UltraHigh Energy Cosmic Rays Corrected for Galaxy Magnetic Field Models: FRIs & BL Lacs (Galactic Plane sources?)

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Nagar & Matulich 2008, A&A, 488, 879
Nagar & Matulich, A&A, submitted

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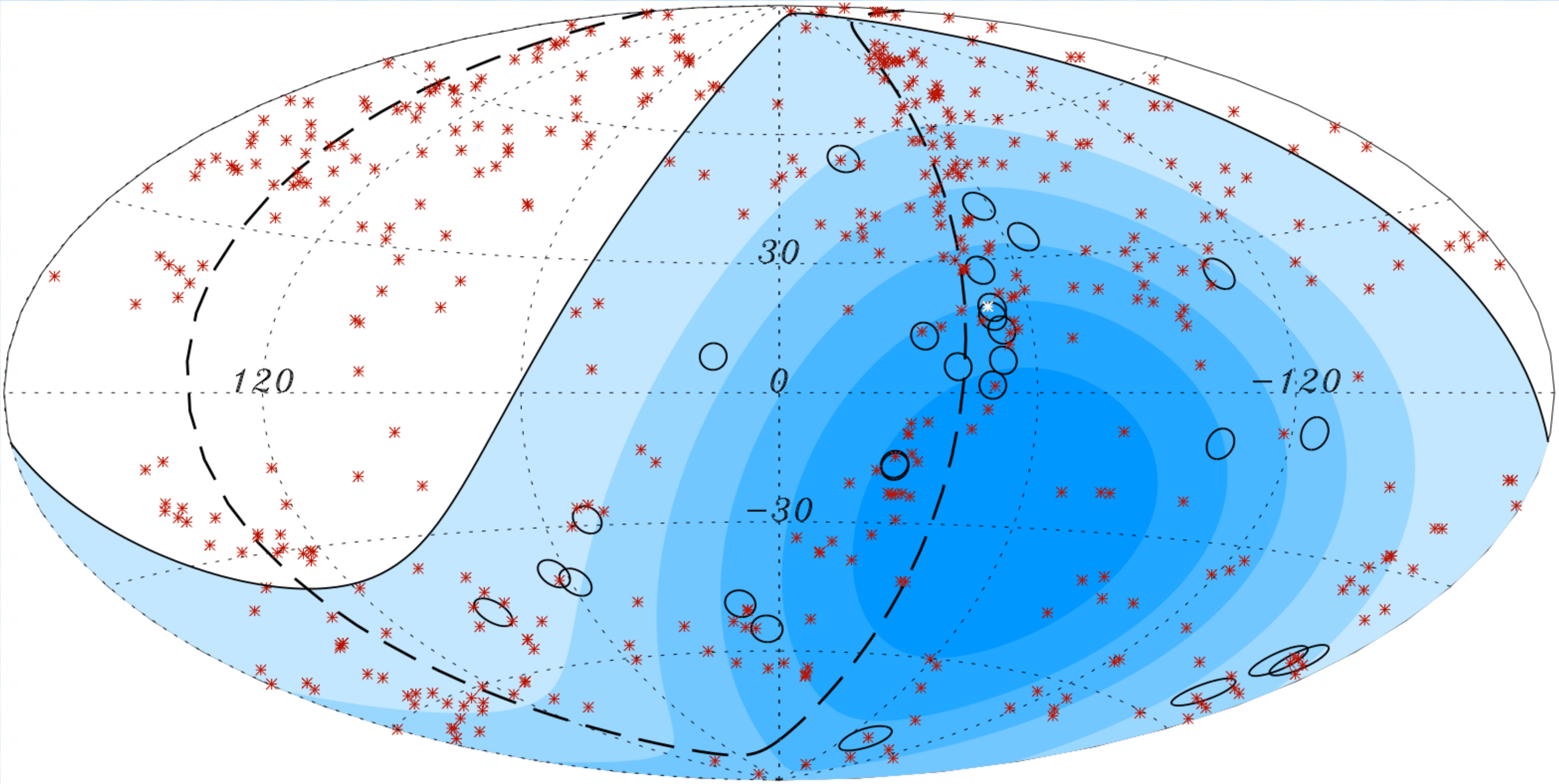
Overview

- UHECRs and nearby extended Radiogalaxies: inital
- Galactic and Extragalactic Magnetic Fields
    - Monte Carlo
    - UHECR trajectories
    - Potential source populations

Pierre Auger Collaboration et al. 2007, Science

(after 3 years of partial operation)



- The 27 UHECRs with E > 56 EeV are not isotropic
- Correlation with nearby AGNs (Veron-Cetty & Veron catalog)

George et al. 2008:

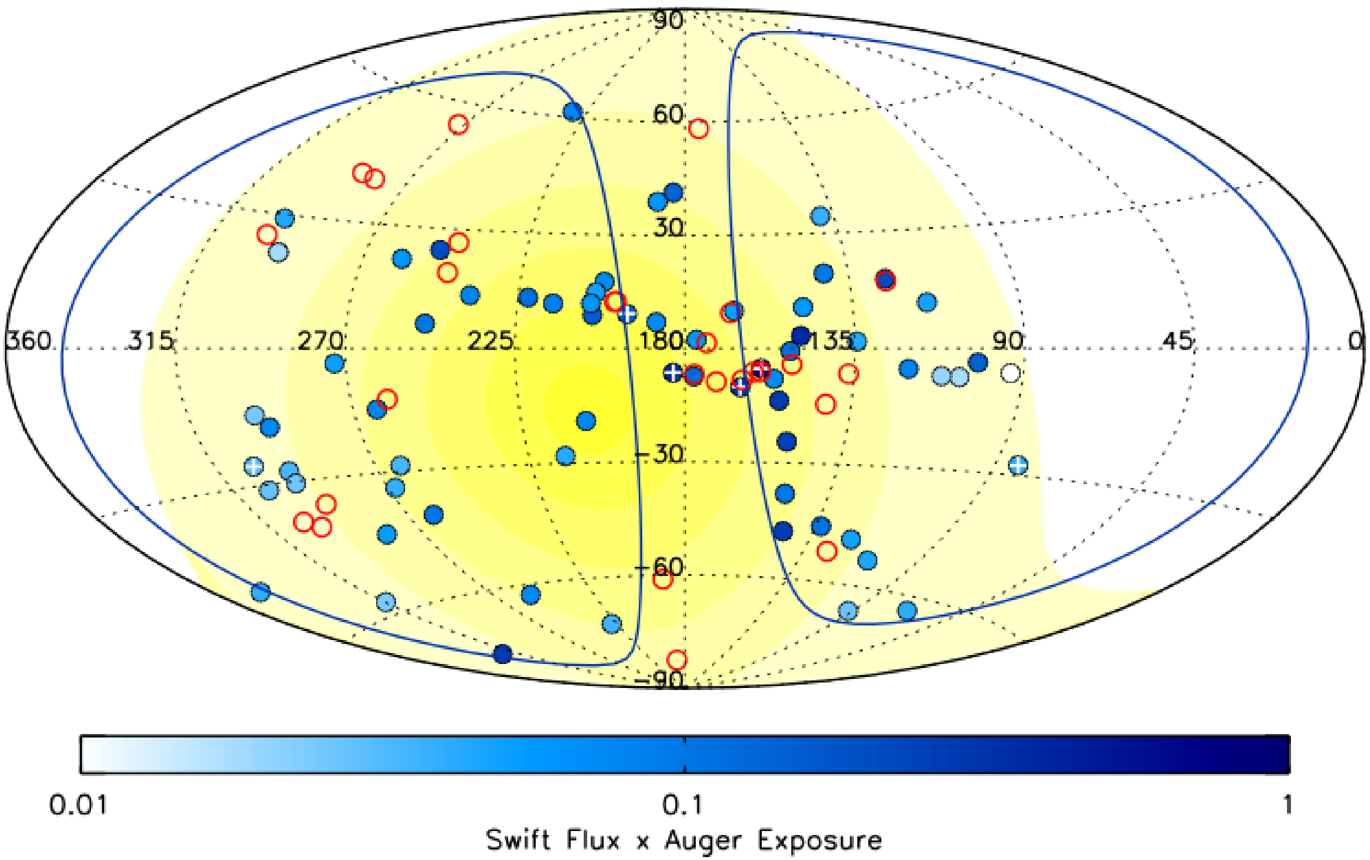
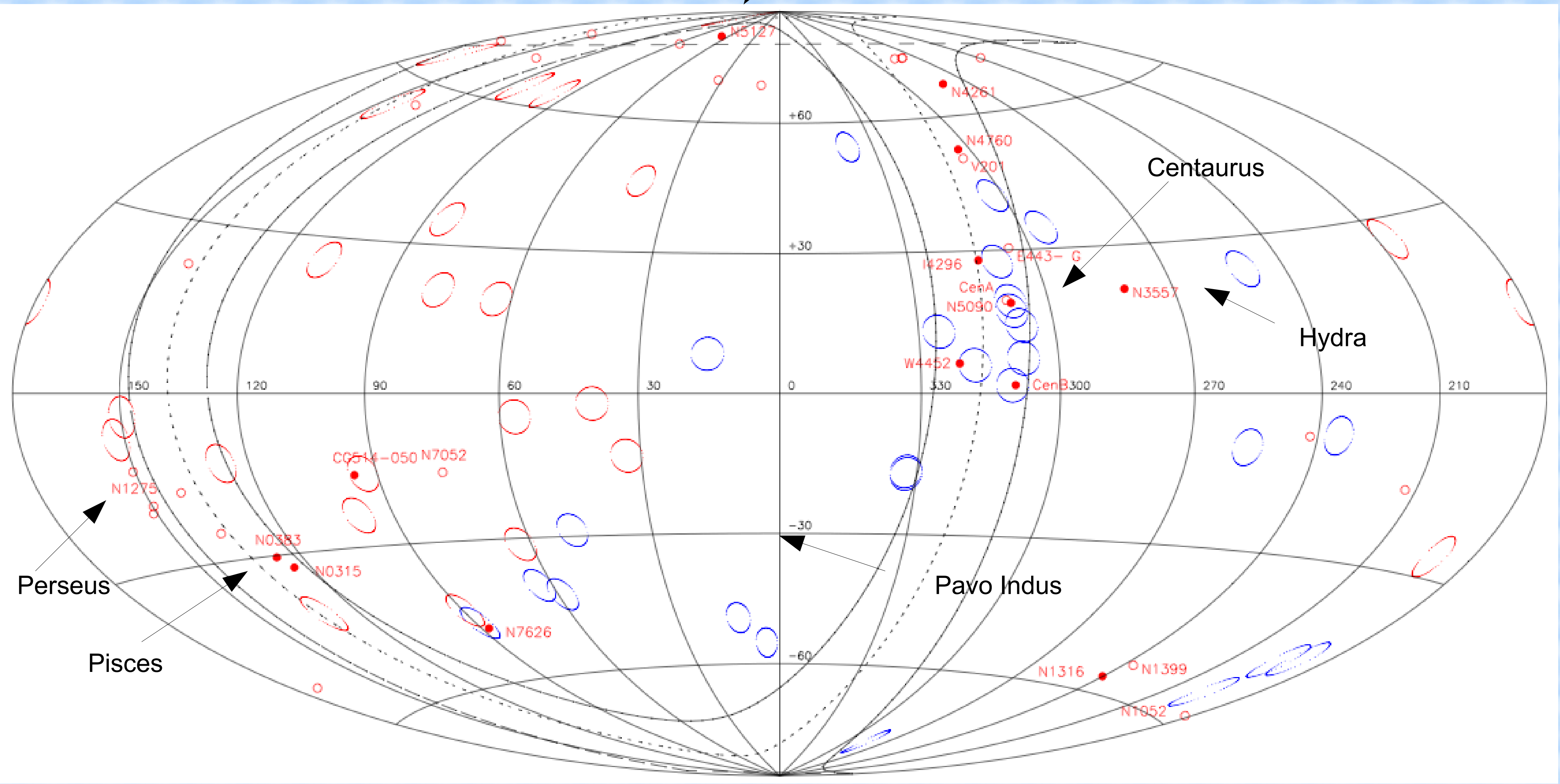


Figure 1. Map of Auger UHECRs (open red circles) and BAT AGN within 100 Mpc (filled blue circles) in supergalactic coordinates (de Vaucouleurs et al. 1976). The blue colour depth is scaled by the hard X-ray flux and Auger exposure, relative to Cen A. The 6 AGN in the catalogue within 20 Mpc are marked 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%

D < 75 Mpc Radiogalaxies



- D < 75 Mpc
- Red solid symbols: D < 75 Mpc and radio extent > 180kpc
- Were we all tracing the same underlying population?

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D < 75Mpc radiogalaxies

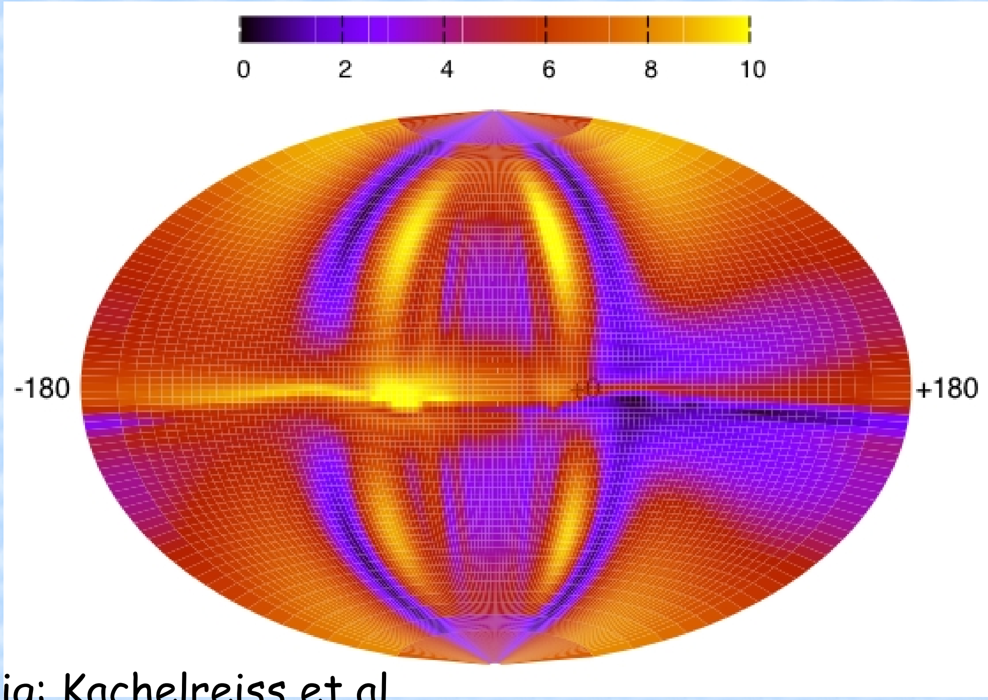
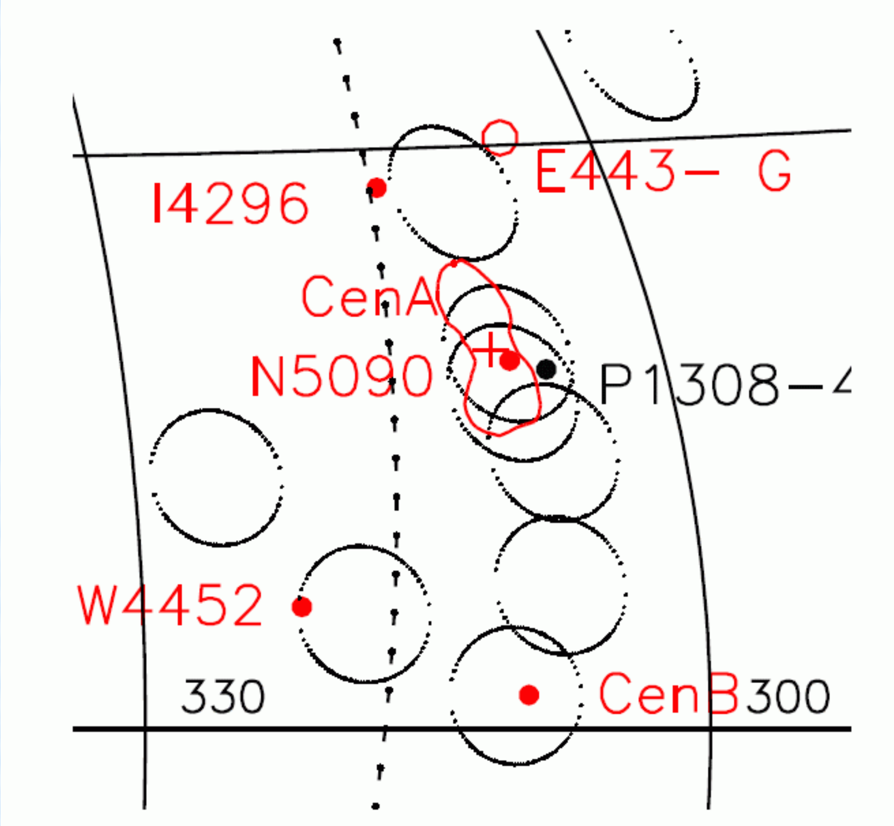


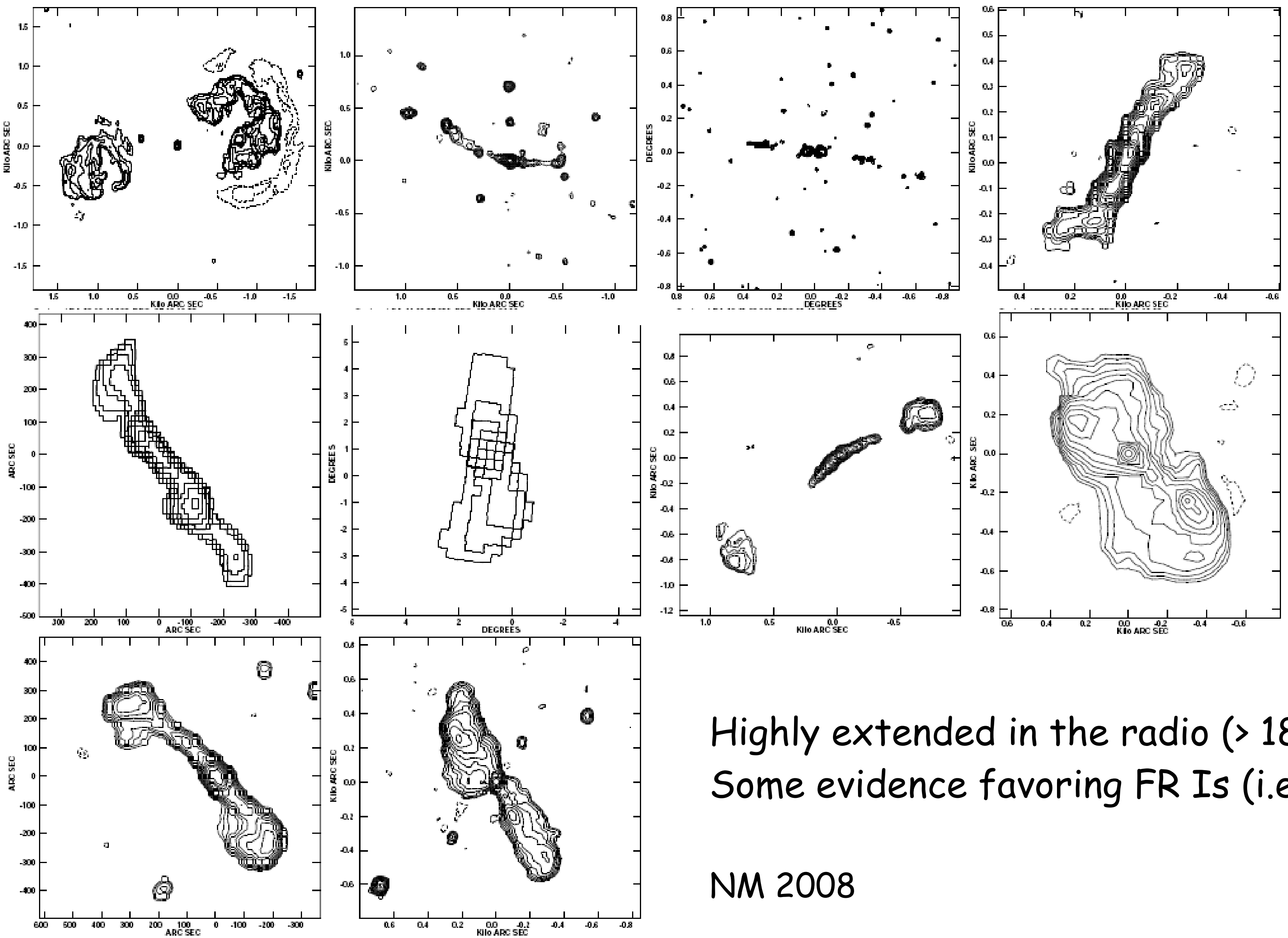
Fig: Kachelreiss et al.



The Cen A region

- 8 of 27 UHECRs within 3.5deg of extended radiogalaxies
- 6 of 10 extended radiogalaxies matched to UHECRs
    - 3 of 4 remaining are in areas of low exposure time (and clusters)

Radiogalaxy morphologies



Highly extended in the radio (> 180kpc)
Some evidence favoring FR Is (i.e. “BL Lacs)”

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Radiogalaxies

- Several previous works attempted correlations with BL Lacs
  - we are doing the same (as long as the lobes are mirrors)
  - extra selection on radio extent (difficult for BL Lacs)
- Relatively low incompleness for extended nearby FRI and BL Lacs
- Propagation time delay:
  - do jet-flux weighted catalogs make sense for R.G.s?
  - we have some history in the jets and lobes .

Ghisellini et al. : galaxies from HIPASS

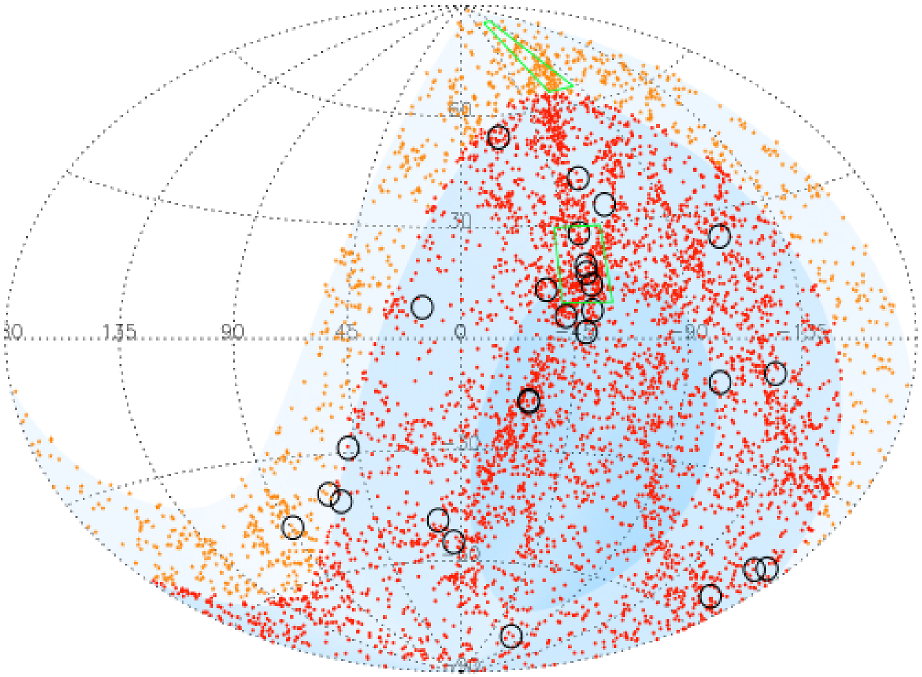


Figure 1. H I Parkes All–Sky Survey (HIPASS) galaxies (solid filled symbols) and the 27 AUGER UHECRs (black open circles) in galactic coordinates. Blue levels corresponds to the AUGER relative exposure. The south H I catalogue (HICAT – 4315 sources) and the north extension (NHICAT – 1002 sources) are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

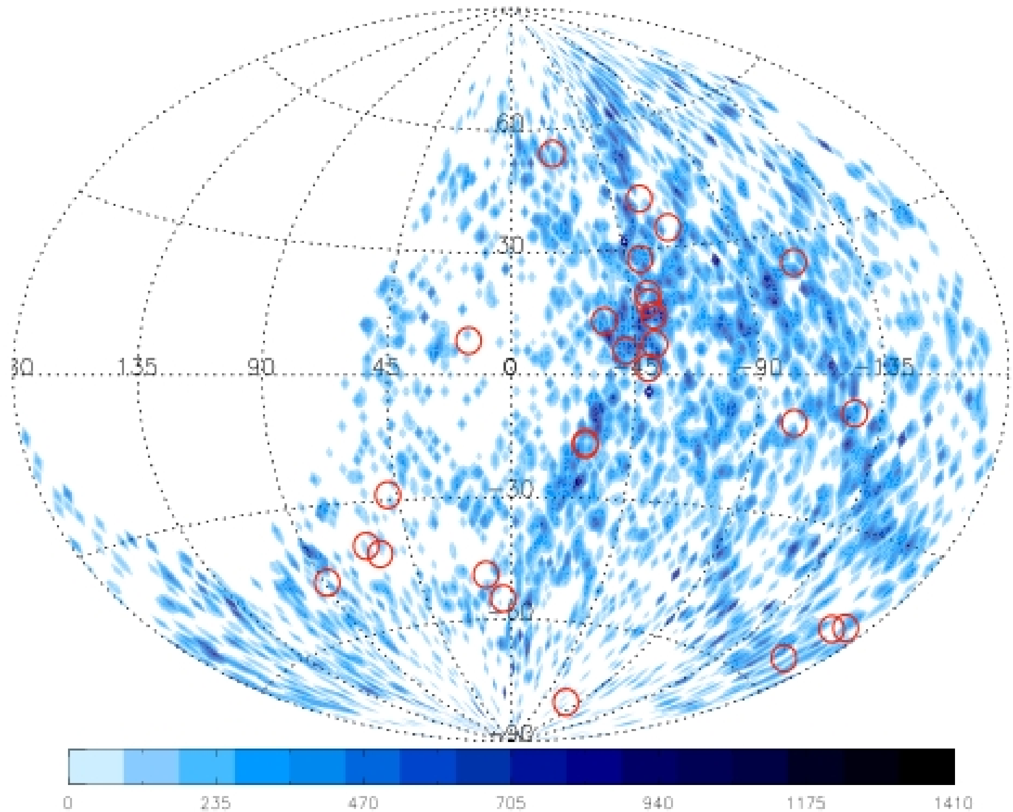
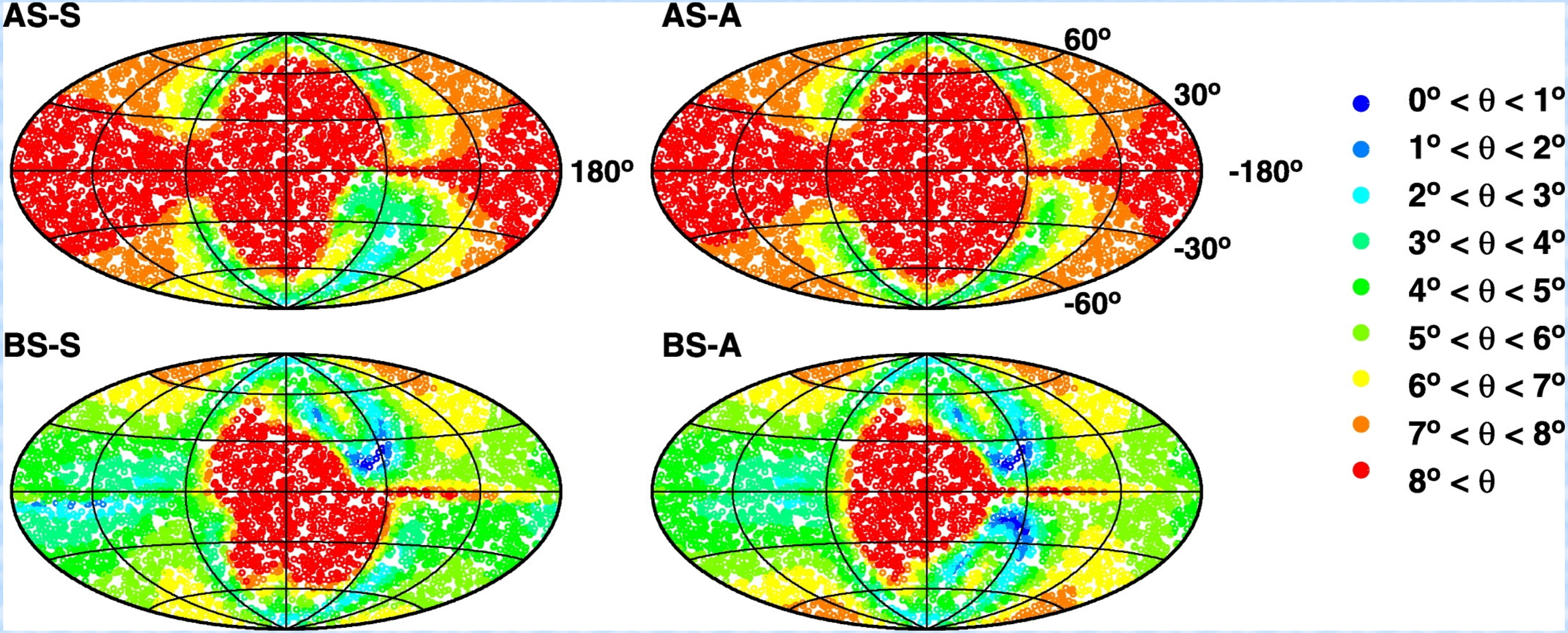


Figure 2. HIPASS galaxy H I flux, in galactic coordinates. Blue levels corresponds to the integrated flux (in bins of $2° \times 2°$ and units of Jy km s^{-1}) of H I emission, multiplied by the relative AUGER exposure. Red circles are the locations of the 27 AUGER UHECRs above 57 EeV.

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

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....)

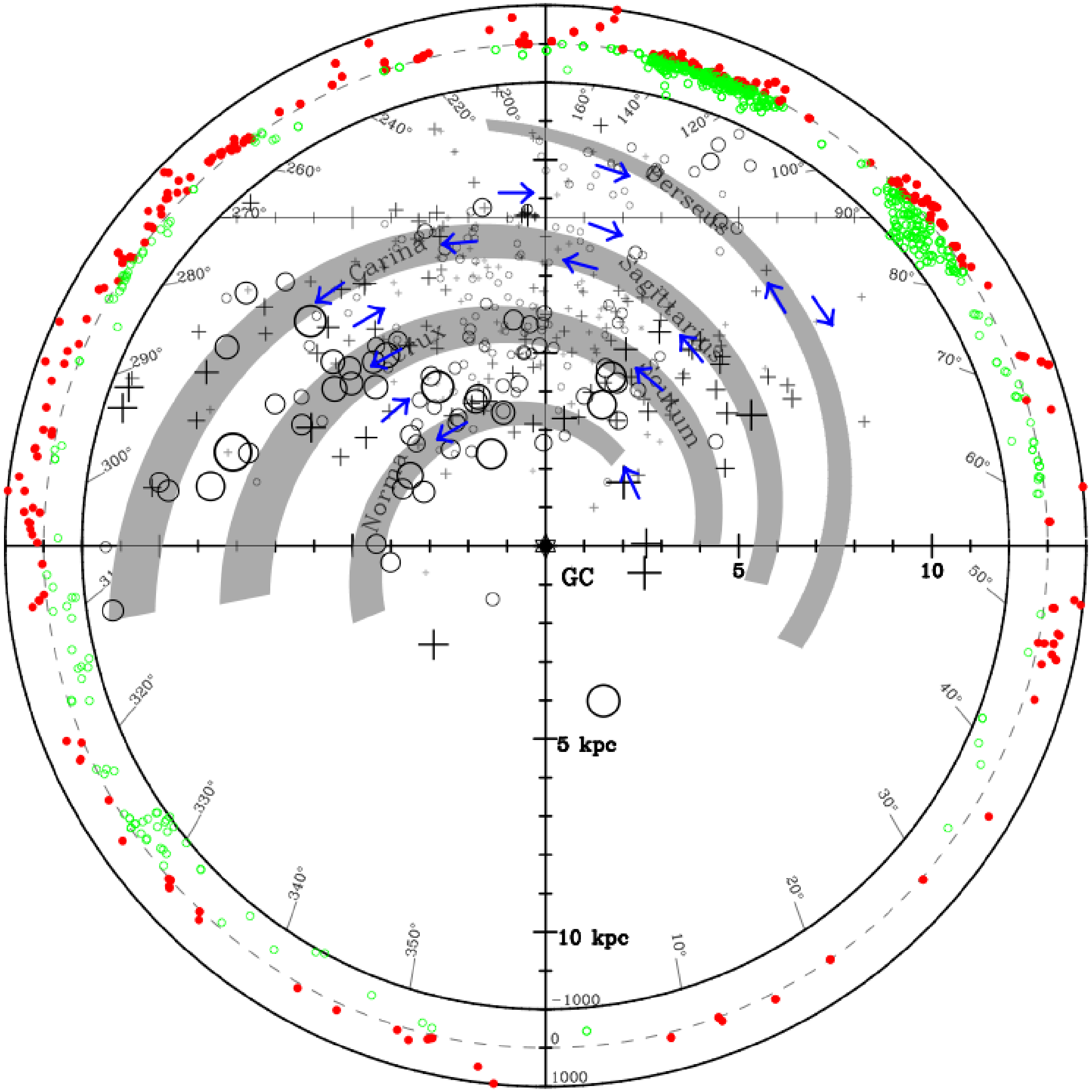


Figure 1. The RM distribution of 374 pulsars with $|b| < 8°$, projected onto the Galactic plane. The linear sizes of the symbols are proportional to the square root of the RM values. The crosses represent positive RMs, and the open circles represent negative RMs. The approximate locations of four spiral 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

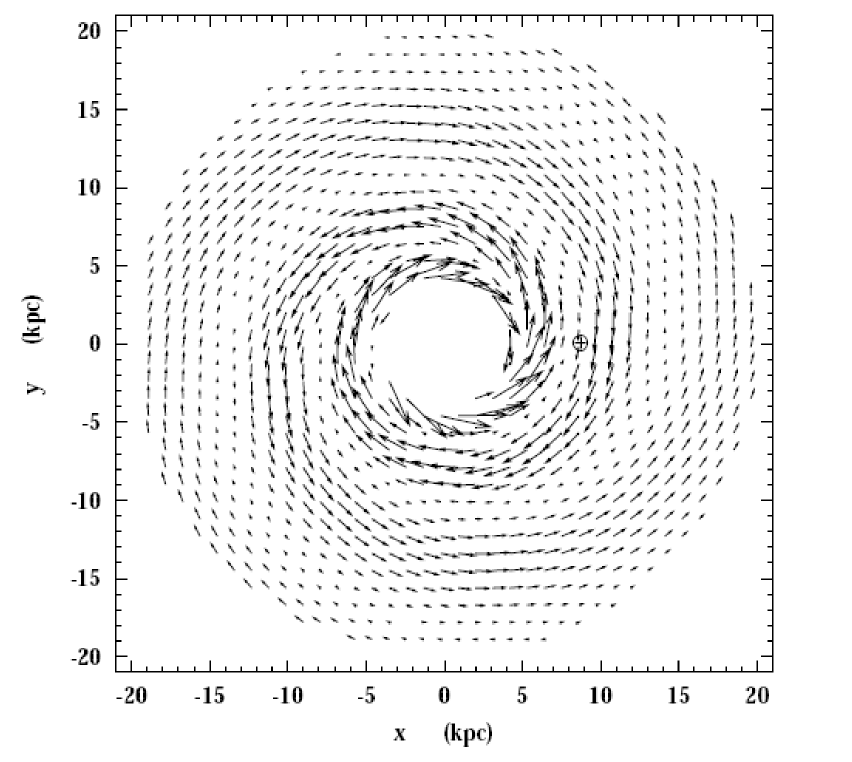
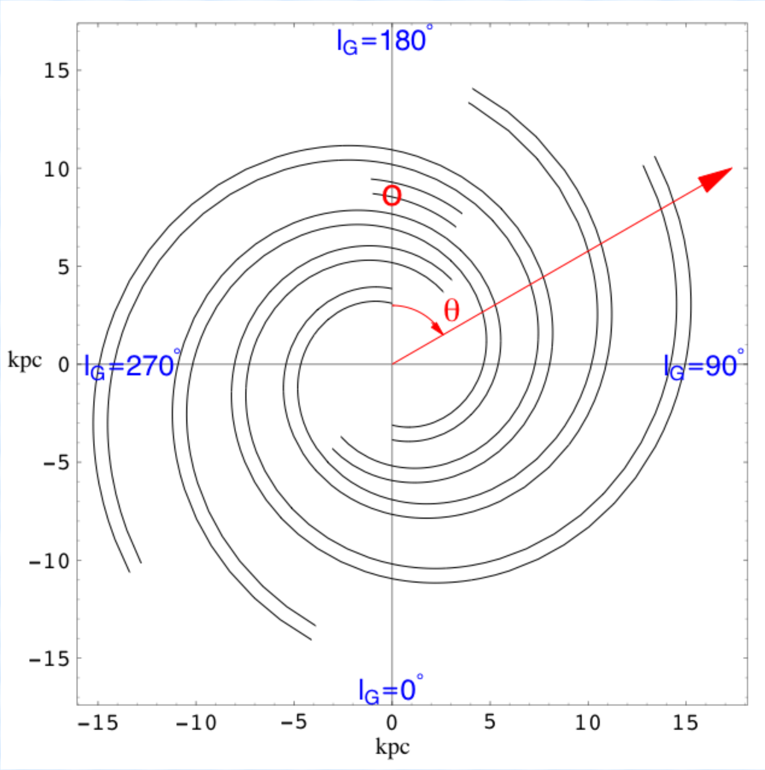


FIG. 1.—Magnetic field configuration in the Galactic plane. The vectors indicate the field direction, and their length is proportional to its magnitude.



Figures from Alvarez-Muniz etal, Kachelriess etal

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

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

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

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

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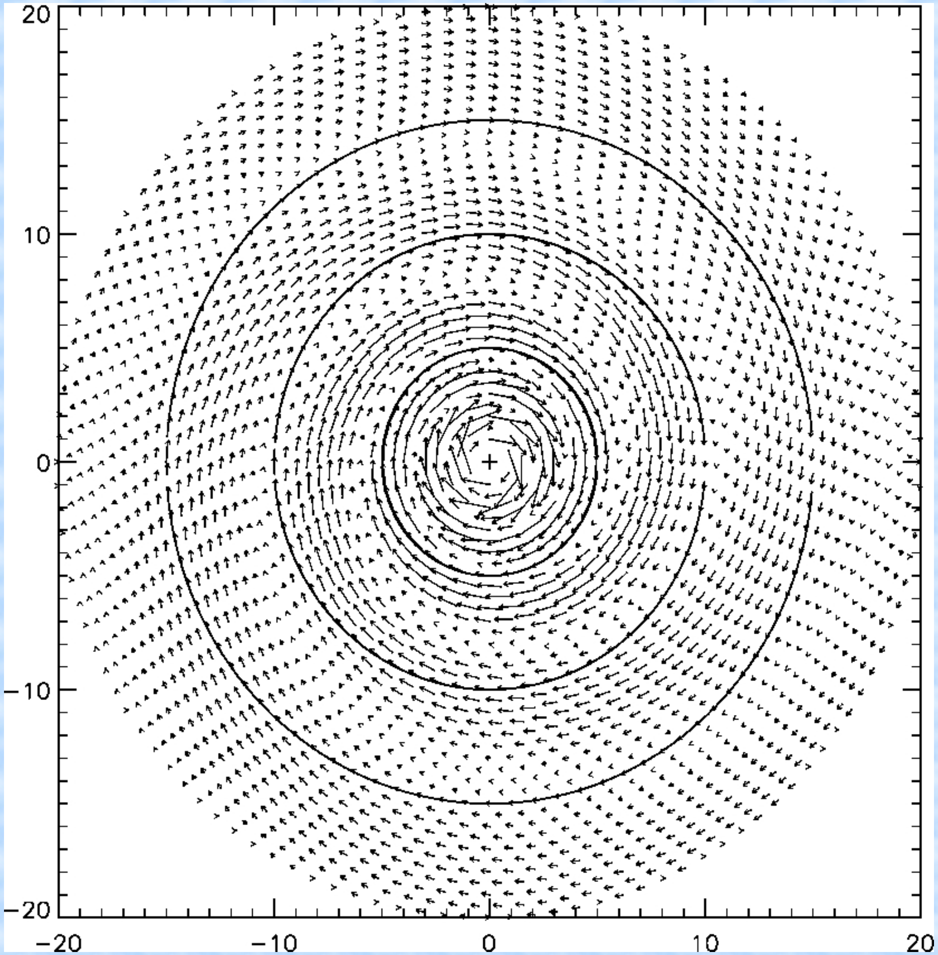
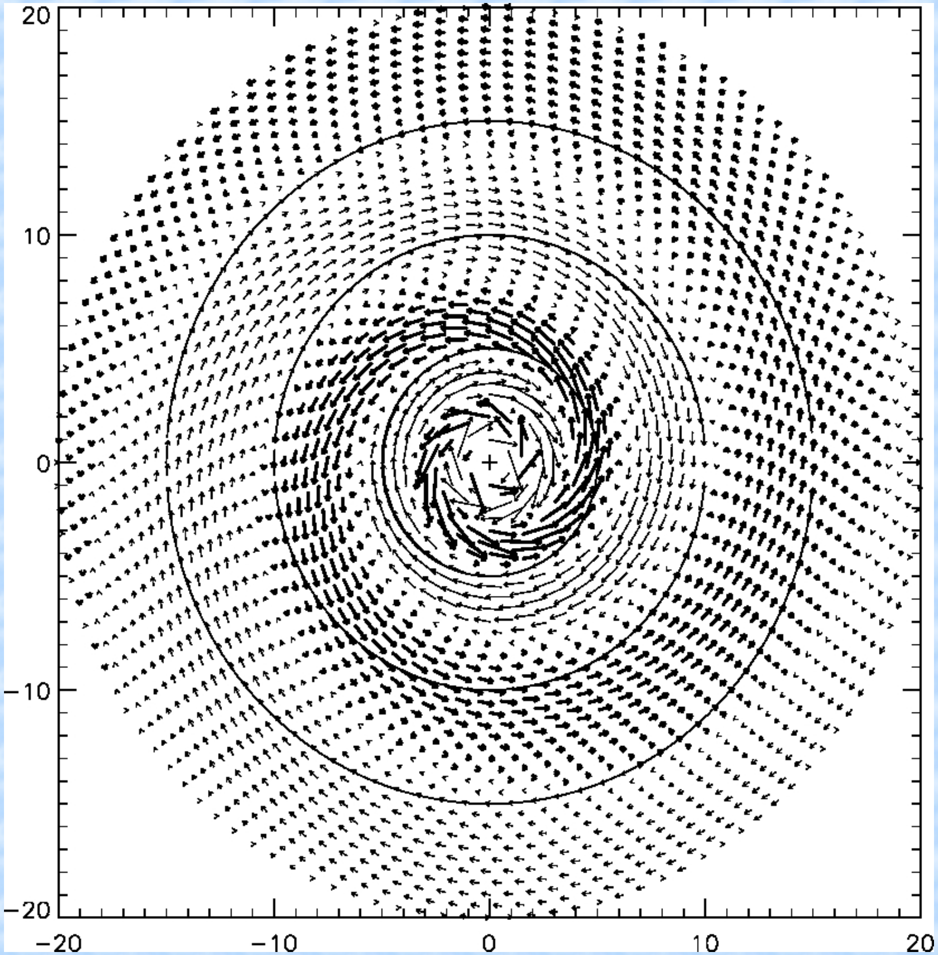
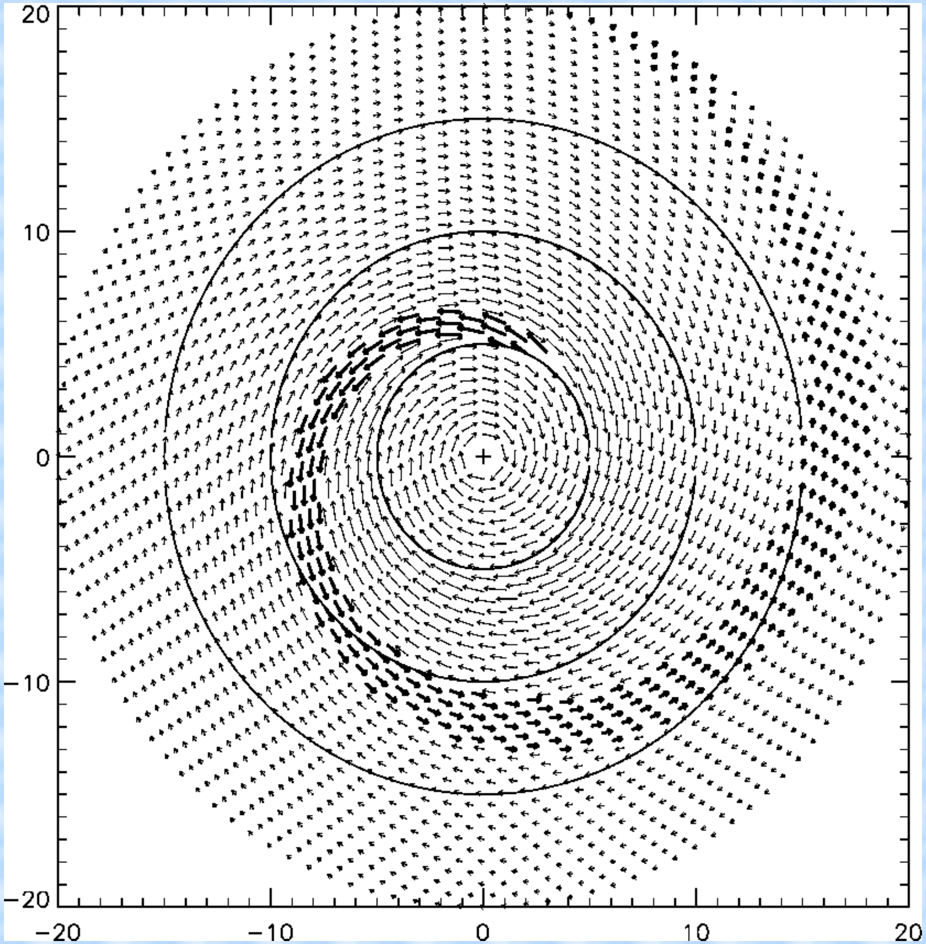


AS-S (AS-A)

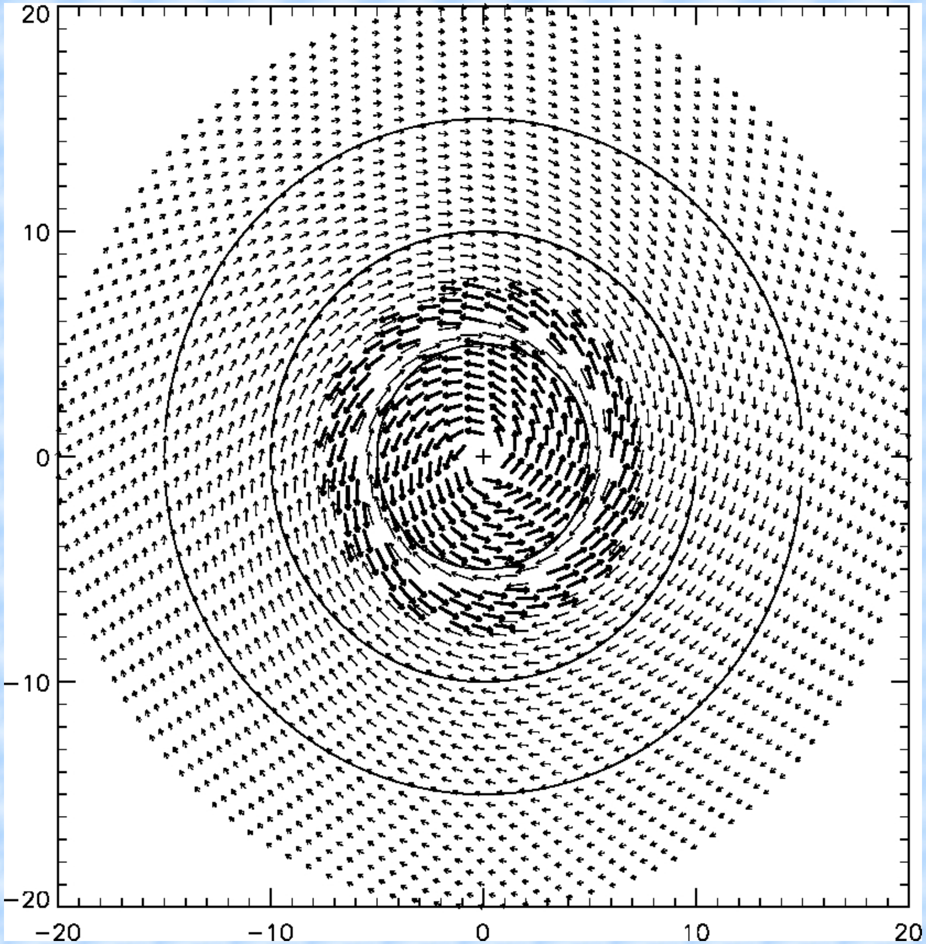


BS-S (BS-A)

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



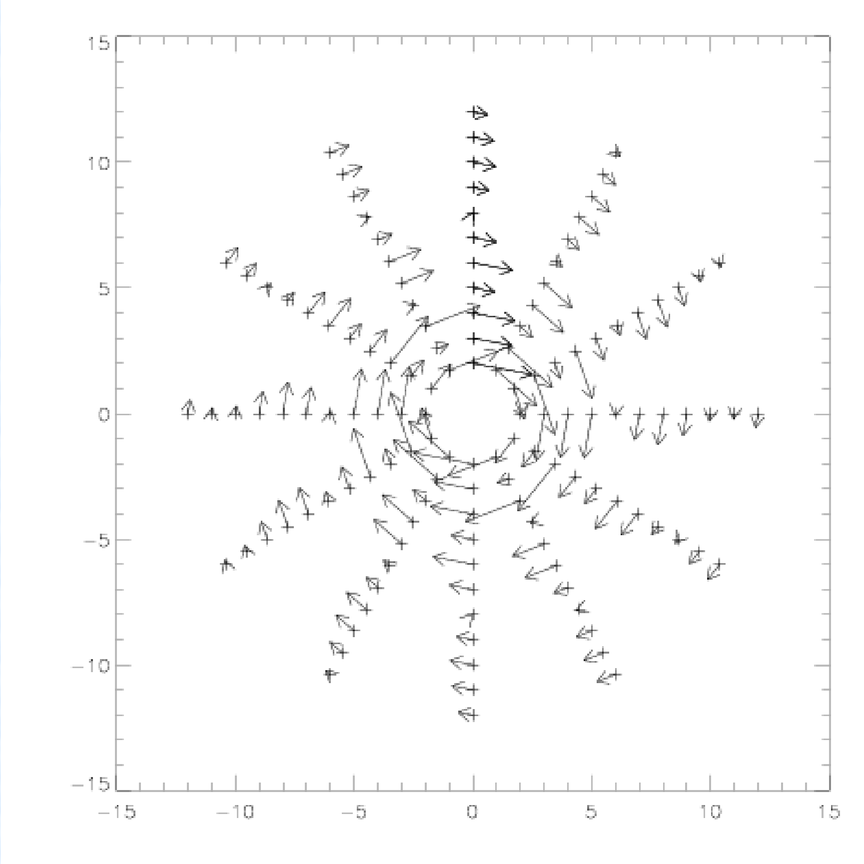
ASS+ARM

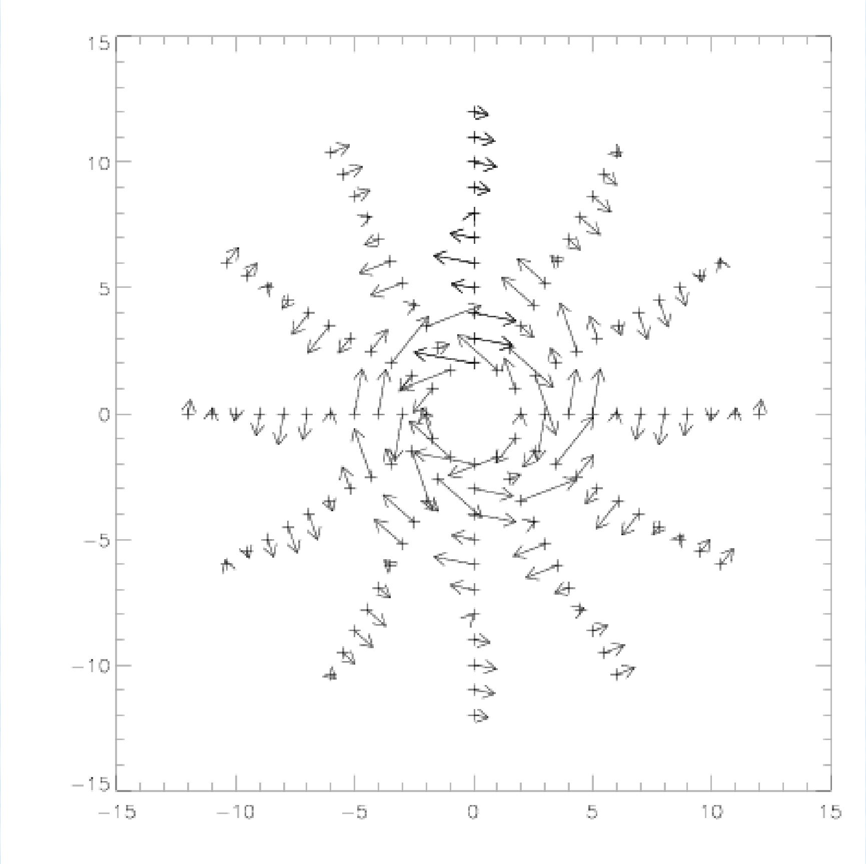


ASS+RING

Sun et al. 2008: disk + halo, but no dipole

Galactic Magnetic Field: disk (toriodal) only



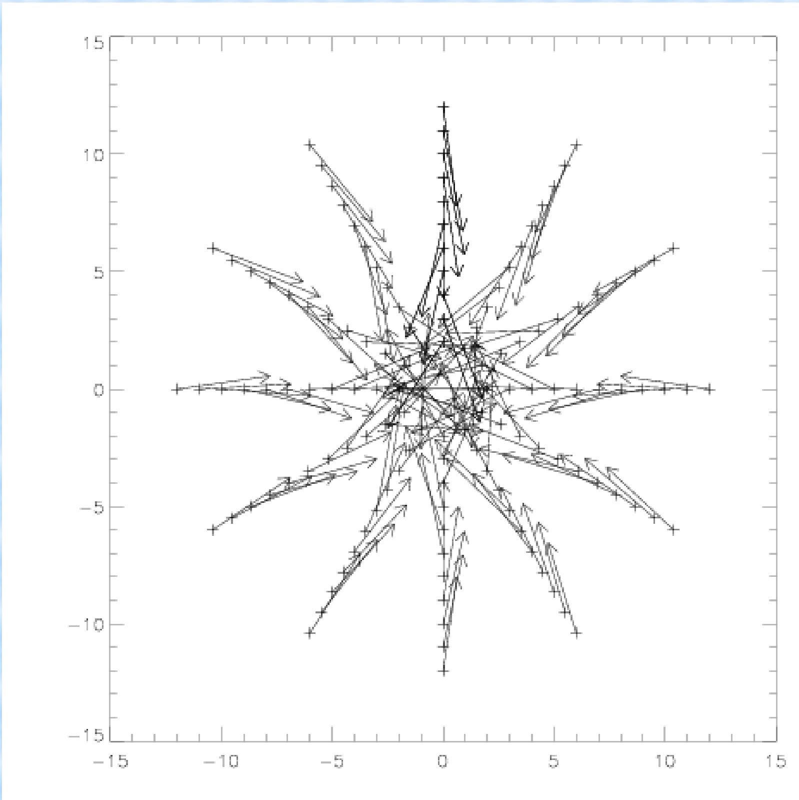


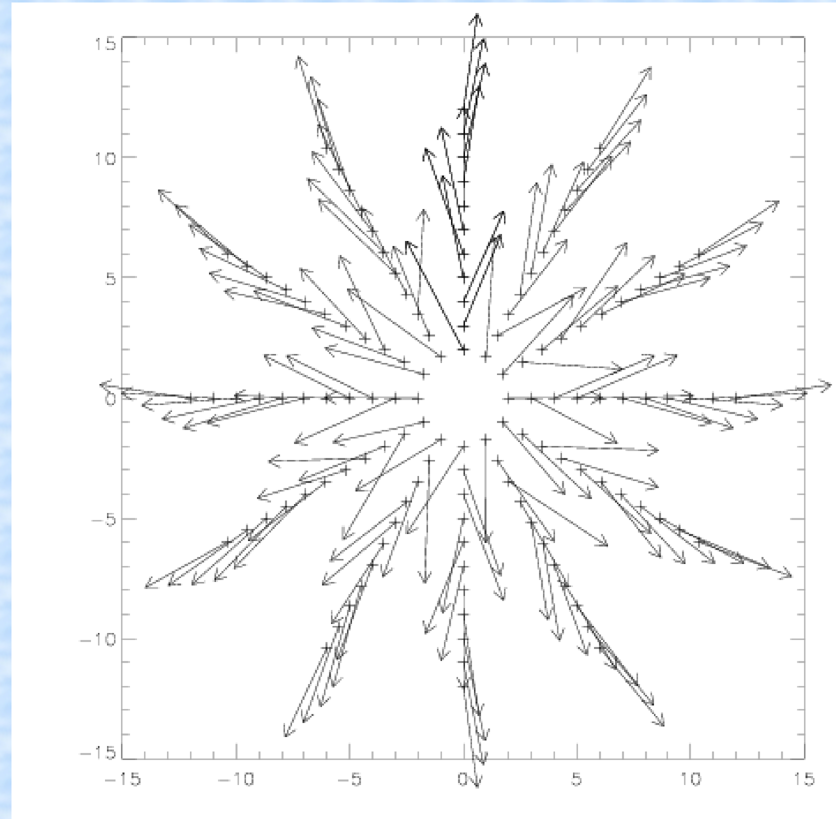
- Axisymmetric (AS)
- AS-A AS-S

Bisymmetric (BS)

BS-A or BS-S

Galactic Magnetic Field: (adding the dipole component)





- z=10pc z= -10pc

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

$$\mu_G \sim 184.2\ \mu G\ kpc^3$$

$0.3\ \mu G$ At the Sun

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Extragalactic B field: model deflections

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

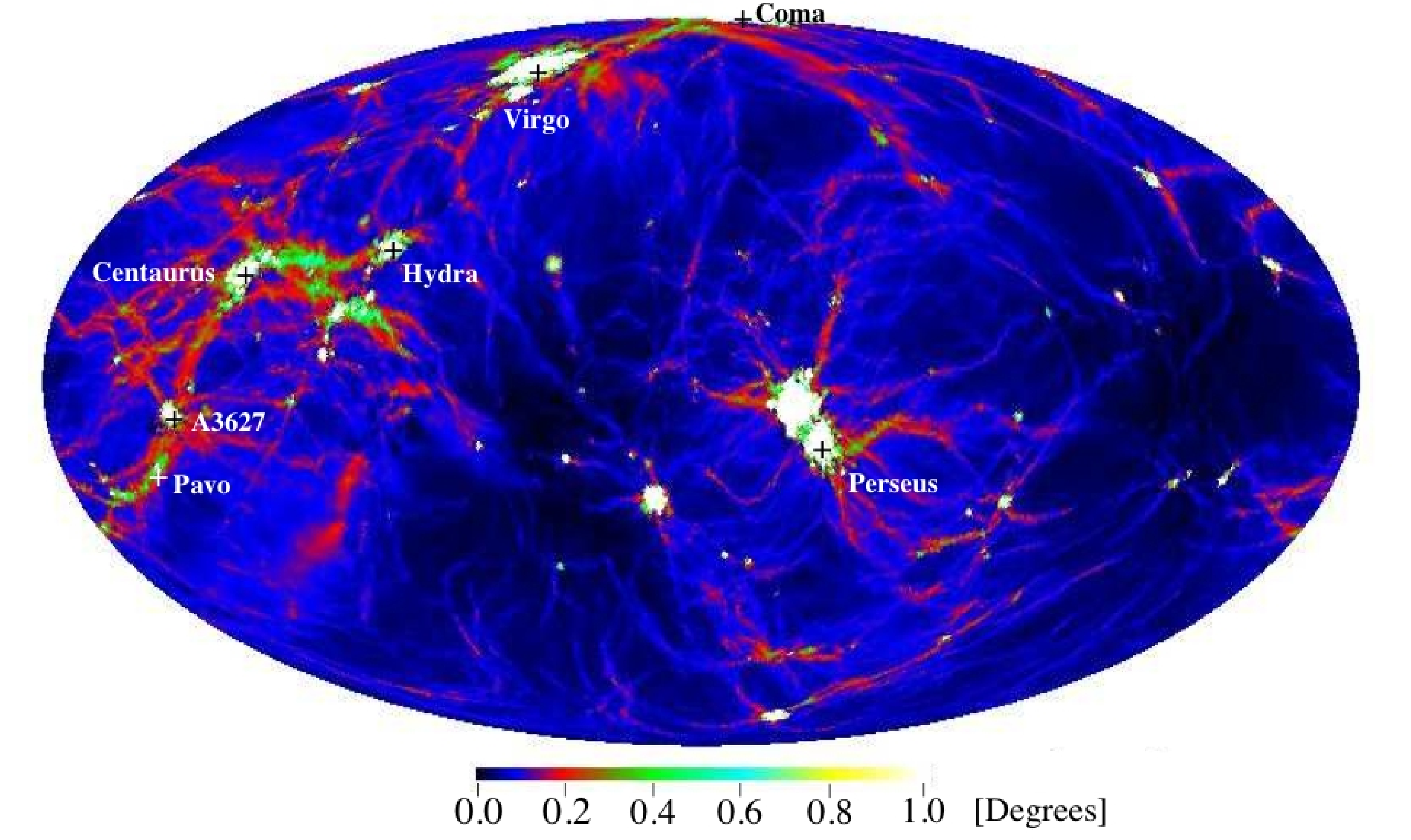
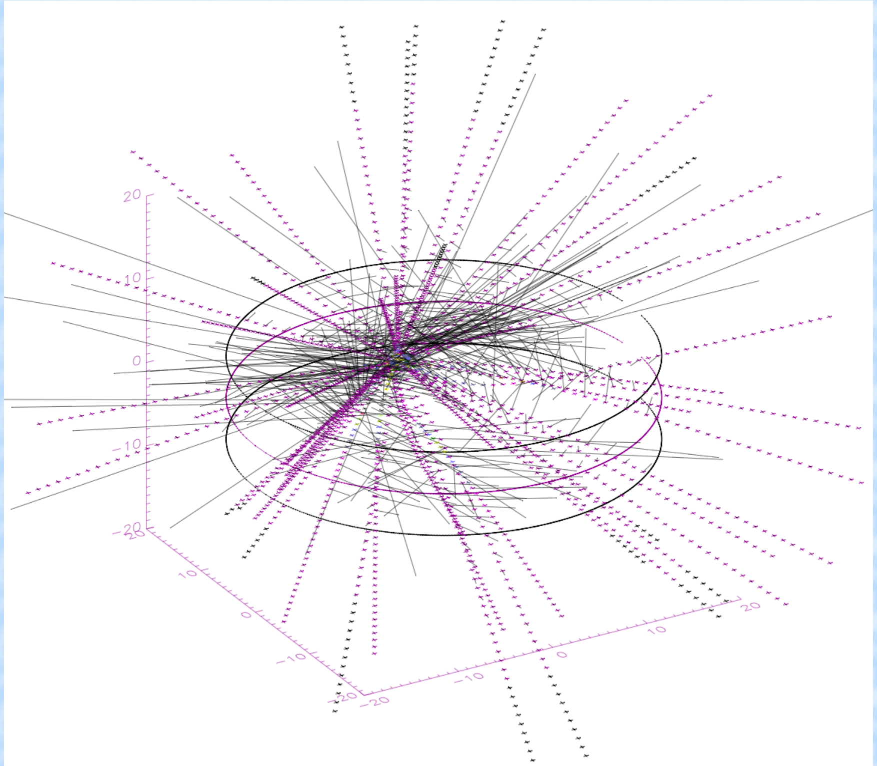


Fig. 13.— Full sky maps of expected deflection angles for protons with the arrival energy $E = 1 \times 10^{20}$ eV.

Dolag et al. 2003 : using Springel's LSS simulations to model intergalactic B fields: deflections <1deg (dominated by cluster fields)

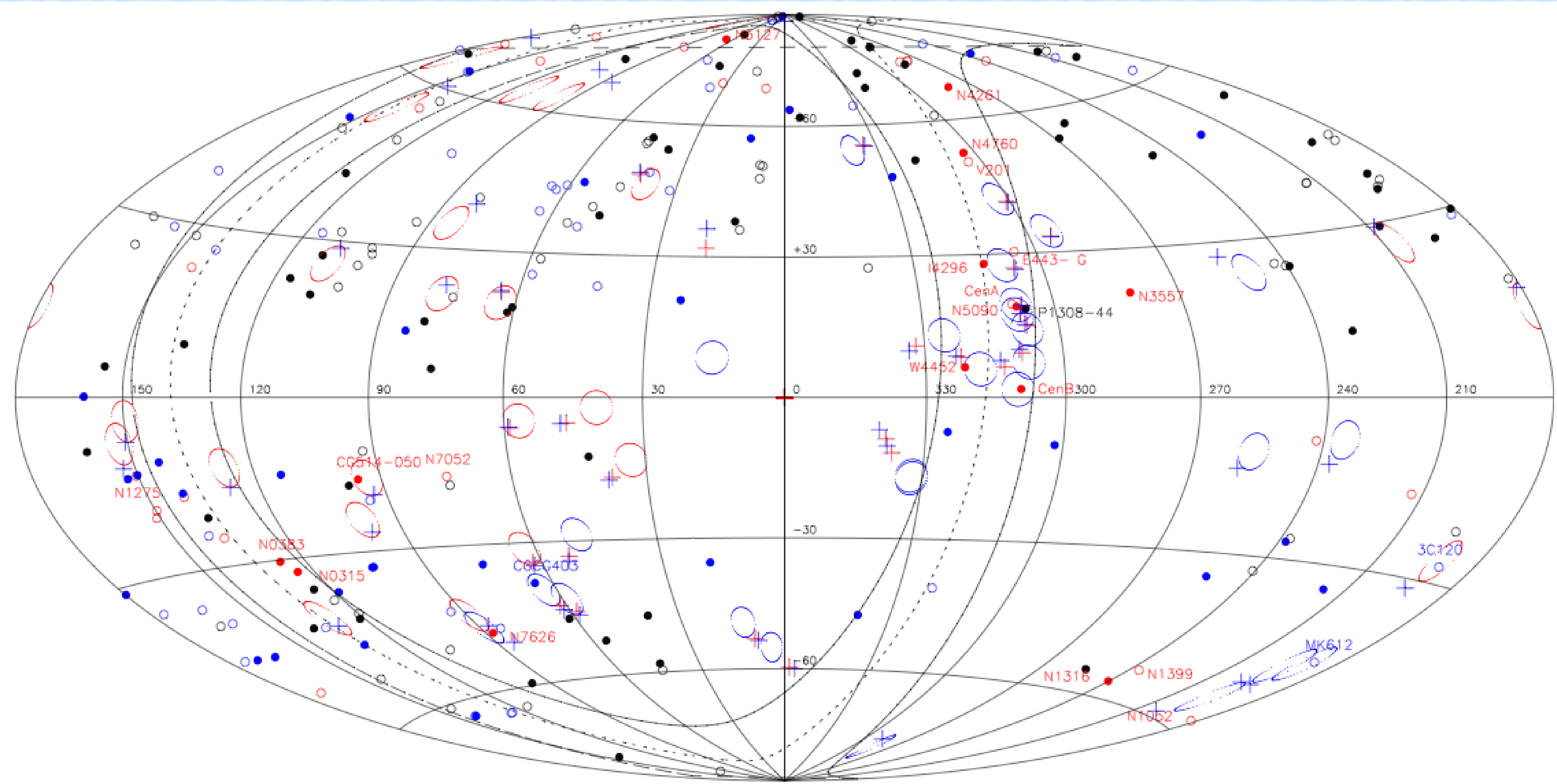
Monte Carlo



following principles in
TS08, TT, MK, PS, many others:
1. shoot antiproton at (l,b) of UHECR
2. each step: calculate Bmodel (x,y,z)
disk+halo+dipole
3. add uncertainty (Gaussian, 1 sigma=50%)
in model GMF in each of Bx,By,Bz
4. Add turbulent field (uniformly distributed
between +/-10microG)
P=100% arms, 20% disk, 1% halo
scale length 50 pc
5. deflect and iterate until D > 40kpc

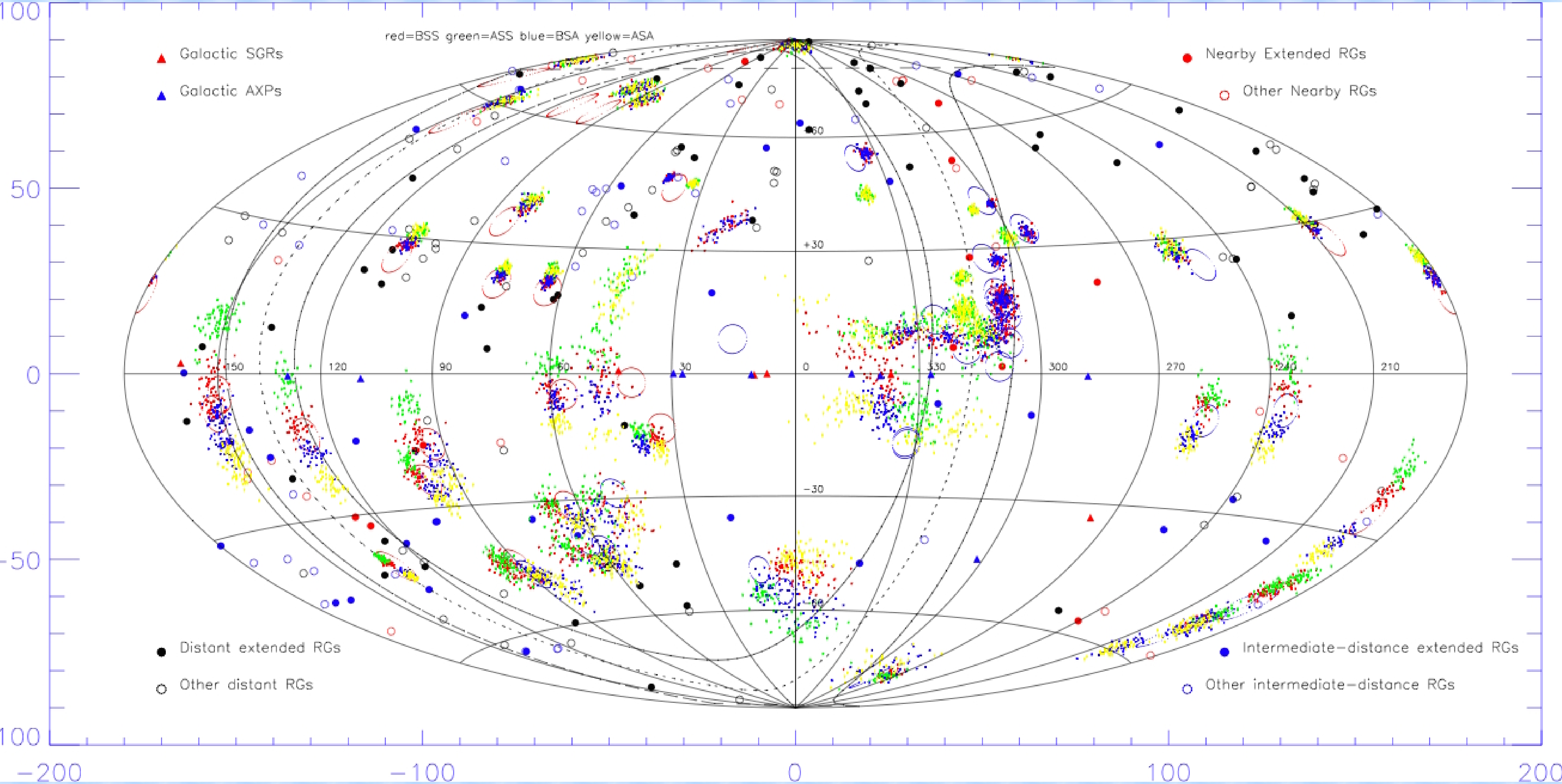
Result: trajectory in Galaxy + "out of Galaxy" arrival direction
models: ASS, ASA, BSS, BSA, Sun et al. (3 models), Sun et al. + dipole
Varied: particle mass & charge, %error, normalizations...

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



- Galaxy middle cross point, and final destination
- D < 75Mpc (NGC6251 @ 116,31 is dark blue)

Radiogalaxies, SGRs & AXPs : BSS, BSA, ASS, ASA



- D < 75 Mpc, 75 < D < 200 Mpc, 200 < D < 500Mpc
- solid symbols: radio extent > 180kpc

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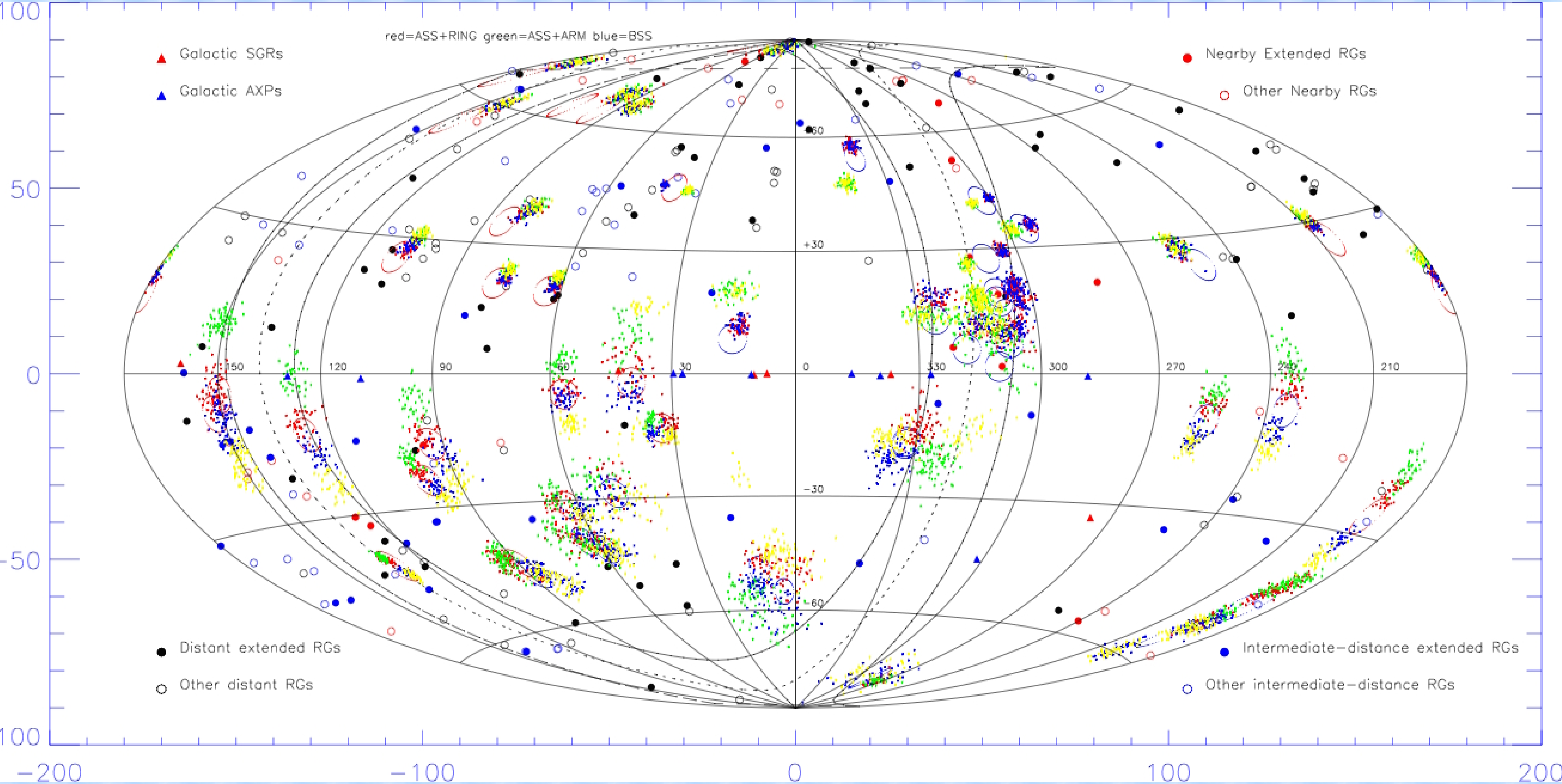
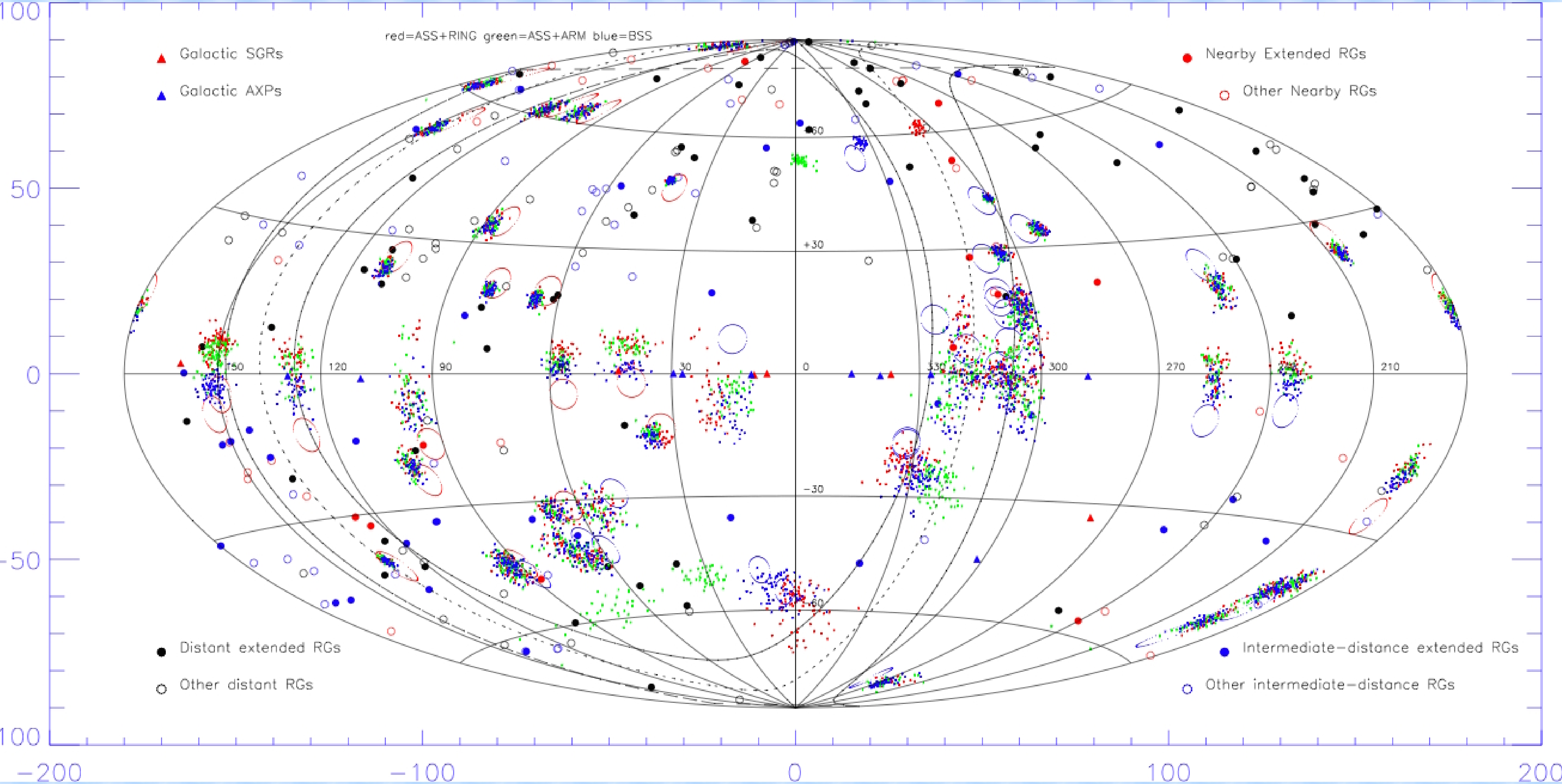
Radiogalaxies, SGRs & AXPs : BSS, BSA, ASS, ASA w/o dipole



- D < 75 Mpc, 75 < D < 200 Mpc, 200 < D < 500Mpc
- solid symbols: radio extent > 180kpc

Radiogalaxies, SGRs & AXPs : ASS+ARM, ASS+RING, BSS(SUN)



- D < 75 Mpc, 75 < D < 200 Mpc, 200 < D < 500Mpc
- solid symbols: radio extent > 180kpc

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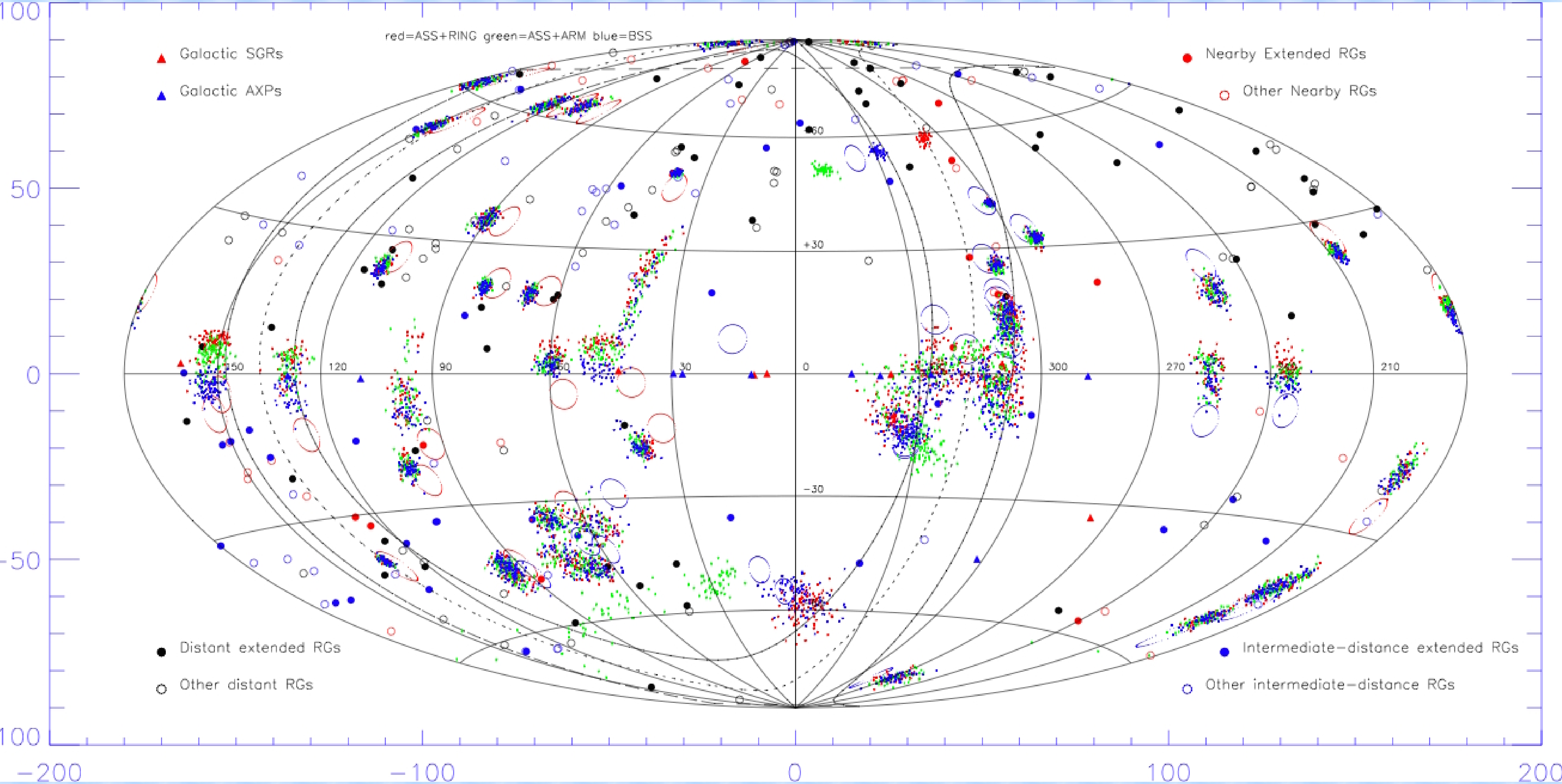
Radiogalaxies, SGRs & AXPs : Sun et al + dipole component



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- D < 75 Mpc, 75 < D < 200 Mpc, 200 < D < 500Mpc
- solid symbols: radio extent > 180kpc

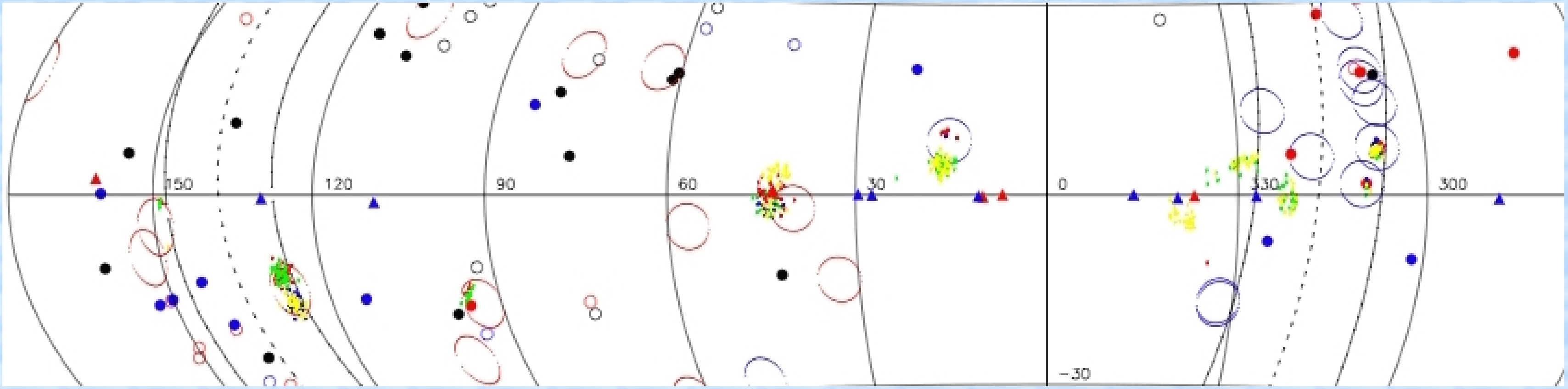
The Numbers

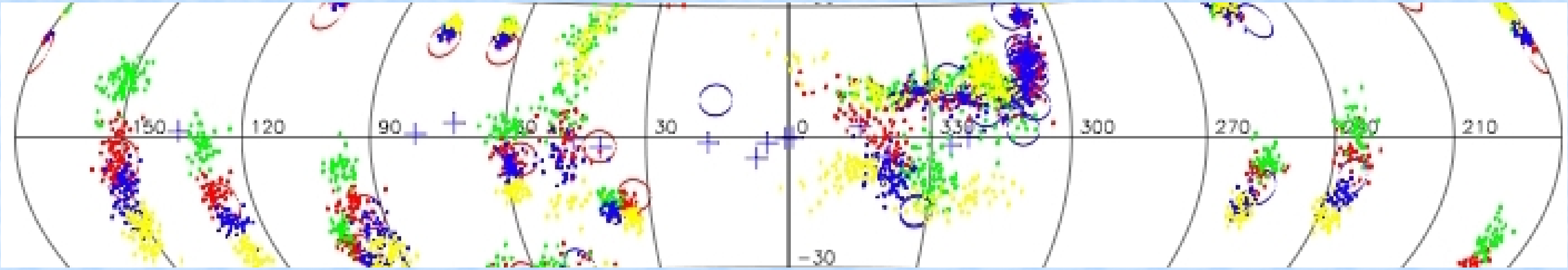
- Use 3.5deg as a "match" (overlap with 10% of MonteCarlo)
- Nearby (D < 75Mpc) extended (LLS > 180kpc):
  - RGs=14 UHECRs=51
    - Match 7 R.G.s with 9 UHECRs
      - With deflections: 8 R.G.s with 10 UHECRs
      - (added NGC5127)
- Nearby + Intermediate (D<200) Extended (LLS > 180kpc)
  - RGs=49 UHECRs=51
    - Match 9 R.G.s with 11 UHECRs
    - With deflections 13 R.G.s with 18 UHECRs
- Distant (> 200Mpc) Extended: do not add significantly
- Best at low D, okay at medium D

Caveats and Comments

- If we want to include nice additional radiogalaxies:
    - Require large(ish) mean free path for UHECRs
    - Or higher source UHECR energies in these few cases
    - cf. previous comments about depression vs. Cutoff
- CGCG 403-019: the nearest BL Lac with extended radio jets
    - A new "Cen A"? : 1 AGASA and 3 Auger events?
- NGC 7626 and NGC 1275 (both D<75Mpc) also potential "doubles"
- <E> similar for "non-matches" and "matches"
    - Would be useful to compare shower characteristics
    - Are these protons vs. heavy?

BSS, BSA, ASS, ASA: <1kpc from SGRs, AXPs





- Microquasars from Paredes et al.

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Summary

- Helps to consider the Galactic Magnetic Field
  - Even if small numbers and uncertainties in GMF
- Source populations:
  - Powerful radiogalaxies + BL Lacs are strong candidates
    - Trace denser clusters rather than overall matter distr.
    - Check with HIPASS, 2MASS etc.?
    - But probably not Dark Matter (no local group signature)
  - a few Galactic Candidates? - not clear, but leave open
  - If we choose: large(ish) UHECR mean free path (~150Mpc)?
- For radiogalaxies:
  - BS-A is the favored GMF model (esp. in 2 regions)
  - Models of Sun et al. + dipole could work too
  - Are we seeing high filament+cluster magnetic fields?
- Test "matches" vs. "non-matches" for heavy vs. Protons (40,40,10?)
- Can we distinguish R.G.s from matter distibution in the future?

Other possibilities

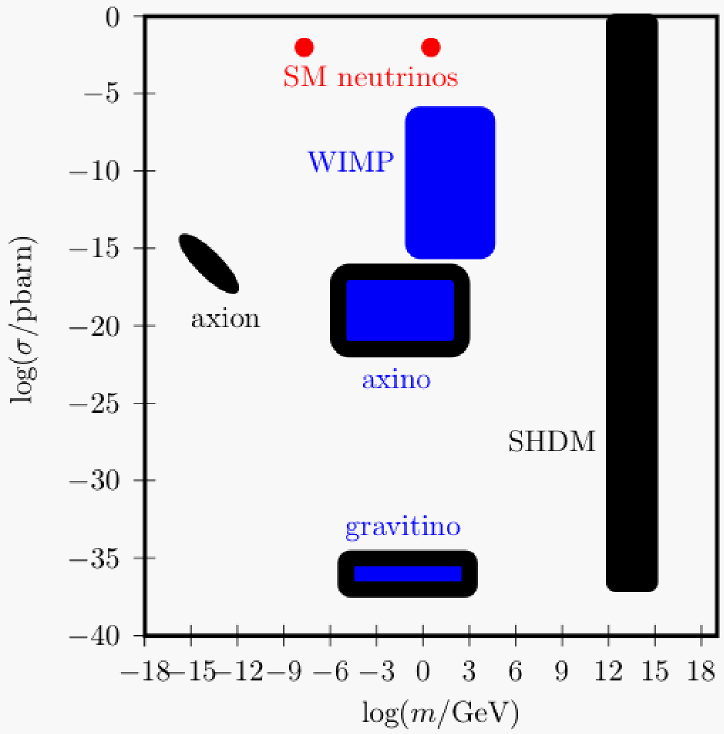

Figure 8.2: A selection of dark matter candidates in the plane cross section versus mass; blue and black corresponds to thermal and non-thermal as main production channel.

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

Particles: help!

- Fermions

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

Leptons spin =1/2

Flavor	Mass GeV/c²	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

Mesons