3D mapping of the magnetized ISM with starlight polarization

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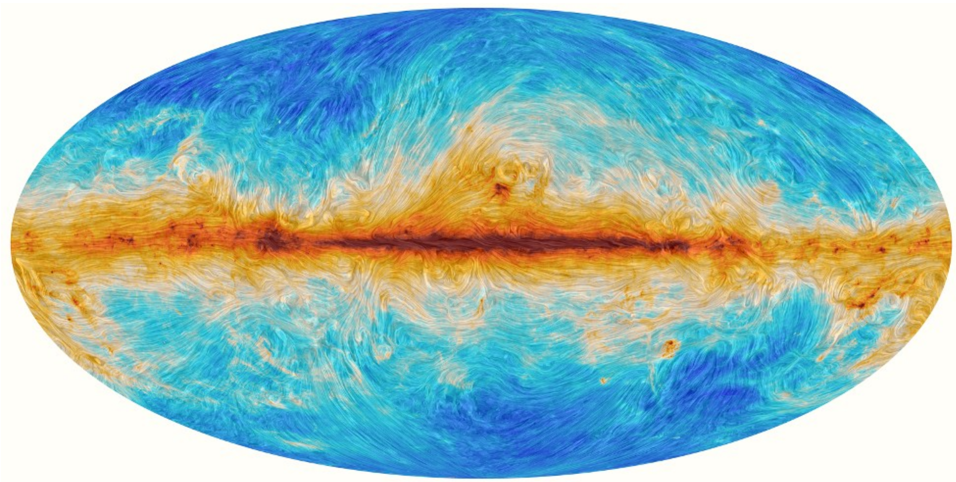
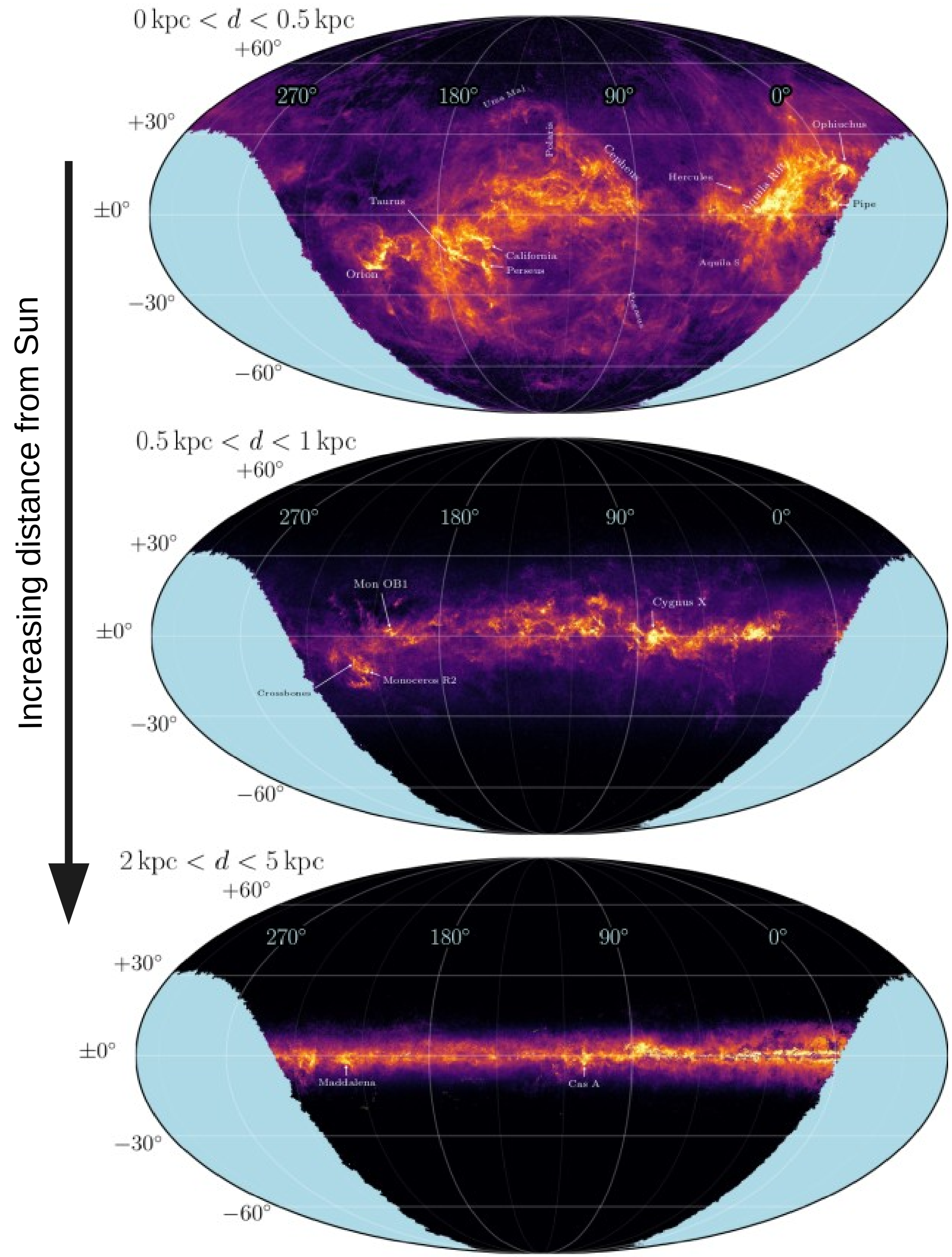
NASA Hubble Fellow
Caltech

B-mode from space
MPA, Munich, 2019

Dust varies along line of sight

'The' dust component



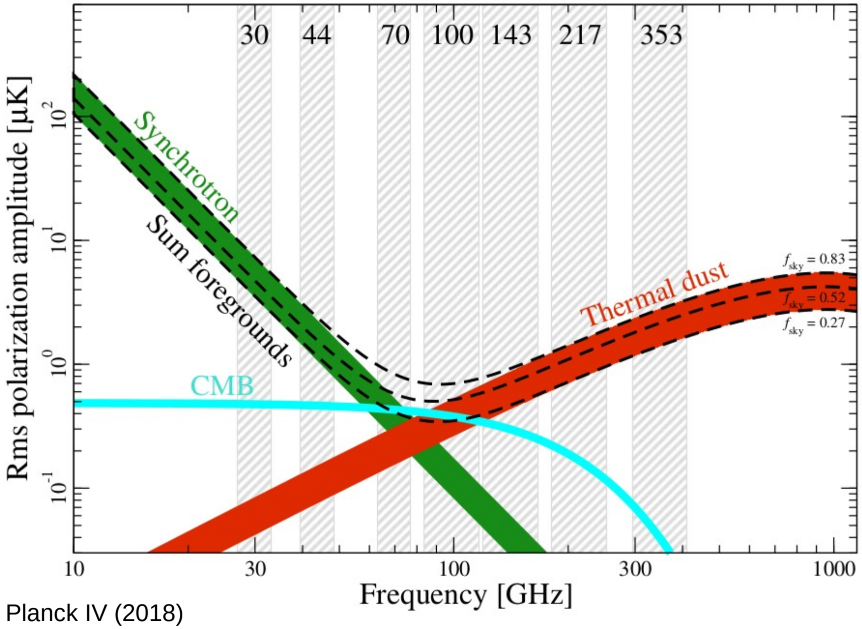


How to go from the *simplest* model to a *plausible* model?

A 3D map of dust extinction from stars: Green et al. (2019)

Parametric modeling of ISM dust: a first approximation

Planck: Modified Black-body is a good fit to dust contribution of intensity + polarization



Planck IV (2018)

- Assume uniform population of dust grains in uniform magnetic field

$$Q_\nu = A^P \cos 2\chi \left(\frac{\nu}{\nu_0}\right)^\beta B_\nu(T) \qquad U_\nu = A^P \sin 2\chi \left(\frac{\nu}{\nu_0}\right)^\beta B_\nu(T)$$

Frequency dependence only by Modified Black-body

- Solve for all foreground model parameters

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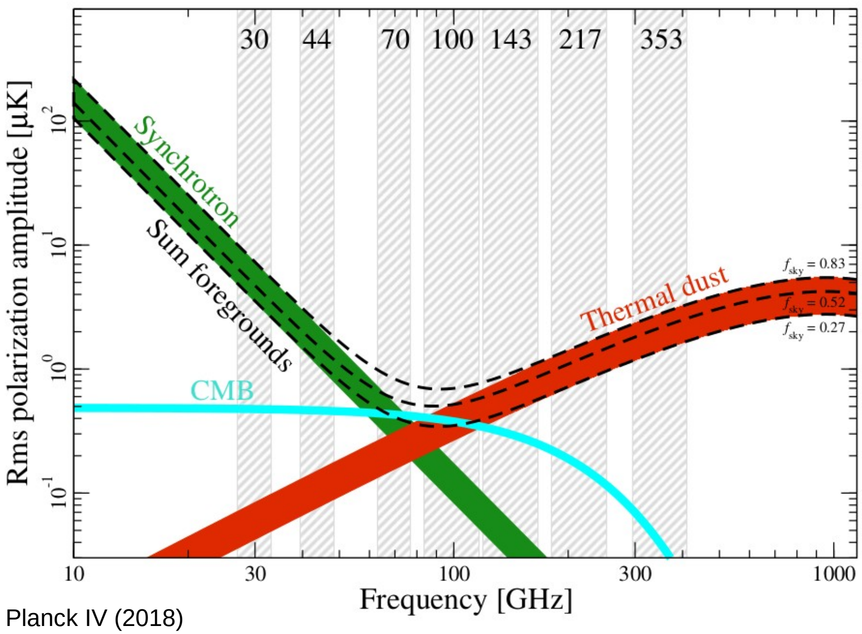

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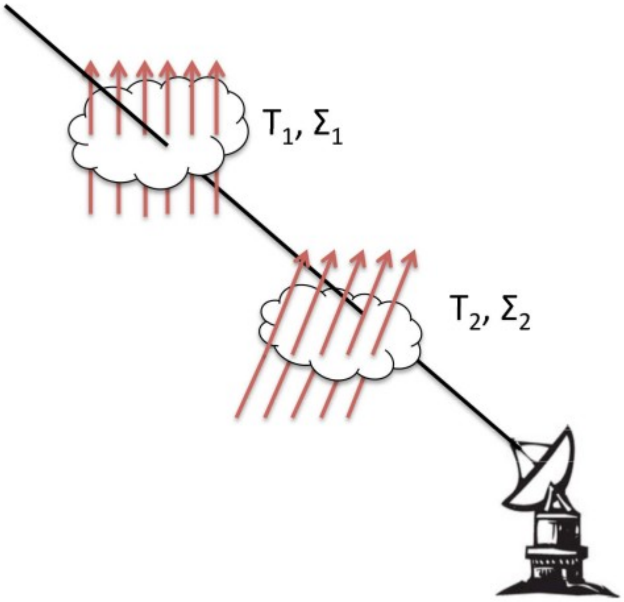
Frequency dependence only by Modified Black-body

- Solve for all foreground model parameters

What accuracy can we reach with this approximation?

WANTED: better approximation to dust modeling



Tassis & Pavlidou 2015

When multiple clouds along the line of sight, single blackbody model assumption breaks down

$$I_{\rm tot} = I_1 + I_2$$

$$Q_{\rm tot} = Q_1 + Q_2$$

$$U_{\rm tot} = U_1 + U_2$$

Multiple dust clouds *in principle* need to be taken into account ...

Poh & Doddelson 2015, Ghosh+ 2017, Adak+ 2017, Hensley & Bull 2017, Martinez-Solaeche+ 2019, Clark & Hensley 2019

…but no consensus as to what the importance of the effect is for foreground subtraction

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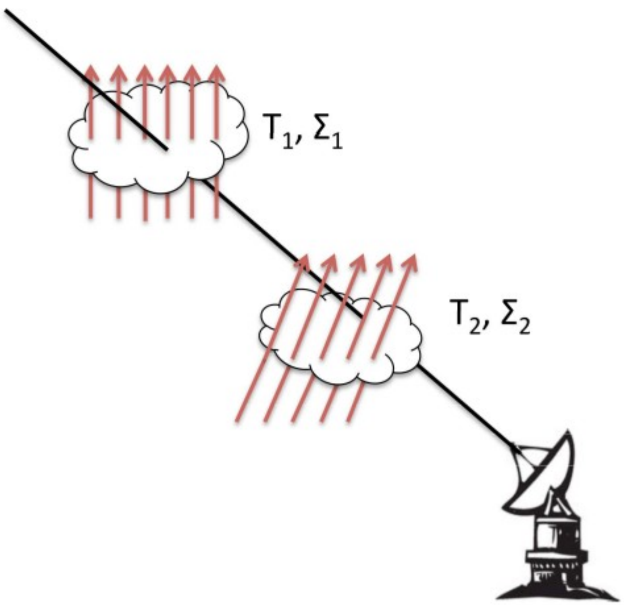

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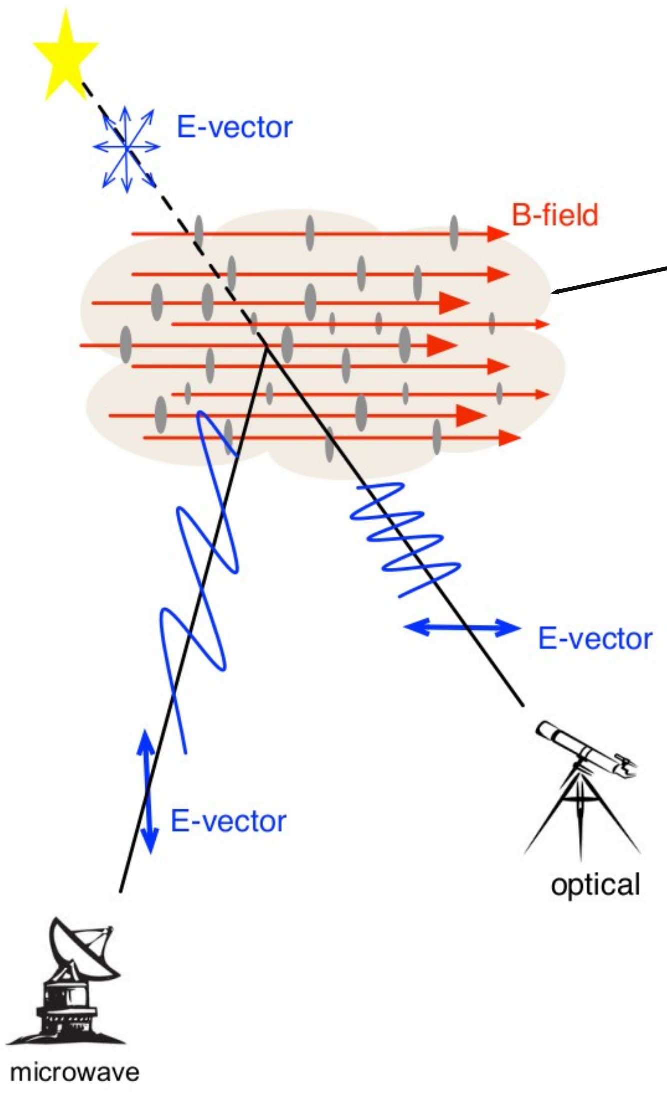
Answer depends on ISM properties!

Need to *measure* ISM properties in 3D

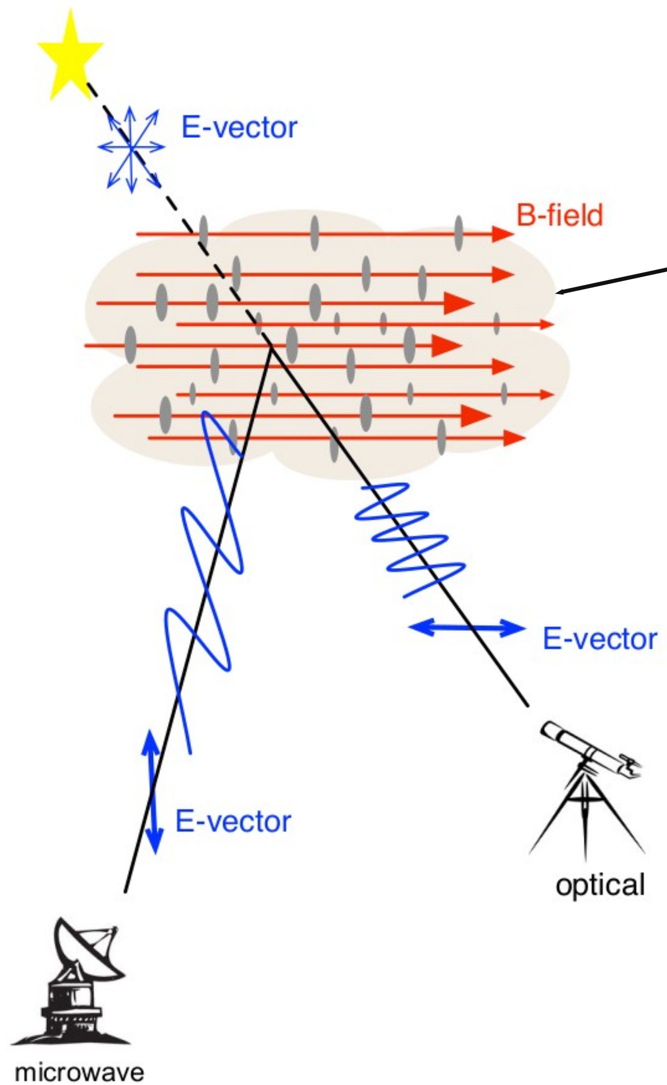
Towards a better approach to dust modeling: starlight polarization



Dust grains aligned perpendicular to magnetic field lines act as a polarizer

Both types of radiation trace component of **B perpendicular to line of sight**

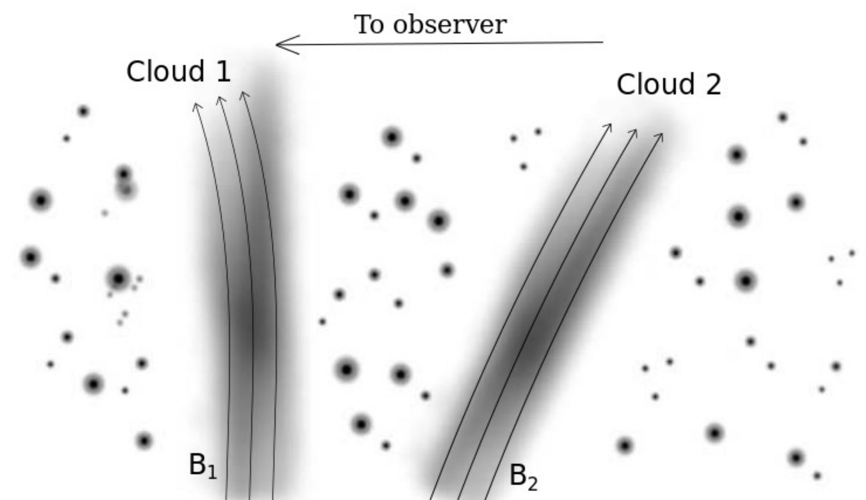
Towards a better approach to dust modeling: starlight polarization



Dust grains aligned perpendicular to magnetic field lines act as a polarizer

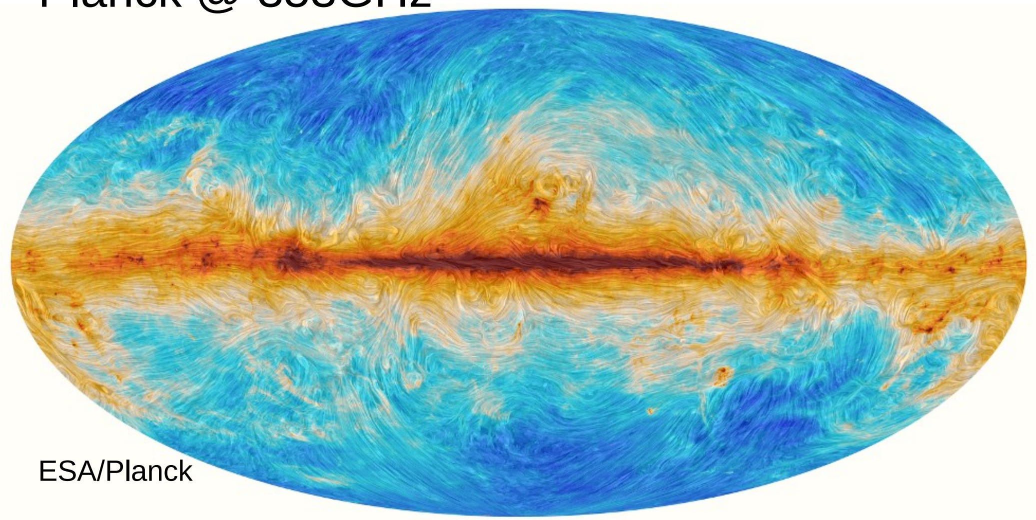
Both types of radiation trace component of **B perpendicular to line of sight**

BUT: stelllar polarization traces signal only out to distance of star!

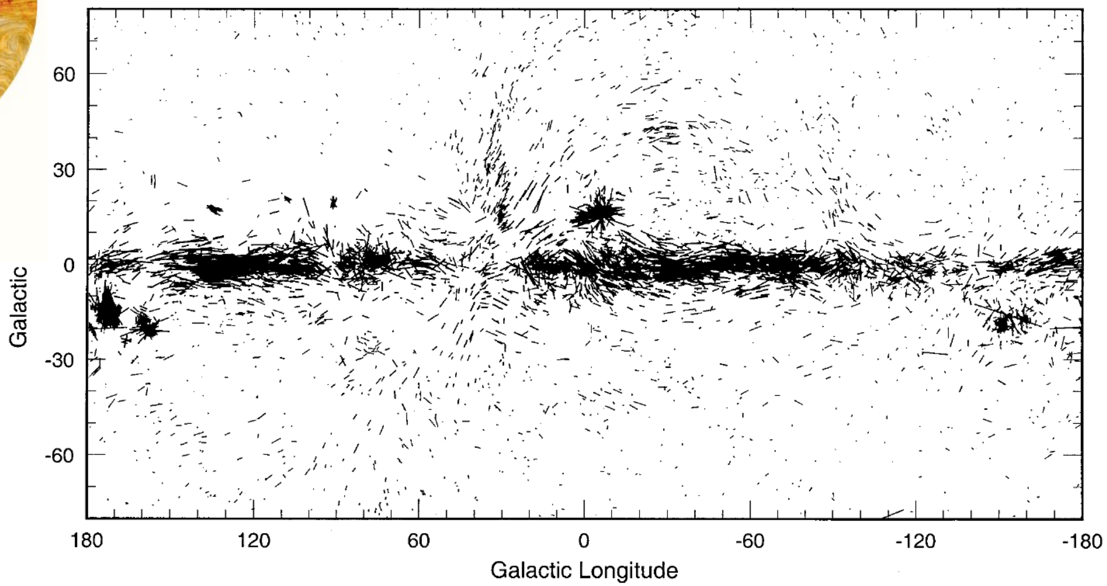


Starlight polarization not well-sampled

Planck @ 353GHz



Starlight polarization (Heiles 2000)



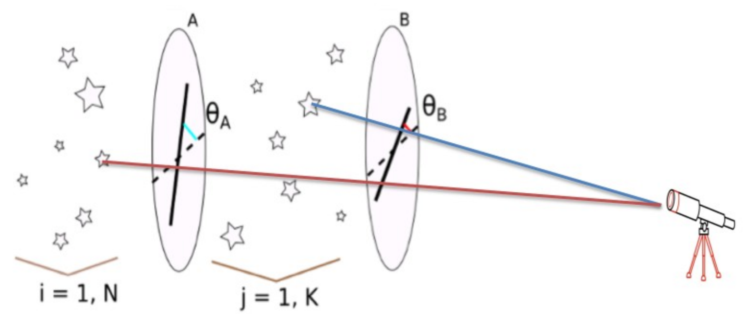
Need orders of magnitude more stellar polarization measurements

A high-accuracy optical polarization survey

PASIPHAE

Tassis+ 2018

Measuring the polarization of millions of stars to tomographically map the ISM magnetic field



Starts in 2020!

Web: pasiphae.science

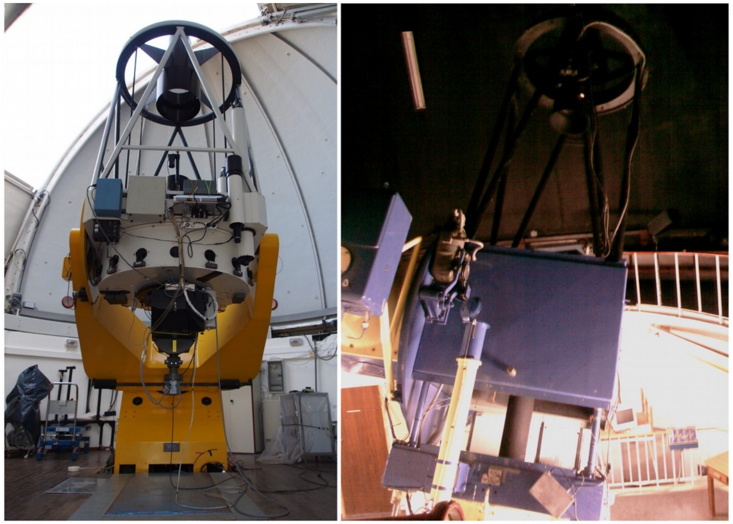
White paper
arXiv:1810.05652

Partner Institutions

University of Crete (PI: K. Tassis)
Caltech
University of Oslo
Inter-University Center for Astronomy and Astrophysics
South African Astronomical Observatory

Key advances of PASIPHAE

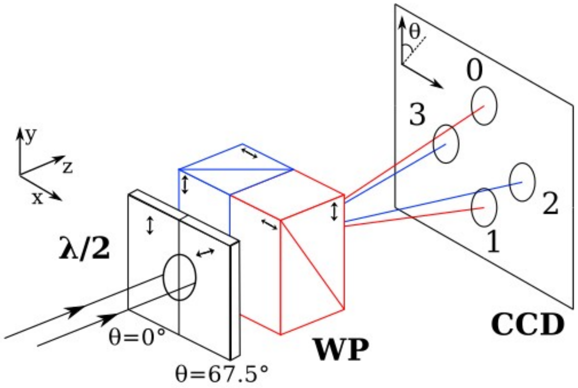
Two 1-m telescopes (North + South)



Single-shot, wide field polarimeters (WALOPs)

0.5x0.5 deg Field of View

Single-shot principle successfully implemented in precursor instrument



Ramaprakash+ 2019

robopol

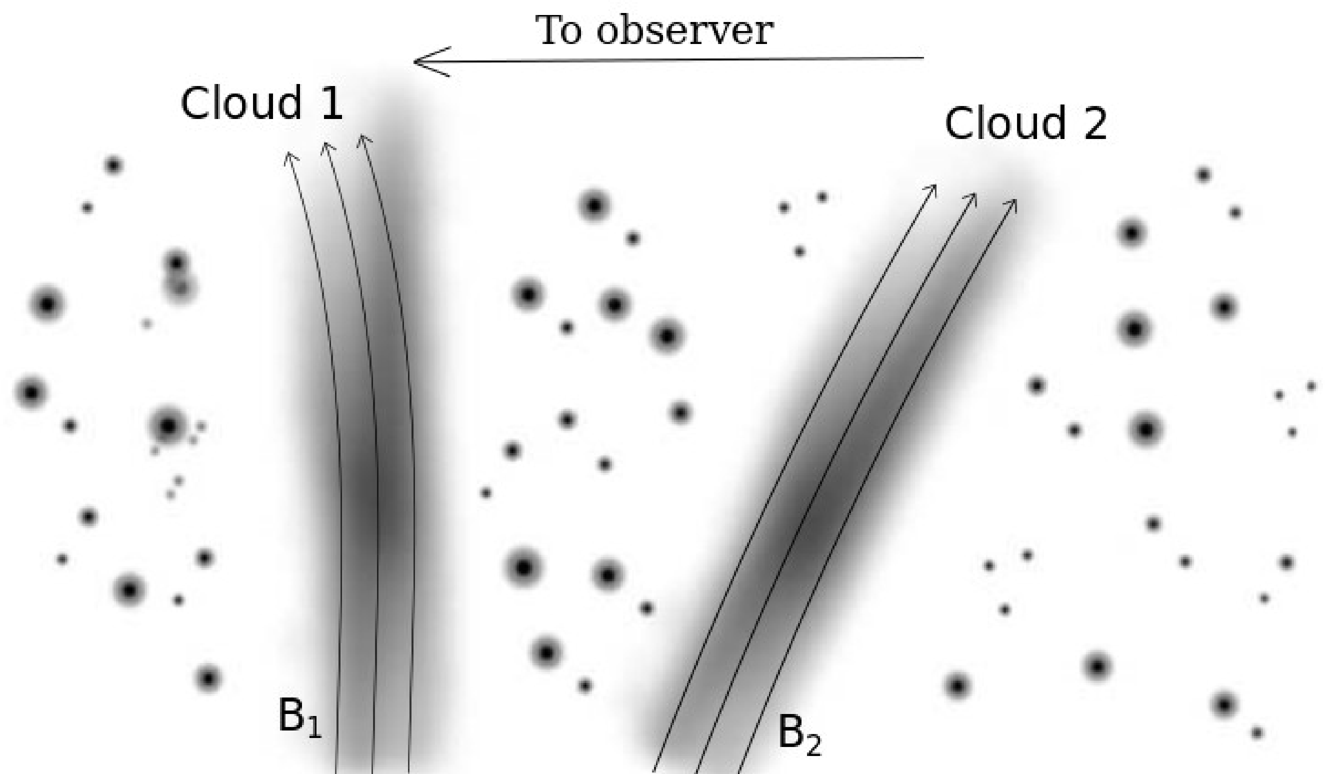
Excellent control of instrument systematics
(0.1% systematic uncertainty in p - unprecedented for wide-field stellar polarimetry)

Skalidis+2018, Ramaprakash+2019

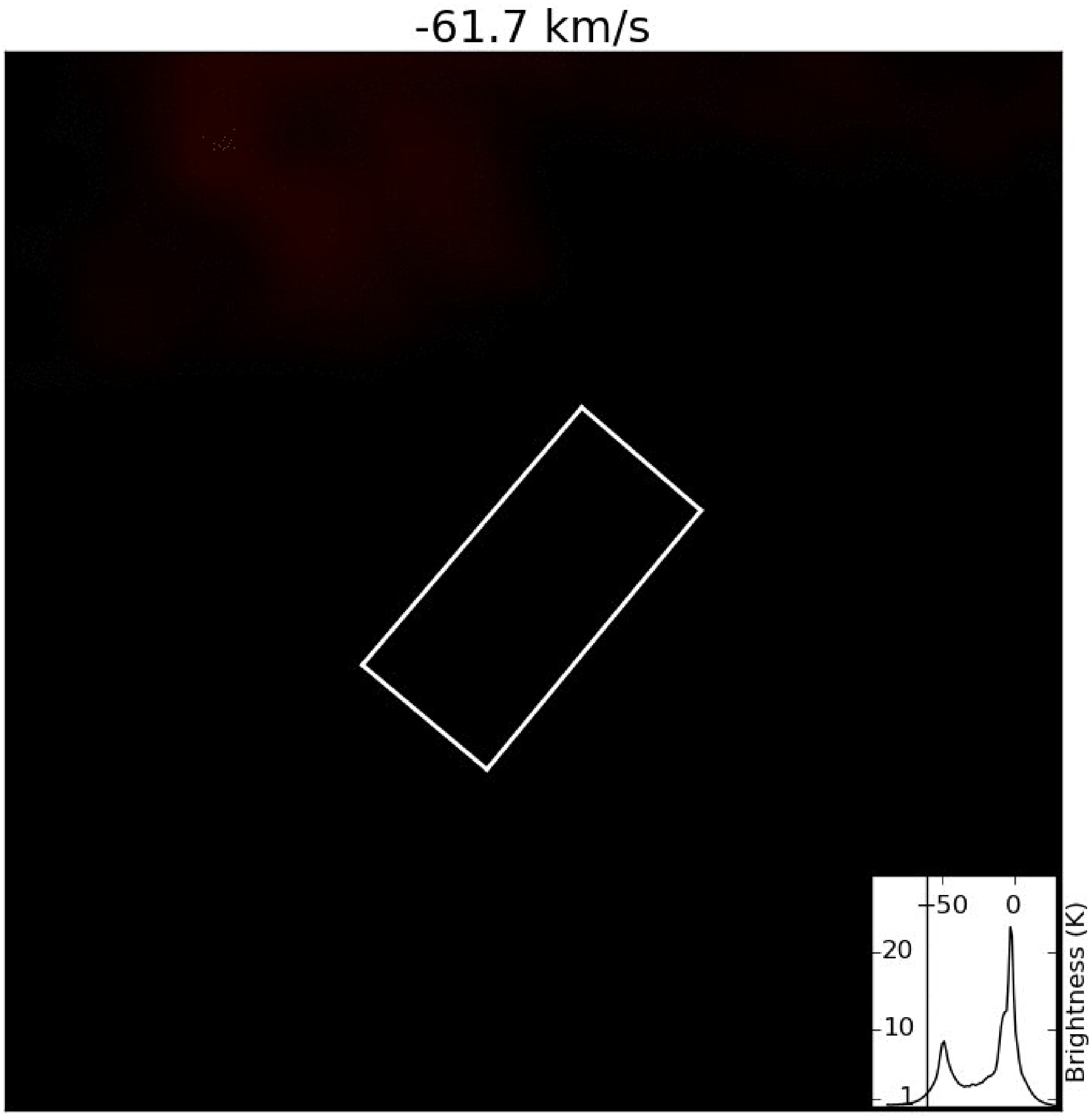
A first look at PASIPHAE-like data

A path-finding survey for PASIPHAE with the RoboPol polarimeter

Deep optical polarization survey

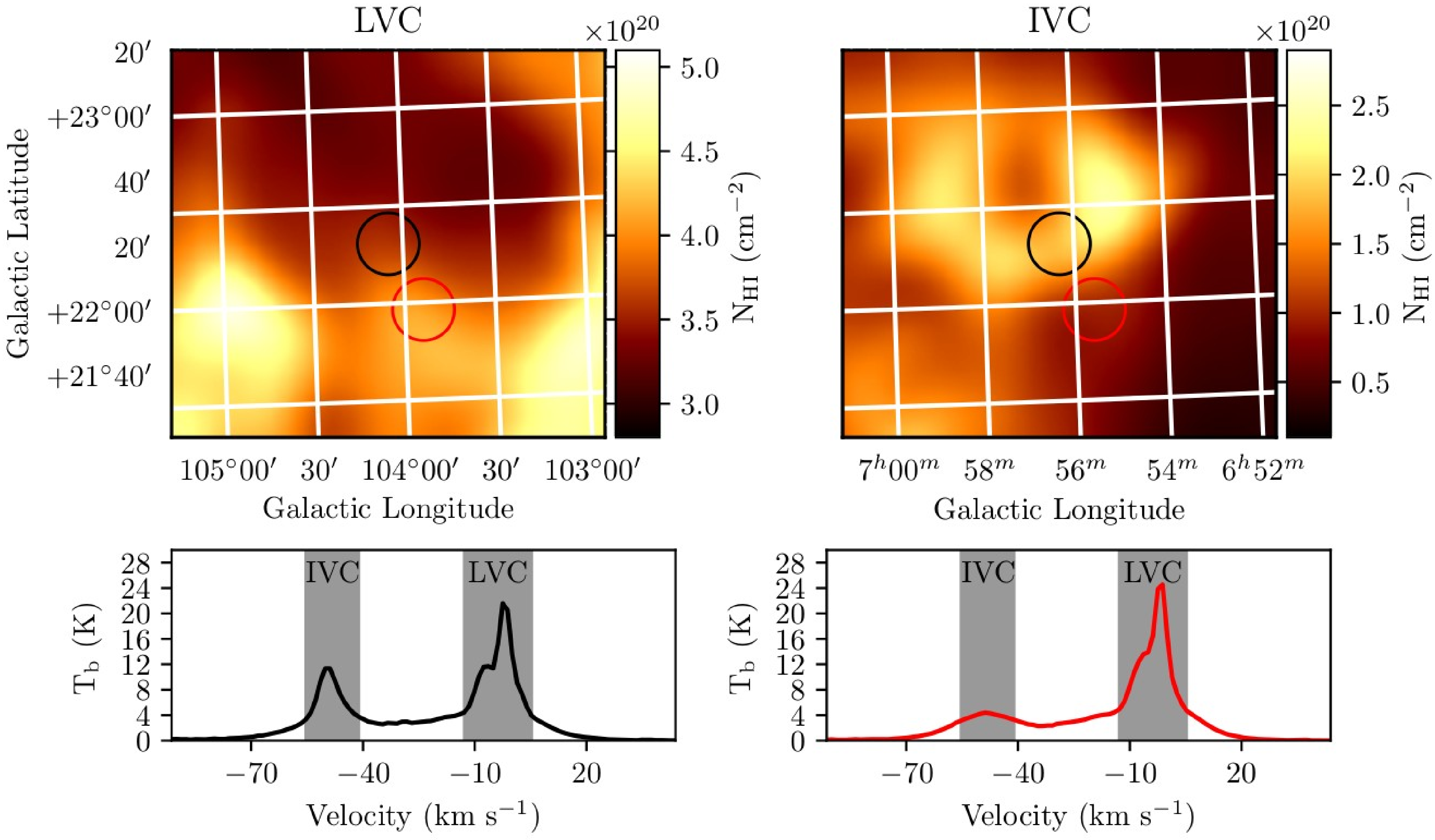


The target region in HI



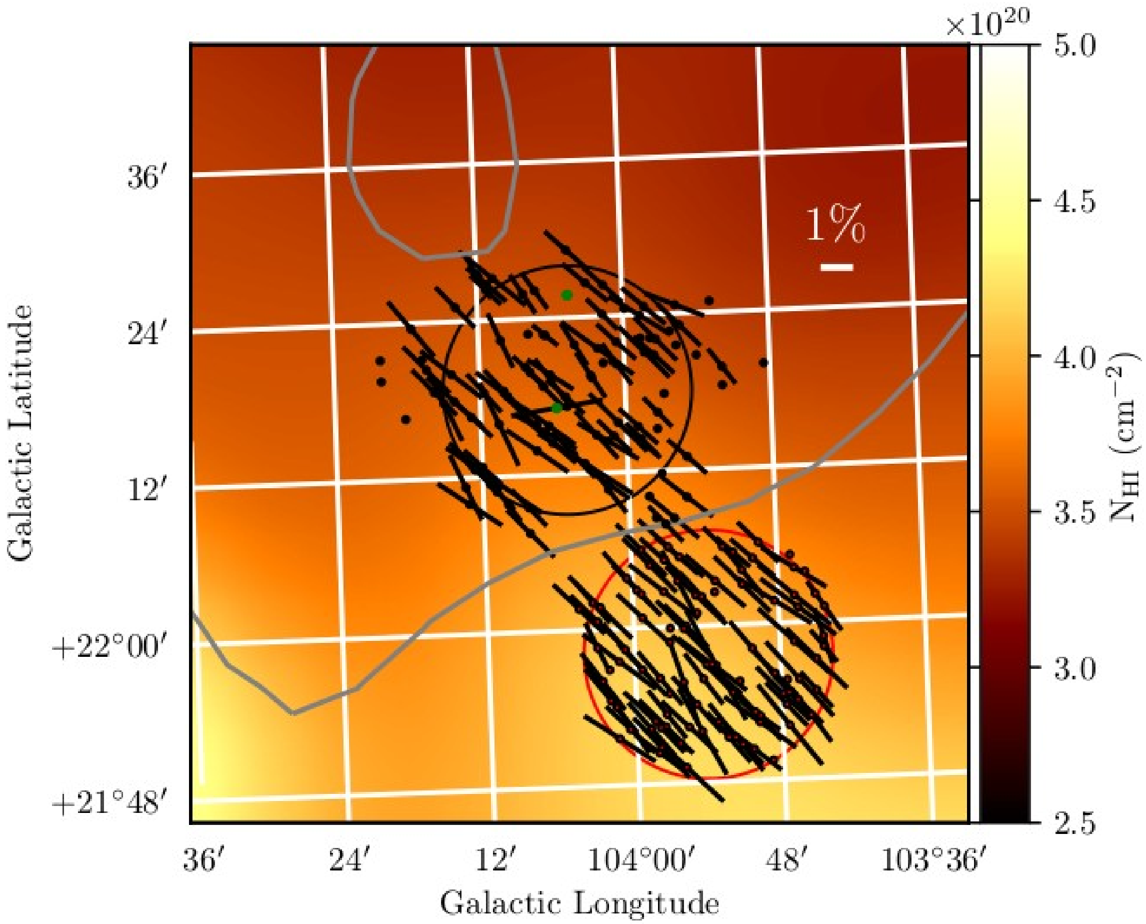
Effelsberg-
Bonn HI
Survey
(Winkel+ 2016)

Two very different clouds
along the same line of sight

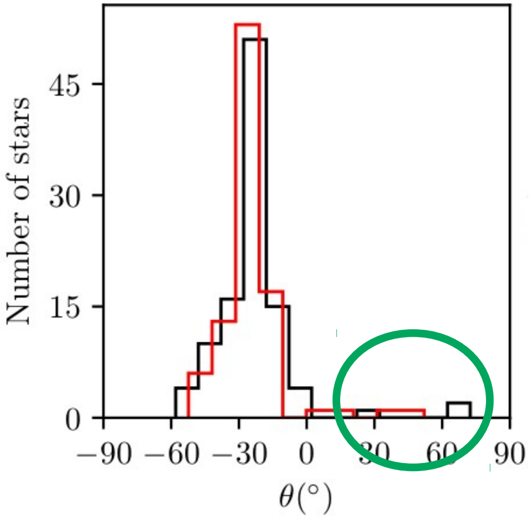


Panopoulou+2019a

Stellar polarizations in 2D



PDF of polarization angle

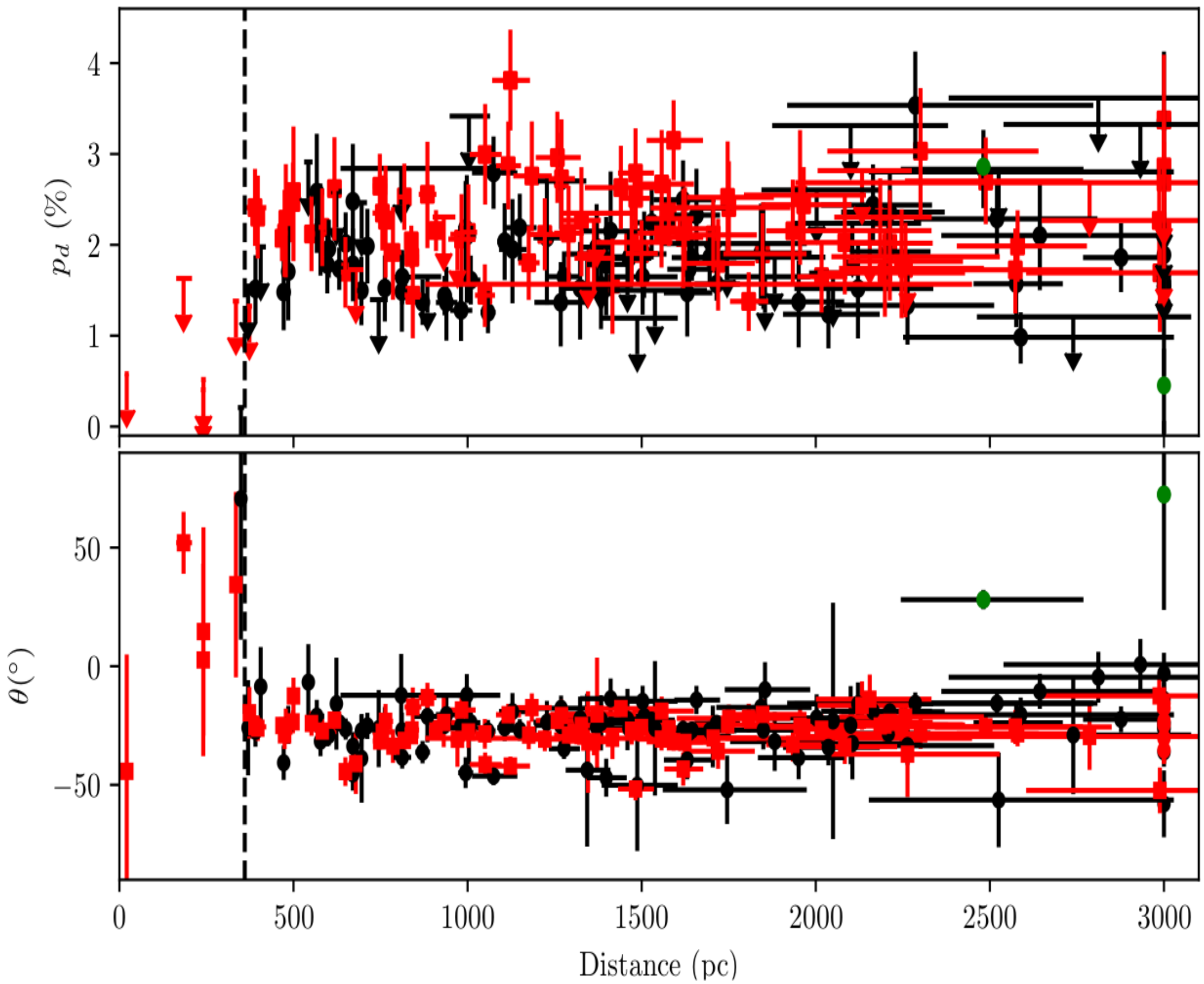


Previously unknown intrinsically polarized sources

No indication of difference between regions by looking at polarization angles in 2D

Panopoulou+2019a

Looking into the line-of-sight dimension with Gaia distances



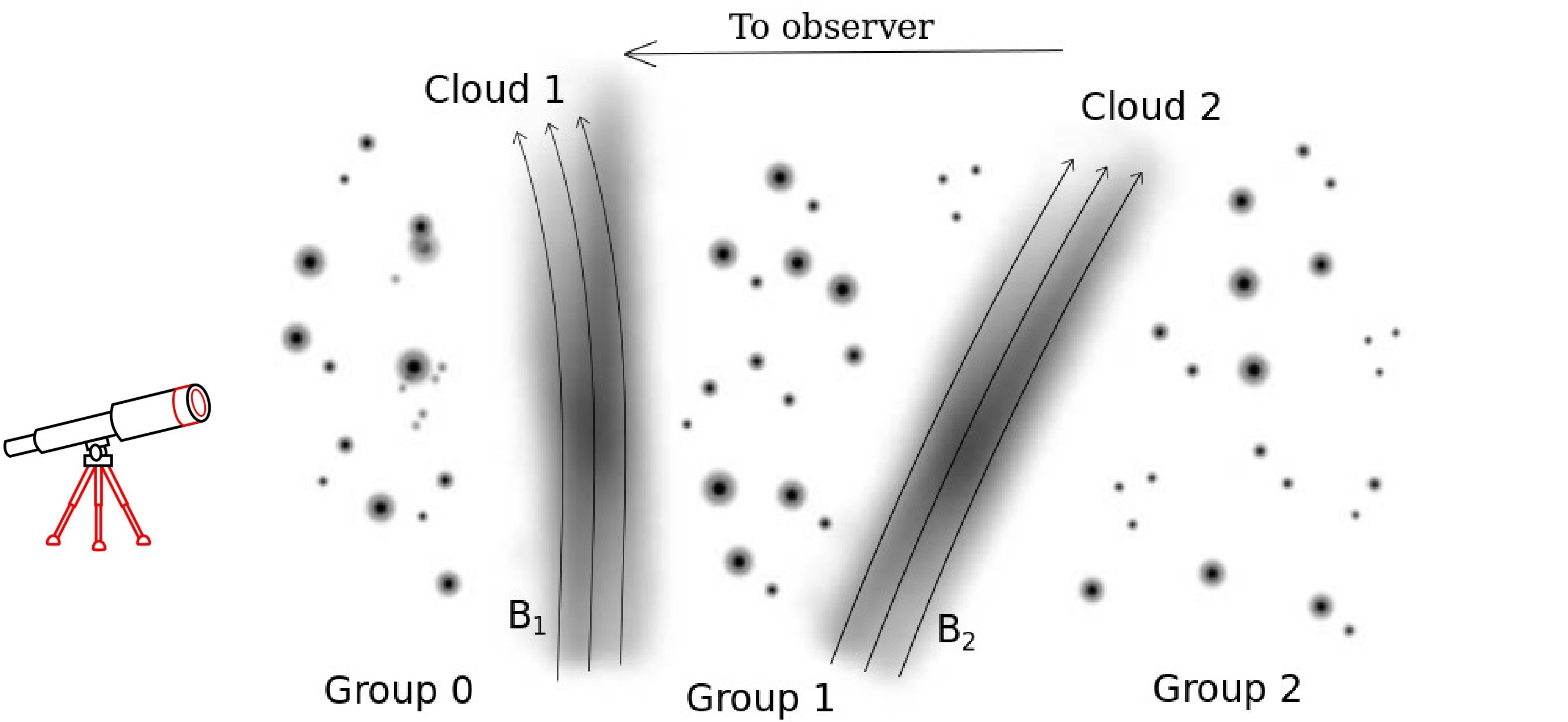
Panopoulou+2019a

Decomposing the polarization properties of the clouds

$$\langle q_{obs} \rangle = 0 \qquad \langle u_{obs} \rangle = 0$$

$$\langle q_{obs} \rangle = \langle q_1 \rangle \qquad \langle u_{obs} \rangle = \langle u_1 \rangle$$

$$\langle q_{obs} \rangle = \langle q_1 \rangle + \langle q_2 \rangle \qquad \langle u_{obs} \rangle = \langle u_1 \rangle + \langle u_2 \rangle$$



Statement of the problem

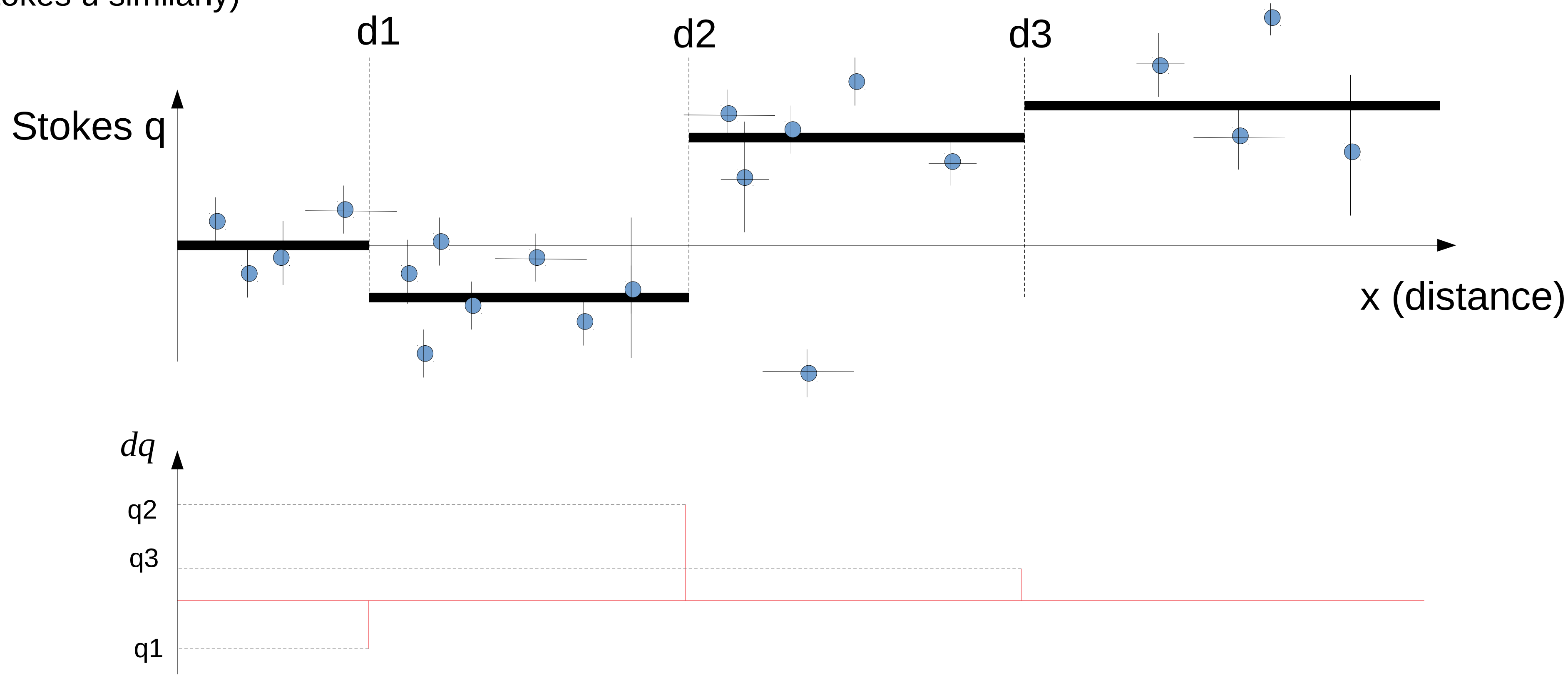
We wish to determine:

$$q(x)=\begin{cases} 0, & 0\leq x<d1 \\ q1, & d1\leq x<d2 \\ q1+q2, & d2\leq x<d3 \\ q1+q2+q3, & d3\leq x<\ldots \end{cases}$$

Unknowns:

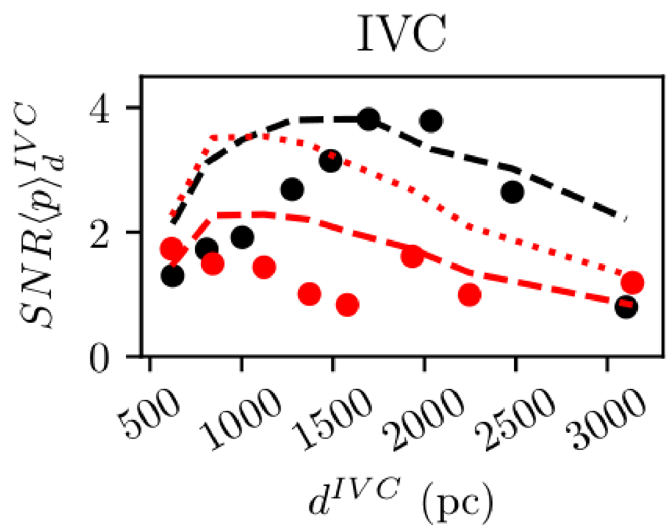
N_{clouds}	Number of clouds
$d1, d2, d3, \ldots$	Location of clouds
$q1, q2, q3, \ldots$	Cloud polarization properties

(And Stokes u similarly)



To locate clouds look for a peak in the derivative of the polarization fraction $p=\sqrt{q^2+u^2}$

We can detect the effect of the second cloud!

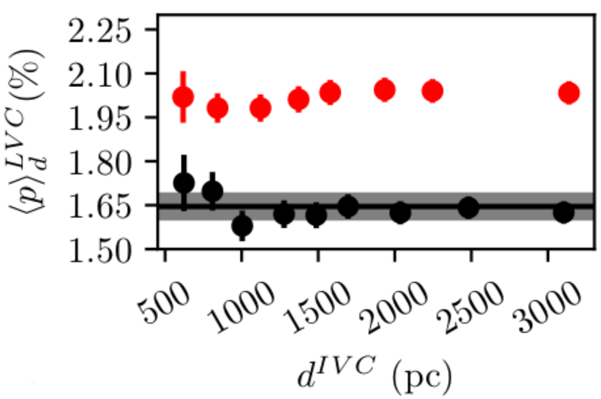


Black points: Peak indicates second cloud

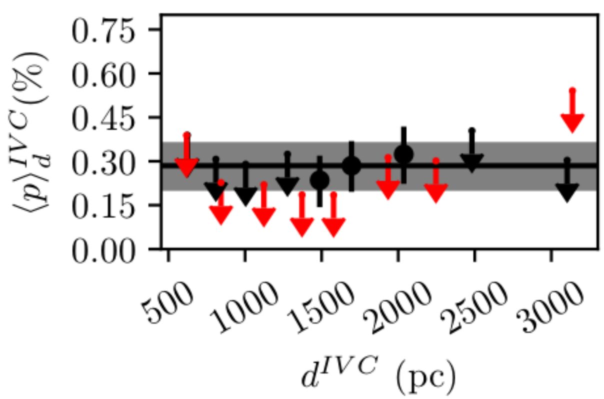
Red points: No peak in region where we don’t expect second cloud to contribute

Now we can decompose the polarization from each cloud...

Nearby cloud



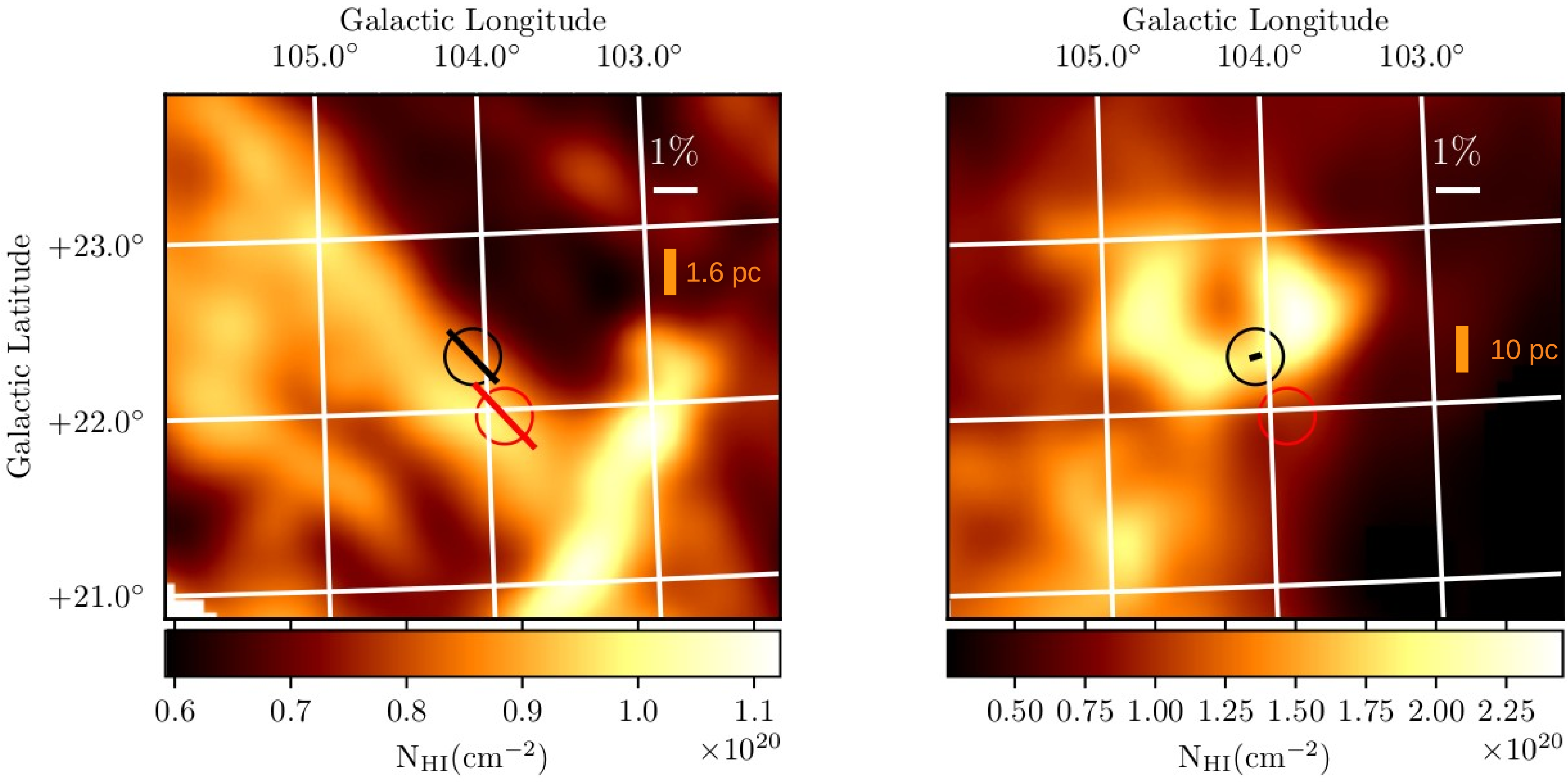
Far cloud



The nearby cloud causes 5-6 times more polarization than the far cloud

Panopoulou+2019a

The magnetic field orientation in each cloud



Panopoulou+2019a

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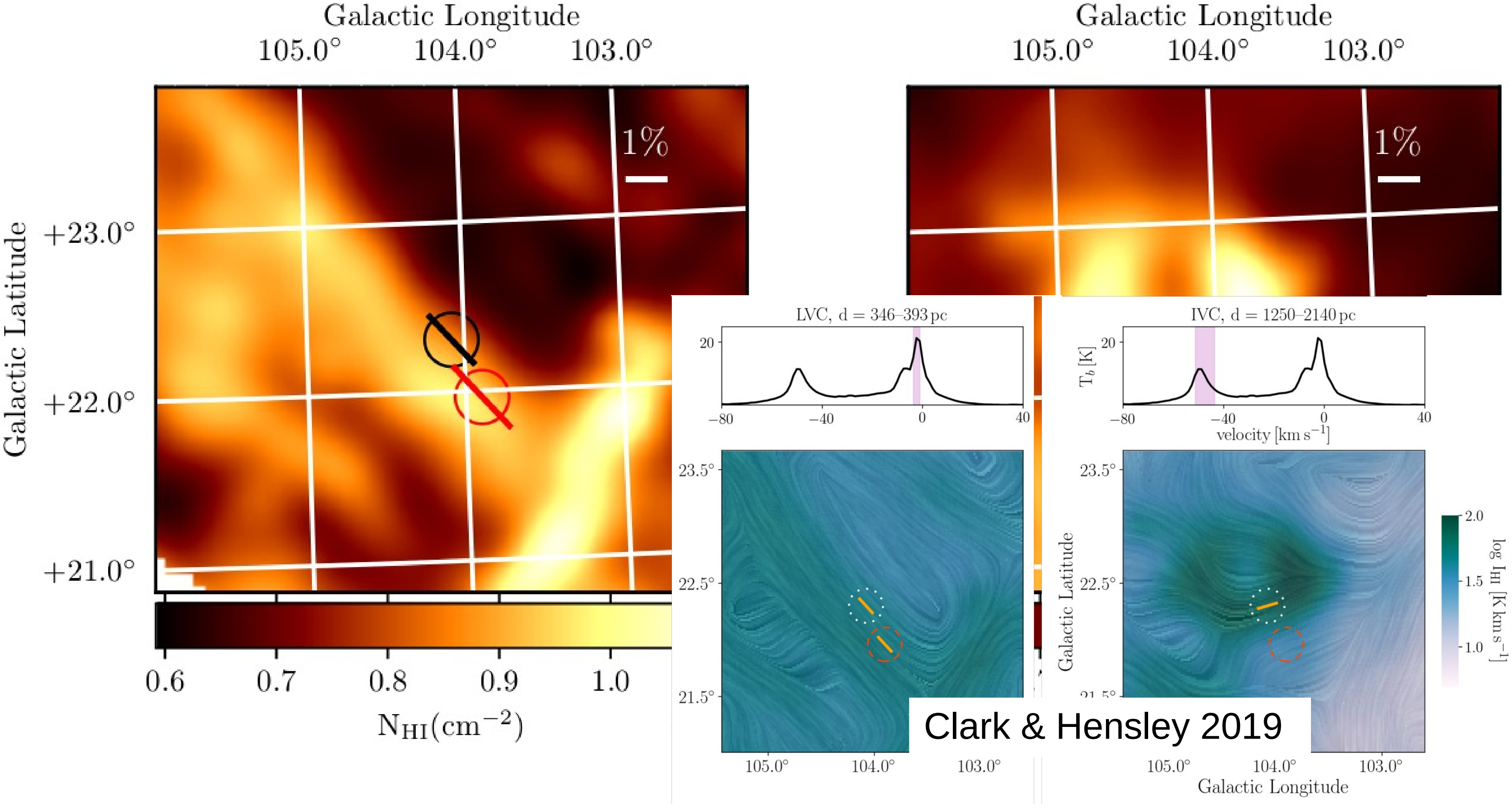
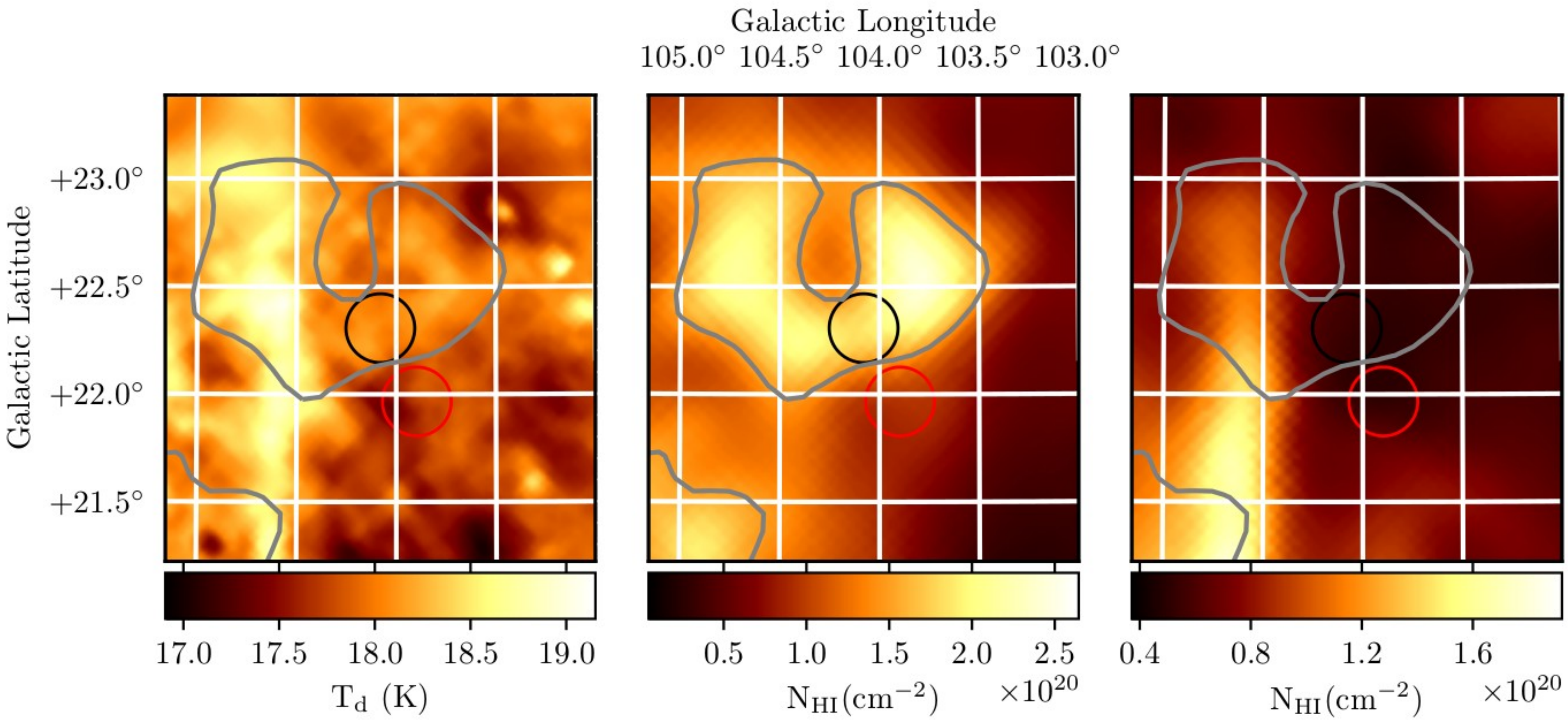


Panopoulou+2019a

Dust temperature too varies along line of sight?



Other IVCs known to have higher dust temperature than local gas (Planck XXIV 2011)

Panopoulou+2019a

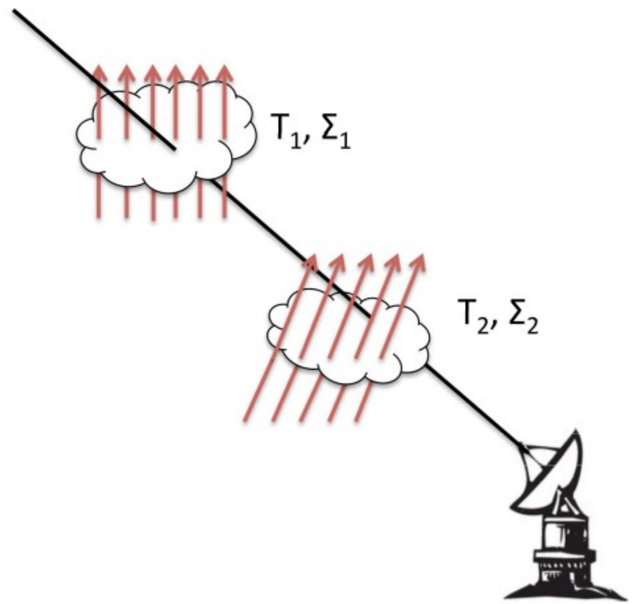
Modeling dust emission from 2 clouds

1. The 2-cloud model:

$$I_{\rm tot} = I_1 + I_2$$

$$Q_{\rm tot} = Q_1 + Q_2$$

$$U_{\rm tot} = U_1 + U_2$$



2. Stokes parameters for each cloud:

$$I_\nu^{C_i} \propto c^{C_i} \left(\frac{\nu}{\nu_0}\right)^{\beta^{C_i}} N_H^{C_i} B(\nu, T^{C_i}),$$

$$Q_\nu^{C_i} = p_\nu^{C_i} I_\nu^{C_i} \cos 2\chi^{C_i}, \quad U_\nu^{C_i} = p_\nu^{C_i} I_\nu^{C_i} \sin 2\chi^{C_i}$$ [7]

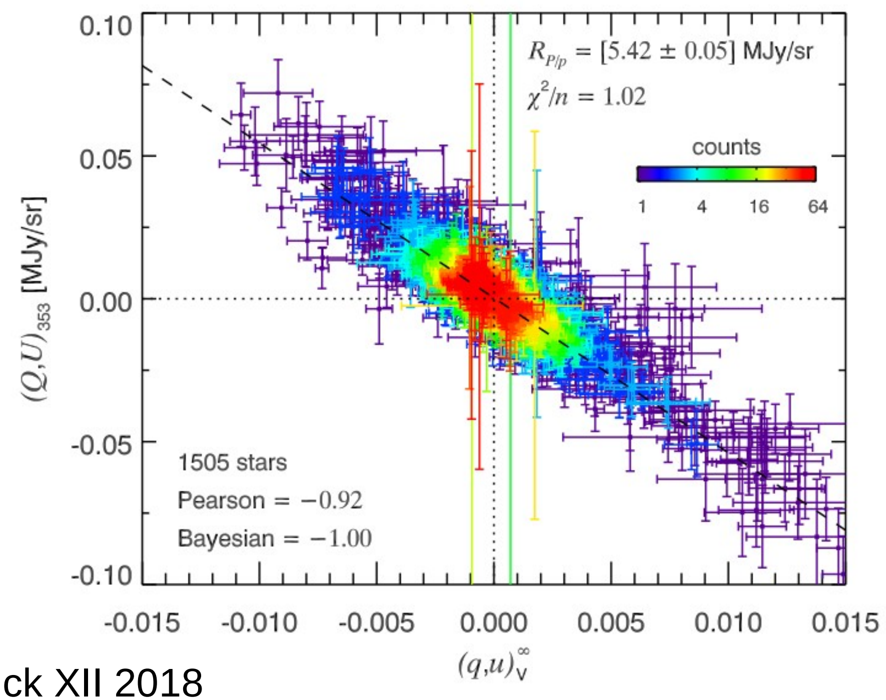
Measured from HI + starlight polarizaton

From educated guesses

c: dust-to-gas mass ratio, N_H: HI column density,
T: temperature, C_i: the i-th cloud, χ = polarization angle (emission)

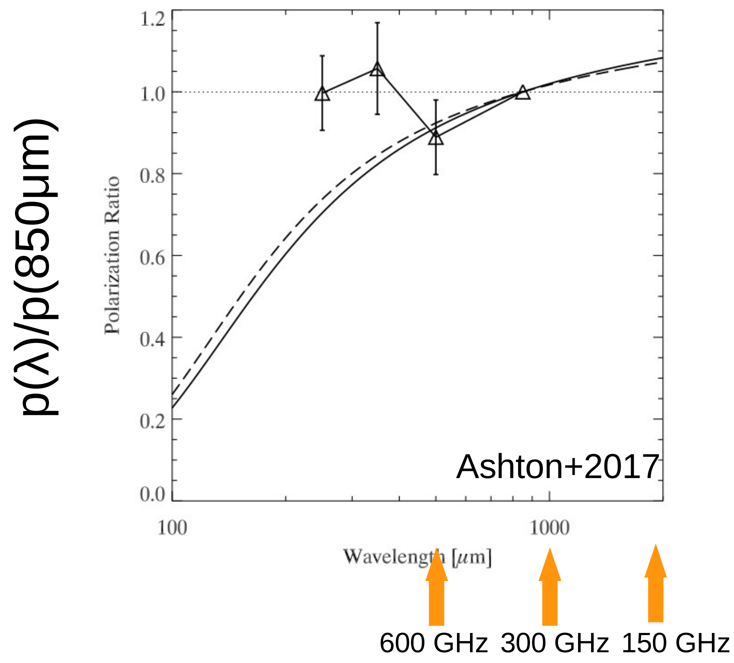
Constraining the unknown parameters

Starlight p is proxy for dust emission P_{353}



Planck XII 2018

Per cloud: p(ν) ~ constant

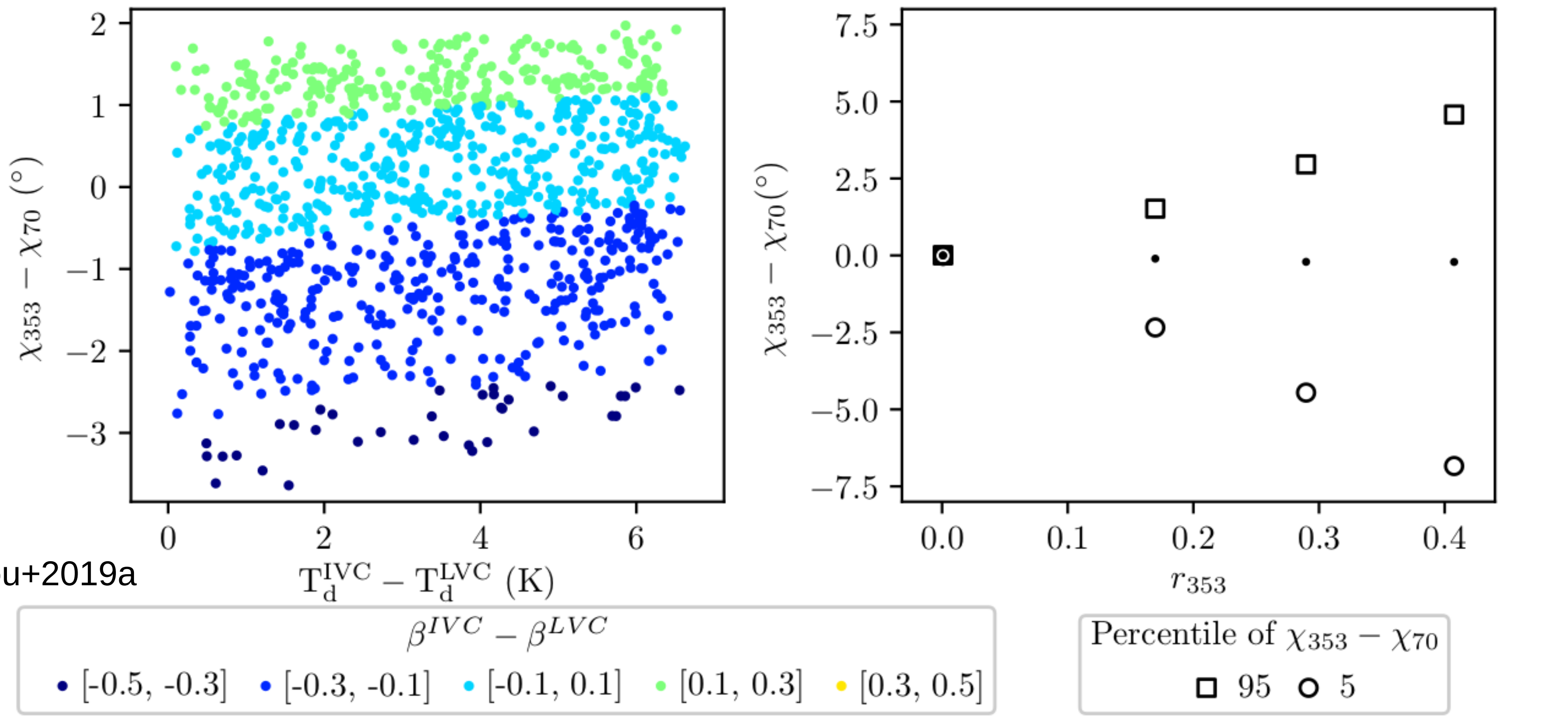


But also just from:

$$p = \frac{\sqrt{Q_\nu^2 + U_\nu^2}}{I_\nu} = \frac{\sqrt{(A^Q)^2 + (A^U)^2}\left(\frac{\nu}{\nu_0}\right)^\beta B_\nu(T)}{A^I\left(\frac{\nu}{\nu_0}\right)^\beta B_\nu(T)}$$

If we assume $P_{353}^{C_1}/p_V^{C_1} = P_{353}^{C_2}/p_V^{C_2}$ and p(ν) ~ const…
the only remaining unknowns are temperature, β

Predicting the polarization angle at different frequencies



Panopoulou+2019a

Polarization angle with 2-cloud model:

$$\chi_\nu = \frac{1}{2}\arctan\frac{r_\nu \sin 2\chi^{C_1} + \sin 2\chi^{C_2}}{r_\nu \cos 2\chi^{C_1} + \cos 2\chi^{C_2}}.$$

$$r_\nu = \frac{P_\nu^{C_1}}{P_\nu^{C_2}} = \frac{p_\nu^{C_1} I_\nu^{C_1}}{p_\nu^{C_2} I_\nu^{C_2}},$$

Summary

Upcoming optical polarization survey & Gaia enables 3D B-field mapping

1st pathfinding demonstration of tomographic capabilities successful

Exciting future prospects for 3D modeling: starlight polarization, HI, dust extinction, MHD simulations...

Thank you