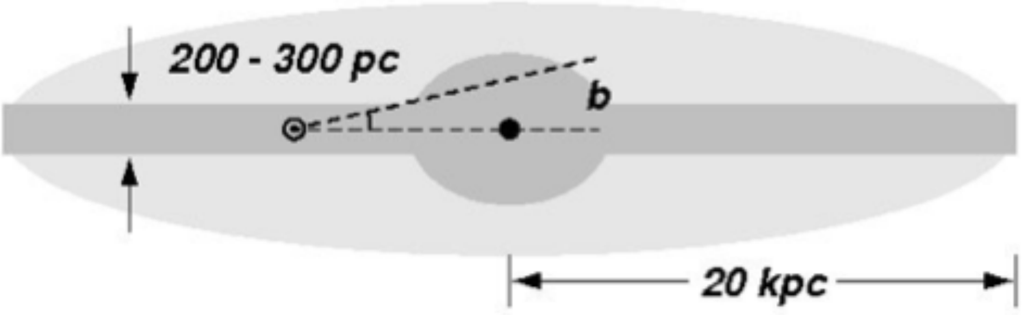
Cosmic rays
Lecture 2 081018

- Slides will be available at:

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



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.

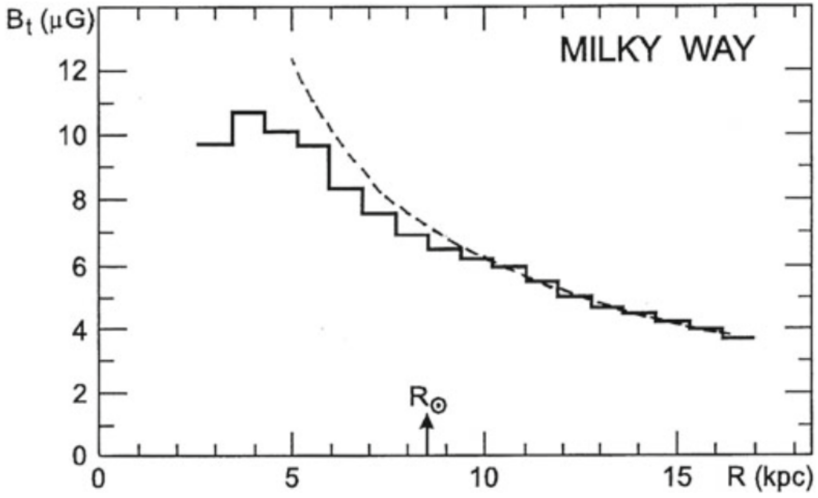
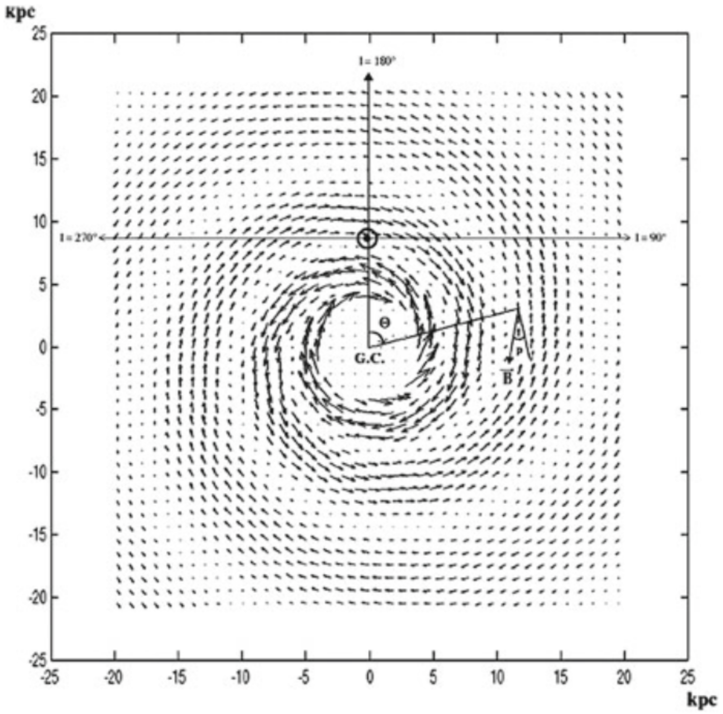


Fig. 2.9 Total magnetic field strength in the Galaxy as a function of the distance from the galactic center. The position of the Sun is indicated by the *arrow* (Battaner et al. 2007). Courtesy of Prof. E. Battaner

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



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

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

Description of the magnetic fields

When B field has irregularities and gradients which are randomly distributed, it can represented as

$$\mathbf{B}(\mathbf{r},t) = \mathbf{B}_0 + \delta\mathbf{B}(\mathbf{r},t)$$

With $\mathbf{B}_0$ average, large scale field and $\delta\mathbf{B}$ random field irregularities.
Since $\delta\mathbf{B}$ is random, then $\langle\delta\mathbf{B}\rangle = 0$, while $\langle\delta B^2\rangle \neq 0$

The average field energy density is $\langle u\rangle = \langle B^2\rangle/8\pi$ in Gauss units

$$\langle B^2\rangle = B_0^2 + \langle\delta B^2\rangle + \underbrace{2\mathbf{B}_0\bullet\langle\delta\mathbf{B}\rangle}_{=0}$$

Consider a fluctuating field B(t). If B(t) is random, it is drawn from a probability distribution P(B). The instantaneous value cannot be predicted, but averages can be precisely defined.
The expectation value of a function of B, f(B), can be defined as an integral over time, or over the distribution

$$\left\langle f(B)\right\rangle = (1/T)\int_{-T/2}^{T/2} f(B(t))\,dt \qquad \left\langle f(B)\right\rangle = \int f(B)P(B)\,dB$$

The average is $<B> = \int B \cdot P(B)dB$ and the variance $\sigma^2 = <B^2> - <B>^2$

Time dependence

The probability distribution contains no information about the time variation $V(t)$

This can be described by the *autocovariance function* $\Psi_V(\tau)$

$$\Psi_V(\tau) = \langle V(t)\ V(t \underset{T \rightarrow \infty}{-\tau)\rangle} = \lim\ (1/T)\int_{-T/2}^{T/2} V(t)V(t - \tau)dt$$

When the autocovariance is normailized by the variance σ, then it is called the *autocorrelation function.*

It ranges from 1 to -1.

The rate at which the autocorrelation function decays as a function of τ, indicates how fast $V(t)$ varies with time.

The Fourier transform of the fluctuating quantity $V(t)$ is

$$\hat{V}(f) = \lim_{T\to\infty} \int_{-T/2}^{T/2} \exp(2\pi i f t) V(t) dt \qquad (1)$$

The inverse transform is

$$V(t) = \lim_{F\to\infty} \int_{-F/2}^{F/2} \exp(-2\pi i f t) \hat{V}(f) df \qquad (2)$$

The Fourier transform is also a random variable.

The *power spectral density S(f)* is defined in terms of the Fourier transform $\hat{V}(f)$

$$S(f) = \langle |\hat{V}(f)|^2 \rangle = \langle \hat{V}(f)\ \hat{V}^*(f) \rangle$$

$\hat{V}^*(f)$ is the complex conjugate i → - i

$$S(f) = \lim_{T\to\infty} \int_{-T/2}^{T/2} \exp(2\pi i f t) V(t) dt \int_{-T/2}^{T/2} \exp(-2\pi i f t') V(t')\ \mathbf{dt'}$$

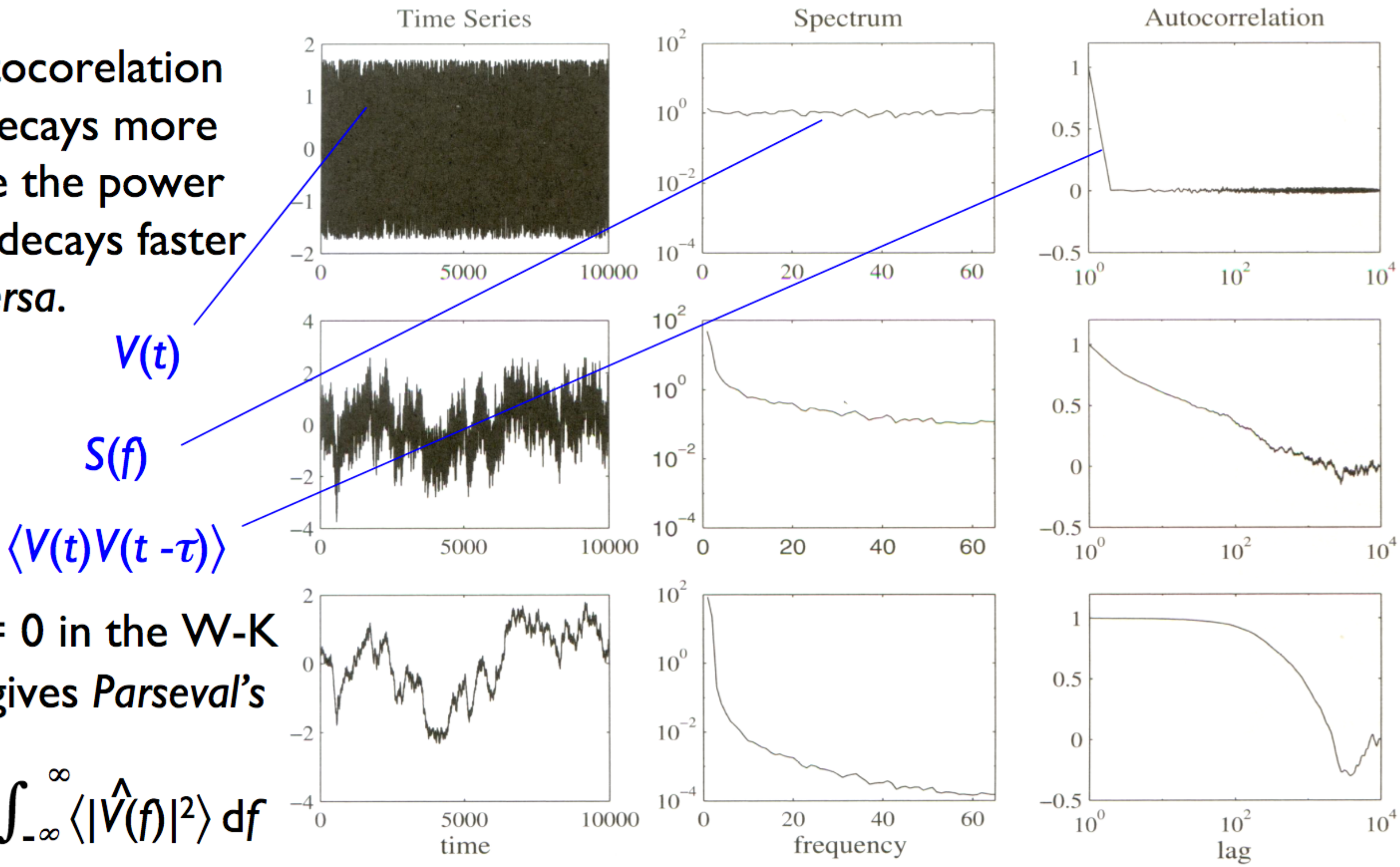
The Fourier transform is defined for positive and negative frequency. If it is defined only for positive frequency, the lower limit is 0, and a factor 2 is introduced in (2).

The power spectrum S(*f*) is related to the autocovariance function by the *Wiener-Khinchin theorem*: Its Fourier transform is equal to the autocovariance $\Psi_V(\tau)$.

$$\int_{-\infty}^{\infty} S(f)\exp(-2\pi i f\tau)\, df = \langle V(t)\ V(t-\tau)\rangle \qquad (3)$$

Conversely, the Fourier transform of the autocovariance gives the power spectrum.

As the autocorelation function decays more slowly, the the power spectrum decays faster and *vice versa*.



Taking $\tau = 0$ in the W-K theorem gives *Parseval's theorem*

$$\langle |V(t)|^2\rangle = \int_{-\infty}^{\infty} \langle |\hat{V}(f)|^2\rangle\, df$$

As an example of the use of the Wiener-Khinchin theorem, consider a relaxation process defined by a relaxation time τ_0.

The relaxation is defined by an exponentially-decaying autocorrelation function

$$\Psi_V(\tau) = \Psi_V(0) \exp[-|\tau|/\tau_0]$$

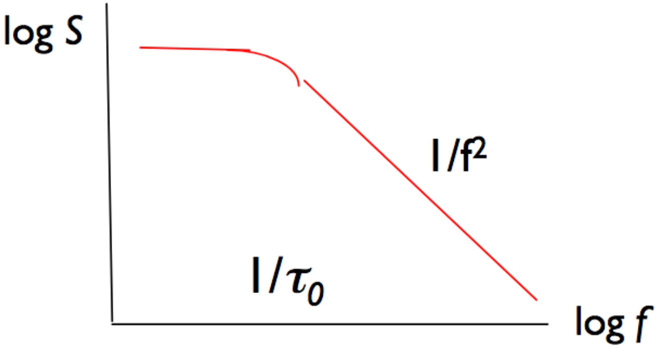
From the W-K theorem $\int_{-\infty}^{\infty} S(f)\exp(-2\pi i f\tau)\, df = \langle V(t)\, V(t-\tau)\rangle = \Psi_V(\tau)$

The inverse relation is $S(f) = \int_{-\infty}^{\infty} \Psi_V(\tau) \exp(2\pi i f\tau)\, d\tau$

$$= \int_{-\infty} \Psi_V(0) \exp[-|\tau|/\tau_0] \exp(2\pi i f\tau)\, d\tau$$

$$= \Psi_V(0)\{\tau_0/(1 + \tau_0^2 f^2)\}$$

The power spectral density corresponding to a single exponential decay is therefore a Lorentzian spectrum with a corner frequency of $1/\tau_0$, and a $1/f^2$ frequency dependence at higher frequency



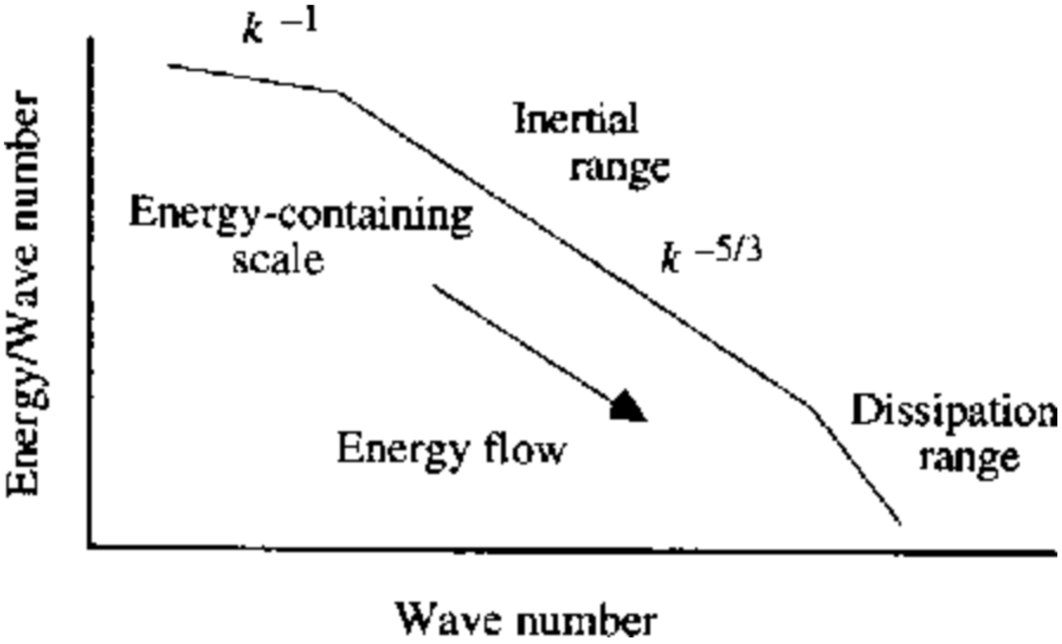
Power Spectrum

- ☐ Field is described as a superposition of plane waves
- ☐ Power spectrum is the Fourier transform of the random field
- ☐ 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

- ☐ Why is it important to CR propagation?
- ☐ Particles interact with field irregularities with a spatial scale λ of the same size as their Larmor through the so-called “cyclotron resonance”
- ☐ As a consequence, CR particles are scattered randomly and their motion can be described as a diffusion process which depends on power spectrum of the B field

Power Spectrum

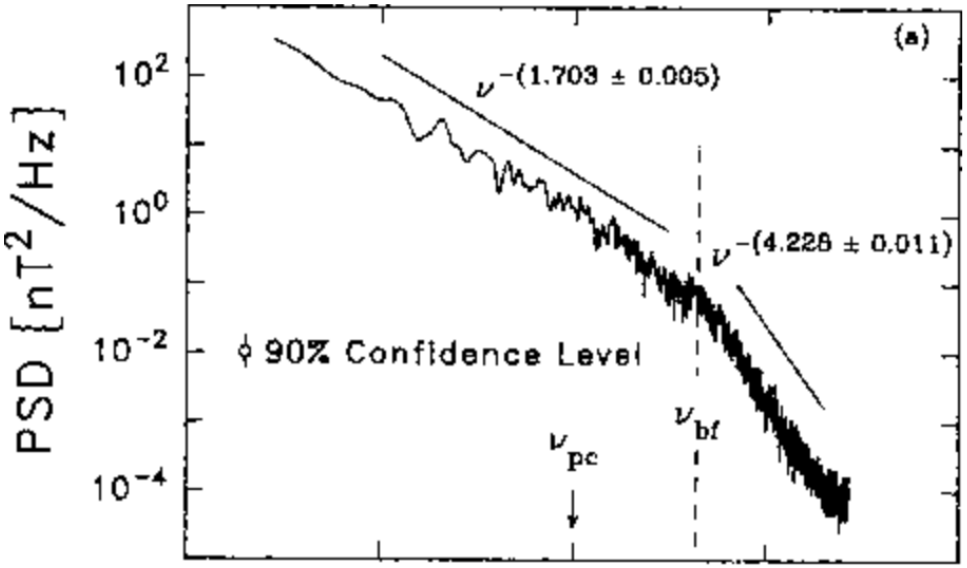
- Most turbulence theories involve the processes by which energy injected into a medium at large spatial scales is converted into motions at smaller and smaller spatial scales (or eddies) until reaching scales at which the turbulence energy interacts directly with individual plasma particles and causes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

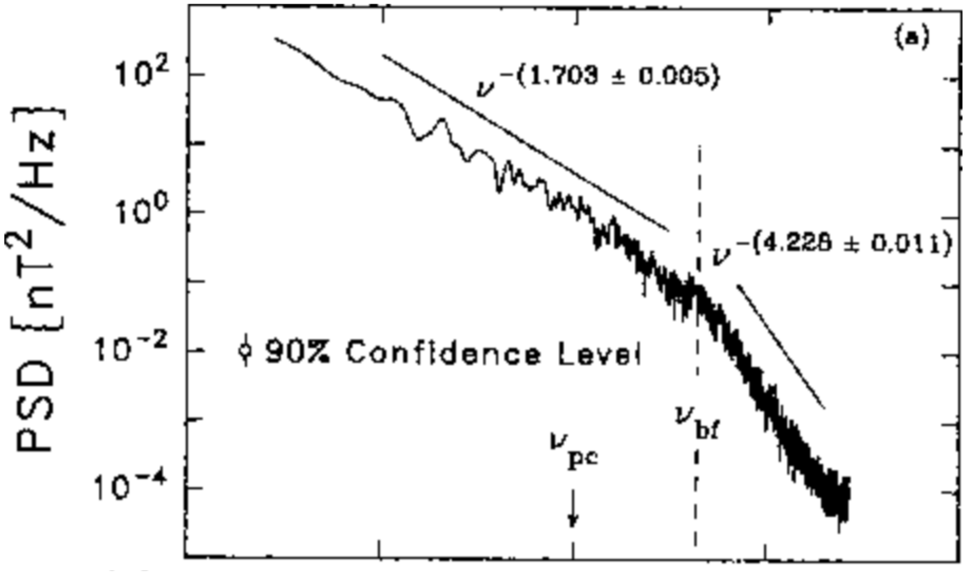
- The process by which wave energy moves to smaller wavenumbers is sometimes called a “turbulent cascade”. This process can be mimicked to some degree by stirring a fluid and watching it come into equilibrium. The range of wavenumbers over which the turbulence energy cascades to smaller wavenumbers is 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

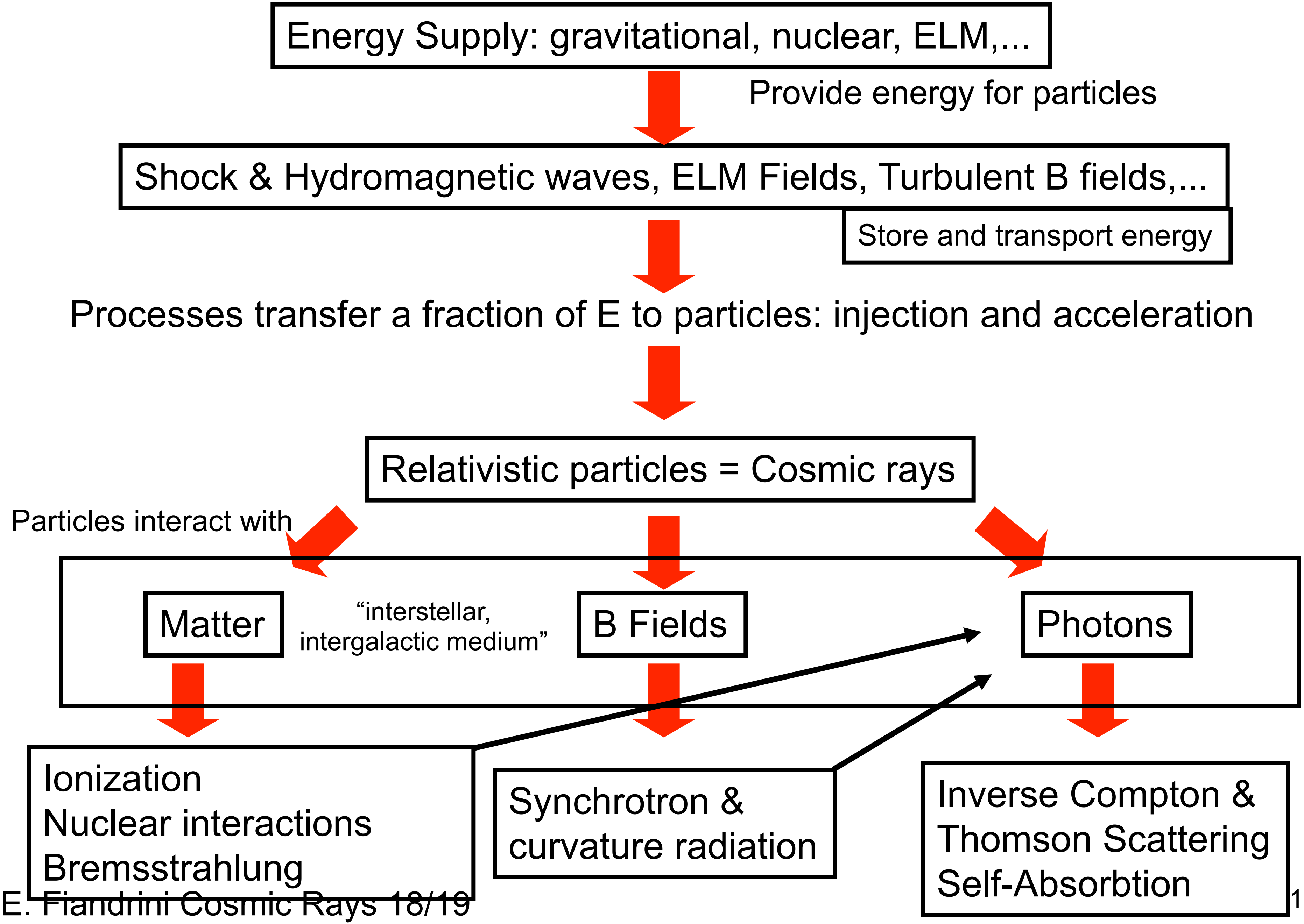
Random field δB

- 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

Formation and Interactions of CR's

- Now we can have a sketch of CR generation and propagation
- What we are interested in is the CR density for any specie at a given position as a function of time and energy (or momentum), $n_i(\mathbf{x},t,E)$, where i runs over all the elements of the periodic table and $dN_i = n_i(\mathbf{x},t,E)d^3\mathbf{x}dE$

Formation and Interactions of CR's



Energy Supply: gravitational, nuclear, ELM,...

Provide energy for particles

Shock & Hydromagnetic waves, ELM Fields, Turbulent B fields,...

Store and transport energy

Processes transfer a fraction of E to particles: injection and acceleration

Relativistic particles = Cosmic rays

Particles interact with

Matter

“interstellar, intergalactic medium”

B Fields

Photons

Ionization
Nuclear interactions
Bremsstrahlung

Synchrotron & curvature radiation

Inverse Compton & Thomson Scattering
Self-Absorbtion

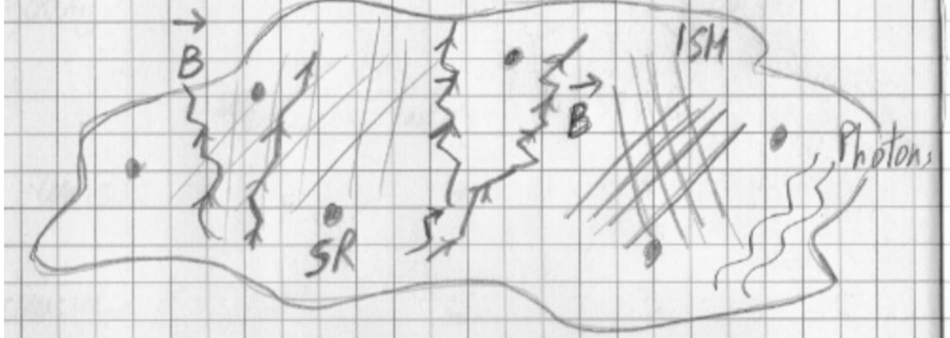
Formation and Interactions of CR's

dn_i/dt = Gain – Loss

Gain = processes that increase the number of particles

Loss = processes that lead to decrease of particles in the phase space volume $d^3\mathbf{x}dE$

$$\frac{\partial n_i}{\partial t} = \left[\text{Gain} - \text{Loss} \right] \text{ in the phase-space cell } d^3x\, dE$$



GAIN

i) Primary sources $q_i(\vec{x}, t, E)$ distribution "Injection spectrum"
(SNR, Pulsars, ...) $\frac{\partial n_i}{\partial t} = q_i$

ii) interactions with ISM: spallation

$$\frac{\partial n_i}{\partial t} = \sum_{j>i} (n_{ISM}\sigma_{ij}\beta c)\, n_j$$ from heavier particles

iii) Radioactive decay from unstable nuclei

$$\frac{\partial n_i}{\partial t} = \sum_j P_{ij} \frac{n_j}{\tau_j}$$

0) CR are mostly charged → curved by galactic field $\vec{B}$

1) Curvature and gradient drift on $\langle B \rangle$
2) Random motion on $\langle \delta B^2 \rangle$ → Diffusion
3) Convection in the ISM

$$\frac{\partial n_i}{\partial t} = \vec{\nabla} \cdot (\hat{D}\, \vec{\nabla} n_i + n_i \vec{V}_{ISM})$$

LOSS

i) disintegration by spallation $\frac{\partial n_i}{\partial t} = -n_{ISM}\sigma_{ip}\beta c n_i$

ii) radioactive decay $\frac{\partial n_i}{\partial t} = -\frac{n_i}{\tau_i}$

iii) continous energy loss in the ISM

$$\frac{\partial n_i}{\partial t} = -\frac{\partial}{\partial E}[\, b(E) n_i \,]$$

$$b(E) = -\frac{dE}{dt} = \left(\frac{dE}{dt}\right)_{Ion} + \overbrace{\left(\frac{dE}{dt}\right)_{Brems} + \left(\frac{dE}{dt}\right)_{IC+S}}^{\text{Radiative}}$$

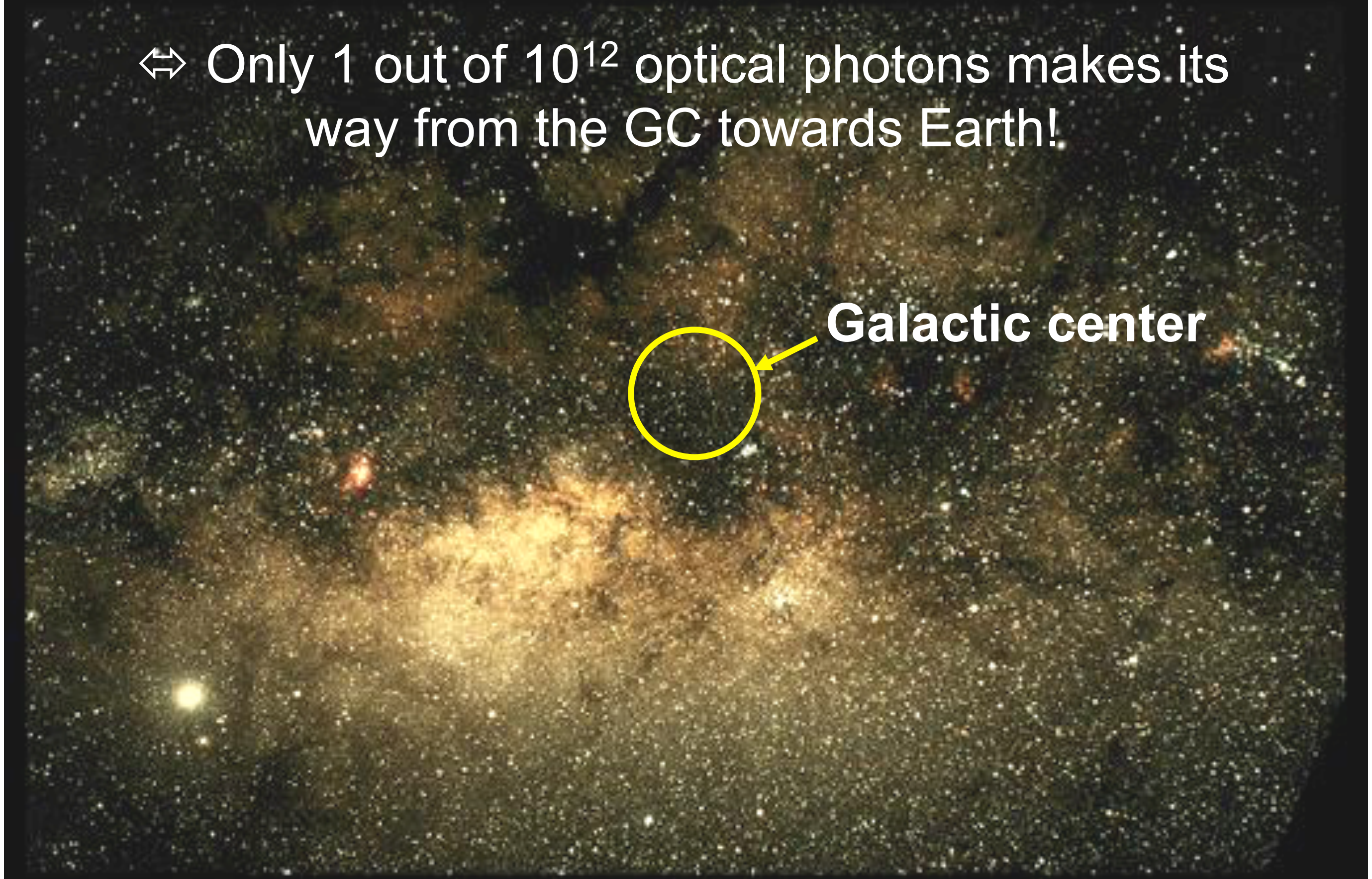
$$\frac{\partial n_i}{\partial t} - \vec{\nabla} \cdot (\hat{D}\, \vec{\nabla} n_i + n_i \vec{V}_{ISM}) = q_i + \sum_{j>i} \left(n_{ISM}\sigma_{ij}\beta c + \frac{P_{ij}}{\tau_j} \right) n_j - n_{ISM}\sigma_{ip}\beta c\, n_i - \frac{n_i}{\tau_i} + \frac{\partial}{\partial E}[b(E) n_i]$$

The Galactic Center

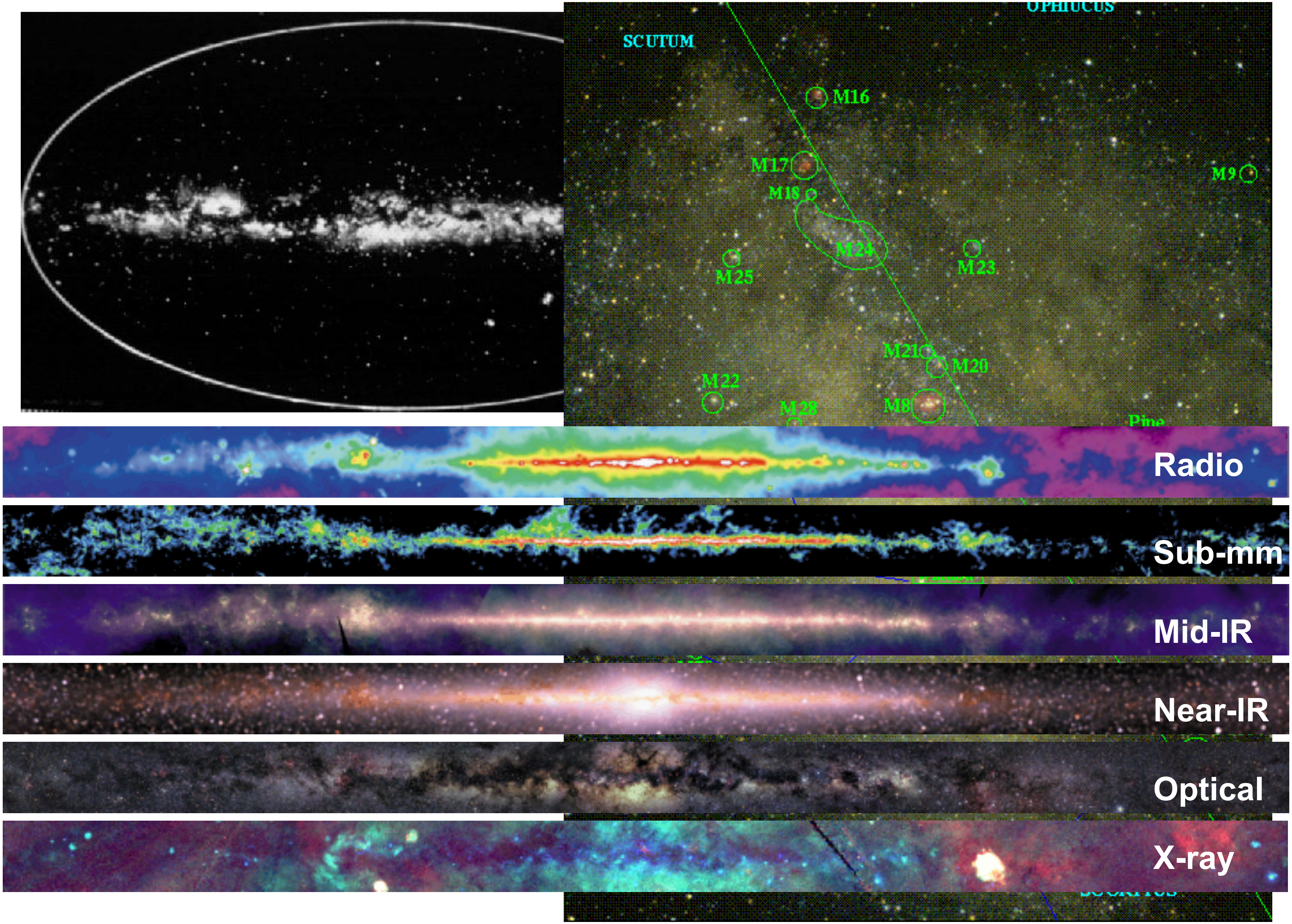
Our view (in visible light) towards the galactic center (GC) is heavily obscured by gas and dust

Extinction by 30 magnitudes

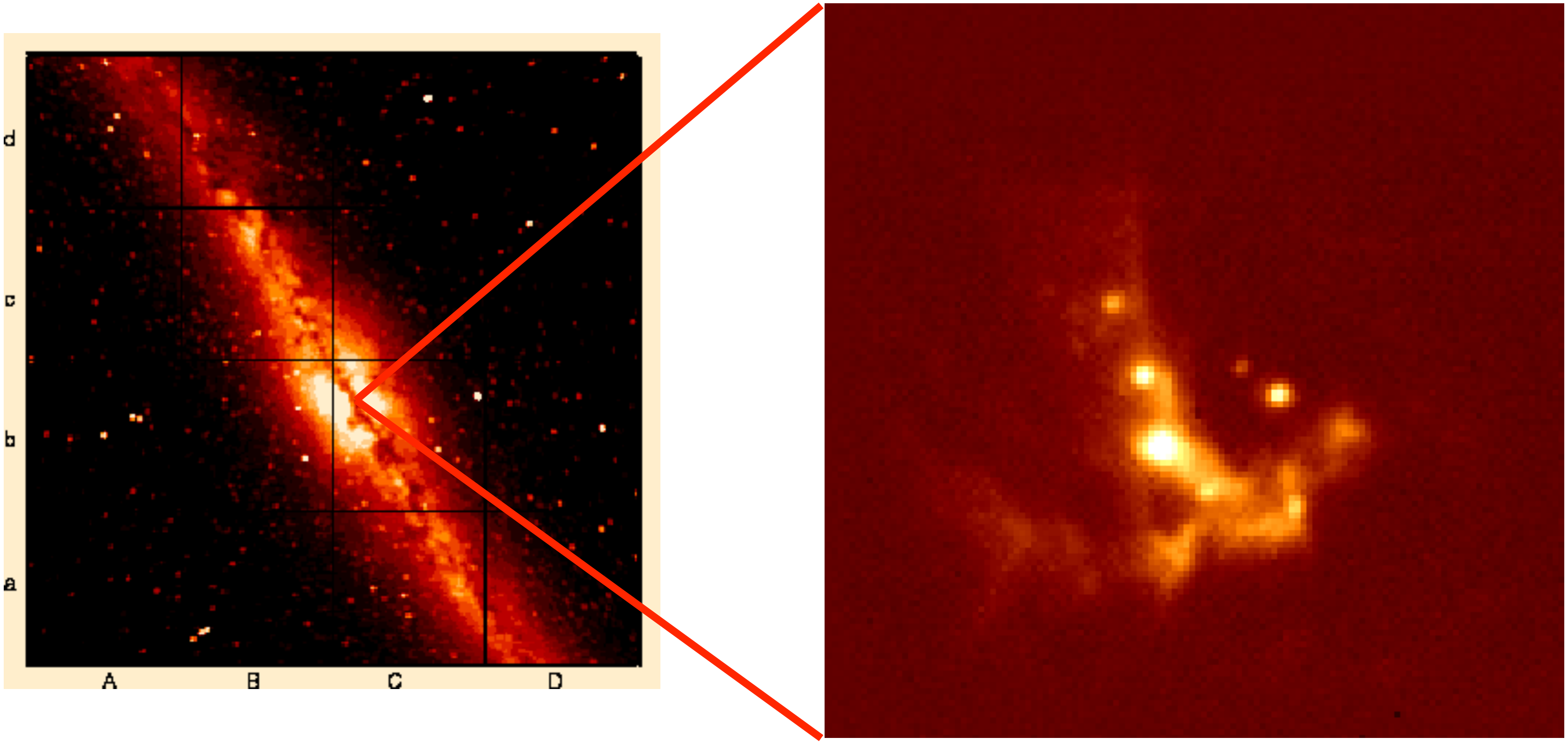
⇔ Only 1 out of 10^{12} optical photons makes its way from the GC towards Earth!



Wide-angle optical view of the GC region


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

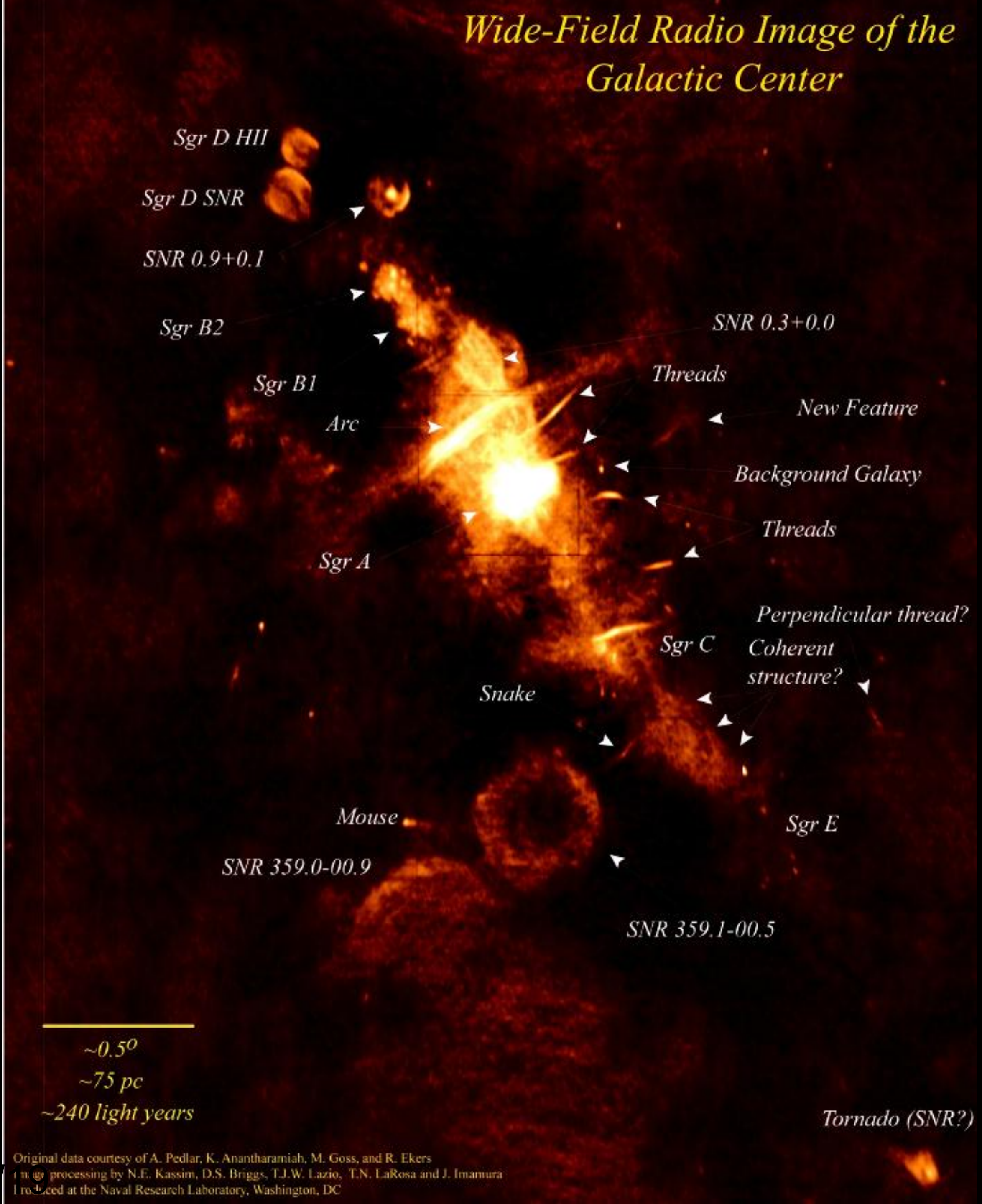
Need to observe the GC in the radio, infrared, or X-ray range



Central 2 pc

Infrared images

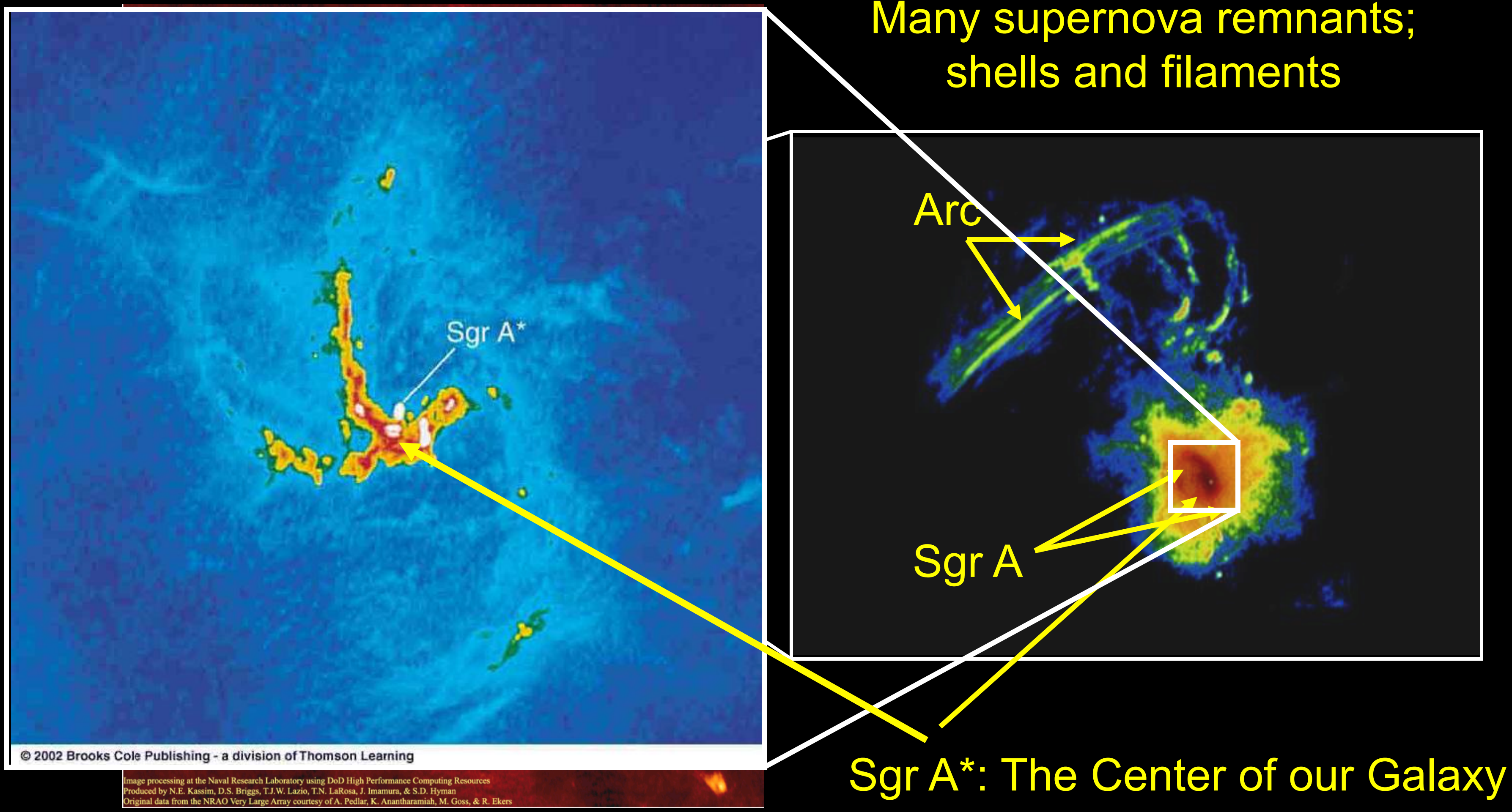
Image from the Very Large Array (VLA) radio telescope in New Mexico.



Wide-Field Radio Image of the Galactic Center

Original data courtesy of A. Pedlar, K. Anantharamiah, M. Goss, and R. Ekers
Image processing by N.E. Kassim, D.S. Briggs, T.J.W. Lazio, T.N. LaRosa and J. Imamura
Produced at the Naval Research Laboratory, Washington, DC

Radio View of the Galactic Center



Many supernova remnants; shells and filaments

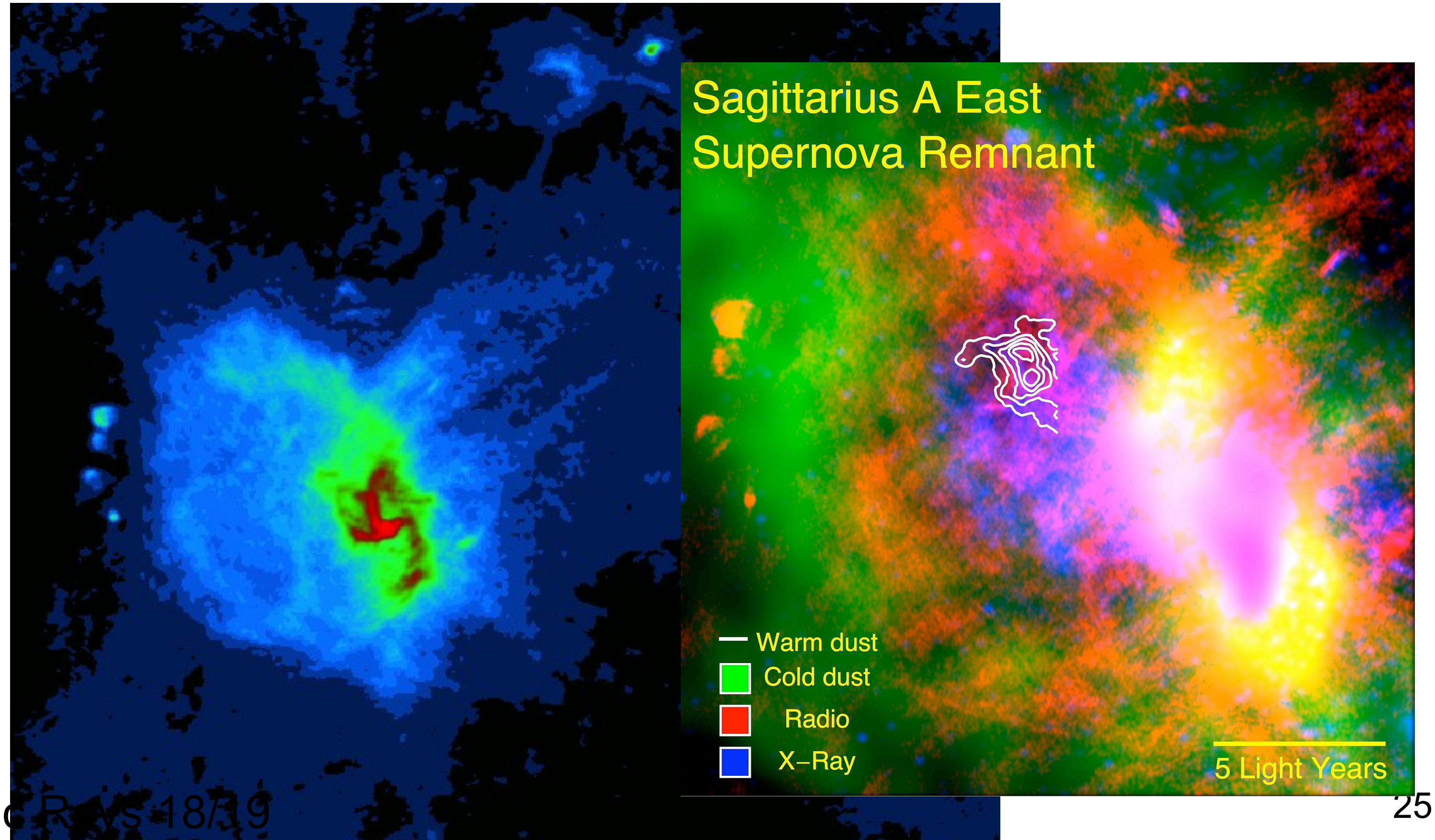
Arc

Sgr A

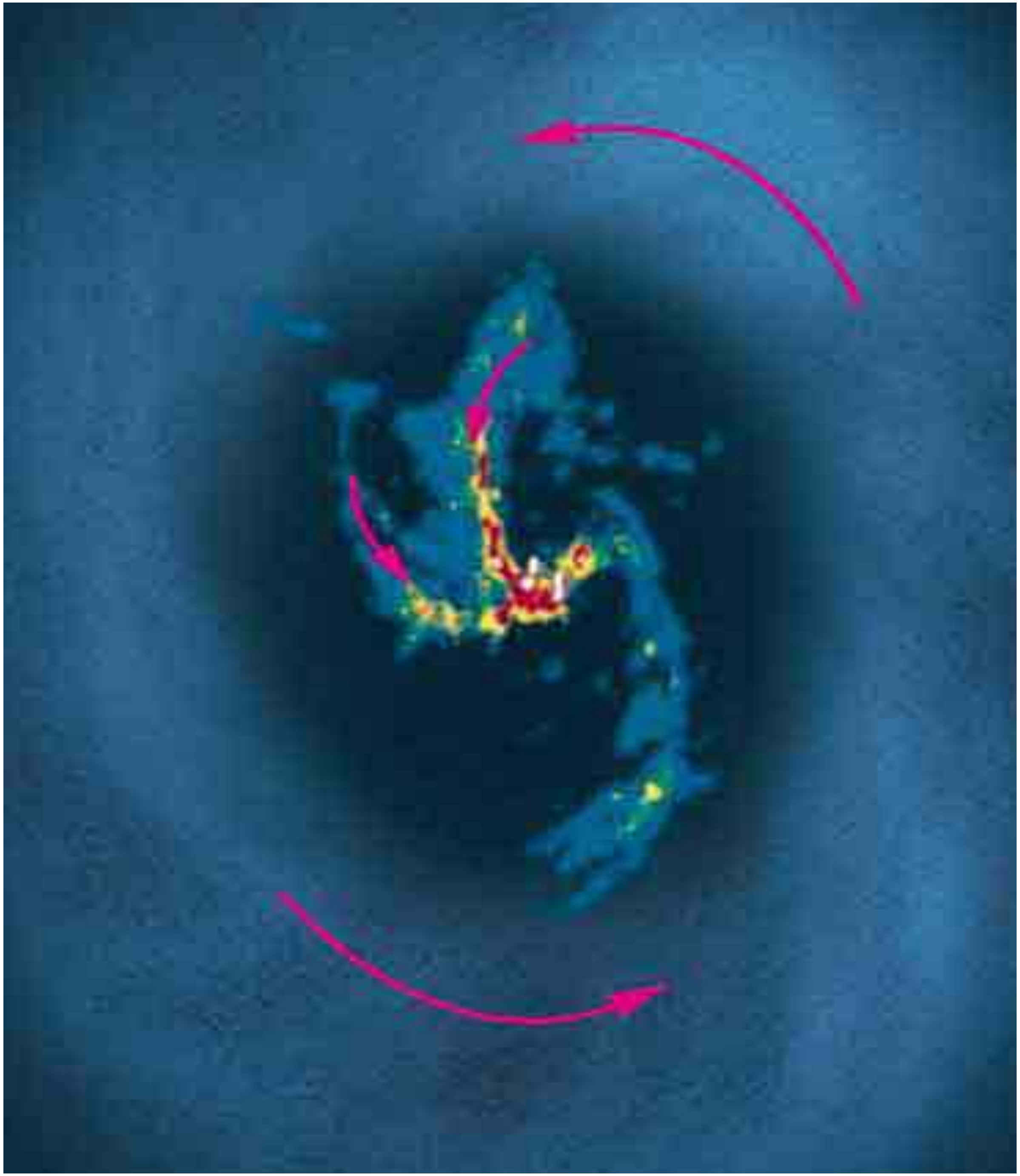
Sgr A*: The Center of our Galaxy

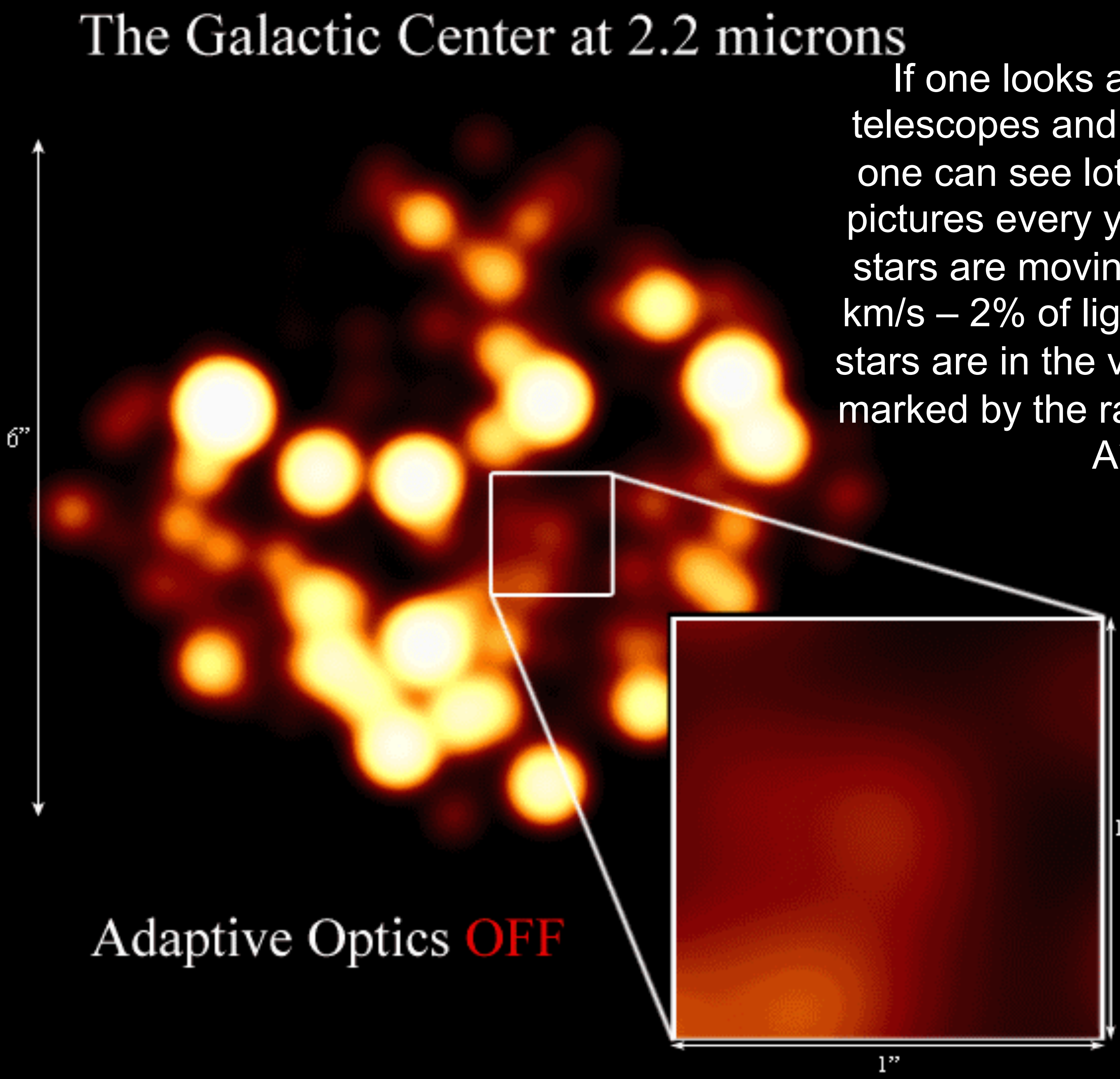
Image processing at the Naval Research Laboratory using DoD High Performance Computing Resources
Produced by N.E. Kassim, D.S. Briggs, T.J.W. Lazio, T.N. LaRosa, J. Imamura, & S.D. Hyman
Original data from the NRAO Very Large Array courtesy of A. Pedlar, K. Anantharamiah, M. Goss, & R. Ekers

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*



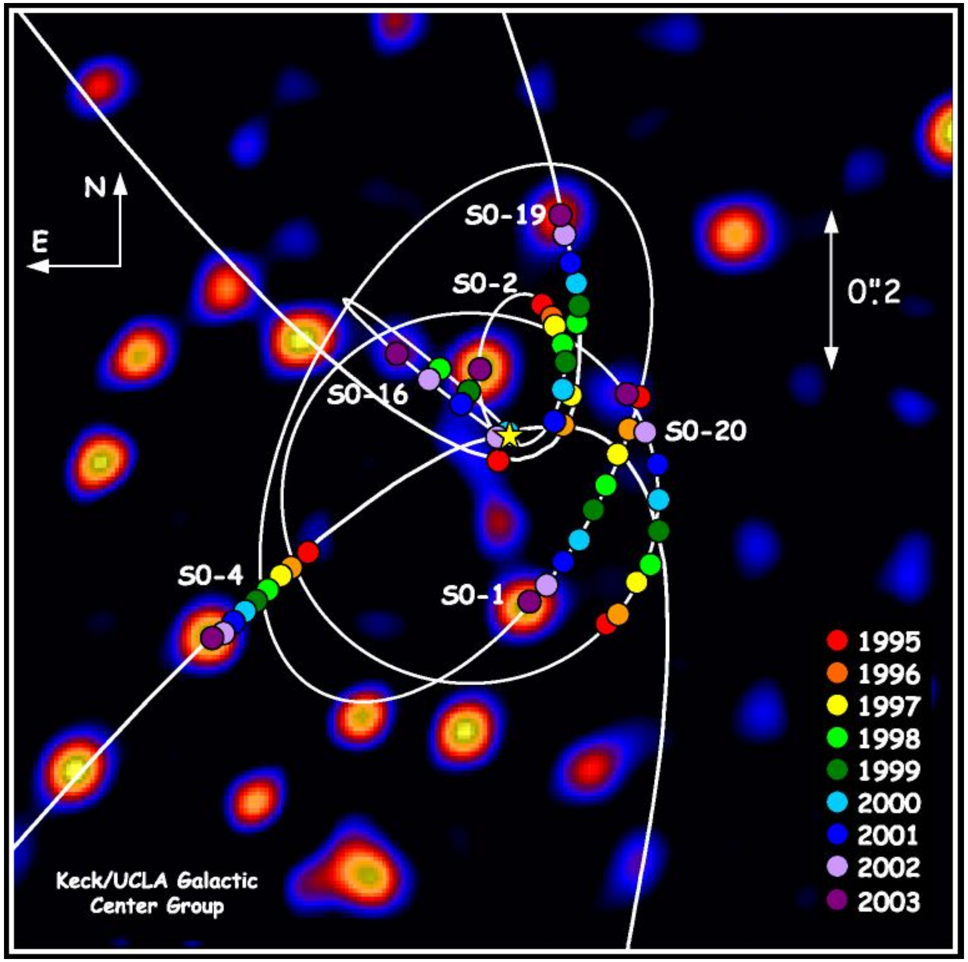


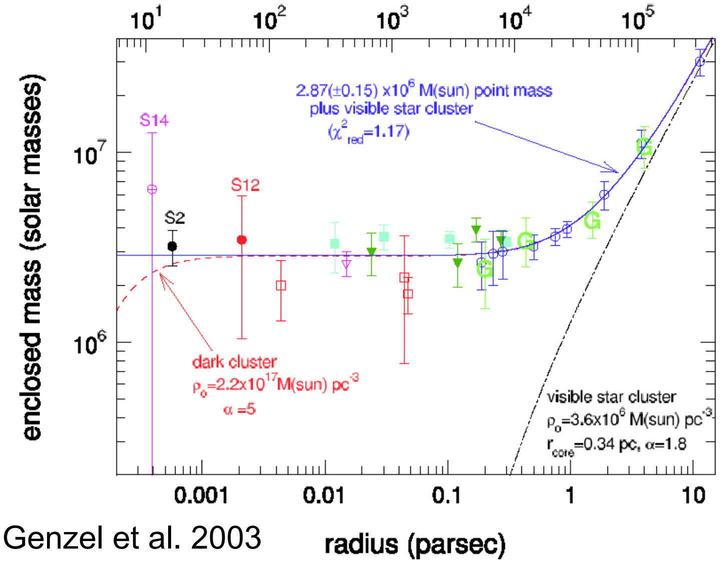
If one looks at this region with big telescopes and near-infrared cameras one can see lots of stars. If one takes pictures every year it seems that some stars are moving very fast (up to 5000 km/s – 2% of light speed!-). The fastest stars are in the very center - the position marked by the radio nucleus Sagittarius A* (cross).

Distance between stars is less that 0.01 pc

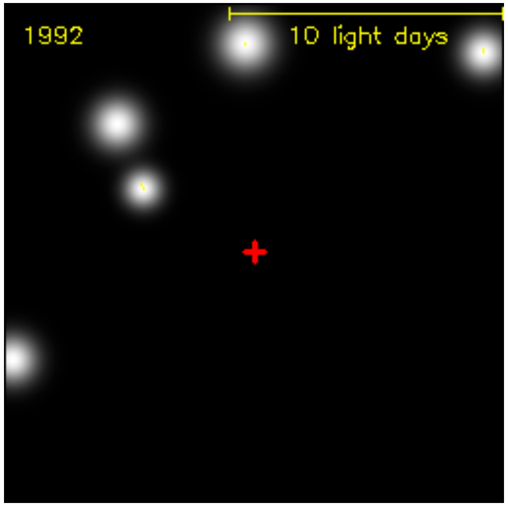
Evidence for a *Supermassive* Black Hole at the Galactic Centre

M= 3.6 x 10^6 Solar Masses

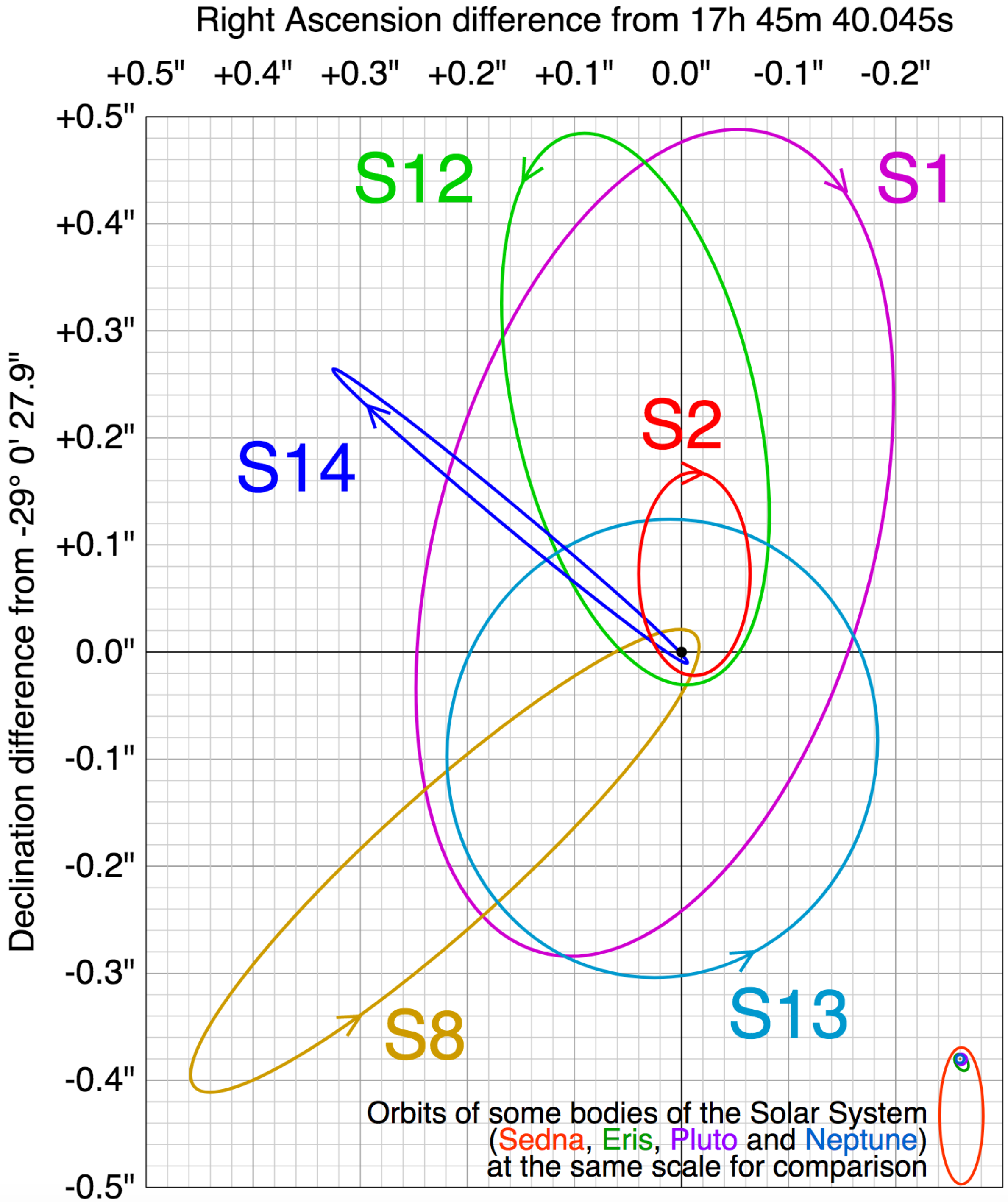




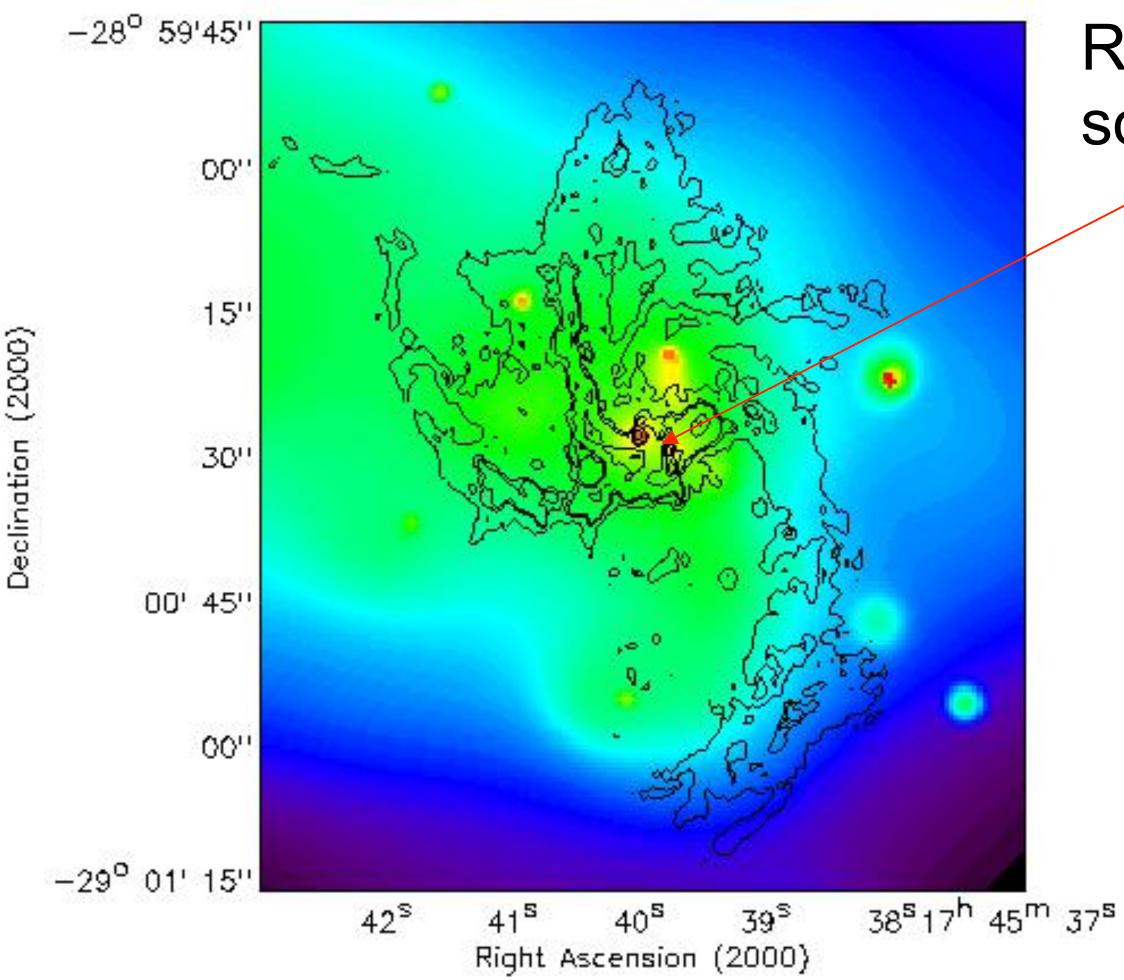
Genzel et al. 2003



The corresponding Schwarzschild radius is 0.08 AU/12 million km; 17 times bigger than the radius of the Sun


Right Ascension difference from 17h 45m 40.045s
+0.5"
+0.4"
+0.3"
+0.2"
+0.1"
0.0"
-0.1"
-0.2"
Declination difference from -29° 0' 27.9"
+0.5"
+0.4"
+0.3"
+0.2"
+0.1"
0.0"
-0.1"
-0.2"
-0.3"
-0.4"
-0.5"
S12
S1
S2
S14
S13
S8
Orbits of some bodies of the Solar System
(Sedna, Eris, Pluto and Neptune)
at the same scale for comparison

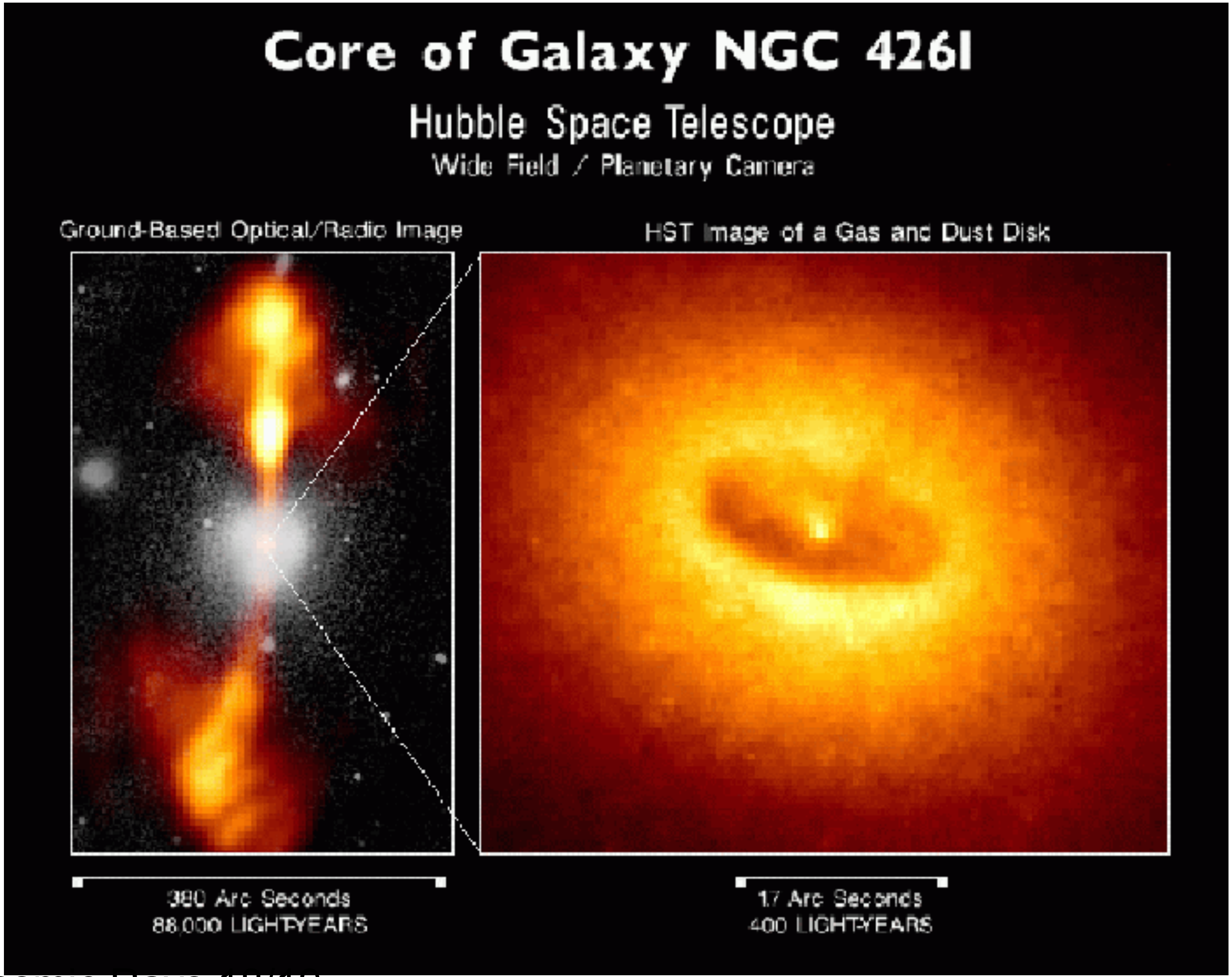
What about X-ray emission due to accretion?



Rather weak X-ray source

Chandra X-ray image of the Sgr A West region

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

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

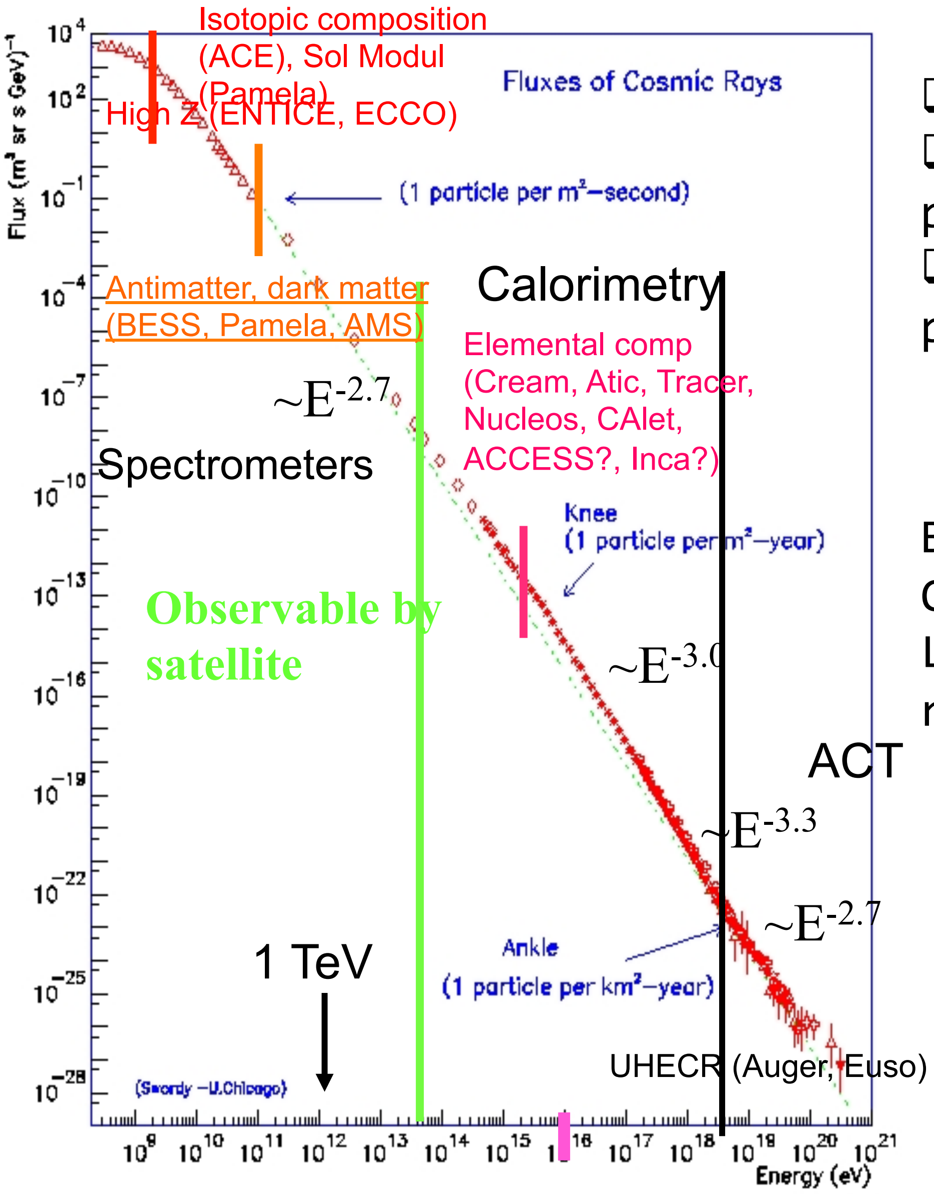
Radio jets but rather weak X-ray emission

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 (?)

Nature's beam calibration



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

Beam calibration:

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

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

Beam Calibration = CR Propagation Models

- The goal of the propagation models is to achieve a reliable physical description of the CR production and propagation through the Galaxy

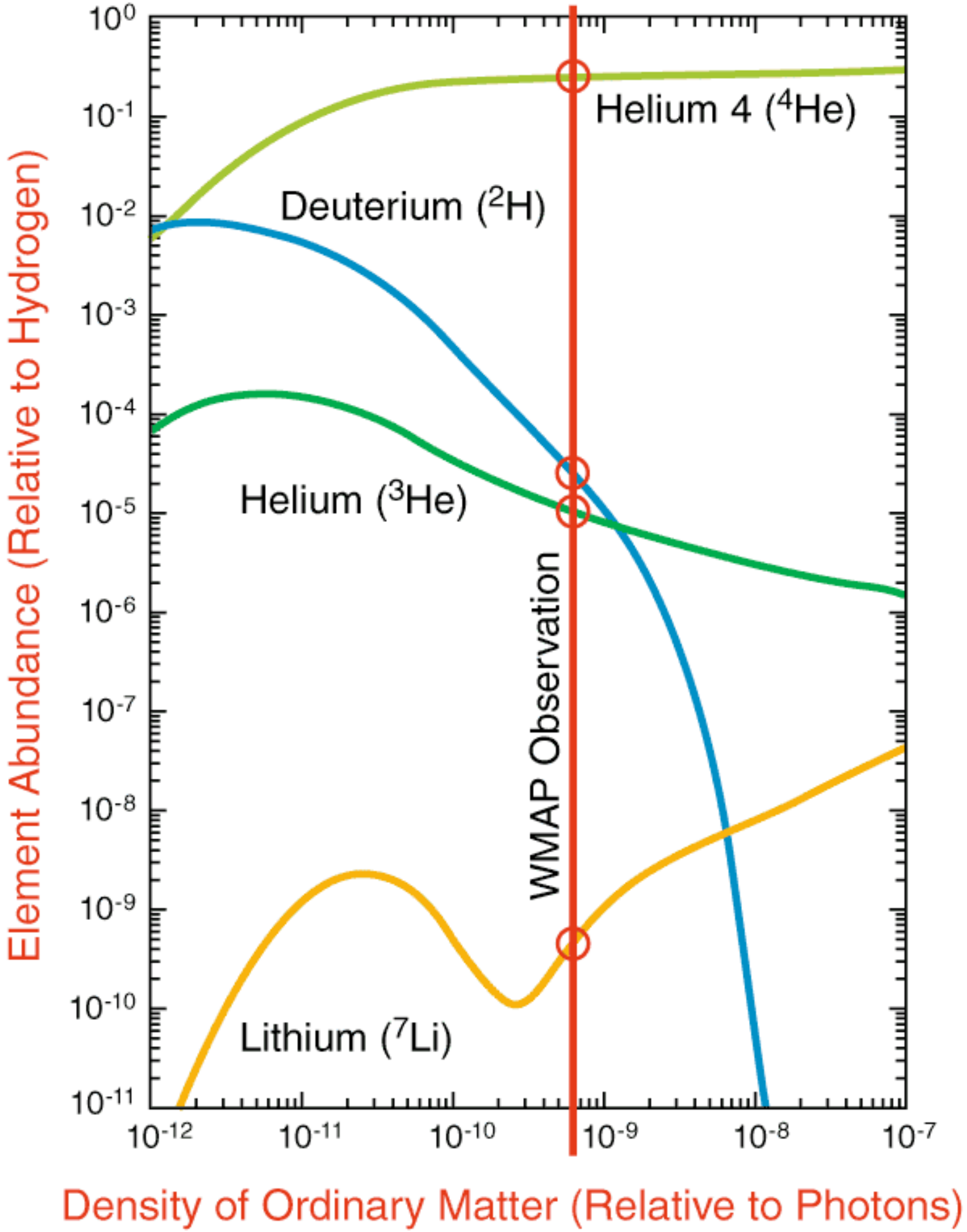
- From the measured fluxes in the heliosphere derive source composition, injection spectra & galactic parameters

- Reliable propagation model is needed for accurate background evaluation for faint signal searches in CR

- Particularly useful measurements to validate propagation models and to constraint their free parameters are flux measurements in a wide energy range of
  - Primary (ratios, eg C/O, fix source abundances)
  - Secondary (secondary to primary ratios, eg B/C, fix the grammage crossed, constraint diff coeff and halo thickness)
  - Radioactive (provide, eg ^{10}Be/^{9}Be, escape time information)

Abbondanze degli elementi nella Galassia

- Le abbondanze “primordiali” degli elementi sono fissate dalla **nucleosintesi primordiale**:
  - 24% (in massa) di 4He
  - 76% (in massa) di H
- La **nucleosintesi** nelle stelle provvede alla sintesi degli elementi più pesanti
- Le esplosioni stellari (per M>> Ms) hanno una vita media << all’età dell’Universo e provvedono a rifornire il mezzo interstellare
- Le percentuali dei vari elementi nella Galassia possono essere dedotte in varie maniere

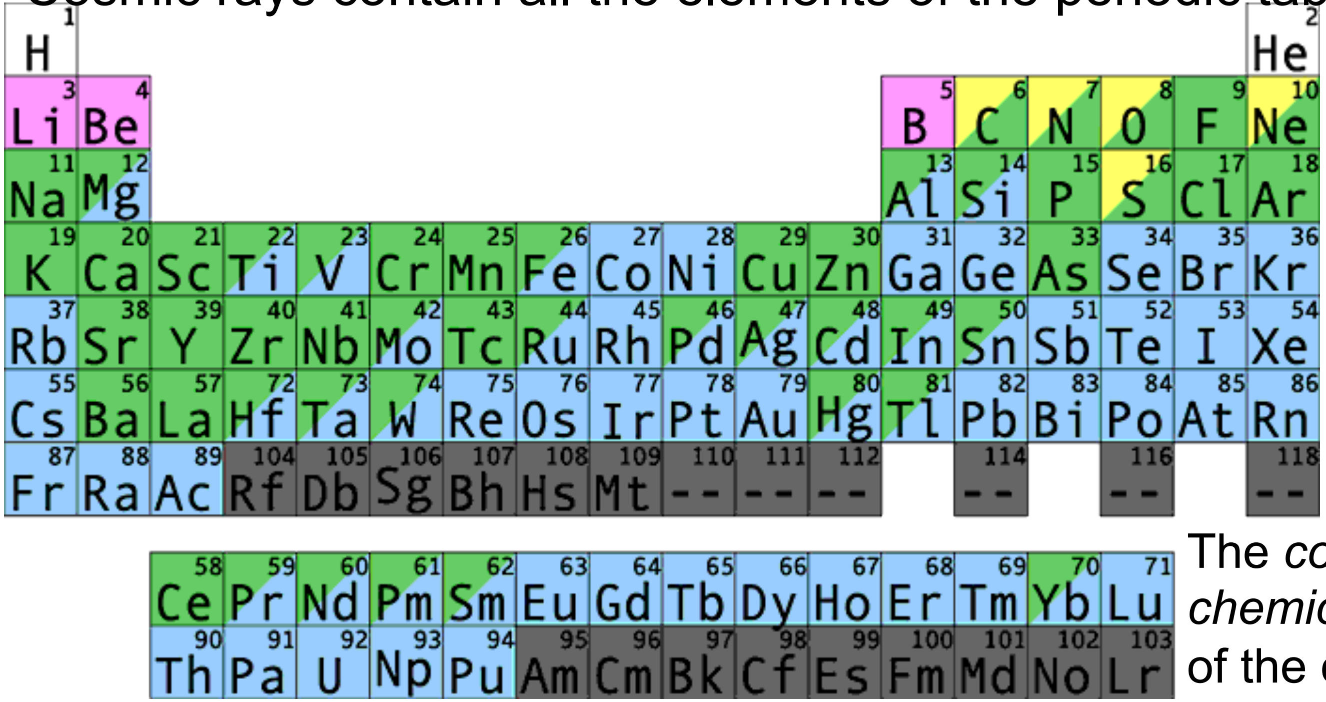


NASA/WMAP Science Team
WMAP101087

Element Abundance graphs: Steigman, Encyclopedia of Astronomy and Astrophysics (Institute of Physics) December, 2000

Chemical composition

Cosmic rays contain all the elements of the periodic table



1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 --	111 --	112 --		114 --		116 --		118 --
		58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu		
		90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr		

White - Big Bang
Pink - Cosmic Rays
Yellow - Small Stars
Green - Large Stars
Blue - Supernovae

The *cosmochemistry* or *chemical cosmology* is the study of the chemical composition of matter in the Universe and the processes that led to the observed compositions. Meteorites and photospheric measurements of solar light are one of the most important tools for studying the chemical nature of the Solar System.

Abundances in Solar System

They are representative of the abundances in the ISM

the chemical composition of the solar system is representative of the part of the Galaxy (the disk) with equal evolution history and the term *cosmic abundances* is sometimes used as a synonym for solar system abundances

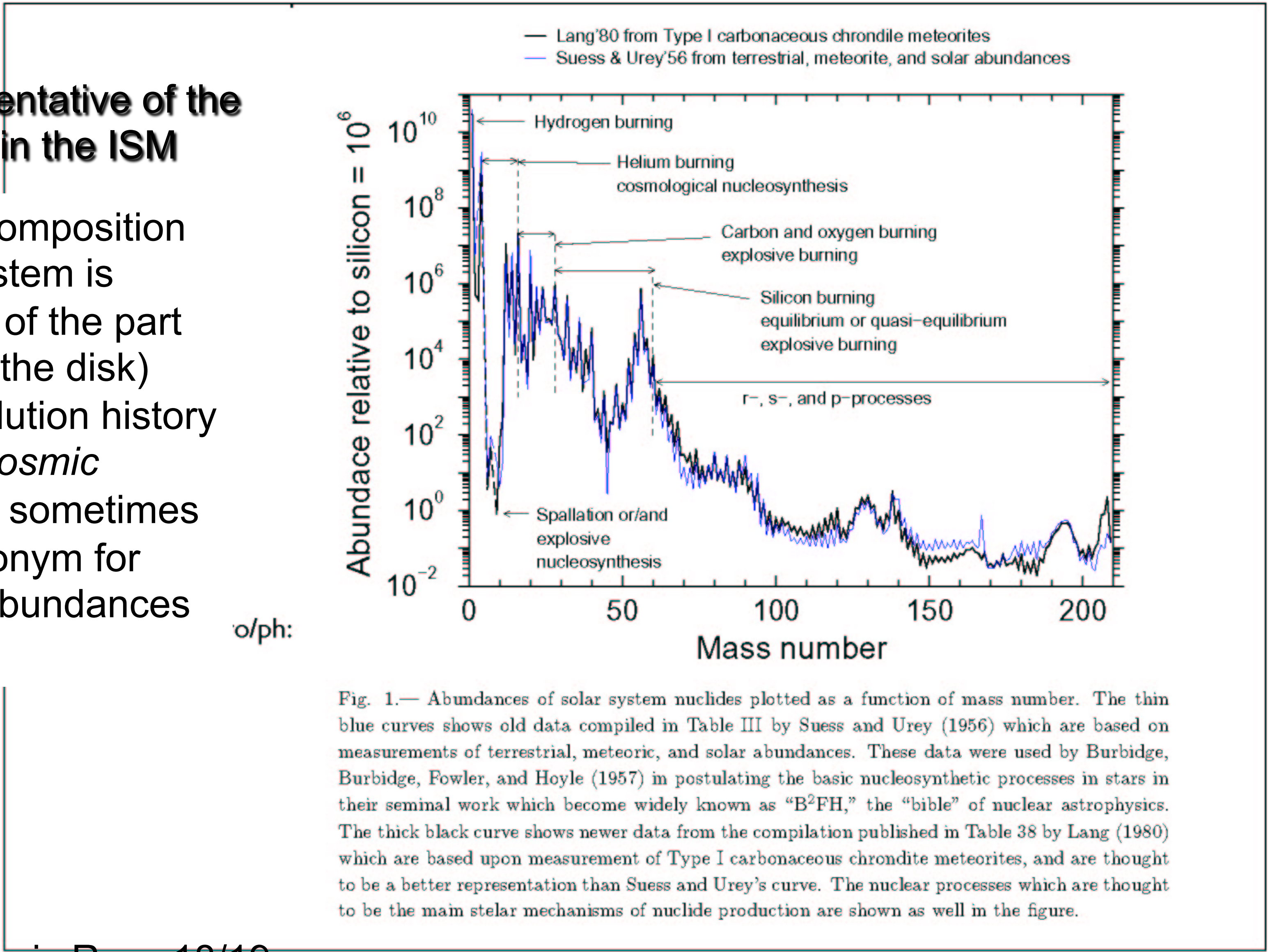


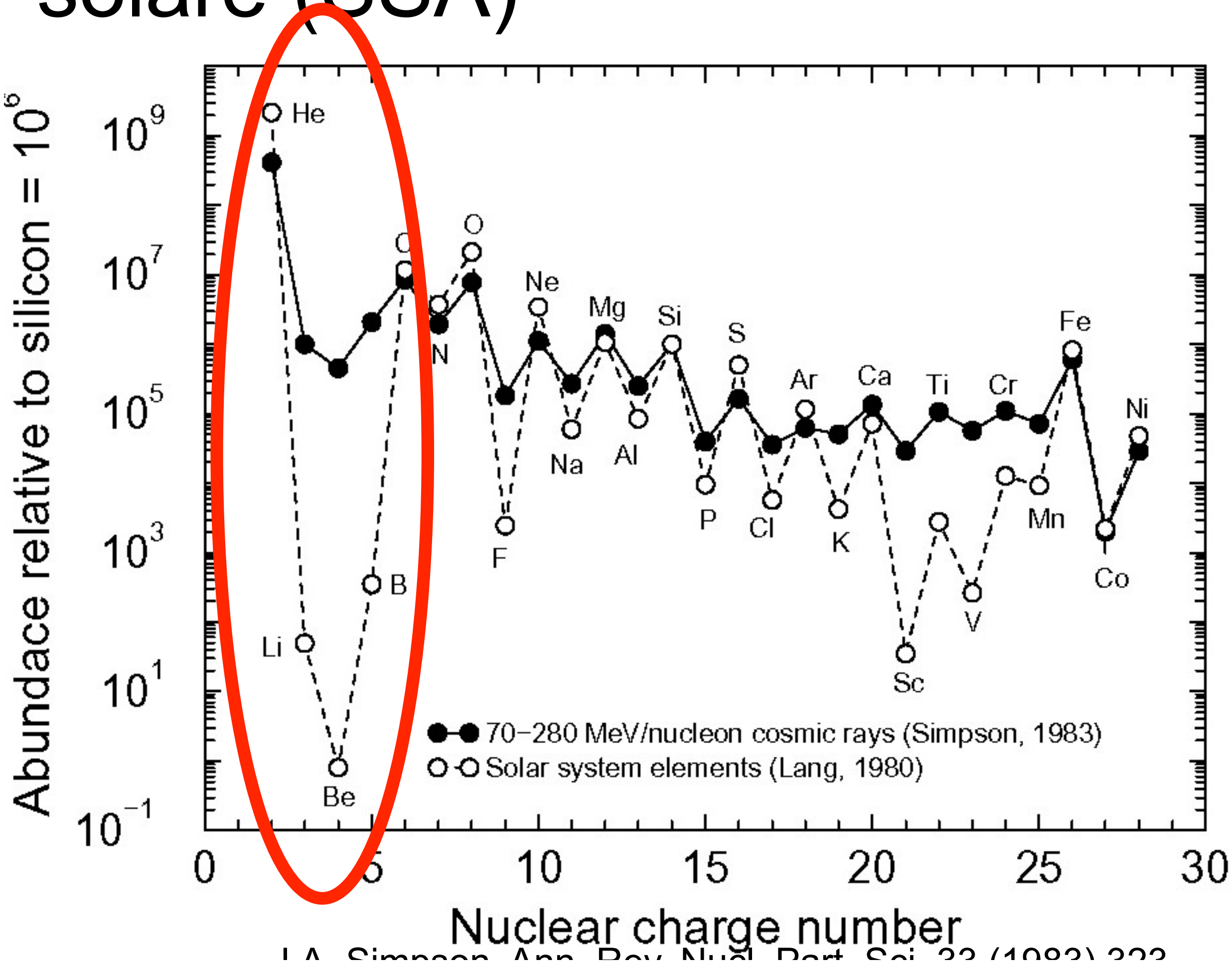
Fig. 1.— Abundances of solar system nuclides plotted as a function of mass number. The thin blue curves shows old data compiled in Table III by Suess and Urey (1956) which are based on measurements of terrestrial, meteoric, and solar abundances. These data were used by Burbidge, Burbidge, Fowler, and Hoyle (1957) in postulating the basic nucleosynthetic processes in stars in their seminal work which become widely known as "B^2FH," the "bible" of nuclear astrophysics. The thick black curve shows newer data from the compilation published in Table 38 by Lang (1980) which are based upon measurement of Type I carbonaceous chrondite meteorites, and are thought to be a better representation than Suess and Urey's curve. The nuclear processes which are thought to be the main stellar mechanisms of nuclide production are shown as well in the figure.

Confronto tra le abbondanze dei vari nuclidi nei RC e nell'ISM

- I RC hanno una composizione chimica analoga a quella del Sistema Solare (Solar System Abundance, SSA)?
- Se sì, questo indica una origine simile a quella del SS.
- Le abbondanze degli elementi nei RC si determinano tramite esperimenti di misura diretta dei RC (vedi.)
- Si notano alcune discrepanze rispetto al SSA, in particolare in corrispondenza al gruppo Li, Be, B e del gruppo prima del Fe → Vedi fig.
- Si nota anche un effetto *pari/dispari*, noto dalla fisica dei nuclei

Abbondanze relative dei RC e del sistema solare (SSA)

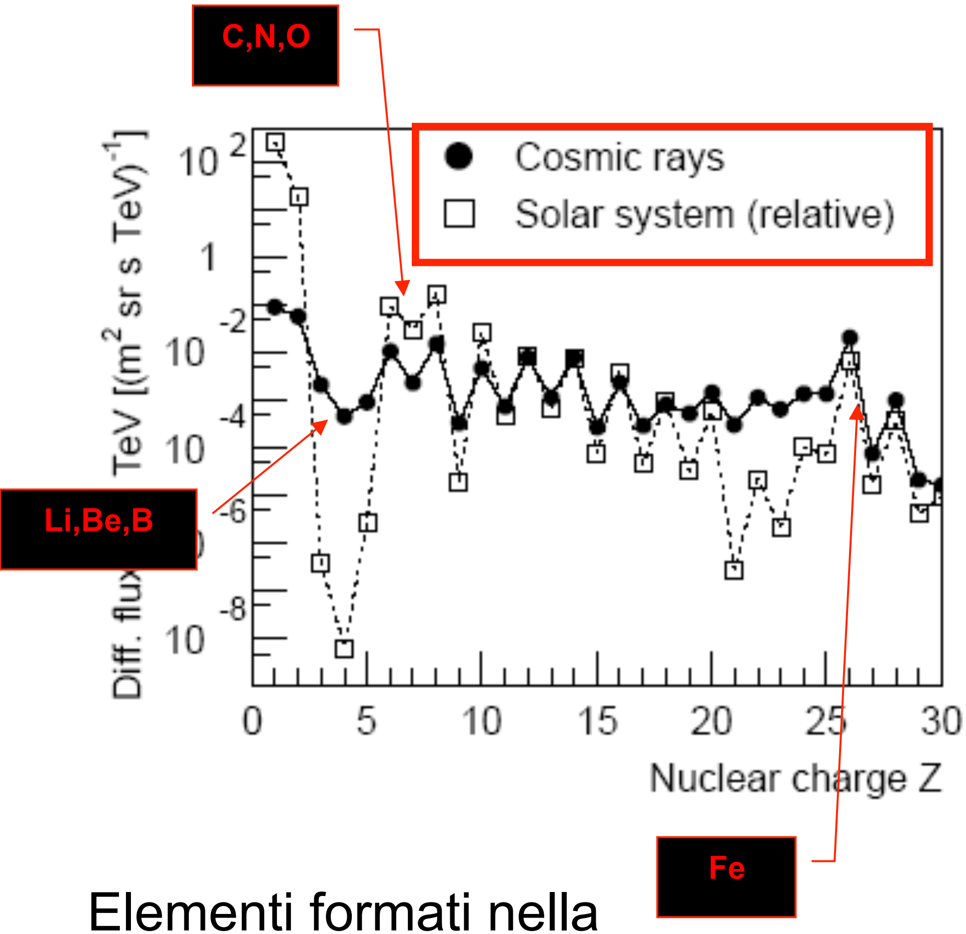
- H e He sono dominanti (98%), leggermente in difetto rispetto SSA
- Buon accordo tra CR e SSA per molti elementi, in particolare C, O, Mg, Fe.
- Elementi leggeri Li, Be, B e quelli prima del ferro Sc,V sono straordinariamente abbondanti nei RC rispetto SSA

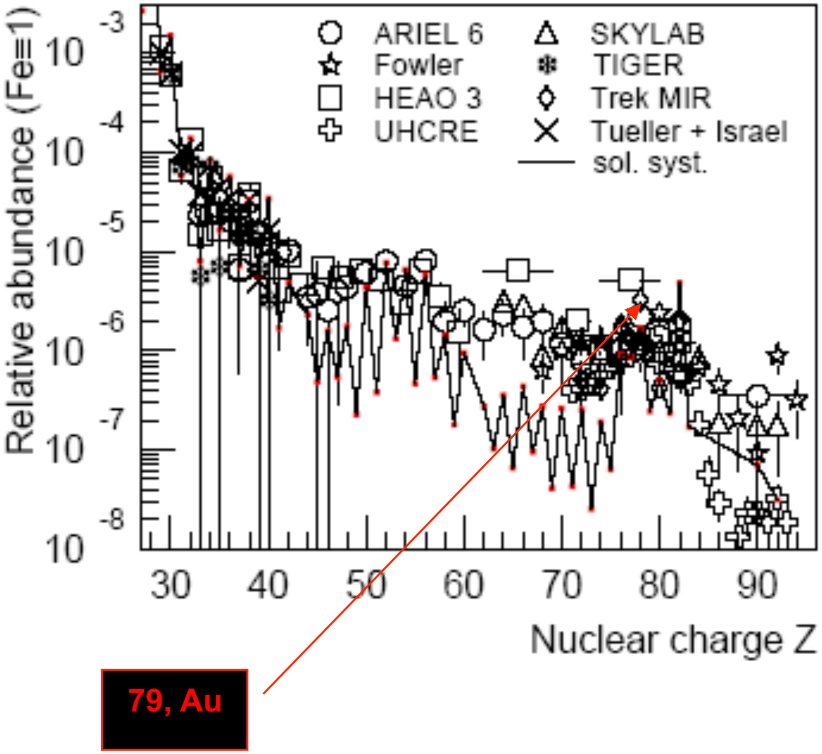


J.A. Simpson, Ann. Rev. Nucl. Part. Sci. 33 (1983) 323

The first conclusion from the data shown is that the accelerated matter arriving on Earth is sampled from a region whose surrounding material has the same chemical composition of our Solar System. This material is plausibly originated by the same mechanism that originated the Sun and the planets, with some exceptions

La composizione Chimica : confronto tra il elementi prima e dopo il Fe



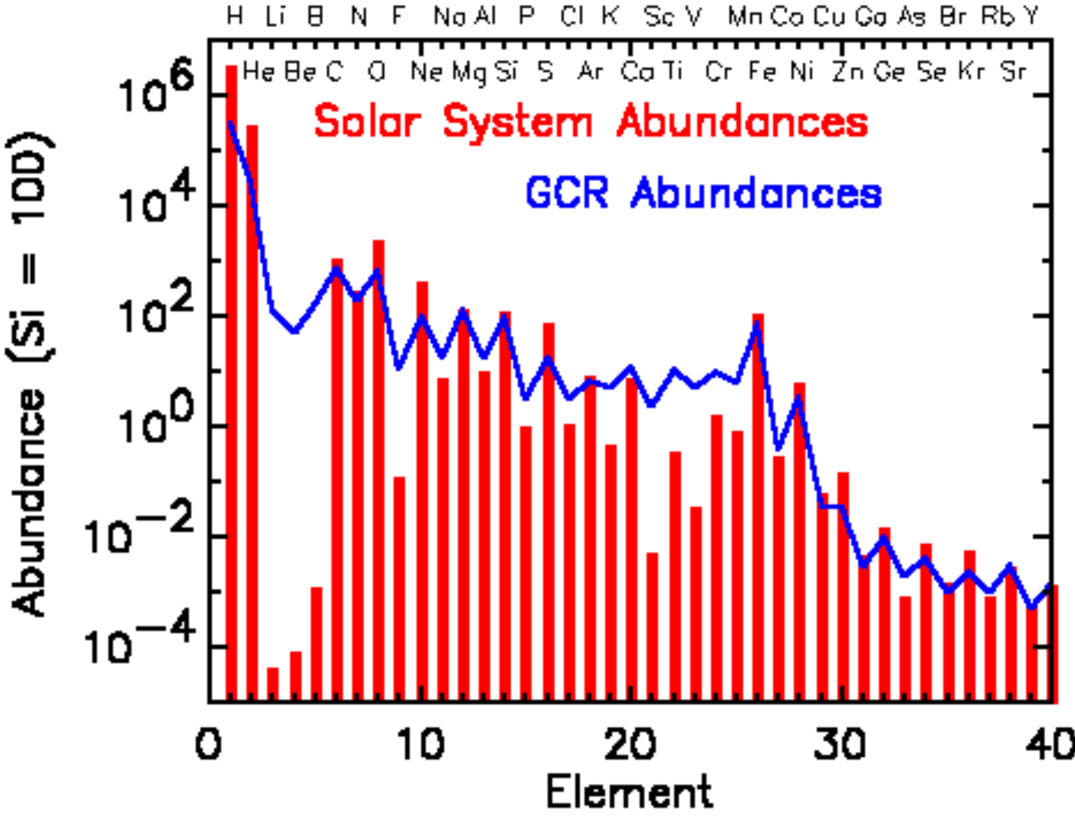


Elementi formati nella
Nucleosintesi stellare

Elementi formati nell'esplosione
(supernova)

La stessa figura…

In addition to stable isotopes, CRs contain long-lived radioactive nuclides, mostly of secondary origin. The observed abundances of these isotopes can be used for establishing various time scales related to the origin of CRs. In particular, secondary isotopes which decay through β± emission have been used as a second method to measure the residence times of CR in the galaxy, τ_{esc}.



CHEMICAL COMPOSITION of CR at LOW ENERGIES

Intensity (E > 2.5 GeV/particle(m^{-2} sr^{-1} sec^{-1})

Nuclear group	Particle charge, Z	Integral Intensity in CR (m^{-2} s^{-1} sr^{-1})	Number of particles per 10^4 protons	
			CR	Universe
Protons	1	1300	10^4	10^4
Helium	2	94	720	1.6×10^3
L (=Li,Be,B)	3-5	2	15	10^{-4}
M(=C,N,O)	6-9	6.7	52	14
Heavy	10-19	2	15	6
VeryHeavy	20-30	0.5	4	0.06
SuperHeavy	>30	10^{-4}	10^{-3}	7×10^{-5}
Electrons	-1	13	100	10^4
Antiprotons	-1	>0.1	5	?