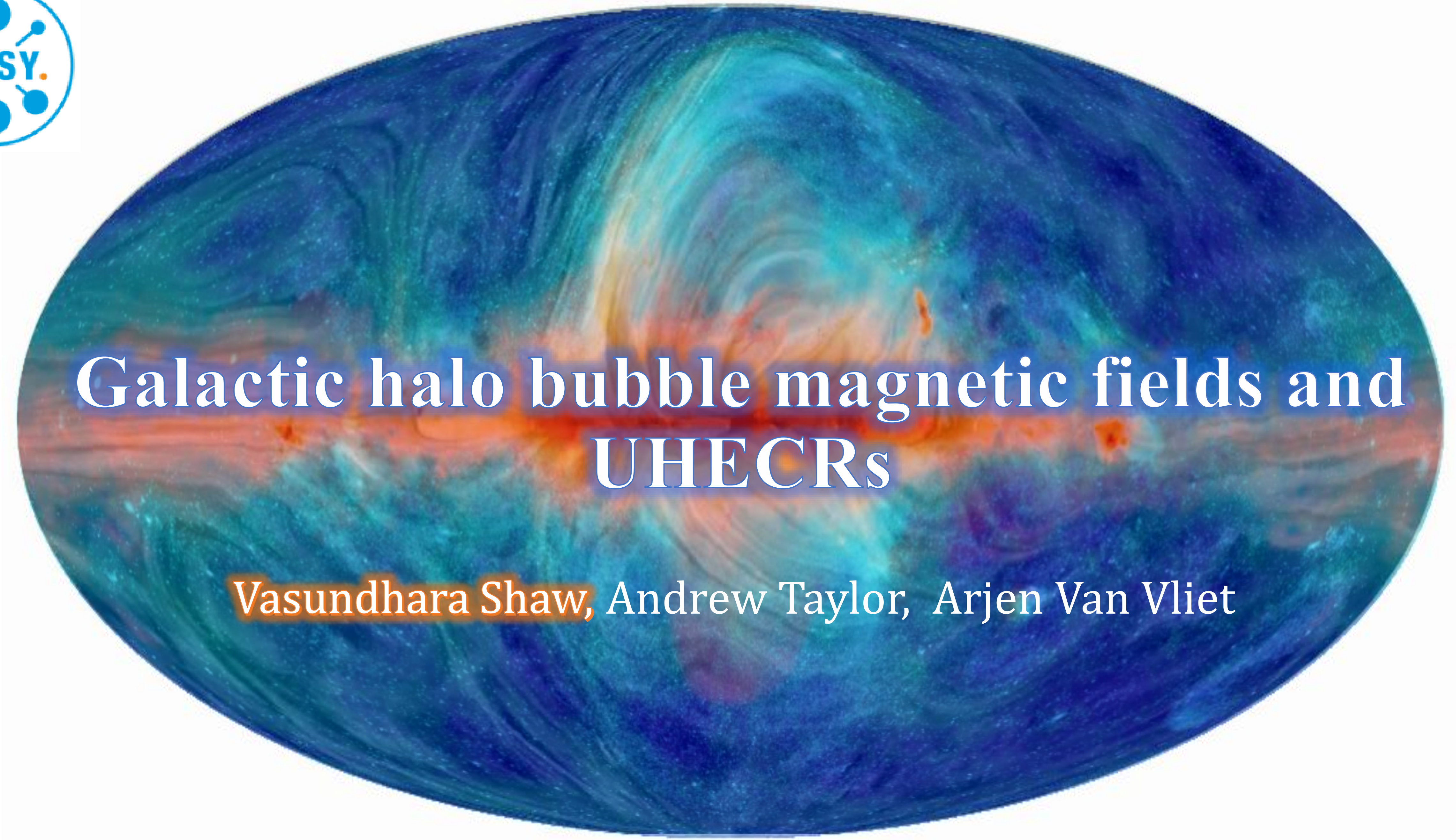


Galactic halo bubble magnetic fields and UHECRs

Vasundhara Shaw, Andrew Taylor, Arjen Van Vliet

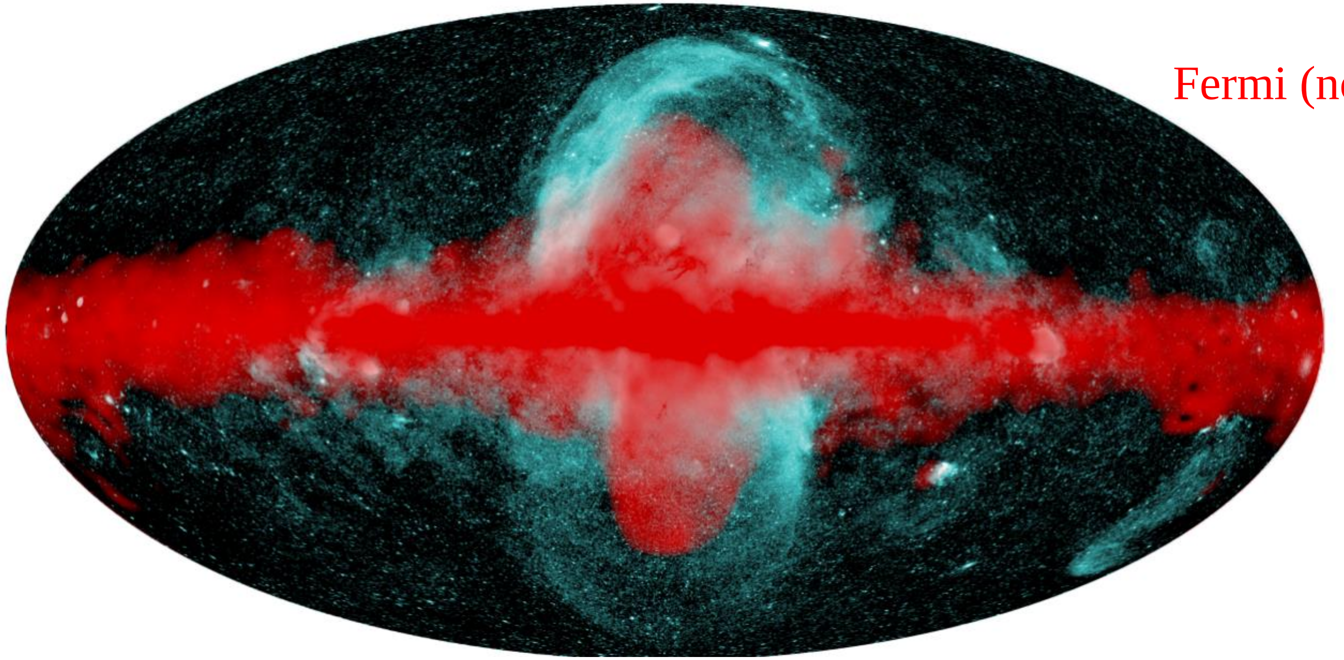
1) https://www.cosmos.esa.int/web/planck/picture-gallery

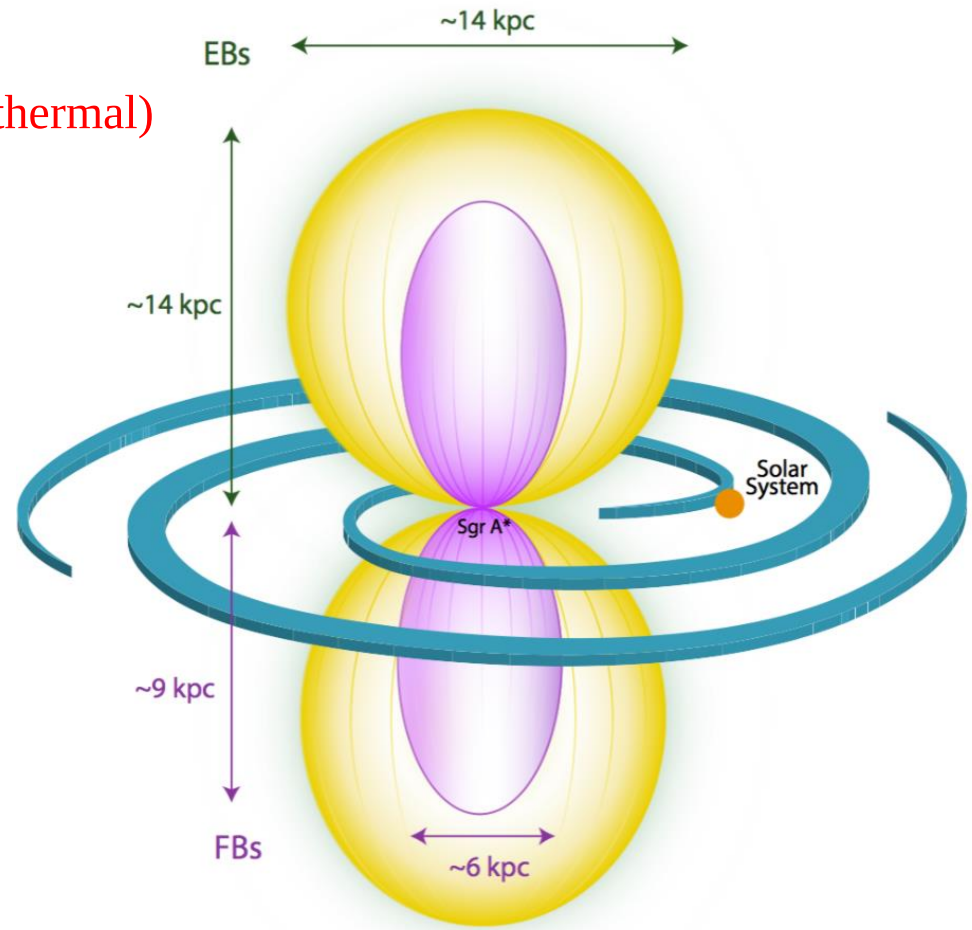
2) Predehl, P., Sunyaev, R.A., Becker, W. et al. Detection of large-scale X-ray bubbles in the Milky Way halo. Nature 588, 227–231 (2020).

Galactic Halo Bubbles

eRosita (thermal)

Fermi (non-thermal)





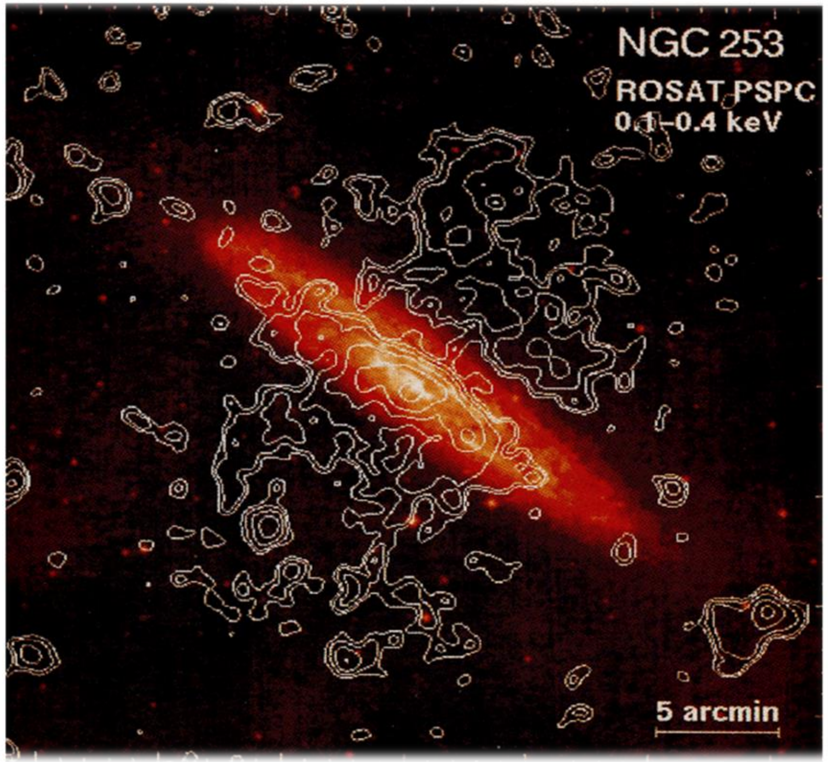
10^{56} erg in X-rays

Total energy10^{54-55} erg in disc

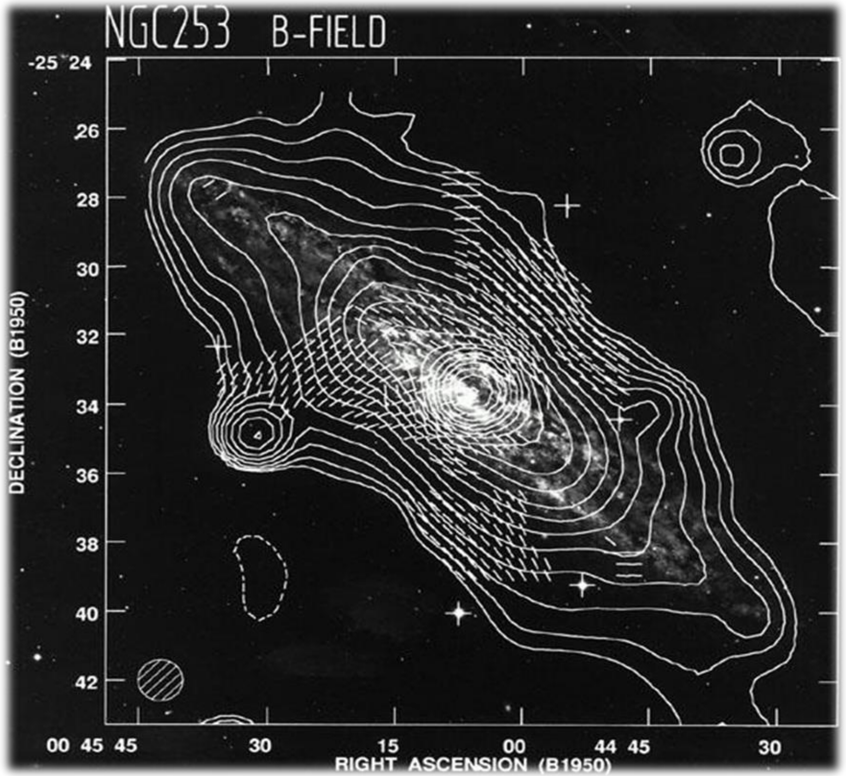
Predehl, P., Sunyaev, R.A., Becker, W. et al. Detection of large-scale X-ray bubbles in the Milky Way halo. Nature 588, 227–231 (2020). https://doi.org/10.1038/s41586-020-2979-0

Large scale structures = large scale fields

(Pietsch et.al 1996)

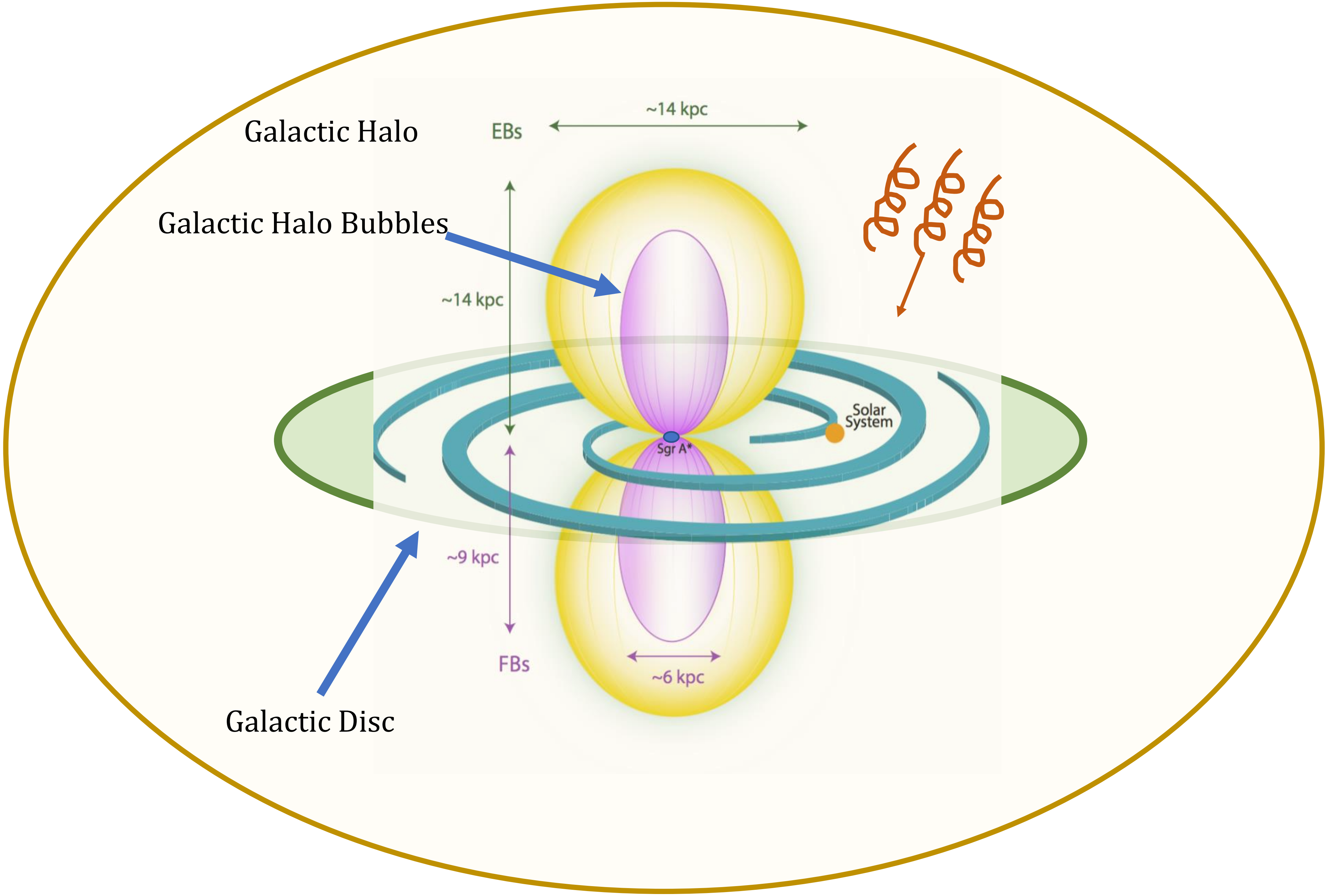


(Beck et.al 1994)



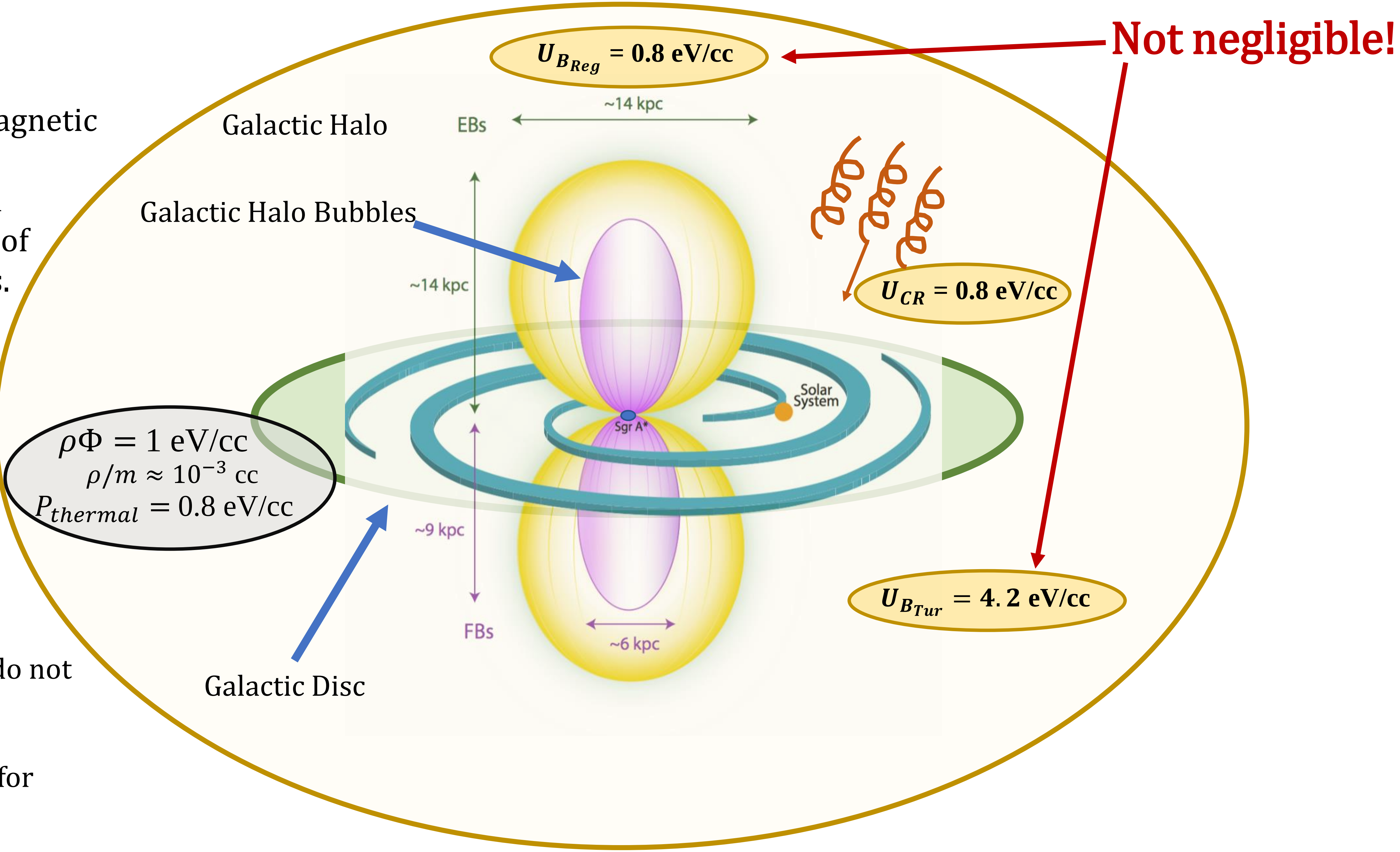
Total radio intensity (*contours*) and magnetic field orientation of NGC 253.

Milky way is not a starburst galaxy yet it has outflow!



Galactic Halo
EBs
~14 kpc
Galactic Halo Bubbles
~14 kpc
Solar System
Sgr A*
~9 kpc
FBs
~6 kpc
Galactic Disc

We need magnetic fields to understand deflections of cosmic rays.

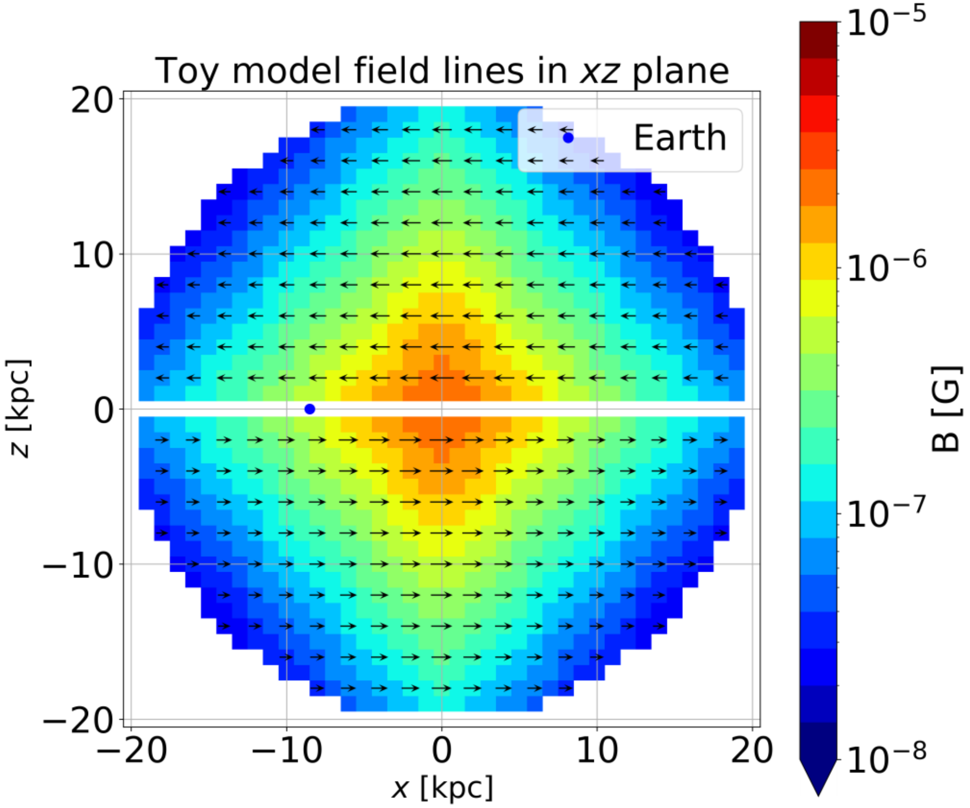


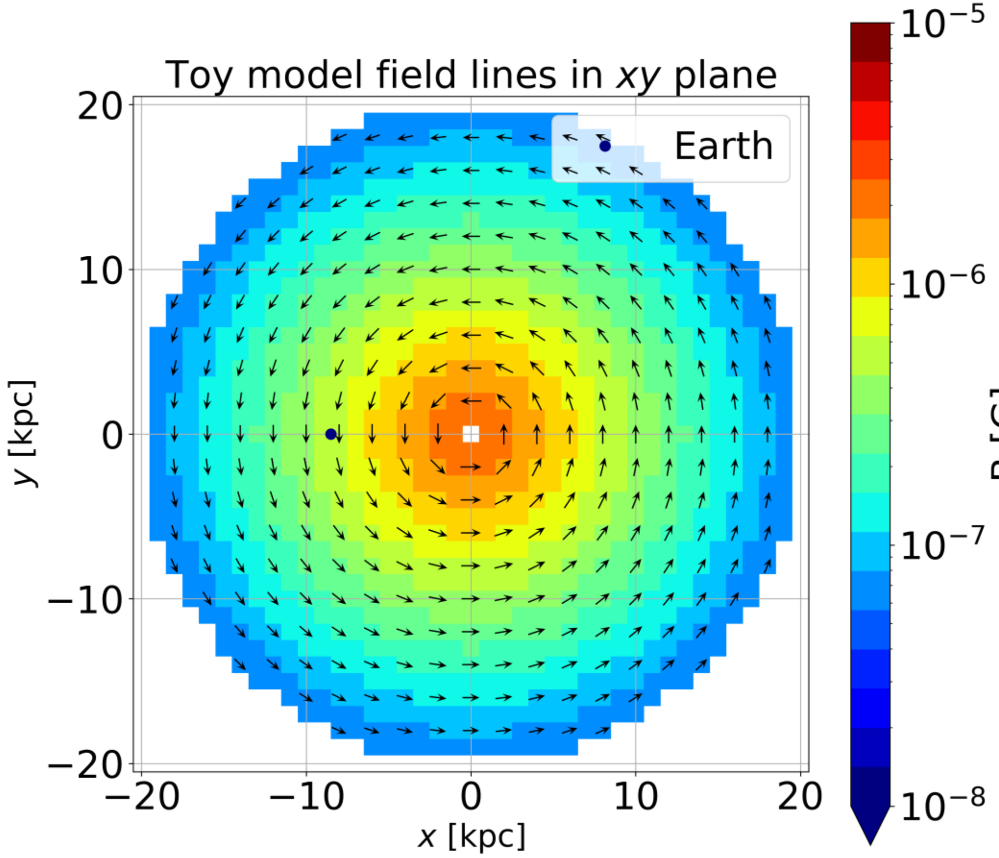
Note: We do not have any accurate estimates for the Halo !

Probing magnetic fields with synchrotron radiation

Toy Model – Structured fields

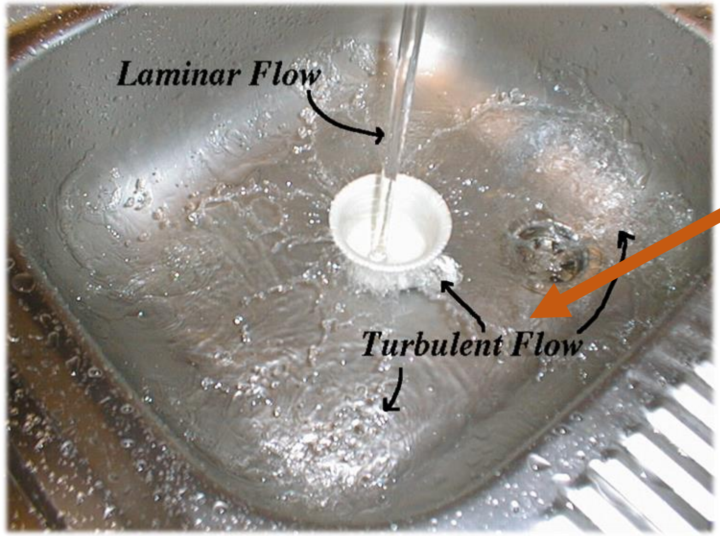
$$B_{\rm tor} = B_{\rm str} e^{(-|z|/Z_{\rm mag})} e^{(-z_{\rm min}/|z|)} e^{(-|r|/R_{\rm mag})}$$





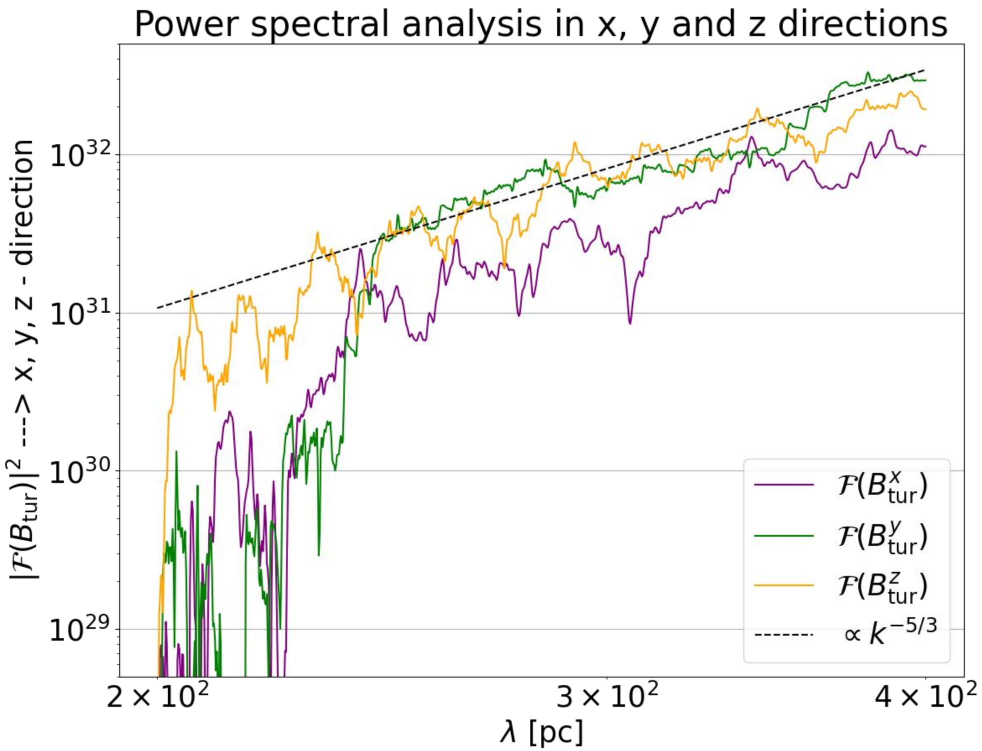
R_{mag} & Z_{mag} = 5 kpc and 6 kpc B_{str} = 3.96 μG

Toy Model –Turbulent fields

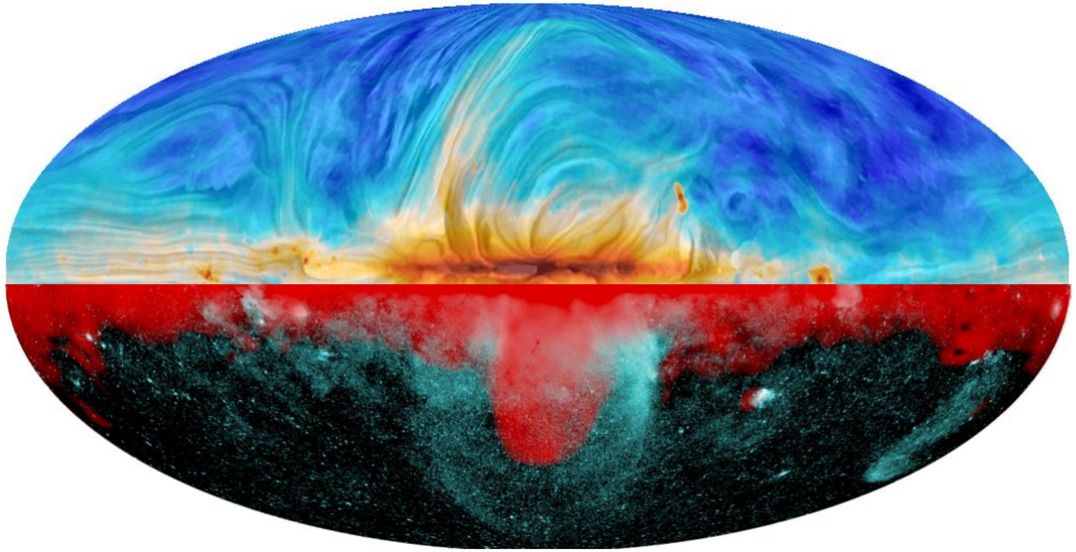


Outflow induces turbulent fields

$\frac{5}{3}$ Kolmogorov spectrum for turbulent fields



Almost same power in each mode



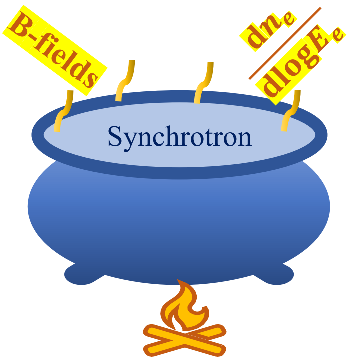
1) https://www.cosmos.esa.int/web/planck/picture-gallery

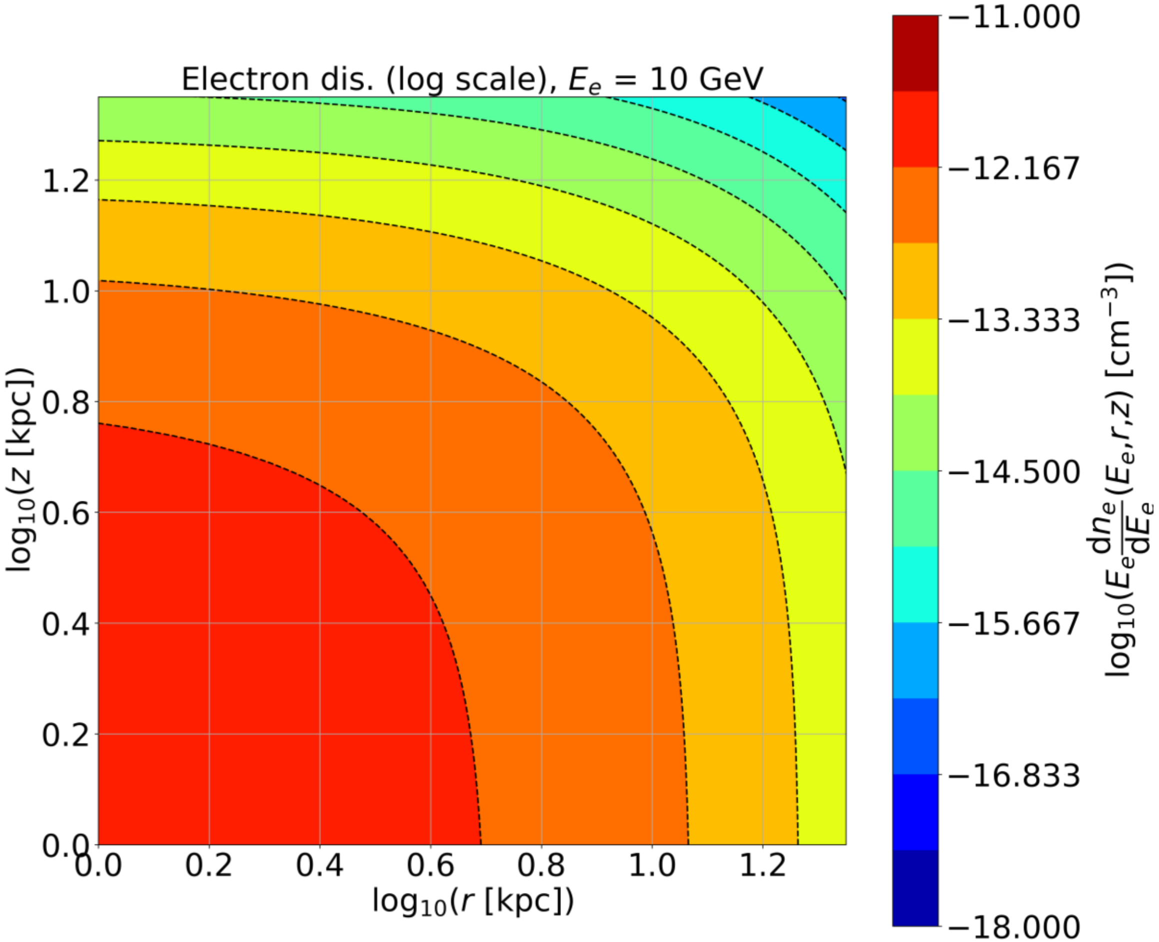
2) Predehl, P., Sunyaev, R.A., Becker, W. et al. Detection of large-scale X-ray bubbles in the Milky Way halo. Nature 588, 227–231 (2020).

Toy Model – non-thermal electron distribution at 10 GeV

$$\frac{\mathrm{d}n_e}{\mathrm{dlog}E_e} = C_{\mathrm{norm}} \left(\frac{E_e}{E_{10\mathrm{GeV}}}\right)^{-p+1} e^{-r/R_{\mathrm{el}}} \,\mathrm{sech}^2\left(\frac{z}{Z_{\mathrm{el}}}\right)$$

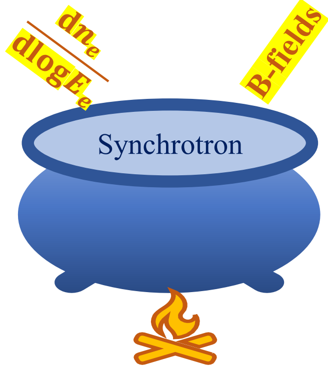
Together magnetic fields and non-thermal electrons give Synchrotron!

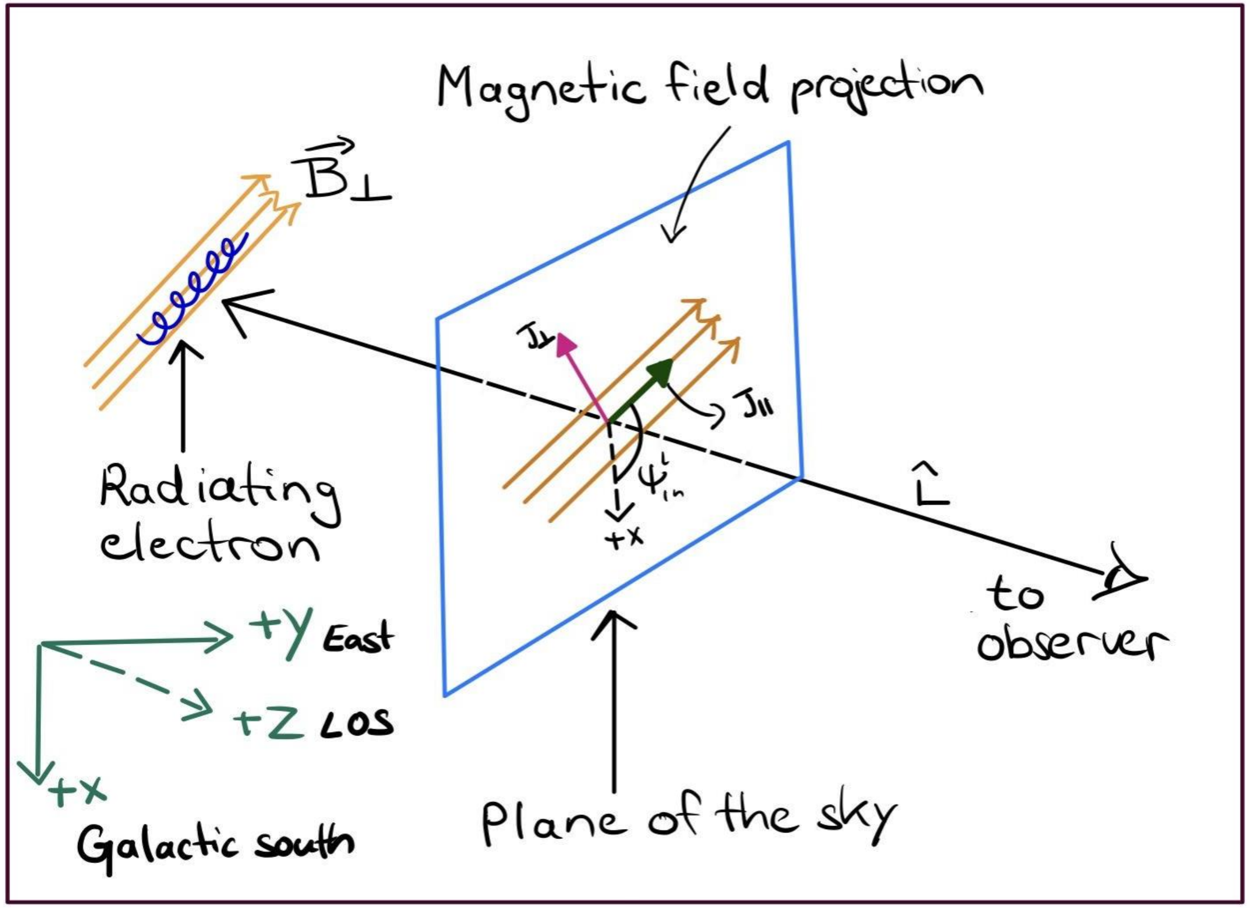




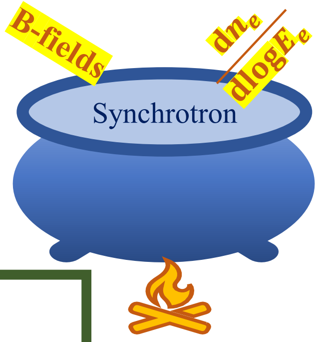
R_{el} & Z_{el} = 5 kpc and 6 kpc

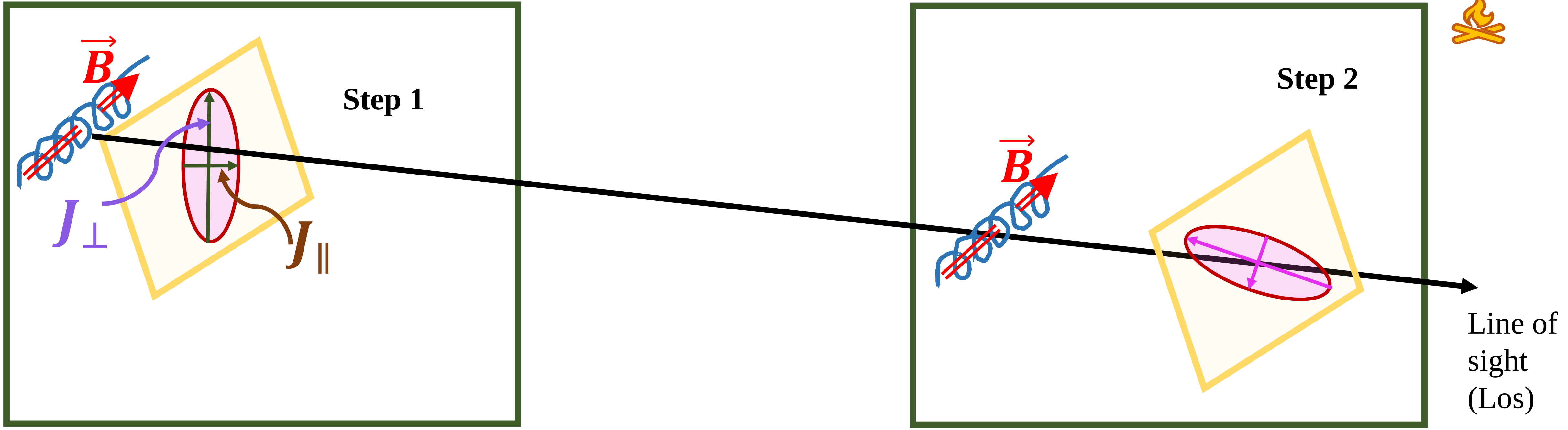
Synchrotron radiation – standard picture



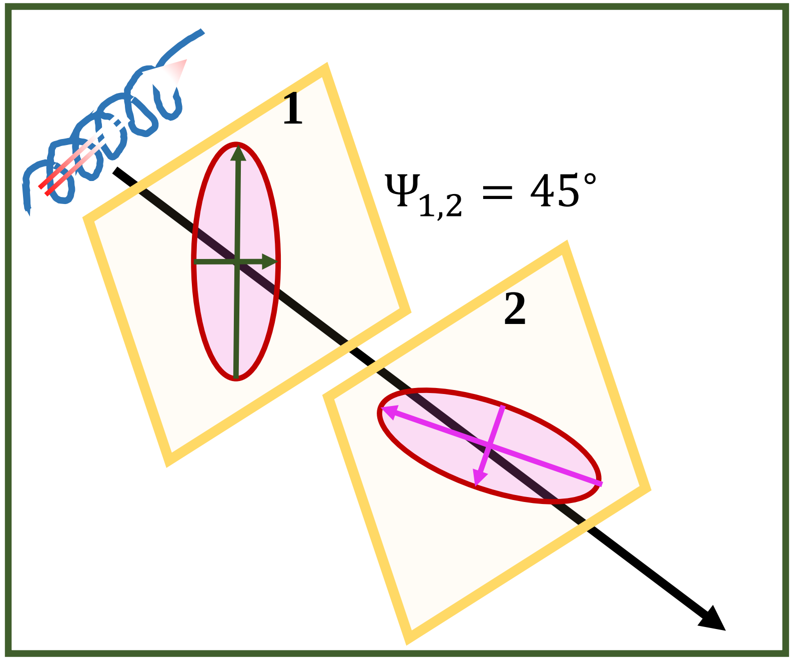


Synchrotron radiation – emission elipses



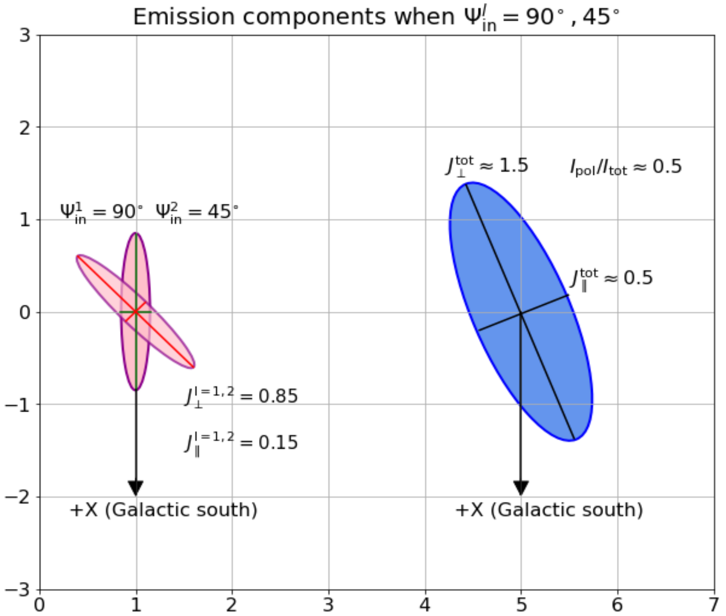


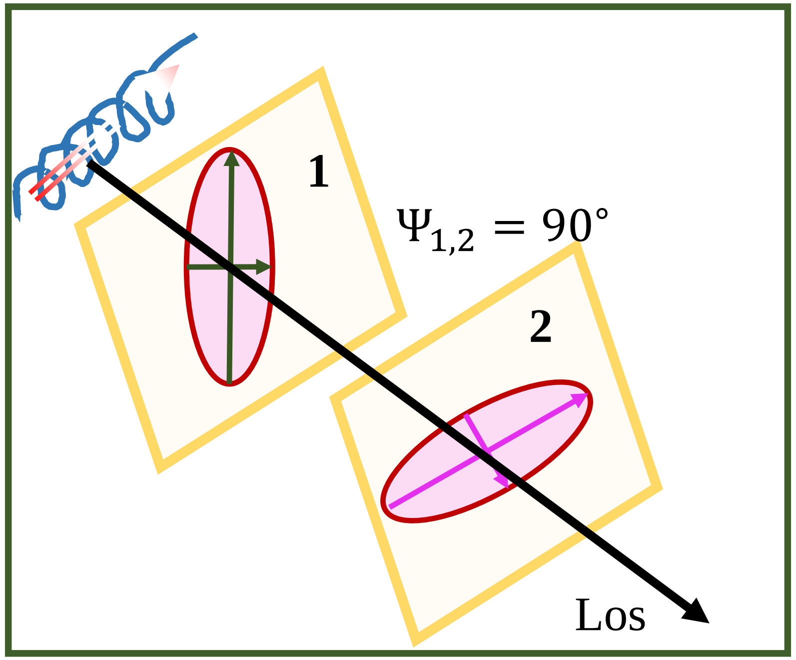
Synchrotron radiation



Polarised synchrotron

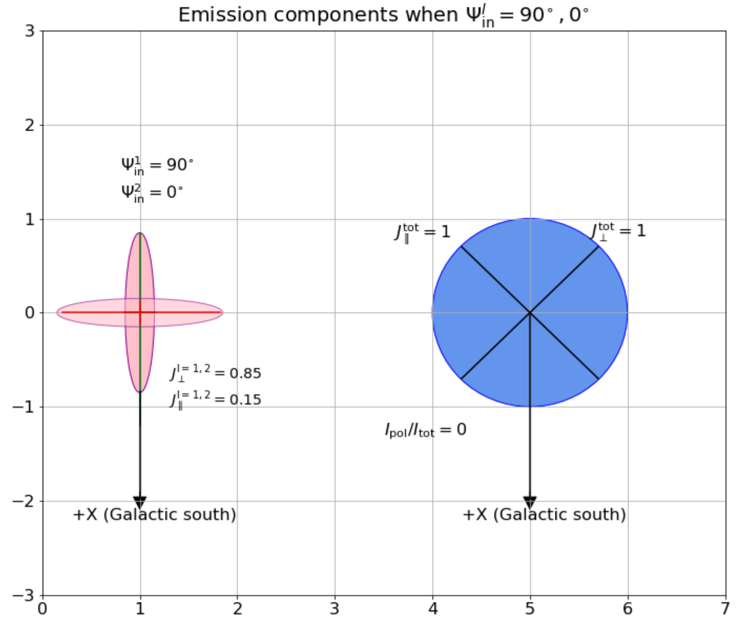
Probes magnetic field strength and geometry





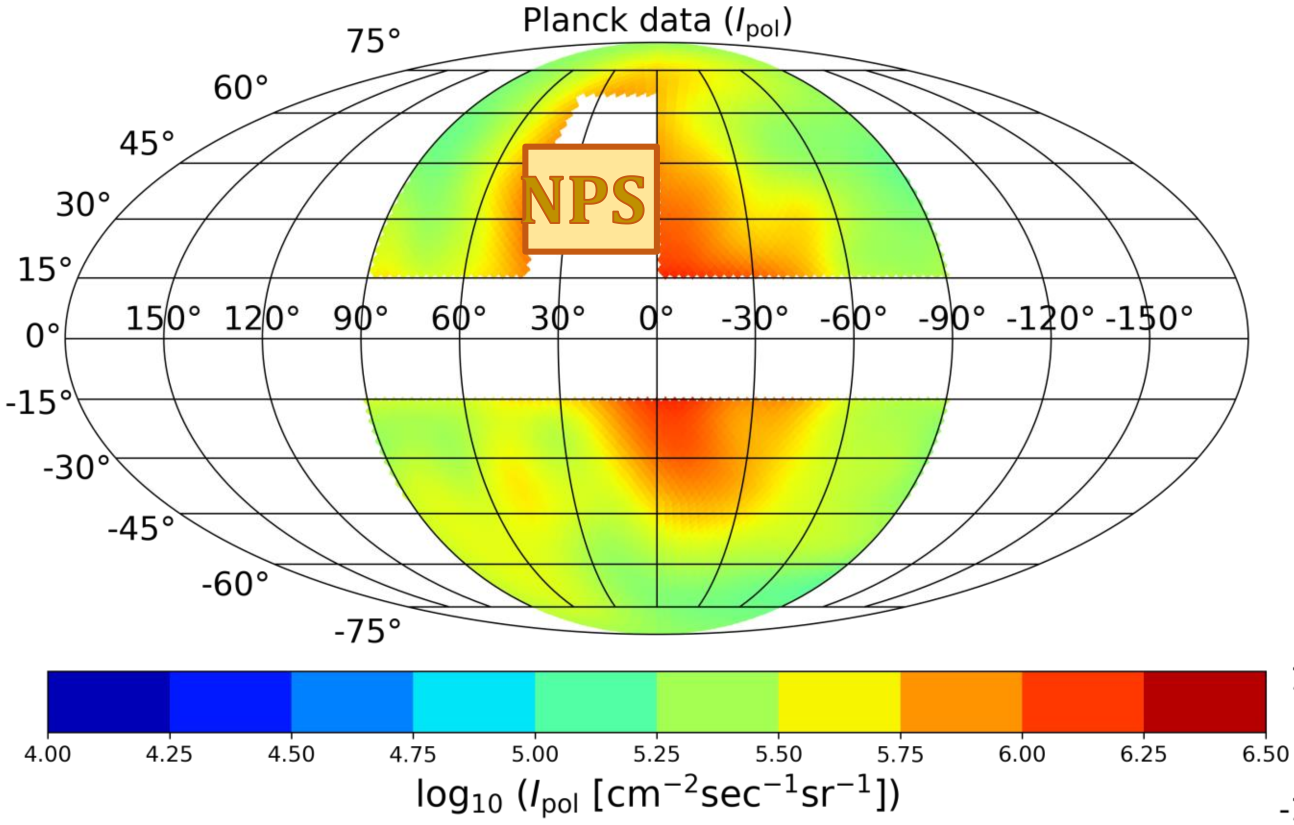
Unpolarised synchrotron

Probes magnetic field strength only

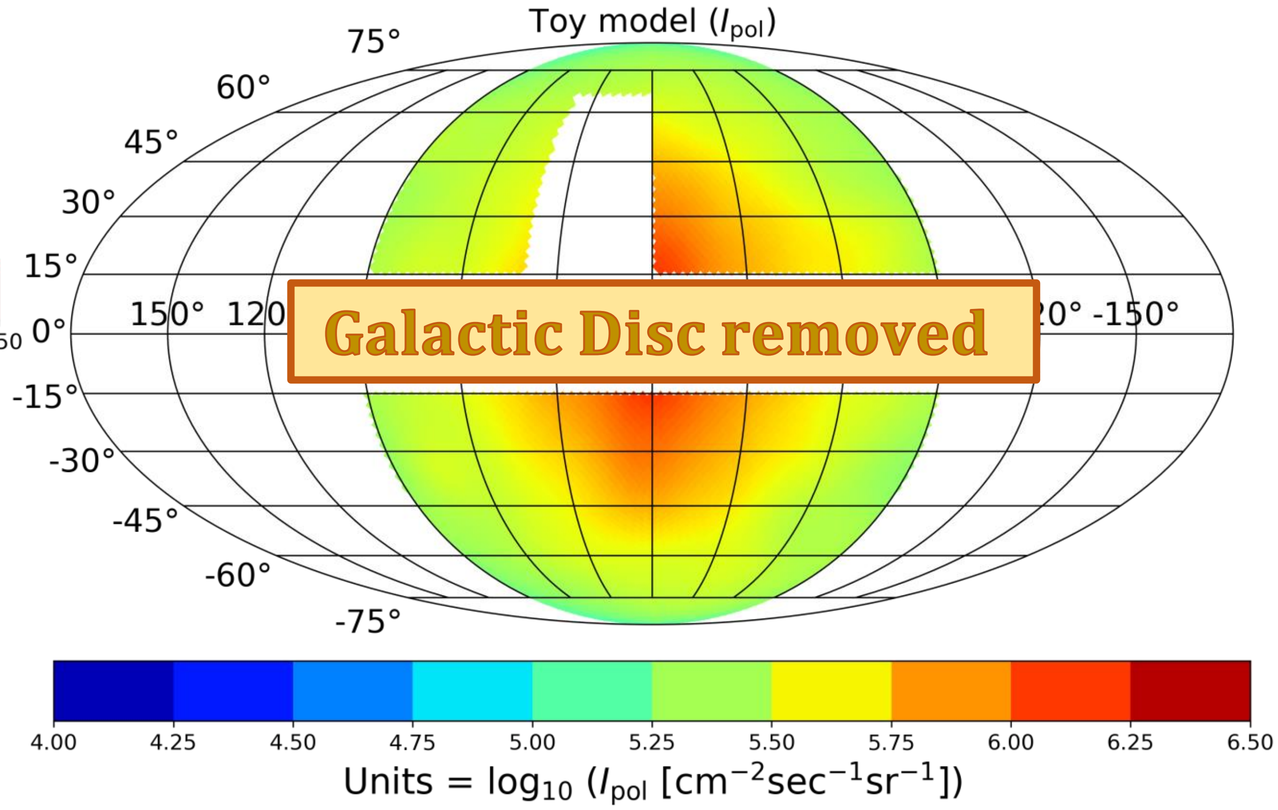


Maximum emission is observed when the electron pitch angles are perpendicular to magnetic fields.

Results – Best fit case

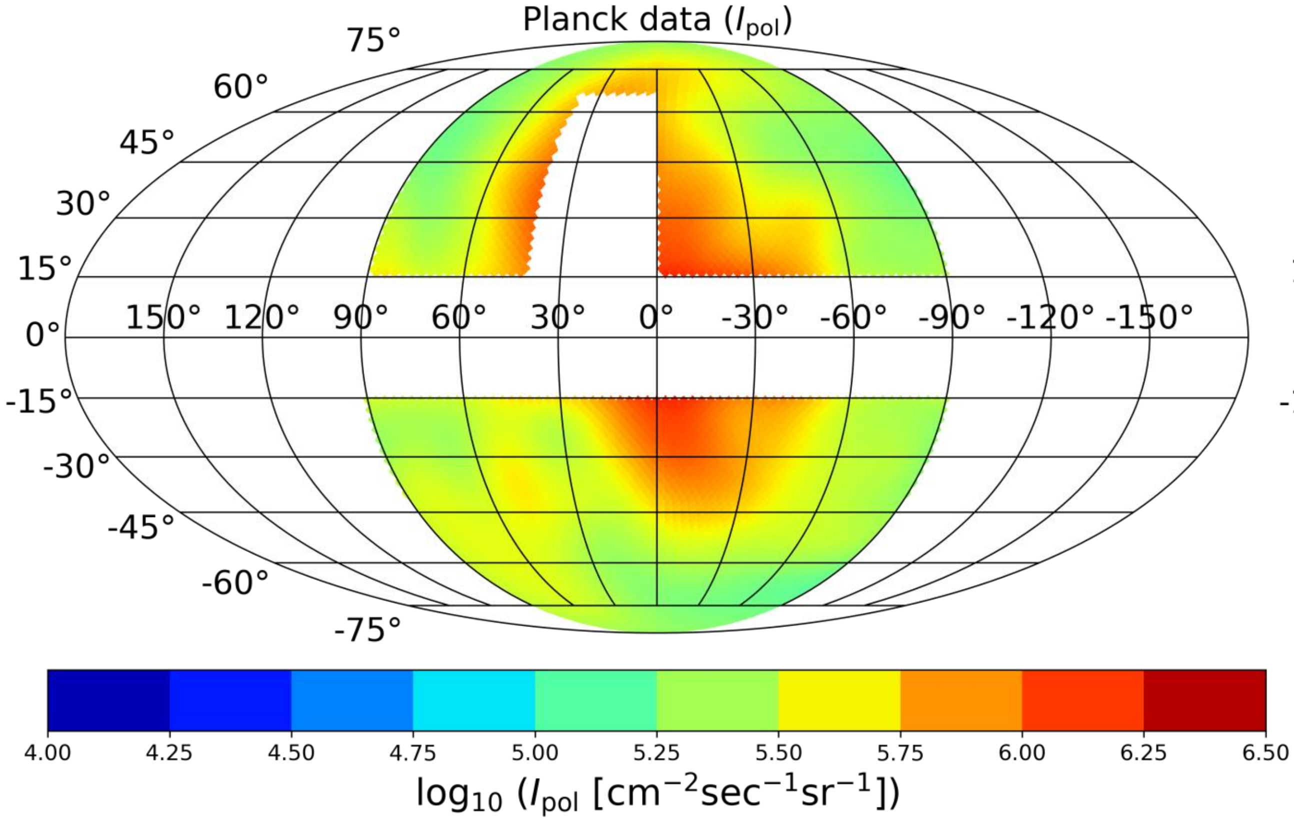


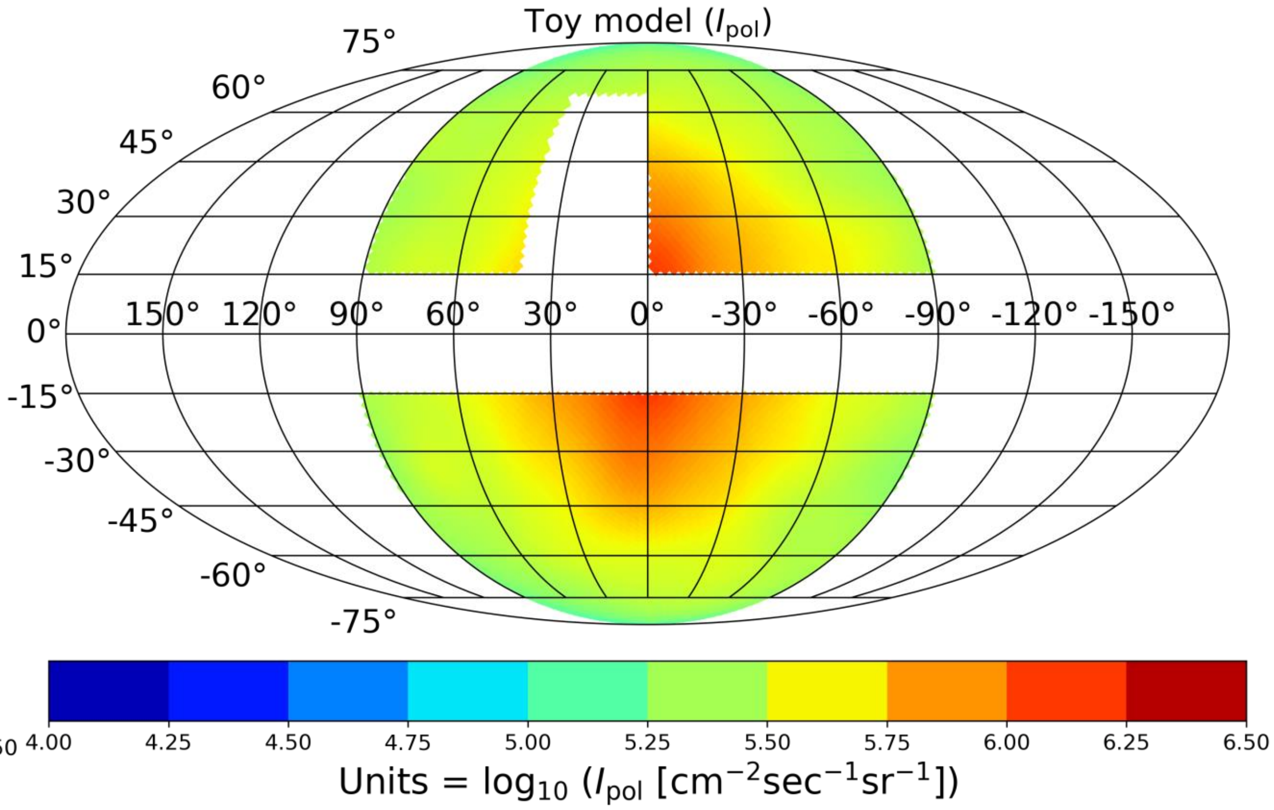
15° Gaussian smoothening



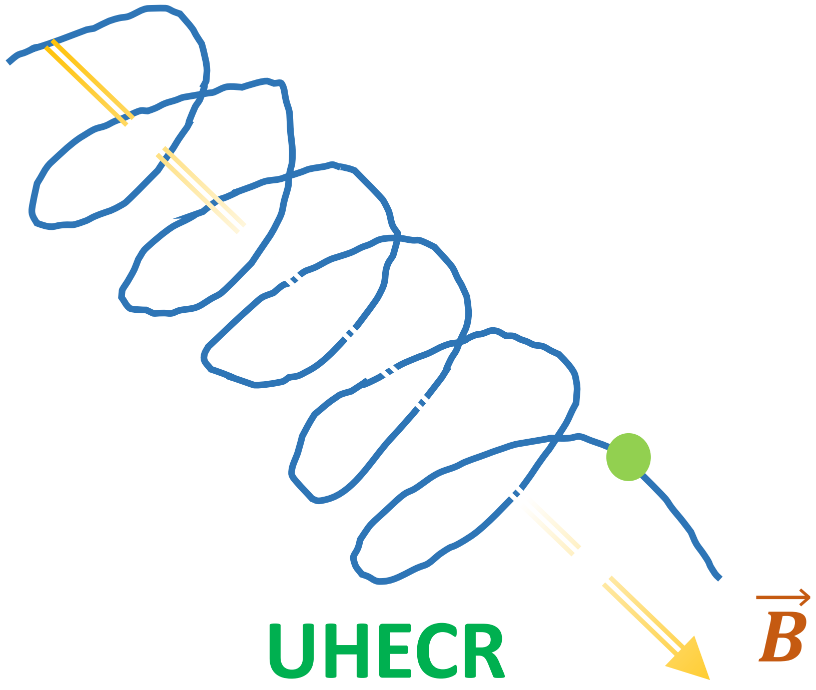
Constraints

Best-fit value with 1σ constraint		
Parameter	Best-fit value	Description
$B_{\rm str}$	$3.96^{+6.63}_{-1.96}$ μG	Structured field strength
$B_{\rm tur}$	$6.72^{+9.97}_{-3.56}$ μG	Turbulent field strength
$R_{\rm Mag} = R_{\rm el}$	5^{+1}_{-0} kpc	Radial cut off
$Z_{\rm Mag} = Z_{\rm el}$	6^{+1}_{-0} kpc	Azimuthal cut off
$\log_{10}(C_{\rm norm}[{\rm cm}^{-3}])$	$-11.72^{+0.62}_{-0.93}$	Electron density at 10 GeV

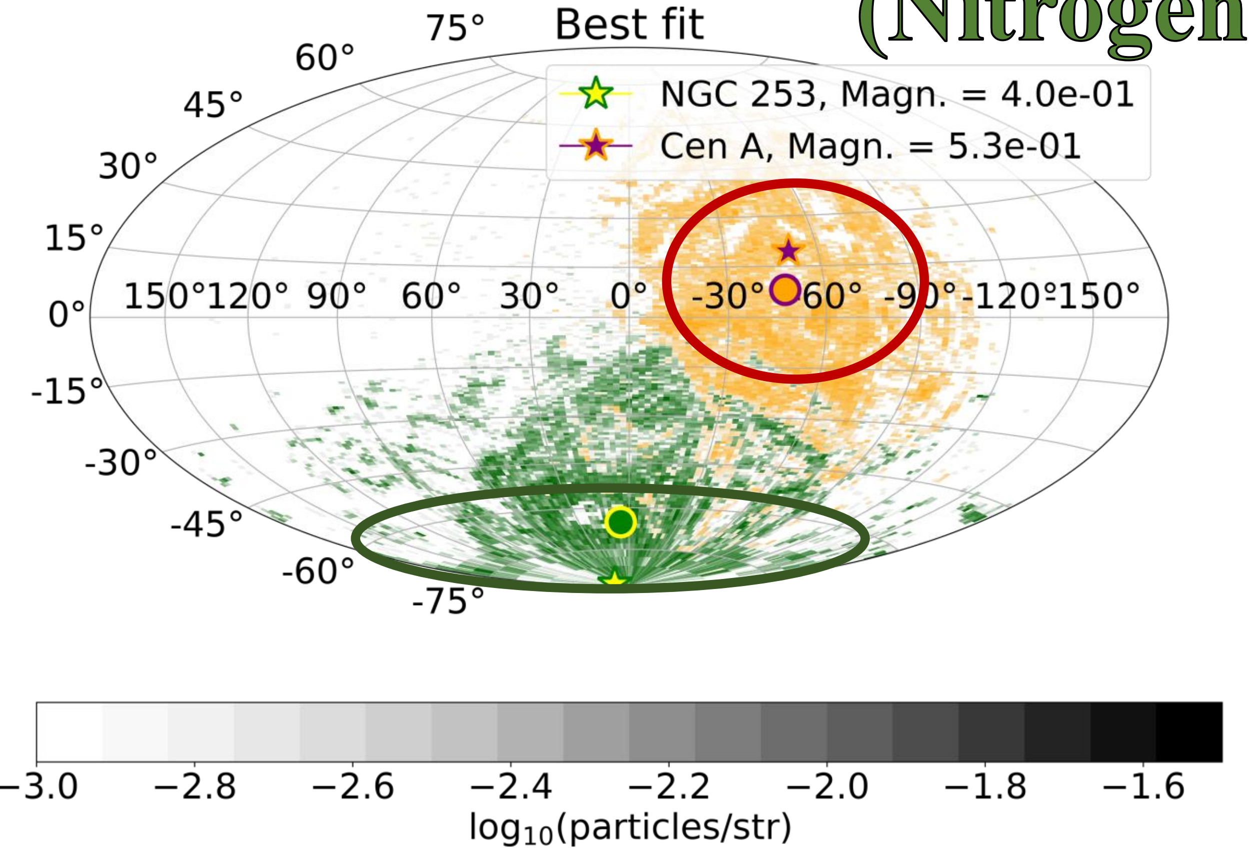




Backtracking of UHECRs through toy model using CRPropa3



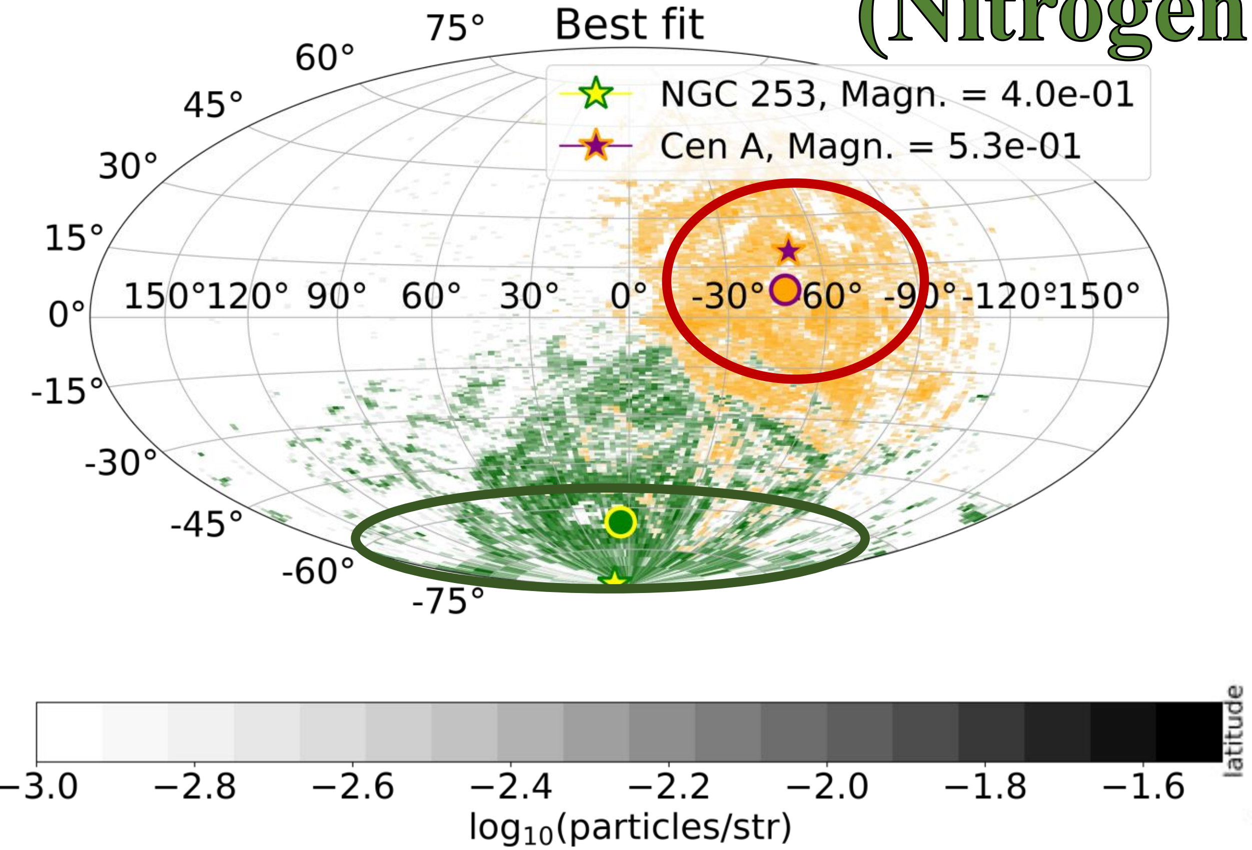
Arrival directions of UHECRs – Toy Model vs Auger (Nitrogen at 40 EeV)

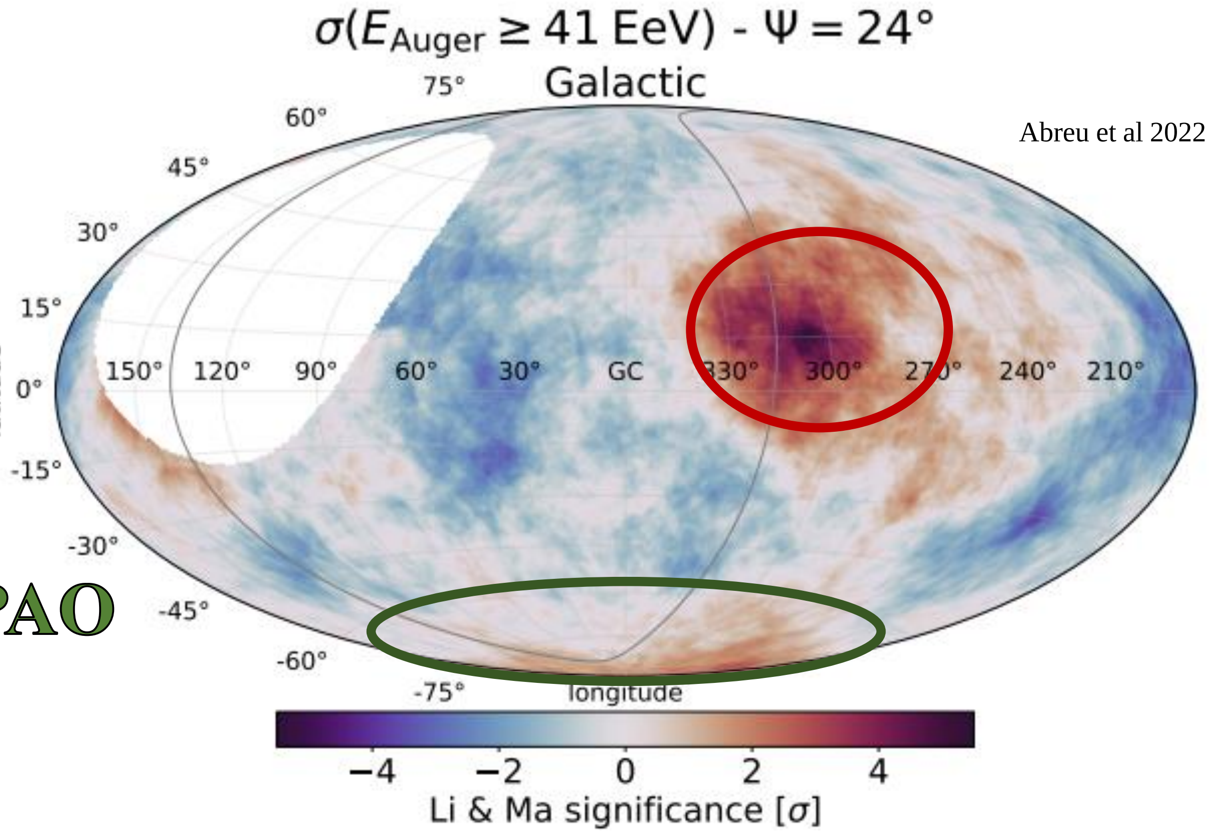


Choice of rigidity & species based on PAO

Aab et al 2014 & 2018

Arrival directions of UHECRs – Toy Model vs Auger (Nitrogen at 40 EeV)



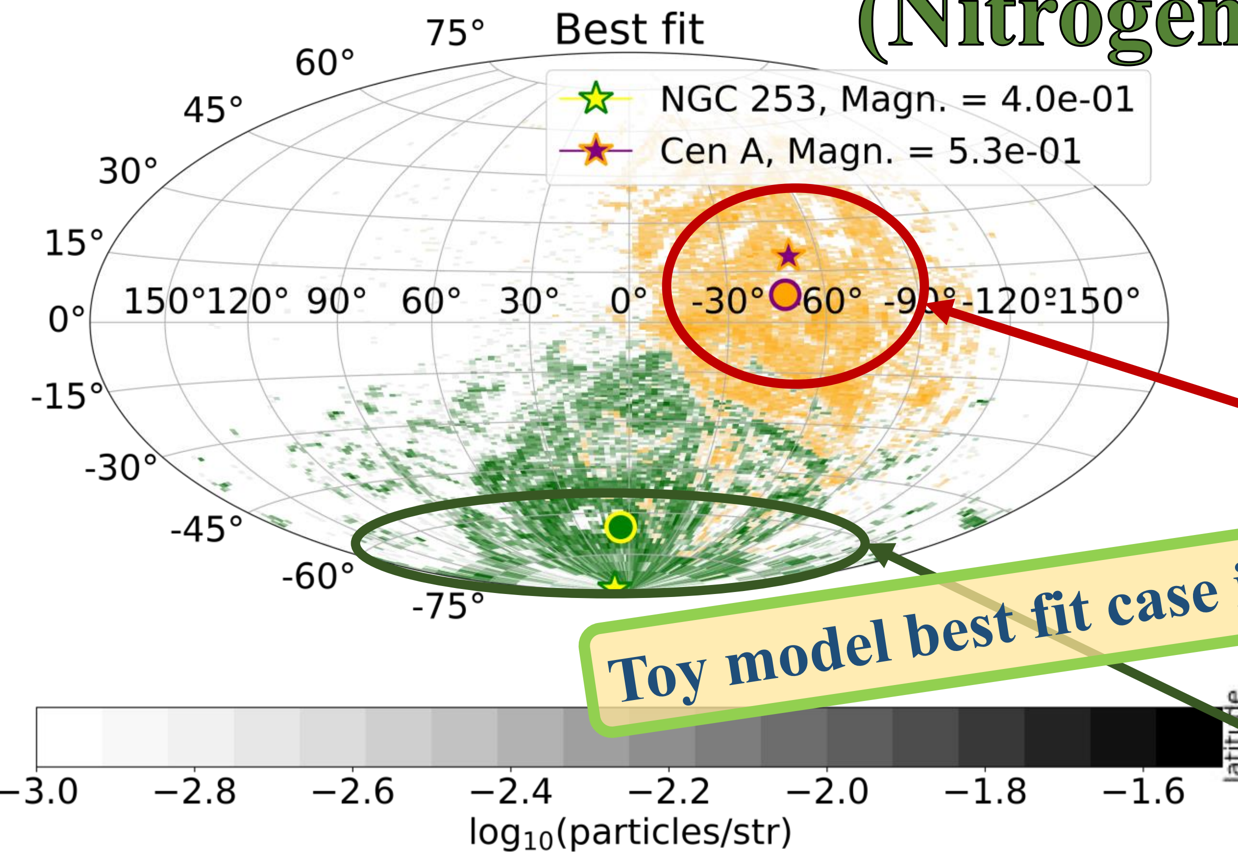


Abreu et al 2022

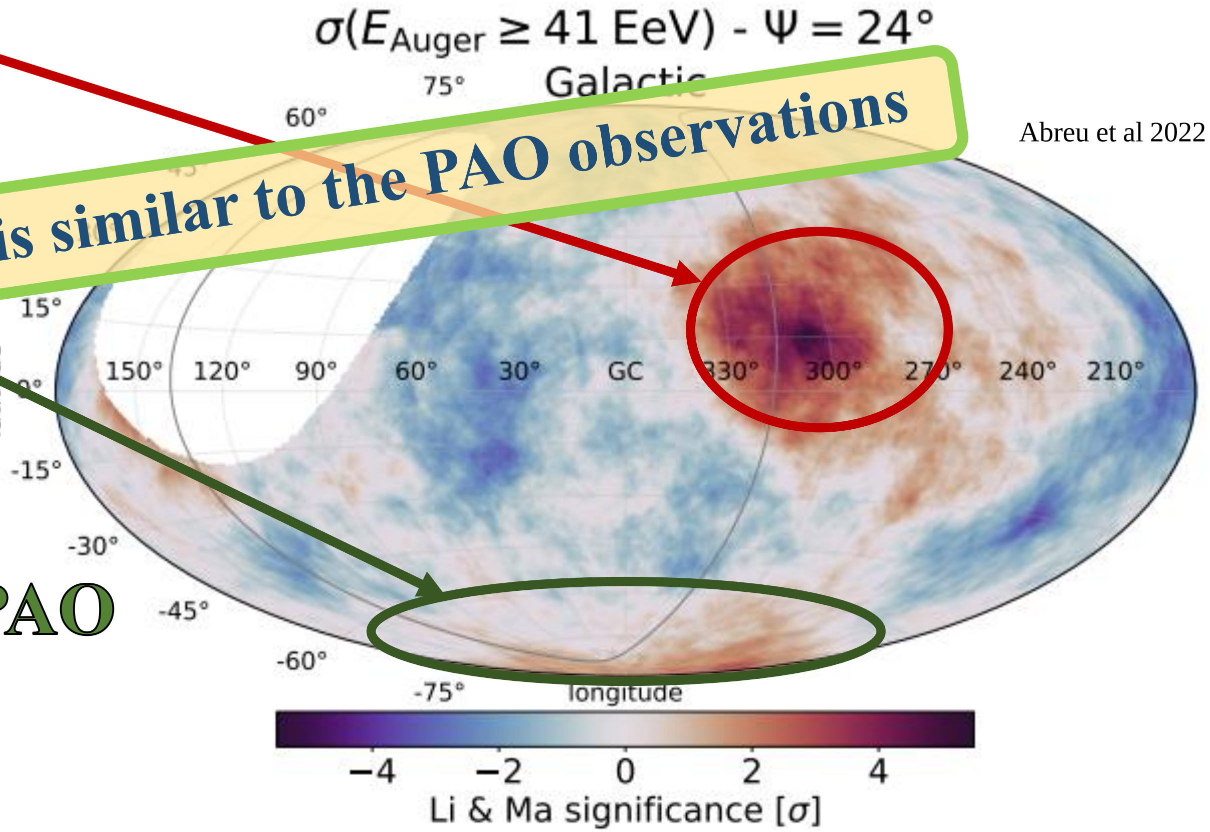
Choice of rigidity & species based on PAO

Aab et al 2014 & 2018

Arrival directions of UHECRs – Toy Model vs Auger (Nitrogen at 40 EeV)



Toy model best fit case is similar to the PAO observations

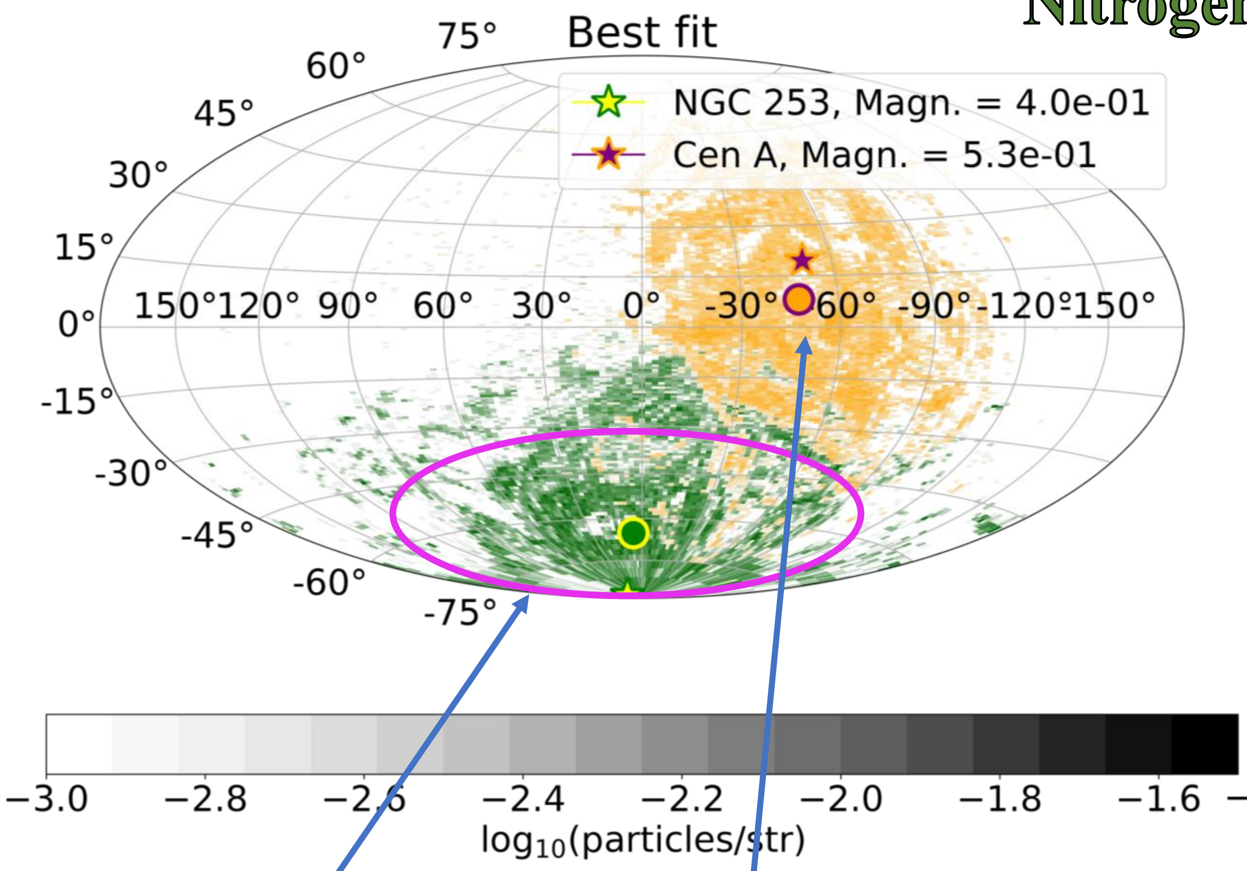


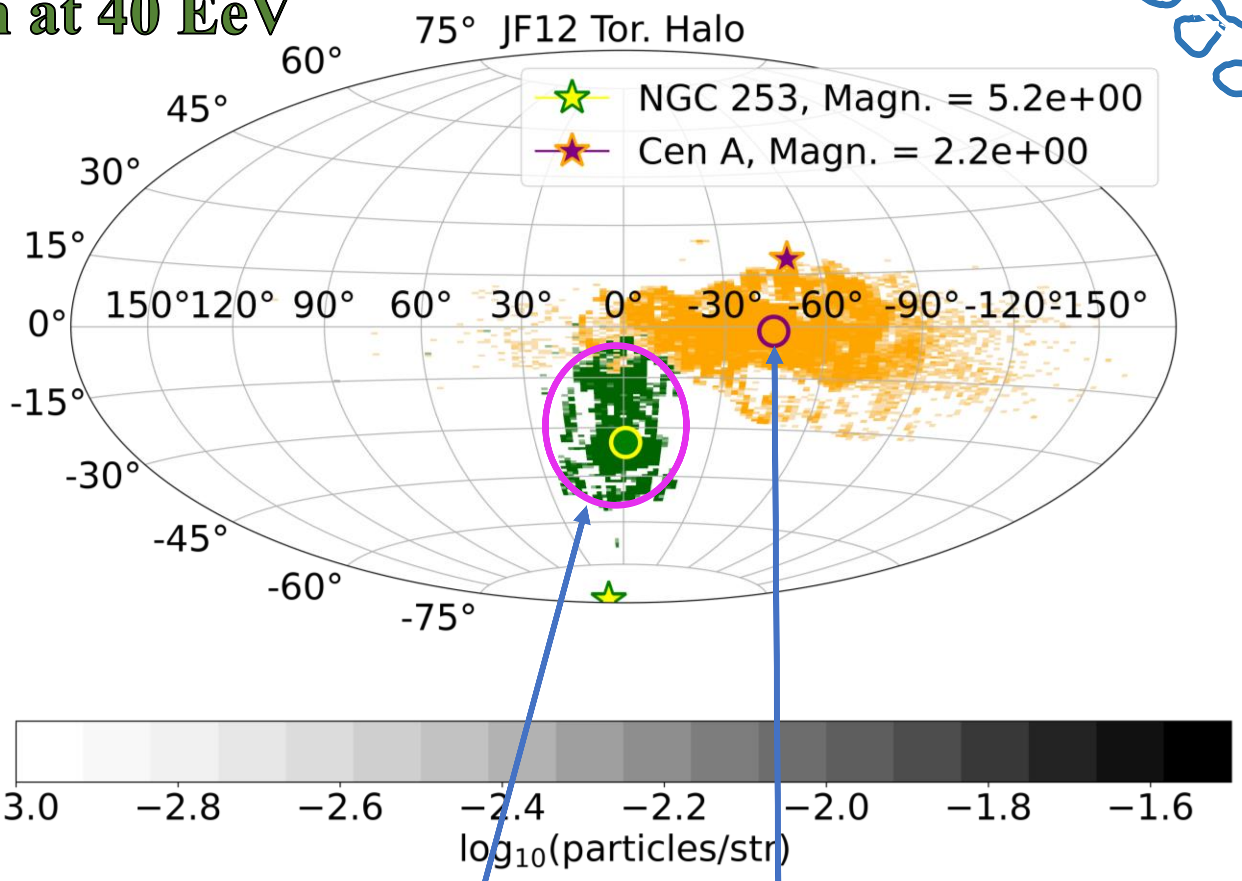
Abreu et al 2022

Choice of rigidity & species based on PAO

Aab et al 2014 & 2018

Toy Model vs JF12 Torroidal Halo
Nitrogen at 40 EeV

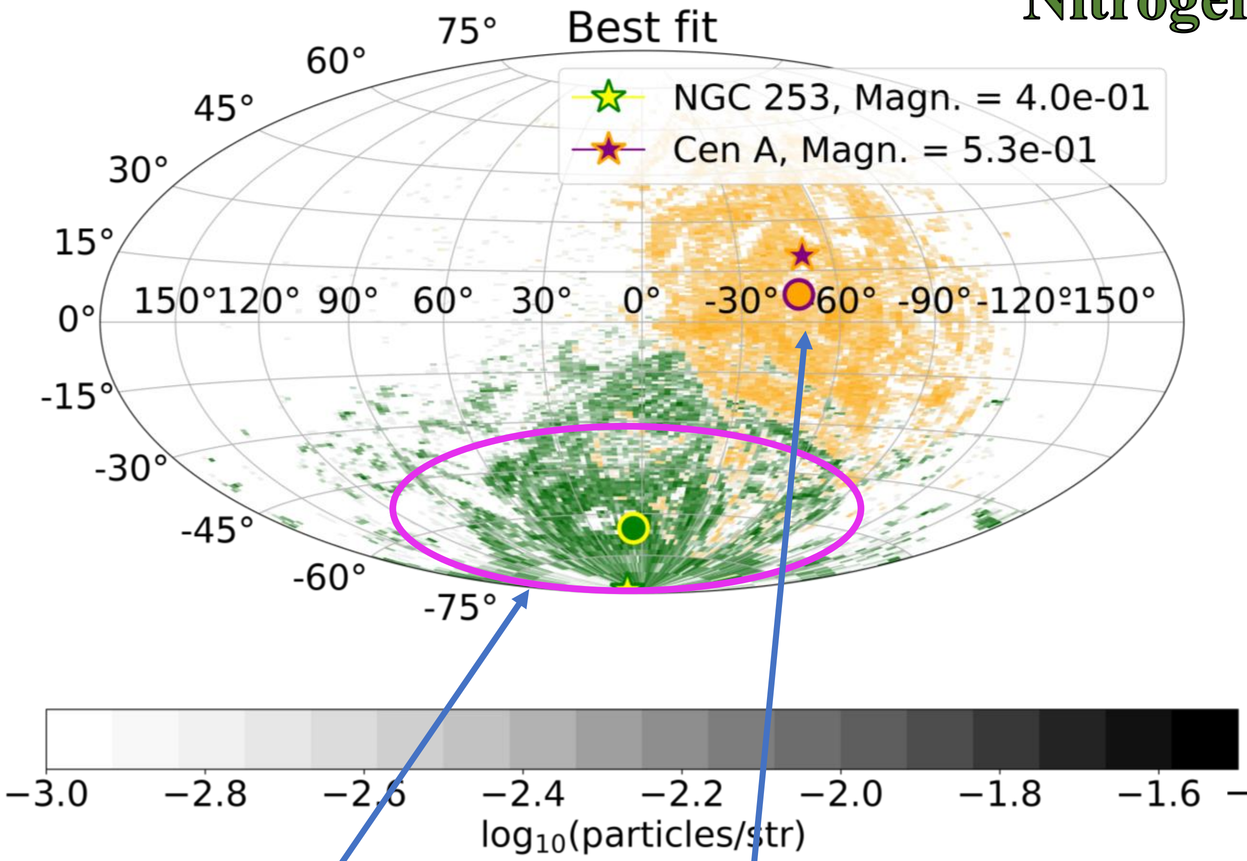


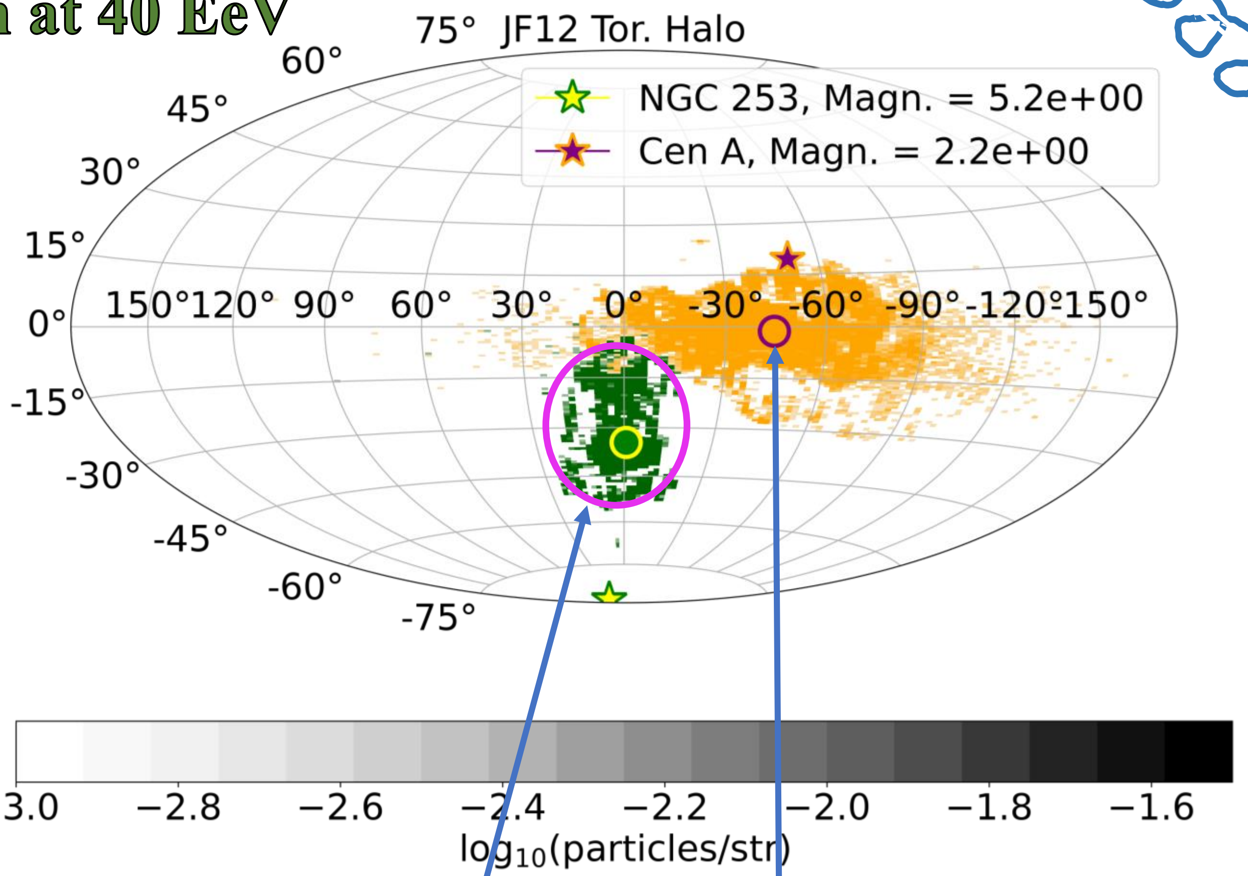


$\sigma_{\mathrm{NGC\,253}} = 32°, \sigma_{\mathrm{Cen\,A}} = 33°$

$\sigma_{\mathrm{NGC\,253}} = 9°, \sigma_{\mathrm{Cen\,A}} = 22°$

Toy Model vs JF12 Torroidal Halo
Nitrogen at 40 EeV





$\sigma_{\mathrm{NGC\ 253}} = 32°, \sigma_{\mathrm{Cen\ A}} = 33°$

$\sigma_{\mathrm{NGC\ 253}} = 9°, \sigma_{\mathrm{Cen\ A}} = 22°$

Structured fields - Overall coherent deflection
Turbulent fields - Spreading out the directions of the particle deflections around this overall deflected direction

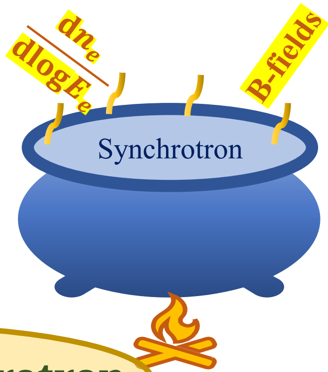
Spreading Effect -Toy model 5-10 times larger than JF12
Deflections are dominated by halo NOT disc

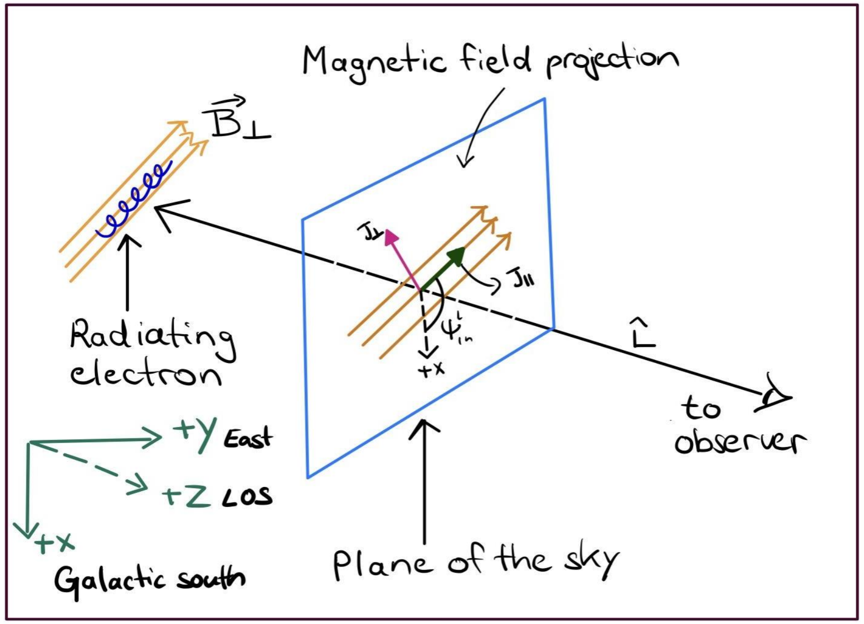
Conclusions & Outlook

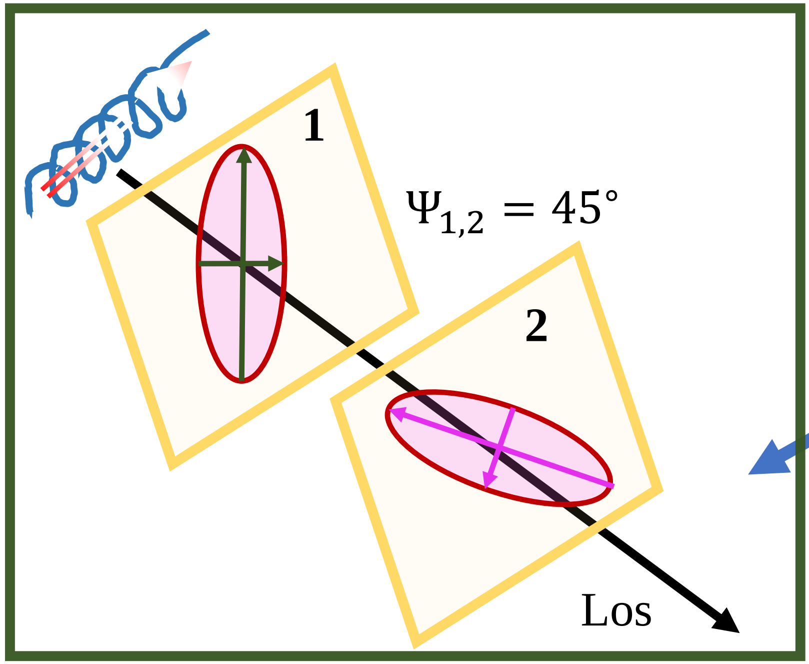
- Our results indicate ~7 μG total fields over a large spatial extent with the height of halo being ~6 kpc in z-direction which is compatible with S-PASS and other observations.
- Arrival direction of cosmic rays is highly tangled with both the structured and turbulent magnetic fields. We find the cosmic ray deflections from our model are similar with NGC 253 and Cen A hotspots from Auger (Abreu et al. 2022).
- Rotation measures from extra-galactic sources like FRBs should be factored in once the MeerKat and FAST data is public.
- C-BASS, Quijote and Lofar data can also be useful for studying the halo at different frequencies in the future.

Extras

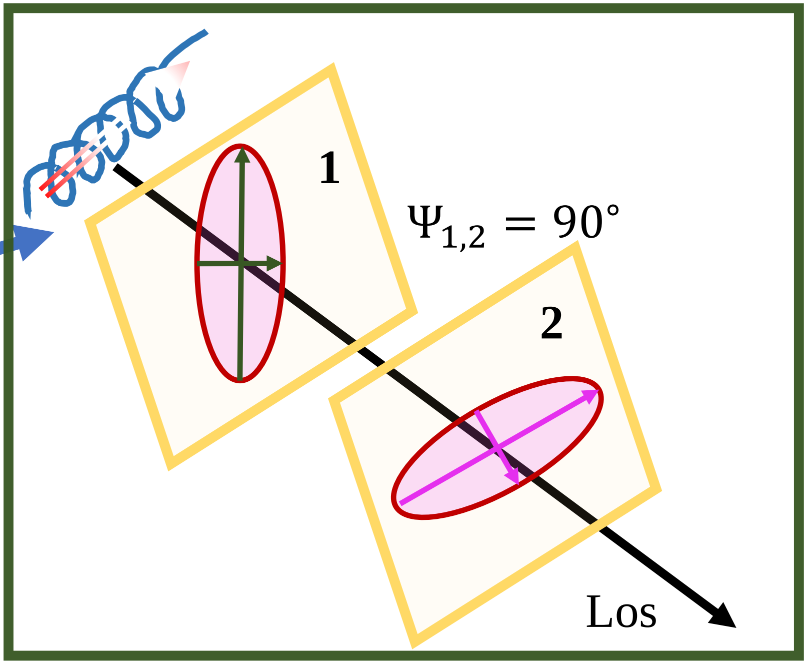
Synchrotron radiation – emission elipses







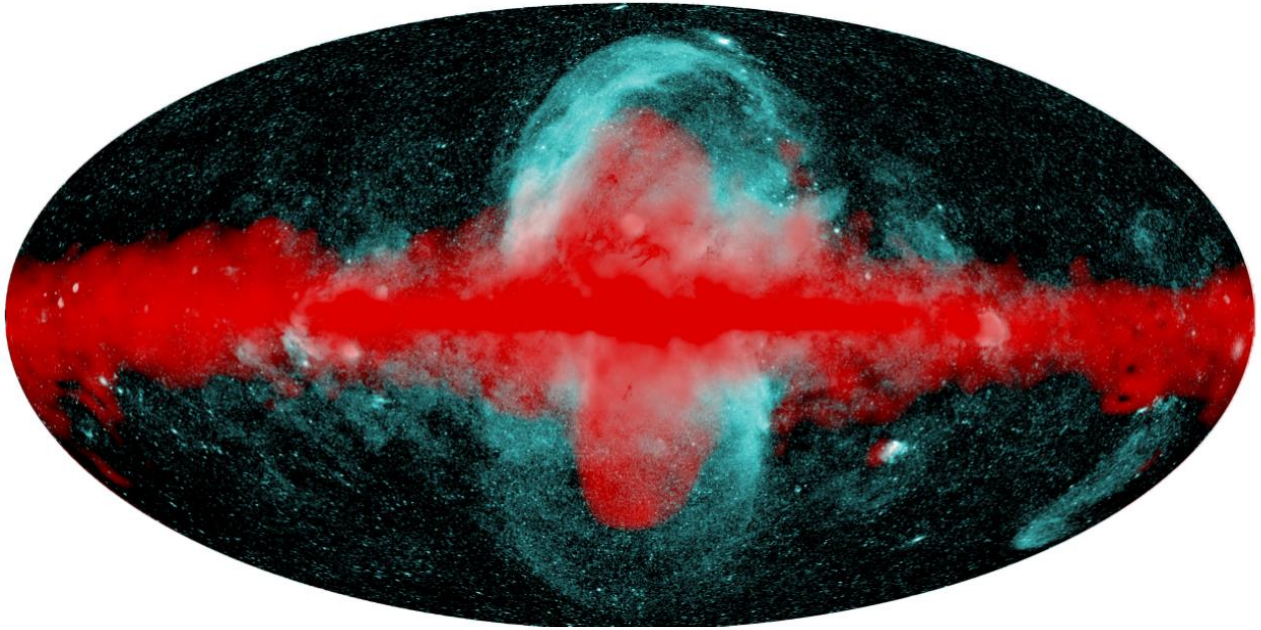
Polarised synchrotron

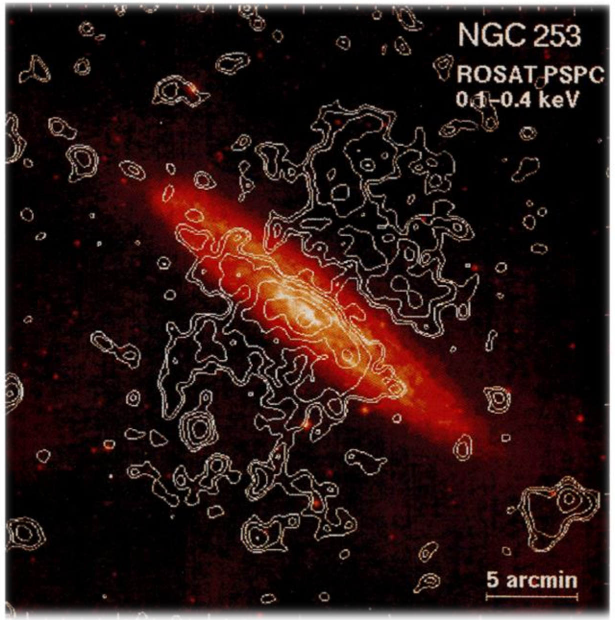


Unpolarised synchrotron

Maximum emission is observed when the electron pitch angles are perpendicular to magnetic fields

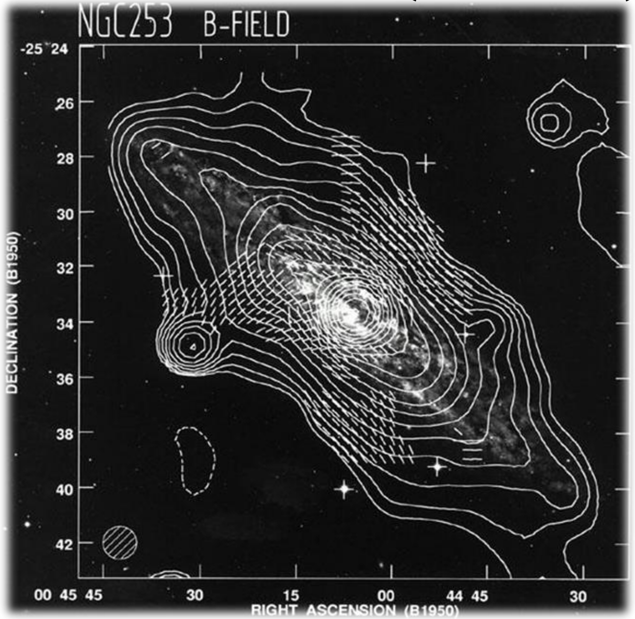
Milky way is not a starburst galaxy yet it has outflow!





Outflows as seen in starburst galaxies!

(Beck et.al 1994)



Total radio intensity (*contours*) and magnetic field orientation of NGC 253.

Large scale structures imply large scale magnetic fields

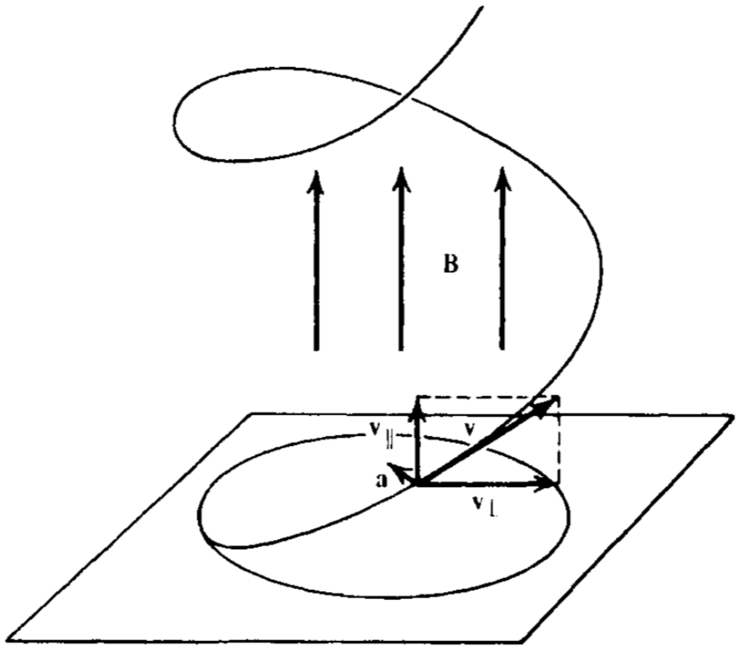
Predehl, P., Sunyaev, R.A., Becker, W. et al. Detection of large-scale X-ray bubbles in the Milky Way halo. Nature 588, 227–231 (2020).

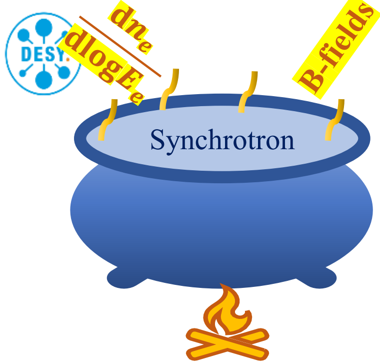
SYNCHROTRON RADIATION

- "Magneto-bremsstrahlung" = Radiation emitted by relativistic charged particles (mostly electrons) due to acceleration ("gyro-motion") in a static magnetic field.

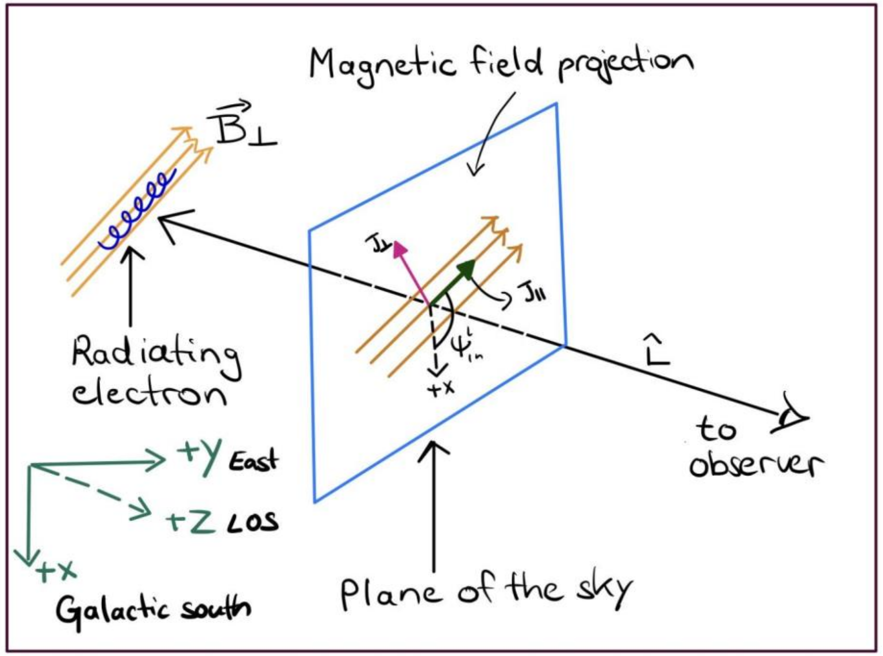
$$< P_{syn} > = \frac{4}{3} c \sigma_T \beta^2 \gamma^2 u_B \;\; \propto \gamma^2 B^2$$

- u_B:magnetic energy density$\left(\frac{B^2}{8\pi}\right)$
- $\beta\gamma$: speed of electron
- σ_T: Thompson scattering





Polarised synchrotron radiation



$$J^l_\perp = \frac{1}{\tau}\int_{\log E_e^{\min}}^{\log E_e^{\max}} \frac{dn_e}{d\log E_e} d\log E_e \left[F\left(\frac{E_\gamma}{E_\gamma^{\rm peak}}\right) + G\left(\frac{E_\gamma}{E_\gamma^{\rm peak}}\right)\right] \quad (3)$$

and

$$J^l_\parallel = \frac{1}{\tau}\int_{\log E_e^{\min}}^{\log E_e^{\max}} \frac{dn_e}{d\log E_e} d\log E_e \left[F\left(\frac{E_\gamma}{E_\gamma^{\rm peak}}\right) - G\left(\frac{E_\gamma}{E_\gamma^{\rm peak}}\right)\right] \quad (4)$$

where

$$\tau^{-1} = \frac{\sqrt{3}\alpha}{4\pi}\frac{B_\perp}{B_{\rm crit}}\frac{m_e c^2}{\hbar}, \qquad E_\gamma^{\rm peak} = \frac{3}{2}\Gamma_e^2\frac{B_\perp}{B_{\rm crit}}m_e c^2,$$

and

$$F(x) = x\int_x^\infty K_{5/3}(x')dx', \qquad G(x) = xK_{2/3}.$$

Extras