

ALL-SKY SURVEY IN POLARIZED LIGHT



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IAG

Universidade de São Paulo



27/Sept/2018

NIKKO - 2018

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- *All-Sky Polarization Survey*



Summary

- **Introduction**
 - Why polarimetry?
 - Need for an All-Sky Optical Polarization Survey
- **The SGMAP Survey**
 - Hiroshima University
 - Status
- **The SOUTH POL Survey**
 - University of Sao Paulo
 - Status
- **Science from a Polarization Survey**
- **Collaboration between SGMAP & SOUTH POL**
 - Participation of TAO

SGMAP project: Summary

(Search for Galactic Magnetic-field by All-sky Polarimetric Survey)

Using a dedicated 1-m class Ground-based Telescope and an optical 2-band (g' , I') Wide-field Polarimeter

Several million stars (< 14 mag, $\delta > -20^\circ$) will be surveyed in optical 2 bands simultaneously

First homogeneous polarimetric survey in northern hemisphere

Development phase

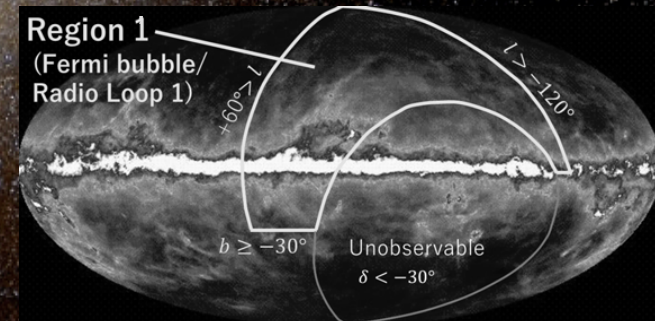
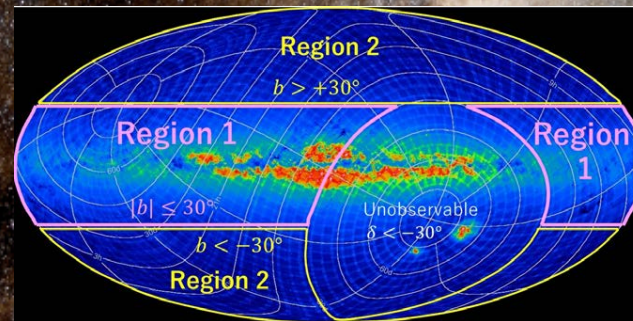
~2.5 yr

Observation period

~4.5 yr

Data analyses phase

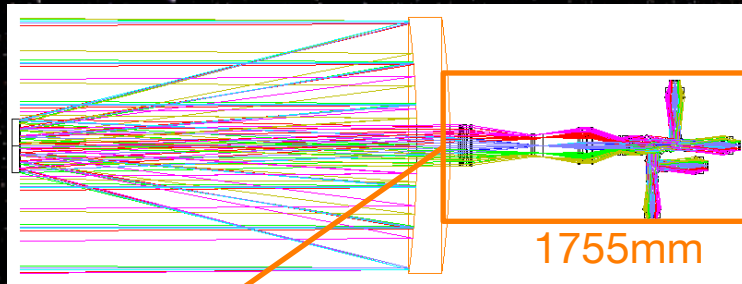
~3 yr



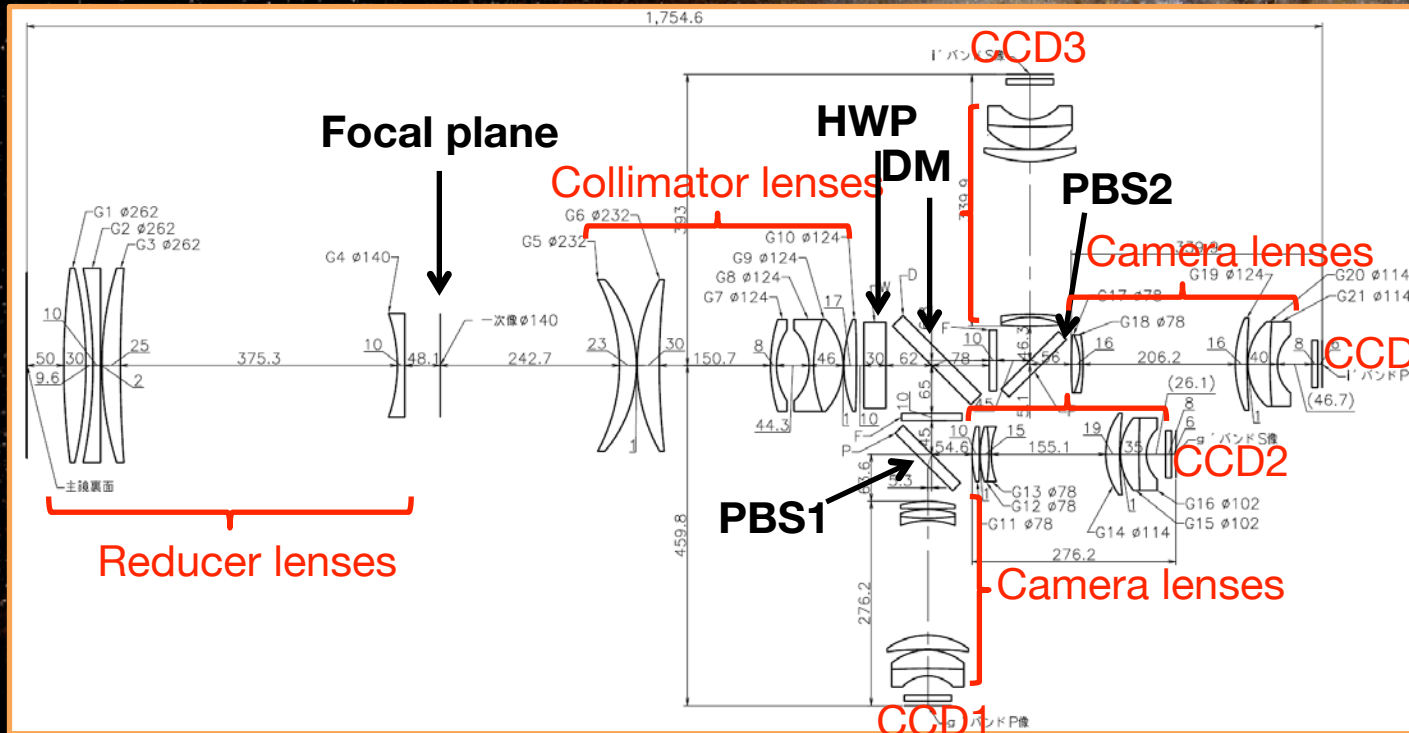
**90% observation time used to cover 60% all-sky within 4.5 yr.
10% for iterative observation of time variables (transients, etc.)**

It is still in a fund-raising phase. The budget is reduced to 2-4 million USD.

SGMAP: Instrument design



Main mirror: $D = 1.50\text{m}$; Secondary: $D = 0.3232\text{m}$;
 Composite F ratio = 6.114 (including reducer);
 Field of View 50' diameter; Final F ratio = 2.02 (at CCD)
 Four 4k4k CCDs; Pixel scale 0.76"/pixel ($15\mu\text{m}$)

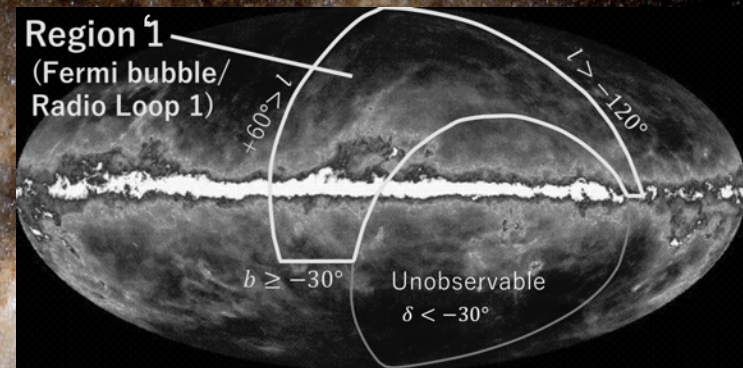
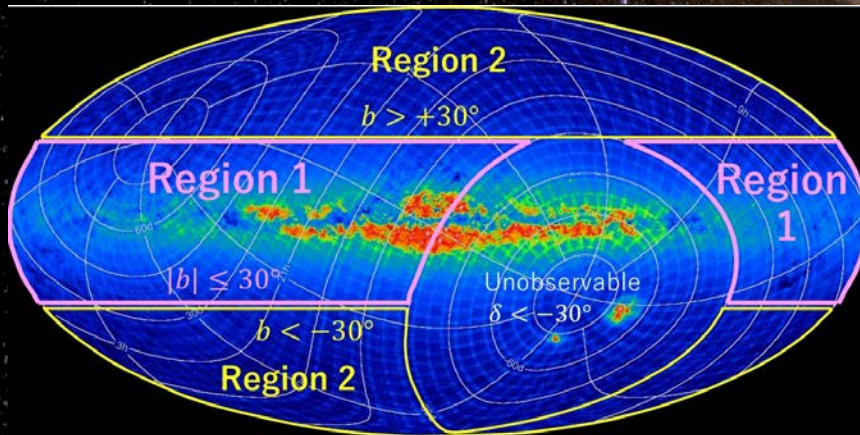


Any incident ray to HWP, DP and PBS is inclined less than 10° against the optical axis to keep their efficiency.

80% encircled energy radius $< 0.7''$ over 50' FoV for g' and i' bands

SGMAP: Survey Plan

- With 40s×4 exposures, $\Delta p=0.15\%$ @ $g'=14.0\text{mag}$
Seeing 1.8", Sky 18mag/arcsec², total efficiency 20%
- 1 set of observation takes 4.6 minutes (with overhead), 100 sets in one night (8 hr)
- Survey speed: 46.4 deg²/day



Region 1: Galactic plane survey

- $|b| < 30^\circ, l = \sim 0 - 220^\circ$ (12000 deg²)
- 12000/46.4 \rightarrow taking 0.71 yr
- Weather factor 0.33 \rightarrow 2.1 yr

Region 2: Mid-high latitude survey

- $|b| \geq 30^\circ$ available from Hiroshima (13200 deg²)
- Weather factor 0.33 \rightarrow 2.4 yr

Region 1': Higher priority for multi-wavelength study of Galactic structures including Radio loop/Fermi bubble region.

SGMAP: Optimistic Schedule

Fiscal Year	Telescope/dome	Instrument	Observation/data reduction
2018	Final selection of candidate telescope	Design completion, fabrication of optical components	
2019	Refurbishment, installation	Detector unit Lens unit Assembling	
2020		Mounting to telescope Experimental observation	Survey obs. starts Region 1
2021-			Obs. Region 1
2023-			Obs. Region 2 Data reduction
2025-			(Obs. Region 2) Data reduction Catalogue release

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SOUTH POL

- **Polarimetry Group at IAG-USP:**

- Antonio Mário Magalhães
- Edgar Ramírez (Postdoc)
- Nadili Ribeiro Grad Students
- Marcelo Rubinho
- Daiane Seriacopi
- Tibério Ferrari
- James Davidson Jr. (U. Virginia, USA)
- Luis Manrique (IAG-USP)
 - Software development

- **Contact:**

antonio.mario@iag.usp.br

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SOUTH POL

- **Close collaborators**
 - **Claudia V. Rodrigues (INPE/DAS)**
 - **Antonio Pereyra (IG, Peru)**
 - **Alex Carciofi (IAG-USP)**
Data Server
 - **IAG-USP**
Enterprise Disks

Funding: 
Fundação de Amparo à Pesquisa do Estado de São Paulo
Sao Paulo State Funding Agency

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SOUTH POL

- **Polarimeter Project**
 - Eng. Lucas Marrara & Equitecs (São Carlos, mechanics)
 - Eng. Carlos E. Fermino, eFe Tecnologias (Araraquara, electronics)
- **External collaborators**
 - Koji Kawabata, U. Hiroshima, Japan
Northern Survey
 - Marijke Harverkorn, U. Radboud, The Netherlands
ISM B-field structure



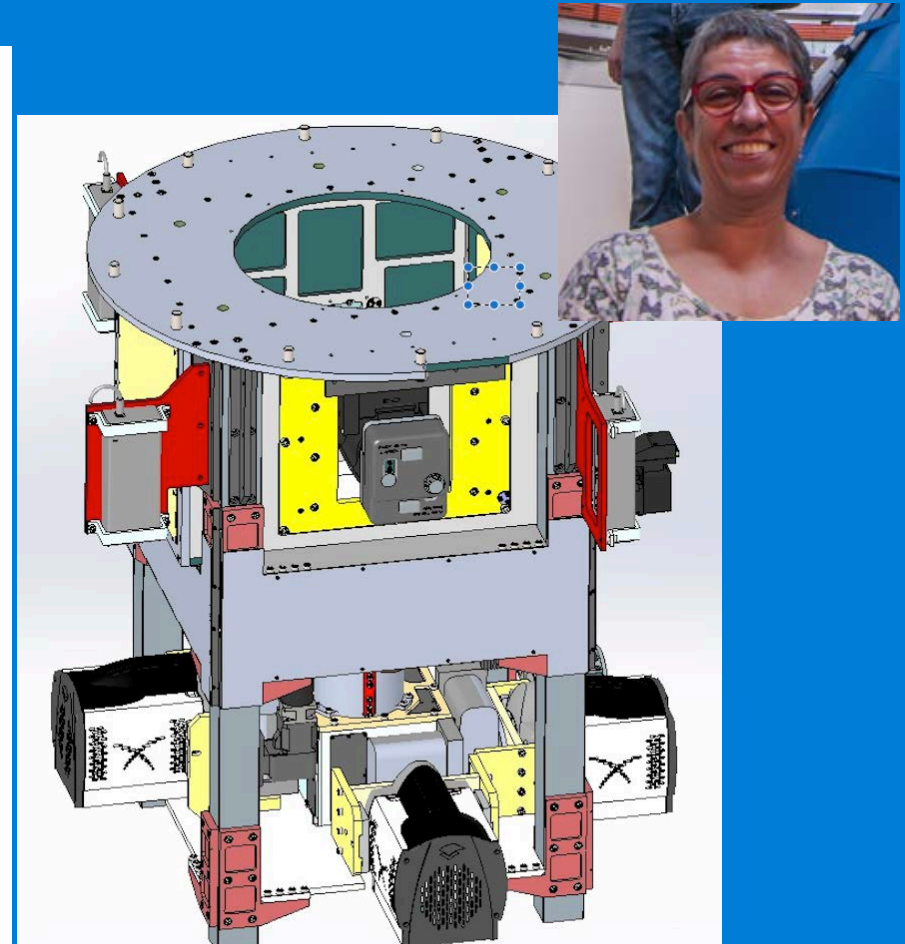
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SPARC4 - Simultaneous Polarimeter and Rapid Camera in 4 Bands

PI: **Claudia Vilega Rodrigues** - Instituto Nacional de Pesquisas Espaciais - Brazil

- ✓ Simultaneous imaging in SDSS griz bands
- ✓ Polarimetry as an option
- ✓ Detectors: Andor Ixon EMCCDs
- ✓ Field of view: 5.6 arcmin x 5.6 arcmin
- ✓ Telescope: 1.6 m in Observatório do Pico dos Dias/Brazil
- ✓ Status:
 - ❖ optics and detectors acquired
 - ❖ machining starting in 2018
 - ❖ first light planned to 2019
- ✓ Funding: INPE, LNA, Finep, Fapesp, INCTA



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SOUTH POL

- **Eng. Carlos E. Fermino**
 - **eFe Tecnologias Industriais**
 - (Araraquara, Sao Paulo state)
 - **eFe**
 - develops mechanical devices & machines
 - electronics circuitry
 - automation control & software
 - mecatronics integration
 - **Costumers**
 - **SOUTH POL** survey
 - **J-PAS** survey (Spain)
 - **Cerenkov Telescope Array** (Italy)
 - **LLAMA** radiotelescope (Brazil & Argentina)





SOUTH POL

- São Paulo state:
 - Latin American state of the future for 2018/2019
 - Chilean regions also fared well

- Source: fDi (14/08/2018)
 - Foreign Direct Investment, service from the Financial Times (UK)
 - <https://www.fdiintelligence.com/Locations/Americas/fDi-s-Latin-American-States-of-the-Future-2018-19-the-winners>

TOP 25 LATIN AMERICAN STATES OF THE FUTURE 2018/19: OVERALL

RANK	STATE	COUNTRY
1	São Paulo	Brazil
2	Buenos Aires Autonomous City	Argentina
3	Mexico City	Mexico
4	Nuevo León	Mexico
5	Querétaro	Mexico
6	Capital District	Colombia
7	Metropolitana de Santiago	Chile
8	Guanajuato	Mexico
9	Rio de Janeiro	Brazil
10	Jalisco	Mexico
11	Antofagasta	Chile
12	Buenos Aires Province	Argentina
13	Coahuila	Mexico
14	Baja California	Mexico
15	Paraná	Brazil
16	Lima	Peru
17	Atacama	Chile
18	Santa Catarina	Brazil
19	Minas Gerais	Brazil
20	Chihuahua	Mexico
21	Rio Grande do Sul	Brazil
22	San Luis Potosí	Mexico
23	Aguascalientes	Mexico
24	Flores	Uruguay
25	México	Mexico

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SOUTH POL

- **Polarimetry at IAG-USP**
– IAGPOL

- 1975-1990: Optical photoelectric polarimeter
- 1977-9: online data reduction (a 1st at LNA/Brazil)

Walter Velloso
& AMM
60cm IAG @ LNA



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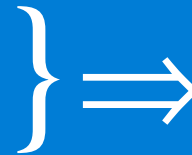
SOUTH POL

- **Polarimetry at IAG-USP**
 - **IAGPOL**

- 1975-1990: Optical photoelectric polarimeter
- 1977-9: online data reduction

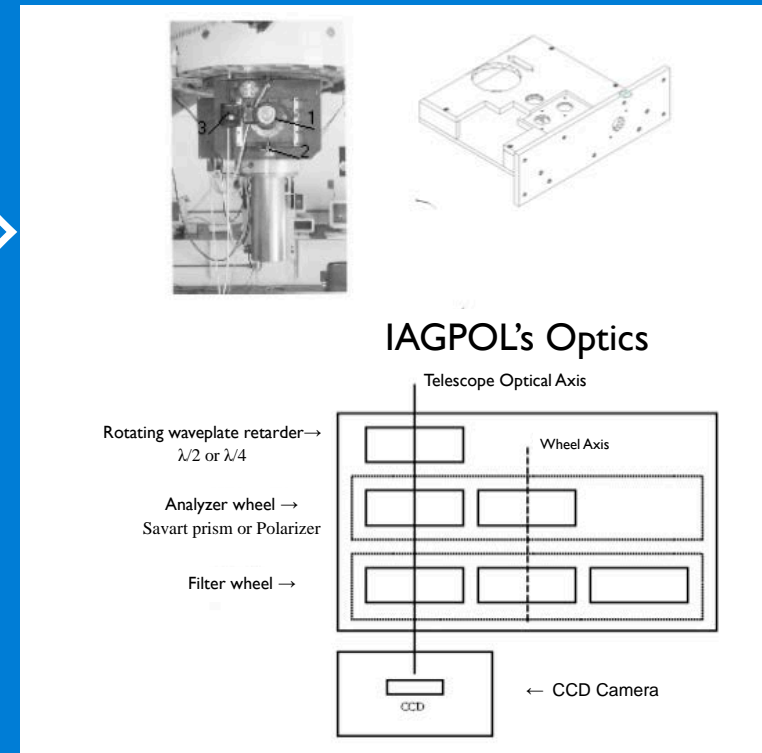
- **Currently:**

- facility instrument at LNA, Brazil
- Optical & NIR polarimetry
- remote observing



- **CHILE connection**

- 1978: IAGPOL run @ CTIO
- 1990-2010: polarimetry imaging @ 1.5m & 0.9m telescopes spectro- @ 4m Blanco telescope



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Introduction

- **Mechanisms that originate optical polarized light:**
 - **Dust scattering**
 - Interstellar Medium
 - Envelopes of Young Stellar Objects
 - Envelopes around AGB stars
 - **Thompson (e^-) scattering**
 - Cosmic Microwave Background
 - Envelopes of Hot Stars
 - **Synchrotron radiation**
 - Active Galactic Nuclei (AGN)
 - AGN hot spots
 - Gamma-ray Bursts (GRBs)
 - **Cyclotron radiation**
 - Magnetic cataclysmic binaries

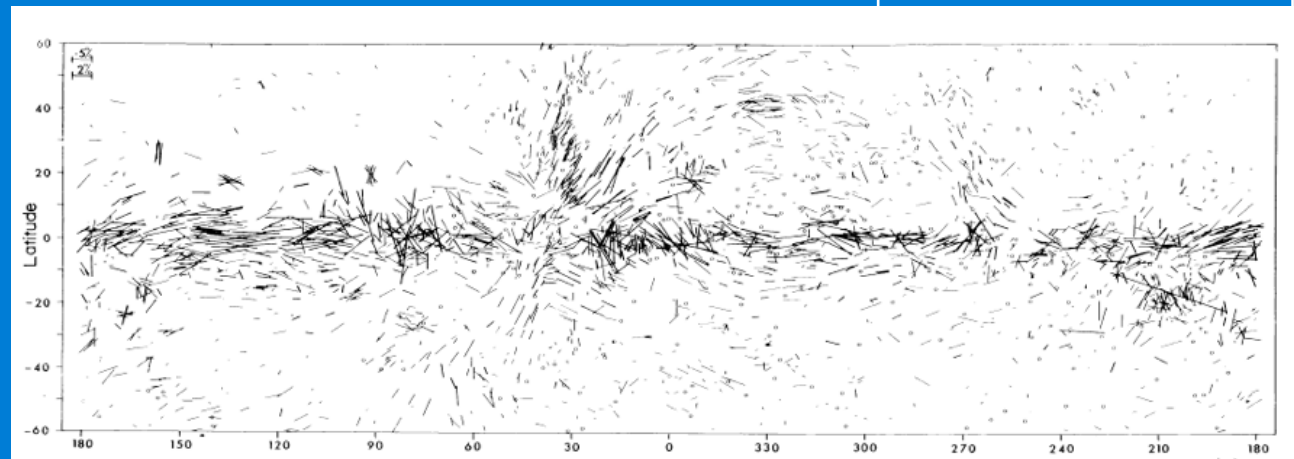
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Introduction

- **Despite the scientific motivation,**
 - No **all-sky** O/NIR polarimetric Survey exists!
 - Eg., interstellar polarization:
 - Heiles' (2000) compilation has $\sim 10,000$ stars
- **SOUTH POL** should provide $\sim 10^7$ $V \lesssim 15$ objects
 - deeper
 - more precise & accurate

Mathewson & Ford 1970



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SOUTH POL

- **SOUTH POL:**
 - Optical survey of the polarized Southern sky
 - FAPESP, PI: A. M. M.
- **Goal:**
 - Polarimetric accuracy of 0.1% at $V \sim 15$
- **Survey's first epoch:**
 - Sky South of Dec -15°
 - Complete in ~ 2 years of observing time
- **It will gradually progress towards North**



SOUTH POL

- **High Galactic Latitude Clouds**
 - From models of stellar population synthesis of the Galaxy:
 - $V \lesssim 15$:
covers 3 kpc towards $b=90^\circ$
 - In other words,
 - Galactic dust layer will be well sampled!

Table 1. Polarimetric accuracy, in %, with the 80cm Telescope(*).

V (mag)	8X60 sec	8X300 sec
10	0.022	0.010
11	0.035	0.016
12	0.055	0.025
13	0.088	0.039
14	0.140	0.062
15	0.223	0.100
16	0.361	0.160
17	0.600	0.263
18	1.051	0.449
19	2.011	0.830

(*). For a 22mag/arcsec^2 , air mass=1, readout noise= $5e^-$.

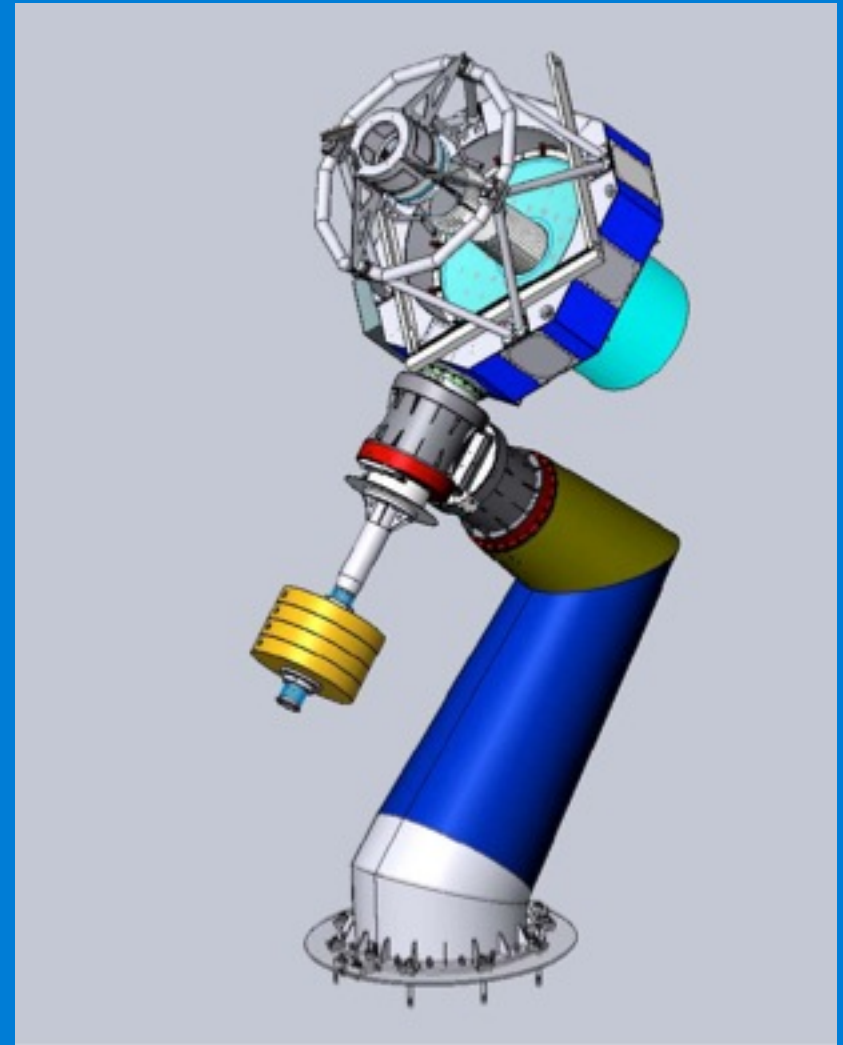
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SOUTH POL

- **T80-S Robotic Telescope**
 - FAPESP - Multi-user equipment grant
 - PI: Claudia de Oliveira (USP)
w/ William Schönell (UFRGS)
Antonio Kanaan (UFSC)
Tiago Ribeiro (LSST)
- CCD:
 - E2V, 9k x 9k, 92mm
 - 2.0 deg² (!)
- Used for initial tests of SOUTH POL polarimeter

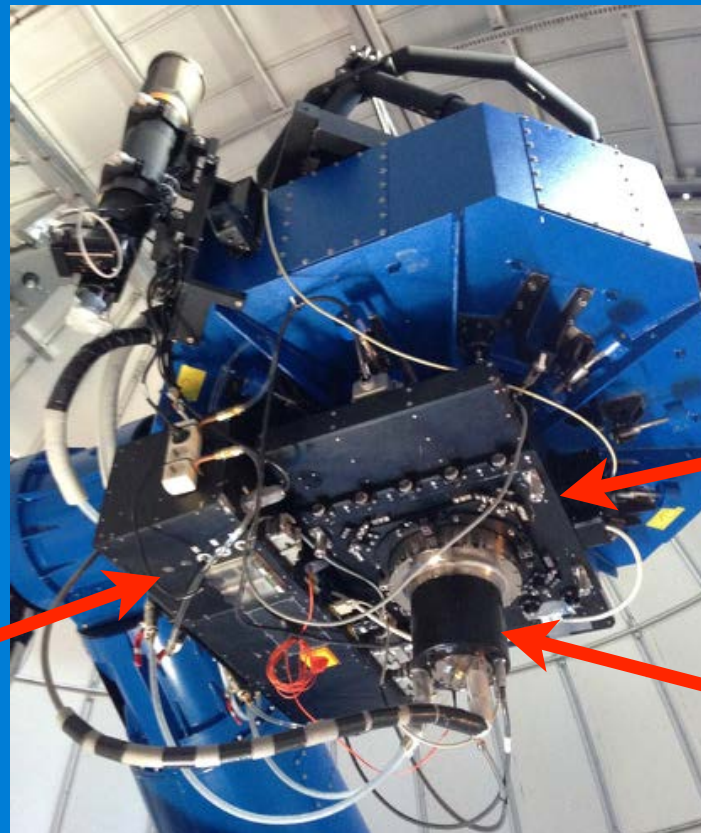


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SOUTH POL

- **T80-S Robotic Telescope**
 - Installed CTIO



T. Ribeiro

Cassegrain
Module

Electronics/Control
Module

Camera

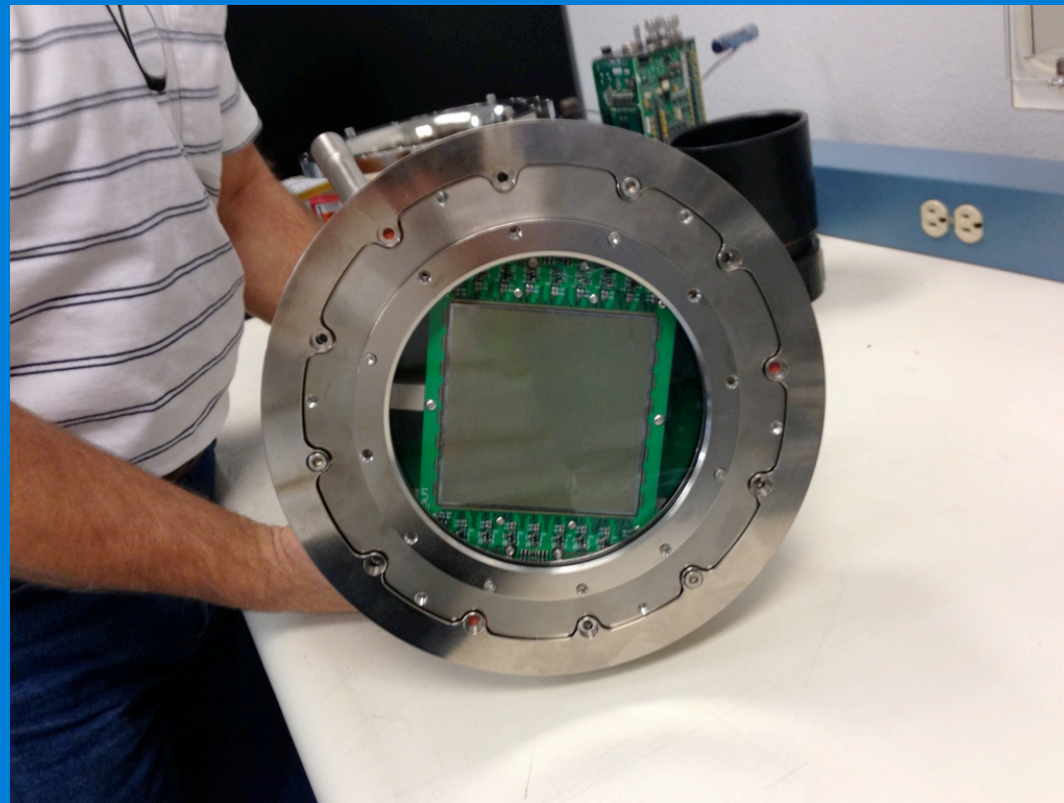
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SOUTH POL

- SI Camera for the T80-S telescope

E2V 9k x 9k CCD

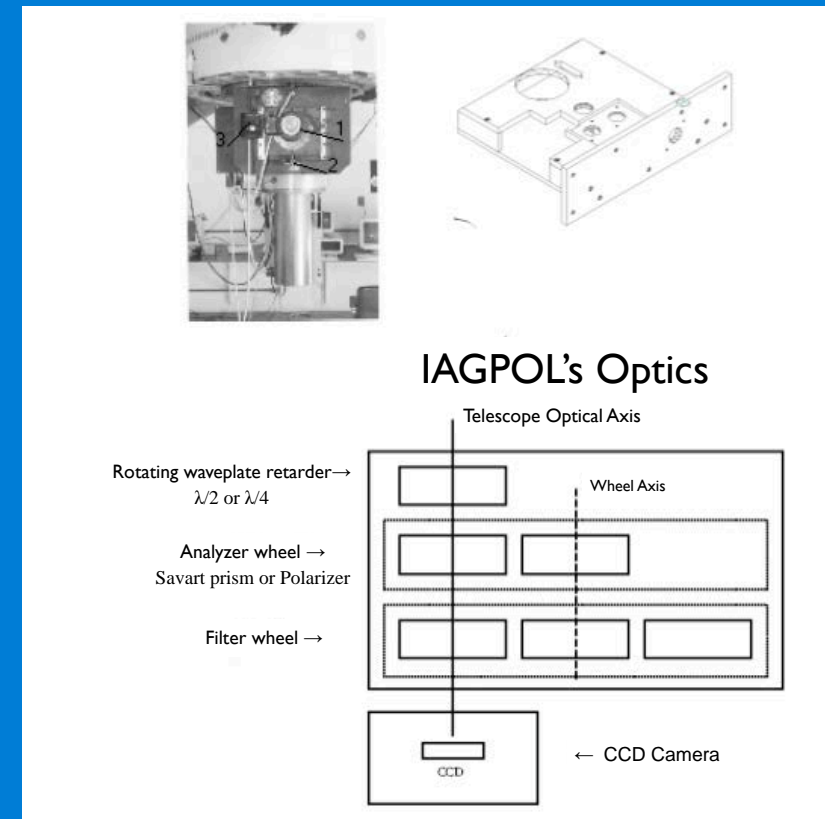


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SOUTH POL

- **Polarimeter for SOUTH POL**
 - PI: A. M. Magalhaes
 - Patterned after IAGPOL
 - **Rotating waveplate**
+
Calcite prism
 - Savart plate
 - **Very accurate**
 - $\sigma_p = 0.002\%$ (or better) possible

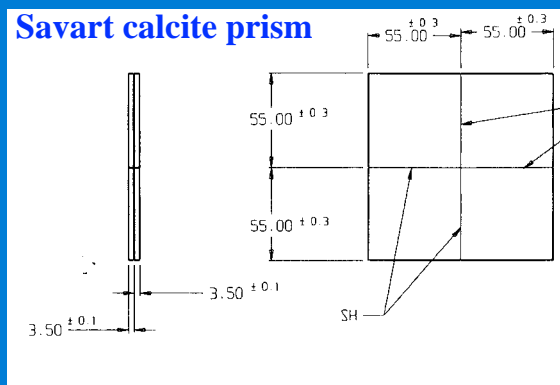


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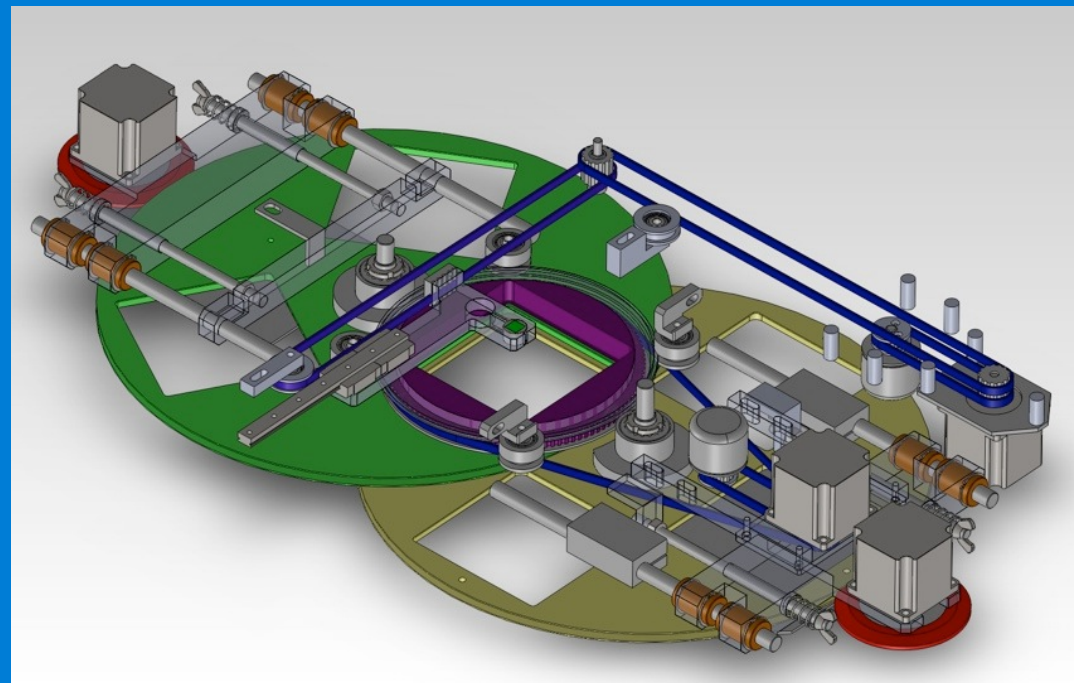
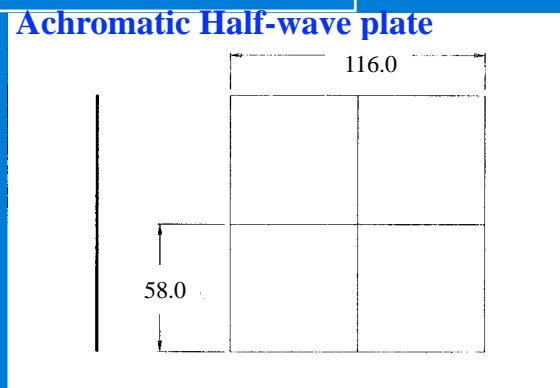


SOUTH POL

- Polarimeter optics & mechanics



116 mm x 116 mm mosaics



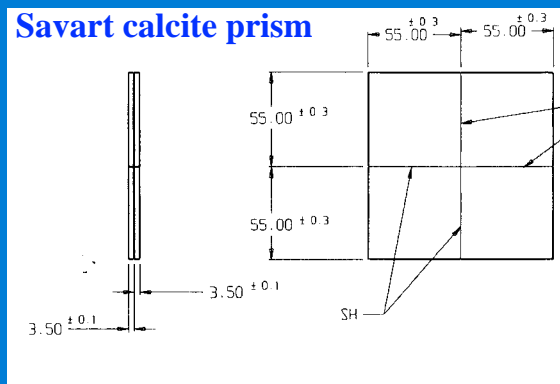
L. Marrara

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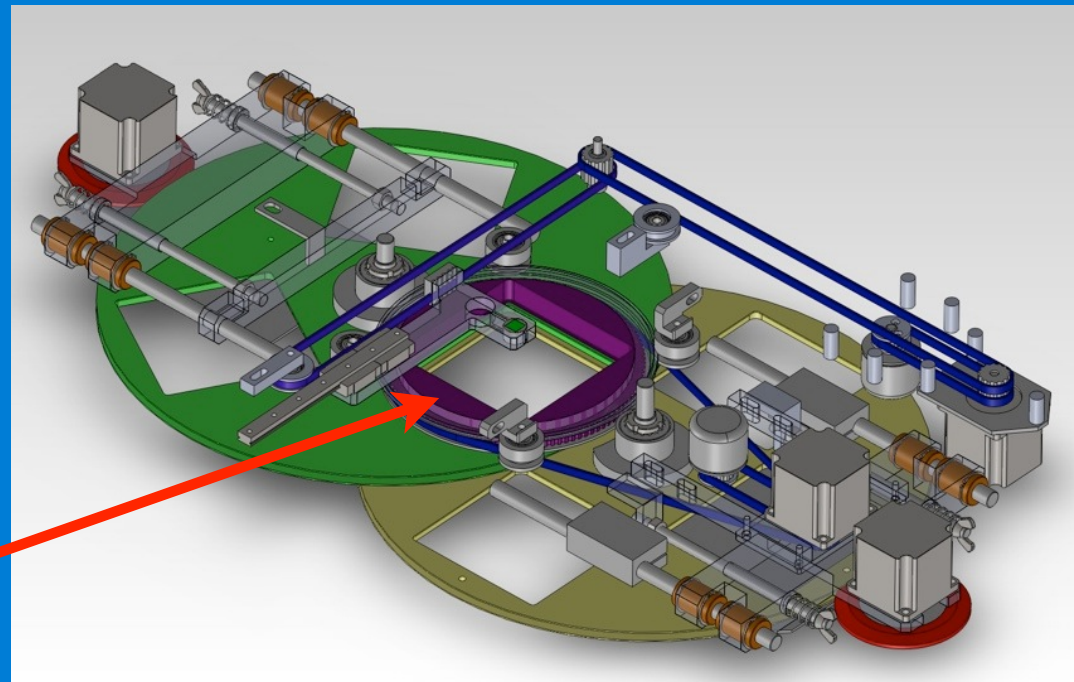
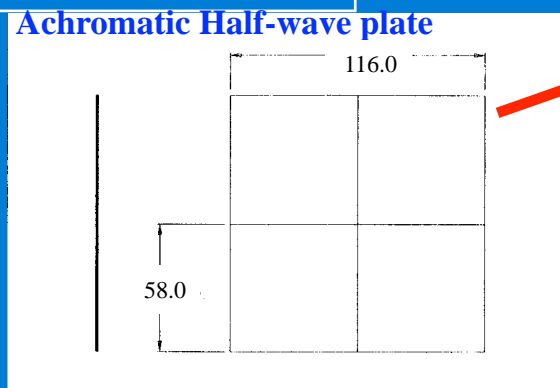


SOUTH POL

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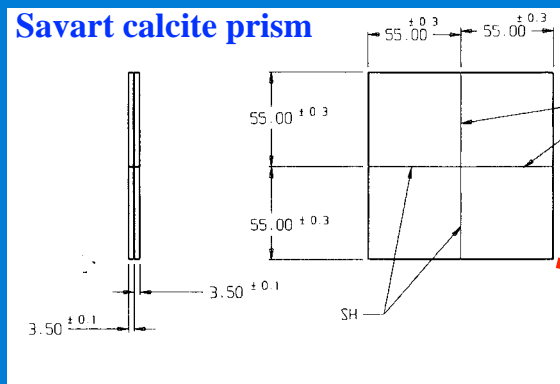
L. Marrara

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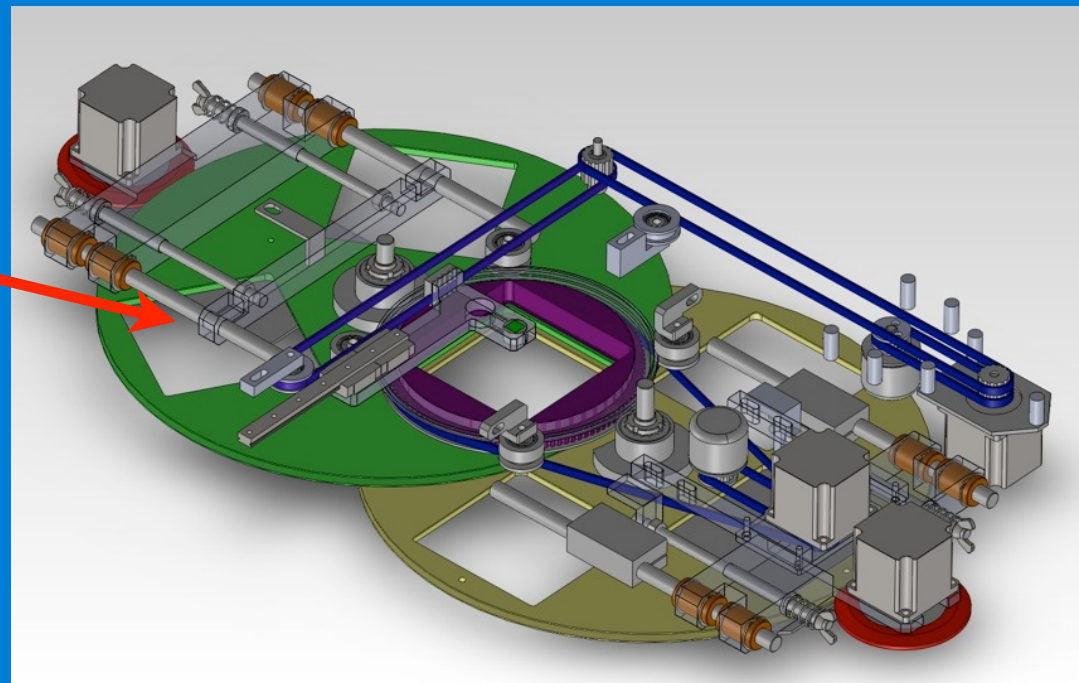
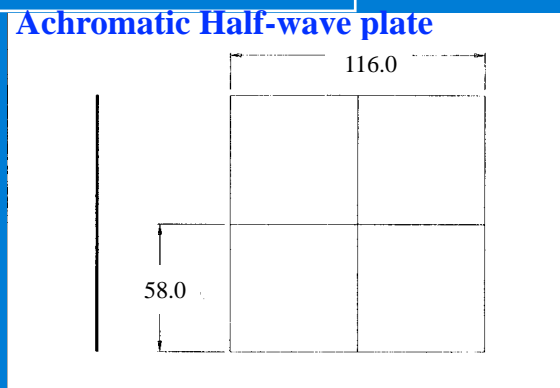


SOUTH POL

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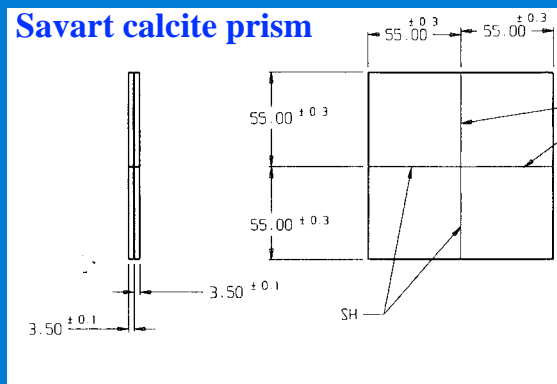
L. Marrara

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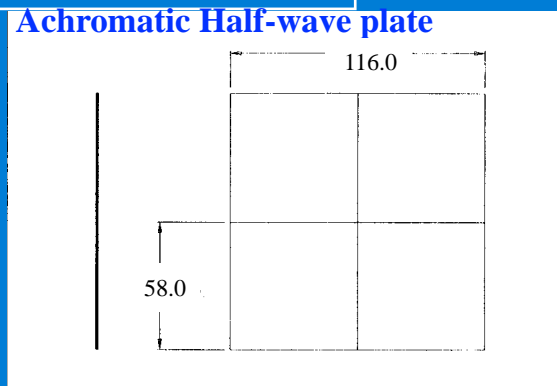


SOUTH POL

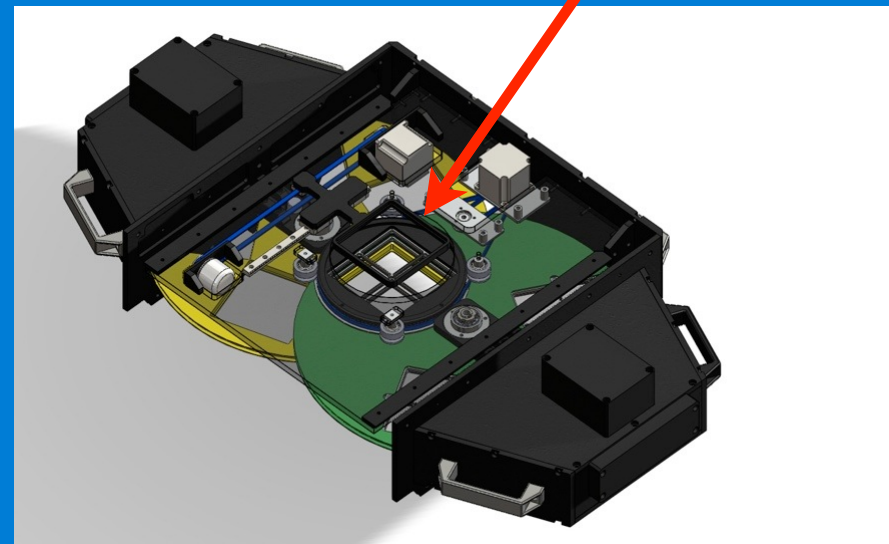
- Polarimeter optics & mechanics



116 mm x 116 mm mosaics



Calibration polarizers

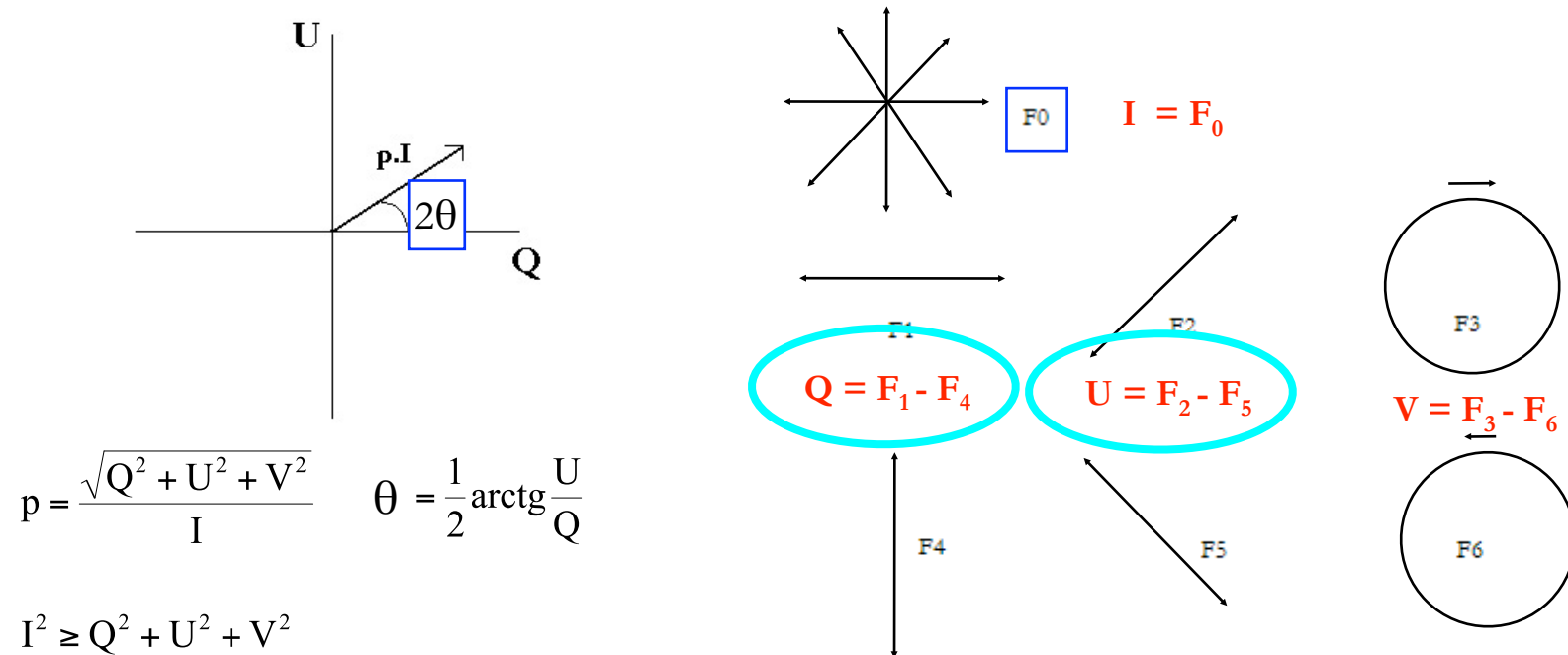




SOUTH POL

- Operational definition of the Stokes parameters [I, Q, U, V]

Consider the following 'filters' that measure the different polarization states:



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SOUTH POL

- Counts @ $\lambda/2$ -waveplate

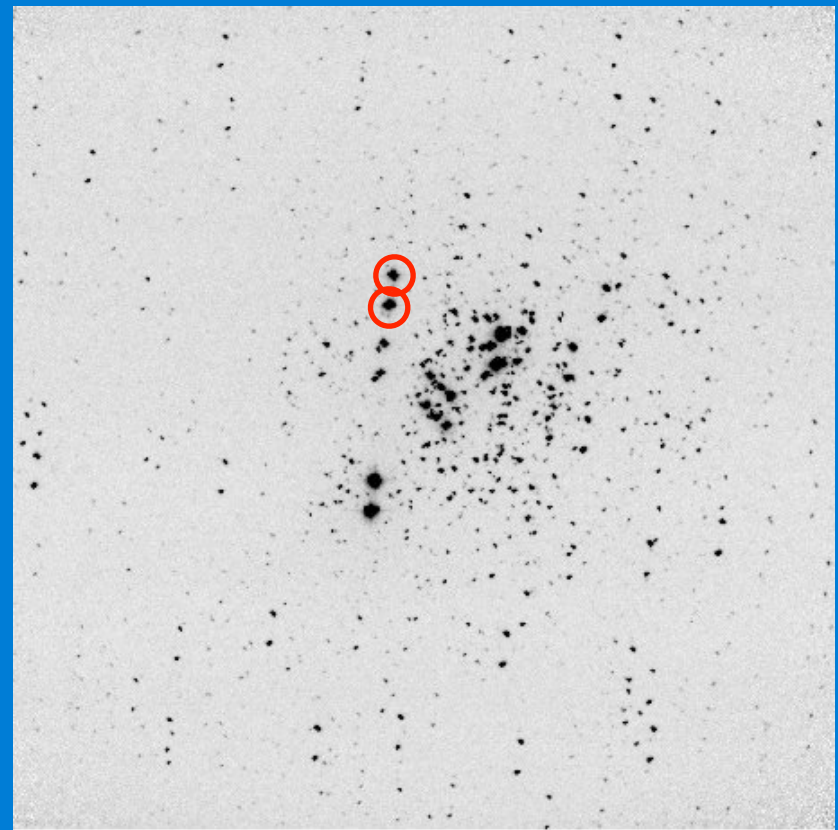
angles ψ_i :

$$z_i = \frac{N_1 - N_2}{N_1 + N_2} \Big|_i = Q \cdot \cos(4\psi_i) + U \cdot \sin(4\psi_i)$$

$$\Rightarrow Q = 1/4 \times [z_1 - z_3 + z_5 - z_7]$$

$$U = 1/4 \times [z_2 - z_4 + z_6 - z_8]$$

κ Crucis



AMM et al. 2005

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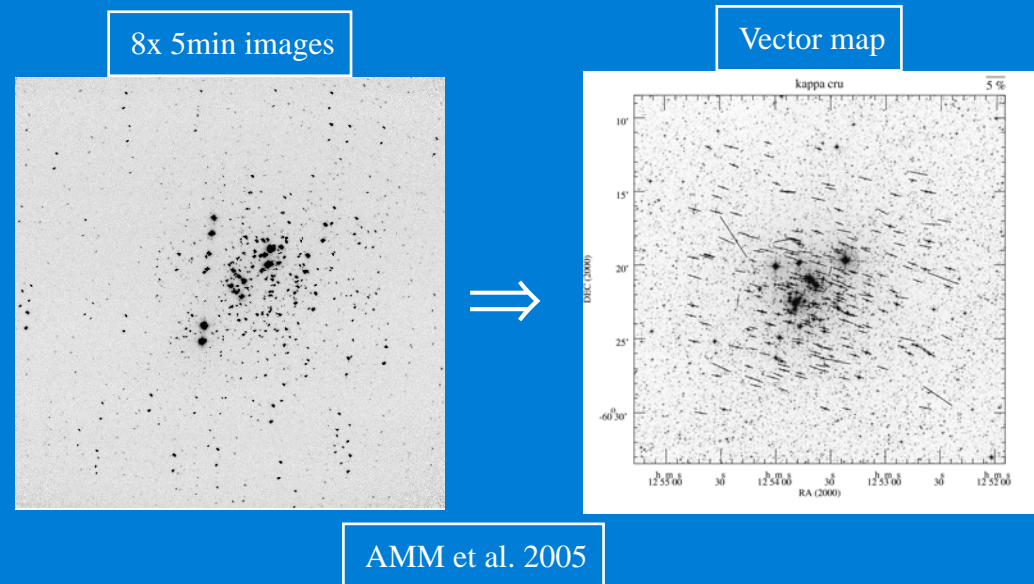


SOUTH POL

Reduction pipeline:

Need to convert
- images @ waveplate positions
to

- bias, flat, image reduction
- polarization catalog
- magnitude catalog
- vector maps, ...



An IDL pipeline has been built for this purpose (Ramírez et al. 2017)

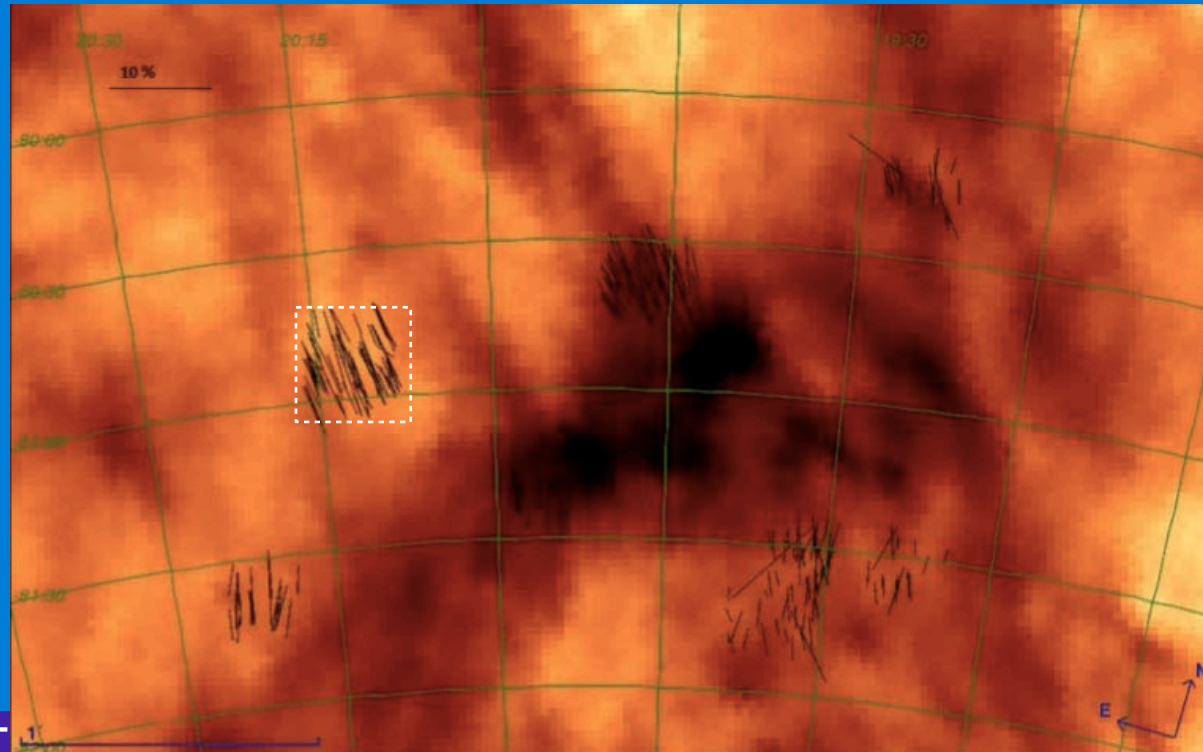
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Why?...

- **Combination of**
 - Wide field, 2 sq. deg optical telescope
 - and
 - Large field Imaging Polarimeter

IAGPOL
footprint



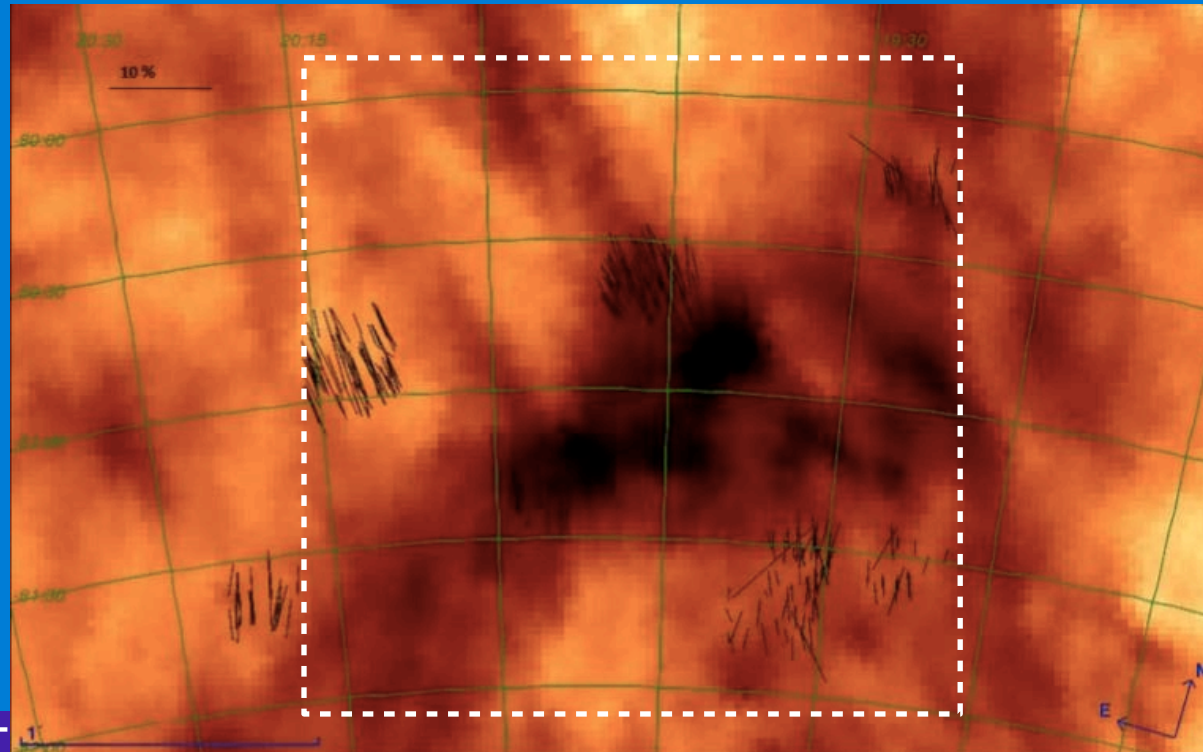
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Why?...

- **Combination of**
 - Wide field, 2 sq. deg optical telescope
 - and
 - Large field Imaging Polarimeter

**SOUTH POL
footprint**



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SOUTH POL

- **Robotic Telescope site**
 - Cerro Tololo Interamerican Observatory, Chile

Cerro Tololo & LNA



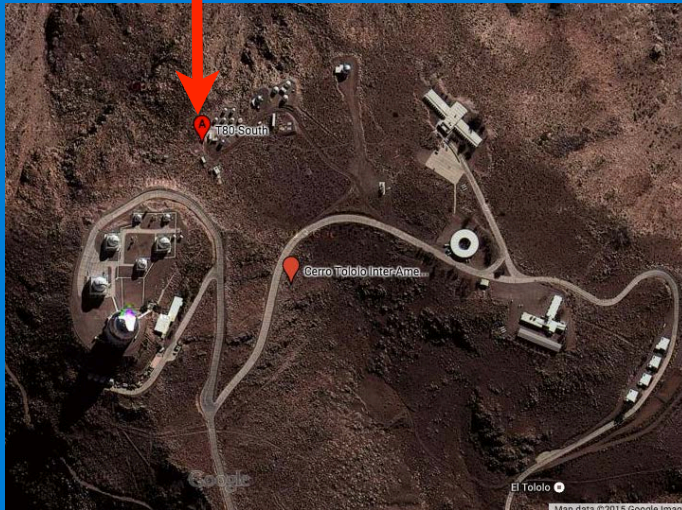
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SOUTH POL

- **Robotic Telescope site**

Cerro Tololo, aerial view



Tiago Ribeiro

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Milky Way at CTIO



AMM 2015

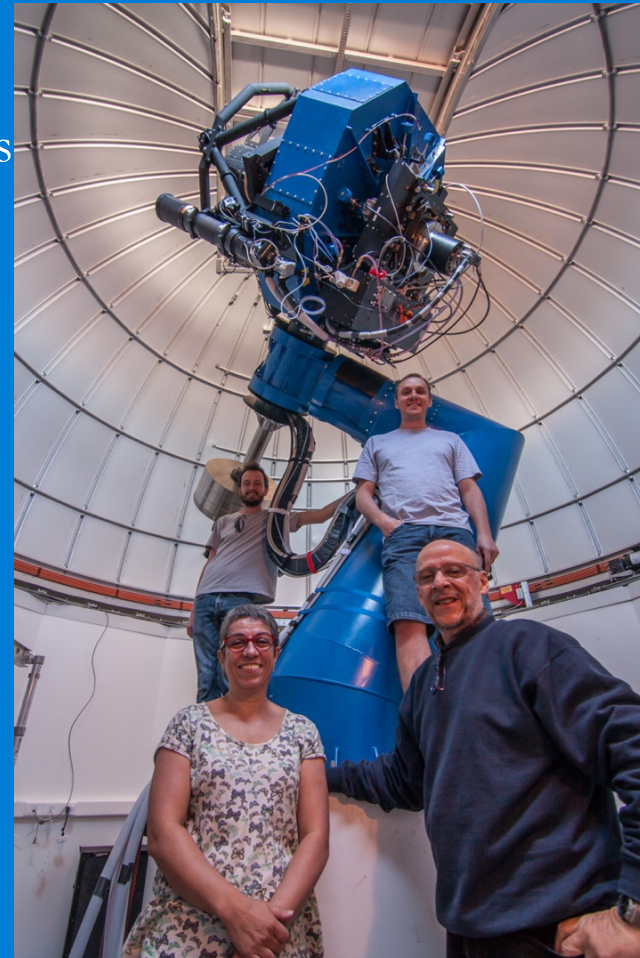


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Commissioning Data

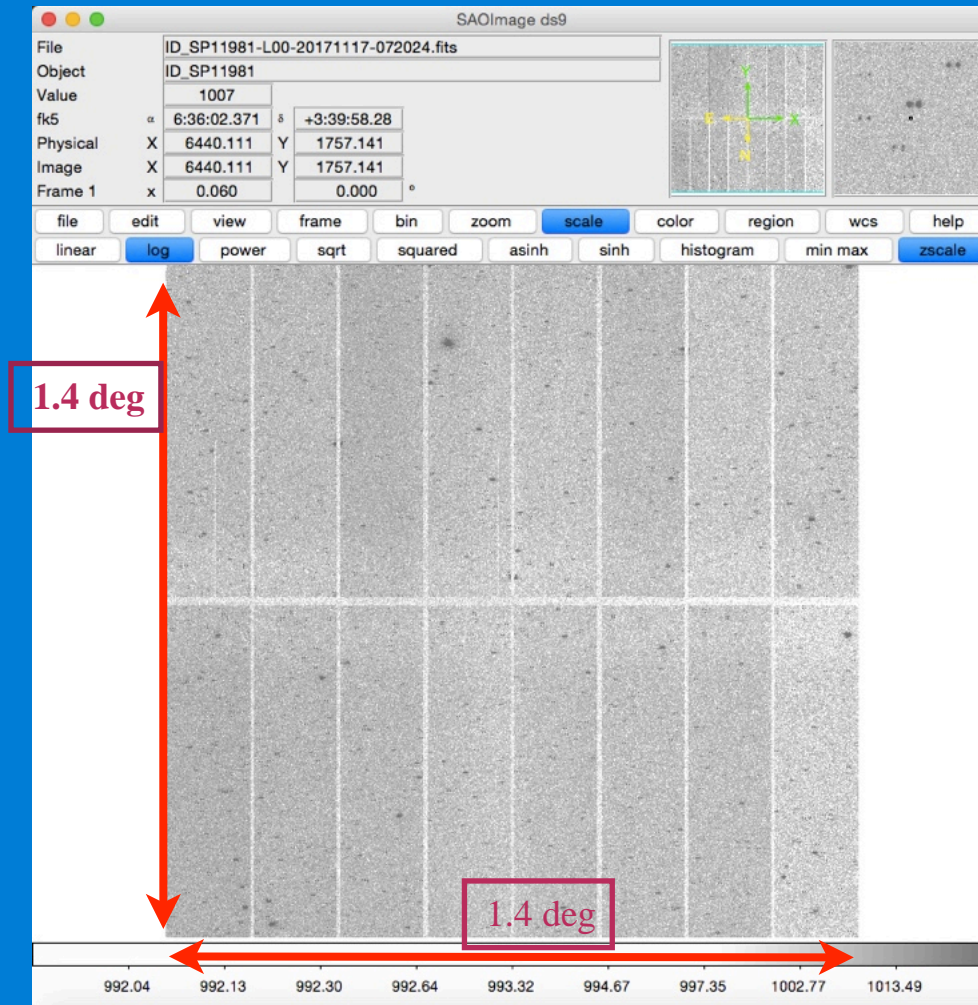
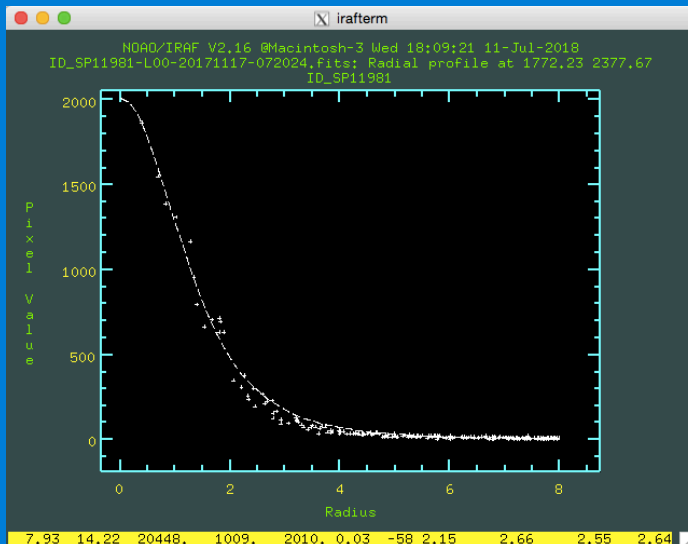
- **Run on November 13-17, 2017**
 - One night (Nov 17) worth of data
 - Six Fields of different characteristics
 - AGN
 - General ISM
 - Open Cluster, ...
 - **Results for Field ID_SP11981**





Commissioning Data

- **Field ID_SP11981**
 - 4 dithered images per waveplate position
 - IT = 4×10 sec
 - @ 8 pos. of waveplate
 - 22.5 deg apart



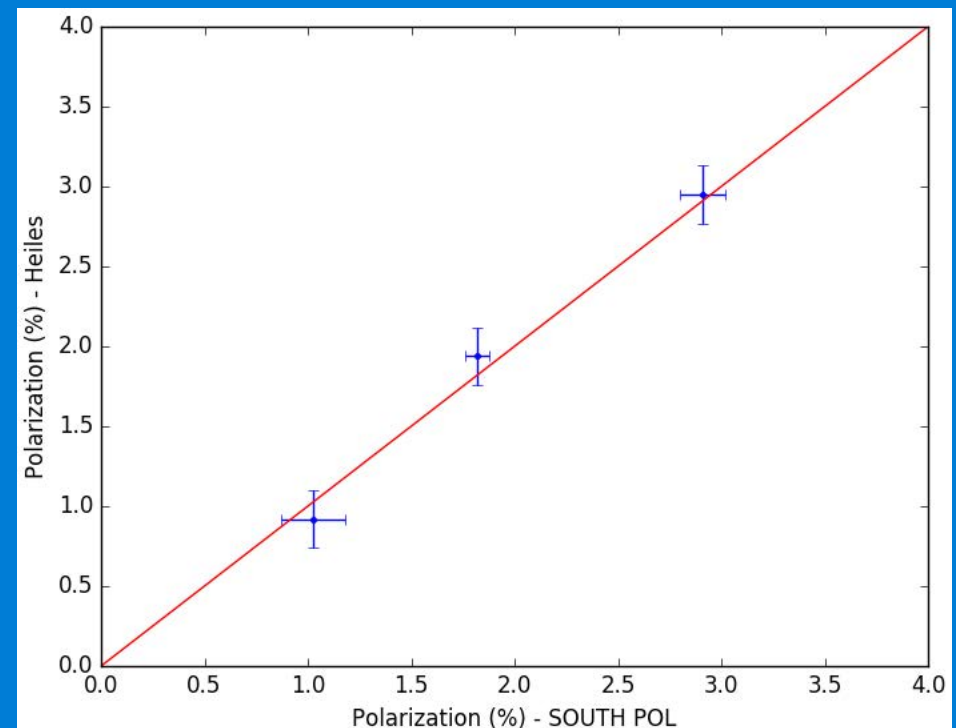
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Commissioning Data

- Three objects with measured polarization (Heiles' 2000) vs. SOUTH POL
- **RESULT:**
GOOD PRECISION

Field ID_SP11981



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Commissioning Data

Field ID_SP11981:

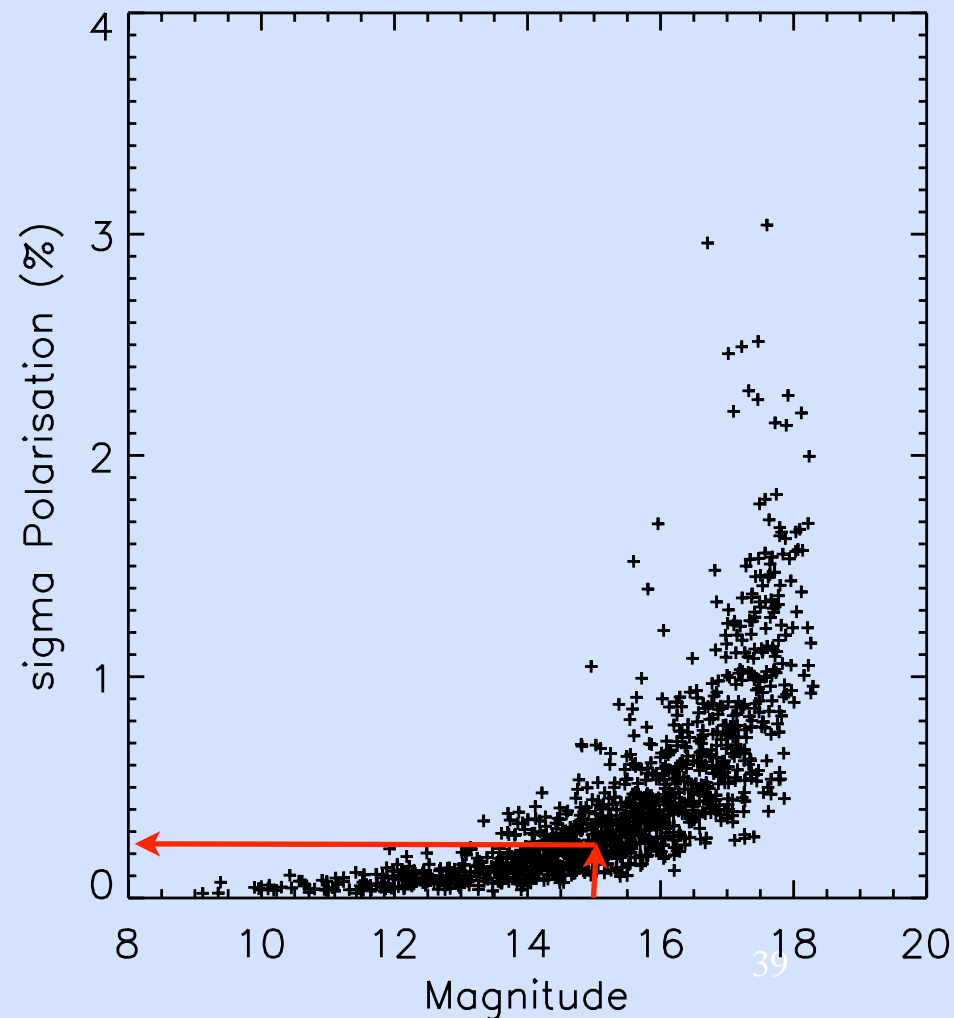
Polarization error
vs.
Magnitude

$\sigma_p = 0.25\%$ @ $V=15$
(40 sec/waveplate)

For a nominal exposure,
300 sec/waveplate:

$\sigma_p = 0.09\%$ @ $V=15$,

very close to the one expected
($\sigma_p = 0.1\%$ @ $V=15$)

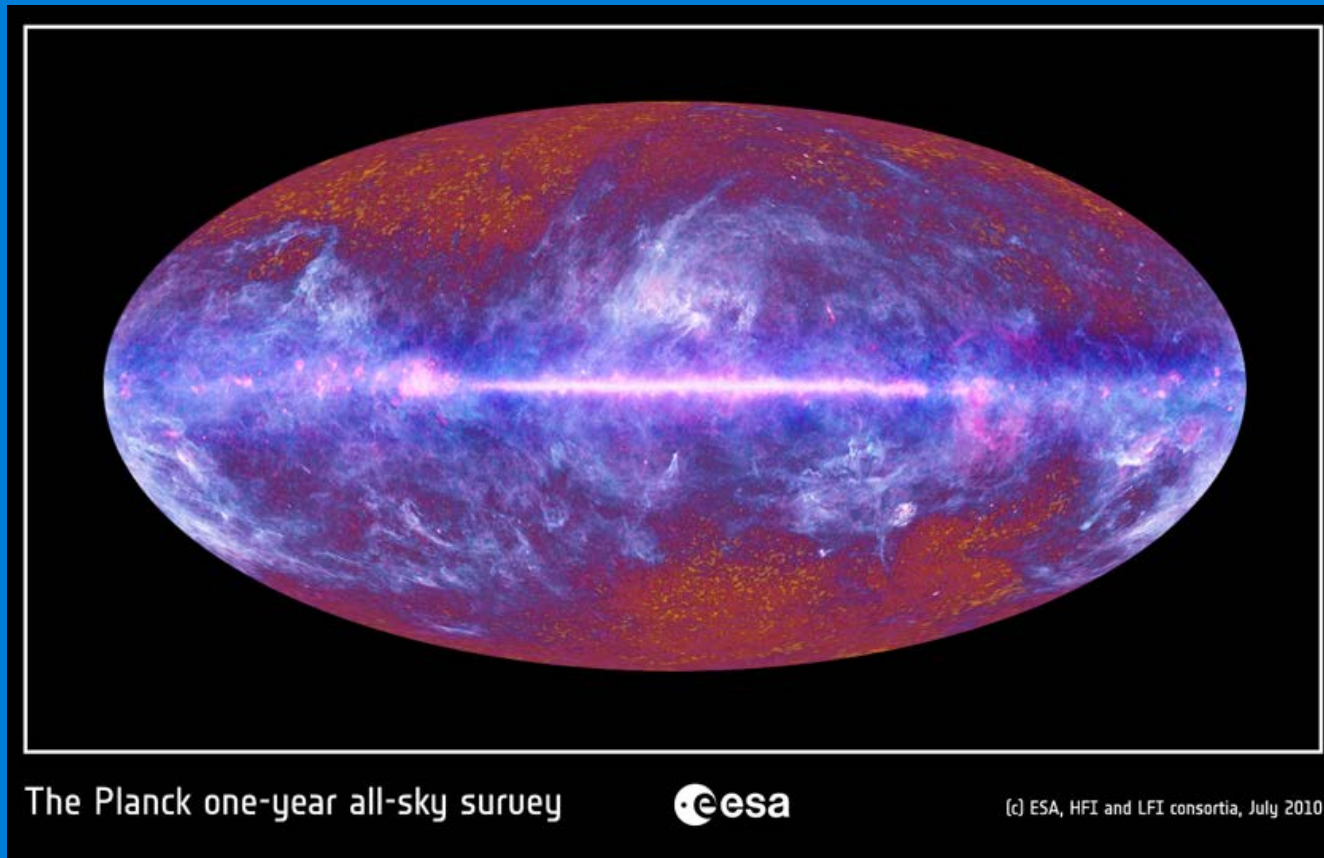


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Impact - CMB

- **Planck All-sky Survey**



The Planck one-year all-sky survey



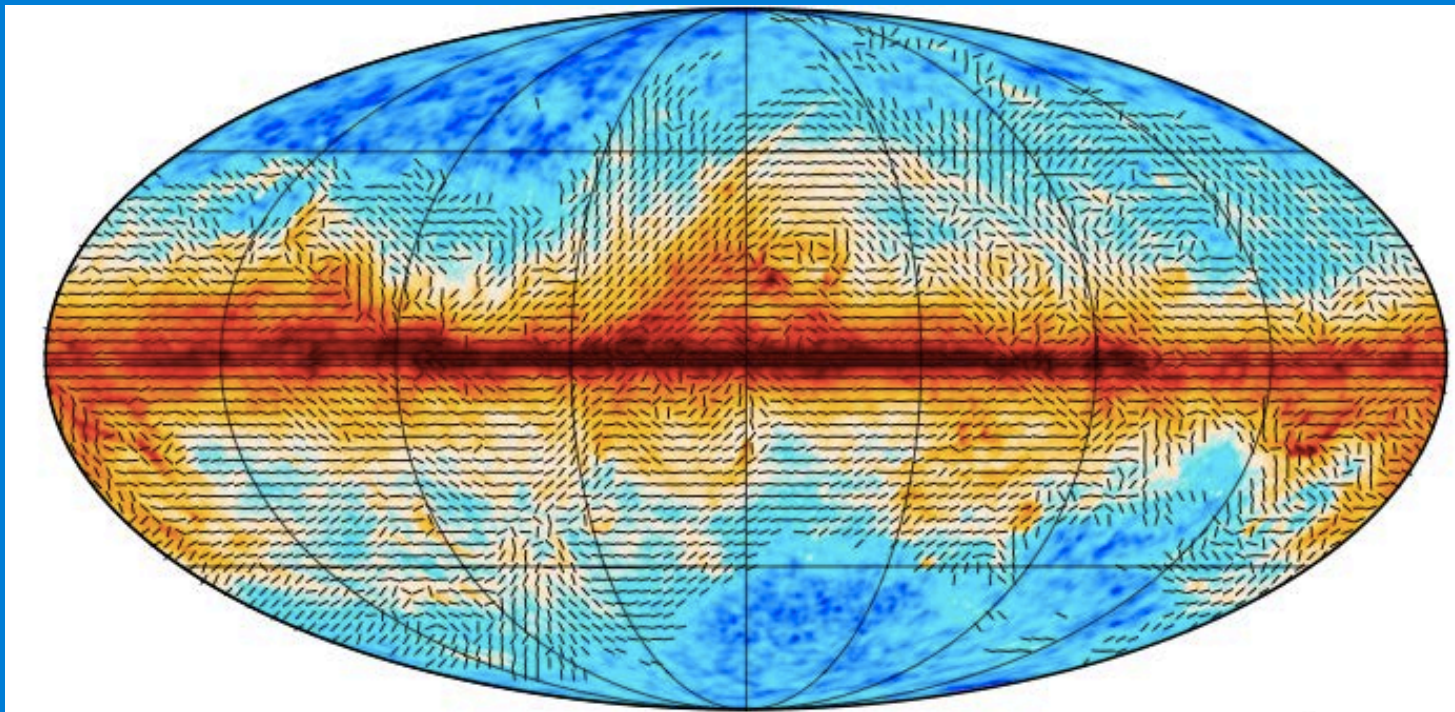
(c) ESA, HFI and LFI consortia, July 2010

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Impact - CMB

- **Planck All-sky Survey**
 - Galactic Dust Emission Polarization in the sub-mm (353 GHz)



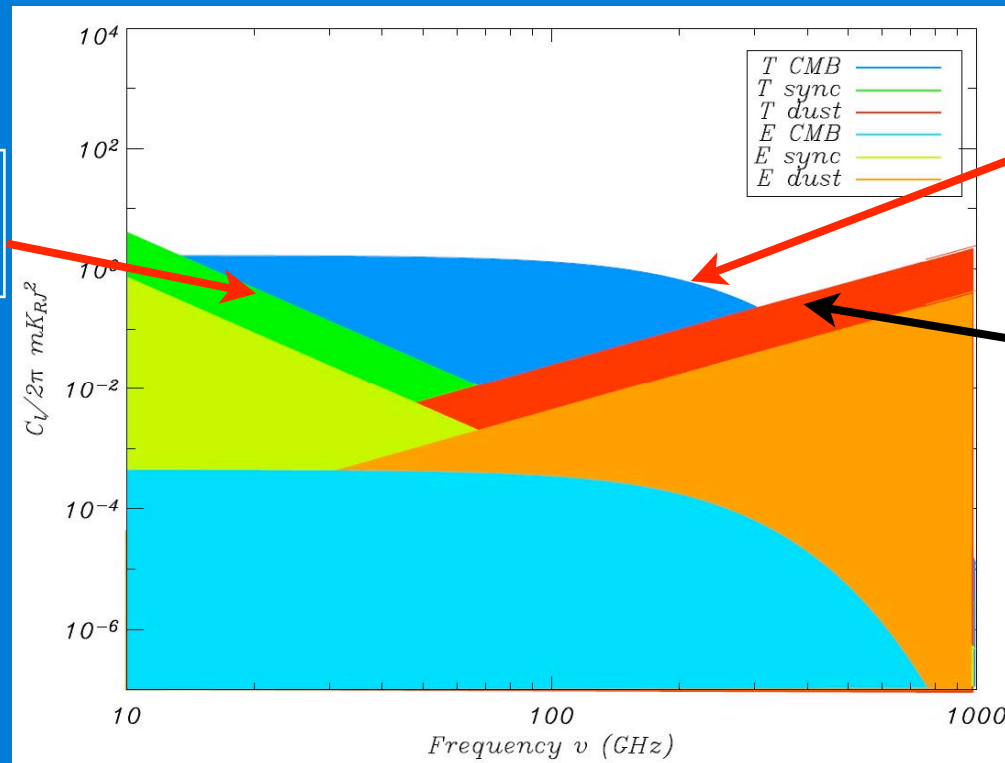
Bernard et al., Planck Collaboration (2014), arXiv

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Impact - CMB

- Galactic Foreground Intensity
 - For WMAP & Planck data



Synchrotron
Foreground

CMB

Dust Foreground

Aumont 09

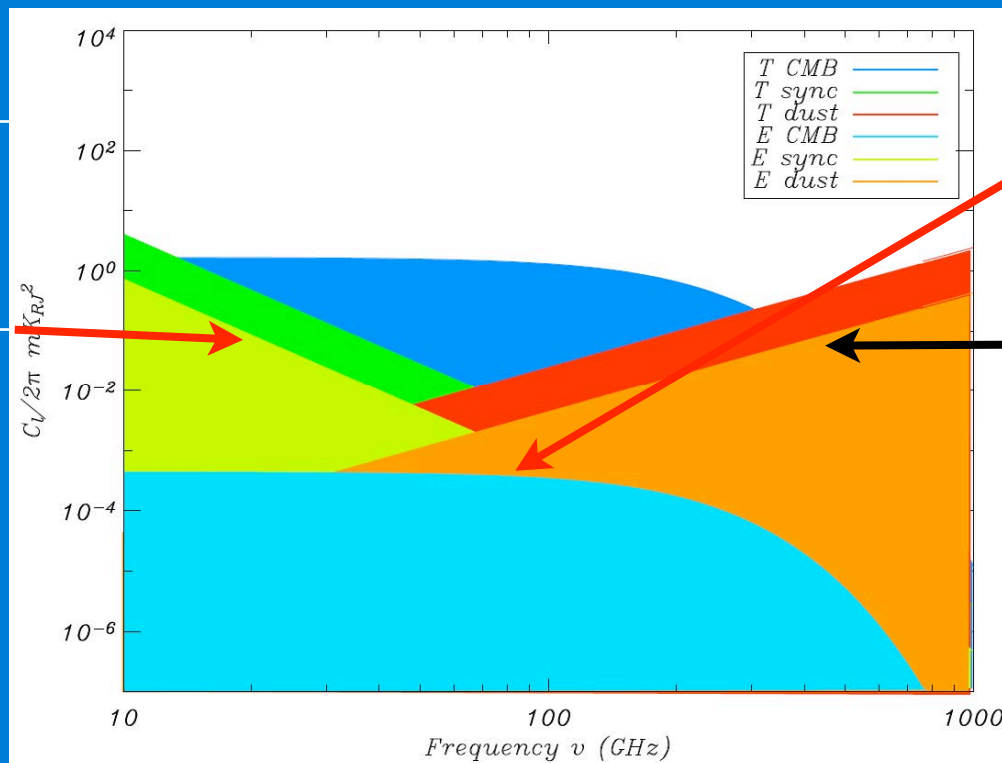
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Impact - CMB

- Galactic Foreground Polarization
 - For WMAP & Planck data

Synchrotron
Foreground
Polarization



CMB
Polarization

Dust Foreground
Polarization

Aumont 09



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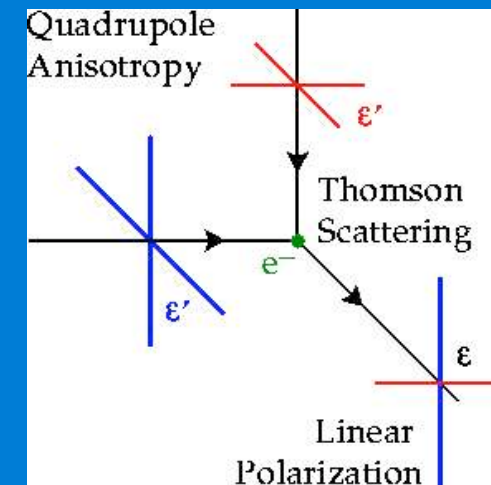


Impact - CMB

- Example of a partially polarized light beam:

Cosmic Microwave Radiation

- hotter: 
- colder: 
- Temperature fluctuations produce a linear polarization of the **CMB**

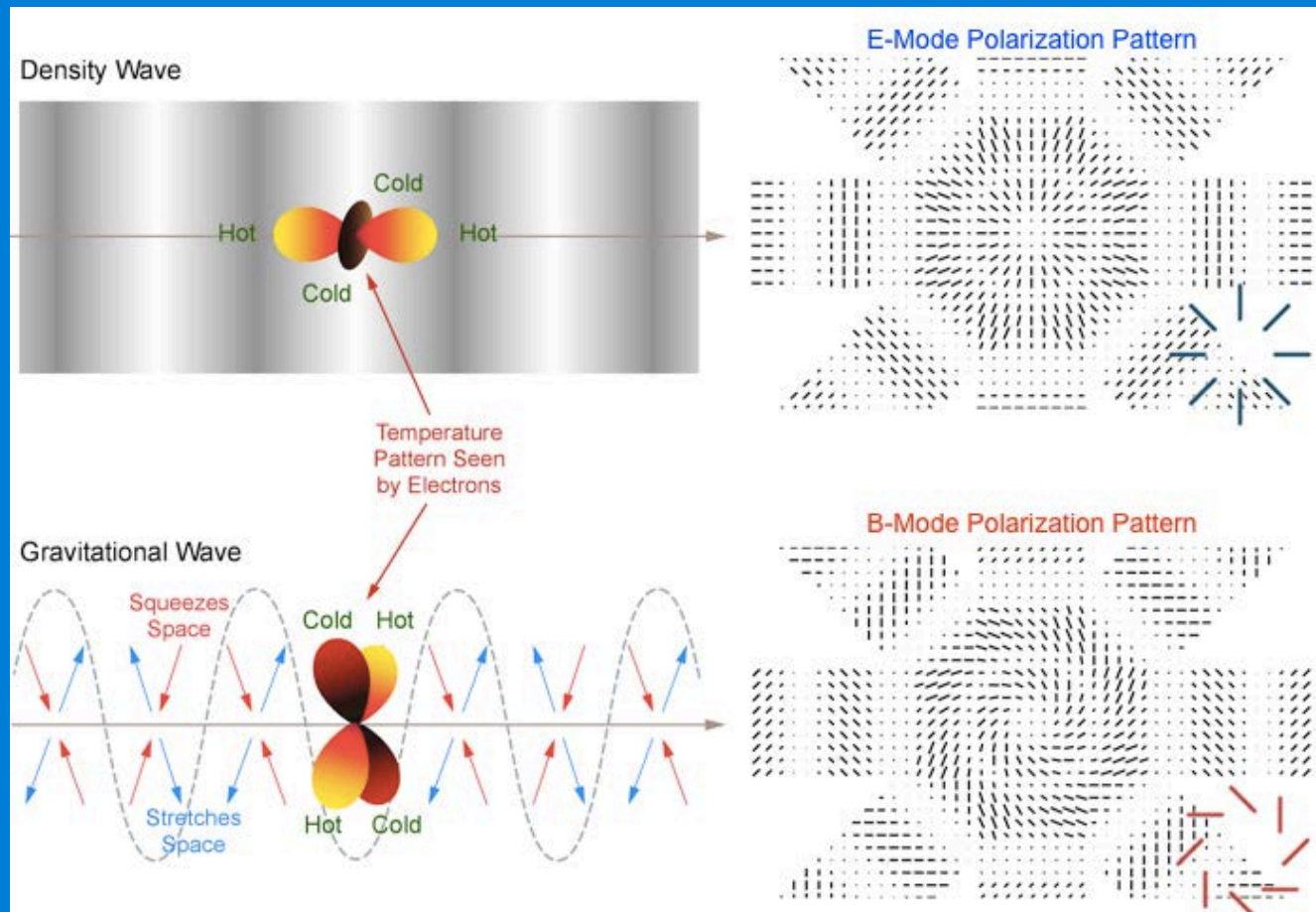


<http://background.uchicago.edu/~whu/polar/webversion/polar.html>

-
- *All-Sky Polarization Survey*



Impact - CMB

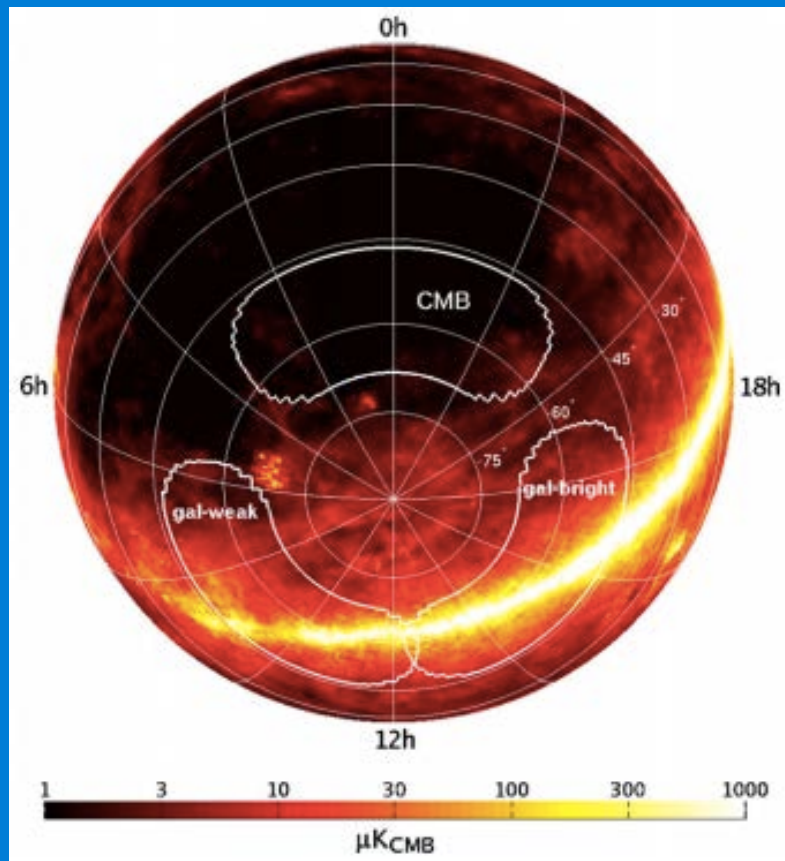


Dowell et al. 2014; BICEP2 Collaboration
45

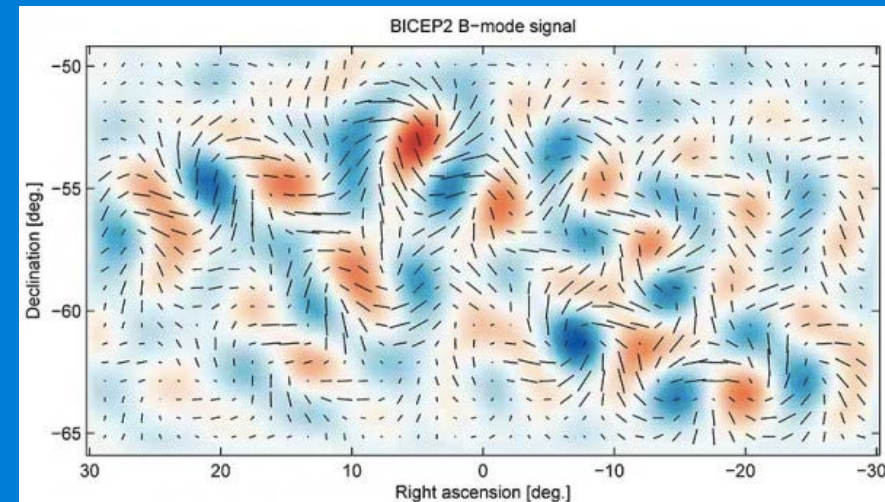
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- *All-Sky Polarization Survey*



Impact - CMB



Chiang et al. 2010



Dowell et al. 2014; BICEP2 Collaboration

Contribution from Galactic Dust to BICEP2 results?

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- *All-Sky Polarization Survey*



Impact - CMB

- For proper subtraction & analysis of CMB polarization:
 - Much improved sampling of starlight polarization is needed
 - **SOUTH POL & SGMAP** will hence be important
 - providing good sampling of interstellar polarization
 - for analysis of past & current missions: WMAP, Planck, BICEP2
 - for future missions: CMB-S4, Spider

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- *All-Sky Polarization Survey*



Impact - Extragalactic Astronomy

- **Identification of EGRET & FERMI sources**
 - highly polarized blazars
- **Known blazars**
 - 450 Blazars with $R < 19$ e $dec < -15^\circ$
 - Massaro et al. (2009)
 - $R_{\text{median}} \sim 17$
 - ⇒ SOUTH POL: unbiased survey
- **Multi-messenger Astrophysics**
 - GW + ELM sources
 - NS + BH event:
 - expected to be very asymmetrical

Table 1. Polarimetric accuracy, in %, with the 80cm Telescope(*).

V (mag)	8X60 sec	8X300 sec
10	0.022	0.010
11	0.035	0.016
12	0.055	0.025
13	0.088	0.039
14	0.140	0.062
15	0.223	0.100
16	0.361	0.160
17	0.600	0.263
18	1.051	0.449
19	2.011	0.830

(*). For a $22\text{mag}/\text{arcsec}^2$, air mass=1, readout noise= $5e^-$.

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- *All-Sky Polarization Survey*



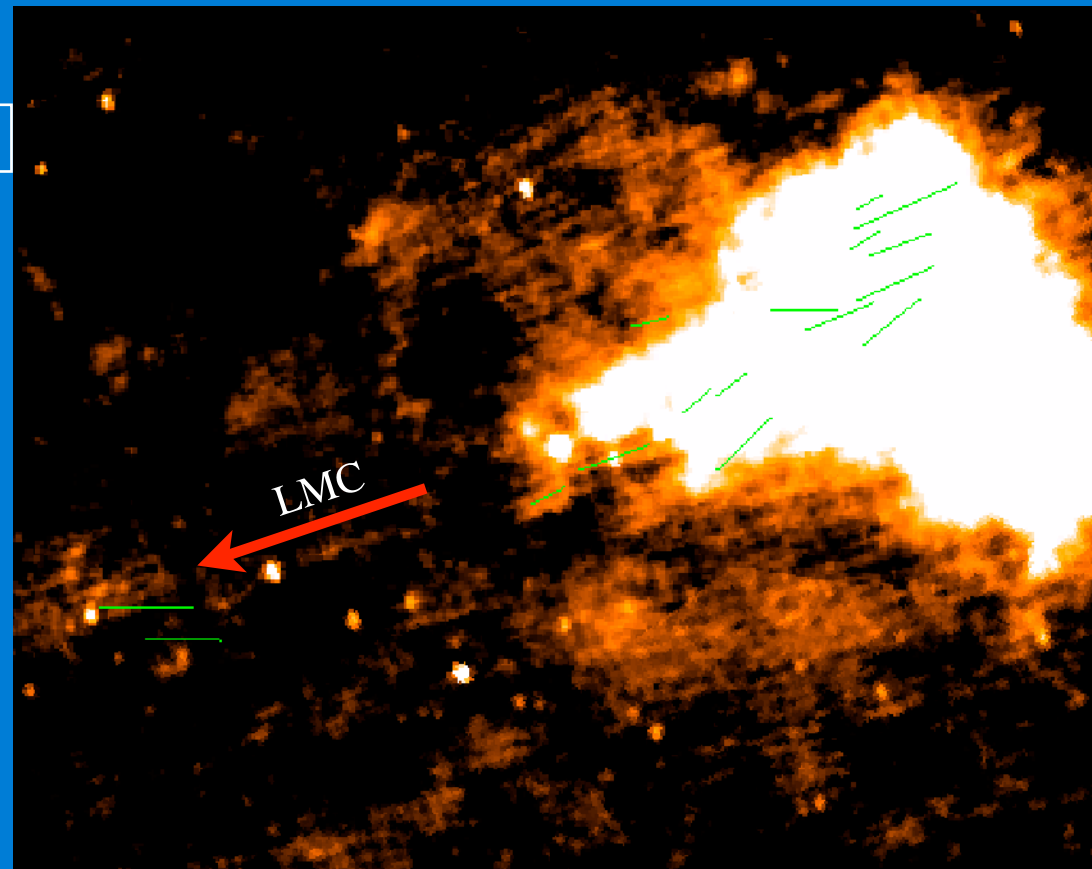
Impact - Extragalactic Astronomy

- Magnetic Field in close-by galaxies

Gomes et al. 2015

SMC Magnetic field
is along
SMC-LMC direction

Also:
Mao et al. 2008, 2012



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- *All-Sky Polarization Survey*

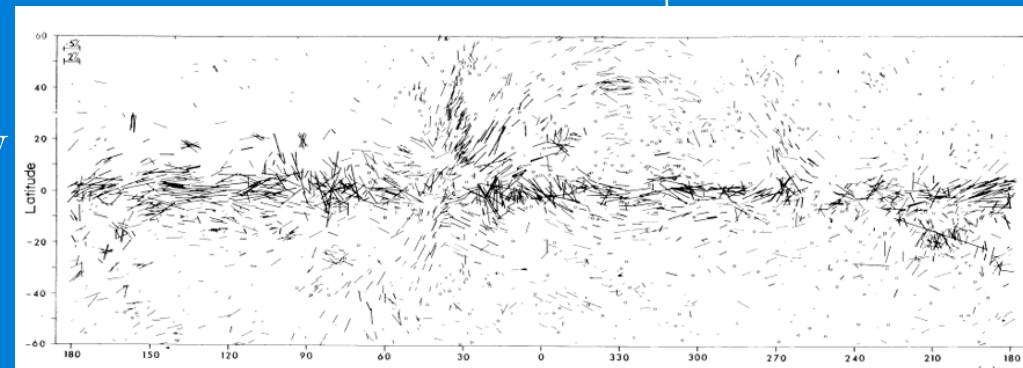


Impact - Galactic Astronomy

- **Interstellar Medium & Star Formation**
 - **Magnetic Field structure of the Galaxy**
 - with parallaxes from GAIA
 - Large (\sim kpc) & small (\lesssim pc) scales

Mathewson & Ford 1970

- **Grain alignment theory**
 - statistically sound basis



- **Magnetic Field topology across Molecular Clouds**
 - From **less dense** regions (optical, SOUTH POL)
to **denser** regions (sub-mm, Planck)

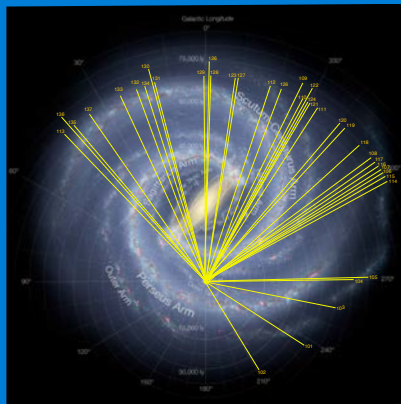
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- *All-Sky Polarization Survey*



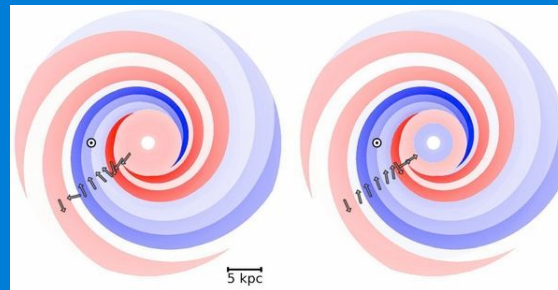
Areas of Research

- **Interstellar Medium & Star Formation**
 - **Magnetic Field structure of the Galaxy**
 - with parallaxes from GAIA
 - Large (\sim kpc) & small (\lesssim pc) scale

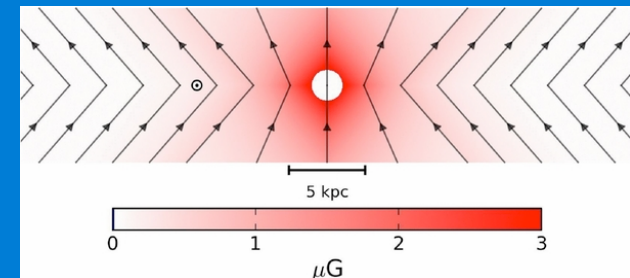
Benjamin



LNA data, Ribeiro et al. 2018



Radio Synchrotron;
Jansson & Farrar 2012



- **3-D structure** of the Magnetic Field (w/ M. Haverkorn/Radboud)
 - In development, using LNA data (Magalhaes et al. 2005)
 - Consistency with Synchrotron, Faraday rotation & Dust Polarization required₅₁

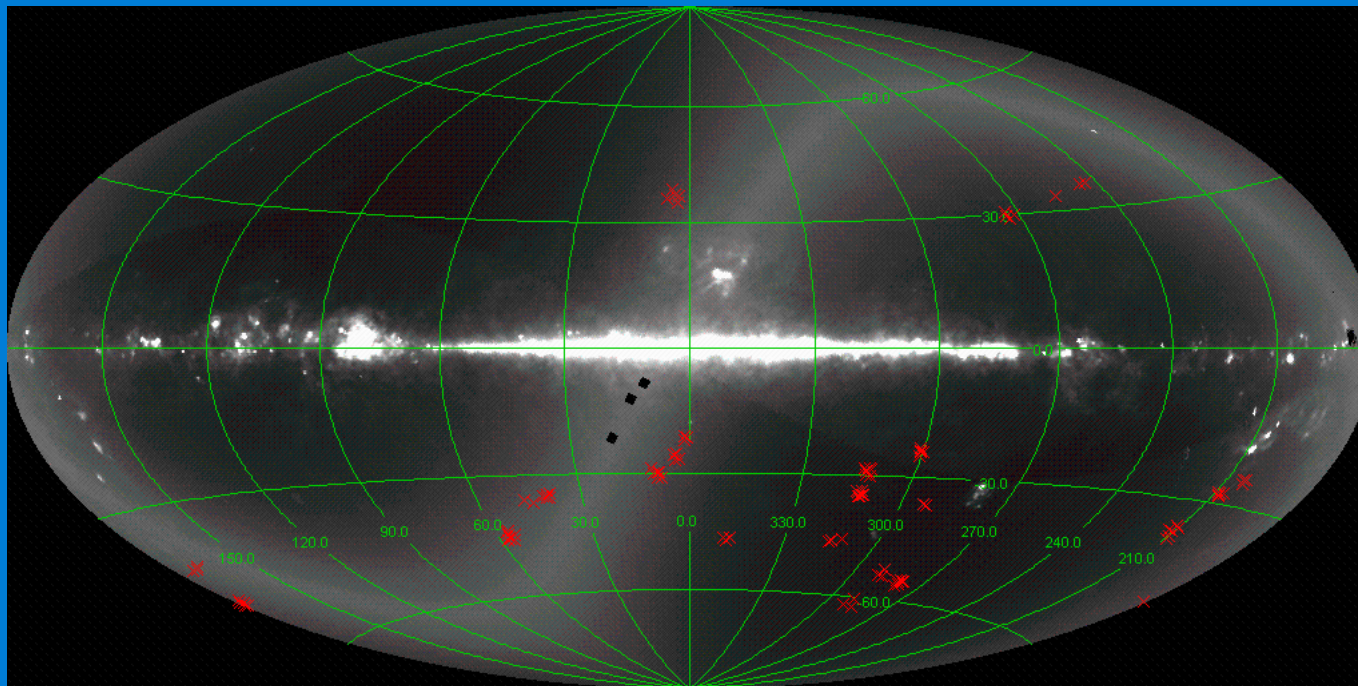
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Impact - CMB

High Galactic Latitude Clouds

- Important for knowledge of Galactic Foreground for CMB
- Provide structure of **B-field** away from the Galactic Plane



x =
Optical Polarization
Survey at IAG

-
- *All-Sky Polarization Survey*



Why?... B-field strength

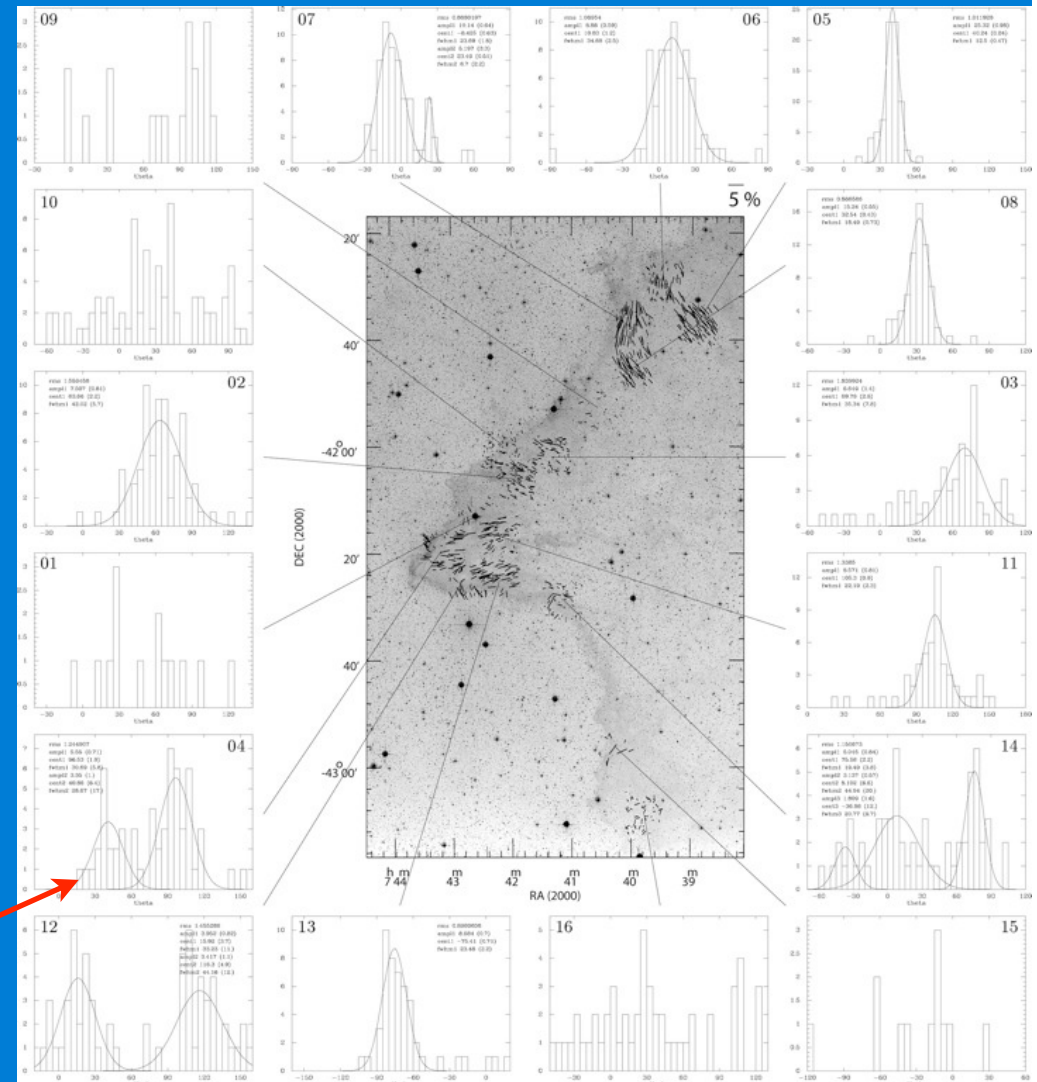
- Chandrasekhar & Fermi method
 - C & F (53)
- Equipartition between kinetic & perturbed magnetic energies
 - + isotropic rms velocity:

$$\frac{1}{2} \rho \delta V_{\text{LOS}}^2 \sim \frac{1}{8\pi} \delta B^2$$

$$\Rightarrow B_{\text{sky}} + \delta B \approx \sqrt{4\pi\rho} \frac{\delta V_{\text{los}}}{\tan(\delta\phi)}$$

Falceta-Gonçalves et al. (08)

Pereyra & AMM 07



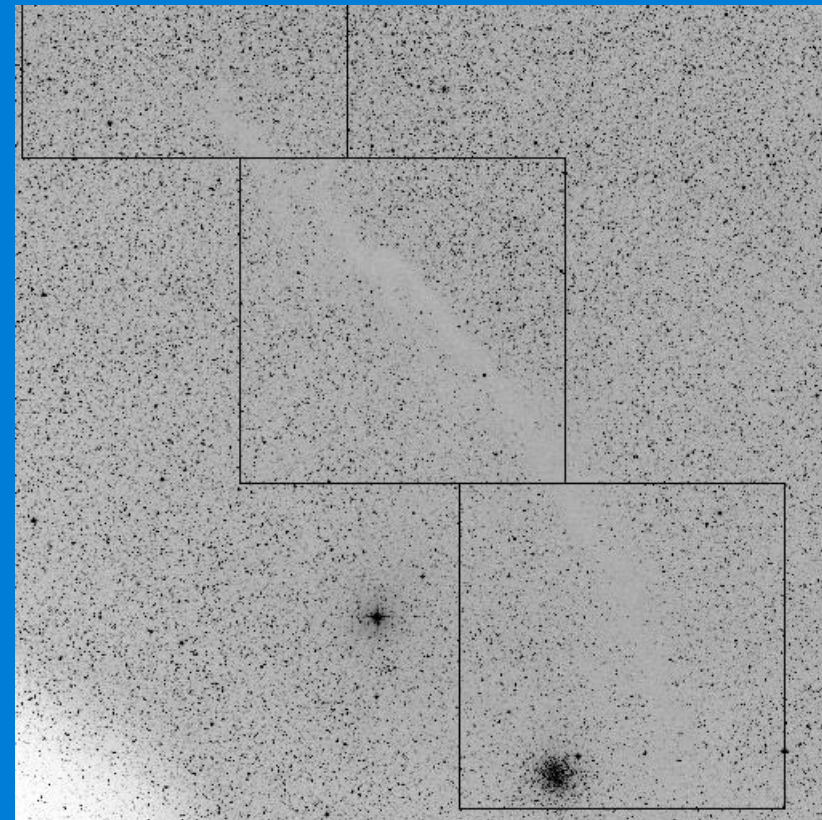
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- *All-Sky Polarization Survey*



Impact - Galactic Astronomy

Magnetic Field in Dark Clouds

- What is the role of **B** in cloud collapse?
- Musca Dark Cloud
 - Pereyra & AMM 2004



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- *All-Sky Polarization Survey*



Impact - Galactic Astronomy

Ribeiro 2013

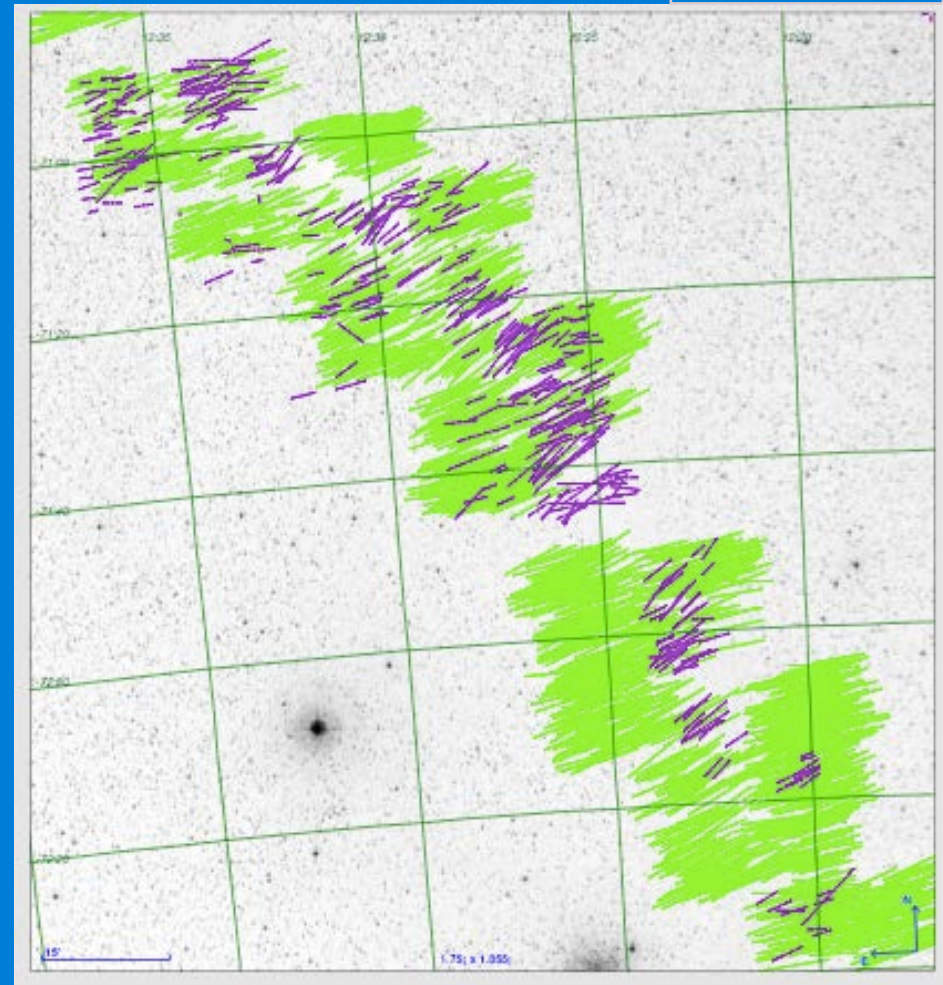
- **Mapping the Musca Dark Cloud**

- Pereyra & AMM 2004
- Ribeiro & AMM 2014

— Visual
— NIR

- **Combination of**
 - Optical (SGMAP+SOUTH POL)
 - NIR (e.g., with TAO 6.5m)
 - ALMA

would be very powerful!



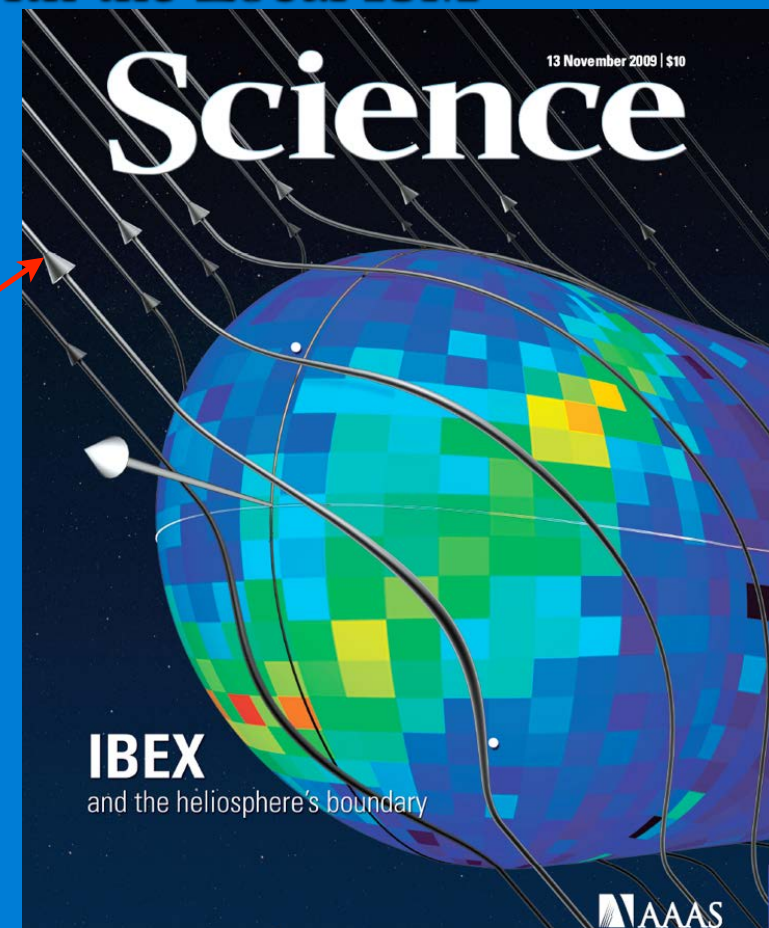
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- *All-Sky Polarization Survey*



Impact - Galactic Astronomy

- **IBEX probe:**
Detection of the SS interaction with the Local ISM
 - ring of energetic particles

Galactic Local Magnetic Field



McComas et al. 2009

www.nasa.gov

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- *All-Sky Polarization Survey*



Impact - Stellar Astrophysics

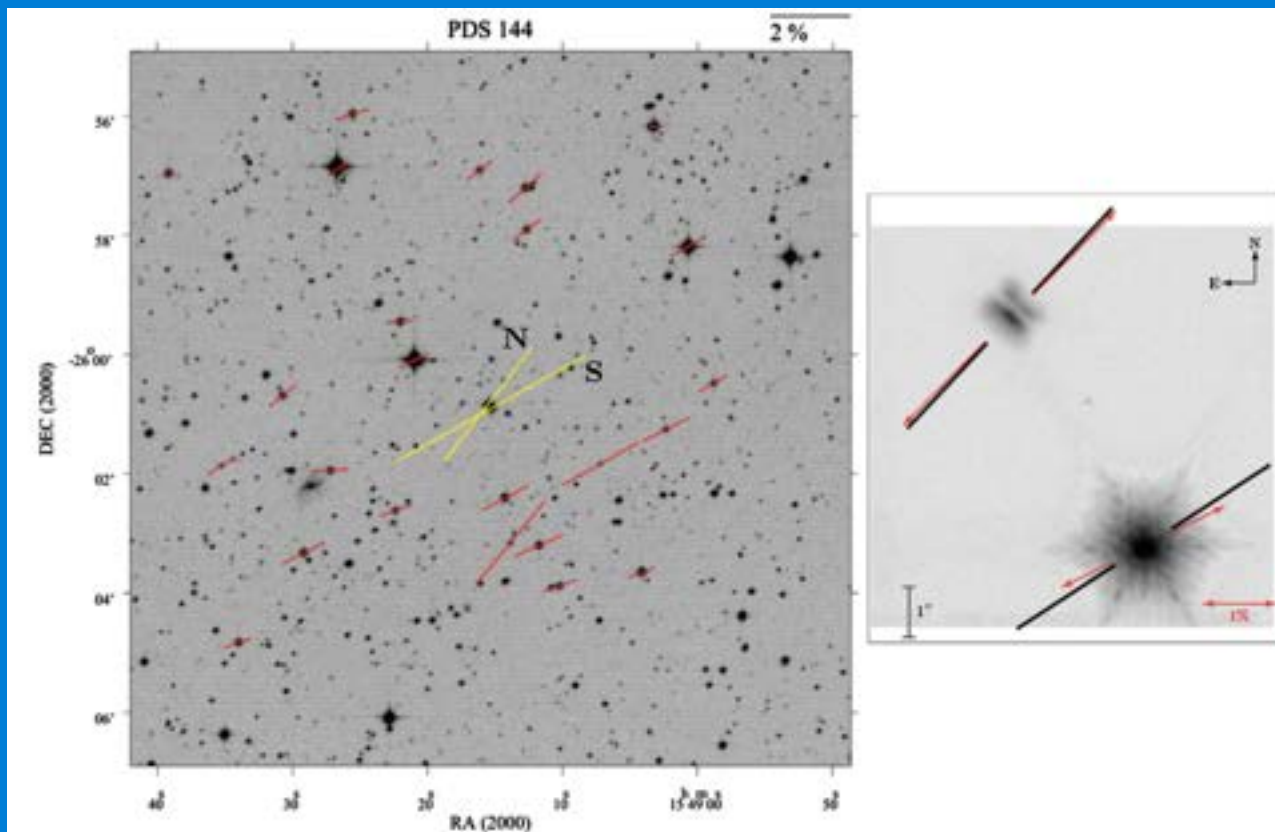
- **Stellar Astrophysics**
 - Statistics & Time evolution of explosive phenomena
 - GRBs
 - GRBs 030329, 130427
 - SNe
 - Circumstellar environments
 - YSOs
 - Evolved objects
 - Galaxy & Magellanic Clouds
 - Census of magnetic White Dwarfs

-
- *All-Sky Polarization Survey*



Impact - Stellar Astrophysics

- Polarimetry of Herbig Ae/Be objects



Pereyra et al. 2012

Rodrigues et al. 2009

Red arrows:
H-band
polarization

PDS144 N:
Keck AO,
(Perrin et al. 2006)

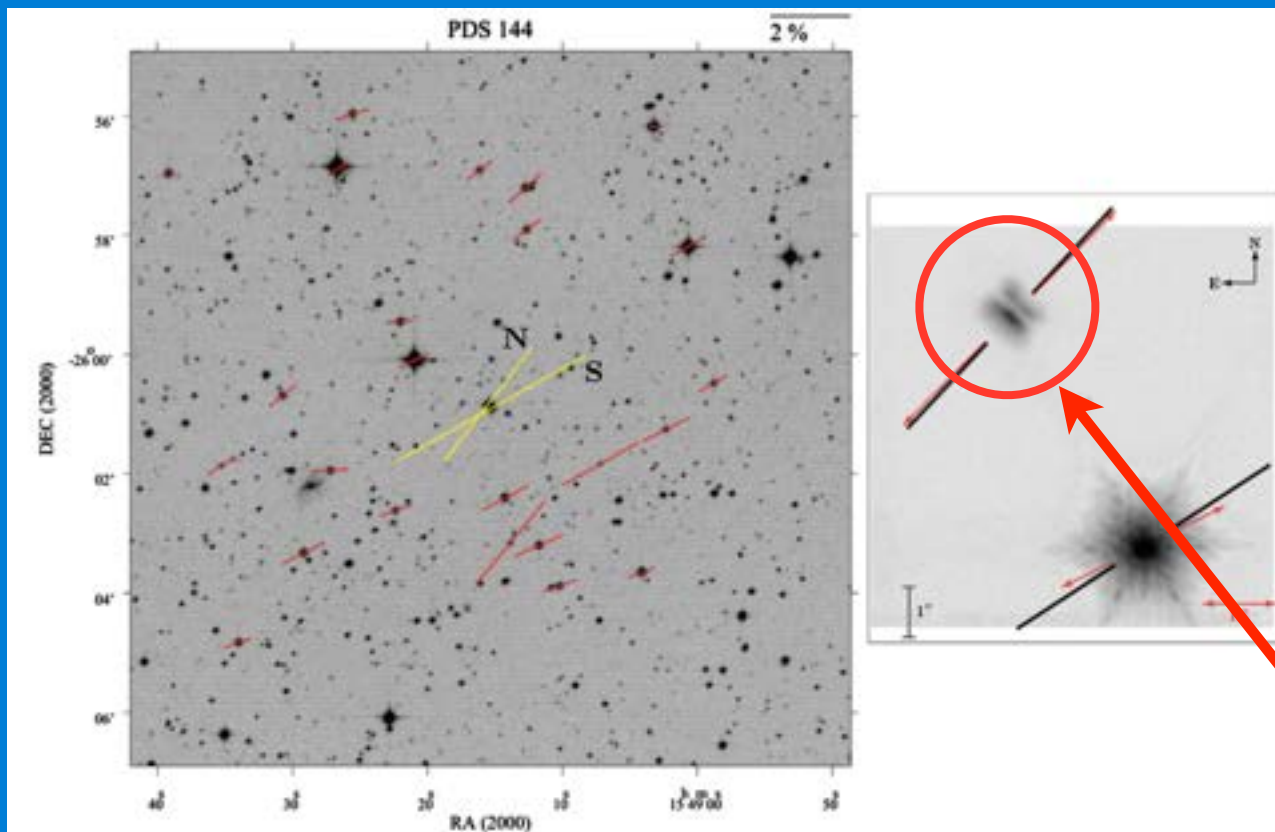
Black arrows:
detected jets
(Grady et al. 2009)

-
- *All-Sky Polarization Survey*



Impact - Stellar Astrophysics

- Polarimetry of Herbig Ae/Be objects



Pereyra et al. 2012

Red arrows:
H-band
polarization

PDS144 N:
Keck AO,
(Perrin et al. 2006)

Black arrows:
detected jets
(Grady et al. 2009)

Polarization is indeed
 \perp to disk

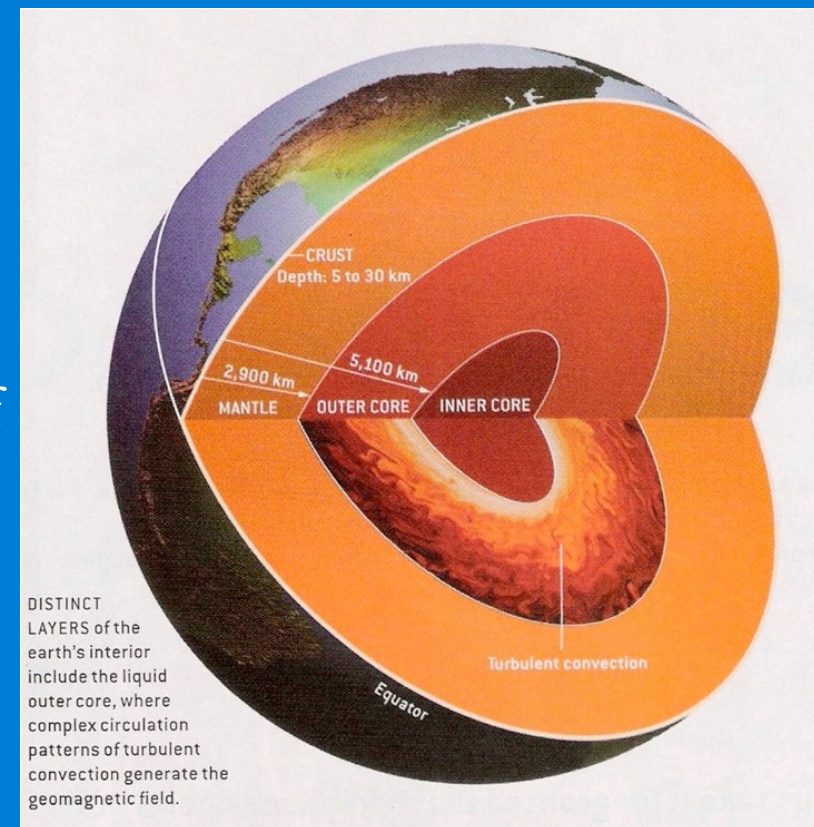
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- *All-Sky Polarization Survey*



Impact - Stellar Astrophysics

- **Origin of Earth's Magnetic Field?**
 - Dynamo from Earth's rotation
 - Earth's rotation is derived from Protosolar Nebula
 - Nebula probably had memory of ISM B field

Connection between
**Earth's Magnetic Field &
Interstellar Field !**



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- *All-Sky Polarization Survey*



Impact: Solar System Astronomy

- **Solar System**
 - Asteroids
 - Determinação de albedos, hence **sizes**
 - Inventory & size distribution
 - Curves of **Polarization vs. phase**:
clarify population divisions among Main Belt, NEOs, etc.

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- *All-Sky Polarization Survey*



Future Meetings

- **Next in the ASTROPOL series:**
 - **ASTROPOL 2020**
 - When: March 2020
 - Where: Hiroshima, Japan
 - Stay tuned...



02

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- *All-Sky Polarization Survey*



Participation of TAO

- Possible installation of SOUTH POL polarimeter @ mini-TAO
 - Feasibility will be object of study (Doi-san, Motohara-san)
 - In addition to general goals of All-sky Polarization Survey
 - Sinergies of 6.5m TAO telescope & polarimetry could be explored
E.g., Optical/NIR study of explosive events (SNe, GRBs, GW+ELM)
 - Unique, competitive capability in the Southern Hemisphere

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- *All-Sky Polarization Survey*



All-Sky Polarization Survey

- **SGMAP + SOUTH POL**
 - unprecedented undertaking in the optical
 - will impact several areas
 - from Cosmology to Solar System studies
 - accuracy of 0.1% down to $V=15-16$
 - will cover **all sky** in first 2-4 observing-yrs

-
-
- *All-Sky Polarization Survey*



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Thank you!

どうもありがとうございました！

Muito obrigado!

Muchas gracias!