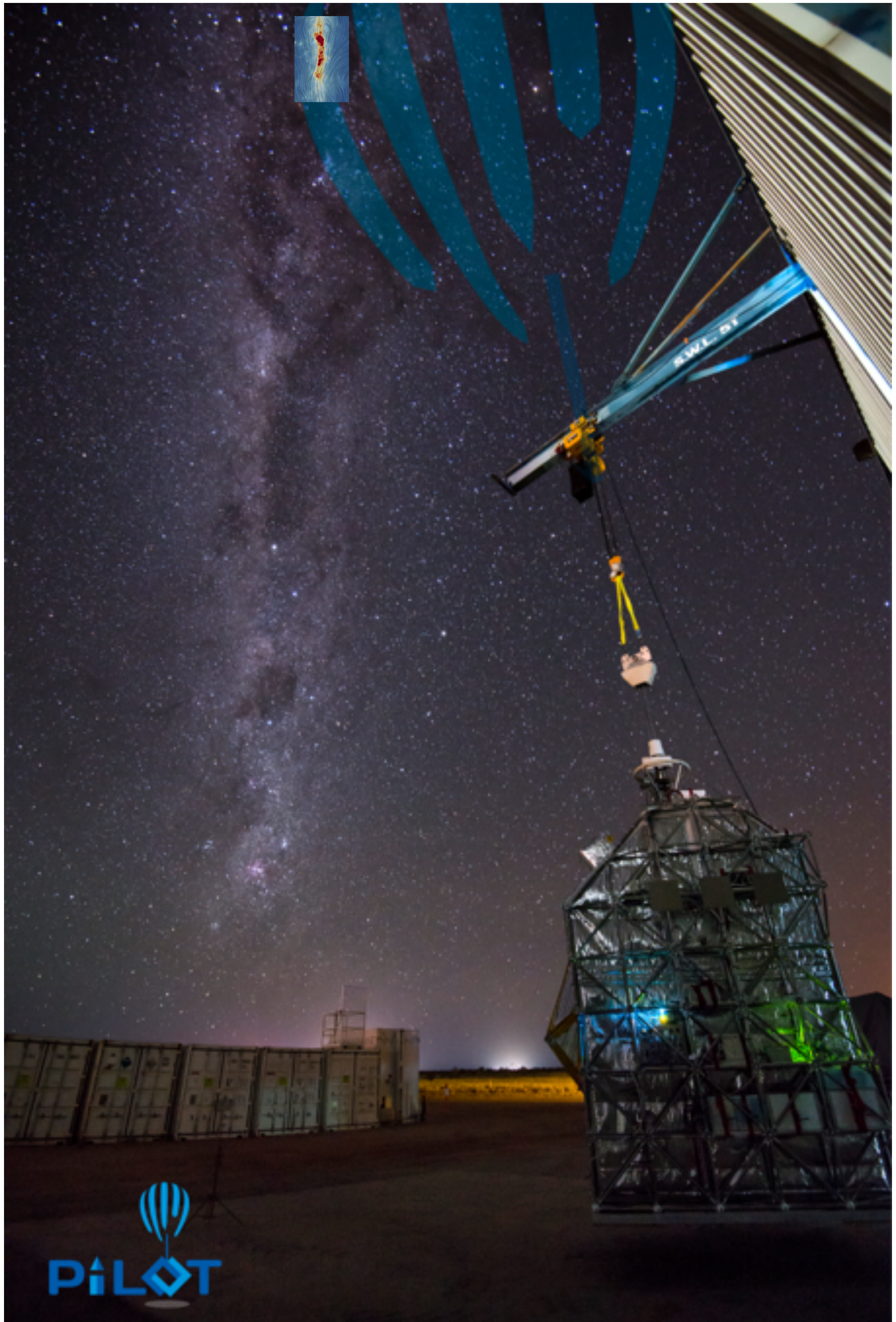


PILOT data processing and first scientific results

A. Mangilli and J.-Ph. Bernard
(IRAP, Toulouse)

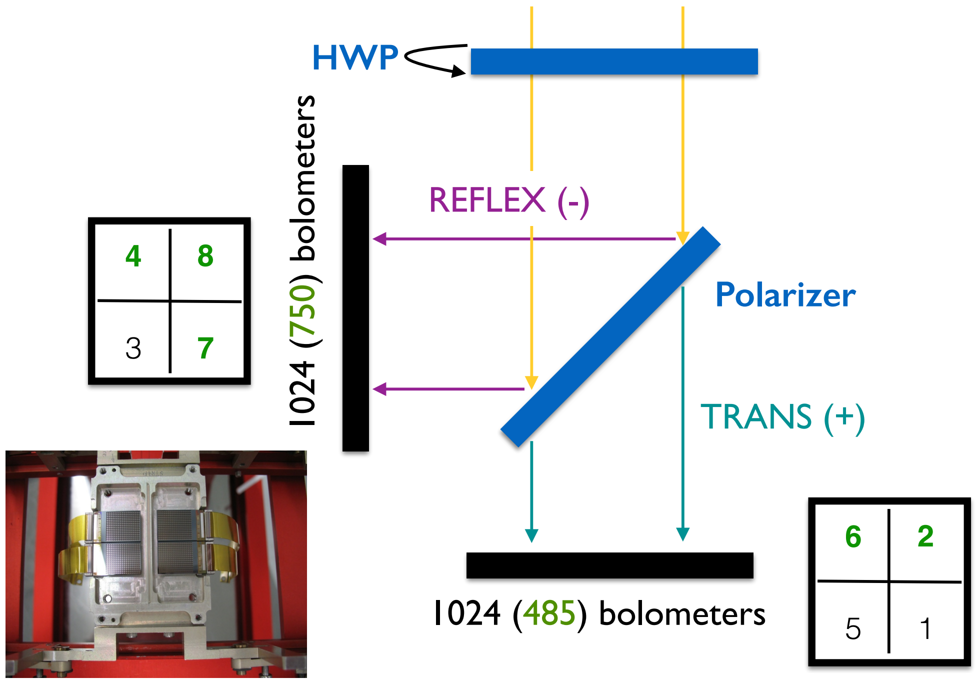
On behalf of the PILOT team

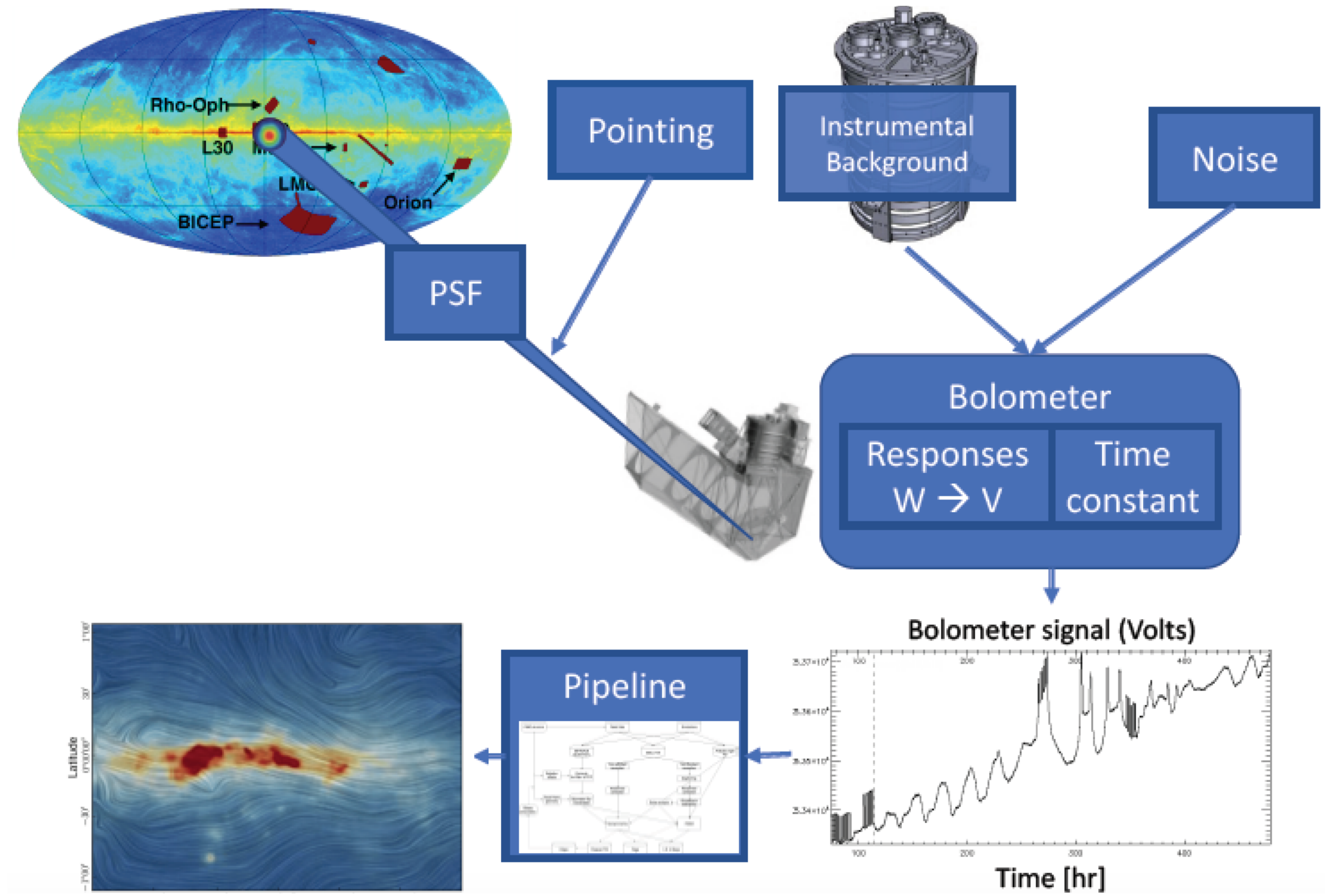
Mainly the data processing team: J. Aumont, J-P. Bernard, G. Foenard, G. de Gasperis, A. Hughes, A. Mangilli, I. Ristorcelli, H. Roussel

irap cnes cnrs

CEA, 9th October 2018

Polarization measurement and data processing



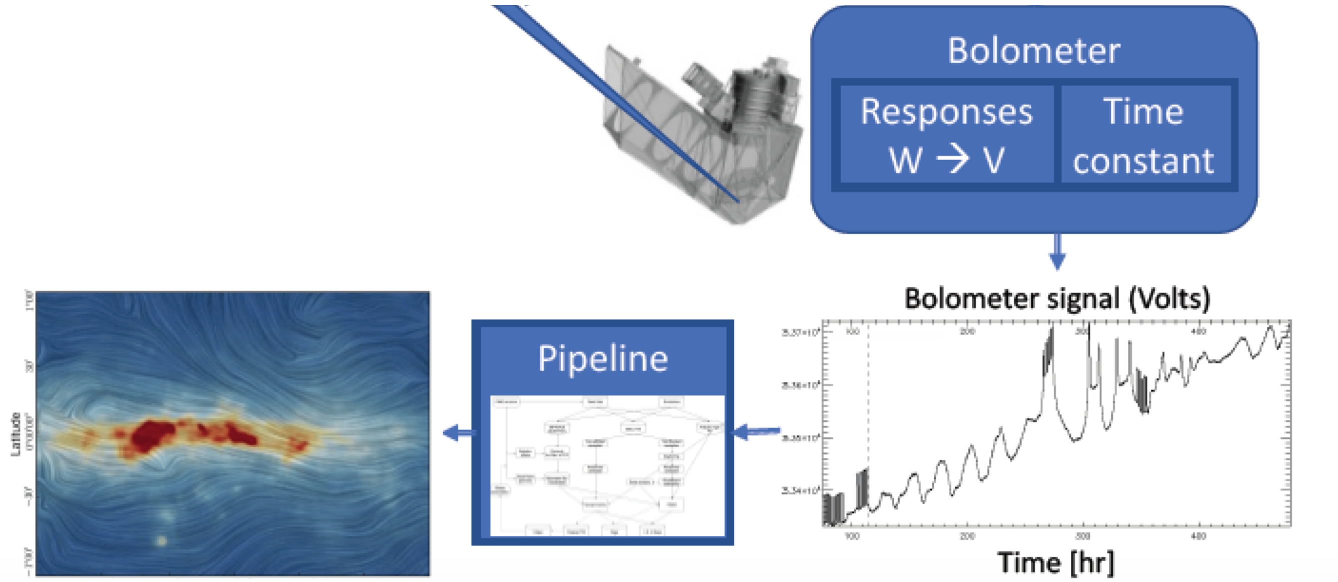


$$m = R_{xy} T_{xy} \times [I \pm Q cos4\omega \pm U sin4\omega] + O_{xy} \; + \; \text{Noise}$$

Observations at >2 HWP angles to reconstruct the Stokes parameters I, Q, U

Main challenges: control of systematics and detector response, 1/f noise

Data processing and map-making



Data processing before the map-making

- Data Calibration: atmospheric response map corrected for time variations using the ICS signal
- Atmospheric subtraction
- Time constant correction

Two different pipelines for the map-making:

- ROMAXPol [De Gasperis et al 2005] :

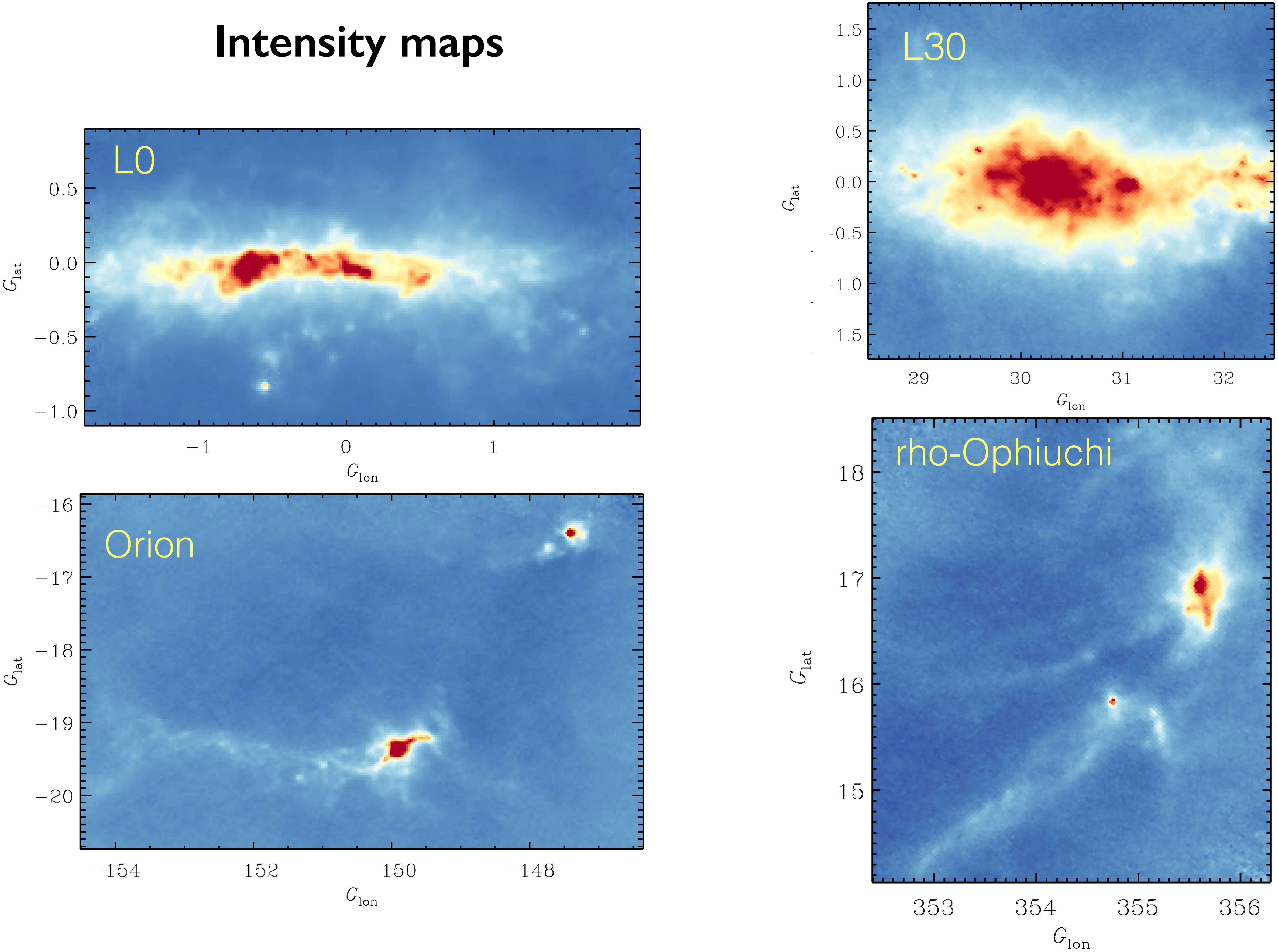
  Developed for Planck, improved version (with residuals and polar errors)

- ScanamorphosPol :

  Based on the Scanamorphos code [H. Roussel, 2013] developed for Herschel

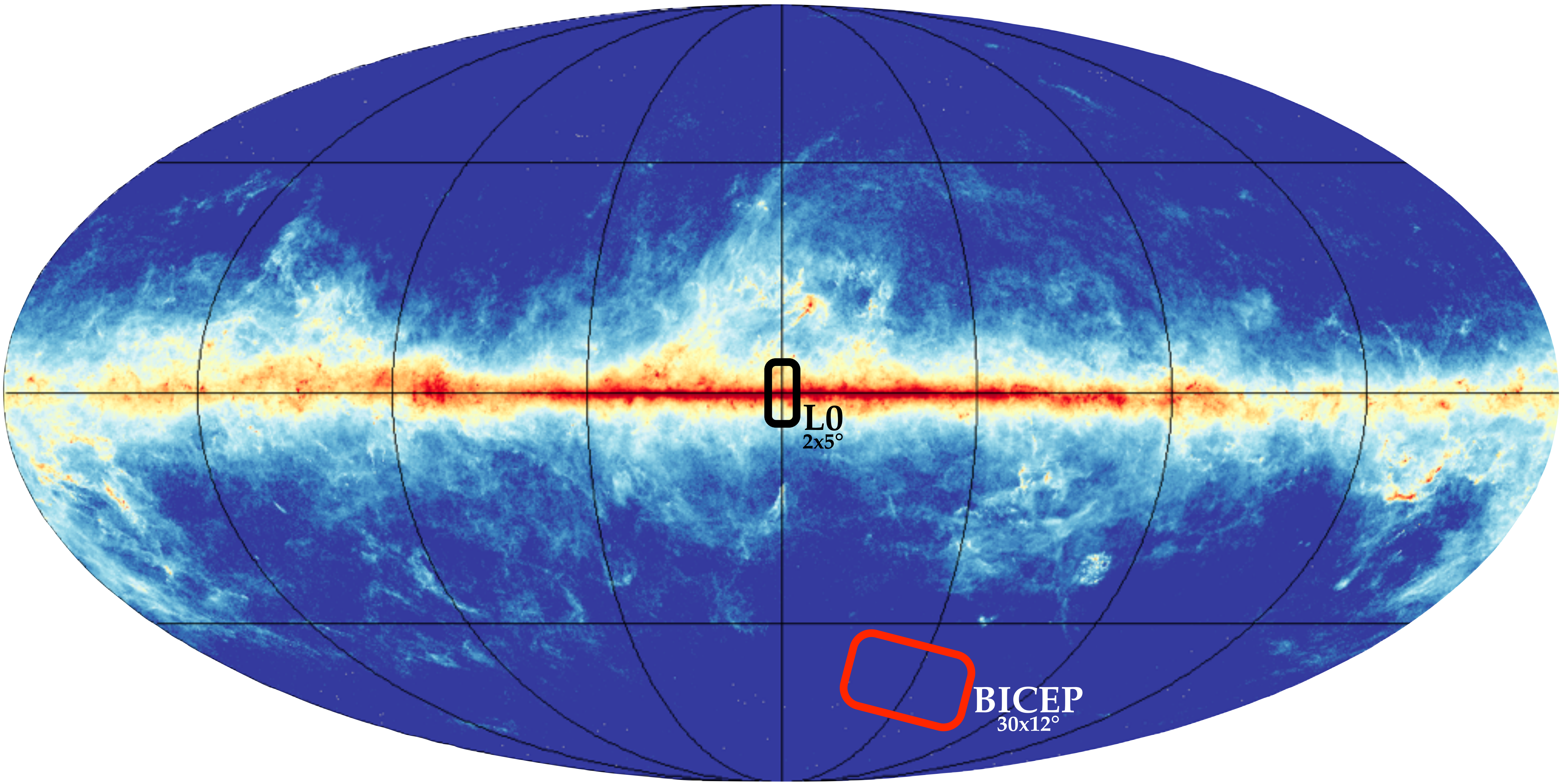
Galactic plane and star forming regions

Intensity maps



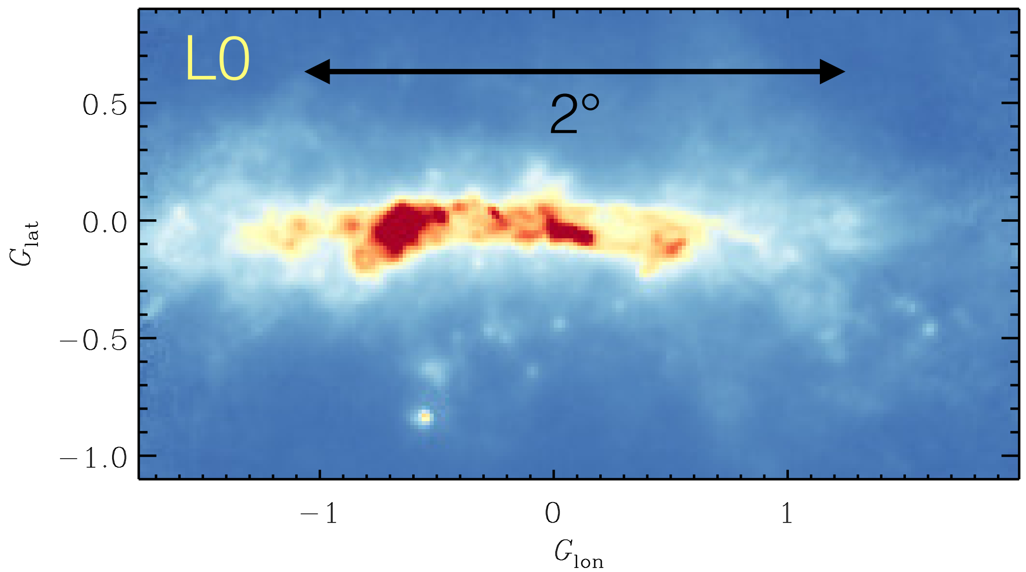
Current targets of the PILOT data analysis

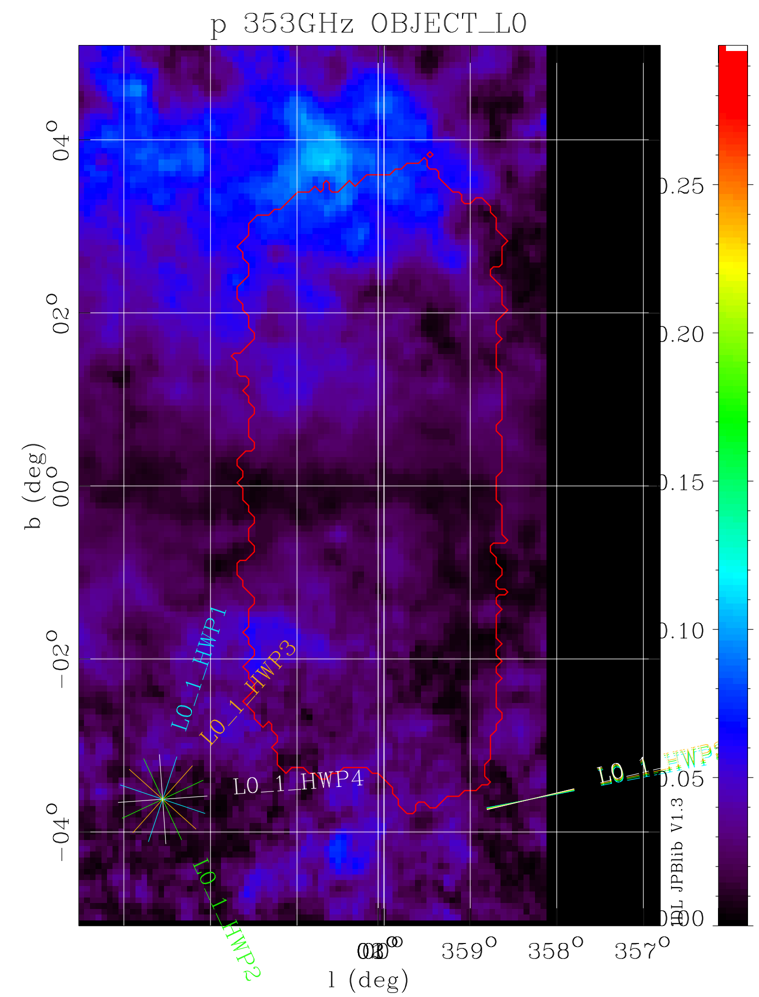
- The galactic center region (L0): **very bright but weakly polarized: challenging!**
- The BICEP field: **weak emission**, polarization fraction ~20 % **: challenging!**



The galactic center region (L0)

[The PILOT Collaboration, Mangilli et al., in prep.]





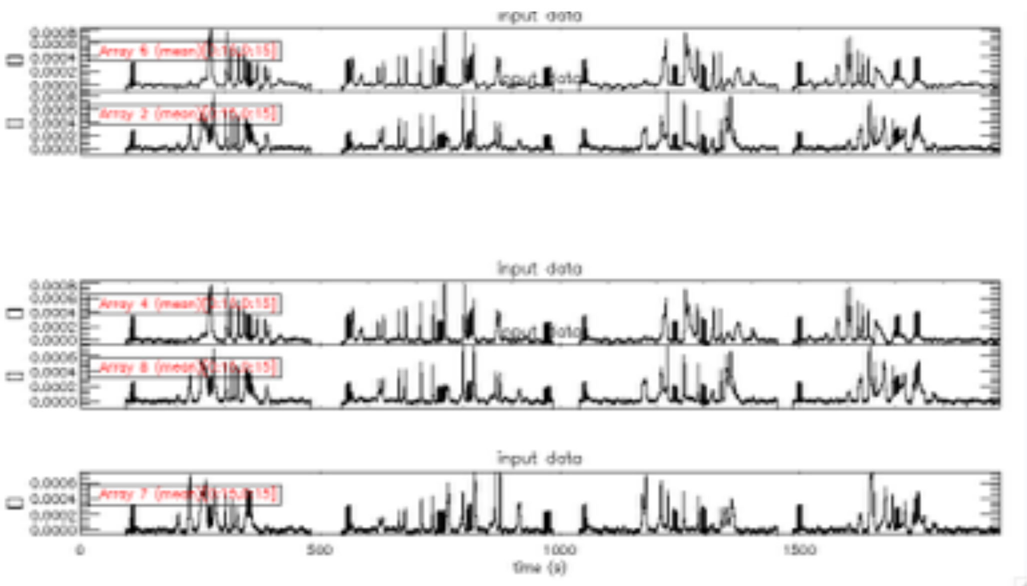
- 4 PILOT observations
- Very bright: check data calibration, detector responses and inter-calibration
- **Unique line of sight** to sample the bulk of the galactic emission
- Steep dust emissivity in intensity $(\beta \geq 2)$ [The Planck Coll., PIR XIX 2015]

  what about the polarized SED?

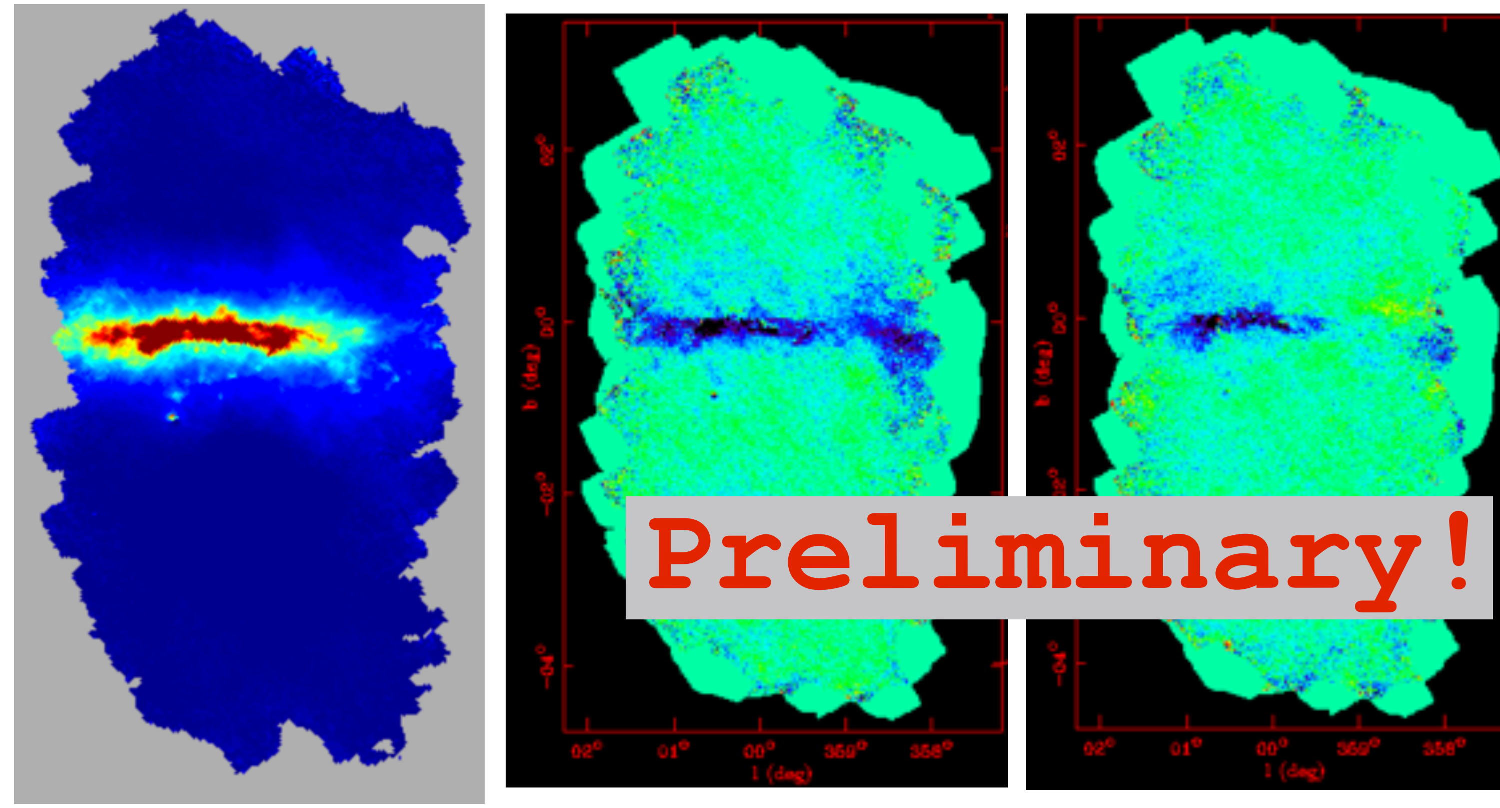
The galactic center region (L0)

[The PILOT Collaboration, Mangilli et al., in prep.]

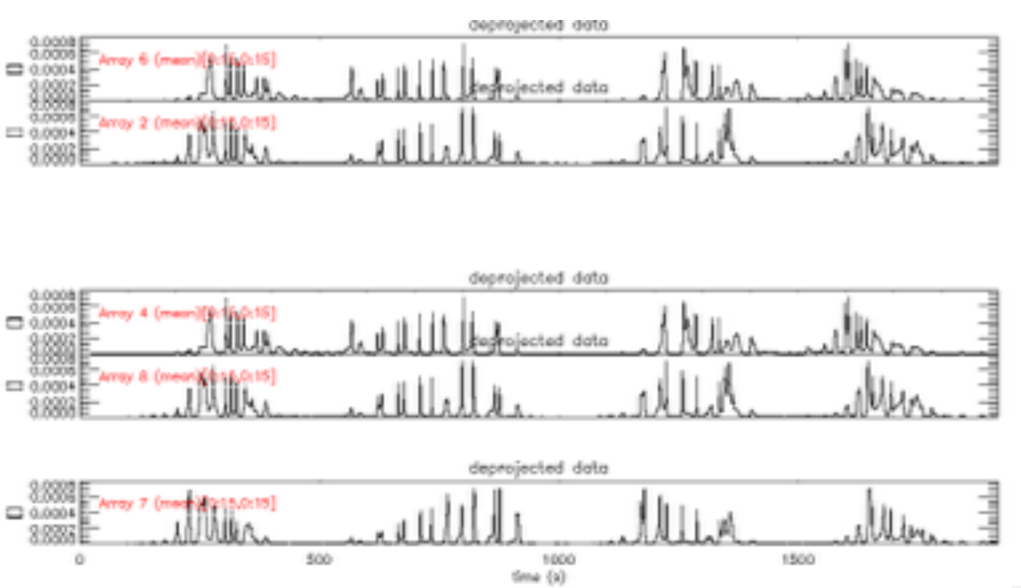
PILOT DATA (full resolution)



Total Intensity | polar Q | polar U



SIMS (Planck, resolution 5')



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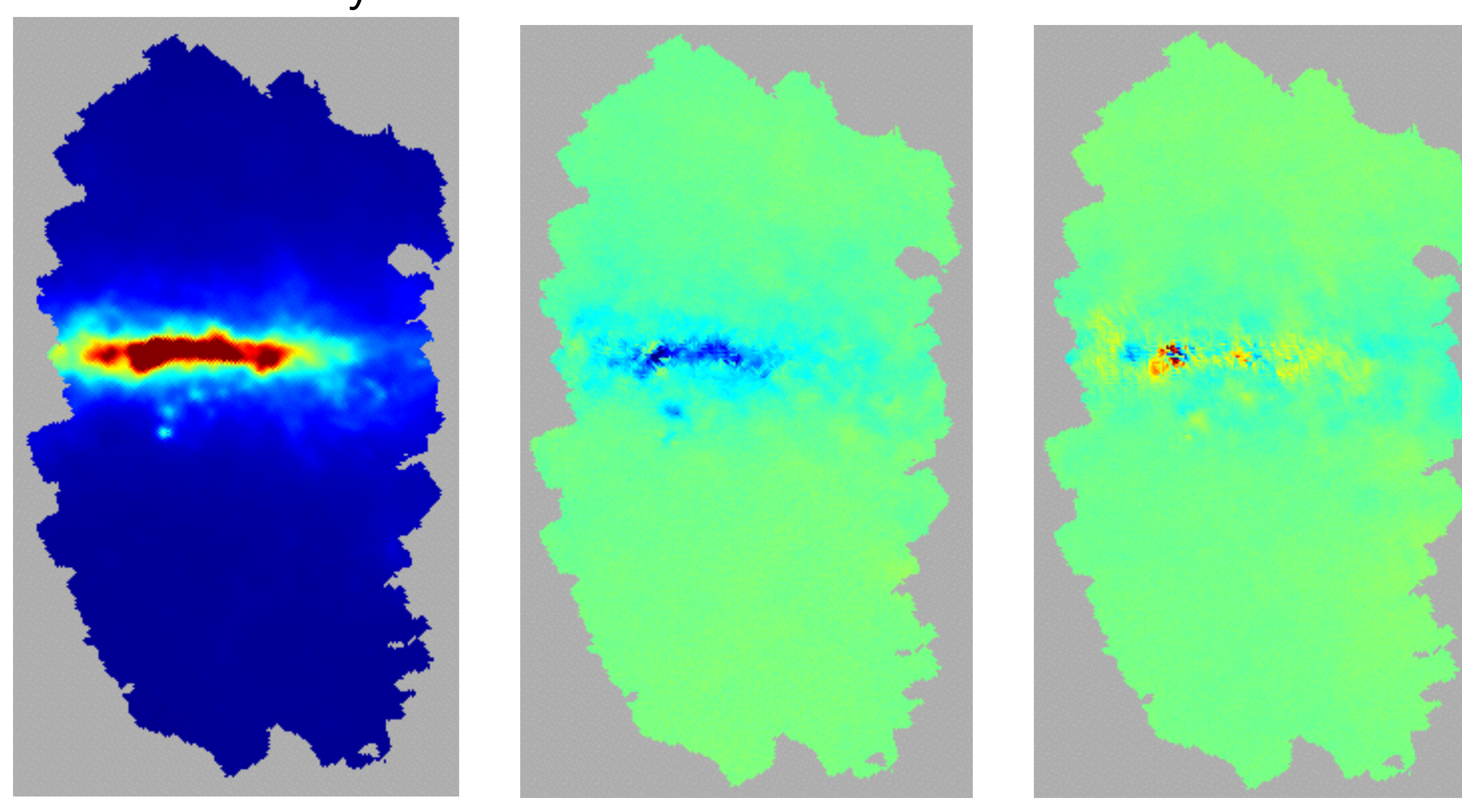
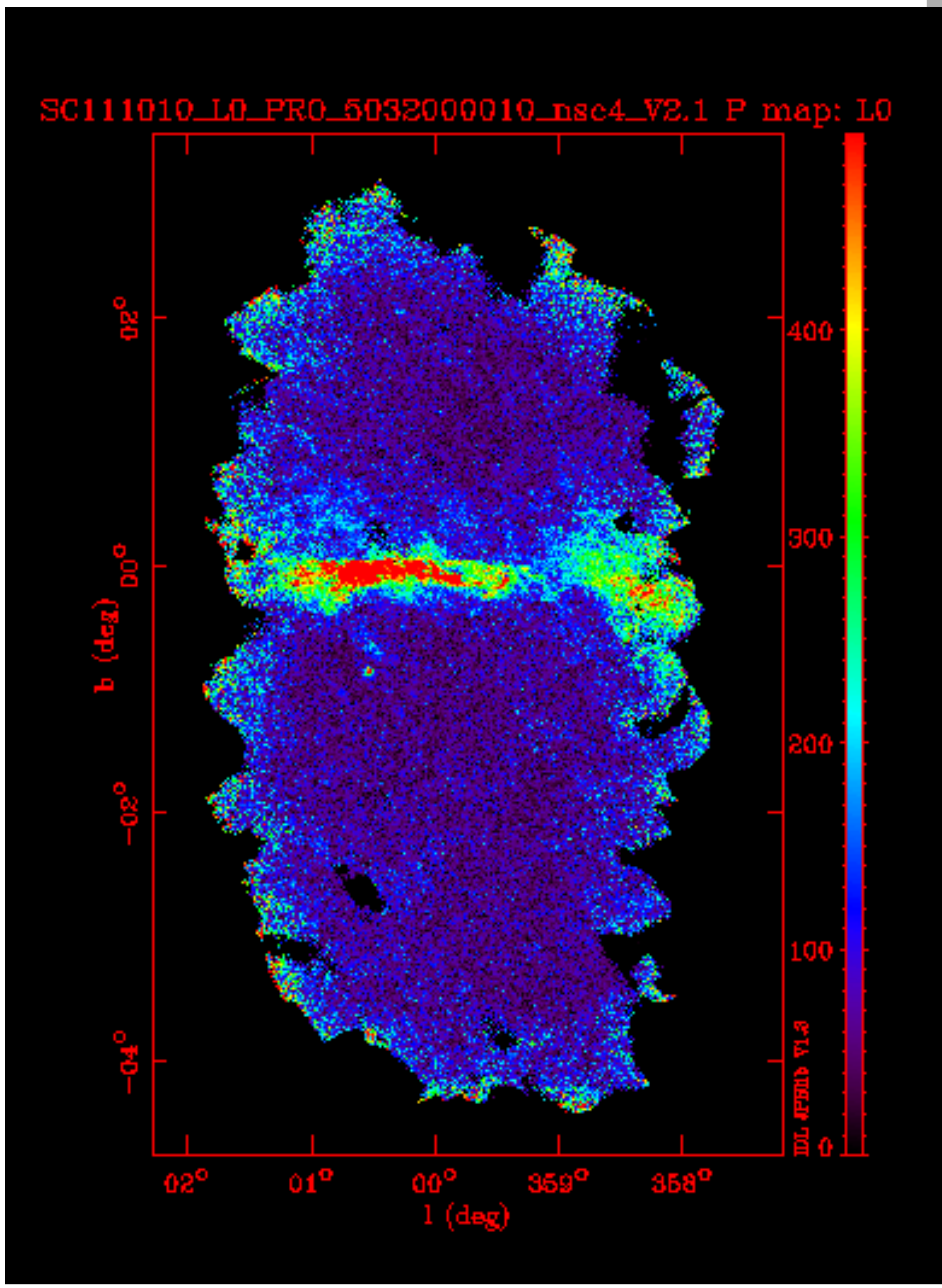
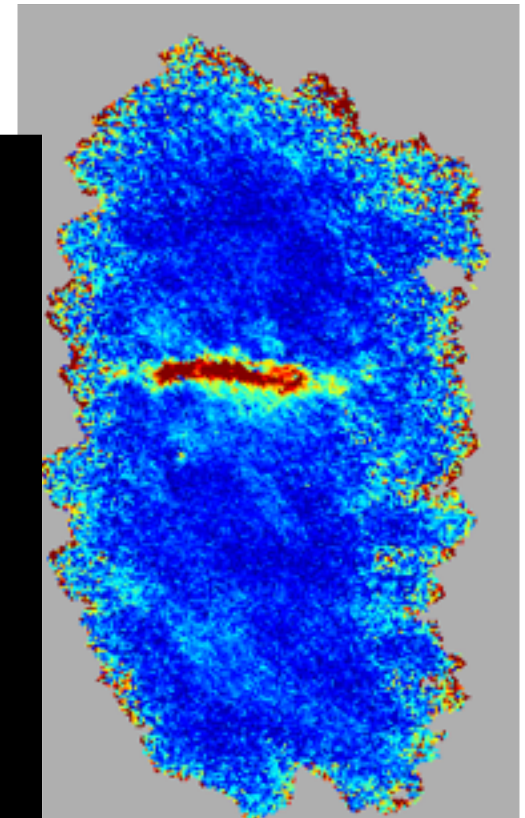


Polarization fraction in the galactic center

[The PILOT Collaboration, Mangilli et al., in prep.]

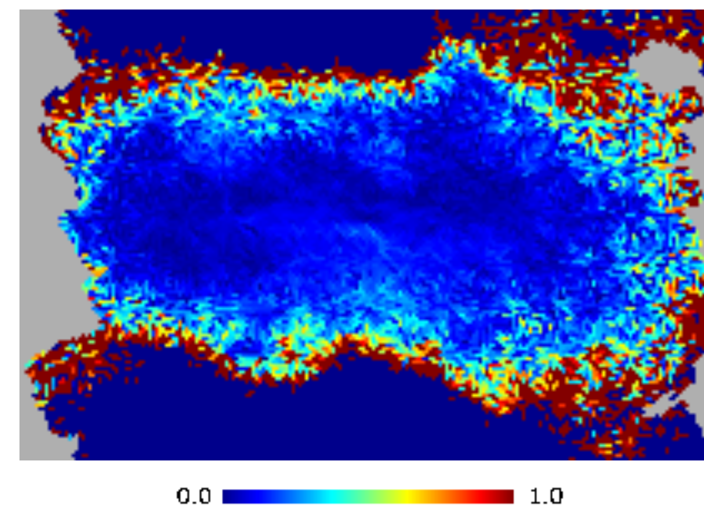
$$P = \sqrt{Q^2 + U^2}$$

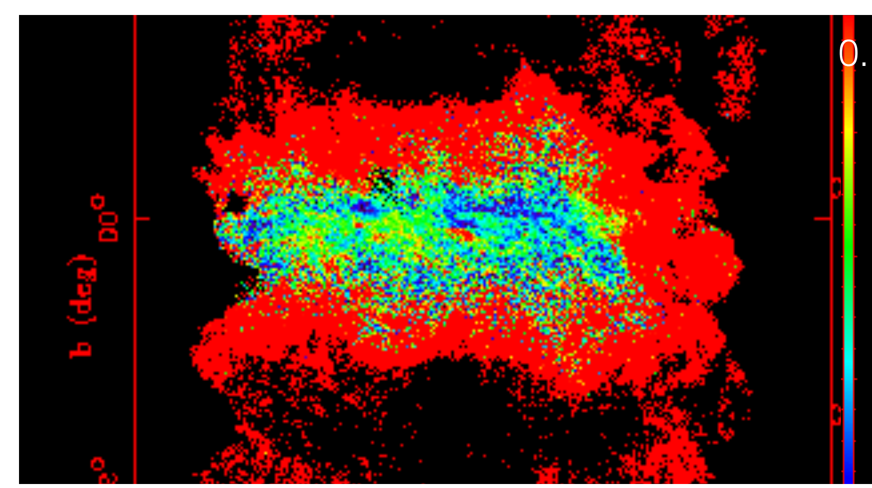




Preliminary!

$$p = \frac{\sqrt{Q^2 + U^2}}{I}$$





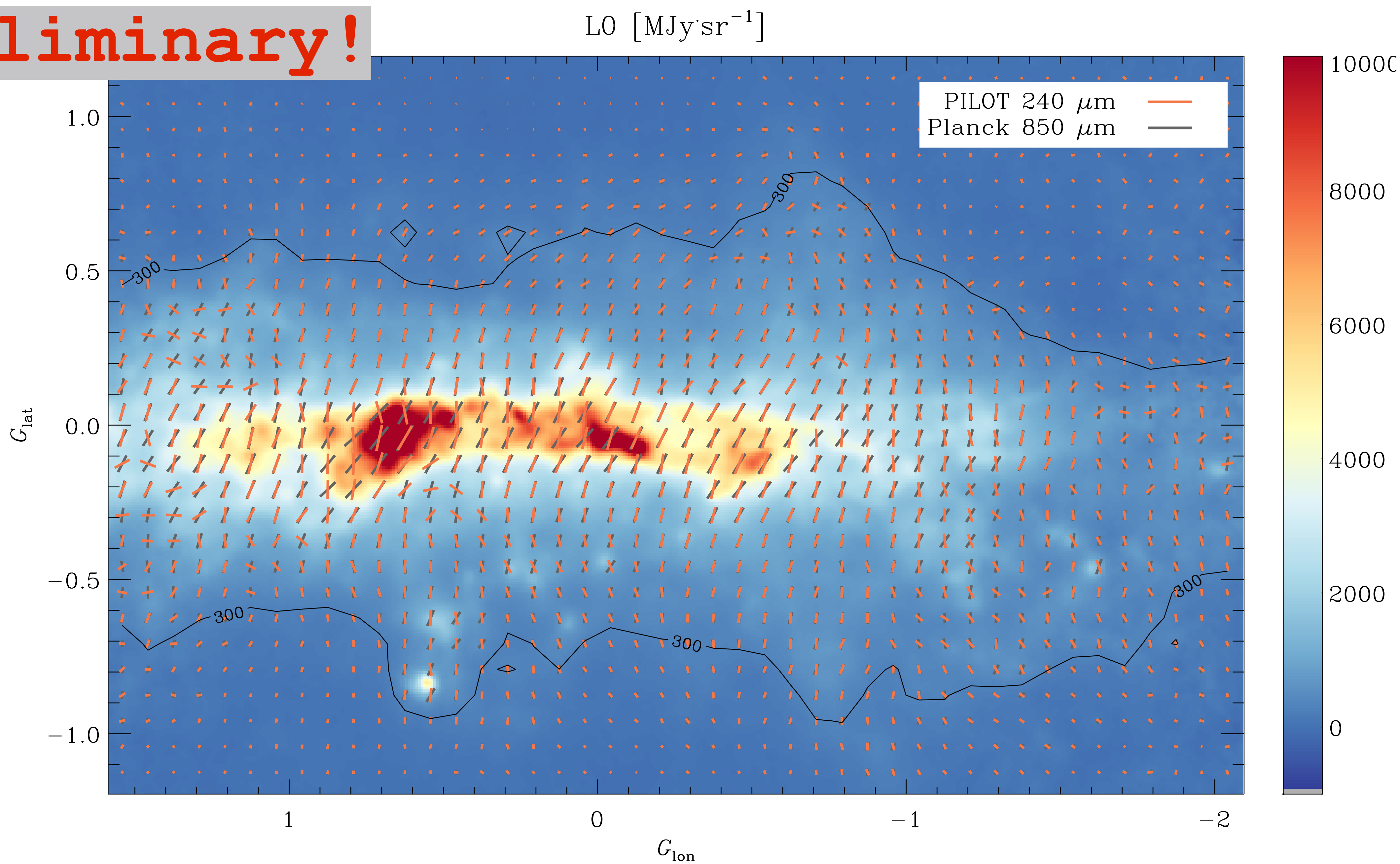
Average PILOT polarization fraction in the galactic plane : few %

L0 polarization angles : PILOT vs Planck

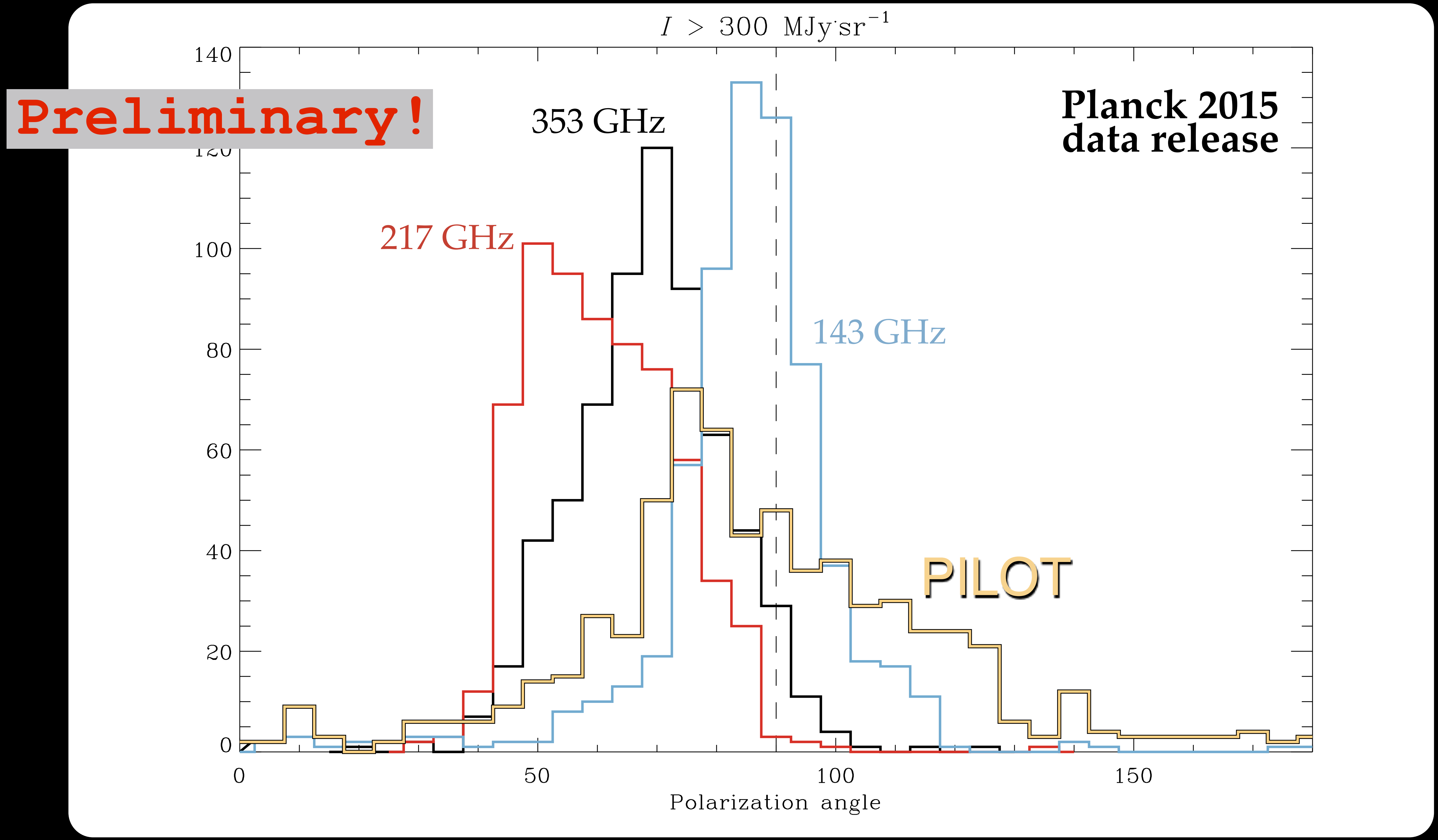
[The PILOT Collaboration, Mangilli et al., in prep.]

$$\psi = 1/2 \arctan(U/Q)$$

Preliminary!



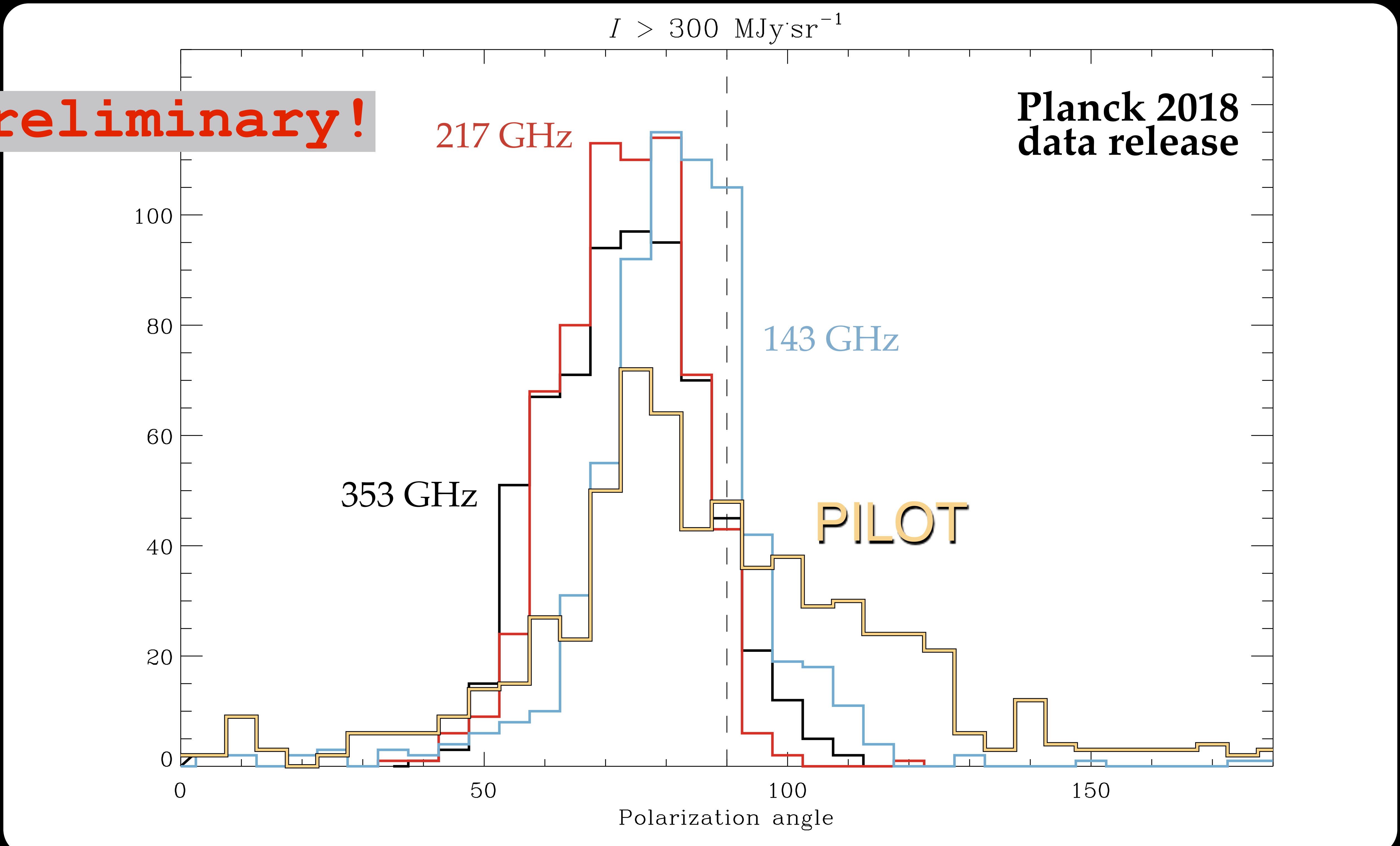
Comparison with Planck



$$\psi = \frac{1}{2} \cdot \mathrm{atan}\left(\frac{U}{Q}\right)$$

[The PILOT Collaboration, Mangilli et al. 2018 in prep.]

Comparison with Planck



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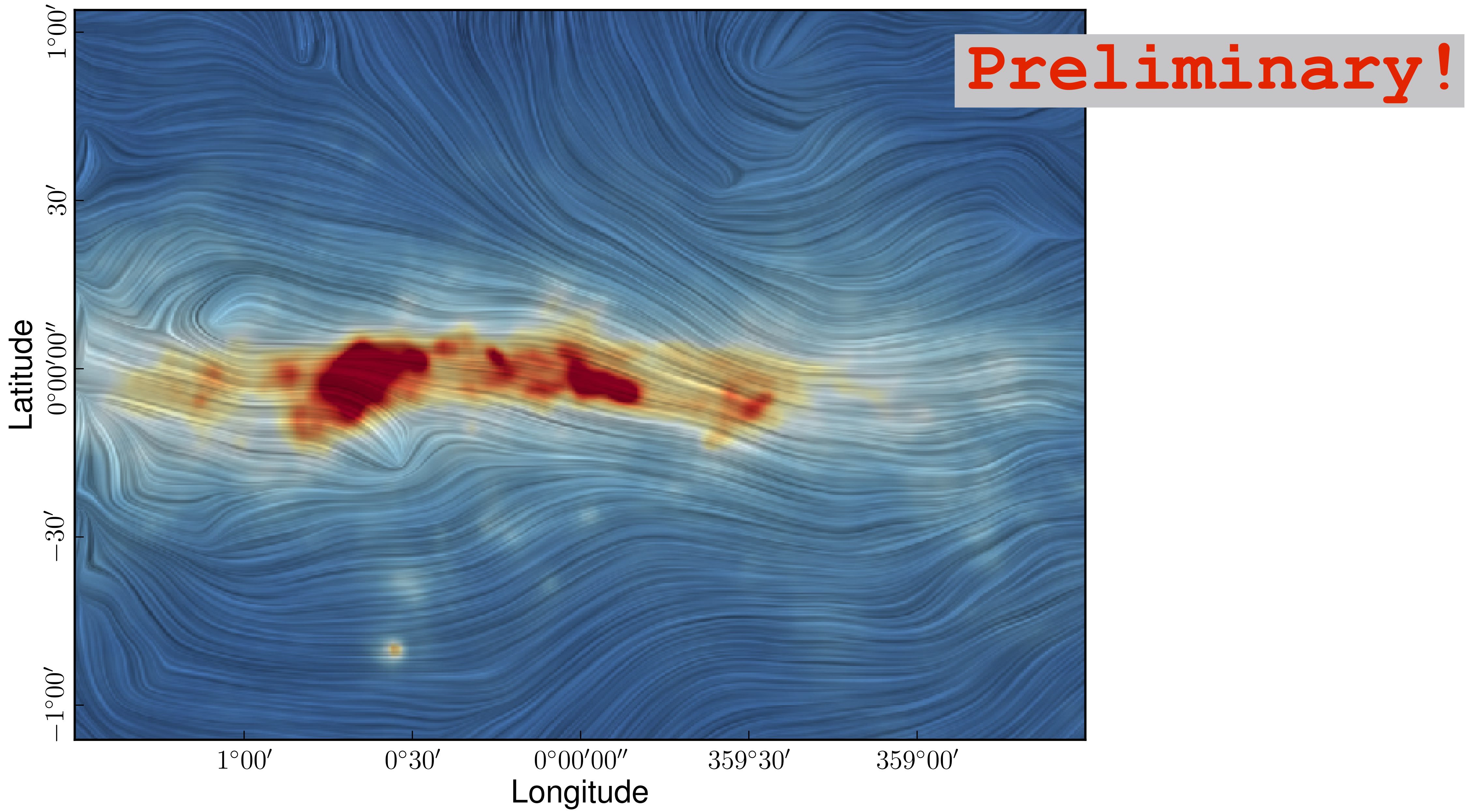
[The PILOT Collaboration, Mangilli et al. 2018 in prep.]

Magnetic field in the L0 region

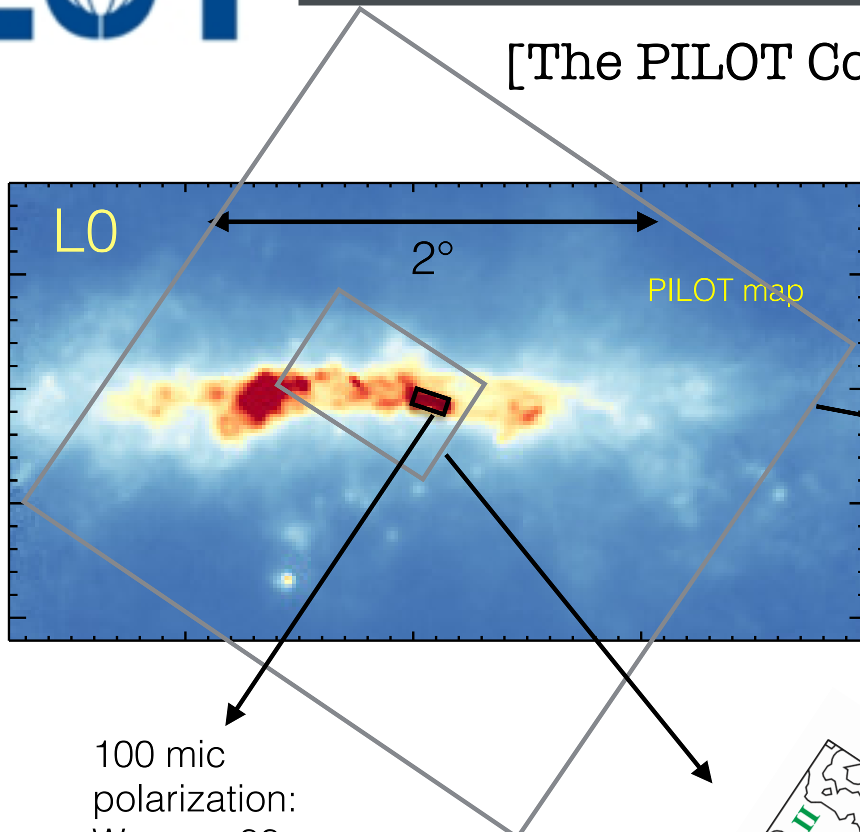
[The PILOT Collaboration, Mangilli et al., in prep.]

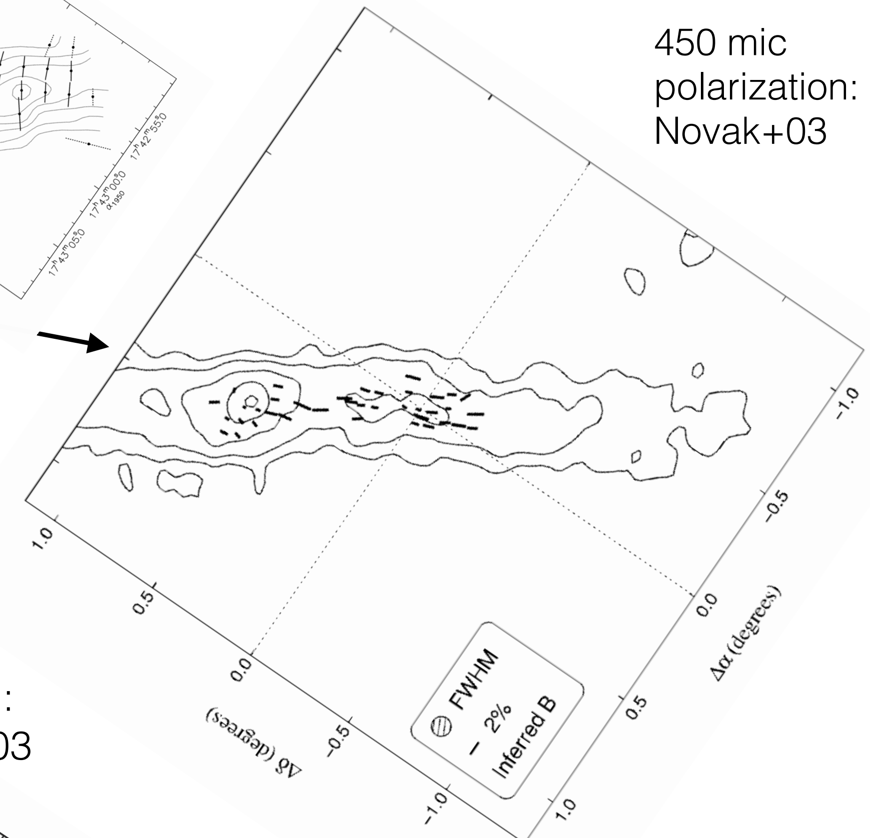


- Pilot analysis on the galactic center confirms a good control of gain inter-calibration
- PILOT finds the orientation of the magnetic field along the galactic plane which is in agreement with expectations and with Planck at lower frequencies
- SED polarization study $p(\nu)$: comparison with other observations on going

Magnetic field in the L0 region

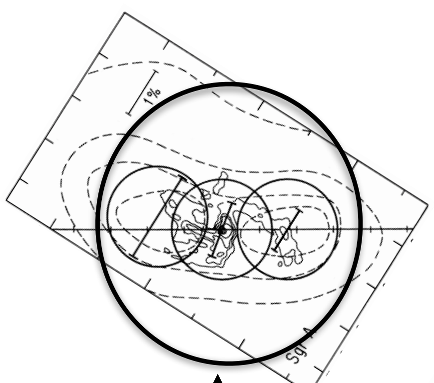
[The PILOT Collaboration, Mangilli et al., in prep.]



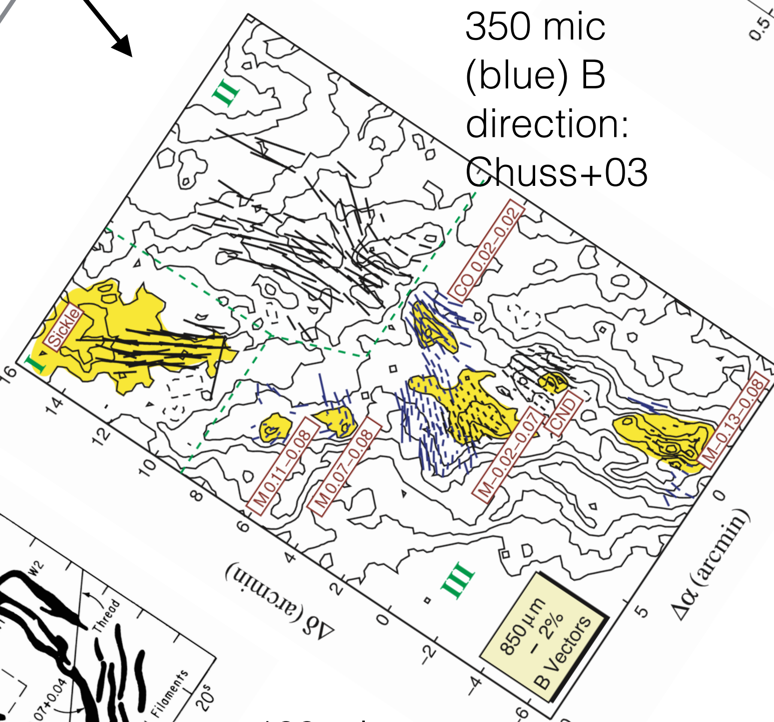


450 mic polarization: Novak+03

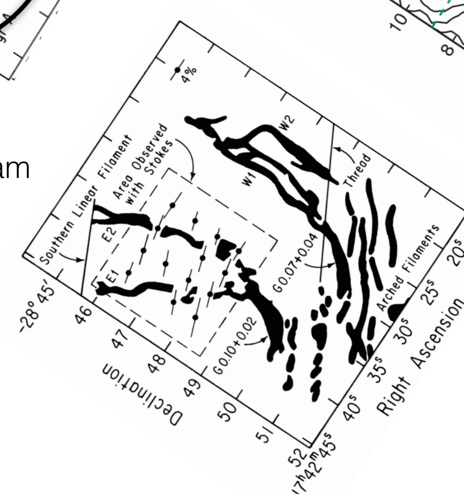
100 mic polarization: Werner+88



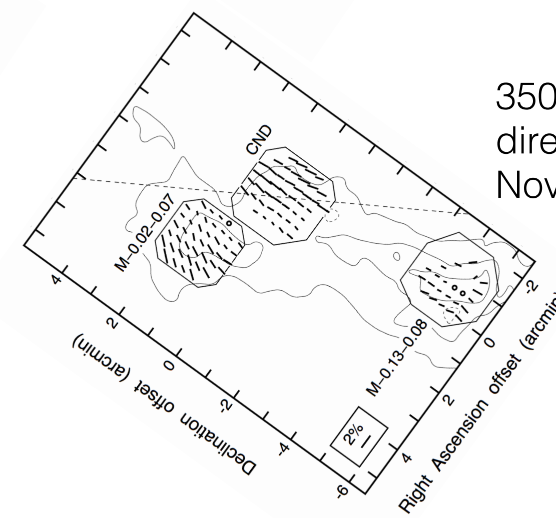
PILOT beam



350 mic (blue) B direction: Chuss+03



100 mic polarization: Morris+92

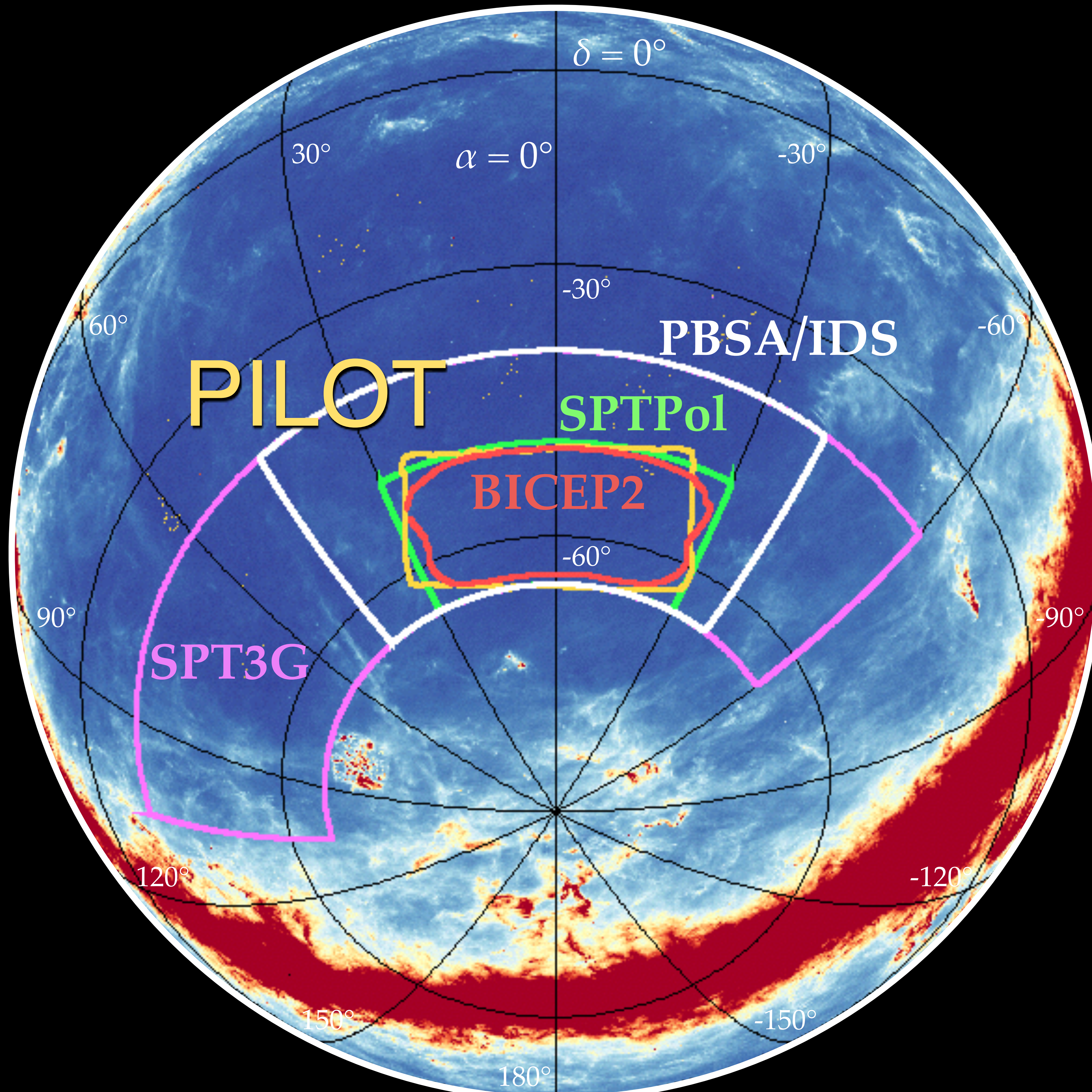


350 mic B direction: Novak+00

PILOT: link in angular resolution and scales between these observations and Planck

Goal : SED from 100µm to 2mm

PILOT – “BICEP” region



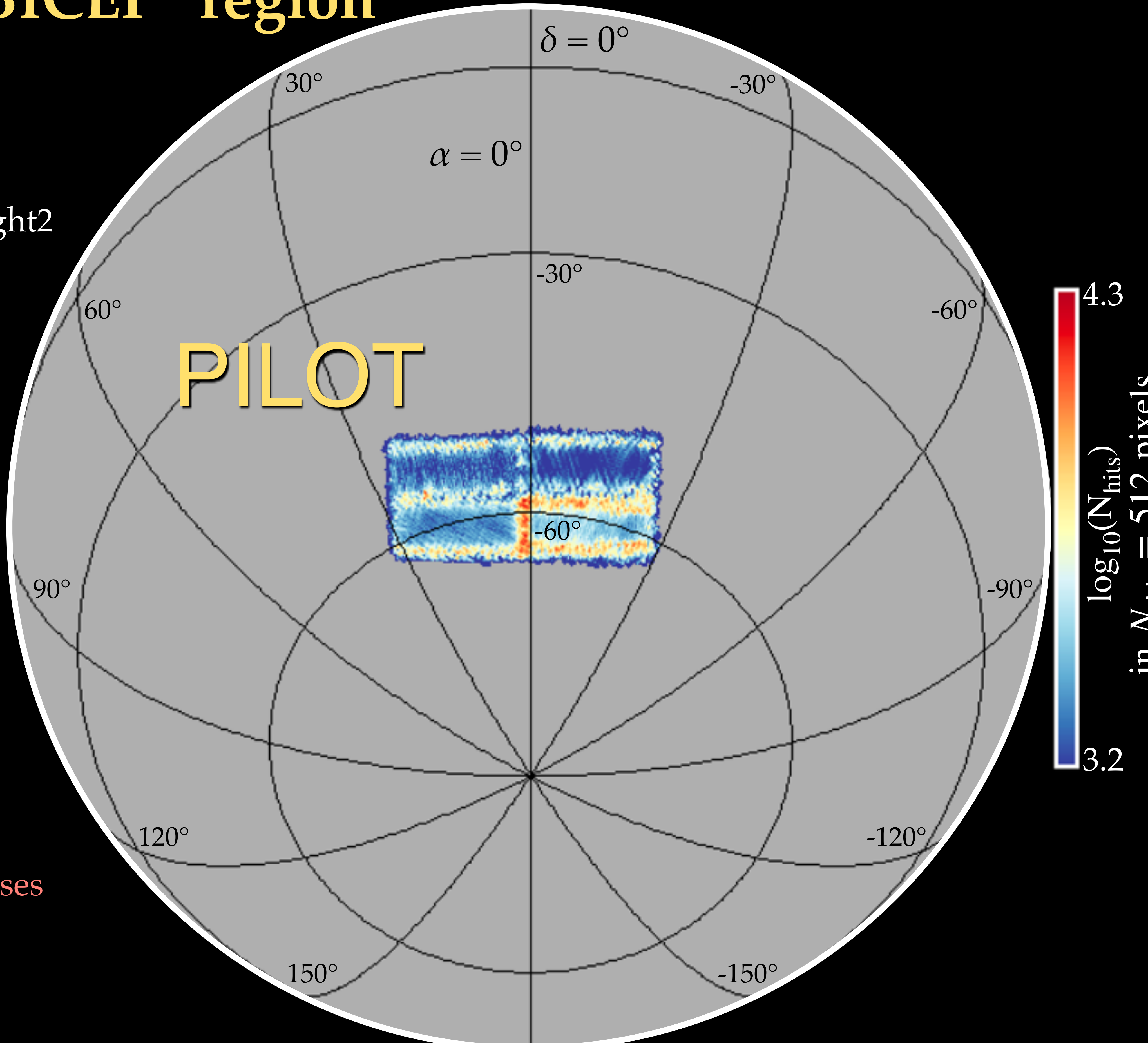
PILOT – "BICEP" region

★ 4.8 h of data during flight2

★ BICEP field observed with 4 tiles, each of them being observed at least twice with 2 different HWP positions

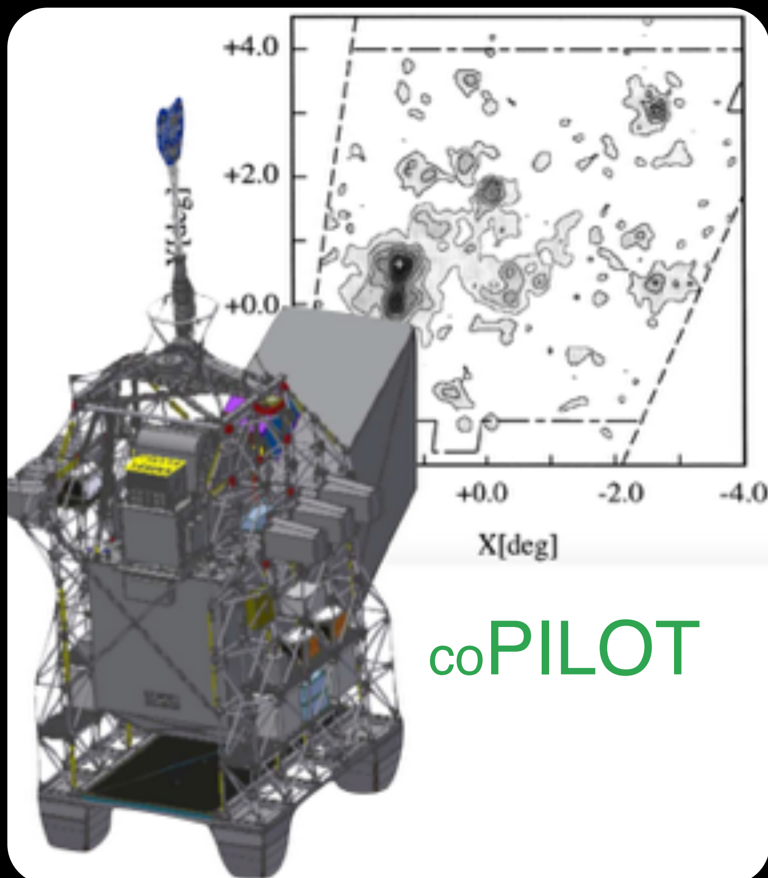
★ Goal signal to noise ratio of ~20 on the polarized intensity integrated over the whole field

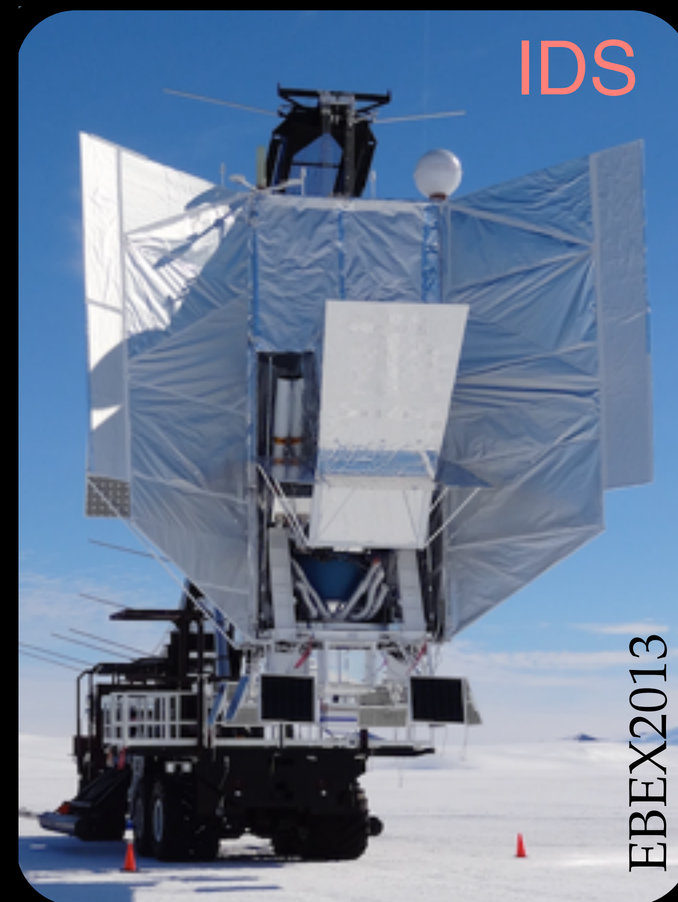
★ Unique data for constraining the SED or for correlation analyses in CMB observations



Discussion ongoing for an MoU with the BICEP team

PILOT – Legacy



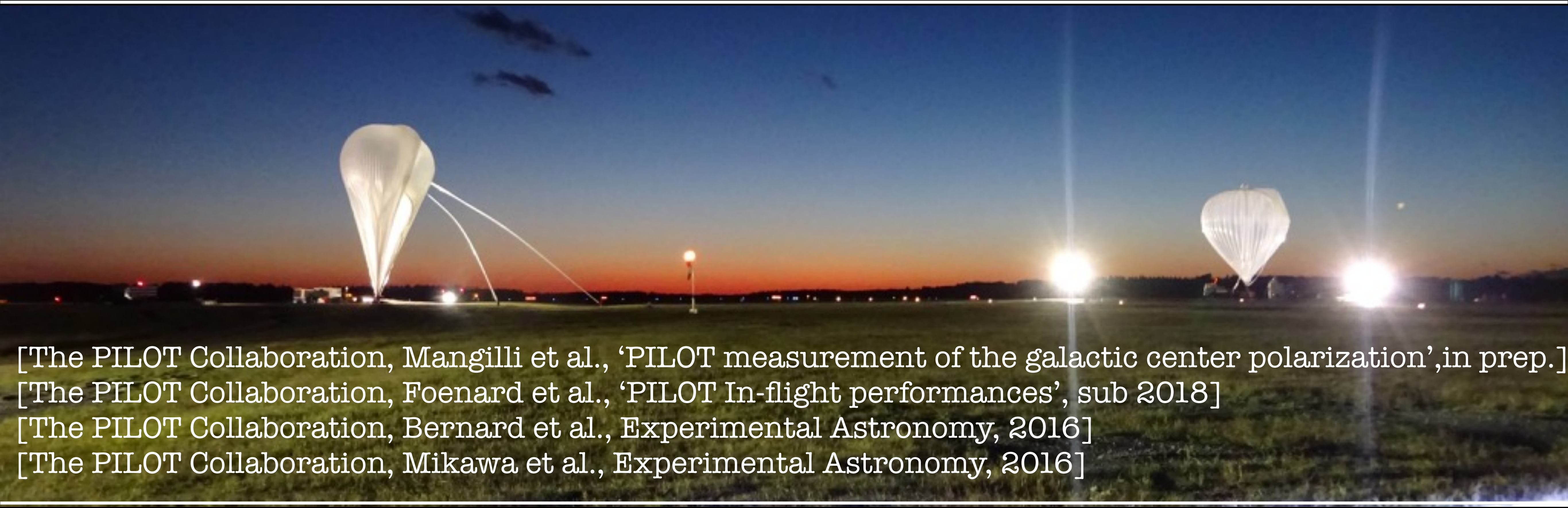


SPICA-Pol

- ★ coPILOT: modification of PILOT will allow very accurate measurements of C+ (158 μm) total intensity. Dark molecular gas distribution in solar neighborhood, nearby galaxies. Phase A at CNES.
- ★ IDS (Inflation and Dust Surveyor): CMB *B*-modes + dust, proposed to NASA 2018. Contribution to provide PILOT attitude control + internal calibration source
- ★ Bebop (sPICA-Pol): polarized instrument on SPICA. Design and science case strongly inspired from PILOT. Accepted in pre-phaseA/0.
- ★ BOOST proposal (IRAP) to lower detector temperature to 150 mK. Increase in sensitivity by 2.7 for PILOT, up to 14 for CoPilot

PILOT – **Summary**

- ★ Operational and instrumental success of the PILOT two flights
- ★ Unique experiment: observation of the dust polarization at 1.2 THz over large regions of the sky relevant for galactic science and for cosmology
- ★ The polarization direction measured in the galactic center region is consistent with expectations and with Planck at lower frequency
- ★ Ongoing work : data processing refinement, uncertainties estimates in map-making, extend the analysis to L30, Rho-Ophiuchi, Orion, …
- ★ PILOT legacy for future instruments
- ★ **Flight#3** in 2019 from the northern hemisphere?



[The PILOT Collaboration, Mangilli et al., 'PILOT measurement of the galactic center polarization',in prep.]
[The PILOT Collaboration, Foenard et al., 'PILOT In-flight performances', sub 2018]
[The PILOT Collaboration, Bernard et al., Experimental Astronomy, 2016]
[The PILOT Collaboration, Mikawa et al., Experimental Astronomy, 2016]

PILOT

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A. Mangilli (IRAP)
L. Montier (IRAP)
B. Mot (IRAP)
F. Pajot (IRAP)
I. Ristorcelli (IRAP)
H. Roussel (IAP)

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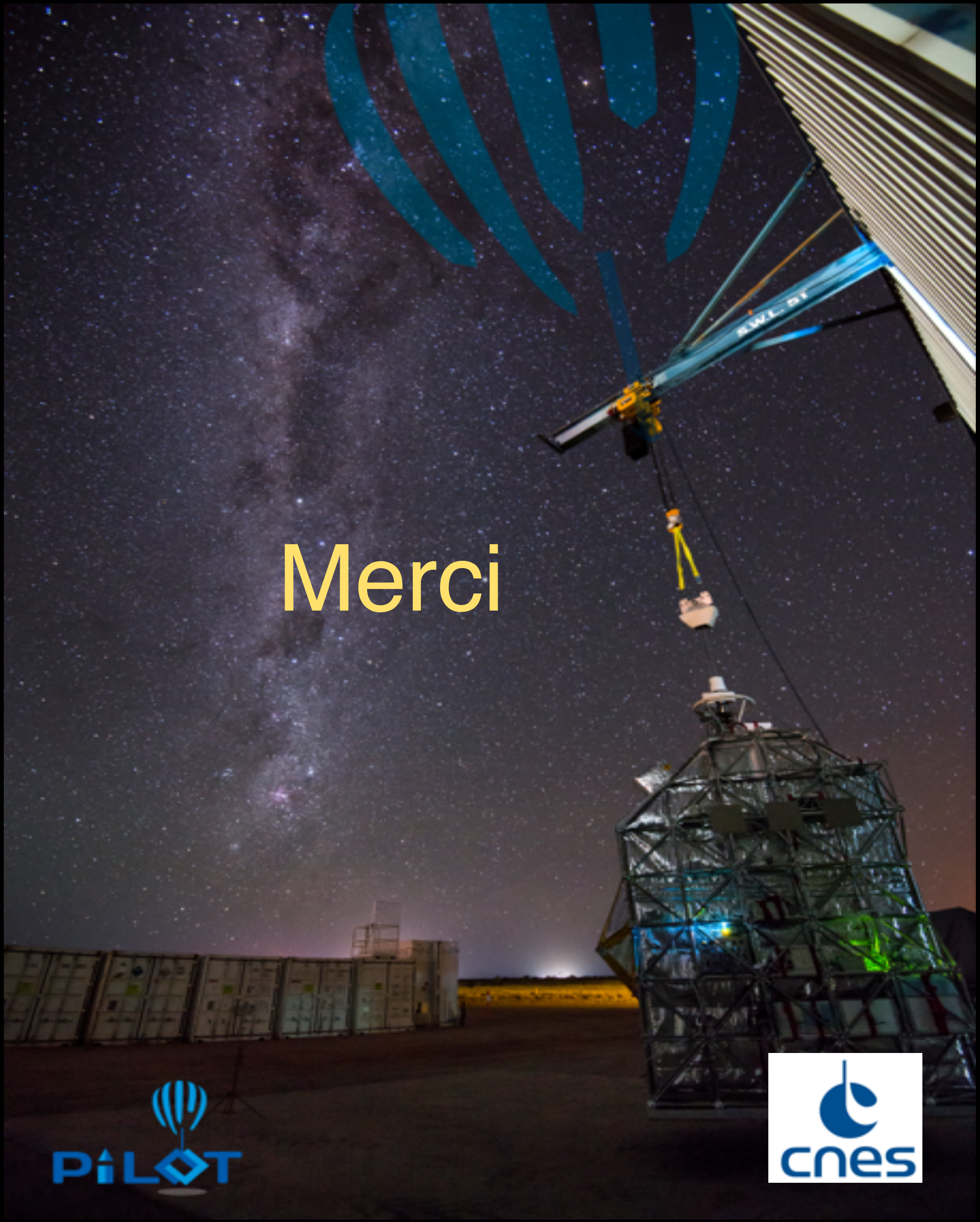
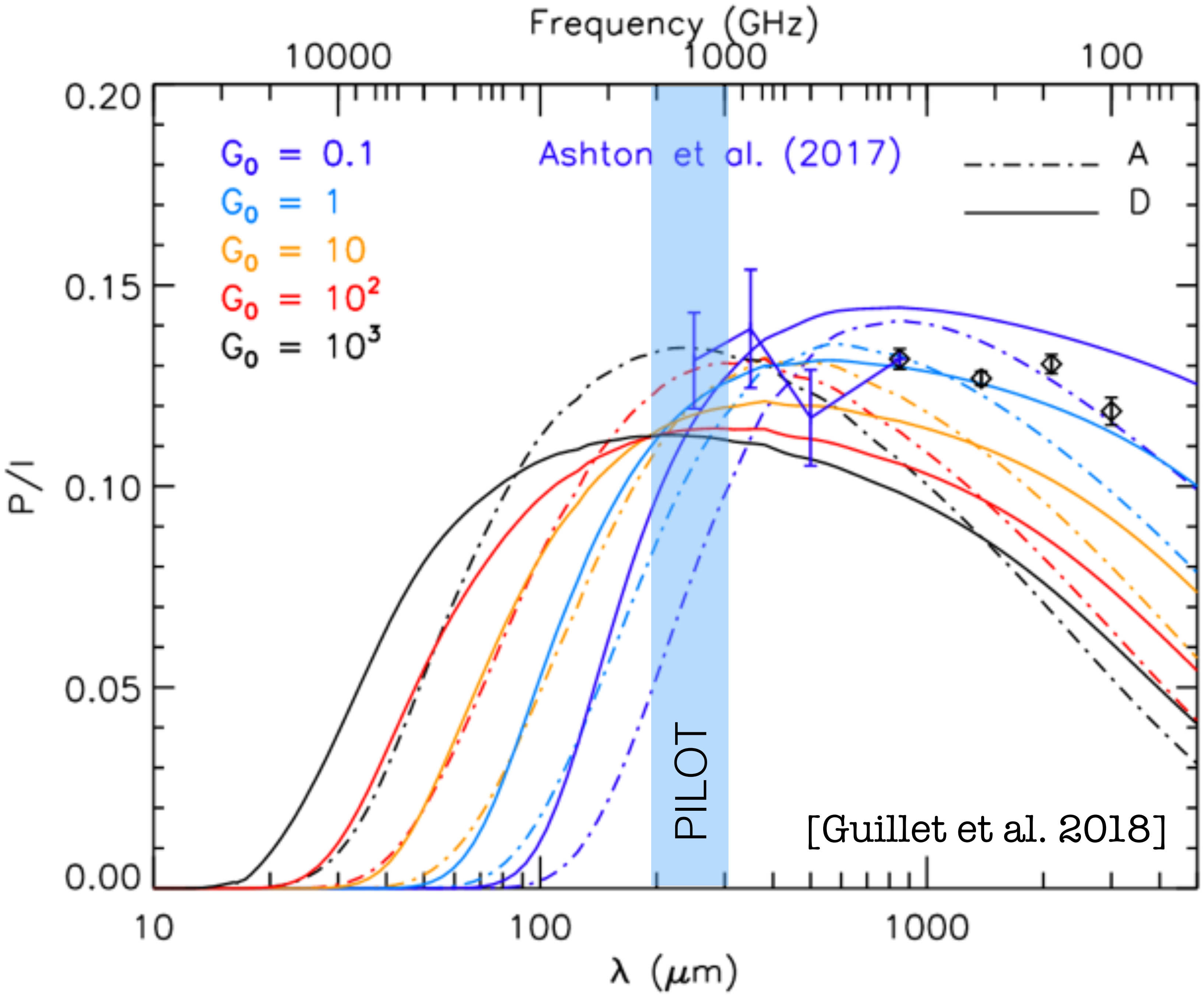
C. Tucker (UK)
G. Pisano (UK)
G. Savini (UK)
P. de Bernardis (Italy)
S. Masi (Italy)
R. Laureijs (NL)
J. Tauber (NL)



What do we know about dust polarization SED ?

We have very little constraints on the dust FIR polarized SED despite the importance for dust models (and CMB foreground)



Only 2 recent FIR measurements (BLASTPol balloon, VelaC, 1°sq):
- [Gandilo et al. 2016]
- [Ashton et al. 2017]

Polarized "emissivity" P353/Pv (emission/extinction ratio): exceeds current model predictions ([Draine and Fraisse 2009]) by ~2.5

[The Planck Coll., PIR XXI 2015]

- Accurate FIR Measurements are critically needed, sampling various environments to link alignment with dust optical properties
- PILOT : unique observations on large sky regions in the FIR

Detector responses

Precisely measure the detector response variations
is crucial for polarisation

- **<u>Temporal</u> detector response variations: Internal Calibration Source (ICS)**

ICS response:

The ground calibration tests have shown that the ICS flux is directly proportional to the squared power dissipated therein

$$\rho_{ICS} = \frac{\Delta^{ICS}_{\text{on}-\text{off}} R_{ref} I^2_{ref}}{\langle R_{\text{on}} (\langle I_{\text{on}} \rangle^2 - \langle I_{\text{off}} \rangle^2) \rangle}$$

[ADU], dim=[16,16,8,N_{seq_calib}]

- **<u>Spatial</u> detector response variations: Atmosphere**

Atmospheric response:

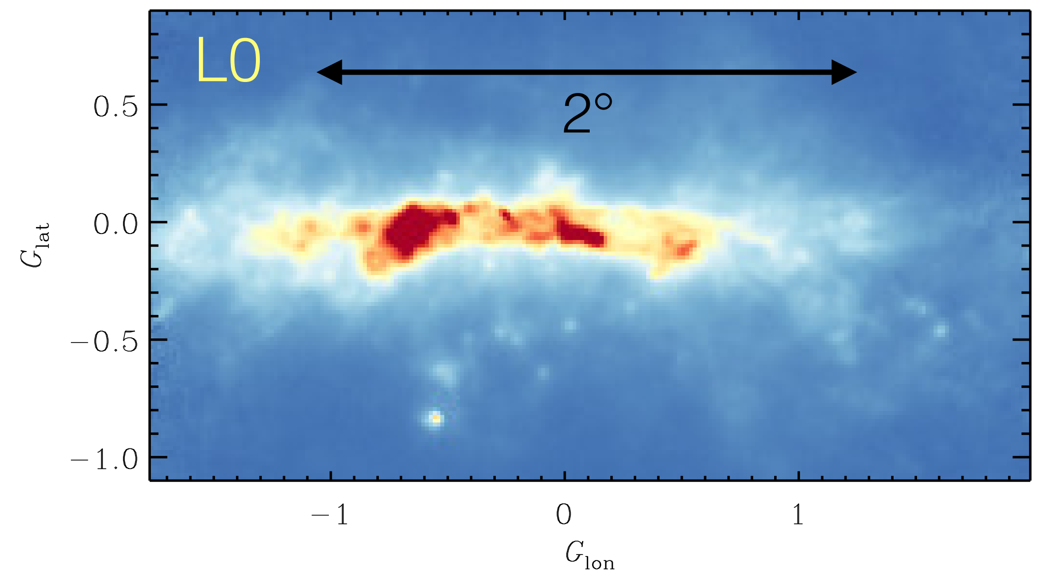
Atmosphere decorrelation from <u>sky-dips or over the whole flight</u>

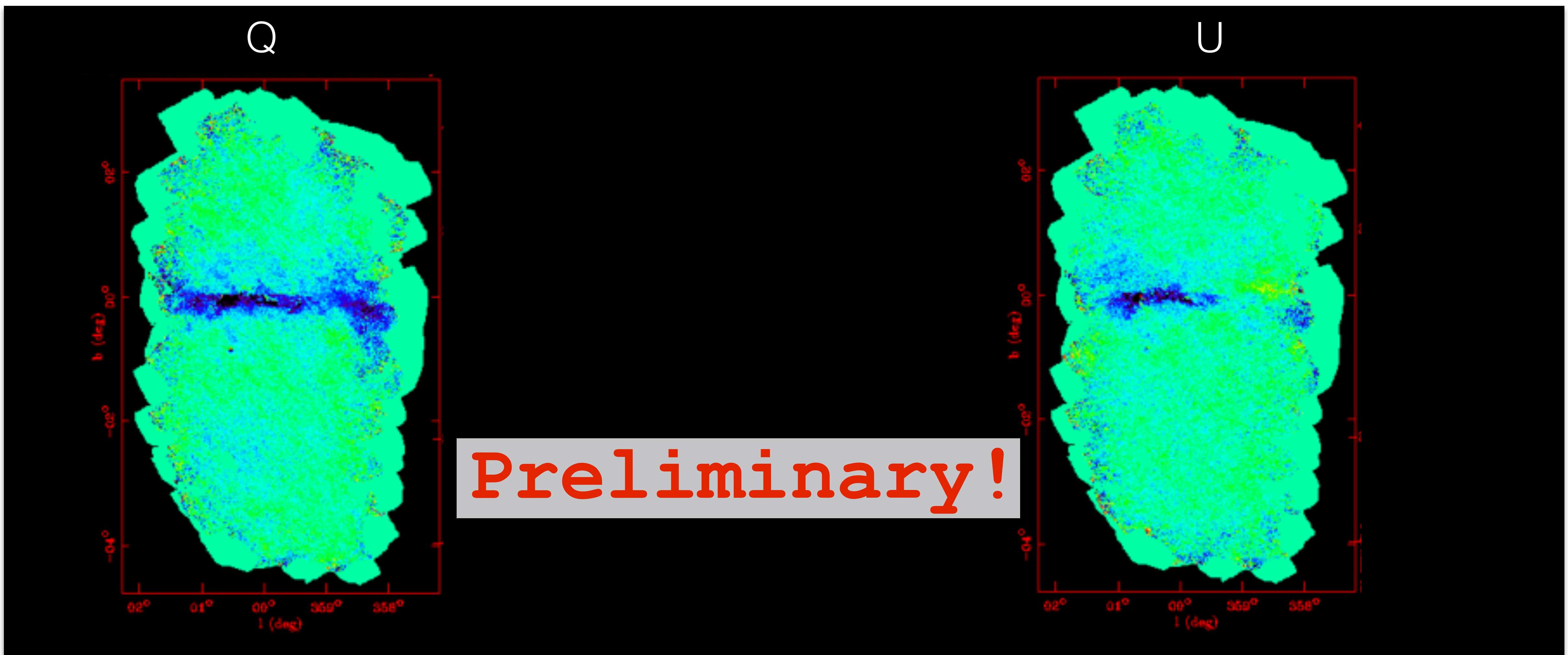
The response is the slope of this correlation

Flight2 observations are done at varying elevation: redundant scan angle + better constrain of the detector response variation.

The galactic center region (L0) maps

[The PILOT Collaboration, Mangilli et al., in prep.]





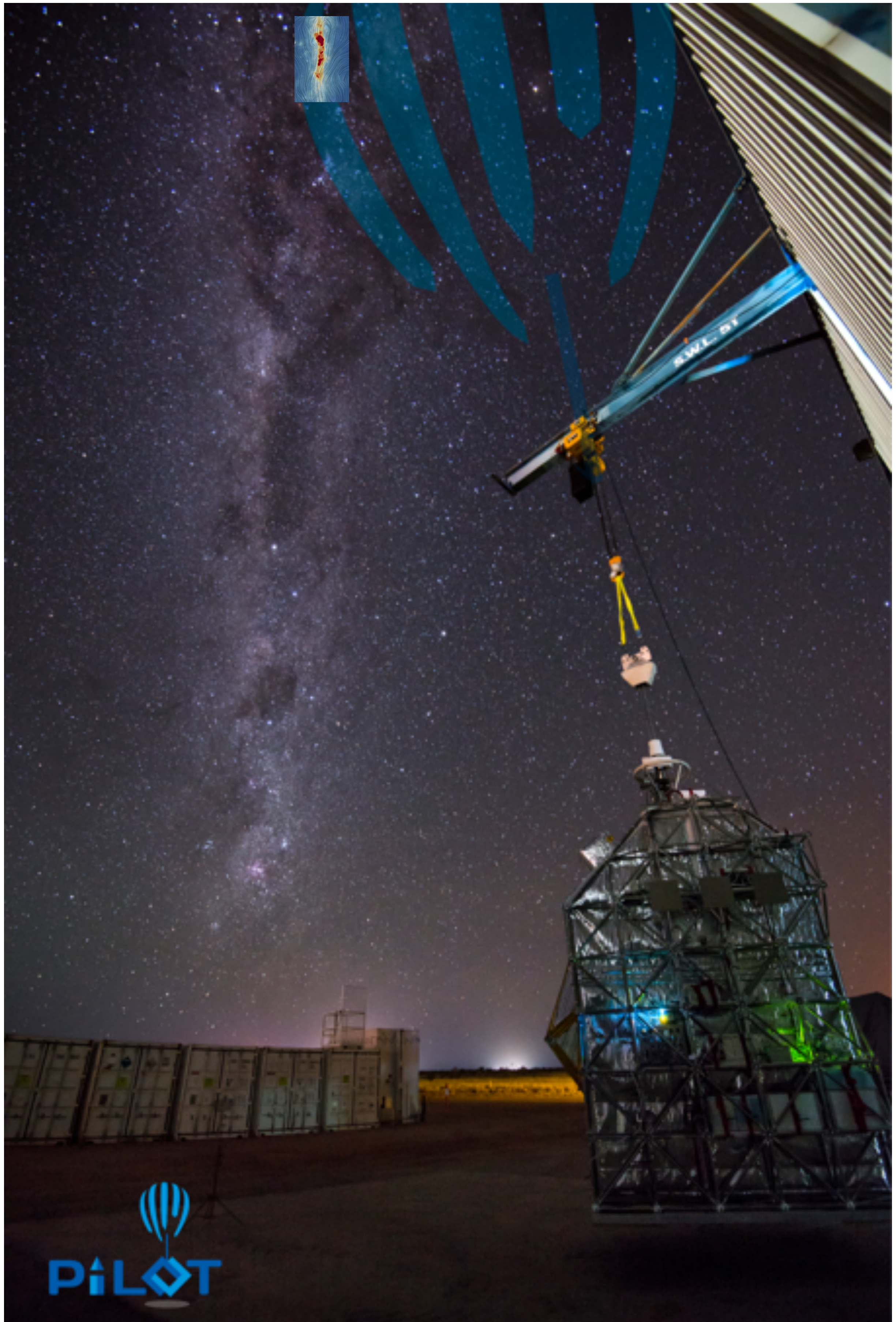
Data Calibration

Current data processing: atmospheric response map corrected for time variations using the ICS signal

$$R(x,y,t) = \frac{\rho_{atmo}(x,y)}{(\rho_{ICS}(x,y))_{normatmo}}\rho_{ICS}(t)$$

Sources of response variations:

- Change in elevation
- Temperature variations
- Instrumental background polarization
- …

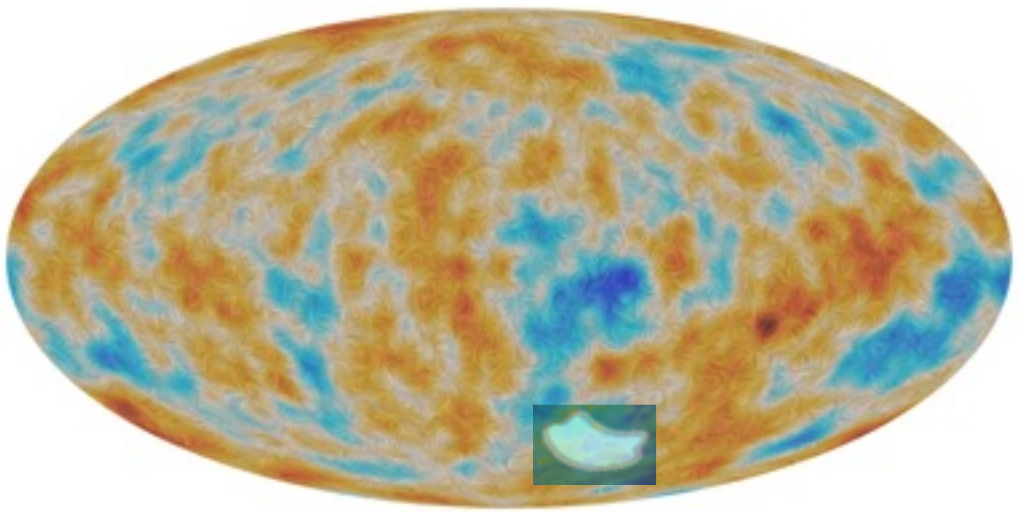


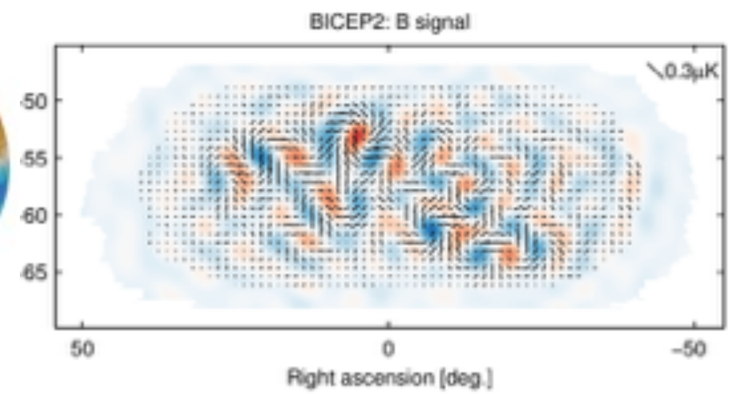
OUTLINE

- PILOT flight#2 in-flight performances summary
- Flight#2 data analysis & preliminary results
- Conclusions and perspectives

La région BICEP : pourquoi c'est intéressant?

L'empreinte des ondes gravitationnelles de l'inflation dans le fond diffus cosmologique






The New York Times
Monday, March 17, 2014 | Today's Paper | Personalize Your Weather
WORLD U.S. NEW YORK BUSINESS OPINION SPORTS SCIENCE ARTS FASHION

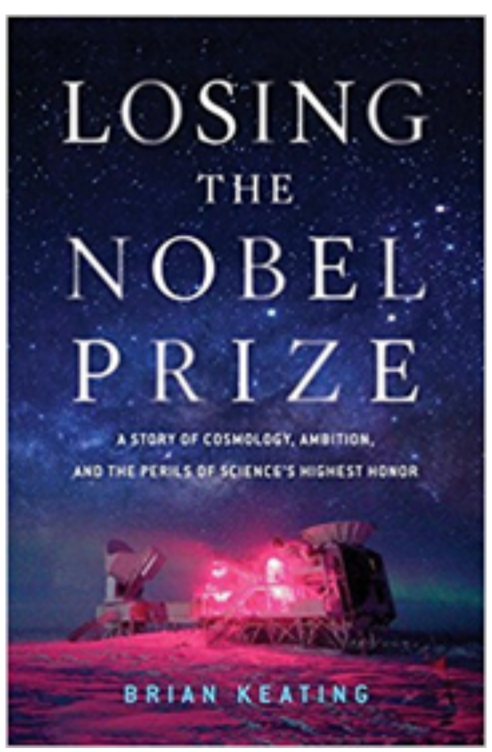
Ripples in Space-Time Support Big Bang

By DENNIS OVERBYE 10:46 AM ET

Astronomers found gravitational waves that buttress the theory of a universe wrenched violently apart around its inception. Above, the telescope used to detect the waves.

Planck : signal mesuré par BICEP est dû à l'émission polarisée des poussières

[Planck&BICEP2 Collaborations PRL 114 (2015), Planck Collaboration PIPXXX A&A (02/2016), Planck Collaboration PIPL A&A(03/2017), Planck Collaboration PIPLIV (sub. A&A 2018)]



Emission polarisée des poussières galactiques : facteur limitant pour la détection des ondes gravitationnelles primordiales dans le CMB

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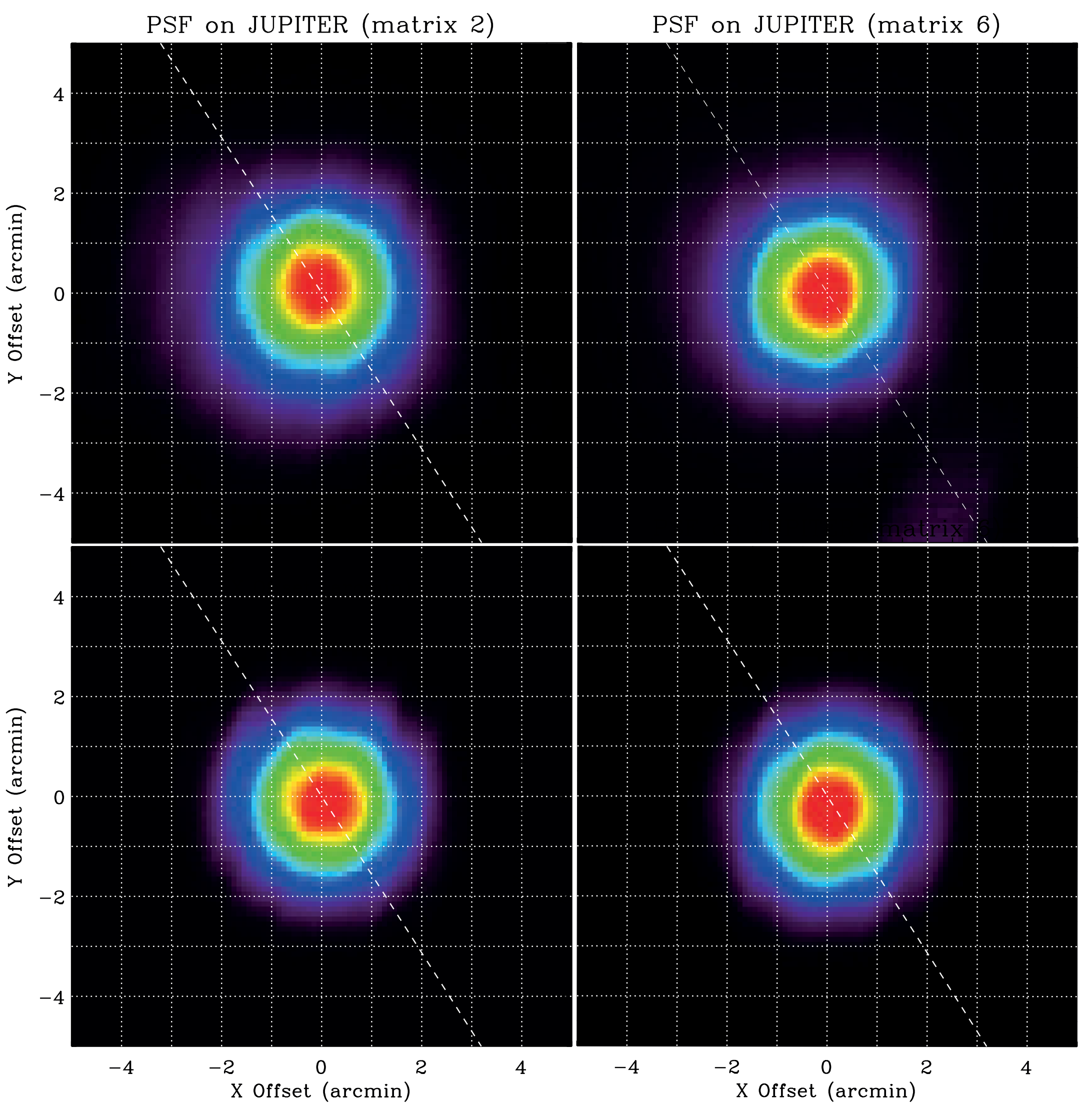
PILOT – In-flight performances

★ In-flight good optical quality and nominal resolution

In-flight Jupiter PSF

Simulations



- In-flight measured PSF on Jupiter is 2.25' ±0.15, sims 2.31'±0.07

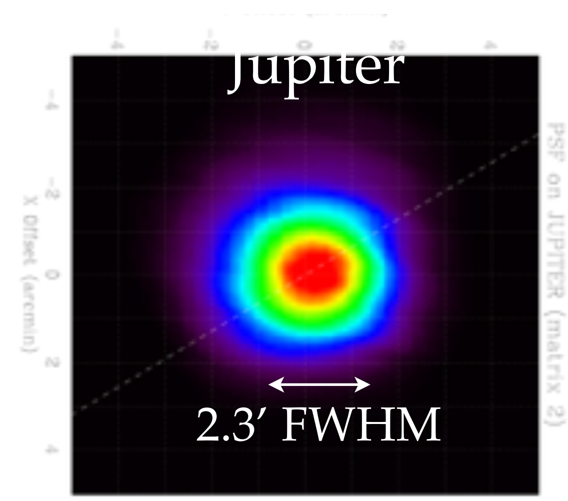
[The PILOT Collaboration, Foënard et al. 2018]

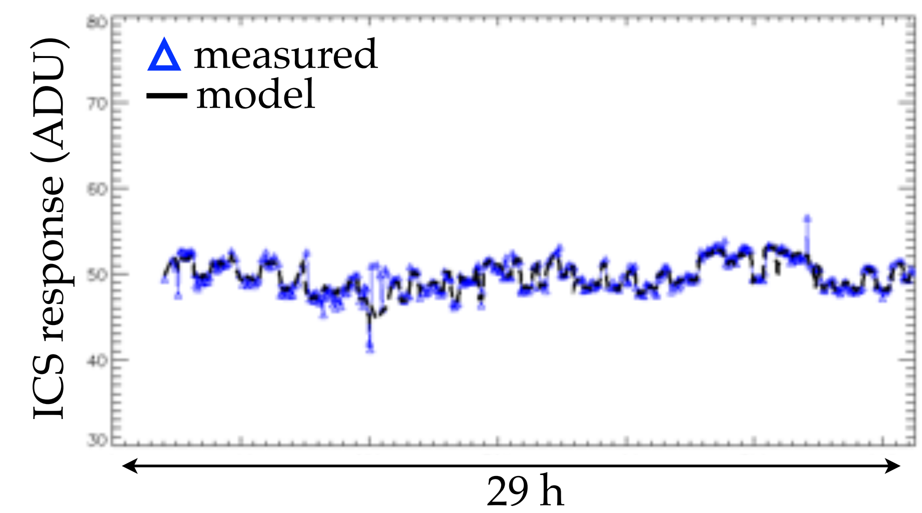
PILOT – In-flight performances

★ In-flight good optical quality and nominal resolution

★ In-flight background has a similar shape but is a factor ~2 stronger than ground measurements. Polarized at 4-10 % level

★ Variation of the detector responses due to polarized background & atmosphere variations. Modelled and corrected to better than 2 %





[The PILOT Collaboration, Foënard et al. 2018]

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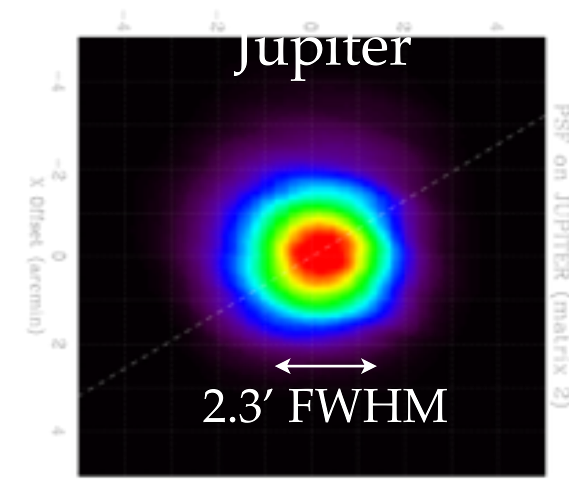

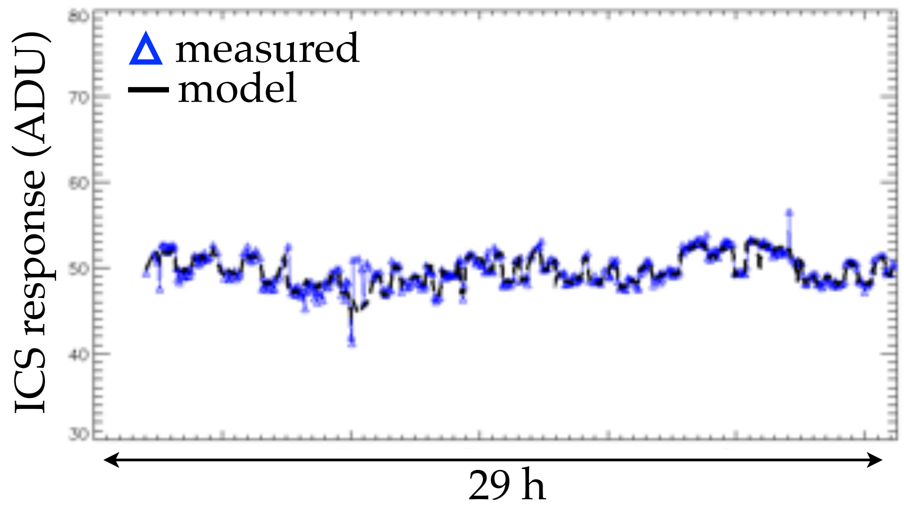

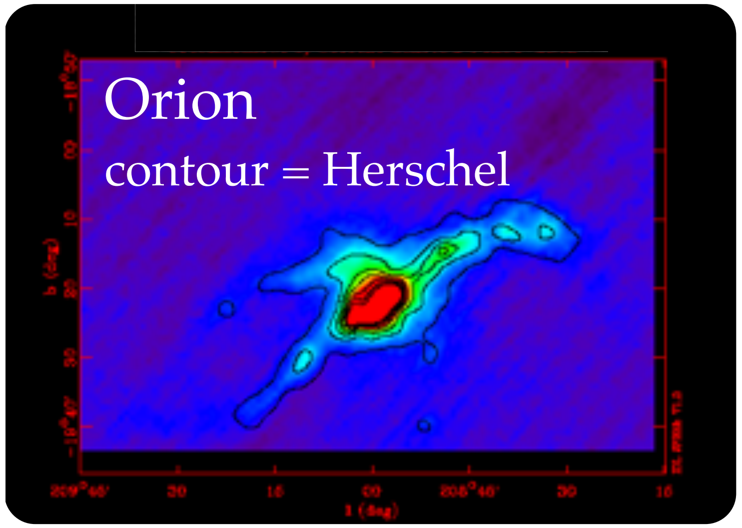

[The PILOT Collaboration, Foënard et al. 2018]

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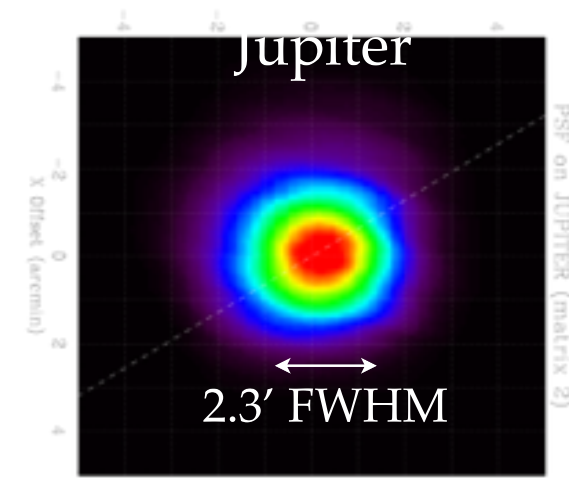
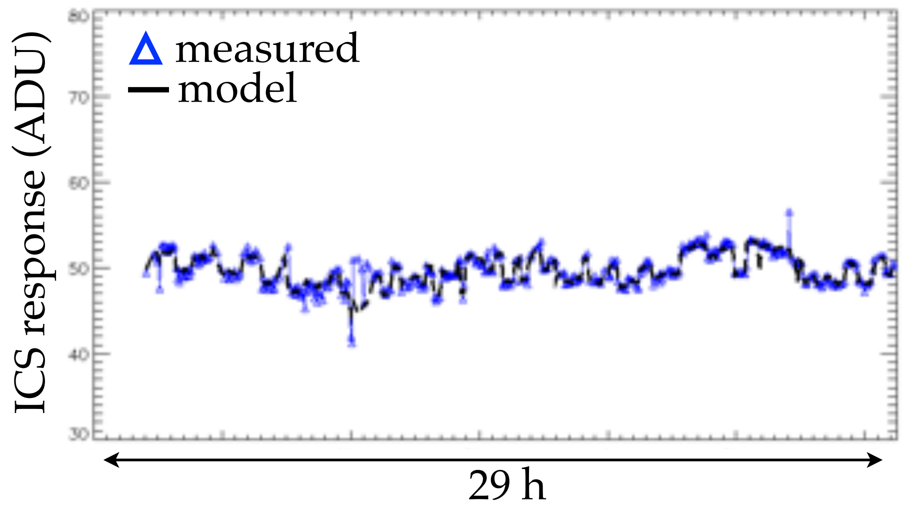
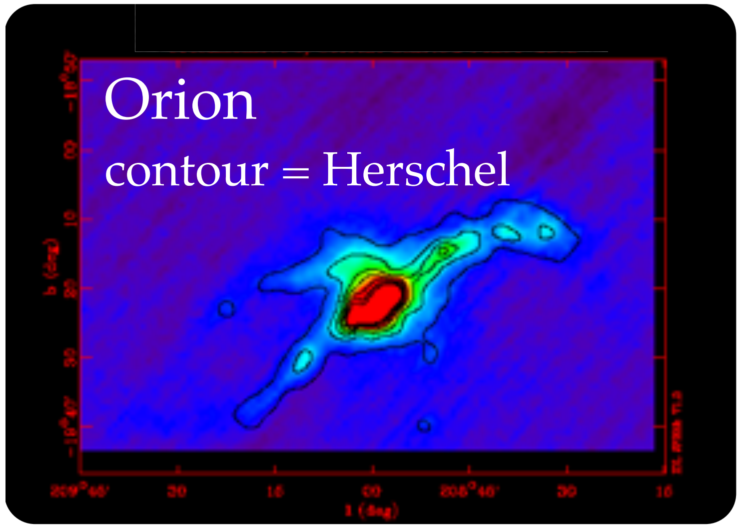
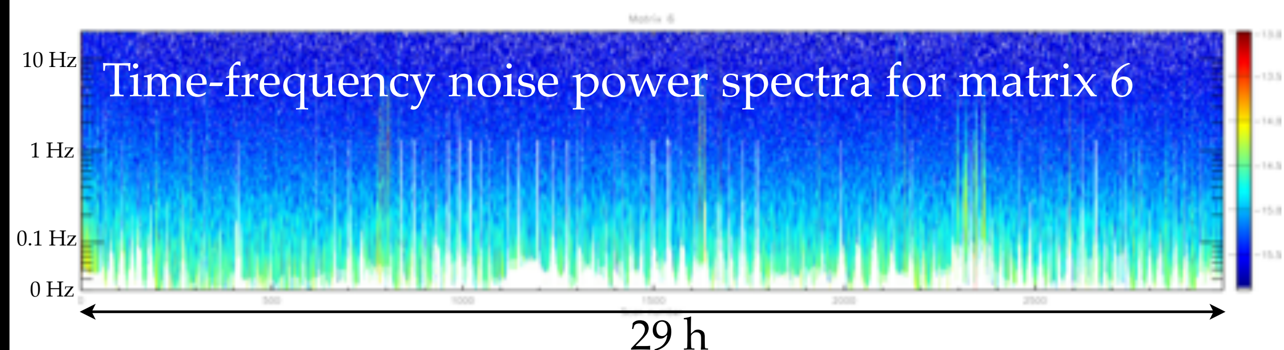
★ In-flight white noise levels as expected; noise stability over the whole flight

+ Significant improvements in ongoing analyses









[The PILOT Collaboration, Foënard et al. 2018]

The ROMAXpol map-making

[De Gasperis et al 2005]

- Data: combination of sky signal + correlated noise

$$\mathcal{D}_t = \frac{1}{2} A_{tp} \left(I_p + Q_p \cos 2\phi_t + U_p \sin 2\phi_t \right) + n_t. =$$

$$= \boldsymbol{A}_{tp} \boldsymbol{S}_p + \boldsymbol{n}$$

pointing matrix | sky signal | noise

generic linear algebra problem whose unknown parameters (the map pixel values) can be constrained by means of the standard Generalized Least Square solution (e.g. Lupton 1993)

$$\widetilde{\boldsymbol{S}_p} = \left(\boldsymbol{A}^t \boldsymbol{N}^{-1} \boldsymbol{A} \right)^{-1} \boldsymbol{A}^t \boldsymbol{N}^{-1} \mathcal{D},$$

$$\boldsymbol{A}_{tp} \equiv \frac{1}{2} \begin{pmatrix} A^1_{tp} & \cos 2\phi_t A^1_{tp} & \sin 2\phi_t A^1_{tp} \\ \vdots & \vdots & \vdots \\ A^k_{tp} & \cos 2\phi_t A^k_{tp} & \sin 2\phi_t A^k_{tp} \end{pmatrix} \qquad \boldsymbol{N} \equiv \langle \boldsymbol{n}_t \boldsymbol{n}_{t'} \rangle = \begin{pmatrix} \langle n^1_t n^1_{t'} \rangle & \cdots & \langle n^1_t n^k_{t'} \rangle \\ \vdots & \ddots & \vdots \\ \langle n^k_t n^1_{t'} \rangle & \cdots & \langle n^k_t n^k_{t'} \rangle \end{pmatrix}$$

- Optimal map-making, largely validated for polarisation

The Scanamorphos map-making

by Hélène Roussel

Tool initially developed to subtract low-frequency noise from Herschel-PACS and SPIRE data both correlated drifts (from thermal fluctuations) and flicker noise

algorithm described in 2013PASP..125.1126R and [H. Roussel, 2013]

principles:

1) assumption that the astrophysical signal is invariant

2) exploiting all the available redundancy (Flight 2 scanning strategy)

3) no explicit filtering and no noise model !

4) all multiplicative effects (flatfield) must be corrected beforehand

iterative process to subtract the (additive) drifts on successively smaller timescales
recorded signal R = time-invariant sky emission S
+ atmosphere + additive drifts D (low-f noise) + white noise + glitches (high-f noise)

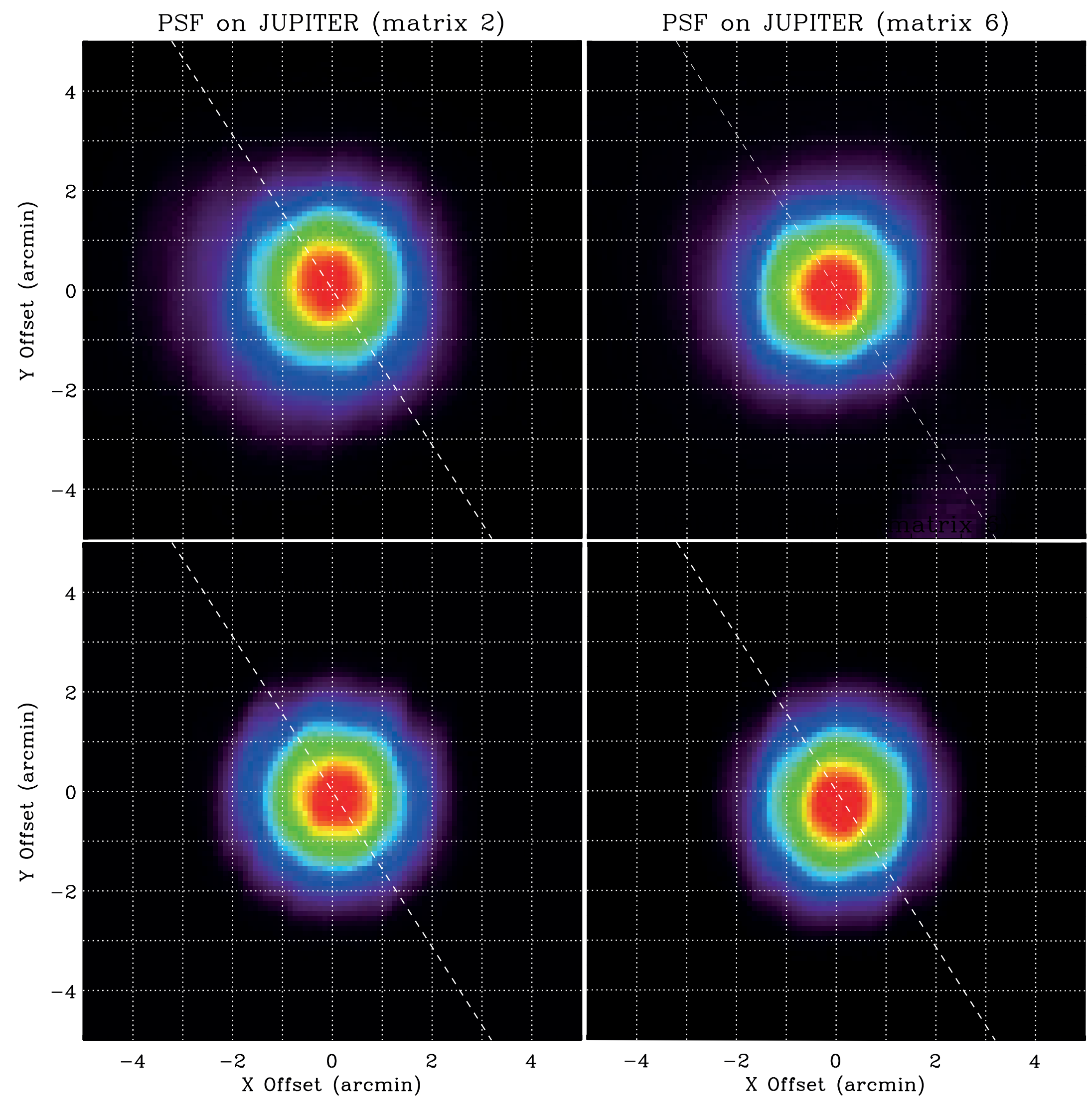
$$R(t, b, \alpha(t)) = S(p, \alpha) + D_{aver}(t) + D_{indiv}(t, b) + HF(t, b)$$

variables: time t, bolometer b, pixel p, analysis angle α (from HWP position + parallactic angle)

In-flight optical performances

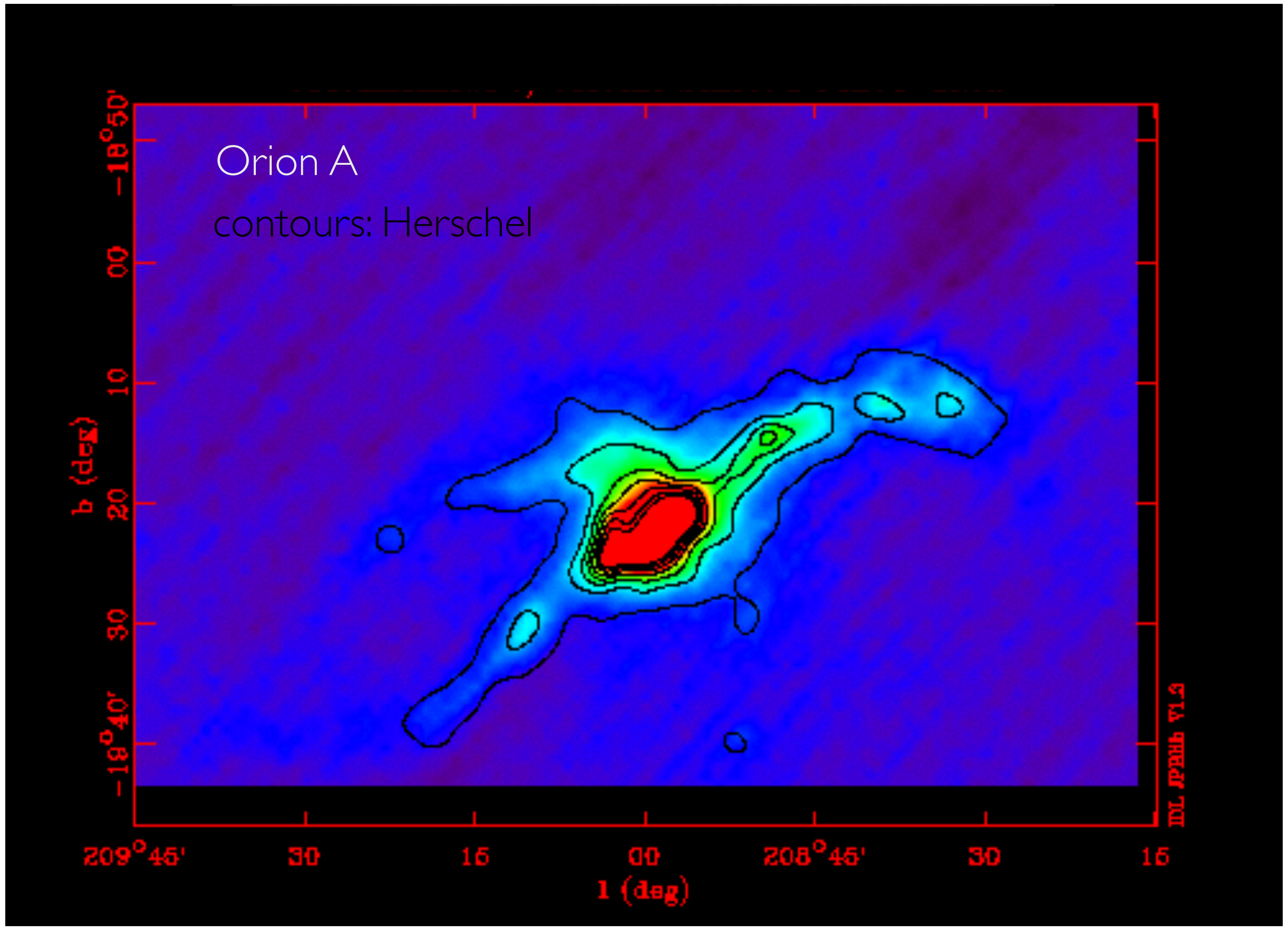
In-flight Jupiter PSF

Simulations



- In-flight measured PSF on Jupiter is 2.25' ±0.15, sims 2.31'±0.07
- In-flight good optical quality and nominal resolution

Pointing



Pointing & focal plane geometry:

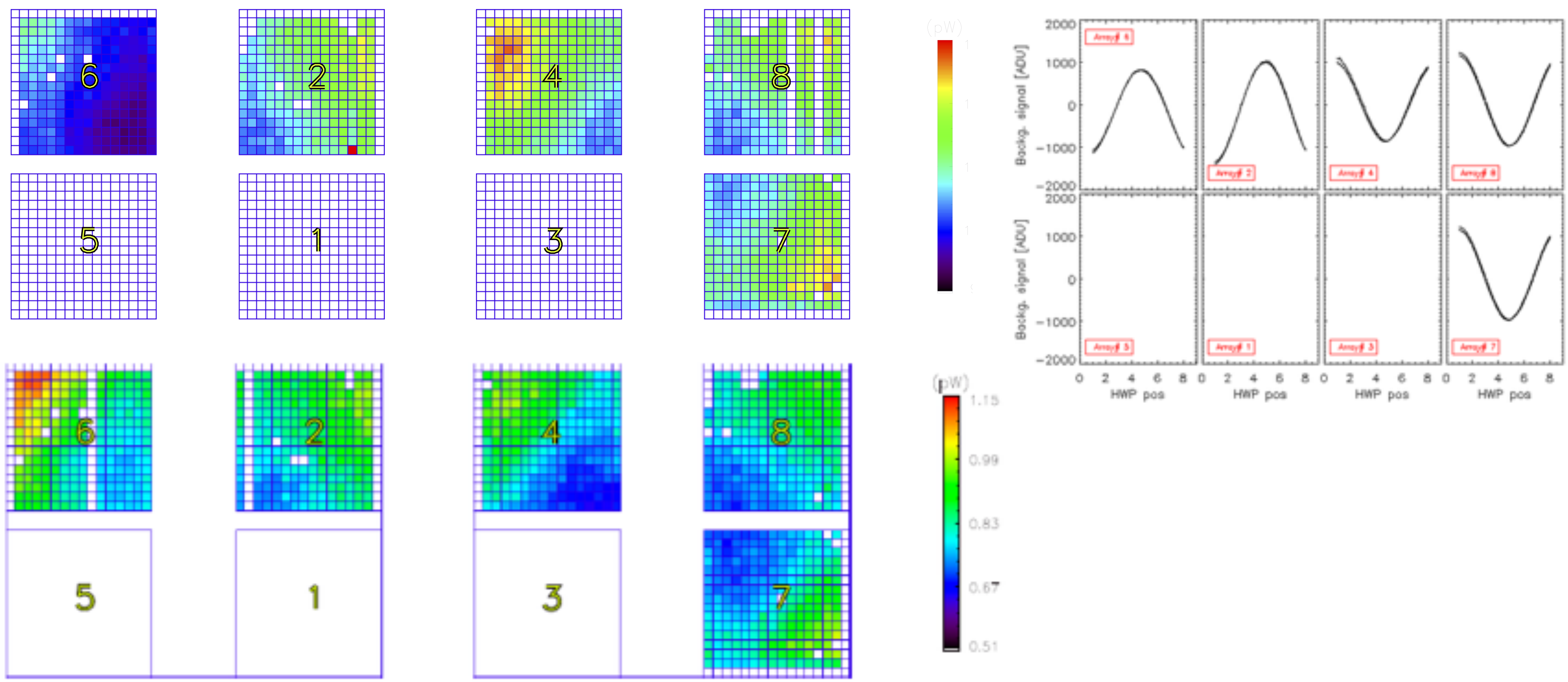
- The Estadius stellar sensor information is corrected for an offset based on comparison with the Herschel image (250 μm) on compact bright sources
- Pointing+focal plane geometry model (elevation + exapodes temperature) describes the offset evolution at better then 1' over the whole flight

In-flight background

- Dedicated observation to precisely constrain the instrumental background polarization

In-flight
(due to the
instrument)

Ground
(due to
atmosphere)



- In-flight background has a similar shape but is a factor ~2 stronger with respect to ground measurements
- The background is polarized (unknown reason) at 4-10%level

Detector responses

Precisely measure the detector response variations
is crucial for polarisation

- **<u>Temporal</u> detector response variations: Internal Calibration Source (ICS)**

ICS response:

The ground calibration tests have shown that the ICS flux is directly proportional to the squared power dissipated therein

$$\rho_{ICS} = \frac{\Delta^{ICS}_{\mathrm{on-off}} R_{ref} I^2_{ref}}{\langle R_{\mathrm{on}} (\langle I_{\mathrm{on}} \rangle^2 - \langle I_{\mathrm{off}} \rangle^2) \rangle}$$

[ADU], dim=[16,16,8,N_{seq_calib}]

- **<u>Spatial</u> detector response variations: Atmosphere**

Atmospheric response:

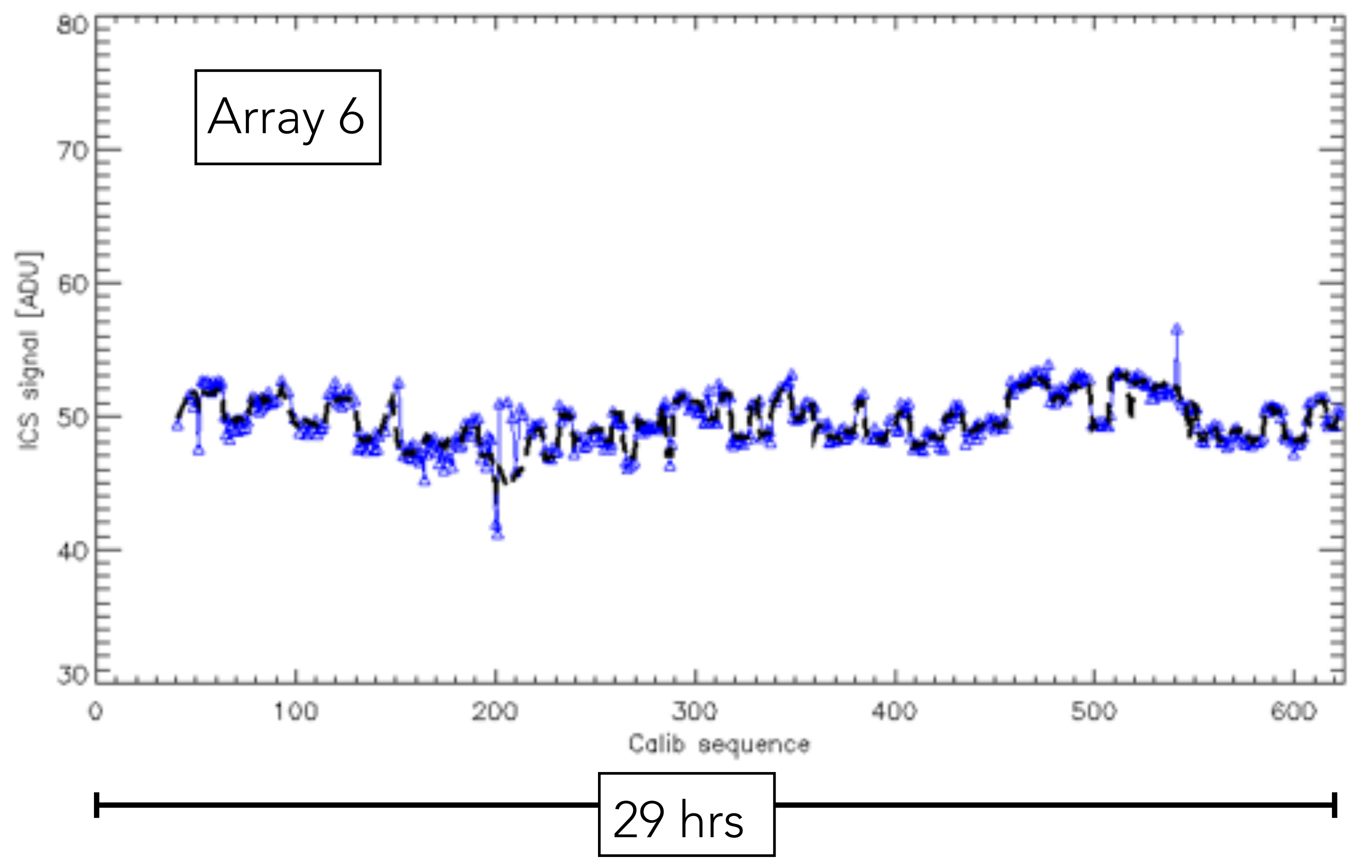
Atmosphere decorrelation from <u>sky-dips or over the whole flight</u>

The response is the slope of this correlation

Flight2 observations are done at varying elevation: redundant scan angle + better constrain of the detector response variation.

Data calibration

- **Temporal detector response variations: Internal Calibration Source (ICS)**



  - Step-like variations due to polarized background & atmosphere variations
  - Linear model parameters: HWP, elevation, altitude + temperatures as e.g. the focal planes temperature and the primary mirror temperature

The model matches the data with good accuracy (2%) over the whole flight

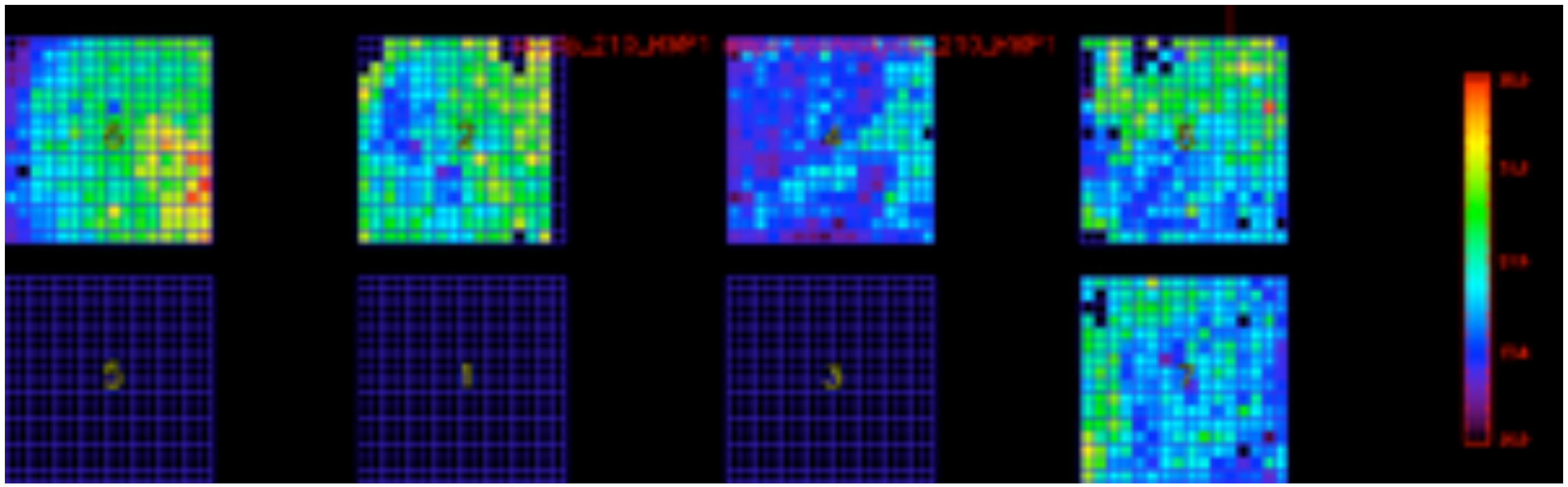
- **Spatial detector response variations:**

Atmosphere: extended and not polarized used to determine the detector response flat-field.

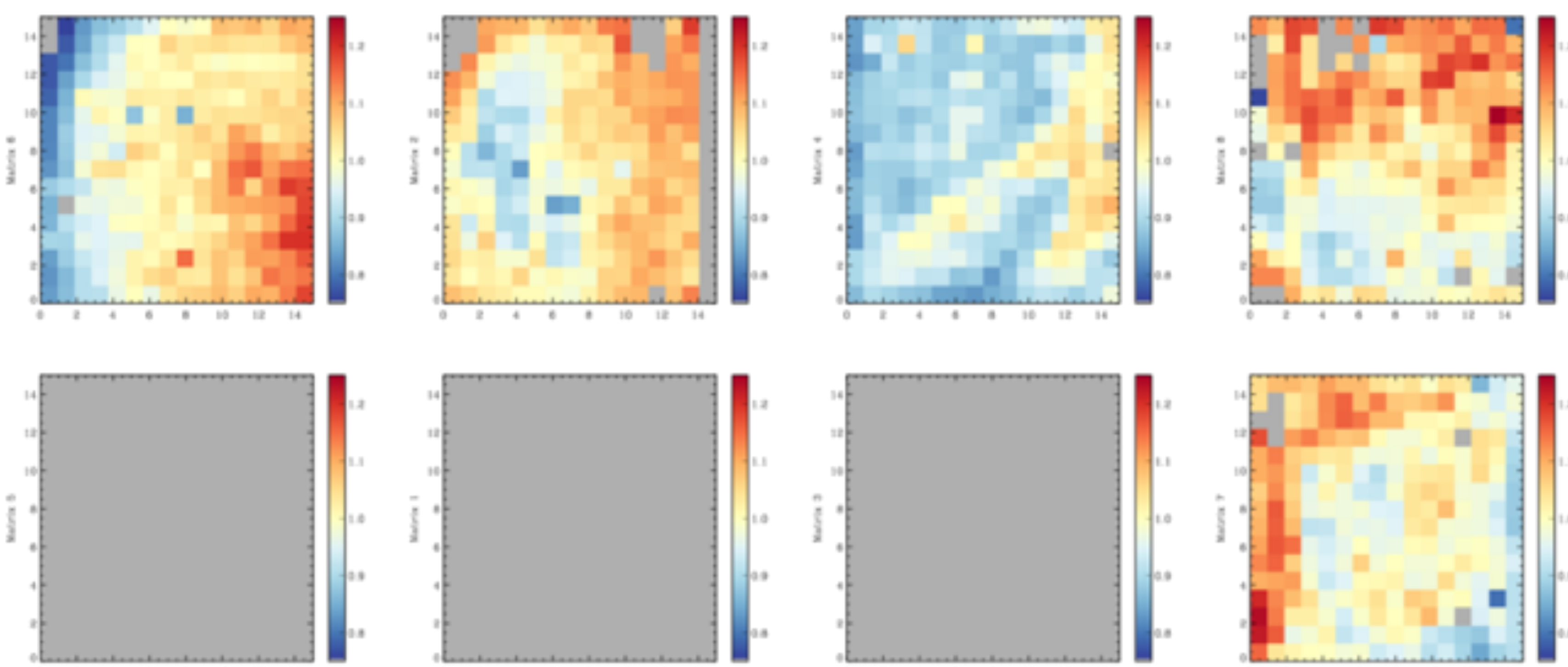
Atmospheric response

normalized (to the FP-average) response

TRANS REFLEX



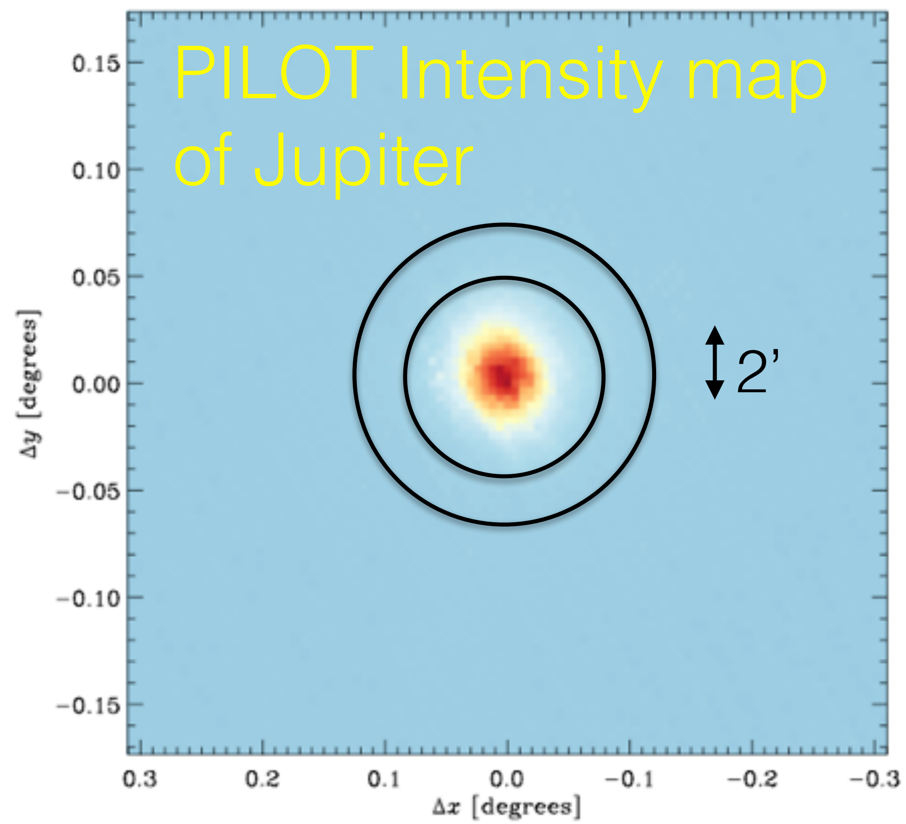
from Skydips atmospheric correlation slope (p1)



from atmospheric correlation slope over the whole flight

Residual polarization

Residual polarization on an unpolarized planet mesures the data calibration accuracy



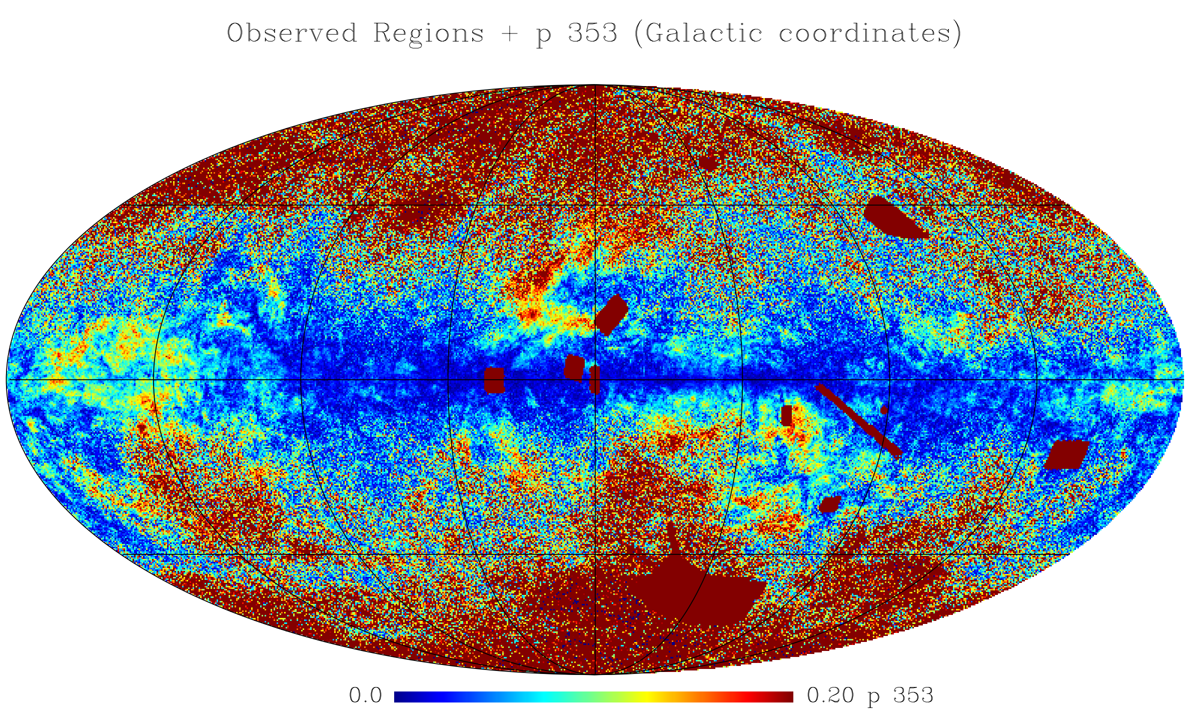
The residual polarization measured through aperture photometry on Jupiter is $\Delta P/I \sim 3\%$

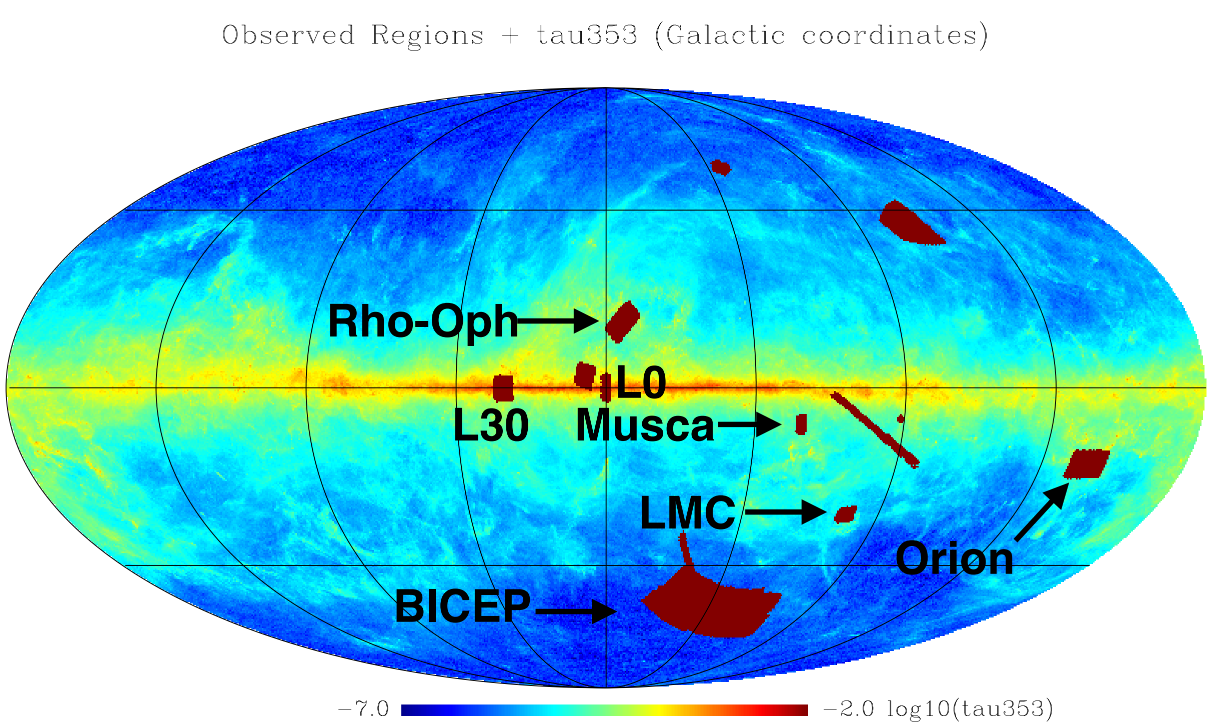
Significant improvement expected, more detailed calibration analysis on-going

Flight2 observations

Sources	Nb scenes	t obs	Map size	scene depth	total depth
		[mn]	[deg x deg]	[Deg^2/h]	[Deg^2/h]
L30	8	72.	5 x 5	187	21
L0	4	32	2 x 5	75	18.8
LMCridge	16	134.4	3.5 x 1	15.7	1.6
LMCridgeBIG	19	232.5	4.0 x 2	39.2	2.0
Orion	6	140.8	5 x 10	127.8	21.3
BICEP	14	290.1	30 x 12	253.1	74.5
Rho-oph	11	268.8	9 x 4	88.4	8.0
Musca	14	185.6	2 x 3	27.0	1.9
JUPITER	5	27.7	3 x 2	65.0	13.0
SATURN	3	23.5	5 x 3.4	130.2	43.0
SkyDip	8	21.3	1 x 32.0		
Total:	104	1428.7 (23.8h)	--	--	--

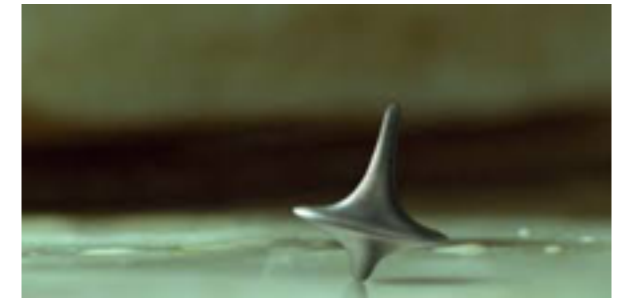
- Galactic plane: L0, L30 (1h30)
- Star forming regions: Orion, Rho-Oph. , Musca (10h)
- Large Magellanic Cloud (6h)
- Diffuse region: BICEP field (5h)
- Planets: Saturn & Jupiter (1h)

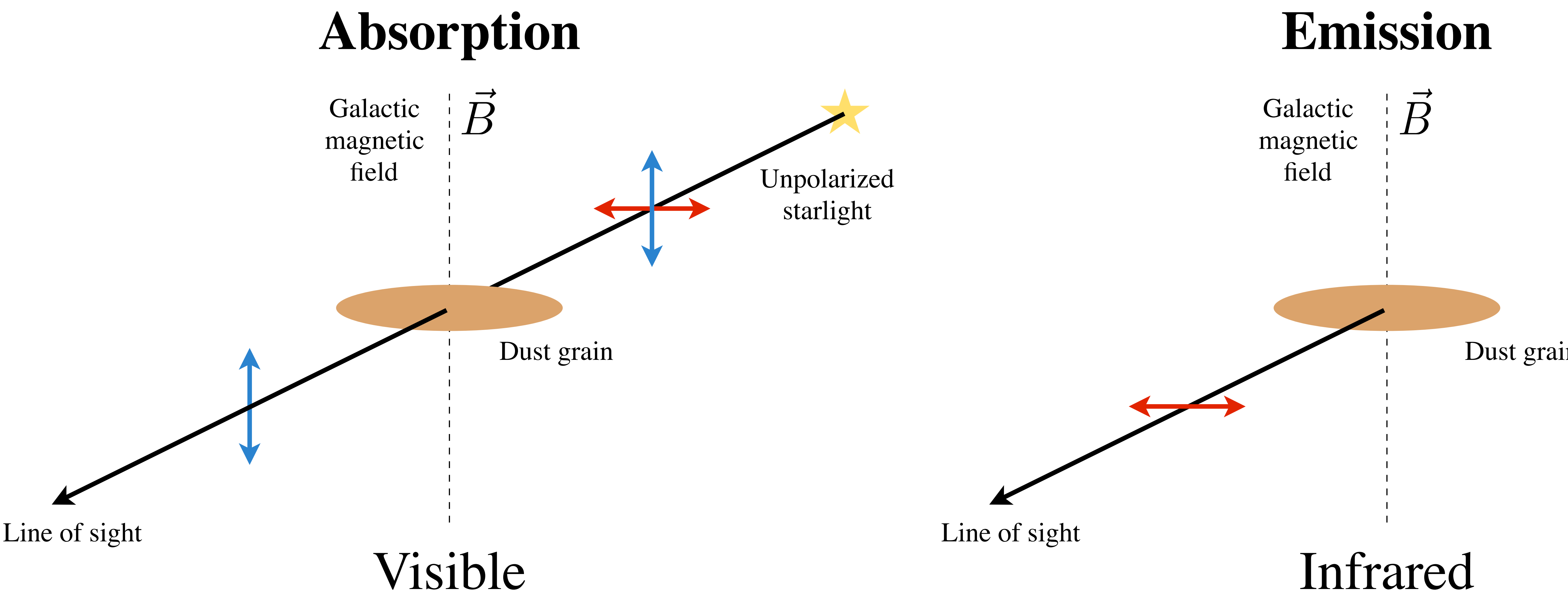




The dust polarization

- Dust grains are elongated and spinning
- Major axis aligned perpendicularly to the magnetic field





Measuring the dust polarization allows to measure the magnetic field orientation