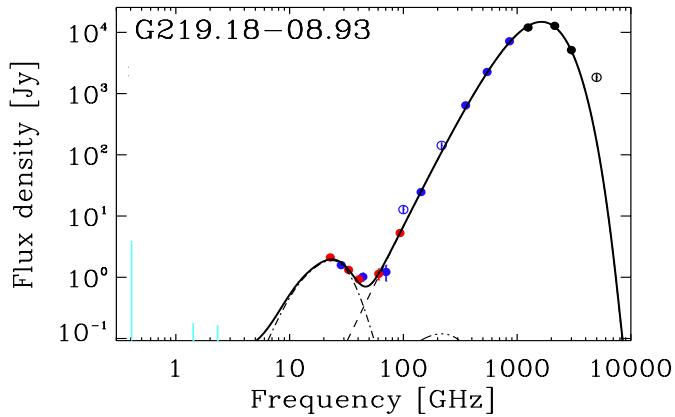
→ Next section (Part 7)

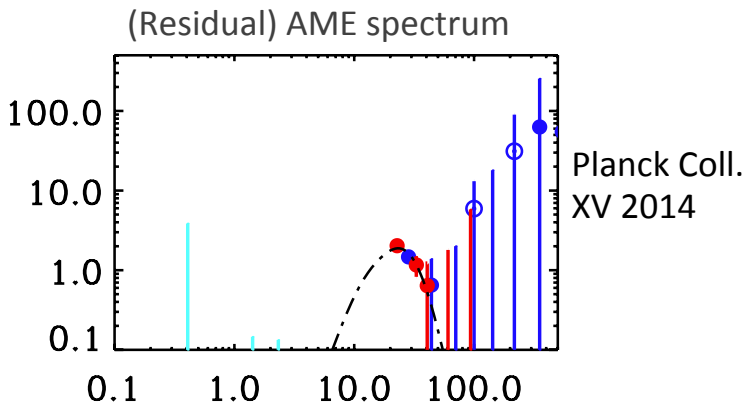
AME – spinning dust – physical models

Collisions with gas, plasma drag, and infra-red photons are three possible mechanisms to spin up (very rapidly!) very small dust grains and to make them radiate at GHz frequencies.



The observed AME spectrum has a parabola shape (in the log(F)-log(v) space):





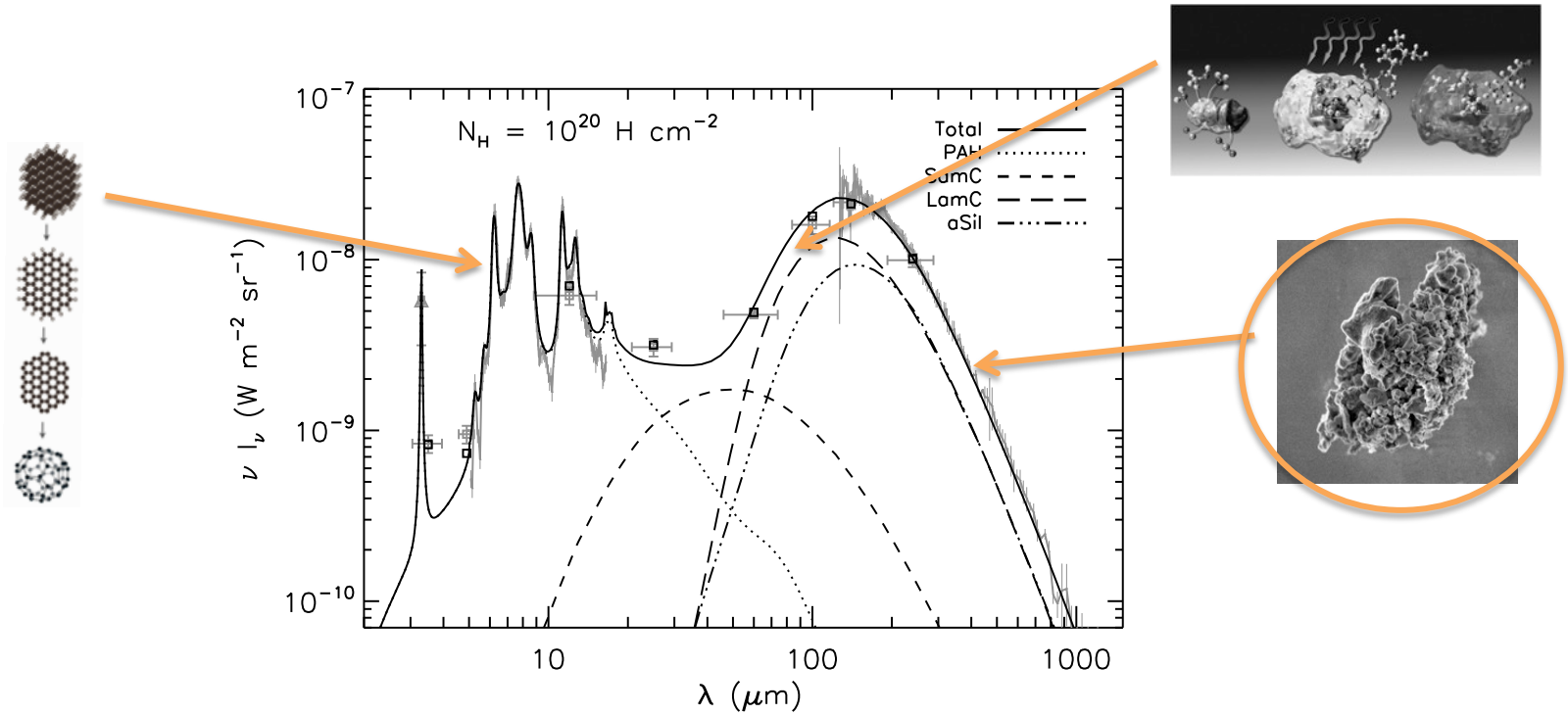
Spinning dust provides a potential diagnostic for interstellar dust properties.
By comparing the observed spectrum with ***physical models*** we can investigate:
→ The density of the medium, the radiation field to which the grains are exposed, the abundance of small grains and PAHs – these particles are very important in the heating and chemistry of the ISM!

7. (Thermal) dust emission

Dust emission

Historically, interstellar dust was first recognized for its obscuring effects – dark lanes seen in the optical images of the Galaxy, due to the absorption/scattering of starlight (later in this section).

With the increased sensitivity in sub-mm/far-infrared instruments, in particular satellites that allowed us to trace the dust emission across the whole sky, dust is increasingly important as a diagnostic of the ISM.



Multiple dust component modelling of the emission from the diffuse high Galactic latitude medium; data from the ISO and COBE satellites (Compiegne et al. 2011).

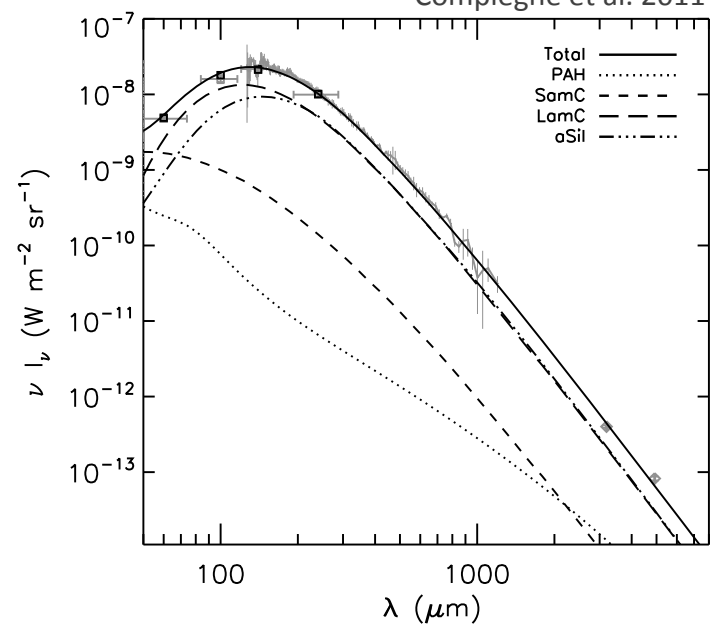
Emission from big dust grains

The long wavelength tail of dust emission is dominated by the emission from the largest grains.

Dust grains are heated by the stellar photons and cool by radiating in the infra-red and sub-mm.

→ They are in *thermal equilibrium with the radiation field* and their emission can be approximated by a **greybody function**, or **modified blackbody** law.

Compiegne et al. 2011



A modified blackbody (MBB) describes the *optically thin thermal emission* of the dust grains and has the form:

$$I_\nu = \boxed{\tau_{\nu_0}\left(\frac{\nu}{\nu_0}\right)^{\beta}} B_\nu(\nu, T_\mathrm{d})$$

The Planck function at a temperature T_D – the dust temperature – is modified by a power law - the dust optical depth/opacity - which has a spectral index β.

Emission from big dust grains – dust properties

The dust optical depth is the product of the dust emissivity cross section per unit mass and the dust mass column density

$$\tau_\nu = \kappa_\nu M_{\rm dust}$$

where $M_{\rm dust} = r\,\mu\, m_{\rm H}\, N_{\rm H}$.

Dust-to-gas mass ratio, ~ 1%

Mean molecular weight and H atom mass

Gas column density

The dust opacity depends on the chemical composition and structure of the grains – but not on their size, when the particles are small compared to the wavelength, as is the case. This means that the spectral index β varies, depending on the properties of the grains.

→ Study of the dust emission spectrum gives constraints on the **properties of interstellar dust**.

Another aspect of great importance when studying the emission of interstellar dust is that its opacity is proportional to the total column density of gas, which is a **measure of the mass** in the interstellar medium (gas and dust are well mixed in the ISM).

Emission from big dust grains – in practice

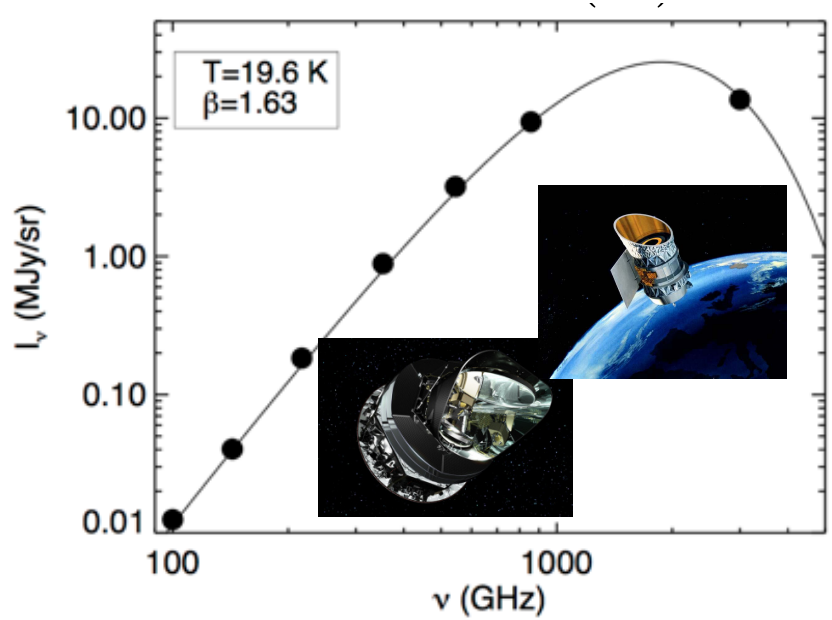
Having a sufficient number of frequency points, we can fit the MBB function for the three unknown parameters:

$$I_\nu = \tau_{\nu_0} \left(\frac{\nu}{\nu_0} \right)^\beta B_\nu(\nu, T_\mathrm{d})$$

this gives us directly the optical depth at a reference frequency ν_0, which we can convert into a column density N_H, and estimate the mass of objects – for which the distance is known.

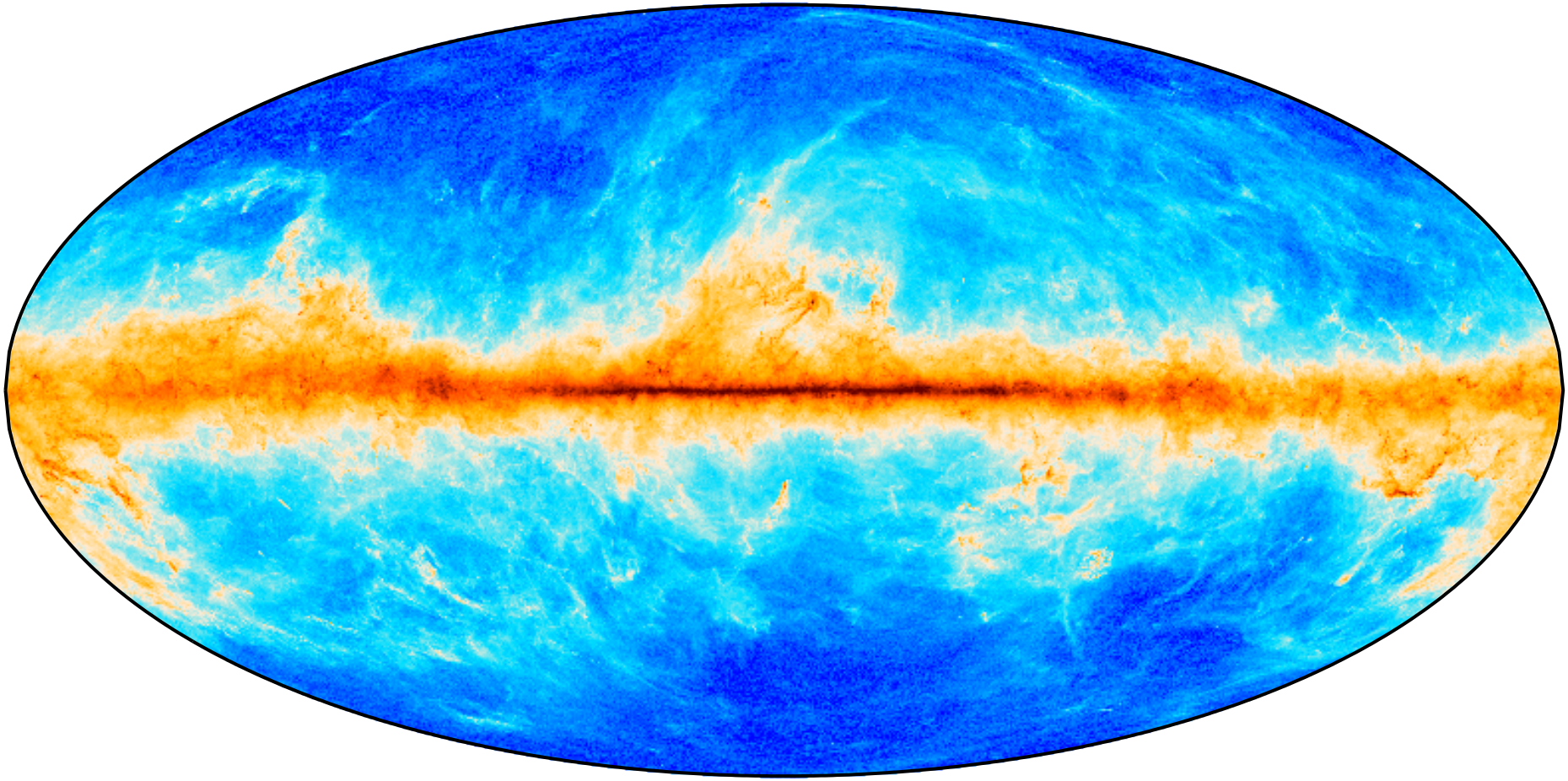
Knowledge of the mass is important to assess the gravitational state of interstellar objects.

6 Planck frequencies (100-857 GHz) and IRAS 3000 GHz



Dust is therefore seen/used as a tracer of interstellar matter.

Dust optical depth – gas column density

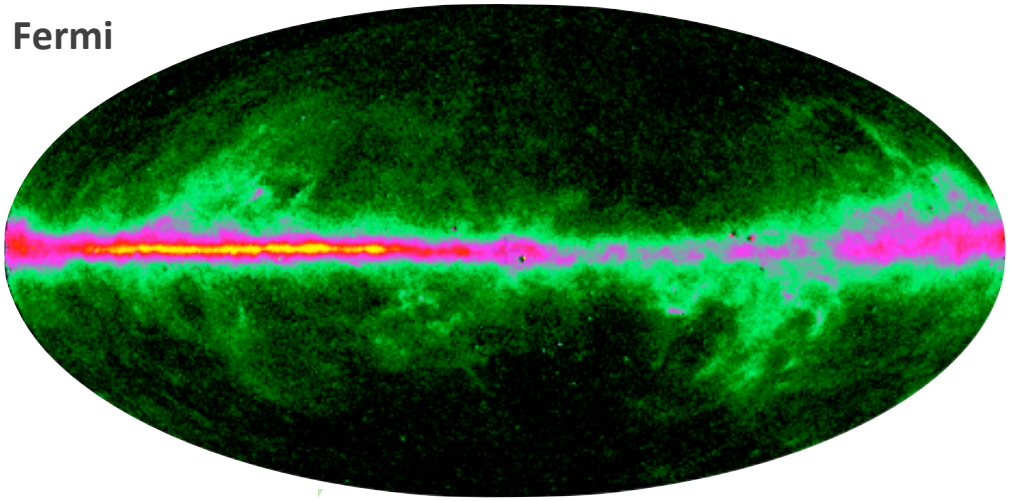


Planck Collaboration XI. (2014)

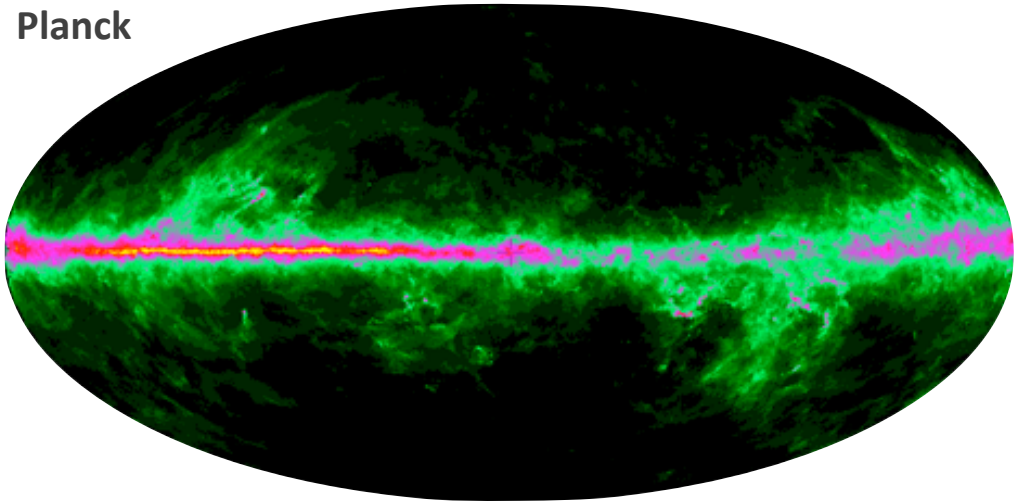
This map gives us an image of the Galaxy's reservoir for star formation, as it traces interstellar gas from all phases.

Dust and γ-rays – gas column density tracers

Fermi



Planck



(Maps centred at l=270°)

I.Grenier 2013 ESLAB

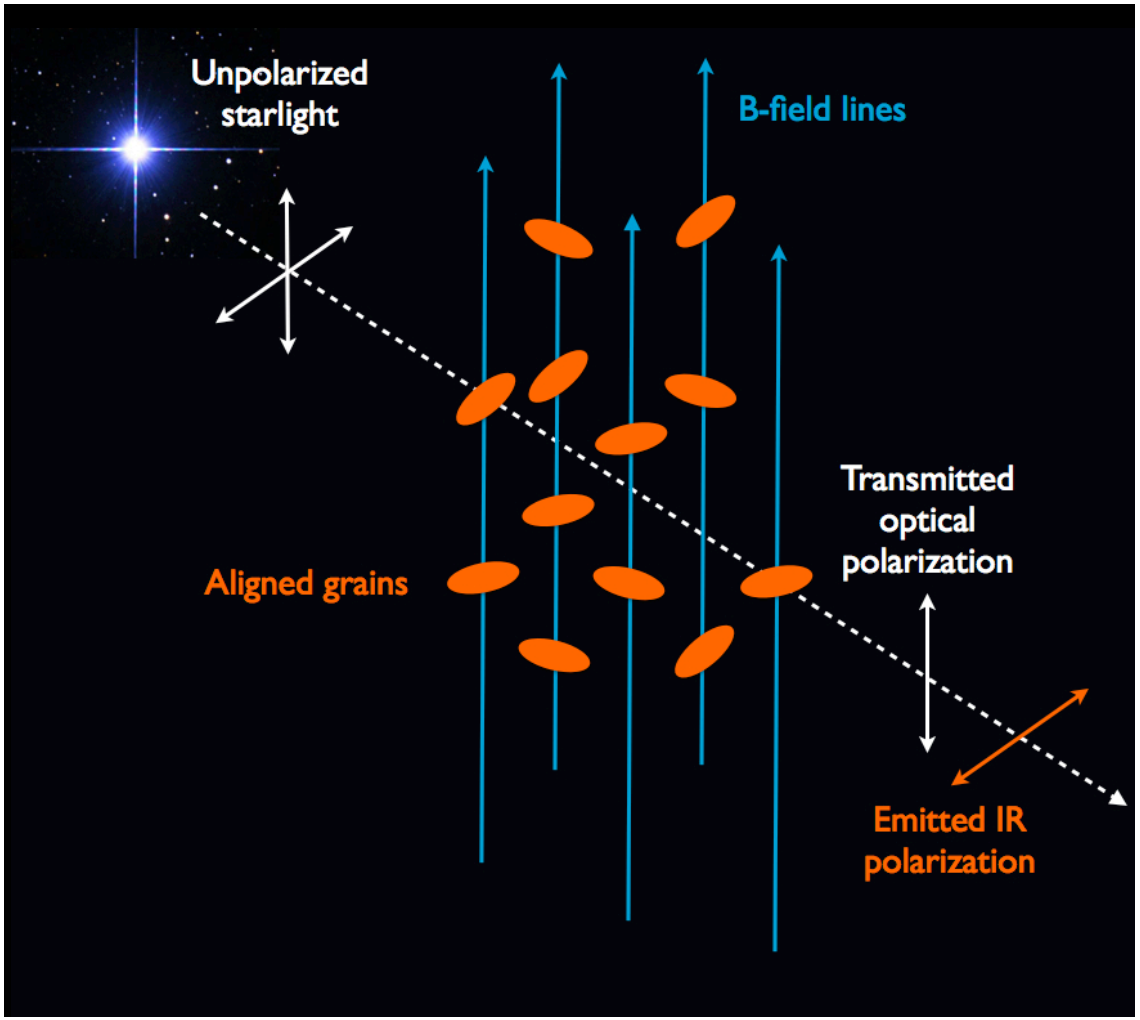
Besides the two γ-ray production mechanisms already mentioned (inverse Compton and Bremsstrahlung), diffuse γ-ray emission also arises from the interaction between **cosmic-ray protons** and all forms of **interstellar gas** (γ-rays are produced from the decay of the generated π^0 particles).

There is therefore a correlation between the diffuse Galactic emission detected with Fermi and with Planck: both are tracing the total gas column density in the ISM.

(Dust maps from Planck are used to separate the different γ-ray components of diffuse emission.)

Dust polarization

Dust emits polarized emission in the sub-mm/far-infrared; dust grains also polarize starlight in the visible/ultraviolet.



- Dust grains are aspherical and rotate at super-thermal velocities along their axis of maximal inertia, which is aligned with the magnetic field (alignment processes still debated).

- Grains **emit** preferentially along their longest axis, therefore the polarization of the emitted wave is **perpendicular** to the magnetic field.

- The **extinction** of starlight by dust grains is higher parallel to the longest axis, thus the incoming light is polarized **parallel** to the magnetic field.

Dust polarization – Stokes parameters

Reminder:

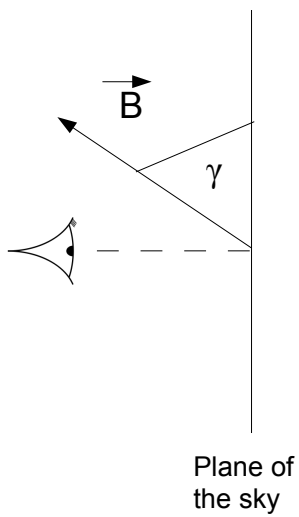
$$Q = P\cos 2\chi$$
$$U = P\sin 2\chi$$
$$P = \sqrt{Q^2 + U^2}$$
$$p = P / I$$

Dust polarized intensity is given by:

$$P = p_0 \cos^2 \gamma$$

Intrinsic polarization fraction (dust properties; degree of alignment)

Angle between the plane of the sky and the magnetic field



Credits: L. Fanciullo

We observe less polarized emission when the field is along the line of sight.

Dust polarization observations – in practice

What can we infer from these observations?

- The polarization fraction gives important constraints on the properties of dust grains (which populations are aligned, with what **alignment efficiency**, etc.) and it can also give indirect information on the 3rd component of the magnetic field, through the $\cos^2\gamma$ term.

- Again – as in the case of synchrotron observations - the ratio between the Q and U Stokes parameters gives **directly the magnetic field orientation**:

$$\chi = 0.5\tan^{-1}(U/Q)$$

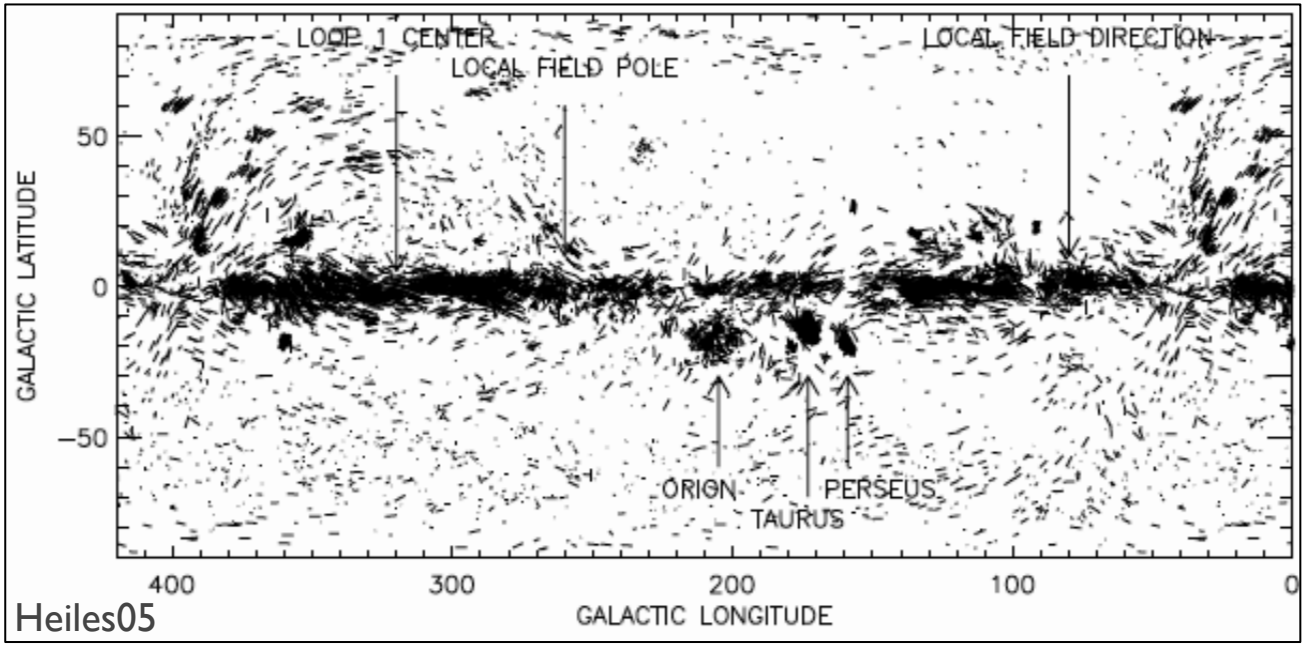
And as we just saw, emission/extinction polarizes light in perpendicular orientations.

→ Using extinction data $\psi_B = \chi$ and using emission data $\psi_B = \chi + \pi/2$

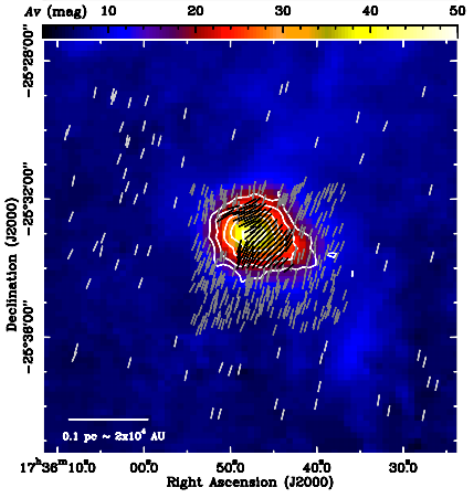
The important aspect of tracing the magnetic field orientation through through dust polarization is that dust is a tracer of interstellar matter, thus we have access to the magnetic field structure in star-forming regions.

The magnetic field of the Milky Way - Dust

Before the Planck all-sky survey we had information on the large scale Galactic magnetic field through dust extinction measurements (towards thousands of stars).



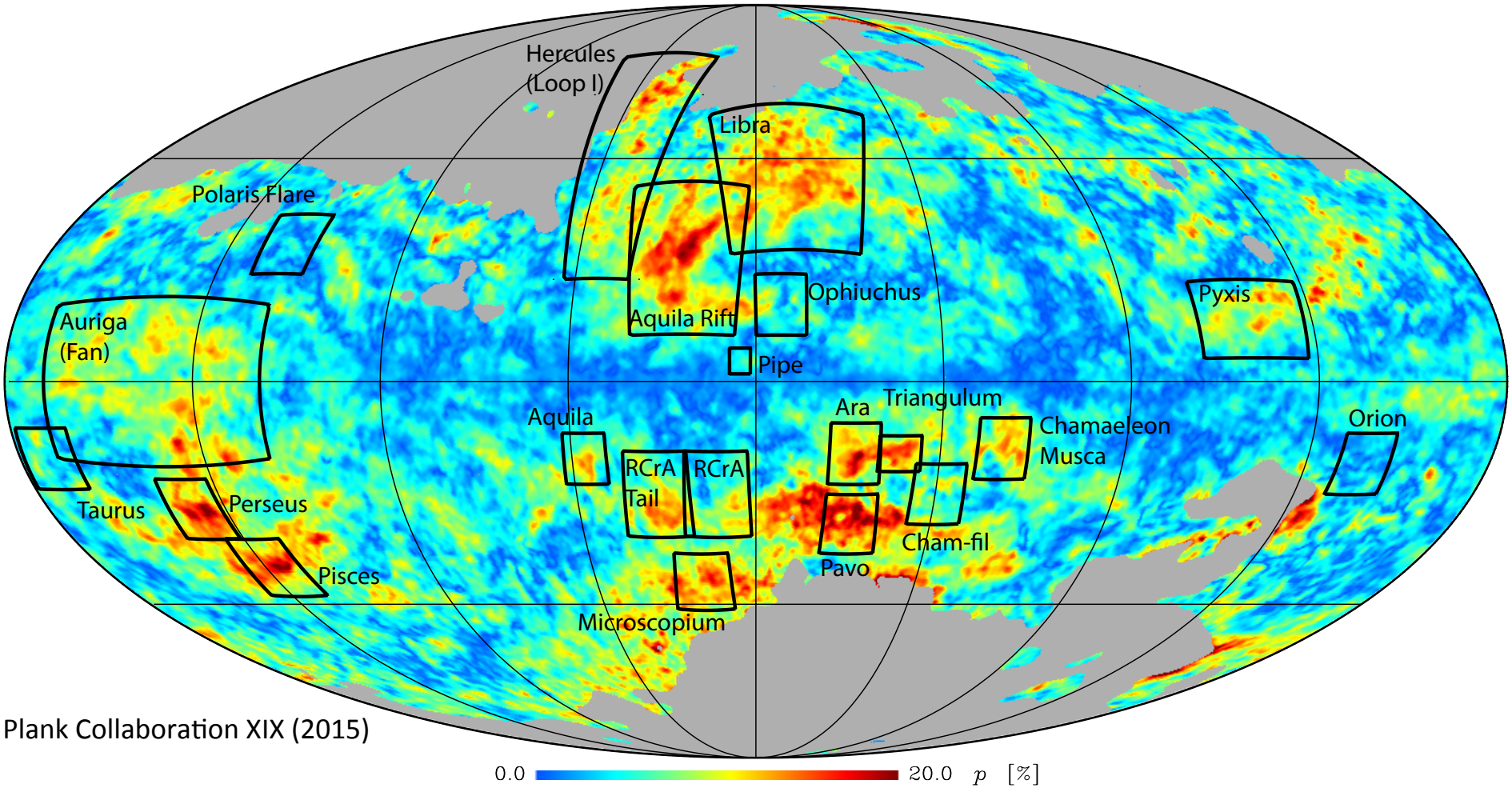
Alves et al. (2014)



Studies of individual regions using dust extinction are restricted to the number of stars in the field (not well sampled); sub-mm observations with balloons or ground based telescopes are restricted to small regions of the sky.

Planck provides the first all-sky fully sampled map of dust polarized emission, from which we can make the link between the small and large scales of the magnetic field.

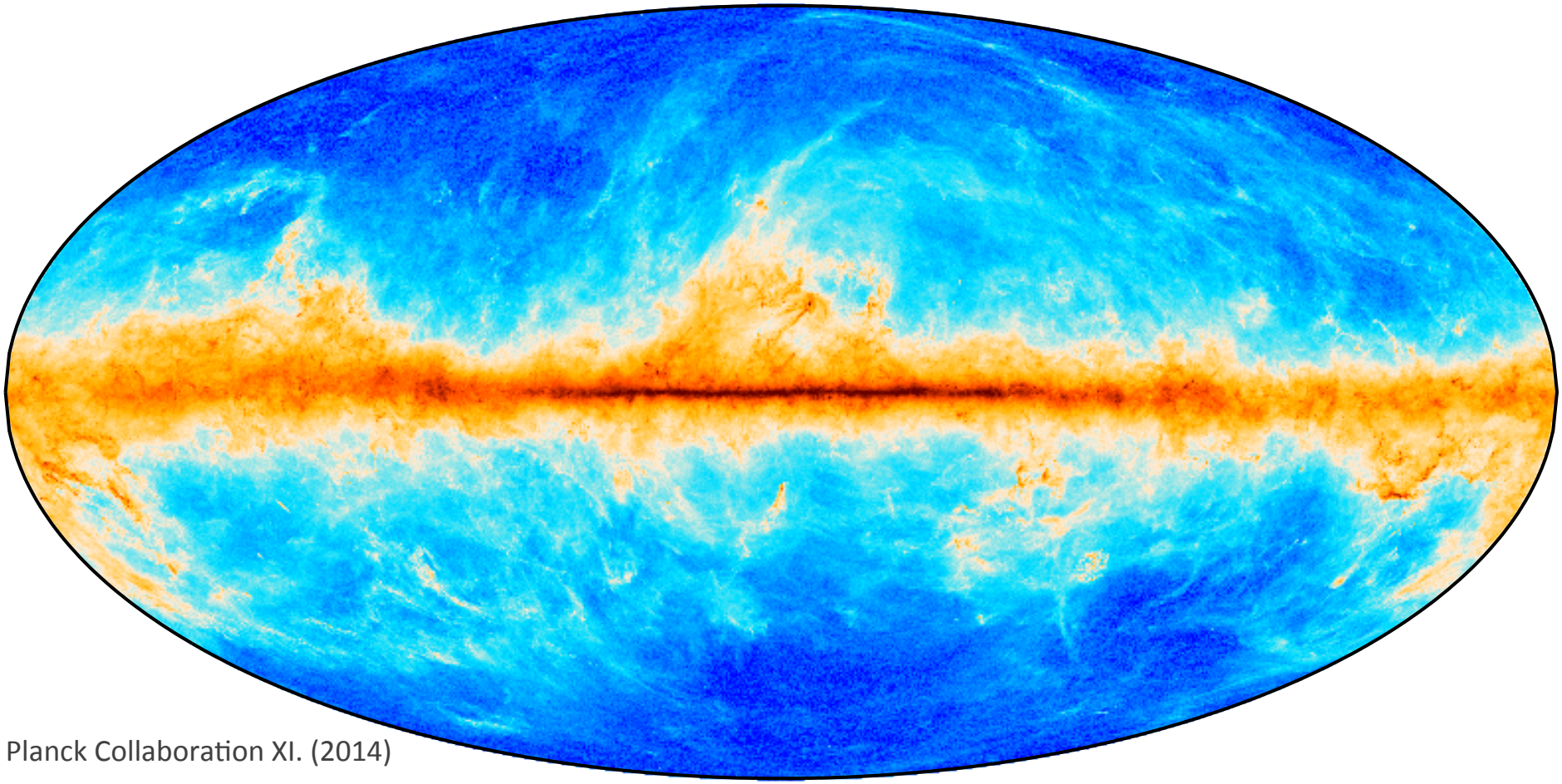
The dust polarized sky



Plank Collaboration XIX (2015)

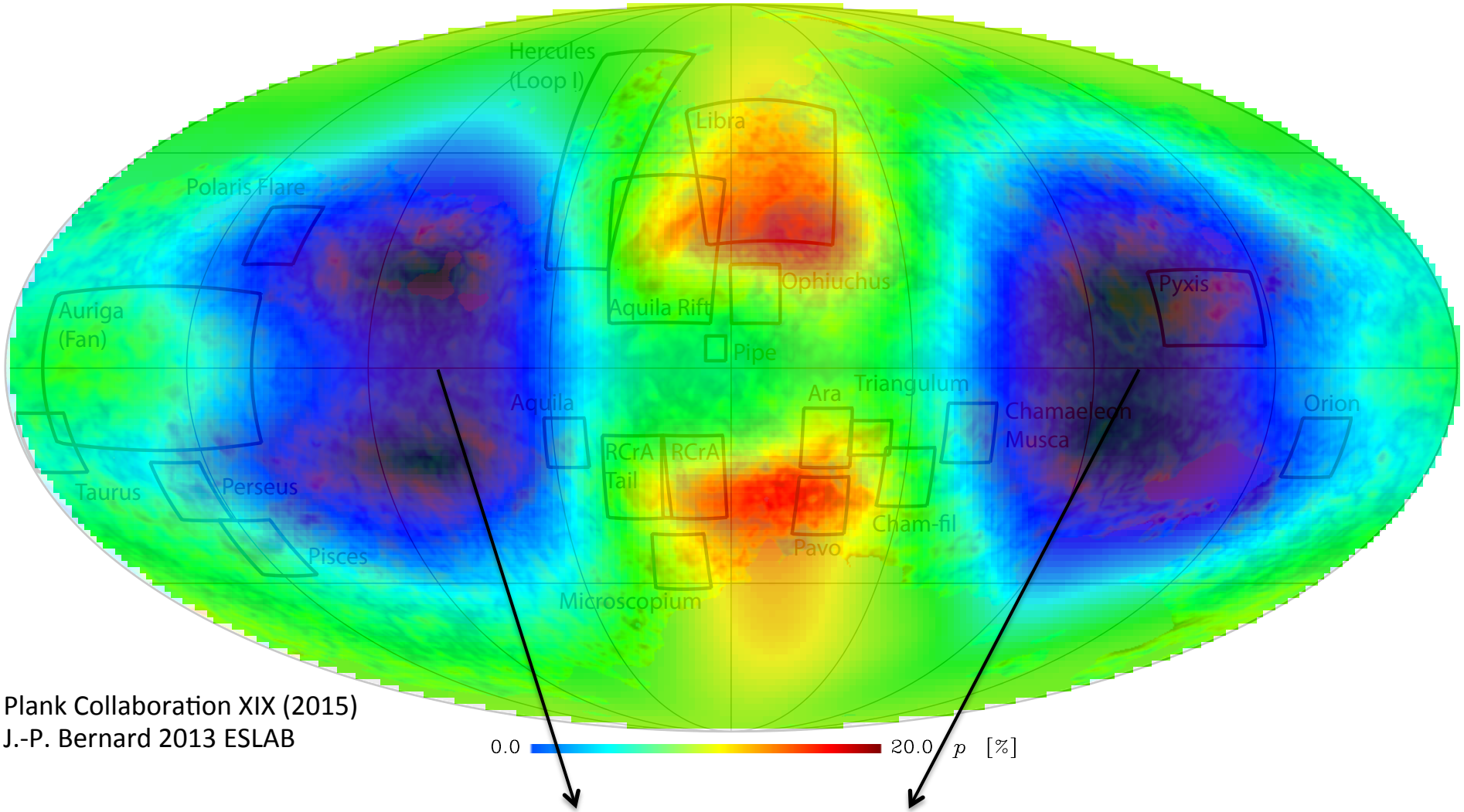
Some regions of very high (~20%) dust polarization fraction (not observed before, unexpected).

The dust unpolarized vs polarized sky



Planck Collaboration XI. (2014)

The dust polarized sky – signature of the large scale magnetic field

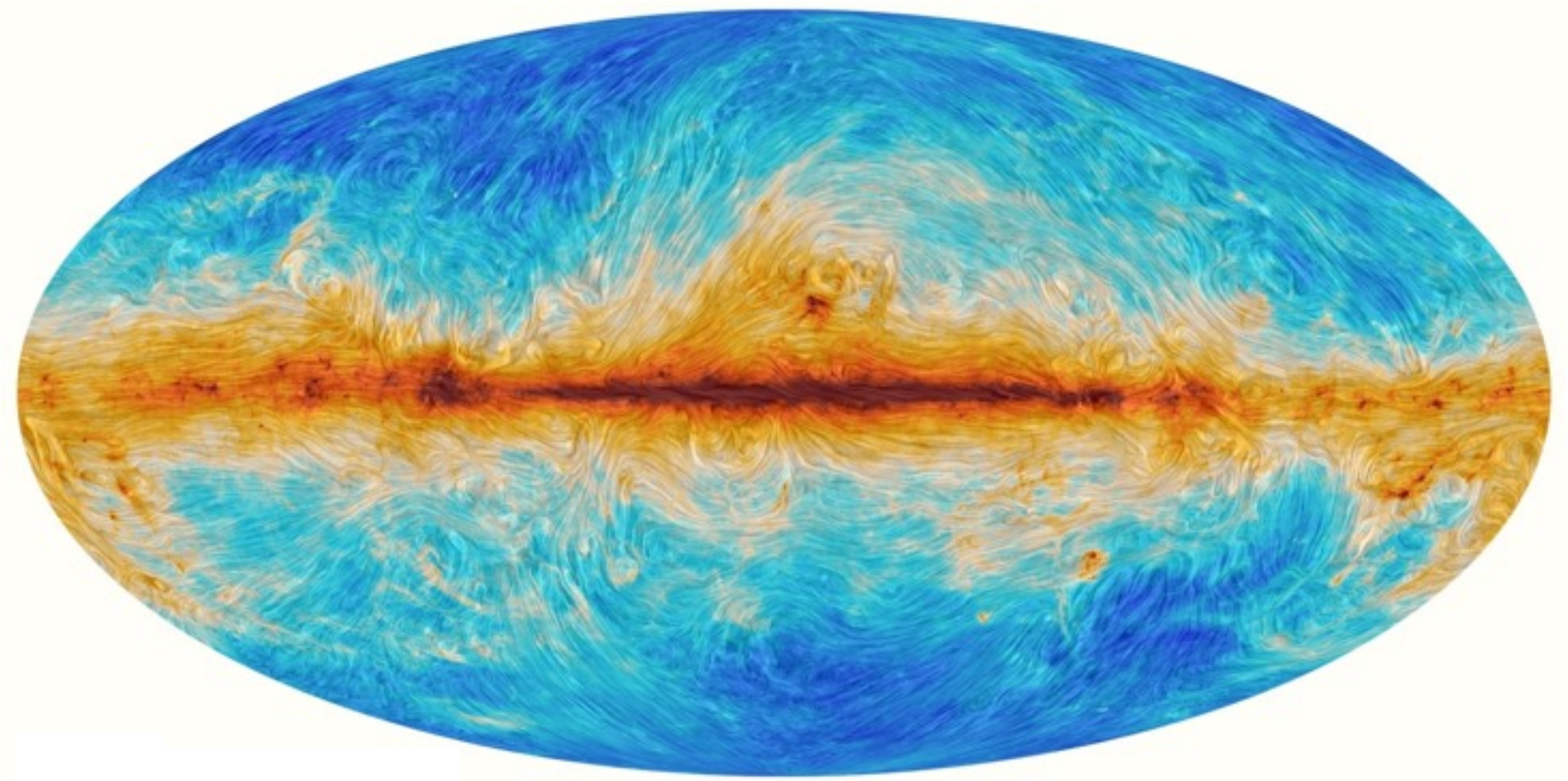


Plank Collaboration XIX (2015)
J.-P. Bernard 2013 ESLAB

Regions where the large scale Galactic magnetic field is approximately along the line of sight:

$$\gamma \approx 0° \Rightarrow p = p_0 \cos^2 \gamma \approx 0$$

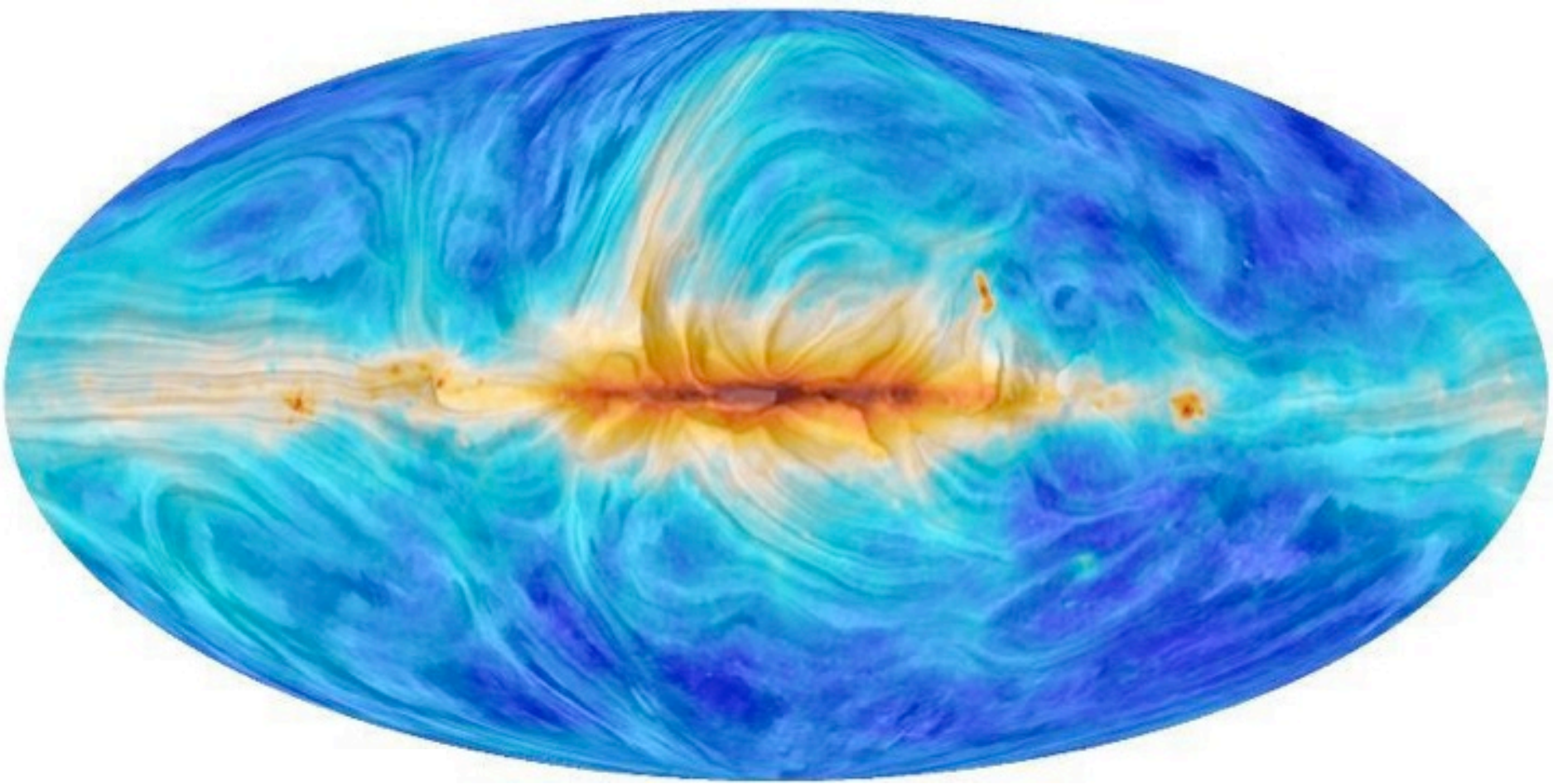
The magnetic field of the Milky Way - Dust



Planck collaboration 2015

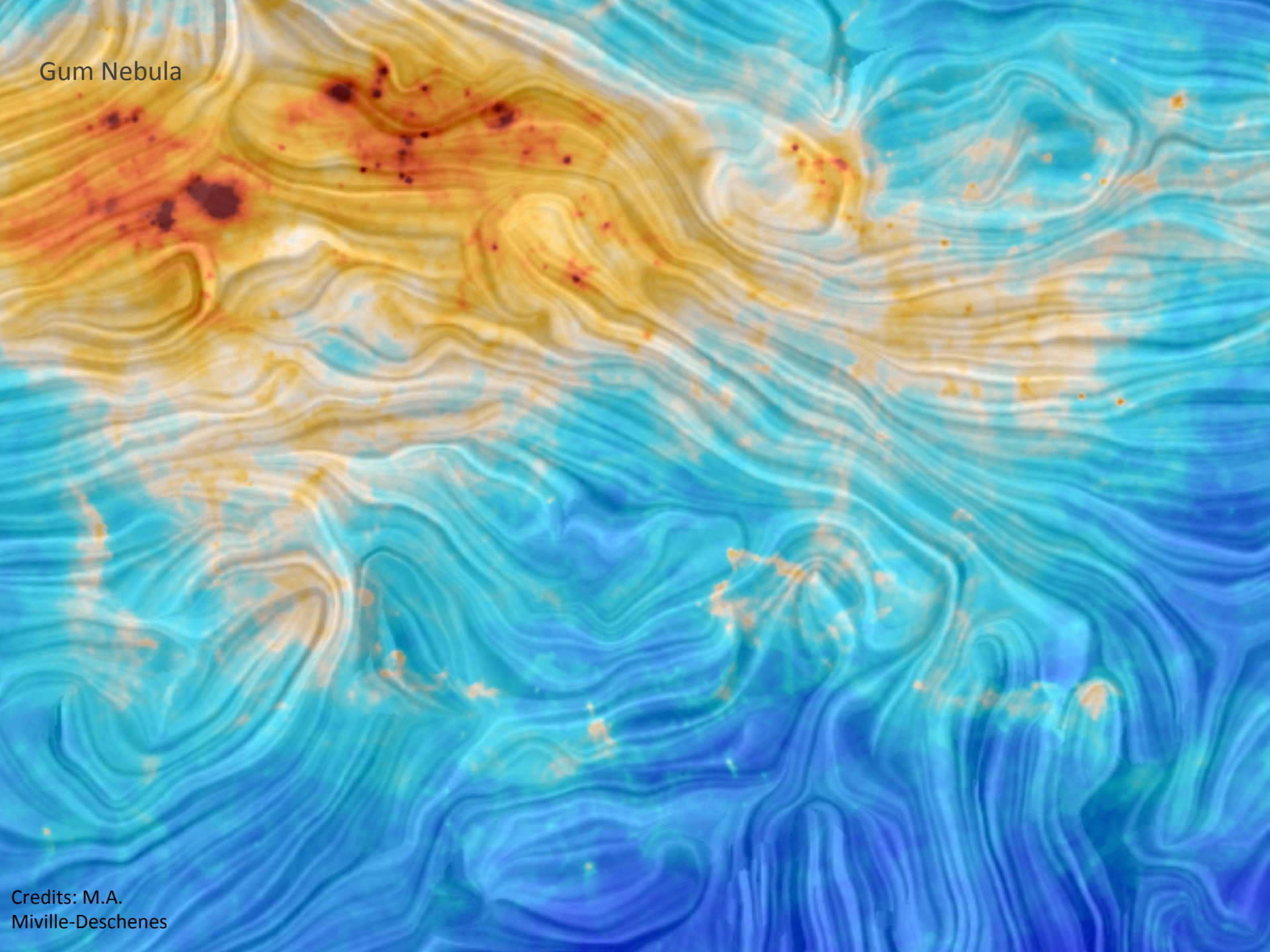
We trace the magnetic field where there is interstellar matter.

The magnetic field of the Milky Way - Synchrotron

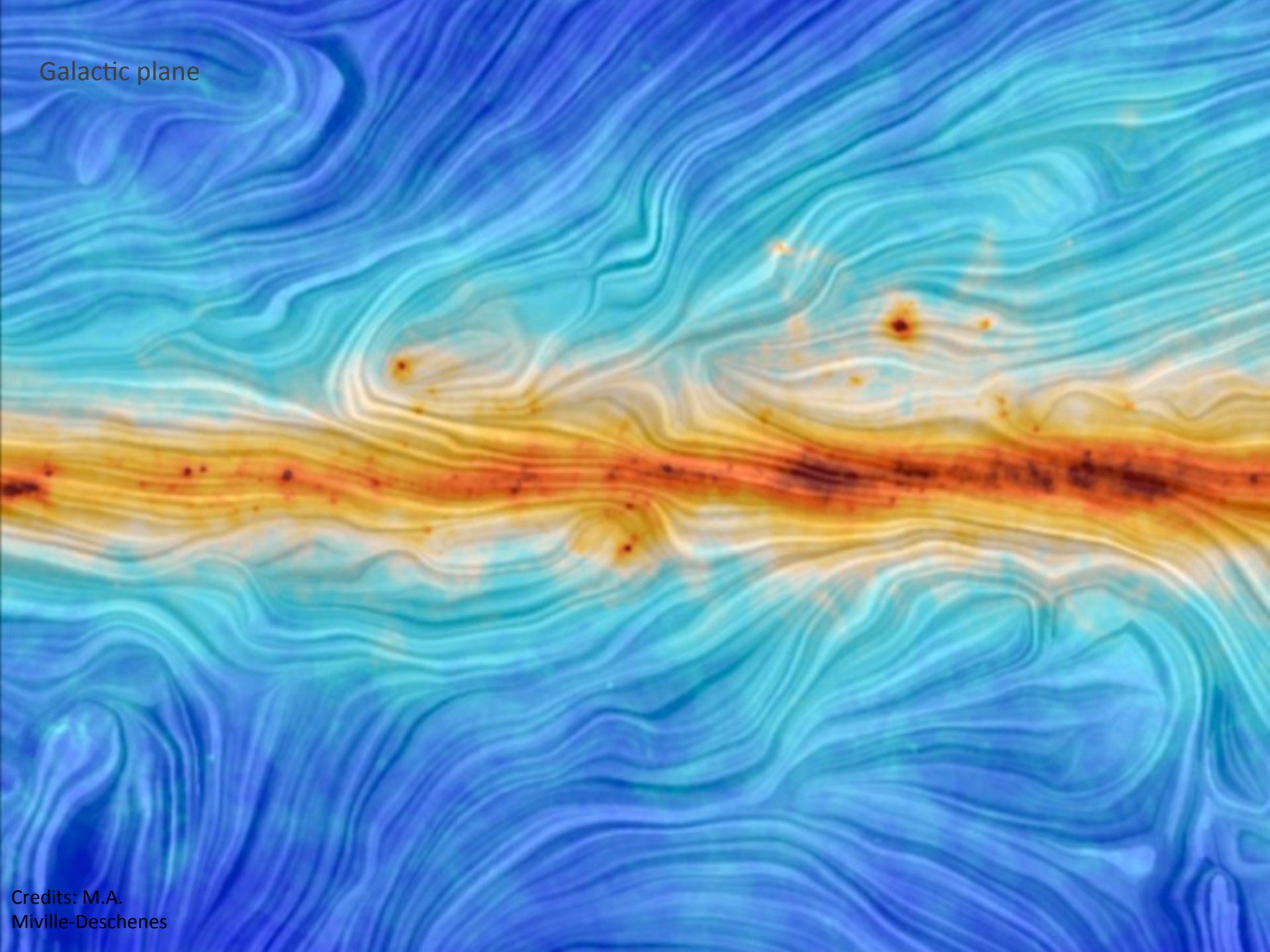


Planck collaboration 2015

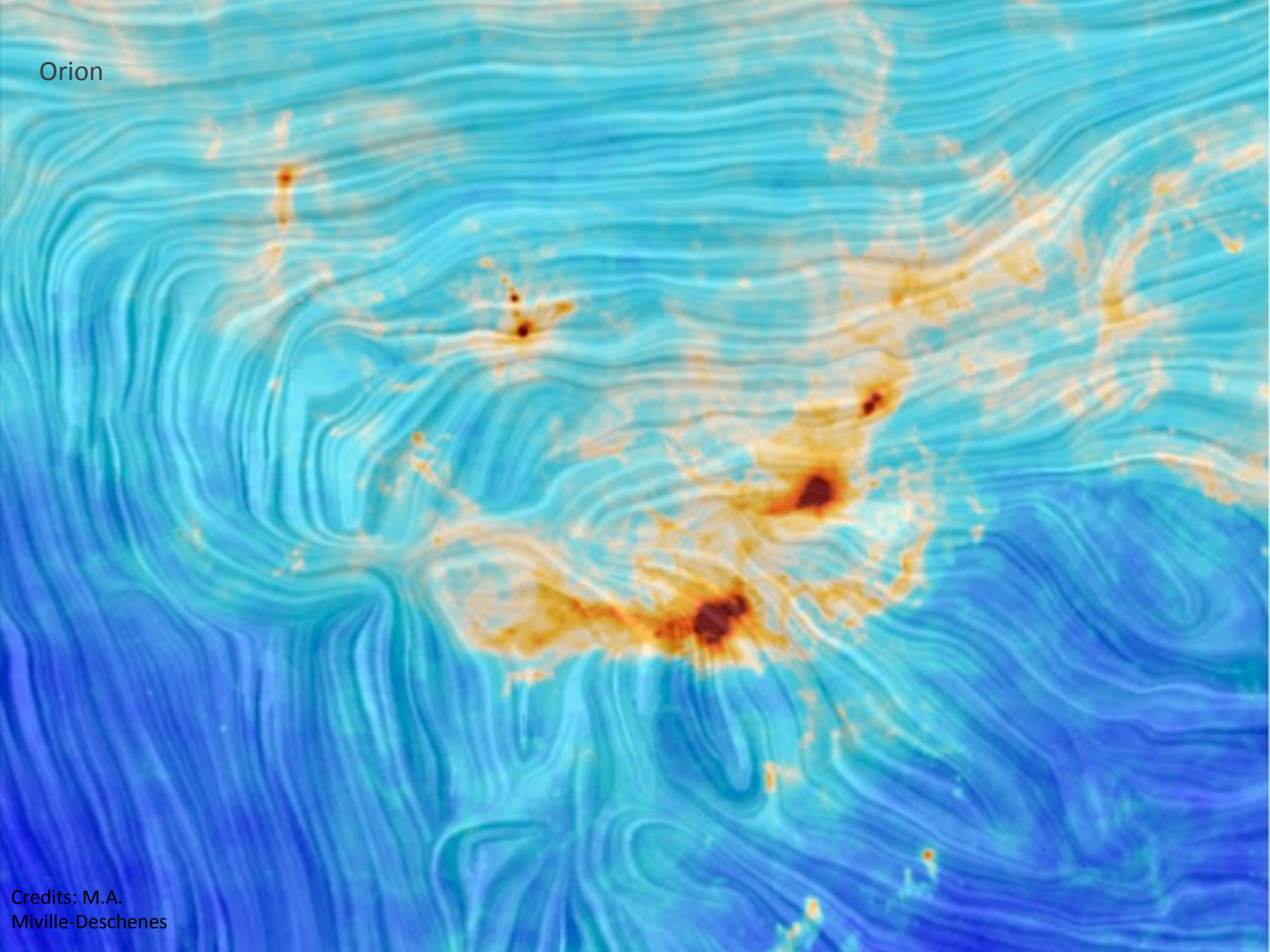
We trace the magnetic field in the much larger volume occupied by the cosmic ray electrons.



Credits: M.A. Miville-Deschenes



Credits: M.A. Miville-Deschenes



Credits: M.A. Miville-Deschenes

Dust polarization: what have we/are we learning?

Which dust grains polarize light?
Probably carbon grains, with ferromagnetic inclusions.

How are dust grains aligned?
(Very likely) By the radiation from the stars, which keeps them spinning and gives them momentum.

What is the structure of the large scale Galactic magnetic field?
Uniform at high Galactic latitudes; affected by stellar feedback (winds, explosions, etc.) in the Galactic plane.

What is the role of the magnetic field in the formation of stars?
The magnetic field does have an influence in how matter is distributed in the ISM. How matter goes from being governed by magnetic forces to gravitational forces is still under study…