Impact of instrumental systematic effects on component separation and large scale B-modes measurements

Clara Vergès

CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

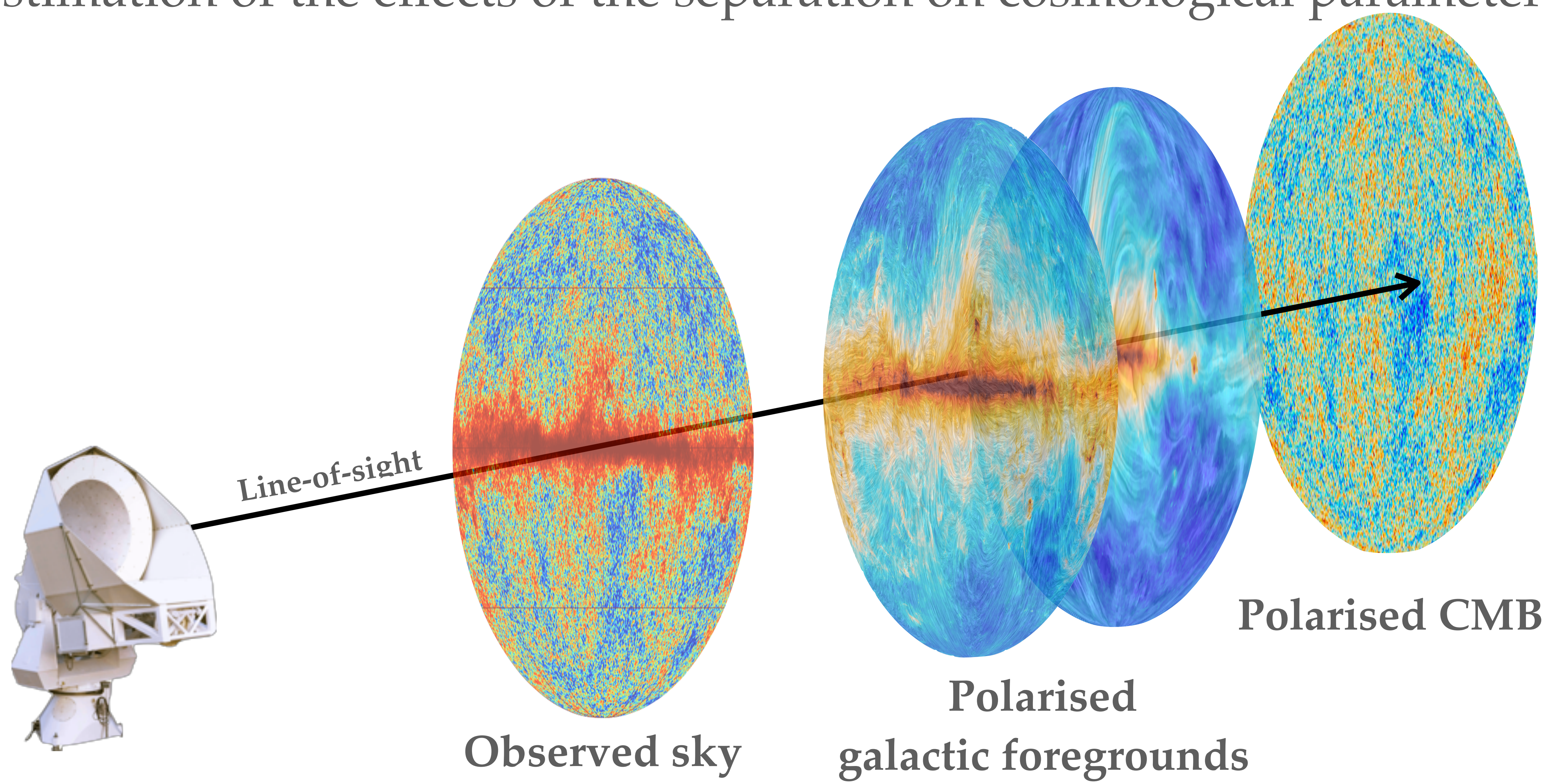
CMB systematics and calibration focus workshop
Kavli IPMU, 30 Nov. - 2 Dec. 2020

Component separation framework

Component separation

Goal = extract CMB signal from multi-component maps

- Measurements of multi-component sky in several frequency bands
- **Separation of sky components** (several methods)
- Estimation of the effects of the separation on cosmological parameters



Parametric component separation

Data model

Multi frequency data set Q and U maps for each observed frequency	=	Standard mixing matrix	Component maps Q and U map at a fiducial frequency for each sky component

Parametrised by **spectral parameters**

Foregrounds emission laws

- Power-law (synchrotron) and modified black body (dust)
- Three spectral parameters (simplest model): one spectral index for each + dust temperature (more complex models can be used)

Interplay with instrumental systematic effects?

New generation experiments

Better sensitivity

- Increased detector count
- Combination of telescopes and data sets

⇒ **Mismatch and variability** in detector properties

Readout

- Increased multiplexing factor
- Multichroic pixels

⇒ possibly **increased crosstalk + inter-band** leakage

⇒ interplay with HWP

Broadband optical components

- Sinuous antennas
- Multilayer HWP

⇒ effective **frequency-dependent polarisation angle**

⇒ interplay with bandpasses + **foreground spectral laws**

Control of systematics in component separation

- Data models
- Calibration procedures
- Component separation procedure itself

Generalised mixing matrix

Data model

Multi frequency data set Pure Q and U maps for each observed frequency	=	Standard mixing matrix	Component maps Q and U map at a fiducial frequency for each sky component

Parametrised by **spectral parameters**

Generalisation

Multi frequency data set Integrated maps for each observed frequency	=	Generalised mixing matrix	Component maps Q and U map at a fiducial frequency for each sky component

Parametrised by **spectral and hardware parameters**
Allows for **Stokes parameters mixing**

We minimise the number of assumptions we have to make about unknown parameters
→ output of map-making might loose their simple physical interpretation as Q/U

Forecasting procedure

Estimate constraints on *r* given foreground templates and instrumental configuration

Estimate mixing matrix parameters
Ensemble-averaged spectral likelihood
- without priors
- with priors

Key features of the new procedure

- **Spectral + hardware** parameters are estimated
- Average over **noise + CMB**
- Ability to include **priors**

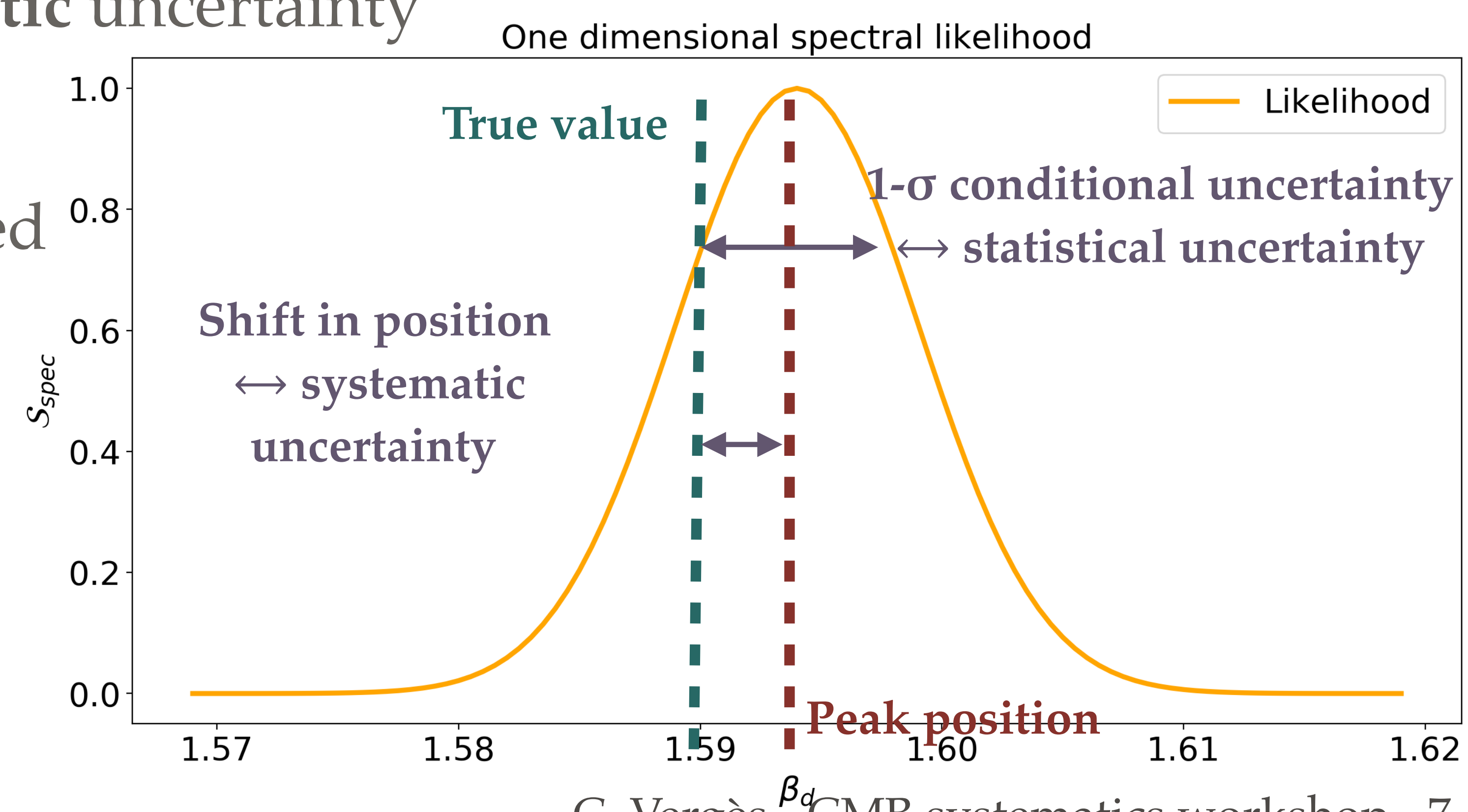
Peak of the ensemble-averaged spectral likelihood

- Ensemble-averaged value of the parameters
- Shift in peak position sources **systematic** uncertainty

Hessian matrix computed at the peak

- Conditional (Hessian) and marginalised (inverse) uncertainties on parameters
- Uncertainty on parameters sources **statistical** uncertainty
- Eigenvalues decomposition

→ degeneracies in the parameter space, priors?



Forecasting procedure

Estimate constraints on *r* given foreground templates and instrumental configuration

Estimate mixing matrix parameters
Ensemble-averaged spectral likelihood
- without priors
- with priors

CMB maps

Foregrounds leakage

Noiseless residuals
- systematic residuals
- statistical residuals

Estimate r and $\sigma(r)$
Ensemble-averaged cosmological likelihood

Key features of the new procedure

- **Spectral + hardware** parameters are estimated
- Average over **noise + CMB**
- Ability to include **priors**

$$C_\ell^{res} = C_\ell^{syst} + C_\ell^{stat}$$

Mismatch between data and model (C_ℓ^{syst})

Statistical uncertainties due to noise and CMB scatter (C_ℓ^{stat})

Worked example: HWP effects

C.Vergès, J. Errard and R. Stompor *Framework for analysis of next generation, polarised CMB data sets in the presence of galactic foregrounds and systematic effects*

Time domain data model

Monochromatic, single layer HWP

- HWP has only one birefringent layer, optimised for the central frequency ν_c
- Continuously rotating polarisation modulator, with angle φ_t
- Straightforward separation of Q and U in map-making using HWP modulation

$$d(\nu_c) = I(\nu_c) + Q(\nu_c) \times \cos(4\varphi_t + 2\psi_t) + U(\nu_c) \times \sin(4\varphi_t + 2\psi_t)$$

Bandpass integration

- Additional coefficients in the data model but no Q and U mixing
- Pure Q/U bandpass averaged-maps for each frequency band can be produced in map-making (and used for component separation)

Multifrequency model

Broadband optical components

- **Q/U mixing** due to HWP + sinuous antenna

→ frequency-dependent polarisation angle

- Interplay with foreground spectral laws

$$\begin{aligned} d(\nu_c) = I(\nu_c) \\ &+ Q(\nu_c) \times \cos[4\varphi_t + 2\psi_t + \phi_{\text{inst.}}(\nu_c)] \\ &+ U(\nu_c) \times \sin[4\varphi_t + 2\psi_t + \phi_{\text{inst.}}(\nu_c)] \end{aligned}$$

Calibration = determine instrumental parameters prior to component separation

e.g. Abitbol et al., *The Simons Observatory: Bandpass and polarization-angle calibration requirements for B-mode searches*, 2020

- Requires extensive calibration campaigns and high precision measurements
- Interplay instrument polarisation angle/foreground can not be exactly modelled, in particular when including bandpasses

→ **Calibration is a necessary step, but we can go further!**

Multifrequency model

Generalised data model: effective mixing of Q and U

$$d(\nu) = \mathrm{I}(\nu)$$
$$+\mathrm{Q}(\nu)[\mathbf{C}_Q \times \cos(4\varphi_t + 2\psi_t) + \mathbf{S}_Q \times \sin(4\varphi_t + 2\psi_t)]$$
$$+\mathrm{U}(\nu)[\mathbf{C}_U \times \cos(4\varphi_t + 2\psi_t) + \mathbf{S}_U \times \sin(4\varphi_t + 2\psi_t)]$$

Mixed Stokes components

C_4 S_4

Bandpass integration

- Changes coefficients of the linear combination of Q and U
- Bandpass-averaged maps are available for each frequency band

→ **must be included step-by-step in the data model**

Output of map-making and input of component separation are NOT pure Q and U maps

Instrument configuration

Hardware configuration

The Simons Observatory: Science goals and forecast, 2018

- 6 frequency bands in 3 dichroic focal planes: {30 and 40 GHz}, {90 and 150 GHz}, {225 and 280 GHz}

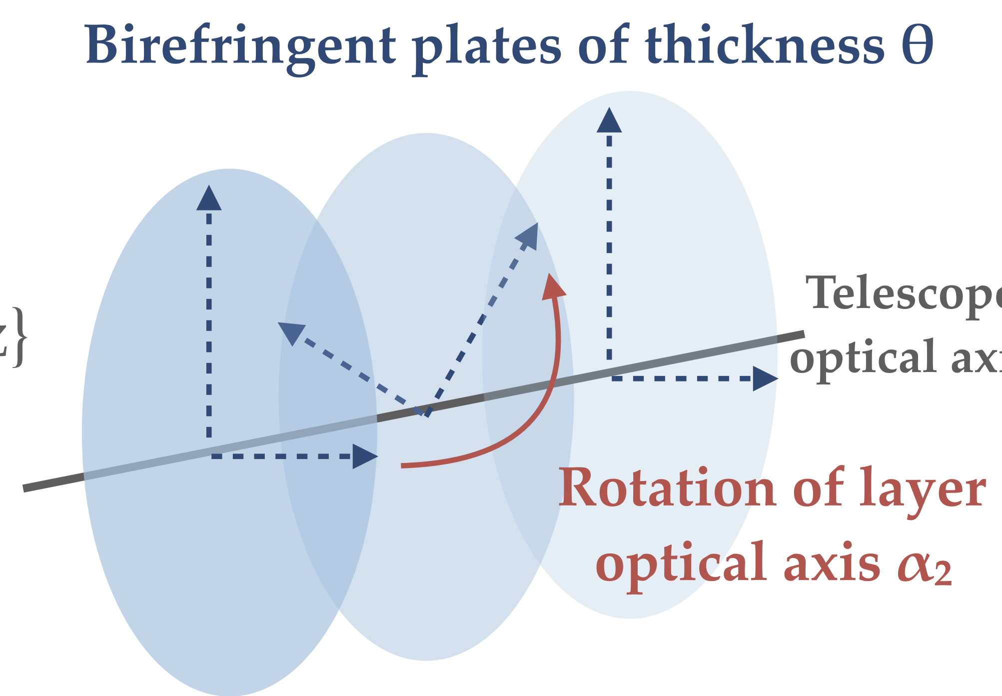
→ **12 parameters**: band-center and bandwidth for each band

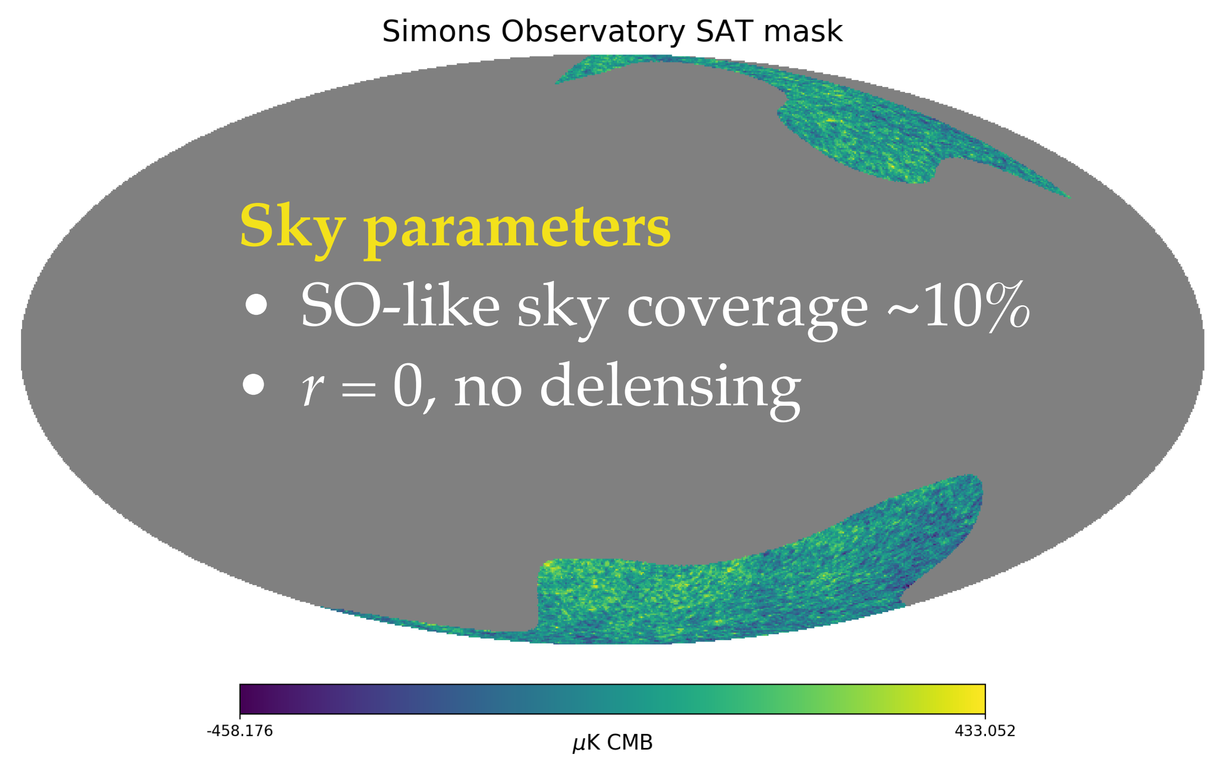
- 3-layer HWP: 1 per telescope

→ **6 parameters**: angle and thickness for each HWP

- Sinuous antennas

→ we fix their parameters for this work





Foreground parameters

- T(dust) is fixed at 19.6K
- No variation of foreground spectral indices

→ **2 parameters**: β(dust) and β(sync.)

Total number of parameters: 20

Uncertainties & Degeneracies

Can we fit for spectral + instrumental parameters? At which cost?

HWP parameters

- Applied to several frequency bands → **well constrained without extra-information**
- No degeneracies
- Do not significantly increase uncertainties on spectral parameters

Bandpass parameters

- Applied to one band only → band-center and bandwidth are (nearly) degenerate for a given band → requires **priors**
- Bandwidth: poorly constrained, but spectral parameters well constrained
- Band-center: well constrained, but spectral parameters poorly constrained

Calibration priors on bandpass parameters → we can fit for all 20 parameters! (foreground + HWP + bandpass)

Statistical residuals

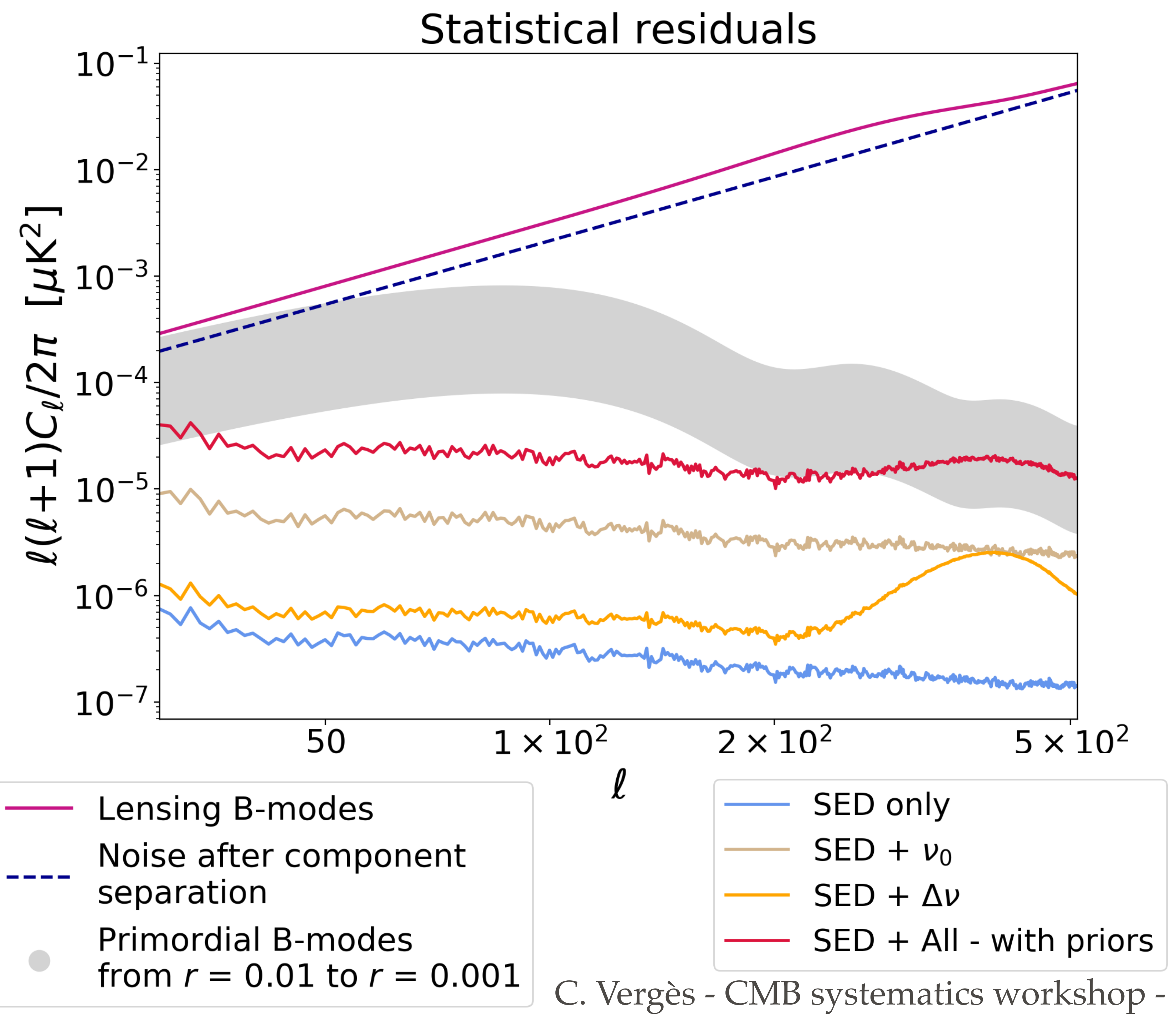
How uncertainties on parameters (spectral/hardware) affect statistical residuals?

Level of residuals

- Set by uncertainty on **spectral parameters**
- Can be controlled with appropriate **calibration priors**

Shape of residuals

- Set by uncertainty on **hardware parameters**
- Leakage of **CMB E-modes to foreground residuals** due to effective parametrisation of CMB by hardware parameters



Cosmological likelihood

How can we deal with (potentially high) statistical residuals in the cosmological likelihood?

Ignore residuals

- Obviously the simplest approach
- Not sufficient when statistical residuals are high → bias on r is on the order of magnitude of $\sigma(r)$

Add instrumental priors to constrain parameters better

- Effectively lowers statistical residuals
- No additional step in data analysis, but requires accurate calibration priors

Deproject statistical residuals

- Modelling of statistical residuals included in the CMB covariance matrix
- Requires model for statistical residuals

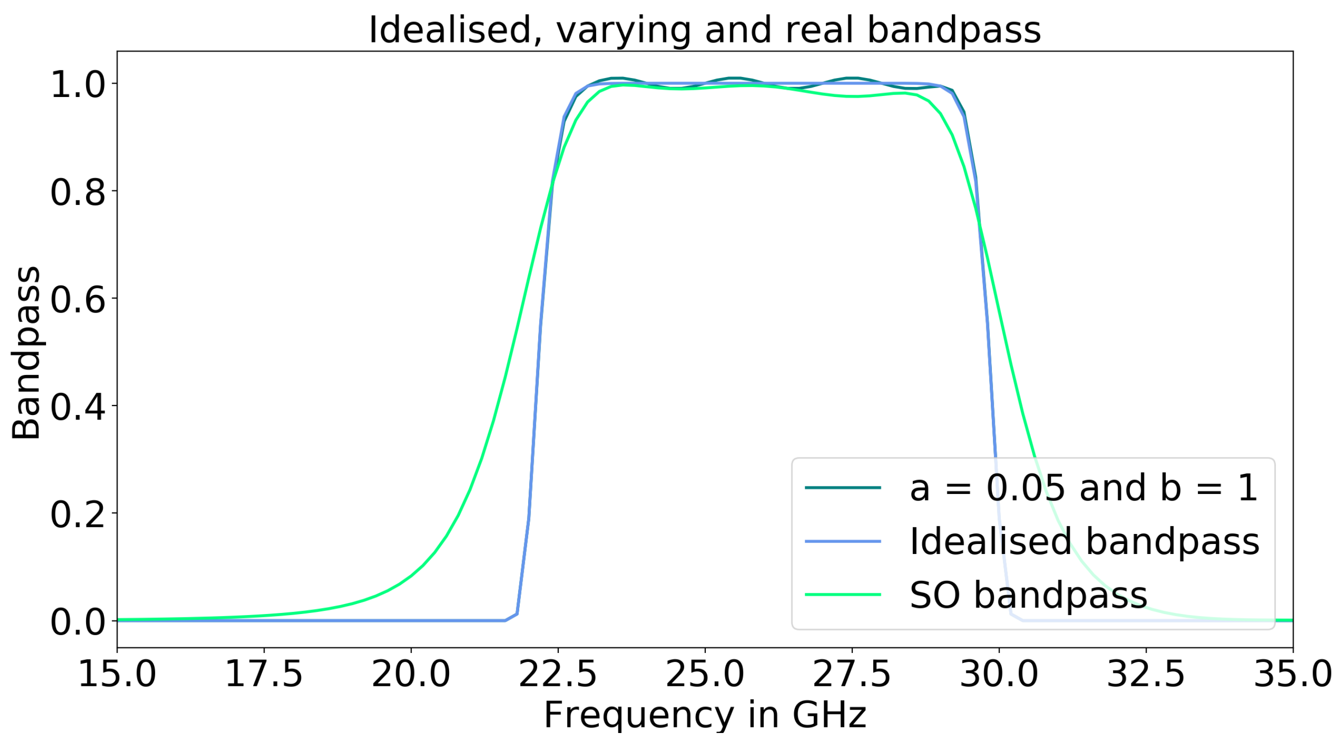
Systematic residuals

Mismatch between instrument model and real instrumental configuration

- Incorrect/simplistic modelling of the instrument
- Average values of detector parameters (bandpass, antennas, gain)

Test case: bandpass variation

- “Controlled” mismatch between realistic bandpass and model
- No significant impact as systematic residuals are dominated by statistical residuals



This type of effects can be investigated further in the proposed framework

Crosstalk

Preliminary study

Configuration

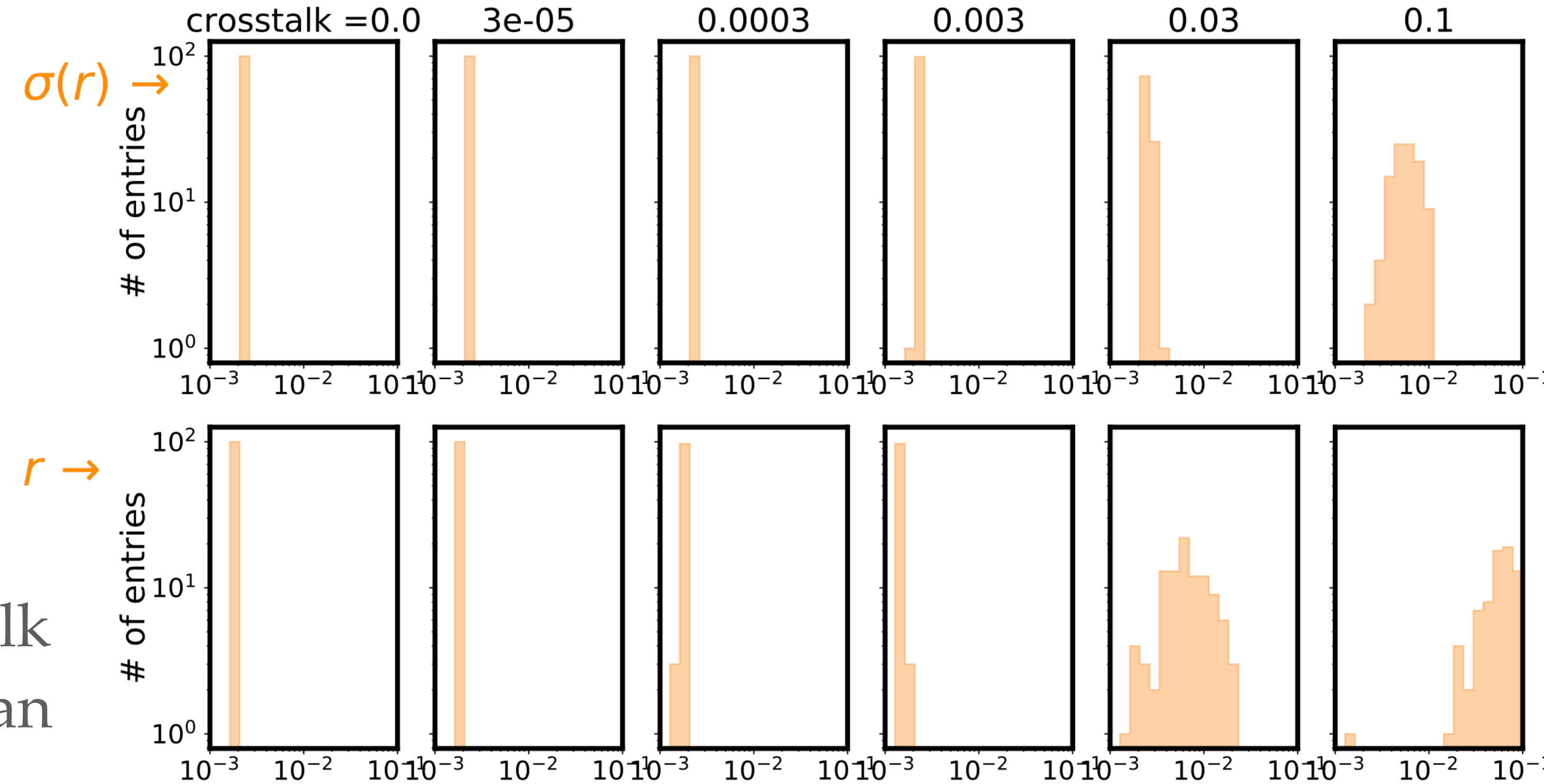
- SO-like configuration
- No bandpass integration nor frequency-dependent effects

Crosstalk model

- Map-level leakage
- Intra-band and inter-band crosstalk
- Random coefficients from Gaussian distribution

Simplified component separation framework

- Crosstalk mixing parameters are not estimated
- Estimation of r and $\sigma(r)$ for various levels of input crosstalk



J. Errard in K. T Crowley et al., *Studies of Systematic Uncertainties for Simons Observatory: Detector Array Effects*, SPIE 2018

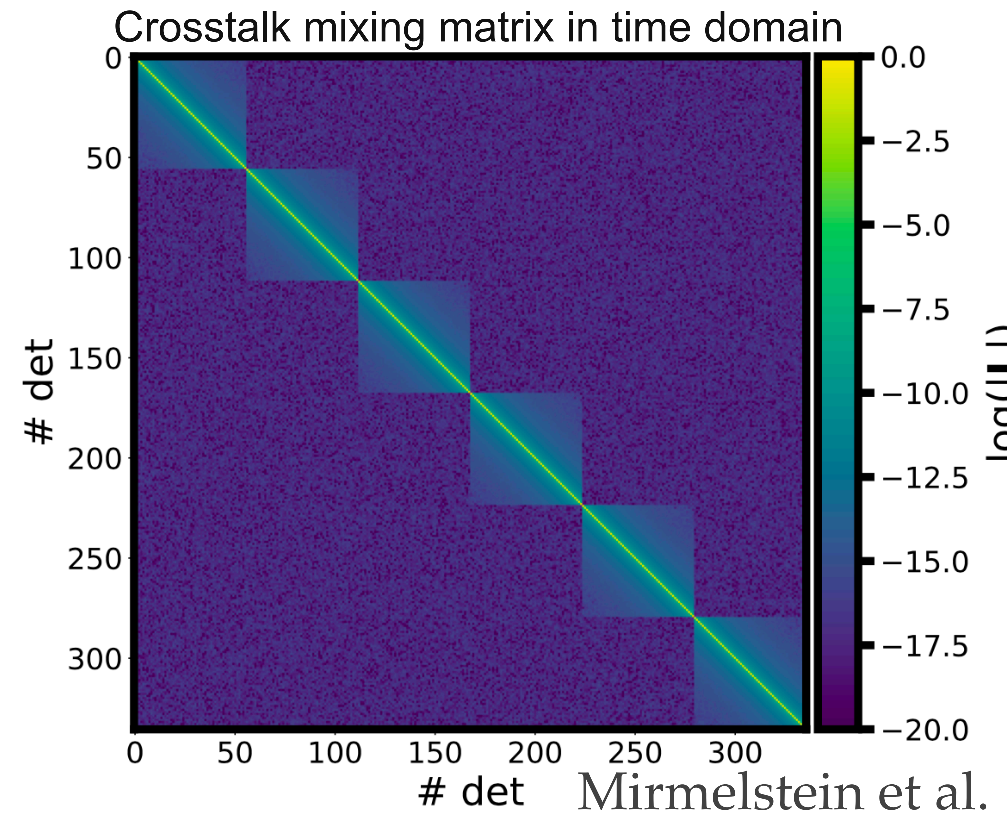
Lessons learned

- Level of crosstalk as we expect for future experiments do not significantly bias r when considered as a single effect
- More accurate model required
- Combine with other effects

Prospects for crosstalk study

Instrument model

- Improve crosstalk model: start from **time-domain** simulations to include parametric crosstalk model based on readout architecture
  → K. T Crowley et al., *Studies of Systematic Uncertainties for Simons Observatory: Detector Array Effects*, SPIE 2018; Mirmelstein et al., *Instrumental systematics biases in CMB lensing reconstruction: a simulation-based assessment*, 2020.
- Include bandpass integration
- Explicitly include HWP effects (Q/U mixing)



Mirmelstein et al.

Component separation framework

- Look for degeneracies with other instrumental parameters of interest
- Estimate crosstalk parameters (if/when possible)

→ impact on statistical residuals if crosstalk parameters can be estimated

- Compute r and $\sigma(r)$
- Investigate systematic residuals due to incorrect/simple crosstalk modelling

Summary

End-to-end framework to include instrumental systematic effects in the component separation process

- **Parametric models** of various elements of the instrument: HWP, bandpass, readout architecture
- **Generalised data model** for the multi-component sky that include in particular Q and U **mixing** and **frequency-dependent effects**

Demonstration in the context of forecasting

- **Analytic insights** → degeneracies/uncertainties, impact on residuals
- Residuals **mitigation strategies** → priors, deprojection of statistical residuals

Future extensions

- **Instrument models** → add more effects, combine them
- **Systematic residuals** → more realistic models for the data, average value of parameters vs. individual measurements, etc.
- **Not limited to forecasting!**