UltraHigh Energy Cosmic Rays (UHECRs): un modelo multi-componente: Radiogalaxias, Magnetars, y algo más?

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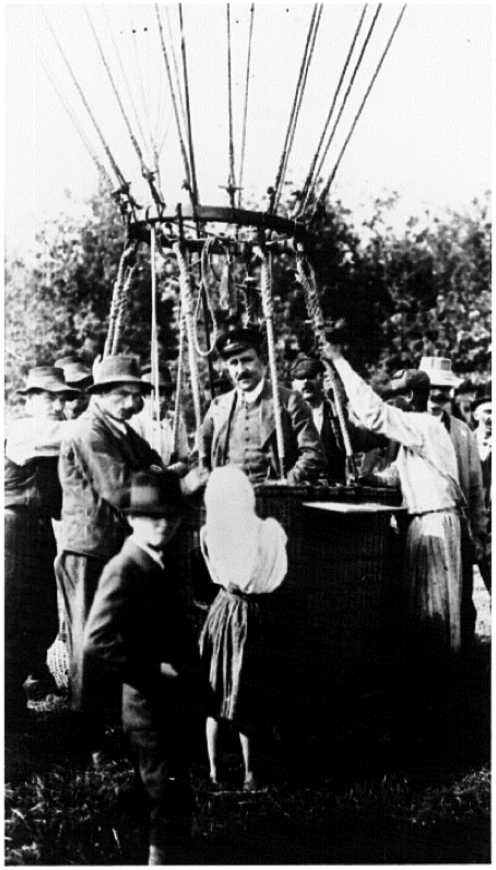
Nagar & Matulich 2008, A&A, 488, 879
Nagar & Matulich, in prep.

Fondos: ALMA, FONDAP, BASAL, Fondecyt

selected graphs and images from the Pierre Auger Collaboration, Kachelriess, and others

The Beginning

PIERRE AUGER OBSERVATORY



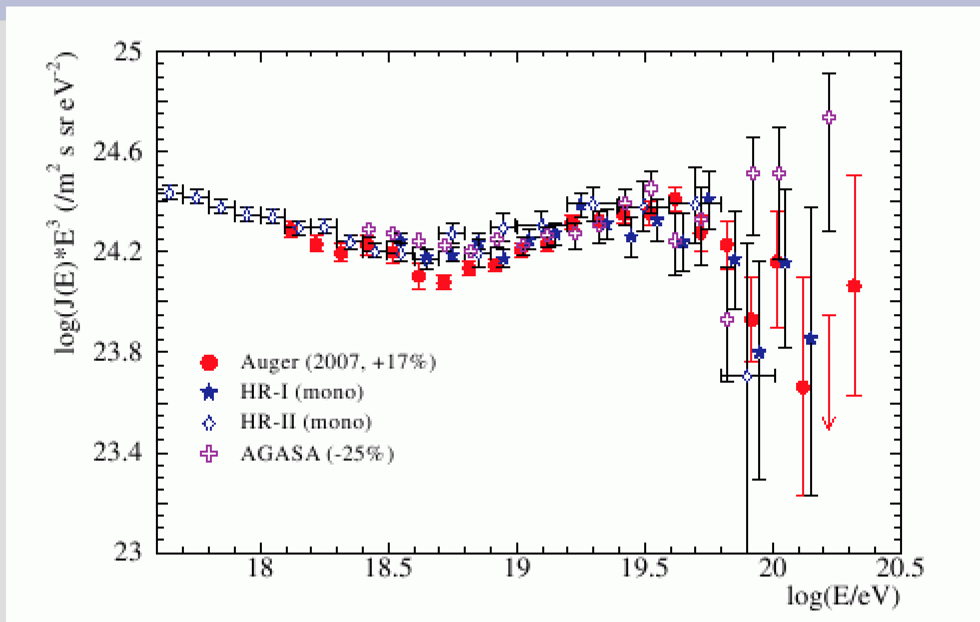
Ever since Victor Hess discovered cosmic rays in 1912, a primary question has been ***"Where do they come from?".*** *After more than 80 years of research this question remains largely unanswered. The origin of the highest energy cosmic rays remains one of the great unsolved mysteries of physics.*

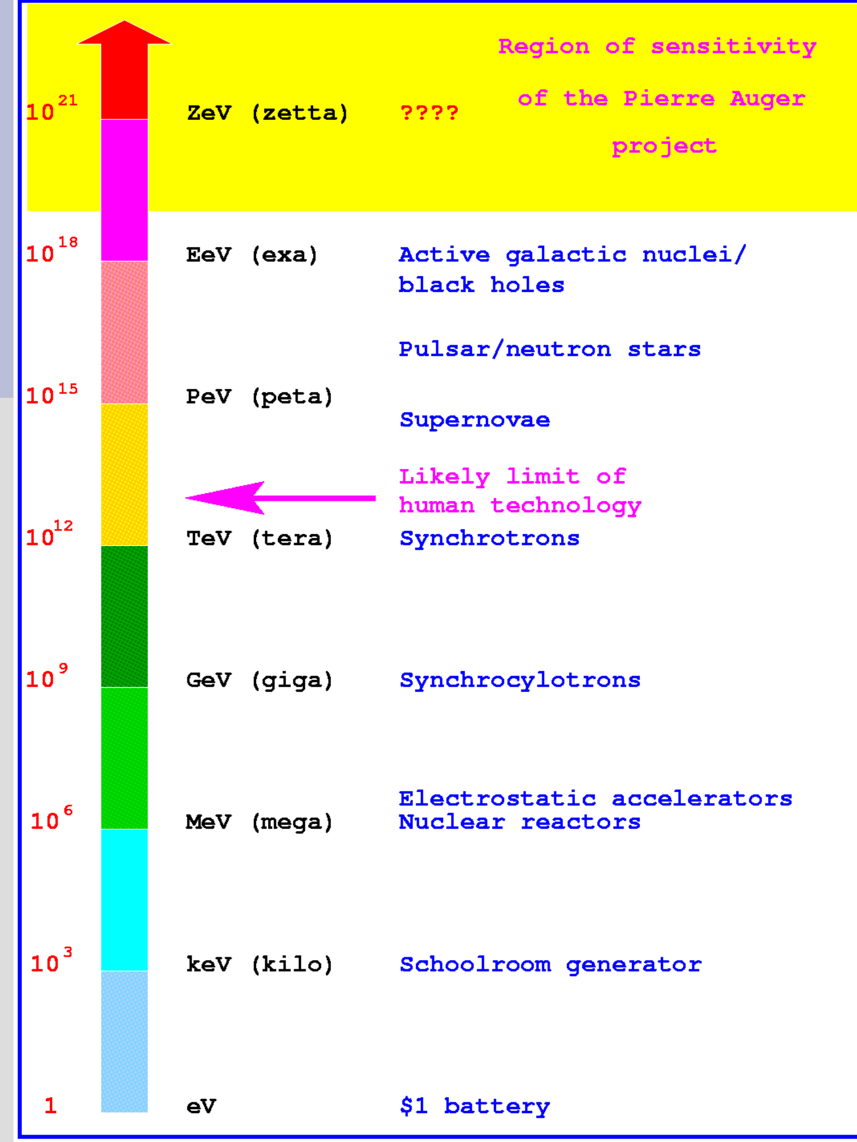
2/18/98

Introducción

- Rayos Cósmicos: definición
- La Vida Secreta de los Rayos Cósmicos
  - Producción, Transportación, Detección
- El Observatorio Pierre Auger
- Resultados recientes sobre la origen de rayos cósmicos
  - Galaxias activas (emission-line or X-ray selected)
  - Radiogalaxias extendidas
  - Magnetars
- Agregando Campos Magenticos: Galáctica y Extragaláctica
  - Deflecciónes y re-analisis
- Resumen y Futuro

"Rayos" Cósmicos (UHECRs)





- protones o núcleos livianos relativistas
    - núcleos mas pesados solo para energias menores
- Energía del partícula > 10 EeV (10^{19} eV)
- Energía más alta detectada: 300 EeV (50 Joules!)

Rayos Cósmicos: Historia

Hess: didn't have a graduate student?

- **1912: R. C. descubierto por Victor Hess**
- **1927:** R. C. detectado in "cloud chamber"
- **1932:** descubrimiento de antimateria por Anderson
- **1937:** descubrimiento del muon (cloud chamber)
- **1938:** descubrimento de cascadas de partículas (Auger; Alps)
- **1949:** teoría de Fermi por aceleración de R.C.
- **1962:** primera detección de un R.C. con energía 100EeV
- **1966:** teoría del "GZK" cutoff
- **1967:** Haverah Park, **1991** Flys Eye, **1994** Agasa, **1995** Auger
- **2007/8:** una solución general?

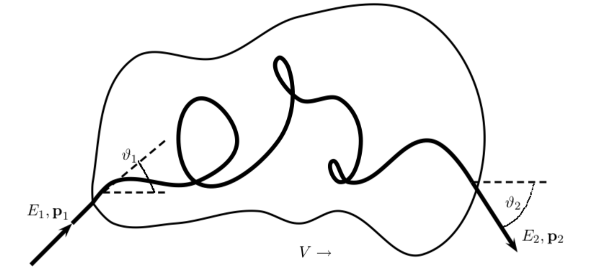
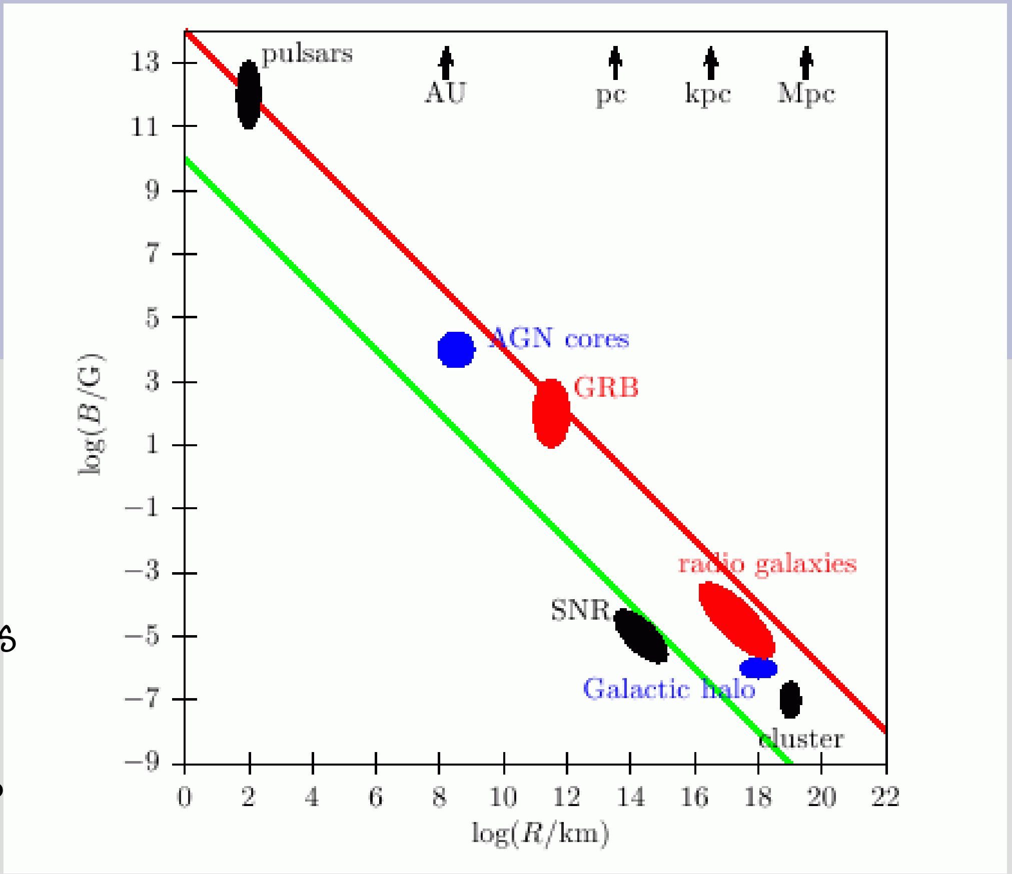


Figure 4.3: A cosmic ray "scattering" elastically at a magnetic cloud moving with velocity V.

Hillas plot
red: 10^{21} eV
green: 10^{20} eV



UHECR: Producción

- Aceleración en choques en plasmas extendidos
  - Radiogalaxias (lobes; Biermann)
  - Choques de acreción en cúmulos de galaxias
  - Choques en galaxias colisionando
- Aceleración en frente de choques (bouncing)
- Aceleración en campos magnéticos fuertes
  - (AGN: chorro/disco; Pulsares y Magnetars: magnetosfera)
- Aniquilación de materia oscura? Evaporación de agujeros negros?
- SNRs and Gamma Ray Bursts (K.E., decay products)
- We see the few lucky "social climber" protons

Ultra High Energy Cosmic Rays: observed spectrum

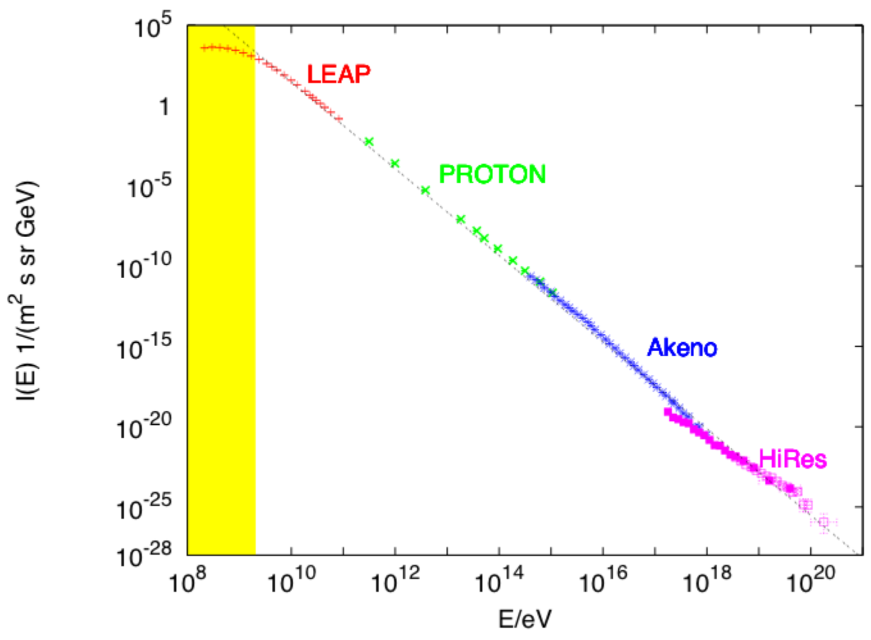
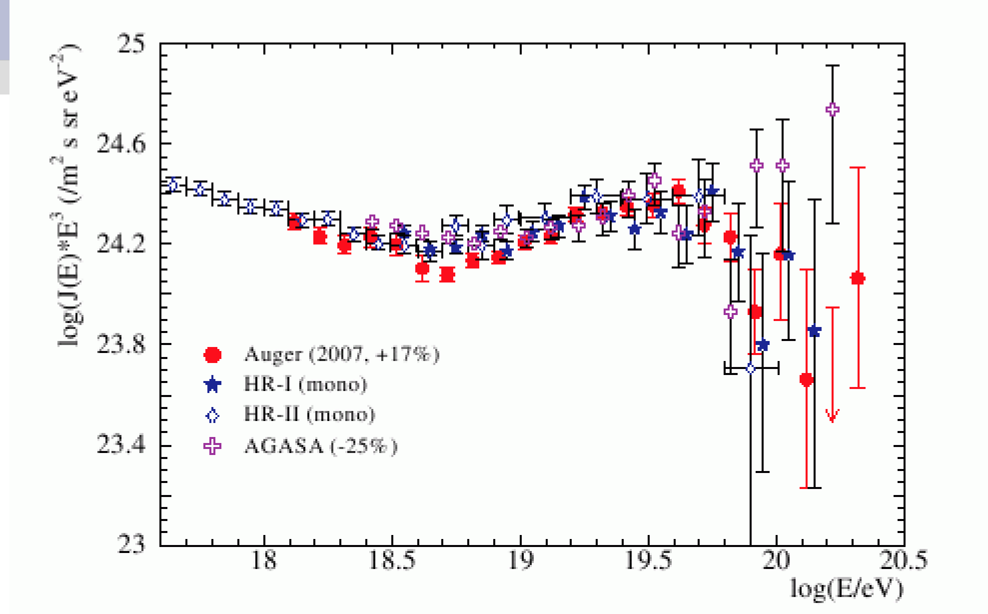
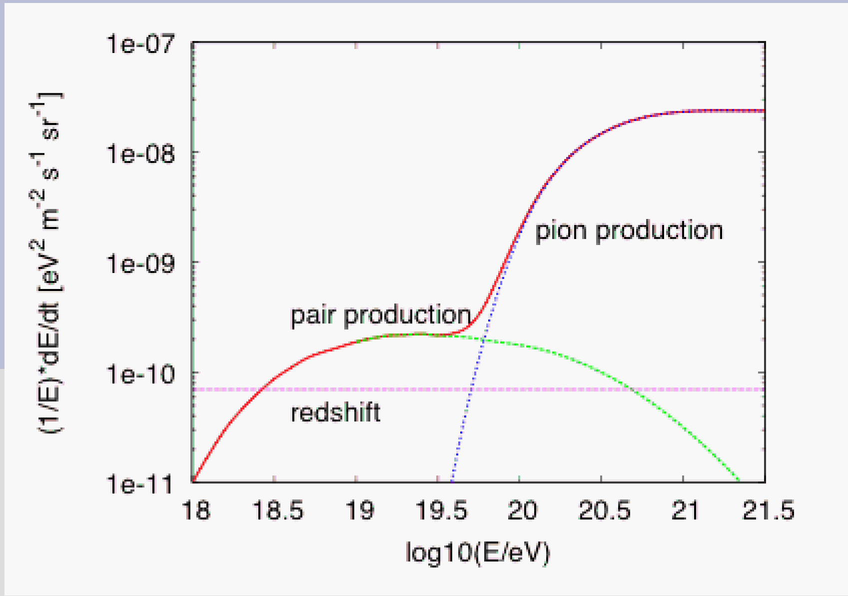


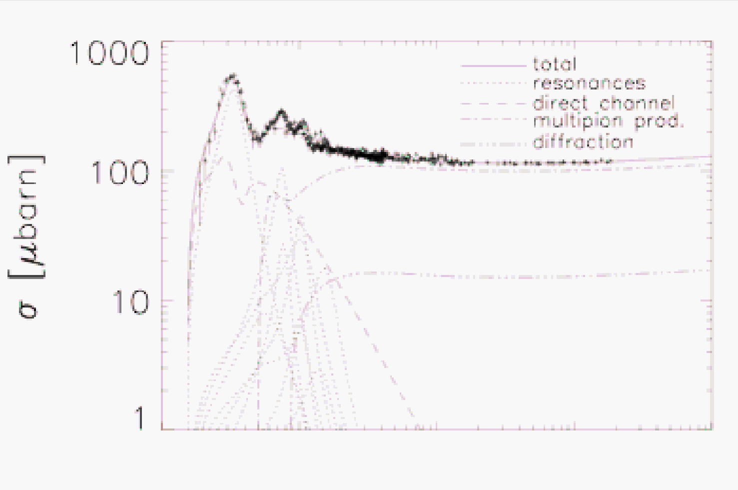
Figure 1.1: The cosmic ray spectrum $I(E)$ as function of kinetic energy E, compiled using results from the LEAP, proton, Akeno, and HiRes experiments [1]. The energy region influenced by the Sun is marked yellow and an $1/E^{2.7}$ power-law is also shown.



Cosmic Ray: Transportación



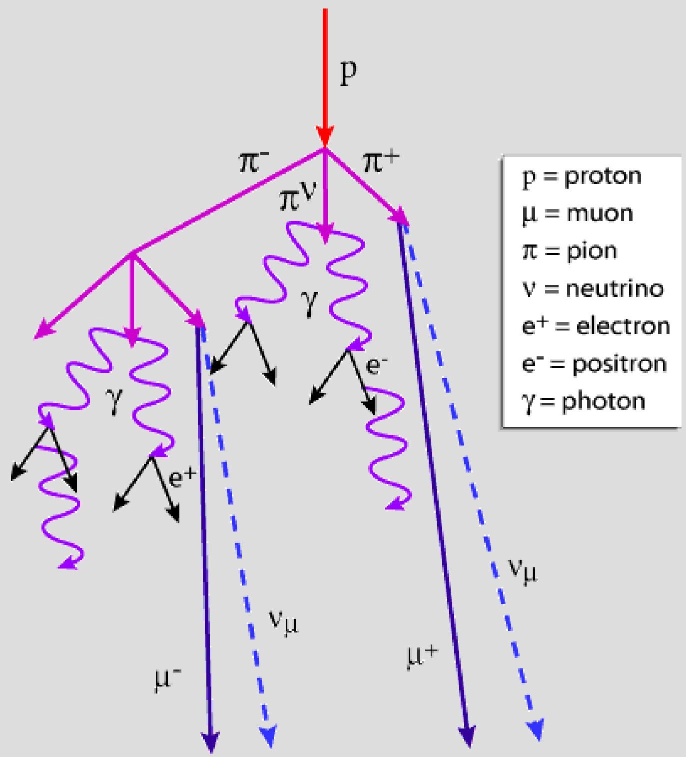
- Dos puntos importantes
  - Gyration alrededor de campos magnéticos
    - Pero campos magnéticos desconocidos
  - El efecto Greisen-Zatsepin-Kuzmin (GZK)
    - Interacción con fotones del CMB -> pion-production
      - UHECR: 30% ? energía perdida
      - UHECR: mean free path: 20 to 200 Mpc?

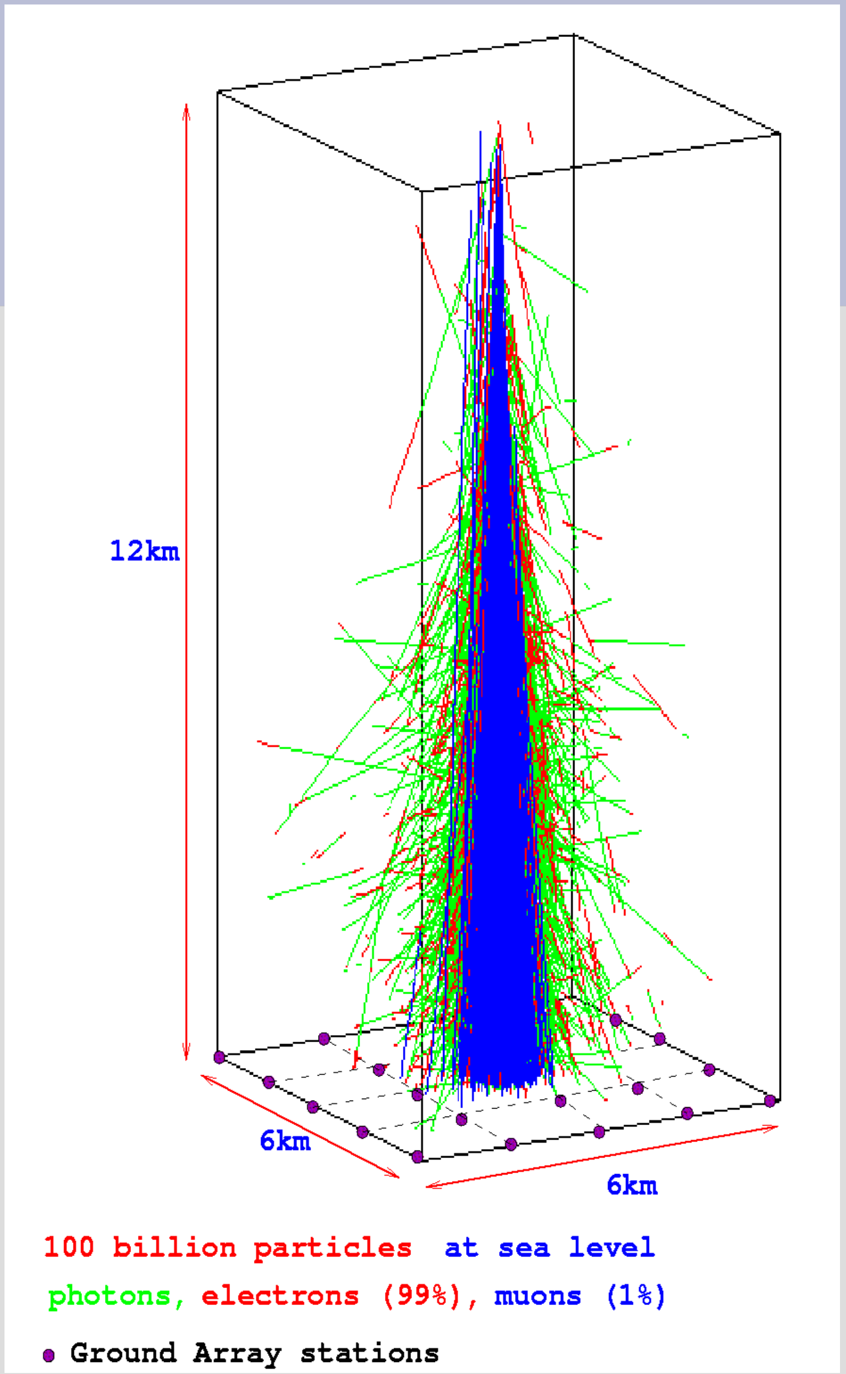


-
- Entonces:
  - Se "ve" solo el universo local (< 200 Mpc?)
  - Con un ángulo de offset (algunos grados para 100EeV?)
    - Astronomía posible solo para E > 50 EeV
  - Y un retraso en tiempo (10^2 años cada Mpc o más?)

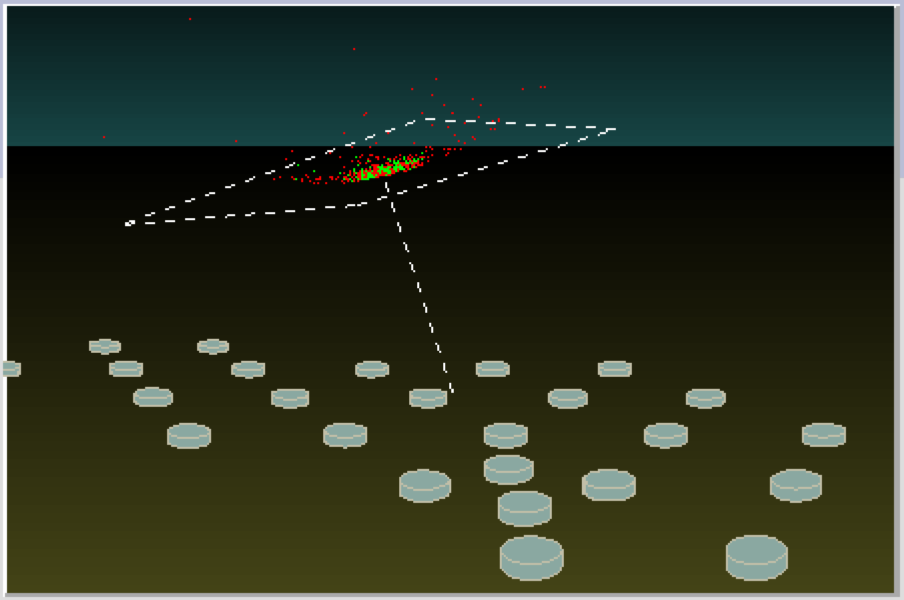
Rayos Cósmicos: Detección

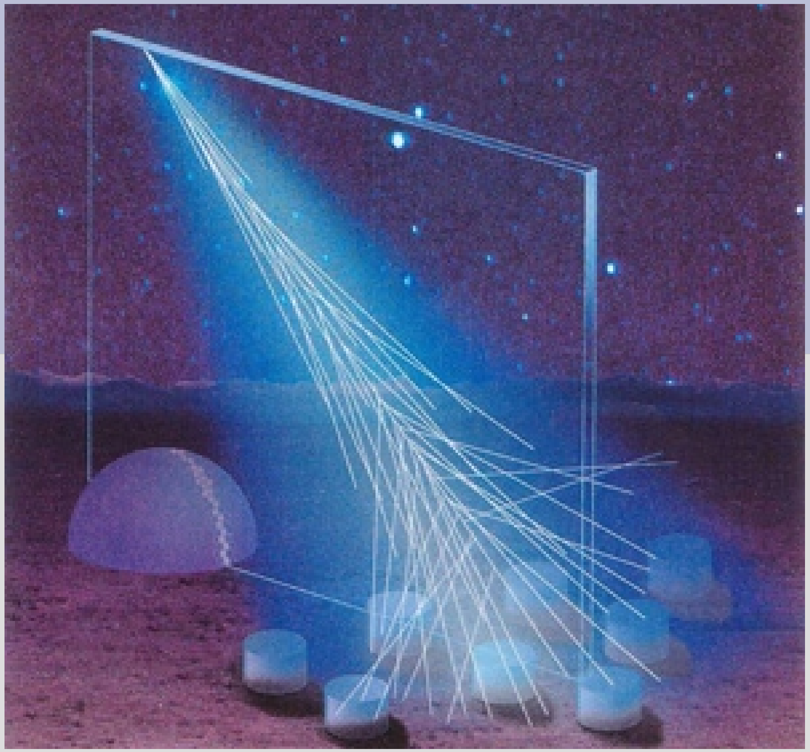
- Cuando un UHECR entra a la atmósfera:
  - colisiones, descomposición
  - crean "duchas" de partículas secundarias y fotones





Rayos Cósmicos: Detección

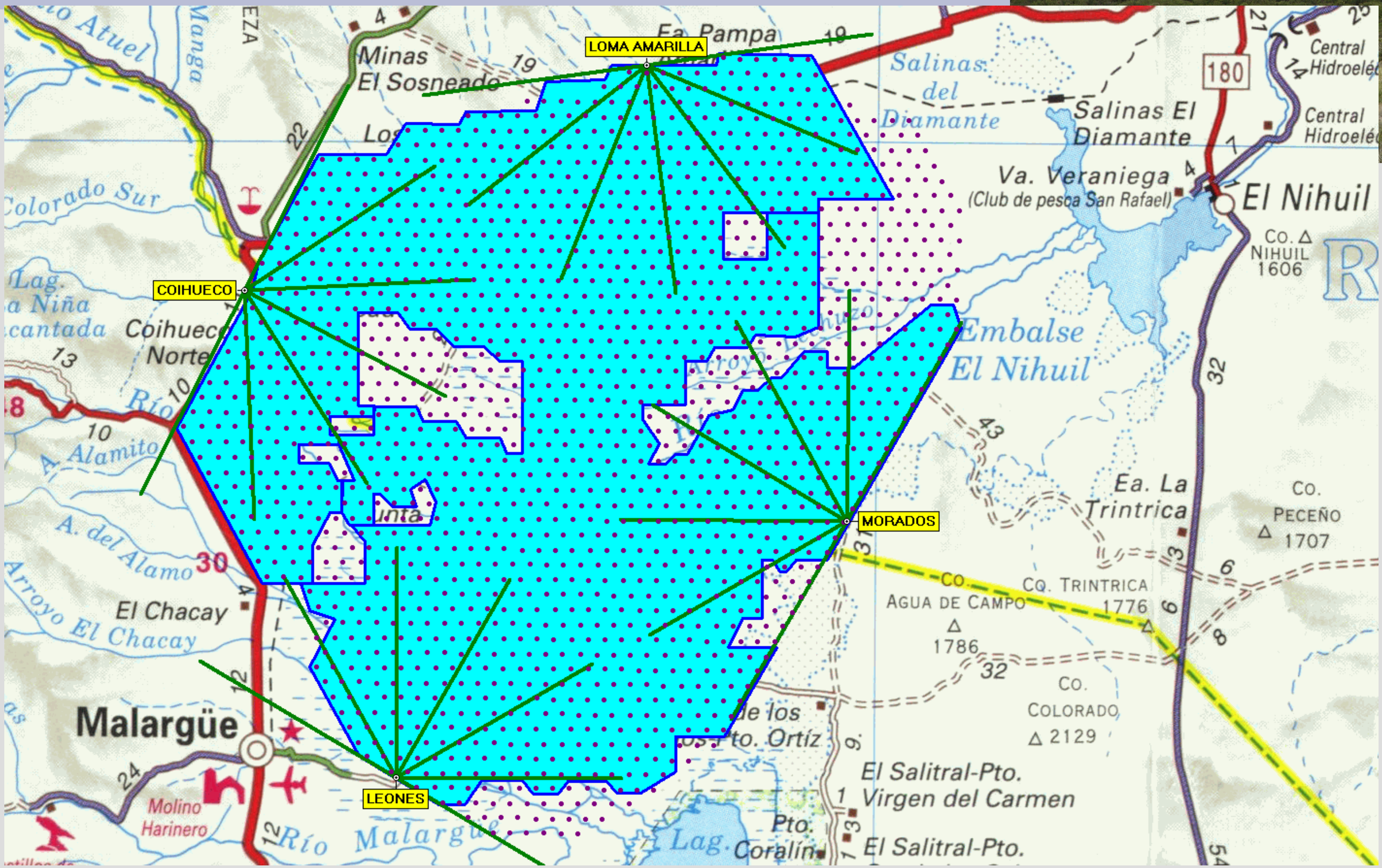




- Puede detectar la "ducha" de partículas segundarias vía:
  - Redes de detectores en la superficie de la Tierra
    - Radiación Cerenkov o detectores de partículas
    - Fluorescencia en la atmósfera
- Los observatorios actuales son híbridos ej. Pierre Auger Observatory
  - Dirección del UHECR original: alrededor de 1 grado (?) (Luna = 0.5 grados)
  - Energía del UHECR original : alrededor de 10% (?)

Pierre Auger Observatory (Sur)

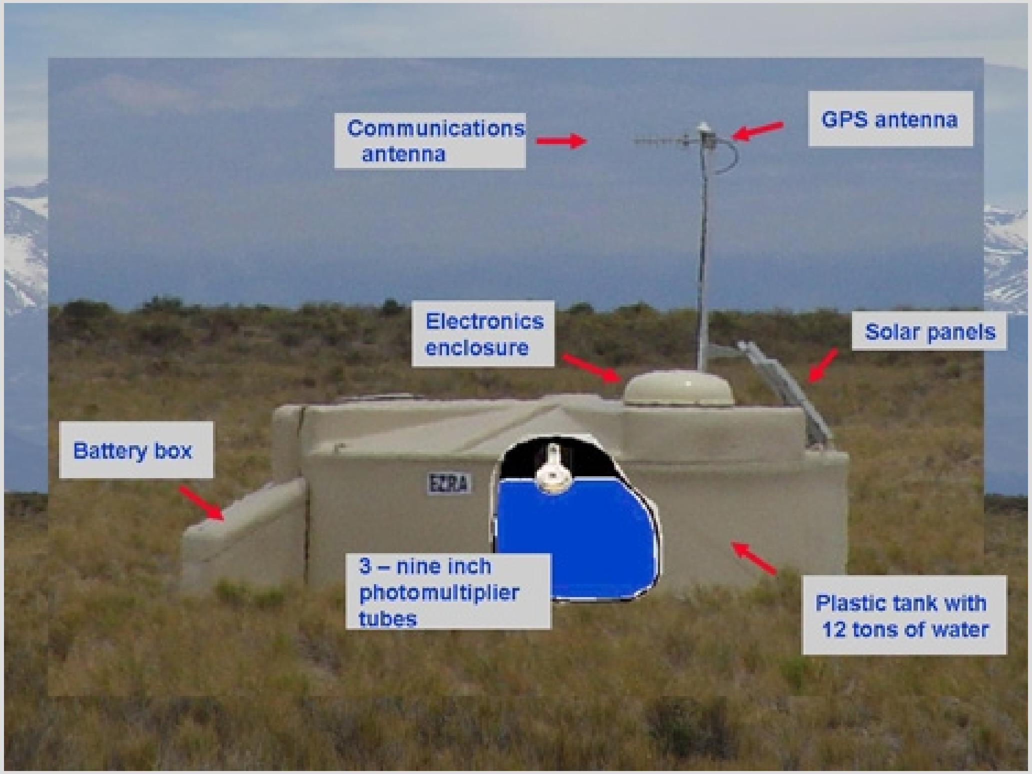
- Argentina: 3000 km^2



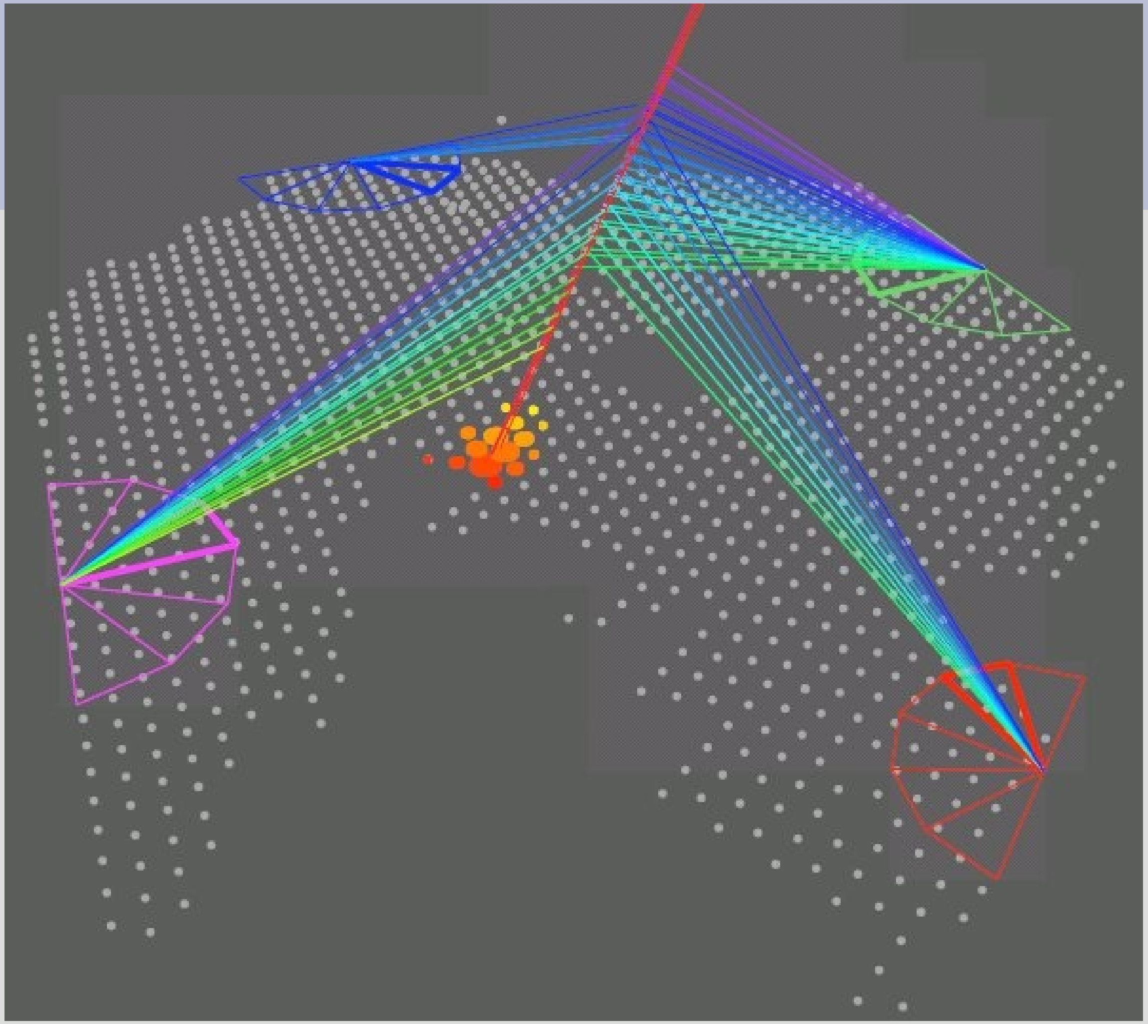
Norte: en construcción en Utah, EE.UU.

Pierre Auger Observatory

detectores Cerenkov

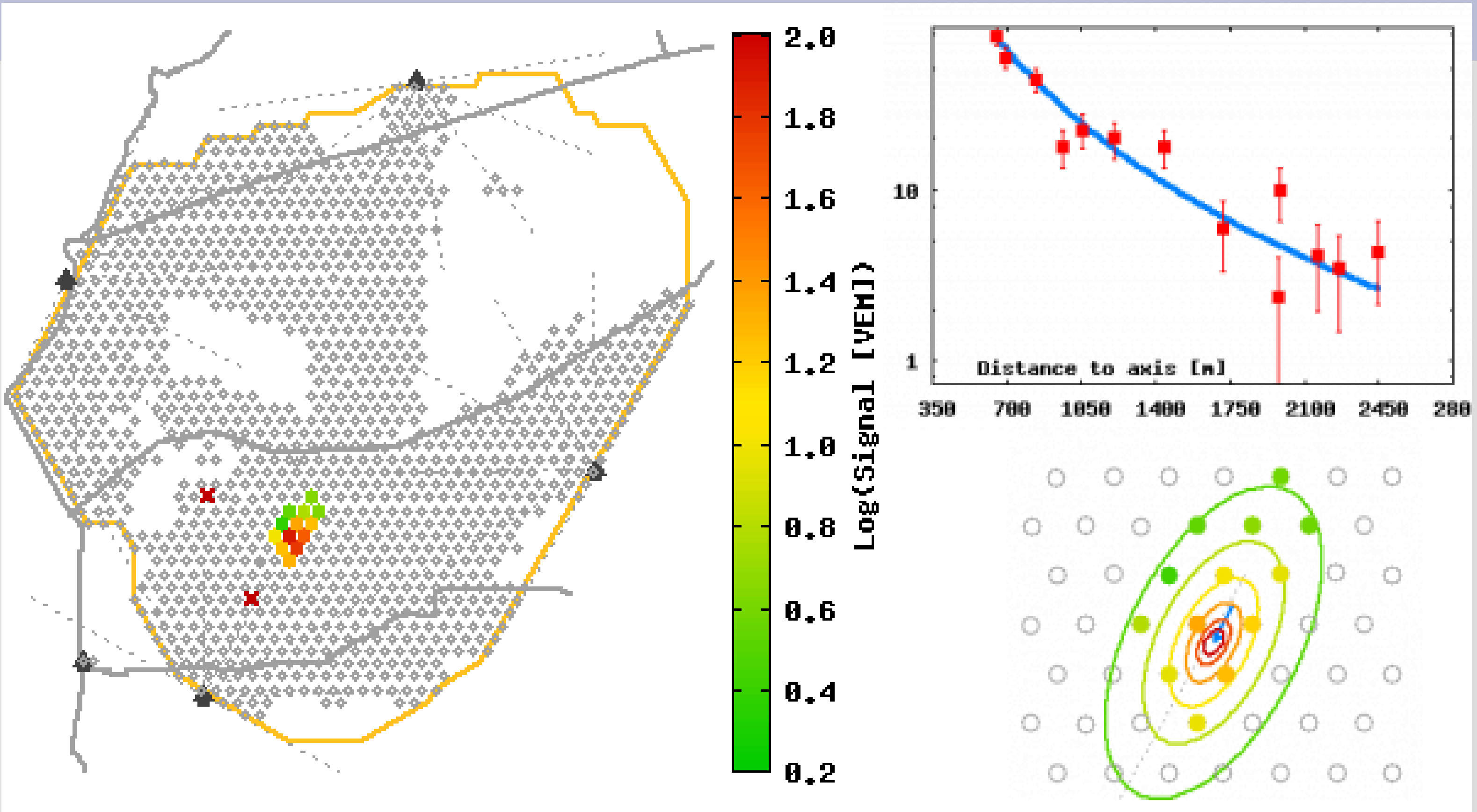


Pierre Auger Observatory



- Hybrid detection
  - Four "fly's eye" telescopes
  - Triangulate each segment of the shower path
  - Calibrate arrival direction and energy of UHECR

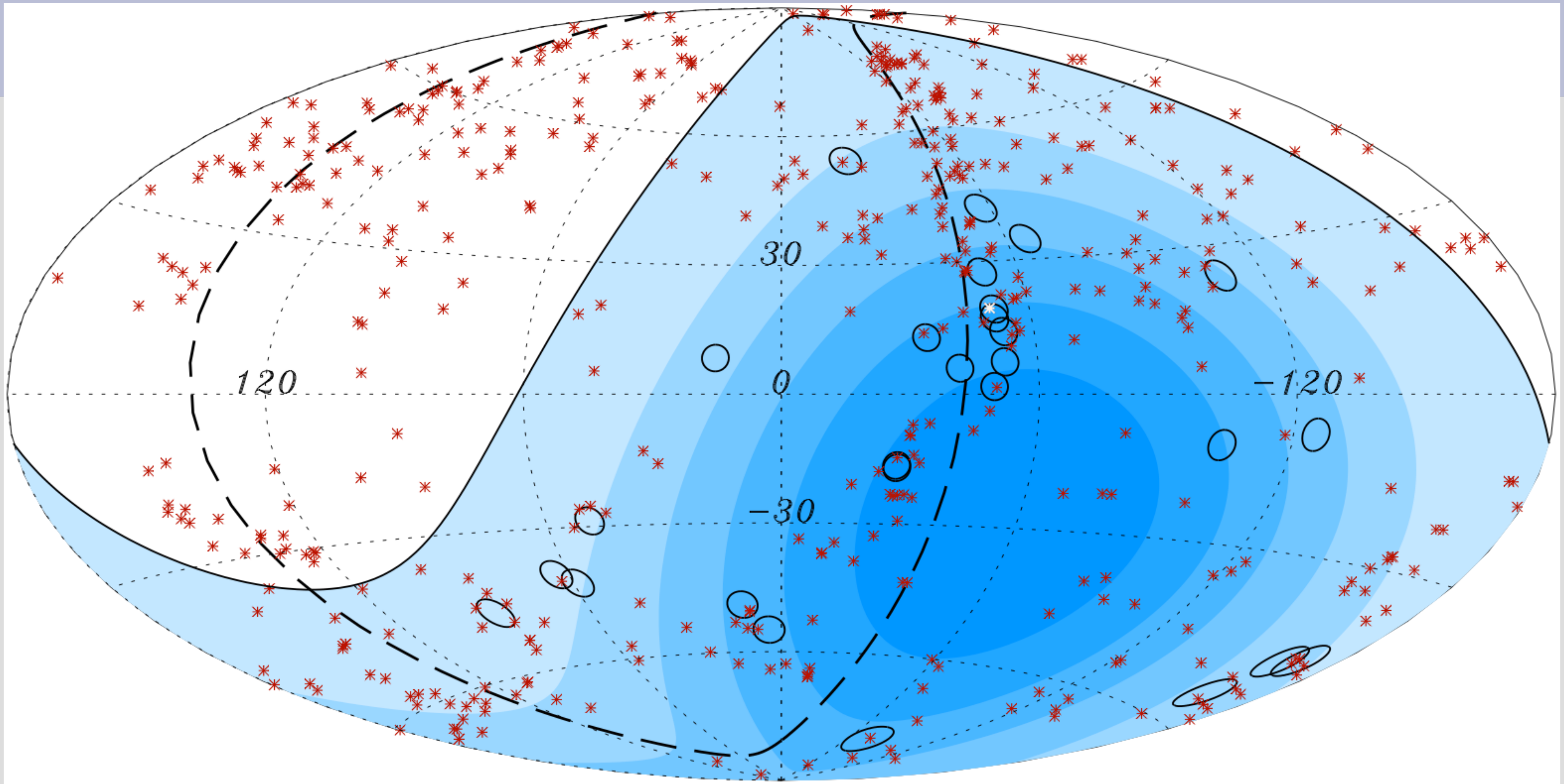
- Ejemplo de un evento UHECR



Each event: only a few stations involved. Large number of stations for collecting area

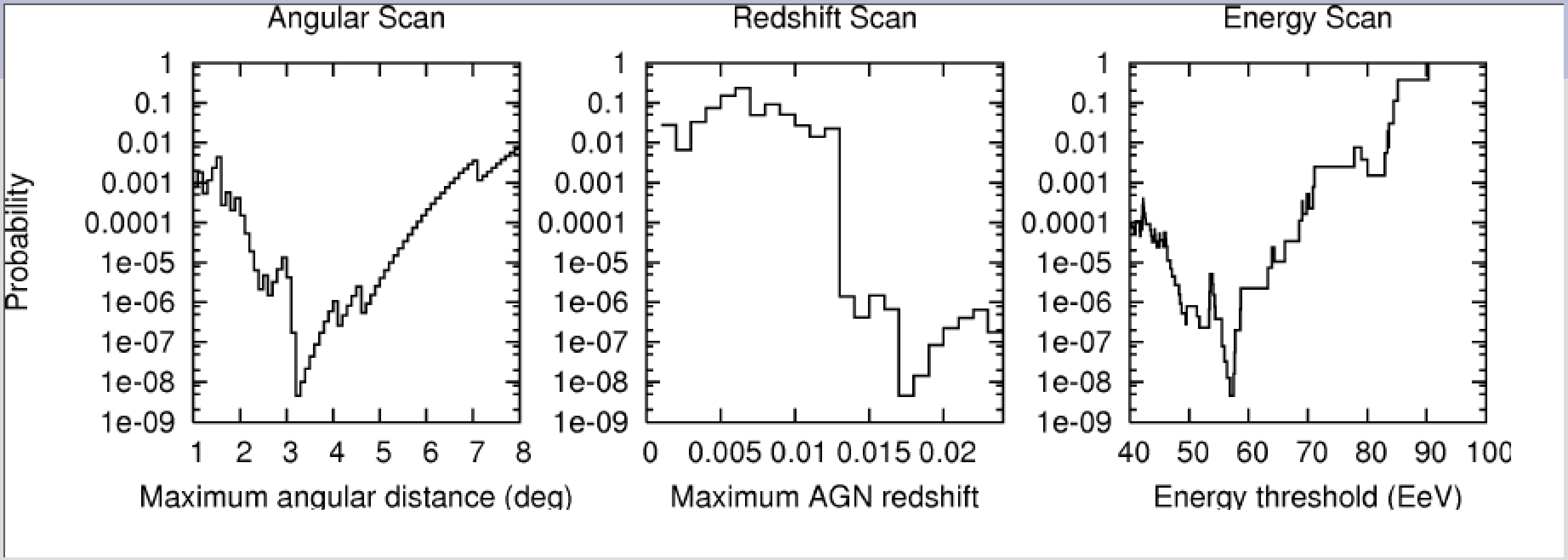
Pierre Auger Collaboration et al. 2007, Science

(after 3 years of partial operation)



- Los 27 UHECRs con E > 56 EeV (círculos) no son isotrópicos
- Correlación con Galaxias Activas cercanas (estrellas rojas)

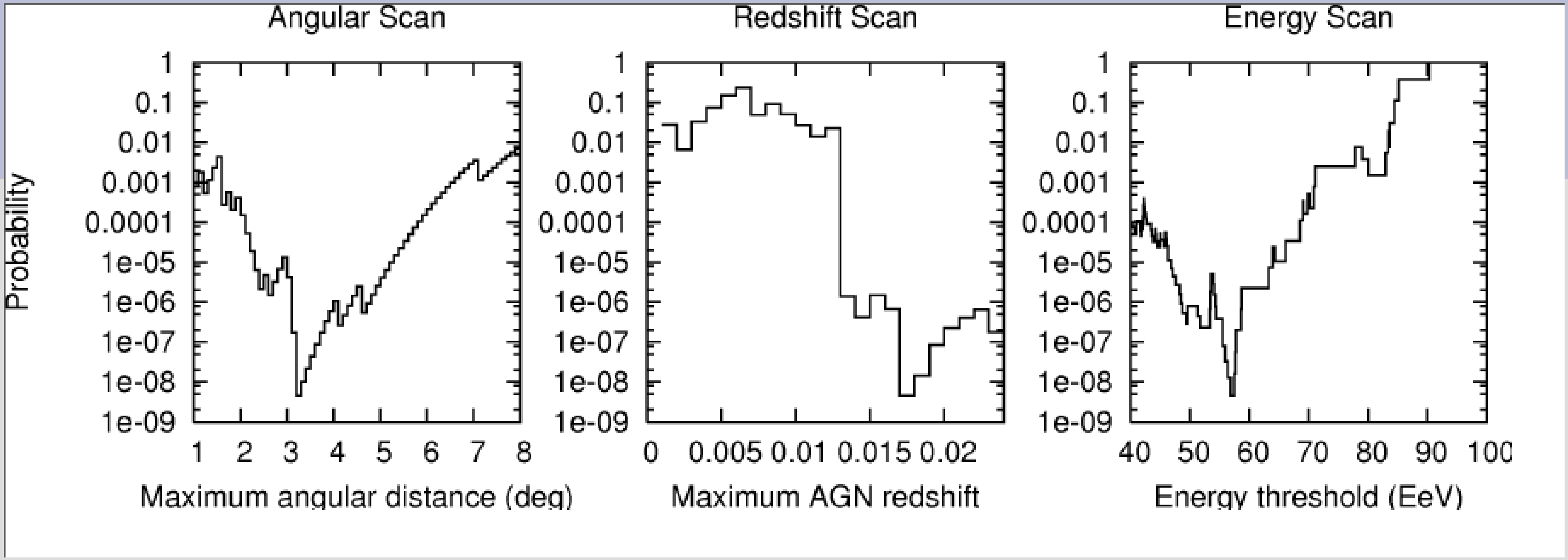
Pierre Auger Collaboration et al. 2007, Science

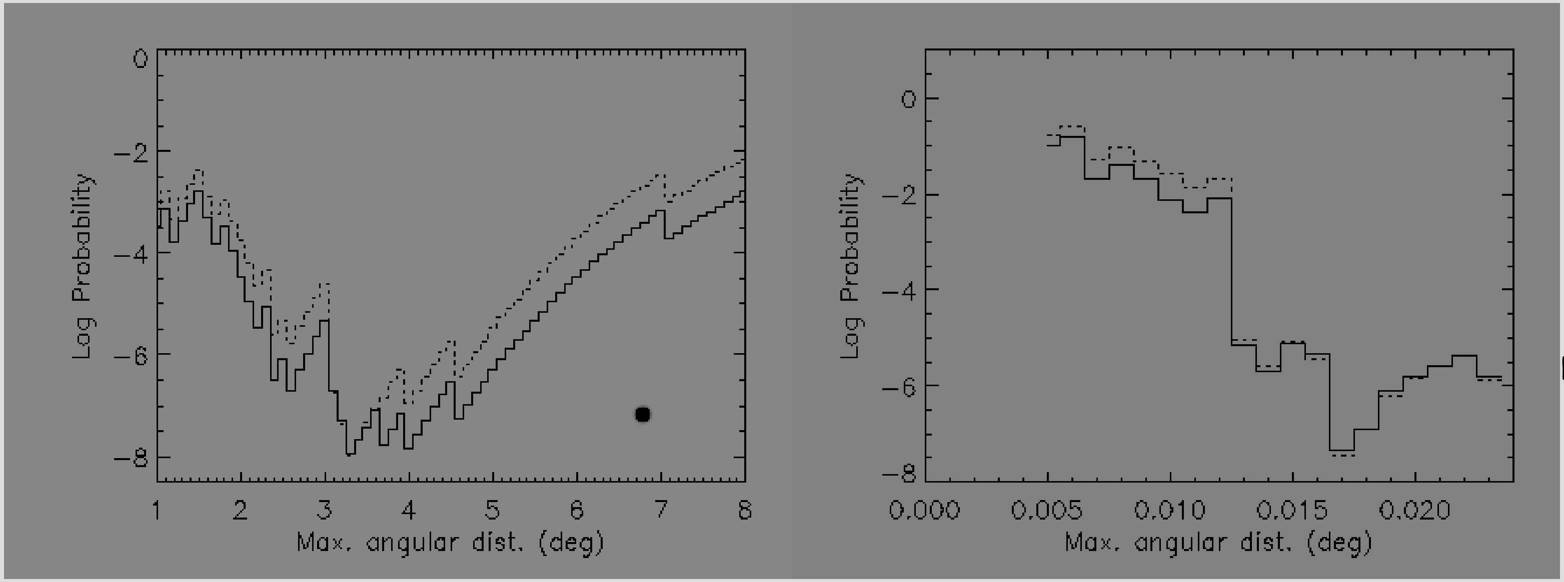


$$\sum_{j=k}^{N} C_j^N p^j (1-p)^{N-j}$$

We found a minimum of P for the parameters $\psi = 3.1°$, $z_{max} = 0.018$ ($D_{max} \leq 75$ Mpc), and $E_{th} = 56$ EeV. For these values, 12 events among 15 correlate with the selected AGN, whereas only 3.2 were expected by chance if the flux were isotropic. This observation mo-

Pierre Auger Collaboration et al. 2007, Science





Nagar & Matulich
2008

George et al. 2008:

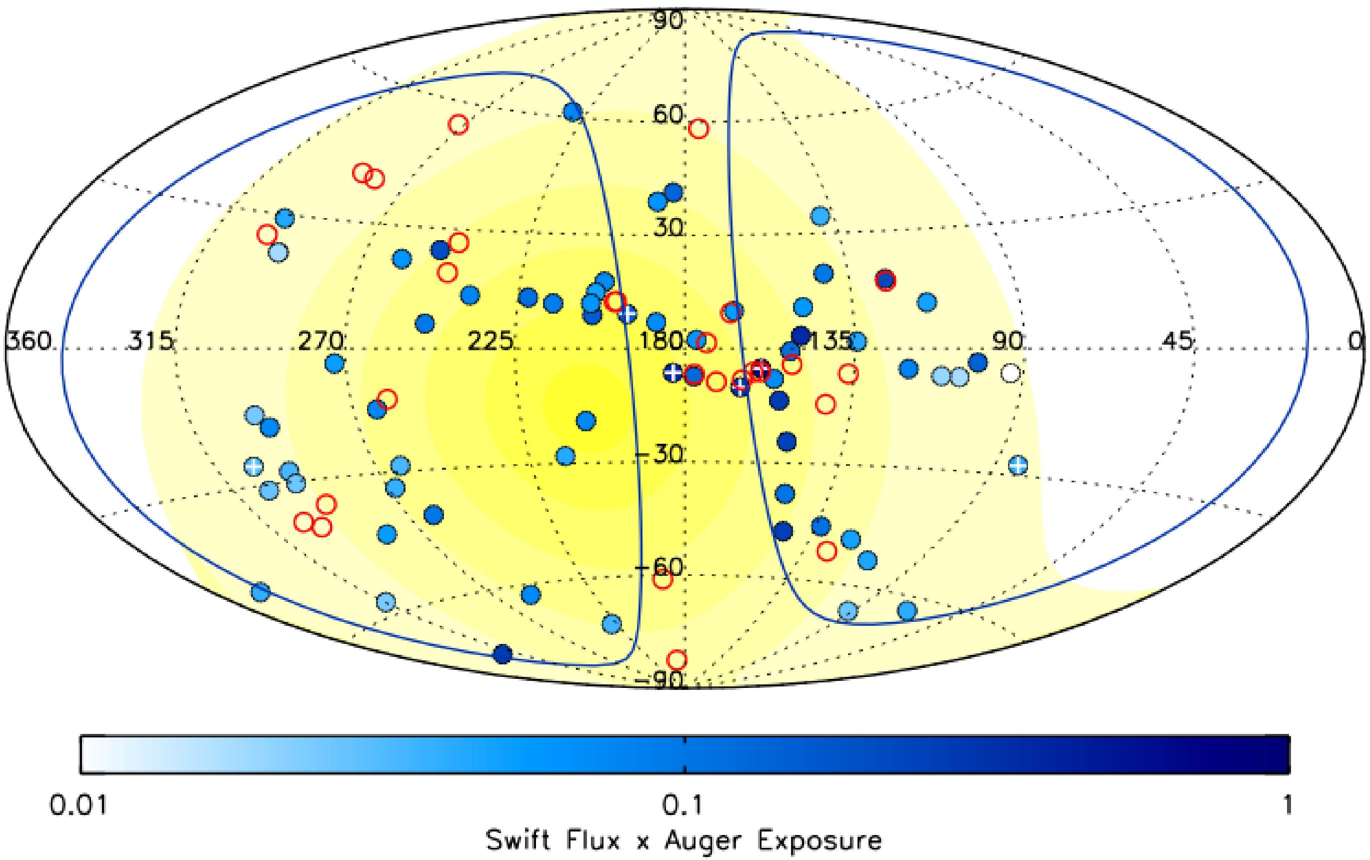
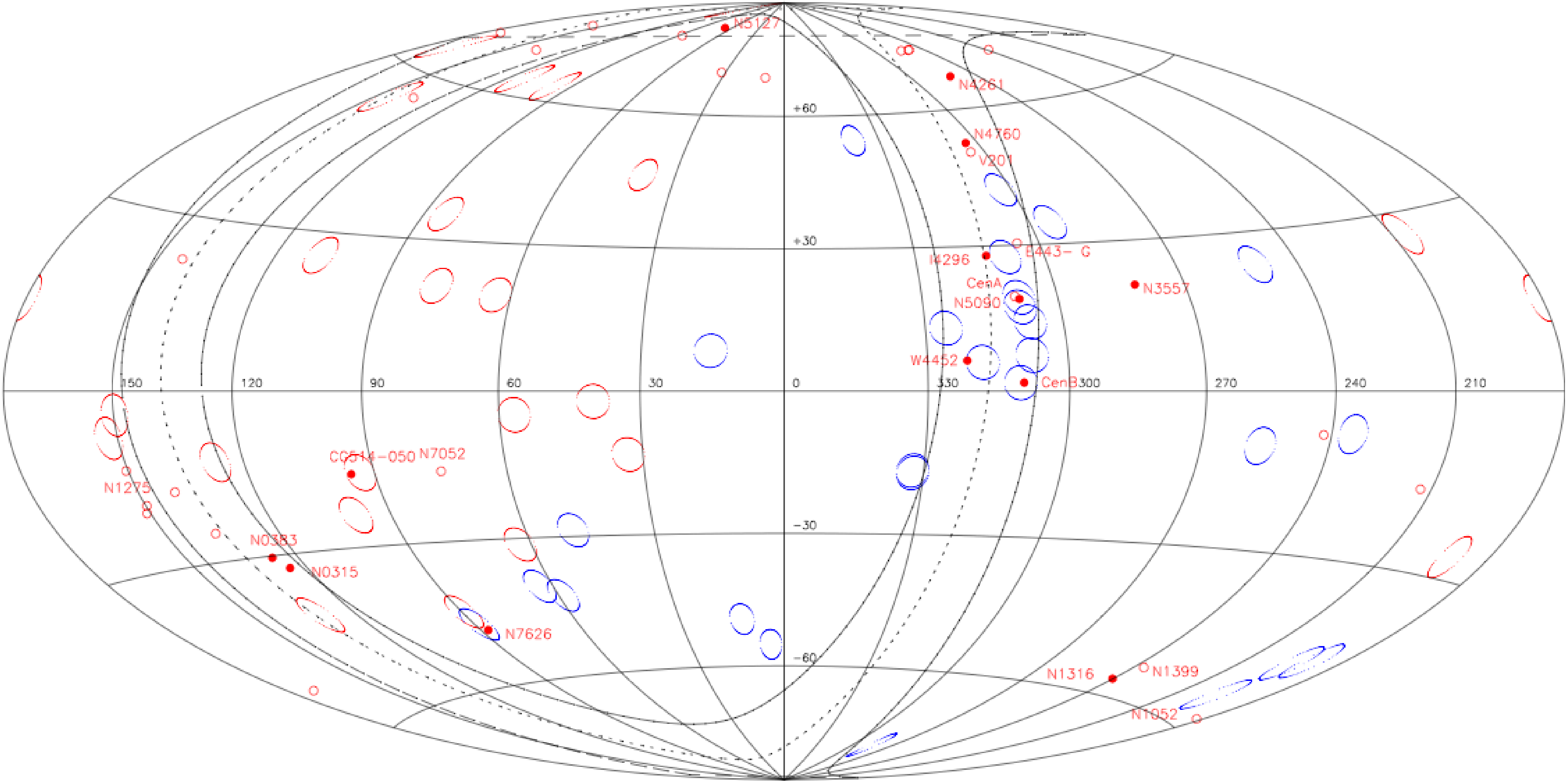


Figure 1. Map of Auger UHECRs (open red circles) and BAT AGN within 100 Mpc (filled blue circles) in supergalactic coordinates (de Vaucouleurs et al. 1976). The blue colour depth is scaled by the hard X-ray flux and Auger exposure, relative to Cen A. The 6 AGN in the catalogue within 20 Mpc are marked with white crosses, with Cen A at $(159.7°, -5.2°)$. Yellow contours have equal integrated exposures. Blue boundaries show where the AGN catalgoue is incompete due to the Galactic plane, $|b| < 15°$.

AGN within 100Mpc (weighted by their hard X-ray flux) are correlated with Auger UHECRs at 98%

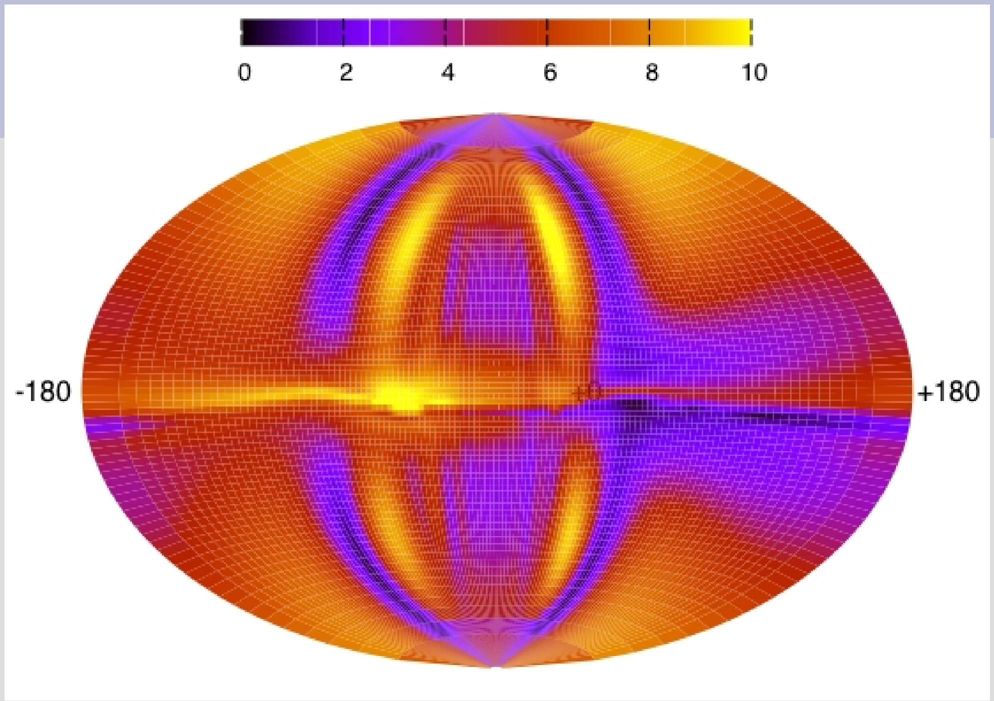
Nuestro Análisis: Radiogalaxias (investigación pre-grado!)

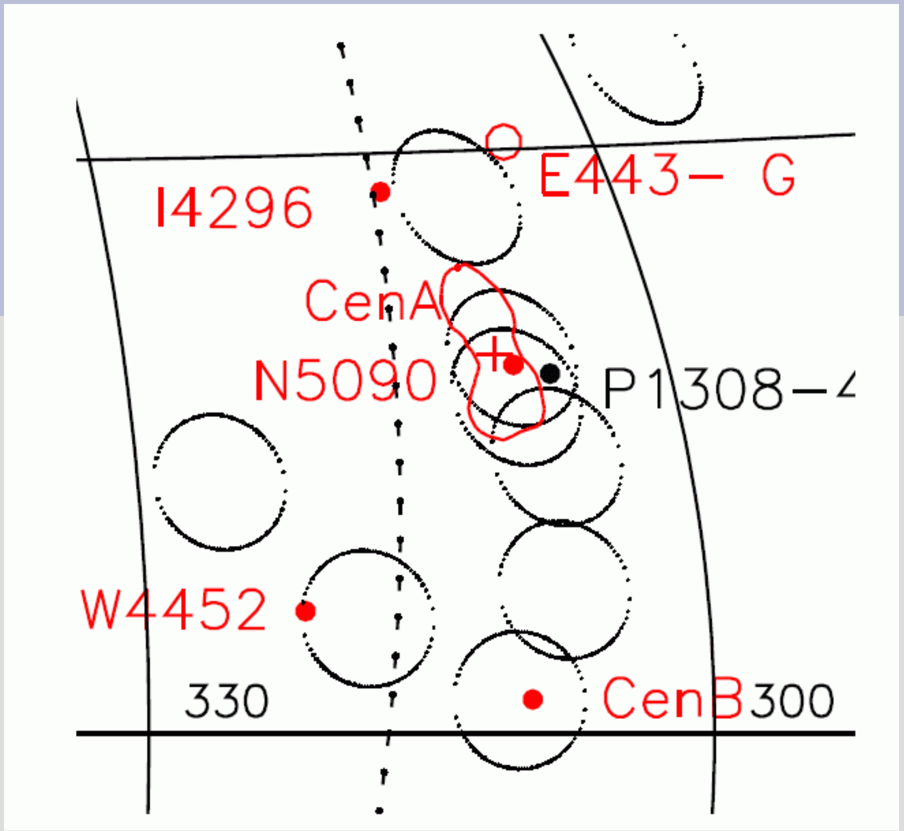


Nagar & Matulich 2008

- D < 75 Mpc
- Red solid symbols: D < 75 Mpc and radio extent > 180kpc
- Is this the reason why the other correlations worked?

D < 75Mpc radiogalaxies





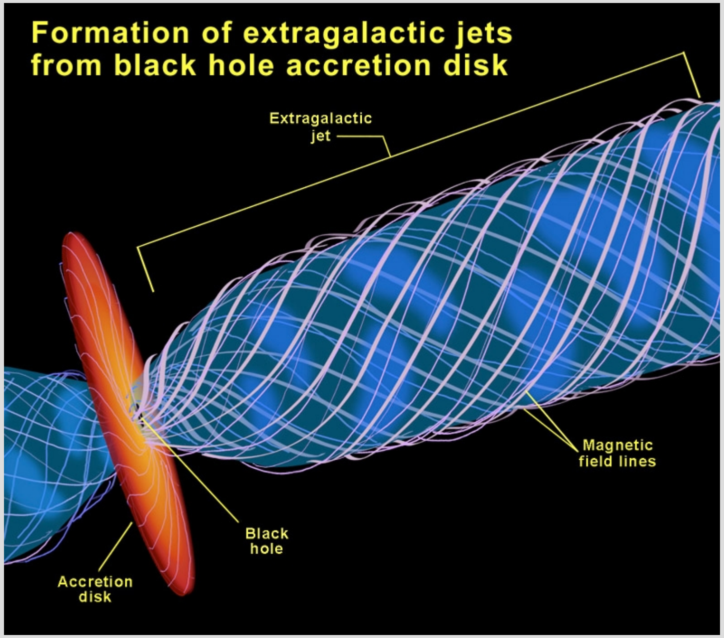
The Cen A region

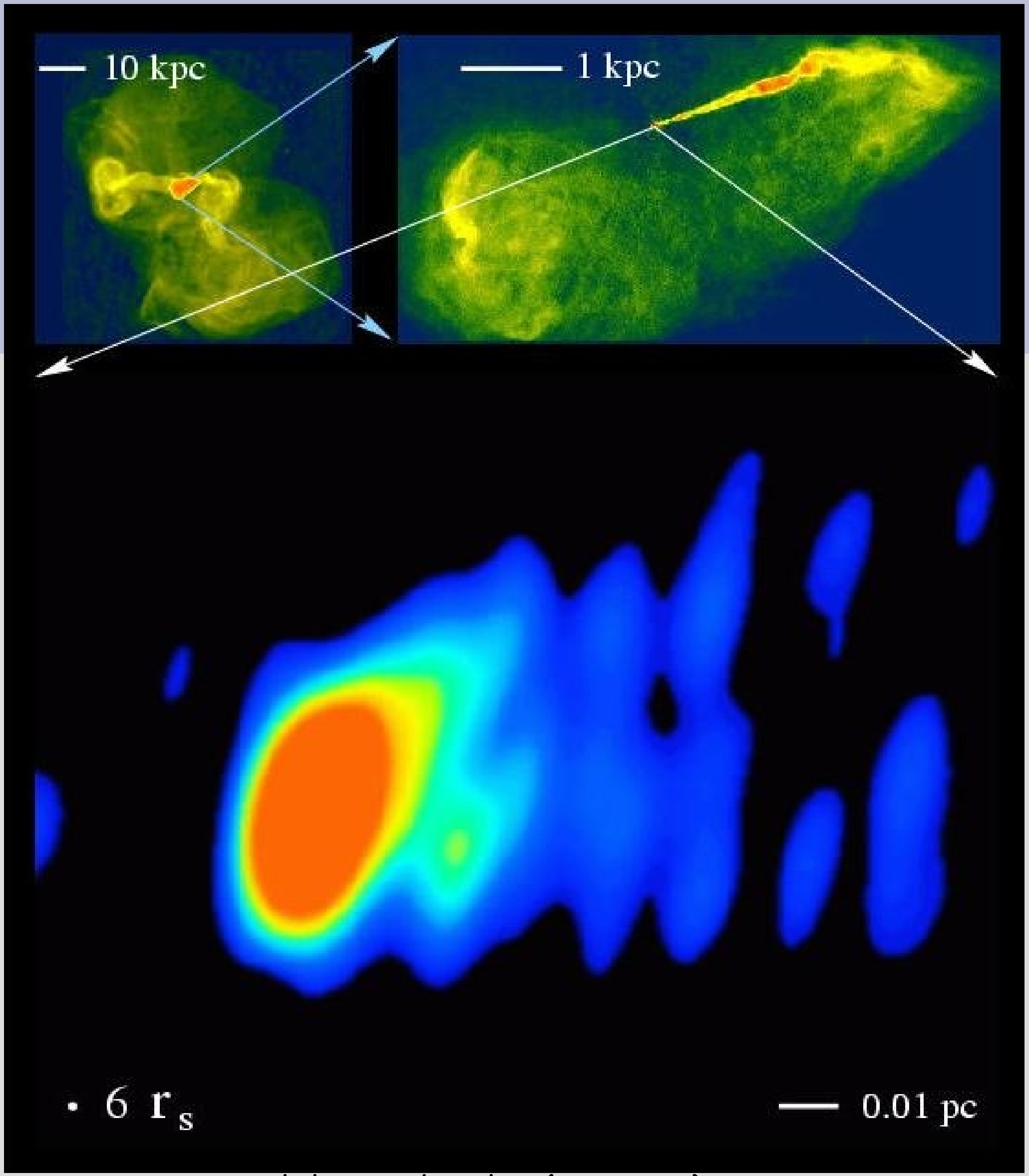
- 8 de 27 UHECRs dentro de 3.5 grados de una radiogalaxia extendida
- 6 de 10 radiogalaxias extendidas y cercanas coinciden a UHECRs
    - 3 de 4 no coinciden en áreas de menos exposición

Radiogalaxias

Chorros de partículas relativistas lanzados de un disco de acreción alrededor del agujero negro.

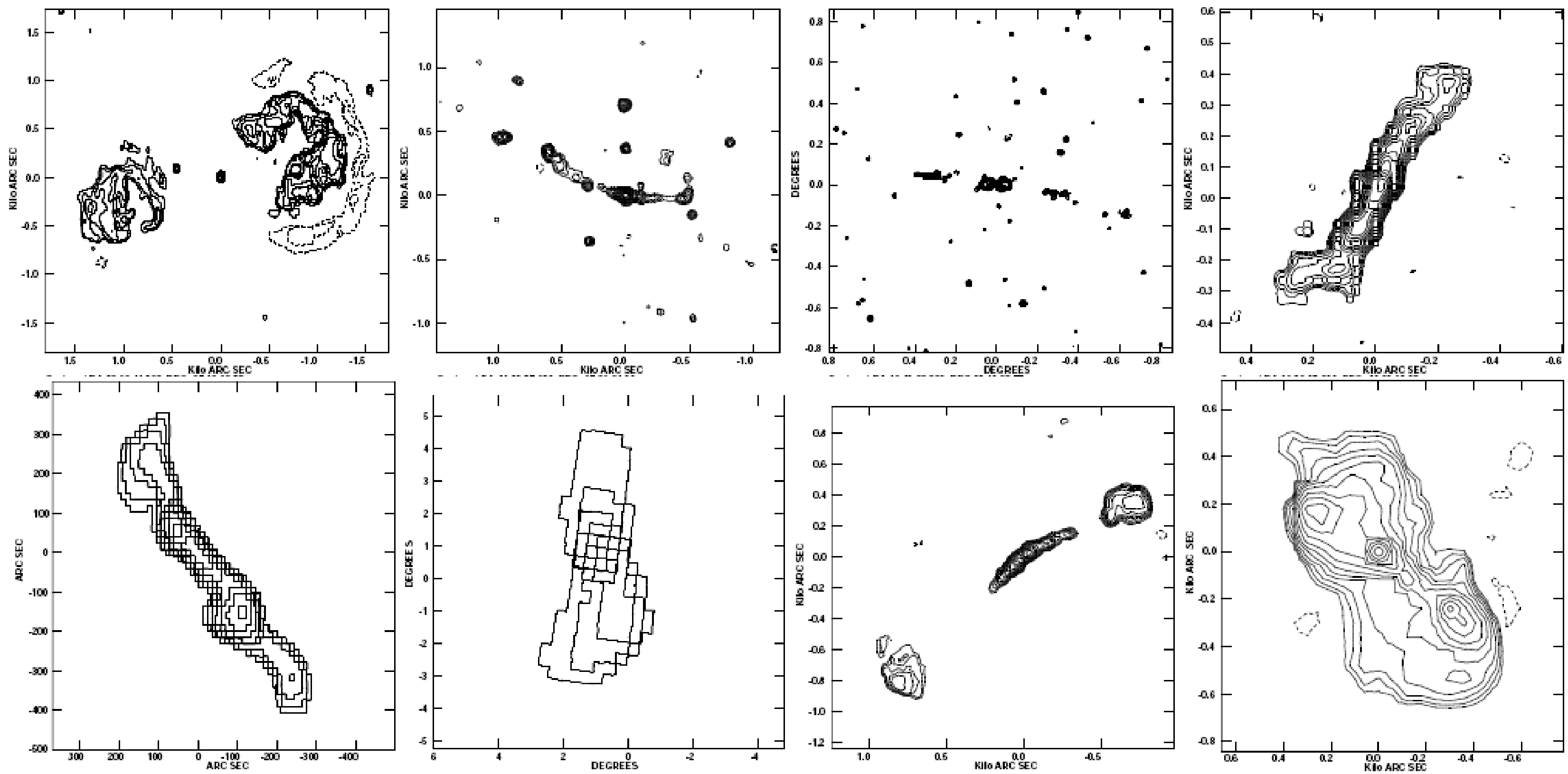
UHECRs desde el base del chorro or desde los "lobes"

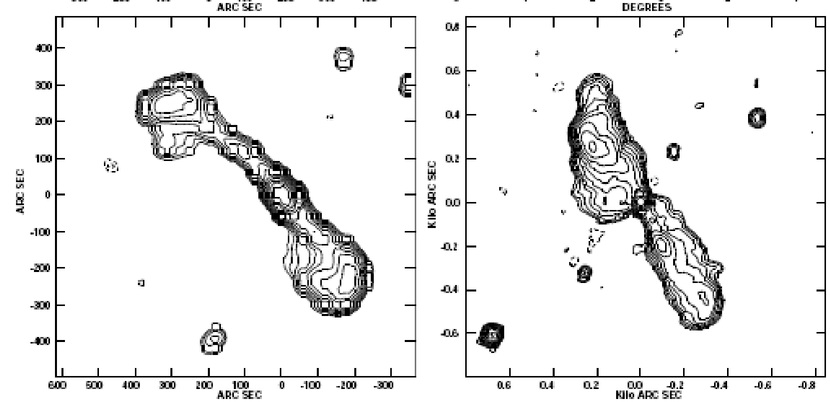




Muy extendido en el radio (> 180kpc)
alguno evidencias en favor de FR IIs

Morfologías de las diez radiogalaxias





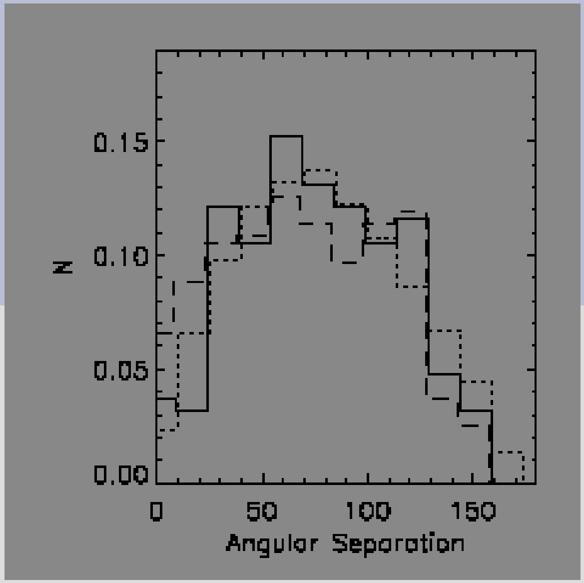
Muy extendido en el radio (> 180kpc)

algunas evidencias en favor de FR IIs

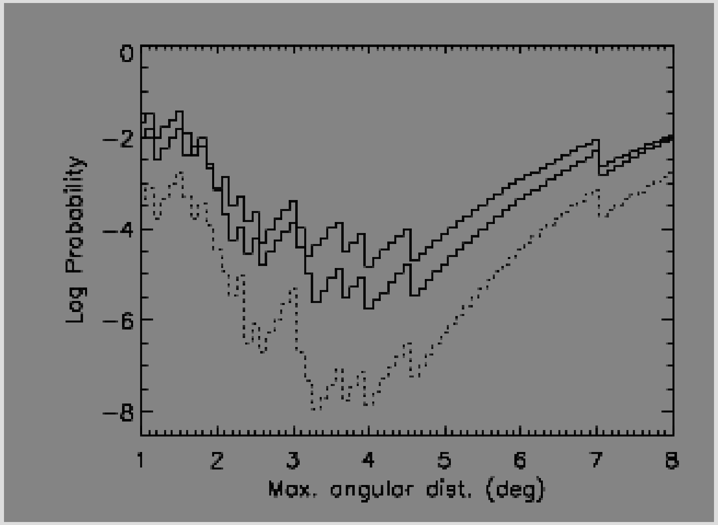
Nagar & Matulich 2008

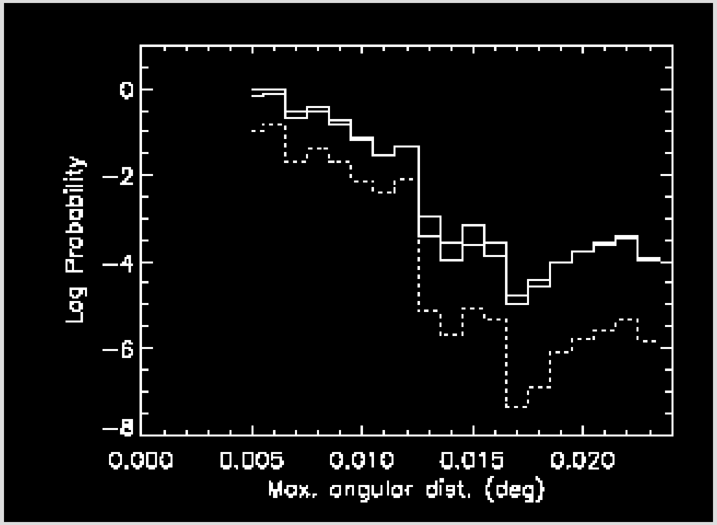
Nuestro Análisis

- Al menos dos componentes
  - Radiogalaxias extendidas cercanas
  - "otros" (talvez isotrópico)

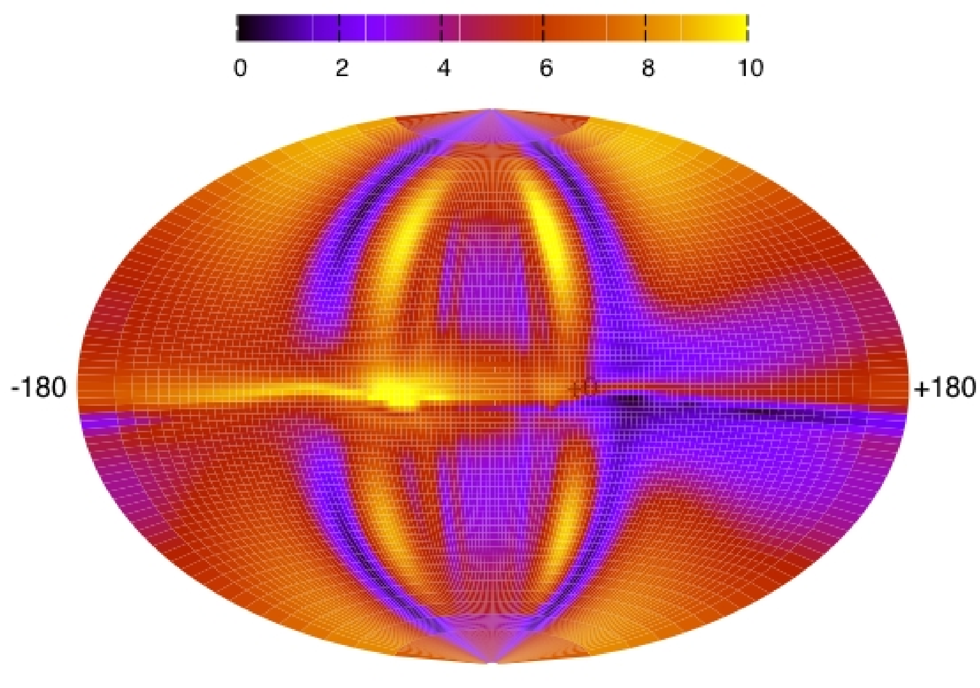


Nagar & Matulich 2008



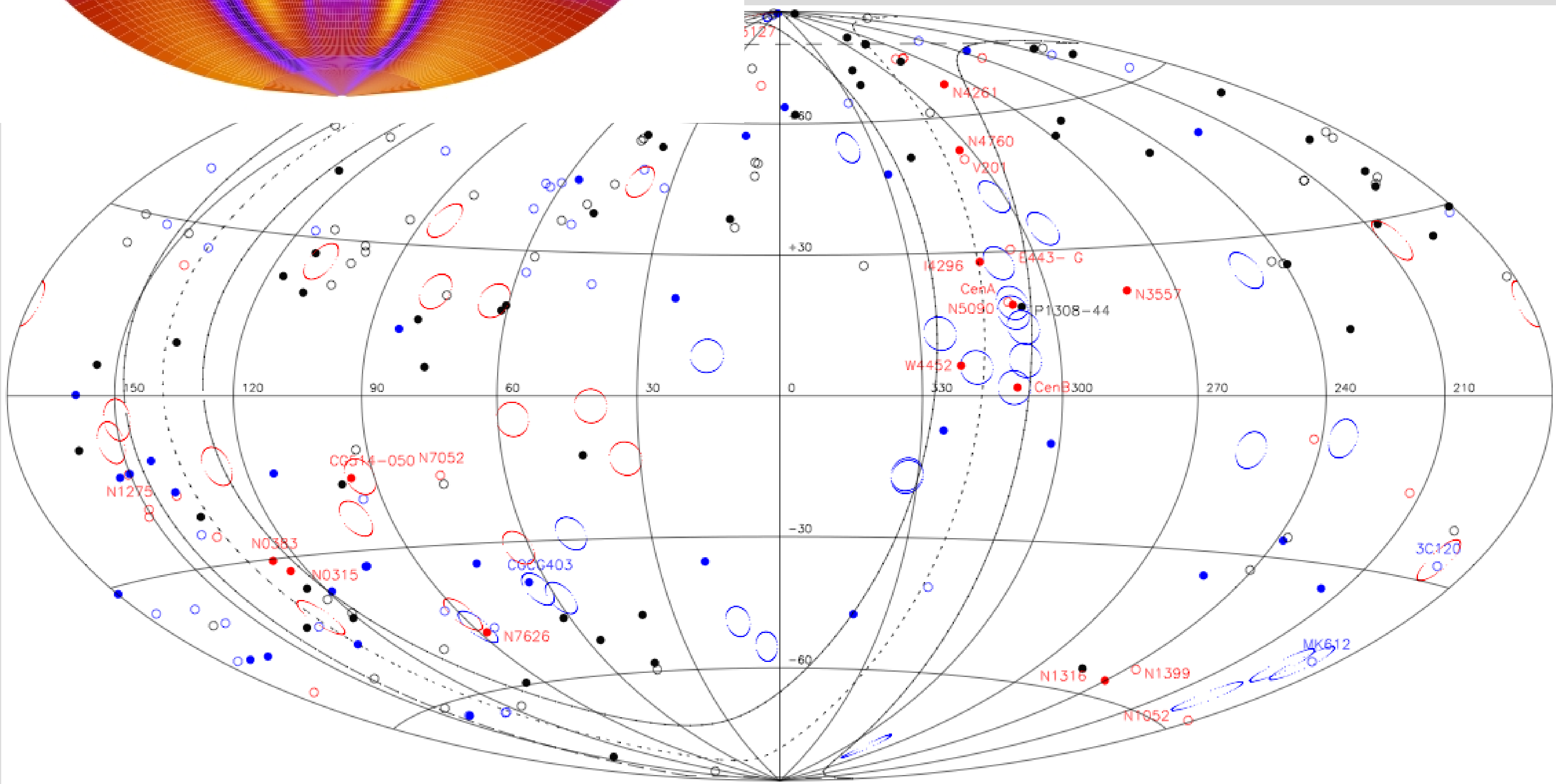


Also should mention two recent astro-phs: Zaw et al., Moskalenko et al.:
bolometric luminosities of V-C&V AGNS used in the Auger correlation

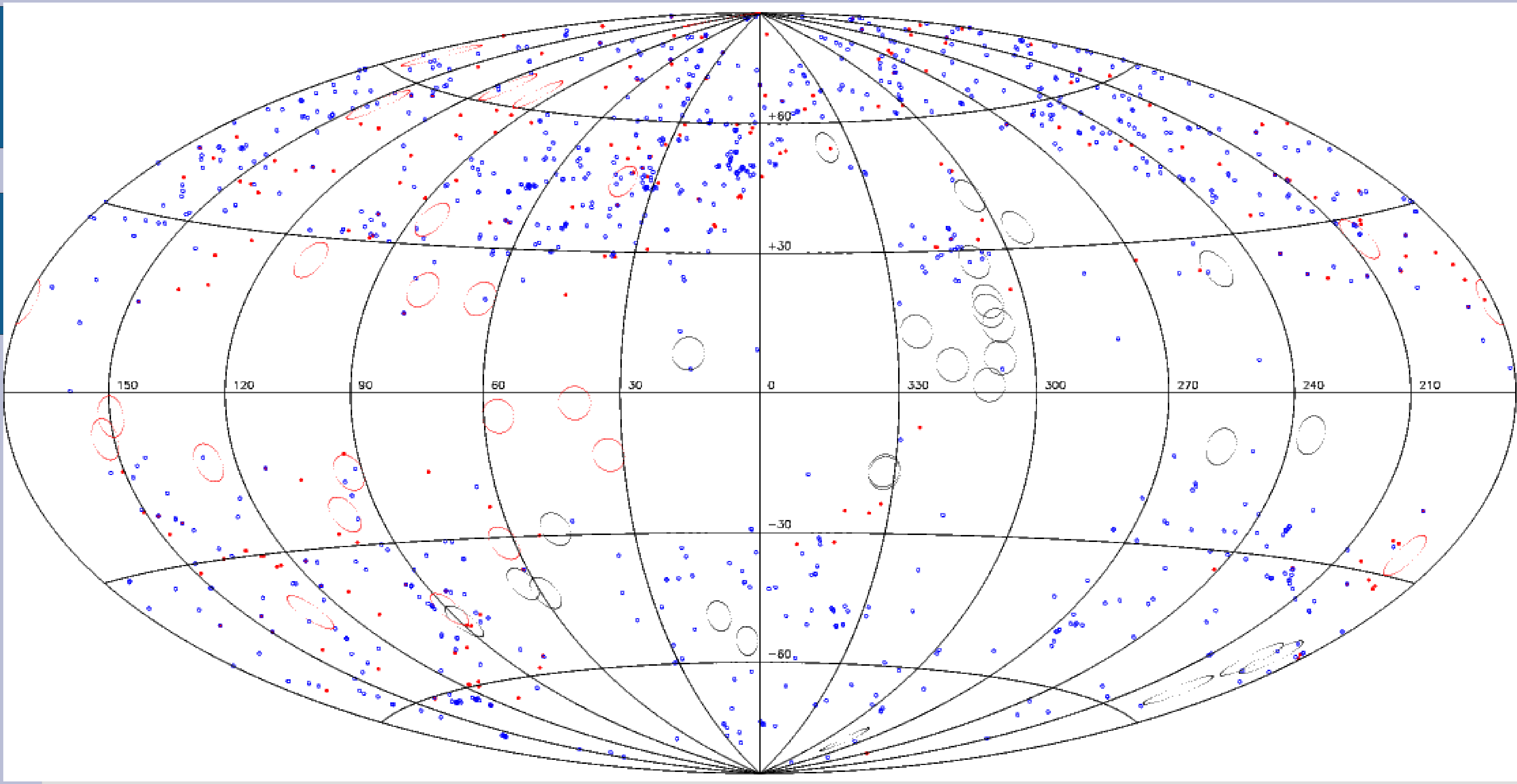


"All" Radiogalaxies

- D < 75 Mpc, 75 < D < 150 Mpc, 150 < D < 200Mpc
- Red solid symbols: D < 75 Mpc, radio extent > 180kpc



Nuestro Análisis: grupos y cúmulos de galaxias



- No correlacionado con cúmulos de galaxias
- Ni Supernovae ni Gamma Ray Bursts (pero retraso del tiempo!)

Ghisellini et al. : galaxies from HIPASS

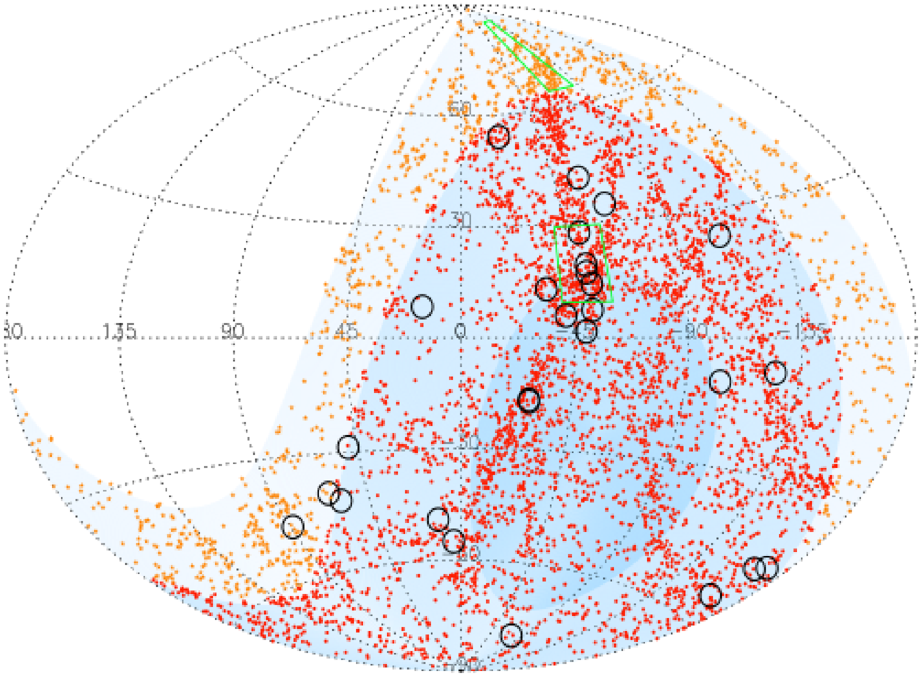


Figure 1. H I Parkes All–Sky Survey (HIPASS) galaxies (solid filled symbols) and the 27 AUGER UHECRs (black open circles) in galactic coordinates. Blue levels corresponds to the AUGER relative exposure. The south H I catalogue (HICAT – 4315 sources) and the north extension (NHICAT – 1002 sources) are shown by red filled circles and orange stars, respectively. The green lines are $20^\circ \times 20^\circ$ boxes centred on the positions of the radio–galaxies M87 (near the north Galactic pole) and Cen A.

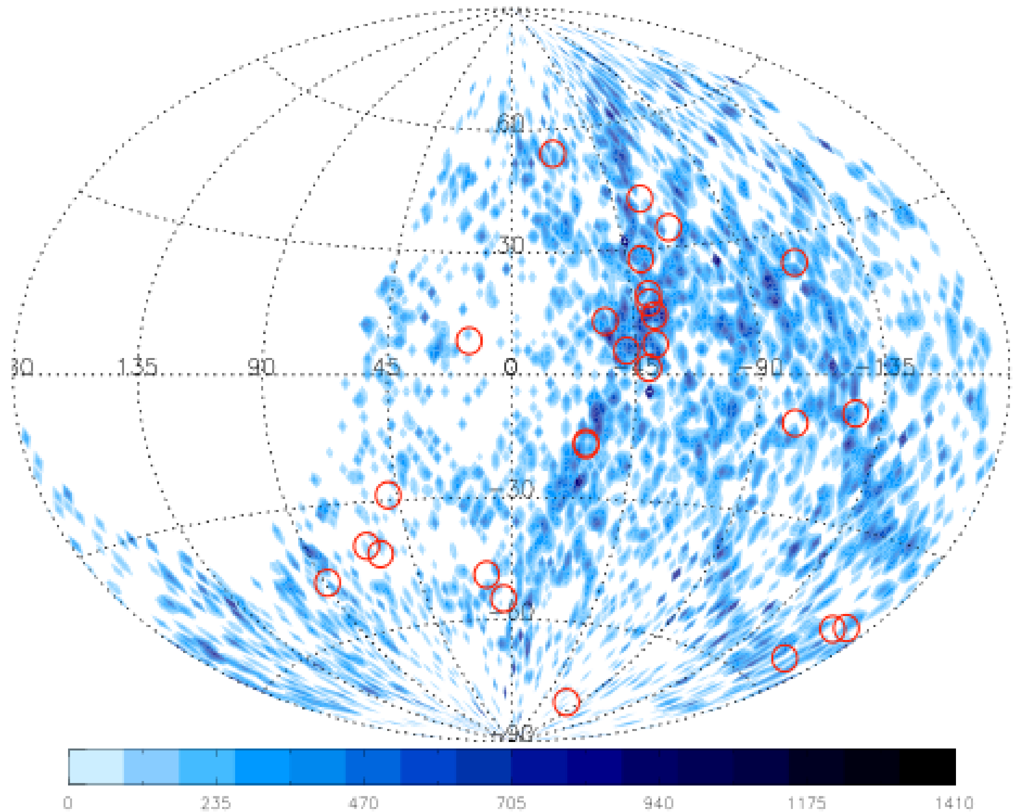


Figure 2. HIPASS galaxy H I flux, in galactic coordinates. Blue levels corresponds to the integrated flux (in bins of $2^\circ \times 2^\circ$ and units of Jy km s^{-1}) of H I emission, multiplied by the relative AUGER exposure. Red circles are the locations of the 27 AUGER UHECRs above 57 EeV.

- 99% correlation between UHECRs and high HI content galaxies
- Ghisellini et al. conclusion: spiral galaxies: magnetars (and/or GRBs)

Comparing the claims thus far

- Pierre Auger Collaboration: UHECRs and Veron AGNs
  - UHECR distribution does not match AGN distribution
  - Can any Veron AGN produce UHECRs ? Probably not
- George et al. : UHECRs and hard X-ray selected AGNs
  - Can any hard X-ray detected AGN produce UHECRs?
- Ghisellini et al.: UHECRs and nearby spiral galaxies (HIPASS)
  - GRBs and Magnetars could are potential UHECR sources
  - Awkward cutoffs for highest statistical correlations
  - UHECR distribution does not match HIPASS distribution
  - UHECRs will almost always be subset of HIPASS..
- Our claim: extended radiogalxies and UHECRs
  - 1 to 1 match between nearby extended (FRII'ish) radiogalaxies and UHECRs
  - Extended radiogalaxies long suspected as UHECR sources
  - Only a subset of UHECRs explained by radiogalaxies (but... part2)

Are we all tracing something else on the Supergalactic Plane?

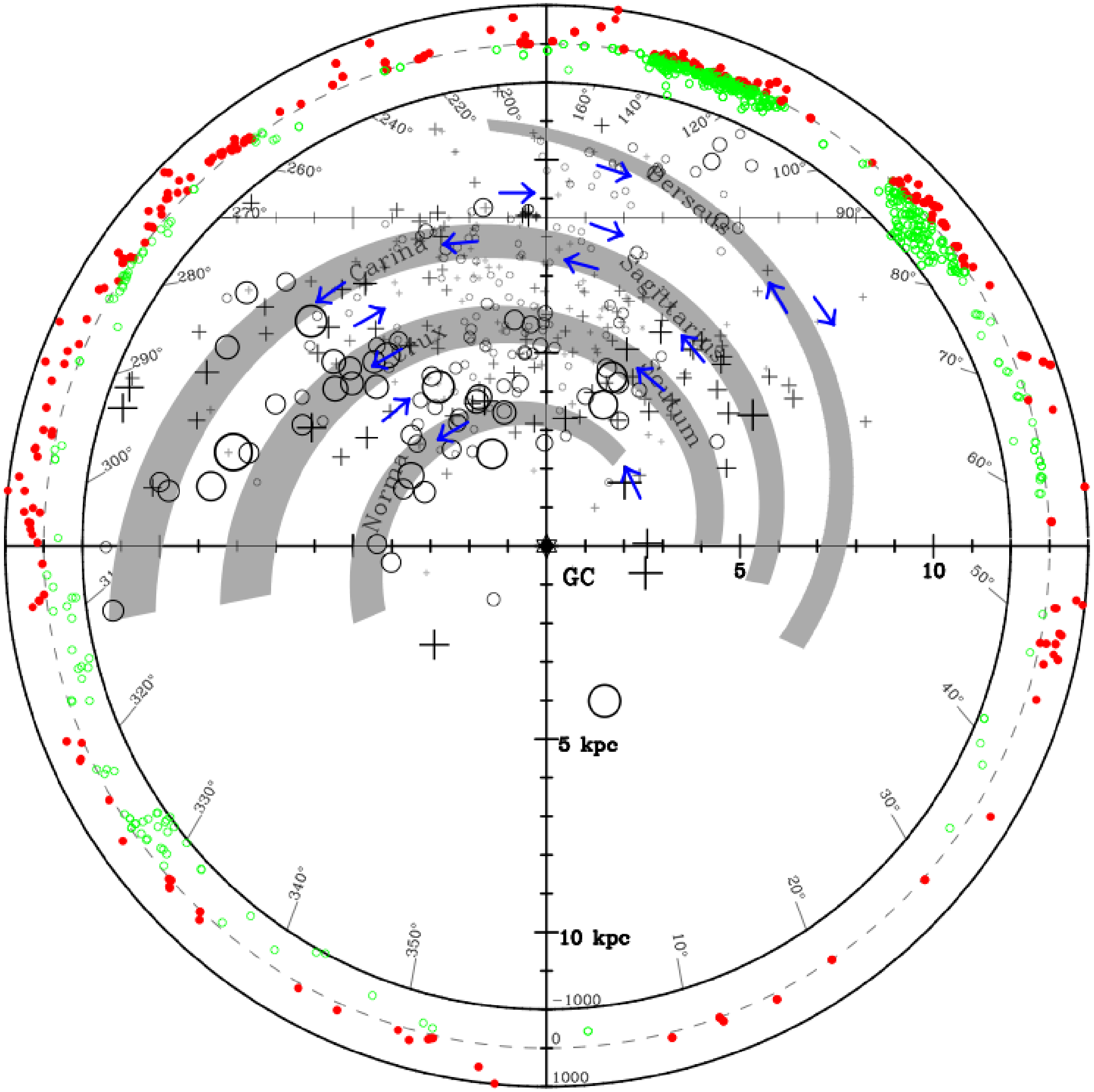


Figure 1. The RM distribution of 374 pulsars with $|b| < 8°$, projected onto the Galactic plane. The linear sizes of the symbols are proportional to the square root of the RM values. The crosses represent positive RMs, and the open circles represent negative RMs. The approximate locations of four spiral arms are indicated. The large-scale structure of magnetic fields derived from pulsar RMs are indicated by thick arrows. See Han et al. (2006) for details. RMs of extragalactic radio sources of $|b| < 8°$ (data from Clegg et al. 1992, Gaensler et al. 2001, Brown et al. 2003, Brown et al. 2007) are also displayed in the outskirt ring. Positive RMs are shown by filled circles and negative RMs by open circles. The RM limits of ± 1000 rad m^{-2} are set at the outer and inner edges of the ring. As one can see from this plot, we have not many measurements for the magnetic fields for the farther half of the Galactic disk. The RMs of extragalactic radio sources become scarcer and scarcer in the region of $|l| < 45°$. The fluctuations in the RM distribution with Galactic longitude are consistent with magnetic field directions derived from pulsar data in the tangential regions in the 4th quadrant.

Han et al. 2007

Galactic Magnetic Field: basic spiral arm model

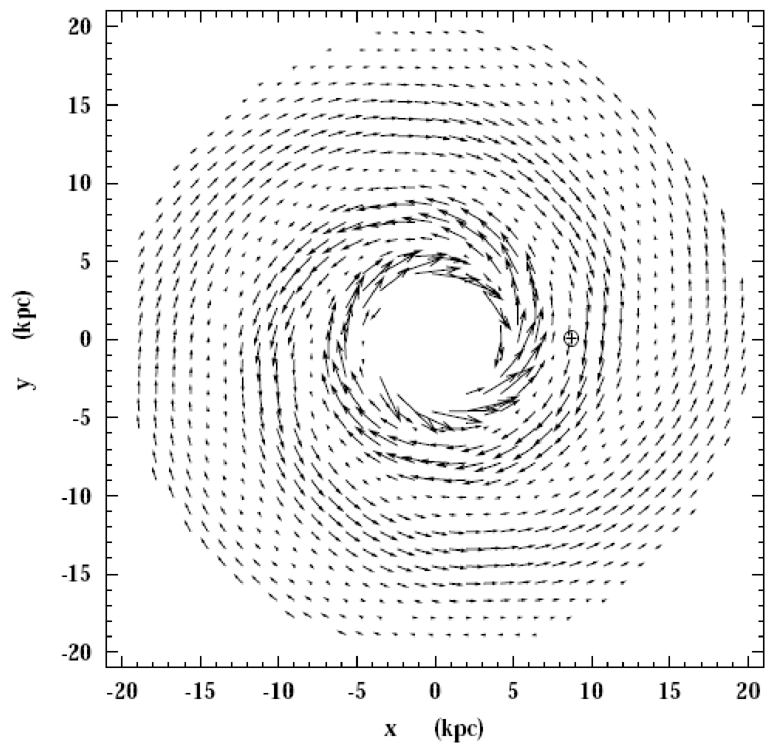
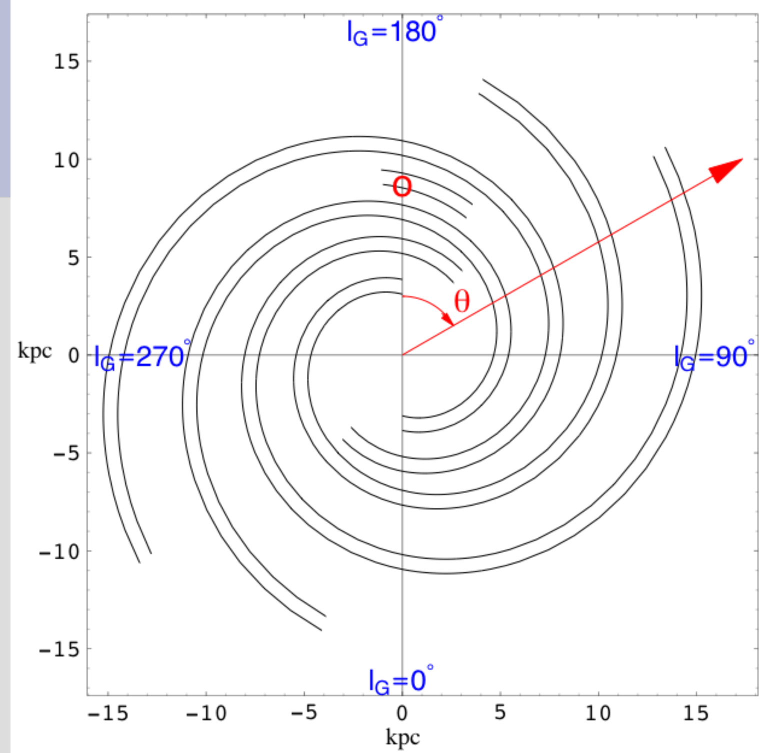


FIG. 1.—Magnetic field configuration in the Galactic plane. The vectors indicate the field direction, and their length is proportional to its magnitude.



Figures from Alvarez-Muniz etal, Kachelriess etal

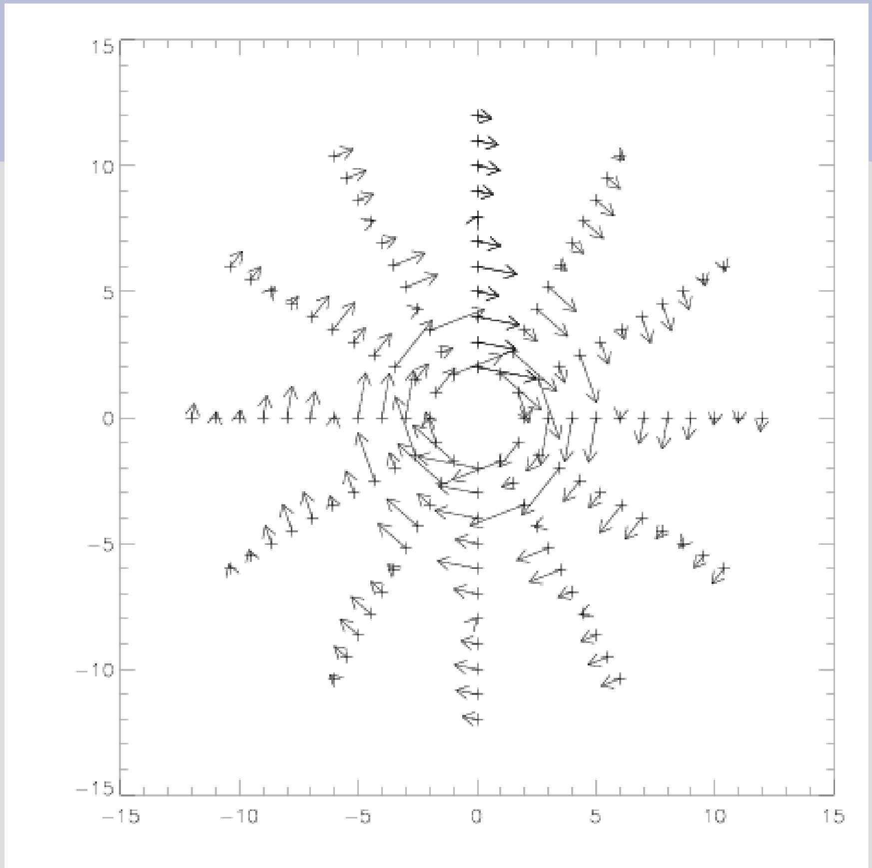
$$b(r_{||}) = B_0 \frac{R_\oplus}{r_{||}}, \qquad B_0 = 4.4\,\mu\mathrm{G},$$

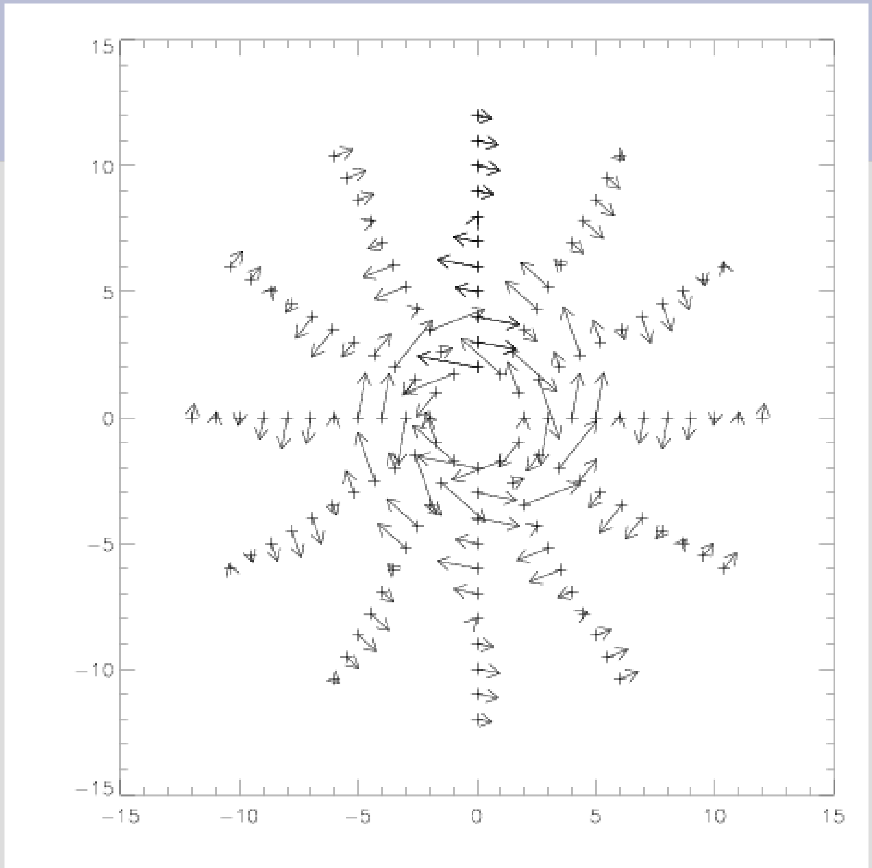
$$B(r_{||},\theta) = \begin{cases} b(r_{||})\cos\left(\theta - \beta \ln \frac{r_{||}}{r_0}\right), & \text{BS}, \\ b(r_{||})\left|\cos\left(\theta - \beta \ln \frac{r_{||}}{r_0}\right)\right|, & \text{AS}. \end{cases}$$

$$\beta = (\tan p)^{-1} = -5.67 \text{ and } r_0 = 10.55 \text{ kpc}$$

$$B_{r_{||}} = B(r_{||},\theta)\sin p, \qquad B_\theta = B(r_{||},\theta)\cos p.$$

Galactic Magnetic Field: model





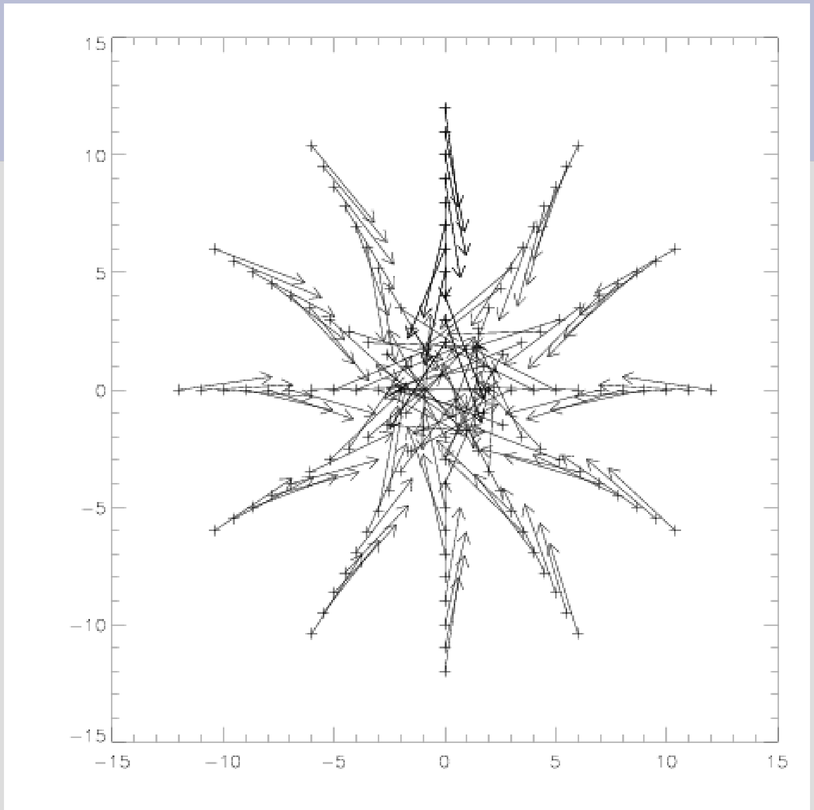
- Axisymmetric (AS)
- AS-A AS-S

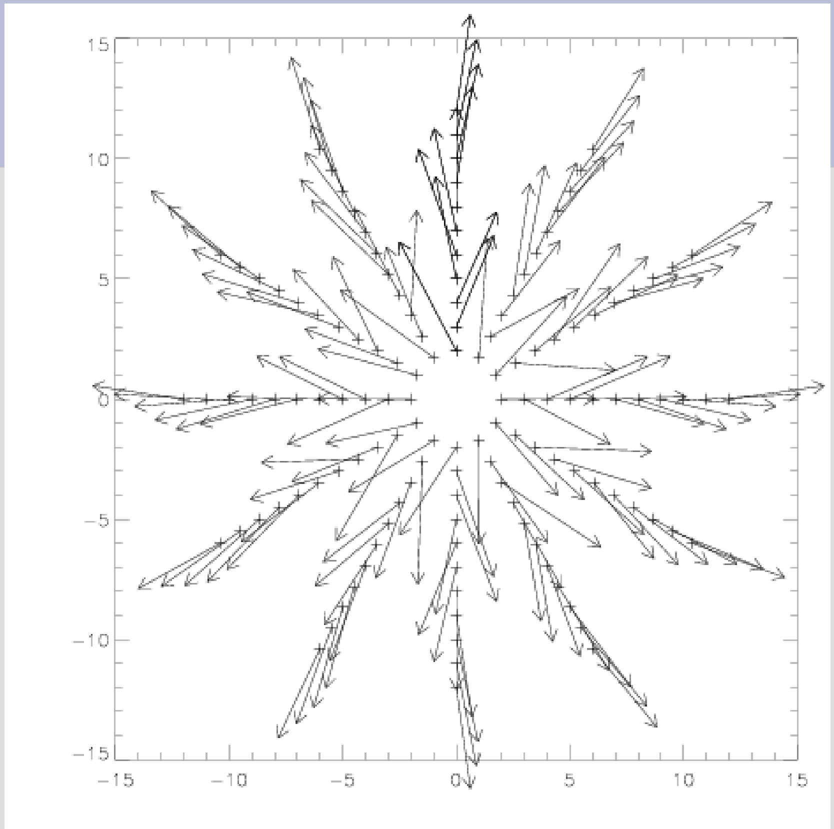
Bisymmetric (BS)

BS-A or BS-S

$$B(r_{||}, \phi, -z) = \begin{cases} B(r_{||}, \phi, z), & \text{S-type parity,} \\ -B(r_{||}, \phi, z), & \text{A-type parity.} \end{cases}$$

Galactic Magnetic Field: model (adding the dipole field)





- z=10pc z= -10pc

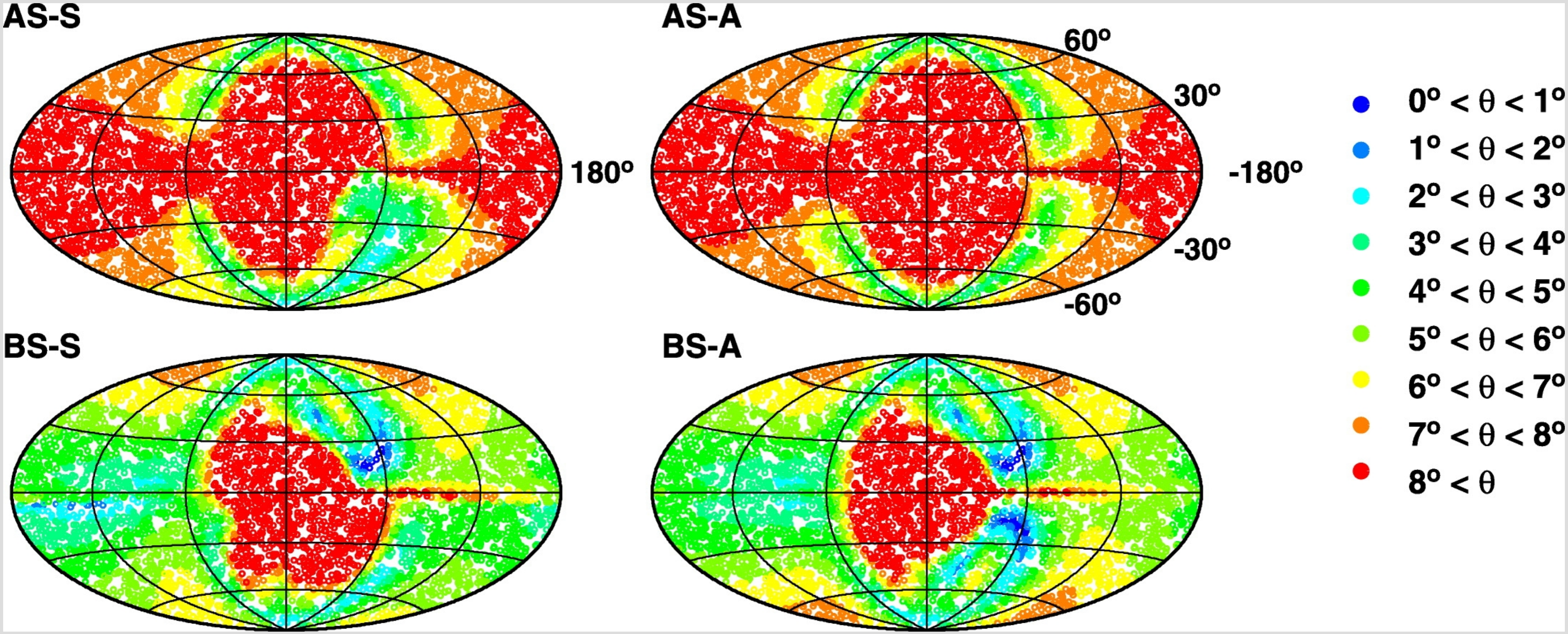
$$B_x = -3\mu_G \sin\theta \cos\theta \cos\varphi / r^3,$$
$$B_y = -3\mu_G \sin\theta \cos\theta \sin\varphi / r^3,$$
$$B_z = \mu_G(1 - 3\cos^2\theta)/r^3,$$

$\mu_G \sim 184.2\ \mu\mathrm{G\ kpc}^3$

$0.3\ \mu\mathrm{G}$ At the Sun

Galactic Magnetic Field: model deflections

$$\vartheta \simeq \frac{d}{R_L} \simeq 0.52^\circ Z \left(\frac{p_\perp}{10^{20}\,\mathrm{eV}}\right)^{-1} \left(\frac{d}{1\,\mathrm{kpc}}\right) \left(\frac{B}{\mu\mathrm{G}}\right)$$



Takami & Sato 2008 for 63 EeV UHECRs (also Kachelreiss et al. 2007, Prouza & Smida 2003, Tinyakov & Tkachev, and several others....)

Extragalactic B field: model deflections

$$\delta_{\rm rms} \simeq \frac{(2dl_c/9)^{1/2}}{R_L} \simeq 0.8^\circ\, Z \left(\frac{E}{10^{20}\,{\rm eV}}\right)^{-1} \left(\frac{d}{10\,{\rm Mpc}}\right)^{1/2} \left(\frac{l_c}{1\,{\rm Mpc}}\right)^{1/2} \left(\frac{B}{10^{-9}\,{\rm G}}\right) .$$

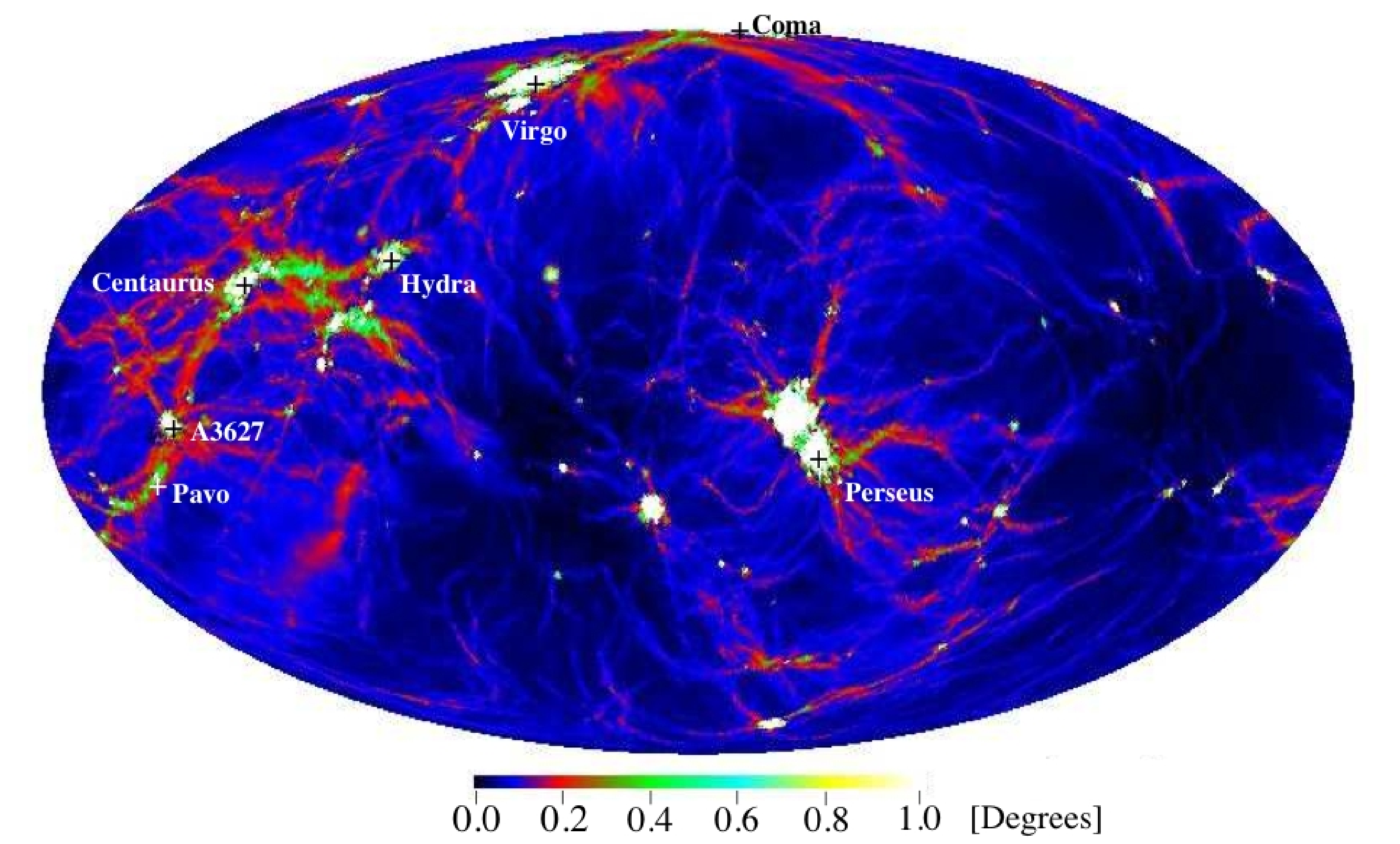


Fig. 13.— Full sky maps of expected deflection angles for protons with the arrival energy $E = 1 \times 10^{20}$ eV.

Dolag et al. 2003 : using Springel's LSS simulations to model intergalactic B fields

Extragalactic B field: model deflections

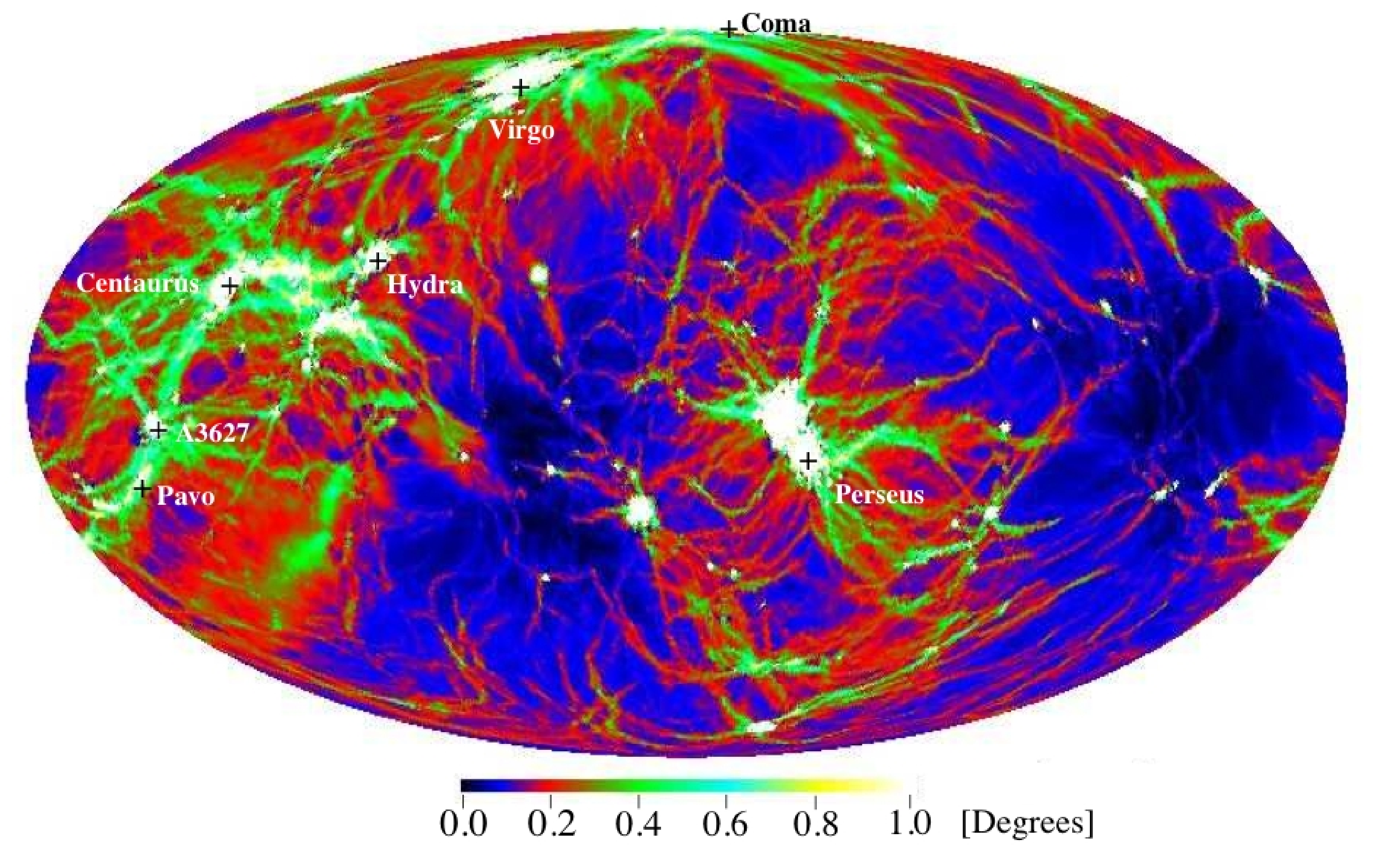
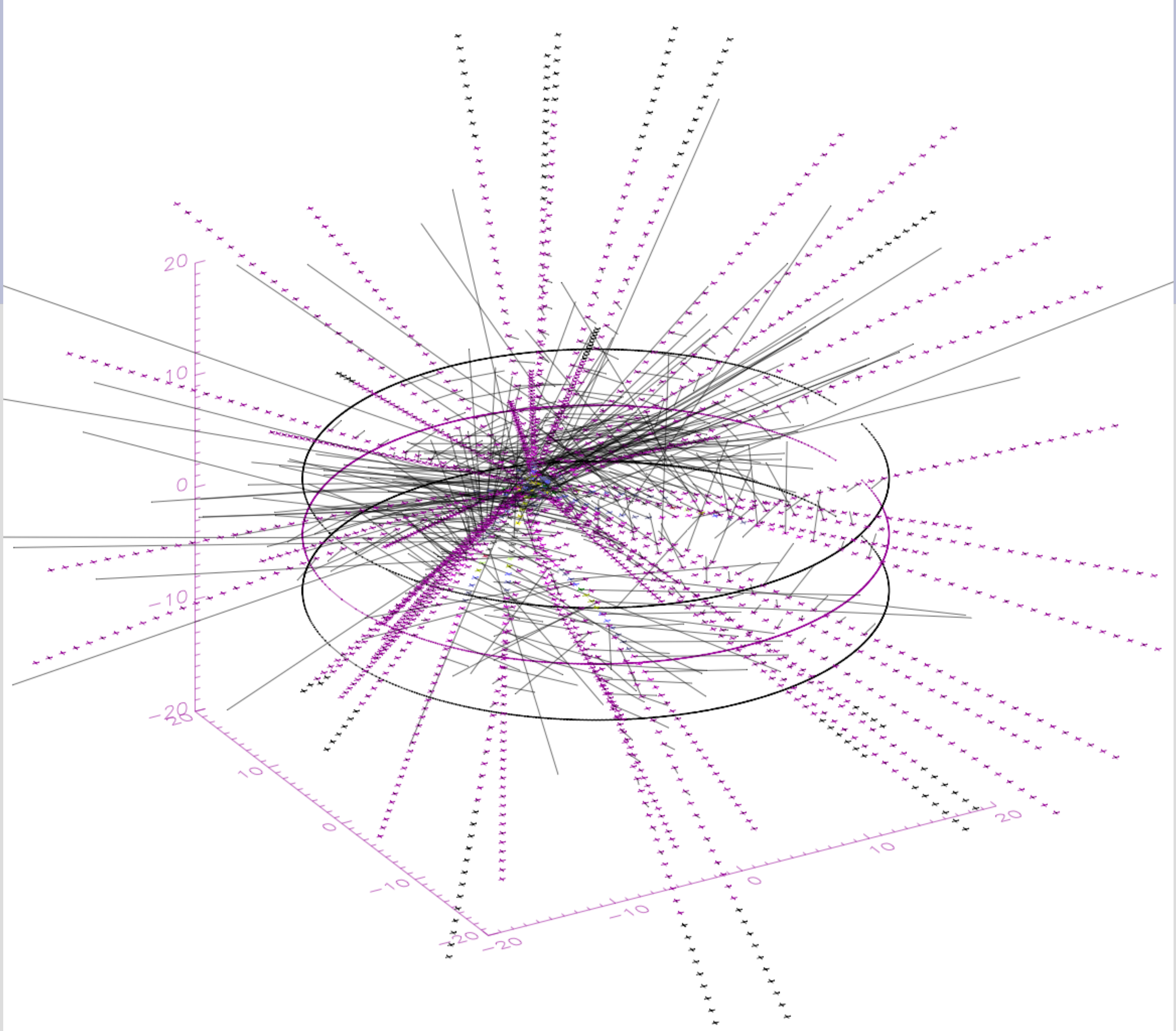


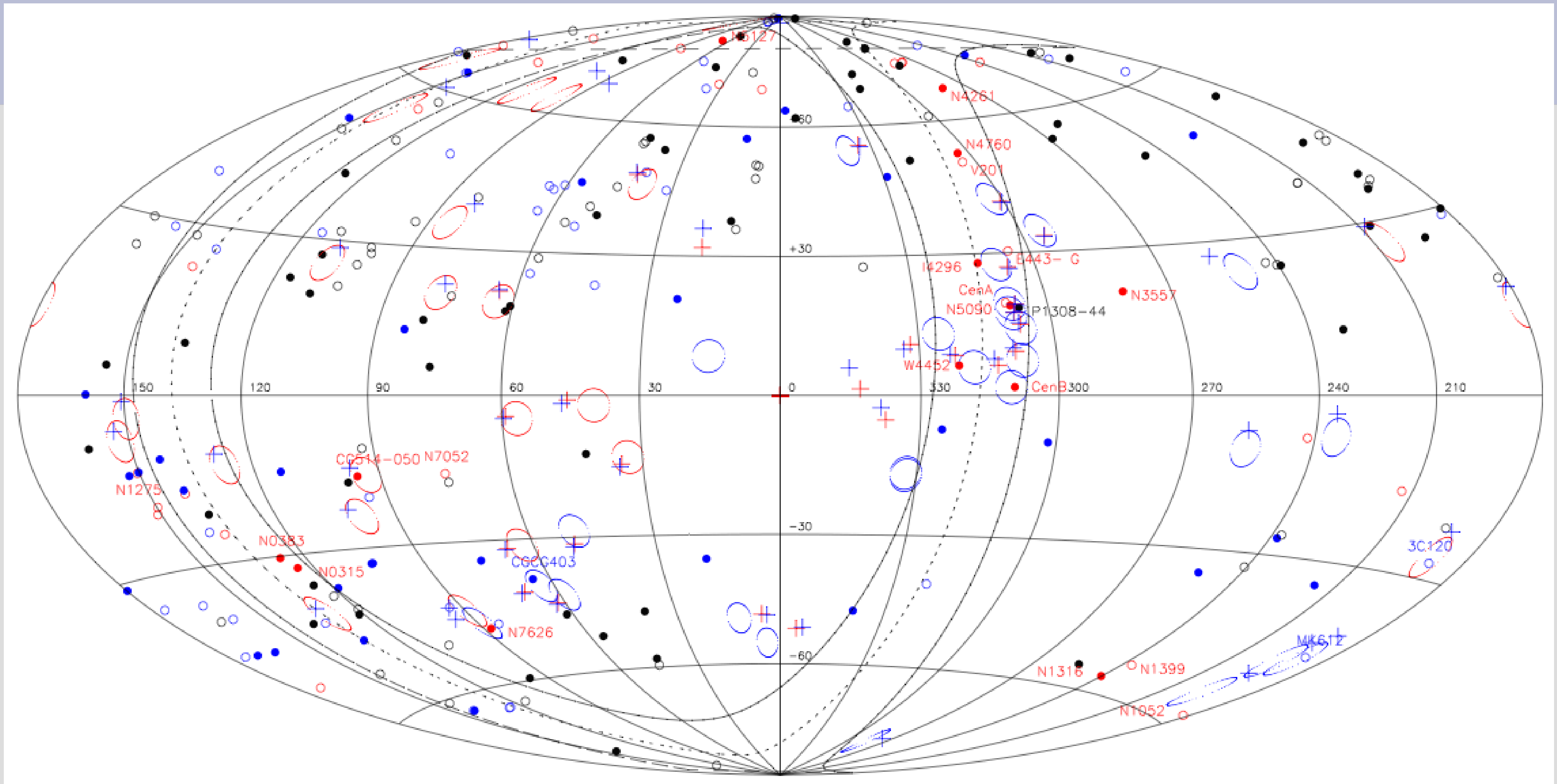
Fig. 14.— Full sky maps of expected deflection angles for protons with the arrival energy $E = 4 \times 10^{19}$ eV. The

Summary: expected deflections are mainly due to intervening clusters and total deflection is within 1 degree



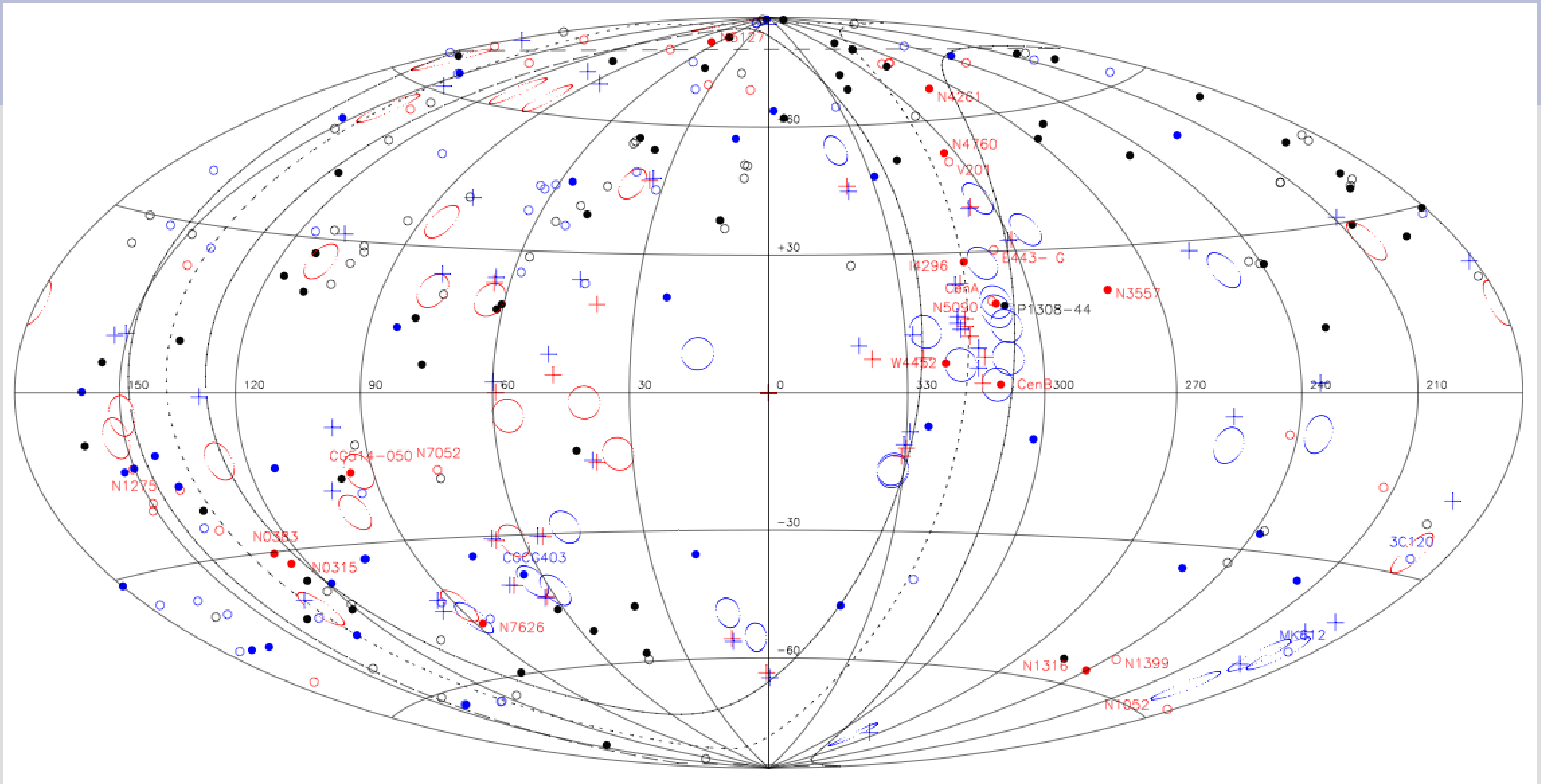
Shoot positrons from the earth (l,b), at each step: UHECR p,v plus model B field used to calculate (linearized) deflection, iterate..

UHECRs in a Galactic B Field: BS-S + dipole



We calculated the original direction of all Auger & Agasa UHECRs
for various Galactic magnetic fields (blue cross = orig. direction)

UHECRs in a Galactic B Field: AS-S + dipole



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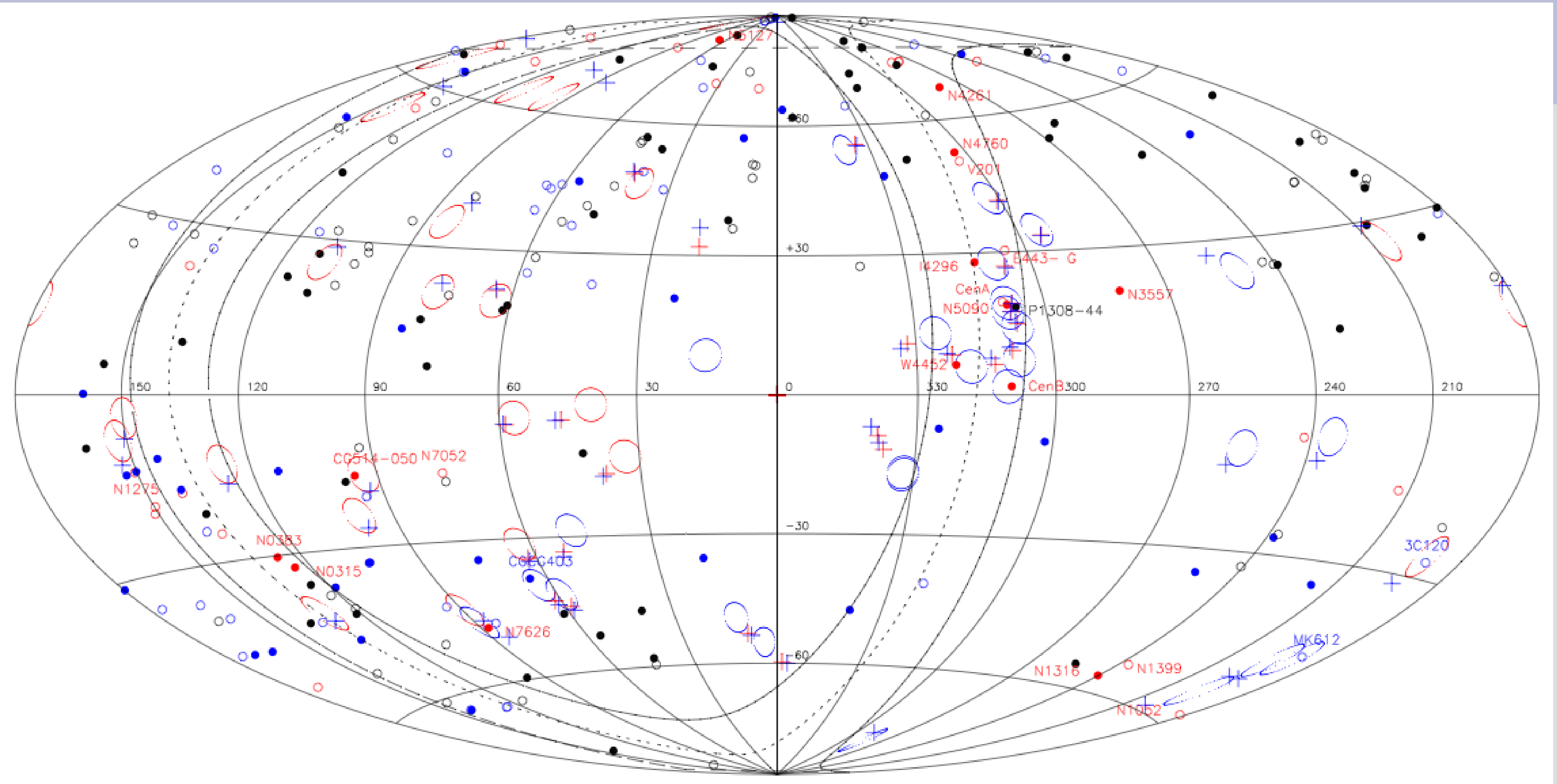
UHECRs in a Galactic B Field: BS-A + dipole



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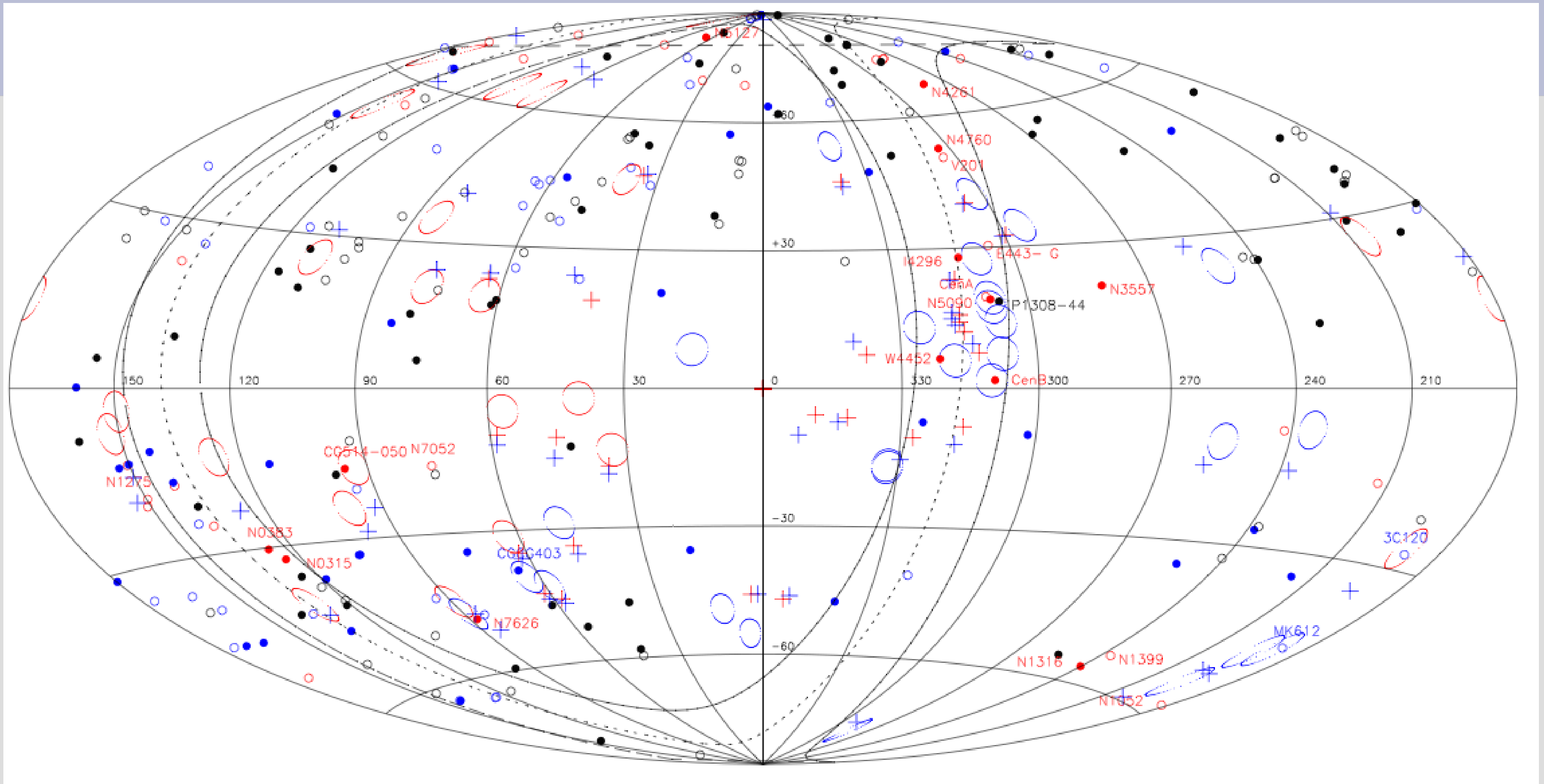
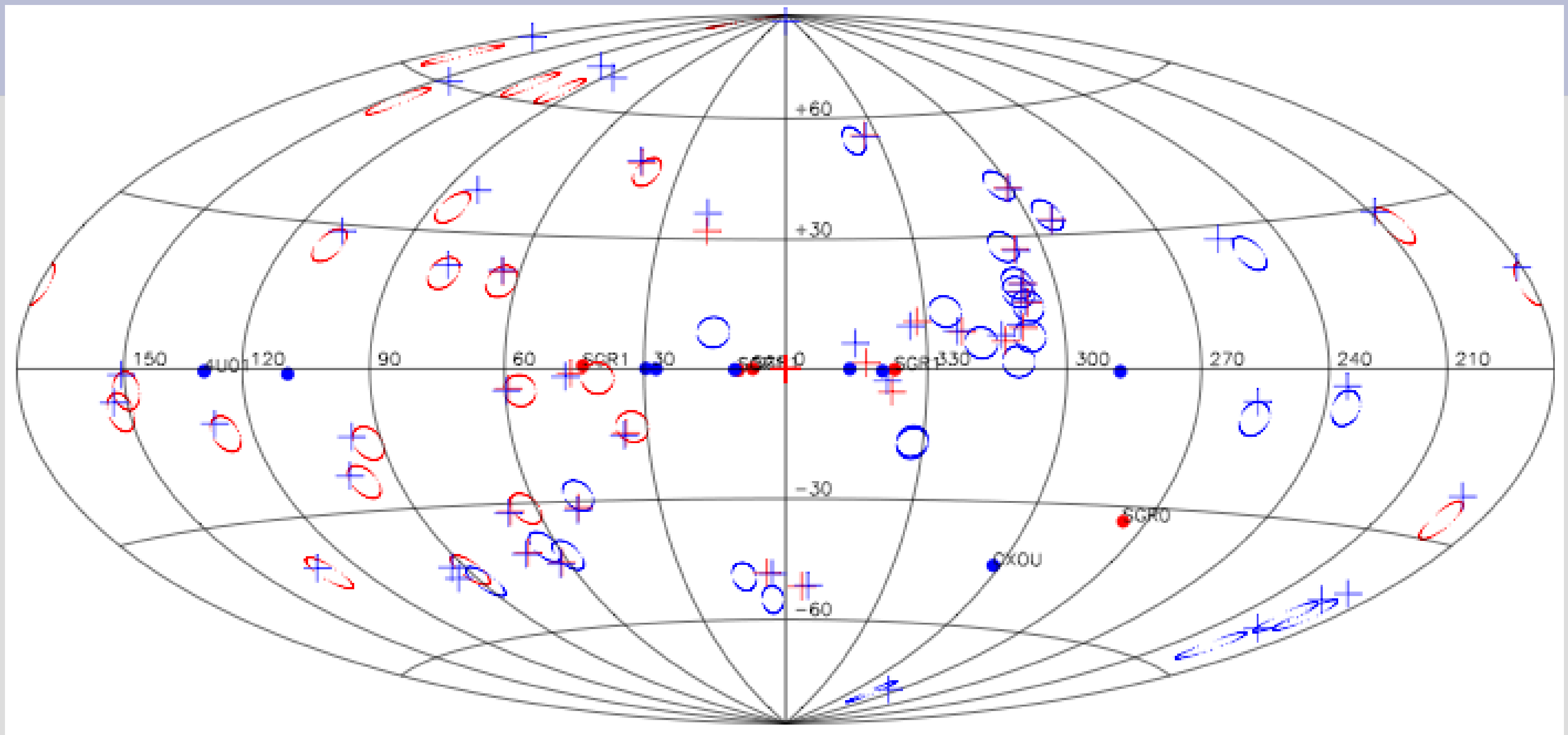
UHECRs in a Galactic B Field: AS-A + dipole

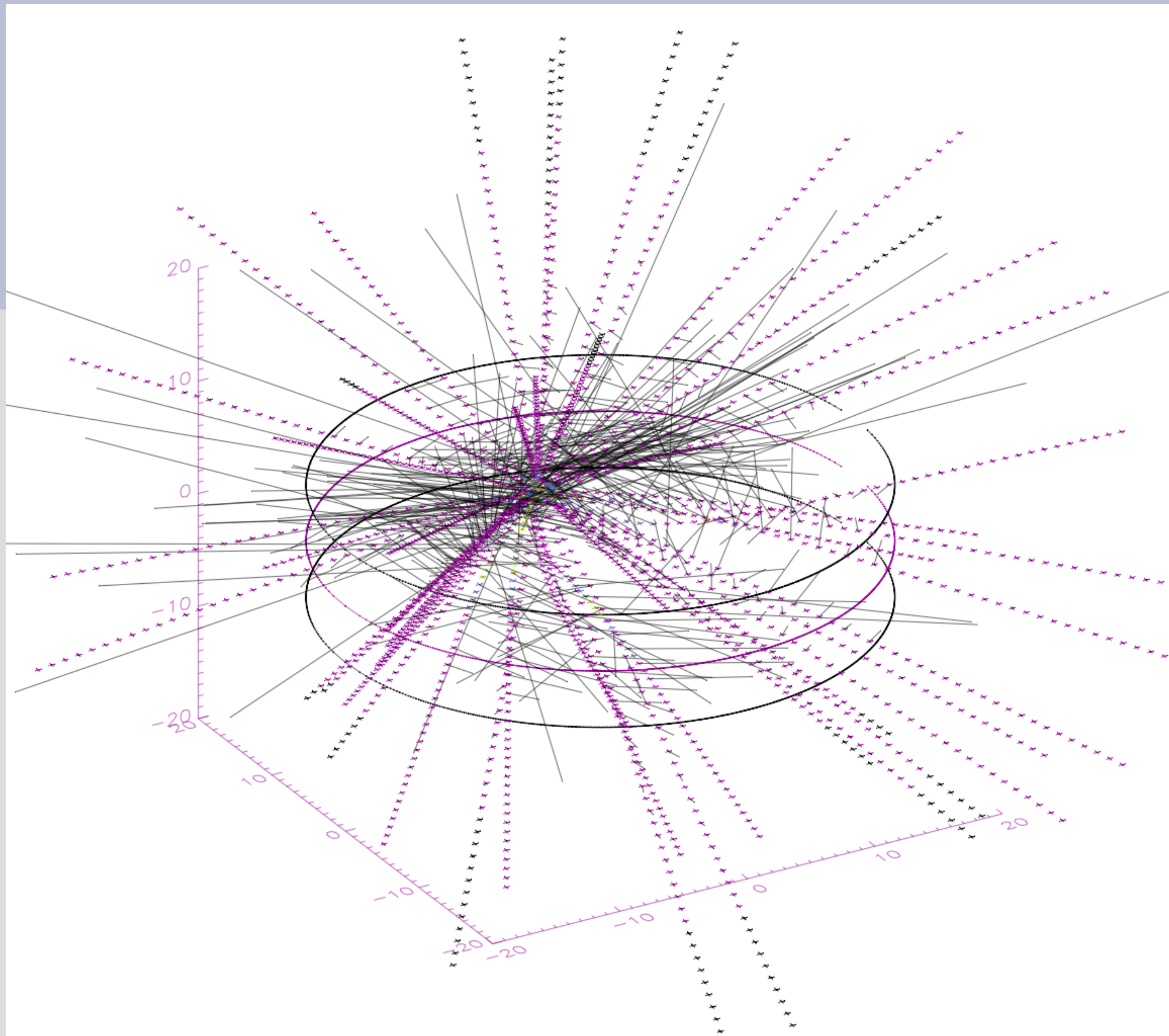


- Extragalactic deflection to be added in all cases

Galactic B Field: BSS + dipole vs. Galactic Magnetars

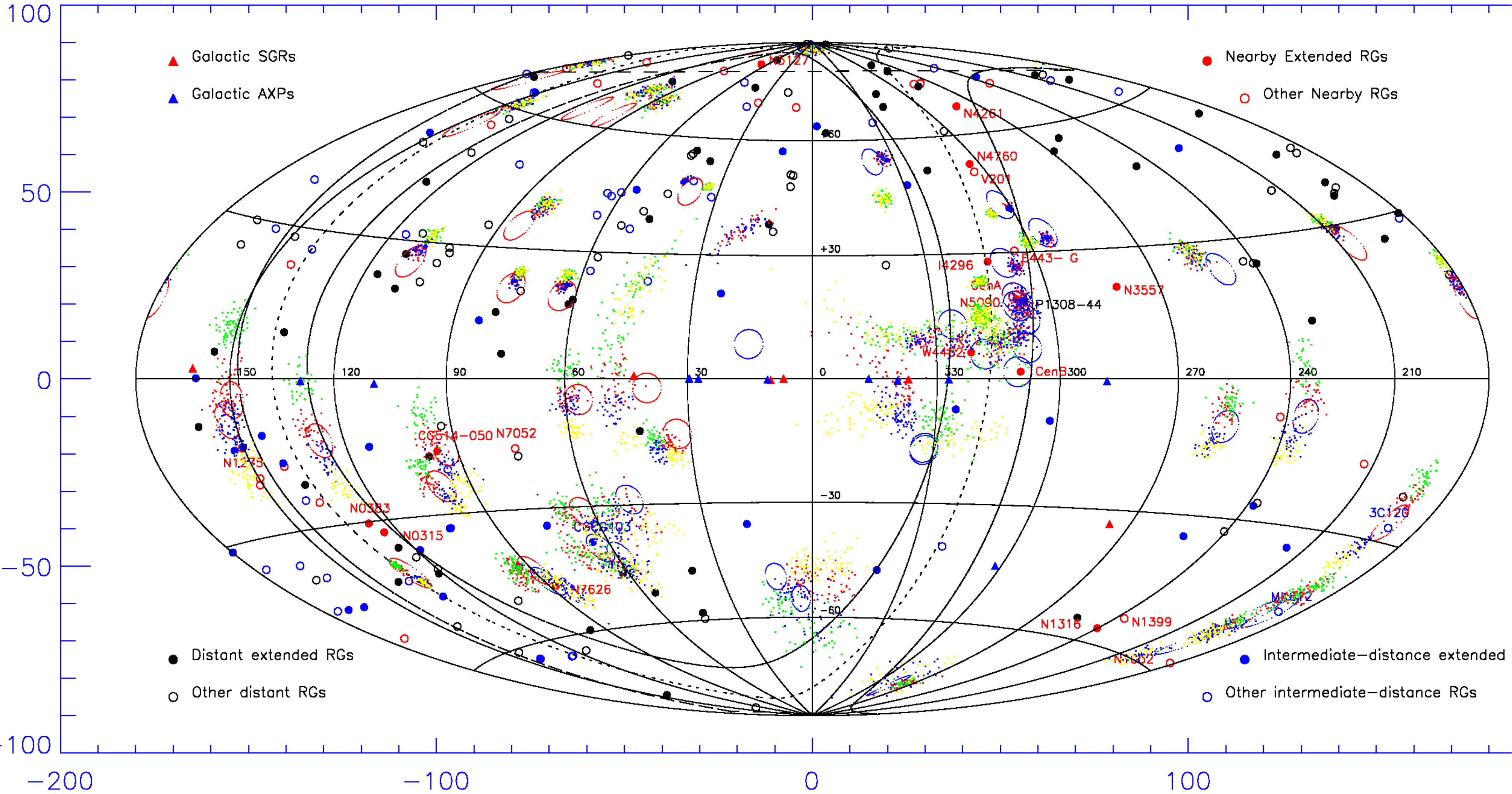


- Red: Soft Gamma Ray Repeaters (SGRs; high energy transient bursts)
- Blue: Anamalous X-ray Pulsars (AXPs; persistent pulsations, rapid spin down, sometimes SGR-like bursts)



Need to include Monte-Carlo for each UHECR : at each step calculate model B field, add uncertainty + turbulent field -> deflection -> iterate

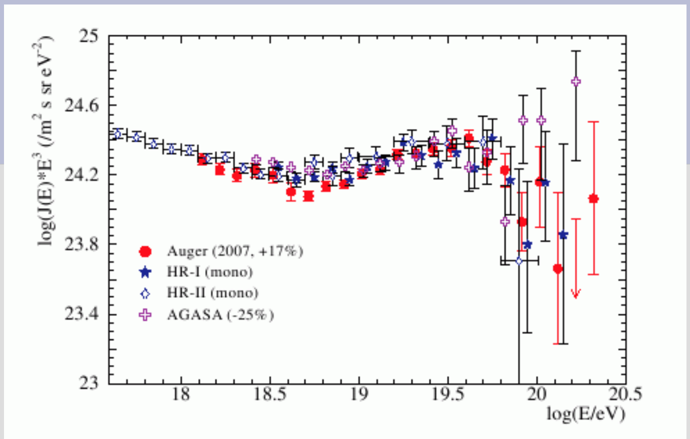
Mixed BSS and ASA: radiogalaxies + Galactic SGRs + extragal?



err B = 50% Turbulent: 50pc scale length, max field 10microG, diff probabilities for spiral arms, disk, halo

BSS=red ASS =green BSA=blue ASA=yellow

In preparation (Nagar & Matulich Paper II)



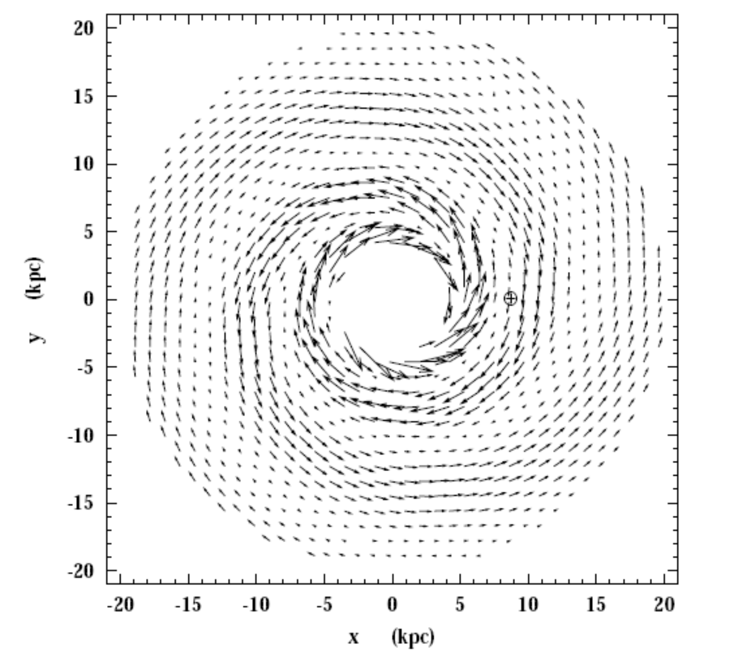
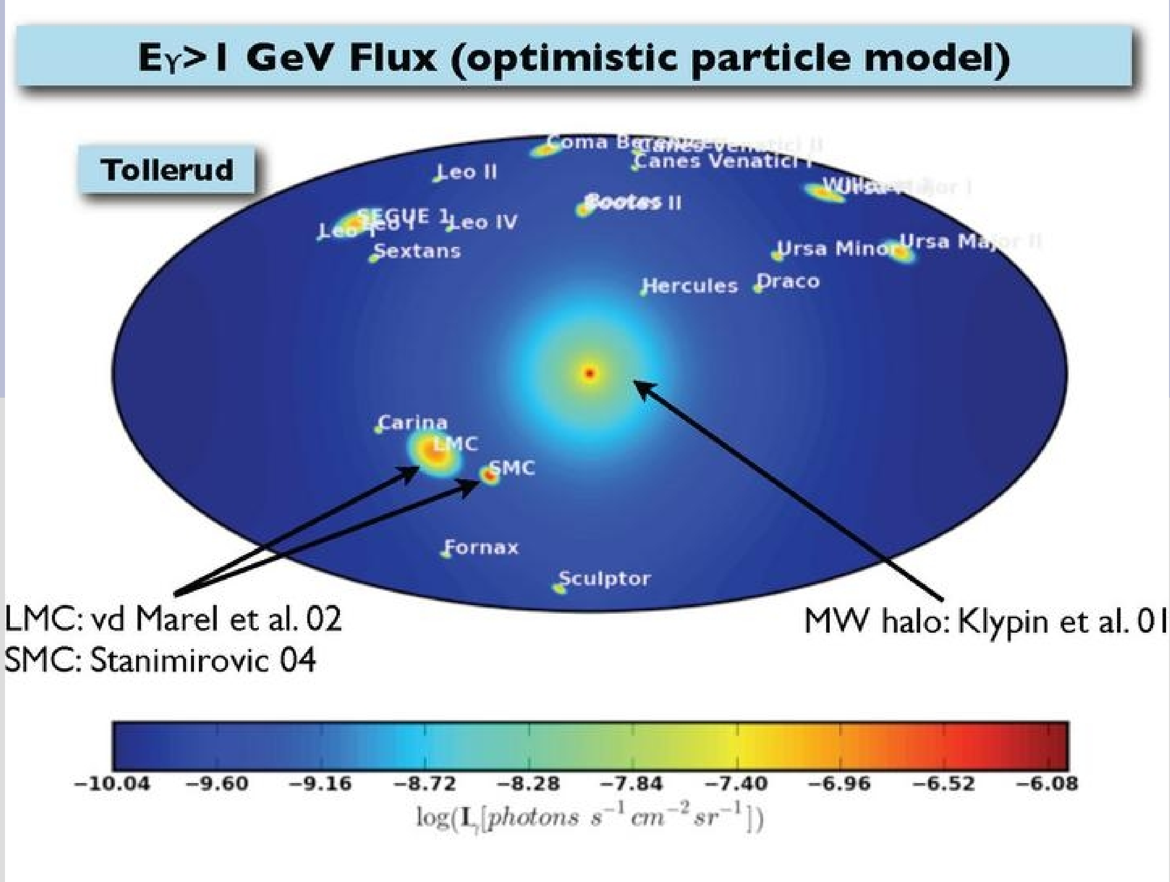


FIG. 1.—Magnetic field configuration in the Galactic plane. The vectors indicate the field direction, and their length is proportional to its magnitude.

- Monte Carlo:
  - Galactic B field models/data + uncertainties
  - Turbulent field (upto 10 microG ?)
  - Radiogalaxies + Galactic magnetars?
  - Thus constrain B field models...
  - Multiple event matches: trajectories and delays
  - Investigate "empty sky" (after deflections) UHECRs
- UHECR spectrum from radiogalaxies (distance + GZK)

Other possibilities



James Bullock

- Dark matter anhilation
- micro (primordial?) Black Hole evaporation
- GRBs : difficult to test directly (time delay)
- Current statistics too poor to fully discuss these...

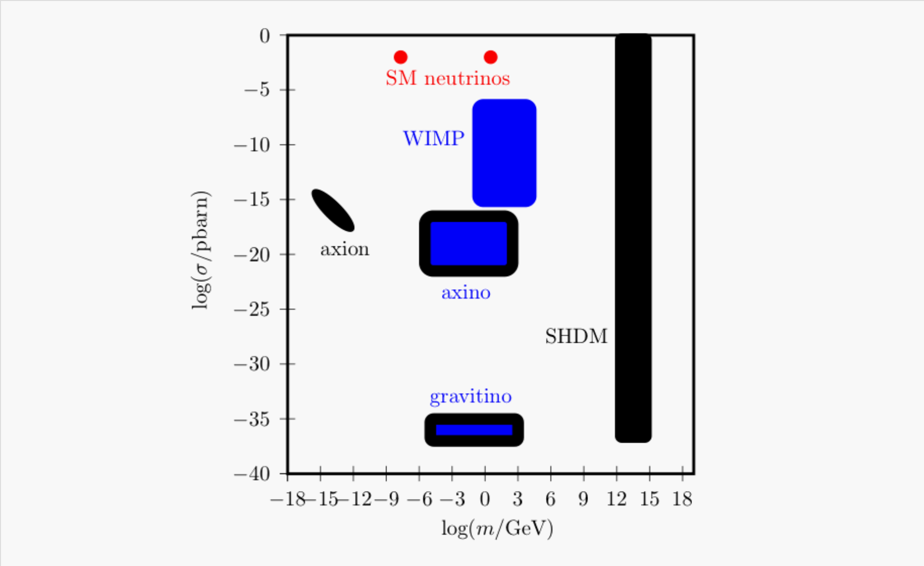


Figure 8.2: A selection of dark matter candidates in the plane cross section versus mass; blue and black corresponds to thermal and non-thermal as main production channel.

Resúmen

- Radiogalaxias cercanas y extendidas son fuentes de UHECRs
    - Fuerte evidencia estadisticalmente
- agregando campos magneticos:
    - puedemos explicar > 50% de UHECRs con radiogalaxias
- Magnetars (esp. Galacticos) tambien candidatos
- Hard X-ray emitting AGNs: candidatos potenciales
- Necesitamos explicaciones más exoticos actualmente?
- Campos Magneticos importantes támbien en estas energias
- Con mejor estadistica (PAO ahora en "full" operación)
    - Map campos magneticos: Galacticos y Intergalacticos
        - Galactic evolution, star formation ......
    - Entender los aceleradores de altisima energias
    - Calientamente de IGM por UHECRs

Particles: help!

- Fermions

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2				Quarks spin =1/2		
Flavor	Mass GeV/c^2	Electric charge		Flavor	Approx. Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0		u up	0.002	2/3
e electron	0.000511	–1		d down	0.005	–1/3
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0		c charm	1.3	2/3
μ muon	0.106	–1		s strange	0.1	–1/3
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0		t top	173	2/3
τ tau	1.777	–1		b bottom	4.2	–1/3

Mesons