

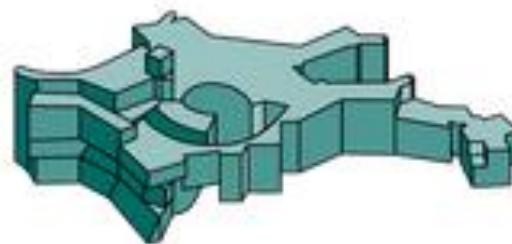
Cosmic birefringence

Searching for parity-violating physics with the CMB polarization

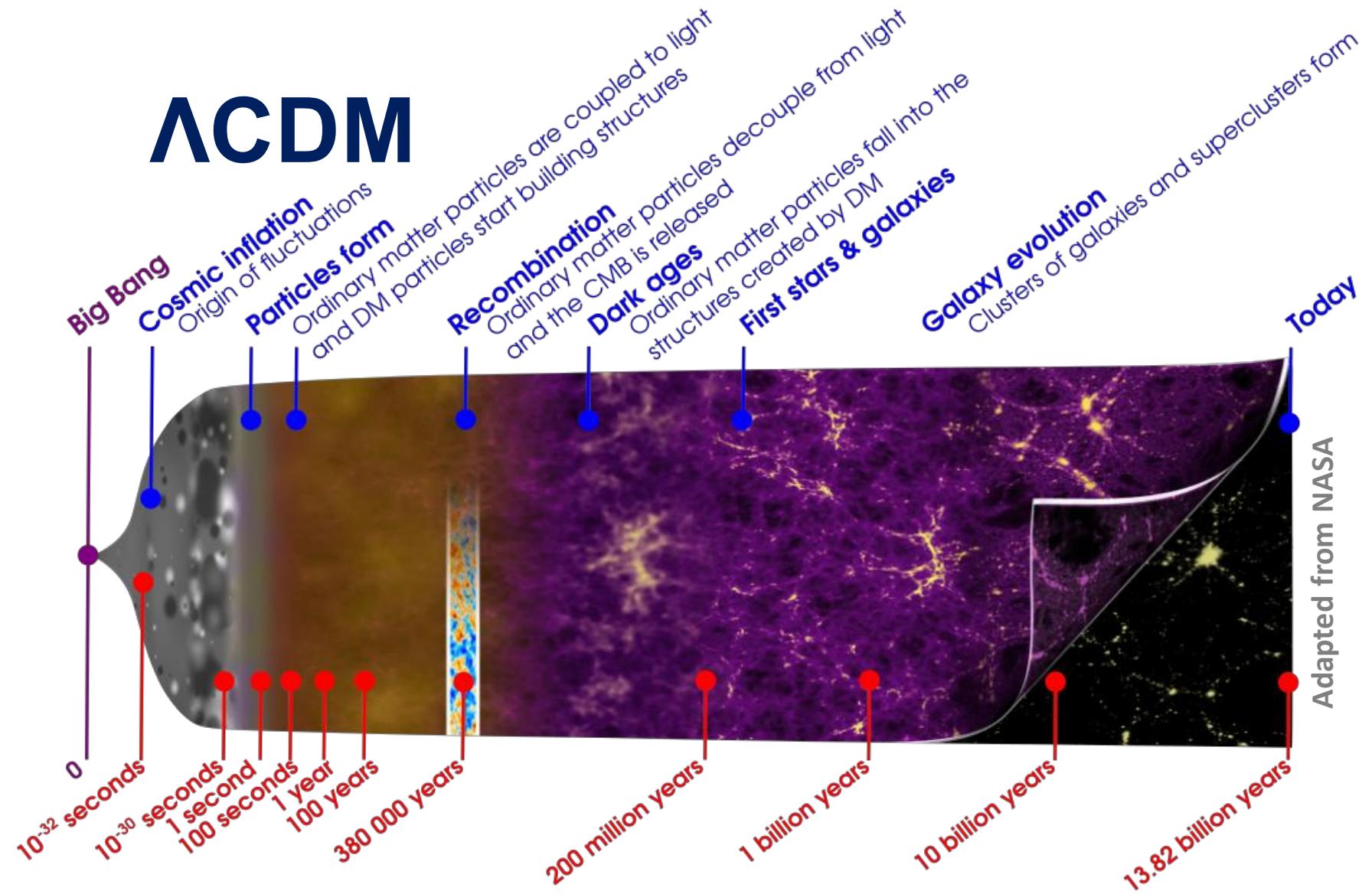
Patricia Diego-Palazuelos

Copernicus Webinar and Colloquium Series
October 24th 2023

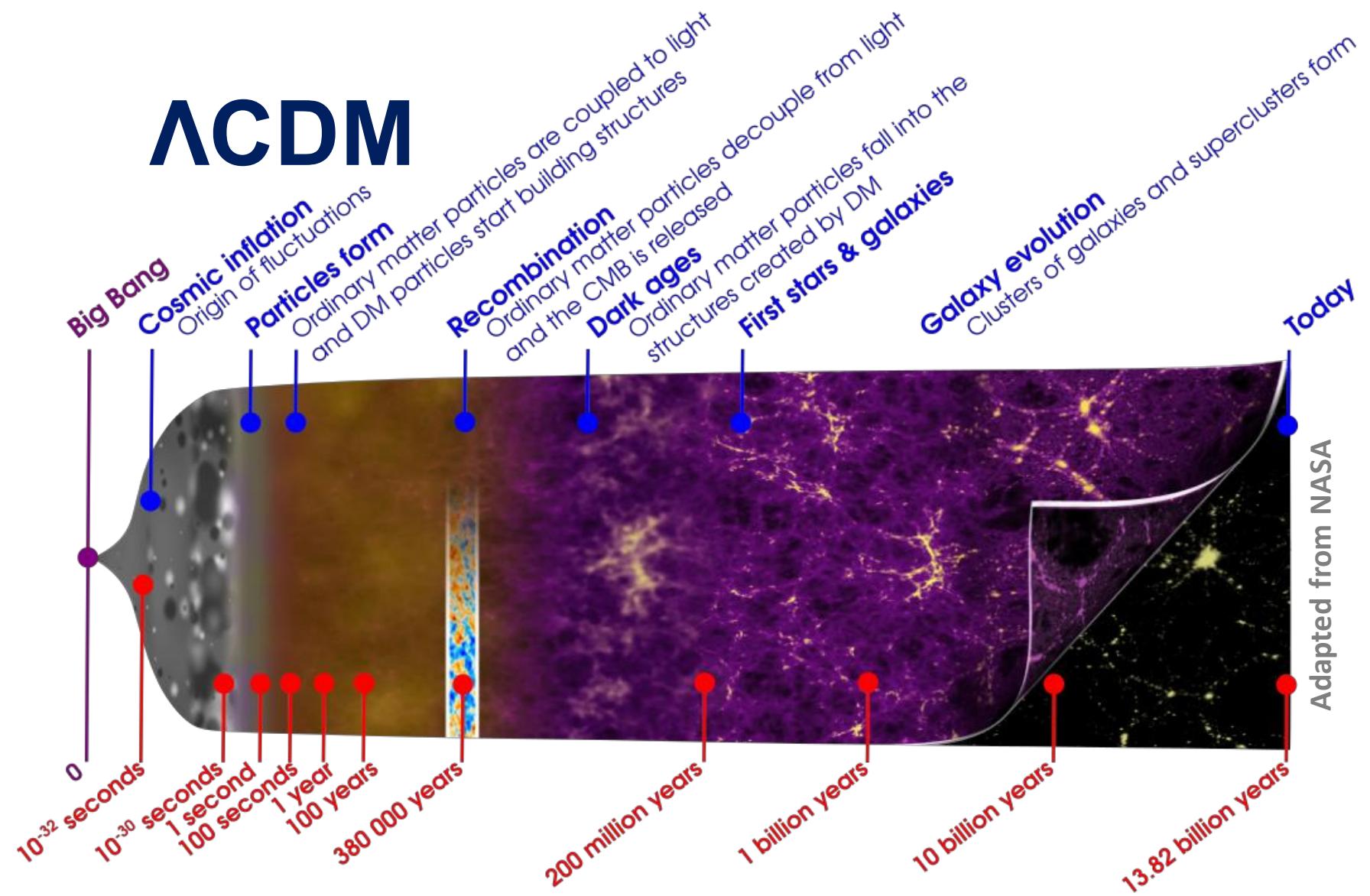
**MAX PLANCK INSTITUTE
FOR ASTROPHYSICS**



Λ CDM



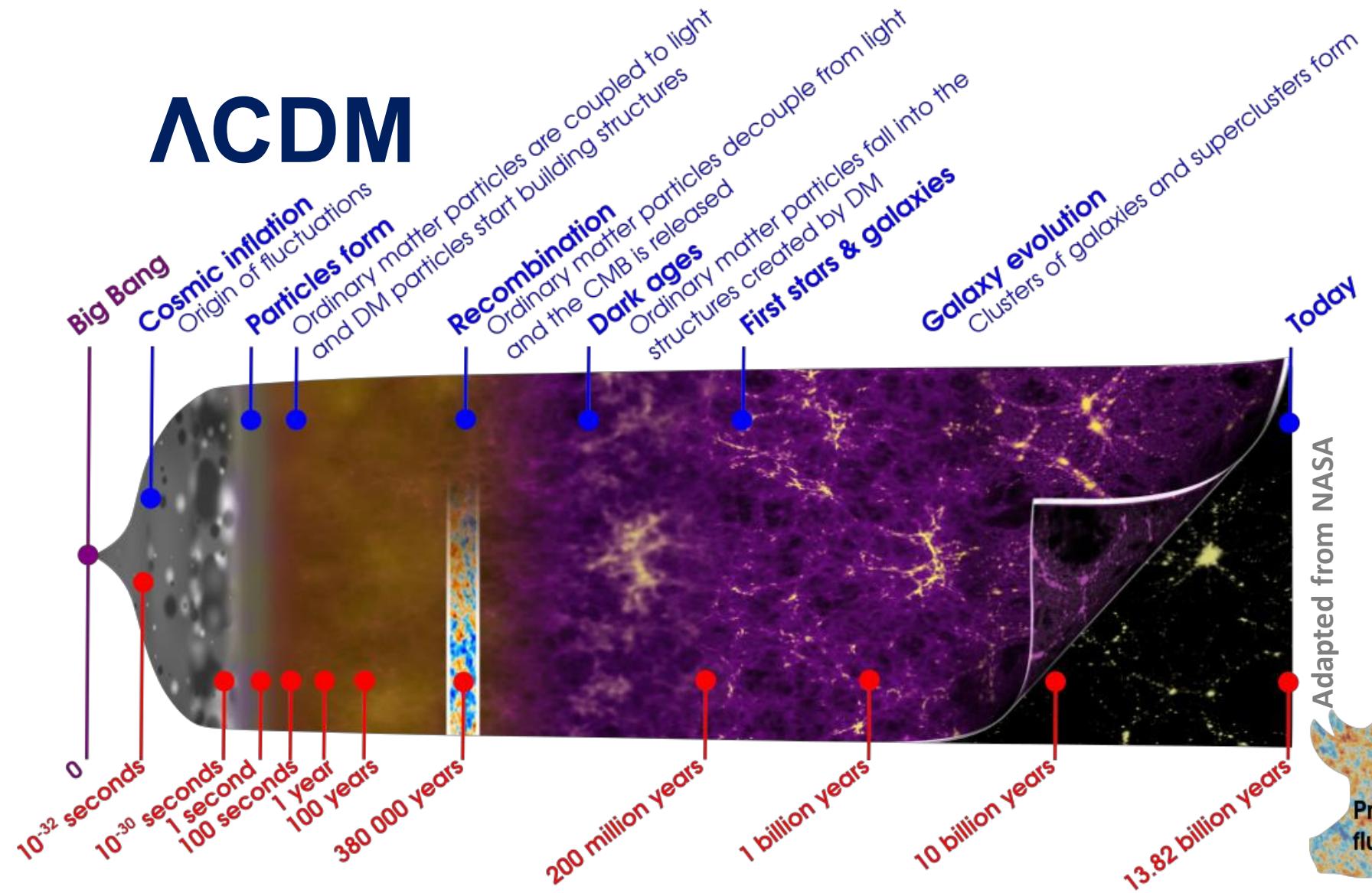
Λ CDM



From CMB temperature and polarization anisotropies we can learn about...

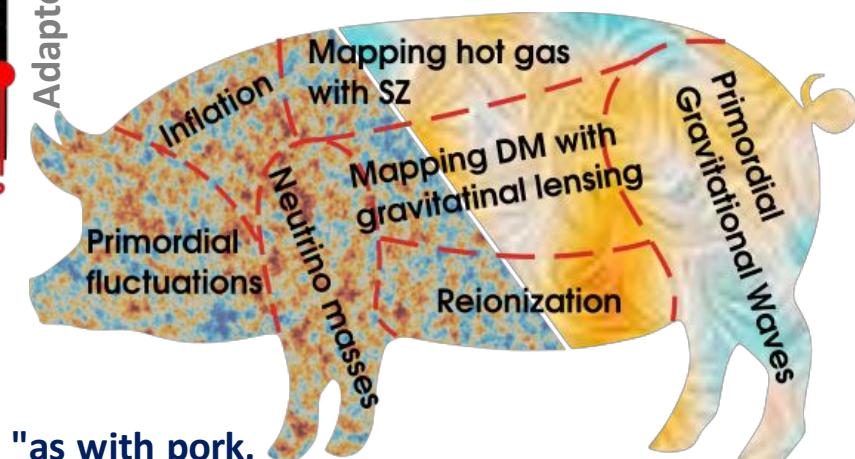
- Inflation
- Primordial fluctuations
- Inflationary gravitational waves
- Epoch of reionization
- Map hot gas through SZ effect
- Map DM through gravitational lensing
- Constraint neutrino masses and other light relics
- Galactic astrophysics
- ...

Λ CDM



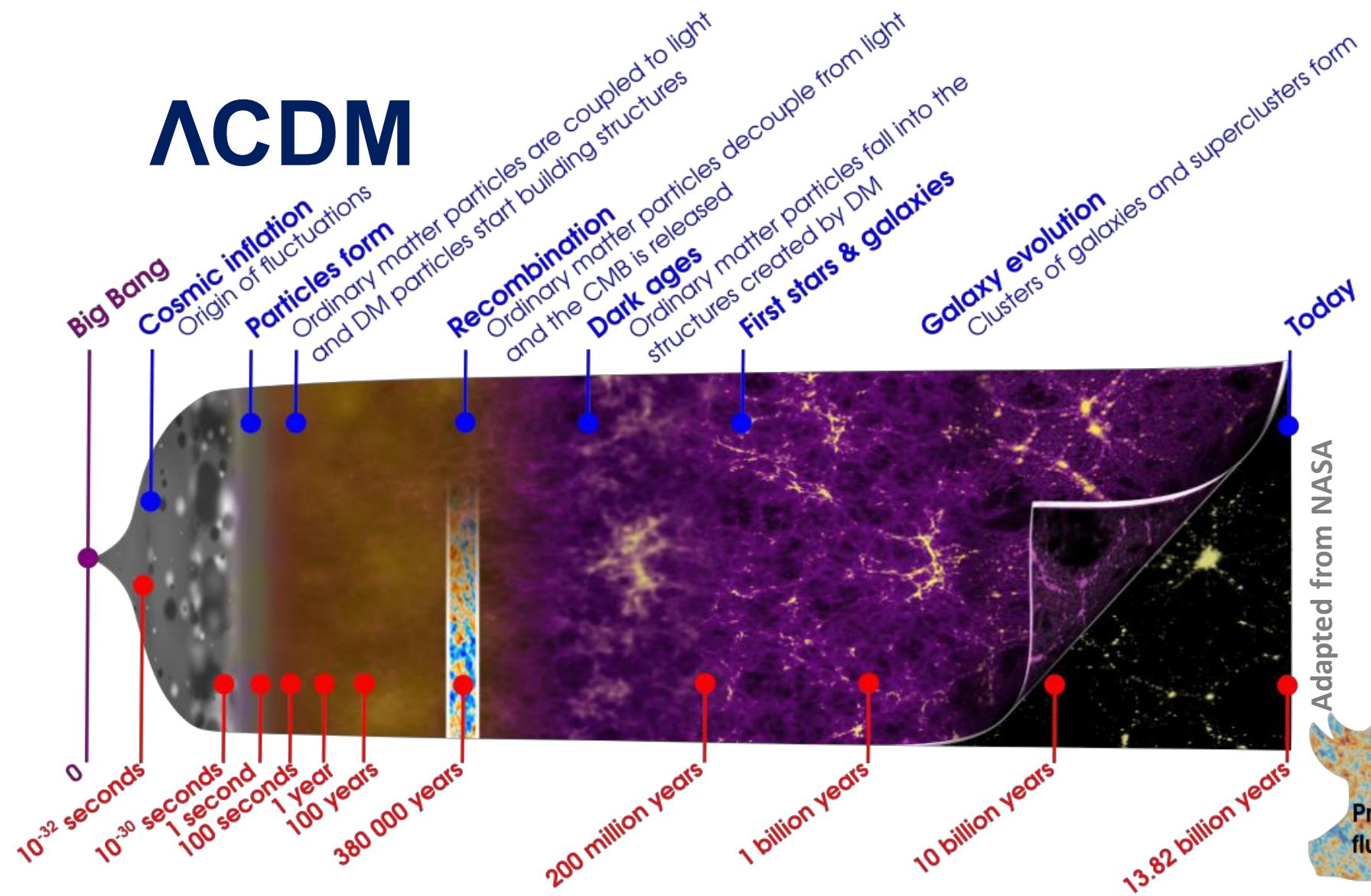
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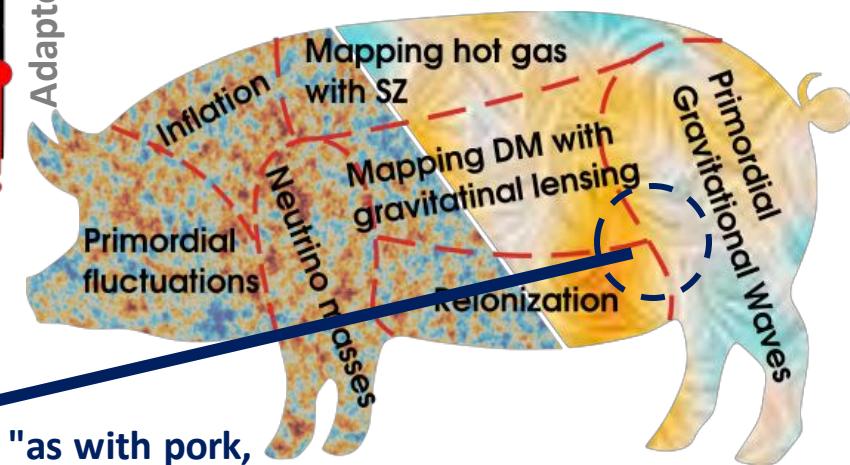
"as with pork,
we'll seize even its stroll"

Λ CDM



From CMB temperature and polarization anisotropies we can learn about...

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- Primordial fluctuations
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- ...



Use CMB polarization to search for parity-violating physics in the Universe

"as with pork,
we'll seize even its stroll"

Polarization primer

Cabella & Kamionkowski 2003 [arXiv:astro-ph/0403392]

Linearly polarized light propagating along the z direction

$$E_x = a_x \cos(\omega t - \delta_x) \quad E_y = a_y \cos(\omega t - \delta_y)$$

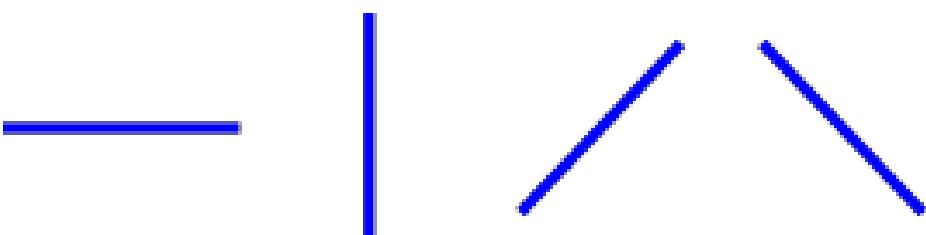
can be described through the Stoke's parameters

$$I = a_x^2 + a_y^2$$

$$Q = a_x^2 - a_y^2$$

$$U = 2a_x a_y \cos(\delta_x - \delta_y)$$

Relative to the chosen coordinate system



$$Q > 0$$

$$U = 0$$

$$Q < 0$$

$$U = 0$$

$$Q = 0$$

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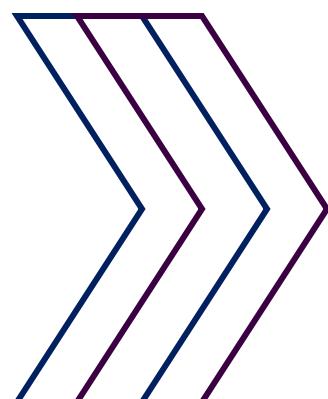
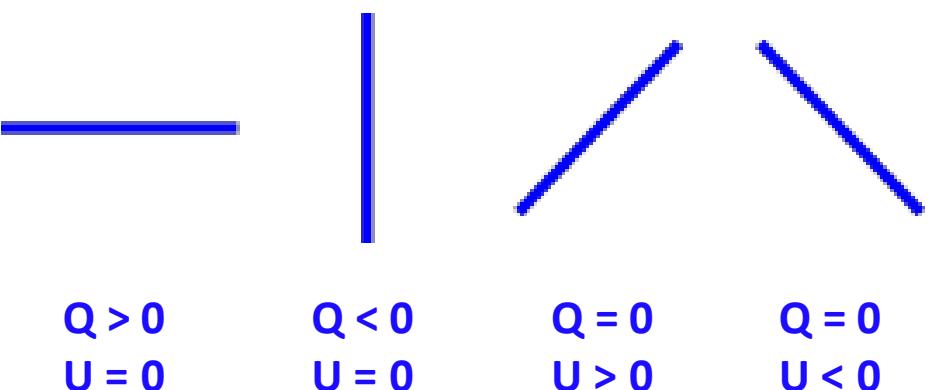
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Helmholtz's theorem

Express vector fields as the sum of curl-free and divergence-free fields

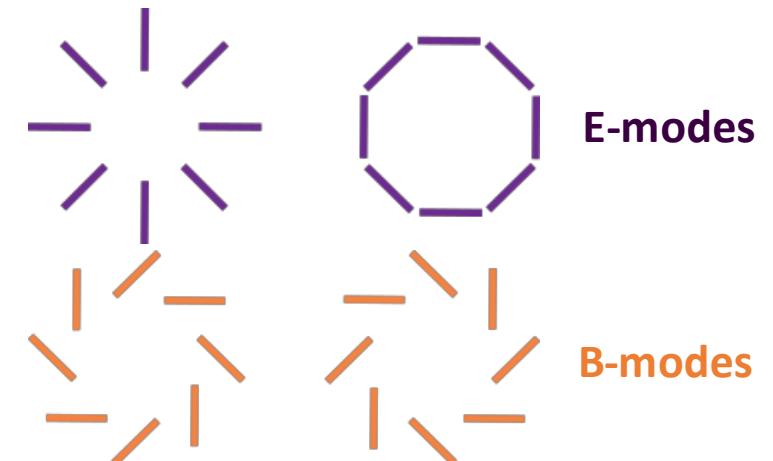
Q and U define a spin-2 field

$$P_{ab} = \frac{1}{2} \begin{pmatrix} Q(\vec{r}) & U(\vec{r}) \\ U(\vec{r}) & -Q(\vec{r}) \end{pmatrix}$$

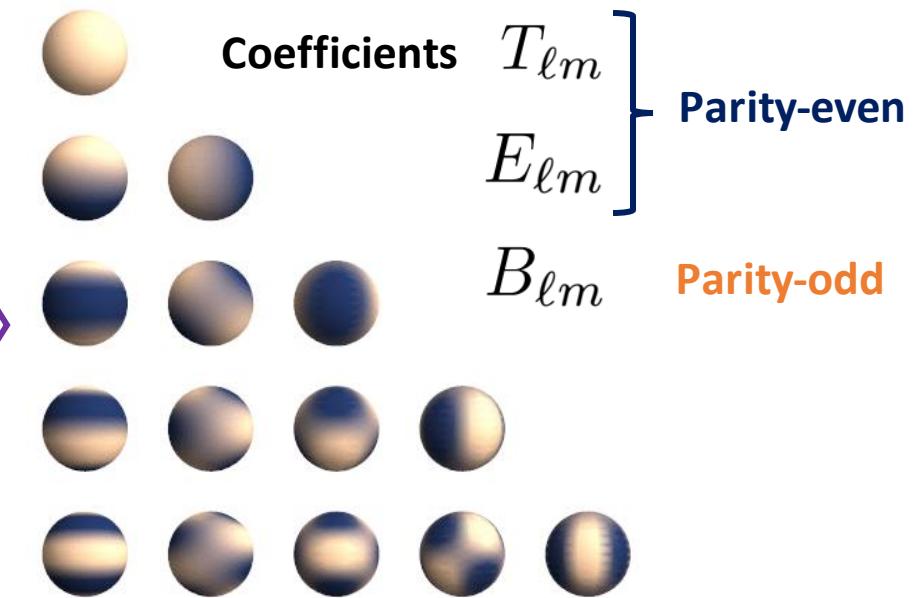
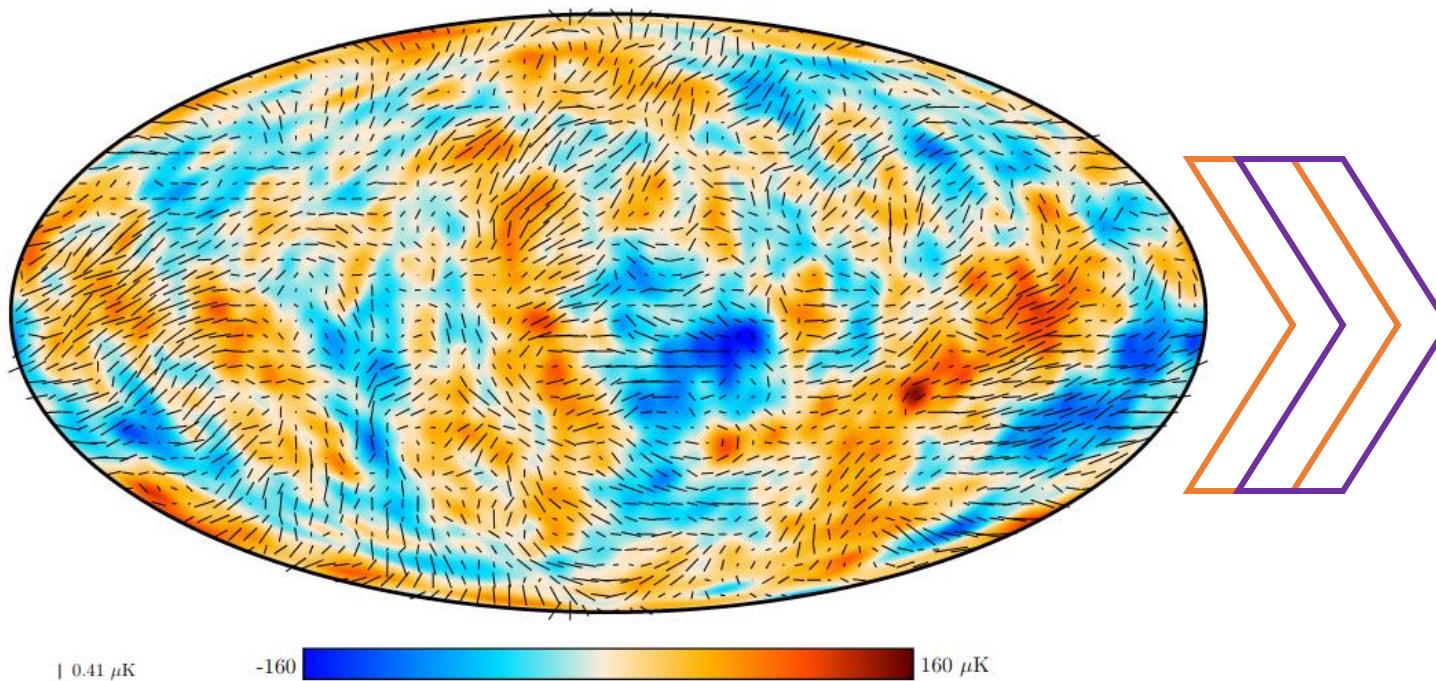
Express the polarization field in terms of its gradient and curl components

$$\nabla^2 E = \partial_a \partial_b P_{ab} \quad \nabla^2 B = \epsilon_{ac} \partial_b \partial_c P_{ab}$$

Locally independent

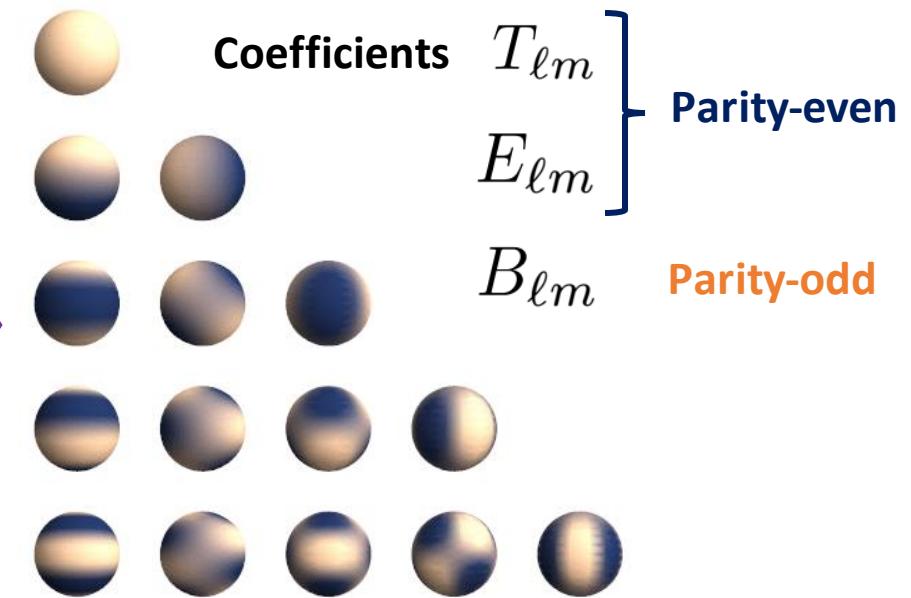
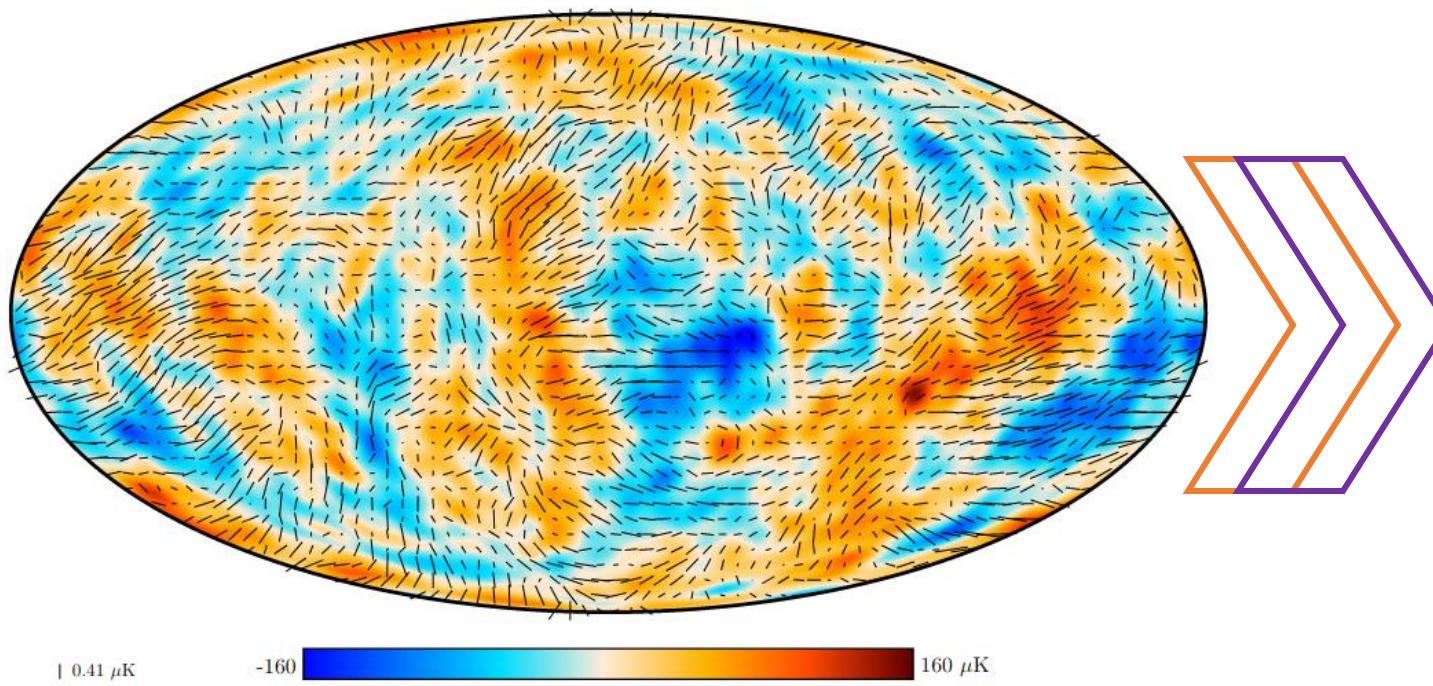


Decompose CMB maps into spherical harmonics



Zaldarriaga & Seljak 1997, PRD, 55, 1830
Kamionkowski et al 1997, PRD, 55, 7368

Decompose CMB maps into spherical harmonics

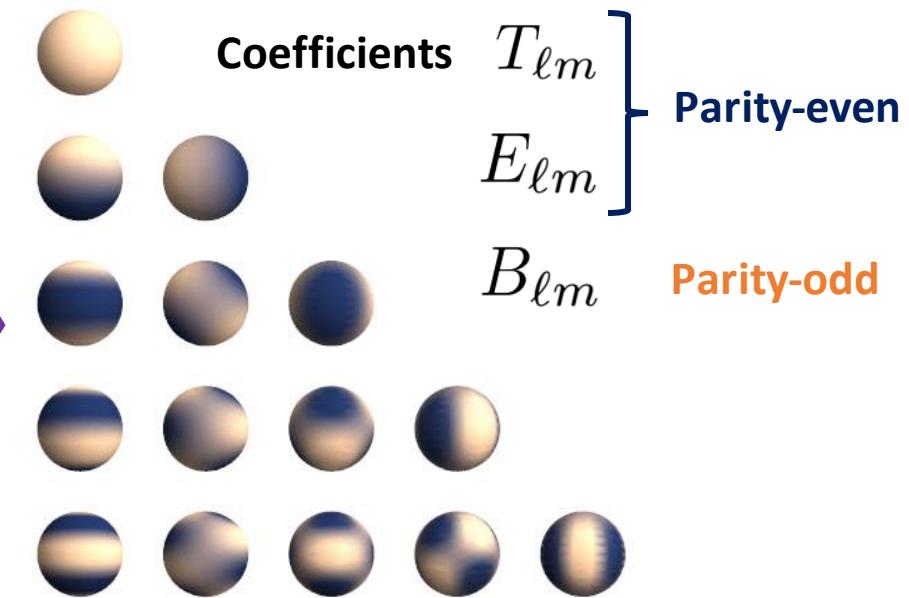
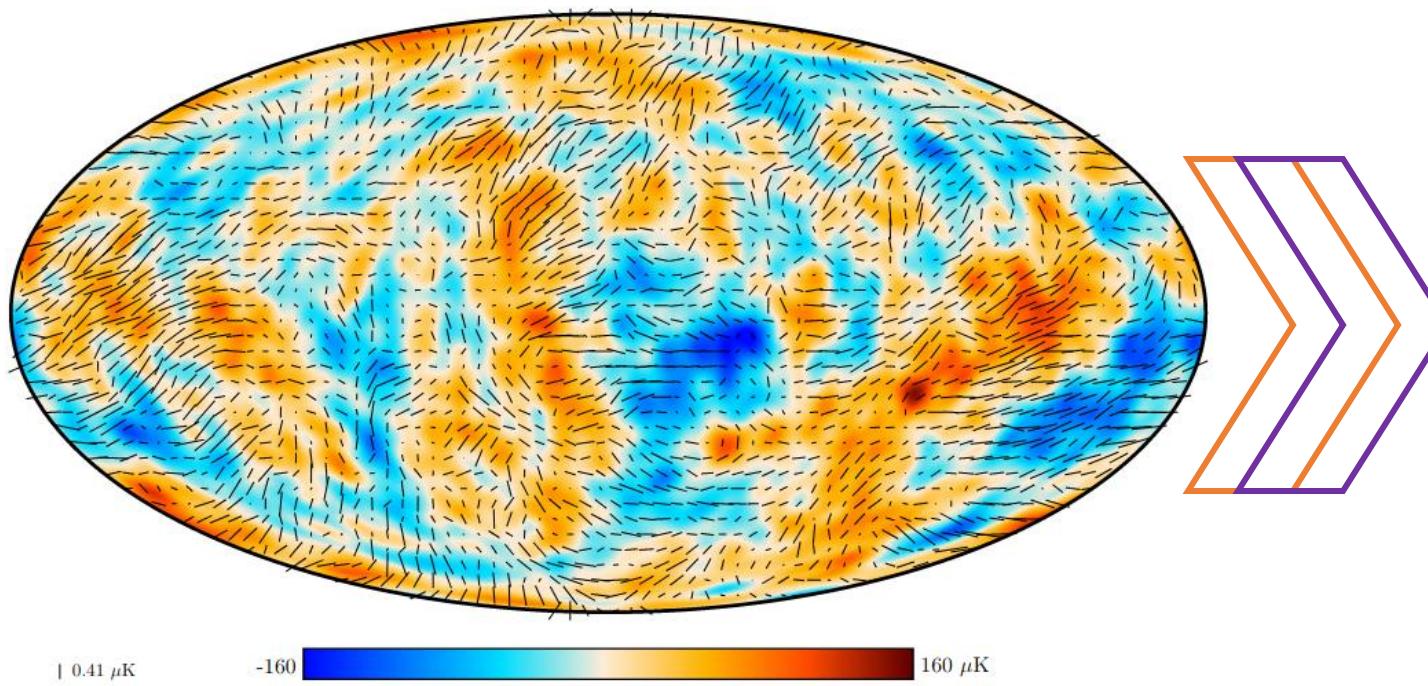


Zaldarriaga & Seljak 1997, PRD, 55, 1830
Kamionkowski et al 1997, PRD, 55, 7368

Analyzing CMB polarization in terms of spherical harmonics

$$\left. \begin{aligned} \langle E_{\ell m} E_{\ell' m'}^* \rangle &= \delta_{mm'} \delta_{\ell\ell'} C_\ell^{EE} \\ \langle B_{\ell m} B_{\ell' m'}^* \rangle &= \delta_{mm'} \delta_{\ell\ell'} C_\ell^{BB} \\ \langle E_{\ell m} B_{\ell' m'}^* \rangle &= \delta_{mm'} \delta_{\ell\ell'} C_\ell^{EB} \end{aligned} \right\} \begin{array}{l} \text{Parity-even} \\ \text{Parity-odd} \end{array}$$

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ΛCDM

The statistics of CMB anisotropies must be invariant under parity transformation

$EB \neq 0$ evidence of parity-violating physics
Lue et al 1999, PRL, 83, 1506

DM/DE could be a parity-violating pseudoscalar field $\phi(-\vec{n}) = -\phi(\vec{n})$

Chern-Simons coupling to EM $\frac{1}{4} g_{\phi\gamma} \phi F_{\mu\nu} \tilde{F}_{\mu\nu}$

Axion-like particles

Marsh, Phys Rep 643 1 (2016)

Early Dark Energy

Murai et al, PRD 107 L041302 (2023)

Eskilt et al, PRL 131 121001 (2023)

rotation of the plane of linear polarization clockwise on the sky



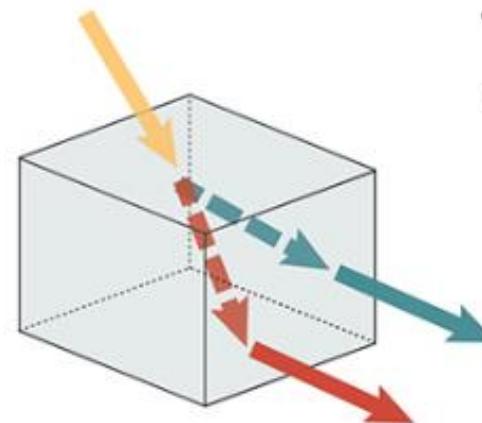
Carroll et al 1990, PRD, 41, 1231

Carroll & Field 1991, PRD, 43, 3789

Harari & Sikivie 1992, PLB, 289, 67

$$\beta = -\frac{1}{2} g_{\phi\gamma} \int \frac{\partial \phi}{\partial t} dt$$

Cosmic birefringence



BIREFRINGENCE Birefringence describes the optical property where a ray of light is split by polarization into two rays taking slightly different paths.

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Cosmic birefringence

Faraday rotation from primordial magnetic fields

Subramanian 2016, Rep Prog Phys, 79, 076901

Superluminal Lorentz-violating electrodynamics emerging from a non-vanishing Weyl tensor

Shore 2005, Nucl Phys B, 717, 86118

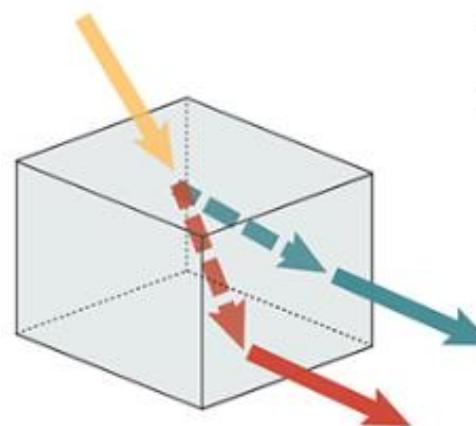
Quantum gravity models that modify the dispersion relation of photons

Gleiser & Kozameh 2001, PRD, 64, 8, 083007

$$\beta \propto \nu^{-2}$$

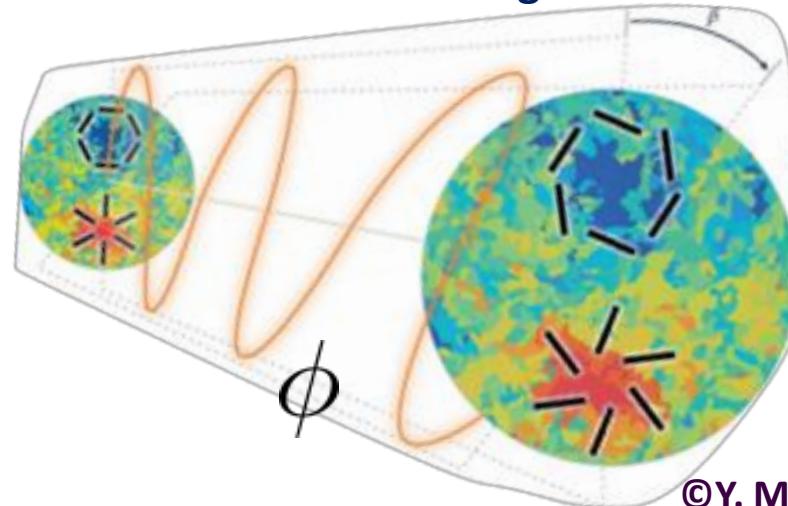
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$$\beta \propto \nu^2$$



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Cosmic birefringence



©Y. Minami

Cosmic birefringence rotates the intrinsic signal

$$\begin{pmatrix} E_{\ell m}^o \\ B_{\ell m}^o \end{pmatrix} = \begin{pmatrix} \cos(2\beta) & -\sin(2\beta) \\ \sin(2\beta) & \cos(2\beta) \end{pmatrix} \begin{pmatrix} E_{\ell m}^{\text{cmb}} \\ B_{\ell m}^{\text{cmb}} \end{pmatrix}$$

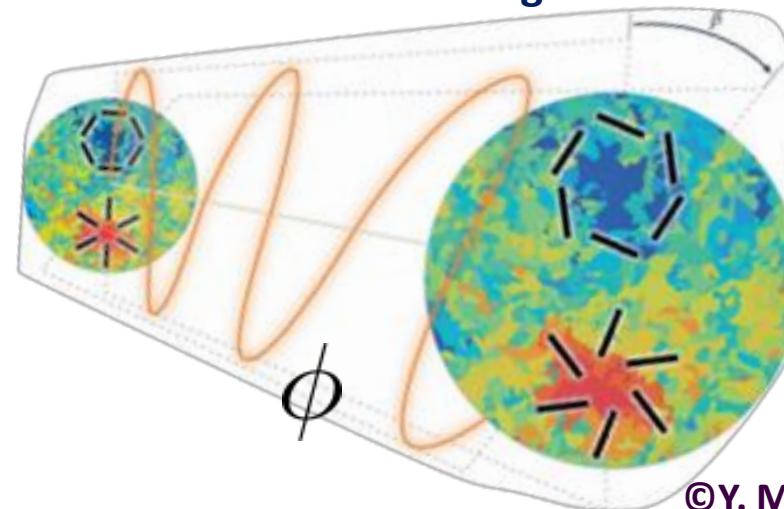
so the observed angular power spectrum becomes

$$C_\ell^{EB,o} = \frac{1}{2} \sin(4\beta) (C_\ell^{EE,\text{cmb}} - C_\ell^{BB,\text{cmb}}) + \cos(4\beta) C_\ell^{EB,\text{cmb}}$$

0

Λ CDM

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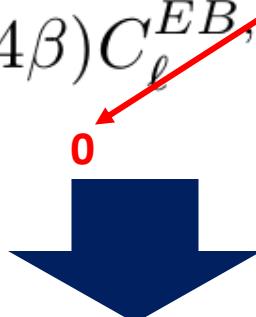
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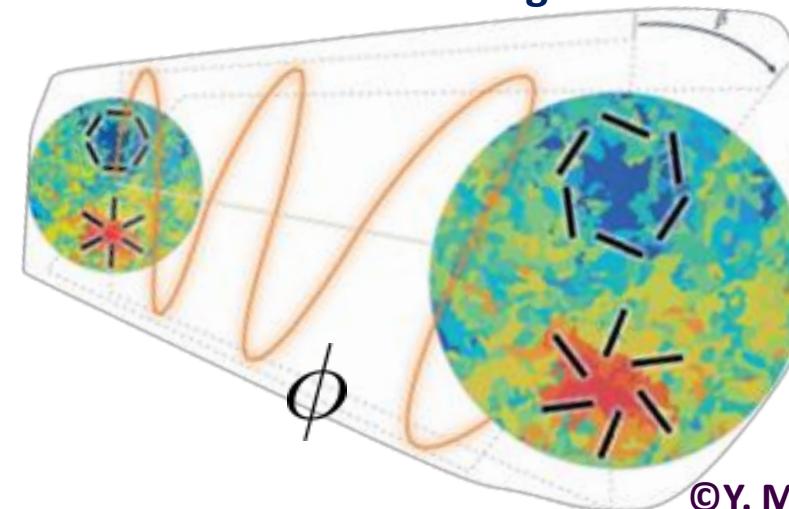
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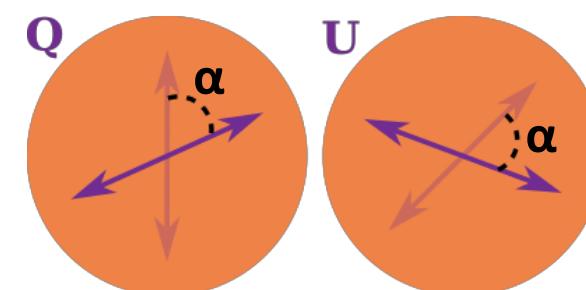
Cosmic birefringence



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OR

Miscalibration of the detector's polarisation angle



Unknown α miscalibration

Completely degenerate with birefringence

Krachmalnicoff et al 2022, JCAP, 01, 039

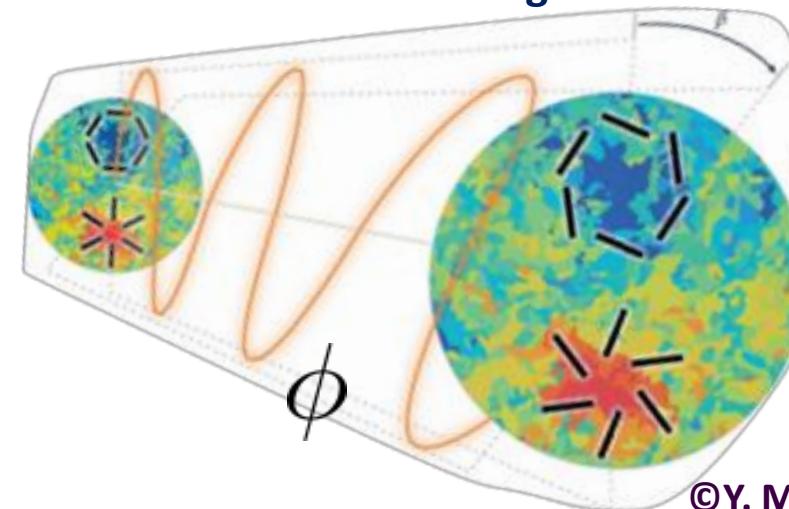
The observed signal is actually

$$\begin{pmatrix} E_{\ell m}^o \\ B_{\ell m}^o \end{pmatrix} = \begin{pmatrix} \cos(2\alpha + 2\beta) & -\sin(2\alpha + 2\beta) \\ \sin(2\alpha + 2\beta) & \cos(2\alpha + 2\beta) \end{pmatrix} \begin{pmatrix} E_{\ell m}^{\text{cmb}} \\ B_{\ell m}^{\text{cmb}} \end{pmatrix}$$

so that EB yields $\alpha + \beta$

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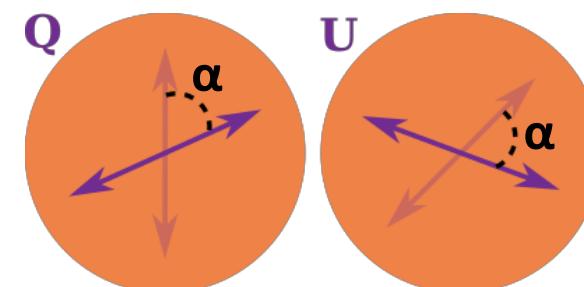
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Requires absolute calibration of instrumental polarisation angles

Previous measurements limited to $\approx 0.5^\circ - 1^\circ$

Wu et al 2009, PRL, 102, 161302
QUaD

$$\beta = 0.55^\circ \pm 0.82^\circ \text{ (stat)} \pm 0.5^\circ \text{ (sys)}$$

WMAP 9-year

Hinshaw et al 2013, ApJS, 208, 19

$$\beta = -0.36^\circ \pm 1.24^\circ \text{ (stat)} \pm 1.5^\circ \text{ (sys)}$$

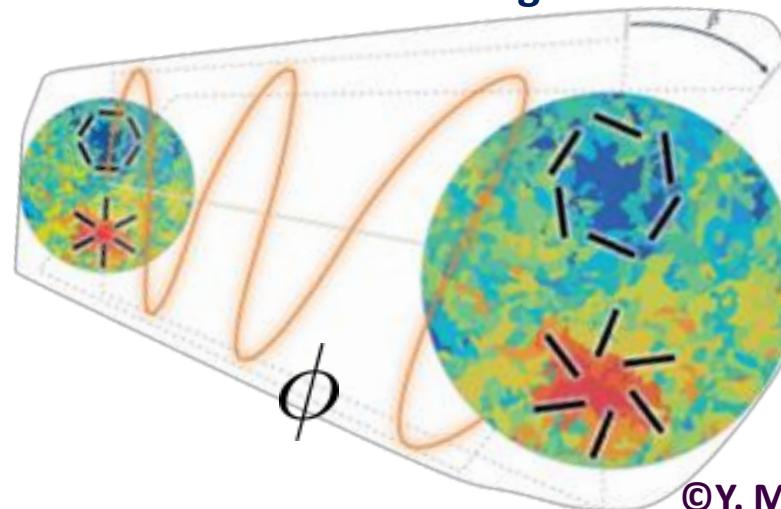
Planck 2016

Planck XLIX 2016, A&A, 596, A110

$$\beta = 0.31^\circ \pm 0.05^\circ \text{ (stat)} \pm 0.28^\circ \text{ (sys)}$$

⋮

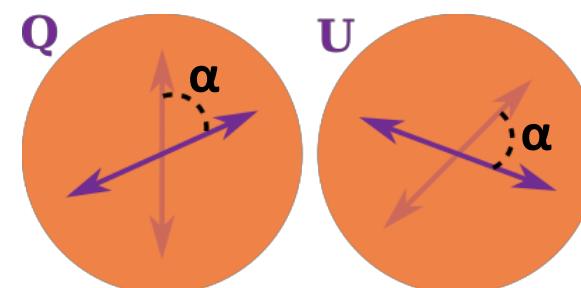
Cosmic birefringence



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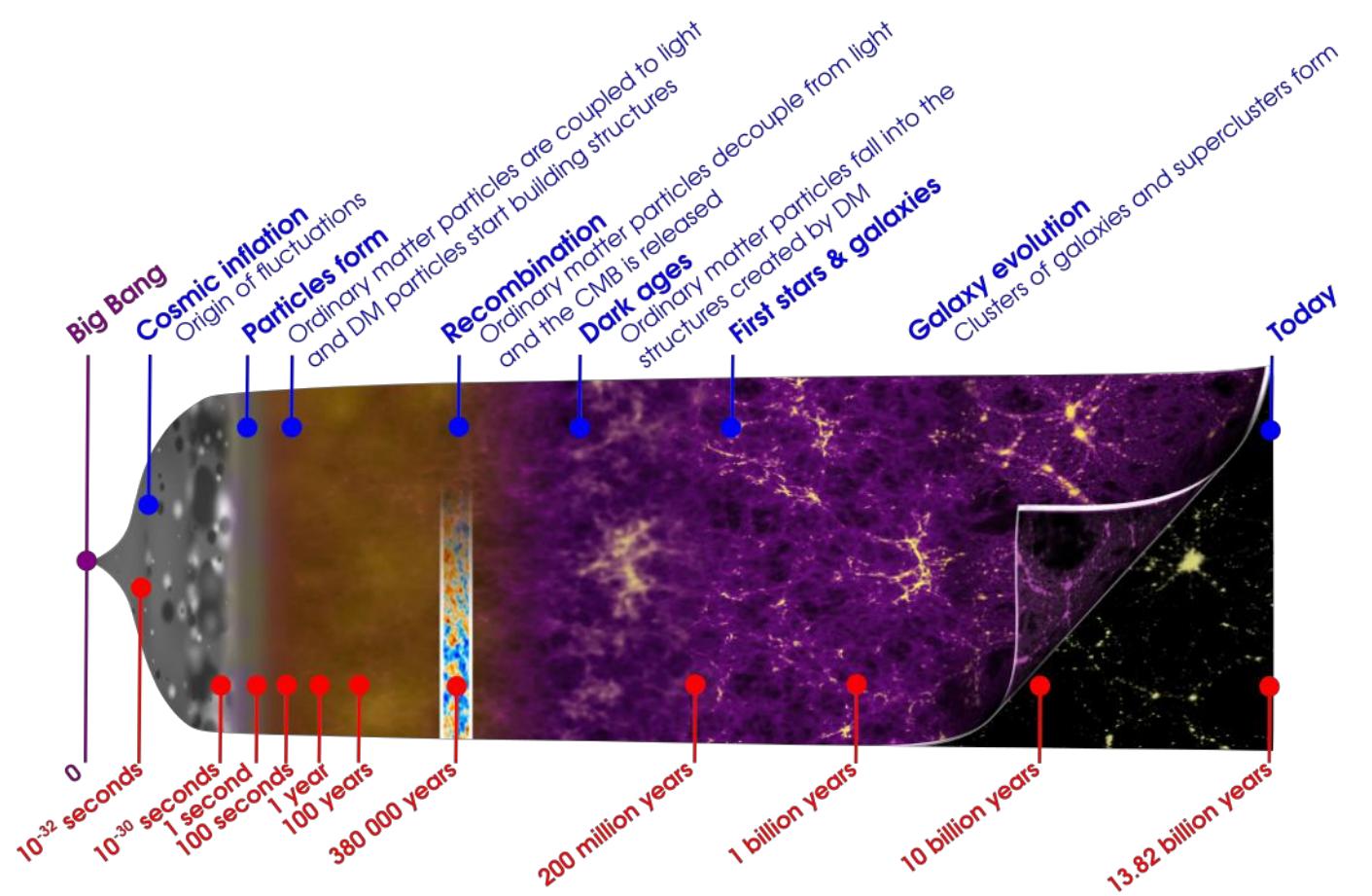
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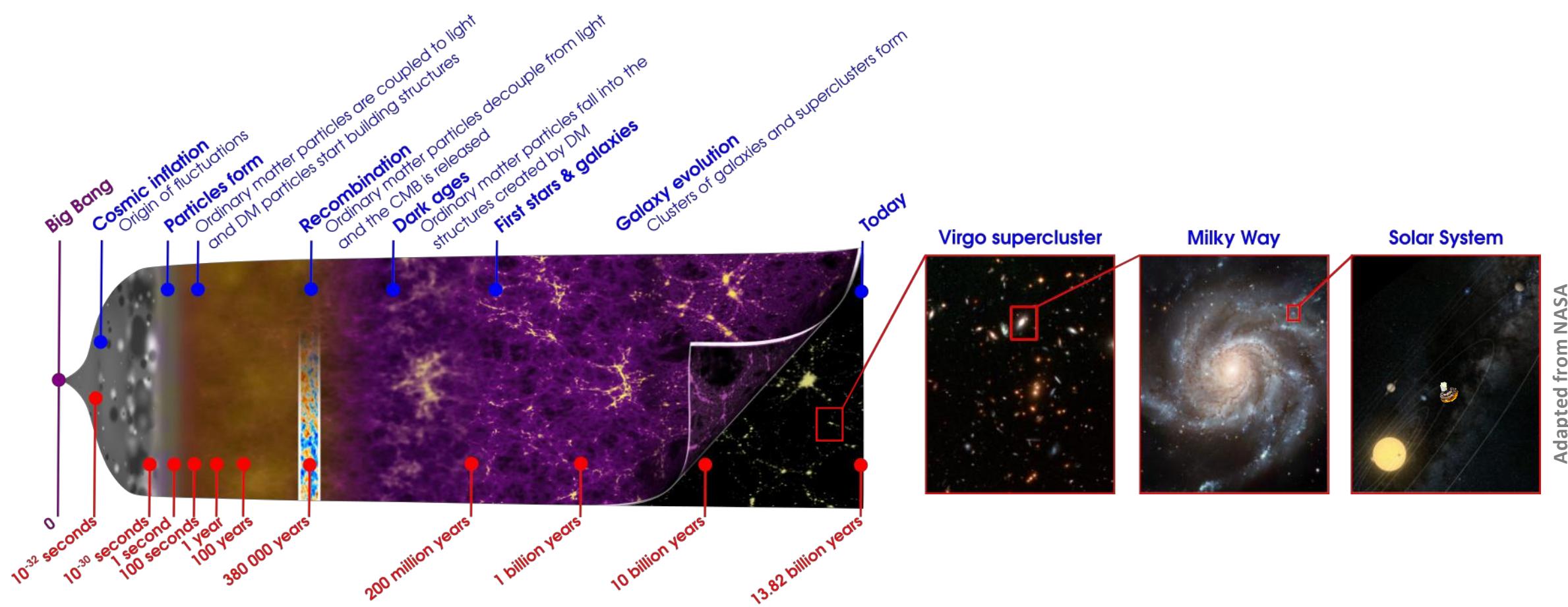
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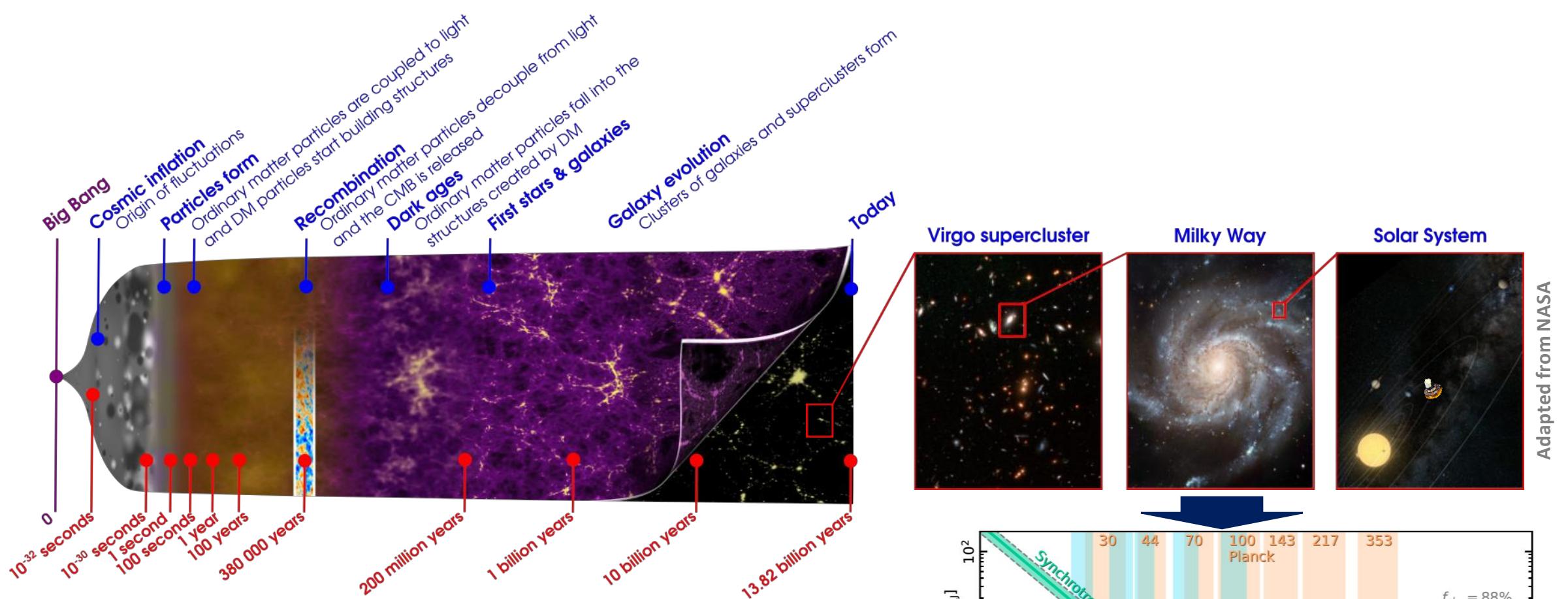


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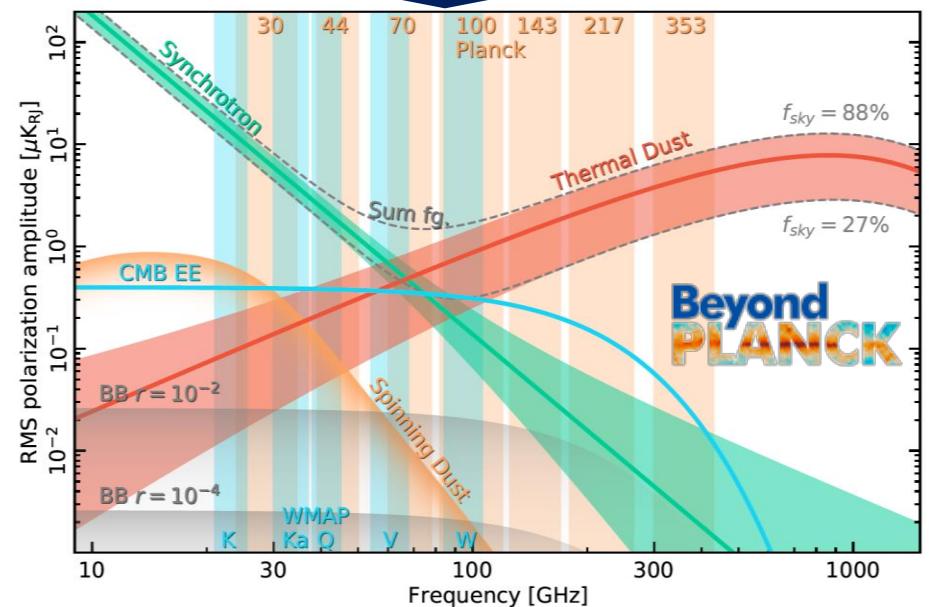
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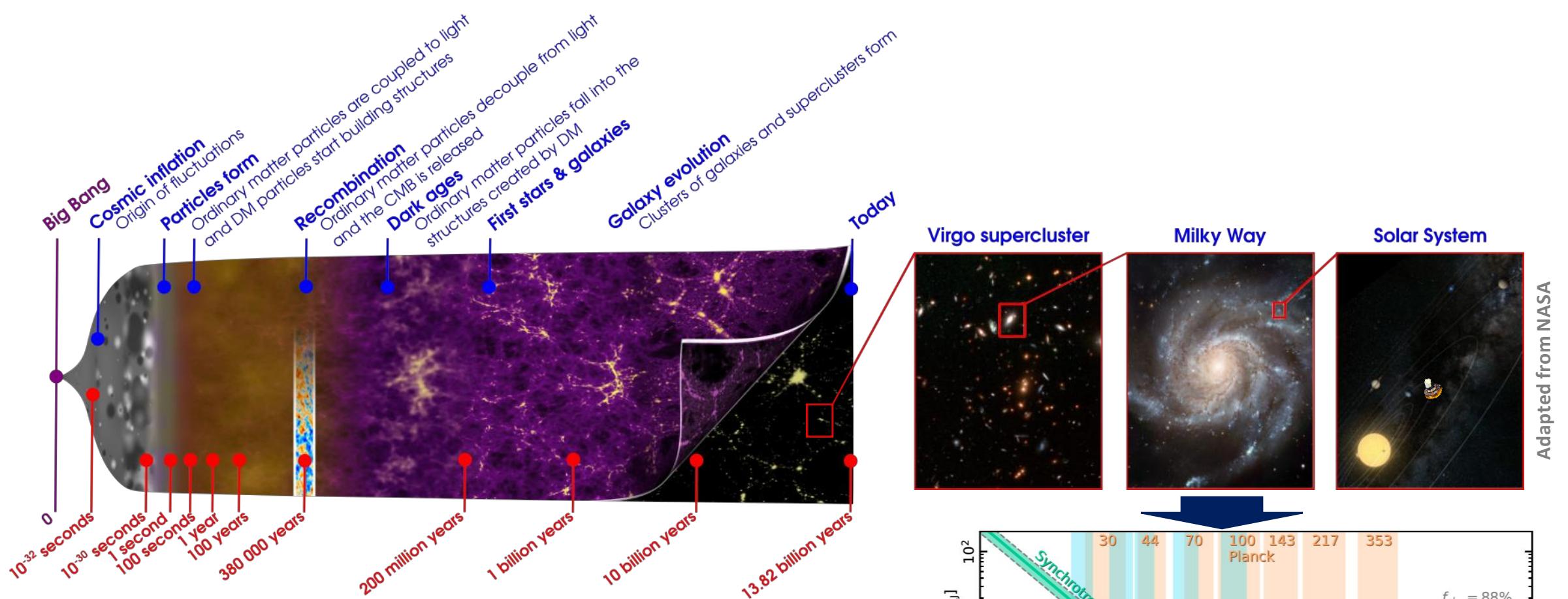






Adapted from NASA





Adapted from NASA

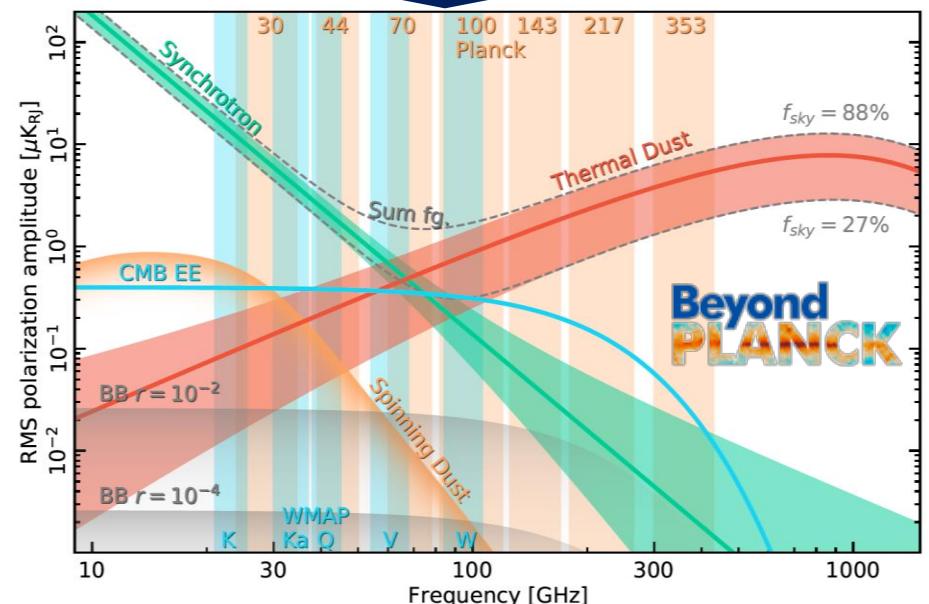


Birefringence depends on the propagation length of photons

Galactic foreground emission is not significantly affected by cosmic birefringence

Use foregrounds as our calibrator

Minami et al 2019, PTEP, 083E02



Self-calibrate signal against foreground emission

Observed signal is a rotation of the CMB and Galactic foreground emissions

$$\begin{pmatrix} E_{\ell m}^o \\ B_{\ell m}^o \end{pmatrix} = \begin{pmatrix} \cos(2\alpha) - \sin(2\alpha) \\ \sin(2\alpha) \quad \cos(2\alpha) \end{pmatrix} \begin{pmatrix} E_{\ell m}^{fg} \\ B_{\ell m}^{fg} \end{pmatrix} + \begin{pmatrix} \cos(2\alpha + 2\beta) - \sin(2\alpha + 2\beta) \\ \sin(2\alpha + 2\beta) \quad \cos(2\alpha + 2\beta) \end{pmatrix} \begin{pmatrix} E_{\ell m}^{cmb} \\ B_{\ell m}^{cmb} \end{pmatrix}$$

so the observed EB angular power spectrum is

$$C_\ell^{EB,o} = \frac{\tan(4\alpha)}{2} \left(C_\ell^{EE,o} - C_\ell^{BB,o} \right) + \frac{1}{\cos(4\alpha)} C_\ell^{EB,fg} + \frac{\sin(4\beta)}{2\cos(4\alpha)} \left(C_\ell^{EE,cmb} - C_\ell^{BB,cmb} \right)$$

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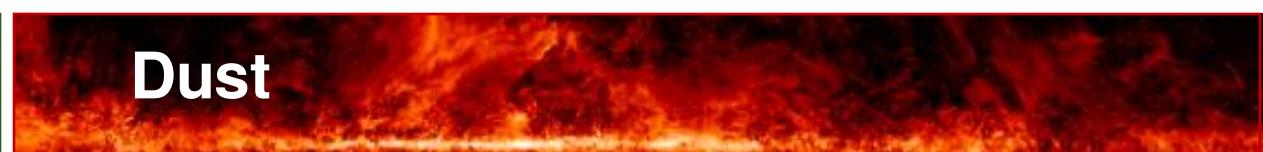
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Synch EB statistically compatible with null

Martire et al, JCAP 04 003 (2022)

QUIJOTE, MNRAS 519 3383 (2023)



Misalignment between dust filaments and Galactic magnetic fields creates TB and EB correlations

Planck reported :

- **Dust TB > 0**
- **A hint of dust EB > 0**

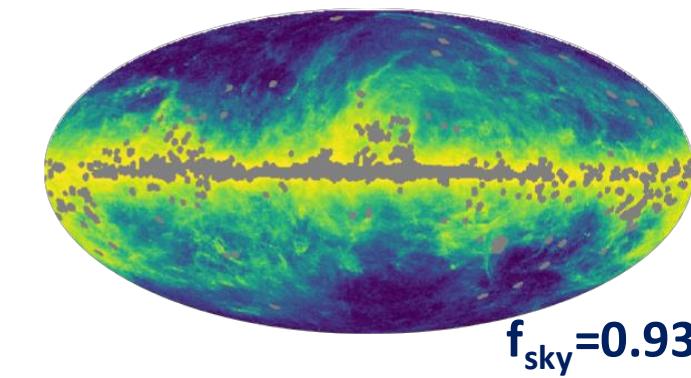
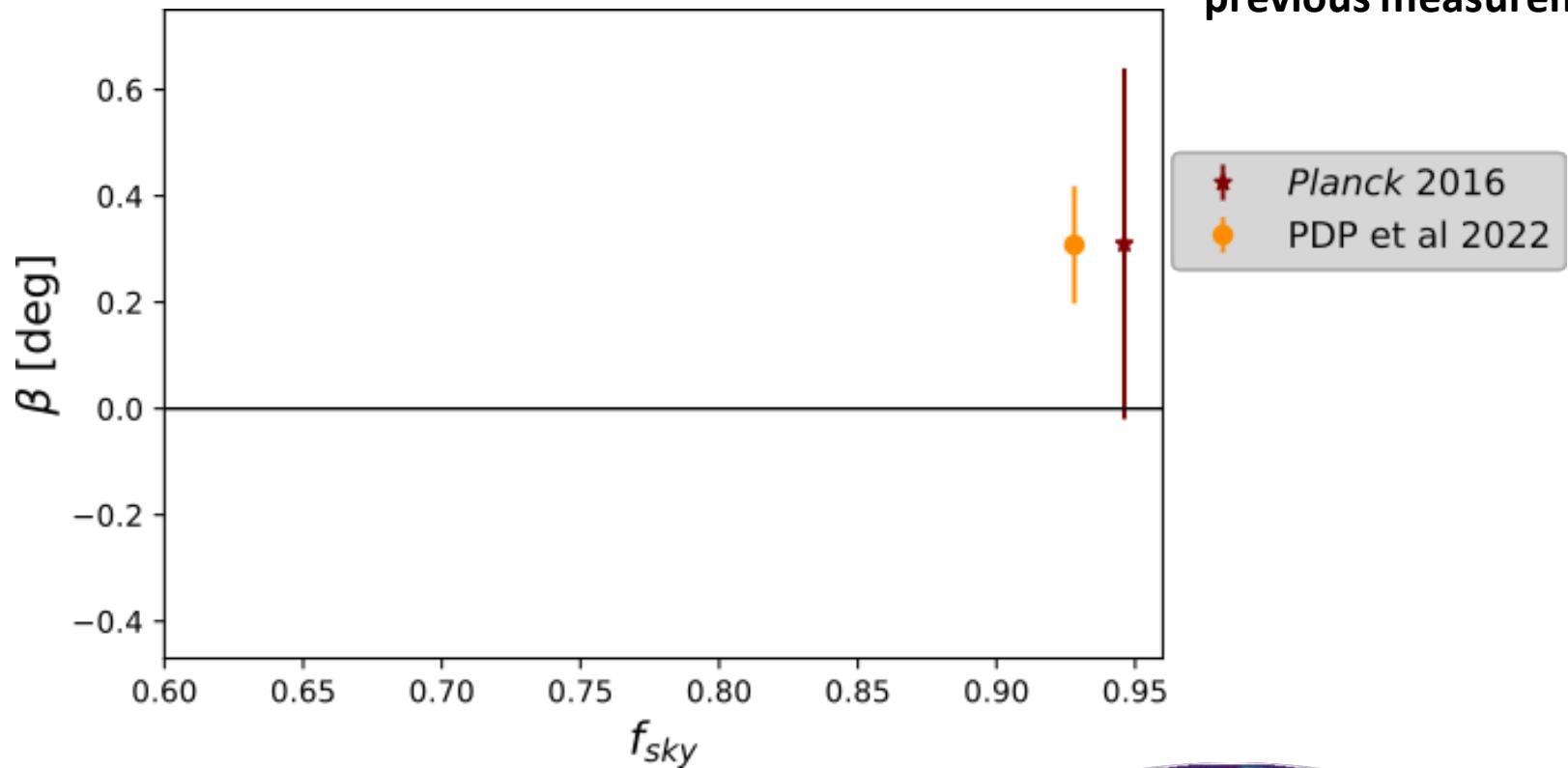
Clark et al, ApJ 919 53 (2021)

Cukierman et al, ApJ 946 106 (2023)

Planck, A&A 641 11 (2020)

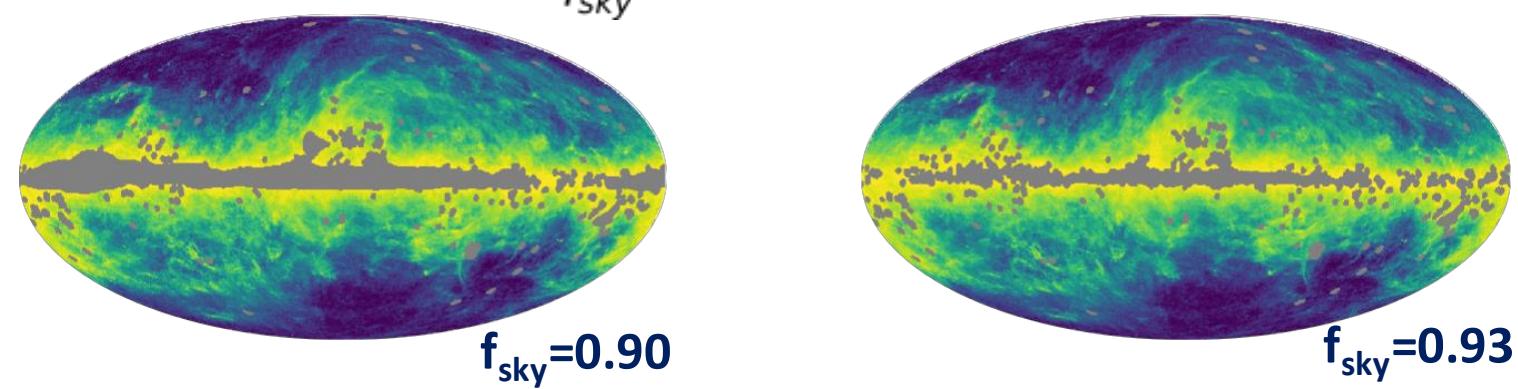
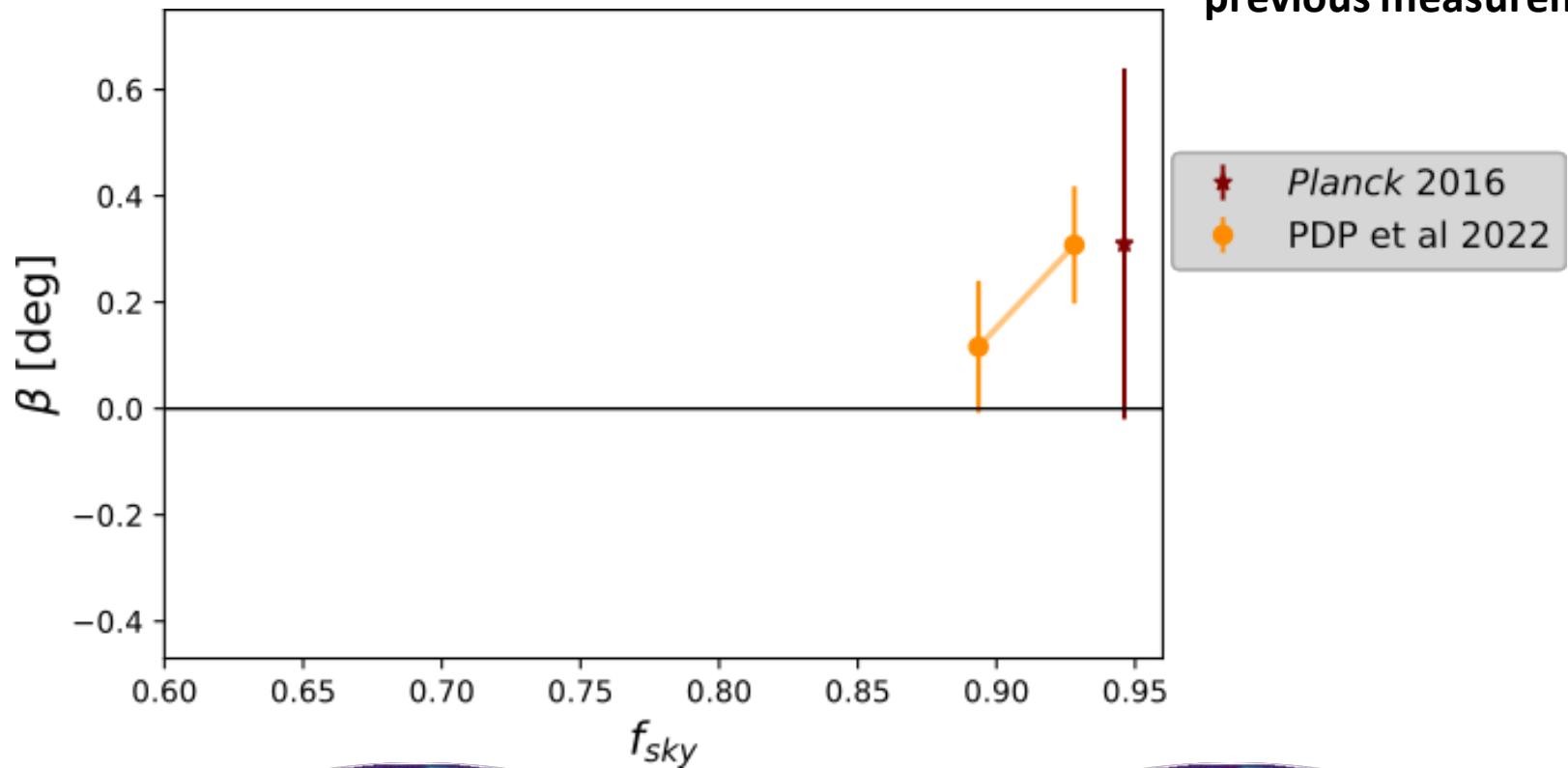
Detecting the impact of dust EB in NPIPE 100, 143, 217, 353GHz data

For nearly full-sky: $\beta = 0.30^\circ \pm 0.11^\circ$ (2.7σ) → Consistent with and more precise than previous measurements!



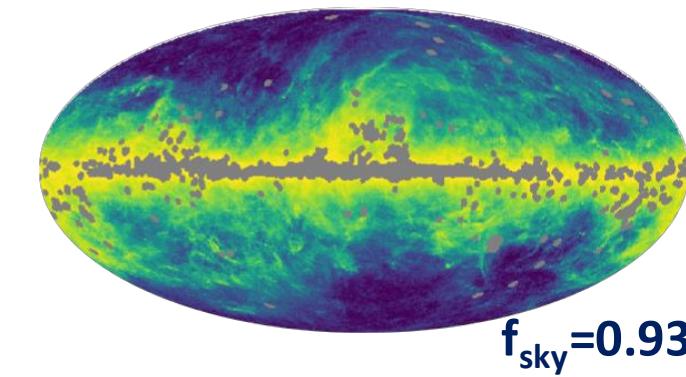
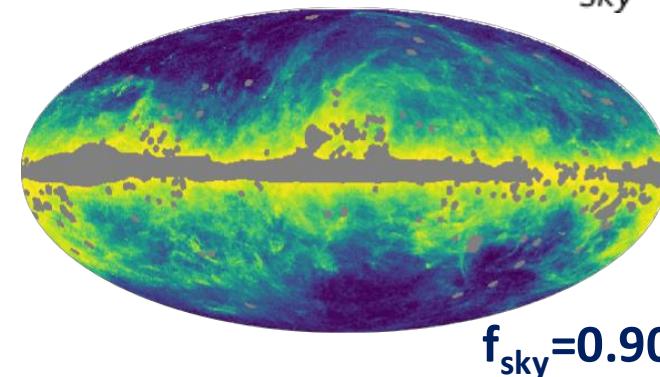
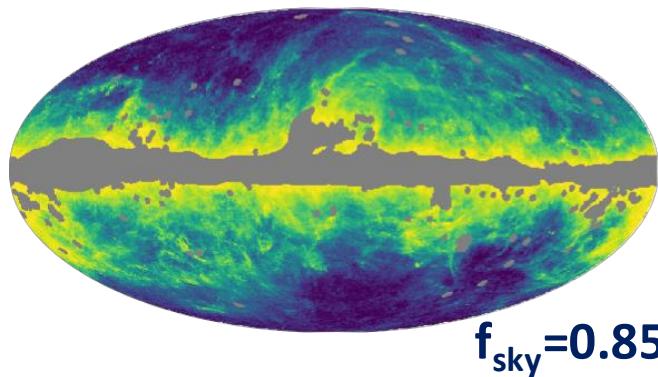
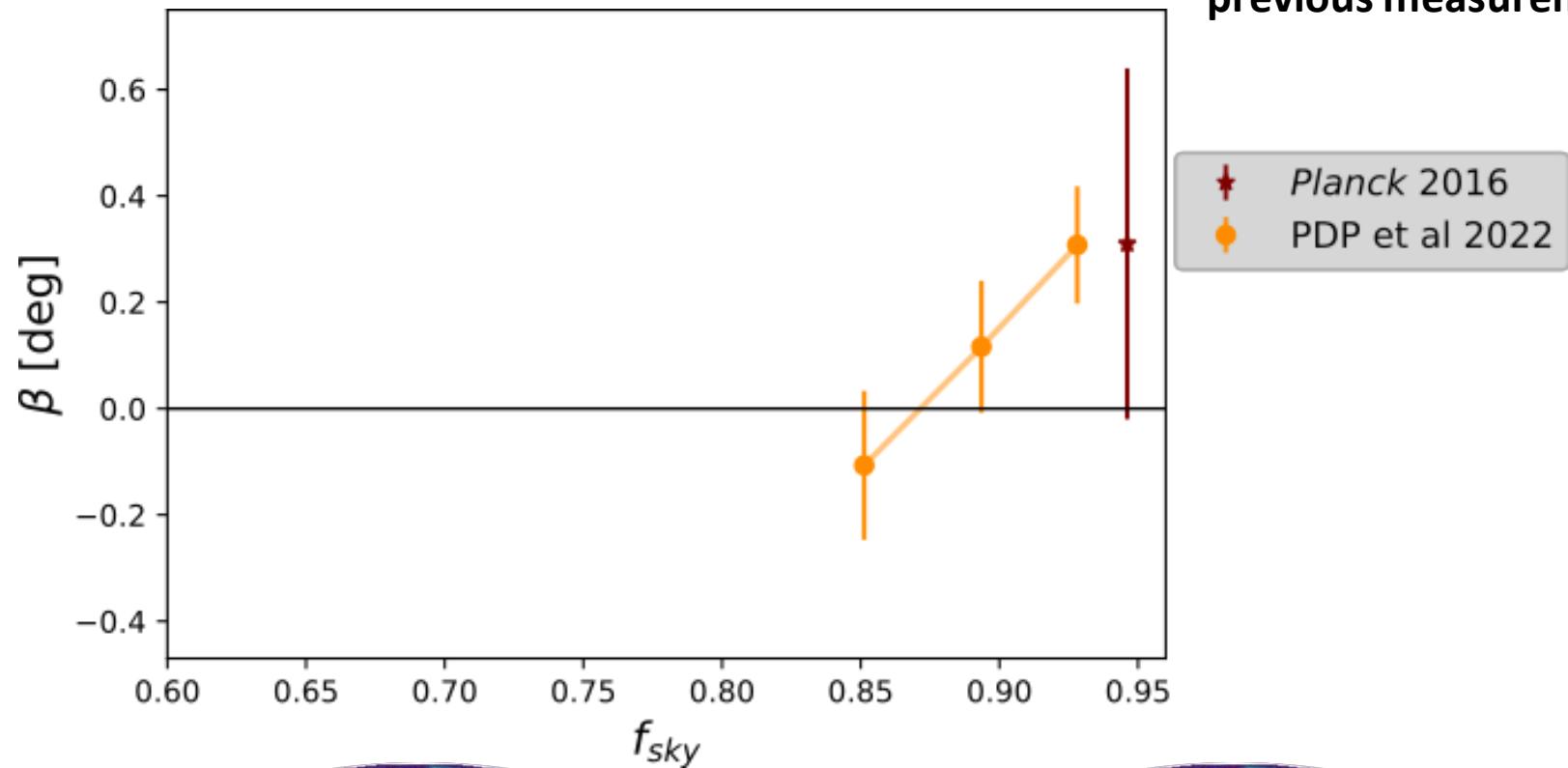
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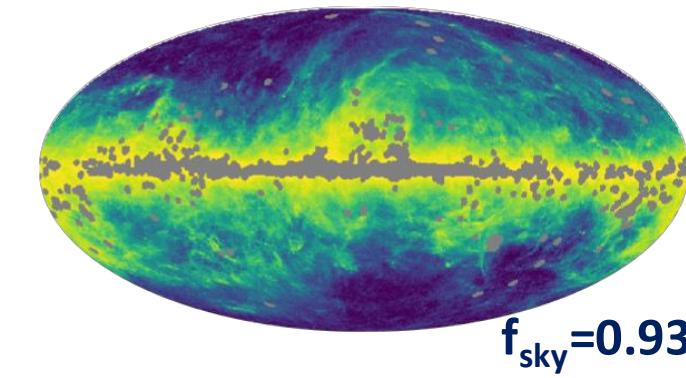
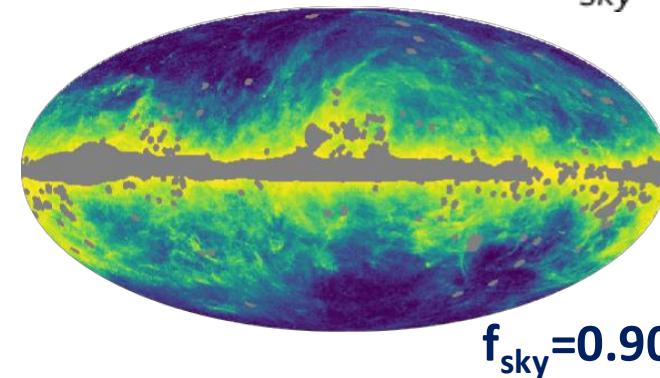
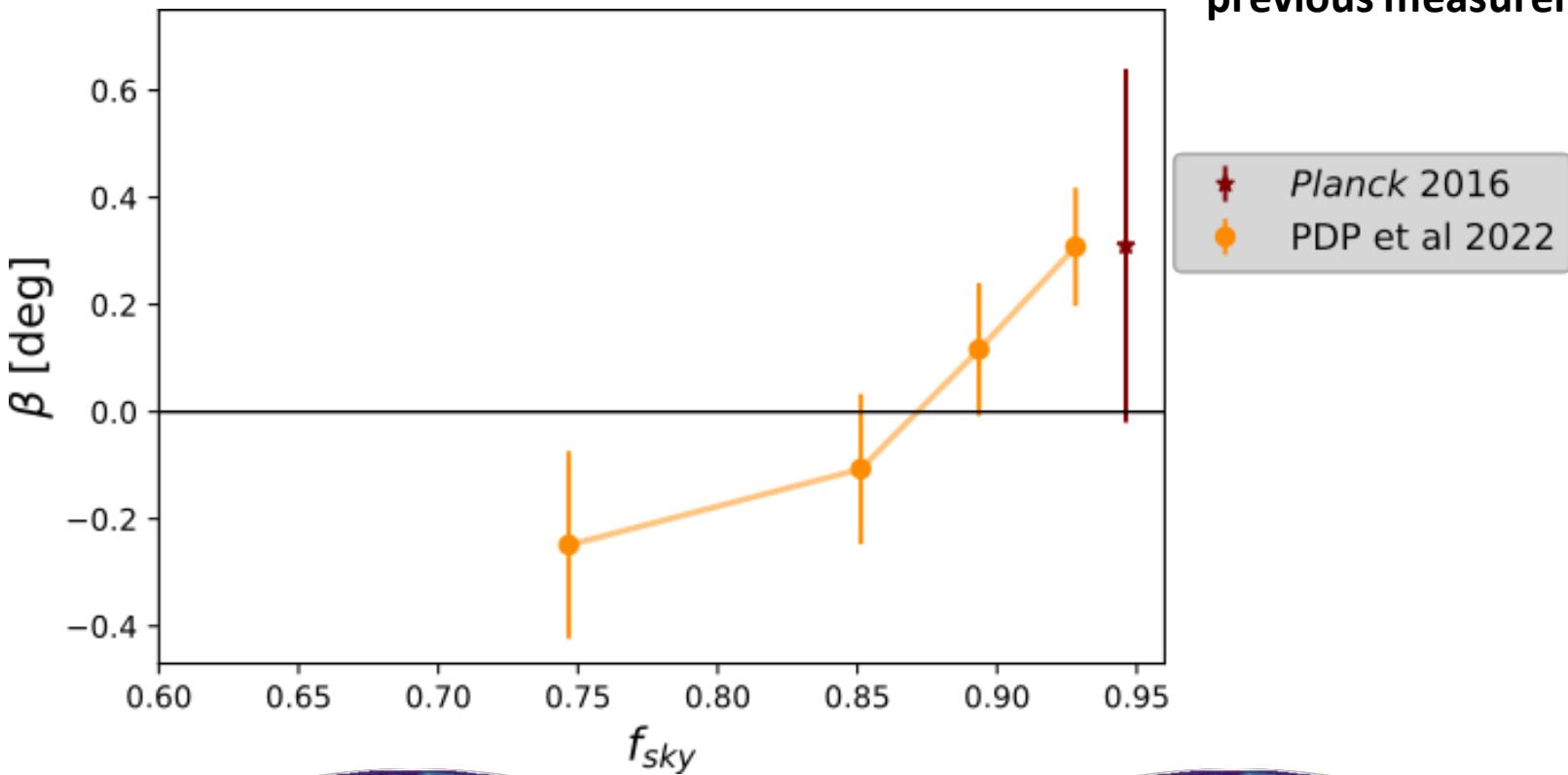
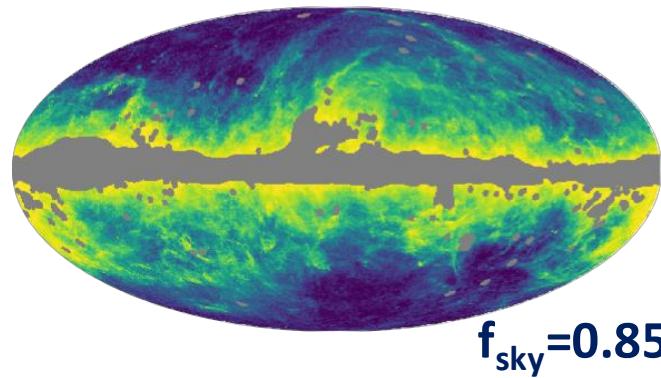
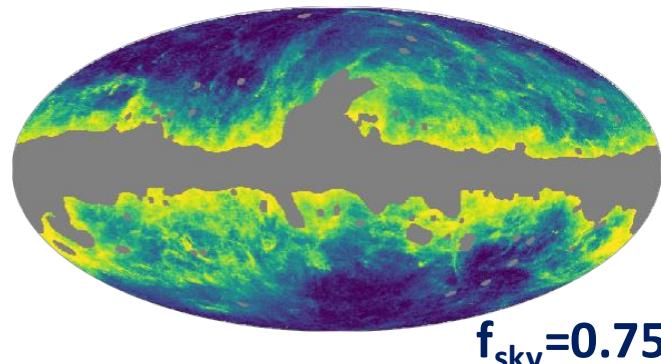
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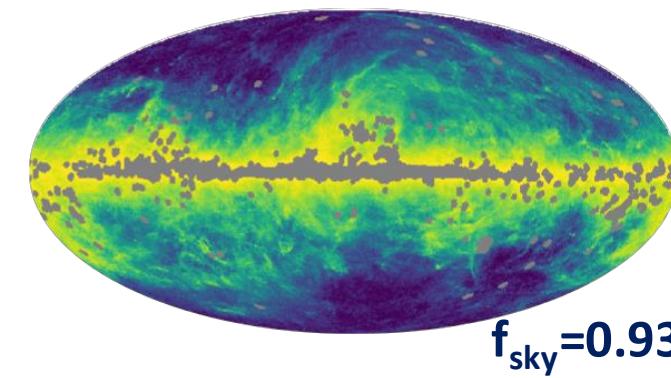
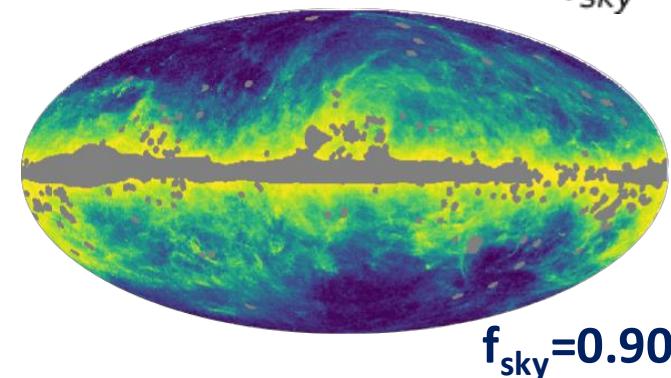
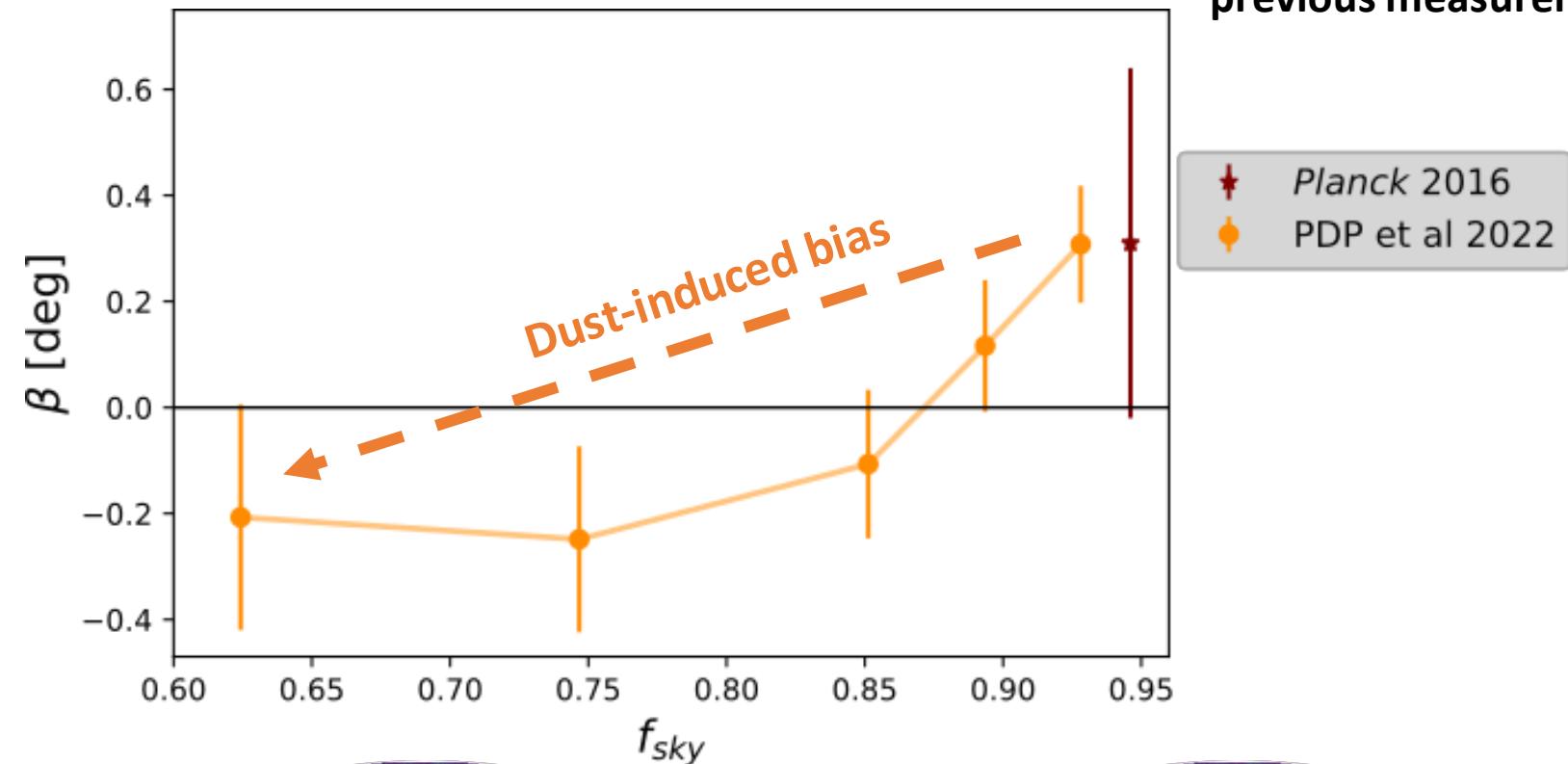
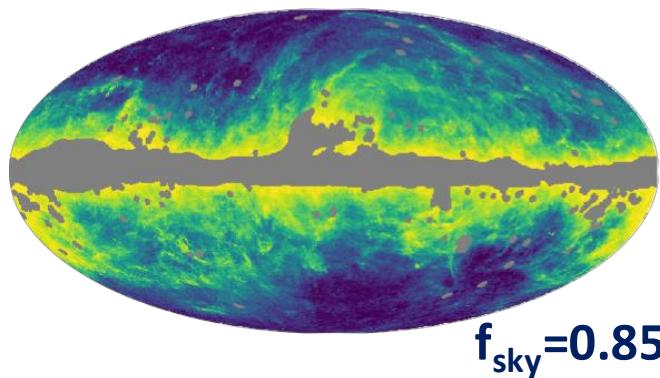
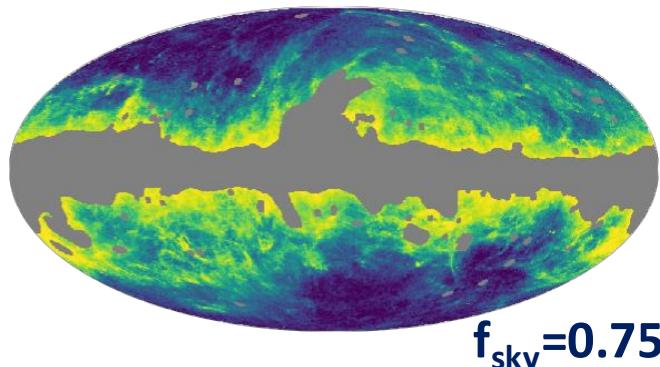
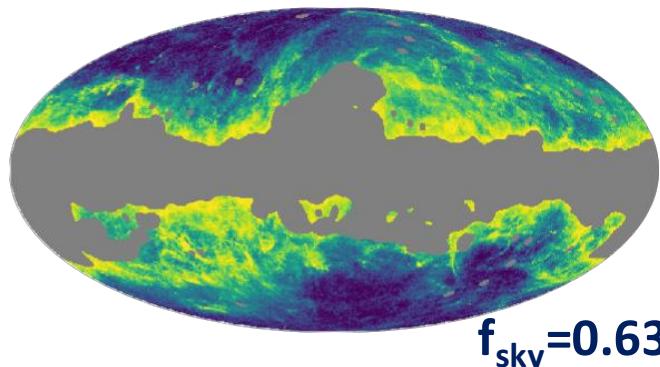
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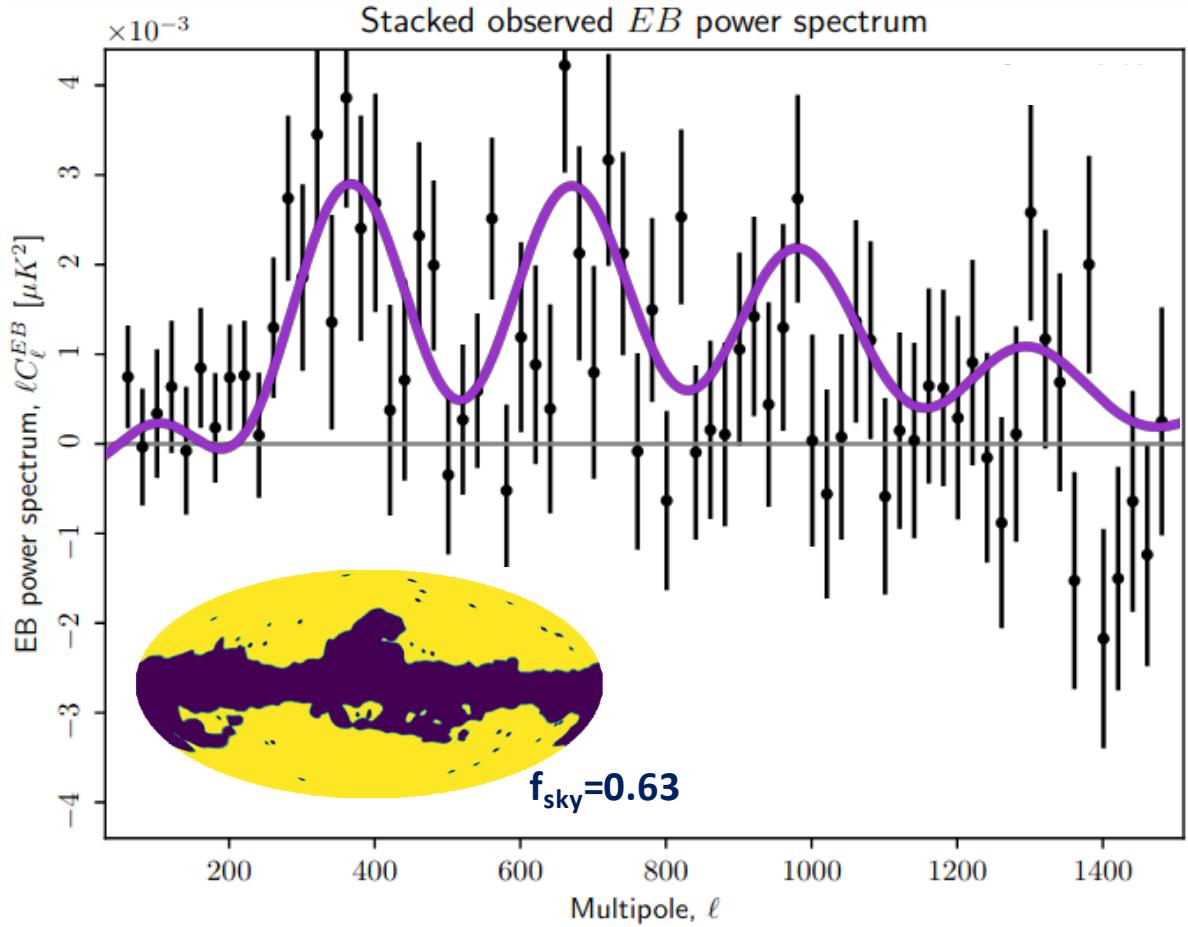
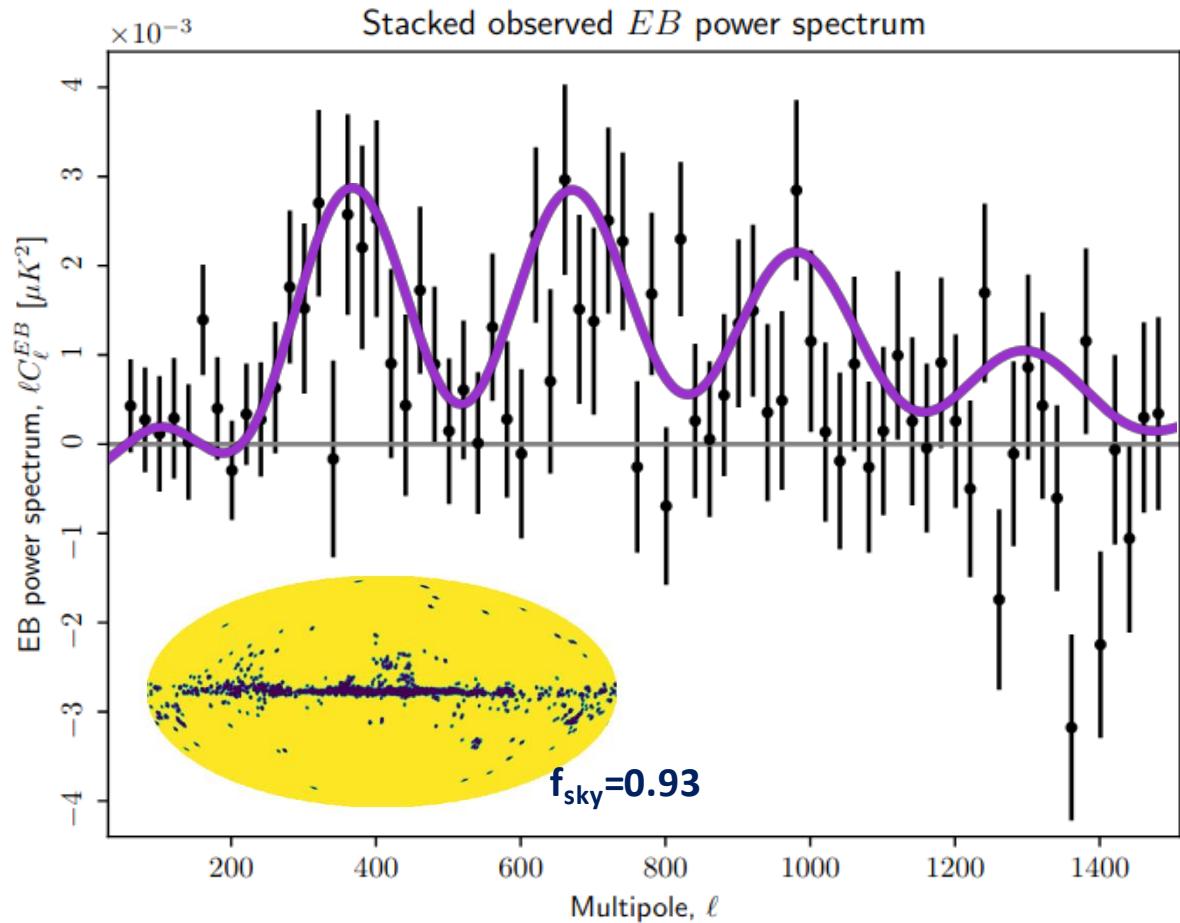


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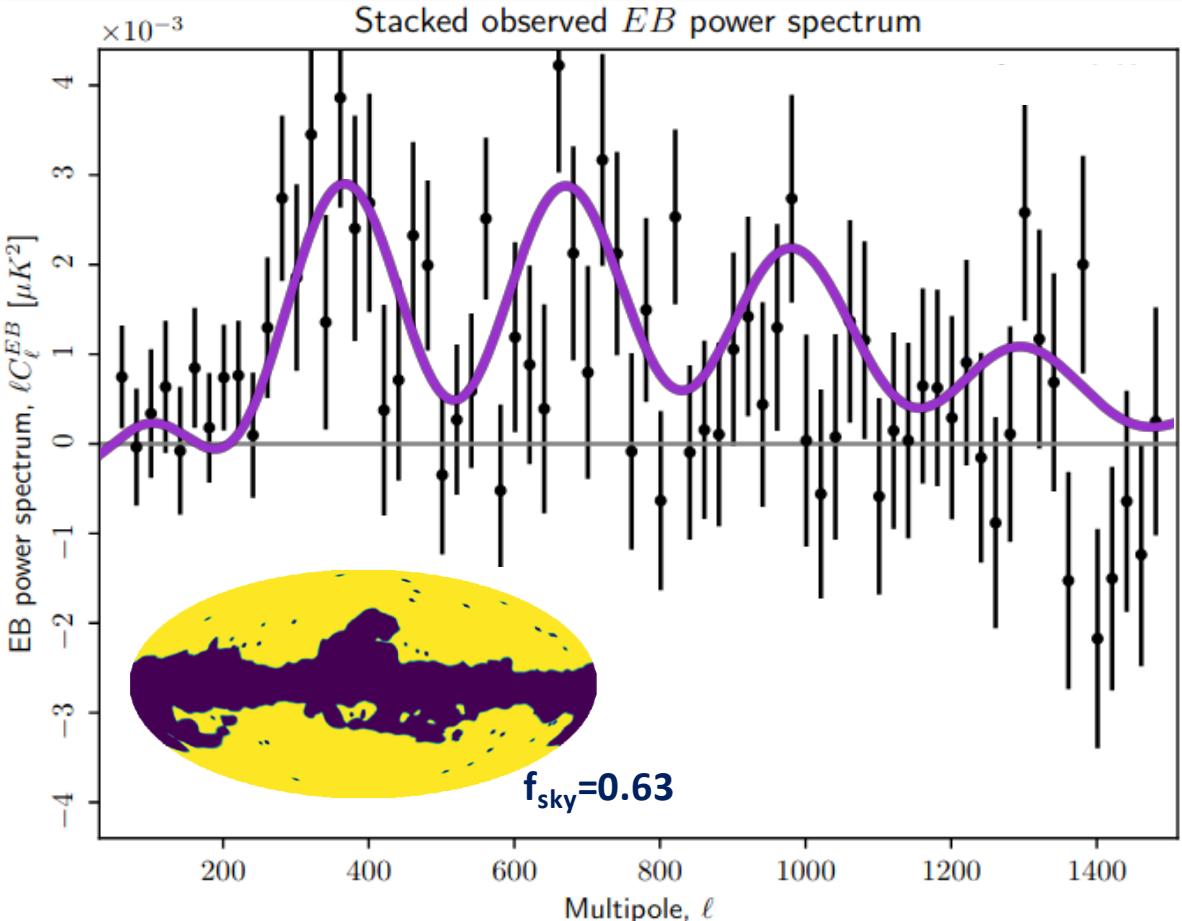
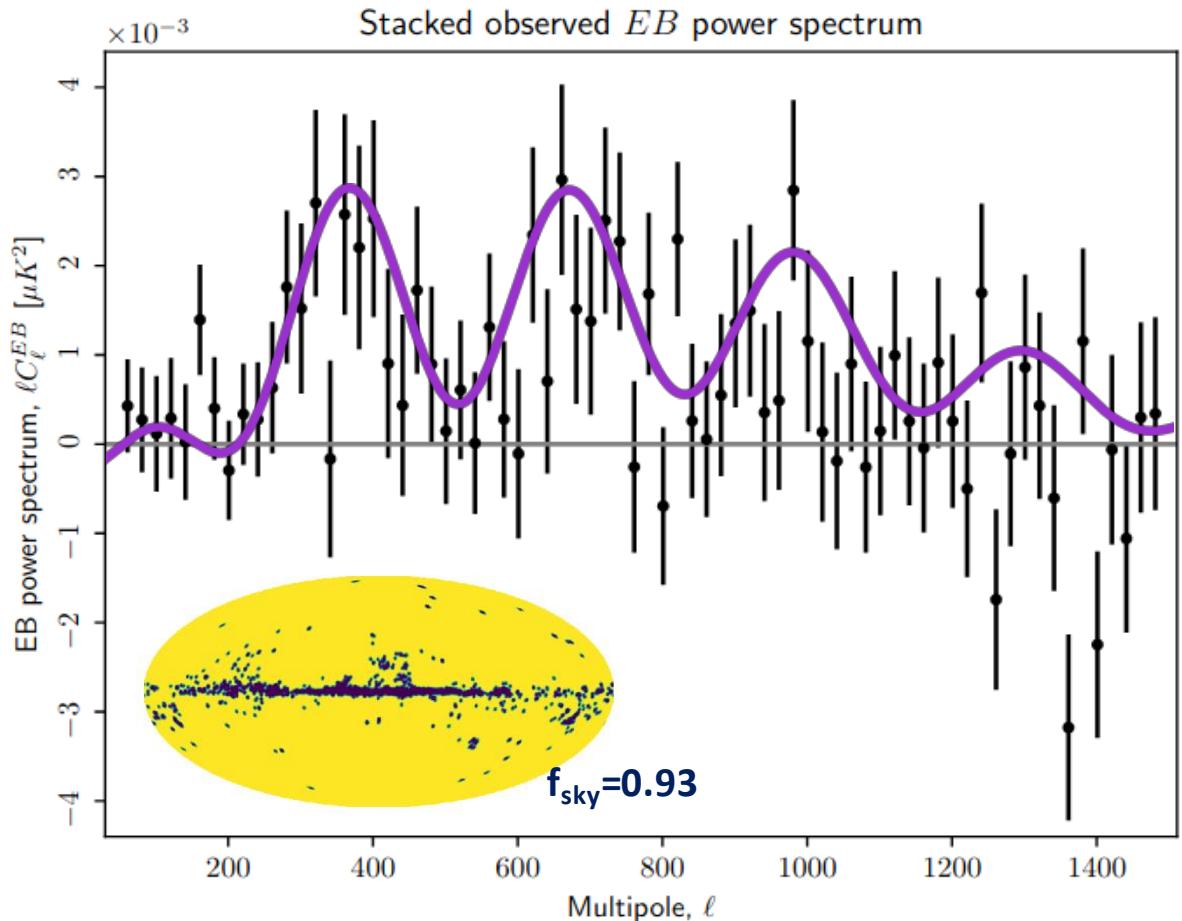


The EB signal created by birefringence exists regardless of the Galactic mask ...



Eskilt & Komatsu 2022, PRD, 106, 063503

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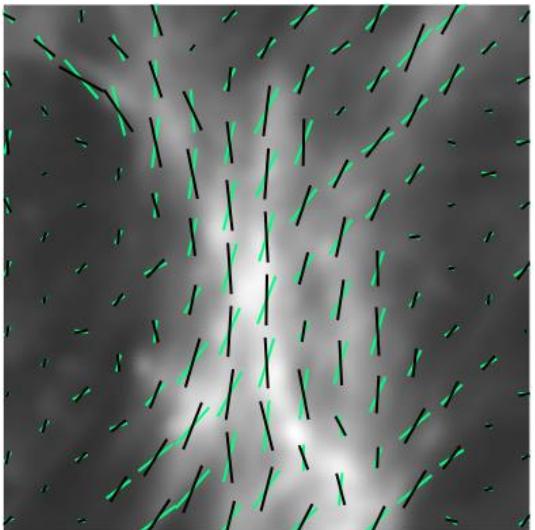


Eskilt & Komatsu 2022, PRD, 106, 063503

... but our inferred value of α depends on Galactic dust

$$C_\ell^{EB,o} = \frac{\tan(4\alpha)}{2} \left(C_\ell^{EE,o} - C_\ell^{BB,o} \right) + \boxed{\frac{1}{\cos(4\alpha)} C_\ell^{EB,fg}} + \frac{\sin(4\beta)}{2\cos(4\alpha)} \left(C_\ell^{EE,\text{cmb}} - C_\ell^{BB,\text{cmb}} \right)$$

Misalignment between dust filaments and the Galactic magnetic field



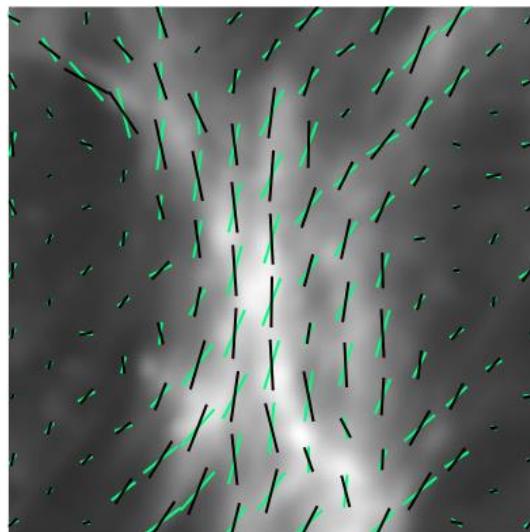
$$C_{\ell}^{EB, \text{dust}} \approx A_{\ell} C_{\ell}^{EE, \text{dust}} \frac{C_{\ell}^{TB, \text{dust}}}{C_{\ell}^{TE, \text{dust}}}$$

Take dust C_{ℓ} to be that of NPIPE @ 353GHz

A_{ℓ} free amplitude parameter

$$0 \leq A_{\ell} \ll 1$$

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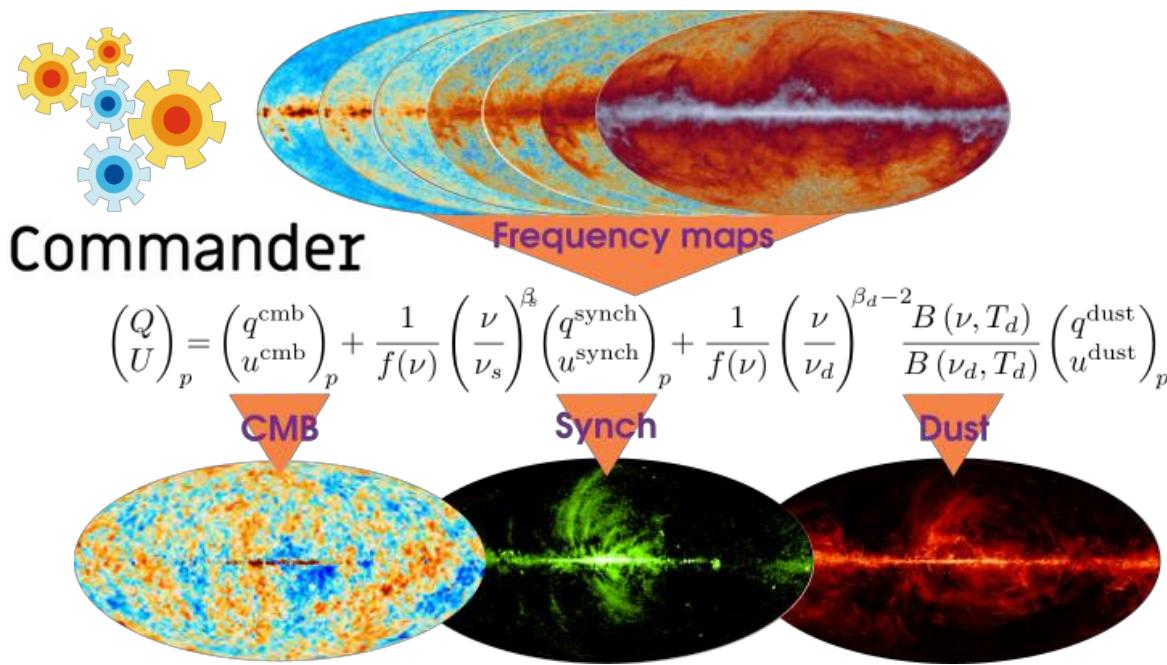
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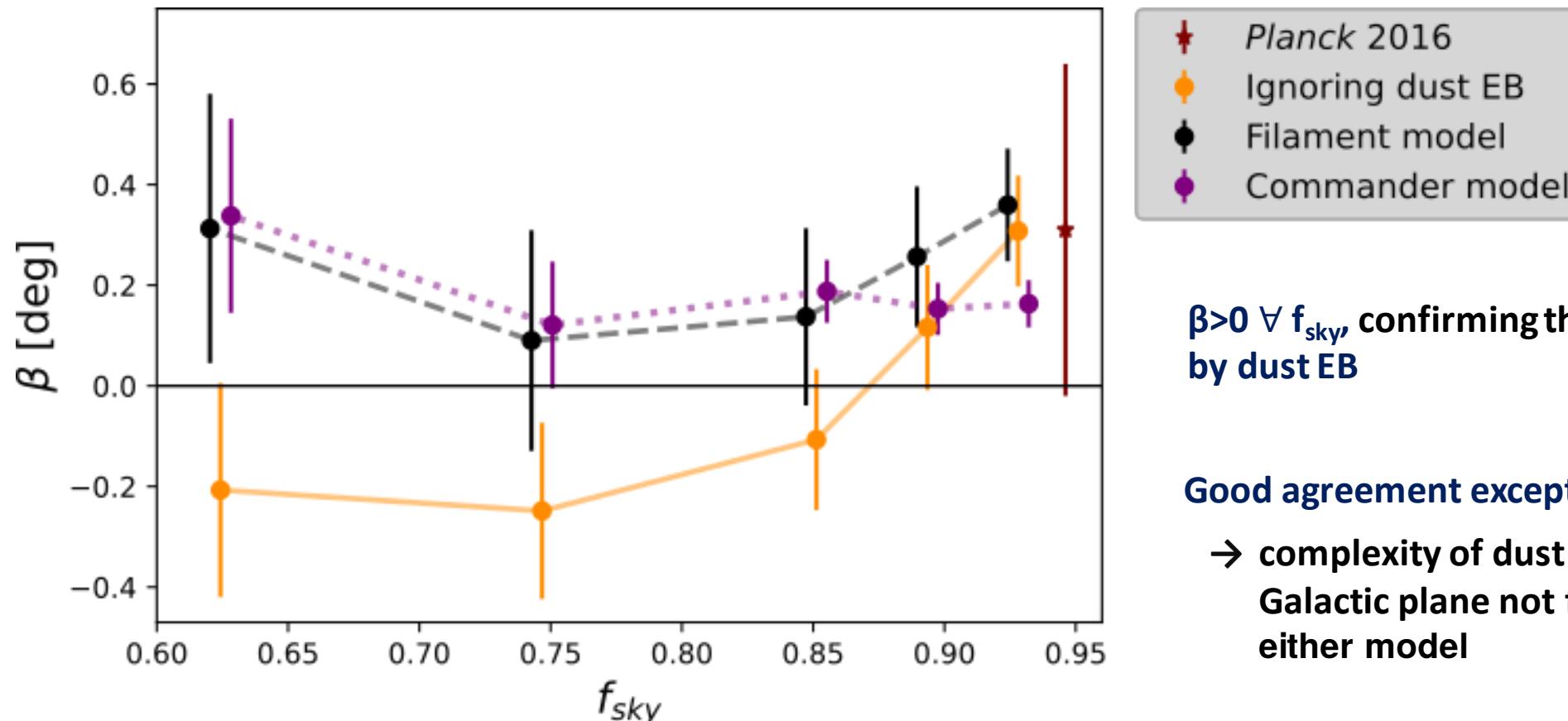
Take the Commander sky model as our foreground model



$$C_\ell^{EB, \text{dust}} \approx \mathcal{D} C_\ell^{EB, \text{Commander}}$$

\mathcal{D} free amplitude parameter

After correcting for dust EB in NPIPE 100, 143, 217, 353GHz data

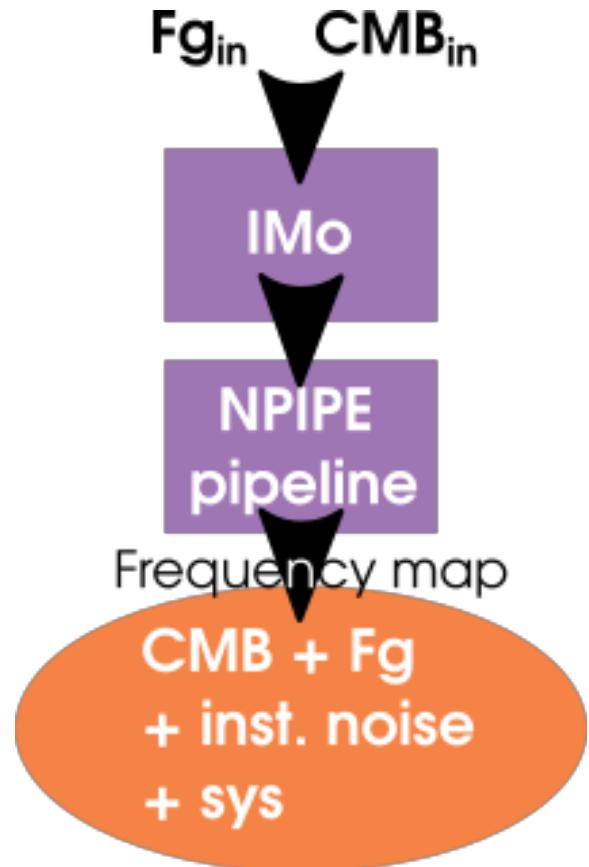


$\beta > 0 \forall f_{\text{sky}}$, confirming that the decline was caused by dust EB

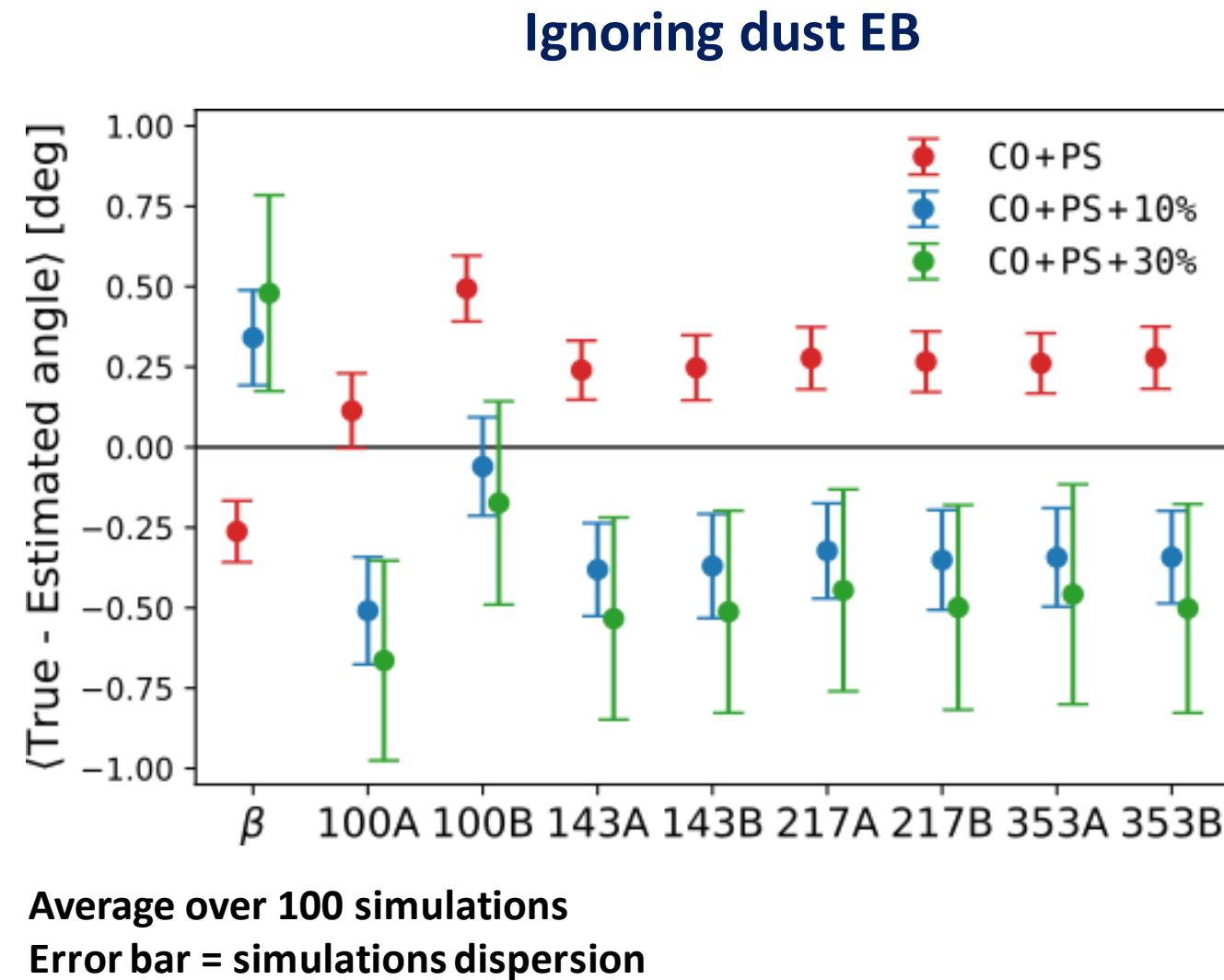
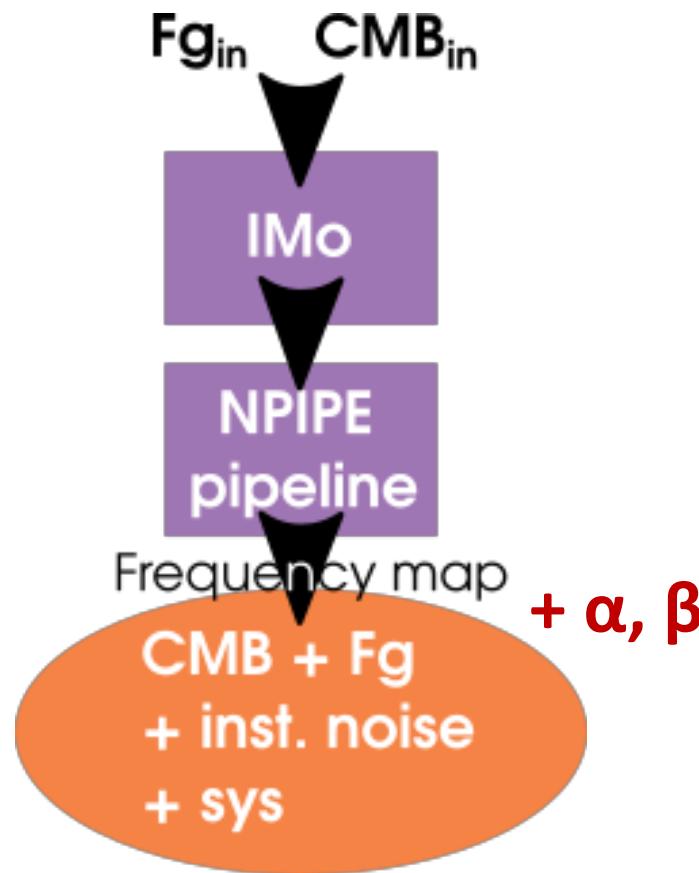
Good agreement except at $f_{\text{sky}} = 0.93$

→ complexity of dust emission near the Galactic plane not fully captured by either model

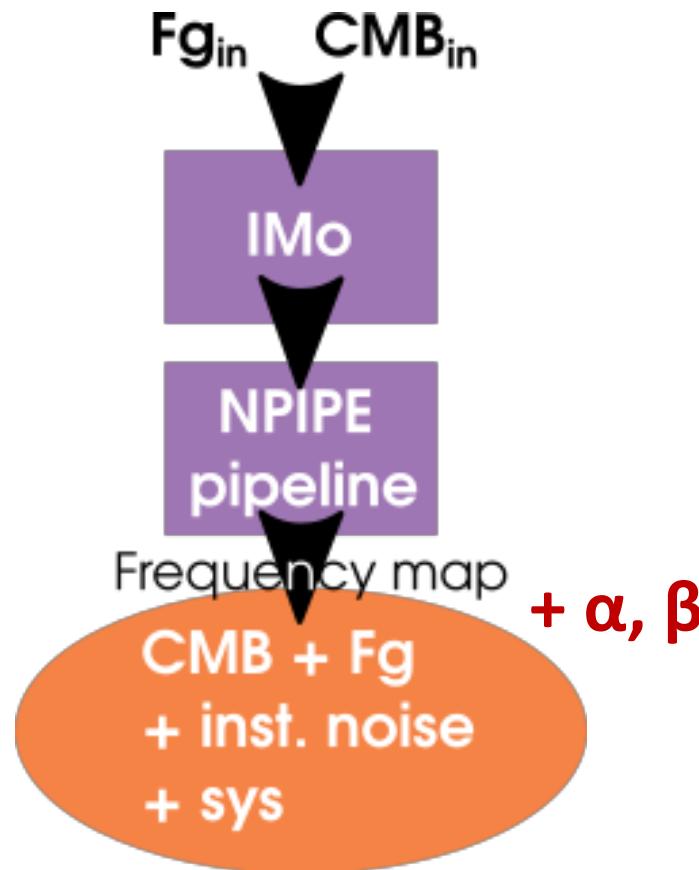
NPIPE end-to-end simulations



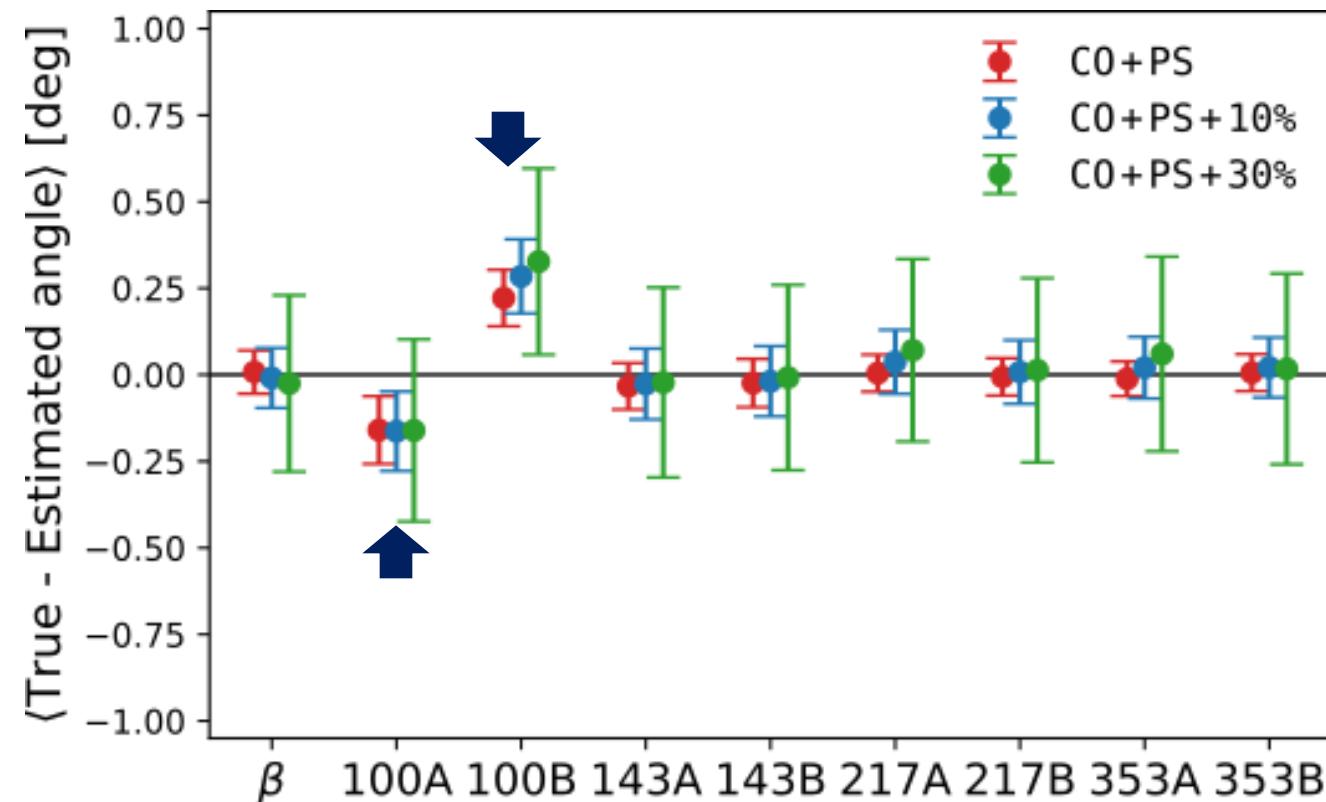
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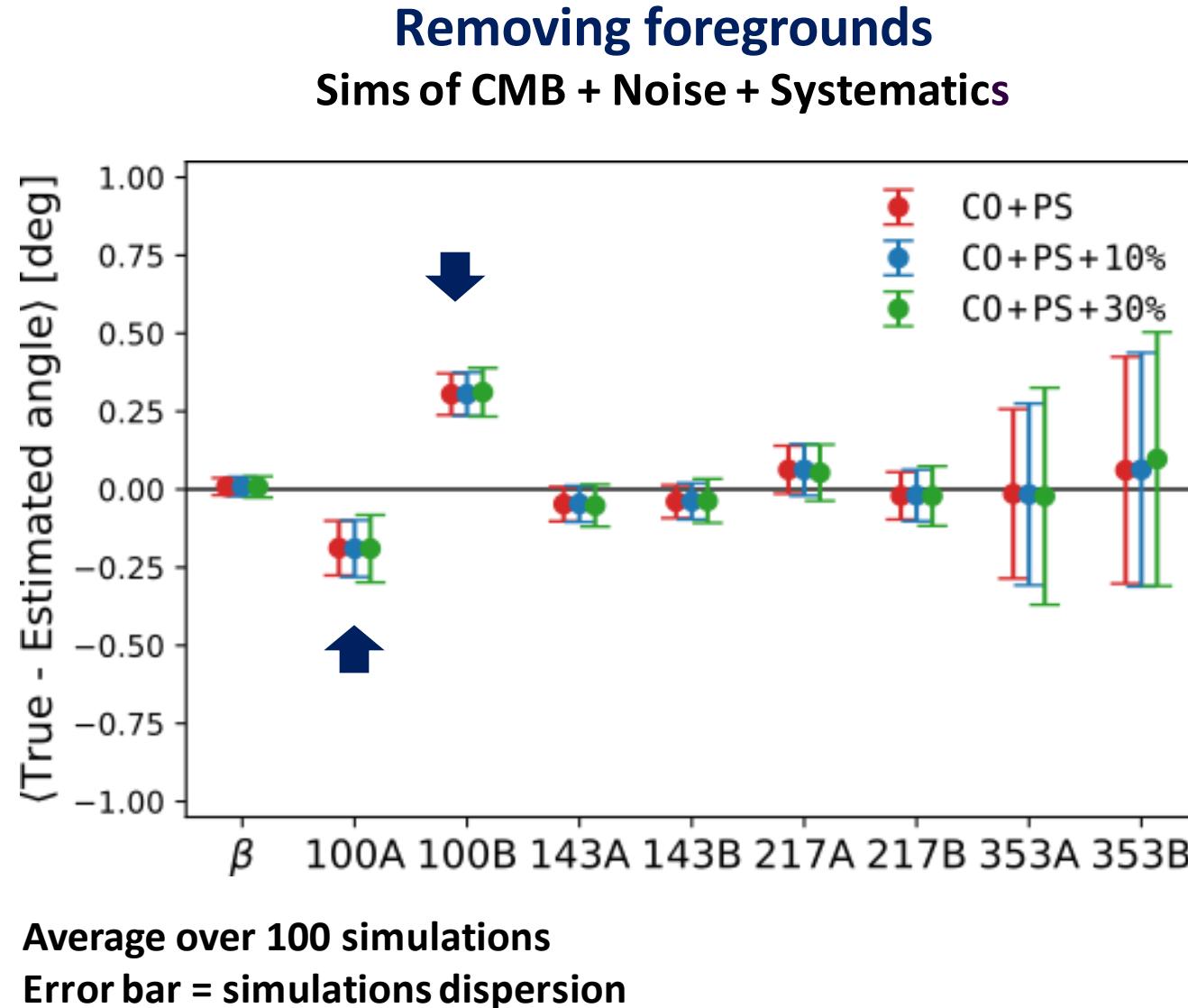
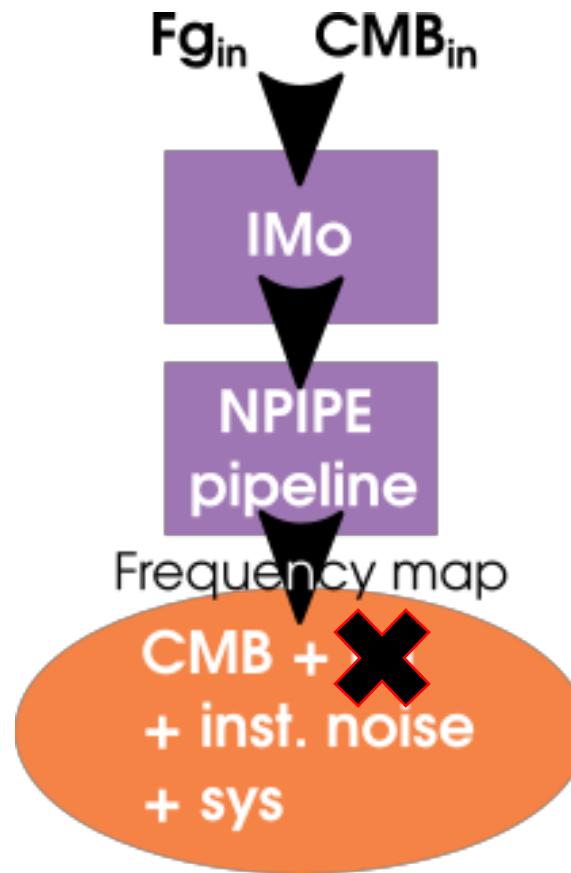


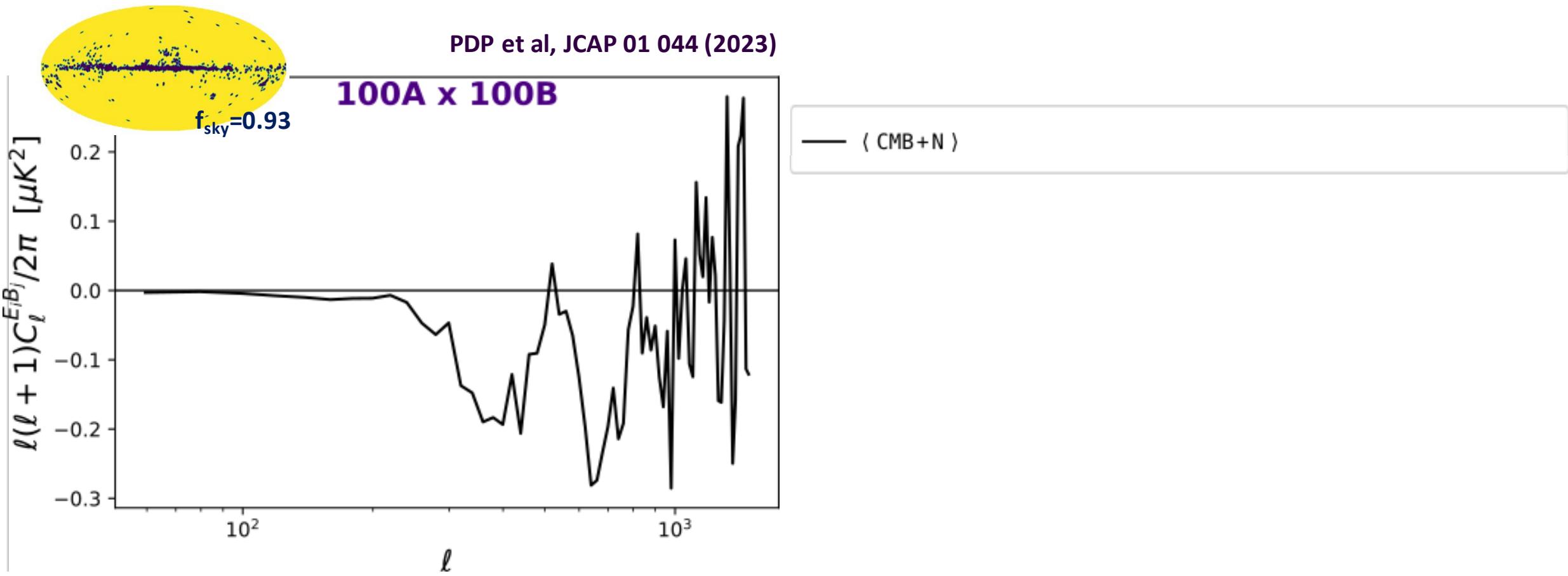
Correcting for dust EB Exact description of the fiducial foreground model



Average over 100 simulations
Error bar = simulations dispersion

NPIPE end-to-end simulations





Intensity-to-polarization leakage \rightarrow $C_\ell^{EB} \propto C_\ell^{TT}$

Cross-polarization effect \rightarrow $C_\ell^{EB} \propto C_\ell^{EE}$

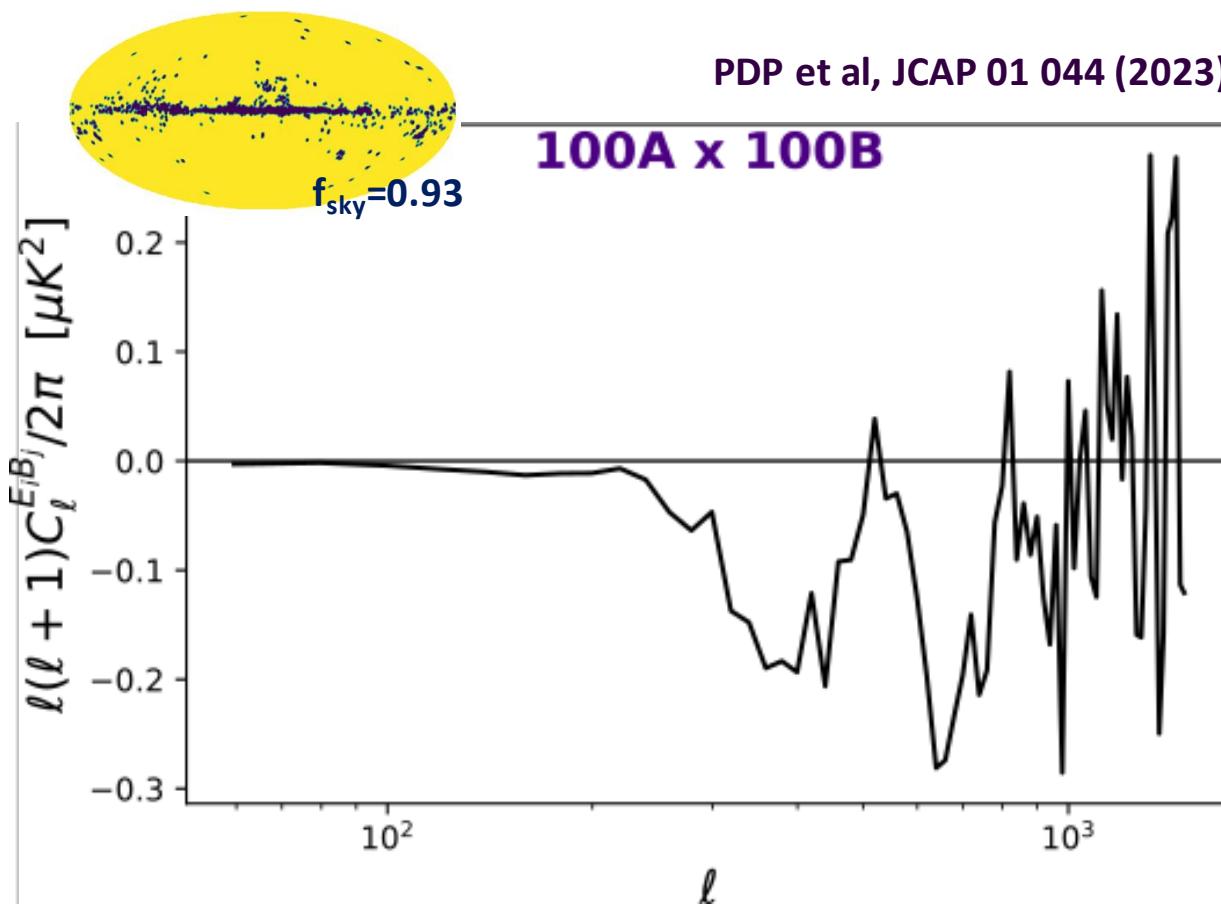
Beam leakage

$$C_\ell^{EB} = \omega_{\ell,\text{pix}}^2 \sum_{XY} W_\ell^{EB,XY} C_\ell^{XY,\text{cmb}}$$

$$XY \in \{TT, EE, BB, TE\}$$

QuickPol's polarization matrices

Hivon et al, A&A 598 A25 (2017)



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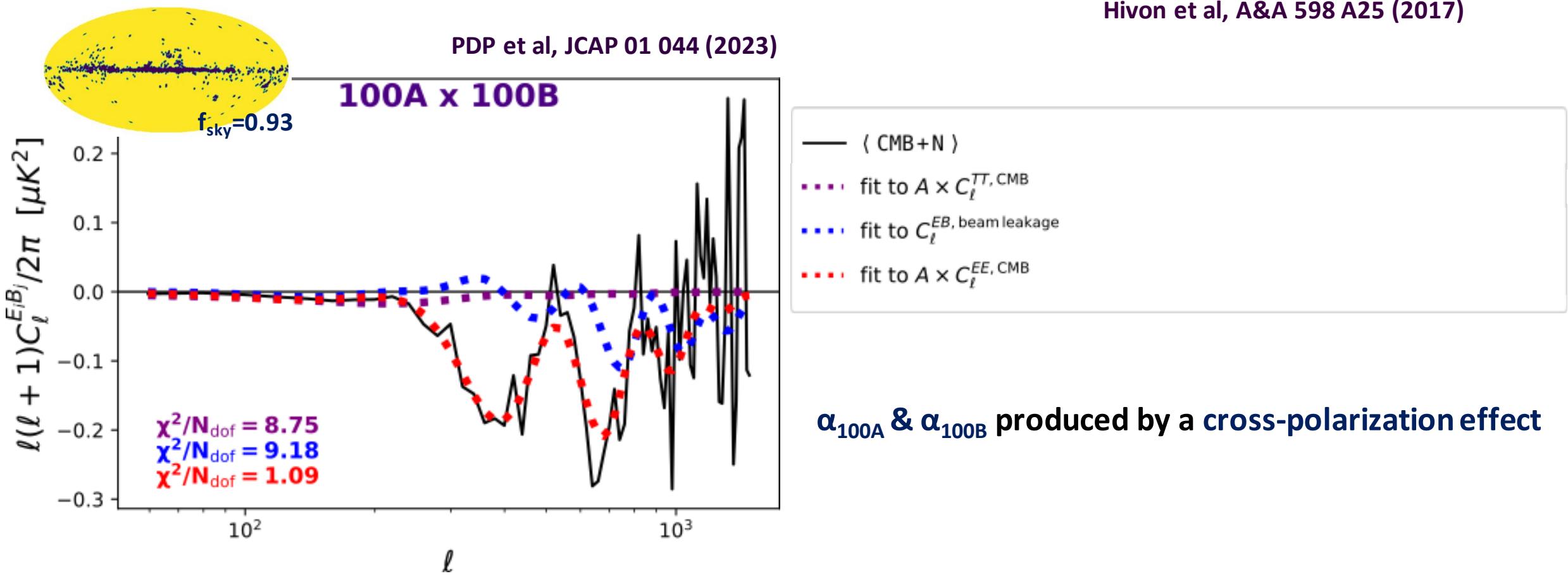
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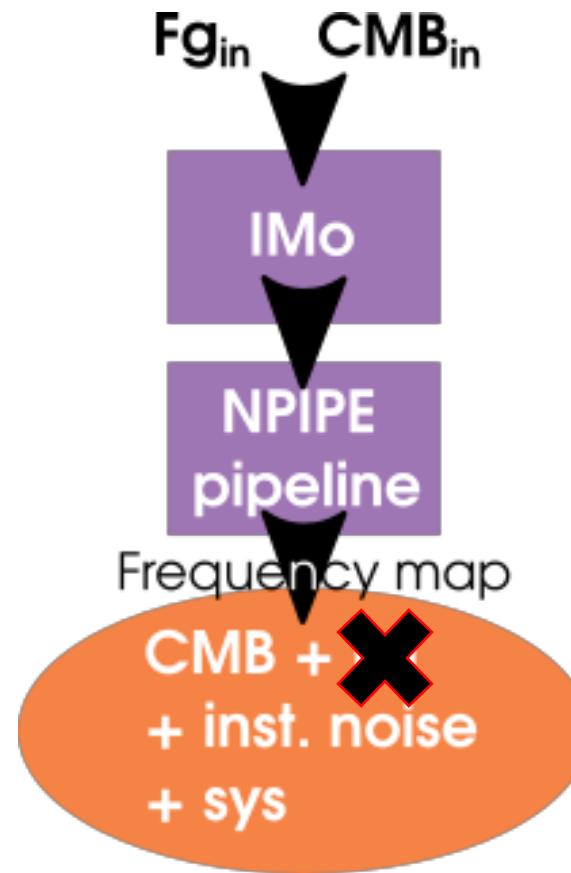
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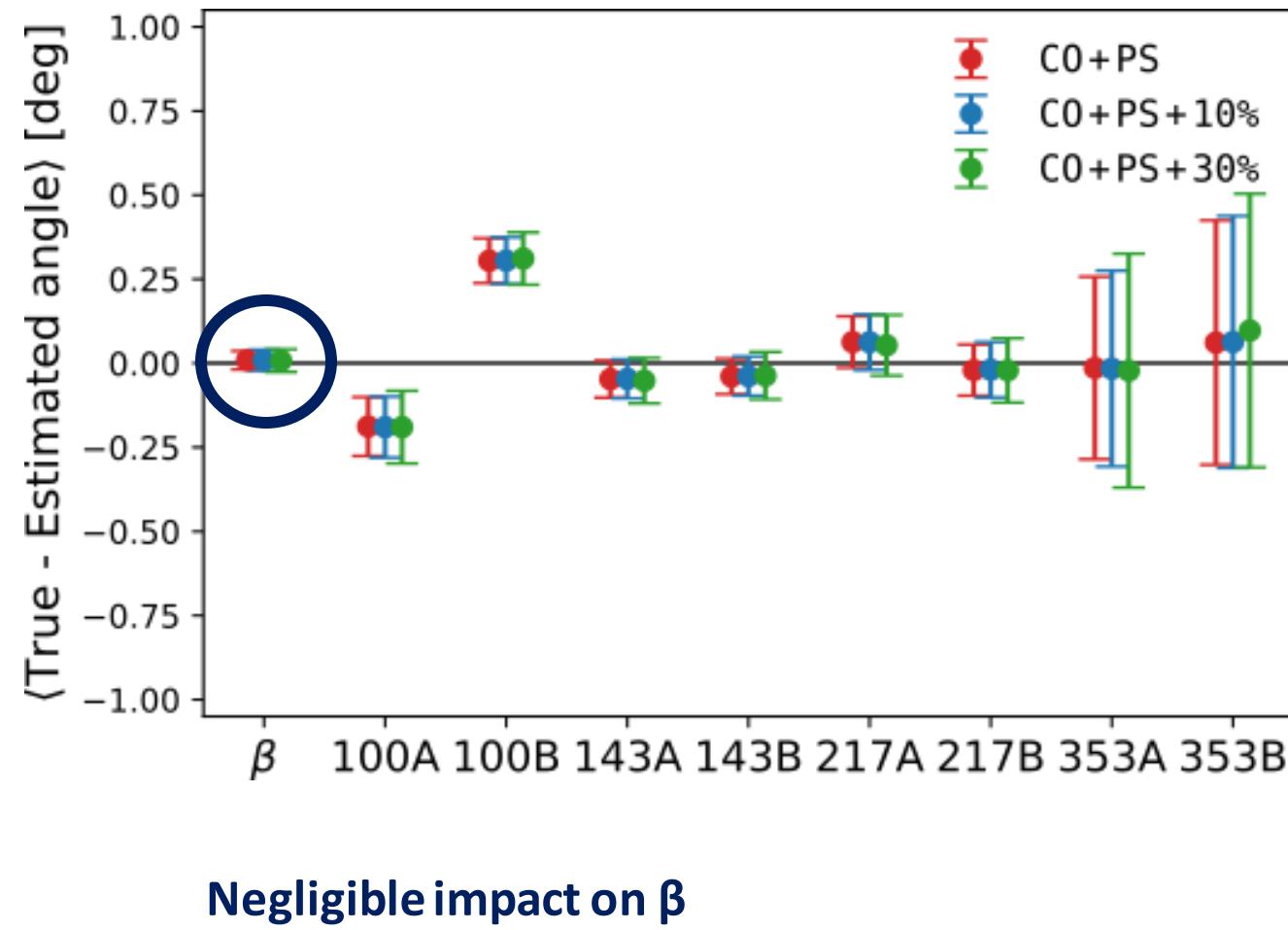
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NPIPE end-to-end simulations



Removing foregrounds Sims of CMB + Noise + Systematics



$$\langle \beta_{\text{sys}} \rangle = 0.009^\circ \pm 0.003^\circ \text{ vs } \sigma_{\text{stat}} = 0.11^\circ$$

Status of birefringence measurements

Our methodology allows for a systematic-free measurement of birefringence...

Planck HFI PR4

$$\beta = 0.30^\circ \pm 0.11^\circ \quad (2.7\sigma)$$

... but it's quite sensitive to the EB correlation of Galactic foreground emission

PDP et al 2022, PRL, 128, 091302

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BICEP3: rotating polarized source allowing foreground-independent calibration
systematic error of $<0.1^\circ$ with a $\approx 0.03^\circ$ statistical uncertainty on the calibration of polarization angles

Cornelison & Vergès Proc SPIE Int Soc Opt Eng 12190 (2022) 829

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Planck HFI+LFI PR4 + WMAP-9y $\beta = 0.342^\circ \pm 0.093^\circ \quad (3.6\sigma)$

Eskilt & Komatsu, PRD 106 063503 (2022)

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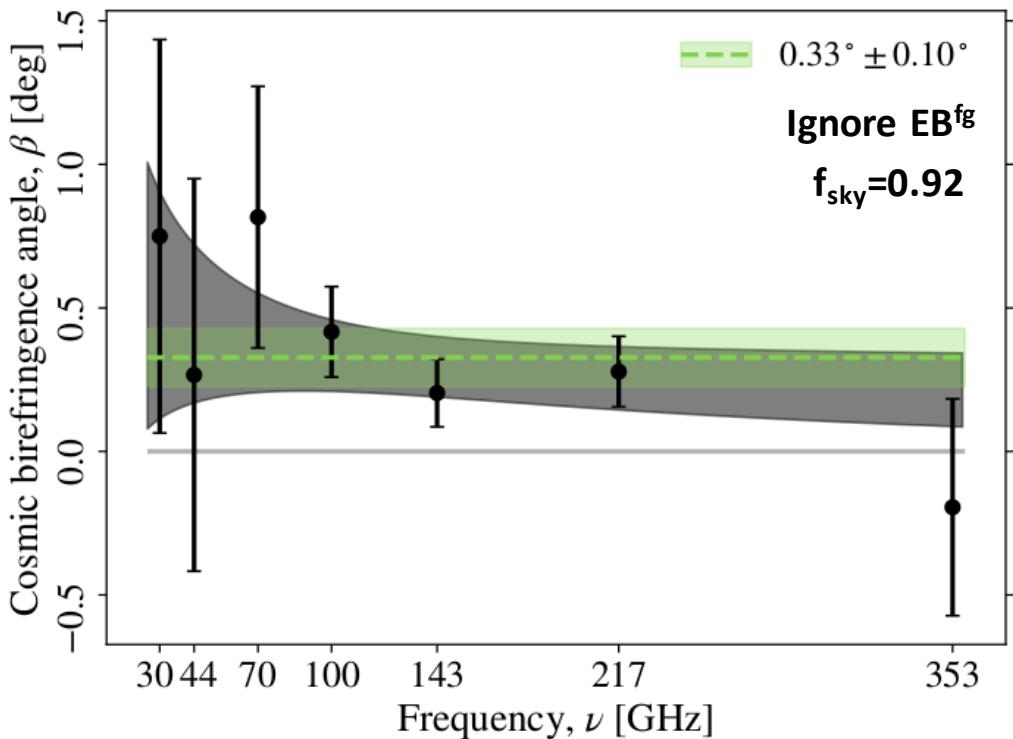
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What is the origin of the signal?

- Frequency dependence
- Time dependence
- Isotropy/anisotropy
- Evolution over cosmological scales

Frequency-dependent constraints on cosmic birefringence from the LFI and HFI Planck data release 4

Eskilt 2022, A&A, 662, A10

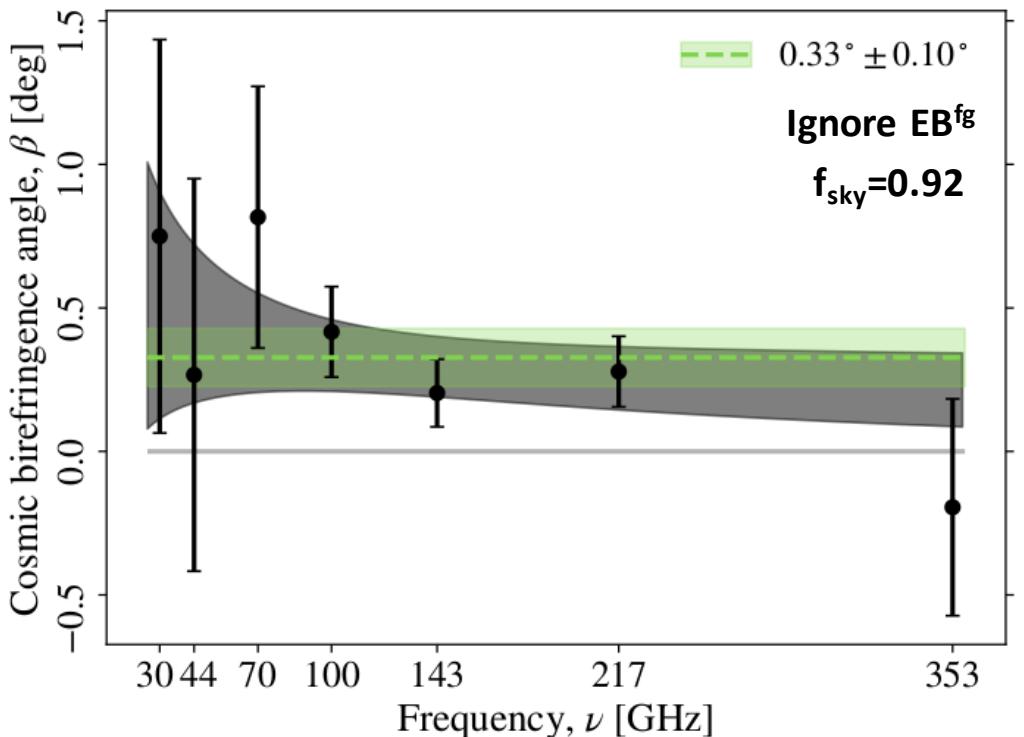


First follow-up work adding *Planck* low-frequency bands
→ $\beta = 0.33^\circ \pm 0.10^\circ$ (3.3σ) for nearly full-sky data

$$\beta_\nu = \beta_o (\nu/\nu_o)^n \begin{cases} \beta_o = 0.29^{+0.10}_{-0.11} \text{ deg} \\ n = -0.35^{+0.48}_{-0.47} \end{cases}$$

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Forcing an integer index

n	$\Delta\chi^2$ - Ignore EB^{fg}	$\Delta\chi^2$ - Model EB^{fg}
2	8.21	9.45
1	4.67	5.60
0	0.00	0.00
-1	0.38	0.75
-2	2.25	3.01

Data seems to favor a frequency-independent birefringence
 → Quantum gravity theories: $\beta \propto v^2$
 → Lorentz-violating electrodynamics: $\beta \propto v$
 → Chern-Simons coupling to light pseudoscalar field: $\beta \propto v^0$
 → Faraday rotation from primordial magnetic fields: $\beta \propto v^{-2}$

Chern-Simons coupling to a light ($m < 10^{-27}$ eV) pseudoscalar field

$$\mathcal{L} = -\frac{1}{2}\partial^\mu\phi\partial_\mu\phi - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{4}g_{\phi\gamma}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

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Kamionkowski & Riess 2022 [arXiv:2211.04492]

Early Dark Energy (EDE)

Early-time solution to the Hubble tension that
modifies the sound horizon, increasing the H_0
inferred from CMB data

Fluid that behaves like a cosmological constant
before matter-radiation equality ($\approx 10\%$
contribution to the total energy density briefly
before recombination) and decays faster than
radiation afterward so that late-time evolution
is unchanged

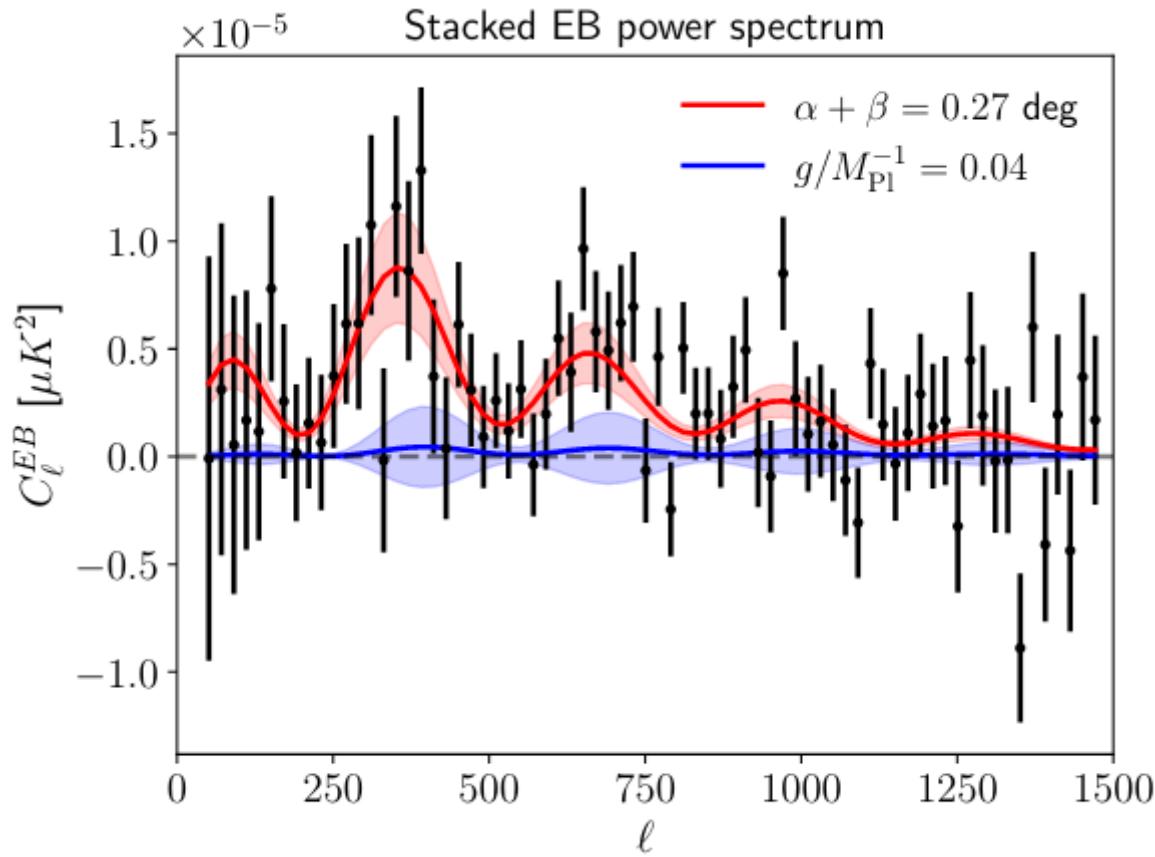
Marsh 2016, Phys Rep, 643, 1

Axion-like particles (ALP)

Canonical pre-recombination EDE

$$V(\phi) = V_0 \left[1 - \cos \left(\frac{\phi}{f} \right) \right]^3$$

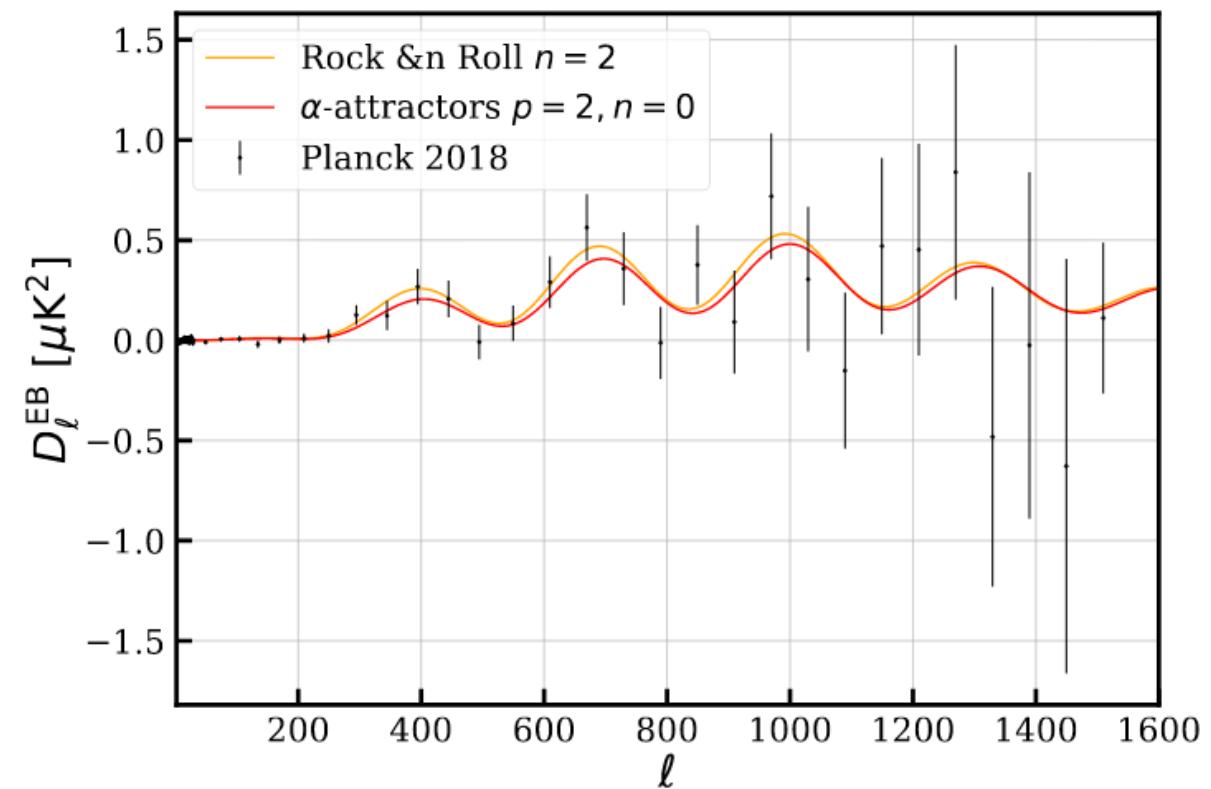
+

post-recombination birefringence **α -attractor**

$$V(\phi) = V_0 \tanh^4(\phi / \sqrt{6\alpha_1} M_{\text{Pl}})$$

Rock & Roll

$$V(\phi) = V_0 \left(\frac{\phi}{M_{\text{Pl}}} \right)^4$$



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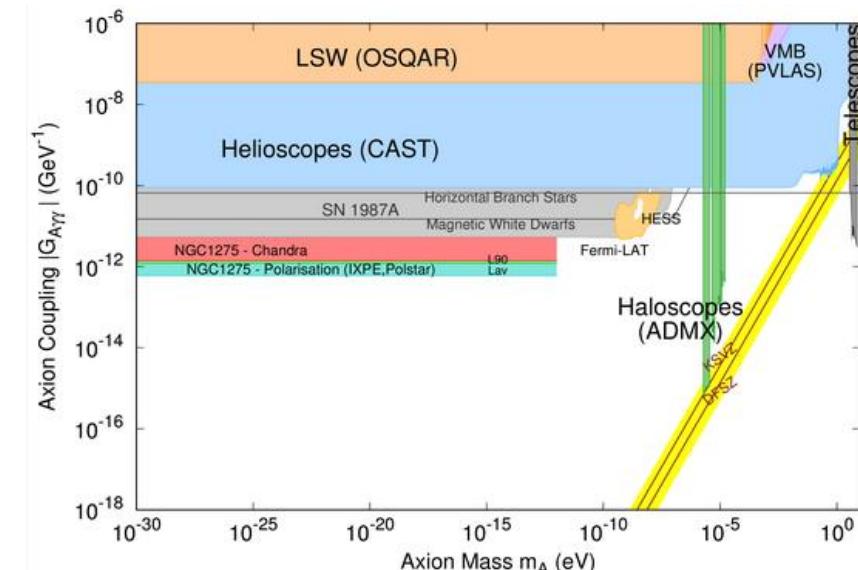
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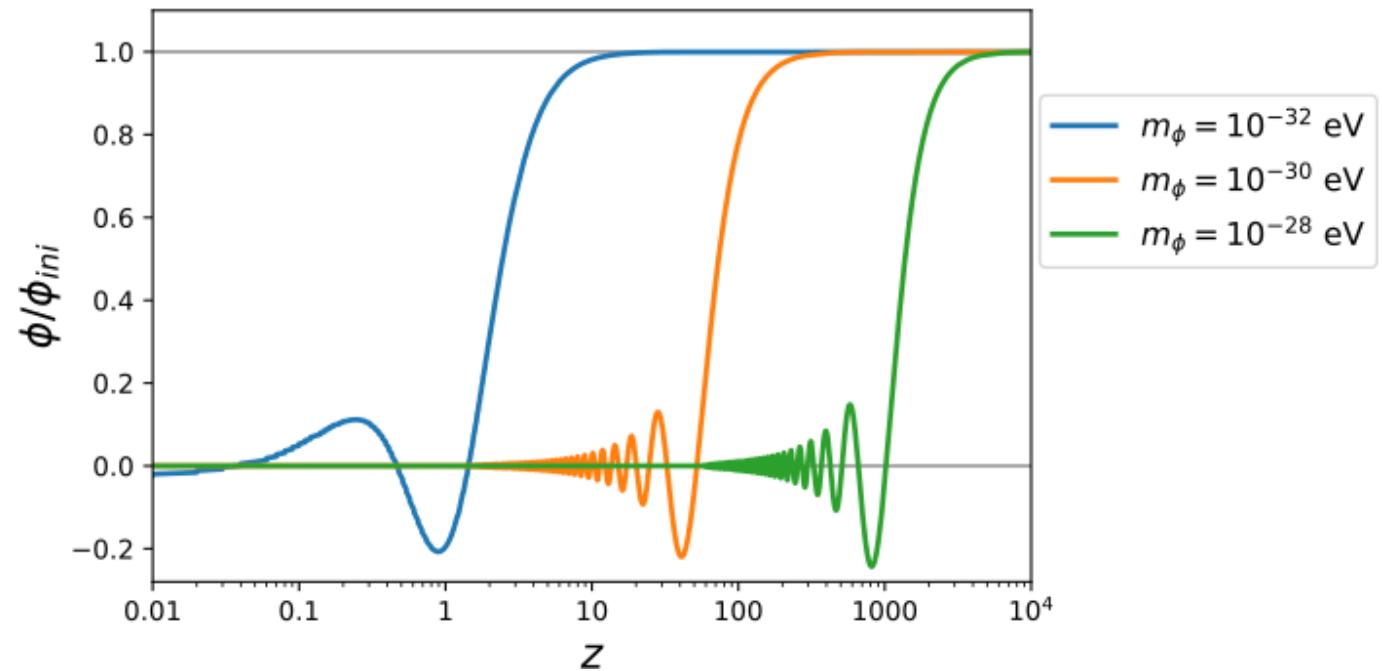
Initially proposed to solve the strong-CP problem
Evolved beyond the QCD axion to the more general ALP from supersymmetry or string theories



Day & Krippendorff 2018, Galaxies 2018, 6(2), 45

ALP as dark energy

$$10^{-32} \text{ eV} \lesssim m_\phi \lesssim 10^{-28} \text{ eV}$$

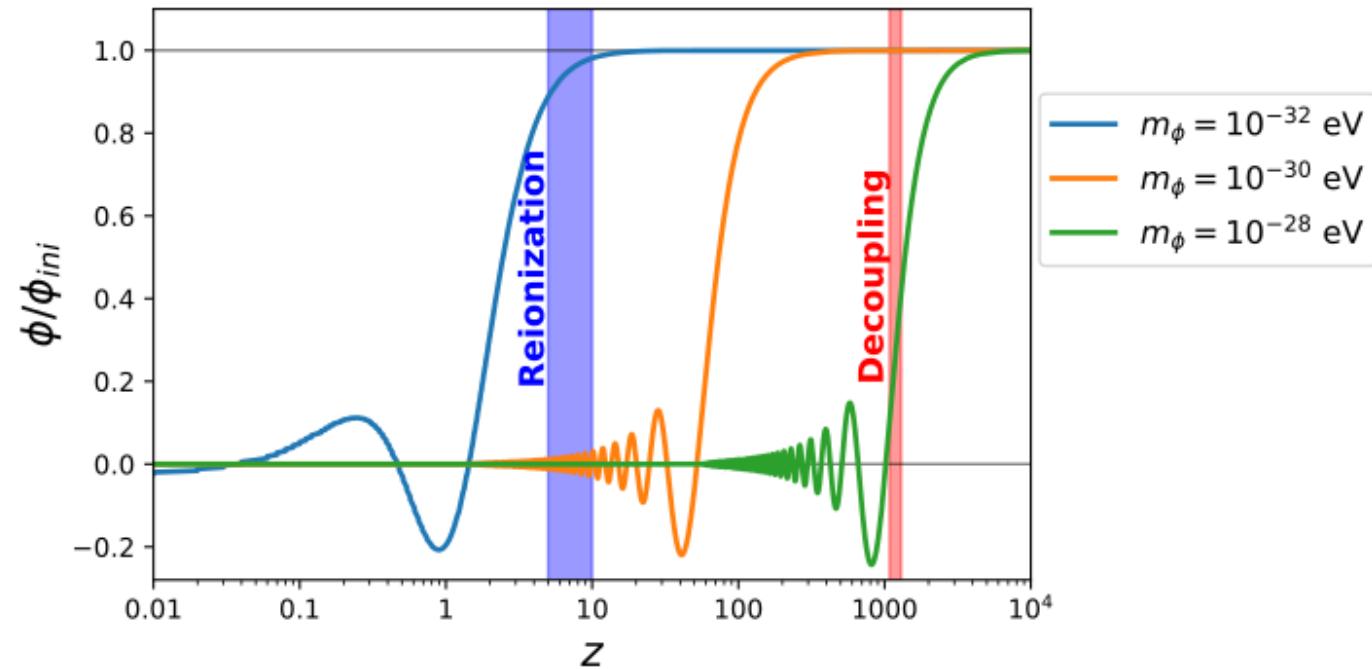


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$$\beta(z) = \begin{cases} 0 & \text{for } z = 0 \\ \beta_{\text{rei}} & \text{for } 0 < z \leq 10, \\ \beta_{\text{rec}} & \text{for } 10 < z \end{cases}$$

CMB photons emitted at **recombination** and **reionization** will suffer different rotations



ALP as dark energy

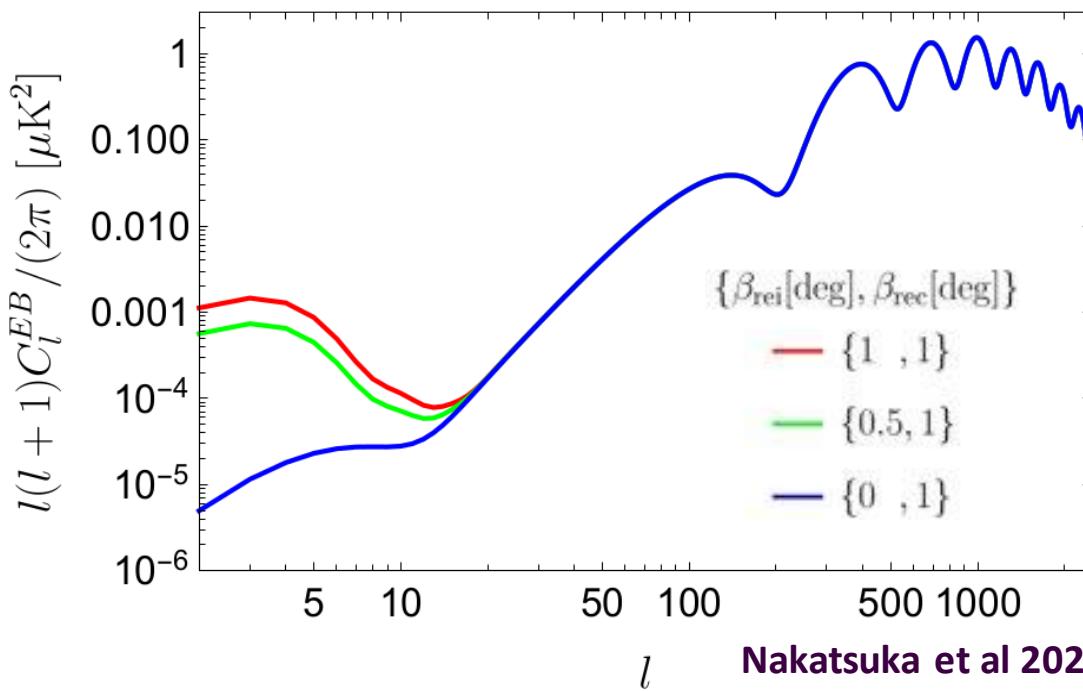
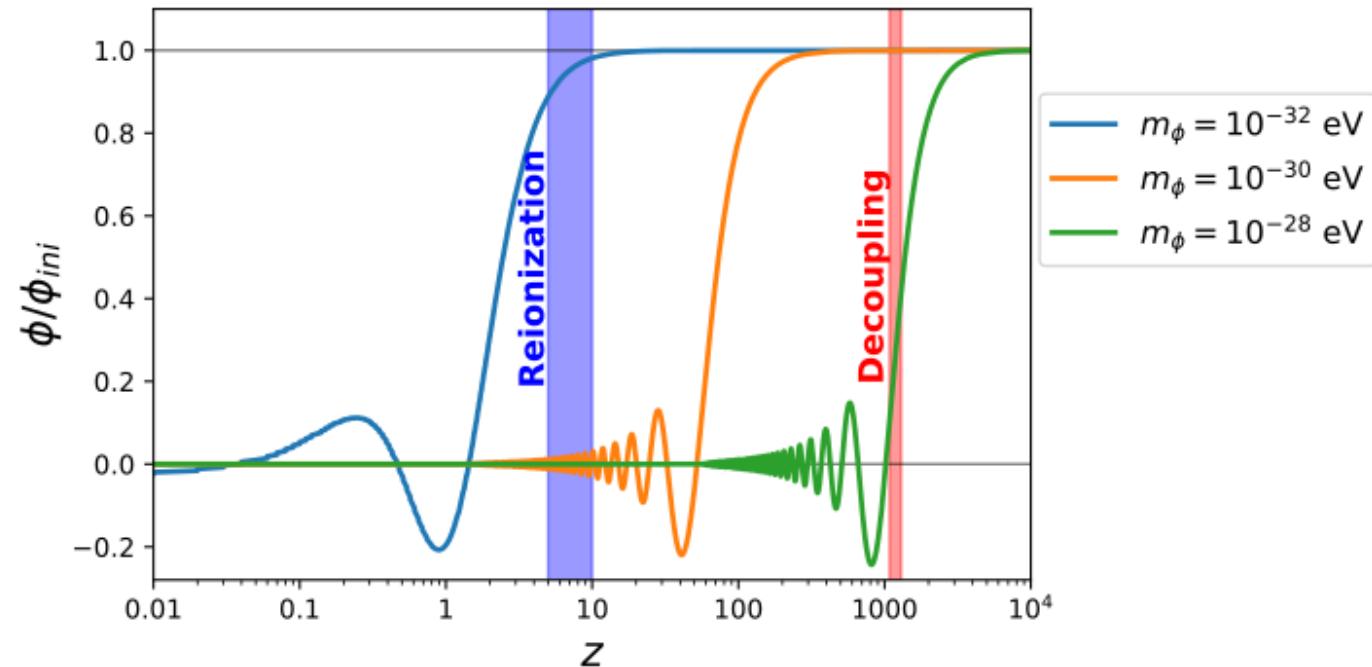
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$$\begin{aligned} C_\ell^{EB,o} \approx & \frac{1}{2} \sin(4\beta_{\text{rec}}) C_\ell^{E_{\text{rec}} E_{\text{rec}}} \\ & + \frac{1}{2} \sin(4\beta_{\text{rei}}) C_\ell^{E_{\text{rei}} E_{\text{rei}}} \\ & + \sin(2\beta_{\text{rec}} + 2\beta_{\text{rei}}) C_\ell^{E_{\text{rec}} E_{\text{rei}}} \end{aligned}$$

Tomographic view of the ALP field at $z \approx 10$ and $z \approx 1000$



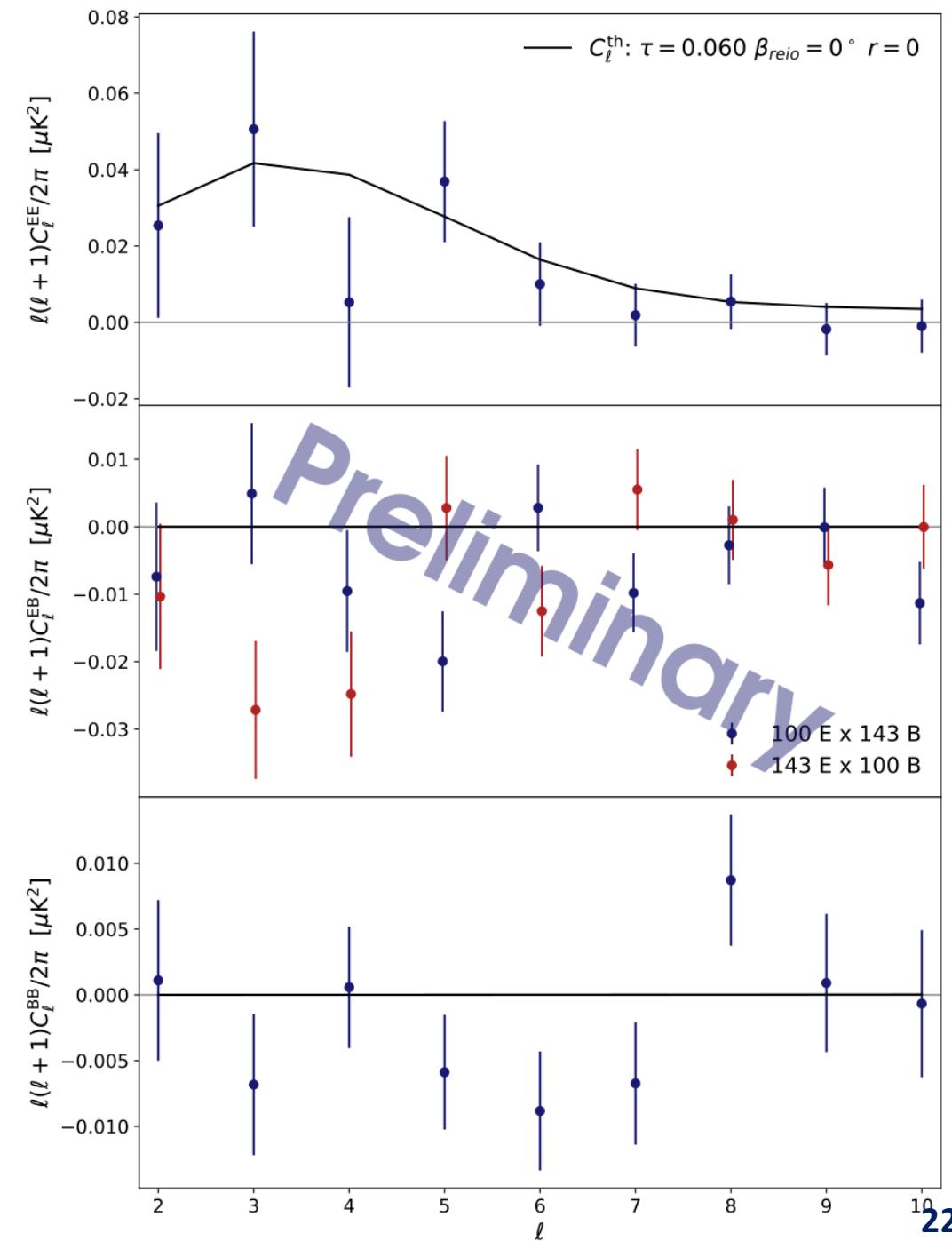
Measuring β_{reio} from $\ell \leq 10$

Work with CMB instead of frequency maps

Remove foregrounds by fitting and subtracting templates of synchrotron and dust emission

CMB spectra from 100 GHz x 143 GHz of *Planck SRoll2.0*

Delouis et al, A&A 629 A38 (2019)



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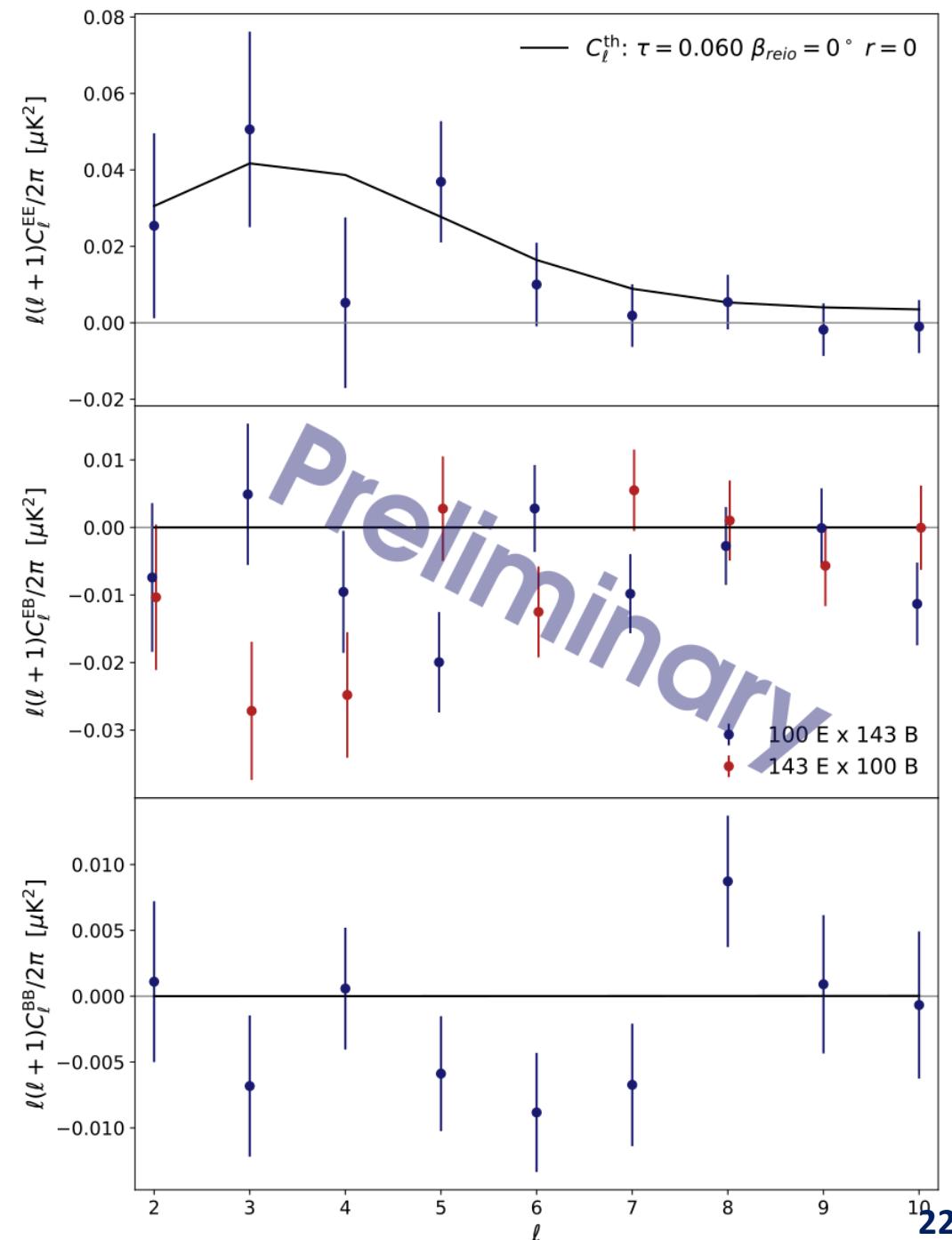
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Delouis et al, A&A 629 A38 (2019)

$$P(\Theta|d, \mathcal{M}) \propto \mathcal{L}(d|\Theta, \mathcal{M}) \Pi(\Theta|\mathcal{M})$$

Sample over $\Theta = \{\tau, \beta_{\text{reio}}, \beta_{\text{dec}}, \alpha_{100}, \alpha_{143}, r=0\}$

Gaussian prior on $\beta_{\text{dec}}, \alpha_{100}, \alpha_{143}$ from high- ℓ analysis



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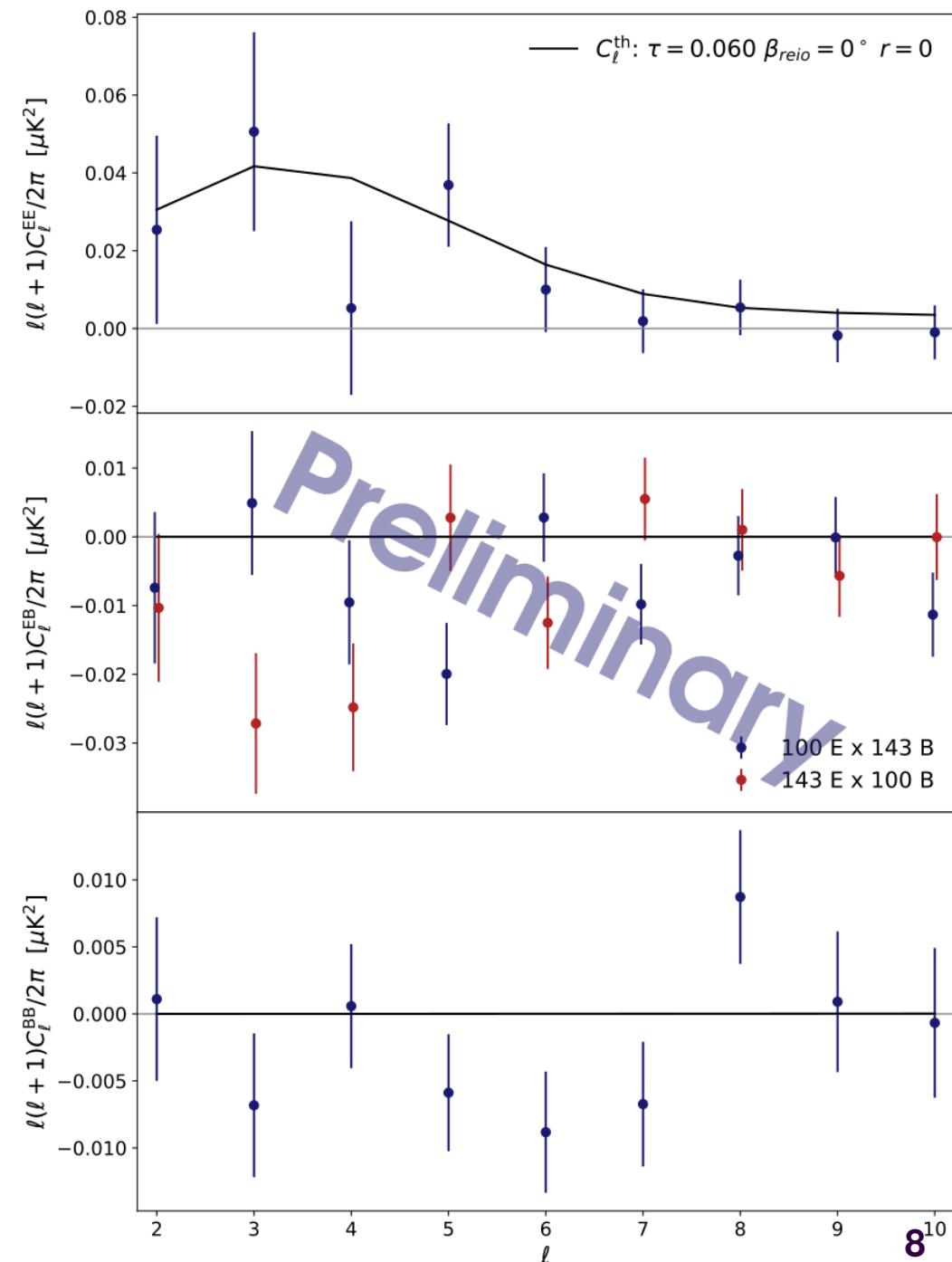
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momento

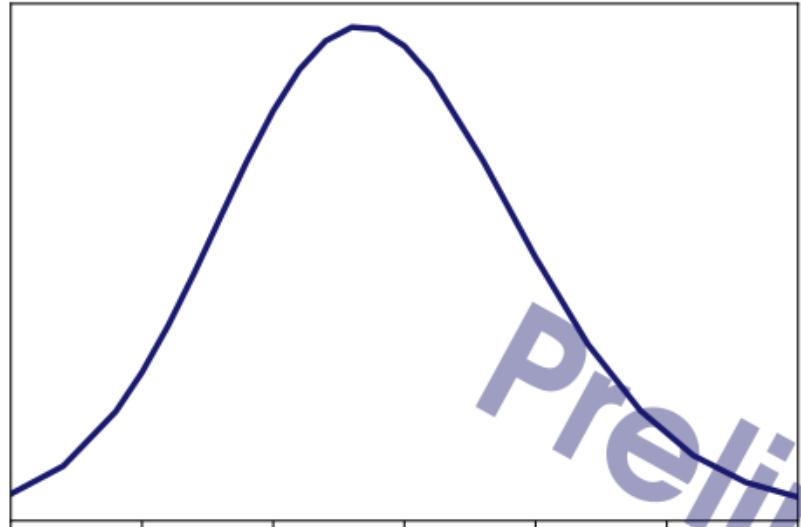
Semi-analytical likelihood-approximation based on the principle of maximum entropy

Gratton [arXiv:1708.08479]

de Belsunce et al, MNRAS 507 1072 (2021)
de Belsunce et al, MNRAS 518 3675 (2023)



EE – BB information

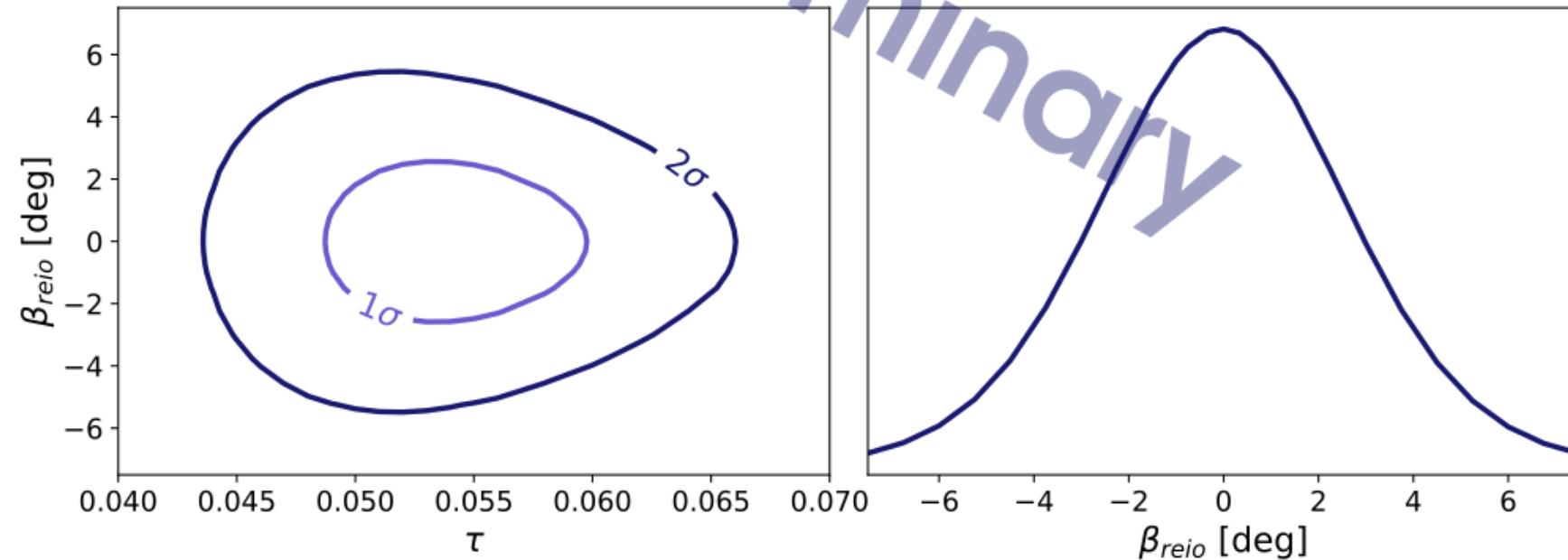


Recover the expected τ - β_{reio} degeneracy

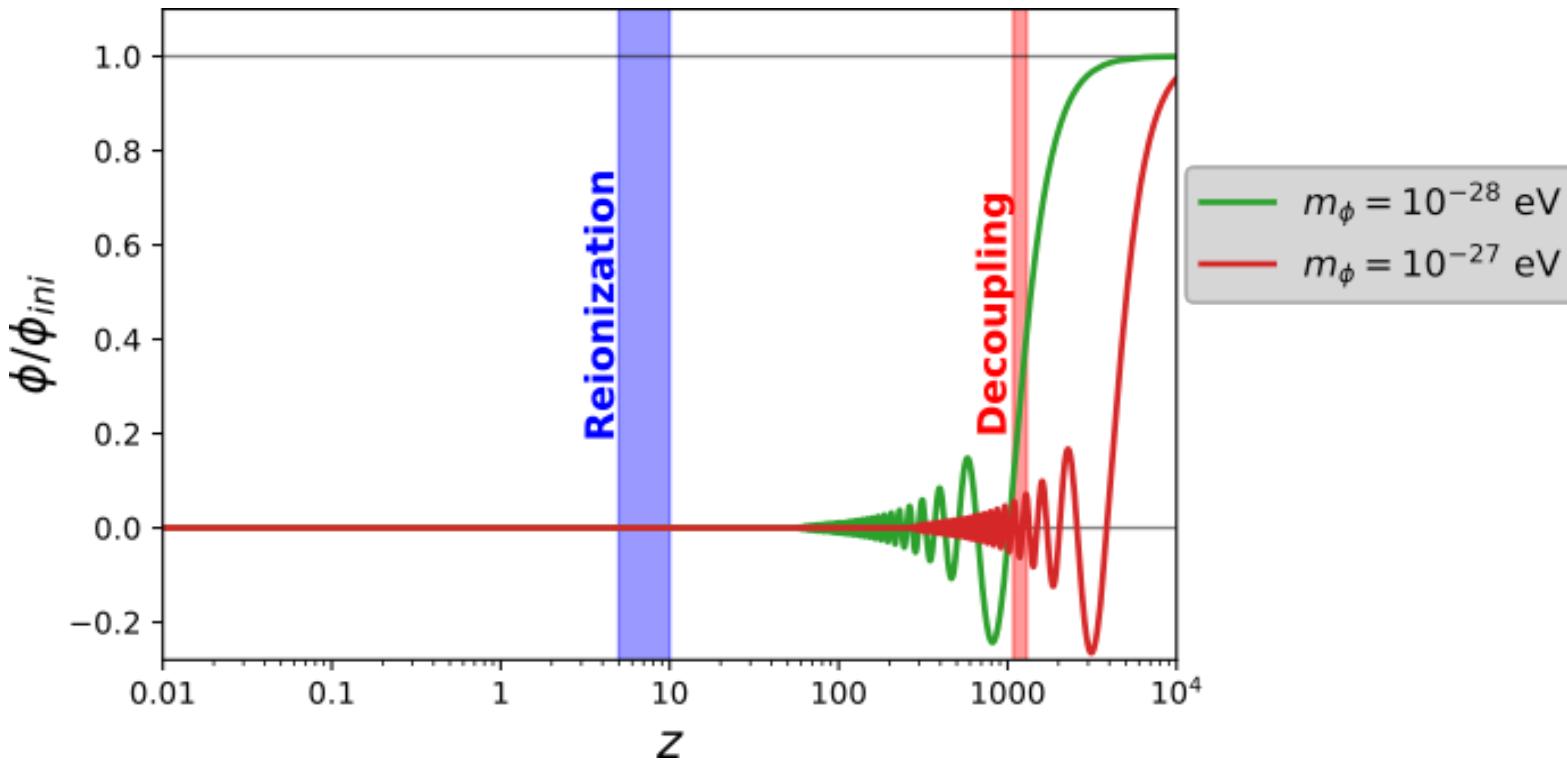
$$C_\ell^{EE,o} \approx \cos^2(2\alpha + 2\beta_{reio}) C_\ell^{EE,reio}$$

$$C_\ell^{BB,o} \approx \sin^2(2\alpha + 2\beta_{reio}) C_\ell^{EE,reio}$$

$$C_\ell^{EB,o} \approx \frac{1}{2} \sin(4\alpha + 4\beta_{reio}) C_\ell^{EE,reio}$$



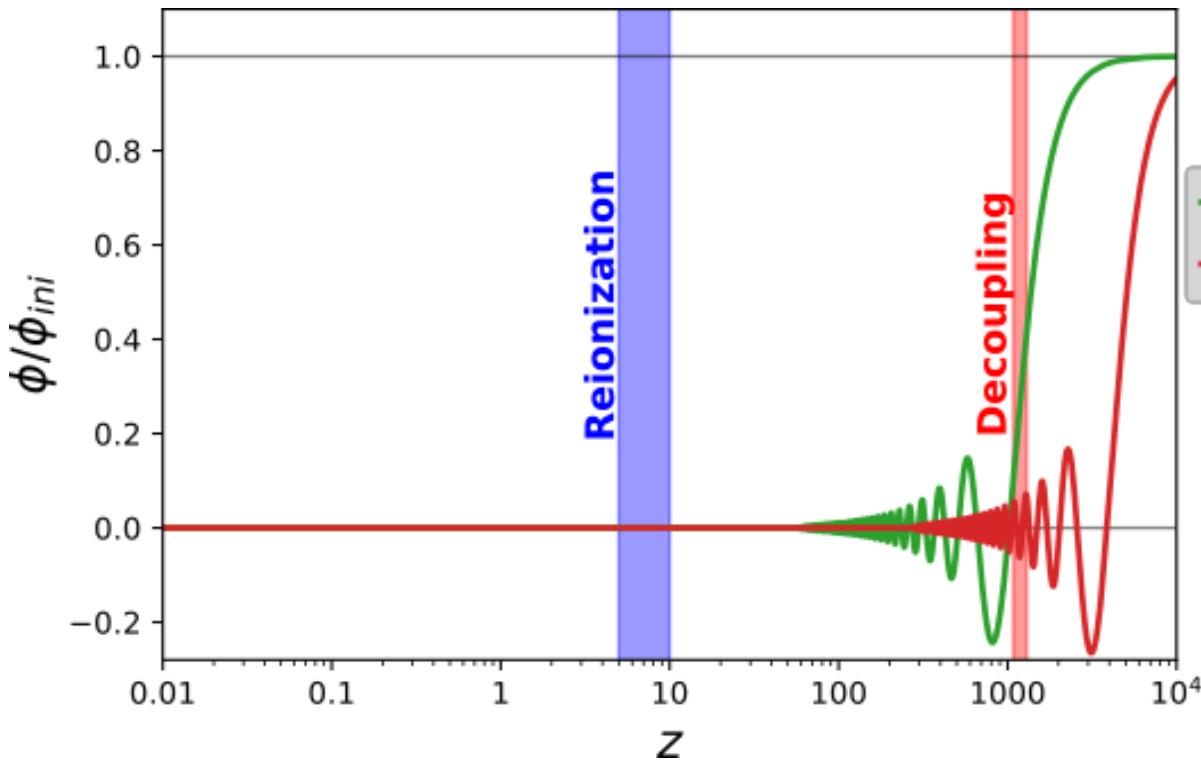
Best fit	
τ	0.054 ± 0.005
β_{reio} [deg]	-0.02 ± 2.68
β_{dec} [deg]	0.38 ± 0.15
α_{100} [deg]	-0.38 ± 0.16
α_{143} [deg]	0.06 ± 0.15



ALP as dark matter
 $10^{-28} \text{ eV} \lesssim m_\phi$

Fedderke et al, PRD 100 015040 (2019)

$$(Q \pm iU)(t, \vec{n}) = J_0[g_{\phi\gamma}\phi_{\text{dec}}]\exp[\mp 2i(\frac{g_{\phi\gamma}}{2}\phi_0 \cos(m_\phi t + \delta))](Q \pm iU)_0(\vec{n})$$



ALP as dark matter
 $10^{-28} \text{ eV} \lesssim m_\phi$

(Q,U) rotating as if the polarisation angle oscillated
with a period

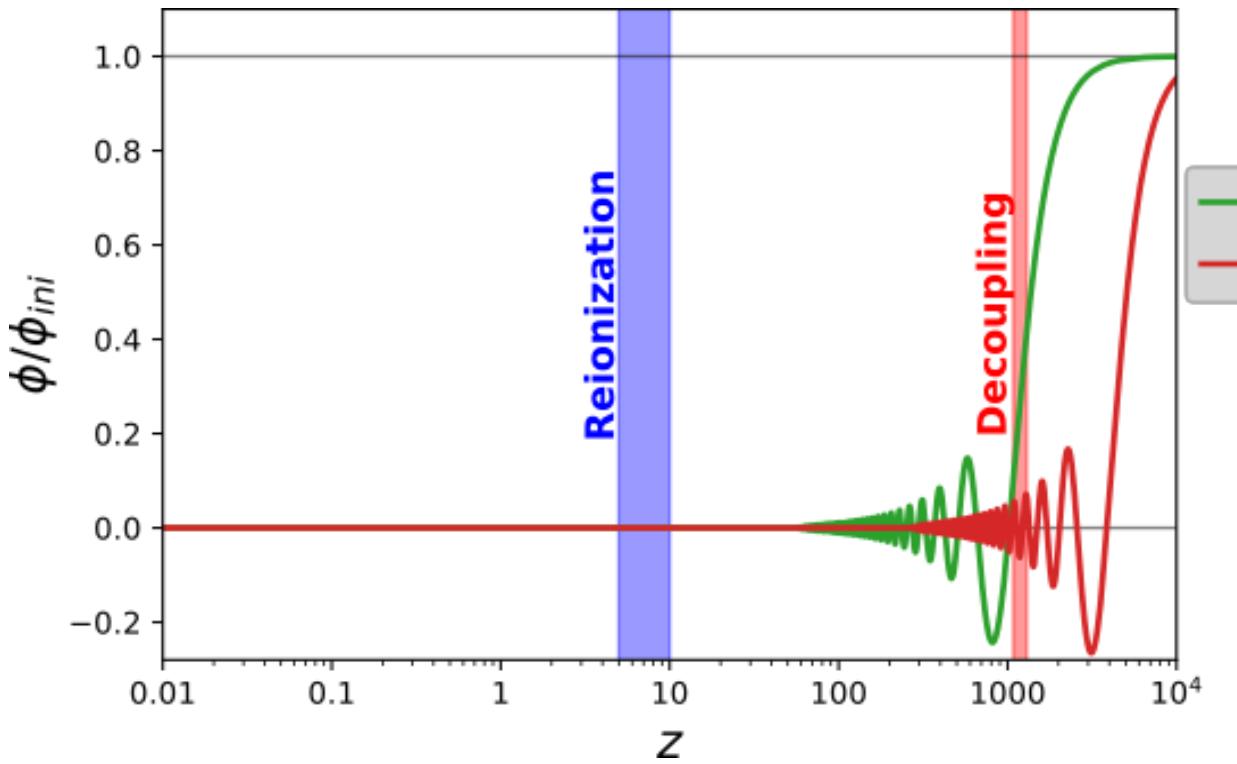
$$T_\phi \sim 1 \text{ y} \left(\frac{10^{-22} \text{ eV}}{m_\phi} \right)$$

Planck, LiteBIRD $\sim 1 \text{ y}$ $10^{-24} \text{ eV} \leq m_\phi \leq 10^{-19} \text{ eV}$
BICEP/Keck, SPT $\sim 1 \text{ h}$

Fedderke et al, PRD 100 015040 (2019)

Oscillation depending on ALP field at absorption

$$(Q \pm iU)(t, \vec{n}) = J_0[g_{\phi\gamma}\phi_{\text{dec}}] \exp[\mp 2i(\frac{g_{\phi\gamma}}{2}\phi_0 \cos(m_\phi t + \delta))] (Q \pm iU)_0(\vec{n})$$



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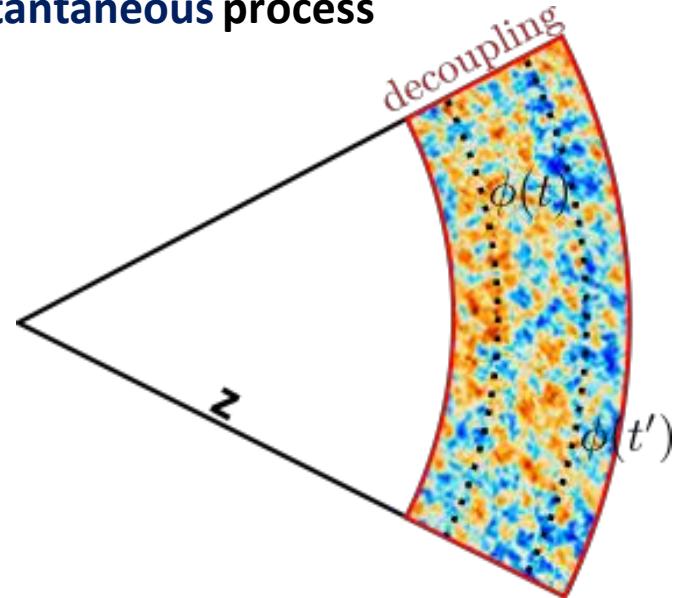
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Fedderke et al, PRD 100 015040 (2019)

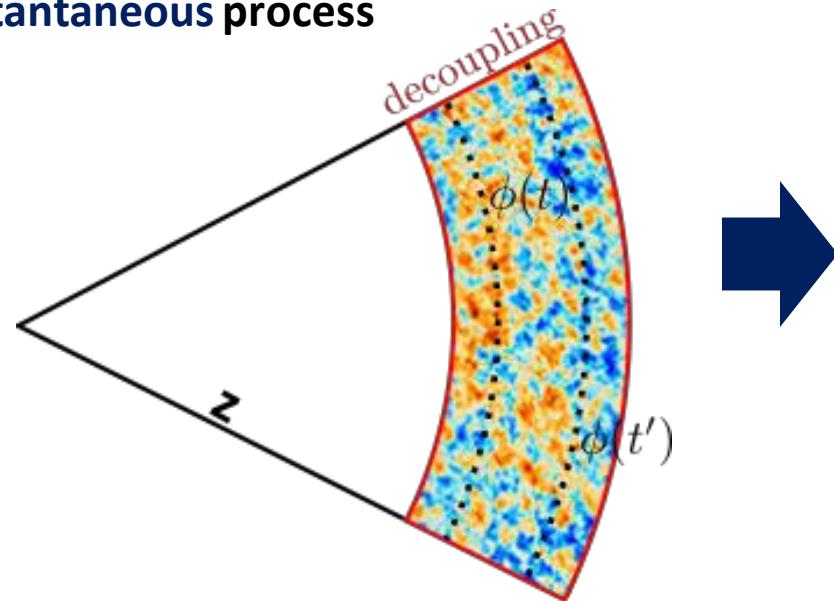
Oscillation depending on ALP field at absorption

$$(Q \pm iU)(t, \vec{n}) = \underbrace{J_0[g_{\phi\gamma}\phi_{\text{dec}}]}_{\text{Washout depending on ALP field at emission}} \exp[\mp 2i(\frac{g_{\phi\gamma}}{2}\phi_0 \cos(m_\phi t + \delta))] (Q \pm iU)_0(\vec{n})$$

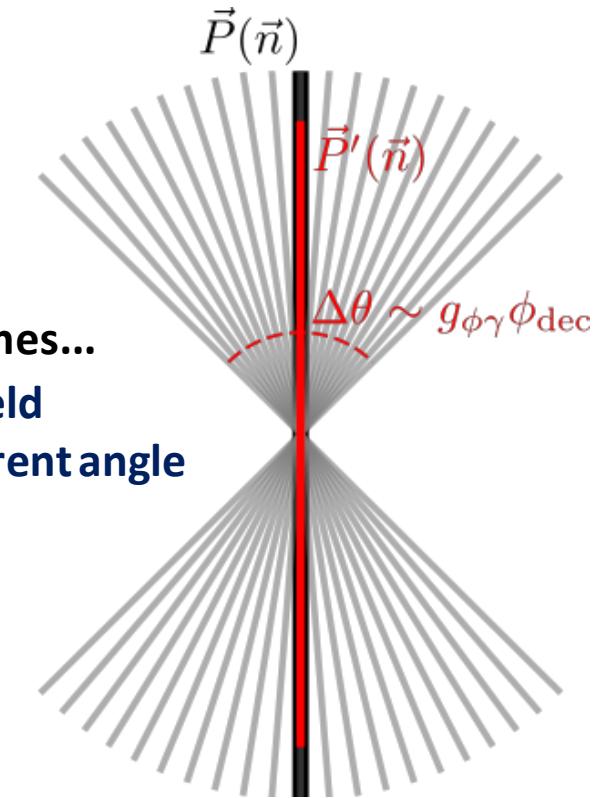
Washout is a consequence of decoupling not being an instantaneous process



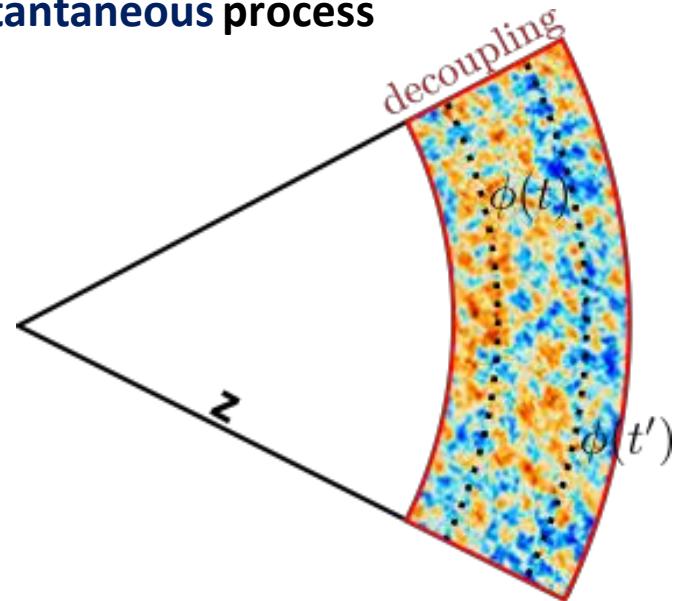
Washout is a consequence of decoupling not being
an instantaneous process



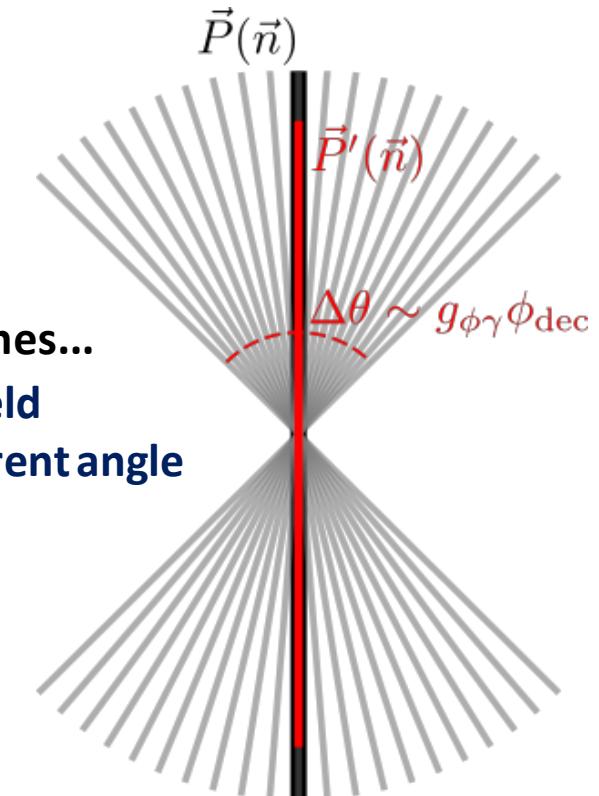
Photons emitted at different times...
... see a slightly different ALP field
... are rotated by a slightly different angle



Washout is a consequence of decoupling not being an instantaneous process



Photons emitted at different times...
... see a slightly different ALP field
... are rotated by a slightly different angle



CMB detectors do an incoherent sum over the fanned-out states



Reduction of polarization intensity

$$J_0[g_{\phi\gamma}\phi_{\text{dec}}] \approx 1 - \frac{1}{4}(g_{\phi\gamma}\phi_{\text{dec}})^2$$

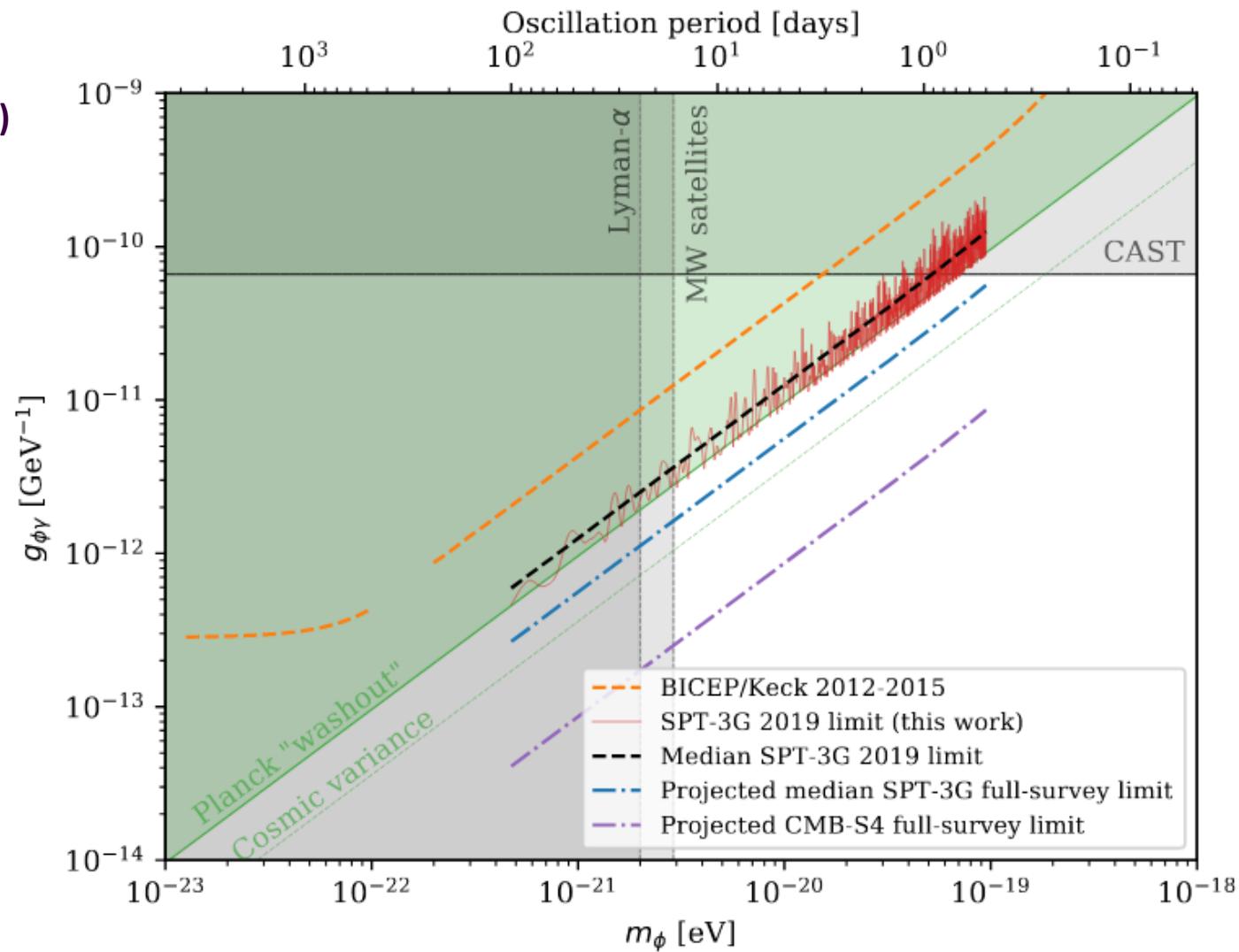
Constraints from time-dependent birefringence

Planck washout

Fedderke et al, PRD 100 015040 (2019)

$$g_{\phi\gamma} \lesssim 9.6 \times 10^{-13} \text{ GeV}^{-1}$$

$$\times \left(\frac{m_\phi}{10^{-21} \text{ eV}} \right) \times \left(\kappa \times \frac{\Omega_c^0 h^2}{0.11933} \right)^{-1/2}$$



Constraints from time-dependent birefringence

Planck washout

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SPT-3G data

Ferguson et al, PRD 106 042011 (2022)

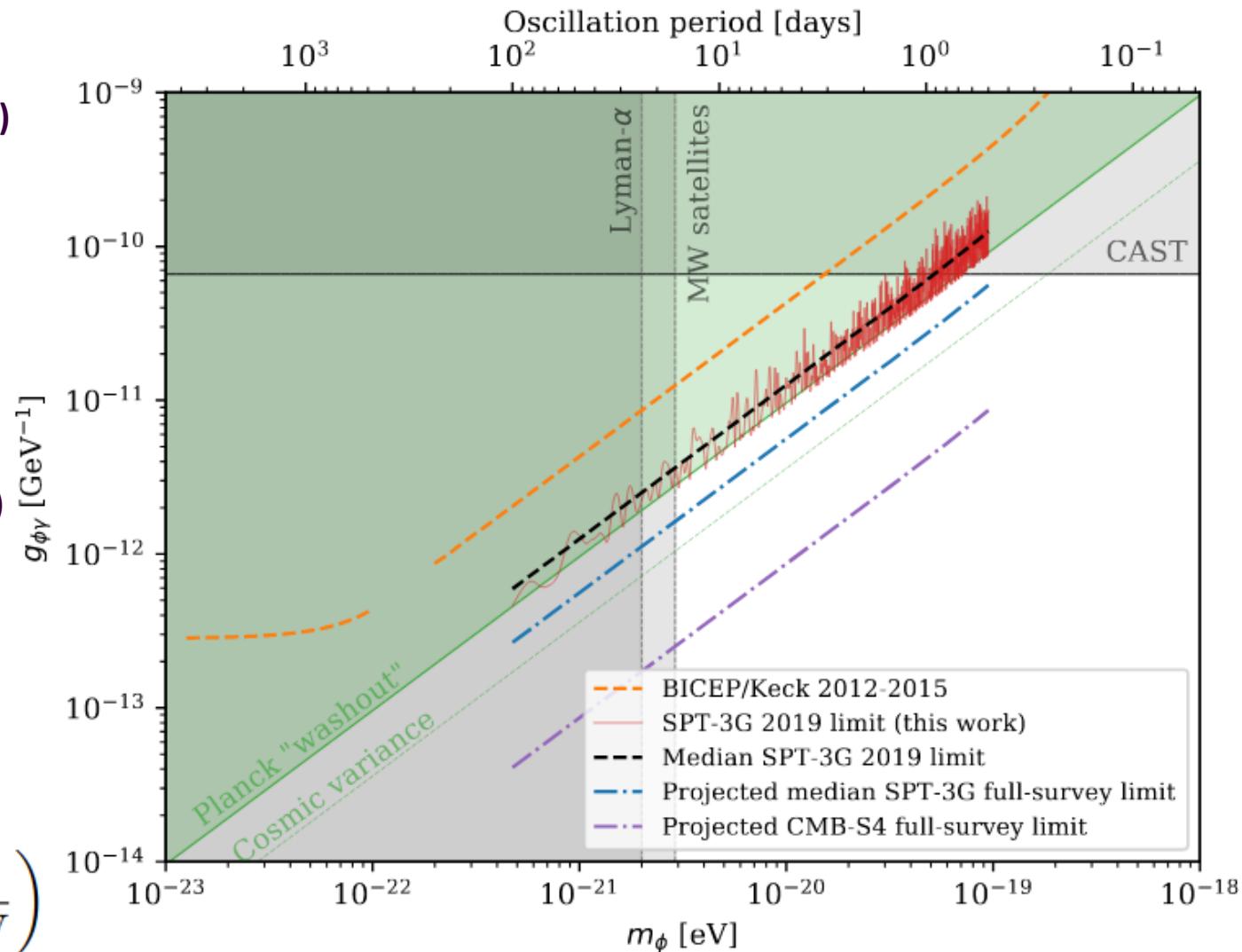
For periods $1 \text{ day} \leq T_\phi \leq 100 \text{ days} \dots$

... probing $10^{-22} \text{ eV} \leq m_\phi \leq 10^{-19} \text{ eV}$

... upper limit $(\beta+\alpha)(t) \leq 0.071^\circ$

Assuming DM made of one ALP species with local density of 0.3 GeV/cm^3

$$g_{\phi\gamma} < 1.18 \times 10^{-12} \text{ GeV}^{-1} \times \left(\frac{m_\phi}{1.0 \times 10^{-21} \text{ eV}} \right)$$



Properties of the signal

- Frequency dependence

Eskilt, A&A 662 A10 (2022)

- Time dependence

Fedderke et al, PRD 100 015040 (2019)
Ferguson et al, PRD 106 042011 (2022)
BICEP/Keck XIV, PRD 105 022006 (2022)
POLARBEAR, PRD 108 043017 (2023)

- Isotropy/anisotropy

Namikawa et al, PRD 101 083527 (2020)
Bianchini et al, PRD 102 083504 (2020)
Bortolami et al, JCAP 09 075 (2022)
BICEP/Keck XVII, ApJ 949 2 43 (2023)

Origin of the signal

- Early dark energy

Murai et al, PRD 107 L041302 (2023)
Eskilt et al, PRL 131 121001 (2023)
Yin et al, JCAP 10 007 (2023)

- Axion-like particles

Sherwin & Namikawa, MNRAS 520 3298 (2023)
Nakatsuka et al, PRD 105 123509 (2022)
Greco et al, JCAP 05 026 (2023)
Gasparotto & Sfakianakis, [arXiv:2306.16355]

- Chiral primordial gravitational waves

Fujita et al, PRD 106 103529 (2022)

- Domain walls & cosmic strings

Kitajima et al, JCAP 10 043 (2022)
Winston Yin et al, JCAP 06 033 (2022)