FROM PLANK TO THE FUTURE OF CMB

FERRARA - MAY 2022

PASIPHAE

through the veil of dust

VINCENT PELGRIMS

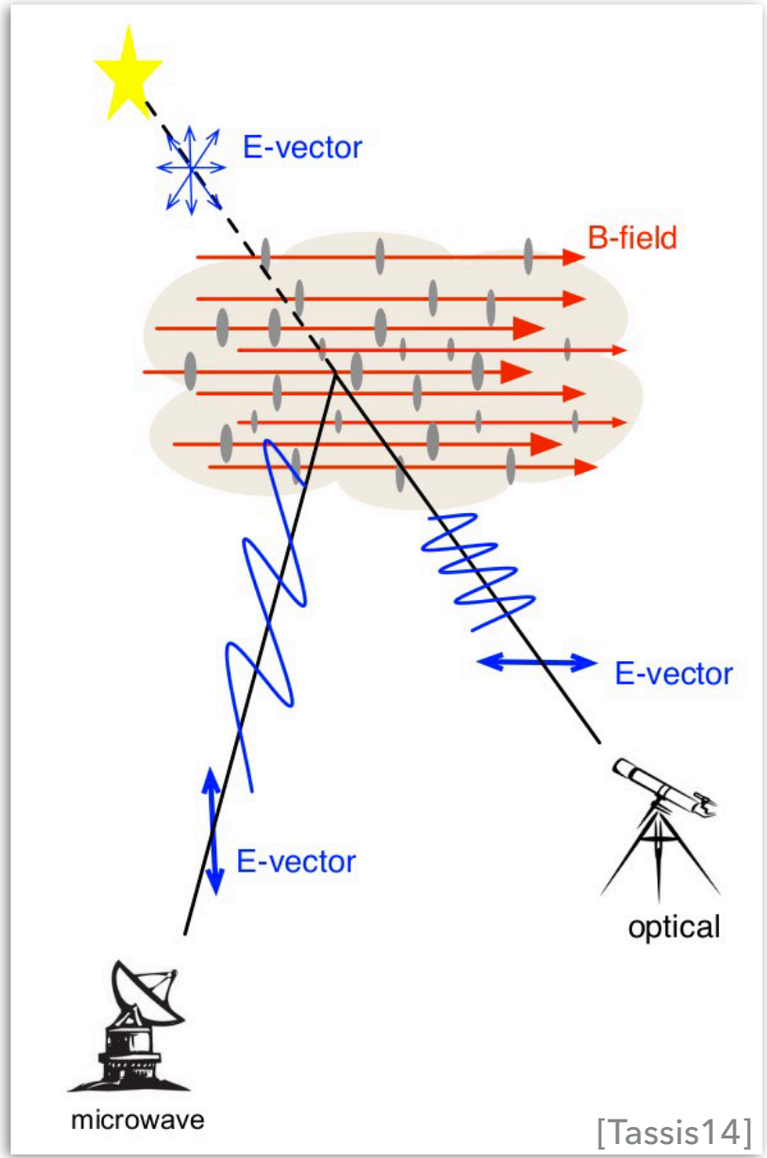
ON BEHALF OF THE PASIPHAE COLLABORATION

INSTITUTE OF ASTROPHYSICS — FORTH,
PHYSICS DEPARTMENT UNIV. CRETE
HERAKLION, GREECE

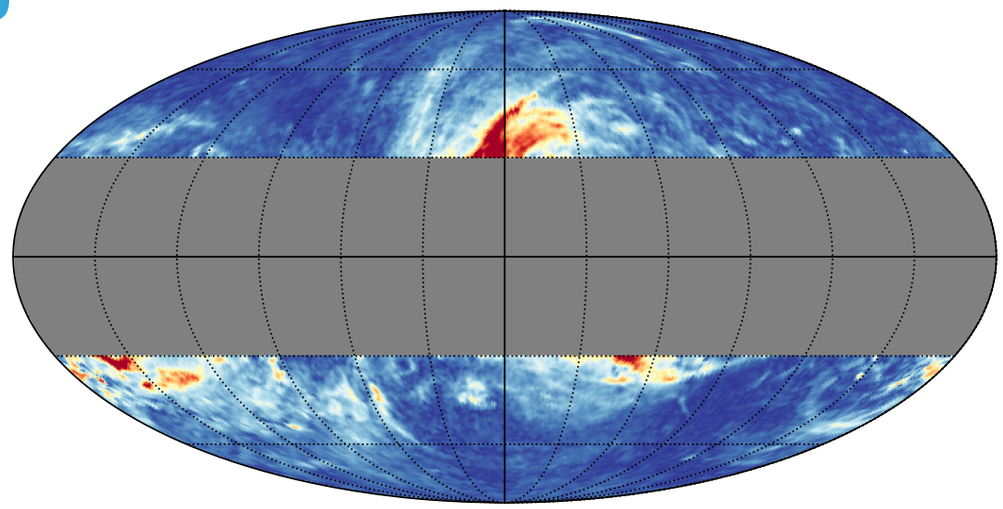
THE FIRST LARGE-SCALE SURVEY OF OPTICAL STARLIGHT POLARIZATION AT HIGH AND INTERMEDIATE GALACTIC LATITUDES

PASIPHAE

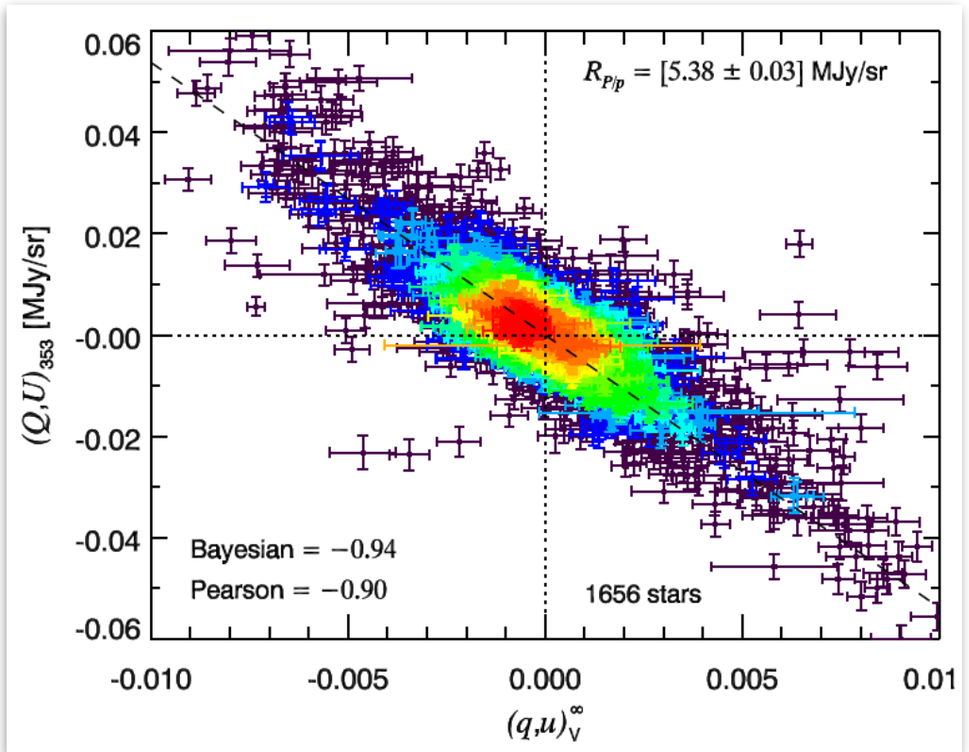
- Mapping dust polarized emission in 3D



[Tassis14]



- Absorption ↔ Emission conversion

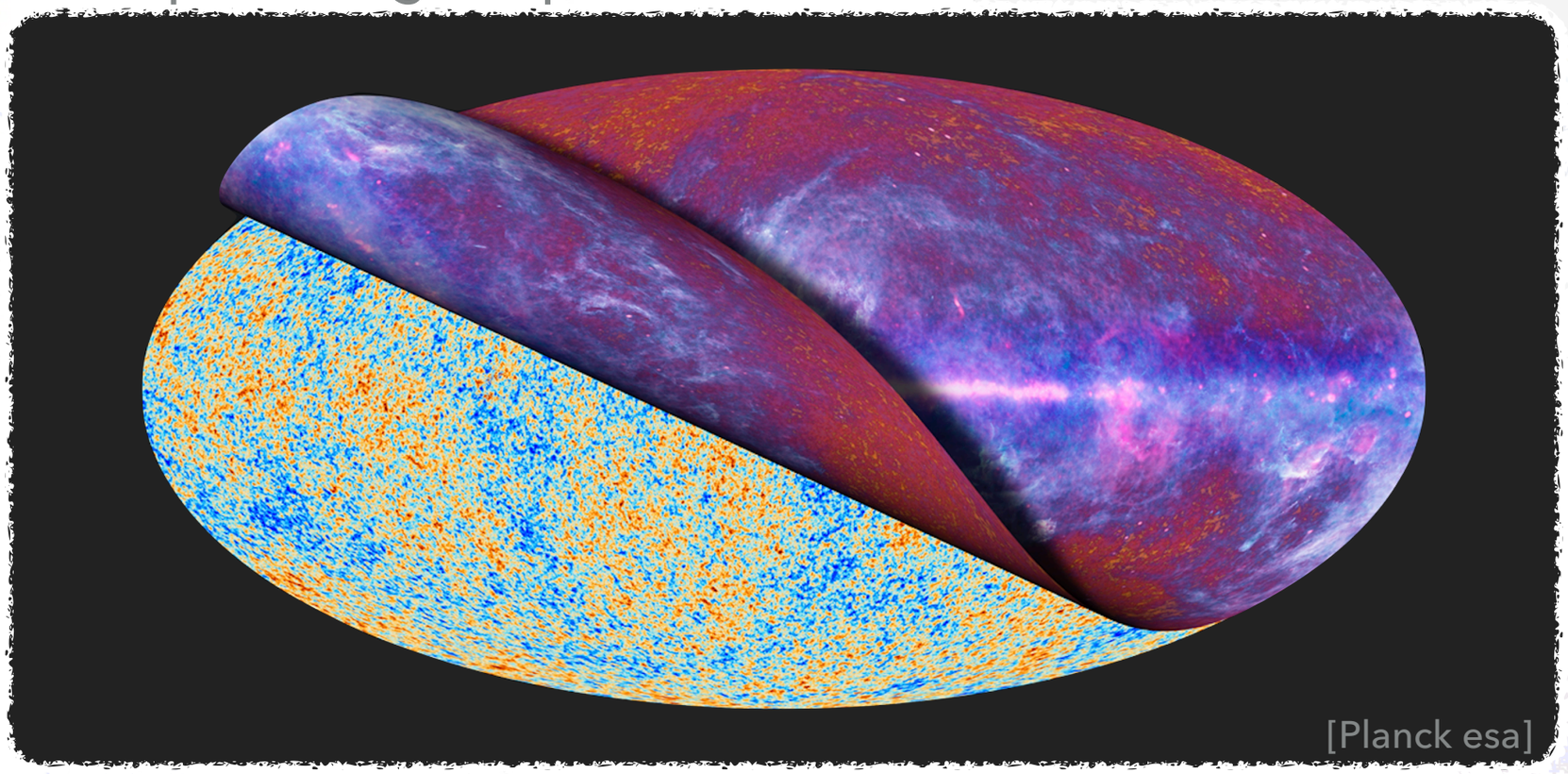


[Planck (XXI 15, XII 20)]

THE FIRST LARGE-SCALE SURVEY OF OPTICAL STARLIGHT POLARIZATION AT HIGH AND INTERMEDIATE GALACTIC LATITUDES

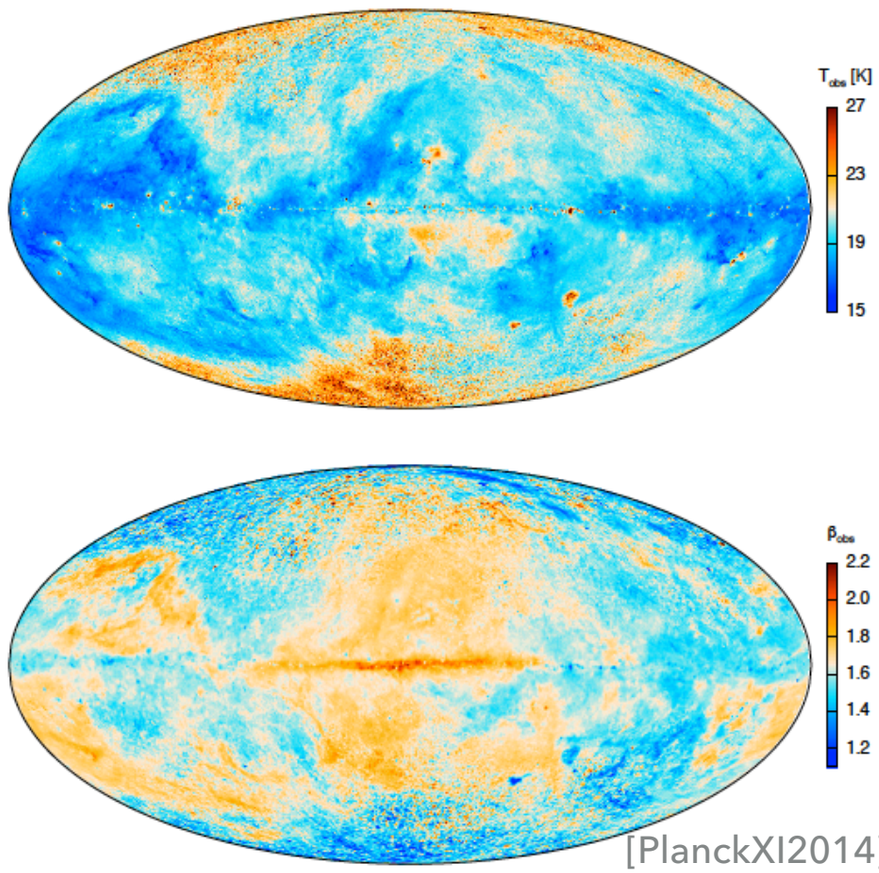
PASIPHAE

- Mapping dust polarized emission in 3D
- Help clearing the path to cosmic inflation



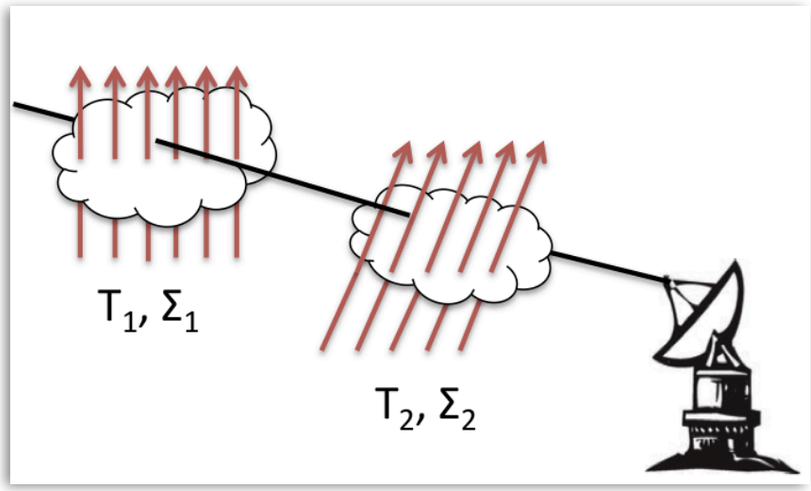
MOTIVATIONS

- Existence of dust SED variations and non-uniform magnetic field orientation
  - induce (LOS-)frequency decorrelation of dust polarization
  - complicate frequency extrapolation for foregrounds' removal
  - Dust SEDs vary across the sky (T, κ)
    [e.g. Finkbeiner+99; Planck (XI 14; IV 20); Irfan+19]



[PlanckXI2014]

  - SEDs vary along LOSs leading to LOS ν-decorrelation from dust clouds [Tassis & Pavlidou 2015]

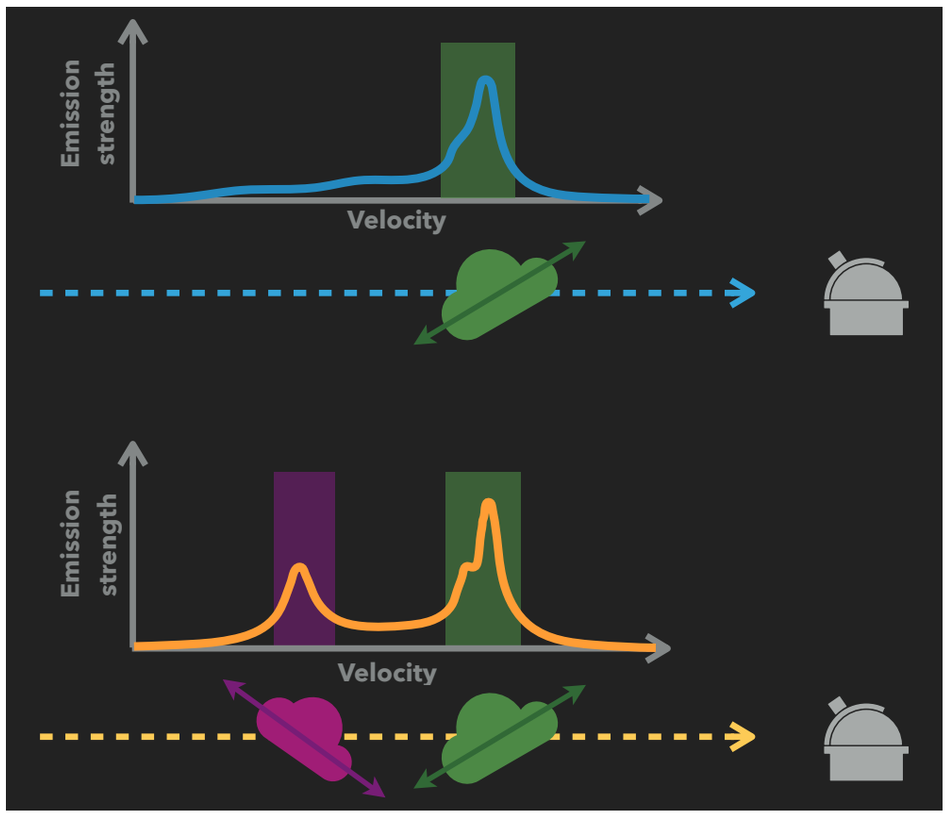


[Tassis&Pavlidou15]

MOTIVATIONS

- SEDs vary along *certain* LOSs leading to LOS ν-decorrelation from dust clouds
  [Pelgrims, Clark, Hensley, Panopoulou et al. 2021]

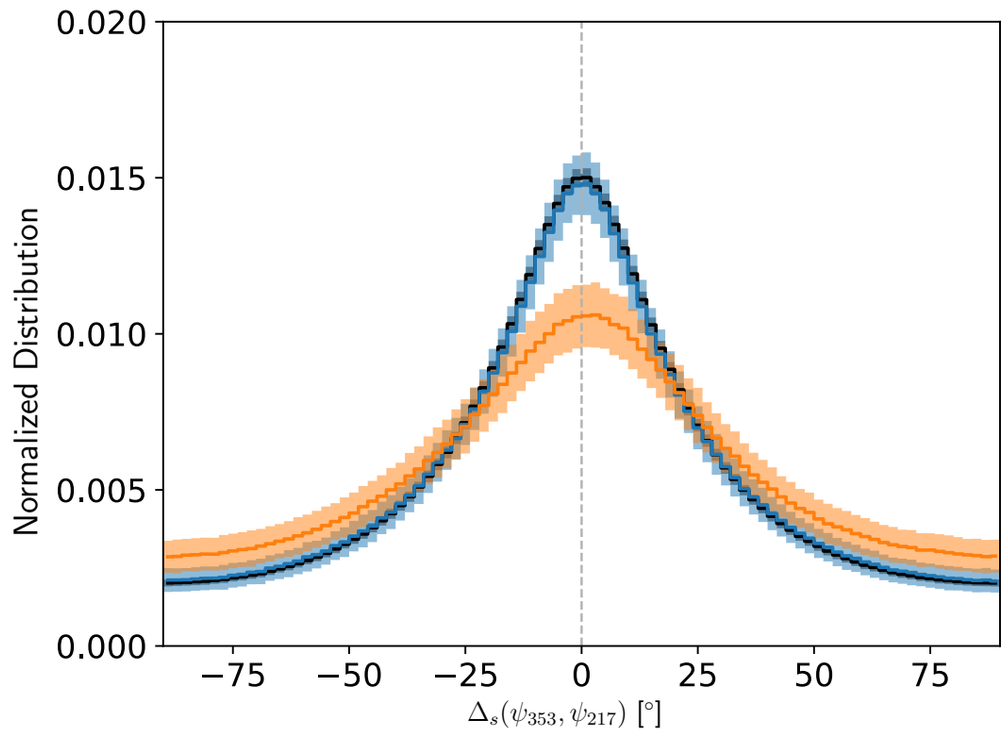
Sightline selection using HI data



#cloud from [Panopoulou & Lenz 2020]

θ_{B} cloud from [Clark & Hensley 2019]

EVPA difference Planck 353-217 GHz



Scatter difference is very significantly larger in target than control
Remains at 2 to 6σ above what noise/ residual systematic can do

MOTIVATIONS

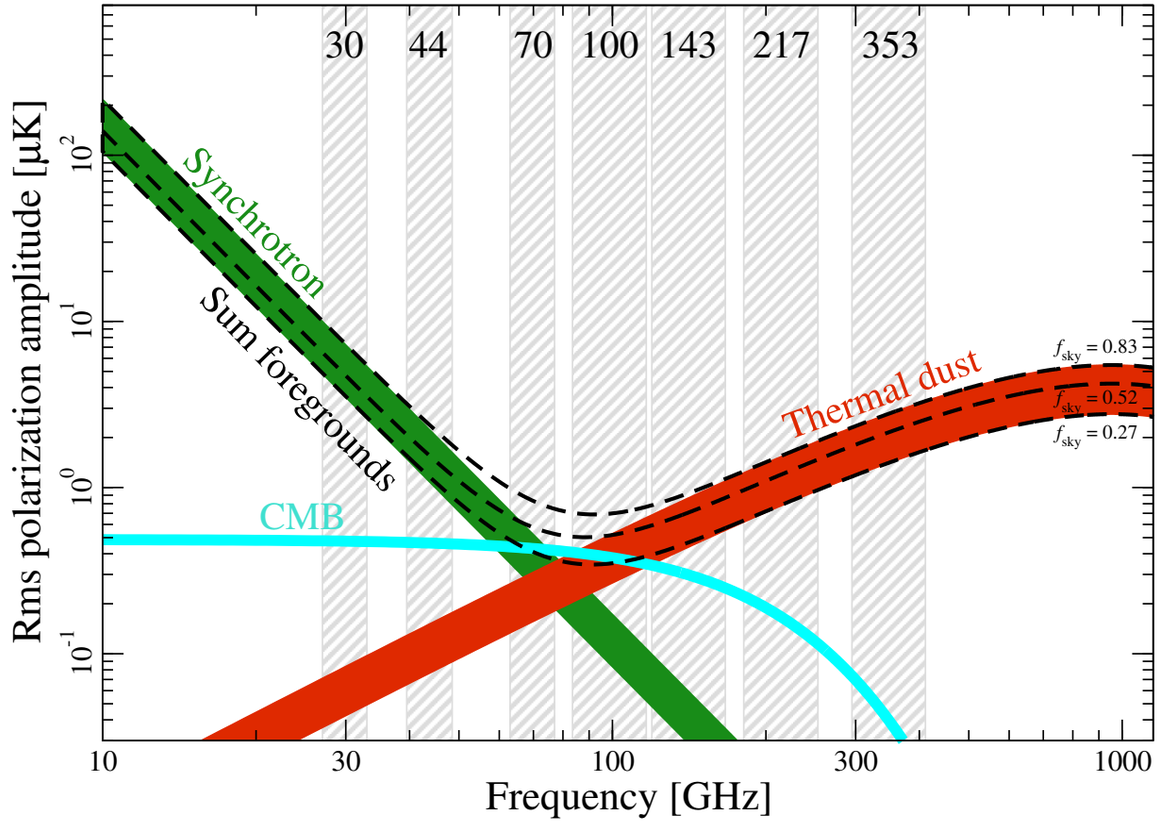
- Existence (LOS-)frequency decorrelation of dust polarization [e.g, Tassis+15; Pelgrims+21]
- Polarization power spectra (E/B, TE, …) depends on
  - Relative orientation between magnetic field and dust clouds
    [e.g., Clark+21; Konstantinou+22]
  - 3D structure of the magnetic field *as seen by us*
    [e.g., Pelgrims+22a; Konstantinou+22]

- We need
  - the 3D geometry of the magnetic field that surrounds us
  - the decomposition of the dust signal into dust clouds

to gain confidence in our statistical characterization of dust foregrounds

GOALS

- build 3D maps of dust clouds and POS orientation of the magnetic field and model SEDs per cloud
  - build frequency-dependent templates of dust foregrounds to break degeneracies and narrow down our uncertainty budget



[Planck 2018]

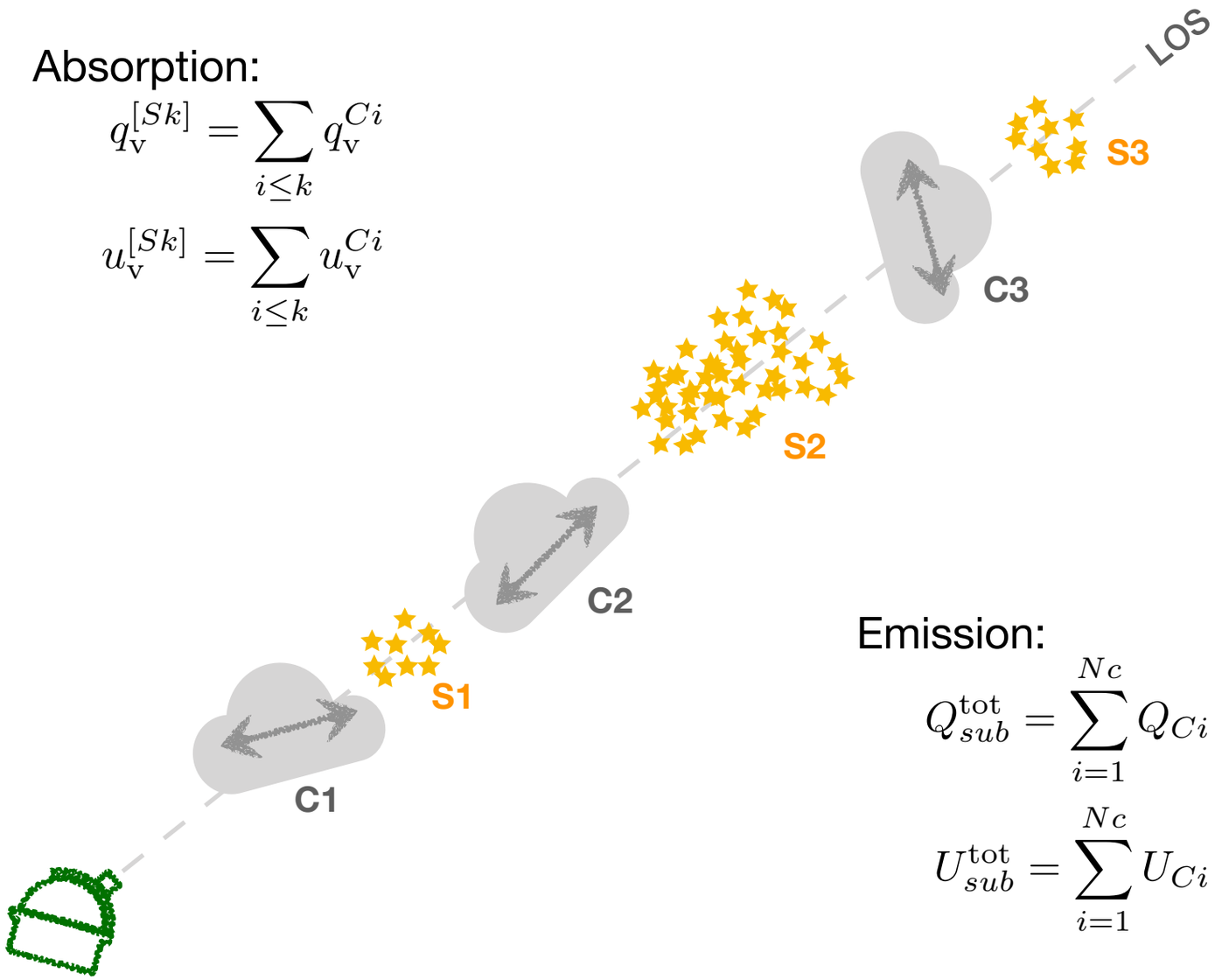
MEANS

- Use starlight polarization data combined to distance measures from Gaia to decompose the signal of the dusty magnetized ISM along distance

Absorption:

$$q_{\rm v}^{[Sk]} = \sum_{i \leq k} q_{\rm v}^{Ci}$$

$$u_{\rm v}^{[Sk]} = \sum_{i \leq k} u_{\rm v}^{Ci}$$



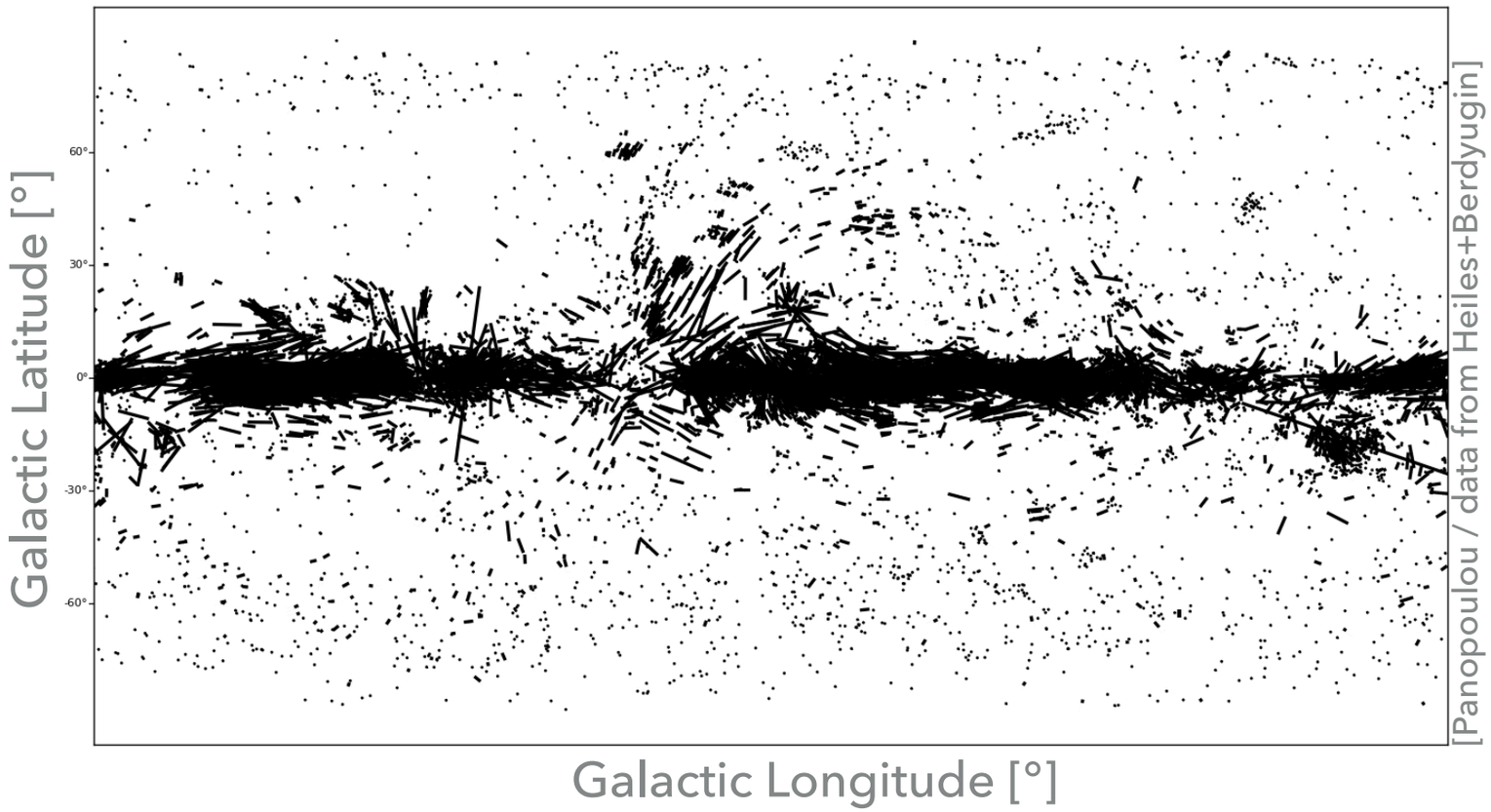
Emission:

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

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

MEANS

- But… cannot be done with current data set: < 1 star per square degree at high |b|



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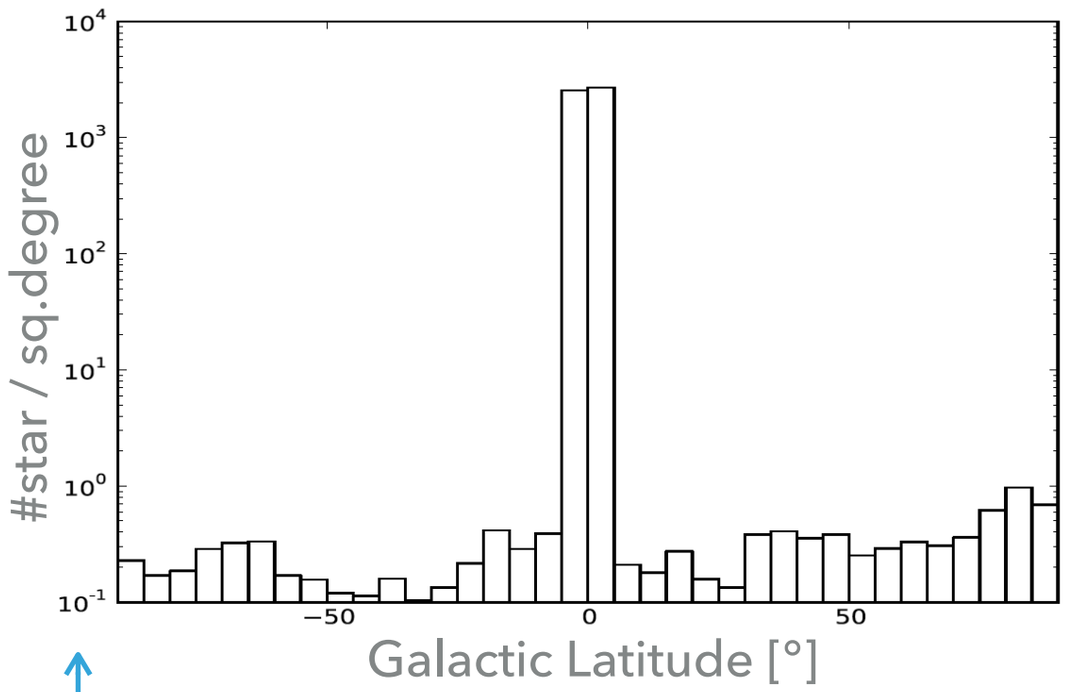
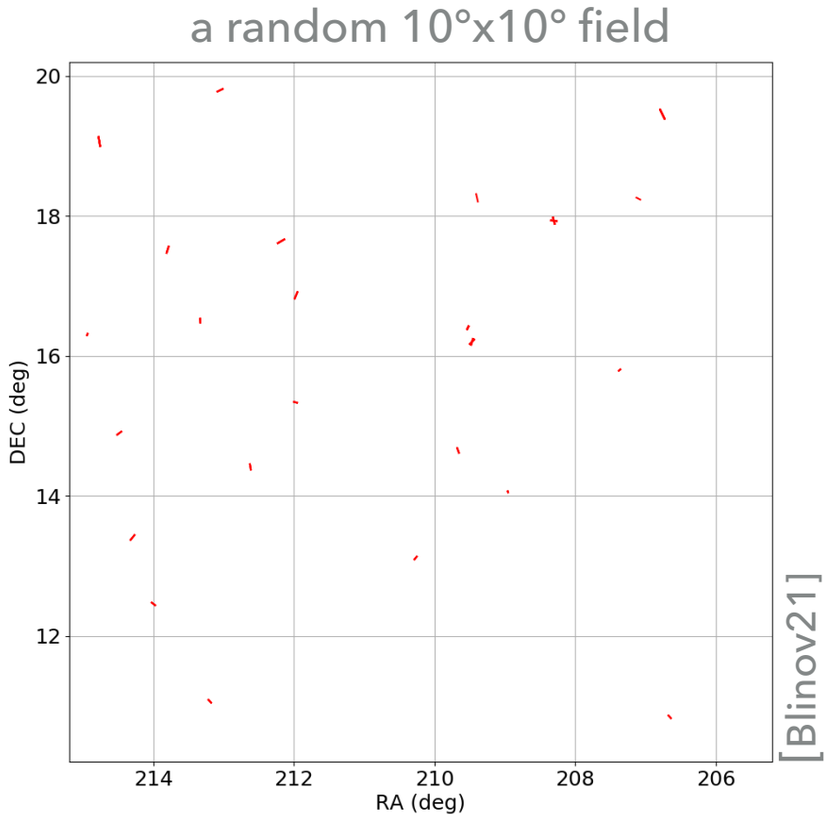


log scale!



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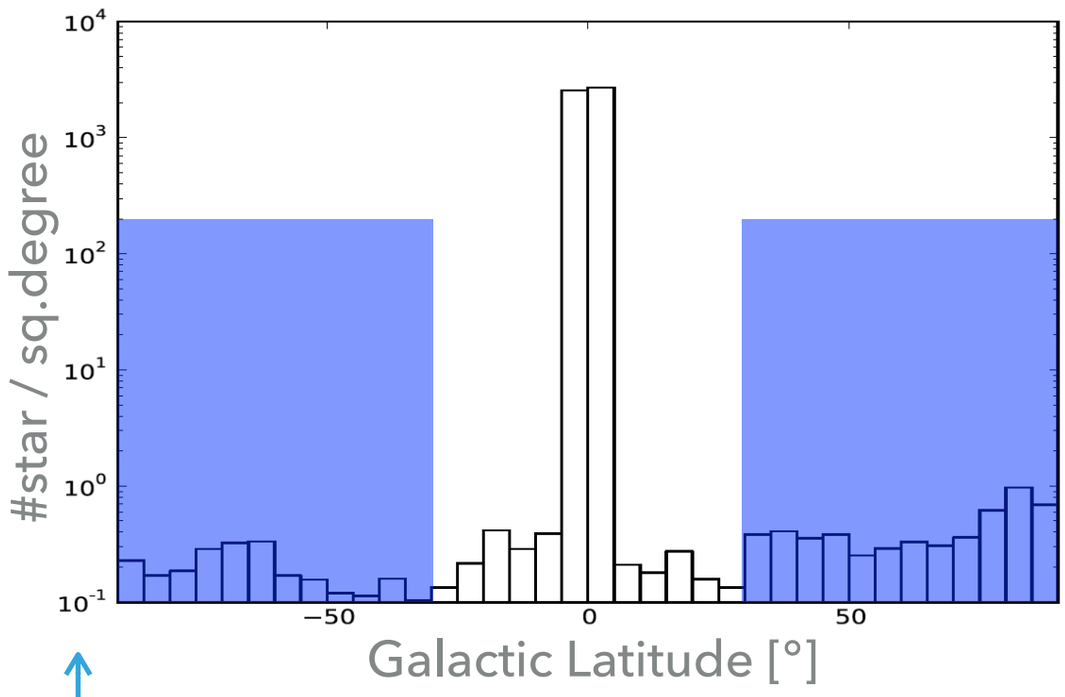
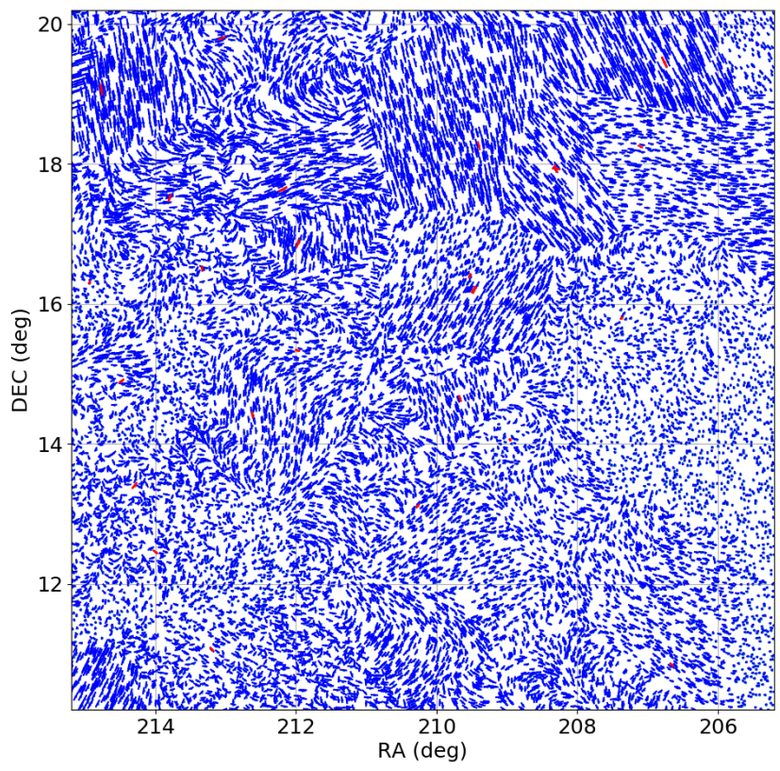
- **PASIPHAE: survey forecast**



a random 10°x10° field



[Blinov21]

THE COLLABORATION

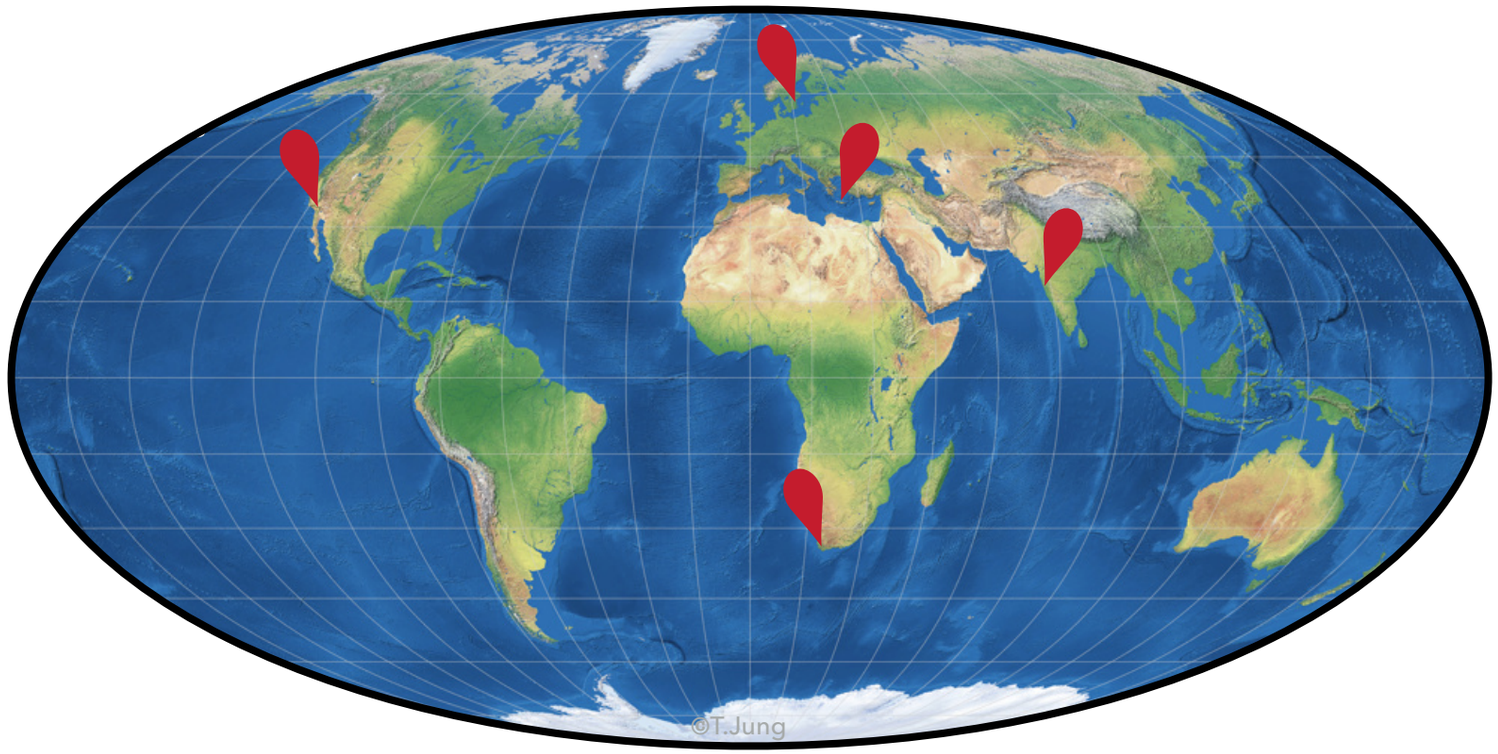
PI: K. Tassis (IA–FORTH/UOC)

Co-I's: S. Potter, A. Readhead, A. Ramaprakash, I. Wehus

5 nods:

- IA-FORTH/UOCrete (Greece)
- IUCAA (India)
- SAAO (SouthAfrica)
- Caltech (US)
- ITA (Norway)

Collaboration: ~23 members



FUNDINGS

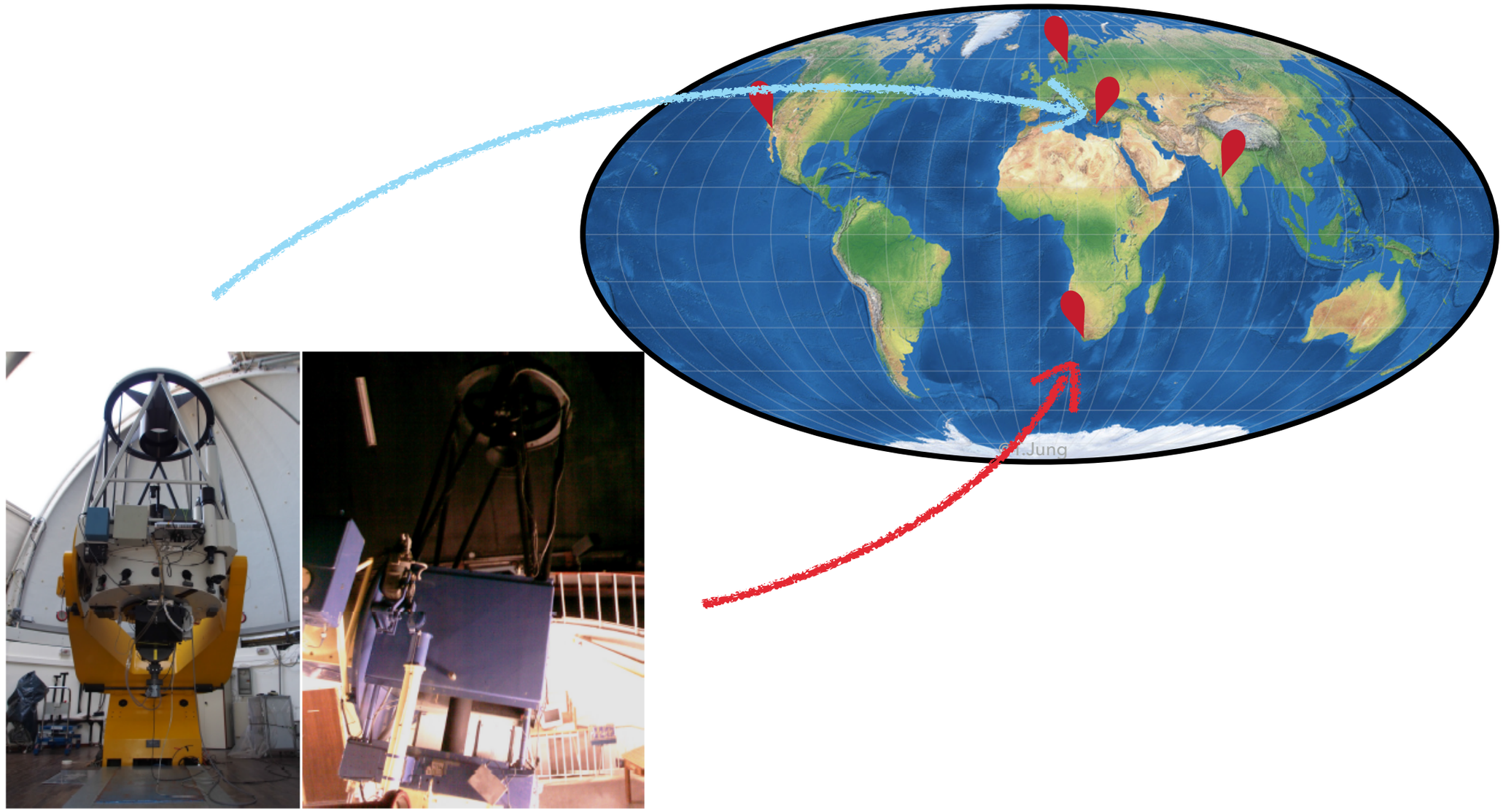
PASSIPHAE

THE SURVEY

Two telescopes

- Skinakas 1.3m, FoV: 30’x30’
- SAAO 1.m, FoV: 34’x34’

Two instruments: WALOP’s



THE SURVEY

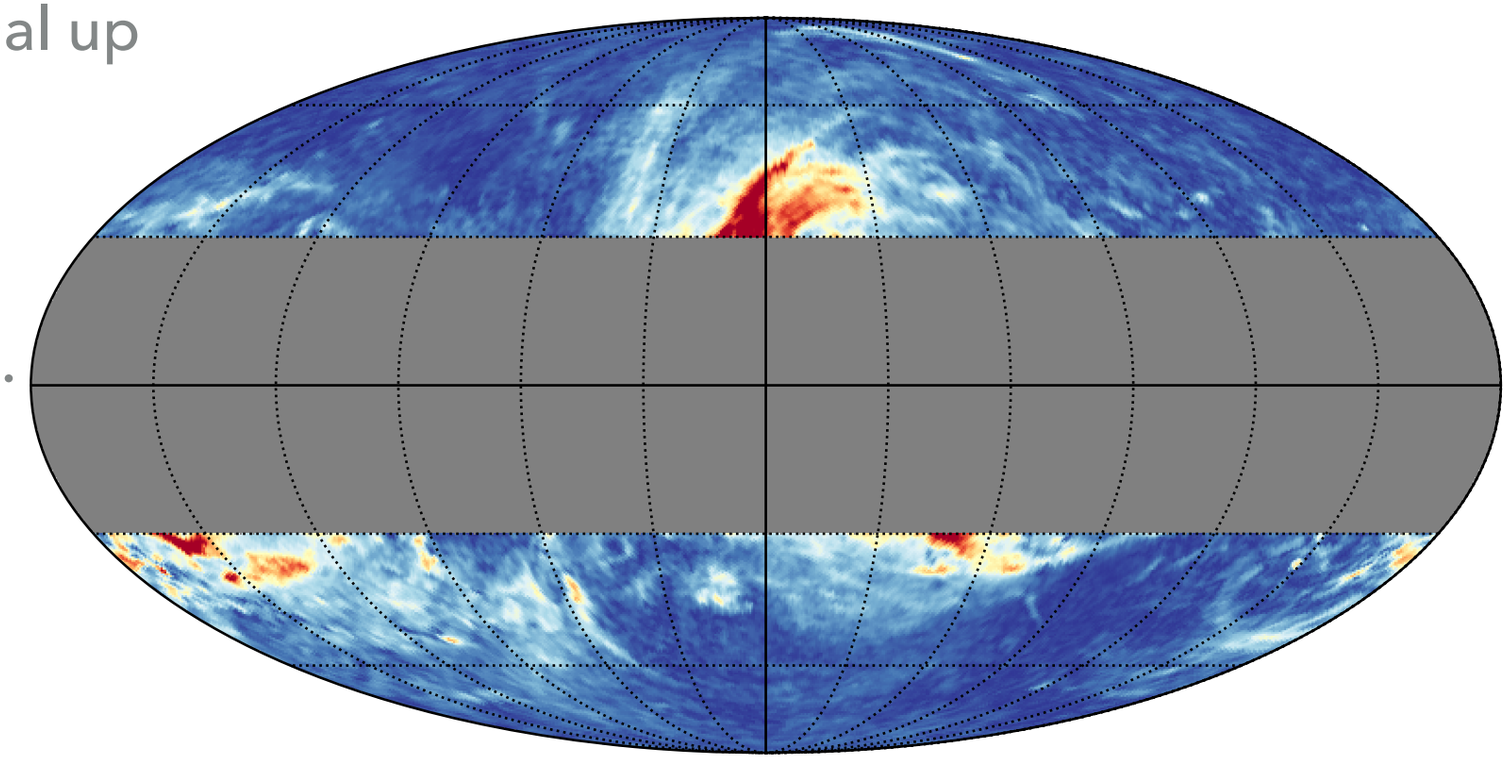
PASIPHAE

Two phases:

1. *shallow* survey down to Rmag = 15 for ~50% of the sky: $|b|$>~30°

   → deep enough to map the dominant clouds contributing to the signal up to ~1–2 kpc distance

   - 2.5 years of observation
   - 15,000 – 20,000 sq.deg.
   - >~ 4 Million stars



2. *deep* survey down to Rmag ~16.5 in selected area
   e.g. those area showing high complexity or increased interests
   - ~1.000 square degree per year

THE CHALLENGES

- Polarimetric instruments for the PASIPHAE program need to be
  - Wide Field of View (high efficiency)
  - High sensitivity: sought signal is low at high $|b|$
  - High accuracy: systematic uncertainty < 0.1% to be photon noise dominated

  → pioneering on all fronts to bring optical polarimetry into the 21st century
- **Instrument design**
  - Calibration scheme:
    - instrument model
    - use of standard stars / Moon flat
  - Survey strategy to optimize observation time and secure science case
    - pointing scheme, exposure time, …
  - Raw data analysis
  - High level analysis, **inversion problem** and exportation to CMB

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    - use of standard stars / Moon flat [Blinov+2022; Maharana+2022b]
  - Survey strategy to optimize observation time and secure science case
    - pointing scheme, exposure time, … [Kiehlmann+2022]
  - Raw data analysis
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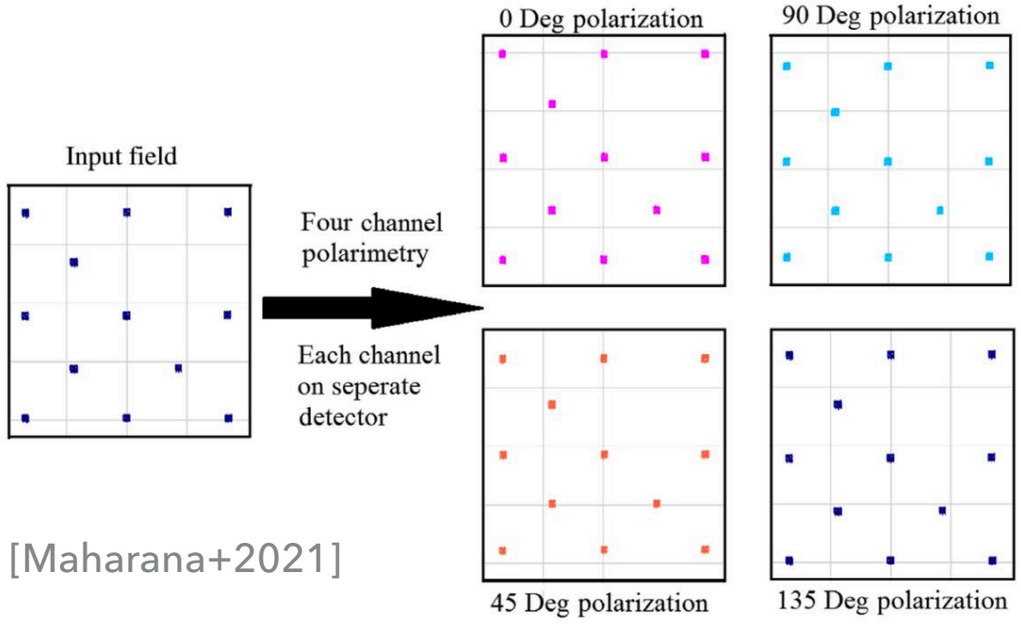
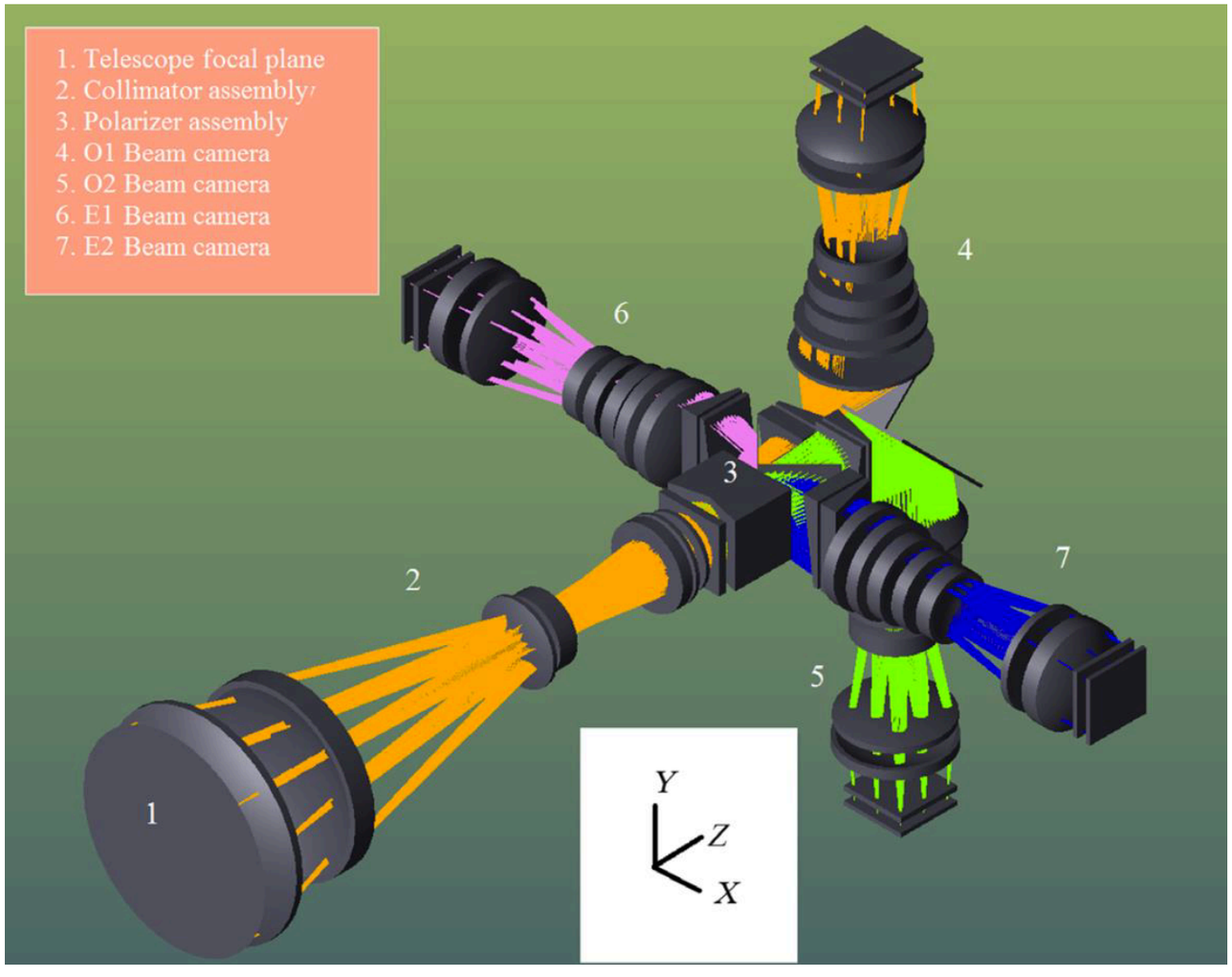
THE INSTRUMENTS

[Maharana & PASIPHAE 2021]

- WALOP (North and South): **W**ide **A**rea **L**inear **O**ptical **P**olarimeter
- Four Camera One-Shot Polarimetry Concept
  - ✓ reduce sky background by factor of 4
  - ✓ no overlap of images from different channels
  - ✓ enable extended object imaging polarimetry for Very Large Field of View



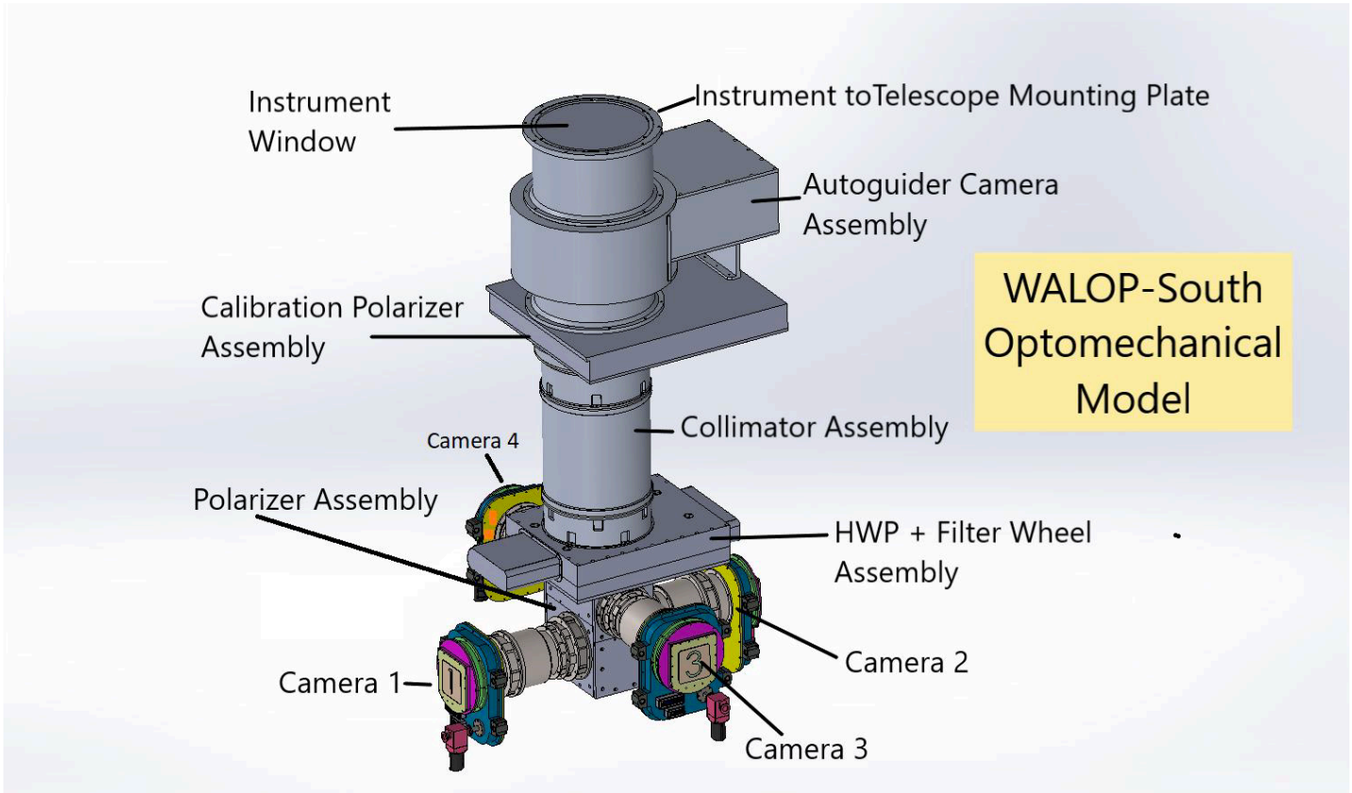
[Maharana+2021]

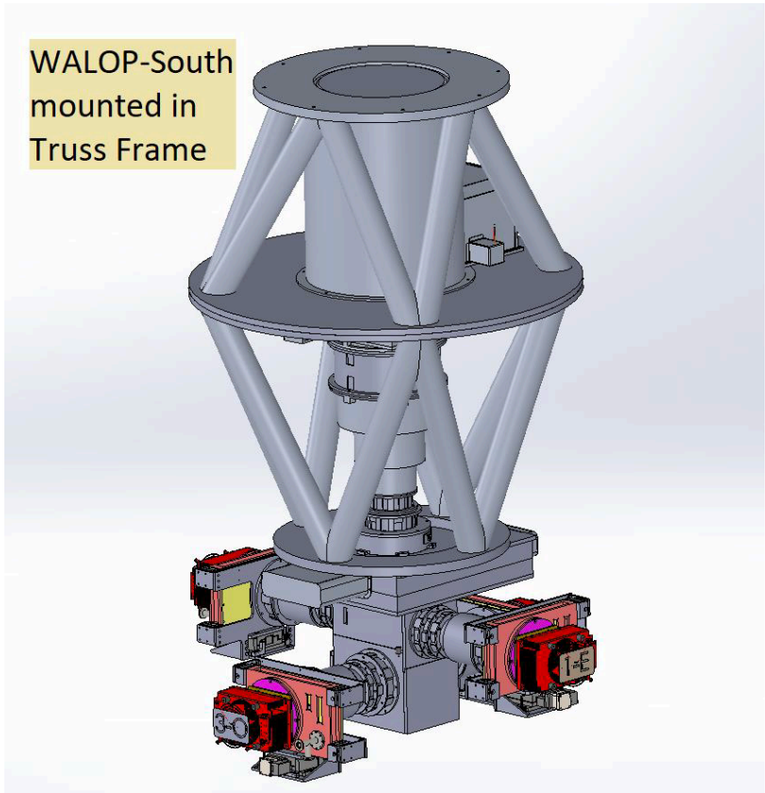


THE INSTRUMENTS

[Maharana & PASIPHAE 2021]

- WALOP South optomechanical design
  - ✓ secure alignments of all the optics
  - ✓ wide FoV: 34 by 34 arcmin
  - ✓ systematic <0.1% across the whole FoV





[Maharana+2021]

All technical goals/requirements are met!

Instrument's construction and assembly are ongoing

CURRENT STATUS

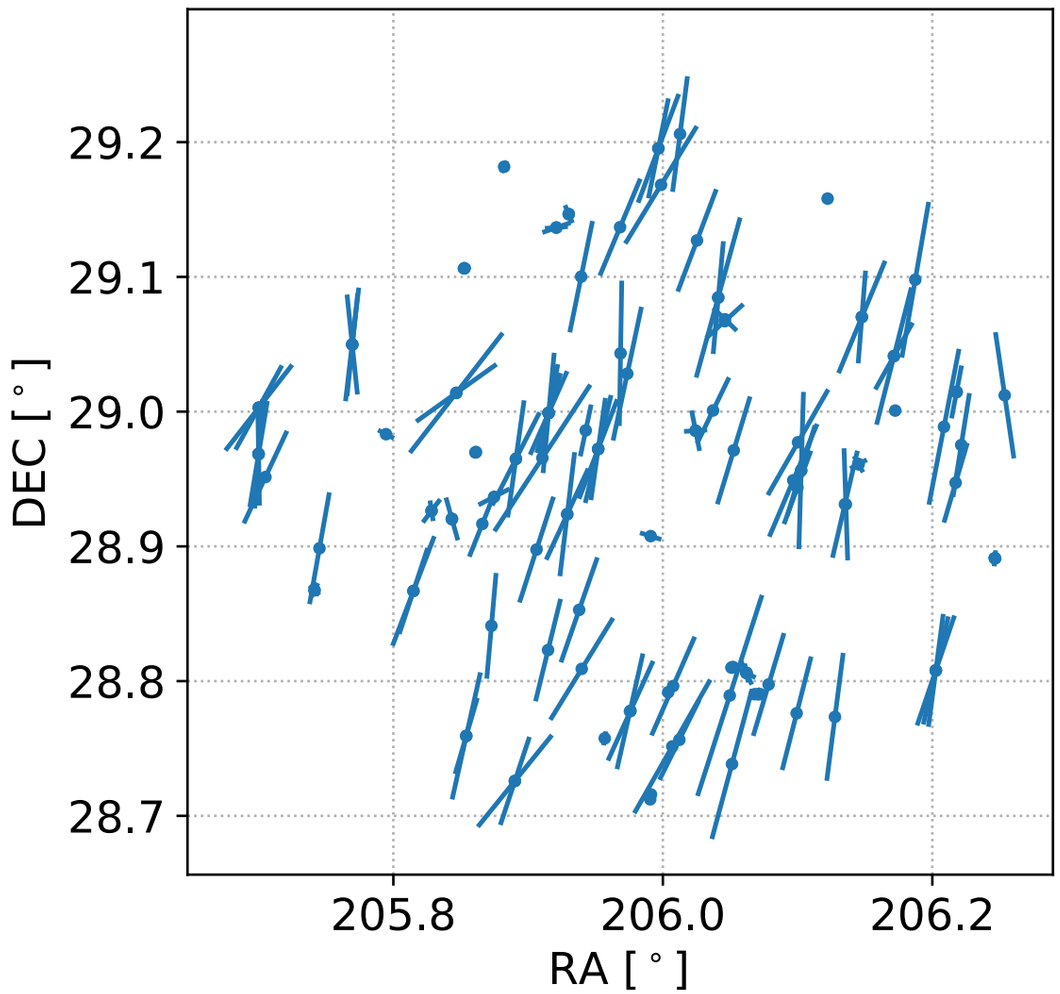
Soon on the sky!

- WALOP–South is scheduled for commissioning during fall 2022!
- WALOP–North will follow in spring 2023

THE INVERSION PROBLEM

[Pelgrims & PASIPHAE 2022]

- Decomposition of starlight polarization signal along distance



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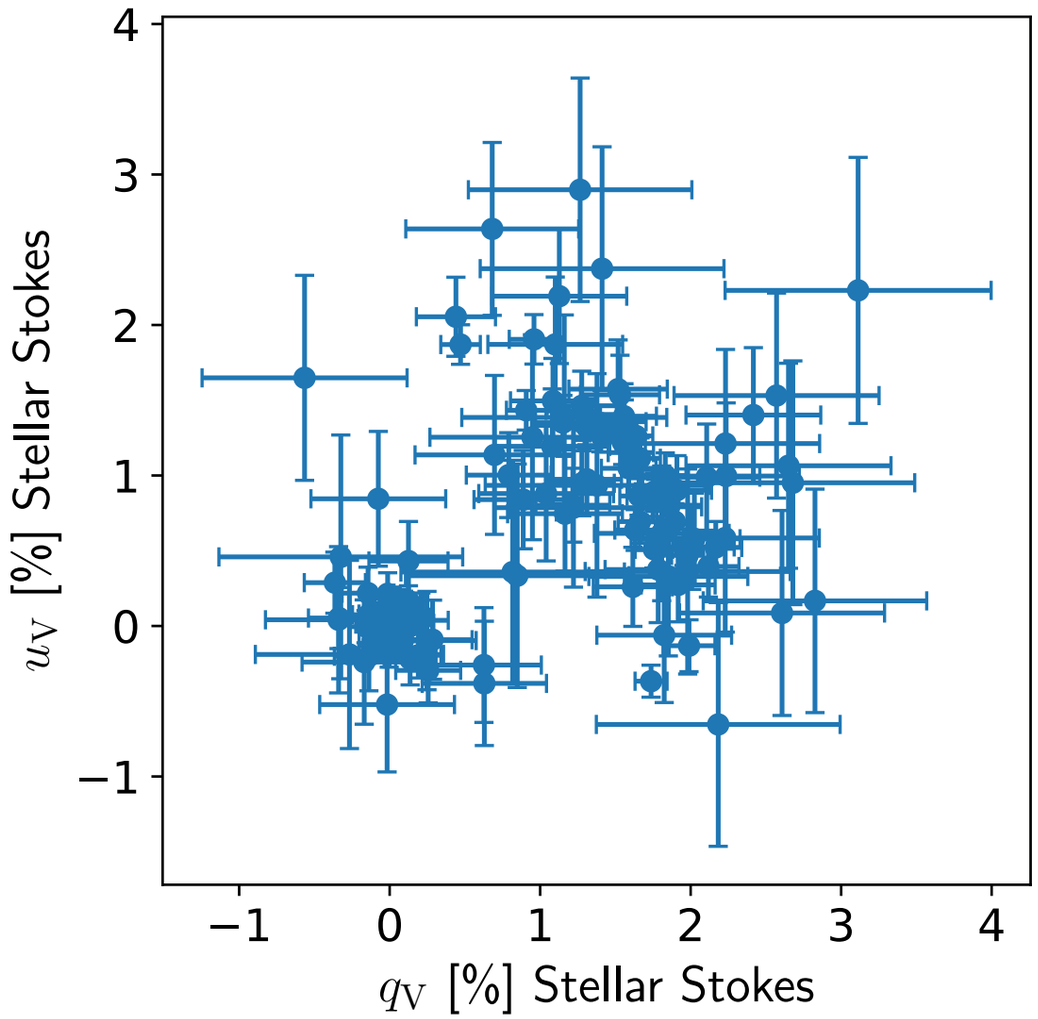

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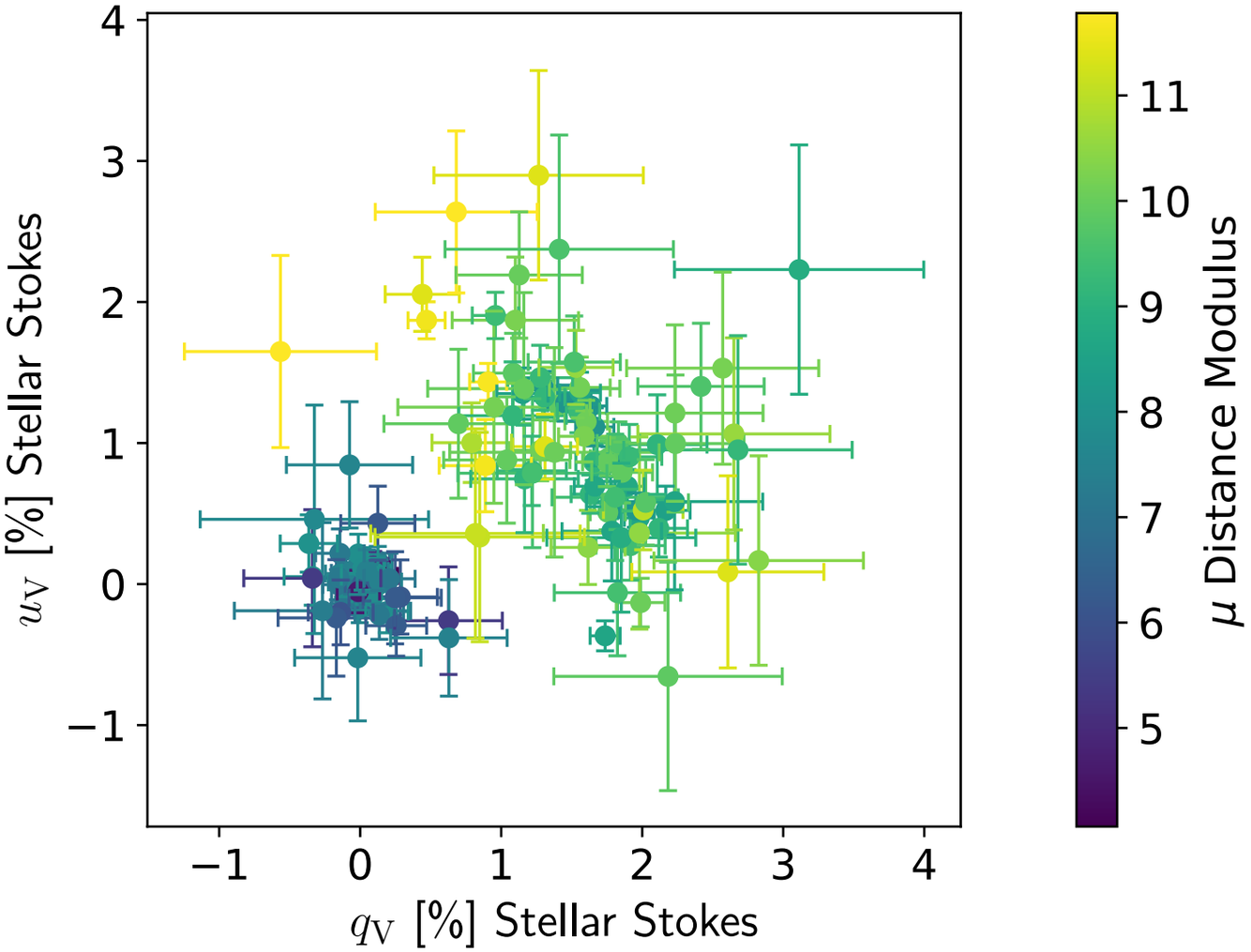

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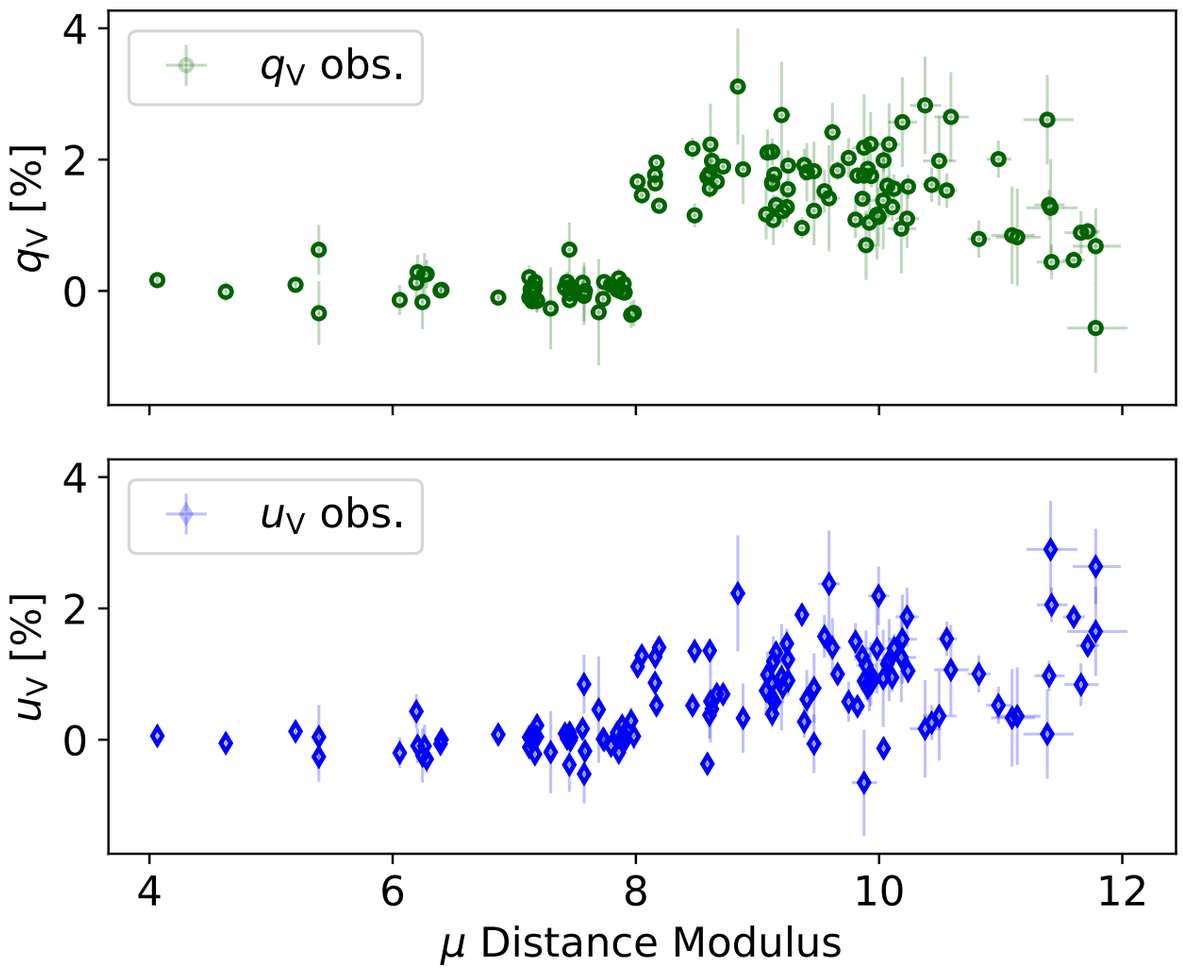

- How many clouds?
- At what distances?
- With what mean polarization?
- With what degree of turbulence?

THE INVERSION PROBLEM

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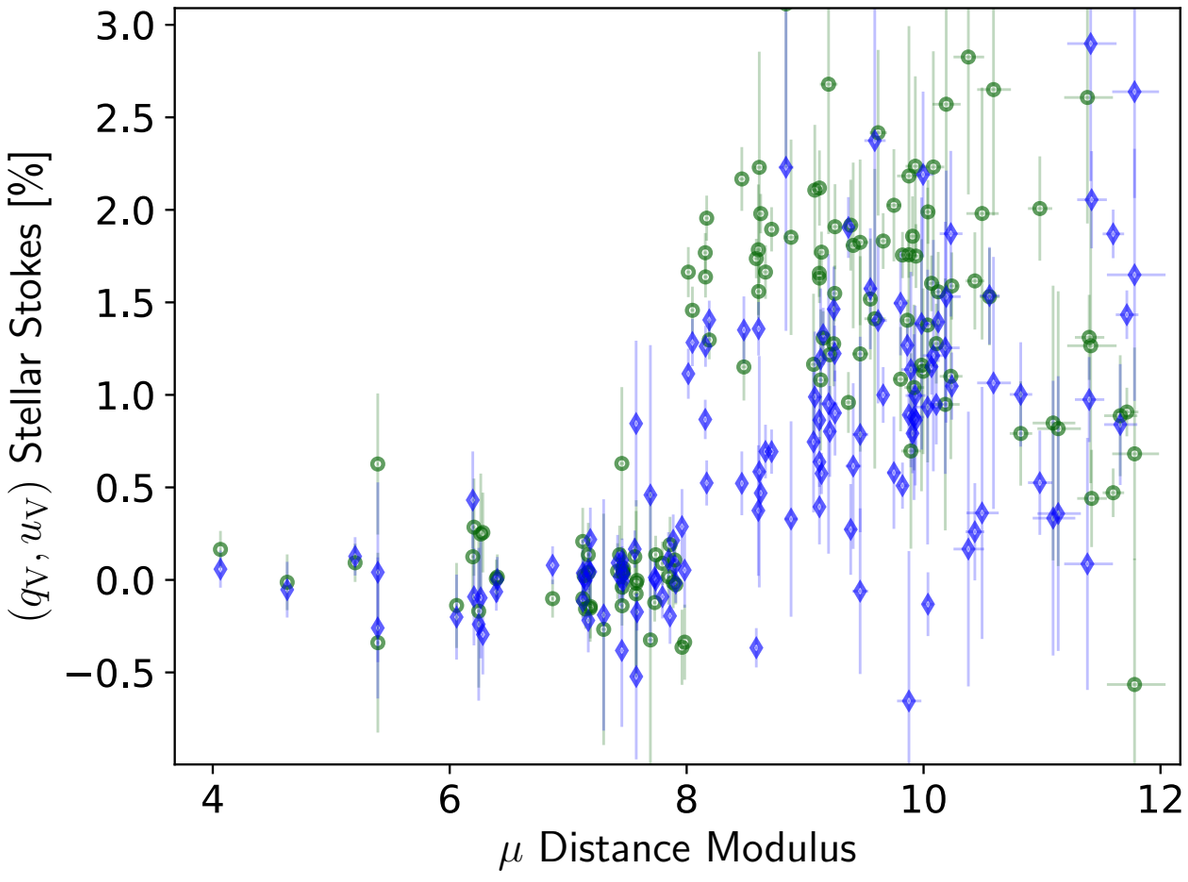

Log-likelihood accounts for

✓ parallax uncertainties

✓ polarization uncertainties

✓ Source of intrinsic scatter in polarization signal (e.g. from turbulence)

THE INVERSION PROBLEM

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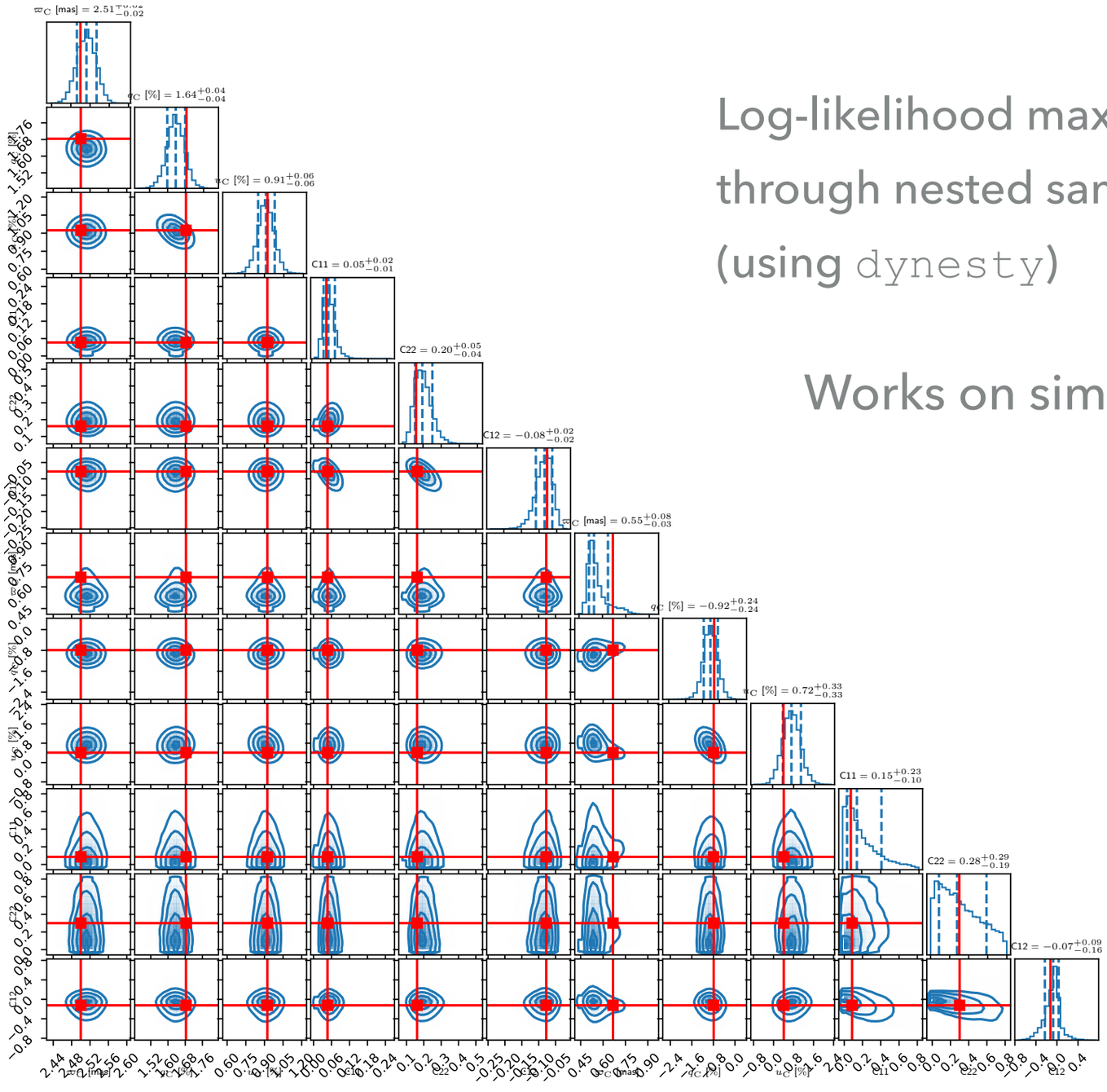


Log-likelihood maximized through nested sampling method (using `dynesty`)

Works on simulated data!

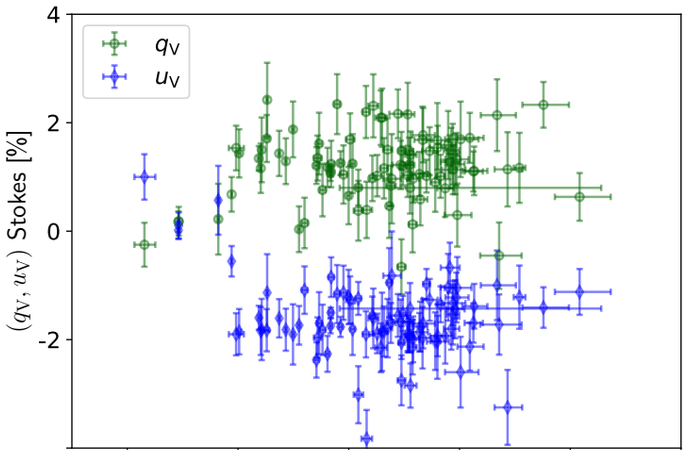
THE INVERSION PROBLEM

[Pelgrims & PASIPHAE 2022]

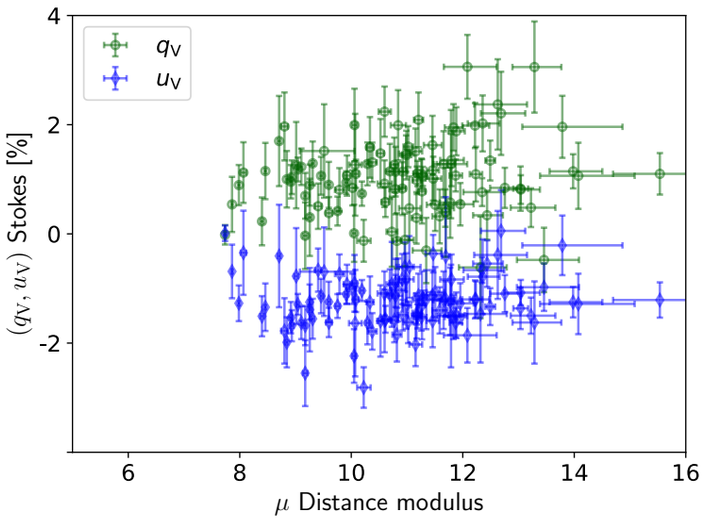
- Decomposition of starlight polarization signal along distance

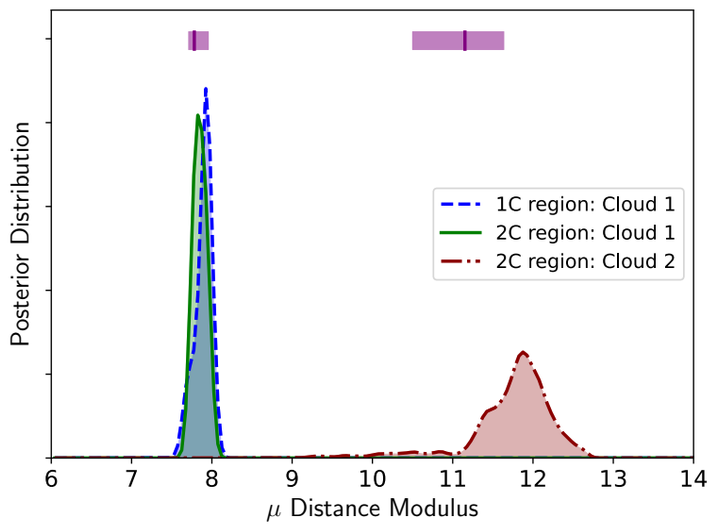
Also works on actual data!

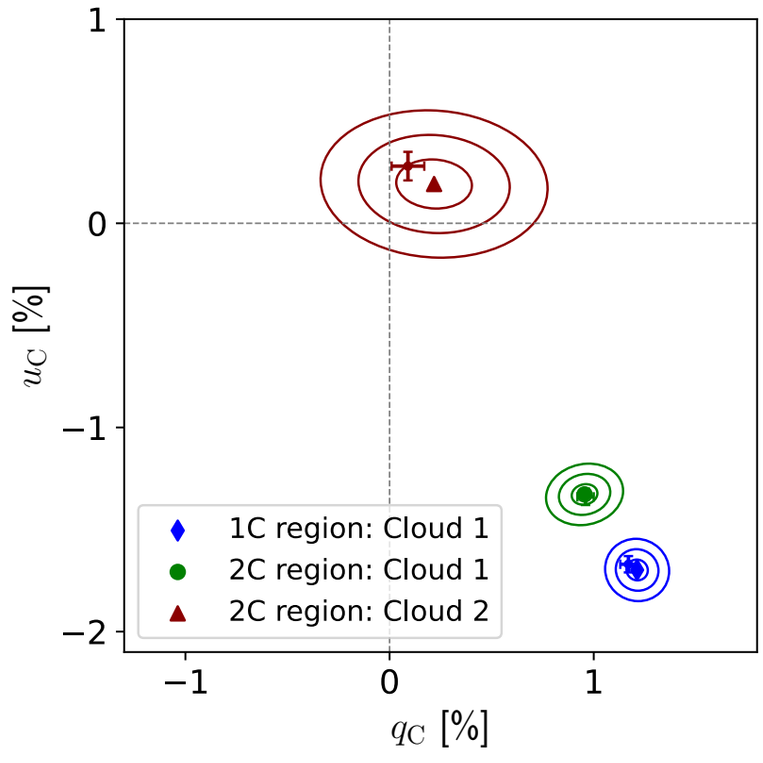
1-cloud LOS



2-cloud LOS







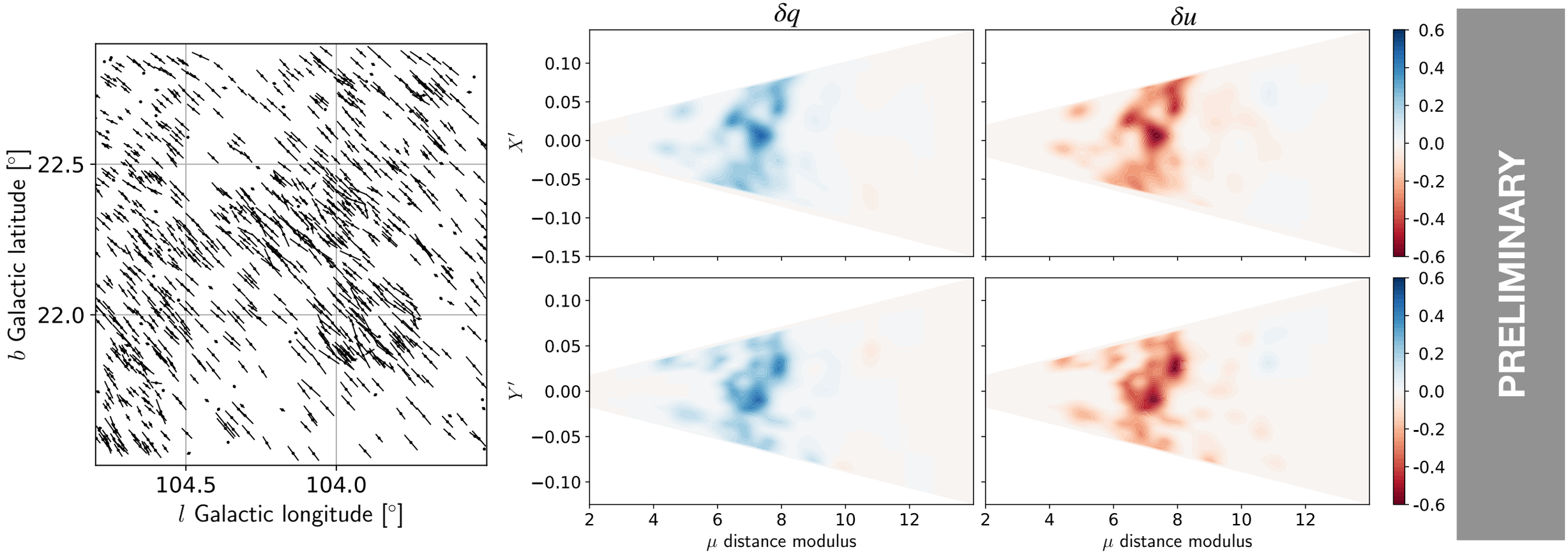
Bayesian Inference of Starlight Polarization in 1D

Soon on the arXiv!

THE INVERSION PROBLEM

[Pelgrims & PASIPHAE 2022b]

- Building the first 3D map of the magnetized dusty ISM from a pilot survey



First 3D map (plane projected) of the differential Stokes parameter of the dust polarization emission!

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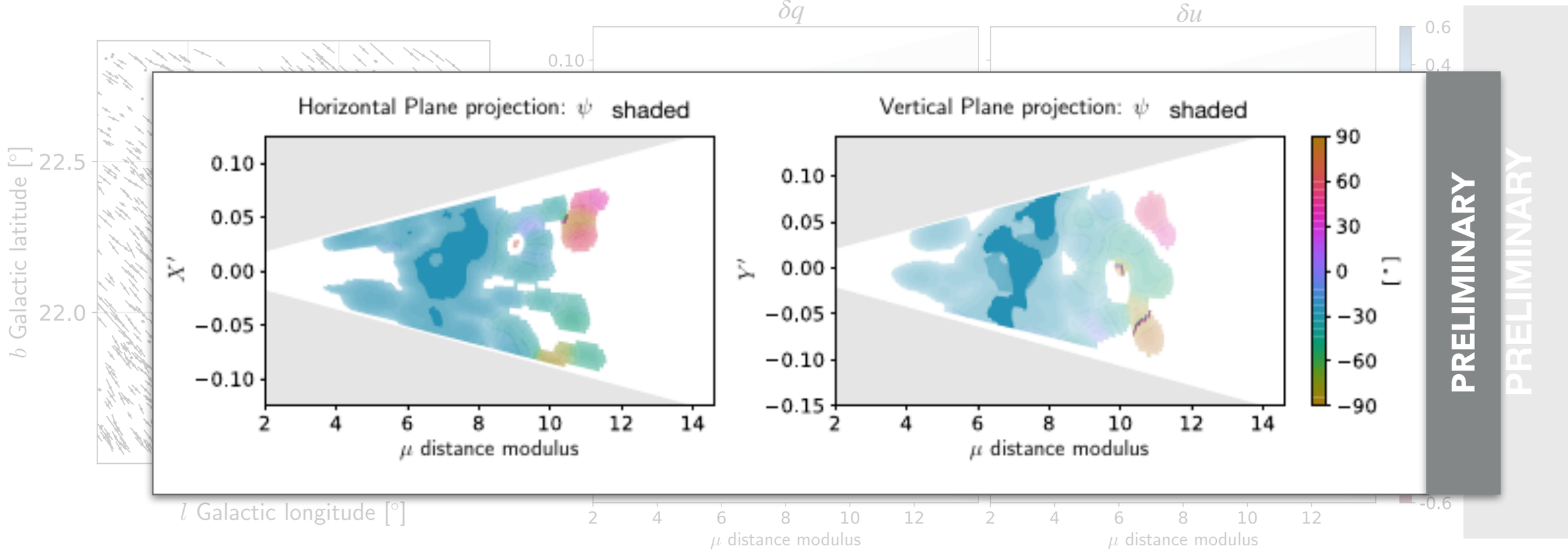


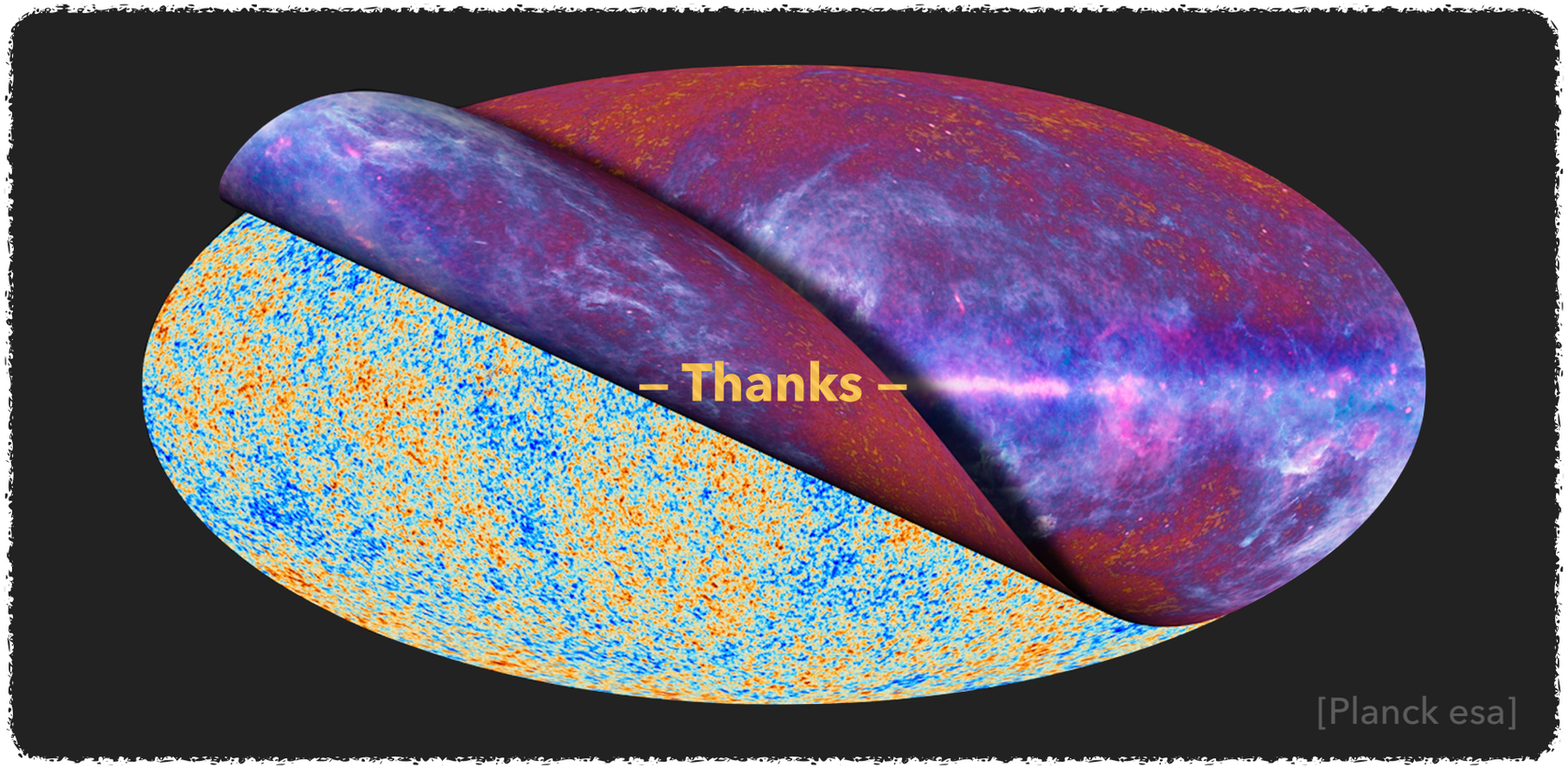
First 3D map (plane projected) of the differential Stokes parameter of the dust polarization emission!

TAKE-HOME MESSAGE

- PASIPHAE will provide 3D maps of the magnetized dusty ISM
  - templates of the Galactic dust polarized emission **agnostic to CMB data**
  - **frequency-dependent** templates if coupled to it

✓ We are getting ready

✓ We will soon be on the sky



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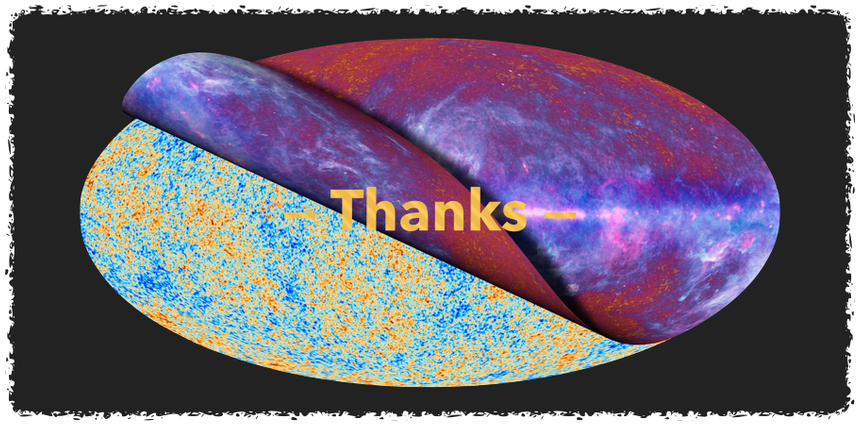


★ Questions?

- Ask me now, later, or even later: pelgrims@ia.forth.gr
- Contact PASIPHAE's PI: Prof K. Tassis: tassis@physics.uoc.gr
- Visit our webpage: http://pasiphae.science/

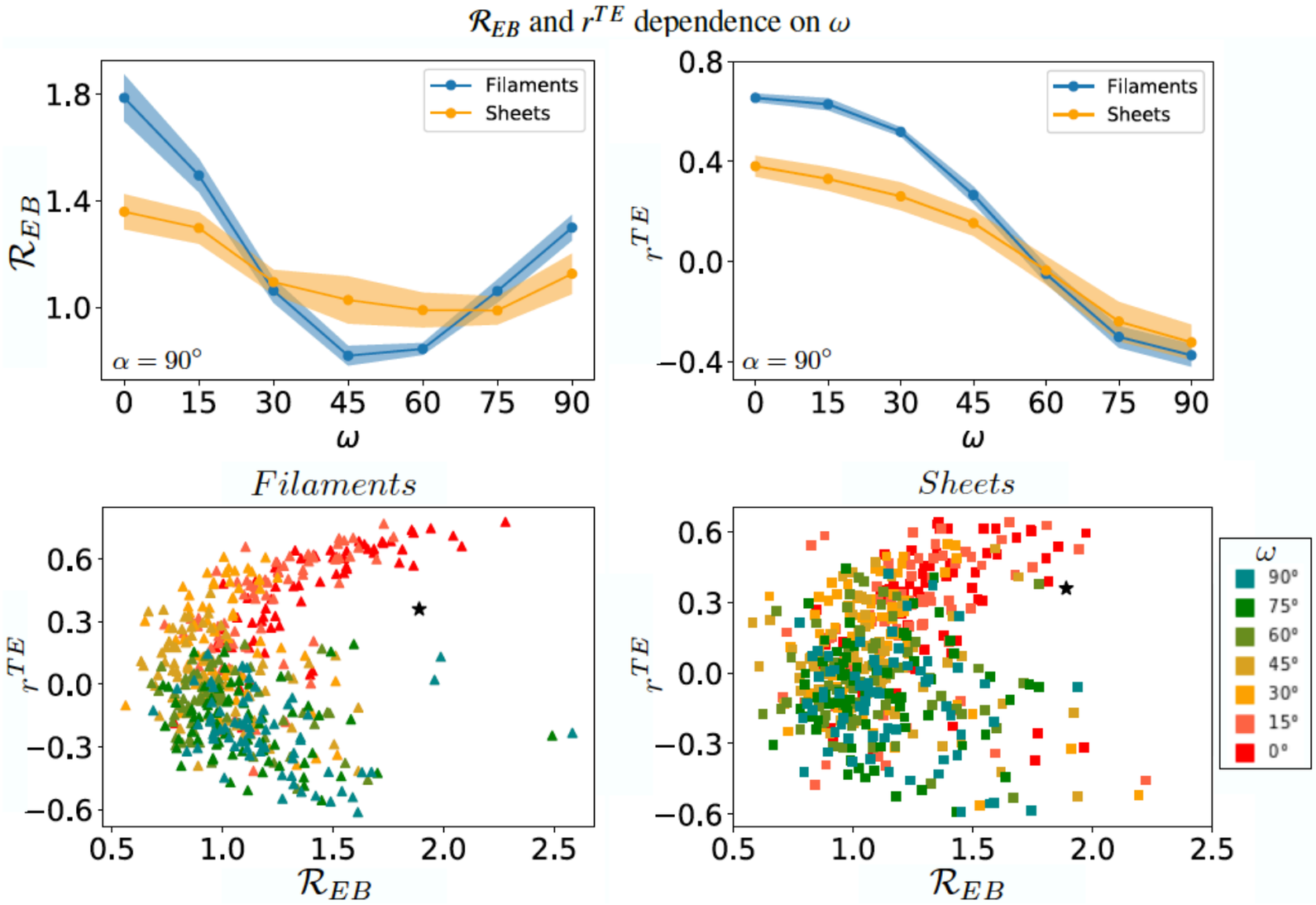
BACKUP —

MOTIVATIONS

- Characteristic of dust polarization power spectra ($\mathcal{R}_{EB}$, r^{TE}, ...) depends on

[Konstantinou, Pelgrims, Fuchs, Tassis 2022]

- Cloud – magnetic field alignment



MOTIVATIONS

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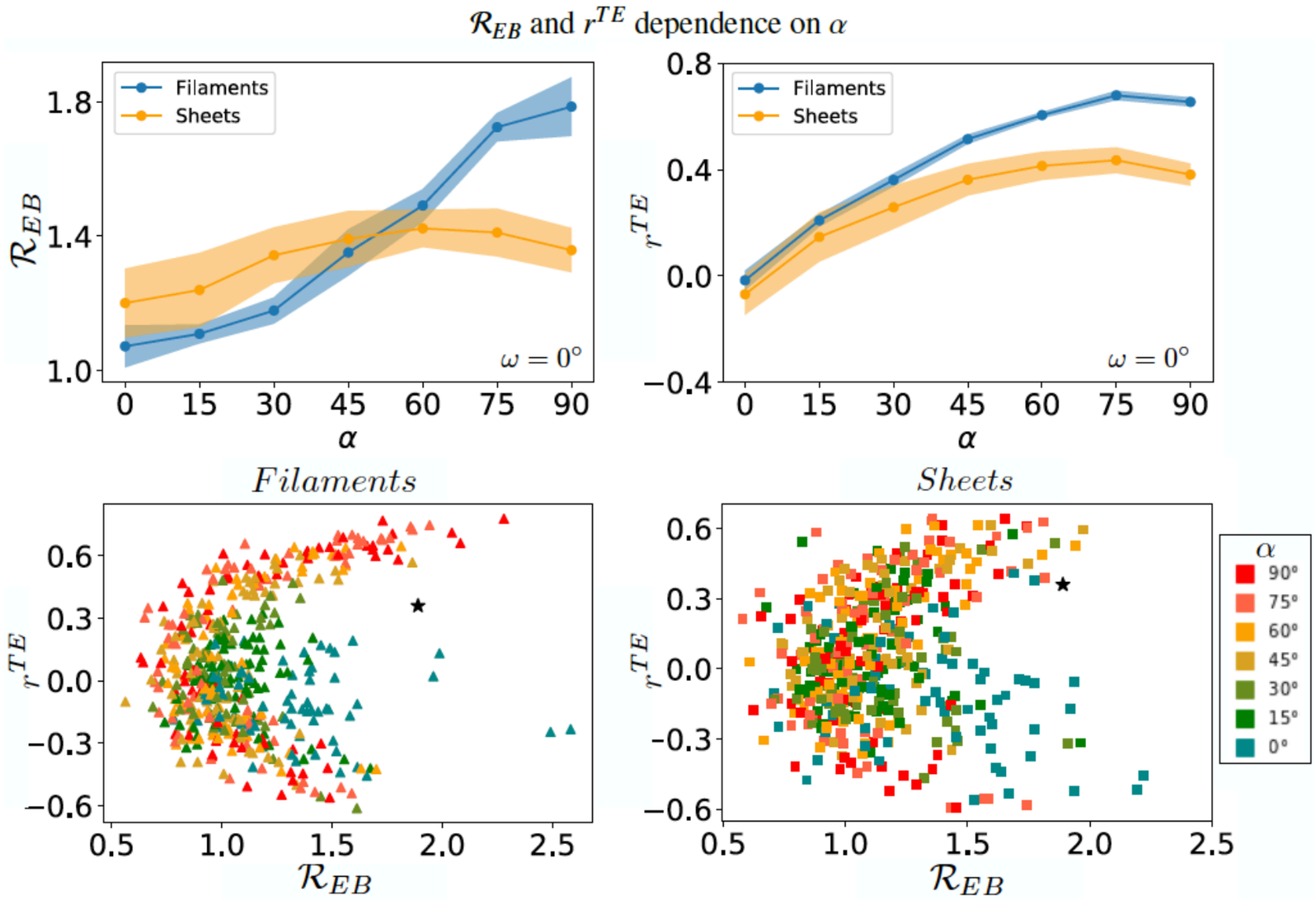
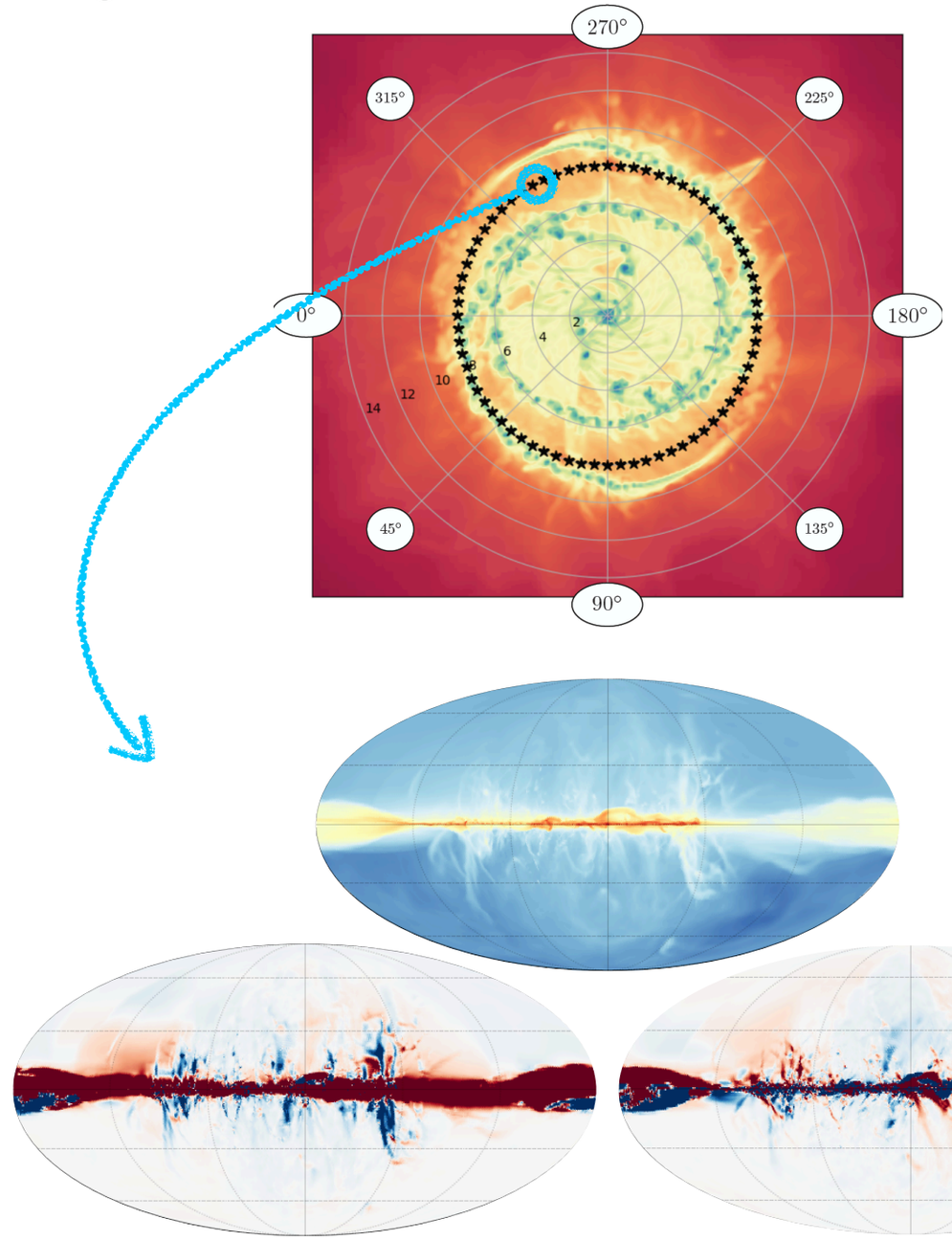
[Konstantinou, Pelgrims, Fuchs, Tassis 2022]

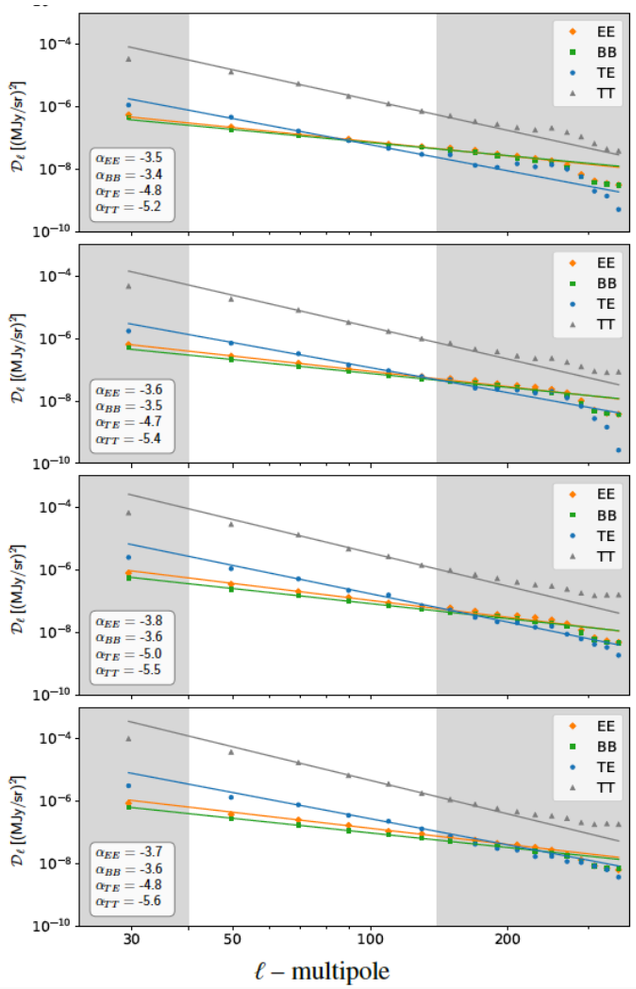
- Viewing angle of 3D B field



MOTIVATIONS

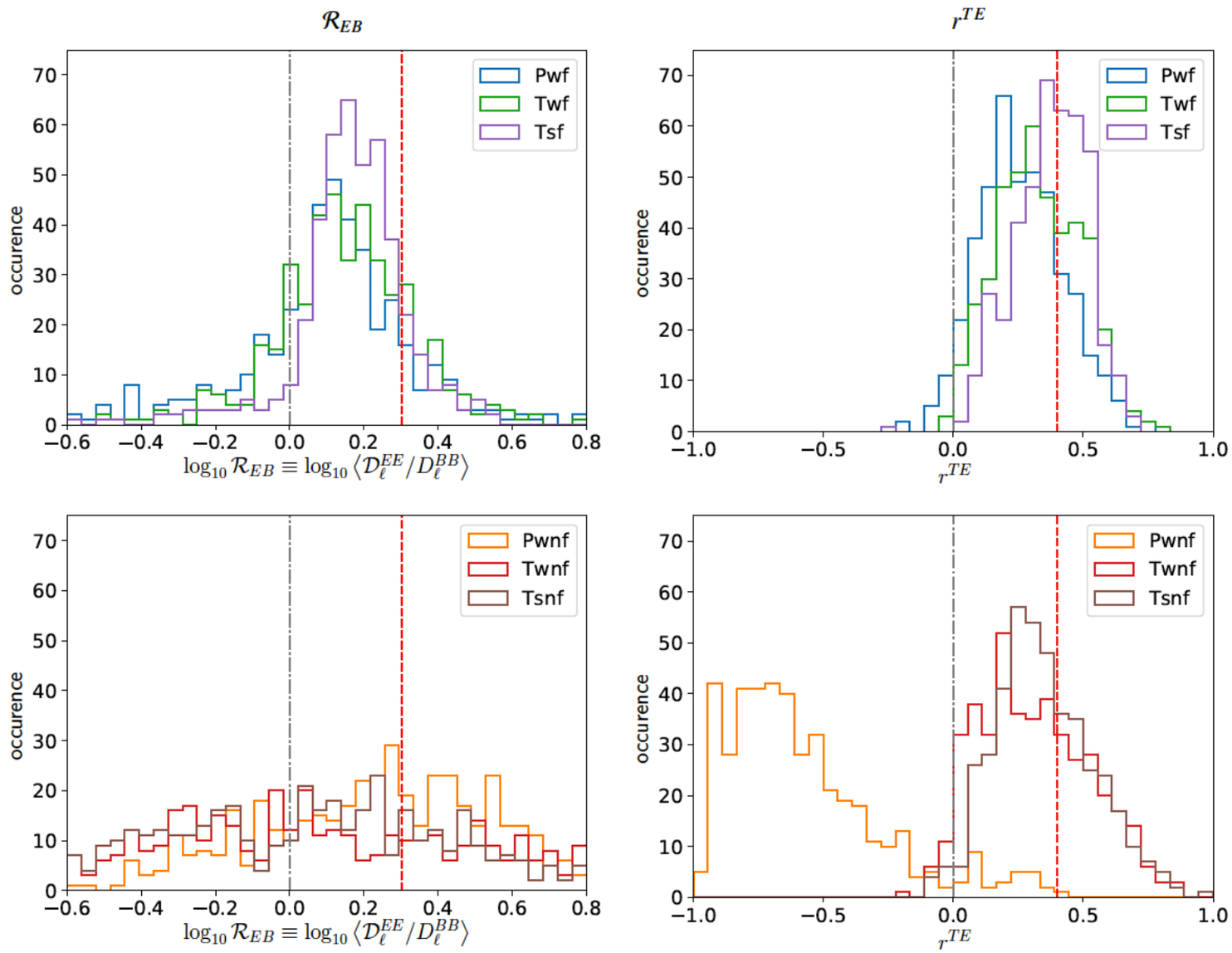
- Characteristic of dust polarization power spectra ($\mathcal{R}_{EB}$, r^{TE}, ...) depends on
- Explains large cosmic variance in simulations [e.g., Pelgrims, Ntormousi, Tassis 2022]





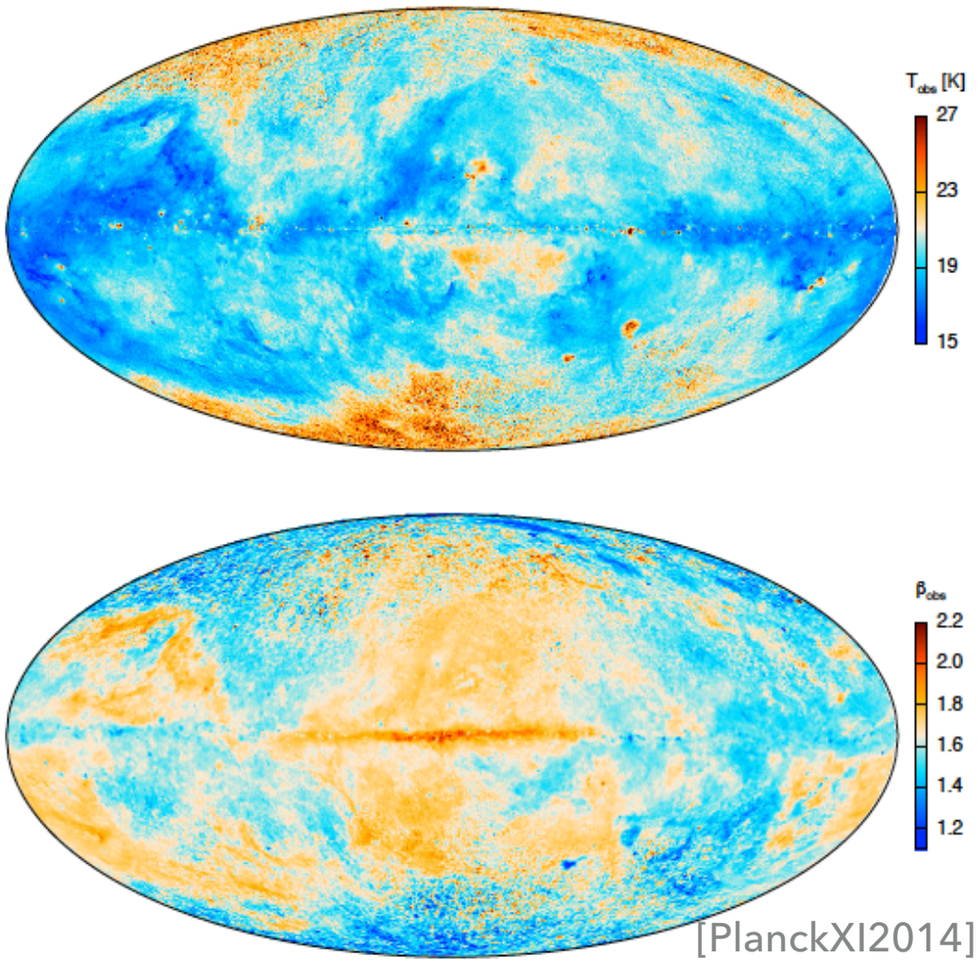
MOTIVATIONS

- Characteristic of dust polarization power spectra ($\mathcal{R}_{EB}$, r^{TE}, ...) depends on
- Explains large cosmic variance in simulations [e.g., Pelgrims, Ntormousi, Tassis 2022] and seen on the sky [e.g. Bracco et al. 2019]



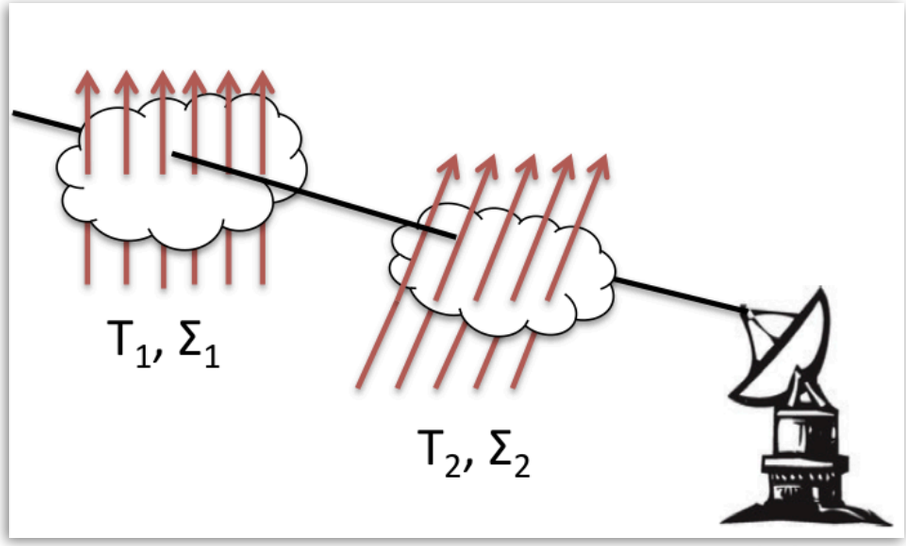
MOTIVATIONS

- Frequency decorrelation of dust polarization signal as due to SED variation
  - Dust SEDs vary across the sky (T, κ)
    [e.g. Finkbeiner+99; Planck (XI 14; IV 20); Irfan+19]



[PlanckXI2014]

  - SEDs vary along LOSs leading to LOS ν-decorrelation from dust clouds [Tassis & Pavlidou 2015]

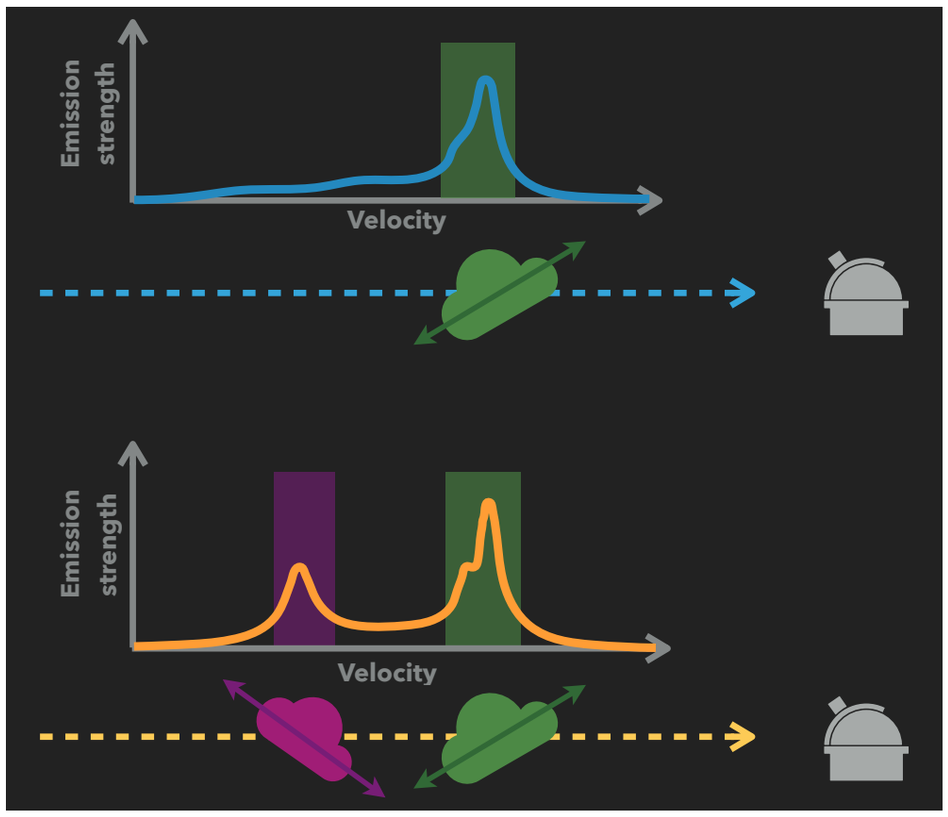


[Tassis&Pavlidou15]

MOTIVATIONS

- SEDs vary along LOSs leading to LOS ν-decorrelation from dust clouds
  [Pelgrims, Clark, Hensley, Panopoulou et al. 2021]

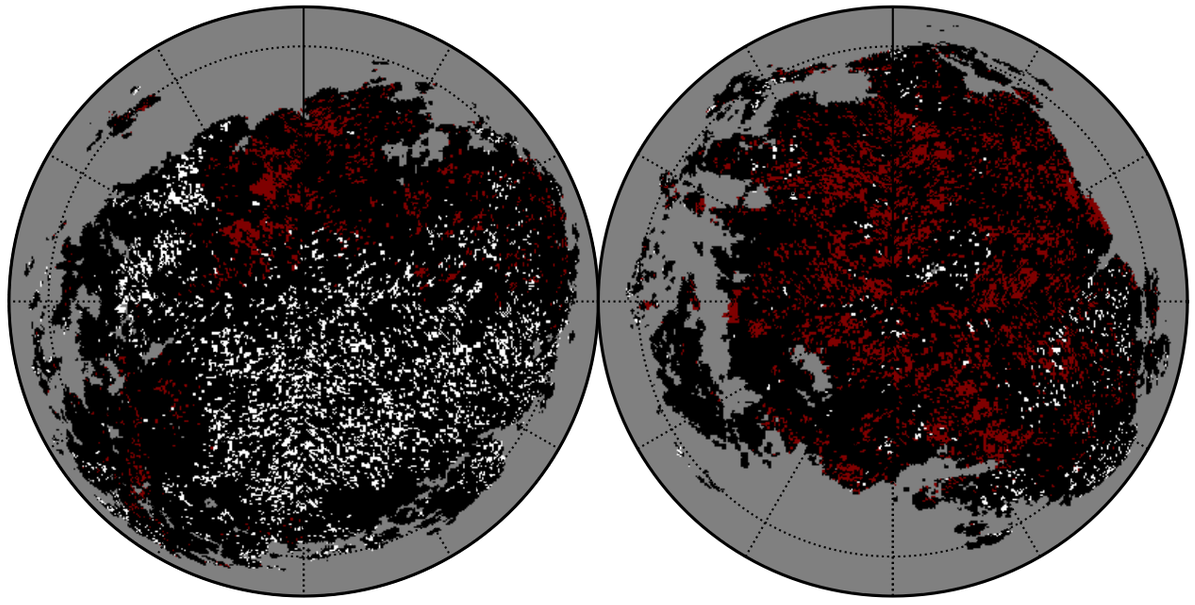
Sightline selection using HI data



#cloud from [Panopoulou & Lenz 2019]

θ_B cloud from [Clark & Hensley 2019]

Sky position of pixel samples



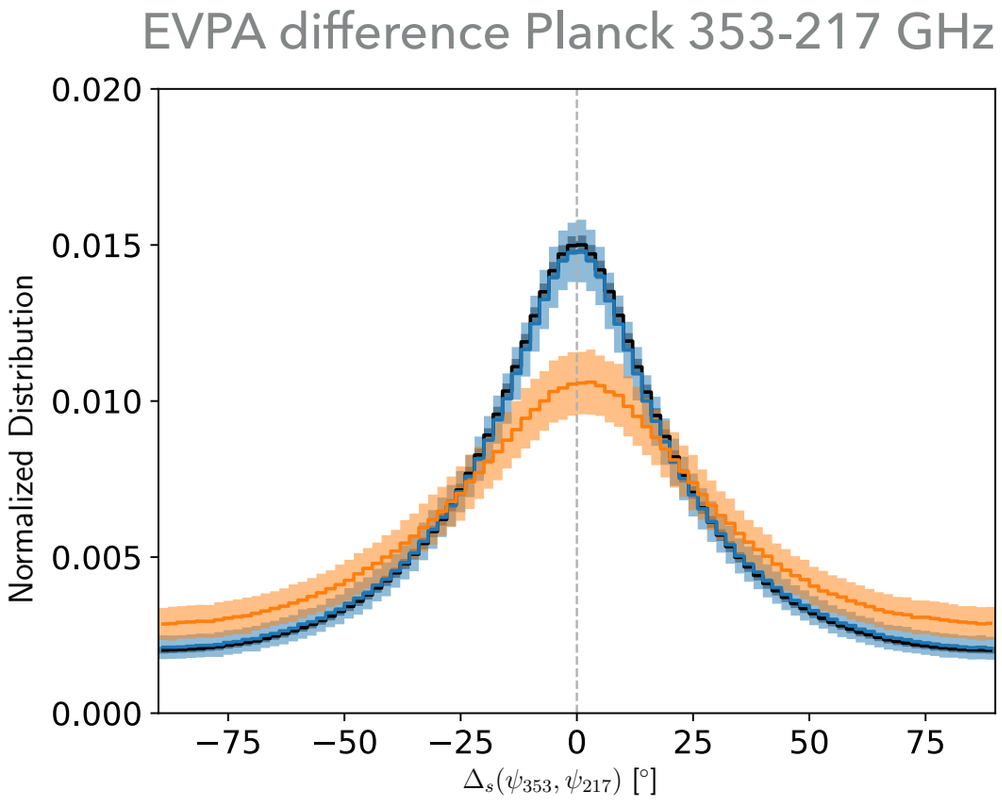
Expectation:

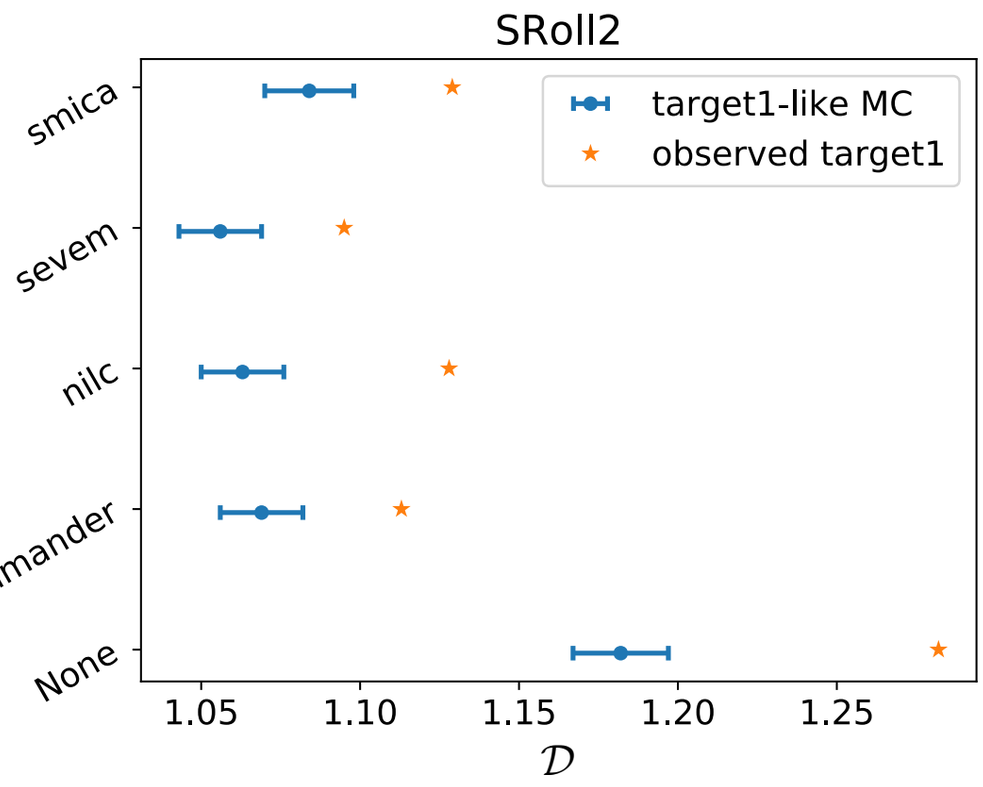
Control = 1 cloud; no LOS ν-decorrelation

Target = 2 *misaligned* clouds; LOS ν-decorrelation

MOTIVATIONS

- SEDs vary along LOSs leading to LOS ν-decorrelation from dust clouds
  [Pelgrims, Clark, Hensley, Panopoulou et al. 2021]



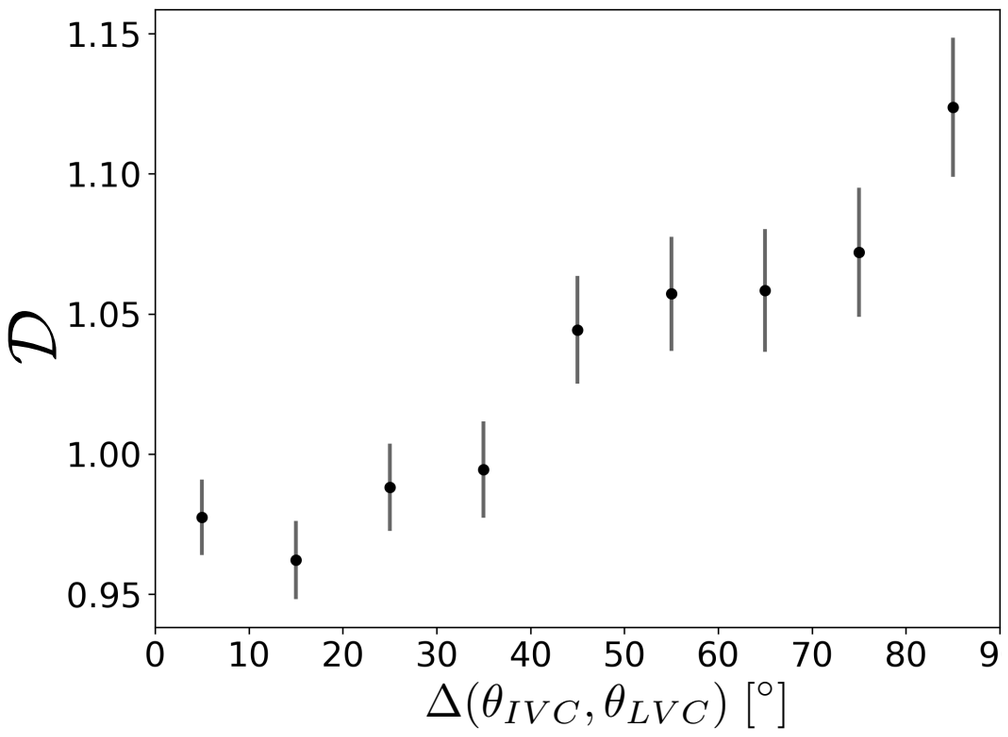


Scatter difference is very significantly larger in target than control
Remains at 2 to 6σ above what noise/residual systematic can do

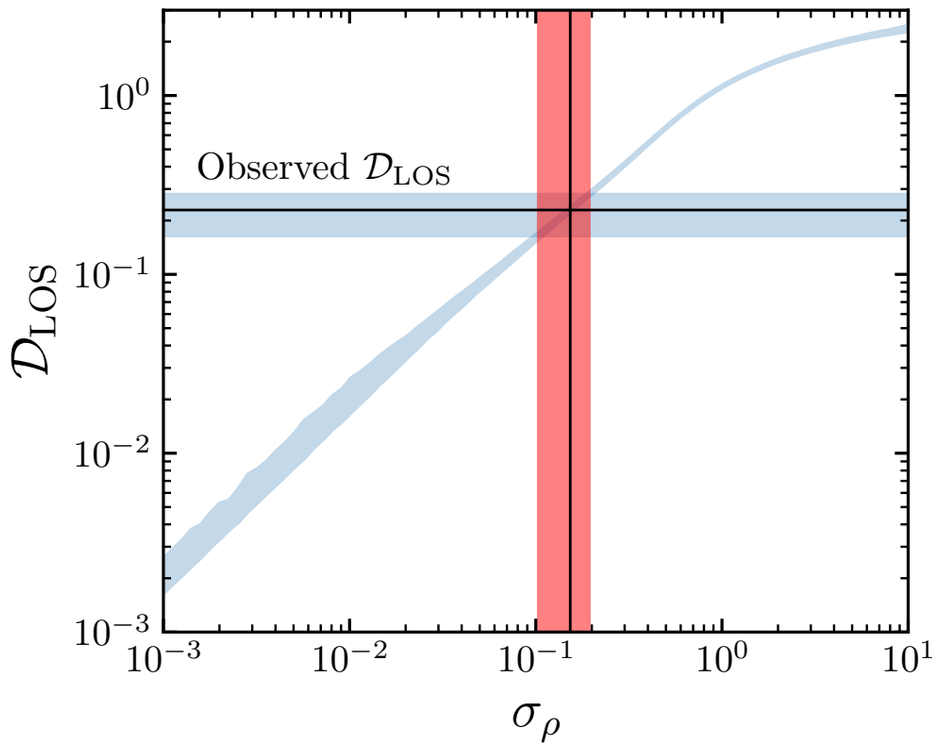
MOTIVATIONS

- SEDs vary along LOSs leading to LOS ν-decorrelation from dust clouds
  [Pelgrims, Clark, Hensley, Panopoulou et al. 2021]

Phenomenology



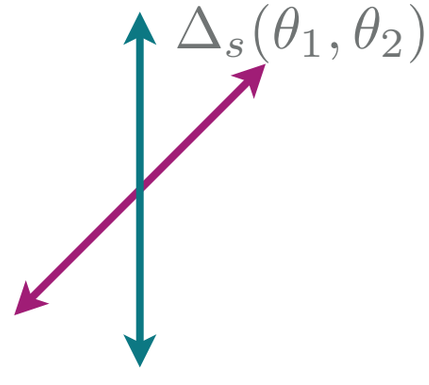
Amplitude of SED variation



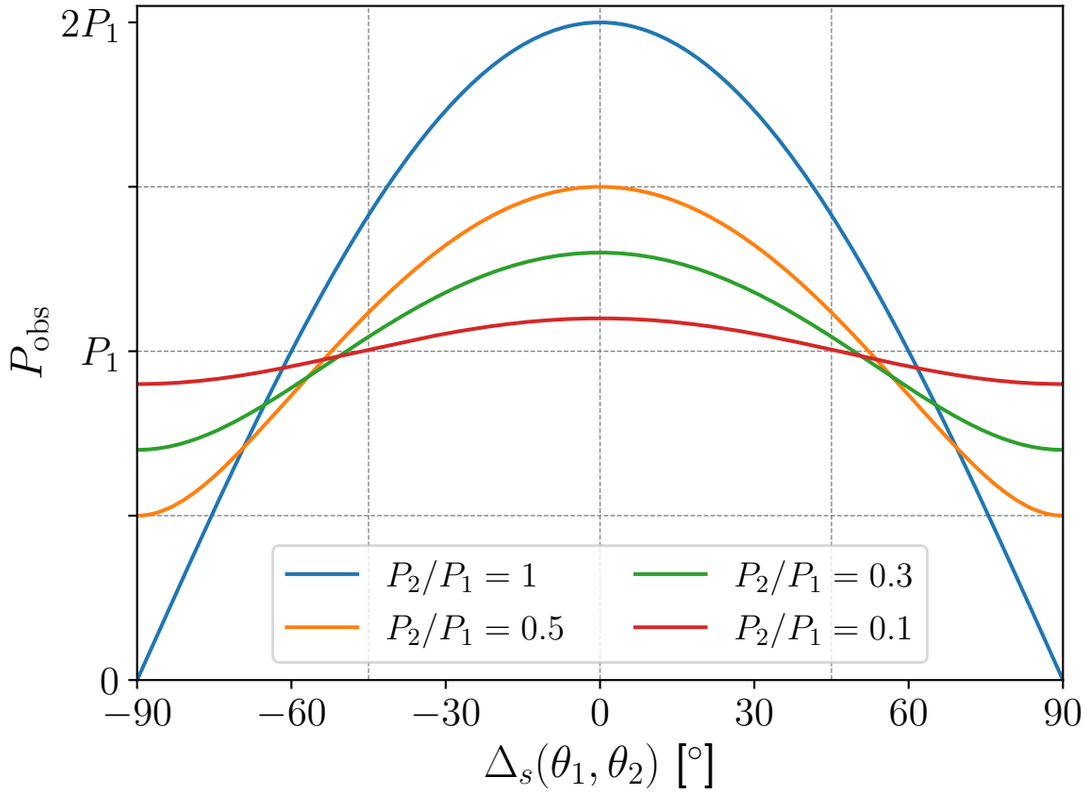
Found and quantified in (noisy) Planck data!

LOS FREQUENCY DECORRELATION

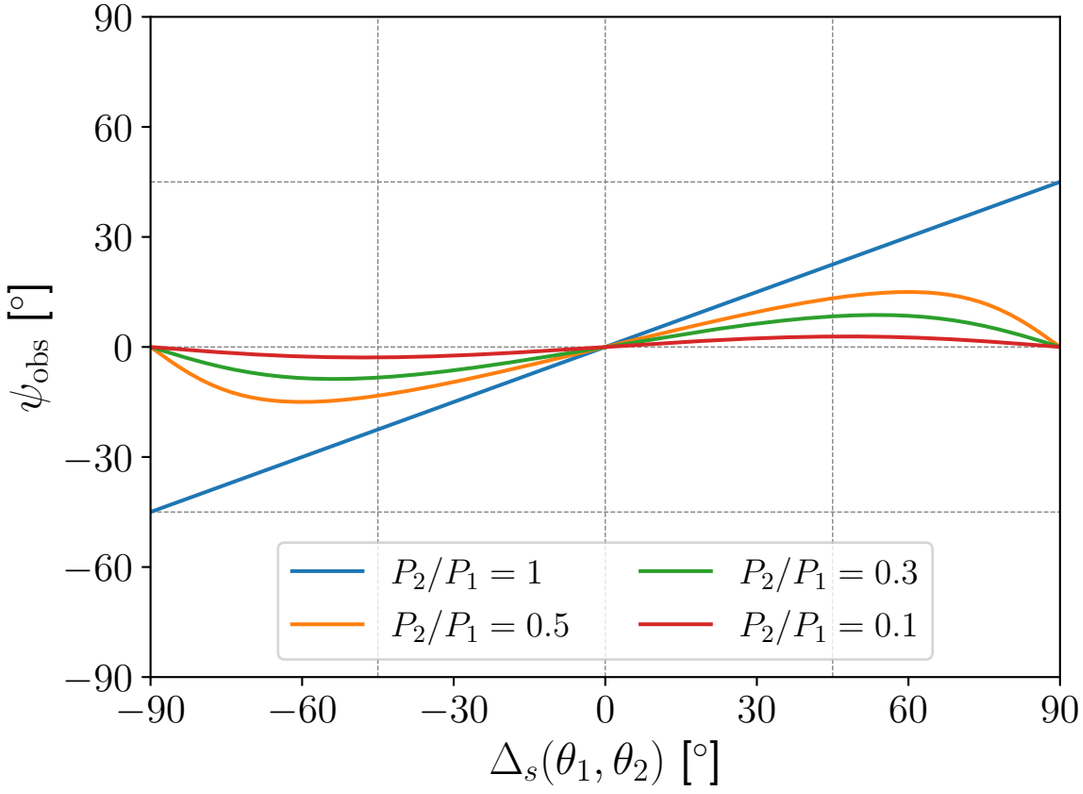
- Observed *P* and EVPA depend on
  - specific P_2/P_1 ratio
  - diff. in POS ***B*** field orientation in each cloud



Polarized intensity



EVPA



LOS FREQUENCY DECORRELATION

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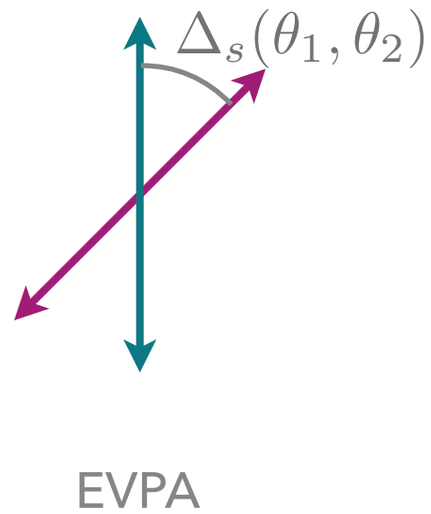
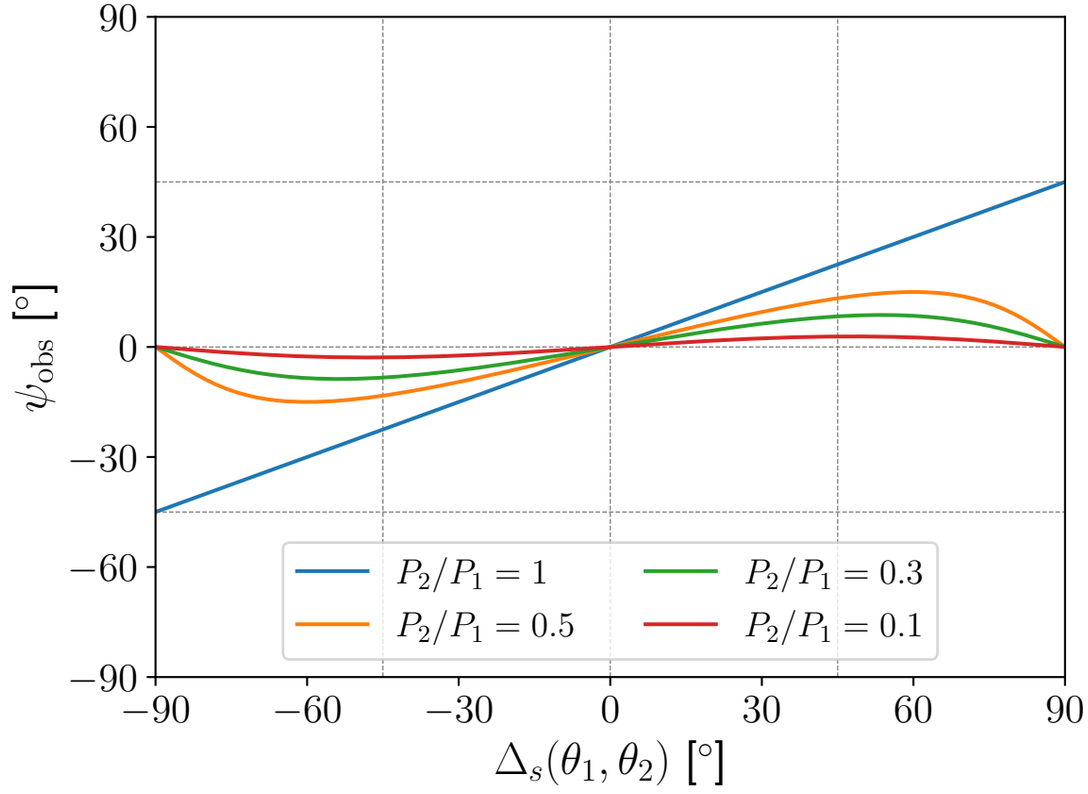


- SEDs difference in P_1 and P_2 implies

➡ frequency dependence of P_2/P_1

➡ frequency dependence of EVPA!

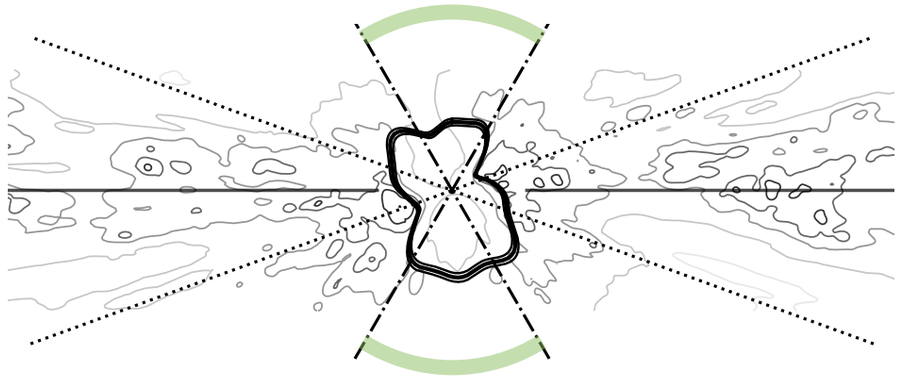


MOST OF THE DUST SIGNAL COMES FROM THE NEAR

Past « achievements » of starlight polarization

- was used to identify the wall of the Local Bubble as the dominant source of polarized signal at 353 GHz at high Galactic latitudes [Skalidis&VP19]

- assists in modeling the dust polarization sky in picking right modeling approach [Alves+18; VP+20]



- LB shell shape from 3D dust extinction map
- ***B*** from fit of Q and U at $|b|$>60°