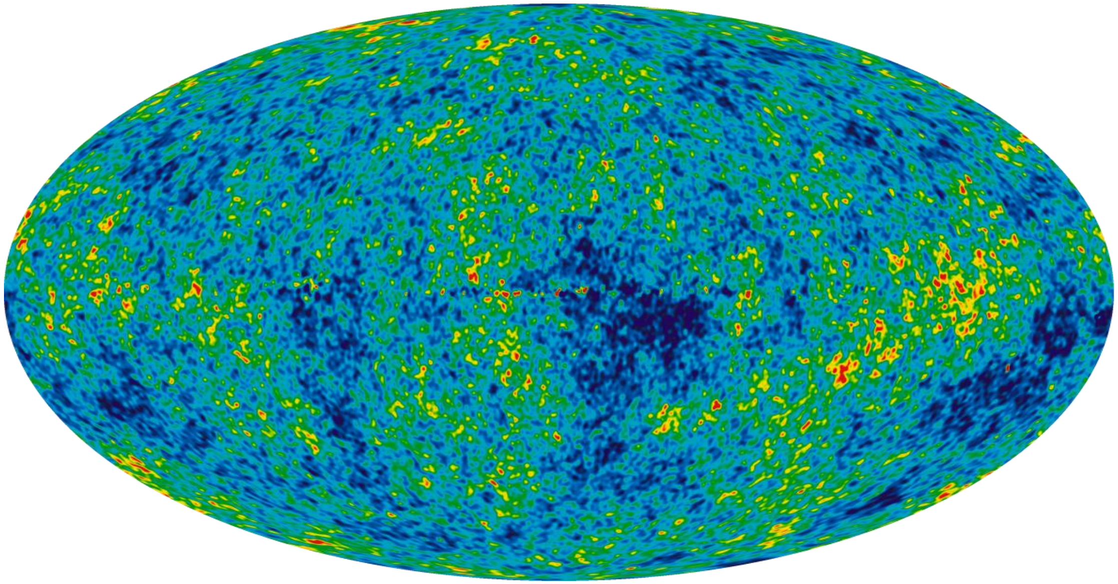
Cosmic Ray Anisotropy



Part 1
Introduction

Part 2
Methods and Applications

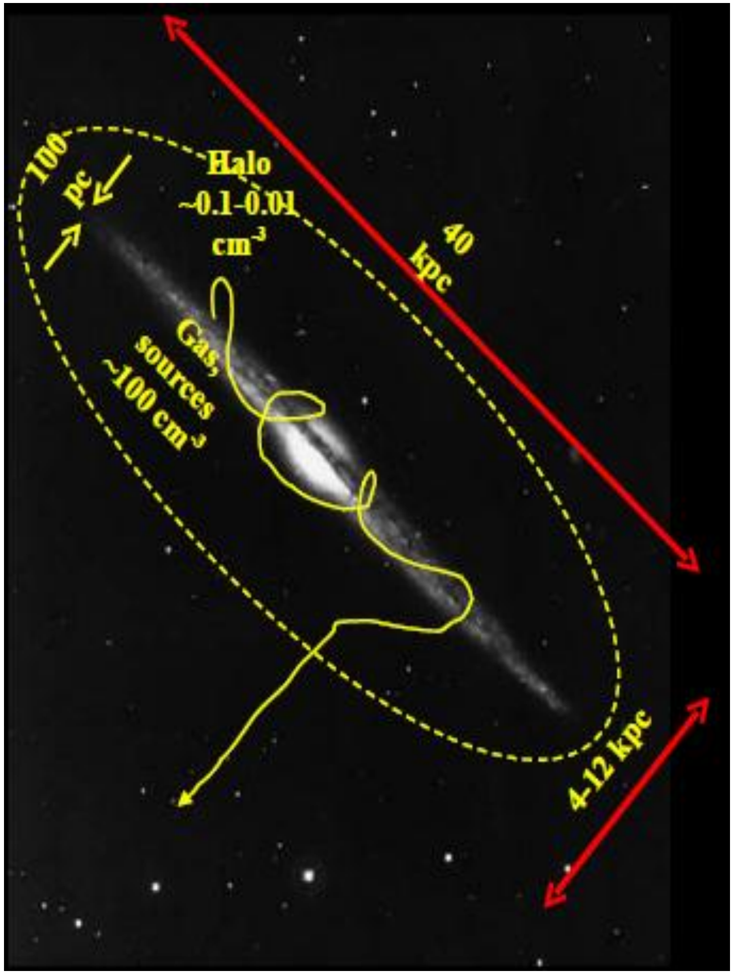
M. Nicola Mazziotta
INFN-Bari
mazziotta@ba.infn.it

MAPSES, Lecce 2011

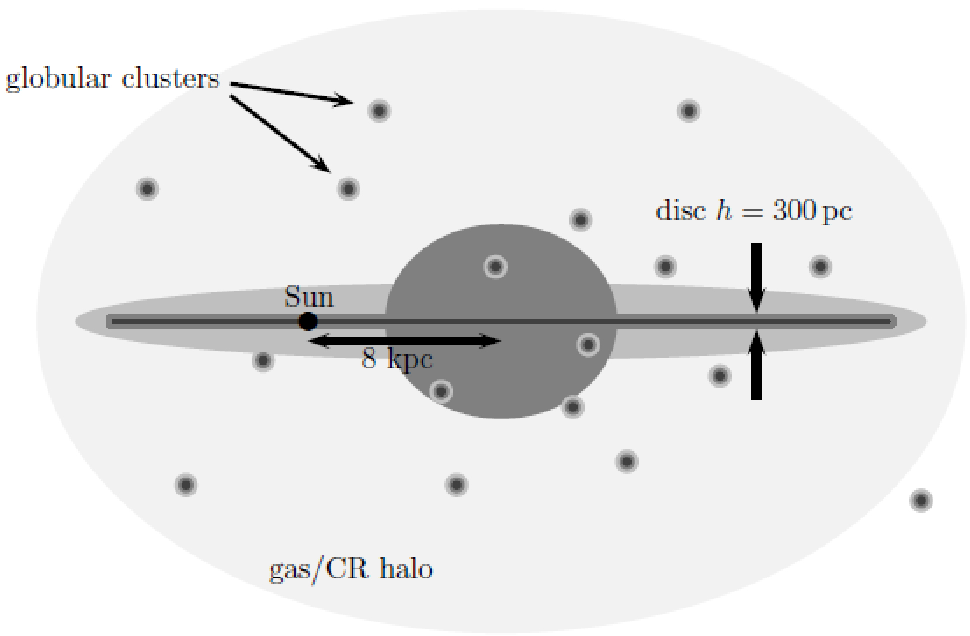
PART 1: INTRODUCTION

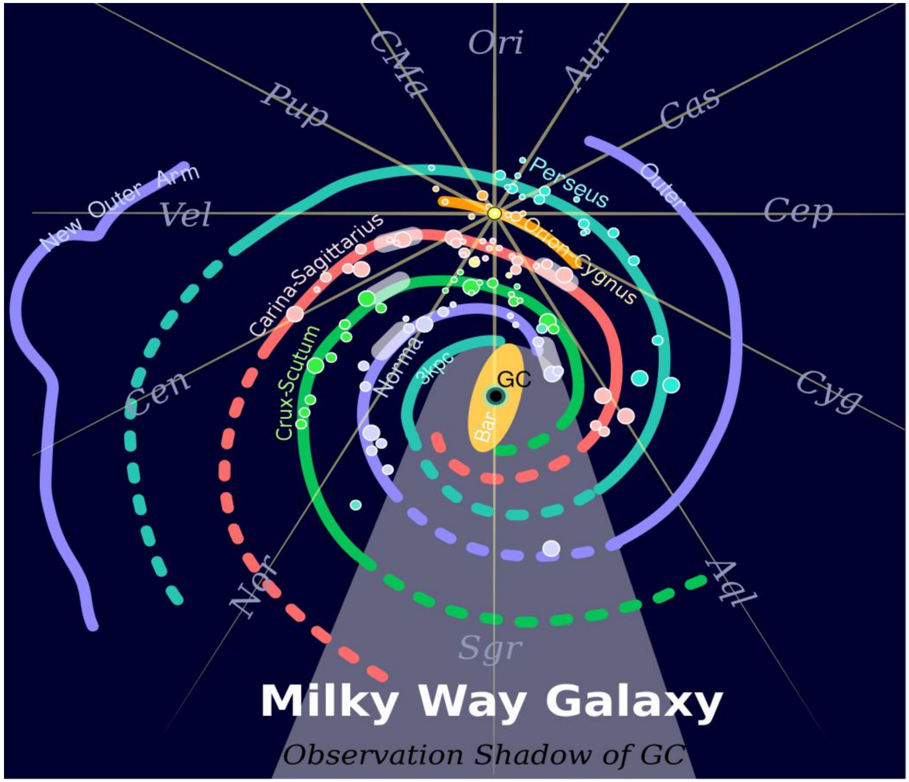
Galactic cosmic rays

- High-energy (GeV–TeV) charged primary Cosmic Rays (CRs) are believed to be produced in our galaxy, most likely in Supernova Remnants (SNRs)
- CRs injected into ISM propagate for millions of years before escaping to intergalactic space
- Particle interactions with interstellar gas, radiation and magnetic fields produce EM radiation from radio to gamma rays, and other secondaries ($e^{\pm}$, nuclei, etc.)
- During the transport from their source of origin to our solar system, CRs scatter on random and irregular components of the μG Galactic Magnetic Field (GMF), which almost isotropize their directions.
- Contrary to hadronic CRs, high-energy (>GeV) Cosmic Ray Electrons and Positrons (CREs) propagating in the GMF lose their energy rapidly through synchrotron radiation and by inverse Compton collisions with low-energy photons of the interstellar radiation field.



The Milky Way





- Left: Schematic picture of the Milky Way with a gas and dust disc, an extended halo of gas and cosmic rays, surrounded by globular clusters.
  - Everything is immersed in a halo of dark matter.
- Right: Maps of the Milky Way's spiral structure
  - Orion–Cygnus Arm contains the Sun and Solar System

Propagation Equation

For a particular particle species:

n = CR density per unit of p at $\vec{r}$

$$\frac{\partial n(\vec{r},p,t)}{\partial t} = q(\vec{r},p)$$

sources (SNR, nuclear reactions…)

Diffusion

$$+\vec{\nabla}\cdot[D_{xx}\vec{\nabla}n - \vec{V}n]$$

Diffusive reacceleration
(diffusion in the momentum space)

$$+\frac{\partial}{\partial p}\left[p^2 D_{pp}\frac{\partial}{\partial p}\frac{n}{p^2}\right]$$

convection
(Galactic wind)

E-loss

$$-\frac{\partial}{\partial p}\left[\frac{dp}{dt}n - \frac{1}{3}p\vec{\nabla}\cdot\vec{V}n\right]$$

fragmentation

$$-\frac{n}{\tau_f} - \frac{n}{\tau_d}$$

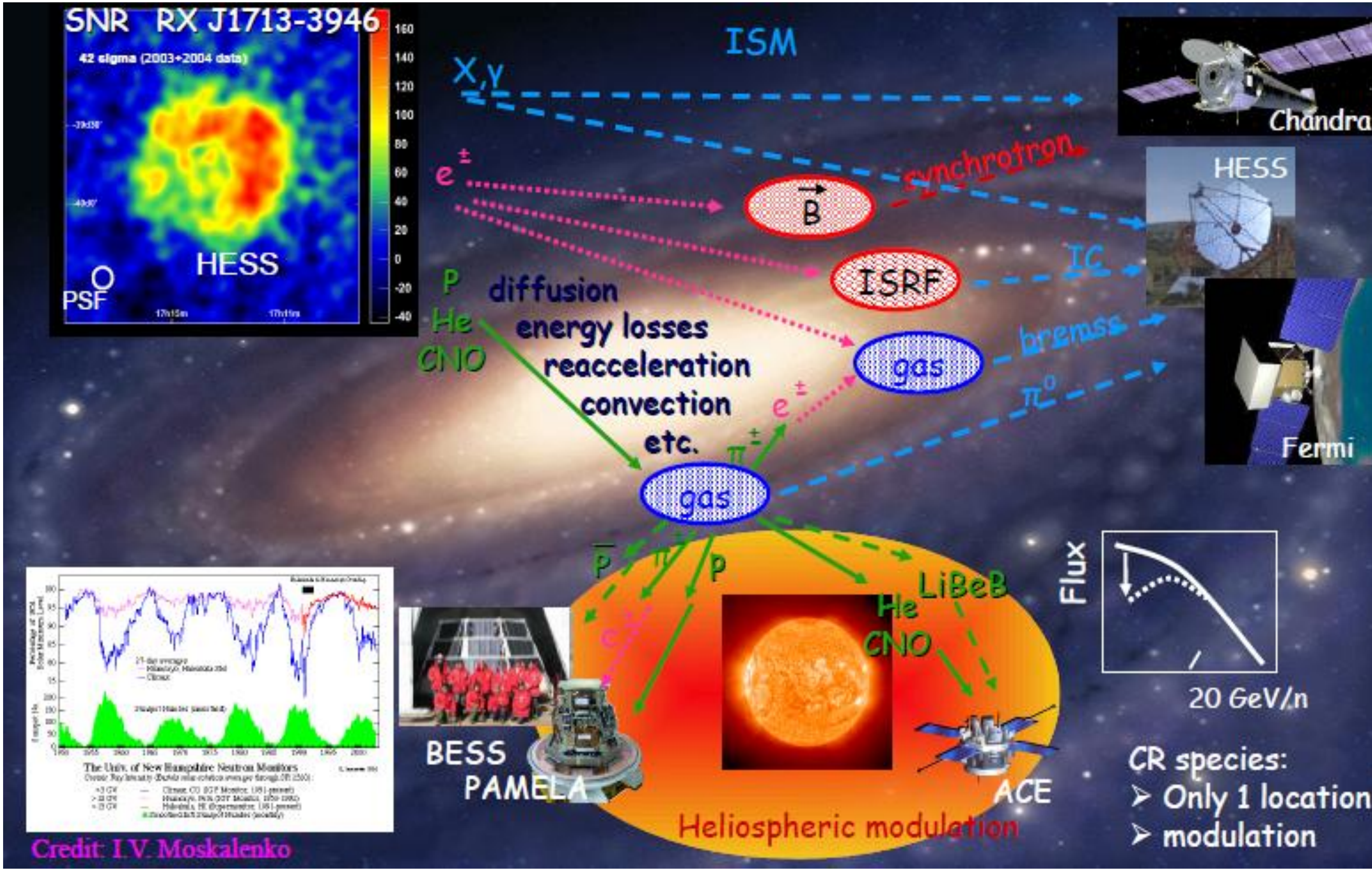
radioactive decay

+ boundary conditions

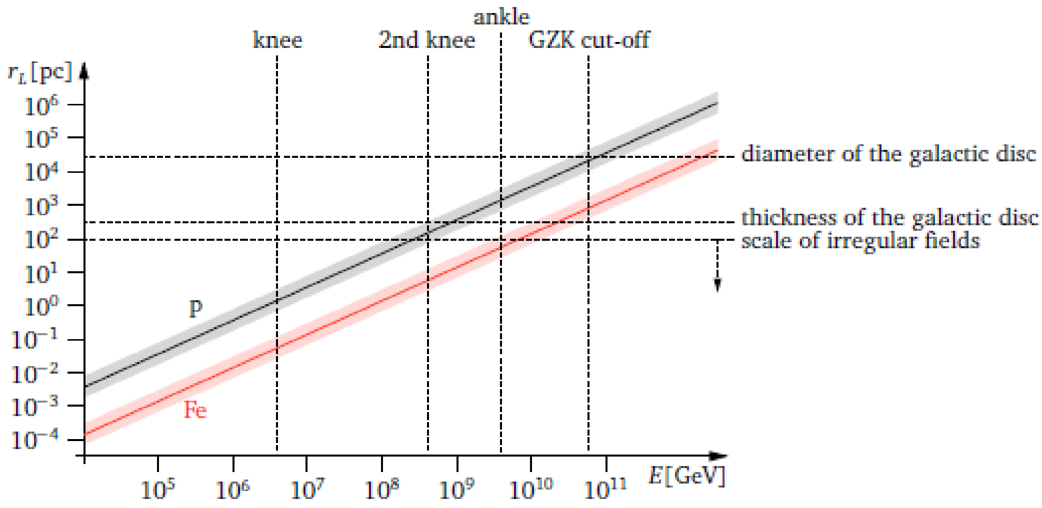
Propagation Equation (cont'd)

- $n(\vec{r}, p, t)dp = 4\pi p^2 f(\vec{p})dp$, where $f(\vec{p})$ is the phase-space density
- D_{xx}= spatial diffusion coefficient $\sim 10^{28}\,\frac{cm^2}{s}$ at energy $\sim \frac{1GeV}{n}$ and increases with rigidity as $R^{0.3} - R^{0.6}$
  - It is, in general, a function of $\left(\vec{r}, \beta = \frac{v}{c}, \frac{p}{Z}\right)$, where Z is the charge and p/Z determines the gyroradius in a given magnetic field (aka Larmor radius), $r_g = \frac{pc}{ZeB} = \frac{R}{B} \approx \frac{E\left(10^6 GeV\right)}{Z\,B(\mu G)}pc$
- D_{pp}= momentum diffusion coefficient
  - D_{pp} is related to D_{xx} by $D_{xx}D_{pp} \propto\ p^2$, whit the proportionality constant dependent on the theory of stochastic reacceleration
  - $D_{xx}D_{pp} = (pV_a)^2/9$, where V_a is the Alfén velocity ~ 30 km/s
- $\vec{V}$ is a function $\vec{r}$ of and depends on the nature of the galactic wind
- $\vec{\nabla} \cdot \vec{V}$ represents the adiabatic momentum gain or loss in the momentum flow of gas
- τ_f is the time scale for loss by fragmentation
- τ_d is the time scale for radioactive decay

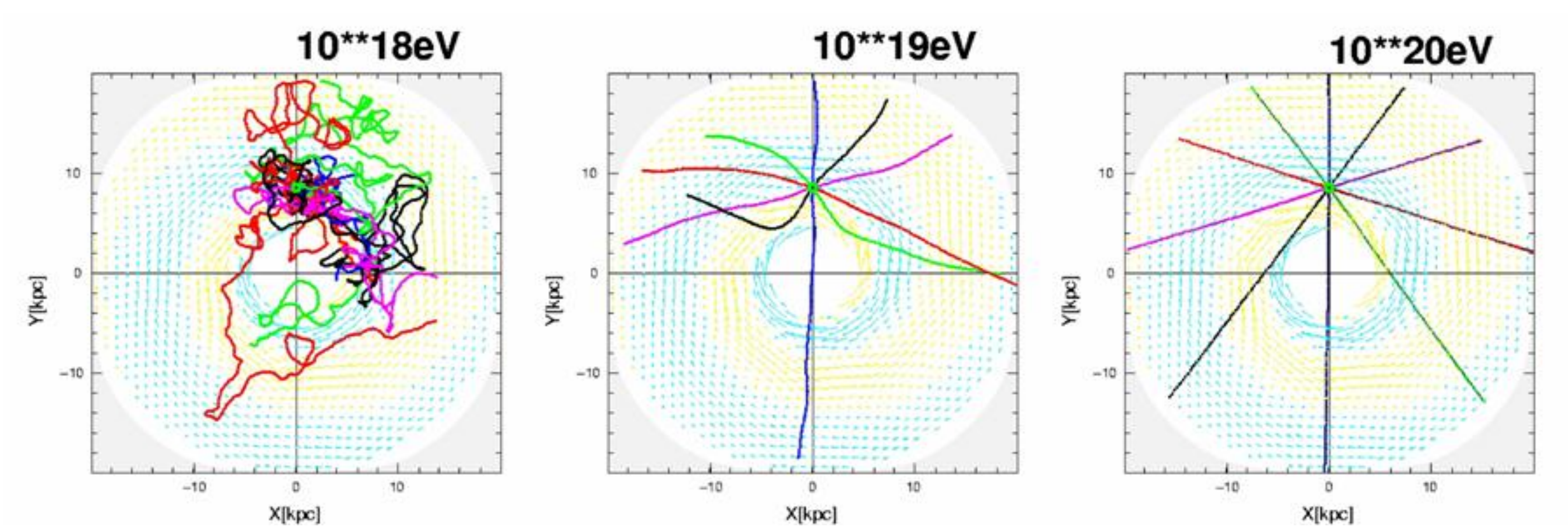
CR propagation in the ISM



Gyroradius – Larmor radius



Gyroradii of protons and iron nuclei as a function of energy: magnetic fields of 3μG (solid lines), 1.4μG (upper edges of shaded areas) or 6μG (lower edges) were assumed.



Random walks

- The concept of CR diffusion explains why charged particle have highly isotropic distribution.
  - On the microscopic level, the diffusion of CRs results from particle scattering on random magnetized plasma (i.e. magnetohydrodynamic, MHD, waves and discontinuity)
- After N steps $\vec{l_i}$ of the same size $|\vec{l_i}| = l$ a particle that started at zero is at the position $\vec{d} = \sum_{i=1}^{N} \vec{l_i}$
  - We assume that the direction of each step $\vec{l_i}$ is chosen randomly.
- Then the scalar product of $\vec{d}$ with itself is $\vec{d} \cdot \vec{d} = \sum_{i=1}^{N} \sum_{j=1}^{N} \vec{l_i} \cdot \vec{l_j}$
- Splitting the sum into the diagonal and the off-diagonal terms, we obtain $d^2 = Nl^2 + 2l^2 \sum_{i=1}^{N} \sum_{j<i}^{N} \cos\theta_{ij} \approx Nl^2$
- By assumption, the angles θ_{ij} between $\vec{l_i}$ and $\vec{l_j}$ are chosen randomly and thus the off-diagonal terms cancel against each other.

Diffusion equation

- The diffusion equation can be written as: $\frac{\partial n}{\partial t} - \vec{\nabla} \cdot \left(D\vec{\nabla} n\right) = Q$
- Assuming that D is independent on the position, the diffusion equation can be transformed into the free Schrödinger equation substituting $D \leftrightarrow \hbar^2/(2m)$ and $t \leftrightarrow -it$.
- Hence we can borrow the free propagator for a non-relativistic particle as Green's function $G(r)$ for the diffusion equation with $D = const.$ and obtain with the mentioned substitutions, $G(r) = \frac{1}{(4\pi Dt)^{\frac{3}{2}}}\, e^{-\frac{r^2}{4Dt}}$
- Thus the mean distance traveled outward is $\propto \sqrt{Dt}$, as in a random walk with $< r^2 > \sim N l^2$
- Connecting the two pictures, we obtain $\mathrm{D} \sim \frac{N l^2}{t} \sim v l$ with $v = \frac{N l}{t}$
- Therefore, the diffusion coefficient D can be estimated as the product of the cosmic ray velocity $v \approx c$ and its mean free path l.
- A more precise analysis gives $D = l\, v/3$, where the factor three reflects the number of spatial dimensions.

Diffusion coefficient

- We estimate now the energy-dependence of D(E) and its numerical value for a cosmic ray propagating in the Galactic disc
- We start picturing its propagation as a random-walk caused by scatterings on magnetic clouds of size r_0
- Then one can distinguish two different regimes:
  - At low energies, i.e. when the Larmor radius is smaller than the size r_0 of magnetic clouds with density ρ, the angles between the entrance and the exit directions are isotropically distributed
  - Since the direction is on average changed considerably in each scattering process, the mean free path l_0 is simply the distance between clouds, $l_0 = \frac{1}{\sigma\rho} \sim \frac{1}{r_0^2\rho}$ and thus $D_0 = \frac{1}{3} l_0 v = \frac{1}{3} c \frac{1}{r_0^2 \rho} \sim \mathrm{const}$

Diffusion coefficient (cont'd)

- At high energies, cosmic rays are deflected in each cloud only by a small angle $\theta \sim r_0/r_g$
- The directions are uncorrelated and thus the mean deflection is zero, $<\theta>=0$, and the variance is given again by the result for a random-walk, $<\theta^2> \sim N(r_0/r_g)^2$
- The effective free mean path l_0 is the distance after which $<\theta^2> \sim 1$
- Hence the energy dependence of the diffusion coefficient is $D(E) = \left(\frac{r_g}{r}\right)^2 D_0 \propto E^2$
- The transition between these two regimes happens when $r_g(E_{cr}) = r_0$
  - Numerically, this energy is given by $E_{cr} \approx 10^{15} eV(B/\mu G)(r_0/pc)$

- Obviously, the picture of magnetic clouds or domains with an unique size r_0 is an oversimplification

Realistic picture for D

- In a more realistic picture, there is a distribution of magnetic field fluctuations that can be easiest characterized by the spectrum of its Fourier components, $< B^2(k) > \propto \ k^{-\alpha}$
- Charged particles scatter mainly at field fluctuations which wave numbers k matches their Larmor radius, $k \sim 1/r_g$.
- If the amplitude of this resonant magnetic field fluctuation is δB_{res}, then $D \approx \left(\frac{\delta B_{res}}{B}\right)^{-2} \frac{v r_g}{3}$
- Thus the energy dependence of D below E_{cr} is determined by the power-spectrum of magnetic field fluctuations.
- The size r_0 of magnetic field domains is in this picture replaced by the correlation length l_c, i.e. the length scale below the field is smooth.
- An estimation of the diffusion coefficient $D_{xx} \approx 2 \times 10^{27}\ \beta\ \left(\frac{R}{GV}\right)^{\alpha}\ cm^2\ s^{-1}, where\ \alpha \approx 0.3 - 0.5$

Cosmic ray intensity

- The intensity, I, is the number of incident particles per unit solid angle, per unit time on an unit are perpendicular to the direction of observation
  - Thus its units are $[I] = cm^{-2}s^{-1}sr^{-1}$
- The particle flux $F_\Omega = \int I \cos\theta \, d\Omega$, where θ is the angle between the normal to the area and the particle velocity direction, and $d\Omega$ is the element of solid angle.
- For isotropic intensity the particle flux from one hemisphere through a planar detector is $F = 2\pi \int_0^{\pi/2} I \cos\theta \sin\theta \; d\theta = \pi I$
- Again, for isotropic intensity, the number density of cosmic rays with velocity v is $n = \frac{4\pi}{v} I$
- In case of not monoenergetic particles, the differential intensity $I(E)$ is such that $I(E)dE$ is the intensity of particles in the energy range from E and $E+dE$
  - $n = 4\pi p^2 f(p) \implies I(E) \propto p^2 f(p)$

Diffusion and cosmic ray anisotropies

- Anisotropy of CRs is usually defined as $\delta = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$, where I_{max} and I_{min} are the maximum and minimum intensity with respect to directions at a given point.
- In case of the dipole anisotropy, $I = I_0 + I_1 \cos\theta$, we get $\delta = I_1 / I_0$
- For isotropic intensity, if the particle flux through a surface at right angle to the direction $\theta = 0$ is $F(0)$, and the flux through the opposite direction $\theta = \pi$ is $F(\pi)$, then the resultant flux is $F(\pi) - F(0) = \int_0^{\pi} I \ \cos\theta \, d\Omega = \frac{4\pi}{3} I_1$
- On the other hand, for diffusion law is valid, $F(\pi) - F(0) = -D\vec{\nabla}n$
- Comparing the two equations we obtain $I_1 = -\frac{3}{4\pi} D\vec{\nabla}n$

Diffusion and cosmic ray anisotropies (cont'd)

- Then the dipole anisotropy is $\delta = \frac{3(F(\pi)-F(0))}{4\pi I_0} = \frac{3D}{c}\frac{|\vec{\nabla}n|}{n}$, where the relation $I \approx I_0 = \frac{v}{4\pi} n \approx \frac{c}{4\pi} n$ is used and ultra relativistic particles are considered.
- The experimental results for δ provide thus information on D
- For an estimate we set $|\vec{\nabla}n| \approx \frac{n}{h}$ where h is the characteristic scale on which n changes.
  - With h ~ 100 pc and using D ~ 10^{27} cm^2 s^{-1}, it follows δ ~ 10^{-3}
- The diffusion time is $\tau_{diff} = \frac{R_{diff}^2}{2D(E)} \approx \frac{R_{diff}^2}{2D_0}(\frac{E}{E_0})^{-\alpha}$
- The amplitude of the dipole anisotropy $\delta \sim \frac{1}{\tau_{diff}} \sim E^{\alpha}$

Single source anisotropy

- The general solution for the diffusion equation is given by the Green function: $n \propto e^{-\frac{r^2}{4Dt}}$
  - *D is the diffusion coefficient,* $D=D_0(E/E_0)^{\alpha}$
    - $D_0 \approx 5.8 \times 10^{28}$ cm^2 s^{-1}, $\alpha = 0.3$ *and* $E_0 \approx 4$ GeV
- For a single source with age t_k at the distance r_k, the anisotropy towards its direction is given by $\delta_k = \frac{3r_k}{2ct_k}$
- However, the total anisotropy due to a distribution of sources in the sky is given by $\delta = \frac{\sum_k n_k \delta_k \vec{r}_k \cdot \vec{r}_{max}}{\sum_k n_k}$, where $\vec{r}_{max}$ is the direction of maximum intensity.

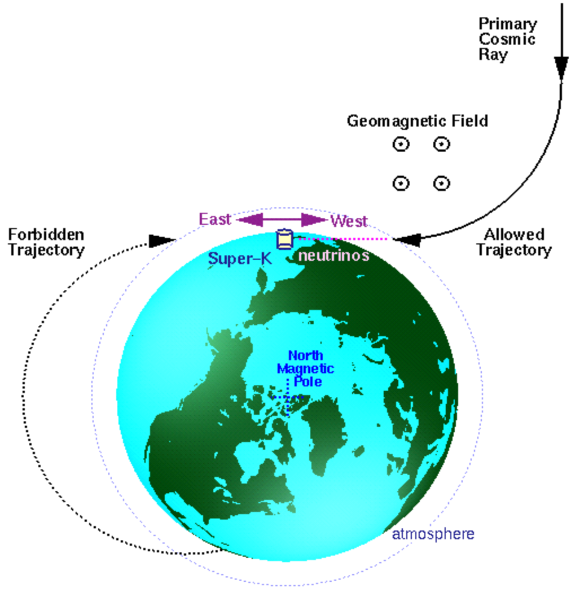
Source	Distance (pc)	Age (yr)	Dipole Anisotropy (%)
Geminga	157	$3.7\ 10^5$	0.2
Monogem	290	$1.1\ 10^5$	1.2
Vela	290	$1.1\ 10^4$	13

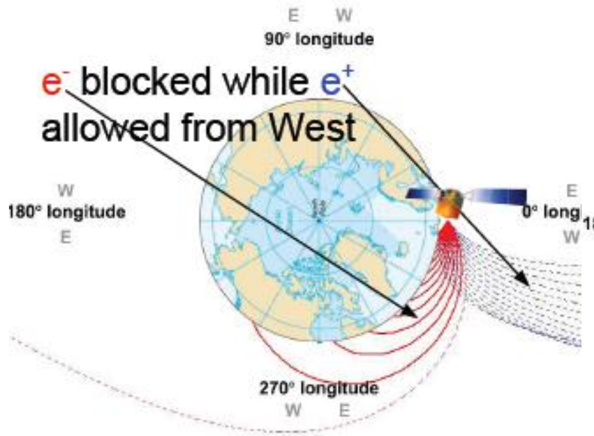
Diffusive propagation of electrons

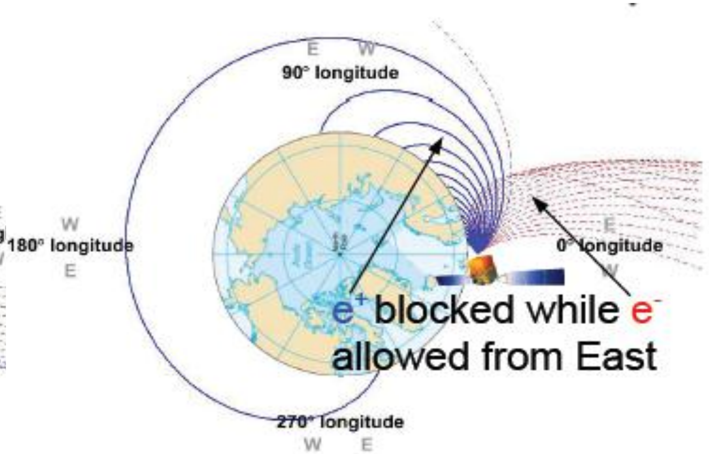
- Since high-energy cosmic ray electrons (CRE) above 10 GeV lose their energy mainly via the synchrotron and inverse Compton processes while propagating through the Galaxy, the energy-loss rate is given by $\frac{dE}{dt} = -bE^2$ with $b = \frac{4\sigma c}{3(mc^2)^2}\left(\frac{B^2}{8\pi} + w_{ph}\right)$
  - Here, E is the electron energy, m is the mass of electron, c is the speed of light, B is the magnetic field strength in the Galaxy, w_{ph} is the energy density of interstellar photons, and σ is the cross-section for Compton scattering.
- Typically quoted value of the energy-loss coefficient of b is $b \approx 1.4 \times 10^{-16}$ GeV^{-1} s^{-1}
- CREs lose almost all of their energy E after a time T:
  - $T = 1/bE \approx 2 \times 10^5\ yr/E(TeV)$
- CREs can diffuse over a distance $R=(2DT)^{1/2}$ during the lifetime T
  - $R \approx 1.6\ (0.75)\ kpc$ for $E=100\ GeV\ (1\ TeV)$
- Such high-energy CREs might originate from a highly anisotropic collection of a few nearby sources

Latitude and East-West effect

- We measure cosmic rays after they traversed the magnetic field of the Earth
- An isotropic cosmic ray flux remains isotropic propagating through a magnetic field as long as the phase space is simply connected
  - This is a consequence of Liouville theorem
- In other words, a necessary condition is that all trajectories starting from the point considered on Earth (after reversing the charge of the particle) reach $r=\infty$
- At low energies, this condition may be violated, because trajectories can be deflected back to the Earth or trapped within a finite distance r
- In this case, the magnetic field does induce anisotropies in the observed flux







Latitude and East-West effect (cont'd)

- Consider a particle of charge Ze with orbit in the equatorial plane of a dipole with magnetic moment M
- Equating the centrifugal and the Lorentz force gives $Ze\left|\vec{v}\times\vec{B}\right| = \frac{mv^2}{r}$, with $B = \frac{\mu_0}{4\pi}\frac{M}{r^3}$
- The radius of the orbit is $r = \sqrt{\frac{\mu_0}{4\pi}\frac{ZeM}{p}}$
- Setting r = $R_\oplus$ and using M = 8 × 10^{22} Am as magnetic moment of the Earth, it follows $\frac{p}{Z} = \frac{\mu_0}{4\pi}\frac{eM}{R_\oplus^2} \approx 60\ GeV$
- This is the minimal momentum of a proton (electron) able to reach the Earth from the East (West), if its orbit is exactly in the (magnetic) equatorial plane.
- Towards the poles, the influence of the dipole field becomes weaker $\left|\vec{v}\times\vec{B}\right|$, and the cutoff momentum becomes thus smaller. Thus the integrated cosmic ray intensity increases with latitude for charged particles ("latitude effect").

Astronomical coordinate systems

- Spherical Coordinates:
  - A direction in three dimensional space, such as the arrival direction of a cosmic ray particle at the location of an experiment, is mathematically represented by a three dimensional unit vector.
  - The vector connects from the origin of the coordinate system to a point on the sphere of unit radius.
  - The fixed vector length eliminates one degree of freedom.
  - The remaining two degrees of freedom are usually specified by means of two angles.
- Since the problem of describing a location on the unit sphere matches the problem of describing a geographical location on Earth, it is practical to adopt the geographical terminology.
  - The x-y-plane and the z-axis of the coordinate system are called the equatorial plane and the polar axis, respectively.
  - The afore mentioned angles can be chosen to correspond to latitude and longitude.
  - The latitude is defined as the angle between a given unit vector and its projection onto the equatorial plane.
  - The longitude indicates the angle between that projection and the positive x-axis.
  - As a consequence of this definition, latitude values are contained in the range between $-\pi/2$ and $\pi/2$, whereas longitude values range between 0 and 2π.

The Celestial Sphere

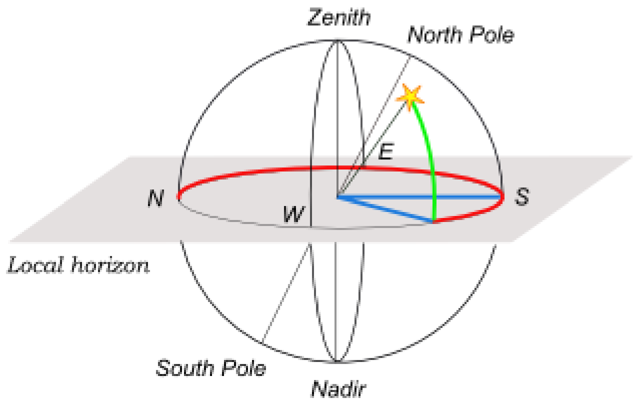
- When observing astronomical objects like stars or galaxies, there is no apparent way to measure their distance from Earth.
- From this fact evolved the concept of the celestial sphere.
  - The celestial sphere is an imaginary sphere of infinite radius, with the Earth at its center
- All astronomical objects are thought to lie on this imaginary sphere.
  - From this point of view, the distances of those objects are not taken into account anymore, but only the directions from which they are observed.
- A coordinate system on the celestial sphere must be defined. Such reference frame can be defined in several ways
  - Some are bound to an observer on Earth, providing constant coordinates for fixed viewing directions.
  - Others are bound to the sky and maintain constant coordinates for the fix stars.
- Because of the celestial sphere's arbitrary large radius, not only the Earth but the whole solar system virtually concentrates in a single point in the center of the sphere
  - This obviously only holds true for the observation of remote astronomical objects, for which the approximation of infinite distances is valid.
  - However, for close-by objects such as the Sun, the Moon and the planets of our solar system, the situation is much more complicated and the parallax effects should be taken into account

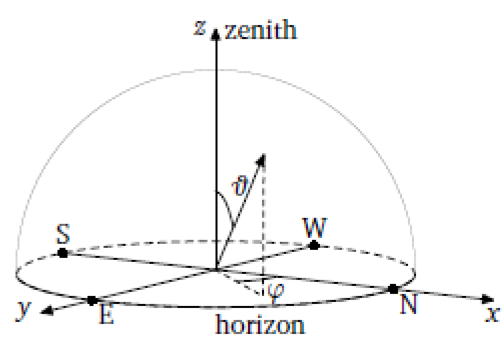
Coordinate systems

- Horizontal coordinate system
- Equatorial coordinate system
  - based on Earth rotation
- Ecliptic coordinate system
  - based on Solar System rotation
- Galactic coordinate system
  - based on Milky Way rotation
- Supergalactic coordinate system
  - based on plane of local supercluster of galaxies

Horizontal Coordinates

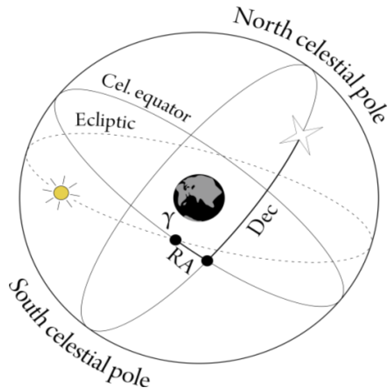
- The horizontal coordinate system relates points on the celestial sphere with viewing directions for an observer on Earth.
- The horizontal coordinates of a specific astronomical object therefore depend on the location of the observer, as well as on the time of the observation.
- The local horizon, i.e. a tangential plane touching Earth at the place of the observer, corresponds to the equatorial plane of this spherical coordinate system.
- In ground cosmic ray experiments, horizontal coordinates are the natural choice for specifying arrival directions of cosmic rays, as reconstructed from experimental data.





Equatorial coordinate system

- The equatorial coordinate system aims to eliminate the dependence on the observer's time and location when describing a point on the celestial sphere.
- The celestial equatorial plane, is the projection of the Earth's equatorial plane onto the celestial sphere.
- The celestial North and South poles are the intersections of the celestial sphere with the prolongation of the Earth's polar axis.
- As for all spherical coordinate systems, the definition of an equatorial plane alone yields the latitude-like coordinate, the declination δ.
- The longitude-like component of the equatorial coordinates is called the right ascension α. It measures the angle of an object east of the apparent location of the center of the Sun at the time t of the March equinox, a position known as the vernal equinox point or the first point of Aries

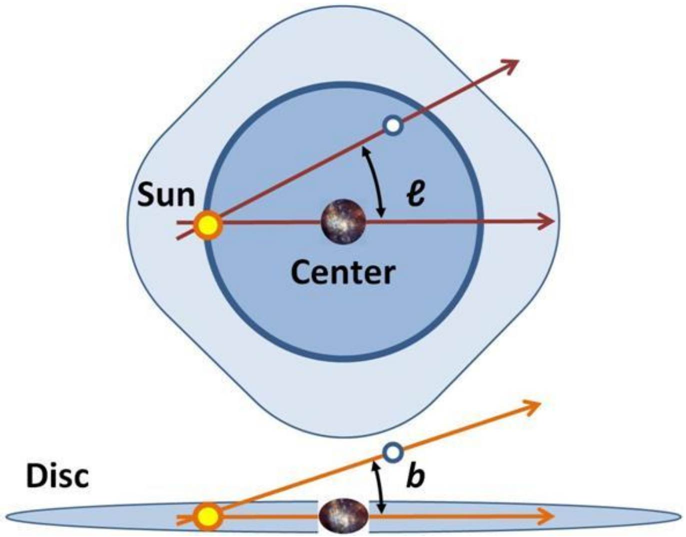


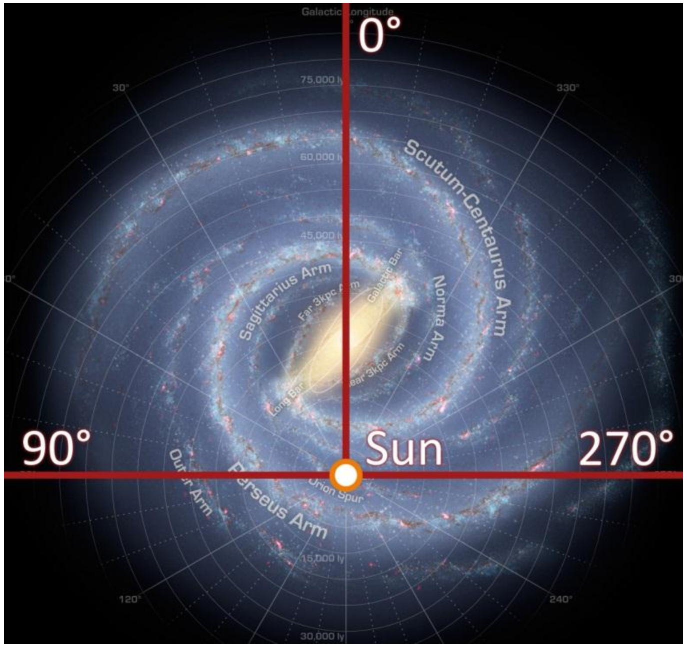
Sidereal Time and Hour-Angle

- Sidereal time is kept with respect to the position of distant stars: a star is observed to return in the same position in the sky after exactly 24 sidereal hours have elapsed
  - Each sidereal day is slightly shorter than the solar day: 24 hours of sidereal time corresponding to 23h 56m of solar time
- The Greenwich sidereal time (GST) is the sidereal time measured on the Greenwich meridian (longitude 0°).
- Local sidereal time (LST) is the sidereal time measured on a given meridian
  - Longitudes West give LST earlier than GST and longitudes East later
- Right ascension may be converted into hour-angle, $H = LST-\alpha$, where LST is the Local Sidereal Time
- One sidereal hour later (approximately 0.997269583 solar hours later), the Earth's rotation will make that star appear to the west of the meridian, and that star's hour angle will be +1 sidereal hour.

Galactic coordinate system

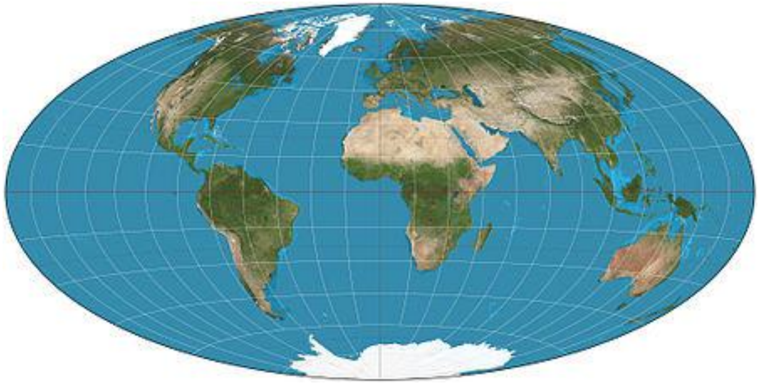
- The galactic coordinate system uses the projection of the plane of our Galaxy onto the celestial sphere as its equatorial plane.
- Thus, points on the galactic plane have a galactic latitude b=0◦, with the galactic center at a galactic longitude l=0◦.





Map projection

- A map projection is any method of representing the surface of a sphere or other three-dimensional bodis on a plane.
- Map projections are necessary for creating maps
  - All map projections distort the surface
- Equal-area map projections:
  - Aitoff
  - Hammer
  - Mollweide



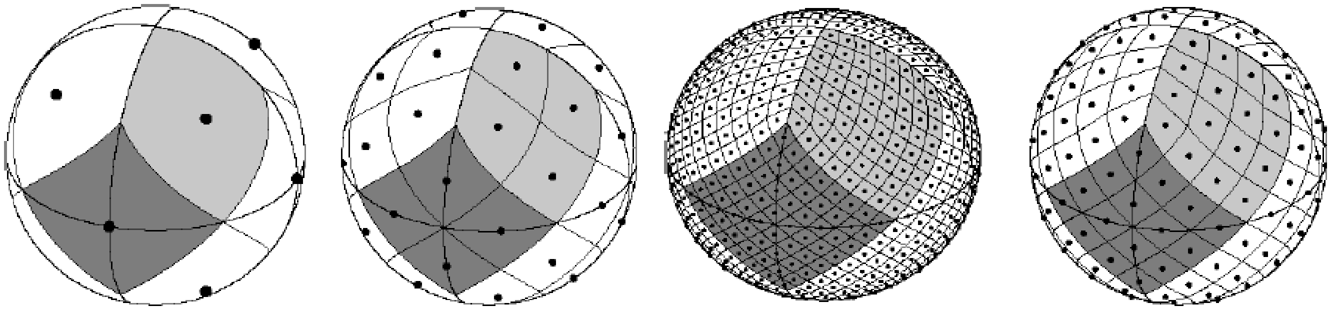
Hammer

Aitoff

Mollweide

HEALPix map

- HEALPix - Hierarchical Equal Area iso-Latitude Pixelization is a versatile data structure with an associated library of computational algorithms and visualization software that supports fast scientific applications executable on large area surveys in the form of discretized spherical maps http://healpix.jpl.nasa.gov/
- Originally developed to address the data processing and analysis needs of the present generation of cosmic microwave background (CMB)
- HEALPix is a partition of the sphere into exactly equal area quadrilaterals of varying shape. The base-resolution comprises twelve pixels in three rings around the poles and equator.
- The resolution of the grid is expressed by the parameter N_{side} which defines the number of divisions along the side of a base-resolution pixel that is needed to reach a desired high-resolution partition
  - The total number of pixels is $N_{pix} = 12\ N_{side}^2$



N_{side} = 1, 2, 4 and 8

Compton-Getting effect

- Compton and Getting first discussed that a relative motion of observer and cosmic ray sources results in an anisotropic cosmic ray flux
- CRs of greater intensity arriving from the direction of motion and those of less intensity arriving from the opposite direction
- The dipole anisotropy due to the Compton-Getting effect has the amplitude

$$\delta_{CG} = \frac{I_{max}-I_{min}}{I_{max}+I_{min}} = \left(2 - \frac{d \ln I}{d \ln E}\right)\frac{u}{c} = (2+\alpha)\frac{u}{c}$$

since $I(E) \sim E^{-\alpha}$

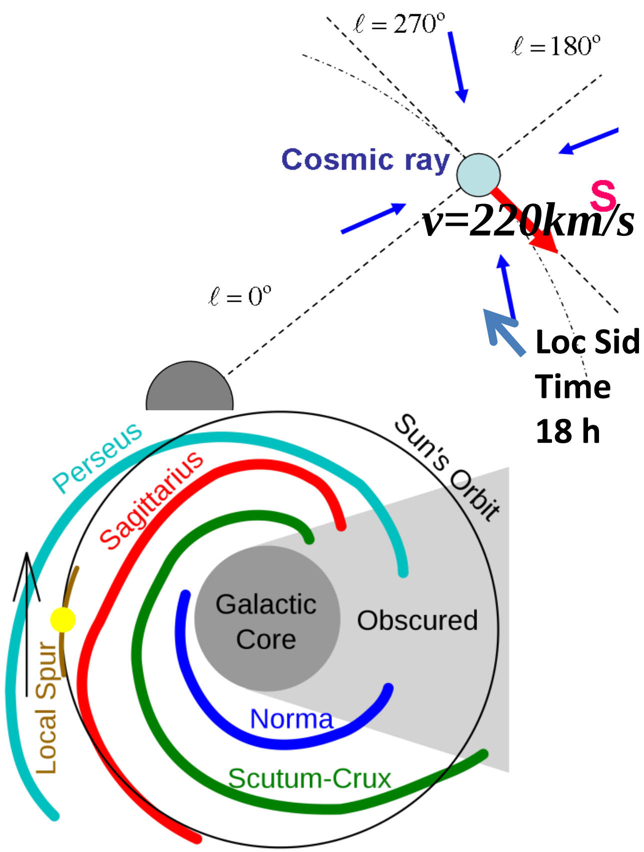
Solar motion around the Galactic center:

Local Sidereal time anisotropy

Differential energy spectrum of CR $\propto E^{-\alpha}$

$$\frac{\Delta Intesity\ (\psi)}{< Intesity >} = \frac{\Delta Rate\ (\psi)}{< Rate >} \propto (2+\alpha)\frac{v}{c}\cos(\psi) \propto 10^{-4}\cos(\psi)$$

ψ is the angle with respect to the direction of motion



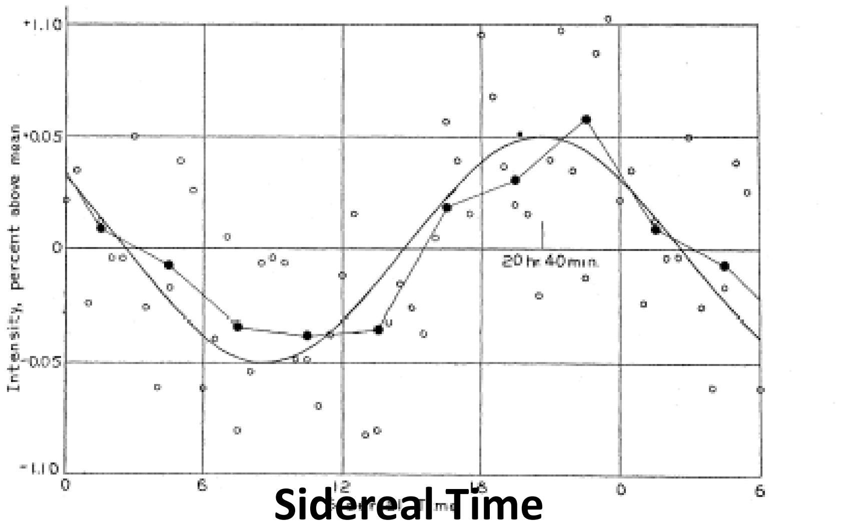
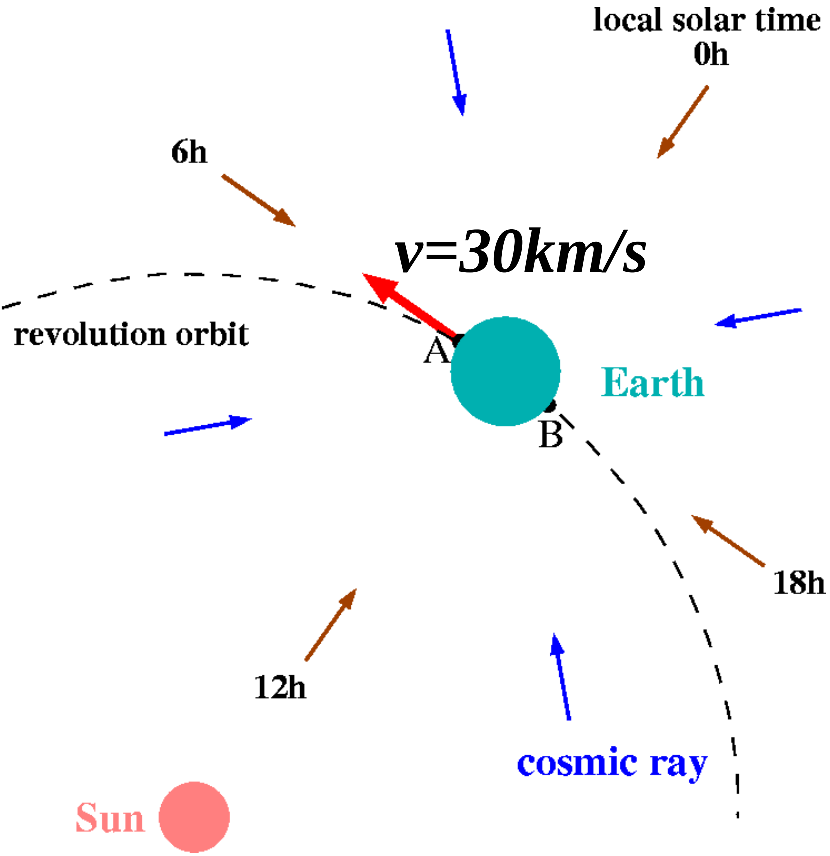


FIG. 2. Percentage variation in intensity of the cosmic rays with sidereal time. Curve, predicted effect due to galactic rotation. Data, Hess and Steinmaurer; open circles, half-hour means; solid circle, 3-hour means.

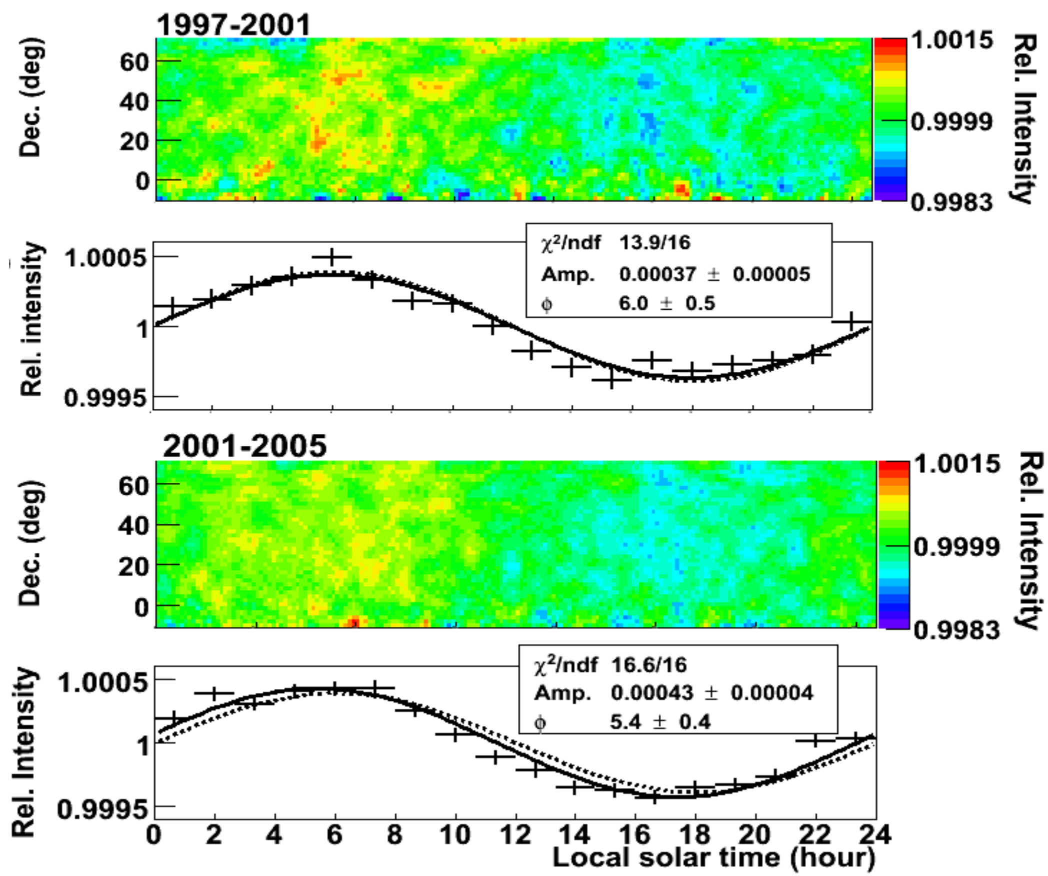
Terrestrial orbital motion around the Sun

Local Solar time anisotropy



Tibet measurement in solar time

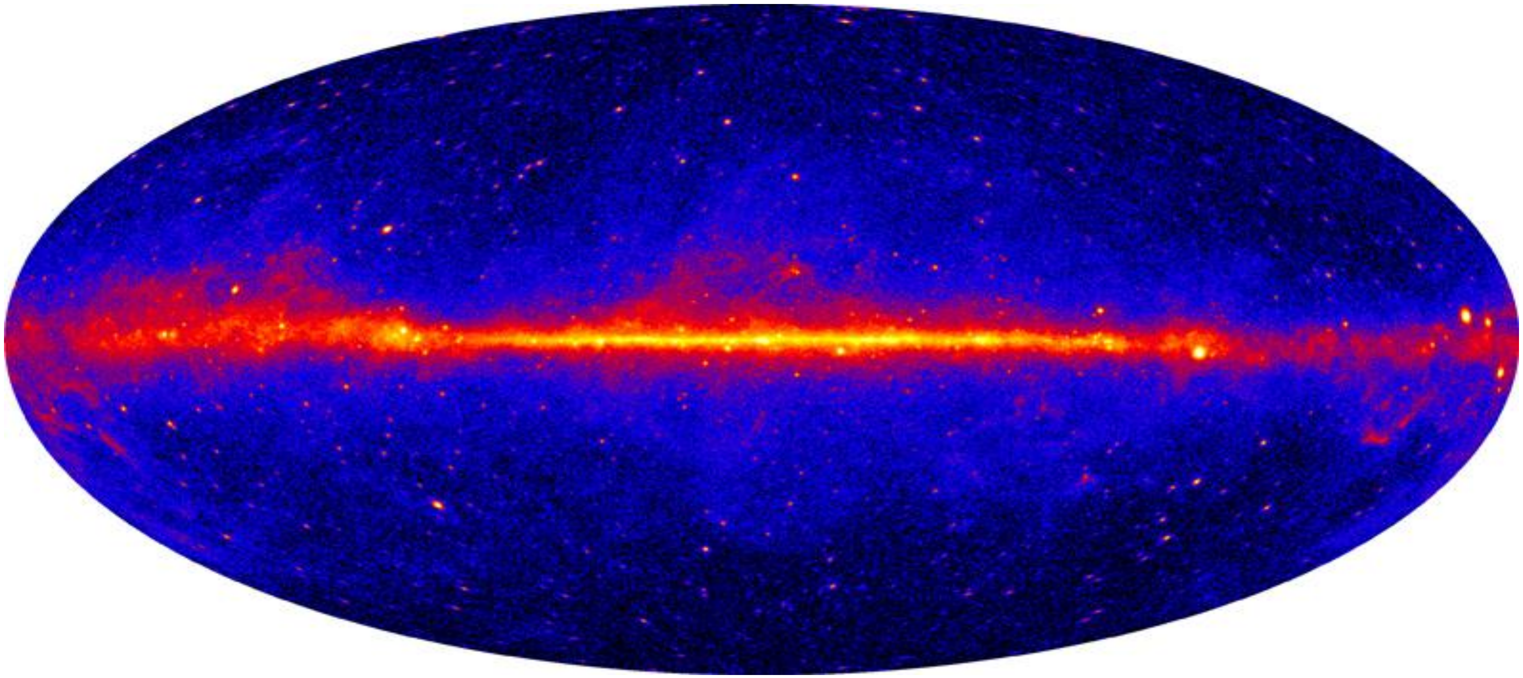
M. Amenomori, et al. Science 314, 439 (2006)



Search for radiation anisotropies

- Cosmic microwave background (CMB) radiation
- Gamma ray
- …
- Same tools and methodologies

Gamma-ray anisotropy searches

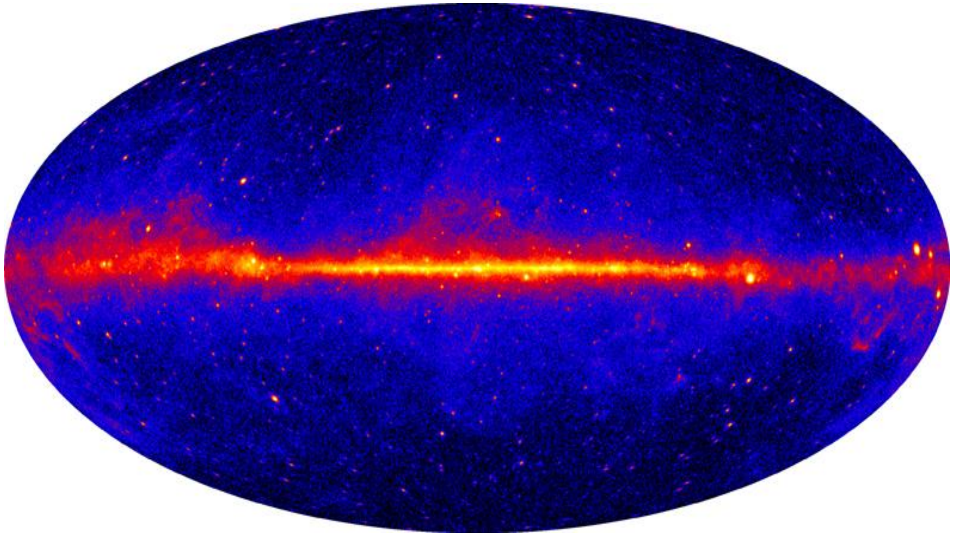


Credit: NASA/DOE/International LAT Team

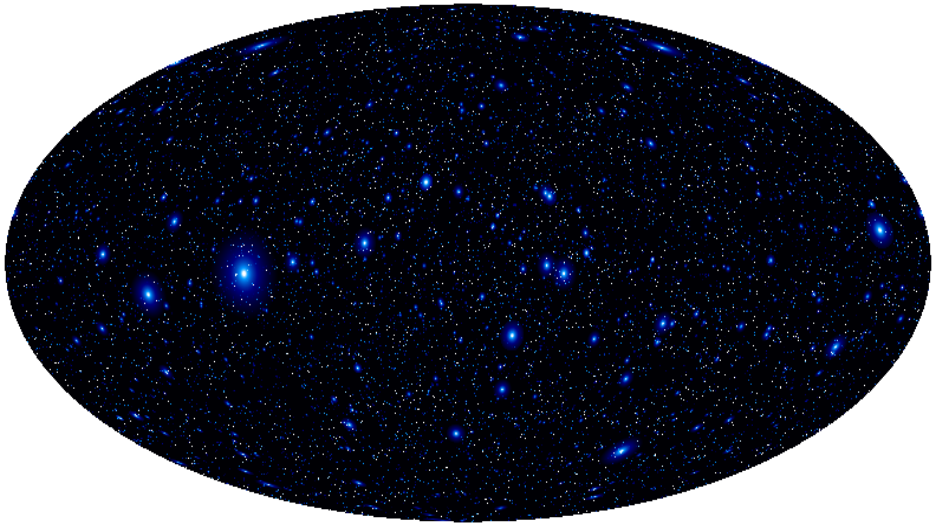
- This all-sky view from Fermi reveals bright emission in the plane of the Milky Way (center), bright pulsars and super-massive black holes, i.e. the gamma-ray sky is not isotropic!
- Possible anisotropies in the diffuse gamma-ray background could due to the contribution of unresolved sources (blazar, dark matter, ecc.)

Detecting unresolved sources with anisotropies

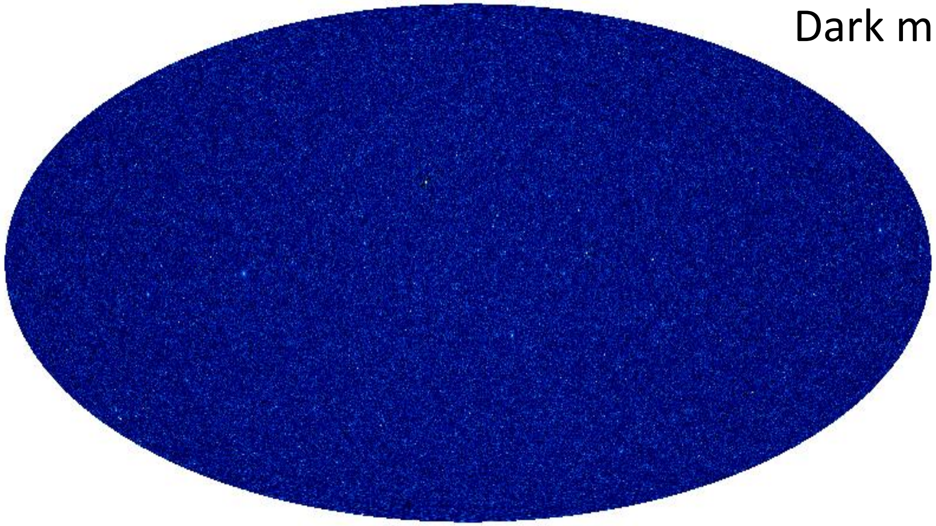
Bright Sources + diffuse +…



Faint Sources



Dark matter?

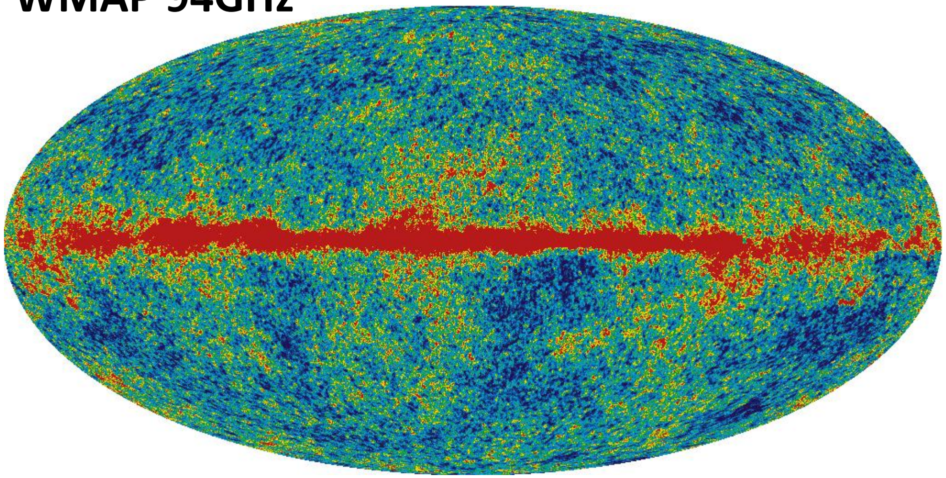


Isotropic gamma-ray background (IGRB)

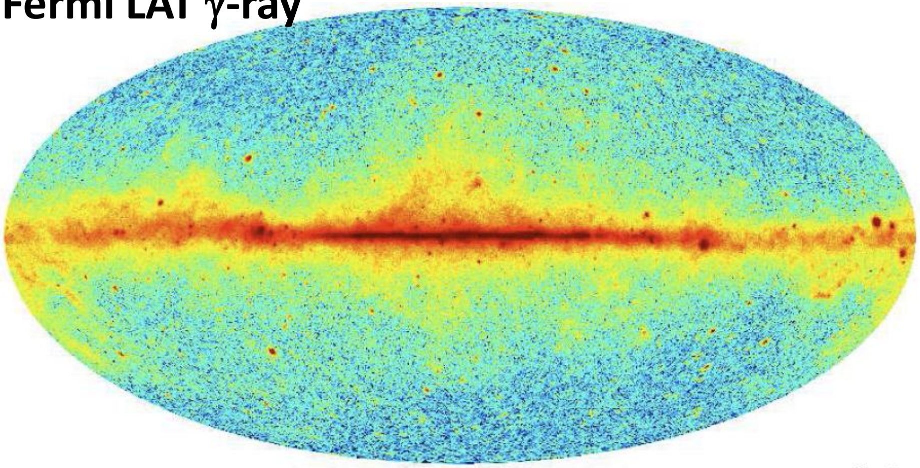
- IGRB is used to refer to the observed diffuse gamma-ray emission which appears isotropic on large angular scales but may contain anisotropies on small angular scales.
- The IGRB describes the collective emission of unresolved members of extragalactic source classes and Galactic source classes that contribute to the observed emission at high latitudes, and gamma-ray photons resulting from the interactions of ultra-high energy cosmic rays with intergalactic photon fields
- The IGRB contains angular information in the form of fluctuations on small angular scales
  - The statistical properties of these small-scale anisotropies may be used to infer the presence of emission from unresolved source populations.
  - If some component of the IGRB emission originates from an unresolved source population, rather than from a perfectly isotropic, smooth source distribution, the diffuse emission will contain fluctuations on small angular scales due to the varying number density of sources in different sky directions.

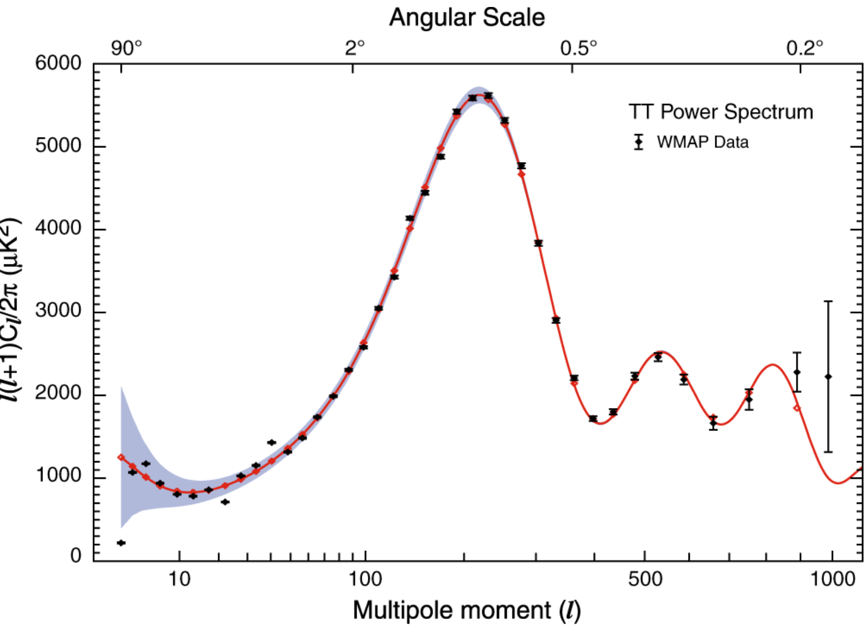
Using Fermi Data, just like WMAP

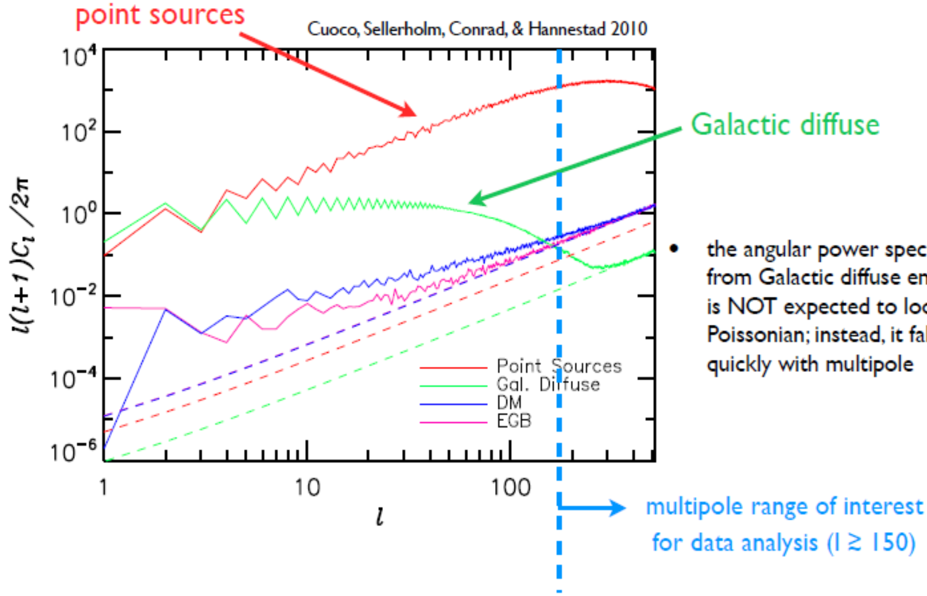
WMAP 94GHz



Fermi LAT γ-ray







- the angular power spectrum from Galactic diffuse emission is NOT expected to look Poissonian; instead, it falls off quickly with multipole