SOUTH POL

Revealing the Polarized Southern Sky

Antonio Mário Magalhães

IAG
Universidade de São Paulo

FAPESP
Fundação de Amparo à Pesquisa do Estado de São Paulo

SOUTH POL

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- Marcos **Diaz** (**IAG-USP**)
- Alex **Carciofi** (**IAG-USP**)
- Claudia V. **Rodrigues** (**INPE/DAS**)
- Antonio **Pereyra** (**Obs. Nacional, RJ**)

Funding:

- **Polarimeter Project**
  - Keith **Taylor**
  - Eng. Lucas **Marrara** (São Carlos, mechanical design)
  - El. Eng. Carlos Eduardo **Fermino** (Solunia, Araraquara)

Summary

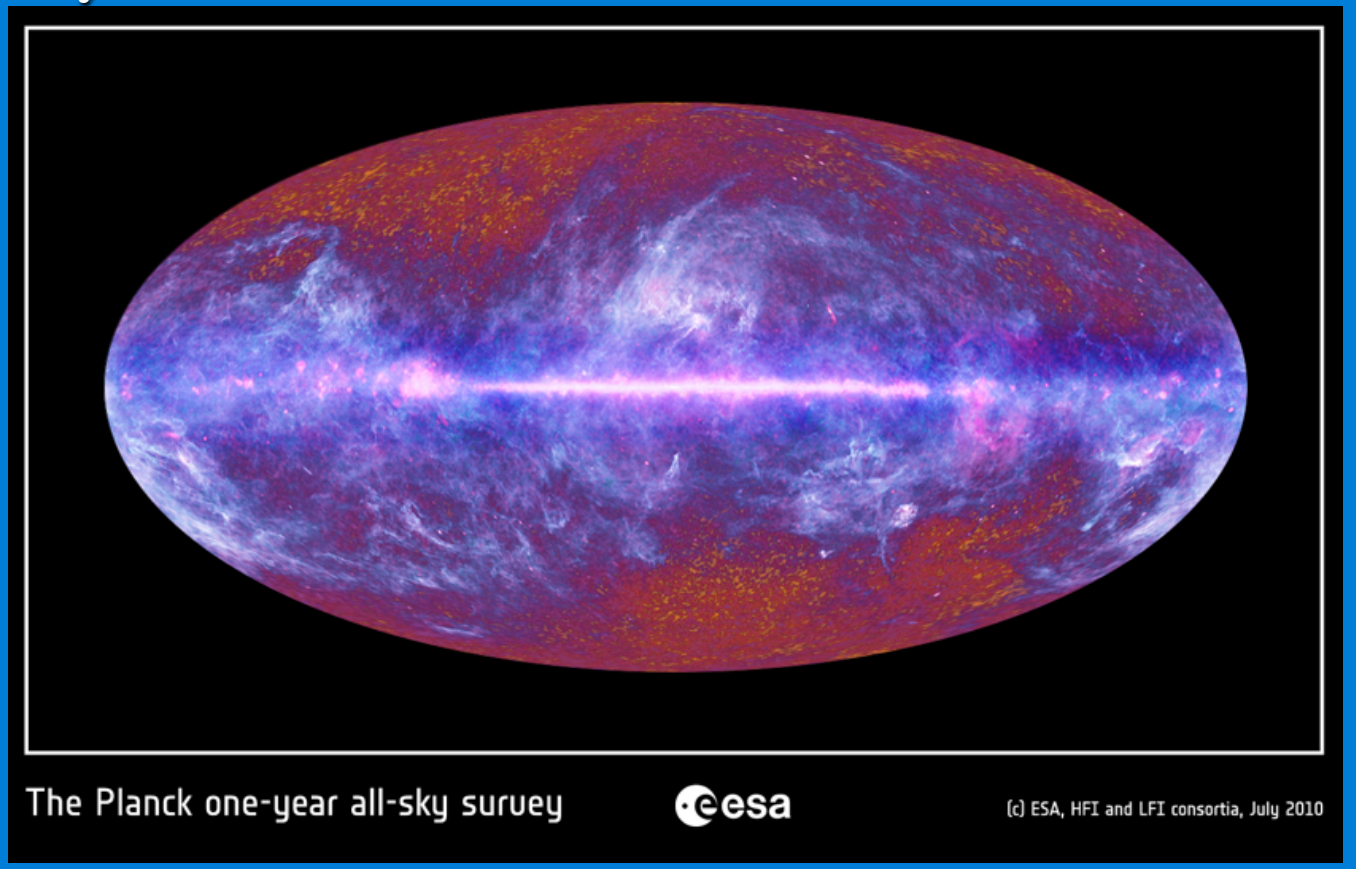
- **INTRODUCTION**
- **SOUTH POL**
  - What?... Why?... How?...
- **SOUTH POL's Impact**
  - CMB
  - Extragalactic Astrophysics
  - Interstellar Medium (ISM)
    - Galaxy & Magellanic Clouds
    - Dark clouds
  - Stellar Astrophysics
  - Solar System
- **FUTURE**
- **CONCLUSIONS**

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

Introduction

- **Sky in the sub-mm: Galactic Dust Emission**

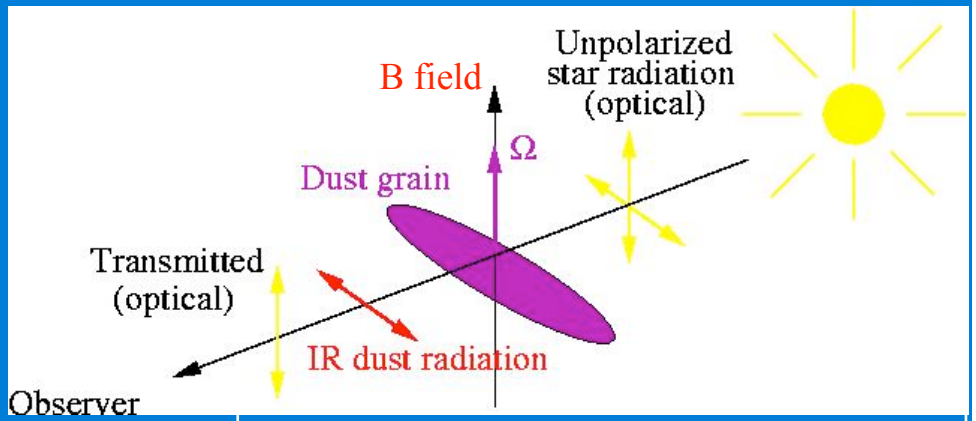


Introduction

- **Polarization arises from**
  - **Dust grains**

    aligned by

  - ISM's **Magnetic Field, B**

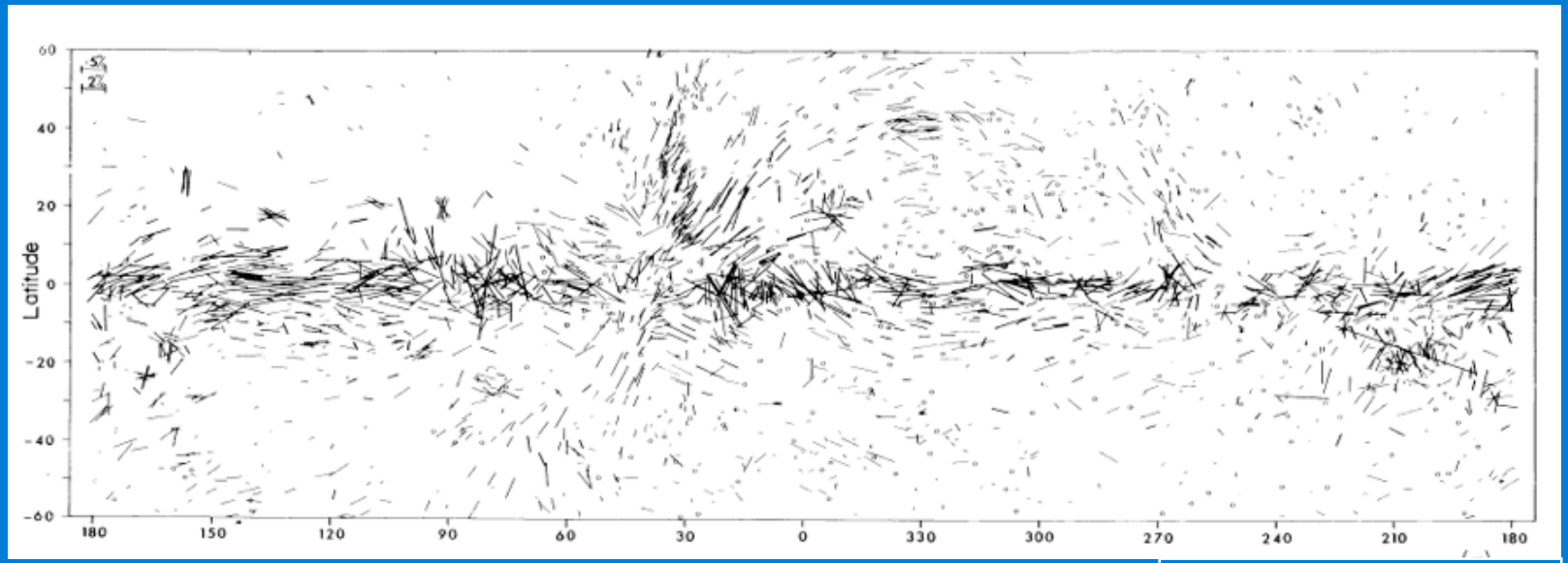


adapted from Ponthieu, Lagache; www.planck.fr

- **Polarization provides info on**
  - **Dust properties**
    - size distribution, composition
  - **B_{sky}**
    - B component projected on the sky

Introduction

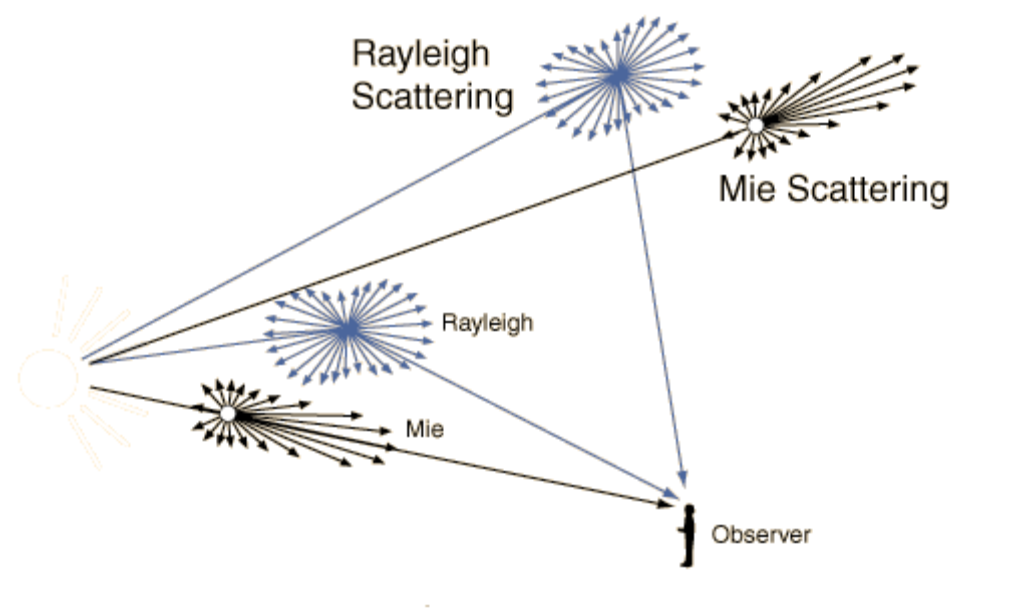
- **Optical Starlight Polarization: Galactic Magnetic Field**



Mathewson & Ford 1970

Introduction

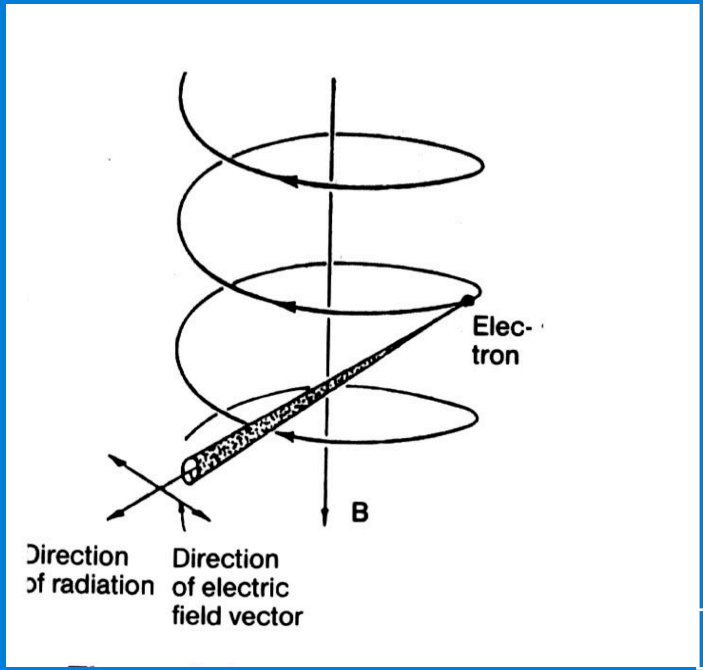
- **Polarization by Scattering**
  - **Rayleigh pattern: electrons, atoms, small dust grains**
    Mie pattern: dust



http://www.giangrandi.ch/optics/polarizer/polarizer.shtml

Introduction

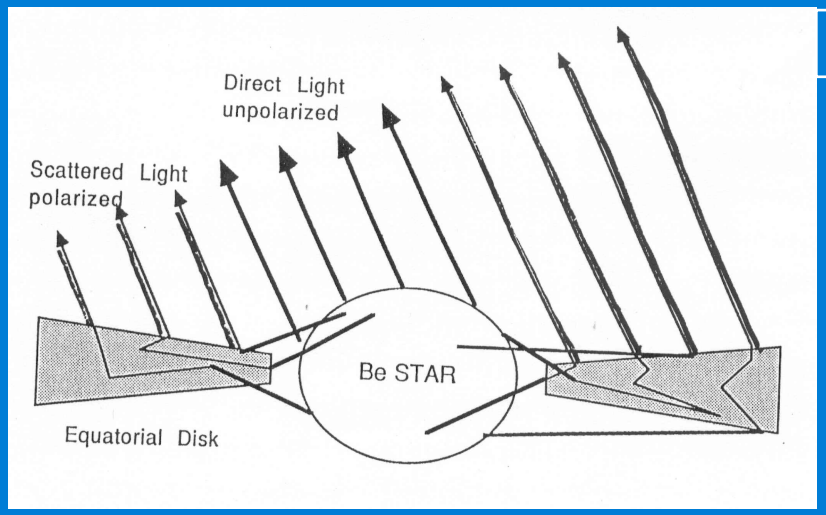
- **Polarization from Synchrotron Radiation:**
  - relativistic electrons



Karttunen et al. 1996

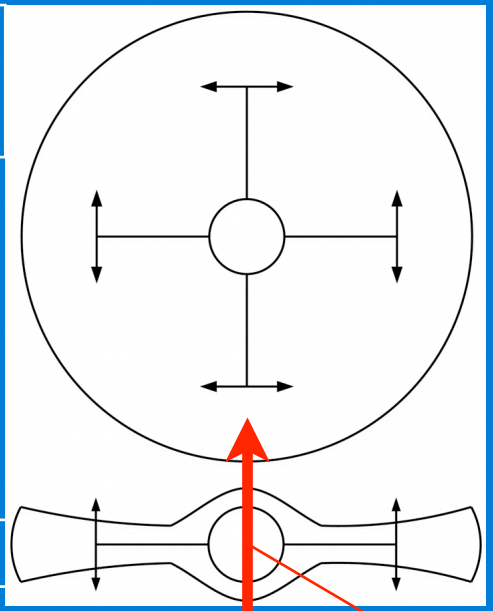
Introduction

- Polarization by **e⁻ scattering** in Stellar Envelopes



Be disk

pole-on →
No net polarization



edge-on →

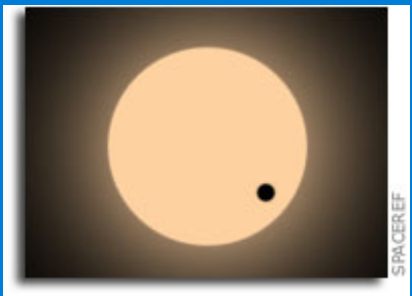
Net **Polarization** ⊥ to **disk orientation**

- Direct, unpolarized stellar flux: $\mathbf{I_n}$
- Polarized, scattered light in the envelope: $\mathbf{I_p}$
- Resulting polarization fraction, **p**:

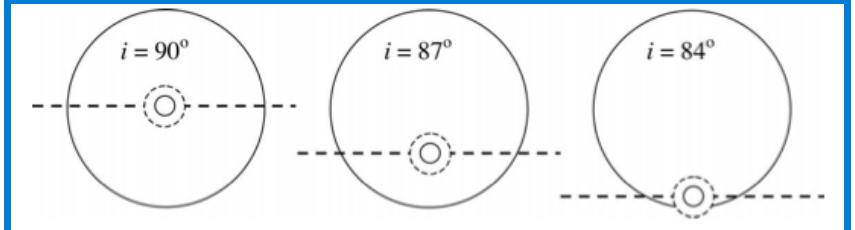
$$p = \frac{I_p}{I_n + I_p}$$

Introduction

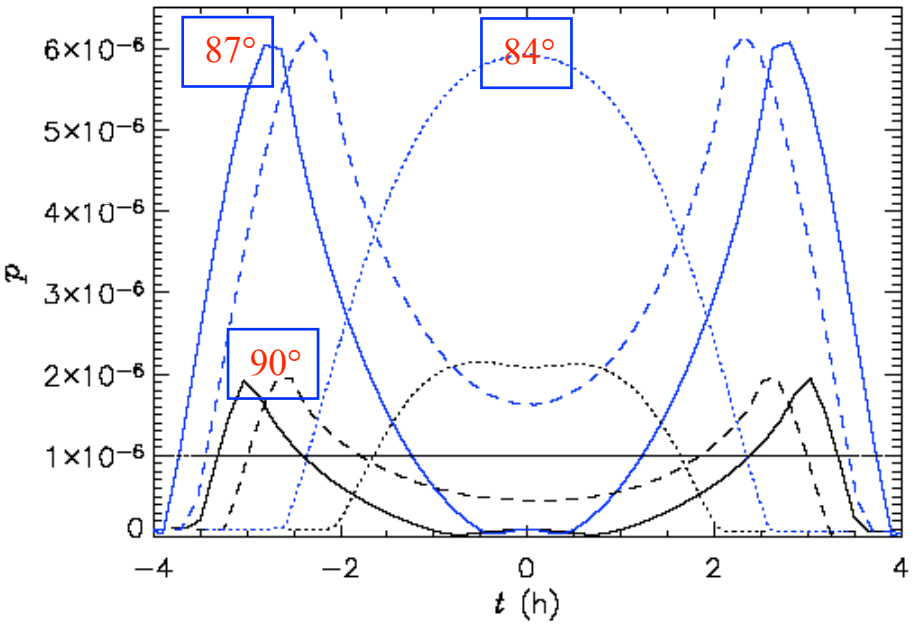
Polarization from an Exoplanet occultation



SpaceRef



Polarization as a function of time & inclination

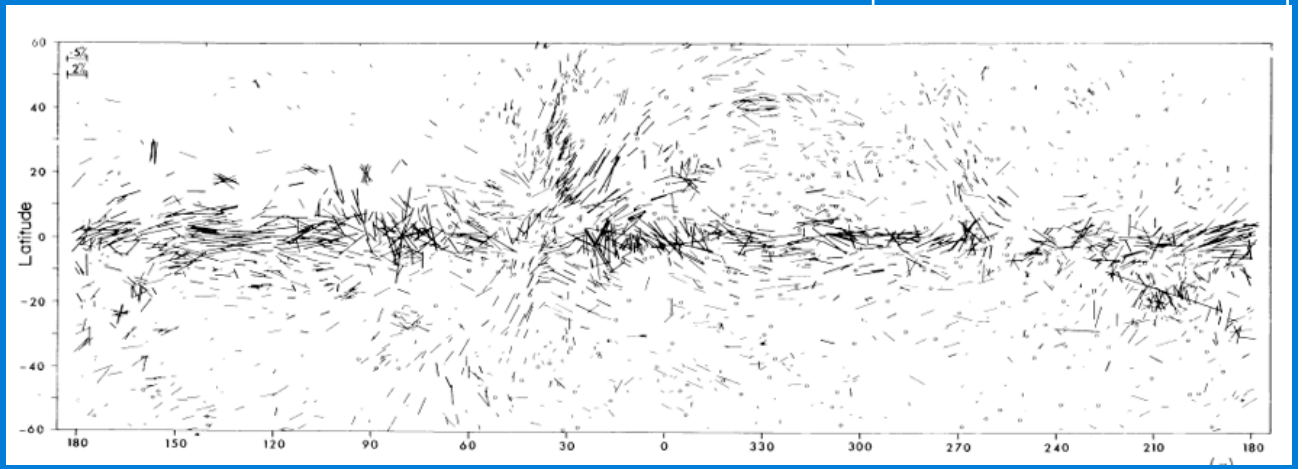


Carciofi & Magalhães 2005

Introduction

- **Despite the scientific motivation,**
  - No all-sky O/NIR polarimetric Survey exists!
  - Eg., interstellar polarization:
    - Heiles' (2000) compilation has ~10,000 stars
- **SOUTH POL should provide ~$10^{3\text{-}4}$ more objects**
  - deeper
  - more precise & accurate

Mathewson & Ford 1970



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  - Extragalactic Astrophysics
  - Interstellar Medium (ISM)
    - Local ISM
    - Galaxy & Magellanic Clouds
    - Dark clouds
  - Stellar Astrophysics
  - Solar System
- **FUTURE**
- **CONCLUSIONS**

What?...

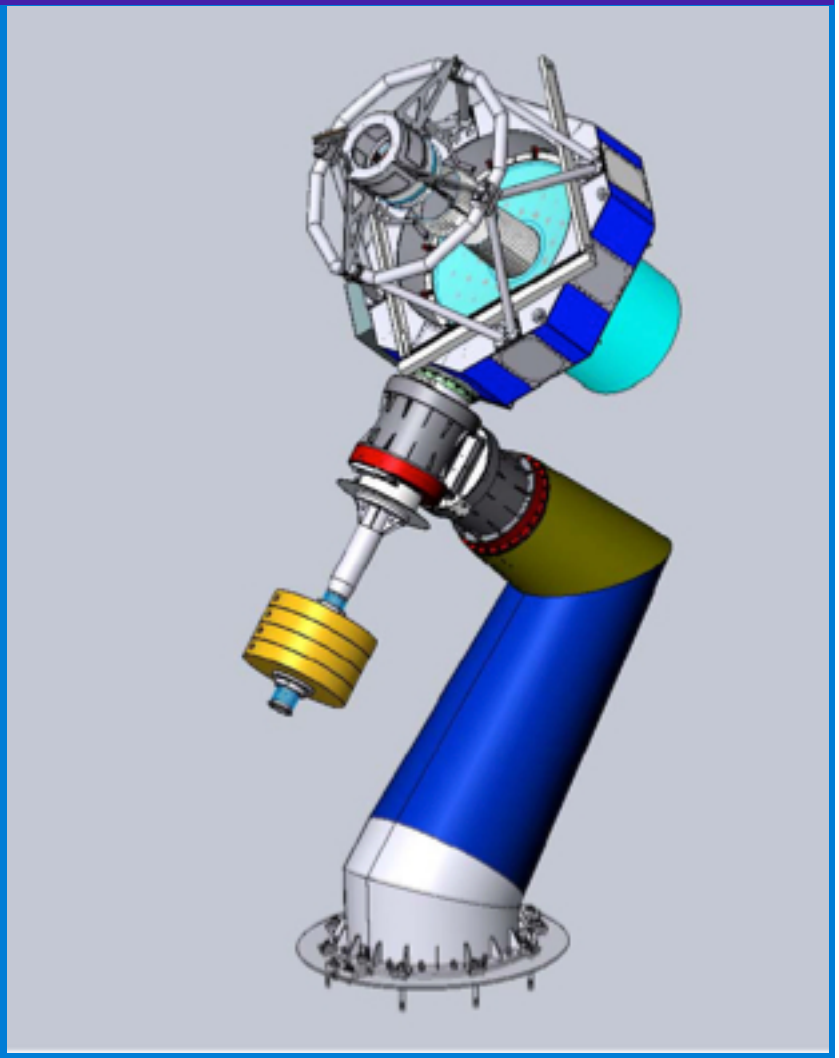
- **SOUTH POL:**
  - **Optical survey of the polarized Southern sky**
    - FAPESP, PI: A. M. Magalhães
- **Goal:**
  - Polarimetric accuracy of 0.1% at V~15-16
- **Survey's first epoch:**
  - Sky South of Dec -15°
  - Complete in ~ 2 years
- **It will gradually progress towards North**

How?...

- **T80S Robotic Telescope**
  - FAPESP, PI: C. M. de Oliveira,
  - To be installed in 2013 @ CTIO
    - support for J-PAS (B. Ascaso's talk)

Table 1: Summary of the performance of the T80 design

	Performances of design
Aperture	0.840 m diameter
Plate scale	55.56 arcsec/mm
Focal length	3712 mm
Field of view	110 mm (1.7°) with optimized image quality
	155 nm (2.4°) with limited performances
Image Quality	50% EE = 5 µm / 0.28 arcsec (diameter)
	80% EE = 13 µm / 0.72 arcsec (diameter)
Distortion	0.6%



- CCD:
  - EEV, 9k x 9k, 92mm
  - 2.0 deg^2 (!)

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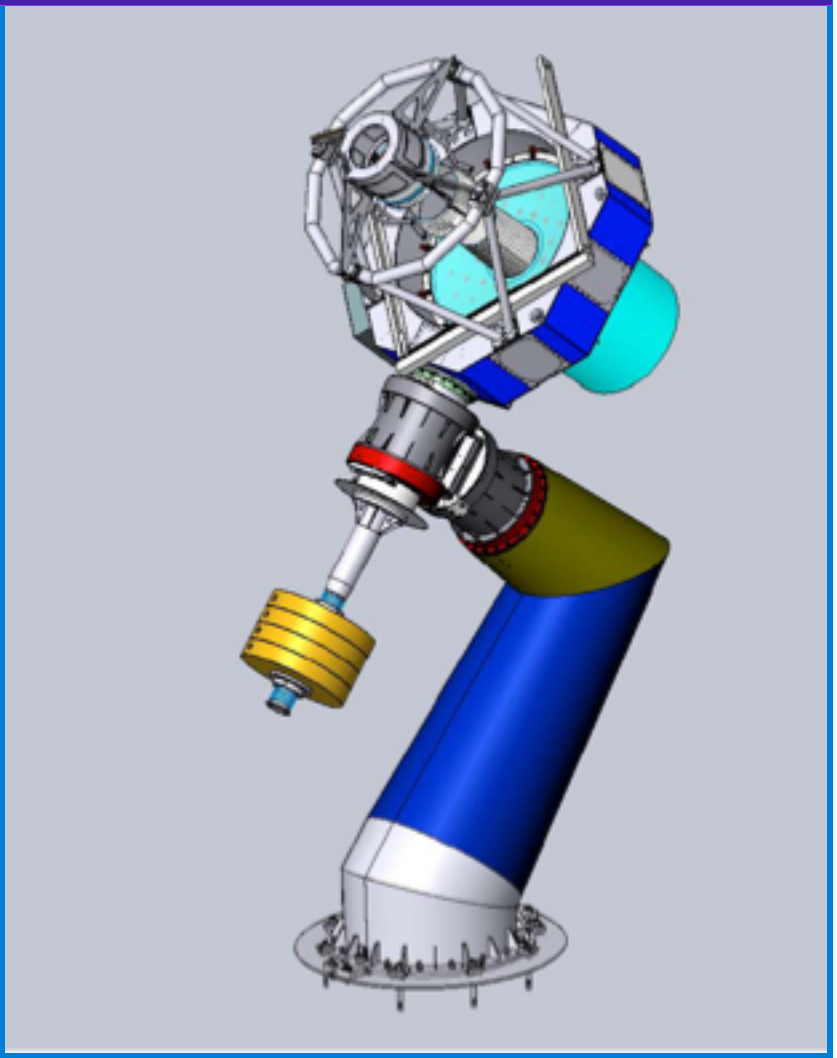
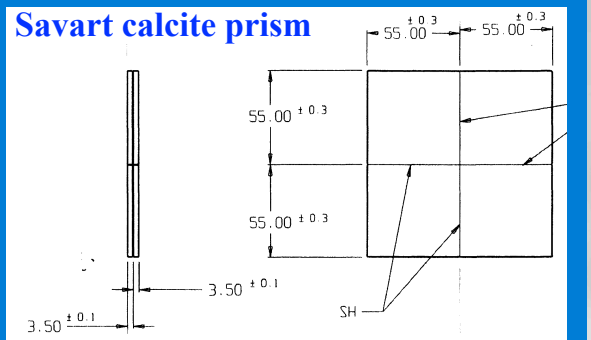


SOUTH POL

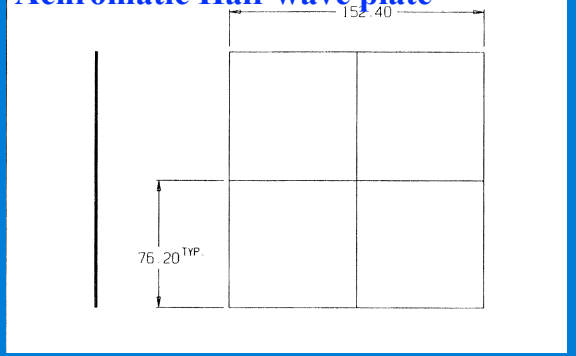
- Polarimeter optics & mechanics

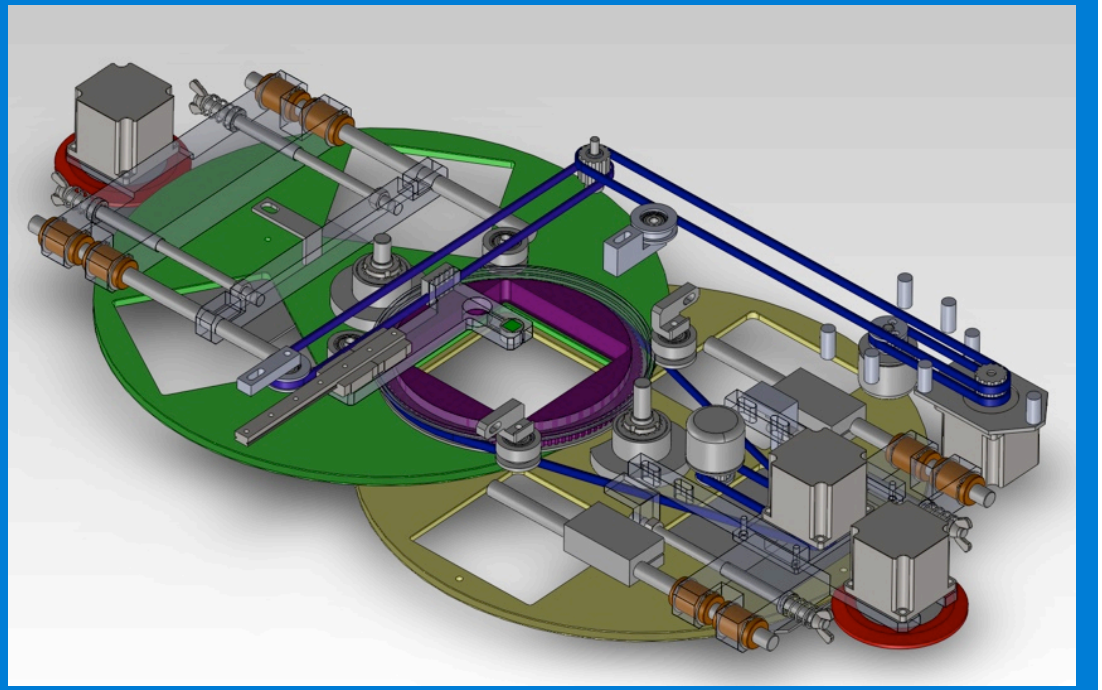
Savart calcite prism



120 mm x 120 mm mosaics

Achromatic Half-wave plate

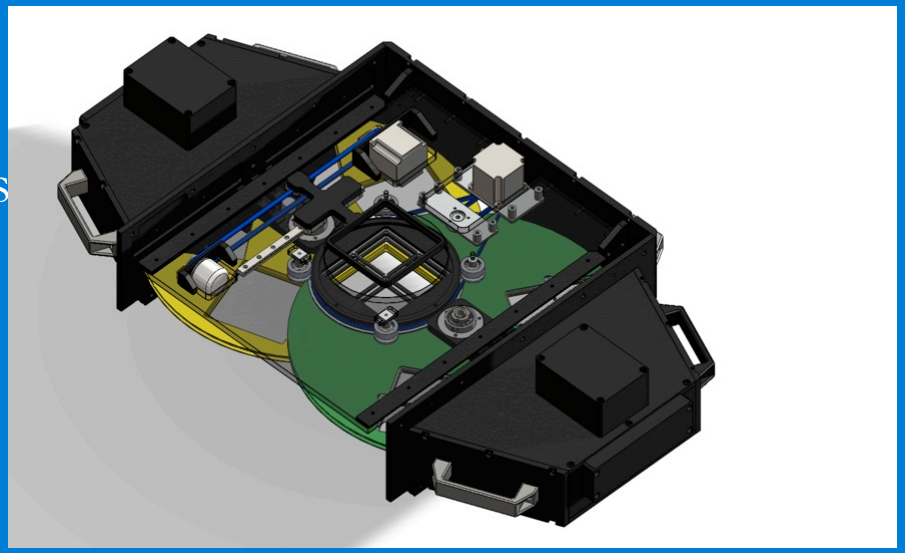




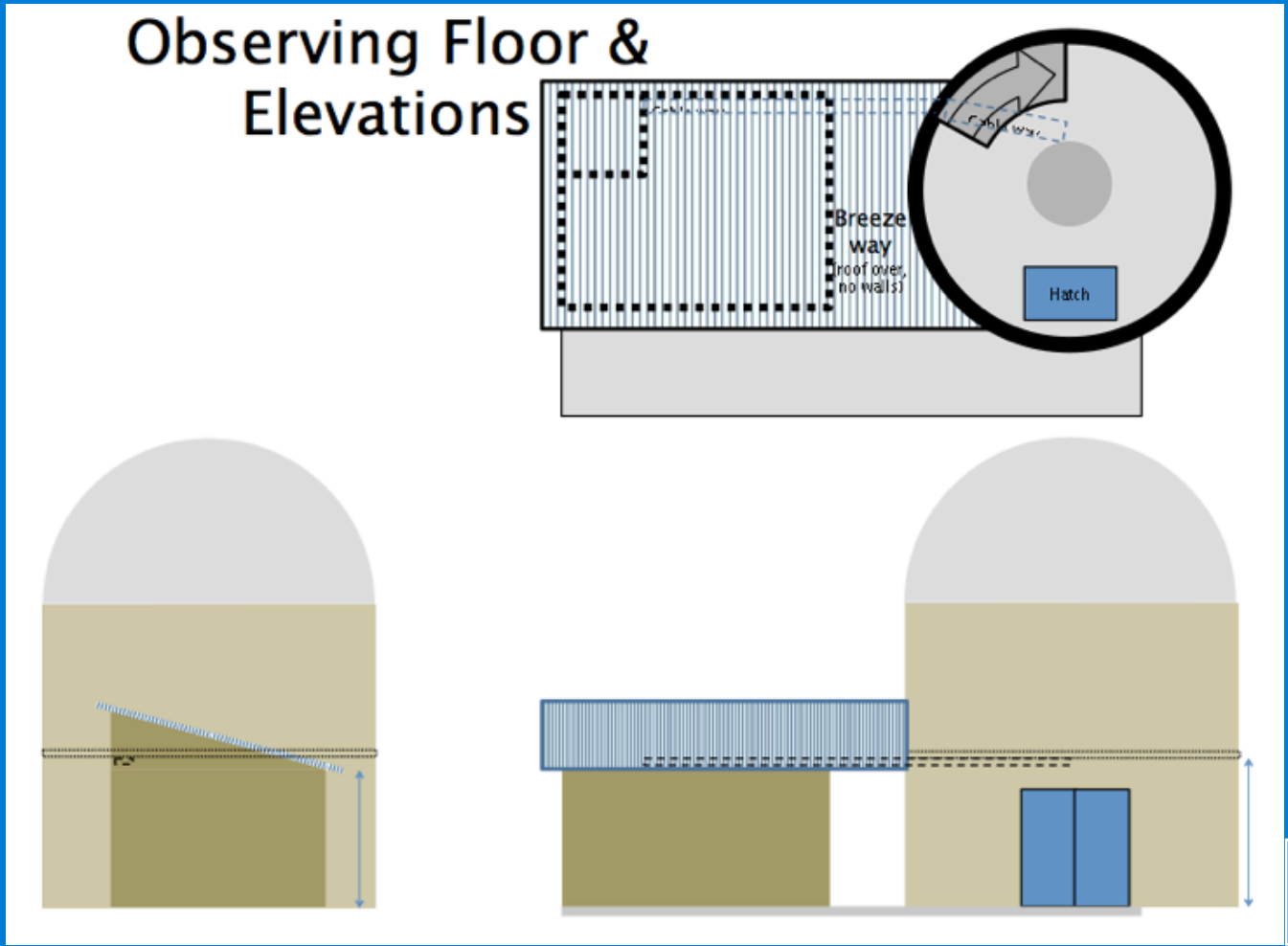
L. Marrara

How?...

- **Polarimeter status**
  - Optical components
    - to be delivered by November/2012
  - Mechanics & Electronics
    - to be delivered by March/2013
  - Reduction pipeline
    - in the works
    - built from an existing one



SOUTH POL



S. Heathcote, CTIO

SOUTH POL

Site




S. Heathcote, CTIO

How?...

- **Optical/NIR Technique**
  - Similar to IAGPOL
    - Magalhães et al. 1996
  - Rotatable waveplate
    +
    calcite prism
    +
    detector (**CCD** or **NIR array**)

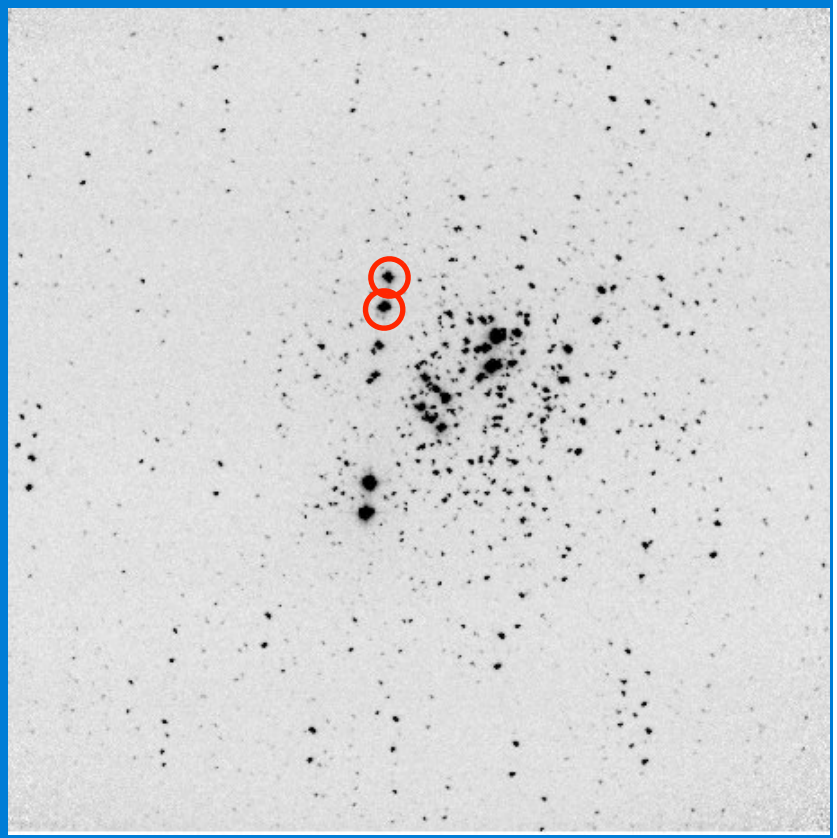
- **Counts @ waveplate angles ψ_i:**

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

$$\Rightarrow \mathbf{Q} = z_1 - z_3 + z_5 - z_7$$

$$\mathbf{U} = z_2 - z_4 + z_6 - z_8$$

κ Crucis

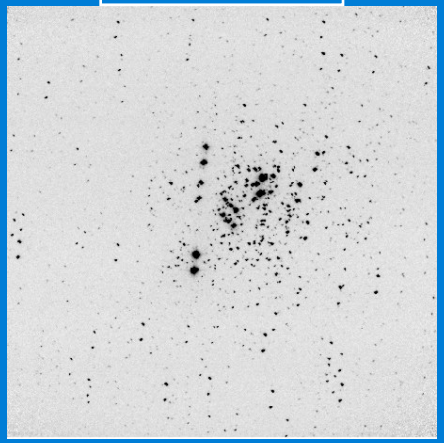


Magalhães et al. 2005

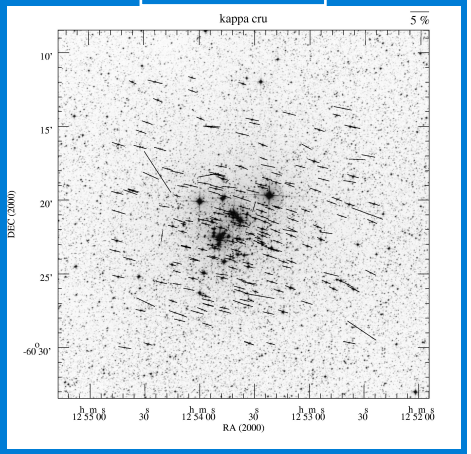
How?...

- **Polarimeter**
  - Patterned after IAGPOL
  - Rotating waveplate
    +
    Calcite prism
    - Savart plate
  - Very accurate
    - σ_P=0.002% (or better) possible

8x 5min images



Vector map

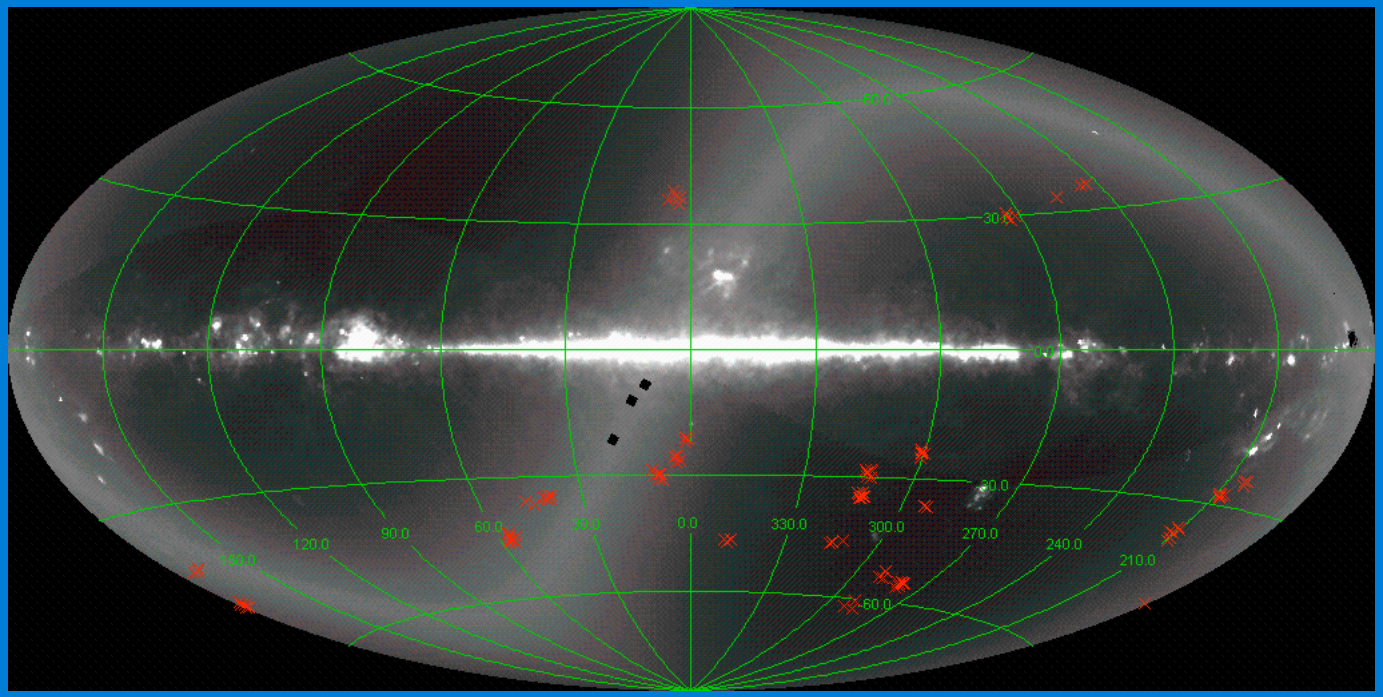


Magalhaes et al. 2005

High Latitude Clouds

Optical/NIR IAG Survey of ISM Polarizatin

- Regions from COBE/DIRBE (Reach et al. 98)



× =
Optical Polarization Survey at IAG

How?...

- **High Galactic Latitude Clouds**
  - We **need** V~15-16 background stars to map B-field
  - Av~0.3 typically

    $\Rightarrow P_V \lesssim 0.1\text{-}1.0\%$
  - For $P/\sigma_P = 5$,

    if P~0.5%

    $\Rightarrow \boxed{\sigma_{P(\text{needed})} = 0.1\%}$

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

V (mag)	8×60 sec	8×300 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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Como?...

- **High Galactic Latitude Clouds**
  - From **models of stellar population synthesis** of the Galaxy:
    - V ≲ 15:

      covers 3 kpc towards b=90°
  - In other words,
    - **Galactic dust layer will be well sampled!**

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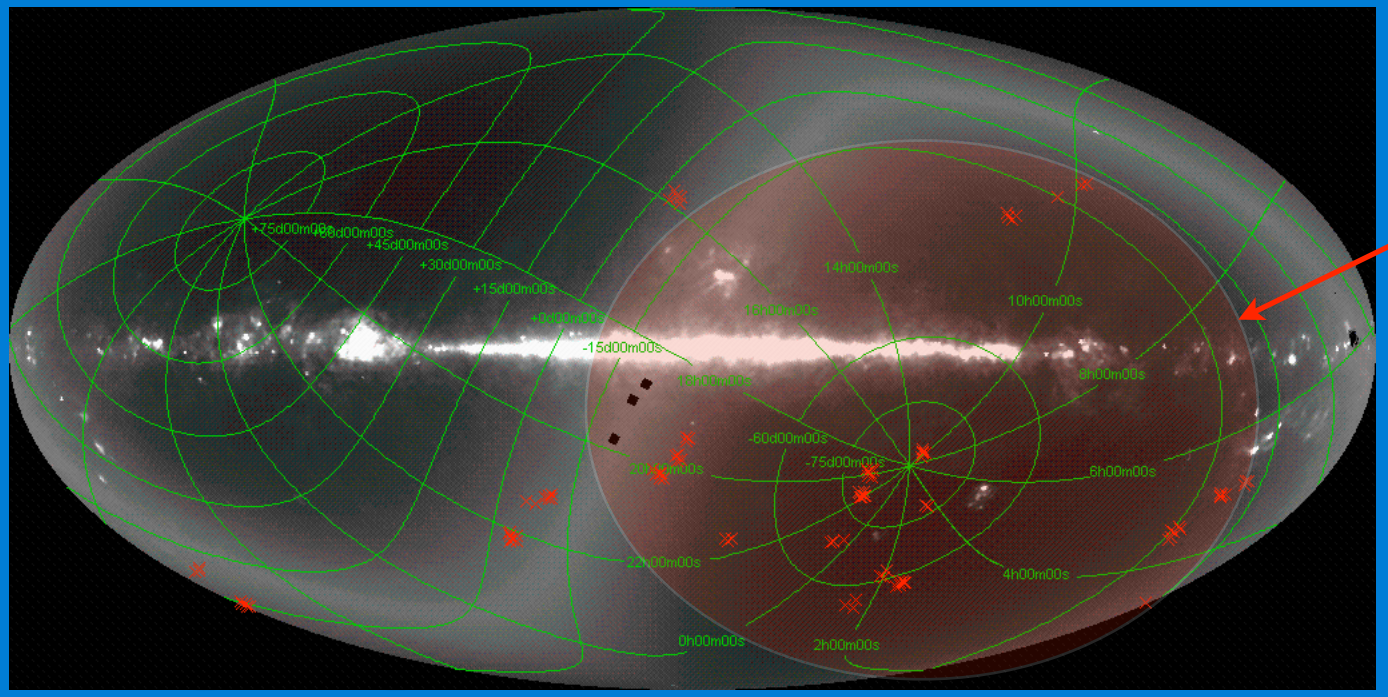
What?

- **SOUTH POL:**
  - Optical survey of the polarized Southern sky



Dec ≤ -15°

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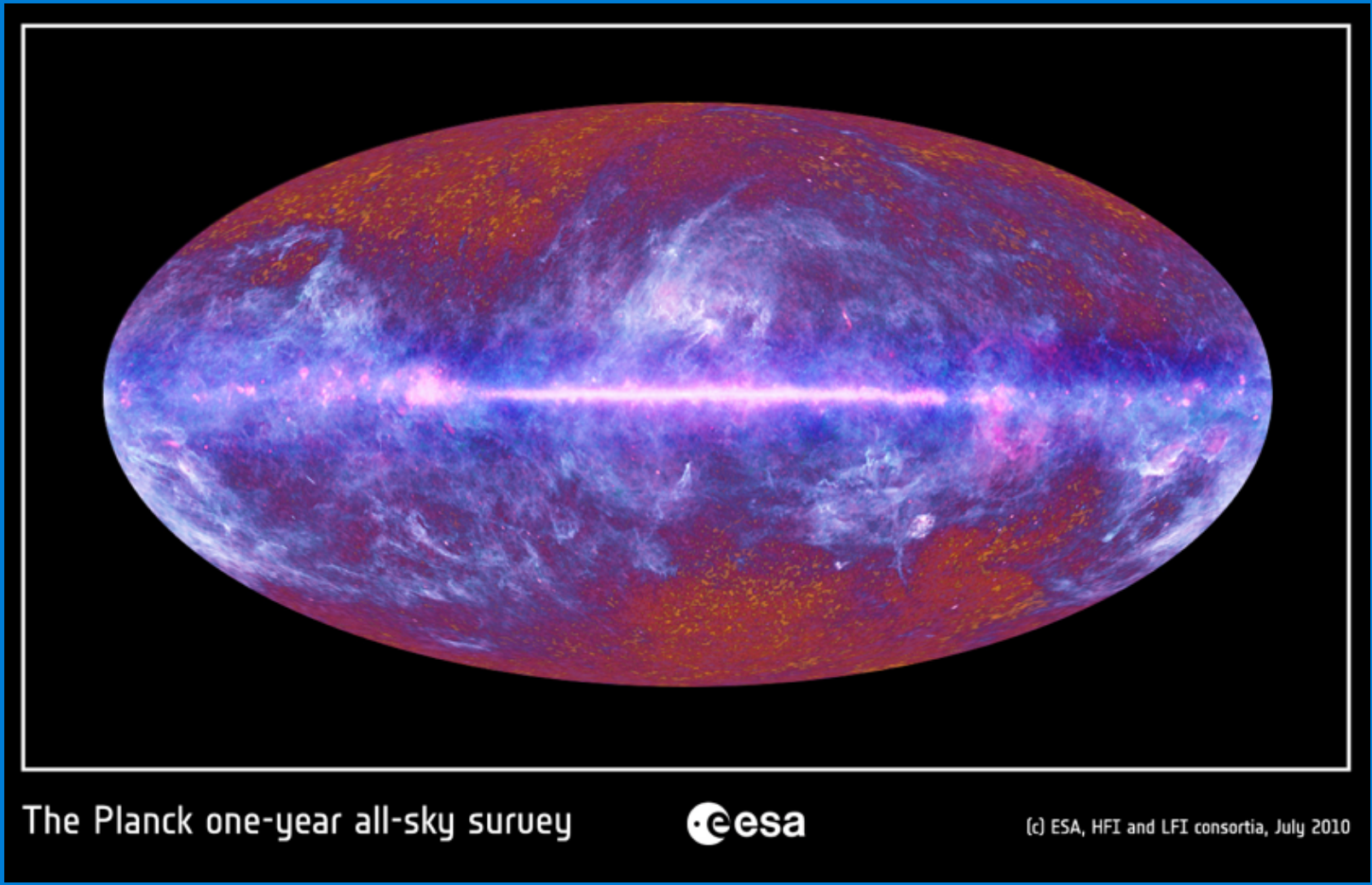
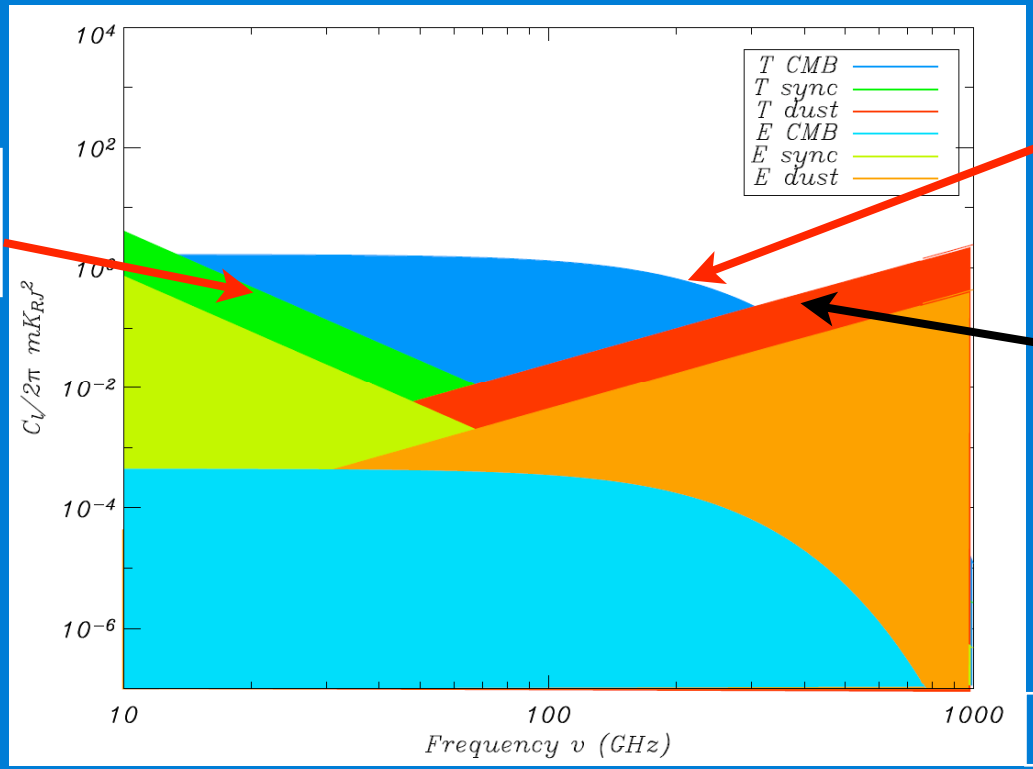
Impact - CMB


The Planck one-year all-sky survey
esa
(c) ESA, HFI and LFI consortia, July 2010

Impact - CMB

- **Galactic Foreground Intensity**
  - **For WMAP & Planck data**



Synchrotron Foreground

CMB

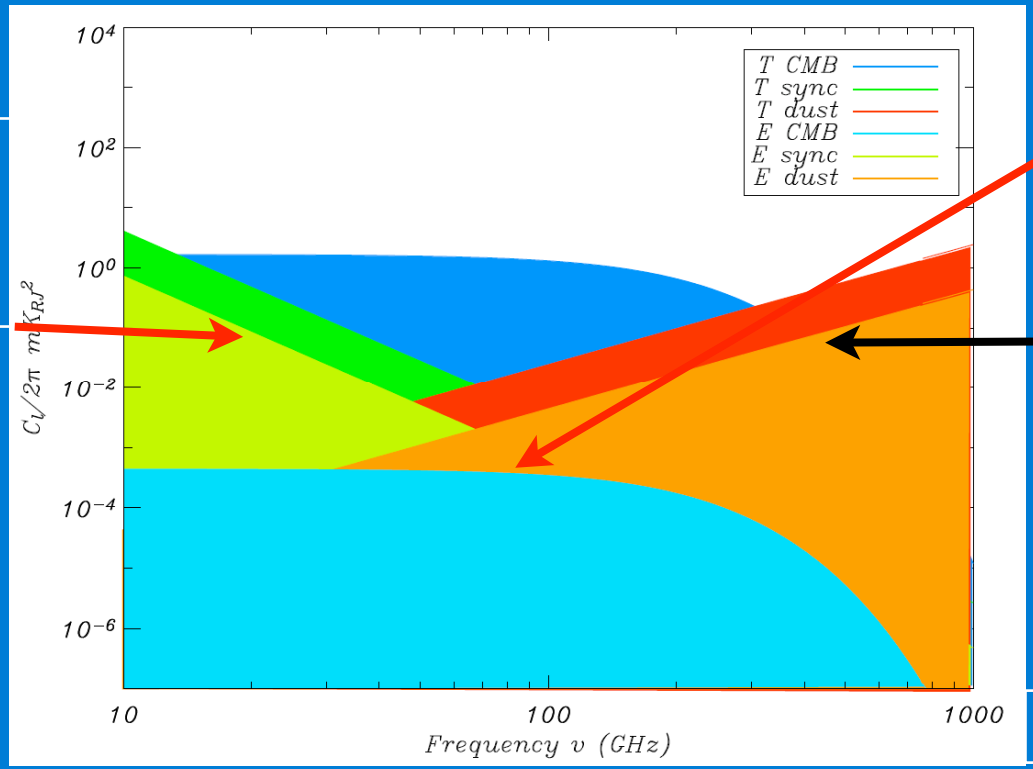
Dust Foreground

Aumont 09

Impact - CMB

- **Galactic Foreground Polarization**
  - **For WMAP & Planck data**

Synchrotron Foreground **Polarization**



CMB **Polarization**

Dust Foreground **Polarization**

Aumont 09

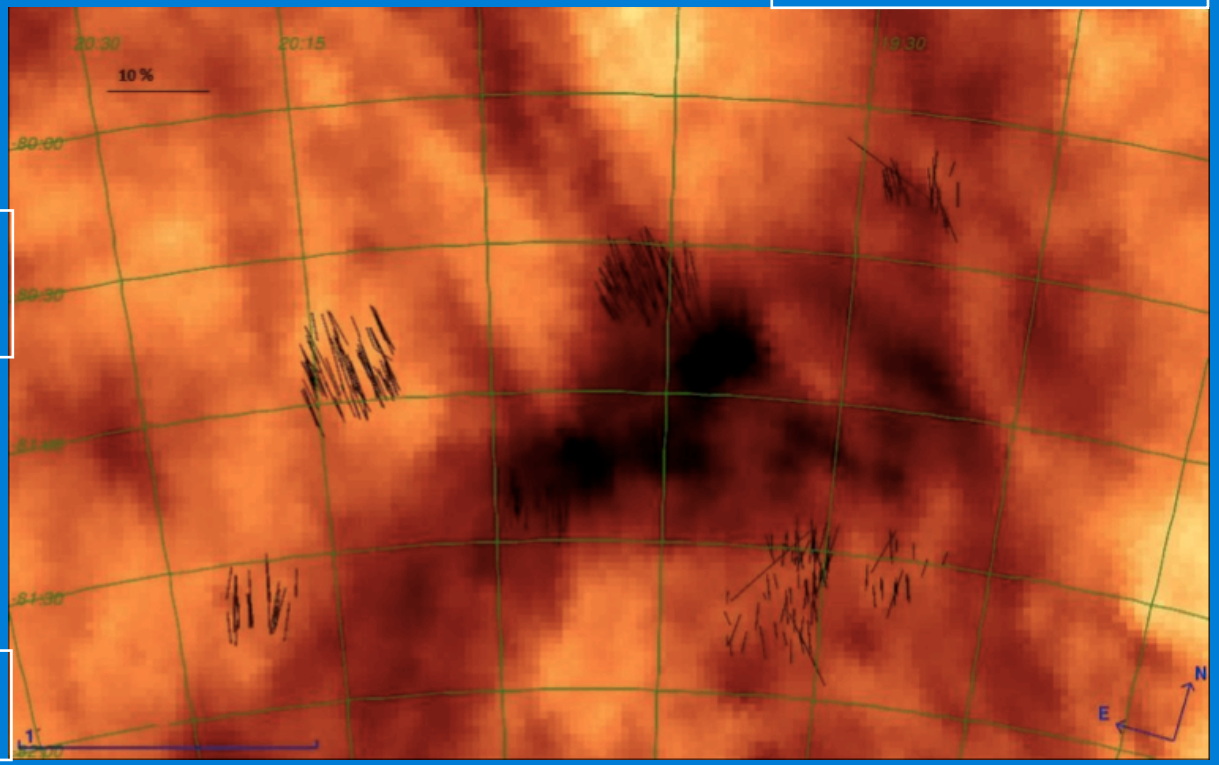
Impact - CMB

- **For proper subtraction & analysis of CMB polarization:**
  - **Much improved sampling of starlight polarization is needed**
  - **SOUTH POL will hence be important**
    - **providing good sampling of interstellar polarization**
    - for analysis of past & current missions: WMAP, Planck
    - for future missions: CMBPol (USA), COrE (ESA)

Impact - CMB

- **High Latitude Clouds**

Fields towards DIR313-29



Magnetic field along ISM filaments ⇒

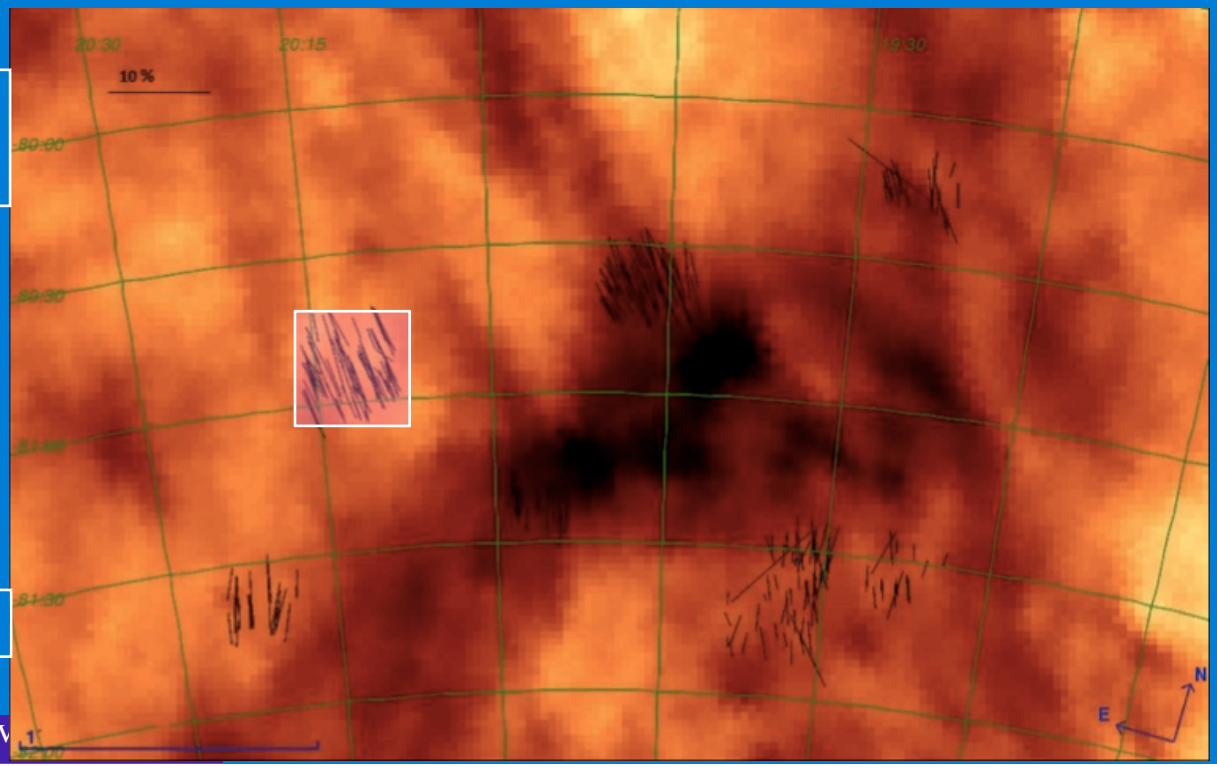
Cassia Fernandez & Tiberio Ferrari

2º x 3º

Impact - CMB

- **Combination of**
  - Southern 80cm Robotic Telescope in Chile
  - Large field Imaging Polarimeter
    - 2.0 sq.deg.

IAGPOL footprint



Cassia Fernandez

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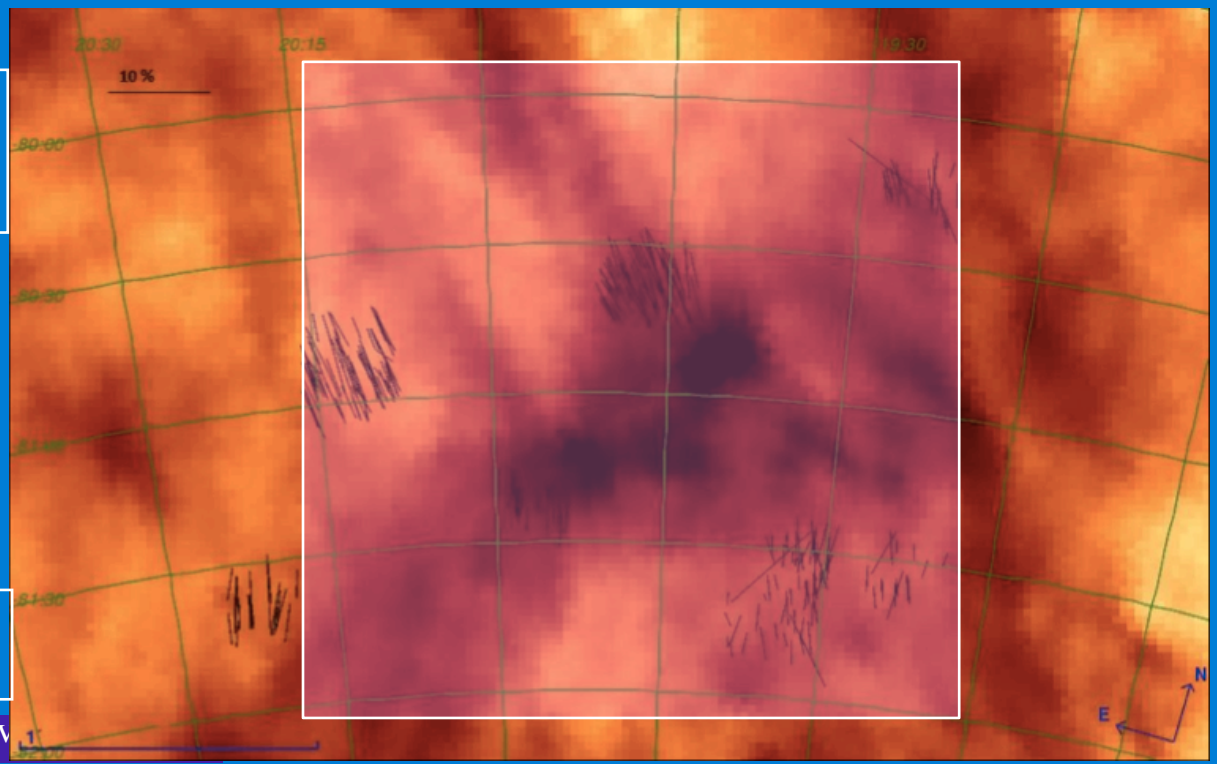
South Pol footprint



Cassia Fernandez & Tiberio Ferrary

Impact - Extragalactic Astronomy

- **Extragalactic Astronomy**
  - **Many blazars will probably be discovered**
  - EGRET & FERMI sources with V~19
    - will be identified
  - Magnetic Field structure of interacting systems
    - eg., Magellanic Clouds

Impact - Extragalactic Astronomy

- **SOUTH POL & AGN (cont.)**
  - Indentification of EGRET sources
    - highly polarized blazars
    - (polarization variability)
  - Indentification of FERMI sources
    - ~1,000 sources
      - Abdo et al. 2010
  - **Study of known blazars**
    - 450 Blazars with R<19 e dec<-15°
      - Massaro et al. (2009)
    - R_{median}~17

⇒ SOUTH POL: unbiased survey

⇒ : will allow correlation w/ FERMI blazars

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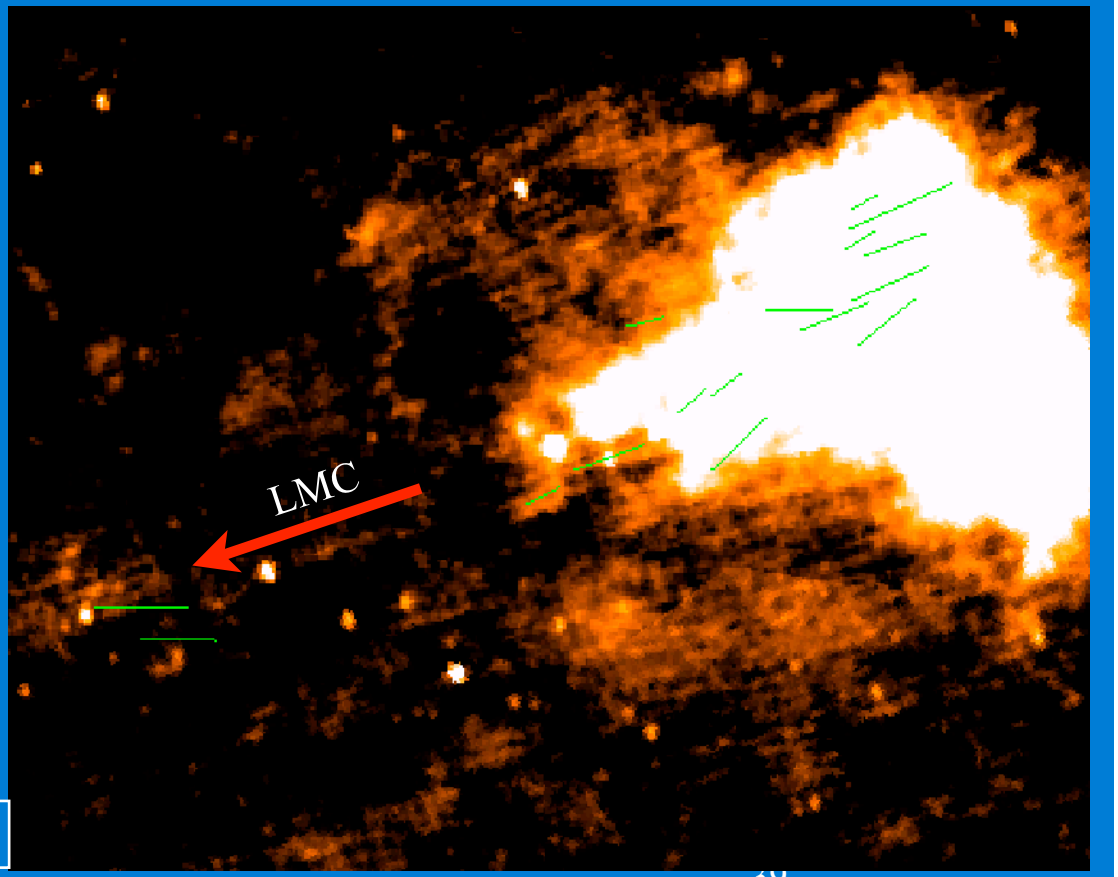
Impact - Extragalactic Astronomy

- **Magnetic Field in close-by galaxies**

SMC Magnetic field is along SMC-LMC direction

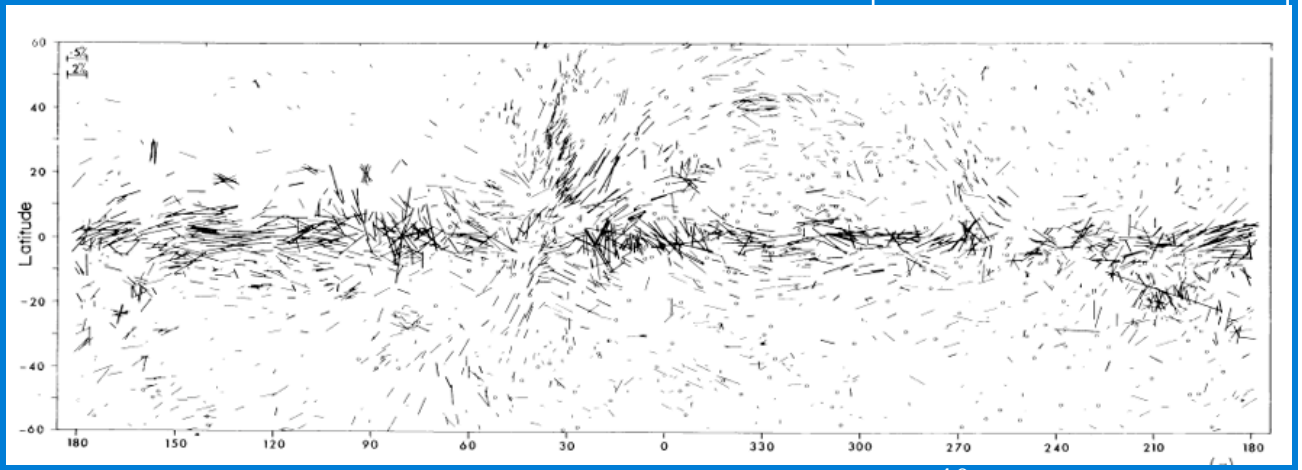


Gomes et al. 2012

Impact - Galactic Astronomy

- **Interstellar Polarization**
  - SOUTH POL should provide ~$10^{3\text{-}4}$ more objects
    - deeper
    - more precise and accurate
- **Combination of SOUTH POL and GAIA**
  - **3-D Mapping of ISM Magnetic Field!**

Mathewson & Ford 1970



Impact - Galactic Astronomy

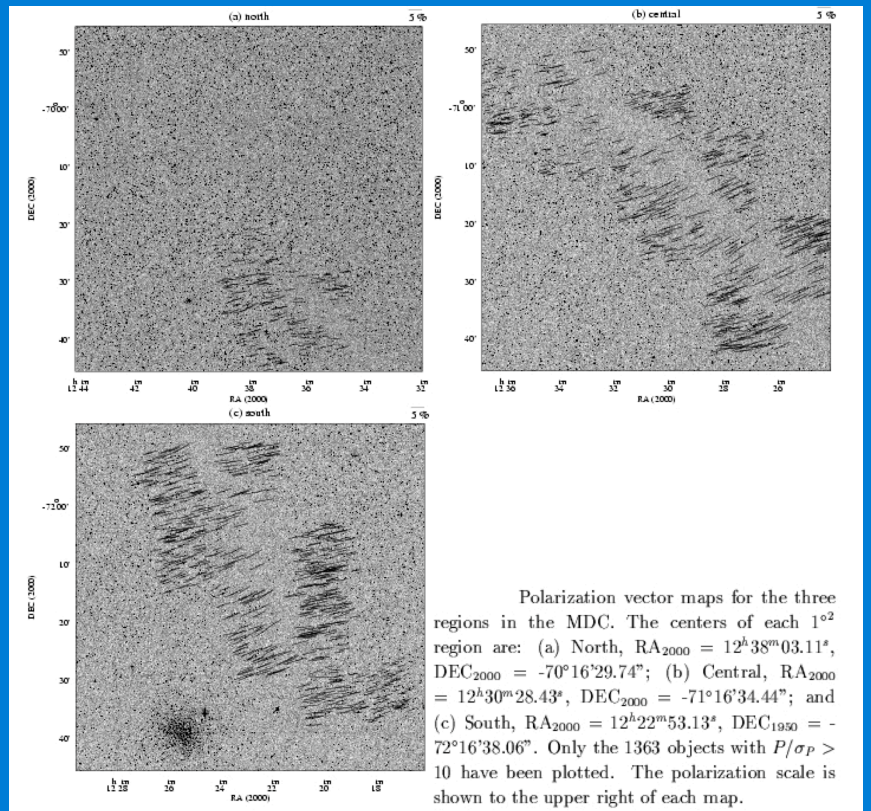
- **Galaxy, Interstellar Medium & Star Formation**
  - Magnetic Field structure of the Galaxy
    - **with paralaxes from GAIA**
    - On large (~kpc) & small (≲ pc) scales
  - Tests for grain alignment theories
  - Magnetic Field **topology across Molecular Clouds**
    - **From less dense regions** (optical, SOUTH POL)
      to denser regions (sub-mm: Planck, ALMA, APEX)

Impact - Galactic Astronomy

Magnetic Field in Dark Clouds

- What is the role of **B** in cloud collapse?

- **Mapping the Musca Dark Cloud**
  - Pereyra & Magalhães 04



Polarization vector maps for the three regions in the MDC. The centers of each $1^{\circ}.2$ region are: (a) North, $RA_{2000} = 12^h38^m03.11^s$, $DEC_{2000} = -70°16'29.74"$; (b) Central, $RA_{2000} = 12^h30^m28.43^s$, $DEC_{2000} = -71°16'34.44"$; and (c) South, $RA_{2000} = 12^h22^m53.13^s$, $DEC_{1950} = -72°16'38.06"$. Only the 1363 objects with $P/\sigma_P > 10$ have been plotted. The polarization scale is shown to the upper right of each map.

Impact - Stellar Astrophysics

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

Impact - Stellar Astrophysics

- **Polarimetry of Herbig Ae/Be objects**
  - Statistics of

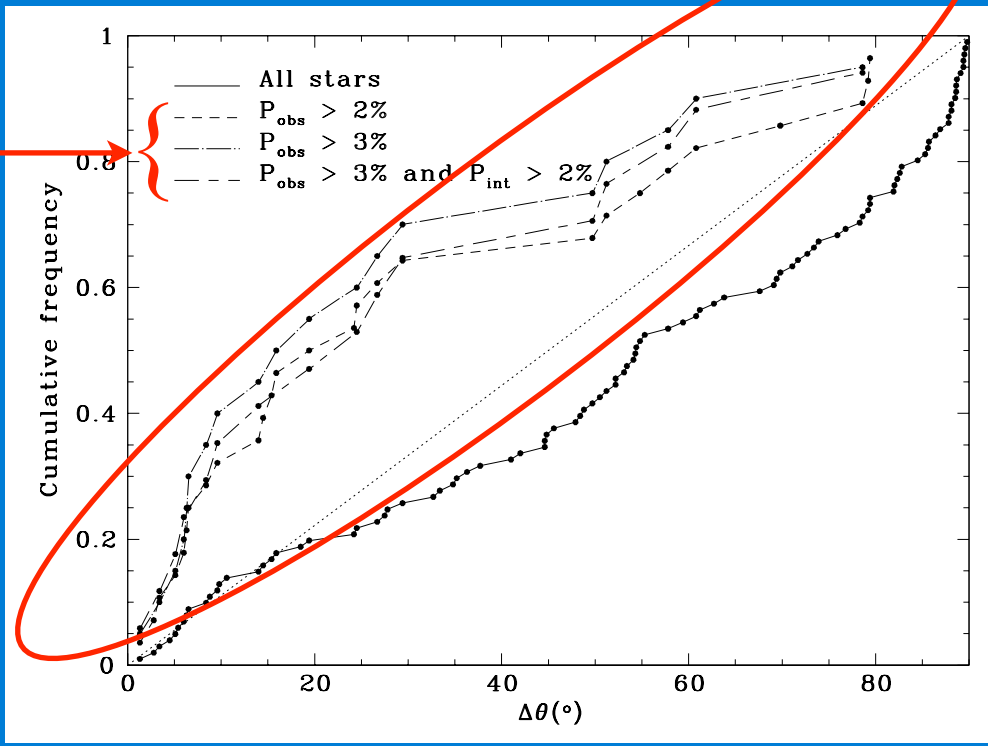
    $\Delta\theta$ = Intrinsic PA - ISM Pol PA

    Rodrigues et al. 2009

  – For the more highly polarized stars:

    $\Delta\theta \rightarrow$ **parallel**

    to ambient B-Field

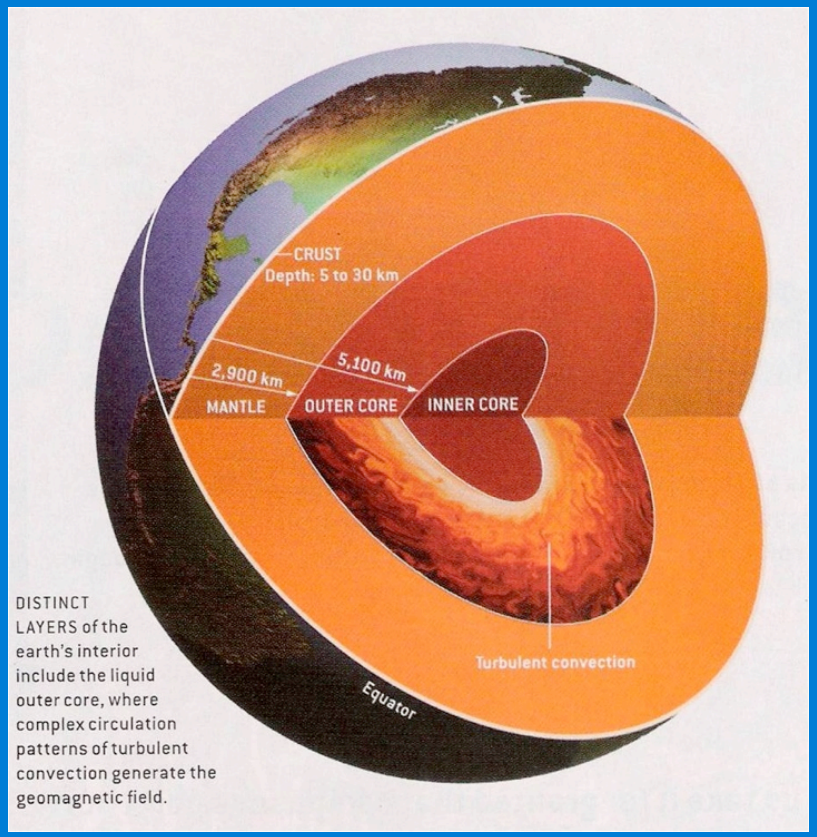


Envelopes have memory of ISM B-field !

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** !



DISTINCT LAYERS of the earth's interior include the liquid outer core, where complex circulation patterns of turbulent convection generate the geomagnetic field.

Impact - Solar System Astrophysics

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

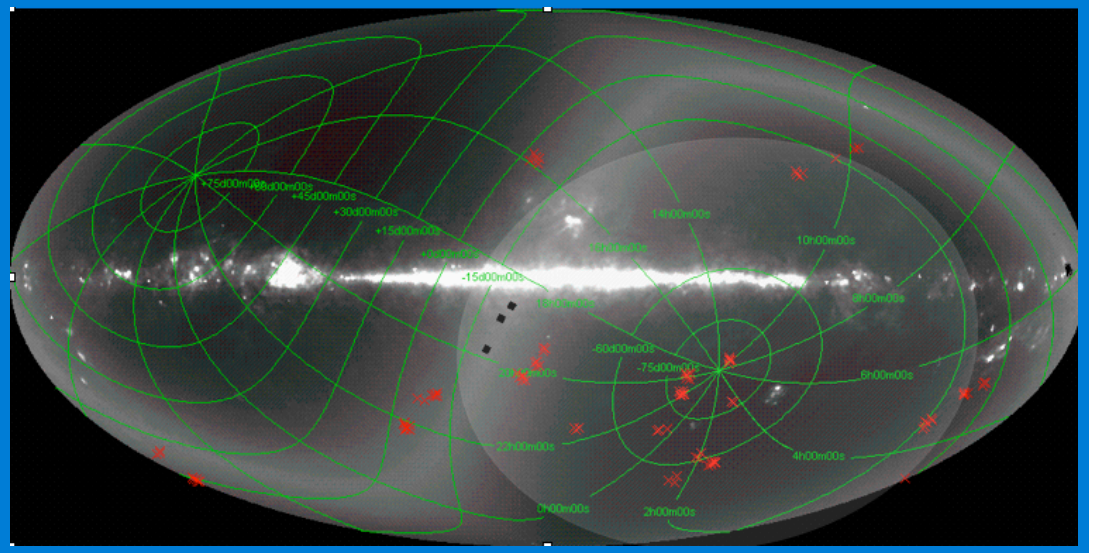
Summary

- **INTRODUCTION**
- **SOUTH POL**
  - What?... Why?... How?...
- **SOUTH POL's Impact**
  - CMB
  - Extragalactic Astrophysics
  - Interstellar Medium (ISM)
    - Galaxy & Magellanic Clouds
    - Dark clouds
  - Stellar Astrophysics
  - Solar System
- **FUTURE**
- **CONCLUSIONS**

Future

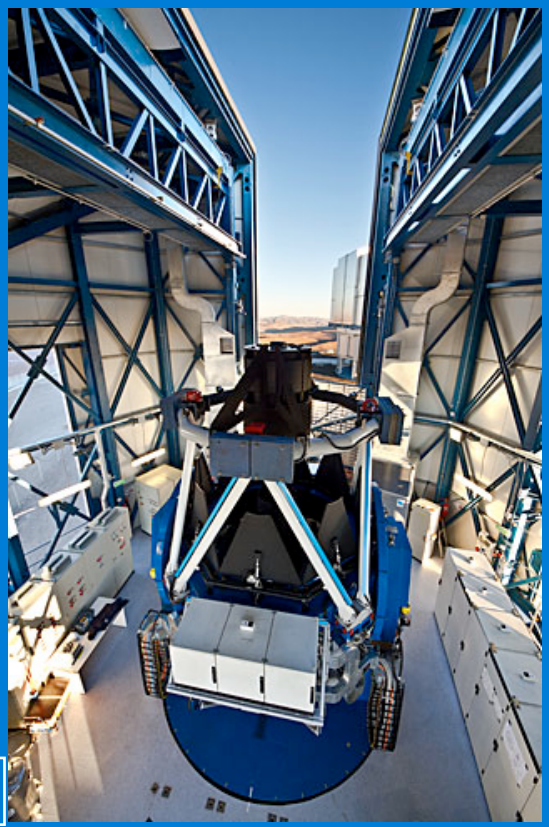
- **SOUTH POL**
  - Extension to angularly extended (i.e., > 8") objects
  - Additional Linear Pol. epochs
  - Circular Pol. survey

- **NORTH POL**
  - Northern Extension



Future - ESO Role

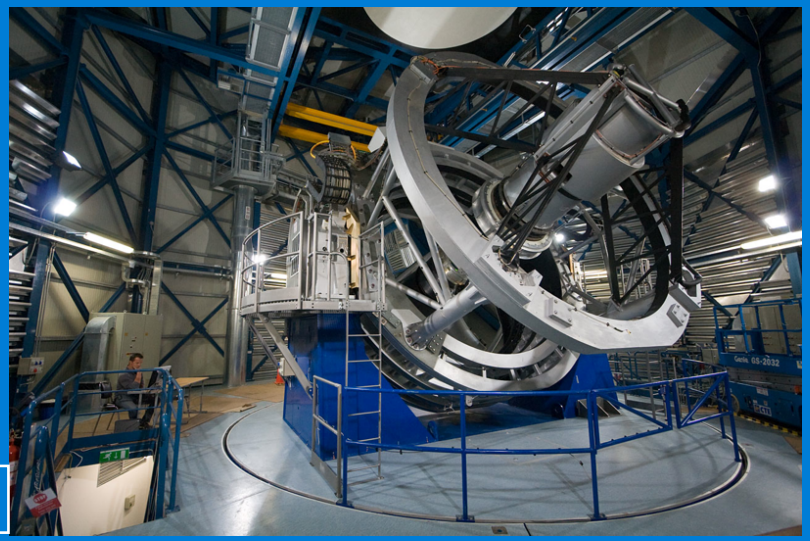
- **Optical Polarization Survey with VST**
  - ESO/Paranal
  - 2.6m optical tel.; 1° x 1° field
  - Accuracy of 0.1% up to V~18
  - **Probe larger volume of the Galaxy**
    - Magnetic Field of the ISM, with GAIA
  - **Sinergy with ALMA**
    - **Star formation from large to small scales**
  - **Identification of fainter blazars/AGN**
  - **Pathfinder / Support for E-ELT**



ESO

Future - ESO Role

- **NIR Polarization Survey with VISTA**
  - 4.1m tel.; 1.6° x 1.6° field
  - H-band
  - **Galactic Plane**
    - Spitzer's Dark Clouds
    - Star formation regions, ISM
  - **Selected Regions**
    - Dark clouds
    - Magellanic Clouds



ESO

Concluding Remarks

- **SOUTH POL**
  - Measure polarized sky between -15° < dec < -90°
    - in its first two years
  - Accuracy of ~0.1% para V=15

- **Optical/NIR Pol Surveys are unprecedented**
  - Scientifically opportune
  - Sinergy with Planck, ALMA & Gaia
  - ESO would play an important role

- **They will impact several areas**
  - from Cosmology to Solar System studies
  - Important for E-ELT