— BE.HEP —

K U Leuven, June 21, 2024

Galactic magnetic field deflection of astroparticles and 3D mapping

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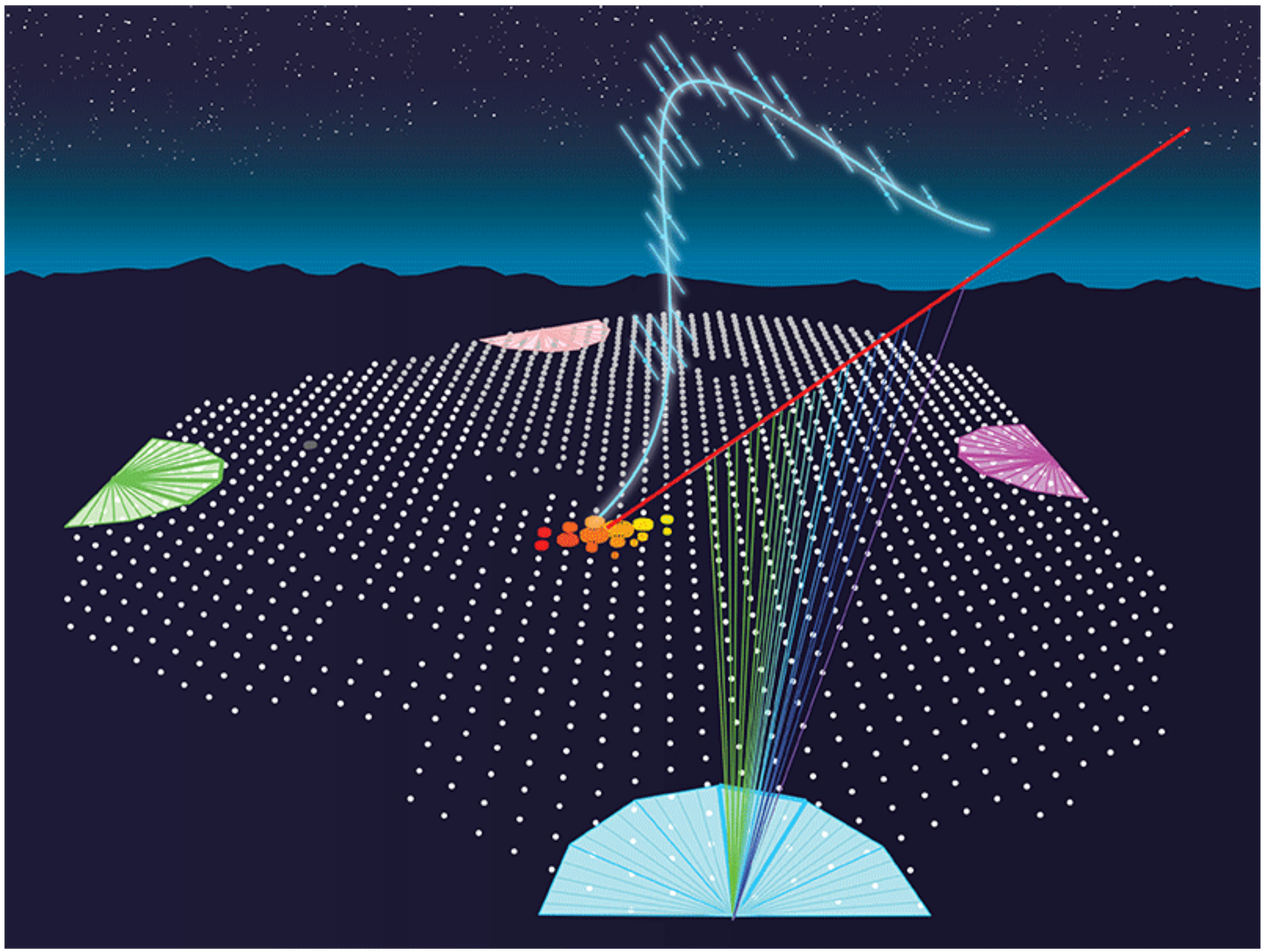
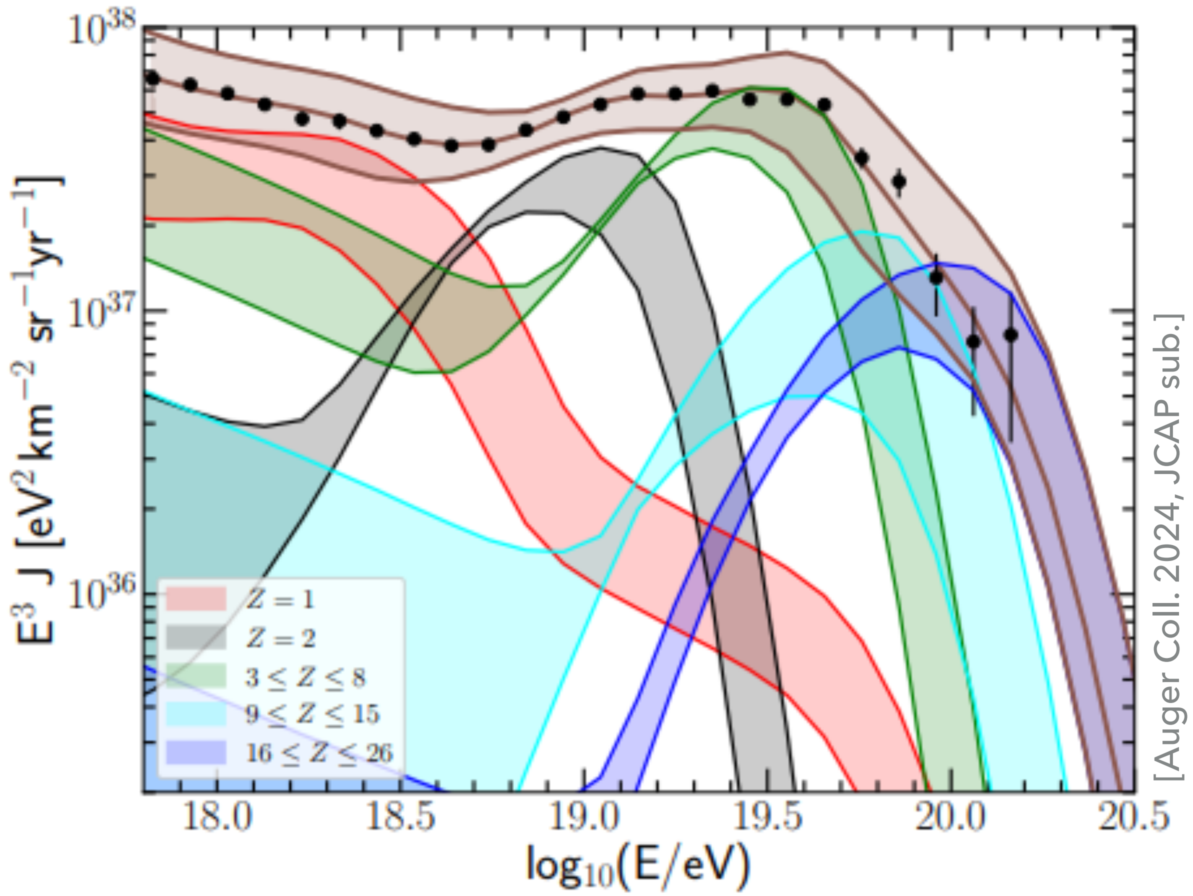
PIERRE AUGER OBSERVATORY



- ★ World's largest observatory for UHECR studies
  - Surface detector
  - Fluorescent detector
  - Radio detector
- ★ Covers ~3000 km^2
- ★ Operating since 2004

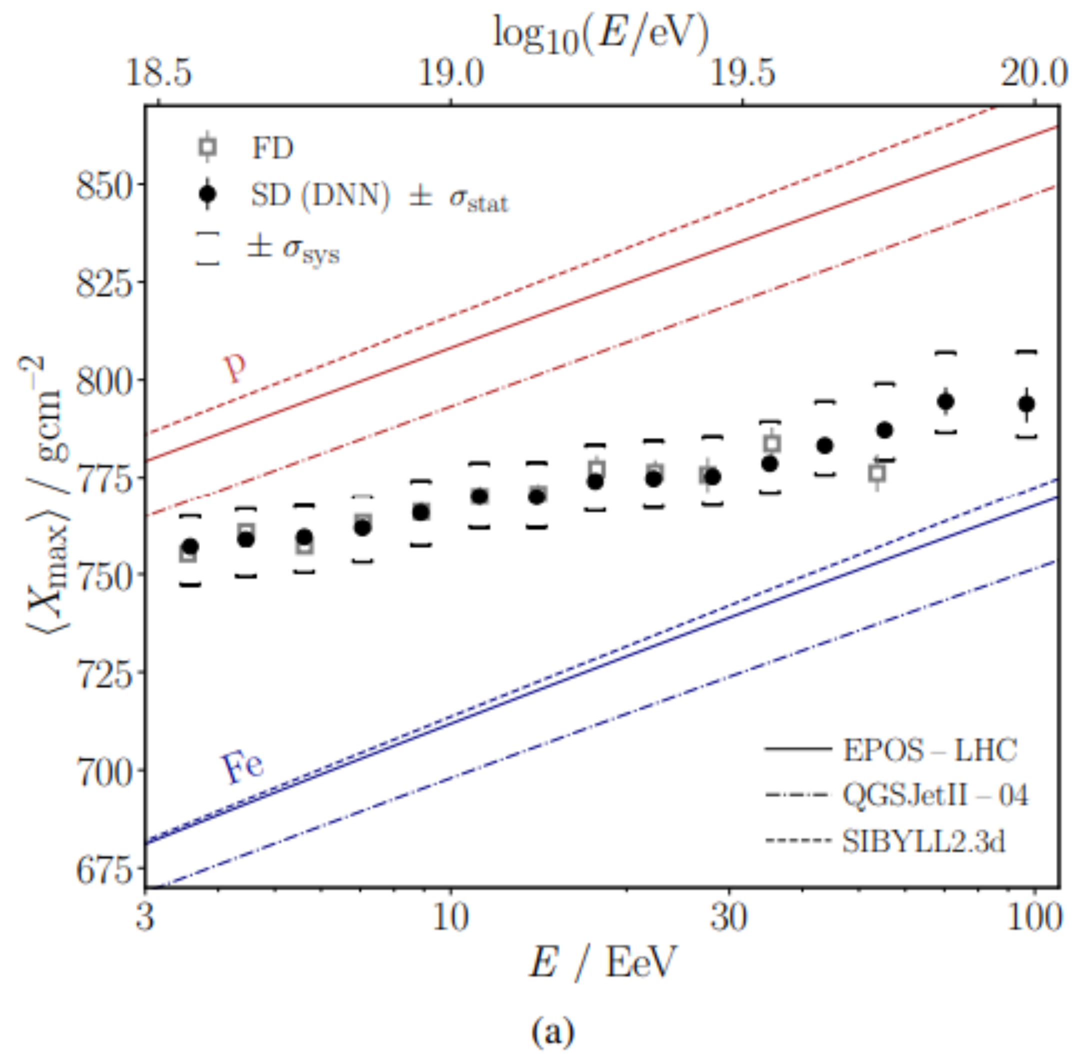
PIERRE AUGER OBSERVATORY — RESULTS HIGHLIGHTS I

★ New features in the energy spectrum



[Auger Coll. 2024, JCAP sub.]

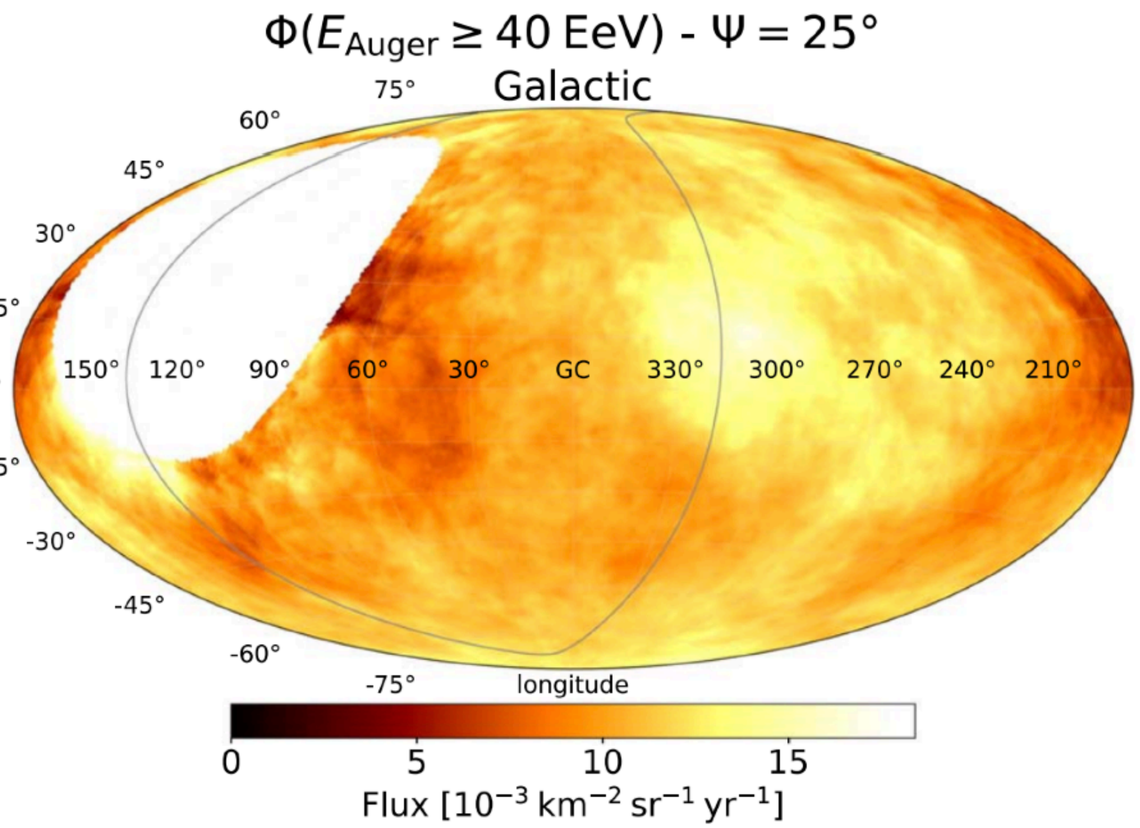
★ Energy dependence of composition



[Auger Coll. 2024, PRL sub.]

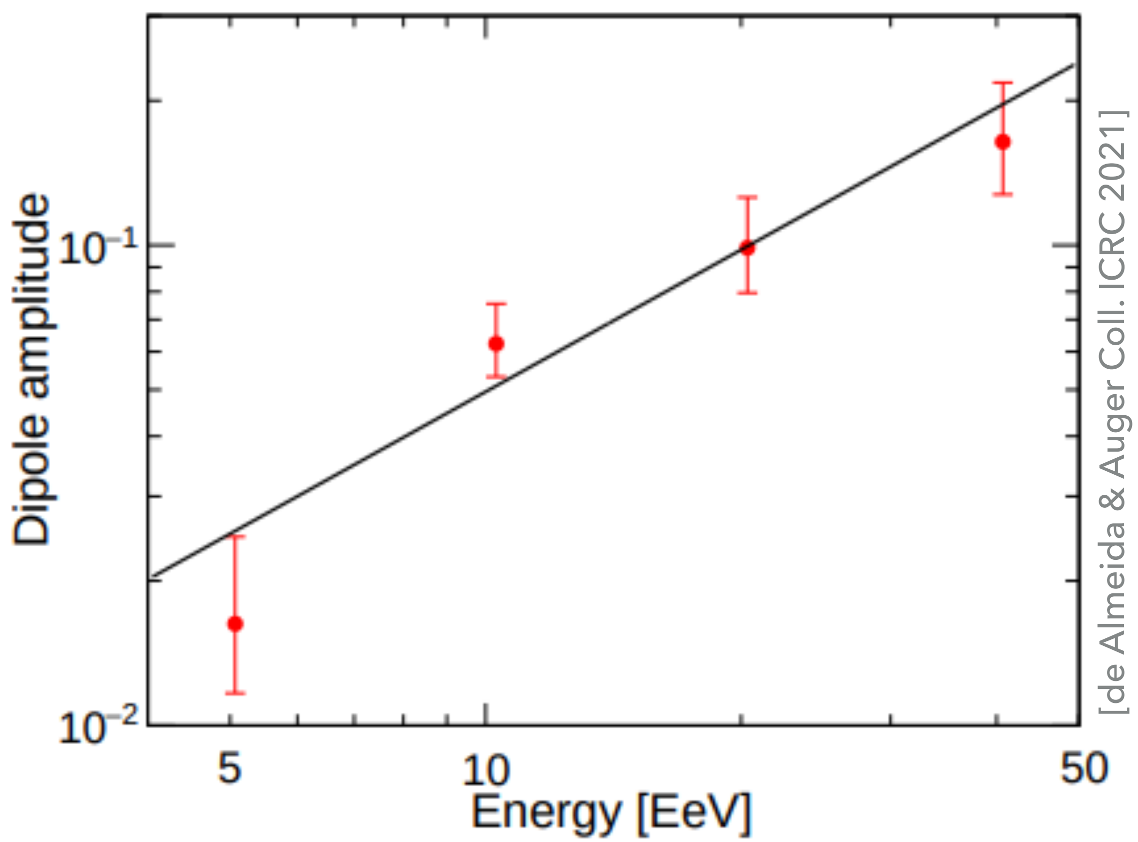
PIERRE AUGER OBSERVATORY — RESULTS HIGHLIGHTS II

★ Anisotropies in arrival directions



[Auger Coll. 2022 ApJ]

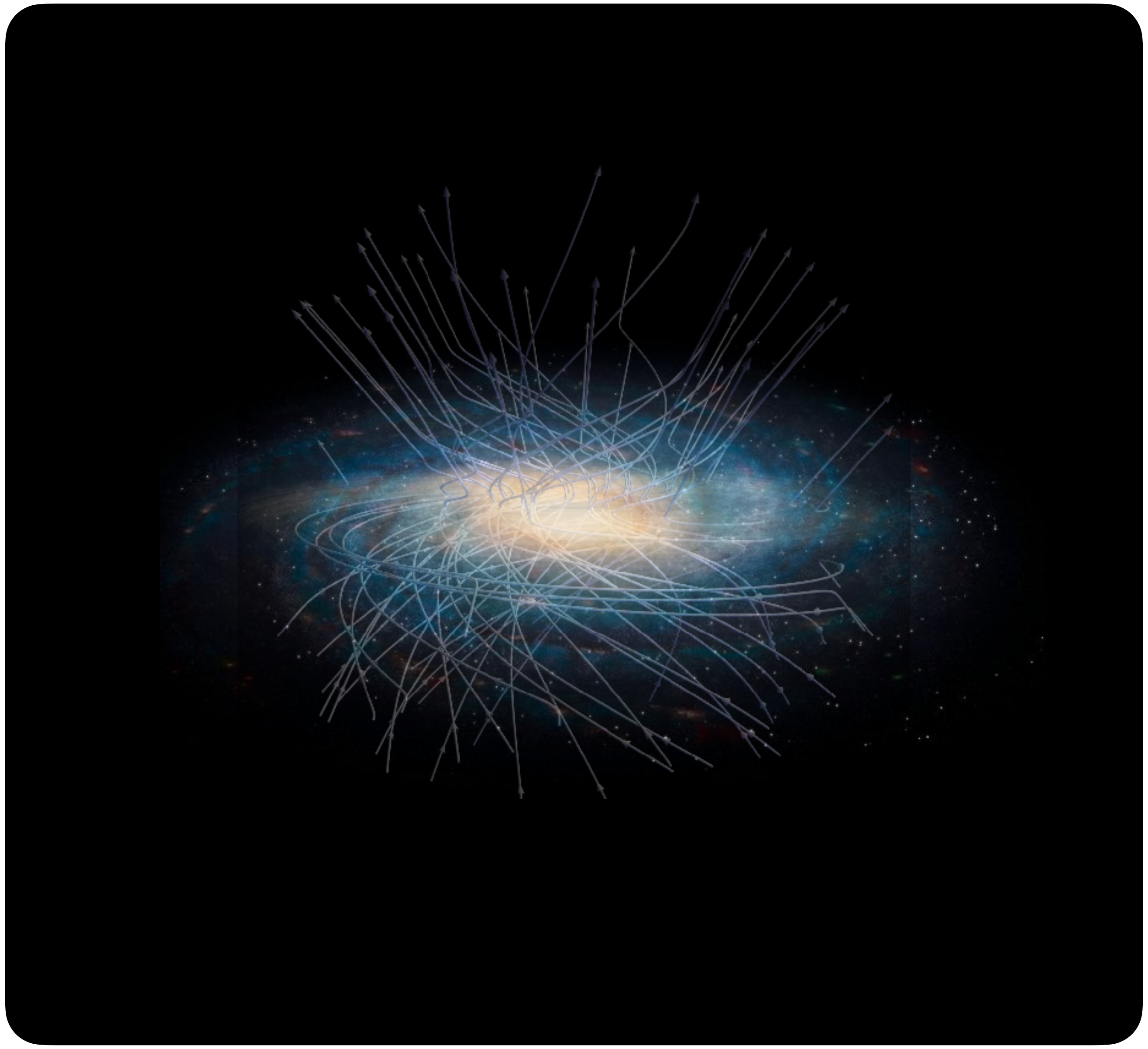
★ Energy dependence of dipole amplitude



[de Almeida & Auger Coll. ICRC 2021]

UHECR AND GALACTIC MAGNETIC FIELD (GMF)

★ The magnetized Milky Way acts as a foreground for charged astroparticles

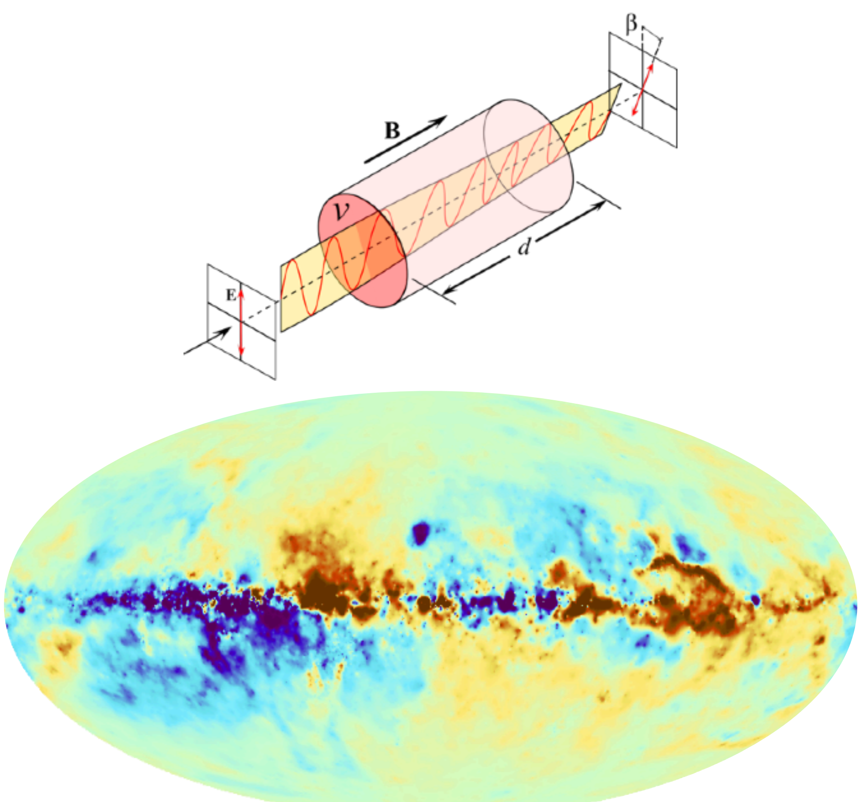


GALACTIC MAGNETIC FIELD (GMF) OBSERVABLES

★ The magnetized Milky Way acts as a foreground for charged astroparticles, and other extragalactic and cosmological signals; in intensity and polarization

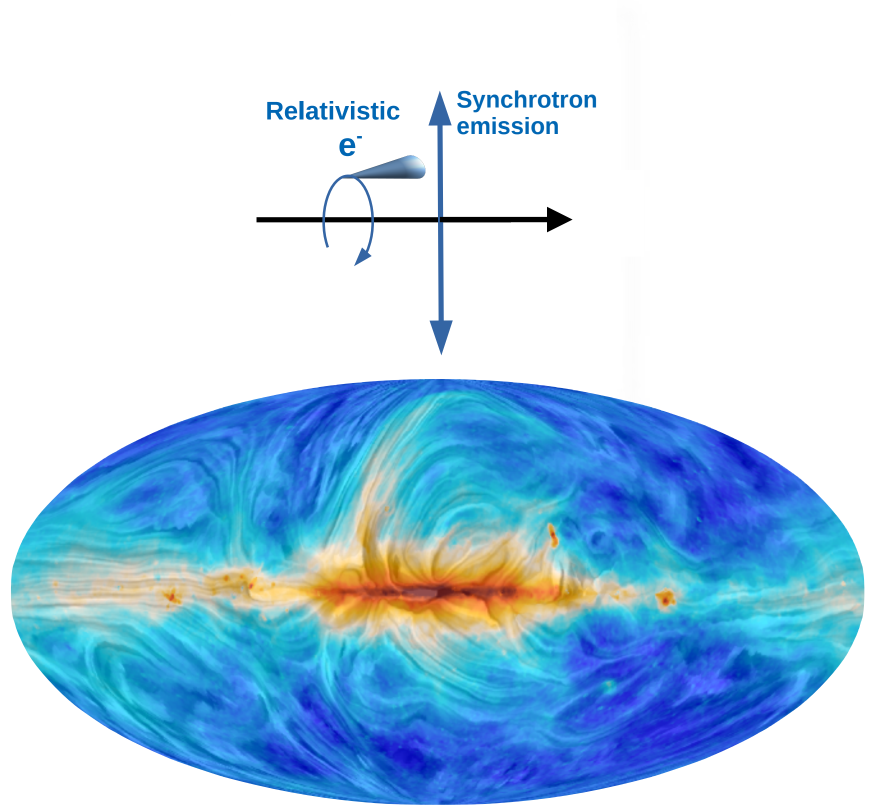
★ Matter of the interstellar medium and GMF:

Faraday rotation
(th. e^- T>10^5 K)

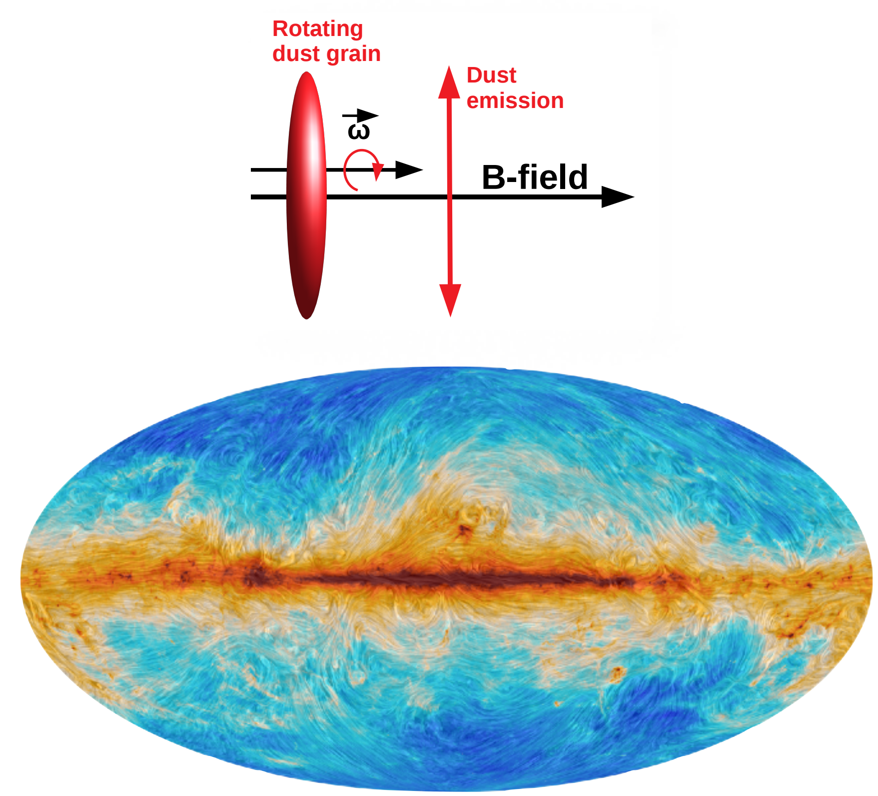


[Hutschenreuter+22]

Synchrotron emission
(rel. e^- E~10 GeV)



Dust emission
(grains T~20 K)



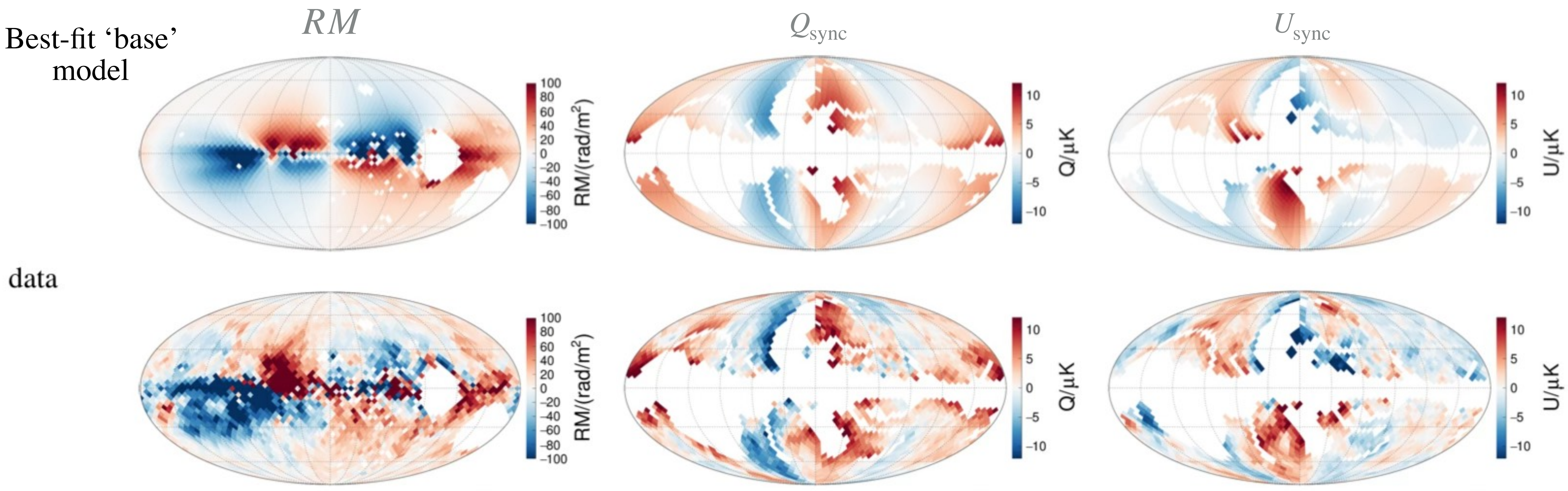
[Planck I 2015]

GMF MODELING — CURRENT STATUS I

★ 3D models for matter components and GMF are integrated along sightlines

★ predictions (RM, synchrotron Q and U) compared to observables in a likelihood analysis

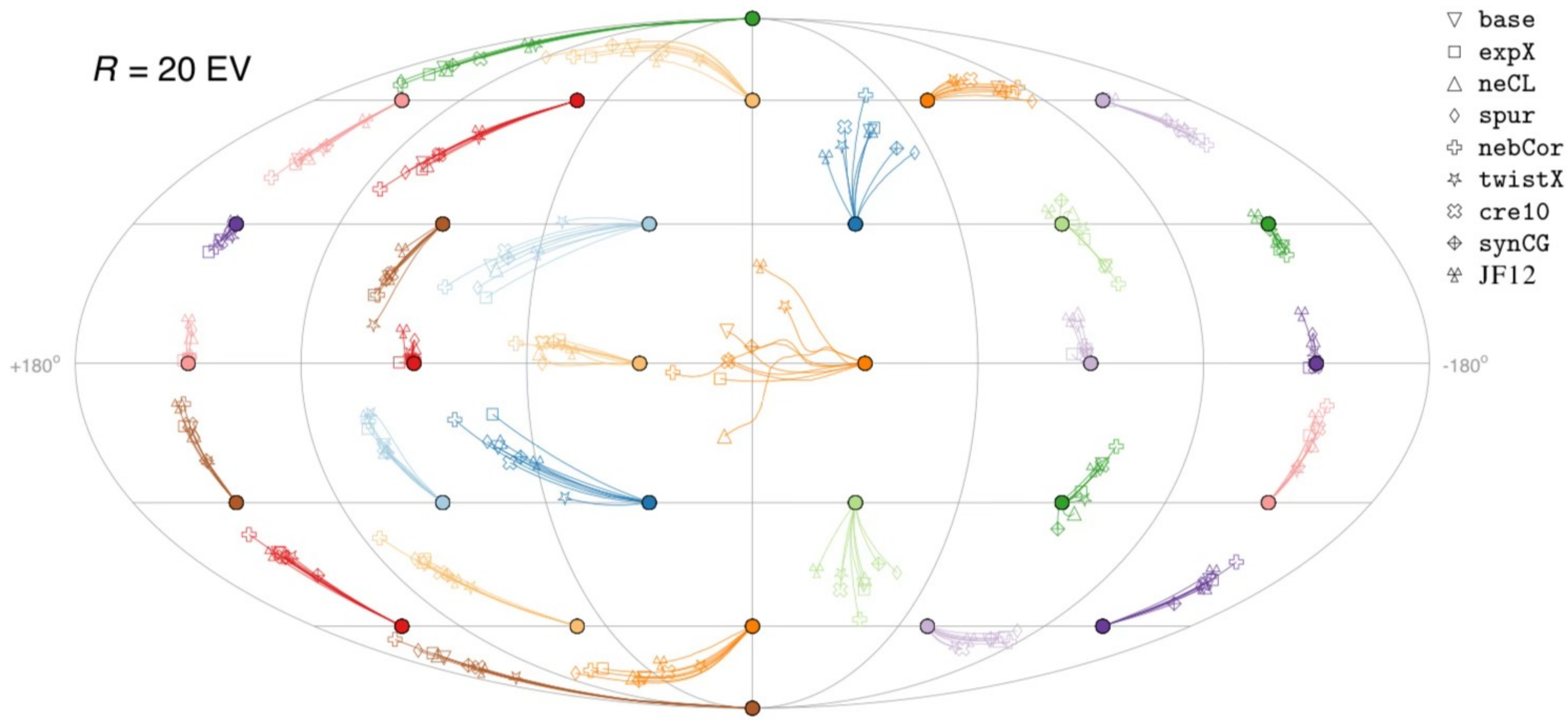
⟶ most recent update: [Unger & Farrar 2024, ApJ]
tested an ensemble of 9 GMF models



GMF MODELING — CURRENT STATUS II

[Unger & Farrar 2024, ApJ]

★ predictions of UHECR deflections for rigidity $R = E/Z = 20$ EV from best-fit models

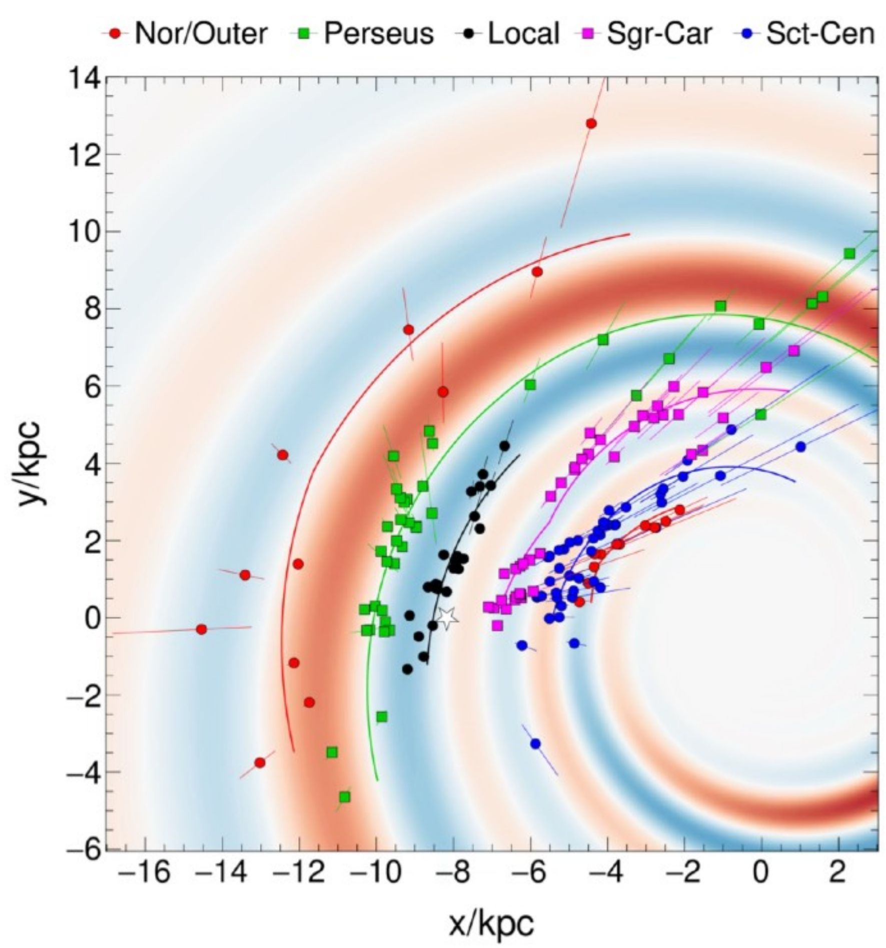


✓ The scatter between predicted deflections from viable models < predicted deflections

GMF MODELING — MAIN LIMITATION

★ Line-of-sight integrated nature of the observables

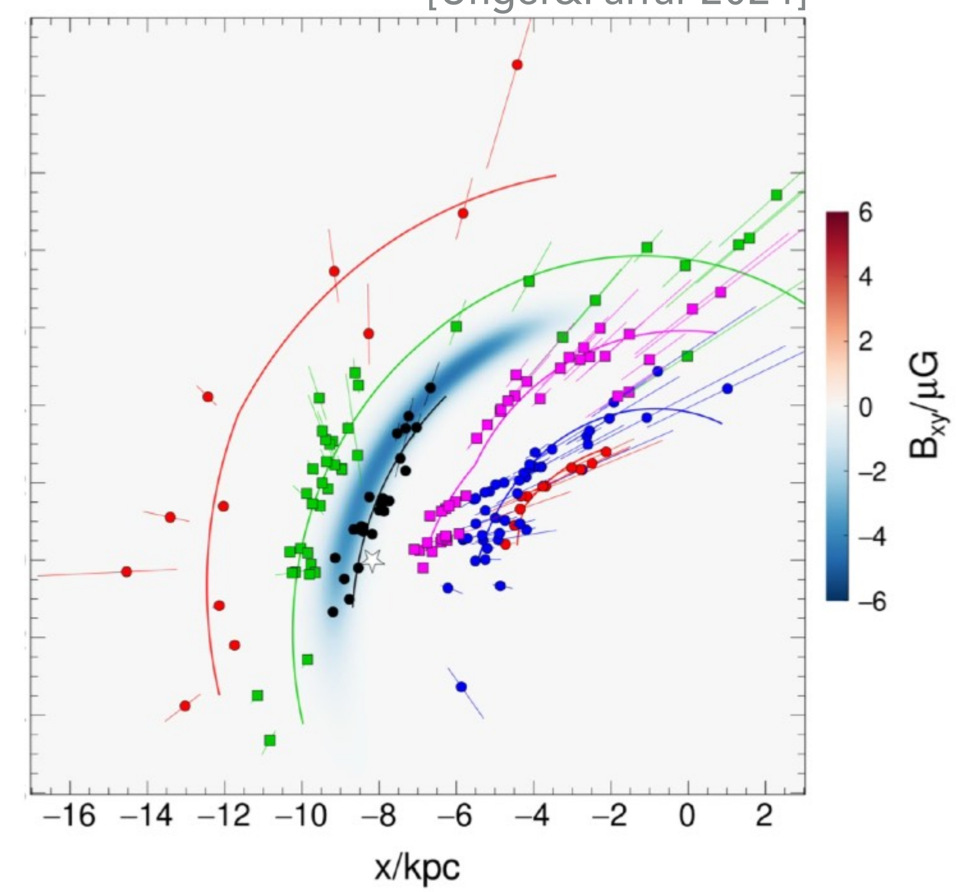
⟶ lack of *local* constraints to break confusion and degeneracies



a: Grand-design spiral

← ? →

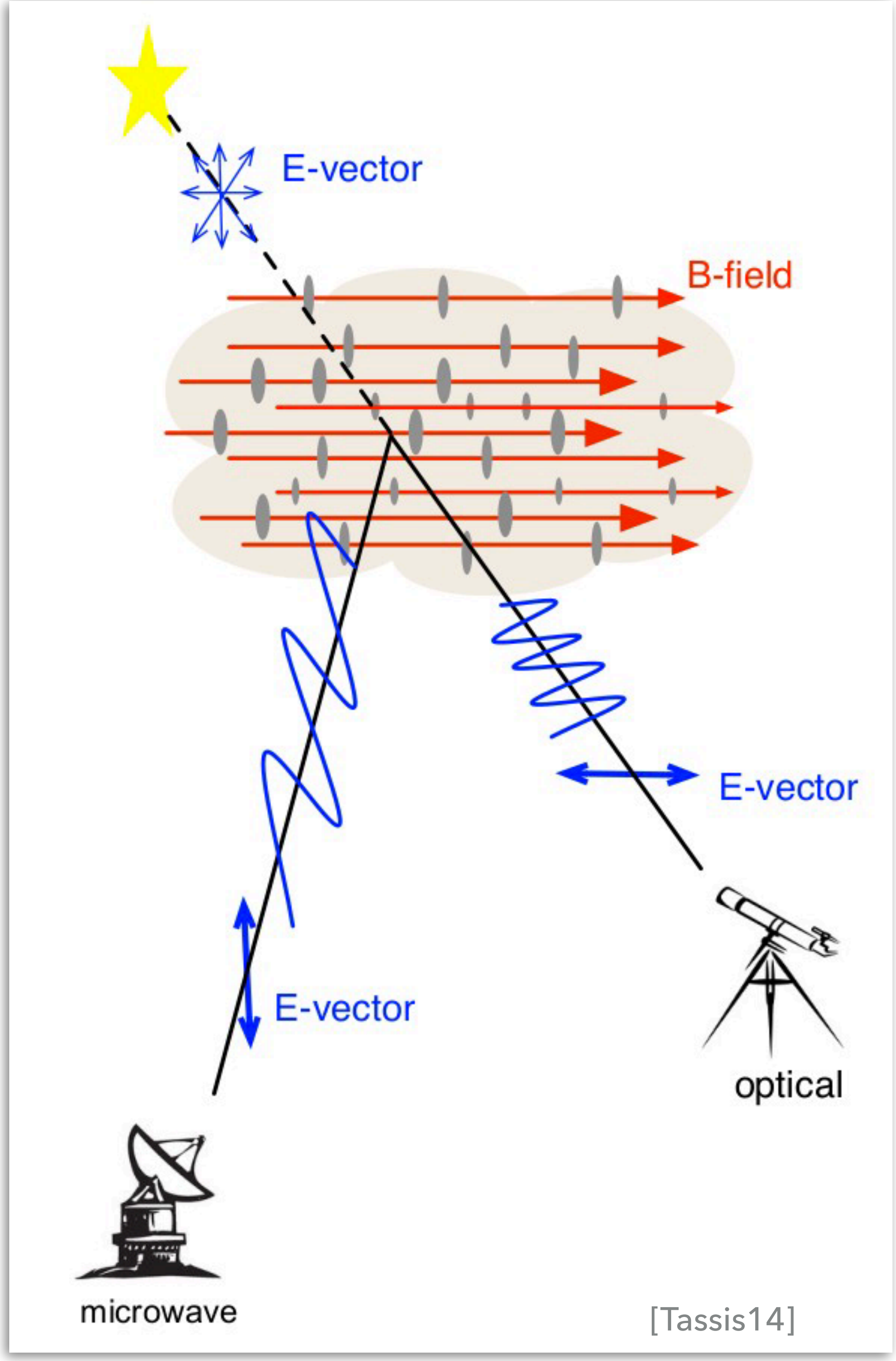
[Unger&Farrar 2024]



b: Spiral spur.

GMF MODELING — A WAY FORWARD

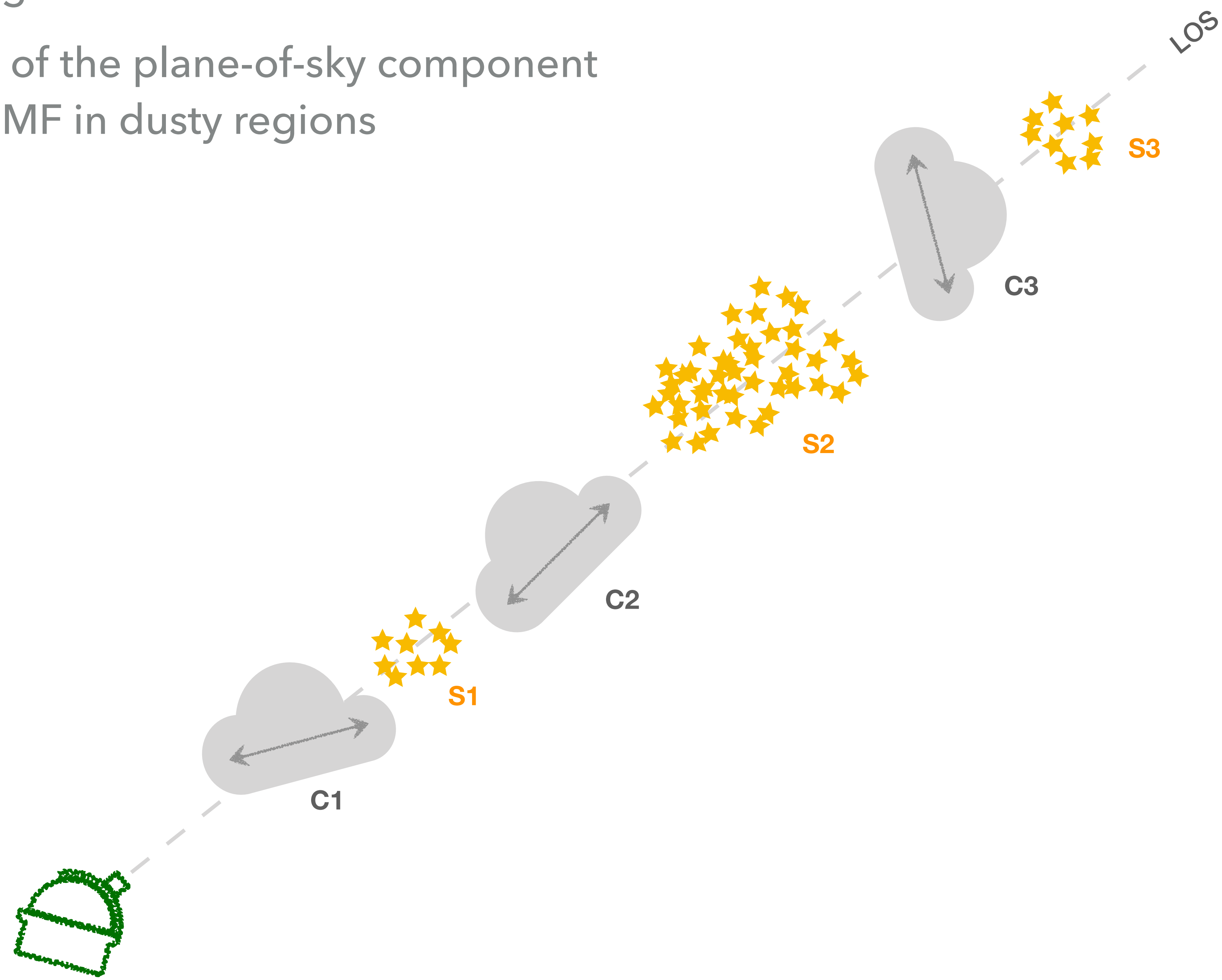
★ Aspherical dust grains in the magnetized interstellar medium
  - emit polarized light in the sub-mm (foreground to the CMB)
  - induce a net polarization to incoming light in the visible due to dichroic absorption



TOMOGRAPHY OF THE DUSTY MAGNETIZED INTERSTELLAR MEDIUM

★ Starlight polarization + star distance (Gaia)

- a unique probe to break the line-of-sight degeneracies
- 3D map of the plane-of-sky component of the GMF in dusty regions



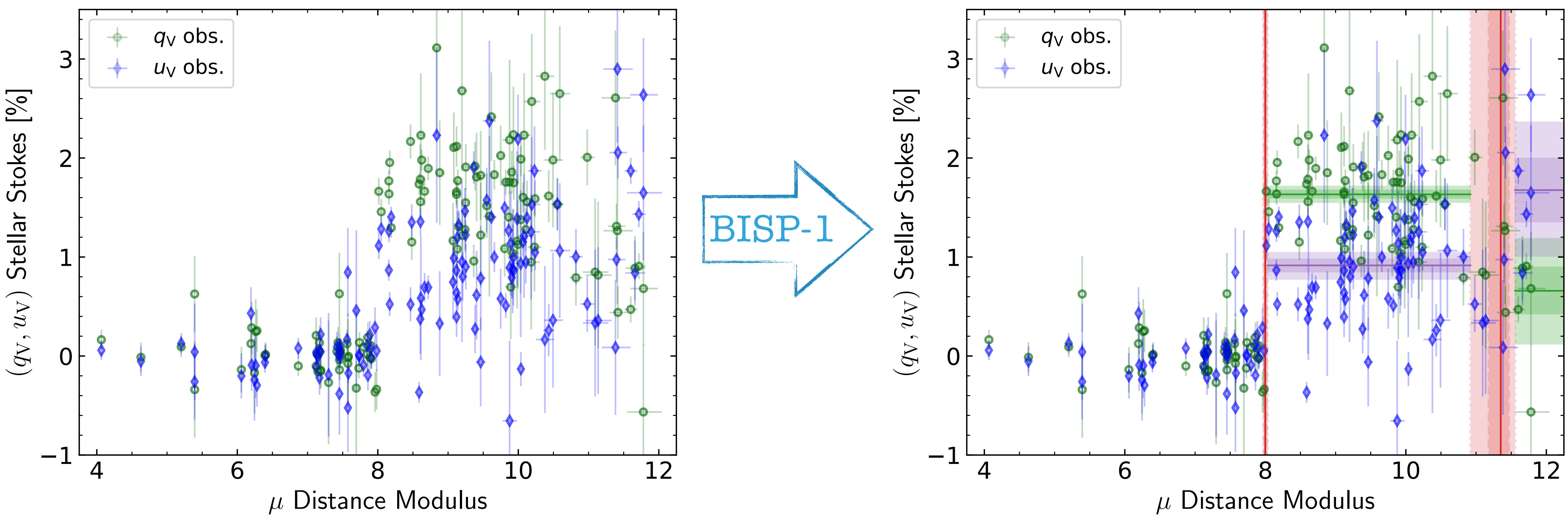
BAYESIAN INFERENCE OF STARLIGHT POLARIZATION IN 1D — BISP-1

[Pelgrims et al. 2023, A&A 670, A164]

★ Bayesian method to retrieve the number of clouds, their distances, and their polarization properties from stellar data on polarization and distance only

★ Likelihood that accounts for
- parallax uncertainties
- polarization uncertainties
- intrinsic scatter from ISM turbulence

✓ publicly available: https://github.com/vpelgrims/bisp_1

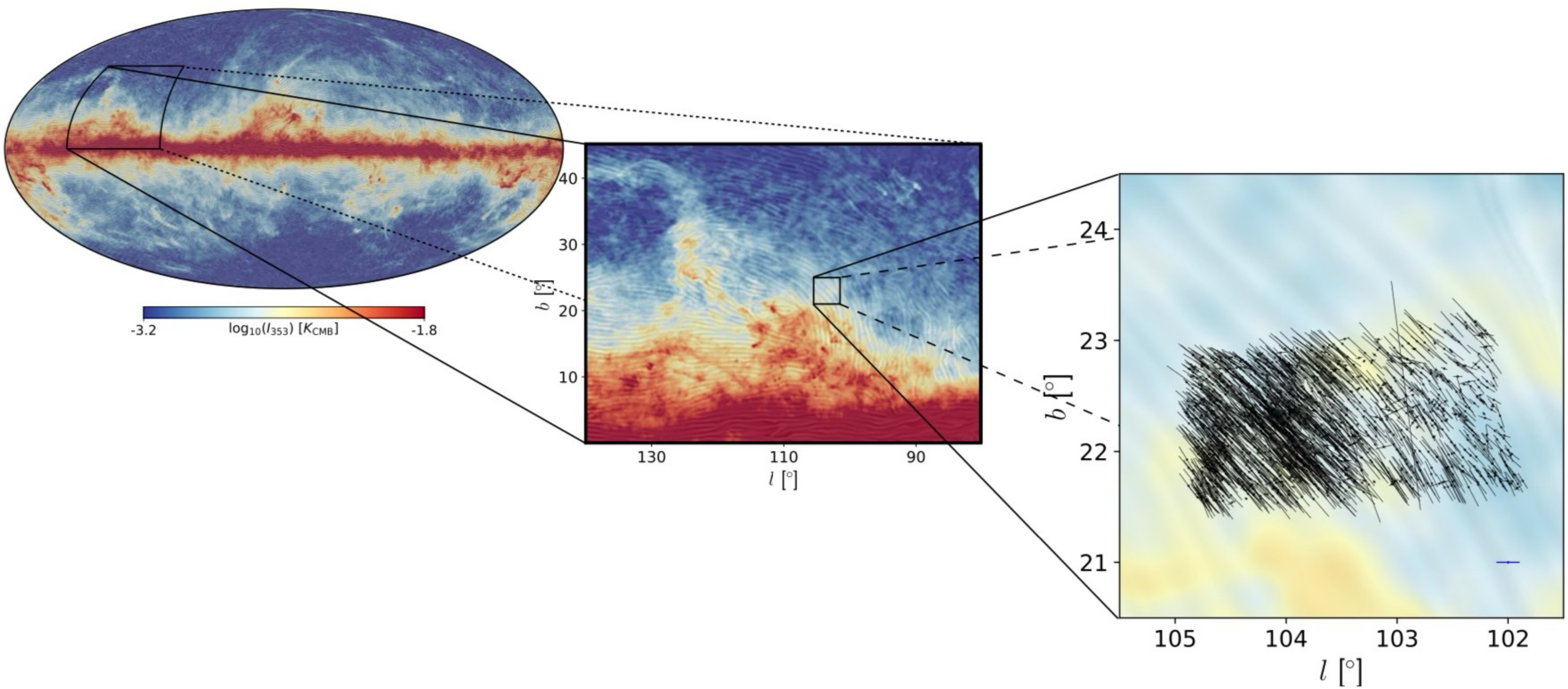


FIRST DEGREE-SCALE 3D MAP OF THE DUSTY MAGNETIZED ISM

[Pelgrims et al. 2024, A&A 684, A162]

★ BISP-1 embedded in a 3D-mapping pipeline

⟶ demonstration on the PASIPHAE-pathfinding survey (~4 sq.deg.)

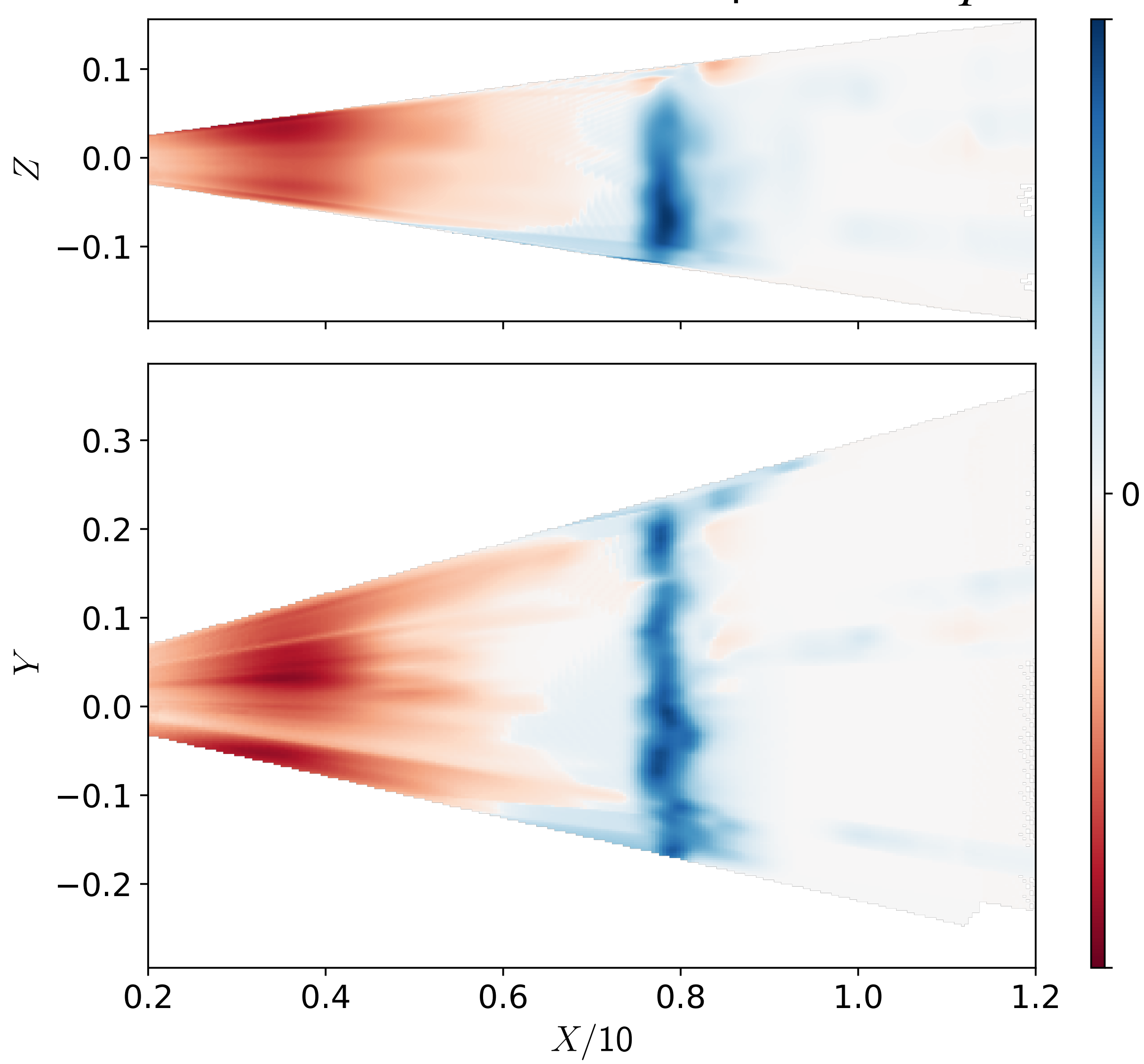


FIRST DEGREE-SCALE 3D MAP OF THE DUSTY MAGNETIZED ISM

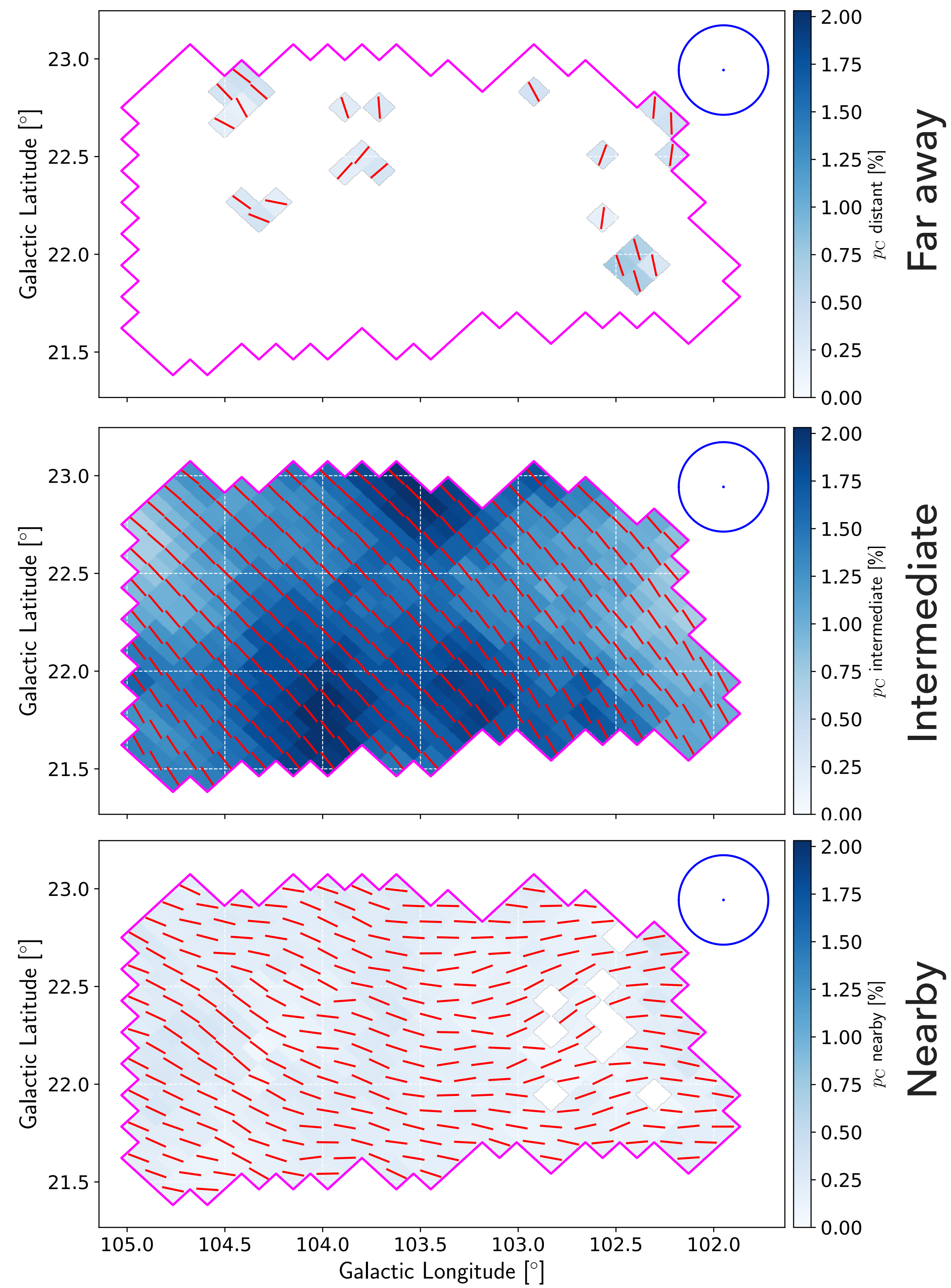
[Pelgrims et al. 2024, A&A 684, A162]

★ Found several dust clouds and measured the plane-of-sky component of the Galactic magnetic field which permeates them

Plane projections
differentials of the Stokes parameter q



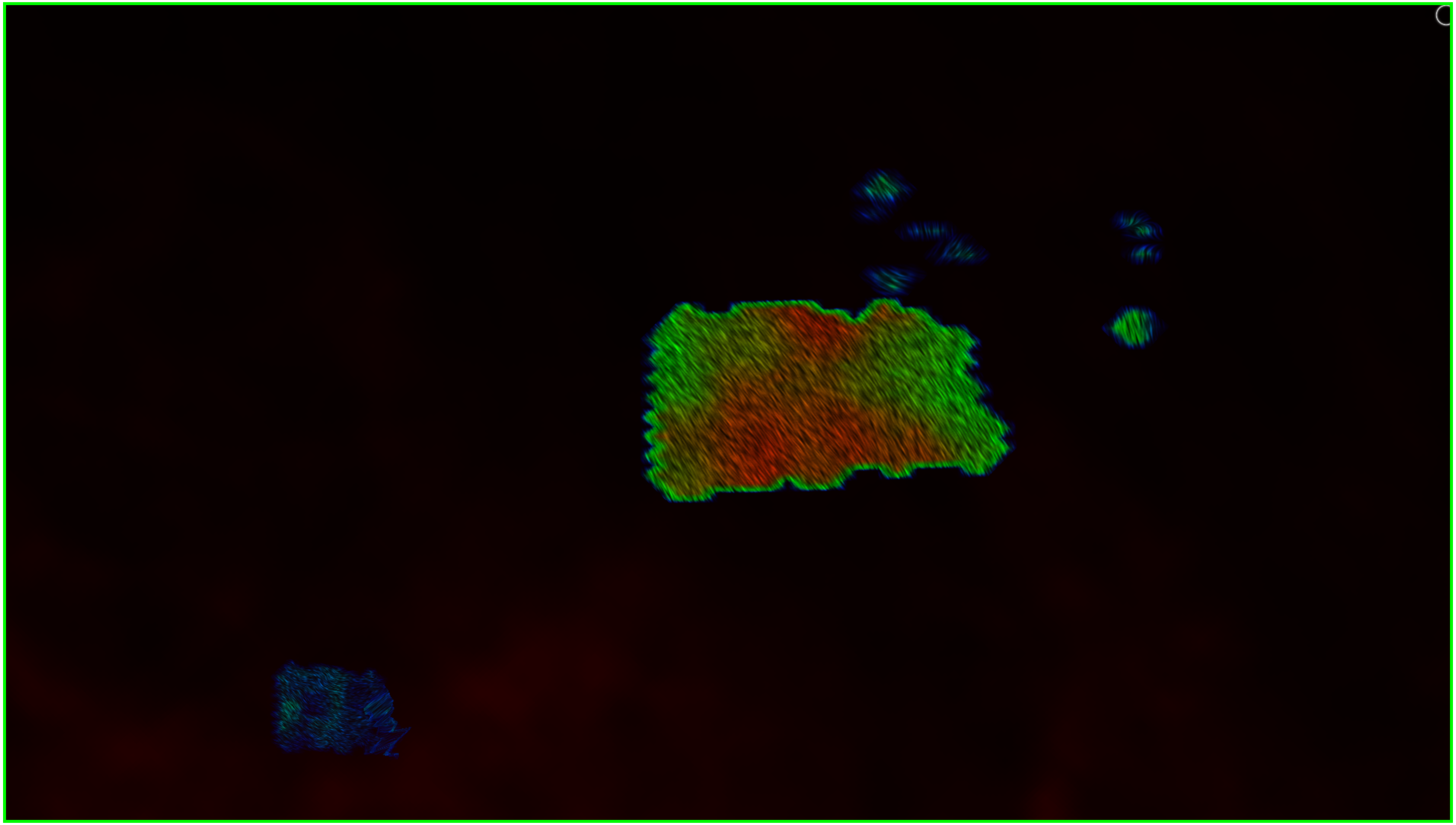
Clouds' polarization degree and angle



FIRST DEGREE-SCALE 3D MAP OF THE DUSTY MAGNETIZED ISM

[Pelgrims et al. 2024, A&A 684, A162]

★ Visualization within ASTERION [video: https://www.youtube.com/watch?v=dB_6J1zhmPI]

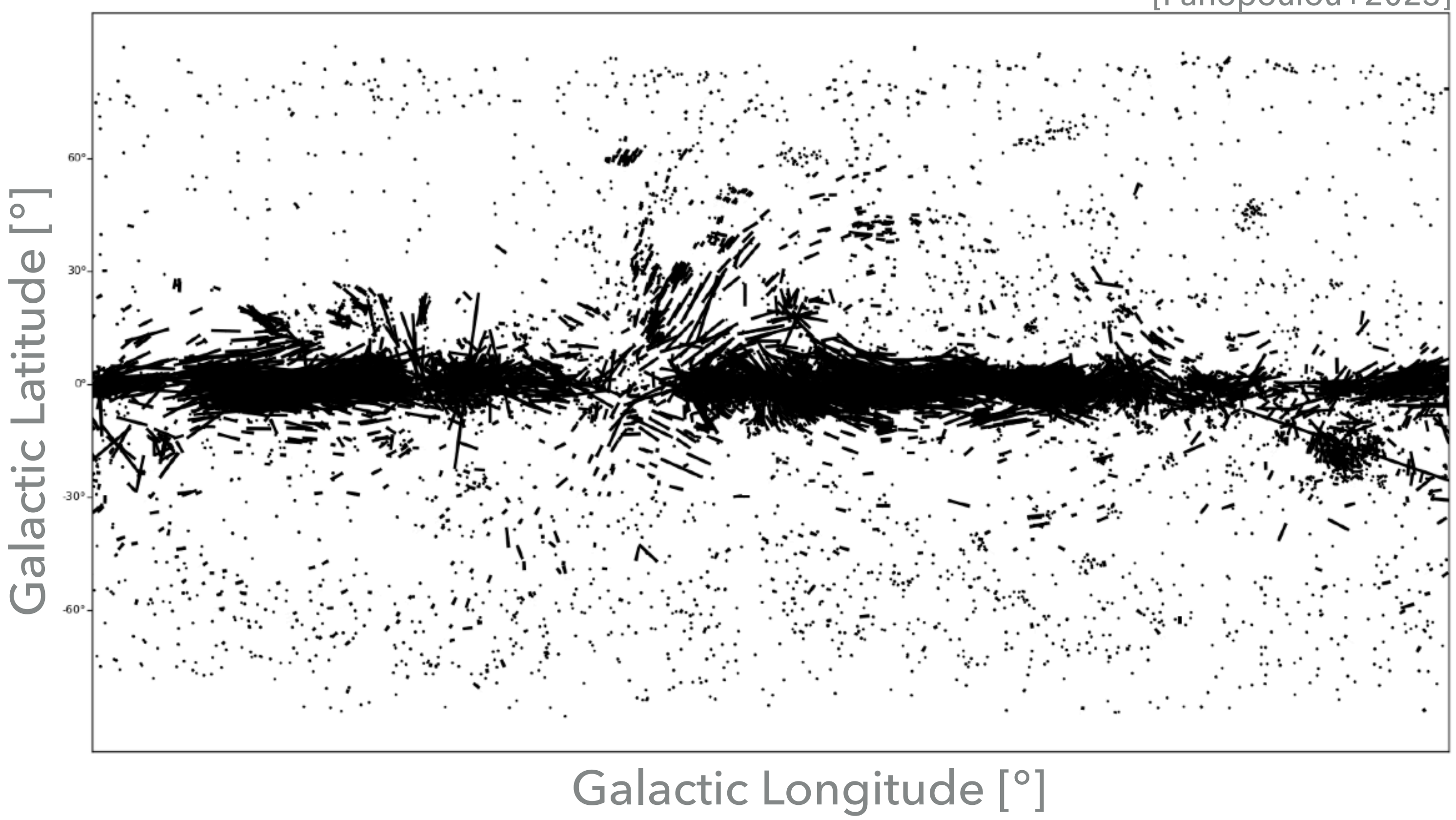


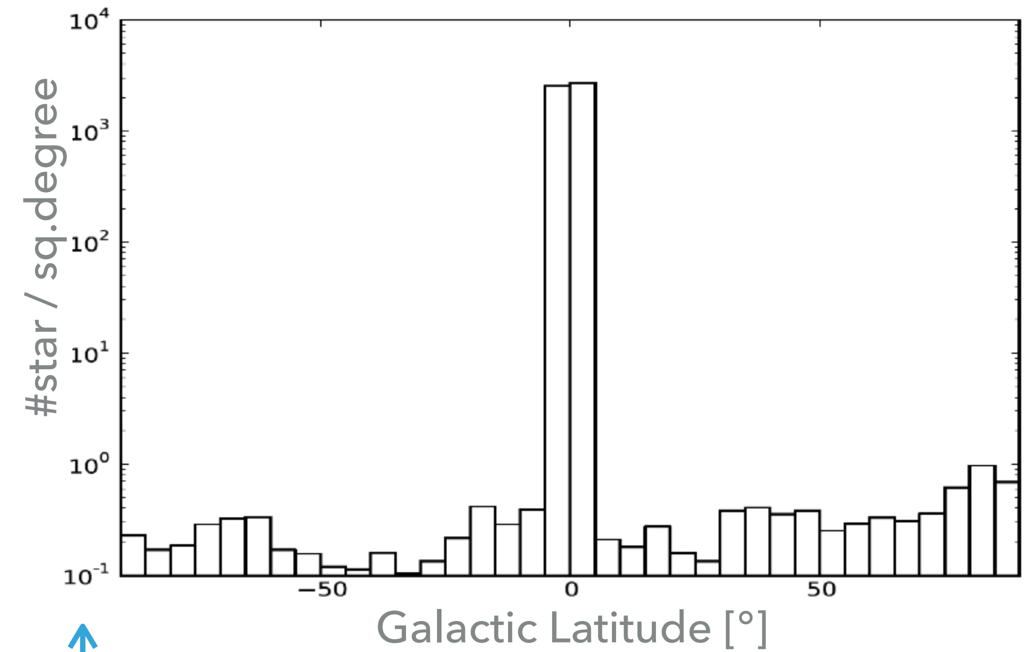
STARLIGHT-POLARIZATION-BASED TOMOGRAPHY OF THE GMF — CURRENT STATUS

★ 3D mapping for large volume of the Milky Way requires large data sample

- cannot be done with current data set: < 1 star per square degree at high latitude

[Panopoulou+2023]





log scale!

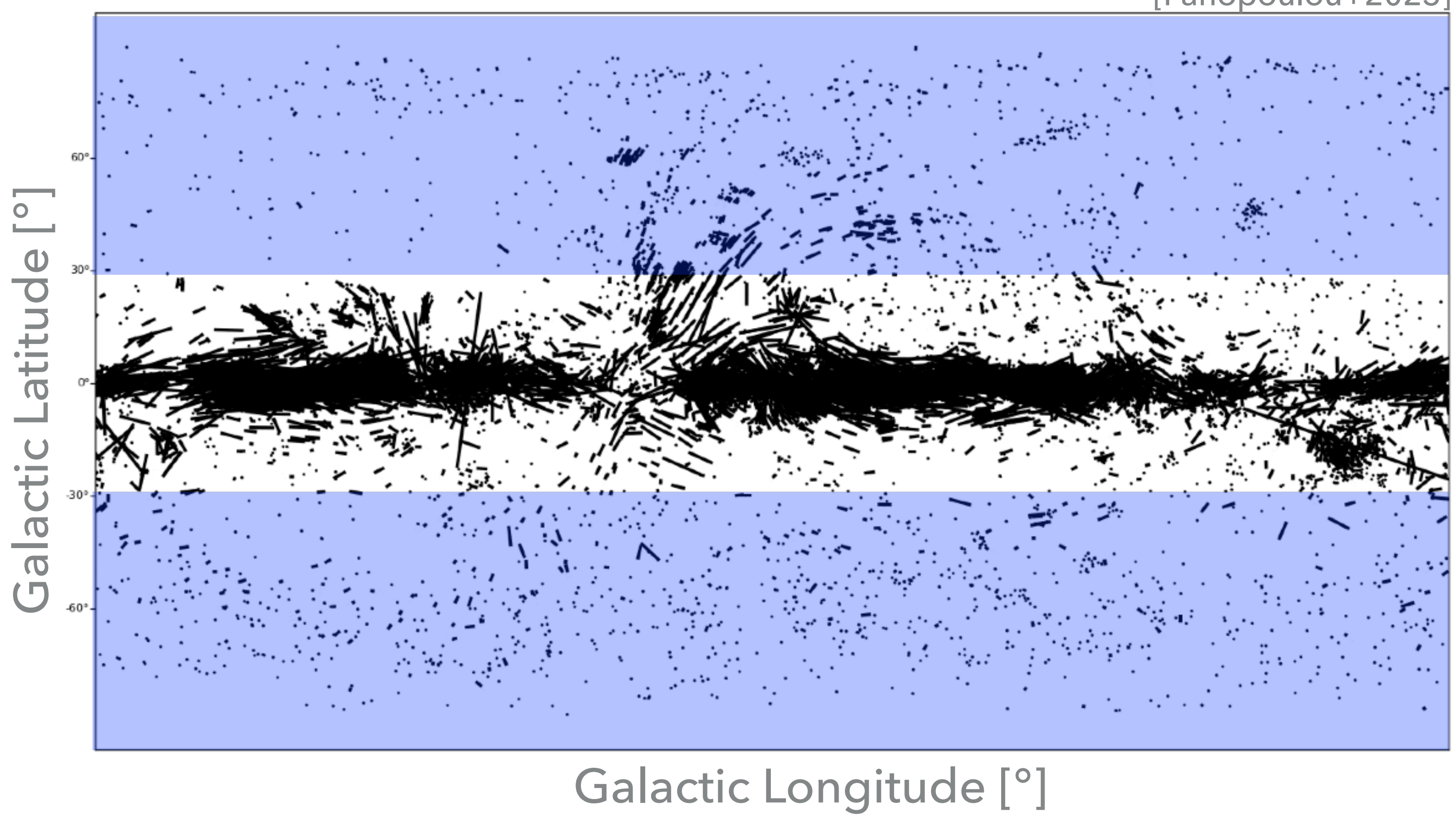
STARLIGHT-POLARIZATION-BASED TOMOGRAPHY OF THE GMF — CURRENT STATUS

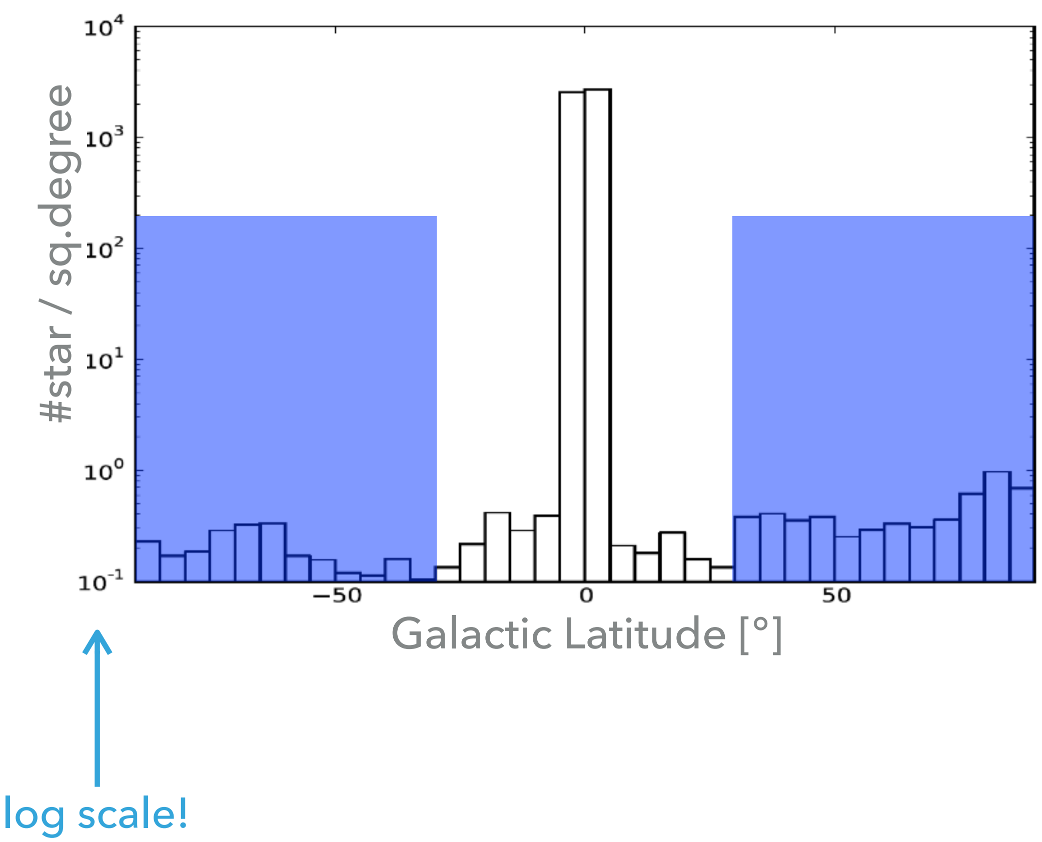
★ 3D mapping for large volume of the Milky Way requires large data sample

✓ about to change thanks to forthcoming surveys: PASIPHAE, South-Pol, SGMAP, VSTpol

✤ PASIPHAE on sky this summer! Survey plan: 4M stars with $\sigma_p \lesssim 0.1\,\%$

[Panopoulou+2023]





STARLIGHT-POLARIZATION-BASED TOMOGRAPHY OF THE GMF — PROMISES

★ 3D map of the plane-of-sky component of the GMF in dusty regions

- up to 1 or 2 kpc from the Sun

★ accurate model for the dust polarized emission,
the most significant limitation to study the primordial Universe (inflation)
based on the Cosmic Microwave Background polarization

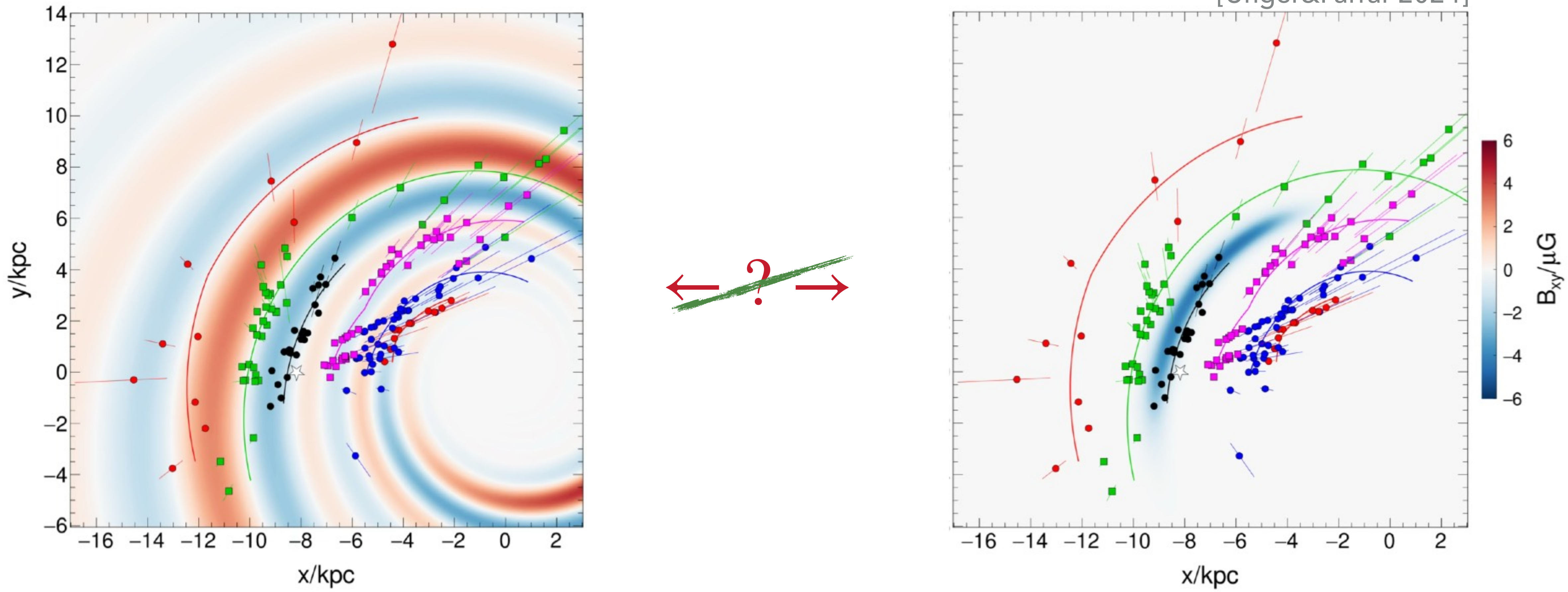
★ Local measurements of the orientation of $\mathbf{B}_{\rm POS}$ and constraints on its amplitude
$\longrightarrow$ Breaking line-of-sight degeneracy in 3D parametric modeling

TOMOGRAPHY OF THE DUSTY MAGNETIZED ISM AND GMF MODELING

★ Local measurements of the orientation of $\mathbf{B}_{\mathrm{POS}}$

⟶ Breaking line-of-sight degeneracy in 3D parametric modeling

[Unger&Farrar 2024]



⟶ improve UHECR backtracking

TAKE-HOME MESSAGE

★ Pierre Auger Observatory is leading to great insights into UHECR properties up to EeV

- Dipole anisotropy
- New features in the energy spectrum
- Energy dependence of composition

★ Effects of GMF need to be included to improve our understanding (source, nature)

- Current GMF models are good (correction uncertainties<corrections in backtracking)
- Degeneracy among models need to be broken to move forward

★ Starlight-polarization-based tomography will make it possible to break the degeneracies due to line-of-sight integrated nature of observables

- Improvements in 3D reconstruction of the GMF
  - UHECR backtracking
  - propagation effects
- Improvements in modeling and characterization of foregrounds to the Cosmic Microwave Background polarization $\longrightarrow$ study of inflation in cosmology

– thanks –

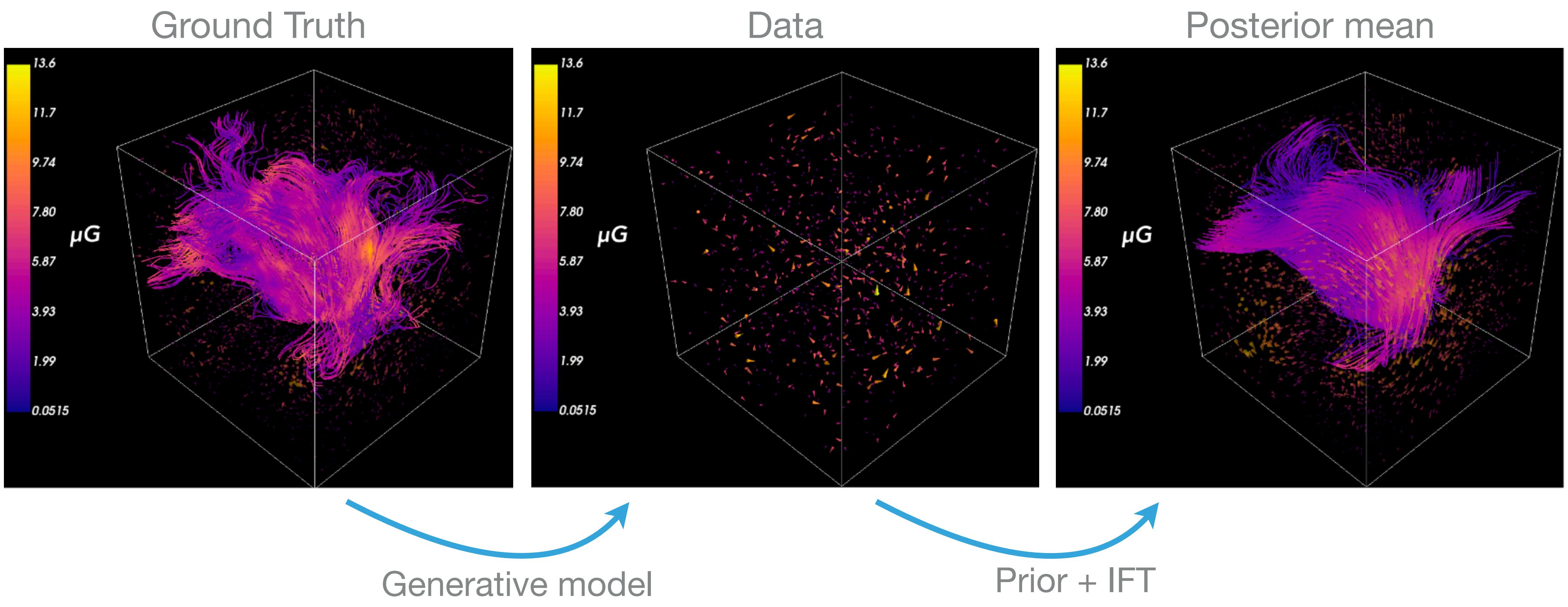
BACKUP —

TOMOGRAPHY OF THE DUSTY MAGNETIZED ISM AND GMF MODELING

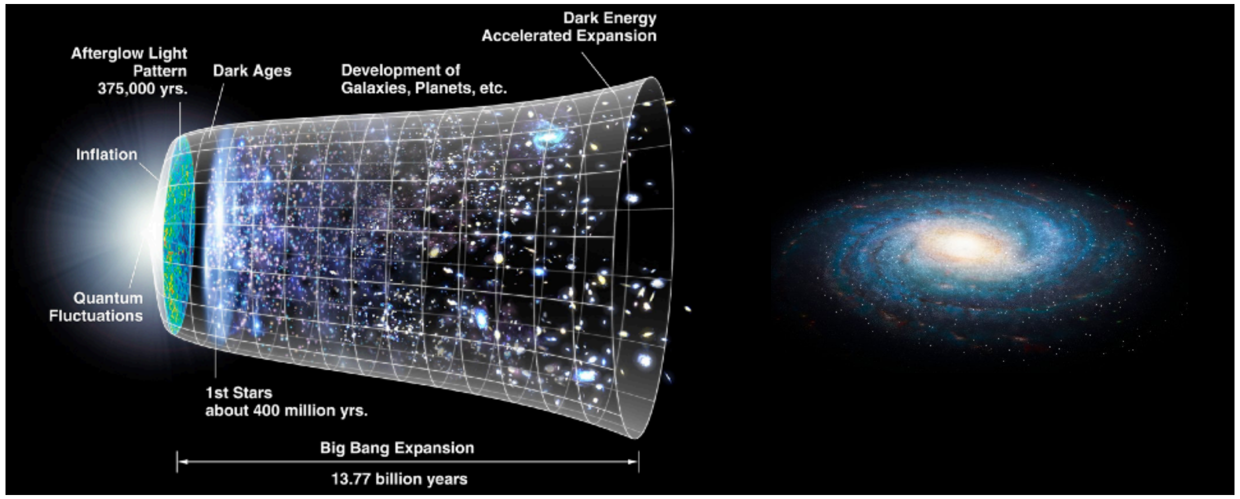
★ Local measurements of the orientation of $\mathbf{B}_{\mathrm{POS}}$

⟶ Breaking line-of-sight degeneracy in 3D parametric modeling

⟶ or used to reconstruct the GMF in 3D using Information Field Theory [Tsouros+ 2024, A&A]



FOREGROUNDS TO COSMIC MICROWAVE BACKGROUND POLARIZATION

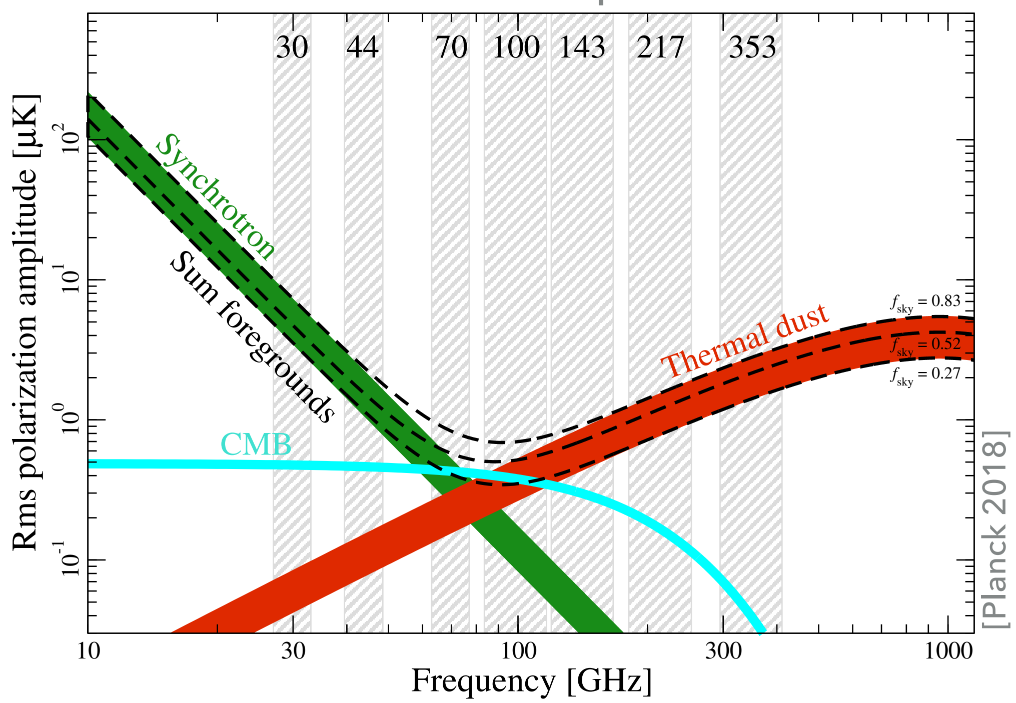


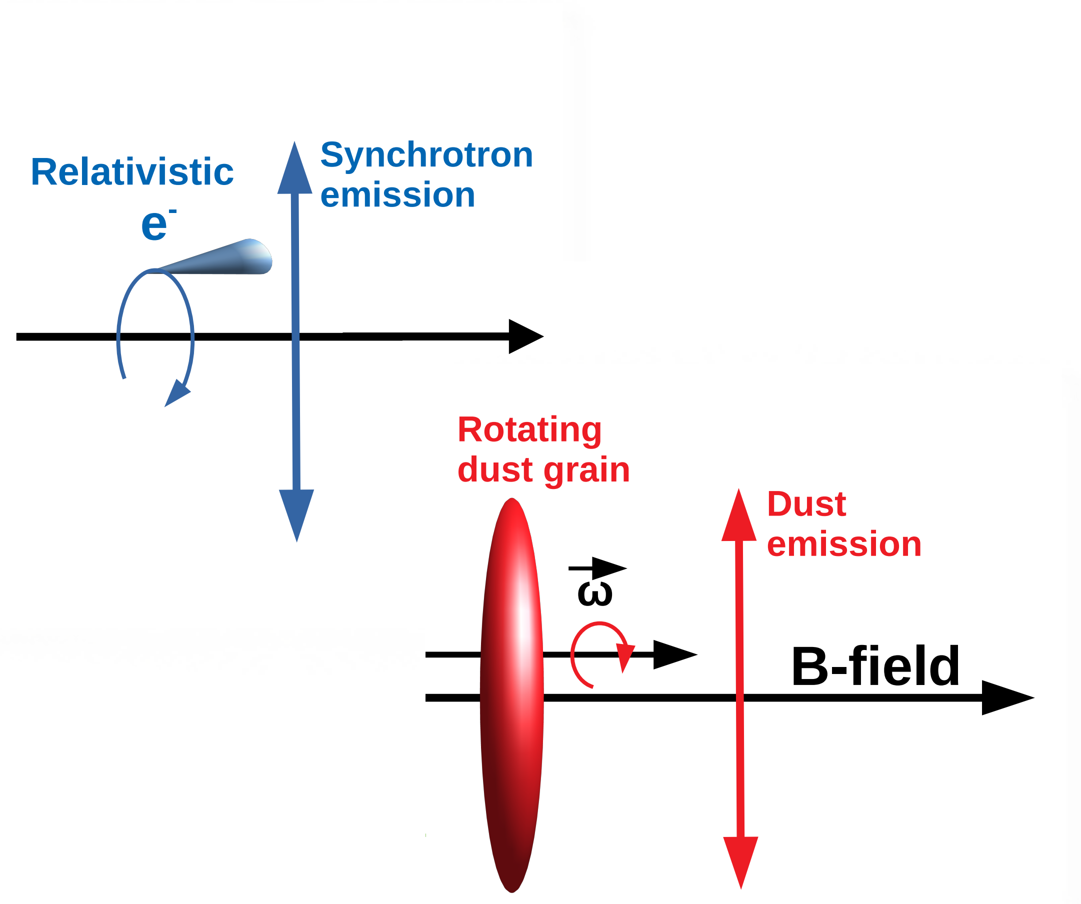
B modes from

- gravitational waves (inflation)
- gravitational lensing by LSS
- **Galactic polarized emission**

⇒ CMB polarization is *always* subdominant, at all frequencies, all scales, everywhere

Polarized components





FOREGROUNDS TO COSMIC MICROWAVE BACKGROUND POLARIZATION

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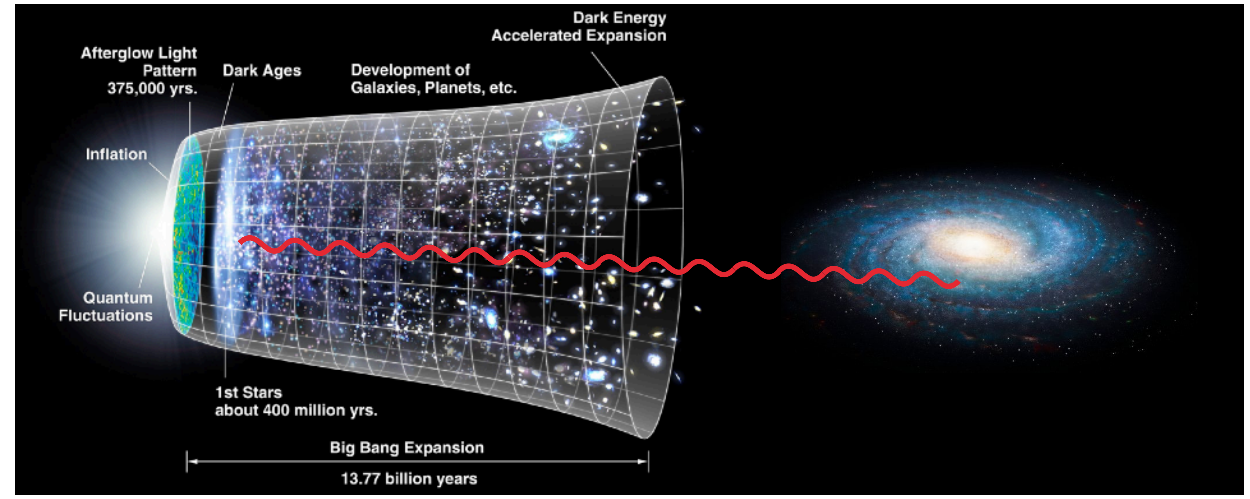
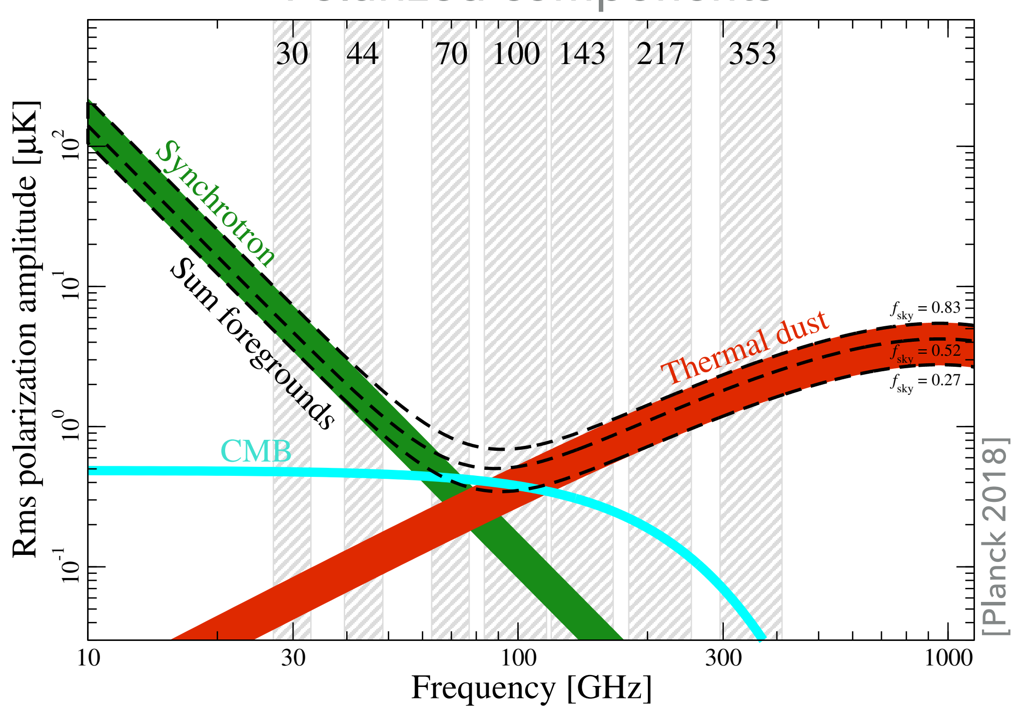
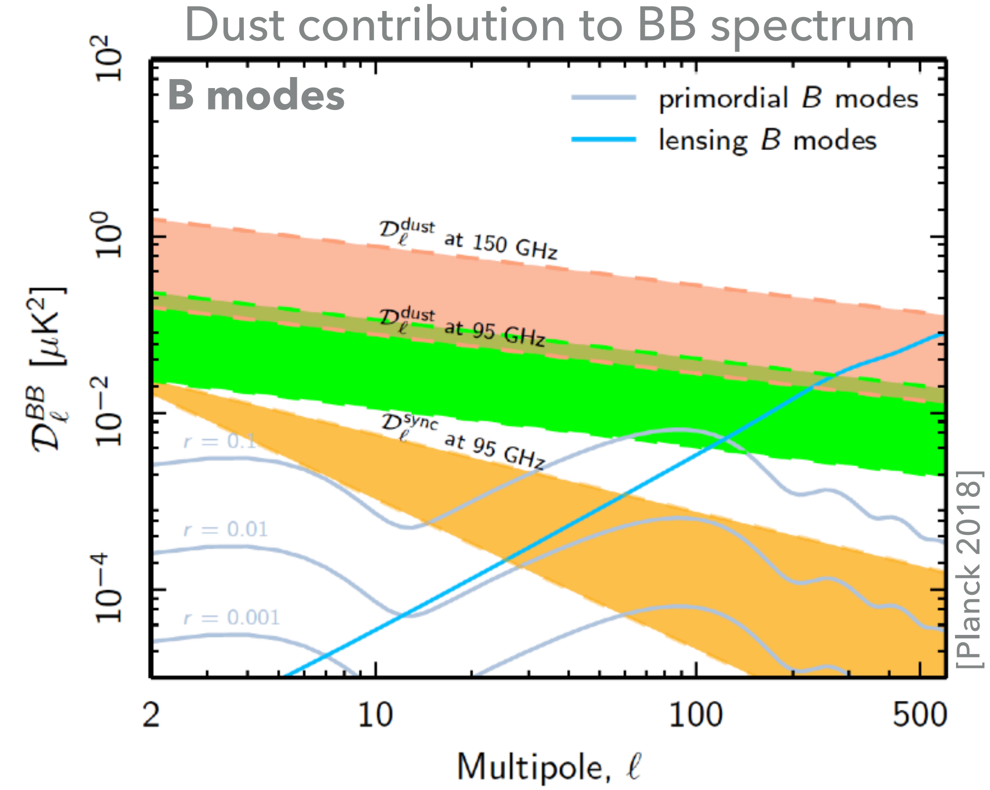


Polarized components

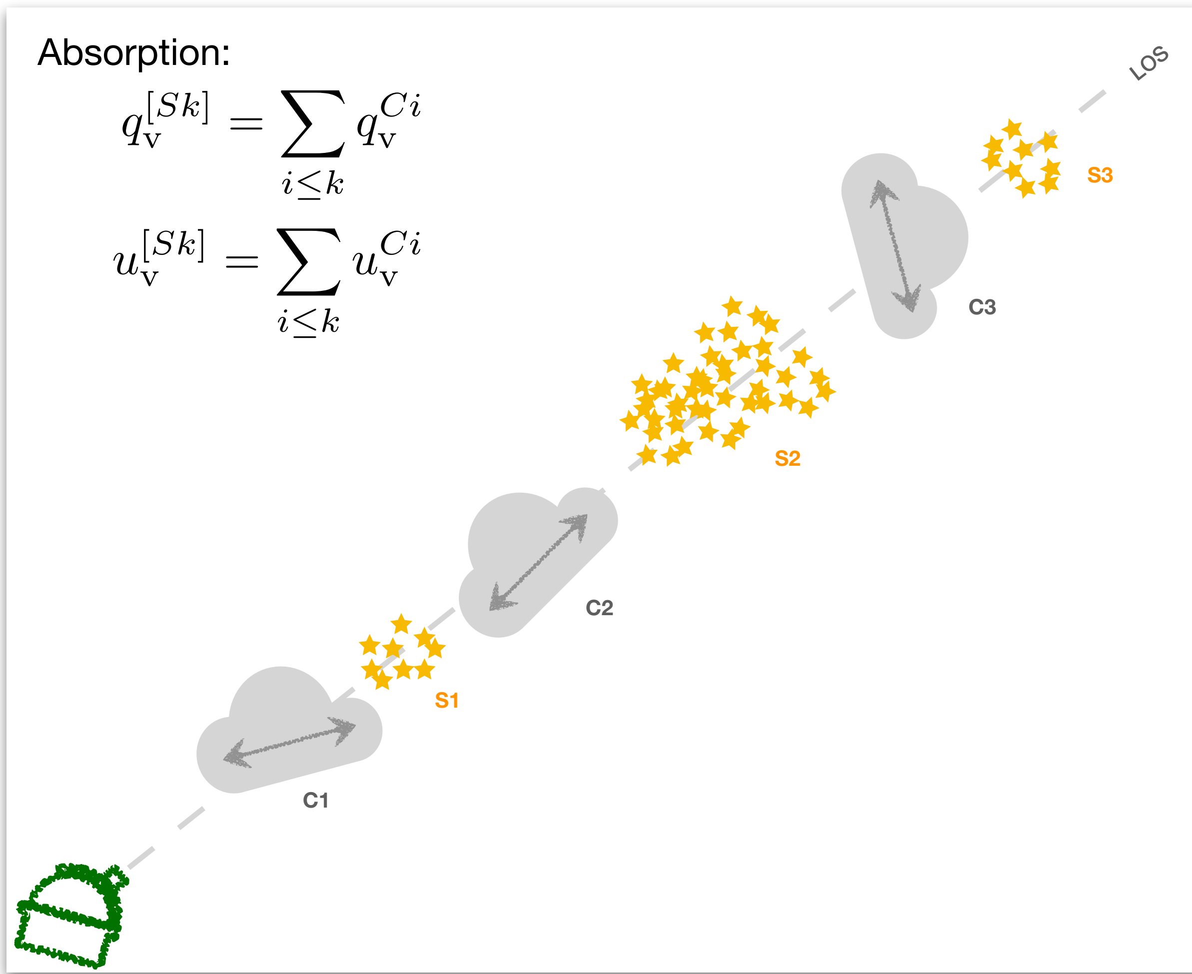


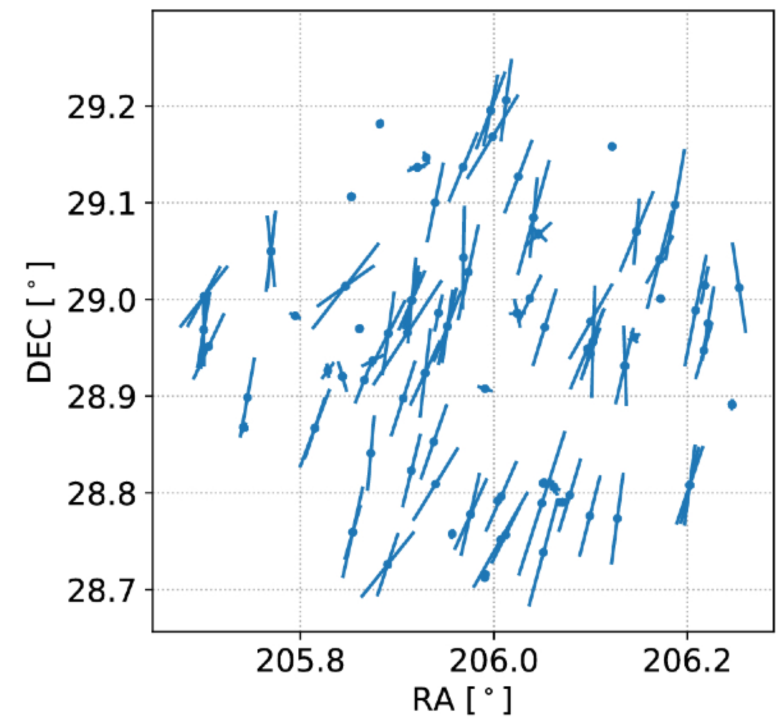
Dust contribution to BB spectrum

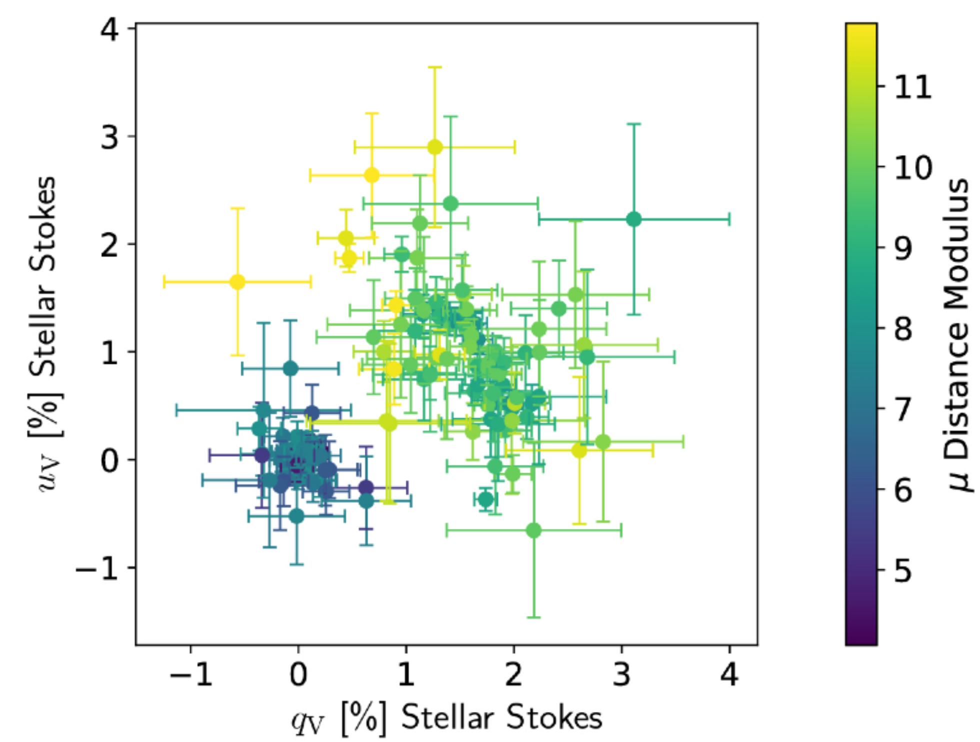


STARLIGHT-POLARIZATION-BASED TOMOGRAPHY

Decomposition of starlight polarization signal along distance **???**







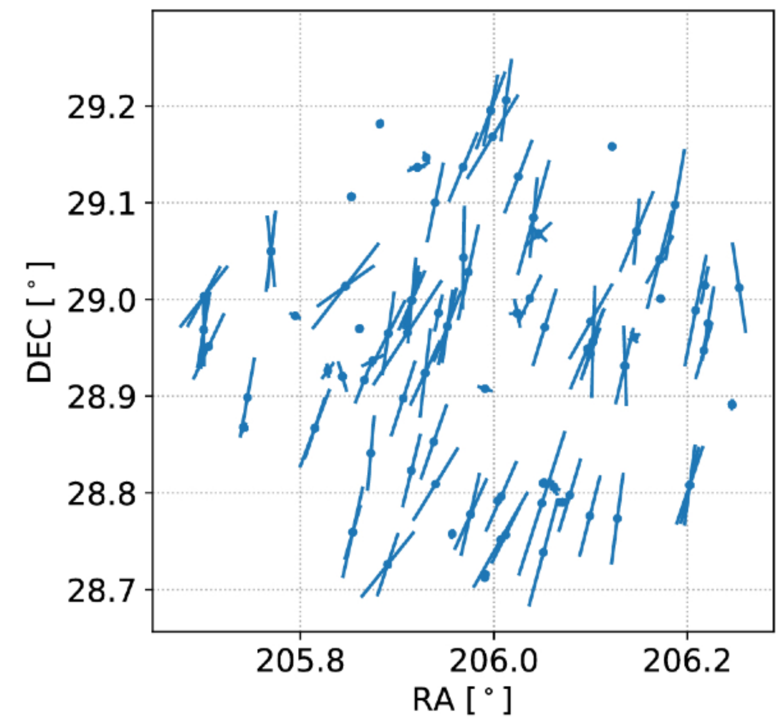
THE INVERSION PROBLEM

[Pelgrims & PASIPHAE 2023]

Decomposition of starlight polarization signal along distance

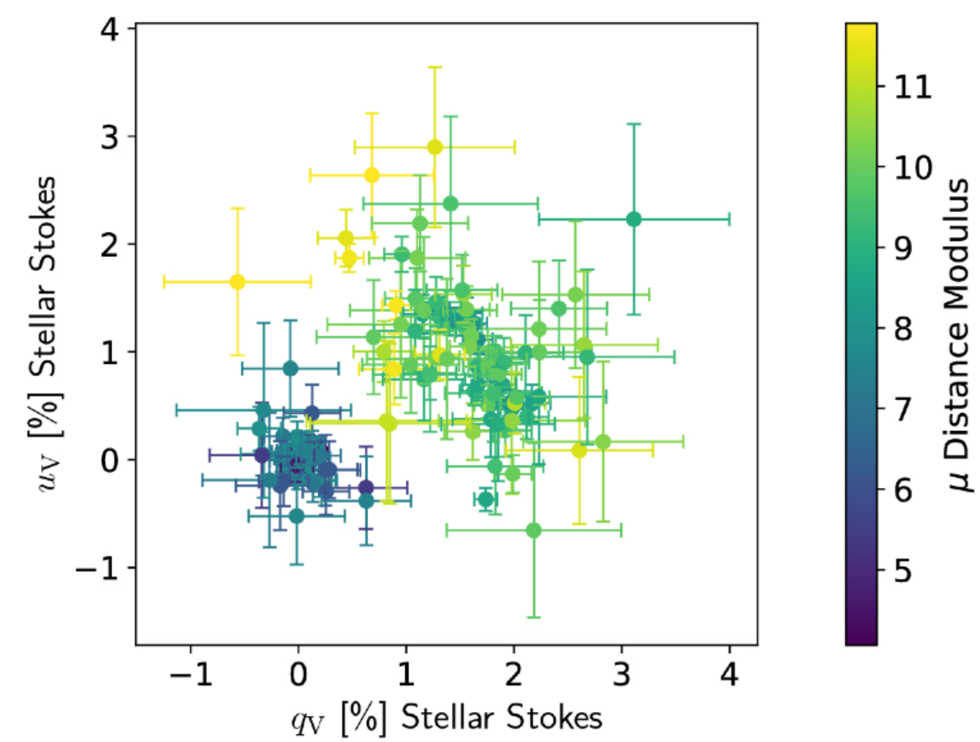
✓ Targets:

- ✓ unknown number of clouds along LOS
- ✓ unknown distances of the clouds
- ✓ unknown mean polarization in clouds
- ✓ unknown contribution from turbulence



◉ Goals:

- ✓ **recover the unknowns**
- ✓ **within a reliable statistical framework**
- ✓ **that leads to well-defined posterior distributions on model parameters**

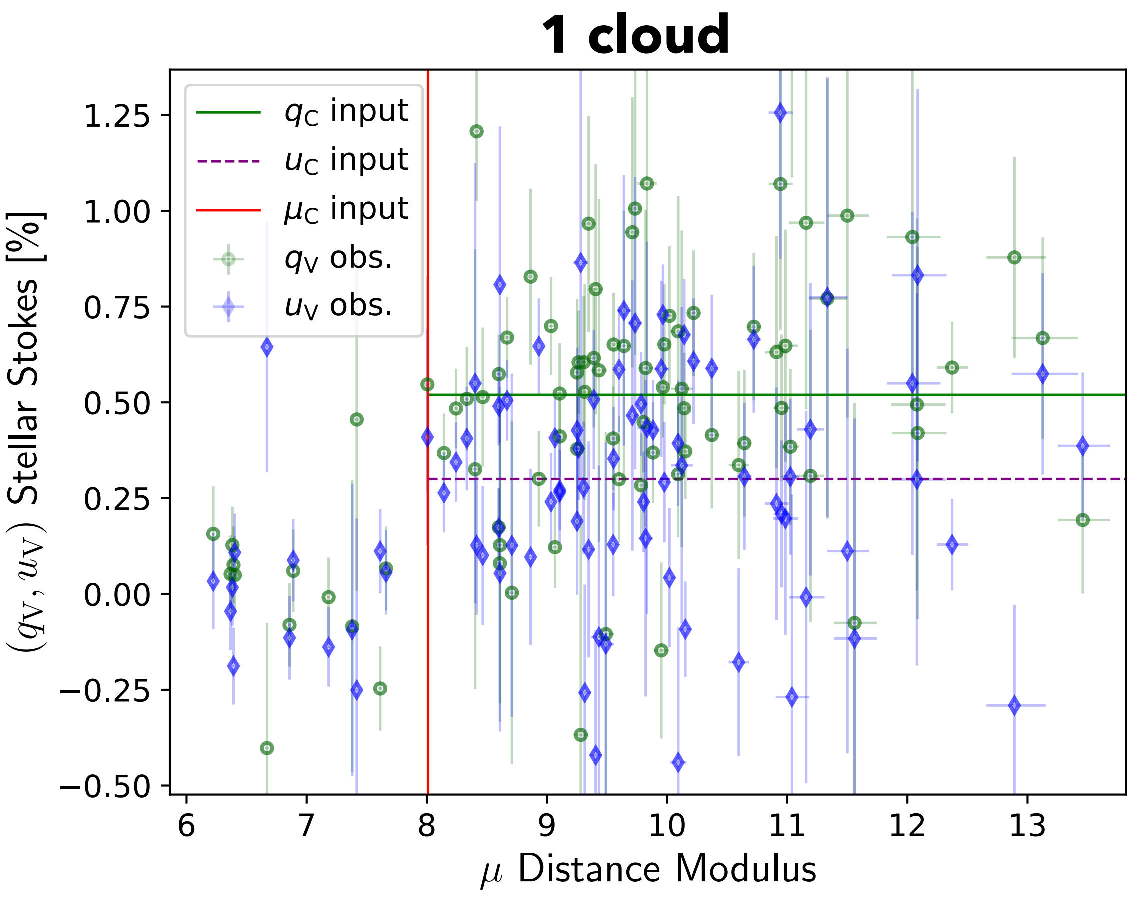


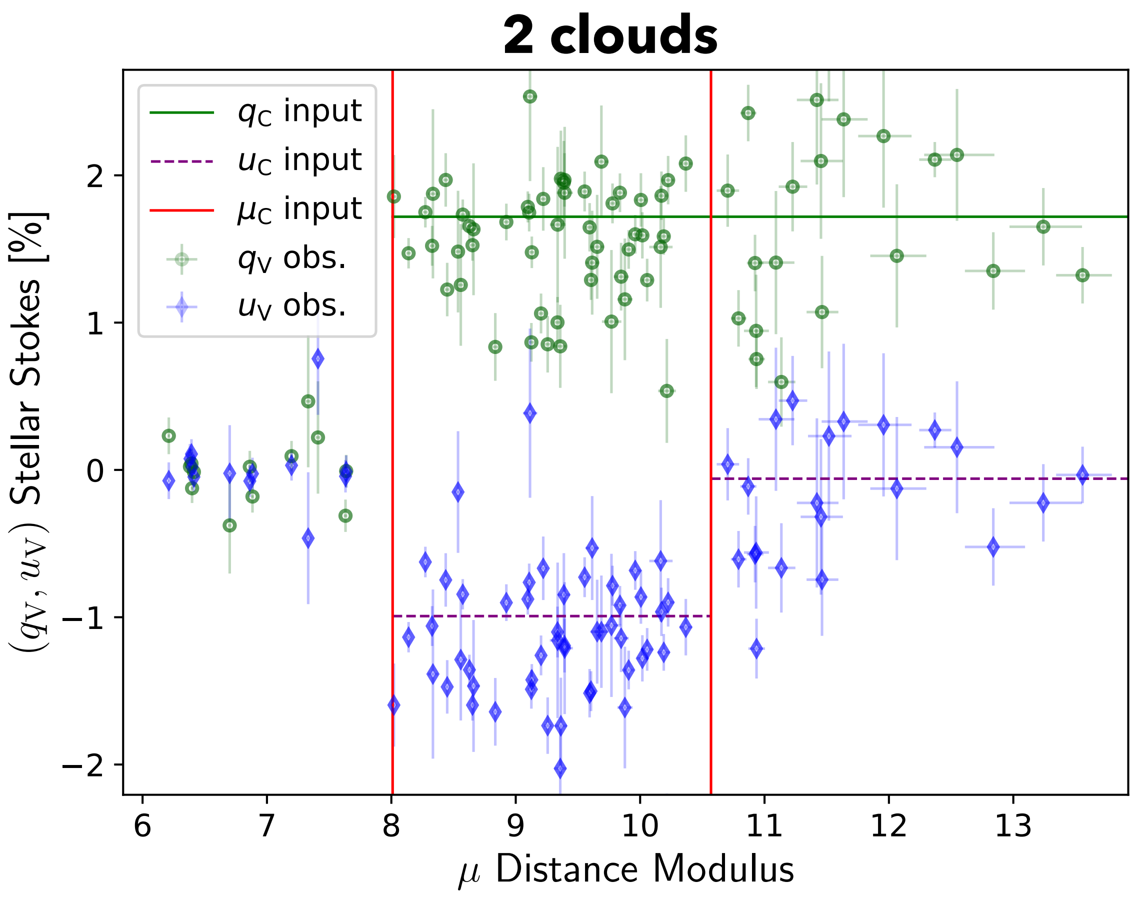
THE INVERSION PROBLEM

[Pelgrims & PASIPHAE 2023]

Typical (simulated) data for 30′-diameter ‘beam’

- ‘observed’ values (mean+turbulence) with Gaia and PASIPHAE noise

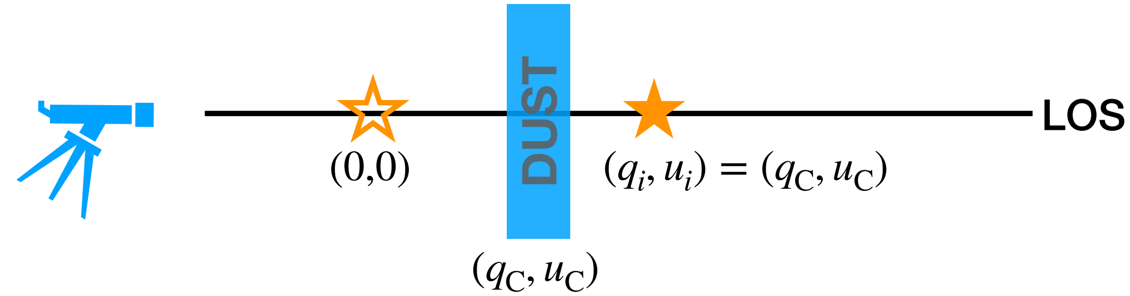




Increment can be either positive, negative or null depending on POS position angle

THE INVERSION PROBLEM

[Pelgrims & PASIPHAE 2023]



Data equation: 1-cloud case

- ✓ cloud signal for star i in a beam

$$\mathbf{m}_i = \begin{pmatrix} q_C \\ u_C \end{pmatrix} + \mathrm{G}_2(\mathbf{0},\, C_{\mathrm{int}})_i$$

- ✓ intrinsic scatter (scatter in the beam from turbulence) = bivariate normal (G_2)

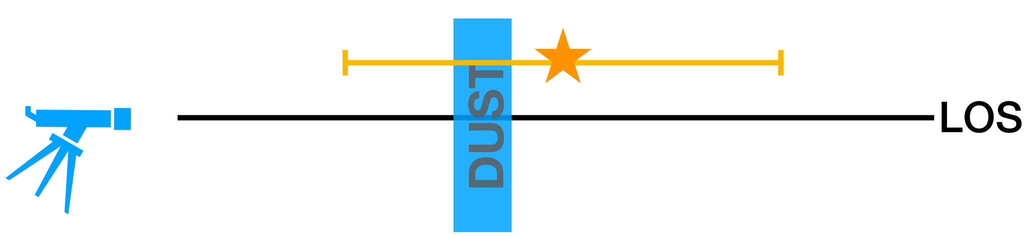
$$\text{where} \quad \begin{pmatrix} q_C \\ u_C \end{pmatrix} = P_{\max}\, \cos^2 \gamma_{\mathbf{B}} \begin{pmatrix} \cos[2\psi_{\mathbf{B}}] \\ \sin[2\psi_{\mathbf{B}}] \end{pmatrix}$$

- ✓ foreground/background implemented using Heaviside function
- ✓ noise and intr. scatter add up

$$\mathbf{s}_i = \mathbf{m}_i\, H(d_i - d_C) + \mathbf{n}_i$$
$$= \begin{cases} \bar{\mathbf{m}} + \mathrm{G}_2(0, C_{\mathrm{int}} + C_{\mathrm{obs},i})_i & \text{if } d_i > d_C \\ \mathbf{0} + \mathrm{G}_2(0, C_{\mathrm{obs},i})_i & \text{otherwise,} \end{cases}$$

- ✓ parallax uncertainties dealt with likelihood of composite model (foreground + background) with analytical coefficients

$$\mathcal{L}_i\,(\varpi_C, \bar{\mathbf{m}}, C_{\mathrm{int}})$$
$$= \int_0^{\infty} \mathrm{d}\varpi_i^0\; P\left(\varpi_i, \mathbf{s}_i \,|\, \varpi_i^0,\, \bar{\mathbf{m}}_i,\, C_{\mathrm{int}},\, \sigma_{\varpi_i},\, C_{\mathrm{obs},i}\right)$$
$$= \underbrace{\int_0^{\varpi_C} \mathrm{d}\varpi_i^0\; P\left(\varpi_i, \mathbf{s}_i \,|\, \varpi_i^0,\, \bar{\mathbf{m}},\, C_{\mathrm{int}},\, \sigma_{\varpi_i},\, C_{\mathrm{obs},i}\right)}_{\text{background}}$$
$$+ \underbrace{\int_{\varpi_C}^{\infty} \mathrm{d}\varpi_i^0\; P\left(\varpi_i, \mathbf{s}_i \,|\, \varpi_i^0,\, \mathbf{0},\, \sigma_{\varpi_i},\, C_{\mathrm{obs},i}\right)}_{\text{foreground}}$$

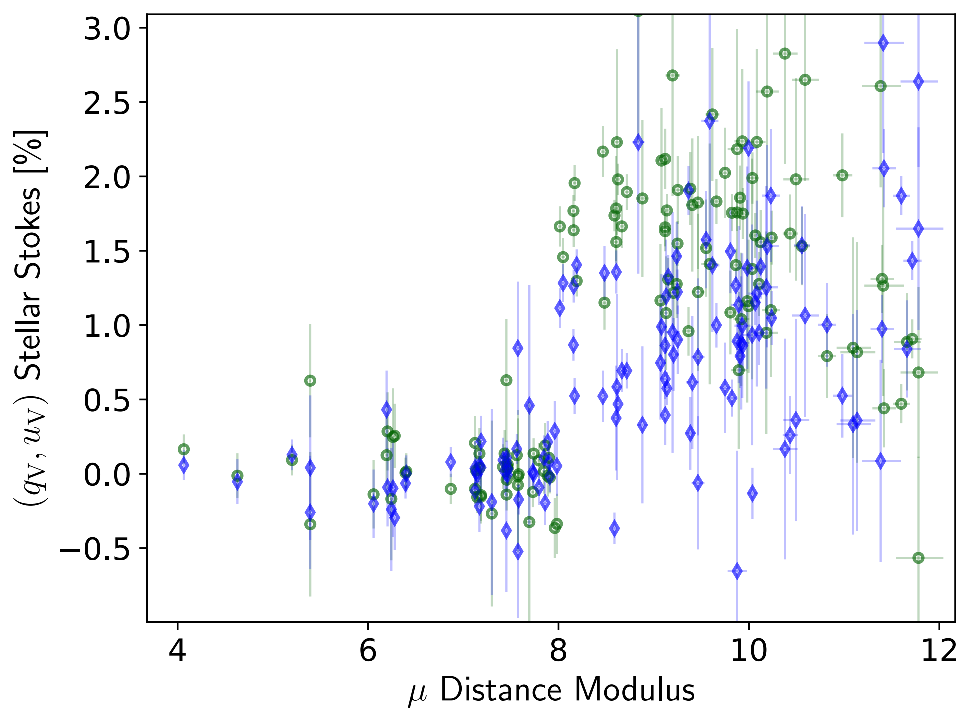


THE INVERSION PROBLEM

[Pelgrims & PASIPHAE 2023]

- Straightforward generalization to N-cloud cases

$$
\begin{aligned}
&\mathcal{L}_i\left(\{\varpi_{\rm C}^{[k]}, \bar{\mathbf{m}}^{[k]}, C_{\rm int}^{[k]}\}\right) \\
&= P_{0,i}\, P\left(\mathbf{s}_i = \mathbf{0} \,|\, C_{{\rm obs},i}\right) \\
&\quad + P_{1,i}\, P\left(\mathbf{s}_i = \bar{\mathbf{m}}^{[1]} \,|\, C_{{\rm obs},i} + C_{\rm int}^{[1]}\right) \\
&\quad + \ldots \\
&\quad + P_{N_c,i}\, P\left(\mathbf{s}_i = \sum_{k=1}^{N_c} \bar{\mathbf{m}}^{[k]} \,|\, C_{{\rm obs},i} + \sum_{k=1}^{N_c} C_{\rm int}^{[k]}\right).
\end{aligned}
$$

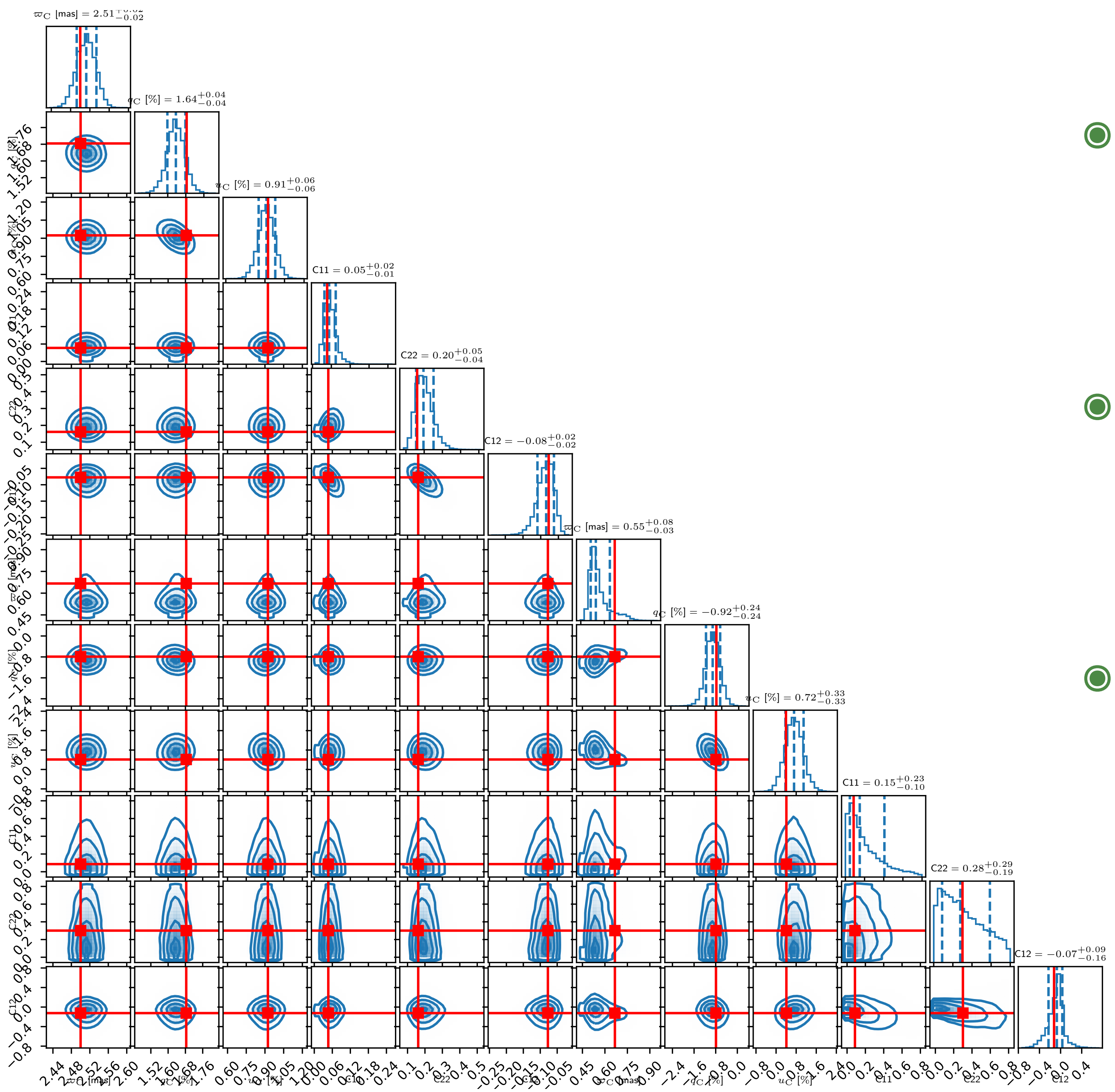


- Likelihood that accounts for
  - ✓ parallax uncertainties
  - ✓ polarization uncertainties
  - ✓ source of intrinsic scatter in the beam
  - Layer model with 6 param. per layer

THE INVERSION PROBLEM

[Pelgrims & PASIPHAE 2023]

Implementation and validation



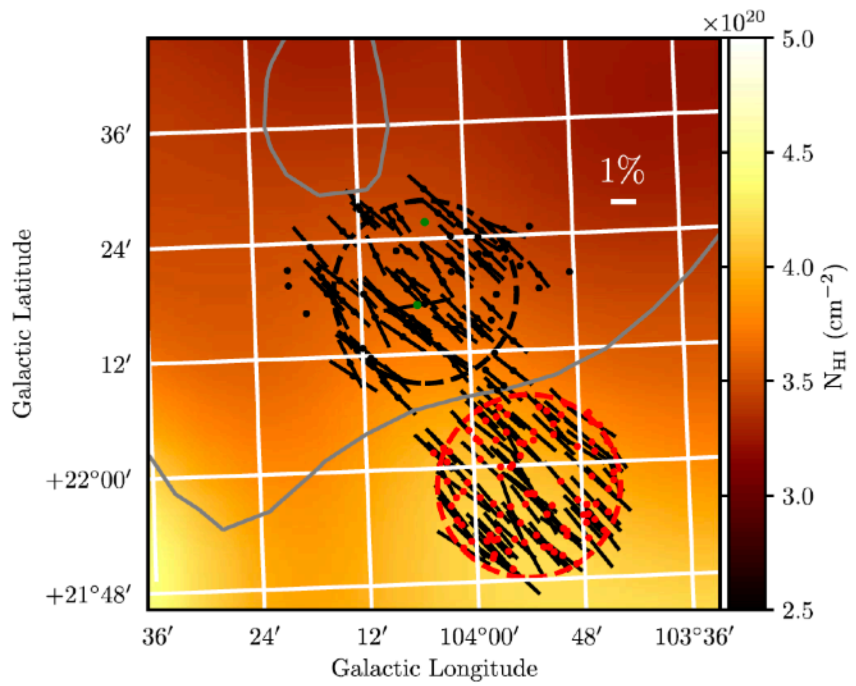
- Log-likelihood maximized through nested sampling method (using `dynesty`)
- Model selection (number of clouds) based on statistical criterion
- Works well on simulated data!

THE INVERSION PROBLEM

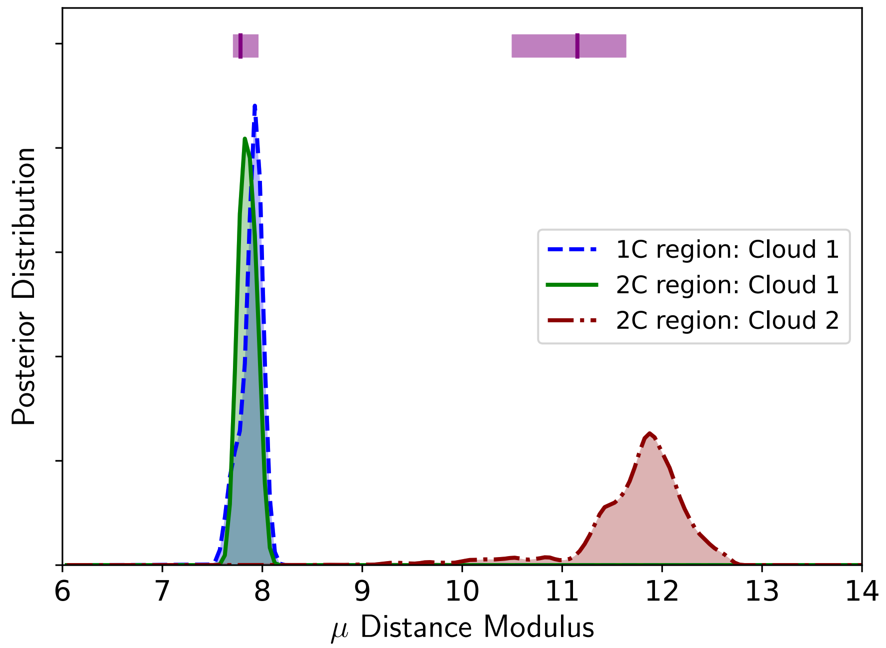
[Pelgrims & PASIPHAE 2023]

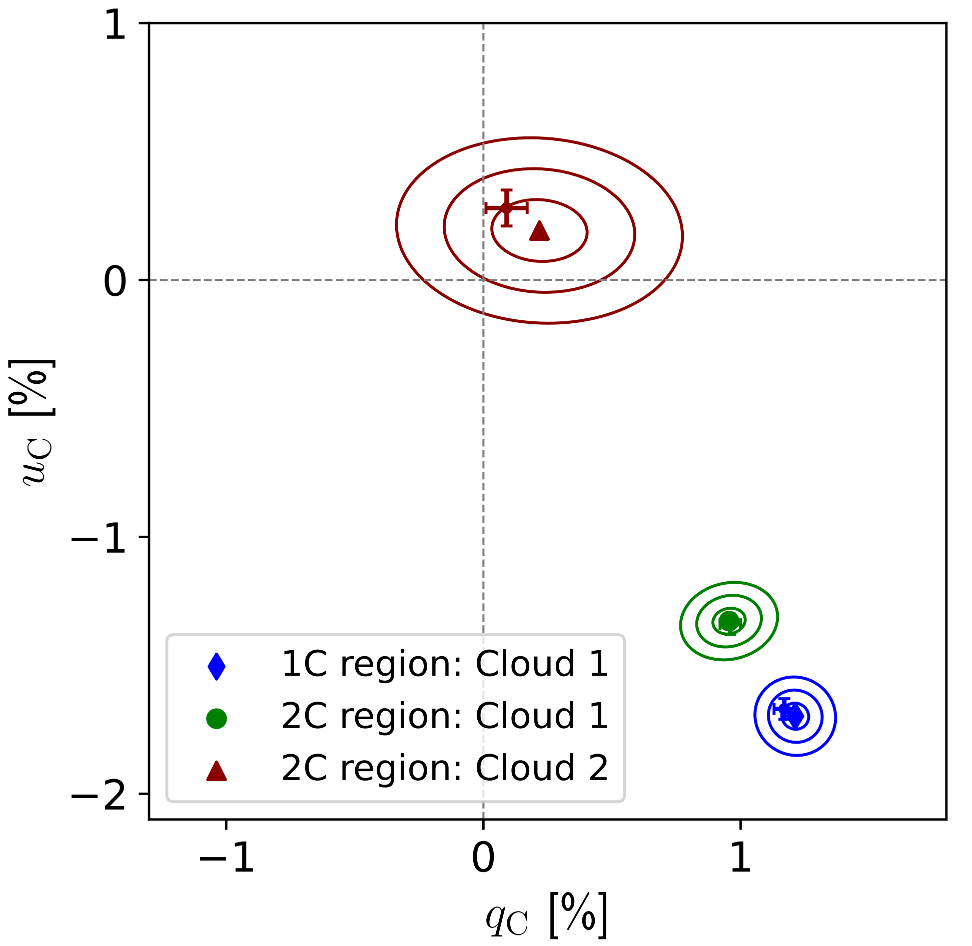
✓ Also works on actual data!

- two 'beams' of [Panopoulou+19]



- Very consistent results on cloud parameters
- Fully agnostic to external data sets
- Robust reconstruction with full posteriors





BISP-1: Bayesian Inference of Starlight Polarization in 1D

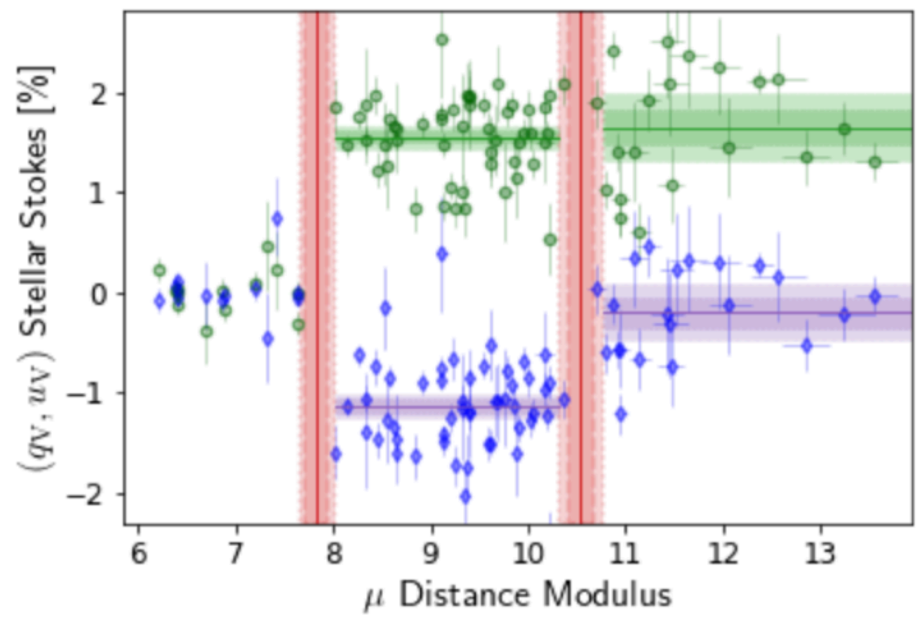
- publicly available: https://github.com/vpelgrims/bisp_1
- all details in Pelgrims et al. 2023, A&A 670, A164

```
mystars = bisp.Stars('sample_2C.csv')
mypriors = bisp.Priors(mystars)
mylos = bisp.Bisp(mystars,mypriors,dlogz=0.05,maxiter=200000)
#
mylos.run_OneLayer()
print('OneLayer done.')
mylos.run_TwoLayers()
print('TwoLayers done.')
mylos.run_ThreeLayers()
print('ThreeLayers done.')
mylos.run_FourLayers()
print('FourLayers done.')
```

```
#print cloud properties
mylos.TwoLayers.printCloudProperties()
```

Clouds	plxC	err_plxC	qC	err_qC	uC	err_uC	dMaha0
Cloud 0	2.7203	0.1396	0.0156	0.0006	-0.0114	0.0006	54.5692
Cloud 1	0.7840	0.0442	0.0009	0.0018	0.0094	0.0016	6.8883

```
# look at the summary plot in (q,u)-mu plane
mylos.stars.showData_QUMU()
mylos.TwoLayers.overPlot_QUMUClouds()
```

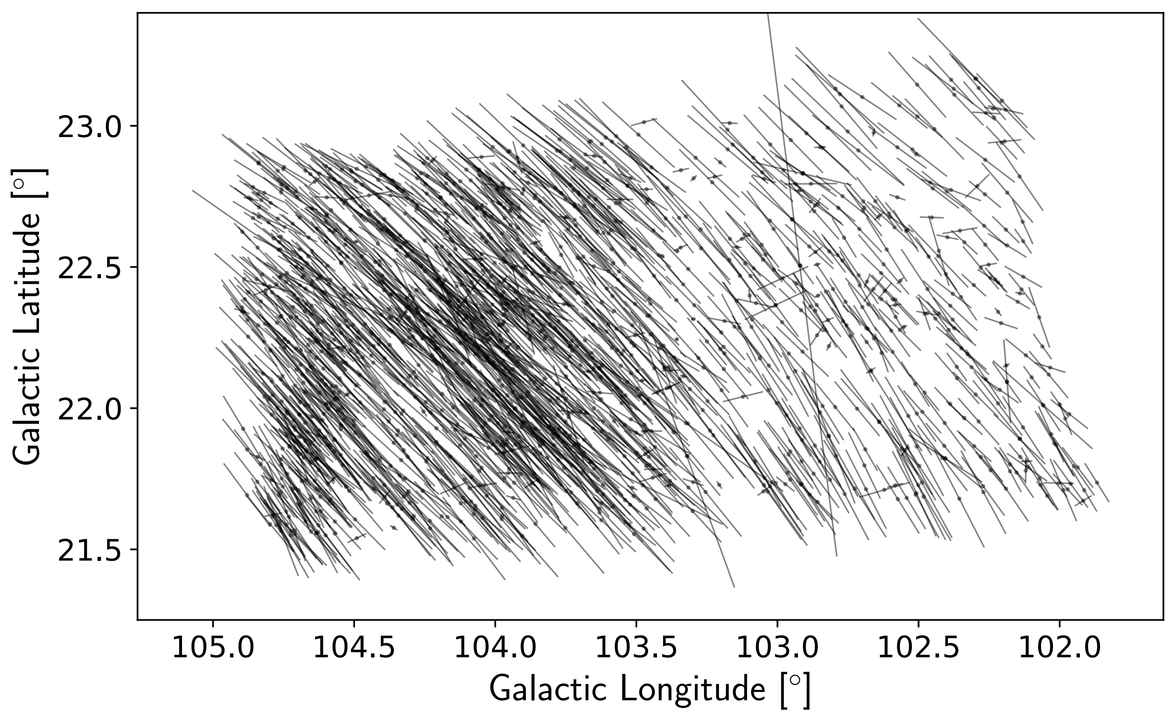


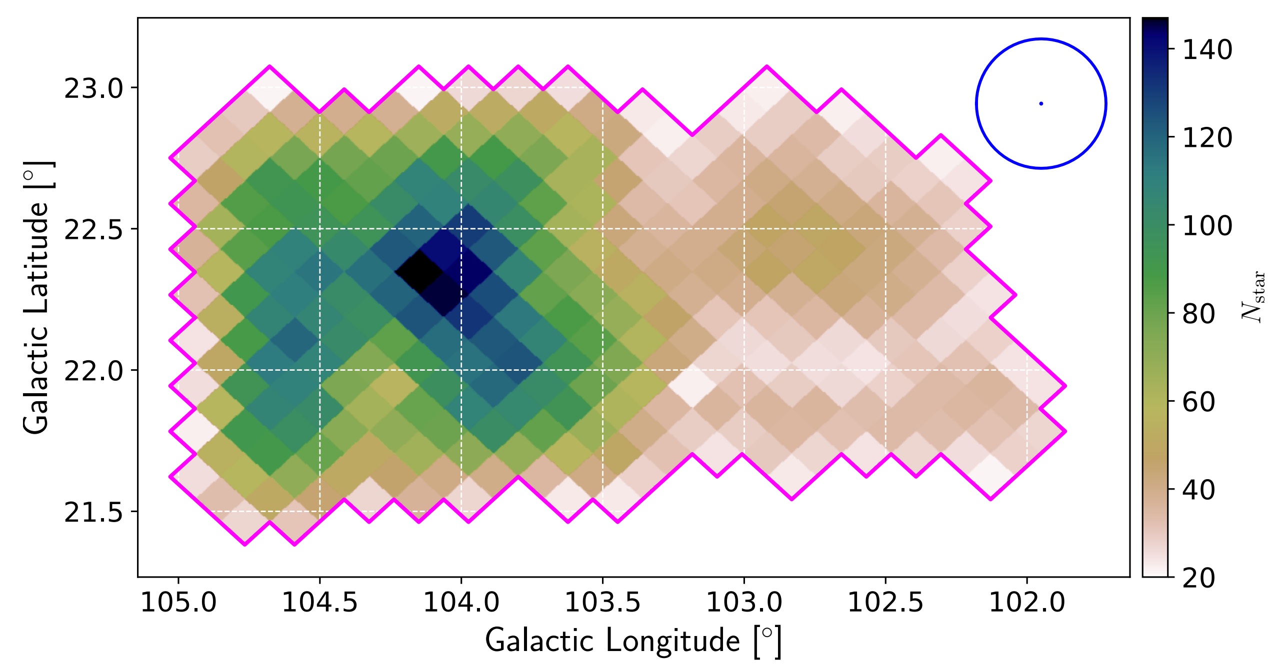
THE FIRST DEGREE-SCALE 3D MAP OF THE DUSTY MAGNETIZED ISM

[Pelgrims & PASIPHAE 2024]

PASIPHAE-pathfinding survey using RoboPol at Skinakas Observatory

- ~1600 stars; inhomogeneous depth/exposure time; ~160 hours from 2019 to 2022
  - ✓ Moving window scan,
  - ✓ apply BISP-1 to every overlapping beam (twice to better correlate beam at small distances)



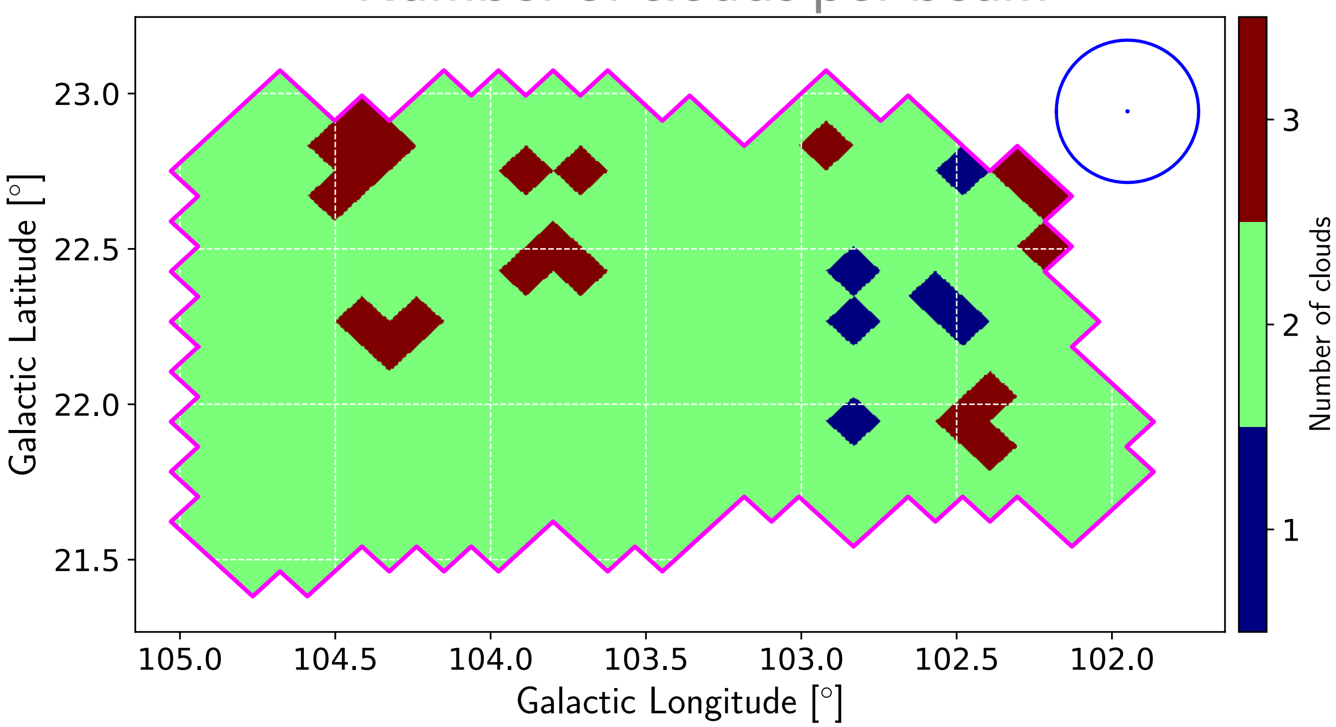


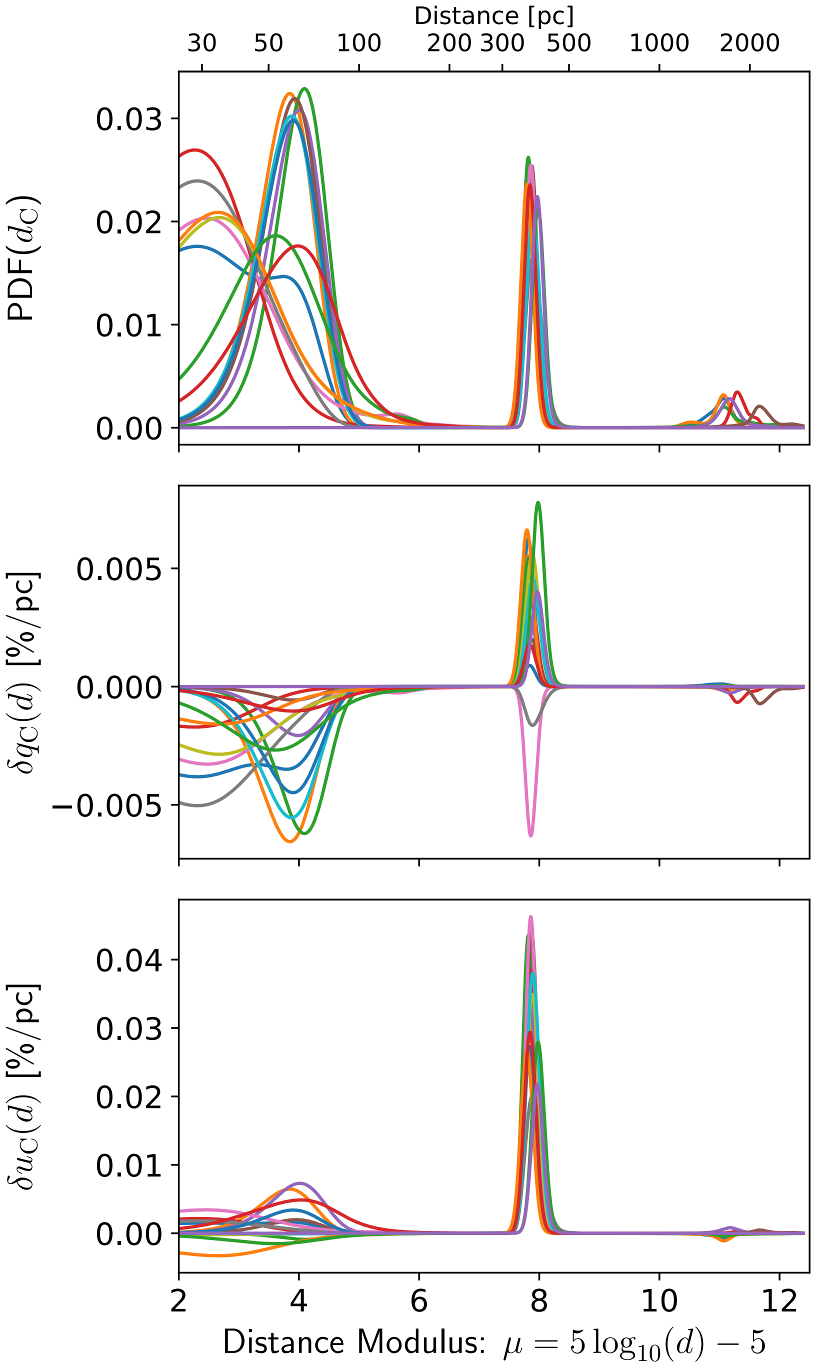
THE FIRST DEGREE-SCALE 3D MAP OF THE DUSTY MAGNETIZED ISM

[Pelgrims & PASIPHAE 2024]

PASIPHAE-pathfinding survey using RoboPol at Skinakas Observatory

- ✓ Moving window scan,
- ✓ apply BISP-1 to every overlapping beam
- ✓ model selection
- ✓ construction of radial profiles



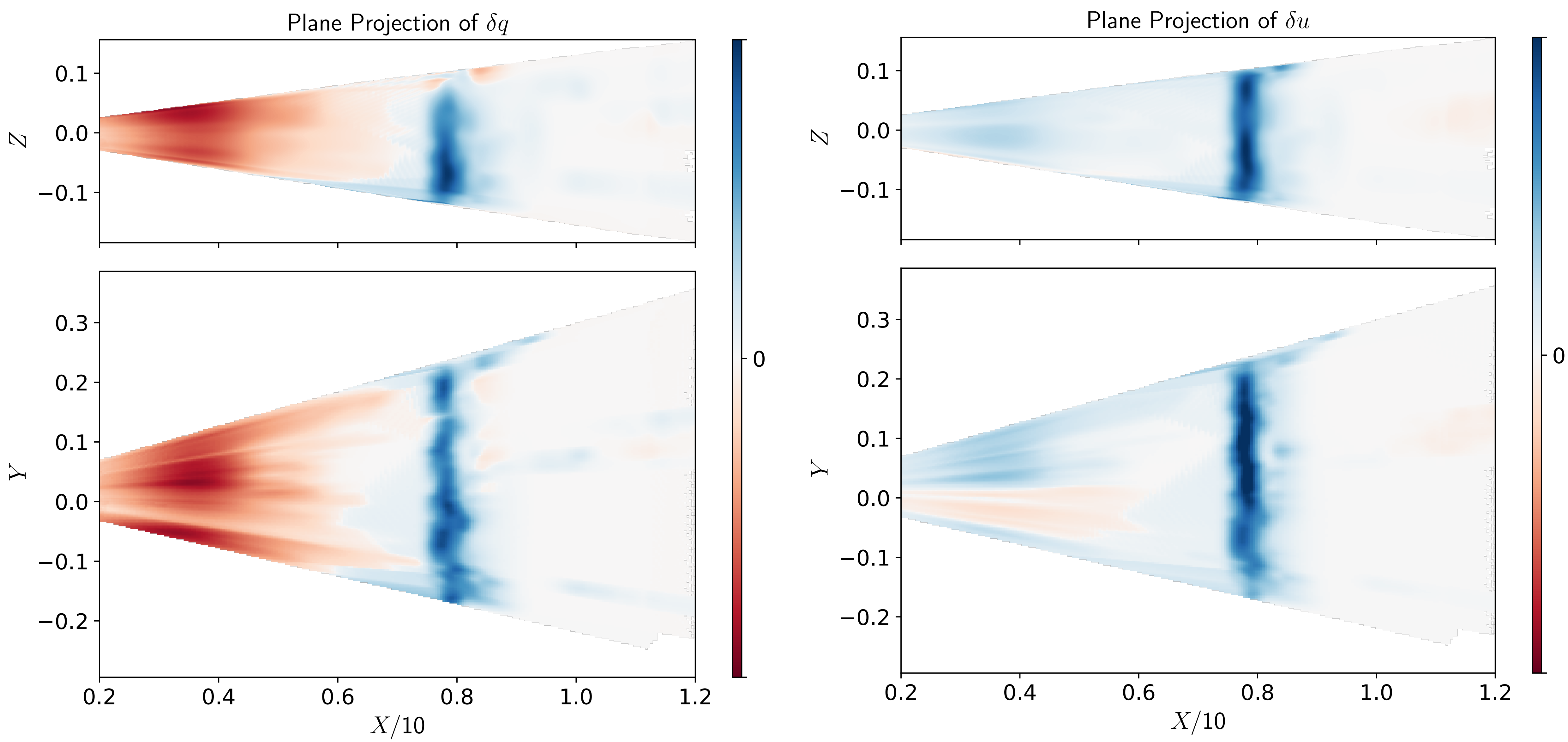


THE FIRST DEGREE-SCALE 3D MAP OF THE DUSTY MAGNETIZED ISM

[Pelgrims & PASIPHAE 2024]

The first 3D map of the dusty magnetized ISM for a ~4 sq.deg. region

✓ Plane projections of the differentials of the Stokes parameters

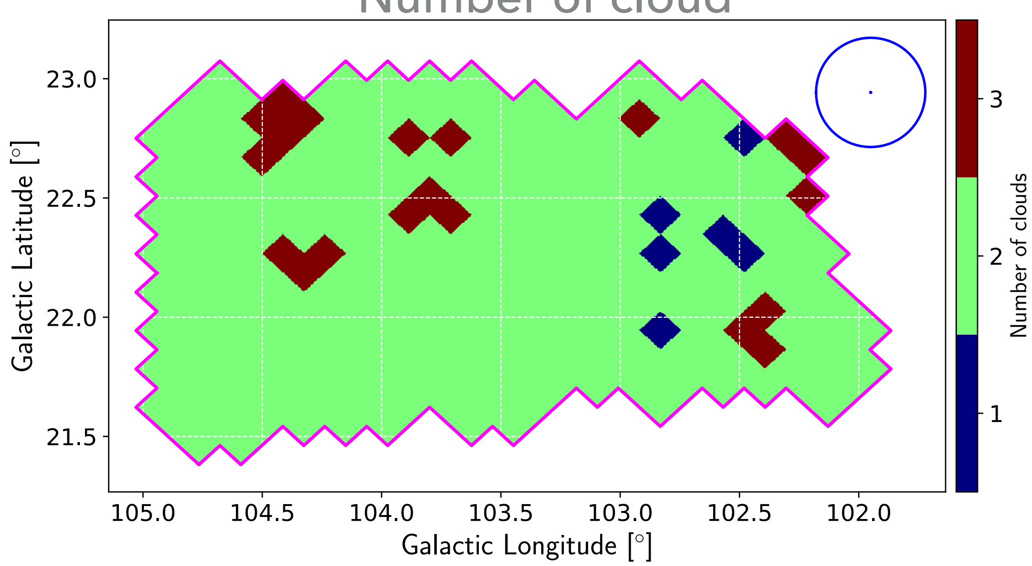


THE FIRST DEGREE-SCALE 3D MAP OF THE DUSTY MAGNETIZED ISM

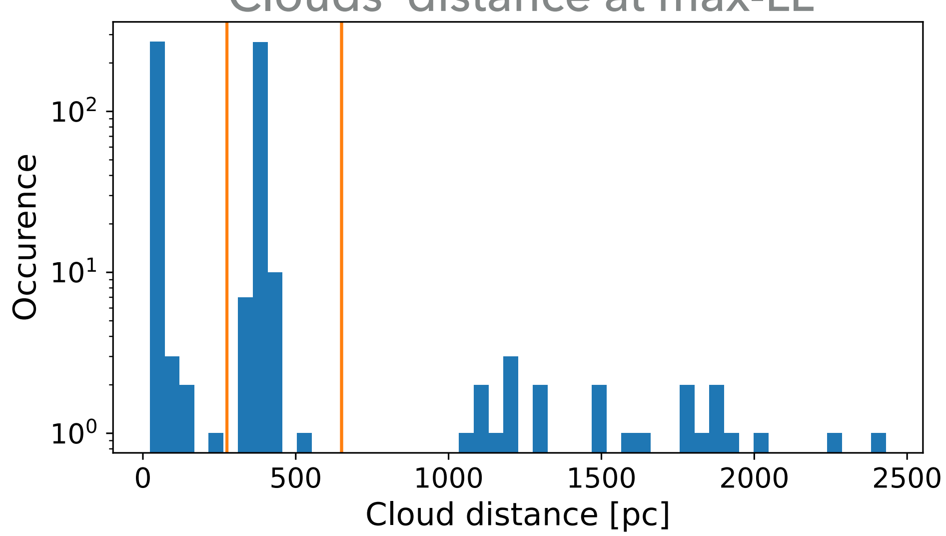
[Pelgrims & PASIPHAE 2024]

- Decomposition in components

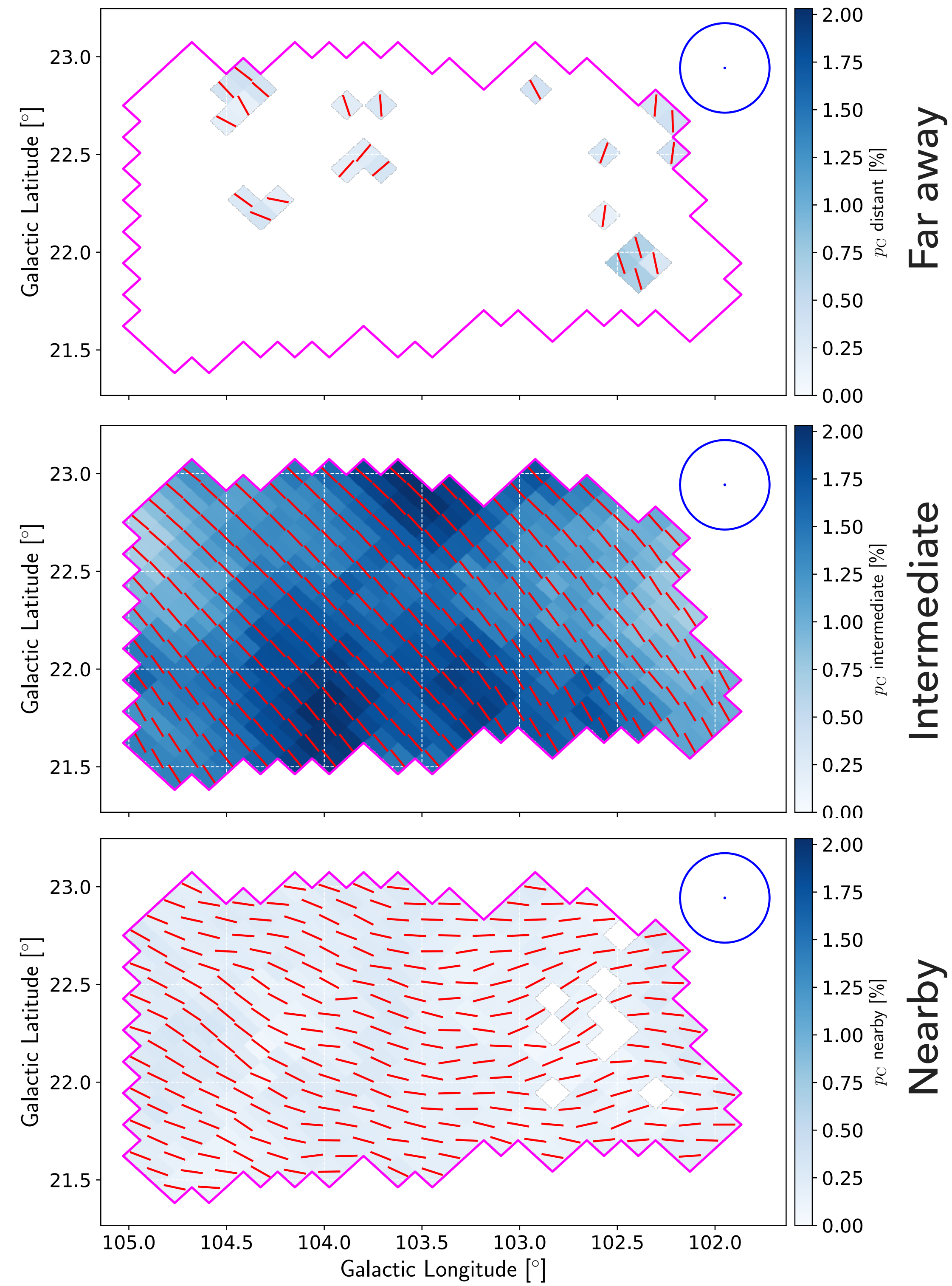
Number of cloud



Clouds' distance at max-LL



Clouds' polarization degree and angle

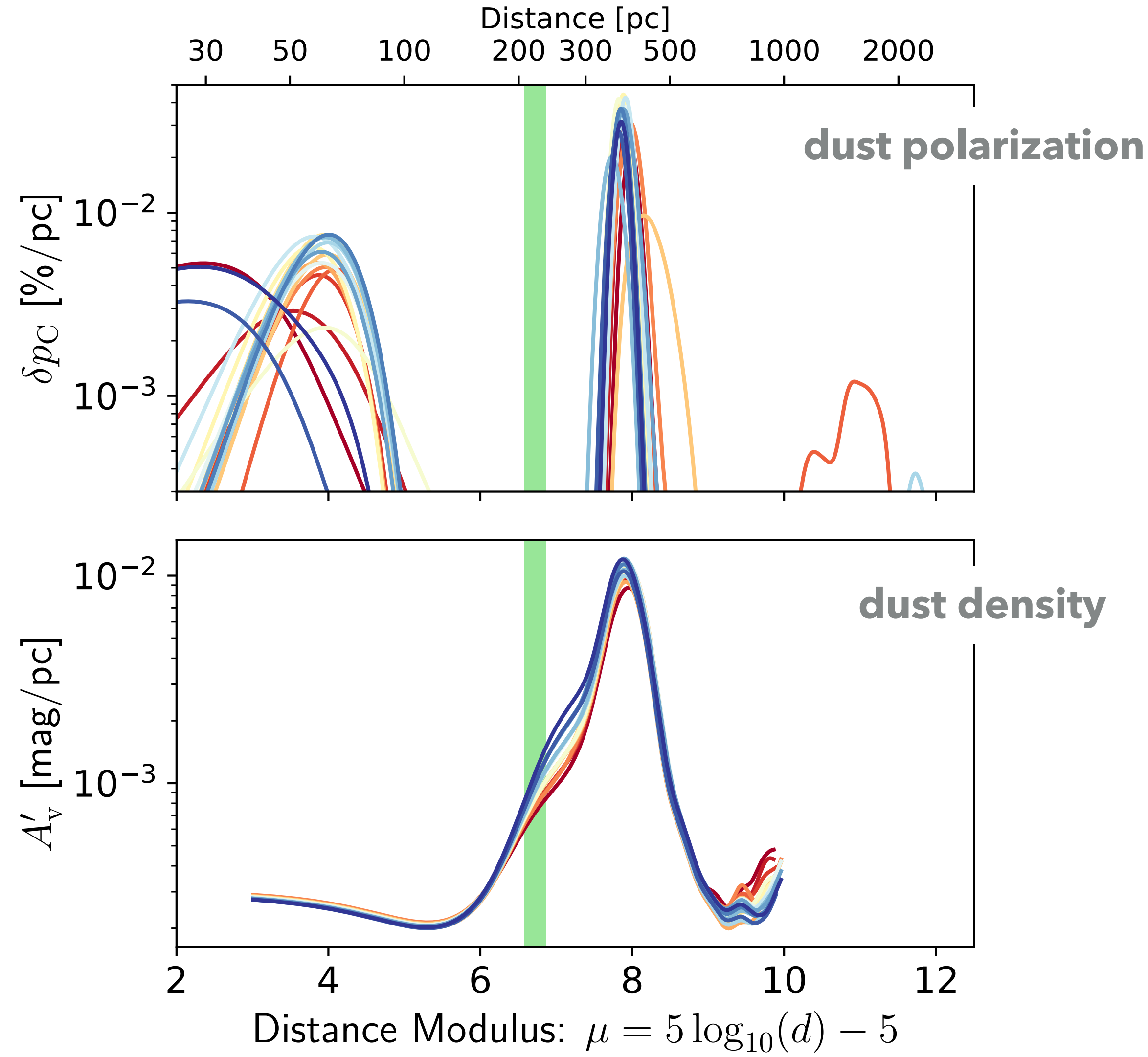


THE FIRST DEGREE-SCALE 3D MAP OF THE DUSTY MAGNETIZED ISM

[Pelgrims & PASIPHAE 2024]

- Corroborating cloud detections from starlight polarization

a) with dust density distribution [Lallement+19]

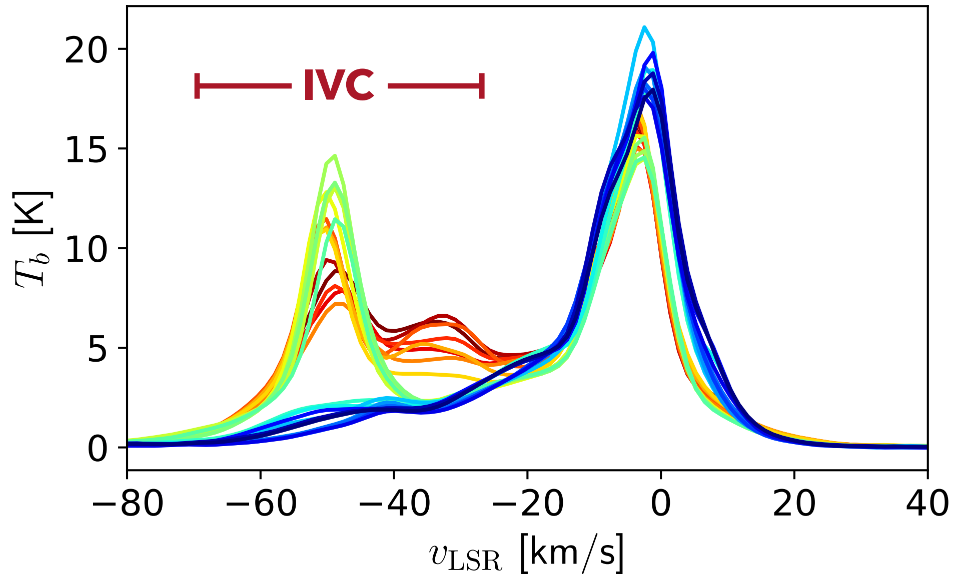


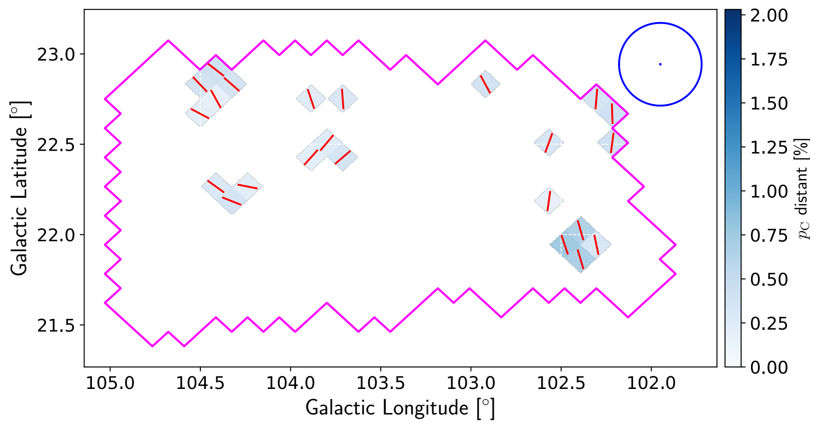
THE FIRST DEGREE-SCALE 3D MAP OF THE DUSTY MAGNETIZED ISM

[Pelgrims & PASIPHAE 2024]

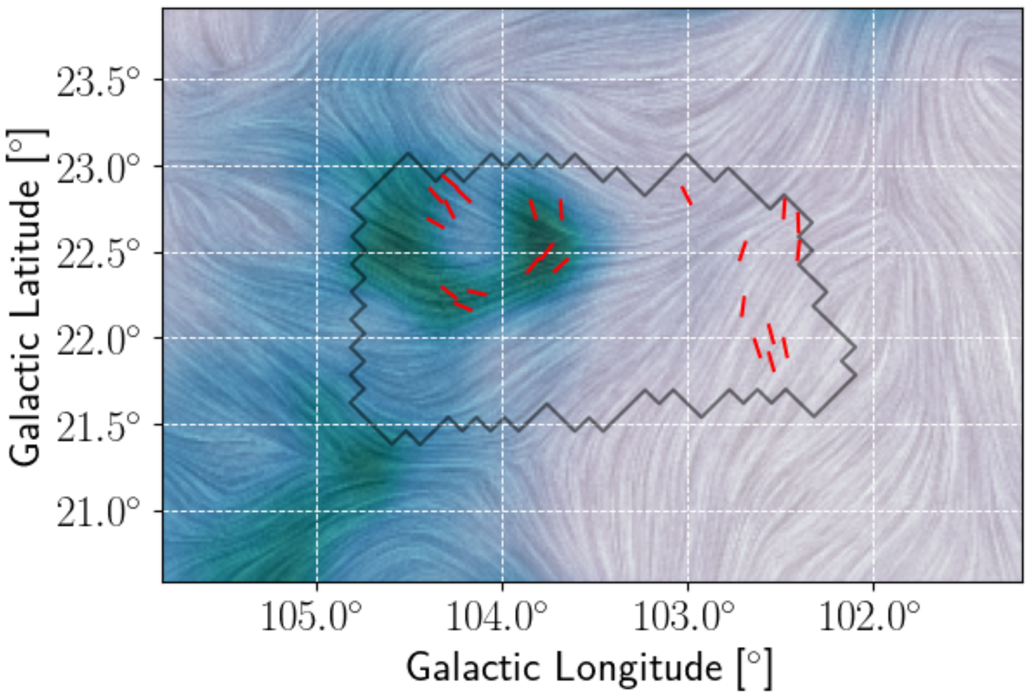
- Corroborating cloud detections from starlight polarization

b) with HI velocity spectra [HI4PI Coll.]





c) with HI fibers orientation [Clark&Hensley19]



THE FIRST DEGREE-SCALE 3D MAP OF THE DUSTY MAGNETIZED ISM

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- Corroborating cloud detections from starlight polarization

a) with dust density distribution [Lallement+19]

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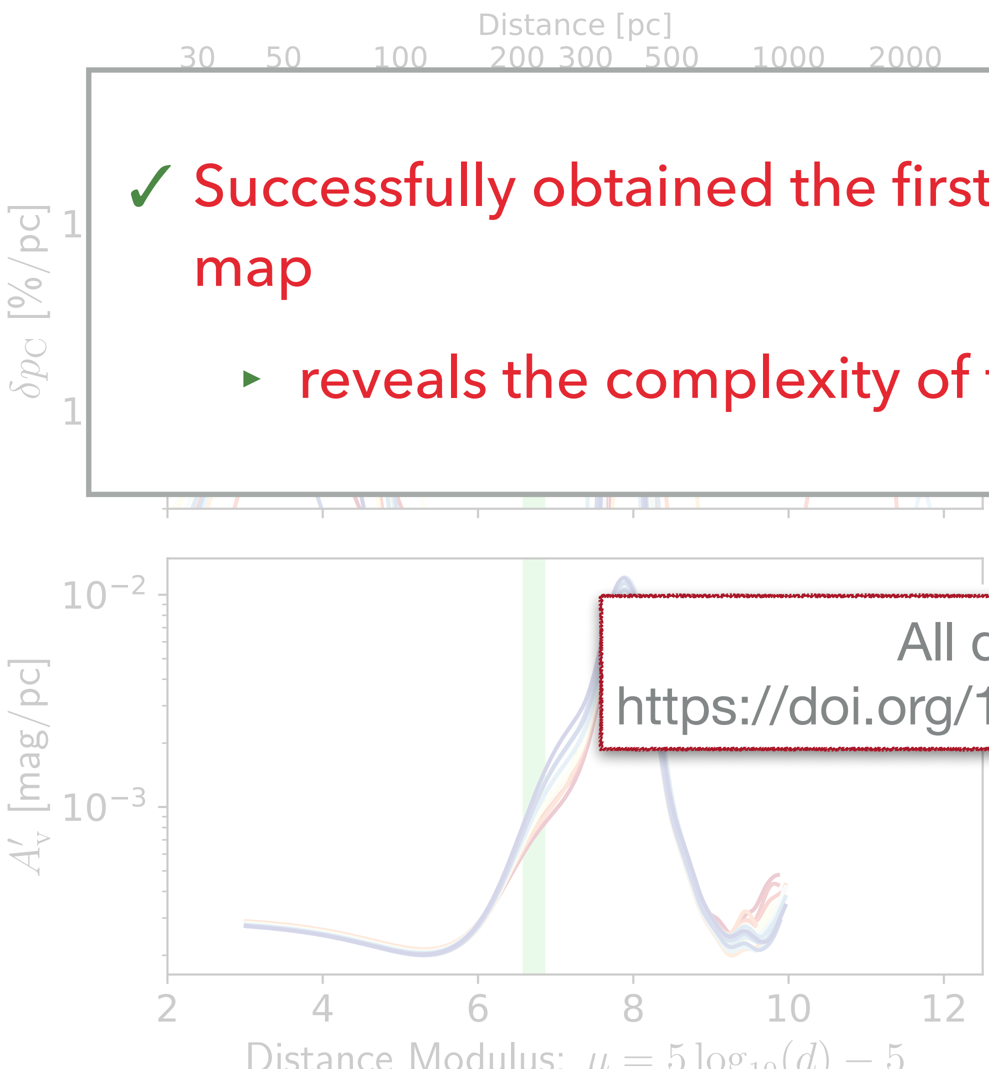
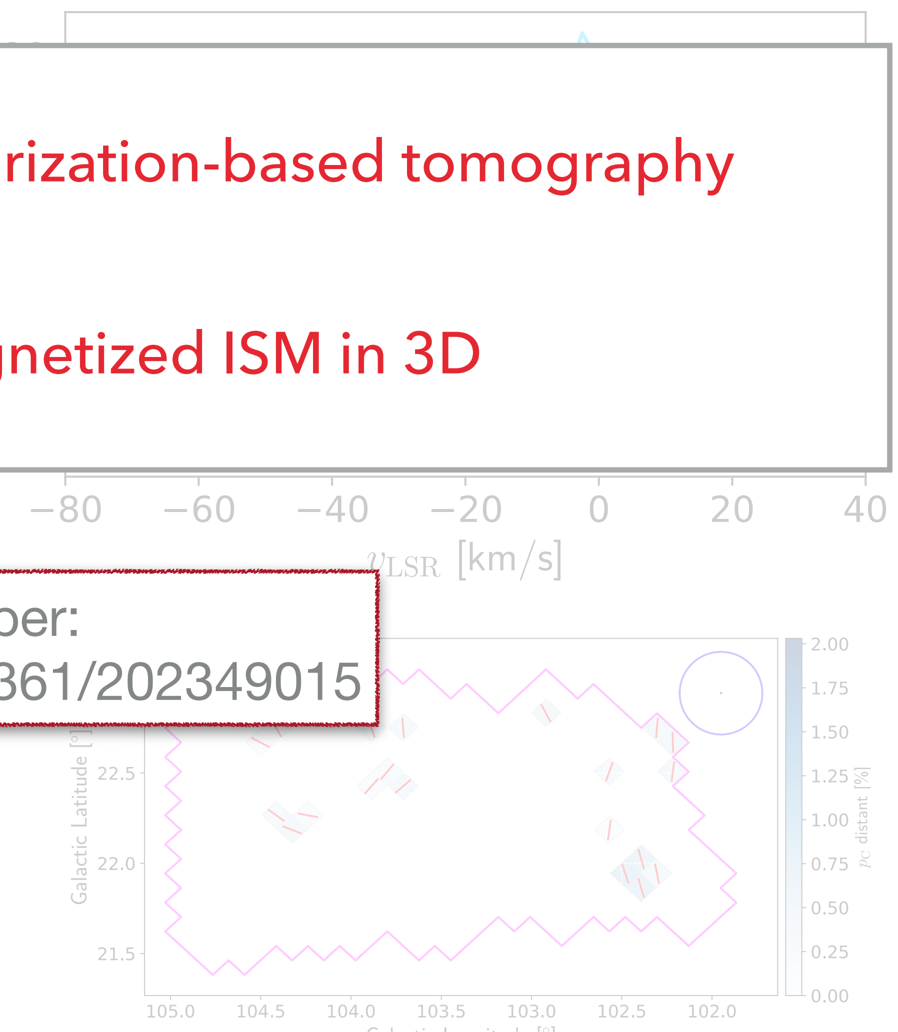




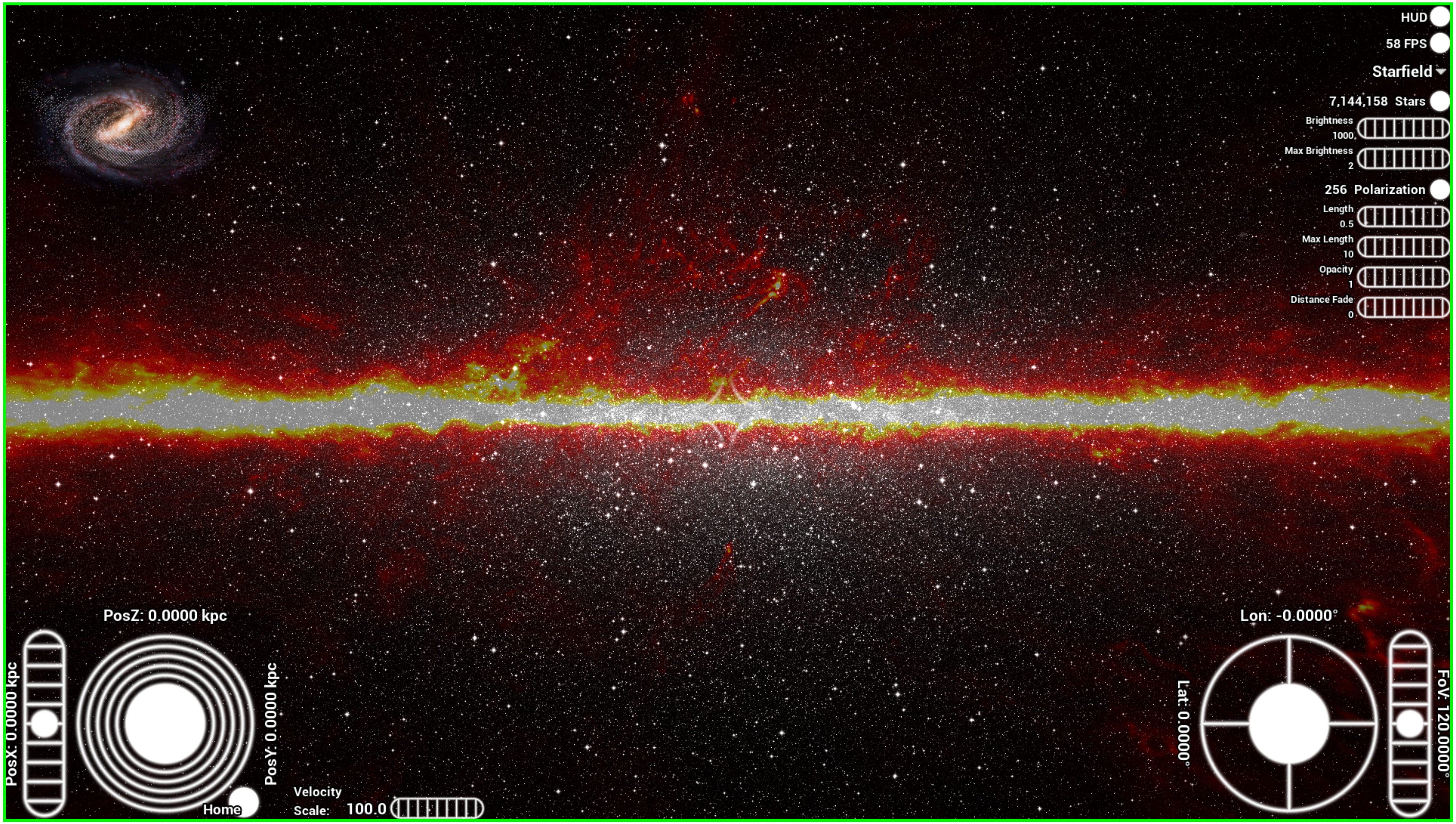
✓ Successfully obtained the first starlight-polarization-based tomography map

- reveals the complexity of the dusty magnetized ISM in 3D

All details in our paper:
https://doi.org/10.1051/0004-6361/202349015

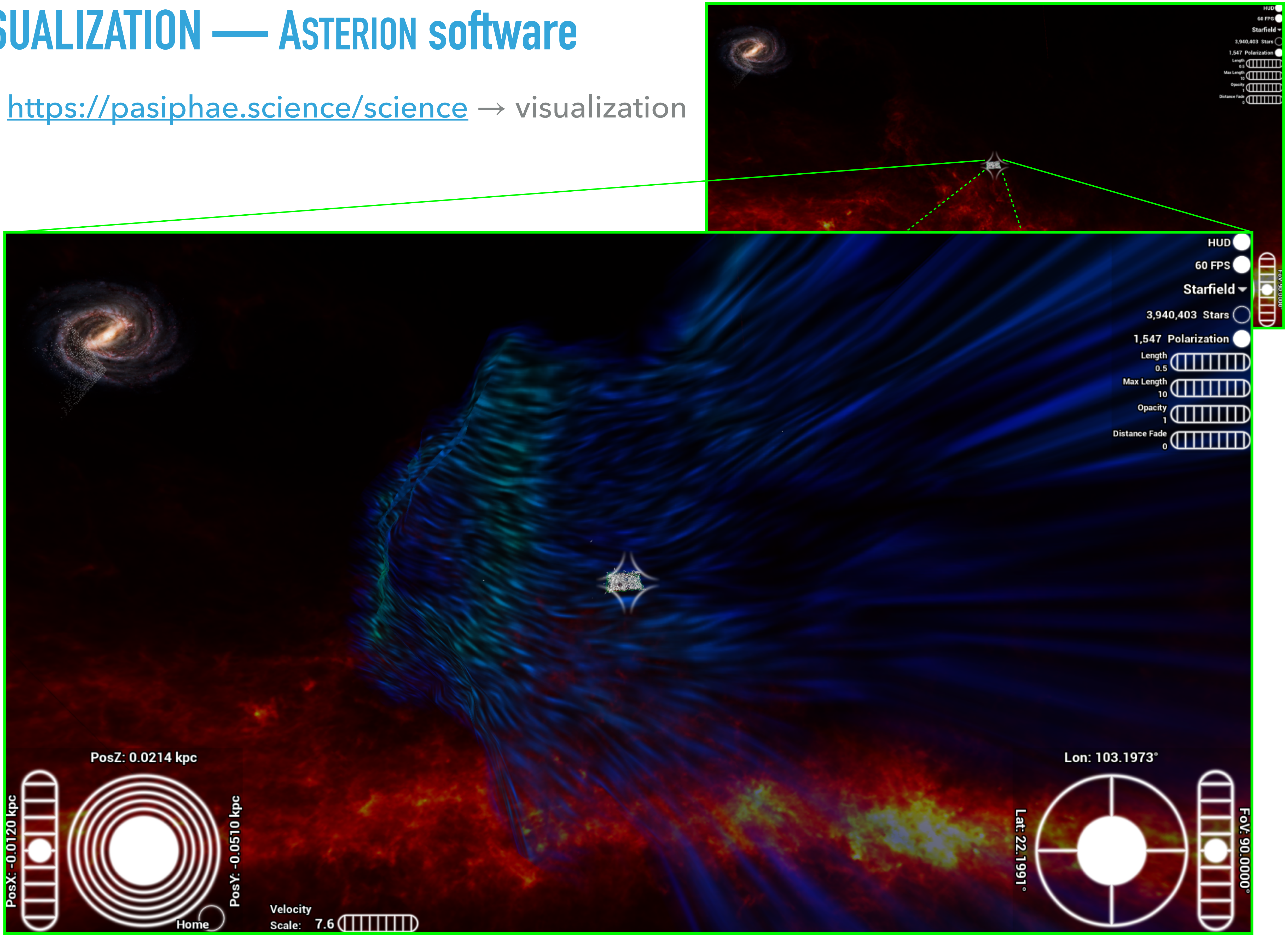
VISUALIZATION — ASTERION software

- https://pasiphae.science/science → visualization

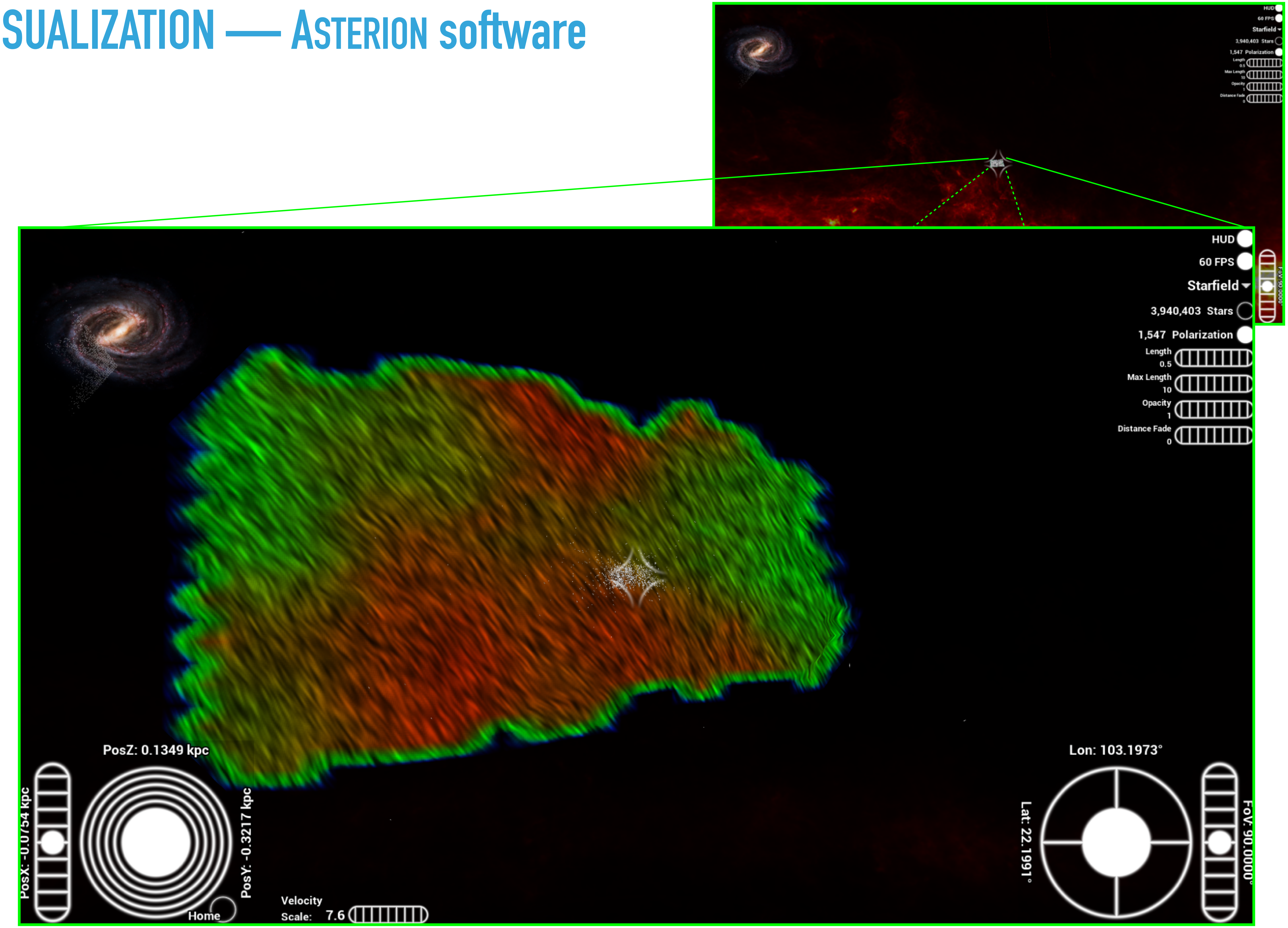


VISUALIZATION — ASTERION software

- https://pasiphae.science/science → visualization



VISUALIZATION — ASTERION software



PERSPECTIVES

PASIPHAE
through the veil of dust to inflation

will deliver ~4M stars at $|b|$>30deg
- ✓ map the dominant clouds up to ~1–2 kpc distance
- ✓ obtain local constraints on $\overrightarrow{\mathbf{B}}_{\perp}$

✓ Open the way to several studies

- ✓ modeling dust as CMB foreground
  - templates of dust polarized emission independent of CMB data
  - decomposition of dust polarized emission along distance at angular scale of 1° or better
  - definition of dust clouds in 3D

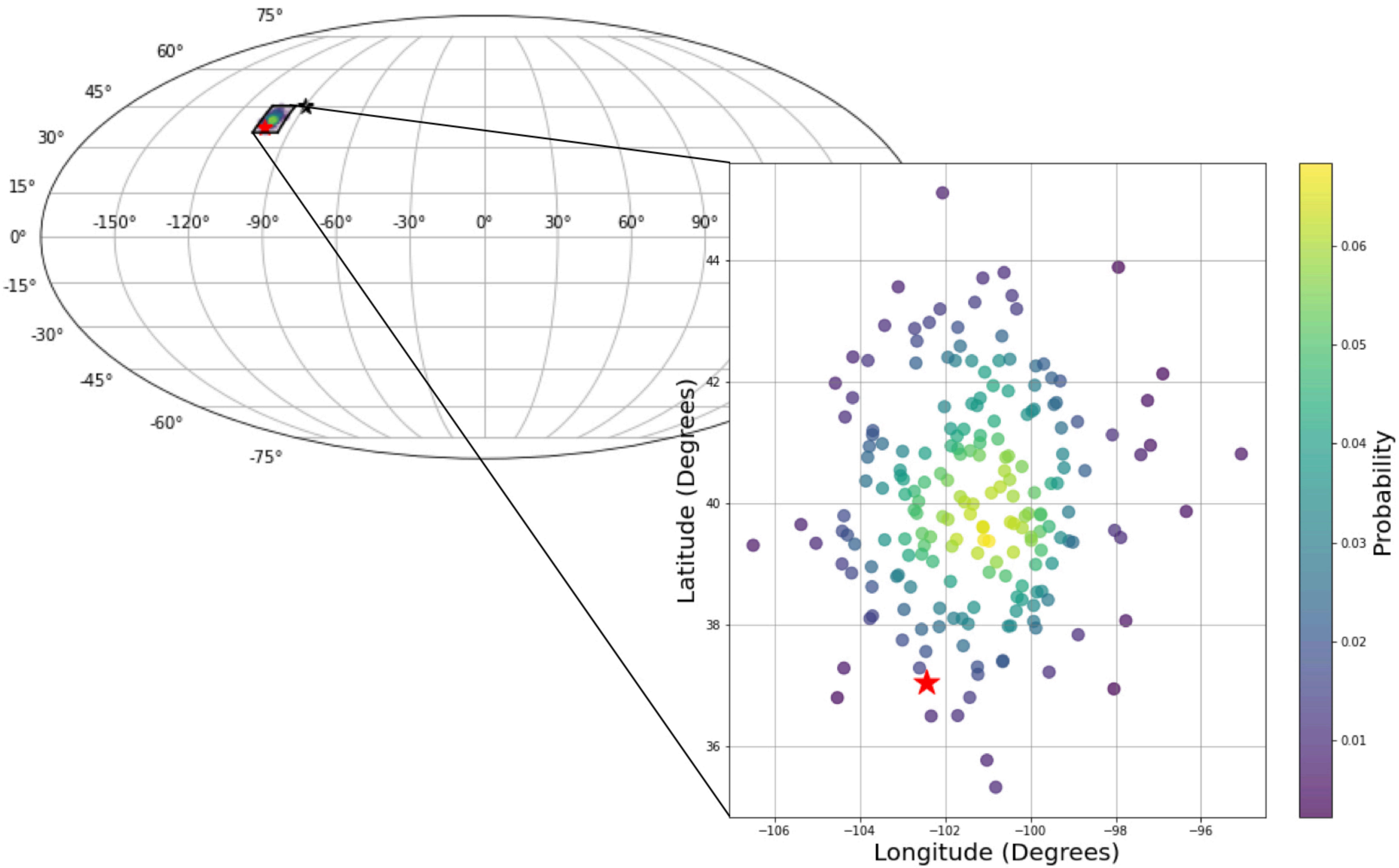
  ⇒ improve multi-ν modeling of dust foreground

- ✓ GMF modeling and related studies (e.g. UHECRs)
  - **local** measurements of GMF properties (differential >< LOS-integrated constraints)

- ✓ physics of the ISM
  - 3D correlation function of the dusty magnetized ISM
  - astrophysical dust
  - multi-phase ISM
  - magnetometry of the GMF

SPARSE CONSTRAINTS TO CONTINUOUS CONSTRAINTS

[Tsouros+2024]



GALACTIC MAGNETIC FIELD MODELS AND UHECR BACK-TRACKING

Different ‘viable’ GMF models still do not converge

In November in Science: [Telescope Array Coll. 2023]

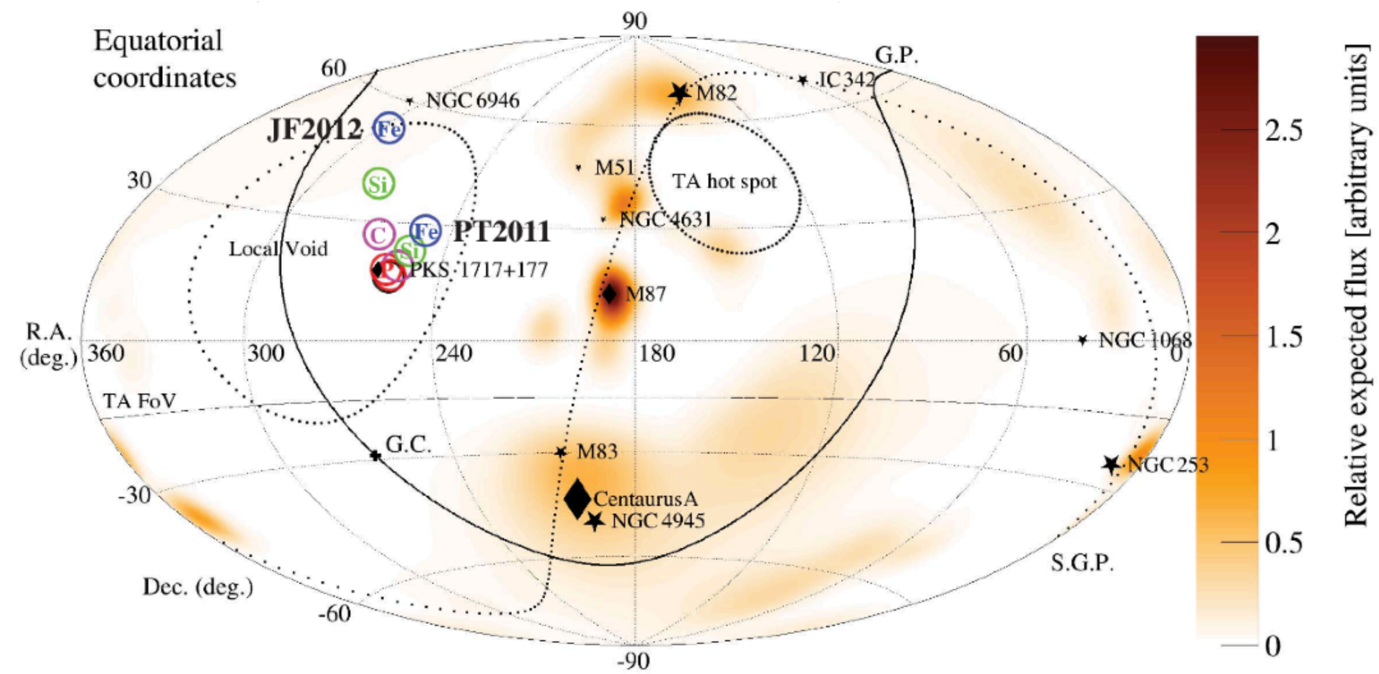
RESEARCH ARTICLE

ASTROPARTICLE PHYSICS

An extremely energetic cosmic ray observed by a surface detector array

Telescope Array Collaboration*†

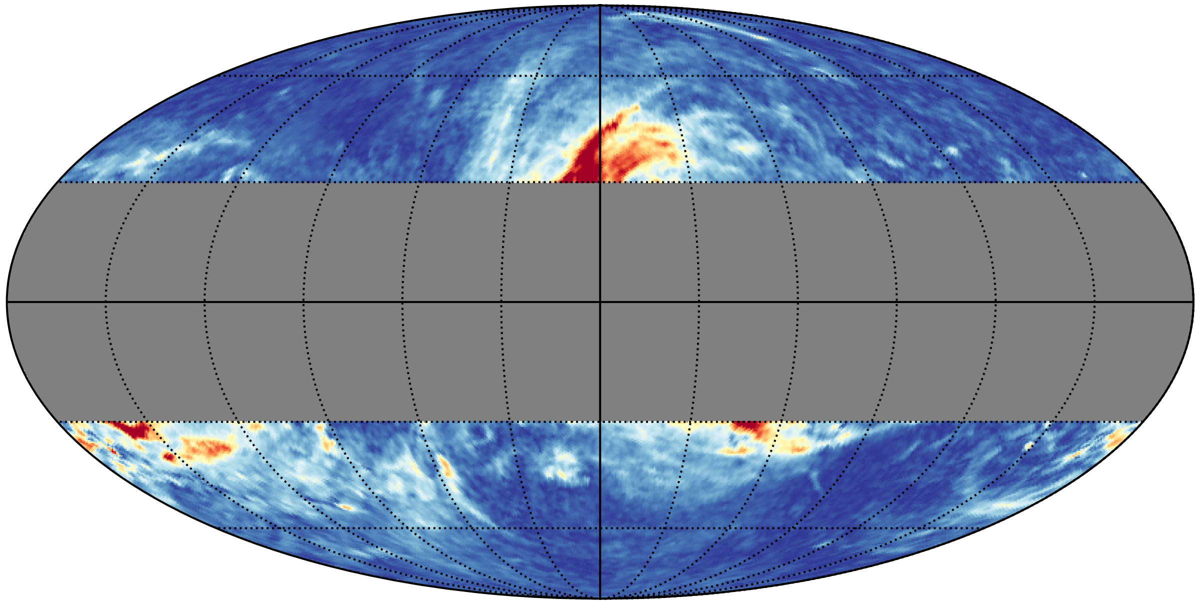
Cosmic rays are energetic charged particles from extraterrestrial sources, with the highest-energy events thought to come from extragalactic sources. Their arrival is infrequent, so detection requires instruments with large collecting areas. In this work, we report the detection of an extremely energetic particle recorded by the surface detector array of the Telescope Array experiment. We calculate the particle's energy as 244 ± 29 (stat.) $^{+51}_{-76}$ (syst.) exa–electron volts (~40 joules). Its arrival direction points back to a void in the large-scale structure of the Universe. Possible explanations include a large deflection by the foreground magnetic field, an unidentified source in the local extragalactic neighborhood, or an incomplete knowledge of particle physics.

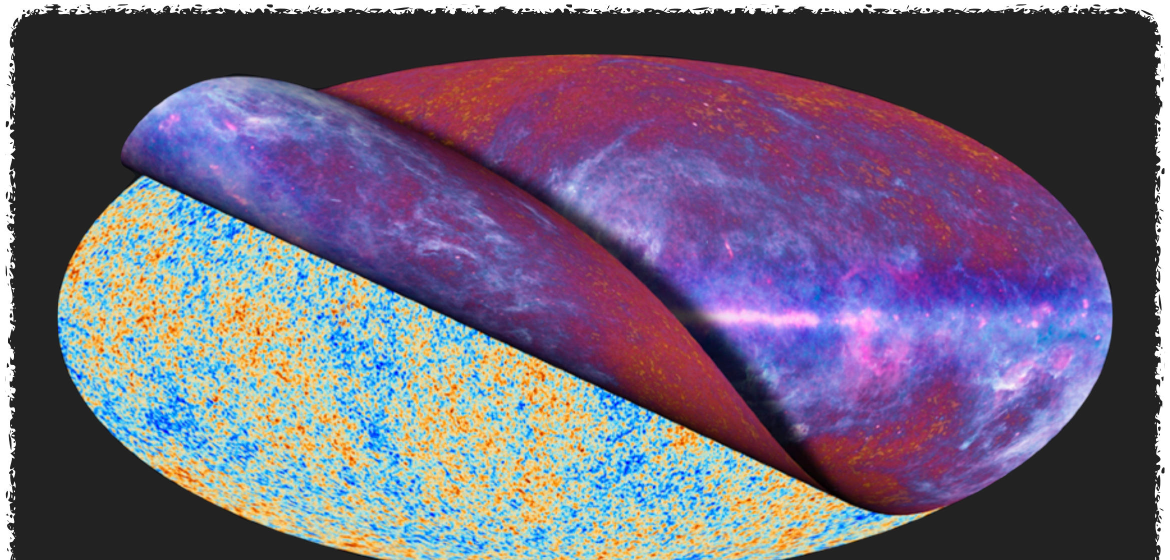


⇒ GMF modeling still needs improvement!

PASIPHAE

- the first large survey of optical starlight polarization at high and intermediate Galactic latitudes
- to map the dust polarized emission in 3D



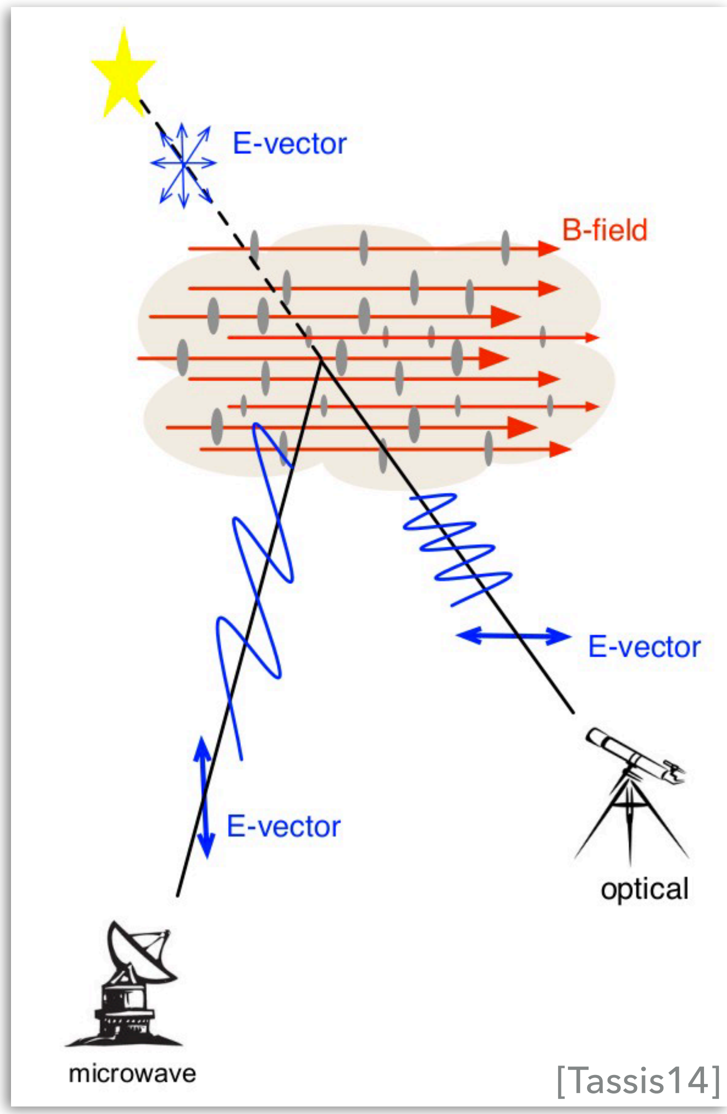


[Planck esa]

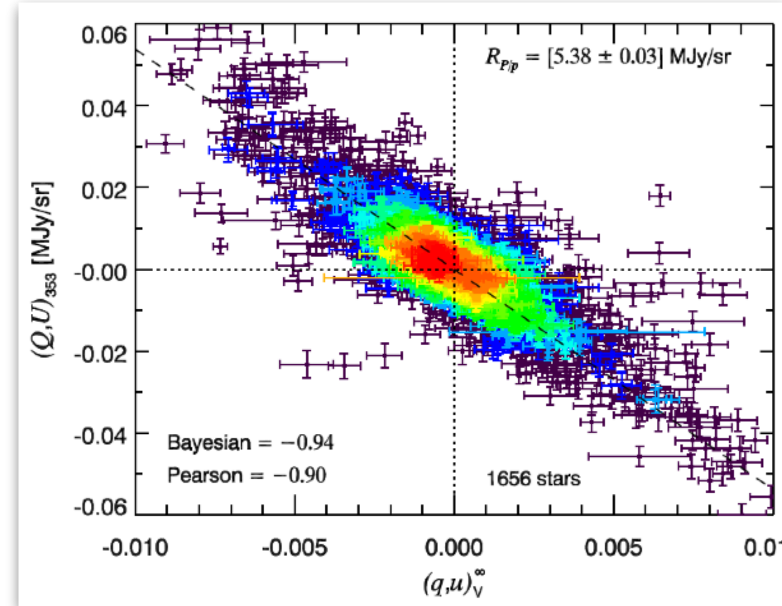
- to answer the needs to account for 3D effects in the characterization and modeling of foregrounds to CMB polarization [Tassis+15, Tassis+18, Pelgrims+21, Ritacco+23, ...]
- to help clearing the path to cosmic inflation

PASIPHAE from starlight to dust emission templates

- Starlight polarization + distance (Gaia)
  - ✓ 3D map of the POS GMF in dusty regions
  - ✓ decompose dust polarized emission



- Absorption ↔ Emission conversion

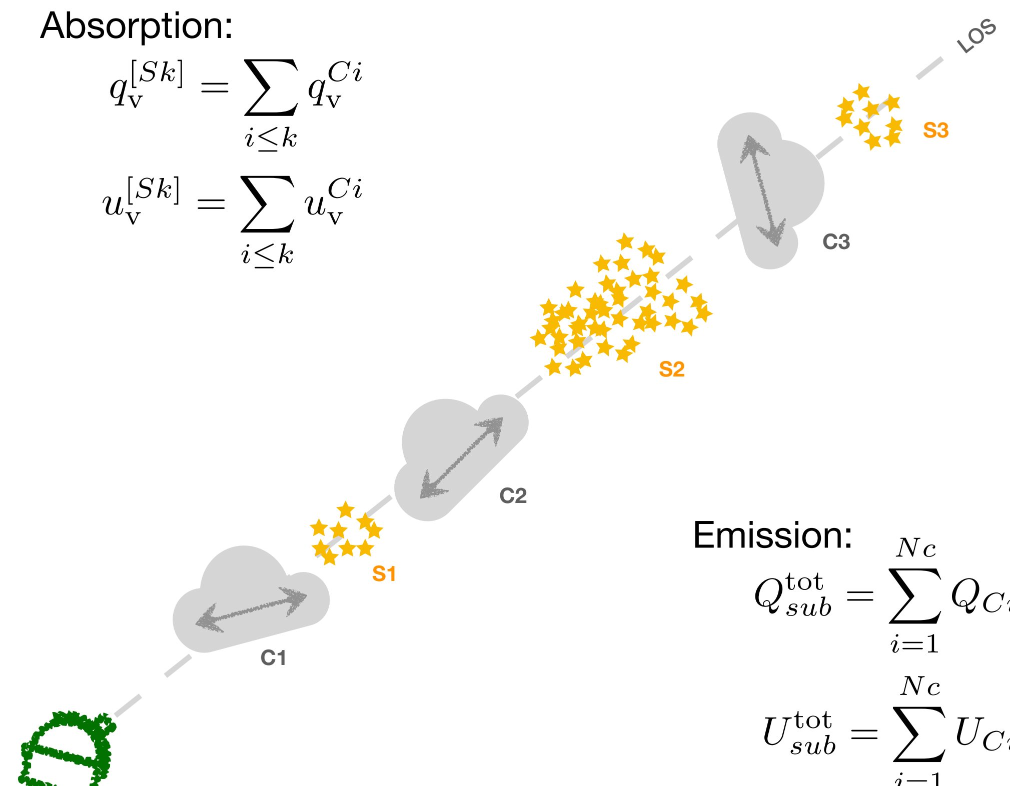


[Planck (XXI 15, XII 20)]

Absorption:

$$q_V^{[Sk]} = \sum_{i \leq k} q_V^{Ci}$$

$$u_V^{[Sk]} = \sum_{i \leq k} u_V^{Ci}$$



Emission:

$$Q_{sub}^{tot} = \sum_{i=1}^{Nc} Q_{Ci}$$

$$U_{sub}^{tot} = \sum_{i=1}^{Nc} U_{Ci}$$