UNIVERSITY OF COLOGNE

ICRR Institute for Cosmic Ray Research University of Tokyo

Institute of Physics Academia Sinica

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

Cosmic Rays: from the Galaxy and beyond

IMPRS Recruitment Workshop

Keito Watanabe, 13.11.2023

Thesis Supervisor: Prof. Dr. Stefanie Walch-Gassner

Project Supervisors: Dr. Anatoli Fedynitch, Dr. Francesca Capel, Prof. Dr. Hiroyuki Sagawa

Self-Introduction

- Born in Nagano, Japan
- Graduated from University of Alberta in June 2021 with BSc Physics Honours
- Currently enrolled at the University of Cologne in MSc Physics with scholarship

Research work so far:

- Analysis of performance of hadronic interaction models (University of Alberta, 2019)
- Developing high-performance tracking code for geomagnetic rigidity cutoffs (ICRR, 2020)
- Investigation of Origins of NRFs (Master's Thesis, University of Cologne)
- Bayesian source-UHECR analysis & impact of GMF and mass composition (ICRR, 2021; MPP, 2022; *Poster in ICRC2023*, *paper in prep.*)

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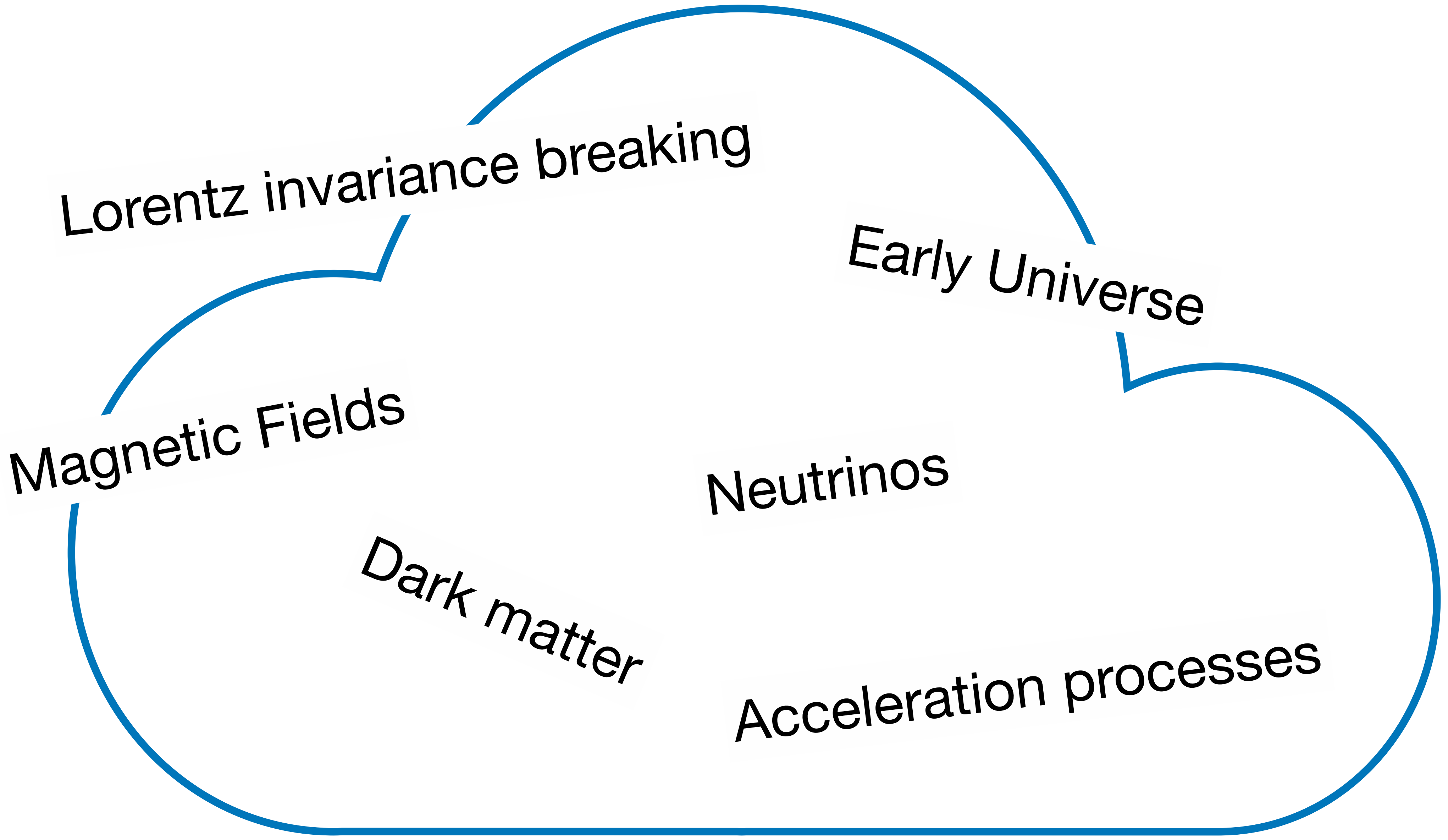
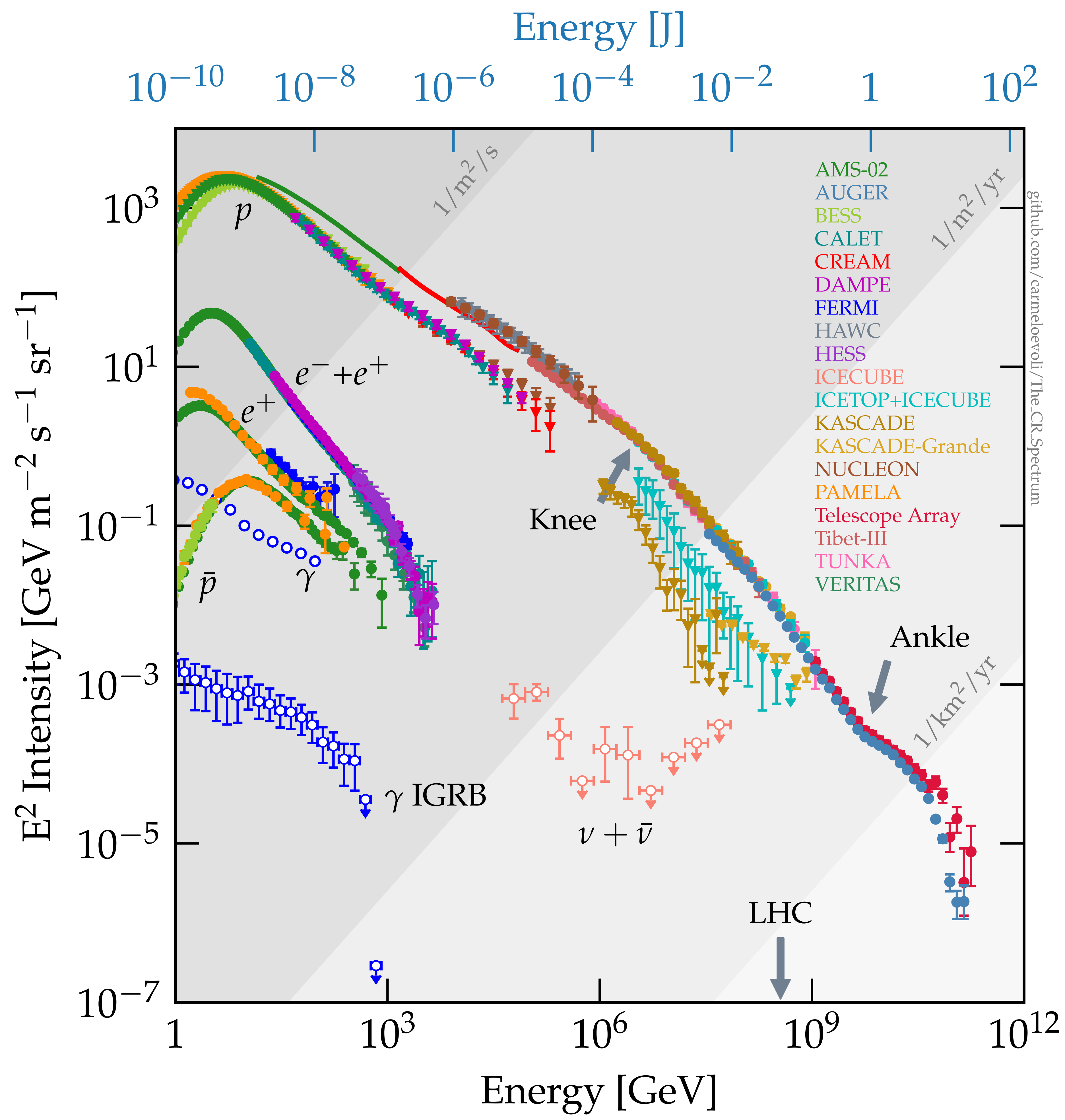
Cosmic Rays (CRs)

✦Charged particles (protons, electron, nuclei) that originate from outside the Solar System

✦Allows fundamental understanding of particle physics & astrophysics!



C. Evoli (2020), 10.5281/zenodo.7948212

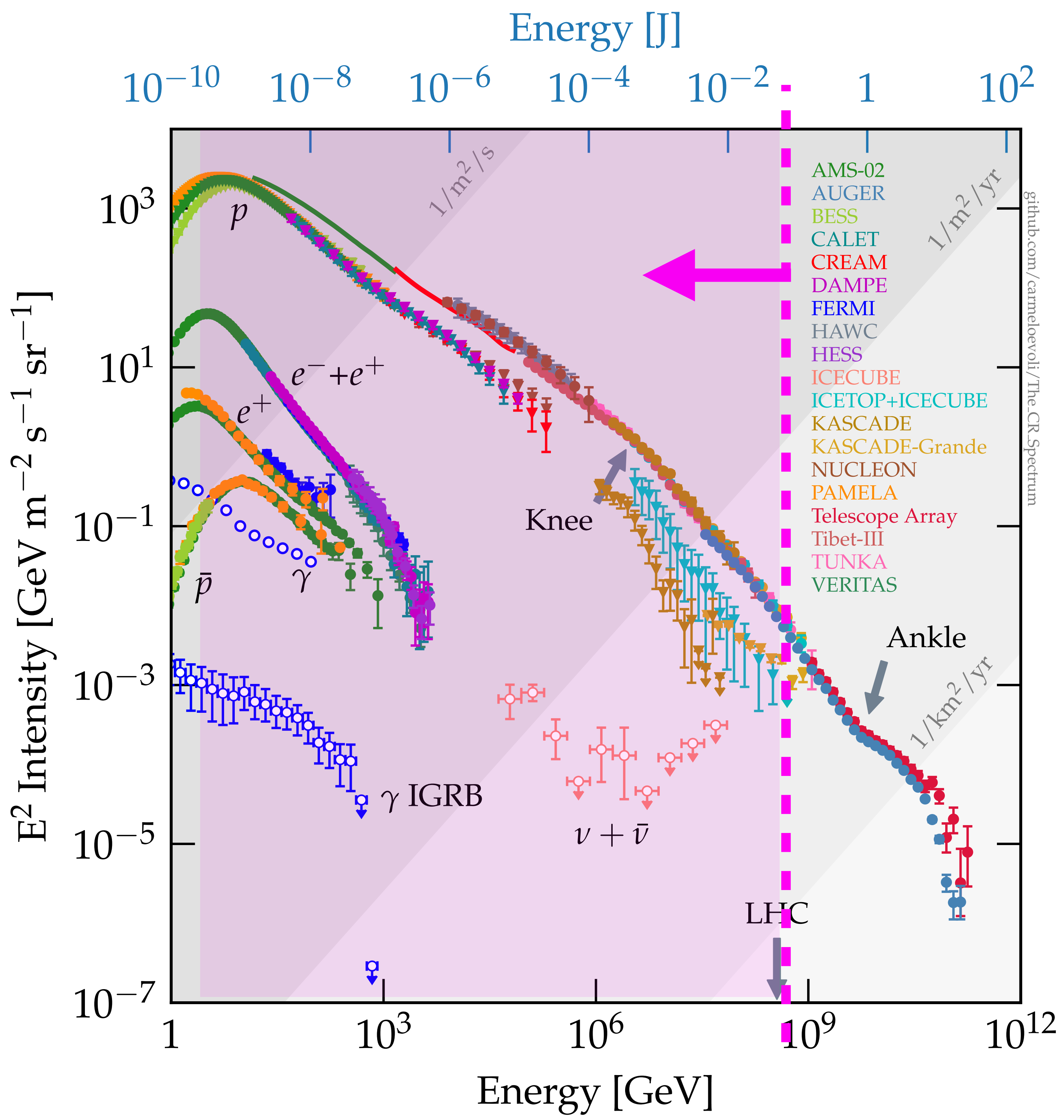


✦Spans over **12 orders of magnitude** in energy, and 30 orders of magnitude in flux!

Investigating the Origins of Non-Thermal Radio Filaments (NRFs)

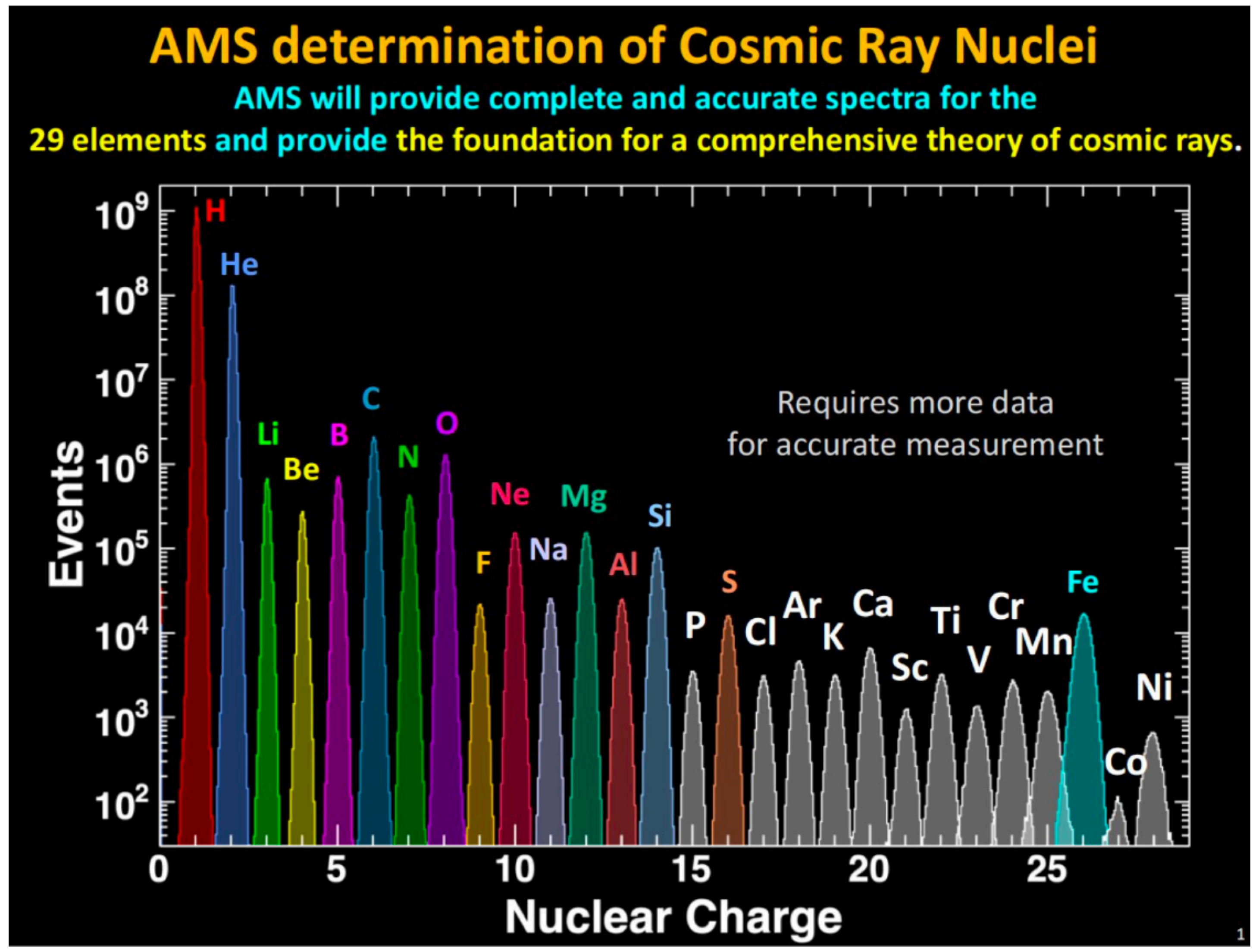
Galactic CRs

- Ranges from ~**GeV to PeV** energies
- 90% protons, ~10% Helium, <1% heavier nuclei
- Observed through direct or indirect measurements

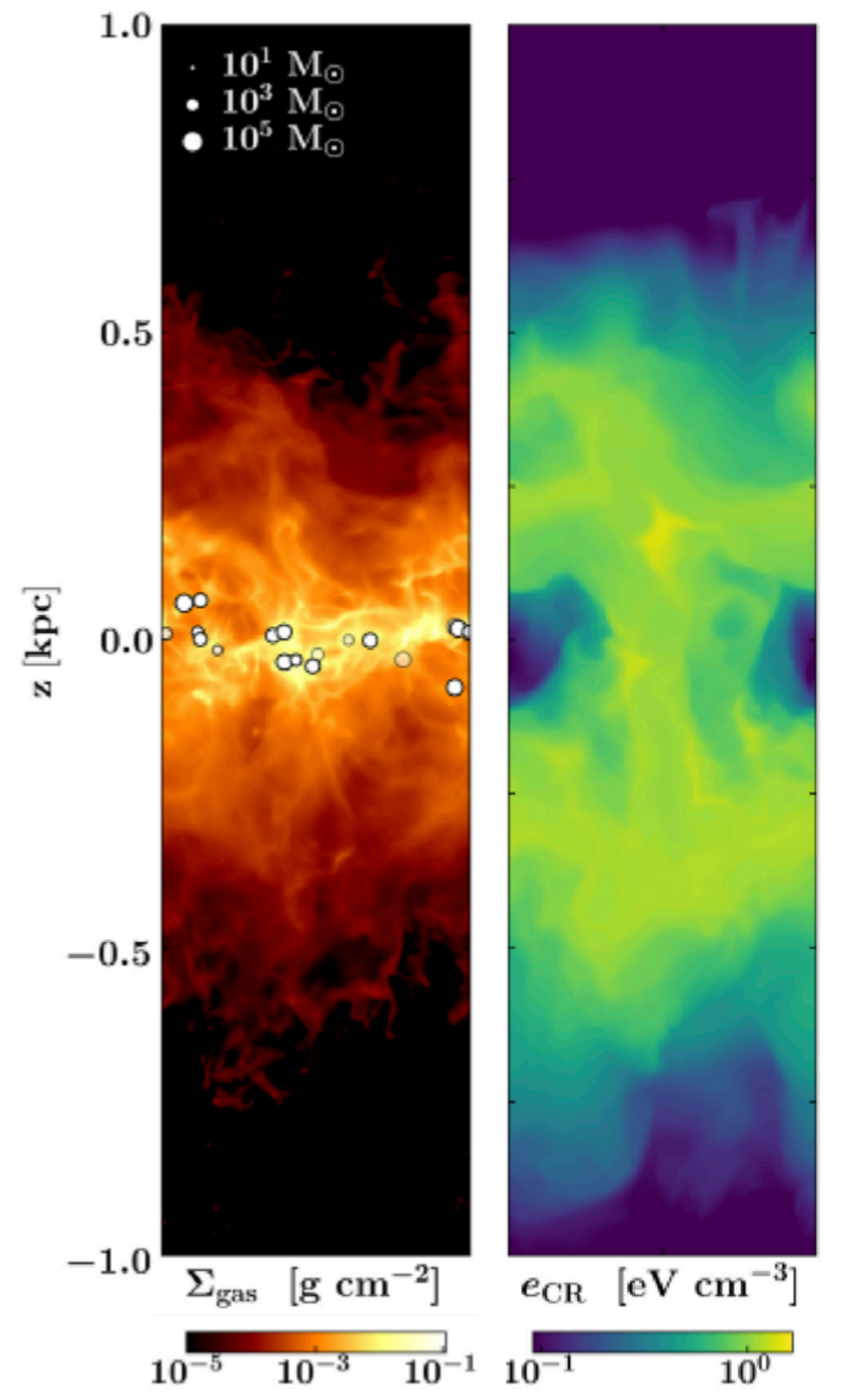


C. Evoli (2020), 10.5281/zenodo.7948212

AMS



Rathjen et al. 2021, MNRAS 504, 1

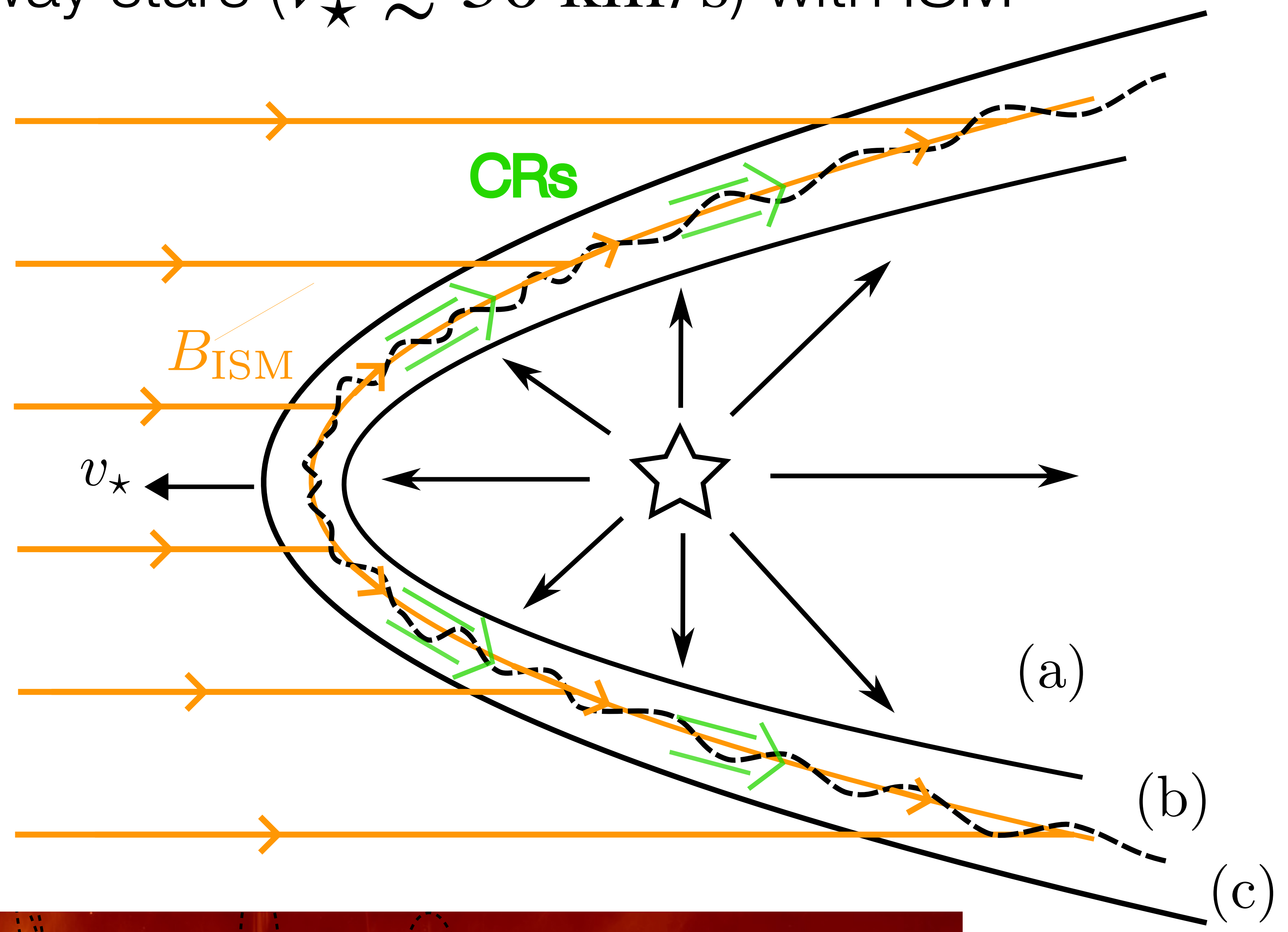


Plays dynamical role in our Galaxy through feedback processes

Stellar Bow Shocks

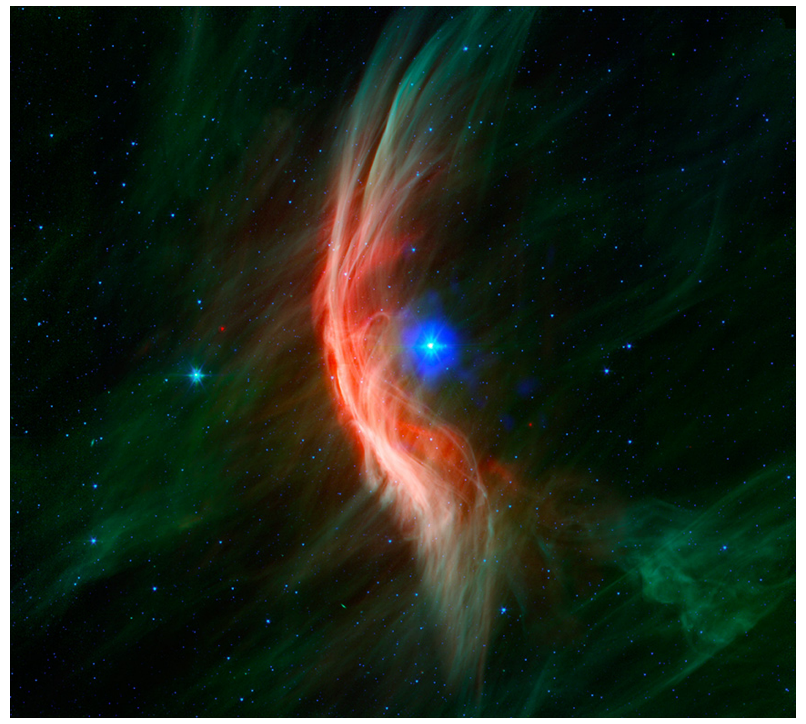
Generated from interactions from winds of massive ($M \geq 8\mathrm{M}_\odot$) runaway stars ($v_\star \gtrsim 30\ \mathrm{km/s}$) with ISM

- Three regions:
  - (a): hypersonic stellar winds, spherically symmetric when static
  - (b): shocked stellar winds
  - (c): shocked ISM
- CR accelerate at shock & diffuse onto draped magnetic field lines



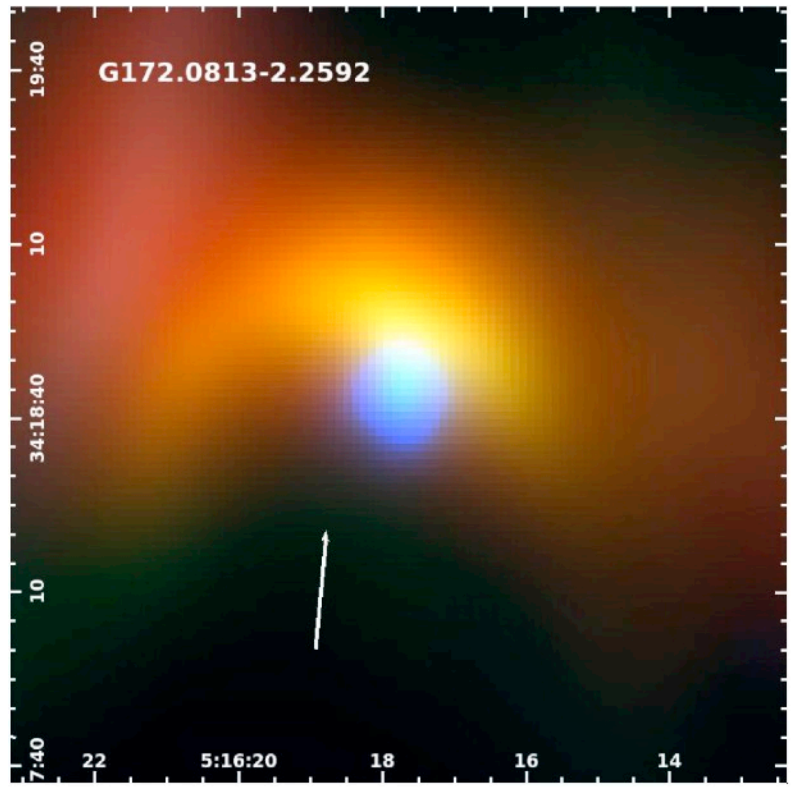
Observed throughout our Galaxy!

NASA/JPL-Caltech

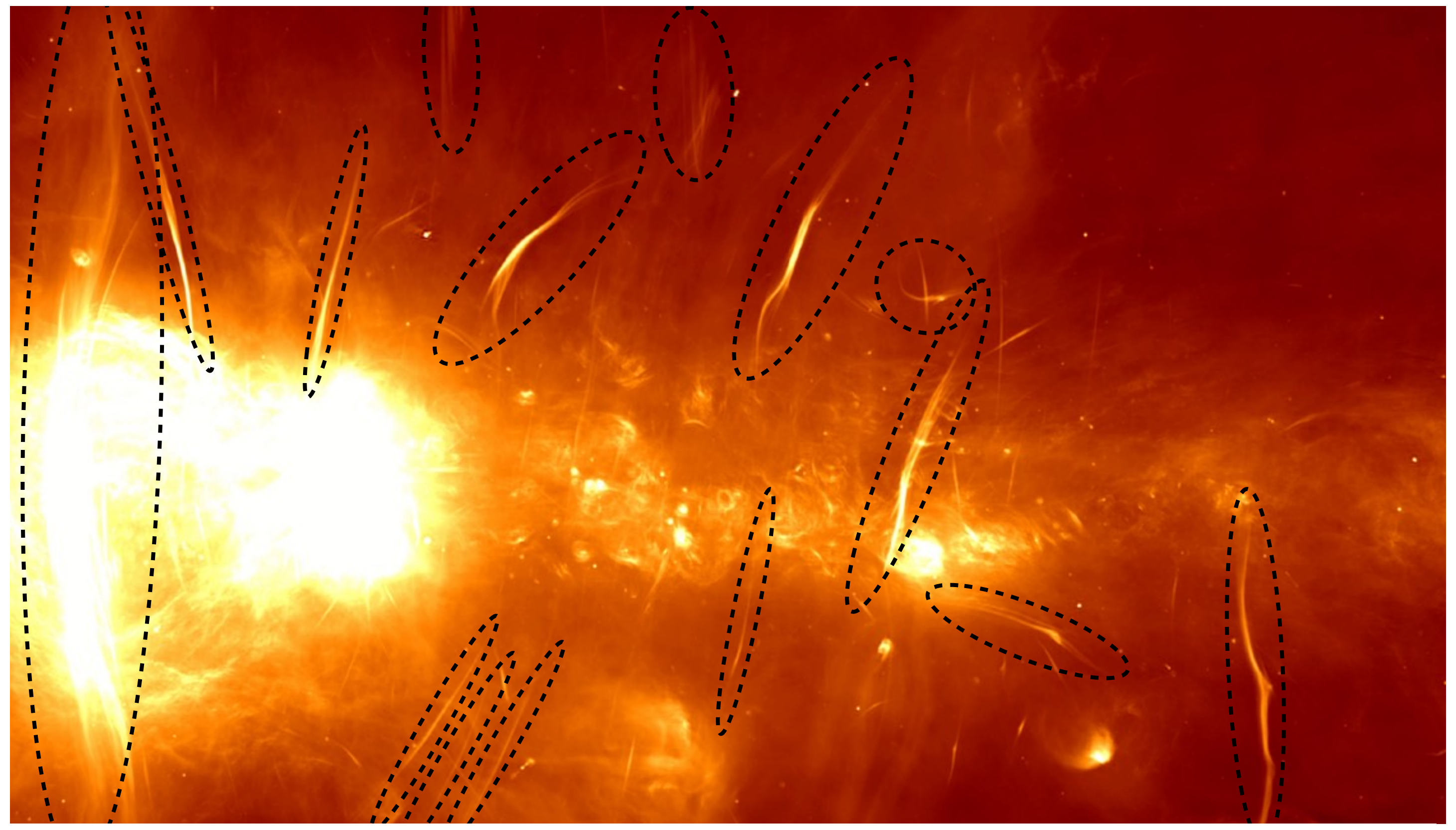


ζ Ophiuchi

Kobulnicky et al. 2016, ApJS 227 18



AE Aurigae



Bill Cotton/SARAO

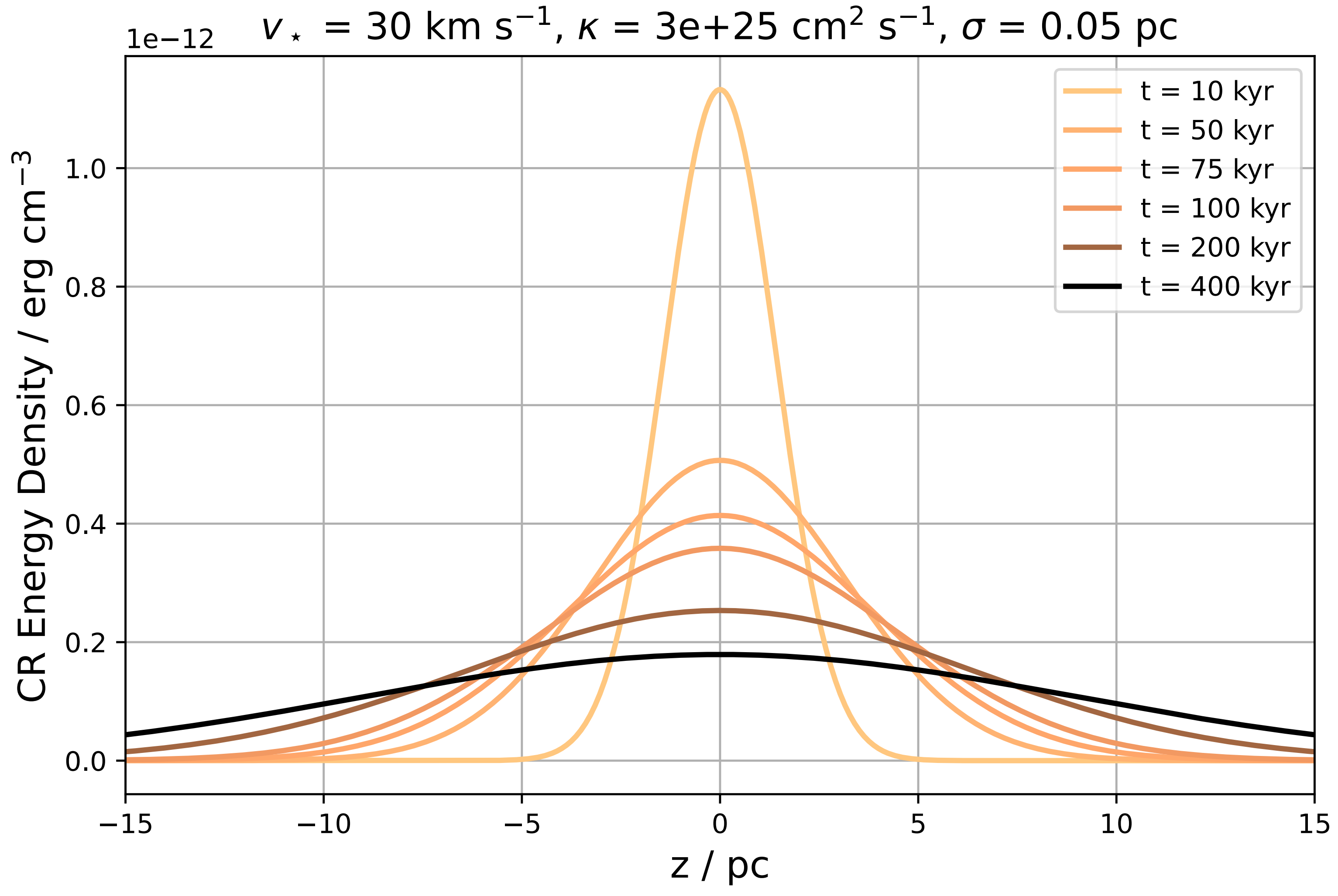
Non-thermal Radio Filaments in the Galactic Center?

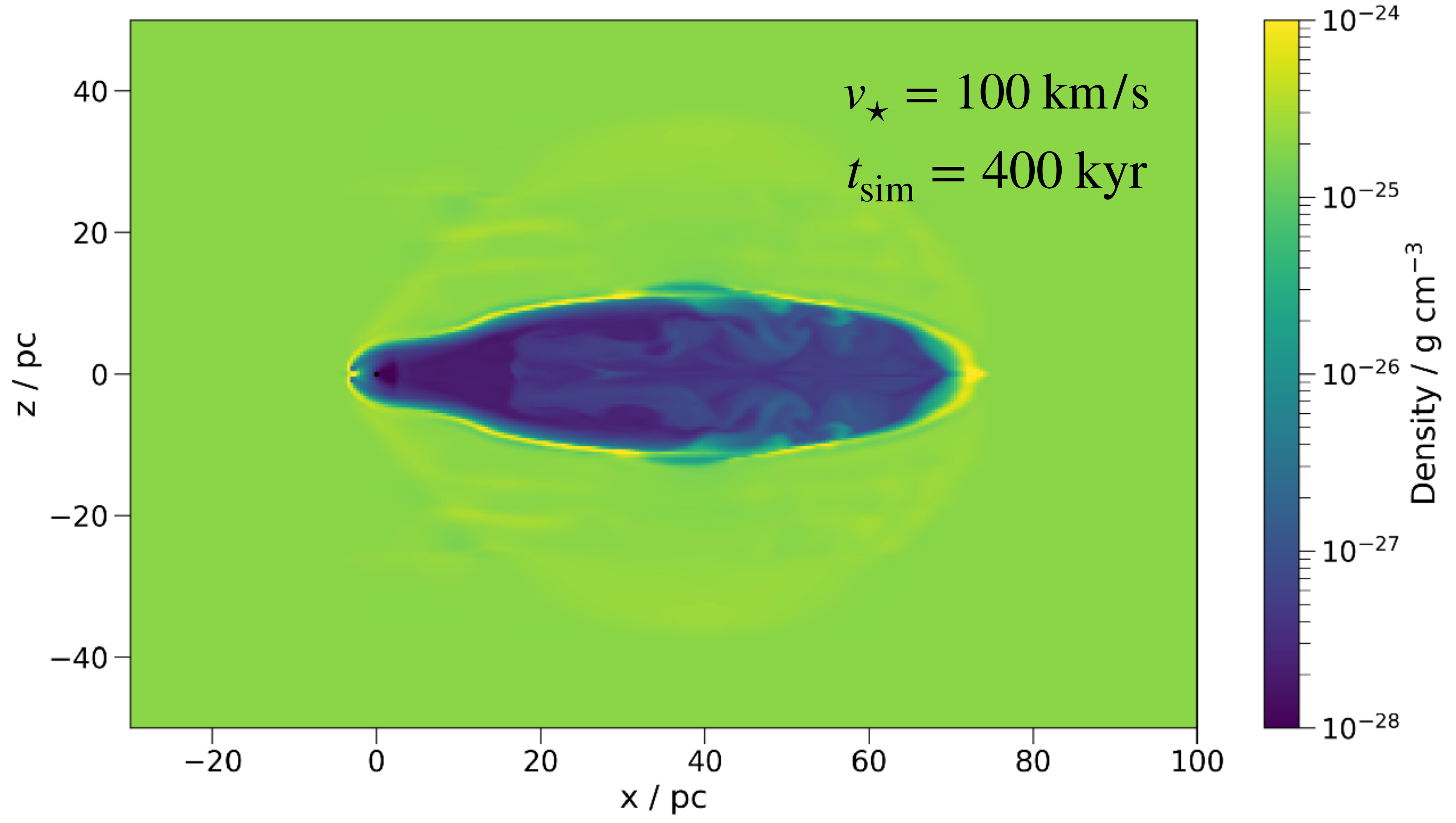
Investigating the Origin of NRFs

Thesis Project: Investigating whether **stellar bow shocks** is an origin for **non-thermal radio filaments** (NRFs)

Achievements:

- **Constructed** fully analytical 1-D diffusion-only model for CR diffusion on bow shock
- **Performed** 3D MHD simulations of stellar bow shocks in ambient ISM
- **Implemented** on-the-fly shock finding using gradient-based approach





Outlook:

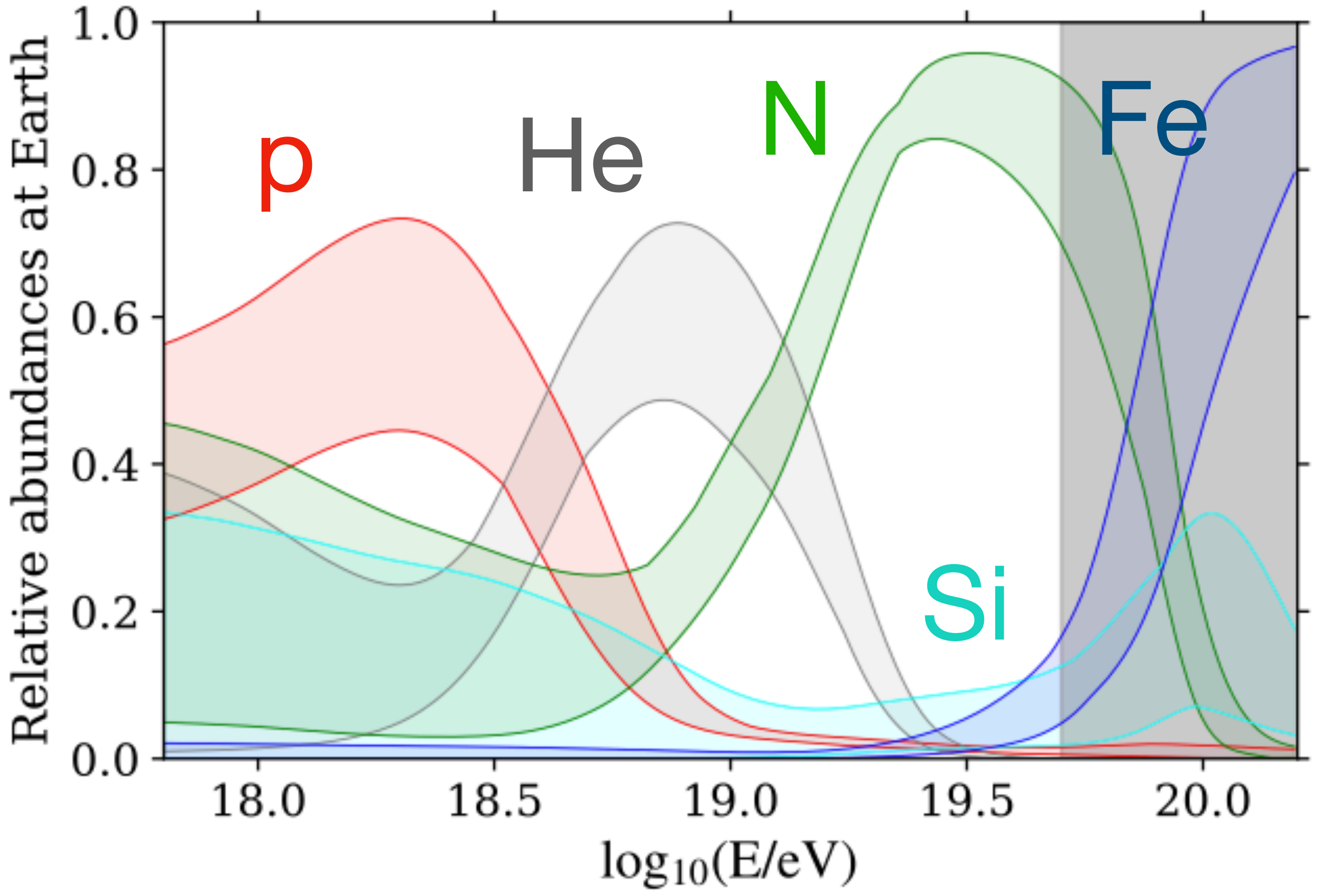
- **Implement** CR injection scheme at runtime
- **Perform** 3D *CR*-MHD simulation and **construct** emission maps to compare with observations

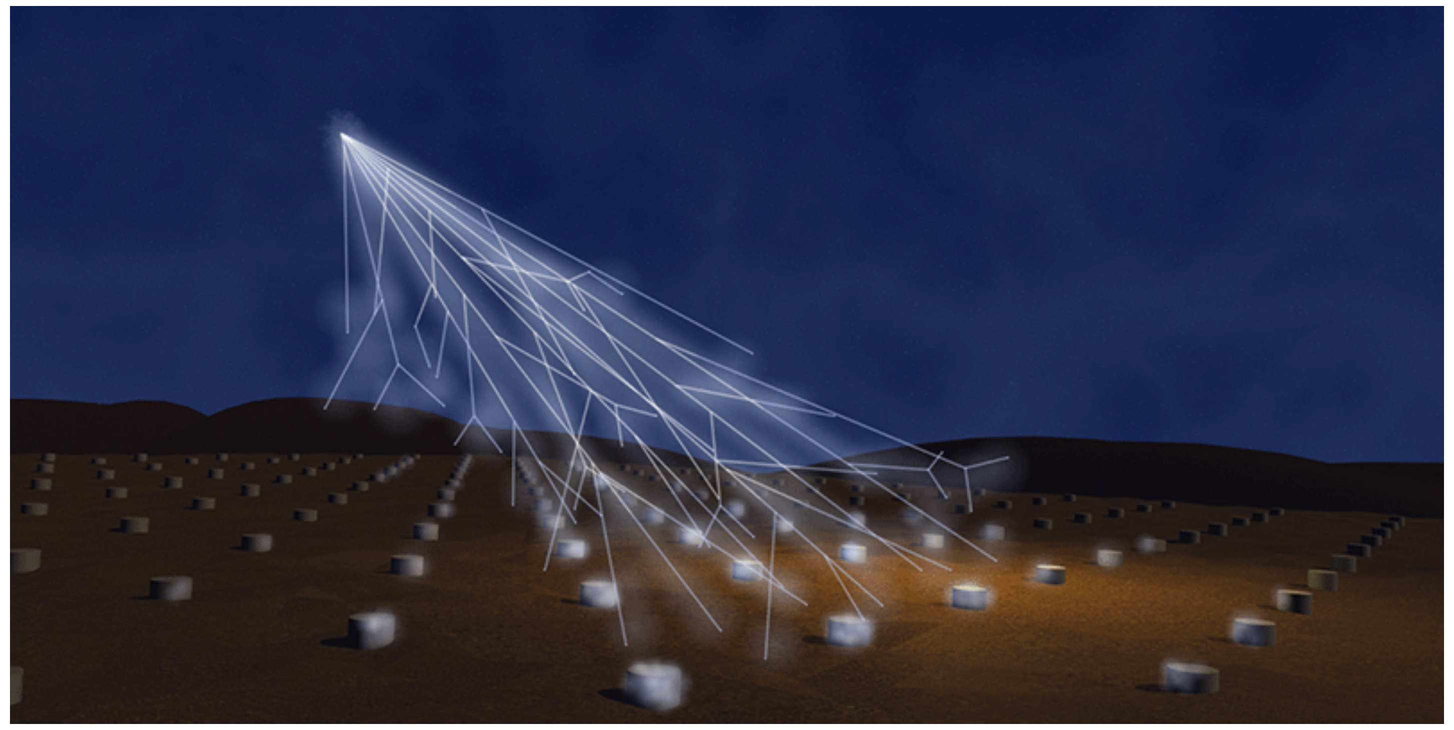
Bayesian source-UHECR Association Analysis

Ultra-High-Energy Cosmic Rays

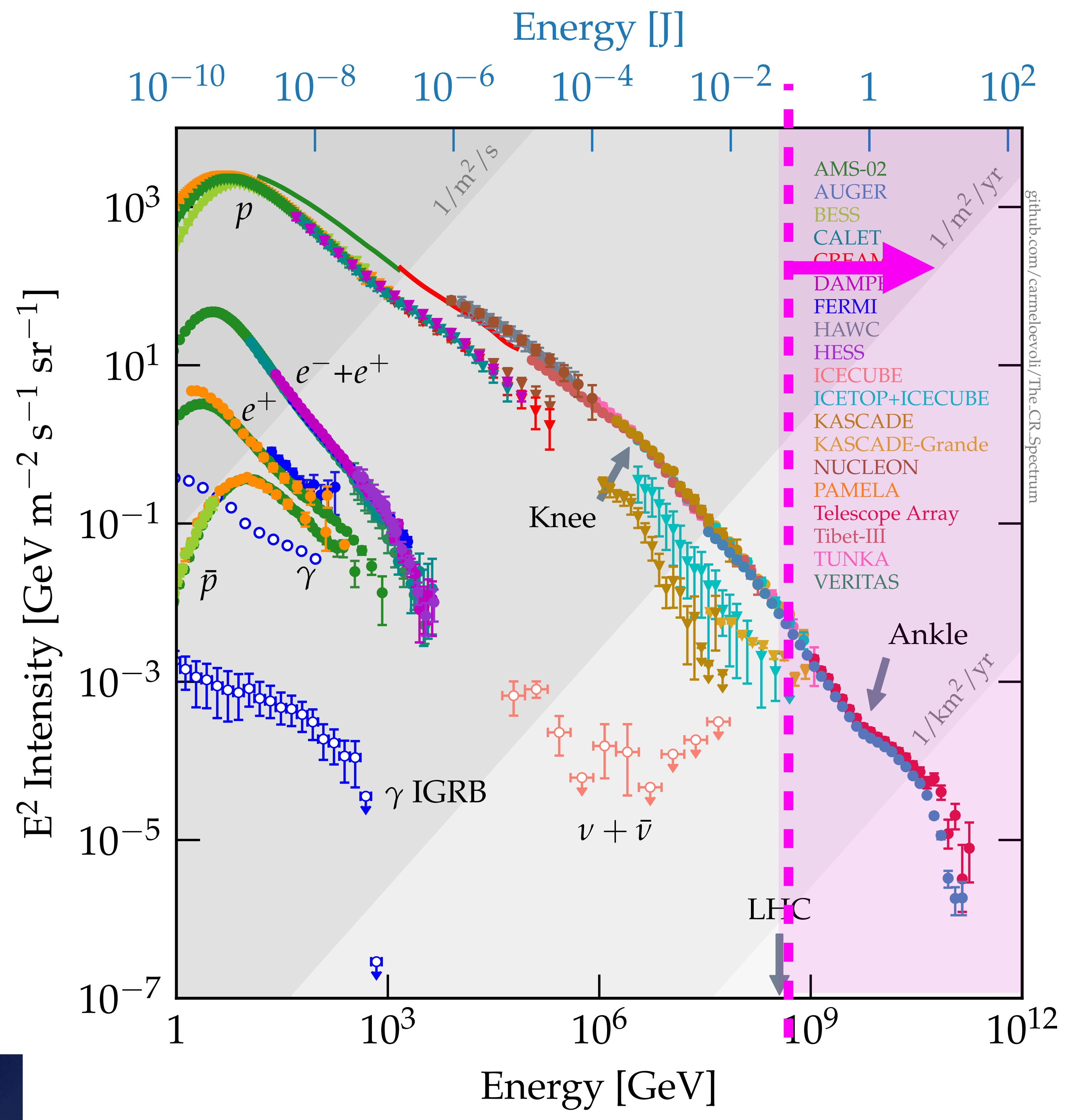
- Energies in **EeV (10^9 GeV)** and above!
- Composition not well known, but mainly from proton to iron
- Indirect detection from air showers

Pierre Auger Coll. 2023, JCAP05, 024





ASPERA / G.Toma / A. Saftoiu

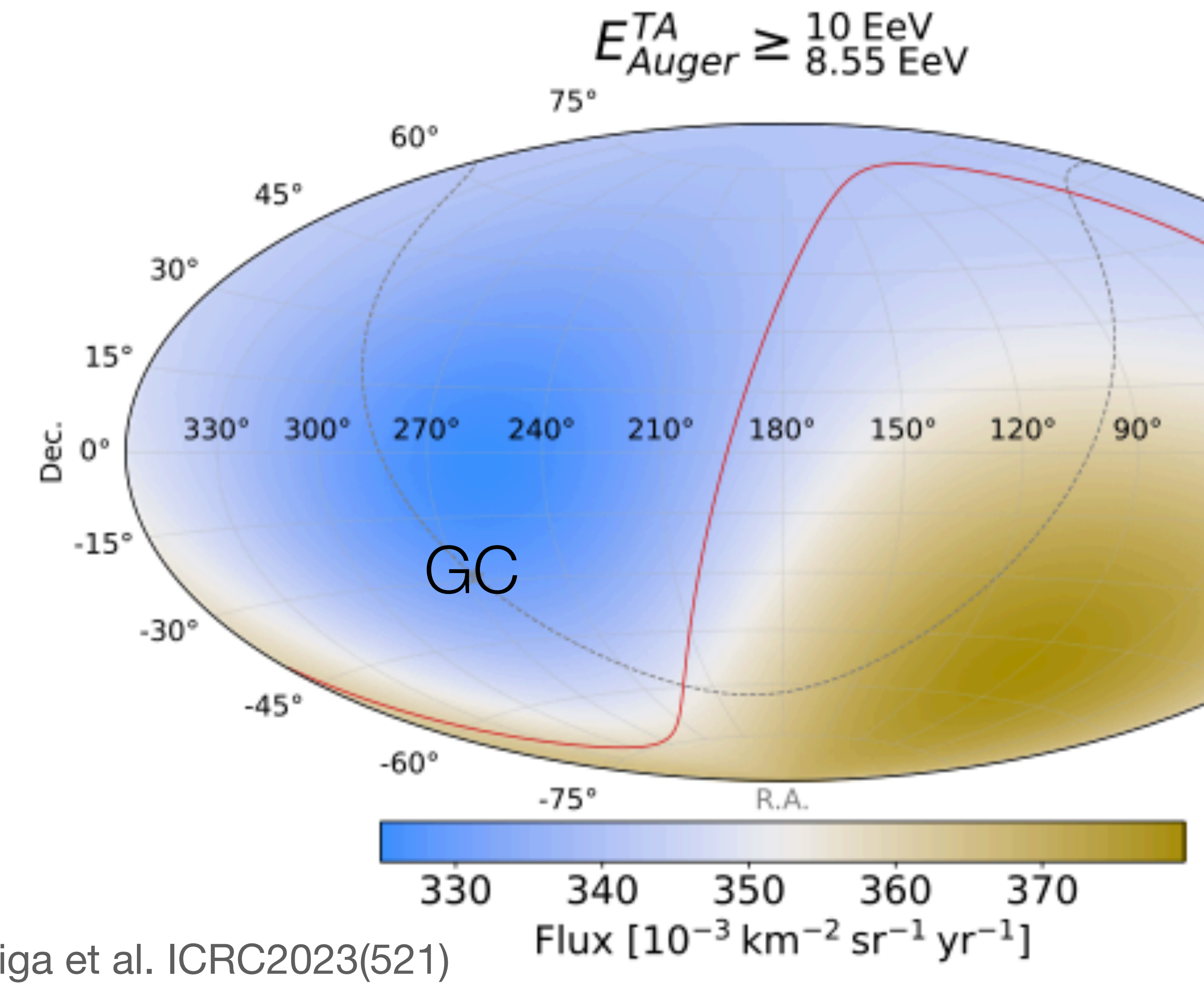


C. Evoli (2020), 10.5281/zenodo.7948212

(Possible) Sources of UHECRs

Sources of UHECRs have **not yet** been identified!

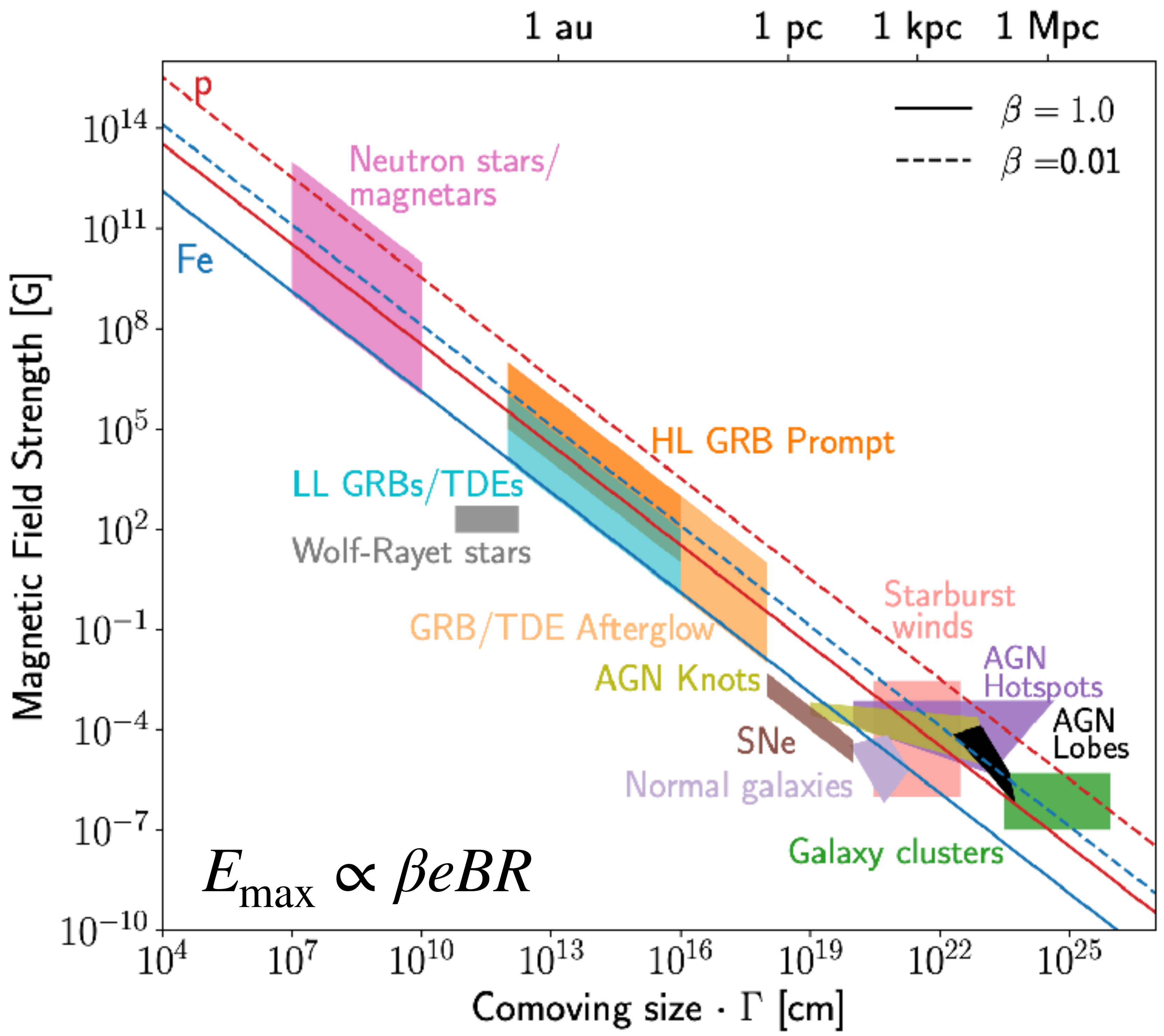
- Extragalactic origin (> 6.9σ)
- Starburst Galaxies?
- AGN / Blazars?



Equatorial Coordinates

Caccianiga et al. ICRC2023(521)

Batista *et al* 2019 *Front.Astron.Space Sci.* **6,** *23*

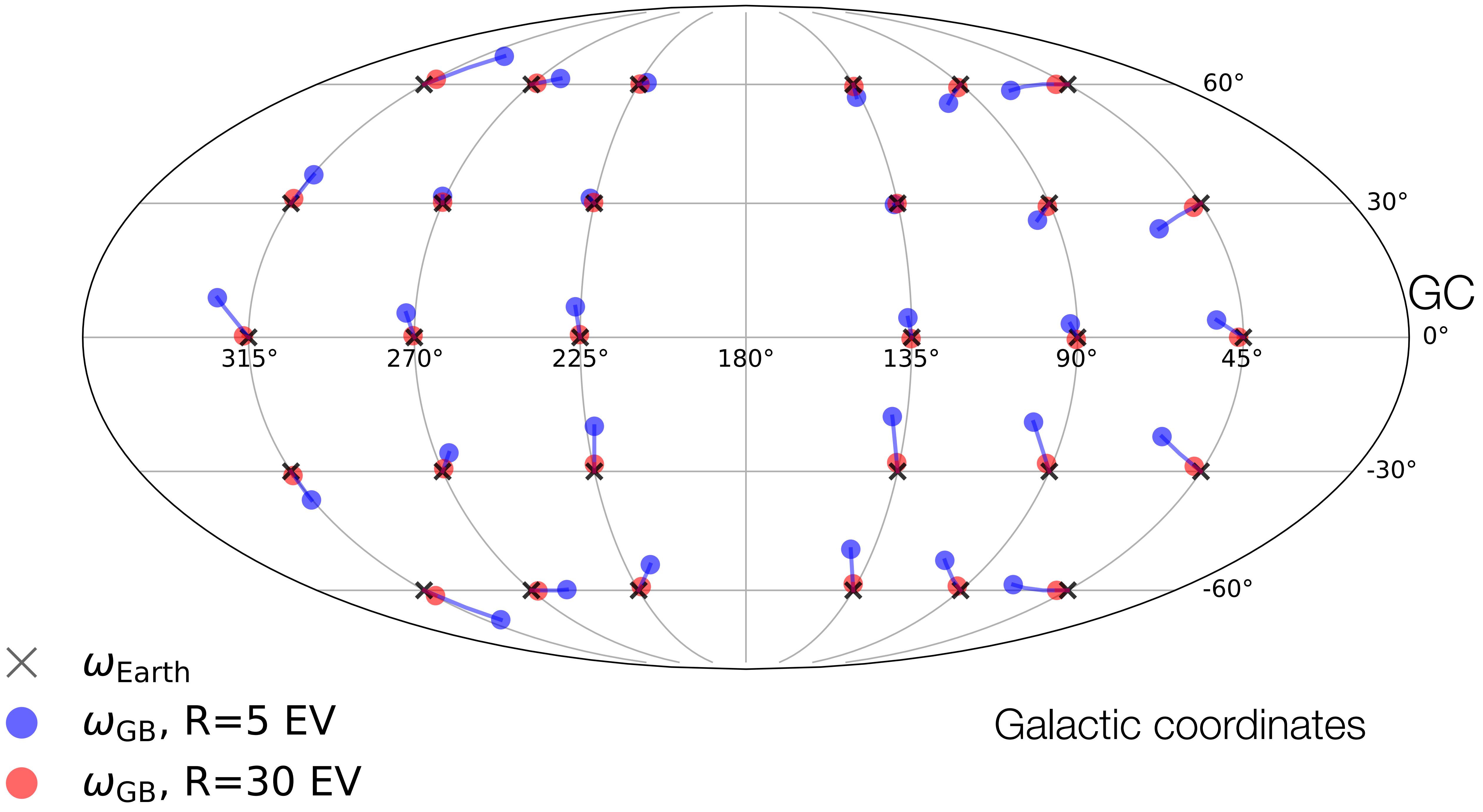


Hillas plot for CRs with $E_{\rm max} \sim 100\ \rm EeV$

Difficulties of Source Associations

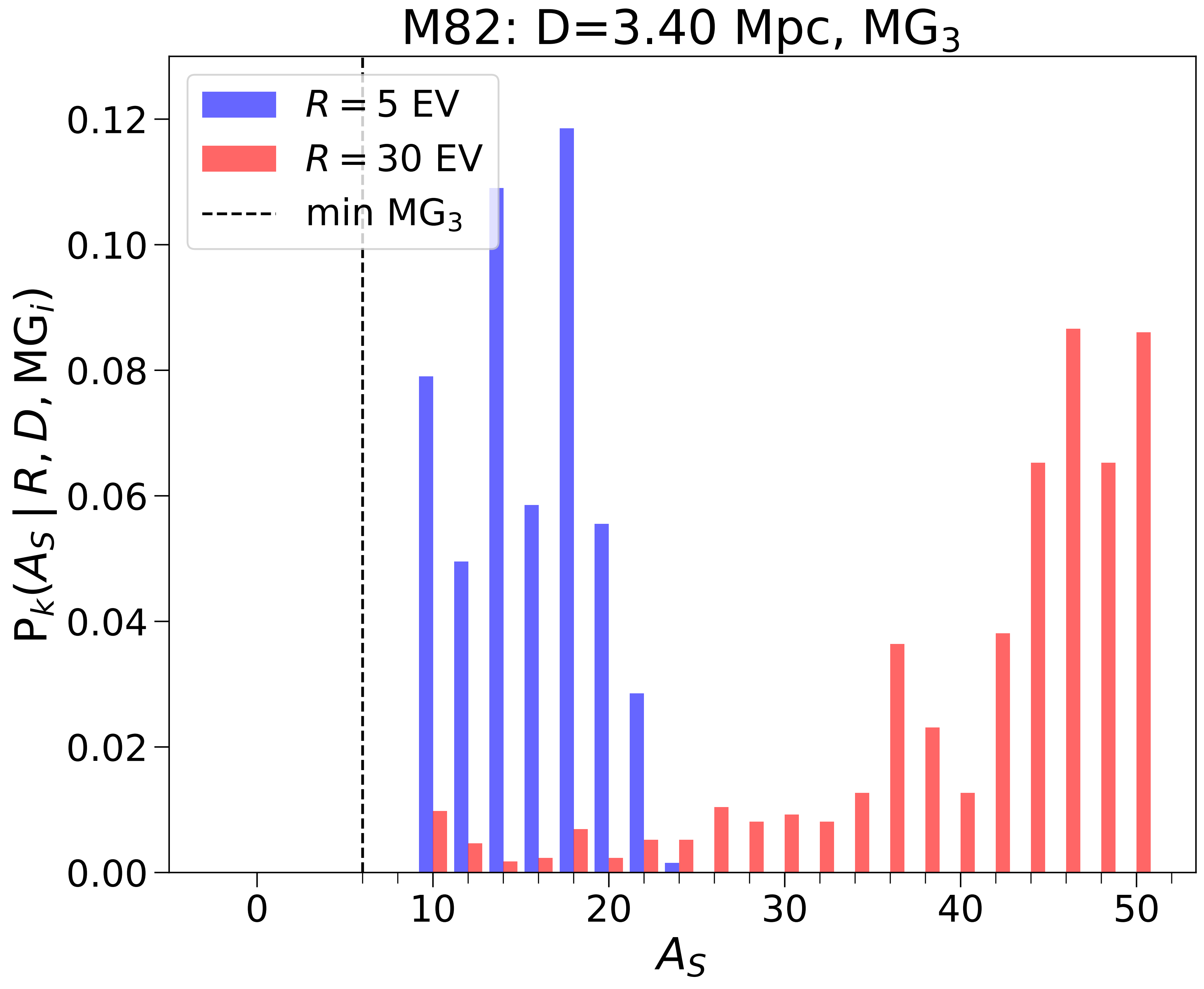
GMF (& EGMF) deflections causes UHECR anisotropy

- Energy, direction, and composition dependent!



Rigidity: $R = E/Z$

MG_3: UHECRs from Be to Ne



Energy losses throughout propagation

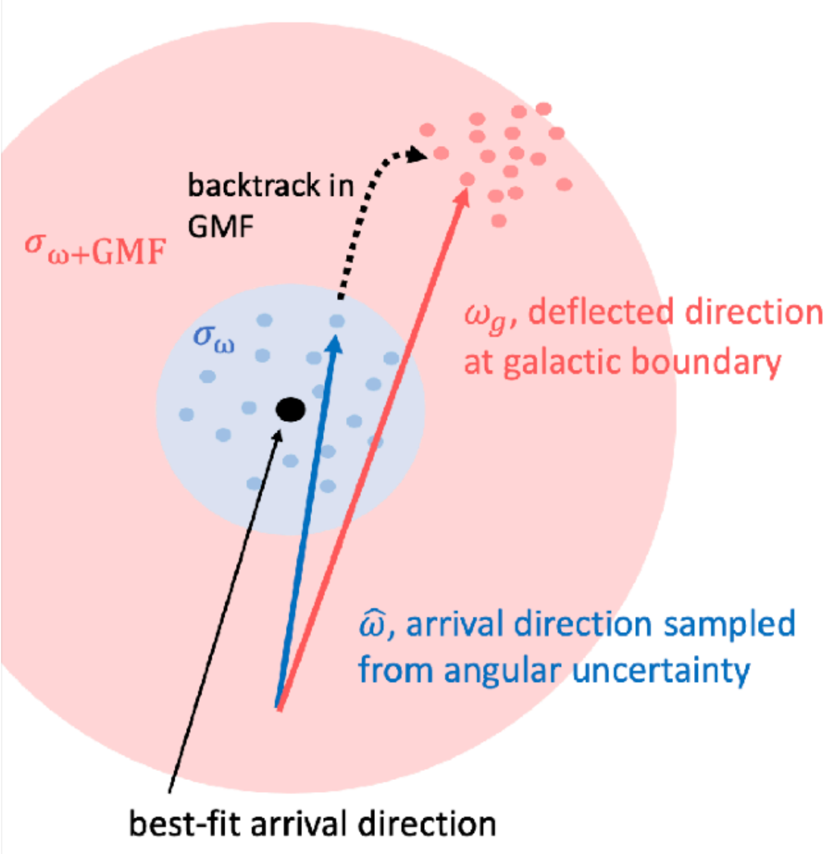
$\rightarrow$ Source composition $\neq$ arrival composition!

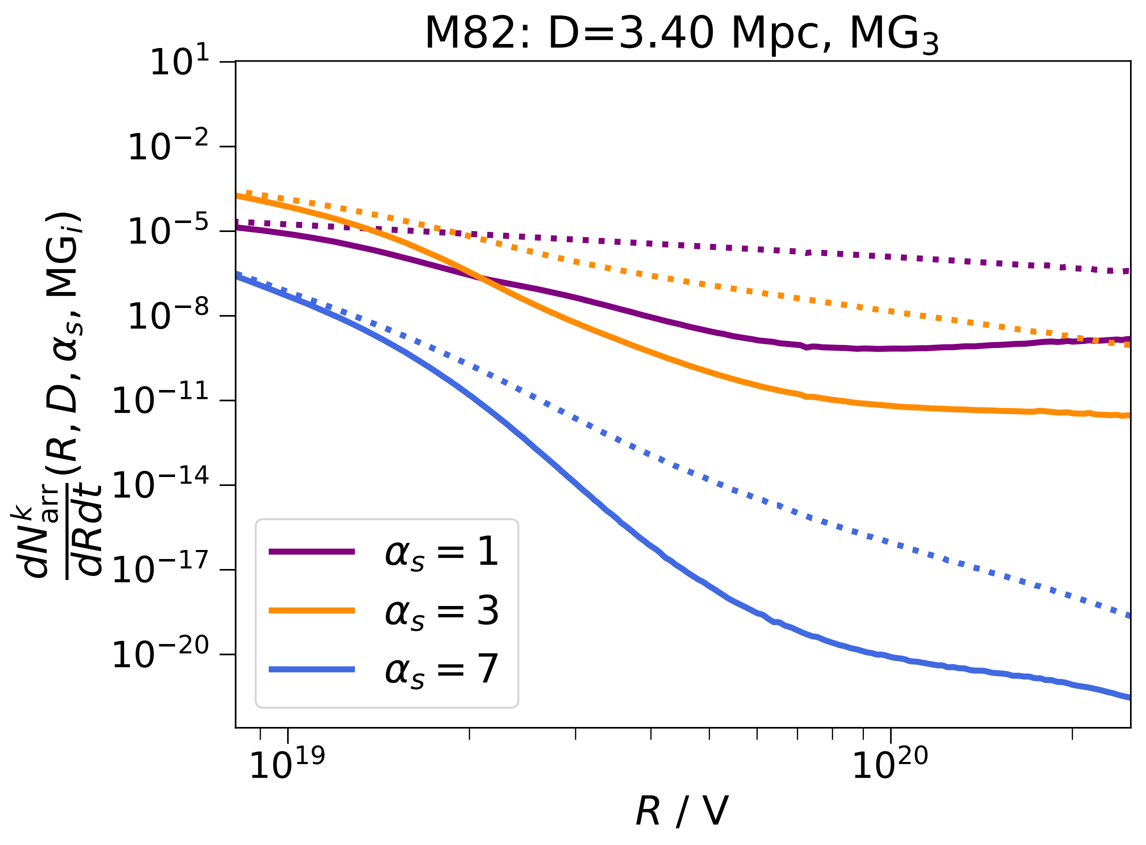
Source Association Analysis

Bachelor Project: Constraining possible sources of UHECRs using Bayesian analysis framework

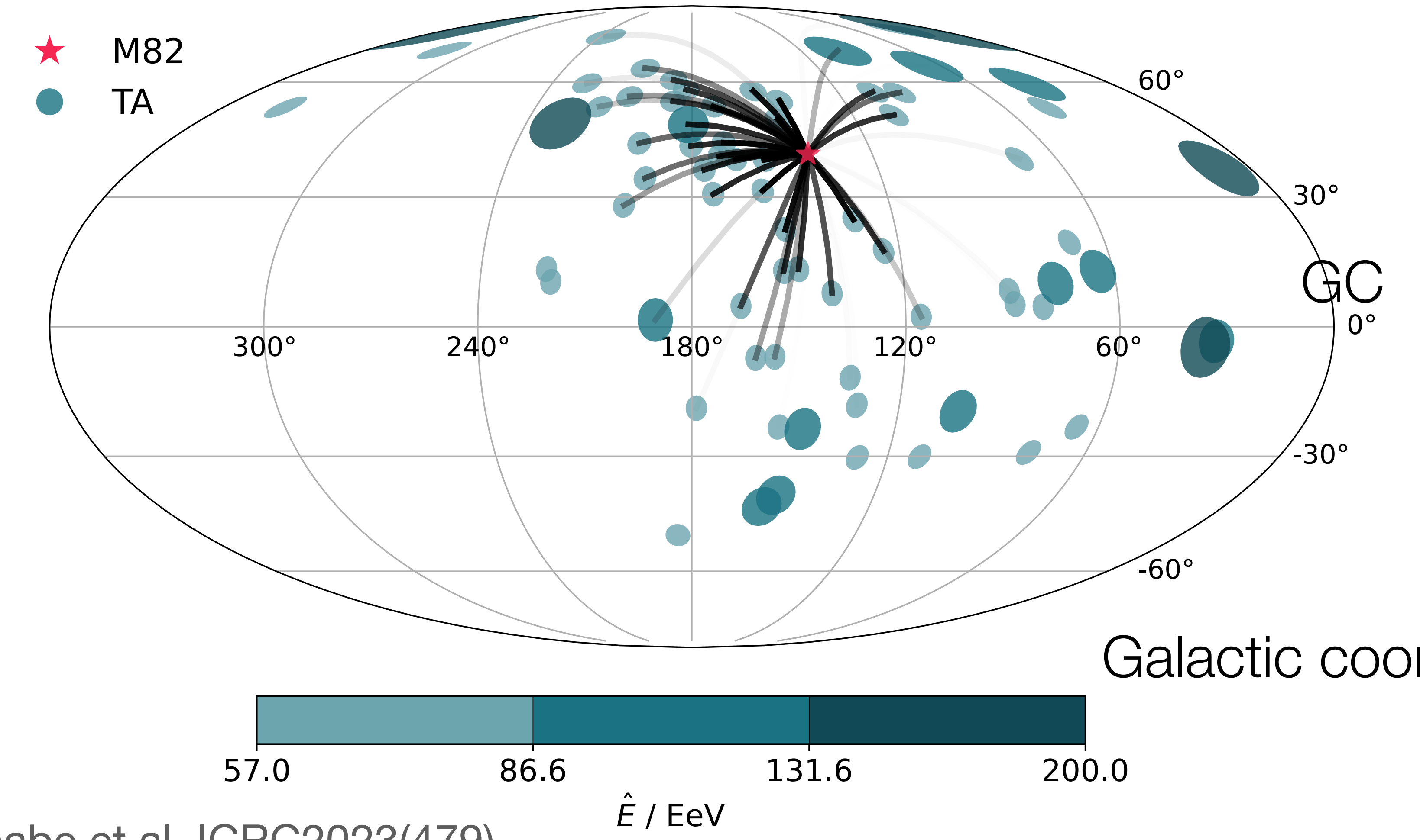
Achievements:

- **Analysed** the impact of source associations with data from Northern vs Southern sky
- **Implemented** novel framework to include GMF deflections & energy losses using existing propagation frameworks
- **Verified** new framework through simulations





Watanabe et al. ICRC2023(479)



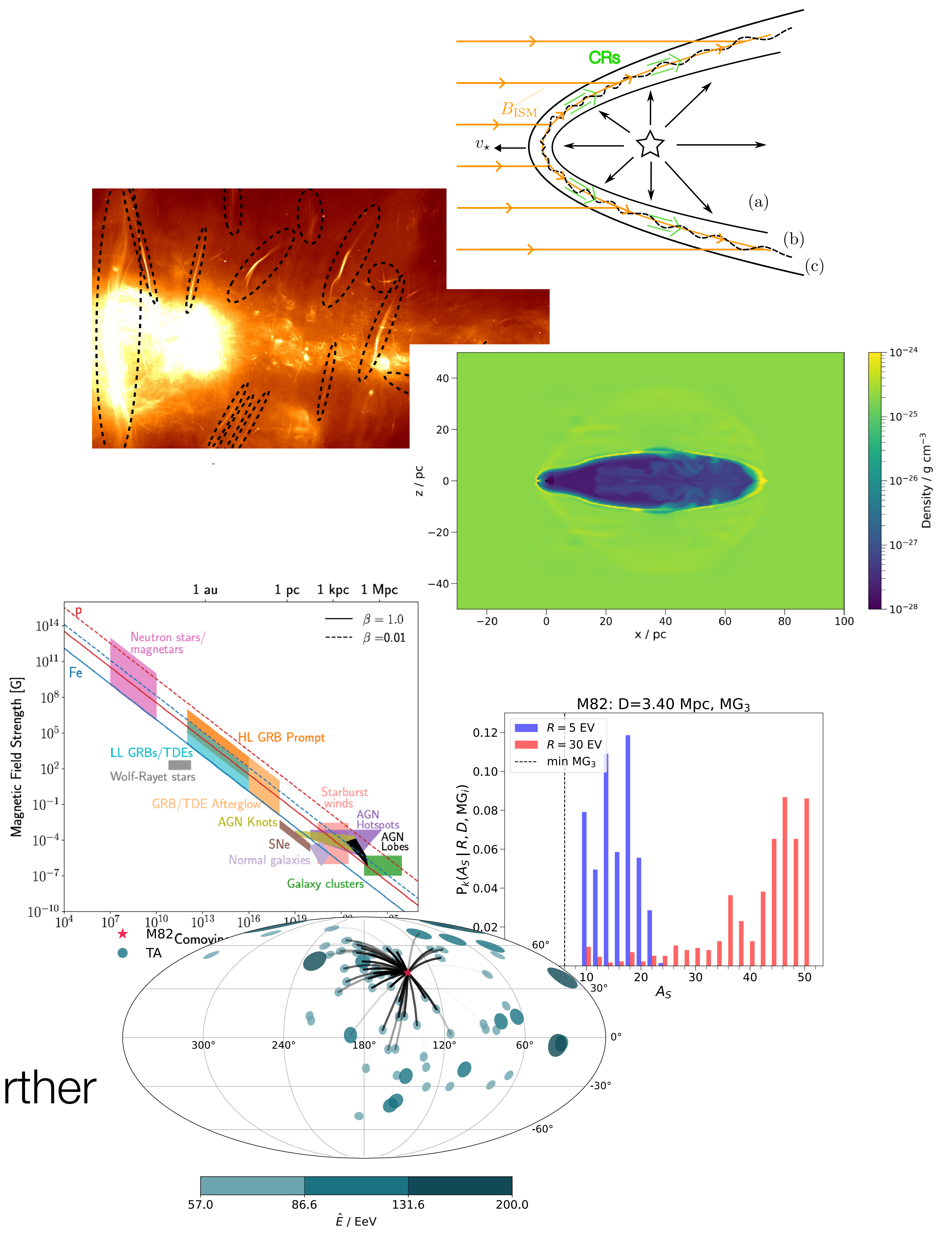
Galactic coordinates

Watanabe et al. ICRC2023(479)

Outlook:

- **Employ** direction-dependent GMF deflection model
- **Apply** framework for various configurations

Conclusion & Outlook



Galactic CRs

- Stellar bow shocks are sources of CRs and are observed within the Galaxy
- May be a possible origin for non-thermal radio filaments in our Galaxy
- Use 3D CR-MHD simulations to verify if they can form these filaments

UHECRs

- Sources of UHECR not known, but most likely from extragalactic origin
- Source-UHECR associations are challenging due to GMF & energy losses
- Utilise Bayesian analysis framework to constrain possible sources of UHECRs incorporating such effects

Outlook for PhD:

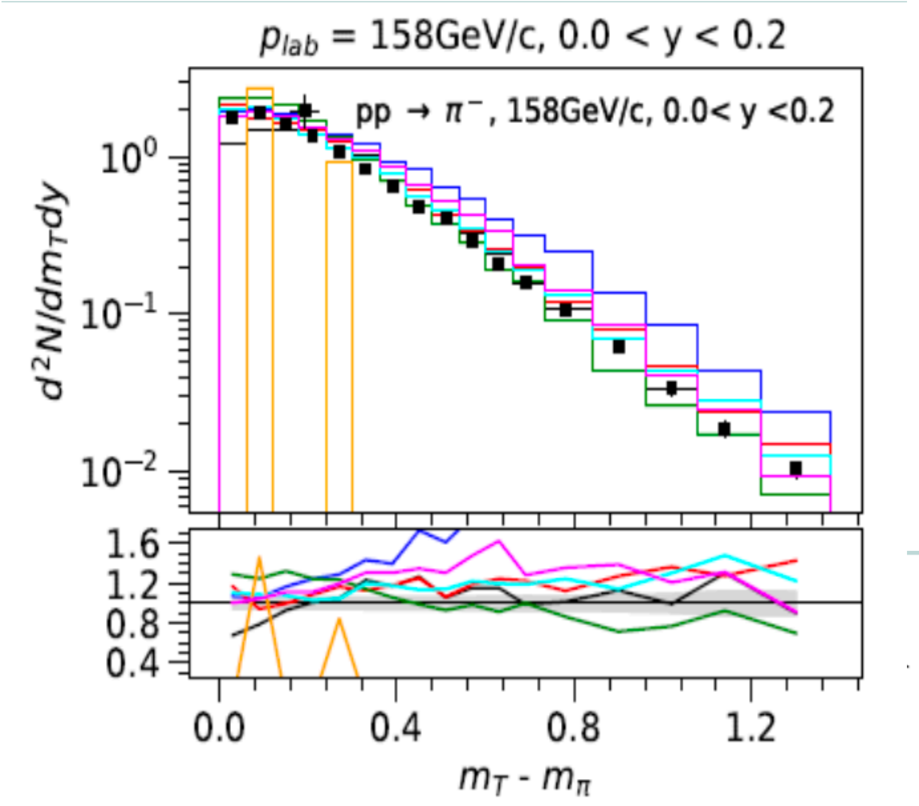
- Utilise knowledge of CR acceleration to improve source models of UHECRs → further constrain source-UHECR associations
- Incorporate multiple messengers (ex. γ-rays) into analysis framework

Thanks for listening!

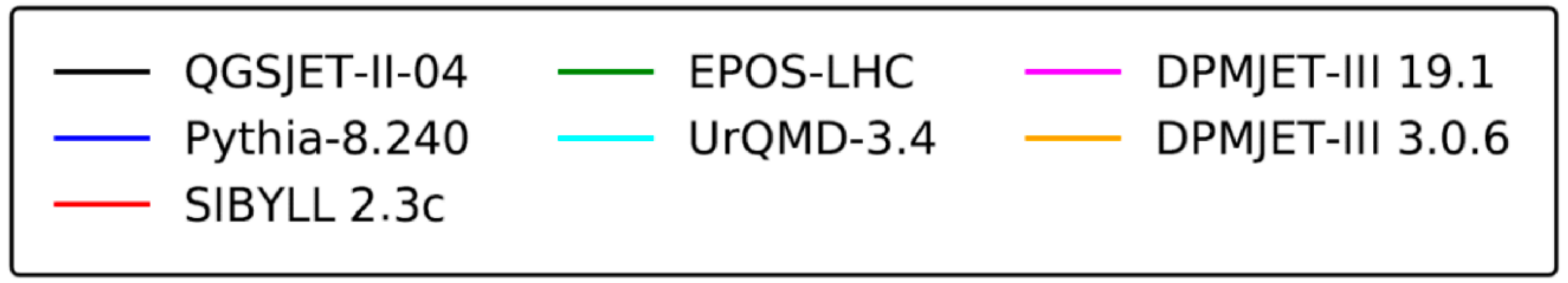
Backup

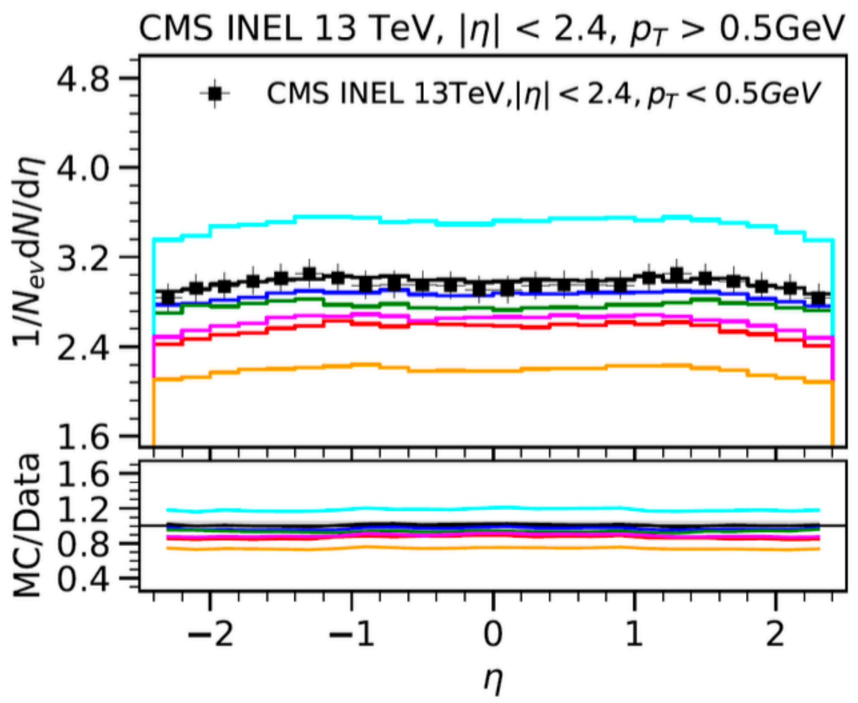
Analysing the Performance of Hadronic Interaction Models

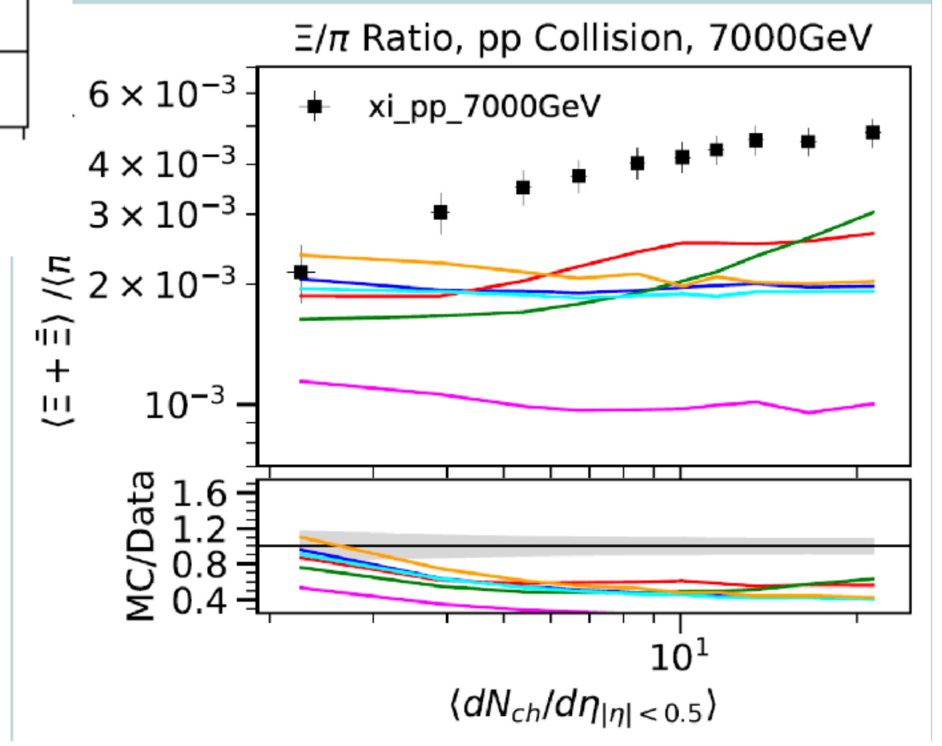
1. Assess the performance of current MC event generators by comparing to experimental data at various energies & projectile / target configurations



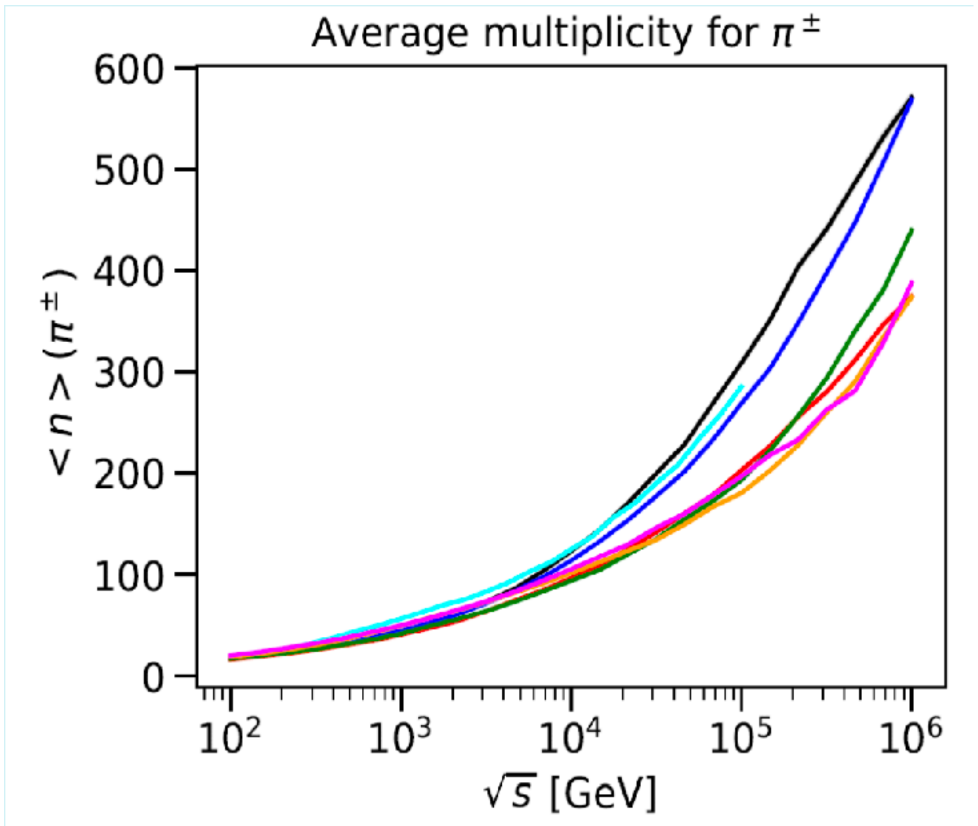
- Collider experiments (ALICE, CMS, ATLAS, PHOBOS, LHCb)
- Fixed Target experiments (NA25, NA49, NA61)

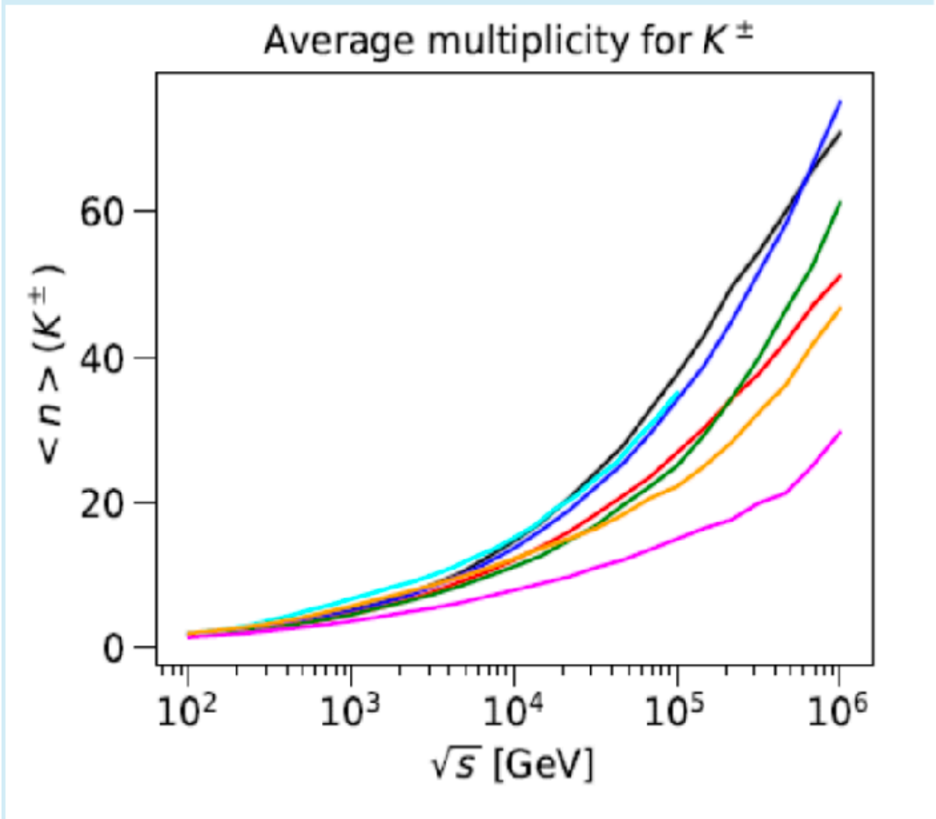




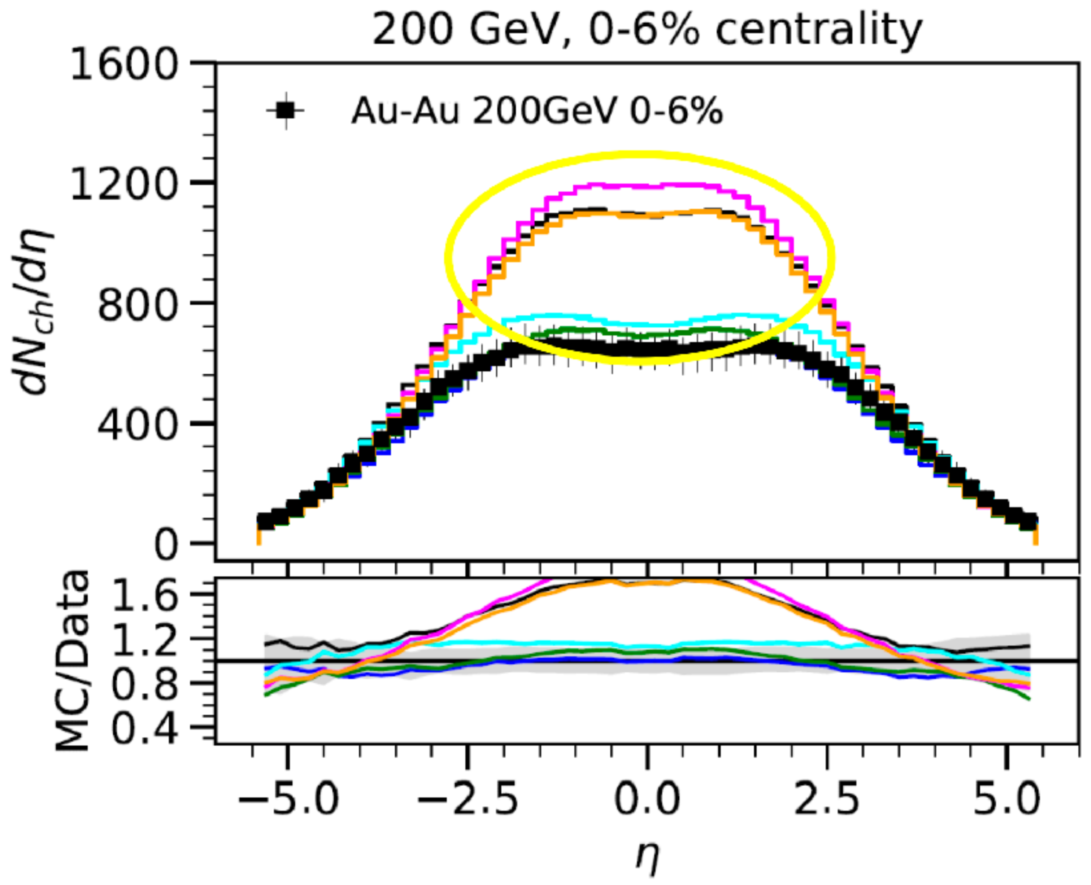


2. Apply event generators to physically motivated configurations (e.g. p + Air collisions)





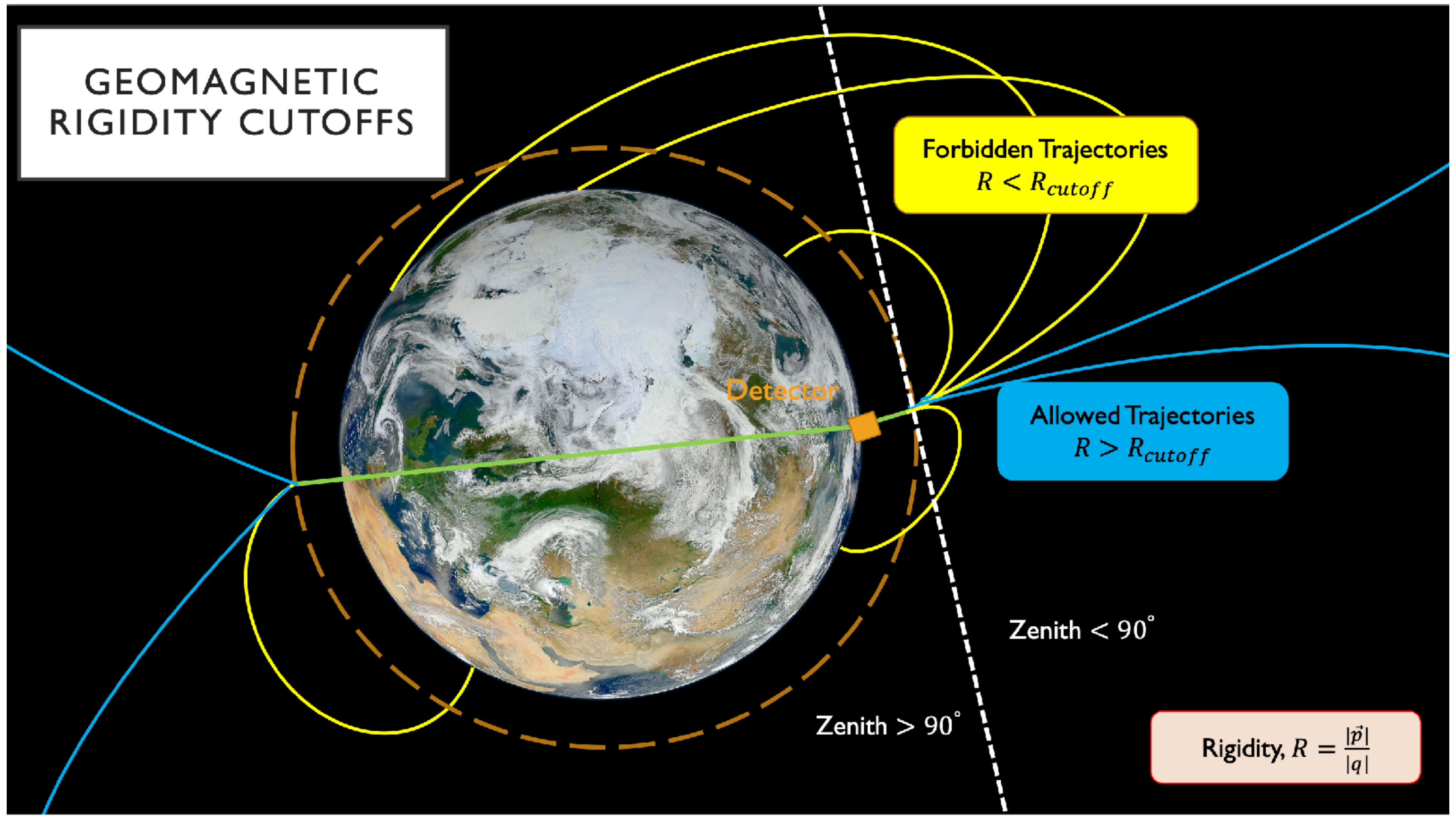
3. Tune parameters in event generators to fit the observed data & with other MC models

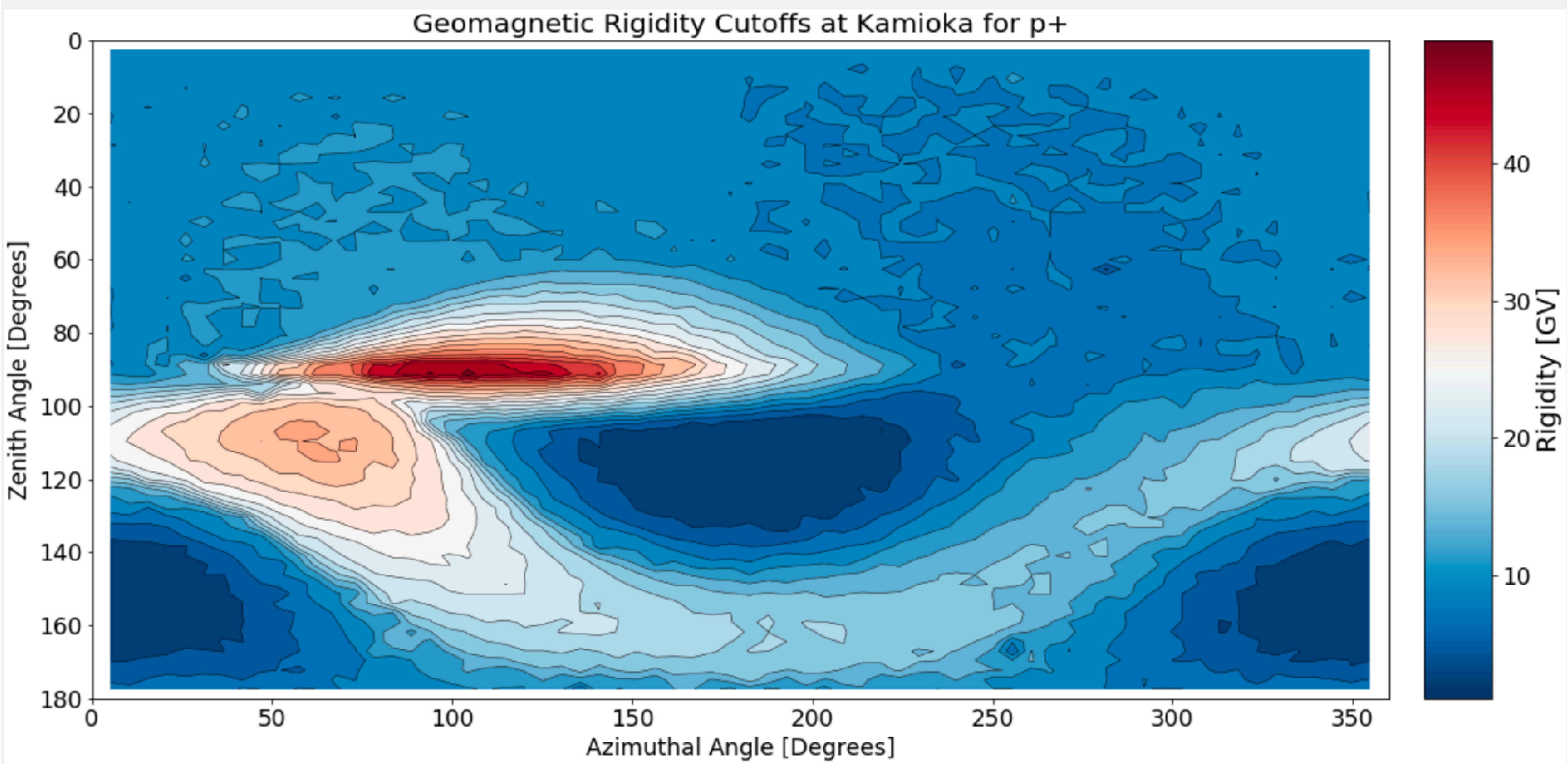


Simulating Geomagnetic Rigidity Cutoffs

Rigidity cutoff: Threshold rigidity to filter cosmic rays arriving outside the magnetosphere

- Crucial for atmospheric flux calculations & radiation shielding
- Direction-dependent -> requires full phase space calculation
- Backtrack cosmic rays within the geomagnetic field (IGRF model), accept / reject sampling based on threshold value
- Optimised utilising Python + C++ framework





Left: Geomagnetic rigidity cutoff at Kamioka, Japan

-> Consistent with other works (e.g. Gaisser & Honda, 2000)

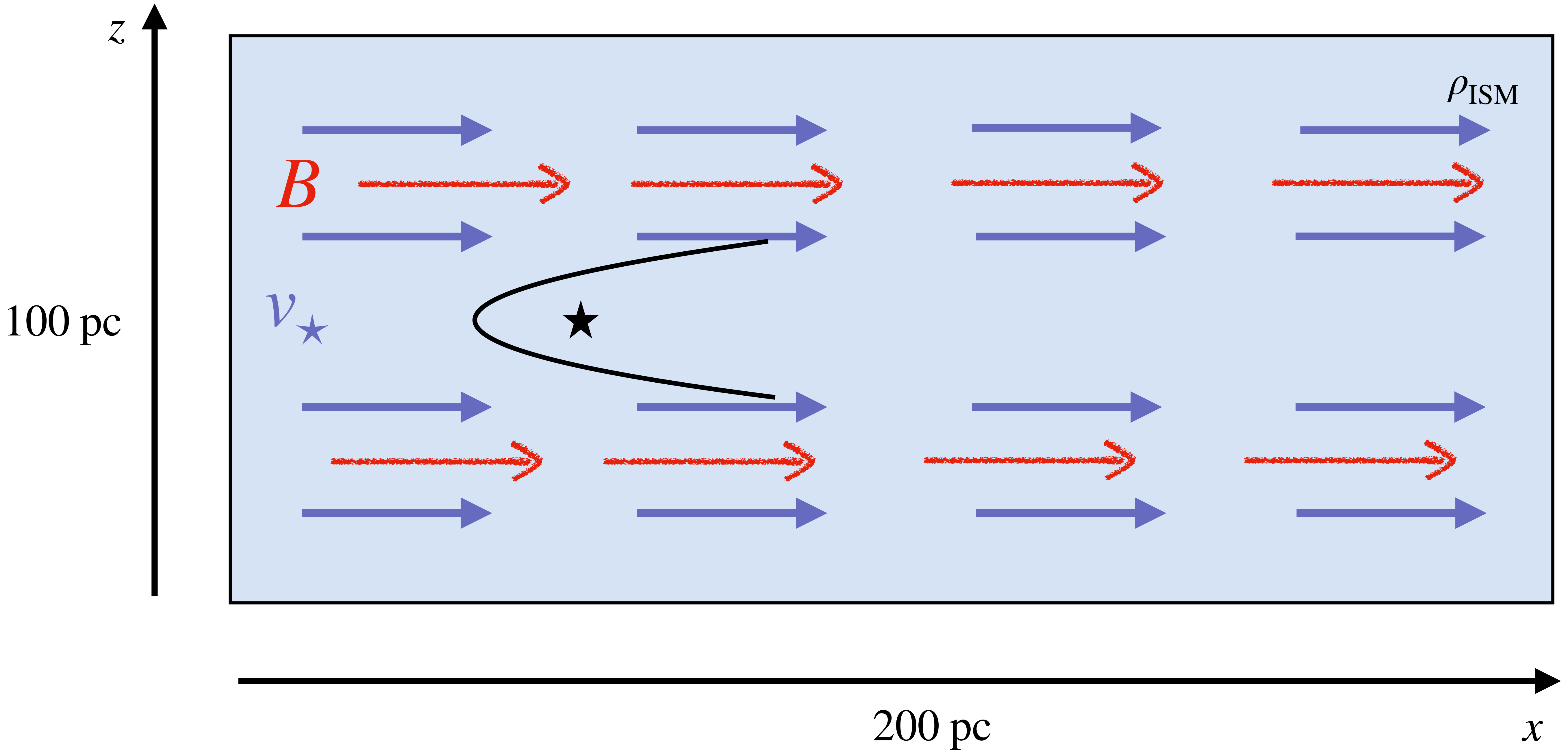
Publicly available on GitHub: https://github.com/kwat0308/gtracr

Investigating the origins of NRFs

Simulation Setup

Place single massive star ($M = 30\ M_\odot$) in elongated box with ambient ISM of velocity $v_\star$

- Box of size (200, 100, 100) pc with highest resolution of ~ 0.5 pc
- Inflow + Outflow BC in x, periodic BC in (y, z)
- Warm Ionised Medium, no chemical network:
  - T = 10^4 K, $\rho_{\rm ISM} = 2 \times 10^{-25}$ g cm^{-3}, $\mu = 0.61$, $\gamma = 5/3$
- Assume weak magnetic field $B = 10\ \mu$G
- Radiative cooling for optically thin plasma with $Z = Z_\odot$ (Plewa 1995, Koyama & Inutsuka 2000)
- Consider both $\vec{B} \perp v_\star$, $\vec{B} \parallel v_\star$ cases

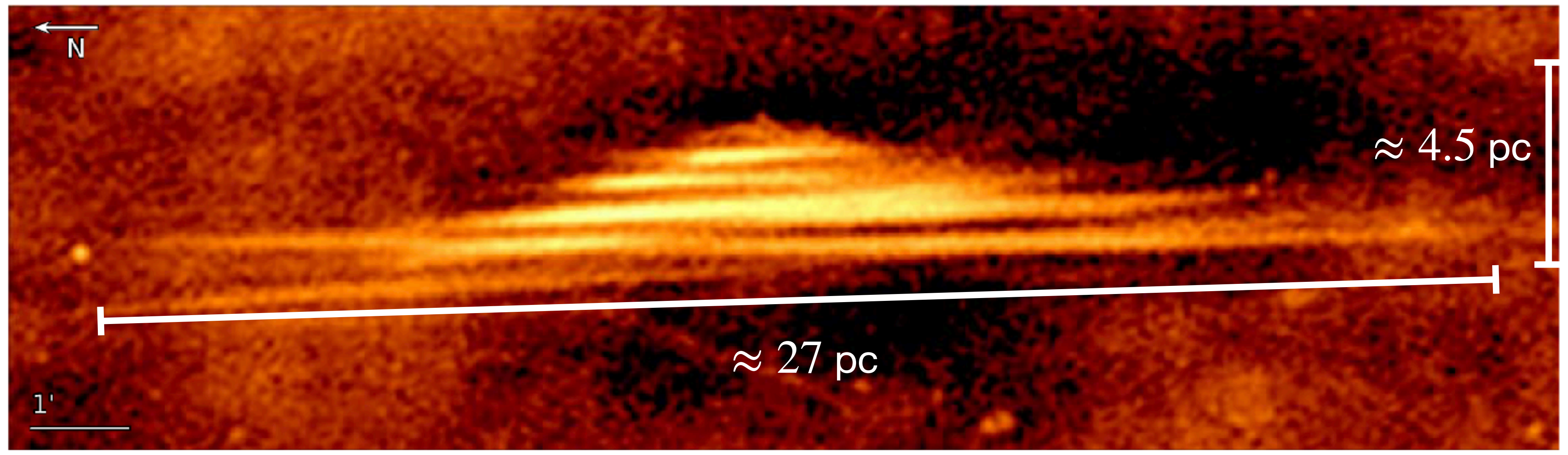


Investigating the origins of NRFs

Analytical Solution

Assume 1-D diffusion-only model, perpendicular to star velocity

$$\epsilon_{\mathrm{CR}}(t,z) = \frac{\epsilon_0'}{\sqrt{2\pi\sigma_t^2}} \exp\left(-\frac{z^2}{2\sigma_t^2}\right) \qquad \sigma_t^2 = \sigma^2 + 2\kappa t$$

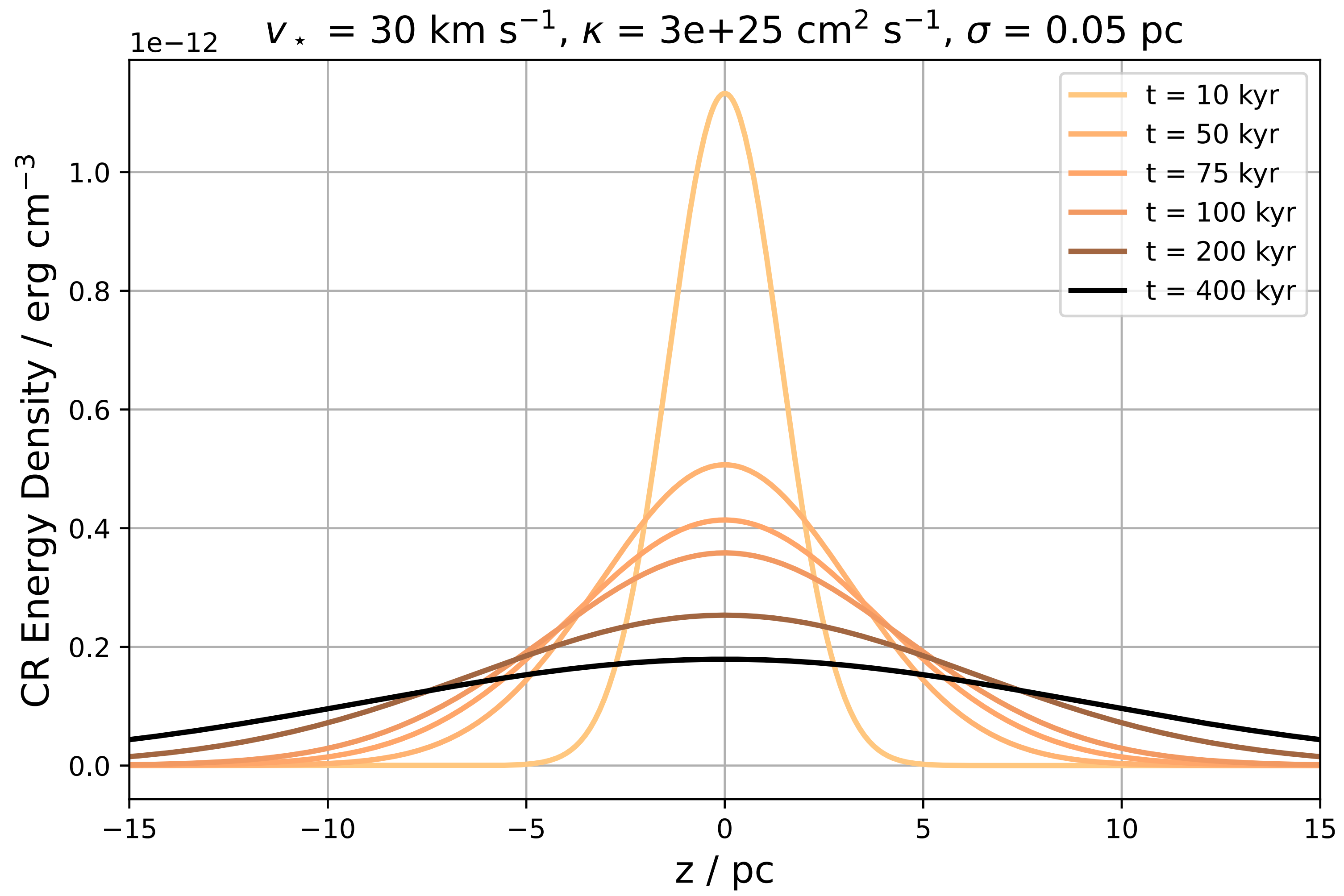


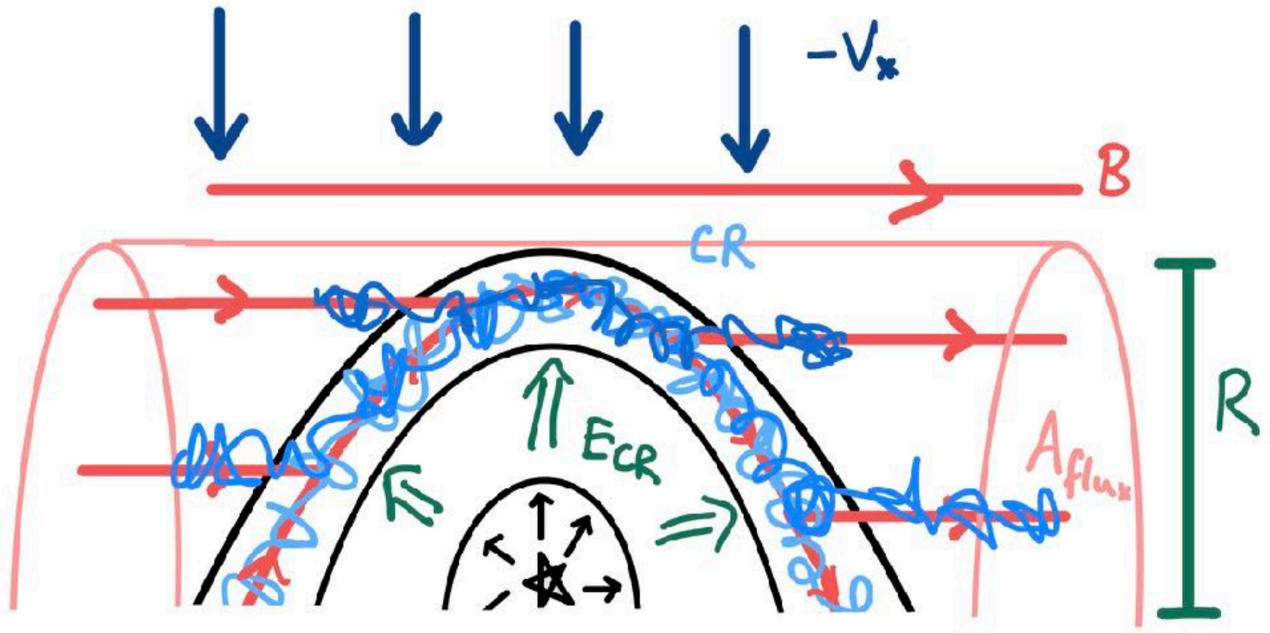
Thomas, Pfrommer & Enßlin, APJ 890:L18 (2020)

Initial condition evaluated from injection at bow shock

Stand-off Radius: $$R = \left(\frac{\dot{M} v_w}{4\pi(\rho_{\mathrm{ISM}} v_\star^2 + P_{\mathrm{ISM}} + B^2/8\pi)}\right)^{1/2}$$

CR Energy p.u. area: $$\epsilon_0' = \frac{E_{\mathrm{CR}}}{A_{\mathrm{flux}}} = \frac{E_{\mathrm{CR}}}{\pi R^2} = \frac{f_{\mathrm{esc}} \xi L_w}{\pi R v_\star}$$

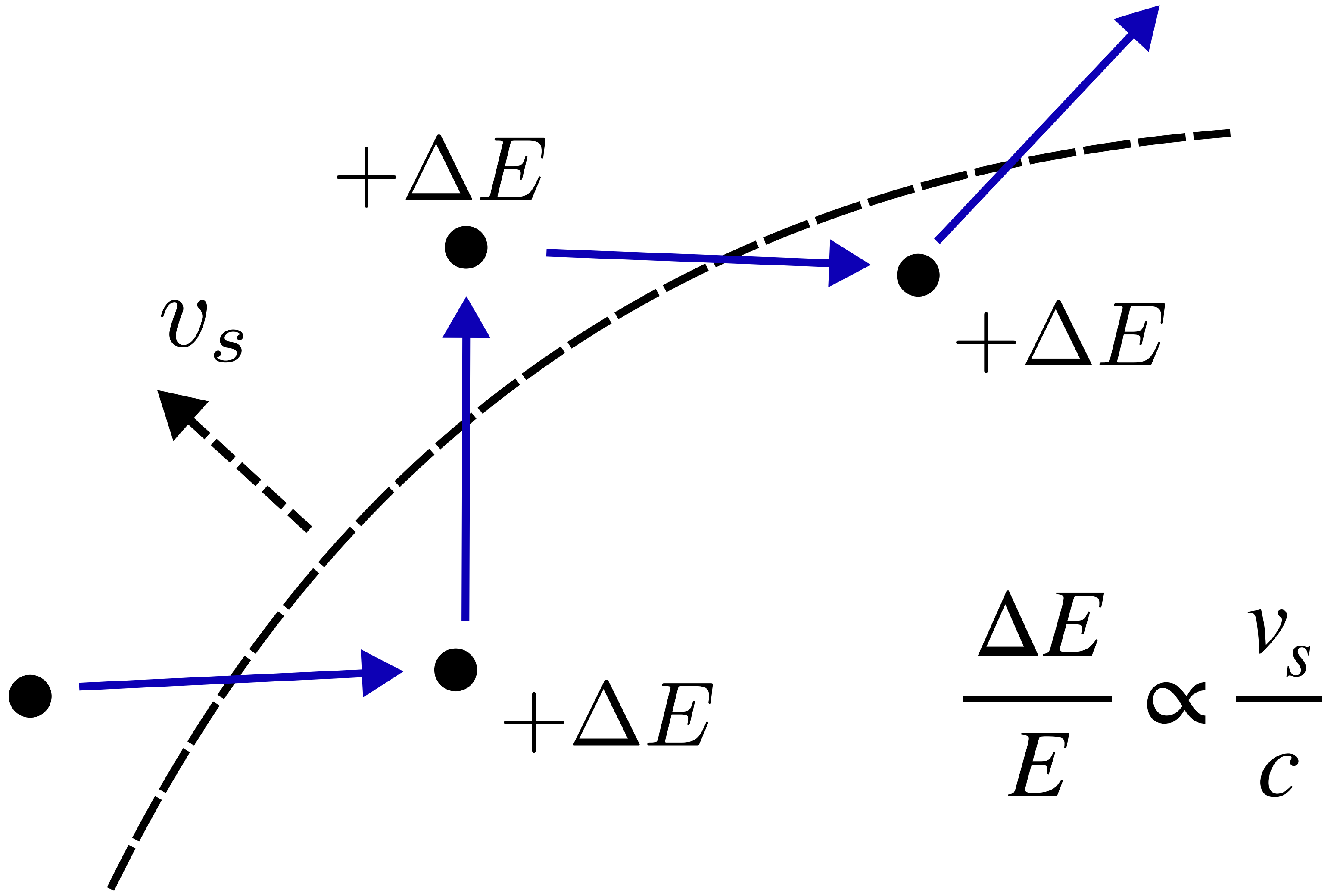




Sources of Galactic CRs

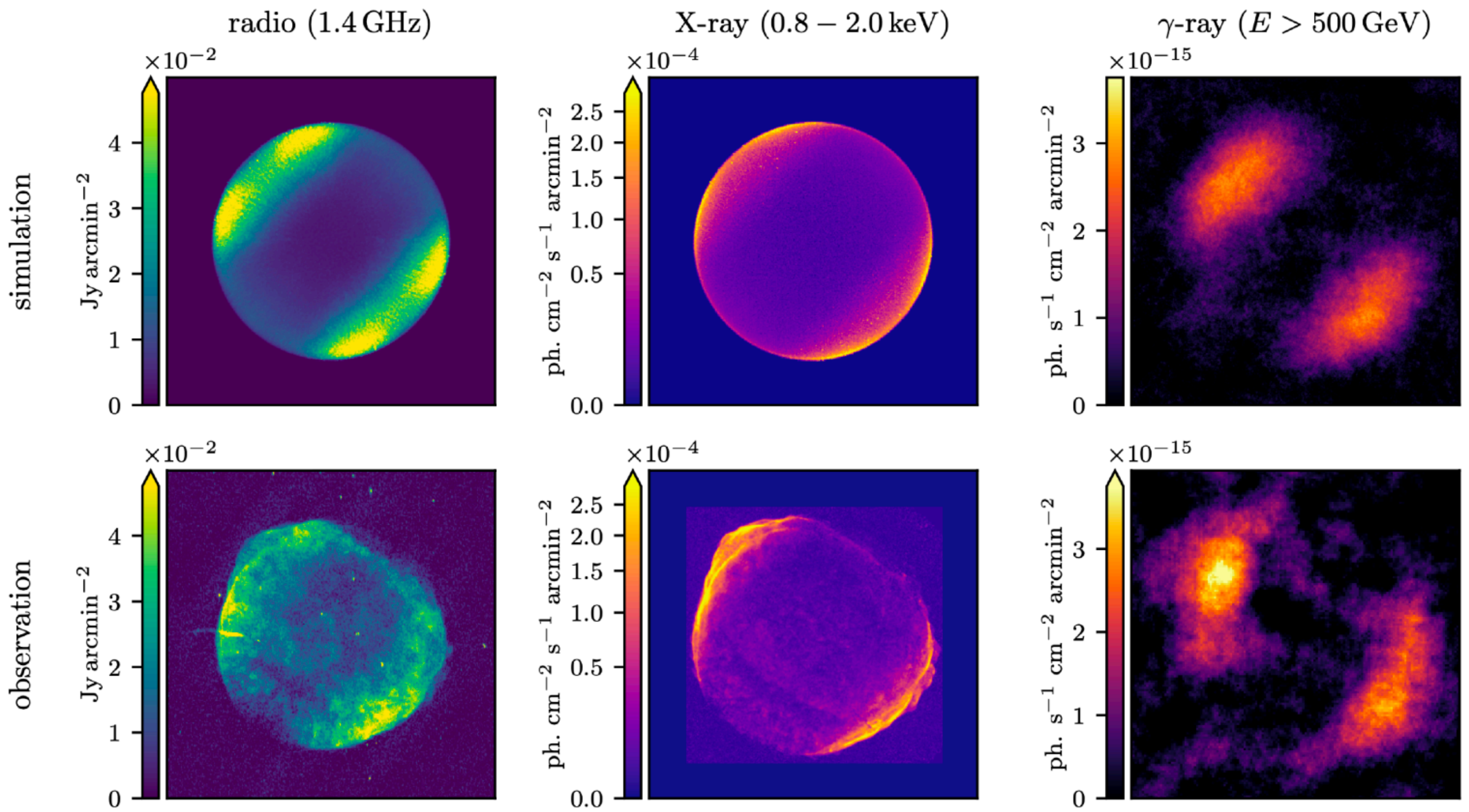
Through diffusive shock acceleration on astrophysical shocks

- Supernovae remnants
- Stellar winds / pulsar wind nebulae
- Termination shocks from massive runaway stars



Example of diffusive shock acceleration

Winner et al. 2020, MNRAS 499, 2



Multi-wavelength emission of SN1006

Optical (red) & X-ray (blue) emission of Crab Nebula

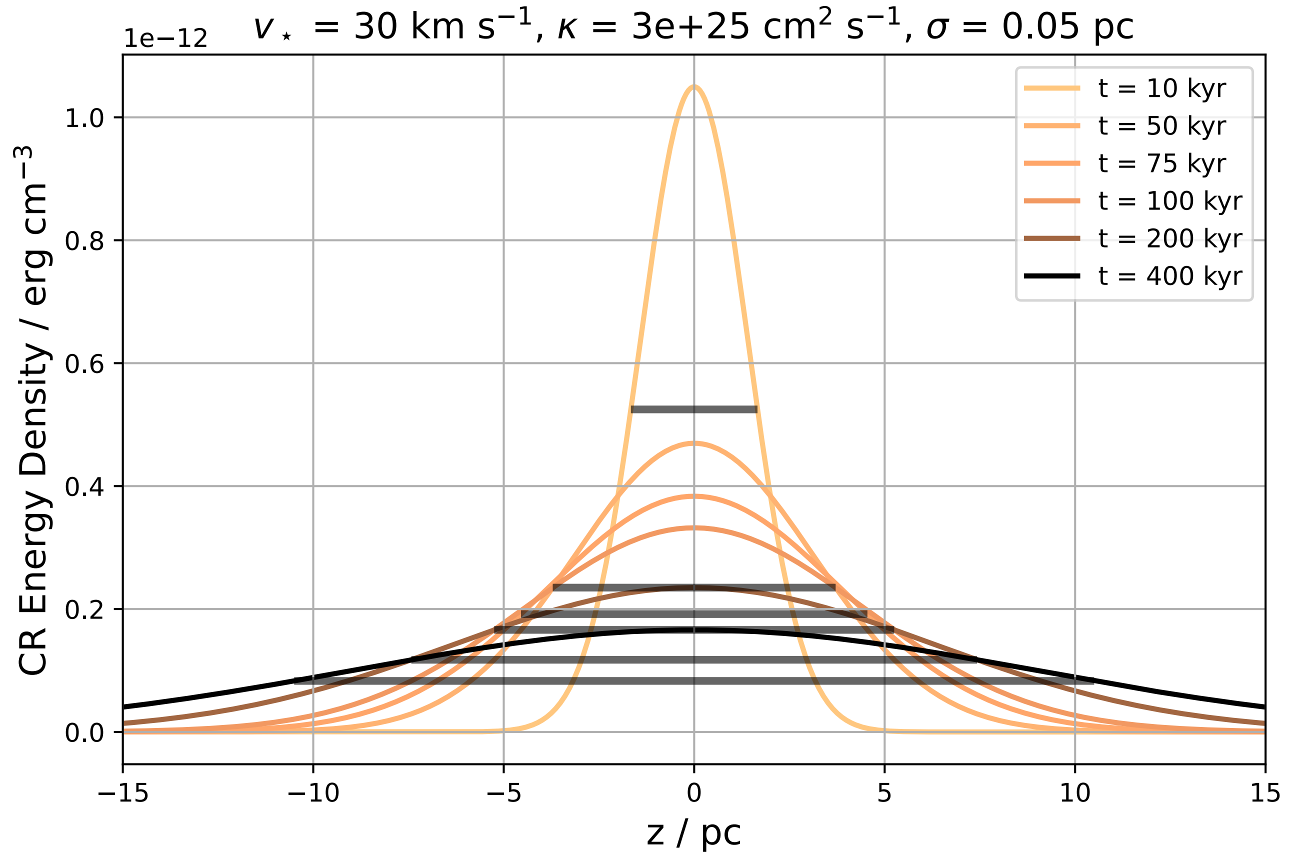
NASA/CXC/ASU/J.Hester et al.

Evidence through:

- Synchrotron emission (radio, X-ray)
- Inverse Compton scattering (X-ray, γ-ray)

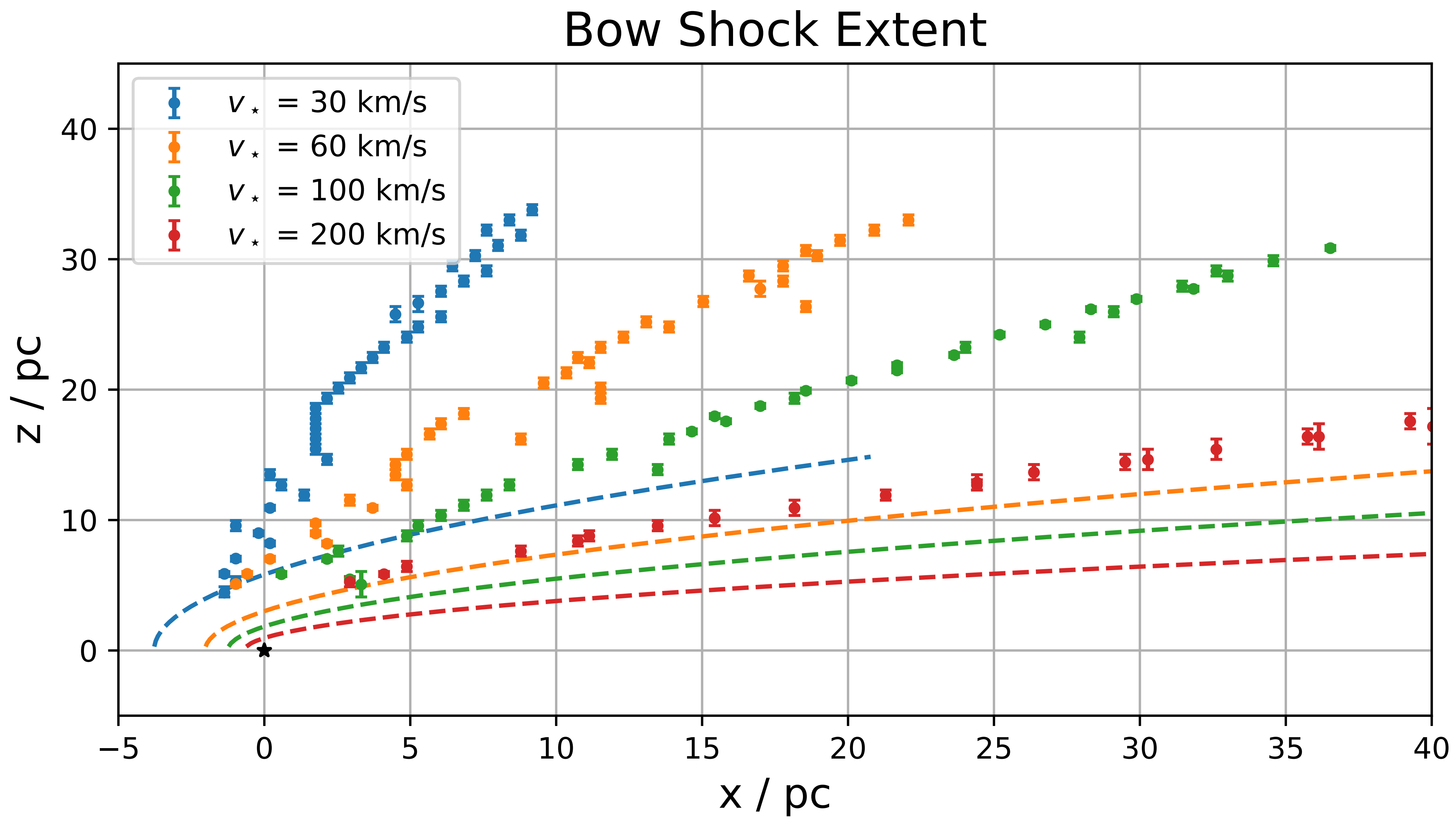
Investigating the origins of NRFs

Comparison with Analytical Results



Numerical results from same simulation setup **without** radiative cooling

Numerical extent from maximum width of bow shock at each time



Analytical bow shock extent from FWHM:

$$z_{\text{bow}} = \frac{1}{2}\text{FWHM} = \sqrt{2\ln 2}\,\sigma_t \qquad x_{\text{bow}} = v_\star t$$

Large deviations with analytical results (~ 15 pc)

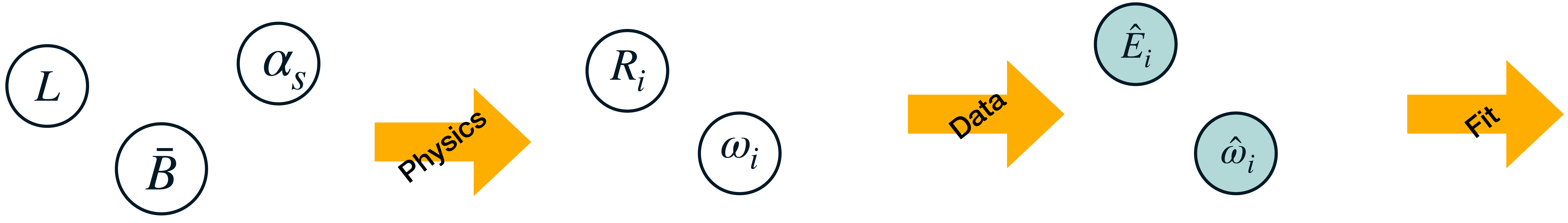
- No radiative cooling here -> will reduce extent of shock
- Only diffusion included, but CRs undergo advection & streaming
- Purely 1-D model, but CR transport is in 3D

Bayesian Hierarchical Modelling

Highest-level parameters (hyperparameters)

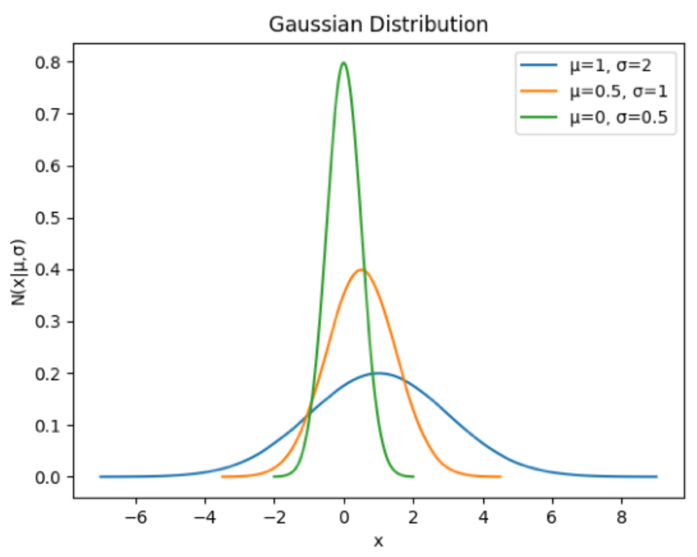
Parameters

Observed Data

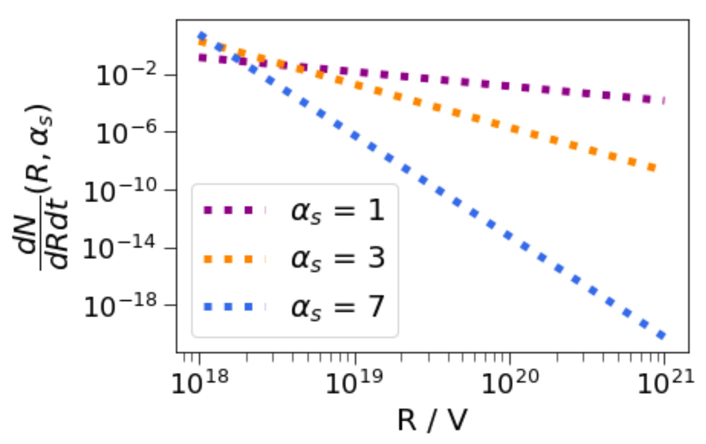


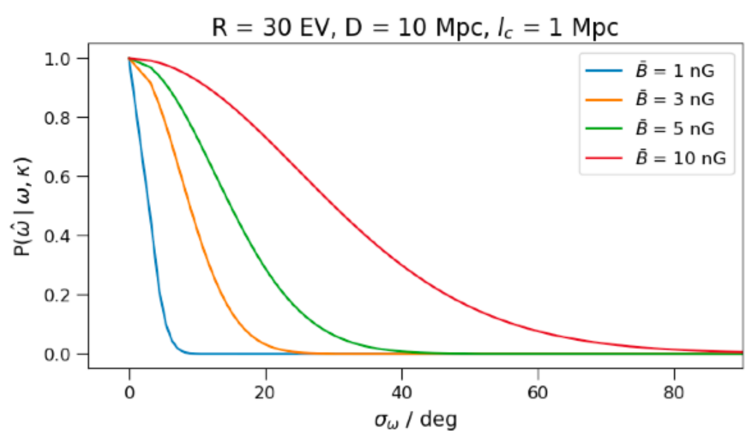
Construction of **Marginalised likelihood (evidence)** through integration

Sampled via **hyperpriors**

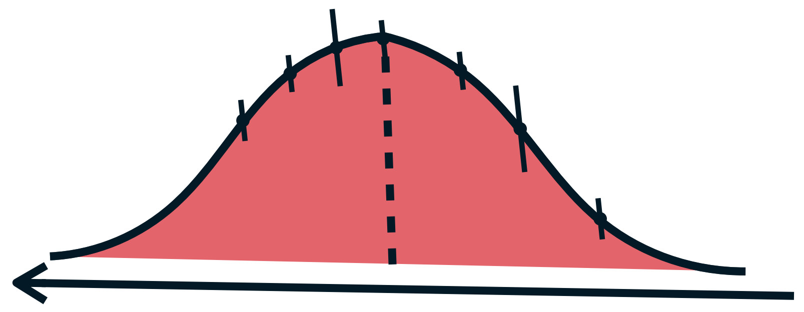


Sampled via **prior distribution**, with hyperparameters as arguments





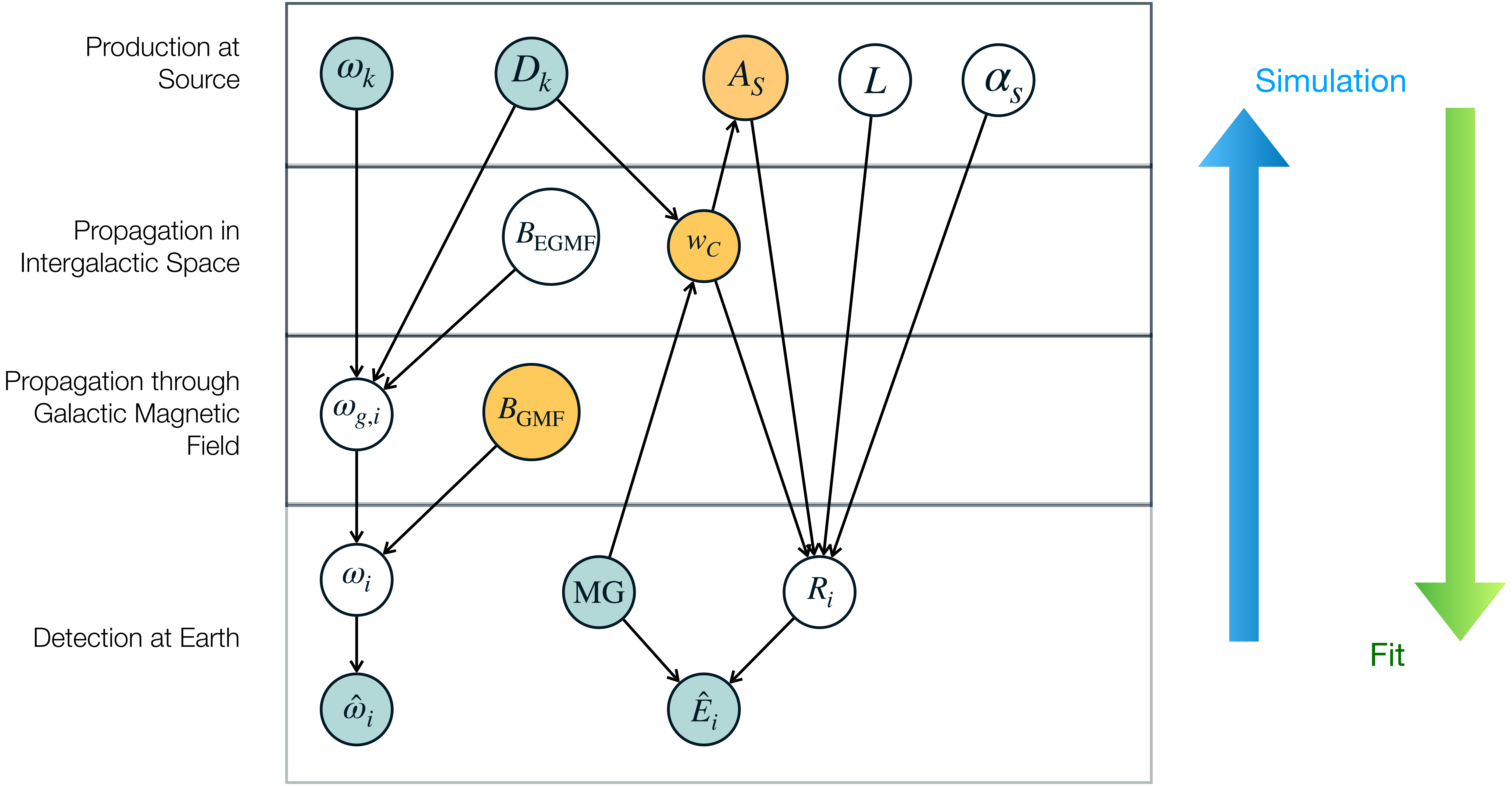
Sampled via **likelihood (sampling distribution)**



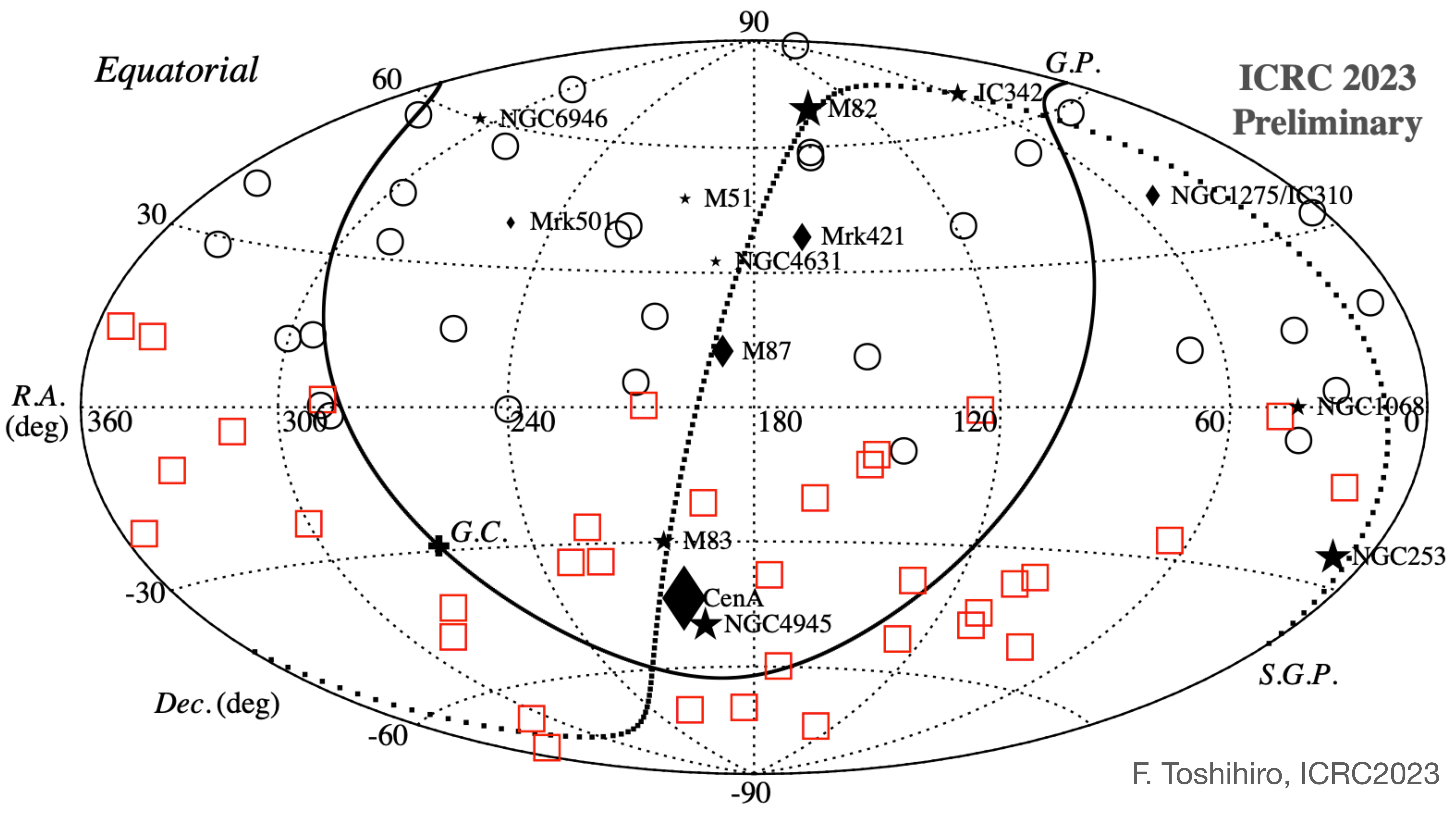
Posterior Distribution through Bayes Theorem

$$\mathrm{P}(L, \alpha_s, \bar{B} \quad \hat{E}_i, \hat{\omega}_i) = \frac{P(\hat{E}_i, \hat{\omega}_i \quad R_i, \omega_i, L, \alpha_s, \bar{B}) \; P(R_i, \omega_i \quad L, \alpha_s, \bar{B}) \; P(L, \alpha_s, \bar{B})}{\mathrm{P}(\hat{E}_i, \hat{\omega}_i \quad L, \alpha_s, \bar{B})}$$

Hierarchical Framework



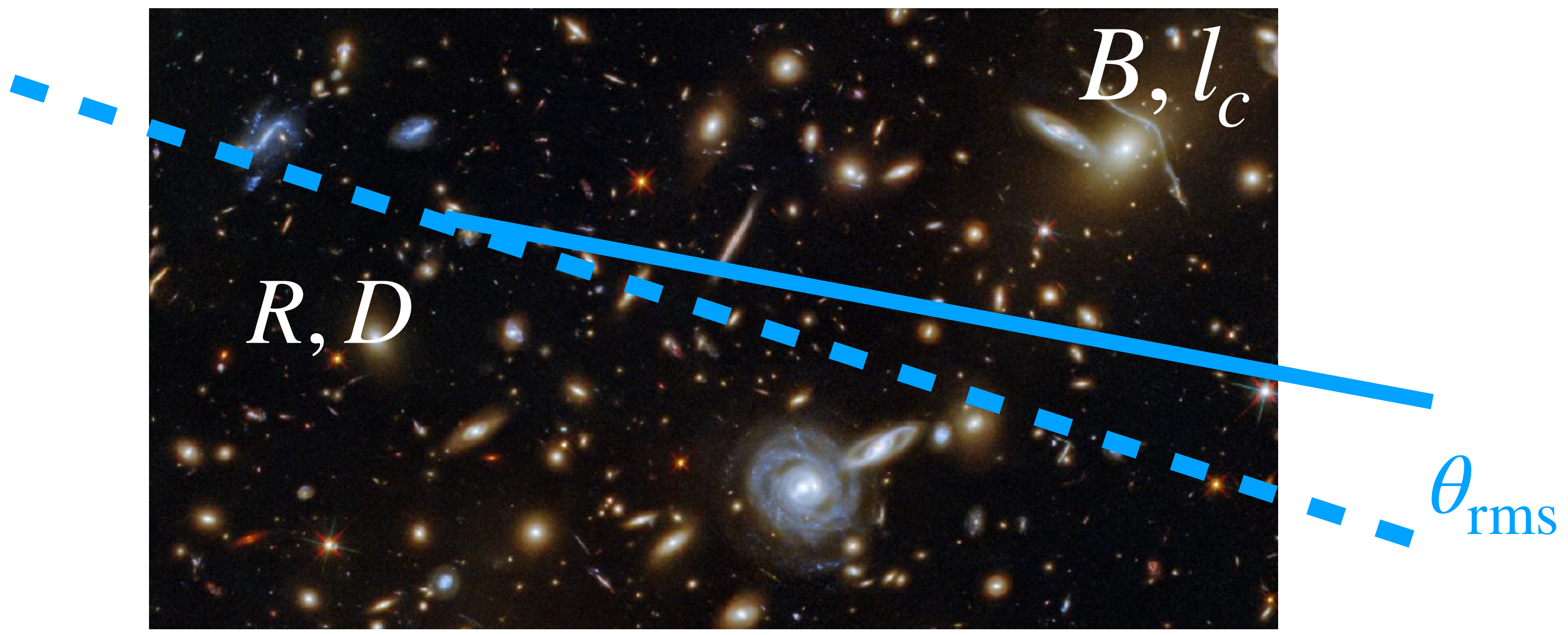
Difficulties of Source Association



F. Toshihiro, ICRC2023

Extragalactic magnetic fields

EGMF deflections:



$$\theta_{\rm rms} \approx 2.3^\circ \left(\frac{R}{50\ \rm EV}\right)^{-1} \left(\frac{\bar{B}}{1\ \rm nG}\right) \left(\frac{D}{10\ \rm Mpc}\right)^{1/2} \left(\frac{l_c}{1\ \rm Mpc}\right)^{1/2}$$

F. Vazza et al. 2014 **MNRAS**

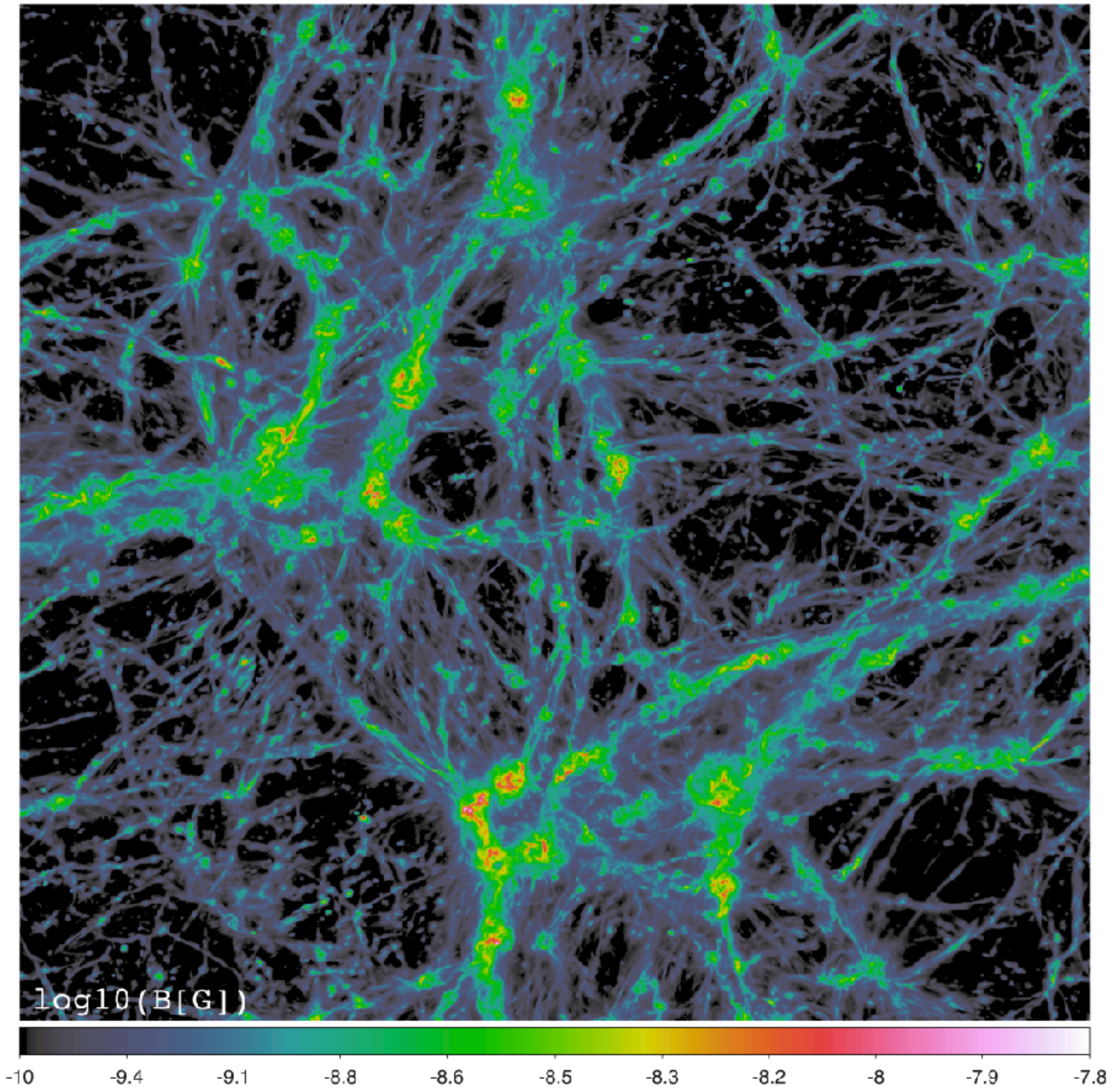
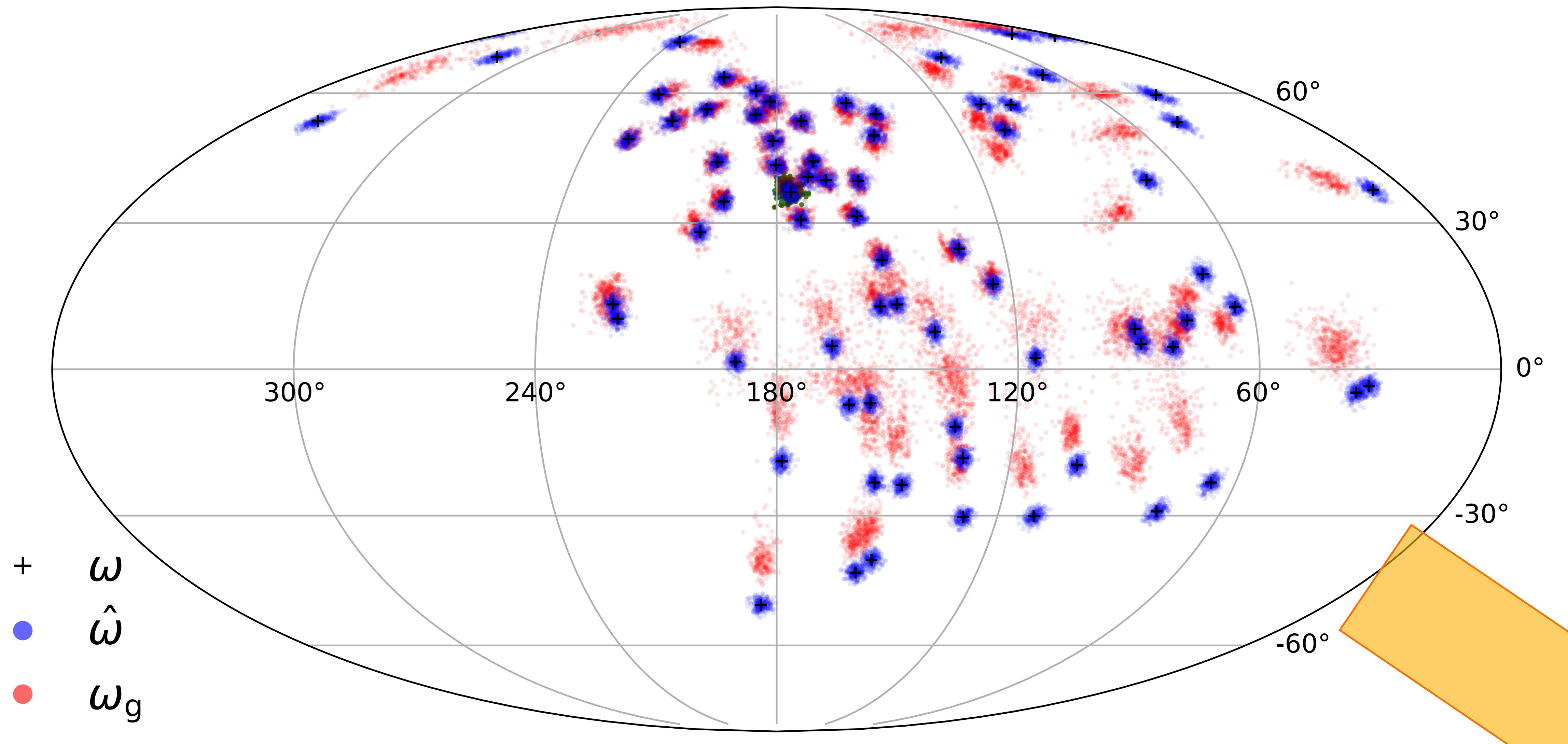


Figure 13. Projected (density weighted) magnetic field intensity for our 2400^3 simulation of a $(50\ \rm Mpc)^3$ volume at $z = 0$.

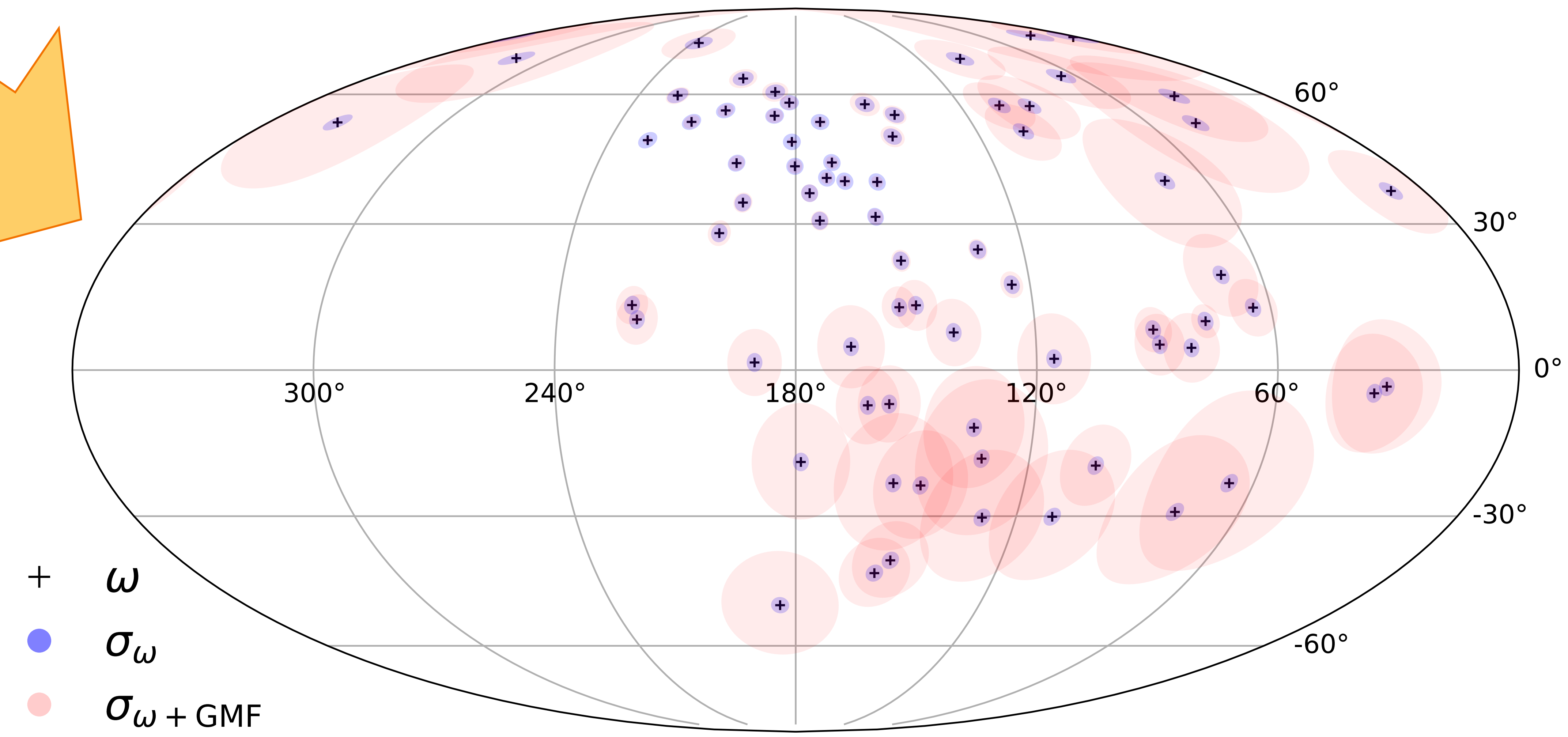
Impact of Galactic Magnetic Field (GMF)



UHECRs: 72 public events from TA with $E_{th} > 57$ EeV
(R. U. Abbasi *et al* 2014 *ApJL* **790** L21)

Blue events are sampled from experimental angular uncertainty σ_ω

Red events are deflected via GMF with CRPropa3



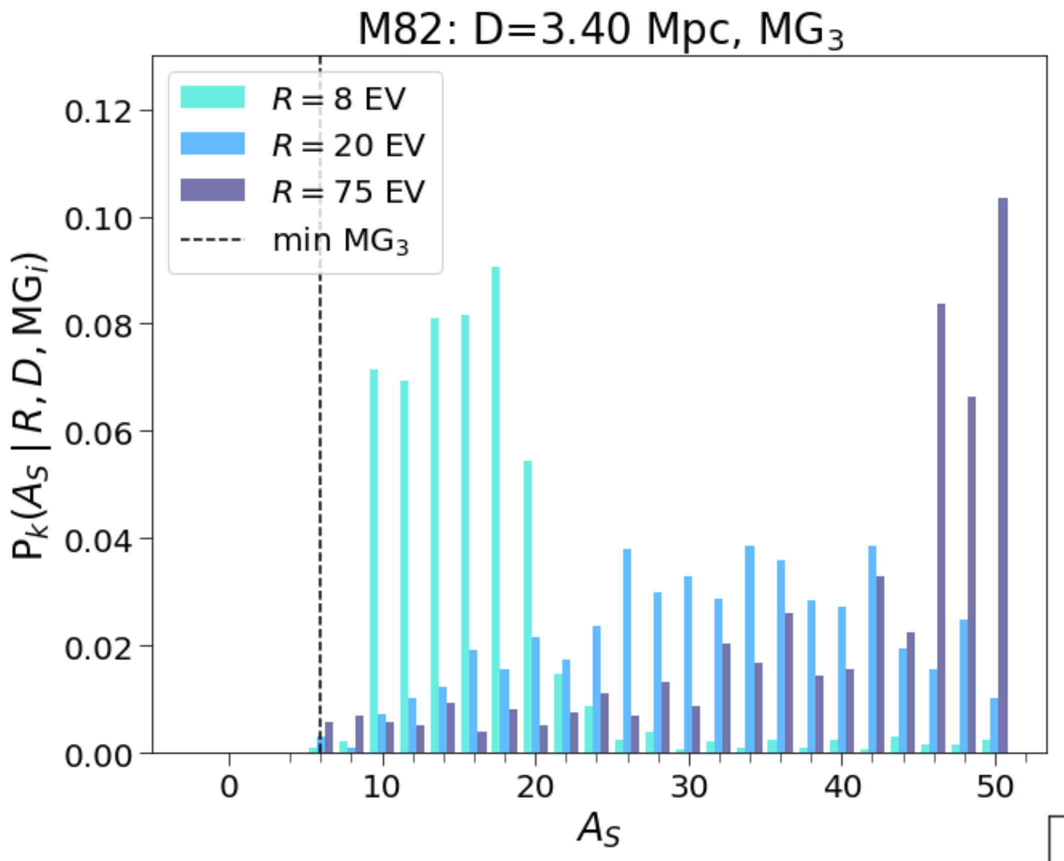
Effective Approach: Construct **new** search radii $\sigma_{\omega+\mathrm{GMF}}$ $\Rightarrow$ κ_{GMF} from backtracked samples

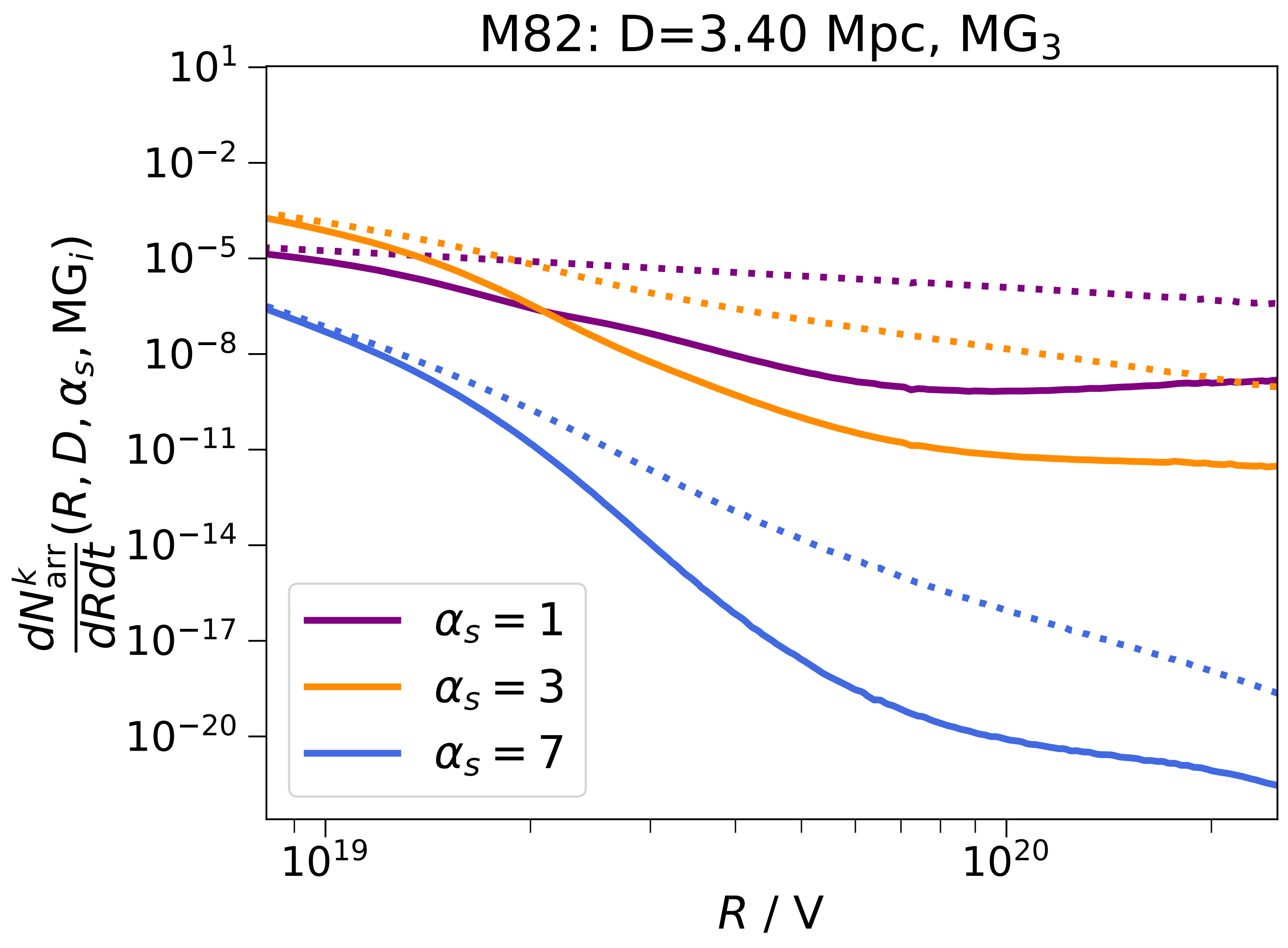
Energy / Mass Losses

$1 \leq A < 2$ MG1	$2 \leq A < 8$ MG2
MG3 $8 < A \leq 20$	MG4 $20 \leq A \leq 54$

Categorisation of **mass groups**
(Dembinski et al. PoS(ICRC2017))

- Energy / mass loss treated under **constant rigidity approximation**
- Source spectrum weighted using **inferred source compositions** for a given mass group
- Rigidities ($R = E/Z$) sampled from arrival rigidity spectrum, calculated by propagating source spectrum with R-dependent **transfer matrices** $w_C(R, A_S, A_E)$





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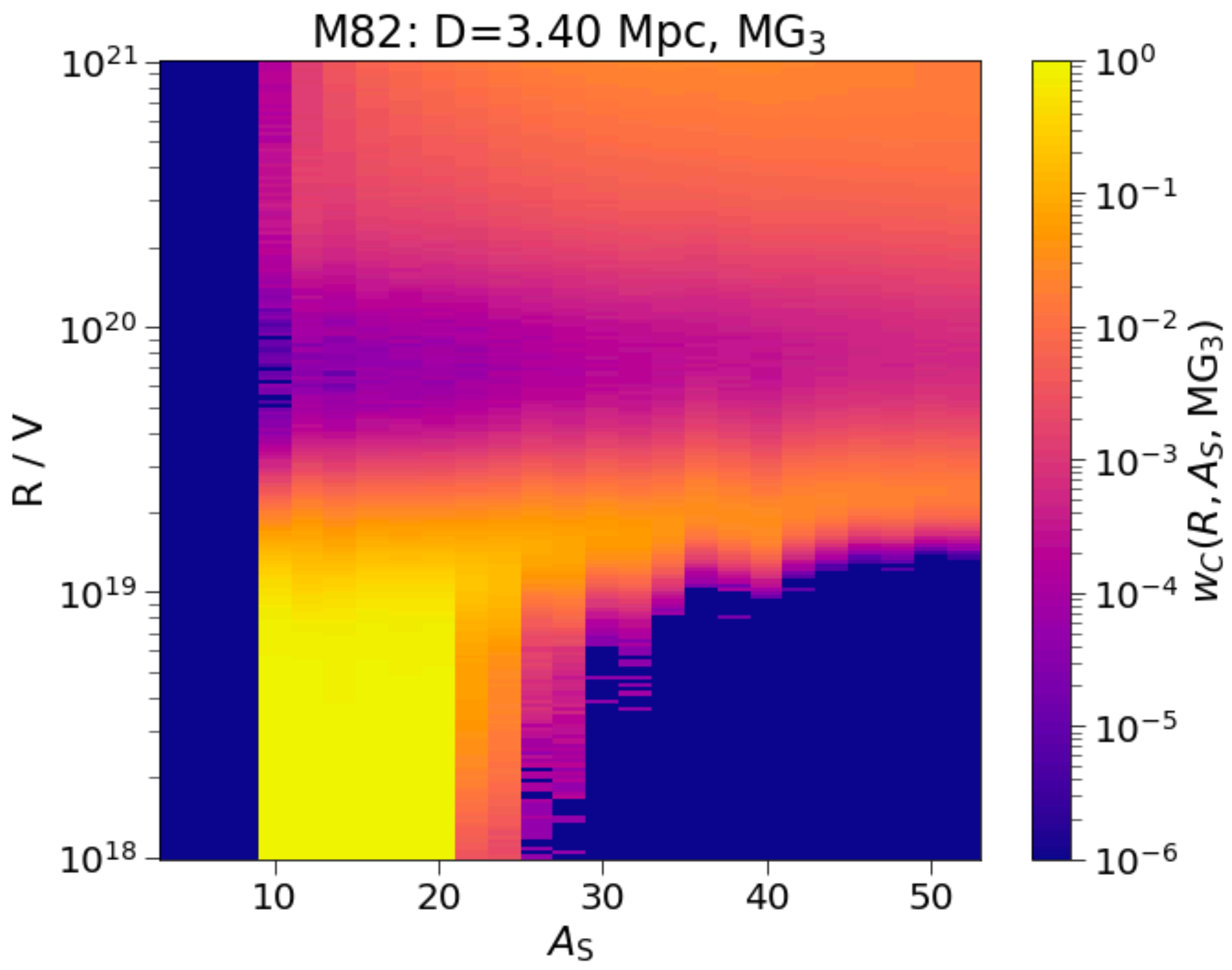

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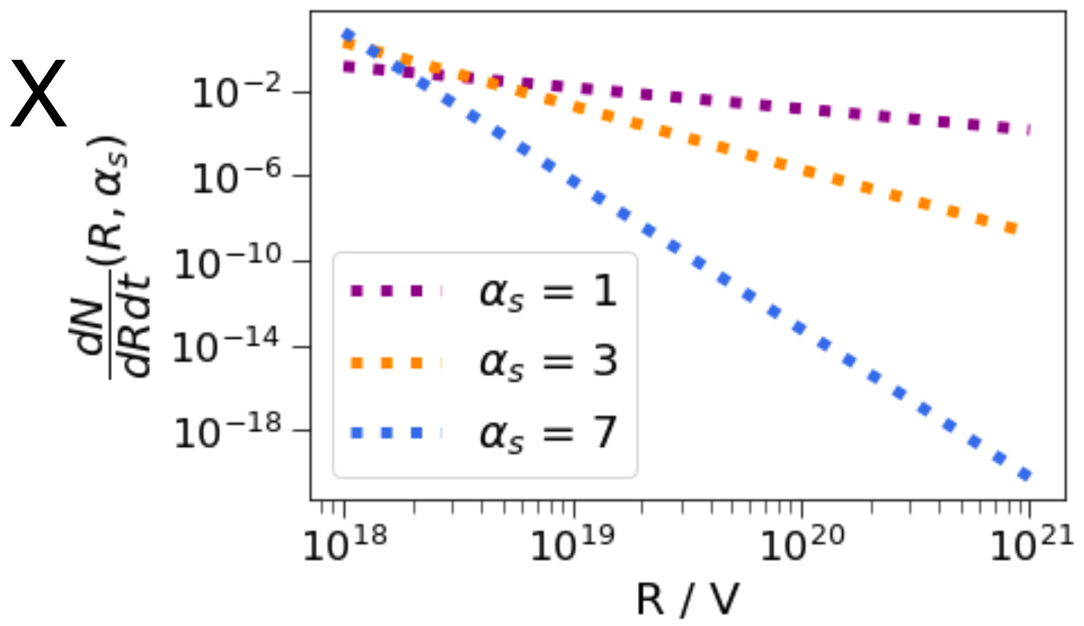
X

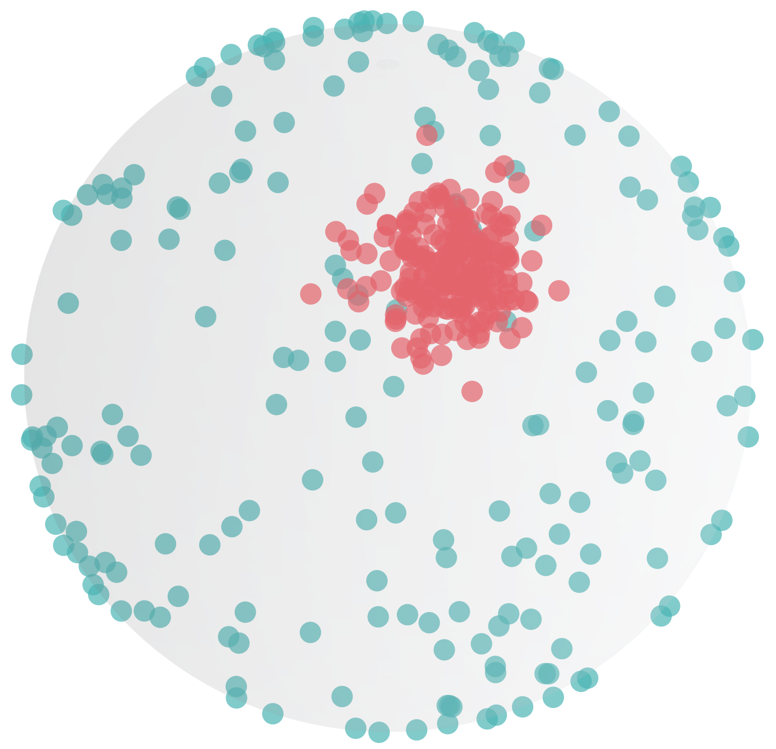


$$\frac{d\,N^k_{\rm arr}}{dRdt} = w_C(R, A_S, A_E) \star P_k(A_S \quad R, {\rm MG}_i)\, R^{-\alpha_s}$$

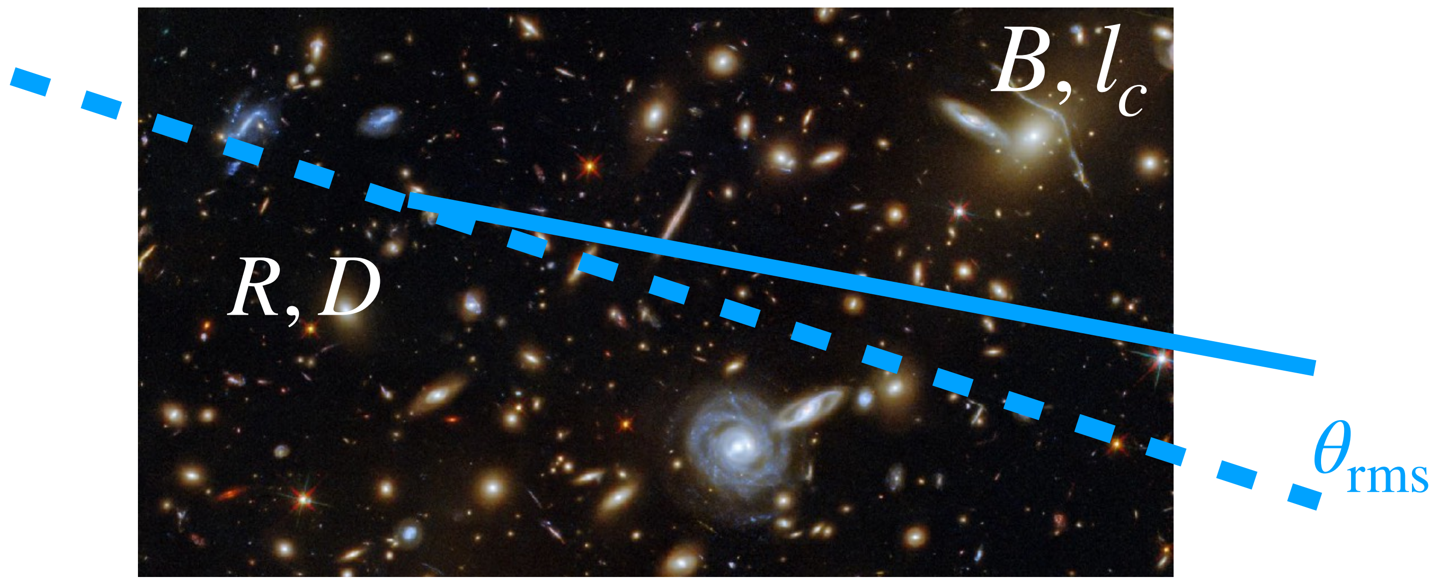
Analysis Framework

- **Bayesian Hierarchical Model** based on Capel & Mortlock 2019
- Determine source parameters from **spatial + energy associations**
- Include GMF effects from **backtracking** using CRPropa (Batista et al. 2022)
- Propagation losses included by sampling from **arrival rigidity spectrum**, calculated by propagating source spectrum $\propto R^{-\alpha_s}$ with transfer matrices $w_C(R, A_S, D, \mathrm{MG}_i)$ using CRPropa

$$f = \frac{F_s}{F_0 + F_s}$$

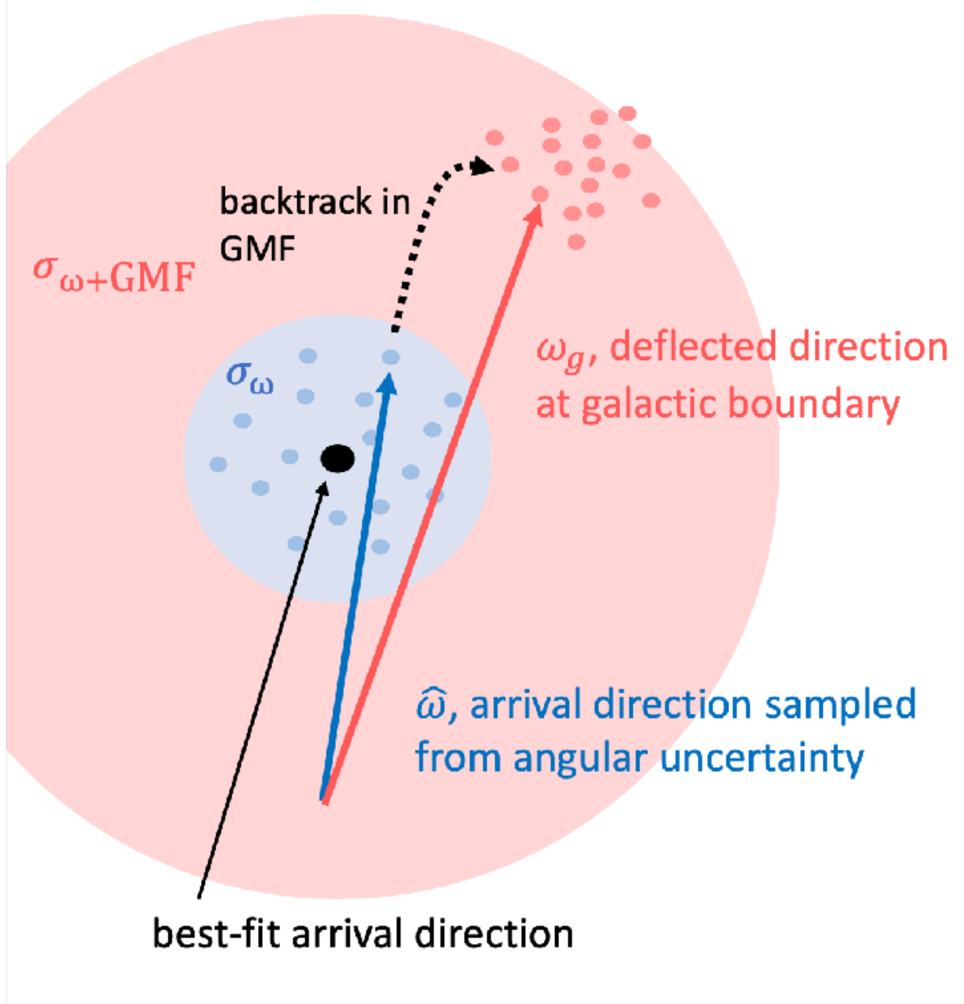


EGMF deflections:



$$\theta_{\mathrm{rms}} \approx 2.3^\circ \left(\frac{R}{50\ \mathrm{EV}}\right)^{-1} \left(\frac{\bar{B}}{1\ \mathrm{nG}}\right) \left(\frac{D}{10\ \mathrm{Mpc}}\right)^{1/2} \left(\frac{l_c}{1\ \mathrm{Mpc}}\right)^{1/2}$$

GMF deflections:



Propagation Losses: