POLARBEAR:
calibration strategy, systematics simulations, lessons learned

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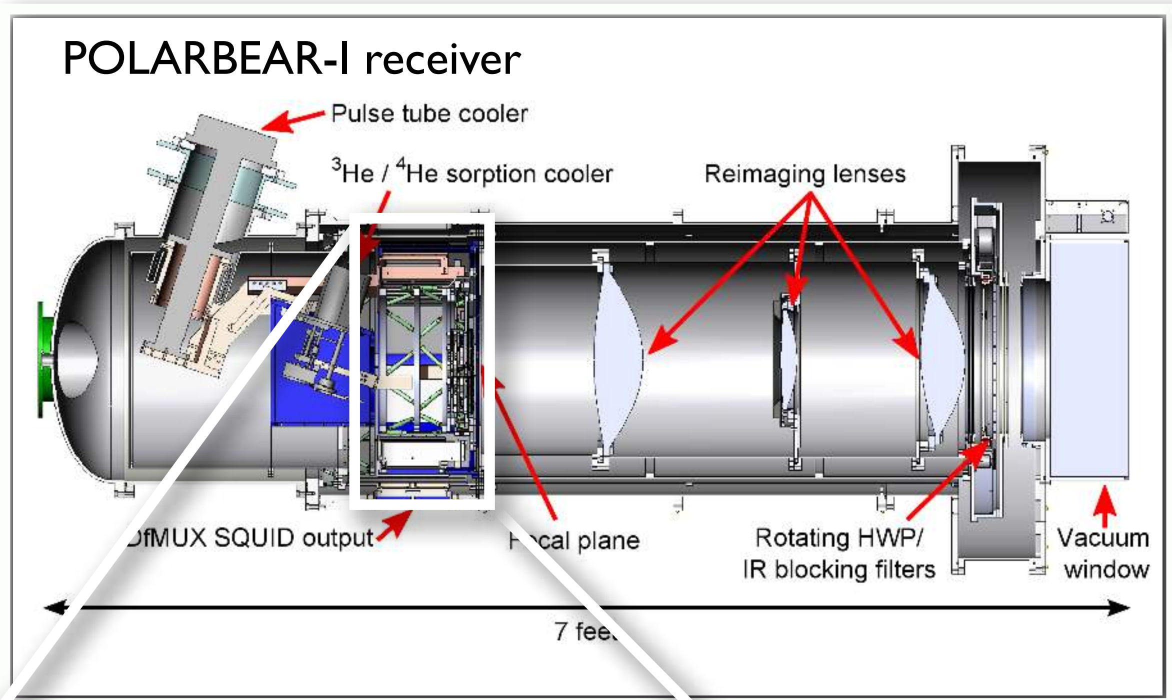
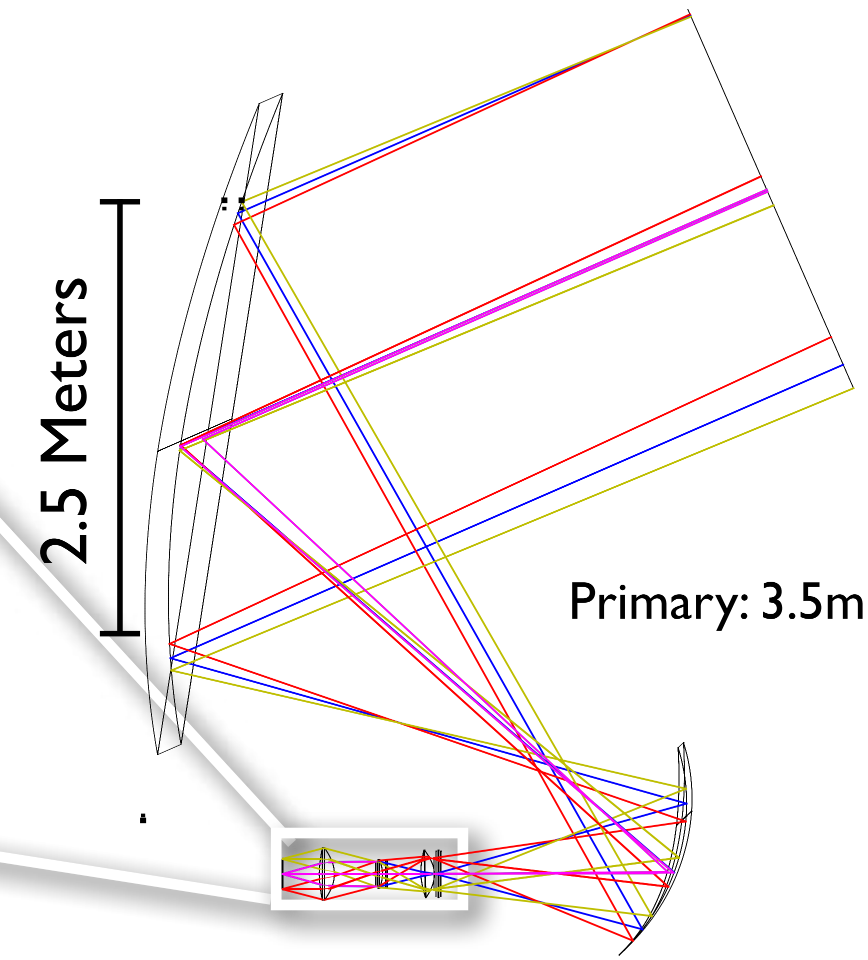
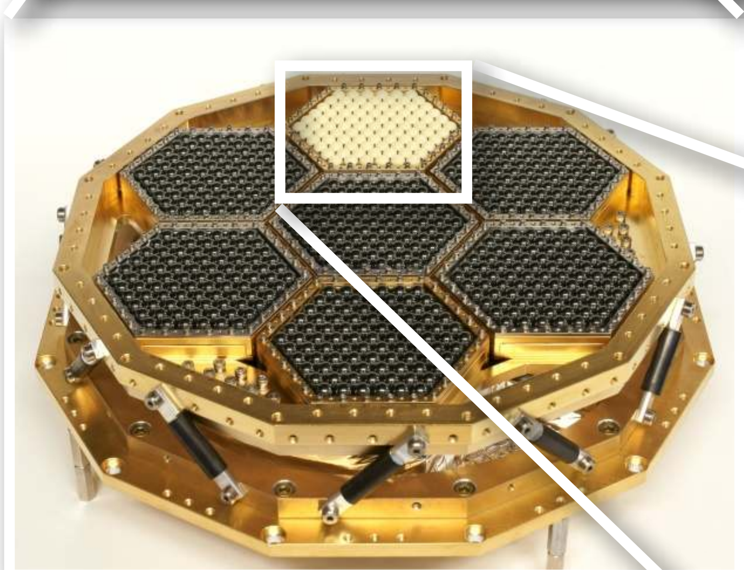
PRIFYSGOL CAERDYDD





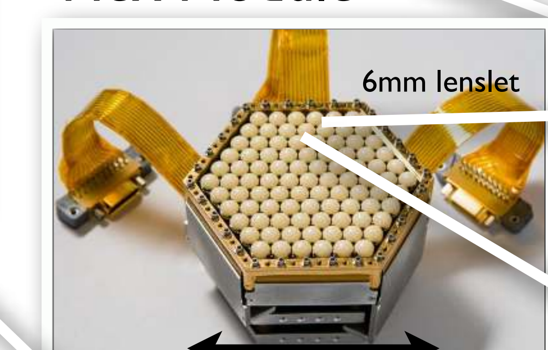
Huan Tran Telescope

Focal plane



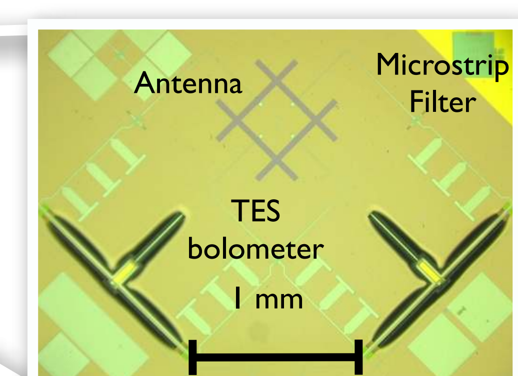
1274 bolometers @ 150 GHz
Cooled to 250 mK

Hex Module



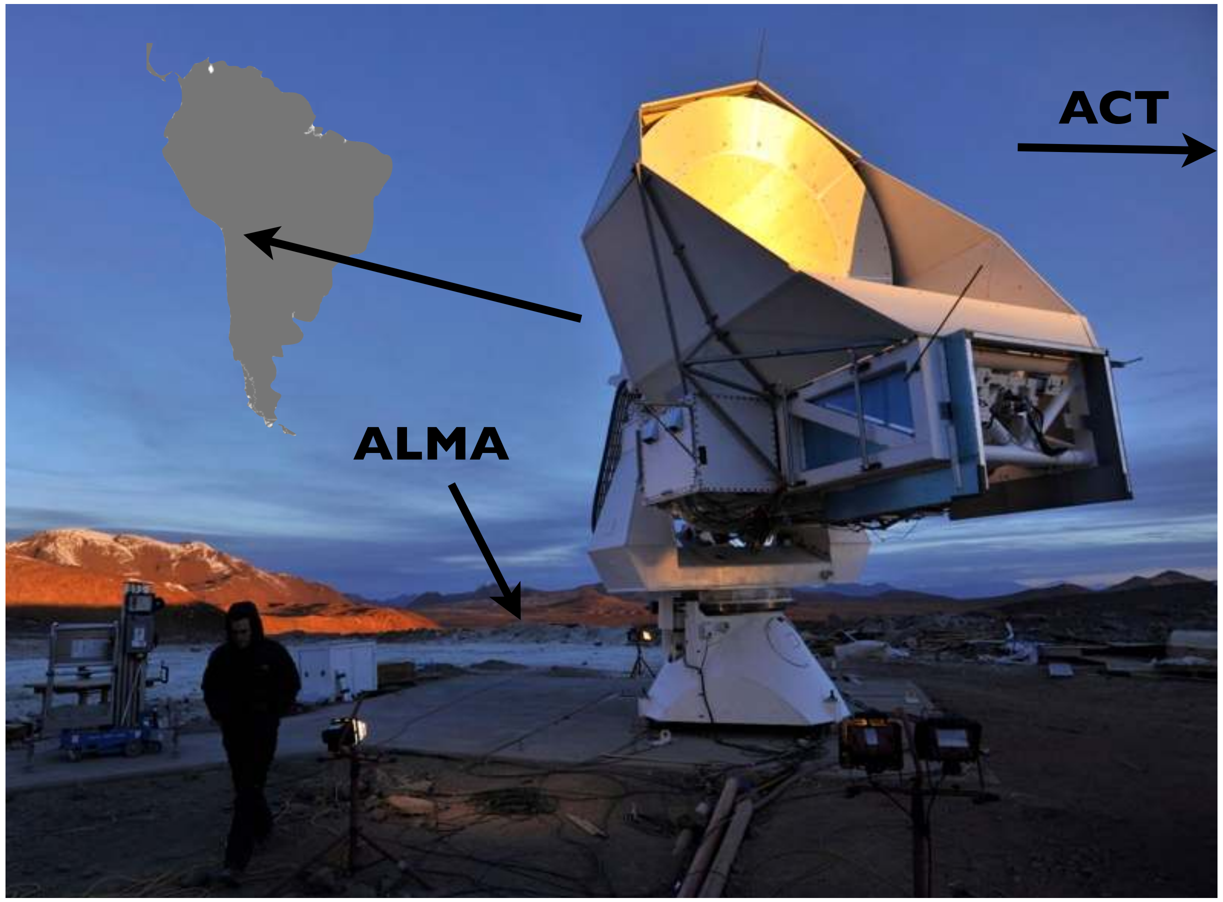
8cm

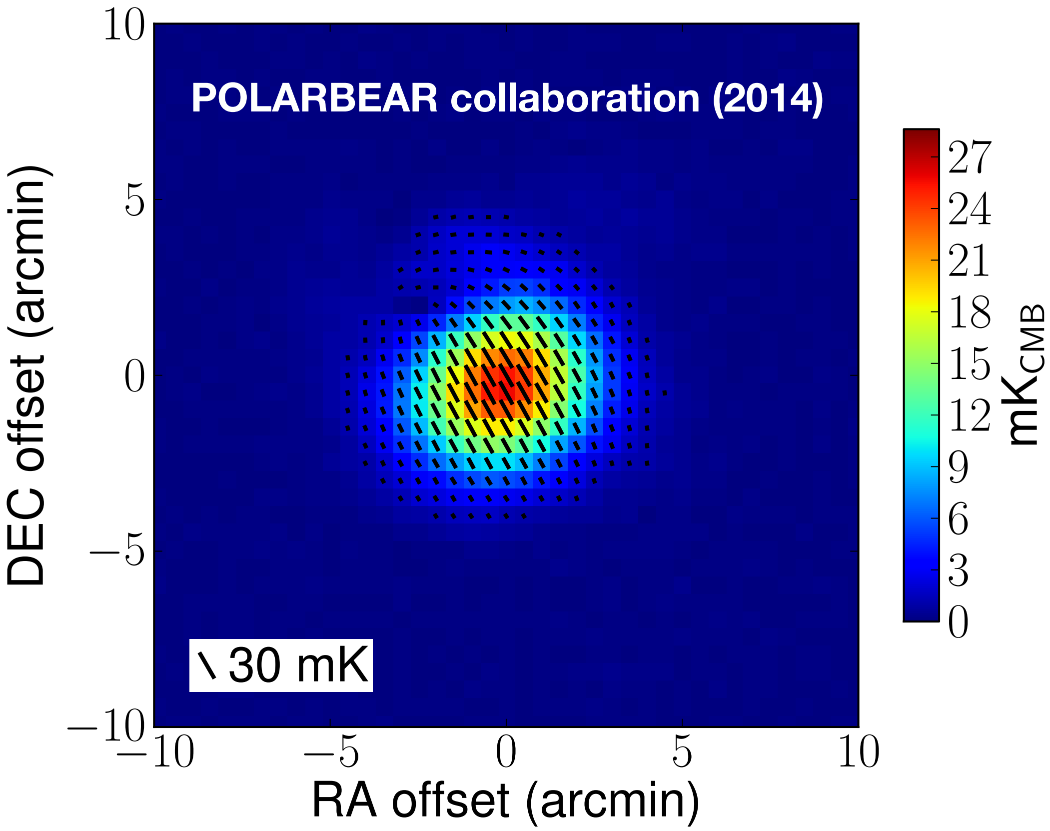
$$d^t(t) = g_{top}\left[I(\hat{n}(t)) + Q(\hat{n}(t))\cos(2\psi(t)) + U(\hat{n}(t))\sin(2\psi(t))\right]$$
$$d^b(t) = g_{bot}\left[I(\hat{n}(t)) - Q(\hat{n}(t))\cos(2\psi(t)) - U(\hat{n}(t))\sin(2\psi(t))\right]$$

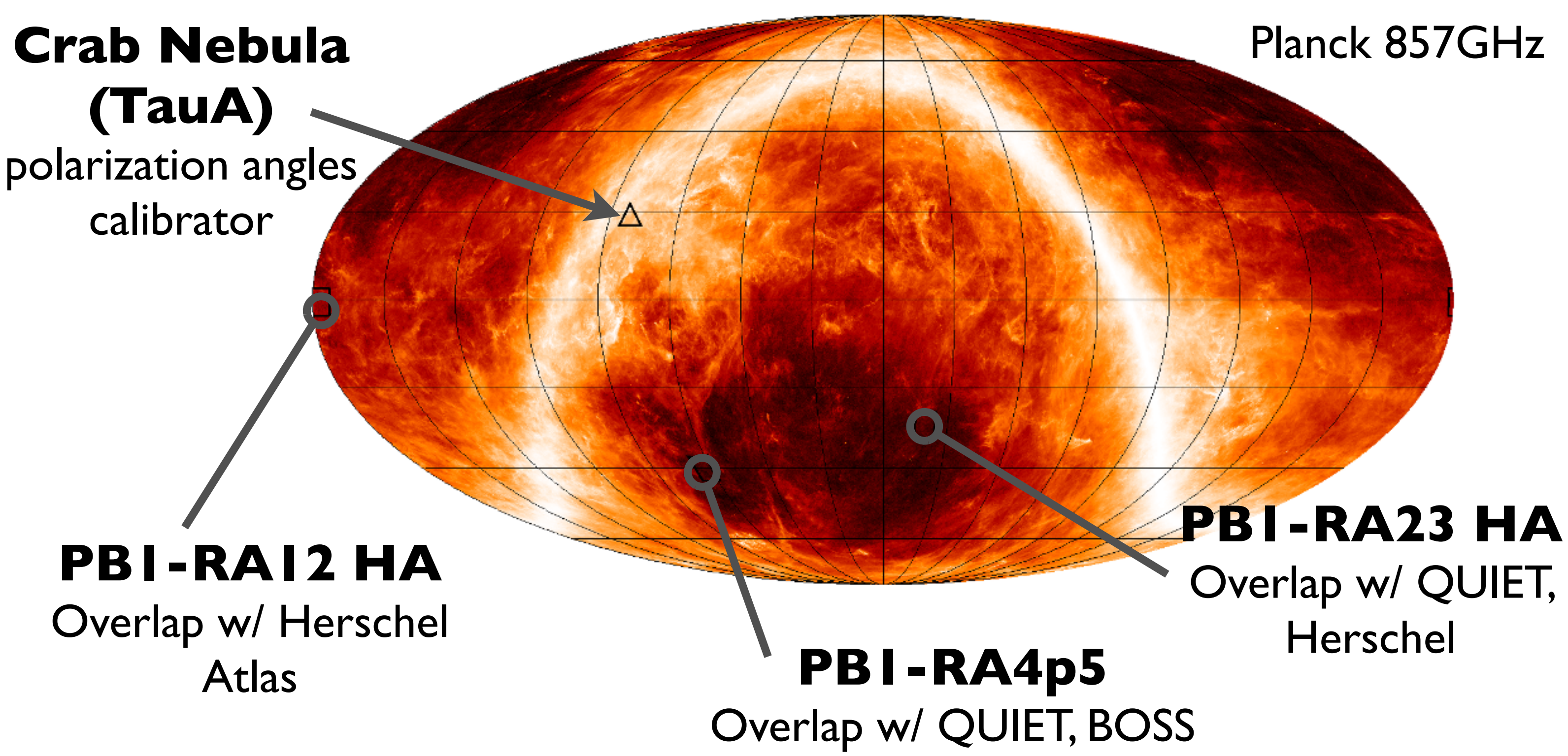


The POLARBEAR experiment

- Targeting large and small scales B-modes for lensing and inflation
- First 2 seasons: deep 5x5 patches integration for sub-degree signal
  - Deepest high-res CMB maps to date?
- 2014: new WHWP for large scales.



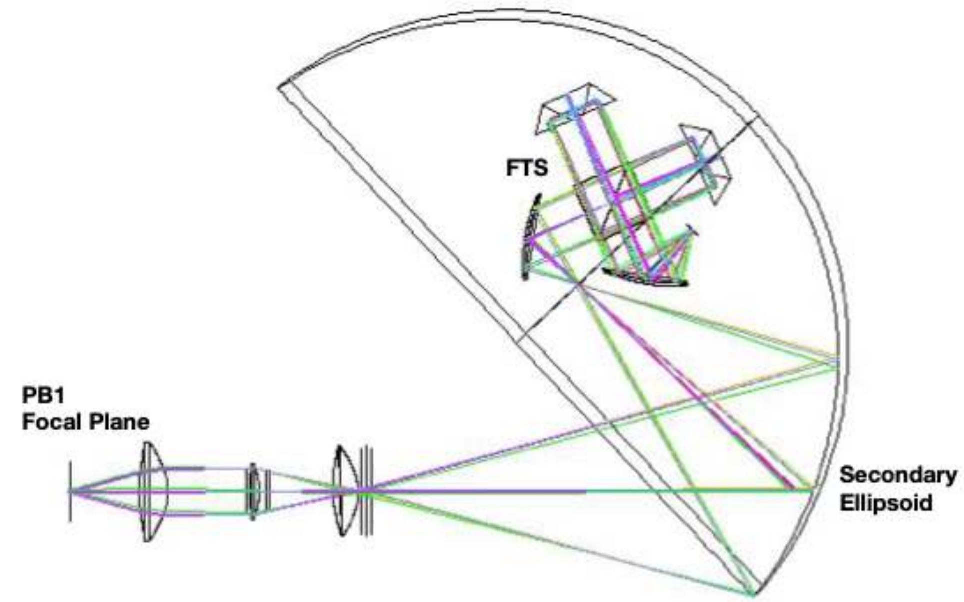


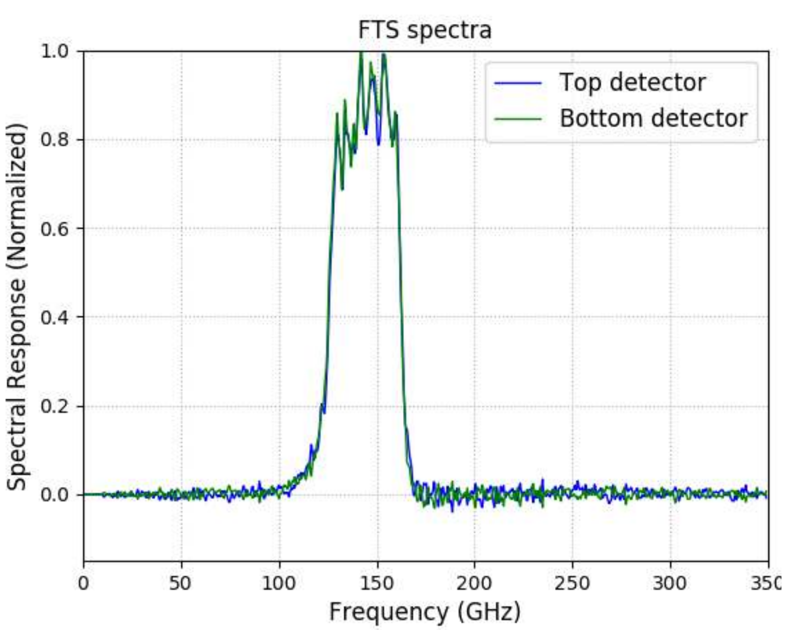


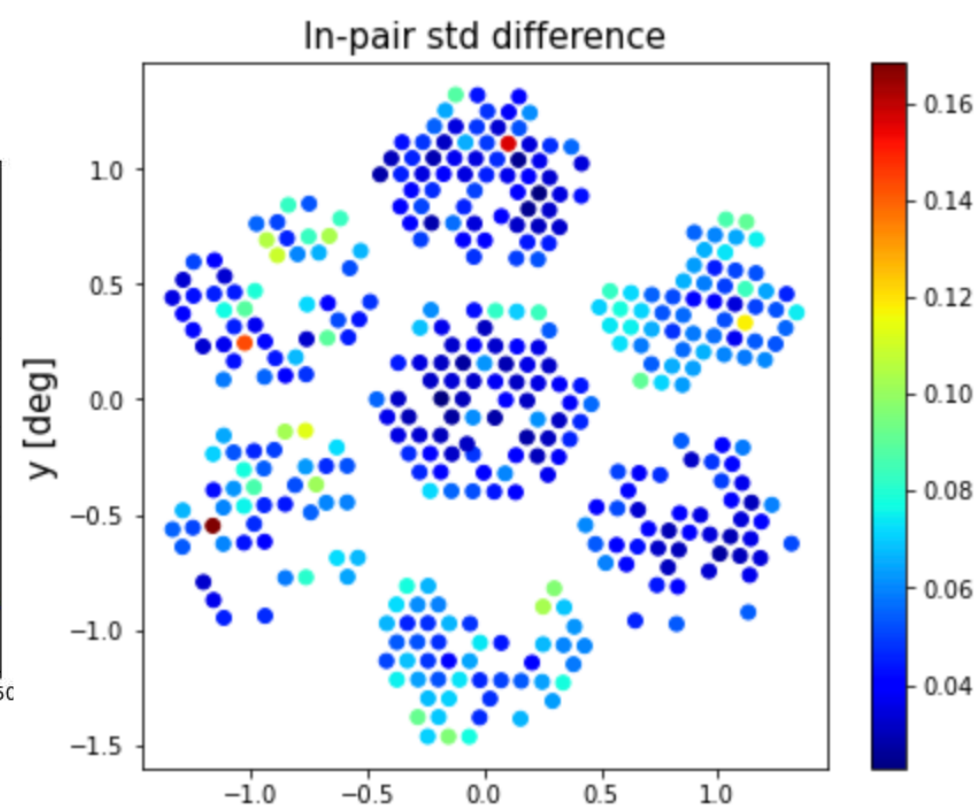
Bandpass characterization

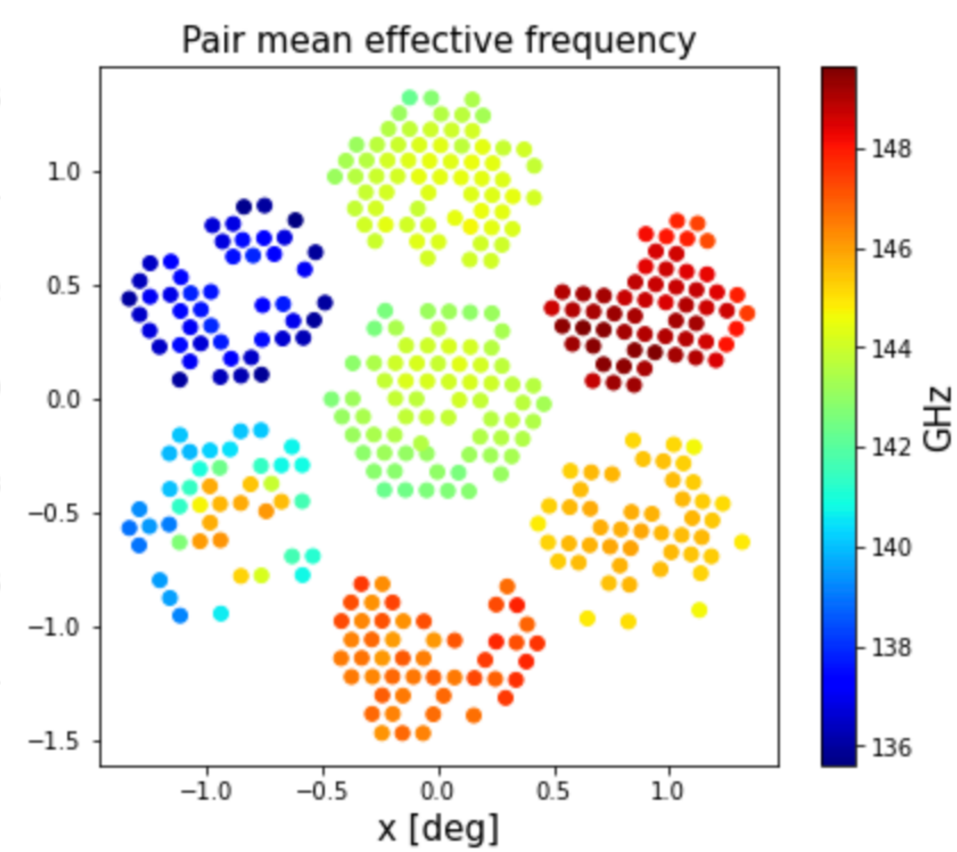
- Martin-Puplett interferometer with custom optical coupling and continuously rotating grid.

Wafer	# Detectors	Band Center (GHz)		Bandwidth (GHz)		Pixel In-band Fractional Diff
		AVG	STD	AVG	STD	AVG
8.2.0	106	136.9	0.7	30.4	1.8	0.059
9.4	107	146.9	0.5	32.8	1.6	0.062
10.1	113	142.1	2.5	31.8	1.8	0.062
10.2	149	143.5	0.5	32.6	1.1	0.041
10.3	133	148.7	0.6	31.0	1.9	0.062
10.4	154	144.0	0.5	32.2	1.2	0.044
10.5	113	145.5	0.4	31.8	1.3	0.041





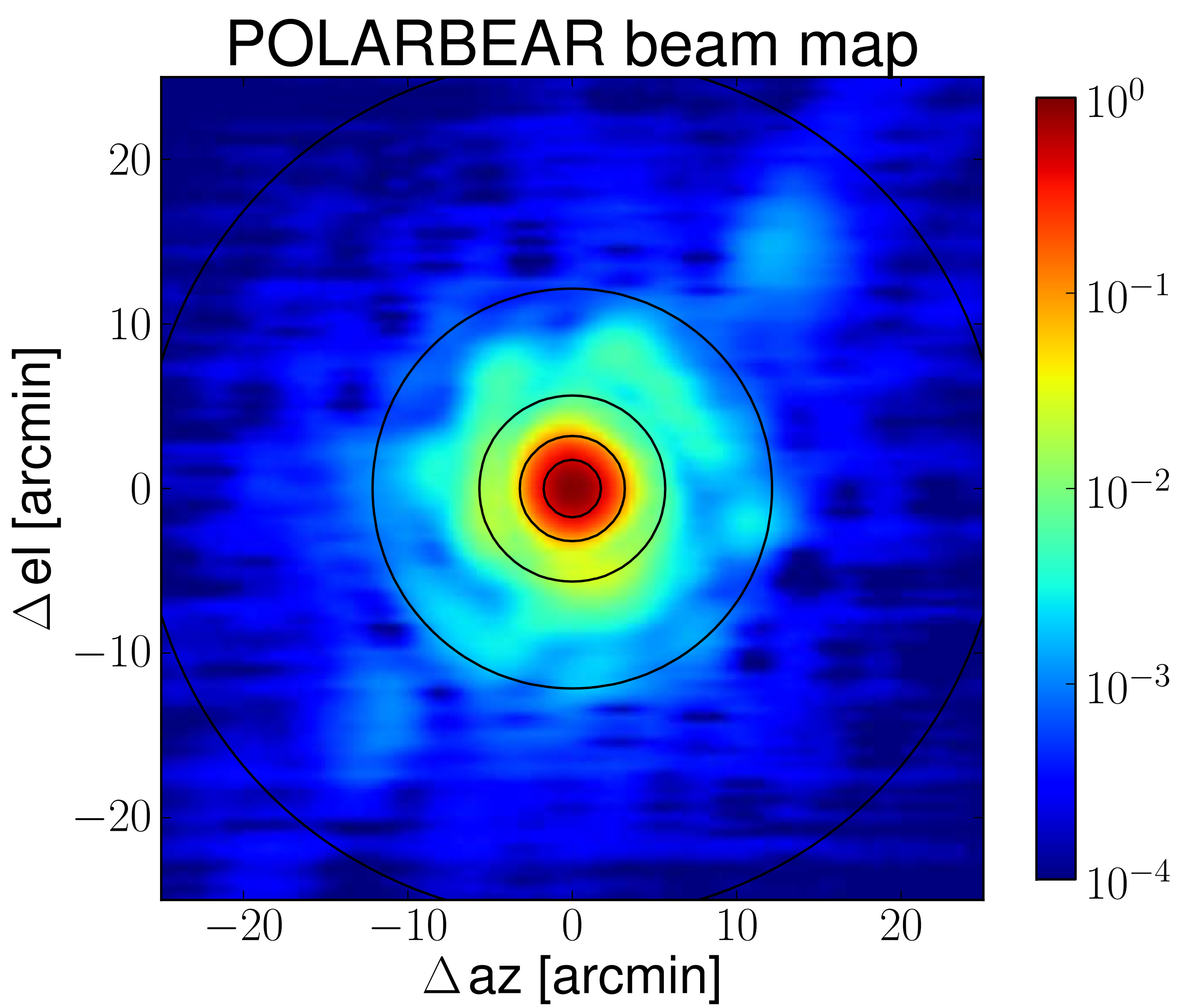


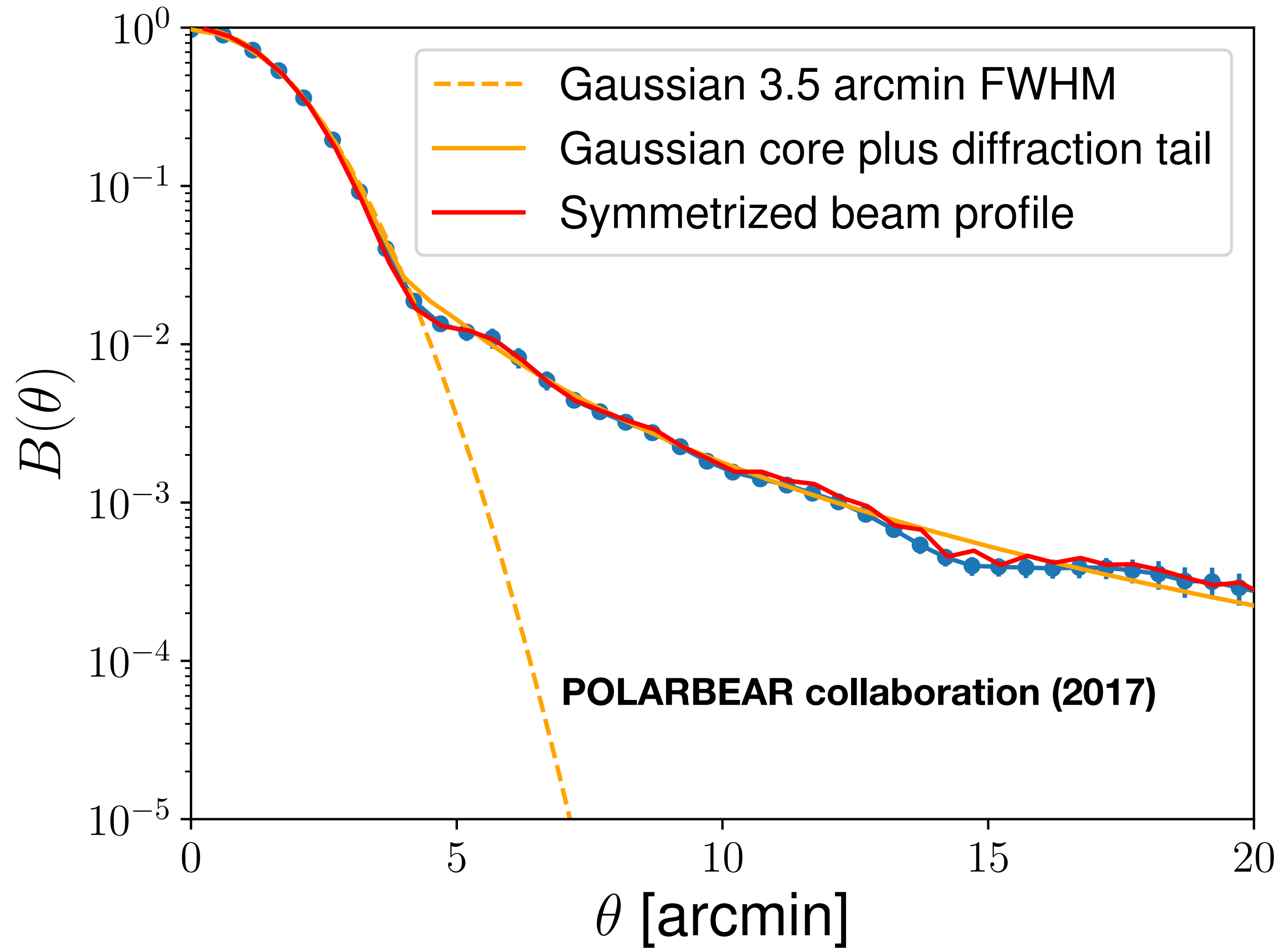


Matsuda+ (2019)

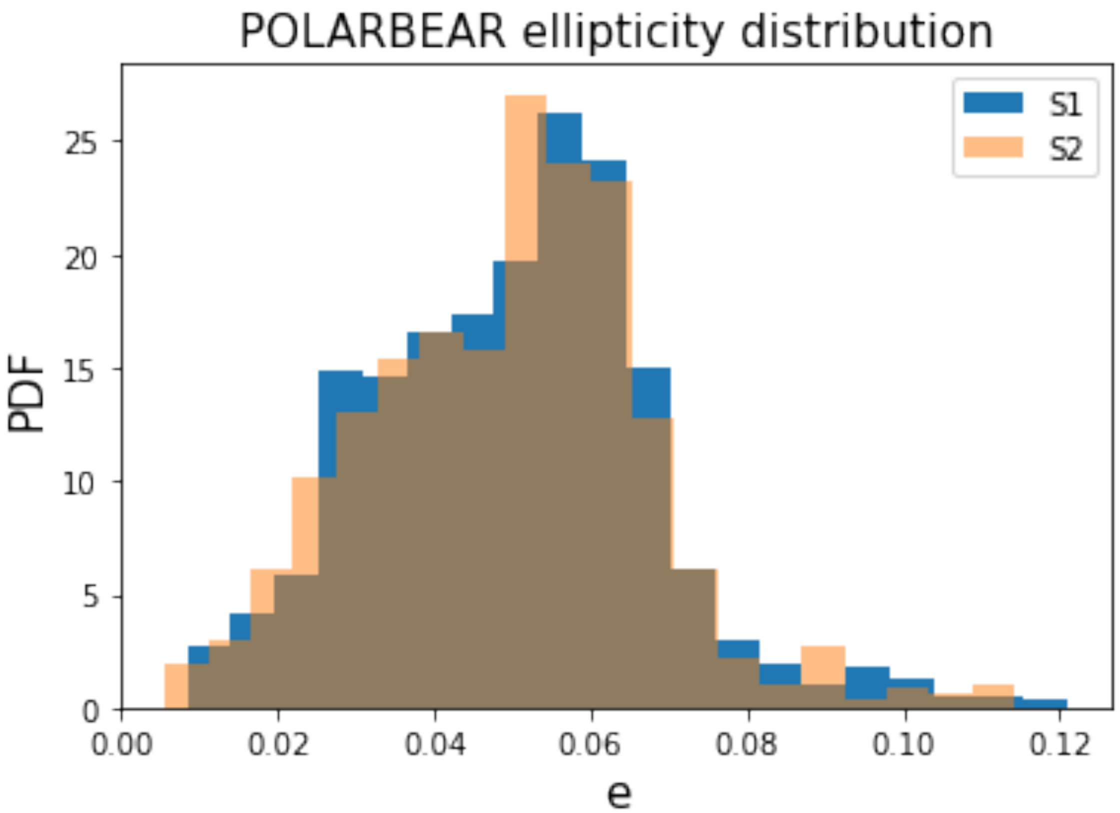
Beams and pointing

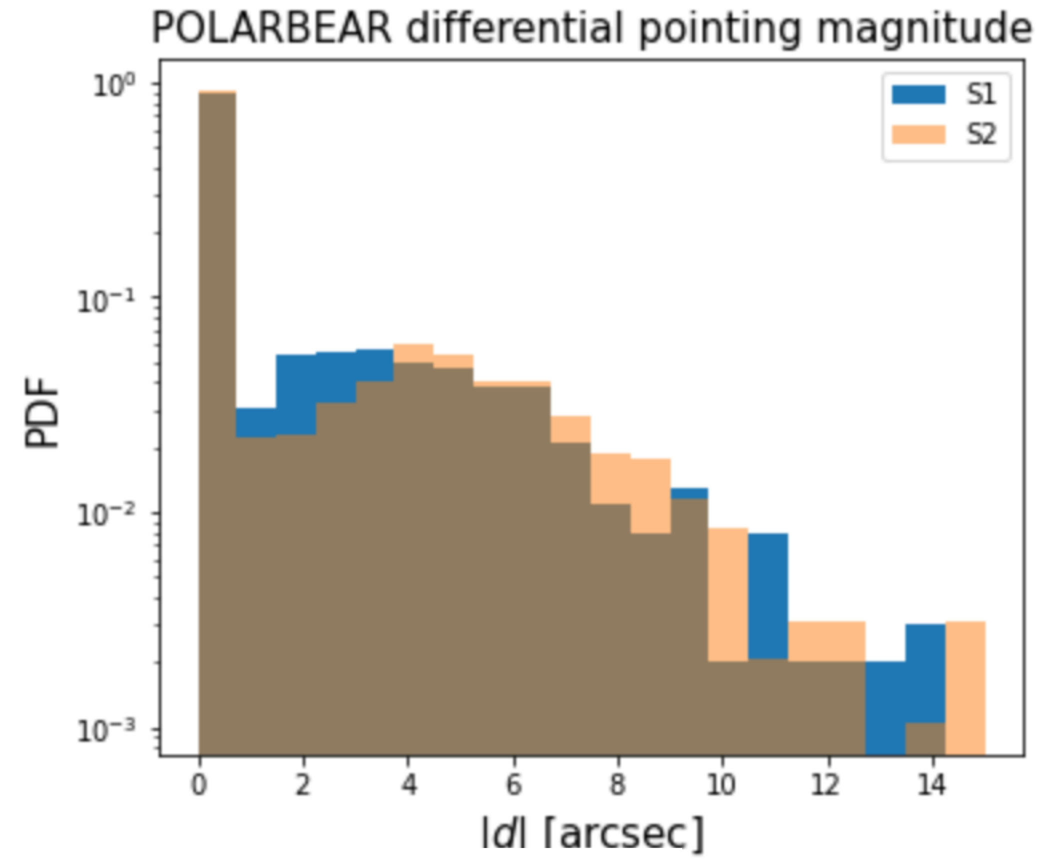
- Pointing reconstructed with a variety of sources (galaxies, planets) and elevation ranges
  - Degraded (but accounted for) by solar irradiance, elevation…
- Daily planets raster scans allowed per detector beam reconstruction and calibration.
  - reconstructed cross-talk matrix and test diffraction tail with bandpass measurements.

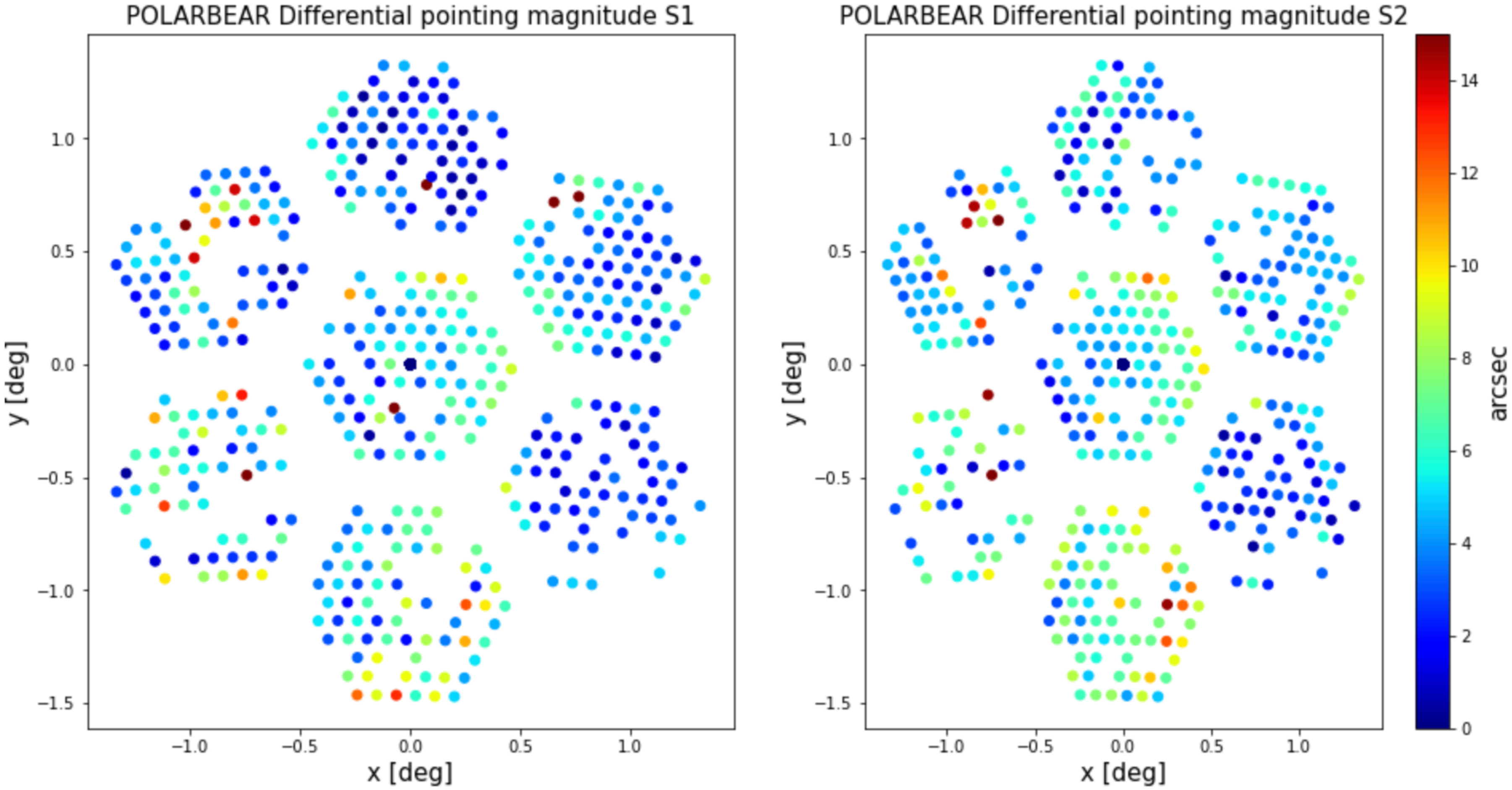




Beams properties and stability

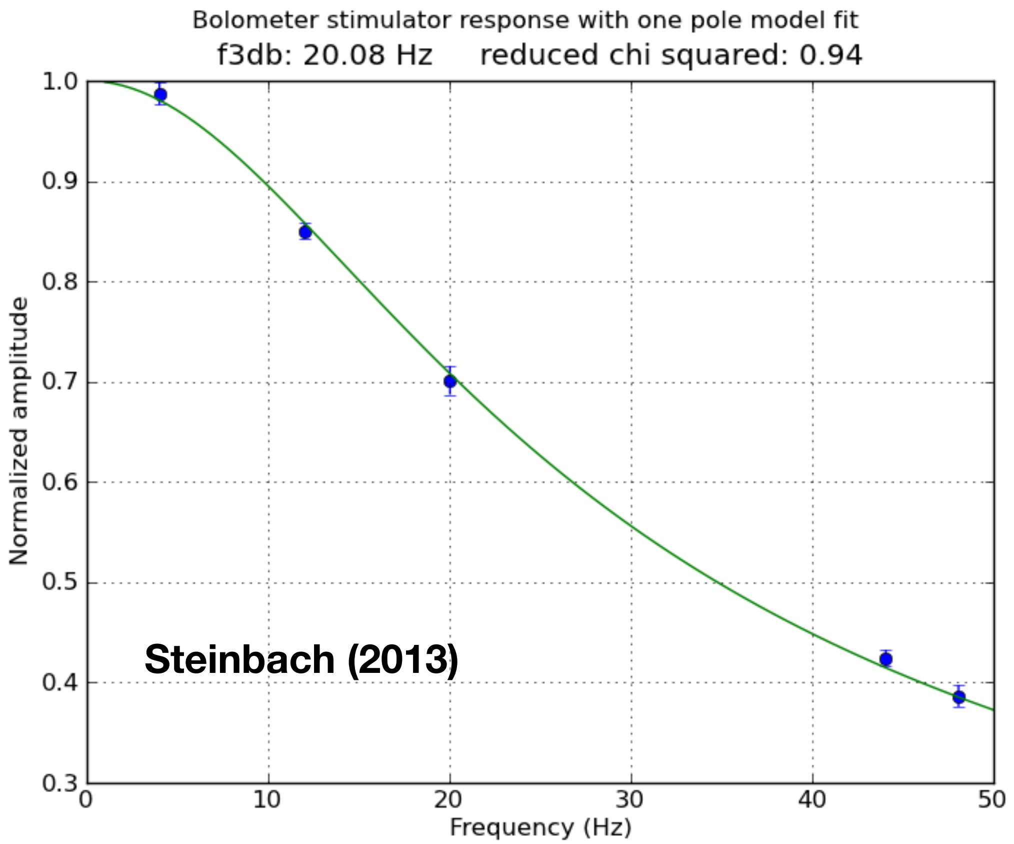


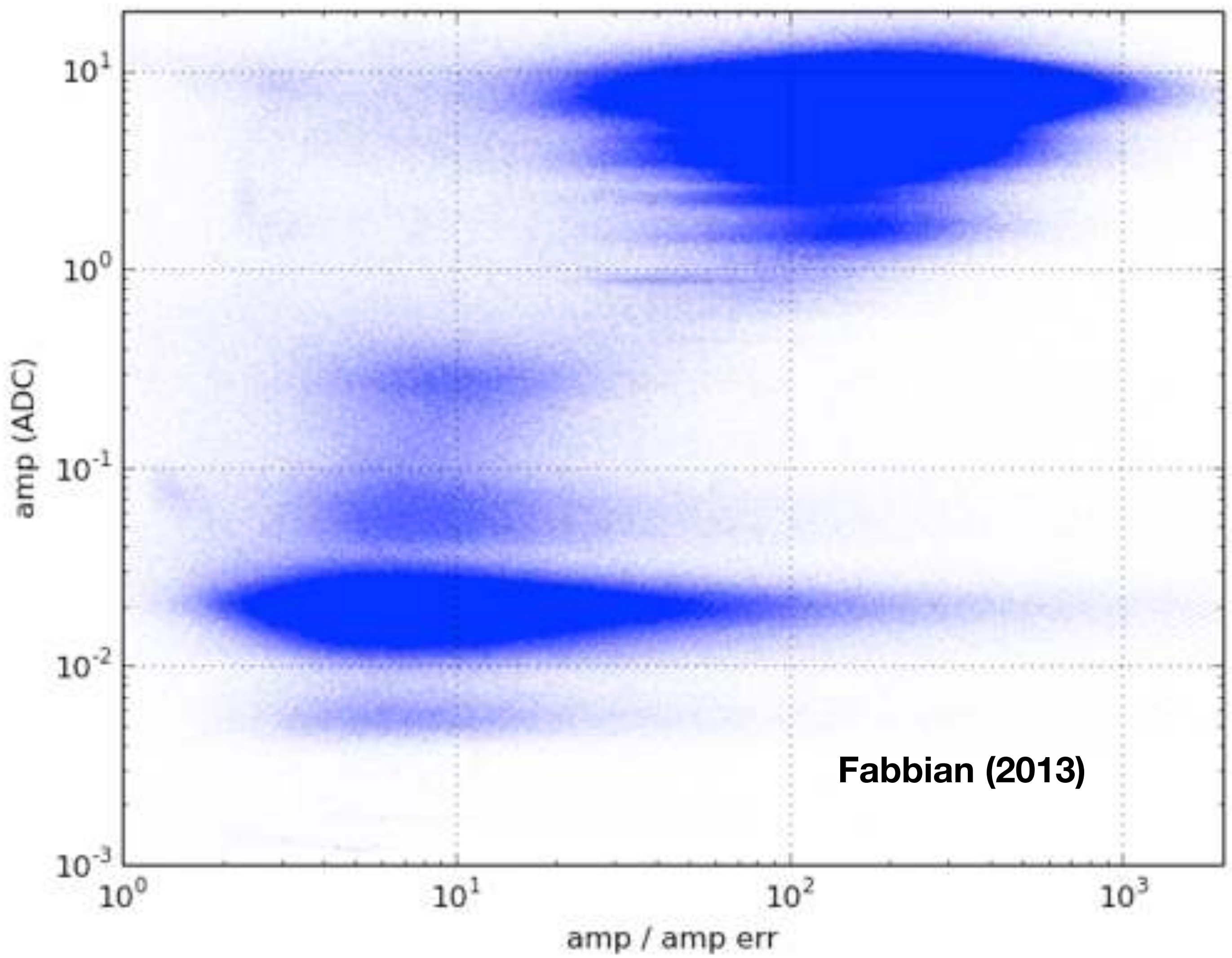


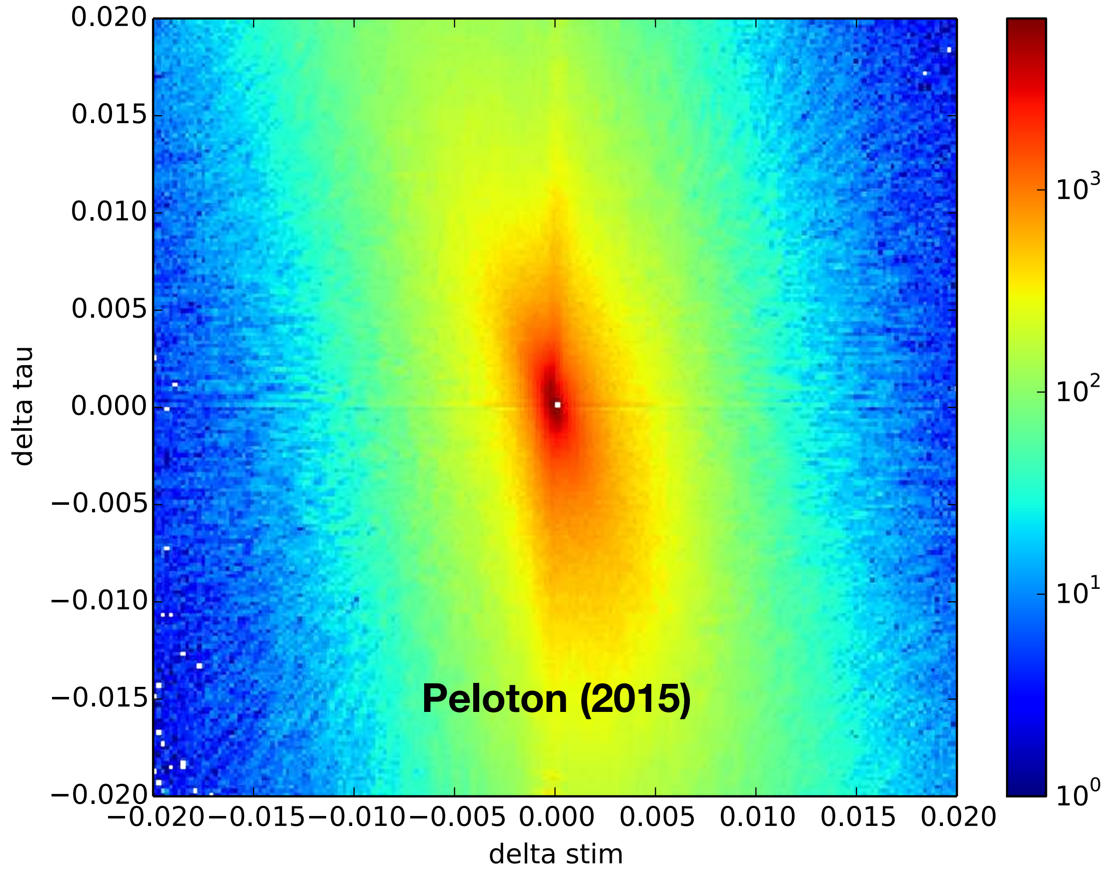


Stimulator relative calibration

- 700K ± ~ 60mK source chopped at 4-30Hz
- $A(\omega) = G/\sqrt{1+\omega\tau}$, time constant ~1ms
- < 1% gain in ~ minutes, sub % validated on TQ, TU.
- Operated for rasters and every 5 science scans.







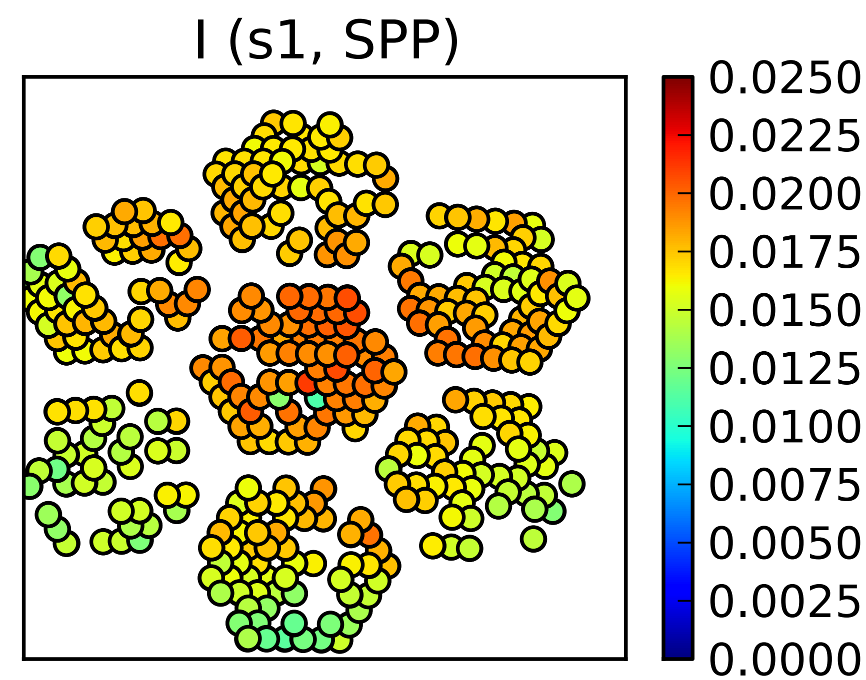
From stimulator to

- Stimulator is not stable enough / thermally isolated: can’t provide absolute scale
- Illumination from waveguide is not perfectly uniform: planets are needed e.g. Saturn

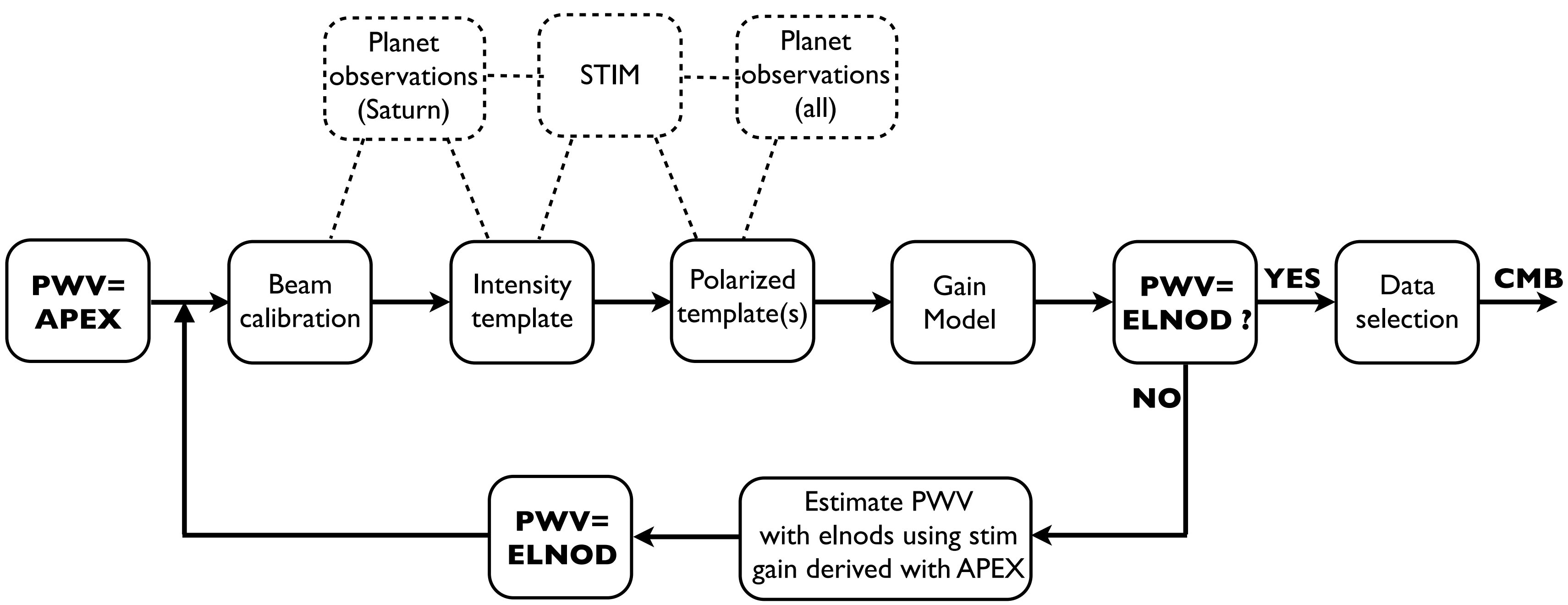
Transmission — Gaussian main lobe — Sidelobes

$$G_{ch,obs} = \alpha(obs)\frac{I_1(ch,obs) + I_2(ch,obs)}{T_{\rm sat}\pi r^2_{\rm sat}(obs)}$$

Planet temperature — Apparent size



- Planet gain to estimate effective stimulator temperature Ieff and use it to compute KRJ/ADC

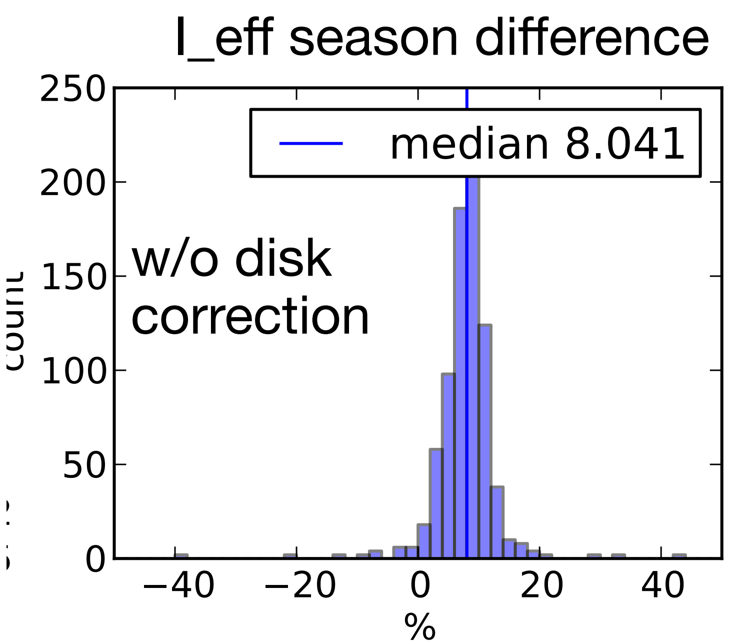


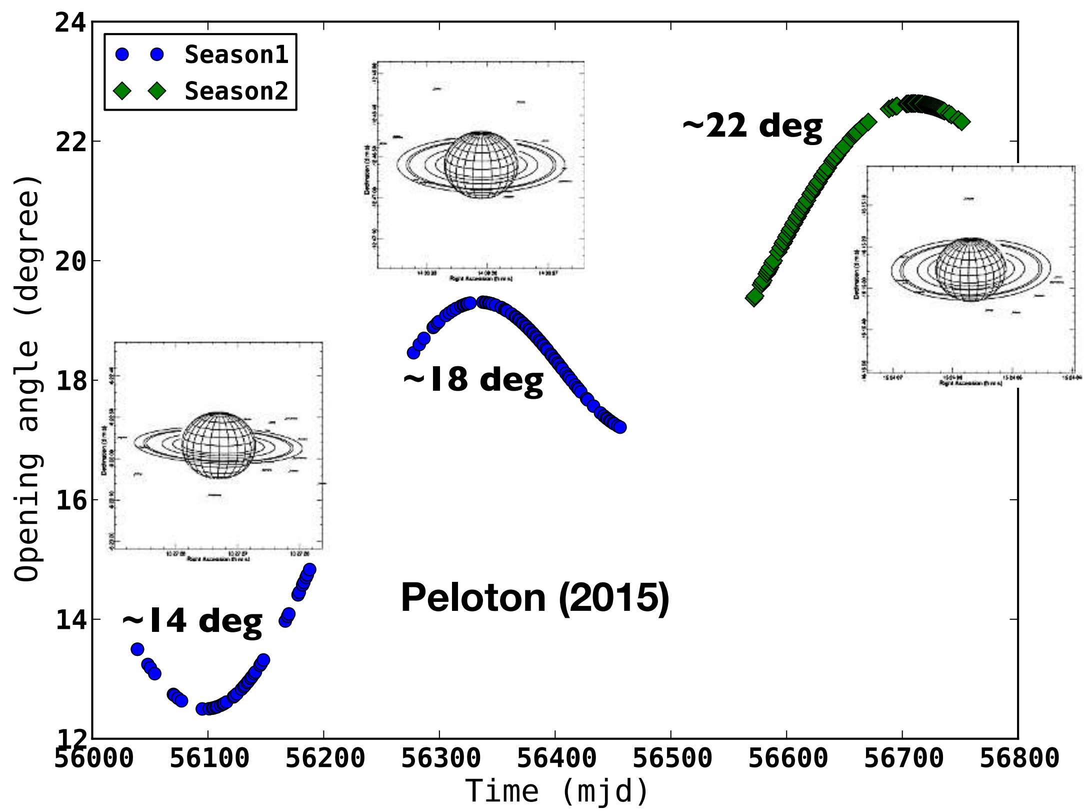
Absolute calibration on Planck

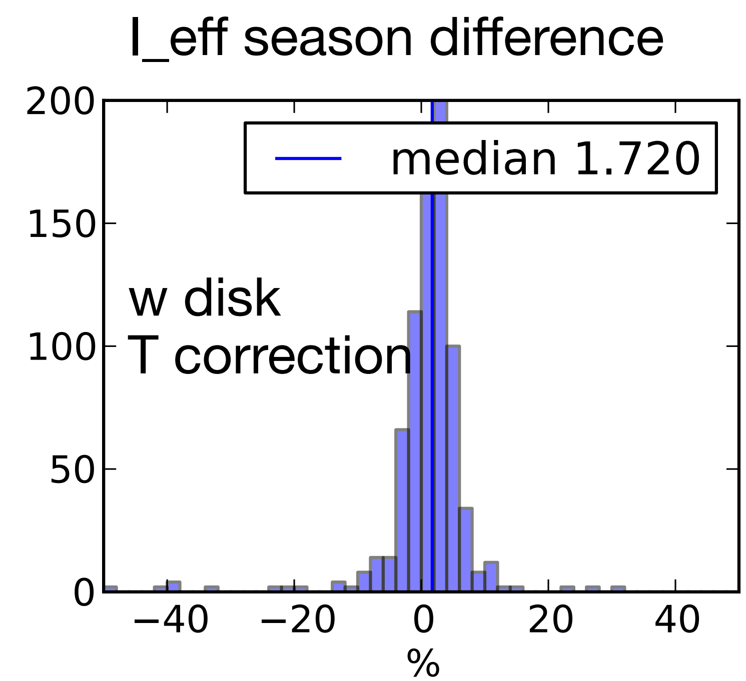
Fabbian (2013)
Peloton (2015)

Gain estimation pt 2

- You need to know your celestial source very well i.e avoid Saturn and use Jupiter





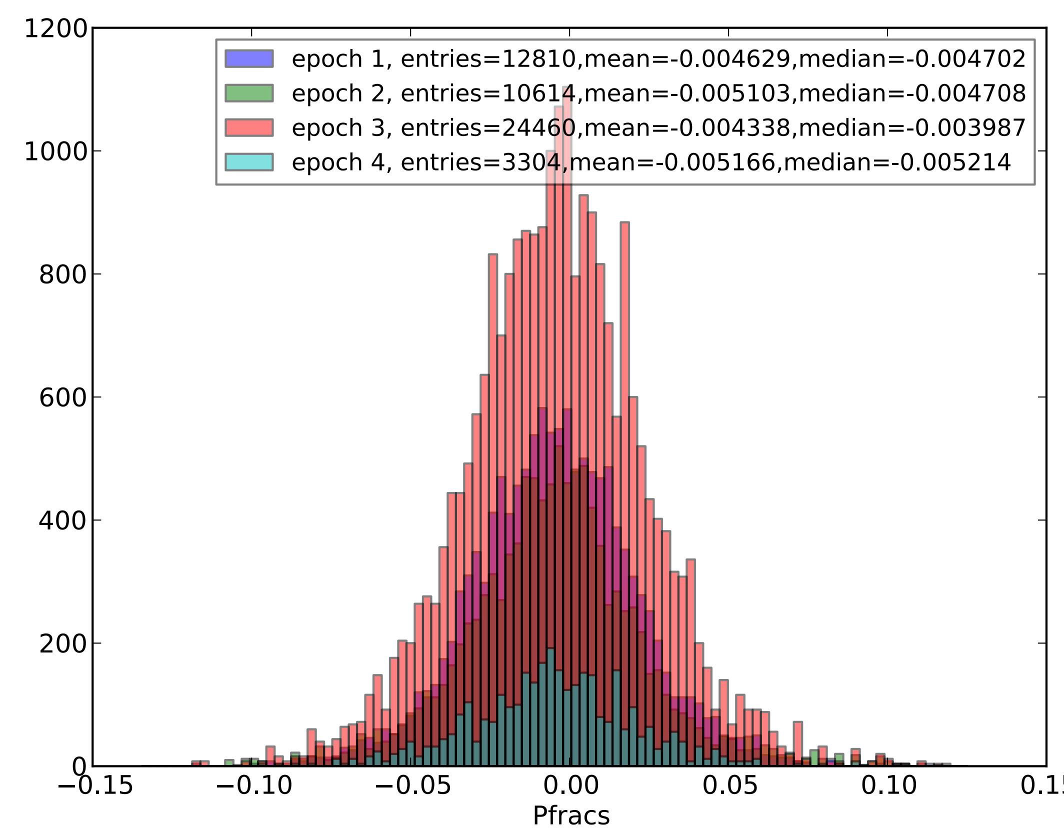


- Account for residual polarized intensity (~0.5%)

$$I^{eff}_{p,top}(\theta_{HWP}) = I^{eff}_{p}(1 + P_{frac,p}(\theta_{HWP}))$$

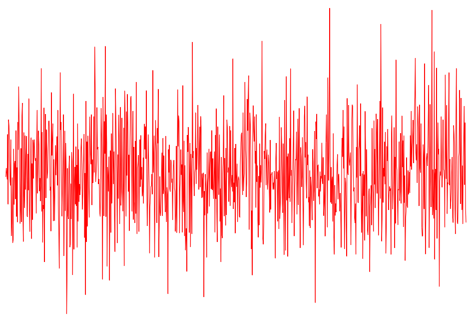
$$P_{frac,p,obs}(\theta_{HWP}) = \frac{T^{eff}_{top,obs}(\theta_{HWP}) - T^{eff}_{bottom,obs}(\theta_{HWP})}{T^{eff}_{top,obs}(\theta_{HWP}) + T^{eff}_{bottom,obs}(\theta_{HWP})}$$

$$= O_{NR} + P_a \cos(4\theta_{HWP} - 2\alpha)$$



Analysis framework: the importance of redundancy

$$\mathbf{d} = \mathbf{A} \cdot \mathbf{s} + \mathbf{n}$$



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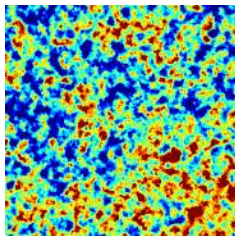
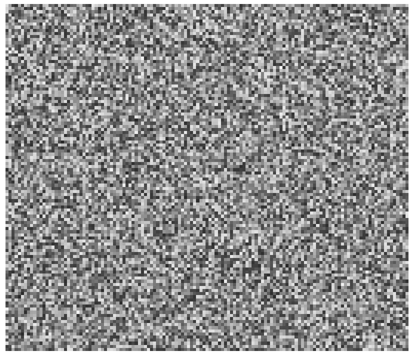
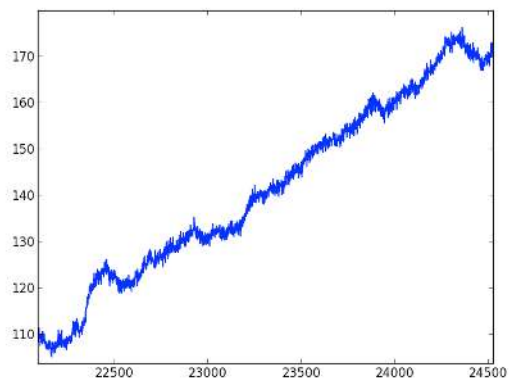
$\Big($  $\Big)$ $+$



$$\mathbf{N} \equiv \langle \mathbf{n}^{\mathsf{T}} \mathbf{n} \rangle \longrightarrow \hat{\mathbf{s}} = (\mathbf{A}^{\mathsf{T}} \mathbf{N}^{-1} \mathbf{A})^{-1} \mathbf{A}^{\mathsf{T}} \mathbf{N}^{-1} \mathbf{d}$$

Analysis framework: the importance of redundancy

$$\mathbf{d} = \mathbf{A}\mathbf{s} + \mathbf{T}\mathbf{y} + \mathbf{n}$$



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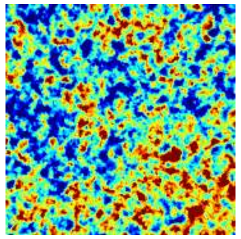
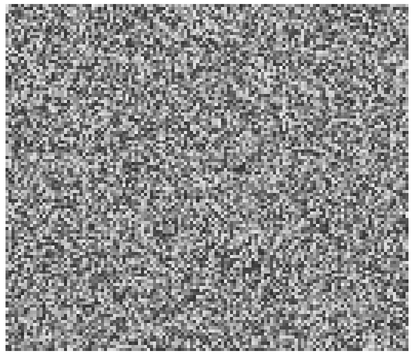
$\Big($  $\Big)$ $+$



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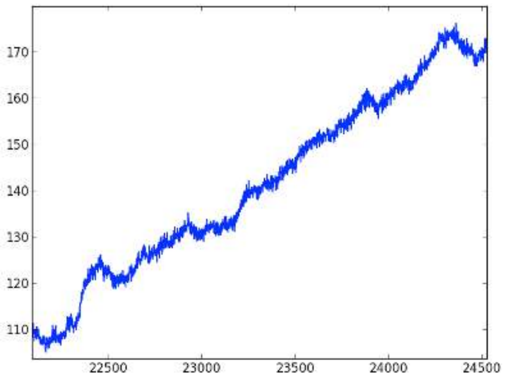
Analysis framework: the importance of redundancy

$$\mathbf{d} = \mathbf{A}\mathbf{s} + \mathbf{T}\mathbf{y} + \mathbf{n}$$



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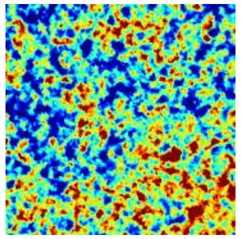
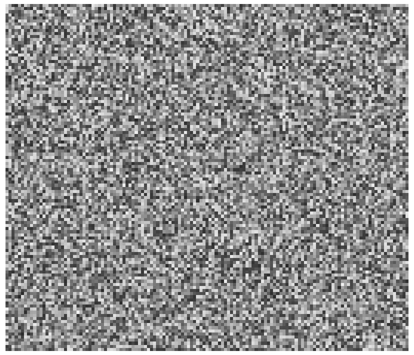
$\Big($  $\Big) +$



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$\ldots$

$$\mathbf{F_T} \equiv \mathbf{N}^{-1} - \mathbf{N}^{-1}\mathbf{T}(\mathbf{T}^\top\mathbf{N}^{-1}\mathbf{T})^{-1}\mathbf{T}^\top\mathbf{N}^{-1}$$

$$\hat{\mathbf{s}} = (\mathbf{A}^\top\mathbf{F_T}\mathbf{A})^{-1}\mathbf{A}^\top\mathbf{F_T}\mathbf{d}$$

- Filtered mapmaking

$$\hat{s} = (A^T N^{-1} A)^{-1} A^T N^{-1} F d$$

- Flat-sky MASTER power spectrum estimation with daily cross-spectra

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Cross check and validation

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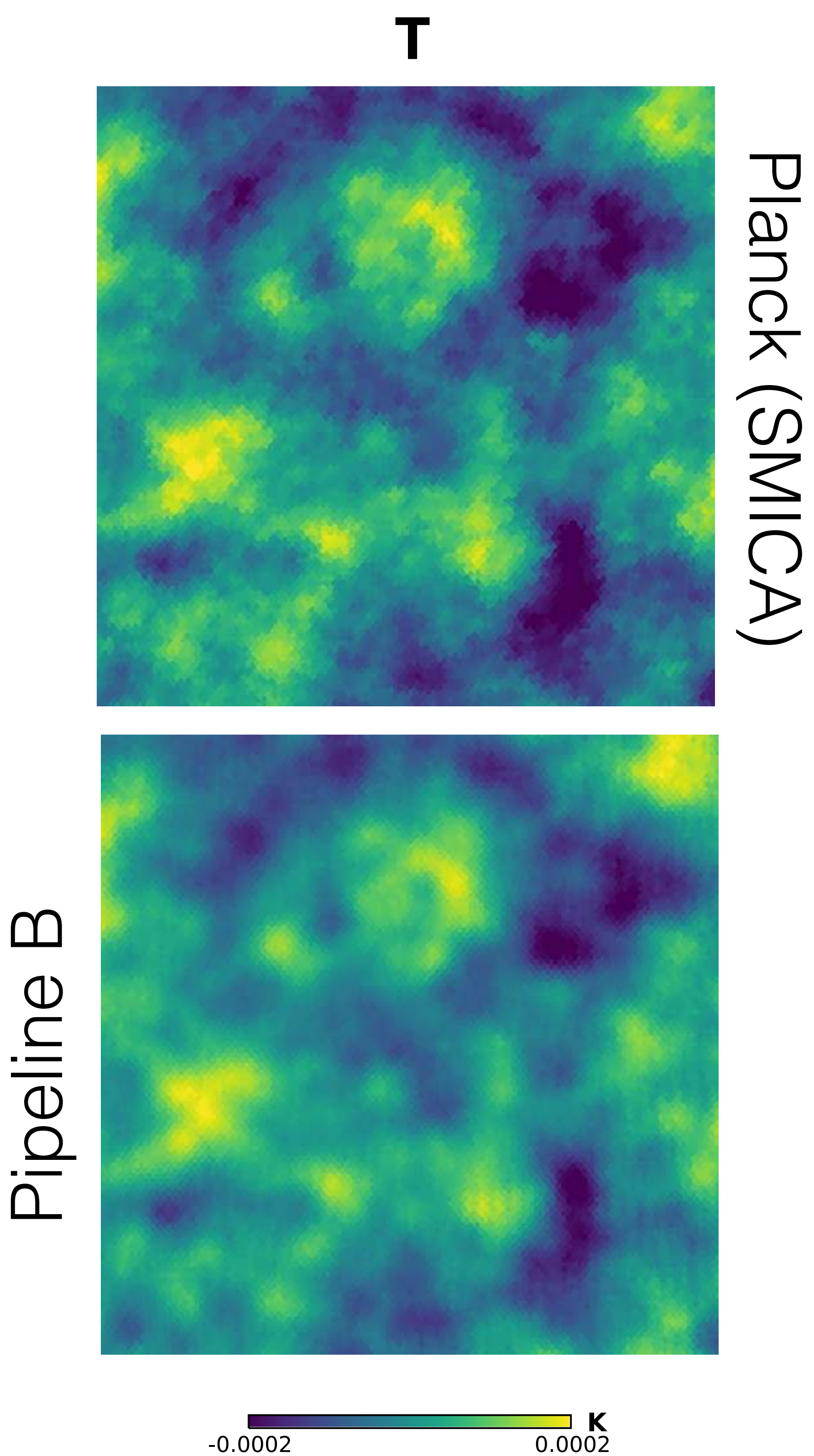
- Unbiased mapmaking

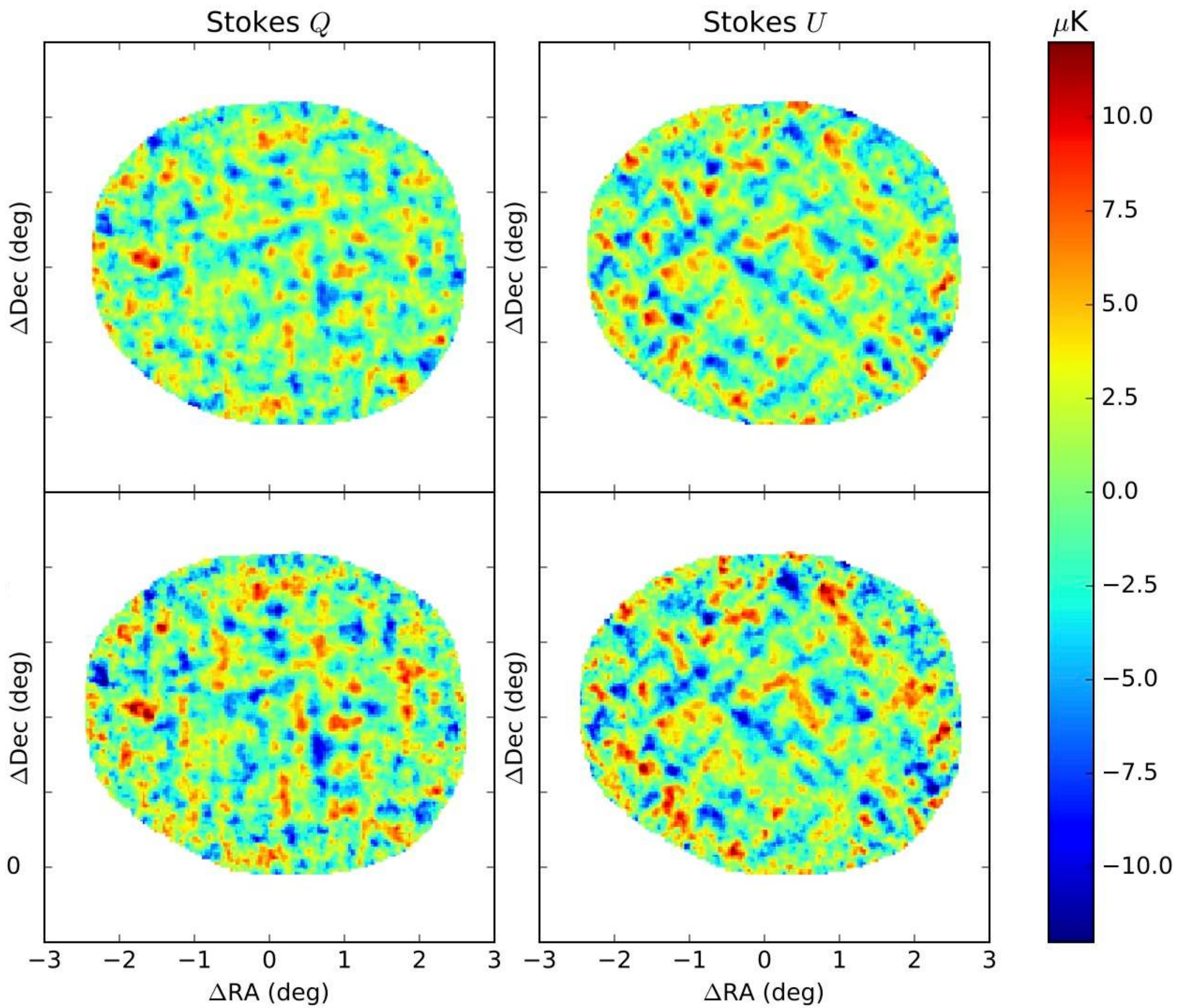
$$(A^T F A)\hat{s}_{ith} = A^T F d$$

- Curved sky pure-pseudo power spectrum estimation

Recovered CMB maps



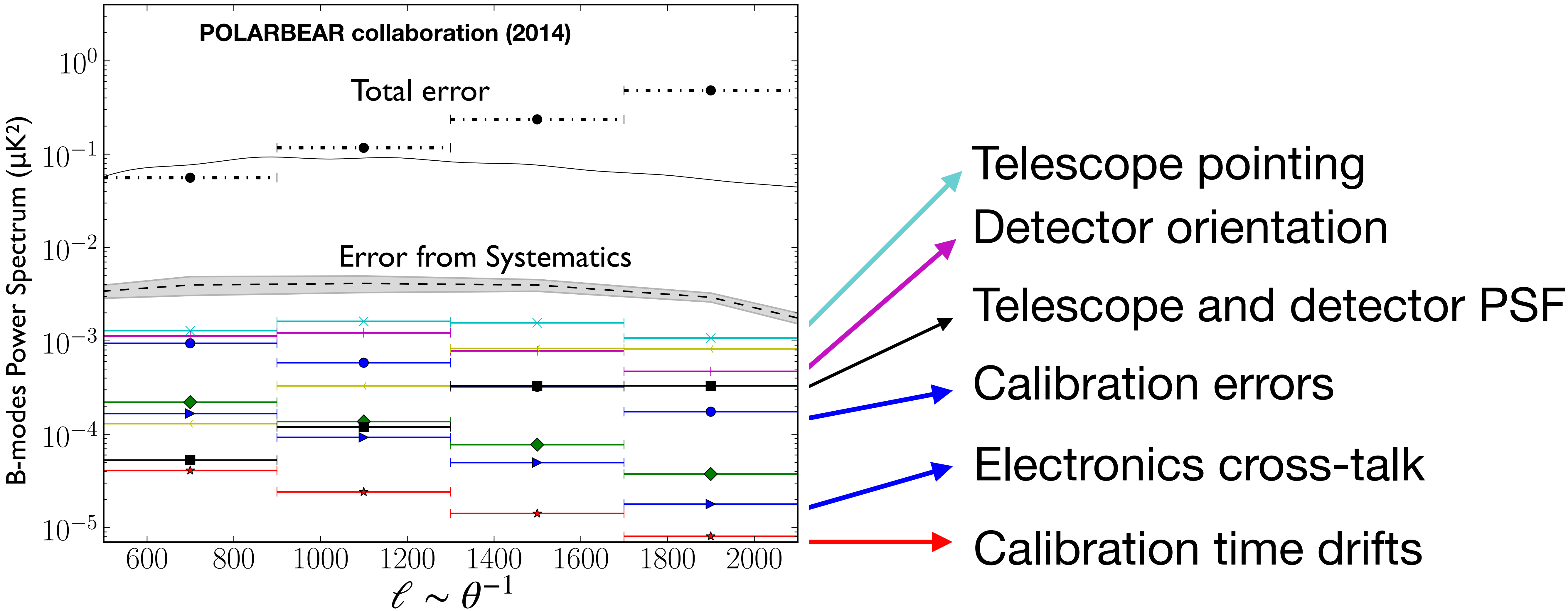
Poletti, Fabbian+(2017)



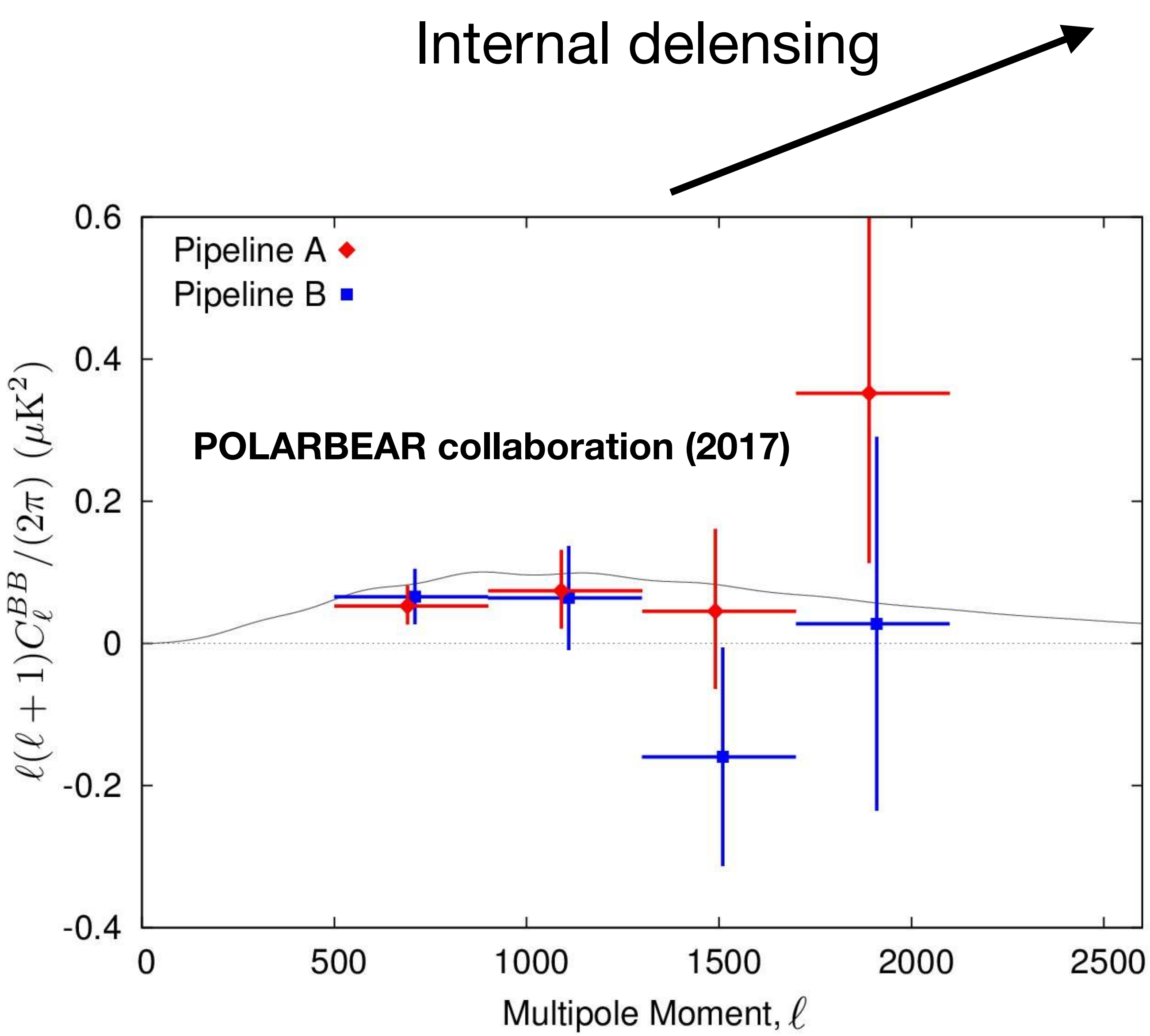
POLARBEAR collaboration (2017)

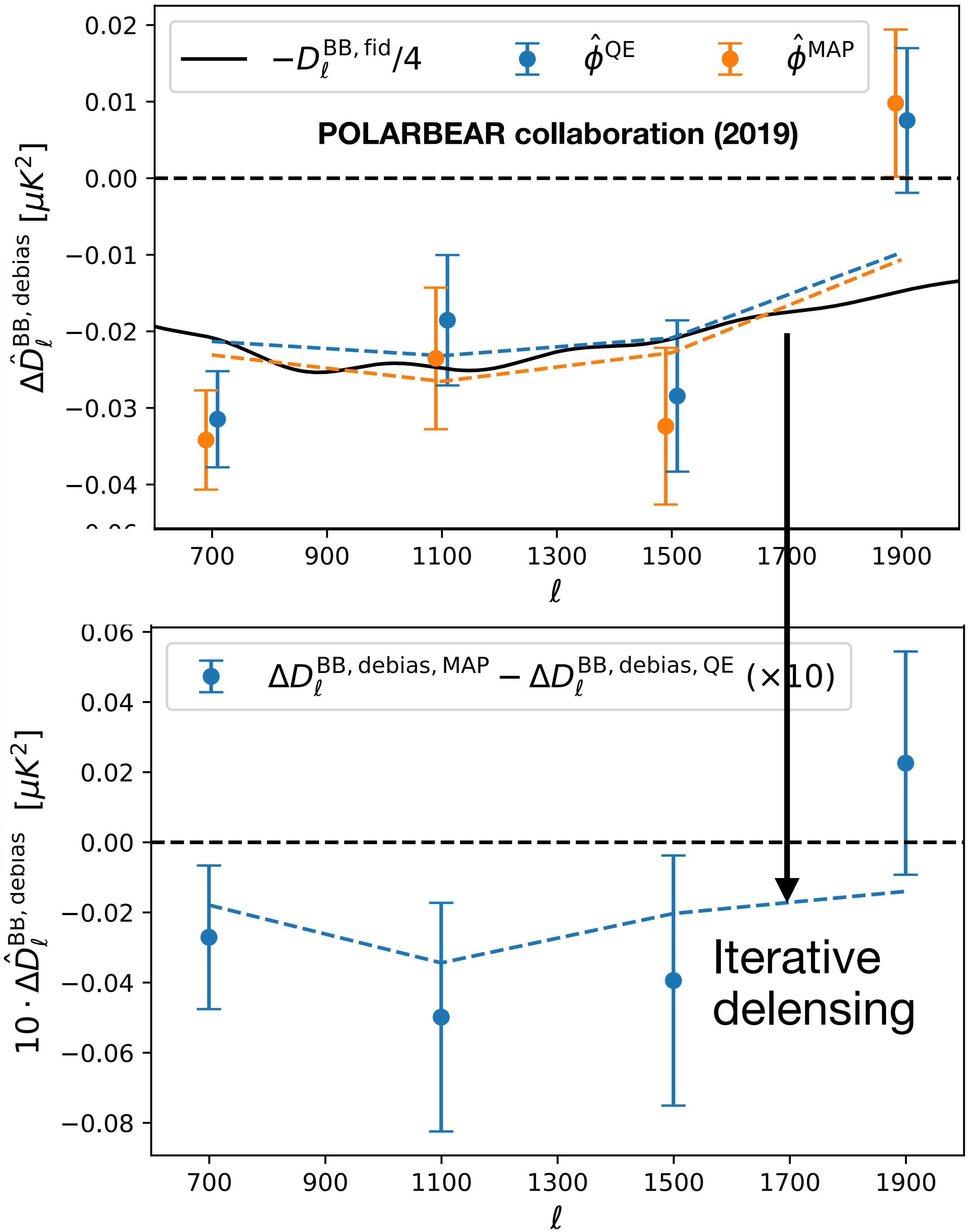
Validation

- Fully blind analysis: data selection and without EE, BB, EB spectrum inspection
- Null test suite for systematics control (>10 data splits, per patch…)
- End-to-end simulation of instrumental systematics to propagate uncertainties on science results.



Summary of major results

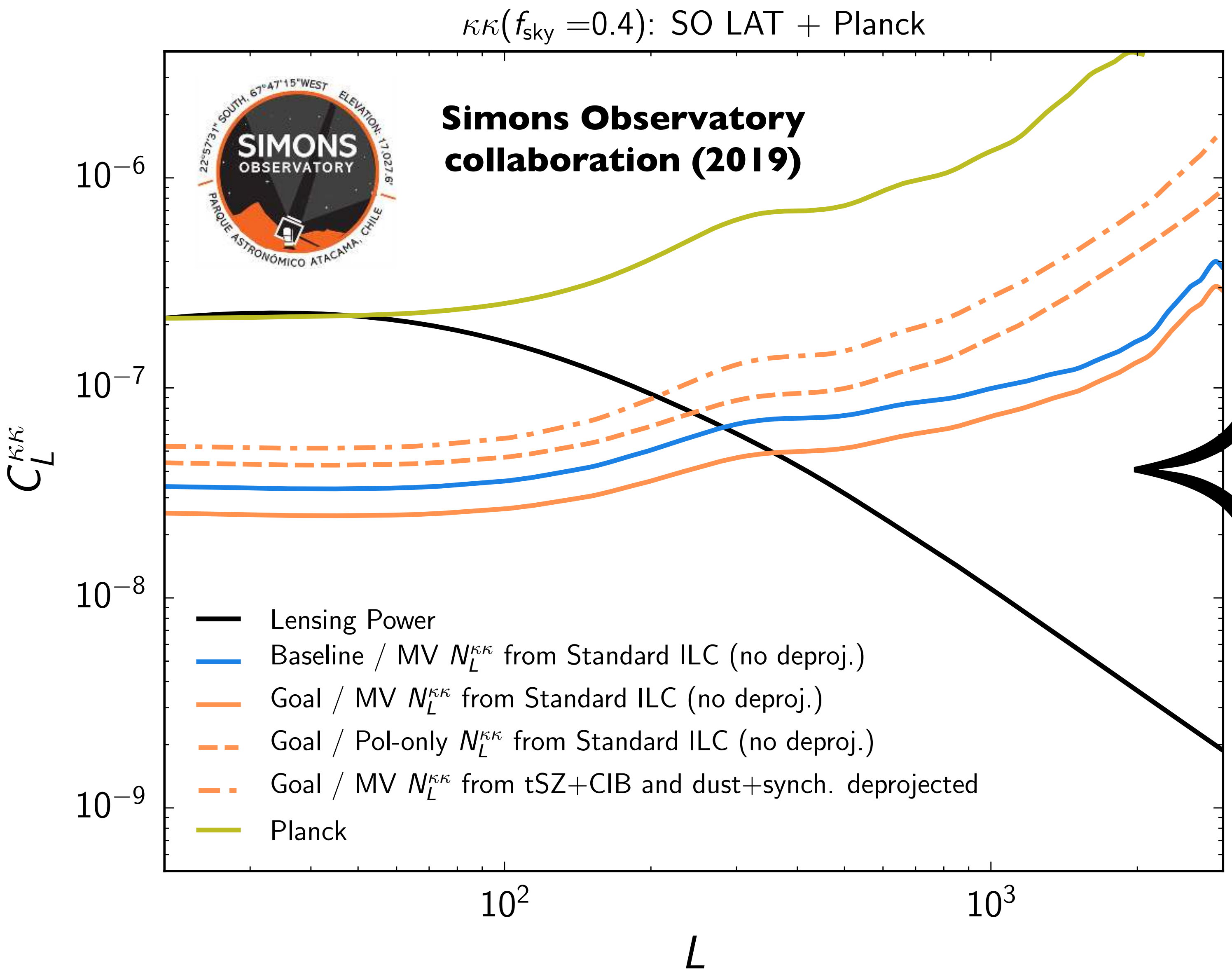




- Plus 1st measurement of polarization lensing (2014)

What we expect in the coming years

- SO will measure CMB lensing potential at >100σ significance, even higher precision for S4.
- CMB lensing will soon start imaging non-linear structures on large sky fractions



- Instrumental effects. Mirmelstein, GF+(2021)
- Analysis systematics / new estimators Fabbian+(2020) Lembo, GF+(2021)
- Theoretical systematics Beck, GF+(2018) Fabbian+(2019)
- Galactic and extragalactic foregrounds. Sailer+(2021,2022, 2023) Piccirilli, GF+(2024)

Instrumental systematics impact on CMB lensing

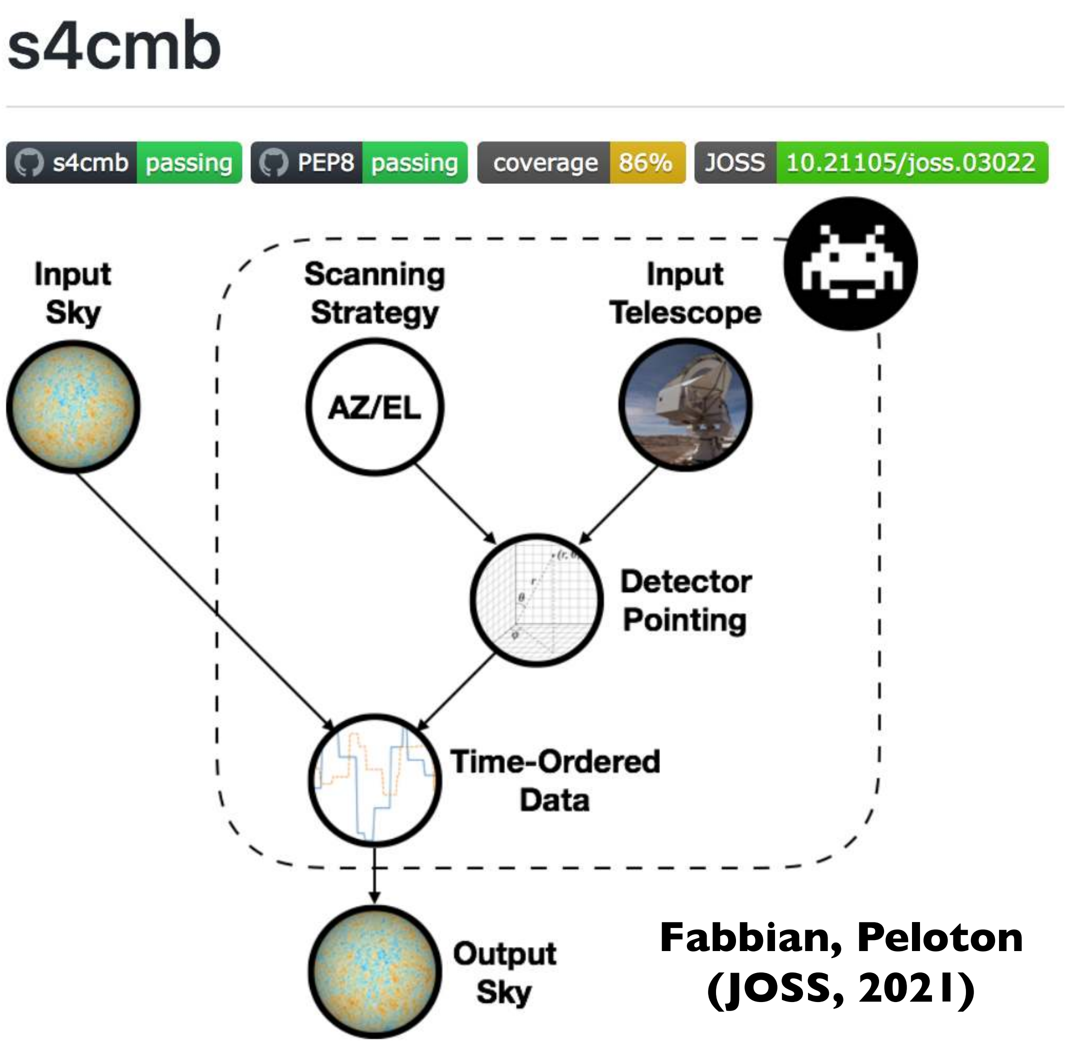
- First End-to-end simulation approach from TOD to lensing reconstruction (s4cmb).

- 6300 detectors in 4 wafers, ~4deg FOV, 15% efficiency, Q/U pixel modulation.

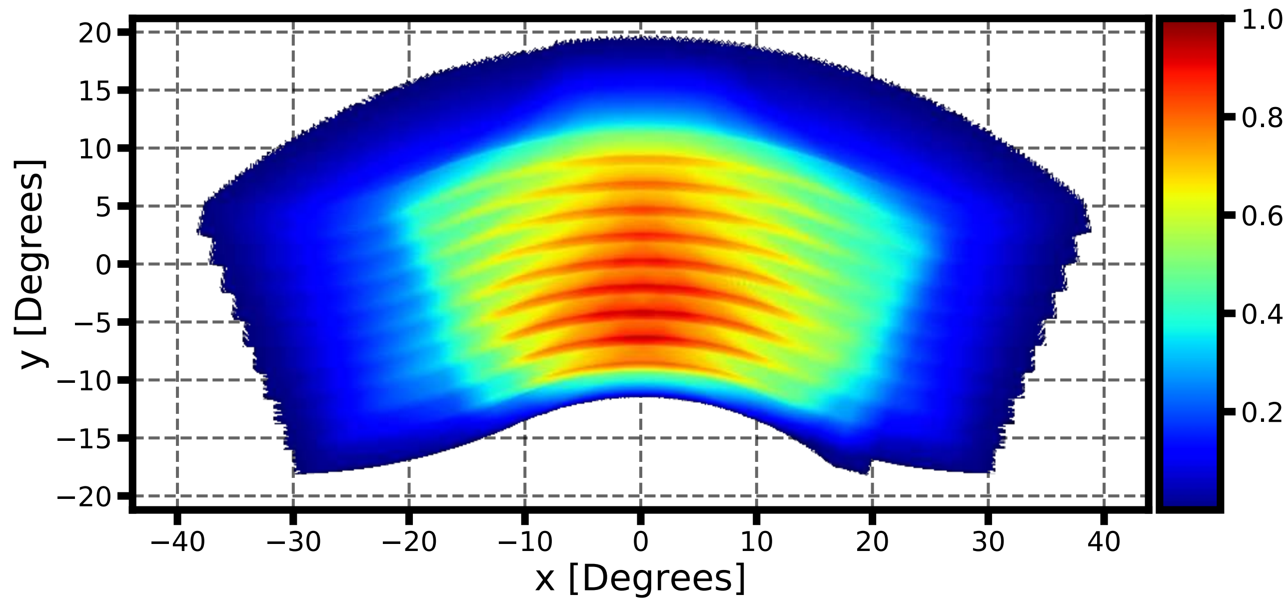
- Reduced observing time to produce full-survey SO/S4 like sensitivity map.

  - Conservative, reduced cross-linking (12 days, effective 5-6h of data).

- Lensing reconstruction with QE including optimal κ-filtering



Fabbian, Peloton (JOSS, 2021)



Mirmelstein, Fabbian, Lewis, Peloton (2021)

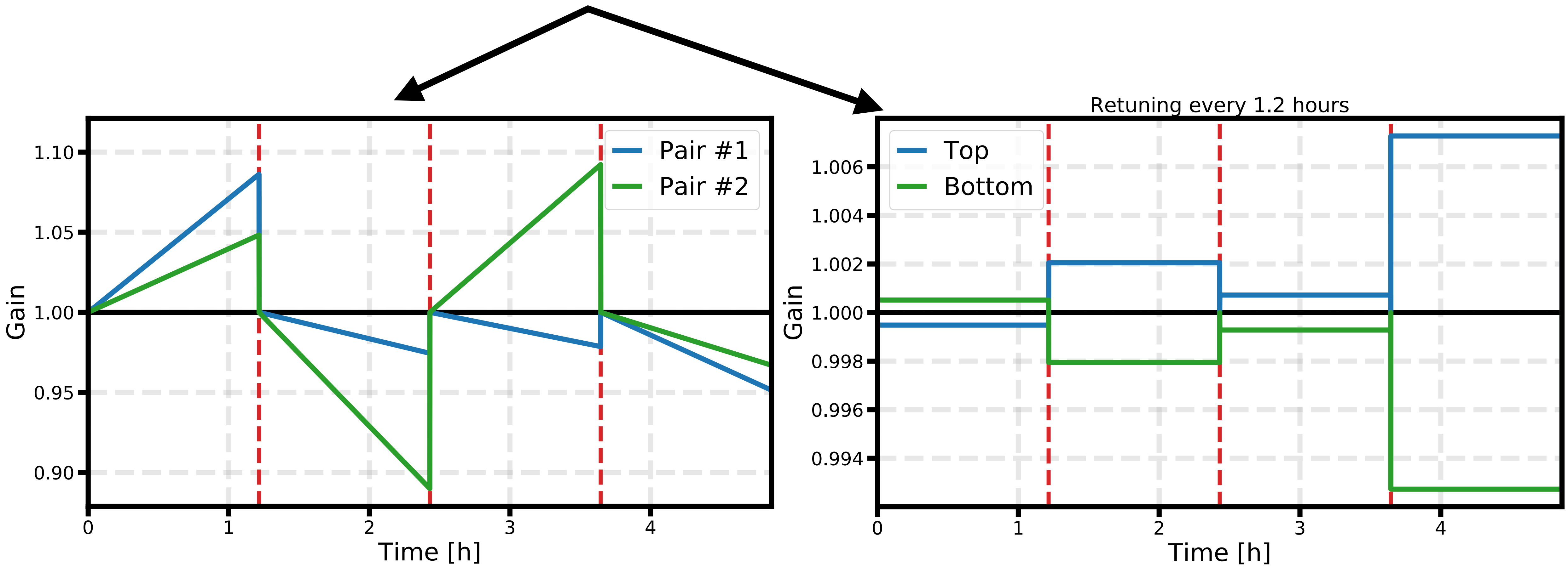
Instrumental systematics modelling: calibration

- Per detector modeling with parameters informed by current constraints

$$d_{top} = g_{top} b_{top} \circledast \left[T + Q\cos(2\psi) + U\sin(2\psi) \right],$$

$$d_{bottom} = g_{bottom} b_{bottom} \circledast \left[T - Q\cos(2\psi) - U\sin(2\psi) \right]$$

Pair-differencing mapmaking



- Common and per-pair linear gain drifts N(0,5%) $g(t) = 1 + \Delta g (t \mod t_R)/t_R$

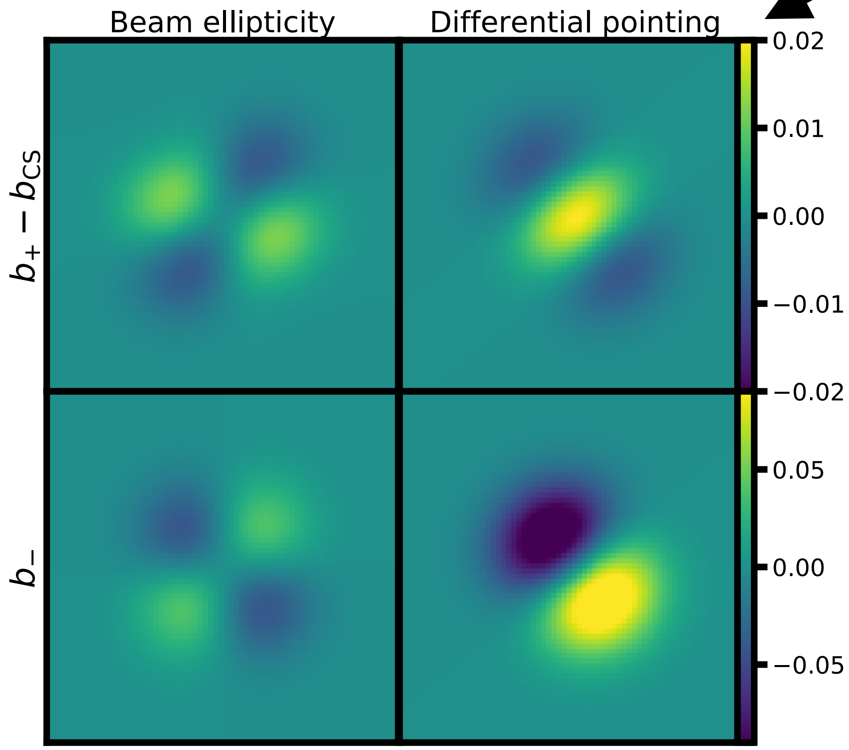
- Inter-calibration errors between detectors (no bandpasses)

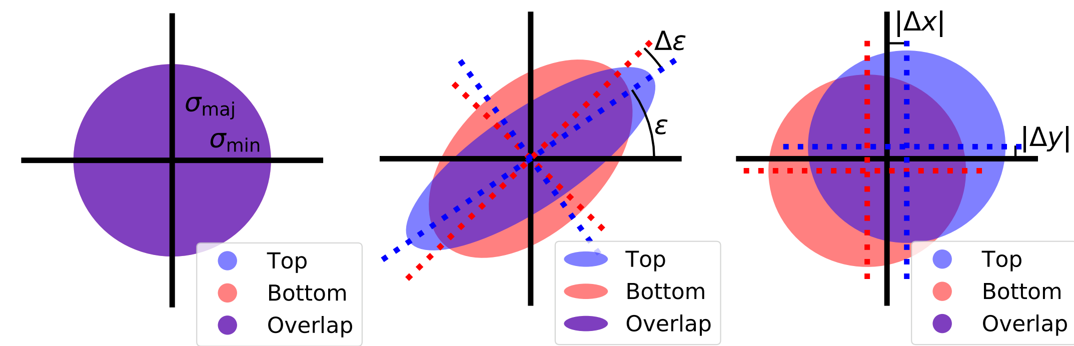
Instrumental systematics modelling: beams, pointing

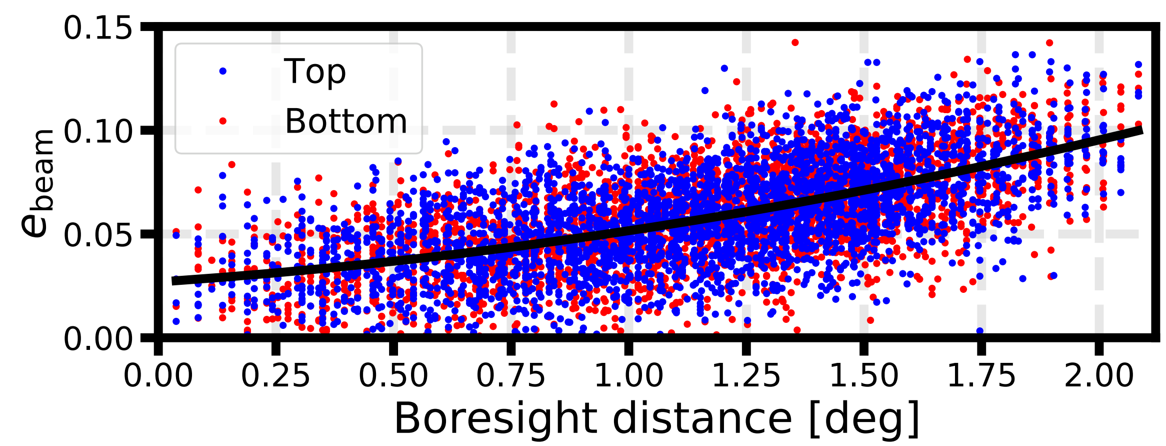
- Per detector modeling with parameters informed by current constraints

$$d_{top} = g_{top} b_{top} \circledast \left[T + Q\cos(2\psi) + U\sin(2\psi)\right],$$

$$d_{bottom} = g_{bottom} b_{bottom} \circledast \left[T - Q\cos(2\psi) - U\sin(2\psi)\right]$$







- Beams convolution as series expansions $b(\mathbf{x}) \approx \alpha_0 b_{CS}(\mathbf{x}) + \alpha_{1,i}\frac{\partial b_{CS}(\mathbf{x})}{\partial x^i} + \alpha_{2,ij}\frac{\partial^2 b_{CS}(\mathbf{x})}{\partial x^i \partial x^j},$

- Ellipticity 5% including optical distortion and diff. pointing ~10”, pointing jitter as N(3”,13”).

Lensing reconstruction results

$$T(\mathbf{l}), E(\mathbf{l}), B(\mathbf{l}), \times T(\mathbf{l}'), E(\mathbf{l}'), B(\mathbf{l}'), \longrightarrow \hat{\phi}_{\mathbf{L}} \equiv \left(\hat{\phi}^{QE}_{\mathbf{L}} - \langle \hat{\phi}_{\mathbf{L}} \rangle_{MC}\right) \xrightarrow{\text{Noise debasing}} \hat{C}^{\phi\phi}_{L} \equiv C^{\hat{\phi}_1\hat{\phi}_2}_{L} - N^{(0),RD}_{L}.$$

Masking and noise effects

From MC w/o systematics

Sensitive to effective data power spectrum

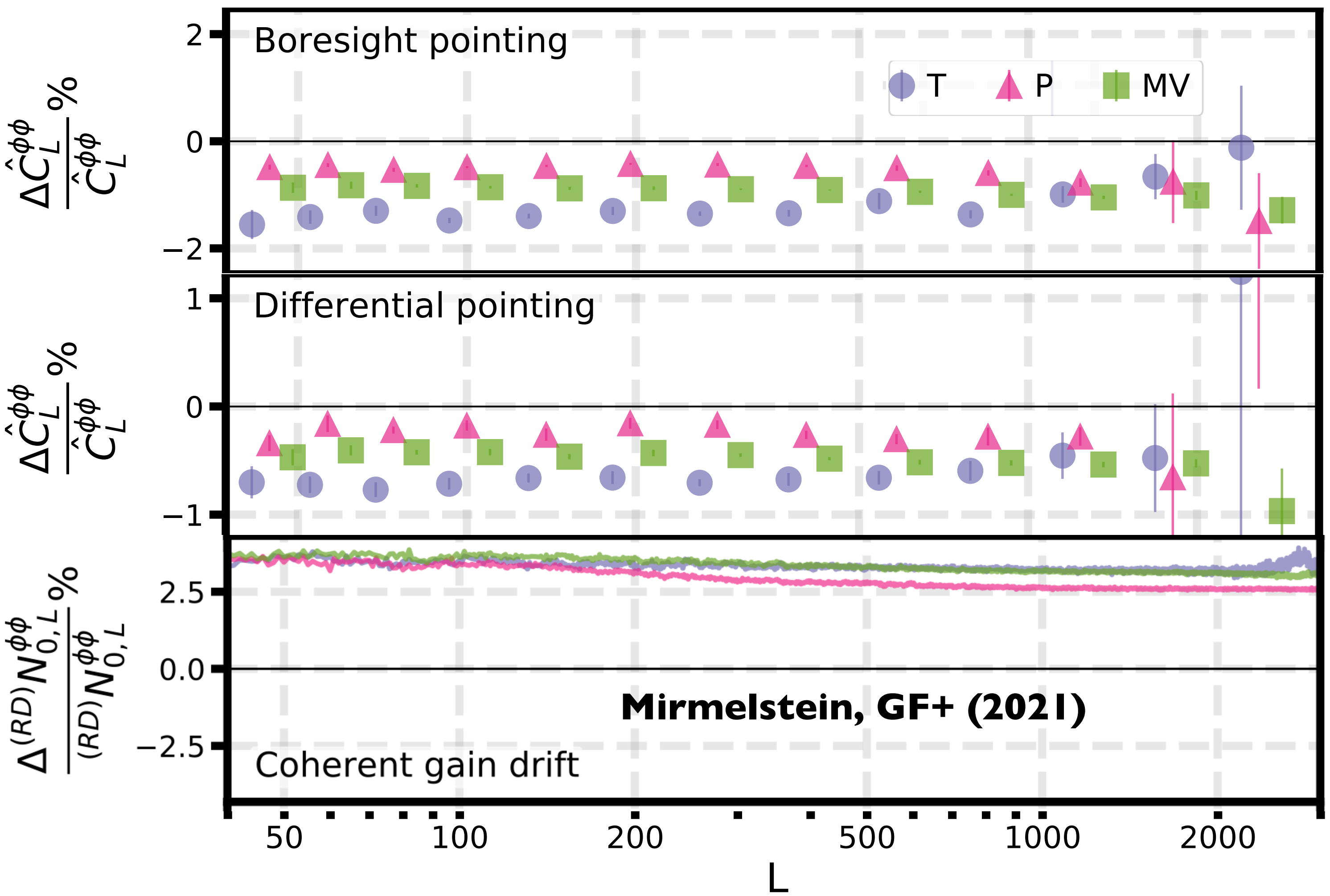
Lensing reconstruction results

$T(\mathbf{l}), E(\mathbf{l}), B(\mathbf{l}), \times T(\mathbf{l}'), E(\mathbf{l}'), B(\mathbf{l}'),$ → $\hat{\phi}_{\mathbf{L}} \equiv \left(\hat{\phi}^{QE}_{\mathbf{L}} - \langle \hat{\phi}_{\mathbf{L}} \rangle_{MC}\right)$ —Noise debasing→ $\hat{C}^{\phi\phi}_{L} \equiv C^{\hat{\phi}_1\hat{\phi}_2}_{L} - N^{(0),RD}_{L}$.

Masking and noise effects

From MC w/o systematics

Sensitive to effective data power spectrum



Systematics	T	P	MV
Beam ellipticity	0.06	0.00	0.01
Differential pointing	0.27	0.09	0.28
Boresight pointing	0.52	0.20	0.52
Polarization angle	0.05	2.20	0.60
Incoherent gain drift	0.36	0.05	0.04
Coherent gain drift	0.56	0.28	0.64
Calibration mismatch	0.38	0.11	0.09
Crosstalk	0.11	0.06	0.03

Optimal solution TBD

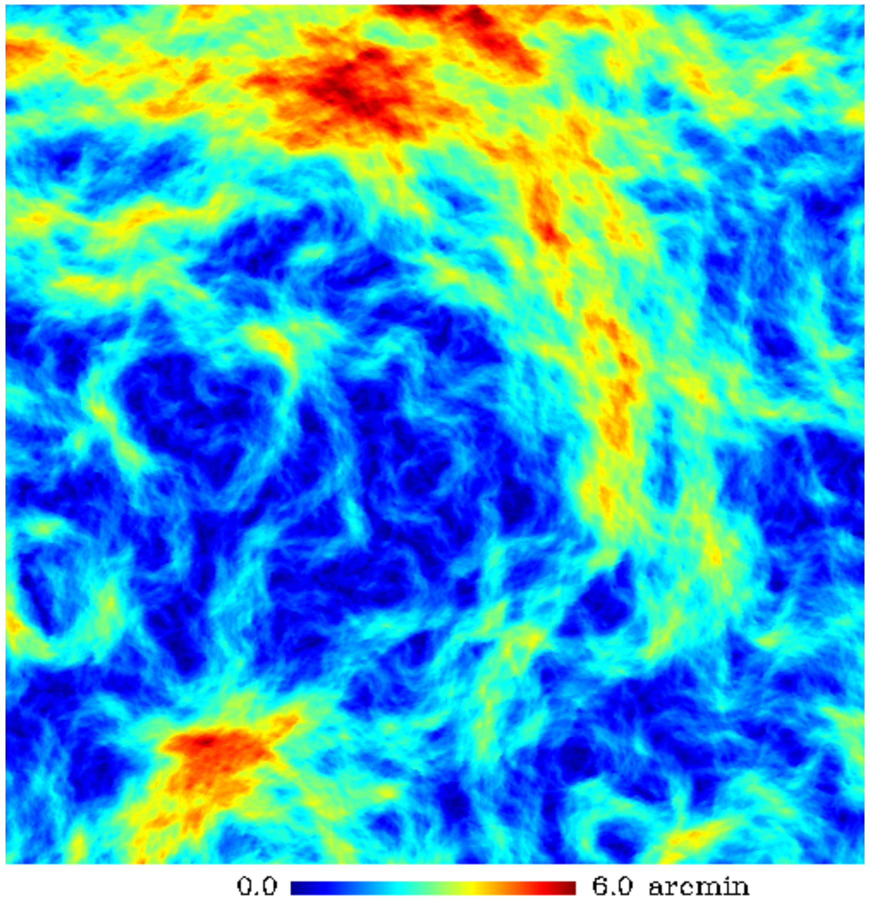
Below ~1σ on $A_{\rm lens}$

Some new internal null tests

- Lensing beyond the usual modeling

$$\mathbf{d}(\boldsymbol{\theta}) = \nabla \phi^{eff}(\boldsymbol{\theta})$$

- Null test approach also be extended (ongoing work)

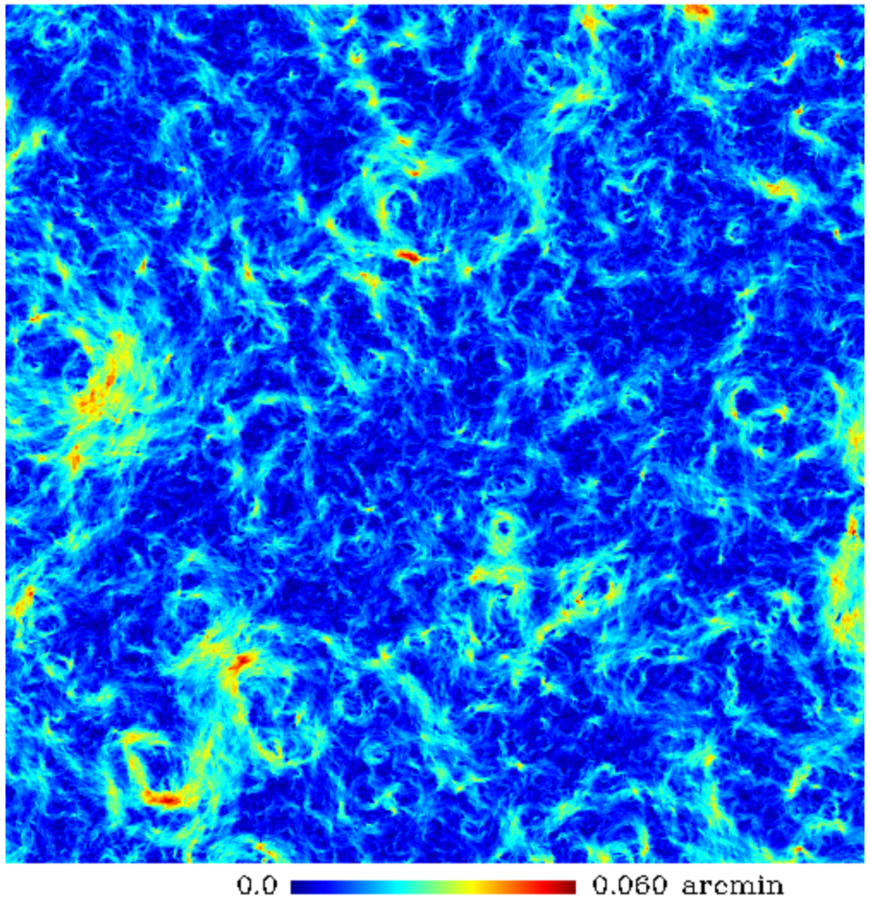


Some new internal null tests

- Lensing beyond the usual modeling

$$\mathbf{d}(\boldsymbol{\theta}) = \nabla \phi^{eff}(\boldsymbol{\theta}) + \nabla \times \Omega^{eff}(\boldsymbol{\theta})$$

Fabbian+ (2017)
Fabbian, Lewis+(2019)
Lewis & Pratten (2016)



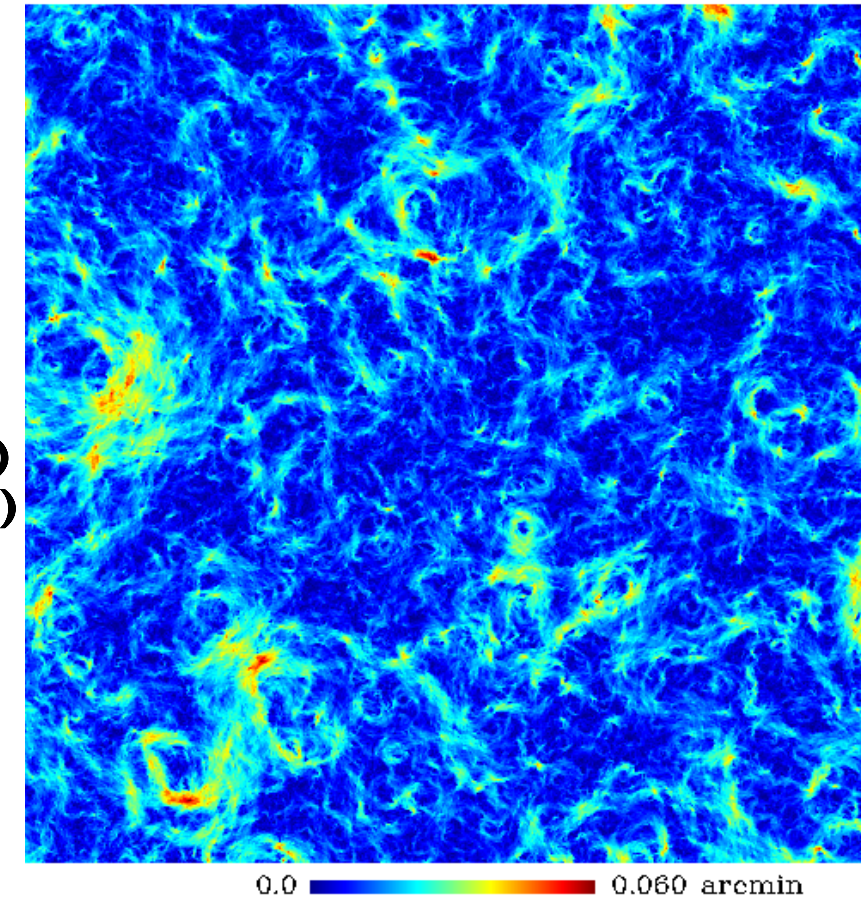
- Null test approach also be extended (ongoing work)

Some new internal null tests

- Lensing beyond the usual modeling

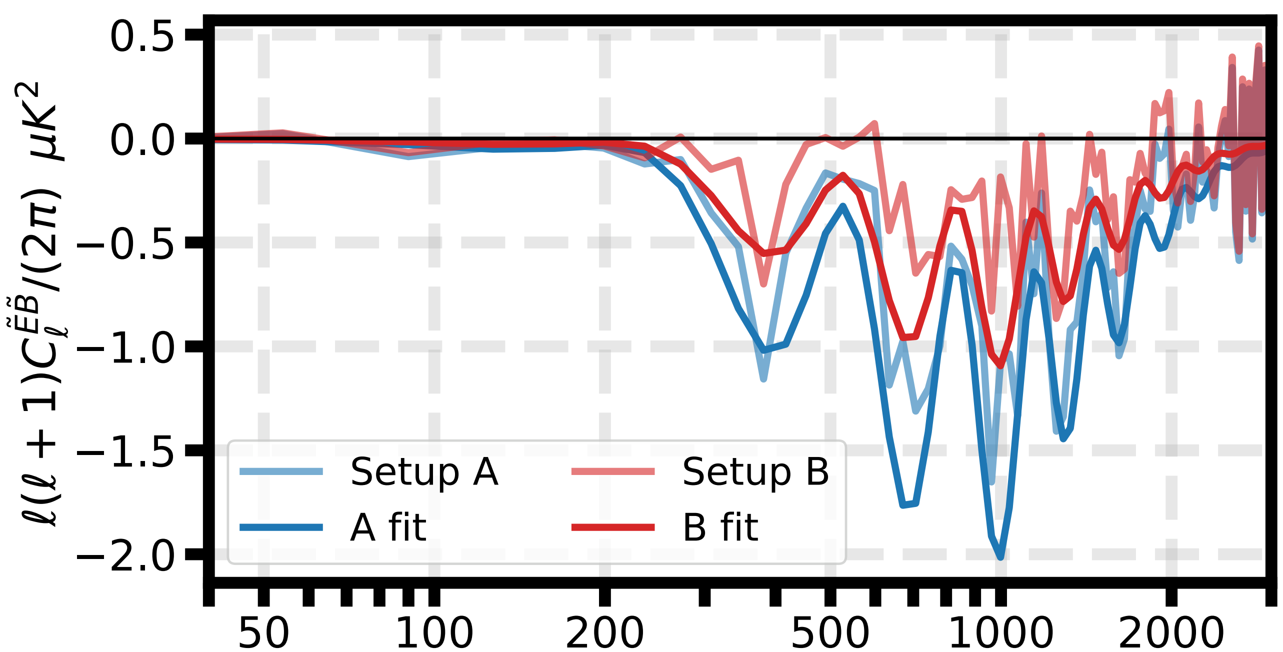
$$\mathbf{d}(\boldsymbol{\theta}) = \nabla \phi^{eff}(\boldsymbol{\theta}) + \nabla \times \Omega^{eff}(\boldsymbol{\theta})$$

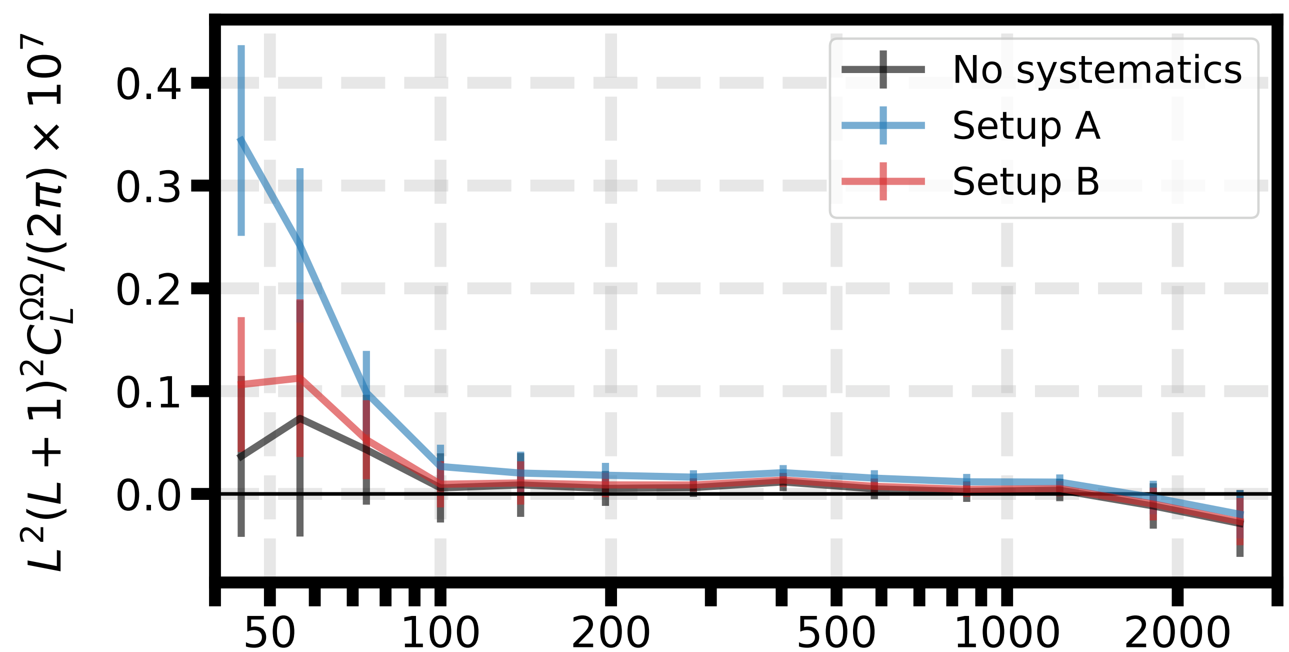
Fabbian+ (2017)
Fabbian, Lewis+(2019)
Lewis & Pratten (2016)



- Null test approach also be extended (ongoing work)

- Curl-mode diagnostic: useful for pol. angle systematics and error model testing.





Mirmelstein, GF+ (2021)

Conclusions

- POLARBEAR delivered robust measurements of CMB polarization
  - ➡ Unique deep data set and data analysis approach
  - ➡ 1st CMB polarization lensing, lensing B-modes, internal B-modes delensing.
  - ➡ Deep cross-correlation with HSC lensing, birefringence, atmosphere polarization…

- Lessons learned / legacy:
  - ➡ Calibration time is not wasted.
  - ➡ Sub % relative calibration achievable with stimulator, % absolute calibration hard with planets.
  - ➡ Analysis and calibration strategy redundancy crucial to deliver robust results.
  - ➡ Characterization of systematics error is crucial: estimate and quote it!
  - ➡ Be ready to propagate systematics in all scientific analyses.

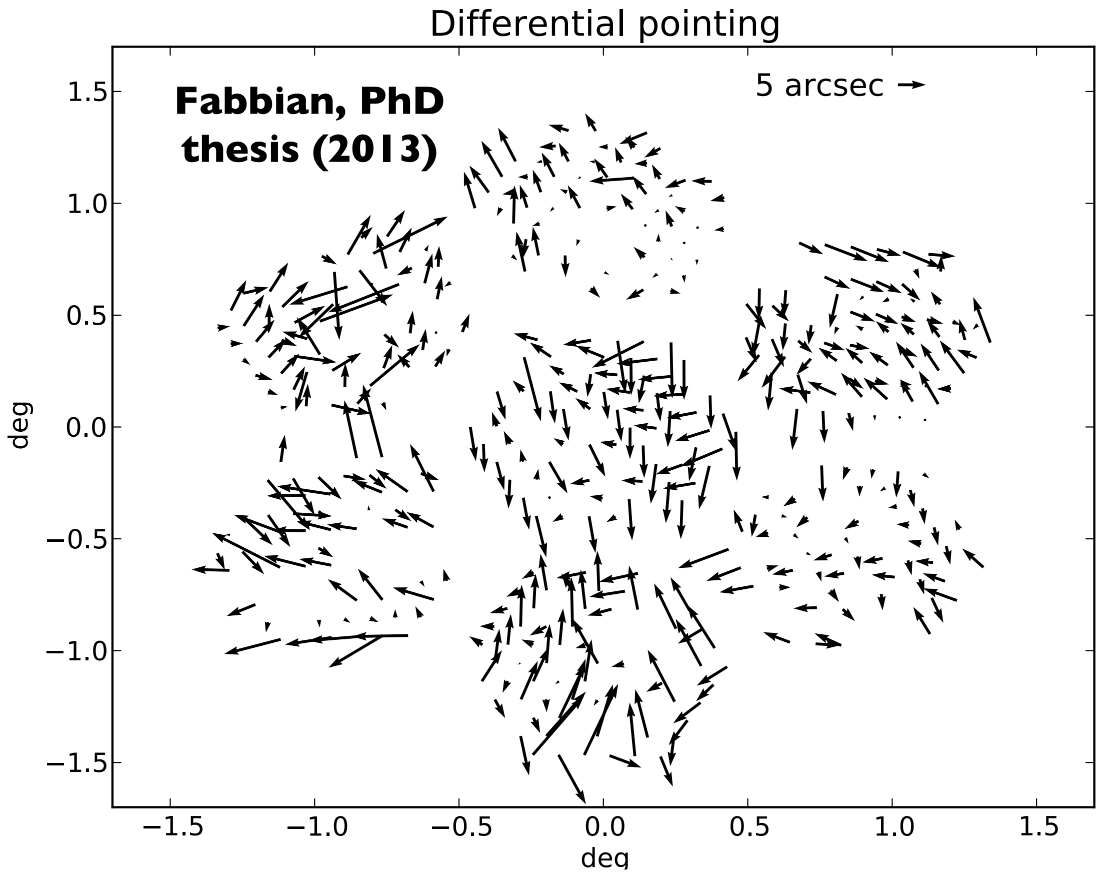
Systematics error example

- Differential pointing: two detectors looking in different direction

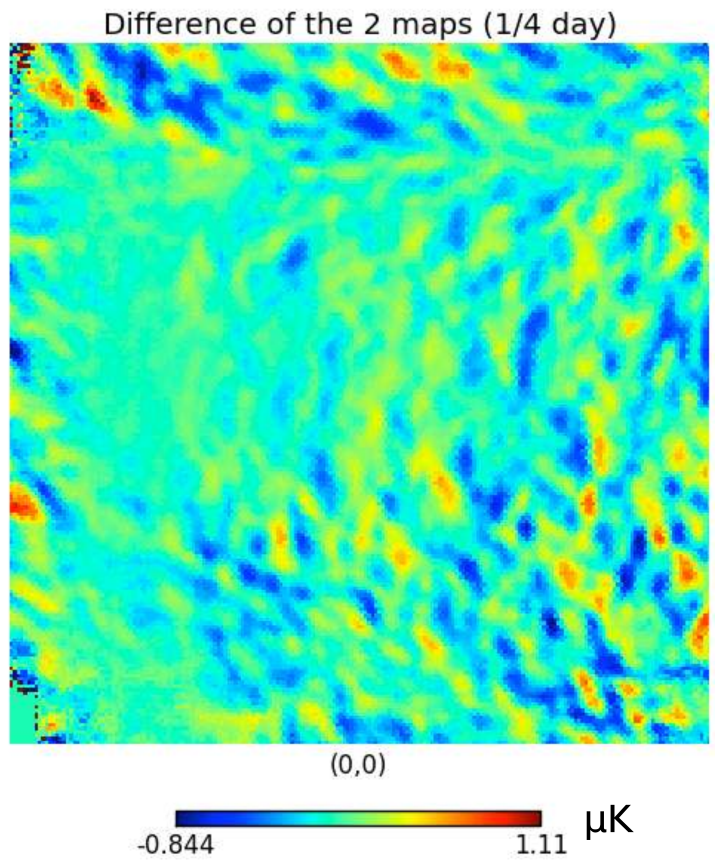
$$d^t(t) = g_{top}\,[I(\hat{\mathbf{n}}(t)) + Q(\hat{\mathbf{n}}(t))\cos(2\psi(t)) + U(\hat{\mathbf{n}}(t))\sin(2\psi(t))]$$
$$d^b(t) = g_{bot}\,[I(\hat{\mathbf{n}}(t)) - Q(\hat{\mathbf{n}}(t))\cos(2\psi(t)) - U(\hat{\mathbf{n}}(t))\sin(2\psi(t))]$$

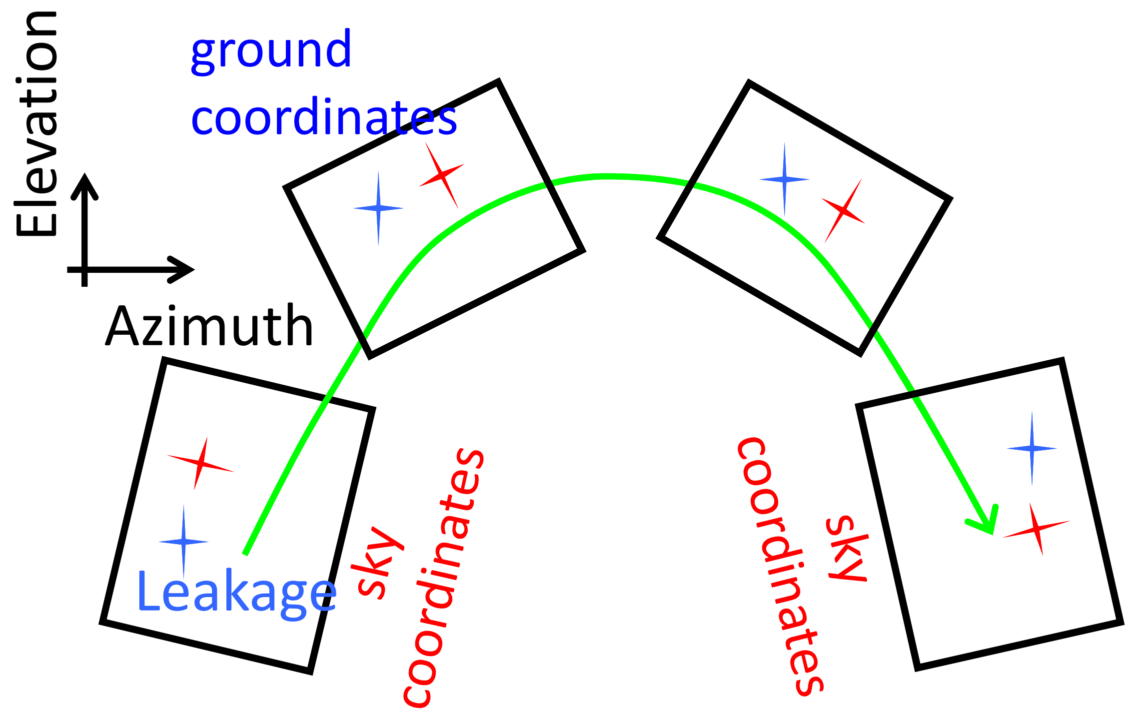
- Temperature to polarization leakage can prevent detection of B-modes

- Polarization modulation can reduce it



Q





Systematics error example

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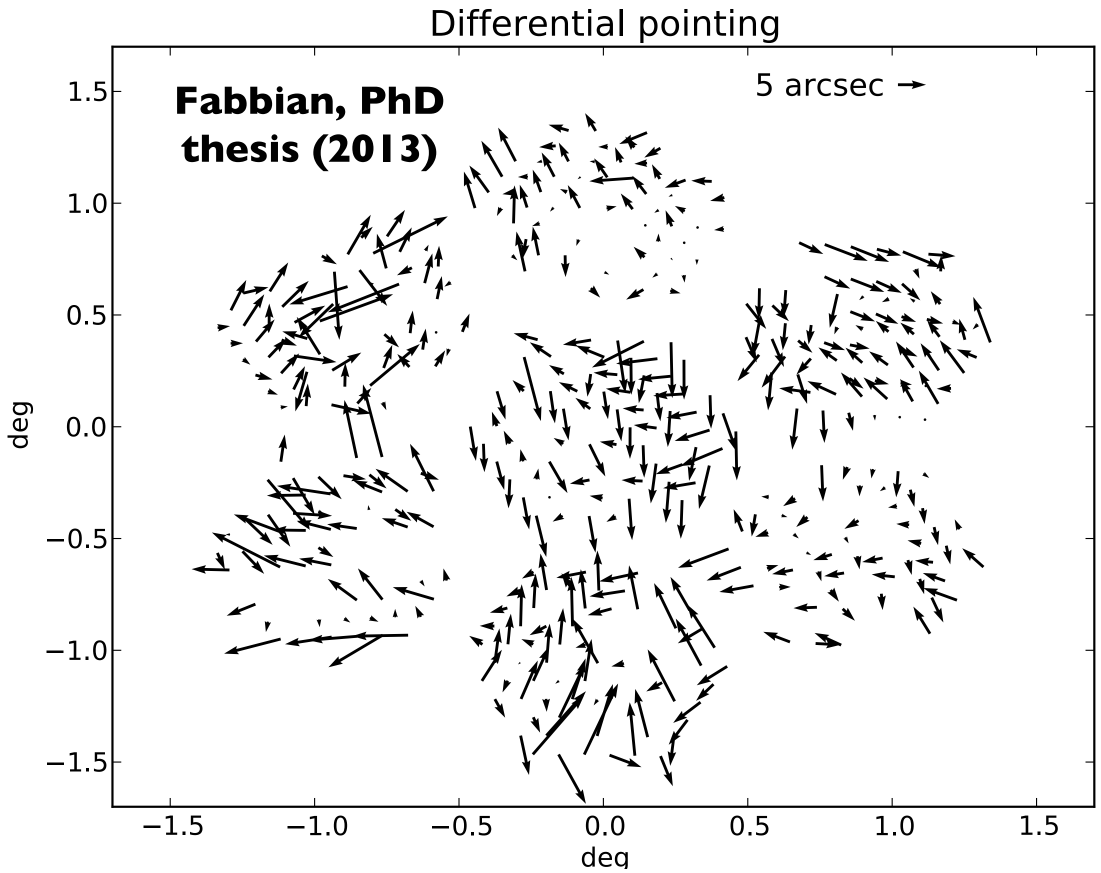

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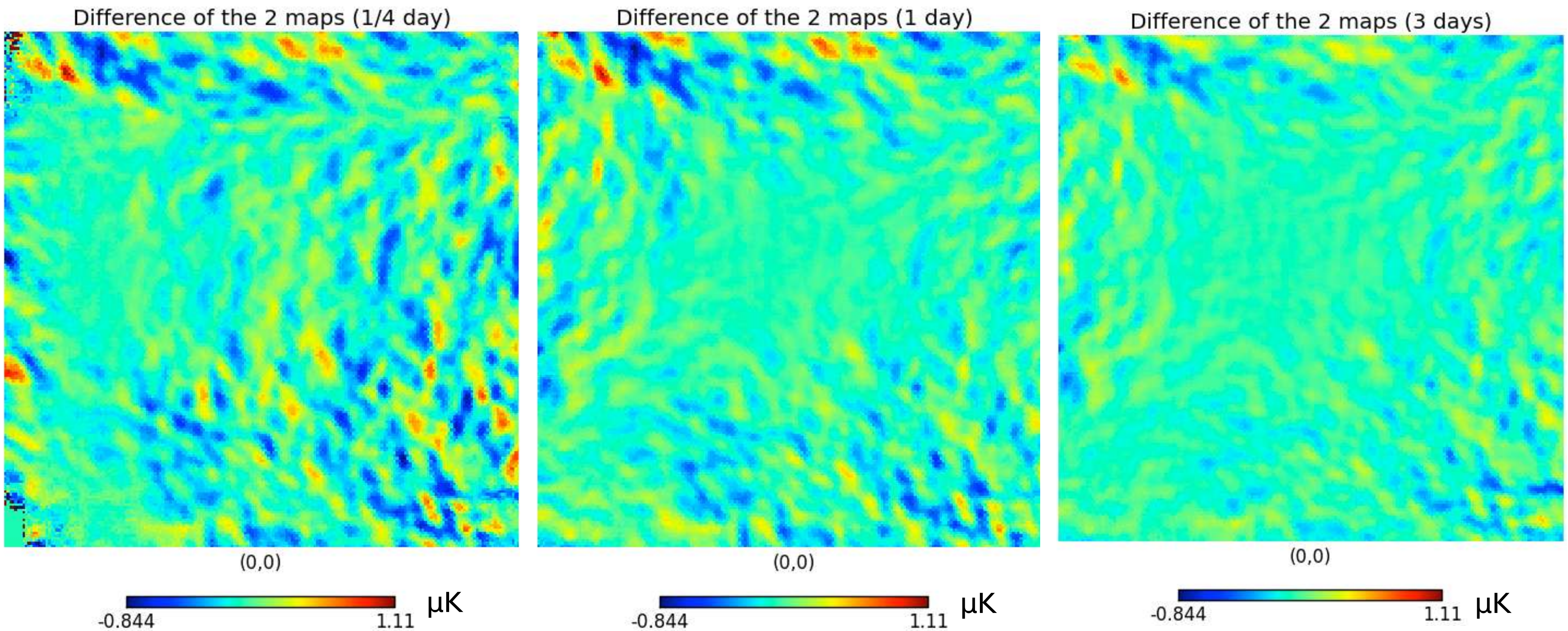
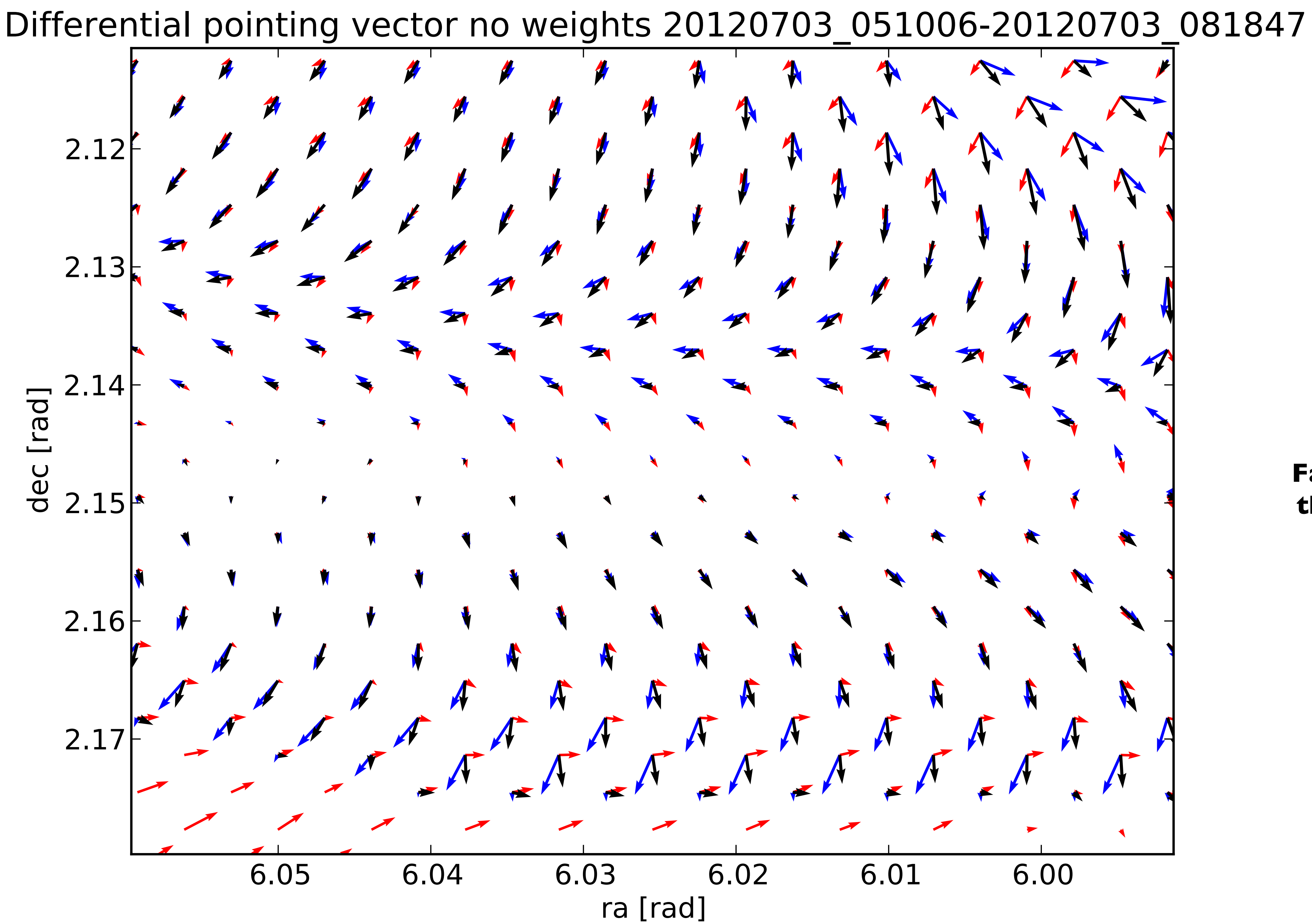


Systematic errors estimation & cross-linking

- Cross linking and sky rotation from mid latitude site reduce efficiently systematics effects



Fabbian, PhD thesis (2013)

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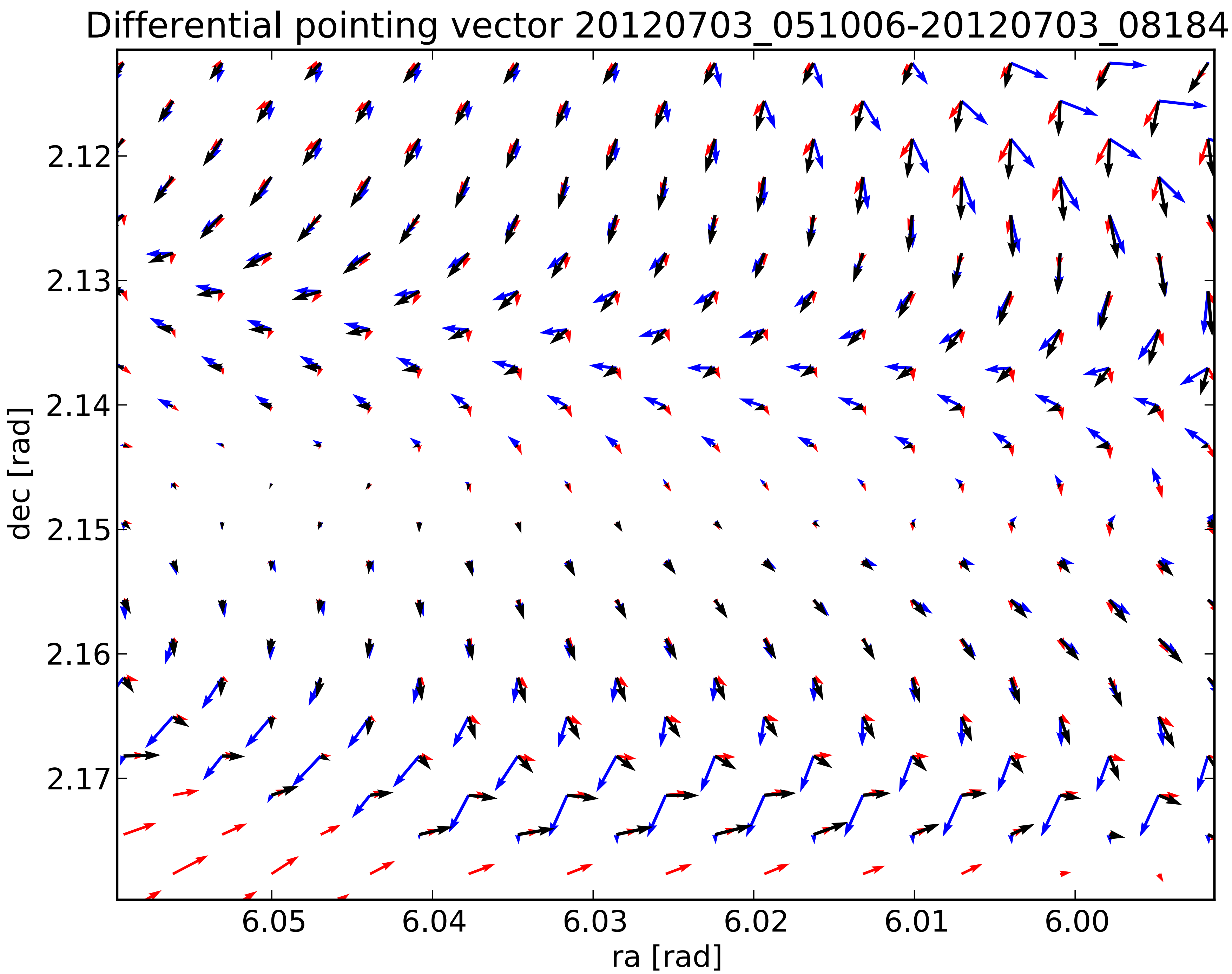
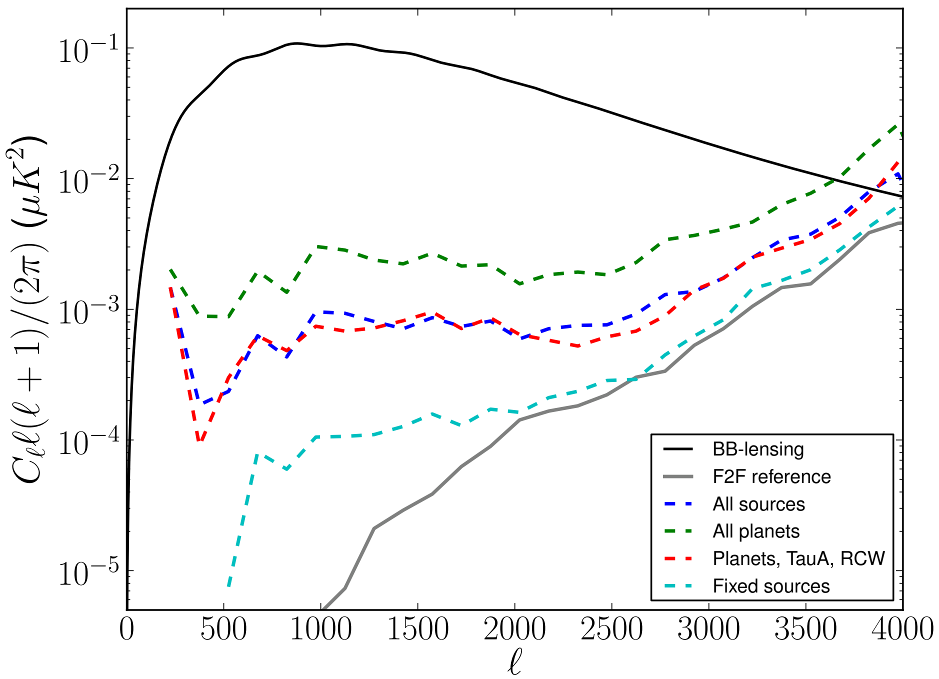


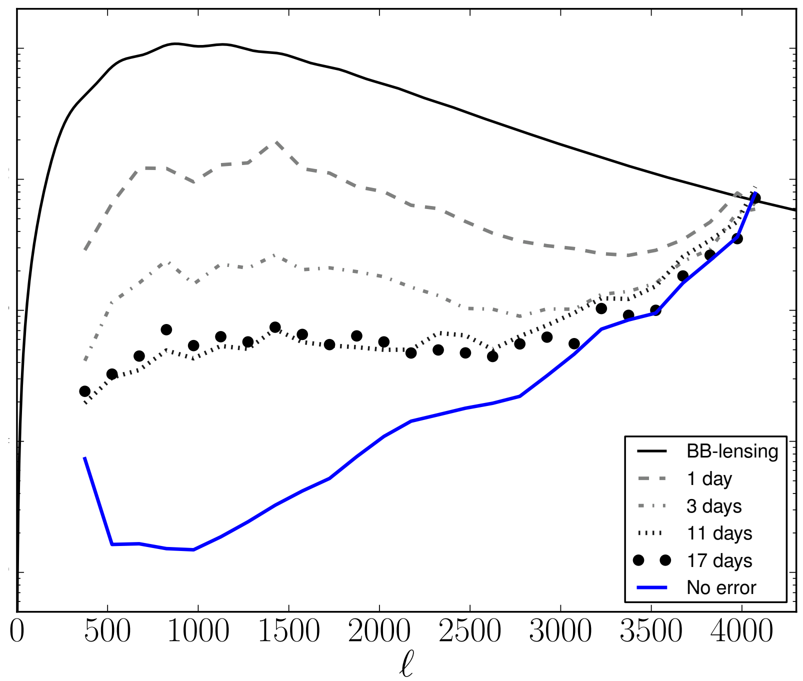
Fabbian, PhD thesis (2013)

Systematic error examples

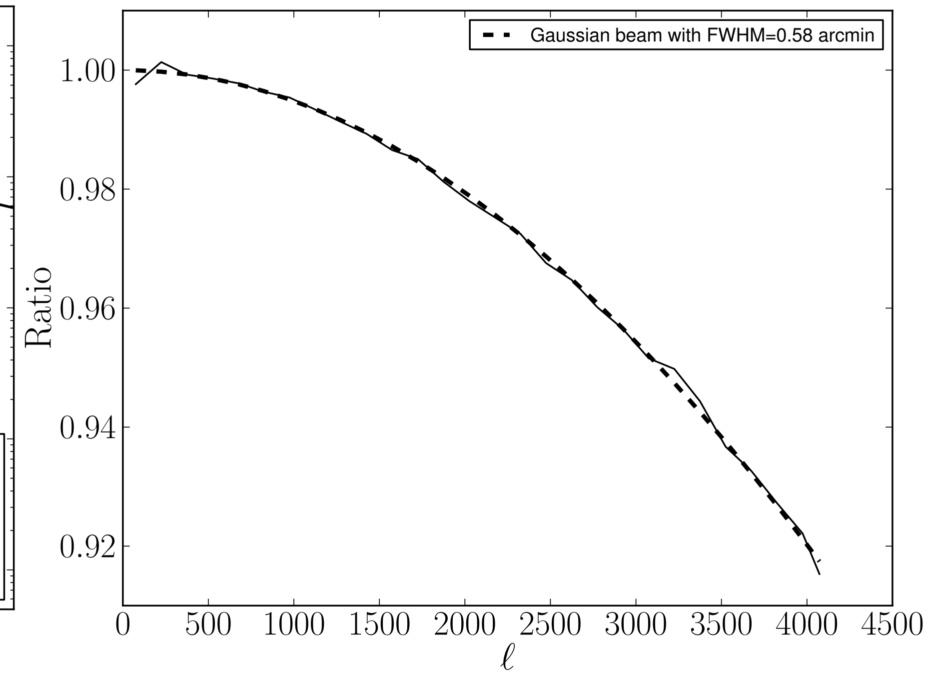
Pointing model



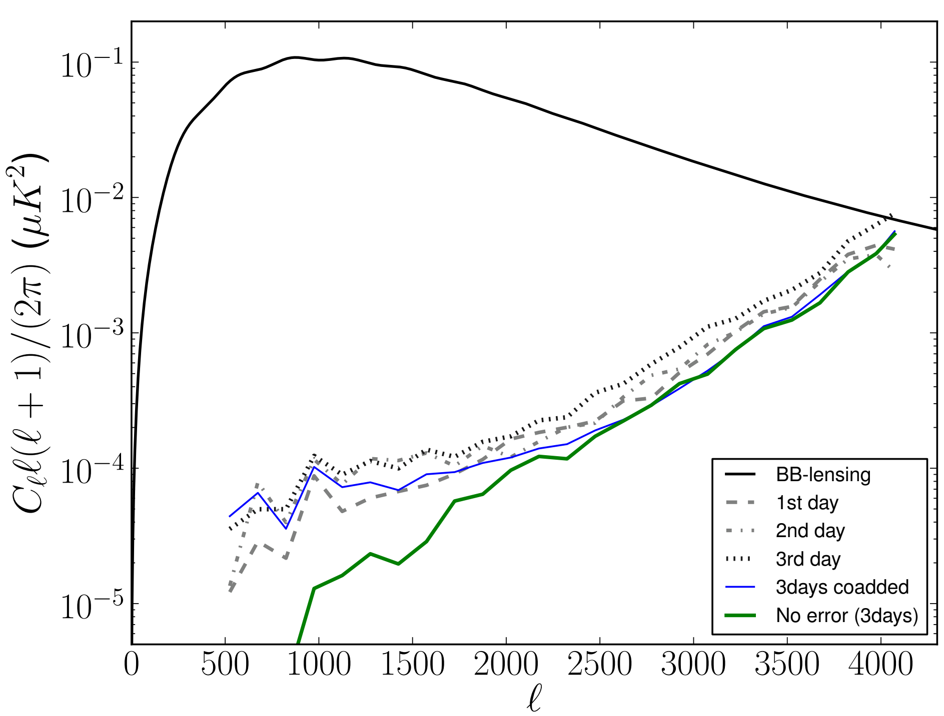
Differential pointing



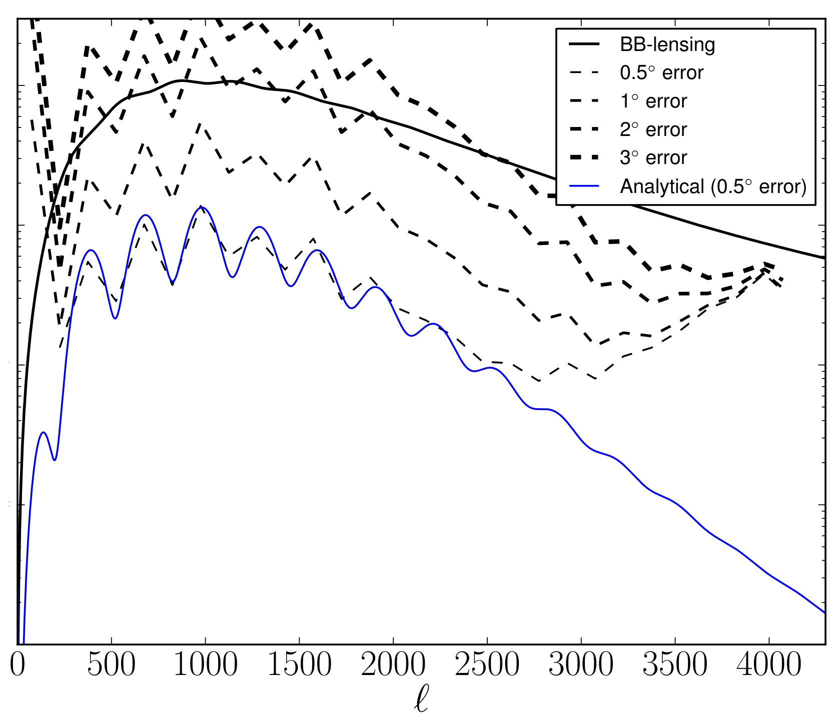
Pointing errors



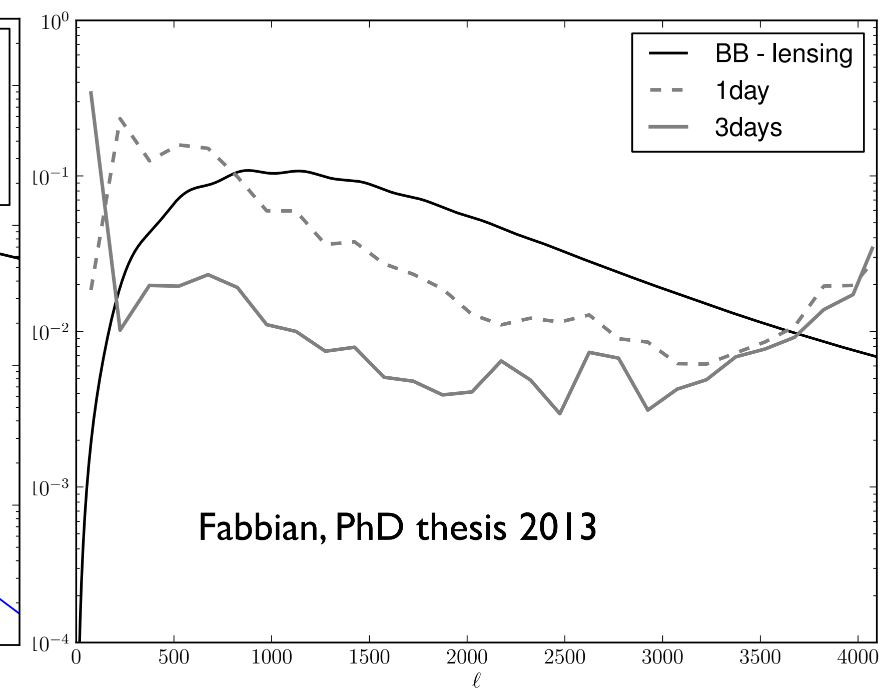
Detector polarization errors



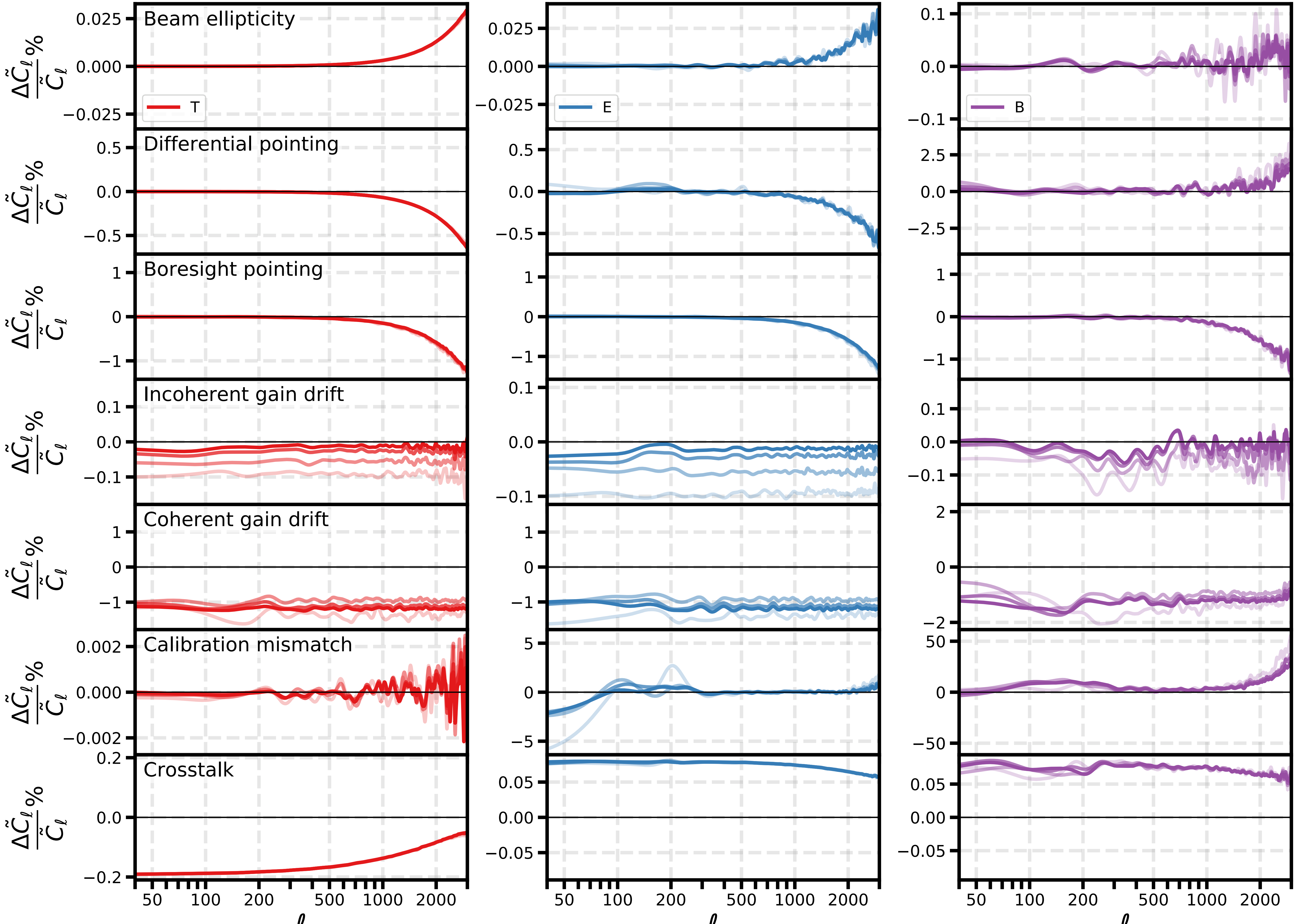
Systematic polarization angle error



Gain model error



Fabbian, PhD thesis 2013



Mirmelstein, GF+ (2021)