Lecture 1 021019

- Slides will be available at:

https://www.fisgeo.unipg.it/~fiandrin/didattica_fisica/cosmic_rays1920

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, Astrofis. 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

Cosa sono i raggi cosmici?

- Flussi di particelle energetiche neutre (fotoni, ν) e cariche elettricamente (raggi cosmici carichi...p,e-,e+, anti-p, nuclei) che raggiungono la sommita' dell'atmosfera terrestre dallo spazio

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

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

Nuove leggi della fisica derivate dall'osservazione astrofisica

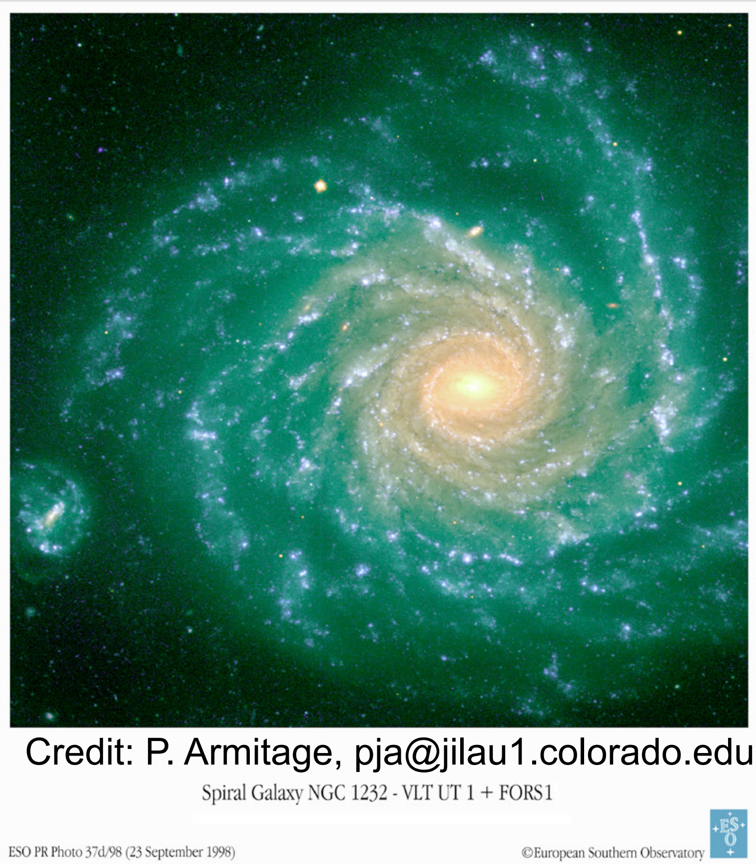
OSSERVAZIONI

- **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

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

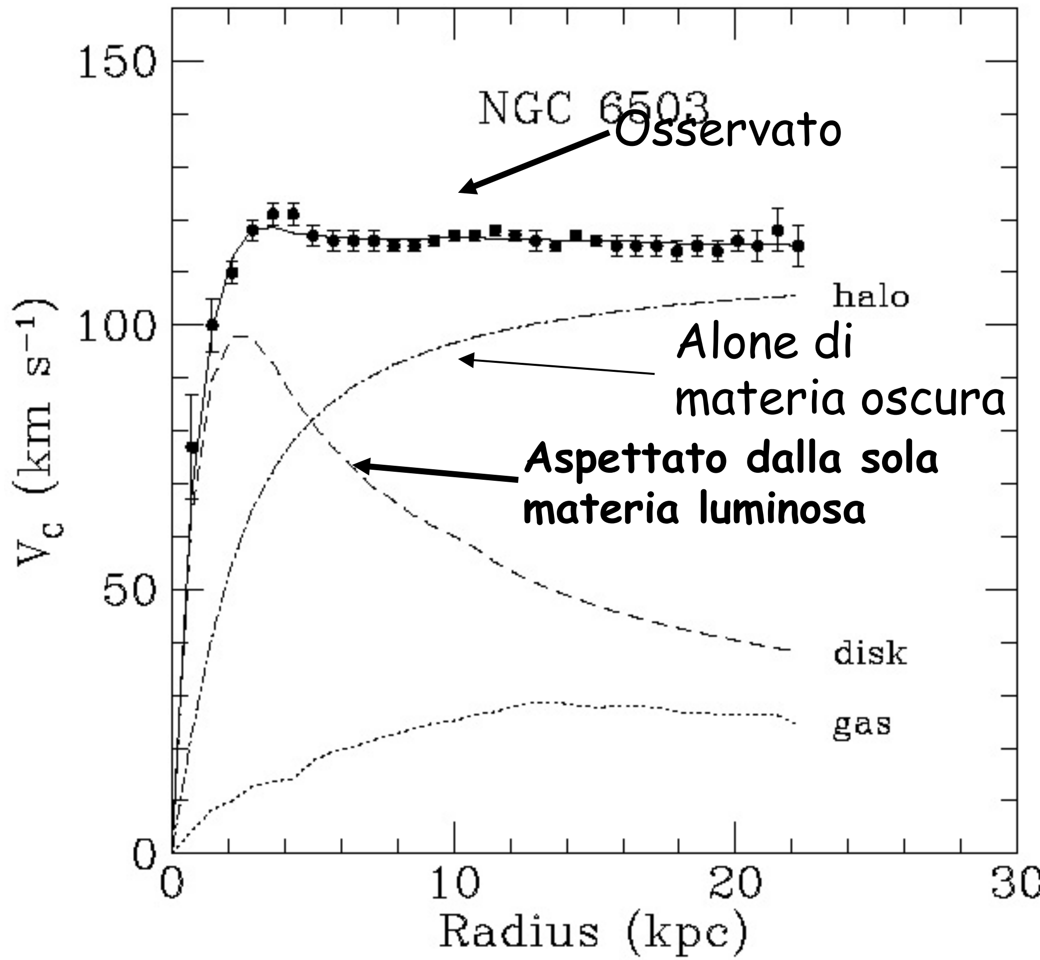
Observations of the brightness of distant supernovae suggest presence of **dark energy** - not understood at all.

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

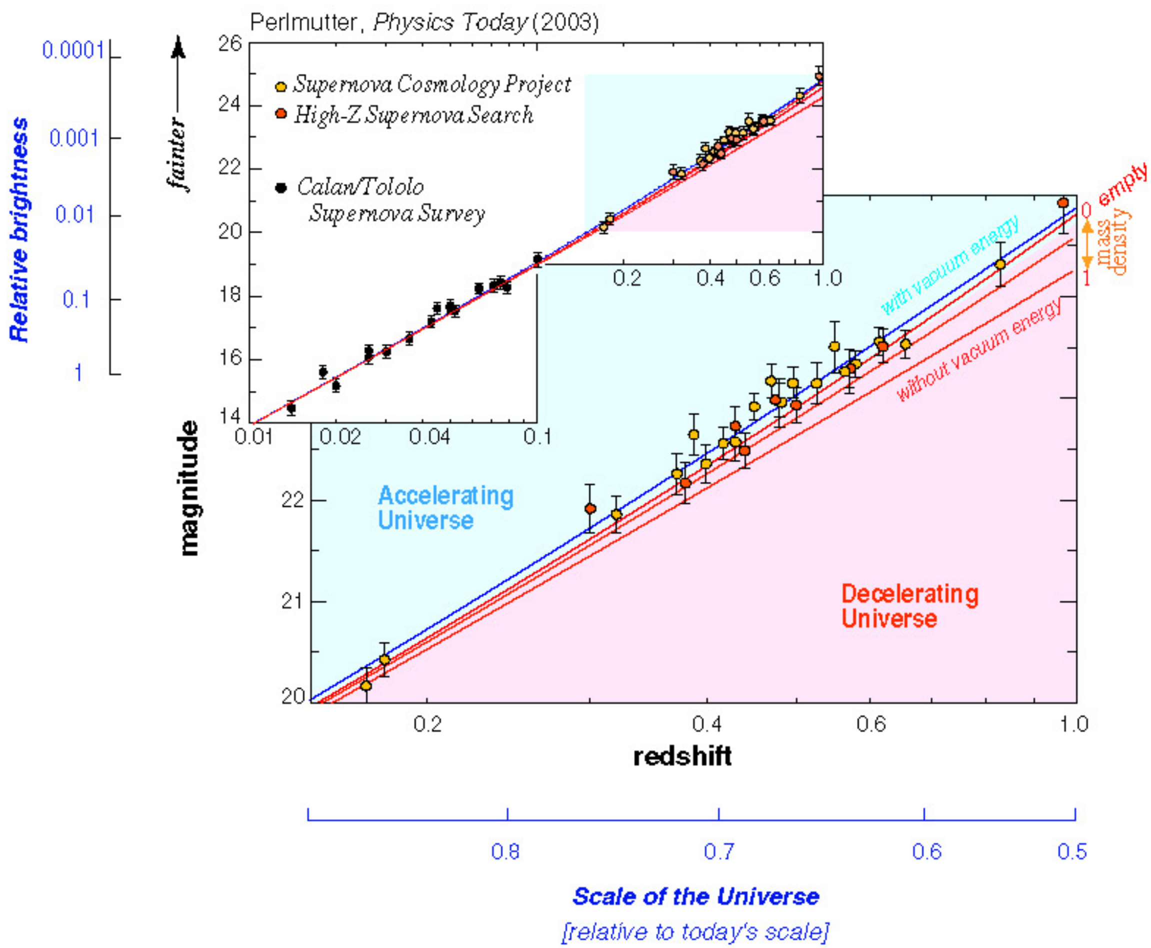
Materia oscura

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

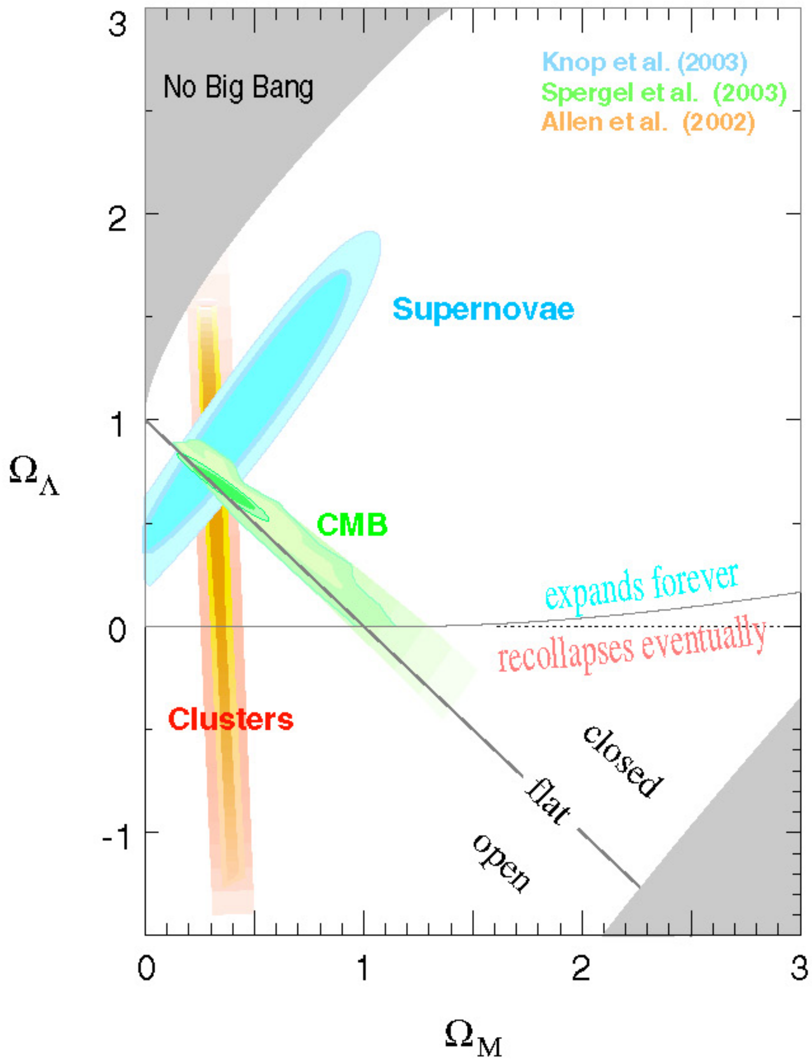


La legge di Hubble ci dice che la velocita' di recessione delle galassie e' proporzionale alla distanza dall'osservatore

$$V = H_o \times D$$

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%)x10^9 anni

2- 4.9% Materia visibile

26.8% Materia oscura→ sconosciuta

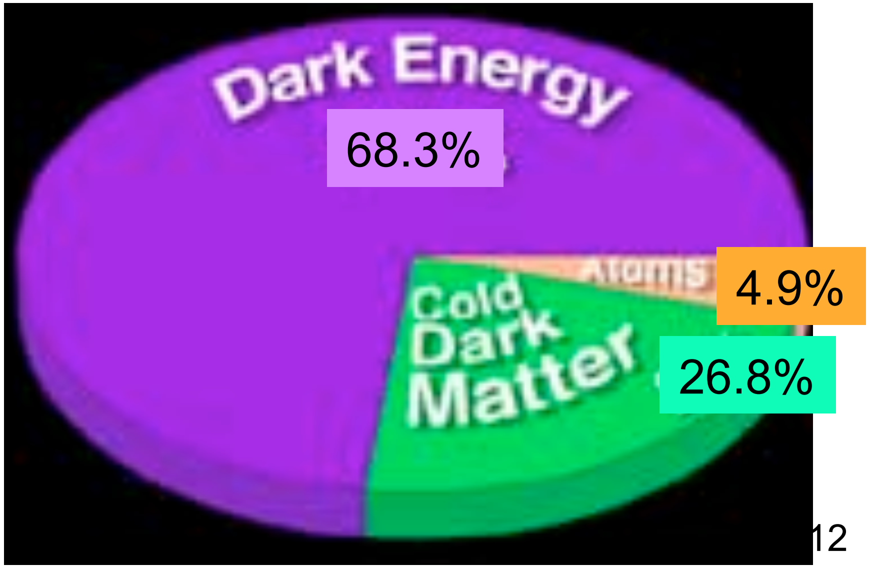
68.3% Energia oscura→ sconosciuta^2

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!!

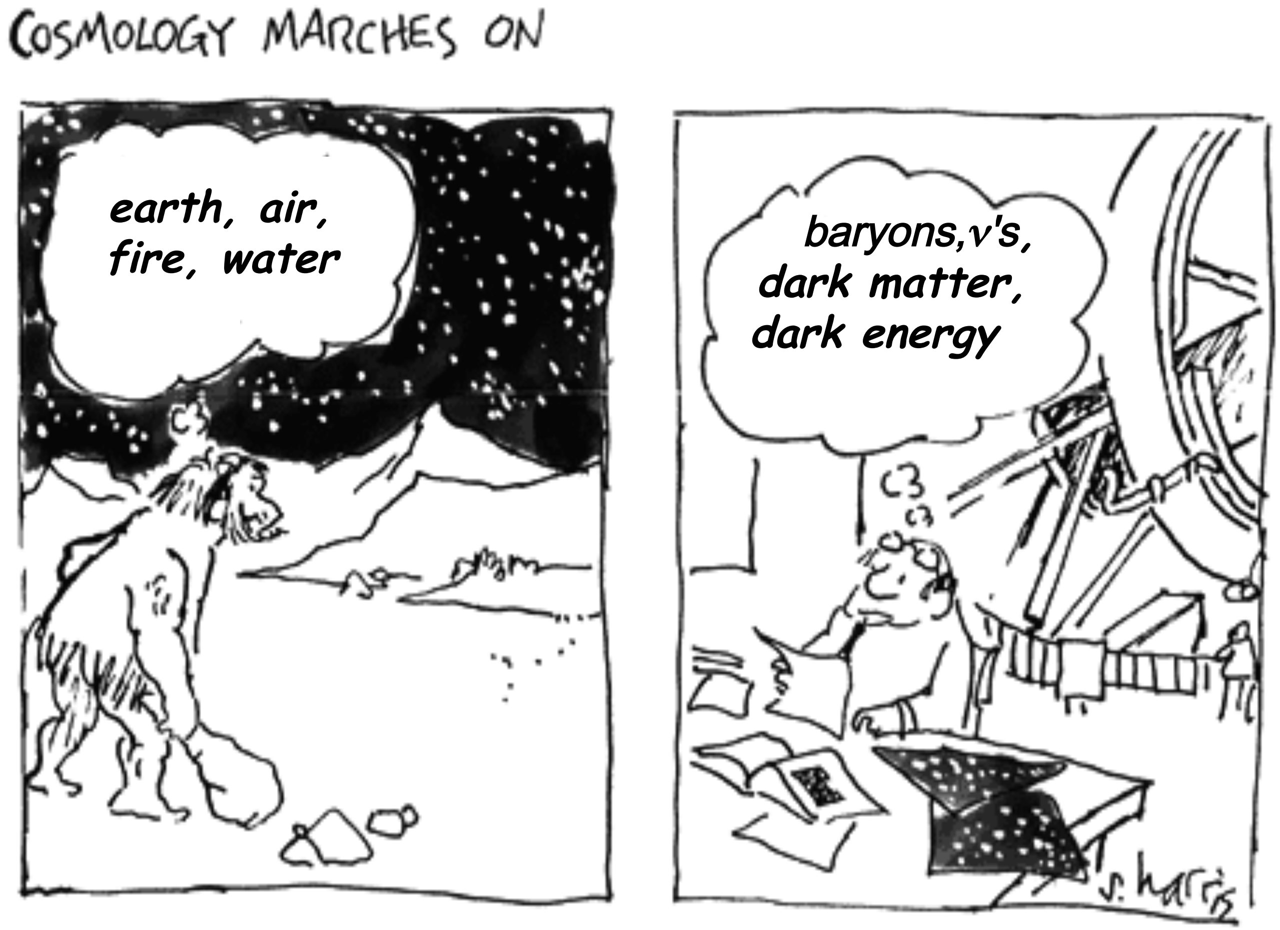


Abbiamo oggi una visione complessiva dell'Universo

Abbiamo misurato –con precisione!- il contenuto energetico dell'universo, Ω: 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, ν) e cariche elettricamente (raggi cosmici carichi...p,e-,e+, anti-p, nuclei)

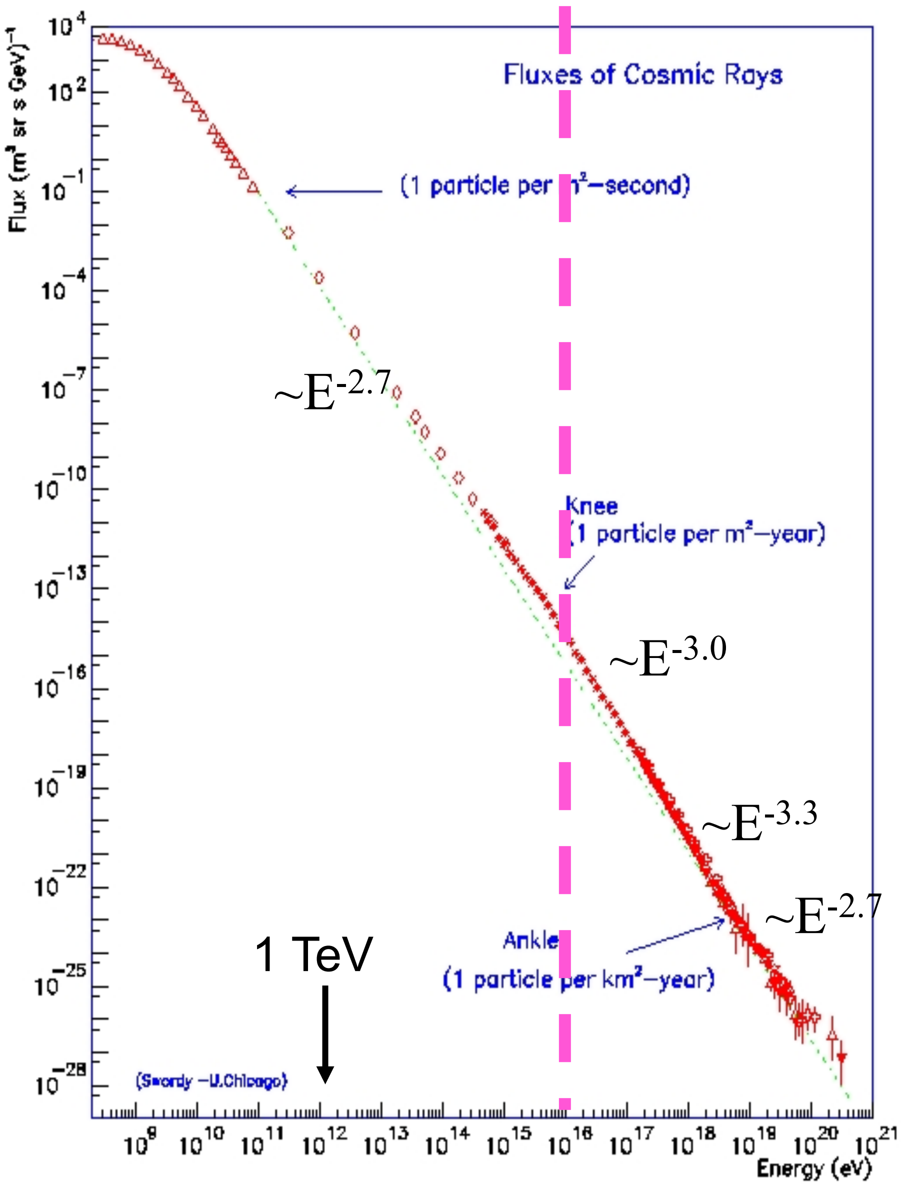
Osservabili

- 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, γ,ν → Composition
- Energy distribution → Flux and Spectrum
- Arrival Direction → Anisotropy
- Variability → Light curve

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

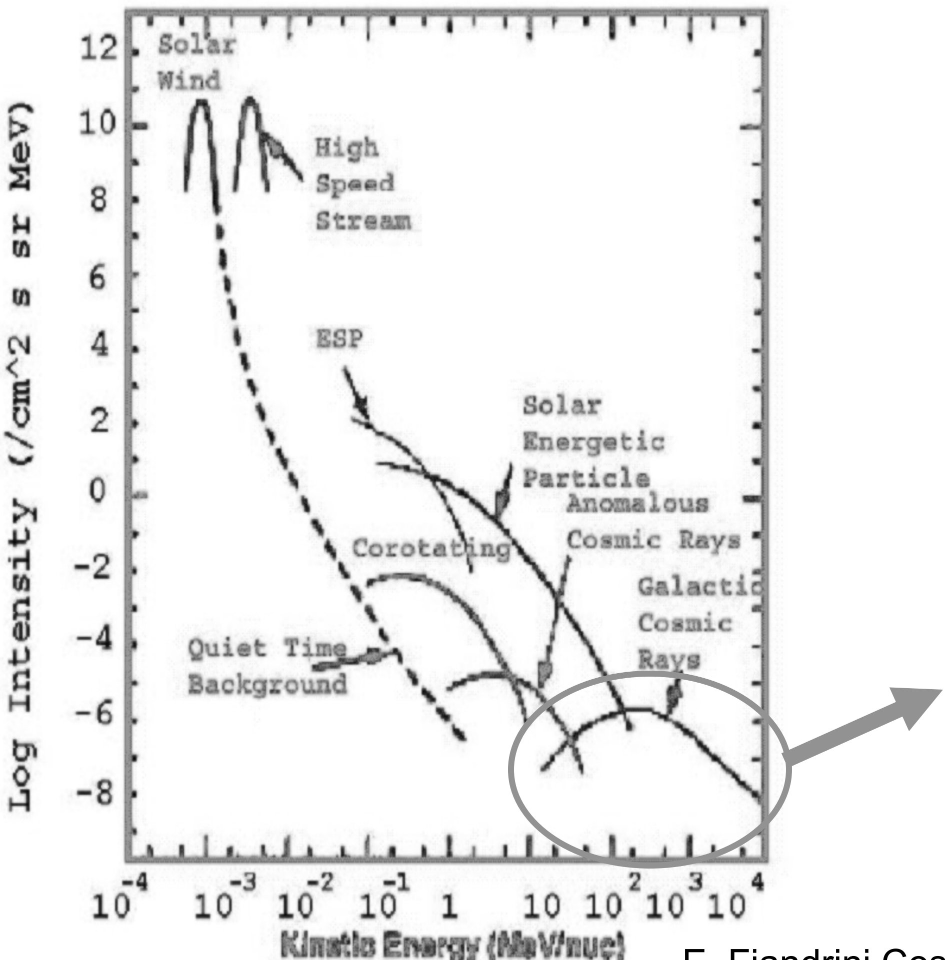
Beam calibration:

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

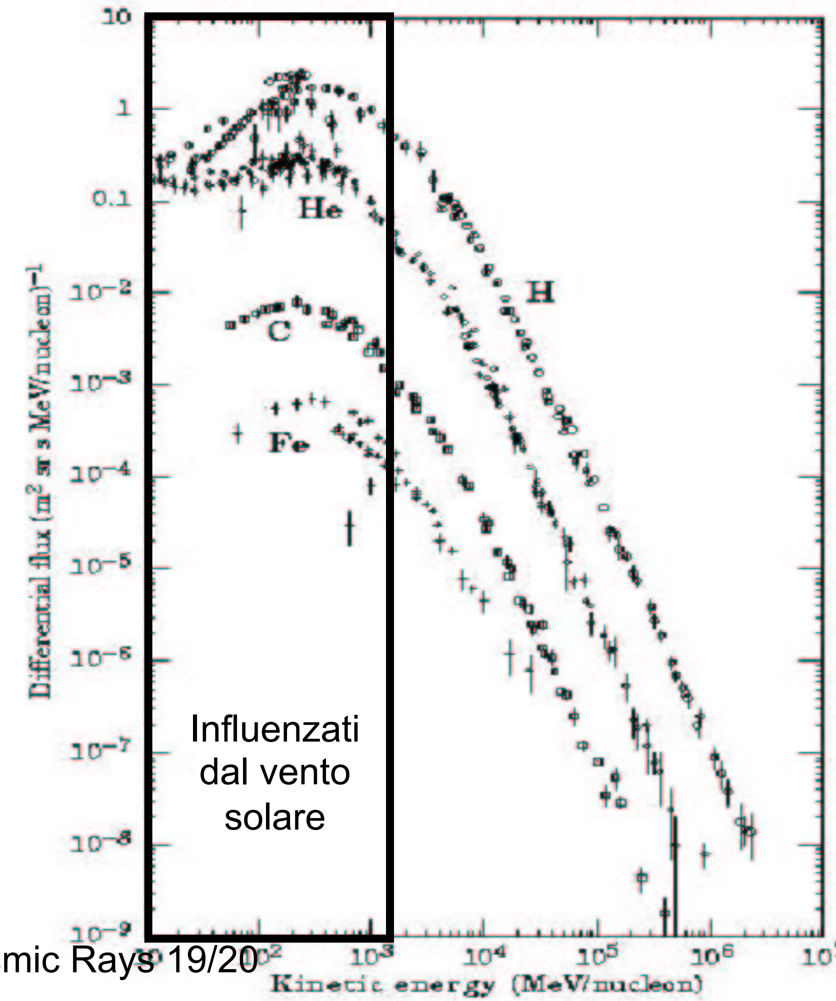
Beam Calibration = CR Propagation Models needed for accurate background evaluation of faint signal searches in CR

Cosmic ray spectra

Particles produced in the heliosphere



Galactic and extragalactic particles



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)

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 2π radians

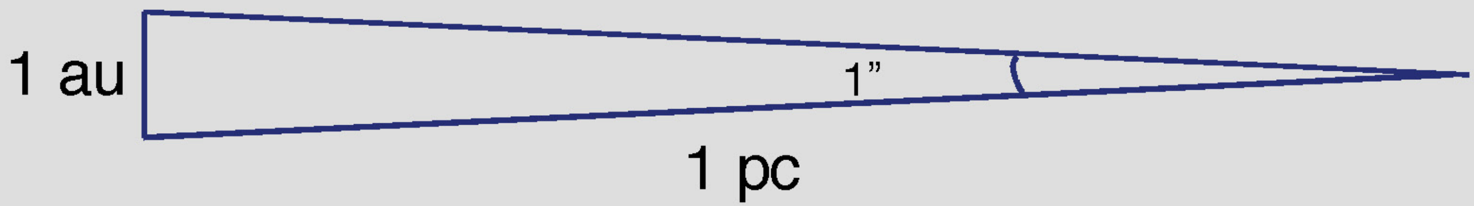
$$1^\circ = \frac{2\pi}{360} \text{ radians} = 0.01745\ldots \text{ radians}$$

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

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

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.



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

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

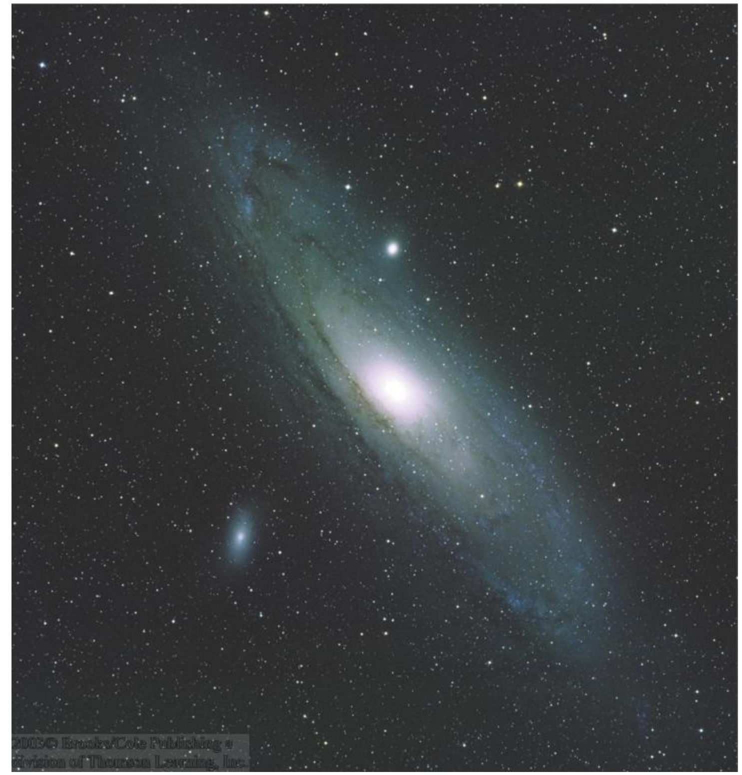
Sizes of galaxies usually measured in kpc (galaxy scales are 10-100 kpc).

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

Local environment: Milky Way

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

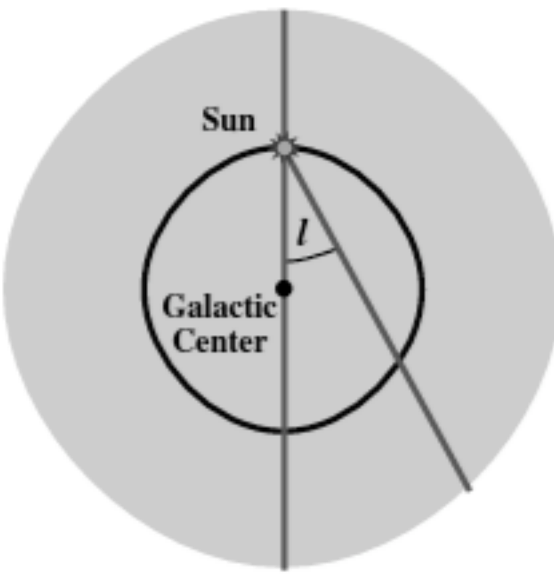
We see most of the Milky Way as a faint band of light across the sky

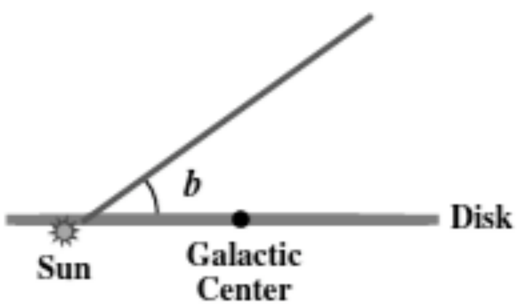


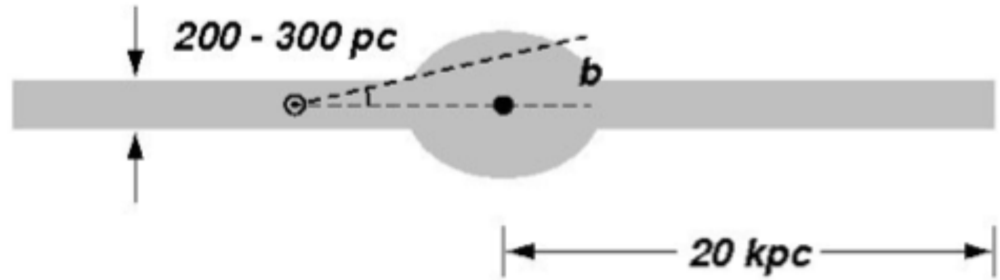
From the outside, our Milky Way might look very much like our cosmic neighbor, the Andromeda galaxy

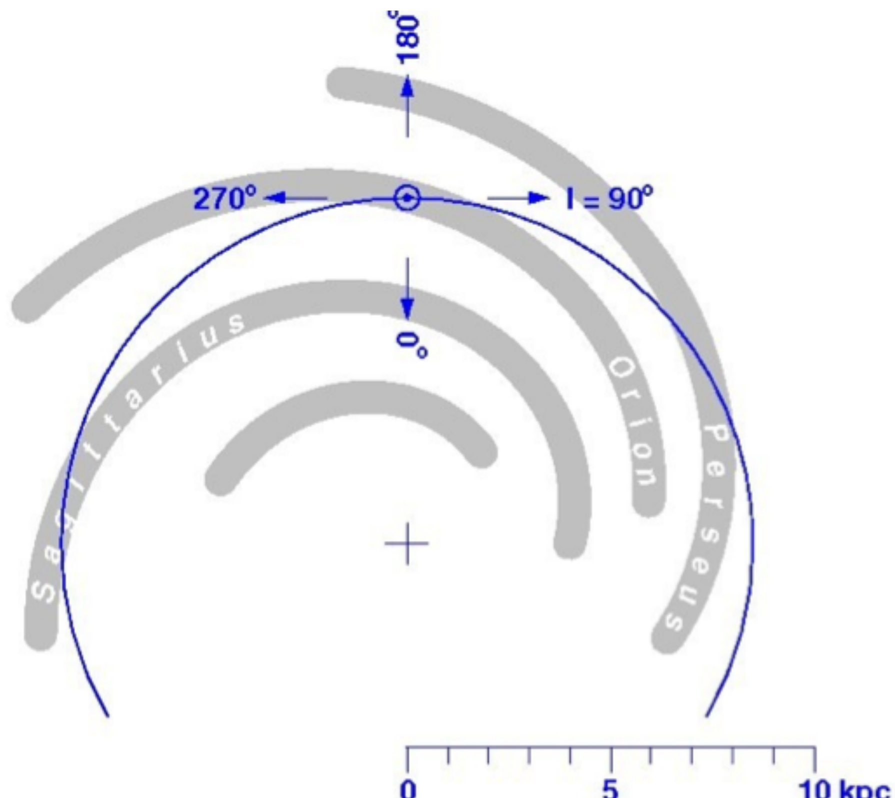
Define Galactic Coordinates
b = galactic latitude in degrees above/ below Galactic disk
l = galactic longitude in degrees from Galactic Center

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

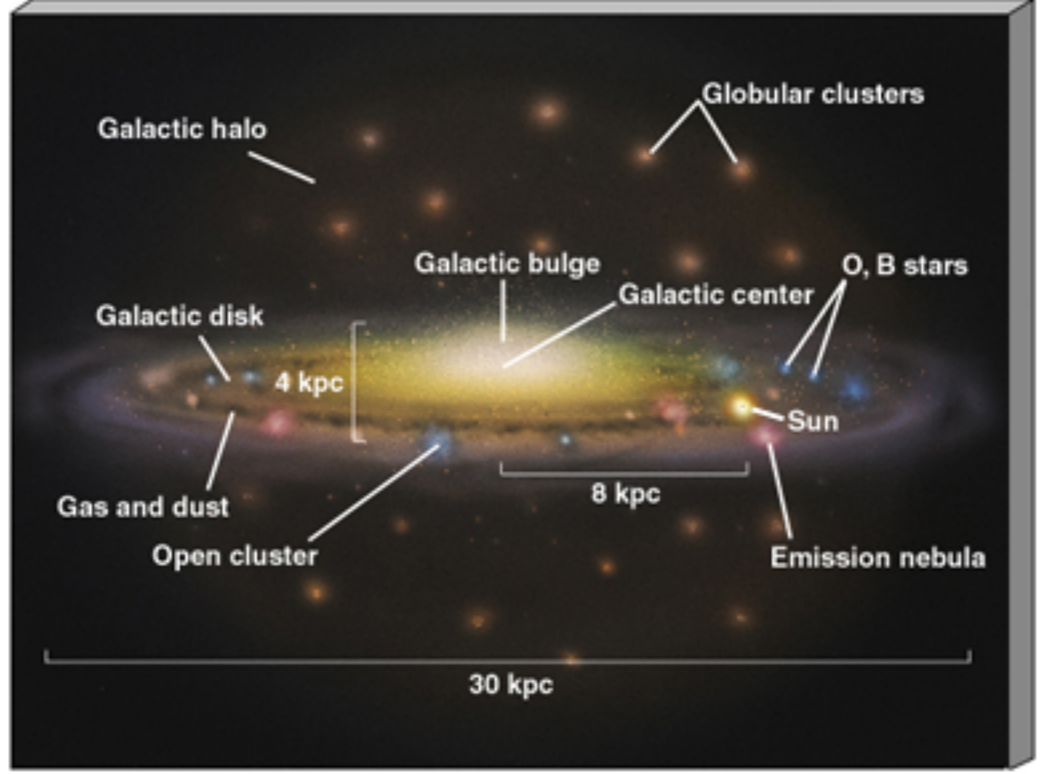
- young and old stars
- open star clusters
- gas & dust clouds (ISM)
- Magnetic fields

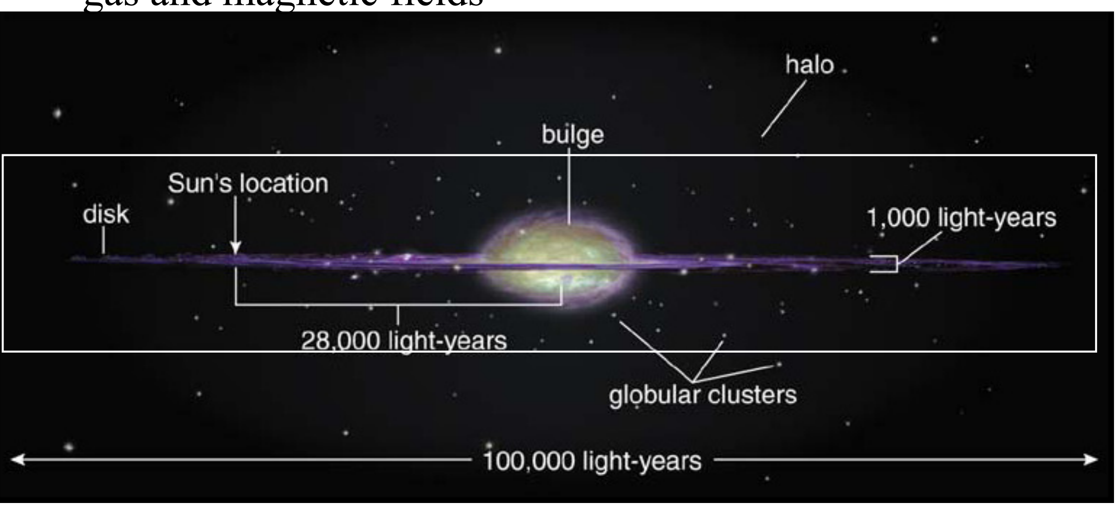
Bulge

- 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:

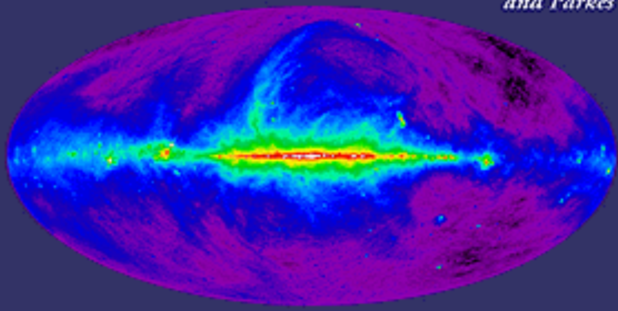
- ❑ Stars
- ❑ Dust
- ❑ Cold and hot gas of the InterStellar Medium
- ❑ Magnetic Fields
- ❑ Cosmic rays

(...and dark matter...)

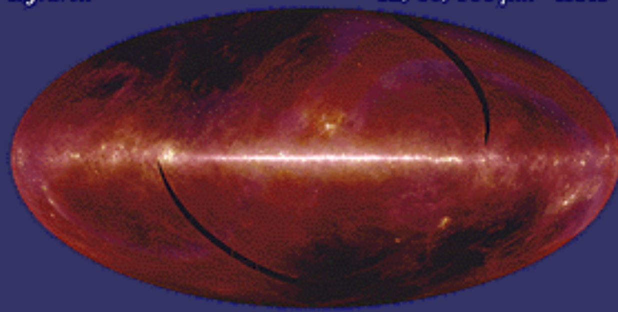
Some stars are sources of cosmic rays

Relevant for cosmic rays propagation and acceleration

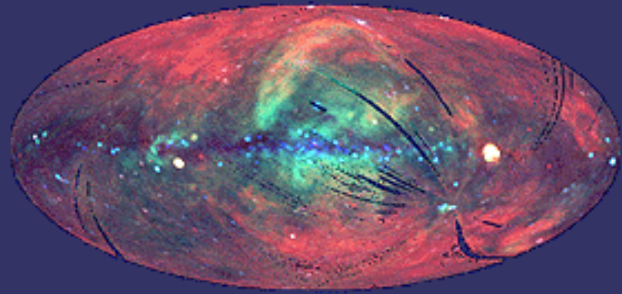
Radio Continuum (408 MHz) Bonn, Jodrell Bank, and Parkes



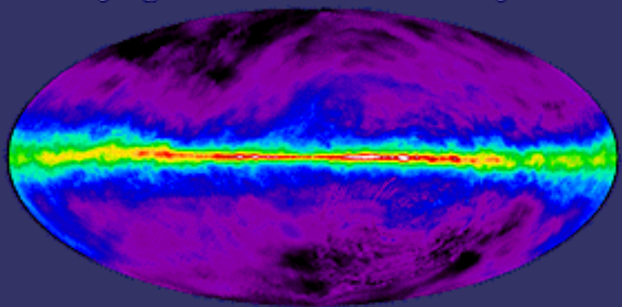
Infrared 12, 60, 100 μm IRAS



X-Ray 0.25, 0.75, 1.5 KeV ROSAT/PSPC

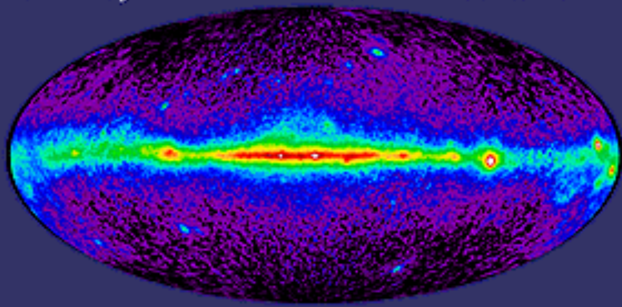


Atomic Hydrogen 21 cm Dickey-Lockman

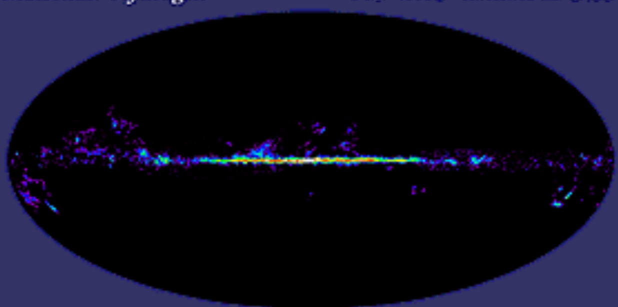


Multiwavelength vision must be used to see different components of the galaxy

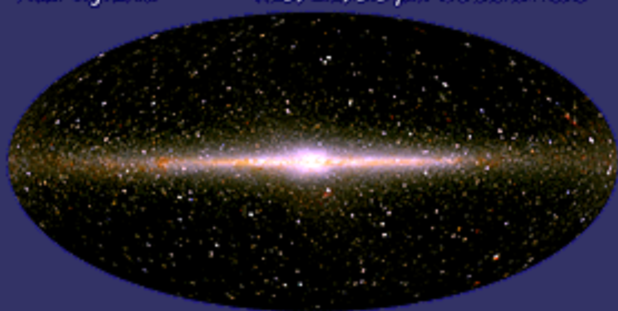
Gamma Ray >100MeV CGRO/EGRET



Molecular Hydrogen 115 GHz Columbia-GISS



Near Infrared 1.25, 2.2, 3.5 μm COBE/DIRBE

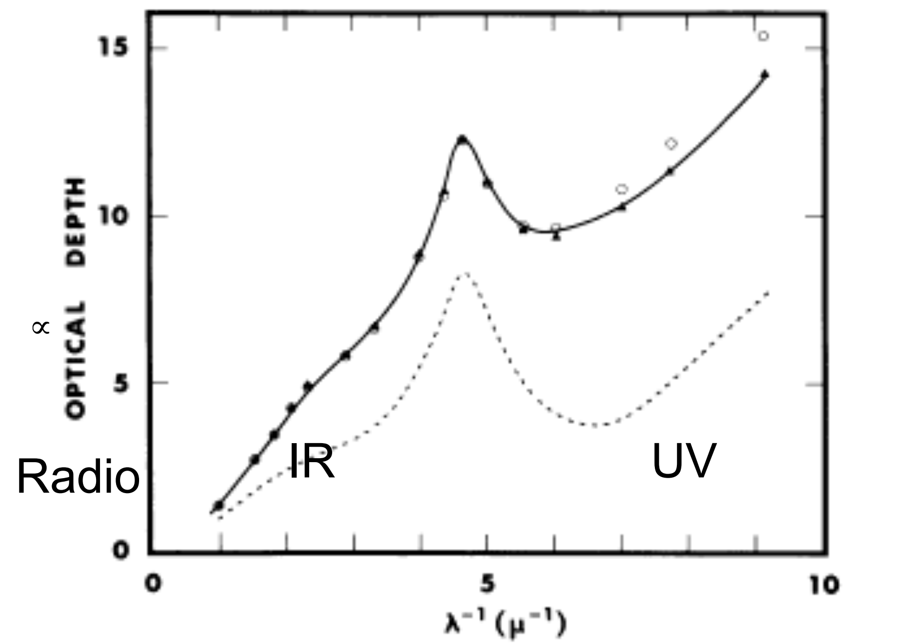


Optical A. Mellinger Photomosaic

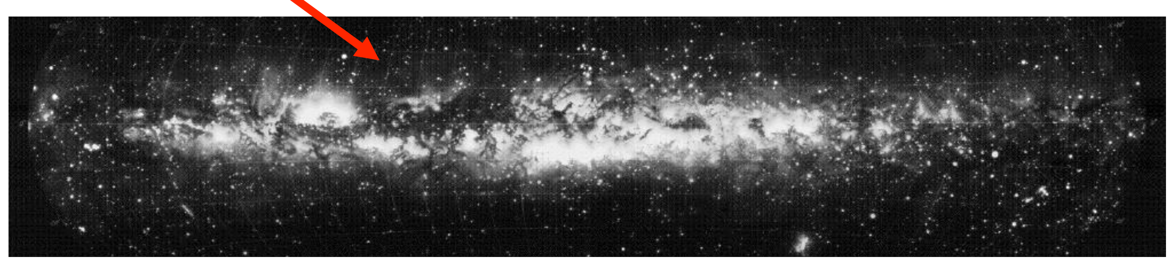
Multiwavelength needed because the optical band is obscured by the interstellar dust

- 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)

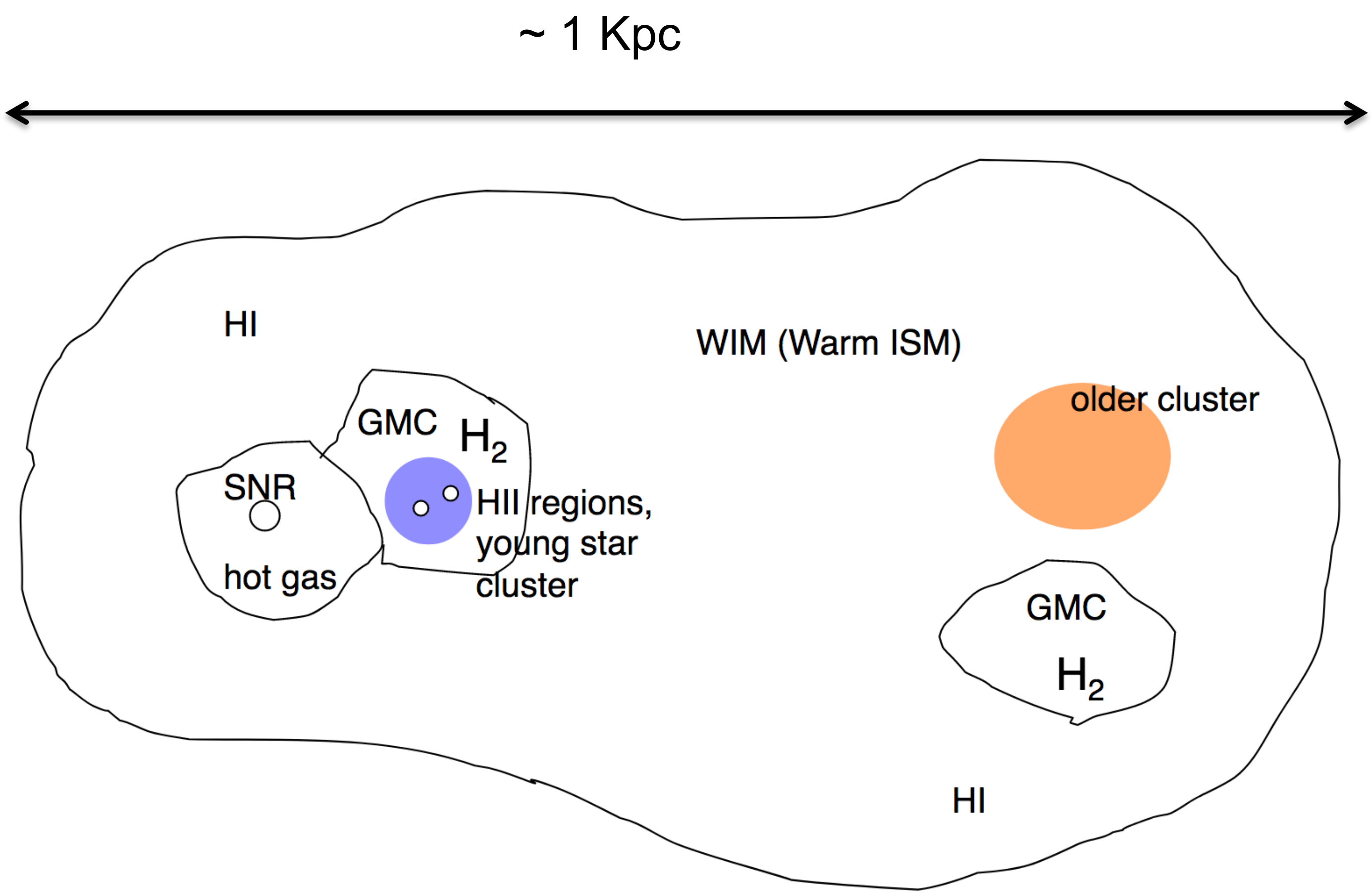
- General properties:
  - Mainly confined to galactic disks
  - Enormous range in temperature $T \sim 10\text{-}10^7$K
  - Enormous range in density $n \sim 10^{-3}\text{-}10^7$cm-3
  - Even the most dense regions are close to vacuum (cf n air~3×10^{19}cm^{-3})
  - Far from thermal equilibrium → complex 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 0.01cm^{-3}	X-ray emission
dust grains	mostly in disk $\approx 1\%$ of mass	$20...100$K size ≈ 2000Å	reddening/absorption of starlight, IR emission
magnetic fields	everywhere	μGauss	polarization of stars, Zeeman effect, synchrotron radiation
cosmic rays	everywhere	energies up to 10^{20}eV	air showers

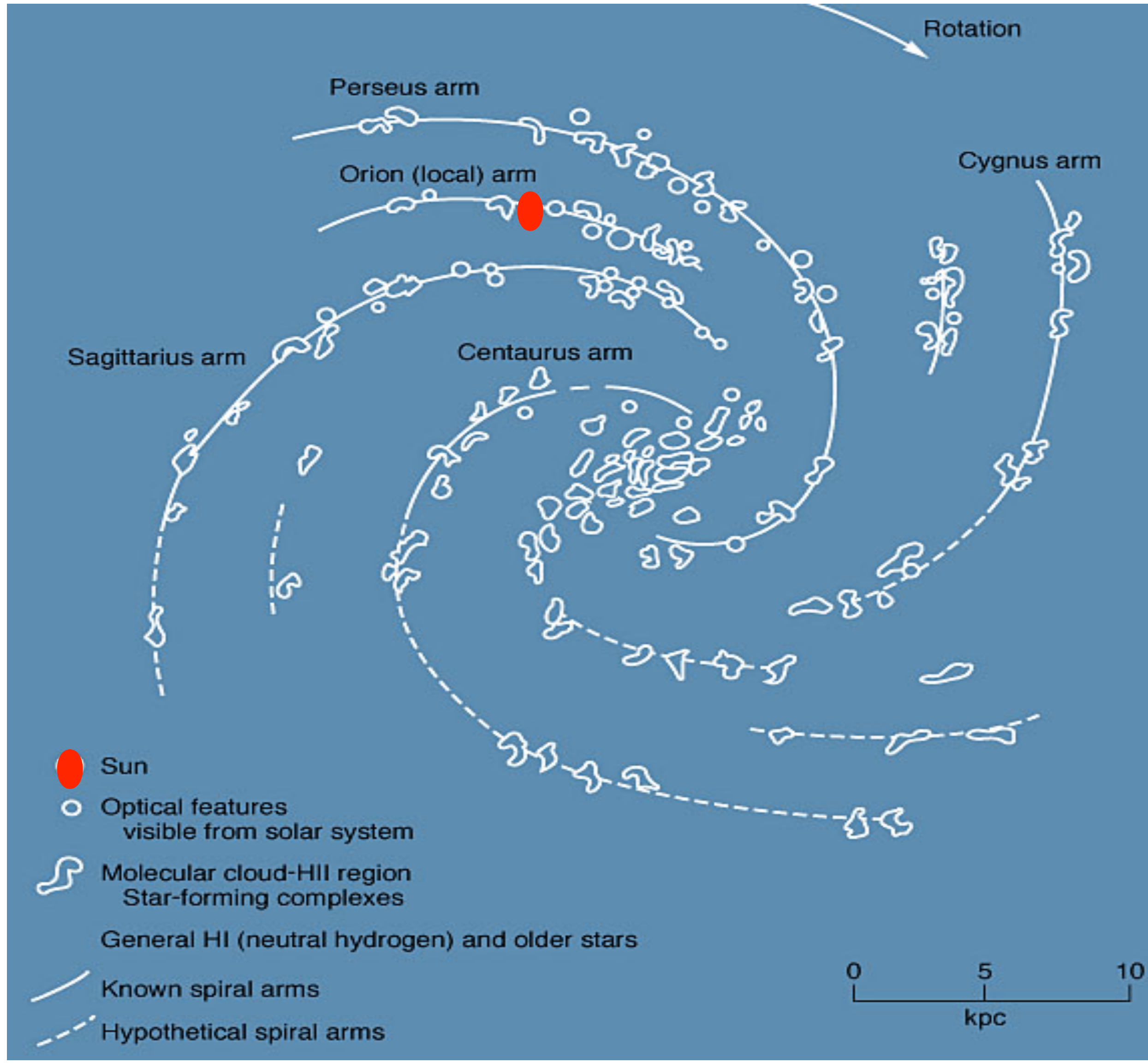
The total mass of the ISM in the Milky Way amounts to $\approx 15\%$ of the mass in stars, which is a typical value for spiral galaxies in general.

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

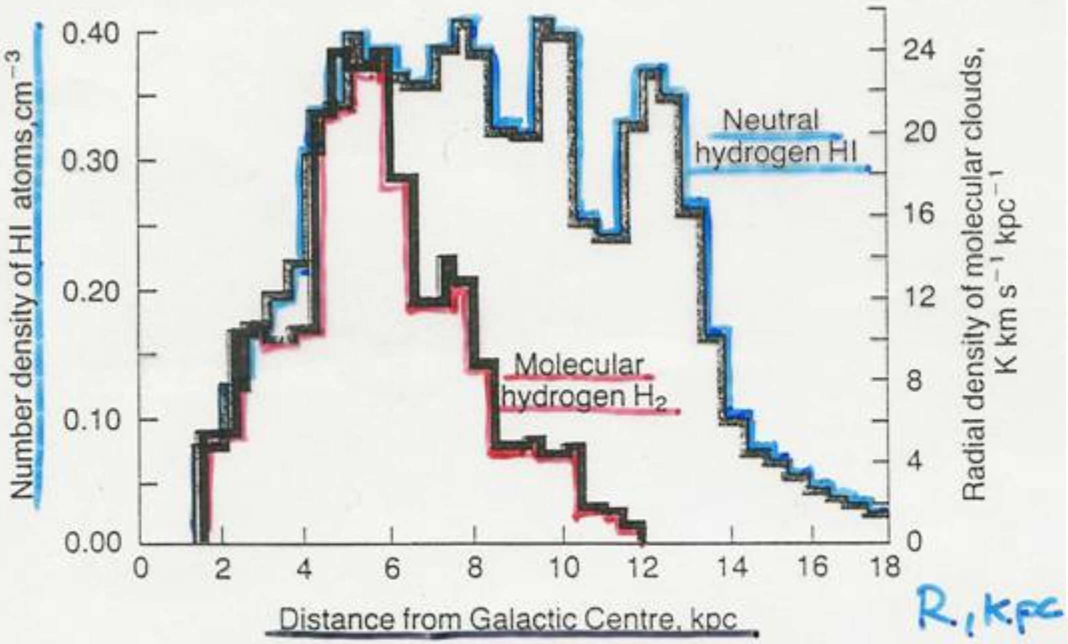


Figure 17.2. The radial distribution of atomic and molecular hydrogen as deduced from radio surveys of the Galaxy in the 21-cm line of atomic hydrogen and from millimetre surveys of the molecular emission lines of carbon monoxide, CO. (After D. Michalis and J. Binney (1981). *Galactic astronomy: structure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

$$\rho_{IG} \approx 1 \text{ p/cm}^3 = 1.6\times10^{-24} \text{ g/cm}^3$$

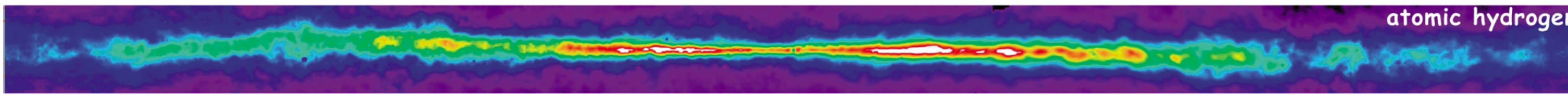
IL MEZZO INTERSTELLARE

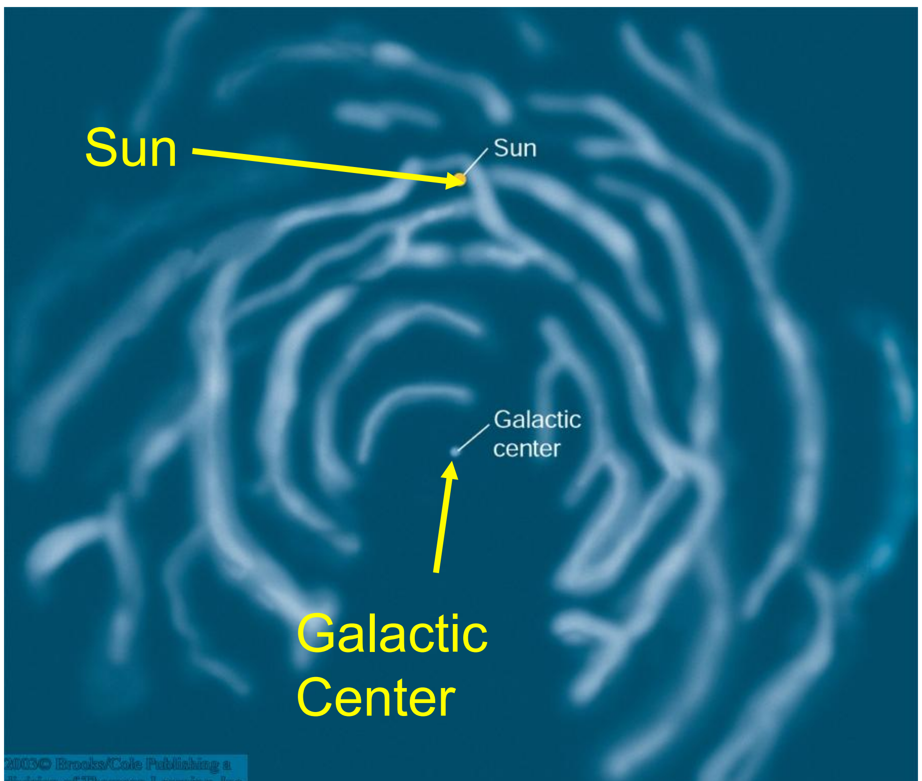
NOME	COSTITUENTI	Rivelati da...	% VOLUME e MASSA del Mezzo Int.		N cm^{-3}	T (K)
MOLECOLARI NUBI	H_2, CO, CS etc	Linee molecolari Emiss. Polveri	~0.5%	40%	1000	10
NUBI DI H NUBI DIFFUSE	H, C, O neutri	linea di 21 cm Linee Assorbim.	5%	40%	1-100	80
INTER NEBULE	H, H^+, e^- (ionizz. 10%)	21 cm + assorbim.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

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)

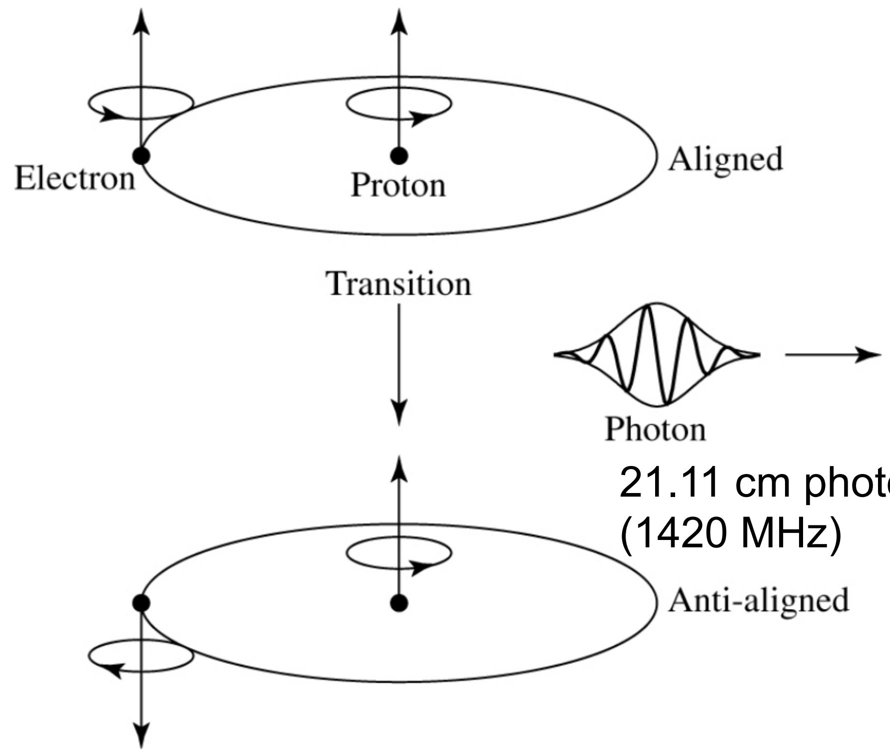
Spontaneous Transition

The lifetime in the upper state ~ 11 million years (i.e. transition probability $2.9\times10^{-15}\ s^{-1}$

…rare to happen, but many atoms

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

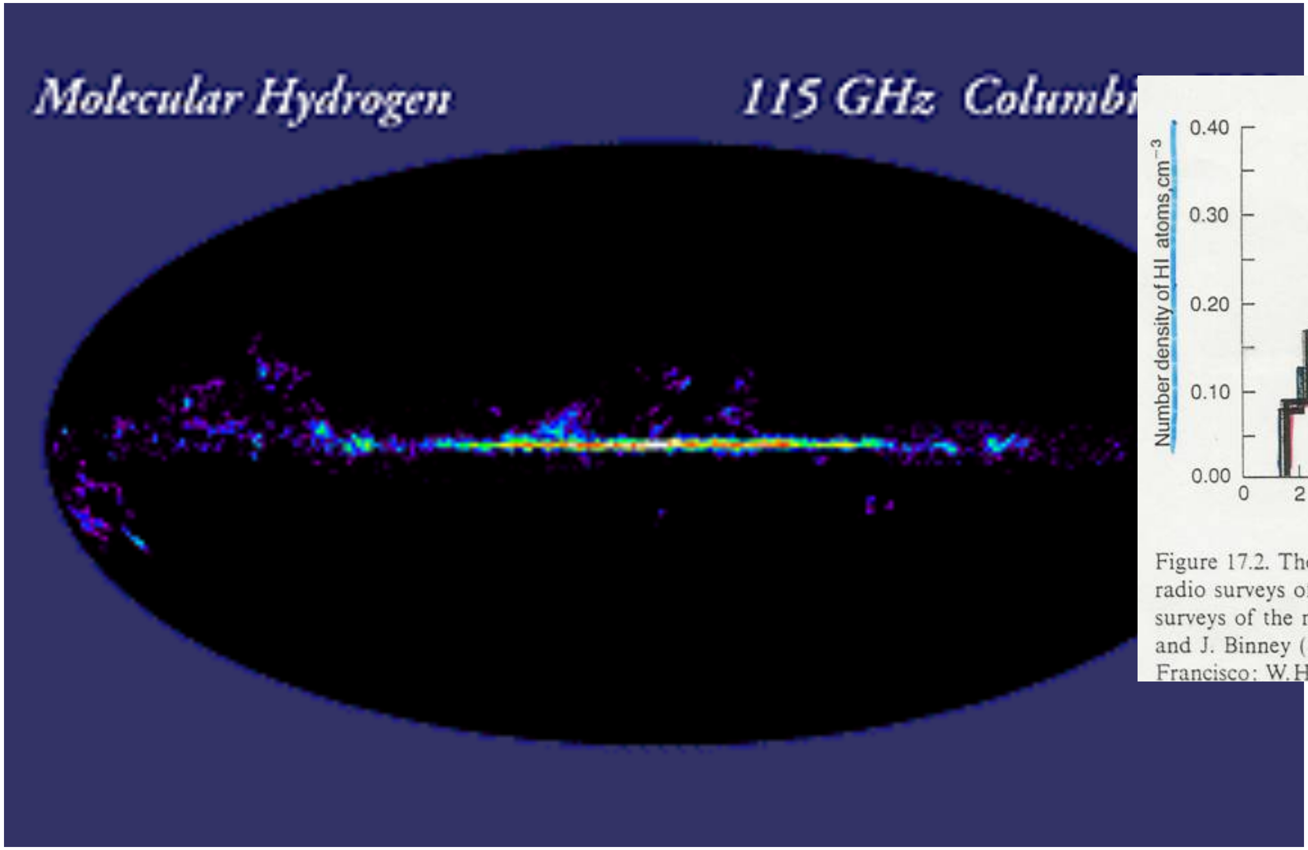
Detailed surveys of intensity and doppler shift → maps of velocity and density of HI in the galaxy



21.11 cm photon (1420 MHz)

Also used in NMR

Molecular Hydrogen H_2



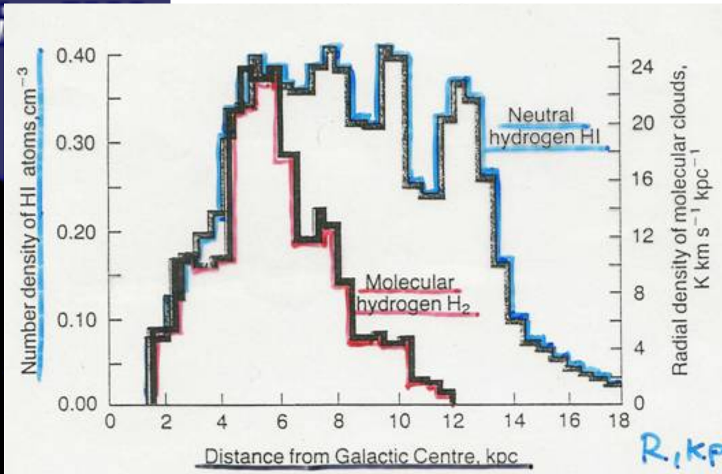
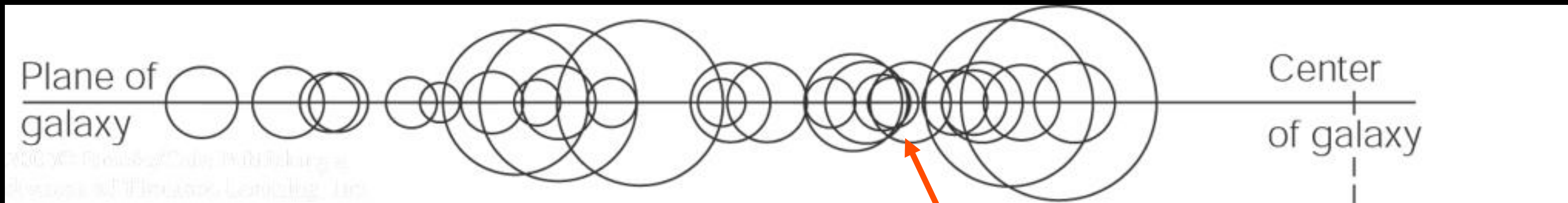


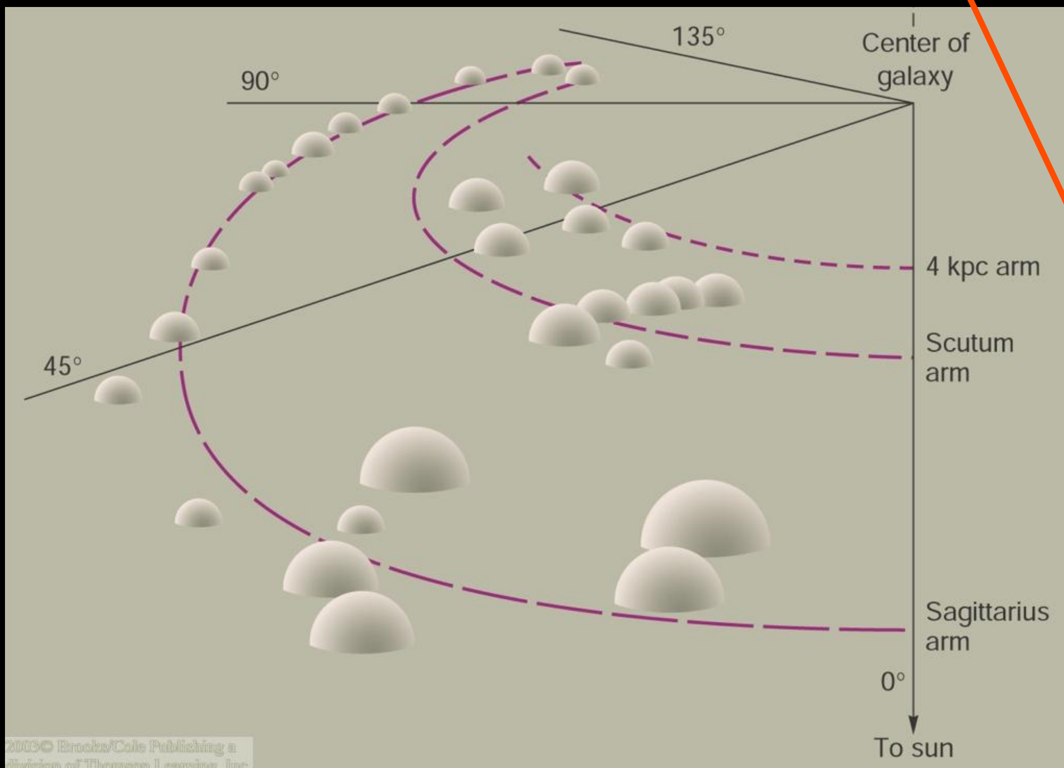
Figure 17.2. The radial distribution of atomic and molecular hydrogen radio surveys of the Galaxy in the 21-cm line of atomic hydrogen and surveys of the molecular emission lines of carbon monoxide, CO. (Aft and J. Binney (1981). *Galactic astronomy: structure and kinematics*, pp. Francisco: W.H. Freeman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

Tracing Molecular Clouds



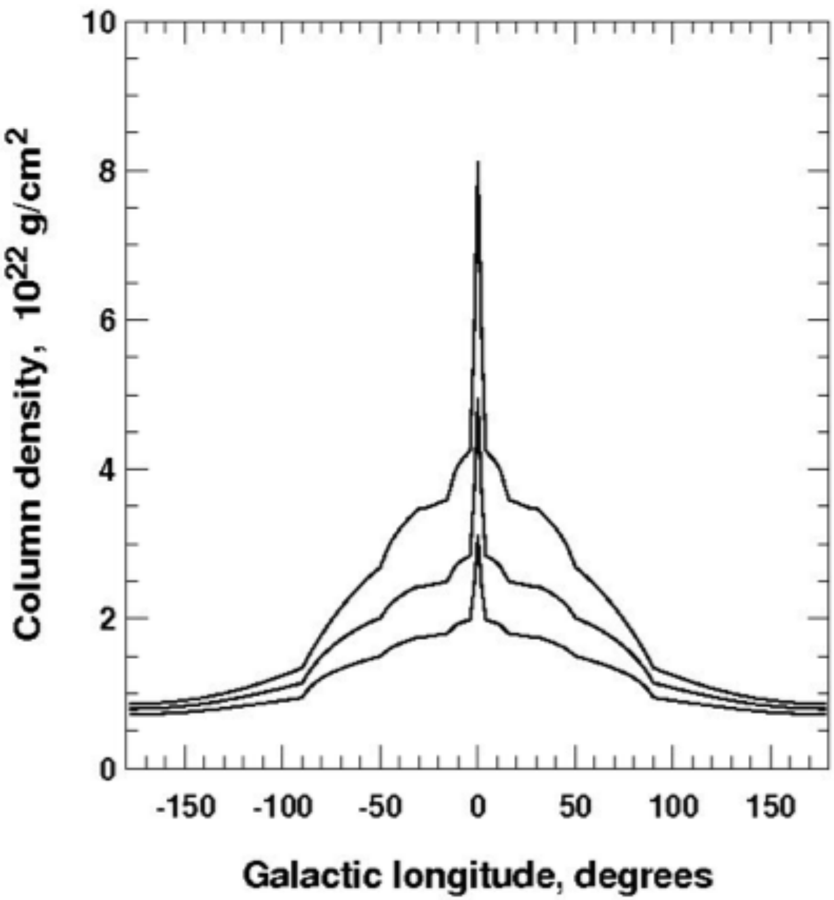


Molecular Clouds are concentrated along spiral arms

Radio emission of the CO molecule can be used to trace the distribution of molecular clouds

In some directions, many molecular clouds overlap

Clouds can be disentangled using velocity information

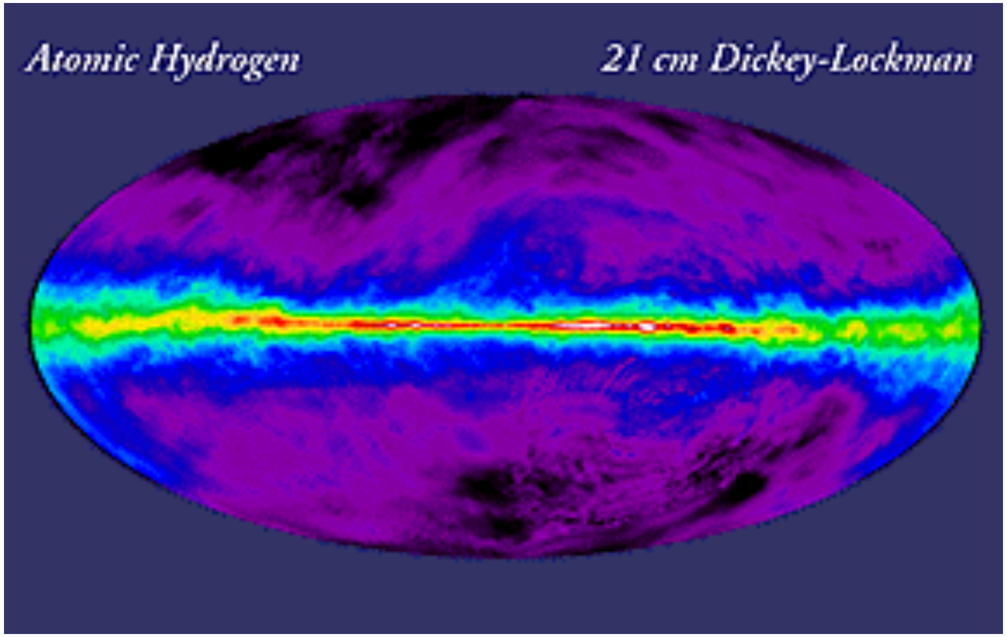


The matter density is not uniform. The sketch on the left gives an idea about the column density in the Galaxy 2, 5, and 10 deg around the galactic plane.

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 : $\sigma_c \approx 10^{-15}$ 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

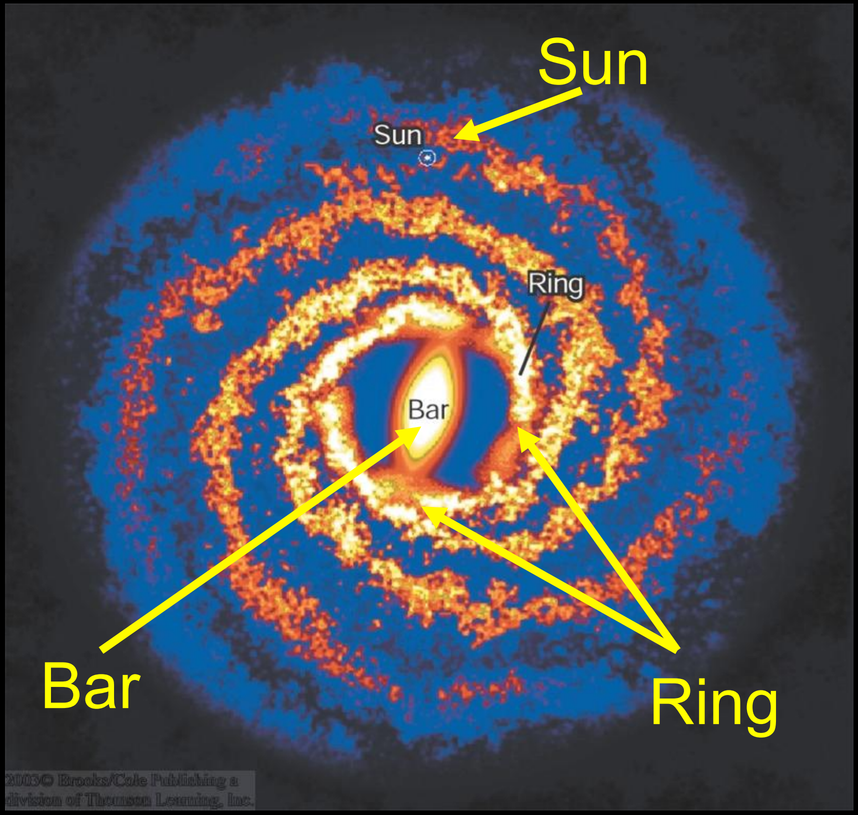
→ Most atoms will be in their ground state.

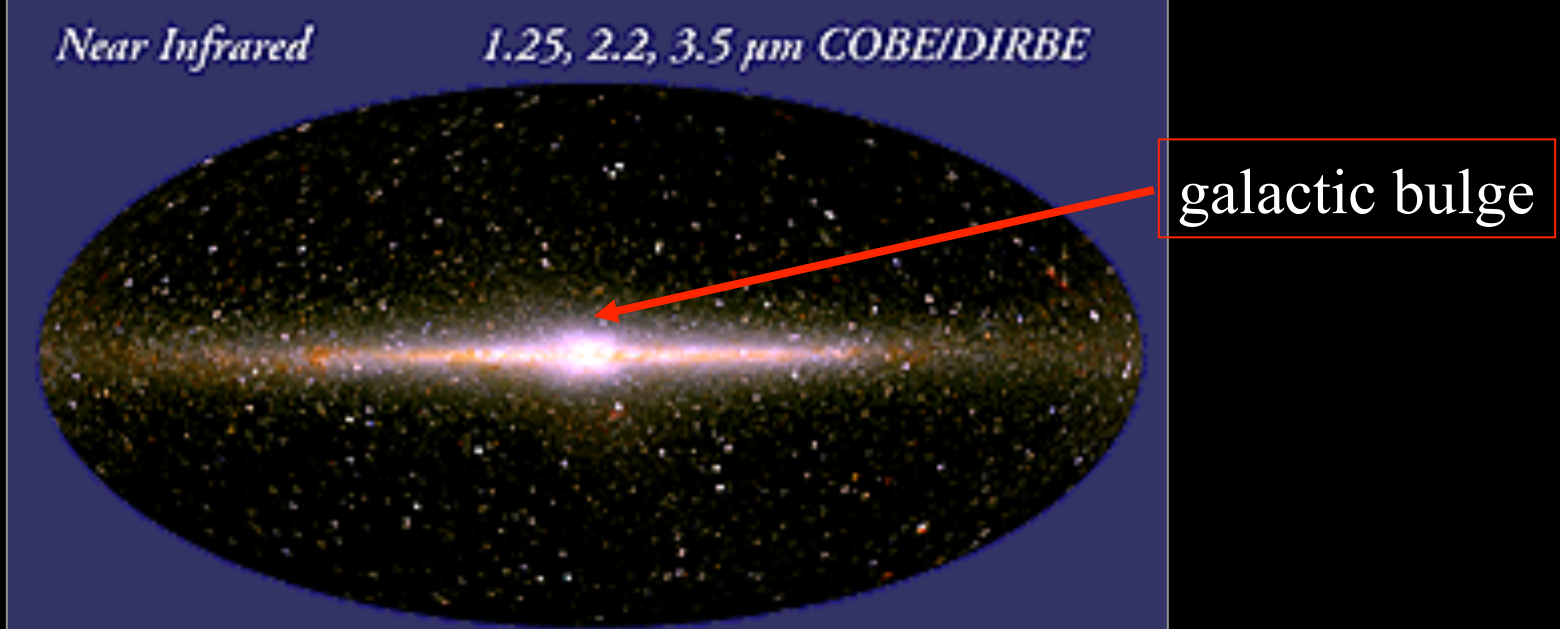
And collisions do not play any role in the gas

Structure of the Milky Way

Distribution of stars and neutral hydrogen

Distribution of dust

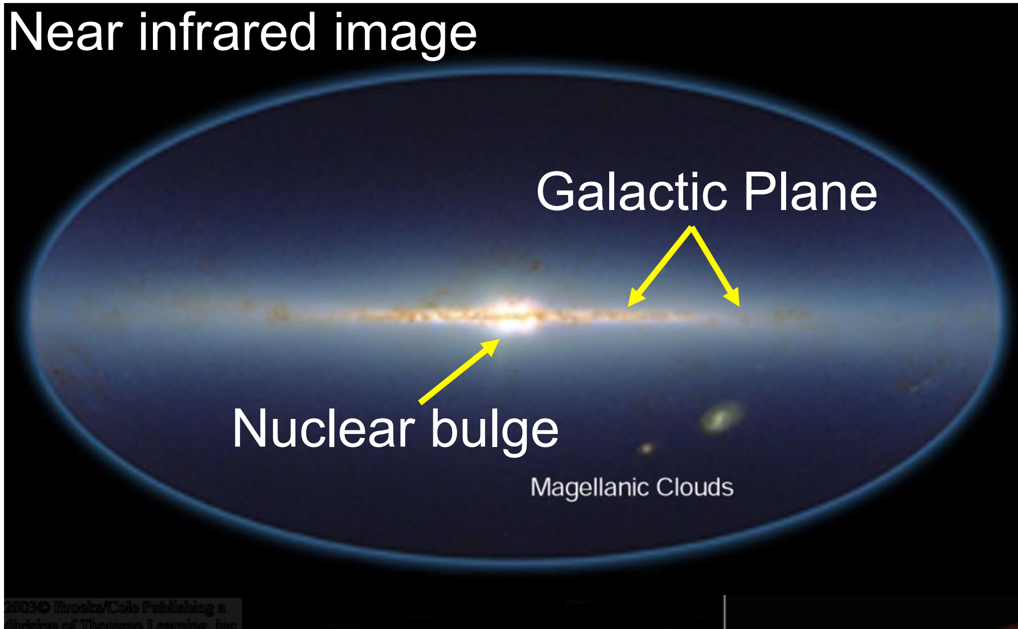




Distribution of Stars

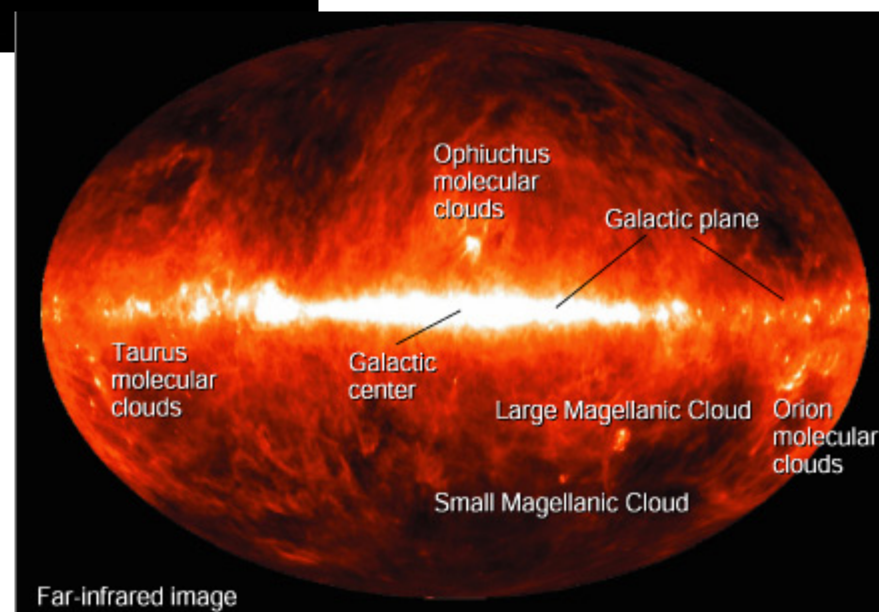
Interstellar dust is visible

Infrared View of the Milky Way

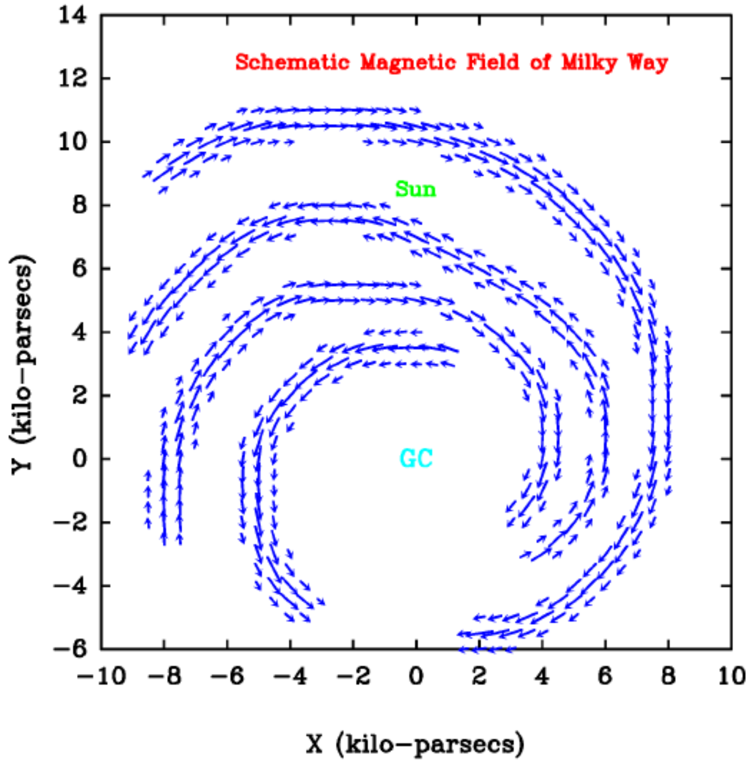


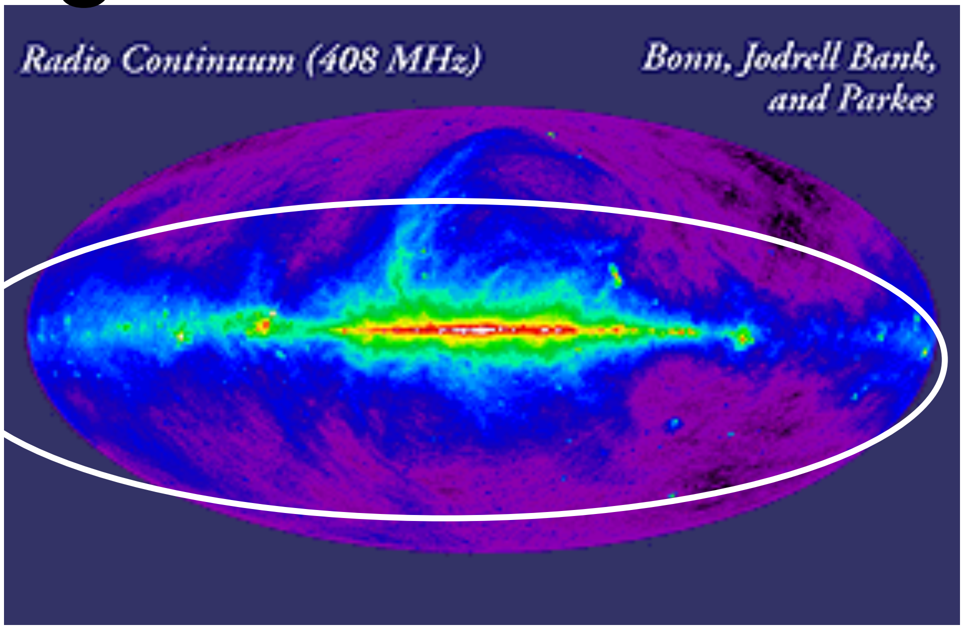
Interstellar dust (absorbing optical light) emits mostly infrared

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 x10^{-10} T(or 3 μG) (±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

- Any linearly polarized wave can be considered as a superposition of two counter-handed circularly polarized waves of the same amplitude.

- These waves have slightly different velocities while propagating through the medium (different refractive index). Hence a difference in phase appears.

- Faraday rotation is the phenomenon that rotates the orientation of wave's linear polarization while propagating in a medium with magnetic field.

- The rotation angle is directly proportional to the parallel component of the field as well as to the square of wavelength →

$$\beta = RM \cdot \lambda^2 \quad (1)$$

Faraday rotation

where RM is the Rotation Measure, a parameter which indicates the strength of the effect and depends on the numerical density of electrons and the magnetic field.

$$RM = \frac{e^3}{2\pi m_e^2 c^4} \int_0^l n_e(s) B_{\parallel}(s) dl \qquad (2)$$

- The effect caused by free electrons: the electric field of a circularly polarized wave causes circular motions of electrons which in turn yield a new field parallel or anti-parallel to the external field.
- Thus, by assuming the electron density we compute the magnetic field strength in the line-of-sight B_p .

Faraday rotation

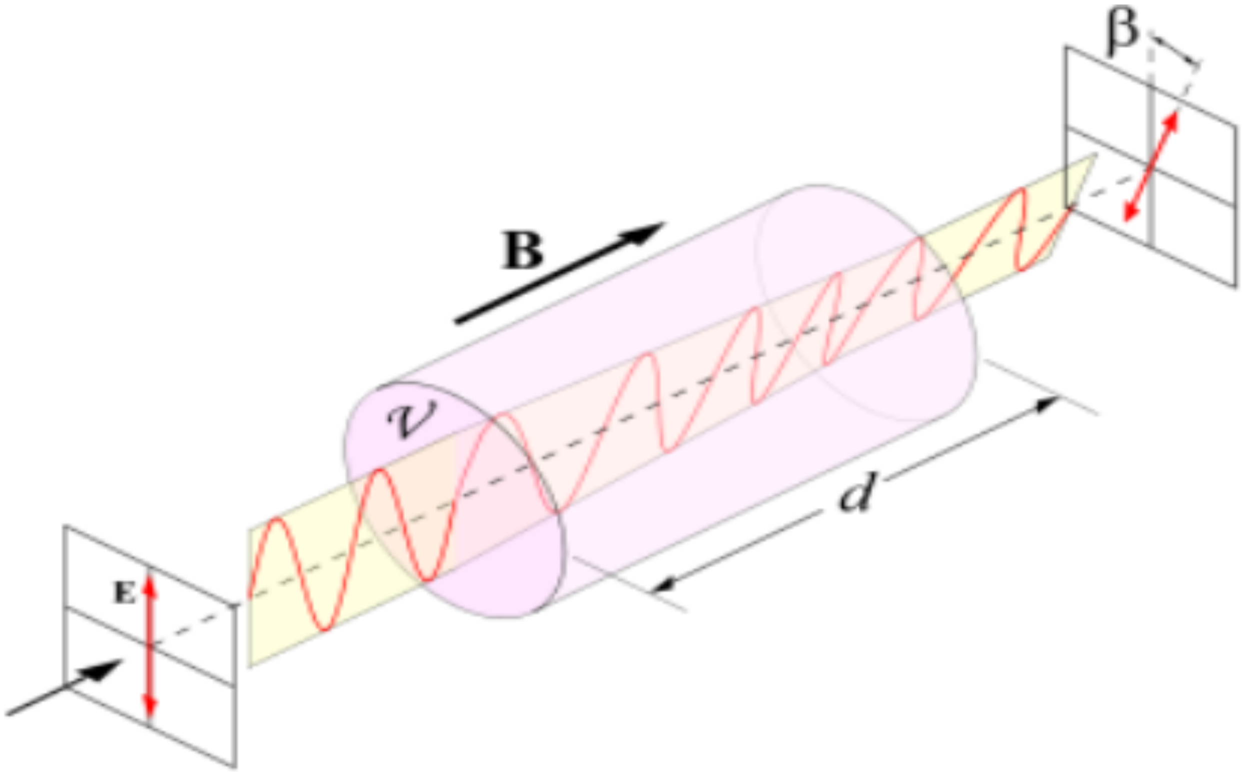


Figure 2: Faraday rotation in a magnetized gas.

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

Faraday Rotation

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

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

- 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

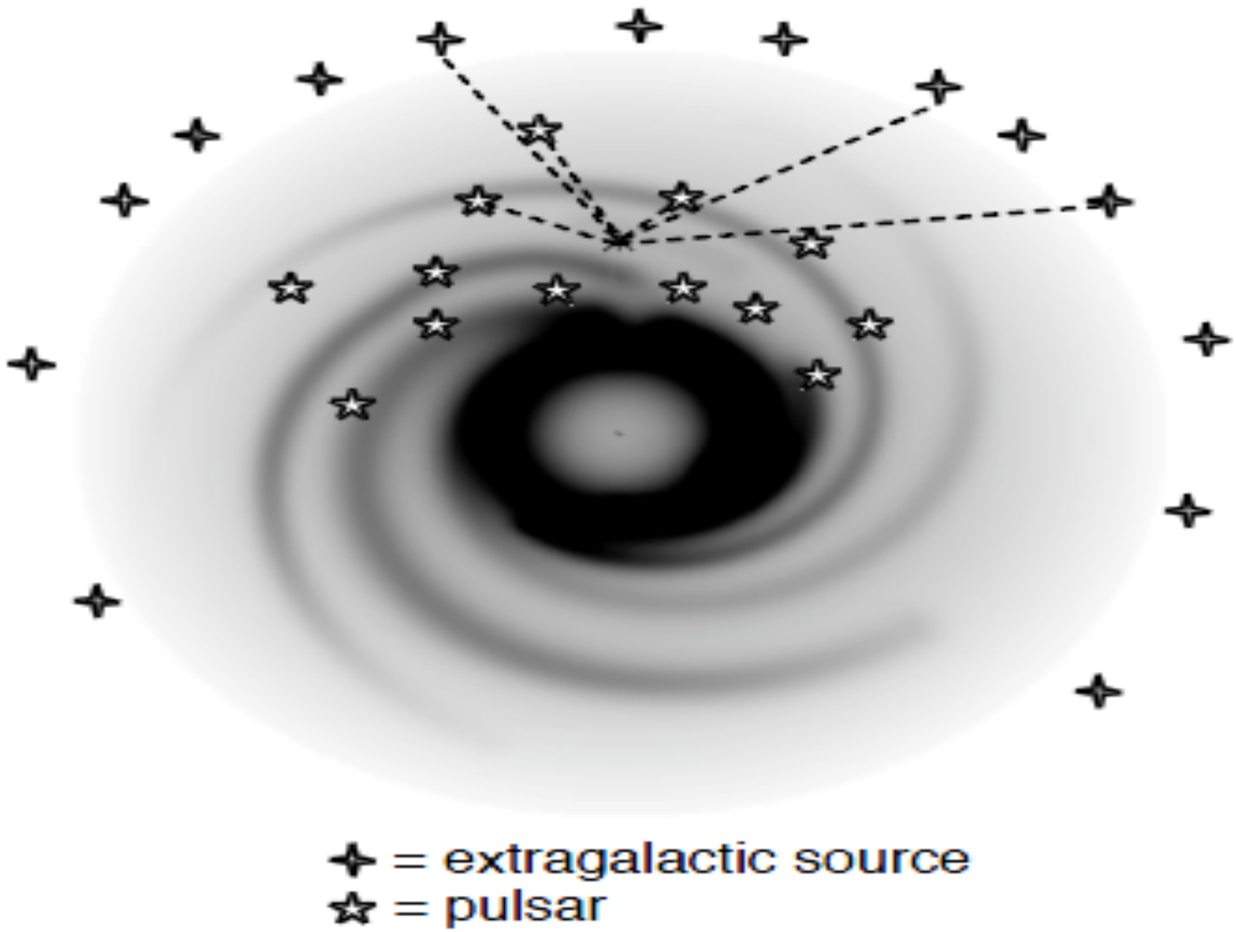
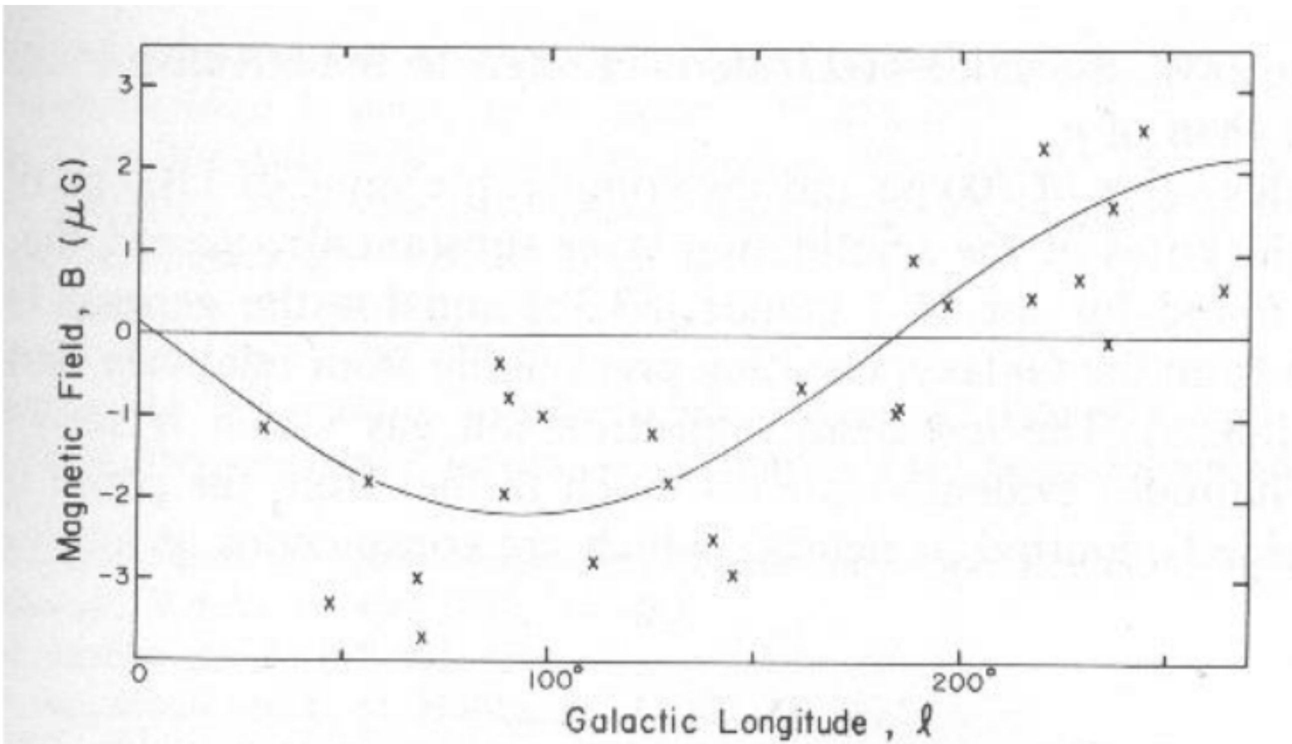


Figure 3: Pulsar and extragalactic sources distribution in our galaxy.

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.