Looking for Signatures of the Galactic Magnetic Field in Cosmic Ray Maps

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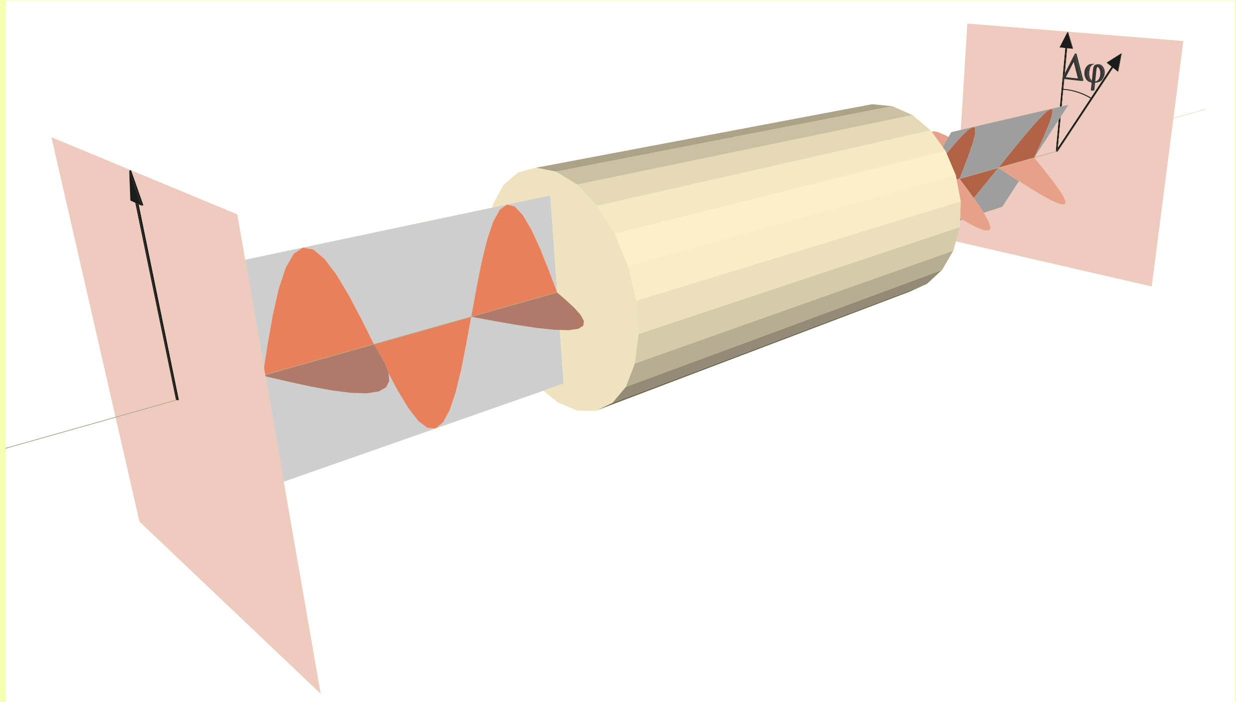
how do we study cosmic magnetic fields?

methods of measurement

- ✦ Zeeman effect
- ✦ synchrotron light polarization
- ✦ Faraday rotation
- ✦ starlight polarization

Faraday rotation



Zeeman effect

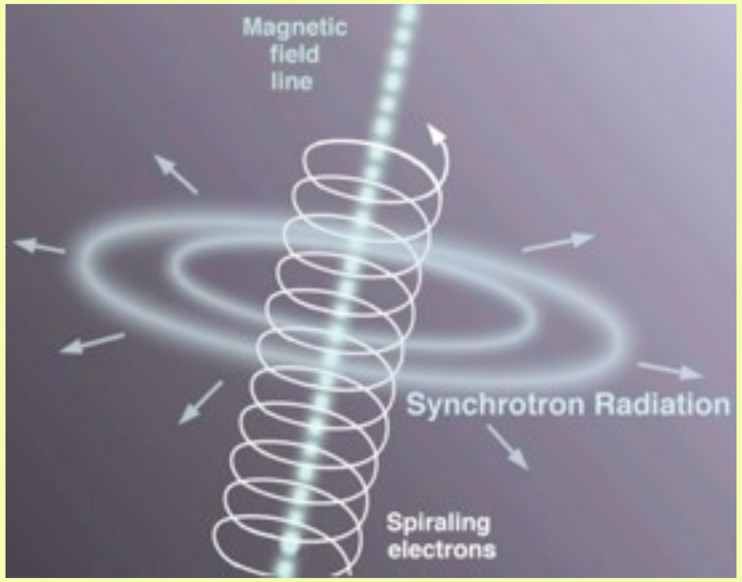
- ✦ splitting of spectral lines

$$B = \frac{m_e c}{e} \Delta E$$

starlight polarization

✦ alignment of dust grains with the magnetic field of the medium

synchrotron light polarization



cosmic rays and cosmic magnetic fields

cosmic rays

✦ can be deflected by magnetic fields, depending on the energy and composition

✦ for ultra-high energy cosmic rays (uhecrs), the Larmor radius is usually greater than the coherence length of the fields

✦ the propagation of cosmic rays depend on the intervening magnetic fields

cosmic magnetic fields

✦ not well-comprehended due to difficulties on the measurement

✦ determine the propagation of cosmic rays

cosmic magnetic fields and uhecrs

✦ the comprehension of cosmic magnetic fields can contribute to a better understanding of the propagation of uhecrs

✦ deflection of uhecrs can contribute to study the cosmic magnetic fields

✦ why not use uhecrs to study cosmic magnetic fields?

the galactic magnetic field

✦ the disk region can be modeled by a logarithmic spiral with pitch angle p:

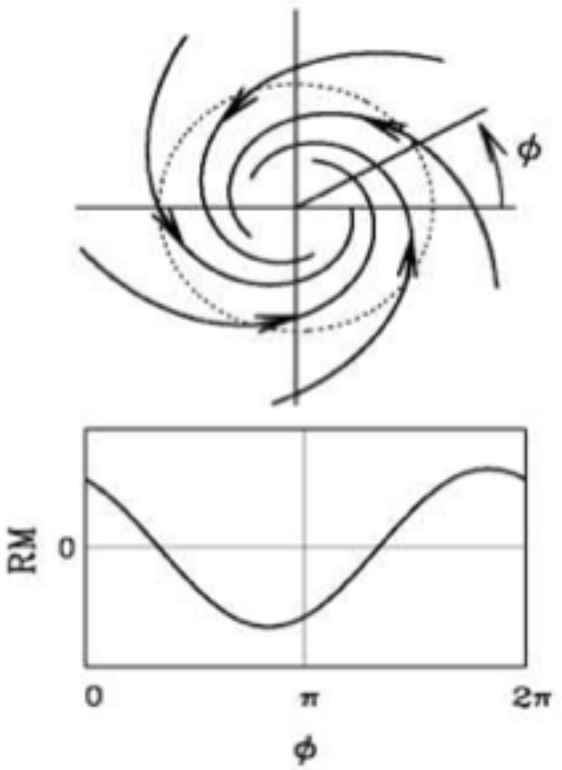
$$R_{spiral} = R_0 \exp\left(\theta \tan p\right)$$

✦ the magnetic field in the disk is given by

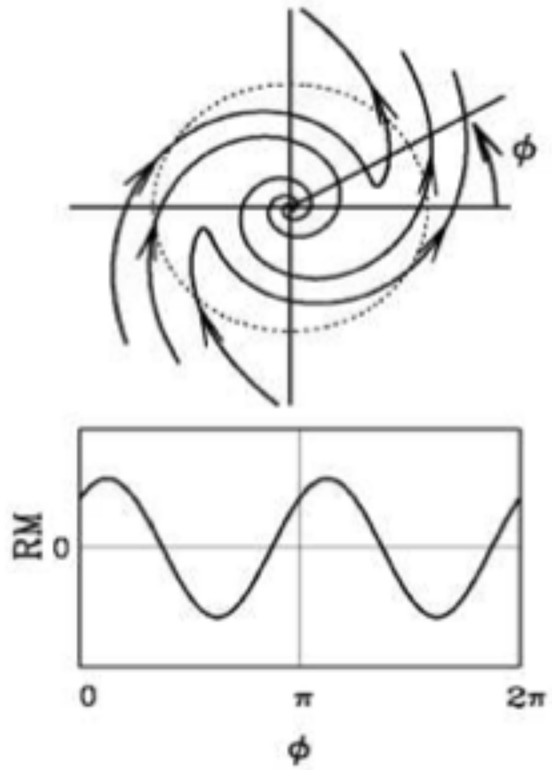
$$\vec{B}(r,\theta) = B(r,\theta)\left(\hat{\theta}\cos p + \hat{r}\sin p\right)$$

where B(r, θ) depends on the model adopted

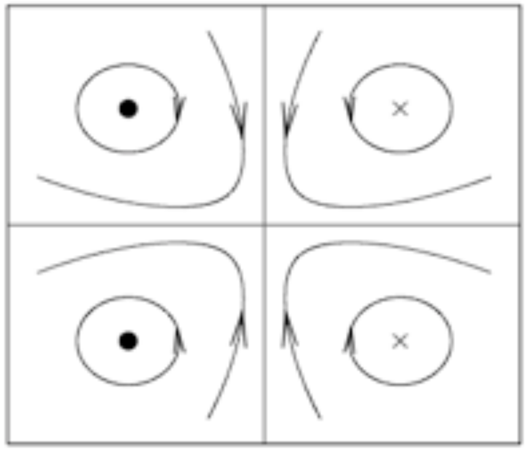
ASS (AxisSymmetric Spiral)



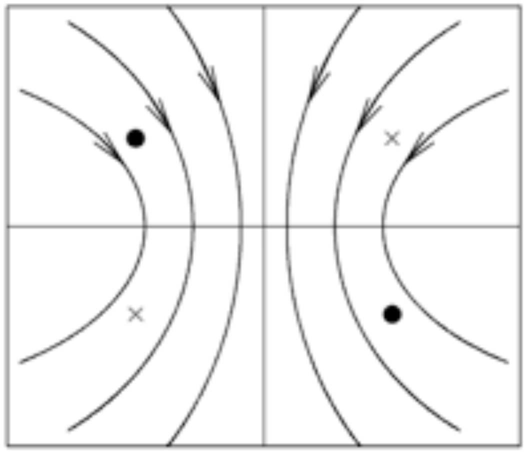
BSS (BiSymmetric Spiral)



Symmetric (-S)
[even parity in z]



Antissymmetric (-A)
[odd parity in z]



the galactic magnetic field

the Milky Way

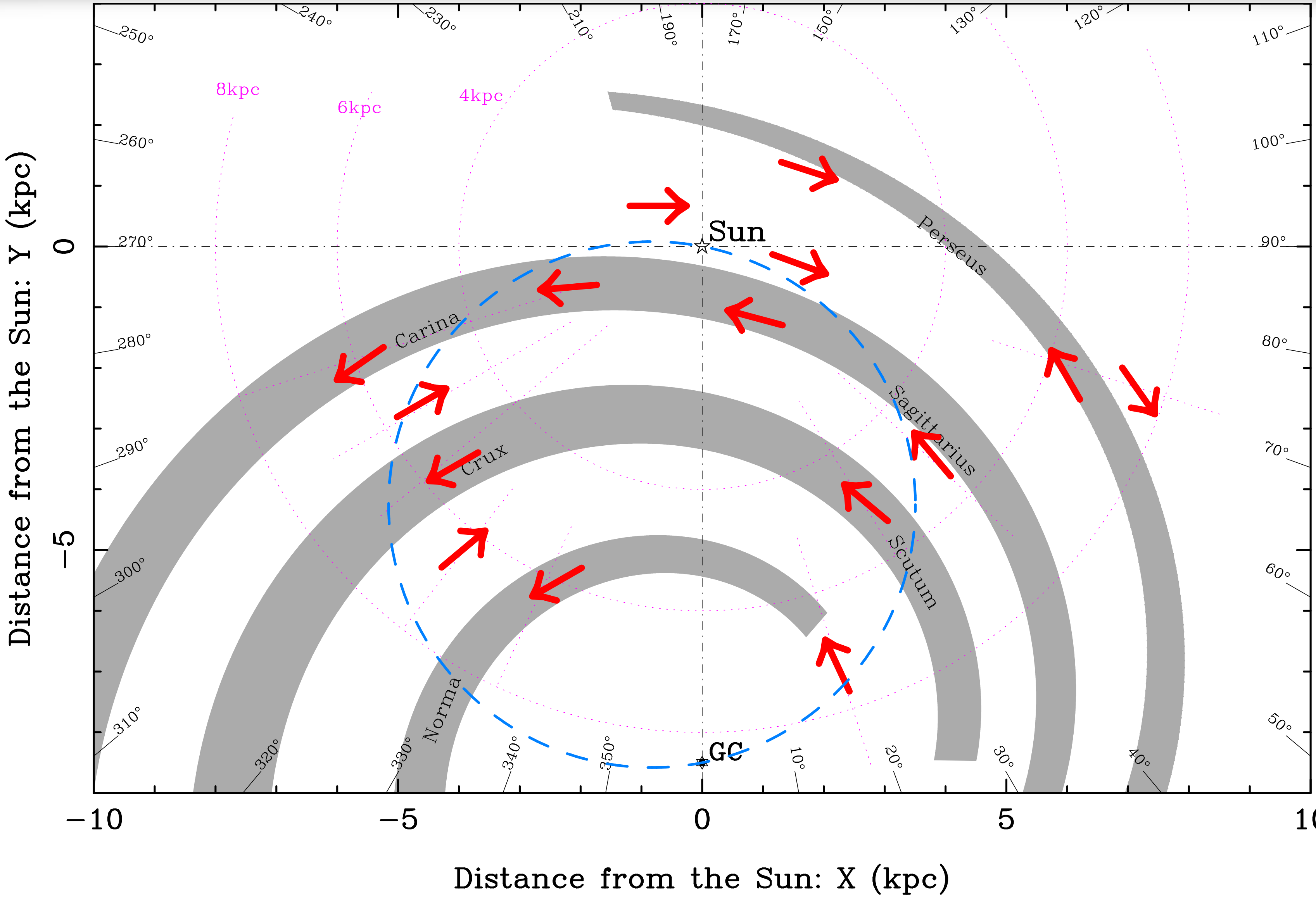
✦ barred spiral

✦ diameter: ~ 30 kpc

the galactic magnetic field (gmf)

✦ regular component (disk and halo)

✦ turbulent component



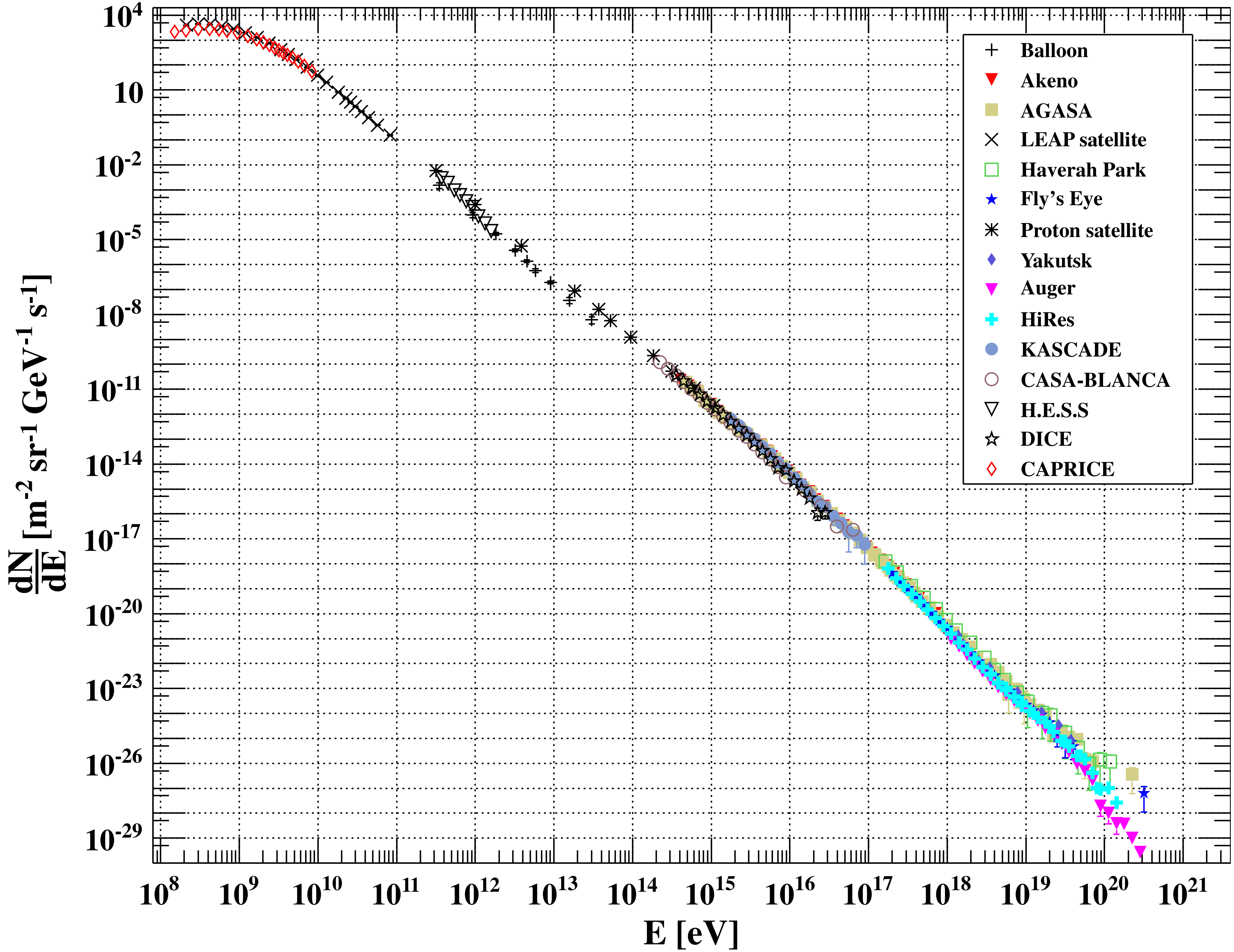
GMF: what do we know?

✦ there are some field reversals

✦ a single model might not be capable to fully describe the field

✦ there is a halo component with unknown symmetry

a little bit about cosmic rays: spectrum



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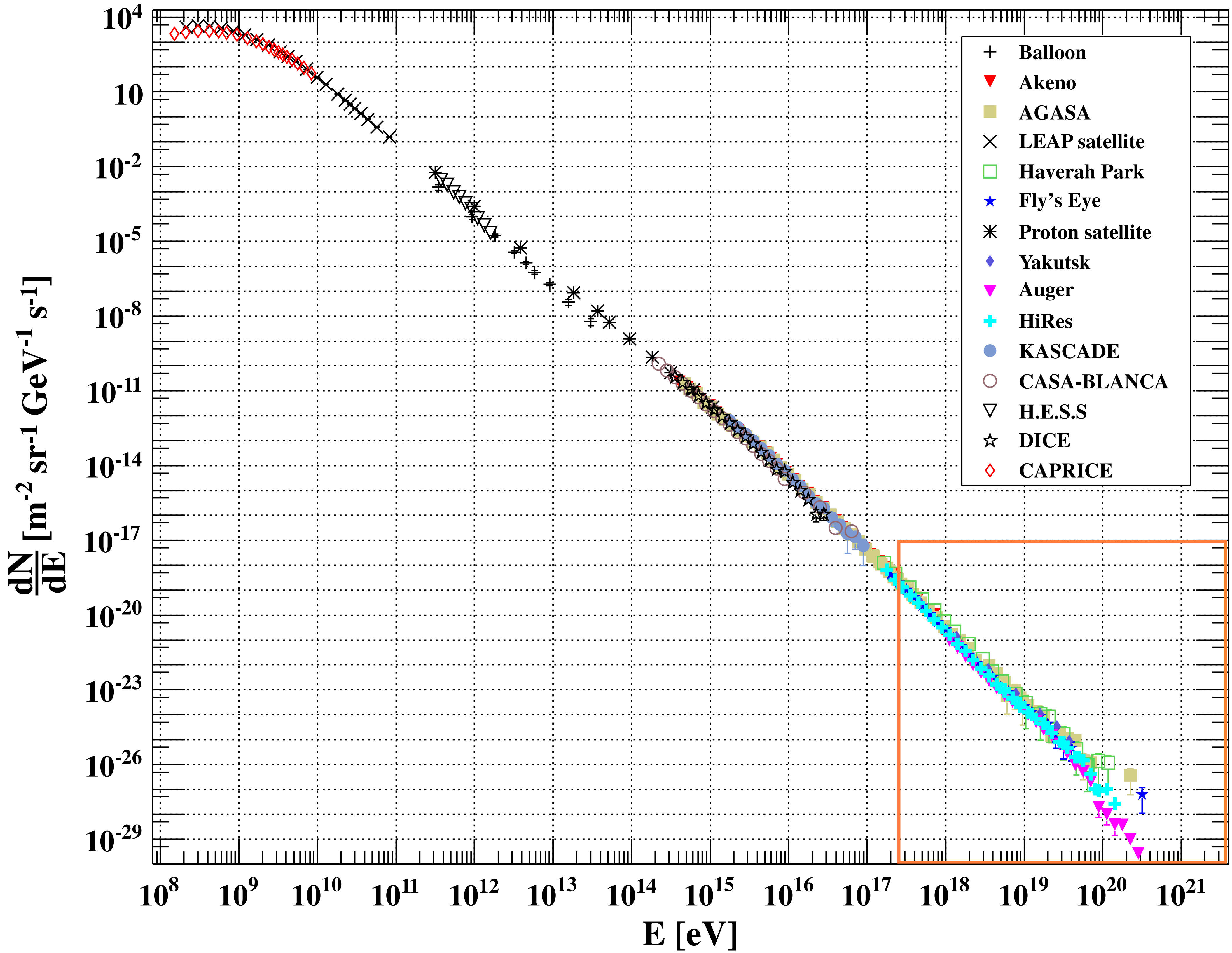

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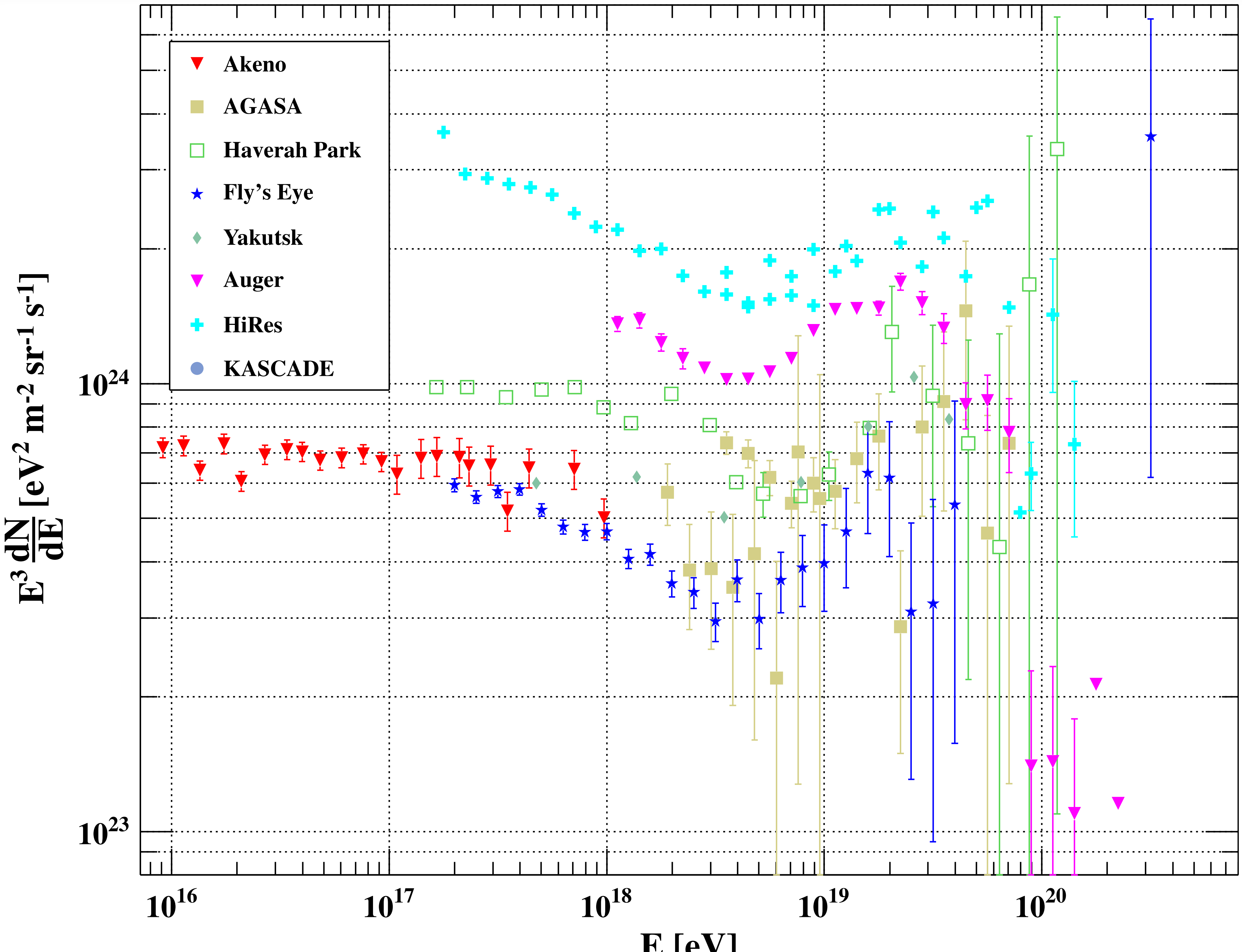


a little bit about cosmic rays: possible sources

Hillas condition

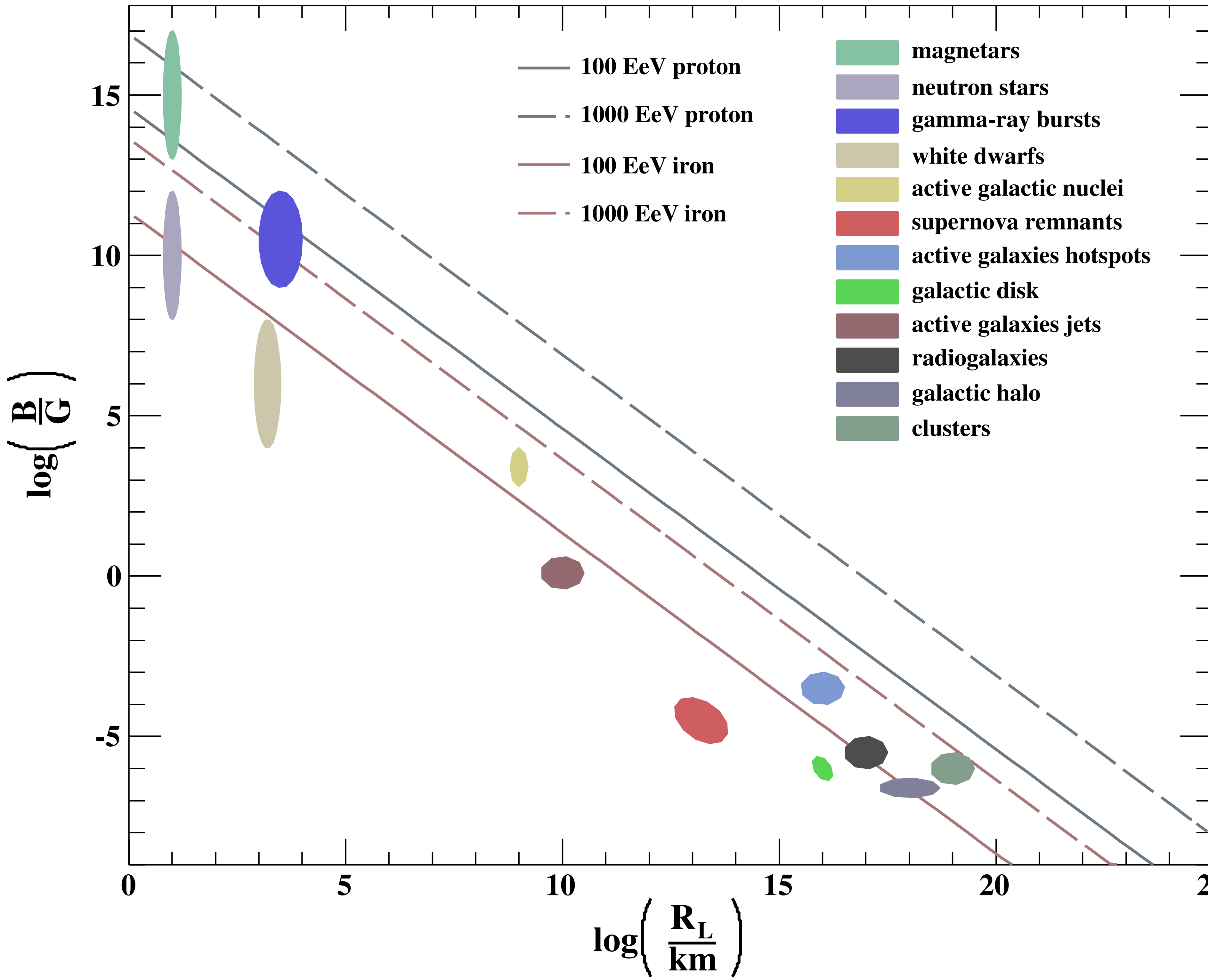
$$E_{max} \sim 2\beta c Z e B R_L$$

source spectrum

$$\frac{dN}{dE} = E^{-\alpha}$$

compatible with models of stochastic acceleration (shock waves)

Hillas diagram



a little bit about cosmic rays: deflections

extragalactic magnetic field: regular component

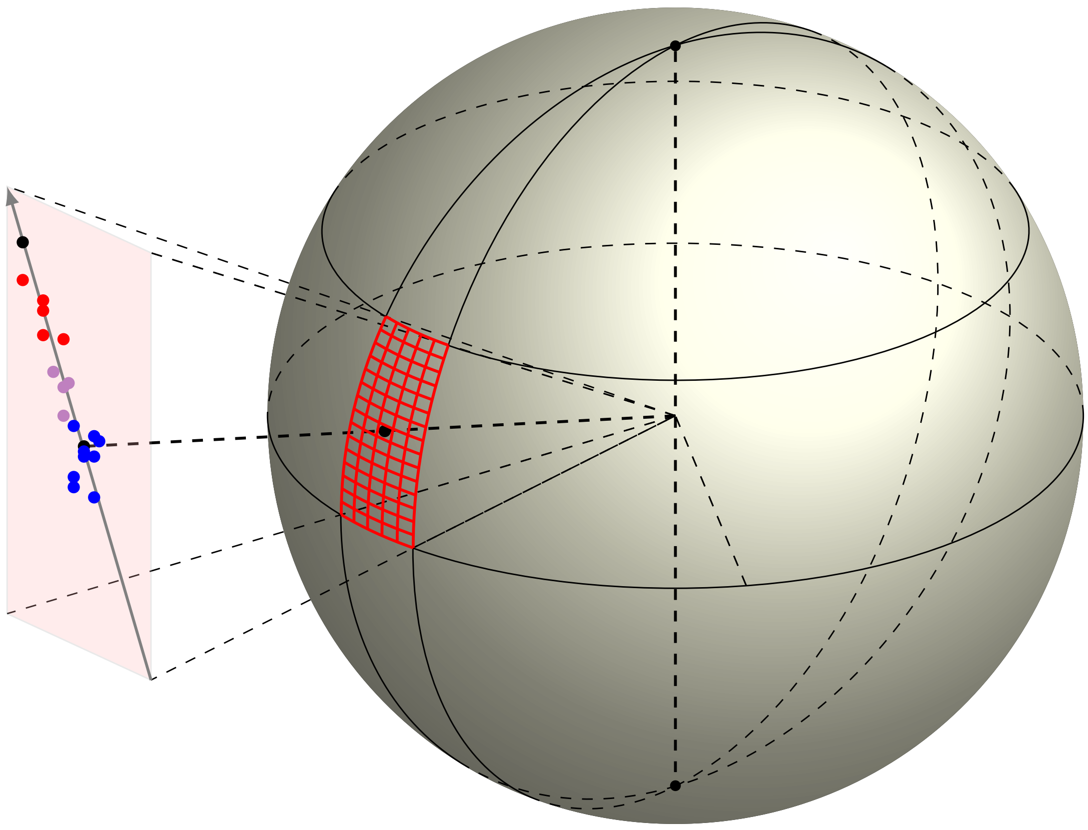
$$\delta_{EGMF} \approx 0,53^\circ Z \left(\frac{D}{100\ \mathrm{Mpc}}\right)\left(\frac{100\ \mathrm{EeV}}{E}\right)\left(\frac{\langle B\rangle}{10^{-2}\ \mathrm{nG}}\right)$$

extragalactic magnetic field: random component

$$\delta_{rms} = 0,01^\circ Z \frac{L_c}{L}\left(\frac{\mathrm{EeV}}{E}\right)\left(\frac{B_{rms}}{5\ \mu\mathrm{G}}\right)\left(\frac{L}{2\ \mathrm{kpc}}\right)^{\frac{3}{2}}\sqrt{\frac{50\ pc}{L_c}}$$

galactic magnetic field: regular component

$$\delta_{reg} = 16^\circ \frac{20\ \mathrm{EeV}}{E/Z}\left|\int_0^L \frac{d\vec{l}}{3\ \mathrm{kpc}} \times \frac{\vec{B}}{2\ \mu\mathrm{G}}\right|$$



extragalactic magnetic field: random component

$$\delta_{rms} = \frac{1}{\sqrt{2}}\frac{ZeB_{rms}}{E}\sqrt{LL_c} \approx 5,8^\circ \left(\frac{10^{19}\ \mathrm{eV}}{E/Z}\right)\left(\frac{B_{rms}}{4\ \mu\mathrm{G}}\right)\sqrt{\frac{L}{3\ \mathrm{kpc}}}\sqrt{\frac{L_c}{50\ \mathrm{kpc}}}$$

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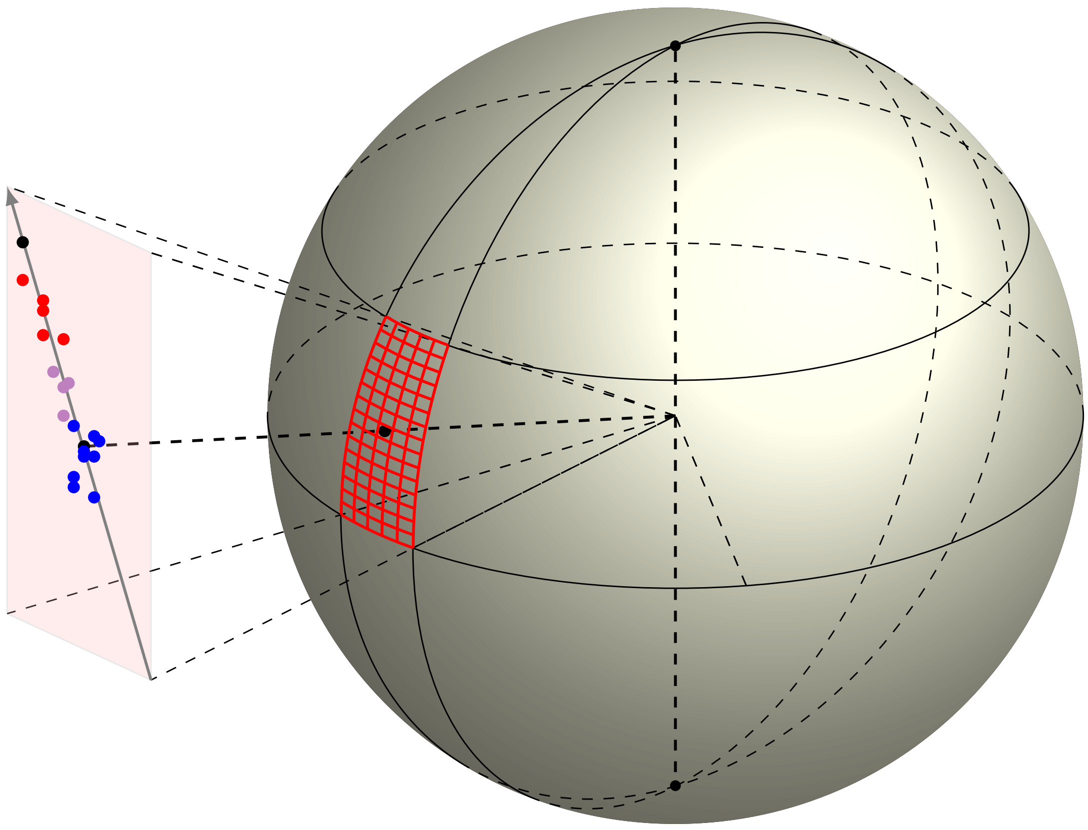

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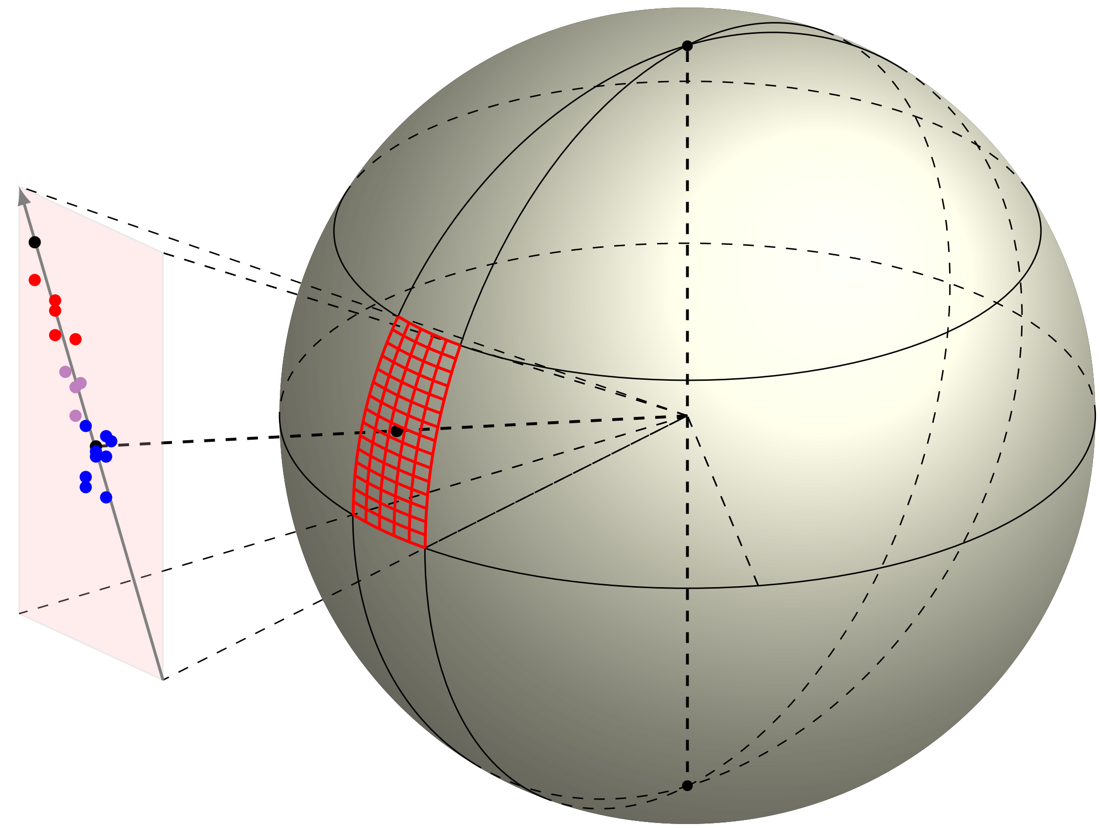

$$\delta \propto E^{-1}$$

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pattern matching on the sphere

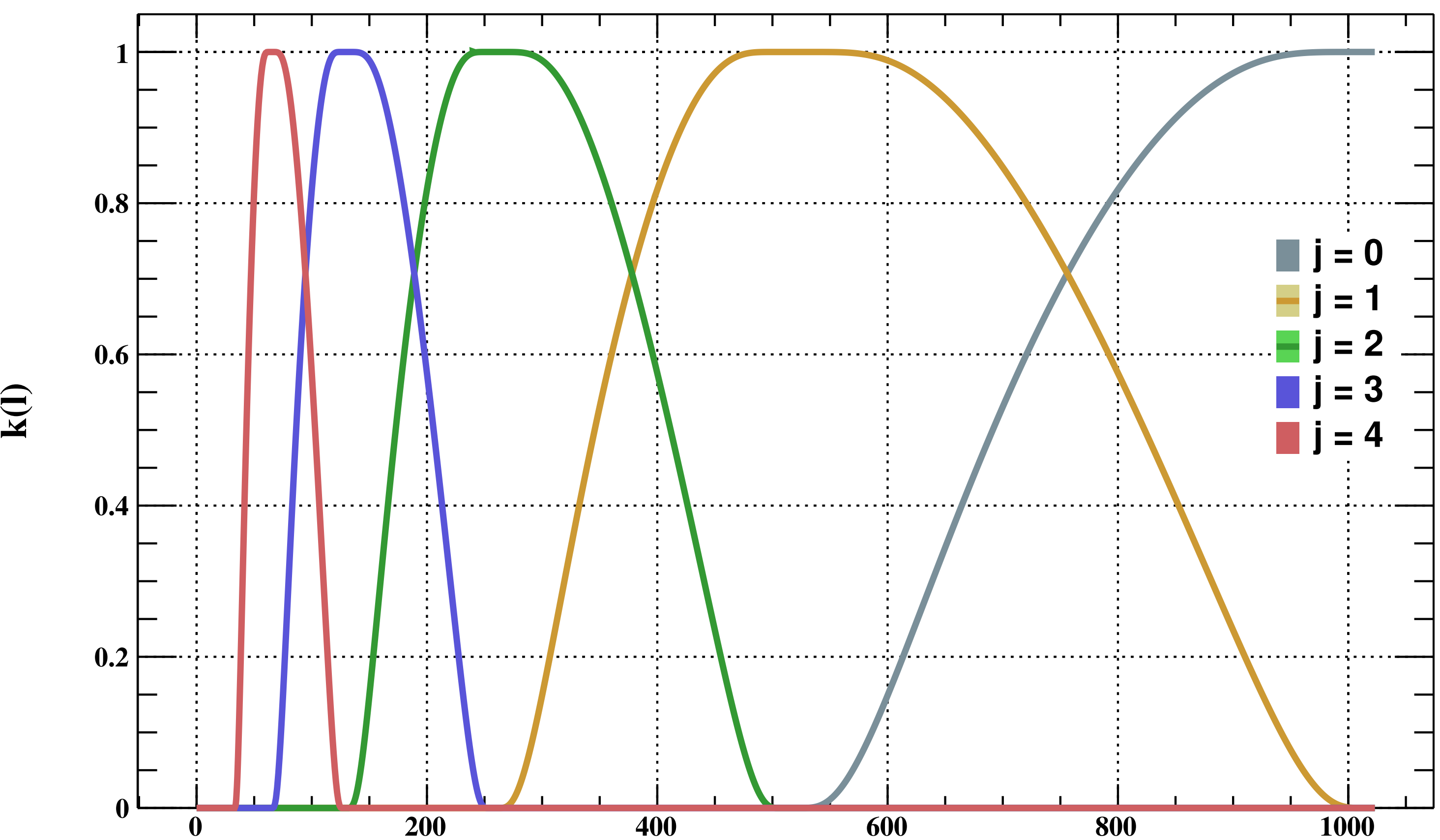
pattern matching algorithm

✦ $f(\theta,\varphi)$ → pattern; $h(\theta,\varphi)$ → signal

✦ correlation of h with rotated versions of f

$$C = \int_{\mathbb{S}^2} f(\omega)\overline{\Lambda(g)h(\omega)}d(\cos\theta)d\varphi$$

✦ if f is a wavelet, the equation above corresponds to the spherical wavelet transform of the signal h



✦ the wavelets used in this work are steerable (factorable in harmonic space)

$$b_{lm} = k(l)S_{lm}$$

✦ the optimization of the algorithm is achieved by writing f and h in terms of spherical harmonics

$$f(\theta,\varphi) = \sum_{l=0}^{B-1}\sum_{|m|\leq l} a_{lm}Y_{lm}(\theta,\varphi)$$

✦ therefore the correlation is given by

$$C = \sum_{l=0}^{B-1}\sum_{|m|\leq l}\sum_{|m'|\leq l} \overline{a_{lm}}b_{lm'}D^l_{mm'}(\alpha,\beta,\gamma)$$

B: band limit

$J=\log_\alpha B$: number of scales

α: scale parameter (fixed in 2)

j: some scale

N: azimuthal band limit

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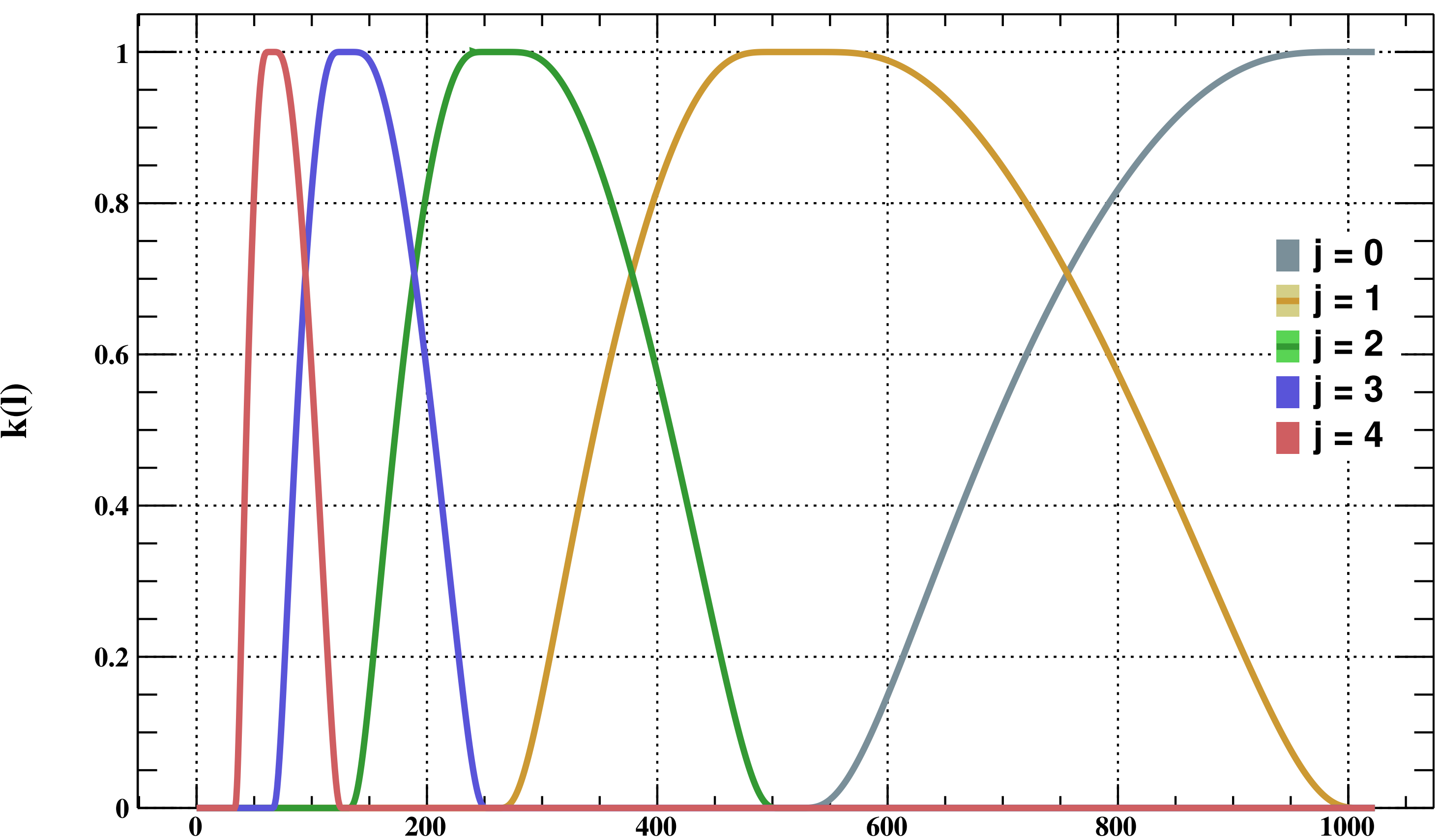

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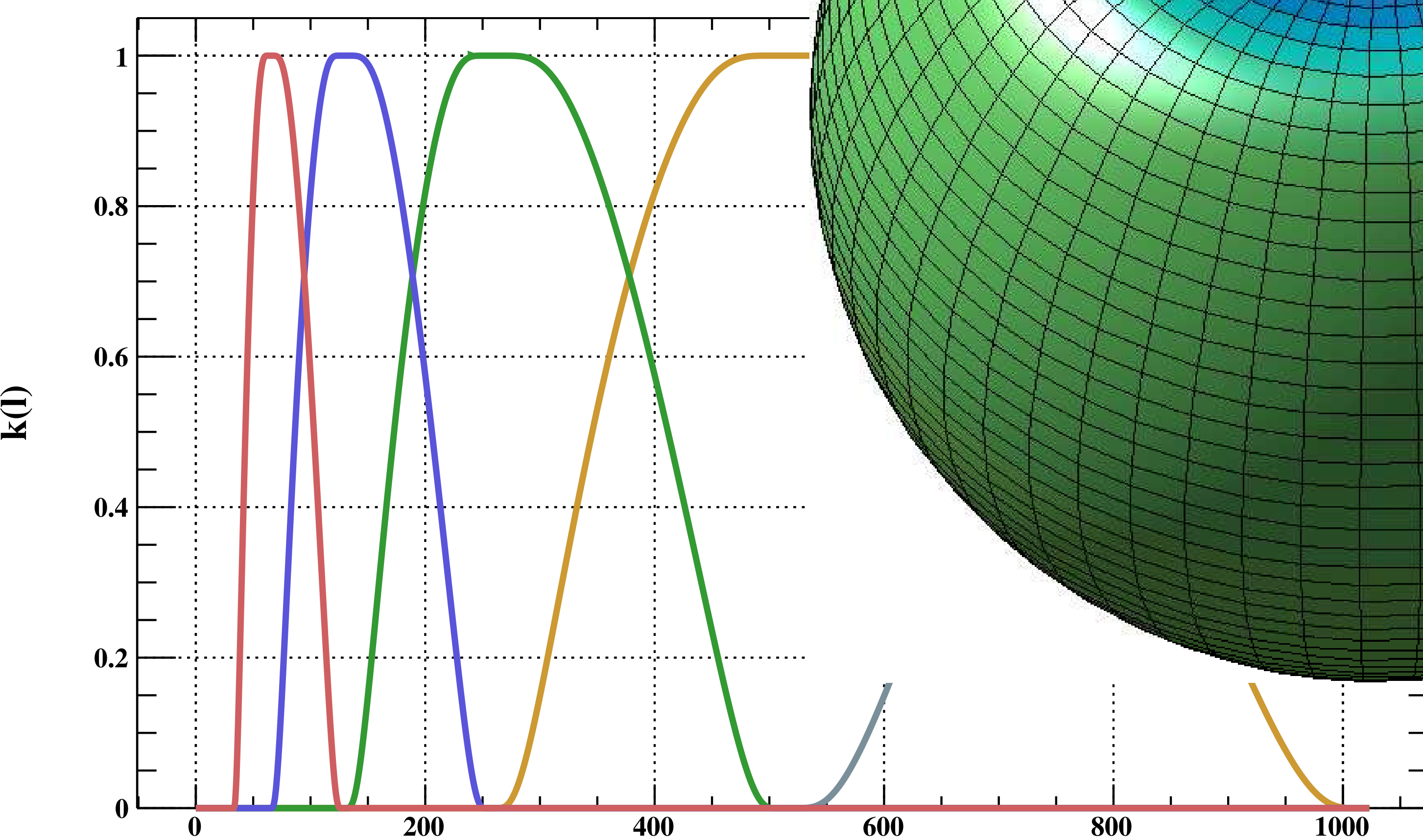

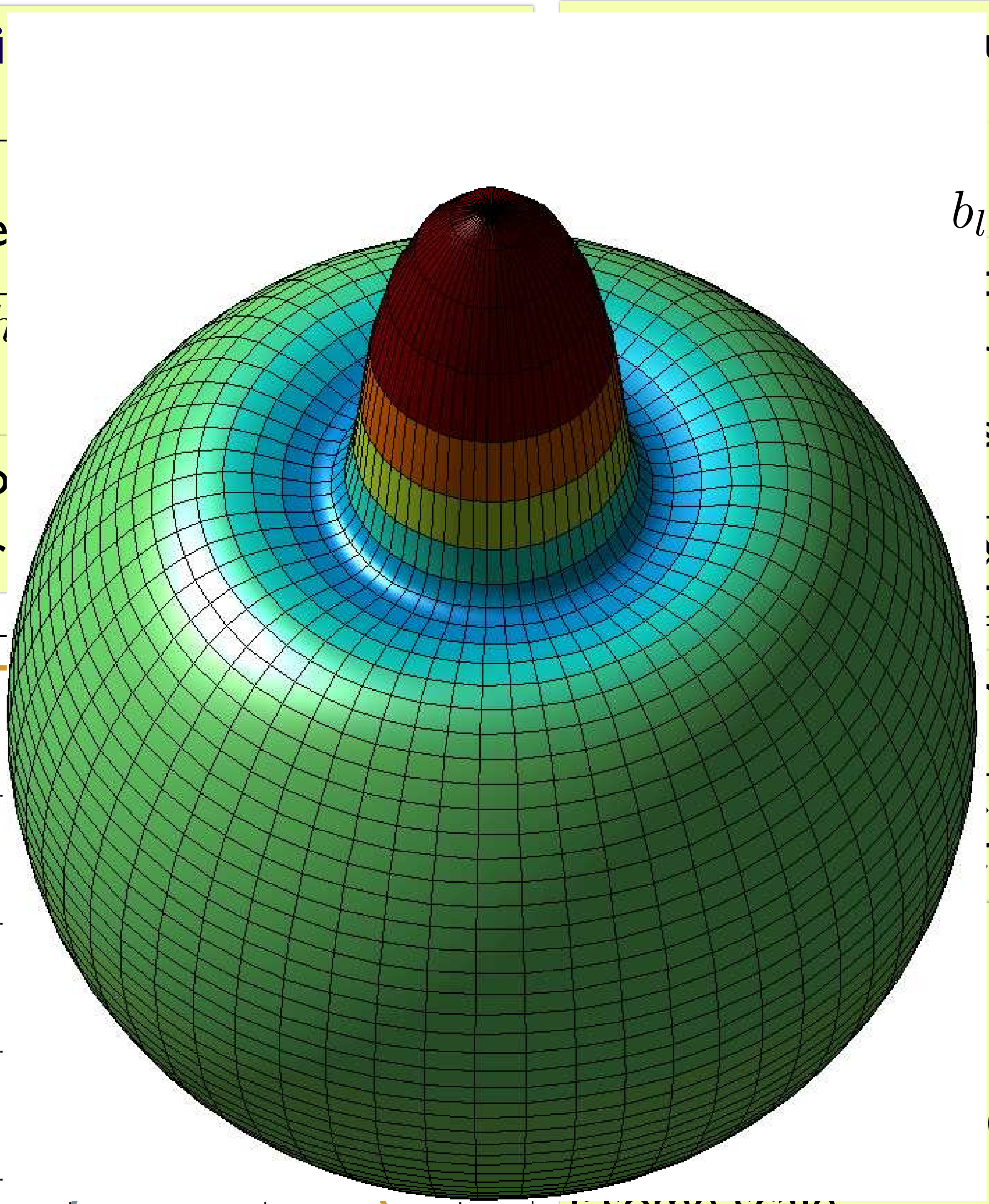

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scales

(fixed in 2)

j: some scale

N: azimuthal band limit

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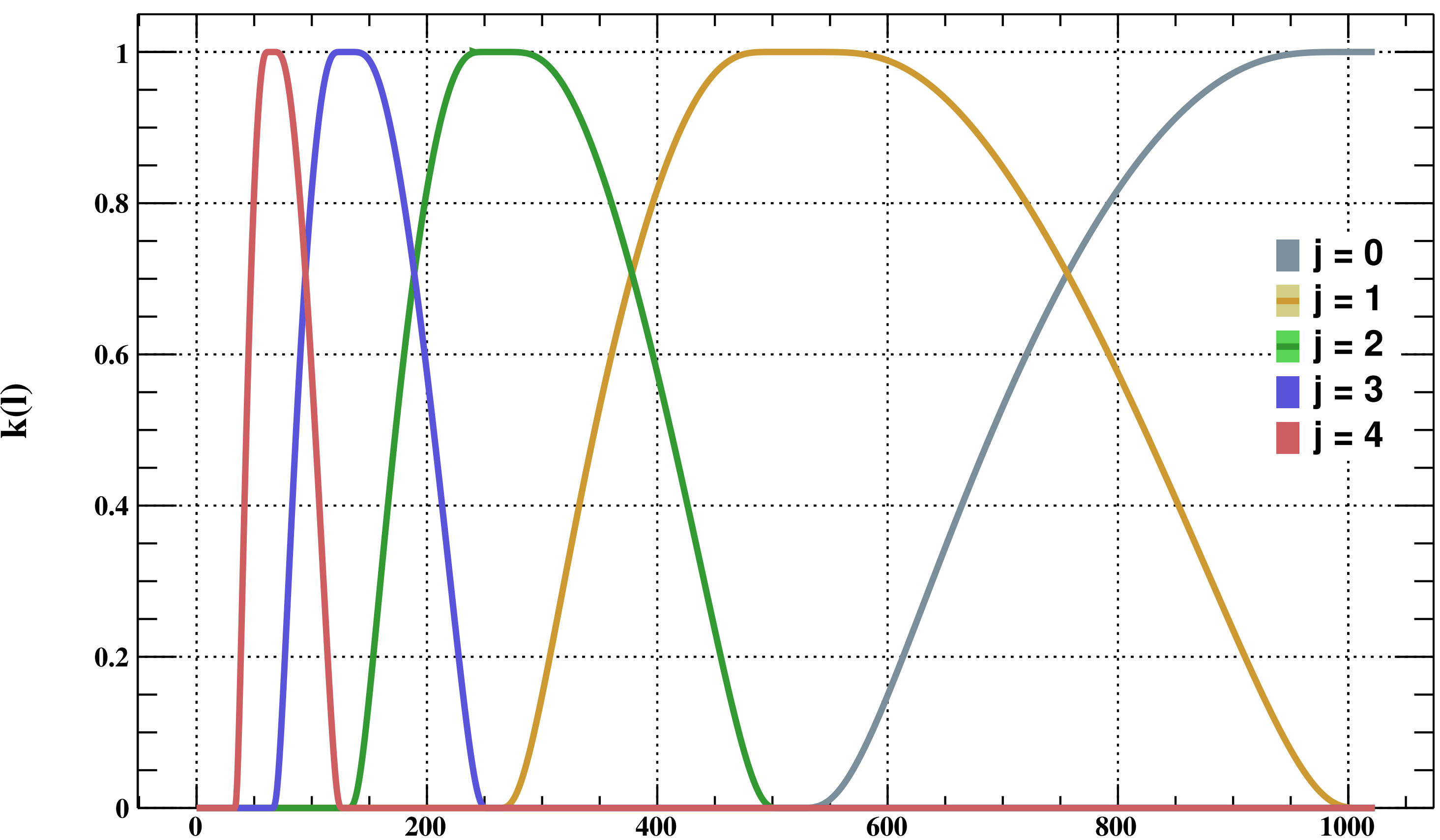

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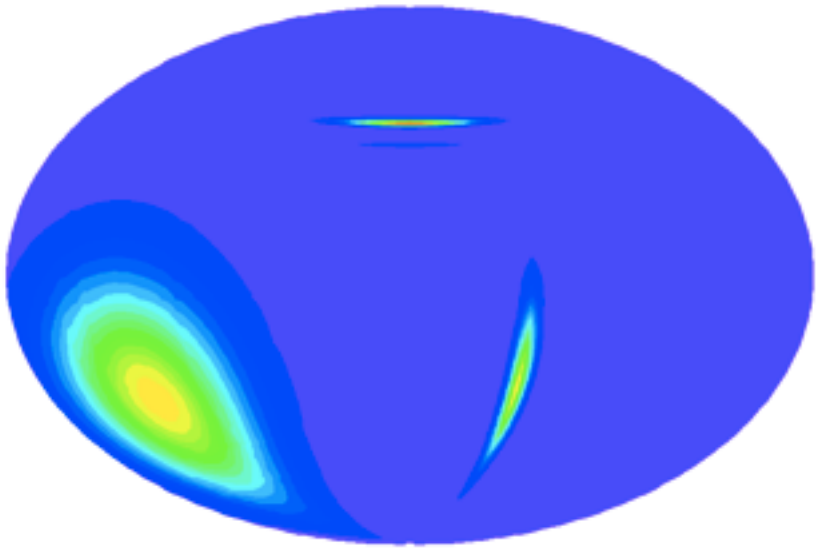
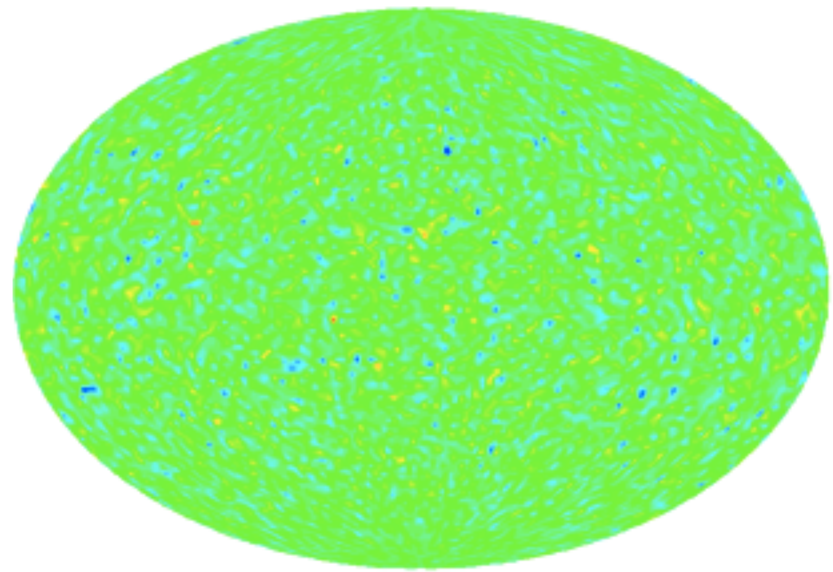
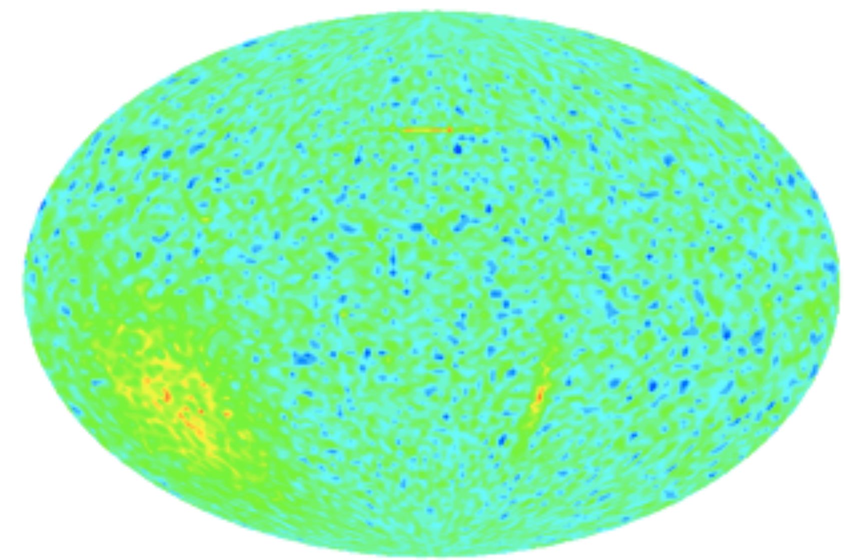
pattern matching on the sphere

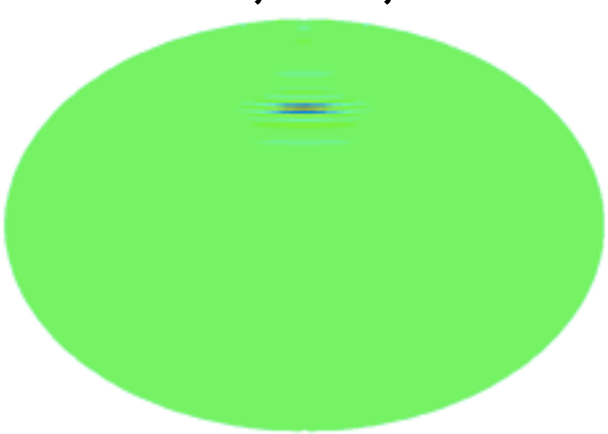
signal + noise = sum



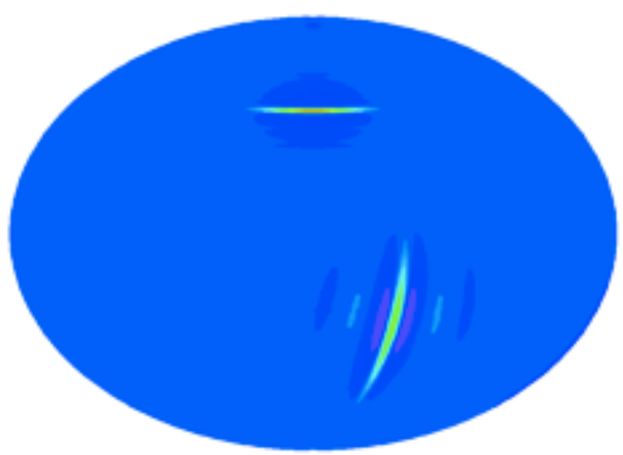




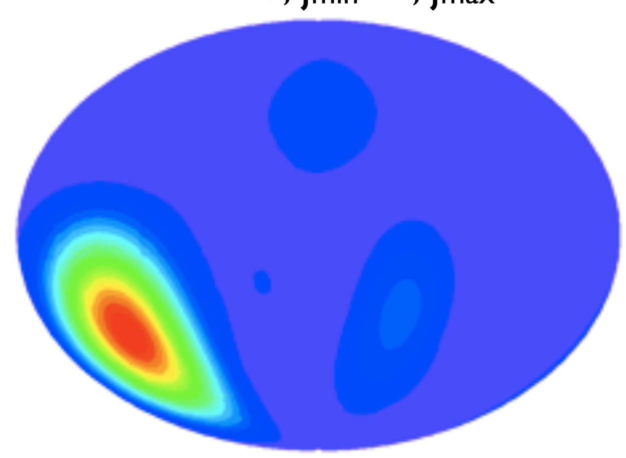
B=256, j_{min}=0, j_{max}=0



B=256, j_{min}=0, j_{max}=3



B=256, j_{min}=5, j_{max}=7



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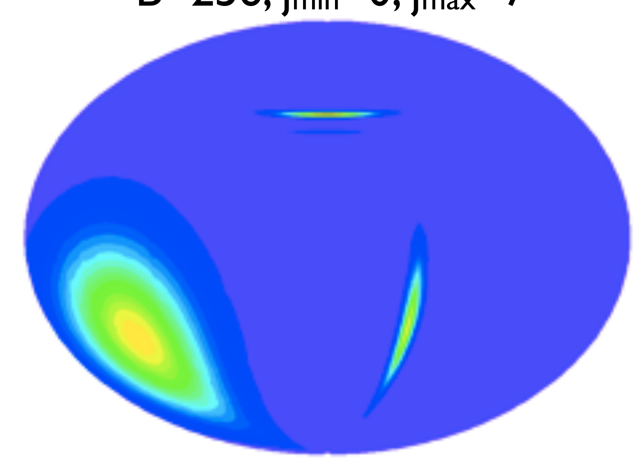


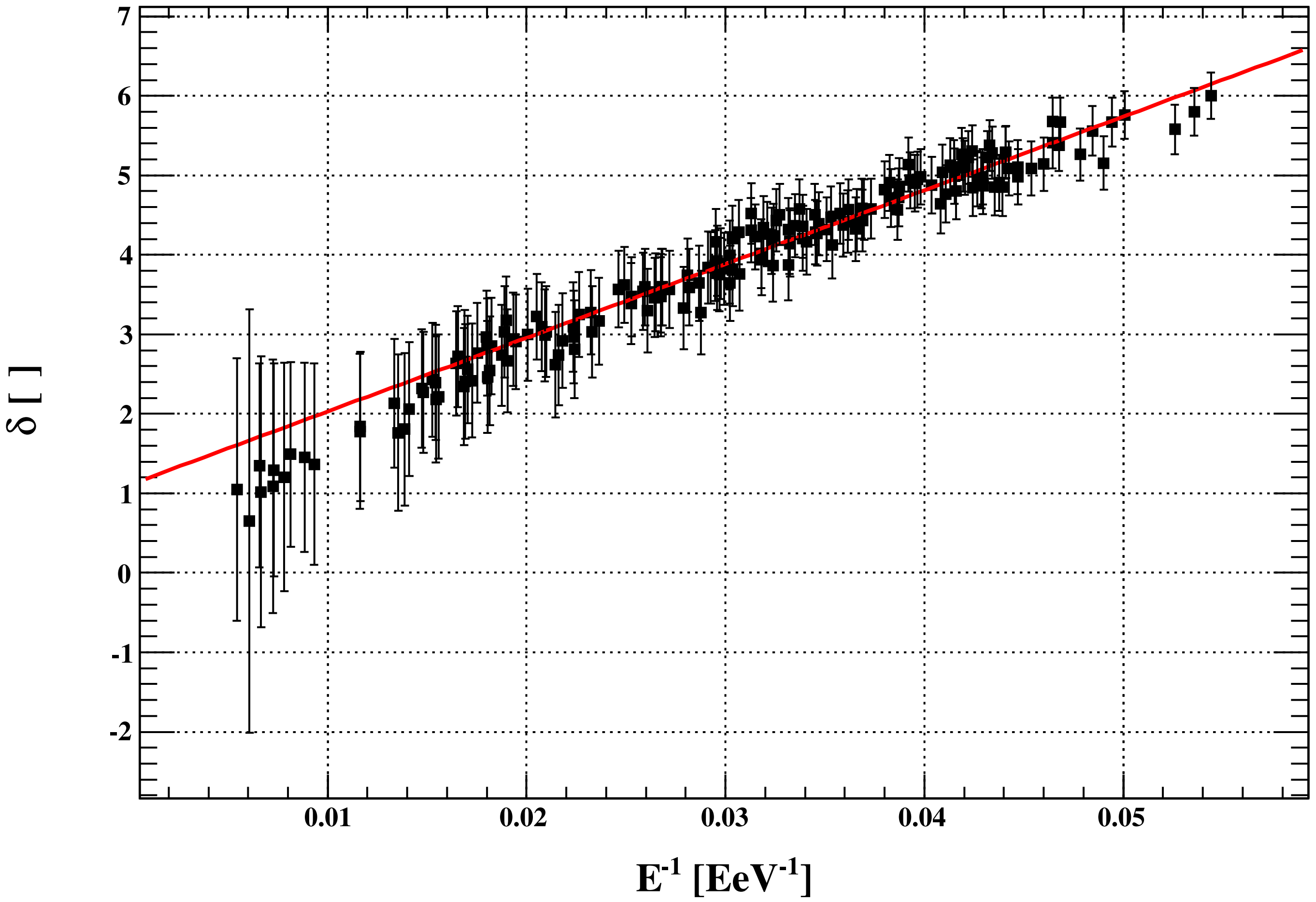
SWAT package: www.ifi.unicamp.br/~mzimbres

identifying multiplets

✦ we seek a rotated version of some pattern

✦ when the wavelet coefficient is high, this means that the pattern has been found

✦ we can obtain Euler angles associated to the orientation of the multiplet

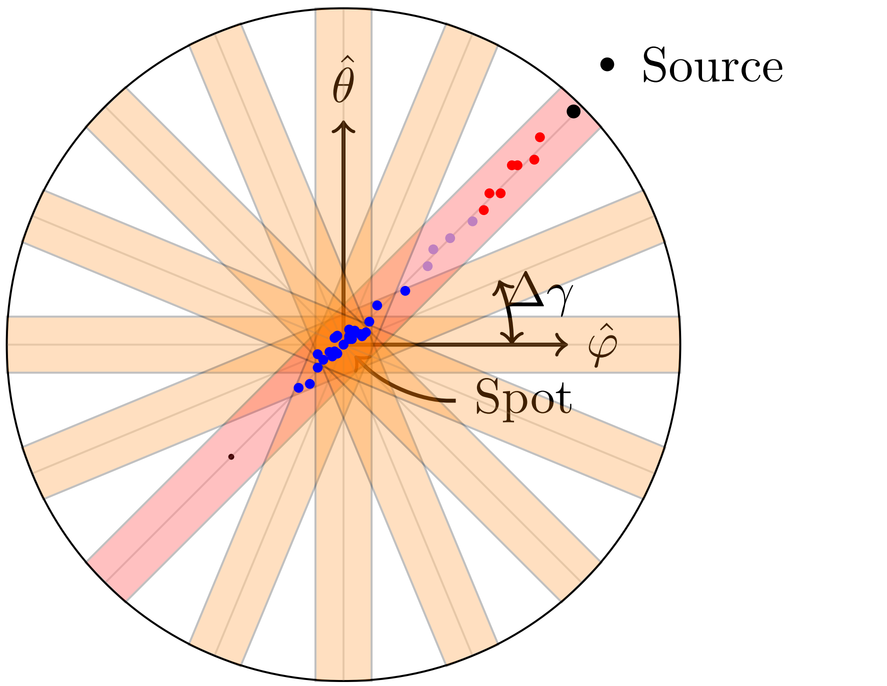


✦ for events coming from the same source the expected deflection is

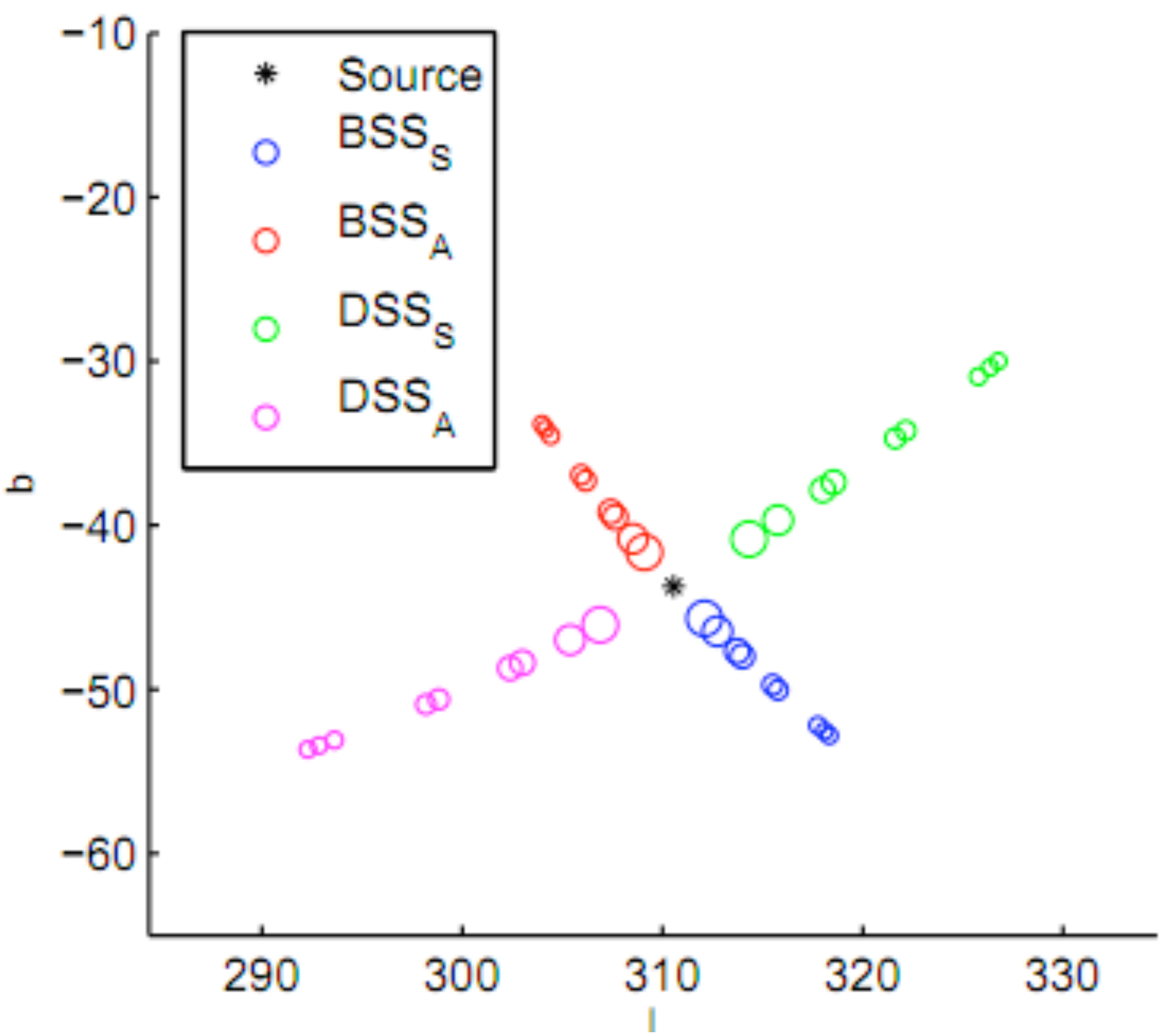
$$\delta = \frac{Ze}{E}\int_0^L d\vec{l} \times \vec{B}$$

✦ for multiplets we expect a high value for the correlation coefficient of the graph deflection versus inverse of the energy

✦ if this coefficient is high we count the number of events within a stripe of arbitrary dimensions



gmf and multiplets



R. Jansson, G. Farrar. ICRC 2007.

reference simulations

✦ Stanev (ASS-A, BSS-S)

✦ HMR (ASS-A, ASS-S, BSS-A, BSS-S)

✦ SRWE (BSS, ASS+RING)

expectations

✦ analyse the behavior of the orientation of the multiplets for different models

what for?

✦ the search and identification of multiplets in data detected by cosmic ray experiments, such as Auger, allow us to constrain models of the galactic magnetic field

conclusion

✦ the orientation of the multiplets can constrain gmf models and allow us to set limits for them

Stanev model

BSS-S

$$B(r,\theta) = B_0(r)\cos\left(\theta - \frac{1}{\tan p}\ln\frac{r}{r_0}\right)$$

ASS-A

$$B(r,\theta) = B_0(r)\left|\cos\left(\theta - \frac{1}{\tan p}\ln\frac{r}{r_0}\right)\right|$$

halo field

$$|B(r,\theta,z)| = |B(r,\theta)|\exp\left(-\frac{|z|}{z_0}\right)$$

radial component

$$B_0(r) = \frac{3R}{r}\ \mu\mathrm{G}$$

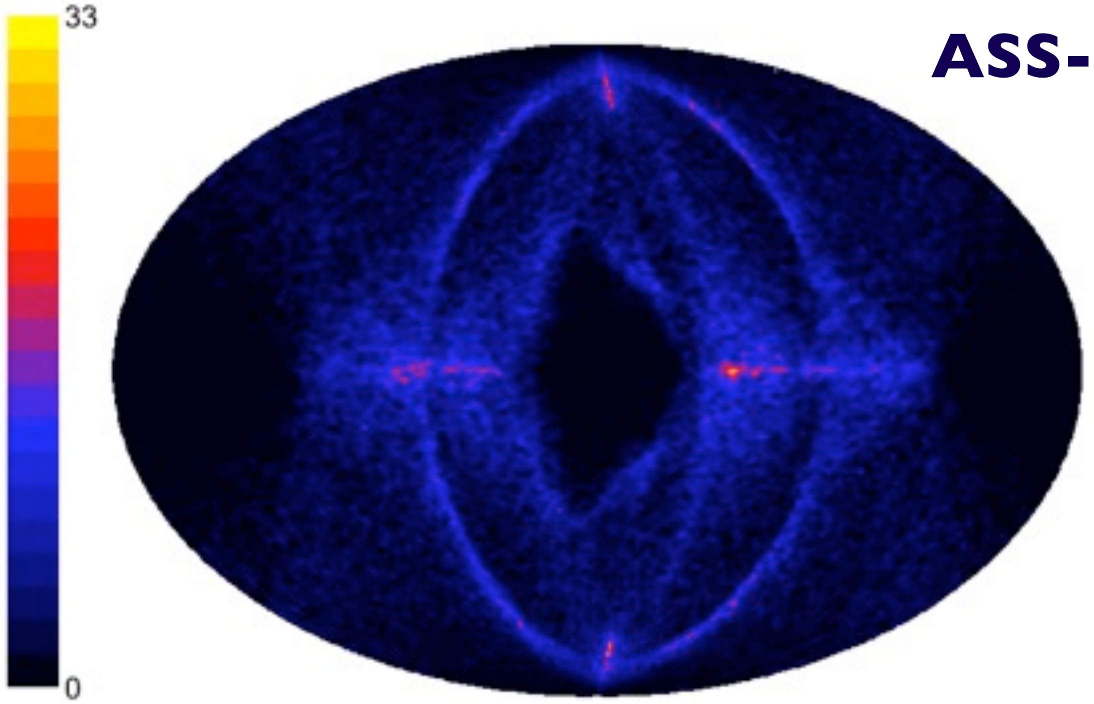
parameters

z_0=1 kpc if $|z|<0.5$ kpc and 4 kpc otherwise

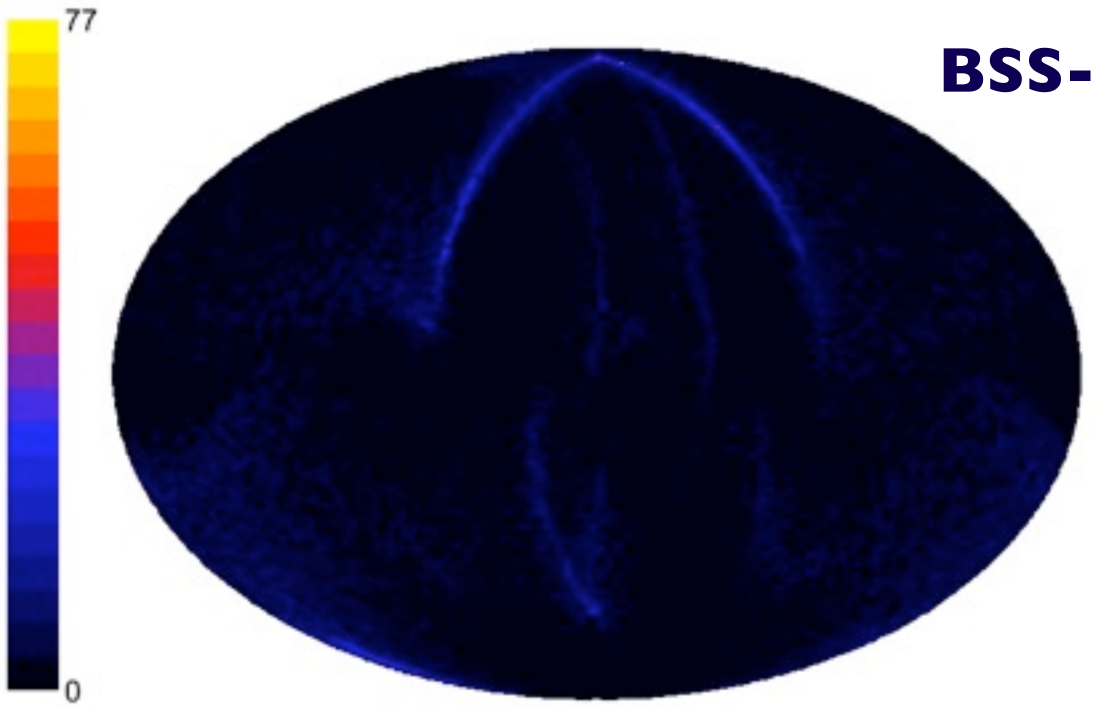
$p=-10^\circ$

r_0=10.55 kpc

R=8.5 kpc



ASS-A



BSS-S

Harari, Mollerach and Roulet model

BSS

$$B(r,\theta) = B_0(r)\cos\left(\theta - \frac{1}{\tan p}\ln\frac{r}{r_0}\right)$$

ASS

$$B(r,\theta) = B_0(r)\cos^2\left(\theta - \frac{1}{\tan p}\ln\frac{r}{r_0}\right)$$

radial component

$$B_0(r) = \frac{3R}{r}\tanh^3\left(\frac{r}{r_1}\right)\ \mu\mathrm{G}$$

halo field

$$\vec{B}_{-S}(r,\theta,z) = \vec{B}(r,\theta)\left[\frac{1}{2\cosh\left(\frac{z}{z_0}\right)} + \frac{1}{2\cosh\left(\frac{z}{z_1}\right)}\right]$$

$$\vec{B}_{-A}(r,\theta,z) = \vec{B}_{-A}(r,\theta,z)\tanh\left(\frac{z}{z_2}\right)$$

parameters

z_0=4 kpc

z_1=0.3 kpc

z_2=20 pc

p=-12°

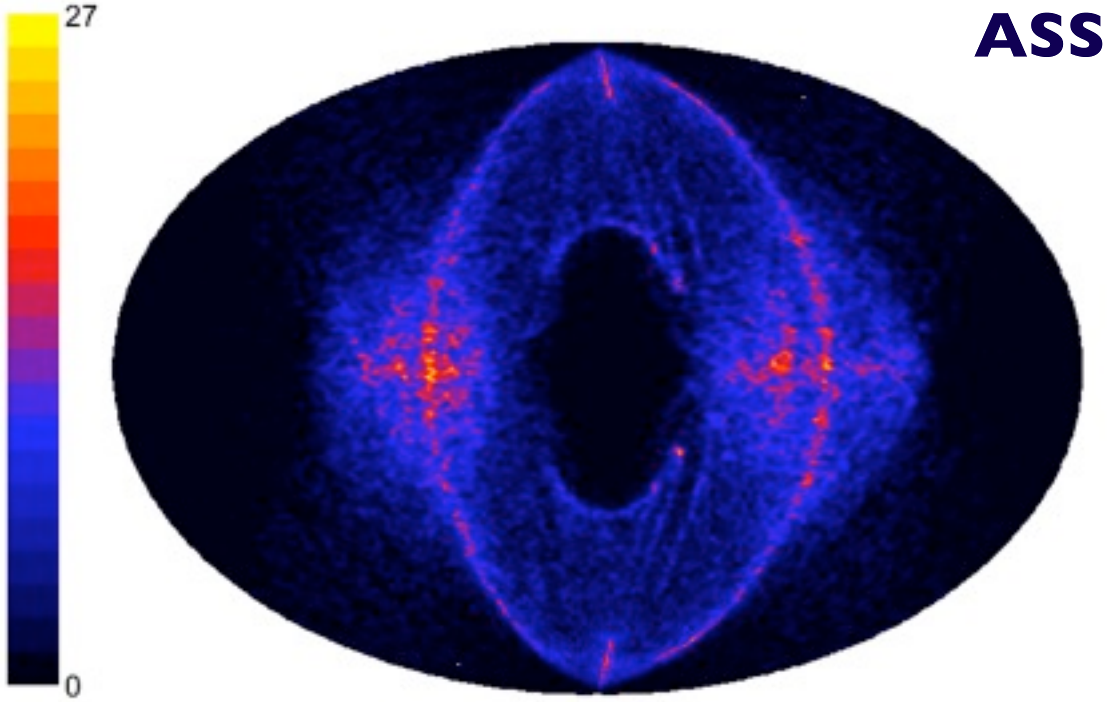
r_0=10.55 kpc

r_1=2 kpc

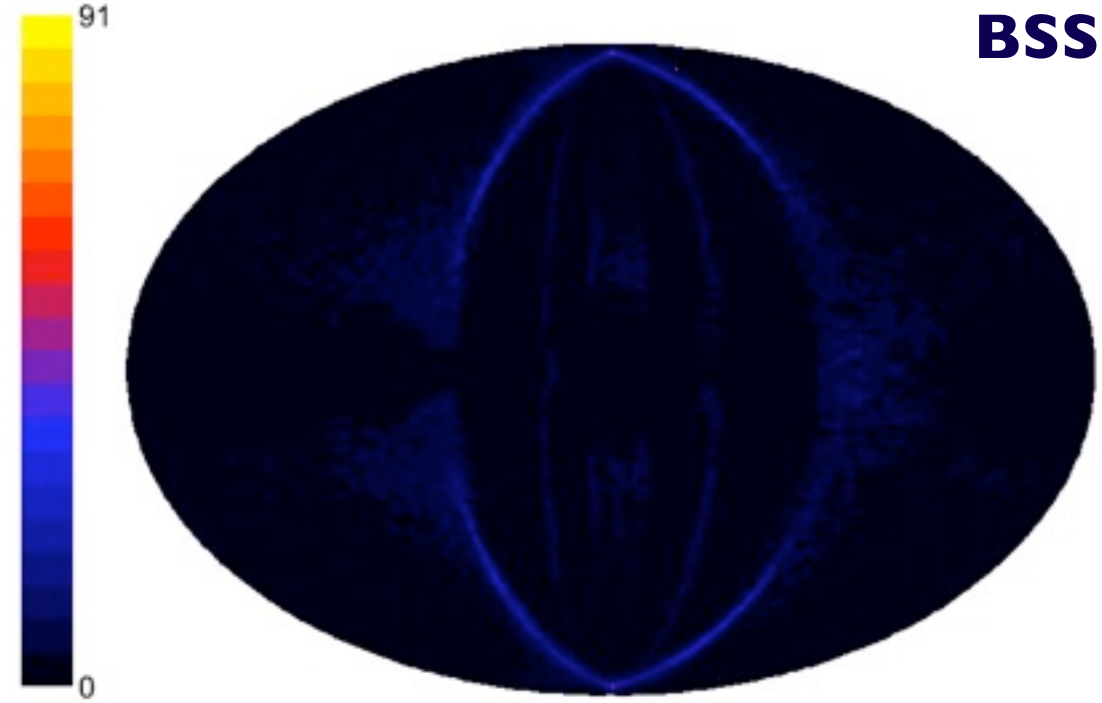
R=8.5 kpc

Harari, Mollerach and Roulet model

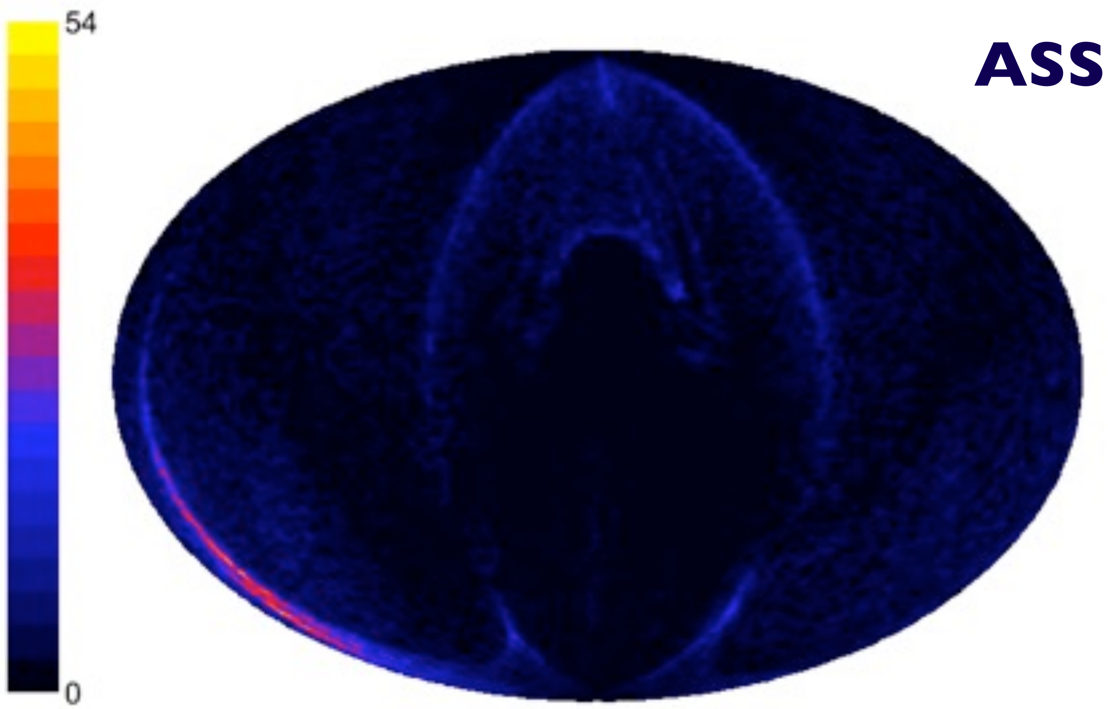
ASS-A



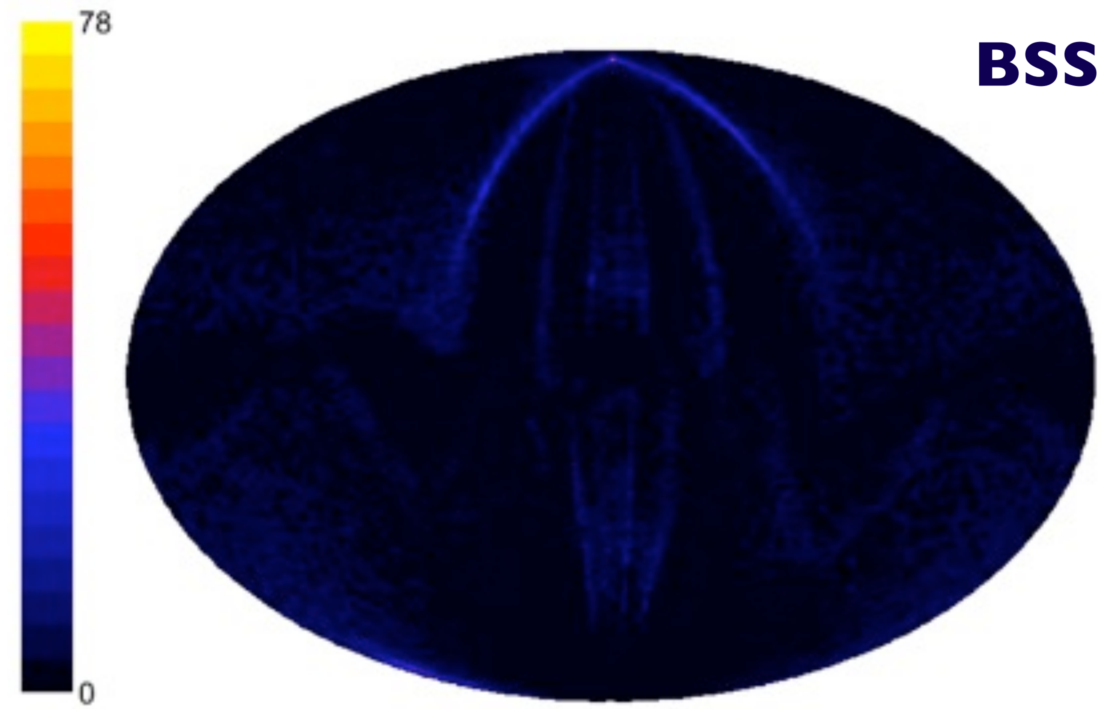
BSS-A



ASS-S



BSS-S



Sun, Reich, Waelkens and Ensslin model

BSS

$$B(r,\theta) = B_0 \cos\left(\theta + \frac{1}{\tan p} \ln \frac{r}{r_0}\right)$$

ASS+RING

$$B(r,\theta) = \begin{cases} B_0 \Xi(r) \exp\left(-\frac{r-R_0}{R_0}\right) & r > R_c \\ B_0 & r \leq R_c \end{cases}$$

radial component

$$\Xi(r) = \begin{cases} +1 & \mathrm{r} > 7,5 \text{ kpc};\ 5 < \mathrm{r} \leq 6 \text{ kpc} \\ -1 & \mathrm{r} \leq 5 \text{ kpc};\ 6 < \mathrm{r} \leq 7,5 \text{ kpc} \end{cases}$$

halo field

$$|B(r,\theta,z)| = |B(r,\theta)| \exp\left(-\frac{|z|}{z_0}\right)$$

parameters

z_0=1 kpc

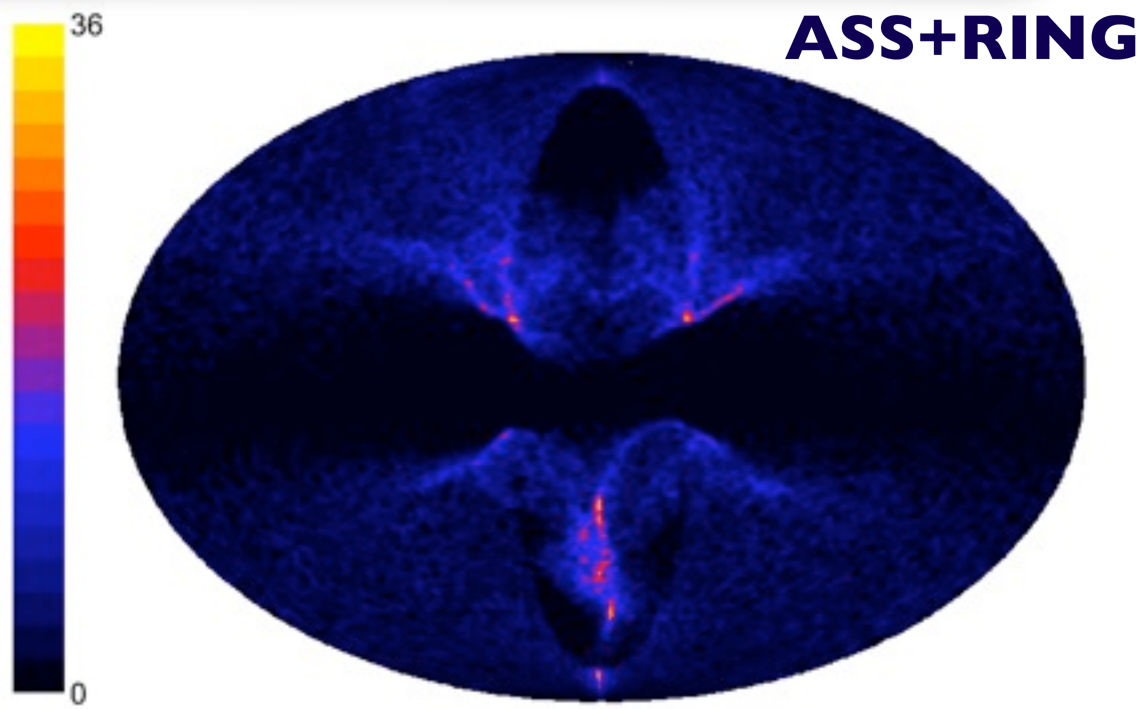
B_0=2 μG R_0= 9 kpc r<6

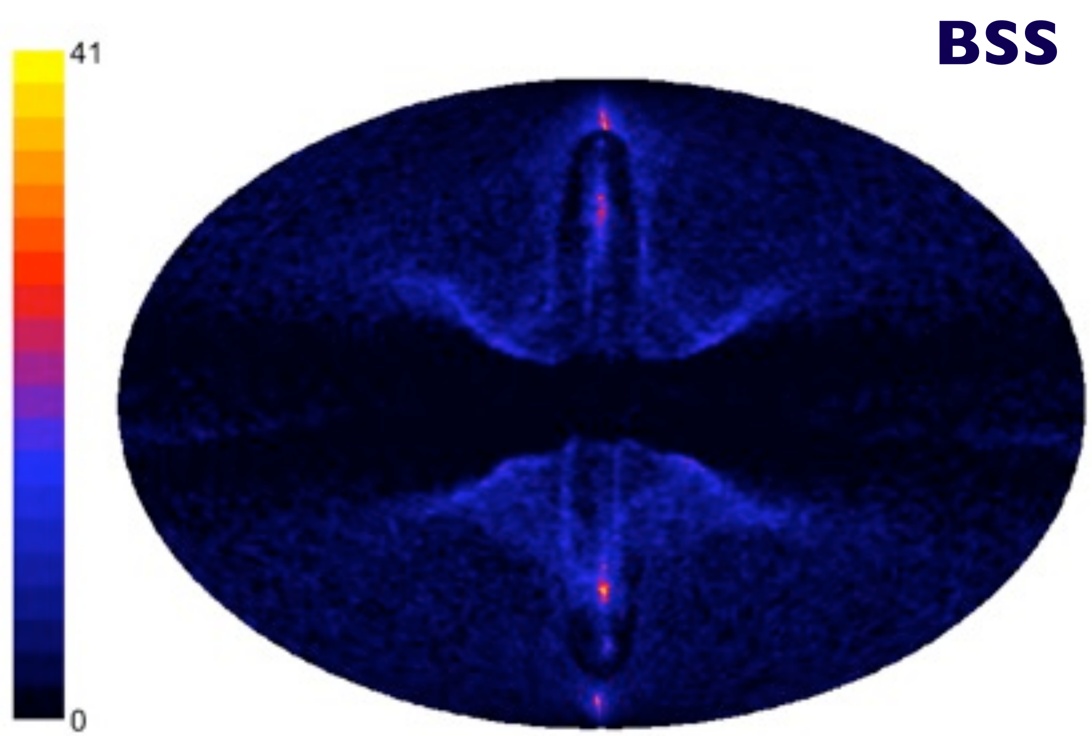
R_0= 6 kpc r>6

R=8.5 kpc

p=-10° se r<6

p=-15° p/ r>6





simulations

sources I

✦ l=-180°, -165°,..., 0°,15°,..., 180°

✦ b=-10°, 0°, 10°

sources II

✦ l=-180°,-135°,..., 0°,45°,..., 180°

✦ b=-90°, -45°, 0°,45°,90°

field models

✦ Stanev (ASS-A, BSS-S)

✦ HMR (ASS-A, ASS-S, BSS-A, BSS-S)

✦ SRWE (BSS, ASS+RING)

information

✦ 50 events simulated

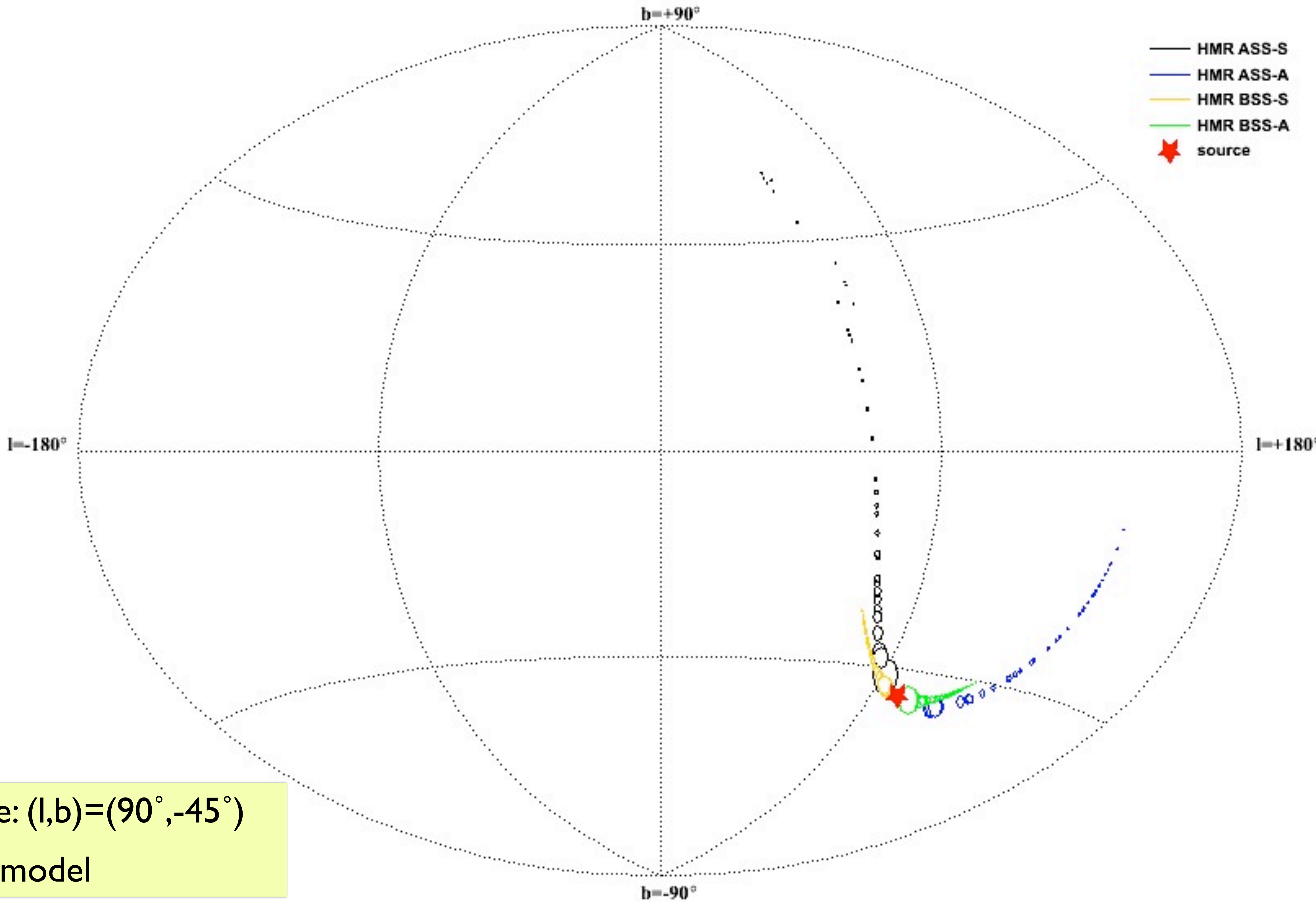
✦ CRT code for tracking

✦ the simulated sources are 20 kpc away (backtracking)

✦ spectral index of the sources: -2.7

✦ energy: between 20 and 200 EeV

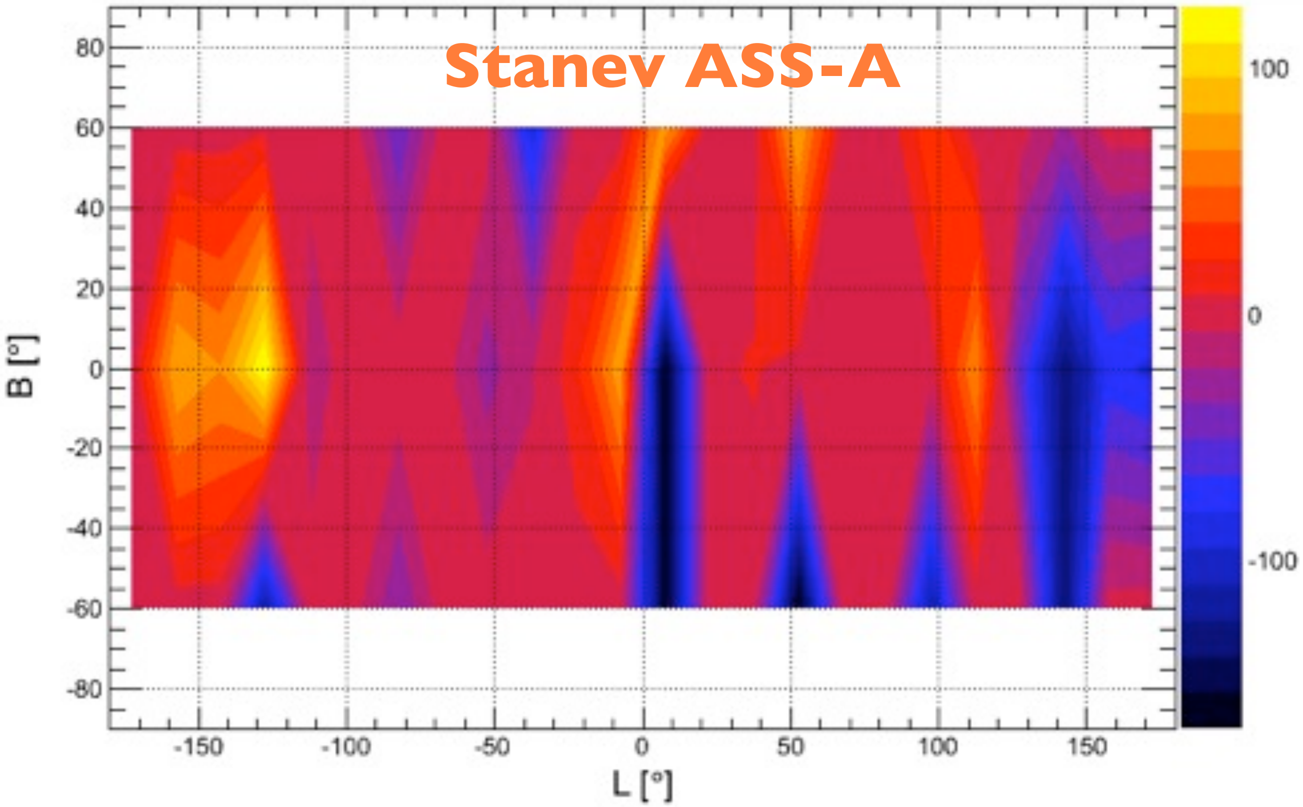
simulations: example

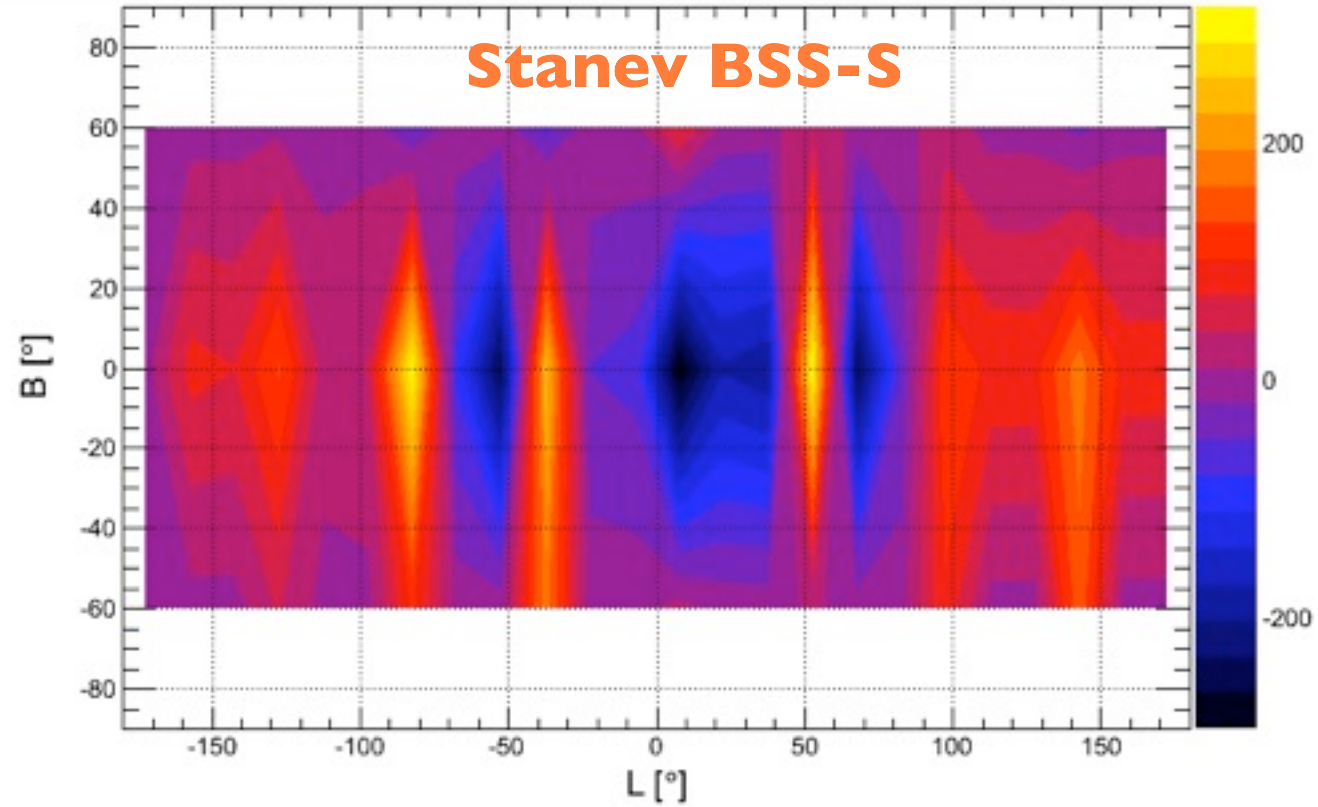


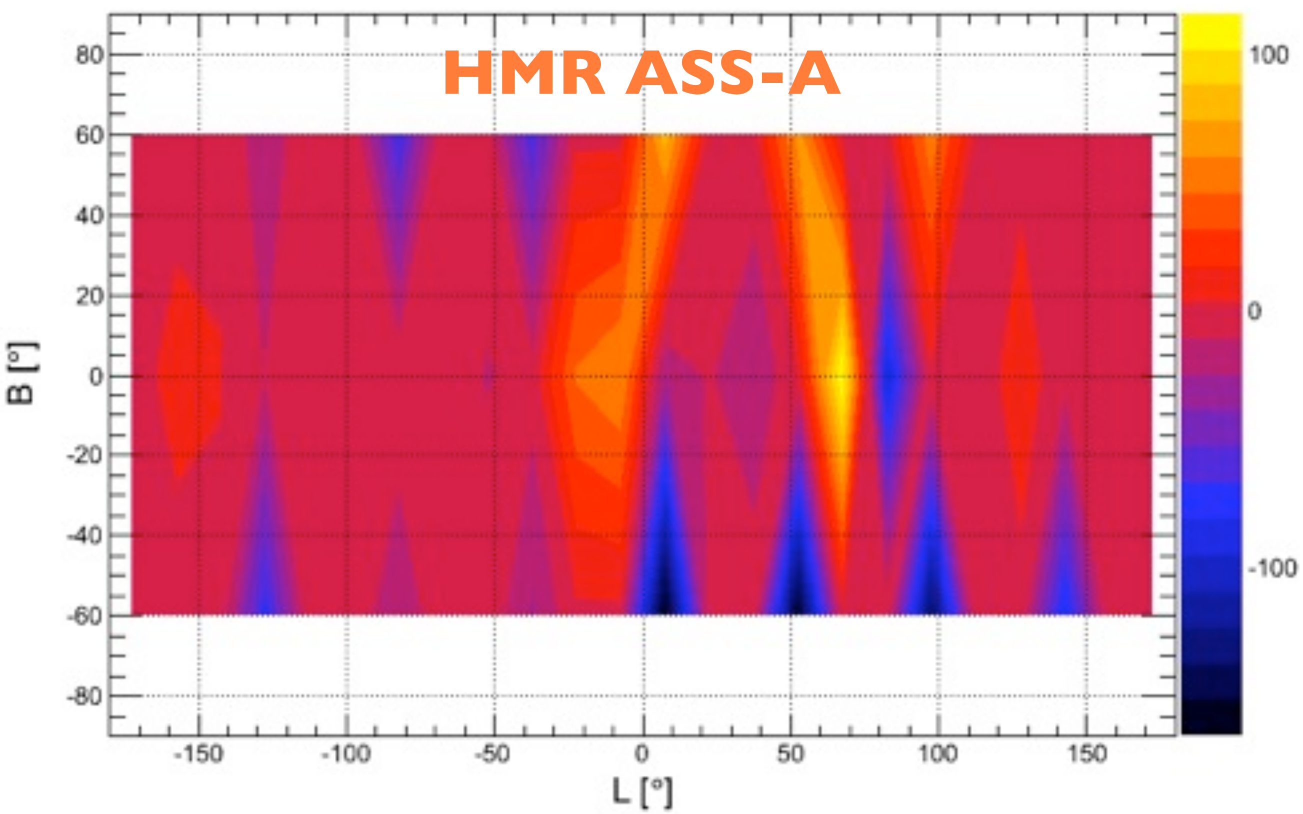
source: (l,b)=(90˚,-45˚)

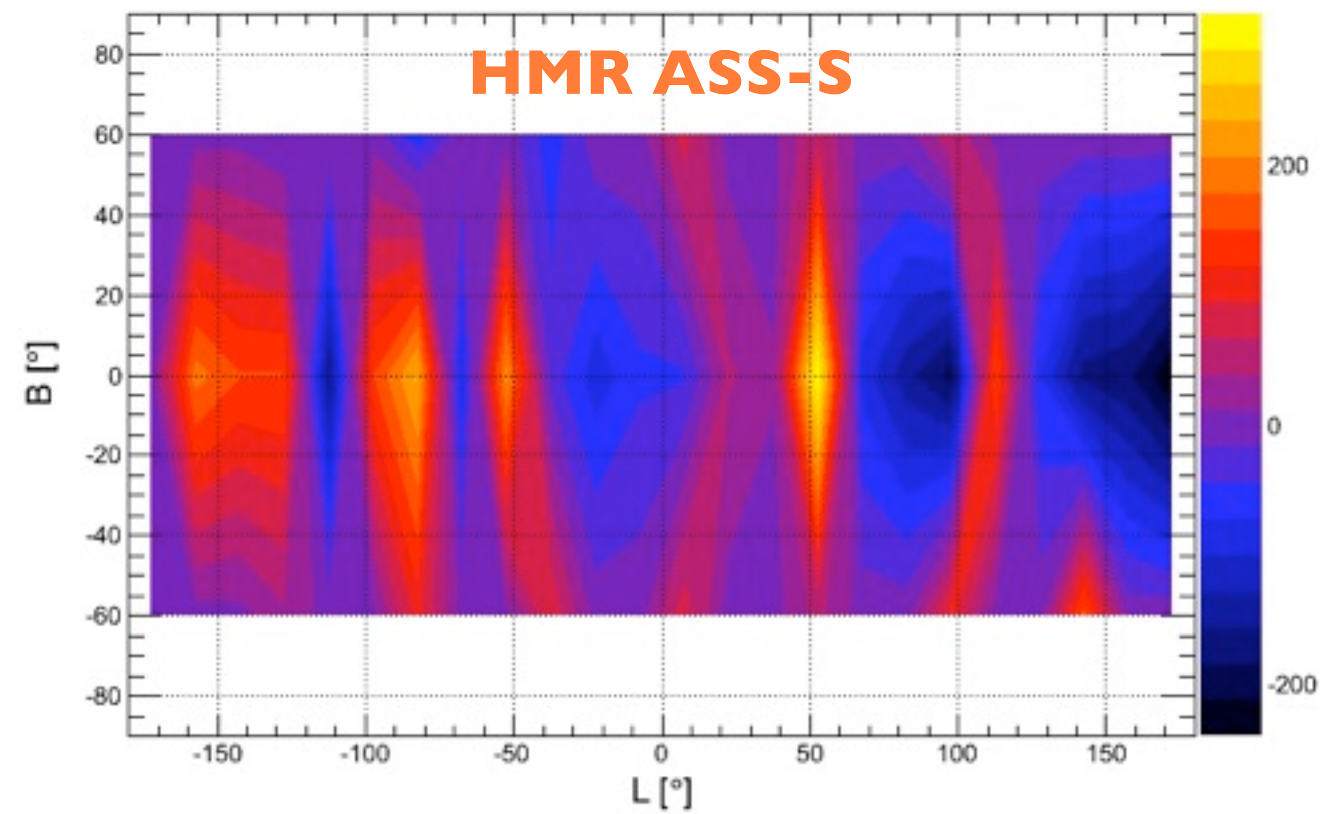
HMR model

orientation of the multiplets: results

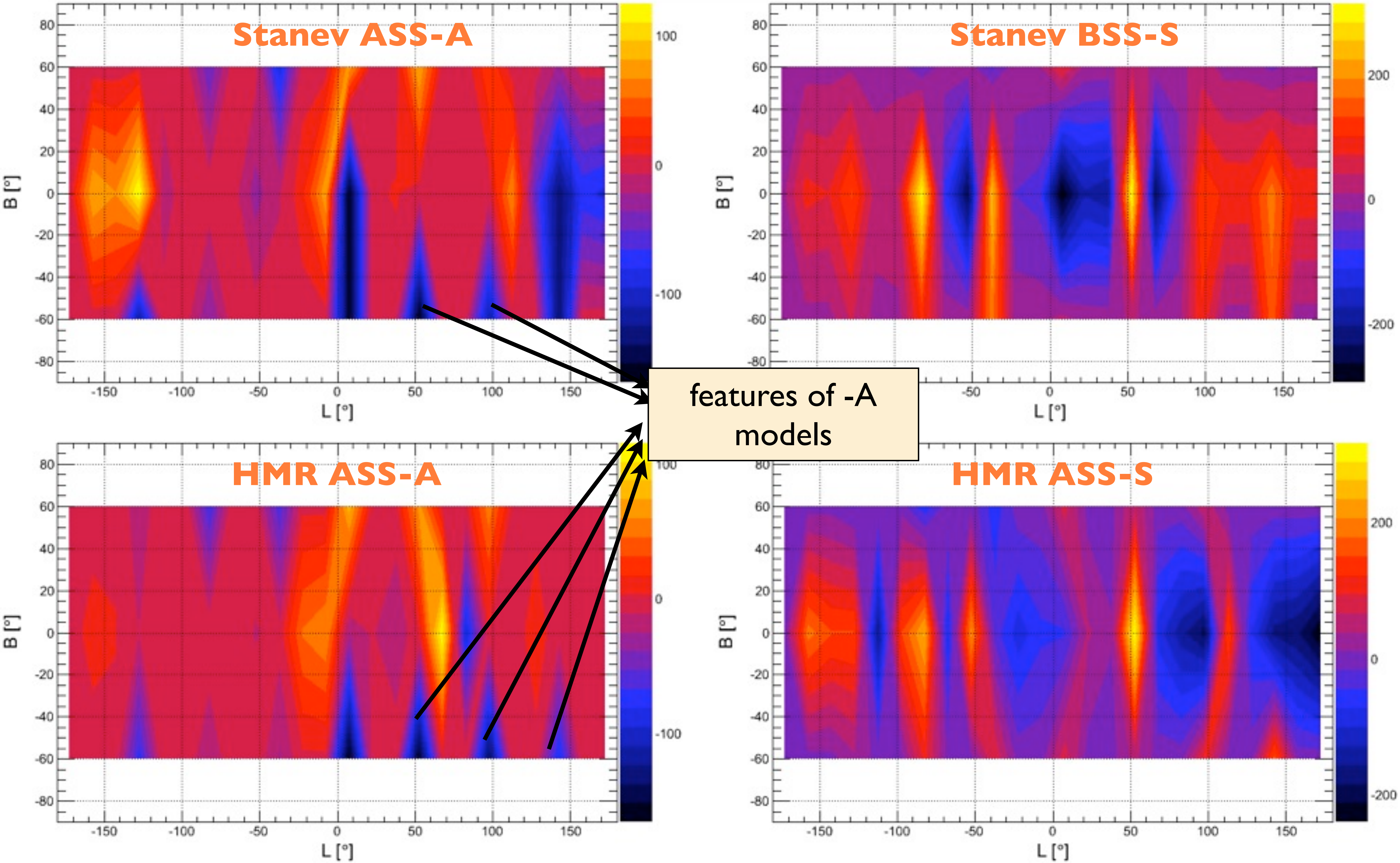




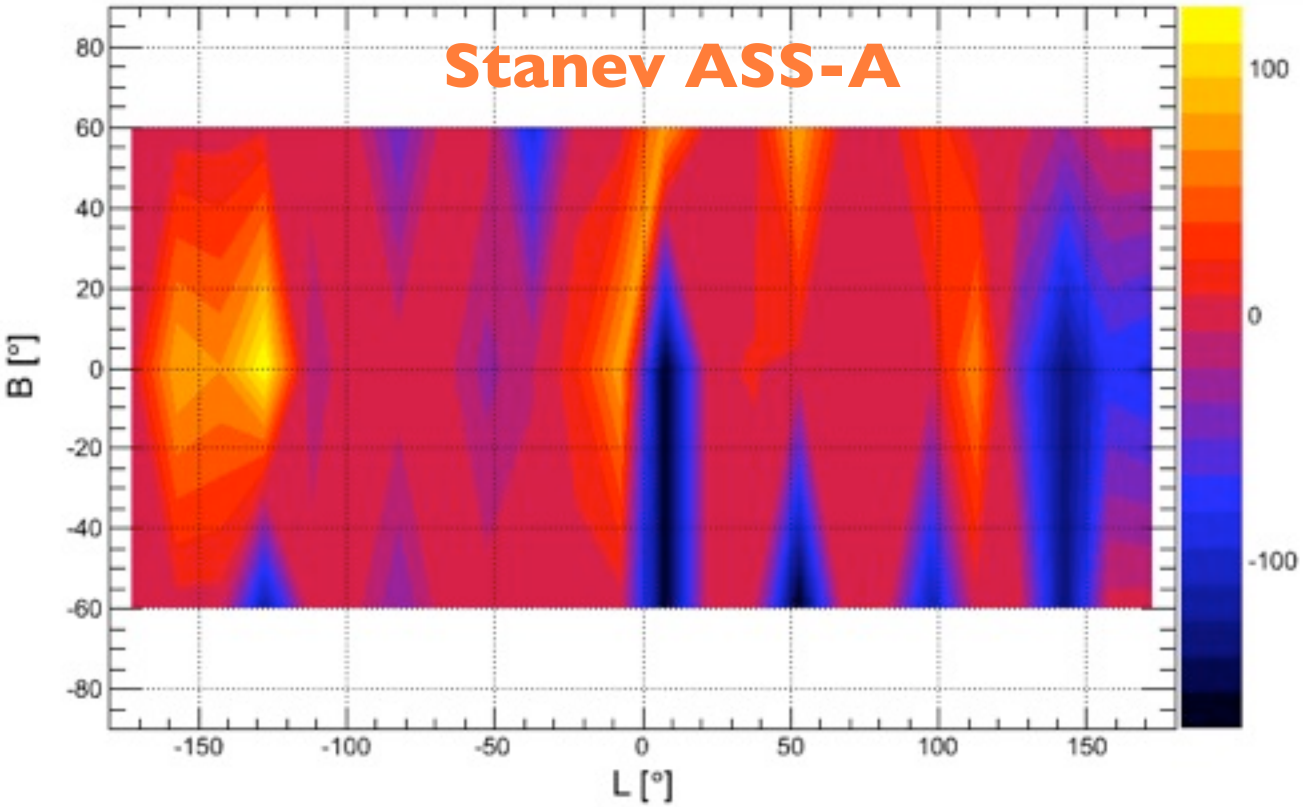


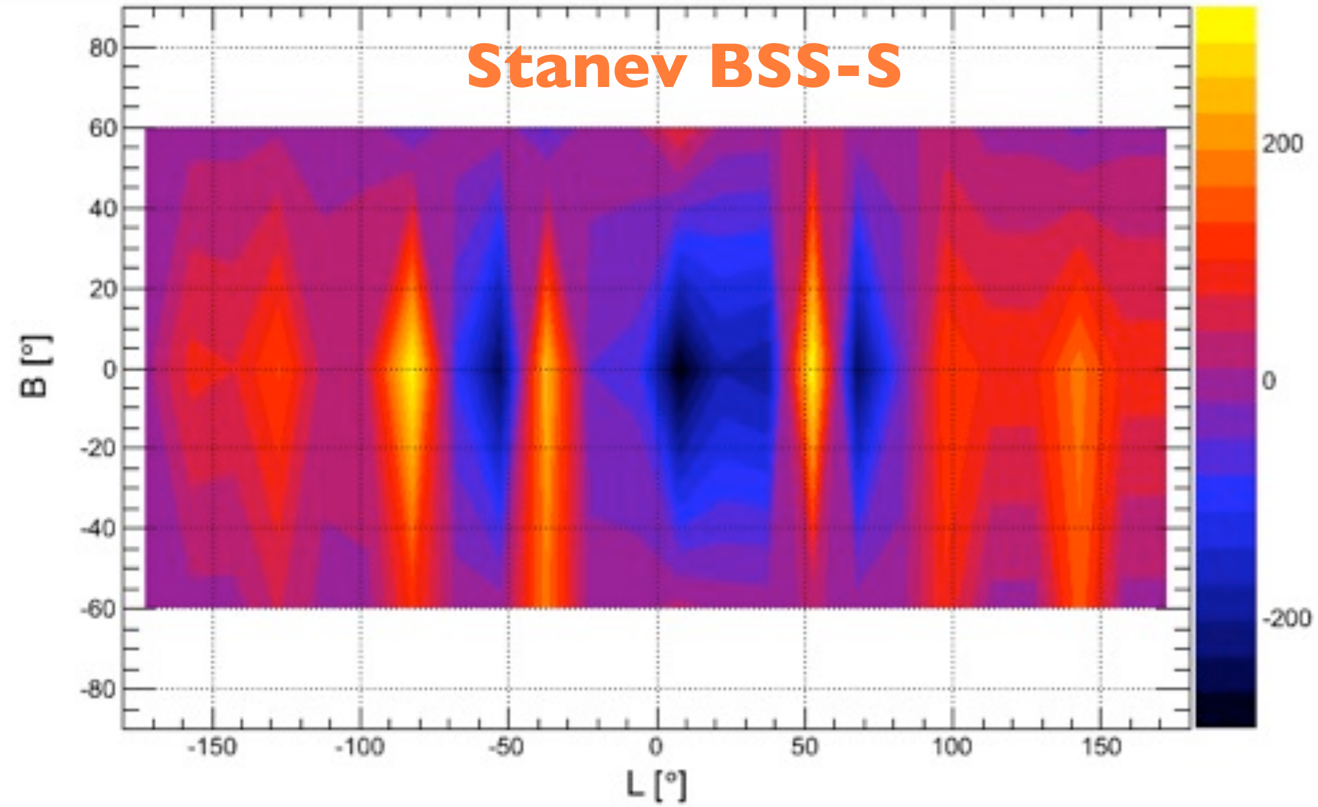


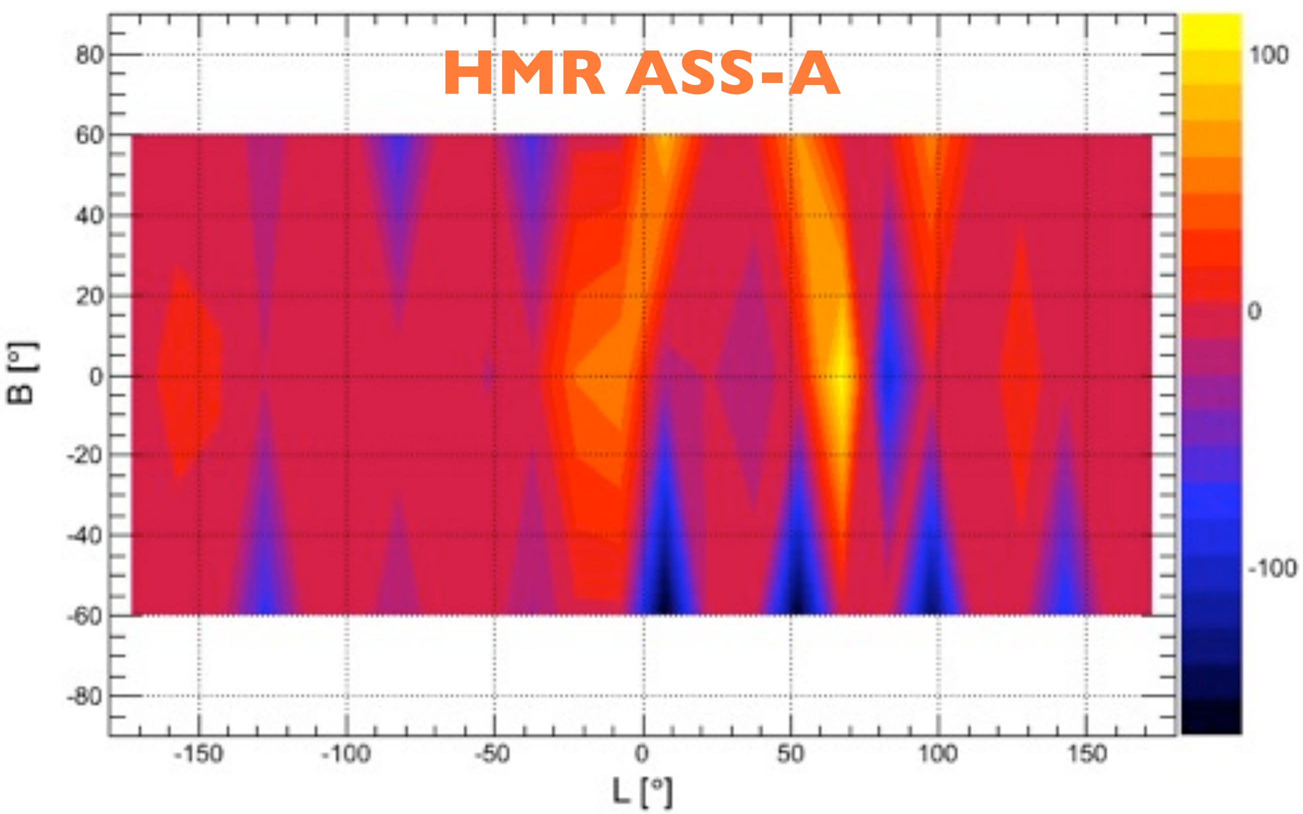
orientation of the multiplets: results

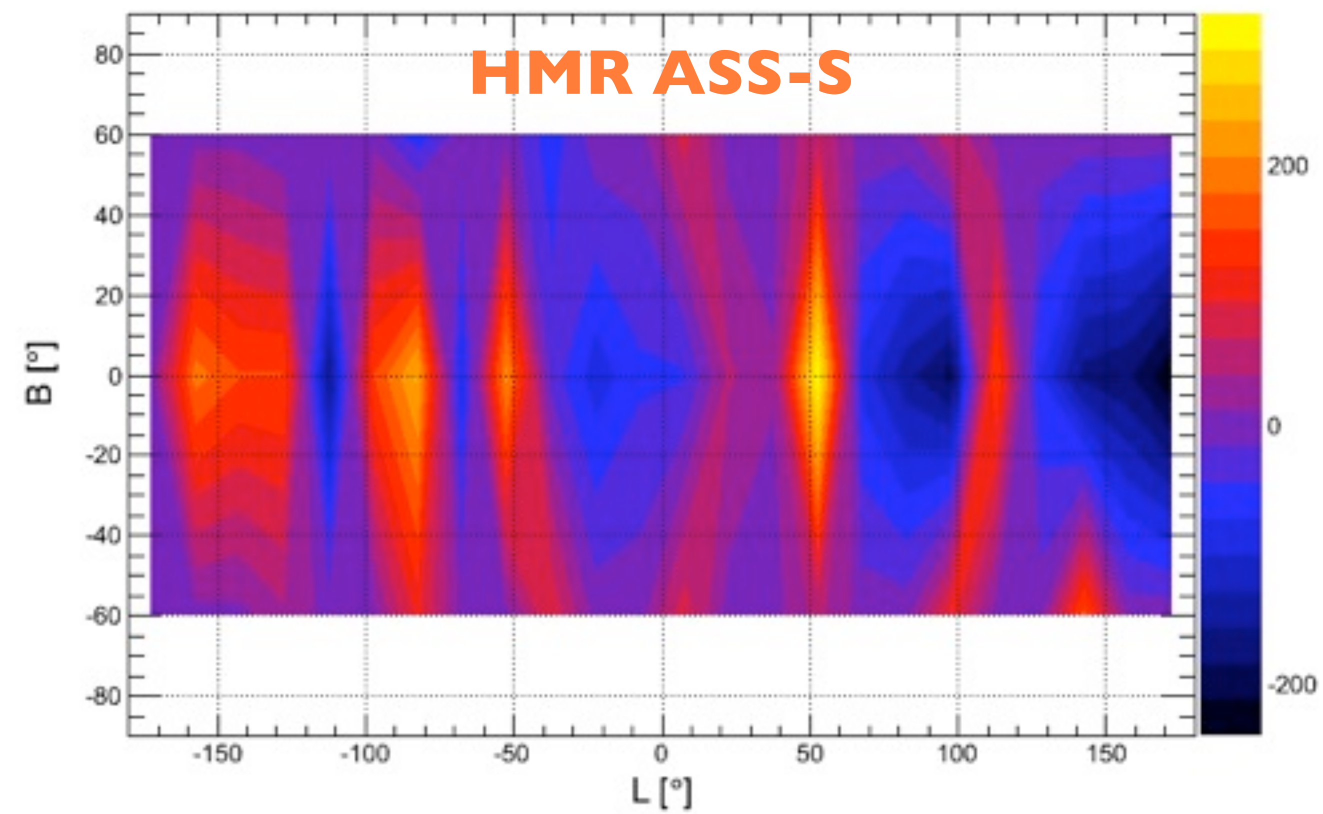


orientation of the multiplets: results

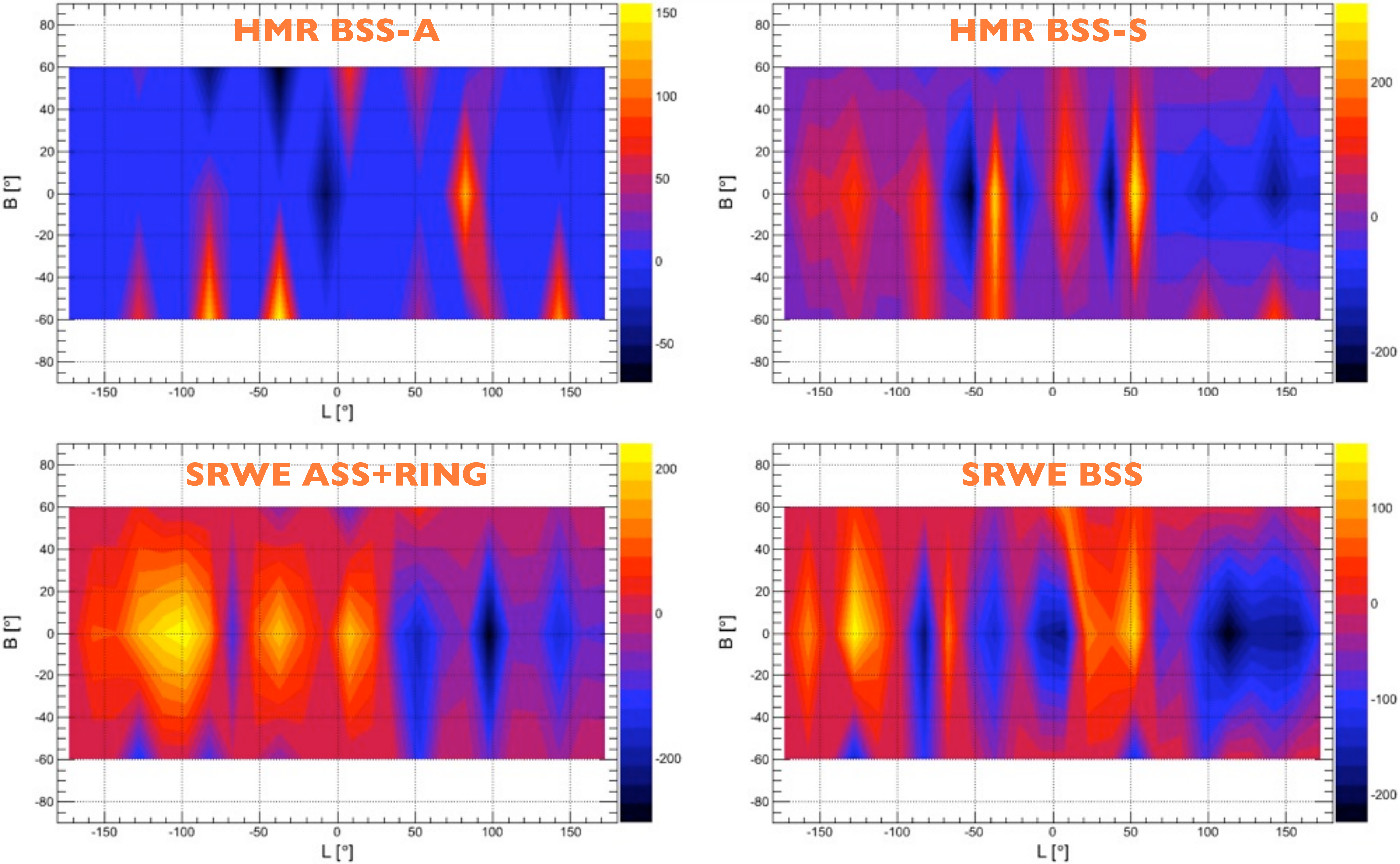




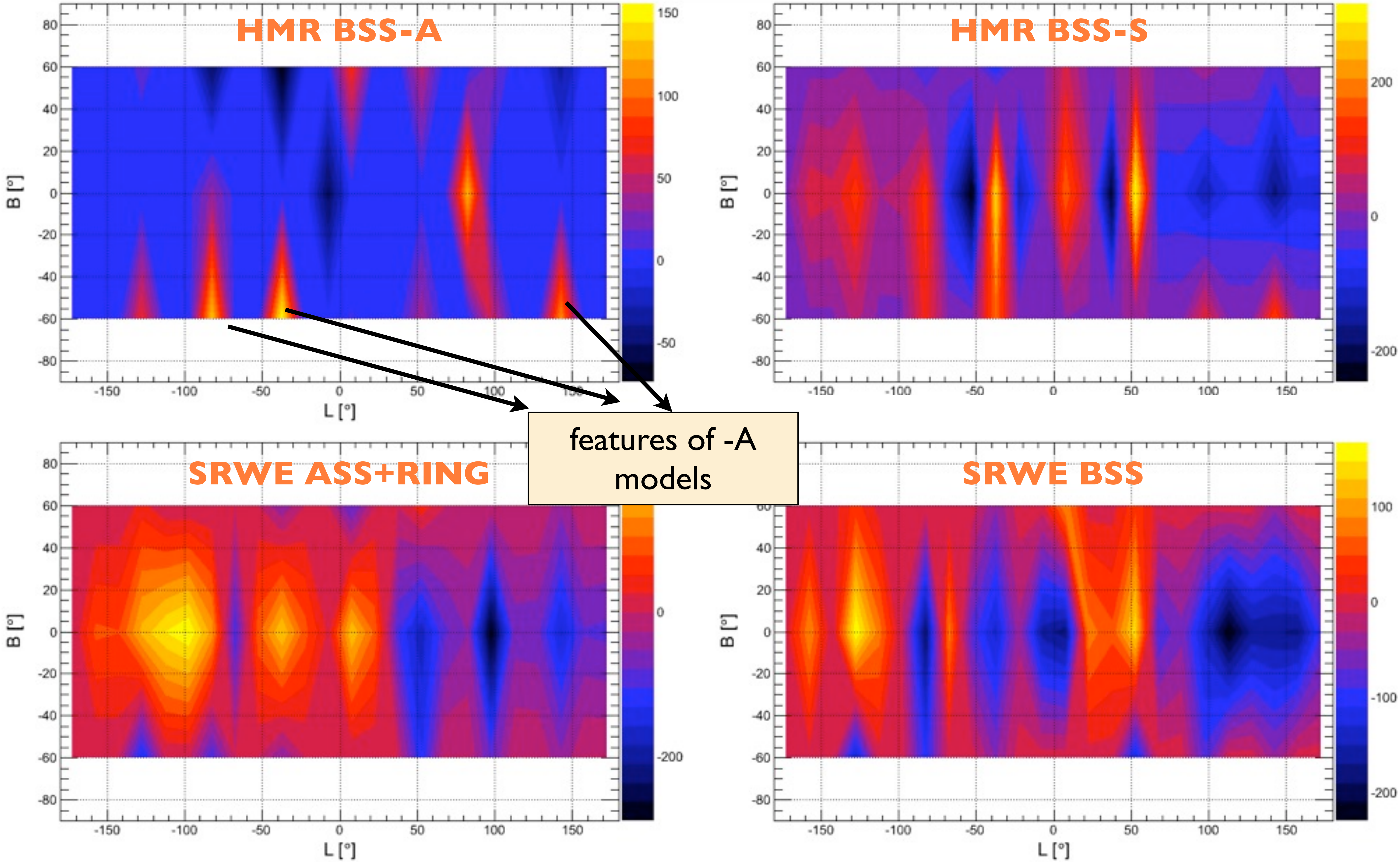




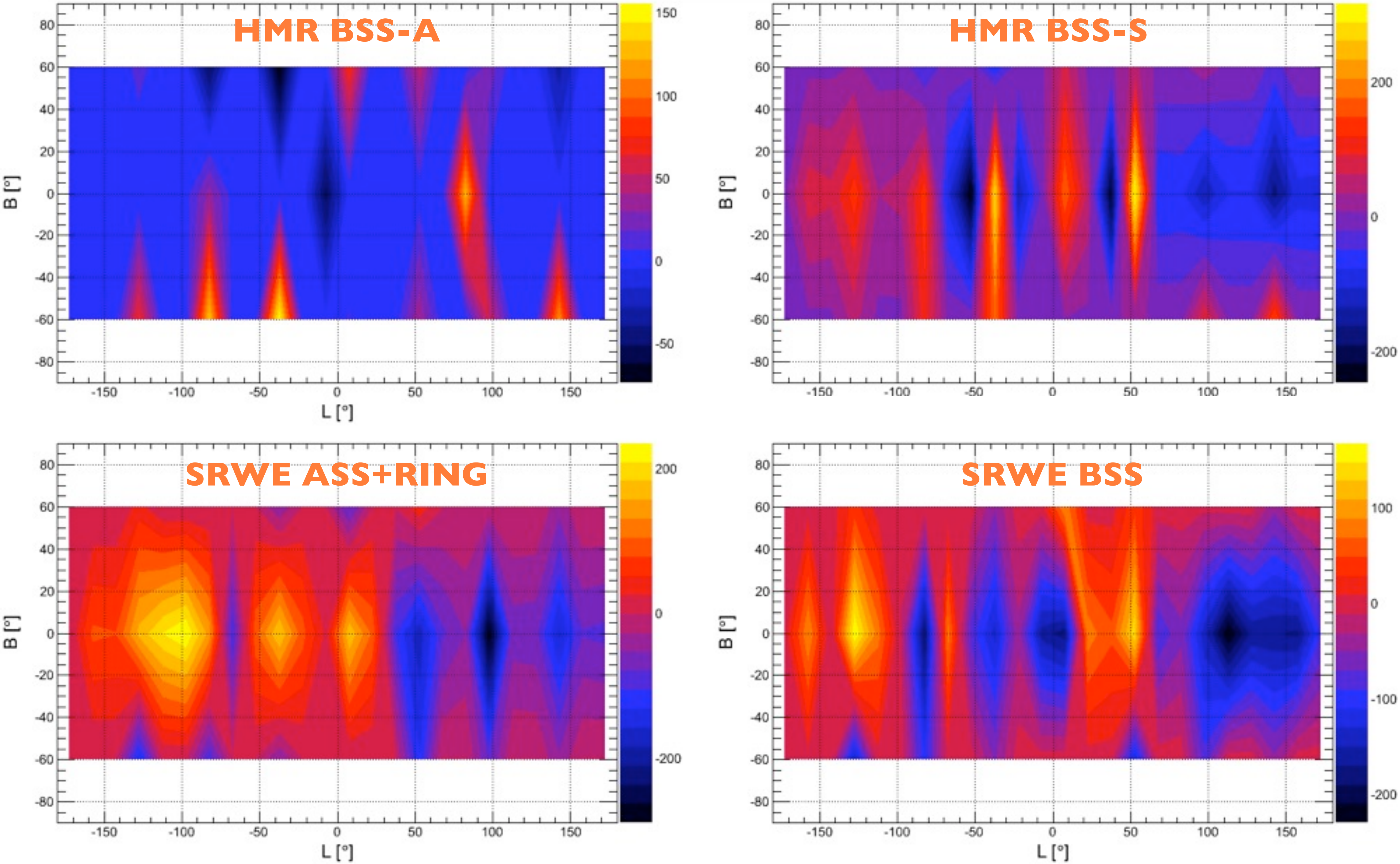
orientation of the multiplets: results



orientation of the multiplets: results



orientation of the multiplets: results



conclusions and perspectives

✦ it was developed a new method to identify structures in uhecrs maps

✦ it is possible to observe a relation between the orientation of the multiplets and their location in the sky

✦ we could clearly distinguish between -A and -S models

✦ analysis using Auger data are currently underway

✦ the comprehension of the cosmic magnetic fields allows us to trace the particles back to their sources (open issue)

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