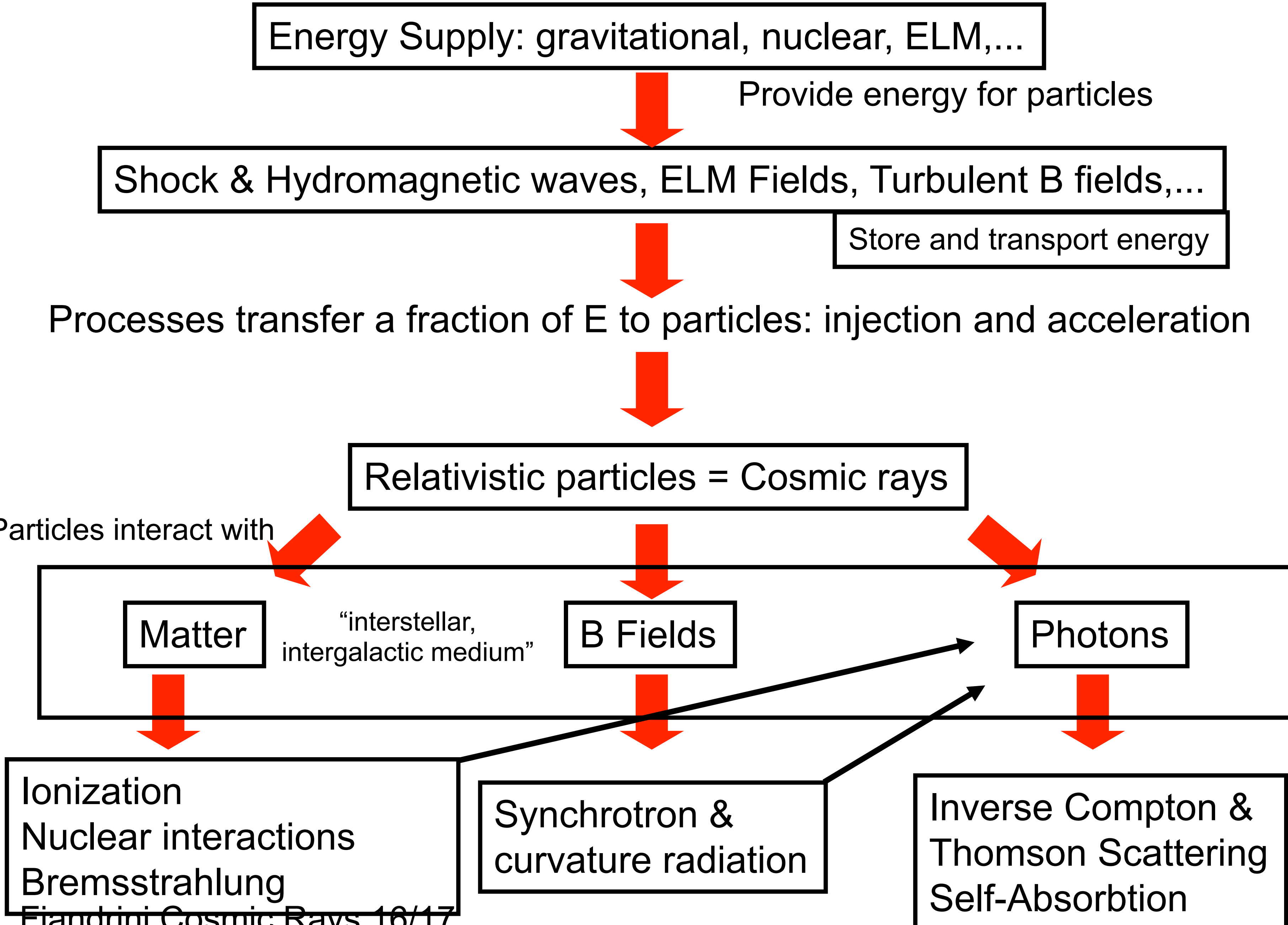
Lecture 3 101016

- Il pdf delle lezioni puo' essere scaricato da
- http://www.fisgeo.unipg.it/~fiandrin/didattica_fisica/cosmic_rays1617/

Formation and Interactions of CR's



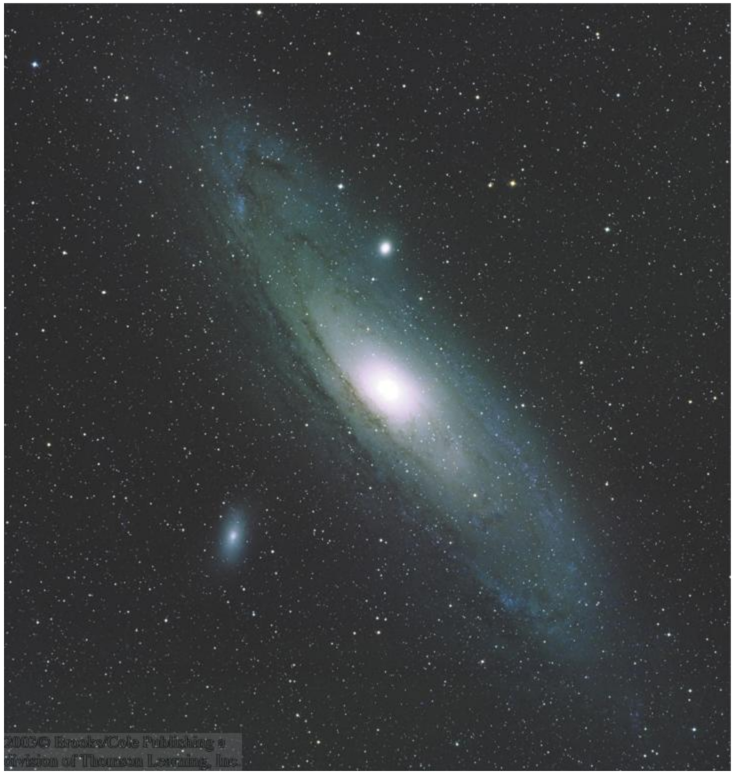
L'ambiente locale

- 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)

L'ambiente locale: la Via Lattea

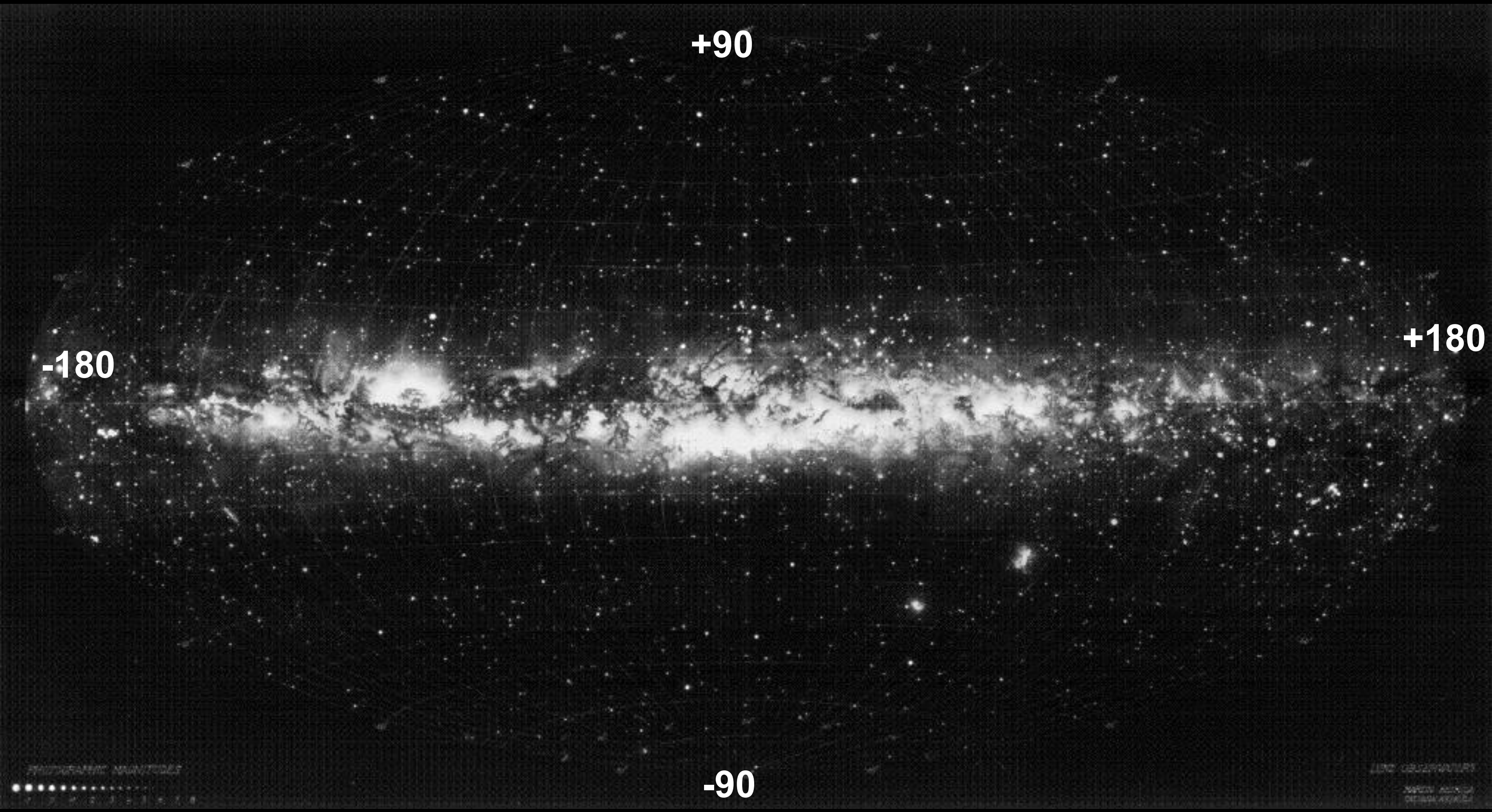


Almost everything we see in the night sky belongs to the Milky Way

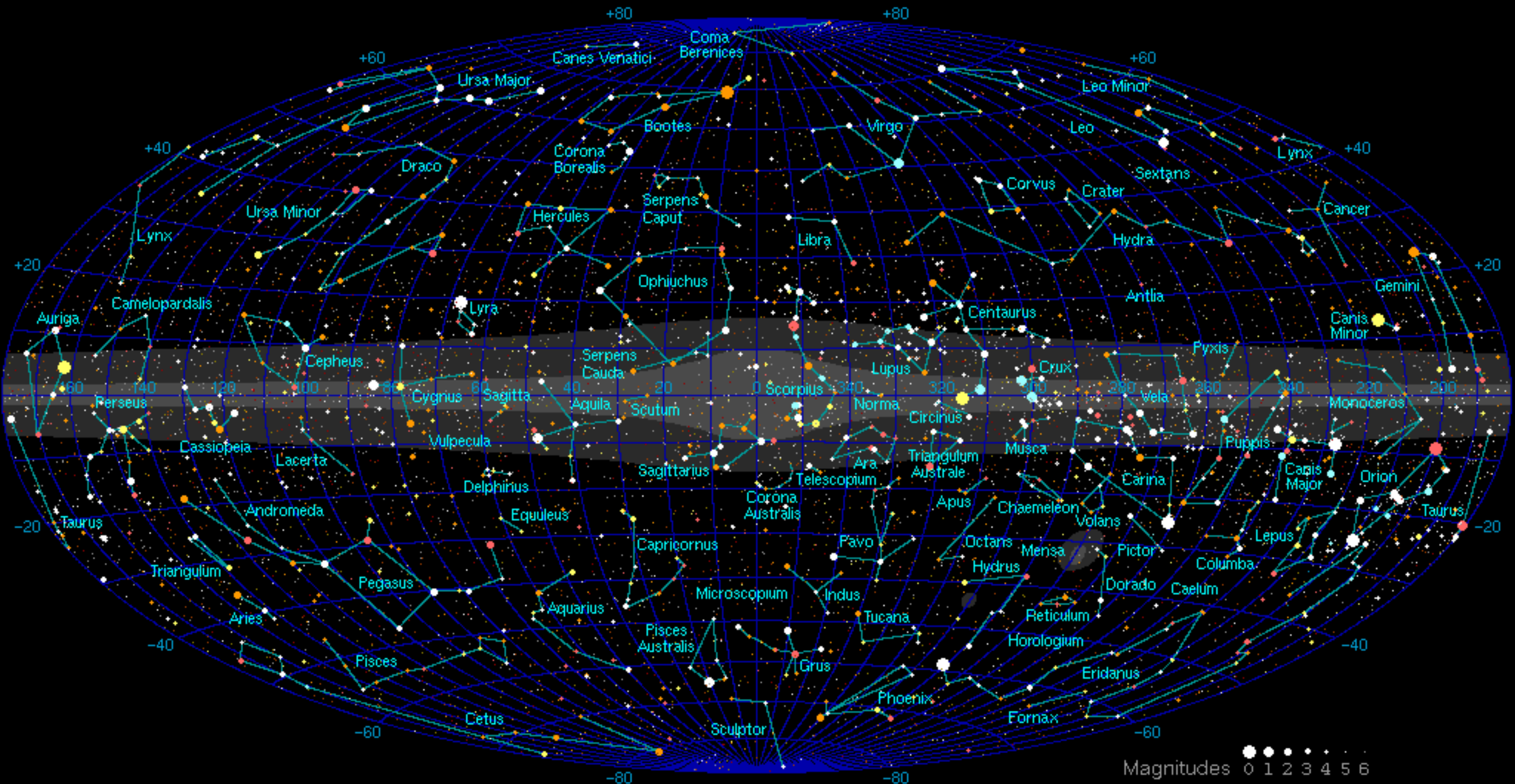
We see most of the Milky Way as a faint band of light across the sky

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

Per migliaia di anni l'uomo ha potuto vedere "questo" cielo



Banda ottica


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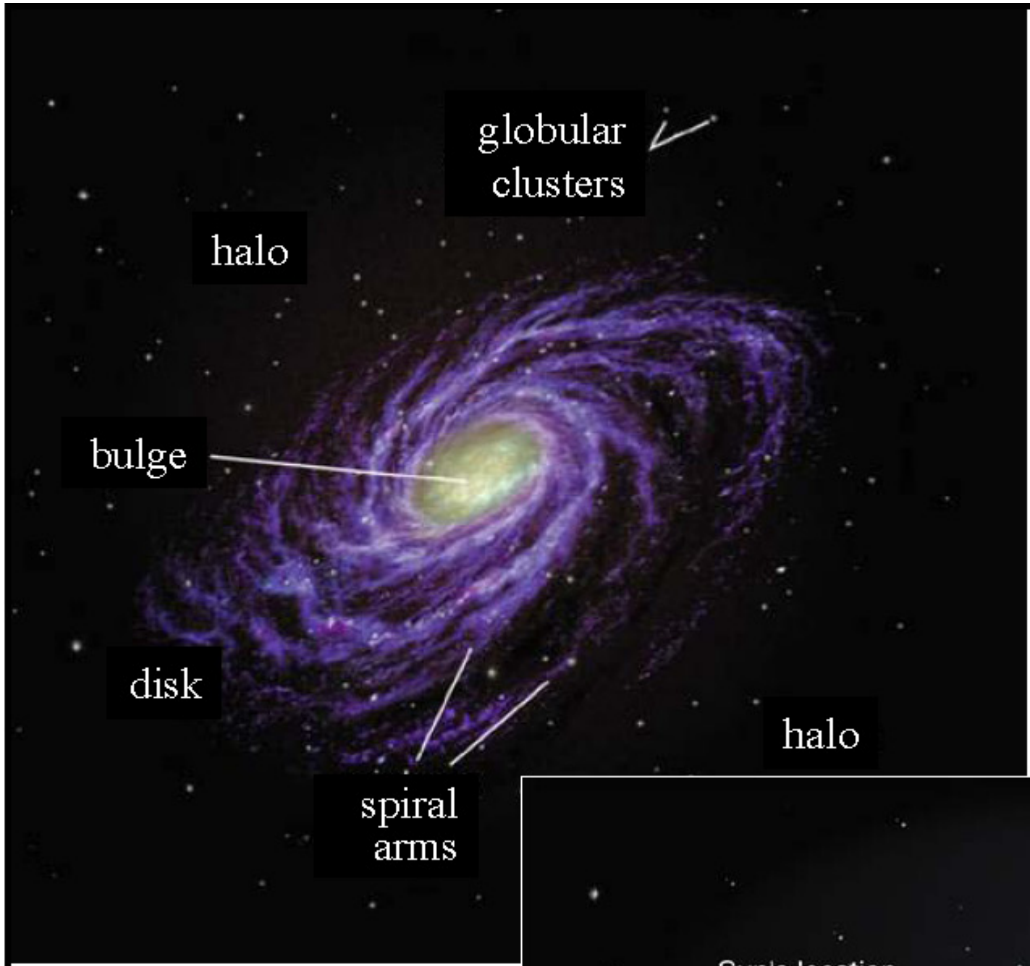
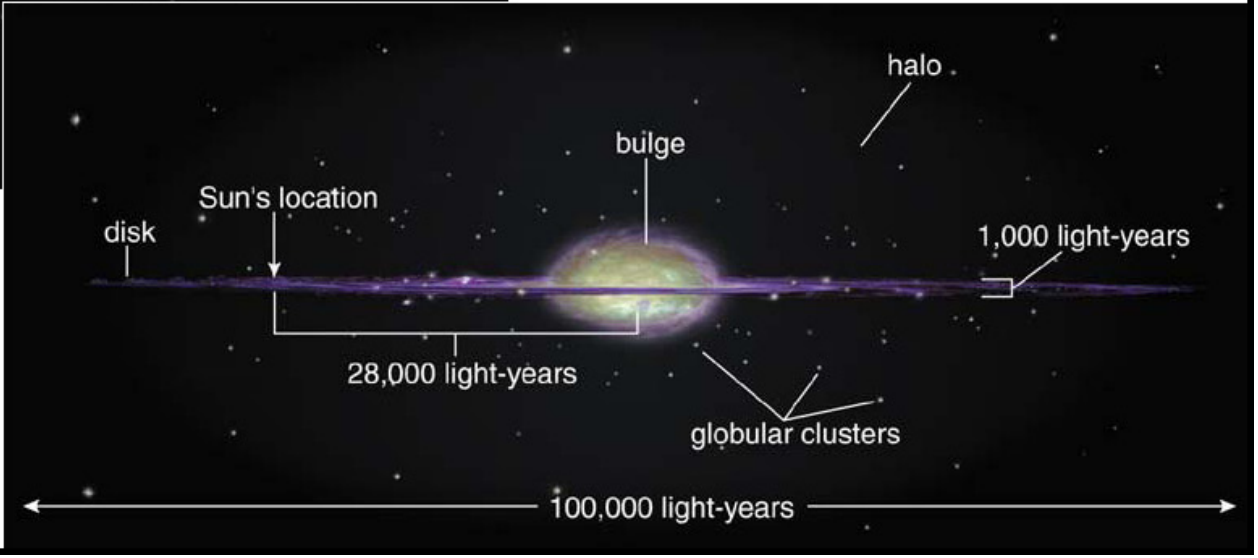
-60
-60
-80
-80
Coma Berenices
Canes Venatici
Ursa Major
Leo Minor
Bootes
Virgo
Leo
Lynx
Draco
Corona Borealis
Sextans
Corvus
Crater
Cancer
Serpens Caput
Ursa Minor
Hercules
Libra
Hydra
Lynx
Gemini
Ophiuchus
Camelopardalis
Antlia
Auriga
Lyra
Centaurus
Canis Minor
Cepheus
Serpens Cauda
Pyxis
Lupus
Crux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

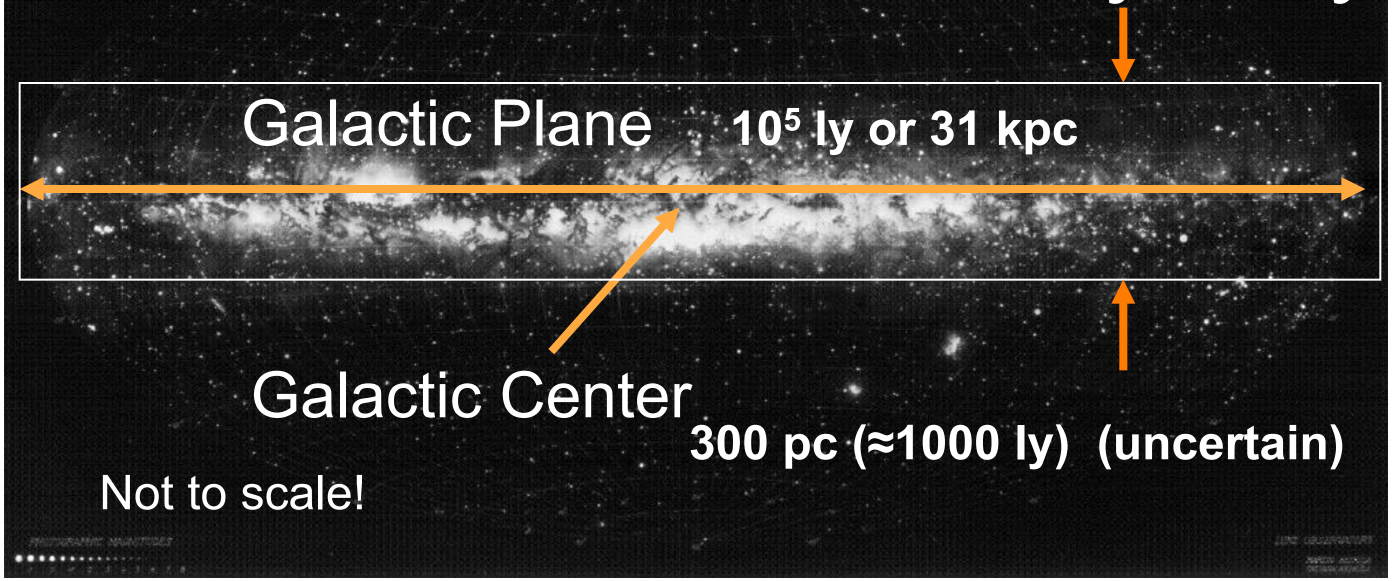
The Milky Way



- 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:

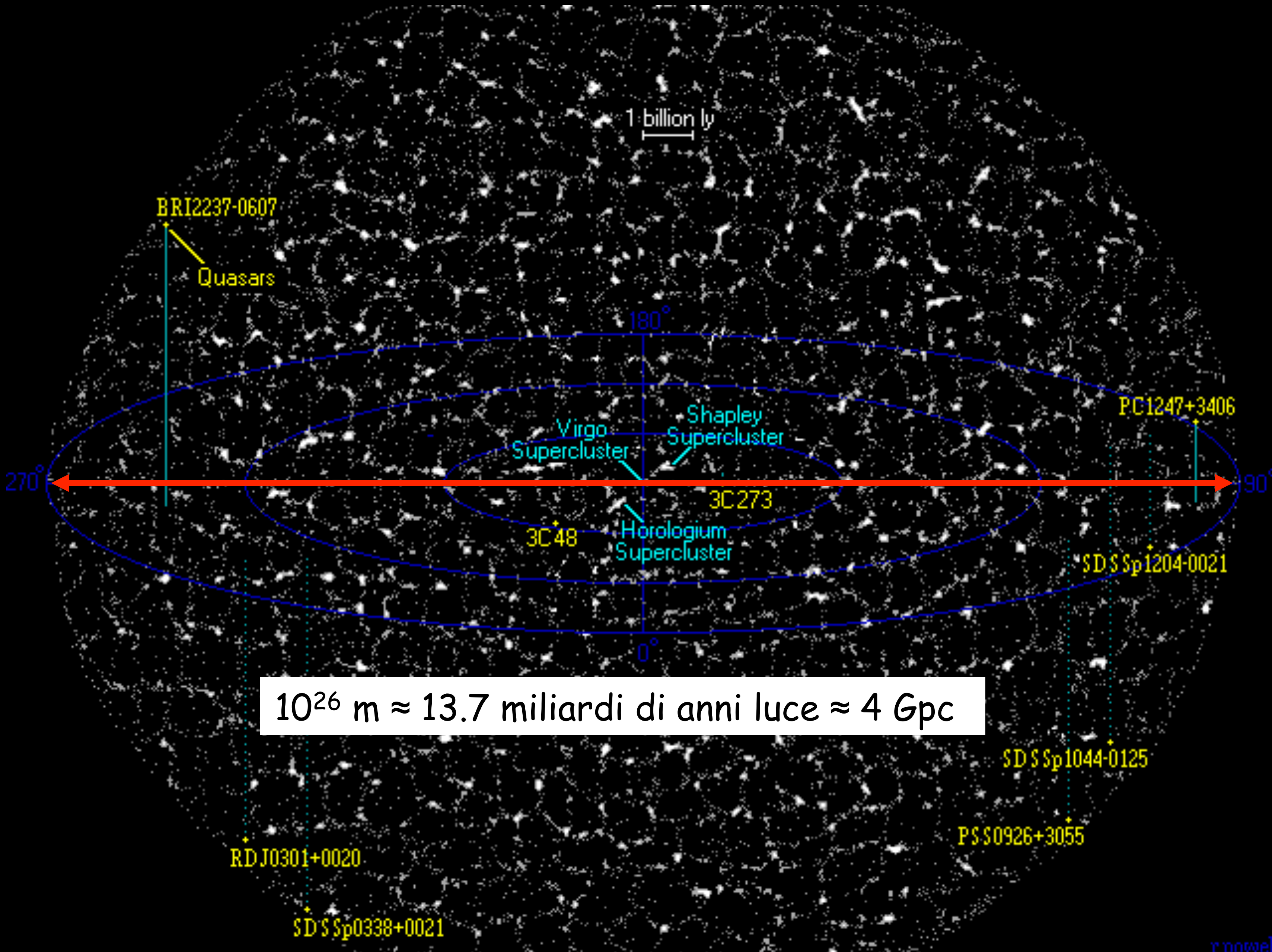
1) We are inside

2) Distance measurements are difficult

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

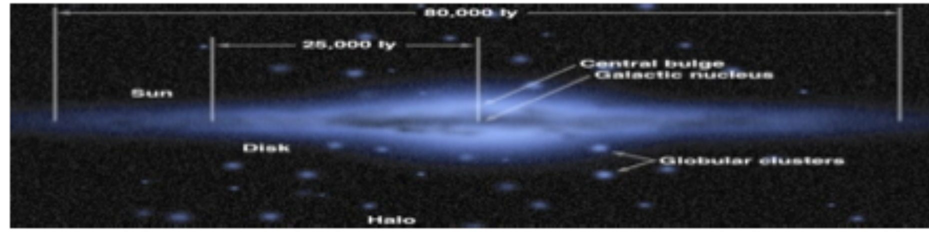
- The Milky Way is the second-largest galaxy in the Local Group, with its stellar disk approximately 100,000 ly (30 kpc) in diameter, and, on average, approximately 1,000 ly (0.3 kpc) thick. As a guide to the relative physical scale of the Milky Way, if the Solar System out to Neptune were the size of 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)

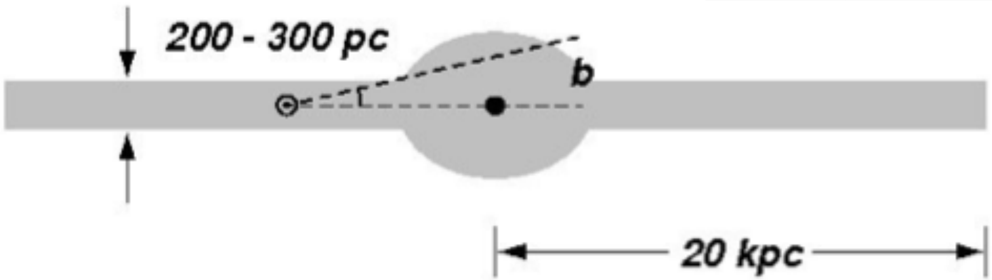
L'intero Universo



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.

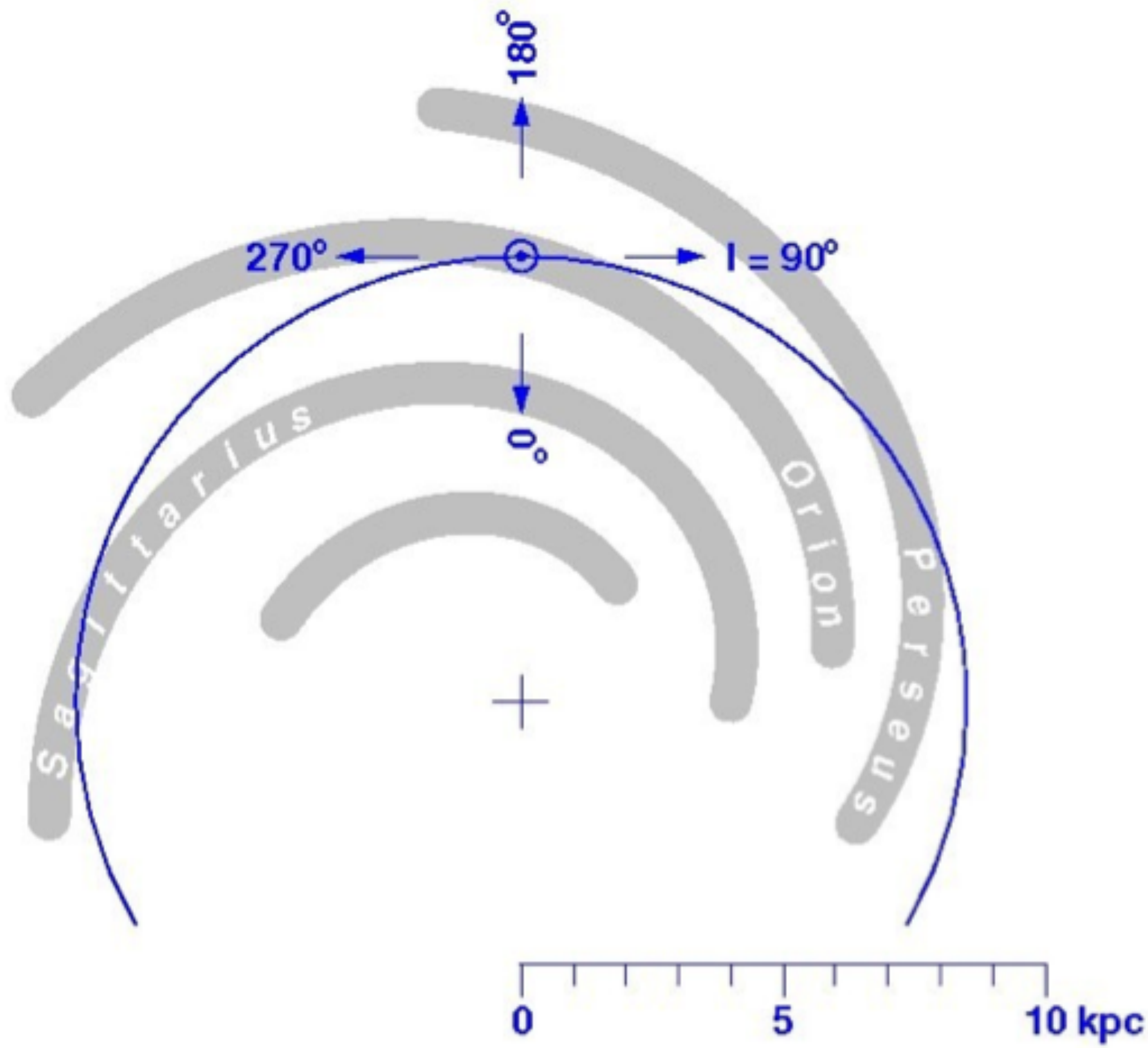
Galactic latitude *b* is the angle at which an object is above the galactic plane.

View of the galactic plane from the galactic North Pole

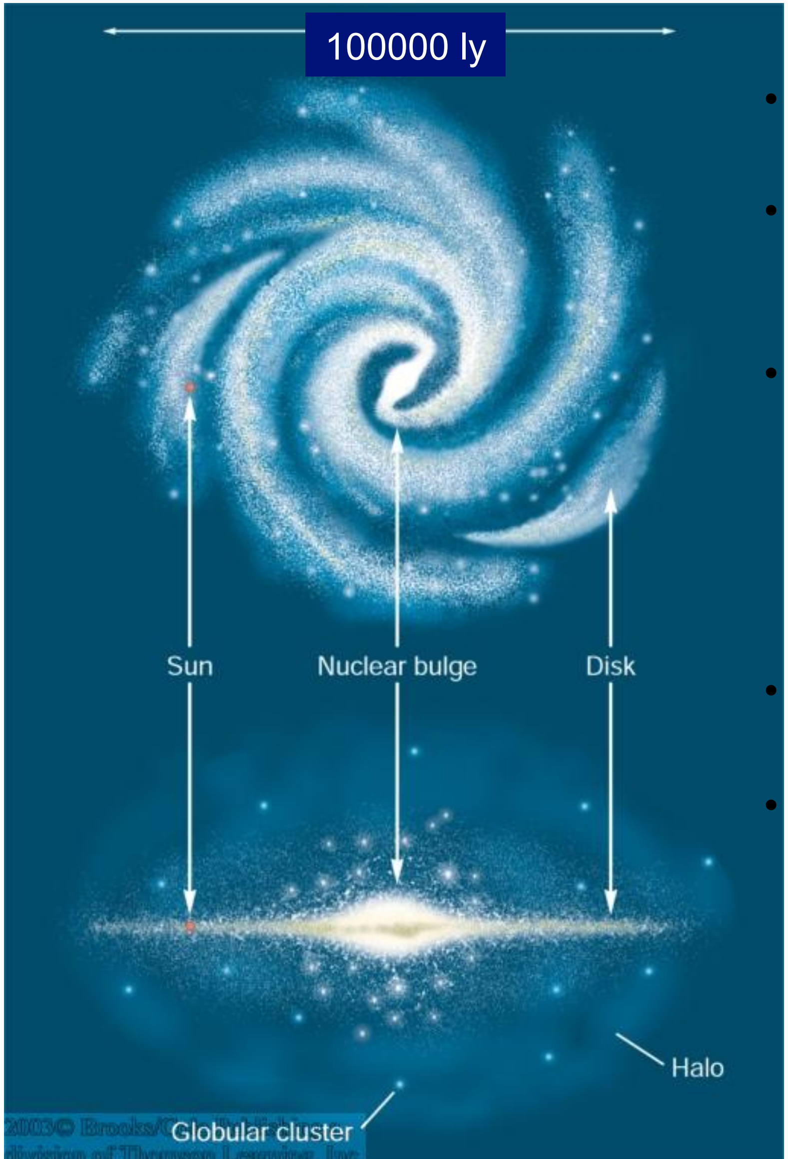
Galactic longitude *l* is measured counter clockwise from the direction of the galactic center.

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 $5.8{\times}10^{11}\ M_\odot$ and $8.5{\times}10^{11}\ M_\odot$ 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 $1\text{–}1.5{\times}10^{12}\ M_\odot$. More-recent studies indicate a mass 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 $6.43{\times}10^{10}\ M_\odot$.
- 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^{++}

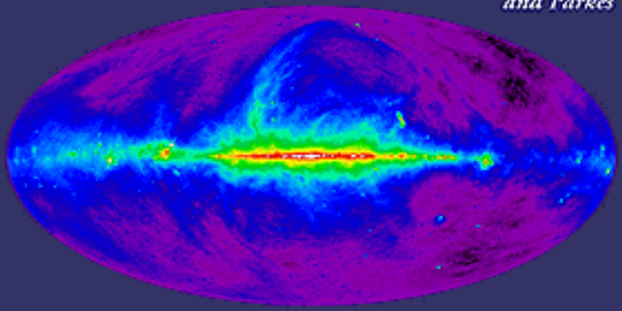
Galaxy

Milky Way we can “see” is made of:

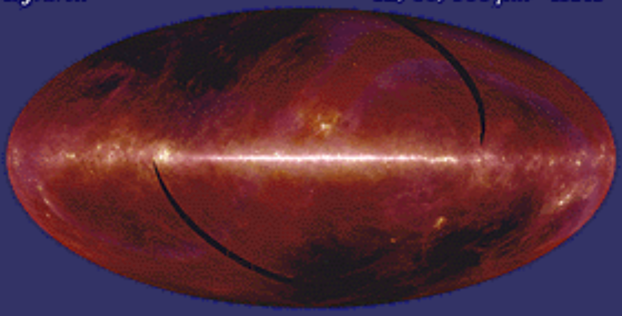
- Stars
- Dust
- Cold and hot gas of the InterStellar Medium
- Magnetic Fields
- Cosmic rays

(...and dark matter...)

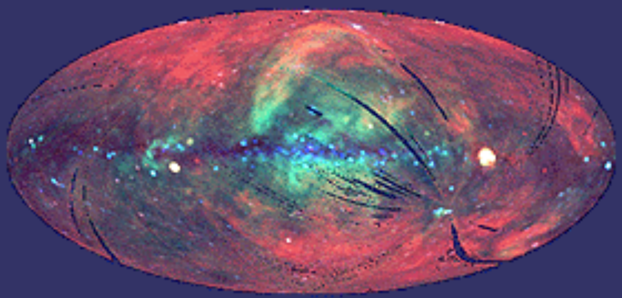
Radio Continuum (408 MHz) Bonn, Jodrell Bank, and Parkes



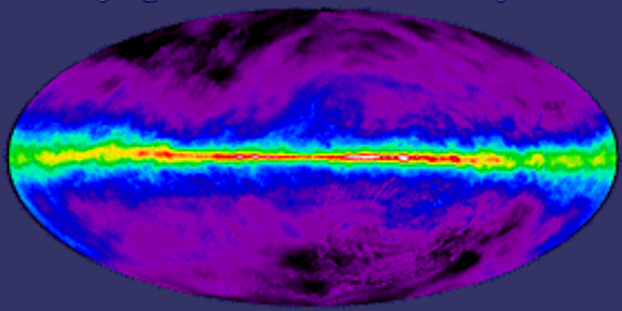
Infrared 12, 60, 100 μm IRAS



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

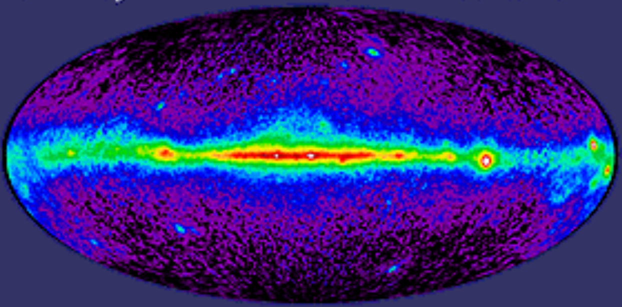


Atomic Hydrogen 21 cm Dickey-Lockman

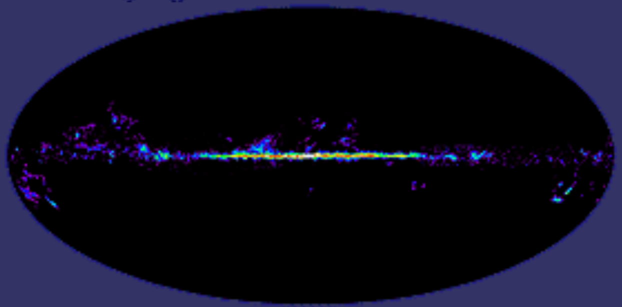


Multiwavelength vision must be used to see different components of the galaxy

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

Constituents of the ISM

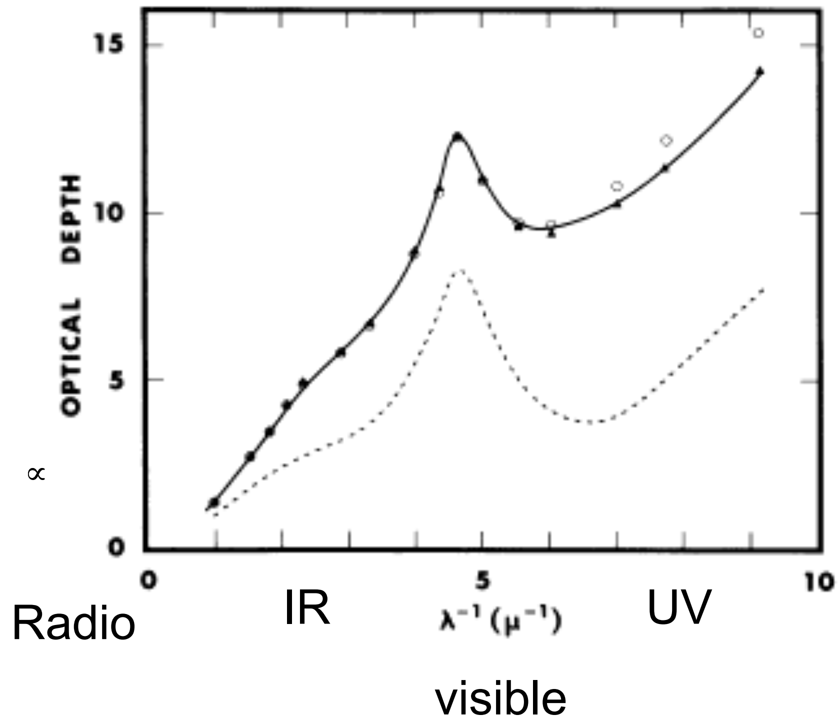
constituents of ISM in Milky Way	where	temperature density ...	how observed
atomic hydrogen HI	in disk, some in halo $\approx 90\%$ of mass, 50% of vol.	$50...300$K $1...100$cm^{-3}	21cm radio line UV absorption lines
molecular hydrogen H_2	dark clouds in disk $\approx 10\%$ of mass, 1% of vol.	$3...100$K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

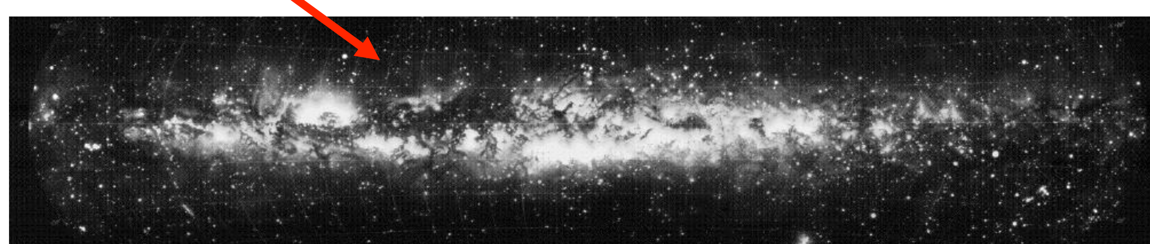
The total mass of the ISM in the Milky Way amounts to $\approx 15\%$ of the mass in stars, which is a typical value for spiral galaxies in general.

Polvere interstellare: estinzione

- 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** – $n_d/n \sim 10^{-12}$

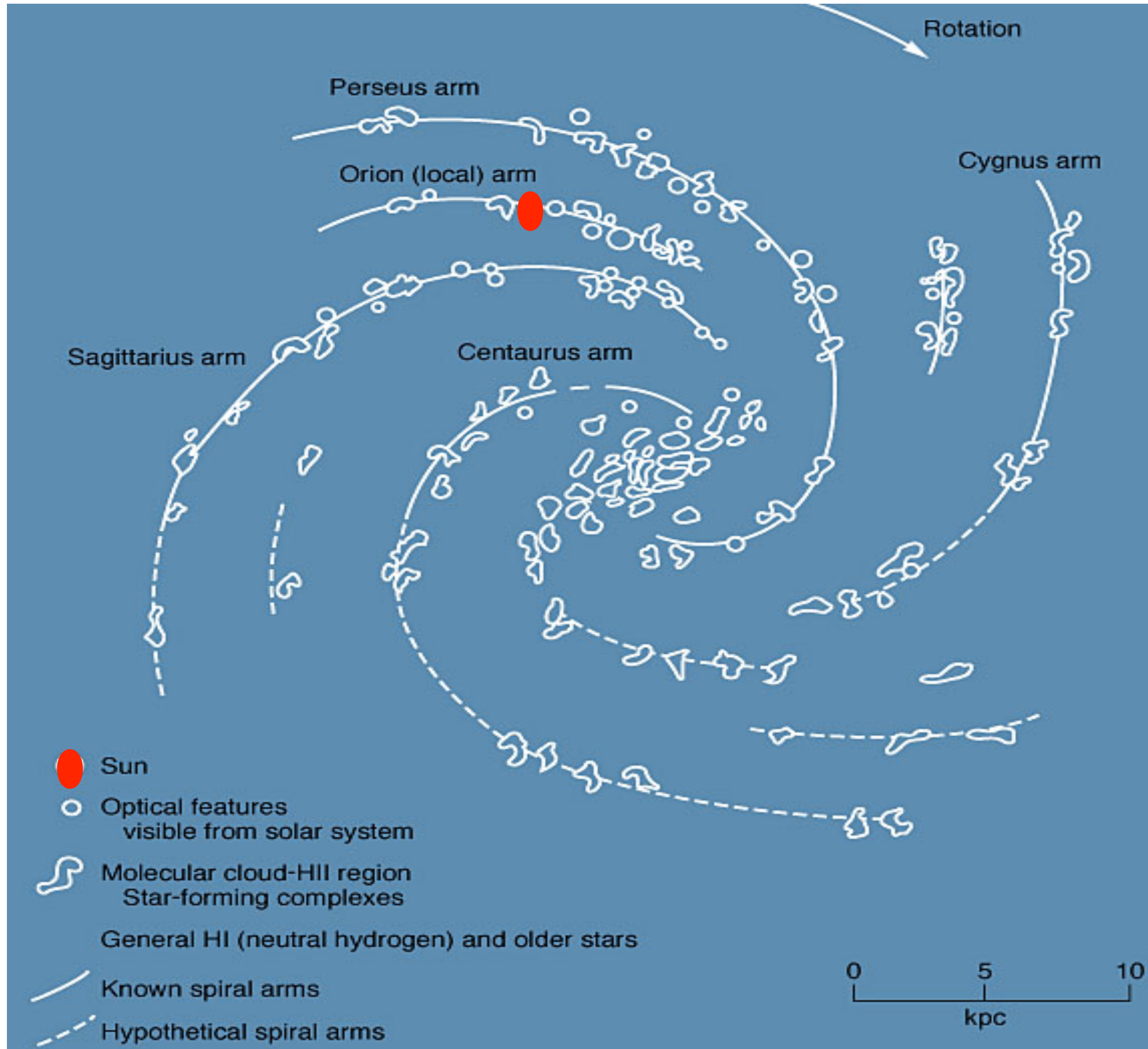
The interstellar extinction curve





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



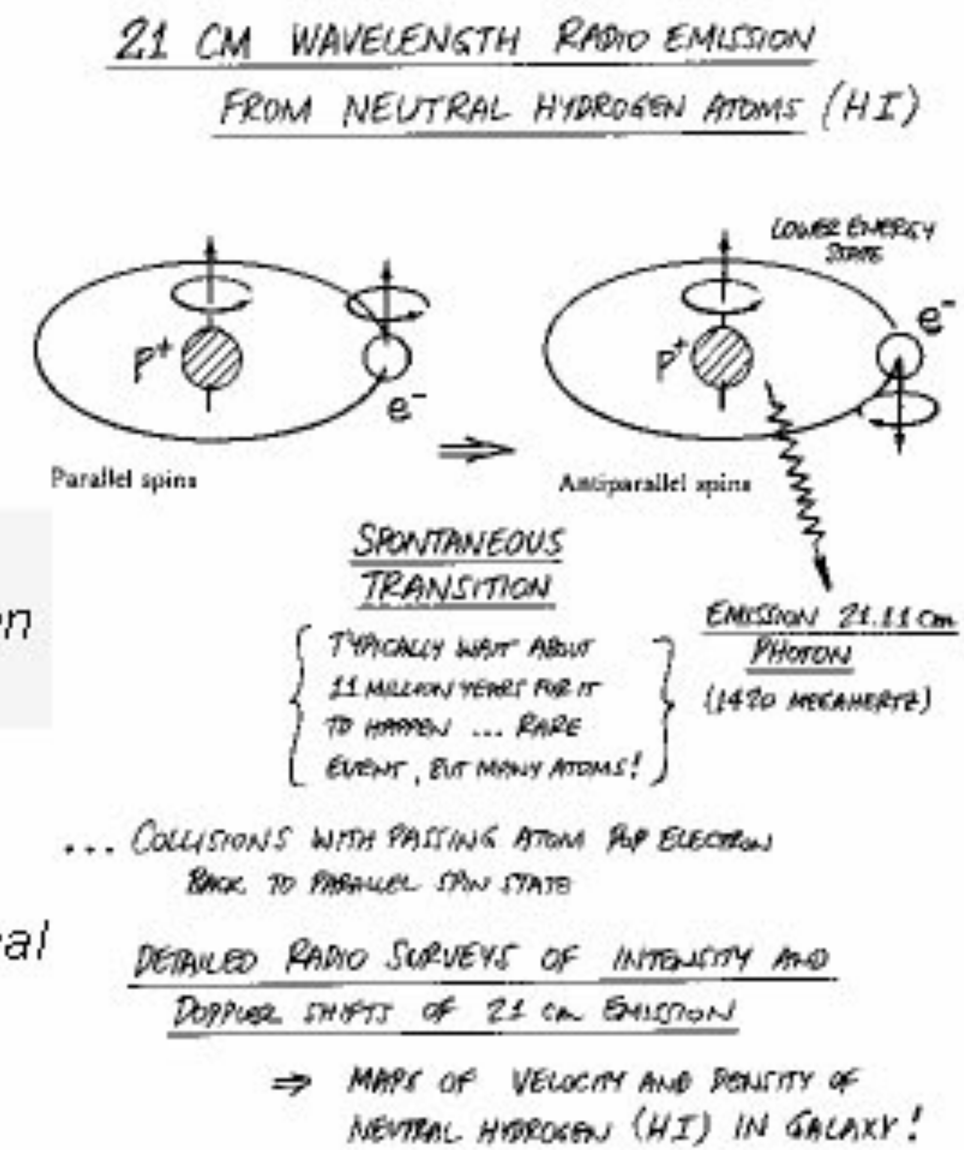
Nubi Gassose

- 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

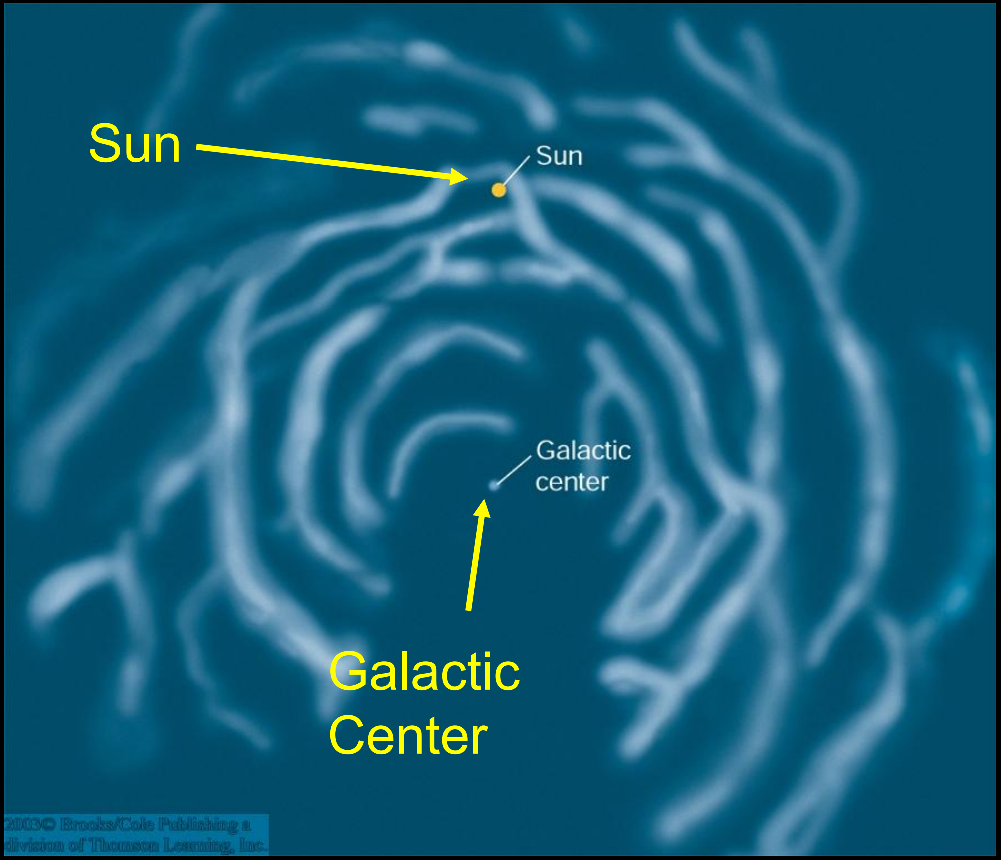
Neutral H consists of a single proton (p) and single e-. p and e- also have spin. The spin of the e-and p can be in either direction - in the classical analogy they are rotating clockwise or anticlockwise around a given axis.

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 $2.9 \times 10^{-15}\ s^{-1}$.
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

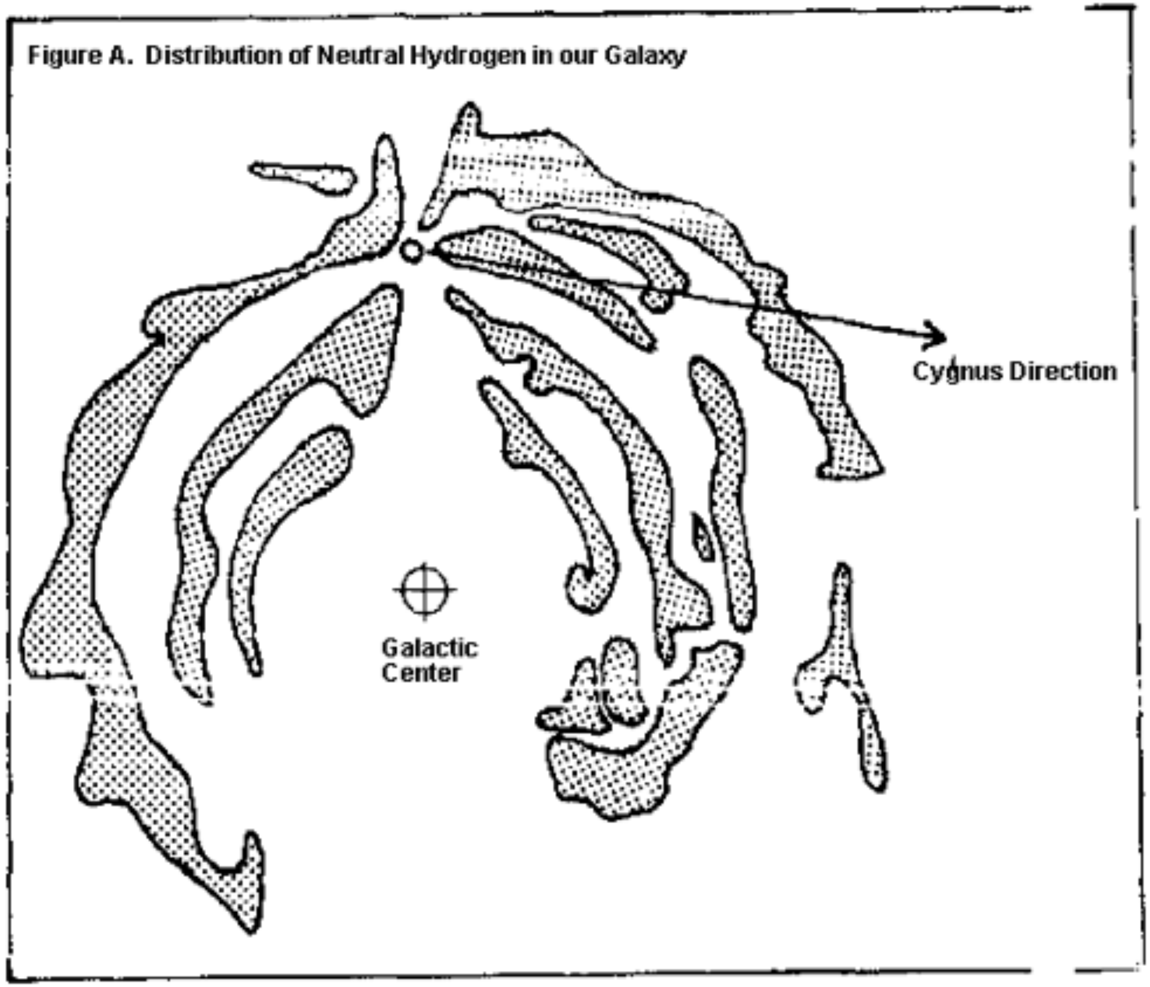
21-cm radio observations reveal the distribution of neutral hydrogen throughout the galaxy



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

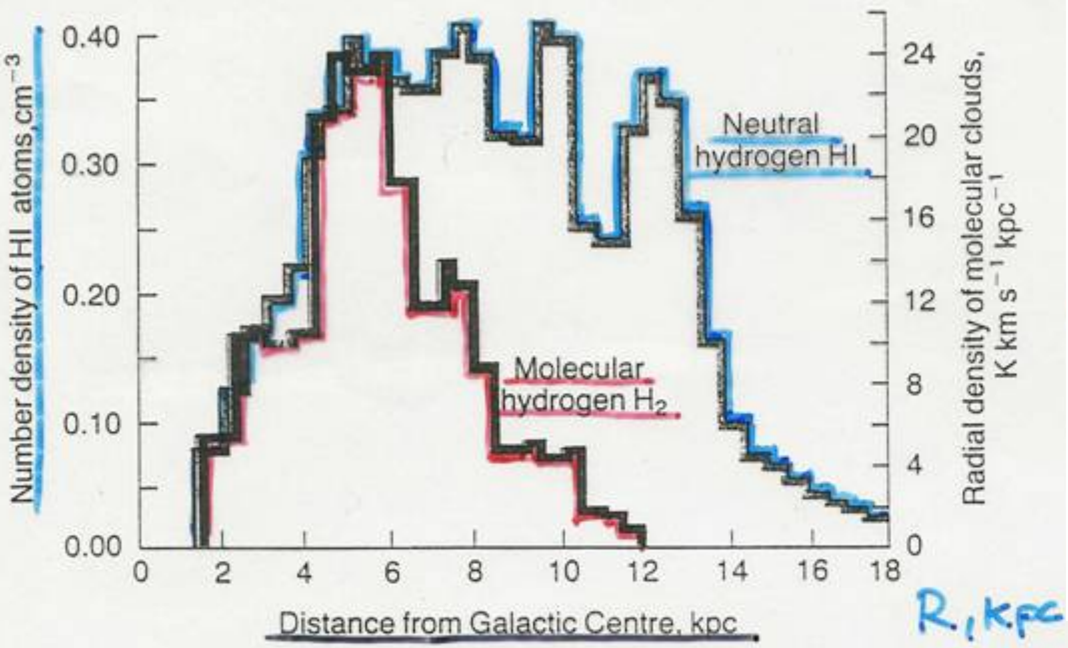


Figure 17.2. The radial distribution of atomic and molecular hydrogen as deduced from radio surveys of the Galaxy in the 21-cm line of atomic hydrogen and from millimetre surveys of the molecular emission lines of carbon monoxide, CO. (After D. Michalis and J. Binney (1981). *Galactic astronomy: structure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

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

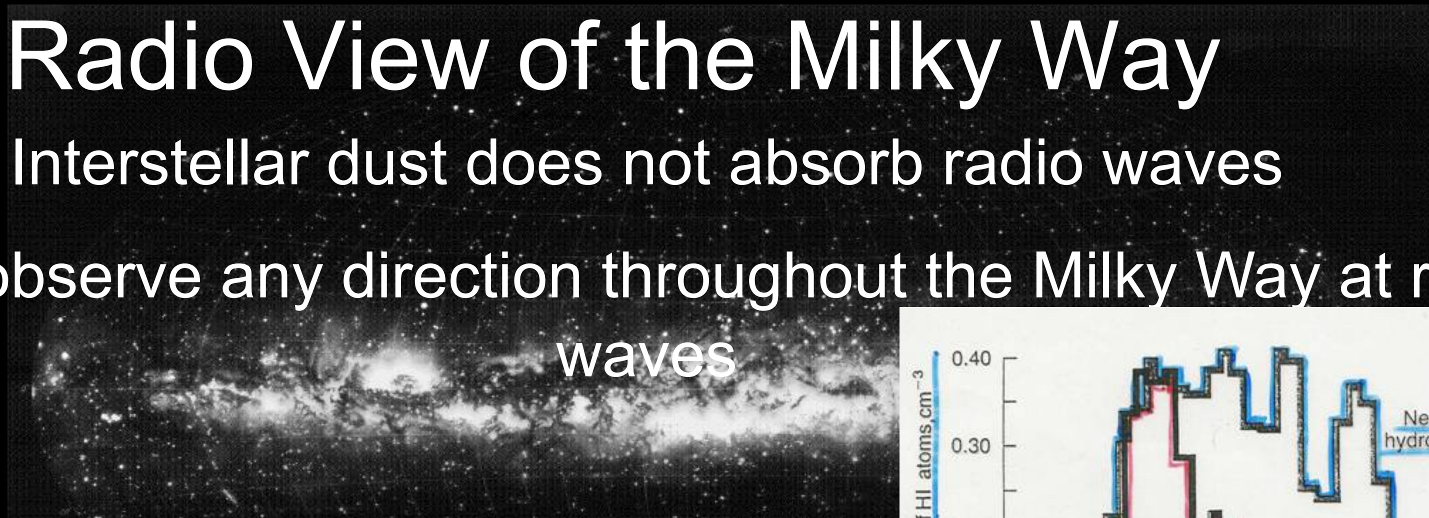
IL MEZZO INTERSTELLARE

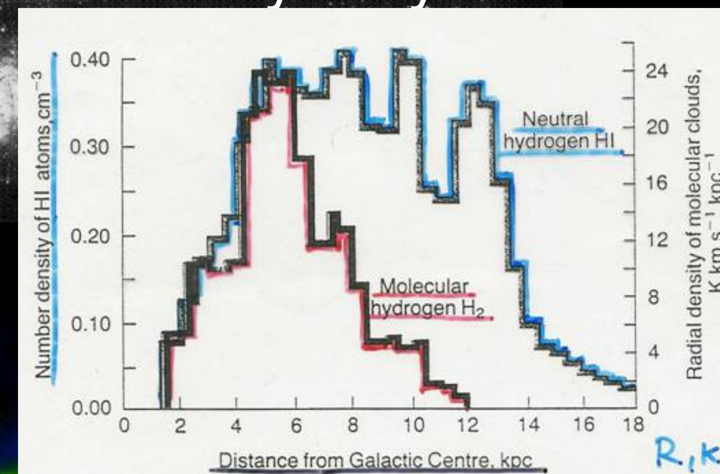
NOME	COSTITUENTI	Rivelati da...	% VOLUME e MASSA del Mezzo Int.		N (cm^{-3})	T (K)
MOLECOLARI NUBI	H_2, CO CS etc	Linee molecolari Emiss. Polveri	~0.5%	40%	1000	10
NUBI DI H NUBI DIFFUSE	H, C, O neutri	linea di 21 cm Linee Assorbim.	5%	40%	1-100	80
INTER NEBULE	H, H^+, e^- (ionizz. 10%)	21 cm + assorbim.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





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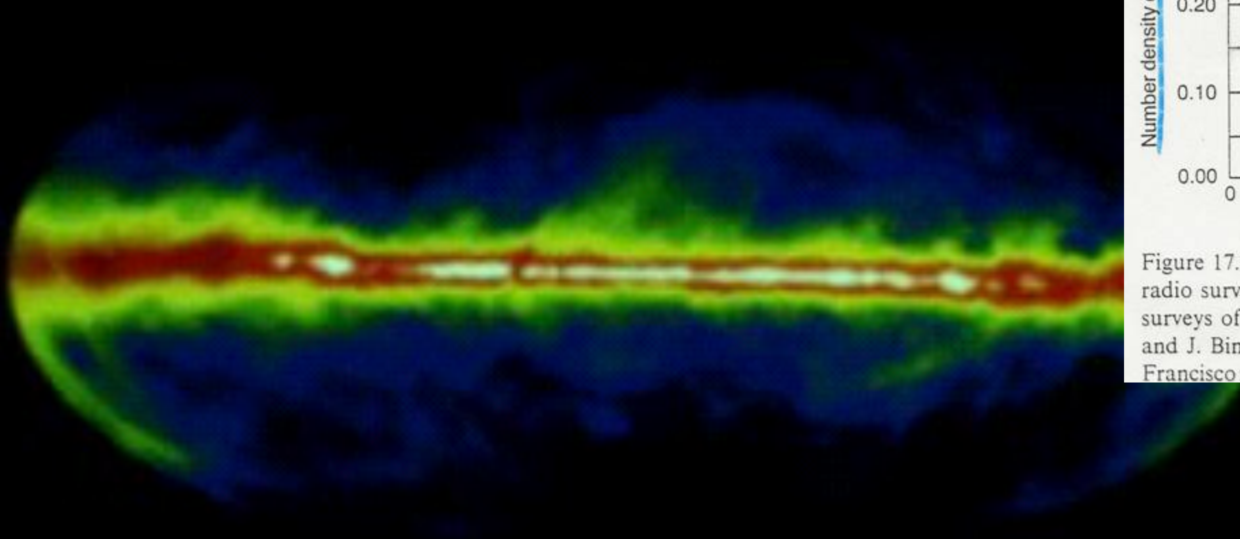


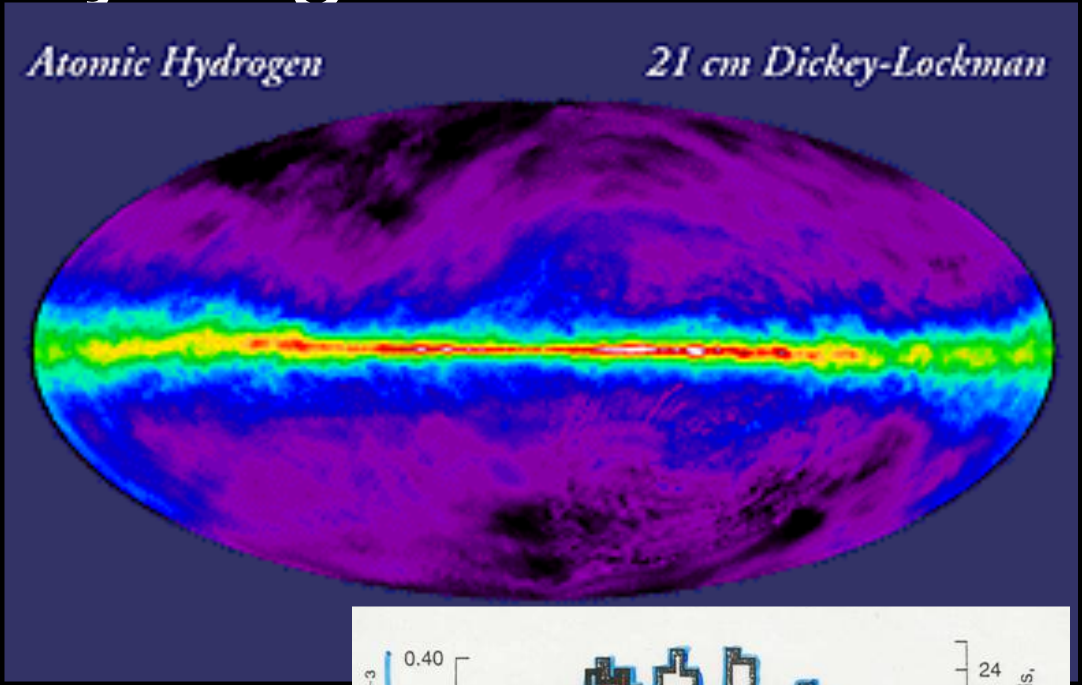
Radio map at a wavelength of 21 cm, tracing neutral hydrogen

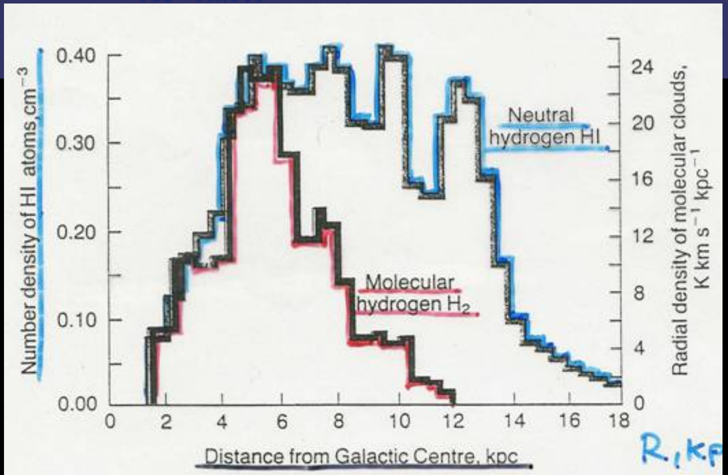
Atomic Hydrogen HI

- **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).





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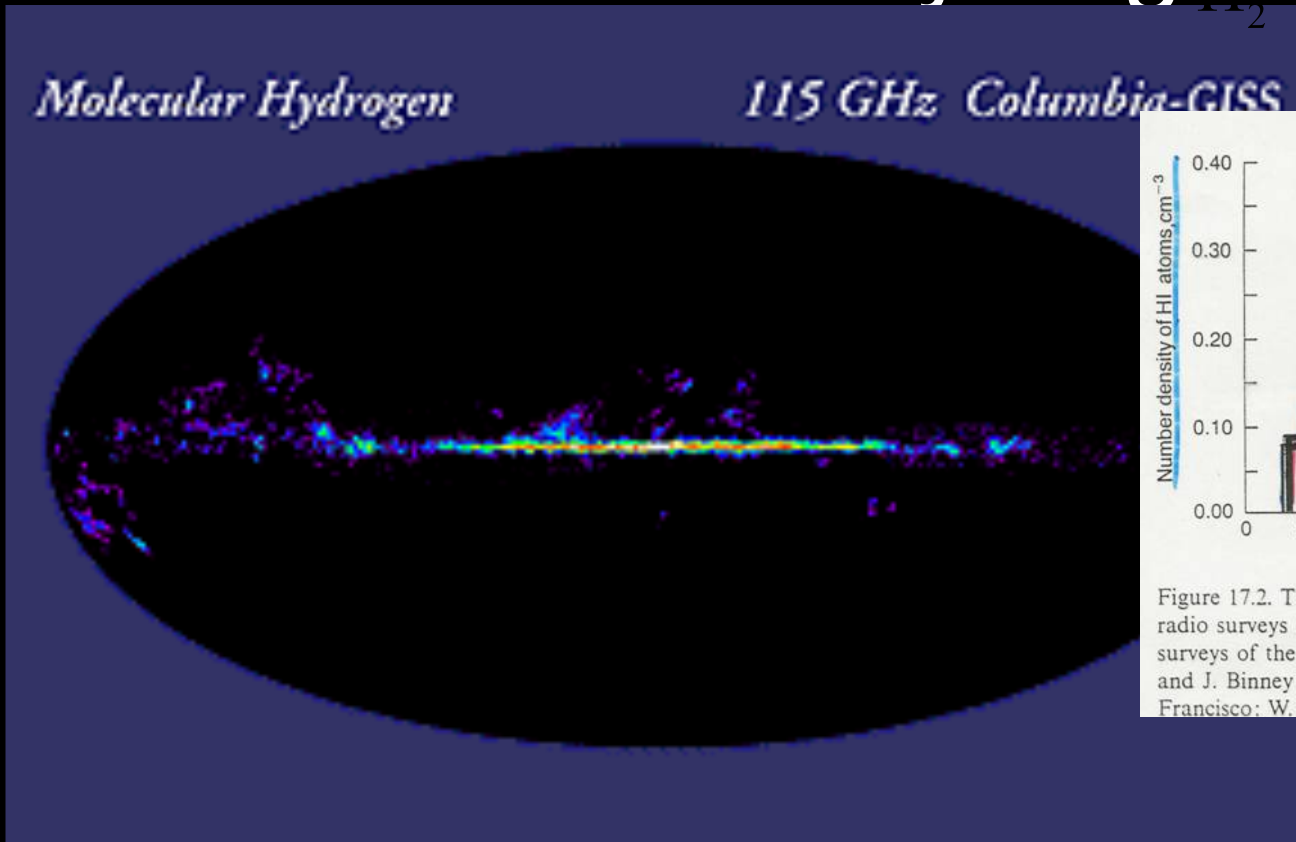
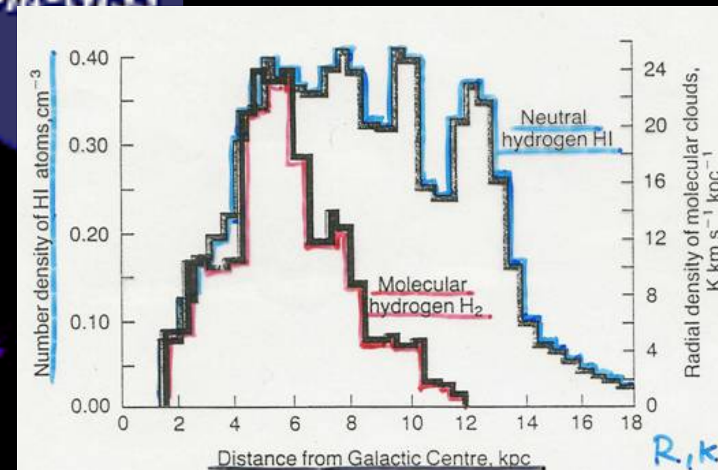
Molecular Hydrogen H_2





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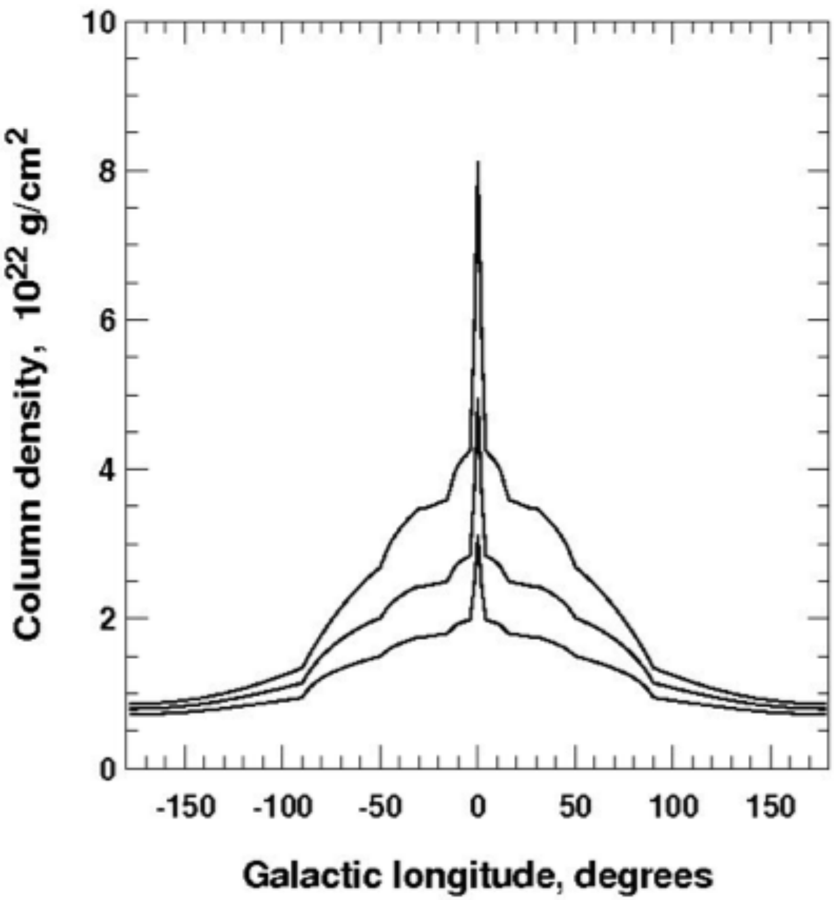
- The **very thin layer** of cold gas clouds is studied mostly via **CO line transitions** (mm waves , 2.6 mm).

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

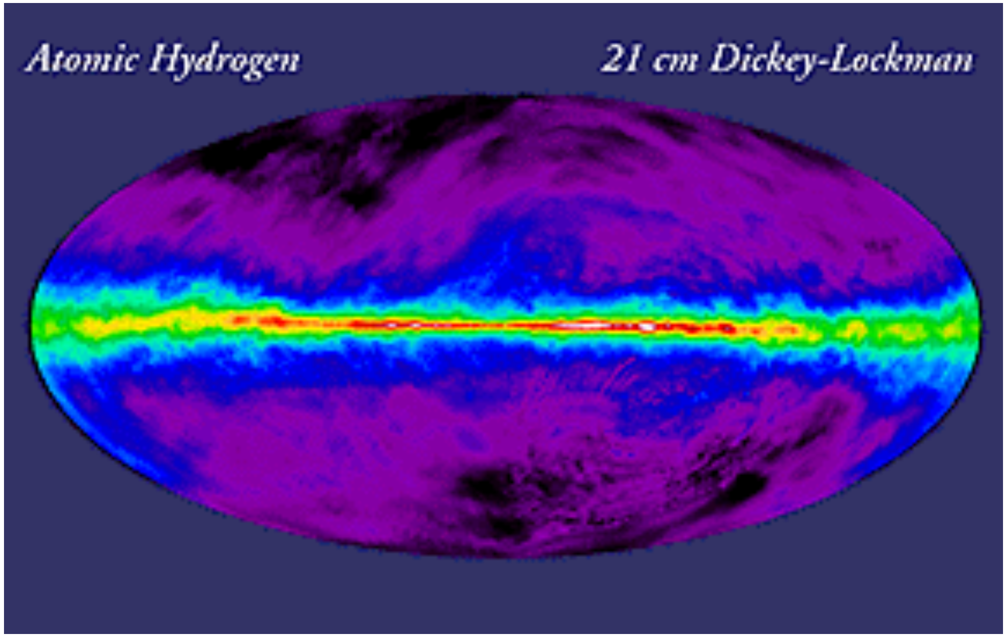


The matter density is not uniform. The sketch on the left gives an idea about the column density in the Galaxy 2, 5, and 10 deg around the galactic plane.

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

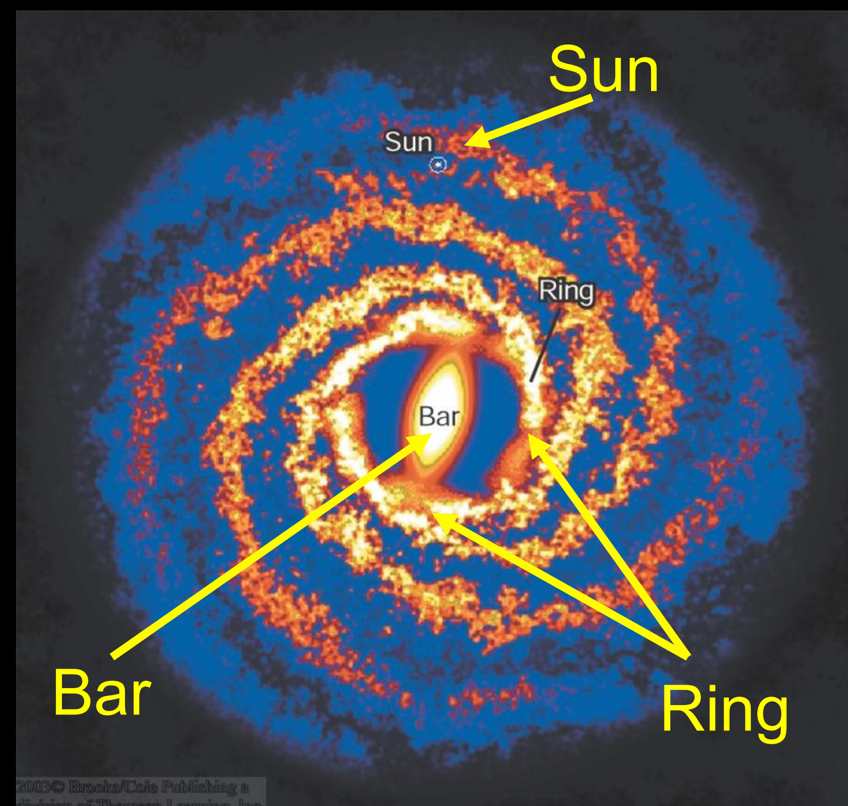
→ Most atoms will be in their ground state.

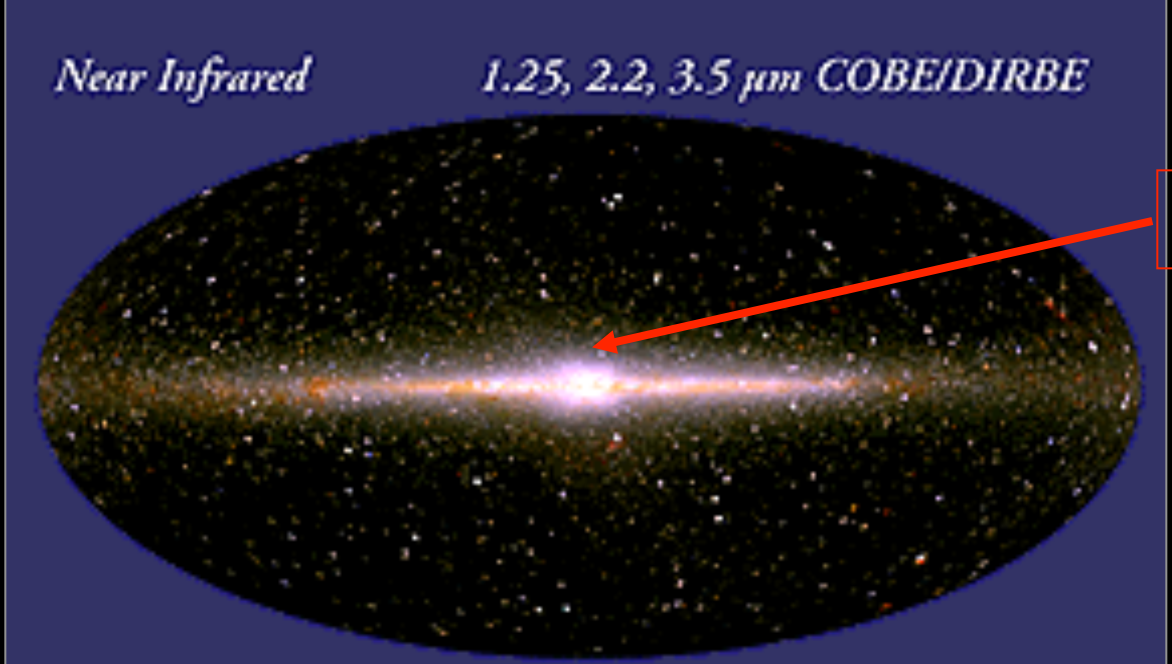
And collisions do not play any role in the gas

Structure of the Milky Way

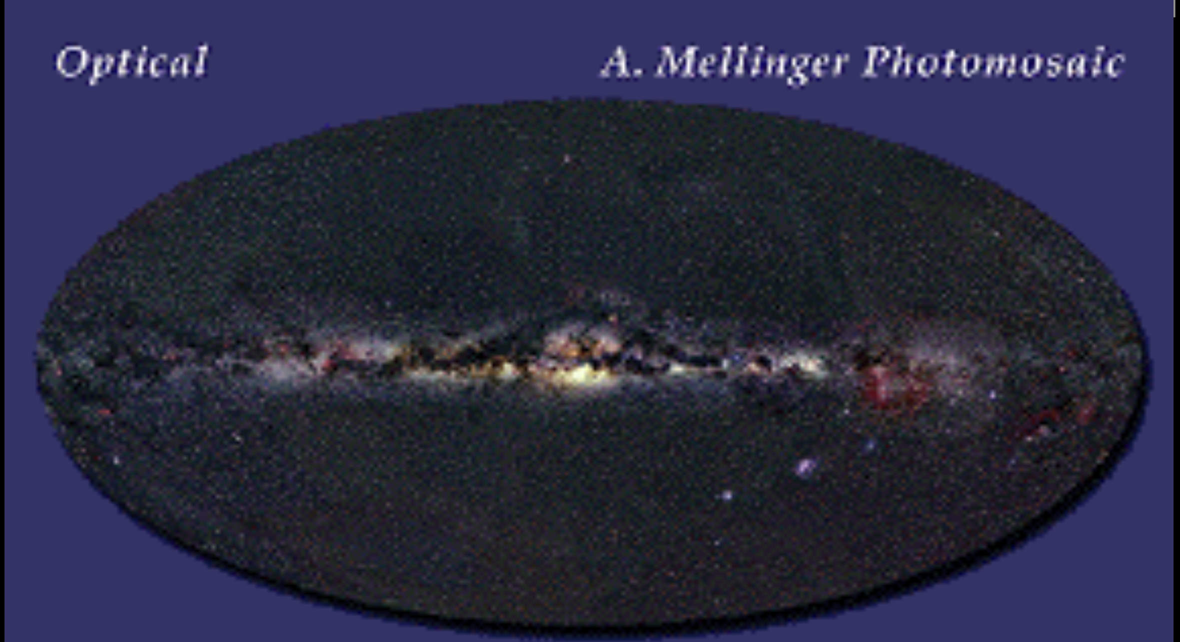
Distribution of stars and neutral hydrogen

Distribution of dust



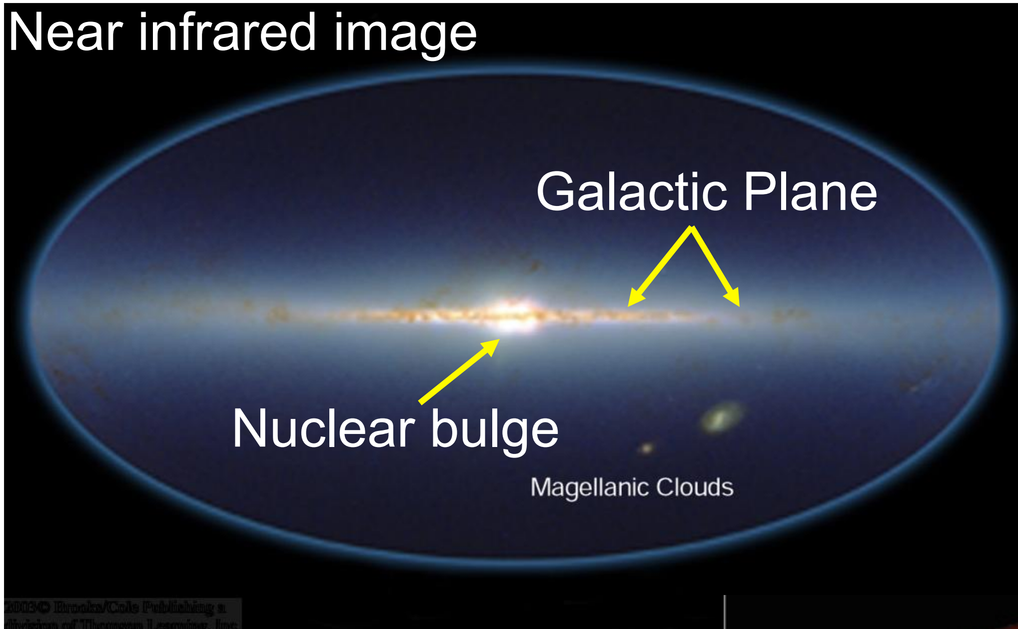


Distribution of Stars



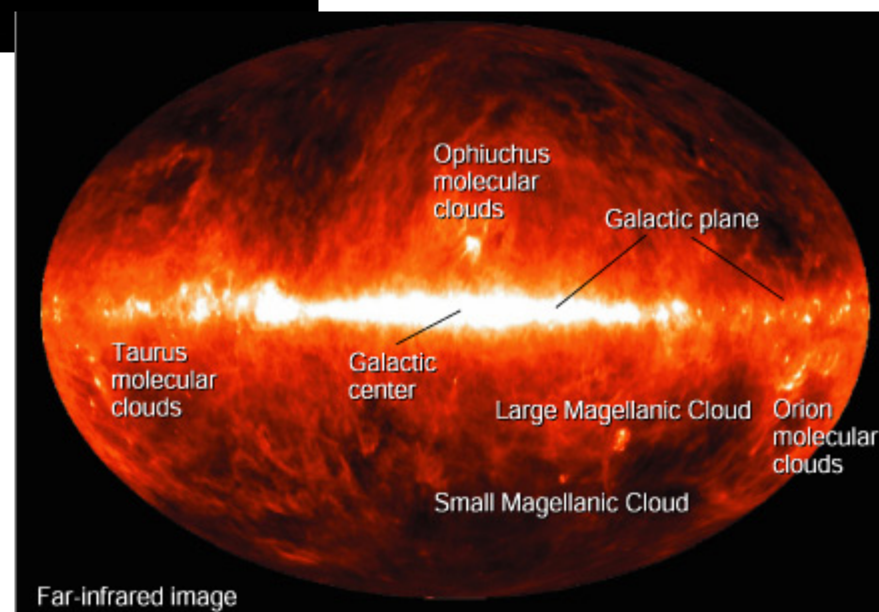
Interstellar dust is visible

Infrared View of the Milky Way

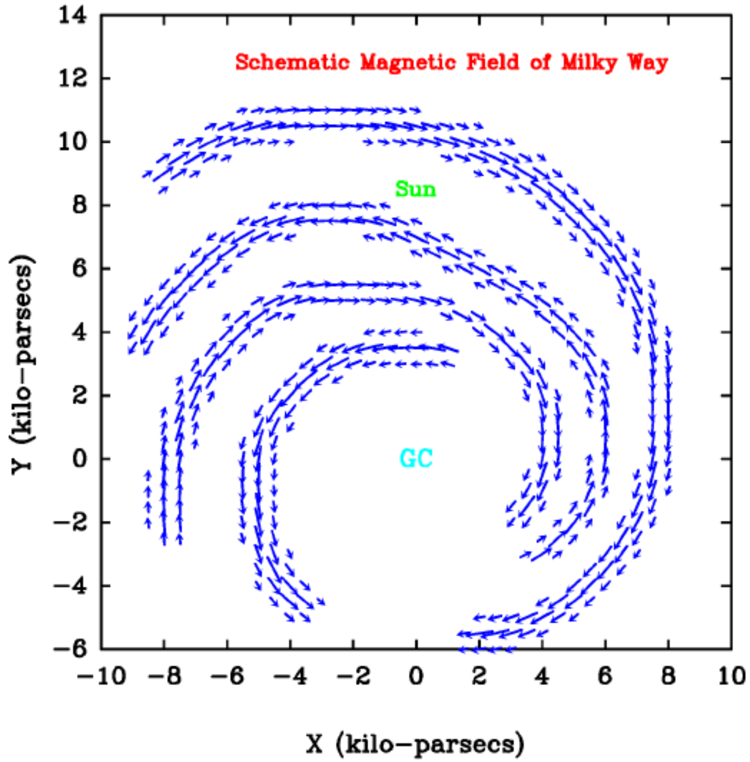


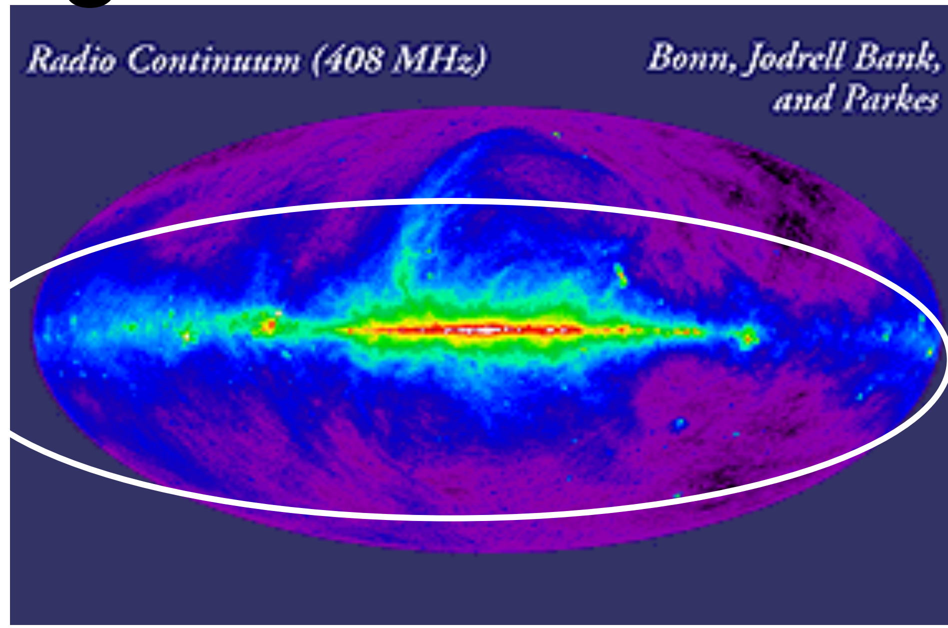
Interstellar dust (absorbing optical light) emits mostly infrared

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



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

Galactic Magnetic Field

- Galactic magnetic field is irregular in the sense that it shows different intensities and directions distributed randomly in the galaxy
- Usually, B is decomposed in two components:
  - Regular, large scale average field B_o
  - Random small scale irregularities $\delta B(x)$ of the field

$$B(x) = Bo + \delta B(x)$$

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 rotate 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 $\longrightarrow$ $\boxed{\beta = RM \cdot \lambda^2}$ (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.

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

- The effect caused by free electrons: the electric field of a circularly polarized wave cause 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

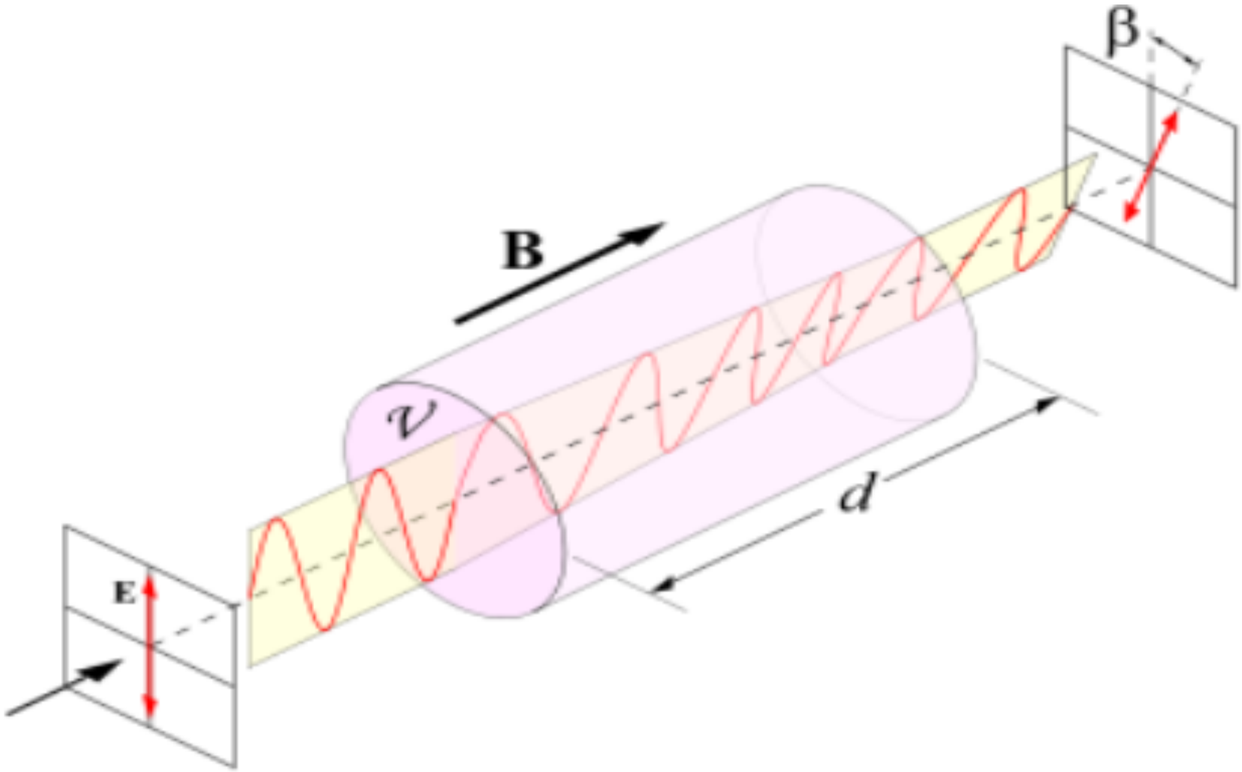


Figure 2: Faraday rotation in a magnetized gas.

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

Faraday rotation

- 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): $\langle B_{\mathrm{P}} \rangle = 1.232 \cdot \frac{RM}{DM}$ (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

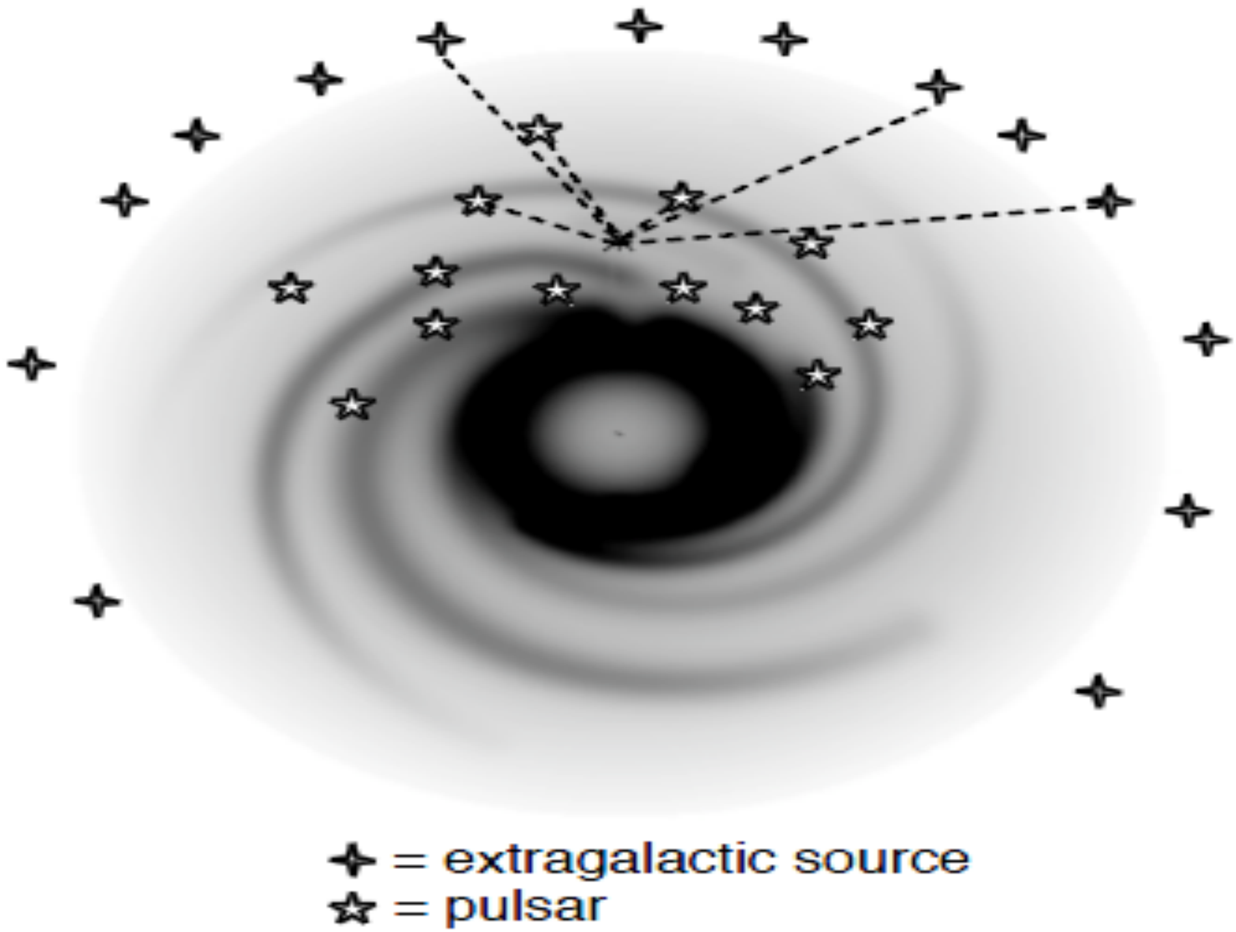


Figure 3: Pulsar and extragalactic sources distribution in our galaxy.

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 (Heiles & Robishaw 2009).

- 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

Galactic disk:

- 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.

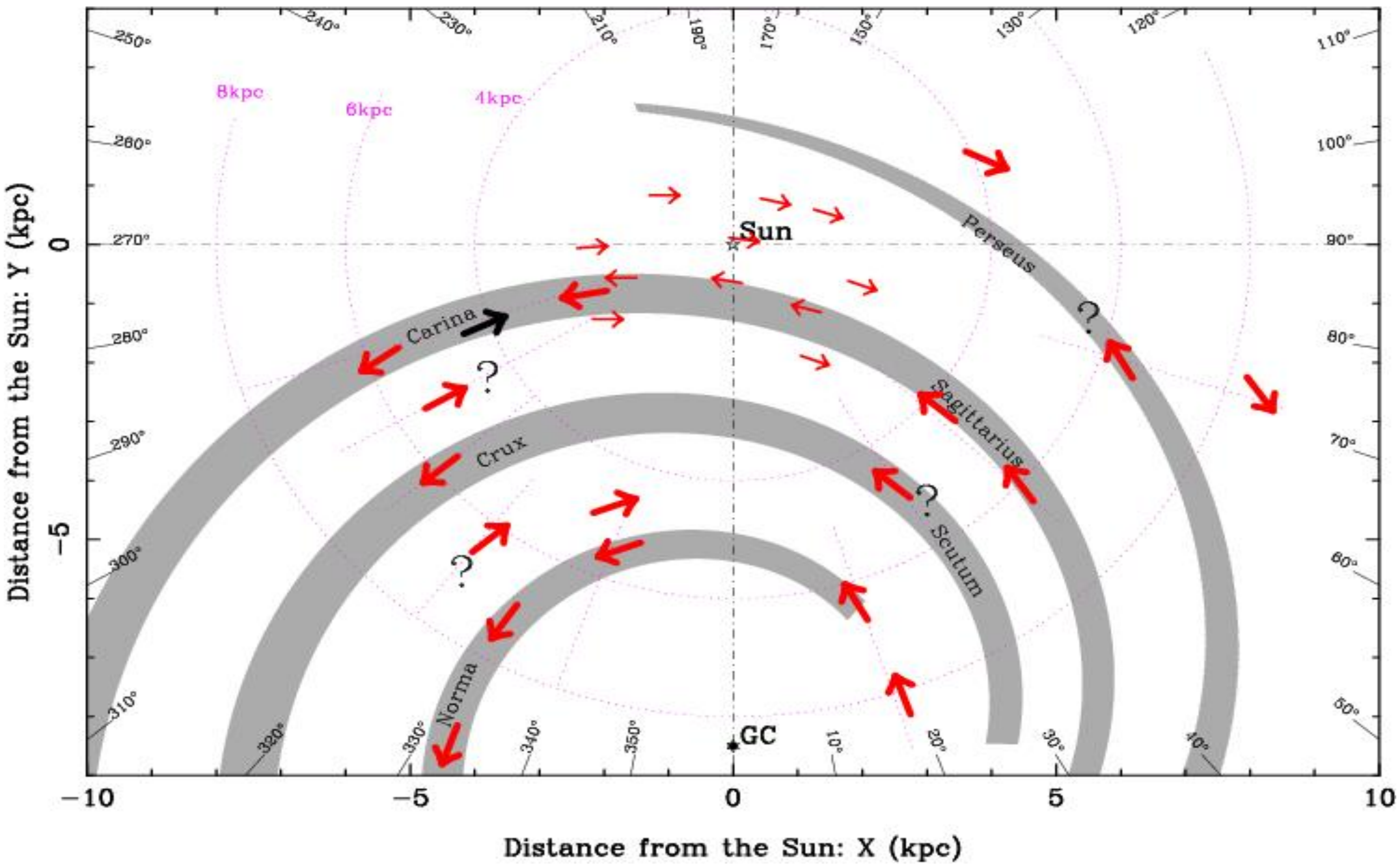
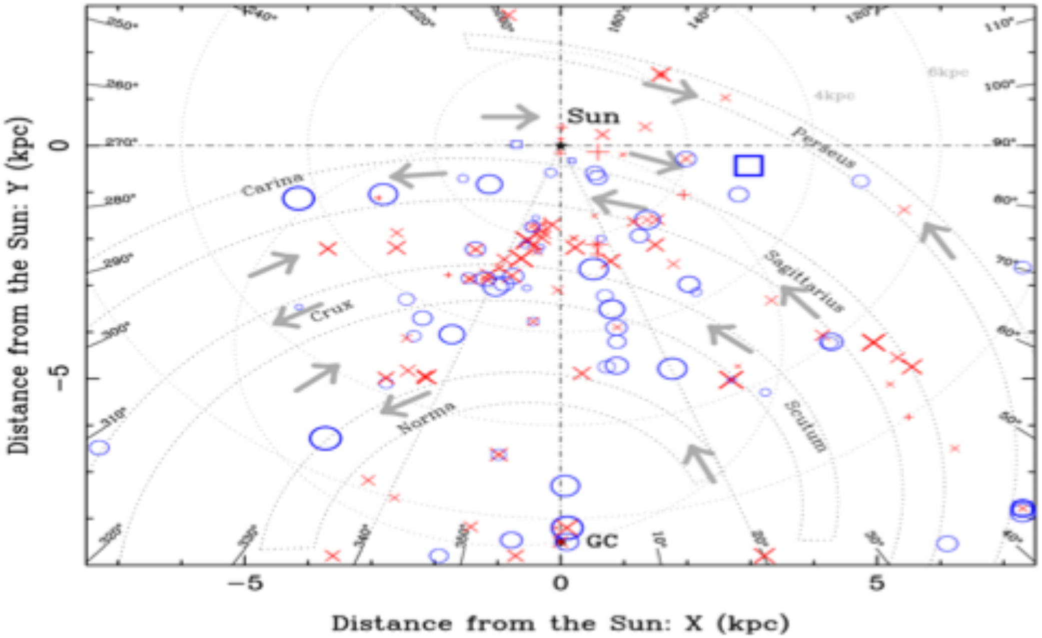


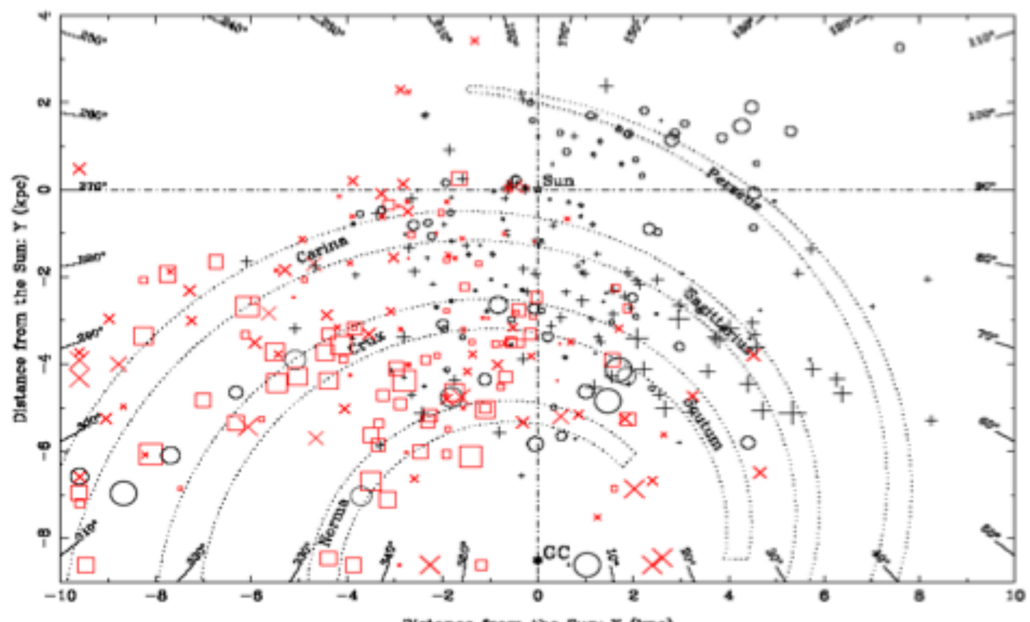
Figure 5: Field orientation in arm and interarm regions in Galaxy.



Data from Zeeman splitting in molecular clouds.

Courtesy of J.L. Han

Data from RM of radio pulsars.



Coherent on 1-10 pc scales

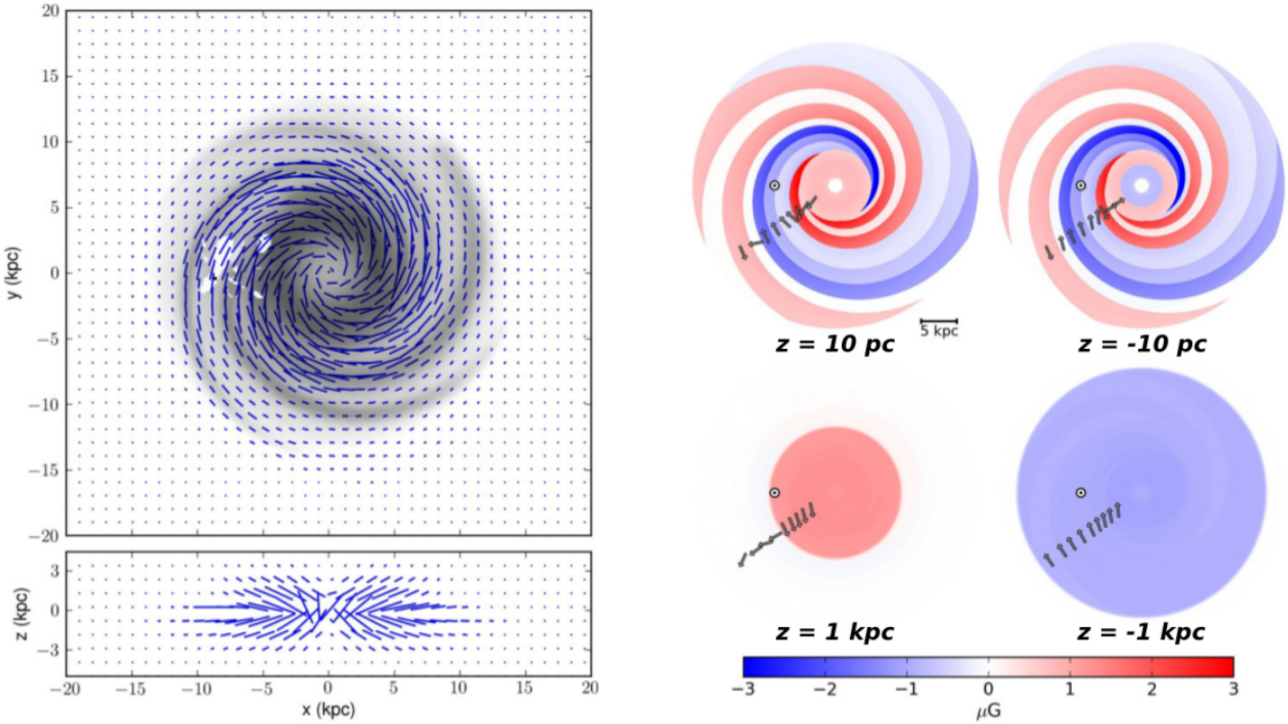
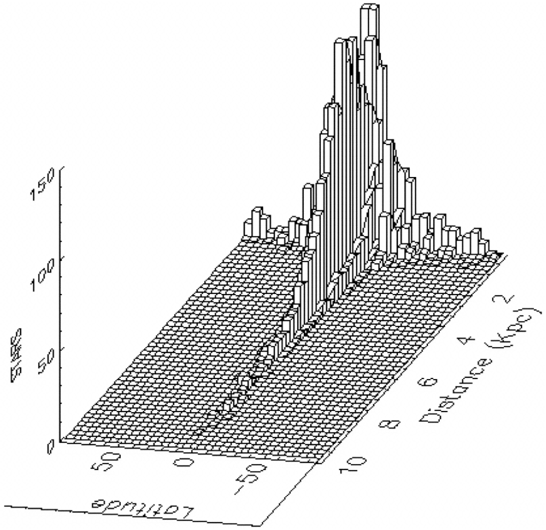


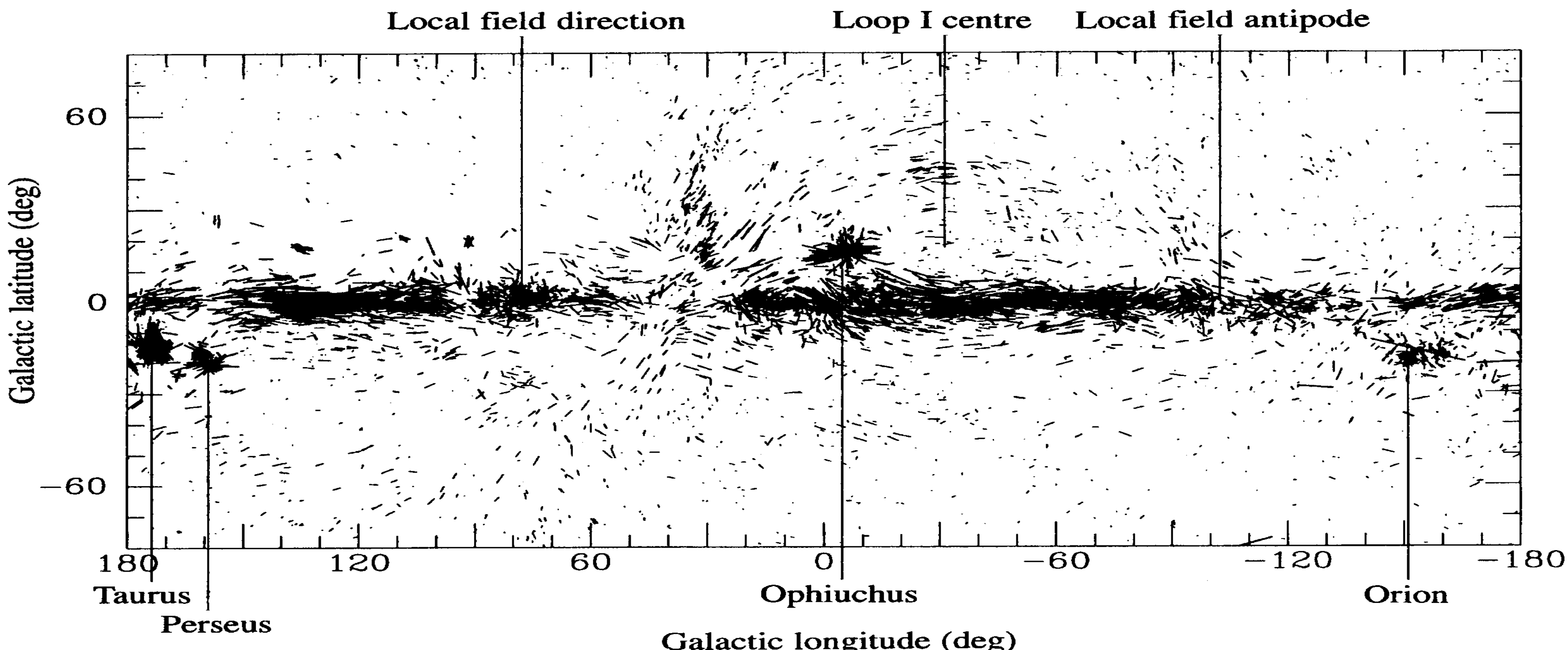
Figura 2.8: Le figure, tratte dall'articolo di Jansson & Farrar [30], mostrano la struttura del campo magnetico della nostra Galassia, ricavate secondo il modello elaborato dagli stessi autori. L'immagine a sinistra descrive la distribuzione delle direzioni e dell'intensità del campo magnetico come sarebbero 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*

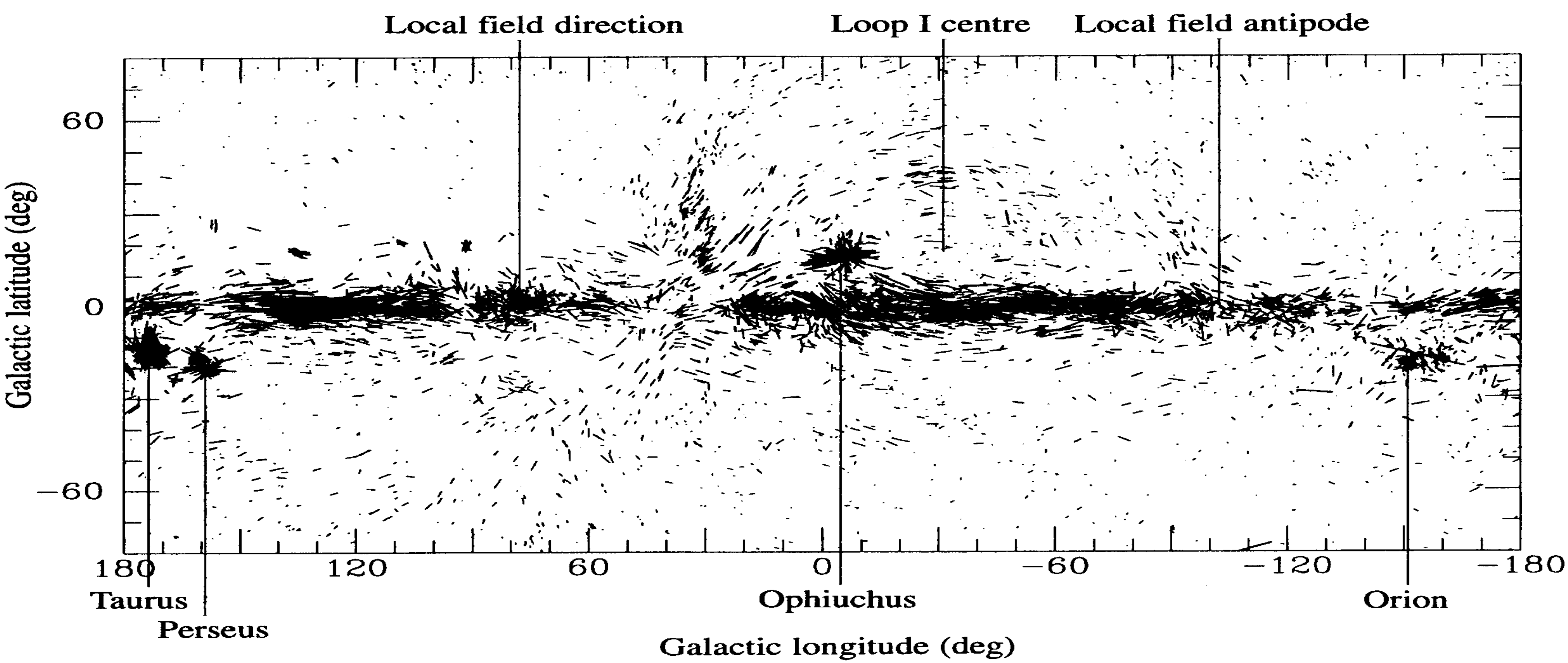


- **9000 stars have polarization measured**
- **mostly nearby (1~2kpc)**
- **polarization percentage increases with distance**



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 10° 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 10° 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.

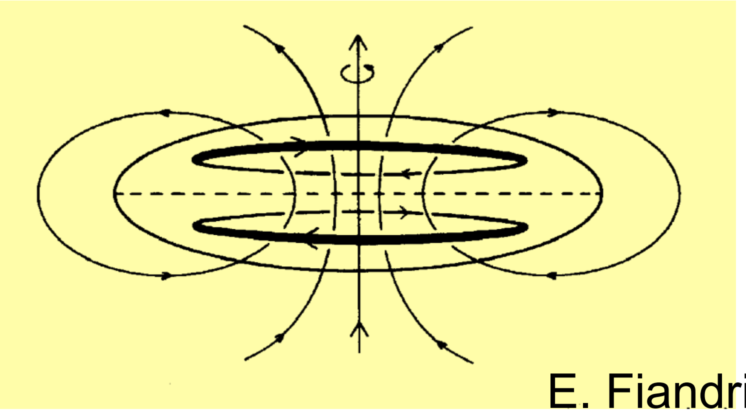


Figure 6: Field configuration for A0 dynamo. Halo field shown.

Magnetic field structure of Milky Way

Central region:

- A few hundred pc region.
- Toroidal field:

  * field indicated by polarized emission from central ring-like molecular cloud zone, Zeeman effect an OH maser emission.

  * field strength: 0.1 mG

  * field orientation: parallel to the galactic plane.
- Poloidal field:

  * field indicated by polarized radio filaments.

  * field strength: few tens of μG.

Magnetic field structure of Milky Way

* field orientation: along the filaments perpendicular to the galactic plane.

- Toroidal fields in the clouds are sheared from poloidal fields.
- Smooth transition from toroidal to poloidal fields at latitudes of $|b| \ f \ 0.4^{o}$.
- Both consistent to large-scale bi-symmetric field.

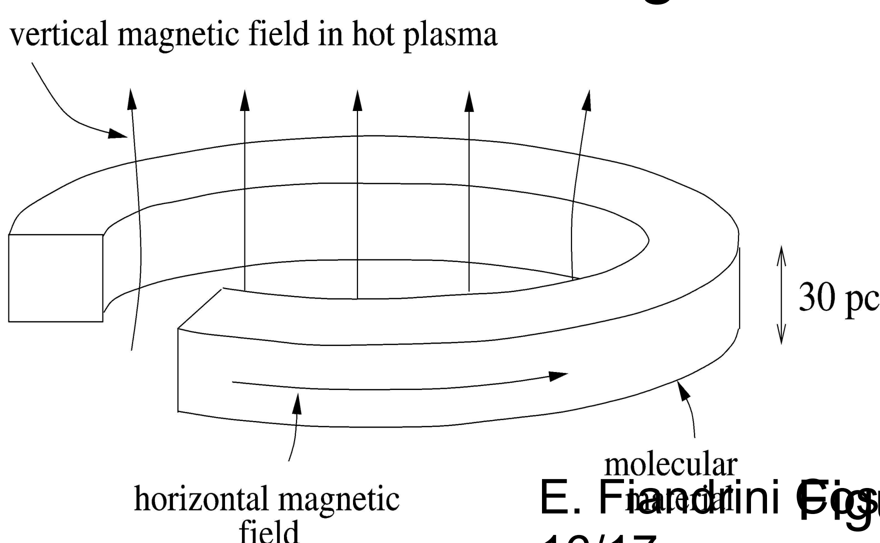
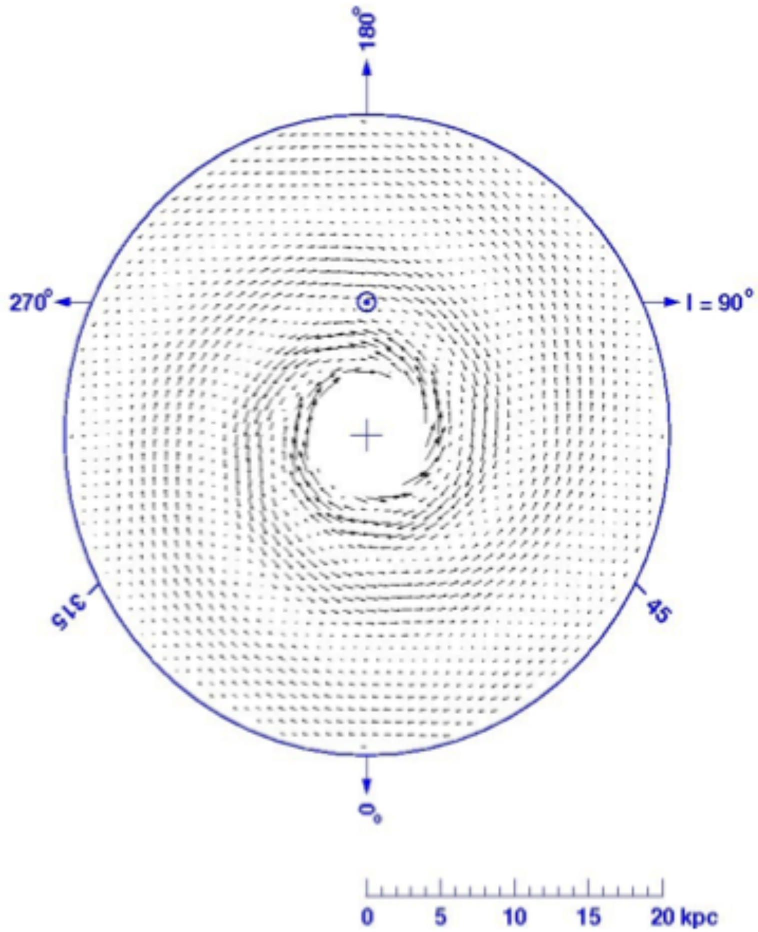


Figure 4: Toroidal and poloidal fields.



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

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.

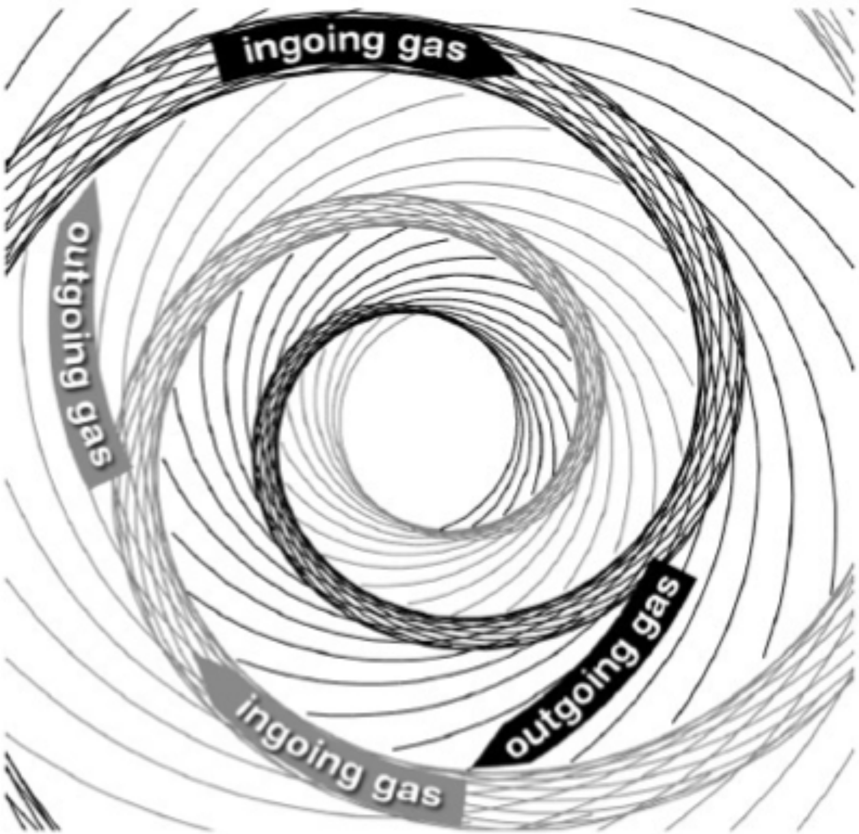
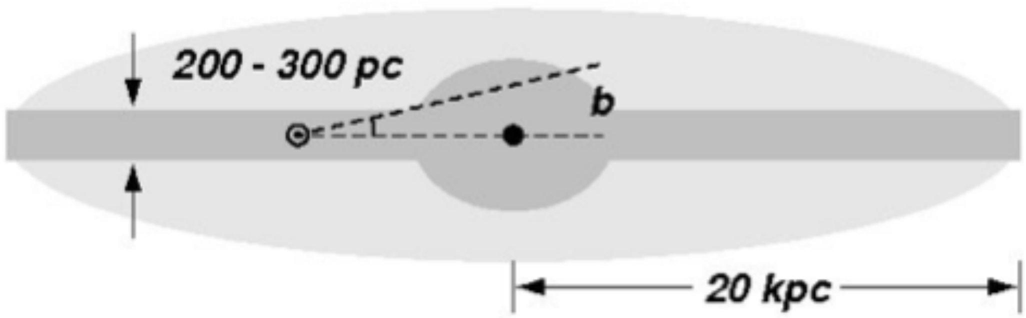


Figure 19: Gas motions in a bisymmetric spiral galaxy.

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.



What is the magnetic field as a function of the distance from the galactic center? Also above and below the galactic plane.

The average magnetic field decreases when we move away from the Galactic center. Measurements are fit with different functions. The easiest one is just linear, based on the the local 2 μG field. In such a Case the field at 4 kpc from the galactic center would be
2 μG 8.5/4 = 4.25 μG.

It is more difficult to estimate the field in the galactic magnetic halo. Cosmic rays, although accelerated in the plane, diffuse away from it and carry with them magnetic field as they do in the Solar system. Most models prefer an exponential dependence with an exponent between 0.5 and 1 kpc. Since the field is stronger around the galactic center and decreases with distance from it the halo would form an ellipse. The details are being investigated now.

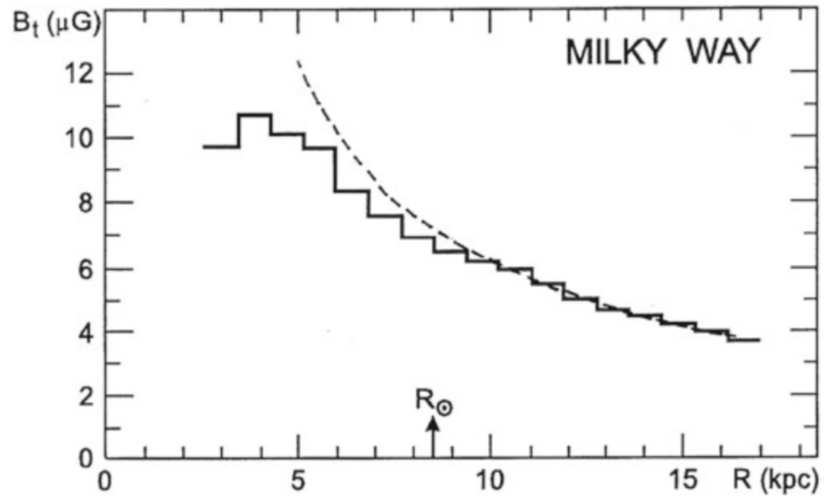
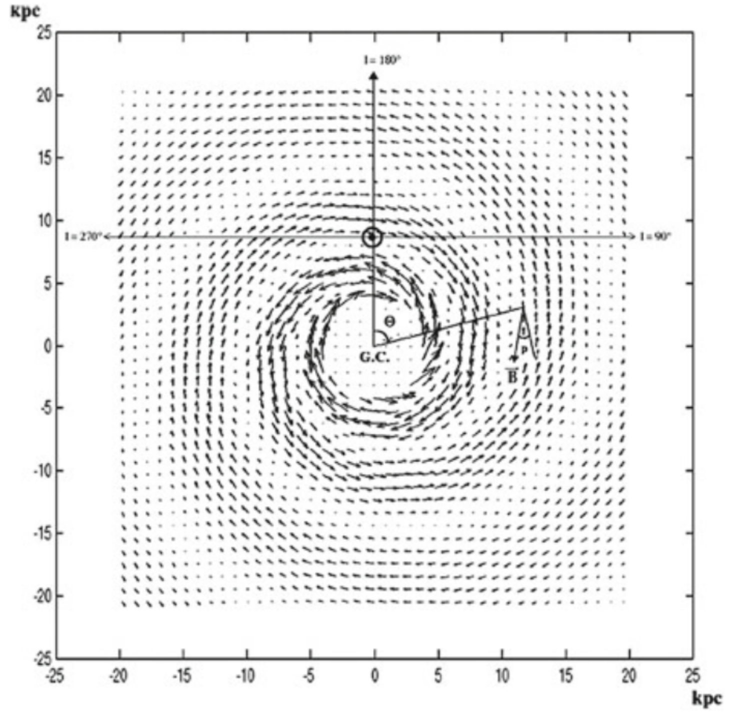


Fig. 2.9 Total magnetic field strength in the Galaxy as a function of the distance from the galactic center. The position of the Sun is indicated by the *arrow* (Battaner et al. 2007). Courtesy of Prof. E. Battaner

Fig. 2.10 The direction and strength of the regular magnetic field in the Galactic plane is represented by the length and direction of the arrows. The intensity of the field inside the circle of radius 4 kpc representing the bulge is assumed to be 6.4 μG (Prouza and Smída 2003). Courtesy Dr. M. Prouza and Dr. R. Smída



Random field δB

- Measurements (eg starlight polariz.) shows that the random field exceeds the mean field by a large factor
- The random field lies mainly parallel to the mean field, while the perp component is much lower $<\delta B_p>/<\delta B_n> \sim 4$
- However from the measurements it's hard to determine the B field power spectrum density

Power Spectrum

- Power spectrum is the Fourier transform of the random field.
- Field is described as a superposition of plane waves
- It gives the energy of the Fourier component at a given wave number k and/or at a given frequency w.
- The wave number k gives the scale of length $\lambda = 2\pi/k$ over which the k-th component is $\neq 0$
- The highest is k, the smallest is the region where the perturbation $\delta B(k)$ acts

$$B_{\text{tot}} = B_0 + \delta b \,, \tag{5}$$

where δb is the combined amplitude of all waves present at the given position. Averaging the energy density over sufficiently large times gives

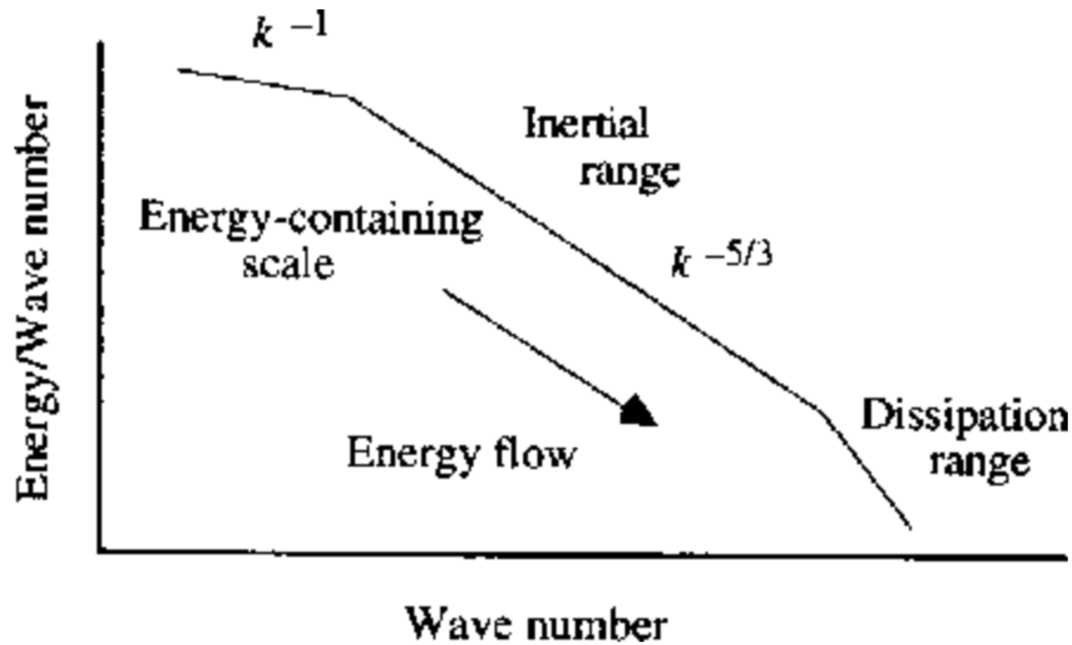
$$B_{\text{tot}}^2 = B_0^2 + \langle \delta b^2 \rangle \,. \tag{6}$$

The total energy density in the waves can be represented as

$$\langle \delta b^2 \rangle = 4\pi \int W_w(k)\, dk \tag{7}$$

Power Spectrum

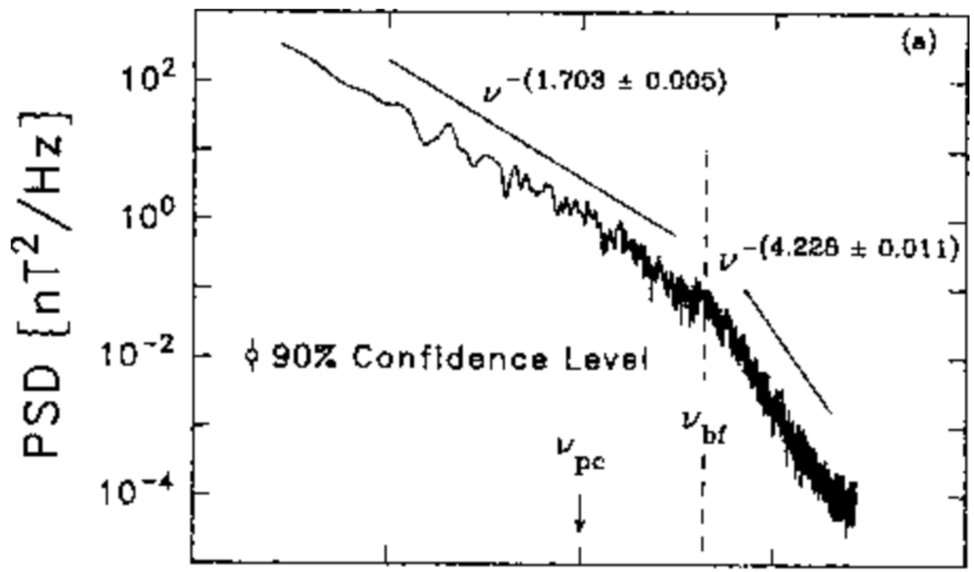
- Most turbulence theories involve the processes by which energy injected into a medium at large spatial scales is converted into motions at smaller and smaller spatial scales (or eddies) until reaching scales at which the turbulence energy interacts directly with individual plasma particles and causes heating.
- Generally speaking, the PSD is described by power laws in k, that depends on k.



Magnetic field power spectrum of solar wind

Power Spectrum

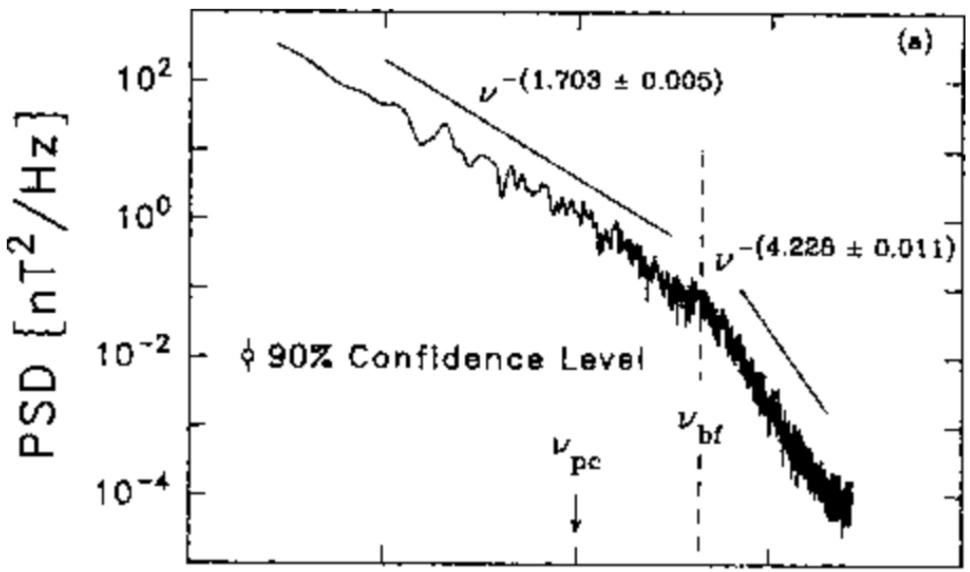
- The process by which wave energy moves to smaller wavenumbers is sometimes called a “turbulent cascade”. This process can be mimicked to some degree by stirrin[g] a fluid and watching it come into equilibrium. The range of wavenumbers over which the turbulence energy cascade[s] to smaller wavenumbers is called the inertial range. Using both gasdynamic (GD[)] and MHD theory, it can be shown using energy balance arguments that the power spectrum in the inertial range should be a power law with spectral index in the range 3/2 - 5/3.
- Kinetic theory is required to understand the dissipation of the turbulence in the so-called ``dissipation range'' at small spatial scales.



Typical spectrum of interplanetary magnetic power spectrun in a given period of the solar activity

Power Spectrum

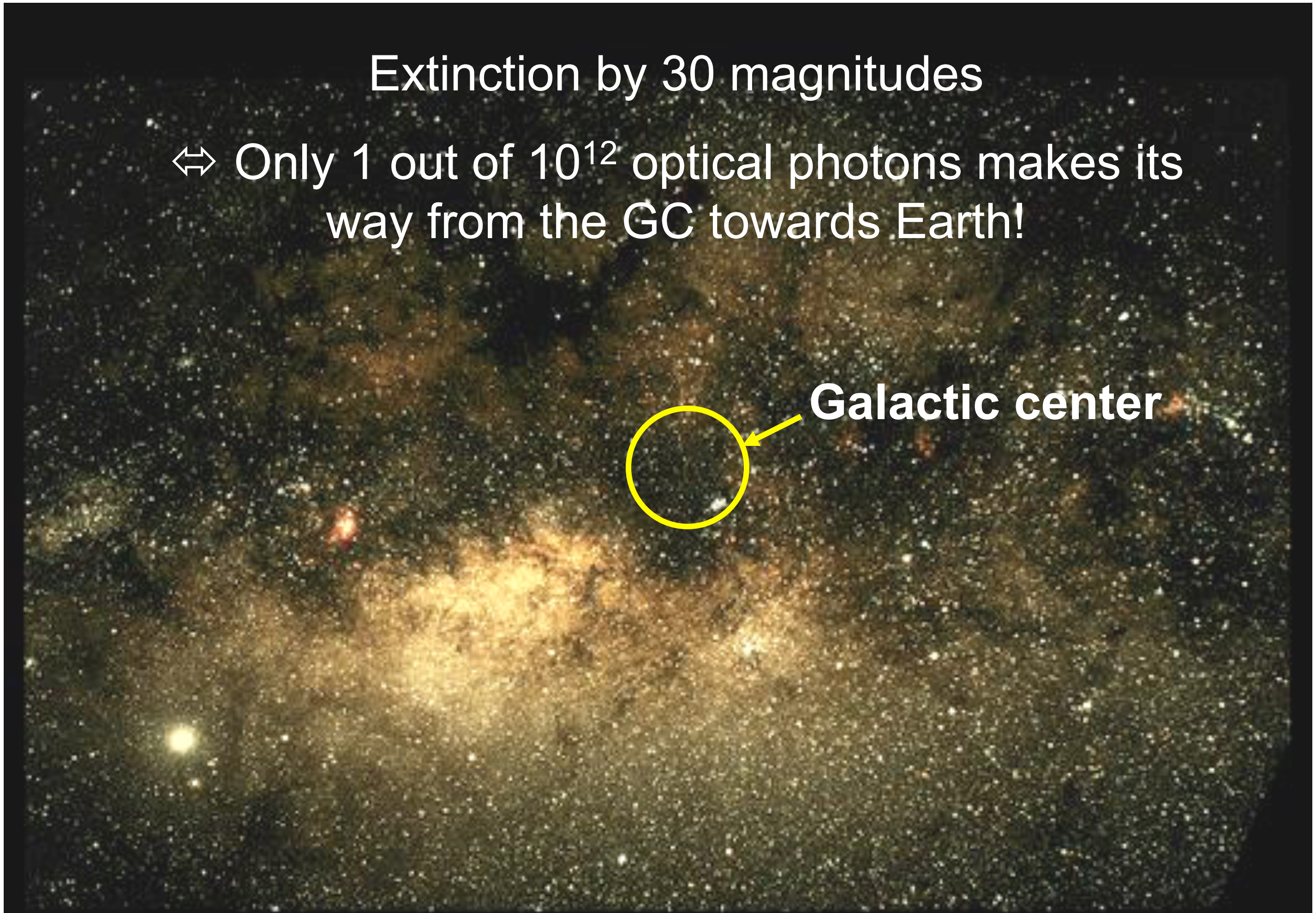
- The power spectrum of the random component of the galactic magnetic field is essential to explain to diffusion of cosmic rays in the galaxy through collisionless scattering over the irregularities



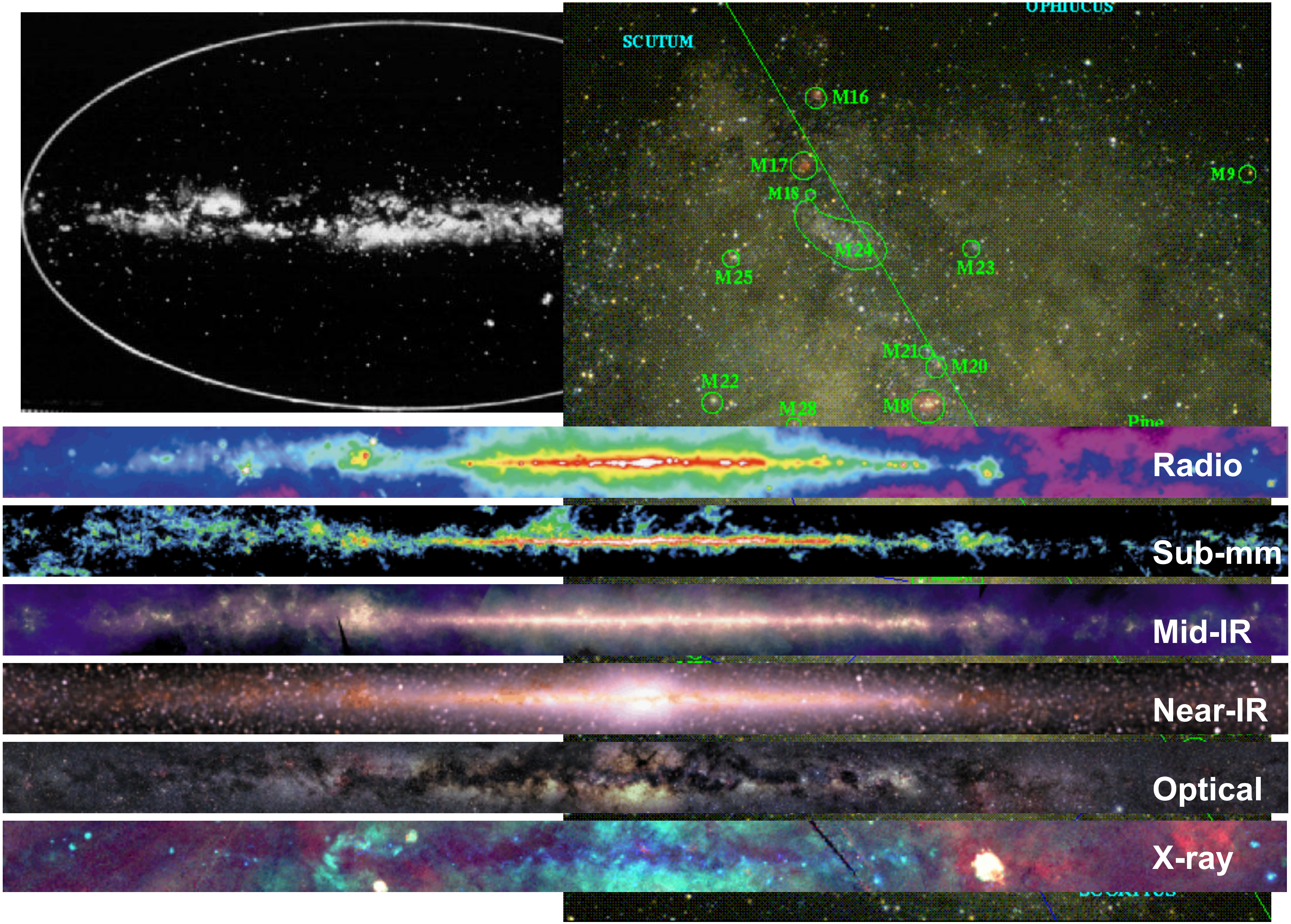
Typical spectrum of interplanetary magnetic power spectrun in a given period of the solar activity

The Galactic Center

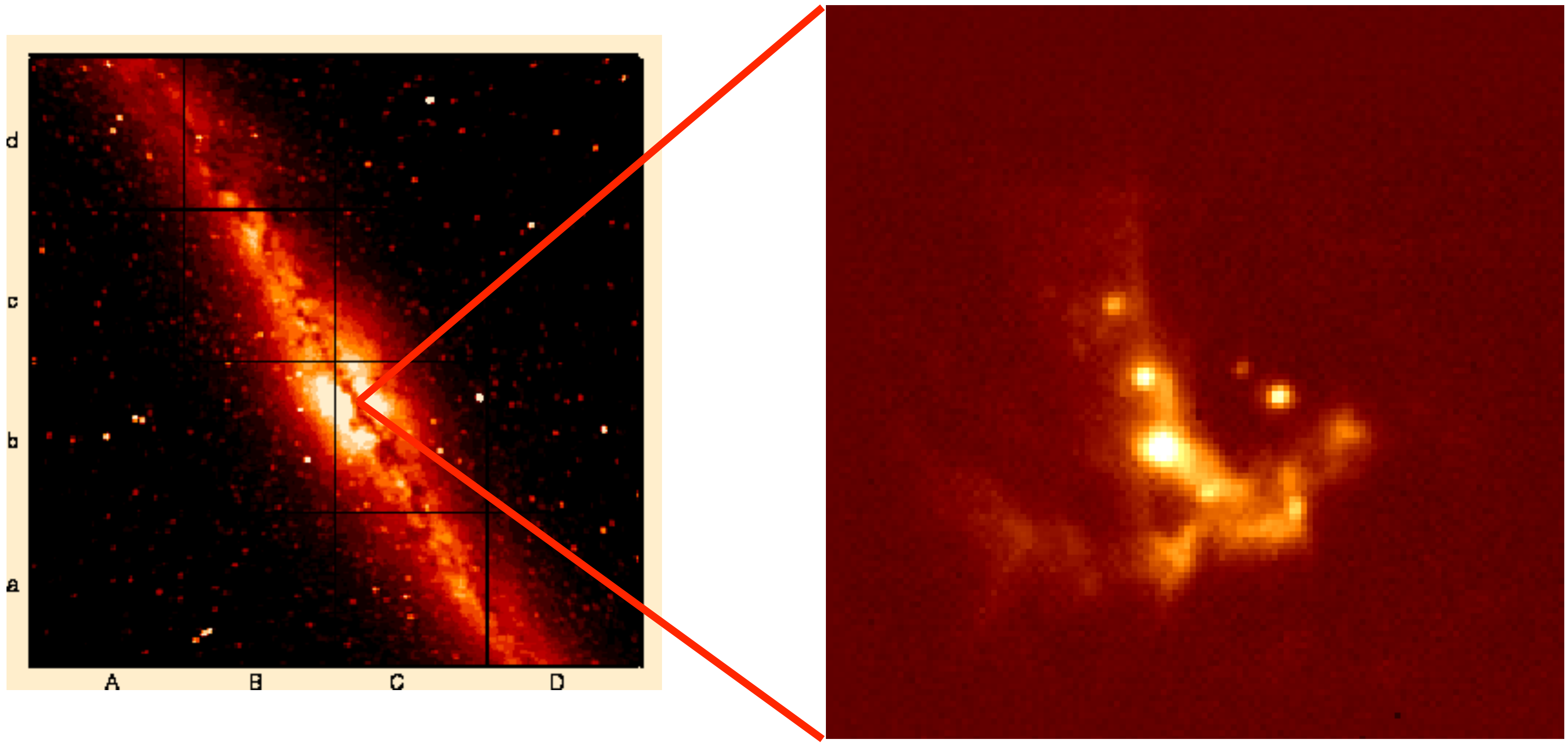
Our view (in visible light) towards the galactic center (GC) is heavily obscured by gas and dust



Wide-angle optical view of the GC region


SCUTUM
M16
M17
M18
M24
M25
M23
M9
M21
M20
M22
M28
M8
Radio
Sub-mm
Mid-IR
Near-IR
Optical
X-ray

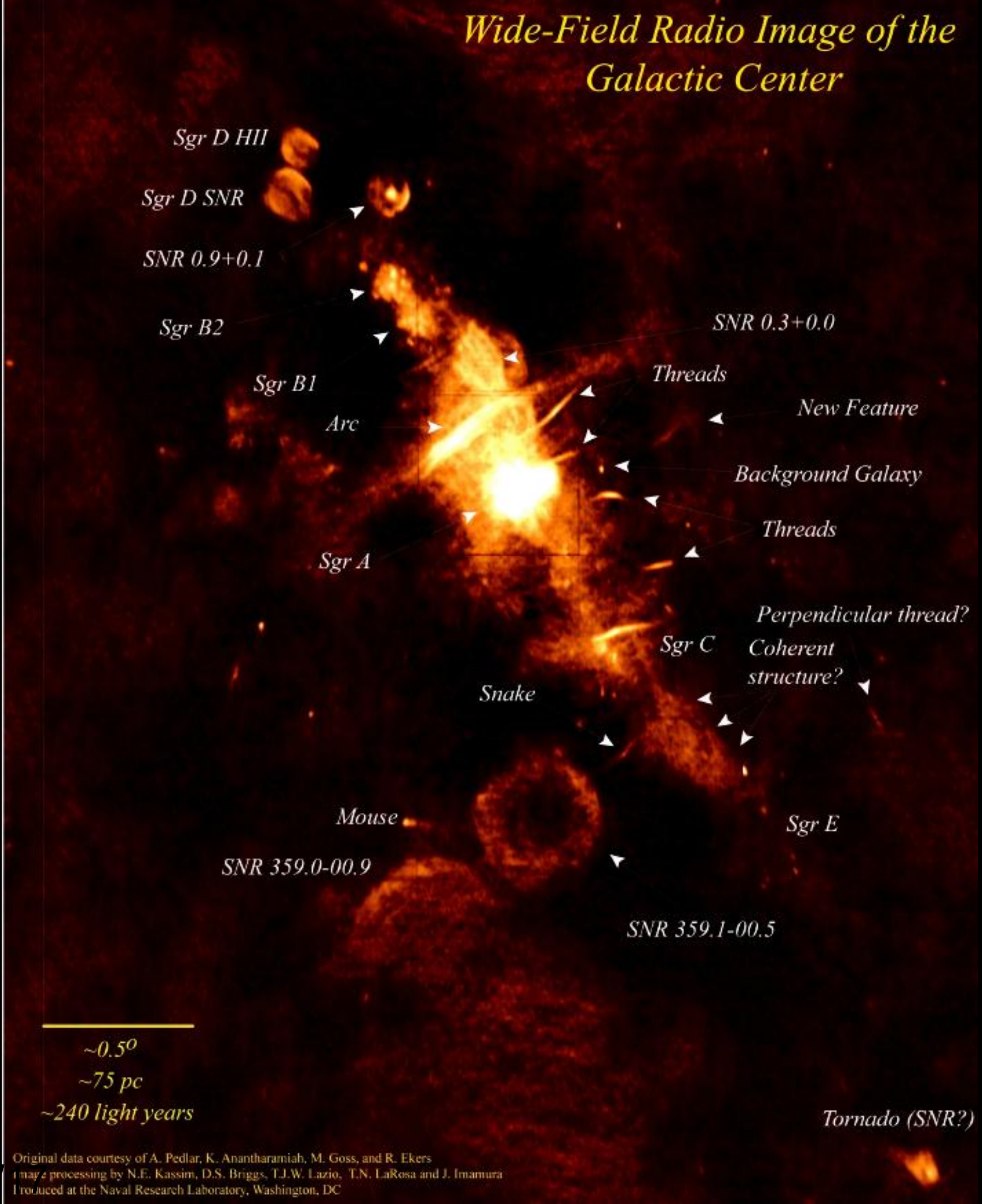
Need to observe the GC in the radio, infrared, or X-ray range



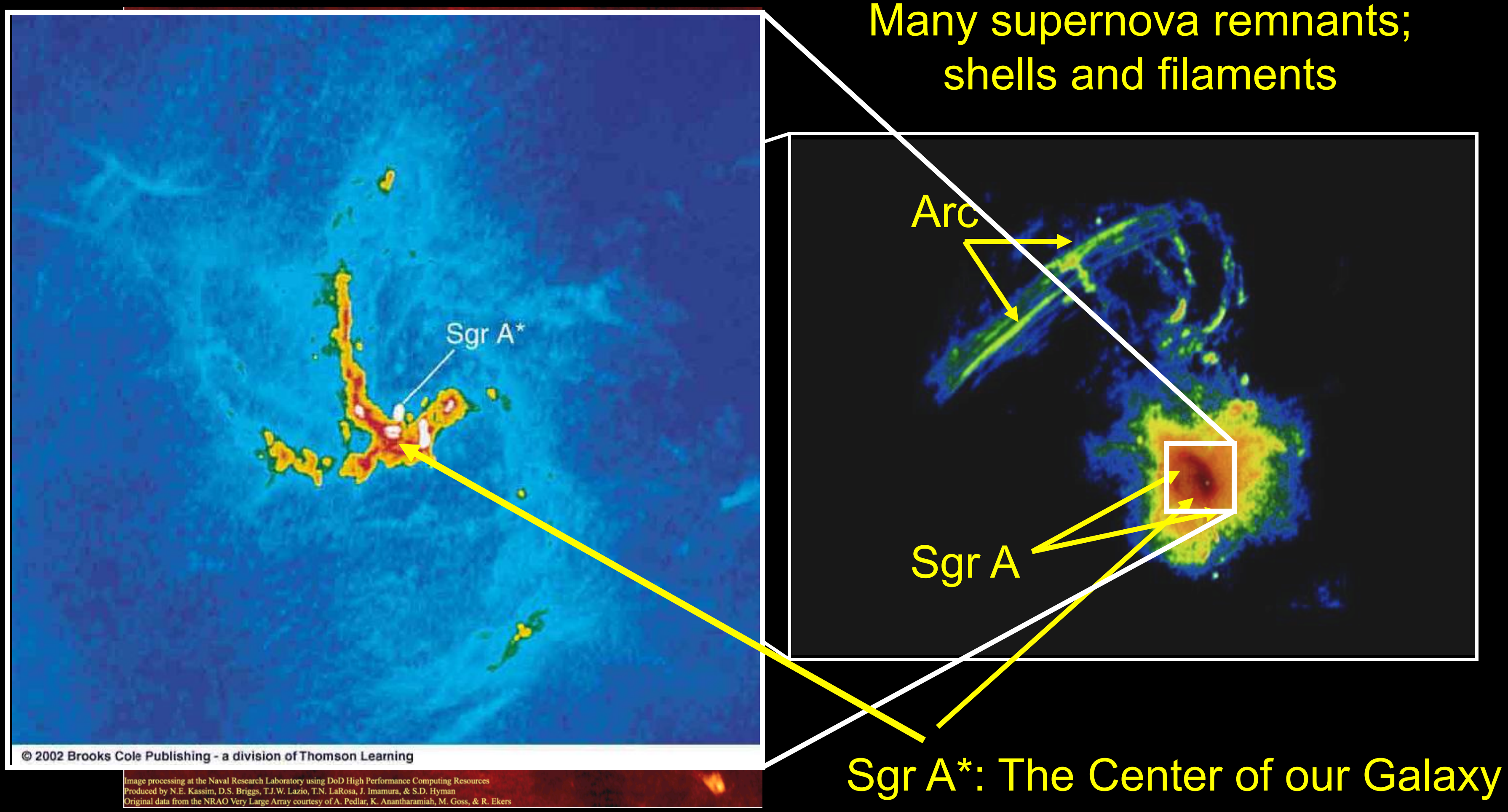
Central 2 pc

Infrared images

Image from the Very Large Array (VLA) radio telescope in New Mexico.

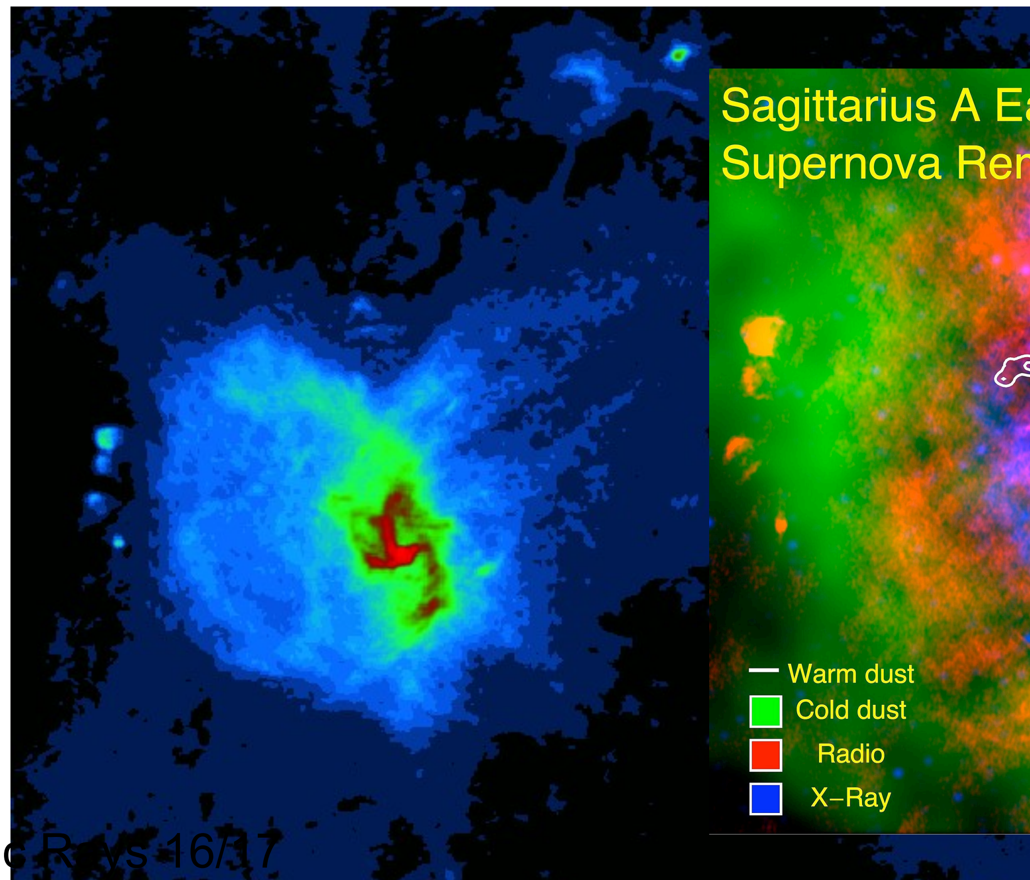


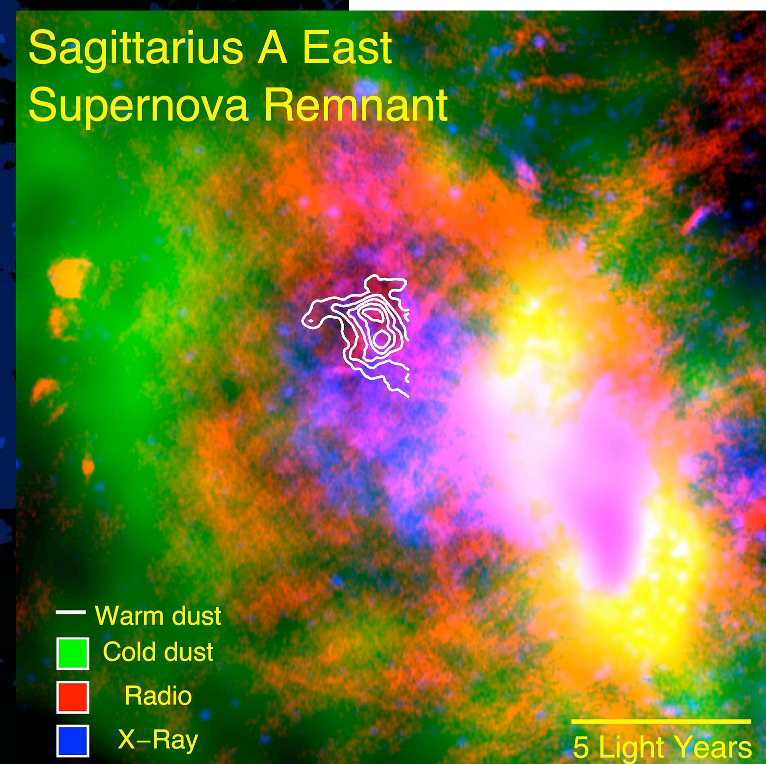
Radio View of the Galactic Center



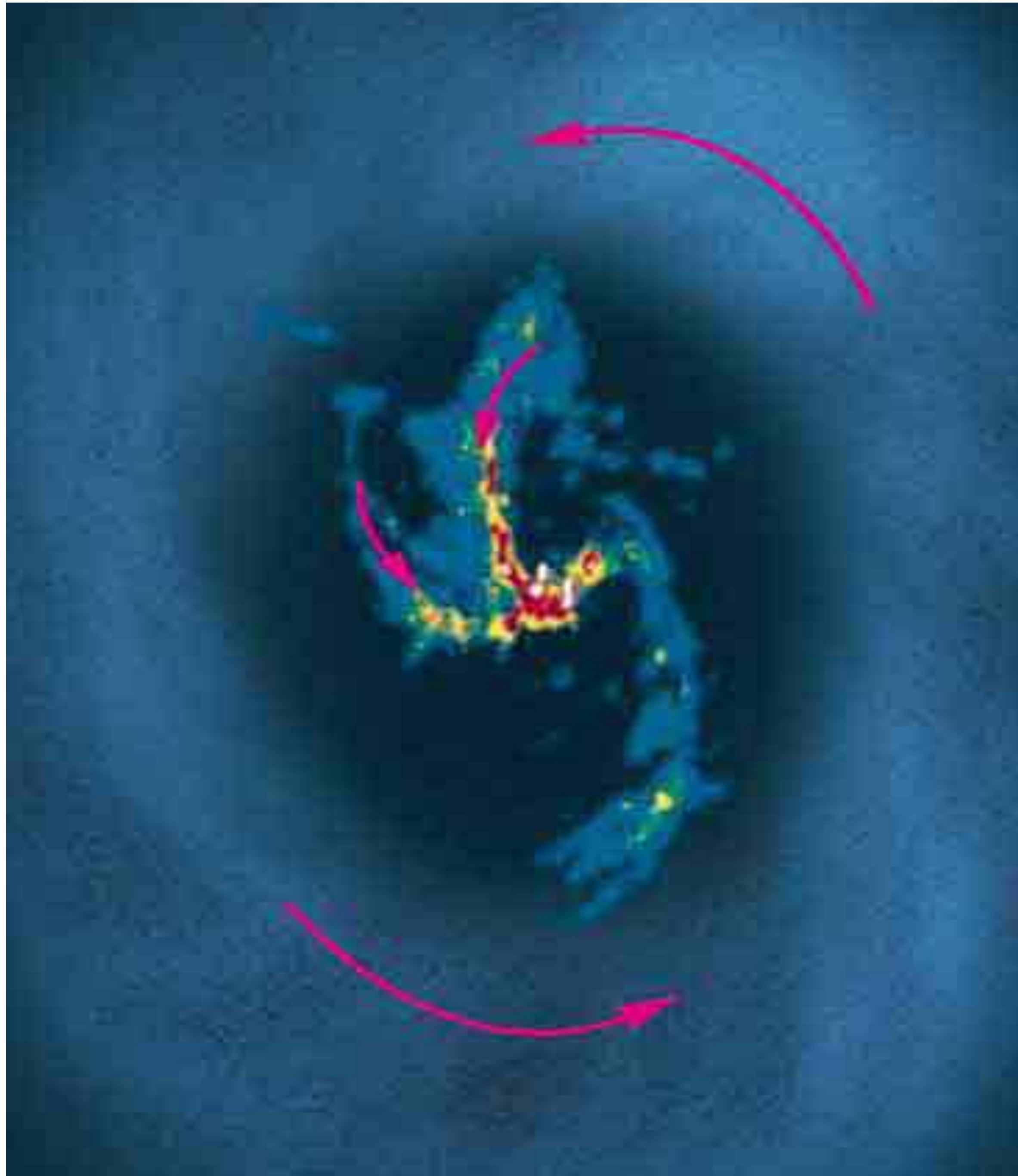
The Galactic Center contains a supermassive black hole of approx. 2.6 million solar masses.

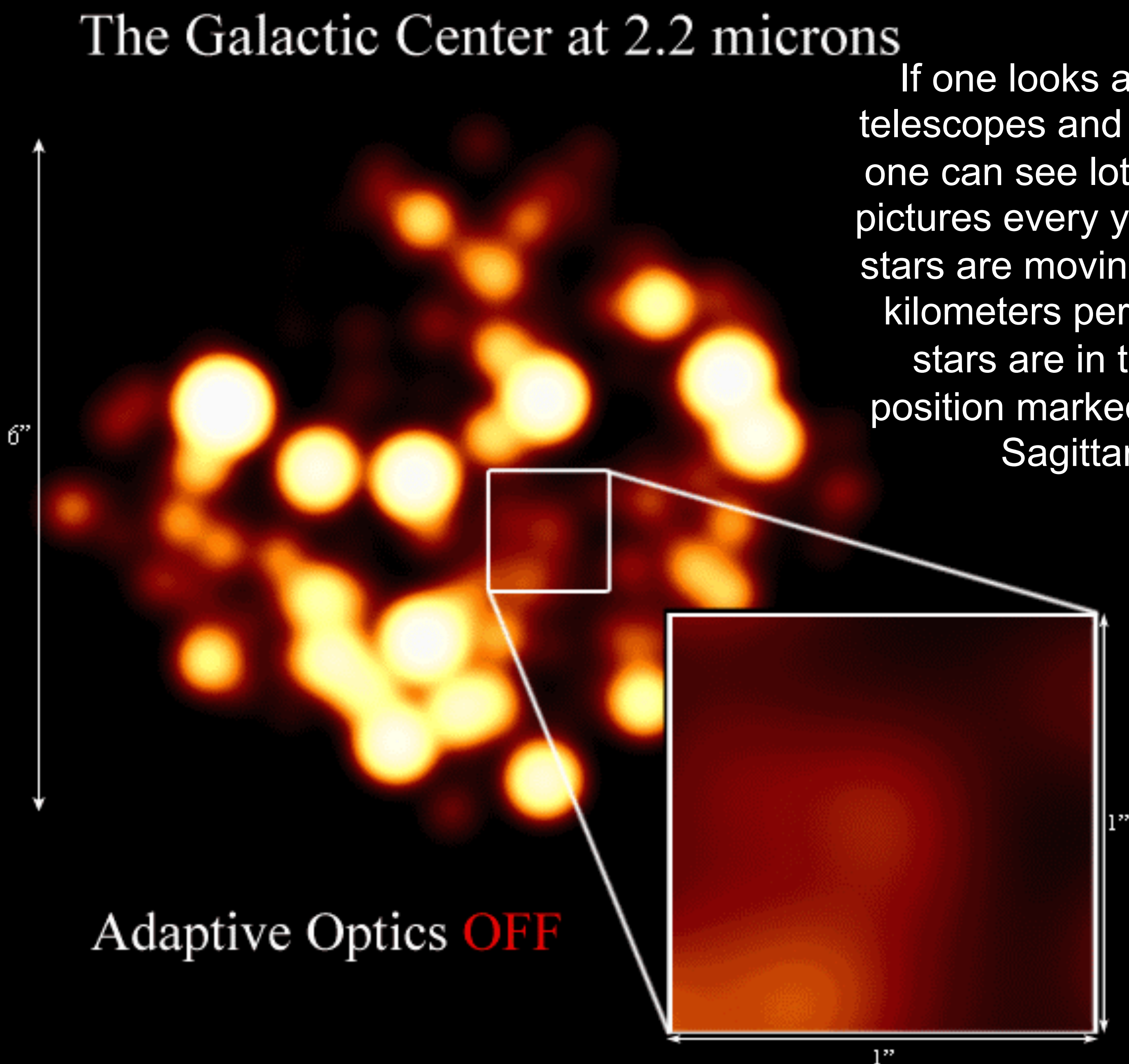
The central radio emission consists of three parts:
Sagittarius A East (blue): a supernova remnant, which was produced by a violent explosion only several tens of thousands of years ago. The origin is unknown. Explanations range from a star disrupted by a black hole to a chain reaction of ordinary supernovae or even a gamma-ray burst.
Sagittarius A West or Minispiral (red): Gas and dust streamers ionized by stars and spiraling around the very center, possibly feeding the nucleus.
Sagittarius A *: A bright and very compact radio point at the intersection of the arms of the Minispiral (difficult to see in this image)



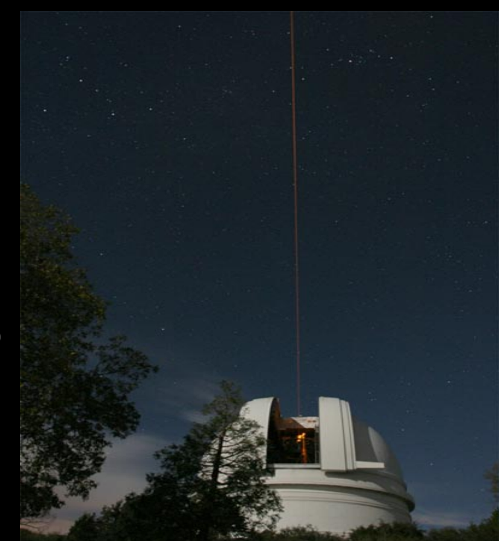


Fast rotation of spiral filaments around Sgr A*



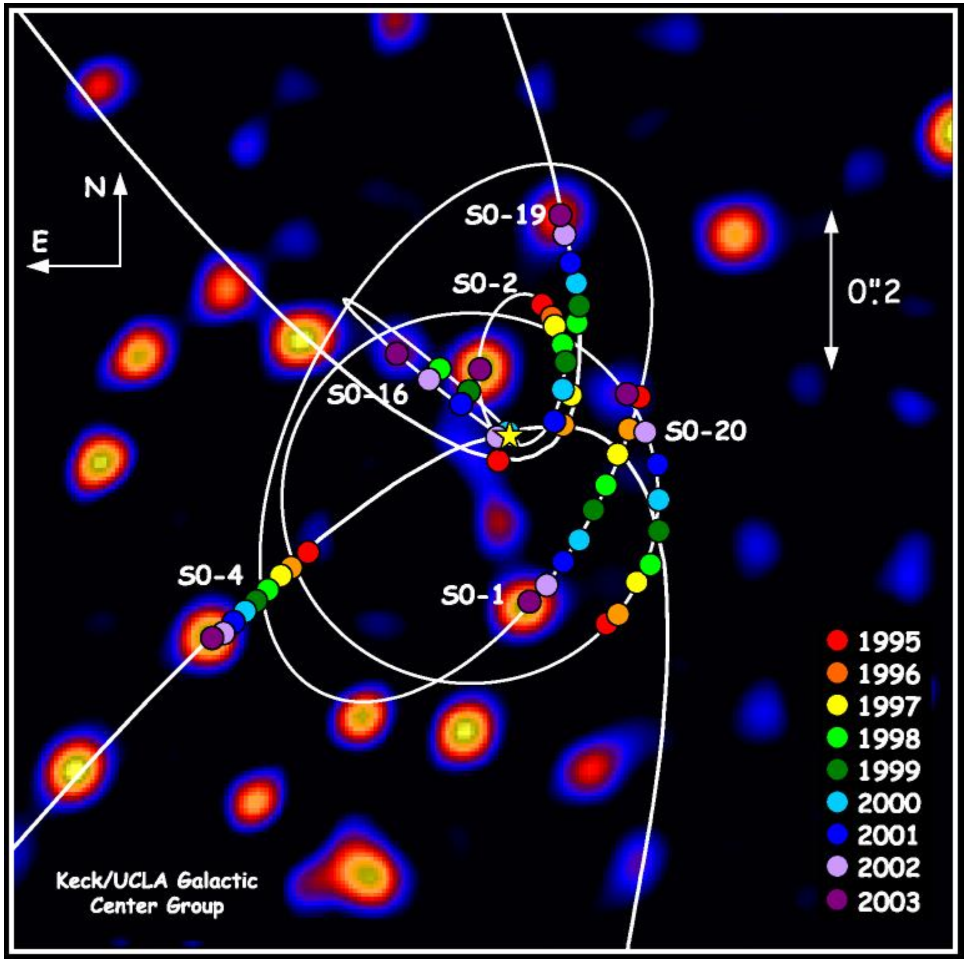


If one looks at this region with big telescopes and near-infrared cameras one can see lots of stars. If one takes pictures every year it seems that some stars are moving very fast (up to 1500 kilometers per second). The fastest stars are in the very center - the position marked by the radio nucleus Sagittarius A* (cross).

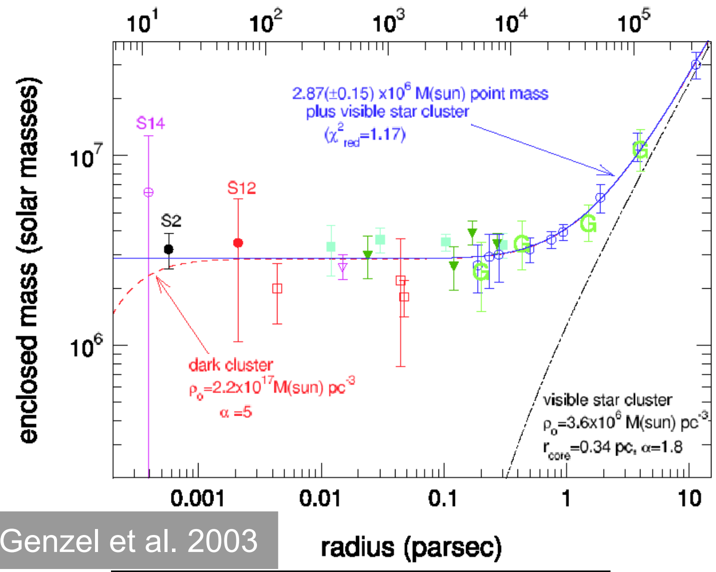


Distance between stars is less that 0.01 pc

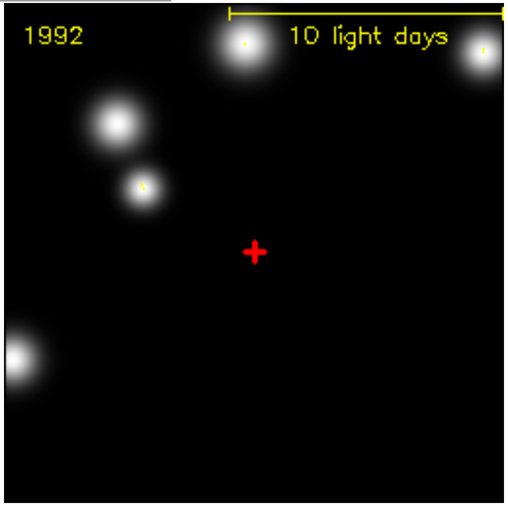
Evidence for a *Supermassive* Black Hole at the Galactic Centre

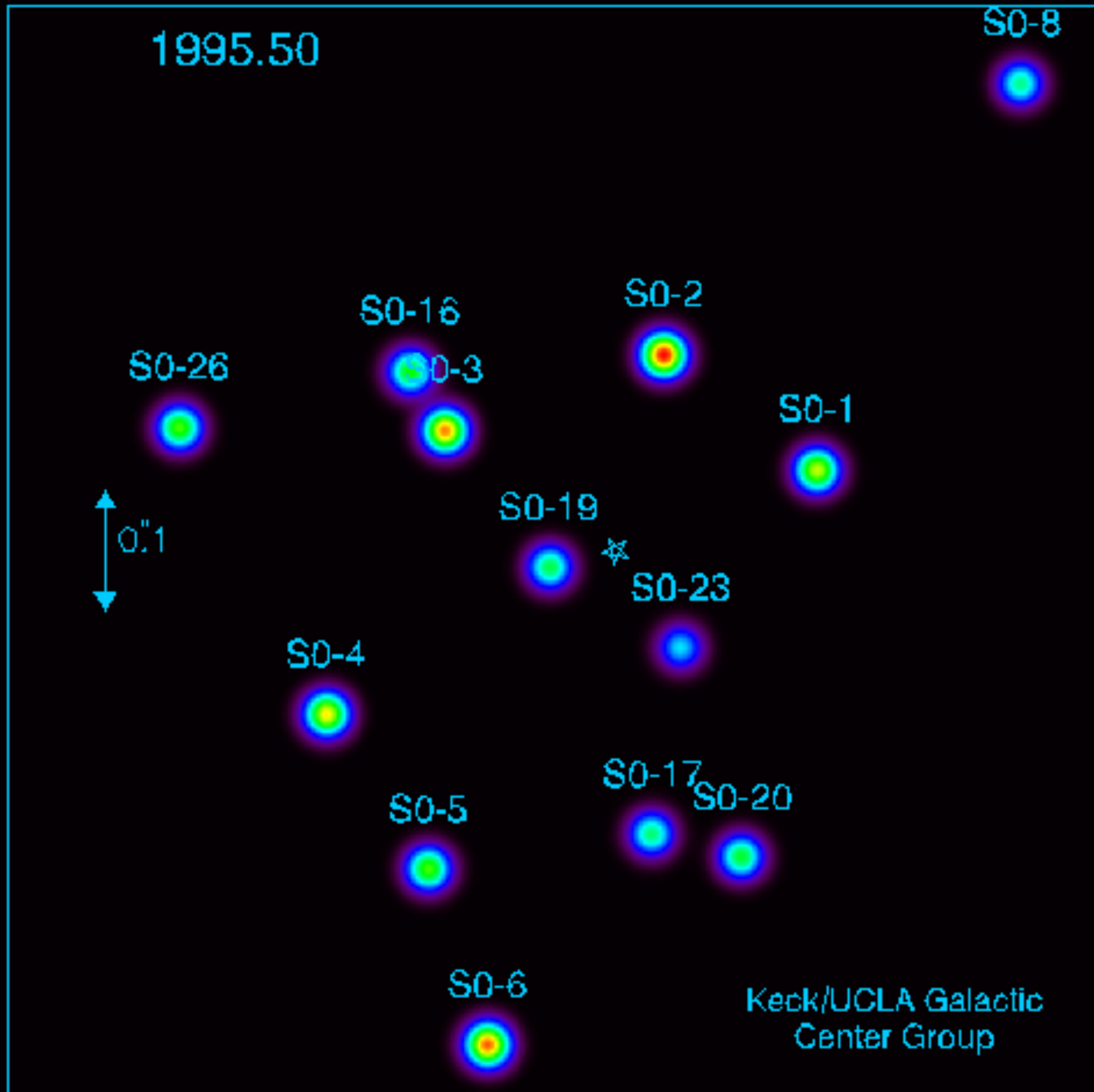


M= 3.6 x 10^6 Solar Masses



Genzel et al. 2003




1995.50
S0-8
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S0-19
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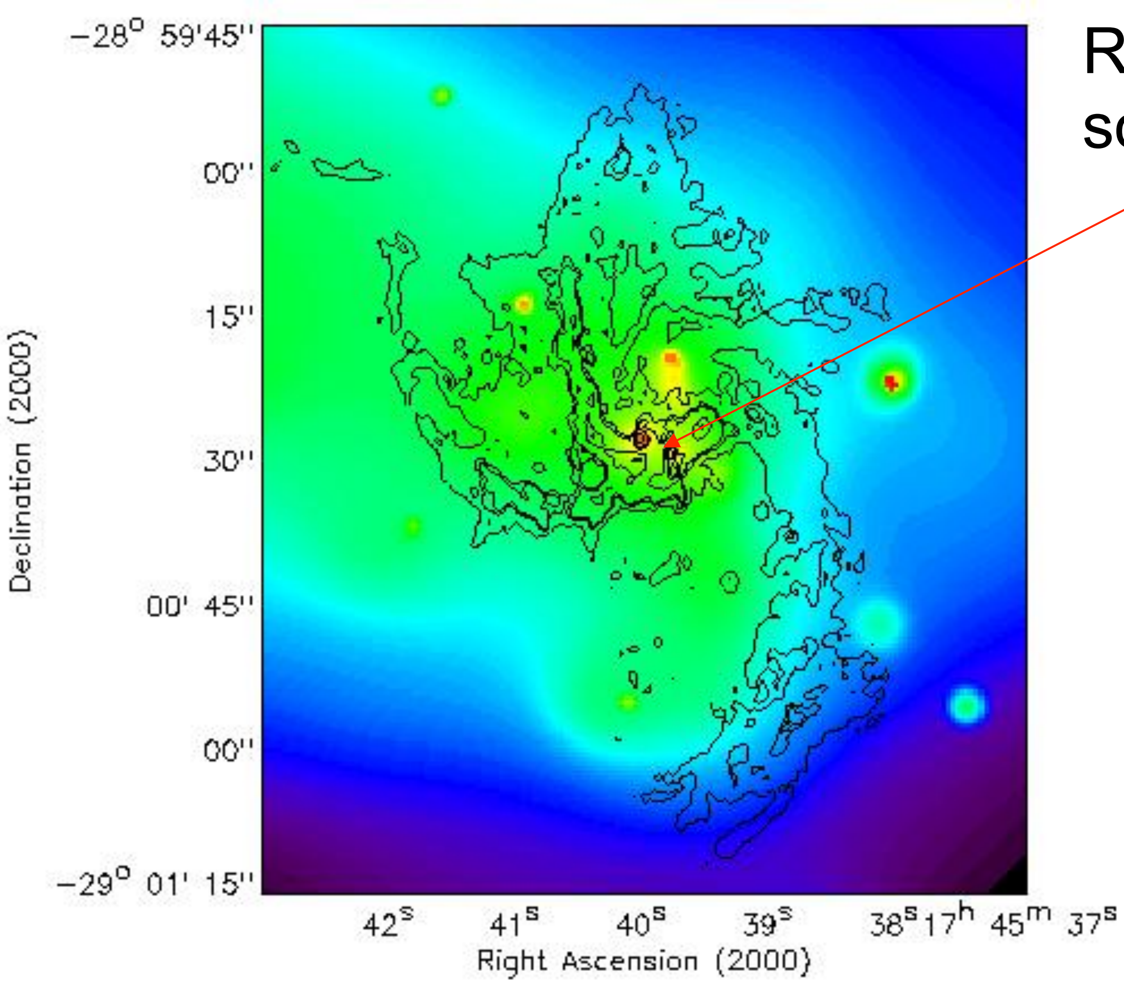
S0-4
S0-17
S0-20
S0-5
S0-6
Keck/UCLA Galactic
Center Group

What about X-ray emission due to accretion?



Rather weak X-ray source

Chandra X-ray image of the Sgr A West region

What we have learnt:

- Milky way structure: thin spiral disk with a nulear bulge and a large halo
- Cold and Hot gas (mainly H, HI e HII) in the InterStellar Medium (ISM)
- Stars: exploding they supply ISM with matter and energy
- Magnetic fields: large scale structure with many random turbulent irregularities
- Supermassive black hole in the center (?)

Messaggeri del cosmo

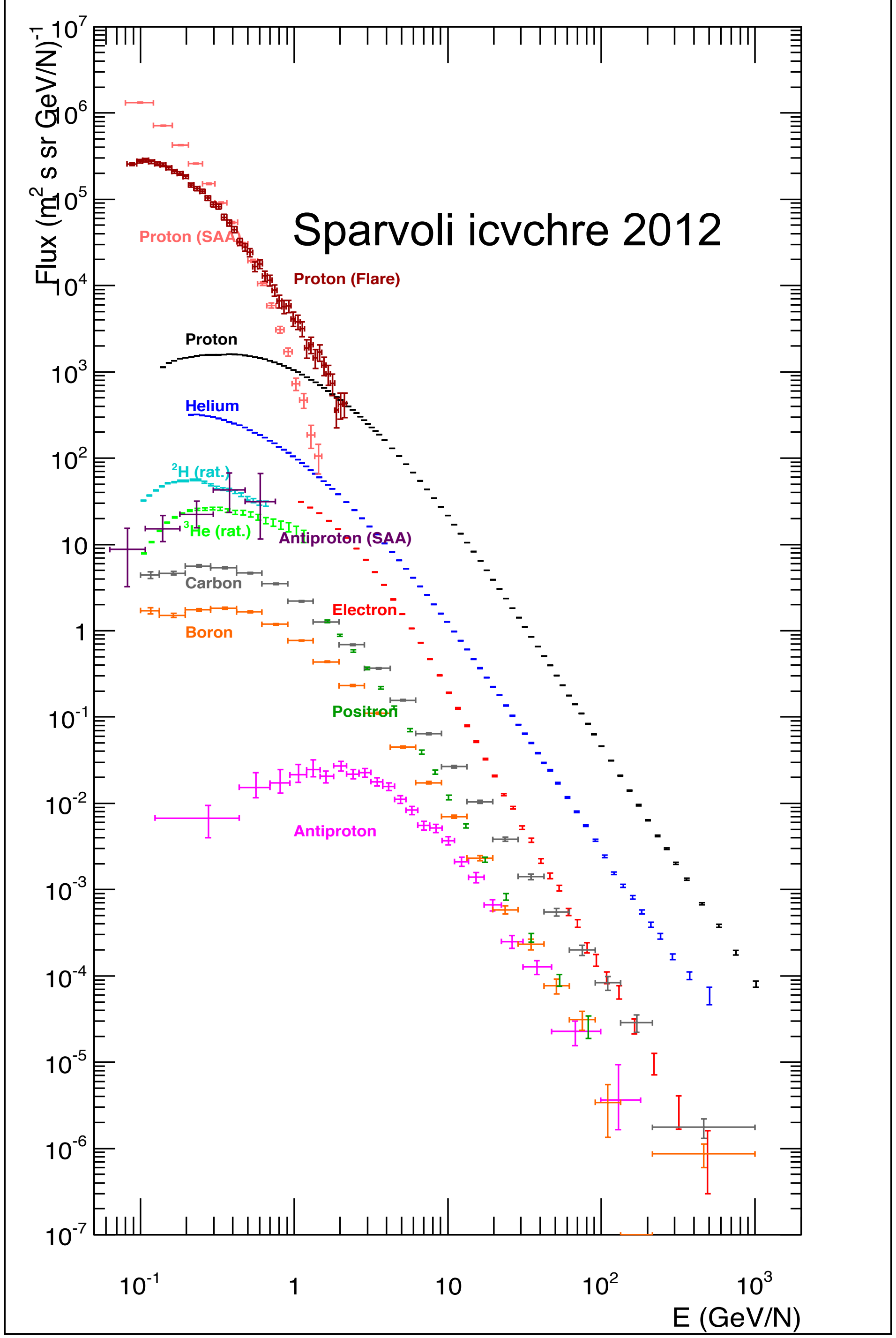
- Cosa trasporta l'informazione dallo spazio alla Terra?

➔ i Raggi Cosmici

Ovvero:

- ▸Radiazione elettromagnetica su tutto lo spettro, cioe' fotoni
- ▸ Flussi di particelle energetiche: neutre (ν) e cariche elettricamente (raggi cosmici carichi... p, e, e+, anti-p, nuclei)

- ❑ Power law for all the particles
- ❑ May be not a single power law (eg spectrum hardening at high E)
- ❑ Non thermal spectra → acceleration mechanisms at work



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

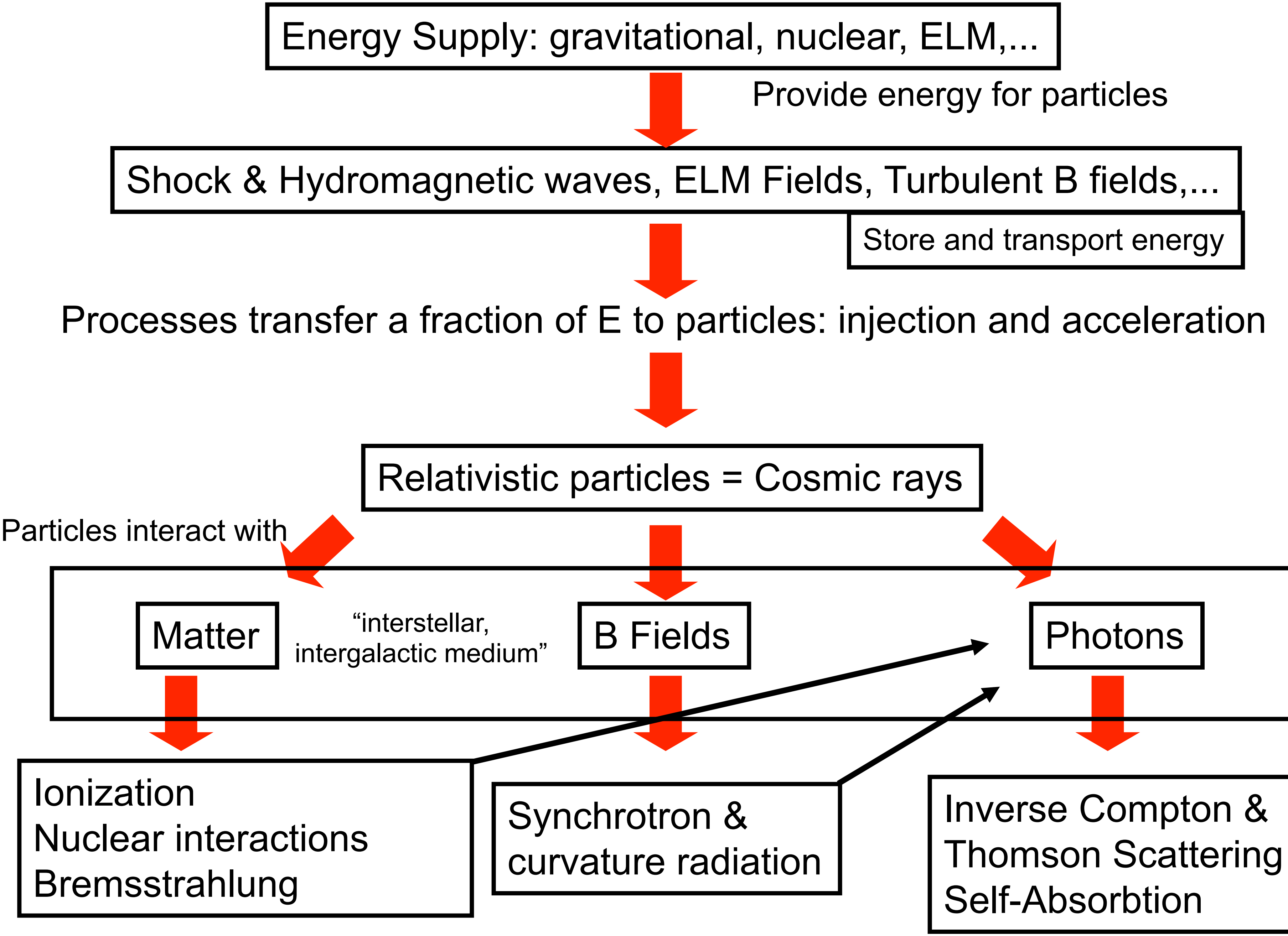
- Quali sono i processi che danno luogo alle popolazioni osservate?

- 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”?

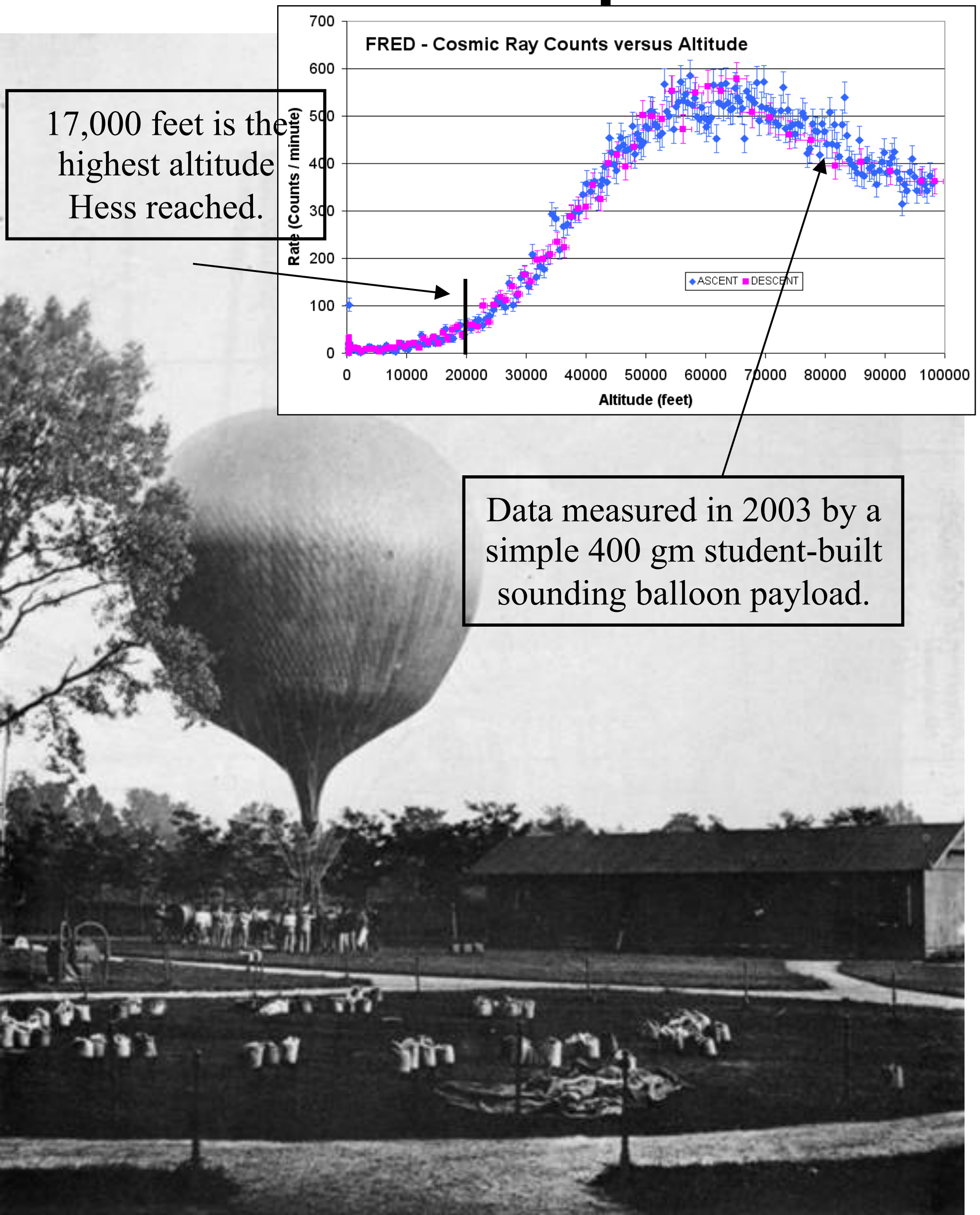
Formation and Interactions of CR's



1.1 Breve storia dei RC

- Scoperta della radioattività (1896) ad Antoine Henri Becquerel
- J. McLennan e E. Rutherford notarono (1903) che un rivelatore completamente schermato non mostrava un segnale nullo, deducendone l'esistenza di una radiazione altamente penetrante.
- Per controllare l'ipotesi che tale radiazione provenisse dalla terra A. Gockel effettuò nel 1910 misure fino all'altezza di 5 km. Il fisico austriaco **Victor Franz Hess** (Nobel nel 1936 per le sue pionieristiche ricerche), ed il fisico W. Kolhorster effettuarono ulteriori misure (1911 - 1914) fino all'altezza di 9 km utilizzando palloni aerostatici.

L’esperimento di Hess



- Nel 1912, Hess caricò su un pallone aerostatico un dispositivo per misurare le particelle cariche.
- Nel volo, si dimostrò come la radiazione aumentava con l’altitudine.
- Questo significava che la radiazione sconosciuta non aveva origine terrestre (come la radioattività naturale) ma proveniva dallo spazio esterno, da cui il nome di **Raggi Cosmici**

- Dopo Hess, fu Millikan, nel 1925, ad interessarsi a questa radiazione, e a lui si deve il nome di ***raggi cosmici***: egli riteneva che fossero composti principalmente da raggi gamma.
- Compton ipotizzò, al contrario, che fossero composti da particelle cariche: successive misurazioni dimostrarono la validità di questa seconda ipotesi. La distribuzione dei RC, infatti, variava con la latitudine magnetica, come ci si attende per le particelle cariche sotto l'influenza del campo geomagnetico terrestre.
- Nel 1930 il fisico italiano Bruno Rossi notò che, se la carica delle particelle era positiva, esse dovevano provenire in maniera preferenziale da est. Thomson dimostrò sperimentalmente la giustezza dell'intuizione dell'italiano.
- A partire dagli anni ’30 sino alla nascita dei primi acceleratori di particelle, la storia della fisica delle particelle coincide con quella dei Raggi Cosmici
- Si pose la questione sull'origine e la provenienza dei raggi primari. Nascita dell’astrofisica dei RC (scuola russa, anni ’60) **The Origin of Cosmic Rays**, Ginzburg&Syrovatskii. (1964)

Understanding the nature of cosmic rays

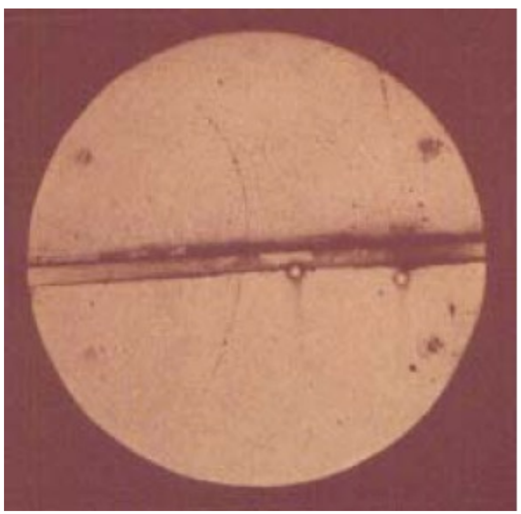
- **1920's** radiation was thought to be some form of high energy photon
  - Hence the name Cosmic **RAYS**
  - **Large debate between the photon camp and those who believed cosmic rays were charged particles (Millikan vs Compton)**
- **1930's** cosmic rays proved to be high energy charged particles **(but were they protons or electrons)**
  - Effects due to Earth's magnetic field (first 'magnetic analyzer')
    - **Latitude survey on-board ships**
    - **East-West Effect**
  - Confirmed CR as positive charged (some believed they were positrons which had been discovered some years earlier)
    - **Penetrating power through blocks of lead proved most primaries were protons (used mountaintop labs for some of these studies)**
  - 1937 - Discovery of muon

Birth of elementary particle physics

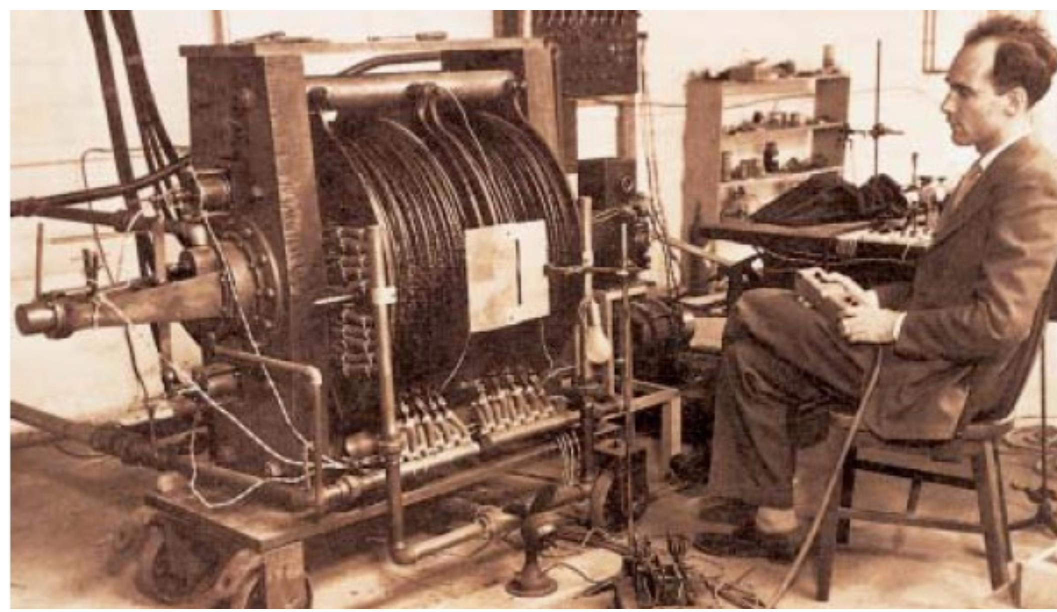
- **40's and 50's** cosmic ray "beam" was used to obtain data for studies of 'elementary particles'.

Particelle scoperte nei RC

- **Il positrone** (1932).
- Carl Anderson osservò delle particelle cariche positivamente, che lasciavano nella camera a nebbia la stessa traccia degli e-. I suoi risultati furono convalidati nel 1933 da Blackett e Occhialini che riconobbero in esse l'antielettrone o positrone proposto teoricamente da Dirac, osservando la conversione di fotoni di alta E in coppie e+e-.
- Vedi: **http://www.infn.it/notiziario/not12/Art1.pdf**



Era dottorando...



- # Il muone (1937).
- Ancora Anderson, notò delle particelle che deviavano in maniera diversa dagli elettroni e da altre particelle note quando queste passavano attraverso un **campo magnetico**. In particolare, queste nuove particelle venivano deflesse ad un angolo minore rispetto agli elettroni, ma più acuto di quello dei protoni. Si assunse che la loro carica fosse identica a quella dell'elettrone e, per rispondere alla differenza di deflessione, si ritenne che avesse una massa intermedia (un valore compreso tra la massa del protone e dell'elettrone).

- Si pensava che fosse la particella ipotizzata da Yukawa per spiegare le interazioni tra nucleoni per formare i nuclei
- Si scoprì che questa particella aveva delle caratteristiche peculiari da renderla il cugino pesante dell'elettrone (esperimento Pacini-Piccioni-Conversi). Leggere l'articolo di Salvini:

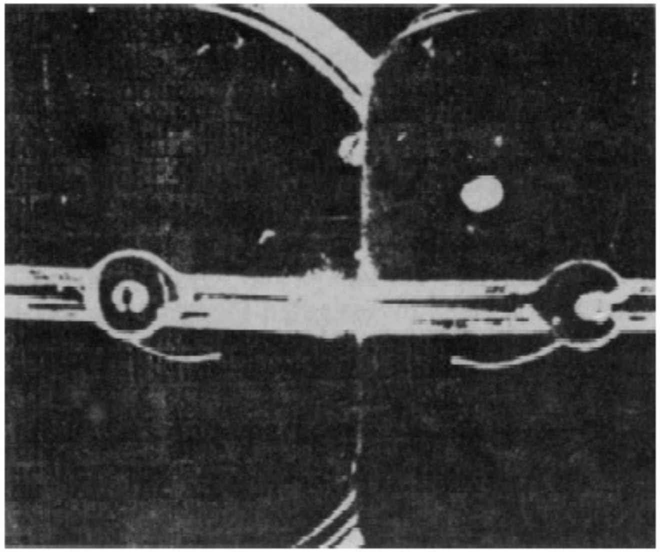
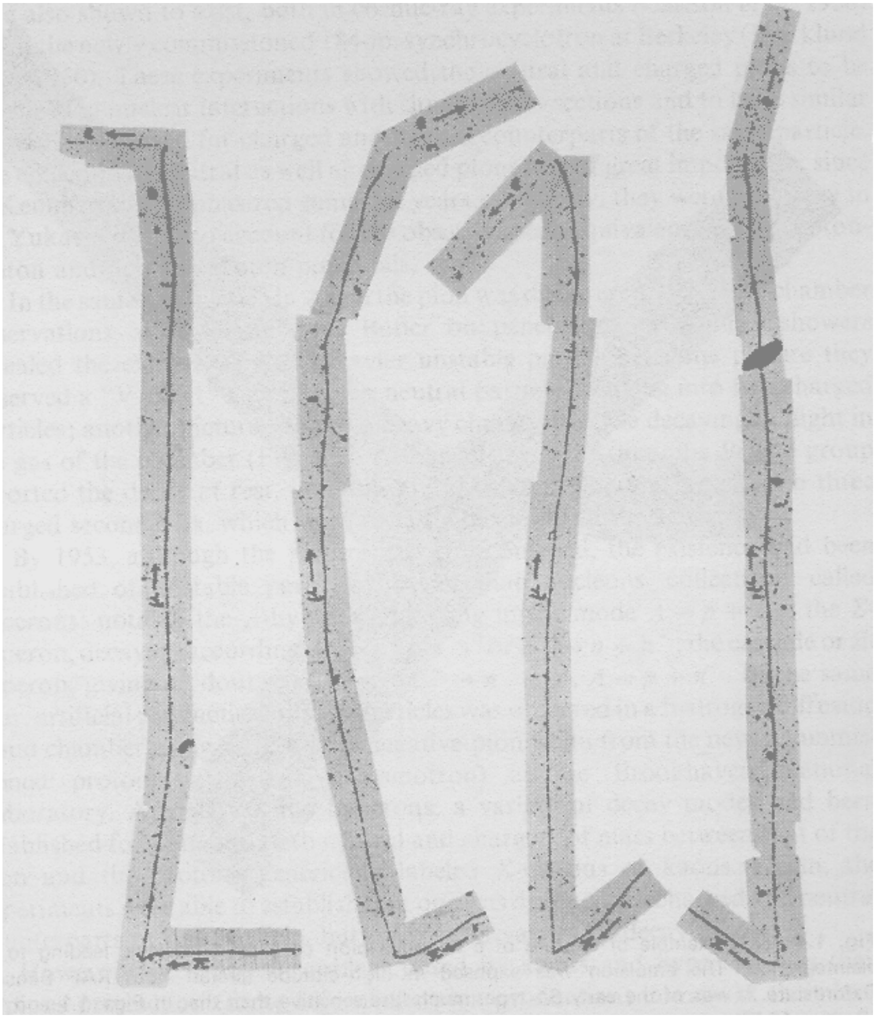


Fig. 1. – Evidenza in camera di Wilson di un muone positivo che traversa un contatore di Geiger entro la camera [1]. La sensibilità della camera non poteva arrivare a rivelare l'elettrone di decadimento.

http://www.lincei.it/pubblicazioni/rendicontiFMN/rol/pdf/S2004-04-21.pdf

- **Il pione (1947).**
- Particella predetta nel 1936 da Hideki Yukawa, il pione si osservò sperimentalmente solo nel 1947 da parte di C.F. Pawel,G. Occhialini e C. Lattes, utilizzando speciali emulsioni fotografiche per registrare la produzione di pioni da parte dei raggi cosmici e il loro successivo decadimento in muoni, che a loro volta decadono in elettroni (o positroni) e in neutrini (invisibili).
- Vedi i filmati:
- **http://www.explora.rai.it/online/doc.asp?pun_id=1140**

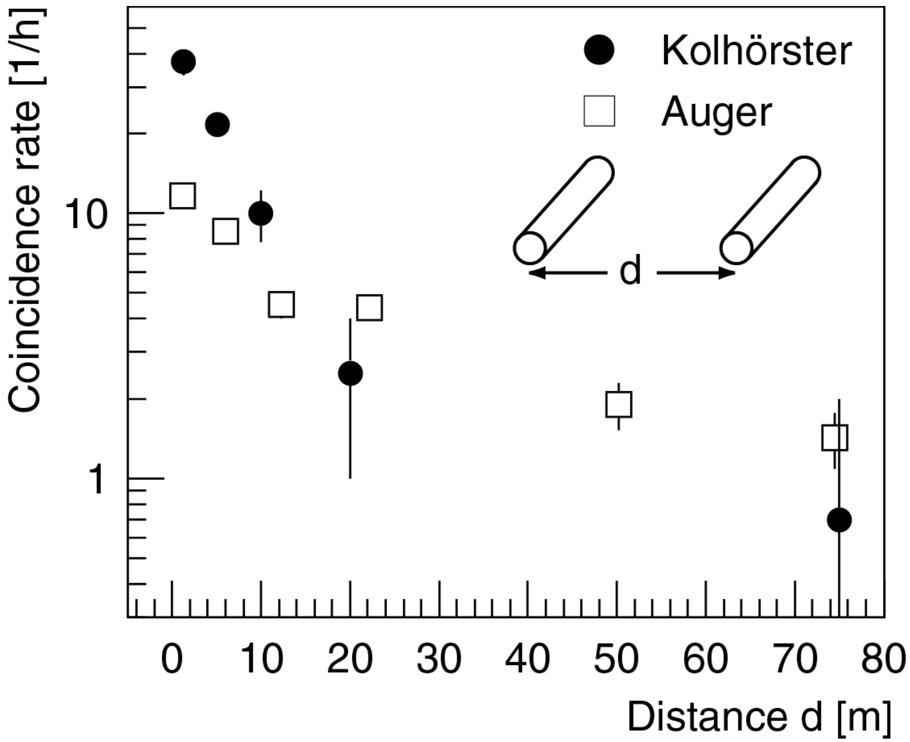


- **Gli "Iperoni" (anni '50), ossia particelle contenenti quark s (Λ, Σ, Ξ, Ω)**

Extensive air showers

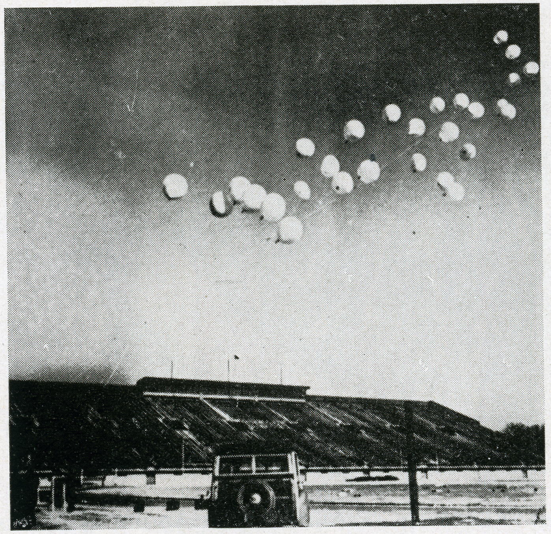
Measuring Cosmic Rays in the Swiss Alps
The author (*left*) and his collaborator, P. Ehrenfest, set up their apparatus in the Jungfraujoch.

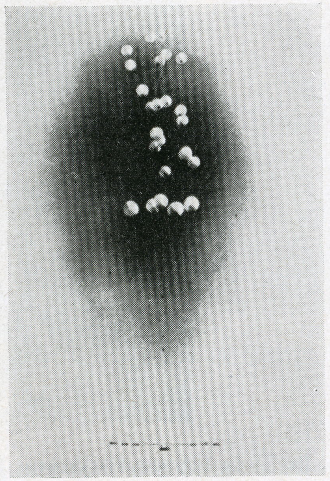
P. Auger
Jungfraujoch



W. Kolhörster et al., Naturwiss. 26 (1938) 576
P. Auger et al., Comptes renduz 206 (1938) 1721

A





B

C

P. Auger

Balloon Flight of January, 1943, Conducted by the Author, Schein, and Rogozinski for the Measurement of Extensive (or Auger-) Showers in the Stratosphere

A. The balloons are assembled on Stagg Field at the University of Chicago, Chicago, Illinois. In the foreground can be seen the long frame which was required for the wide separation of the cosmic-ray counters.

B. The large cluster of balloons as it is about to be released.

C. The balloon train sails into the sky after its release. Suspended below the balloons is the frame supporting the counters and recording apparatus.

Brief Chronology

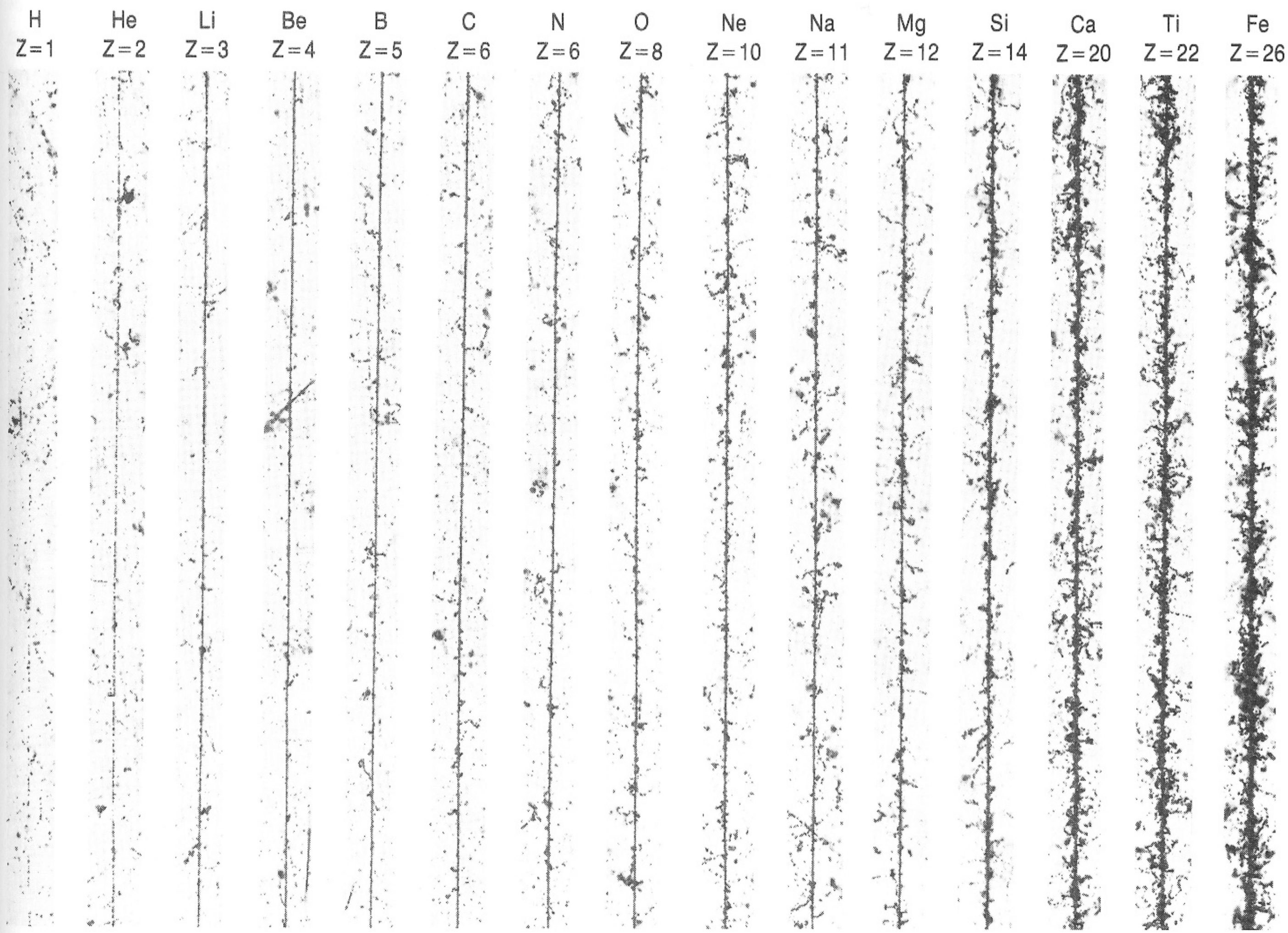
- 1912-15 – Hess and Kolhorster Manned Flights
- 1937 - Mu-Meson Discovered
- 1947 – Pi-Meson Discovered
- 1948 – Discovery of CR Helium and heavy elements
- 1940-50's – CR beam used for Elementary Particle Physics
- 1957 – Sputnik-1 - 'The Dawn of thr Space Age'
- 1961 – Primary Electrons and Gamma rays
- 1966 Discovery of UH (Z>30) Elements in CR
- 1979 – Identification of Anti-protons
- 1970's till – Isotopic Composition at low energy (mainly satellites)

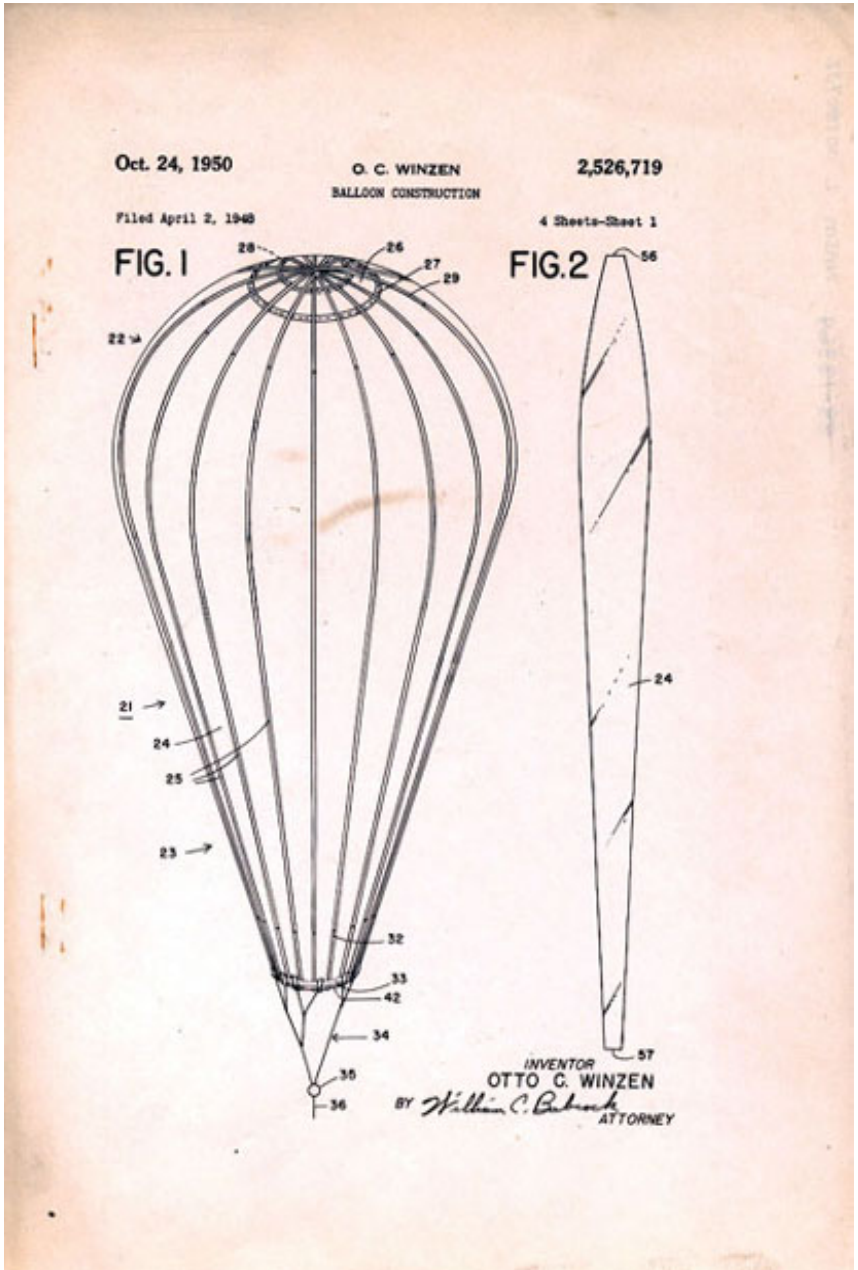
New Detector Technology

- **Geiger-Muller Tubes**
  - Allowed coincidence experiments
  - Used mostly in ground-based experiments
- **Nuclear Emulsion**
  - Particle tracks made visible in thick photographic film (requires darkroom development)
  - Passive detector – Configurable
  - Data collected/analyzed *after* the flight
  - Techniques perfected in labs all over the world
  - Basis of many International collaborations
  - Used continuously for about 60 years

Would benefit both Cosmic Ray and High Energy Physics

Figure 8.3 Tracks of cosmic-ray particles recorded in nuclear photographic emulsions. Nuclei with greater electric charge (Z) produce heavier tracks. These nuclei can eject electrons from atoms through which they pass, and the electrons themselves produce short tracks. This contributes to the track thickness and is especially marked for the heavier particle tracks. Particles can be identified from track structure. In these photographs a typical track thickness is about 2×10^{-4}cm. (P. H. Fowler, University of Bristol).





’ The Age of ‘Plastic’

Otto C. Winzen (1918-76)

- General Mills: developed techniques to produce ultra-thin polyethylene

- Winzen Research Inc. (1949) with wife Vera. Sold poly balloons to ONR

-Projects Helios, Skyhook, Strato-lab, etc.

AF Reconnaissance (Moby Dick)

An Age of Discovery with Balloons

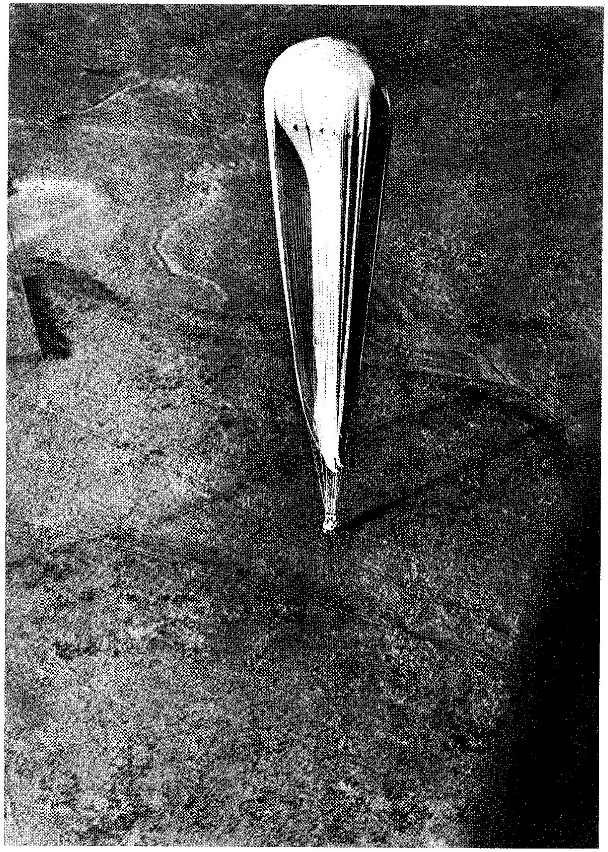


Figure 2.5 *Explorer II. Launched from Rapid City, South Dakota, on November 11, 1935, it touched down near White Lake just over 8 hours later, after a record high-altitude flight. Cosmic ray detecting equipment carried on board included ionization chambers and Geiger counters for W. F. G. Swan of the Bartol Research Foundation, and photographic plates for T. R. Wilkins of the University of Rochester. (Photograph courtesy of Richard H. Stewart and Captain James Haizlip, © 1936 National Geographic Society.)*

- "Rubberized" Balloons (left) give way to the new Plastic Balloons
- Balloon size and thus payload / altitude increases
- New scientific disciplines
  - Propelled Cosmic Ray Physics
  - Beginning of High Energy (then called Elementary Particle) Physics
  - Gamma Ray Astronomy
  - X-ray Astronomy
  - UV Astronomy
  - Aids Solar and Galactic Astronomy
  - Remote Sensing
  - Atmospheric measurements
- High Altitude human flight testing
- Continuing technical advances

Brief Chronology

- 1912-15 – Hess and Kolhorster Manned Flights
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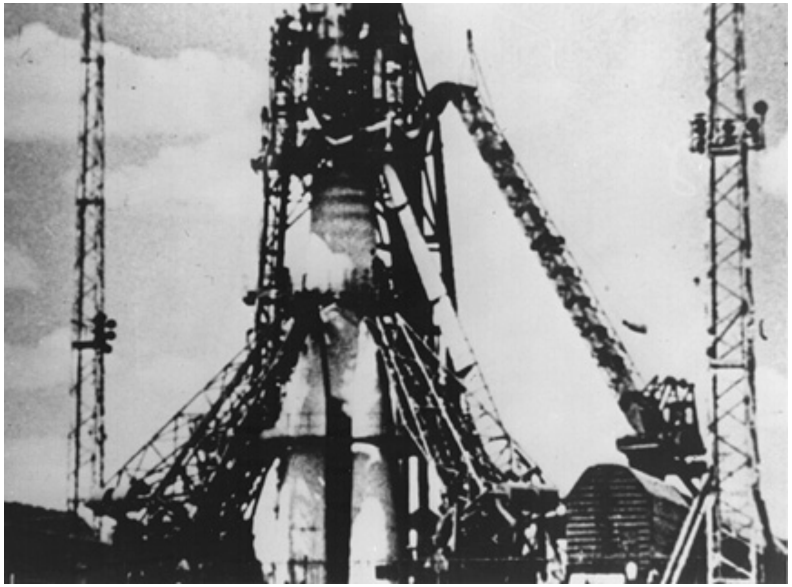
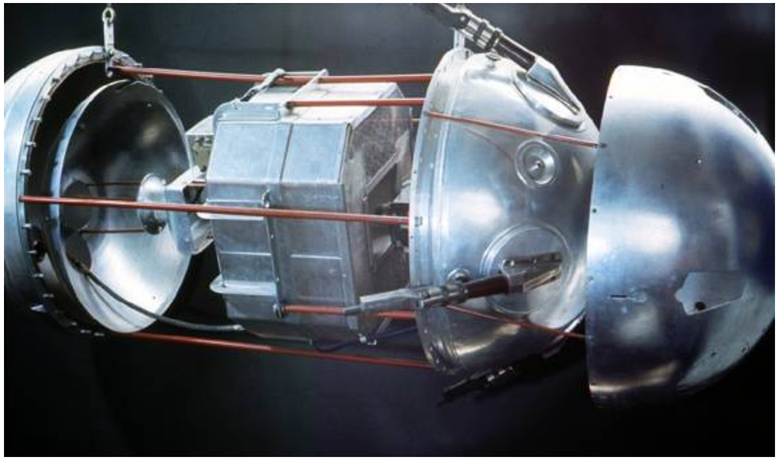
The Dawn of the Space Age – Sputnik-1





1957 October 4
19:12:00 UTC

Baikonur Cosmodrome

83.6 kg

58 cm diameter

4 antennas (2.4 – 2.9 m long)

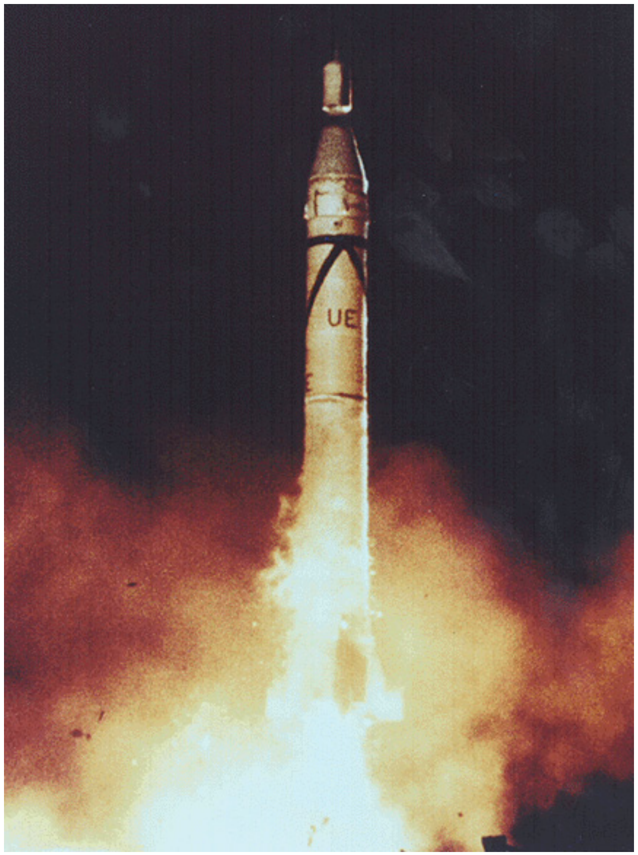
20.005 and 40.002 MHz

92 day lifetime

Iskustvennyi Sputnik Zemli

(Fellow world traveler of the Earth)

The Space Program Evolves



Explorer-I launch Jan. 31, 1958

Sputnik -2 Launched Nov. 3, 1957

Explorer-I Launched Jan. 31, 1958

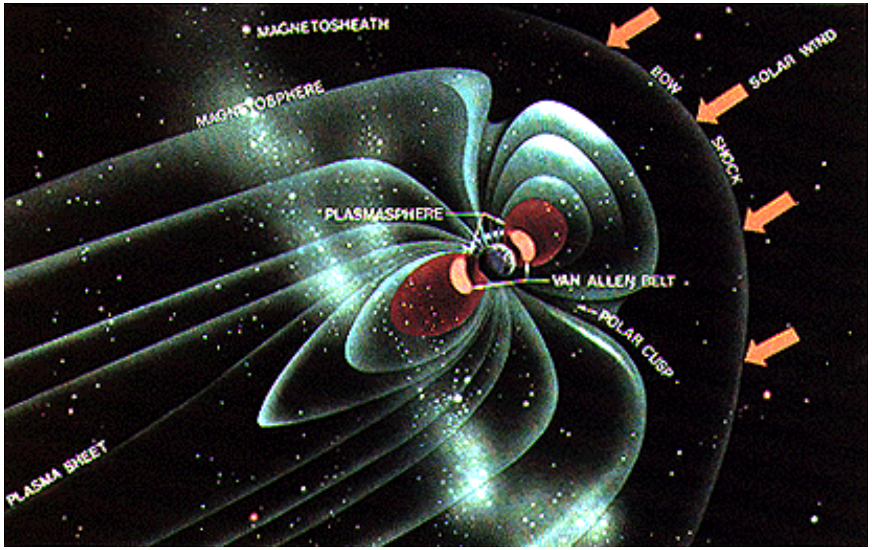
Sputnik – 3 Launched May 15, 1958 (1300 kg – first space environment laboratory)

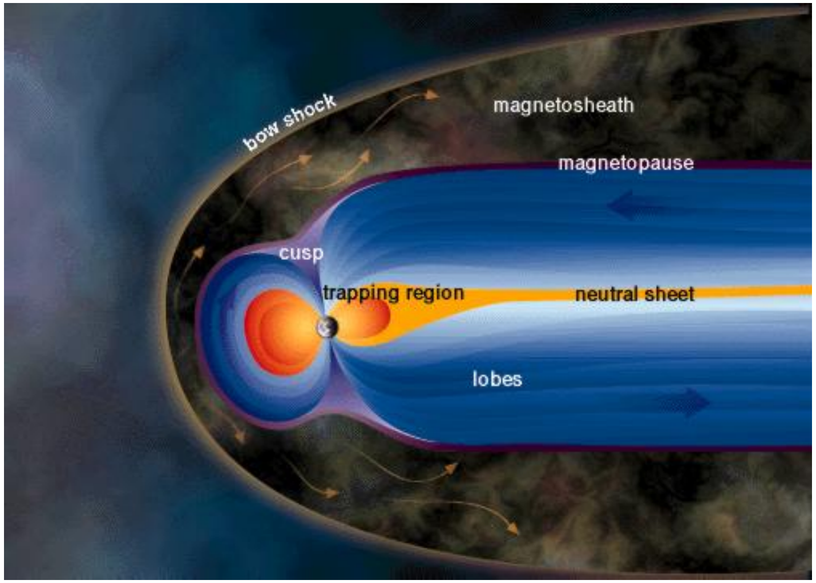
And there were many more satellites …. Explorers, Cosmos, Vanguard, Pioneers, IMP, OGO, OSO, Proton, Voyager, Sokol, to name just a few

And many countries became involved in the Space Adventure

Space Age: Magnetospheric Physics

Explorer-I carried the Geiger-Muller tube radiation experiment of James Van Allen which led to the discovery of trapped particles within the Earth's magnetic field – the 'birth' of Magnetospheric Physics





Dr. William H. Pickering, Dr. James A. Van Allen and Dr. Wernher von Braun (left to right) hoist a model of Explorer I and the final stage after the launch.

HEP -- The Era of Colliders

In the 1950's a number of places, MURA, Novosibirsk, CERN, Stanford, Frascati, and Orsay, developed the technology of colliding beams.(Bruno Touschek, Gersh Budker and Don Kerst, among others, were the people who made this happen.)

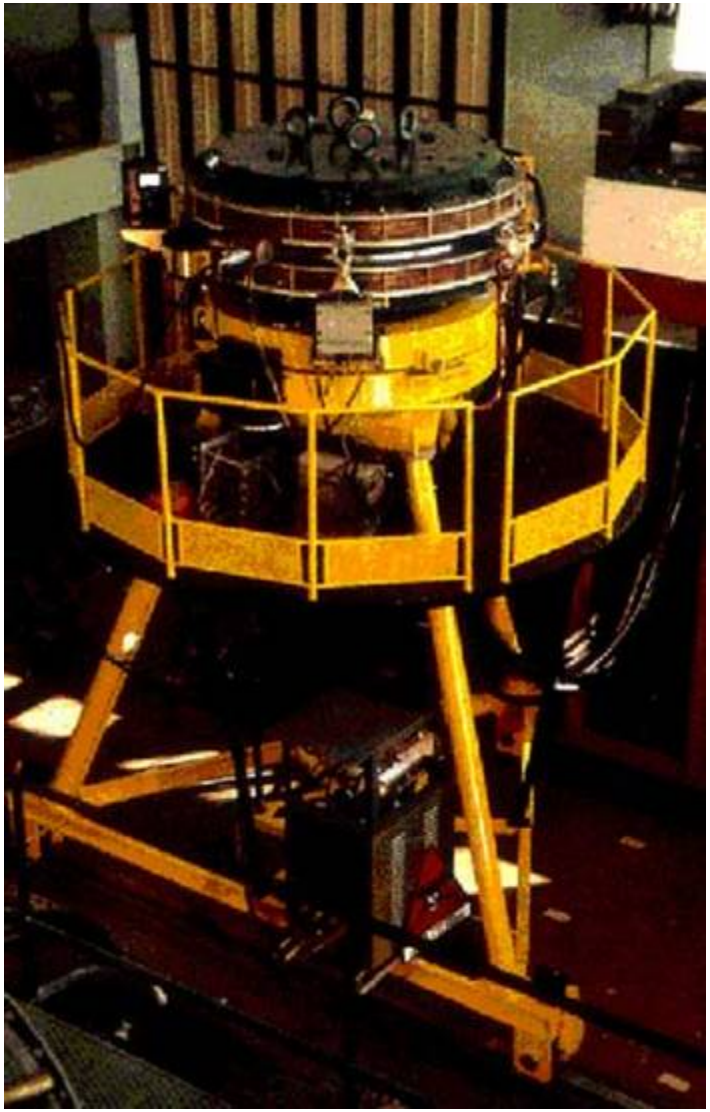
-- Electron – Positron

-- Proton – Proton

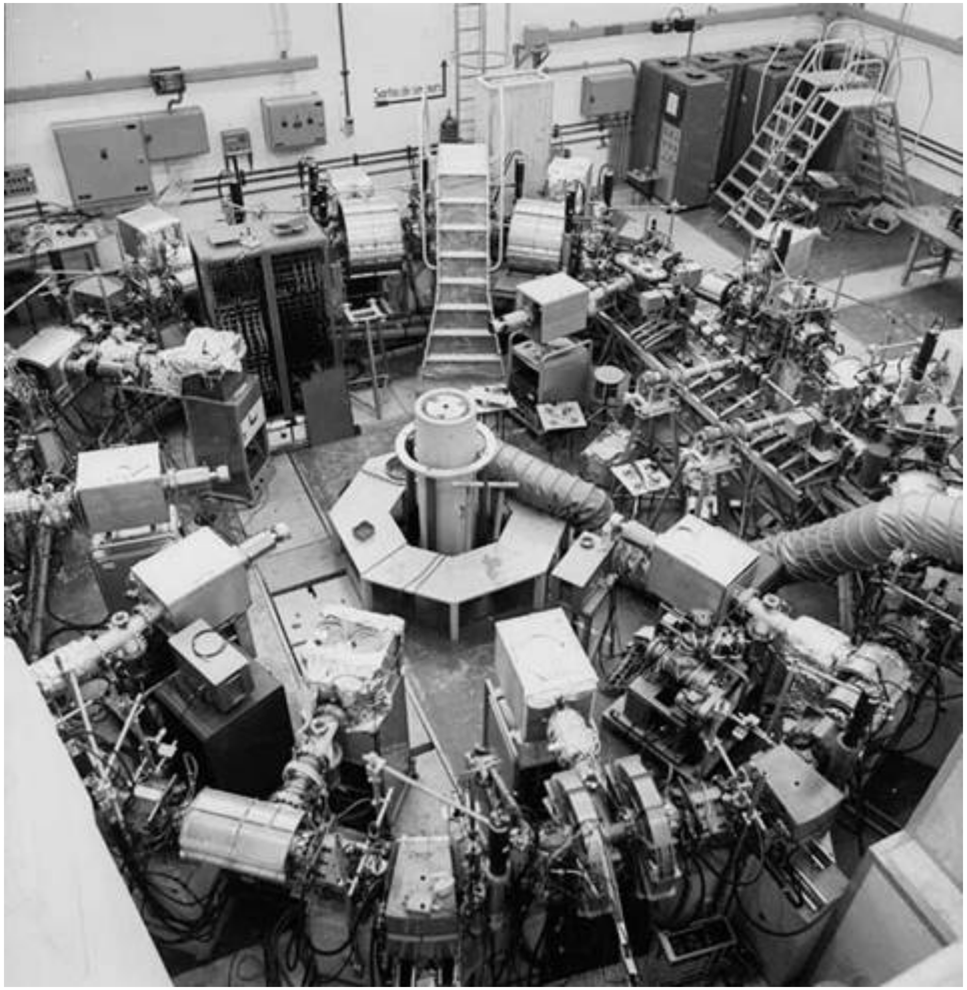
-- Proton -- Anti-proton

-- Heavy Ion

Colliders continue to be the source of the highest energy collisions

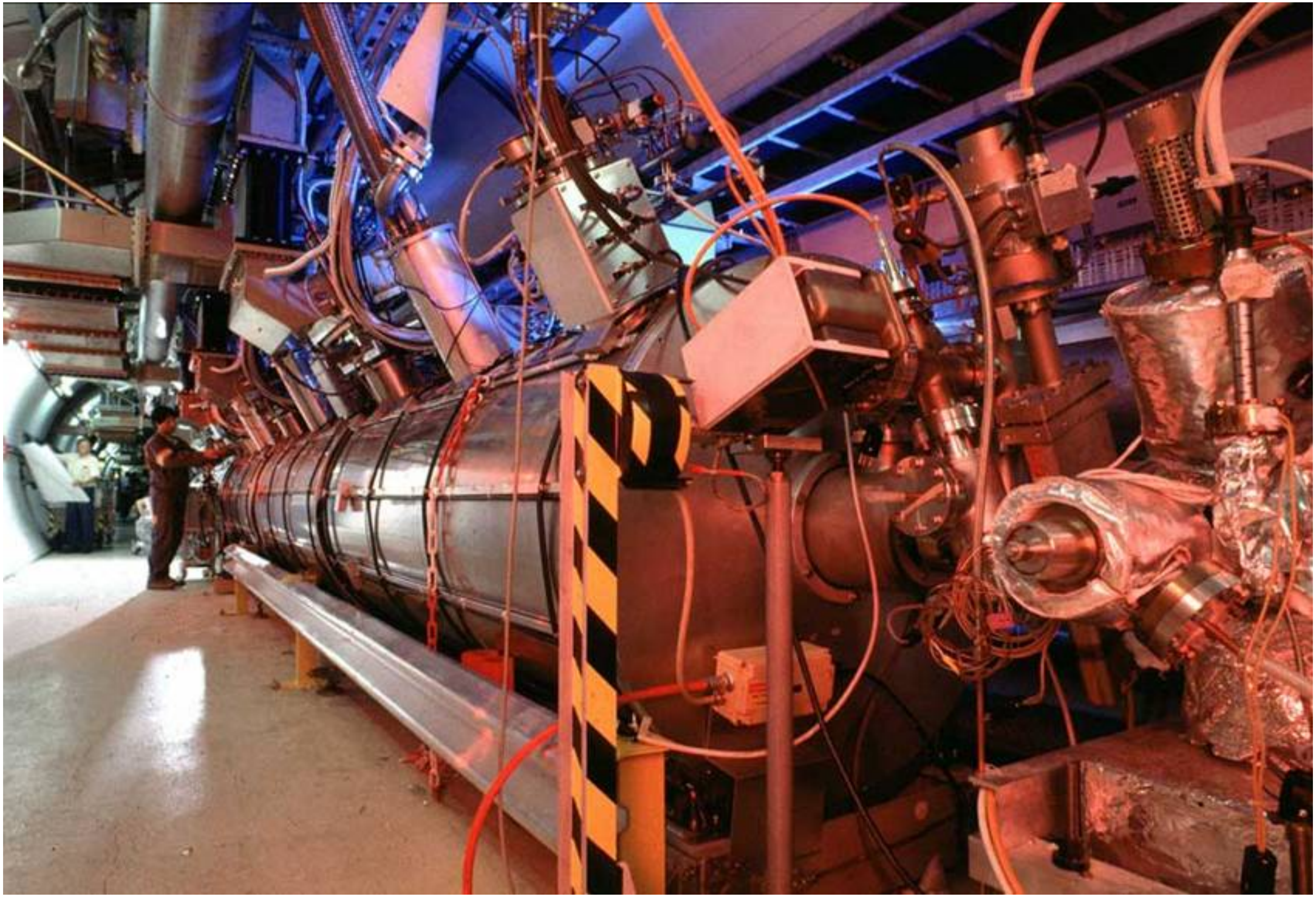


The first electron-positron storage ring, AdA. (About 1960) Built and operated at Frascati, Italy and later moved to take advantage of a more powerful source of positrons in France.



The CERN Electron Storage and Accumulation Ring (CESAR) was built, in the 1960's, as a study-model for the ISR (Intersecting Storage Rings).

The first proton-proton collider, the CERN Intersecting Storage Rings (ISR), during the 1970’s. One can see the massive rings and one of the intersection points.



Superconducting RF cavities at the CERN Large Electron Positron Collider (LEP).

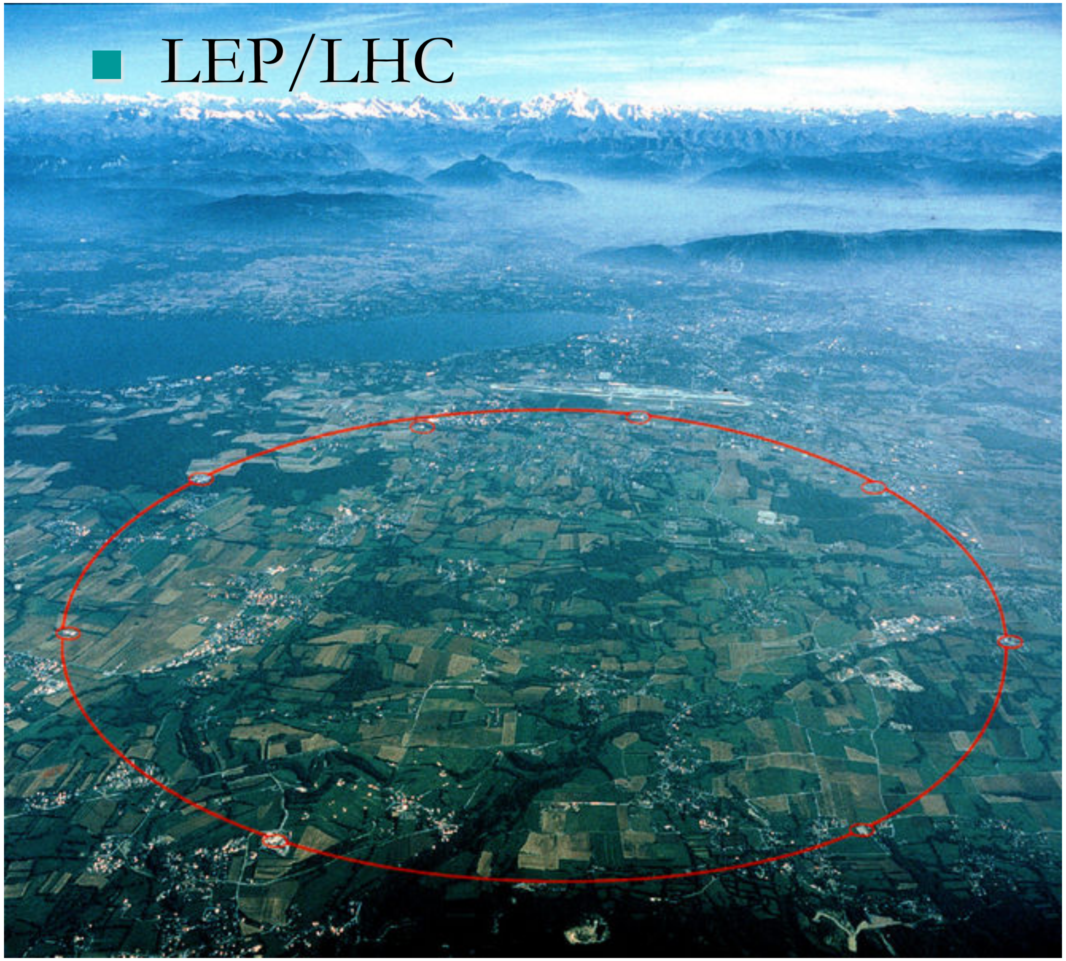
TEVATRON

At

FNAL

The anti-proton source, the "p-bar" source, built in the 1990's at Fermilab. The reduction in phase space density, the proper measure of the effectiveness of the cooling, is by more than a factor of 10^{11}.

…acceleratori

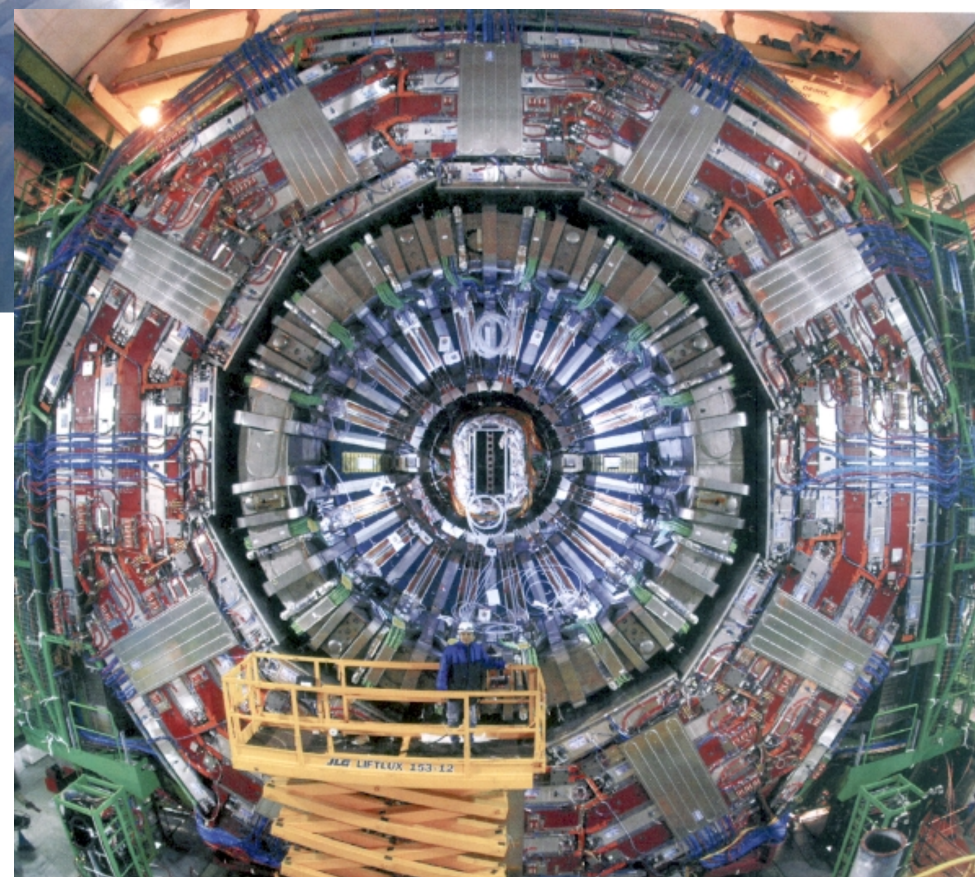


LHC (pp a 7+7 TeV) e' al limite "umanamente" raggiungibie con la tecnologia attuale.

La natura offre un fascio di particelle con energie (per "esperimenti" a bersaglio fisso) di energie fino a $\approx 10^8$ TeV

And Today ……..

The LHC at CERN



And one of the big experiments

CMS

And …. in Space