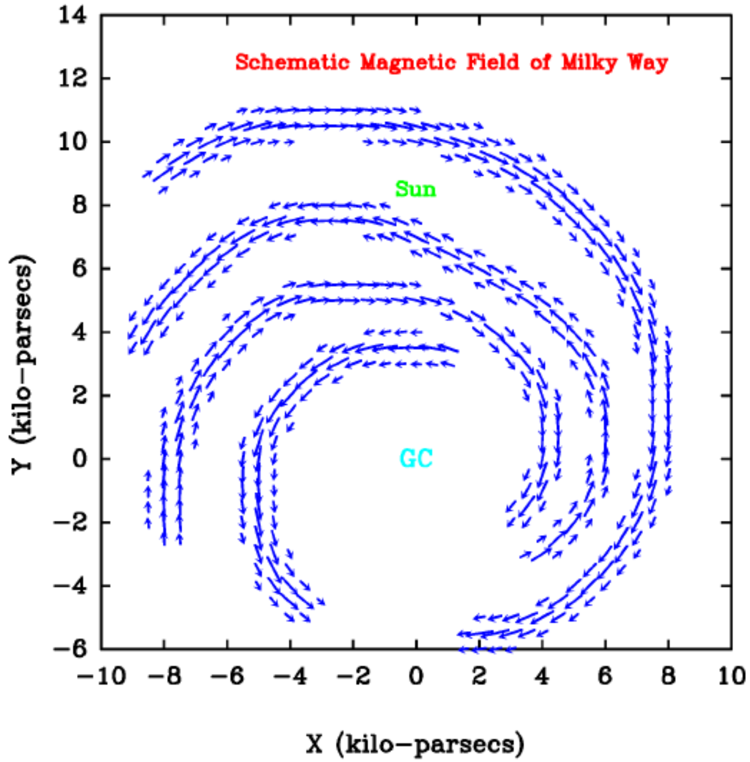
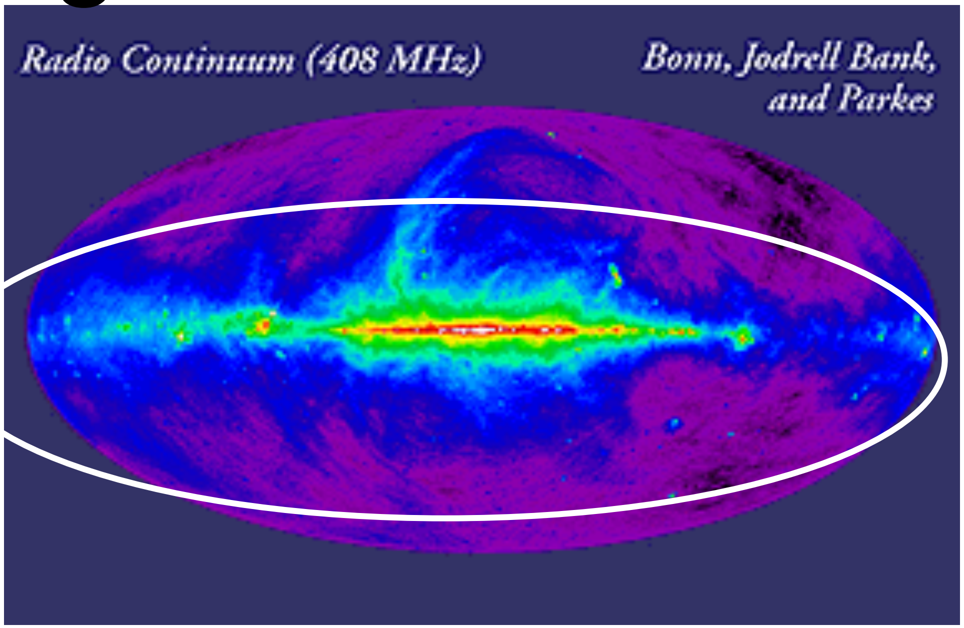
Lecture 4 261017

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

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.

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

- 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

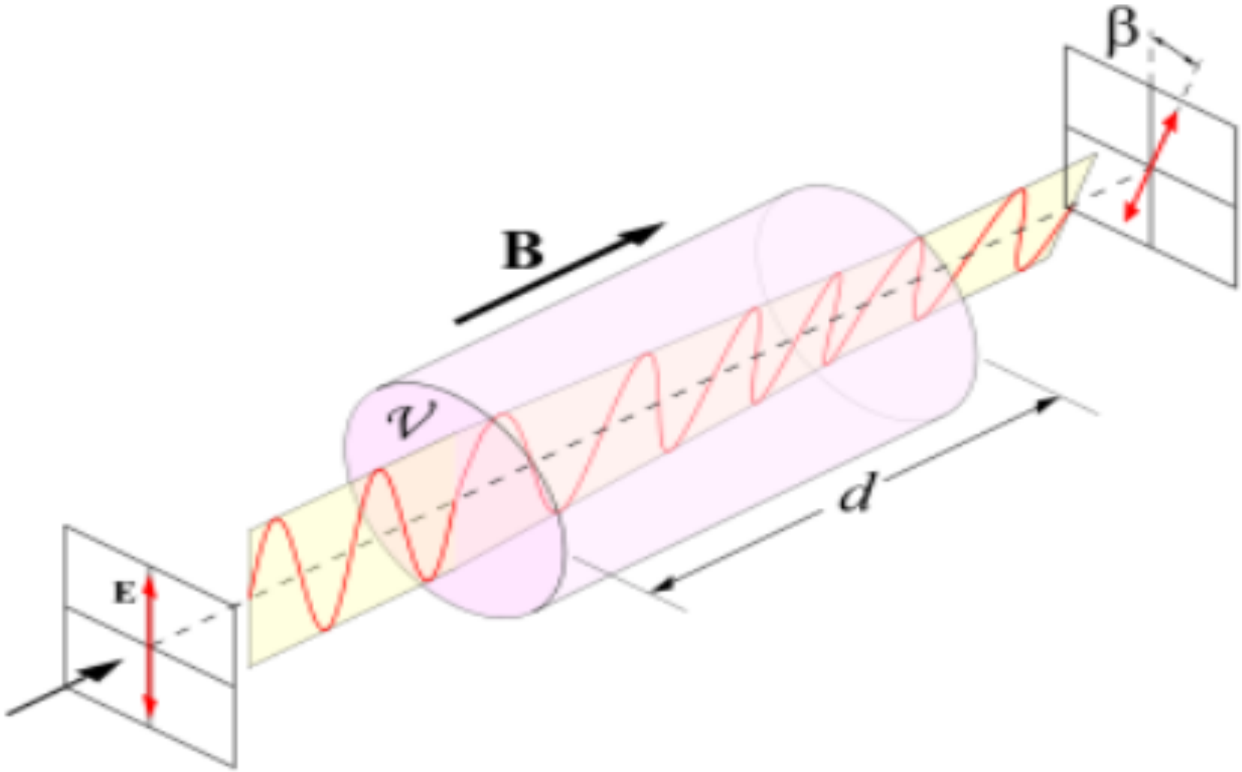


Figure 2: Faraday rotation in a magnetized gas.

- 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

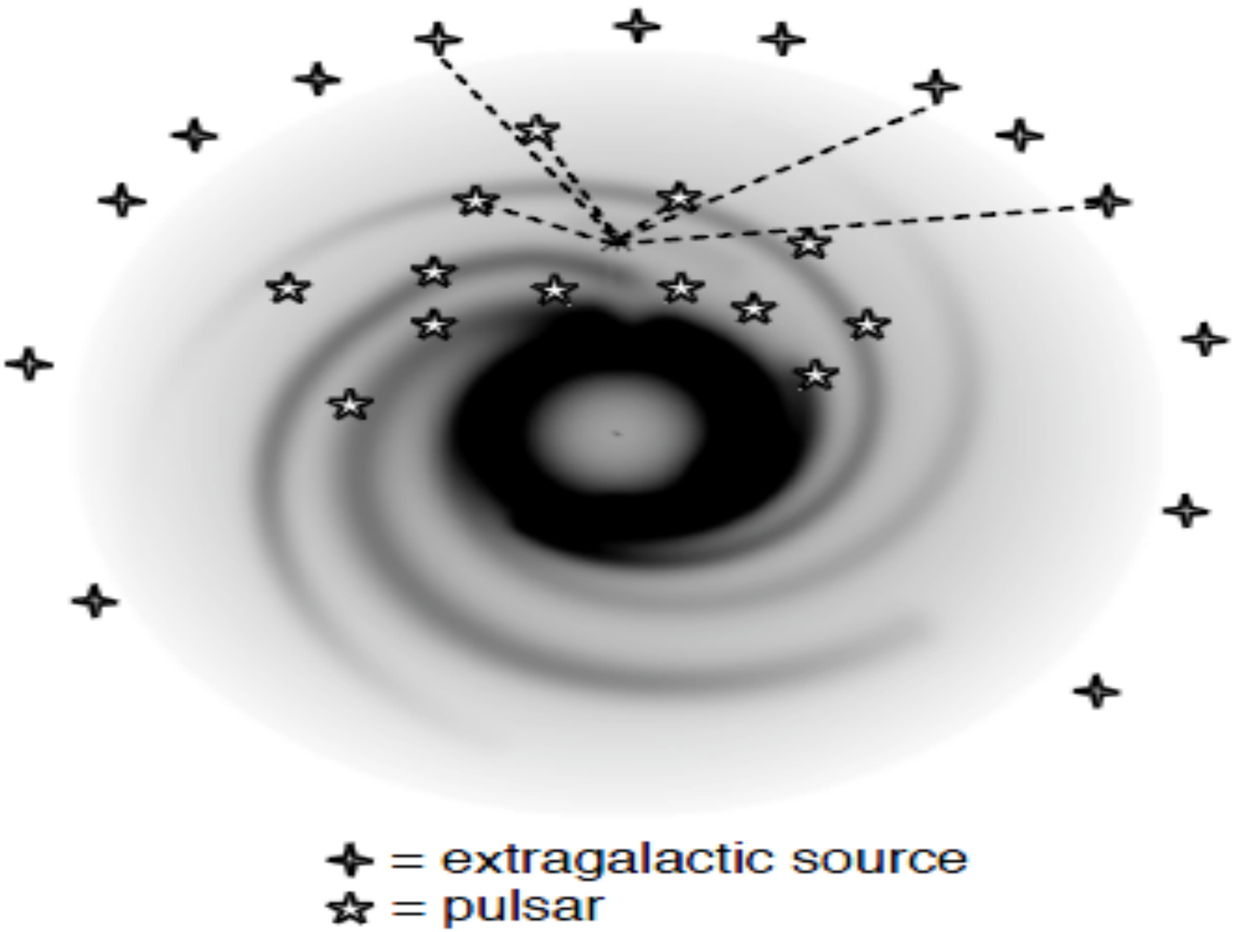


Figure 3: Pulsar and extragalactic sources distribution in our galaxy.

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:

$$U = -m \cdot B$$

$$m = -\mu_B \cdot \frac{L}{\hbar}$$

$$L = m_l \cdot \hbar$$

$$\longrightarrow U = m_l \cdot \mu_B \cdot B$$

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.

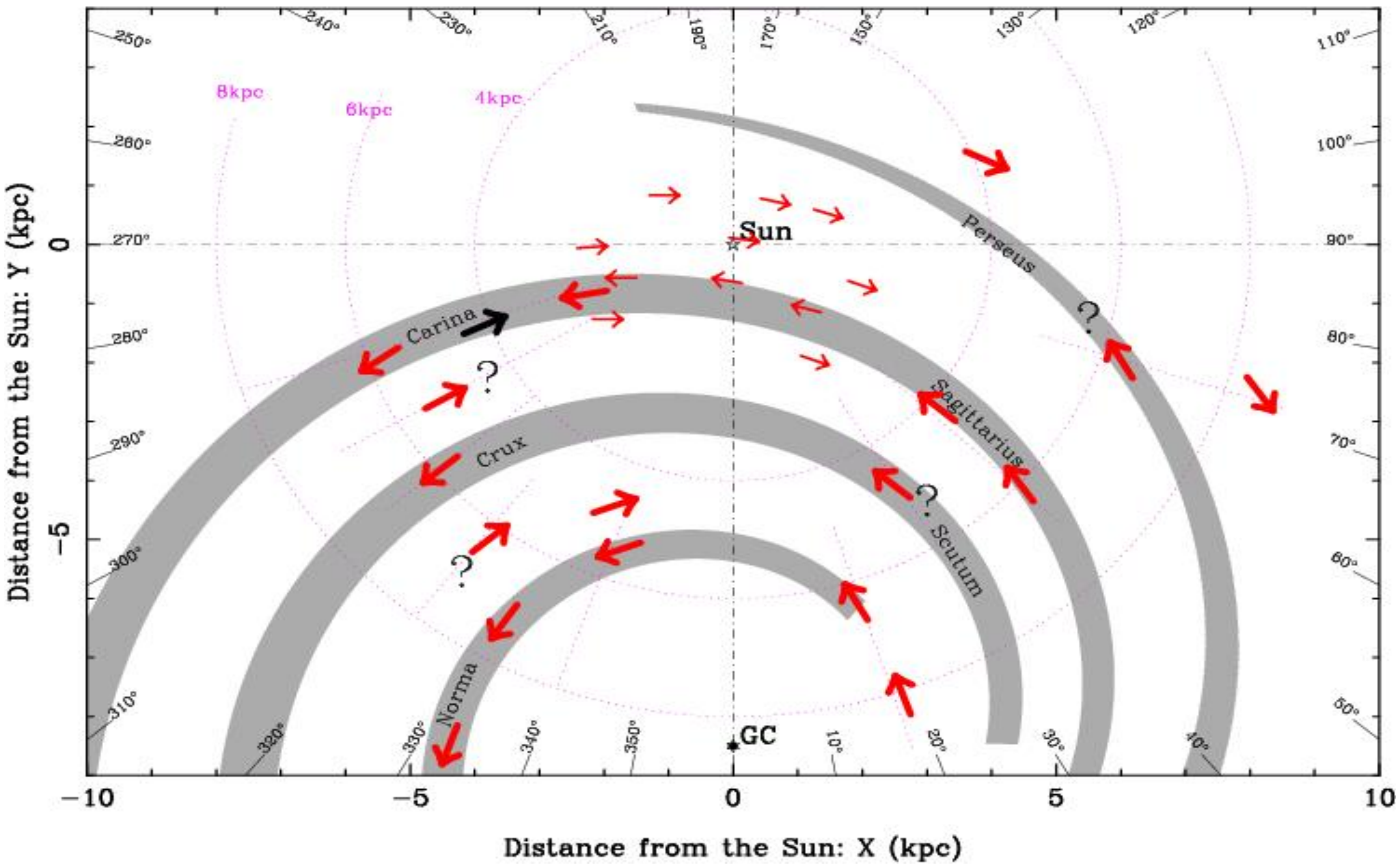
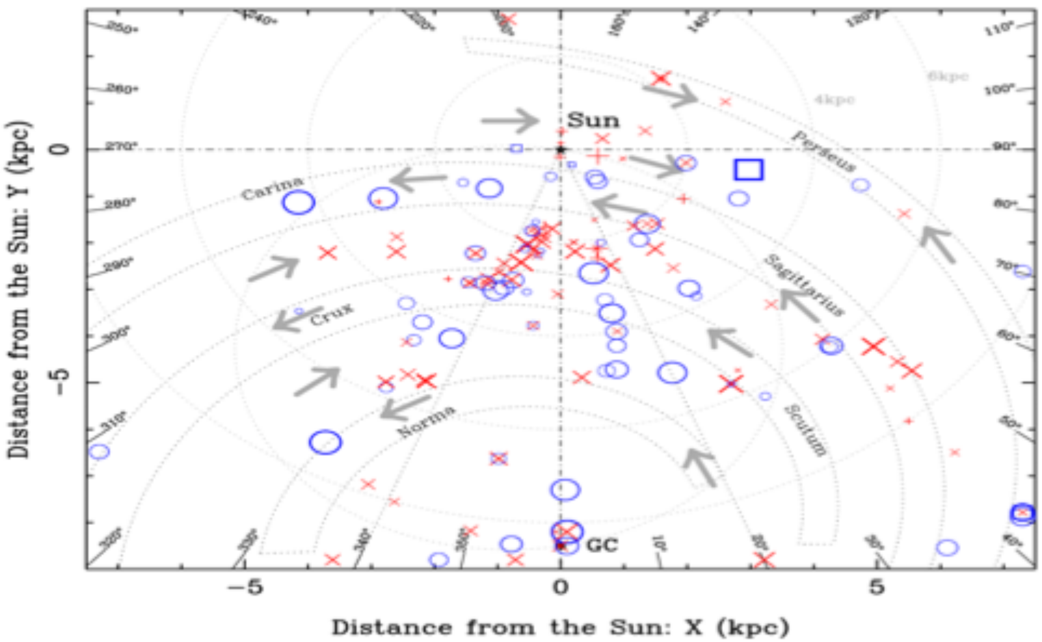


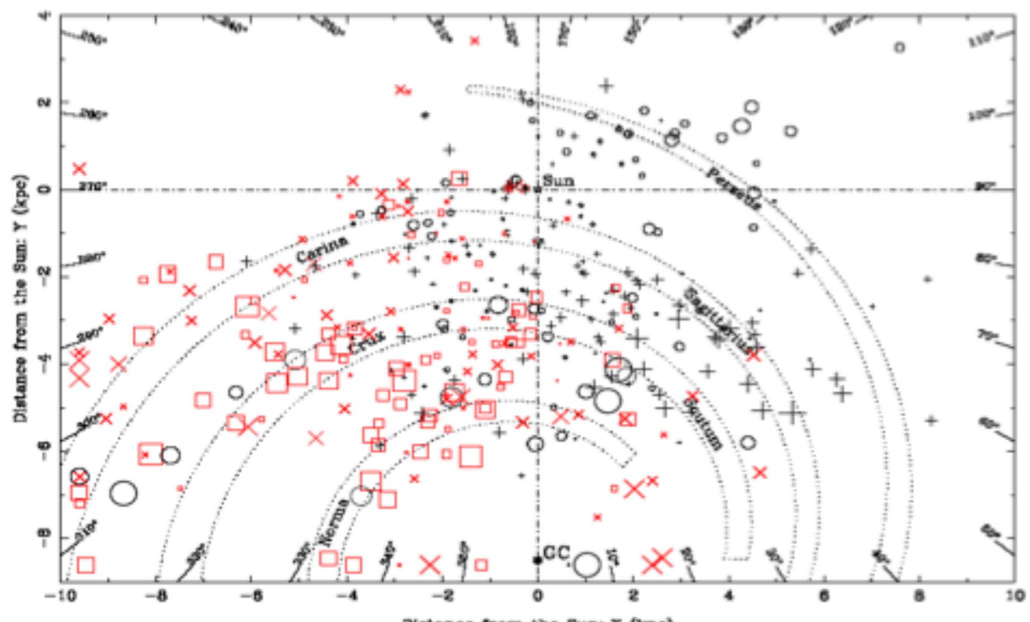
Figure 5: Field orientation in arm and interarm regions in Galaxy.



Data from Zeeman splitting in molecular clouds.

Courtesy of J.L. Han

Data from RM of radio pulsars.



Coherent on 1-10 pc scales

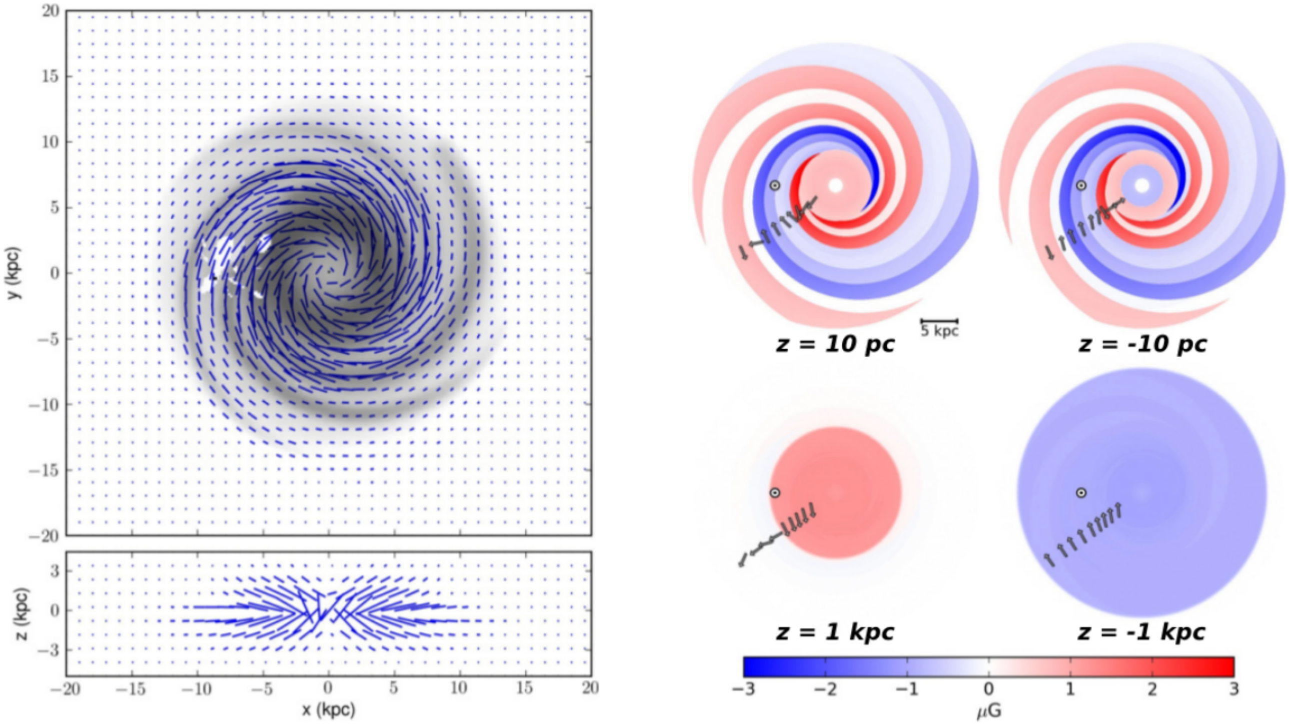
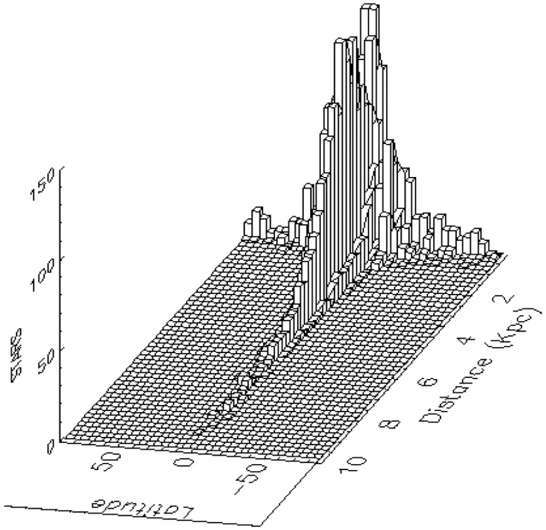


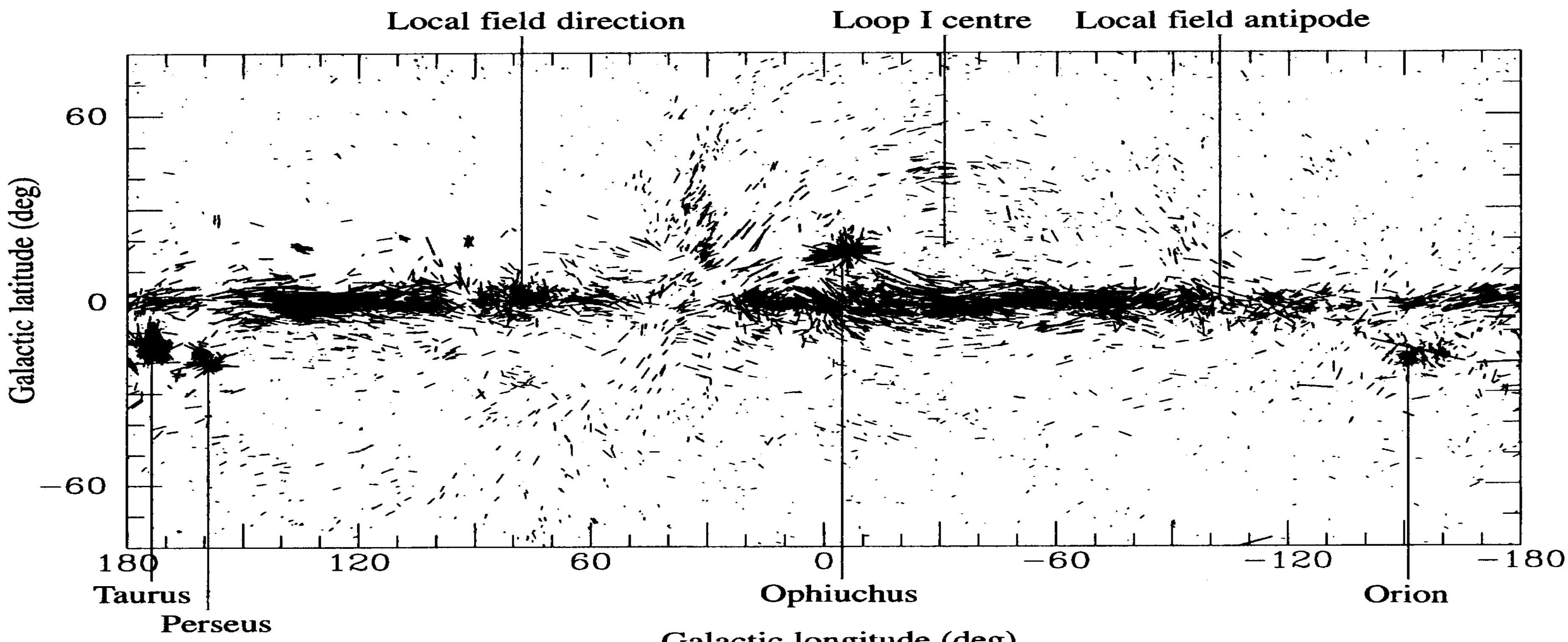
Figura 2.8: Le figure, tratte dall'articolo di Jansson & Farrar [30], mostrano la struttura del campo magnetico della nostra Galassia, ricavate secondo il modello elaborato dagli stessi autori. L'immagine a sinistra descrive la distribuzione delle direzioni e dell'intensità del campo magnetico come sarebbero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



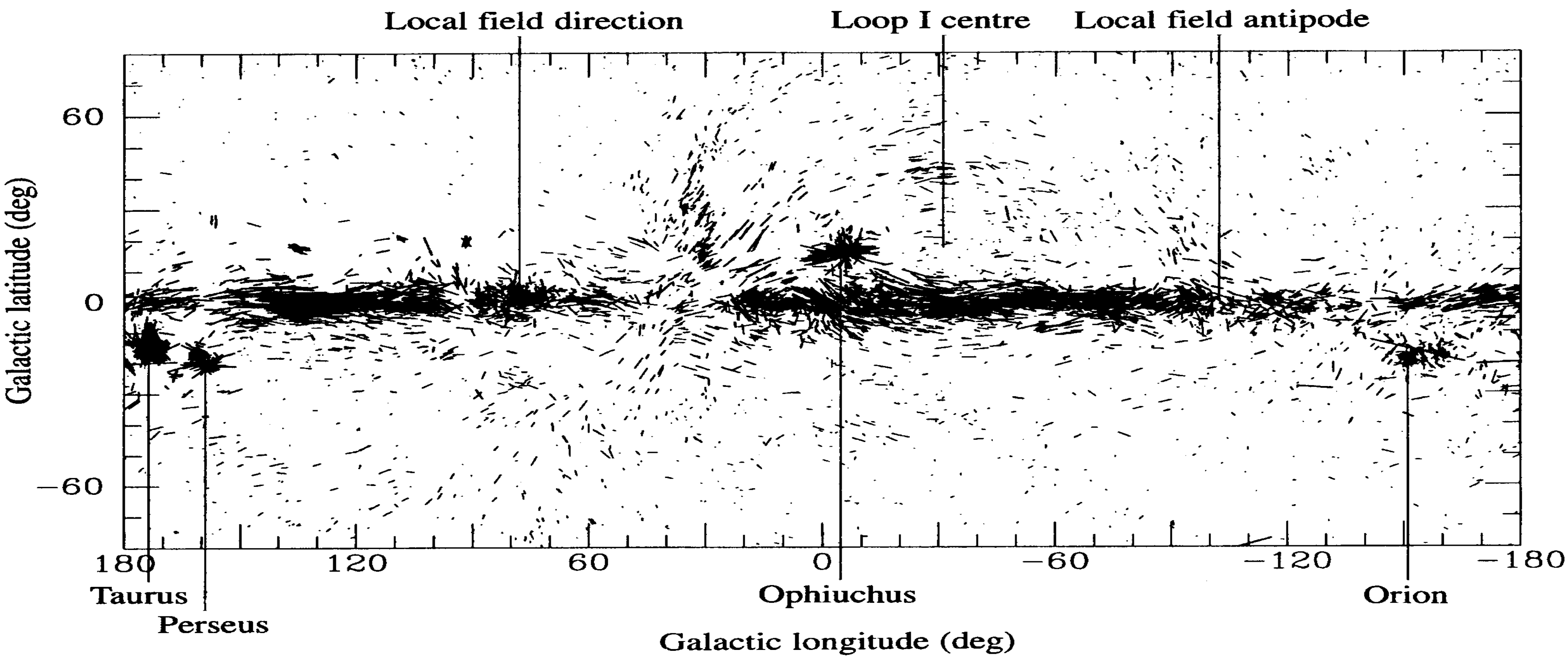
Polarizzazione della luce delle stelle: *local field // arm*

- **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 $B_z\ ;\ 0.2\mu G$.
- 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.

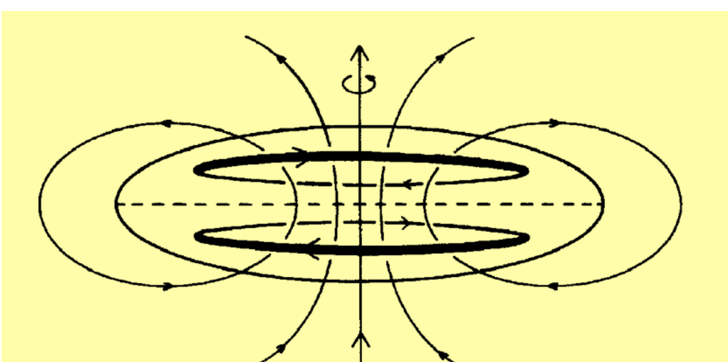


Figure 6: Field configuration for A0 dynamo. Halo field shown.

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.

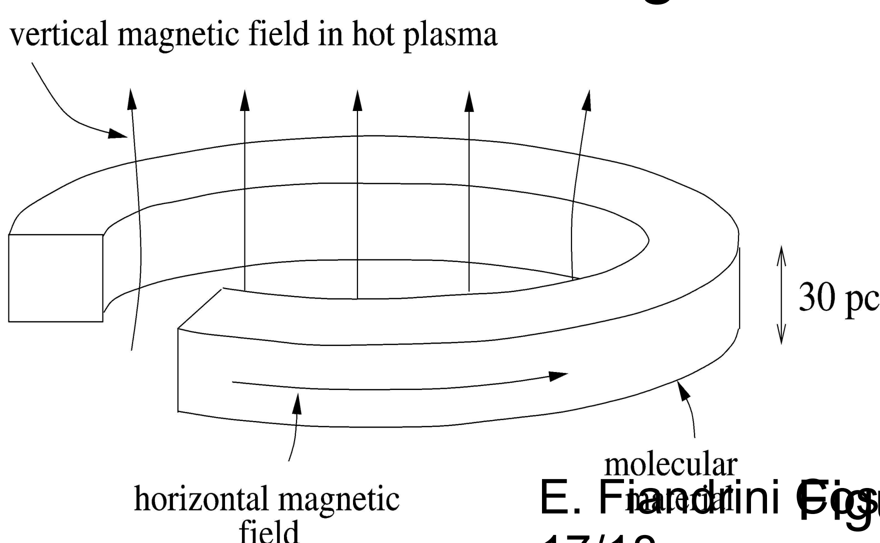
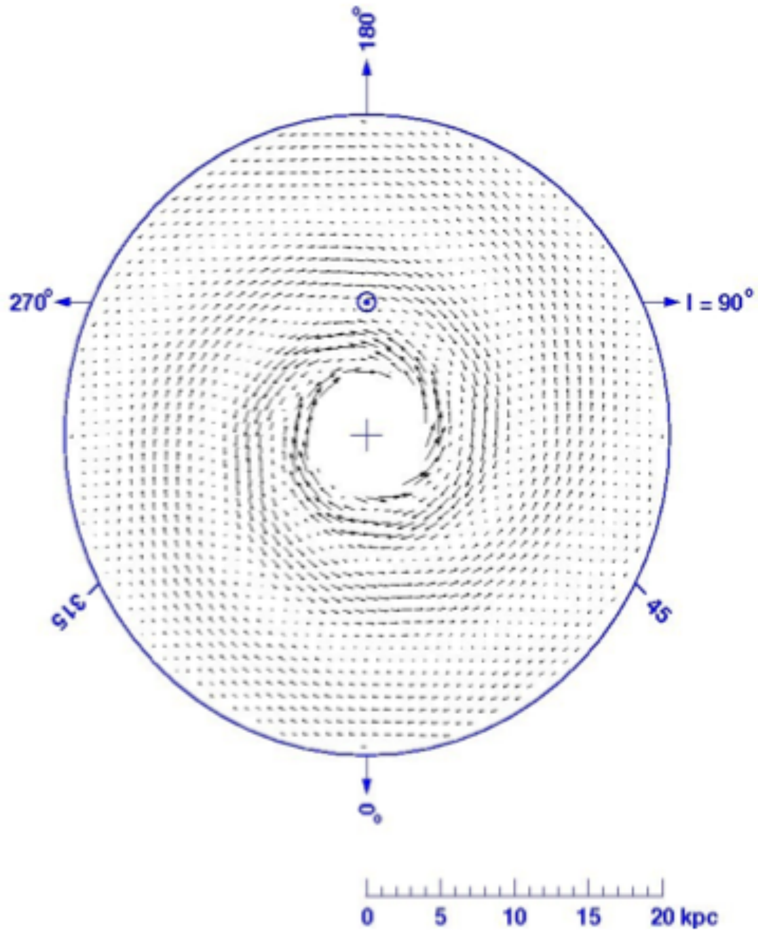


Figure 4: Toroidal and poloidal fields.



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.

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

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

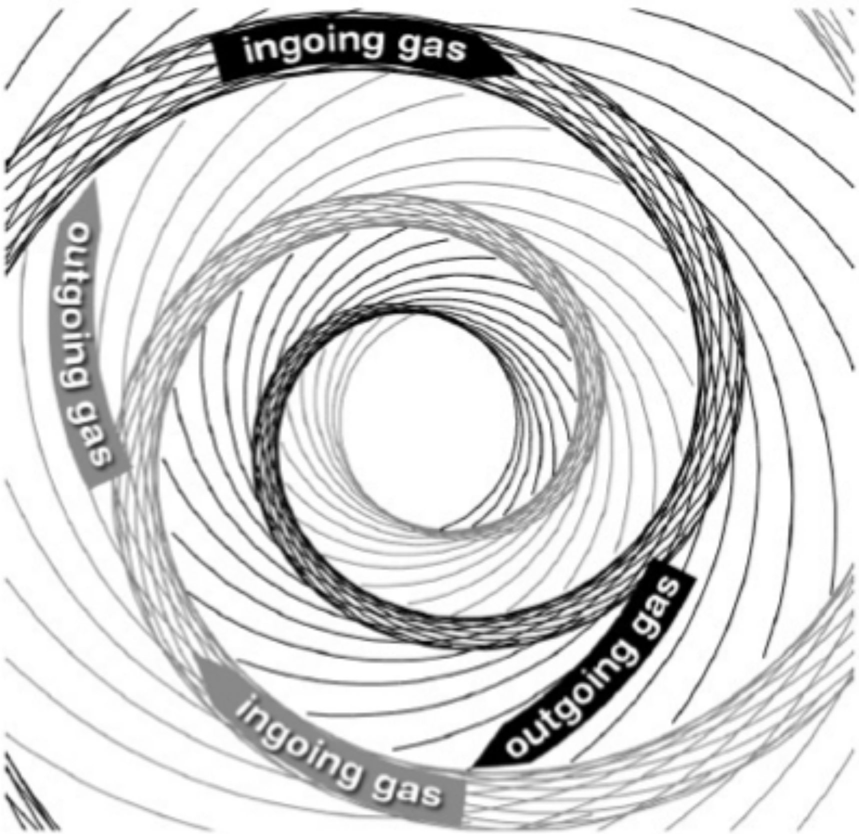
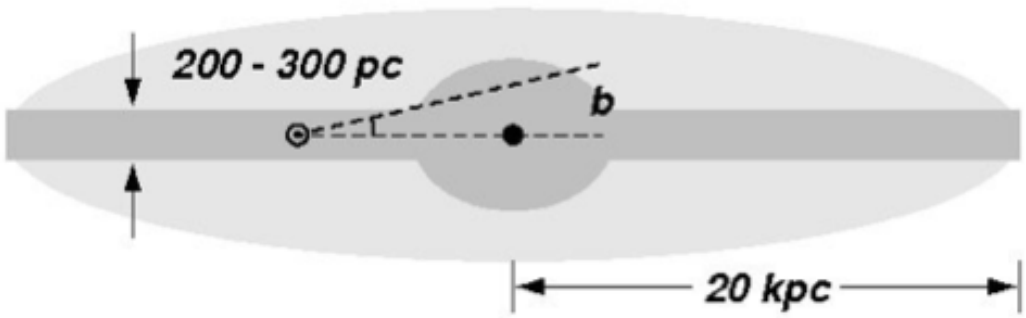


Figure 19: Gas motions in a bisymmetric spiral galaxy.

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.

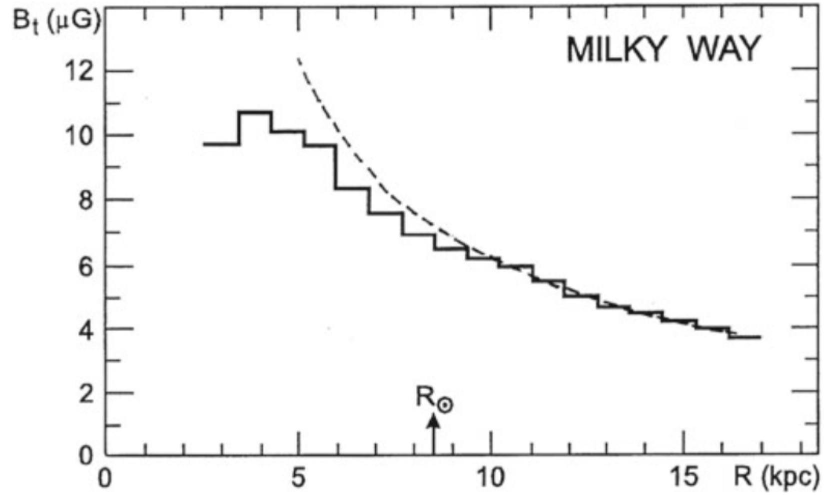
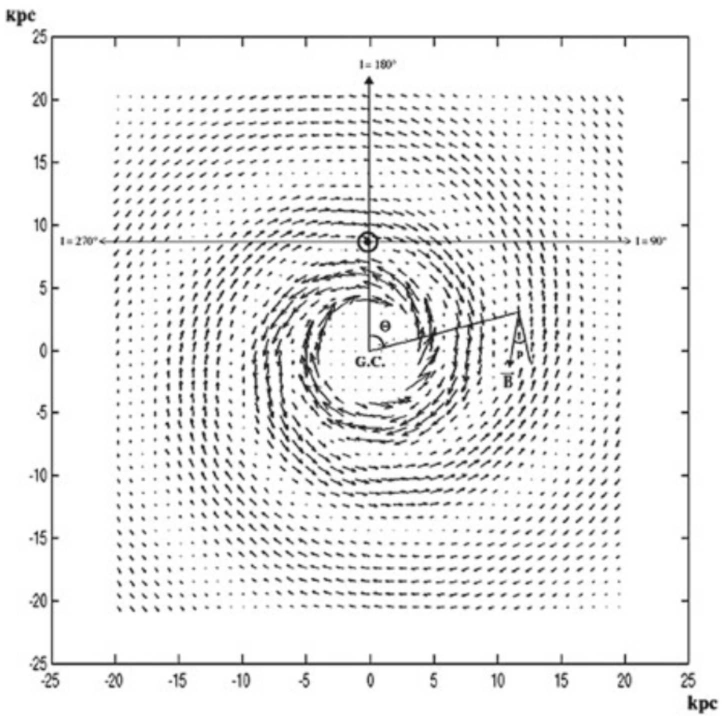


Fig. 2.9 Total magnetic field strength in the Galaxy as a function of the distance from the galactic center. The position of the Sun is indicated by the *arrow* (Battaner et al. 2007). Courtesy of Prof. E. Battaner

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 ≠ 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

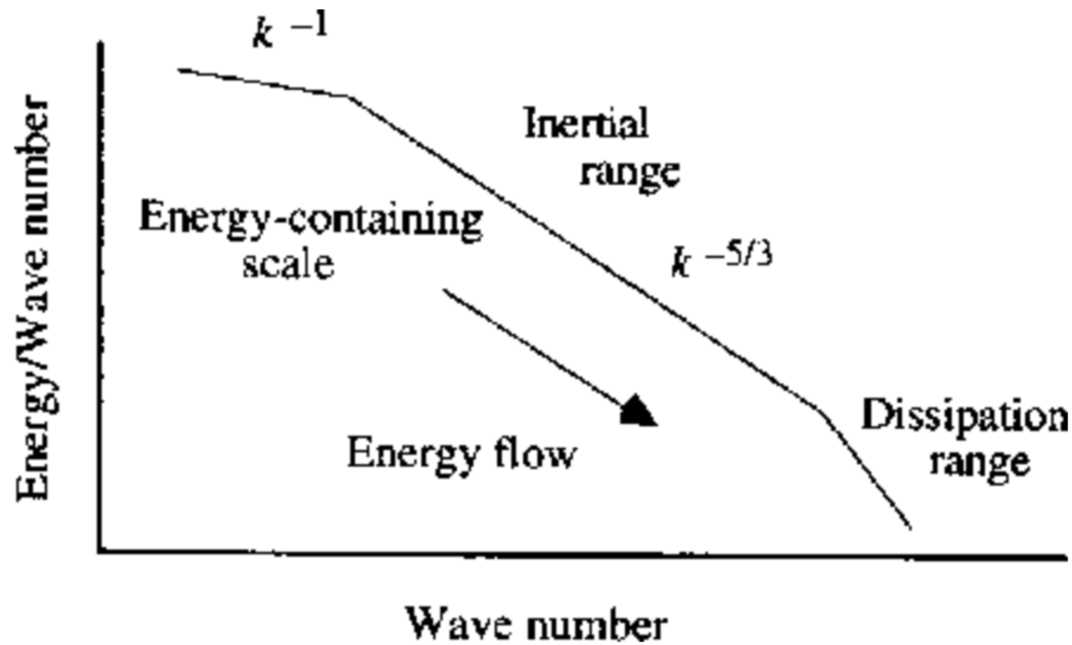
$$B_{\text{tot}}^2 = B_0^2 + \langle \delta b^2 \rangle \,. \tag{6}$$

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

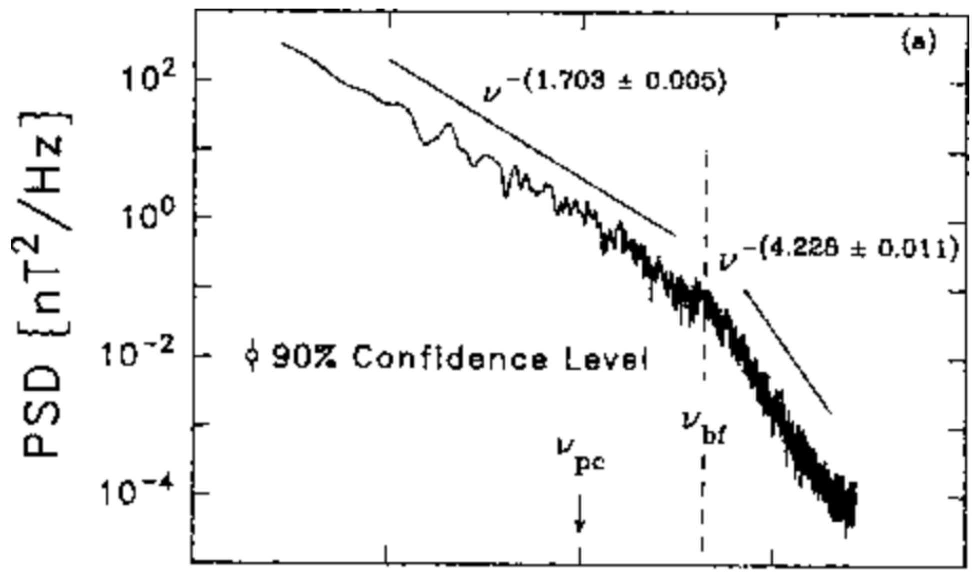
- Most turbulence theories involve the processes by which energy injected into a medium at large spatial scales is converted into motions at smaller and smaller spatial scales (or eddies) until reaching scales at which the turbulence energy interacts directly with individual plasma particles and causes 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

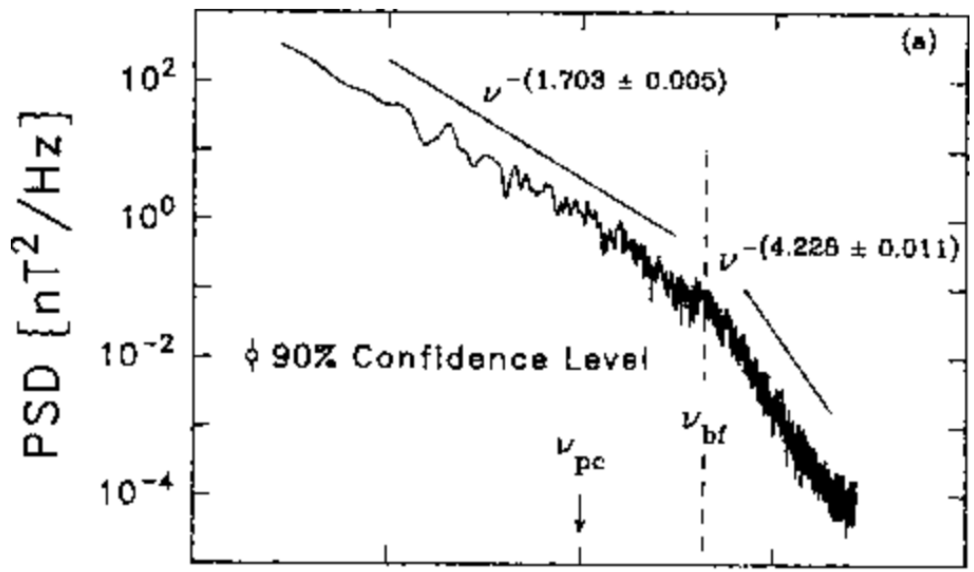
- The process by which wave energy moves to smaller wavenumbers is sometimes called a "turbulent cascade". This process can be mimicked to some degree by stirrin[g] a fluid and watching it come into equilibrium. The range of wavenumbers over which the turbulence energy cascade[s] to smaller wavenumbers 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

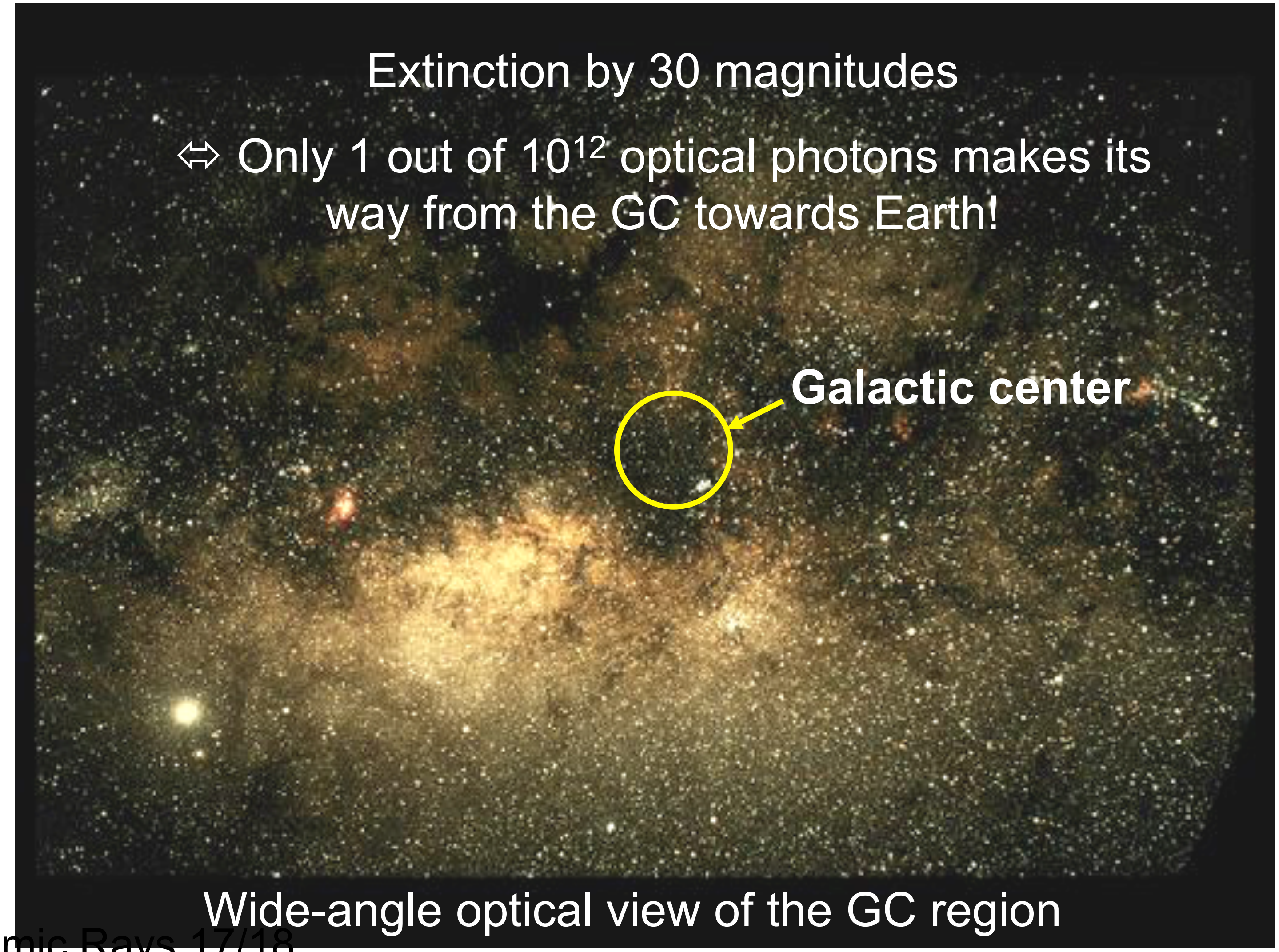
- The power spectrum of the random component of the galactic magnetic field is essential to explain to diffusion of cosmic rays in the galaxy through collisionless scattering over the irregularities



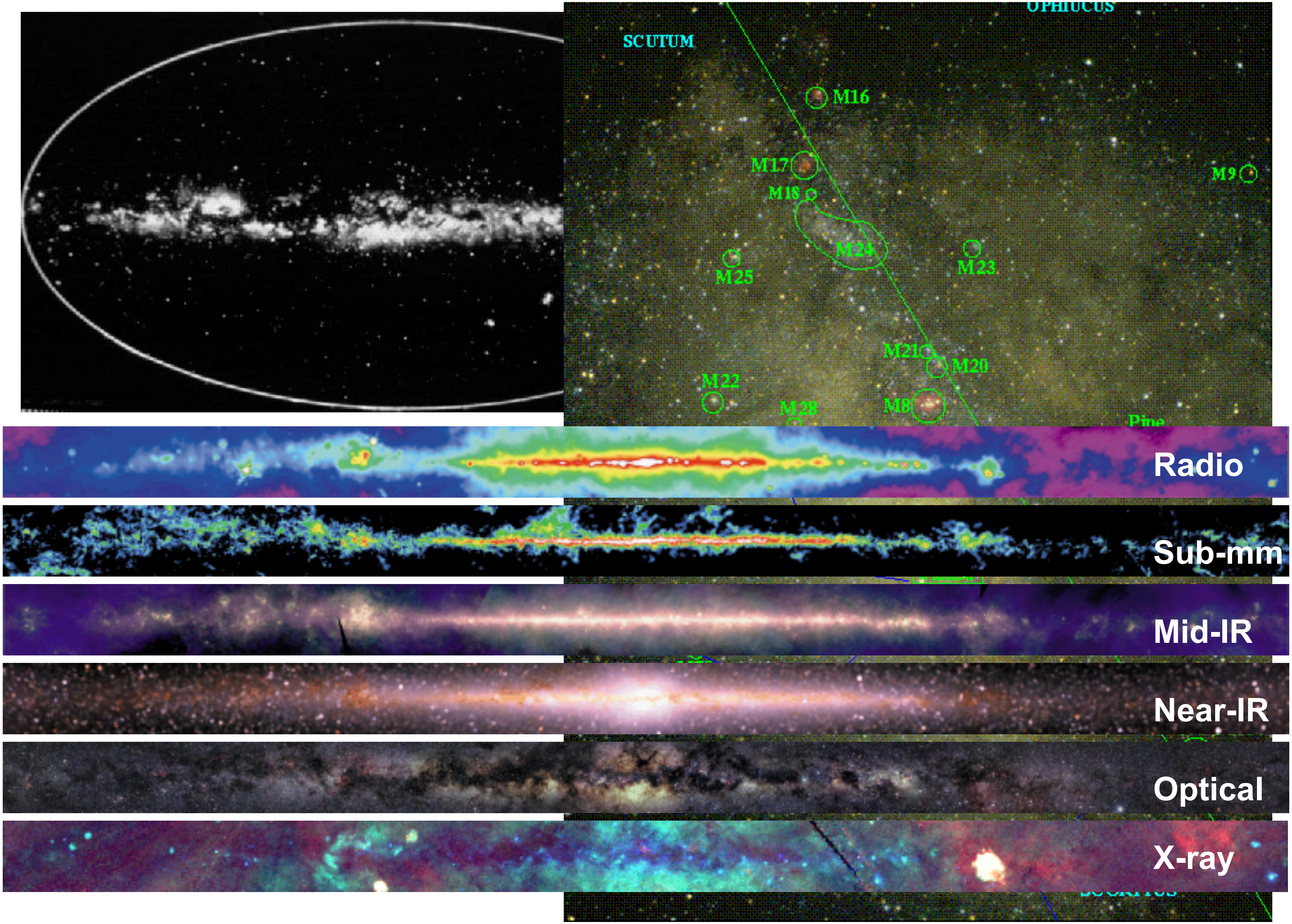
Typical spectrum of interplanetary magnetic power spectrun in a given period of the solar activity

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
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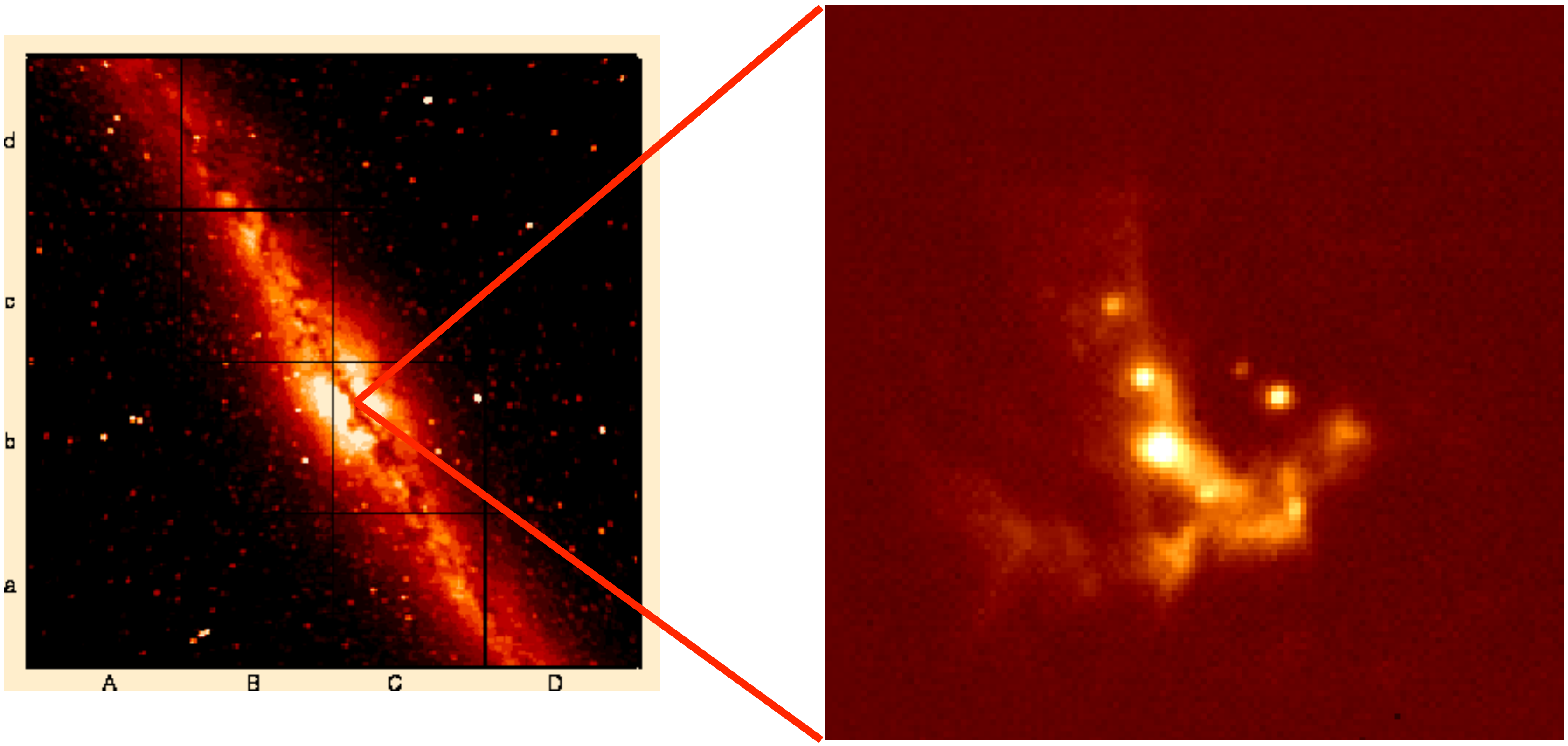
M23
M25
M9
M21
M20
M22
M28
M8
Radio
Sub-mm
Mid-IR
Near-IR
Optical
X-ray

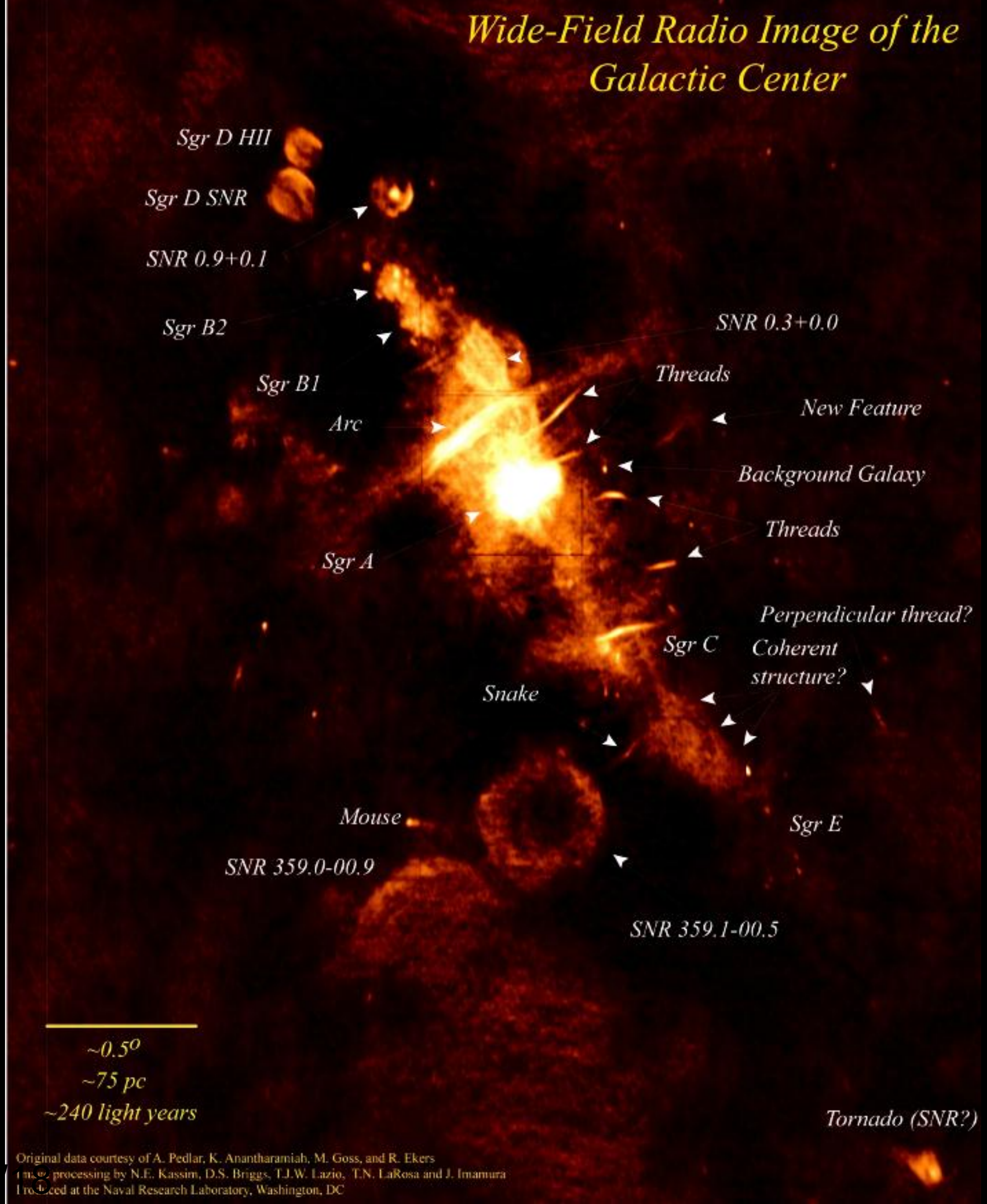
Need to observe the GC in the radio, infrared, or X-ray range



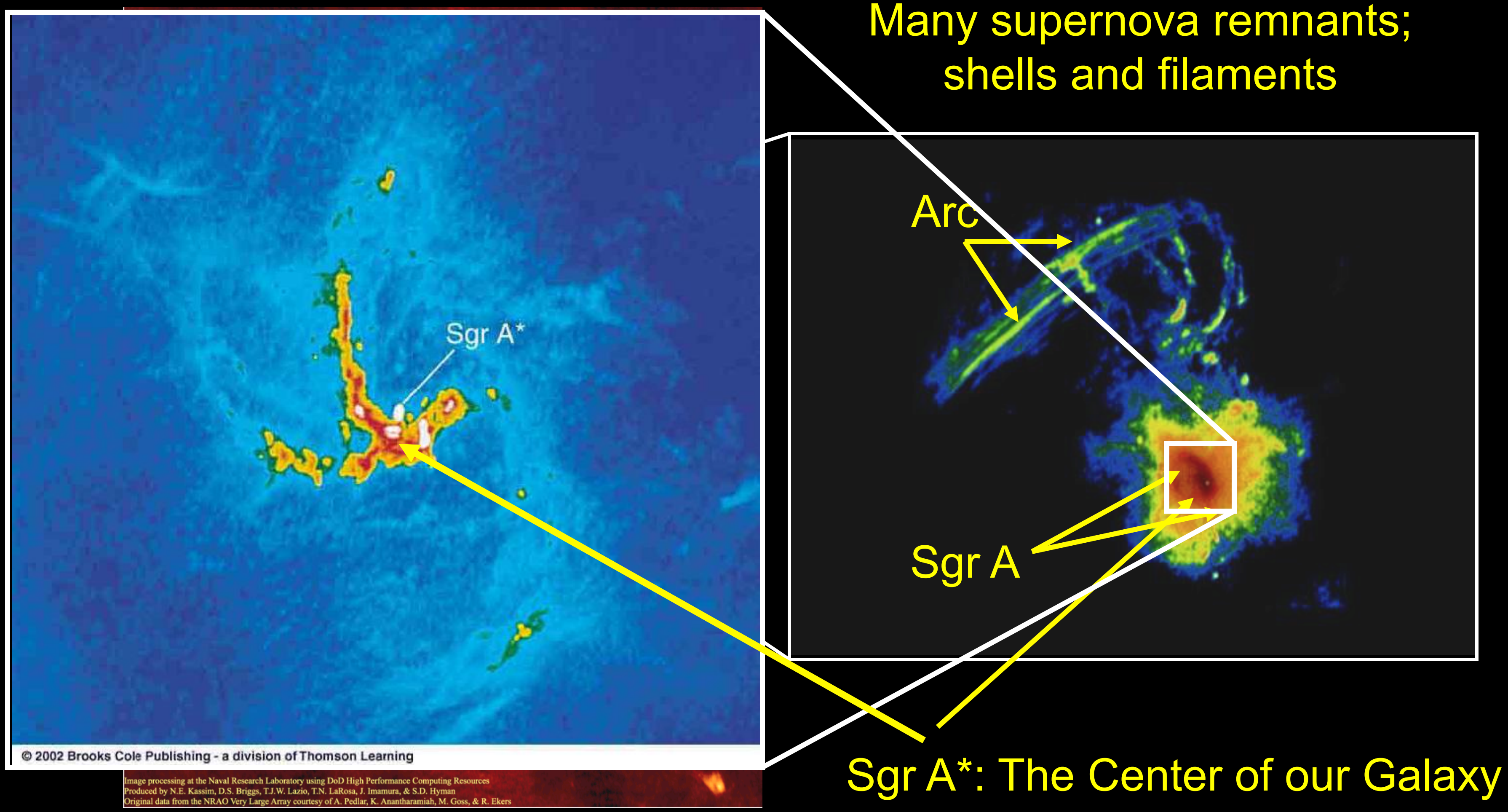
Central 2 pc

Infrared images

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

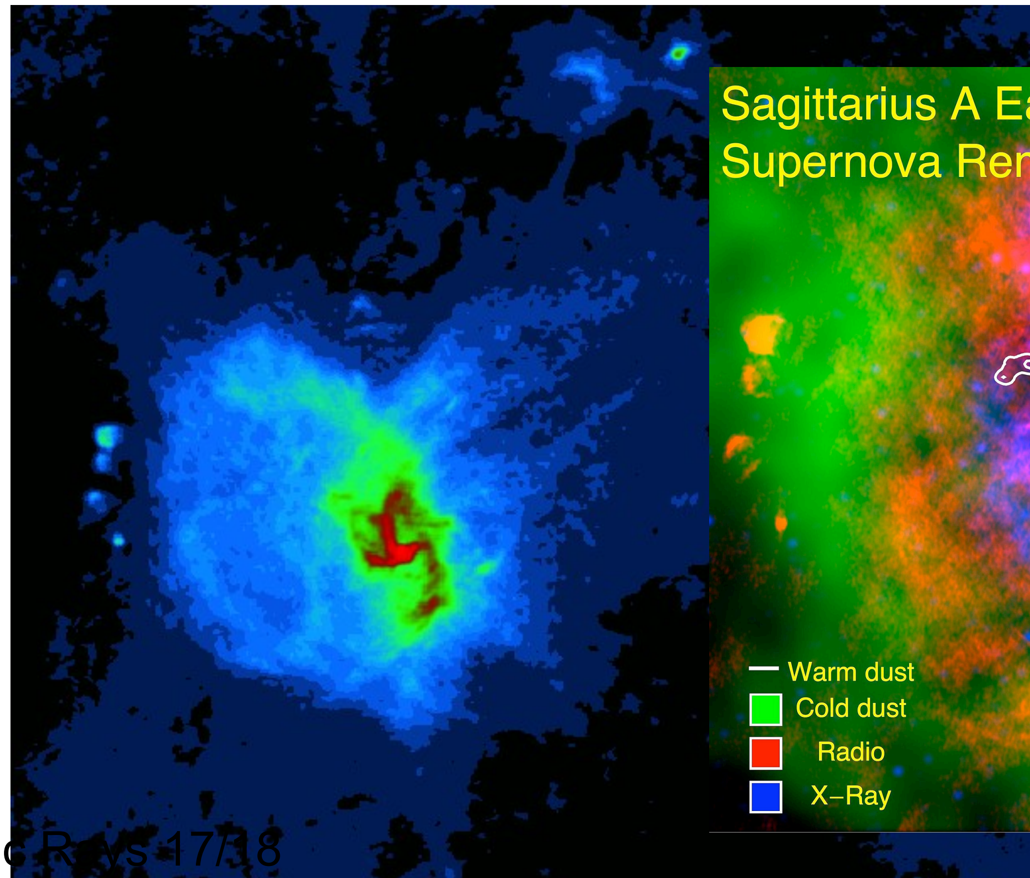


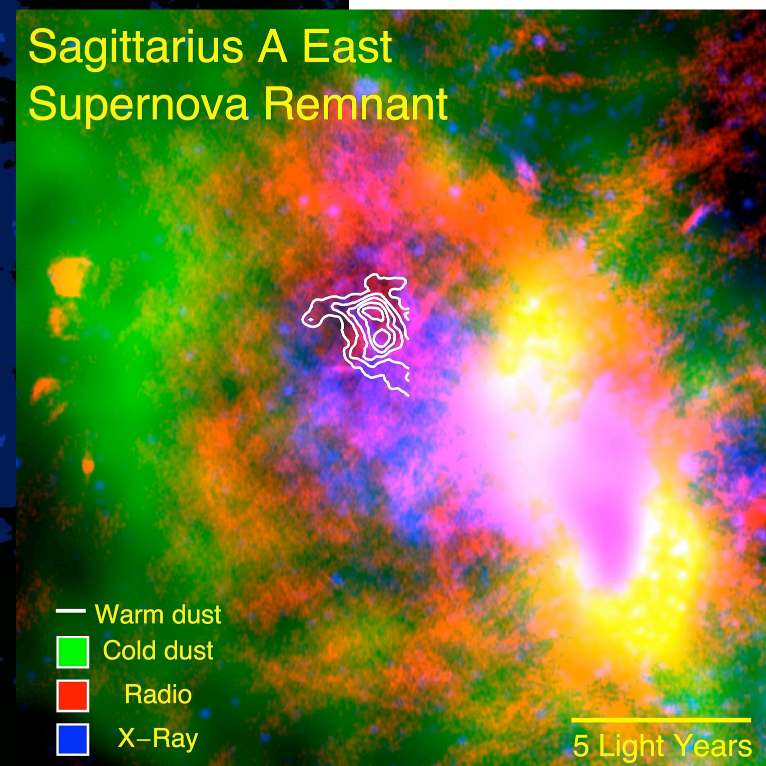
Radio View of the Galactic Center



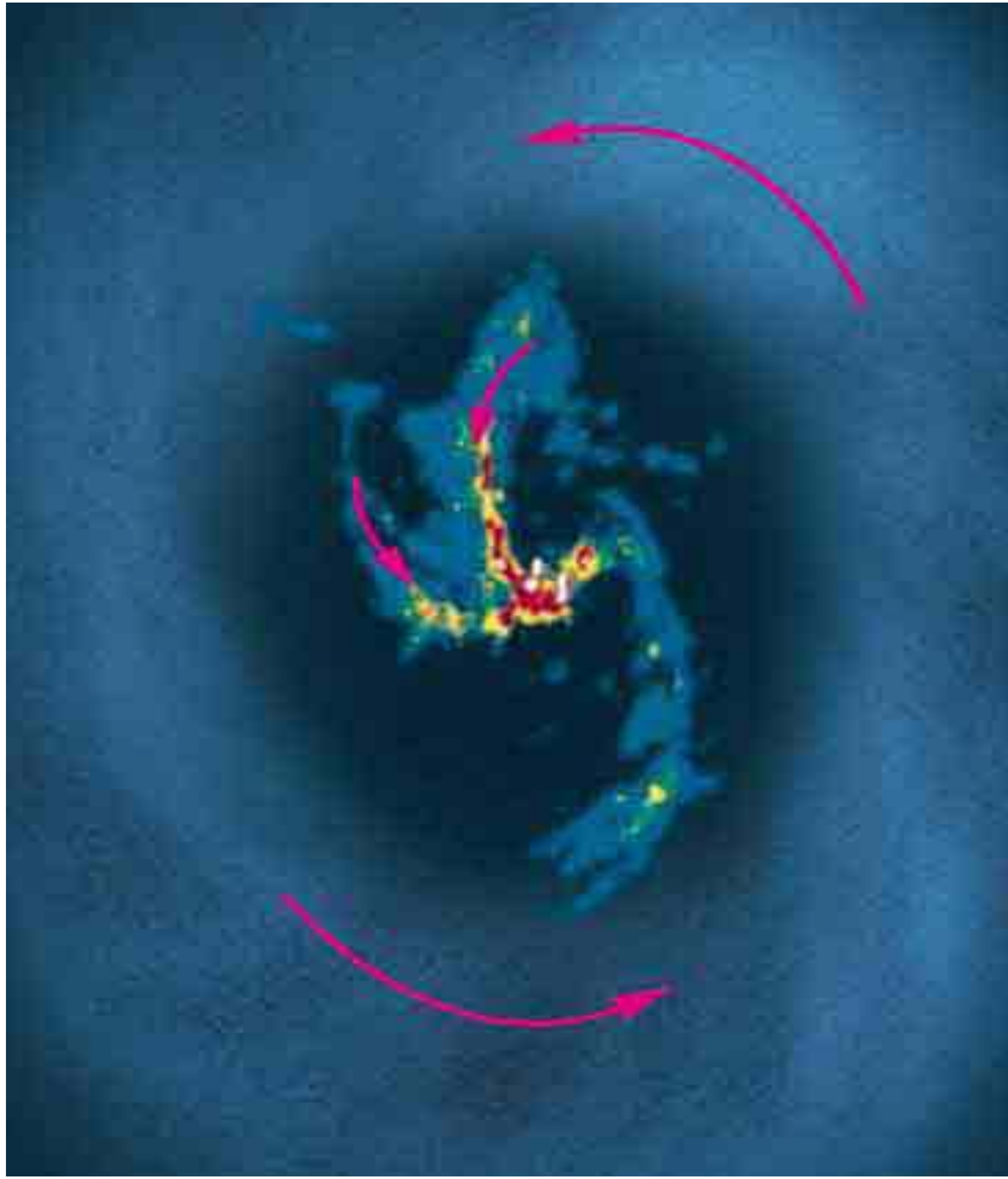
The Galactic Center contains a supermassive black hole of approx. 2.6 million solar masses.

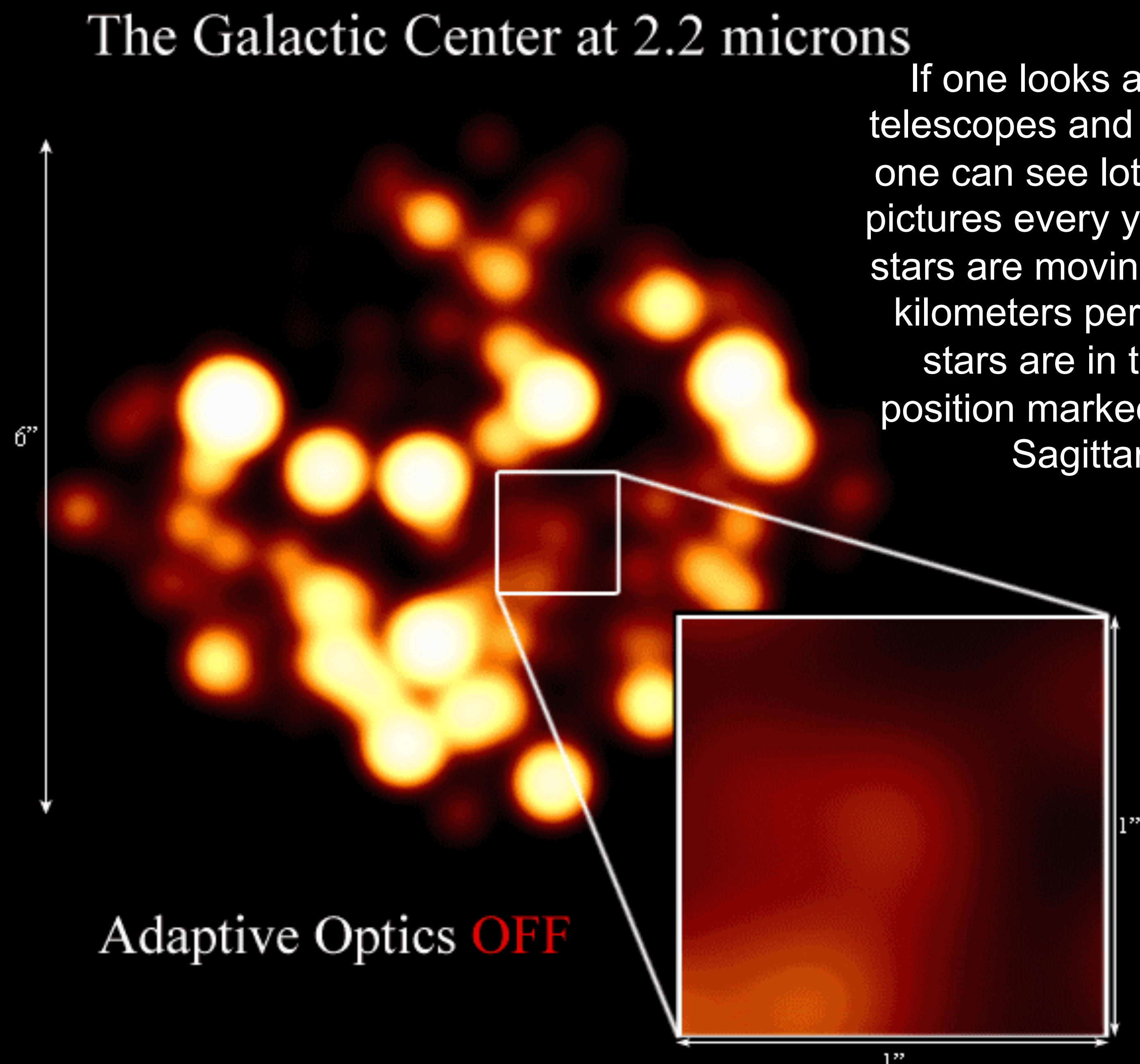
The central radio emission consists of three parts:
Sagittarius A East (blue): a supernova remnant, which was produced by a violent explosion only several tens of thousands of years ago. The origin is unknown. Explanations range from a star disrupted by a black hole to a chain reaction of ordinary supernovae 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)



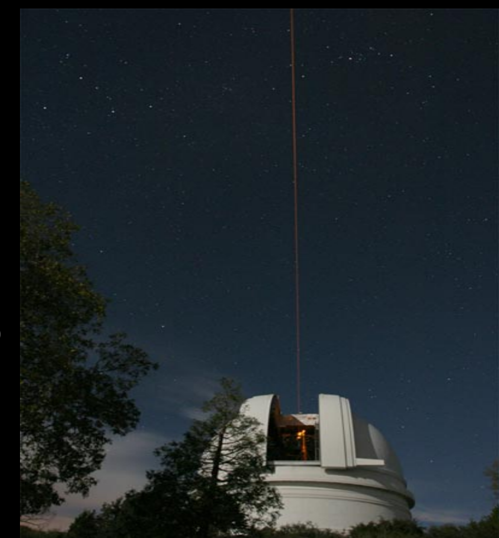


Fast rotation of spiral filaments around Sgr A*



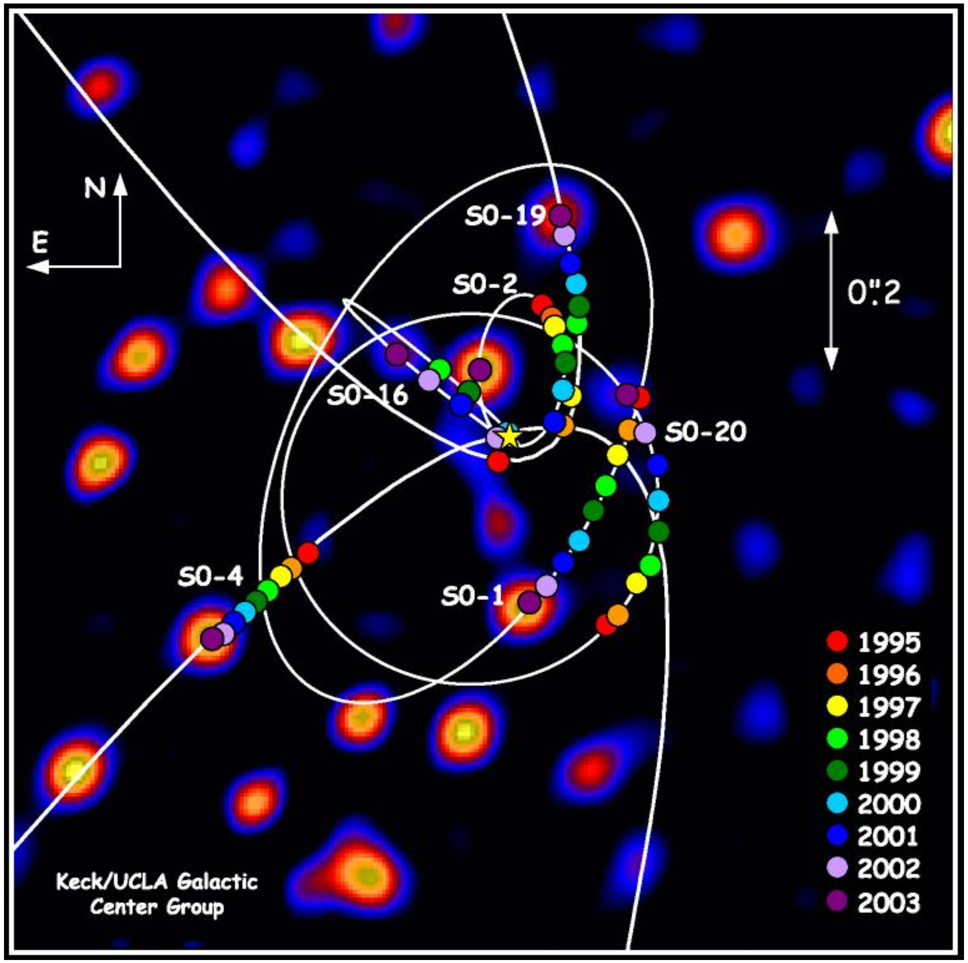


If one looks at this region with big telescopes and near-infrared cameras one can see lots of stars. If one takes pictures every year it seems that some stars are moving very fast (up to 1500 kilometers per second). The fastest stars are in the very center - the position marked by the radio nucleus Sagittarius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

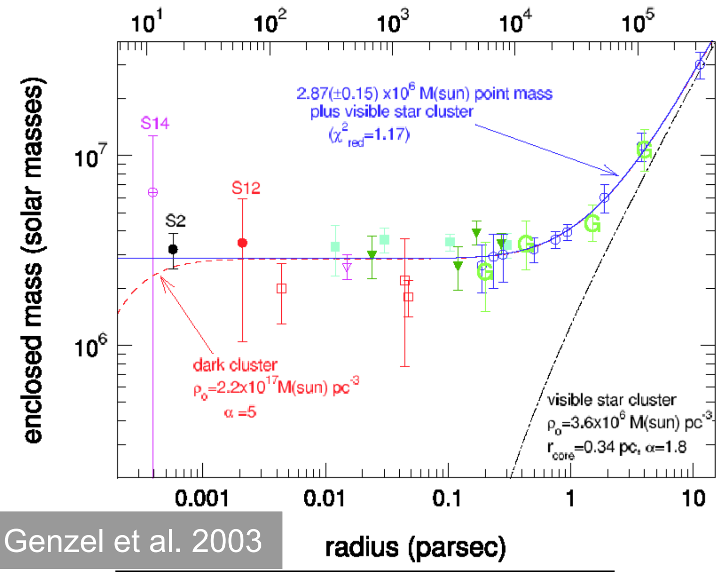


Distance between stars is less that 0.01 pc

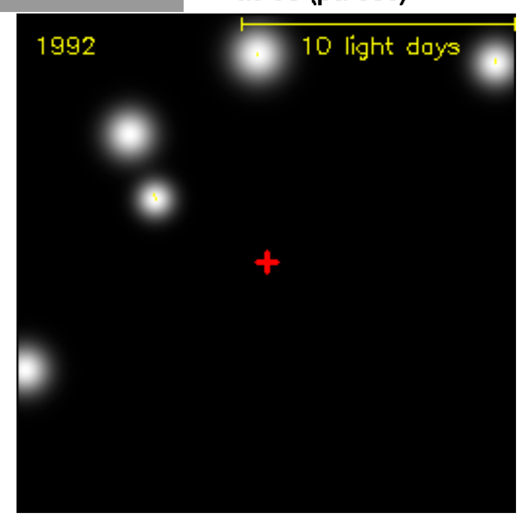
Evidence for a *Supermassive* Black Hole at the Galactic Centre

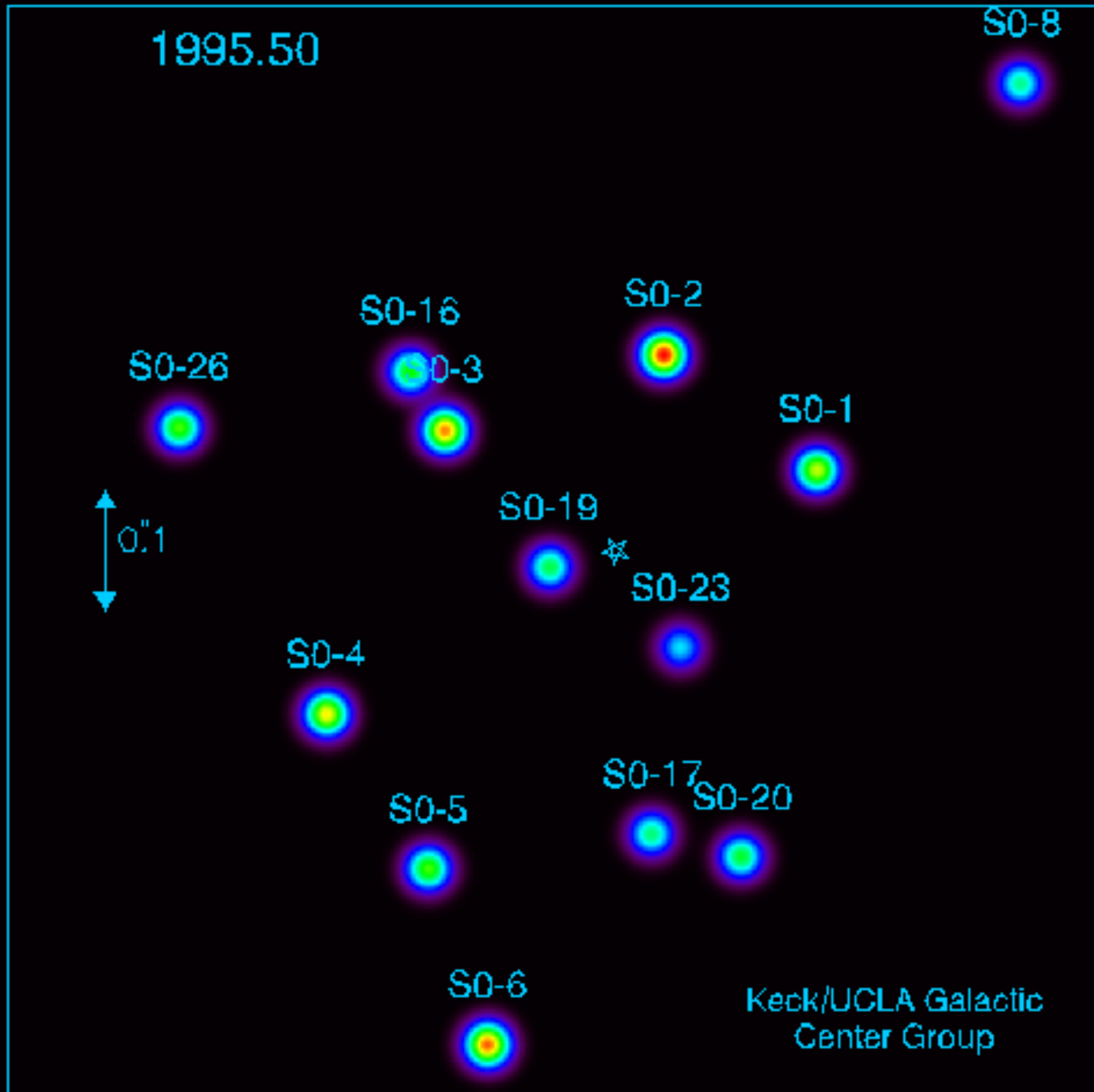


M= 3.6 x 10^6 Solar Masses



Genzel et al. 2003




1995.50
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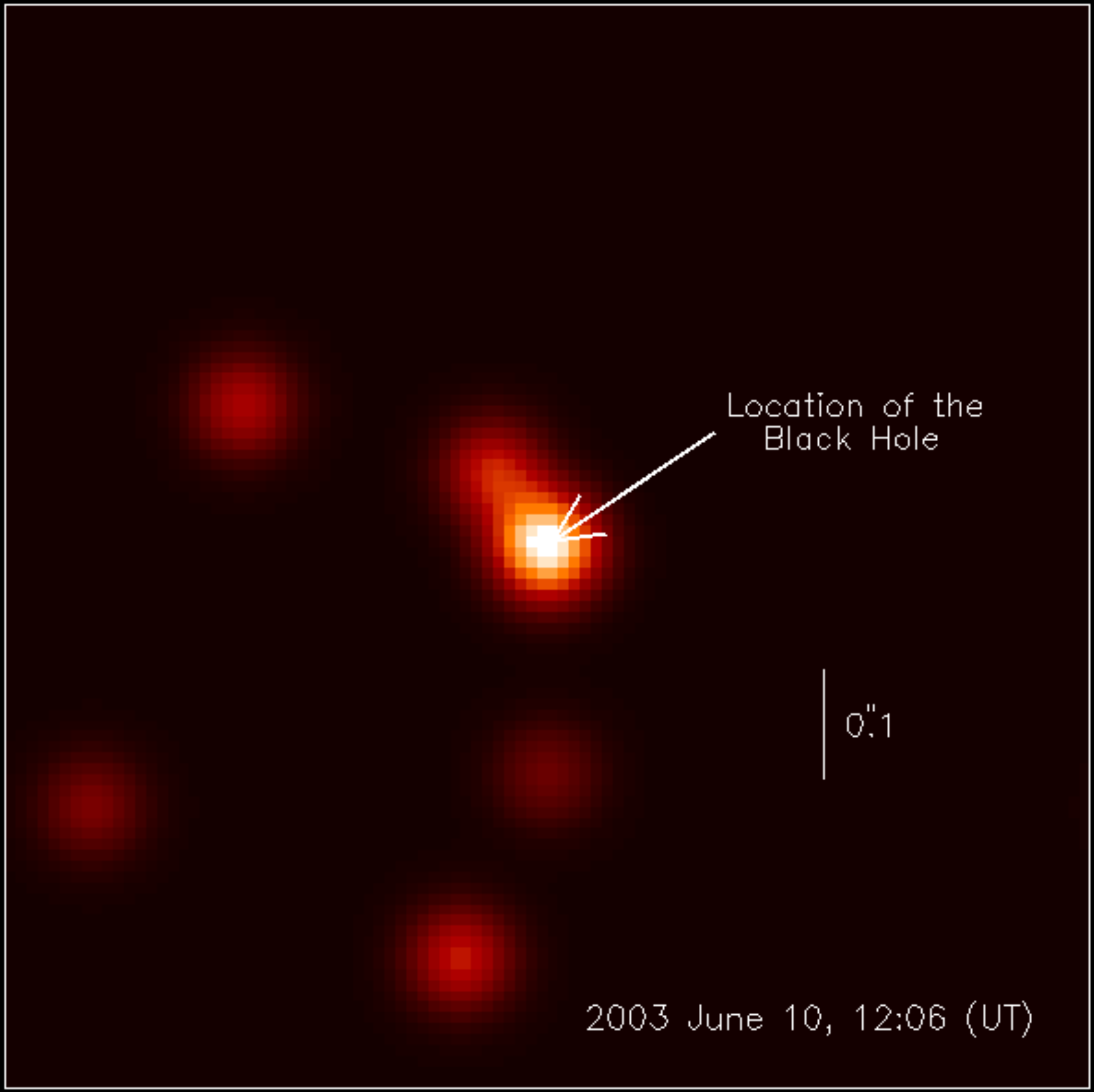
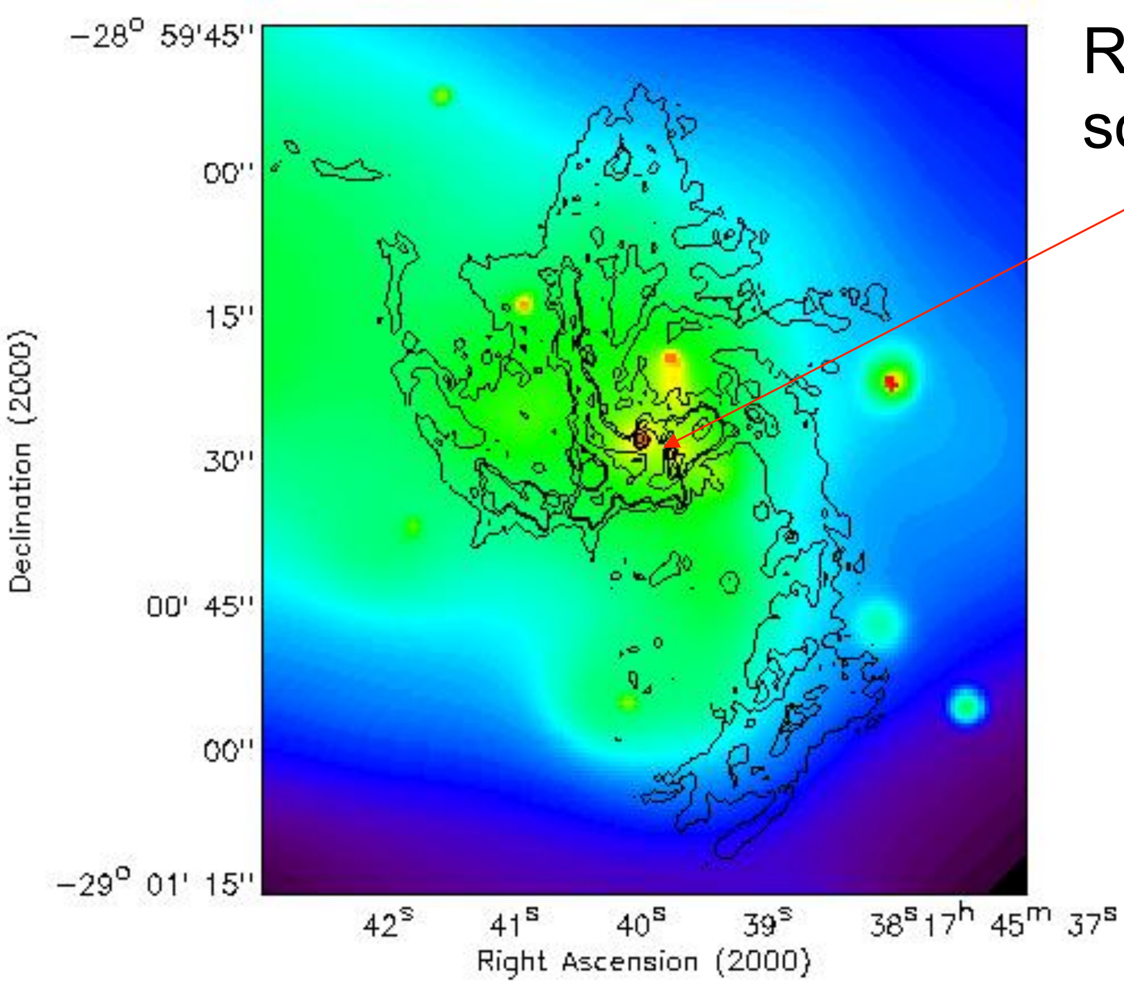
S0-20
S0-5
S0-6
Keck/UCLA Galactic
Center Group

Variable Infrared (3.8 μm) Emission from Sgr A*



What about X-ray emission due to accretion?

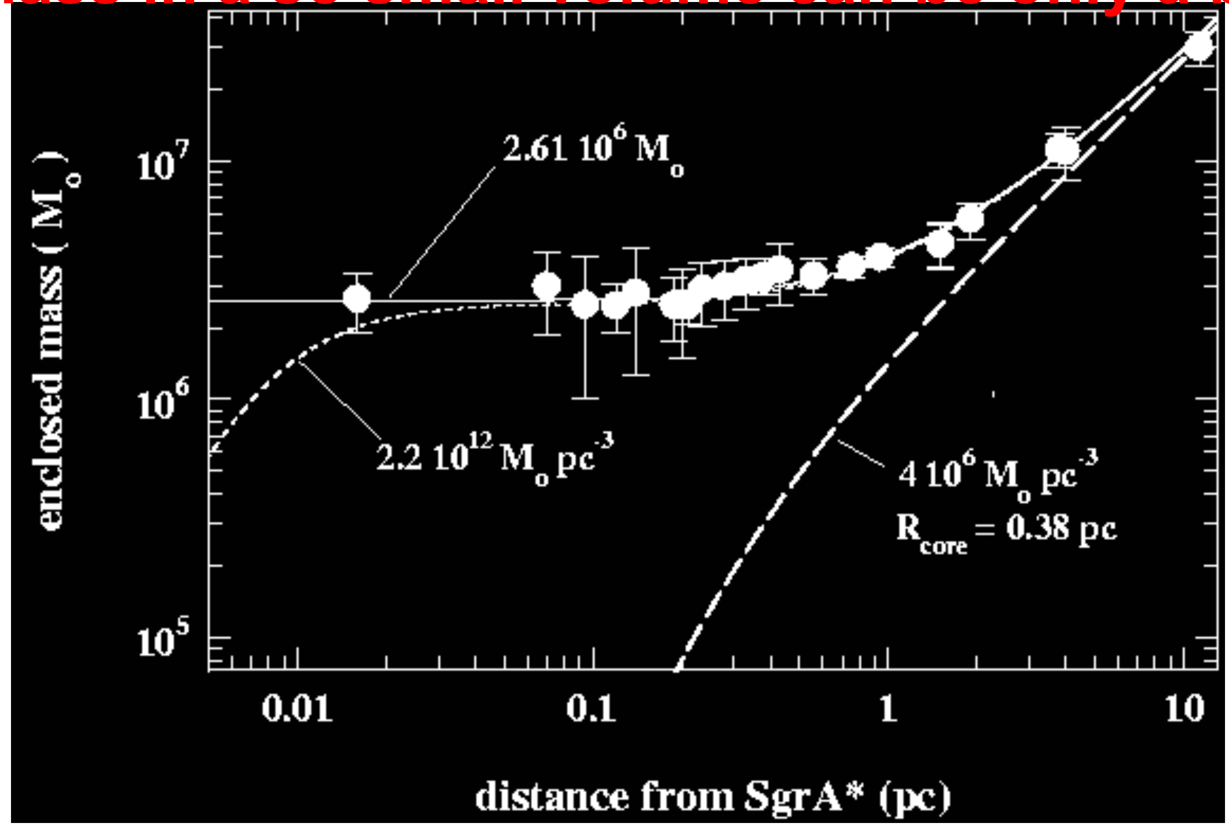


Rather weak X-ray source

Chandra X-ray image of the Sgr A West region

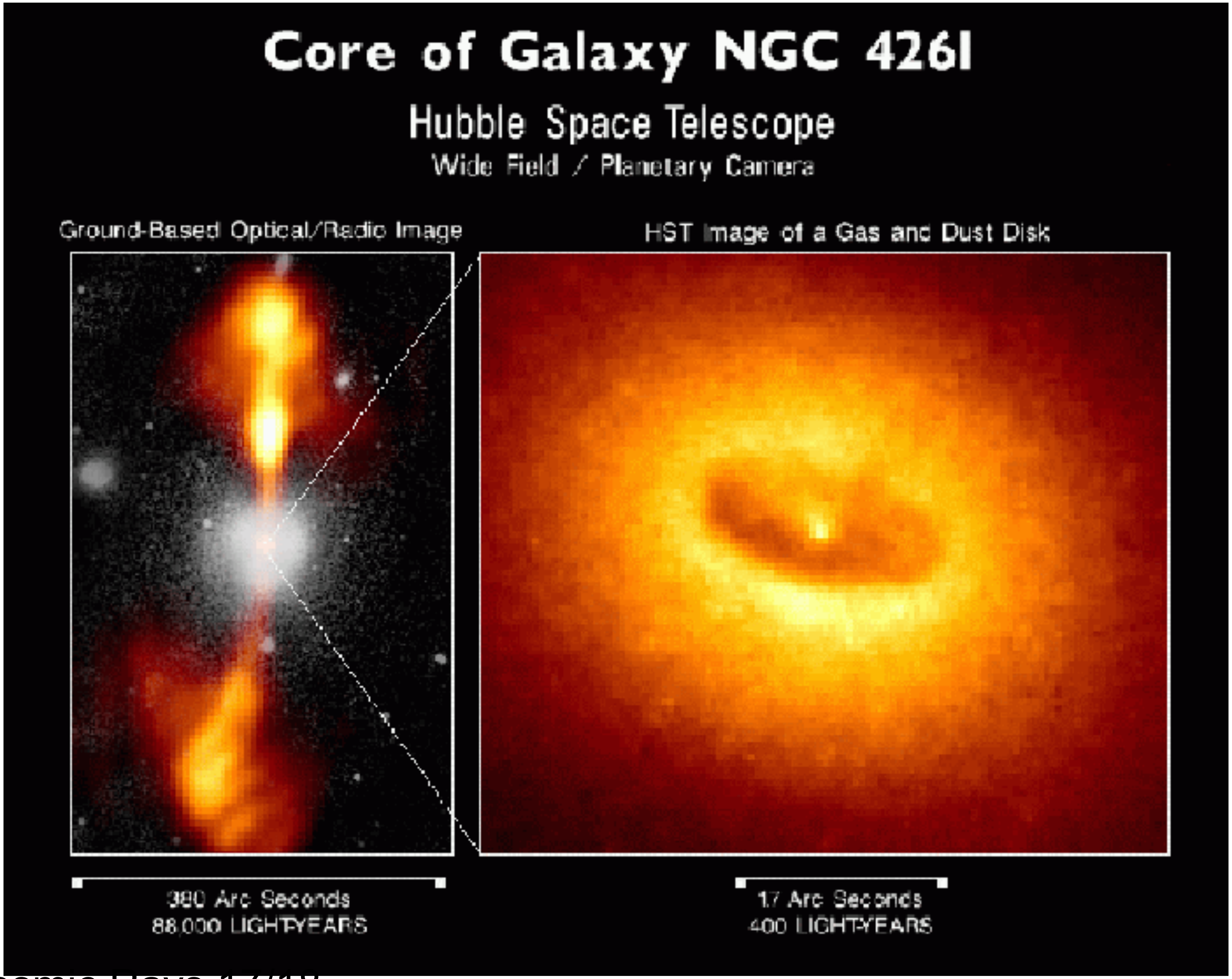
Explanation: the dark mass ~ 2.6 million solar masses

Is this a black hole?!
With that mass in a so small volume can be only a black hole



Rotation curve for the Galactic Center

Cores of other galaxies show an accretion disk with a possible black hole



X-ray View of the Galactic Center

Galactic center region contains many black-hole and neutron-star X-ray binaries

Supermassive black hole in the galactic center is unusually faint in X-rays, compared to those in other galaxies


Chandra X-ray image of Sgr A*

Evidence for a black hole of ~ 3-4 million solar masses:

- Rotation curve indicating an ultra-compact object
- No motion of the central object
- Rapid variability
- Dense stellar population
- Radio jets

Radio jets but rather weak X-ray emission

Other galaxies contain much heavier black holes and stronger activity

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 (?)