ΠΑΝΕΠΙΣΤΗΜΙΟ ΚΡΗΤΗΣ
UNIVERSITY OF CRETE

INSTITUTE OF ASTROPHYSICS

The Magnetic Field in the Galaxy

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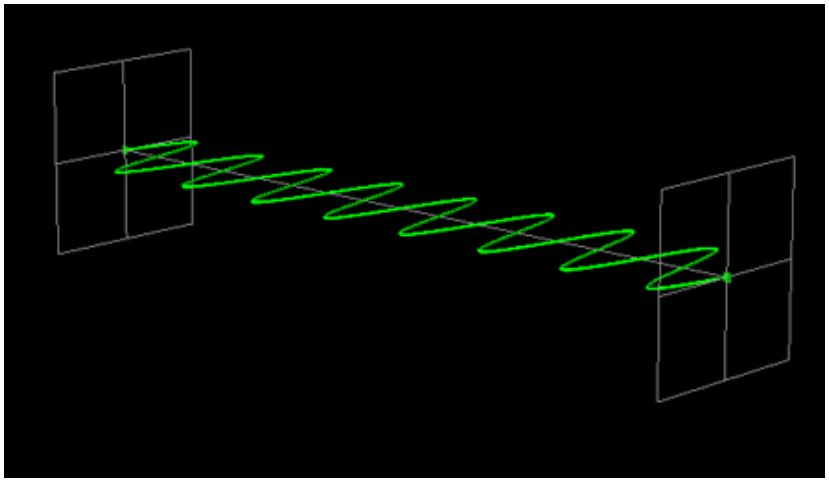
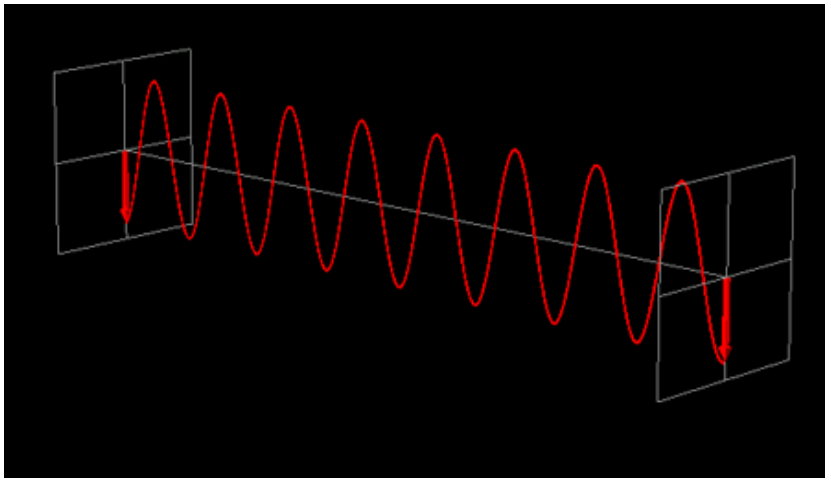
Content

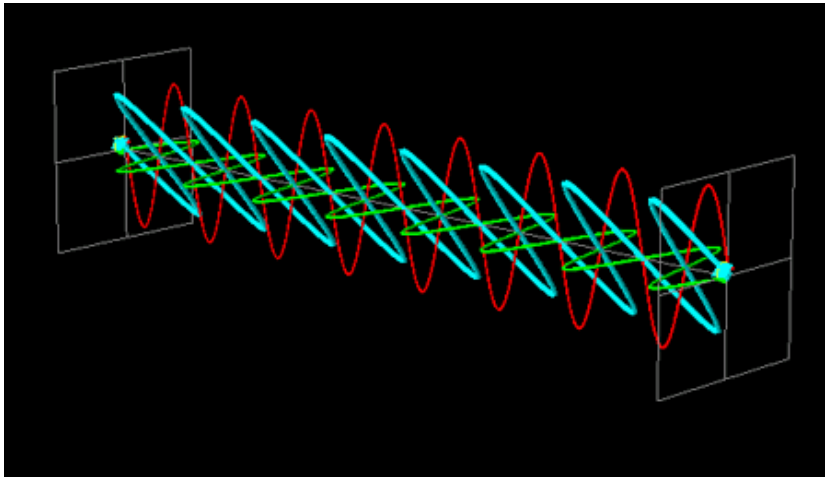
1. Polarization of Light
2. B-Field Probing Radiation Processes
3. Review of Observations and their Implications for B-Field Models
4. Milky Way B-field as a Foreground of CMB Polarization Observations

Polarization



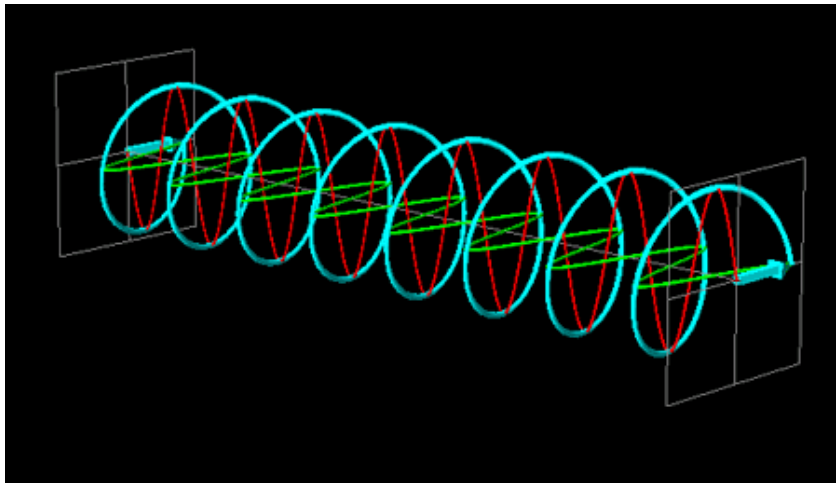


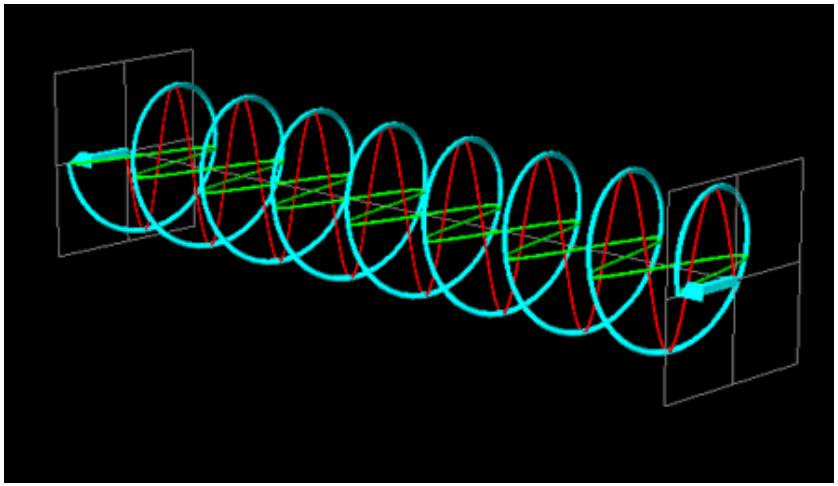
linear



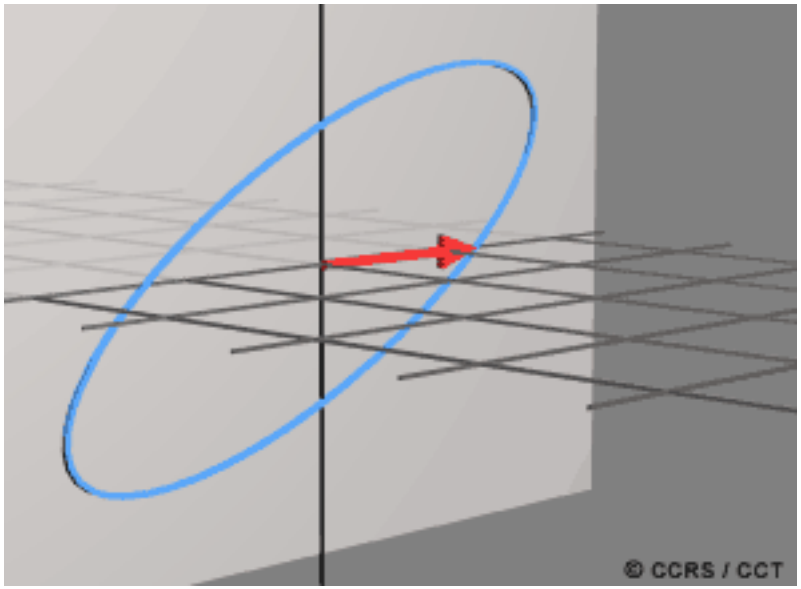
Polarization

circular





Polarization



$$\vec{E}_x(z,t) = E_{0x}cos(kz-\omega t)\vec{x}$$
$$\vec{E}_y(z,t) = E_{0y}cos(kz-\omega t+\epsilon)\vec{y}$$

$$\left(\frac{E_x}{E_{0x}}\right)^2+\left(\frac{E_y}{E_{0y}}\right)^2-2\frac{E_x}{E_0x}\frac{E_y}{E_{0y}}cos\epsilon = sin^2\epsilon$$

An ellipse can be represented by 4 quantities:

1. Size of minor axis
2. Size of major axis
3. Orientation (angle)
4. Sense (CW, CCW)

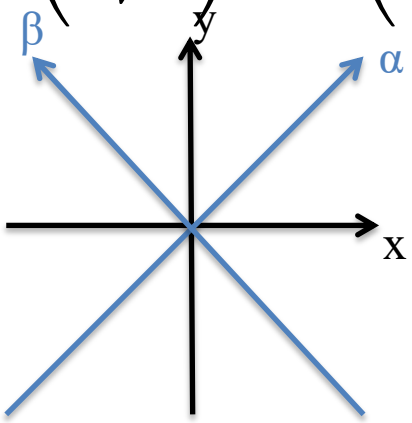
Intensity (square of amplitude) can be written as:

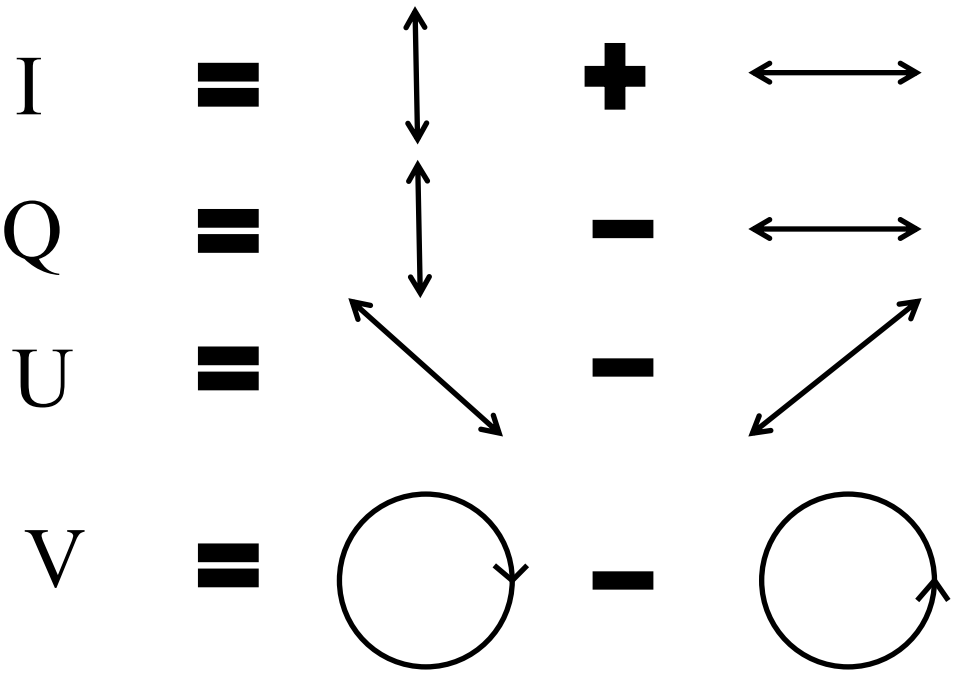
$$(E_{0x}^2+E_{0y}^2)^2 = (E_{0x}^2-E_{0y}^2)^2+(2E_{0x}E_{0y}cos\epsilon)^2+(2E_{0x}E_{0y}sin\epsilon)^2$$

$S_0^2=I^2$ $S_1^2=Q^2$ $S_2^2=U^2$ $S_3^2=V^2$

Stokes Parameters

$$\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} E_{0x}^2 + E_{0y}^2 \\ E_{0x}^2 - E_{0y}^2 \\ 2E_{0x}E_{0y}\cos\epsilon \\ 2E_{0x}E_{0y}\sin\epsilon \end{pmatrix} = 2\begin{pmatrix} \text{intensity} \\ I(0°) - I(90°) \\ I(45°) - I(135°) \\ I(RCP) - I(LCP) \end{pmatrix}$$





Polarization fraction (p) angle (χ)

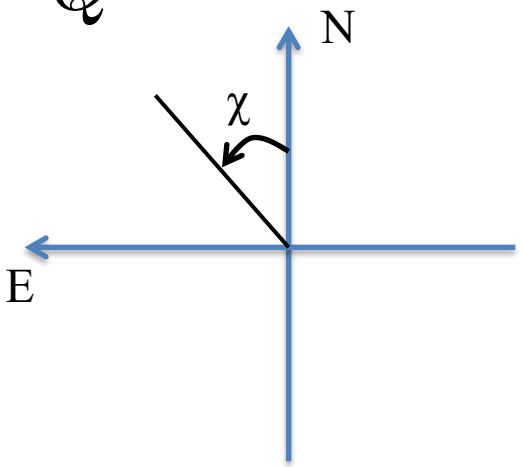
$$(E_{0x}^2 + E_{0y}^2)^2 = (E_{0x}^2 - E_{0y}^2)^2 + (2E_{0x}E_{0y}cos\epsilon)^2 + (2E_{0x}E_{0y}sin\epsilon)^2$$

$$I^2 = Q^2 + U^2 + V^2$$

$$V = 0: \; p = \frac{\sqrt{Q^2 + U^2}}{I}$$

$$\tan 2\chi = \frac{U}{Q}$$

Electric Vector Position Angle (EVPA)



The Interstellar Medium...

...is everything that exists between the stars.

1. Gas
2. Dust
3. Radiation
4. Cosmic Rays
5. Magnetic Fields

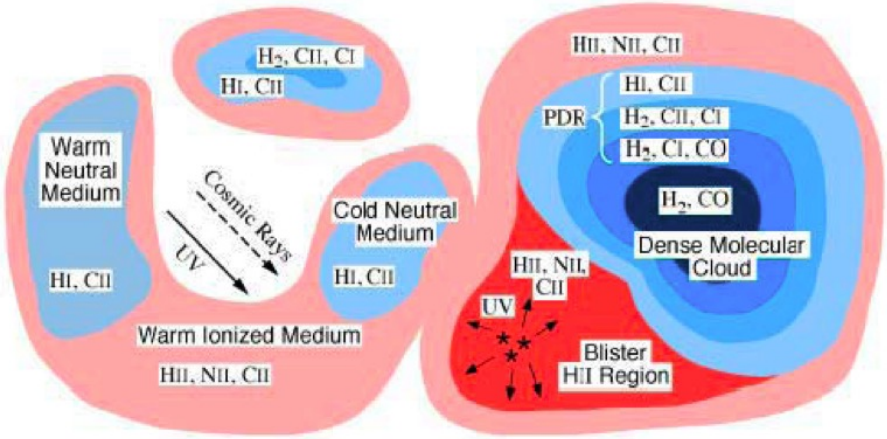
Structure of the ISM

Ionized Gas:

- Very Hot Ionized Medium (HIM)
  $n \sim 0.01\ cm^{-3}$ $T \sim 10^5\ K$
- Warm Ionized Medium (WIM)
  $n \sim 0.1\ cm^{-3}$ $T \sim 10^4\ K$
- HII Regions: $T \sim 10^4\ K$ $n \sim 0.1\text{-}10^4\ cm^{-3}$

Neutral Gas:

- Warm Neutral Medium (WNM)
  $n \sim 1\ cm^{-3}$ $T \sim 6000\ K$
- Cold Neutral Medium (CNM)
  $n \sim 50\ cm^{-3}$ $T \sim 100\ K$



Molecular Gas:

$n \sim 1000\ cm^{-3}$ $T \sim 10\ K$

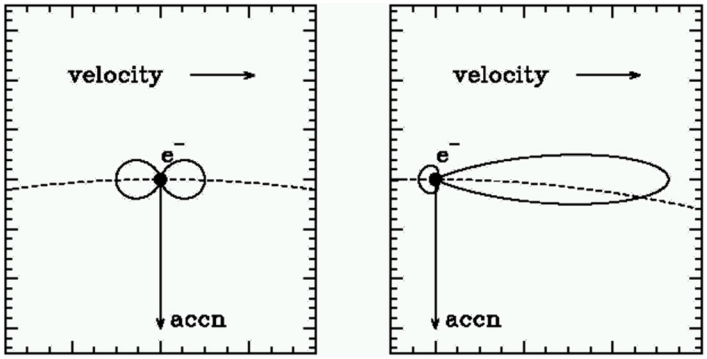
"cores": $n \sim 10^4 - 10^6\ cm^{-3}$ $T \sim 10\ K$

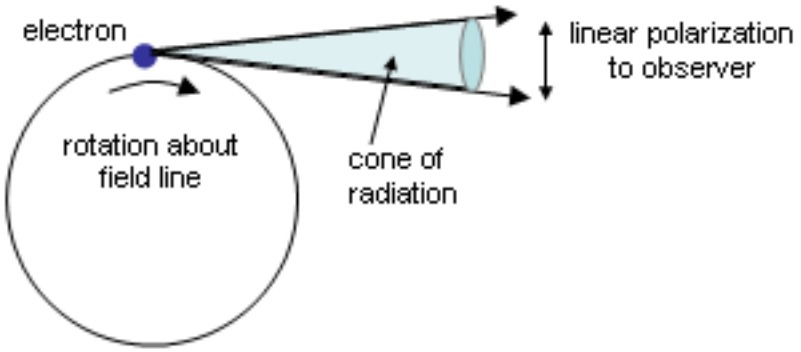
(Ultra High Vacuum: $n \sim 10^6\ cm^{-3}$)

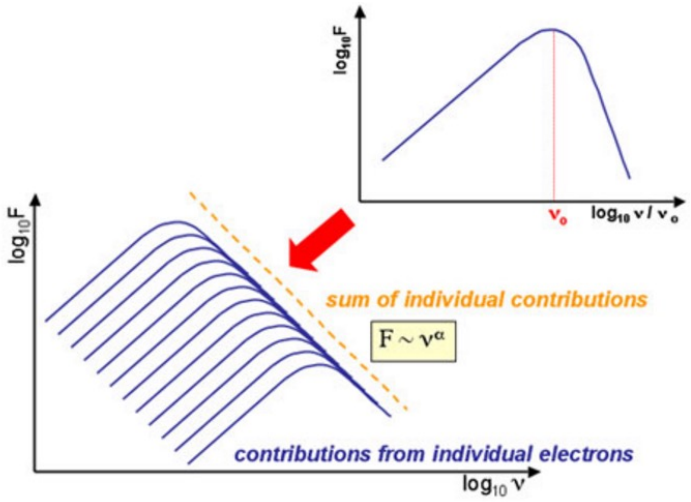
B-Field Probing Radiation Processes

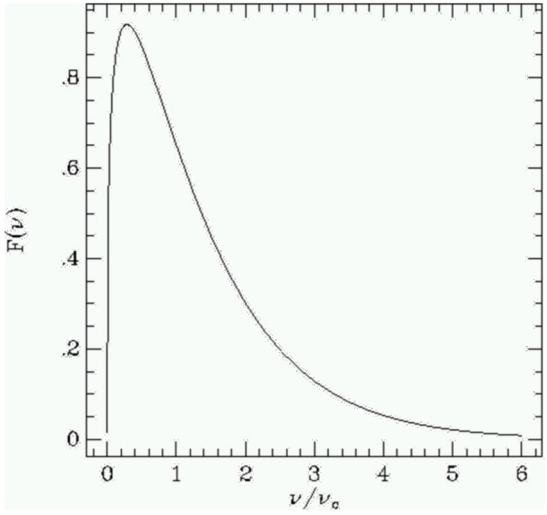
1. Synchrotron Radiation
2. Faraday Rotation
3. Dust Thermal Emission/Absorption
4. Zeeman effect

Synchrotron

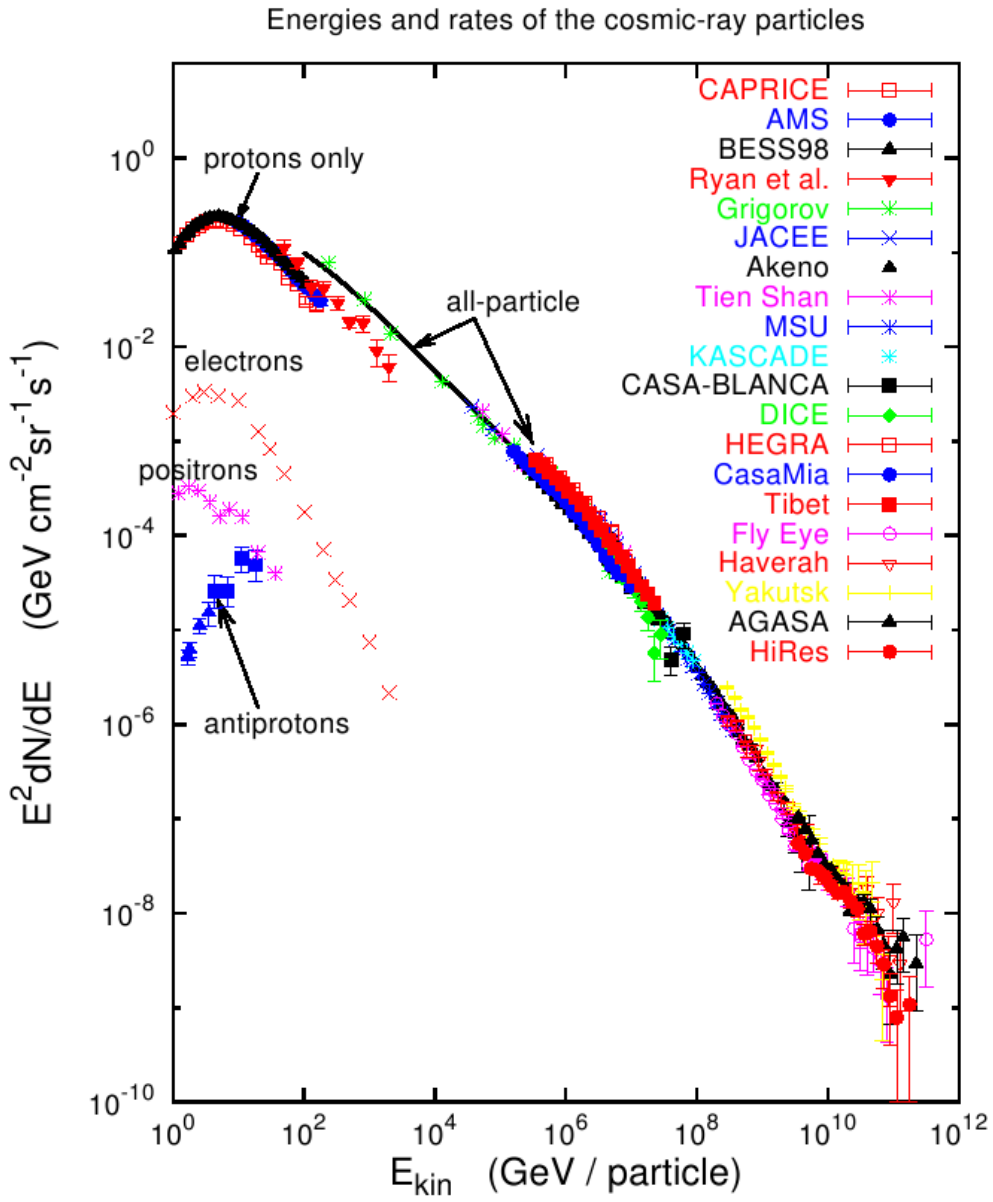








Cosmic Rays



Victor Hess

- Large Range of Energies
- Flux -> Power Law: slope ~ -2.7

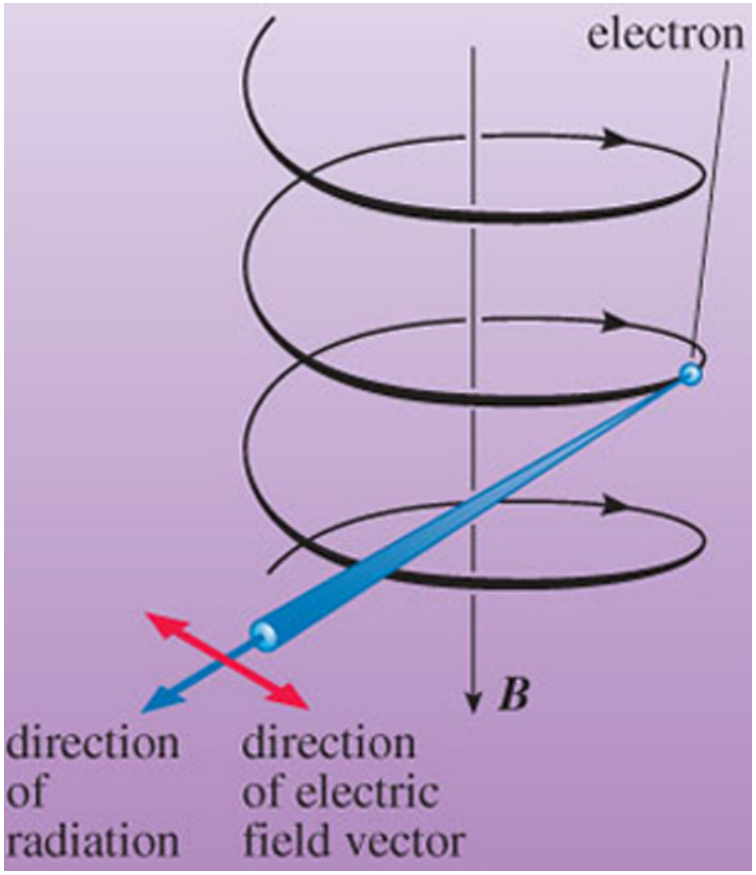
Cosmic Rays + B-field -> synchrotron

Emissivity of power-law distribution of CR e- with slope γ:

$$\varepsilon \sim N_0 \nu^{(\gamma+1)/2} \mathrm{B}_{\perp}^{(1-\gamma)/2}$$

Radiation linearly polarized perp. to B-field with max polarization fraction:

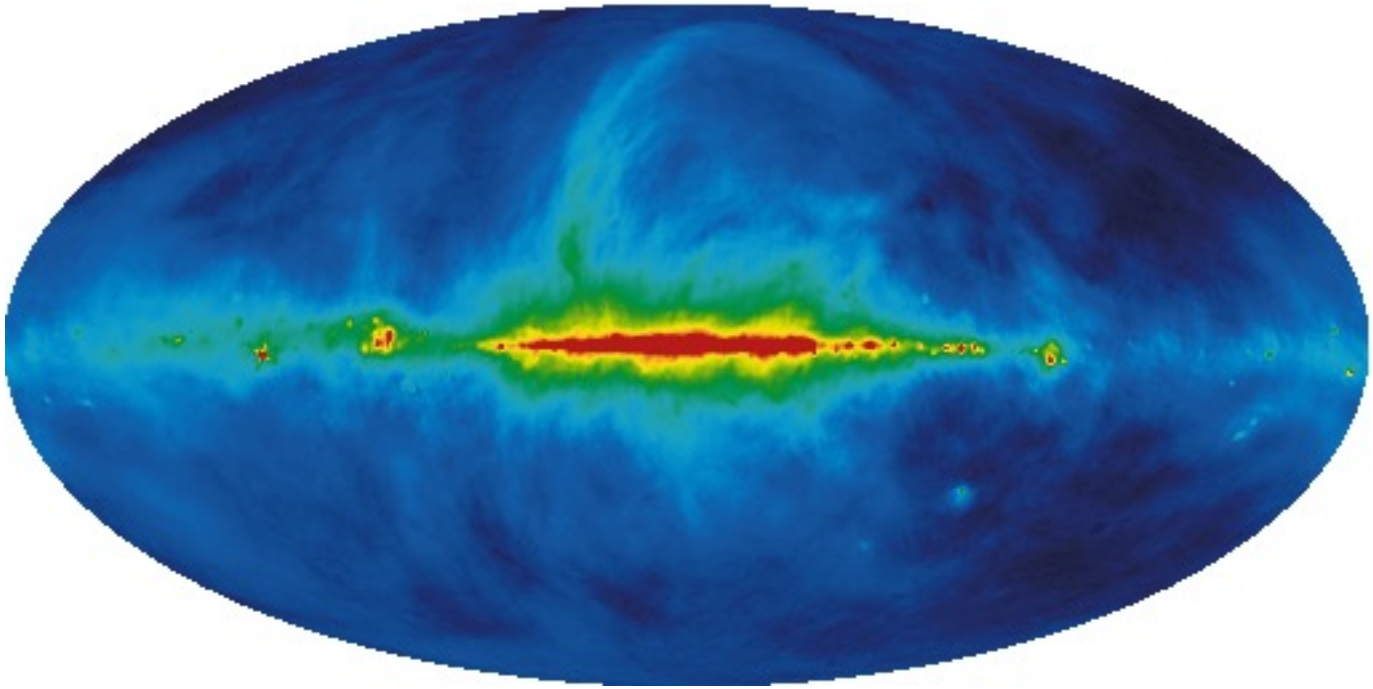
$$p = \frac{1-\gamma}{7/3-\gamma}$$



Credit: open.edu

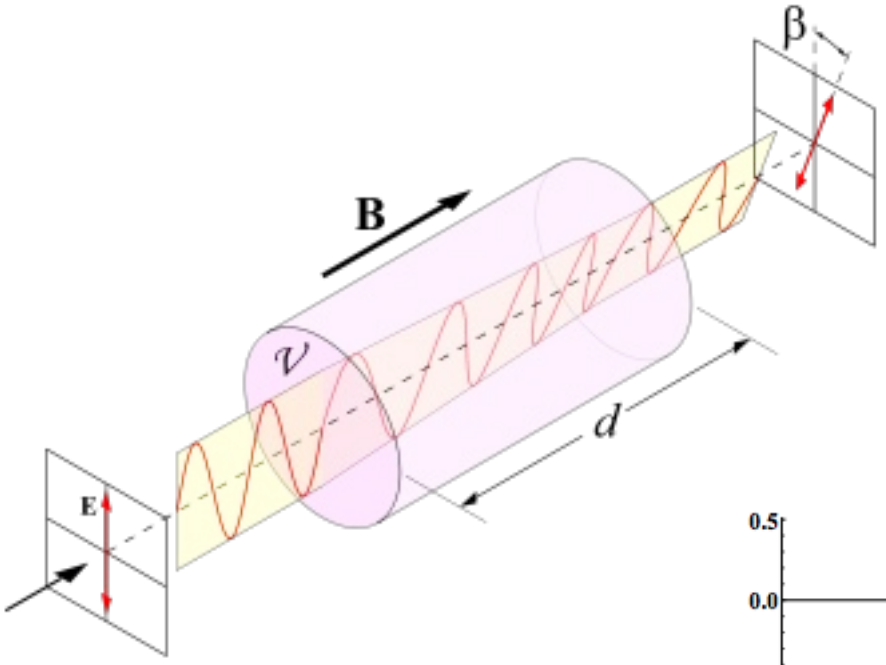
All sky synchrotron emission

408 MHz



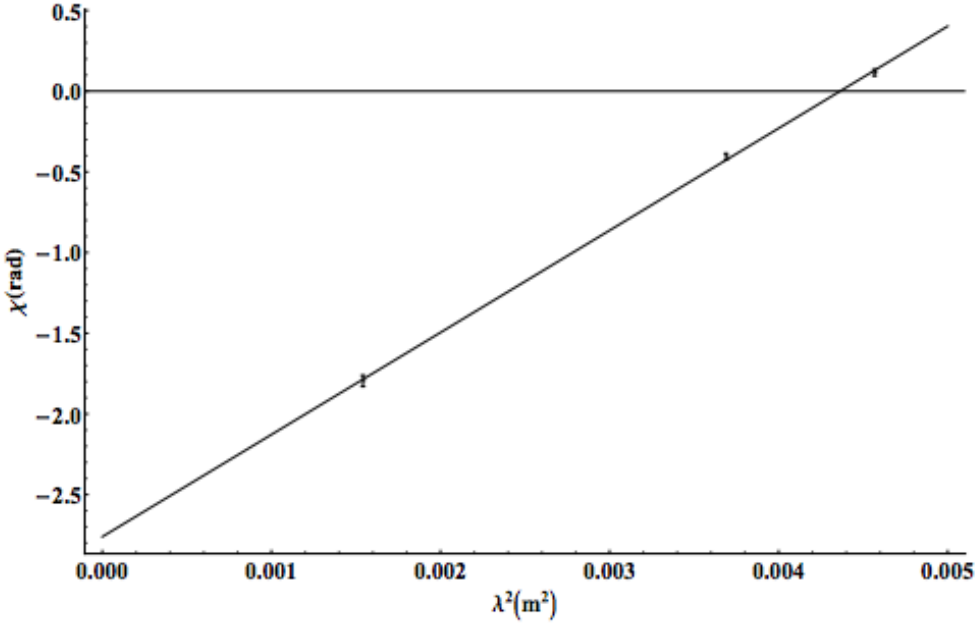
Haslam et al. 1982; Remazeilles et al. 2014

Faraday Rotation (HIM + WIM)



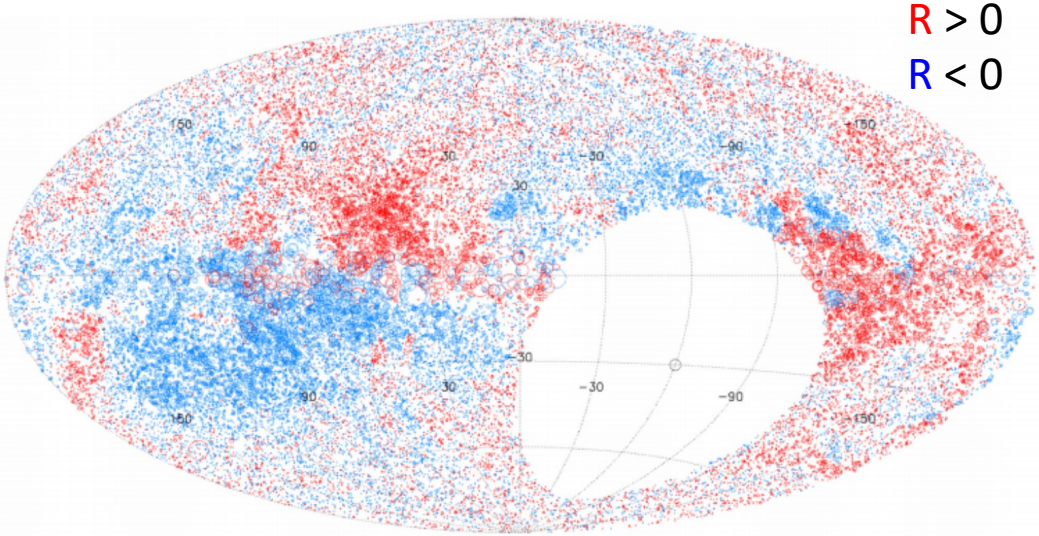
$$\beta = \mathrm{RM}\lambda^2$$

$$\mathrm{RM} = \frac{e^3}{8\pi^2 \varepsilon_0 m^2 c^3} \int_0^d n_e(s) B_{||}(s)\, \mathrm{d}s$$

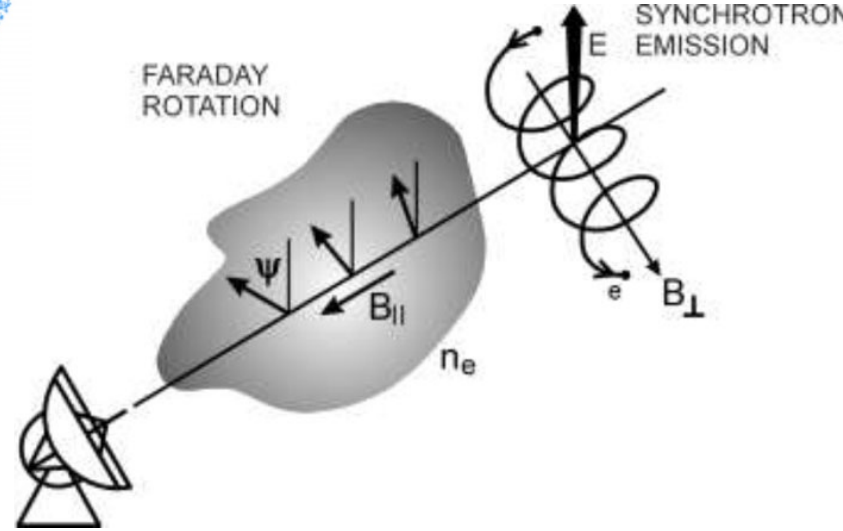


Savage, Spangler,& Fischer 2013

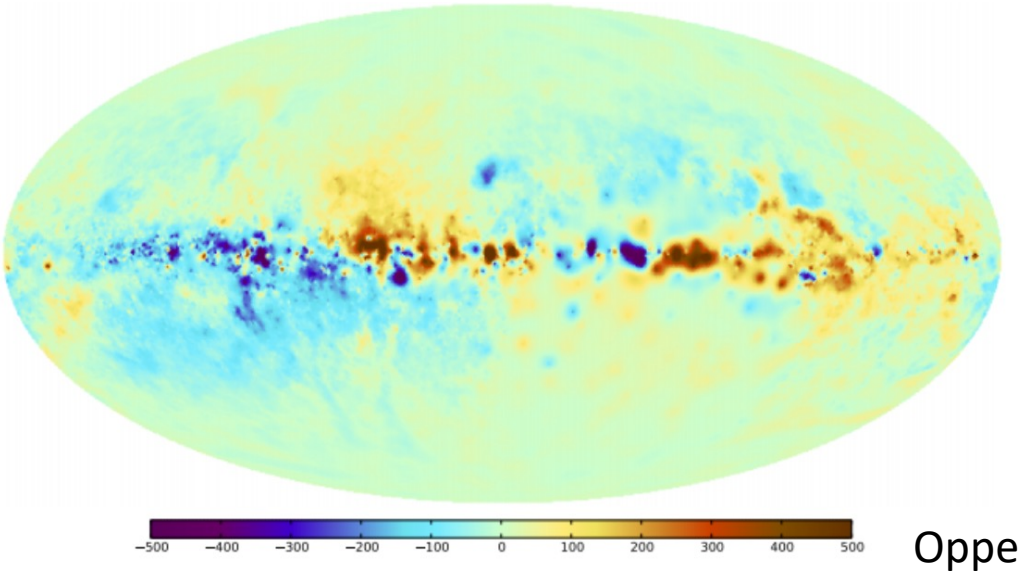
Faraday Rotation (HIM + WIM)



Taylor, Stil, & Sunstrum 2009

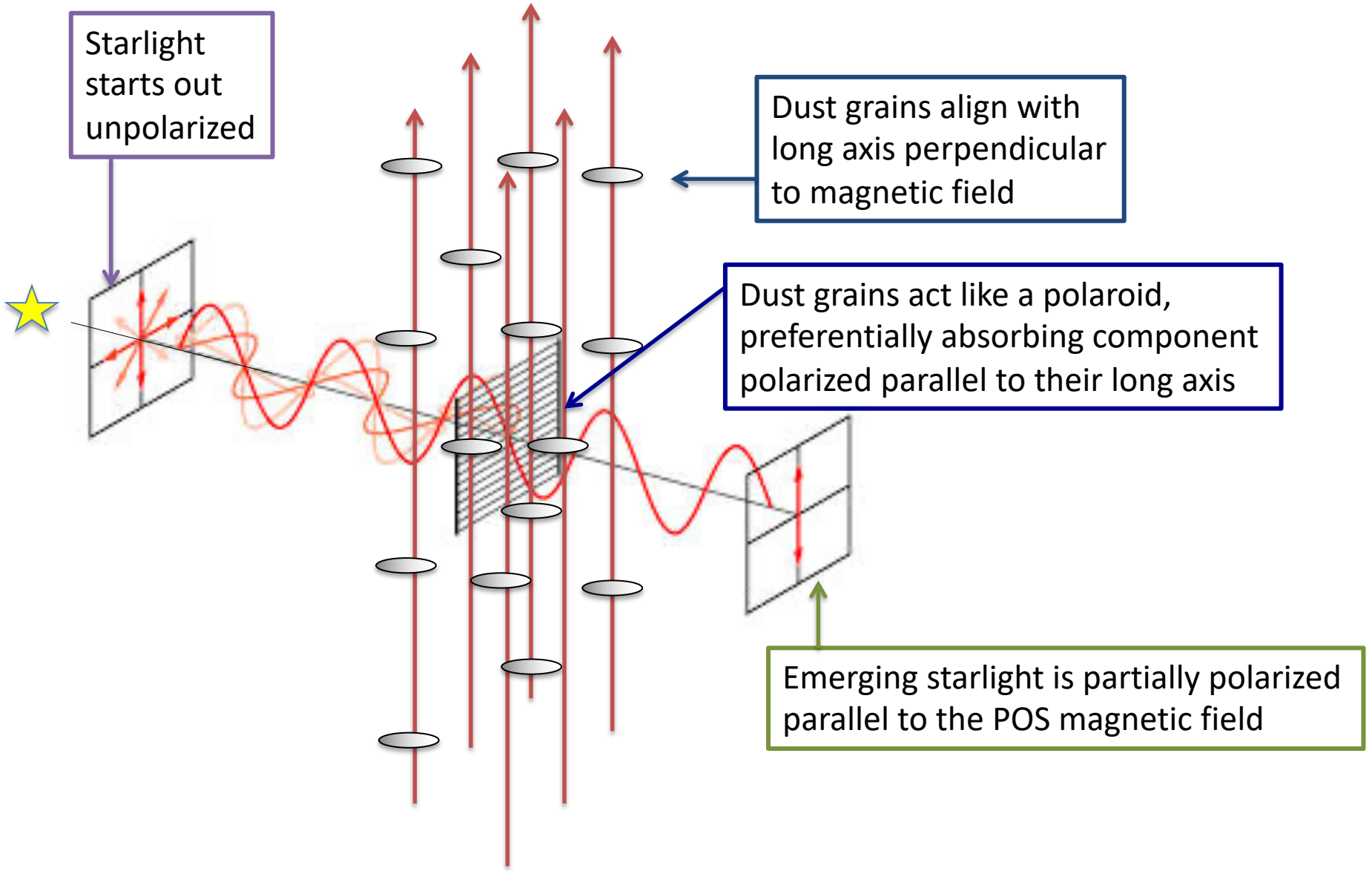


Credit: Beck

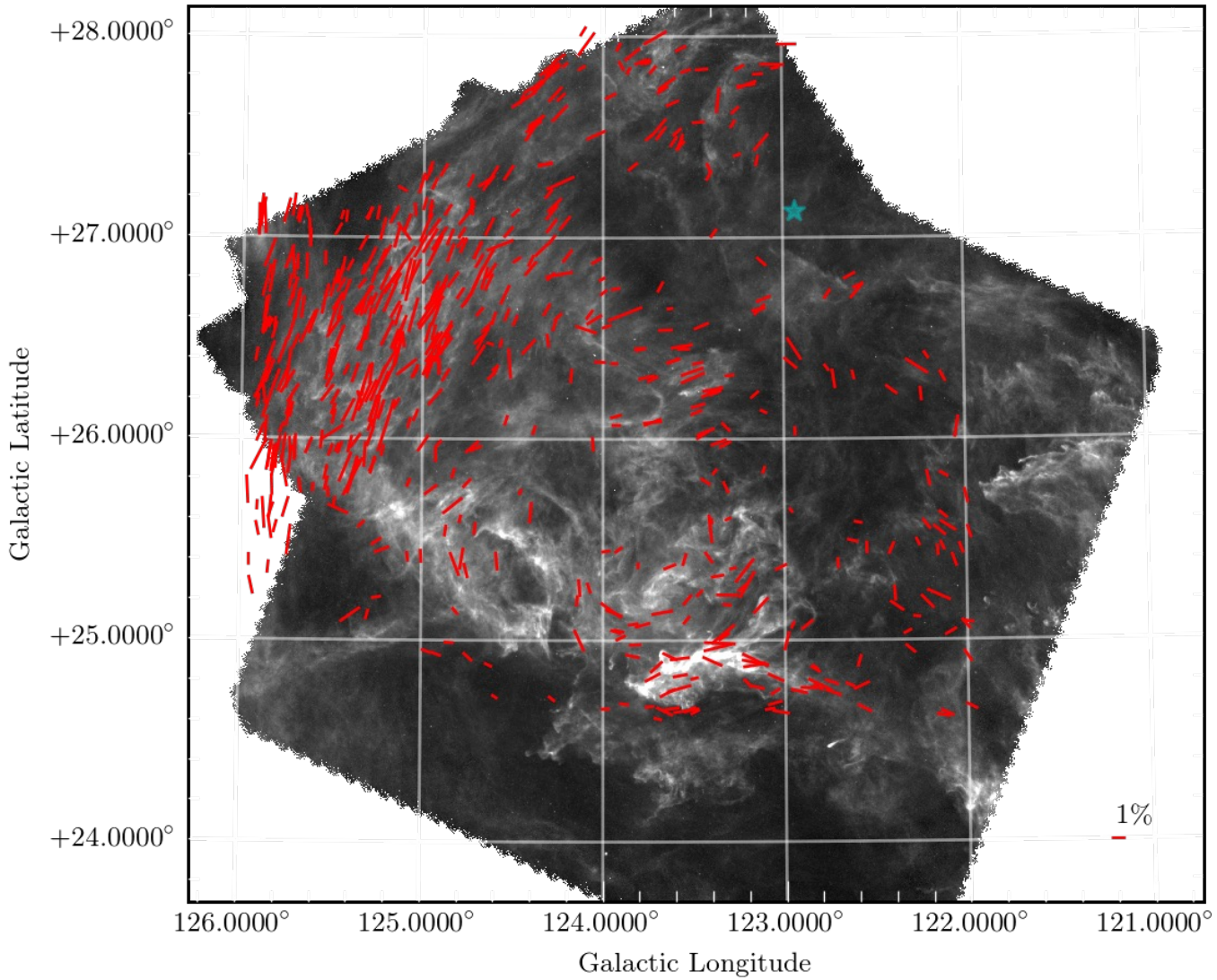


Oppermann et al. 2012

Dichroic absorption of starlight from interstellar dust (CNM)



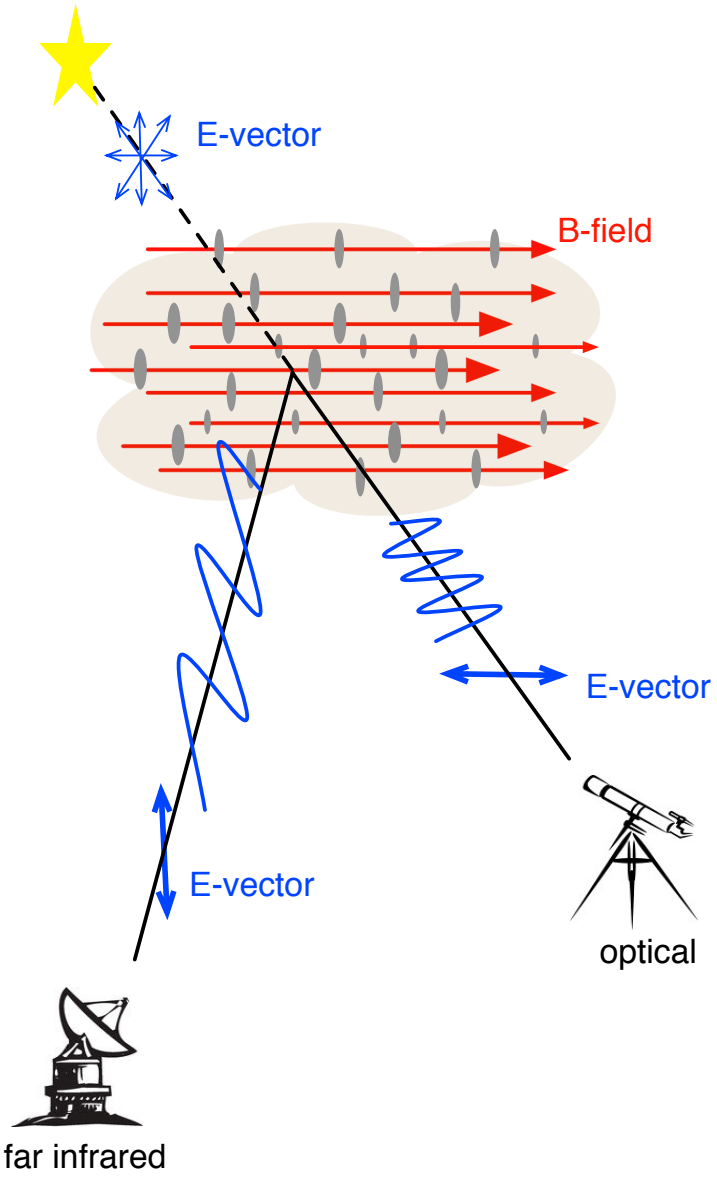
Starlight polarization map of Polaris



robopol

Pqanopoulou et al. 2015

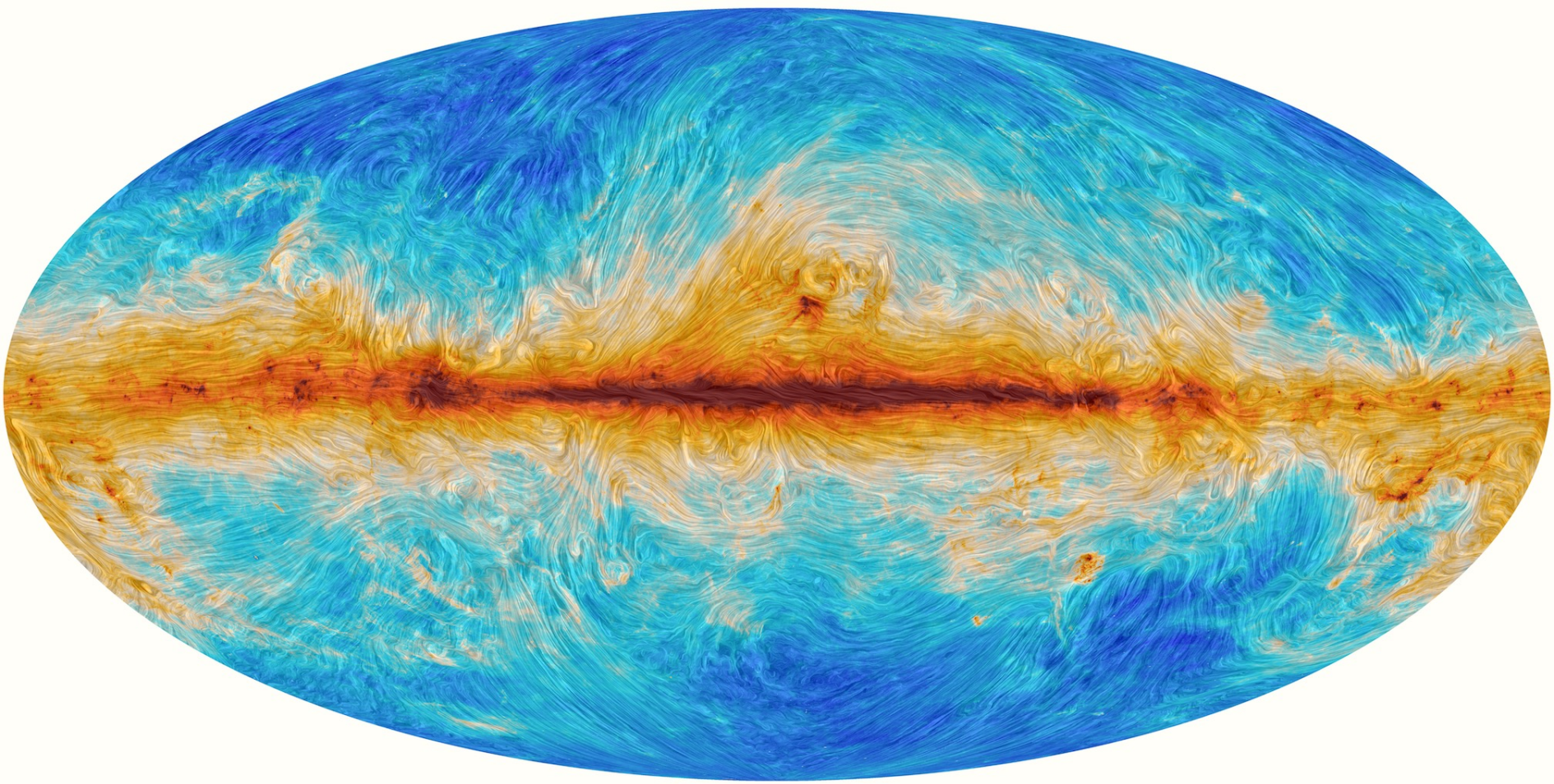
Thermal dust emission also polarized



Absorption Polarization parallel to Bpos

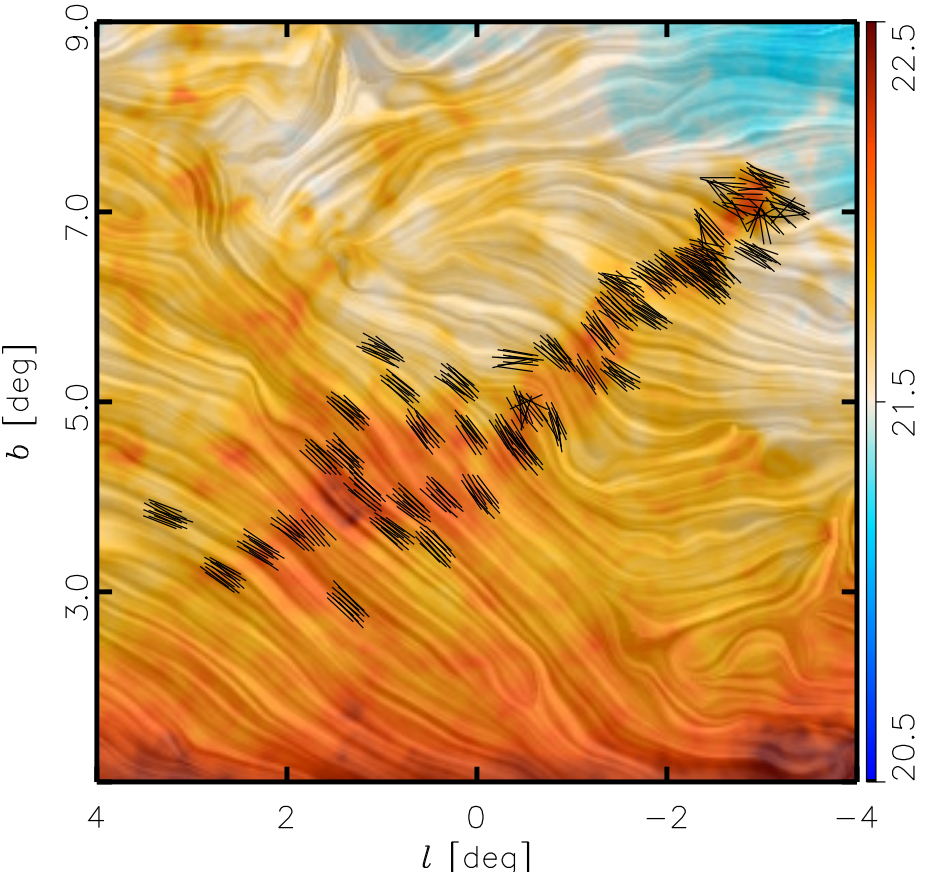
Emission polarization perp to Bpos

Dust Thermal Emission

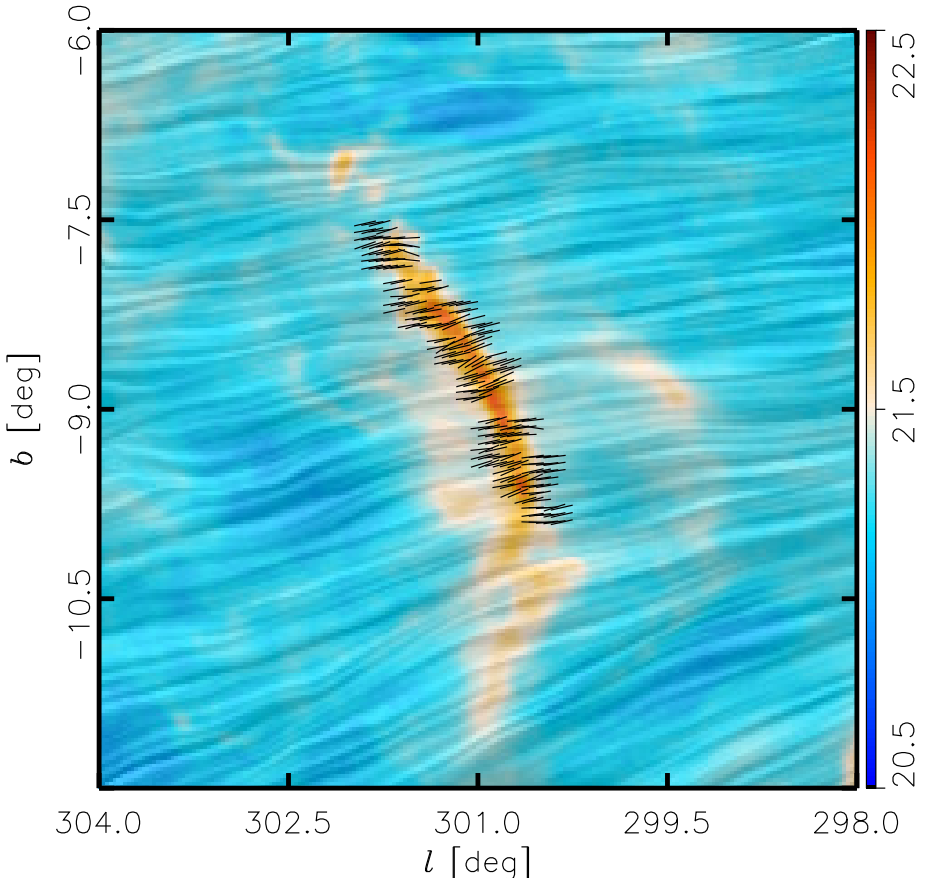


Polarization in Absorption and Emission match

Pipe

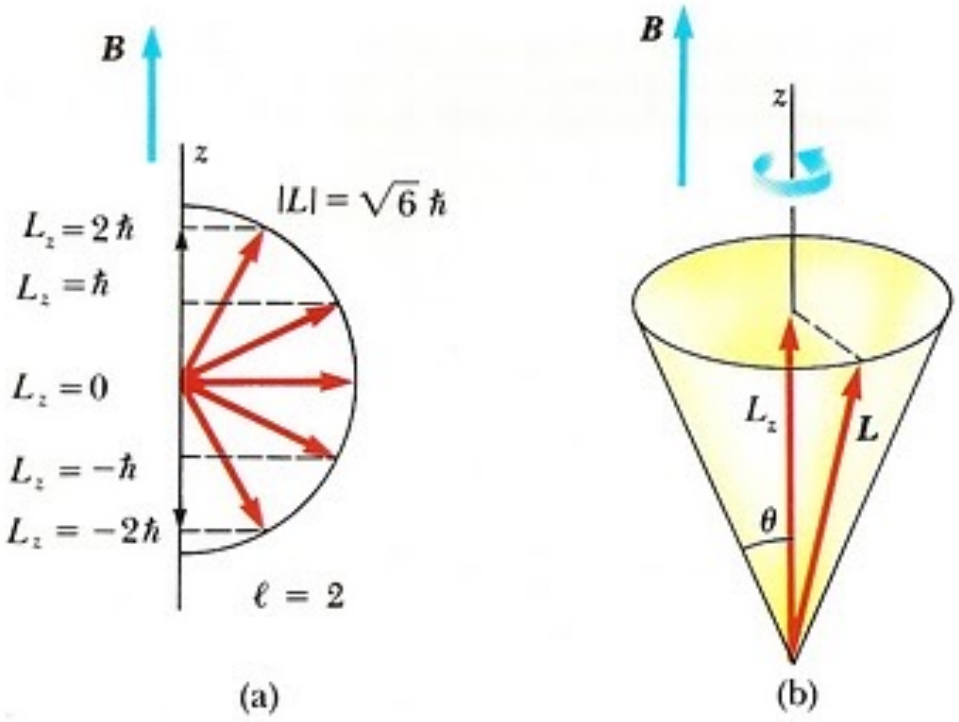


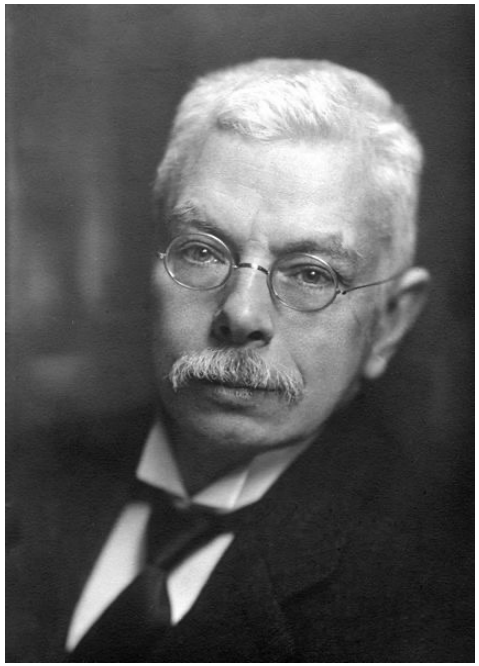
Musca



Soler et sl. 2016

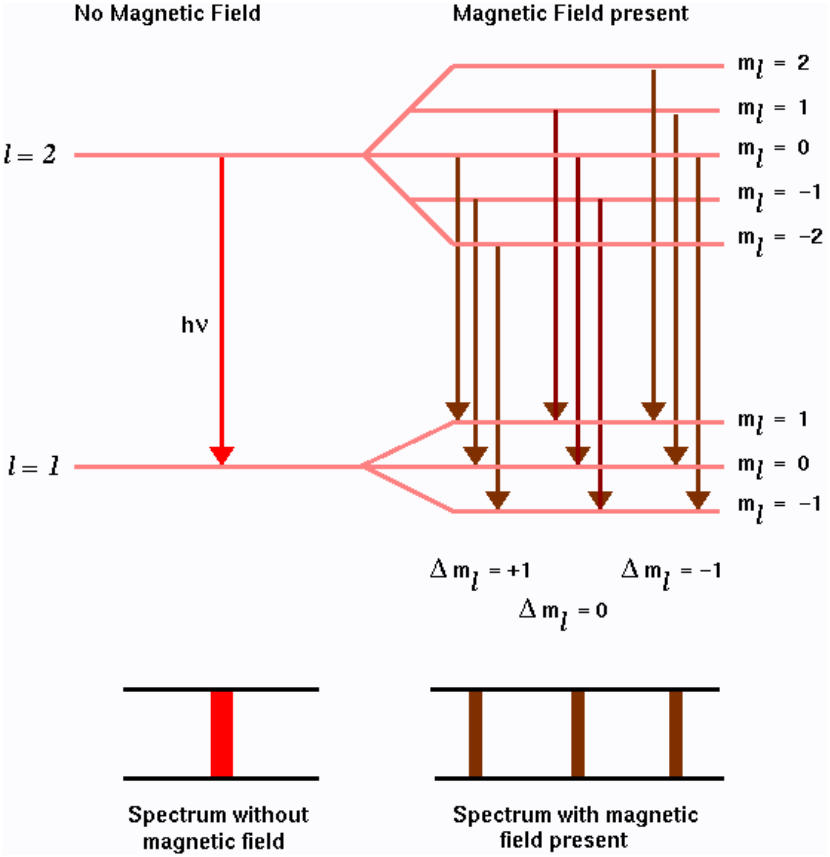
Zeeman Effect

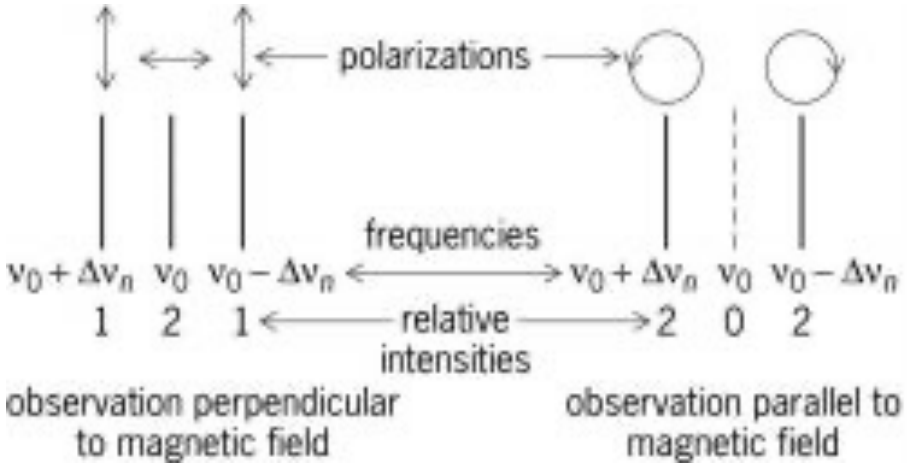




Pieter Zeeman

Zeeman Effect

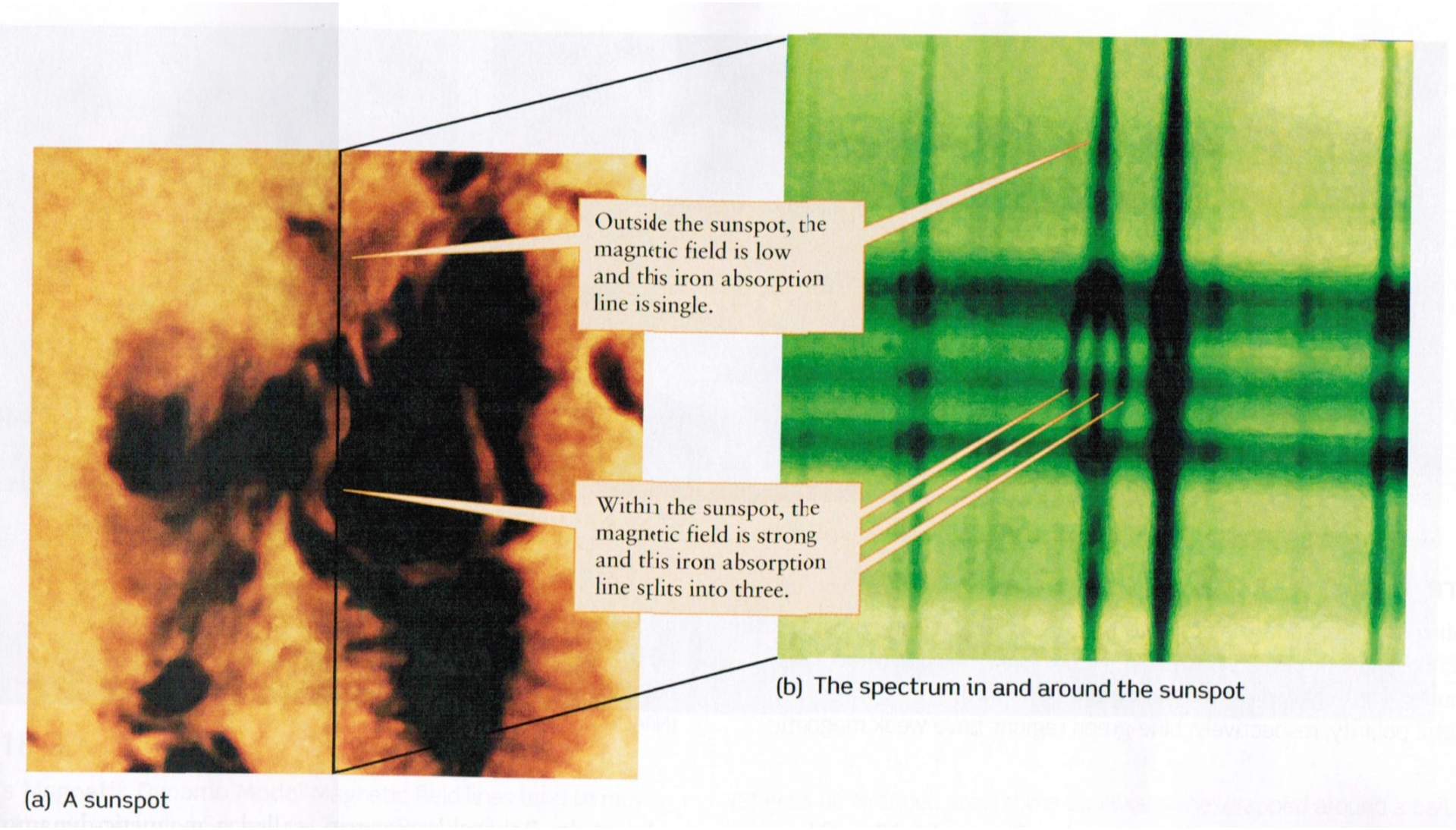




$$\Delta E \propto \Delta\nu \propto B$$

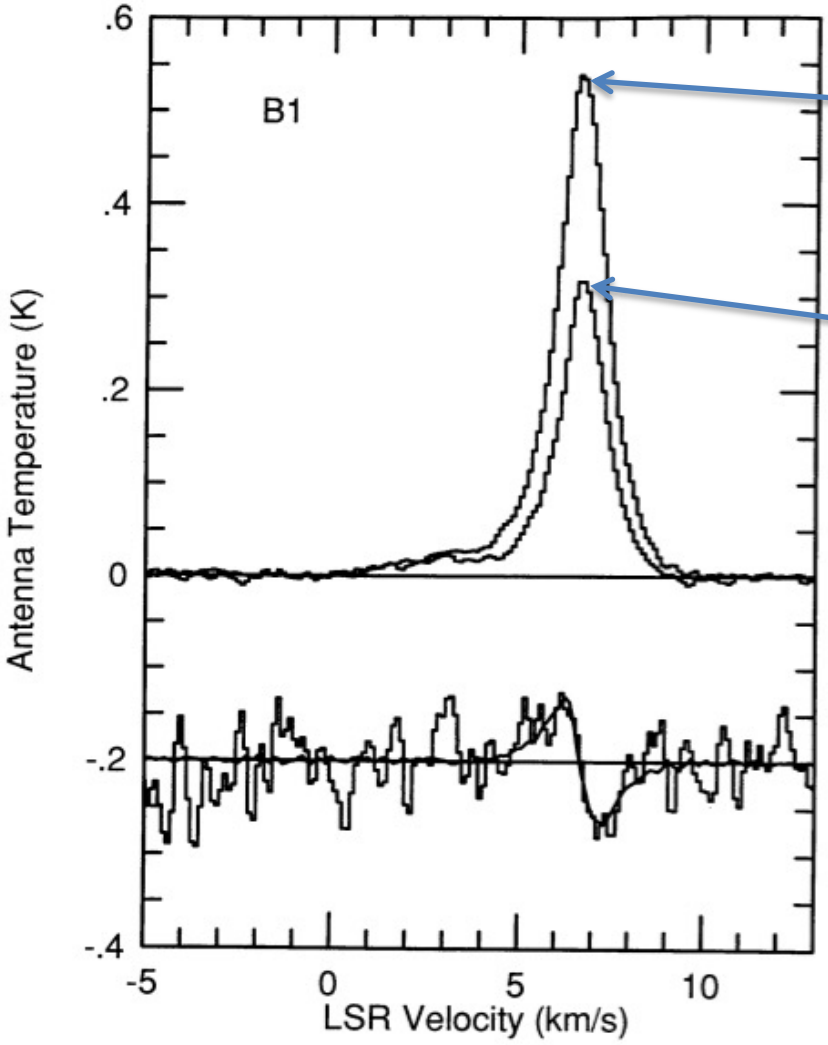
Credit: http://encyclopedia2.thefreedictionary.com/Zeeman+Effect

In the Sun



http://crab0.astr.nthu.edu.tw/~hchang/ga1/f1802-SunspotZeeman.JPG

In the ISM

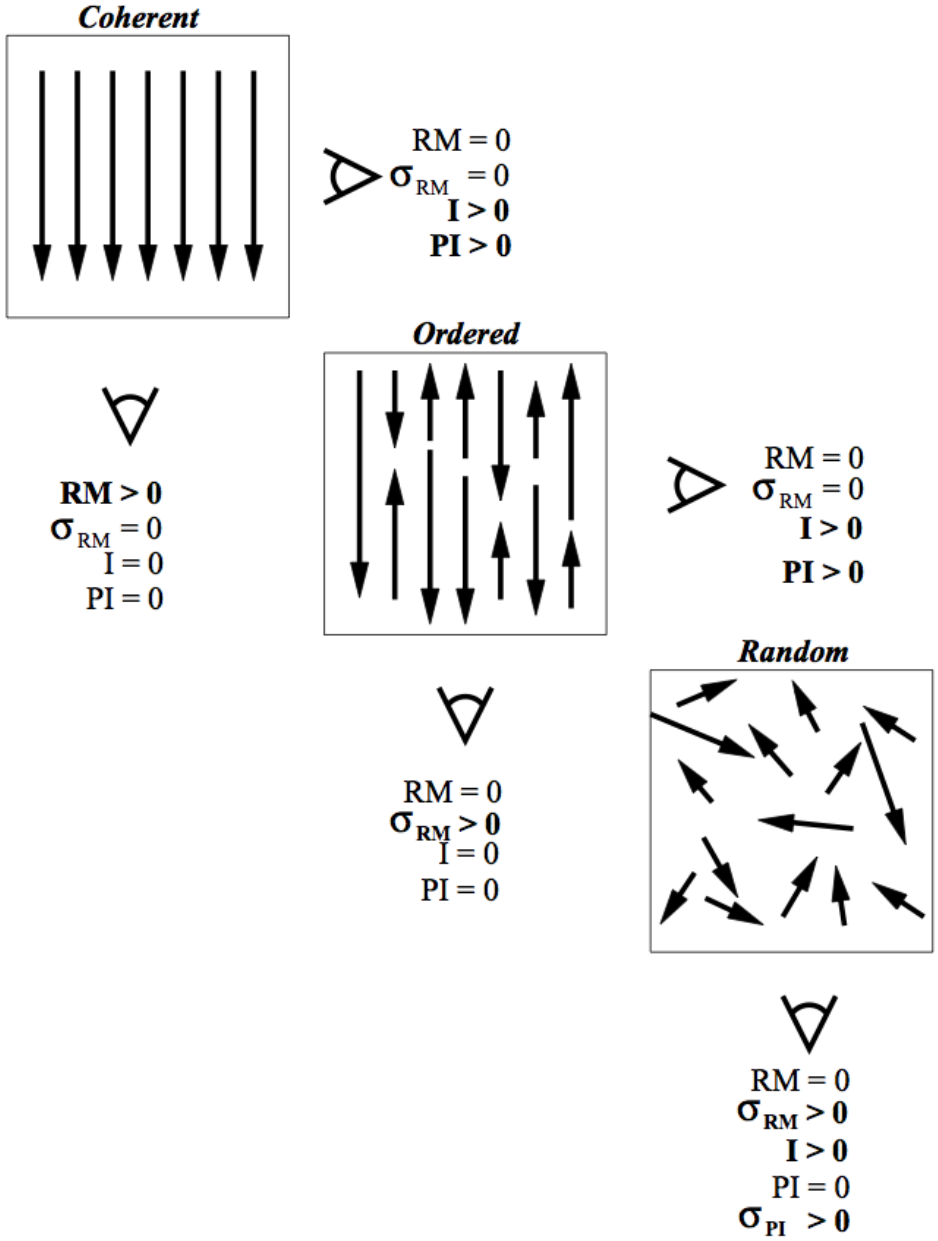


1667 MHz

1665 MHz

Crutcher et al. 1993

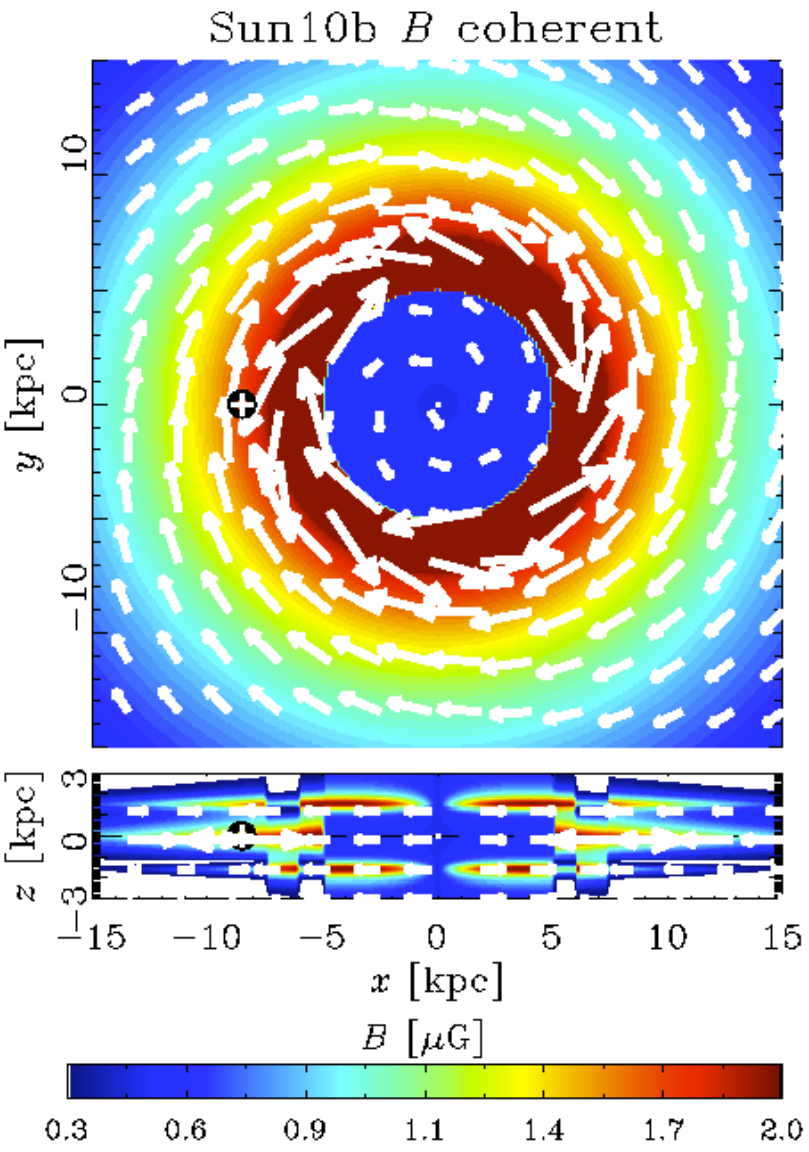
Putting the Diffuse Probes Together

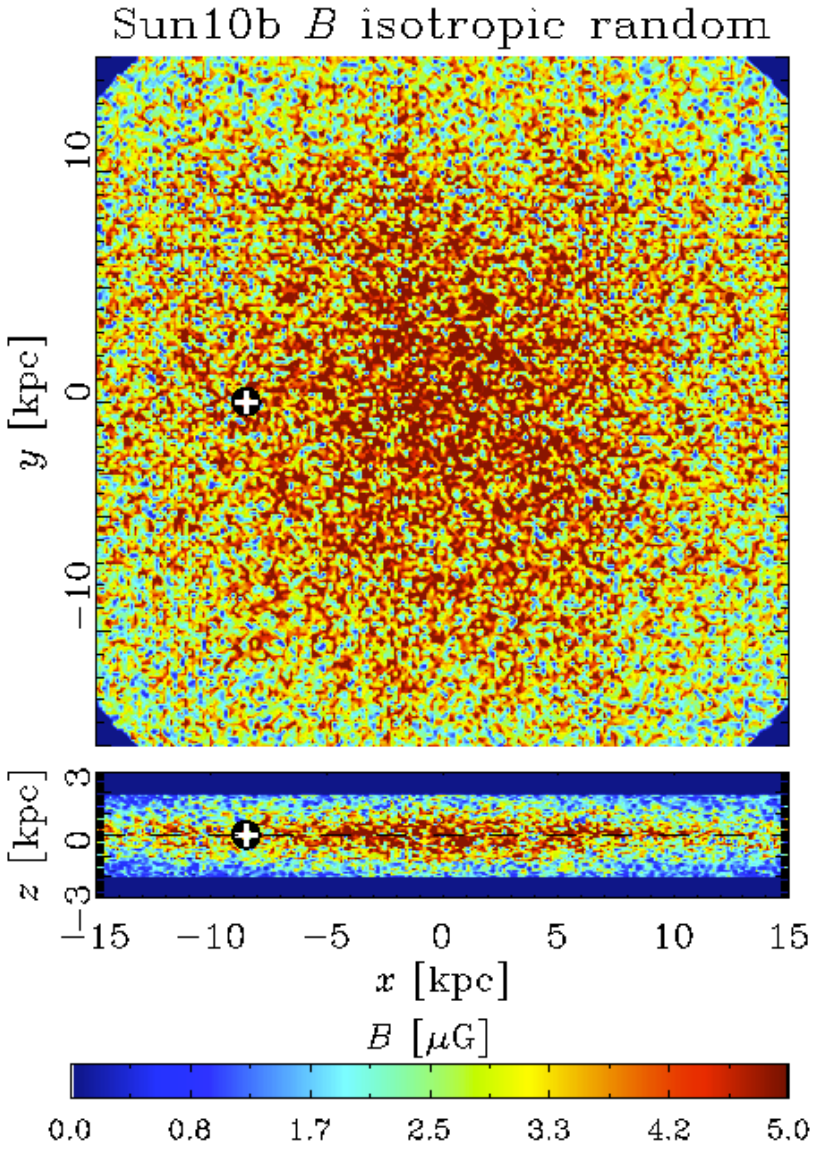


Jaffe 2010

Current Large Scale Models

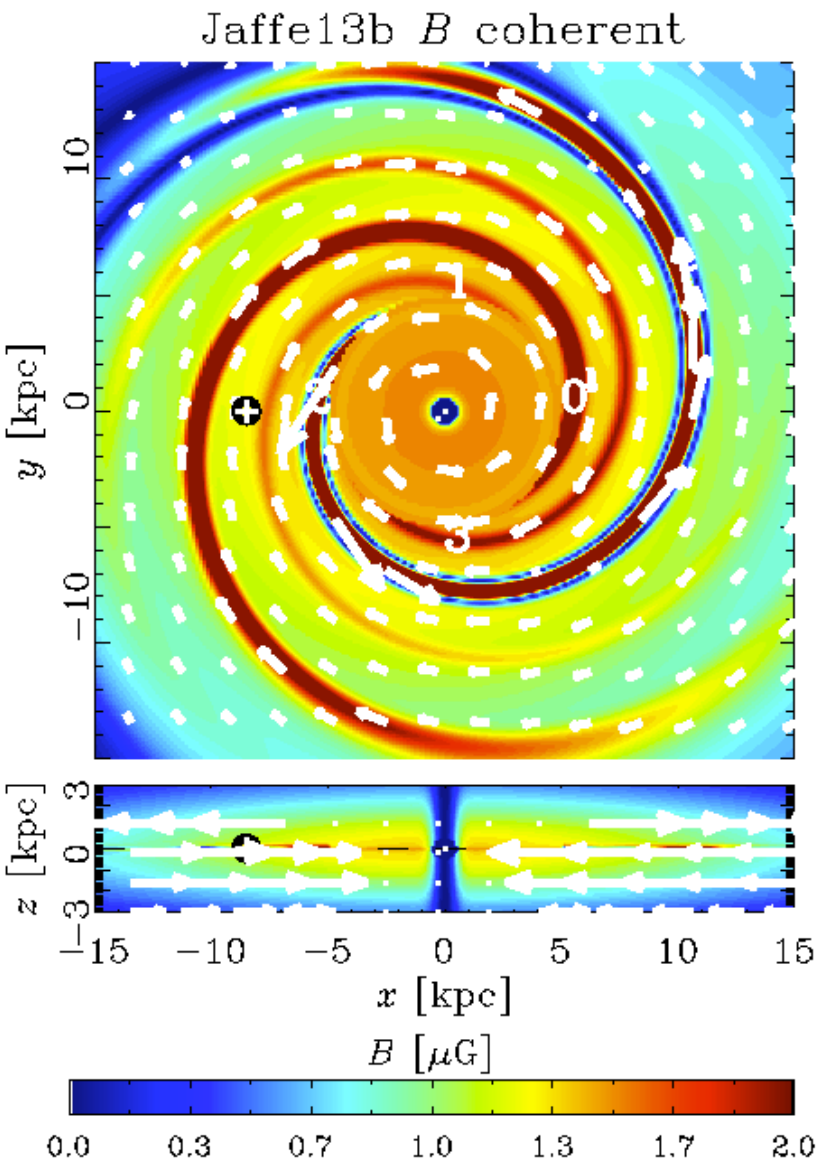
Planck XLII 2016

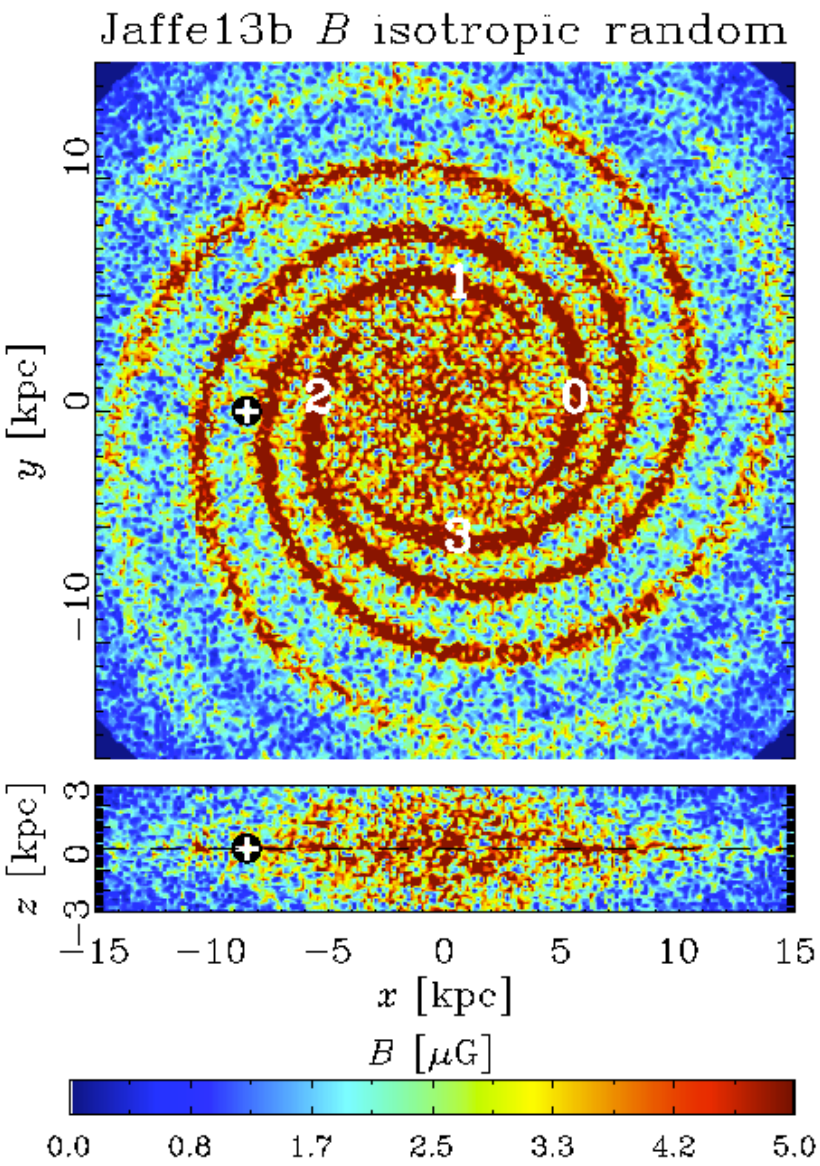




Current Large Scale Models

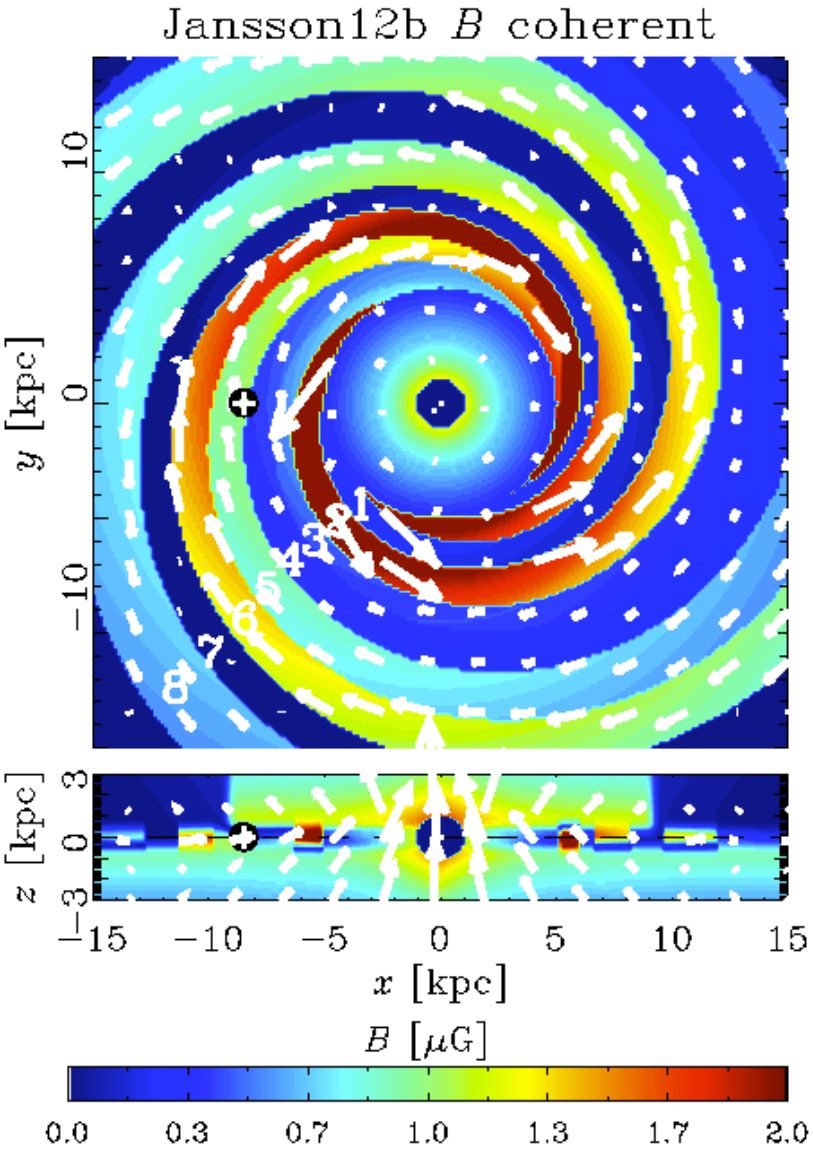
Planck XLII 2016

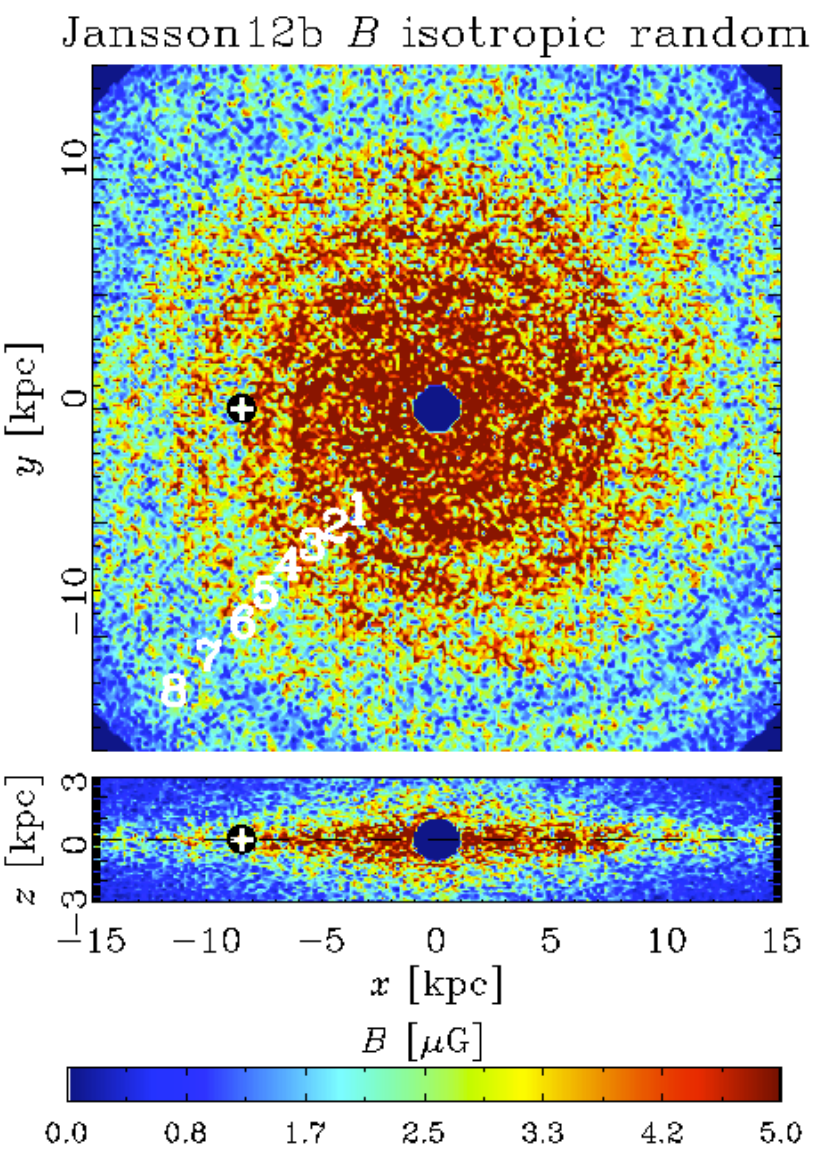




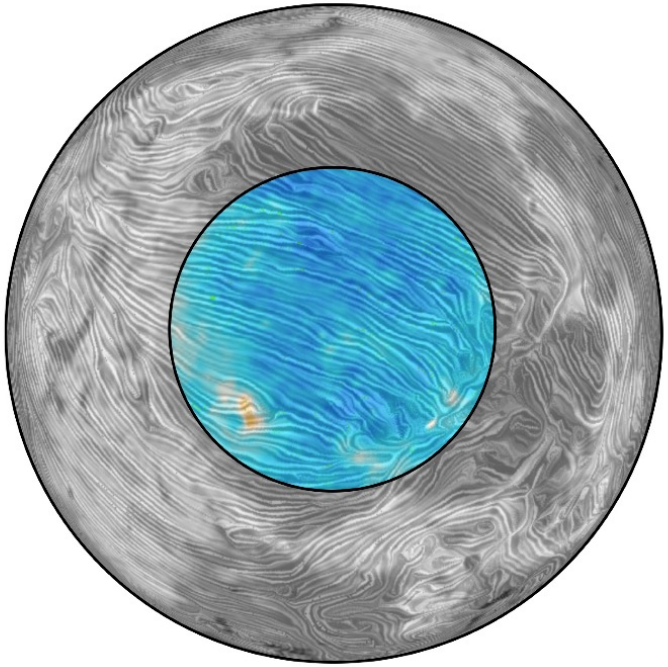
Current Large Scale Models

Planck XLII 2016

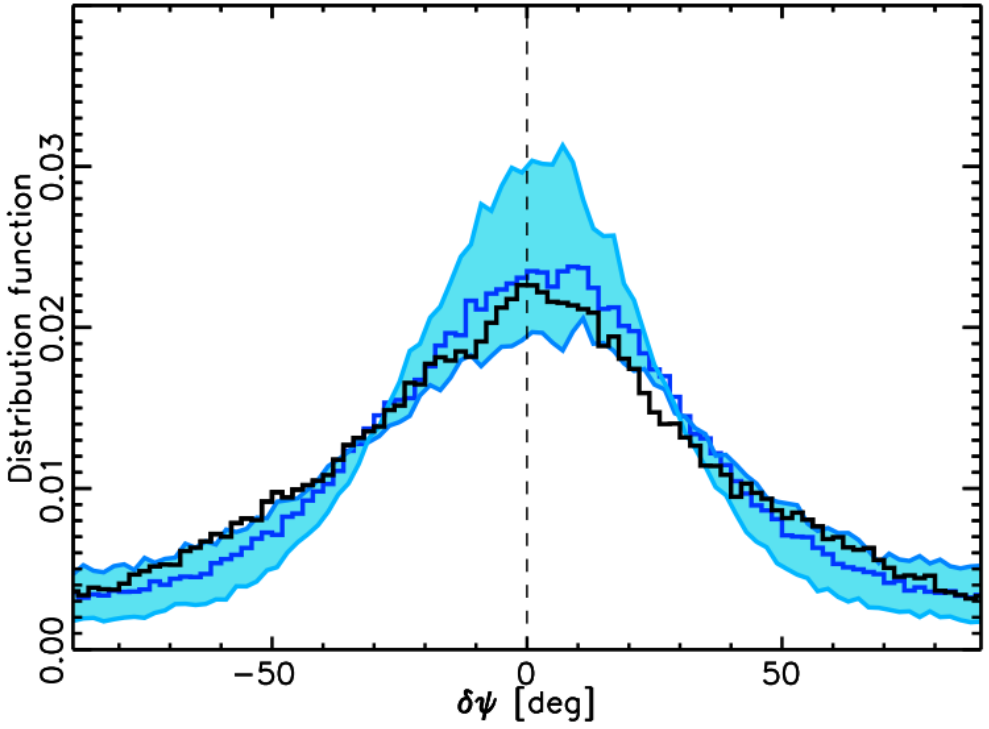




B_t/B_o estimates from Planck



Planck XLIV 2016

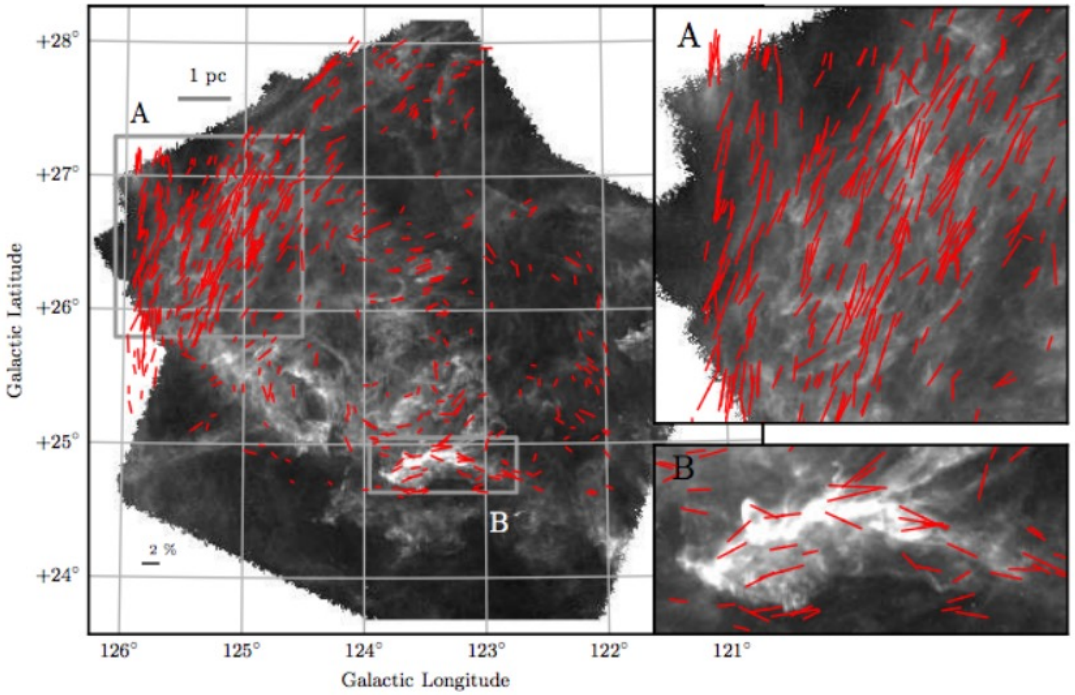


Planck XXXII 2016

$$\frac{B_t}{B_o} = 0.9$$

$$\frac{B_t}{B_o} = \{0.6 - (0.8) - 1\}$$

B_t/B_o estimates in MC



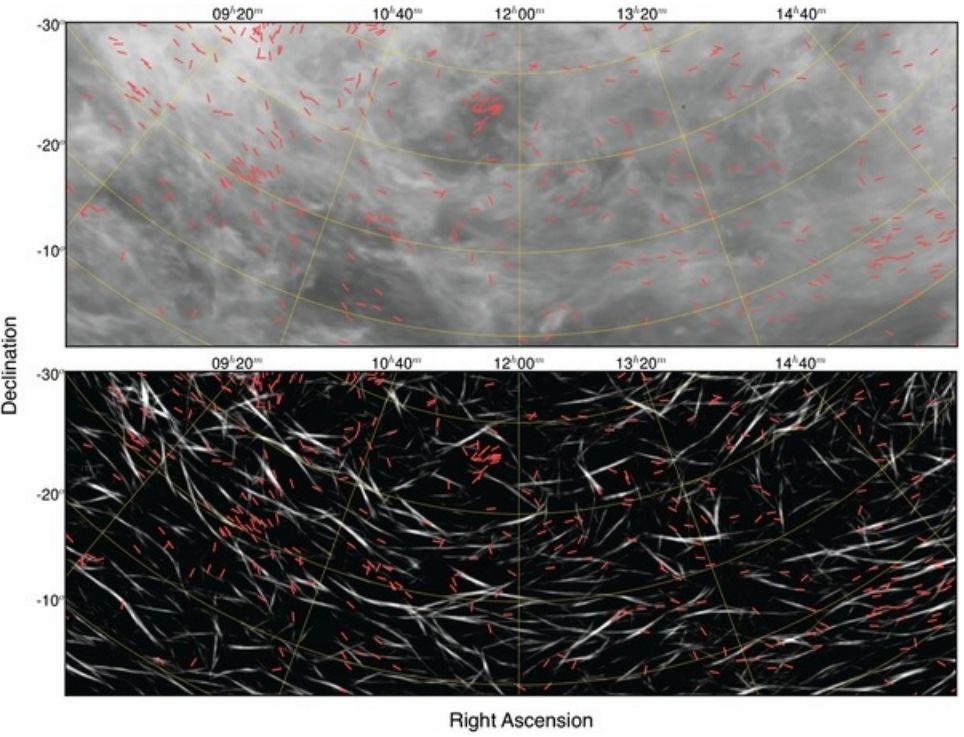
Panopoulou, Psaradaki, KT 2016 analyzed RoboPol data in Polaris Flare and found:

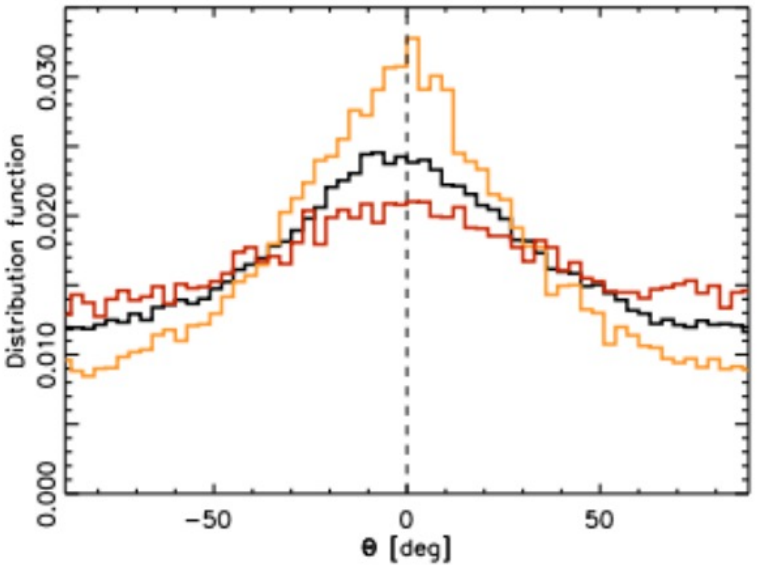
$$\frac{B_t}{B_o} = \{0.2 - 0.8\}$$

Houde et al. 2016 analyzed interferometric data (CARMA) and found:

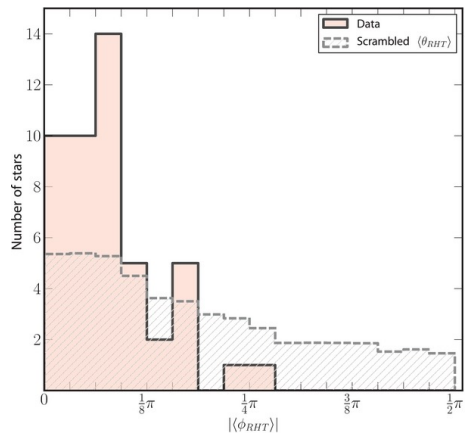
W3(OH)	$\frac{B_t}{B_o} = 0.58$
W3 Main	$\frac{B_t}{B_o} = 0.74$
DR21(OH)	$\frac{B_t}{B_o} = 0.70$

B-Field Correlates with Diffuse ISM Structure



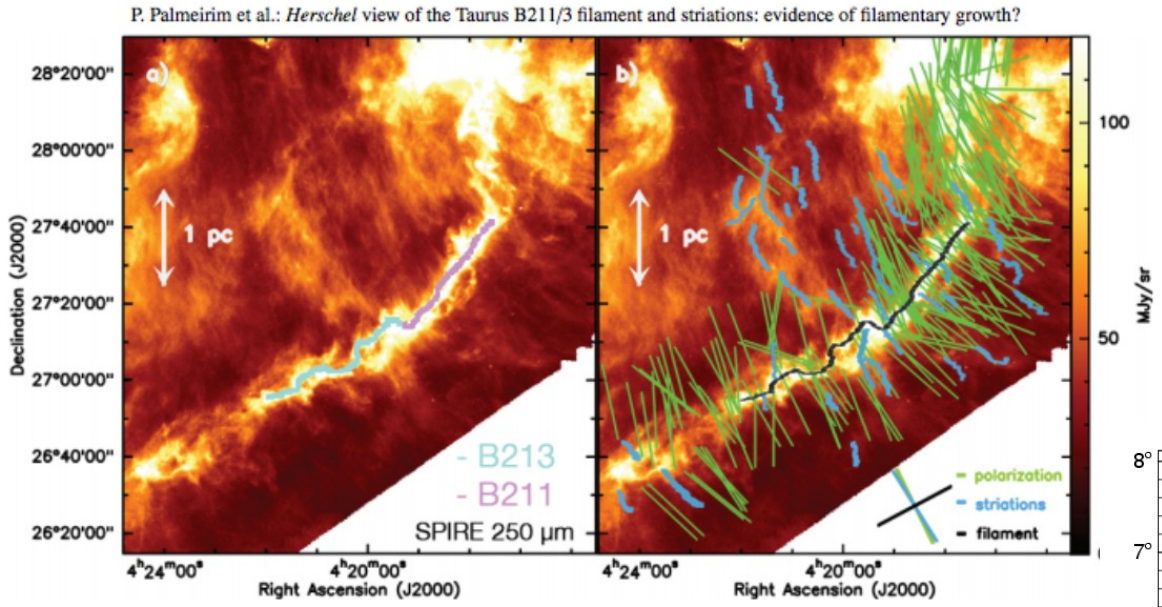


Planck XXXII 2016

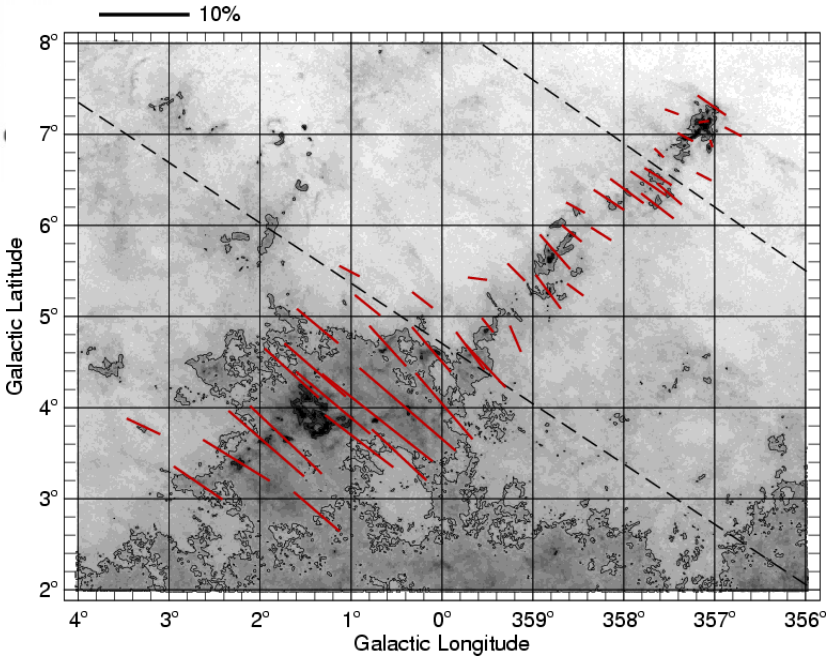


Clark et al. 2014

B-Field Correlates with Molecular Cloud Structure

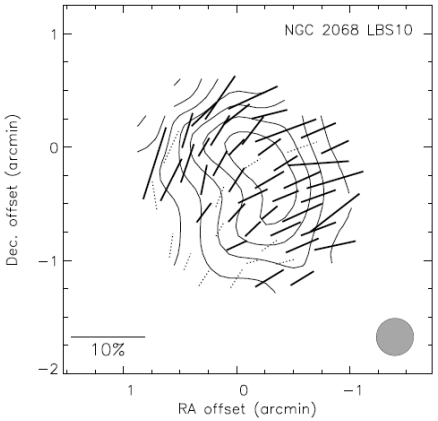


Palmeirim et al. 2013



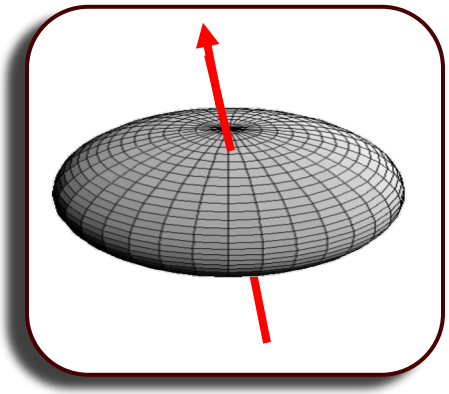
Alves et al. 2008

B-Field Correlates with Molecular Cloud Structure + projection effects

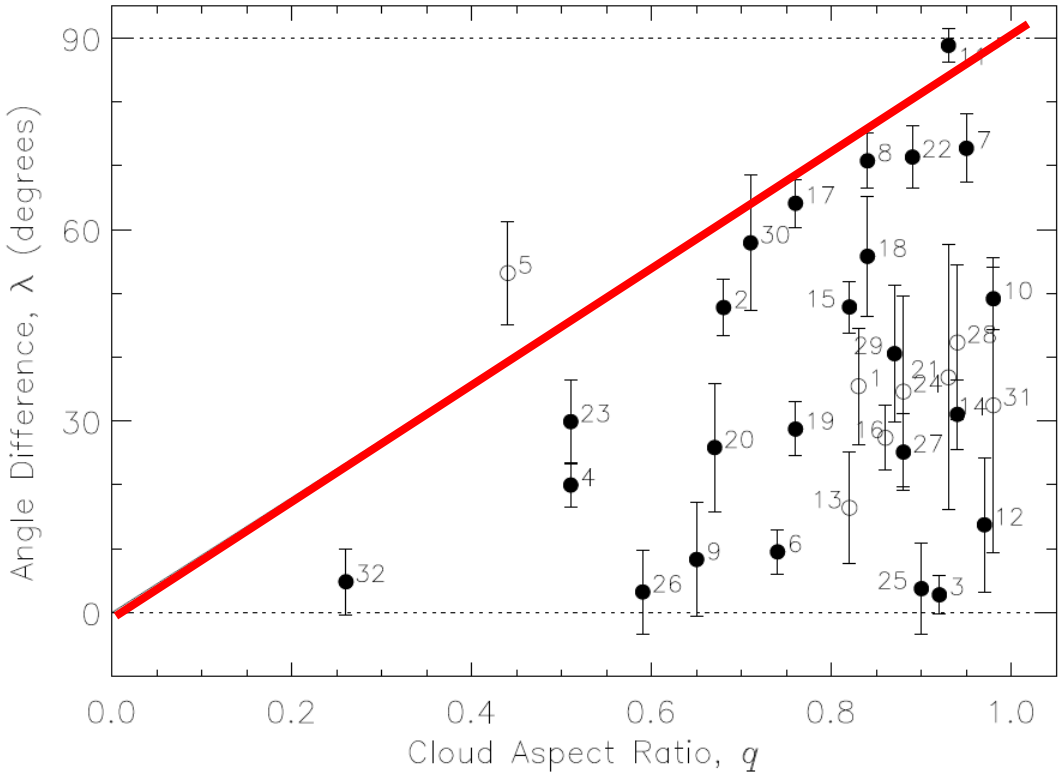


Data from Hertz polarimeter on CSO @ 350 μm

***Random* shapes / B-field orientations hypothesis rejected at the 10^{-7} level**

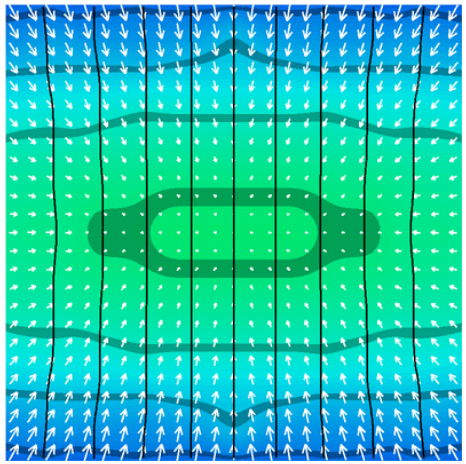


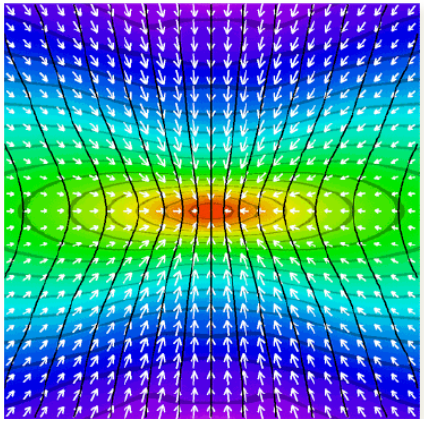
NOT uniformly distributed!



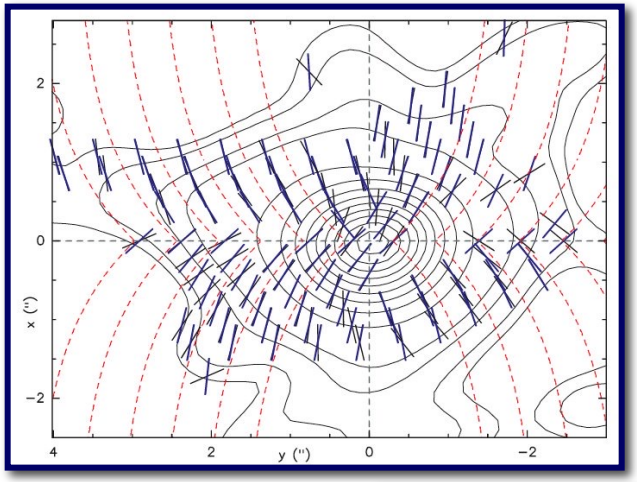
Tassis et al. 2009

B-Field in Molecular Cloud Cores

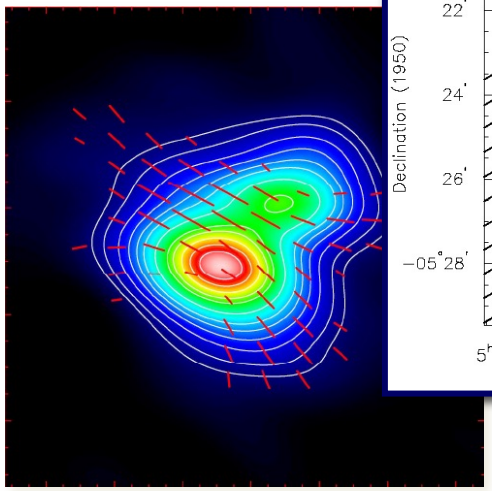


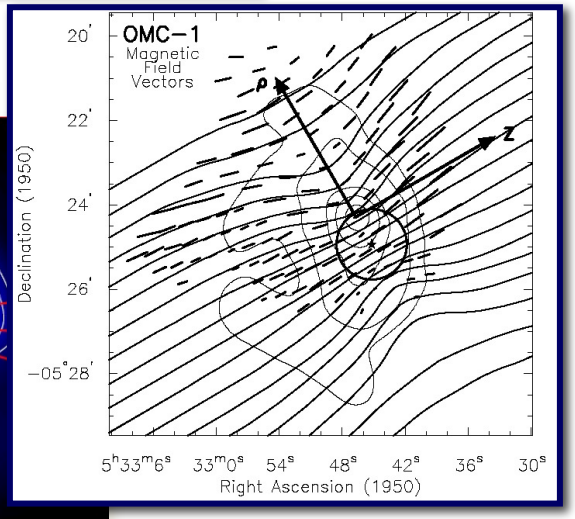


Kunz & Mouschovias 2009



Girart et al. 2009

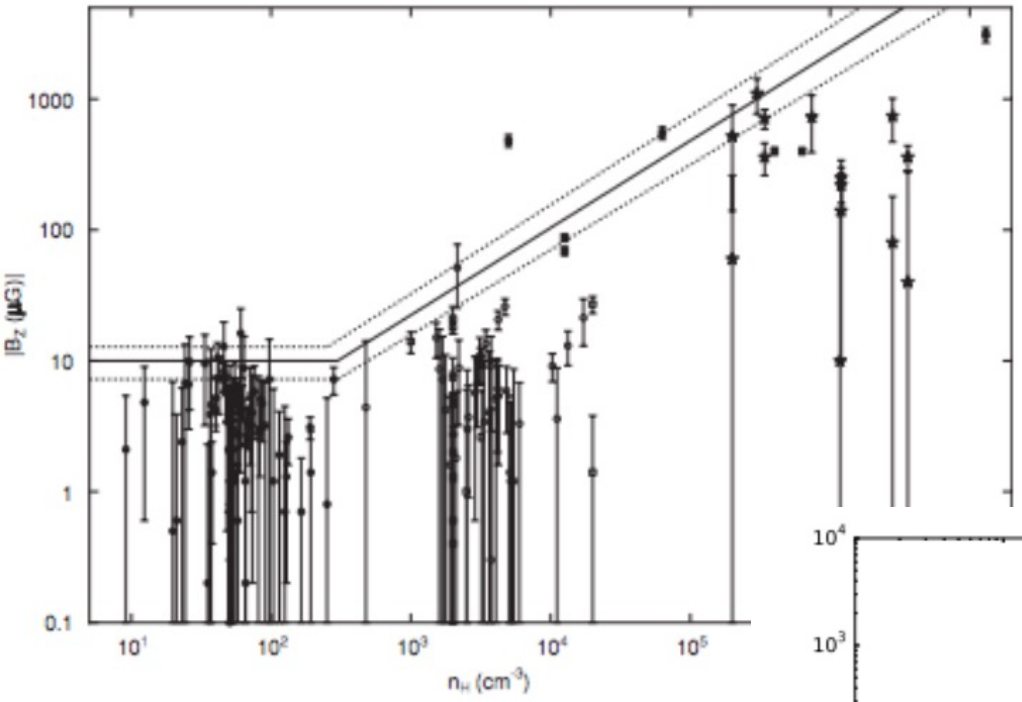




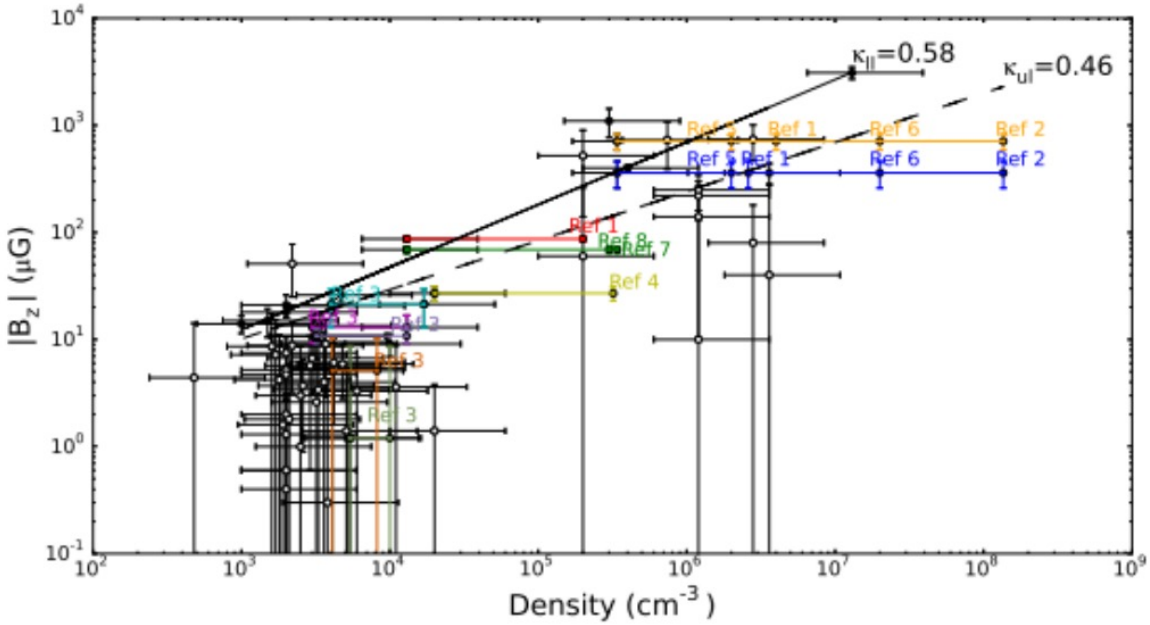
Girart, Rao, & Marrone 2006

Schleuning 1998

B-Field in Molecular Cloud Cores

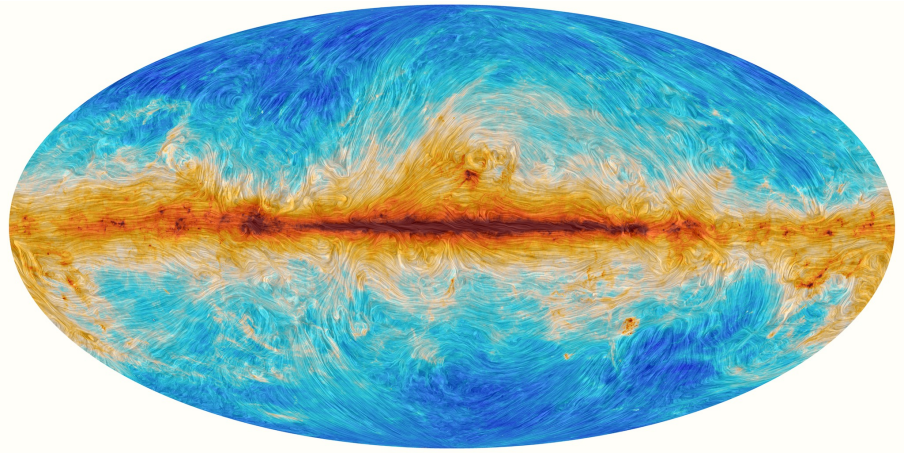


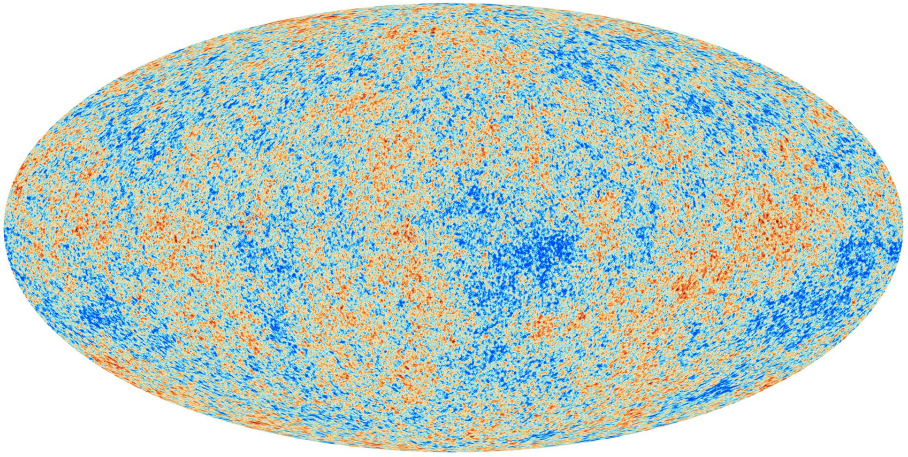
Crutcher et al. 2010



Tritsis et al. 2016

Galactic B-Field and Polarized emission





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Space

Gravitational waves: have US scientists heard echoes of the big bang?

Discovery of gravitational waves by Bicep telescope at south pole could give scientists insights into how universe was born

Stuart Clark

@OrStuClark

Friday 14 March 2014 15.33 GMT

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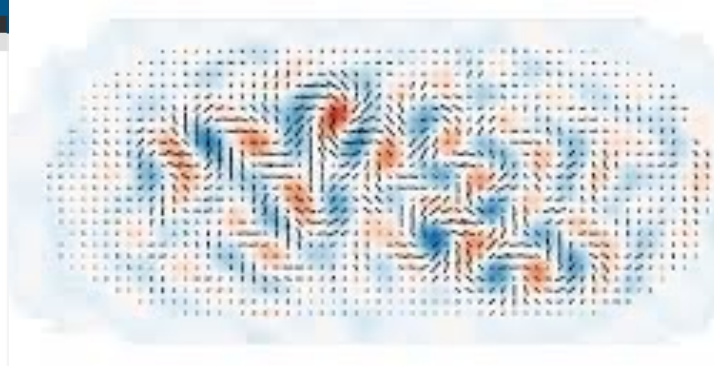
Save for later

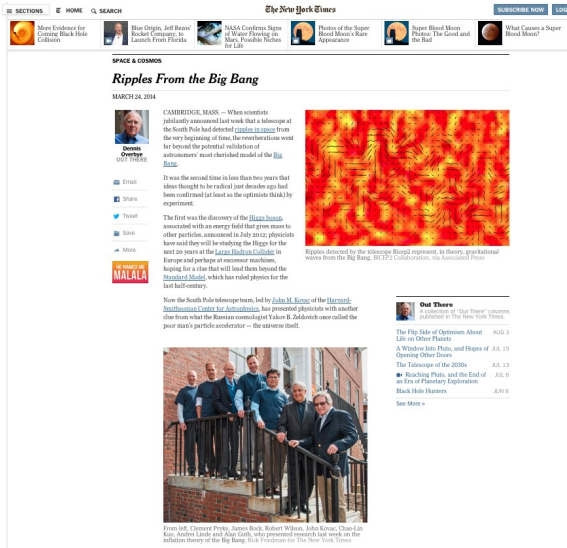
Primordial gravitational waves would provide evidence of inflation in the moments after the big bang. Photograph: Alamy

There is intense speculation among cosmologists that a US team is on the verge of confirming they have detected "primordial gravitational waves" – an echo of the big bang in which the universe came into existence 14bn years ago.

Rumours have been rife in the physics community about an announcement due on Monday from the Harvard-Smithsonian Center for Astrophysics. If there is evidence for gravitational waves, it would be a landmark discovery that would change the face of cosmology and particle physics.

Gravitational waves are the last untested prediction of Albert Einstein's General Theory of Relativity. They are minuscule ripples in the fabric of the universe that carry energy across space, somewhat similar to waves crossing an ocean. Convincing evidence of their discovery would almost certainly lead to a Nobel prize.





The New York Times

SPACE & COSMOS

Ripples From the Big Bang

MARCH 24, 2014

CAMBRIDGE, MASS. — When scientists jubilantly announced last week that a telescope at the South Pole had detected ripples in space from the very beginning of time, the reverberations went far beyond the potential validation of astronomers' most cherished model of the Big Bang.

It was the second time in less than two years that ideas thought to be radical just decades ago had been confirmed (at least so the optimists think) by experiment.

The first was the discovery of the Higgs boson, associated with an energy field that gives mass to other particles, announced in July 2012; physicists have said they will be studying the Higgs for the next 20 years at the Large Hadron Collider in Europe and perhaps at successor machines, hoping for a clue that will lead them beyond the Standard Model, which has ruled physics for the last half-century.

Now the South Pole telescope team, led by John M. Kovac of the Harvard-Smithsonian Center for Astrophysics, has presented physicists with another clue from what the Russian cosmologist Yakov B. Zeldovich once called the poor man's particle accelerator — the universe itself.

Ripples detected by the telescope Bicep2 represent, in theory, gravitational waves from the Big Bang. BICEP2 Collaboration, via Associated Press

From left, Clement Pryke, James Bock, Robert Wilson, John Kovac, Chao-Lin Kuo, Andrei Linde and Alan Guth, who presented research last week on the inflation theory of the Big Bang. Rick Friedman for The New York Times

Out There

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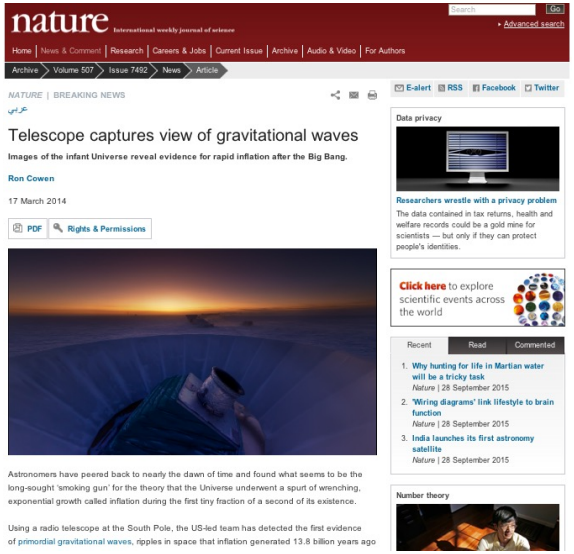

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NATURE | BREAKING NEWS

عربي

Telescope captures view of gravitational waves

Images of the infant Universe reveal evidence for rapid inflation after the Big Bang.

Ron Cowen

17 March 2014

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Astronomers have peered back to nearly the dawn of time and found what seems to be the long-sought 'smoking gun' for the theory that the Universe underwent a spurt of wrenching, exponential growth called inflation during the first tiny fraction of a second of its existence.

Using a radio telescope at the South Pole, the US-led team has detected the first evidence of primordial gravitational waves, ripples in space that inflation generated 13.8 billion years ago

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Researchers wrestle with a privacy problem

The data contained in tax returns, health and welfare records could be a gold mine for scientists — but only if they can protect people's identities.

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Number theory

The New York Times

SPACE & COSMOS

Space Ripples Reveal Big Bang's Smoking Gun

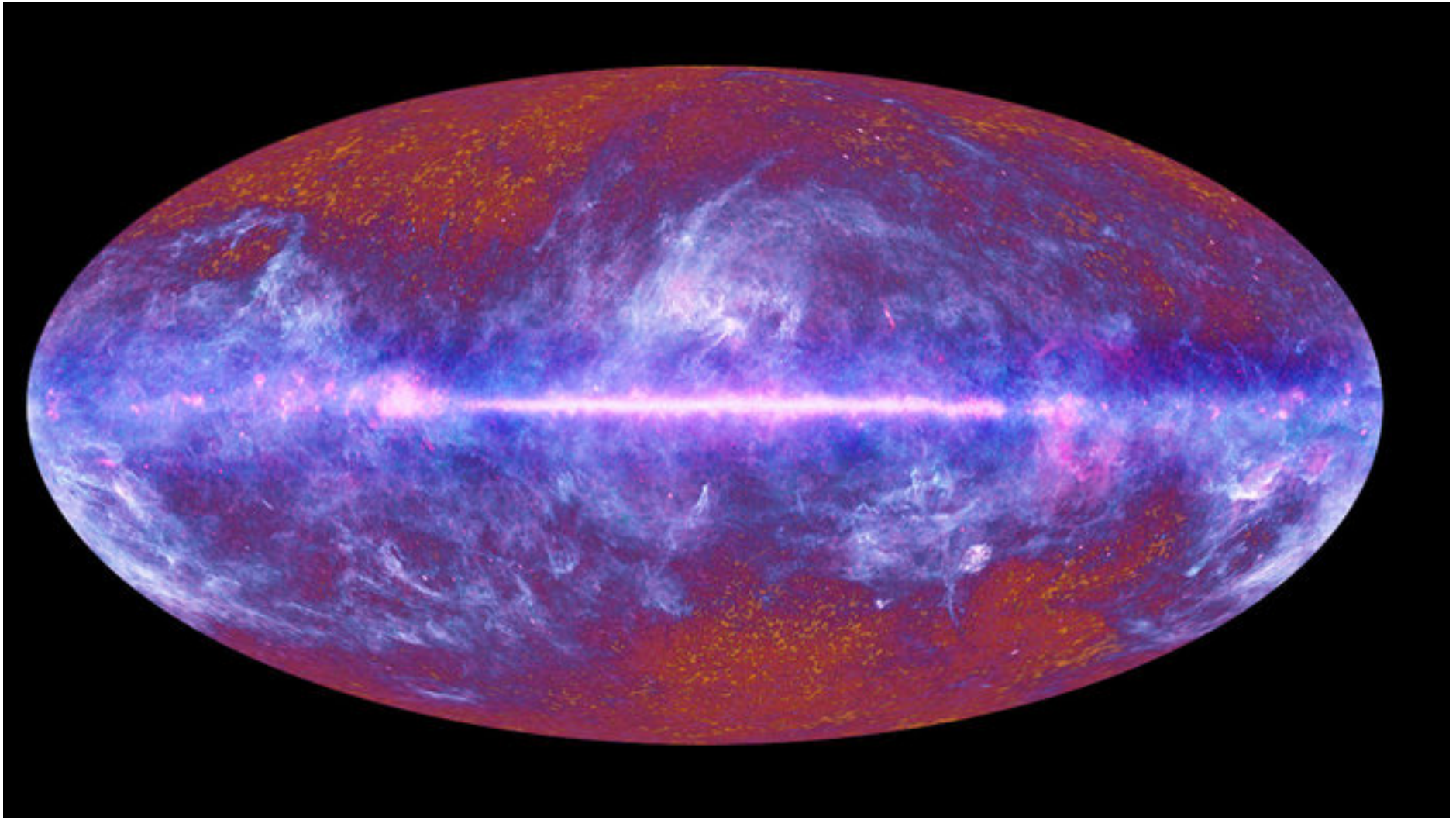
By DENNIS OVERBYE MARCH 17, 2014

Alan Guth was one of the first physicists to hypothesize the existence of inflation, which explains how the universe expanded so uniformly and so quickly in the instant after the Big Bang 13.8 billion years ago. Rick Friedman for The New York Times

CAMBRIDGE, Mass. — One night late in 1979, an itinerant young physicist named Alan Guth, with a new son and a year's appointment at Stanford, stayed up late with his notebook and equations, venturing far beyond the world of known physics.

He was trying to understand why there was no trace of some exotic particles that should have been created in the Big Bang. Instead he discovered what might have made the universe bang to begin with. A potential hitch in the presumed course of cosmic evolution could have infused space itself with a special energy that exerted a repulsive force

Interstellar Dust in the Galaxy



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BICEP2.... Disappointment

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Archive > Volume 510 > Issue 7503 > Column: World View > Article

NATURE | COLUMN: WORLD VIEW

Big Bang blunder bursts the multiverse bubble

Premature hype over gravitational waves highlights gaping holes in models for the origins and evolution of the Universe, argues Paul Steinhardt.

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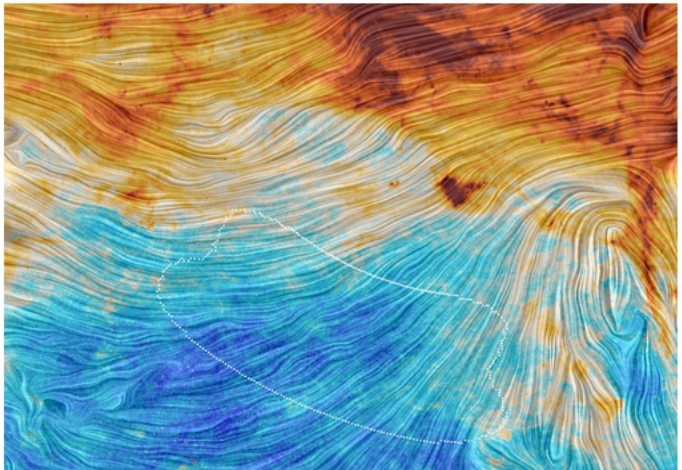
SCIENCE

Speck of Interstellar Dust Obscures Glimpse of Big Ba

By DENNIS OVERBYE JAN. 30, 2015



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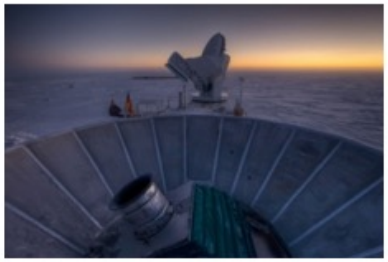
Backlash to Big Bang Discovery Gathers Steam

Physicists cast doubt on a landmark experiment's claim to have observed gravitational waves from the big bang

By Michael D. Lemonick | May 21, 2014



On March 17 Paul Steinhardt, a physicist at Princeton University, abandoned a theory he'd been championing for more than a decade. Known as the "ekpyrotic universe" model, it was an alternative to the prevailing theory of inflation, which says the cosmos expanded faster than the speed of light in the first fraction of a fraction of a second of the

NEWS | *IN DEPTH*

COSMOLOGY

Blockbuster claim could collapse in a cloud of dust

Smoking-gun evidence for cosmic inflation may actually be radiation from within our galaxy

By **Adrian Cho**

Perhaps it was too good to be true. Two months ago, a team of cosmologists reported that it had spotted the first direct evidence that the new-

formed the new analysis. He presented it at Princeton University on 15 May.

BICEP researchers estimated that "galactic foreground" was negligible. They modeled it several ways, as they report in the paper announcing their claim, which has

from within the galax
than they are. So usin
led the researchers t
galactic foreground a
CMB signal.

To test that idea,
Planck data—also scr
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The foreground appe
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BICEP's Kovac say
made it clear that th
how much of their sig
the CMB. And he won
"The six models of po
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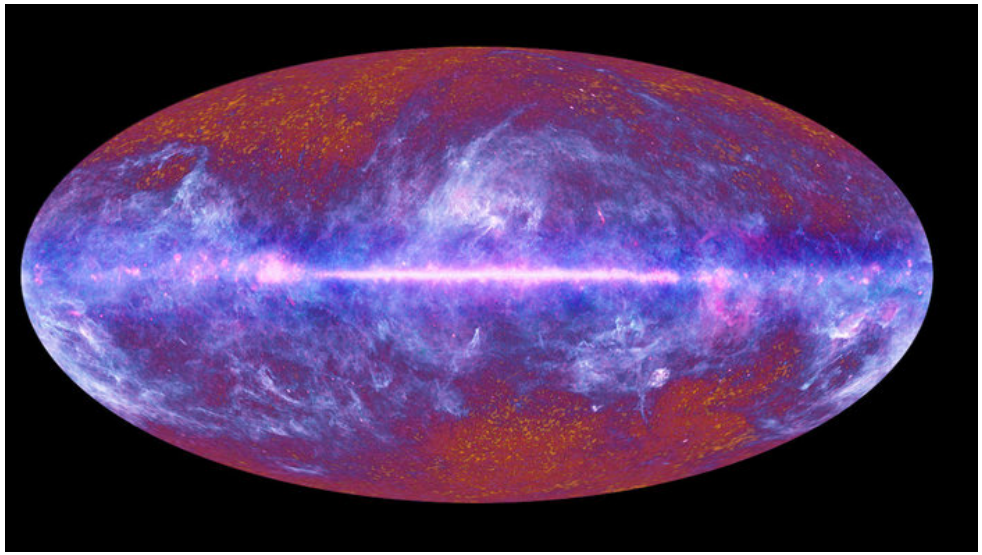
The Problem

Magnetized Galactic dust also emits polarized microwaves



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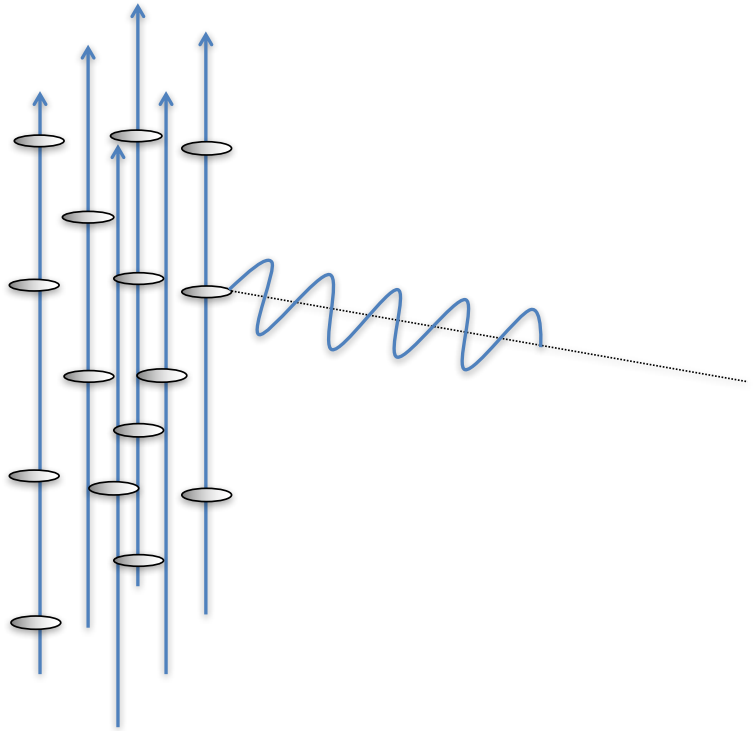

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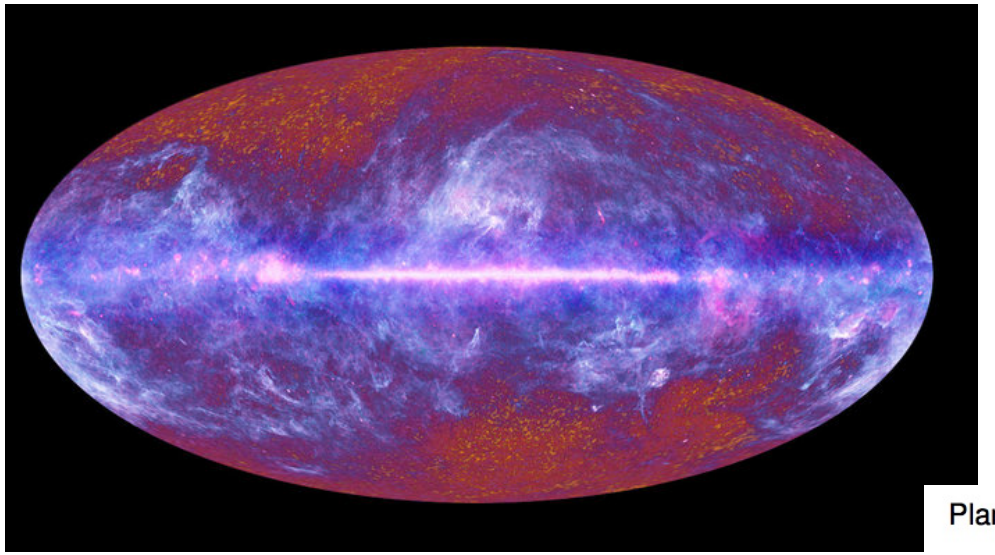

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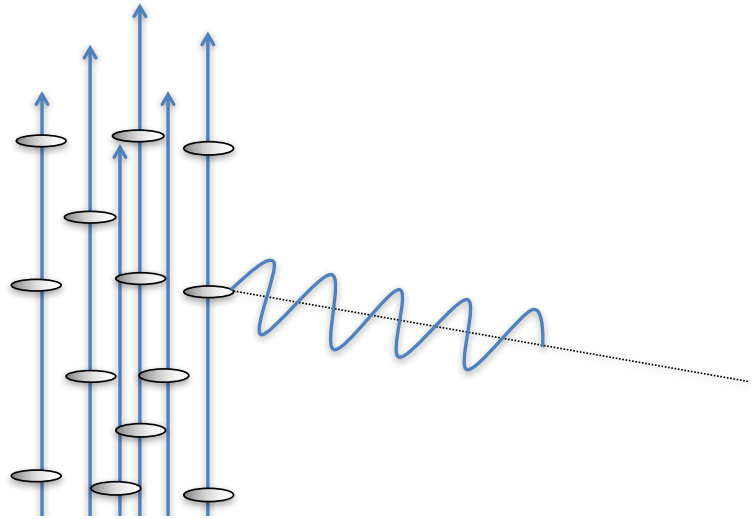
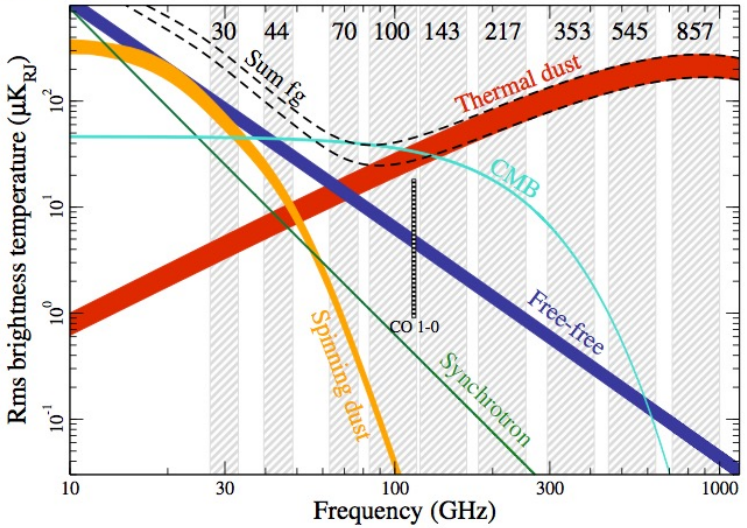


CMB dust emission removal:

Planck 2015 X



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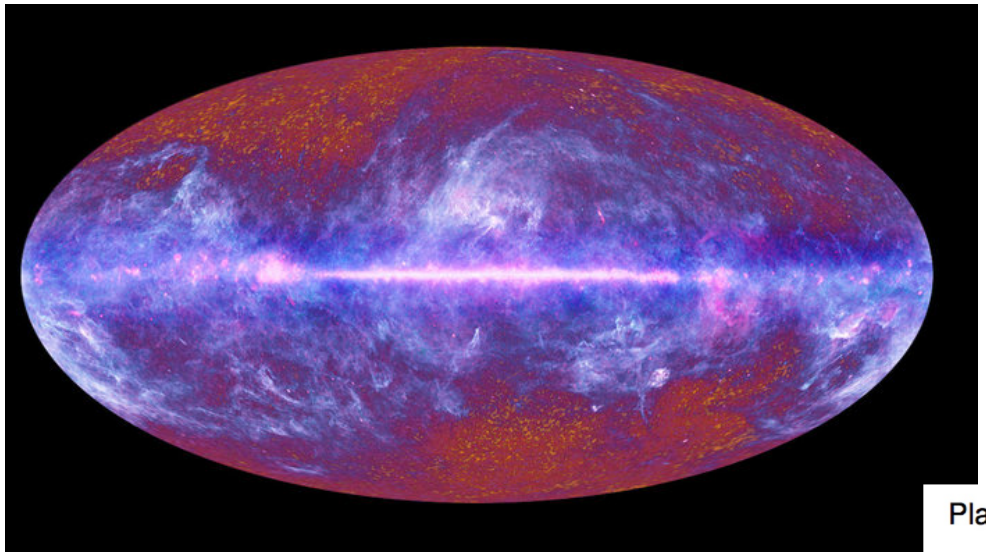

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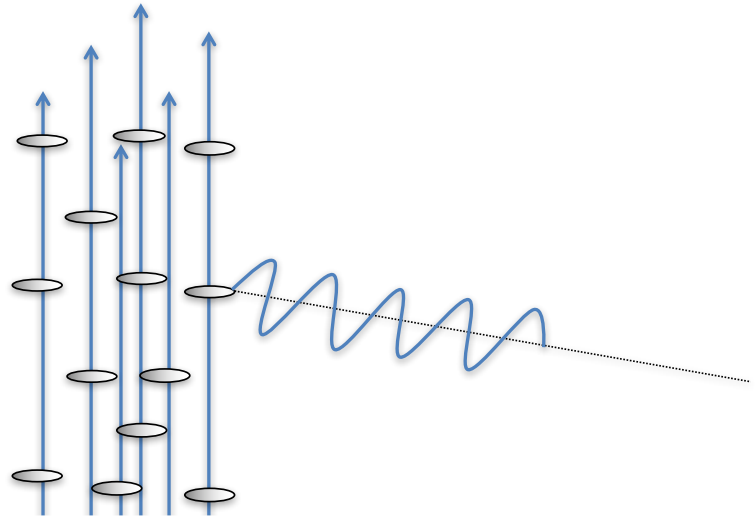

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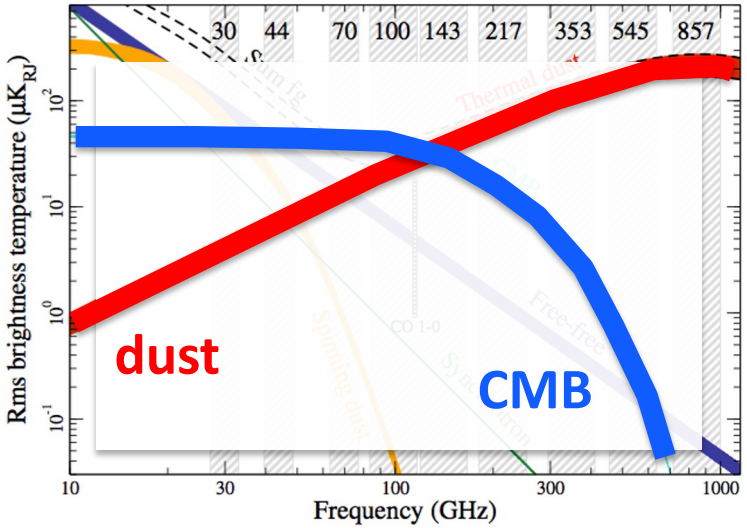

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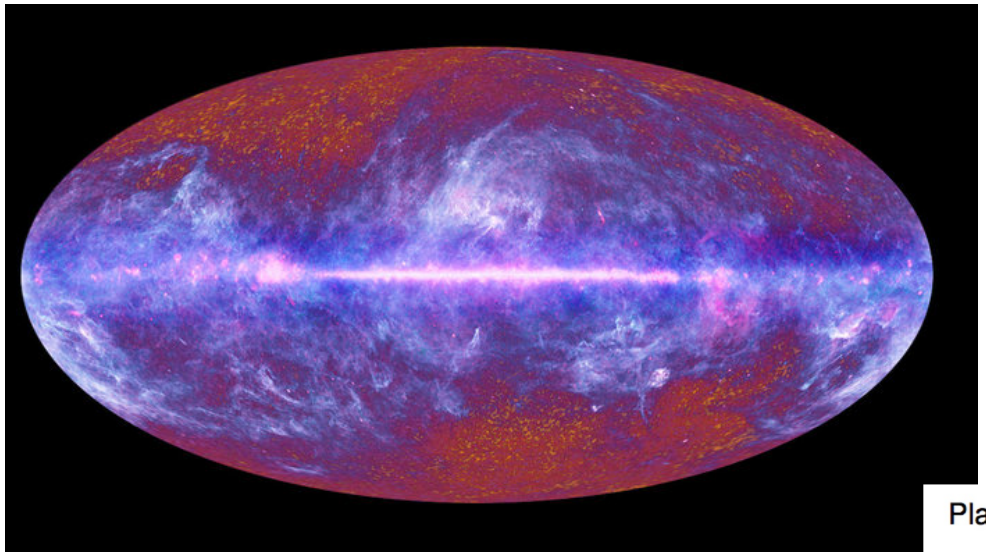

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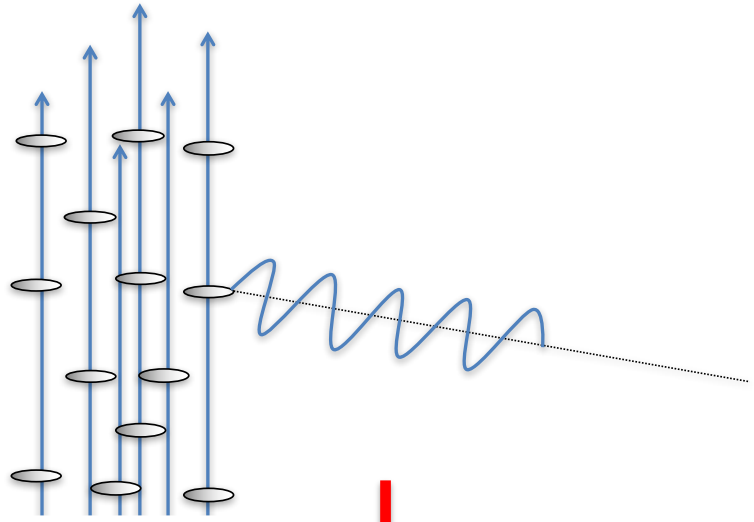
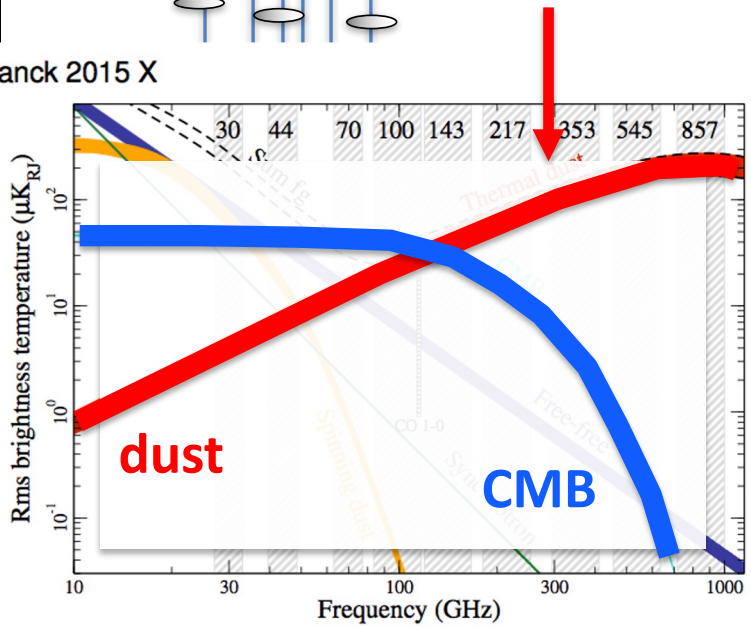


Planck 2015 X



CMB dust emission removal:

- Map at high frequencies
  (dust dominates)

The Problem

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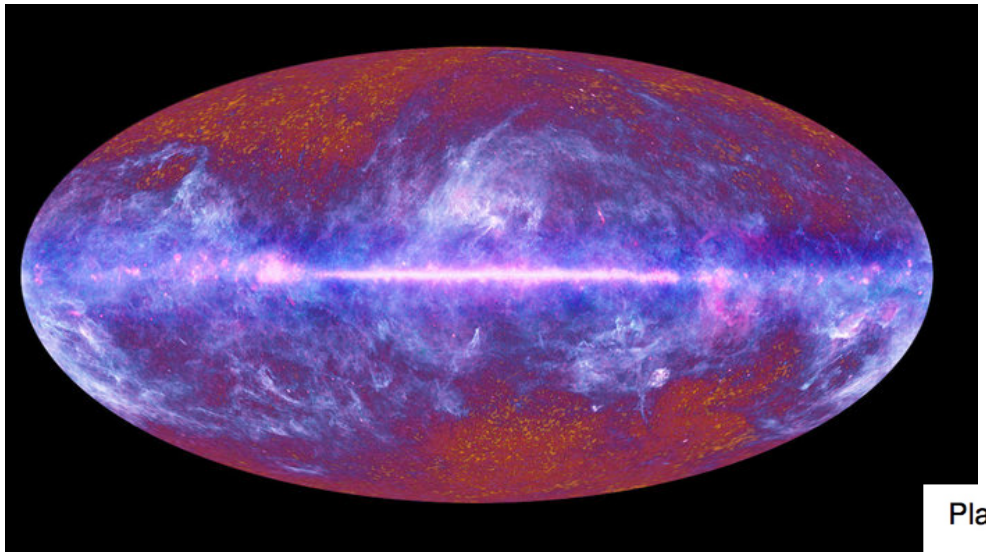

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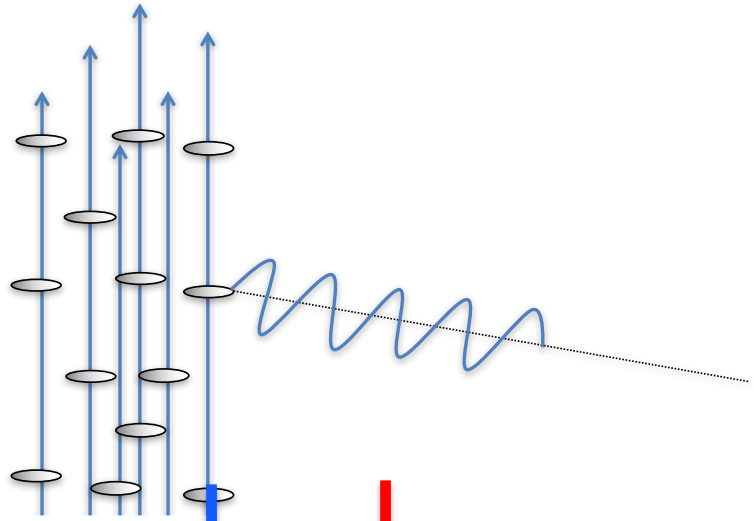

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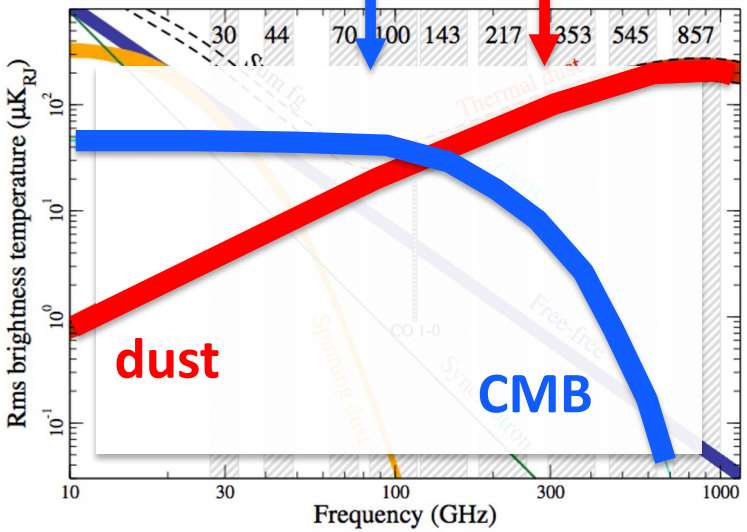
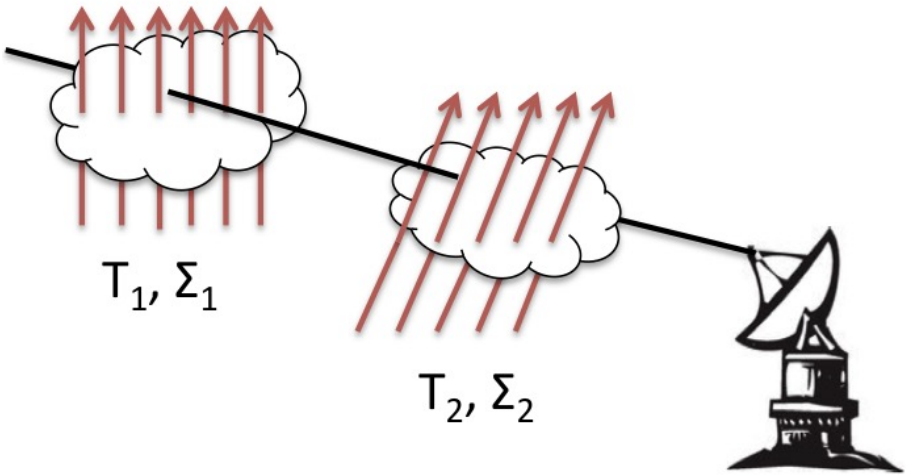


CMB dust emission removal:

- 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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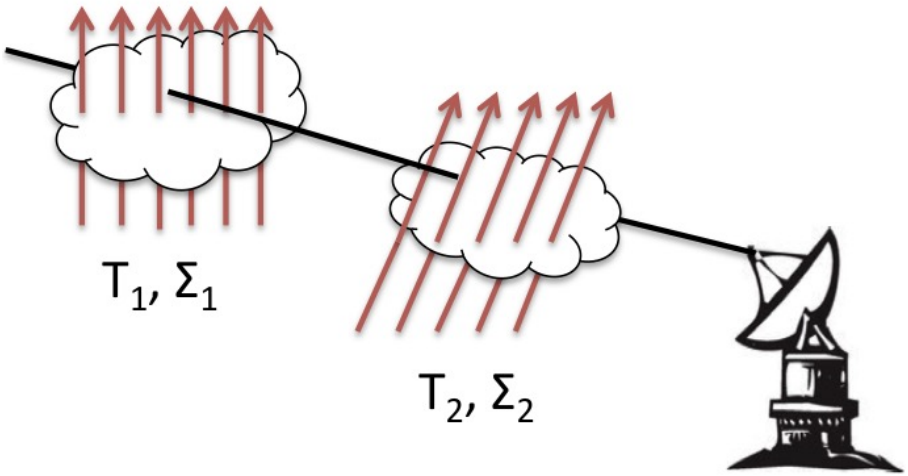


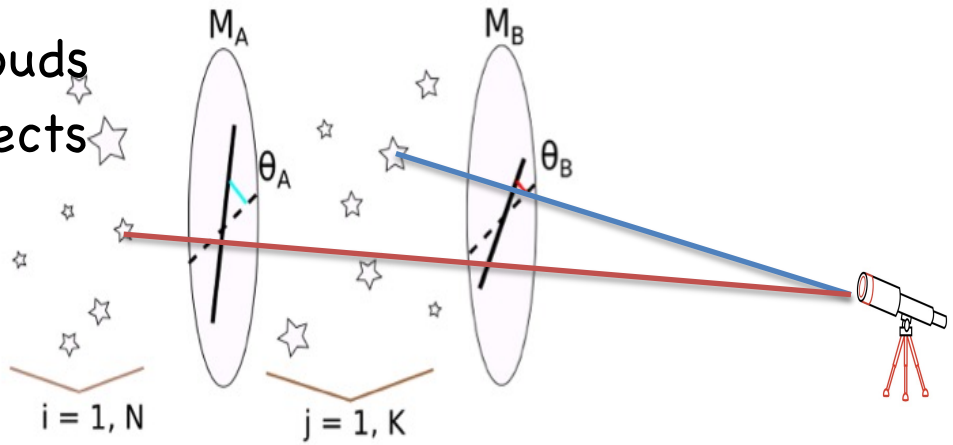
Tassis & Pavlidou 2015

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.

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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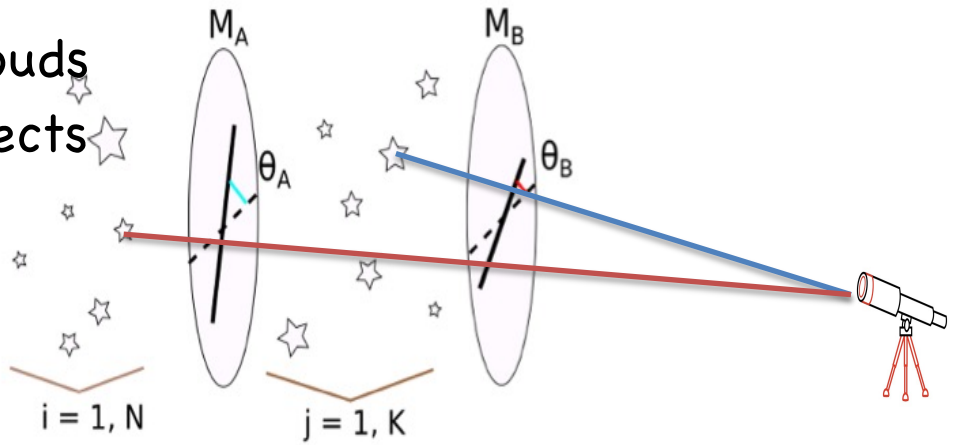

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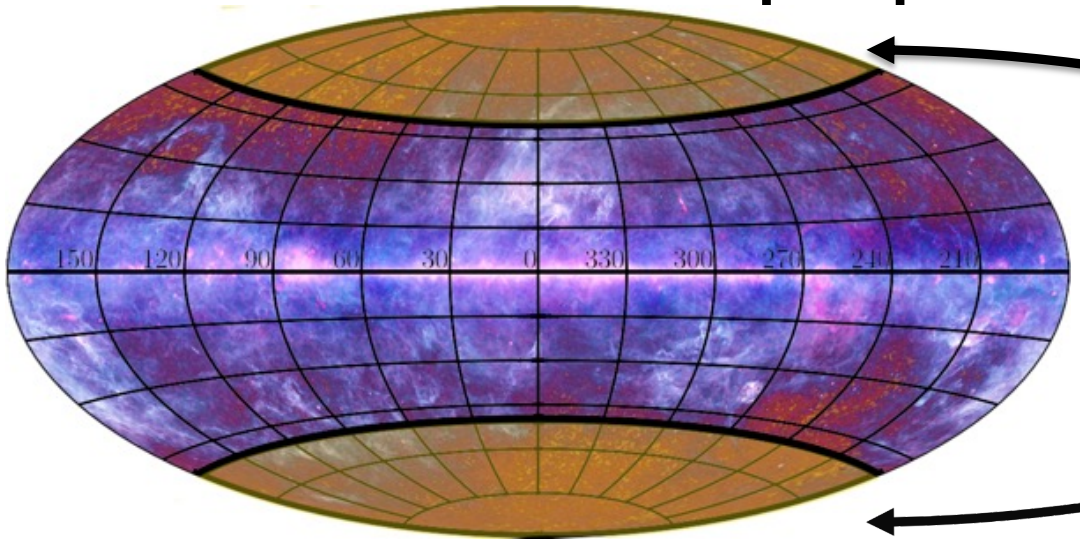
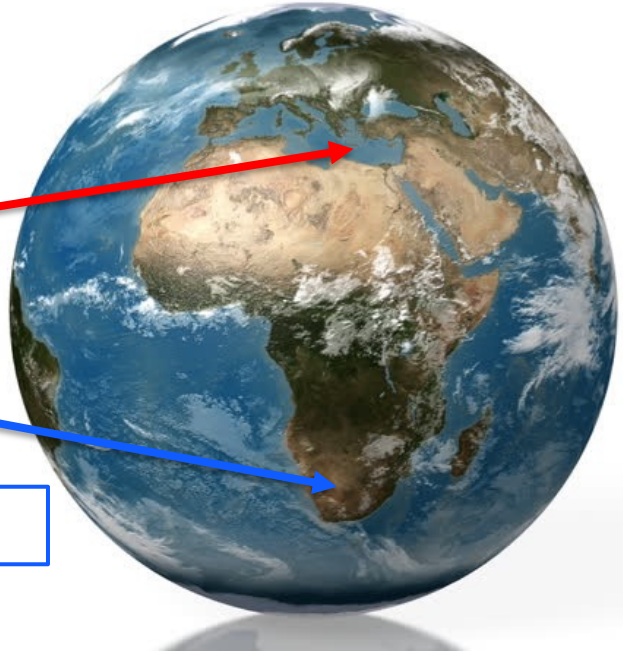


PASIPHAE survey area

Skinakas Observatory, Crete, Greece

PASIPHAE survey sites

SAAO, Sutherland, South Africa

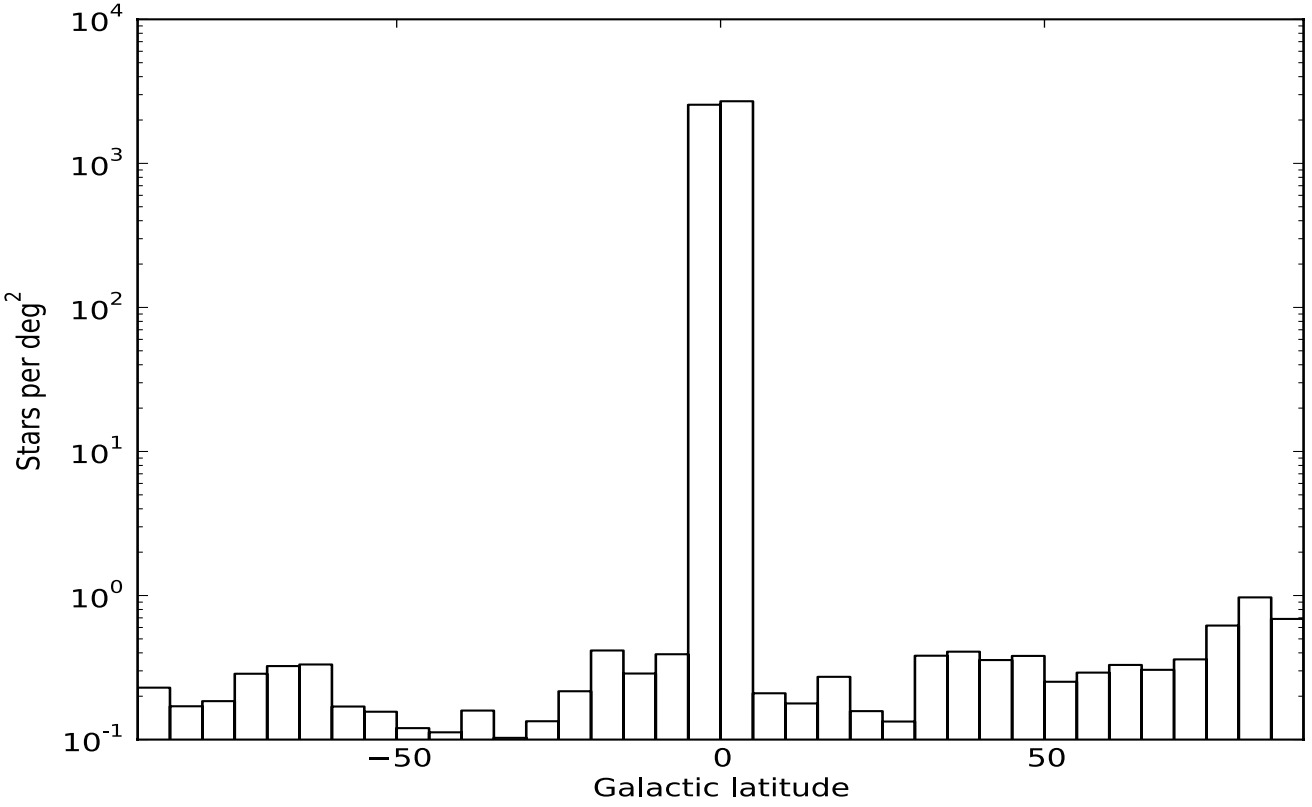


The PASIPHAE survey:

- 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: 15 deg^2/night @ Skinakas + 15 deg^2/night @ SAAO assuming 70% efficiency
- ~ 5,000 deg^2 / yr

PASIPHAE optopolarimetric survey

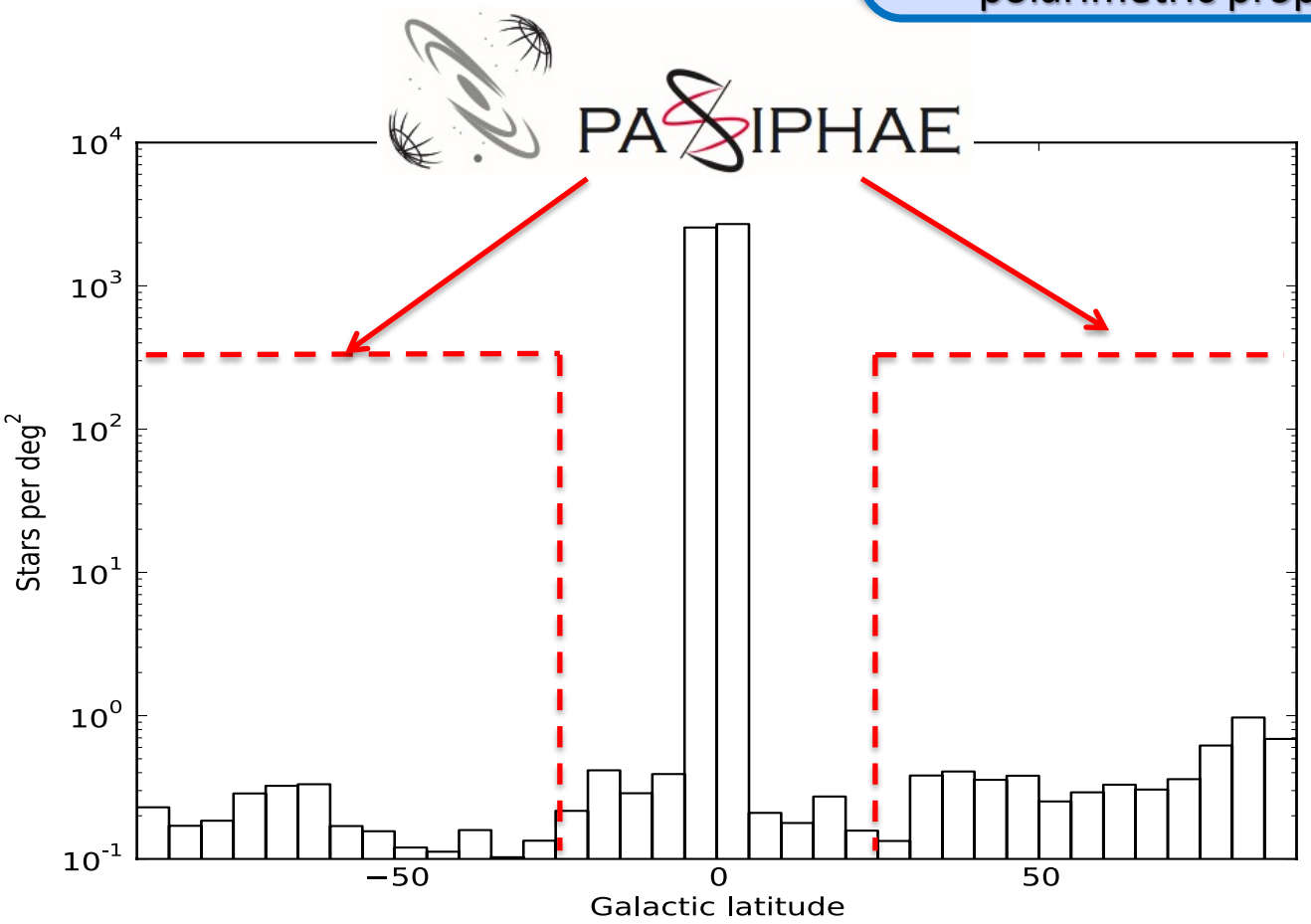
Measure polarization of **several million stars**



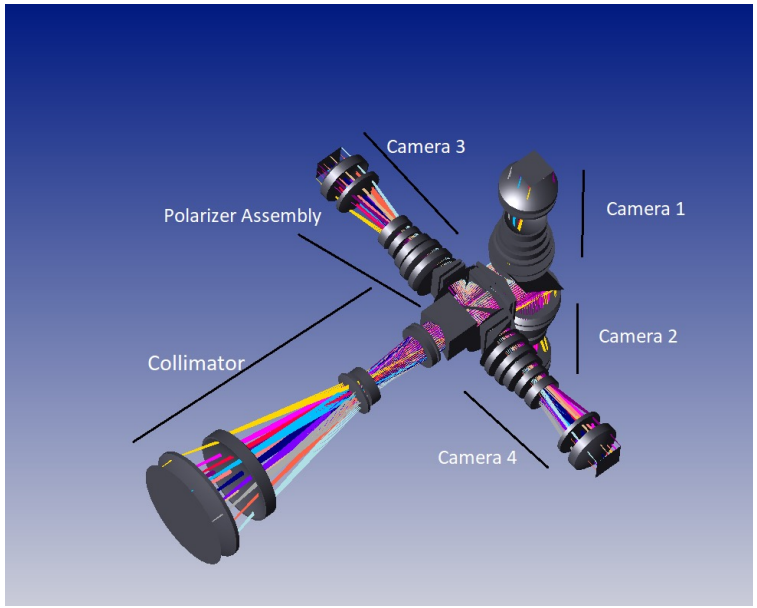
PASIPHAE optopolarimetric survey

Measure polarization of **several million stars**

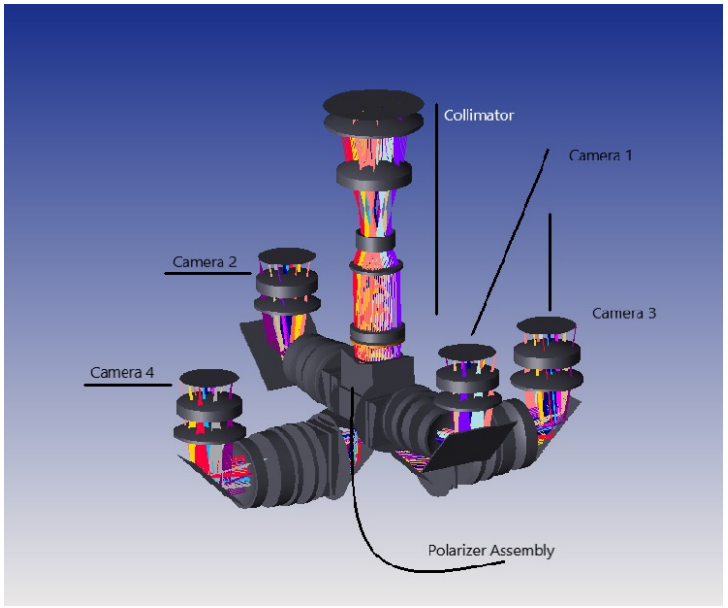
Major Leap:
x1000 improvement
in # of stars with measured
polarimetric properties



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

The PASIPHAE Collaboration

FORTH
FOUNDATION FOR RESEARCH AND TECHNOLOGY - HELLAS

UNIVERSITY OF CRETE

IUCAA

SAAO

CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

UNIVERSITAS OSLOENSIS MDCCCXI

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STAVROS NIARCHOS FOUNDATION

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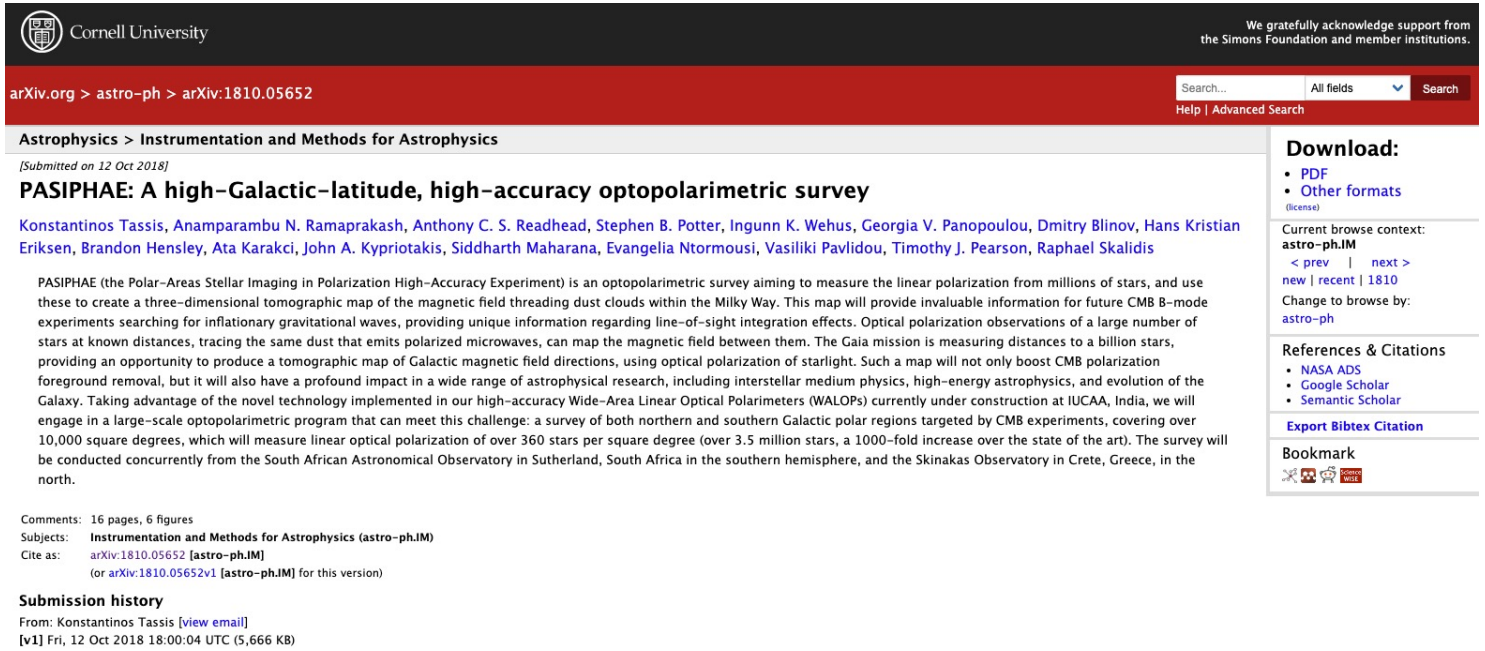
NRF National Research Foundation

More Information

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



Cornell University

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arXiv.org > astro-ph > arXiv:1810.05652

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Astrophysics > Instrumentation and Methods for Astrophysics

[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
Subjects: **Instrumentation and Methods for Astrophysics (astro-ph.IM)**
Cite as: arXiv:1810.05652 **[astro-ph.IM]**
(or arXiv:1810.05652v1 **[astro-ph.IM]** for this version)

Submission history

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News & Comment ›

Editorial
17 May 2021

Pushing the limits of discovery

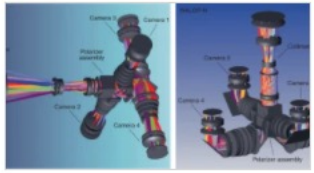
Be it neutrinos, ultra-high-energy photons or gravitational waves, new cosmic messengers have expanded the available discovery space of astronomy by exploring previously inaccessible astrophysical environments.

Mission Control
17 May 2021

Lifting the dusty veil over inflation

Two novel imaging polarimeters are being installed on two 1-m-class telescopes in order to examine dust foregrounds in cosmic microwave background studies as part of the PASIPHAE survey.

A. Ramaprakash, A. C. S. Readhead & K. Tassis



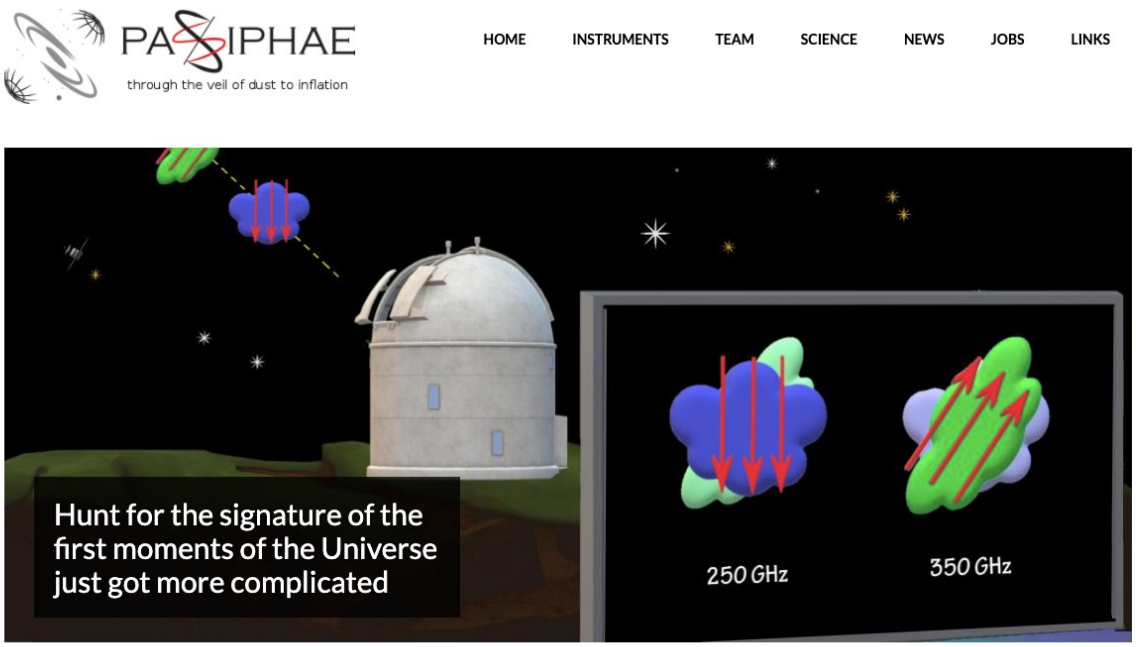
Research Highlight
11 May 2021

The oxygen bait

Luca Maltagliati

More Information

- http://pasiphae.science :



POLAR-AREAS STELLAR IMAGING IN POLARIZATION HIGH-ACCURACY EXPERIMENT

Conclusions

- Polarization is the only probe of B-fields
- B-Field dynamically important at cloud scales and can NOT be ignored
  - $B_t/B_o < 1$
  - *Bpos correlates with cloud structures*
- Polarized Dust emission due to Galactic B-Fields major problem for inflation probing observations – 3D B-Field map necessary

Thank you!