Lecture 3 231017

- Slides will be available at:
- https://www.fisgeo.unipg.it/~fiandrin/didattica_fisica/cosmic_rays1718/

Un modello di Accelerazione dei RC con E>100TeV

L'energia massima fornita ai RC dalle SN ~ 100· Z TeV

Il ***ginocchio*** è indice di qualcosa che varia: interazioni, propagazione, sorgenti…

Consideriamo un modello a cui a variare è la sorgente: **PULSAR**

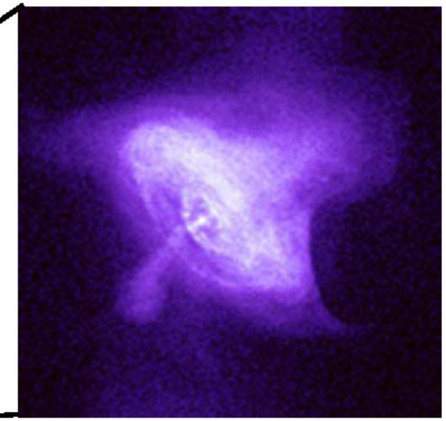
Una Pulsar è una giovane *stella di neutroni (NS)* rapidamente ruotante rispetto ad un asse.

Una NS ha un'altissima densità (quella dei nuclei), massa pari a ~1.4 $M_¤$ (massa sole), e raggio R_{NS}~10 km

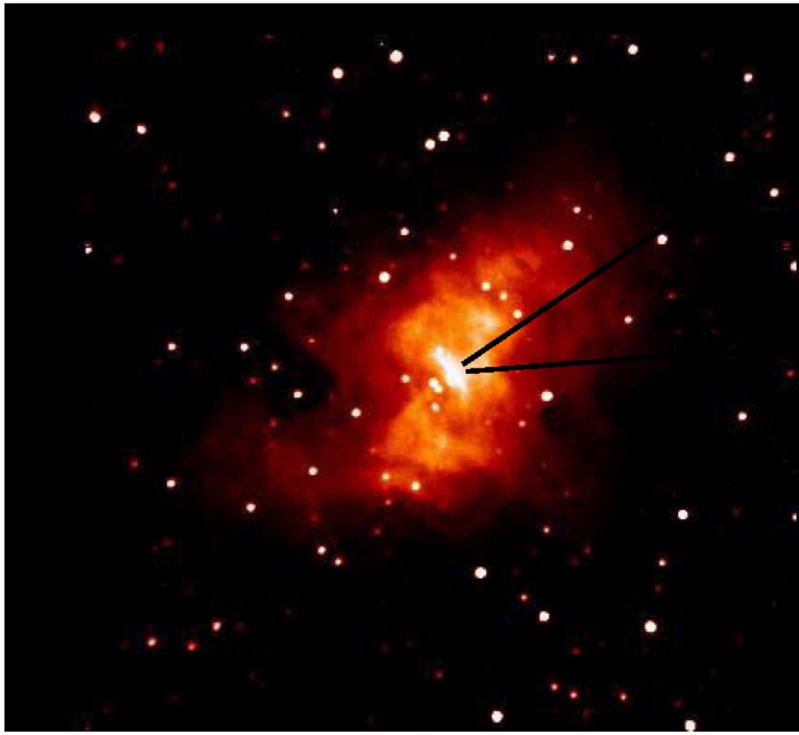
Supponendo un campo magnetico della stella prima del collasso pari a B ~ $B_¤$ ~ 10^{-2} T, per la legge di Gauss:

$$B_{NS} = B\left(\frac{R}{R_{NS}}\right)^2 \cong 10^{-2}T \cdot 10^{10} \cong 10^{8}T$$

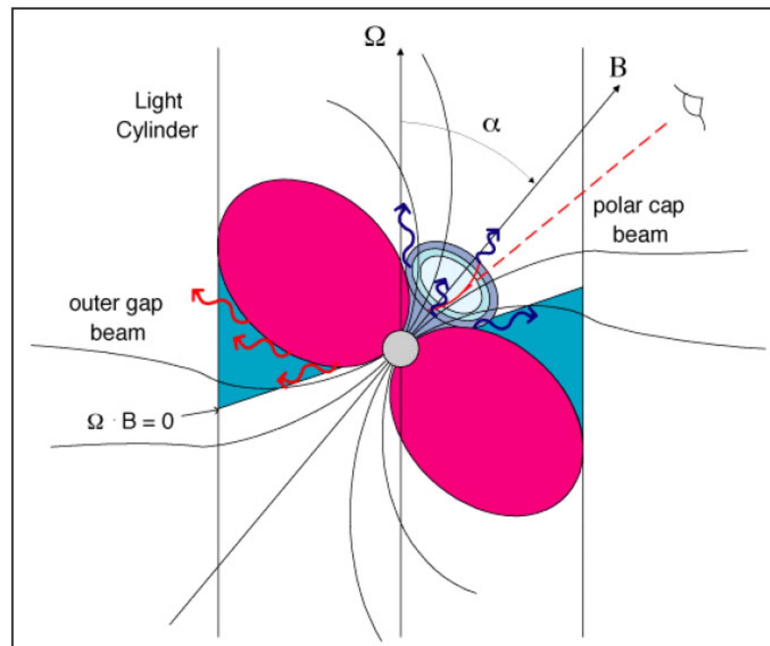
Power Source: Pulsar



Pulsar



Crab Nebula



Emitted beams

- La velocità di rotazione delle pulsar è nota sperimentalmente, e può essere facilmente stimata:

$$\frac{GM^2}{R^2} = M\omega^2_{NS}R \longrightarrow \omega_{NS} \approx 10^3 - 10^4 s^{-1}$$

La Pulsar fornisce energia tramite induzione EM.

L'energia massima fornita ad una particella di carica Ze:

$$\nabla \times \varepsilon = -\frac{1}{c}\frac{\partial B}{\partial t} \longrightarrow \frac{\varepsilon}{L} = \frac{B\omega_o}{c}$$

(ε = campo elettrico indotto su una regione lineare L)

$$E_{Max} = \int Ze \cdot \varepsilon \cdot dx = Ze \cdot B\omega_o L \cdot L / c$$

PULSAR: Massima energia acquisita dalla particella accelerata nel caso di p (Z=1), $B=10^8$ T, $\omega=10^3$ s^{-1}, R=10 km

$$E_{Max} = Ze \cdot B\omega_o L^2 / c =$$

$$= 1.6\times 10^{-19}(C)\cdot 10^8(T)\cdot 10^3(s^{-1})\cdot\left[10^4(m)\right]^2$$

$$= 1.6(J) = 10^{19} eV$$

Potenza richiesta per i RC di energia > 1000 TeV

- Possono poche Pulsar nella Galassia alimentare i RC di energia compresa tra $10^{15}<E_o<10^{19}$ eV?
- Potenza richiesta per un flusso stazionario:

$$P(>E_o) = \frac{\rho_{CR}(>E_o)\cdot V_G}{\tau_F(>E_o)}$$

Stima del tempo di permanenza per $E_o>10^{14}$ eV

$$\tau_F(>100TeV) = \tau_F(>100GeV)\cdot\left(\frac{100GeV}{100TeV}\right)^{+0.6} \approx 10^5\, y$$

La densità di energia:

$$\rho_{cr}(>100TeV) \cong 10^{-4}\, eV/cm^3$$

Da cui possiamo stimare:

$$P(>100TeV) = \frac{\rho_{cr}(>100TeV)\cdot V_G}{\tau_F(>100TeV)} \cong 2\cdot 10^{38}\, erg/s$$

Una sorgente di tale "potenza" può alimentare tutto il flusso di RC galattici nell'intervallo $10^{14}<E_o<10^{19}$. ***E' plausibile?***

Luminosità osservata in r-X

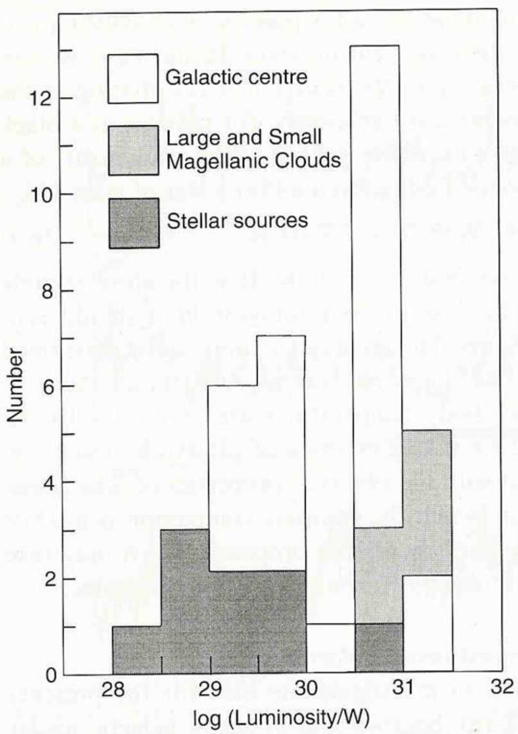


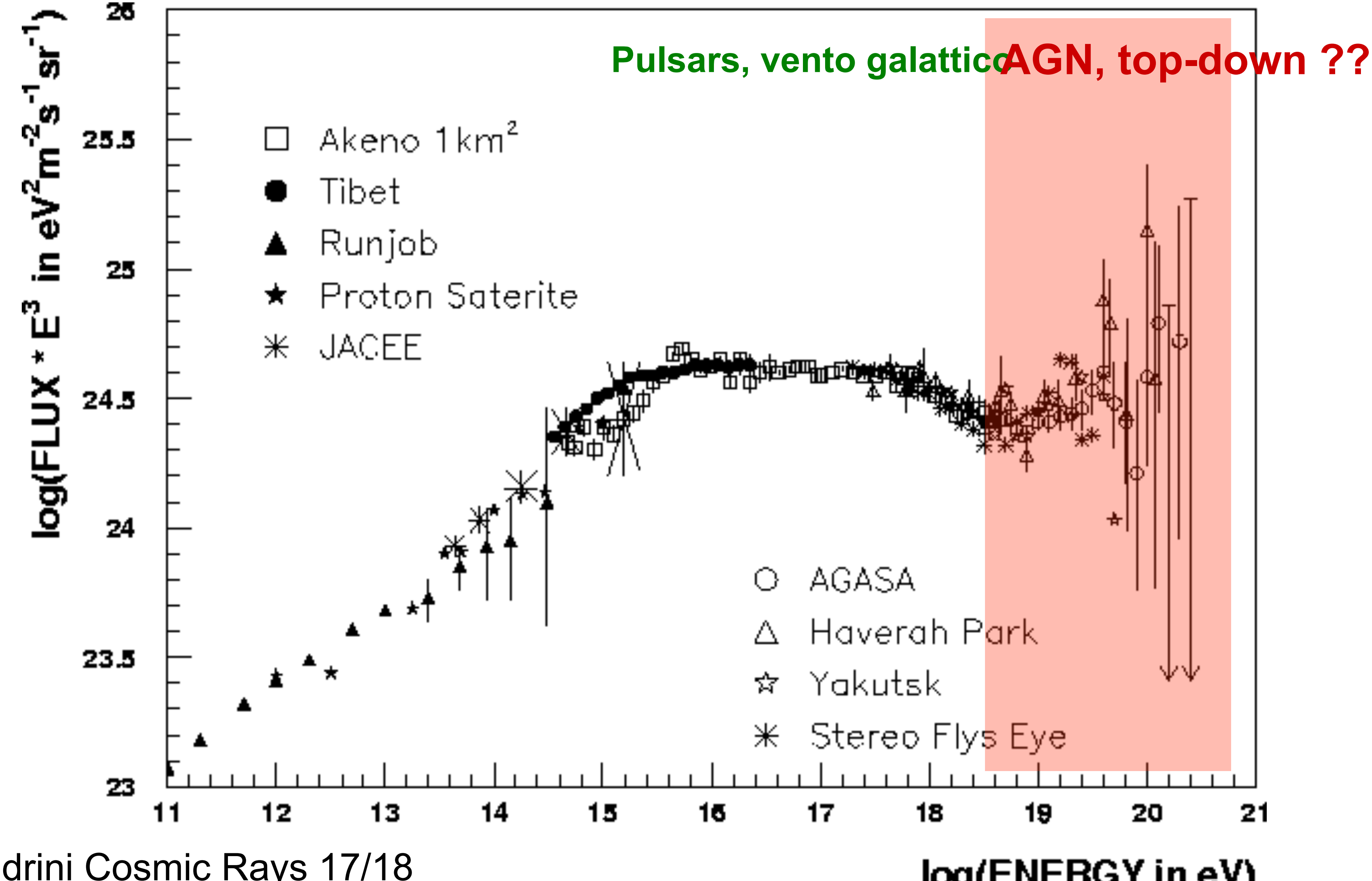
Figure 16.2. A histogram of the X-ray luminosities of bright X-ray sources in the 1–10 keV energy band in our Galaxy and the Magellanic Clouds. The Eddington limiting luminosity for a $1M_{\odot}$ object is 1.3×10^{31} W. (After B. Margon and J.P. Ostriker (1973). *Astrophys. J.*, **186**, 91.)

Le sorgenti binarie di r-X hanno una potenza rivelata dell'ordine di 10^{38} erg/s

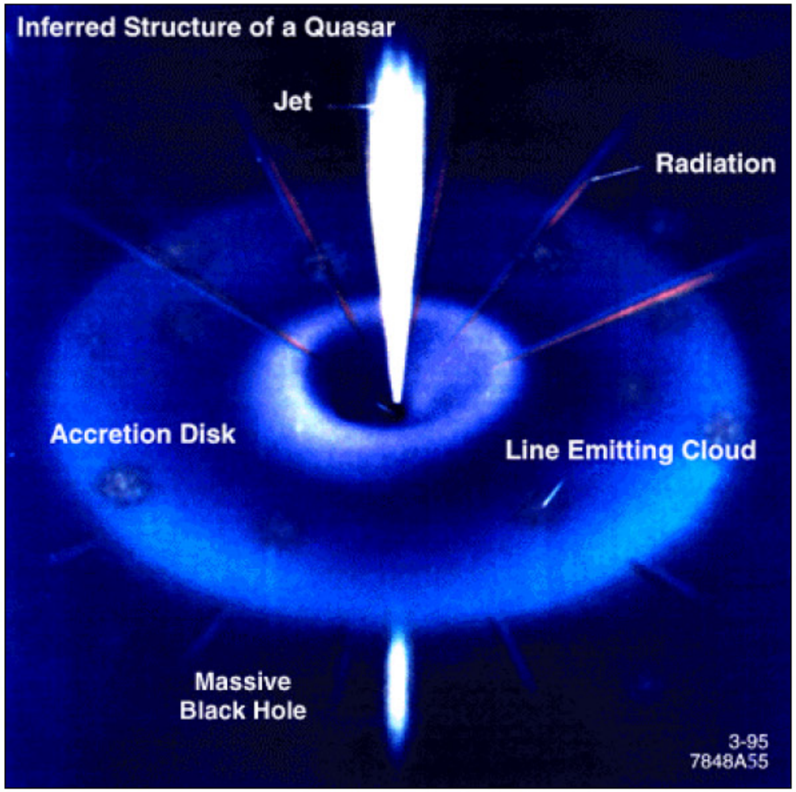
E' plausibile che (poche) sorgenti così potenti possano fornire la stessa quantità di energia sotto forma di RC di E>1000 TeV

Attenzione: le pulsar hanno una vita media stimata di circa 10^7 anni.

I RC di Energia Estrema >10^{18} Ev (Extragalattici?)



Power Source: BH Accretion



AGN model

- AGN are likely powered by accretion onto BH's of mass between $10^6 - 10^9$ solar masses.
- Matter falling in towards BH piles up in a rotating accretion disk.
- Released energy powers a broad spectrum of strong emission and jets of relativistic outflow.

Confinamento dei RC E>10^{19} eV (richiamo)

- Confinamento dovuto al campo magnetico Galattico. Il raggio di curvatura di un nucleo di carica (Ze) in B:

$$mv^2/r = pv/r = ZevB/c$$

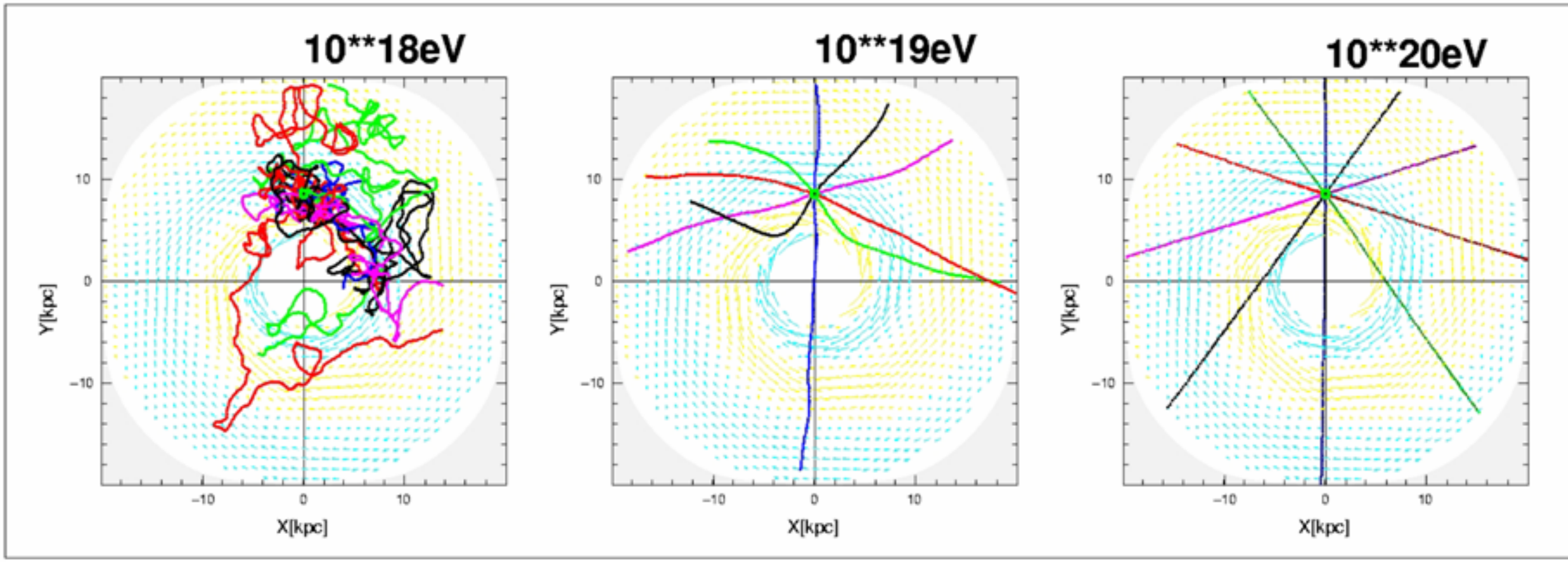
$$r = E/(ZeB)$$

$$r(kpc) \cong \frac{E(EeV)}{ZB(\mu G)}$$

- Per un protone di E~10^{19} eV, r~3.3 kpc (corrisponde a ~10· spessore galattico)
- Un Fe potrebbe restare confinato a 10^{19} eV

$$r=10(EeV)/26\cdot 3(\mu G) \approx 100 \text{ pc}$$

Confinamento 2 (richiamo)



~ 10^{18} eV: RC ben confinati nella galassia

≳ 10^{19} eV: sorgenti extragalattiche

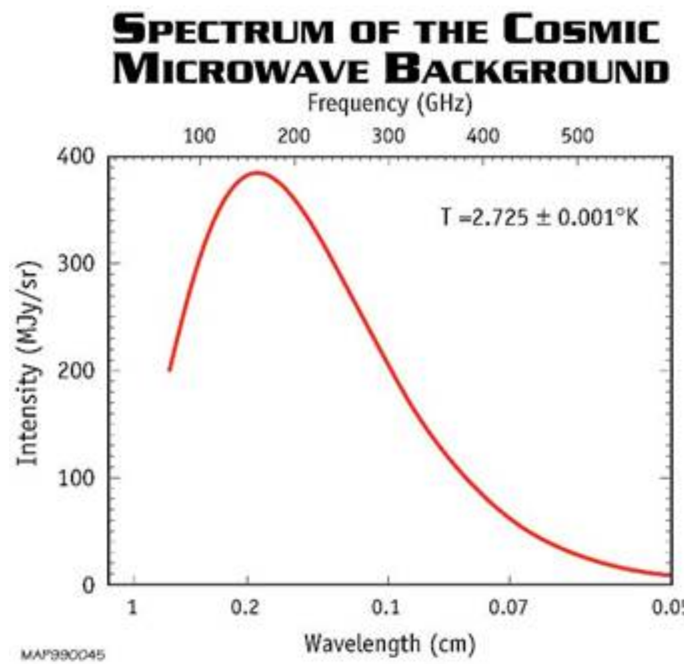
~ 10^{20} eV la deviazione nella galassia è inferiore ad 1°

Volume di confinamento dei RC di origine extragalattico: il Cut-off di Greisen (GZK)

- L' universo è permeato dalla Radiazione Cosmica di Fondo a 3^o K (CMBR) → 160.2 GHz
- CMBR: fotoni di energia

$E\gamma^{CMBR} = h\nu = 2\pi \times 6 \cdot 10^{-22}$ MeV·s $\times 160.2 \cdot 10^9$Hz= **$6 \cdot 10^{-4}$ eV**

- La densità dei fotoni di fondo è $\sim 400/cm^3$
- Il fondo di radiazione pone un limite sulla distanza massima da cui i RC possono provenire.



$G_{reisen}Z_{atsepin}K_{uzmin}$ cutoff
Soglia per reazioni di fotoproduzione

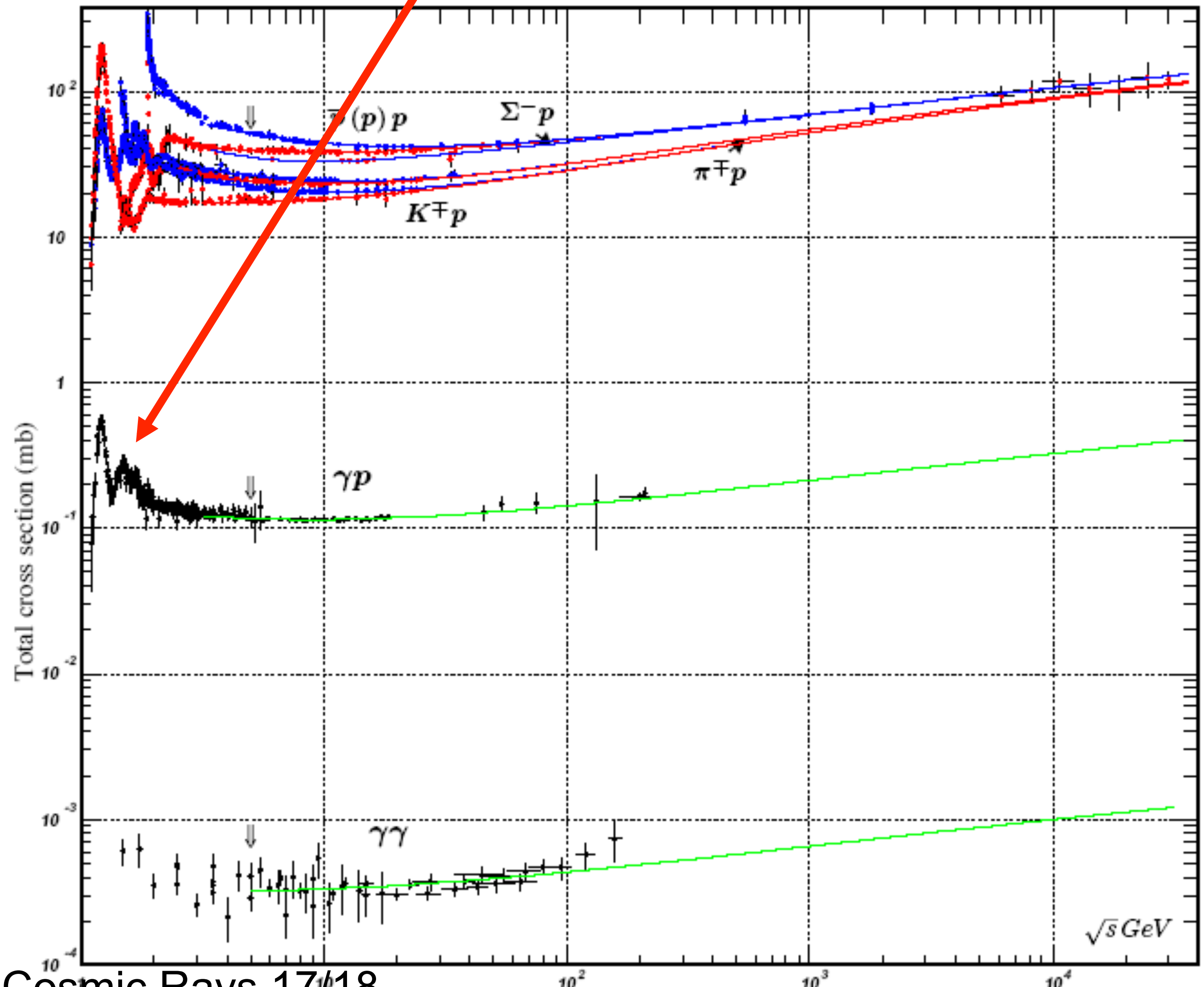
- **Fotoproduzione**: Protoni di alta energia possono interagire con fotoni, producendo un pione:

$$\gamma^{CMBR}+p \rightarrow \Delta^{*}(1236) \rightarrow n+\pi^{+}$$
$$\rightarrow p+\pi^{0}$$

- È necessario essere sopra la soglia di fotoproduzione nel sistema del CM: $E_0^{FP} \approx 300$ MeV
- Il processo ha una sezione d'urto in risonanza

$$\sigma_0^{P} \approx 250\ \mu b$$

Sezione d'urto per la Δ



Soglia per la fotoproduzione (FP)

SdR Laboratorio	SdR protone in quiete	
$p^{\mu} = (\gamma m_p \vec{v}_p c, \gamma m_p c^2)$	$\vec{p}'^{\mu} = (0, m_p c^2)$	
$k^{\mu} = (\frac{E_{\gamma}^{CMBR}}{c} c\hat{k}, E_{\gamma}^{CMBR})$	$\vec{k}'^{\mu} = (E_0^{FP} c\hat{k}' / c, E_0^{FP})$	

- Vogliamo determinare il valore di γ tale che si abbia un valore E_o^{PF} > 300 MeV
- La trasformazione di Lorentz tra i due S $\left[x_0 = \gamma(x_0' + \frac{V}{c} x_1')\right]$

$$E_0^{FP} = \gamma(E_{\gamma}^{CMBR} + \frac{v_p}{c} E_{\gamma}^{CMBR}) =$$

$$= \gamma E_{\gamma}^{CMBR}(1 + v_p / c) \approx 2\gamma E_{\gamma}^{CMBR}$$

E^{FP}_0 = Soglia fotoproduzione (~300 MeV)
E_{γ}^{CMBR}=Energia fotone =hν
γ = boost Lorentz del protone

- Dalla relazione, si ricava il valore di γ necessario per la fotoproduzione nel sistema di riferimento del laborarorio

$$\gamma = \frac{E_0^{FP}}{2E_\gamma^{CMBR}} \approx \frac{300MeV}{2\cdot 4.7\cdot 10^{-4}eV} \approx 3\cdot 10^{11}$$

- L'energia di soglia per i protoni per produrre π è quindi

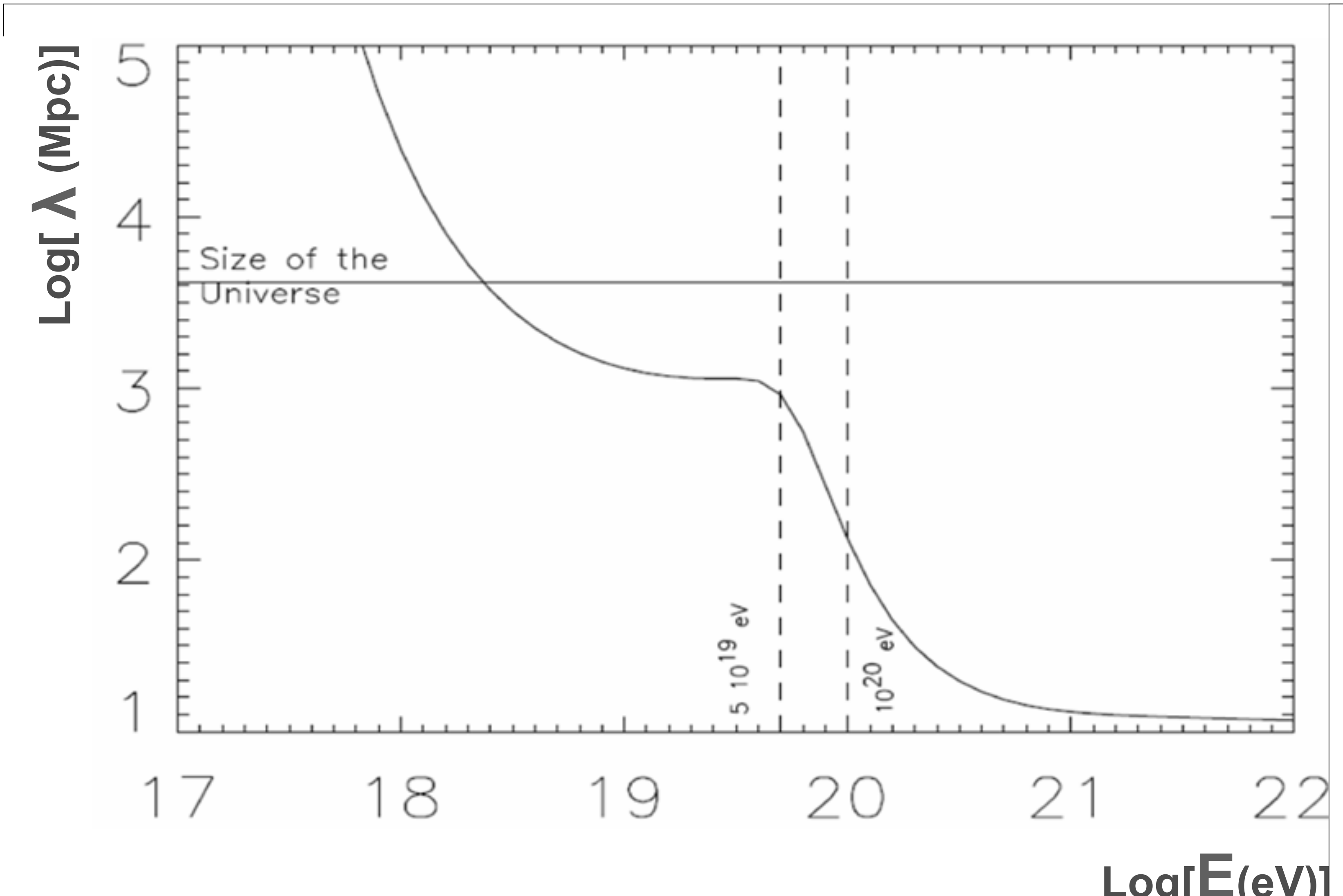
$$E_0^{GZK} = \gamma(m_p c^2) \approx 3\cdot 10^{20} eV$$

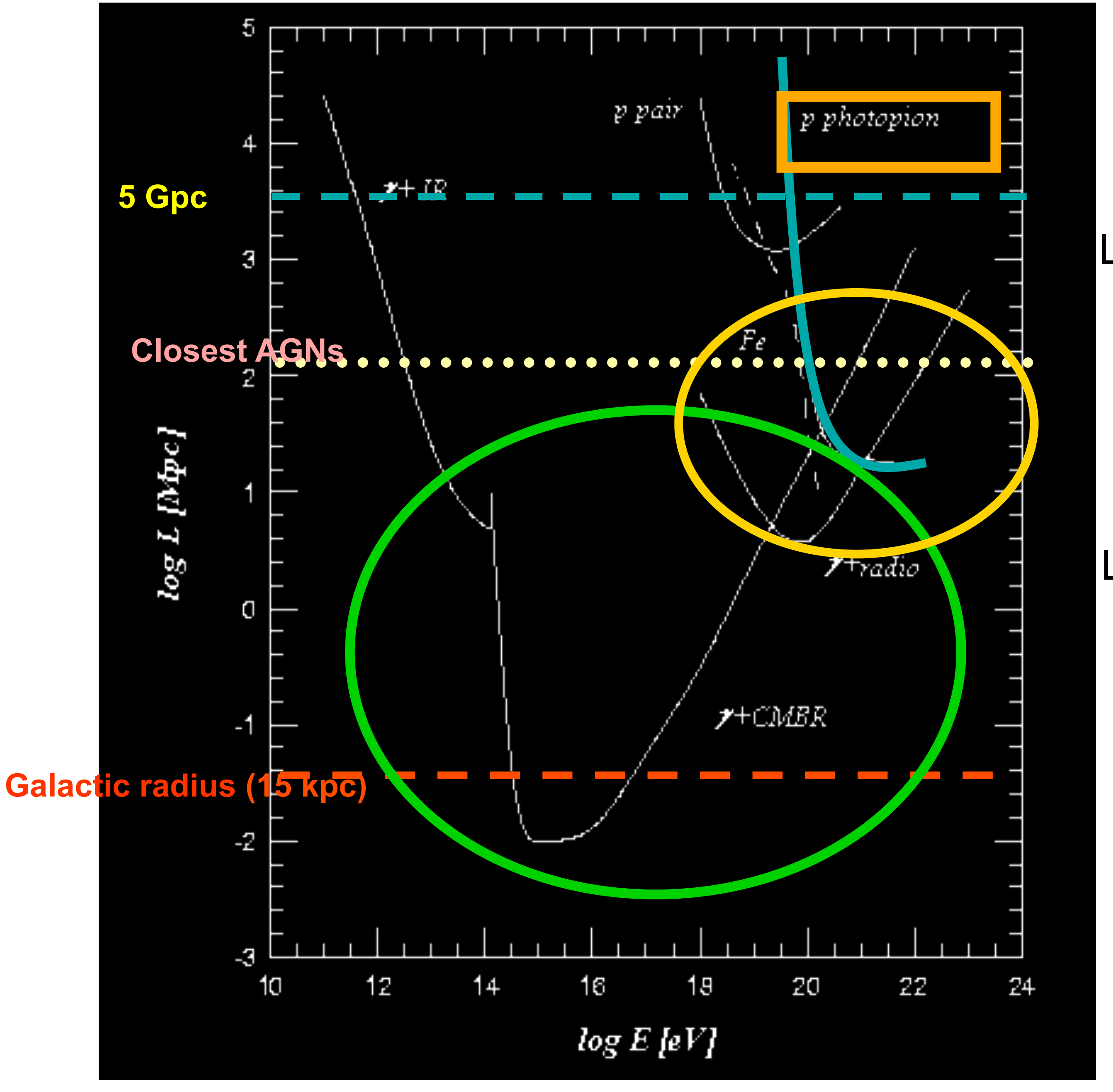
Se l'energia del protone supera E_o^{GZK}, si innesca la FP.
In ogni processo, il p perde circa 1/10 della sua energia
Nota la densità numerica della CMBR (n_γ=400 cm^{-3}), si stima il cammino libero medio del p:

$$\lambda = (\sigma_{\gamma p} n_\gamma)^{-1} = 10^{25} cm = 3Mpc$$

Si può dunque stimare che i p NON possano giungere da distanze superiori a 10×3 Mpc = 30 Mpc

Figura: Risultato di calcoli dettagliati.





L'Universo NON è trasparente ai protoni di altissima energia

L'Universo NON è trasparente ai fotoni di alta energia

Ricerca delle sorgenti

- Nella reazione di fotoproduzione (responsabile del cutoff di GZK) sono prodotti $\pi^{\pm}$, π^0 che decadono:

$$\pi^+ \rightarrow \nu_\mu \mu^+ \rightarrow \nu_\mu \nu_\mu \nu_e e^+$$

$$\pi_0 \rightarrow \gamma\gamma$$

- Neutrini e fotoni di altissima energia possono quindi essere studiati per confermare il meccanismo GZK, e per localizzare le sorgenti di RC a $E > 10^{19}$ eV

Il RC di più alta energia osservato: $\gtrsim 3.2 \cdot 10^{20}$ eV **(?)**

Se le sorgenti **non possono** essere troppo lontane (<30 Mpc), possiamo cercare di localizzarle tramite:

→ Studi di anisotropia con esperimenti di RC

→ Confronto con altre misure astronomiche

- Da dove vengono le particelle che osserviamo, ie quali sono le sorgenti?

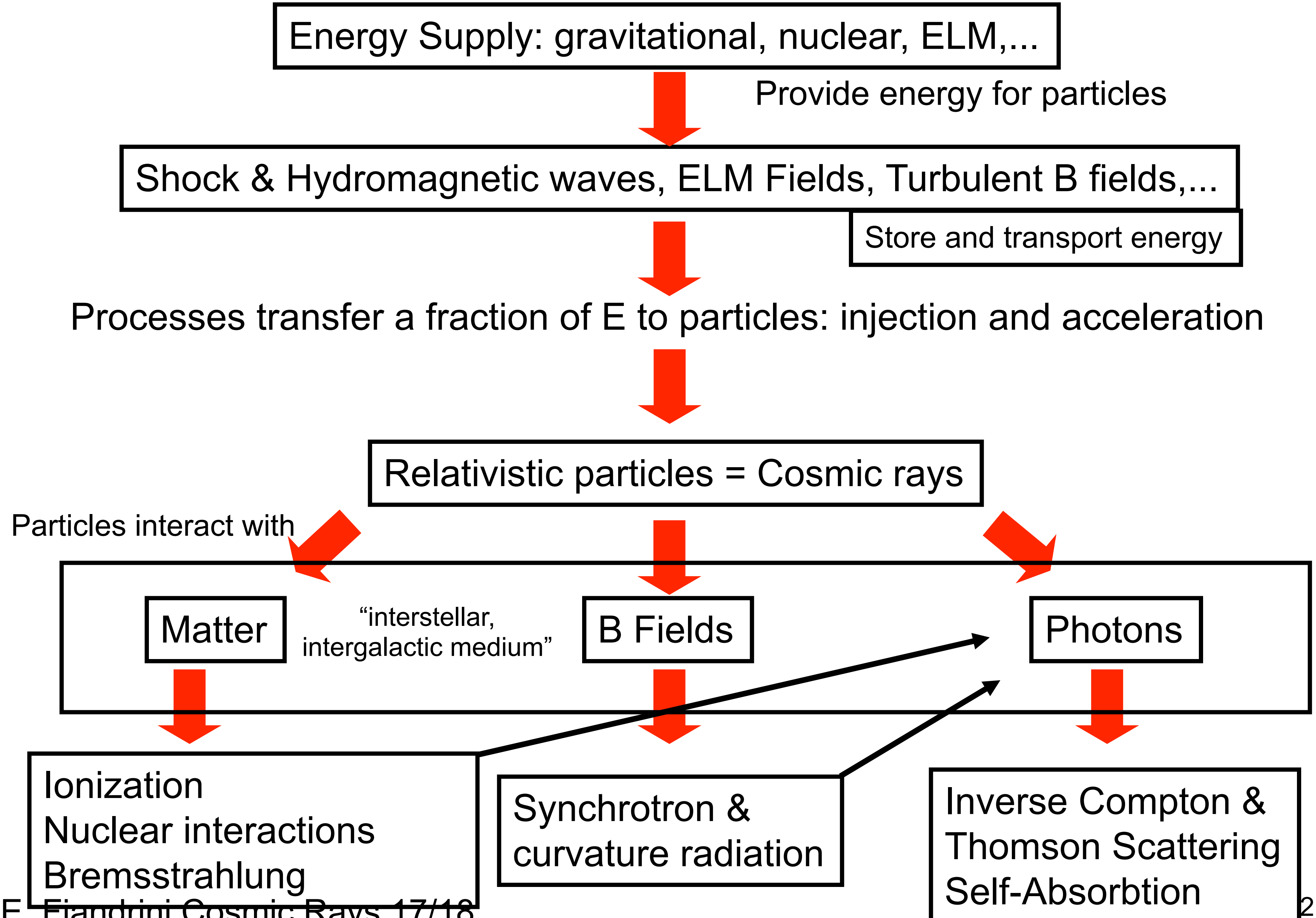
- Quali sono i processi che danno luogo alle popolazioni osservate?

- Qual'e' la distribuzione di materia e campi magnetici negli oggetti che emettono e nel mezzo in cui le particelle si propagano e come influenza le osservabili dei RC?

Fundamental questions remain unanswered!

- **What is the origin of this extra solar system matter?**
  - Do GCR come from a single class of source?
  - Can individual sources be detected?
  - What does the GCR composition tell us about the nucleosynthetic history of this matter?
- **How does this matter get accelerated to such high energies?**
  - Are there different astrophysical sites associated with different energy regimes?
- **Are there signatures of any exotic physics?**
  - Are there anti-matter regions in the universe?
  - Can we detect ‘effects’ associated with “Dark Matter”?

Formation and Interactions of CR's



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

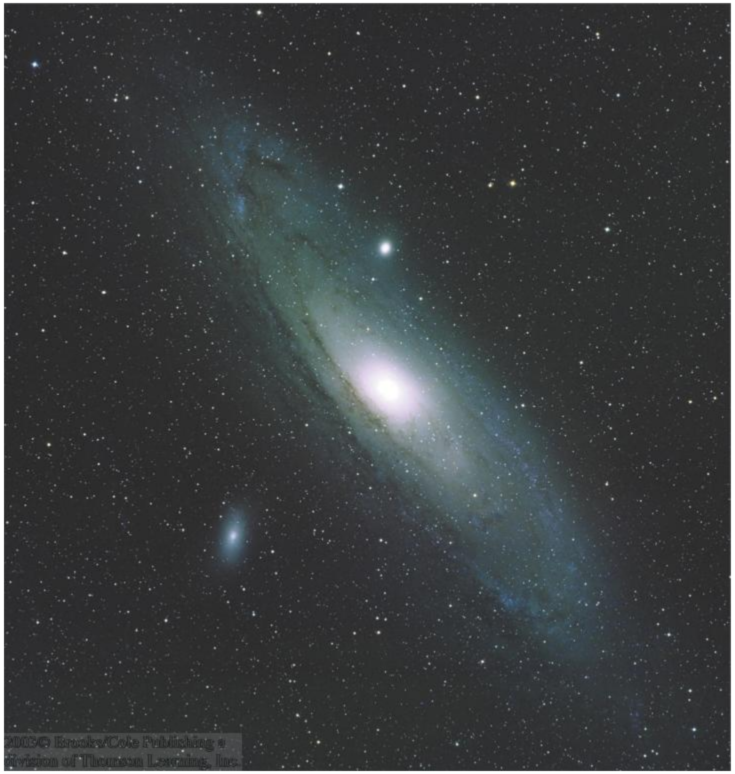
Il sistema solare si trova nella Via Lattea, la nostra galassia

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

Local environment: Milky Way

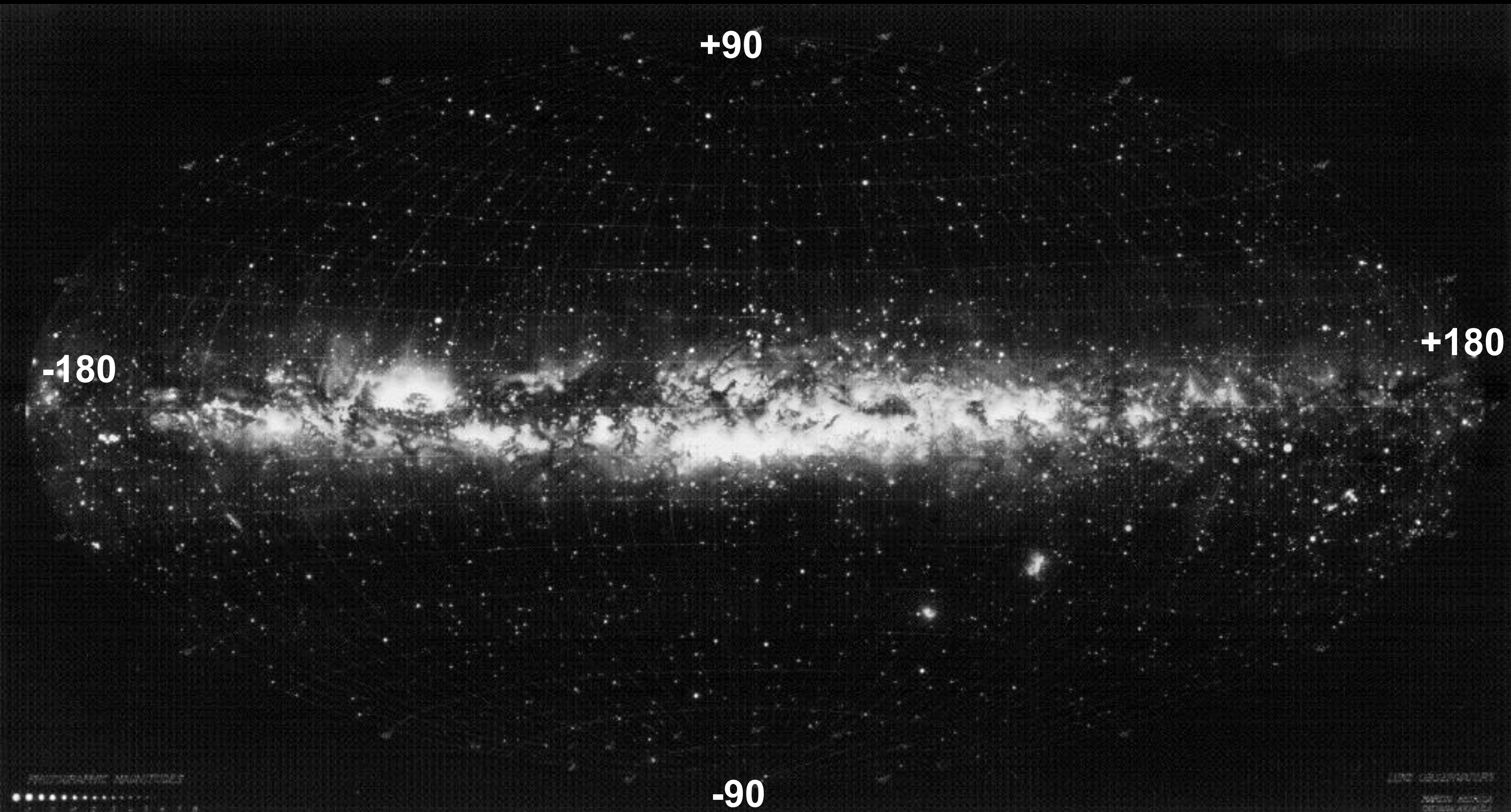
Almost everything we see in the night sky belongs to the Milky Way

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

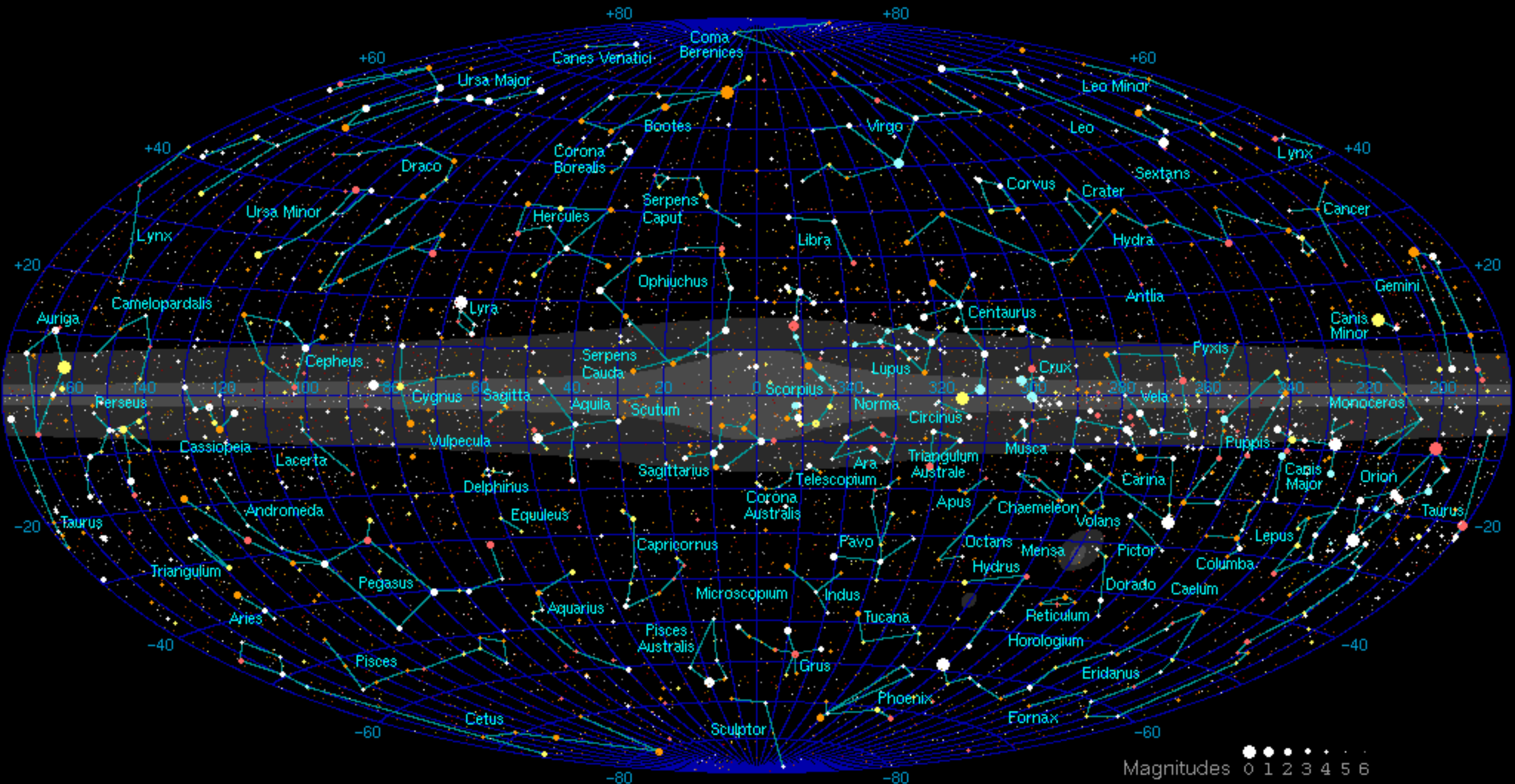


From the outside, our Milky Way might look very much like our cosmic neighbor, the Andromeda galaxy

For thousands of years, mankind could see “this” sky



Optical band


+80
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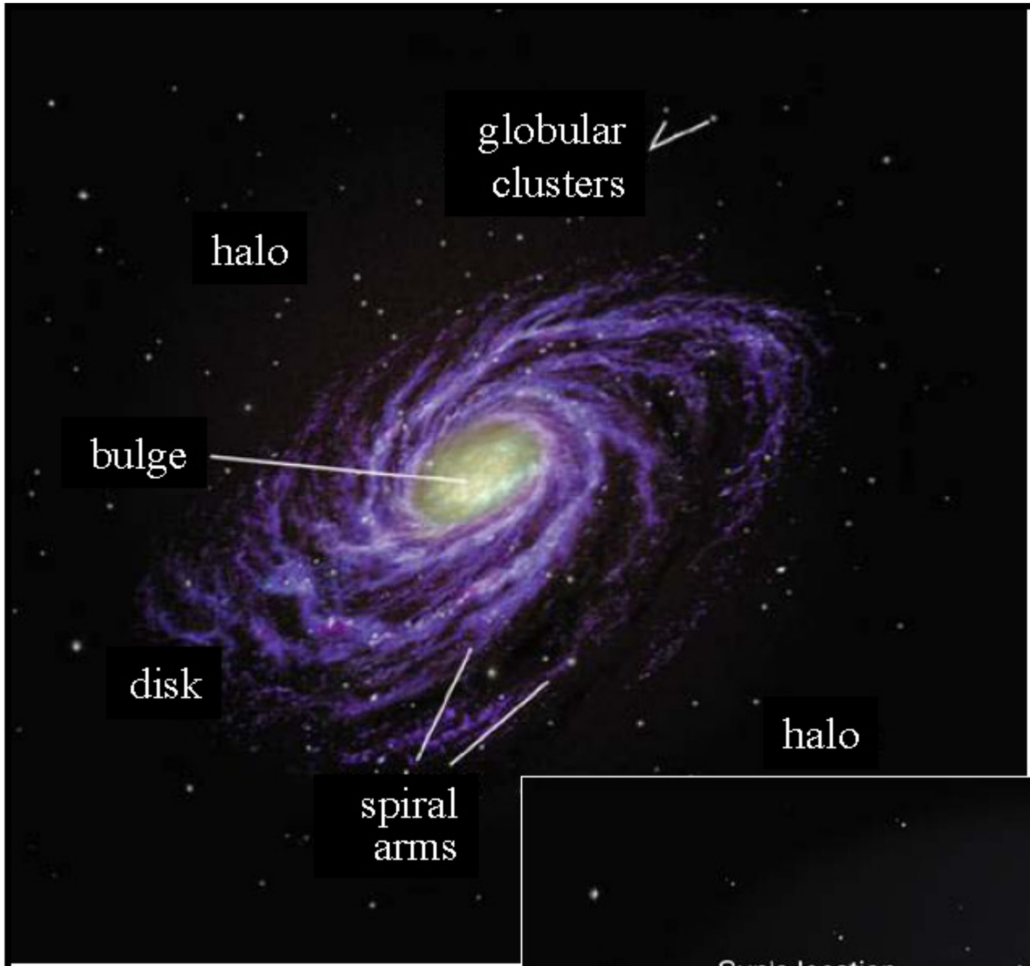
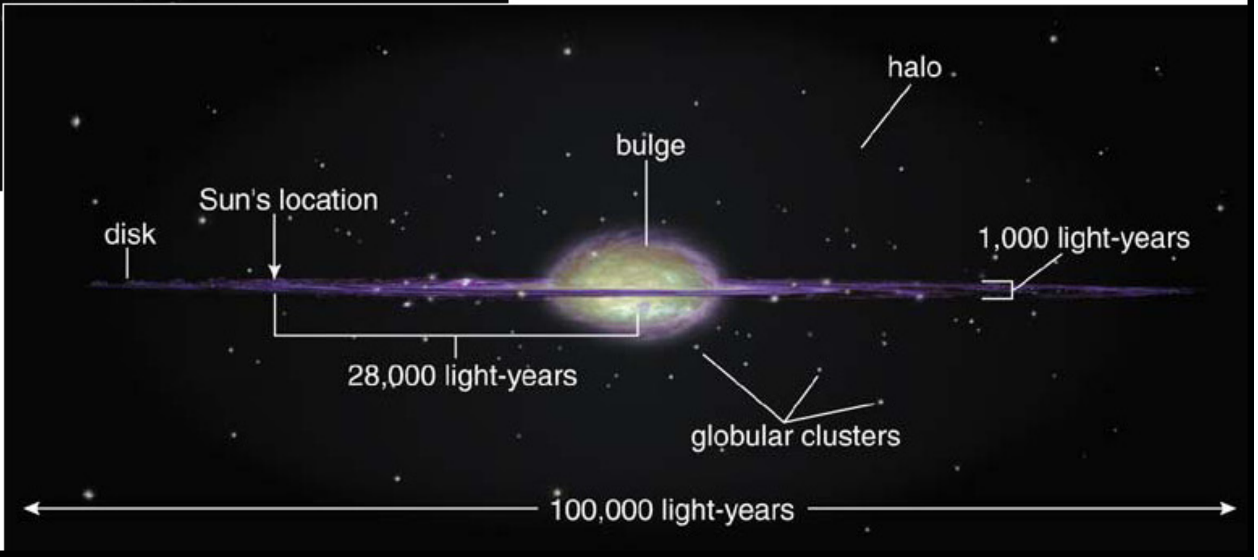
160
140
120
100
80
60
40
20
0
340
320
300
280
260
240
220
200
Coma Berenices
Canes Venatici
Ursa Major
Leo Minor
Bootes
Virgo
Leo
Lynx
Draco
Corona Borealis
Sextans
Corvus
Crater
Serpens Caput
Hercules
Ursa Minor
Libra
Hydra
Cancer
Lynx
Ophiuchus
Gemini
Camelopardalis
Antlia
Auriga
Lyra
Centaurus
Canis Minor
Cepheus
Serpens Cauda
Pyxis
Lupus
Crux
Perseus
Cygnus
Sagitta
Scorpius
Vela
Monoceros
Aquila
Scutum
Norma
Circinus
Vulpecula
Puppis
Cassiopeia
Musca
Lacerta
Sagittarius
Ara
Triangulum Australe
Canis Major
Telescopium
Carina
Orion
Delphinus
Corona Australis
Apus
Chameleon
Andromeda
Equuleus
Taurus
Volans
Taurus
Capricornus
Pavo
Octans
Mensa
Pictor
Lepus
Triangulum
Hydrus
Columba
Pegasus
Microscopium
Indus
Dorado
Caelum
Aquarius
Tucana
Reticulum
Aries
Pisces Australis
Horologium
Pisces
Grus
Eridanus
Phoenix
Cetus
Sculptor
Fornax
Magnitudes 0 1 2 3 4 5 6
r.powell

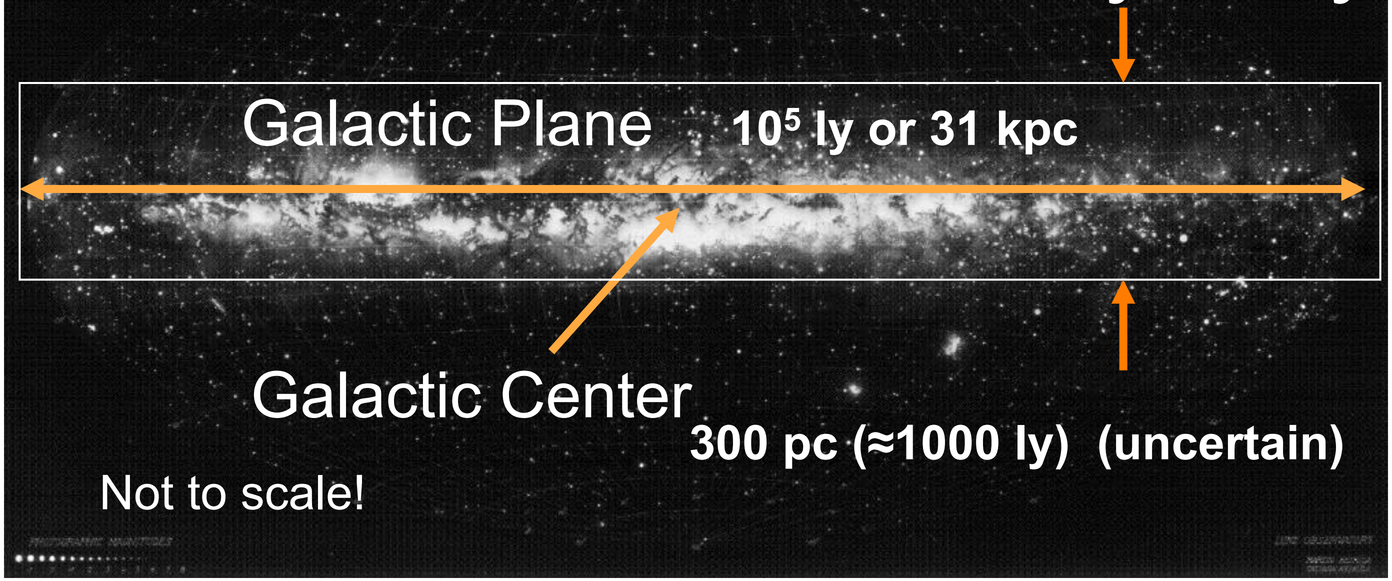
The Milky Way

- Gas, large fraction of stars in thin disk
  - ~1000 LY thick
  - Spiral structure
- Spherical halo
  - ~150 globular clusters
  - Spherical distribution of stars
- Nuclear bulge





The Structure of the Milky Way



The structure is hard to determine because:

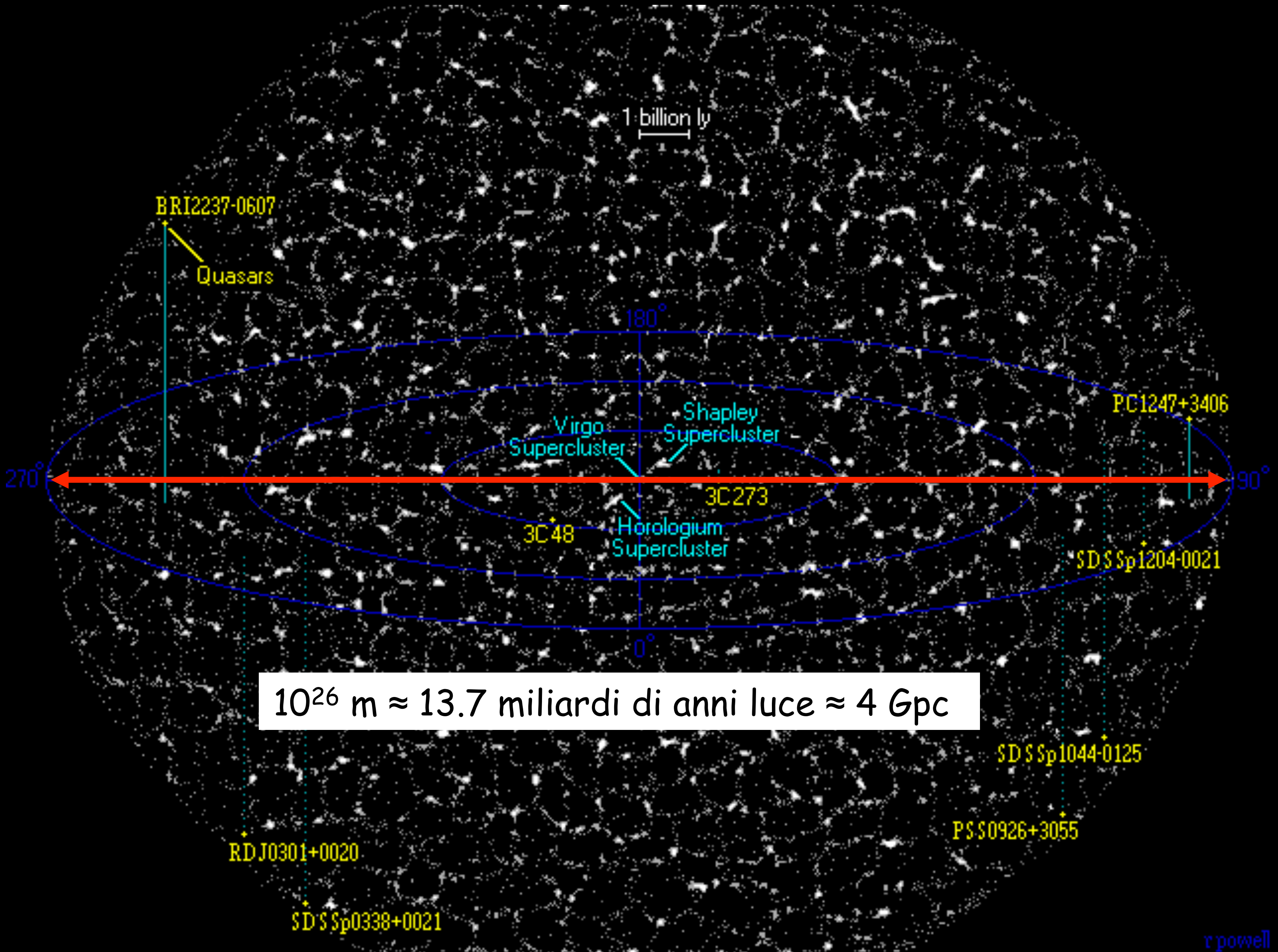
1) We are inside

2) Distance measurements are difficult

3) Our view towards the center is obscured by gas and dust

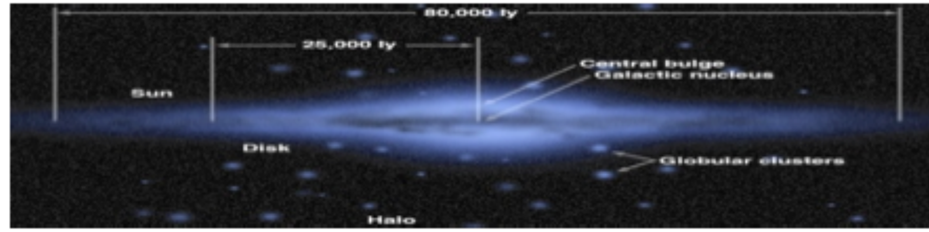
- The Milky Way is the second-largest galaxy in the Local Group, with its stellar disk approximately 100,000 ly (30 kpc) in diameter, and, on average, approximately 1,000 ly (0.3 kpc) thick. As a guide to the relative physical scale of the Milky Way, if the Solar System out to Neptune were the size of a US quarter (25mm), the Milky Way would be approximately the size of the continental United States.
- It looks like a very thin disk with a thickness or halo height << with respect to the disk radius (something like an old long-playing disk)

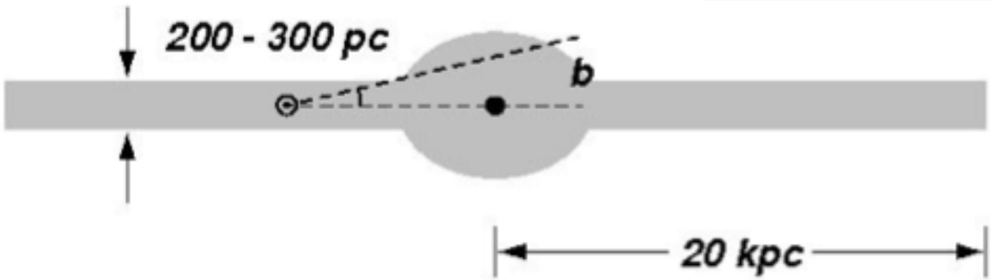
L'intero Universo



10^{26} m ≈ 13.7 miliardi di anni luce ≈ 4 Gpc

Galactic cosmic rays propagation





Side view of the Galaxy

The Solar system is 8.5 kpc away from the galactic center. One *pc* is 3.10^{18} cm, so we are at a distance of $2.55\ 10^{17}$ km and the light from it reaches us after **~28000** years. One pc is the distance at which 1 AU ($149.6\ 10^{6}$ km) is seen at an angle 1 arcsec.

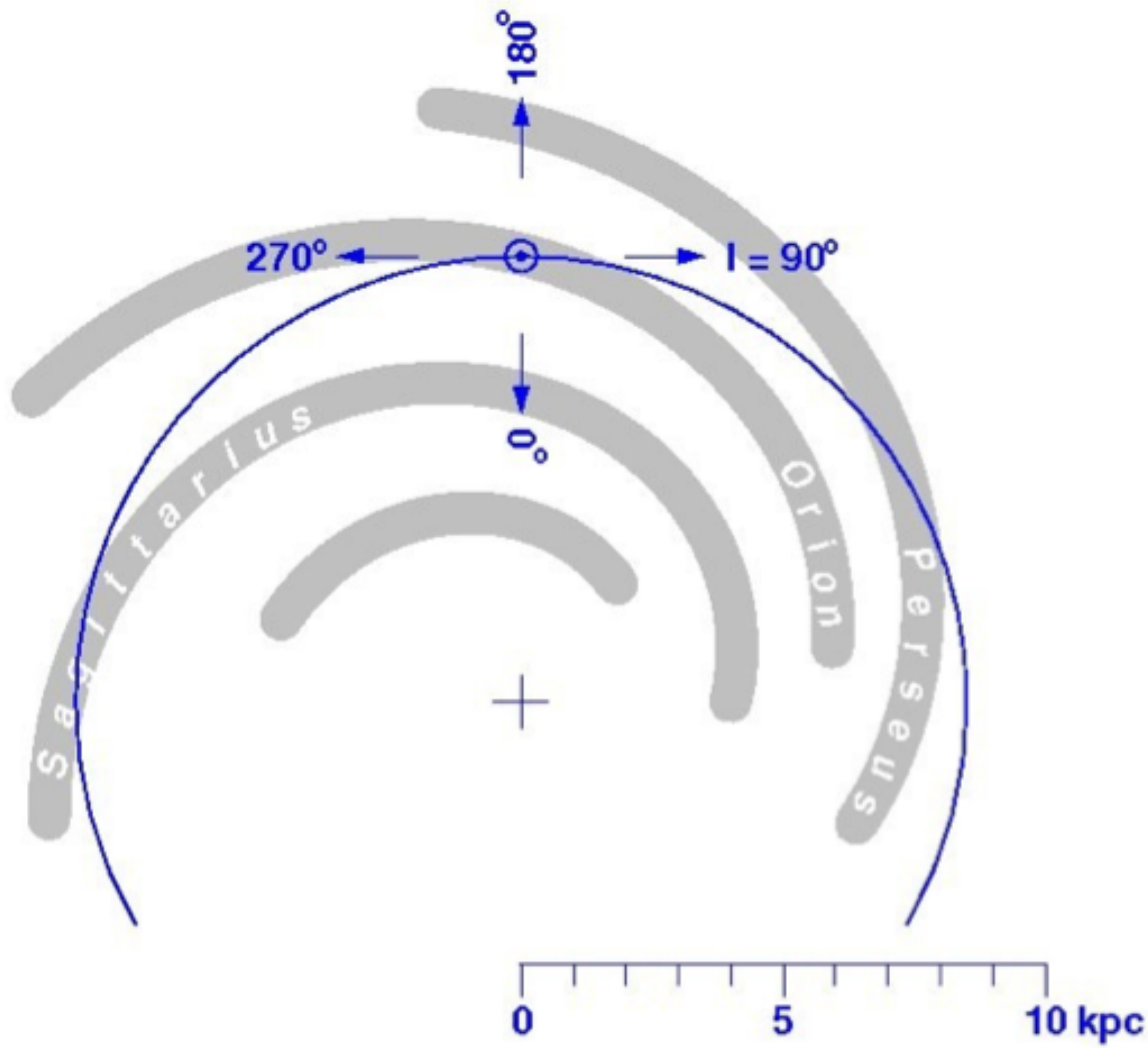
Galactic latitude *b* is the angle at which an object is above the galactic plane.

View of the galactic plane from the galactic North Pole

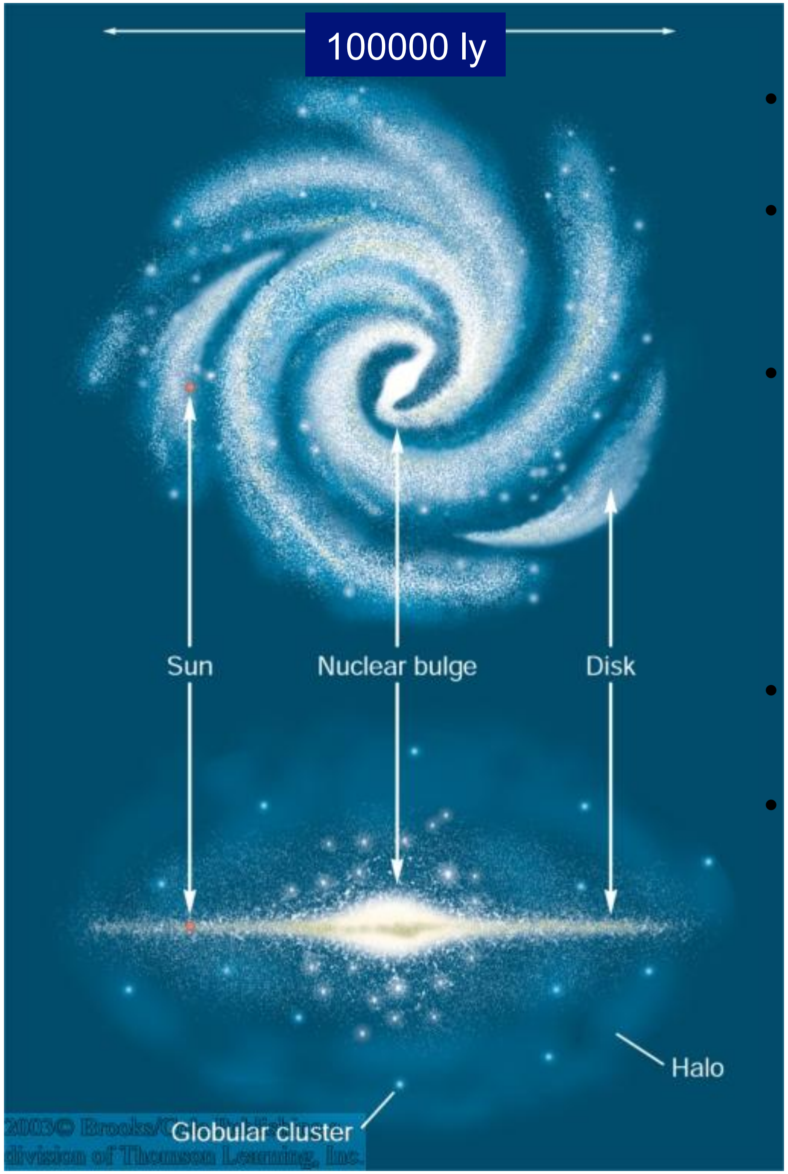
Galactic longitude *l* is measured counter clockwise from the direction of the galactic center.

l and *b* are the galactic coordinates

Most of the matter in the Galaxy is in the galactic arms.



The Mass of the Milky Way



- Estimates of the TOTAL mass of the Milky Way vary, depending upon the method and data used.
- Estimated in the range $5.8\times10^{11}\ M_{\odot}$ and $8.5\times10^{11}\ M_{\odot}$ which is about half the mass of the Andromeda Galaxy.
- 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. Models of the Milky Way suggest that its total mass is $1–1.5\times10^{12}\ M_{\odot}$. More-recent studies indicate a mass as large as $4.5\times10^{12}\ M_{\odot}$ and as small as $0.8\times10^{12}\ M_{\odot}$.
- The total stars mass is estimated to be between $4.6\times10^{10}\ M_{\odot}$ and $6.43\times10^{10}\ M_{\odot}$.
- 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.

Notazione per la ionizzazione

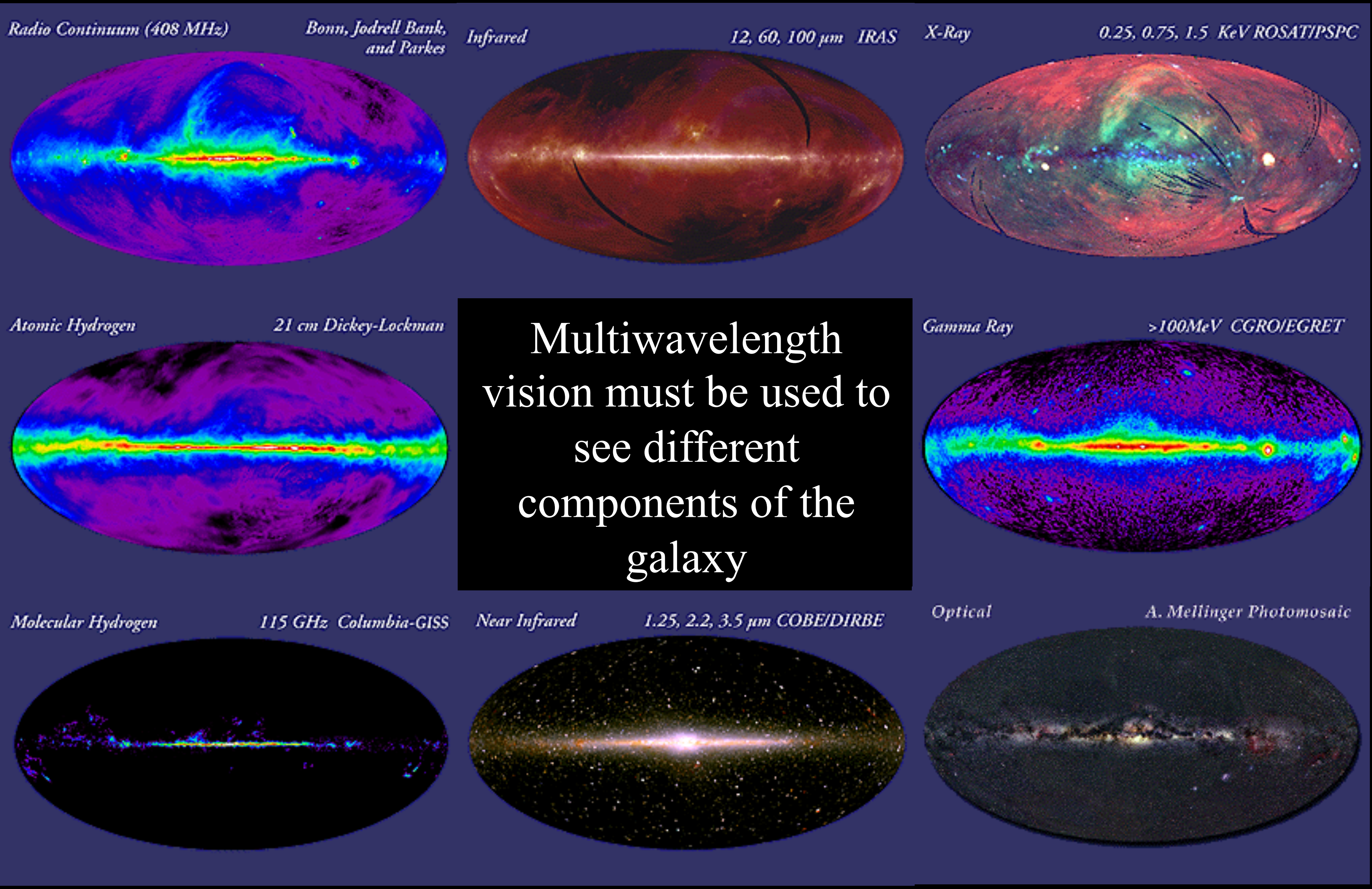
Notation for Degrees of Ionization			
Suffix	**Ionization**	**Examples**	**Chemist's Notation**
I	Not ionized (neutral)	H I, He I	H, He
II	Singly ionized	H II, He II	H^+, He^+
III	Doubly ionized	He III, O III	He^{++}, O^{++}

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...)



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

Constituents of the ISM

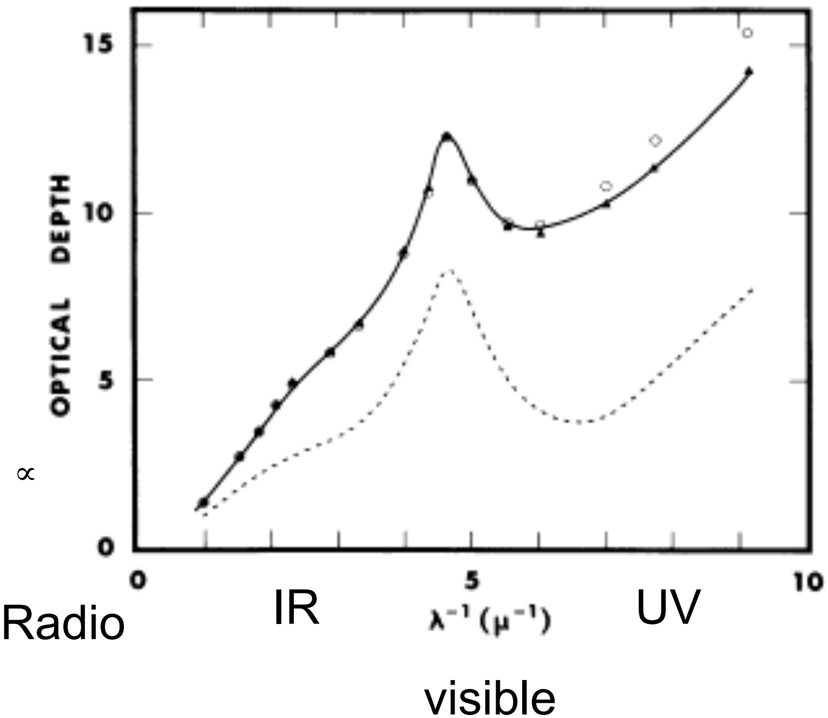
constituents of ISM in Milky Way	where	temperature density ...	how observed
atomic hydrogen HI	in disk, some in halo $\approx 90\%$ of mass, 50% of vol.	$50...300$K $1...100$cm^{-3}	21cm radio line UV absorption lines
molecular hydrogen H_2	dark clouds in disk $\approx 10\%$ of mass, 1% of vol.	$3...100$K $10^2...10^6$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

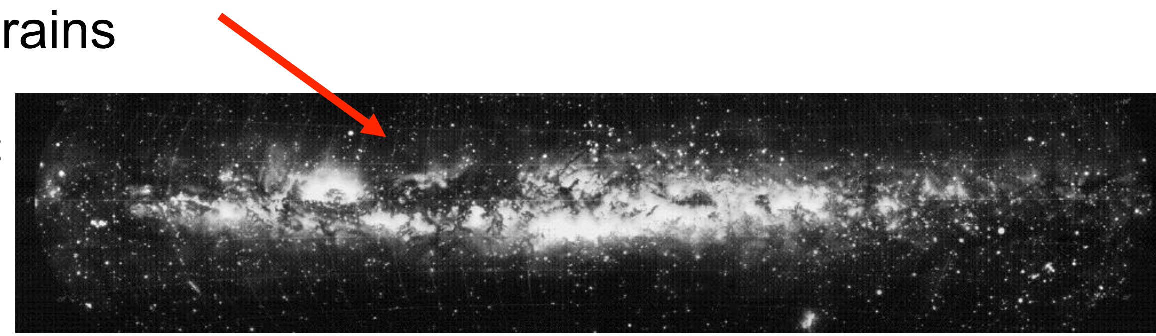
The total mass of the ISM in the Milky Way amounts to $\approx 15\%$ of the mass in stars, which is a typical value for spiral galaxies in general.

Polvere interstellare: estinzione

The interstellar extinction curve

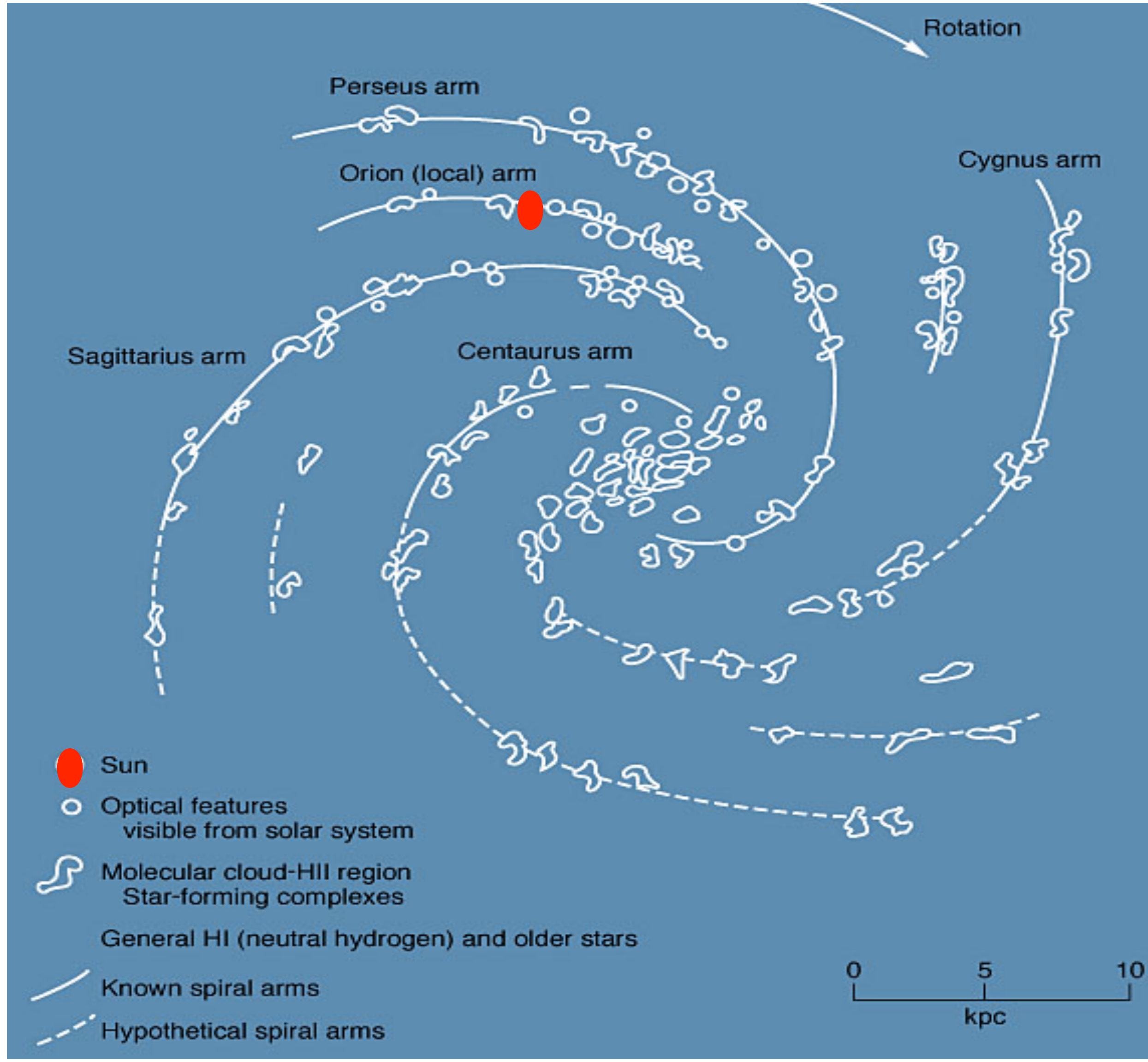
- Interstellar extinction
- absorption plus scattering
- UV extinction implies **small** (100 nm) grains
- Vis. Extinction implies **normal** (1000 nm) grains
- $n(a)da \sim a^{-3.5}da$
- Silicates plus carbonaceous grains
- Mass dust/Mass gas ~ 0.01
- Dense gas – **larger** grains with icy mantles
-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





Gas interstellare

- Il gas interstellare o intragalattico (IG) è il mezzo in cui si formano le stelle.
- Contribuisce per il 5% alla massa della Galassia

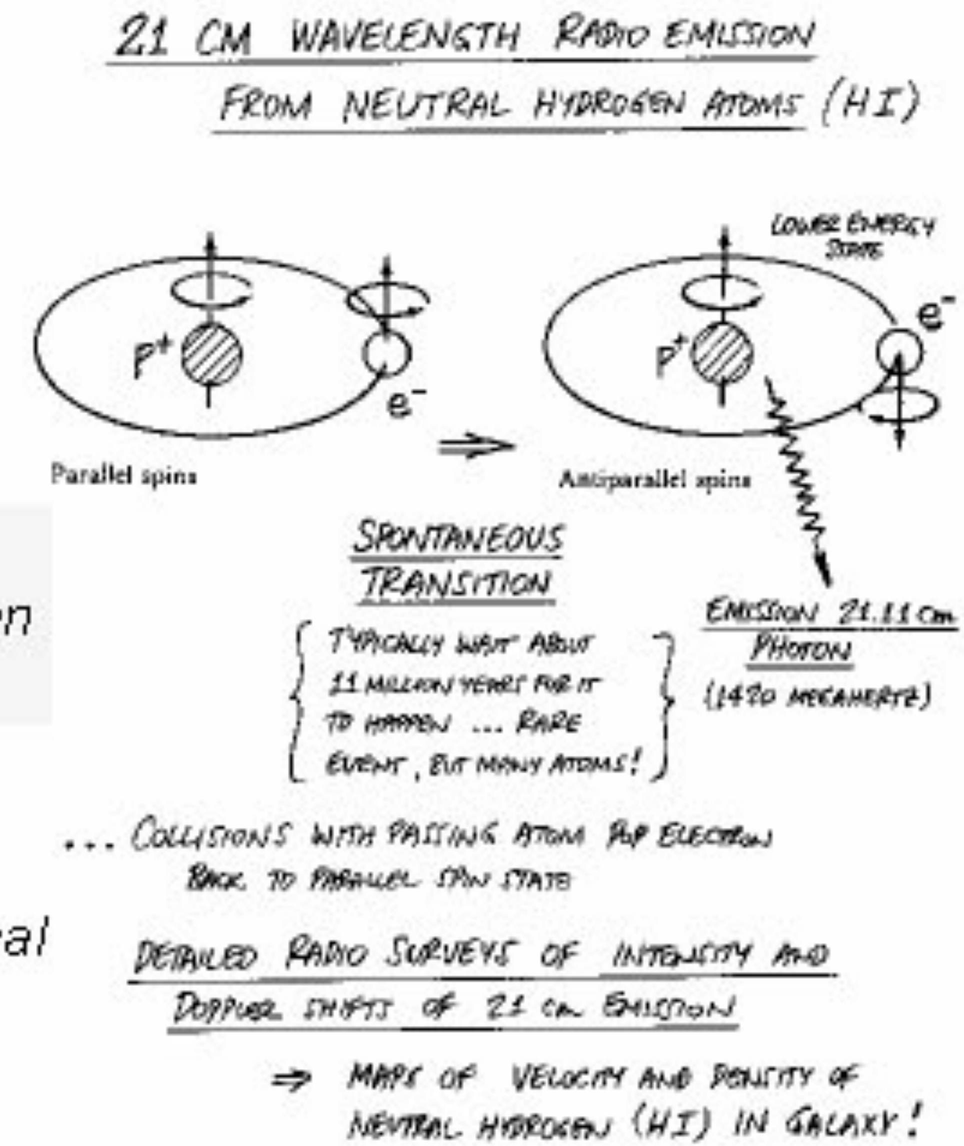


Nubi Gassose

- Scoperte con astronomia radio
- Il gas viene riscaldato da vari meccanismi:
  - Esplosioni di SN
  - Radiazione U.V. da stelle giganti
  - Eccitazione/ionizzazione da RC
- Si raffredda con altri meccanismi:
  - Bremsstrhalung (gas caldi, K>10^7 K)
  - Diseccitazione 10^4 K<T<10^7 K
  - Emissione termica

21 cm emission (radio)

Sampling neutral hydrogen atoms (cold)



also how MRI does it in medical imaging!

Hyperfine splitting

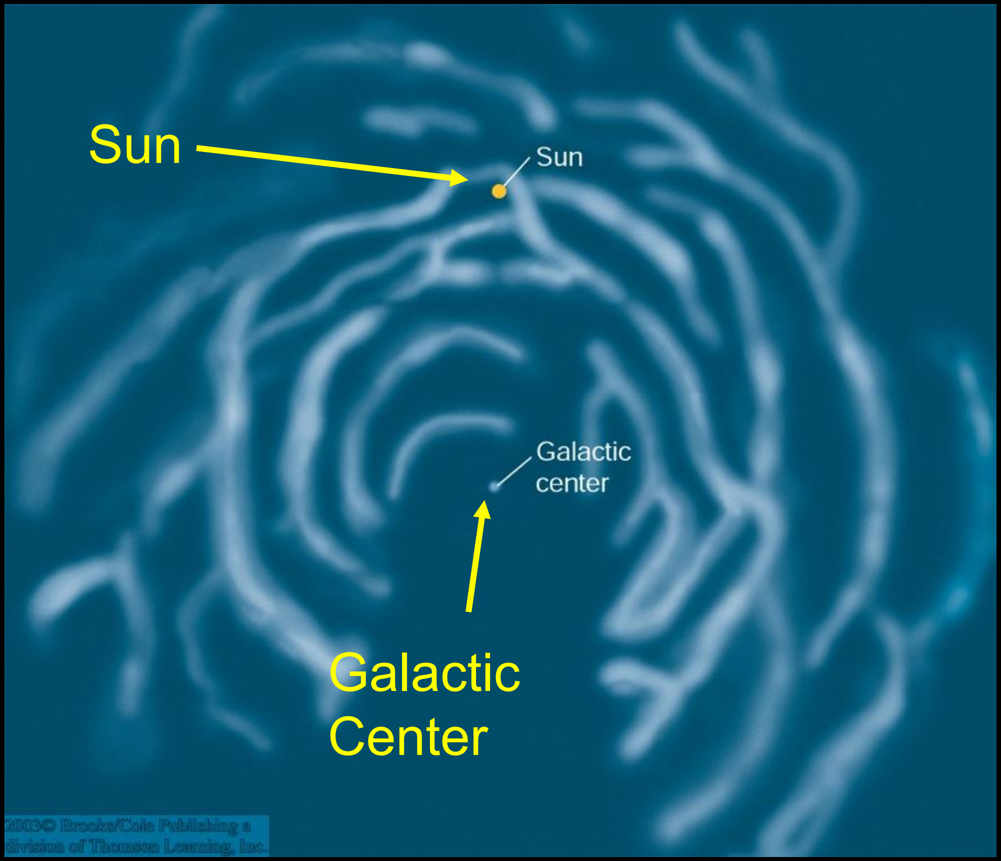
Neutral H consists of a single proton (p) and single e-. p and e- also have spin.
The spin of the e-and p can be in either direction - in the classical analogy they are rotating clockwise or anticlockwise around a given axis.

They may both have their spin oriented in the same direction or in opposite directions. Because of magnetic interactions between the particles, a H atom having the spins of the e- and p aligned in the same direction (parallel) has slightly more energy than one where the spins of the e- and p are in opposite directions (anti-parallel).
The lowest orbital energy state of atomic H has hyperfine splitting arising from the spins of the proton and electron changing from a parallel to antiparallel configuration.

This transition is highly forbidden with an extremely small probability of 2.9×10^{-15} s^{-1}.
This means that the time for a single isolated atom of neutral H to undergo this transition is $\approx 10^7$ years and so is unlikely to be seen in a lab on Earth. However, as the total number of atoms of neutral H in the ISM is very large, this emission line is easily observed by radio telescopes. The resulting emitted radiation has a frequency of 1420.24 MHz, corresponding to a λ = 21 cm

Radio Observations

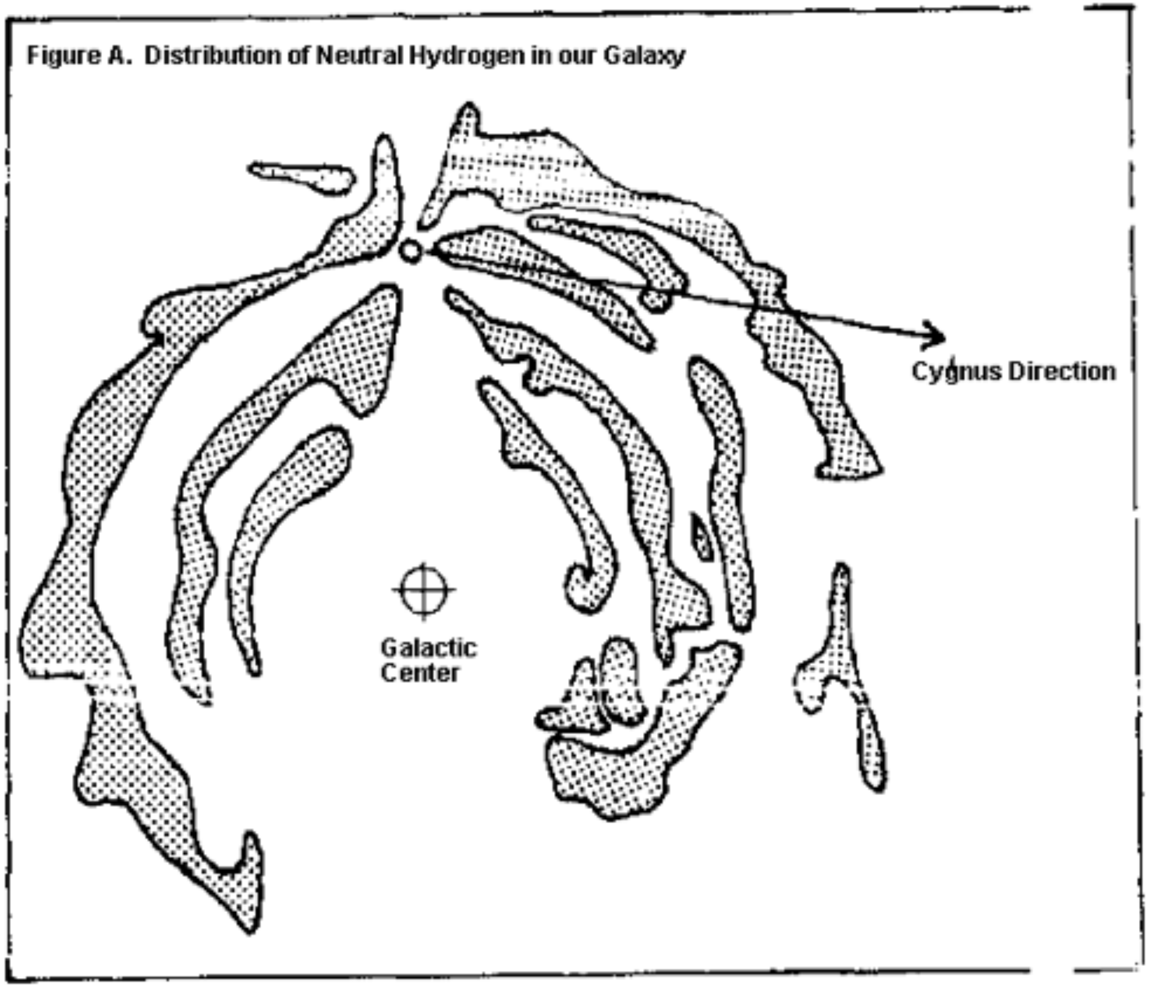
21-cm radio observations reveal the distribution of neutral hydrogen throughout the galaxy



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

Neutral hydrogen concentrated in **spiral arms**

Distribuzione di idrogeno neutro nella Galassia



Densità media del mezzo Interstellare

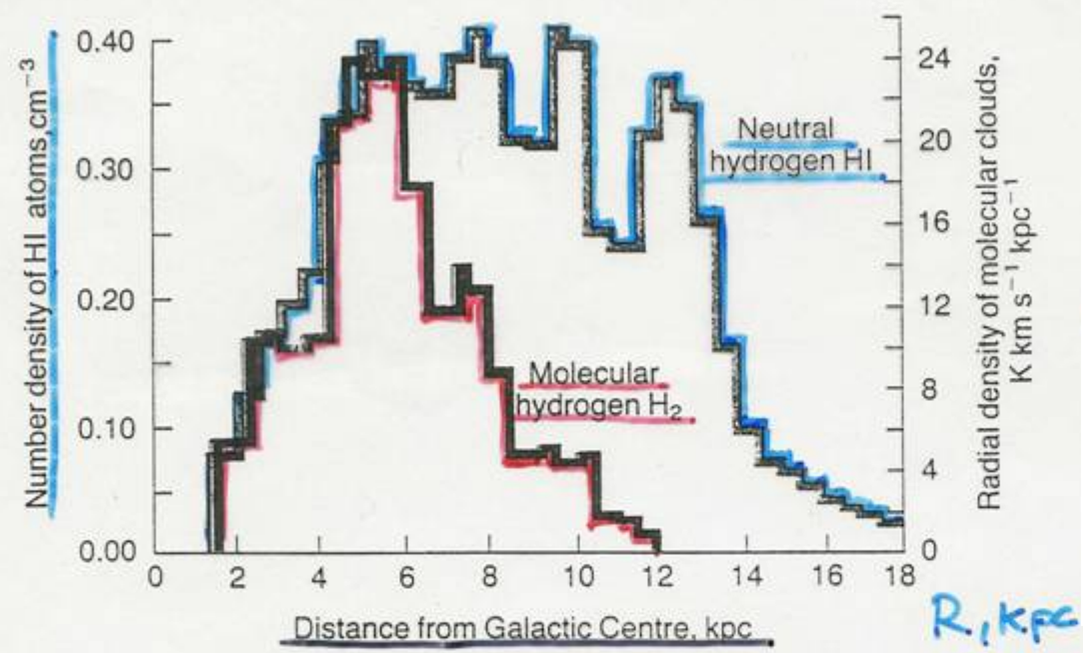


Figure 17.2. The radial distribution of atomic and molecular hydrogen as deduced from radio surveys of the Galaxy in the 21-cm line of atomic hydrogen and from millimetre surveys of the molecular emission lines of carbon monoxide, CO. (After D. Michalis and J. Binney (1981). *Galactic astronomy: structure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

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

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 View of the Milky Way

Interstellar dust does not absorb radio waves

We can observe any direction throughout the Milky Way at radio waves

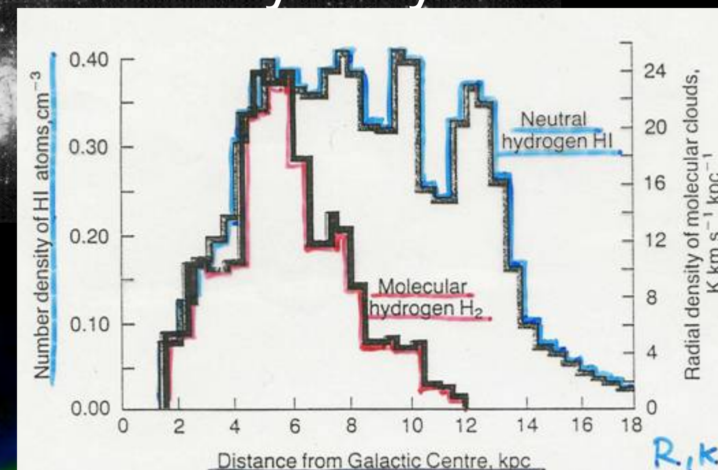
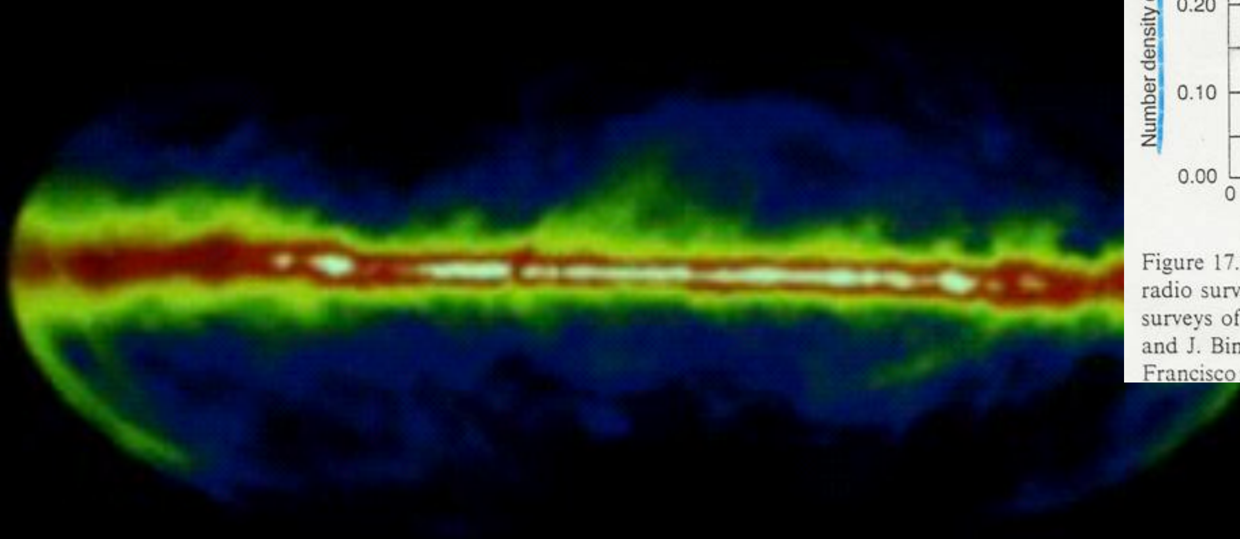


Figure 17.2. The radial distribution of atomic and molecular hydrogen radio surveys of the Galaxy in the 21-cm line of atomic hydrogen and surveys of the molecular emission lines of carbon monoxide, CO. (Aft and J. Binney (1981). *Galactic astronomy: structure and kinematics*, pp Francisco: W.H. Freeman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

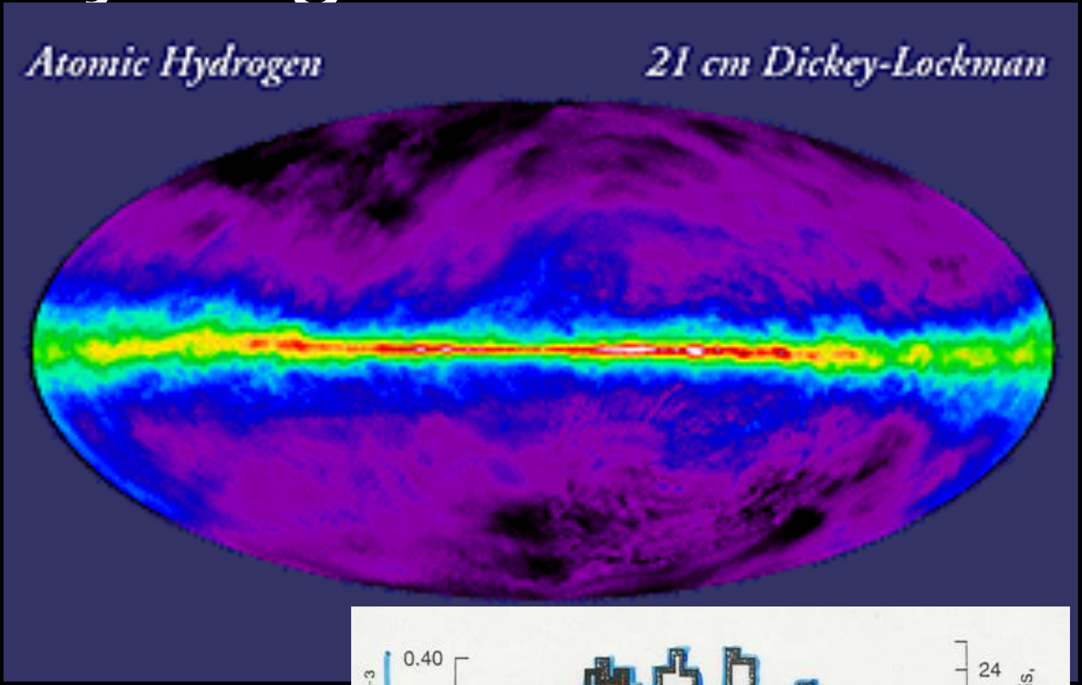


Radio map at a wavelength of 21 cm, tracing neutral hydrogen

Atomic Hydrogen HI

- **Hydrogen** comprises **90%** of the matter in the ISM.

- Most **diffuse H** is in the form of HI in the **disk** with some in the **halo**.



- The thin layer of HI gas can be detected either by **UV absorption lines** and through the **21 cm line** (forbidden hyperfine structure transition).

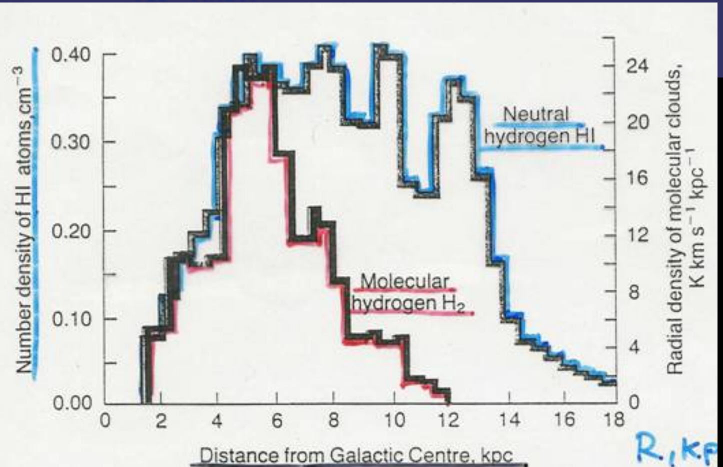


Figure 17.2. The radial distribution of atomic and molecular hydrogen
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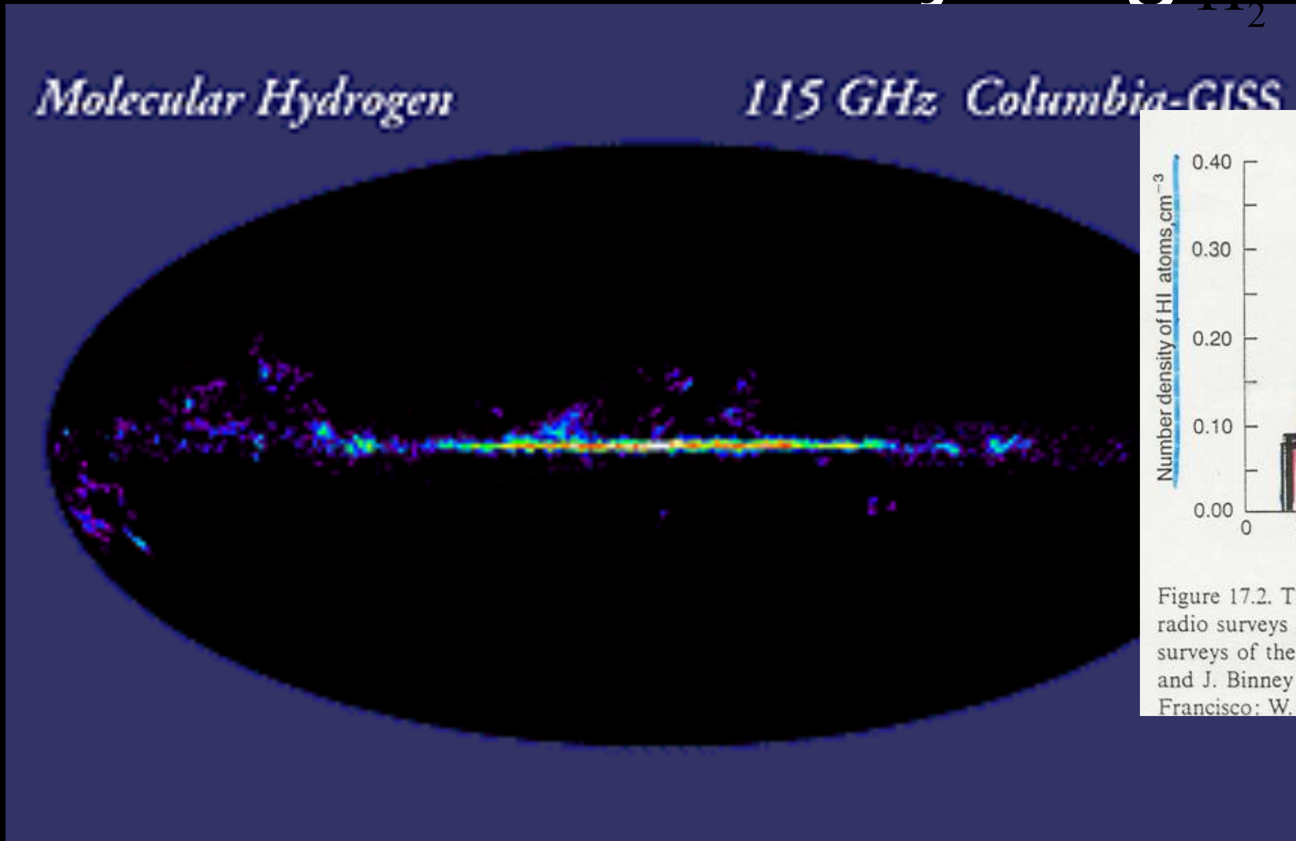
surveys of the molecular emission lines of carbon monoxide, CO. (Aft
and J. Binney (1981). *Galactic astronomy: structure and kinematics*, pp
Francisco: W.H. Freeman and Co.)

Molecular Hydrogen H_2



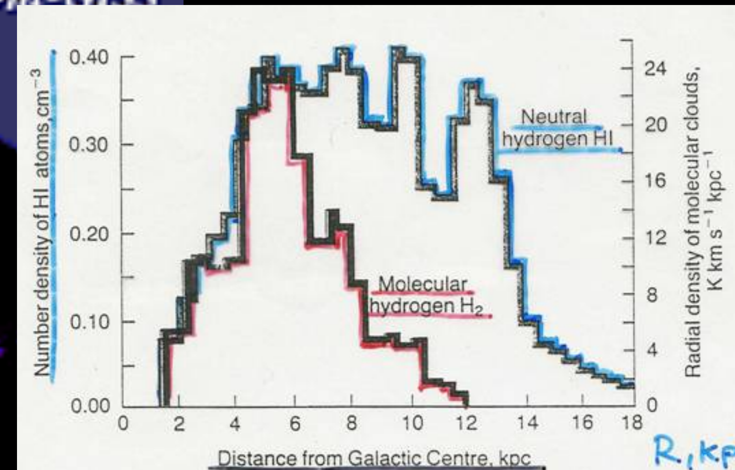
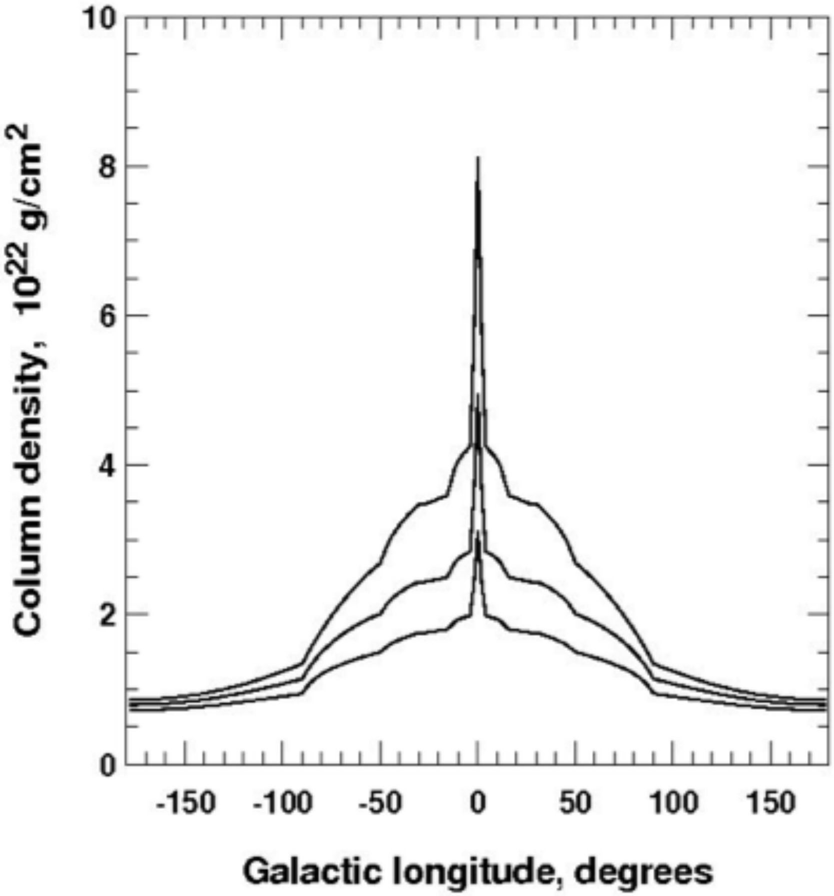


Figure 17.2. The radial distribution of atomic and molecular hydrogen radio surveys of the Galaxy in the 21-cm line of atomic hydrogen and surveys of the molecular emission lines of carbon monoxide, CO. (Aft and J. Binney (1981). *Galactic astronomy: structure and kinematics*, pp Francisco: W.H. Freeman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

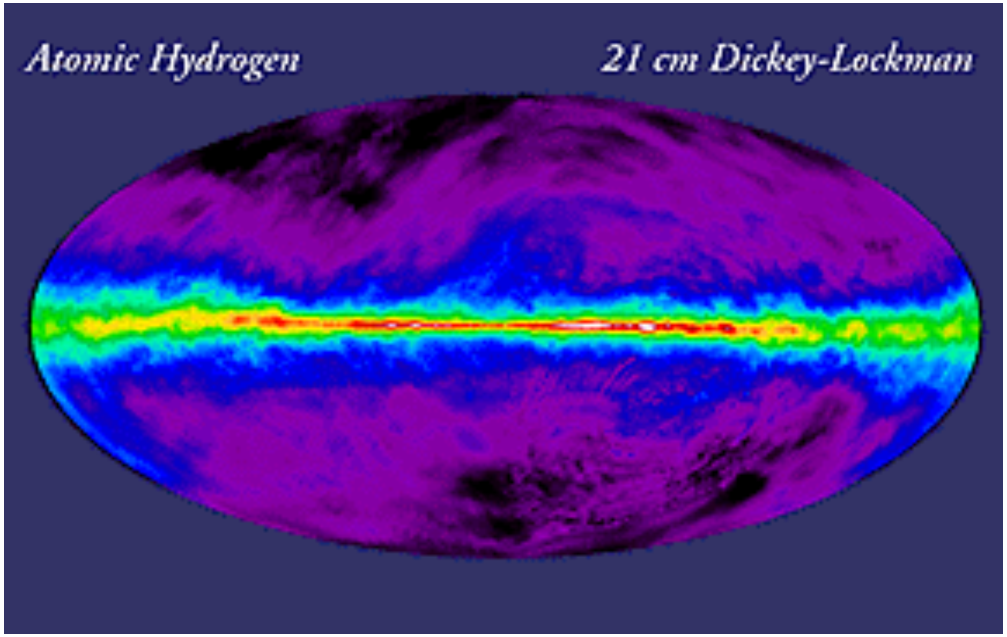


The matter density is not uniform. The sketch on the left gives an idea about the column density in the Galaxy 2, 5, and 10 deg around the galactic plane.

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

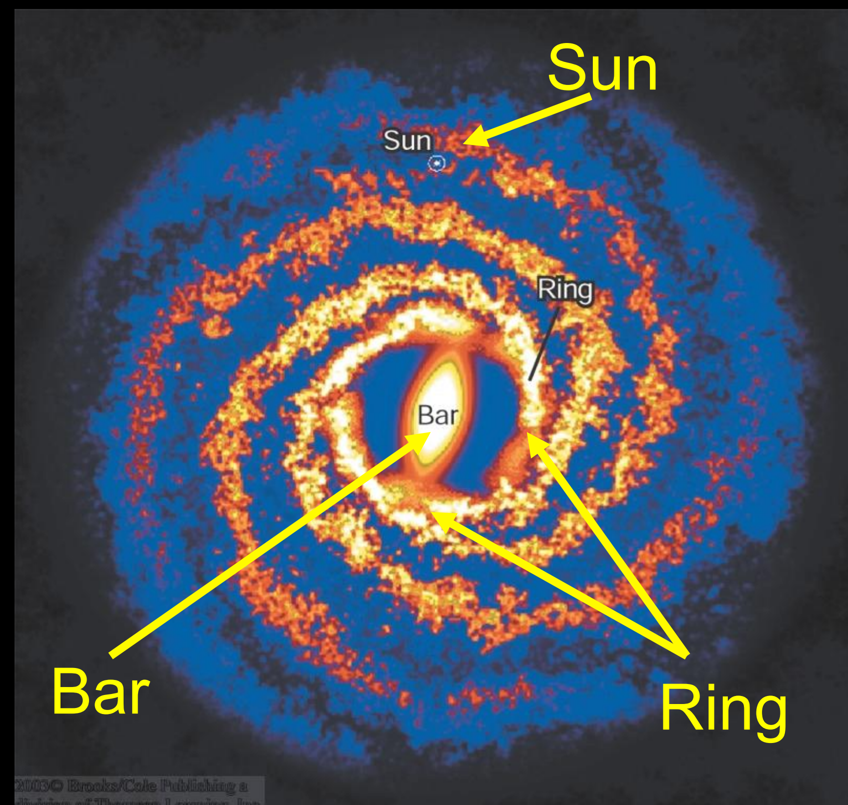
→ Most atoms will be in their ground state.

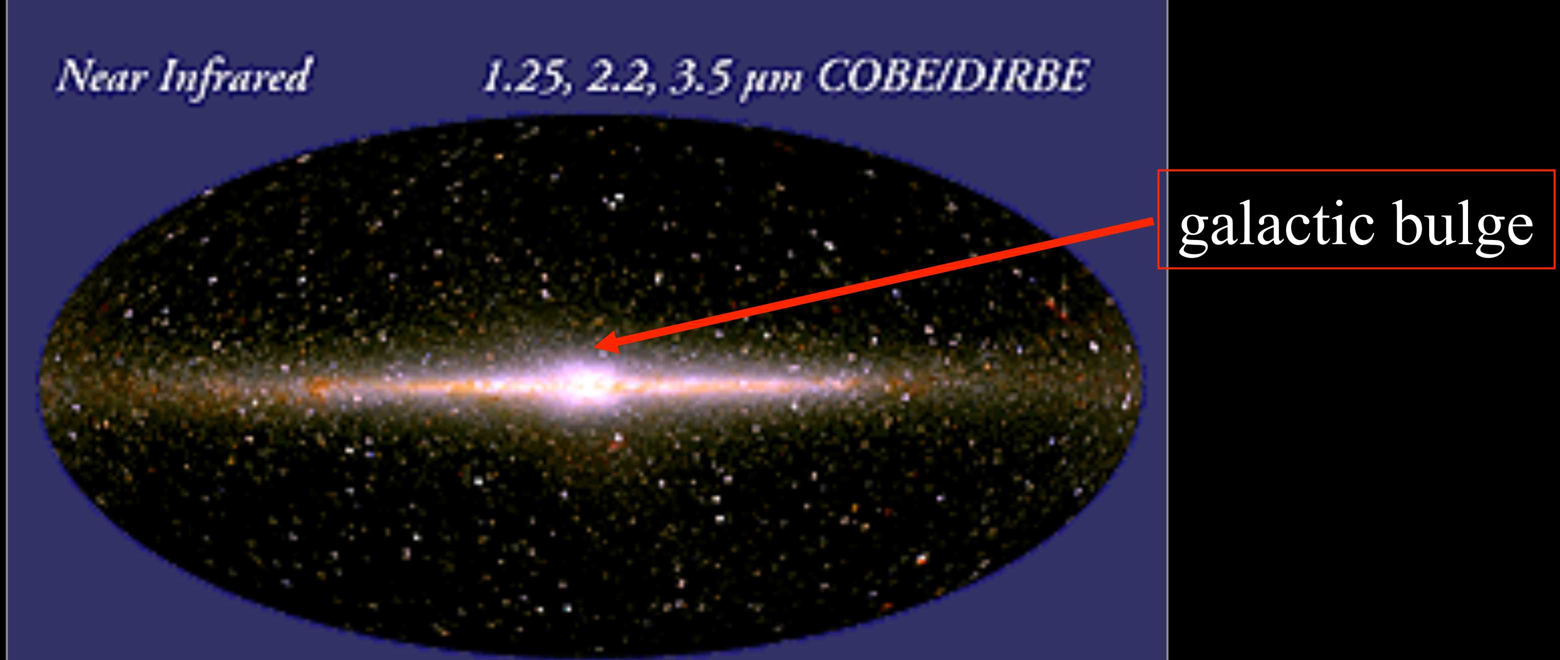
And collisions do not play any role in the gas

Structure of the Milky Way

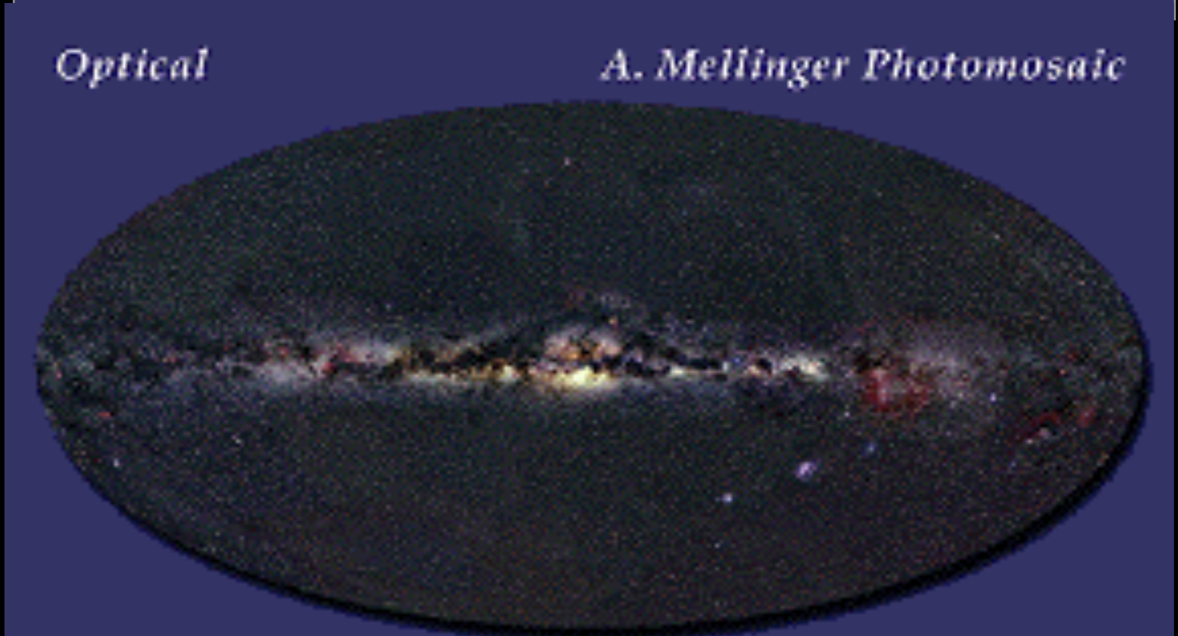
Distribution of stars and neutral hydrogen

Distribution of dust



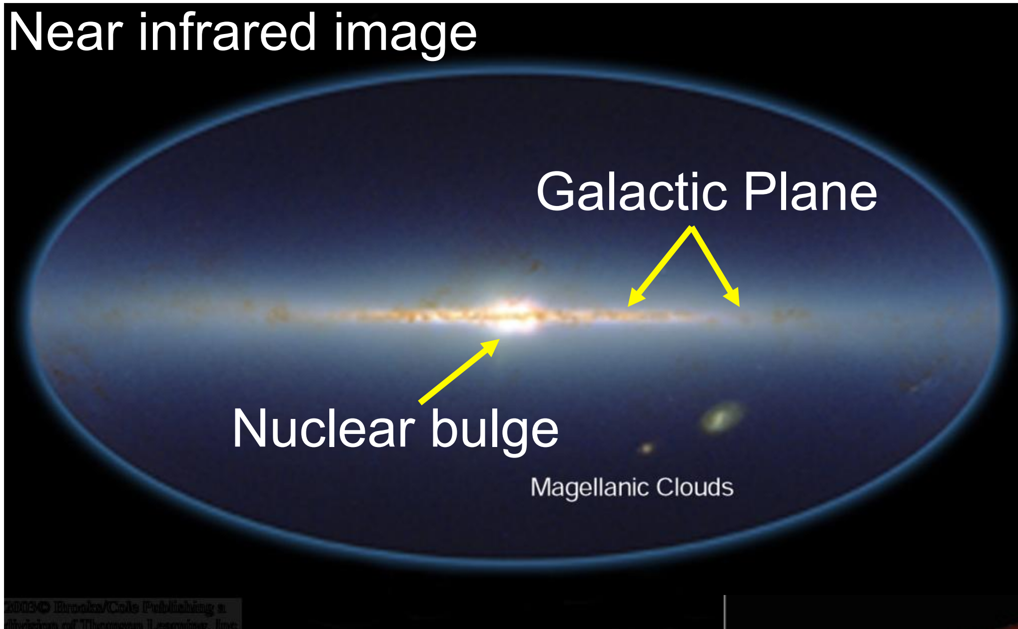


Distribution of Stars



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