PASIPHAE

Through the veil of dust to inflation

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INSTITUTE OF ASTROPHYSICS

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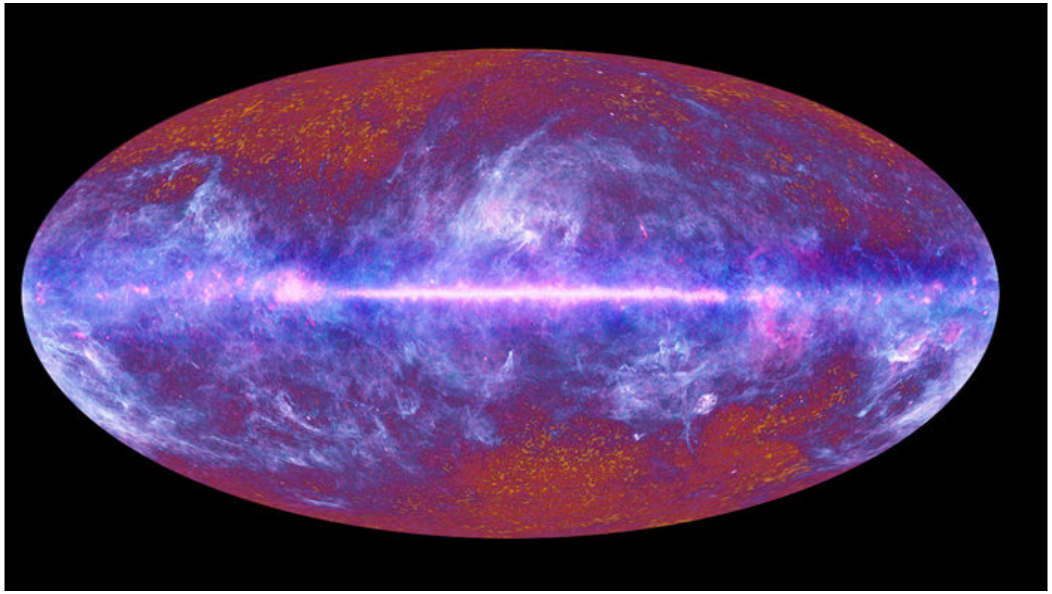
The Problem

Magnetized Galactic dust also emits polarized microwaves



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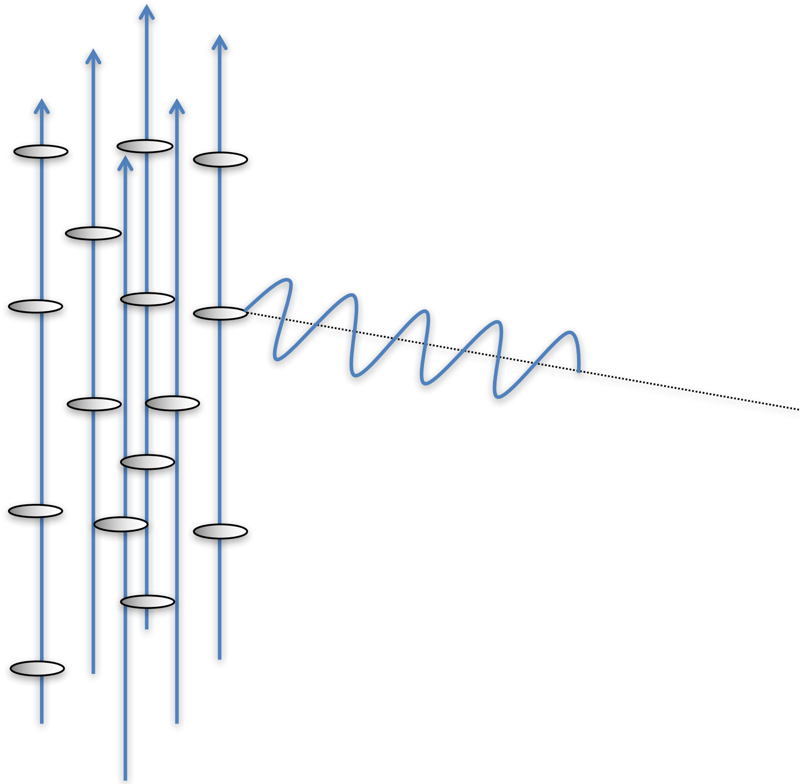

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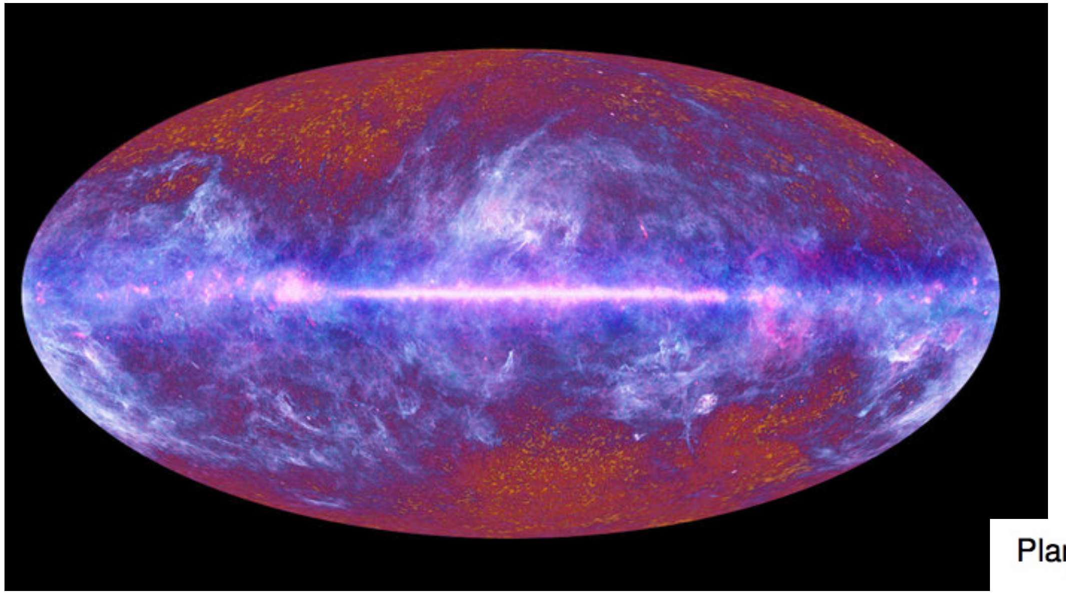

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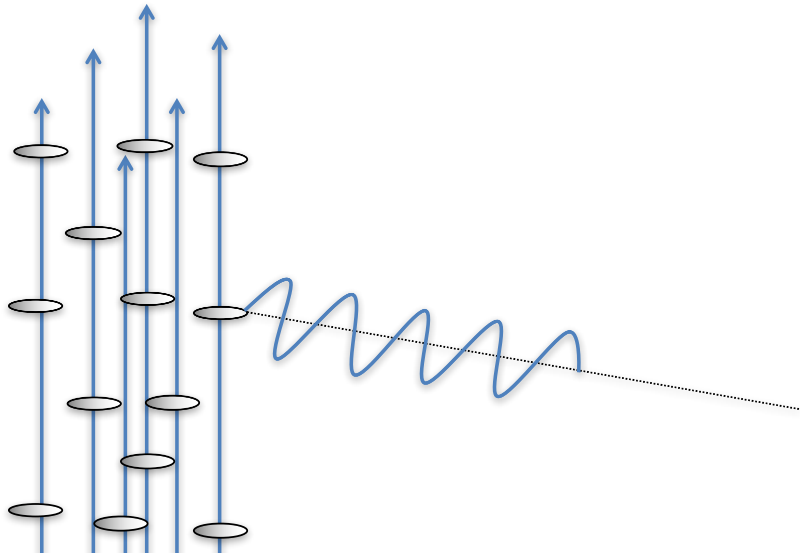
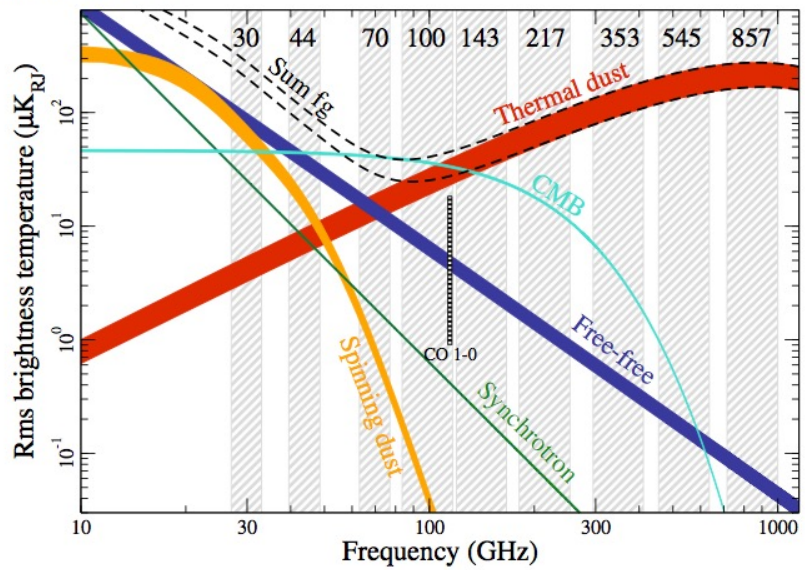


Planck 2015 X



CMB dust emission removal:

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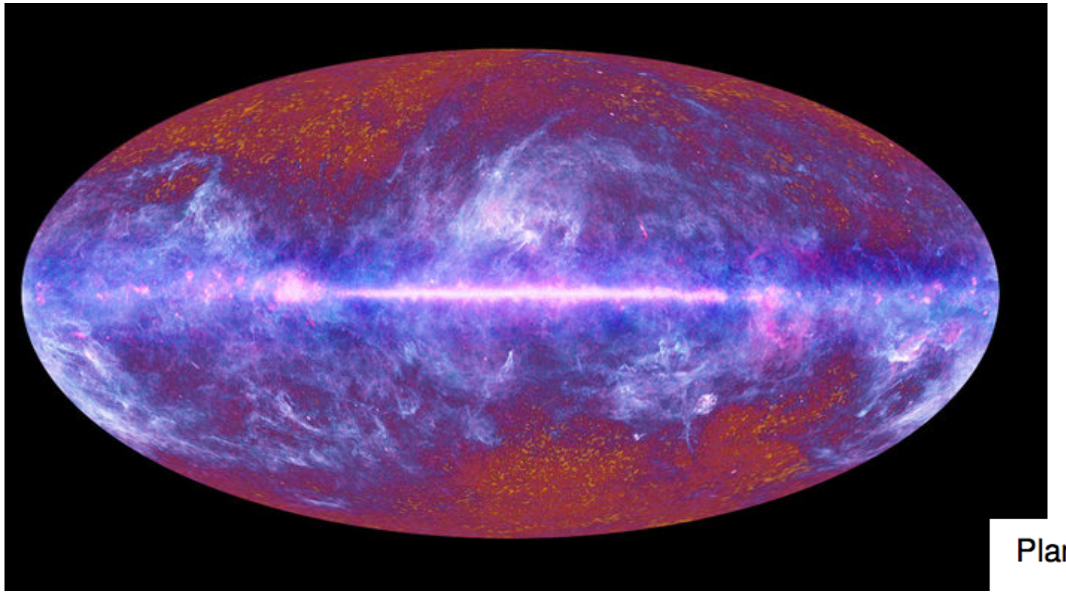
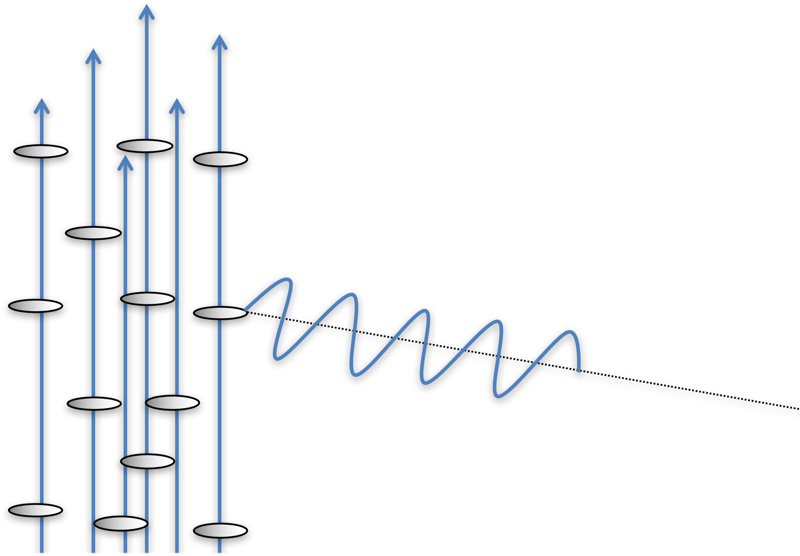


ESA/ LFI & HFI Consortia



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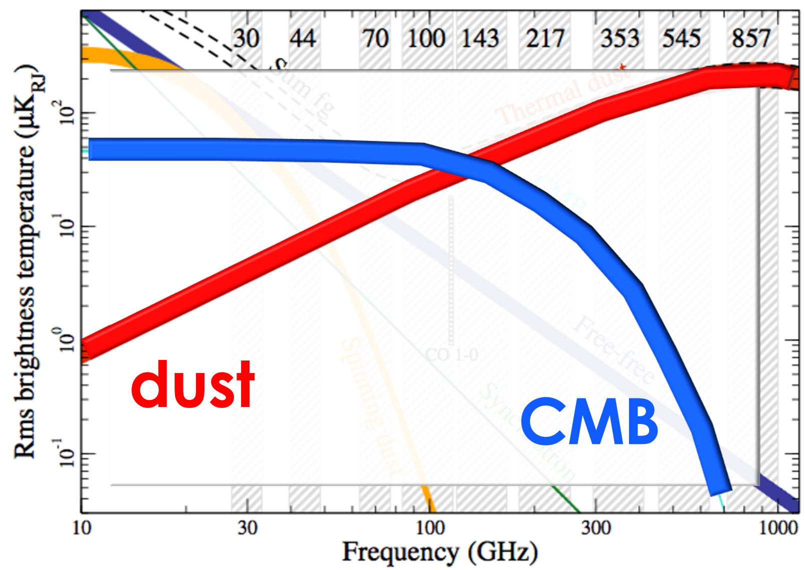

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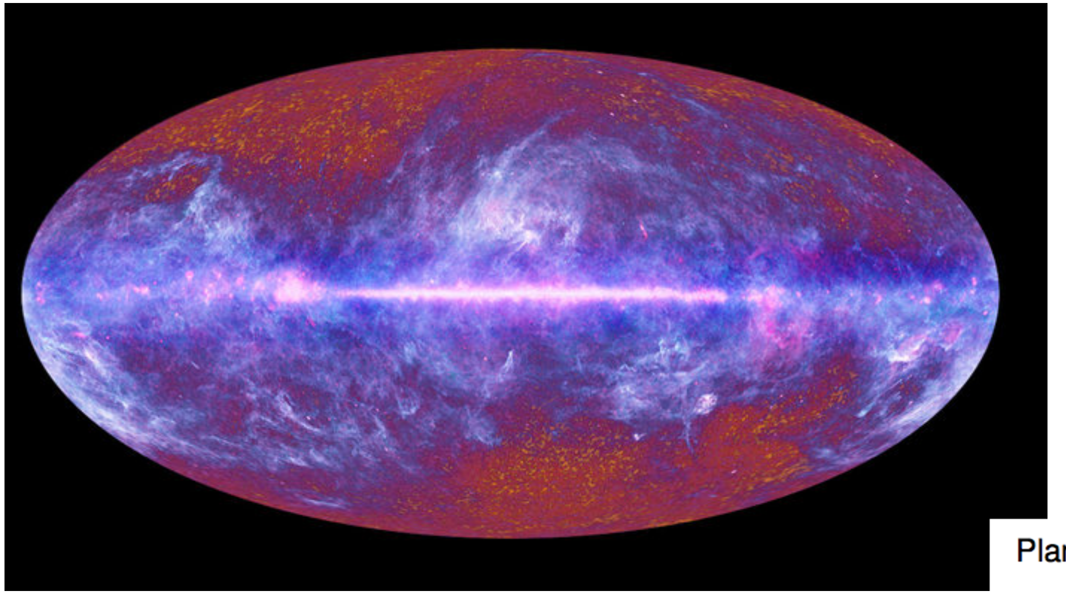

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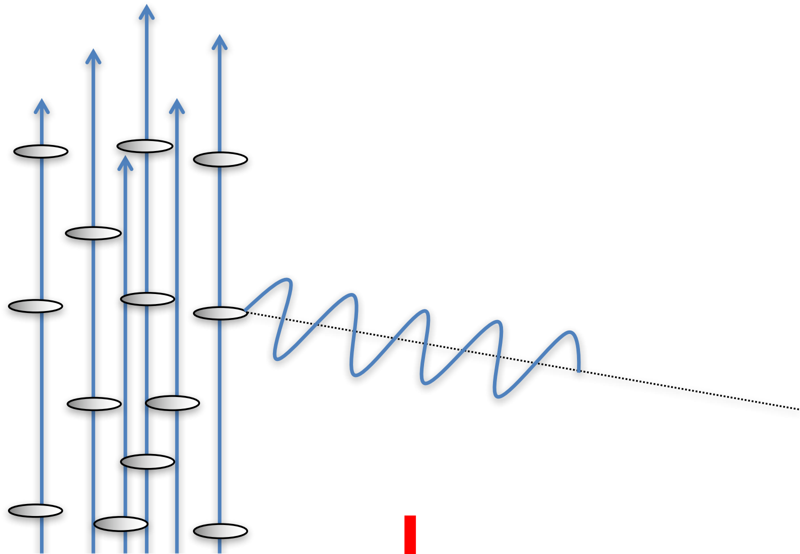

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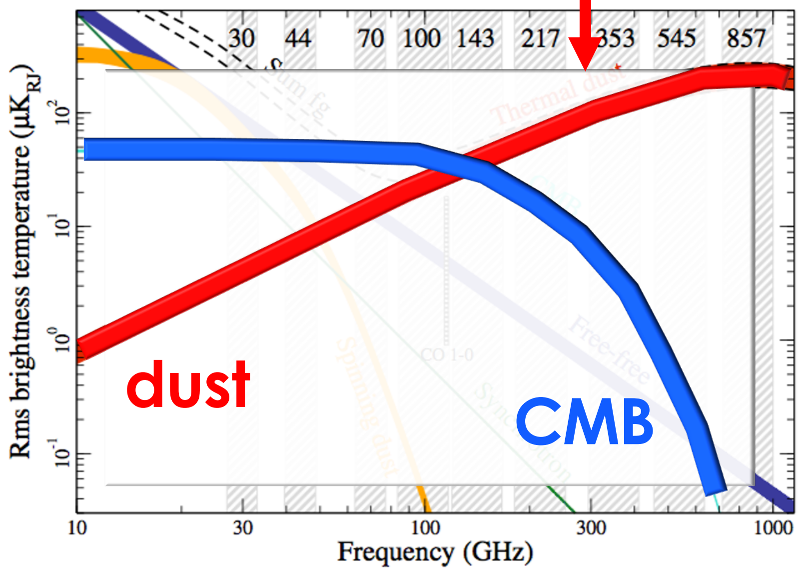

CMB dust emission removal:

- Map at high frequencies
  (dust dominates)

The Problem

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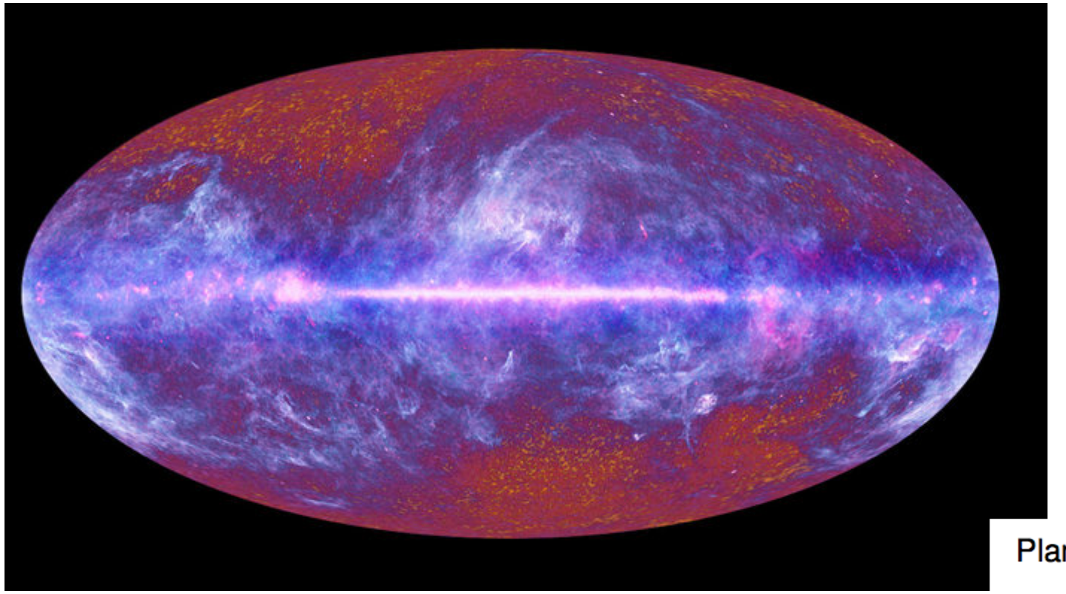
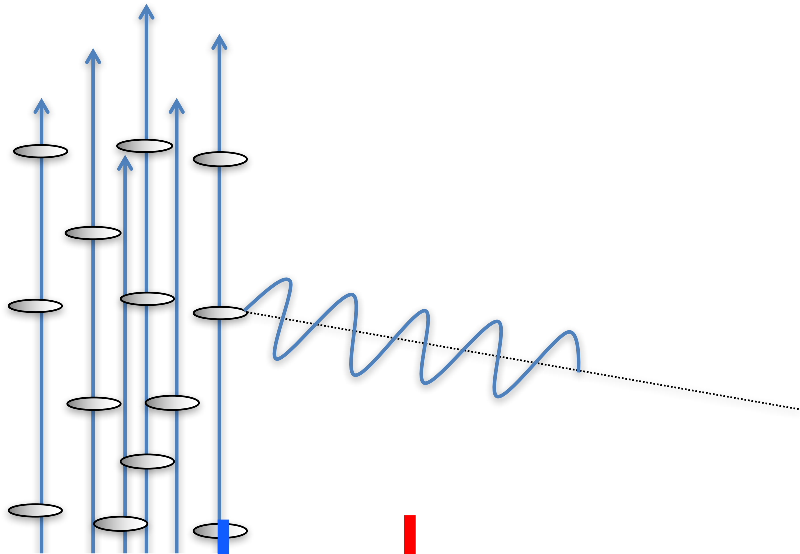
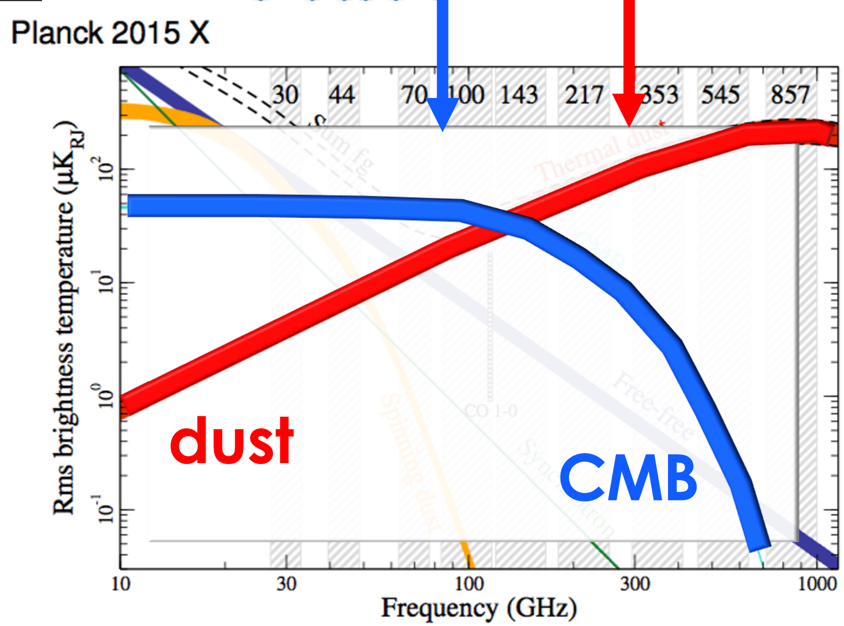


ESA/ LFI & HFI Consortia



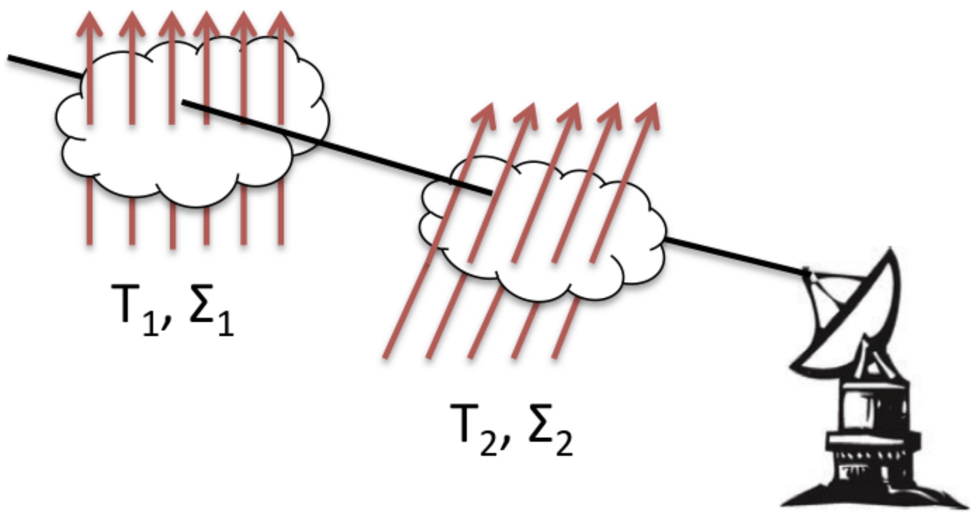


CMB dust emission removal:

- Map at high frequencies
  (dust dominates)
- Subtract from lower frequencies
  (CMB dominates)

“Map & Subtract” cannot work with polarization

Polarization ROTATES between frequencies
because of **multiple clouds** and **misaligned B-fields**



Tassis & Pavlidou 2015

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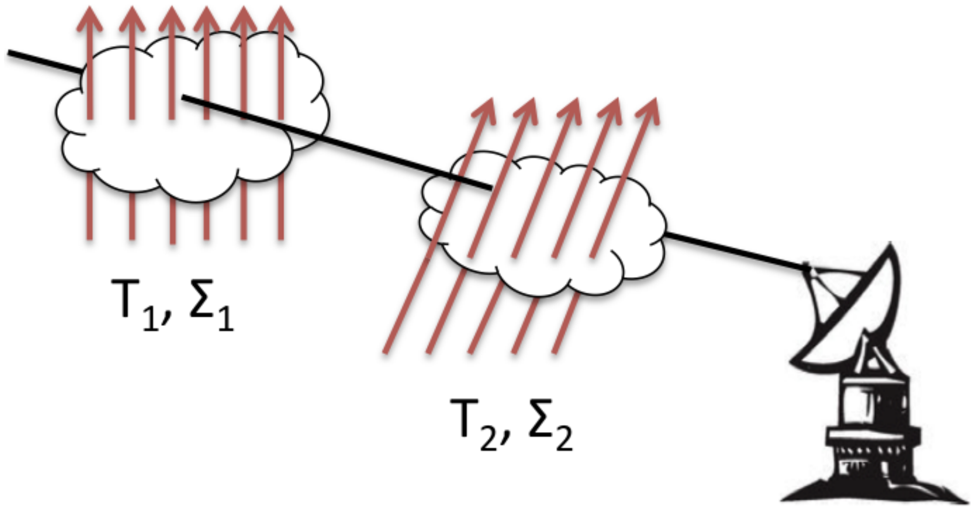


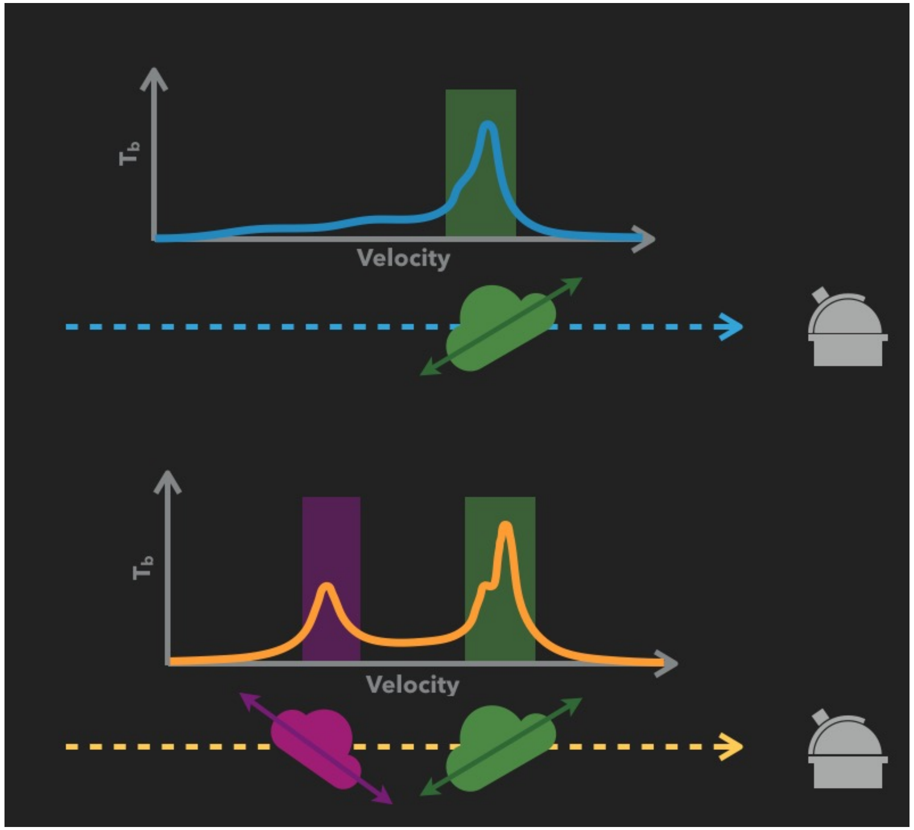
Tassis & Pavlidou 2015

frequency decorrelation ***most unconstrained effect***

Planck Collaboration L 2017, Poh & Dodelson 2017, Hensley & Bull 2017, Puglisi et al 2017, Martizez-Solaeche et al. 2017, Planck Collaboration XXX 2016, Planck 2018 results. XI., BeyondPlanck XIV. 2021, Mangilli et al. 2021, etc.

LOS Decorrelation in Planck data

21cm data to the rescue!



- # of clouds along the los
  (Panopoulou & Lenz 2020)

- direction of B-field from morphology of H clouds
  (Clark & Hensley 2019)

Control ➔ 1 cloud = **no LOS decorrelation expected**
Target ➔ multiple clouds + missaligned = **LOS decorrelation expected**

LOS Decorrelation in Planck data

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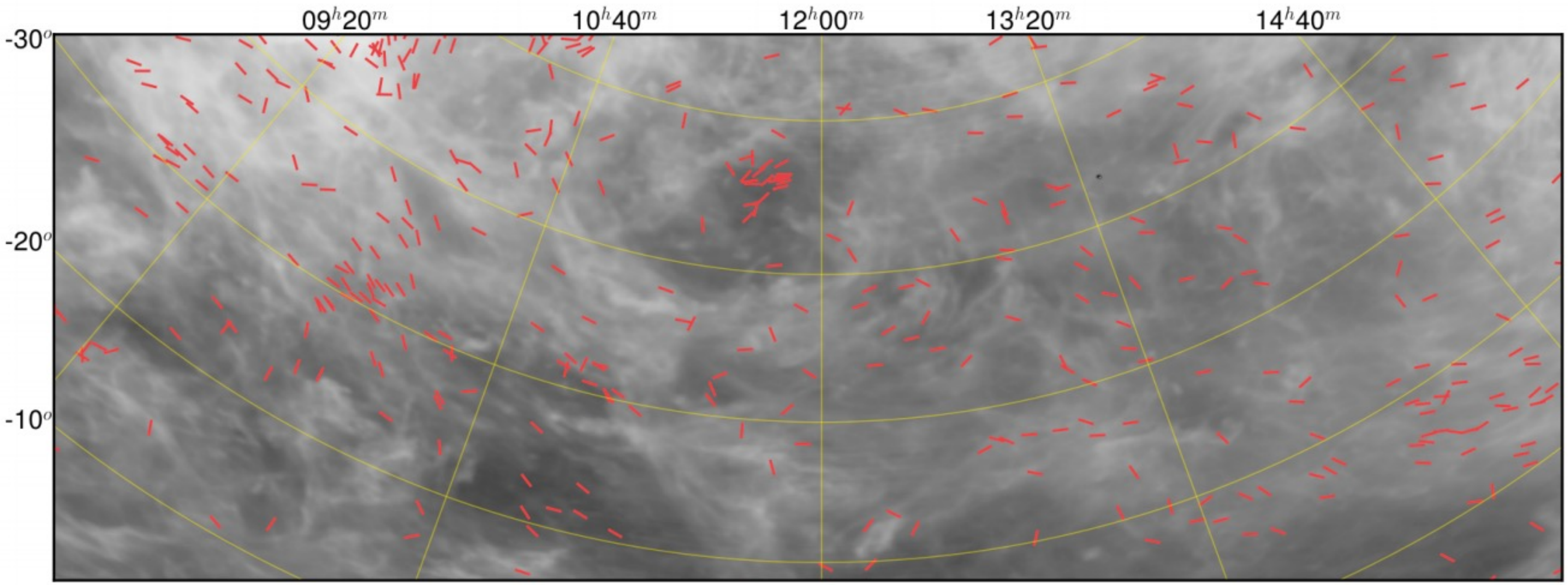

Clark et al. 2014

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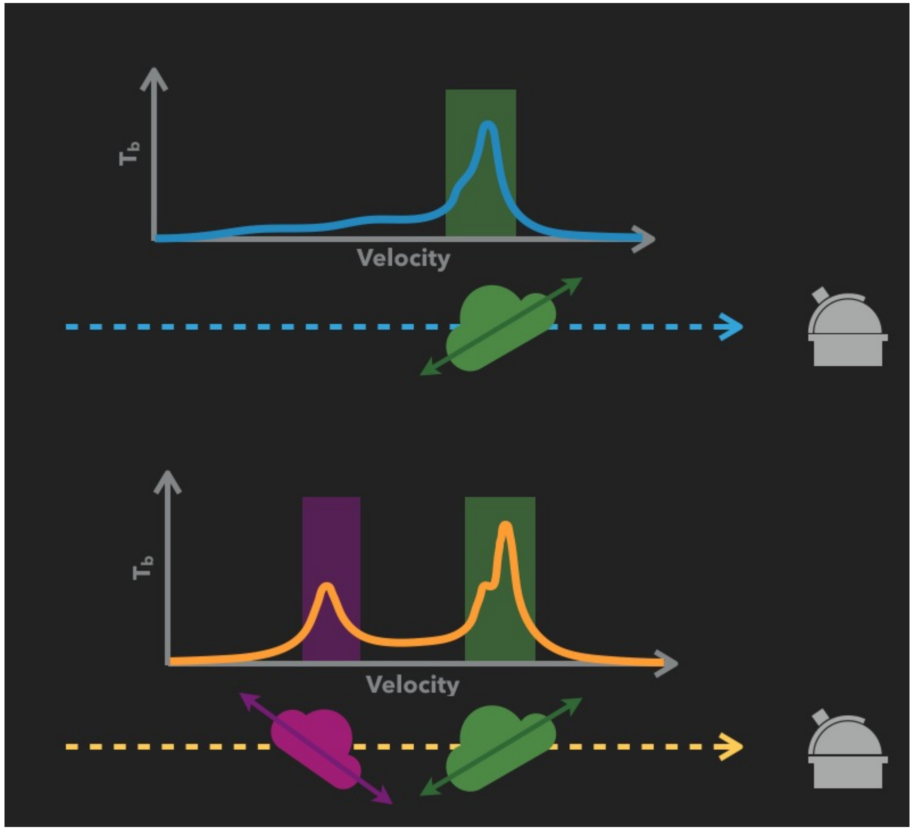

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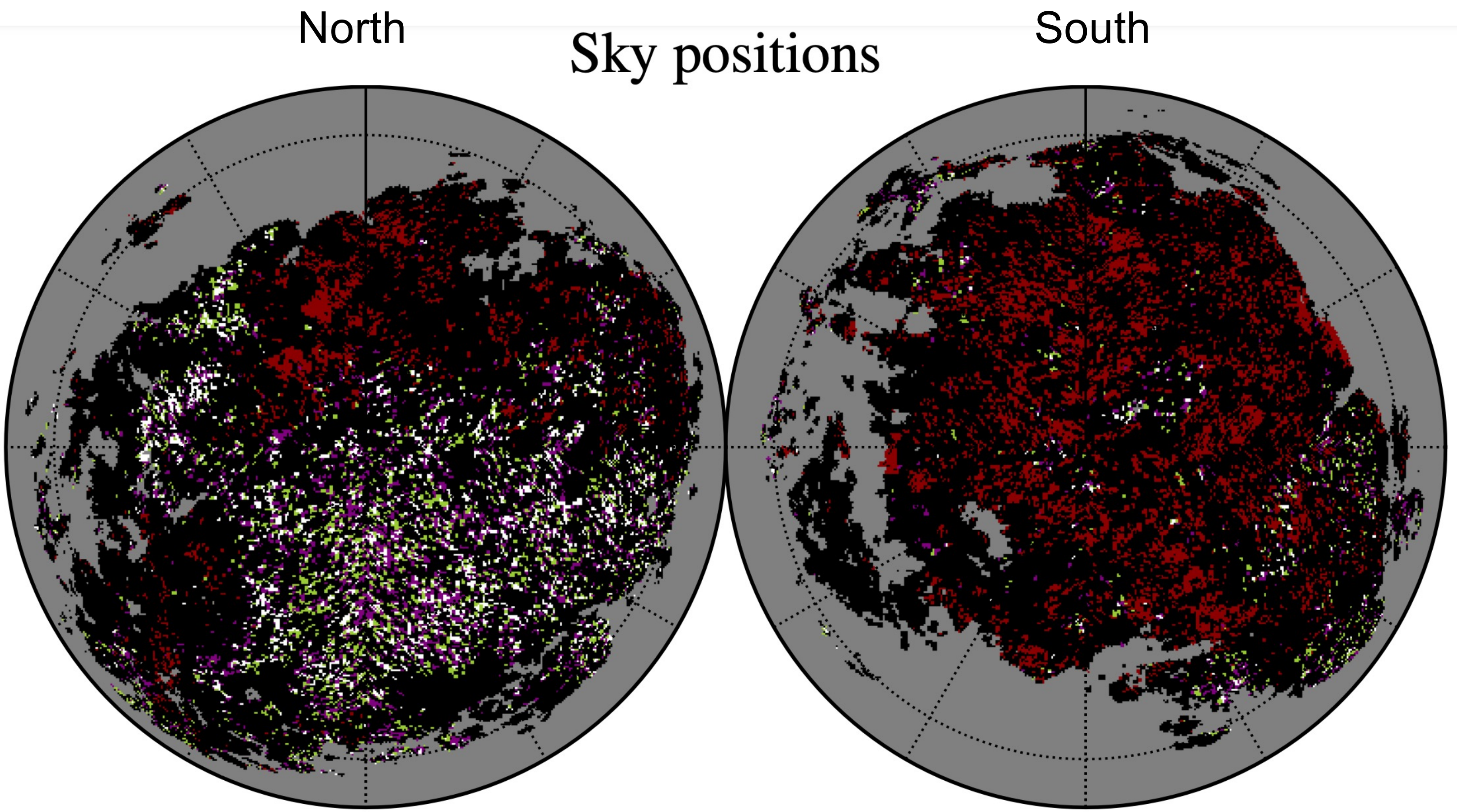

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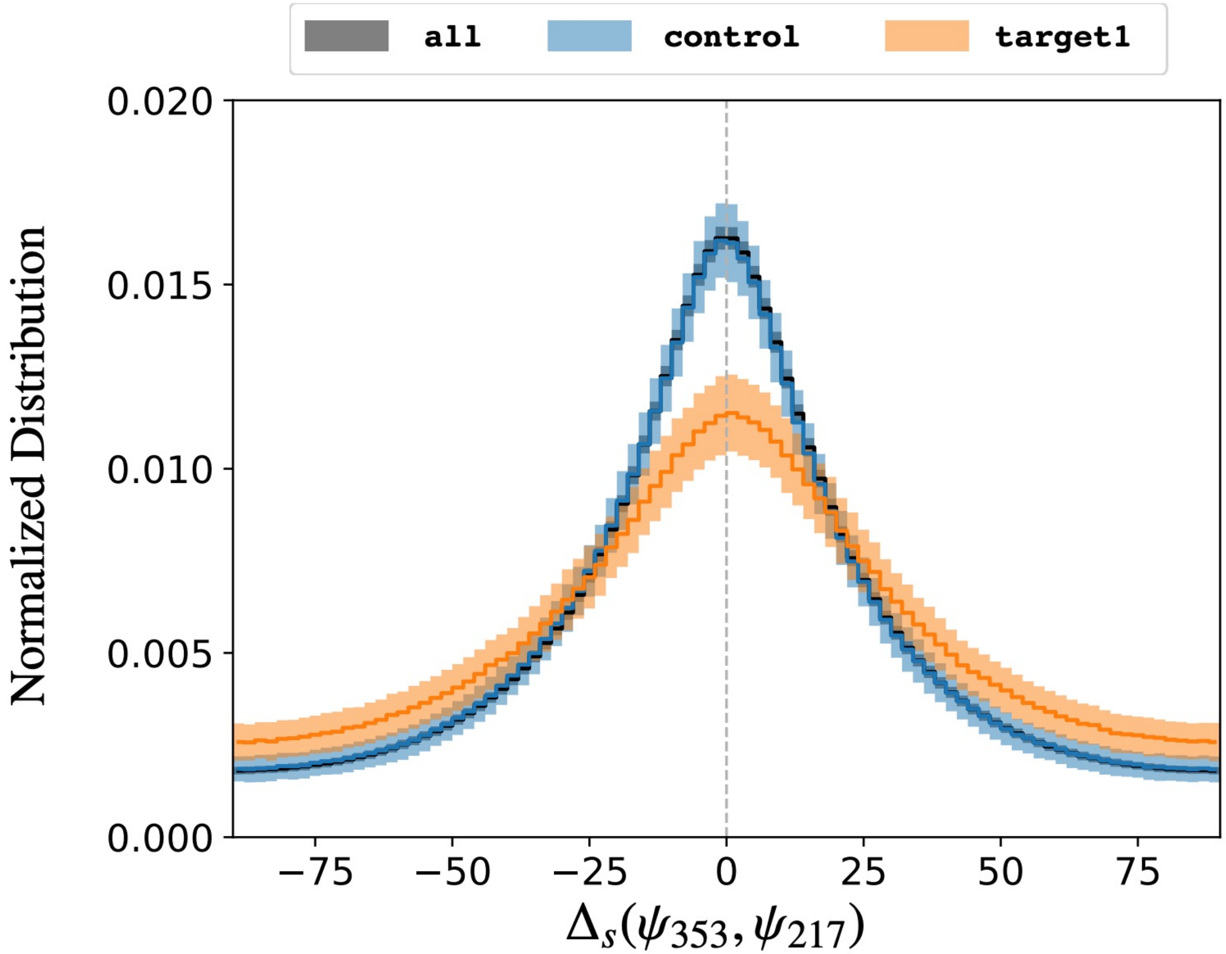
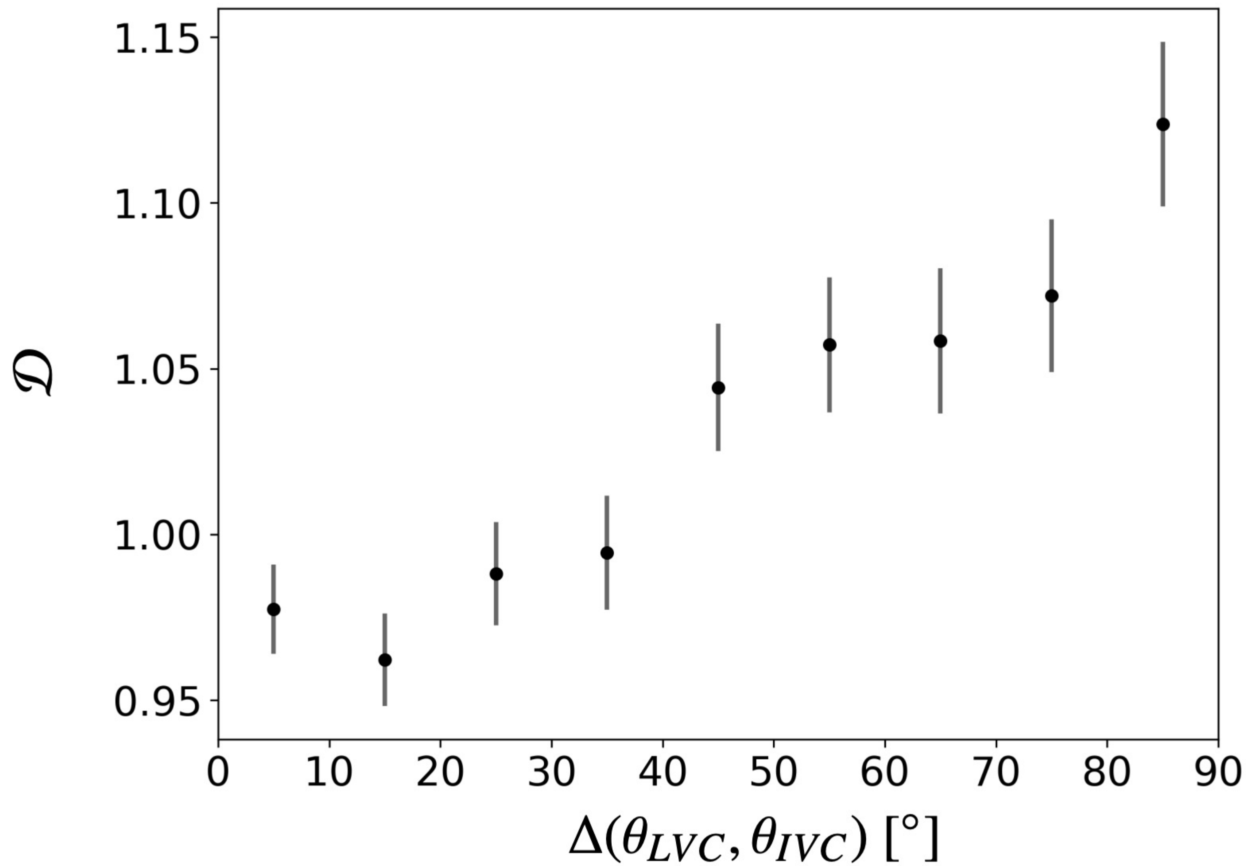


$$\mathcal{D} \equiv S(\{\Delta_s(\psi_{353}, \psi_{217})\})$$

Pelgrims et al. 2021

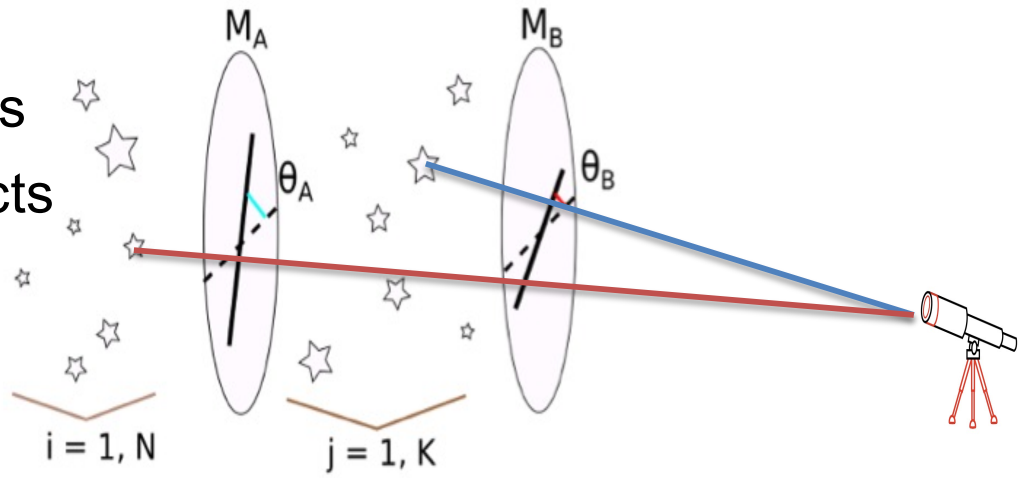
LOS Decorrelation in Planck data



Pelgrims et al. 2021

The Solution: 3D Magnetic Tomography

- Use stars of **known distances** as lamp posts
- Measure **stellar polarization**
  - ✓ get B direction in different clouds
  - ✓ measure and model out 3D effects



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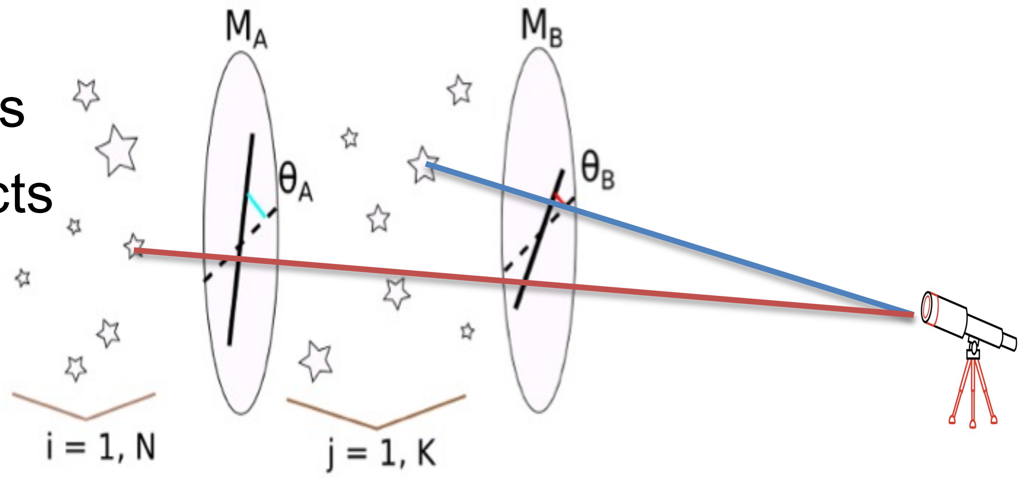


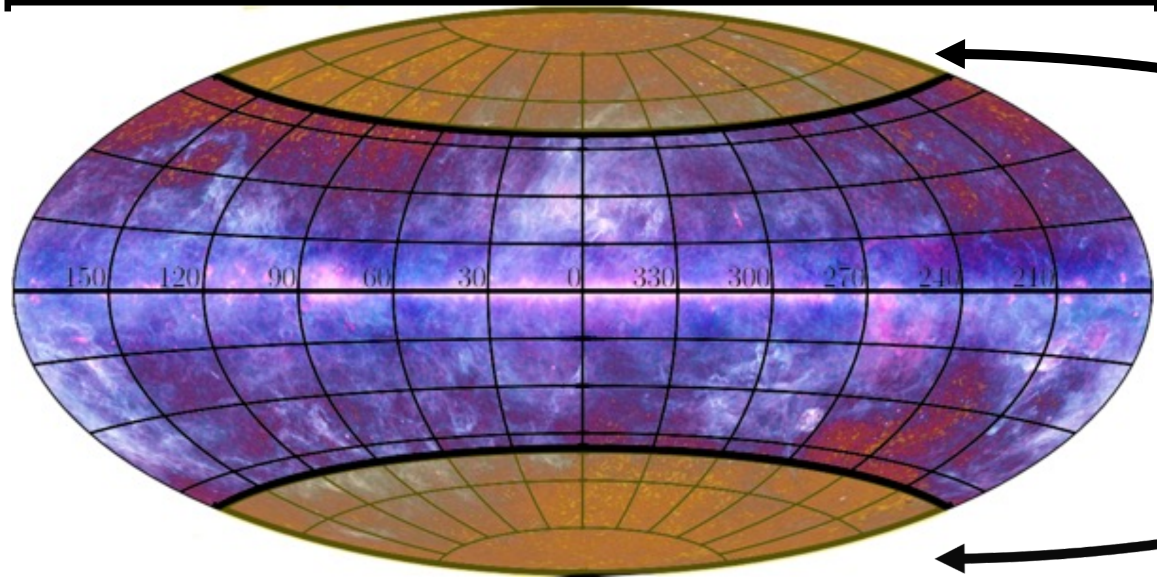
Possible for the first time

PASIPHAE

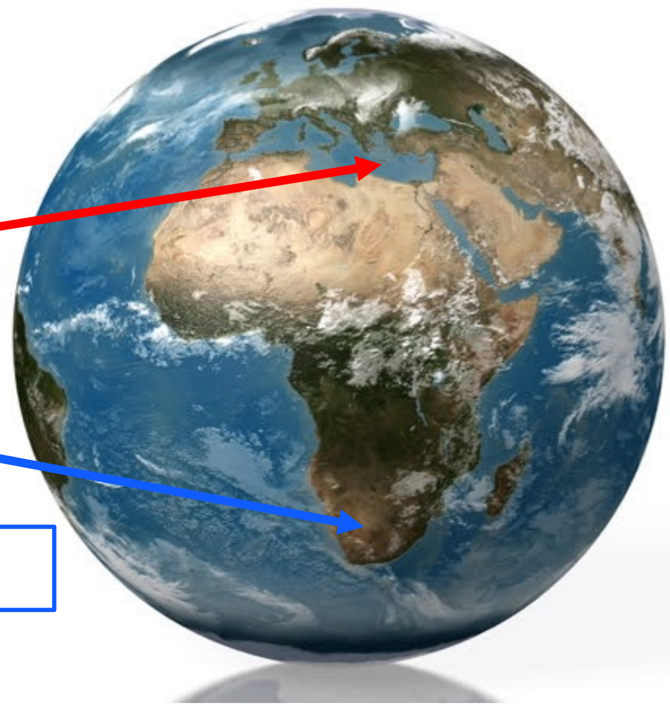
esa

gaia

PASIPHAE optopolarimetric survey



PASIPHAE survey area



Skinakas Observatory, Crete, Greece

PASIPHAE survey sites

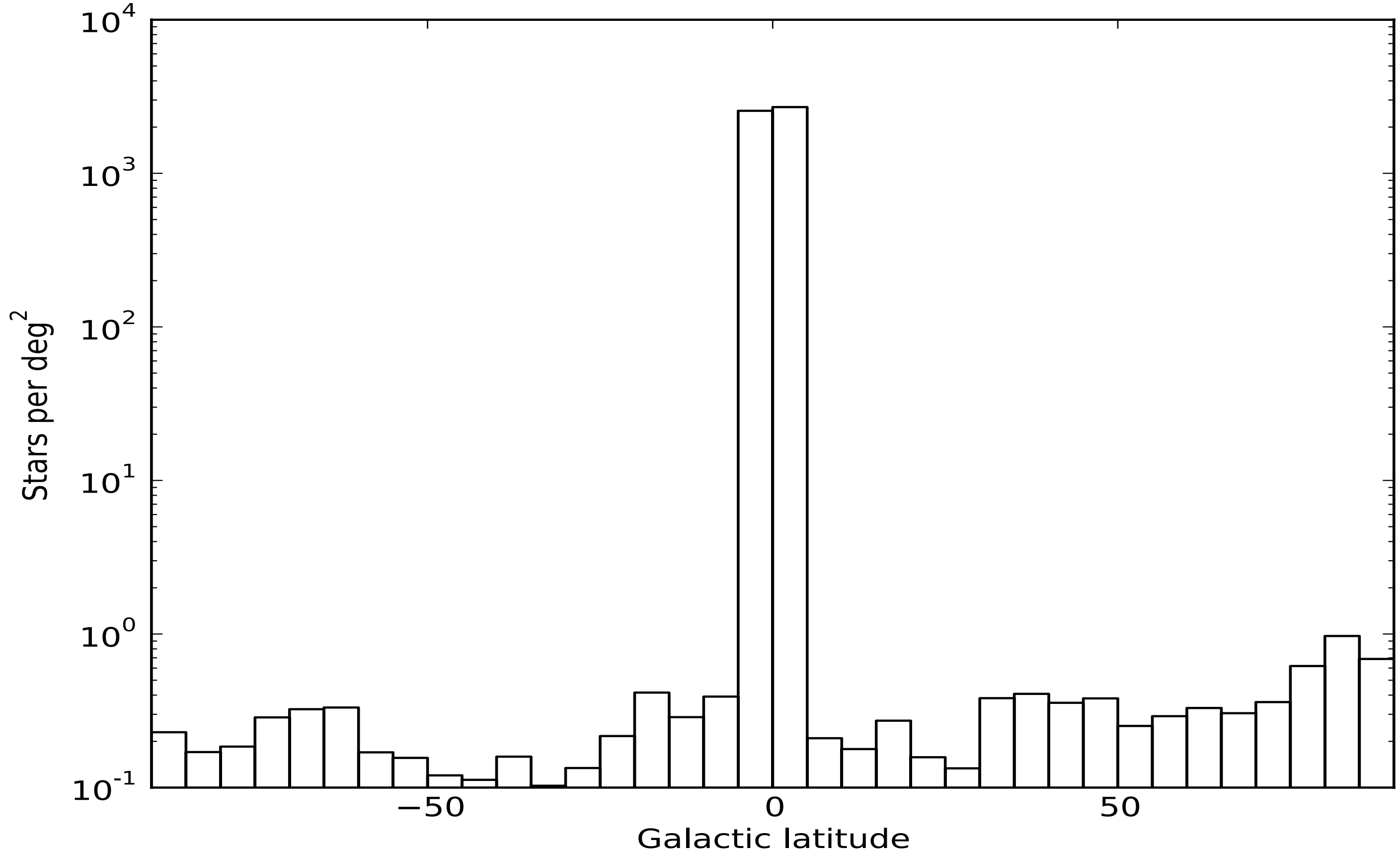
SAAO, Sutherland, South Africa

The PASIPHAE survey:

- Will observe all stars with Rmag ≤ 16
- Will deliver mean polarization down to 0.1% at 3σ for 0.25 deg^2 pixels
- Survey rate: 8 deg^2/night (Skinakas 1.3m) -- 7 deg^2 /night (SAAO1.0 m) assuming 70% efficiency
- ~ 1,500 deg^2 / yr

PASIPHAE optopolarimetric survey

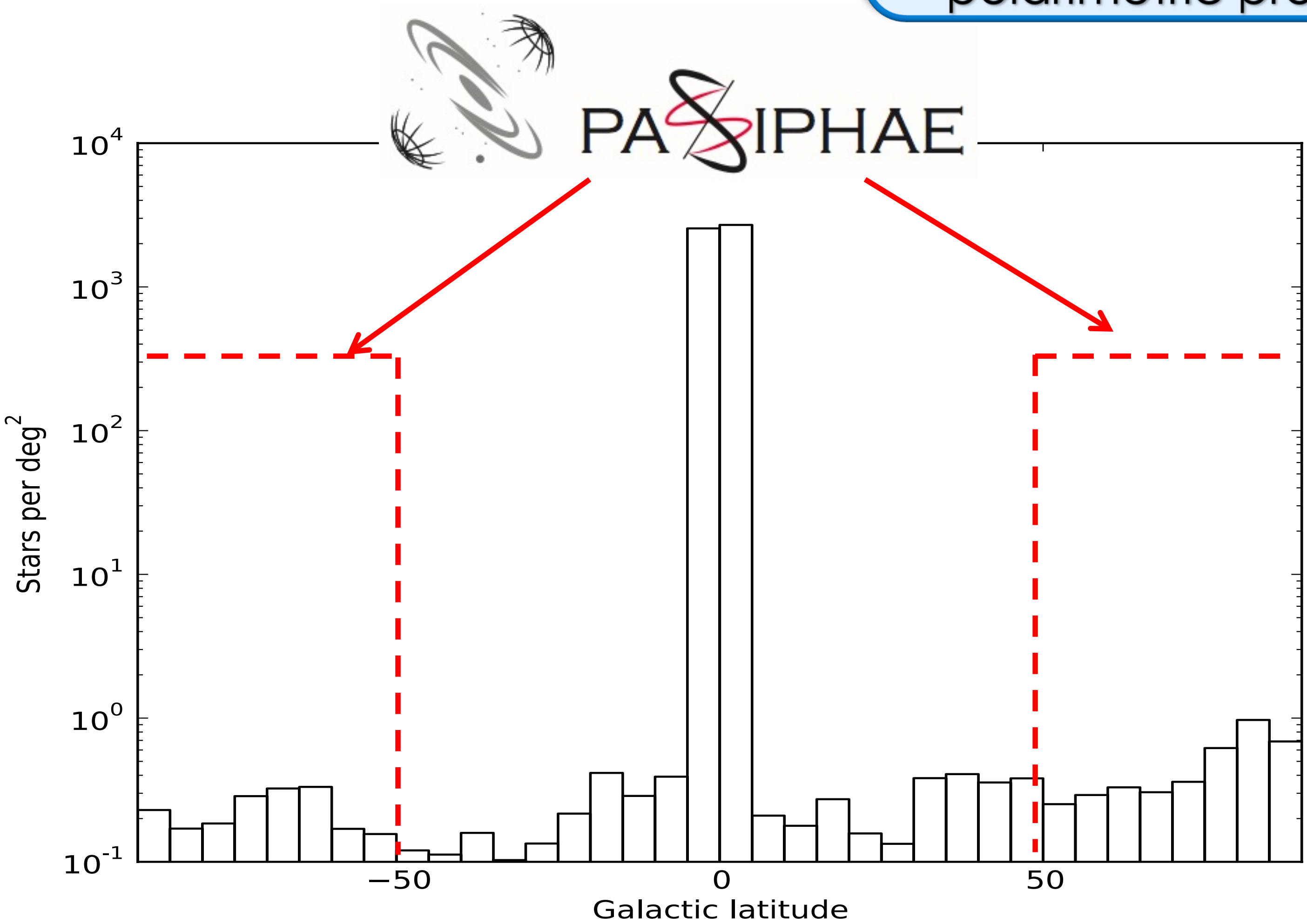
Measure polarization of **several million stars**



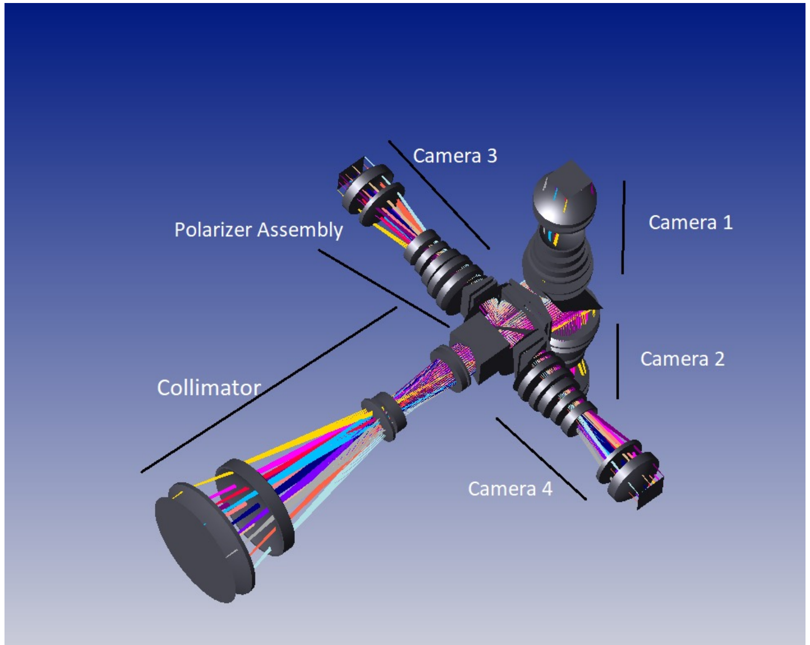
PASIPHAE optopolarimetric survey

Measure polarization of **several million stars**

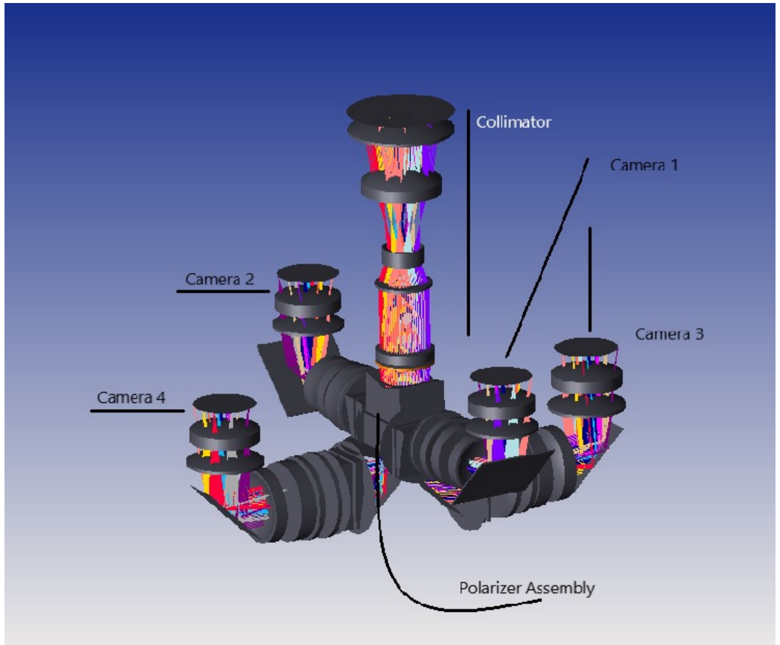
Major Leap:
x1000 improvement
in # of stars with measured
polarimetric properties



WALOPs: the PASIPHAE polarimeters



WALOP - S

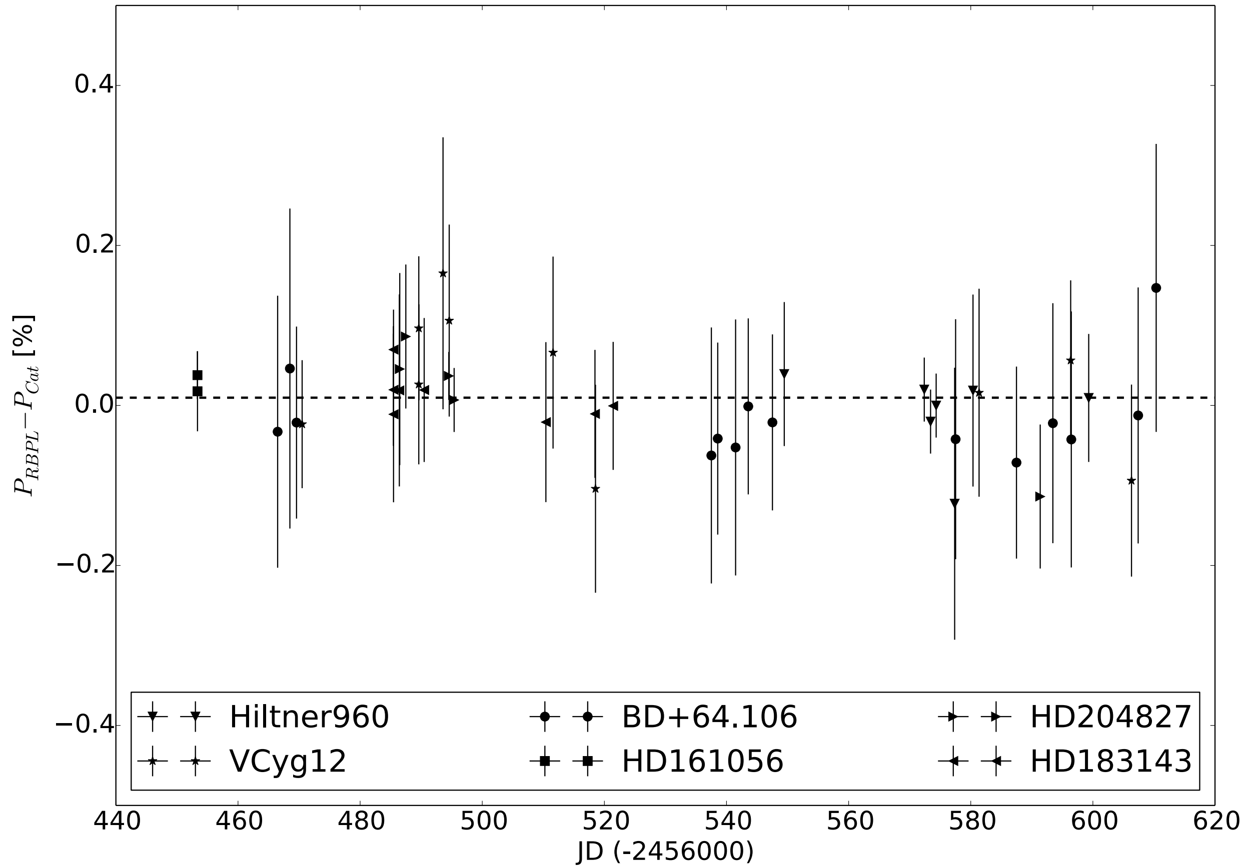


WALOP - N

Wide Area Linear Optical Polarimeter (WALOP)

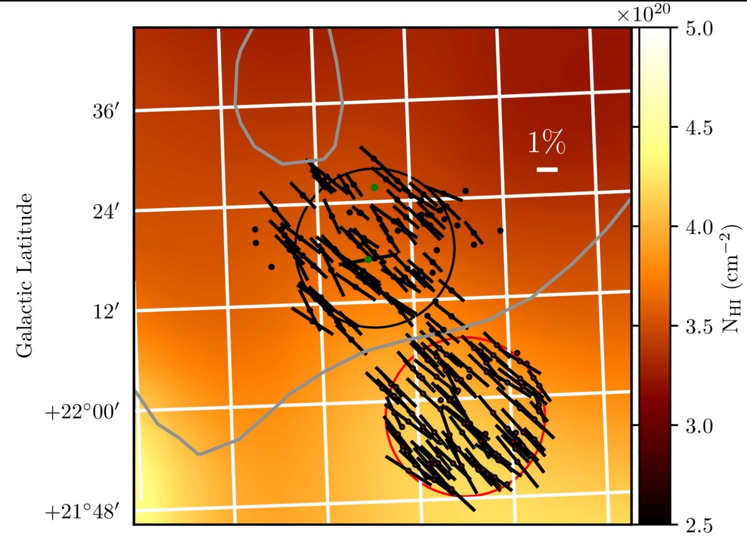
- **Innovative** and **well-tested technology** of RoboPol
- Implements low-systematics design **in a wide field**
- Commissioning by the end of the year

Polarization Systematics



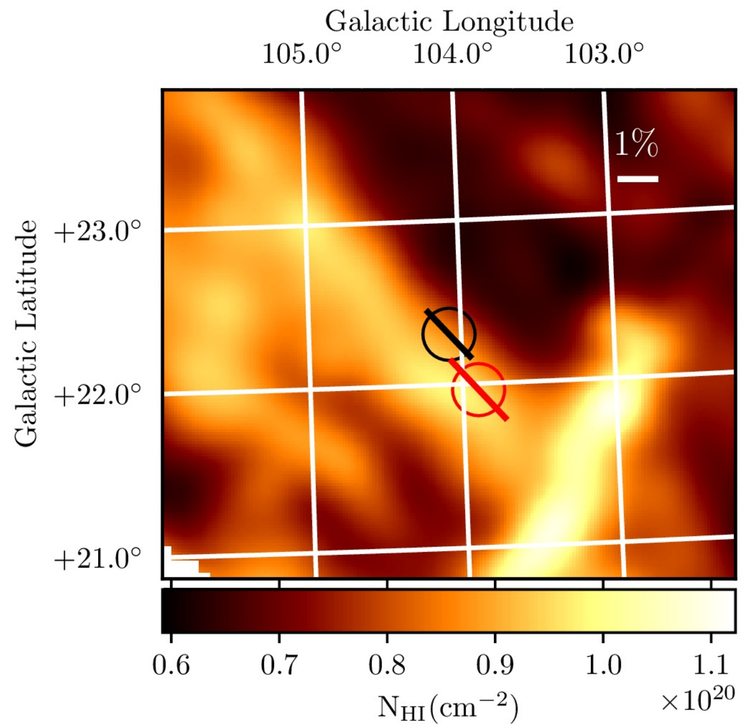
RoboPol standards program

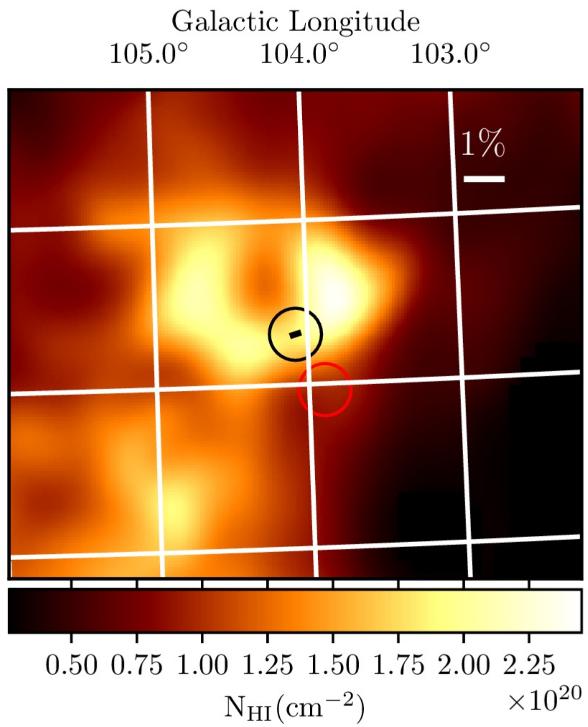
Tomography



robopol

Panopoulou et al. 2019





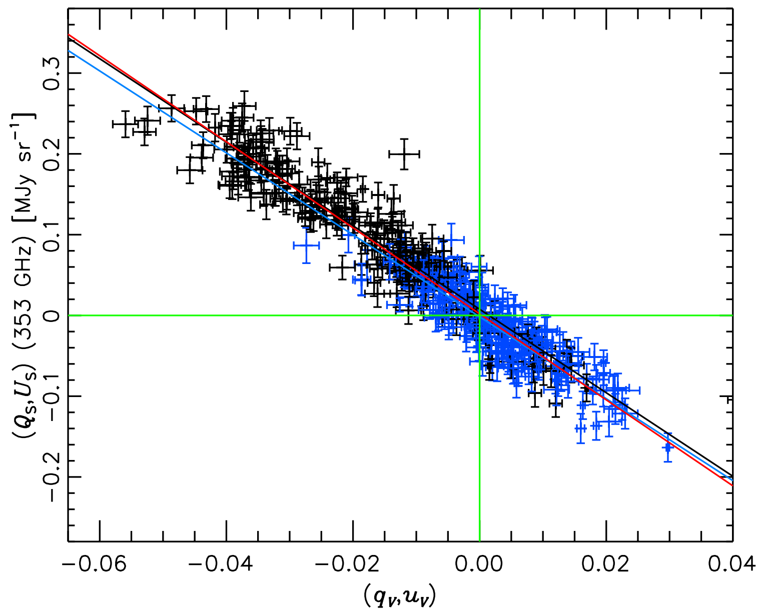
Improving CMB foreground subtraction

Is polarization due to absorption predictive of emission polarization?

YES!

emission, absorption Q,U are tightly correlated

3-d effects can account for most of scatter

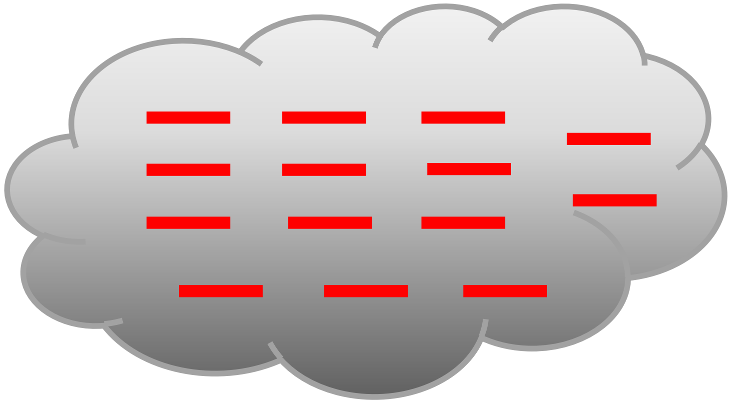


Planck Intermediate results XXI (2015)

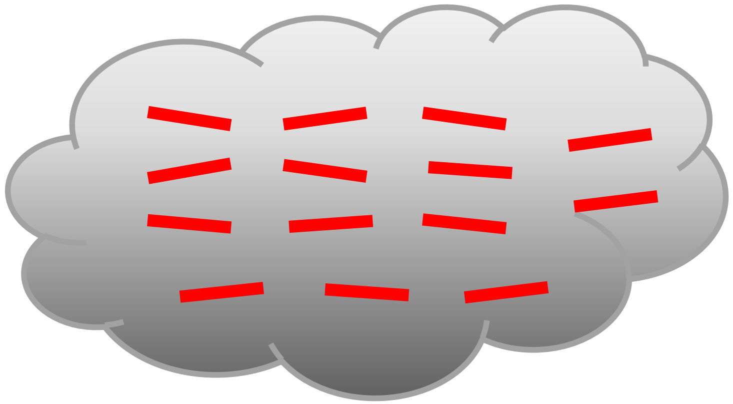
- ✓ Now: modified-black-body model is fitted in **each pixel** (using e.g. Planck data)
- ✓ With PASIPHAE: fit one modified-black-body model for **each cloud**, using: B-field direction from PASIPHAE/Gaia + Planck data (T) + cloud edges, column density from all-sky HI surveys

Getting the value of the B-field

Without Alfvén waves
$(\boldsymbol{B}_{\text{tot}} = \boldsymbol{B}_0)$

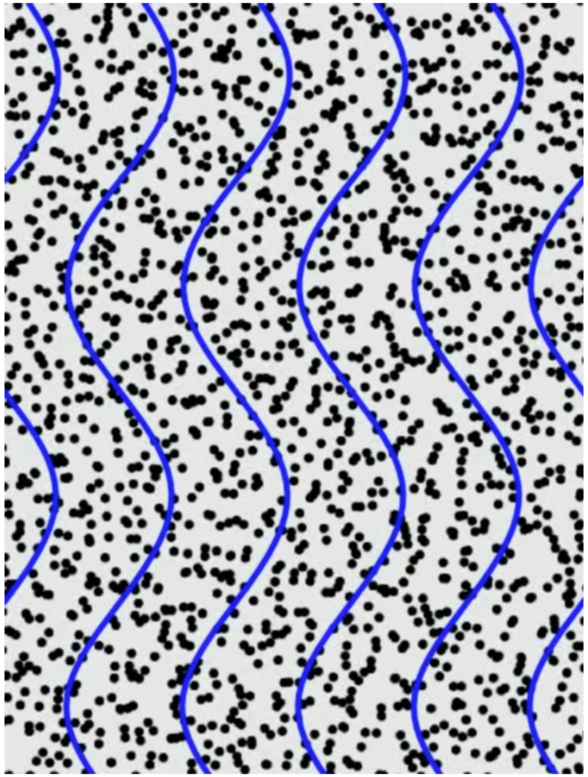


With Alfvén waves
$(\boldsymbol{B}_{\text{tot}} = \boldsymbol{B}_0 + \boldsymbol{\delta B})$



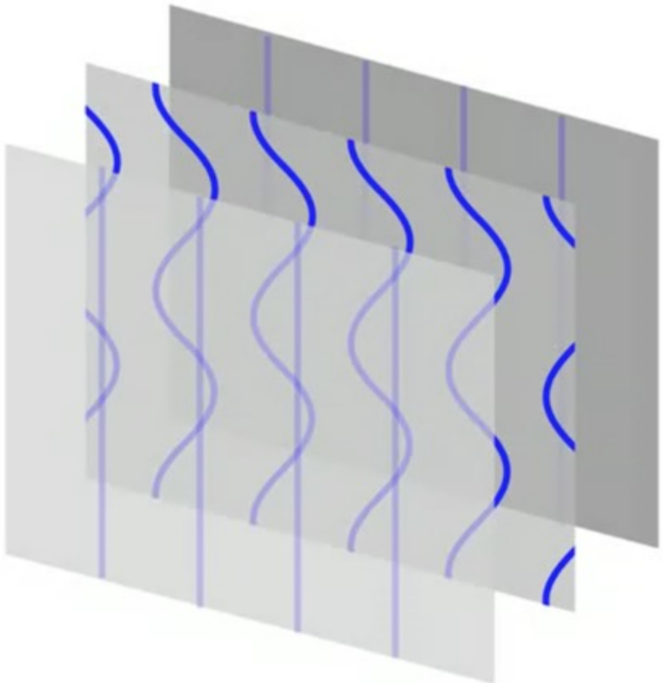
MHD waves – Alfvén waves

Standing waves



Credit: H. Spruit

Traveling waves



DCF method - quantitatively

Magnetic energy density

$$\frac{B^2}{8\pi} = \frac{1}{8\pi}[B_0^2 + 2\,\boldsymbol{\delta B}\cdot\boldsymbol{B_0} + \delta B^2]$$

Alfvén waves transverse:

$\boldsymbol{\delta B} \perp \boldsymbol{B_0} \Longrightarrow \boldsymbol{\delta B}\cdot\boldsymbol{B_0} = 0$

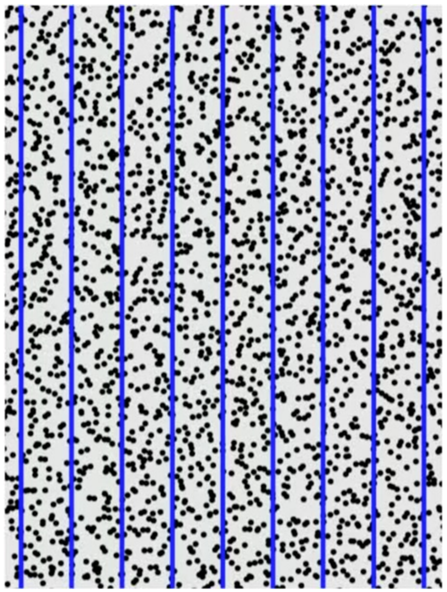
Energy Balance

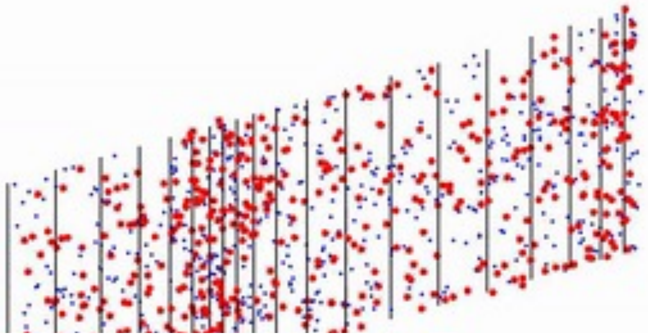
$$\frac{1}{2}\rho\delta v^2 = \frac{\delta B^2}{8\pi}$$

$$B_0 = \sqrt{4\pi\rho}\,\frac{\delta v}{\delta B/B_0}$$

Contamination from compressible modes

- Alfvén waves are coupled with the compressible modes
  Heyvaerts & Priest 1983
- Diffuse ISM clouds are highly compressible with $M_s \sim 3$
  Heiles & Troland 2003
- Compressible modes contribute in δv and $\delta B/B_0$
  Cho & Lazarian 2002





Credit: H. Spruit

Our method

Alfvénic turbulence

- Magnetic field vector

$$\boldsymbol{B} = \boldsymbol{B}_0 + \boldsymbol{\delta B}$$

- Alfvén waves transverse

Goldreich & Sridhar 1995

$$\boldsymbol{\delta B} \perp \boldsymbol{B_0} \Longrightarrow \boldsymbol{\delta B} \cdot \boldsymbol{B_0} = 0$$

- Magnetic energy density

$$\frac{B^2}{8\pi} = \frac{1}{8\pi}[B_0^2 + 2\,\boldsymbol{\delta B} \cdot \boldsymbol{B_0} + \delta B^2]$$

Compressible turbulence

- Magnetic field vector

$$\boldsymbol{B} = \boldsymbol{B}_0 + \boldsymbol{\delta B}$$

- Compressible wave poroperties

Bhattacharjee & Hameiri (1988), Bhattacharjee et al. (1998)

$$\delta\rho \propto \boldsymbol{\delta B} \cdot \boldsymbol{B_0} \qquad \Longrightarrow \qquad \boldsymbol{\delta B} \cdot \boldsymbol{B_0} \neq 0$$

- Magnetic energy density

$$\frac{B^2}{8\pi} = \frac{1}{8\pi}[B_0^2 + 2\,\boldsymbol{\delta B} \cdot \boldsymbol{B_0} + \delta B^2]$$

0th 1st 2nd

Our method

Alfvénic turbulence

$$\frac{1}{2}\rho\delta v^2 = \frac{\delta B^2}{8\pi}$$

$$V_{A,0} = \delta v \left[\frac{\delta \mathrm{B}}{\mathrm{B}_0}\right]^{-1}$$

Davis 1951, Chandrasekhar & Fermi 1953

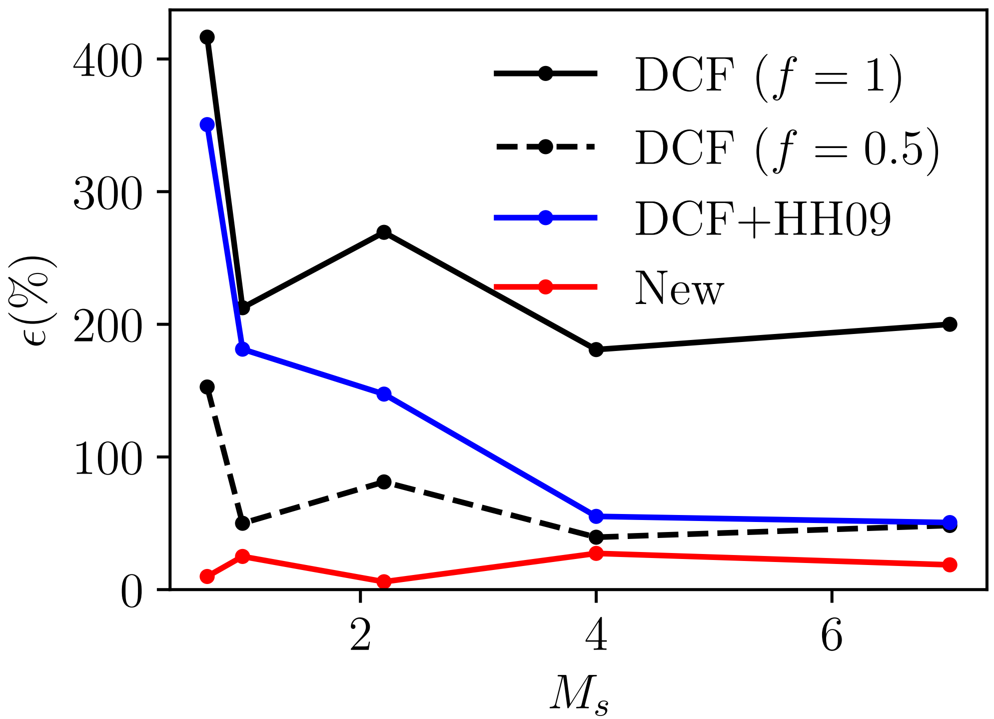
Compressible turbulence

$$\frac{1}{2}\rho\delta v^2 = \frac{\delta B\ B_0}{4\pi}$$

$$V_{A,0} = \delta v \left[\frac{2\delta \mathrm{B}}{\mathrm{B}_0}\right]^{-1/2}$$

Skalidis & Tassis 2021

Comparison between the different methods



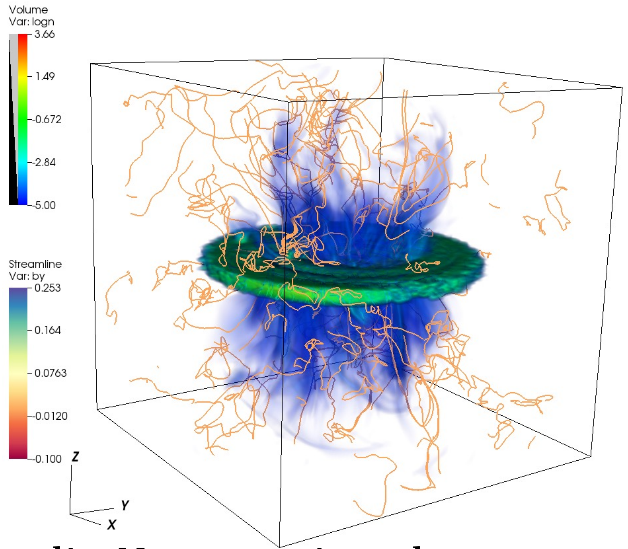
Skalidis & Tassis 2021

- M_A=0.7 for every model
- The absolute mean relative deviation of our method is:

$$\epsilon = 17\,\%$$

Wider Impact

- **3-D Tomographic Map of Galactic B-field:**
  - ✓ **What is the origin of Galactic B-field?**
  - ✓ **Is the B-field dynamically important in interstellar clouds?**
  - ✓ **Where are ultra-high-energy cosmic rays coming from?**



credit: Ntormousi et al. 2020

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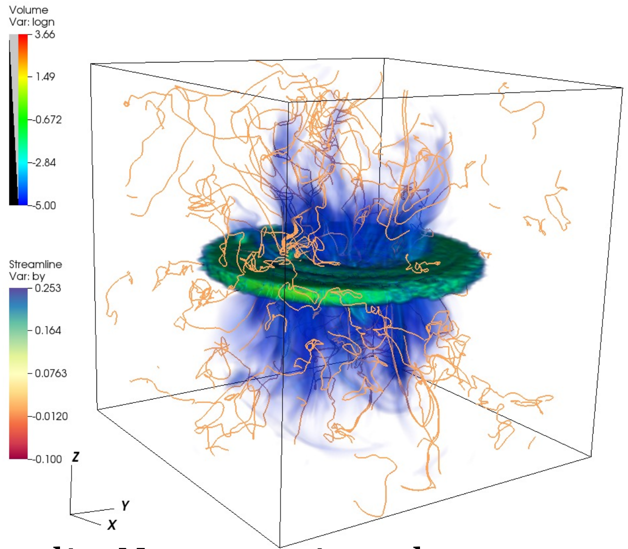

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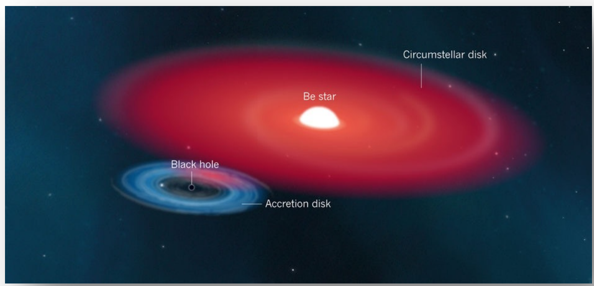
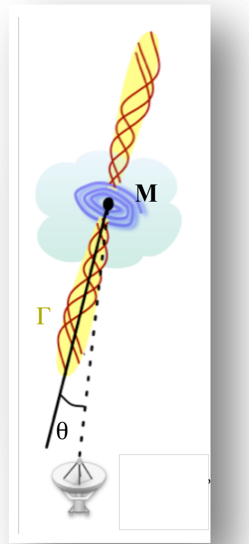
- **Polarimetric Database**
  - ✓ **Stellar Astrophysics**
  - ✓ **High-energy astrophysics**



credit: McSwain 2014



credit: Pavidou 2015

More Information

- PASIPHAE WP on arXiv: **1810.05652 :**

Cornell University

We gratefully acknowledge support from the Simons Foundation and member institutions.

arXiv.org > astro-ph > arXiv:1810.05652

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[Submitted on 12 Oct 2018]

PASIPHAE: A high-Galactic-latitude, high-accuracy optopolarimetric survey

Konstantinos Tassis, Anamparambu N. Ramaprakash, Anthony C. S. Readhead, Stephen B. Potter, Ingunn K. Wehus, Georgia V. Panopoulou, Dmitry Blinov, Hans Kristian Eriksen, Brandon Hensley, Ata Karakci, John A. Kypriotakis, Siddharth Maharana, Evangelia Ntormousi, Vasiliki Pavlidou, Timothy J. Pearson, Raphael Skalidis

PASIPHAE (the Polar-Areas Stellar Imaging in Polarization High-Accuracy Experiment) is an optopolarimetric survey aiming to measure the linear polarization from millions of stars, and use these to create a three-dimensional tomographic map of the magnetic field threading dust clouds within the Milky Way. This map will provide invaluable information for future CMB B-mode experiments searching for inflationary gravitational waves, providing unique information regarding line-of-sight integration effects. Optical polarization observations of a large number of stars at known distances, tracing the same dust that emits polarized microwaves, can map the magnetic field between them. The Gaia mission is measuring distances to a billion stars, providing an opportunity to produce a tomographic map of Galactic magnetic field directions, using optical polarization of starlight. Such a map will not only boost CMB polarization foreground removal, but it will also have a profound impact in a wide range of astrophysical research, including interstellar medium physics, high-energy astrophysics, and evolution of the Galaxy. Taking advantage of the novel technology implemented in our high-accuracy Wide-Area Linear Optical Polarimeters (WALOPs) currently under construction at IUCAA, India, we will engage in a large-scale optopolarimetric program that can meet this challenge: a survey of both northern and southern Galactic polar regions targeted by CMB experiments, covering over 10,000 square degrees, which will measure linear optical polarization of over 360 stars per square degree (over 3.5 million stars, a 1000-fold increase over the state of the art). The survey will be conducted concurrently from the South African Astronomical Observatory in Sutherland, South Africa in the southern hemisphere, and the Skinakas Observatory in Crete, Greece, in the north.

Comments: 16 pages, 6 figures
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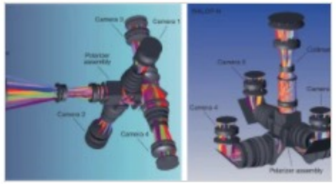
A. Ramaprakash, A. C. S. Readhead & K. Tassis



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More Information

- http://pasiphae.science :

PASIPHAE
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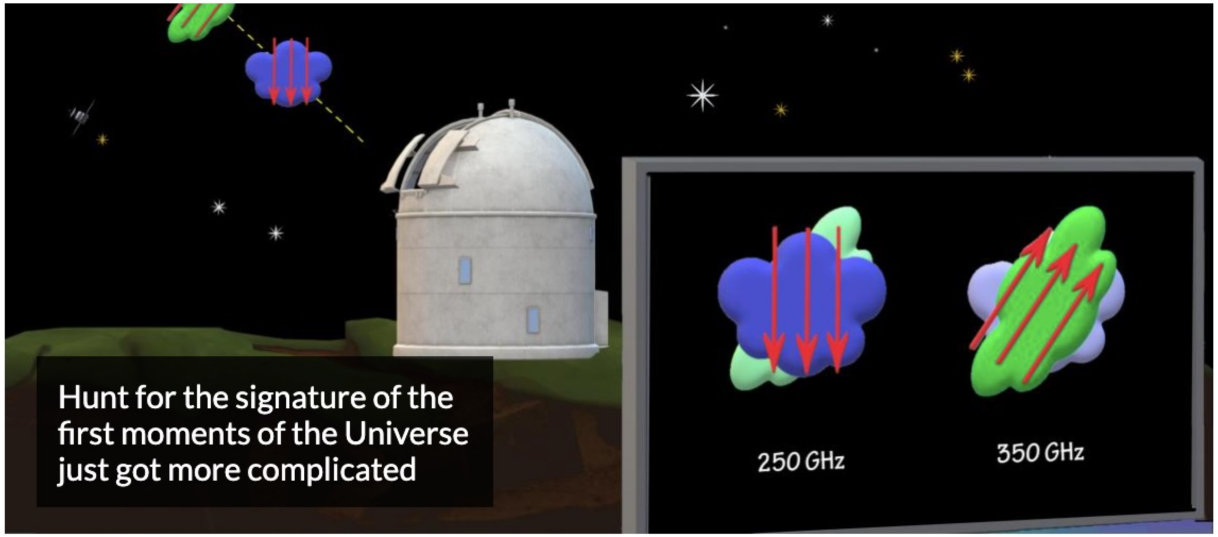

POLAR-AREAS STELLAR IMAGING IN POLARIZATION HIGH-ACCURACY EXPERIMENT

Thank you