Cosmological parameters constraints from CMB data analysis with the South Pole Telescope

Aline Vitrier, 1st year PhD student

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Many thanks to : L.Balkenhol, E. Camphuis, F. Guidi, A. R. Khalife

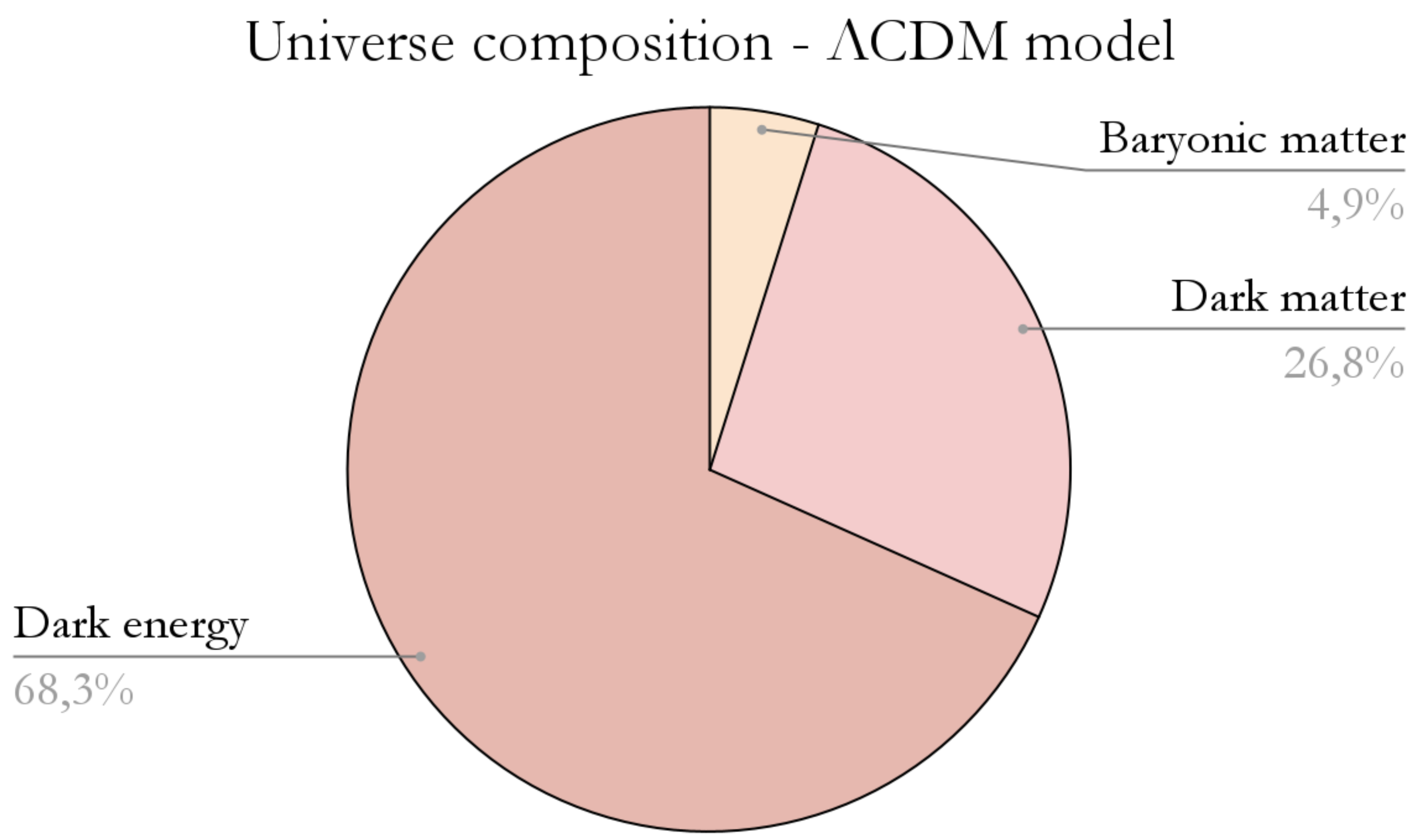
GDR CoPhy - 23/05/2024

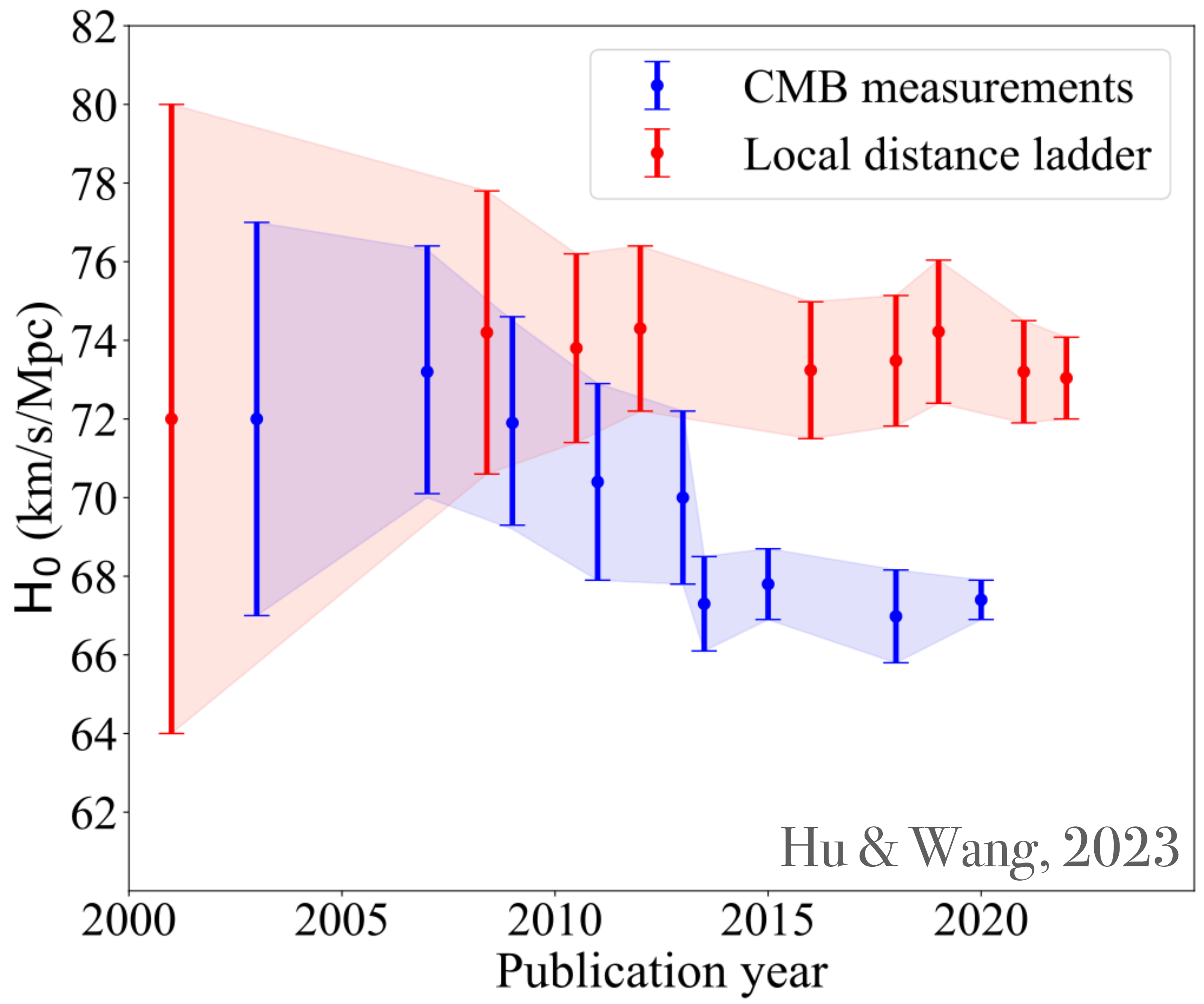
Cosmological context

- Cosmic Microwave Background (CMB) : one of the most powerful probes of the early universe
- Inference of cosmological parameters from the CMB
- Planck final data release confirmed the ΛCDM model to be the best to describe the universe

Why do we need other telescopes and experiments ?

- Add complementary data to Planck's from polarization, from small scales temperature, and from lensing.
- Understand tensions such as the Hubble tension
- Test the ΛCDM model and search for possible physics beyond ΛCDM.

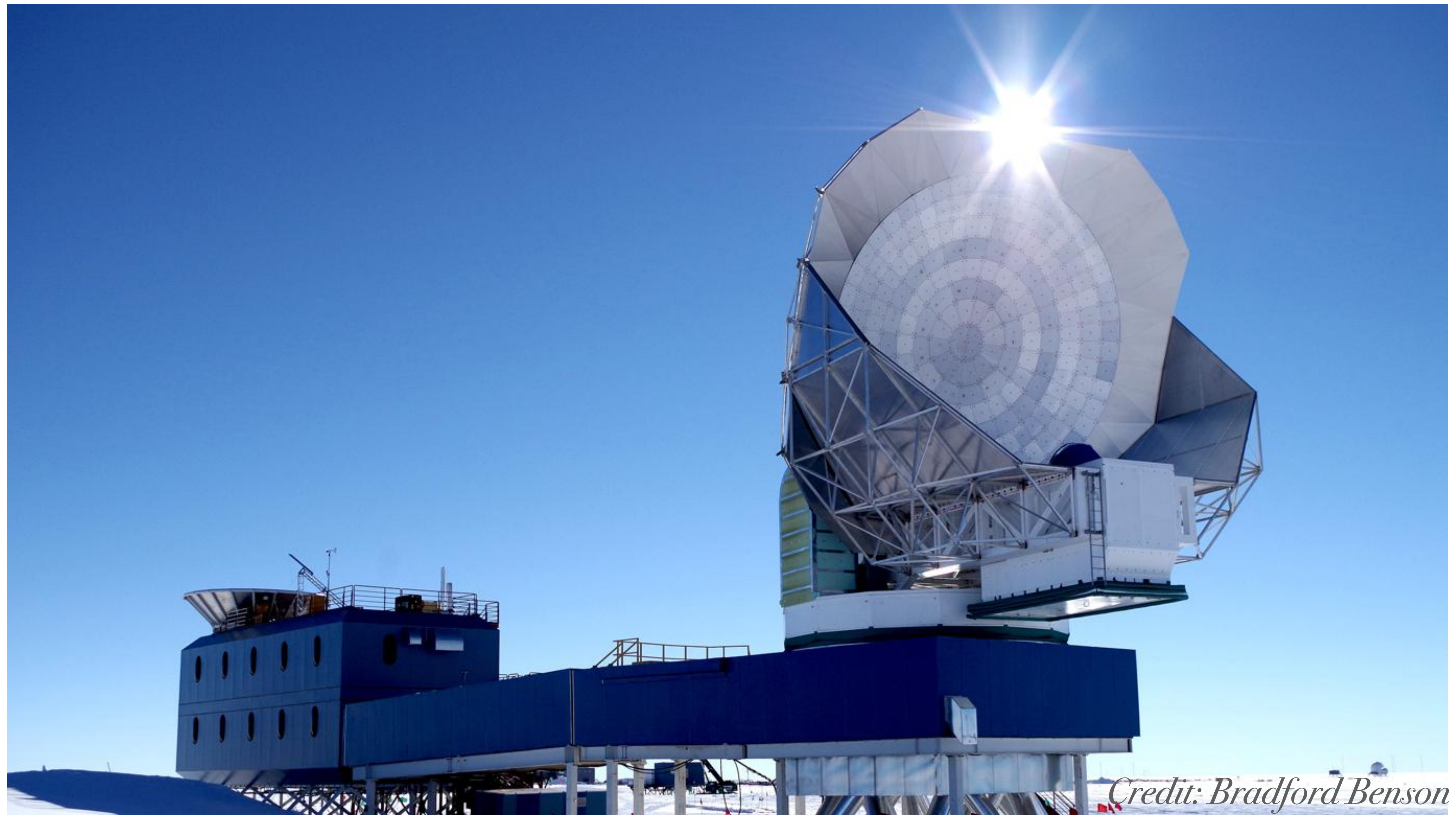


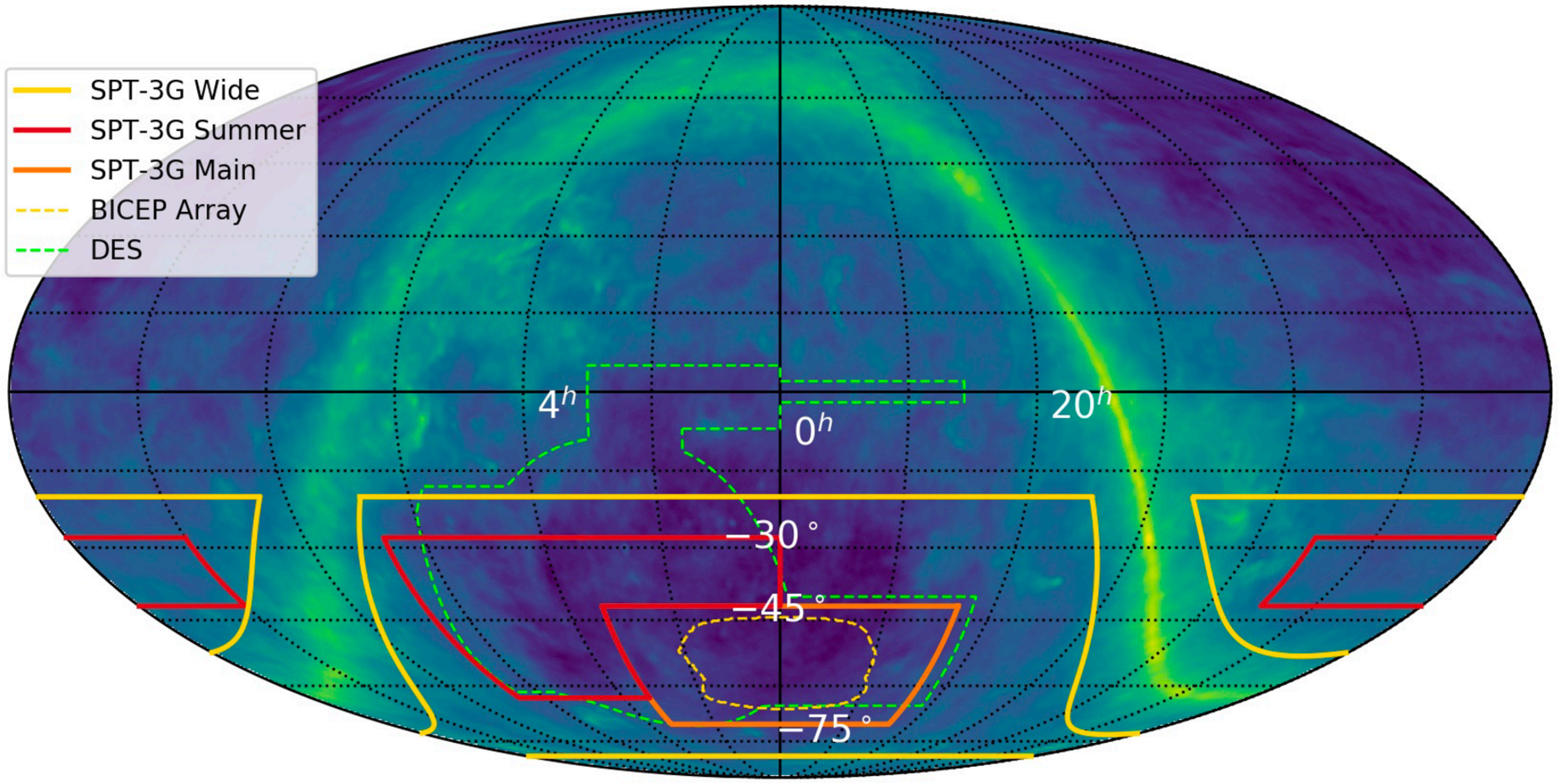


The South Pole Telescope

- 10-meter primary mirror telescope located at the South Pole
- Third generation camera **SPT-3G** since 2018
- 3 frequency bands : 90GHz, 150GHz and 220GHz
- 3 fields of observation with SPT-3G :
  - Winter field (main) : 1500 deg², 6 years of observations during austral winter
  - Summer field : 2600 deg², 4 years of observations during austral summer
  - Wide field : 6000 deg², 1 year of observations in 2024
- All fields combined :

SPT-3G Ext-10k, 25% of the sky





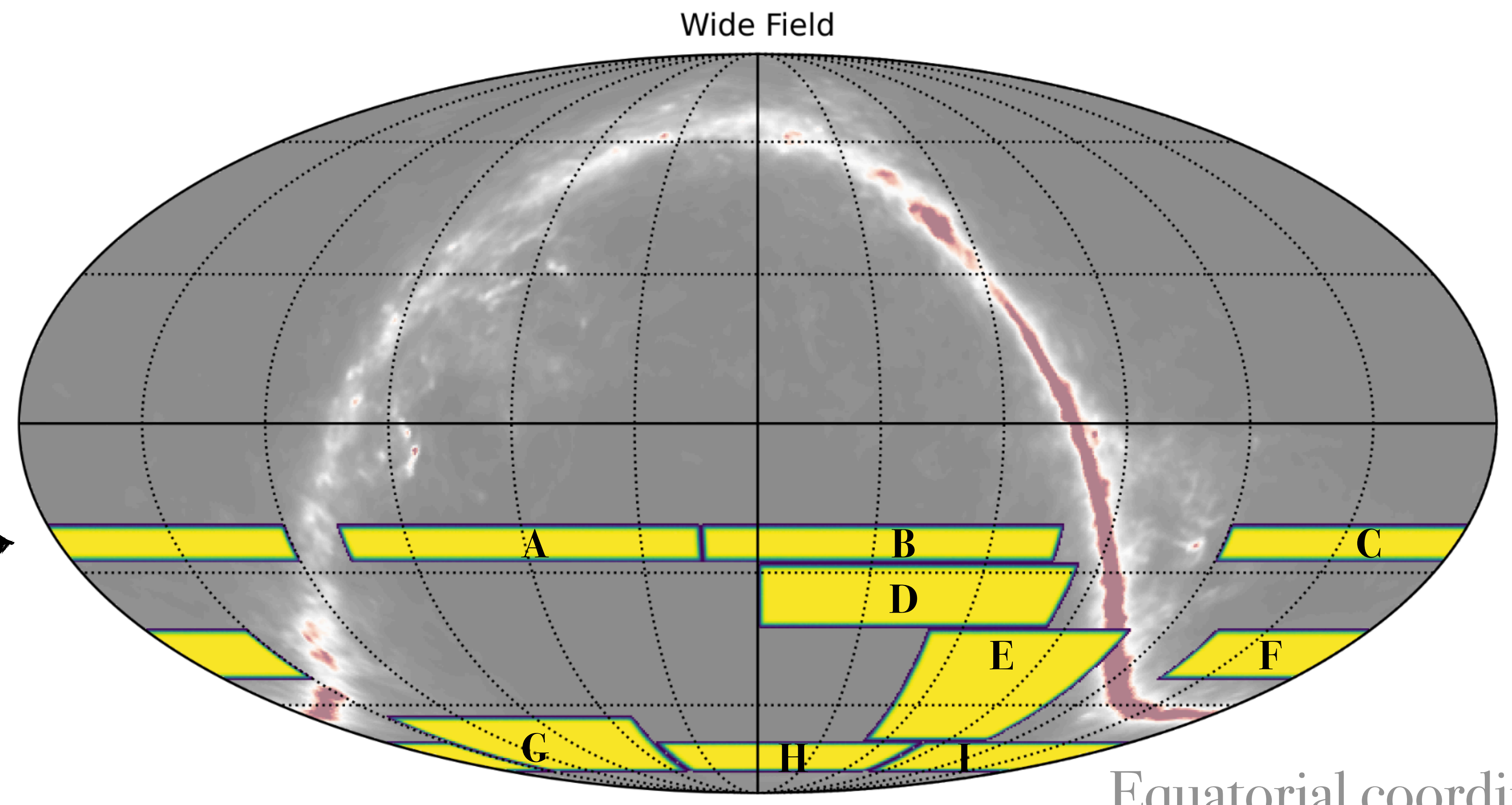
The South Pole Telescope

SPT-3G Wide

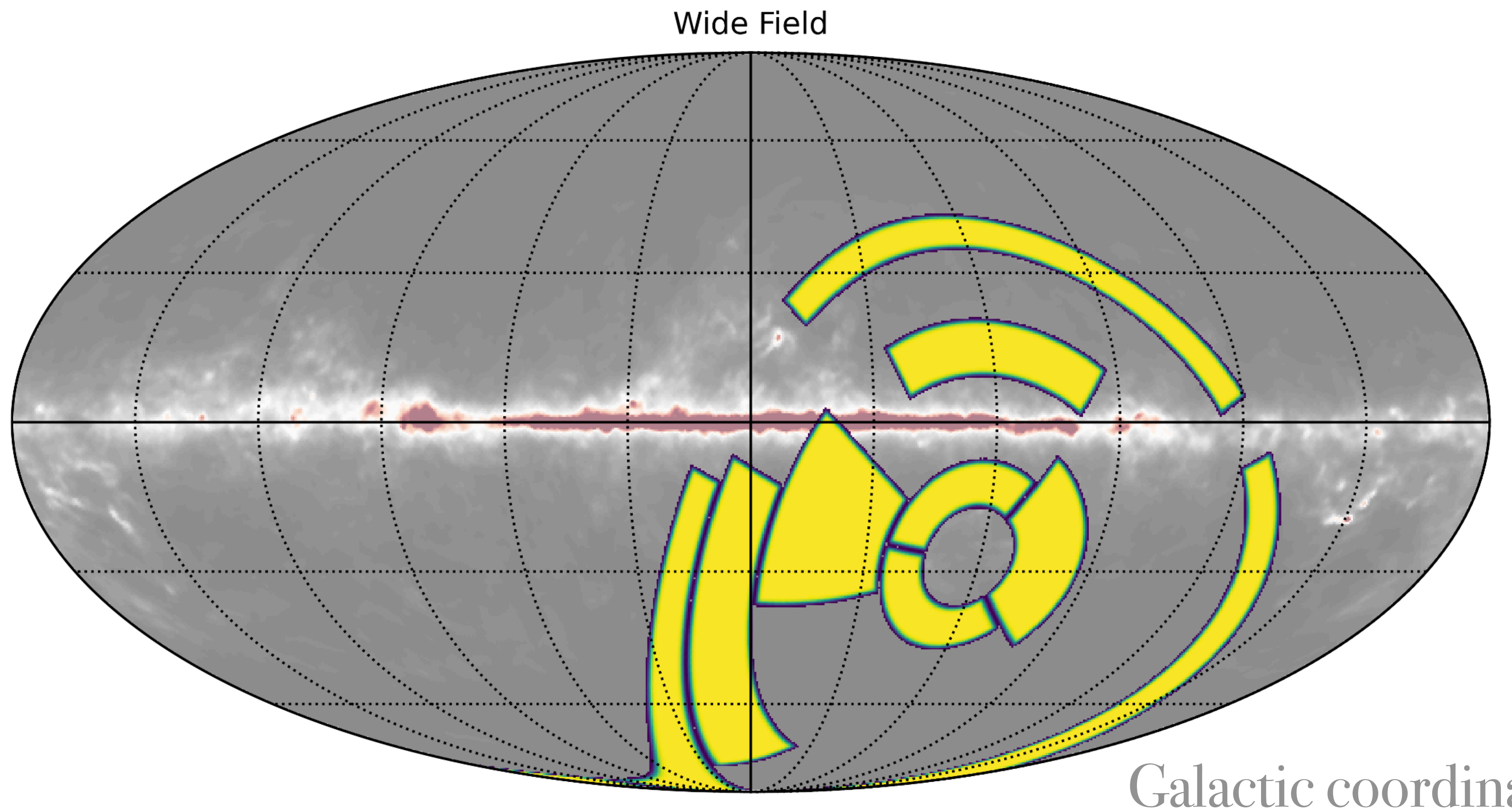
- 14% of the sky
- Divided in 9 subfields (A, B, C, ...)
- Declination from -20° to -80°
- Target noise levels : 13/11.5/42 μK-arcmin at 90/150/220 GHz
  (Planck noise : 78/33/47 μK-arcmin at 100/143/217 GHz)

☑ Production of the binary masks

☑ Apodization of the masks to reduce correlations between modes



Equatorial coordinates

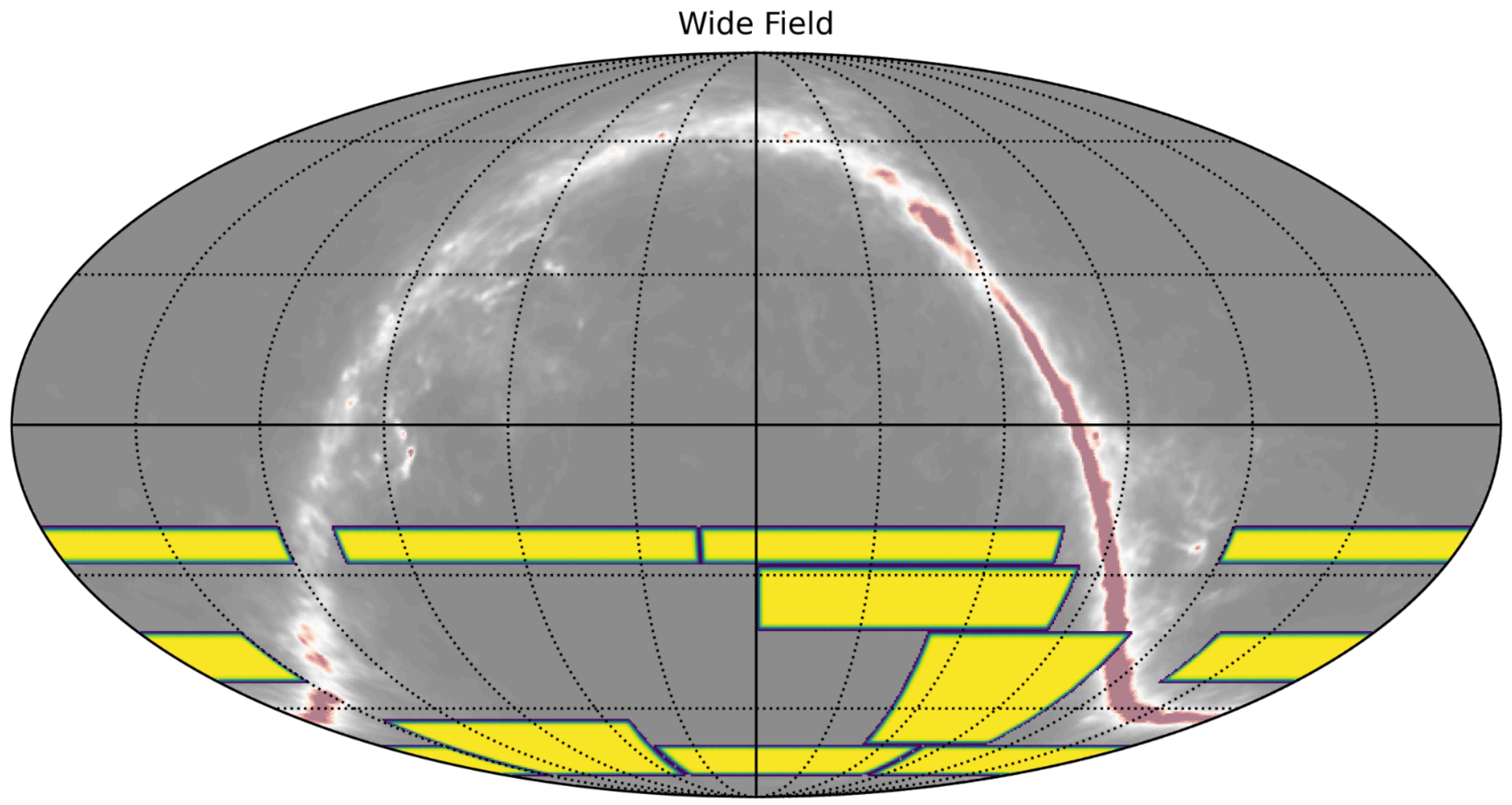


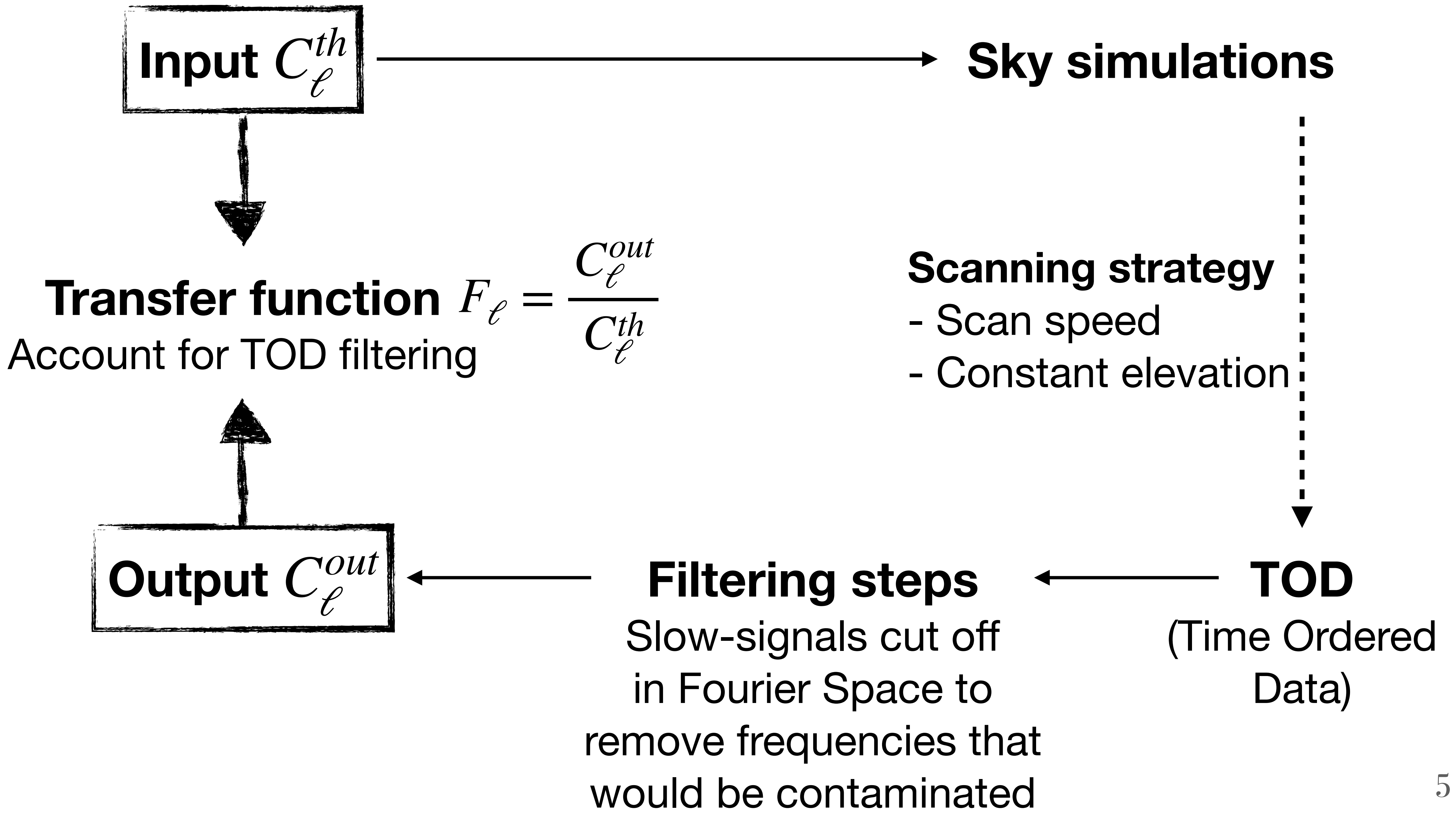
Galactic coordinates

The Wide Field scanning strategy

- The scan goes back and forth from left to right at a constant elevation → induced correlated noise in the scan direction (mostly atmospheric noise)
- Atmosphere varies slowly → high pass filtering to remove low frequencies in Fourier space → **transfer function is a result of filtering**
- We might have different TOD filtering for the different subfields → **different transfer functions**

Conclusion : analysing the fields individually allows to take into account the specificity of each subfields

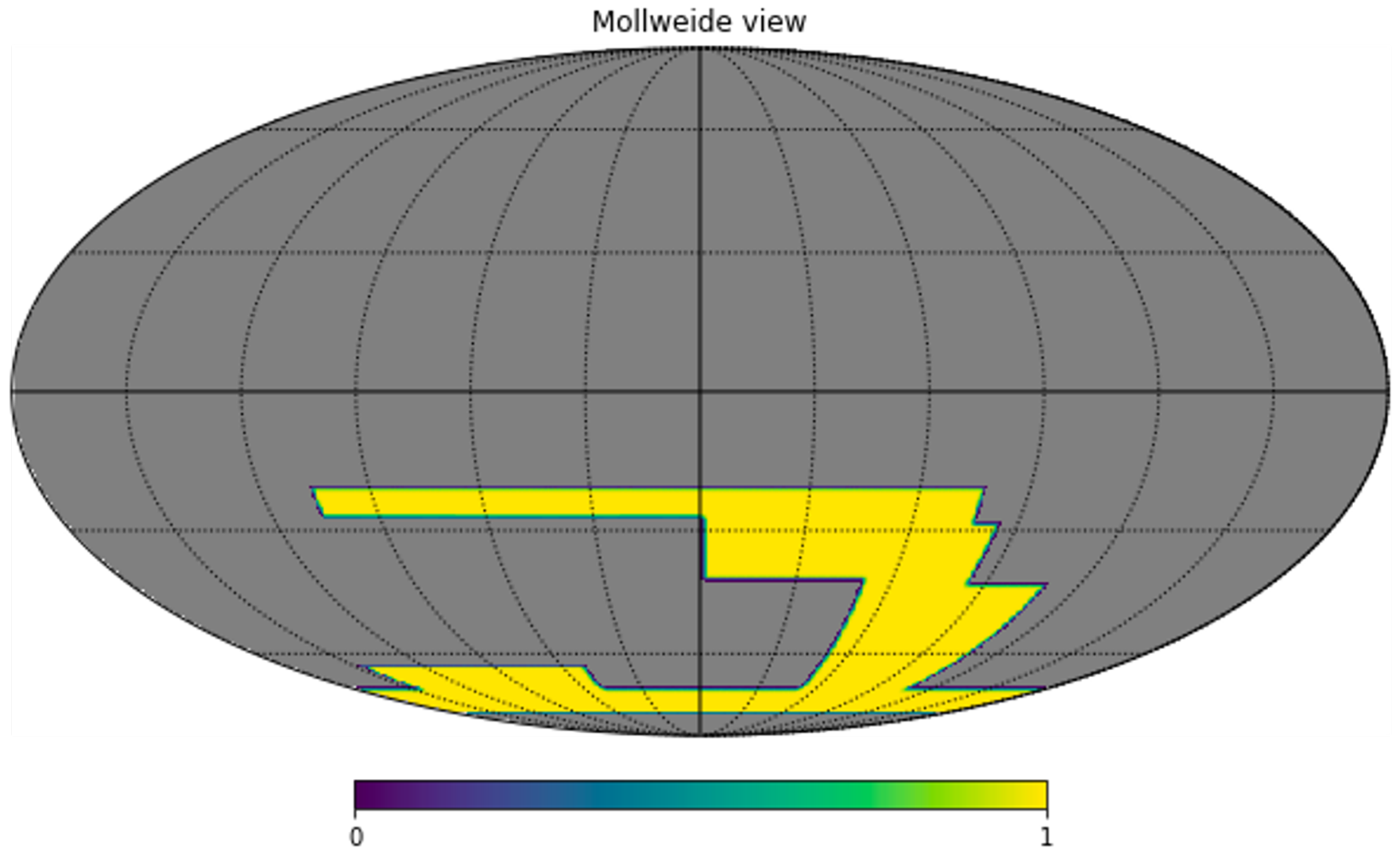




Do we lose constraining power on cosmological parameters by analysing the fields independently of each other ?

We consider 3 different cases for the S field analysis

1. Best case scenario



S_v2

$f_{sky} = 0.0951$

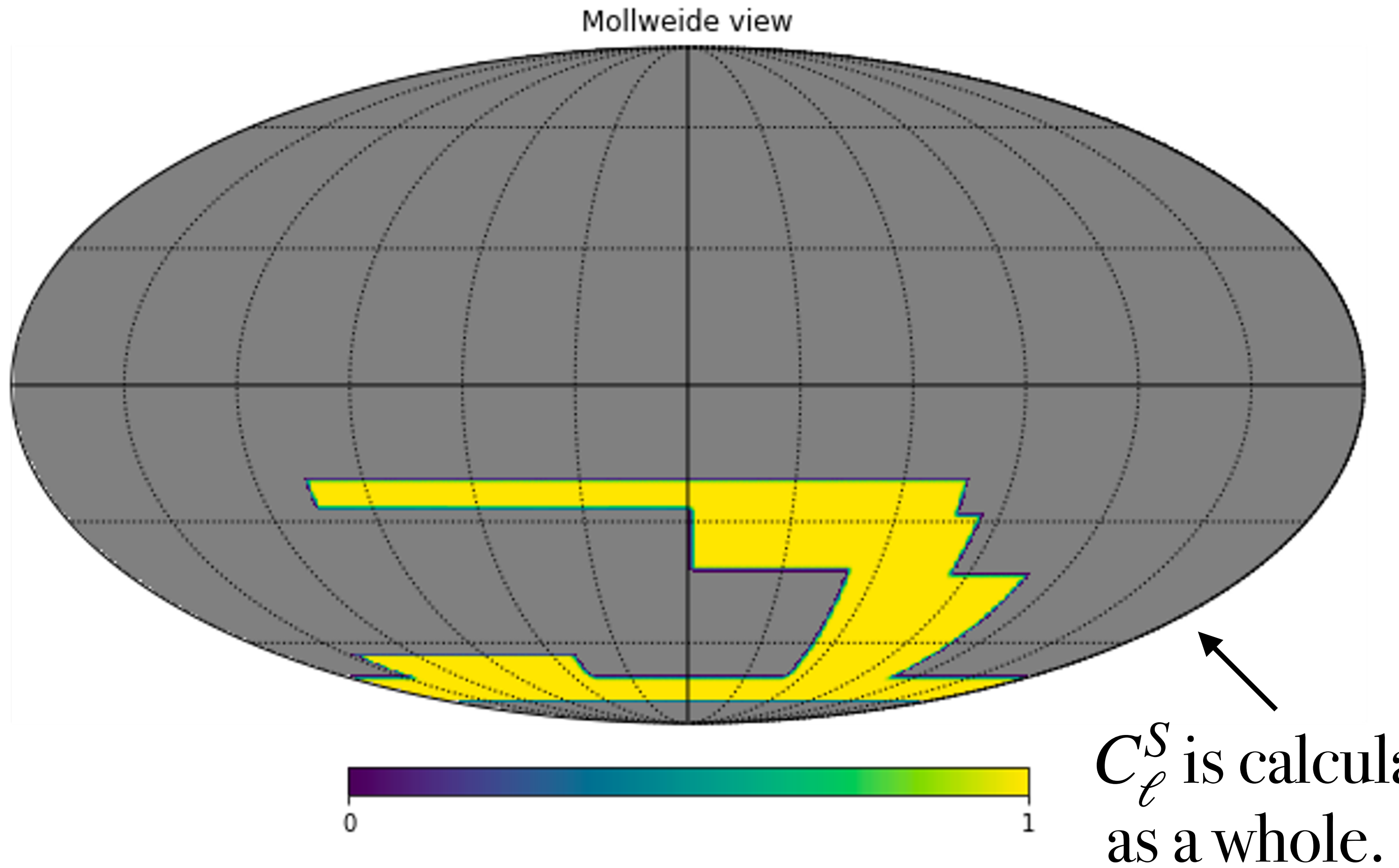
1 mask used in the analysis

Apodization of the binary S mask

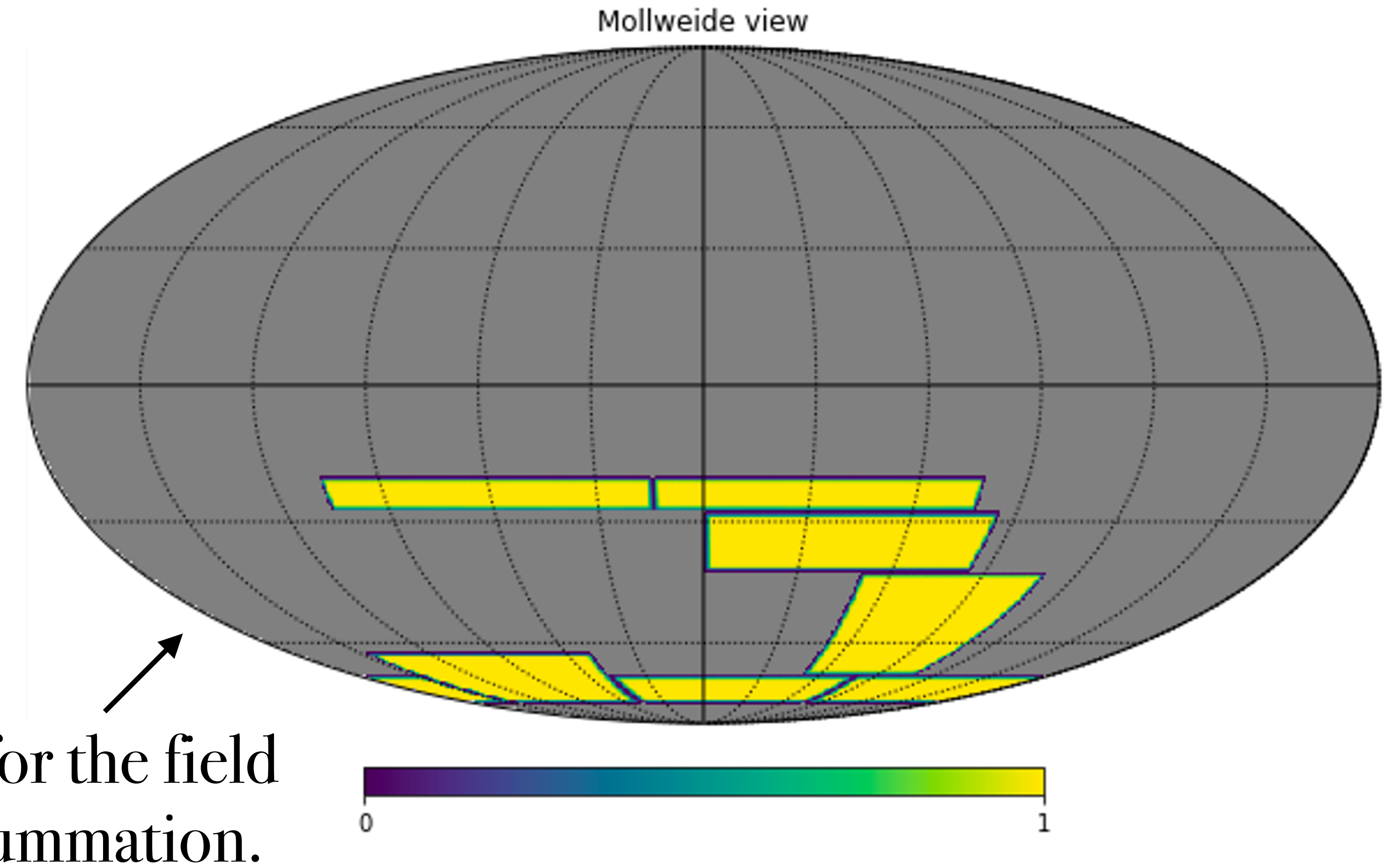
→ **What we would do if we could analyse all the field jointly**

We consider 3 different cases for the S field analysis

1. Best case scenario



2. Intermediate case



C_ℓ^S is calculated for the field as a whole. No summation.

S_v2

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Apodization of the binary S mask

→ What we would do if we could analyse all the field jointly

S

$f_{sky} = 0.0906$

1 mask used in the analysis

Sum of the individual apodized masks

Allows to understand the impact of losing a 5% fsky in the analysis

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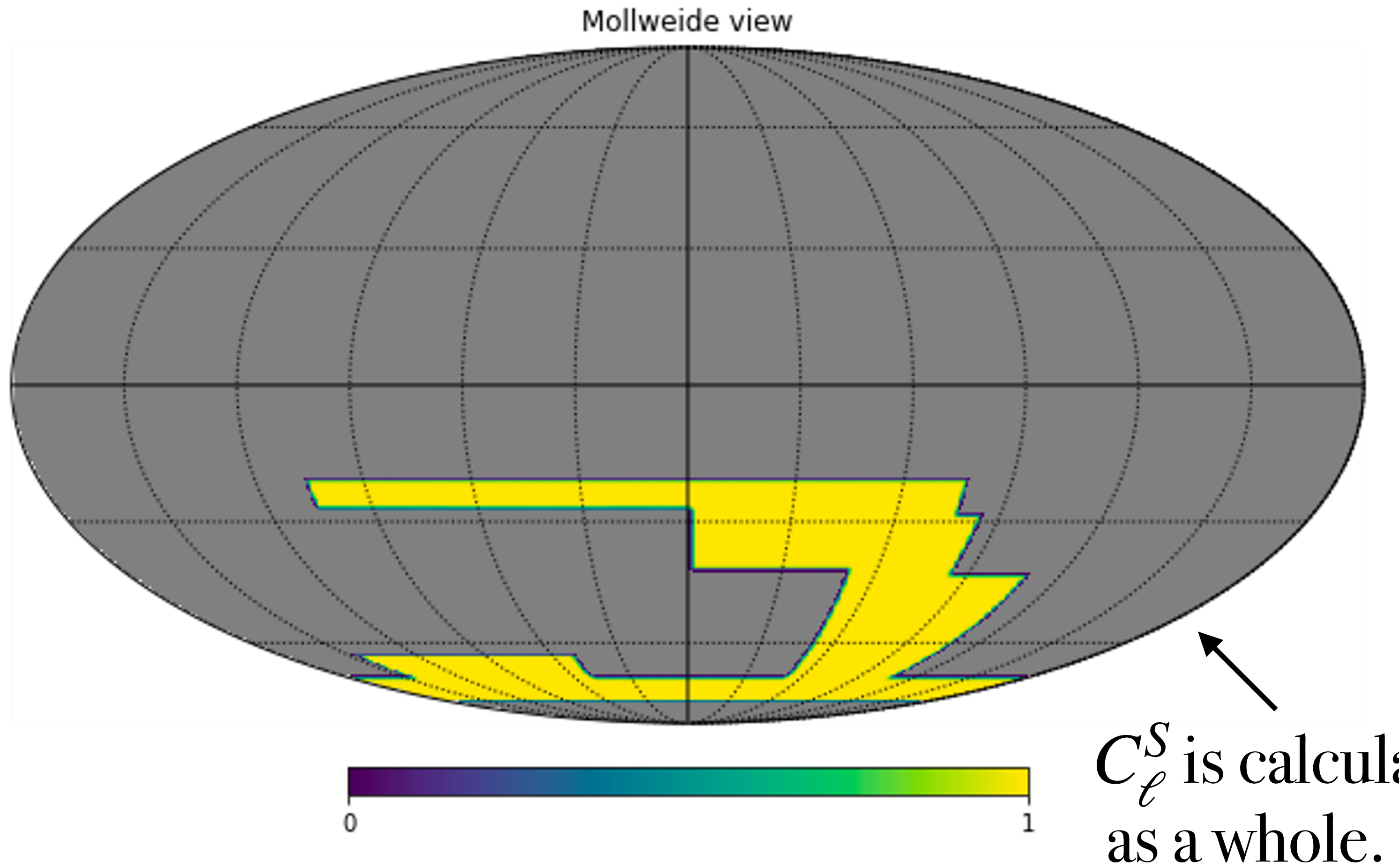

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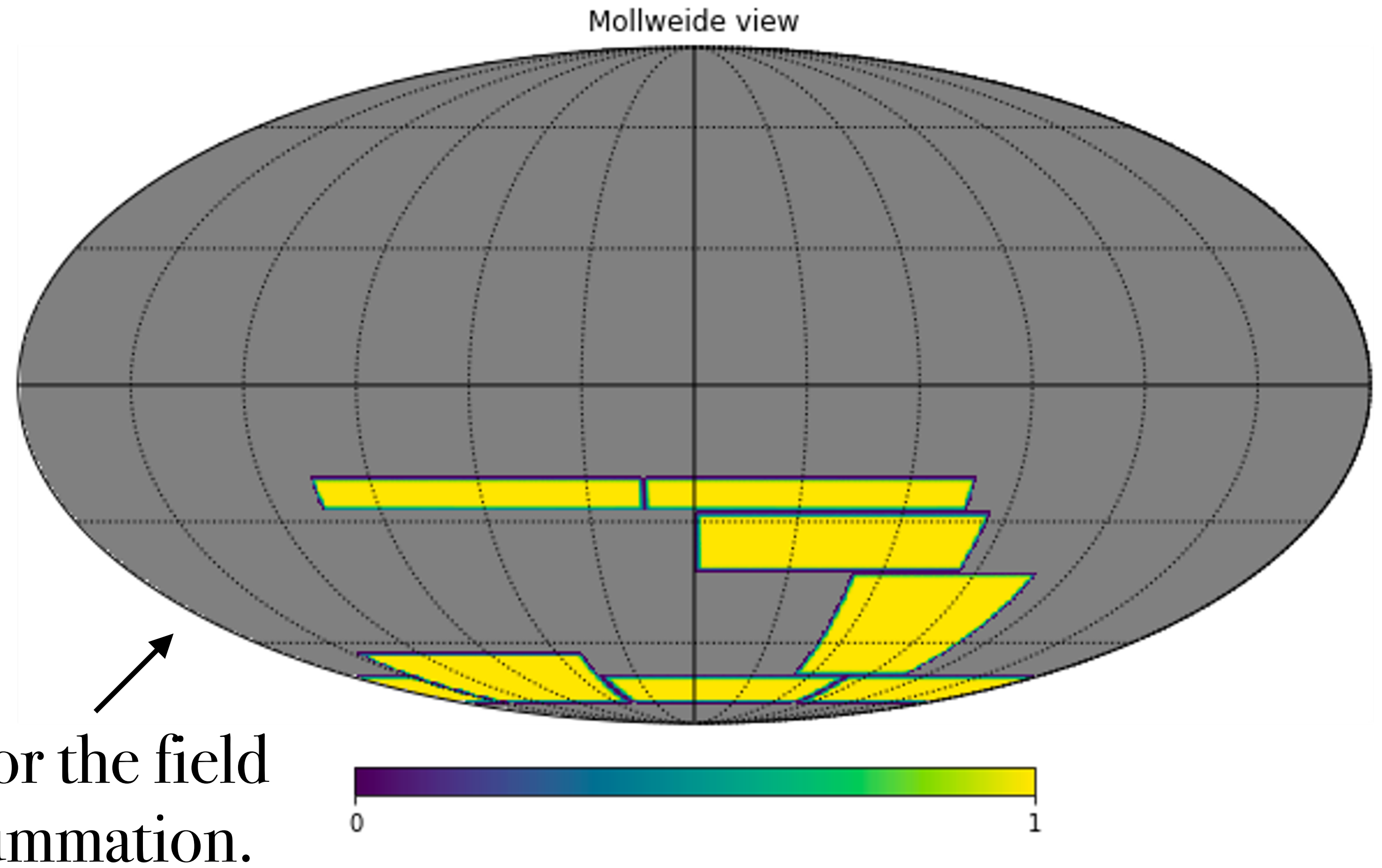

S

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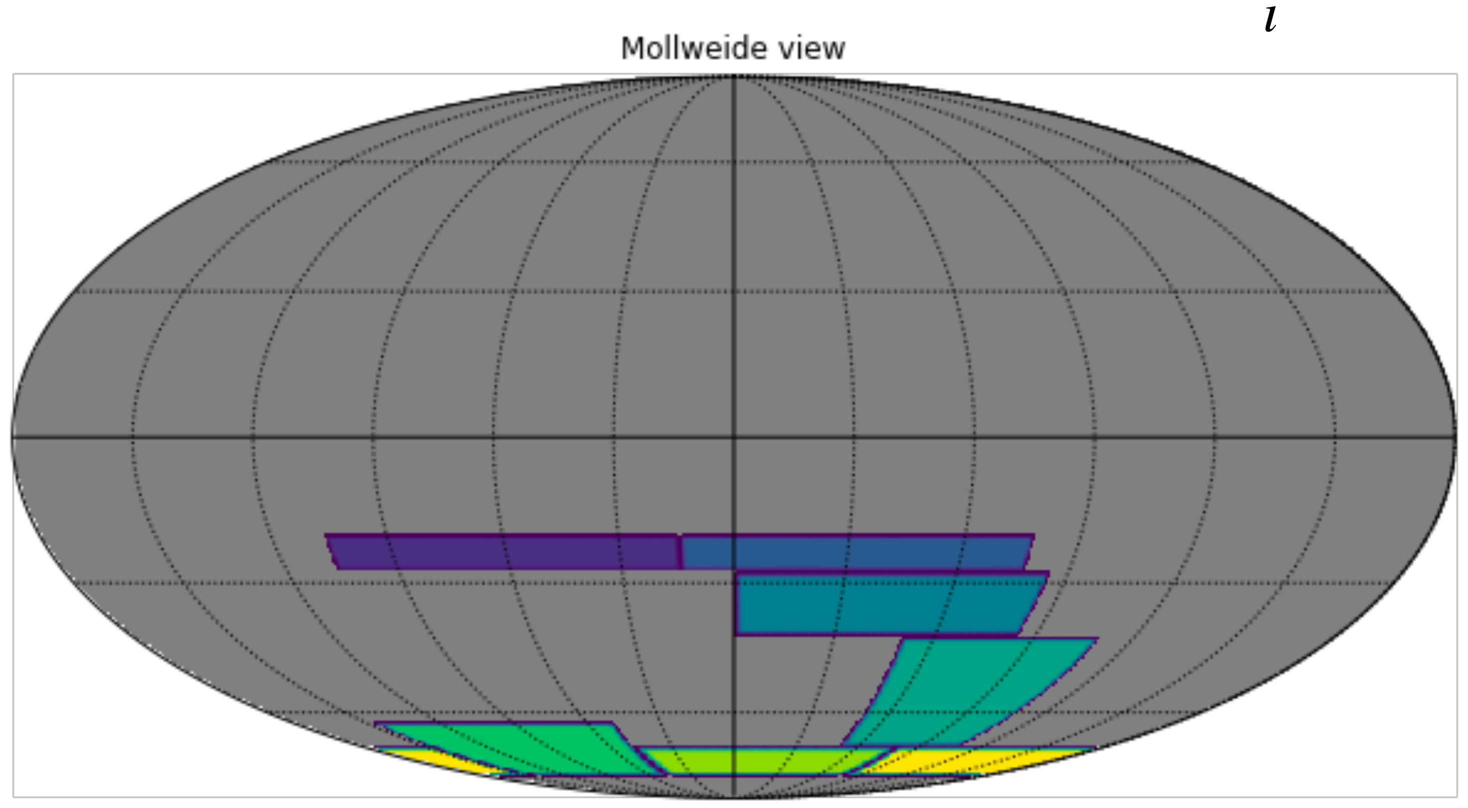
1 mask used in the analysis

Sum of the individual apodized masks

Allows to understand the impact of losing a 5% fsky in the analysis

3. Coaddition $C_\ell^{S,coadd} = \sum_i w_i C_\ell^i$



$$Cov(C_\ell^{S,coadd}, C_\ell^{S,coadd}) = \sum_i w_i^2 Cov(C_\ell^i, C_\ell^i)$$

$i \in \{A, B, D, E, G, H, I\}$

S_coadd

$f_{sky} = 0.0906$

7 masks used in the analysis

Coaddition of the individual power spectra obtained by analysing the subfields independently of each other

Allows to understand the impact of a coadded analysis

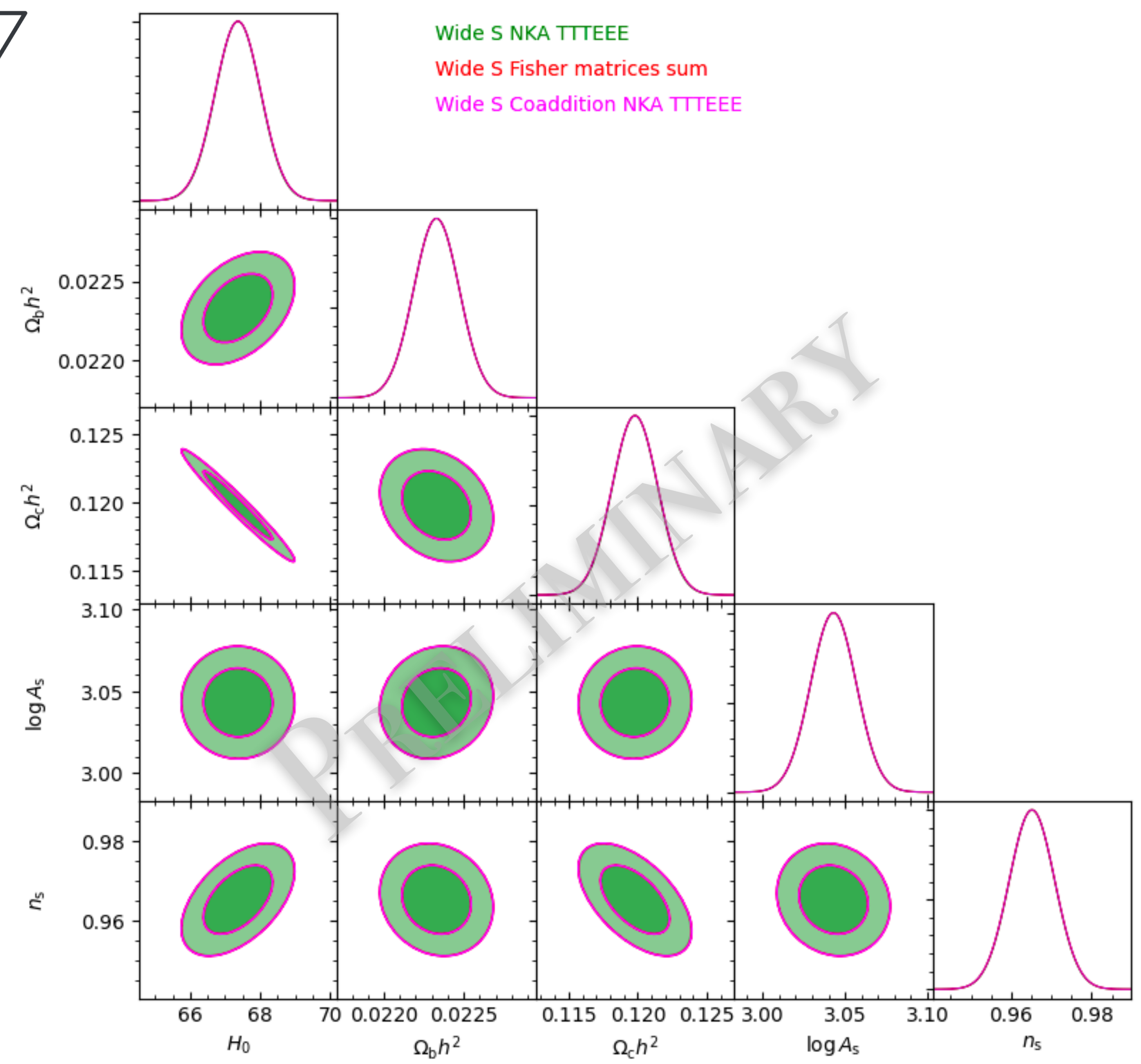
→ What we will probably do

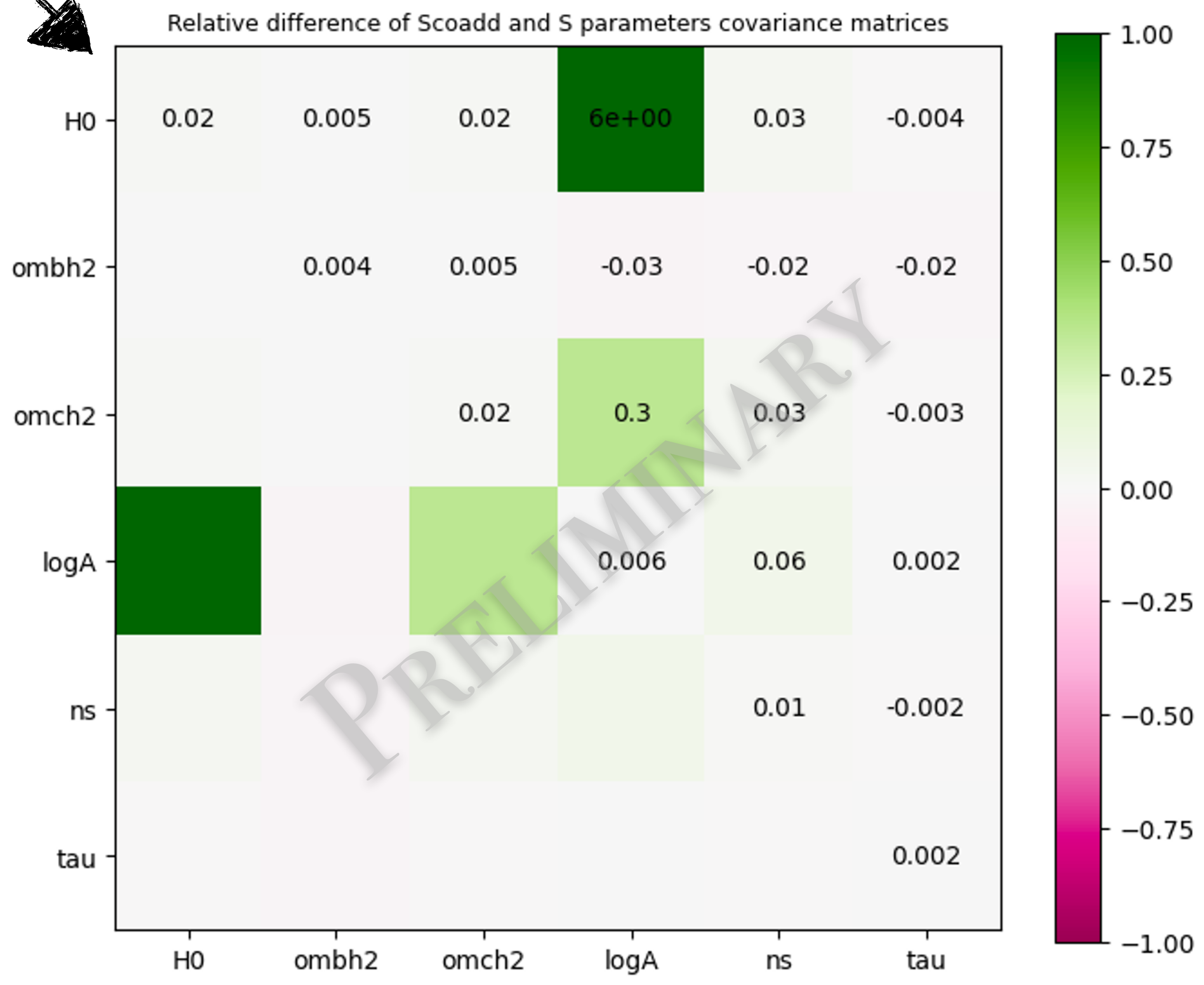
Fisher forecasting and parameters covariance matrix

- By comparing **S_coadd** with **S**, we observe less than a 2% relative difference in the cosmological parameters variance between the 2 analysis.

candl

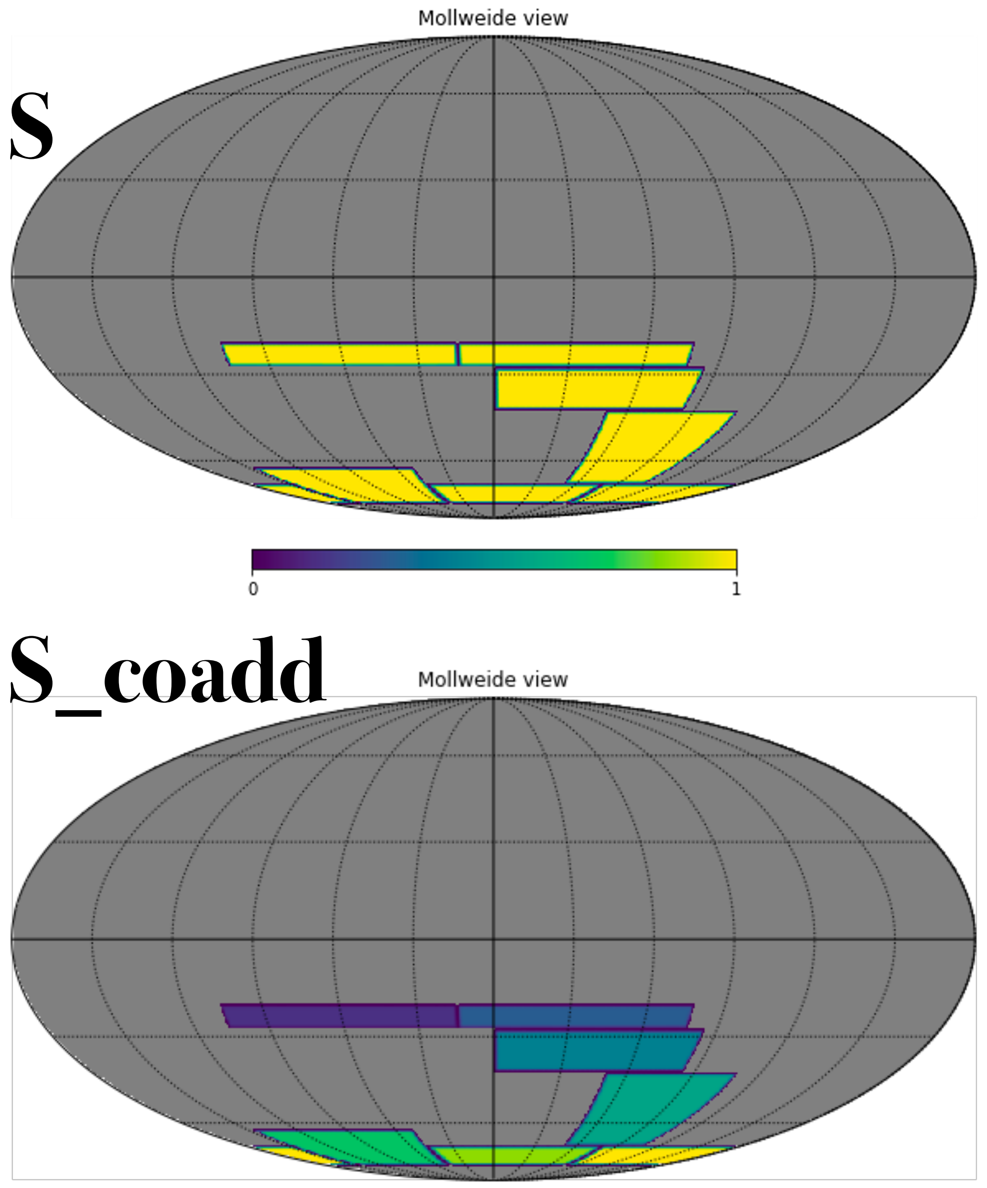
Balkenhol et al., 2024





S

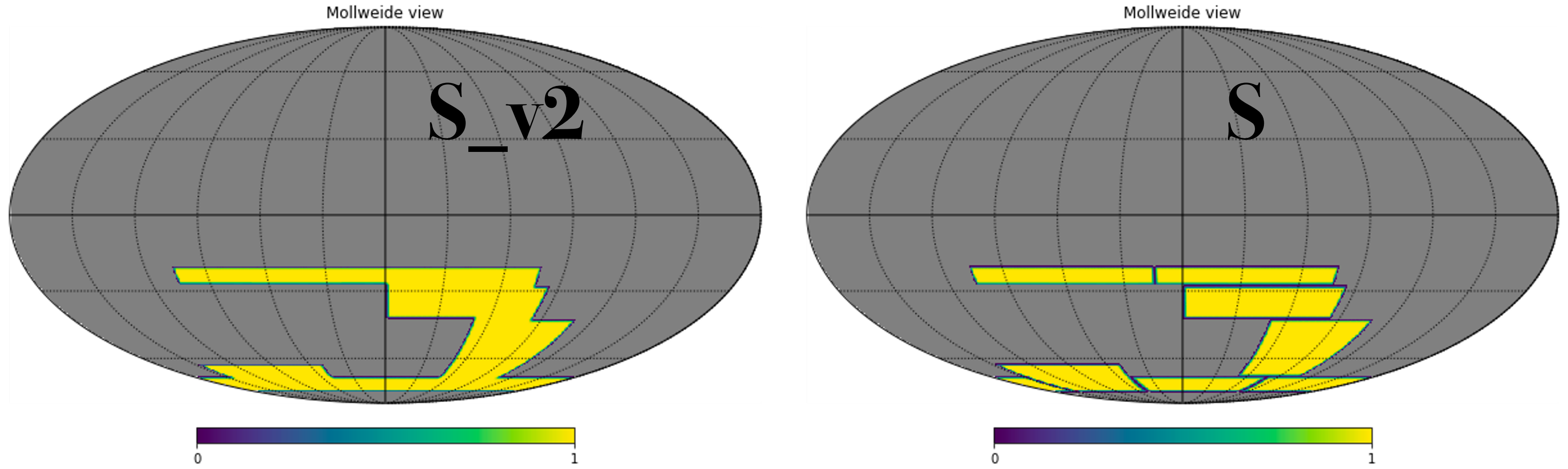
S_coadd

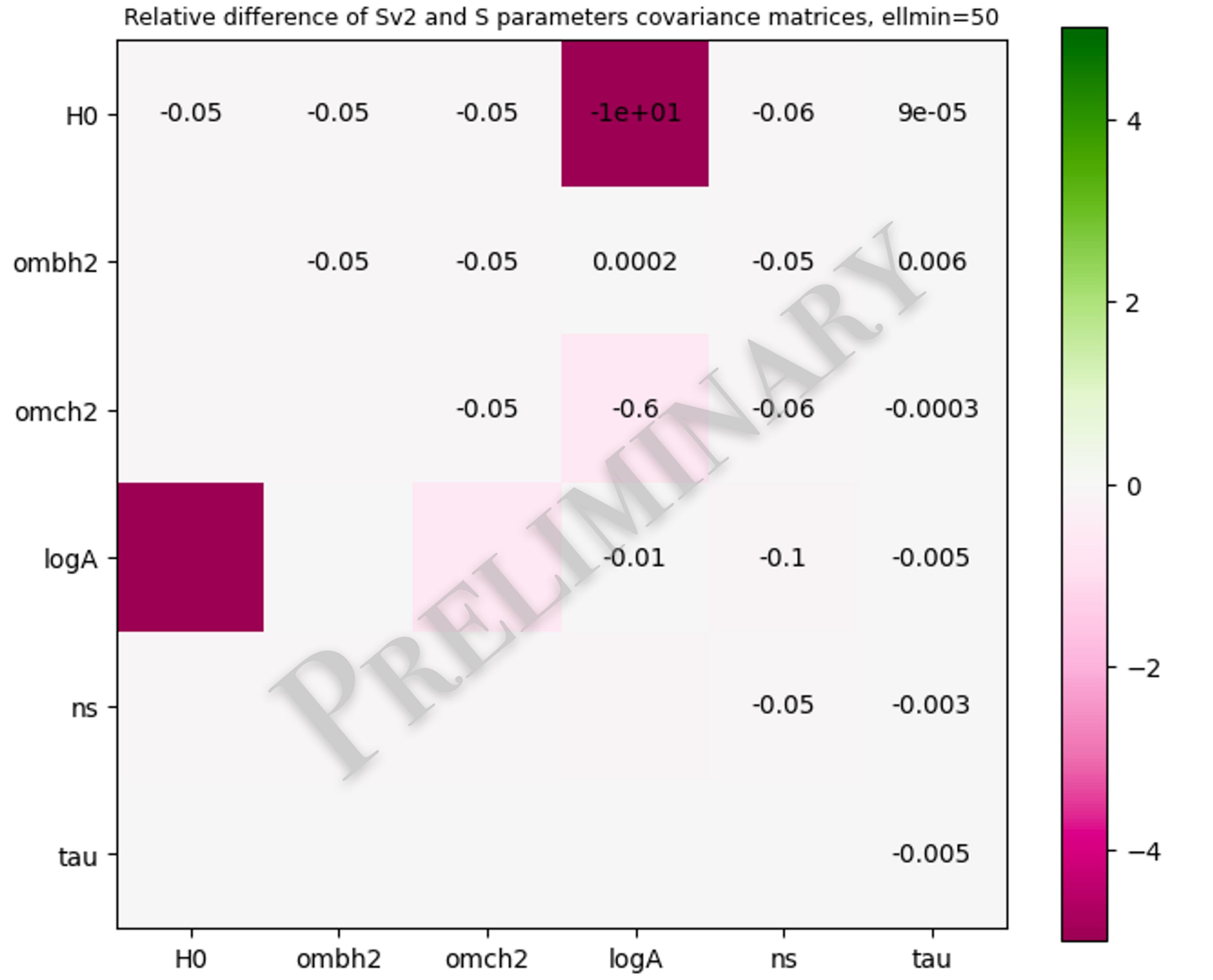


For a same total fsky, the subdivision of the fields in the analysis leads to a 1% increase of error bars.

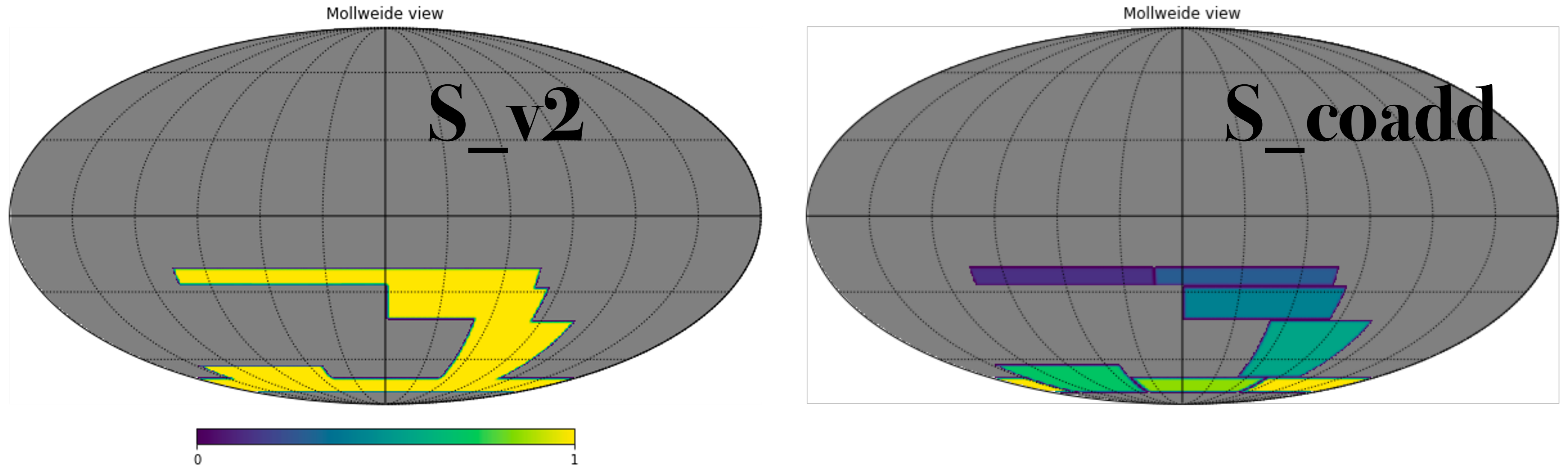
Fisher forecasting and parameters covariance matrix

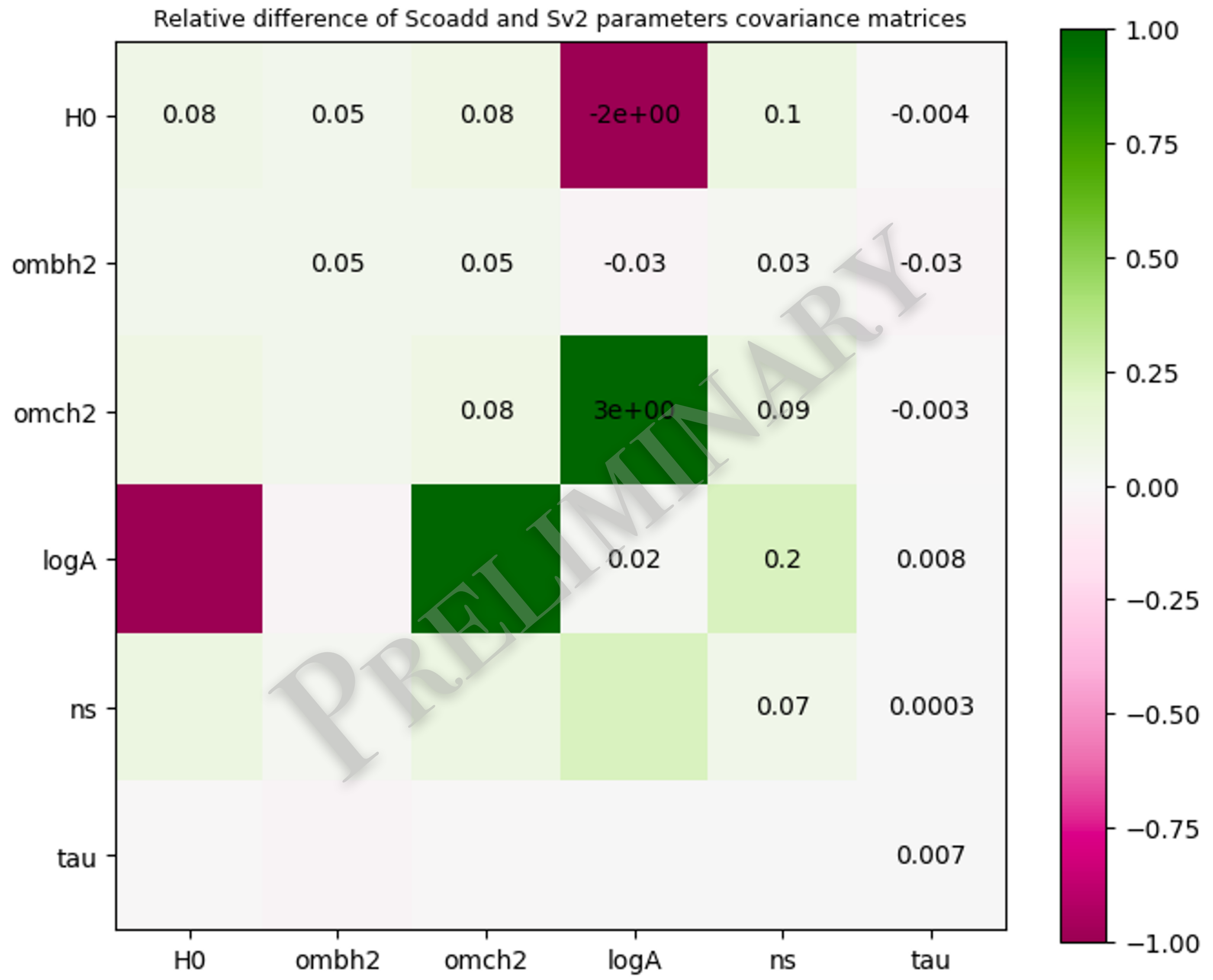
- Comparison between **S_v2** and **S**
  A 5% increase in the fsky value leads to a 2% decrease of error bars.





- Comparison between **S_coadd** and **S_v2**
  In comparison with the best case scenario, the subdivision of the fields in the analysis leads to less than a 8% increase of parameters variance.





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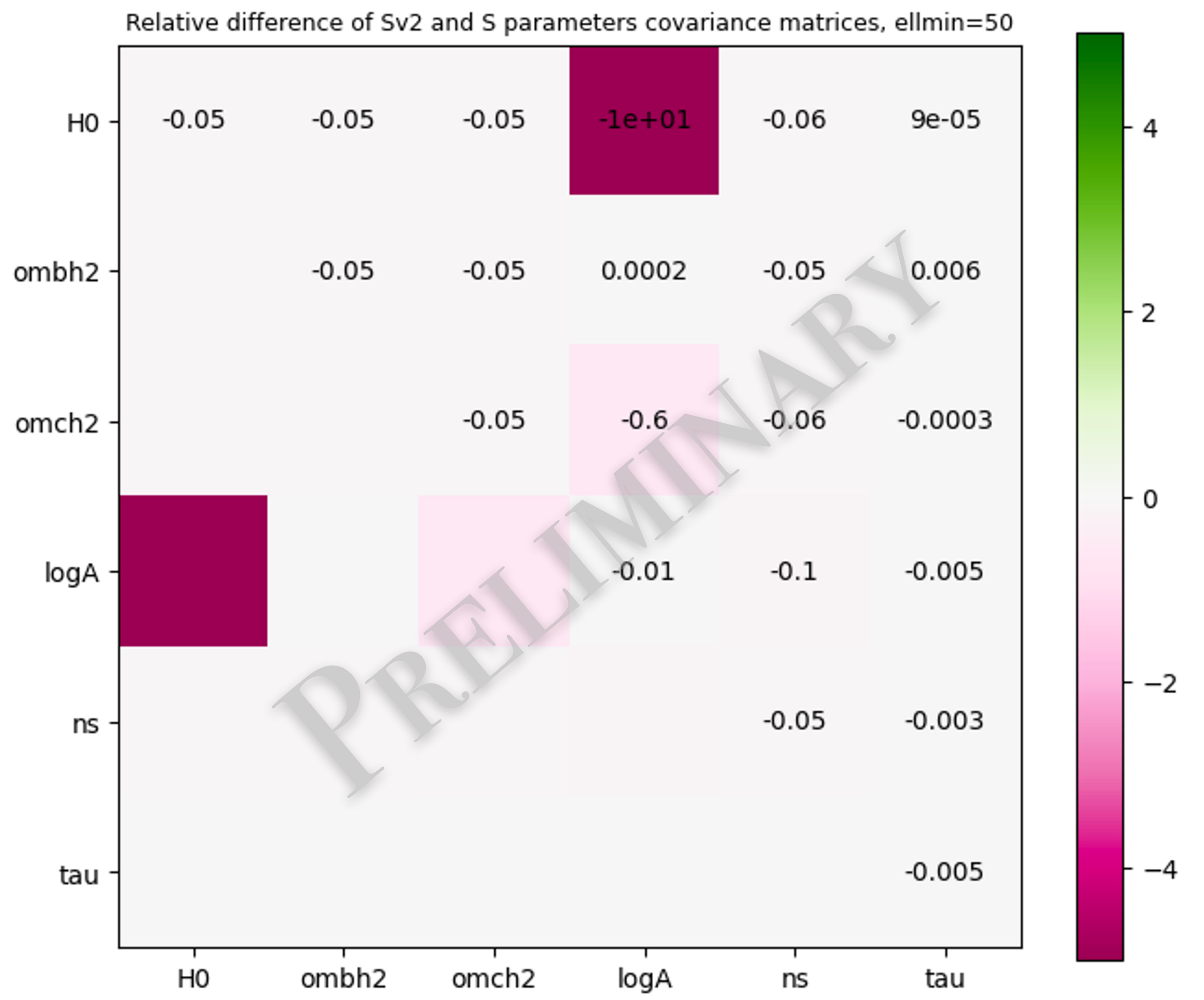

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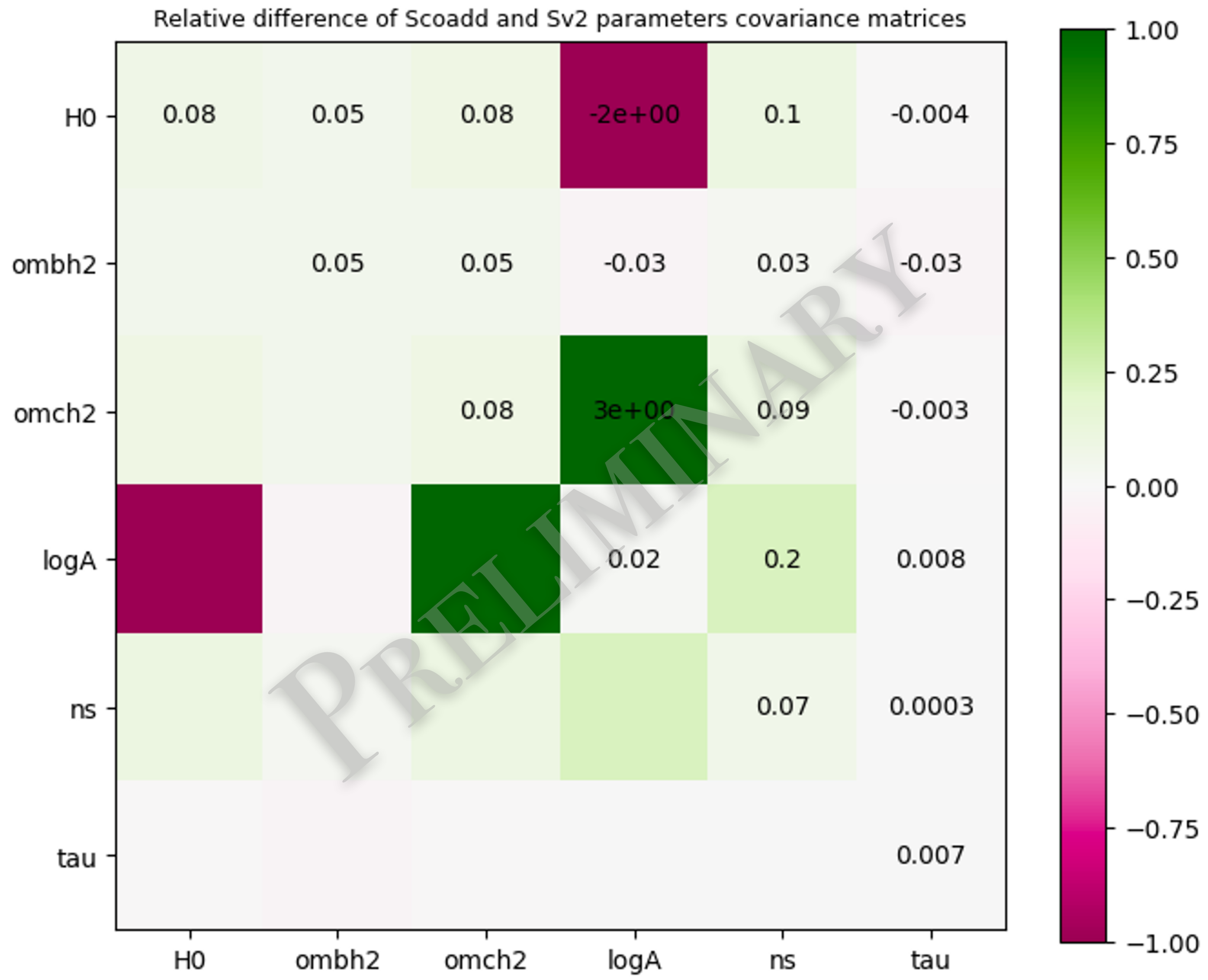

→ **Subdivision of the fields in the analysis leads to a 4% increase of error bars.**

Fisher forecasting and parameters covariance matrix

- Comparison between **S_v2** and **S**
  A 5% increase in the fsky value leads to a 2% decrease of error bars.

- Comparison between **S_coadd** and **S_v2**
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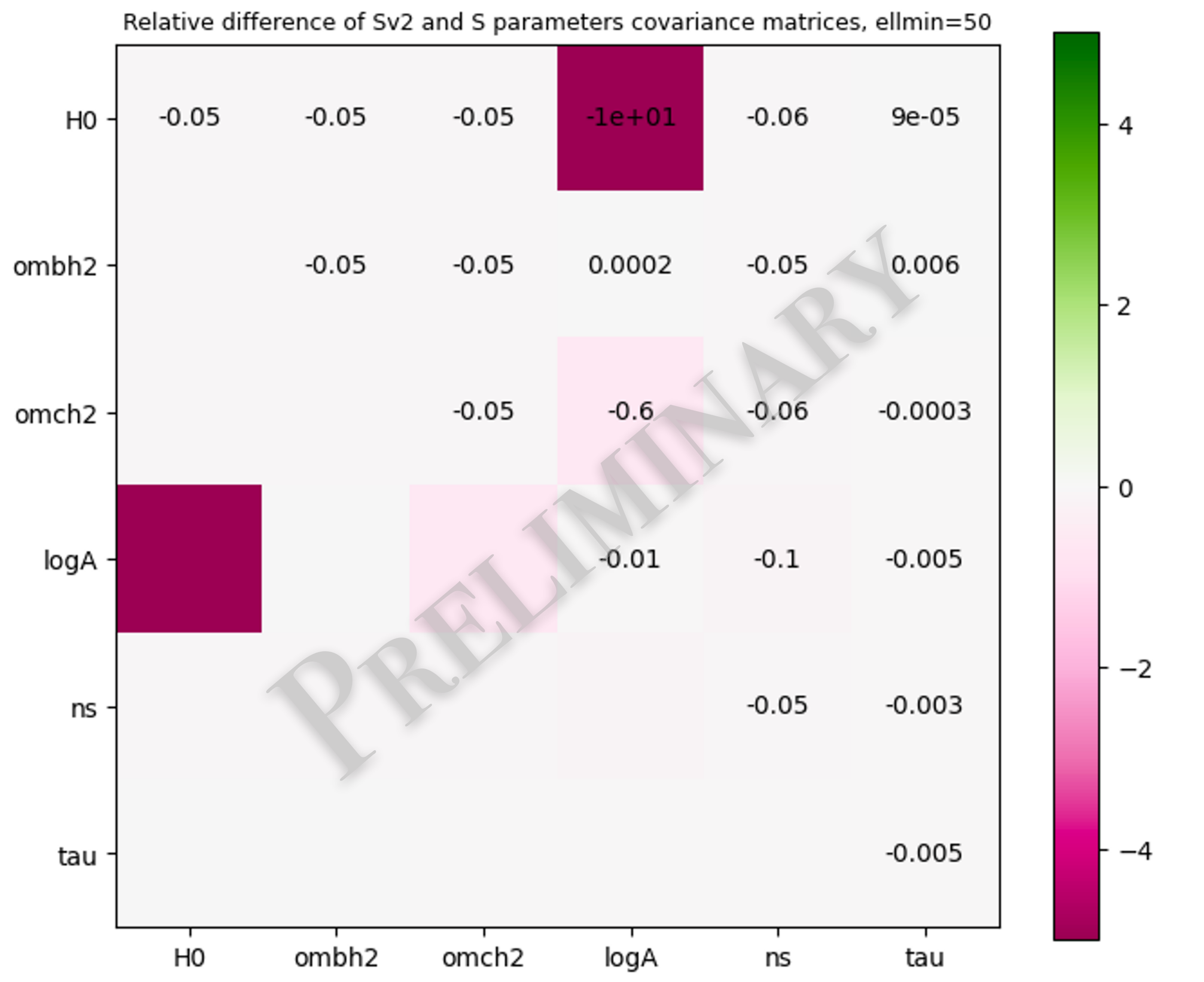
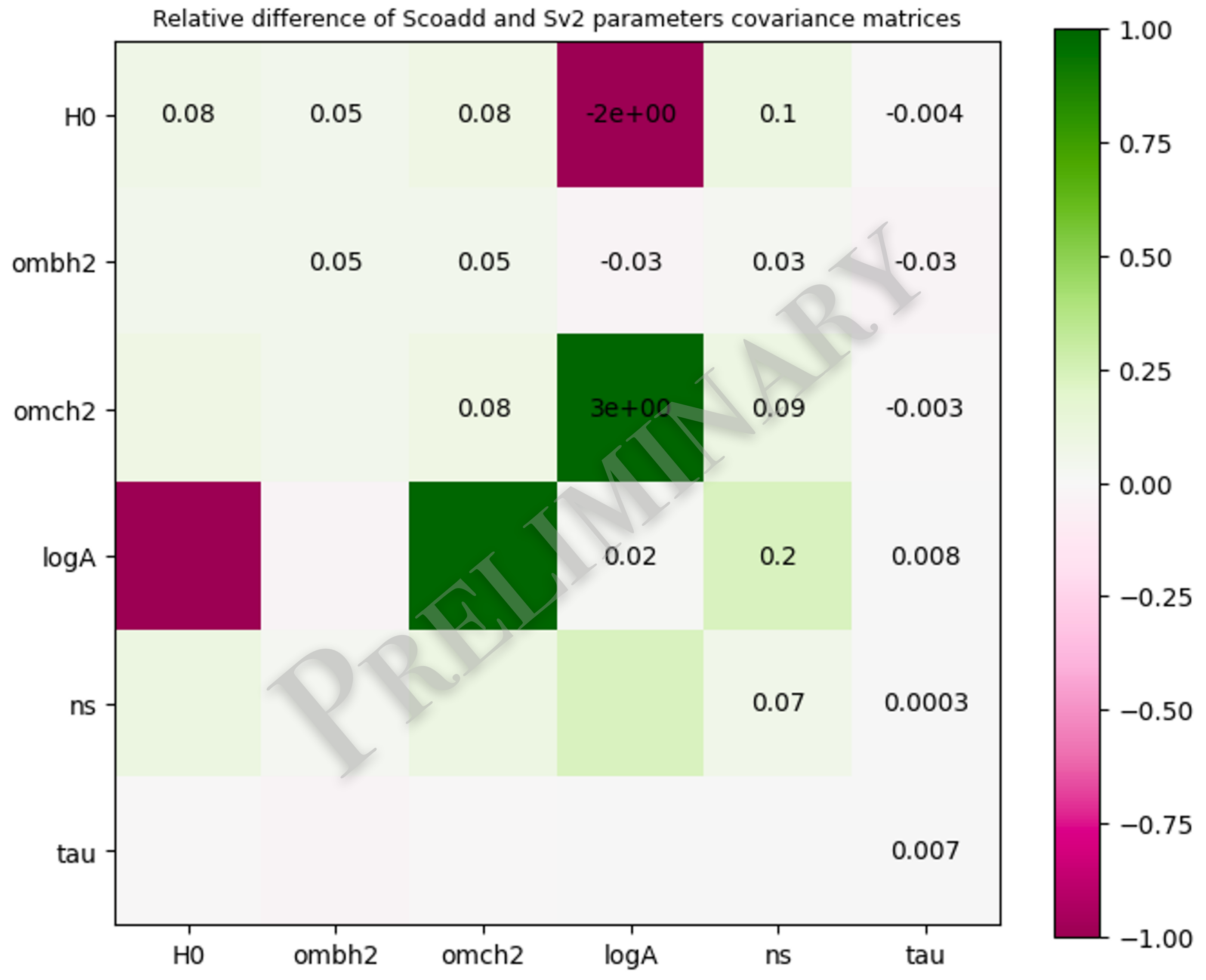
→ **Subdivision of the fields in the analysis leads to a 4% increase of error bars.**

NEGLIGIBLE !

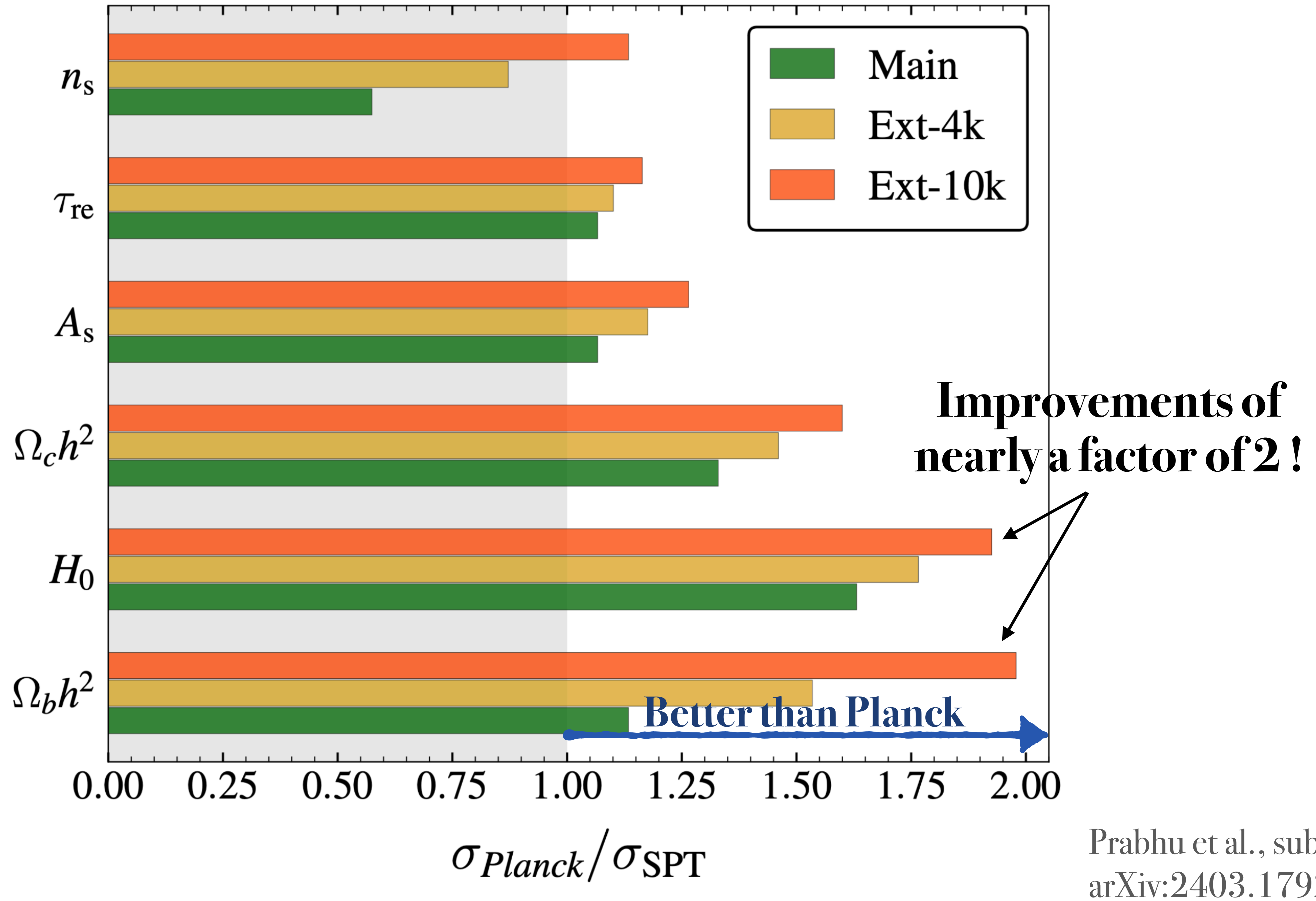




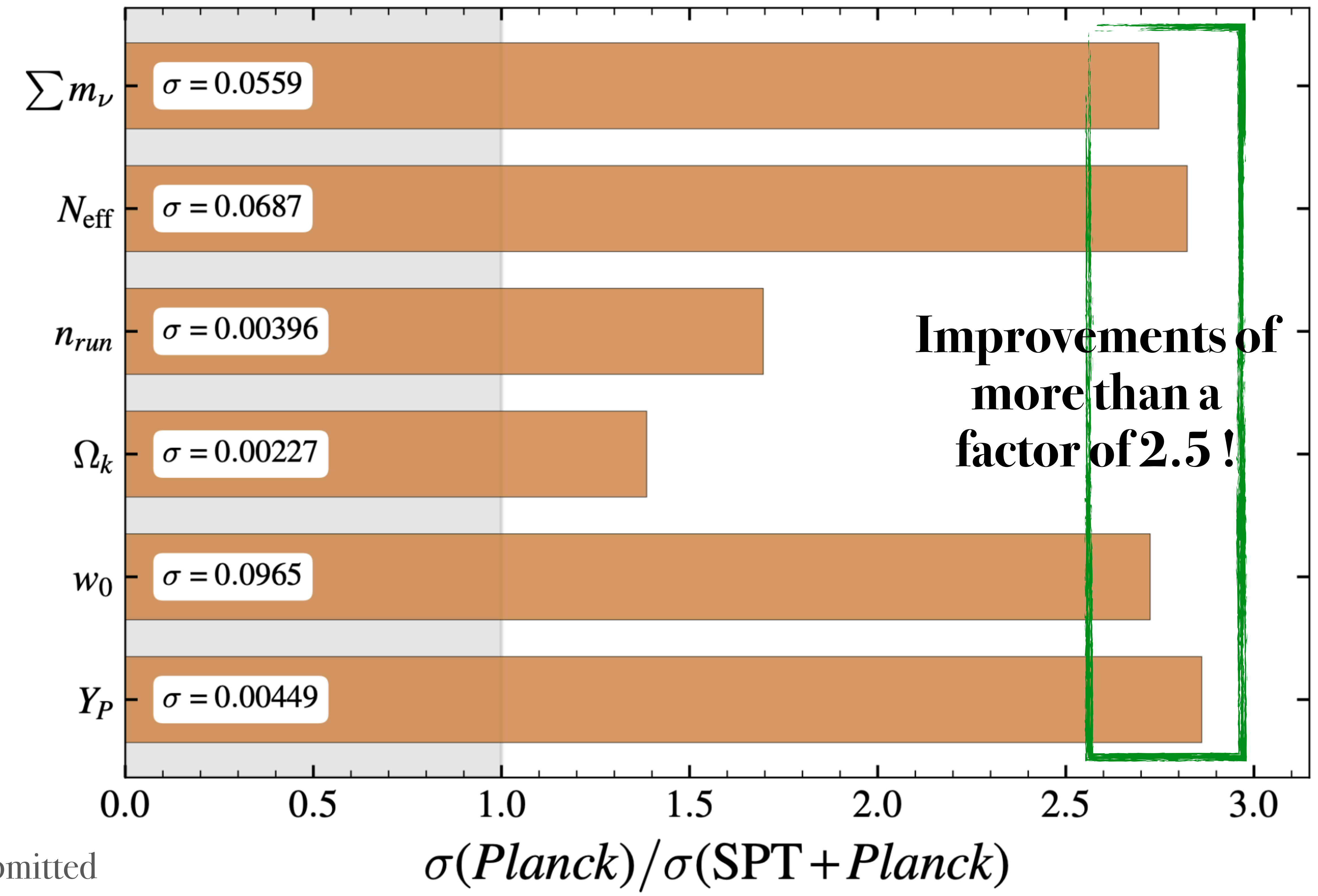
Expected improvements on cosmological parameters

Forecasts from SPT-3G Ext-10k survey

- Constraints on ΛCDM parameters



- Constraints on single-parameter extensions to ΛCDM



Prabhu et al., submitted
arXiv:2403.17925

Expected improvements on cosmological parameters

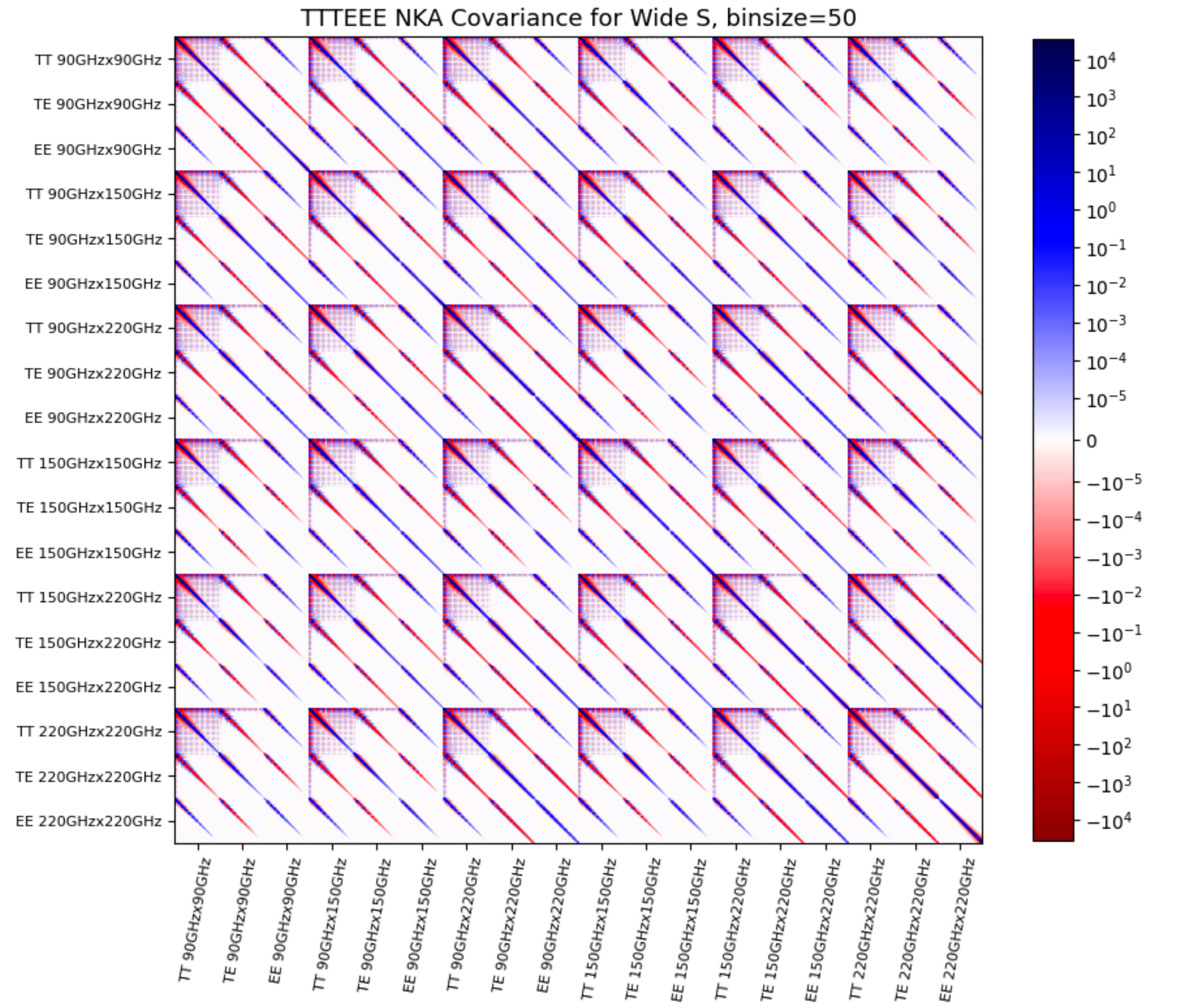
What will be my contribution ?

- Lead the different steps of the Wide field analysis to achieve these improvements.
- Build the Wide field likelihood using the expertise of the Winter and the Summer analysis.

$$\ln L(\theta) = -\frac{1}{2}\left(\hat{\mathrm{C}} - \mathrm{C}(\theta)\right)^T \Sigma^{-1}\left(\hat{\mathrm{C}} - \mathrm{C}(\theta)\right)$$

- ☐ Calibration
- ☐ Transfer function
- ☐ Point sources
- ☐ Foregrounds

Covariance matrix



Conclusion

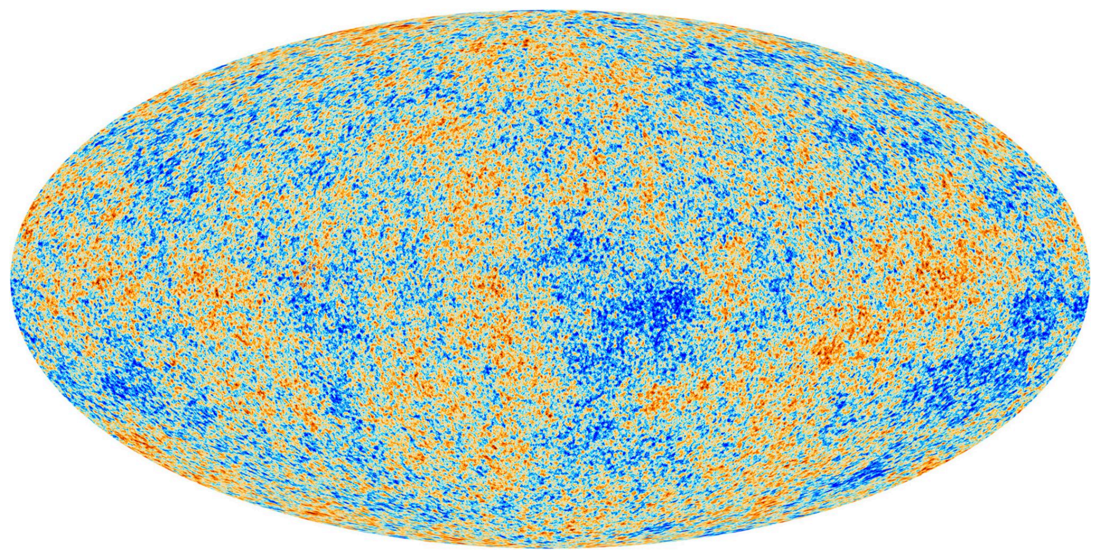
- SPT-3G Wide is a new field of observation covering 14% of the sky.
- We do not lose constraining power by analysing the subfields independently of each other
- SPT-3G Ext-10k forecasts show tighter constraints on all ΛCDM parameters than the ones from Planck.
- Constraints on H_0 should be improved by almost a factor of 2 !

Credit: Keith Vanderlinde

Back-up slides

Impact of a masked sky on the power spectrum analysis

- On the full sky

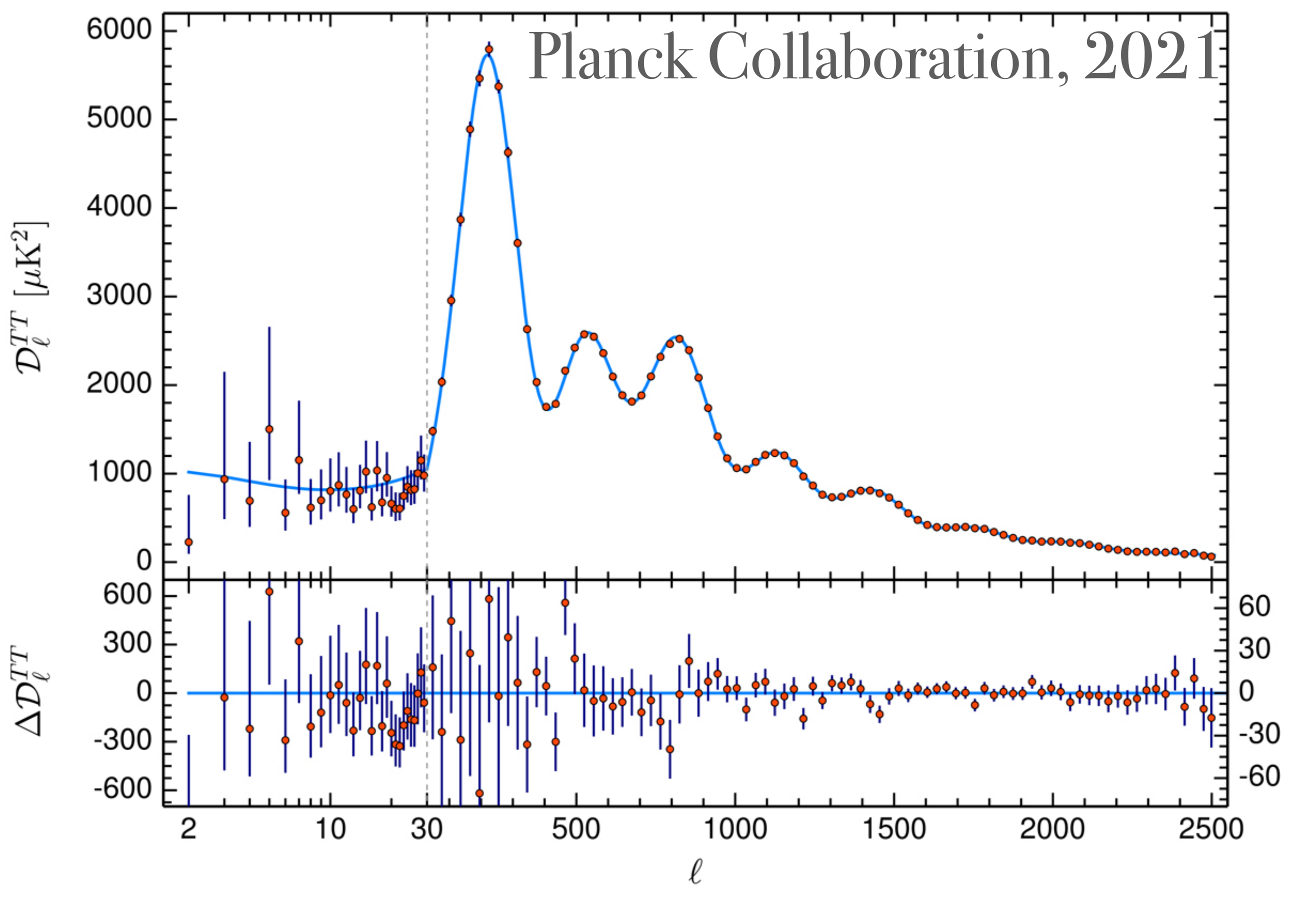


Credit: ESA and Planck Collaboration

$$\Theta(\hat{n}) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\hat{n})$$

$$a_{\ell m} = \int d\hat{n}\, \Theta(\hat{n}) Y^{*}_{\ell m}(\hat{n})$$

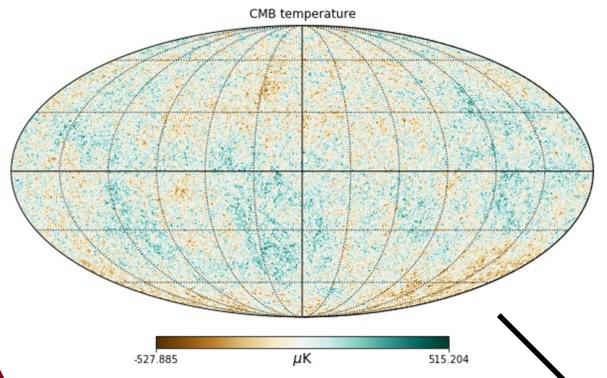
$$\hat{C}_\ell = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} a_{\ell m} a^{*}_{\ell m}$$

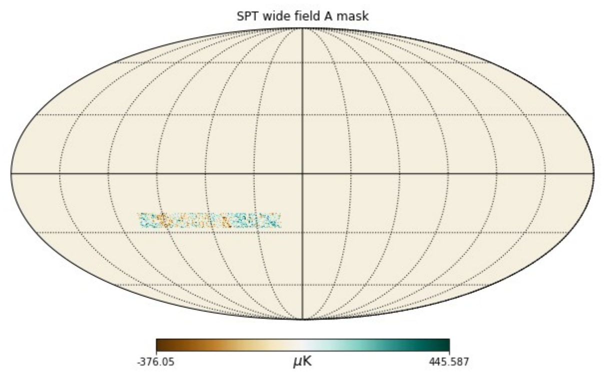


Cosmological parameters

$$\ln L(\theta) = -\frac{1}{2}\left(\hat{\mathrm{C}} - \mathrm{C}(\theta)\right)^T \Sigma^{-1} \left(\hat{\mathrm{C}} - \mathrm{C}(\theta)\right)$$

- When using a mask W





$$\Theta(\hat{n}) \longrightarrow \Theta(\hat{n})W(\hat{n})$$

$$a_{\ell m} \longrightarrow \tilde{a}_{\ell m} = \int d\hat{n}\, \Theta(\hat{n}) W(\hat{n}) Y^{*}_{\ell m}(\hat{n})$$

$$\hat{C}_\ell \longrightarrow \tilde{C}_\ell$$

What we want to know !

and $\langle \tilde{C}_\ell \rangle = \sum_{\ell'} M_{\ell \ell'} C^{th}_{\ell'}$ Hivon et al., 2002

Problem : The inversion of the matrix M is impossible.
Solution : The Polspice program goes to real space and introduces a function $f(\Delta\theta)$ which avoids ringing in the multipole space.

$$f(\Delta\theta) = \frac{1}{2}\left(1 + cos\left(\frac{\pi \Delta\theta}{\sigma}\right)\right)$$

$\Delta\theta$: angular separation in the sky

apodizesigma

☑ Determination of the value of apodizesigma which allows to recover the less biased CMB power spectra in each field.