# Lecture 1 031018

- Slides will be available at:

https://www.fisgeo.unipg.it/~fiandrin/didattica_fisica/cosmic_rays1819

# Program

- Outline of galaxy structure and composition
- Cosmic rays:
  - composition,
  - spectra,
  - Propagation Equation of the CR in the galaxy
  - Nuclear CR Propagation
  - CR Propagation of e+, e-, anti-p, photons
- Hydrodynamics e magnetohidrodynamics
- acceleration models I (fermi acceleration, unipolar inductor, hillas plot)
- acceleration models II (non linear acceleration models)
- solar modulation of the cosmic rays
- experimental tecniques of CR detection, direct e indirect

# Bibliography


- M. Vietri, Astrofisica delle alte energie, Bollati ed.
- Longair, High Energy Astrophysics Vol I & II
- Rybicky&Lightman, Radiative Processes in Astrophysics, Wiley-ch
- M. Spurio, Particles and Astrophysics
- Dispense varie

L’ Universo e’ “IL LABORATORIO” in cui si possono osservare tutte le leggi della natura all’opera, spesso in condizioni limite che non possono essere riprodotte all’interno dei laboratori terrestri

- Applicazione delle leggi note per descrivere fenomeni in condizioni estreme

- Scoperta di nuove leggi della fisica sulla base delle osservazioni sperimentali

Cosmic ray physics is strictly connected to astrophysics
Cosmic rays are generated and propagate in the galaxy
Sources are astrophysical objects (SNR, AGN, Pulsars,…)

Main difference between astrophysics and other branches of physics: **controlled experiments are (almost) never possible**.

This means:

- If many different physical effects are operating at the same time in a complex system, can't isolate them one by one.
- Knowledge of rare events is limited - nearest examples will be distant. e.g. no supernova has exploded within the Milky Way since telescopes were invented.
- Need to make best use of all the information available - many advances have come from opening up new regions of the electromagnetic spectrum.
- Statistical arguments play a greater role than in many areas of lab physics.


Credit: P. Armitage, pja@jilau1.colorado.edu

# Astronomical units

Distance: an **astronomical unit** (AU or au) is the mean distance between the Earth and the Sun (technically the radius of a circular orbit with same period as the Earth).

$$1 \text{ au} = 1.496 \times 10^{13} \text{ cm}$$

Angles: a circle has 360 degrees or $2\pi$ radians

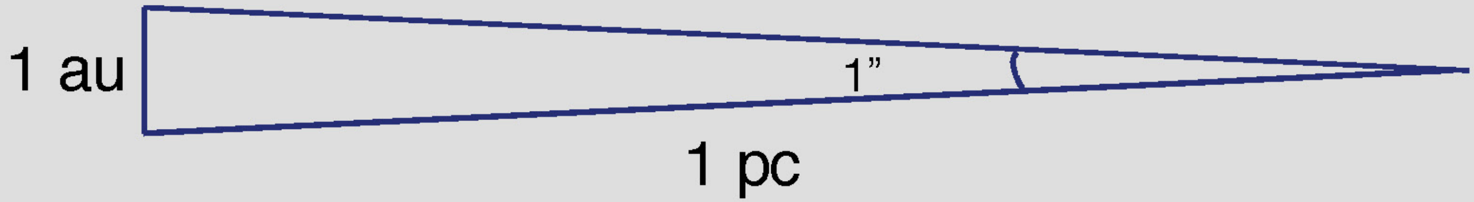
$$1^\circ = \frac{2\pi}{360} \text{ radians} = 0.01745\ldots \text{ radians}$$

$$1 \text{ arcminute} = \frac{1}{60} \text{ degrees}$$

$$1 \text{ arcsecond} = \frac{1}{60} \text{ arcminutes} = 4.85 \times 10^{-6} \text{ radians}$$

Best resolution of optical telescopes (HST) is about 0.1".

A **parsec** (pc) is defined as the distance at which a `ruler' of length 1 au subtends an angle of 1 arcsecond.




$$1'' = \frac{1\ \mathrm{au}}{1\ \mathrm{pc}} \Rightarrow 1\ \mathrm{pc} = \frac{1.496\times10^{13}\ \mathrm{cm}}{4.85\times10^{-6}} = 3.086\times10^{18}\ \mathrm{cm}$$

1 pc = 3.26 light years - roughly the distance to the nearest stars. Convenient unit for stellar astronomy.

Sizes of galaxies usually measured in kpc (galaxy scales are 10-100 kpc).

Cosmological distances are 100s of Mpc to Gpc. Observable Universe is a few Gpc across.

Even if huge progresses have been made during the 50 years, our knowledge of the astrophysical environment is limited

In astrophysics $$1 \approx 10$$

We do not know (yet) well the distribution of matter, radiation fields, particles in our galaxy.. Even less those of other galaxies and of intergalactic space

→ Qualitatively we can account for the observations, quantitatively the uncertainties can of the order of 100% due to lack of data

→ Continous evolution as new data are available

# Nuove leggi della fisica derivate dall'osservazione astrofisica

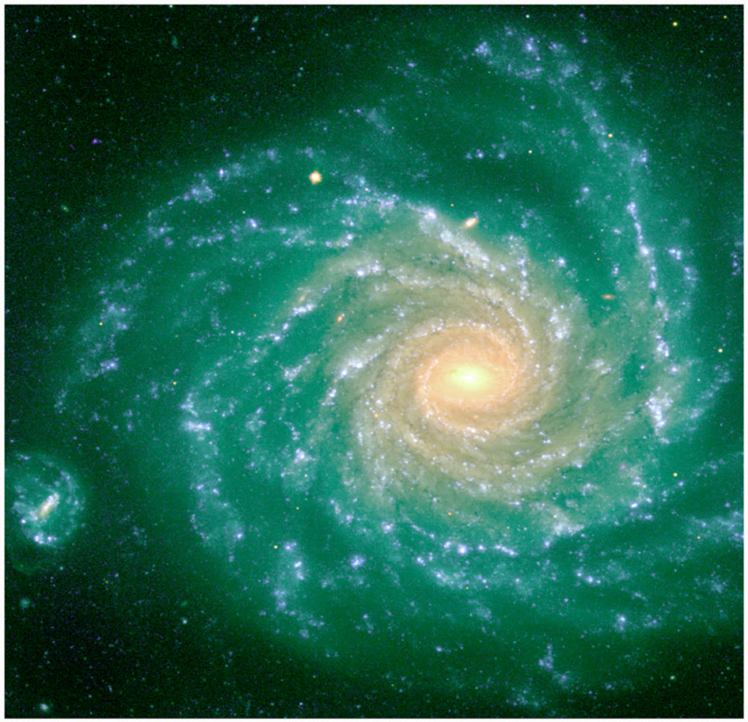
## OSSERVAZIONI

- **Tycho Brahe misura il moto dei pianeti**
- **Leggi di Keplero**
- **Osservazione dello spettro delle stelle (nane bianche)**
- **Formula di Balmer**
- **Perdita di energia per radiazione gravitazionale in sistemi binari**
- **Onde gravitazionali**

## LEGGI

- **Keplero scopre le leggi del moto dei pianeti**
- **Newton: gravitazione universale**
- **Scoperta della serie di Balmer per l'atomo di idrogeno**
- **Teoria di Bohr dell'atomo**
- **Relativita' generale di Einstein**
- **Astronomia gravitazionale**

# "Nuova" fisica fondamentale da osservazioni astrofisiche



Credit: P. Armitage, pja@jilau1.colorado.edu

Spiral Galaxy NGC 1232 - VLT UT 1 + FORS1

ESO PR Photo 37d/98 (23 September 1998) ©European Southern Observatory

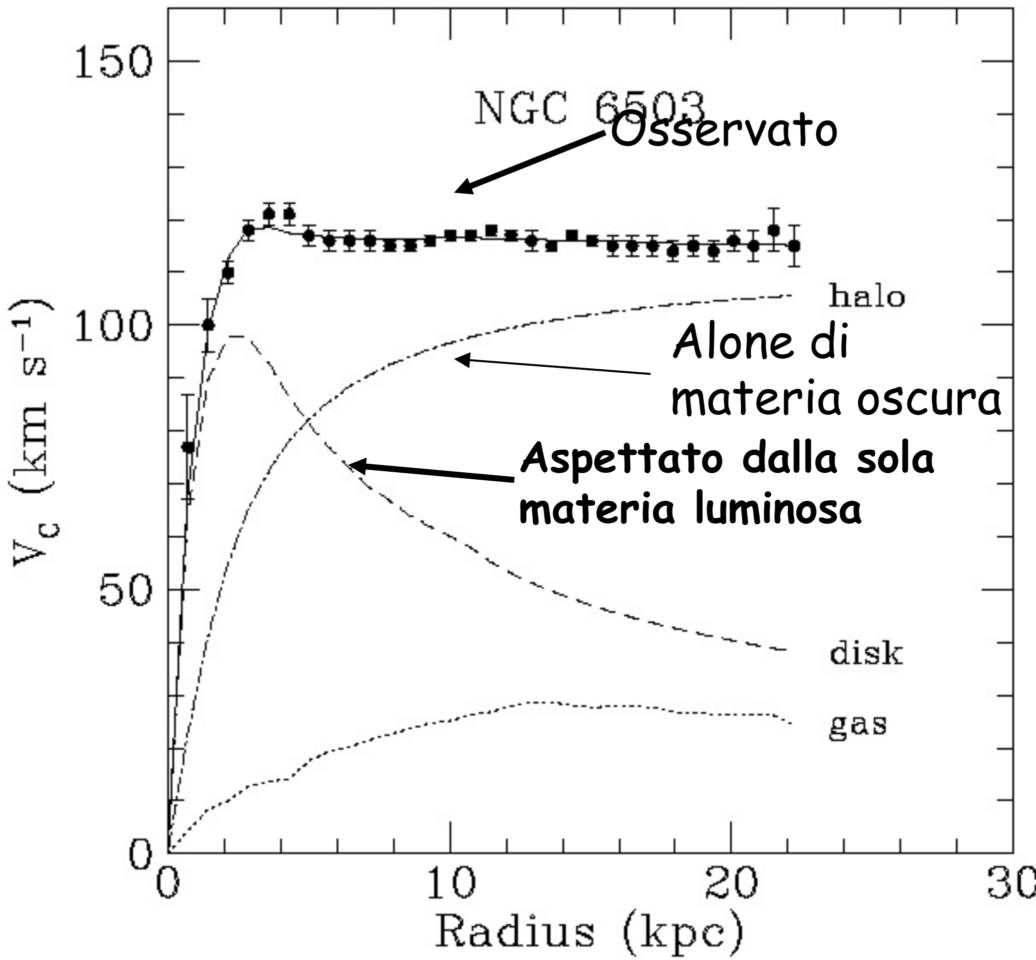
Observations of the rotation curves of spiral galaxies suggest presence of **dark matter** - probably in the form of an unknown elementary particle.

Observations of the brightness of distant supernovae suggest presence of **dark energy** - not understood at all.

Astronomical observations hint at presence of new physics, which may be testable in the lab in the future.

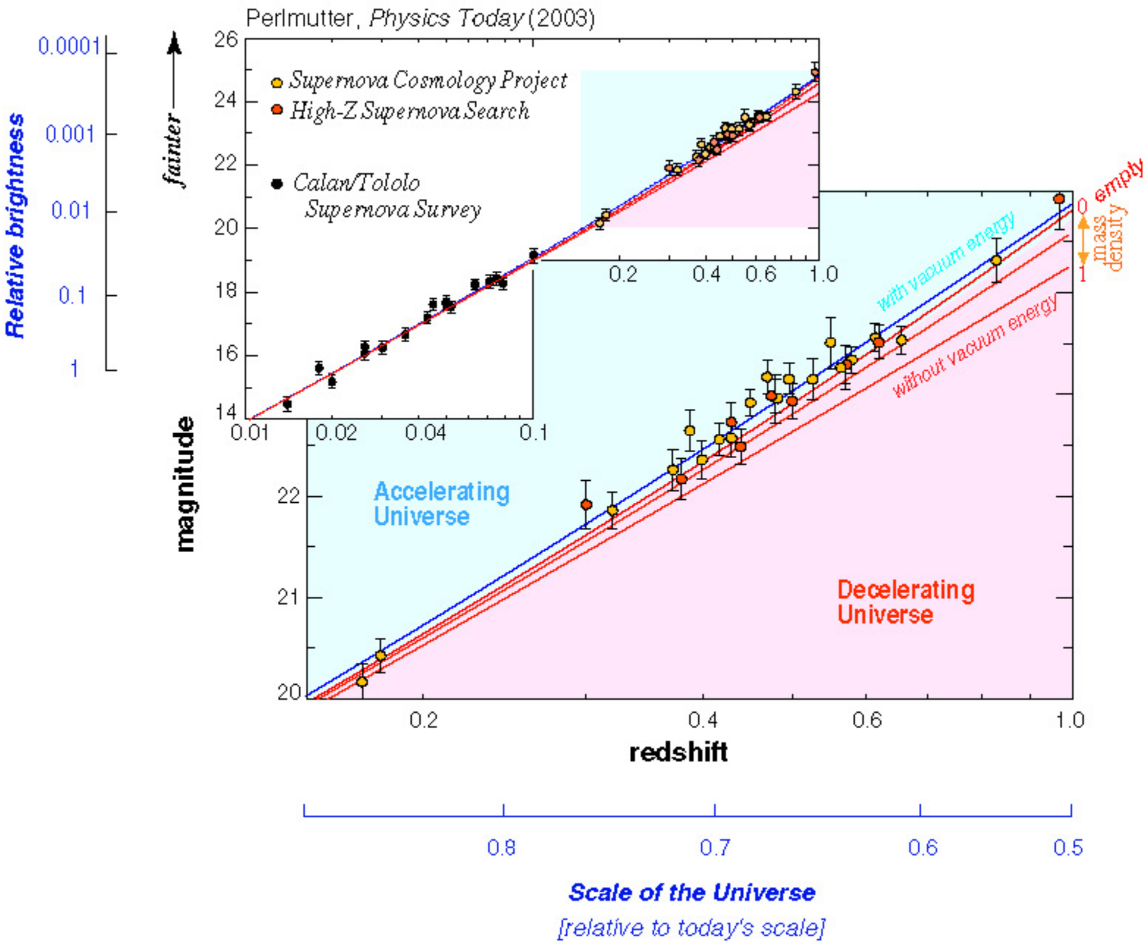
# Materia oscura

La **velocità** di rotazione delle stelle a distanza R dal centro galattico **dipende dalla massa nel volume di raggio R:**
**$V_r=[GM(R)/R]^{1/2}$**
(cfr. Teorema del viriale: per un gruppo di particelle in equilibrio dinamico l'energia cinetica totale delle particelle nel cluster e' 1/2 dell'energia potenziale gravitazionale→T=V/2)




La velocità delle stelle della galassia si misura attraverso lo spostamento Doppler degli spettri di emissione delle righe atomiche

# Energia oscura

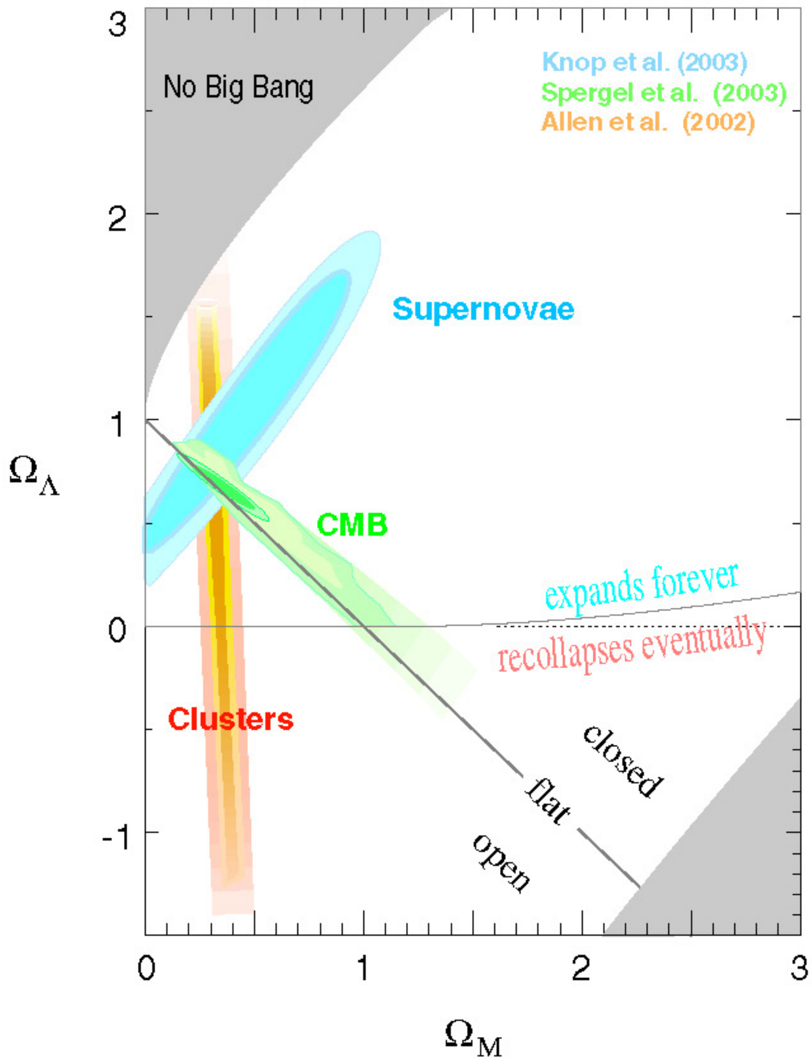



La legge di Hubble ci dice che la velocita' di recessione delle galassie e' proporzionale alla distanza dall'osservatore

$$V = H_o \times D$$

**Con $H_0$ ~71 km/sec/Mpc**

Recenti osservazioni della luminosita' delle supernovae la hanno mostrato deviazioni da questa legge → l'universo ha accelerato la sua espansione negli ultimi 5 mld di anni→ esiste una gravita' “repulsiva”, descritta alla costante cosmologica dell'equazioni di Einstein




Combinando insieme tutte le osservazioni di anisotropia del CMB, della luminosita' delle SN Ia, di rotazione delle galassie e dei clusters di galassie, oggi sappiamo dare una misura dei contributi all'energia dell'universo di tutte le componenti

Figura 1.5: Regioni di confidenza nel piano $(\Omega_m^0, \Omega_\Lambda)$ imposte dai vincoli sull'anisotropia della radiazione di fondo, la dinamica delle strutture su larga scala, e l'analisi delle supernove di tipo Ia [118].

# COSMOLOGIA DI PRECISIONE⇔FISICA FONDAMENTALE

1- Eta' dell' universo 13.7 ± 0.1 (1%)x$10^9$ anni

2- 4.9% Materia visibile

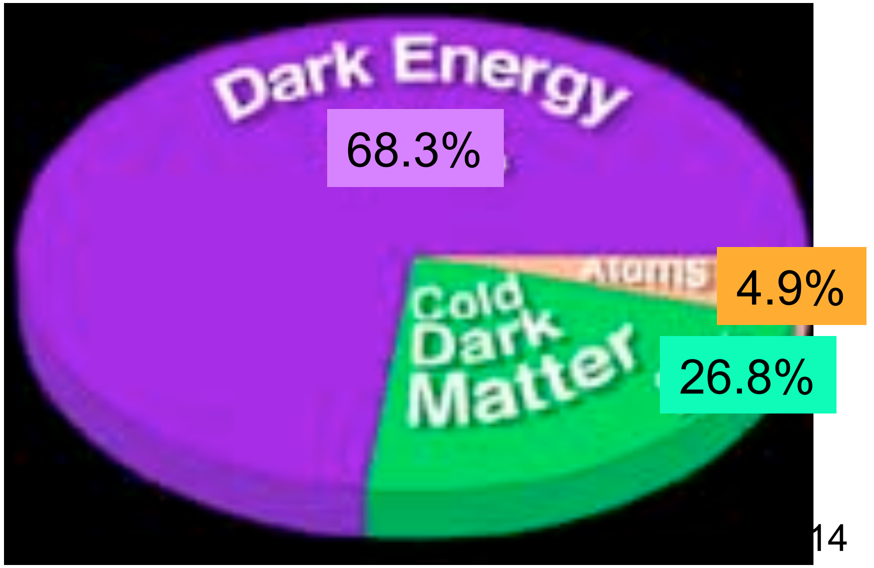
26.8% Materia oscura→ sconosciuta

68.3% Energia oscura→ sconosciuta$^2$

3- Universo e' piatto e si espandera' per sempre

4- Costante di Hubble 67.3(12)km/sec/Mpc

**La materia ordinaria e' solo una piccola frazione della massa-energia totale dell'Universo!!**

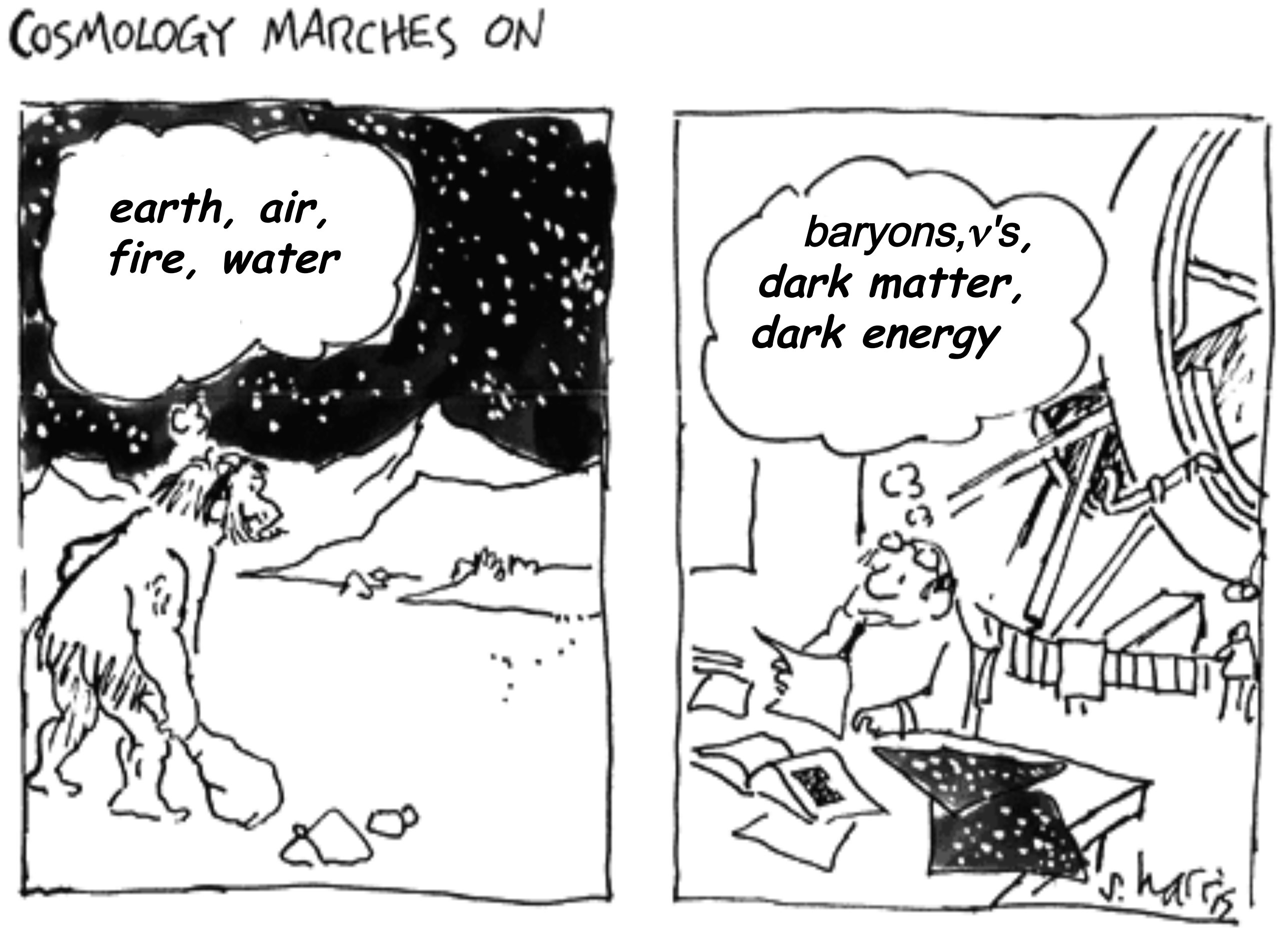


# Abbiamo oggi una visione complessiva dell'Universo

Abbiamo misurato –con precisione!- il contenuto energetico dell'universo, $\Omega$: solo una piccola parte e' composta da materia barionica –quella di cui siamo fatti noi e che sara' oggetto del corso.

Per il resto la *darkness* e' completa

Queste misure sono l'evidenza sperimentale piu' diretta che abbiamo per la necessita' di "nuova" fisica, oltre quella che conosciamo ora




- **we now have a complete census of the Universe…but we don't know what is made of**

# Messaggeri del cosmo

- Cosa trasporta l'informazione a Terra?

➔ i Raggi Cosmici: particelle cariche e neutre che raggiungono la sommita' dell'atmosfera terrestre dallo spazio

**Ovvero:**

- Flussi di particelle energetiche neutre (fotoni, $\nu$) e cariche elettricamente (raggi cosmici carichi...p,e-,e+, anti-p, nuclei)

# Osservabili

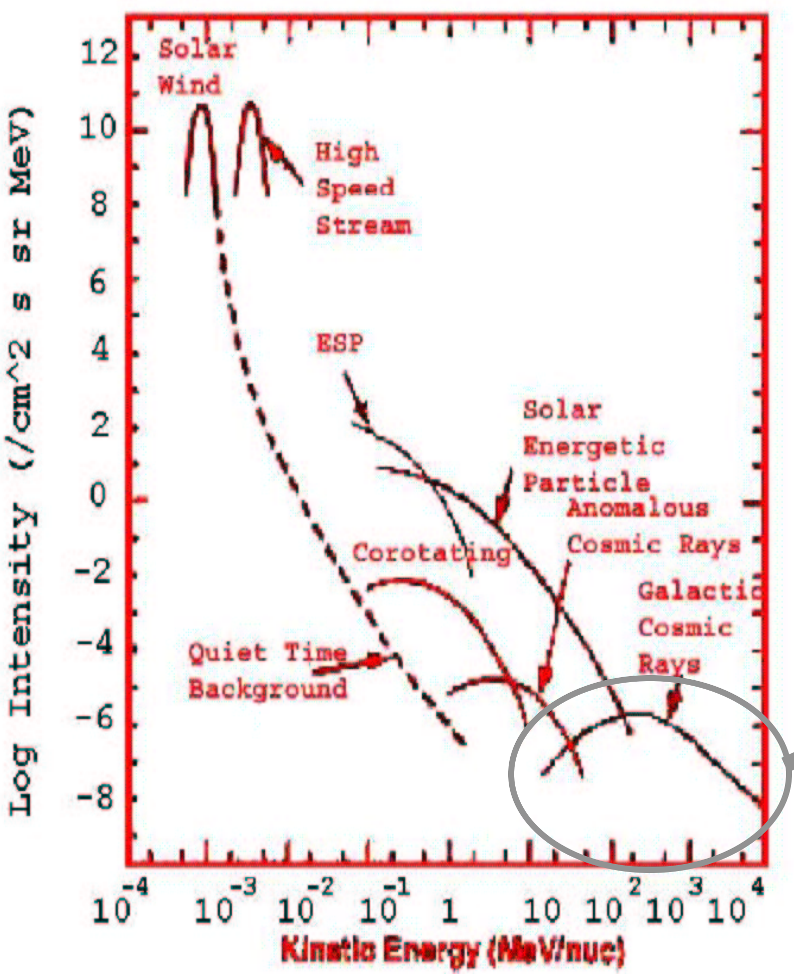
- Osservare i raggi cosmici significa identificare e contare particelle elementari con le tecniche proprie della fisica delle particelle.
- Esperimenti nello spazio, su pallone e a terra, a seconda dell’intervallo di energia con una grandissima varieta’ di tecniche di misura (spettrometri, calorimetri, sciami estesi in atmosfera, radio telescopi, rivelatori X,…)

# Osservabili

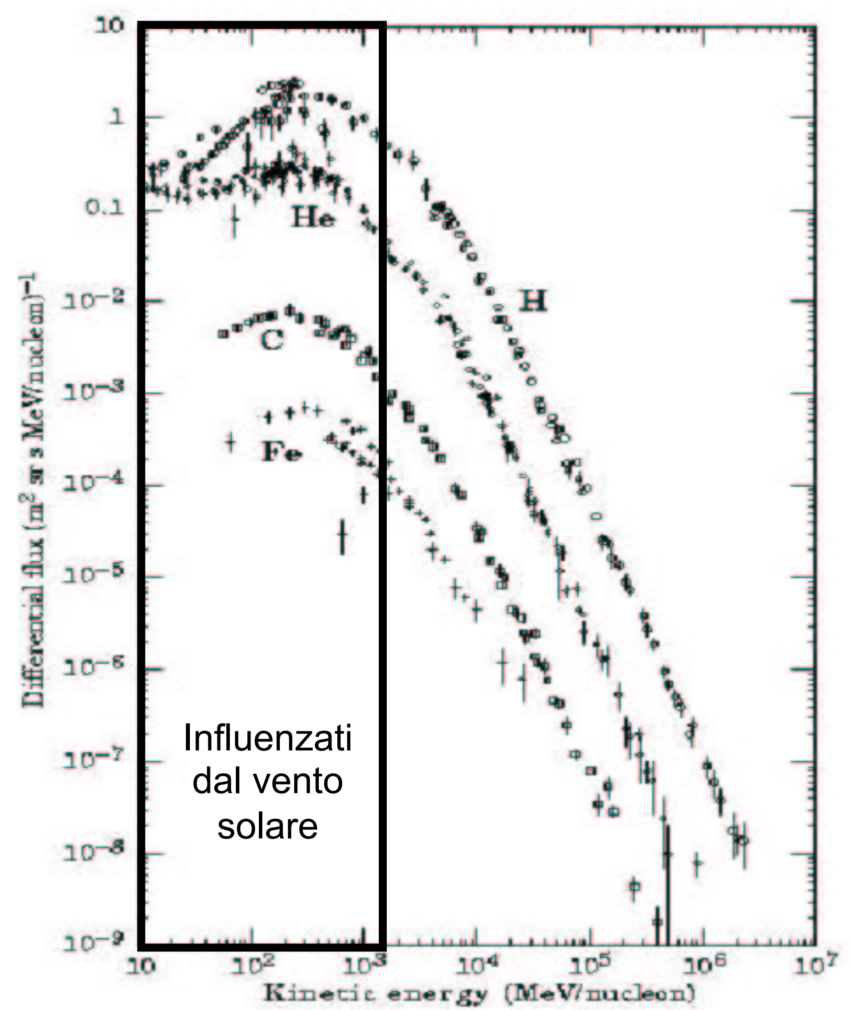
- Particle Type: ch. CR, $\gamma$,$\nu$ → Composition
- Energy distribution → Flux and Spectrum
- Arrival Direction → Anisotropy
- Variability → Light curve

# Cosmic ray spectra

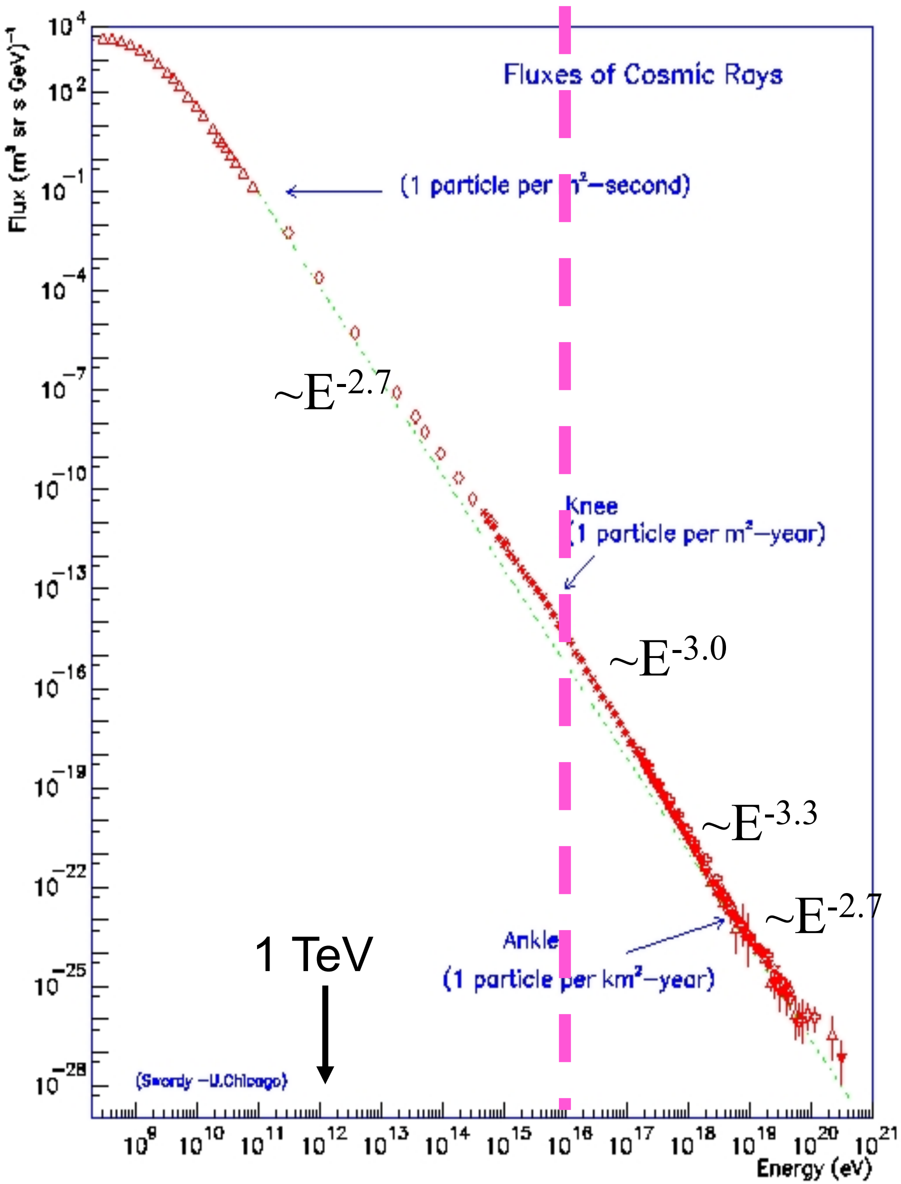
Particles produced in the heliosphere




Galactic and extragalactic particles



# Nature's beam calibration




Man made accelerators

- ❑ Nature gives a very energetic beam
- ❑ She doesn't give us the beam parameters…
- ❑ Get the whole picture → measure precisely the entire CR flux

Beam calibration:

Beam energy←→CR spectrum at Earth
Composition←→CR chemical elements
Luminosity←→CR abundances & reaction rates

Beam Calibration = CR Propagation Models needed for accurate background evaluation of faint signal searches in CR

# Cosa impariamo dai raggi cosmici

- Quali elementi ci sono nell'Universo
- Da dove vengono
- Come sono prodotti
- Come si propagano fino alla Terra

# L'ambiente locale

Per capire l'origine dei RC occorre avere un'idea dell'ambiente in cui essi si propagano
E che contiene i siti in cui avvengono i processi di accelerazione

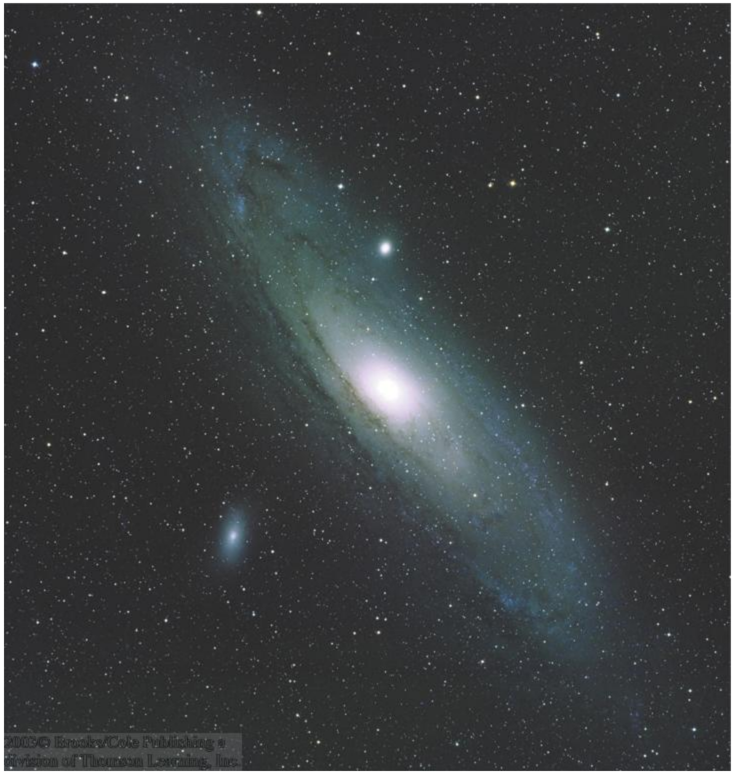
Il sistema solare si trova nella Via Lattea, la nostra galassia

(ma non tutte le sorgenti sono contenute nella galassia in particolare per i fotoni che sono neutri)

# Local environment: Milky Way


Almost everything we see in the night sky belongs to the Milky Way

We see most of the Milky Way as a faint band of light across the sky



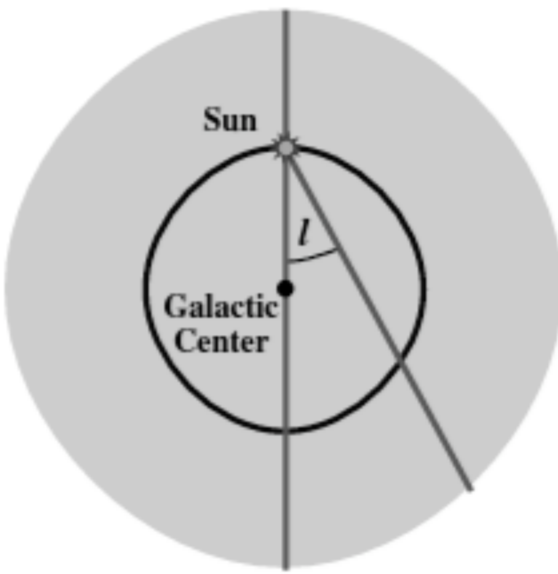
From the outside, our Milky Way might look very much like our cosmic neighbor, the Andromeda galaxy

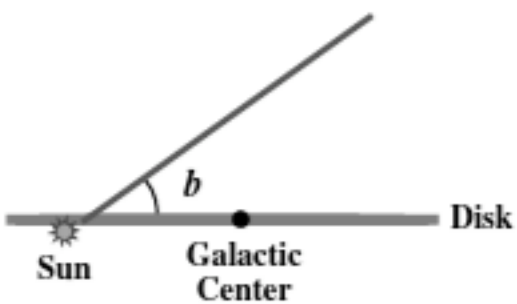
Define Galactic Coordinates

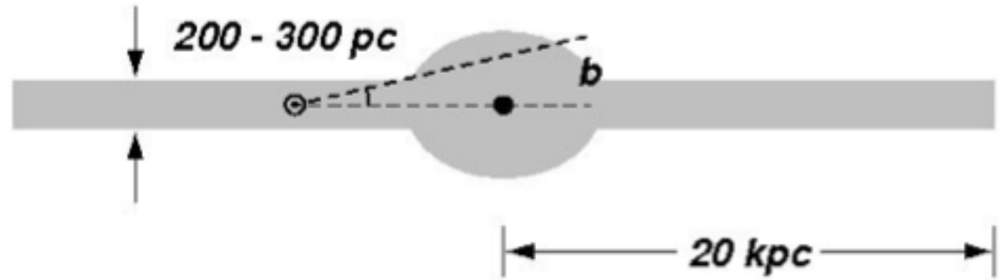
b = galactic latitude in degrees above/ below Galactic disk

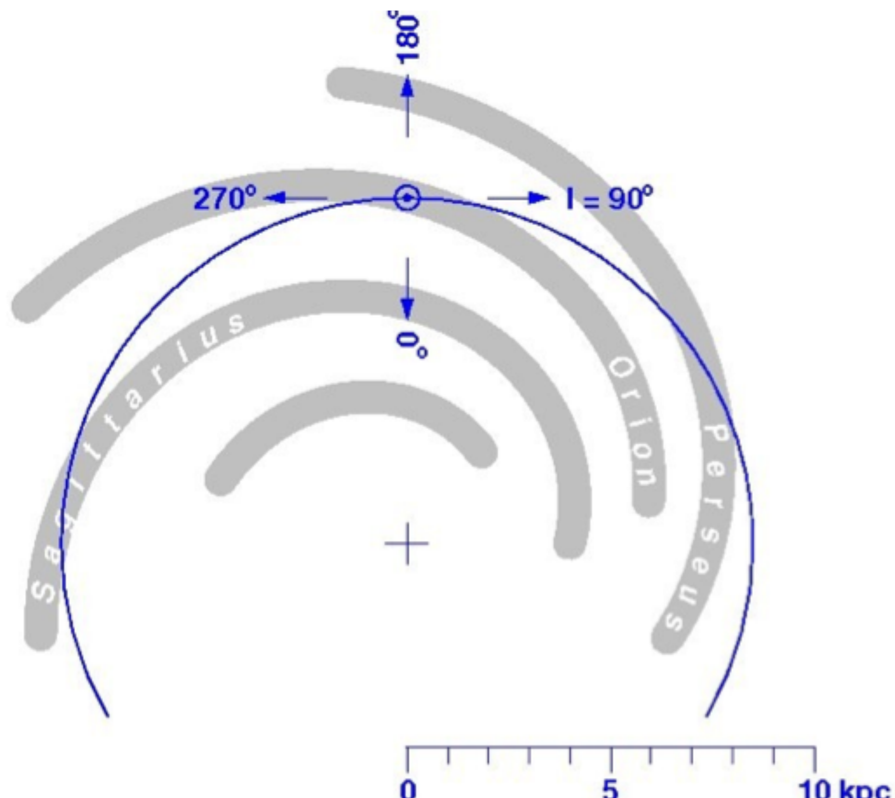
*l* = galactic longitude in degrees from Galactic Center

The solar system is 8.5 kpc away from galactic center



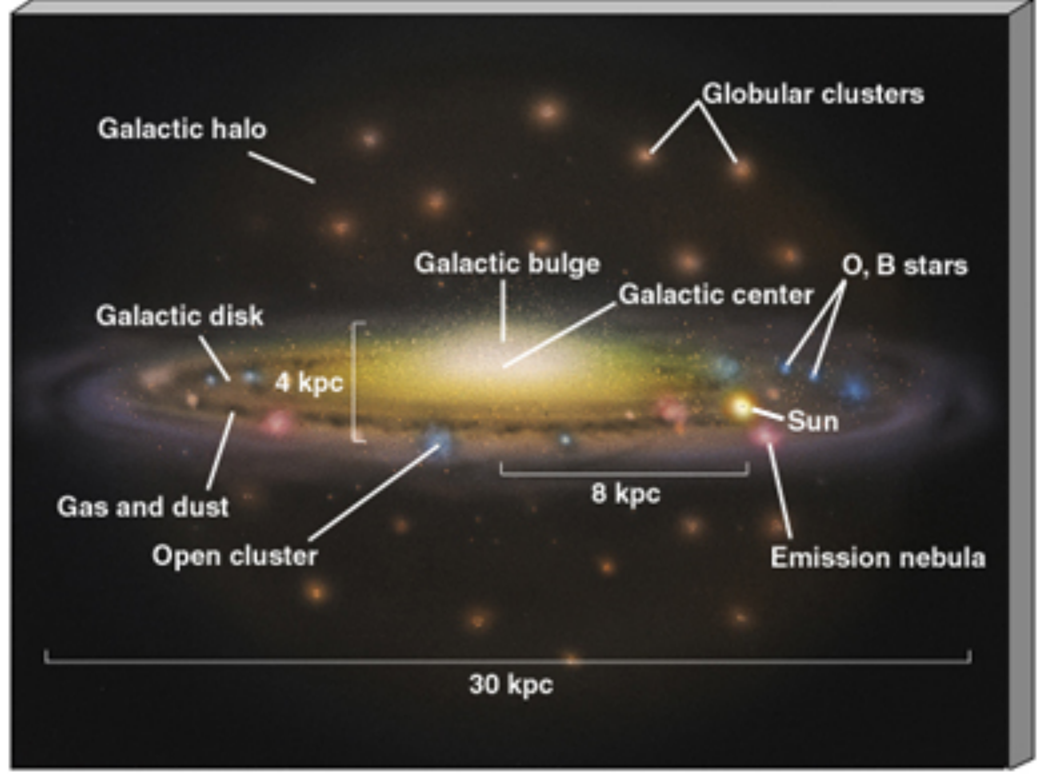



# Anatomy of Our Galaxy

1. Galactic Disk
2. Galactic Bulge
3. Galactic Halo




**Disk**

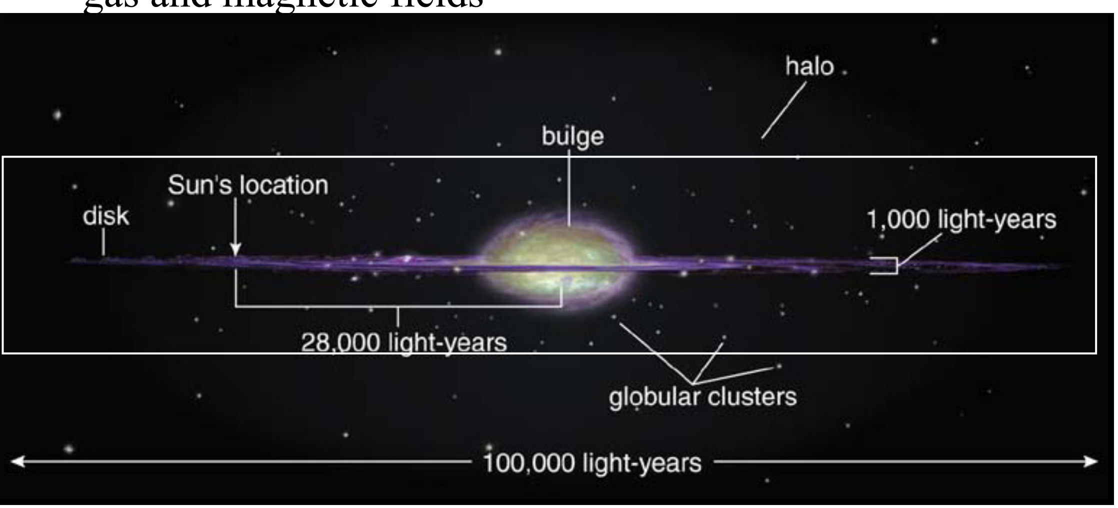
- young and old stars
- open star clusters
- gas & dust clouds (ISM)
- Magnetic fields

**Bulge**

- old stars

**Halo**

- old stars
- globular clusters
- gas and magnetic fields




As a guide to the relative physical scale of the Milky Way, if the Solar System out to Neptune were the size of a 0.5€ (25mm), the Milky Way would be more than the size of the Europe.

It looks like a very thin disk with a thickness or halo height << compared to the disk radius (something like an old long-playing disk)

# Galaxy

Milky Way we can "see" is made of:

- ❑ Stars
- ❑ Dust
- ❑ Cold and hot gas of the InterStellar Medium
- ❑ Magnetic Fields
- ❑ Cosmic rays

(...and dark matter...)

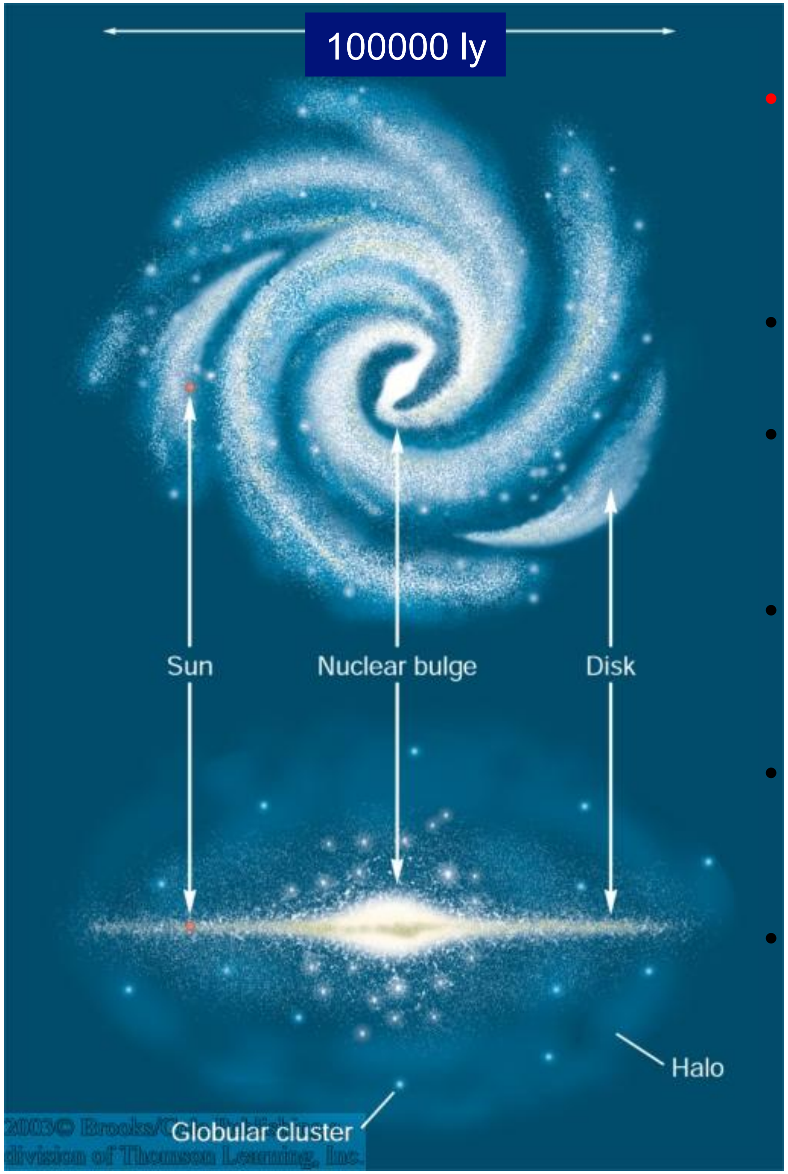
Some stars are sources of cosmic rays

Relevant for cosmic rays propagation and acceleration

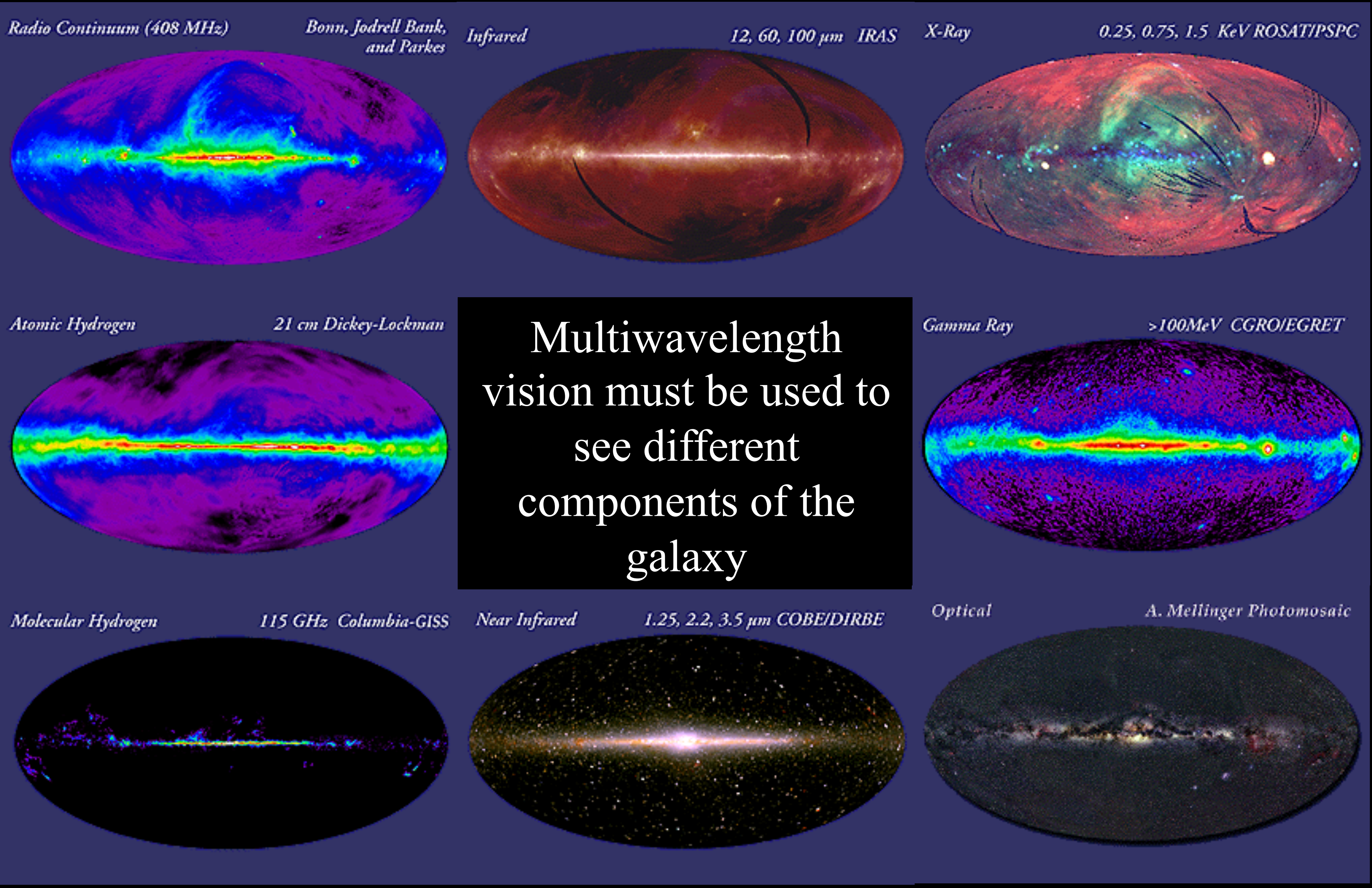
# Notazione per la ionizzazione

| Notation for Degrees of Ionization | | | |
|---|---|---|---|
| **Suffix** | **Ionization** | **Examples** | **Chemist's Notation** |
| I | Not ionized (neutral) | H I, He I | H, He |
| II | Singly ionized | H II, He II | $H^+$, $He^+$ |
| III | Doubly ionized | He III, O III | $He^{++}$, $O^{++}$ |

# The Mass of the Milky Way




- Luminous mass estimated in the range $5.8 \times 10^{11}\ M_\odot \div 8.5 \times 10^{11}\ M_\odot$ ( ~1/2 of the Andromeda Galaxy).
- Models of the Milky Way suggest that its total mass is as large as $4.5 \times 10^{12}\ M_\odot$ and as small as $0.8 \times 10^{12}\ M_\odot$.
- The total stars mass is estimated to be between $4.6 \times 10^{10}\ M_\odot$ and $6.43 \times 10^{10}\ M_\odot$.
- Most of the mass is dark matter. A dark matter halo is spread out relatively uniformly to a distance beyond one hundred kiloparsecs from the Galactic Center.
- There is also interstellar gas, comprising 90% H and 10% He by mass, with 2/3 of the H in atomic form and the remaining 1/3 as molecular hydrogen.
- The mass of this gas is between 10%and 15% of the total mass of the galaxy's stars. Interstellar dust accounts for an additional 1% of the total mass of the gas.

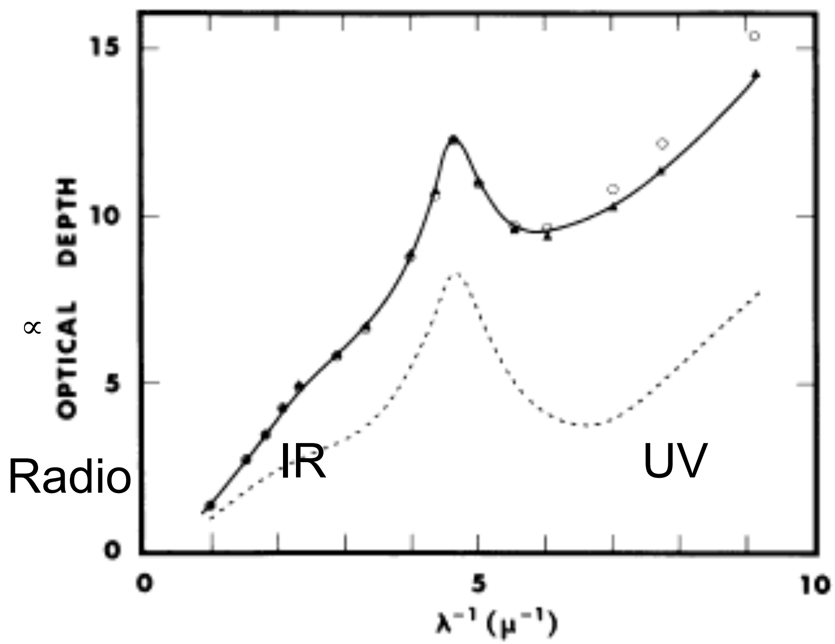



Multiwavelength vision must be used to see different components of the galaxy

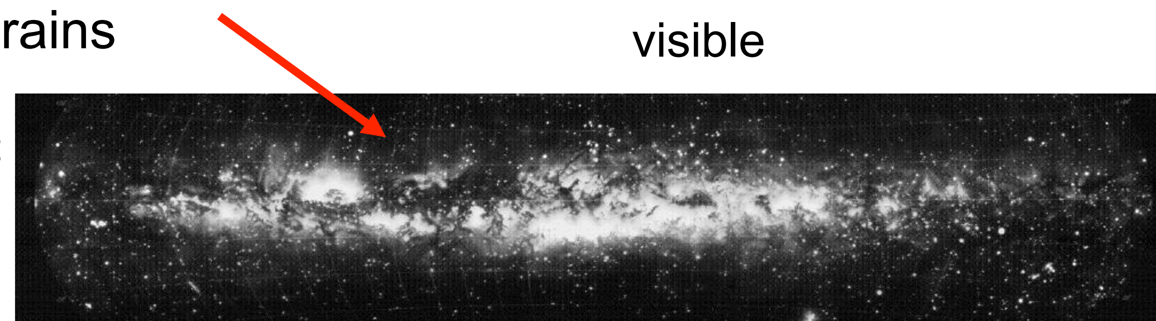
# Multiwavelength needed because the optical band is obscured by the interstellar dust

- Interstellar extinction
  - absorption plus scattering
  - UV extinction implies **small** (100 nm) grains
  - Vis. Extinction implies **normal** (1000 nm) grains
  - $n(a)da \sim a^{-3.5}da$
  - Silicates plus carbonaceous grains
  - Mass dust/Mass gas ~ 0.01
  - Dense gas – **larger** grains with icy mantles
  - **Normal** – $n_d/n \sim 10^{-12}$

**The interstellar extinction curve**




visible



# InterStellar Medium (ISM)

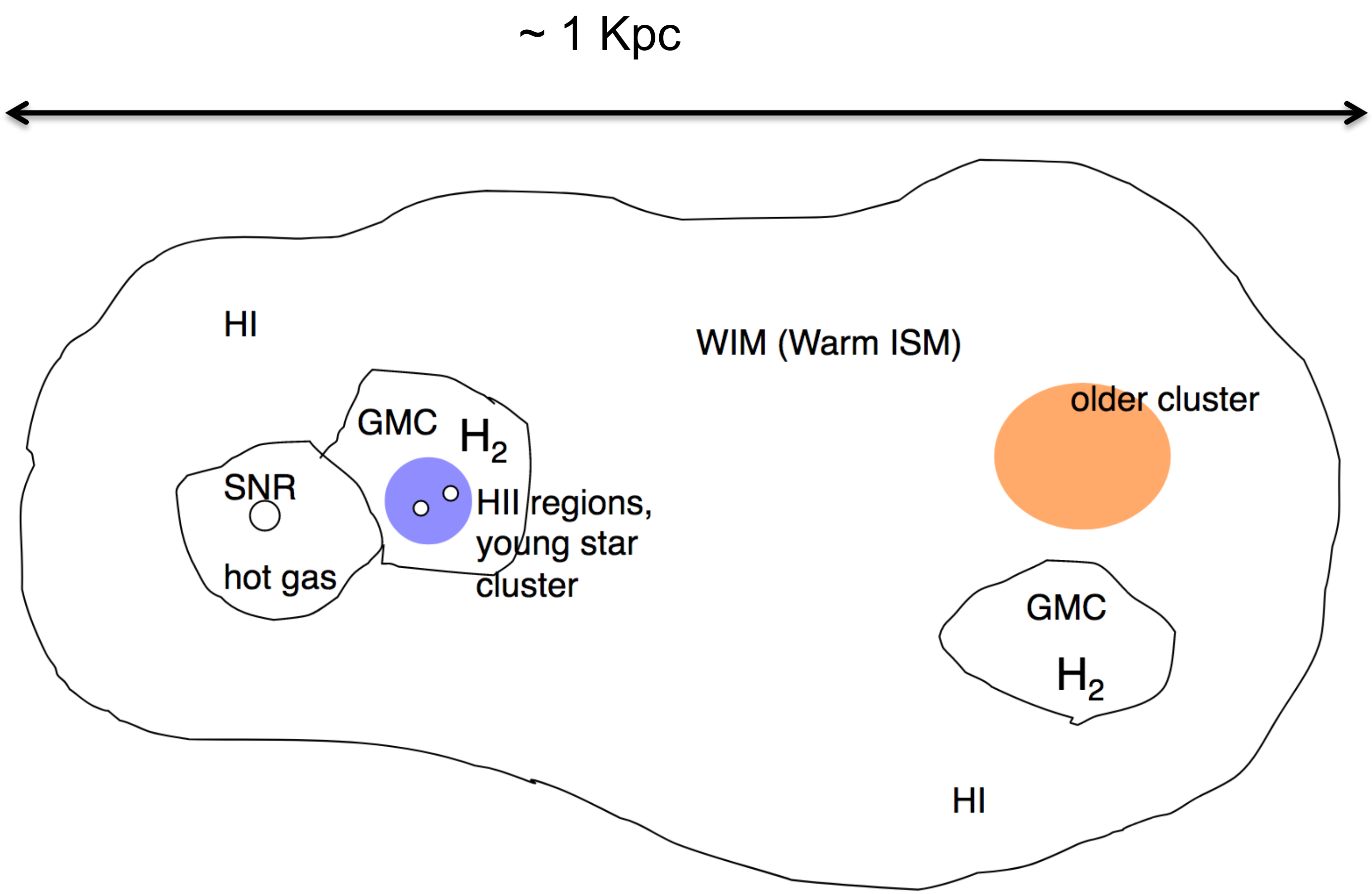
- General properties:
  - Mainly confined to galactic disks
  - Enormous range in temperature T ~ 10-$10^7$K
  - Enormous range in density n ~ $10^{-3}$-$10^7$cm-3
  - Even the most dense regions are close to vacuum (cf n air~$3 \times 10^{19}$cm$^{-3}$)
  - Far from thermal equilibrium → complex processes

# Constituents of the ISM

| constituents of ISM in Milky Way | where | temperature density ... | how observed |
|---|---|---|---|
| atomic hydrogen HI | in disk, some in halo $\approx 90\%$ of mass, 50% of vol. | $50...300$K $1...100$cm$^{-3}$ | 21cm radio line UV absorption lines |
| molecular hydrogen $H_2$ | dark clouds in disk $\approx 10\%$ of mass, 1% of vol. | $3...100$K $10^2...10^6$cm$^{-3}$ | UV absorption lines IR emission lines |
| other molecules CO, HCN, $H_2O$ ... | dark clouds in disk | $3...100$K $10^2...10^6$cm$^{-3}$ | radio and IR emission |
| ionized hydrogen HII | near hot stars, emission nebulae | $5000...10000$K $10^2...10^4$cm$^{-3}$ | optical and IR emission lines, radio continuum |
| hot gas | everywhere | $10^6...10^7$K $0.01$cm$^{-3}$ | X-ray emission |
| dust grains | mostly in disk $\approx 1\%$ of mass | $20...100$K size $\approx 2000$Å | reddening/absorption of starlight, IR emission |
| magnetic fields | everywhere | $\mu$Gauss | polarization of stars, Zeeman effect, synchrotron radiation |
| cosmic rays | everywhere | energies up to $10^{20}$eV | air showers |

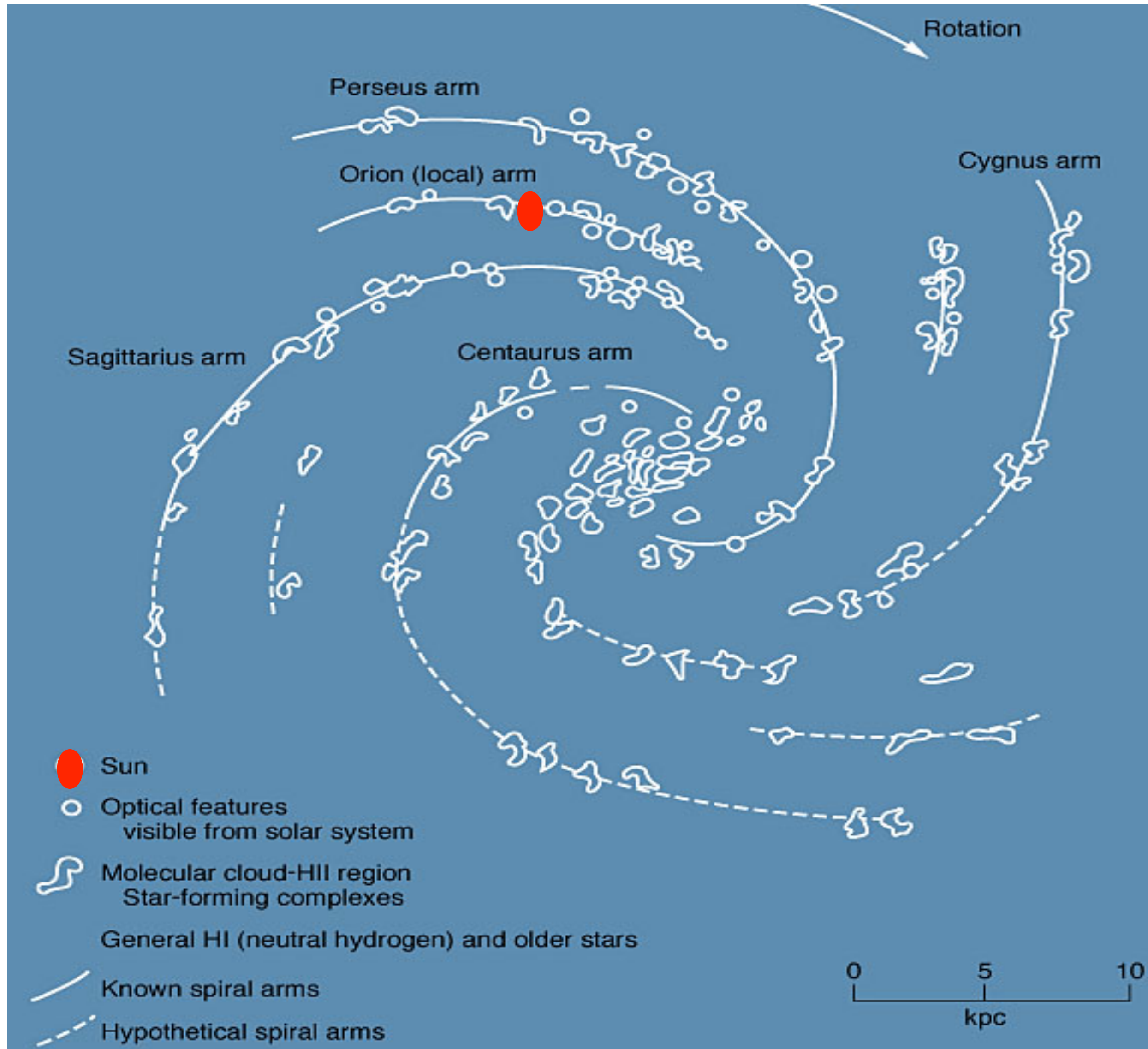
The total mass of the ISM in the Milky Way amounts to $\approx 15\%$ of the mass in stars, which is a typical value for spiral galaxies in general.

The ISM is both complex and dynamic
Different phases of the ISM are mixed and interact each other on different scales:
In the diffuse relatively warm HI,  Giant Molecular Clouds (GMC), HII in star forming regions, hot gas around SuperNova Remnants (SNR) are present



# Gas interstellare

- Il gas interstellare o intragalattico (IG) è il mezzo in cui si formano le stelle.
- Concentrato nei bracci a spirale



# Densità media del mezzo Interstellare

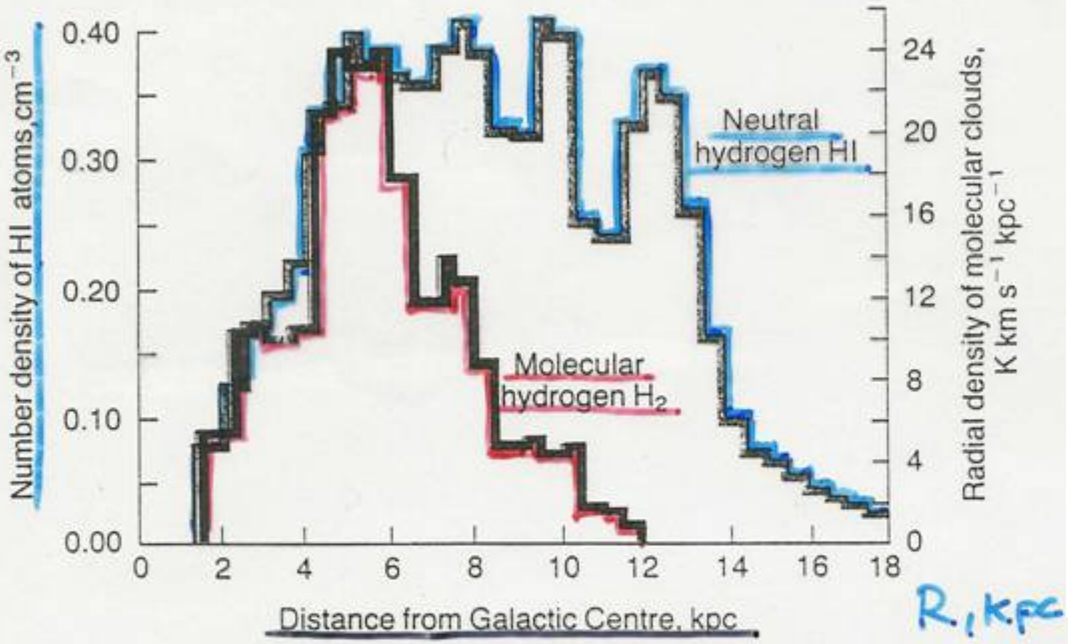



Figure 17.2. The radial distribution of atomic and molecular hydrogen as deduced from radio surveys of the Galaxy in the 21-cm line of atomic hydrogen and from millimetre surveys of the molecular emission lines of carbon monoxide, CO. (After D. Michalis and J. Binney (1981). *Galactic astronomy: structure and kinematics*, pp. 535. 554. San Francisco: W.H. Freeman and Co.)

IL MEZZO INTERSTELLARE

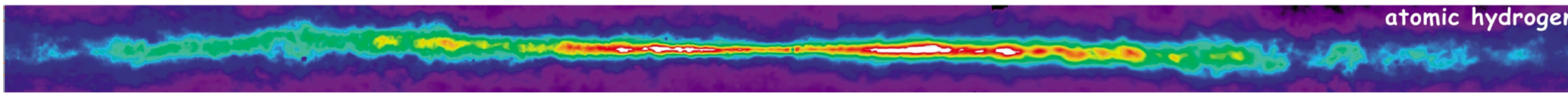
| NOME | COSTITUENTI | Rivelati da... | % VOLUME e MASSA del Mezzo Int. | | N cm$^{-3}$ | T (K) |
|---|---|---|---|---|---|---|
| MOLECOLARI NUBI | $H_2$, CO CS etc | Linee molecolari Emiss. Polveri | ~0.5% | 40% | 1000 | 10 |
| NUBI DI H NUBI DIFFUSE | H, C, O neutri | linea di 21 cm Linee Assorbim. | 5% | 40% | 1-100 | 80 |
| INTER NEBULE | H, $H^+$, $e^-$ (ionizz. 10%) | 21 cm + assorbim. Linee H | 40% | 20% | 0.1-1 | ~$10^4$ |
| CORONE stellari | $H^+$, $e^-$... $O^{5+}$ | soft X (0.1-2 keV) | ~50% | 0.1% | 1000 | $10^6$ |

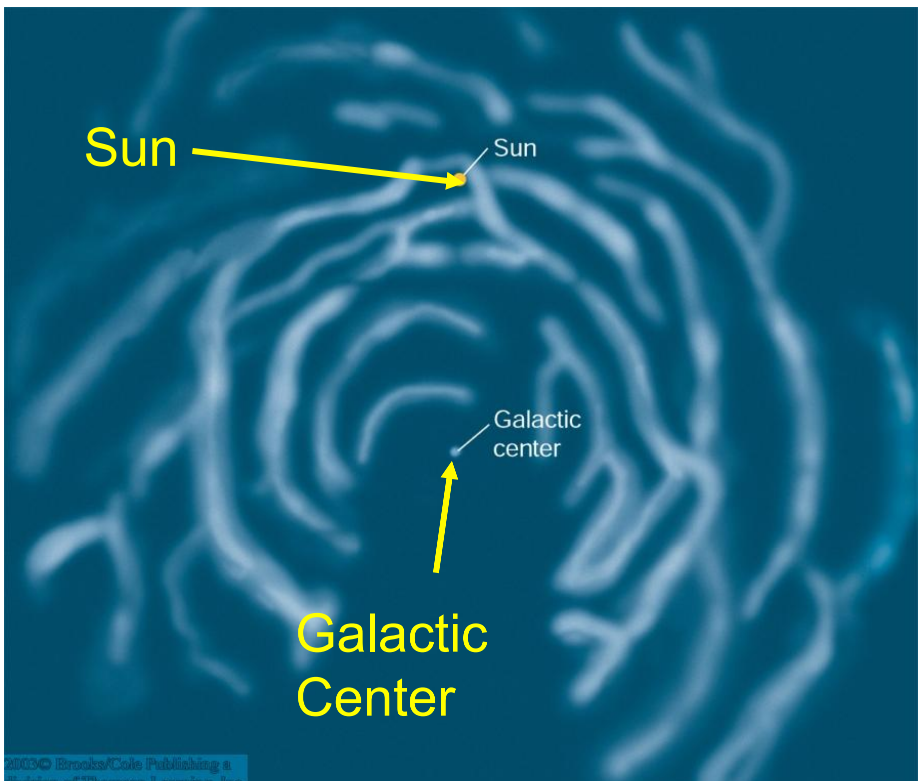
$$\rho_{IG} \approx 1\ p/cm^3 =$$
$$= 1.6 \times 10^{-24}\ g/cm^3$$

# Radio Observations

21-cm radio observations reveal the distribution of neutral hydrogen throughout the galaxy

21 cm hydrogen in the Milky Way.




Distances to hydrogen clouds determined through radial-velocity measurements (Doppler effect!)

Neutral hydrogen concentrated in **spiral arms**

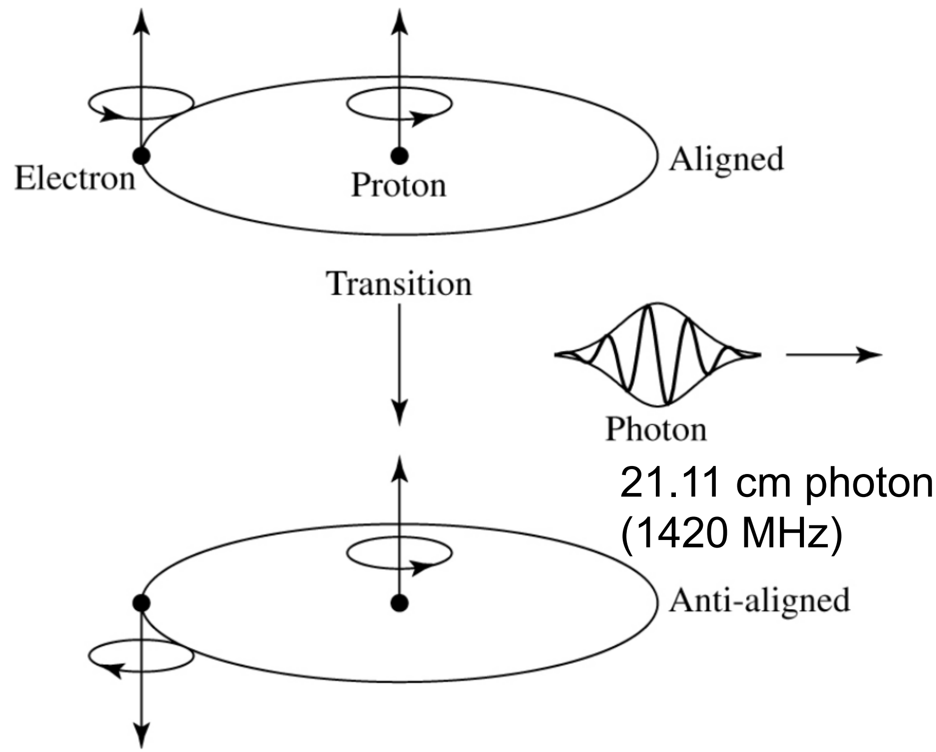
# 21 cm emission (radio)

Spontaneous Transition

The lifetime in the upper state ~ 11 million years (i.e. transition probability $2.9 \times 10^{-15}\ s^{-1}$

…rare to happen, but many atoms

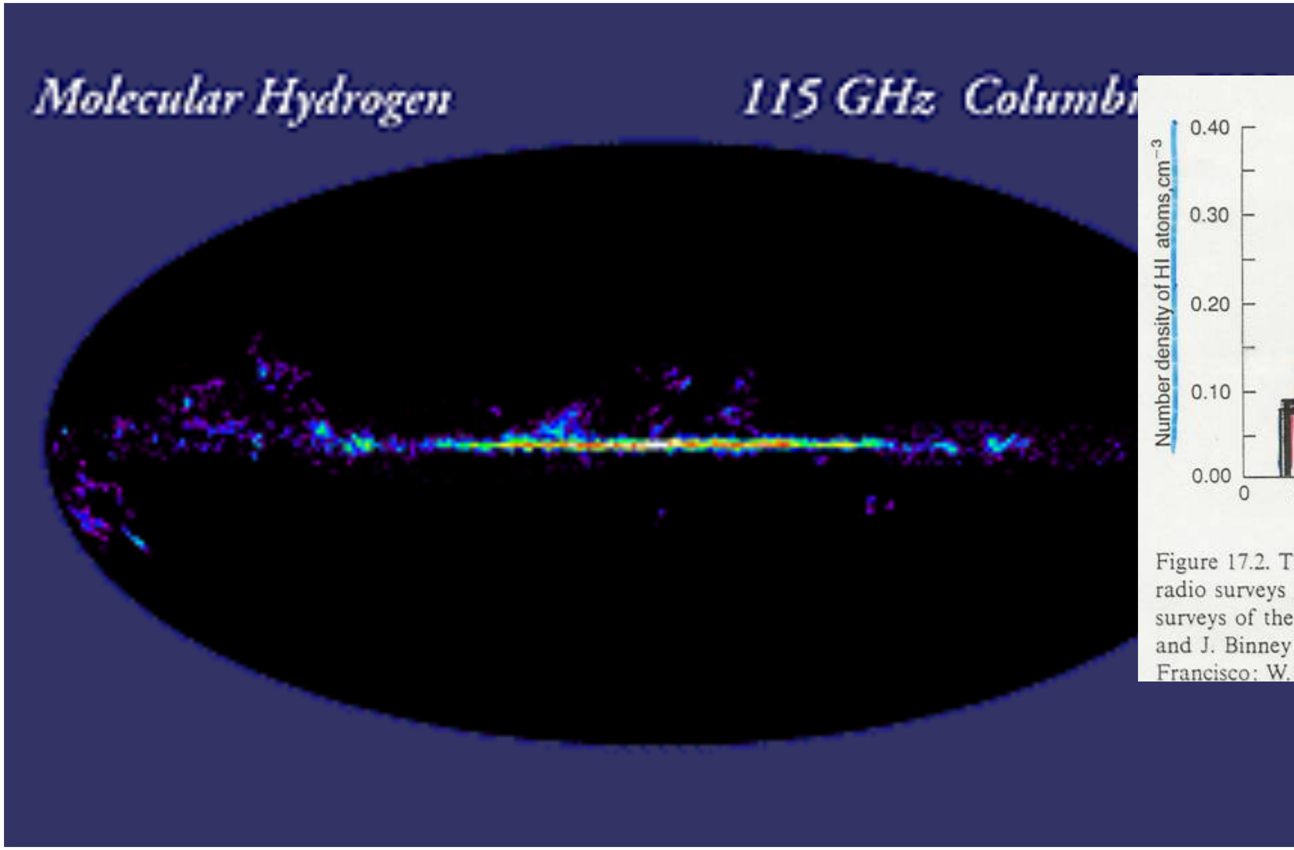
…collisions with passing atoms pop the electron back to parallel state




Detailed surveys of intensity and doppler shift → maps of velocity and density of HI in the galaxy

Also used in NMR

# Molecular Hydrogen $H_2$



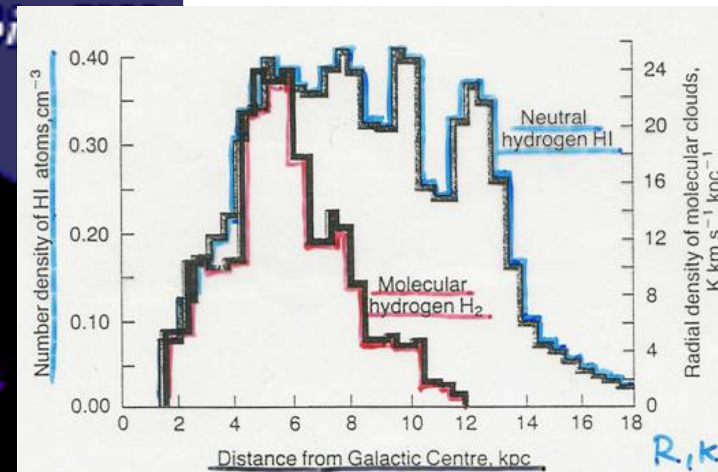
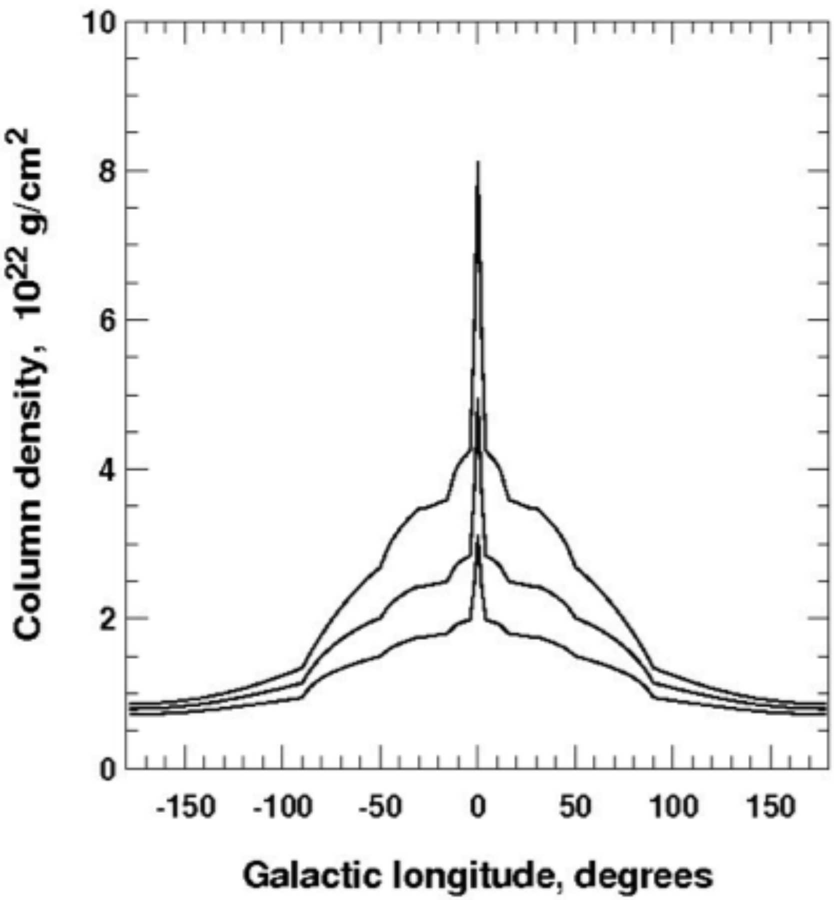




Figure 17.2. The radial distribution of atomic and molecular hydrogen radio surveys of the Galaxy in the 21-cm line of atomic hydrogen and surveys of the molecular emission lines of carbon monoxide, CO. (Aft and J. Binney (1981). *Galactic astronomy: structure and kinematics*, pp. Francisco: W.H. Freeman and Co.)

- The **very thin layer** of cold gas clouds is studied mostly via **CO line transitions** (mm waves , 2.6 mm).

- Molecular clouds are associated with **star-forming regions**.

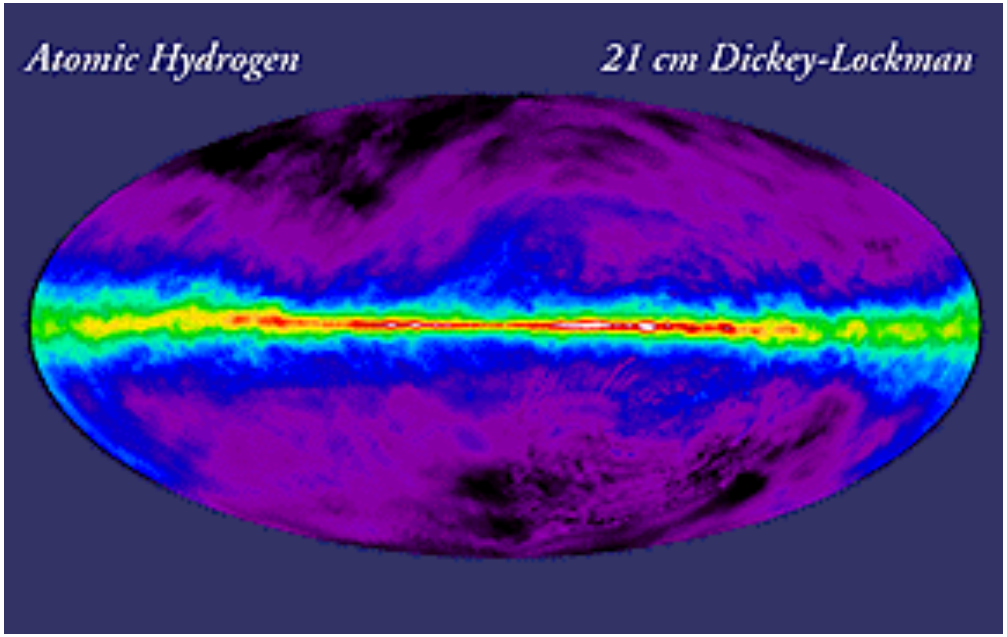



The matter density is not uniform. The sketch on the left gives an idea about the column density in the Galaxy 2, 5, and 10 deg around the galactic plane.

The column density at $l=0$ is not well known. The density distribution is not as symmetric as shown here.

The local densities of atomic and molecular Hydrogen are about 0.45 and 0.2 cm$^{-3}$.

# Physical state of the cool ISM and HI emission




Because the density of the ISM is low, the particles have a large **mean free path**.

$$\lambda \approx \frac{1}{n_H \sigma_c} = \frac{10^{15}}{n_H} \text{cm}$$

collision cross section : $\sigma_c \approx 10^{-15}\ \text{cm}^2$

The typical velocity v of the particles is $\frac{3}{2} m_H v^2 = k_B T$

The collision timescale then is:

$$\tau_c^{-1} = \frac{v}{\lambda} = \left(\frac{2k_B T}{3m_H}\right)^{1/2} n_H \sigma_c = 7 \cdot 10^{-12} \frac{n_H}{cm^{-3}} \left(\frac{T}{K}\right)^{1/2} s^{-1}$$

For $T = 100\,K$ and $n_H = 1 cm^{-3}$ we obtain about 1 collision in 500 yrs.

Because of the low temperatures, the energy available from collisions is of order 0.01 eV whereas H and He need 10eV and 21 eV, respectively to be excited

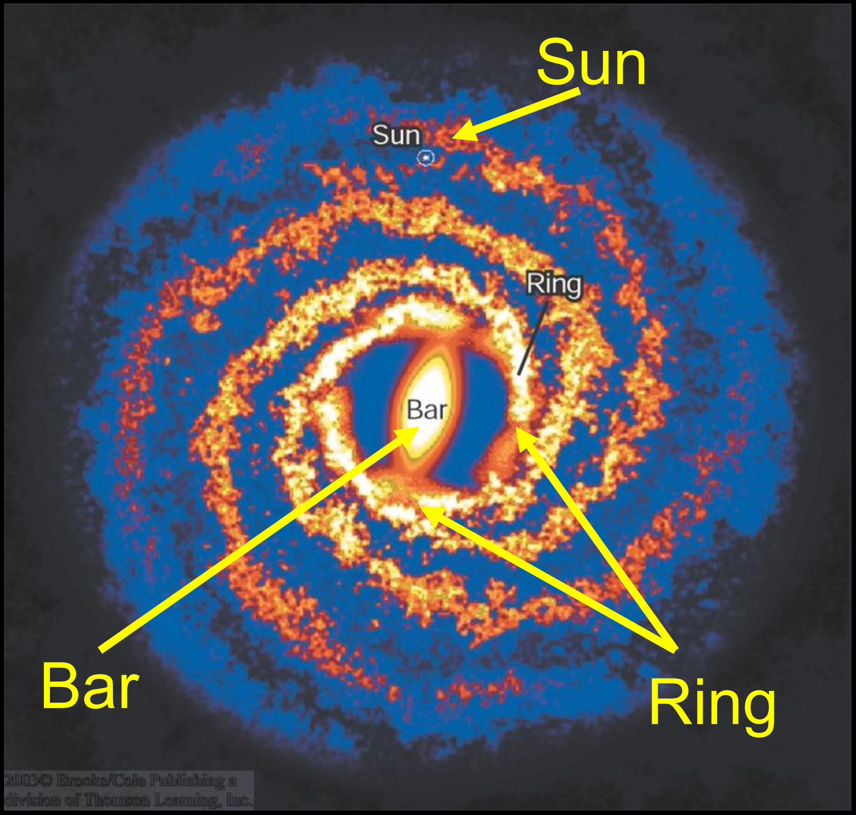
→ Most atoms will be in their ground state.

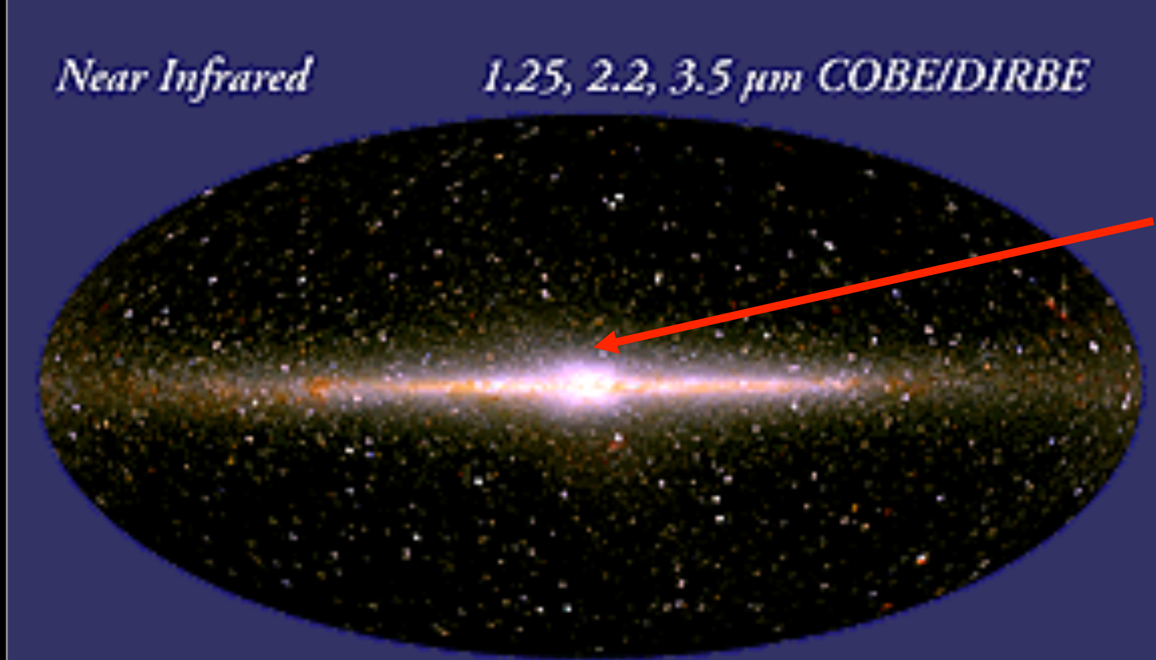
And collisions do not play any role in the gas

# Structure of the Milky Way

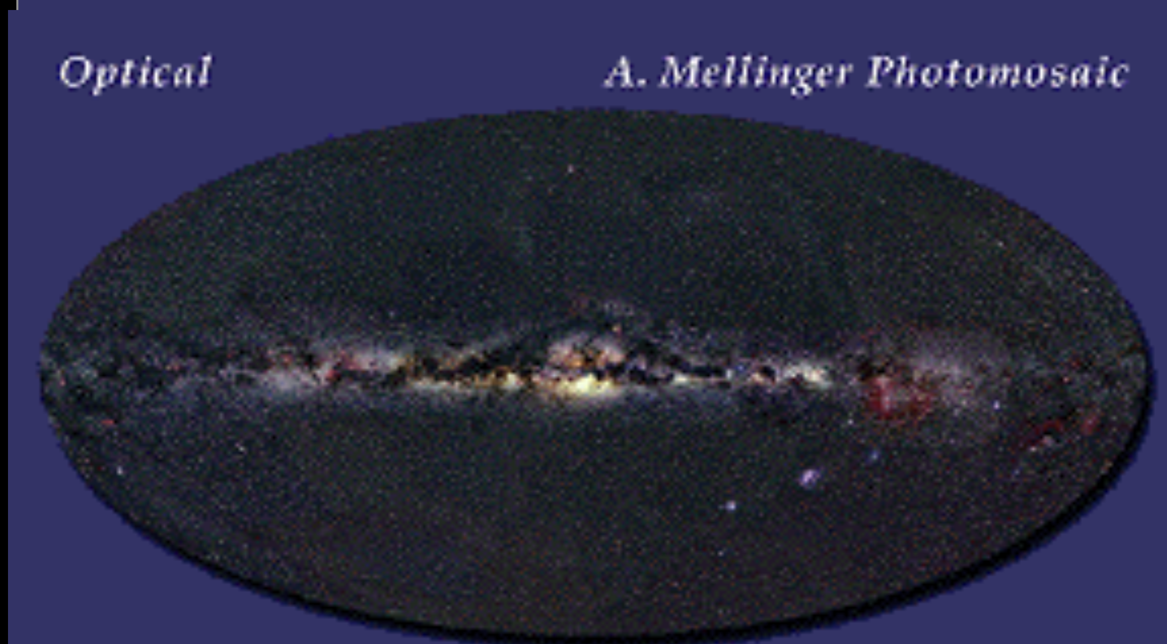
Distribution of stars and neutral hydrogen

Distribution of dust



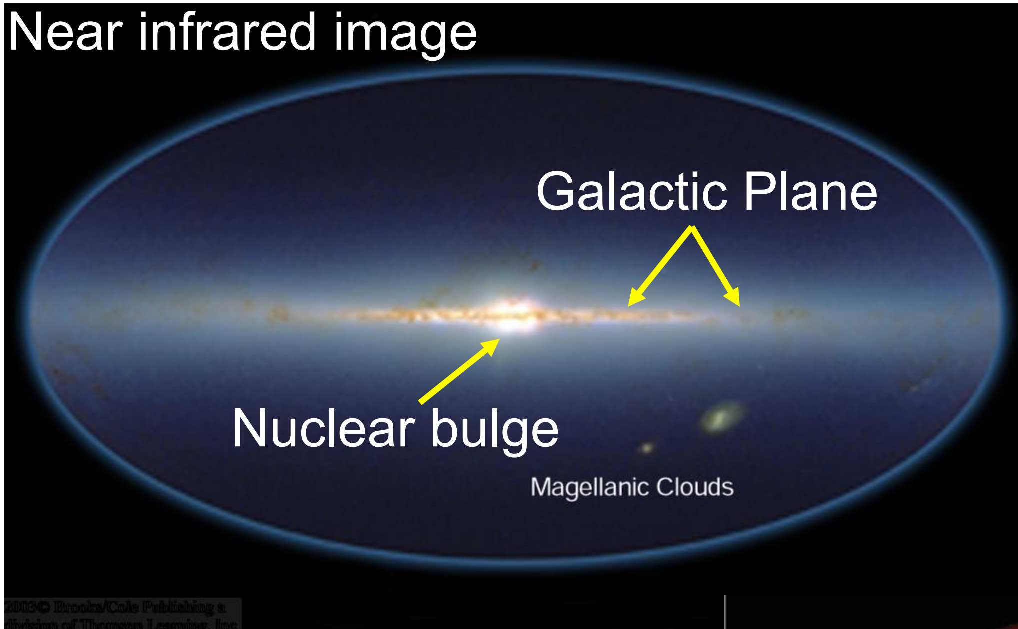


Distribution of Stars



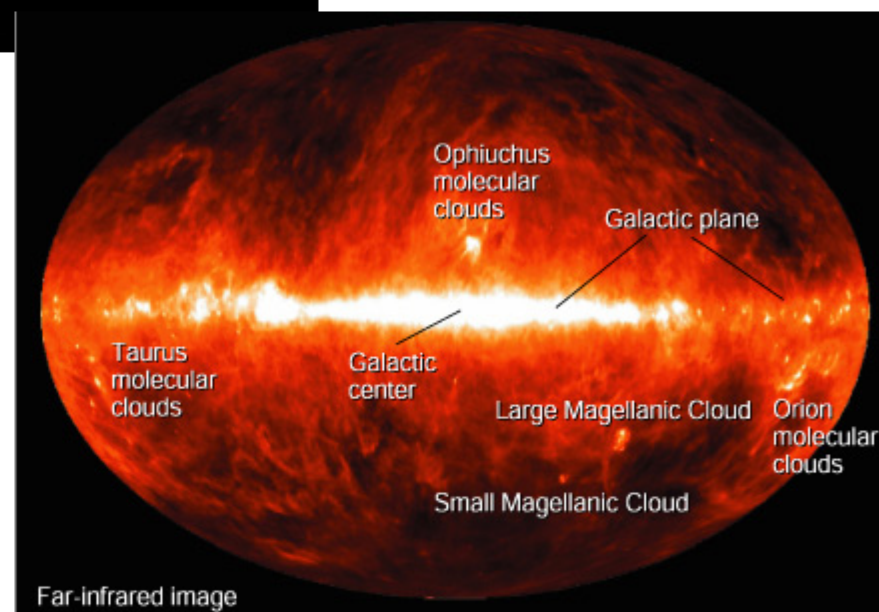
Interstellar dust is visible

# Infrared View of the Milky Way

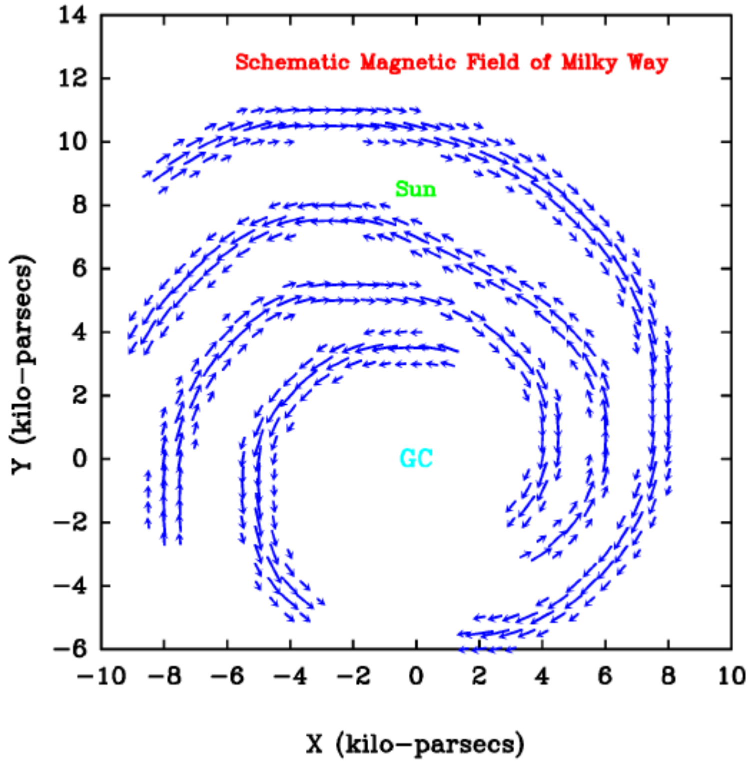


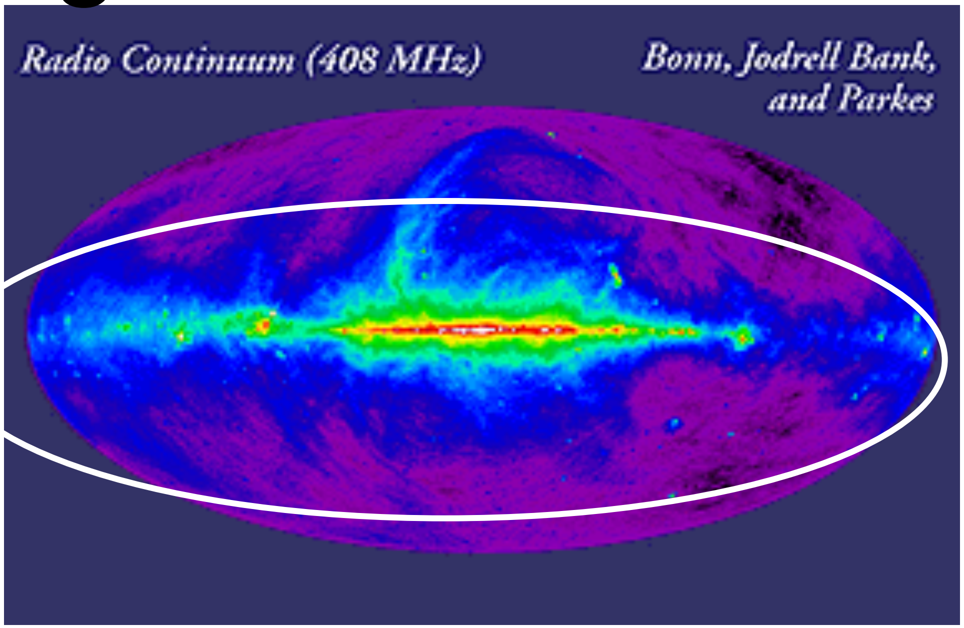

Interstellar dust (absorbing optical light) emits mostly infrared

Infrared emission is not strongly absorbed and provides a clear view throughout the Milky Way



# Galactic magnetic field




Galactic magnetic field is difficult to study (we can't put there a magnetometer)
The average galactic magnetic field is ≈3-6 x$10^{-10}$ T(or 3 $\mu$G) (±100%) directed along the galactic plane with large local irregularities

B field is present in the halo too as revealed by synchrotron emission of e-
It is important for cosmic ray confinement in the galaxy and for their diffusion

# Magnetic field probes

- Magnetic field is determined indirectly by measurements of light:
- Faraday rotation of background radio sources and pulsars.
- Zeeman splitting of radio spectral lines.
- Polarization of starlight.
- Polarization of infrared emission from dust grains and molecular clouds.
- Synchrotron radiation intensity and polarization.

- Note that each probe can reveal only one of the three components of magnetic field (except Zeeman splitting).

# Faraday Rotation

The light from a majority of stellar sources is not polarized to any measurable degree. There are a few exceptions: light from "reddened stars," which has been scattered by grains of dust, often shows signs of polarization due to such scattering, and pulsar light, while not constant in its polarization, can be averaged over a sample of perhaps 100 pulses to give a stable mean polarization [1]. Pulsar light has the added advantage that each pulse contains light of many different frequencies which all originated at the same instant, so the spread of the pulse is due to the frequency-dependent conductivity of the interstellar medium, and thus can be used to determine its path length while in the plasma. For a plasma made up of ions and electrons, we can assume that only the electrons contribute to the conductivity, the ions being so massive as to be practically immobile. The result for an isotropic plasma is well-known,

$$\epsilon = 1 - (\frac{\omega^2}{\omega_p^2})$$

where $\omega_p$ is the plasma frequency, defined by

$$\omega_p^2 \equiv \frac{4\pi n e^2}{m}$$

# Faraday Rotation

Clearly if $\omega < \omega_p$ then $\epsilon$ is negative and the amplitude of the wave falls off exponentially, so $\omega_p$ is also called the *plasma cutoff frequency*, below which there is no propagation of the wave through the plasma.[2] Now consider propagation through such a plasma in the presence of an external magnetic field $(B_0)$. The system is no longer isotropic, but has azimuthal symmetry around the direction of the magnetic field lines. Any plane-polarized wave can be decomposed into a component parallel to the magnetic field and a component perpendicular to the field. Assuming $(B_0)$ is large compared to the magnetic field of the wave, the equation of motion for an electron in the plasma will be

$$m(d\mathbf{v}/dt) = -e\mathbf{E} - (e/c)\mathbf{v} \times \mathbf{B}_0(1)$$

For a circularly polarized incoming wave, we know

$$\mathbf{E}(t) = Ee^{-i\omega t}(\epsilon_1 \epsilon_2)$$

Defining the cyclotron frequency $\omega_B \equiv \frac{eB_{0,parallel}}{mc}$ and solving for the steady-state velocity of the electron, we find

$$\mathbf{v}(t) = \frac{-ie}{m(\omega \pm \omega_B)}\mathbf{E}(t) \tag{2}$$

which gives

$$\epsilon_R = 1 - \frac{\omega_p^2}{\omega(\omega + \omega_B)} \tag{3}$$

for a right-handed polarization, and

$$\epsilon_L = 1 - \frac{\omega_p^2}{\omega(\omega - \omega_B)} \tag{4}$$

for a left-handed polarization.

# Faraday Rotation

A plane-polarized wave can be treated as the superposition of a left-hand and a right-hand circularly polarized wave of equal weight. As a result of the differential in speed between the different left- and right-hand modes, the plane of polarization will rotate as it passes through the plasma. This is called FARADAY ROTATION. In general, the angle through which the electric vector of a circularly polarized wave proceeds is given by

$$\phi = \int_0^d k ds \tag{5}$$

where k is the wave number,

$$k = \frac{\omega}{c}$$

Assuming that $\omega \gg \omega_p$ and $\omega \gg \omega_B$, we can expand k as

$$k \approx \frac{\omega}{c}[1 - \frac{\omega_p^2}{2\omega^2}(1 + \frac{\omega_B}{\omega})] \tag{6}$$

Substituting the known expressions for $\omega_p^2$ and $\omega_b$, we obtain for the Faraday rotation

$$\Delta\theta = \frac{2\pi e^3}{m^2 c^2 \omega^2} \int_0^d n B_{parallel} ds \tag{7}$$

# Faraday Rotation

$$\Delta\theta = \frac{2\pi e^3}{m^2 c^2 \omega^2} \int_0^d n B_{parallel} ds \tag{7}$$

Since $\Delta\theta$ varies with frequency in a known manner, measurements made at different frequencies can be combined to give a value for the integral.[2]

One useful astrophysical application of Faraday rotation is the determination of the magnetic field of the galaxy using extragalactic pulsars. The dispersion relation given in equation (1) leads to an expression for the travel time for a pulse of a given frequency through a path length L of plasma

$$t(\nu) = \frac{L}{c} + \frac{e^2}{2\pi mc} \times \frac{D_m}{\nu^2}$$

where $D_m$ is the "dispersion measure",

$$D_m = \int_0^L n ds$$

$D_m$ can be determined for pulsars based on the frequency spread of what was originally a simultaneous pulse. Then $B_{parallel}$ is directly proportional to the ratio of $\Delta\theta$ to $D_m$, and the constant of proportionality is known.

# Faraday rotation

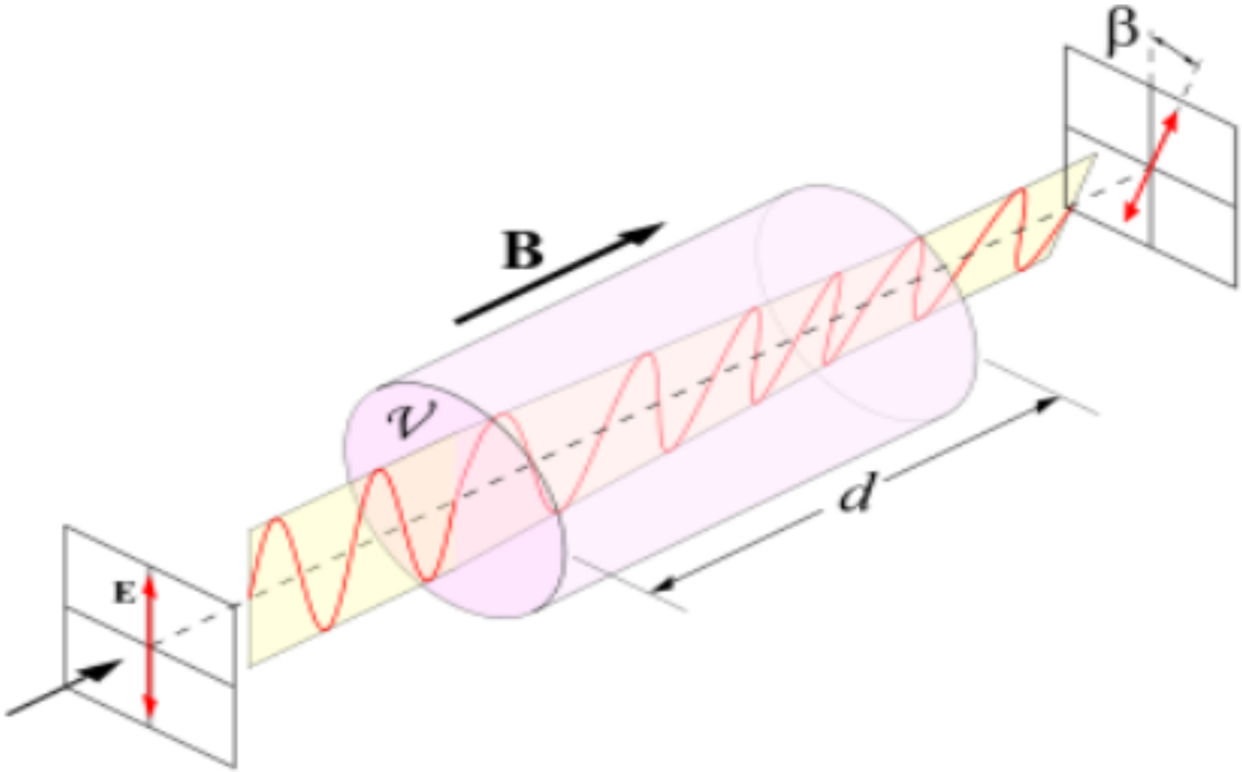



Figure 2: Faraday rotation in a magnetized gas.

- Vital probe from extragalactic sources and pulsars in our galaxy, mainly for the magnetic field of our galaxy.

# Faraday rotation

- Specifically as for the pulsars, which are widely spread in our galaxy, we can use another tool which is the Dispersion Measure DM:

$$DM = \int_0^l n_e dl \qquad (3)$$

- DM is a parameter which indicates the delay of arrival pulses from a pulsar at a range of radio frequencies. Note that each pulse is composed of a wide range of frequencies but each one travels with different speed.

- Thus, combining (2) and (3): $\langle B_\mathrm{P} \rangle = 1.232 \cdot \dfrac{RM}{DM}$ (4)
  This estimation is not dependent on electron density model.
- **Only regular fields give rise to Faraday Rotation while random or anisotropic do not. Proof of large-scale pattern.**

# Faraday rotation

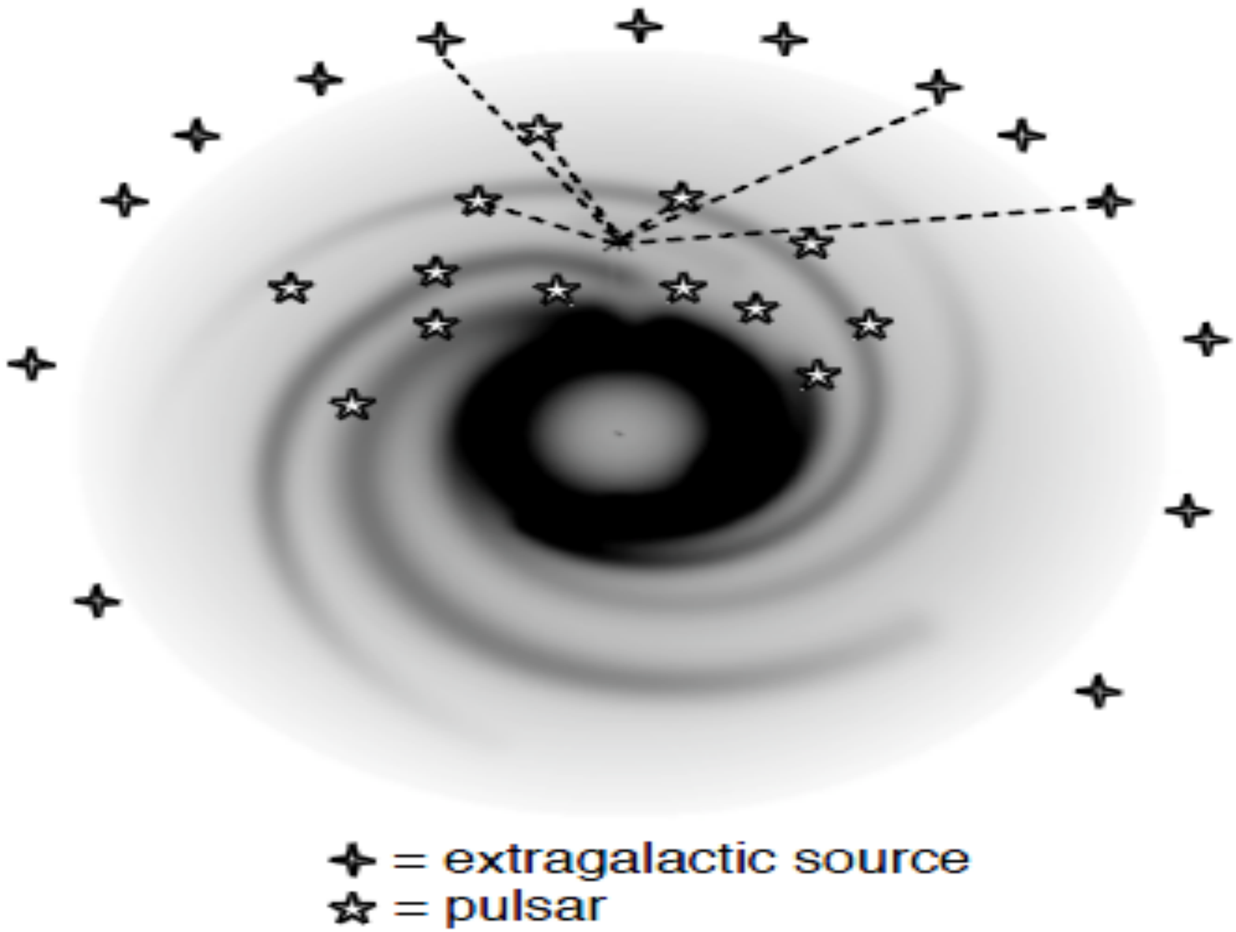
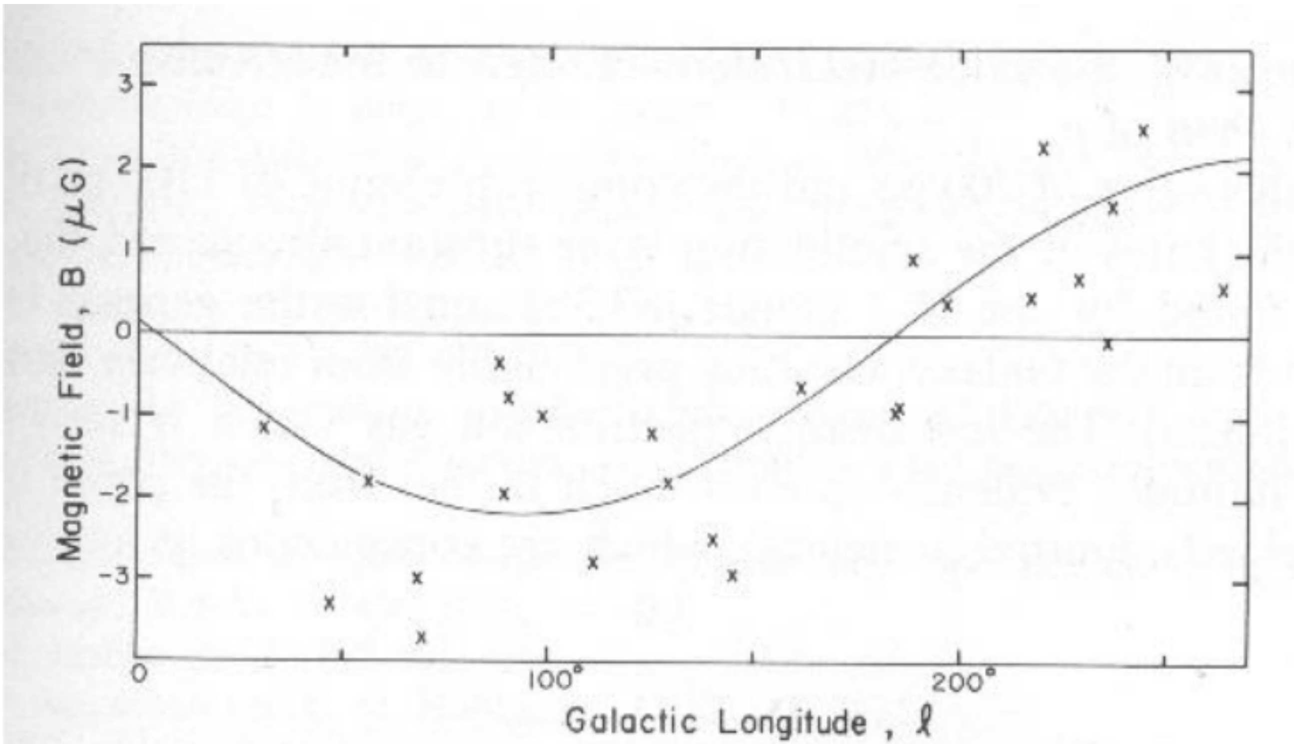



Figure 3: Pulsar and extragalactic sources distribution in our galaxy.

# Faraday Rotation




The above plot was constructed from a study of 26 pulsars; the solid line is the least squares fit, which yields a net value of $(2.2 \pm 0.4) \times 10^{-6}$ gauss for the galactic magnetic field.

# Zeeman splitting

- A probe which is widely used for measurements of the parallel component of the field, in our galaxy, in starbursts galaxies and few nearby galaxies $B_p$.
- It's a way to determine field strength in gas clouds from the emission line of 21 cm, or from maser emission from dense core like galactic nuclei.

- The interacting energy U between the external magnetic field and the magnetic dipole 'nuclei-electron' is:

$$\left.\begin{aligned} U &= -m \cdot B \\ m &= -\mu_B \cdot \frac{L}{\hbar} \\ L &= m_l \cdot \hbar \end{aligned}\right\} \longrightarrow U = m_l \cdot \mu_B \cdot B$$

Which is the energy difference between the two splitted lines.

# Zeeman splitting

- Let $f_0$ be the frequency of the unshifted spectral line, then the frequencies of the splitted lines will be:

$$f = f_0 \pm \frac{e \cdot B}{4\pi \cdot m_e \cdot c}$$

(5), hence measuring the frequencies of the spectral lines, the parallel component of the field is defined.

- **From the change of the circular polarization we extract the average field direction**.

# Polarized emission at optical, infrared and radio synchrotron emission

Starlight polarization:

- Optical linear polarization is the result of scattering from elongated dust grains in the line-of-sight, which are collimated in the interstellar magnetic field (Davies-Greenstein effect).
- Dust grains are not spherical, their long axis is perpendicular to the field and they are spinning rapidly with rotation axis along the magnetic field.

- E vector runs parallel to the field because grains tend to absorb light polarized at the direction of the long axis, thus we measure the vertical component $B_\perp$ .
- Measurements from thousand of stars
- **Reliable detector for distances <3kpc and mainly for small-scale fields.**

# Polarized emission at optical, infrared and radio synchrotron emission

Infrared polarized emission of clouds and dust:

- The same grains that polarize starlight also radiate in the infrared. This thermal emission is polarized owing to the shape of grains as presented above.

- Similarly we estimate the vertical component of the magnetic field $B_\perp$ .

Synchrotron emission:

- Accelerating electrons gyrating magnetic field lines radiate radio synchrotron emission.

# Polarized emission at optical, infrared and radio synchrotron emission

- Significant tracer of magnetic field's strength and orientation, of external galaxies (Beck 2009) and our Milky Way, by measuring the total radio intensity and polarization respectively.
- Polarized emission traces ordered fields while unpolarized synchrotron emission indicate turbulent fields with random directions.
- We estimate the vertical component of the field $B_\perp$.
- The estimation is based on the distribution of relativistic electrons in a range of energies: * widely assumed power law distribution of electrons combined with the equipartition of energy density between magnetic field and cosmic rays lead to:

$$j_{syn} \propto B^{2/7}{}_{\perp}$$

# Polarized emission at optical, infrared and radio synchrotron emission

| Dataset | measures what? | ancillary data | data points | region covered |
|---|---|---|---|---|
| Synchrotron emission | $B_\perp$ orientation | $n_{cre}$ | 3×50k (WMAP) | full sky |
| RM: pulsars | $B_\parallel$ | $n_e$ | 529 | mainly disk; $\lesssim 10$ kpc |
| RM: X-Galactic | $B_\parallel$ | $n_e$ | ∼1500 | roughly uniform |
| Starlight polarization | $B_\perp$ orientation | grain physics | ∼10k | mainly disk; $\lesssim 3$ kpc |
| Zeeman splitting | $B_\parallel$ *in situ* | none | ∼100s | near quadrant |

Table 1: Detectors of galactic magnetic fields.

Best probes for a large-scale field in our galaxy: RM and Zeeman splitting.
The other probes good at revealing field details.

# Magnetic field structure of Milky Way

<u>Galactic disk:</u>

- Ordered (regular or anisotropic) and turbulent field components.
- Large-scale pattern in disk has a strong azimuthal component.
- Small-scale structures also appear.
- Approximately the field follows the logarithmic spiral arms having a pitch angle $10^o$ . Parallel to the adjacent gas.
- Always clockwise in the arm region. Anti-clockwise in the interarm regions displaying field reservals.
- Stronger field and polarized emission in interarm regions .
- Strength near the sun : $6\mu G$ (Beck 2009).
- Norma arm : $4\mu G$.

# Magnetic field structure of Milky Way

- Magnetic field in arms is passive to dynamics.

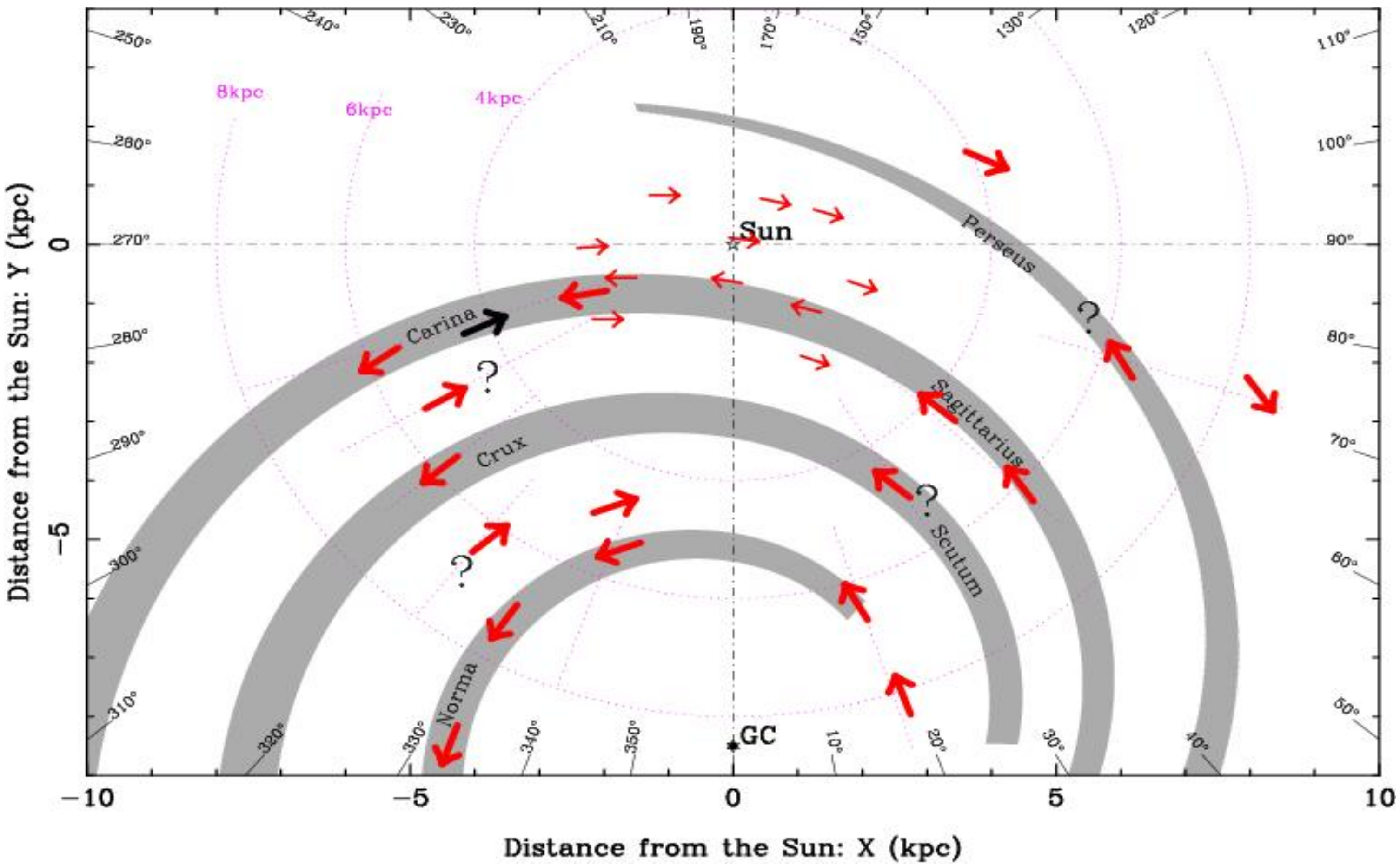



Figure 5: Field orientation in arm and interarm regions in Galaxy.

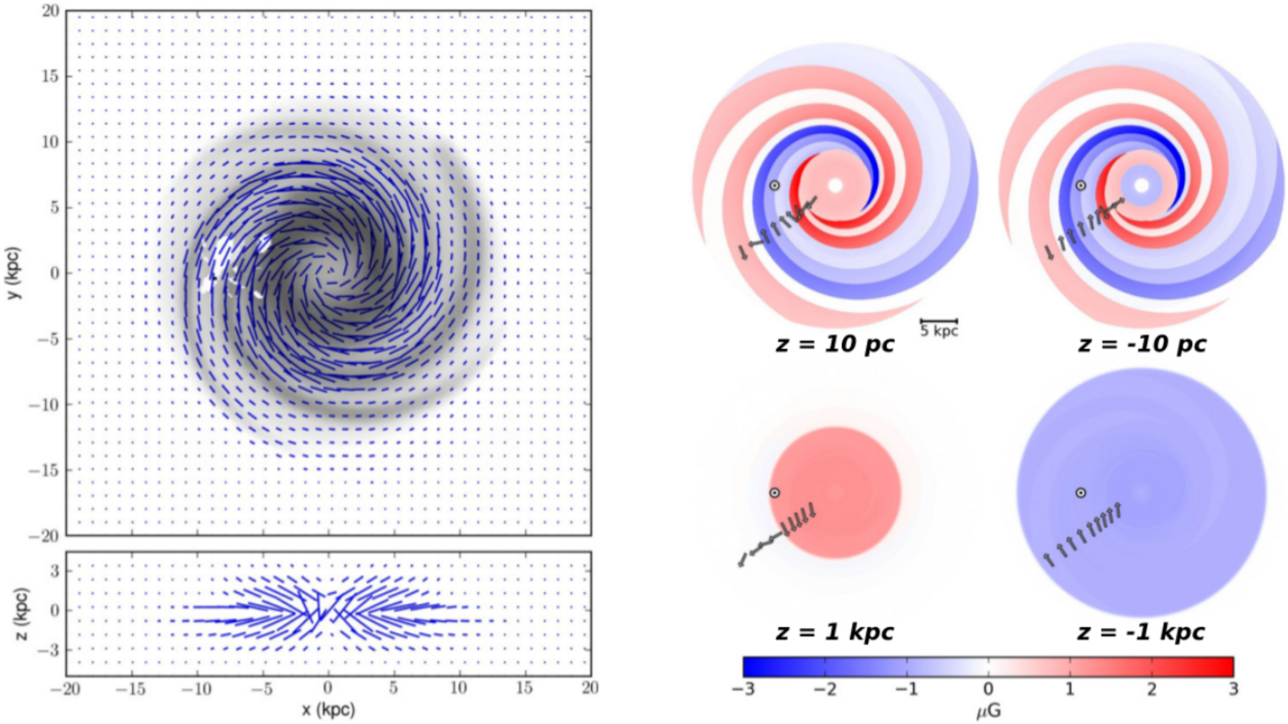
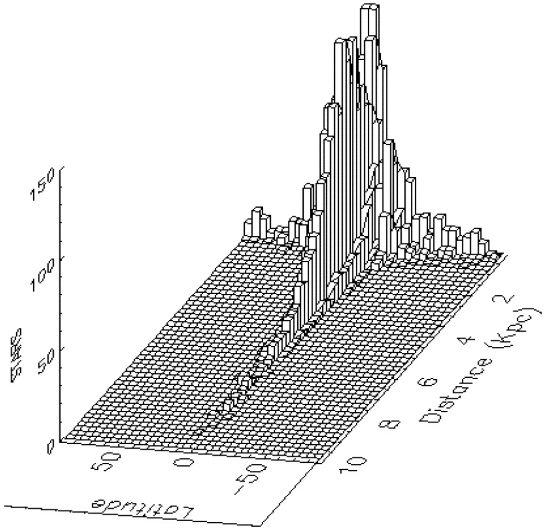


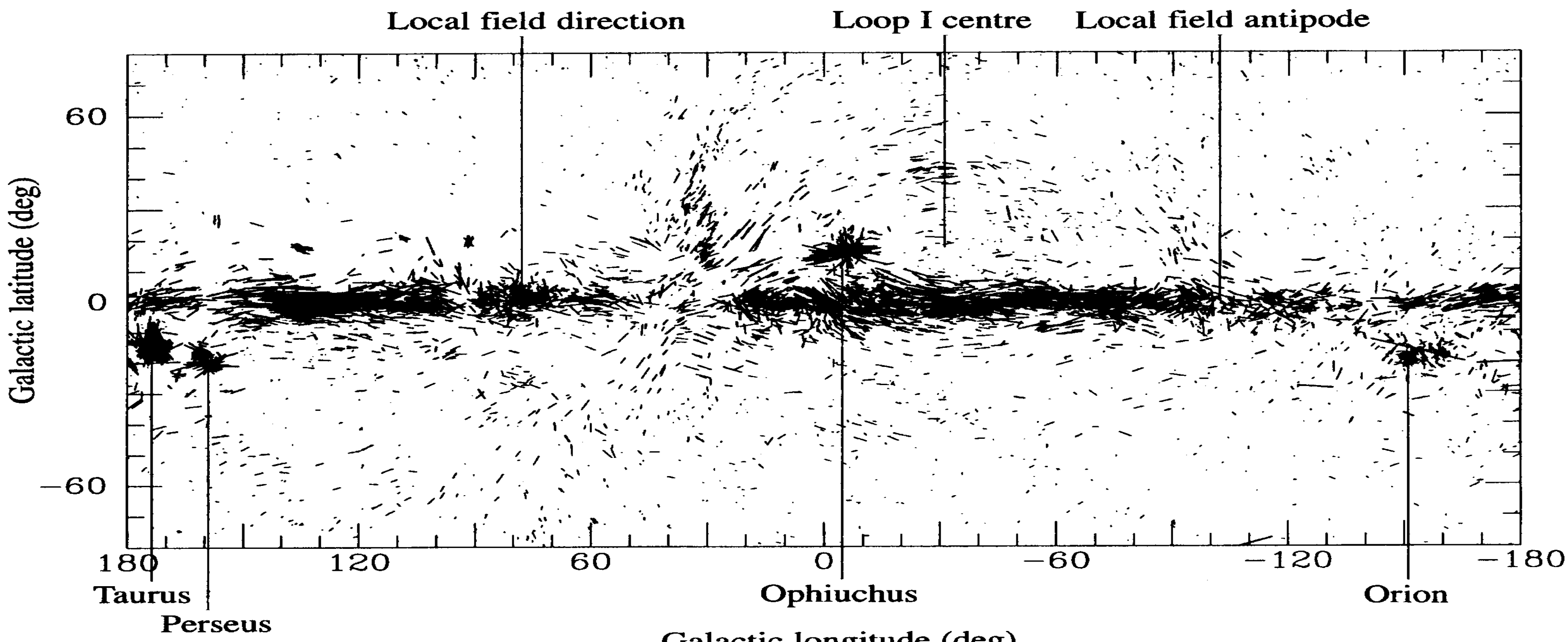

**Figura 2.8:** Le figure, tratte dall'articolo di Jansson & Farrar [30], mostrano la struttura del campo magnetico della nostra Galassia, ricavate secondo il modello elaborato dagli stessi autori. L'immagine a sinistra descrive la distribuzione delle direzioni e dell'intensità del campo magnetico come sarebbero viste da un osservatore esterno alla galassia. Mentre, l'immagine a destra è una raffigurazione schematica della struttura del campo magnetico galattico a diverse altezze dal piano galattico. D. Di Bari, Tesi di laurea, 2015

- Intensità media nel piano galattico: 3-6 μGauss
- Coerenti su scale di 1-10 pc

# Polarizzazione della luce delle stelle: *local field // arm*

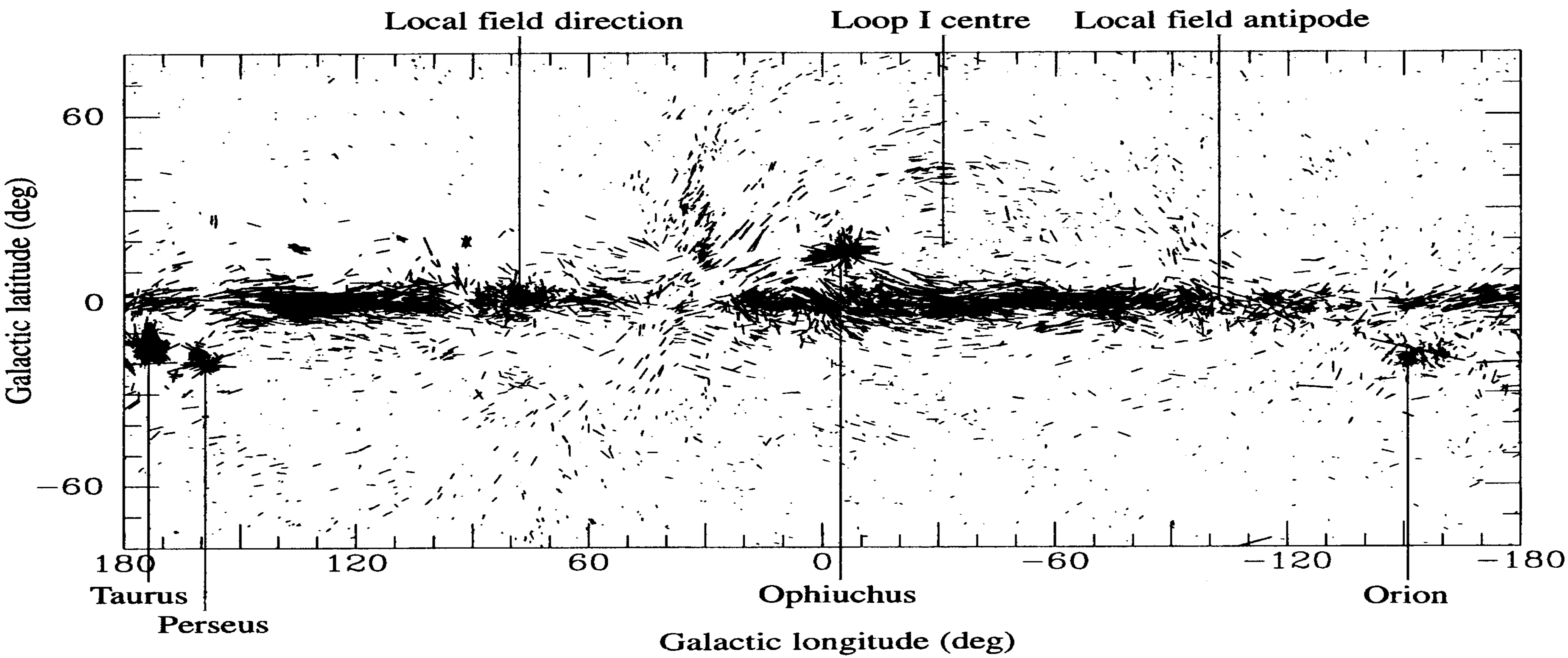



- **9000 stars have polarization measured**
- **mostly nearby (1~2kpc)**
- **polarization percentage increases with distance**




**Zweibel & Heiles 1997, Nature 385,131 Berdyugin & Teerikorpi 2001, A&A 368,635**

- Each line represents the polarization measurement for a star; length is proportional to the fractional polarization and orientation is in the max polariz., which is || B.
- Within 10º from galactic plane, B is generally || to the galaxy plane
- Can be used to derive $B_o/\delta B$ from uniformity of the optical pol data: $B_o/\delta B \sim 0.3 – 1$.
- At positions at 10º off the gal plane there is a considerable small-scale structure
- At high gal latitudes several local interstellar bubbles each produced by multiple supernovae (eg Loop I)



# Magnetic field structure of Milky Way

Halo:

- Weaker fields in halo and less complex.
- Has a significant vertical component $B_z \sim 0.2 \mu G$.
- Best evidence in such a halo is total radio emission at 408 and 1420 Hz, diffuse polarized emission and RM distribution from extragalactic sources.
- Reserval field below and above the disk which is also consistent to the dynamo configuration.

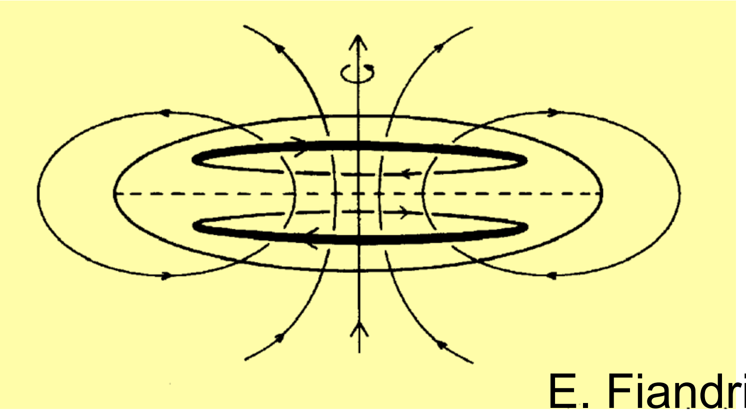
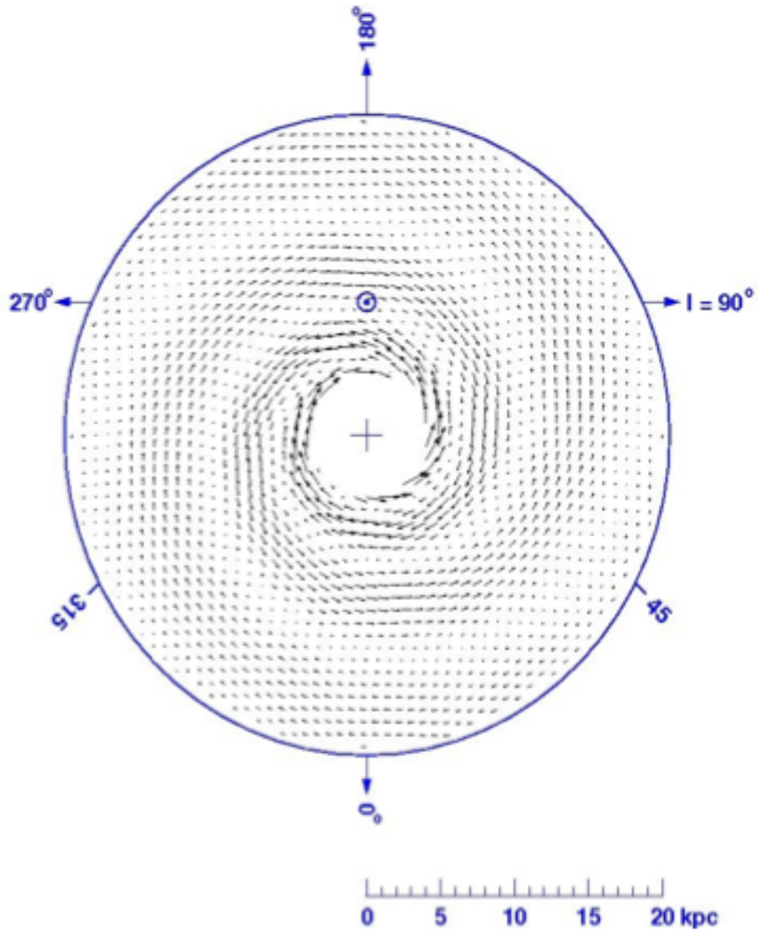


Figure 6: Field configuration for A0 dynamo. Halo field shown.




Galactic magnetic field models:
BSS (bisymmetric) or
ASS (axisymmetric)

$$B(r, \phi) = B_0(r) \cos\left(\phi - \beta \ln \frac{r}{r_0}\right)$$

The field has to decrease with the distance to the galactic center and the galactic plane. The field is not known in the inner 3 kpc around the galactic center, although it is very high.

They may also be different type of field related to the center (dipole field ? Is one of the suggestions.

Local regular field is about 2 μGauss and the total field maybe a factor of 3 higher.

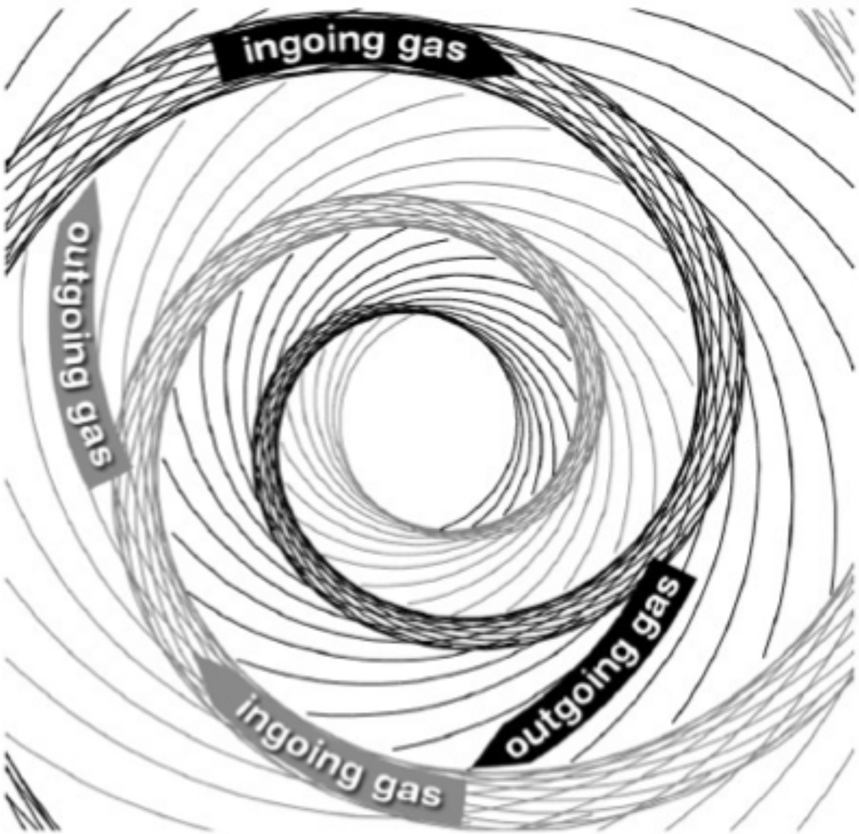


Figure 19: Gas motions in a bisymmetric spiral galaxy.

A graph that appeared recently in astro-ph argueing that the Galactic magnetic field has a bisymmetric structure.

These measurements are very difficult especially in the region of the Galactic center. One can see very different estimates varying from 10 μG up.