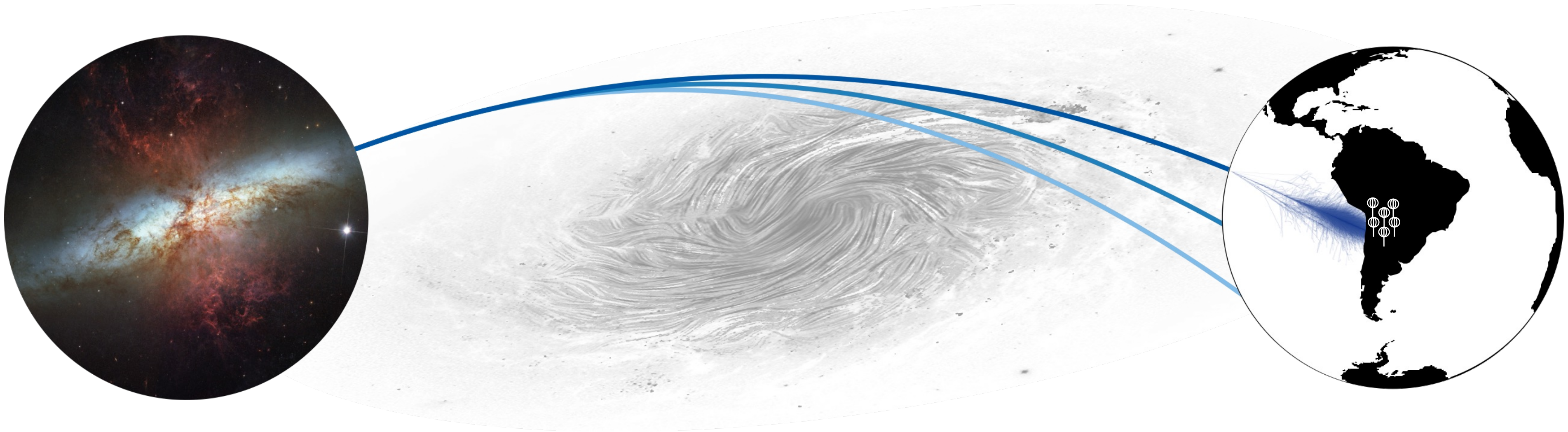
SPONSORED BY THE
Federal Ministry of Education and Research

Physics Institute III A
RWTH AACHEN UNIVERSITY

Applications of Information Field Theory in Astroparticle Physics

MODE Workshop 2024



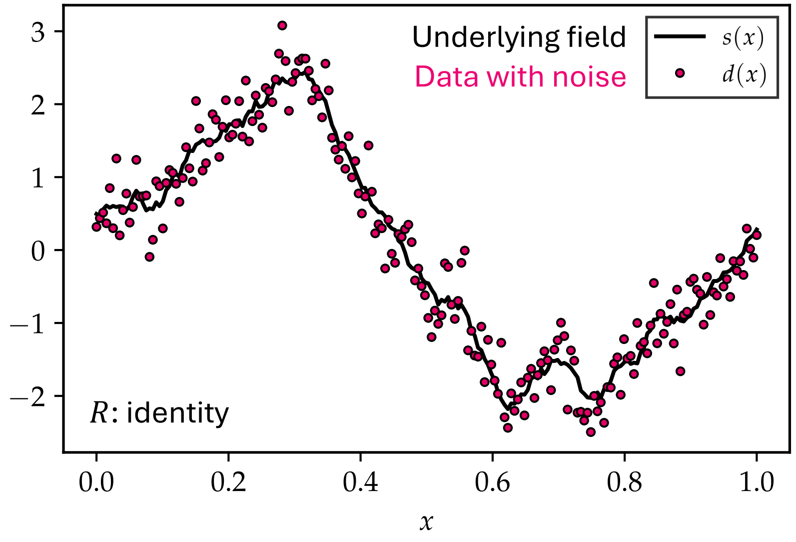
Frederik Krieger, Martin Erdmann, Alex Reuzki, Josina Schulte, Michael Smolka, Maximilian Straub

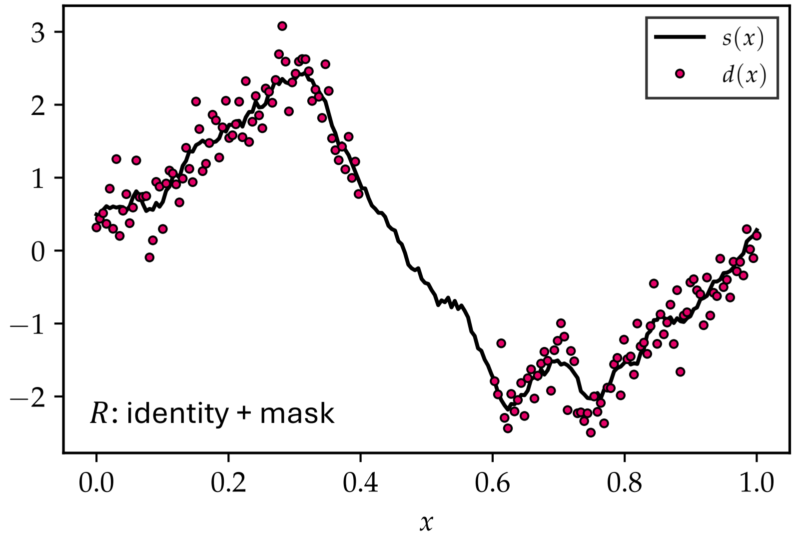
Information Field Theory (IFT)

- Information theory for fields
- Based on Bayesian statistics
- Use physical assumptions via priors
- Learn **correlation structure** of fields
- Invert measurement: $d = R[s] + n$
  - d: Data
  - R: Response
  - s: Field
  - n: noise

Goal: Infer **posterior distribution** of continuous field with **sparse and noisy data** using physical assumptions via priors

Example for measurement





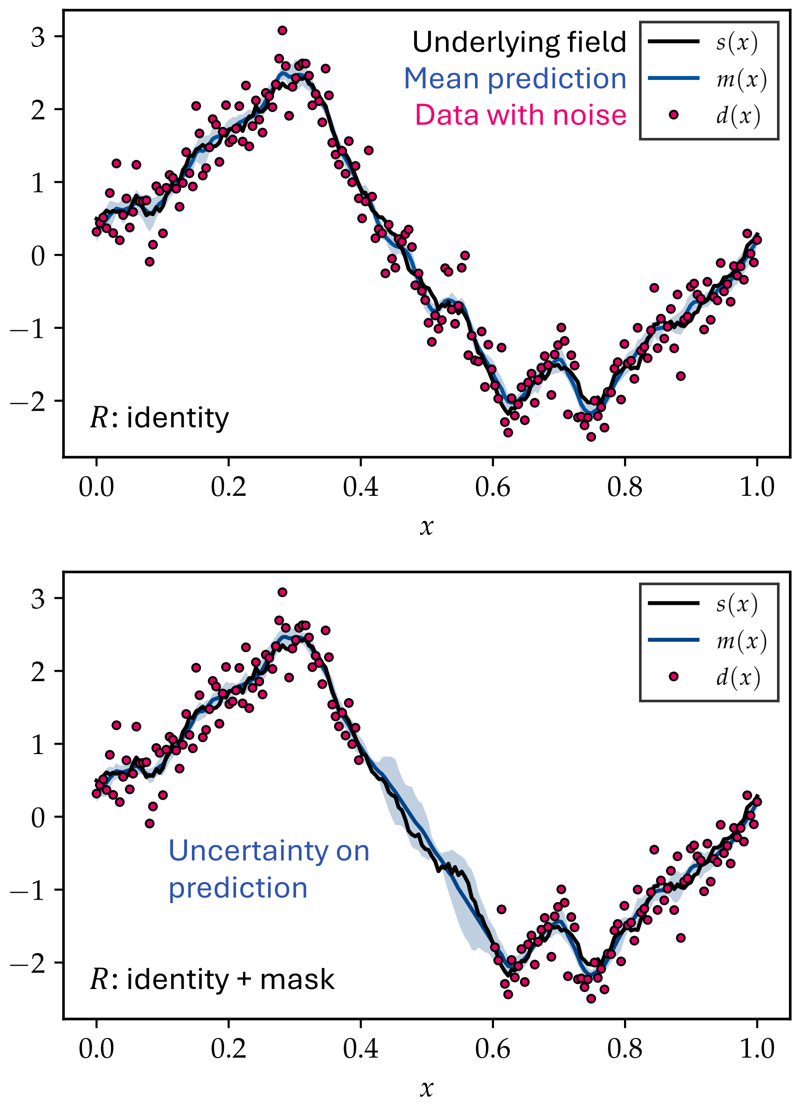
Information Field Theory (IFT)

- Information theory for fields
- Based on Bayesian statistics
- Use physical assumptions via priors
- Learn **correlation structure** of fields
- Invert measurement: $d = R[s] + n$
  - d: Data
  - R: Response
  - s: Field
  - n: noise

Goal: Infer **posterior distribution** of continuous field with **sparse and noisy data** using physical assumptions via priors

$\Rightarrow$ NIFTY

Example for posterior inference



Information Field Theory: Posterior inference

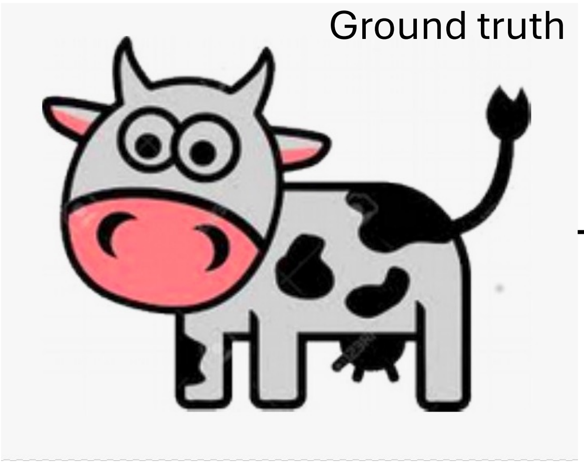
NIFTy

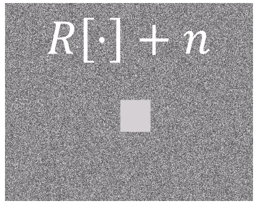
- **N**umerical **I**nformation **F**ield **T**heory
- Software package written in python
- Multiple inference algorithms, e.g.
  - Metric Gaussian Variational Inference (MGVI)
  - Geometric Variational Inference (geoVI)

JAX

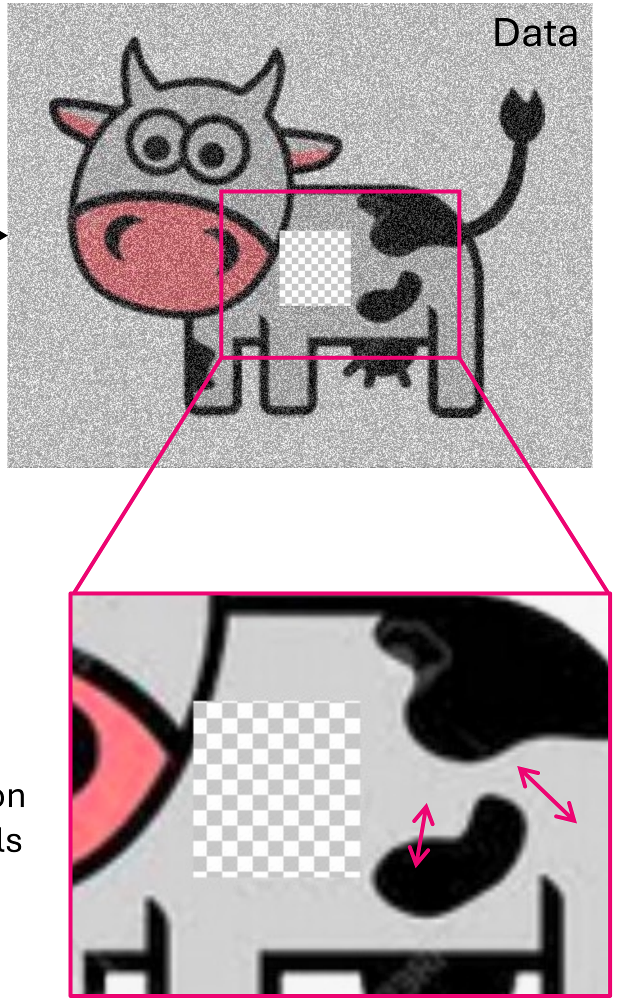
- Open-source machine learning framework from Google
  - NumPy-like syntax
  - Just-In-Time compilation (JIT)
  - Execution on GPUs and TPUs
  - Automatic differentiation
- Forward model "**field → data**" can be written as computational graph with NumPy-like syntax and **differentiable**

Information Field Theory: Correlation structures



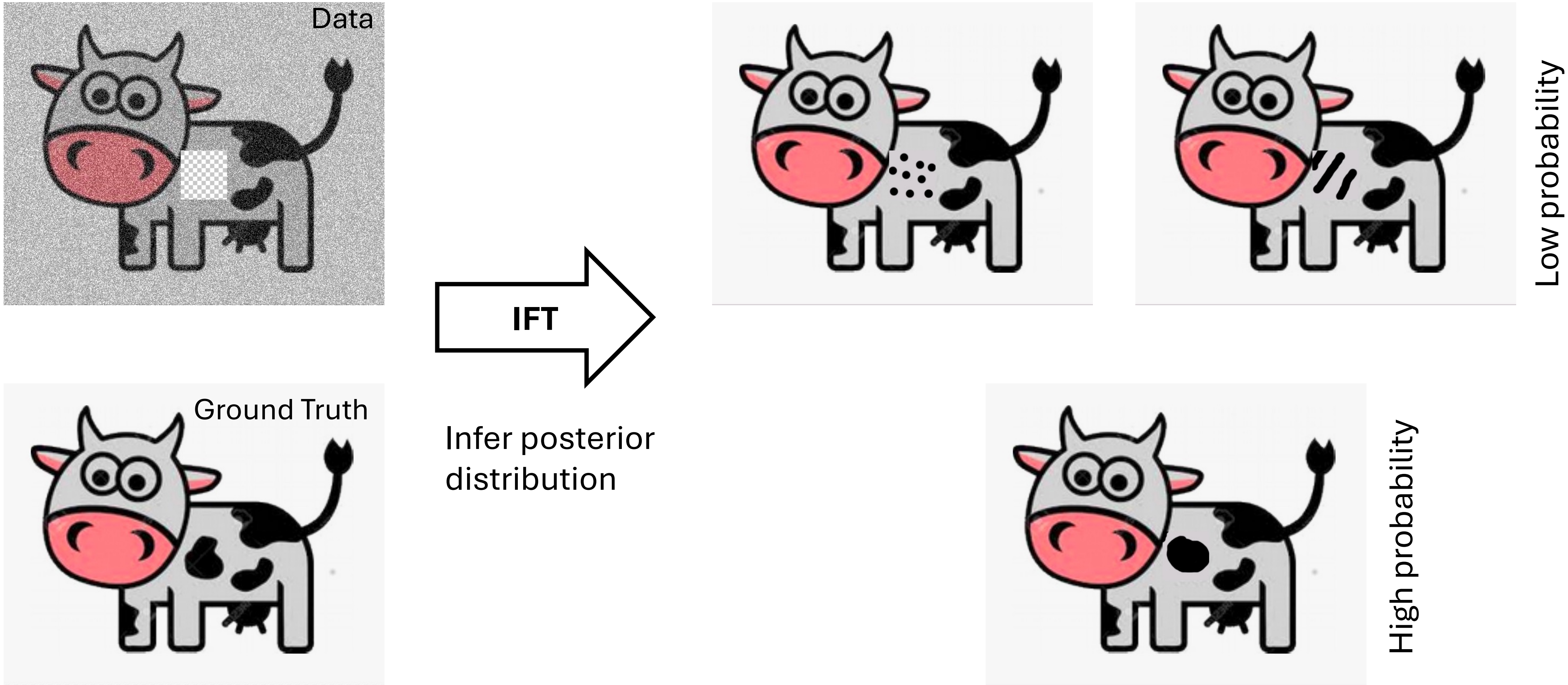


Measurement
- Parts missing
- Noise

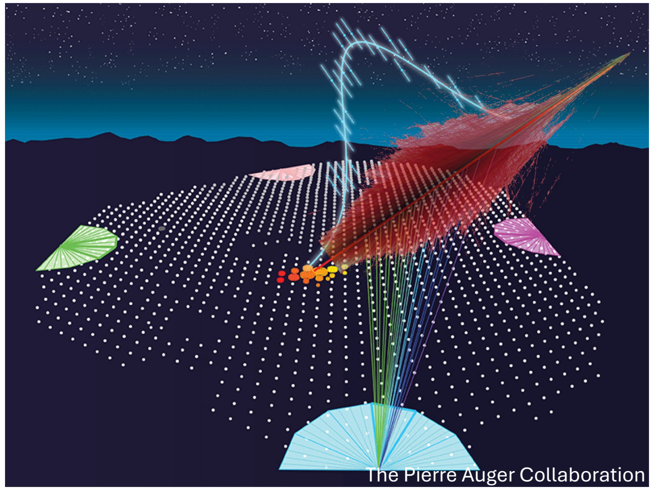


value of pixel contains probabilistic information about neighboring pixels

Information Field Theory: Correlation structures



Applications in astroparticle physics



Ultra-high-energy cosmic rays (UHECRs)

- Charged nuclei moving through the Universe with energies $\geq 10^{18}$ eV that can be detected at Earth
- Origin still uncertain
- Initiate particle shower in atmosphere

1.

Calibration of radio antennas at the Pierre Auger Observatory

- Extensive air showers emit radio signals
- Measurement with radio antennas at the Pierre Auger Observatory in Argentina
- Relative calibration of radio antennas

2.

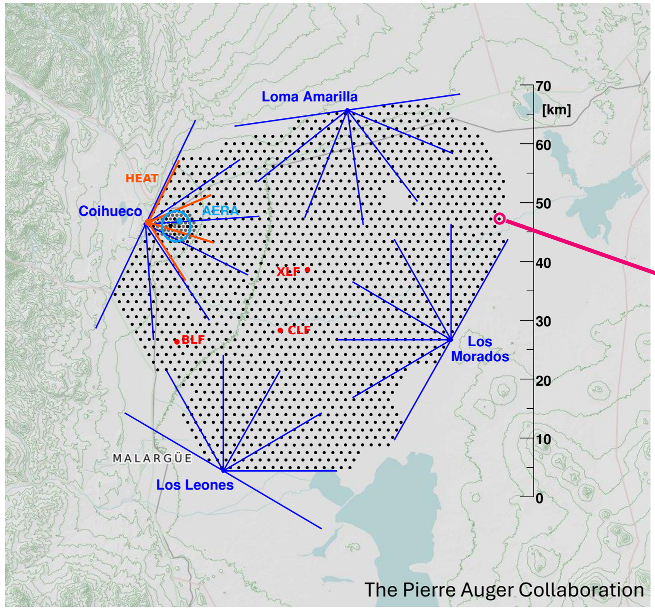
UHECR deflections in the Galactic magnetic field

- Reconstruction of UHECR flux before entering the Galaxy using sparse data of arrival directions measured at Earth
- Pinpoint to possible source directions

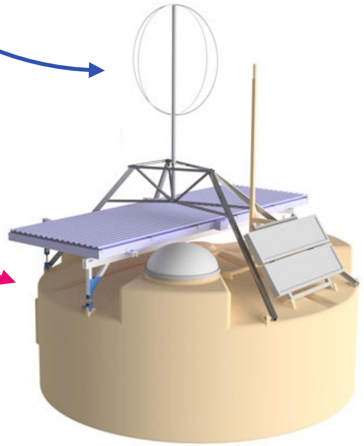
Radio detection of air showers at the Pierre Auger Observatory

The Pierre Auger Observatory

- Located in Argentina
- Hybrid detection of air showers
  - Fluorescence detector
  - Surface detector
  - **Radio detector**



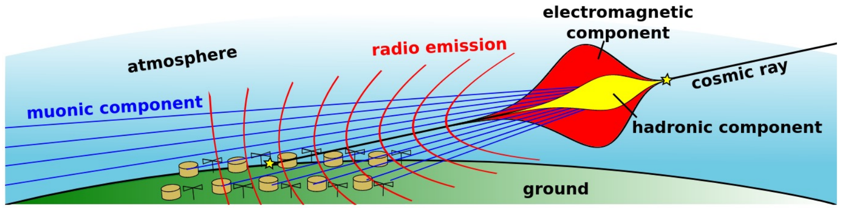
The Pierre Auger Collaboration



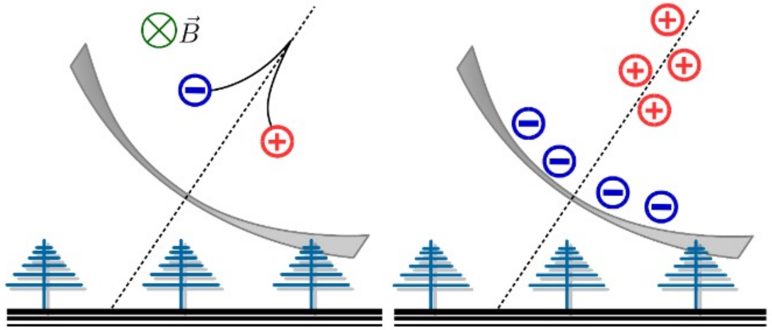
$\times 1660$

Radio emission in air showers

- Geomagnetic effect
  - Deflection of e^- & e^+ in Earth's magnetic field
- Askaryan effect
  - Production of ionized air molecules



E. Holt (2018)

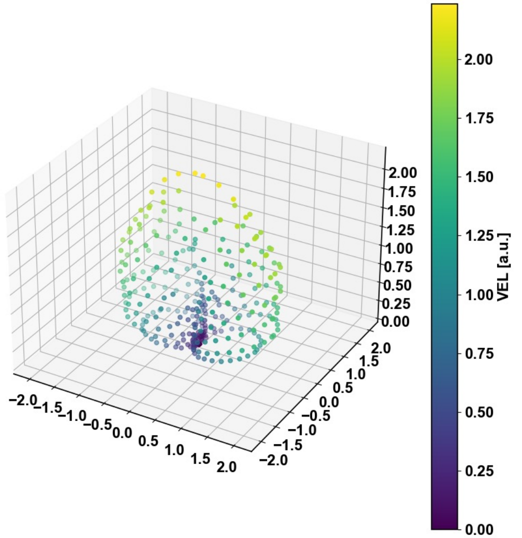


C. Glaser (2017)

Calibration of radio antennas with a drone

- Direction-dependent sensitivity of antennas (*antenna pattern*)
  - Relates incoming electric field to measured voltage in antenna as *Vector Effective Length* (VEL)
- Emit calibration signal from **drone**
- Measure signal amplitude
  - at various points in the sky
  - for multiple frequencies
  - with different polarizations

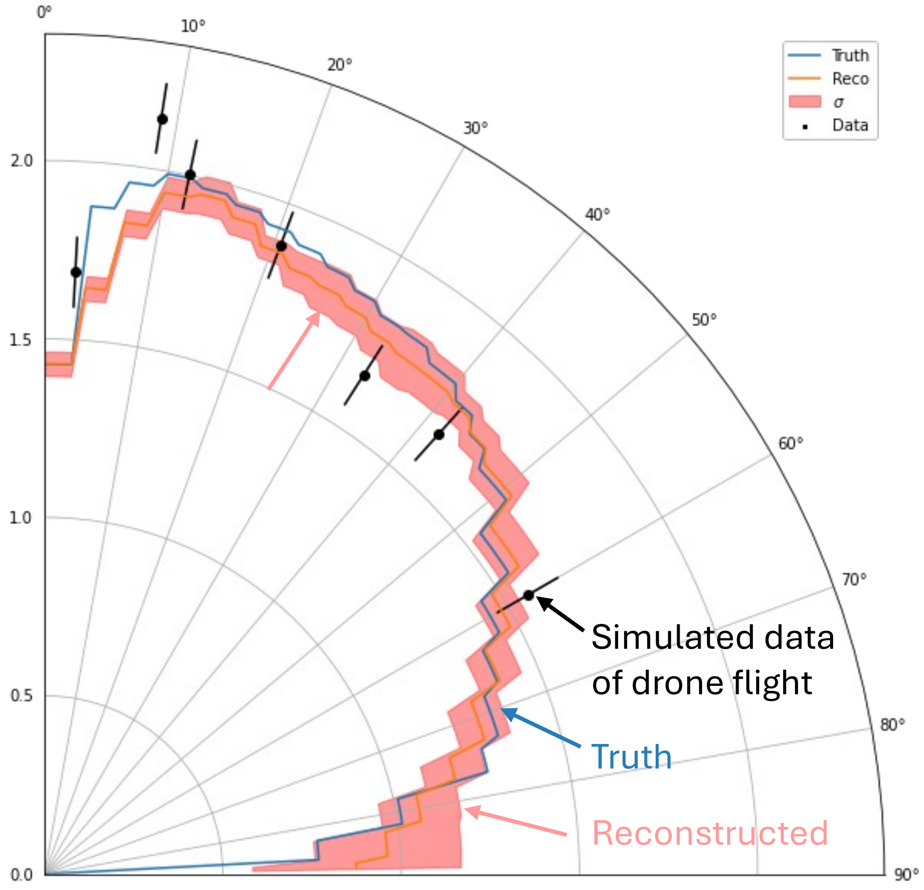
→ **Sparse data** on sphere



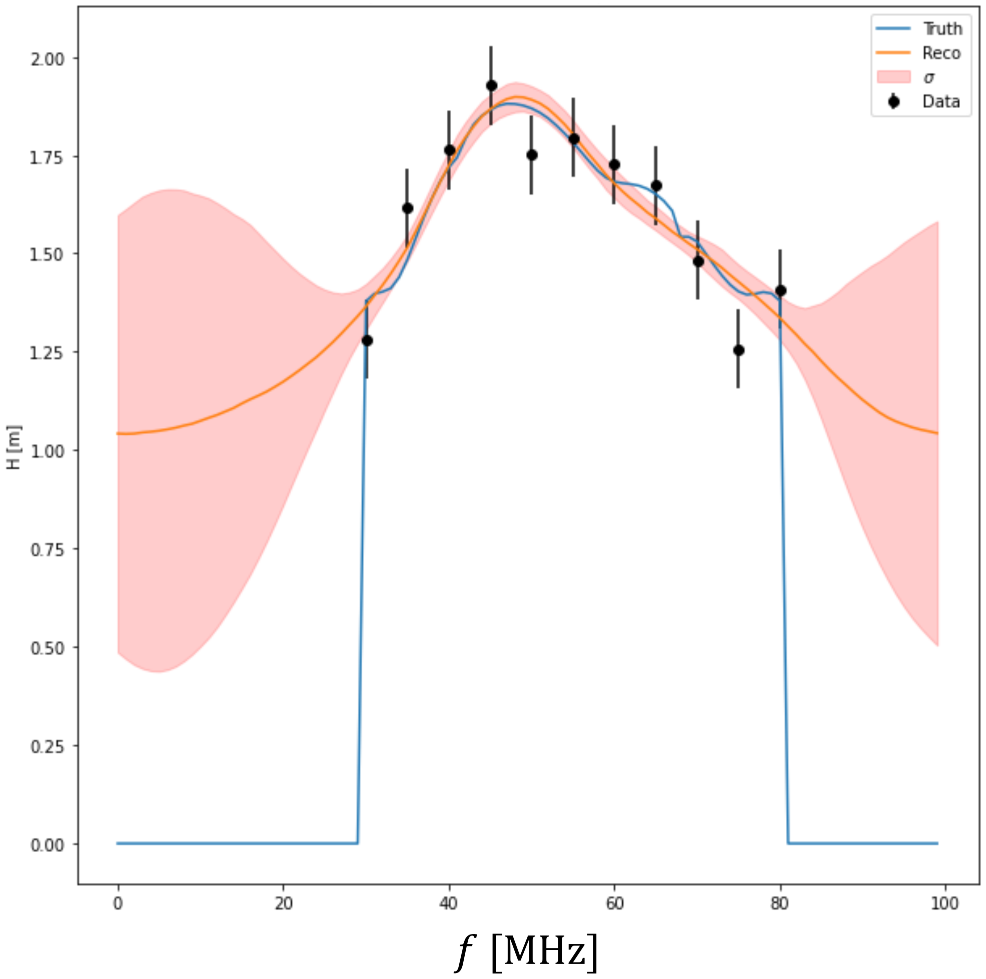
Radio antenna calibration with IFT

1.

Antenna directional dependence



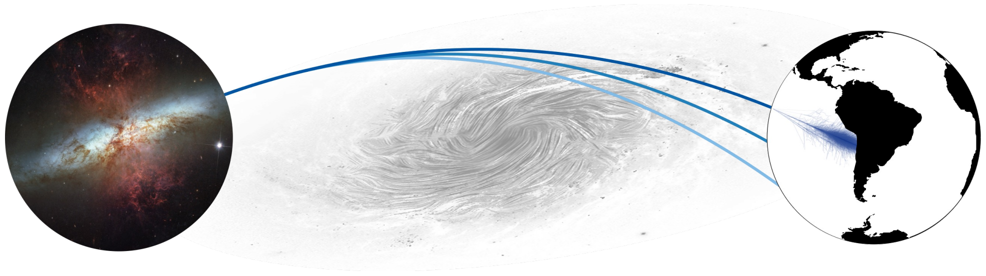
Antenna frequency dependence



Applications in astroparticle physics

Ultra-high-energy cosmic rays (UHECRs)

- Charged nuclei moving through the Universe with energies $\geq 10^{18}$ eV that can be detected at Earth
- Origin still uncertain
- Initiate particle shower in atmosphere



1.

Calibration of radio antennas at the Pierre Auger Observatory

- Extensive air showers emit radio signals
- Measurement with radio antennas at the Pierre Auger Observatory in Argentina
- Relative calibration of radio antennas

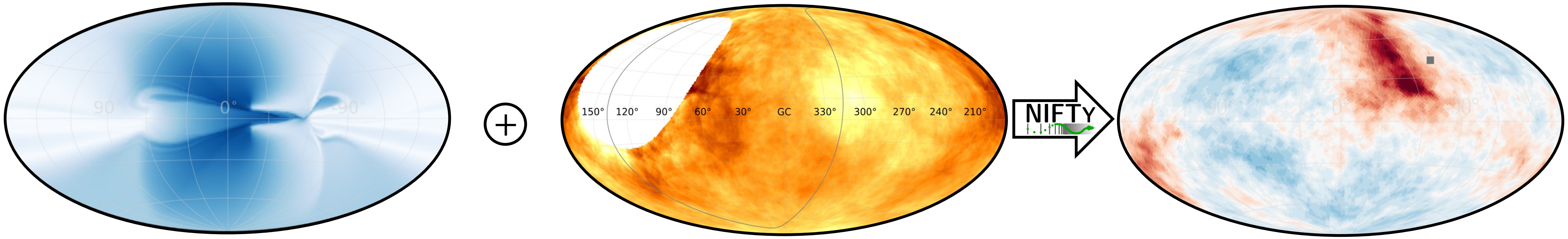
2.

UHECR deflections in the Galactic magnetic field

- Reconstruction of UHECR flux before entering the Galaxy using sparse data of arrival directions measured at Earth
- Pinpoint to possible source directions

UHECR deflections in the Galactic magnetic field (GMF)

GMF lenses | **UHECR flux at Earth** | **Extragalactic illumination map**



By using GMF lenses and UHECR flux measured at Earth → reconstruct extragalactic illumination map

describe deflections in GMF

UHECR flux arriving at the edge of the Galaxy

UHECR deflections in the Galactic magnetic field: Toy model

2.

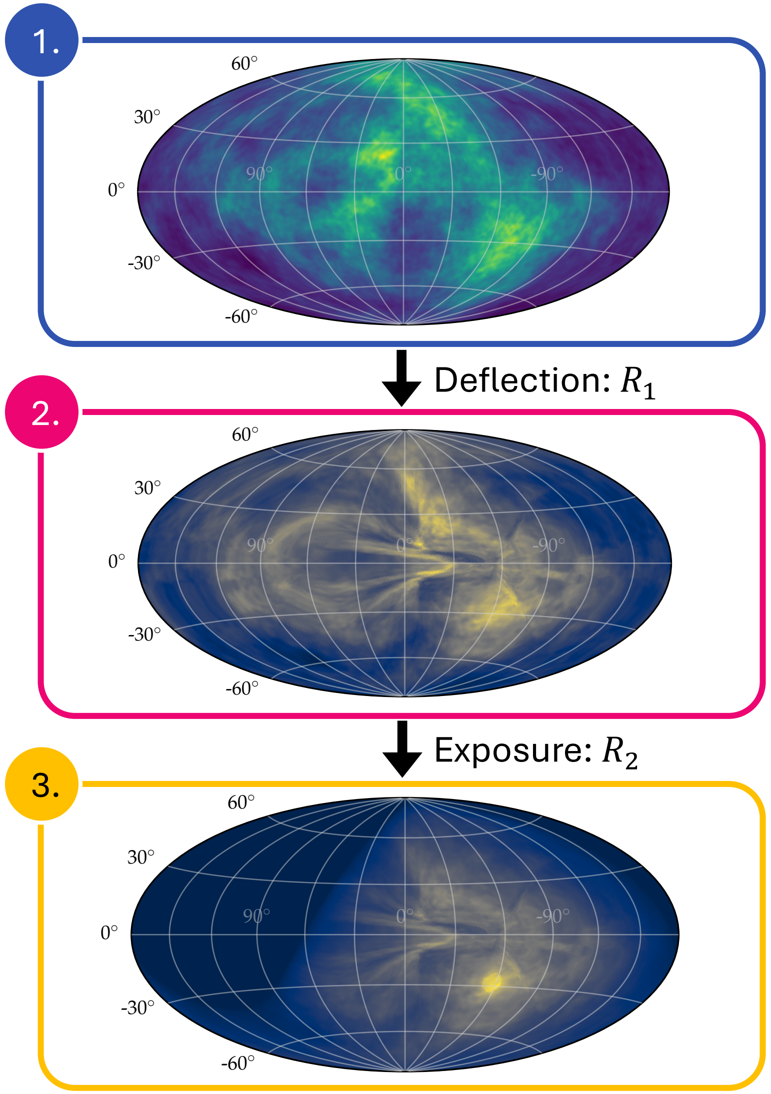
Simplifications

- Composition: only protons
- Fixed energy of $10^{19.2}$ eV
- No turbulent GMF component

Forward model

1) Sample extragalactic UHECR flux map
2) Deflect with GMF lens
3) Apply exposure and norm to number of measured events

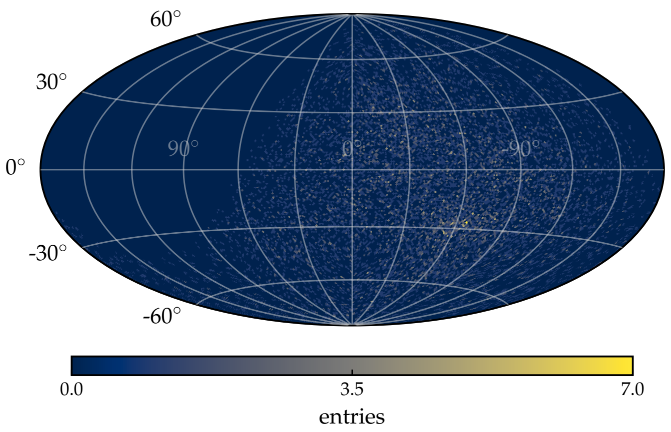
$$d = R[s] + n \qquad R[\cdot] = R_2\big[R_1[\cdot]\big]$$



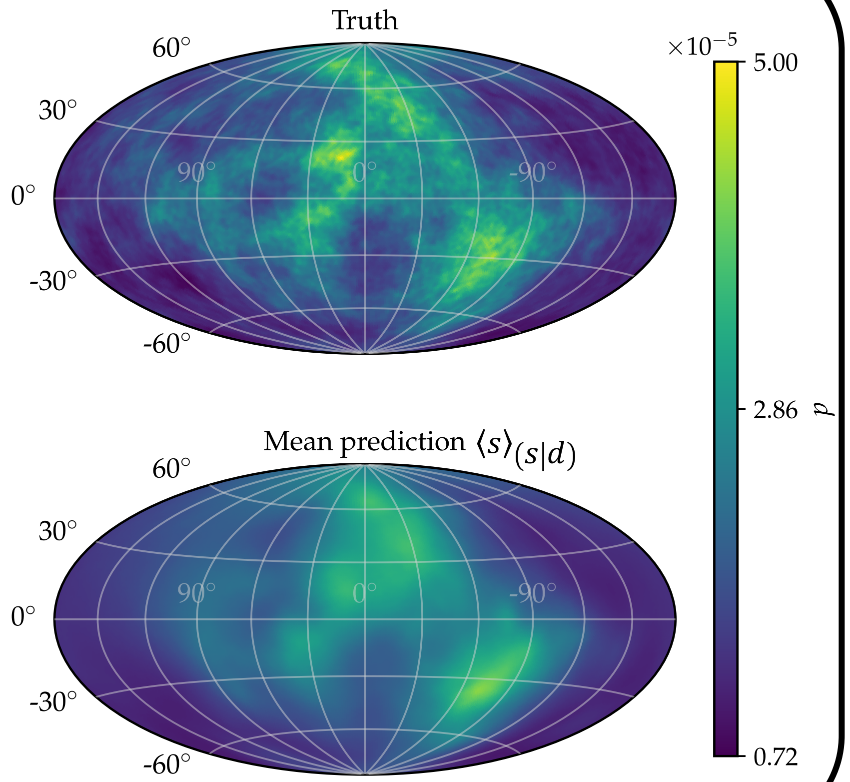
UHECR deflections in the Galactic magnetic field: Exemplary fit

2.

Simulated data d for source distribution

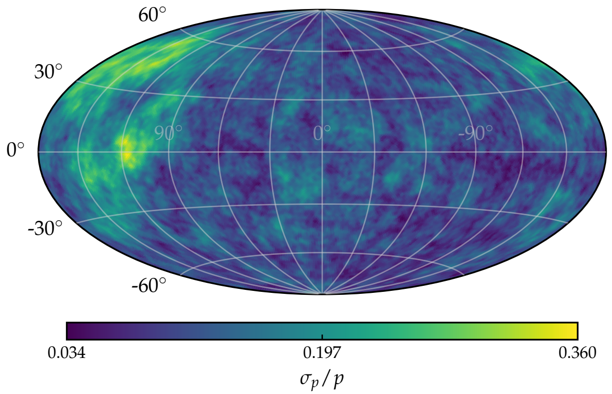


Mean prediction for s

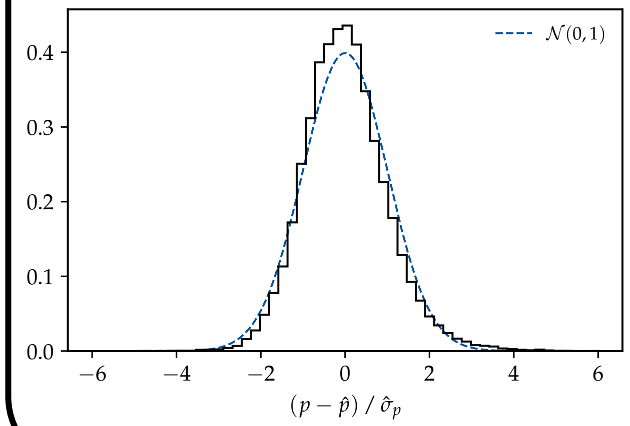


Uncertainty on s

Resolution



Relative difference



$$d = R[s] + n$$

Summary

- **Information Field Theory** as Bayesian framework to infer posterior distributions of continuous fields using sparse and noisy data

- **NIFTy** with underlying machine-learning framework **JAX** used for Just-In-Time compilation, computation on GPUs and **automatic differentiation**

- Promising applications in both **detector calibration** and **analysis** for astroparticle physics
  - Radio detector at the Pierre Auger Observatory
  - Deflections of ultra-high-energy cosmic rays in the Galactic magnetic field

Backup slides

Calibration strategy

Gain Calibration

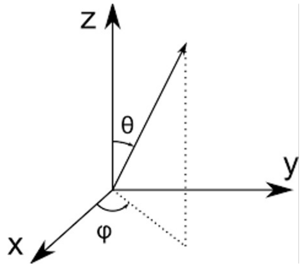
Read-out Voltage — **Incoming electric field**

$$\mathcal{U}(\Phi,\Theta,f) = \left|\vec{H}_k(\Phi,\Theta,f)\right| \cdot \left|\vec{\mathcal{E}}_k(f)\right|$$

Vector Effective Length (VEL)

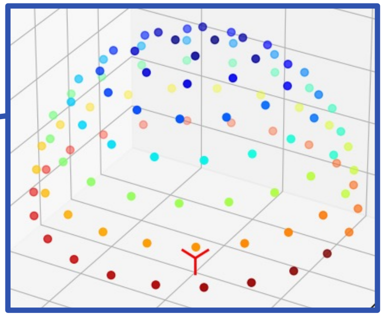
VEL for transmission measurements:

$$|H(\Phi,\Theta,f)| \propto R \cdot \sqrt{P(\Phi,\Theta,f)}$$



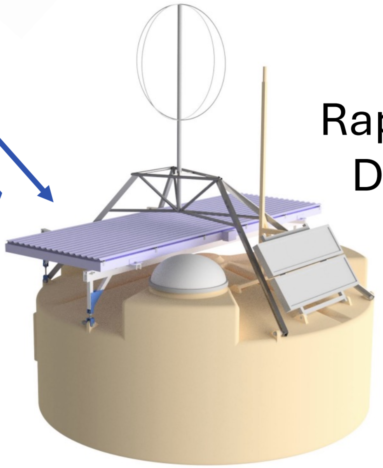
Position (ϕ,θ)

Automated flight



- Fly to **"Waypoints"**
- **Stop** for 6s
- **Automatically aim** at antenna

Distance *R* (far-field)



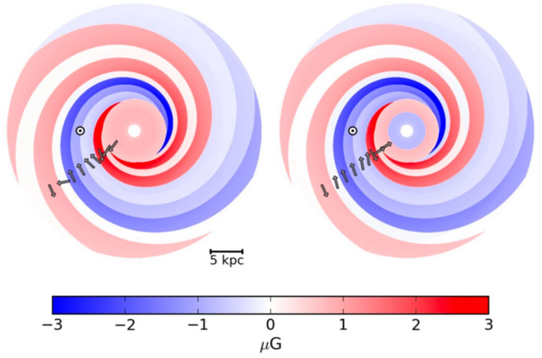
Rapid triggering DAQ (≈ 1 Hz)

UHECR deflections in the Galactic magnetic field

Galactic magnetic field (GMF)

- Order of magnitude: μG
- **Coherent** and **turbulent** component
- Multiple models with large uncertainties (JF12, UF23, ...)

coherent GMF component of JF12 model

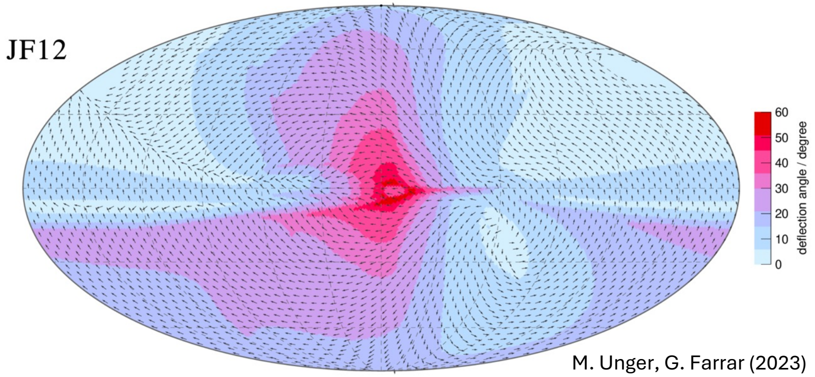


R. Jansson, G. Farrar (2012)

Deflections of UHECRs

- Lorentz force: $\frac{\mathrm{d}\vec{v}}{\mathrm{d}t} = q\ \vec{v} \times \vec{B}(\vec{x})$
- Dependent on initial direction and rigidity $R = \frac{E}{Ze}$ of particle

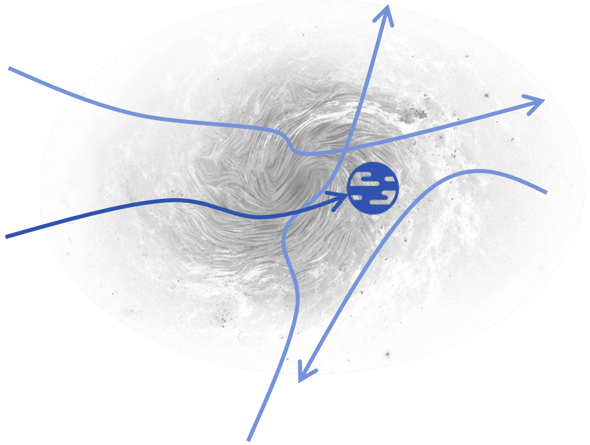
deflection direction & strength of 20 EeV proton



M. Unger, G. Farrar (2023)

GMF lenses for UHECR deflections

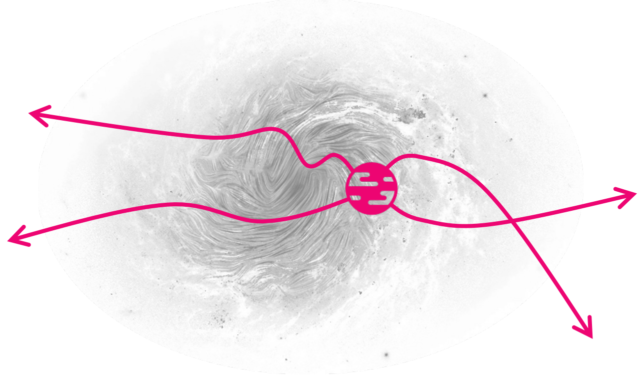
- only tiny fraction of UHECRs that enter the Galaxy arrive at Earth
  → forward simulation is expensive
- **idea**: backpropagation of UHECRs with opposite charge



GMF lenses

- backtracking of N particles originating at Earth in direction of pixel i and count how many CRs are deflected in direction j
- lens is matrix L with entries $L_{ij} = \frac{n(i \to j)}{N}$
- relates detected sky map at Earth $\vec{a}$ to extragalactic illumination map $\vec{b}$ via

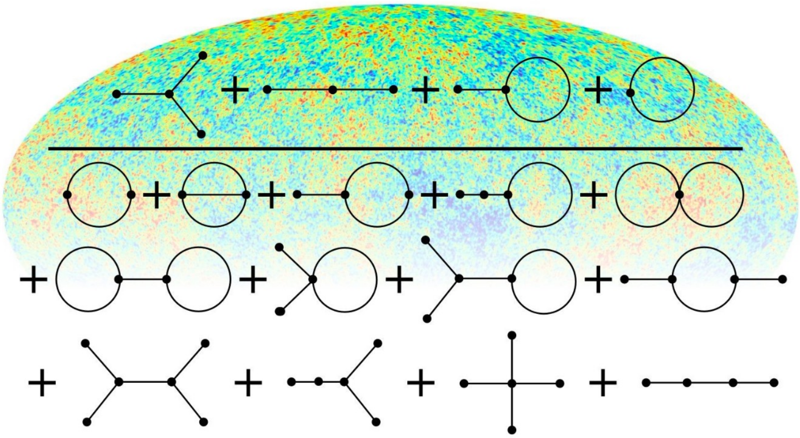
$$\boxed{\vec{a} = L\,\vec{b}}$$



Information Field Theory: Connection to field theory and statistical mechanics

Bayesian probabilities

- $\mathcal{P}(s|d) = \frac{\mathcal{P}(d,s)}{\mathcal{P}(d)} \equiv \frac{e^{\mathcal{H}(d,s)}}{\mathcal{Z}(d)}$
    - $\mathcal{P}(s|d)$: Posterior distribution
    - $\mathcal{P}(d,s)$: Joint probability
    - $\mathcal{P}(d) = \mathcal{Z}(d)$: evidence / partition function
    - $\mathcal{H}(d,s)$: Information Hamiltonian
- Rewriting allows to use techniques from statistical & quantum field theories
- Information is additive: $\mathcal{H}(d,s) = \mathcal{H}(d|s) + \mathcal{H}(s)$



arXiv:1804.03350