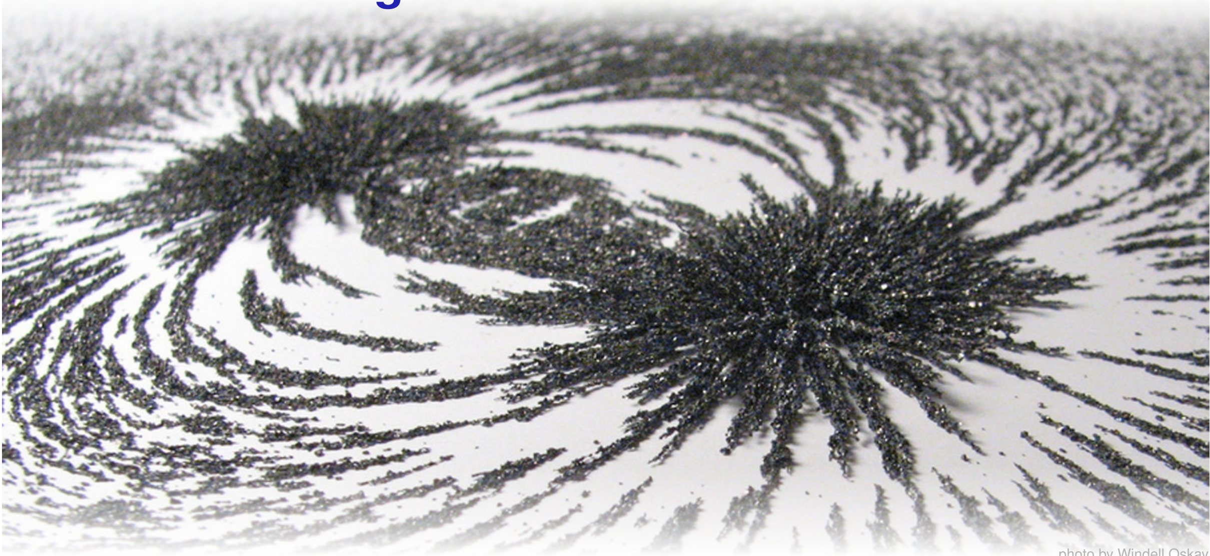
The Galactic Magnetic Field and UHECR Deflections



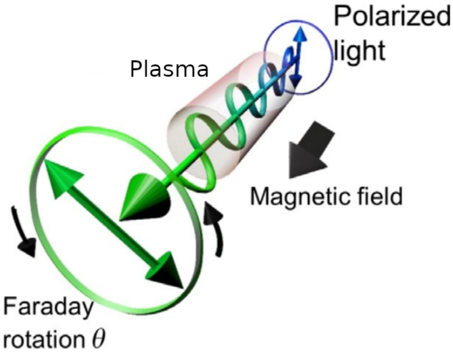
M. Unger, G.R. Farrar *The Coherent Magnetic Field of the Milky Way* ApJ 970 (2024) 95

M. Unger, G.R. Farrar *Where Did the Amaterasu Particle Come From?* ApJL 962 (2024) L5

V. Pelgrims, M. Unger, I.C. Maris *An analytical model for the magnetic field in the thick shell of super-bubbles* arXiv:2411.06277

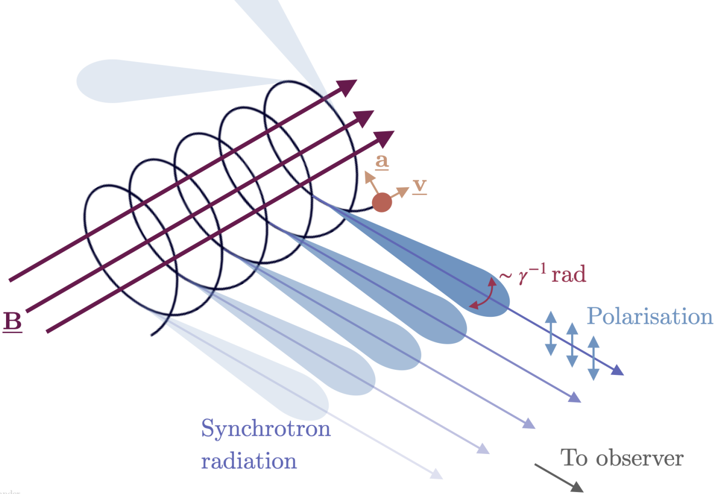
Observational Tracers of the Galactic Magnetic Field (GMF) used in this work

Faraday Rotation
of extragalatic radio sources



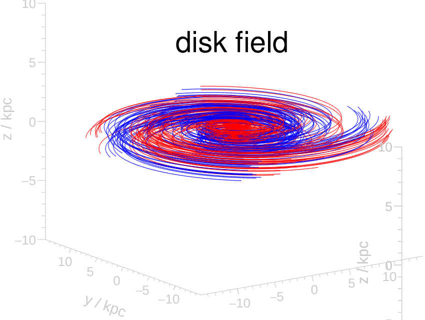
V. Pelgrims

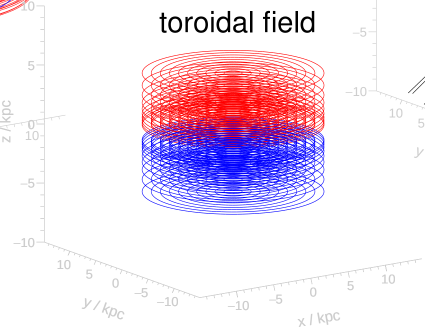
Synchrotron Radiation
of cosmic-ray electrons

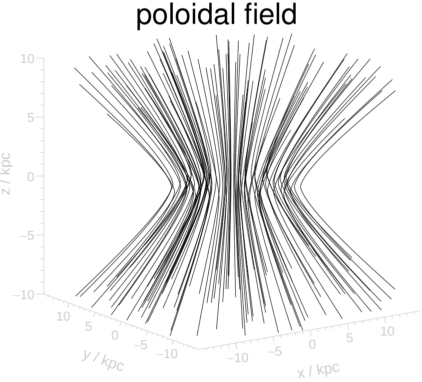


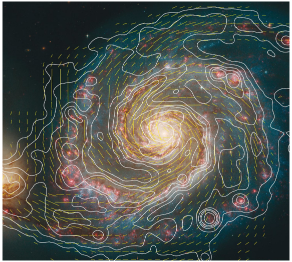
E.L. Alexander

Parametric GMF Components

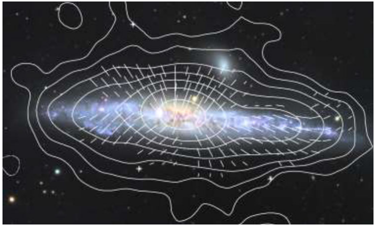




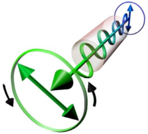


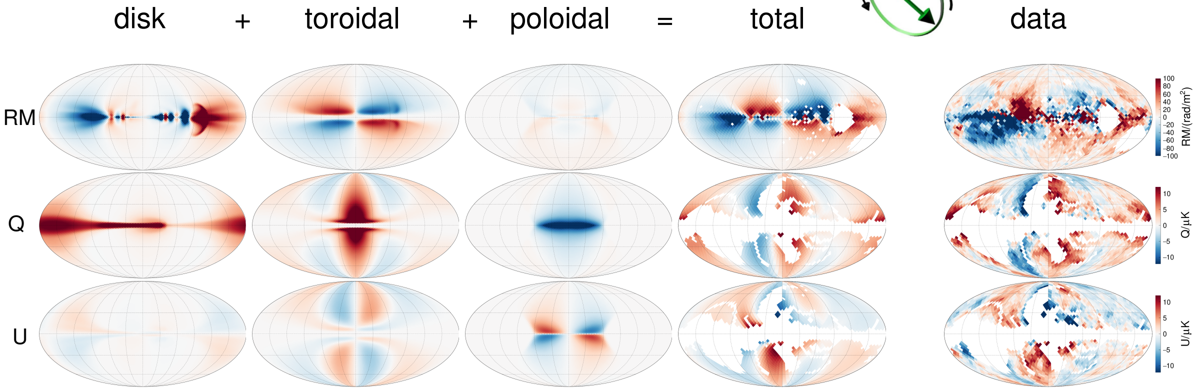


UF23 solenoidal field components
(major refinement of JF12 functions)

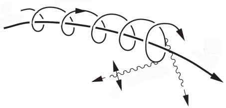


Adjustment of Model Parameters to Data



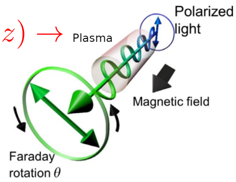


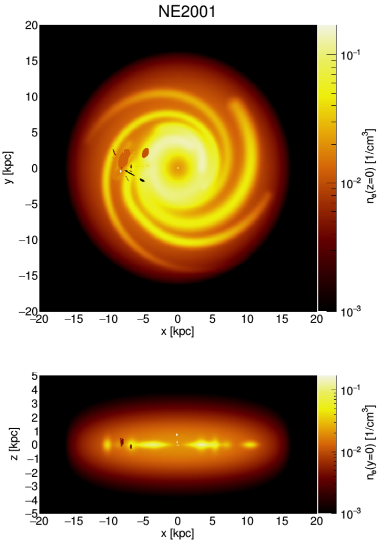
- 6520 data points
- 15-20 parameters
- typical reduced $\chi^2/n_{\mathrm{df}} = 1.2...1.3$, depending on model



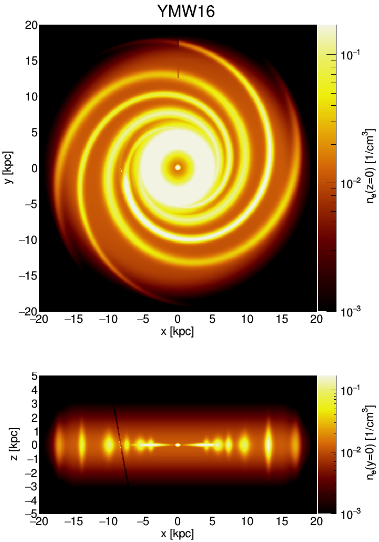
Uncertainties: Thermal Electron Models

$n_e(x, y, z) \rightarrow$





112 pulsar DMs

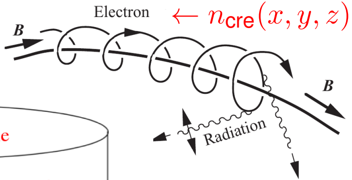


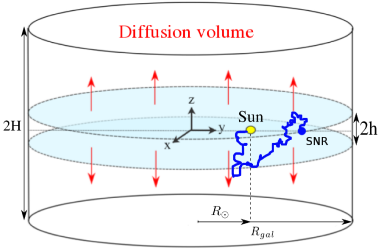
189 pulsar DMs

Cordes&Lazio arXiv:0207156

Yao, Manchester & Wang, ApJ 2017

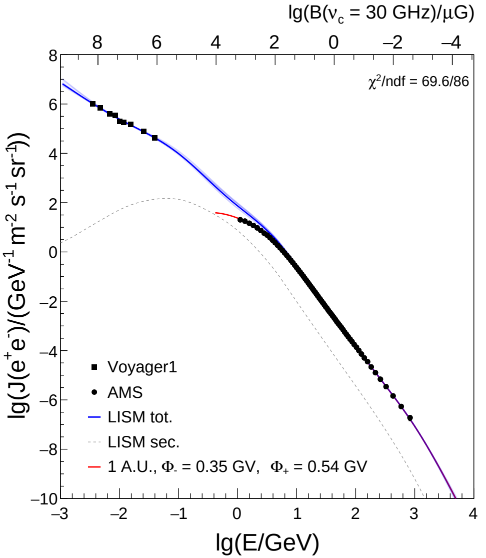
Uncertainties: Cosmic-Ray Electrons





homogenous and isotropic diffusion $D_0 \propto R^\delta$ (rigidity R)

Y. Genolini et al, A&A. **580** (2015) A9

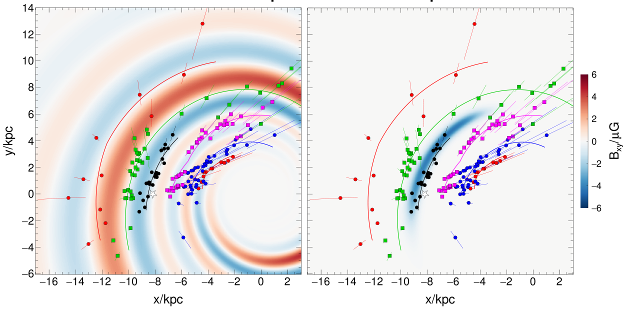


constrained by local lepton flux and D_0/H from B/C

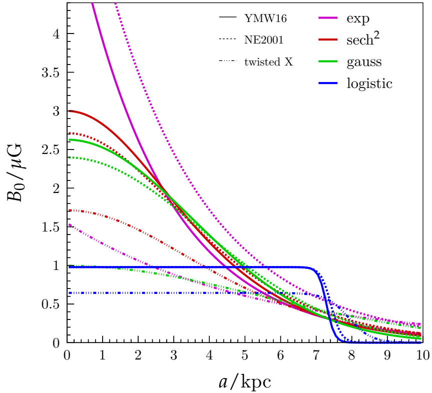
Uncertainties: Model Assumptions

Examples:

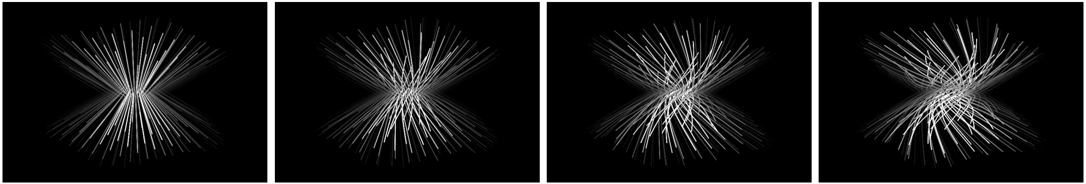
Global Spiral or Local Spur?



radial dependence of X-field?

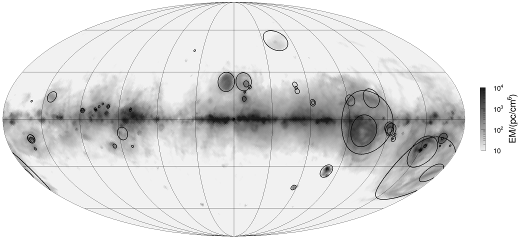


X-field and toroidal field or twisted X-field?

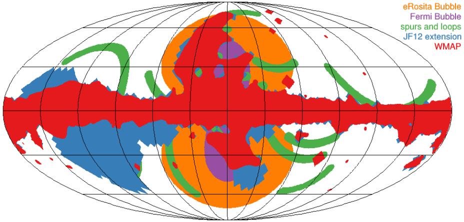


Uncertainties: Foregrounds a) Small-Scale Structures

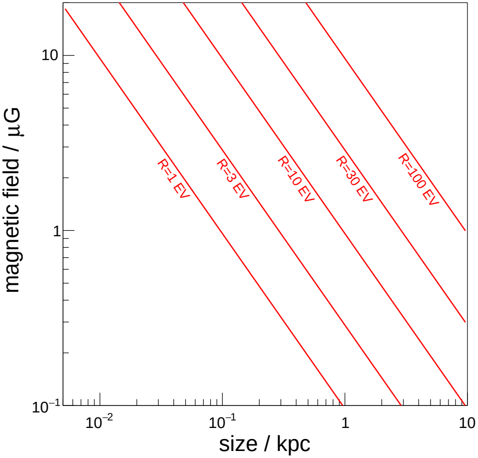
mask HII regions (atypical n_e)



mask loops and spurs (atypical B and n_{cre})



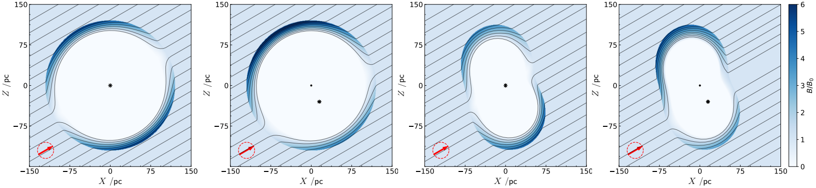
deflection angle < 5°



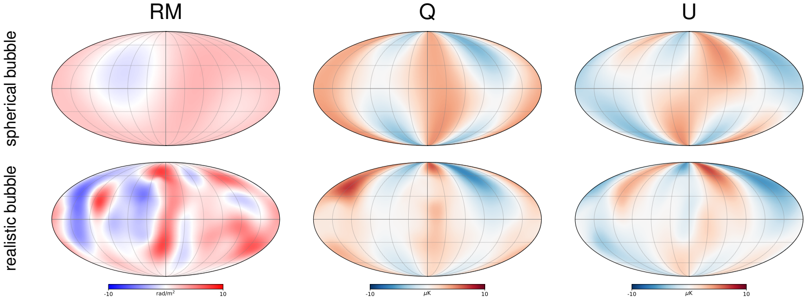
distinction small- and large-scale not always unambiguous, e.g. North Polar Spur or Fan Region (see A. Korochkin's talk)

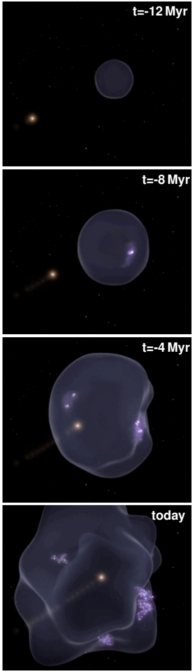
Uncertainties: Foregrounds b) Local Bubble

examples of solenoidal bubble fields:



contribution to Faraday rotation and synchrotron emission:





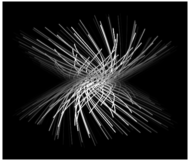
C. Zucker et al. www.cfa.harvard.edu/

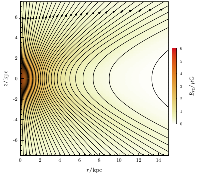
→ for more details check the poster by Vincent Pelgrims! (see also talk by A. Korochkin)

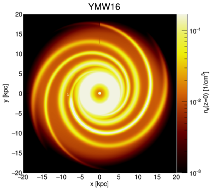
Model Variations

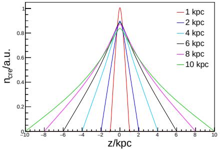
9 variations (subset of ∼<u>200 models</u> giving the greatest diversity of CR deflection predictions):

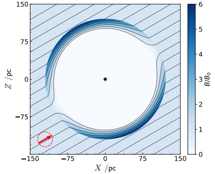
name	variation	χ^2/ndf
`base`	fiducial model	1.22
`expX`	radial dependence of X-field	1.30
`spur`	replace grand spiral by local spur (Orion arm)	1.23
`neCL`	change thermal electron model (NE2001 instead of YMW16)	1.19
`twistX`	unified halo model via twisted X-field	1.26
`nebCor`	n_e-B correlation	1.22
`cre10`	cosmic-ray electron vertical scale height	1.22
`synCG`	use CosmoGlobe synchrotron maps	1.50
`locBub`	local bubble (<u>preliminary</u>, spherical approximation)	1.17



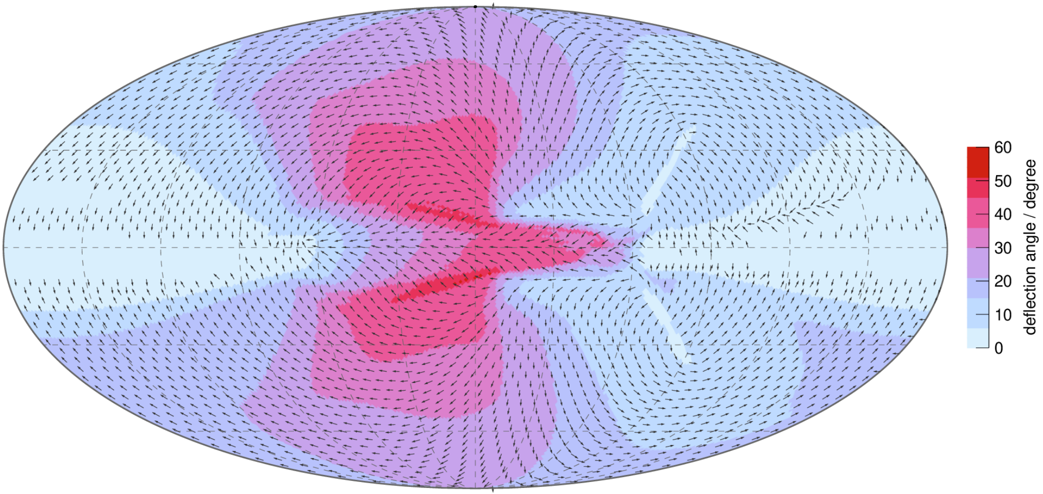




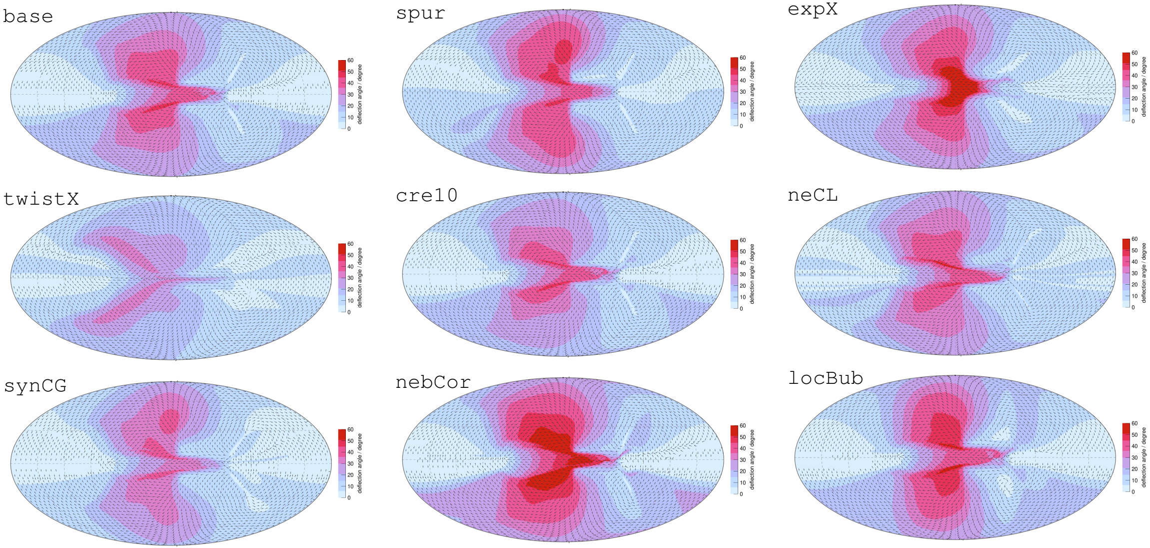




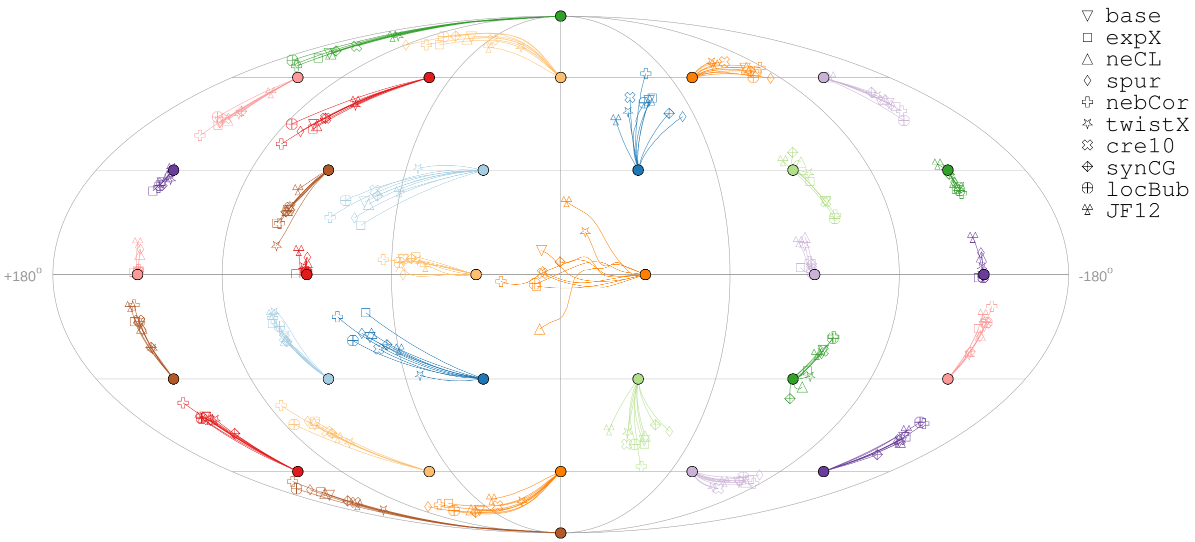
Deflections at 20 EV (base model) (backtracking)



Deflections at 20 EV (backtracking)

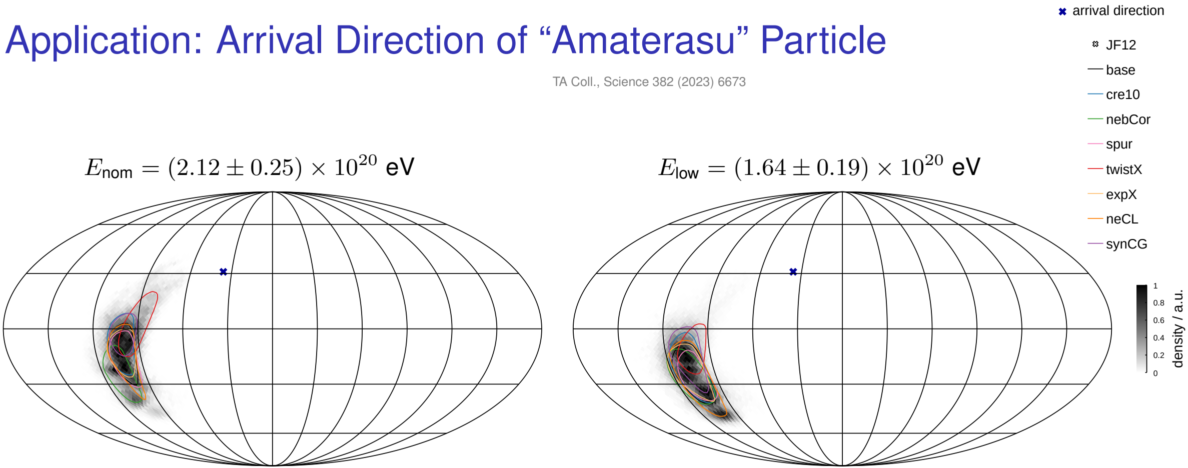


Deflections at 20 EV (backtracking)



Application: Arrival Direction of “Amaterasu” Particle

TA Coll., Science 382 (2023) 6673

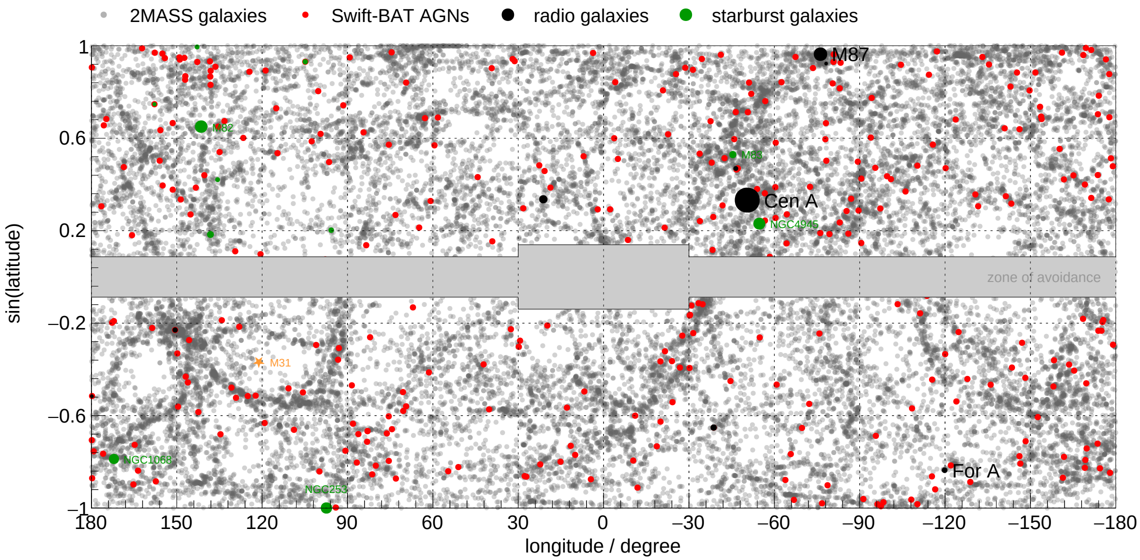


localization uncertainty: 6.6% of 4π or 2726 deg^2

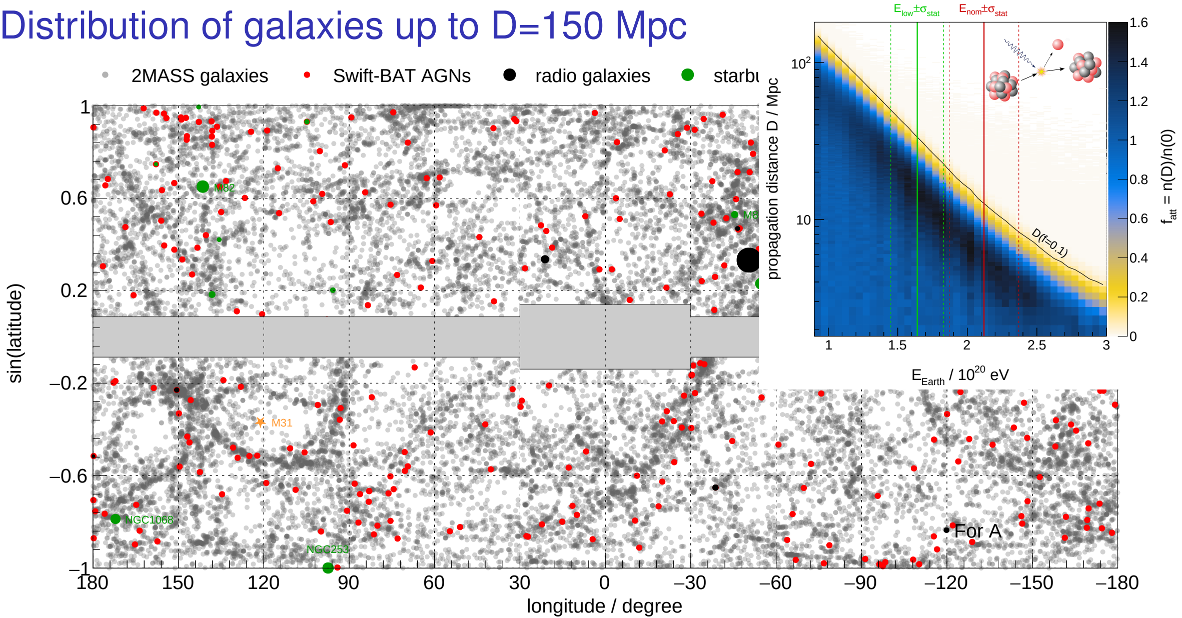
uncertainty of coherent deflection, random field, Galactic variance, TA energy scale, statistical uncertainty of E (assuming Fe)

(MU&G.R. Farrar ApJL 962 (2024) L5)

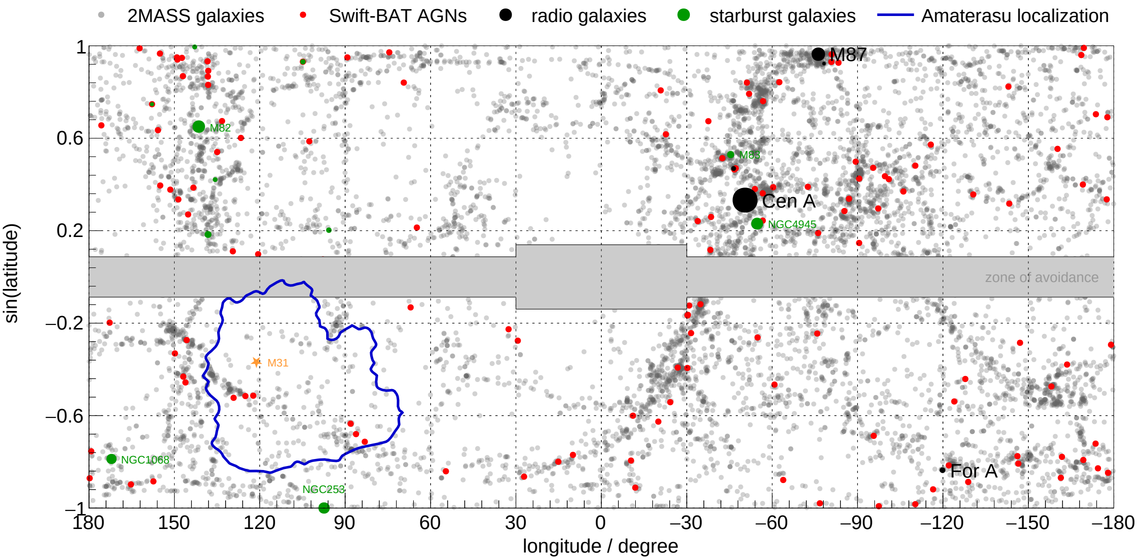
Distribution of galaxies up to D=150 Mpc



Distribution of galaxies up to D=150 Mpc

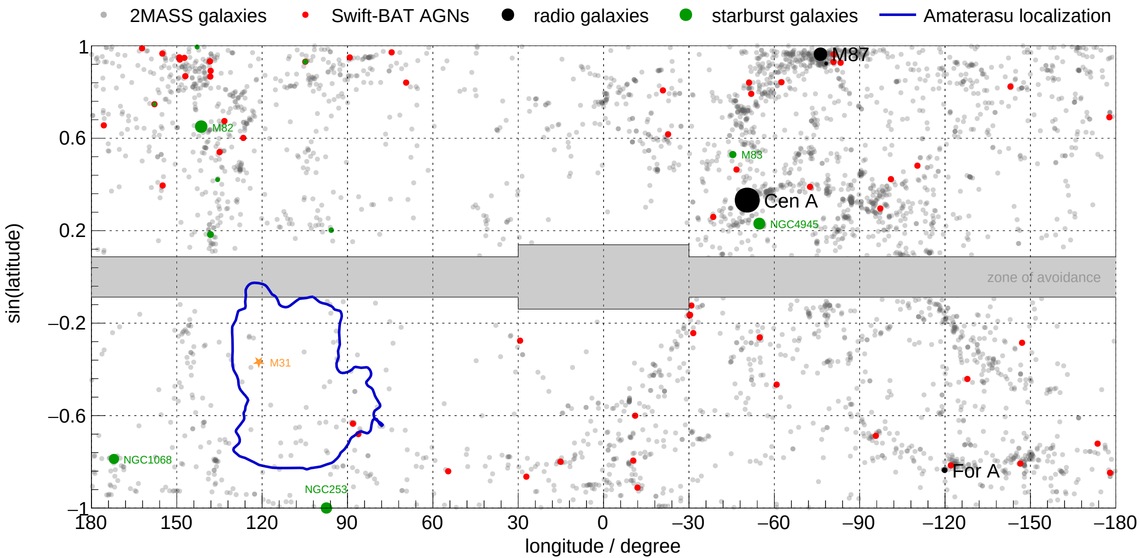


$E_{\mathrm{low}} - 2\,\sigma$, $D_{0.1}$=72 Mpc



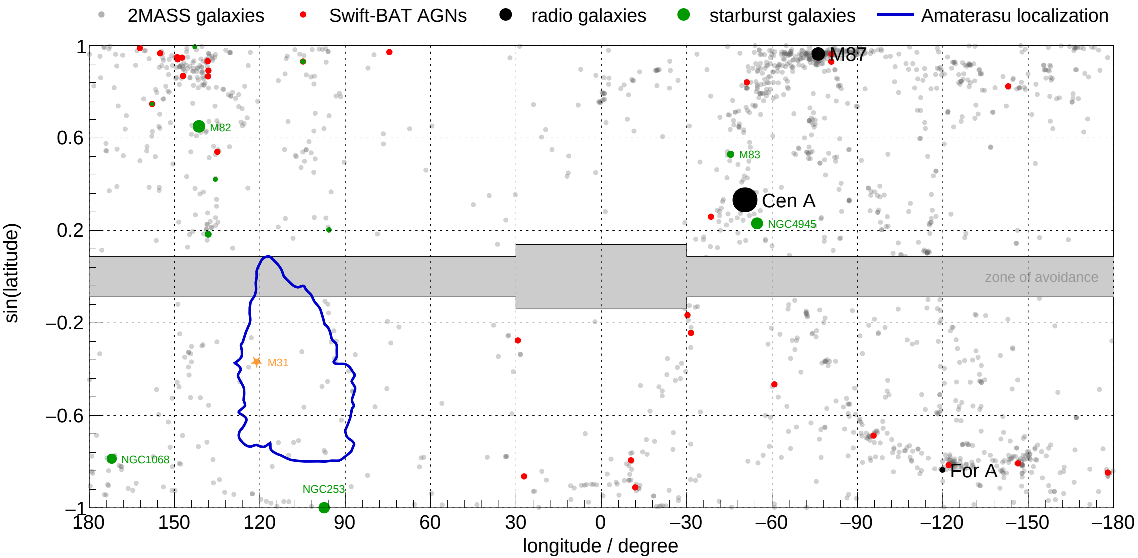
(blue localization contour: $\rho_i < 0.05$ with $\rho_i = \max_{1\leq j\leq 8} \rho_{ij}$ and $\rho_{ij} = N_{ij}/N_{\mathrm{max},j}$, pixel i and model j)

$E_{\text{low}} - 1\,\sigma$, $D_{0.1}$=42 Mpc



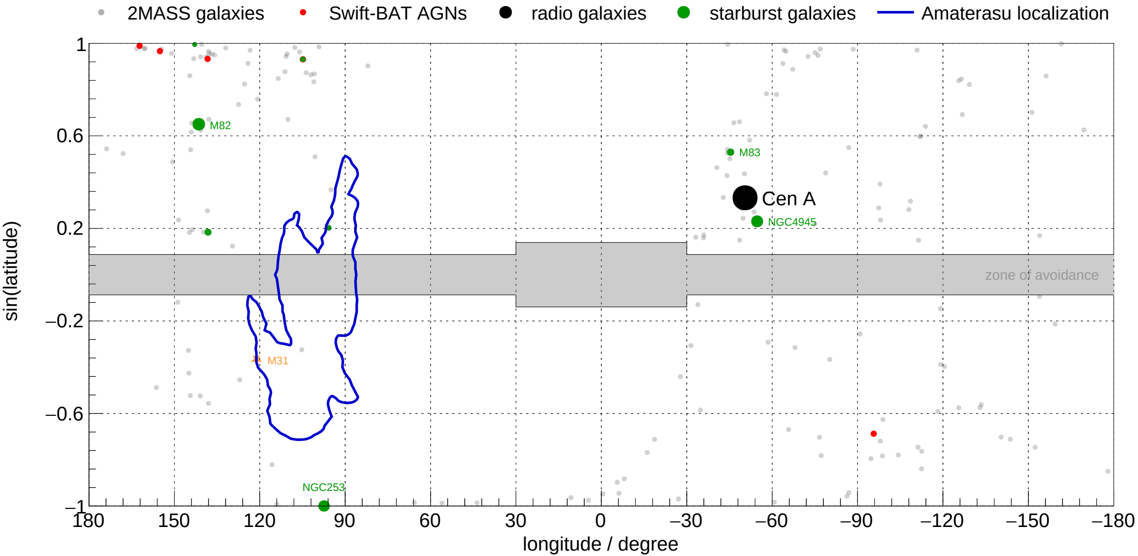
(blue localization contour: $\rho_i < 0.05$ with $\rho_i = \max_{1 \le j \le 8} \rho_{ij}$ and $\rho_{ij} = N_{ij}/N_{\max,j}$, pixel i and model j)

E_{low}, $D_{0.1}$=25 Mpc



(blue localization contour: $\rho_i < 0.05$ with $\rho_i = \max_{1 \le j \le 8} \rho_{ij}$ and $\rho_{ij} = N_{ij}/N_{\text{max},j}$, pixel i and model j)

E_{nom}, $D_{0.1}$=10 Mpc

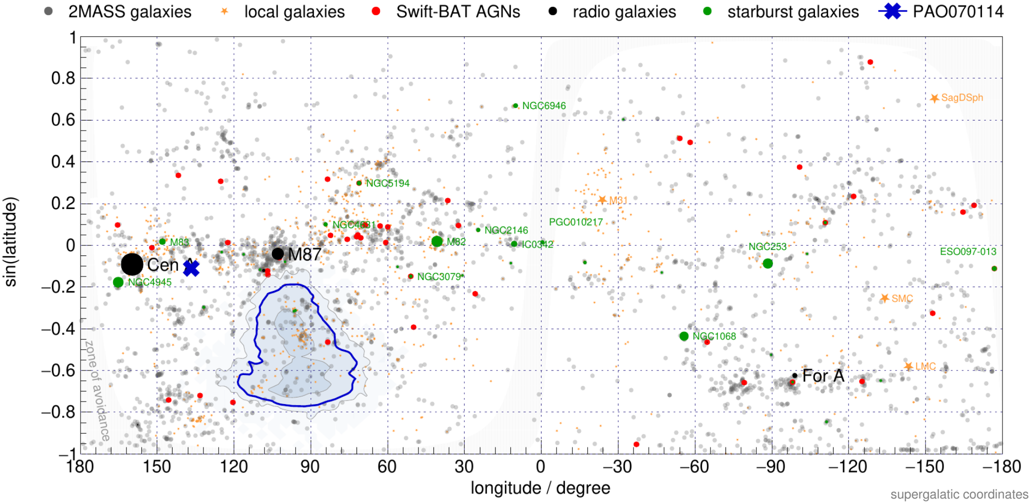


(blue localization contour: $\rho_i < 0.05$ with $\rho_i = \max_{1\leq j\leq 8} \rho_{ij}$ and $\rho_{ij} = N_{ij}/N_{\mathrm{max},j}$, pixel i and model j)

Application: Arrival Direction of the Top 4 Auger Events

Pierre Auger Coll., ApJS 264 (2023) 50

id	E (EeV)	$\sigma_{stat.}$ (EeV)	R.A. (degree)	Dec. (degree)	$\Omega_{loc} / 4\pi$ –	θ_{loc} (degree)
PAO191110	166	13	128.9	−52.0	7.1%	31
PAO070114	165	13	192.9	−21.2	2.4%	18
PAO141021	155	12	102.9	−37.8	6.3%	29
PAO200611	155	12	107.2	−47.6	6.6%	29



supergalatic coordinates

Summary and Outlook

UF23 model ensemble: (MU&G.R. Farrar ApJ 970 (2024) 95)

- fit to newest RM, Q, U data
- major refinement of JF12 GMF components
- uncertainty of coherent GMF for UHECR tracking (...and other applications)
- test association of UHE arrival directions with source candidates

Availability:

- GitHub link (C++)
- CRPropa link (C++)
- gammaALPs link (python)

Next Steps:

- include more data to decrease uncertainties (pulsar RMs, dust, ...)
- explore further sources of uncertainty (functional forms, foregrounds, $n_{\rm e}$, $n_{\rm cre}$)
- extend analysis to turbulent component