Physical Cosmology Group


Physical Cosmology Group
MAX-PLANCK-INSTITUT
FÜR ASTROPHYSIK
13 female,
7 male
20 members from 11 countries
Brazil (1), Canada (1), China (1), Croatia (2),
Germany (4), India (2),
Italy (5), Japan (1), Serbia (1), Spain (1), USA (1)

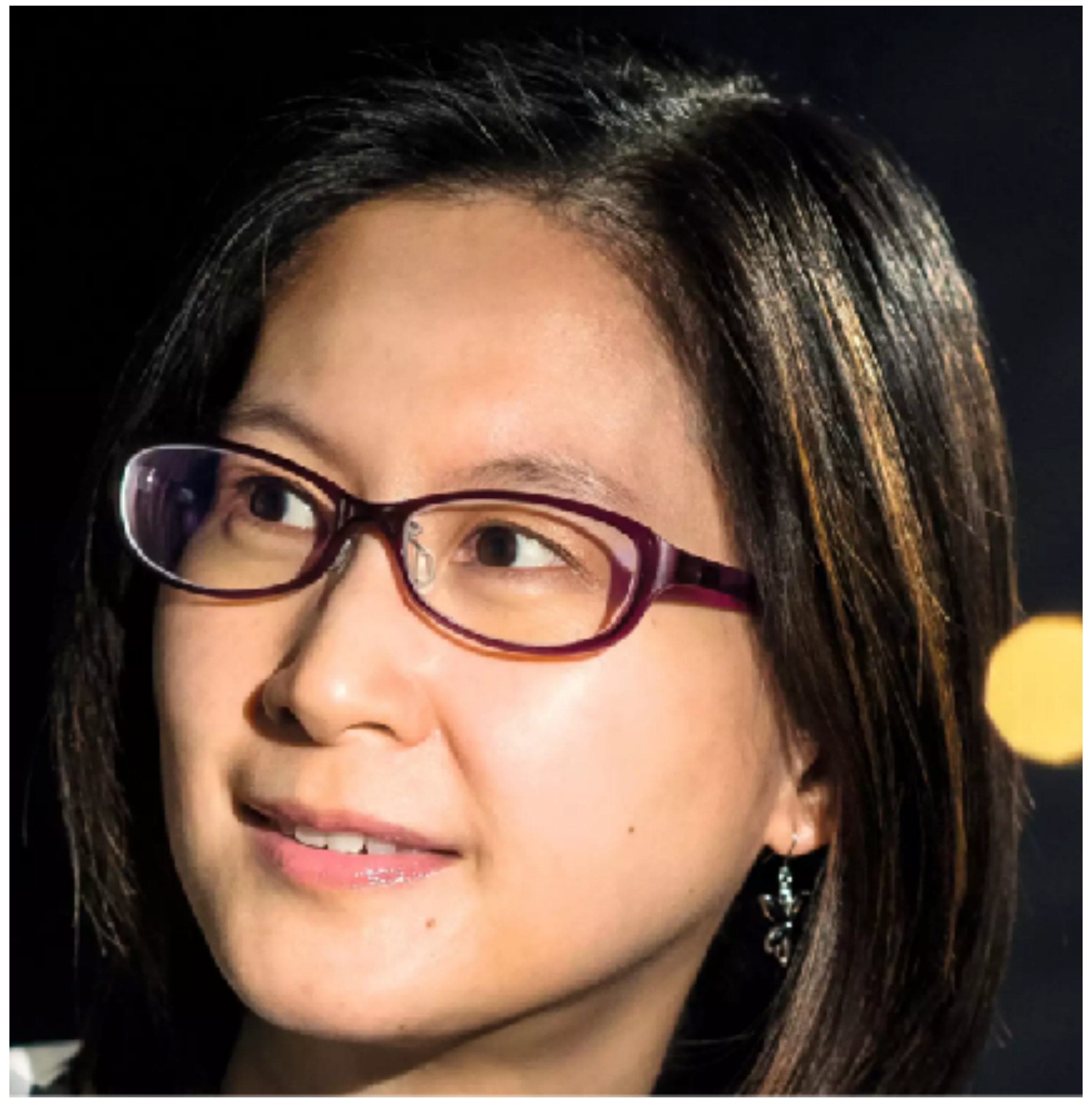
Since the 2019 Fachbeirat

Two have moved to permanent positions in academia

Elisa Ferreira (Postdoc)

↓

**Assistant Professor,
Kavli IPMU, Univ. of Tokyo**



Sherry Suyu (Group Leader)

↓

**W3 Professor, TUM
(First!) Max Planck Fellow@MPA**

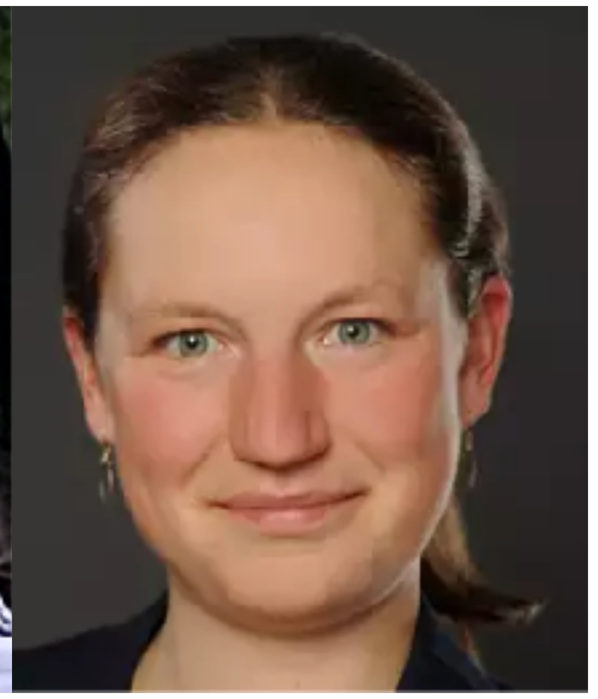
Important Note

- In this presentation, I do not include achievements of Fabian Schmidt's W2 group. His primary research area is the large-scale structure of the Universe.
- See his statement in the Fachbeirat report, and ask him during 10-min interview this afternoon. He is very keen to share his research with you!

PhD students

Postdocs

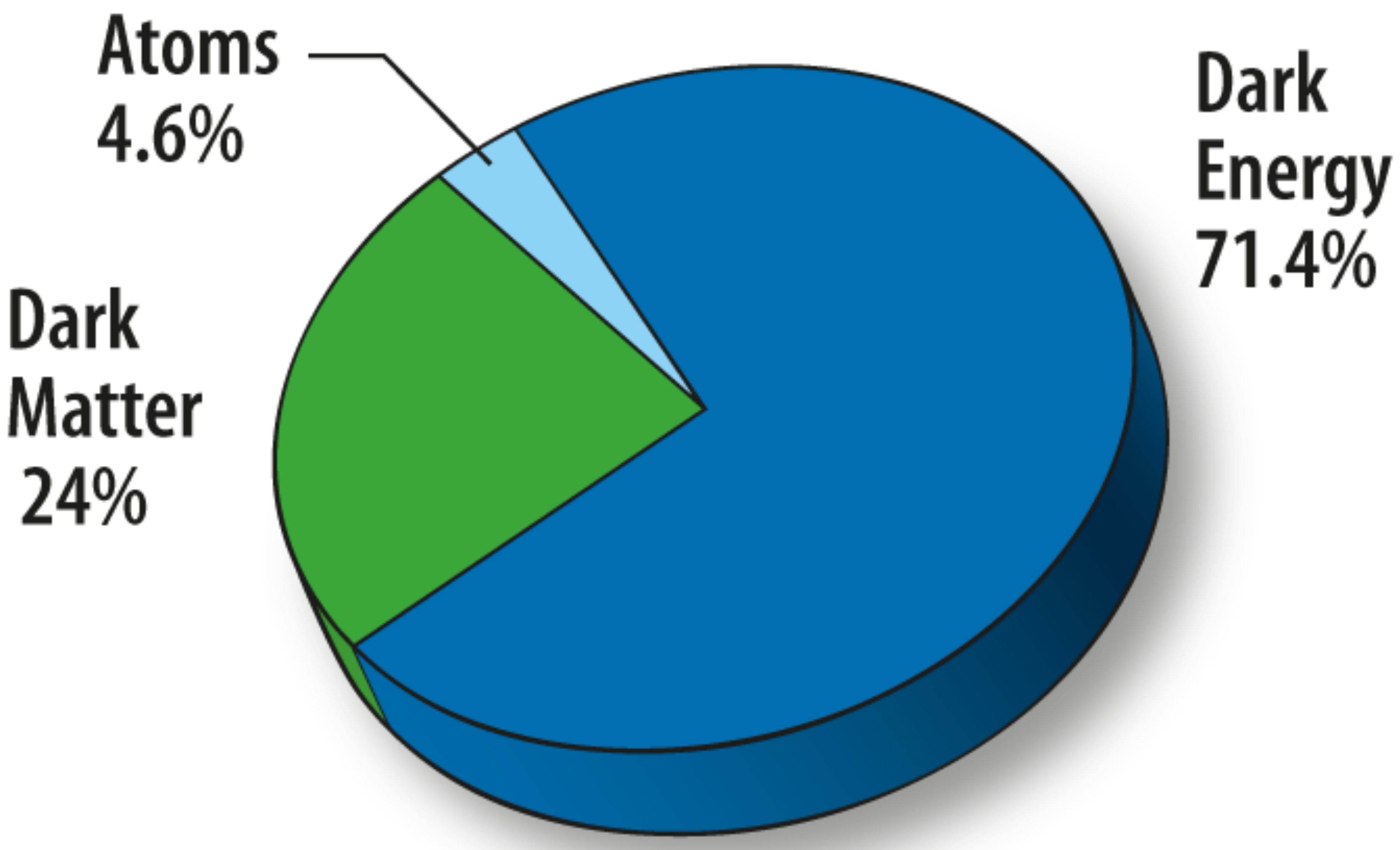
Funded by ERC Grant



Funded by ORIGINS Grant

Main Research Themes

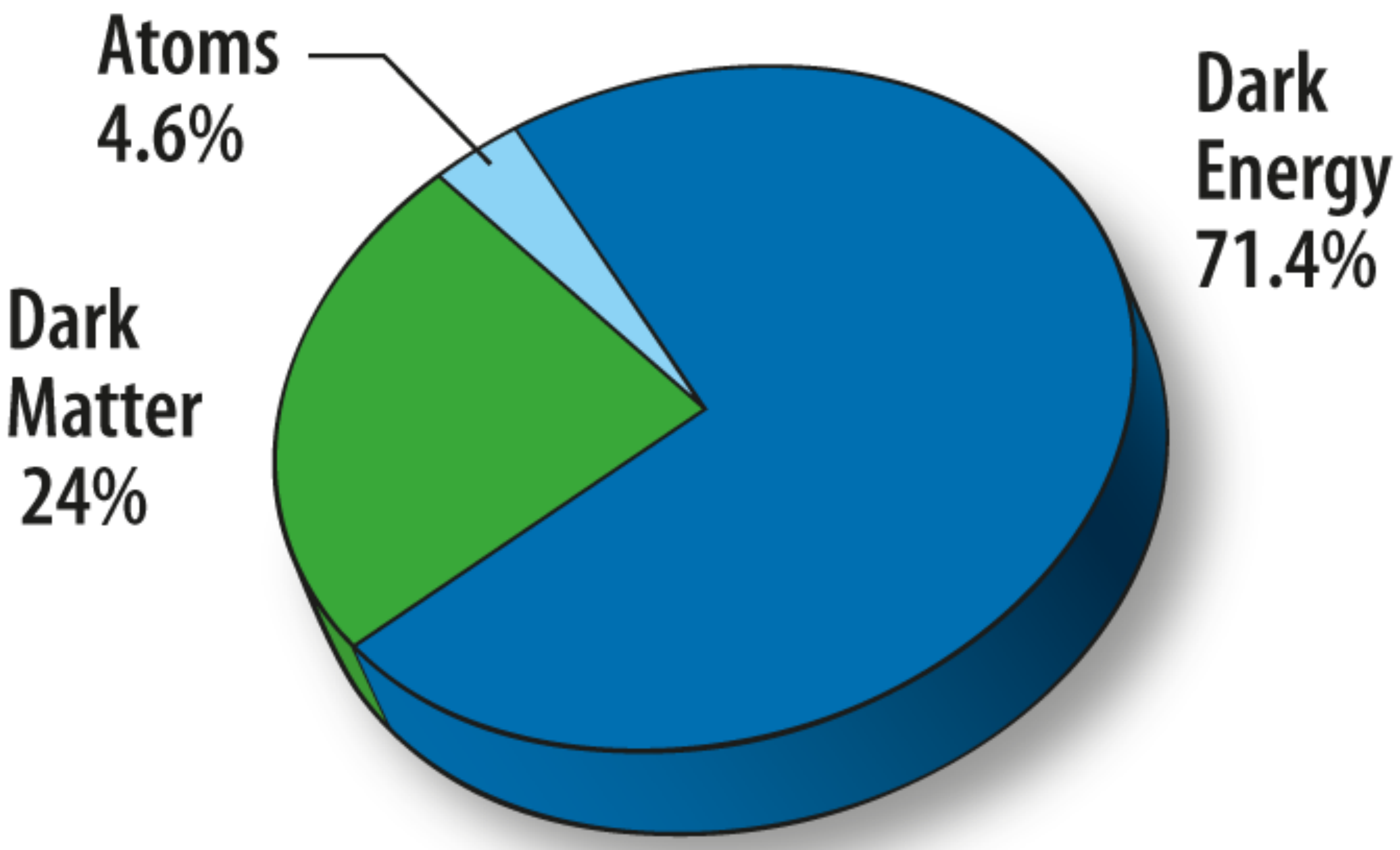
- ***How did the Universe begin?***
  - What is the physics of inflation?
- ***What is the origin of the cosmic acceleration?***
  - What is the nature of dark energy?
- ***What is the nature of dark matter?***
- ***What is the mass of neutrinos?***



We use both theory and observational data to make progress

Main Research Themes

In practice, we do whatever we find interesting at the time.



We use both theory and observational data to make progress

Basic Routine

Interaction with observational efforts is very important to us.

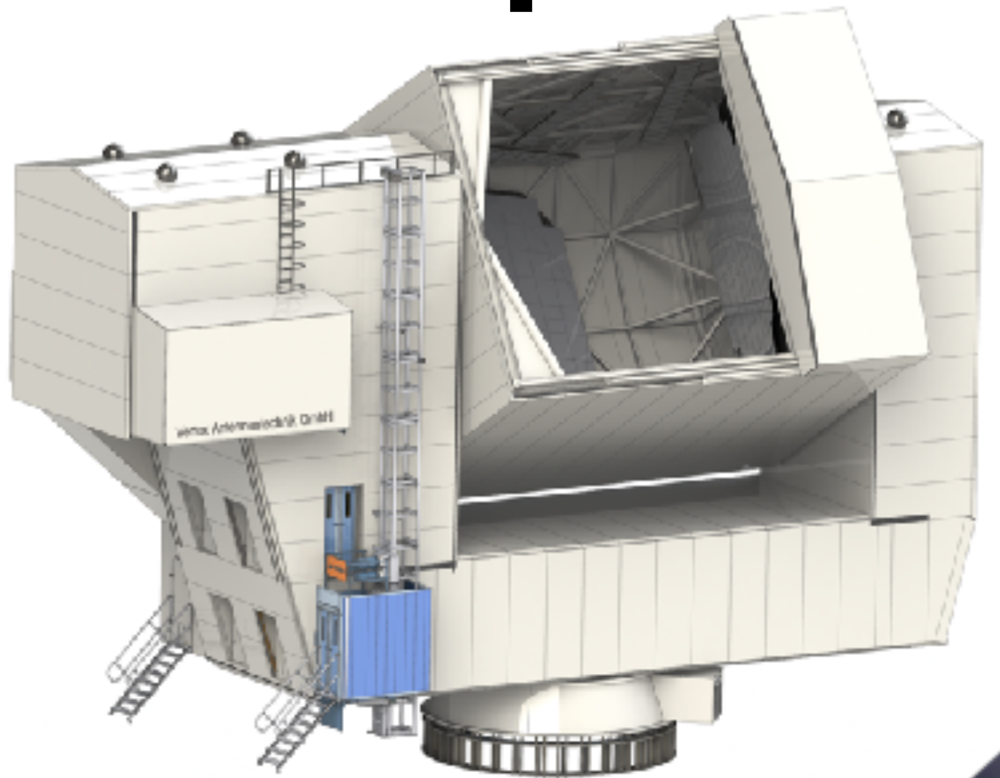
Main Tools

CMB and LSS

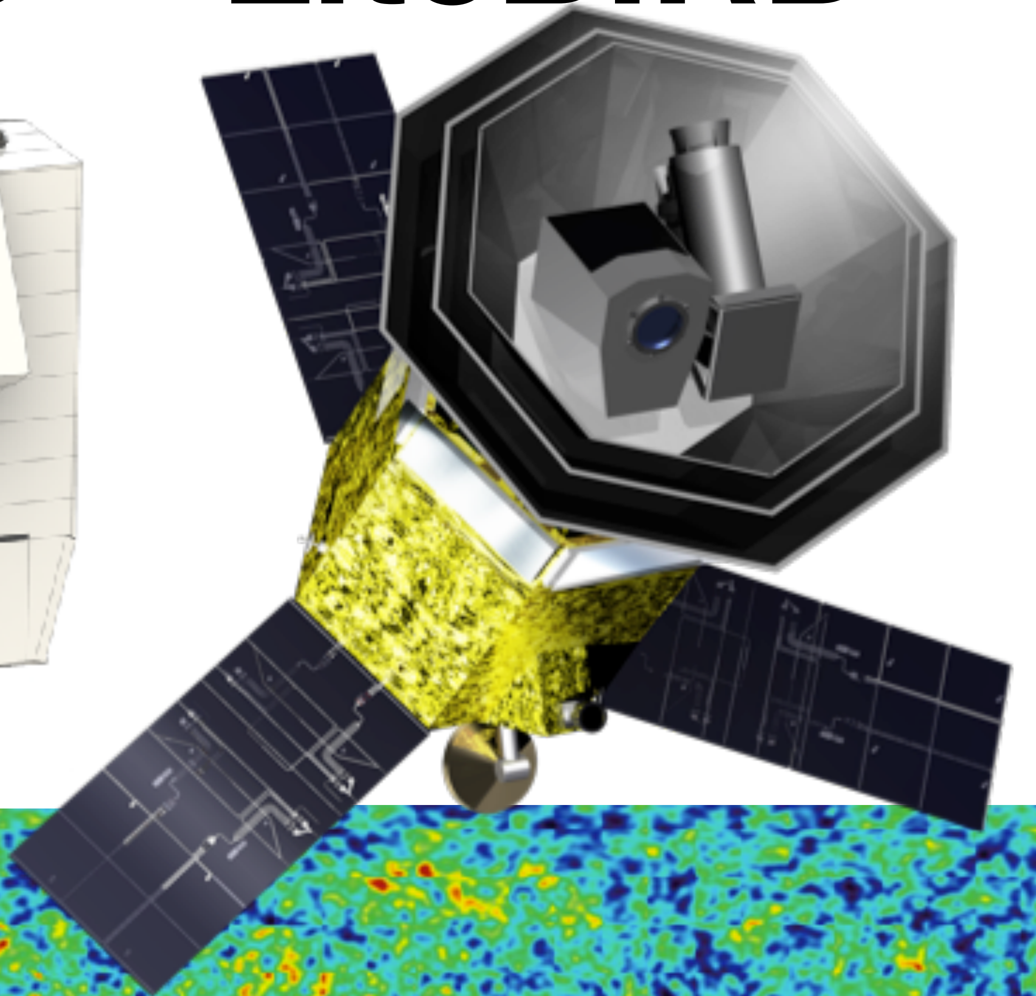
- ***Cosmic Microwave Background (CMB)***
  - Early universe probe: **cosmic inflation**
  - New parity-violating physics (in dark matter and dark energy): **cosmic birefringence**

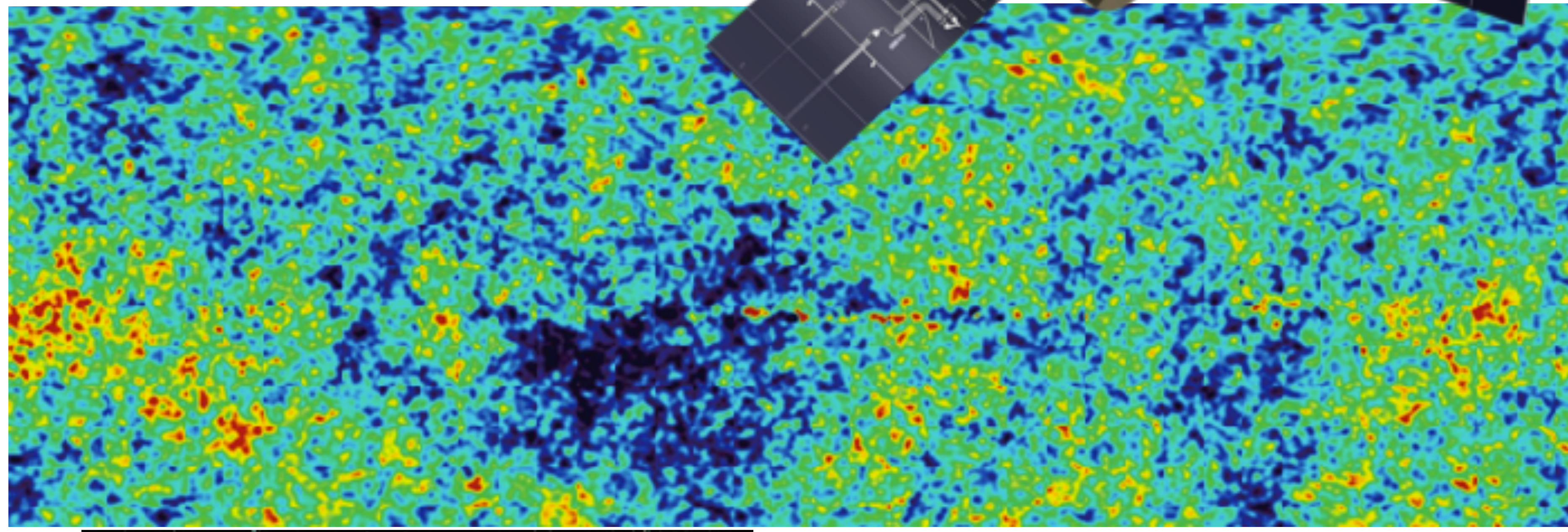
- ***Large-scale structure (LSS): distribution of matter, galaxies, galaxy clusters, and strong lensing***
  - Probing the late-time universe: **dark energy** and **mass of neutrinos**

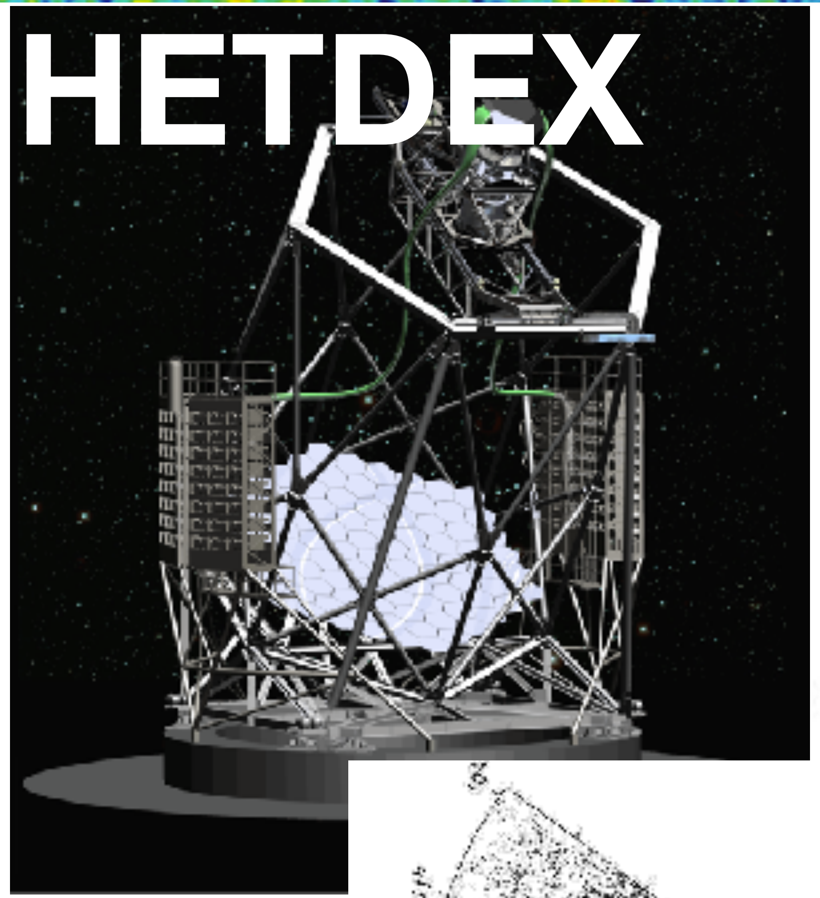
CCAT-prime



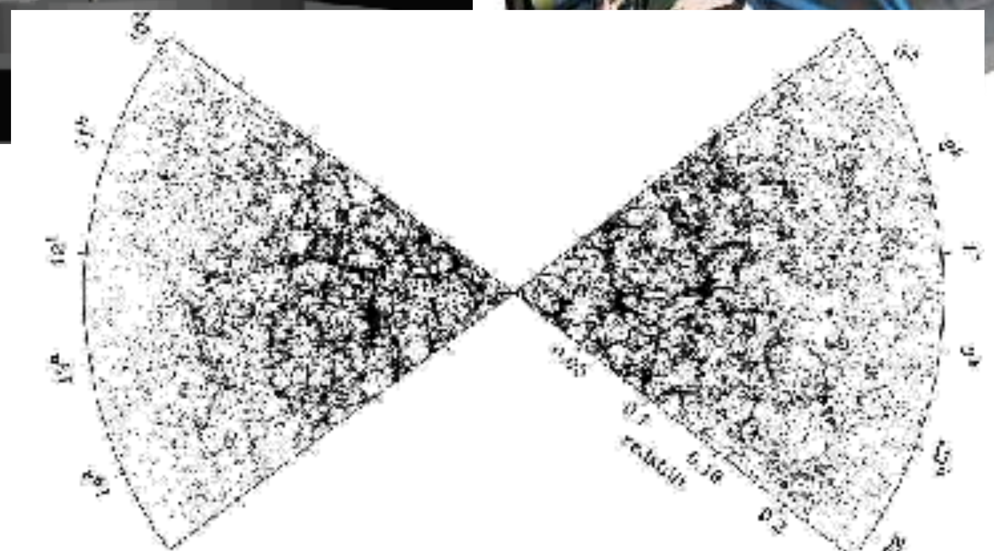
LiteBIRD







PFS



The 2019 Fachbeirat Report

Eiichiro Komatsu

The long-term impact of his CMB work is significantly enhanced by his involvement in the now-selected JAXA-CMB mission LiteBIRD (launch 2028), and the CCAT-prime telescope (first light 2021). Komatsu's involvement with experimental projects such as PFS and HETDEX are textbook examples of how theory and experiment should interact: by getting involved at the early stages of the projects, he and his group have successfully guided the design of the experiments themselves, optimizing and maximizing their scientific return.

- **We continue to provide the theoretical underpinnings for experiments, and are involved in the projects at the most fundamental level.**

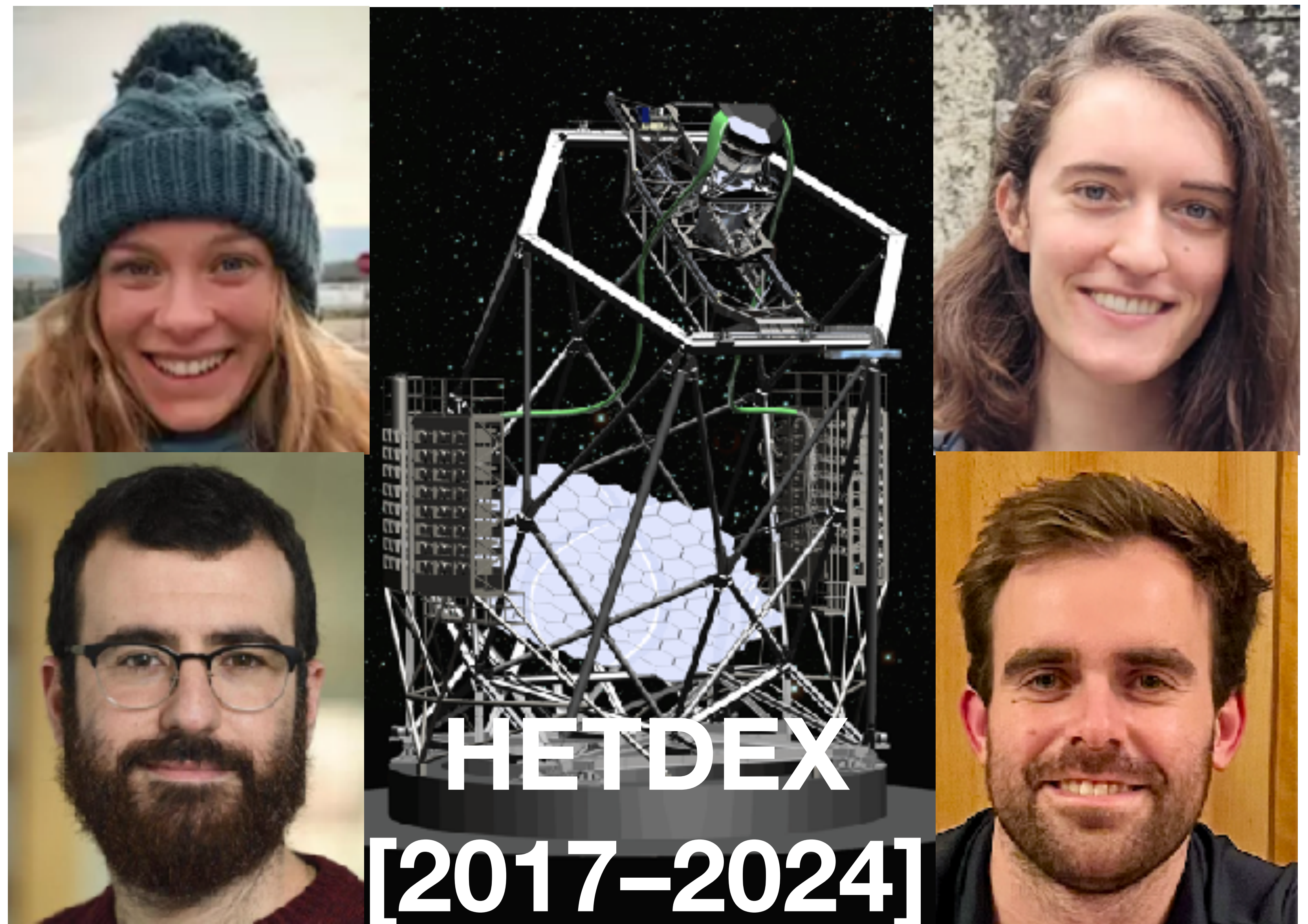
Taking leadership roles in experiments

CMB:
Early Universe Probe

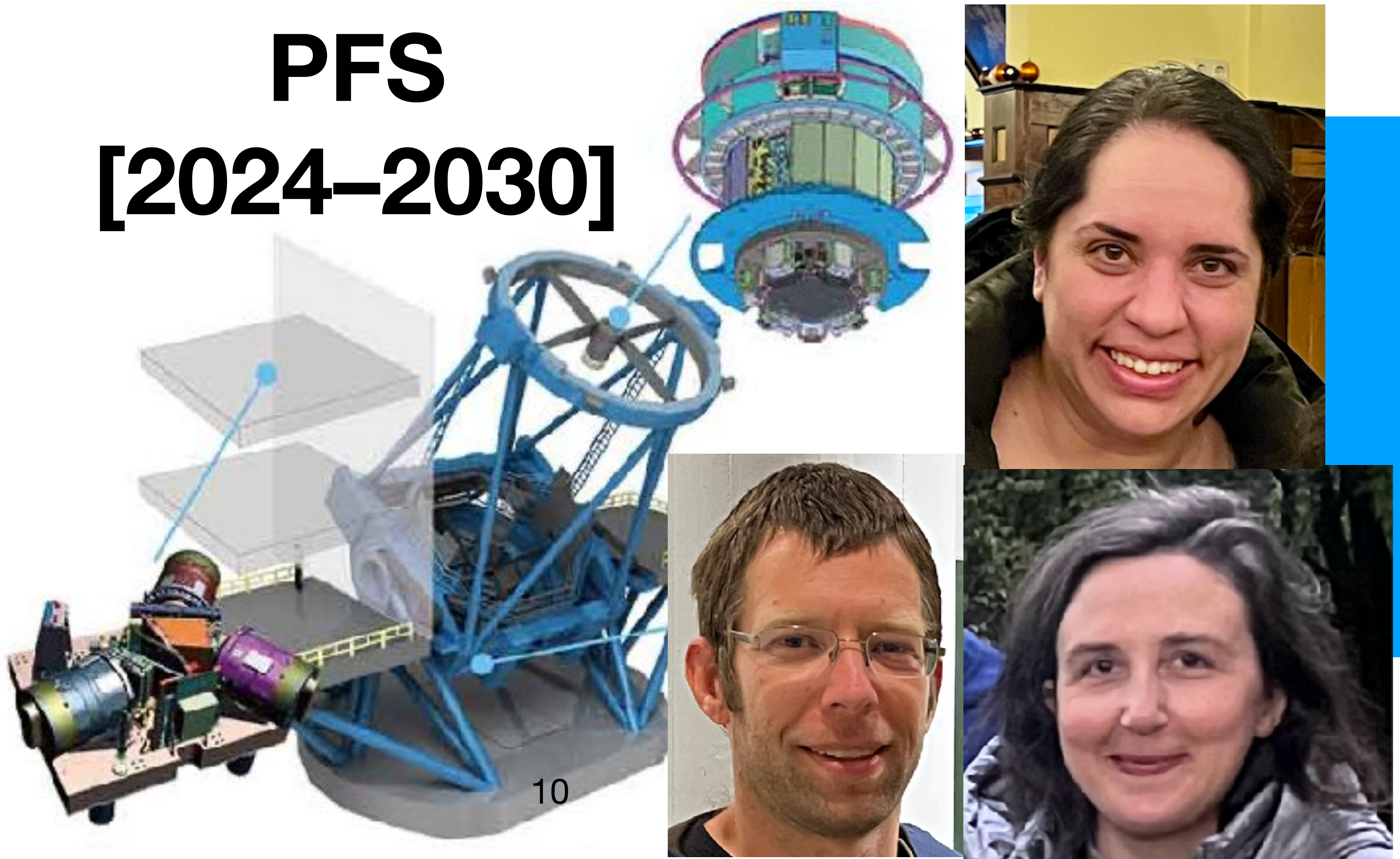
CCAT-prime
[2024–]

LiteBIRD
[2029–]

2022 2023 2024 2025 2026 2027 2028 2029 2030 2031



PFS
[2024–2030]



LSS:
Late Universe Probe

Major contributions to the science papers

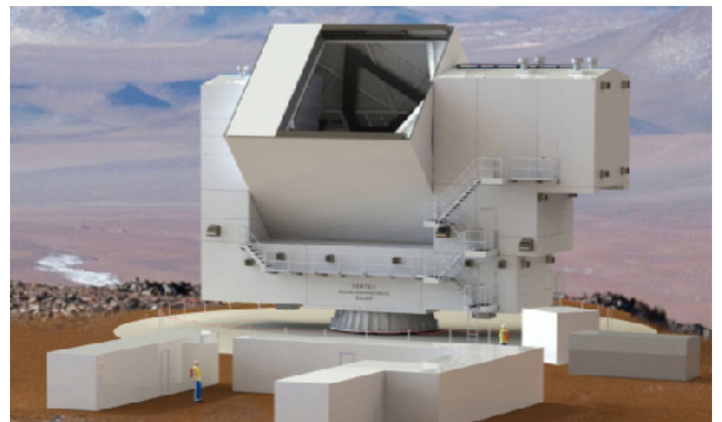
Important milestones for our CMB projects

CCAT-prime Collaboration: Science Goals and Forecasts with Prime-Cam on the Fred Young Submillimeter Telescope

CCAT-PRIME COLLABORATION

Abstract

We present a detailed overview of the science goals and predictions for the Prime-Cam direct detection camera/spectrometer being constructed by the CCAT-prime collaboration for dedicated use on the Fred Young Submillimeter Telescope (FYST). The FYST is a wide-field, 6-m aperture submillimeter telescope being built (first light in mid-2024) by an international consortium of institutions led by Cornell University and sited at more than 5600 meters on Cerro Chajnantor in northern Chile. Prime-Cam is one of two instruments planned for FYST and will provide unprecedented spectroscopic and broadband measurement capabilities to address important astrophysical questions ranging from Big Bang cosmology through reionization and the formation of the first galaxies to star formation within our own Milky Way galaxy. Prime-Cam on the FYST will have a mapping speed that is over ten times greater than existing and near-term facilities for high-redshift science and broadband polarimetric imaging at frequencies above 300 GHz. We describe details of the science program enabled by this system and our preliminary survey strategies.



To appear in ApJS (arXiv:**2107.10364**)

Probing Cosmic Inflation with the LiteBIRD Cosmic Microwave Background Polarization Survey

LiteBIRD Collaboration

LiteBIRD the Lite (Light) satellite for the study of B-mode polarization and Inflation from cosmic background Radiation Detection, is a space mission for primordial cosmology and fundamental physics. The Japan Aerospace Exploration Agency (JAXA) selected *LiteBIRD* in May 2019 as a strategic large-class (L-class) mission, with an expected launch in the late 2020s using JAXA's H3 rocket. *LiteBIRD* is planned to orbit the Sun-Earth Lagrangian point L2, where it will map the cosmic microwave background (CMB) polarization over the entire sky for three years, with three telescopes in 15 frequency bands between 34 and 448 GHz, to achieve an unprecedented total sensitivity of 2.2 μK-arcmin, with a typical angular resolution of 0.5° at 100 GHz. The primary scientific objective of *LiteBIRD* is to search for the signal from cosmic inflation, either making a discovery or ruling out well-motivated inflationary models. The measurements of *LiteBIRD* will also provide us with insight into the quantum nature of gravity and other new physics beyond the standard models of particle physics and cosmology. We provide an overview of the *LiteBIRD* project, including scientific objectives, mission and system requirements, operation concept, spacecraft and payload module design, expected scientific outcomes, potential design extensions and synergies with other projects.

To appear in PTEP (arXiv:**2202.027734**)

HETDEX has arrived! *arXiv:2110.04298, 2110.03843*

World's largest IFU on world's (almost) largest telescope

78 x 448 = 34944 fibers across 22' diameter field-of-view on 10-m telescope

HETDEX
Hobby-Eberly Telescope Dark Energy Experiment

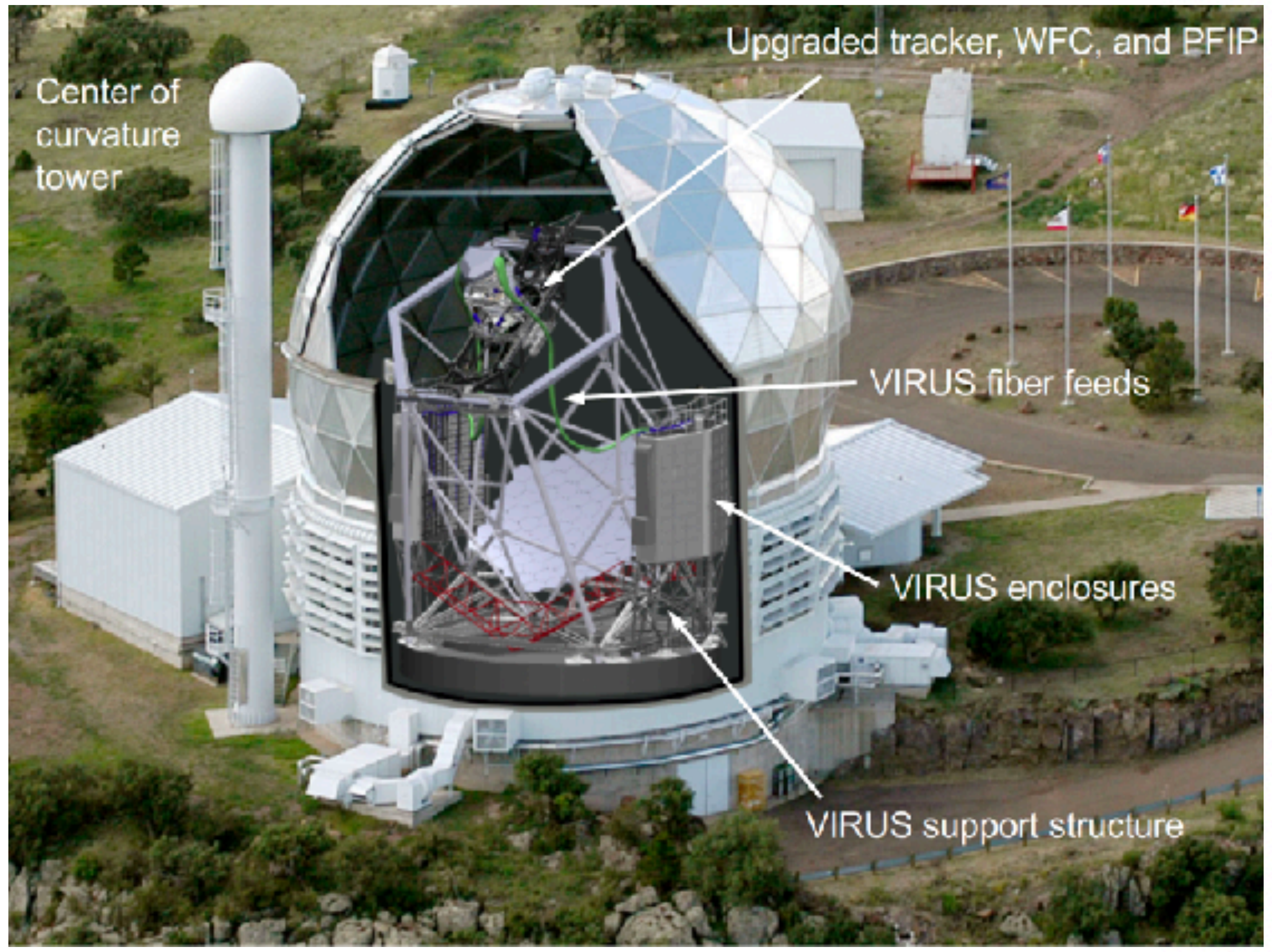
Location
McDonald Observatory (West Texas)

Wavelength Coverage
350–550 nm (Δλ=5.6Å)

Spectrograph Type
Integral Field Unit (IFU)

Field of View
0.1 deg^2 (22' diam.)
~20 Mpc in one go!

Primary Mirror Size
10 m

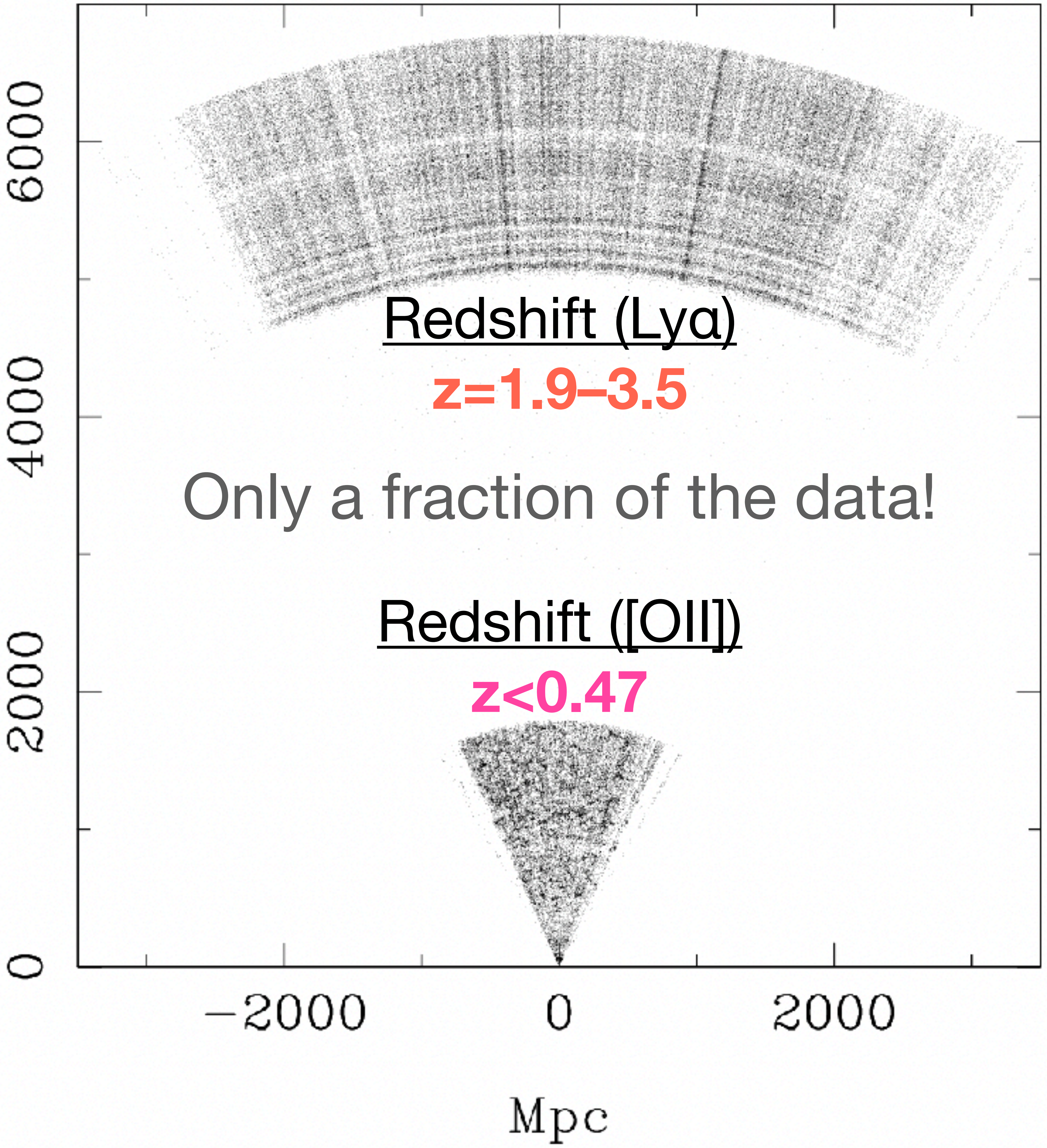


\# of fibers
34,944

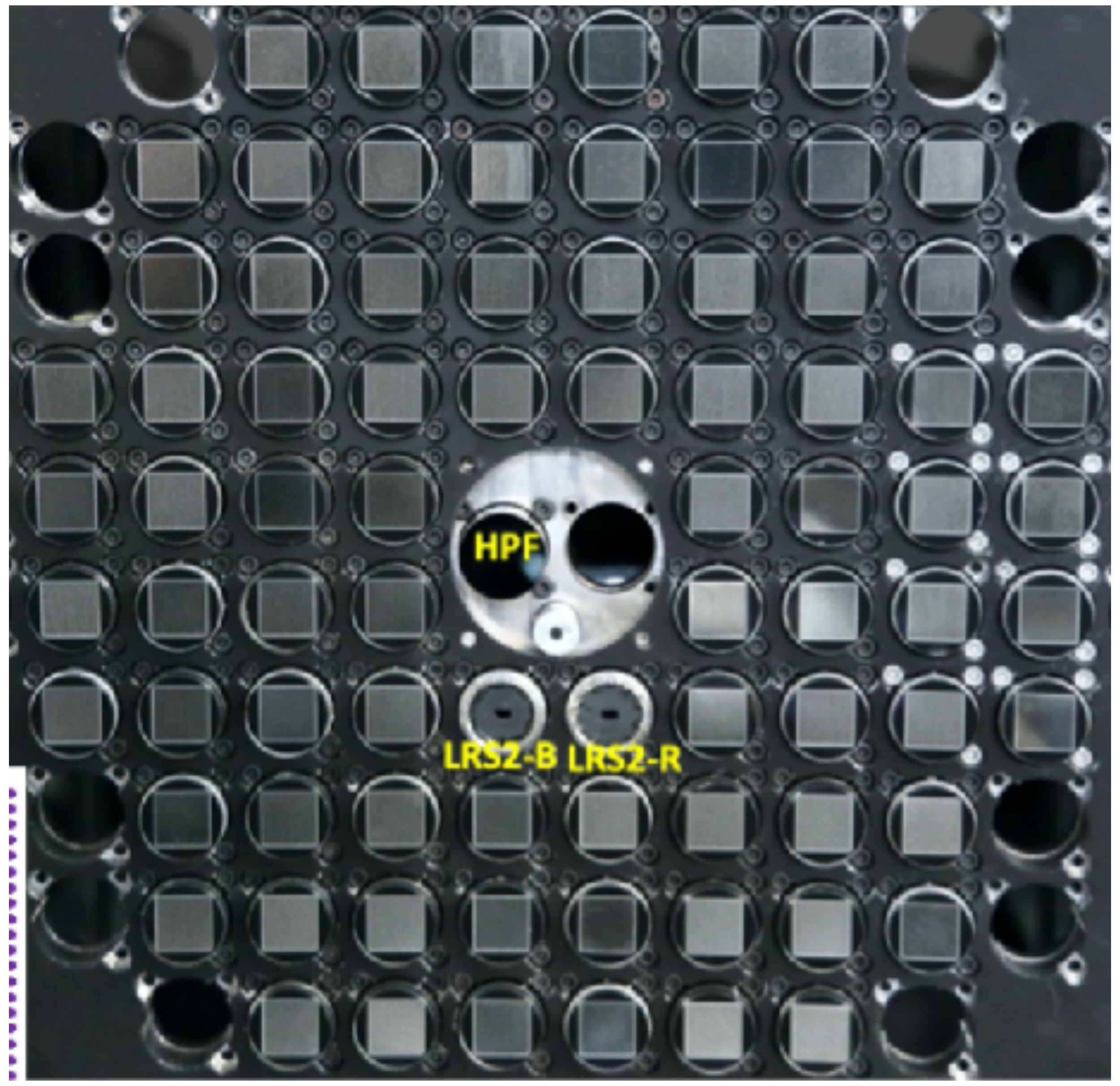
Fiber Diameter
1.5 arcsec

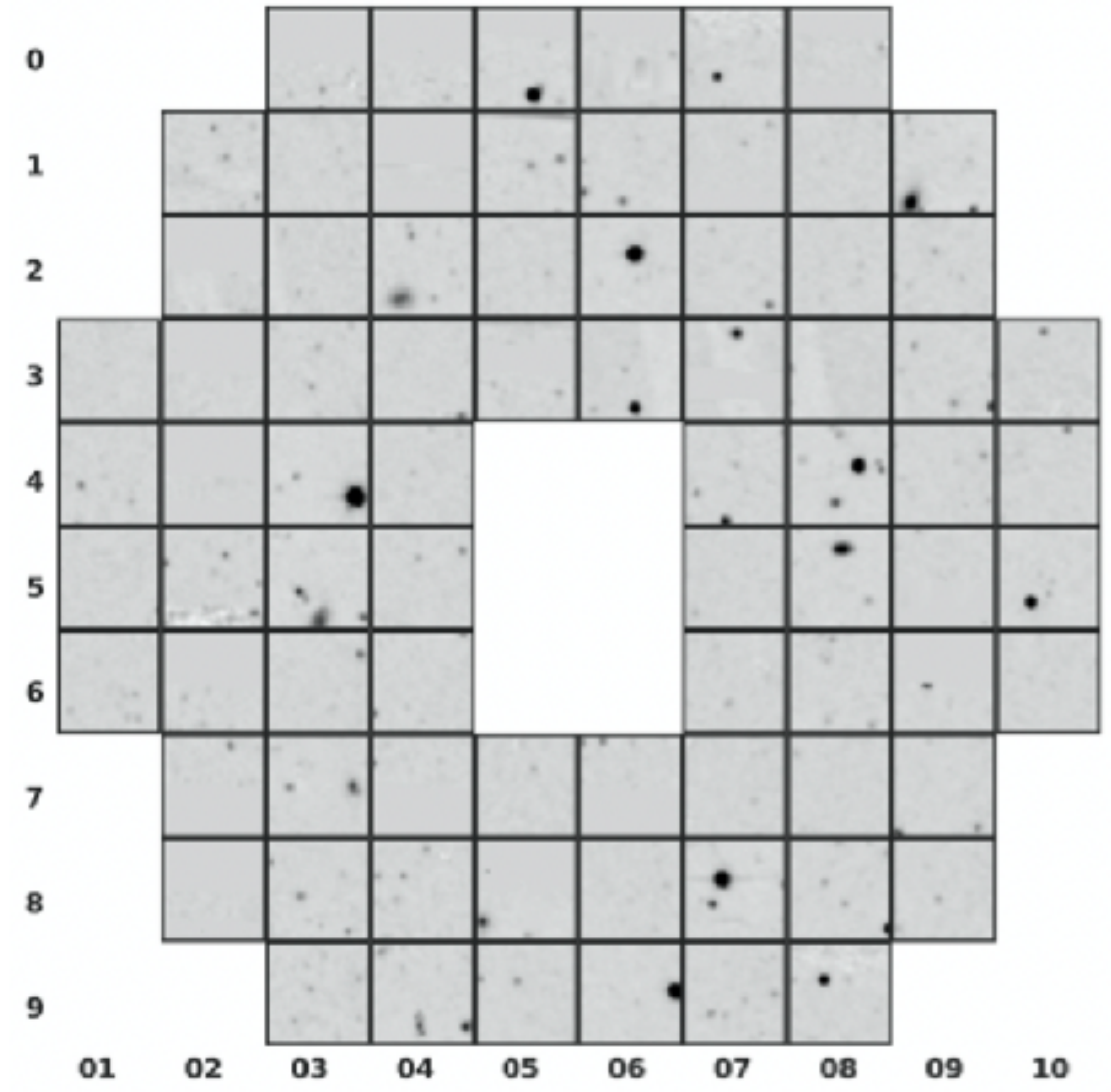
Survey Volume
10.9 Gpc^3

Survey Type
Blind

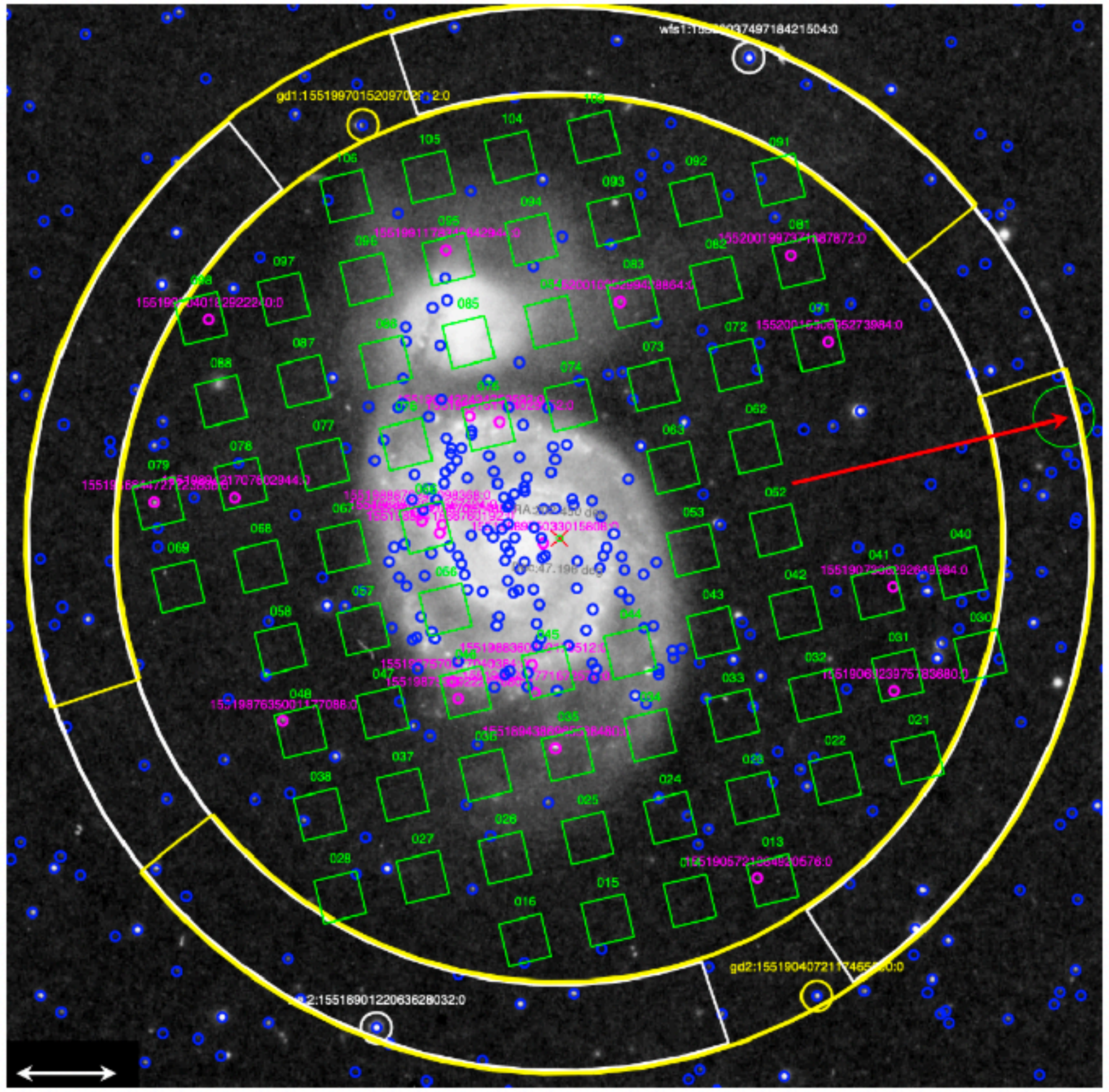


VIRUS on M51 and M101



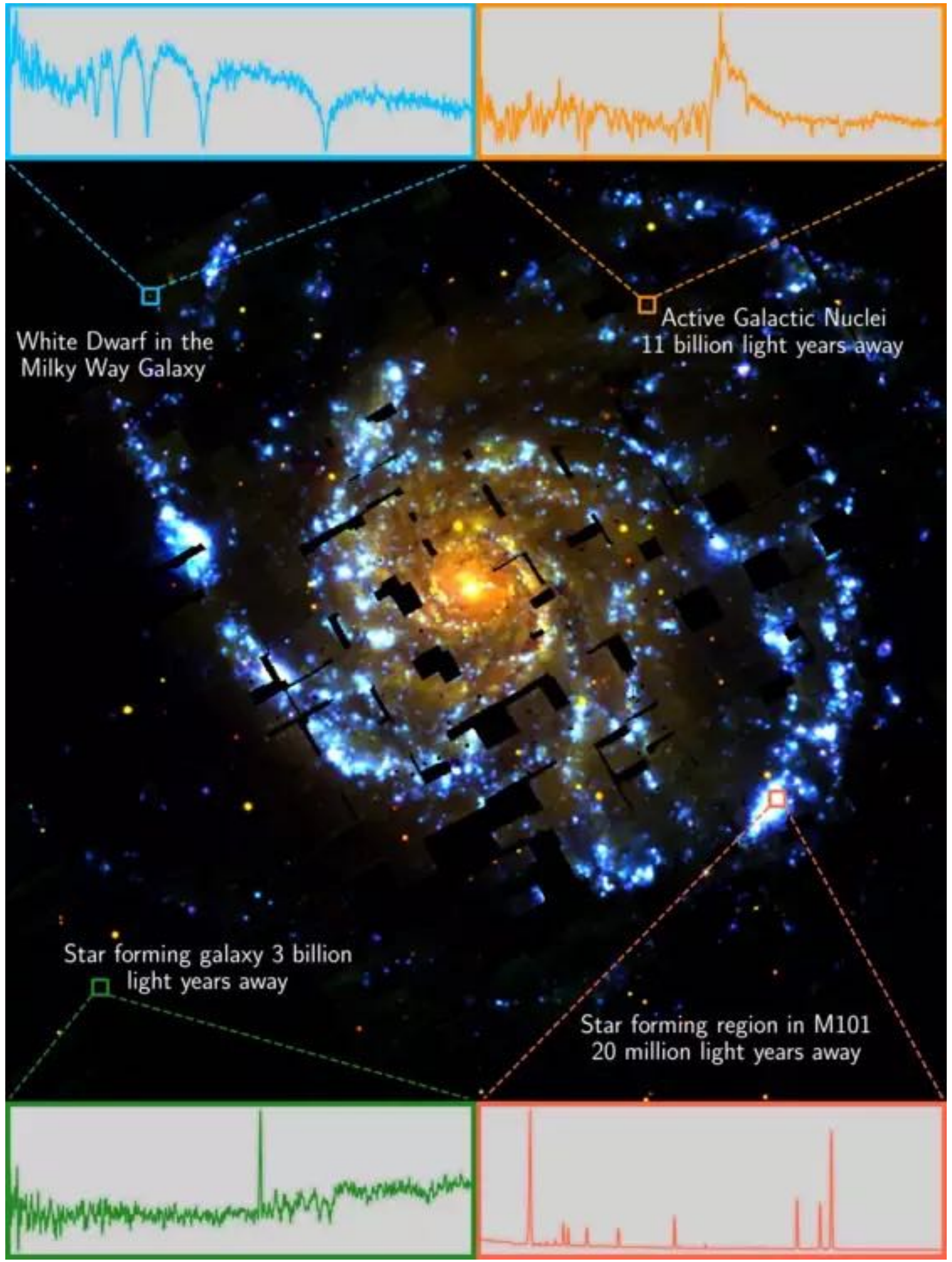


M51



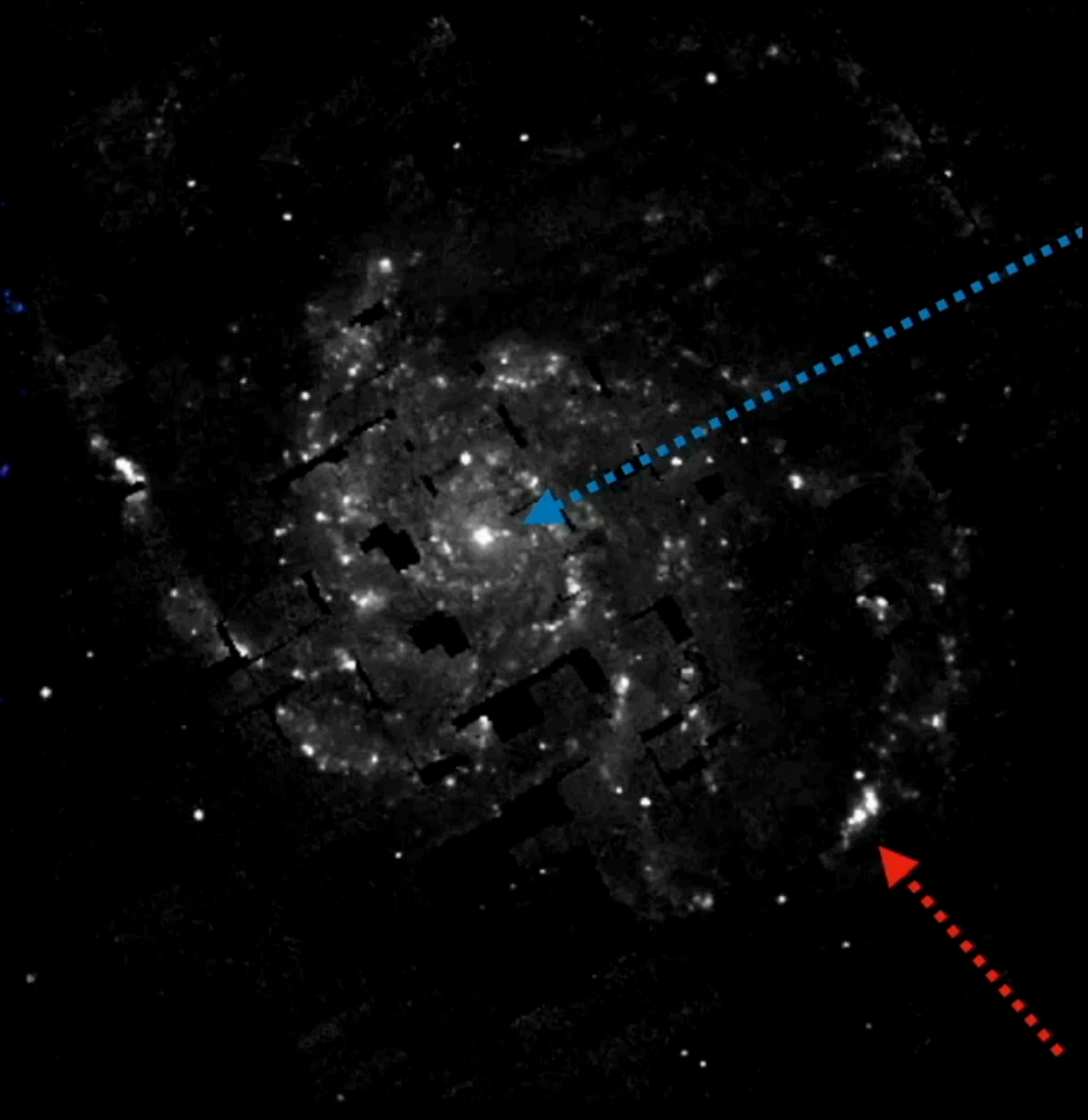
Fill factor ~ 1/4.6

M101

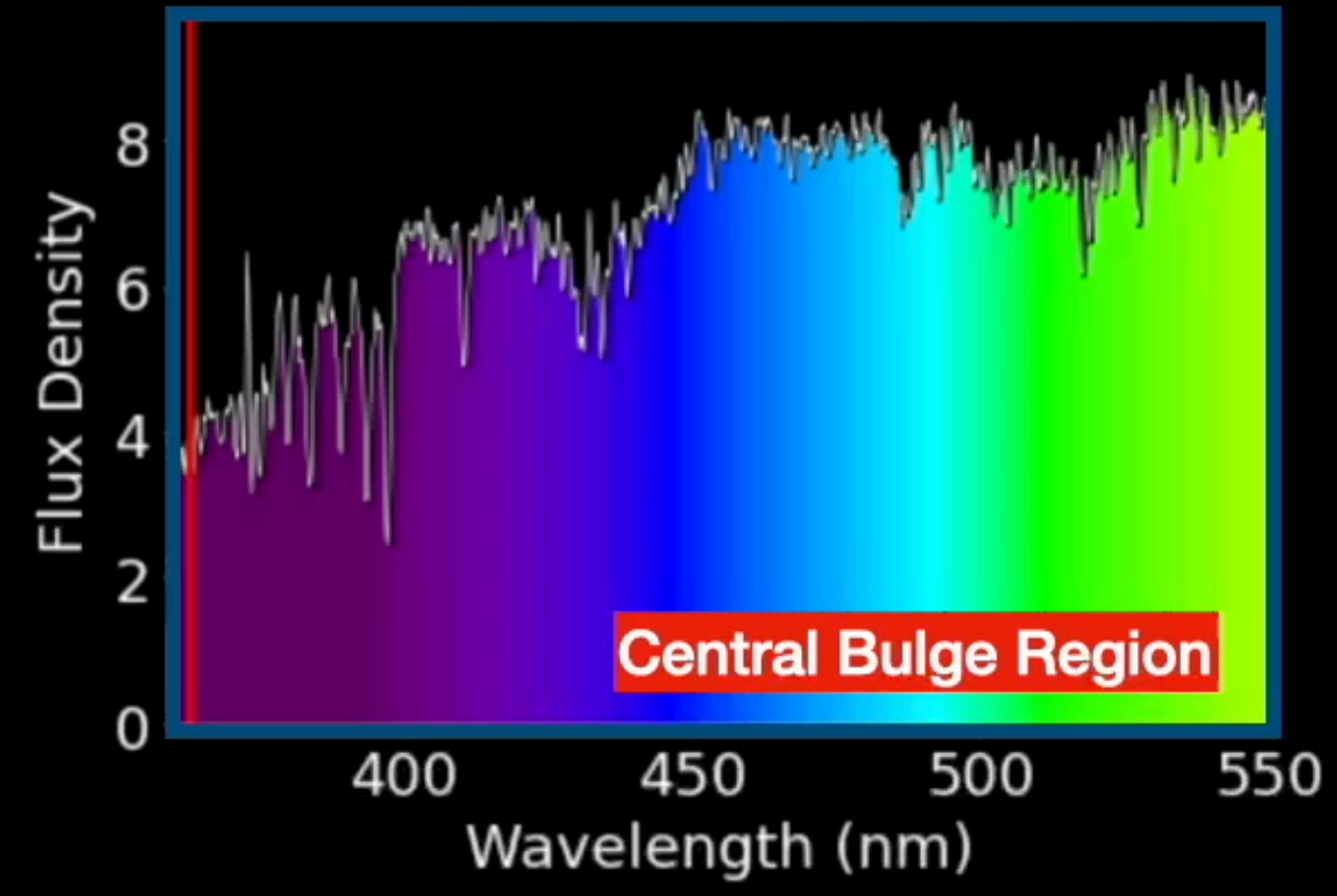


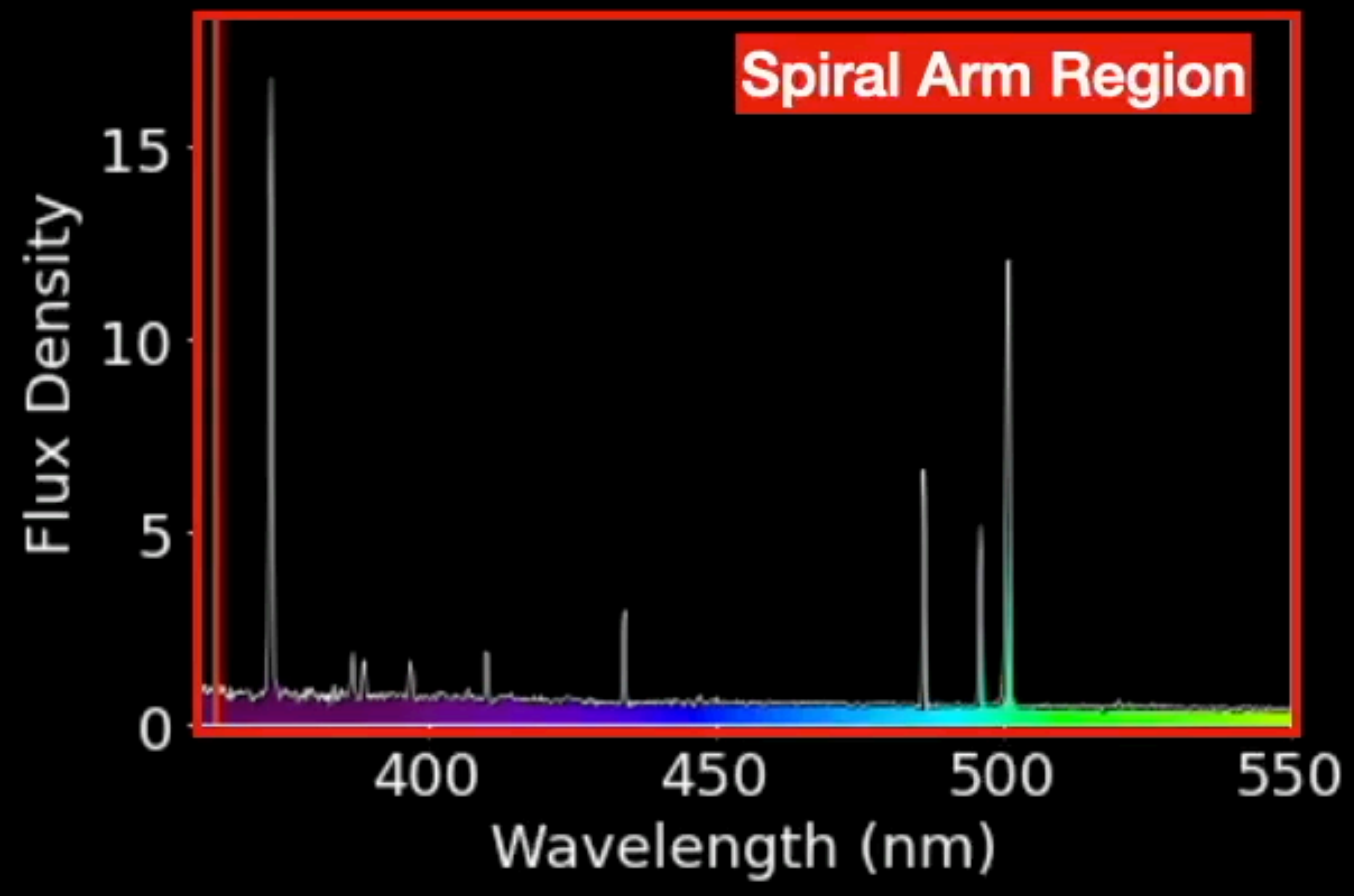
Pinwheel Galaxy from HETDEX

False color image constructed from the HETDEX data cube of the Pinwheel Galaxy

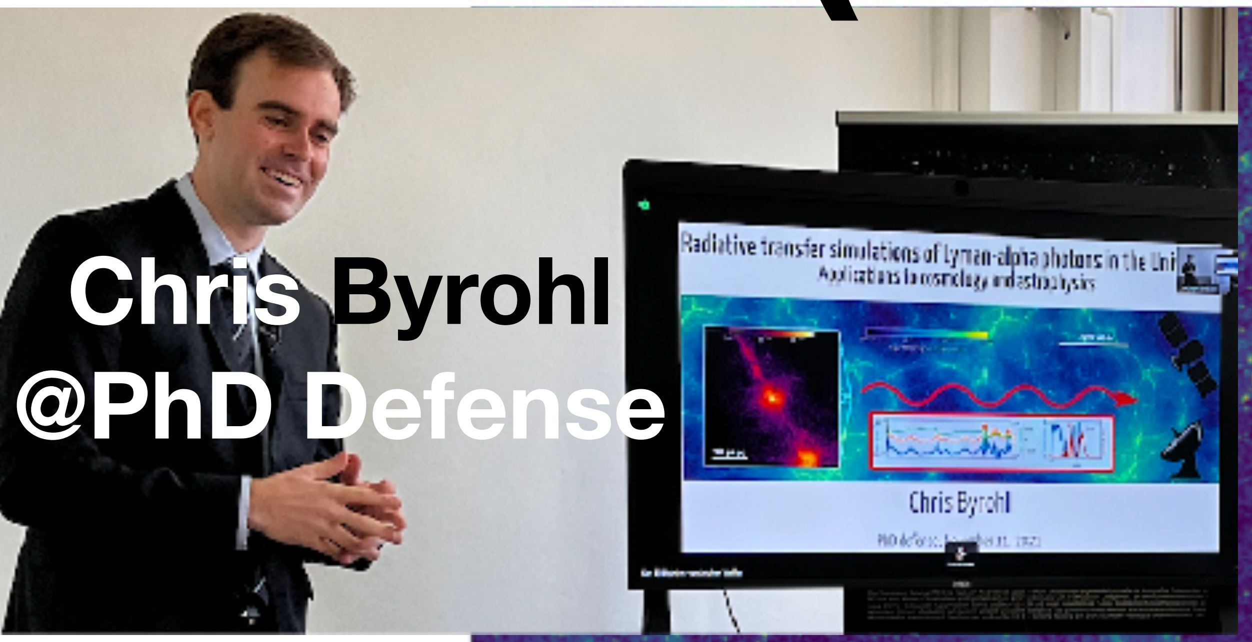


Full spectral scan through the Pinwheel Galaxy HETDEX/VIRUS data cube





Mapping the cosmic web in Lyman-alpha (This is still a simulation, run@MPA)



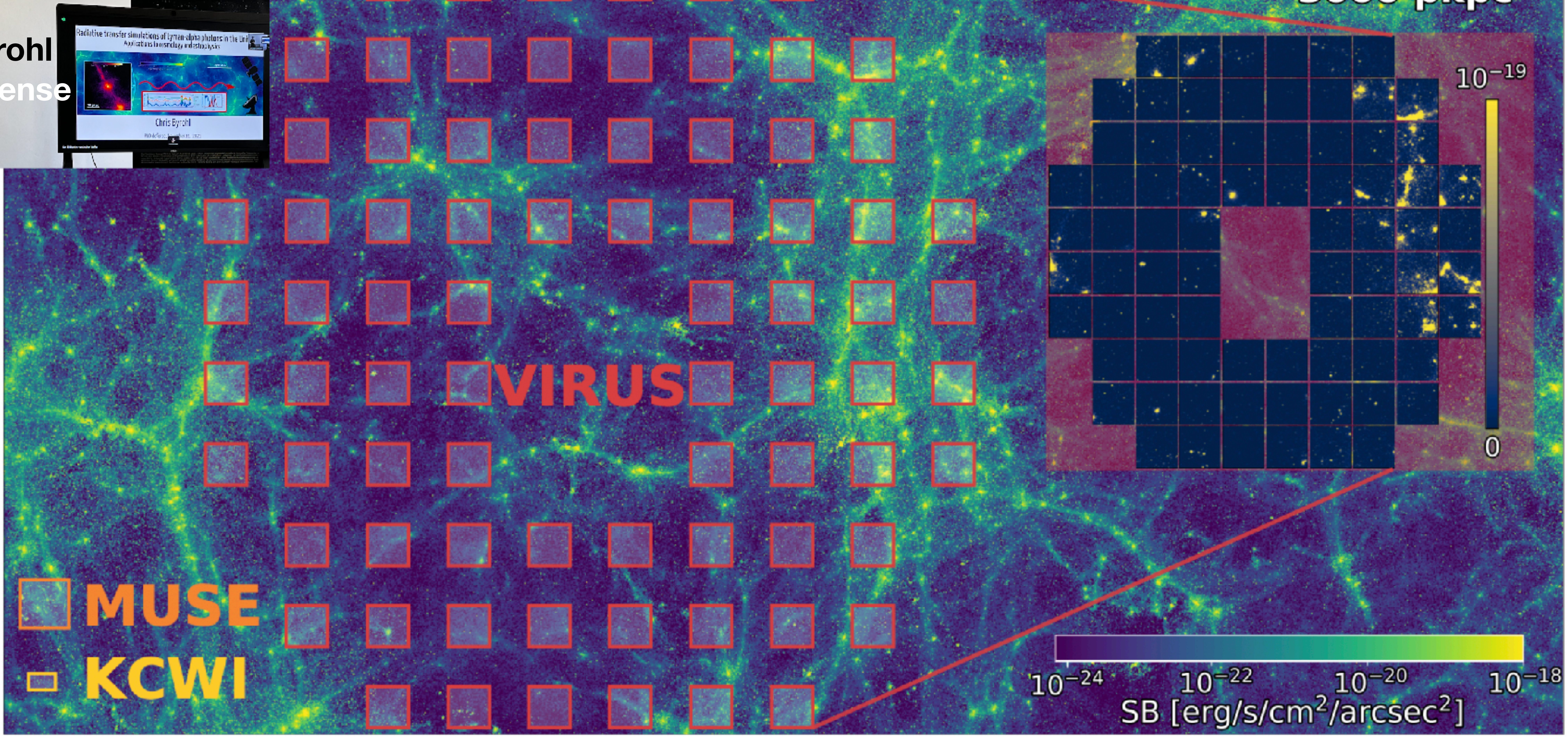


Figure 1: Simulated Lyα surface brightness map at z=2.0 for a slice depth of 5.7Å in the observed frame with the footprints of VIRUS,

Highlights of scientific results, selected from ~40 papers written since the last Fachbeirat

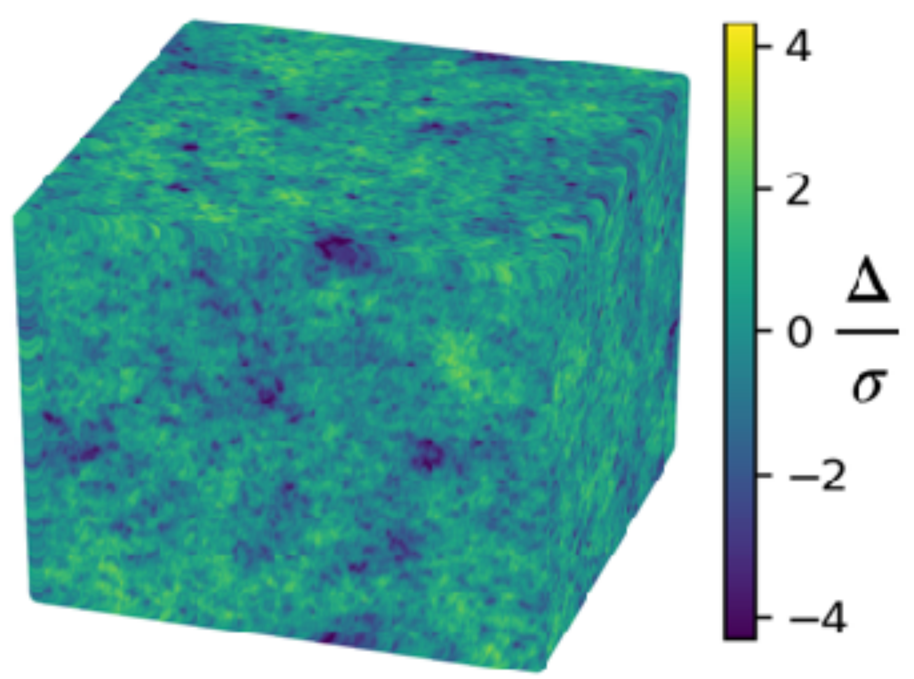
The 2016 Fachbeirat Report

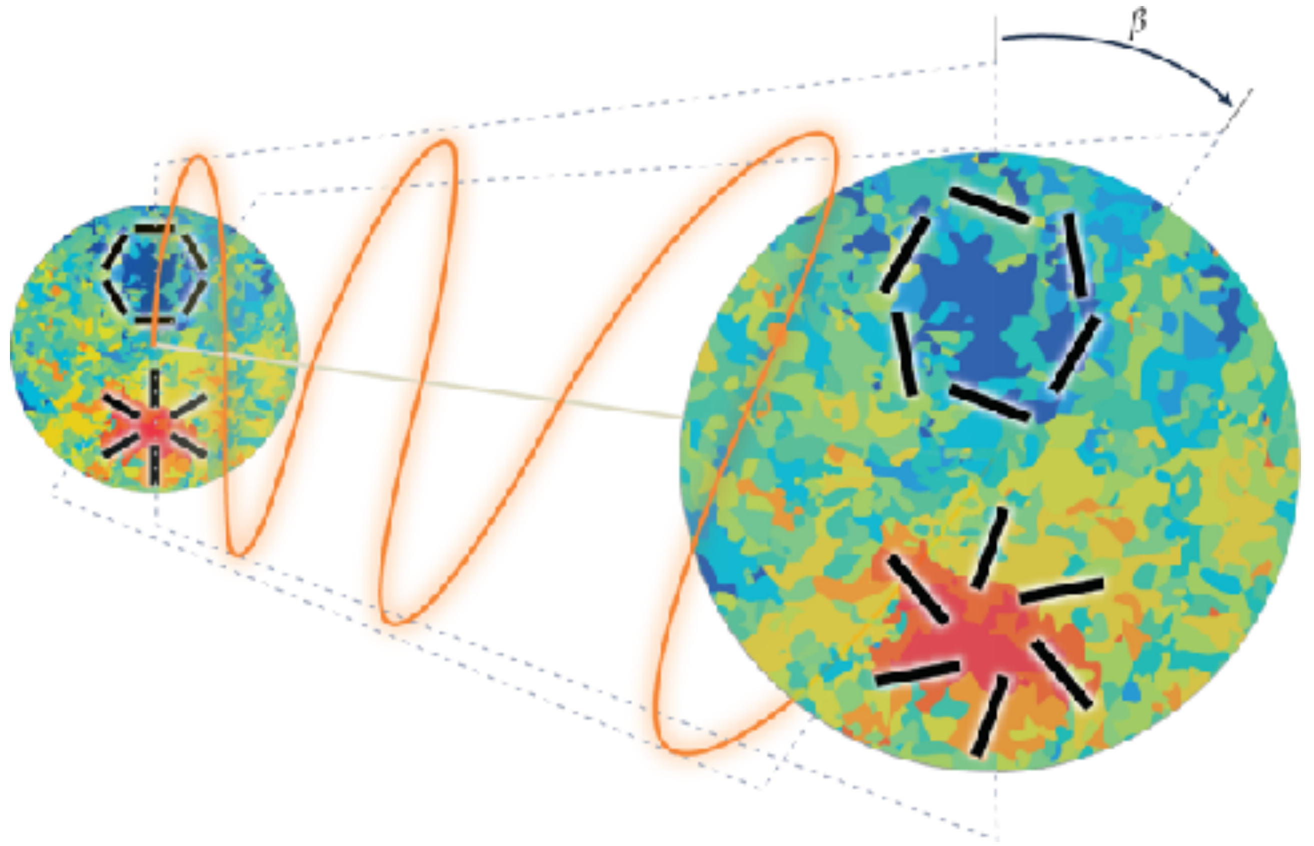
“Innovative, bold ideas that may have wide and long-term repercussions”

Eiichiro Komatsu’s science

Looking ahead, we hope that he may raise his ambitions still further and explore innovative, bold ideas that may have wide and long-term repercussions

- <u>**Achievements along this line since 2020:**</u>
  - A hint of new parity-violating physics in CMB polarisation
  - Truly *ab initio* simulation of inflation

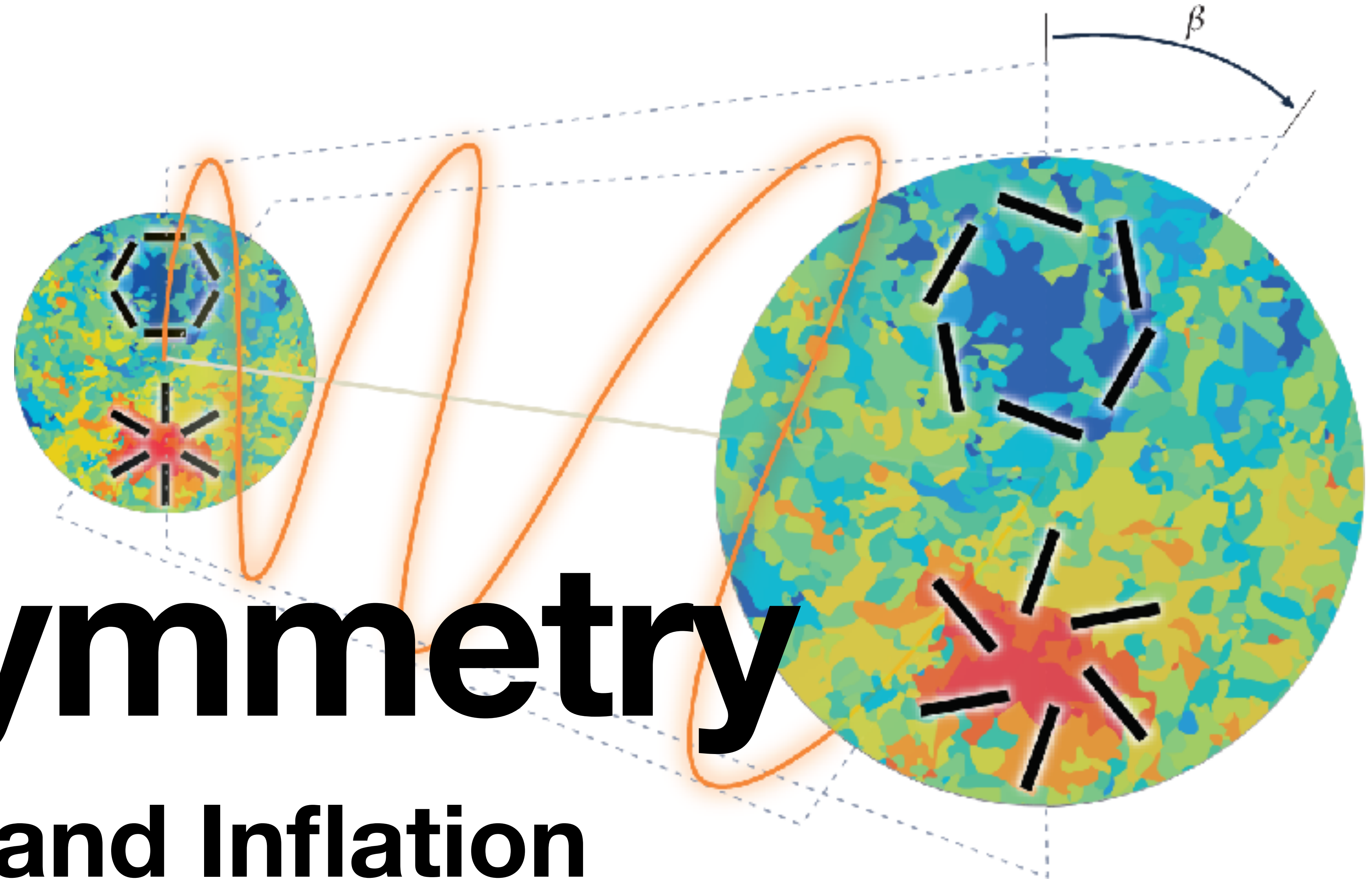




Patricia Diego-Palazuelos
(Univ. Cantabria, Santander)

Johannes Røsok Eskilt
(Univ. Oslo)

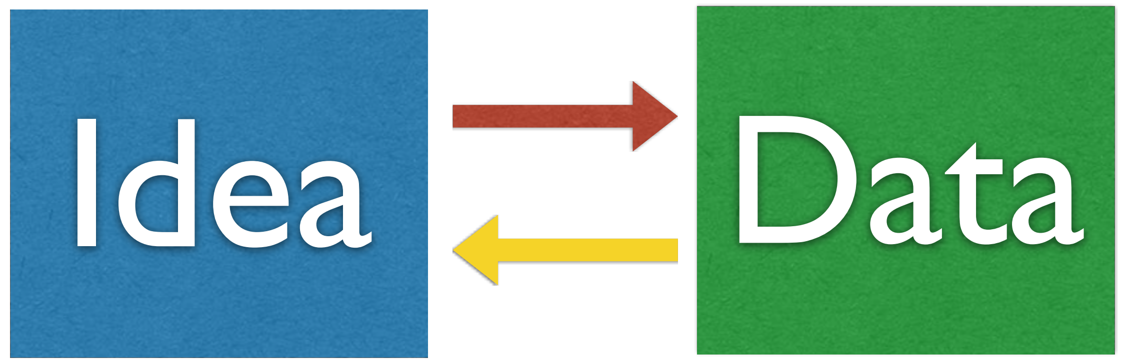
Yuto Minami
(Osaka U.)



Violation of Parity Symmetry

New Probe of Dark Matter, Dark Energy, and Inflation

- *Minami & EK, PRL, 125, 221301 (2020)*
- *Diego-Palazuelos, Eskilt, Minami, et al., PRL, 128, 091302 (2022)*
- *EK, Nature Reviews Physics, 4 (2022)*
- *Eskilt & EK, PRD, 106, 063503 (2022)*
- *Diego-Palazuelos, et al., arXiv:2210.07644*



MAX-PLANCK-INSTITUT
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Monthly Highlight June 2022

Author

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Director
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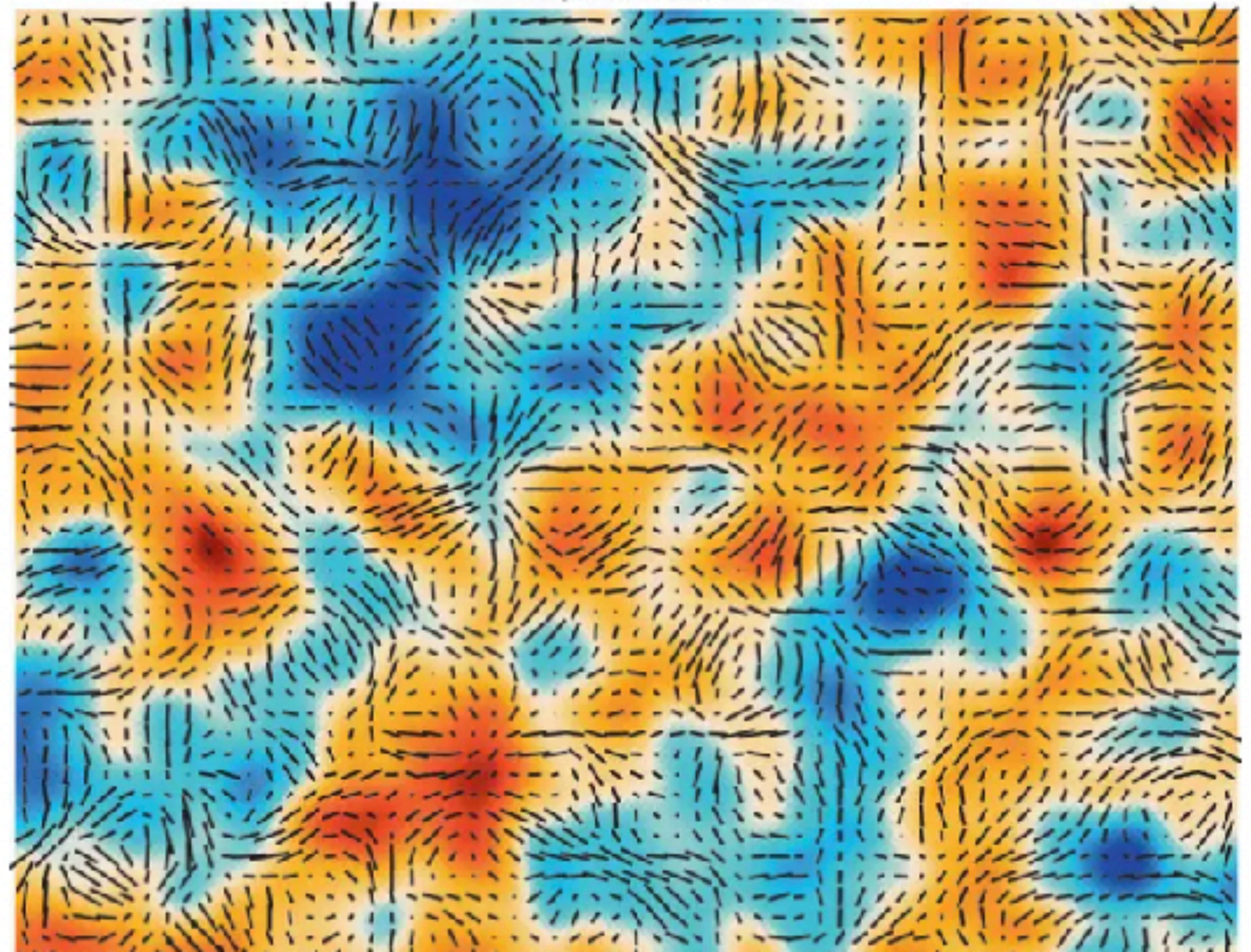
Original publications

ay a menu

New analysis strengthens the hint of new physics in polarized radiation from the early Universe

JUNE 01, 2022

In 2020, a tantalizing hint of new physics violating "parity symmetry" was found in polarization data of the cosmic microwave background obtained with the Planck satellite at high frequencies. Based on the Planck data and a simplified assumption about the impact of the polarized dust emission in the Milky Way, the scientists reported a violation of the symmetry of the laws of physics under inversion of spatial coordinates with 99.2% confidence level. An international team led by MPA director Eiichiro Komatsu has now improved the analysis method. By considering the dust emission explicitly and using more data from not only Planck but also from WMAP the astrophysicists measured the parity-violating signal with 99.987% confidence level. If this should be confirmed in the future as a genuine cosmological signal, it would have profound implications for the fundamental physics behind dark matter, dark energy, and quantum gravity.

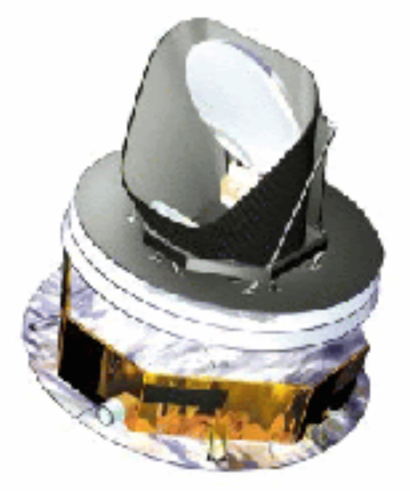


Photons of the cosmic microwave background (CMB), the afterglow of the primordial fireball Universe, are linearly polarized (Figure 1). This pattern can be used to search for new physics violating "parity symmetry" – the symmetry of the laws of physics under an inversion of spatial coordinates. For example, electromagnetism works the same way whether one is in the original system or in a mirrored system with all spatial coordinates flipped. A violation of parity symmetry has only been observed in the weak interaction of the standard model of elementary particles and fields – so far. Can the Universe also violate parity symmetry?

Credit: ESA

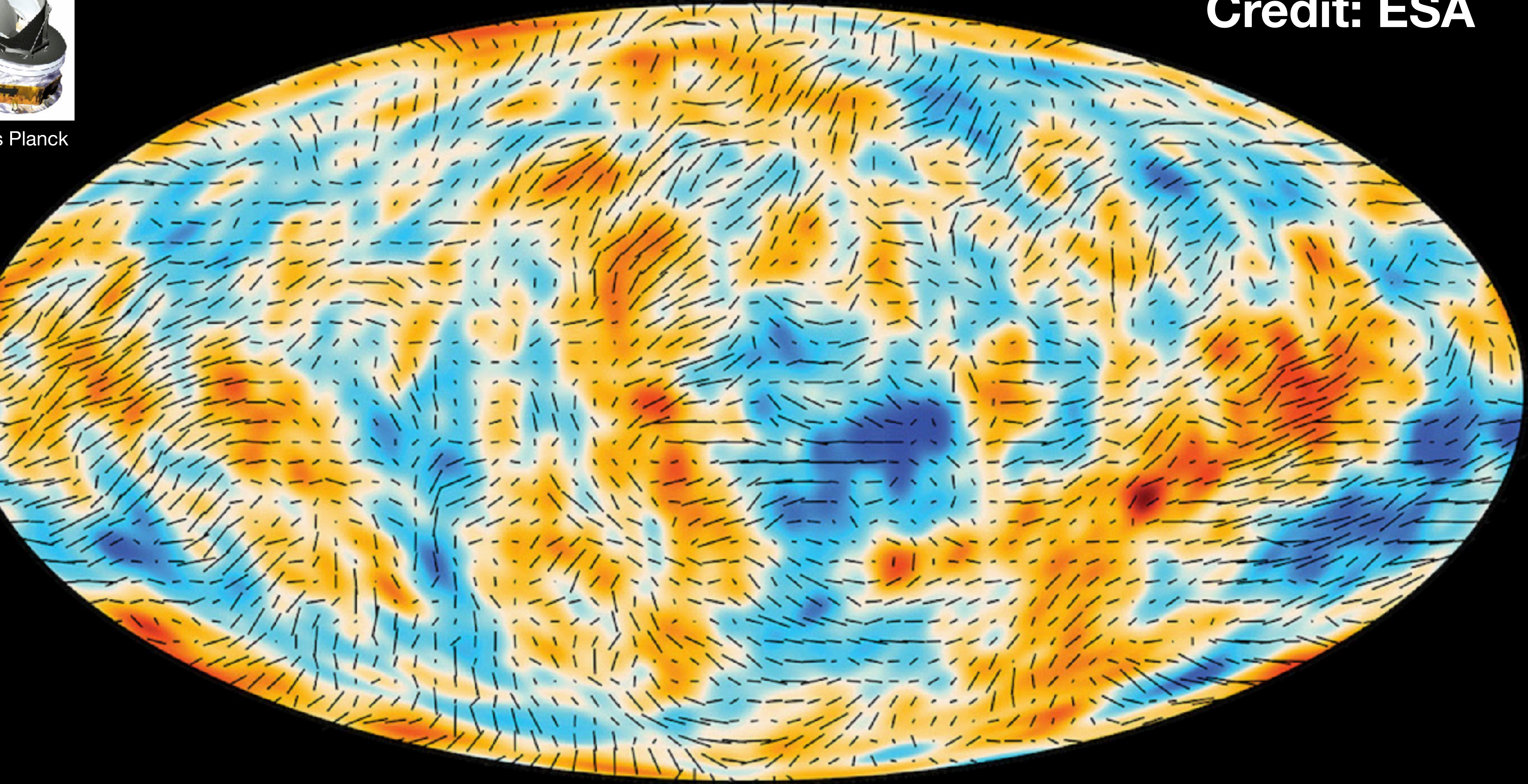
Foreground-cleaned Temperature (smoothed)

Emitted 13.8 billions years ago



ESA's Planck

Credit: ESA



Foreground-cleaned Temperature (smoothed) + Polarisation

Emitted 13.8 billions years ago

Standard Cosmological Model (ΛCDM) Requires New Physics

Physics beyond Standard Model of elementary particles and fields

- **Dark Sector**: What is dark matter (*CDM*)? What is dark energy (*Λ*)?
- **Early Universe**: What powered the Big Bang? What is the fundamental physics behind cosmic inflation?
- *Polarisation* of the CMB may hold the key to the answers.

Standard Cosmological Model (ΛCDM) Requires New Physics

Physics beyond Standard Model of elementary particles and fields

- **Dark Sector**: What is dark matter (*CDM*)? What is dark energy (Λ)?
  - **Cosmic birefringence** in CMB polarisation
- **Early Universe**: What powered the Big Bang? What is the fundamental physics behind cosmic inflation?
  - Imprint of **primordial gravitational waves** in CMB polarisation
- *Polarisation* of the CMB may hold the key to the answers.

nature reviews physics

Available also at arXiv:2202.13919

Review Article | Published: 18 May 2022

New physics from the polarized light of the cosmic microwave background

Eiichiro Komatsu

Nature Reviews Physics (2022) | Cite this article

Metrics

New in cosmology!

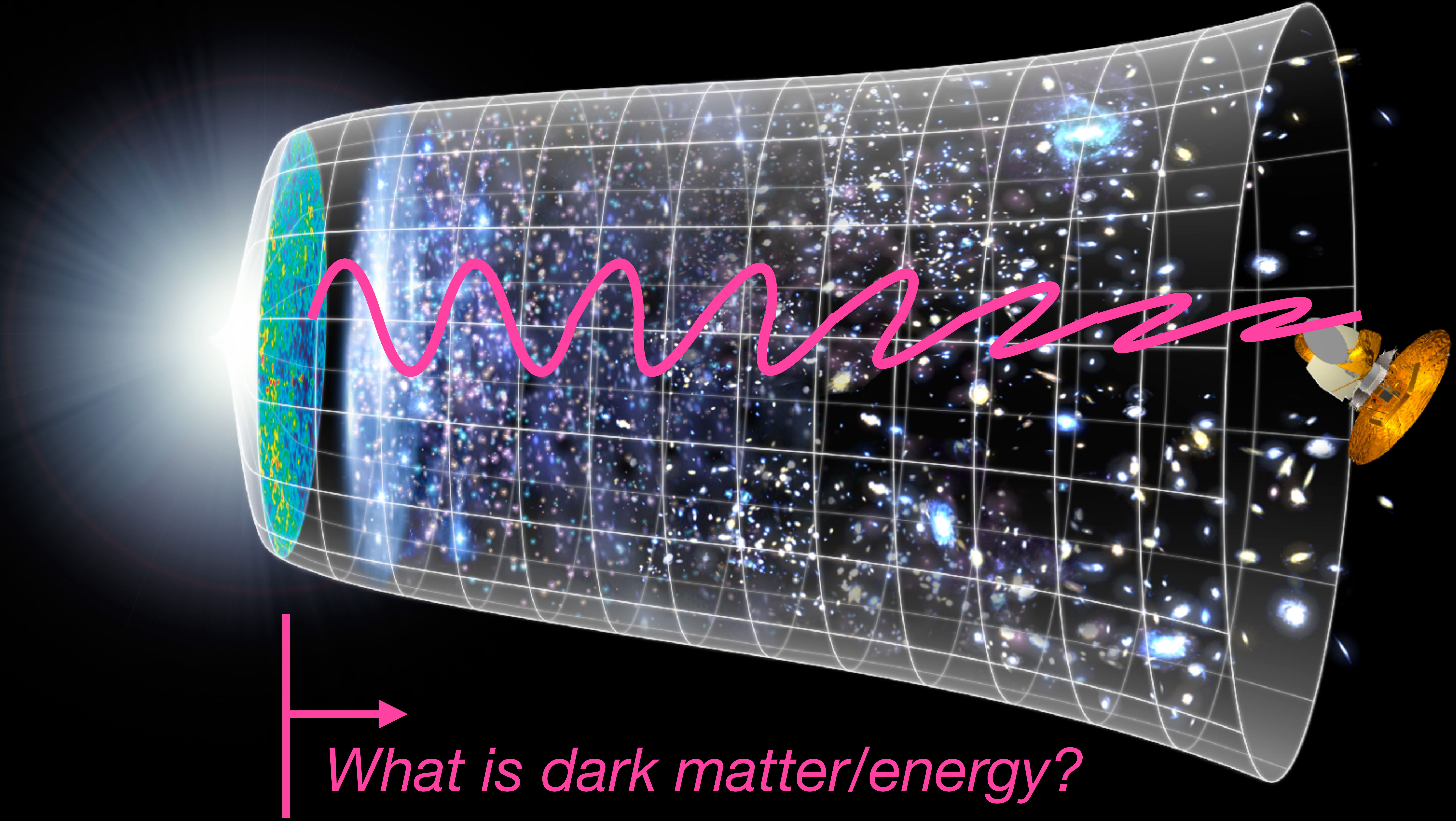
Key Words:

1. Cosmic Microwave Background (CMB)
2. Polarization
3. *Parity Symmetry*


Credit: WMAP Science Team
The surface of "last scattering" by electrons
(Scattering generates *polarisation*!)
What powered the Big Bang?
What is dark matter/energy?

How does the electromagnetic wave of the CMB propagate?

How does the electromagnetic wave of the CMB propagate?



Carroll, Field & Jackiw (1990); Carroll & Field (1991); Harari & Sikivie (1992)

Cosmic Birefringence

The Universe filled with a "birefringent material"

This "axion" field can be dark matter or dark energy!

- If the Universe is filled with a pseudoscalar field (e.g., an axion field) coupled to the electromagnetic tensor via a Chern-Simons coupling:

Ni (1977); Turner & Widrow (1988)

the effective Lagrangian for axion electrodynamics is

Chern-Simons term

$$\mathcal{L} = -\tfrac{1}{2}\partial_\mu\theta\partial^\mu\theta - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + g_a\theta F_{\mu\nu}\tilde{F}^{\mu\nu}, \quad (3.7)$$

$$\tilde{F}^{\mu\nu} = \sum_{\alpha\beta}\frac{\epsilon^{\mu\nu\alpha\beta}}{2\sqrt{-g}}F_{\alpha\beta}$$

where g_a is a coupling constant of the order α, and the vacuum angle $\theta = \phi_a/f_a$ (ϕ_a = axion field). The equations

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \qquad \sum_{\mu\nu} F_{\mu\nu}F^{\mu\nu} = 2(\mathbf{B}\cdot\mathbf{B} - \mathbf{E}\cdot\mathbf{E}) \qquad \sum_{\mu\nu} F_{\mu\nu}\tilde{F}^{\mu\nu} = -4\mathbf{B}\cdot\mathbf{E}$$

Parity Even **Parity Odd**

Carroll, Field & Jackiw (1990); Carroll & Field (1991); Harari & Sikivie (1992)

Cosmic Birefringence

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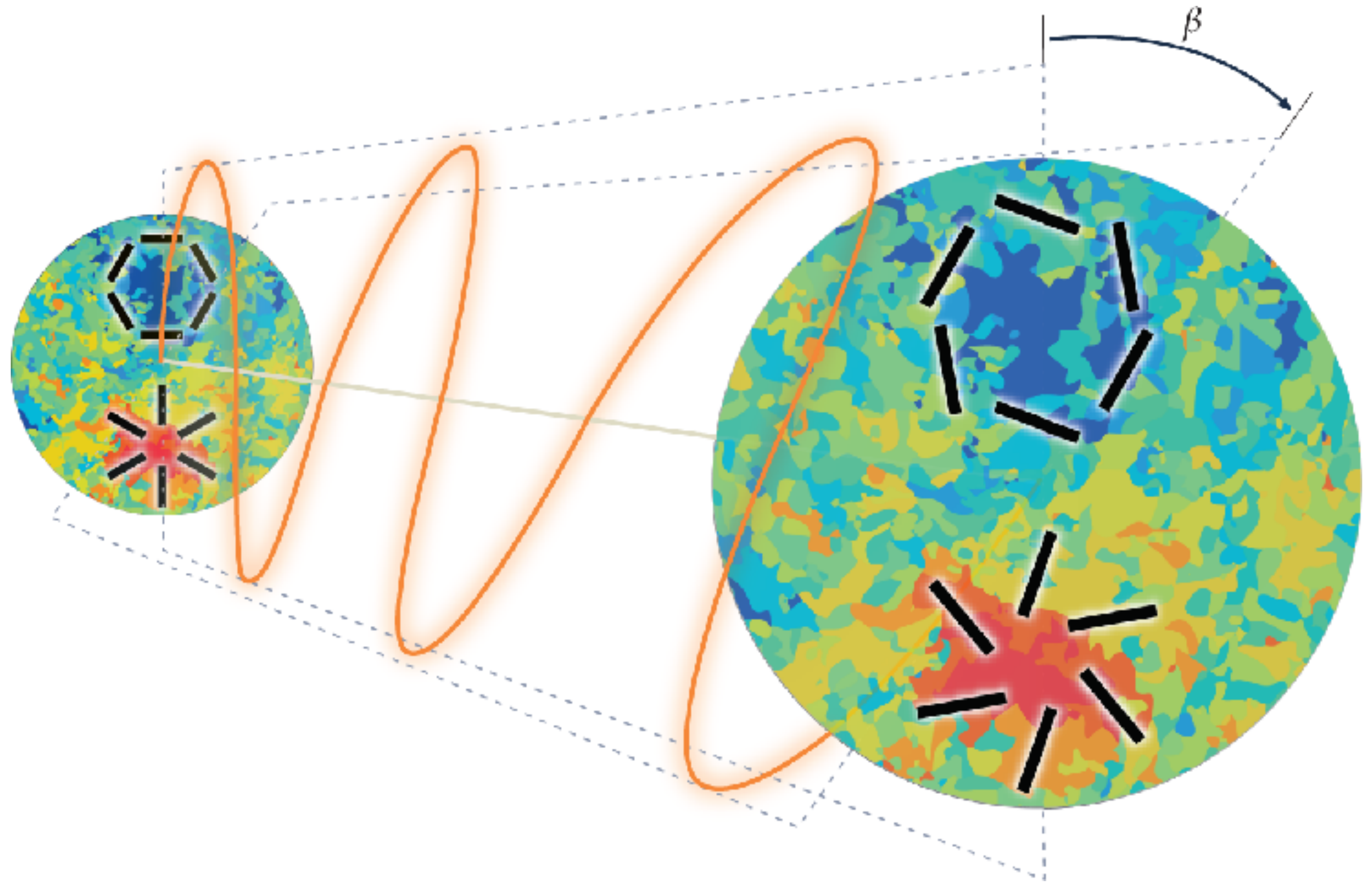


"Cosmic Birefringence"

This term makes the phase velocities of right- and left-handed polarisation states of photons different, leading to **rotation of the linear polarisation direction.**

Carroll, Field & Jackiw (1990); Carroll & Field (1991); Harari & Sikivie (1992)

Cosmic Birefringence

Rotation of the plane of CMB polarisation

This "axion" field can be dark matter or dark energy!

- If the Universe is filled with a pseudoscalar field (e.g., an axion field) coupled to the electromagnetic tensor via a Chern-Simons coupling:

Ni (1977); Turner & Widrow (1988)

the effective Lagrangian for axion electrodynamics is

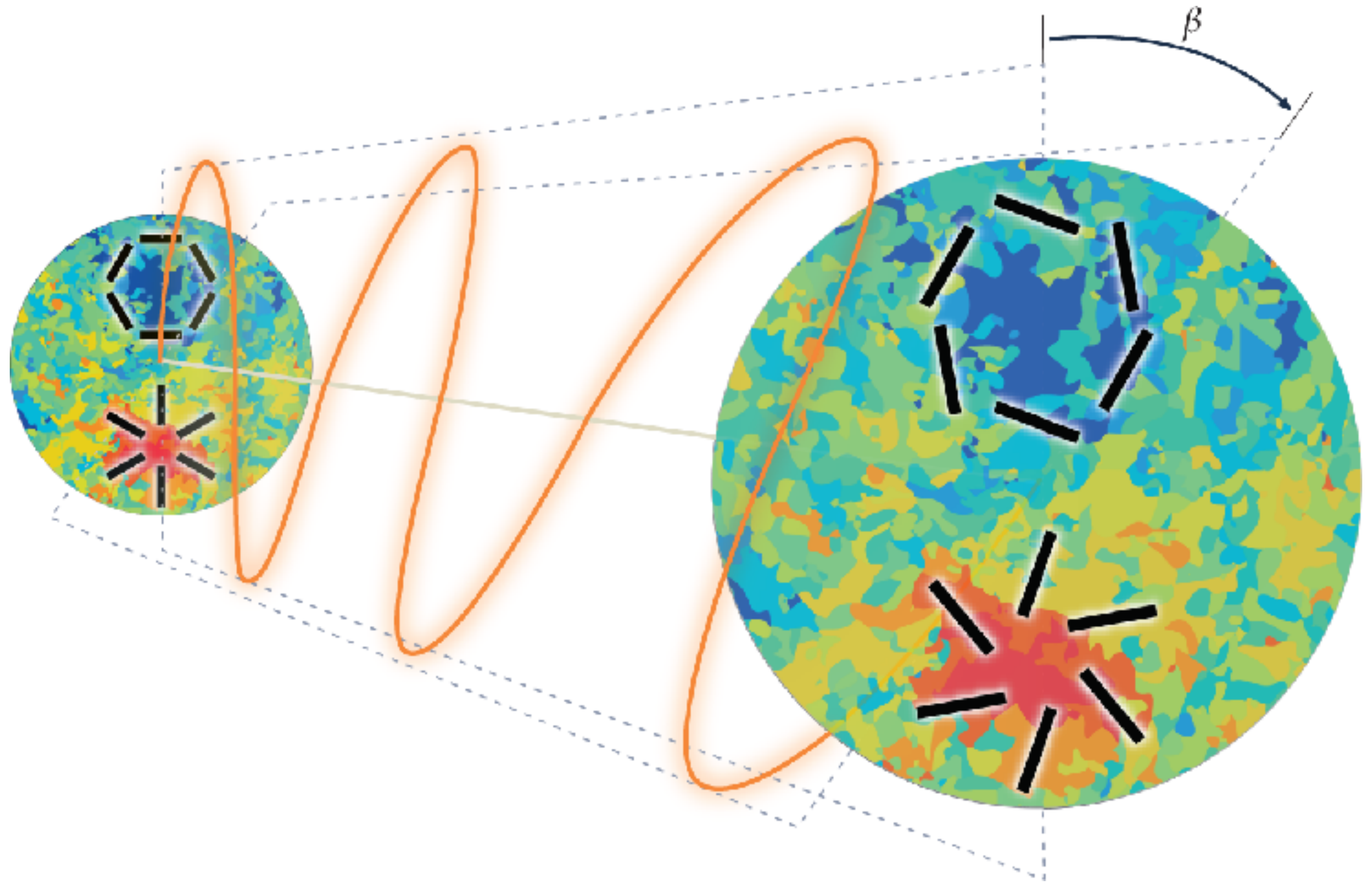
Chern-Simons term

$$\mathcal{L} = -\tfrac{1}{2}\partial_\mu\theta\partial^\mu\theta - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + g_a\theta F_{\mu\nu}\tilde{F}^{\mu\nu}, \qquad (3.7)$$

$$\tilde{F}^{\mu\nu} = \sum_{\alpha\beta} \frac{\epsilon^{\mu\nu\alpha\beta}}{2\sqrt{-g}} F_{\alpha\beta}$$

where g_a is a coupling constant of the order α, and the vacuum angle $\theta = \phi_a / f_a$ (ϕ_a = axion field). The equations

$$\beta = -2g_a \int_{t_{\rm emitted}}^{t_{\rm observed}} dt\, \dot{\theta} = 2g_a\left[\theta(t_{\rm e}) - \theta(t_{\rm o})\right]$$



Motivation

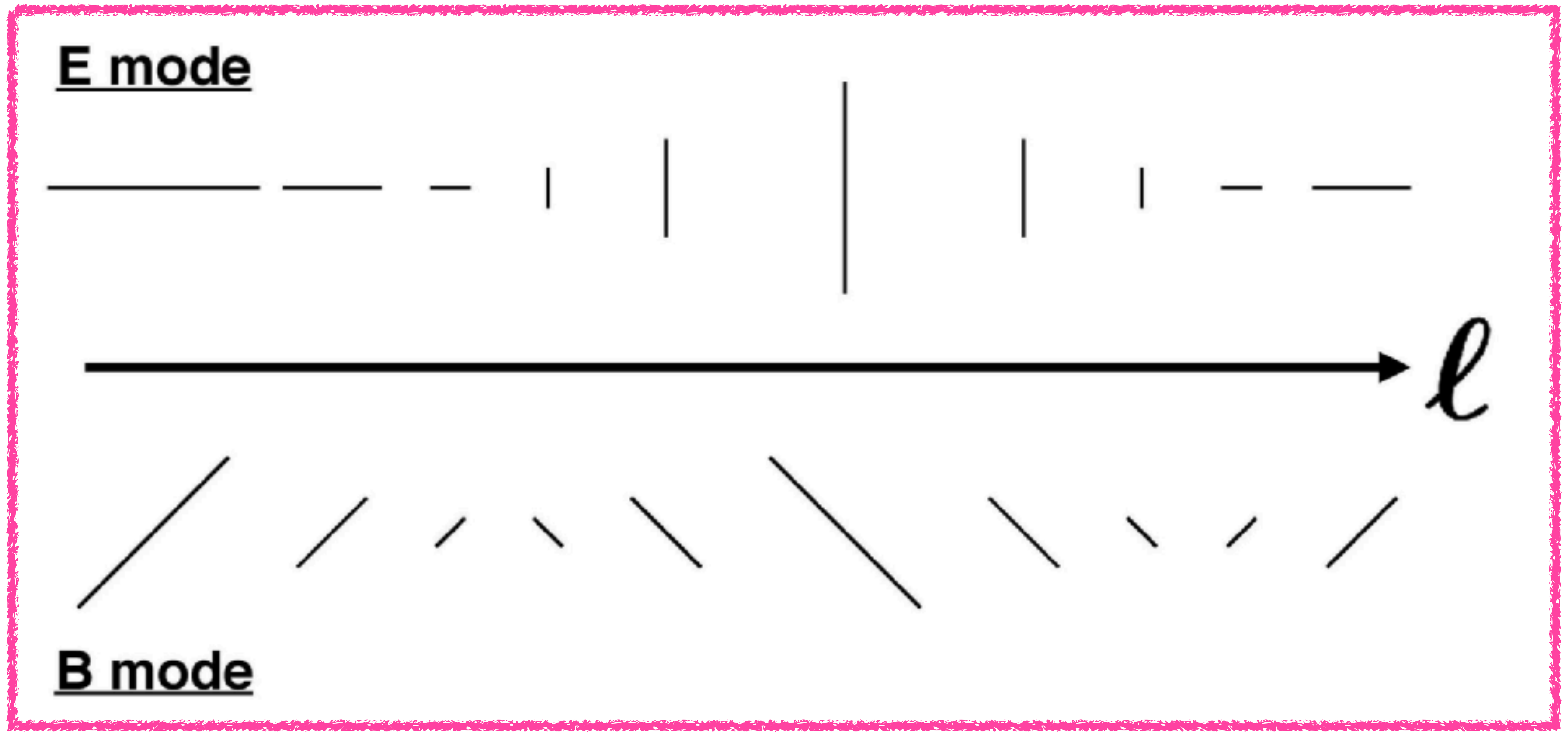
Why study the cosmic birefringence?

- The Universe's energy budget is dominated by two dark components:
  - Dark Matter
  - Dark Energy
- Either or both of these can be an axion-like field!
  - Thus, detection of parity-violating physics in polarisation of the cosmic microwave background can transform our understanding of Dark Matter/ Energy.

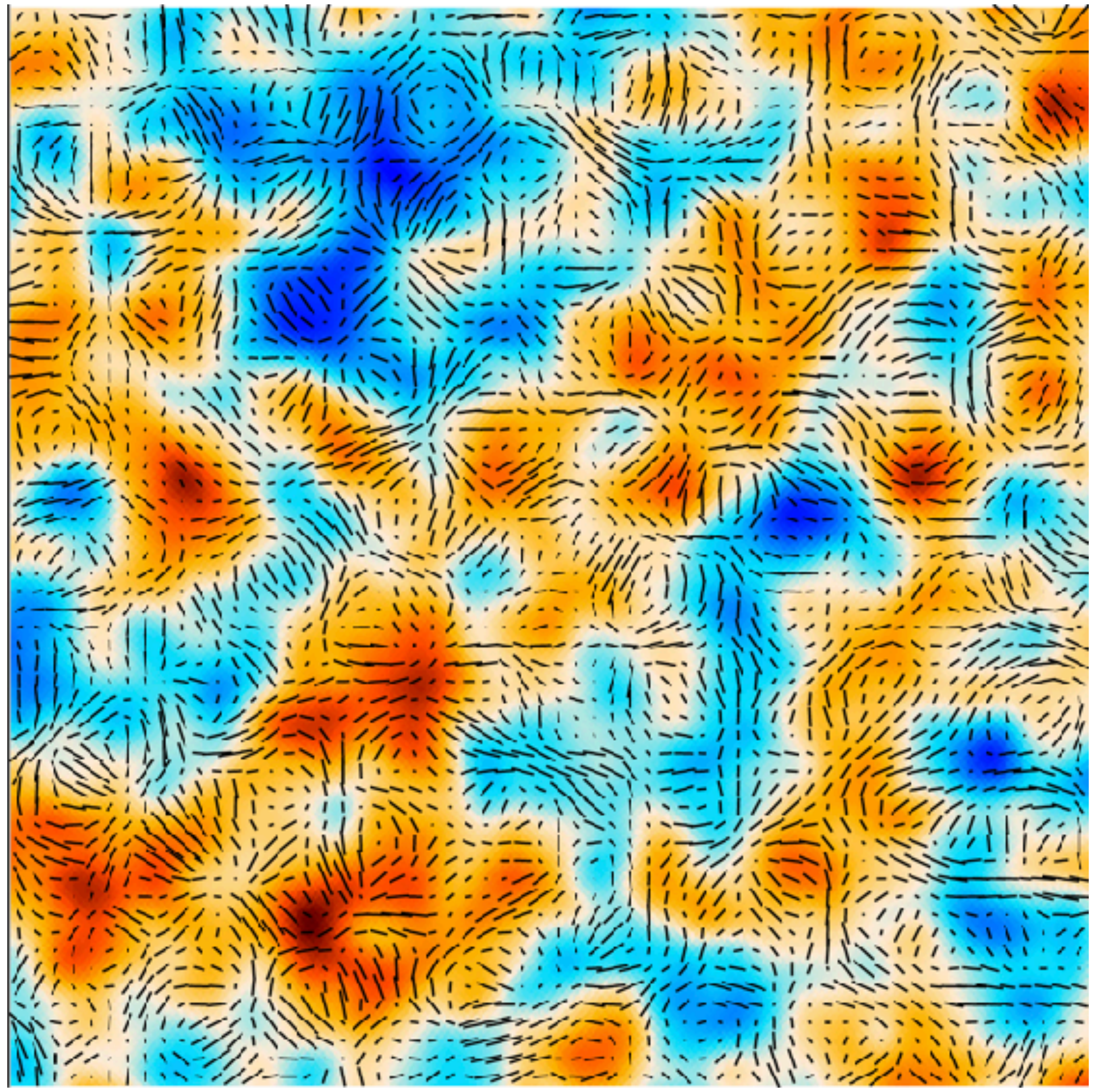
Seljak & Zaldarriaga (1997); Kamionkowski, Kosowsky & Stebbins (1997)

Parity eigenstates: E and B modes

Concept defined in Fourier space



This map is dominated by E-mode polarisation

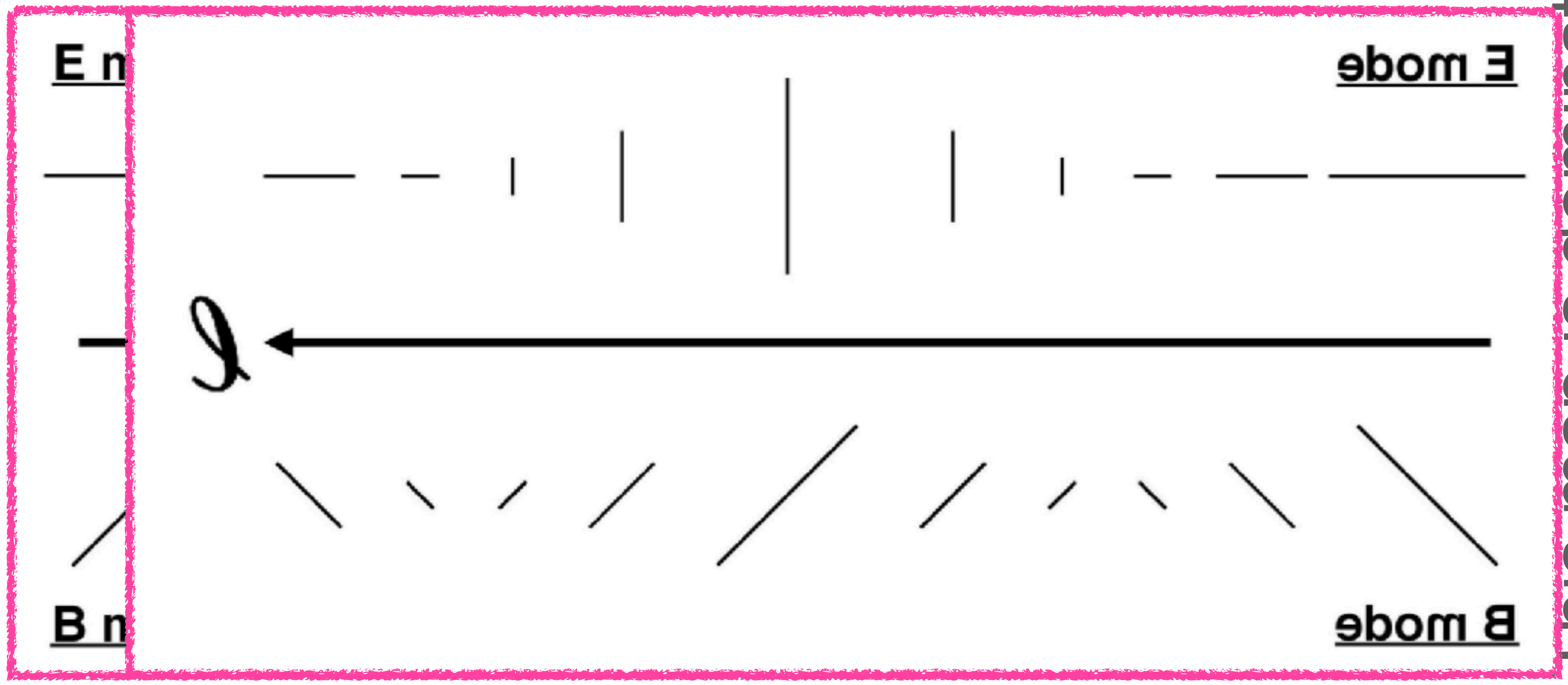


- **E-mode**：Polarisation directions are **parallel or perpendicular** to the wavenumber direction
- **B-mode**：Polarisation directions are **45 degrees tilted** w.r.t the wavenumber direction

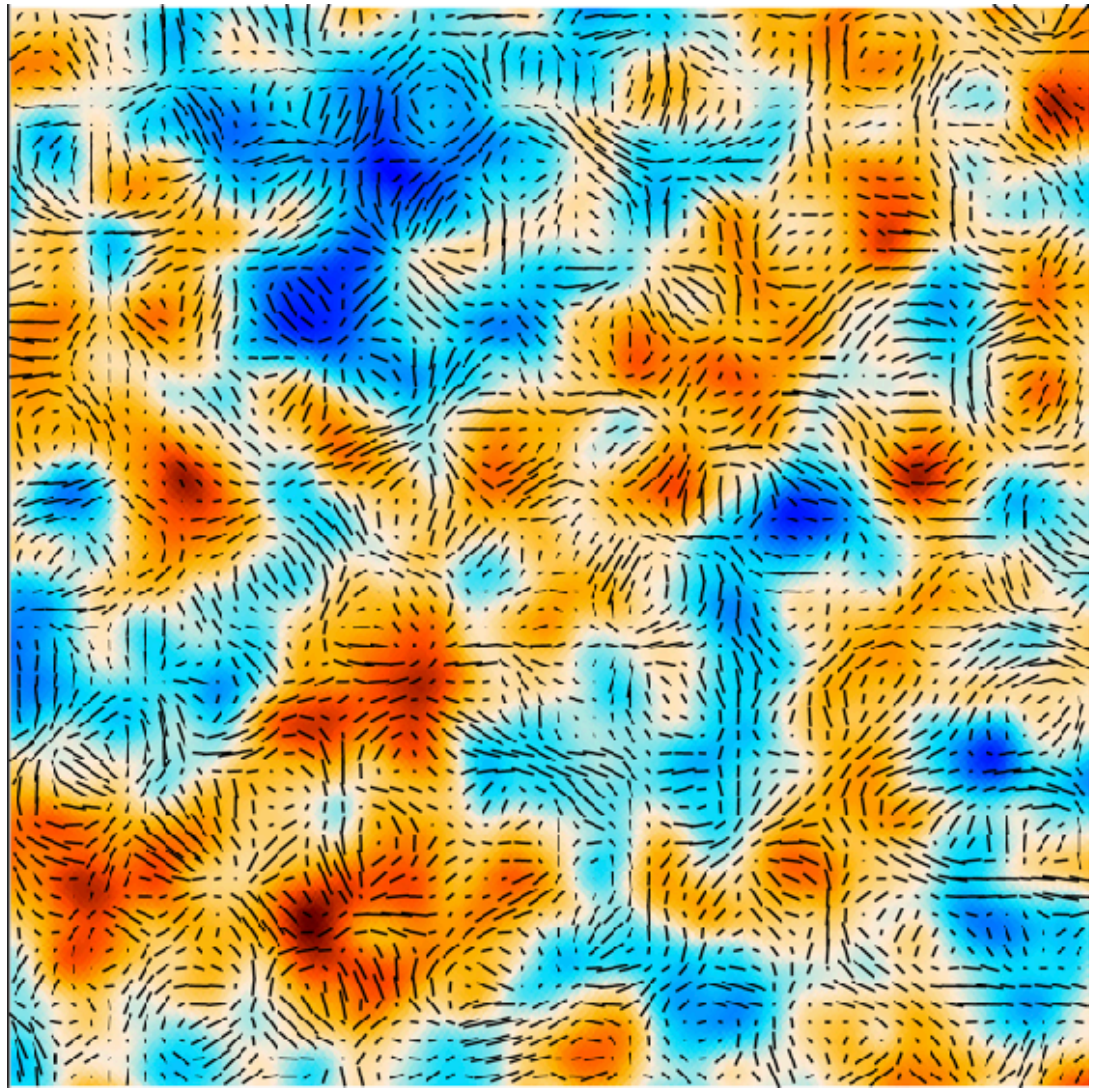
Seljak & Zaldarriaga (1997); Kamionkowski, Kosowsky & Stebbins (1997)

Parity eigenstates: E and B modes

Concept defined in Fourier space



This map is dominated by E-mode polarisation

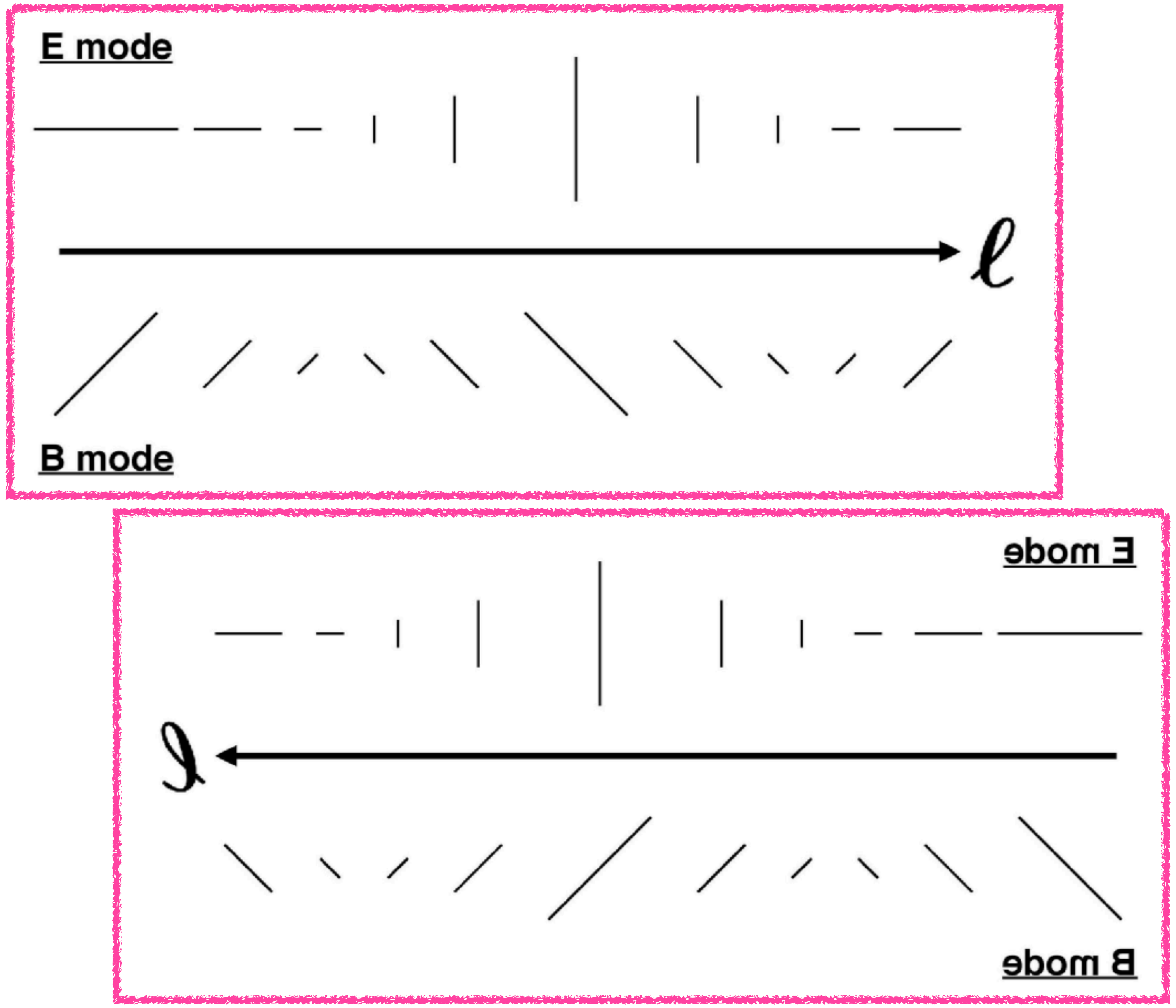


- **E-mode**：Polarisation directions are **parallel or perpendicular** to the wavenumber direction
- **B-mode**：Polarisation directions are **45 degrees tilted** w.r.t the wavenumber direction

Seljak & Zaldarriaga (1997); Kamionkowski, Kosowsky & Stebbins (1997)

Parity Flip

E-mode remains the same, whereas B-mode changes the sign



- Two-point correlation functions invariant under the parity flip are

$$\langle E_{\boldsymbol{\ell}} E^*_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{EE}$$

$$\langle B_{\boldsymbol{\ell}} B^*_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{BB}$$

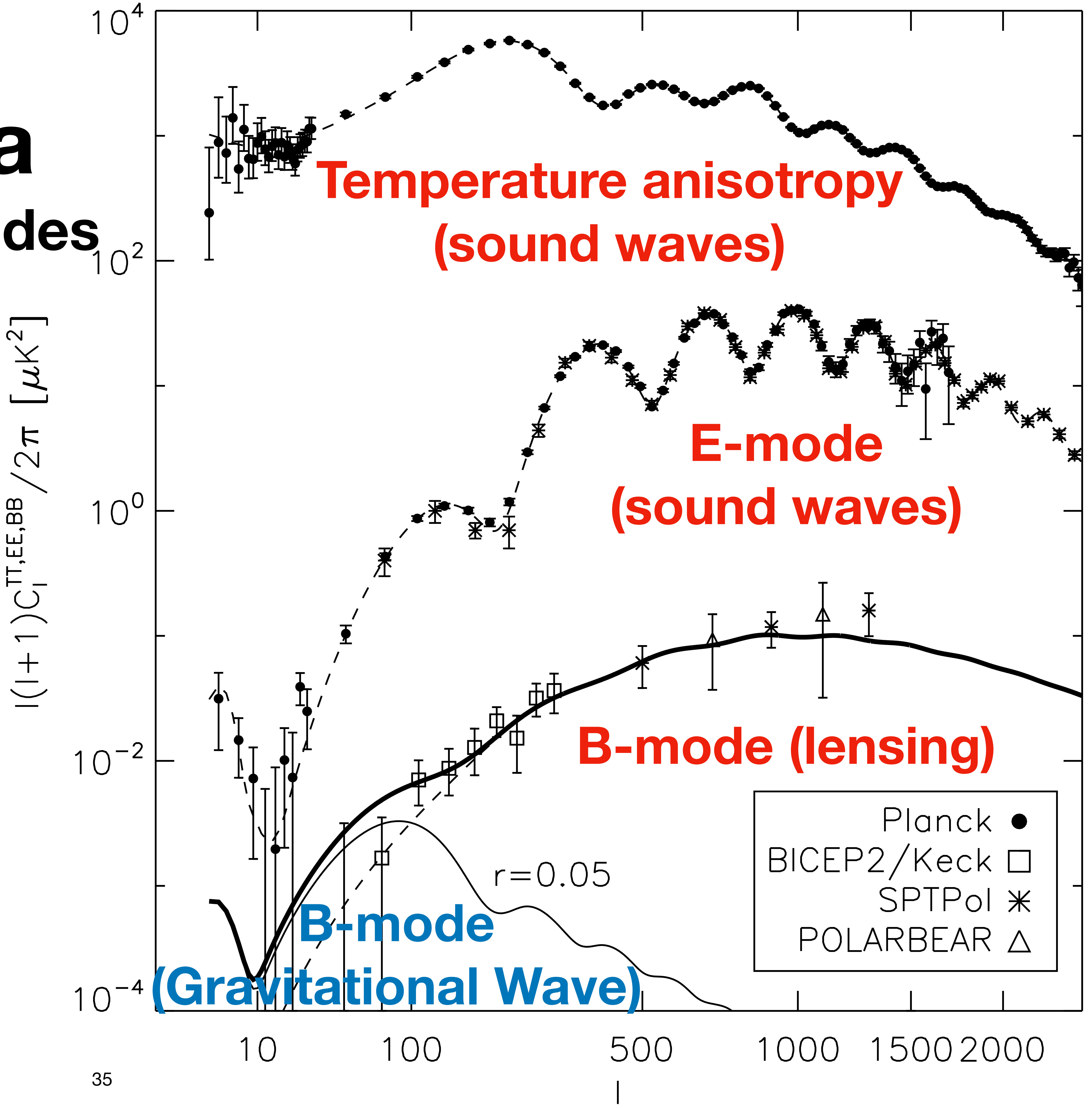
$$\langle T_{\boldsymbol{\ell}} E^*_{\boldsymbol{\ell}'} \rangle = \langle T^*_{\boldsymbol{\ell}} E_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{TE}$$

- The other combinations <TB> and <EB> are not invariant under the parity flip.
  - **We can use these combinations to probe parity-violating physics (e.g., axions)**

CMB Power Spectra

Progress over the last 3 decades

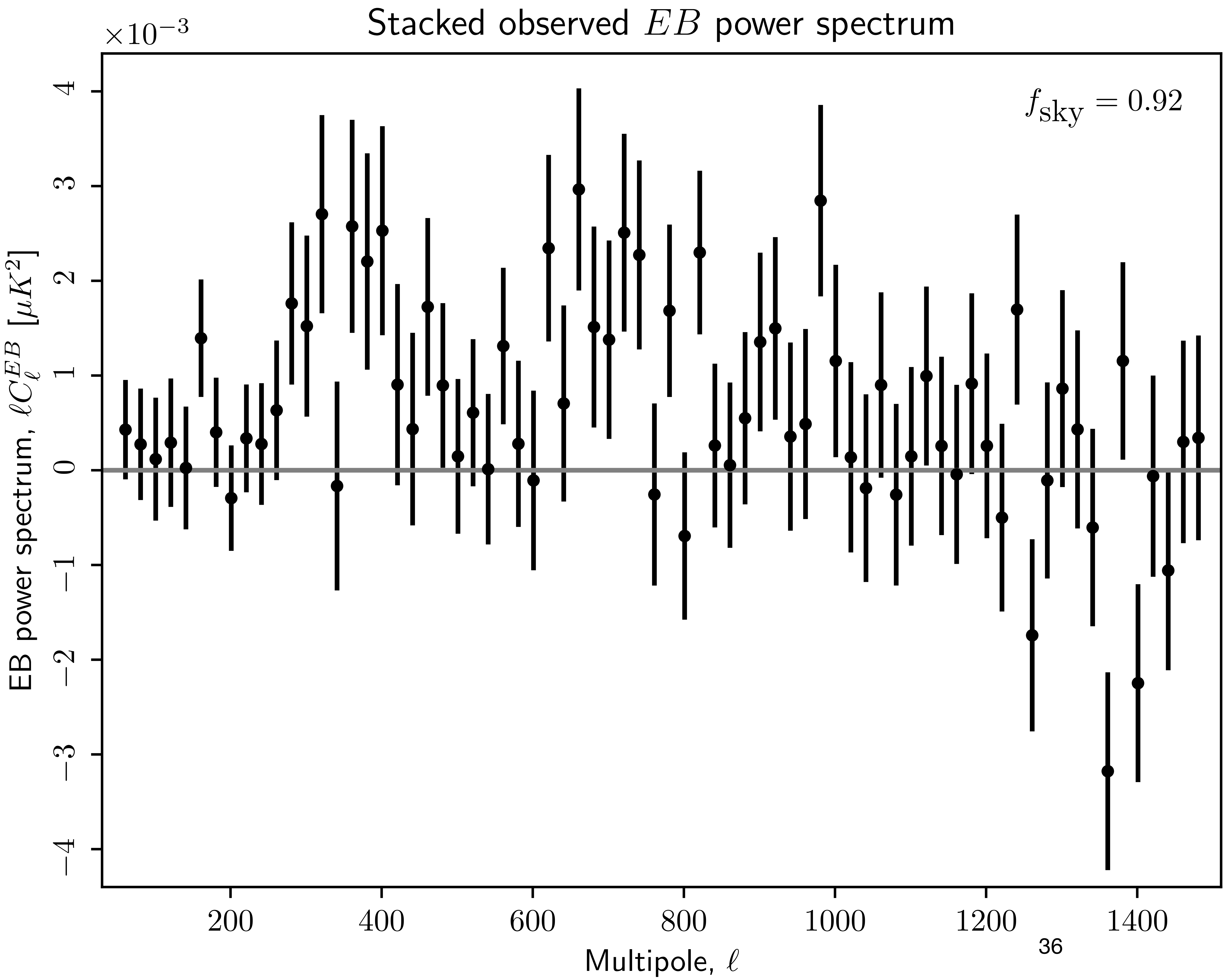
- This is the typical figure that you find in talks and lectures on CMB.
  - The temperature power spectrum and the E- and B-mode polarisation power spectra have been measured well.
- **Our focus is the EB spectrum, which is not shown here.**

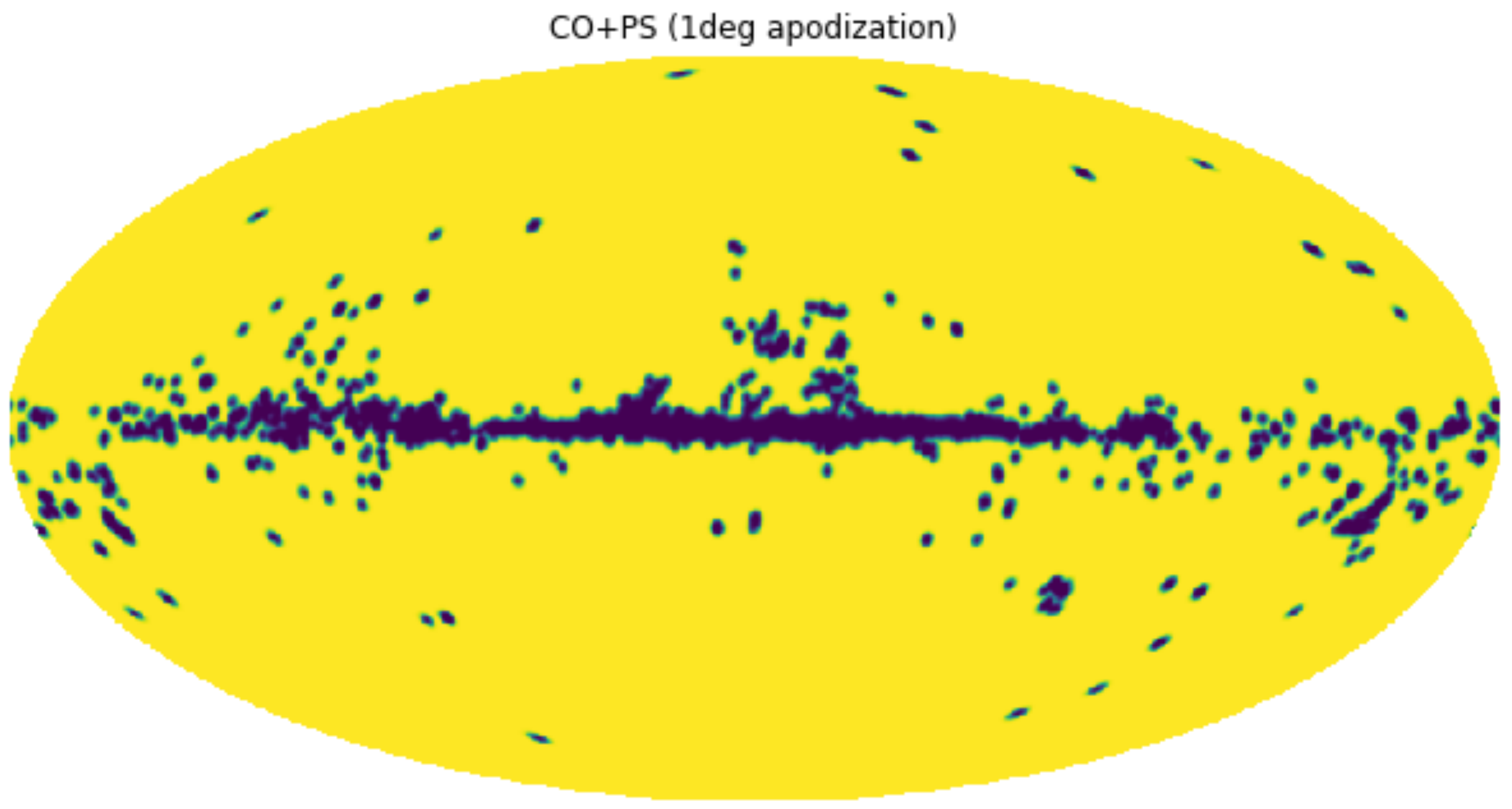


Eskilt & EK (2022)

This is the EB power spectrum (WMAP+Planck)

Nearly full-sky data (92% of the sky)



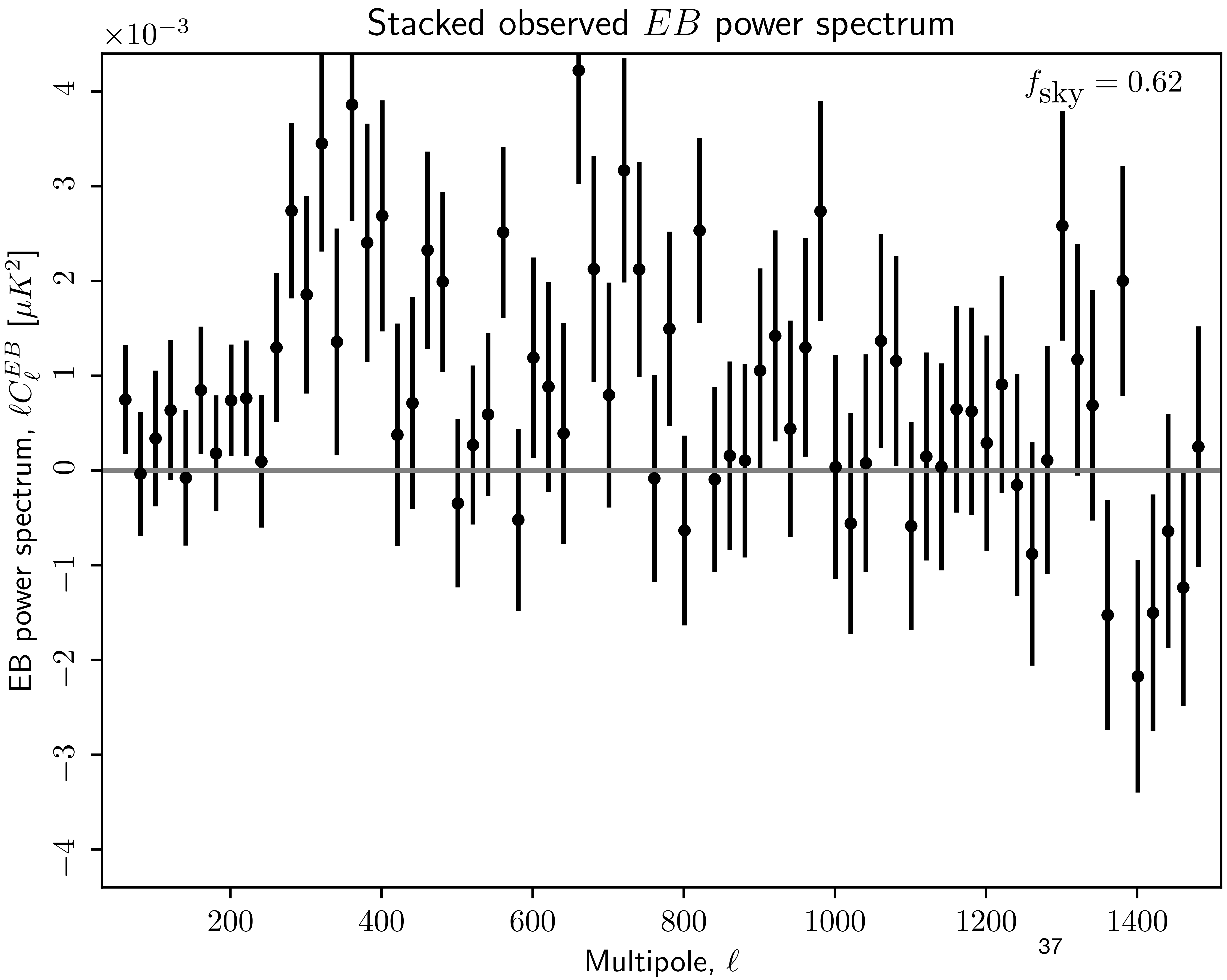


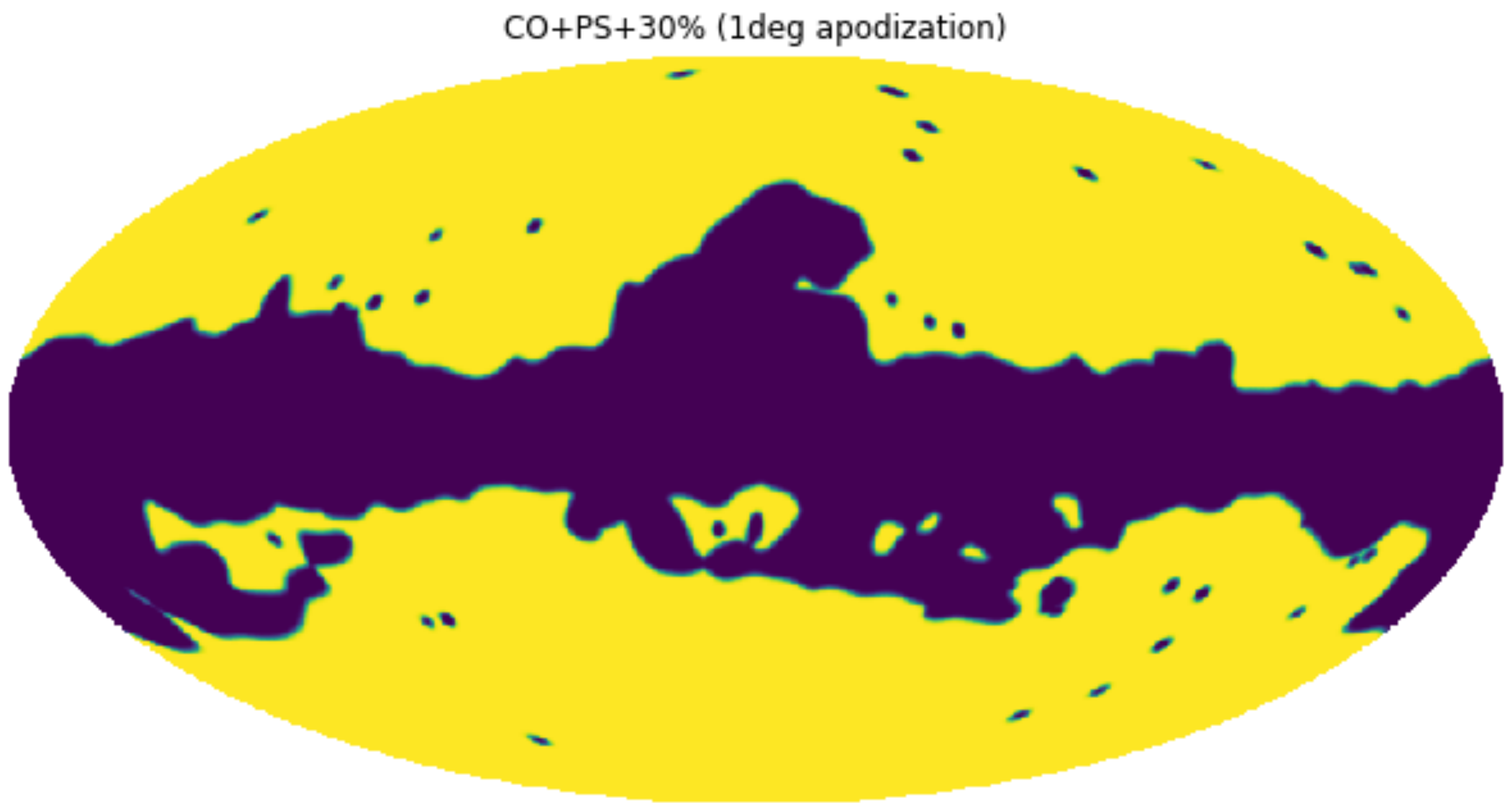
- $\chi^2 = 125.5$ for DOF=72
  - Unambiguous signal of something!

Eskilt & EK (2022)

This is the EB power spectrum (WMAP+Planck)

Galactic plane removed (62% of the sky)



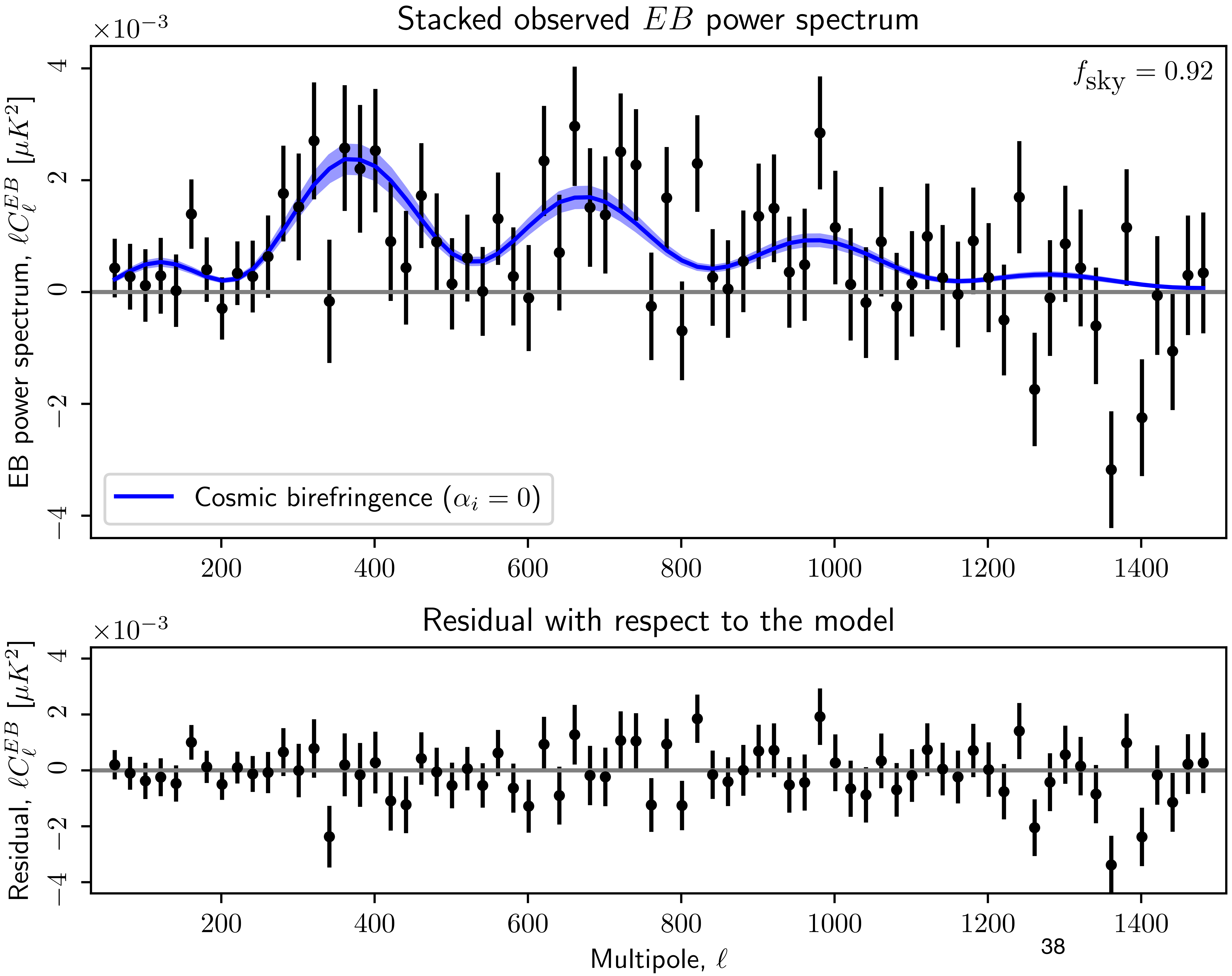


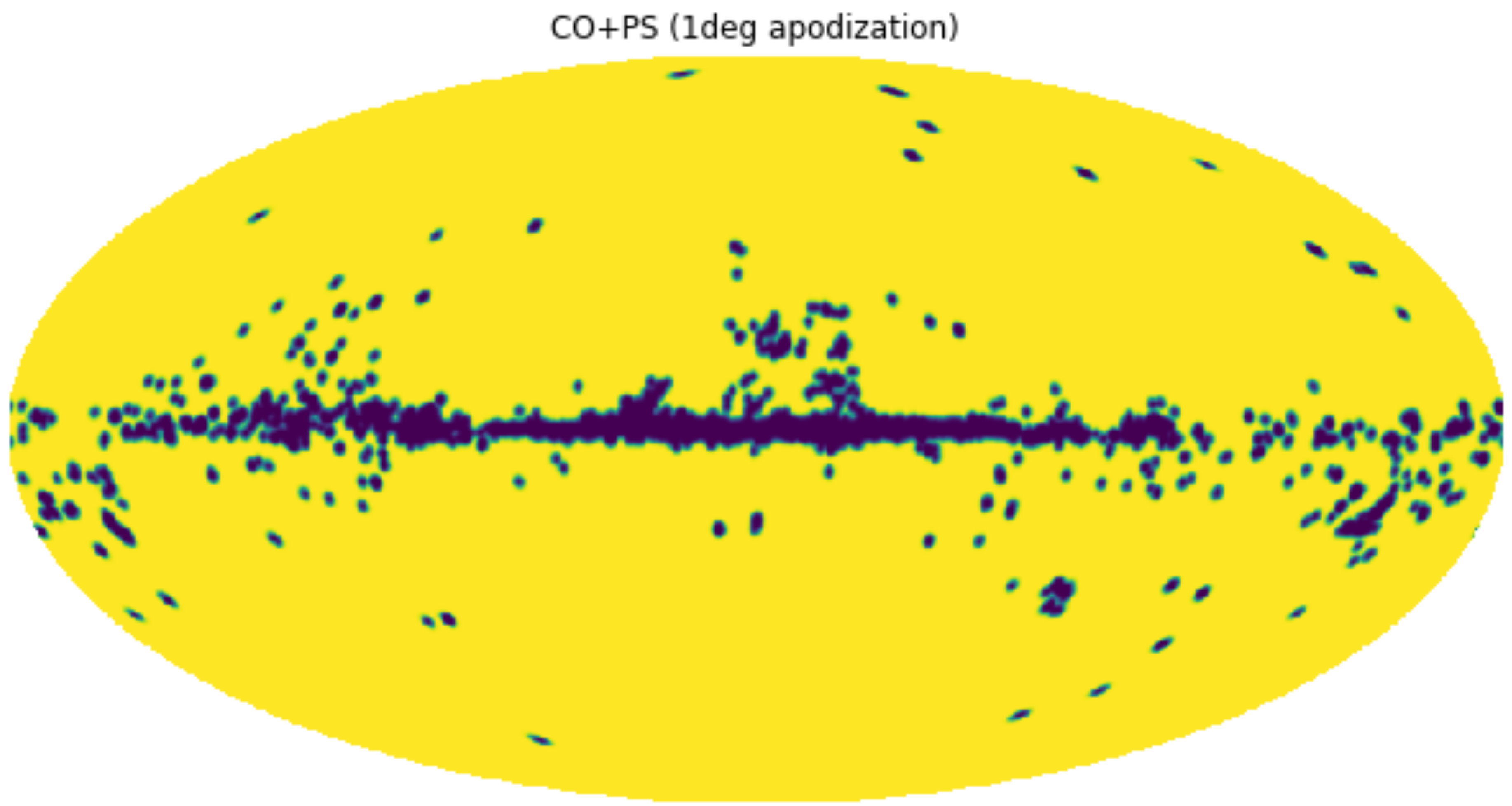
- χ^2 = 138.4 for DOF=72
  - The signal exists regardless of the Galactic mask. This rules out the Galactic foreground.

Eskilt & EK (2022)

Cosmic Birefringence fits well(?)

Nearly full-sky data (92% of the sky)



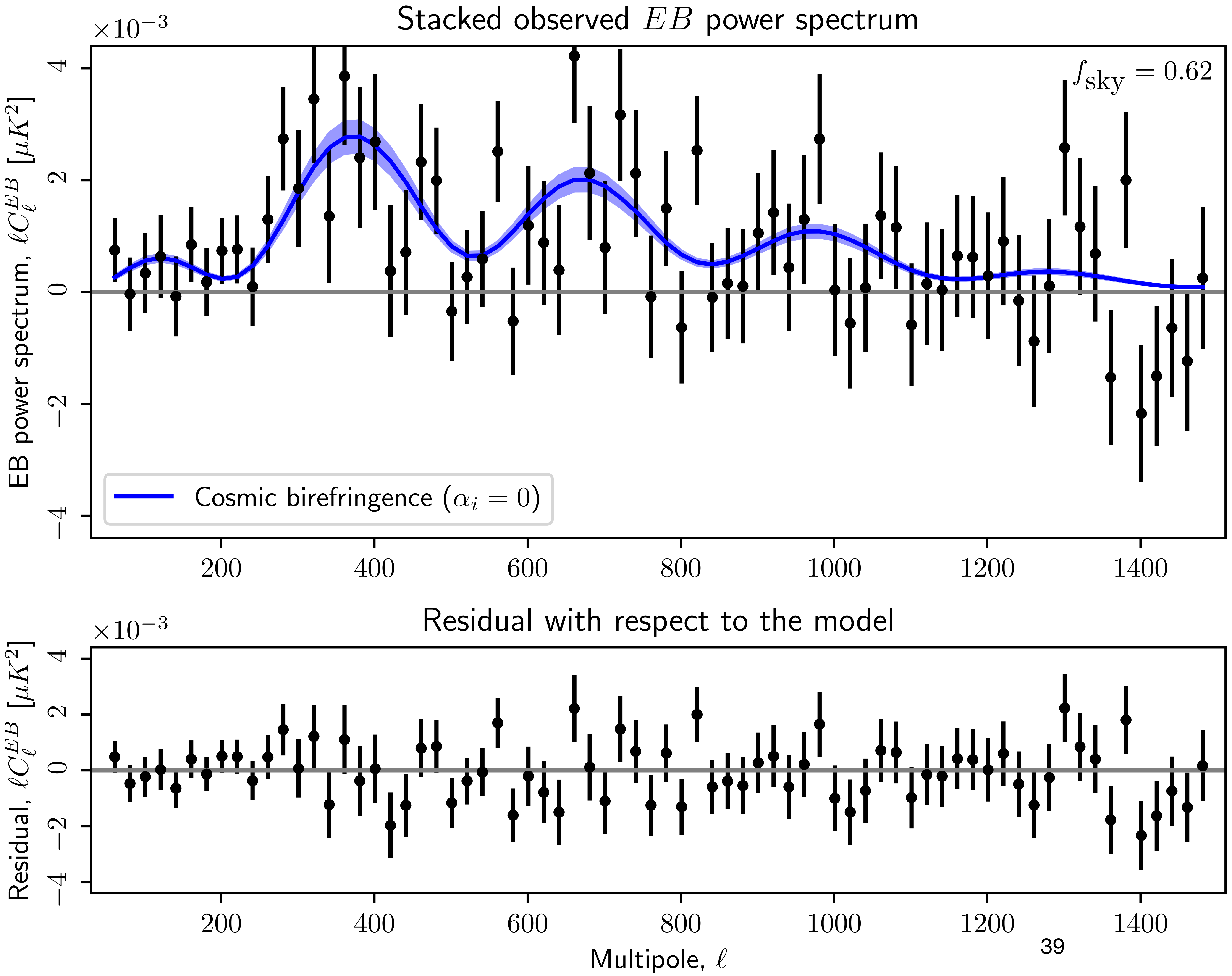


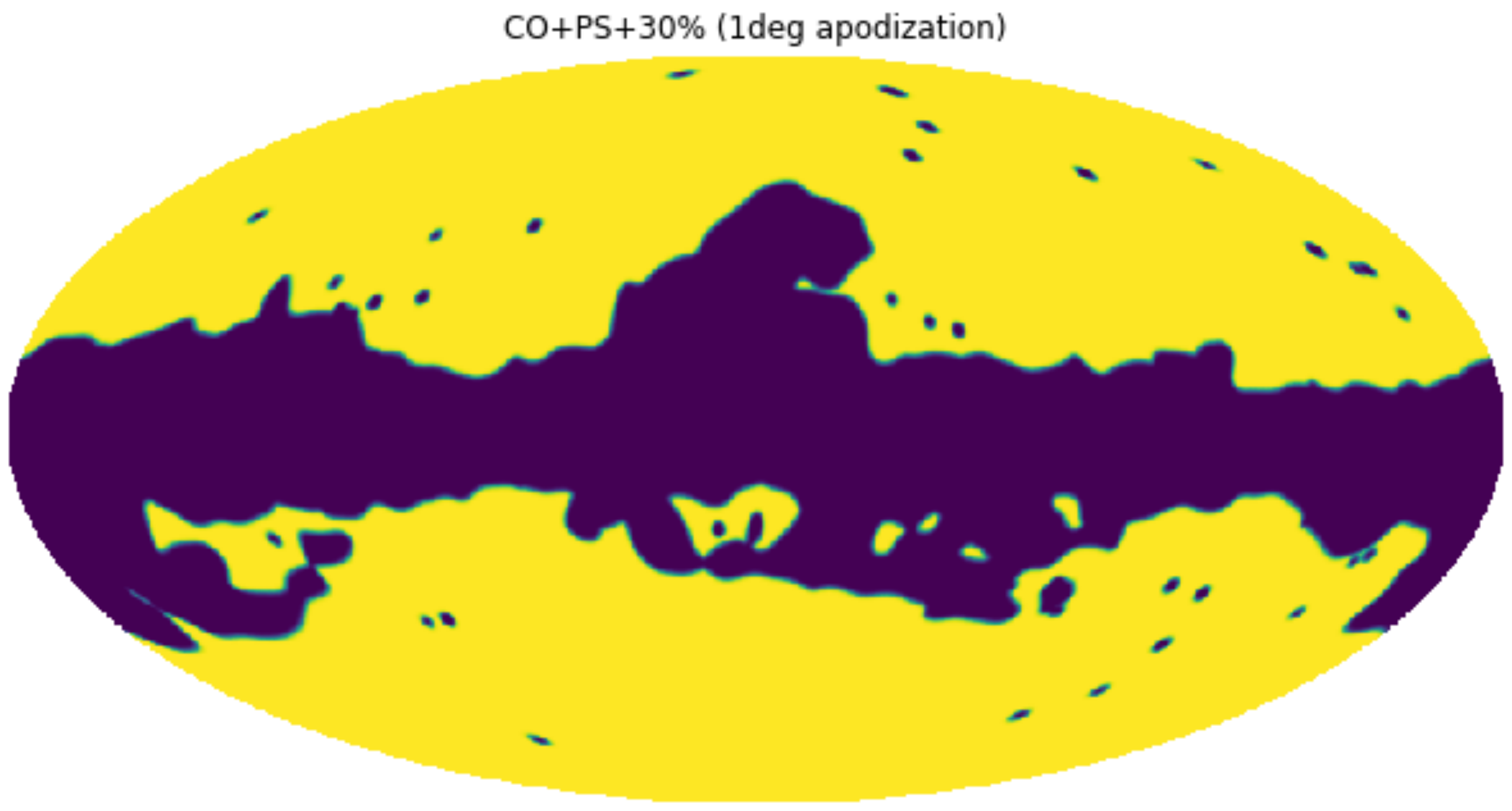
- $\beta = 0.288 \pm 0.032$ deg
- $\chi^2 = 66.1$
  - Good fit! 9σ detection?

Eskilt & EK (2022)

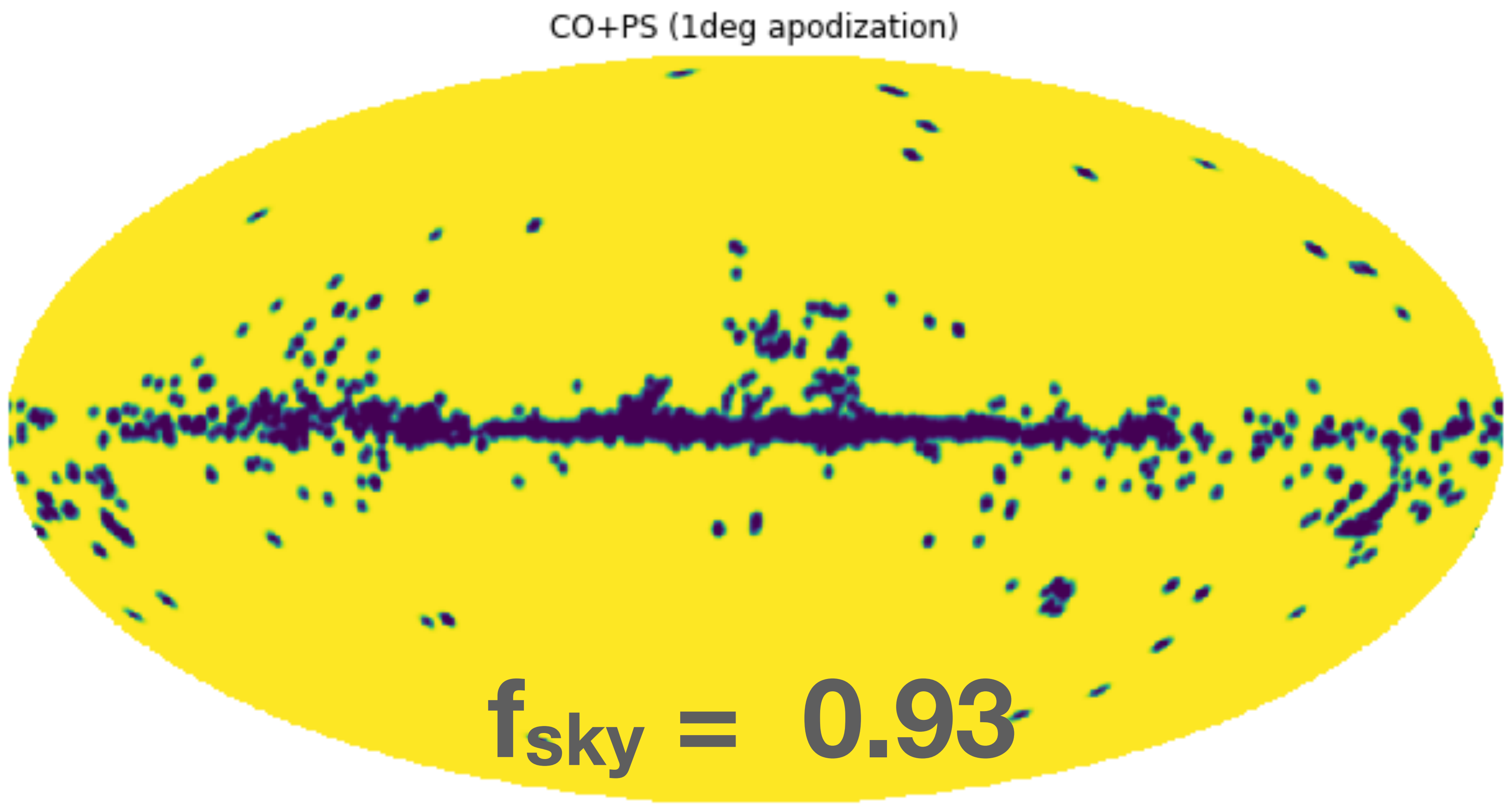
Cosmic Birefringence fits well(?)

Galactic plane removed (62% of the sky)





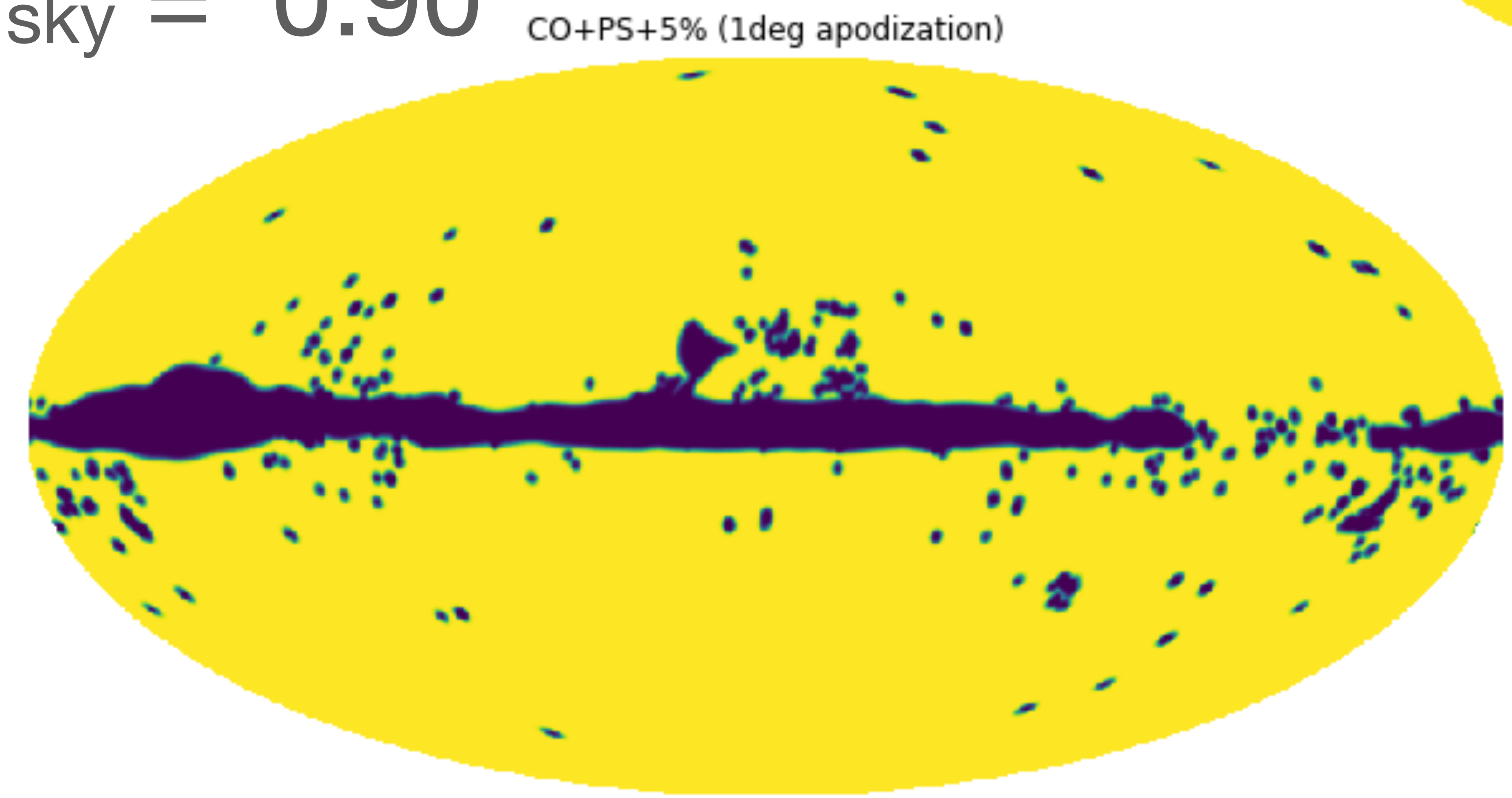
- β = 0.330 ± 0.035 deg
- χ^2 = 64.5
- Signal is robust with respect to the Galactic mask.



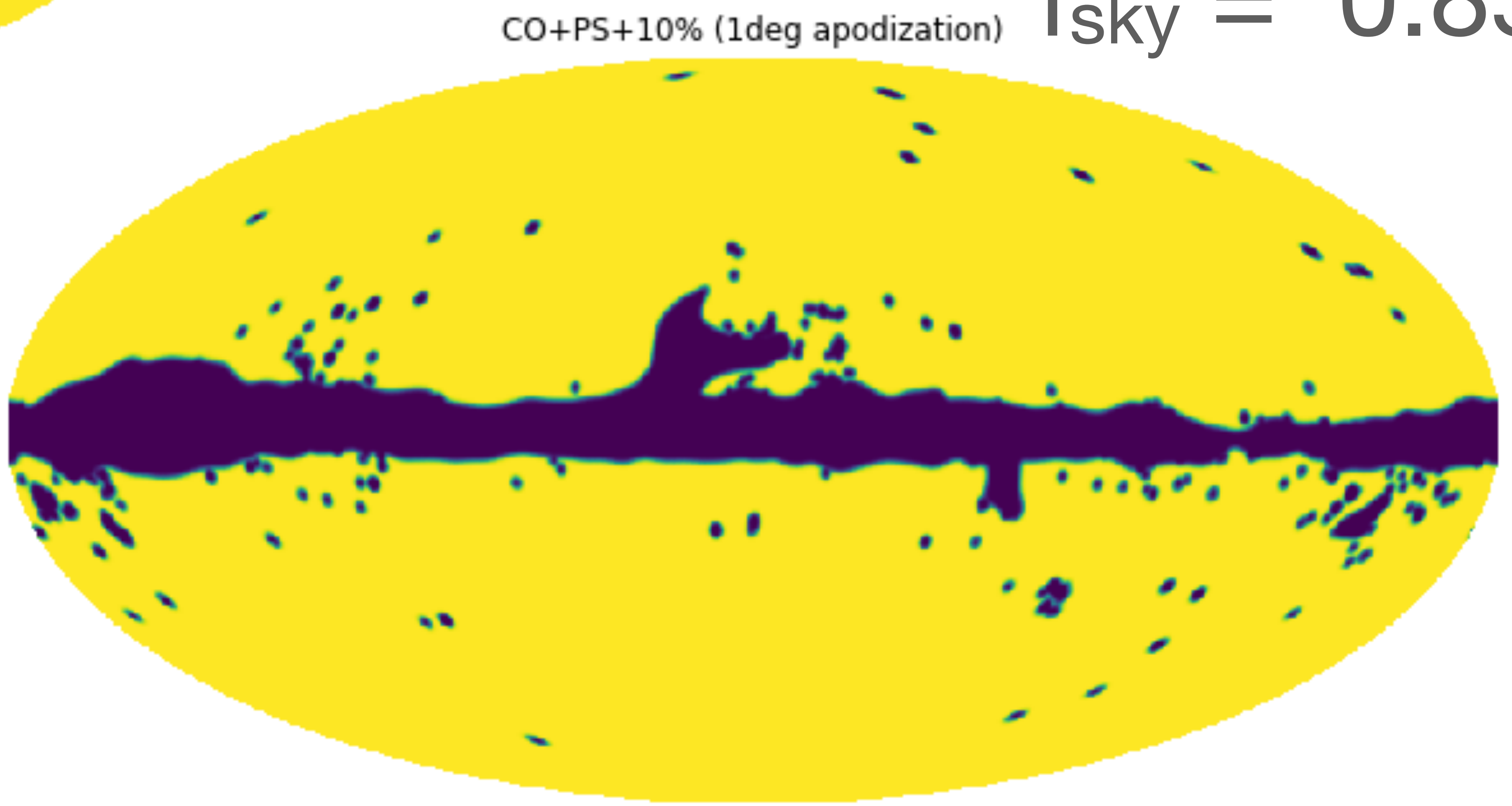
f_{sky} = 0.93

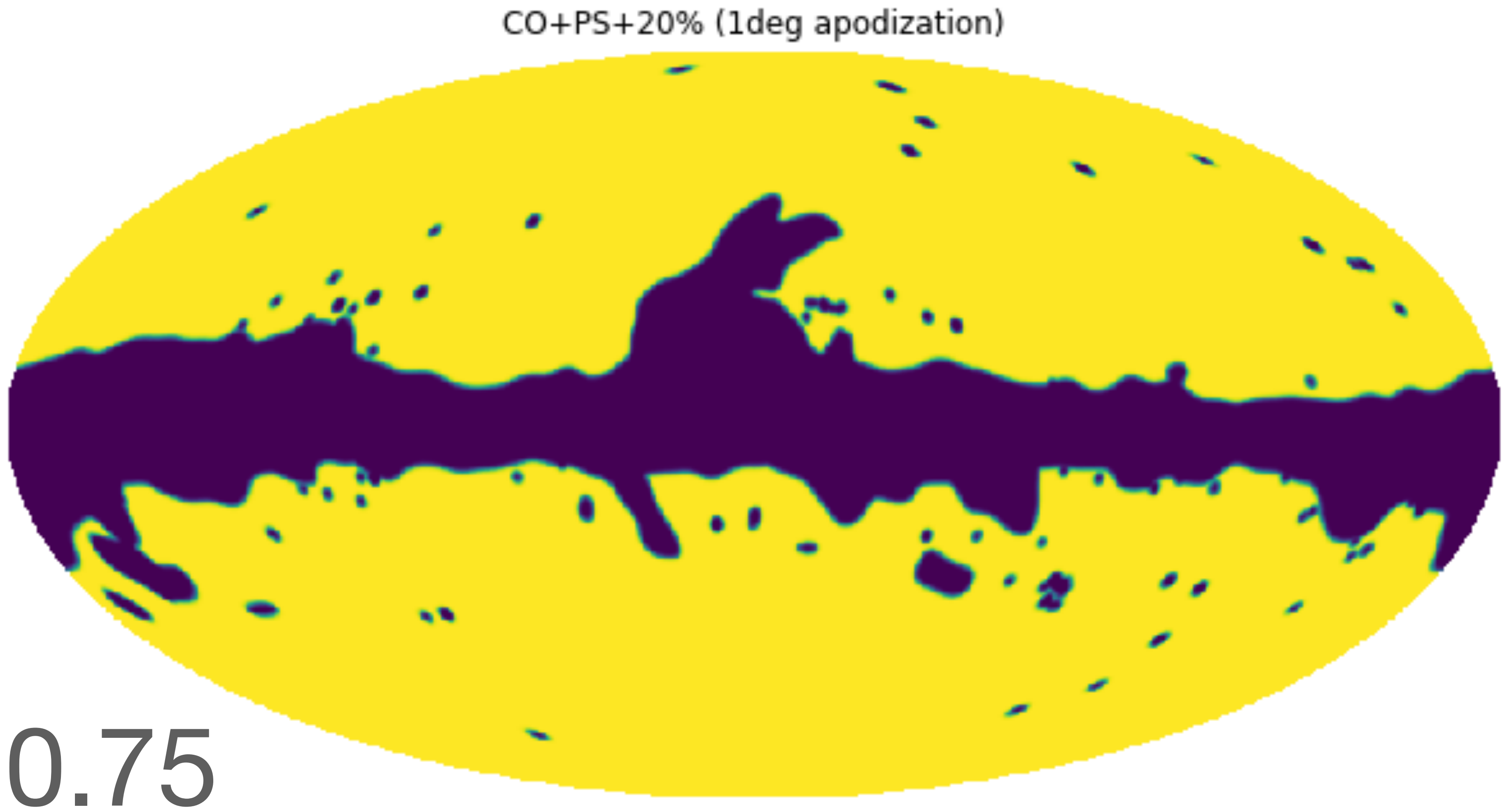
= nearly full sky

f_{sky} = 0.90

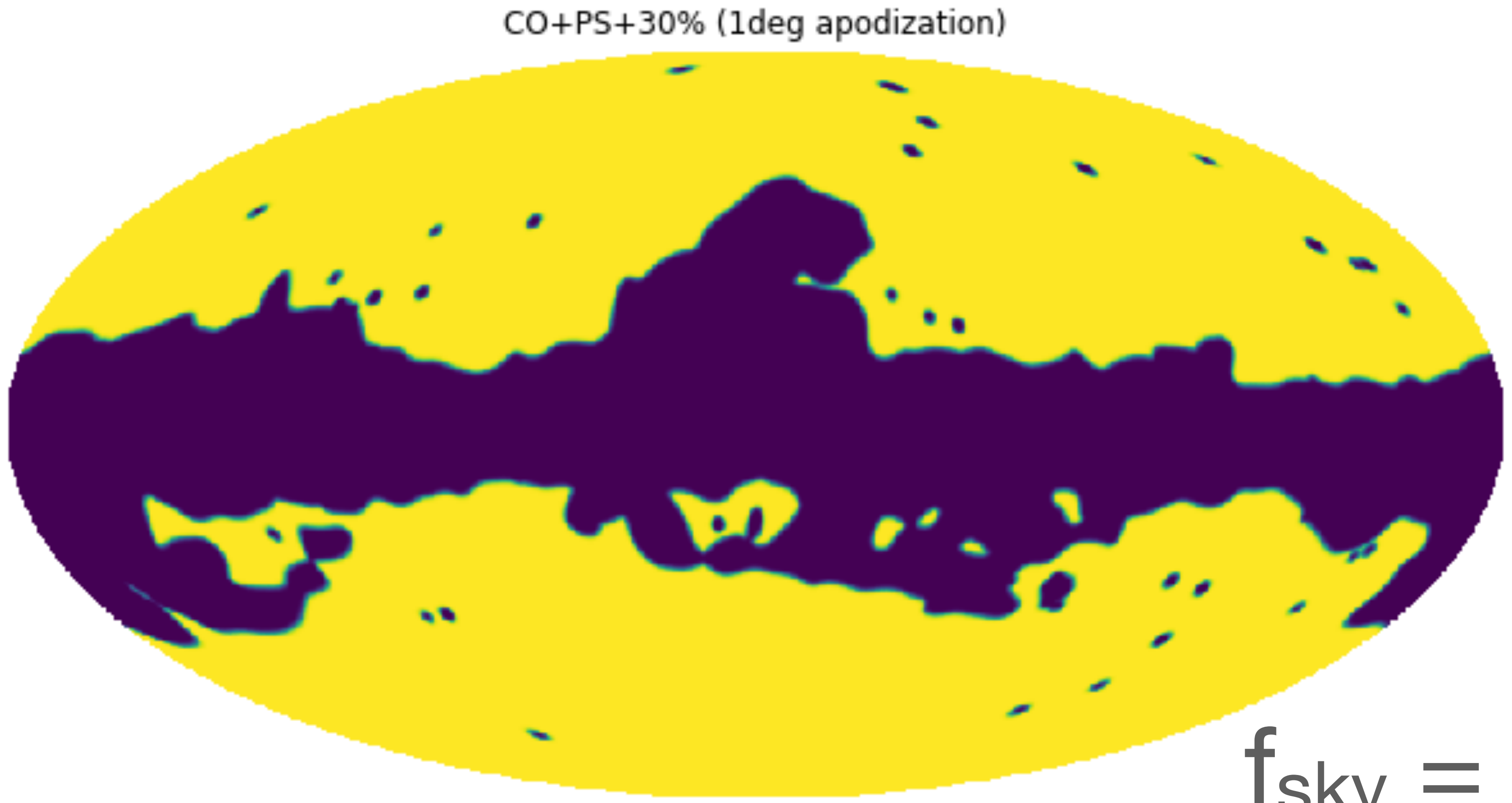


f_{sky} = 0.85

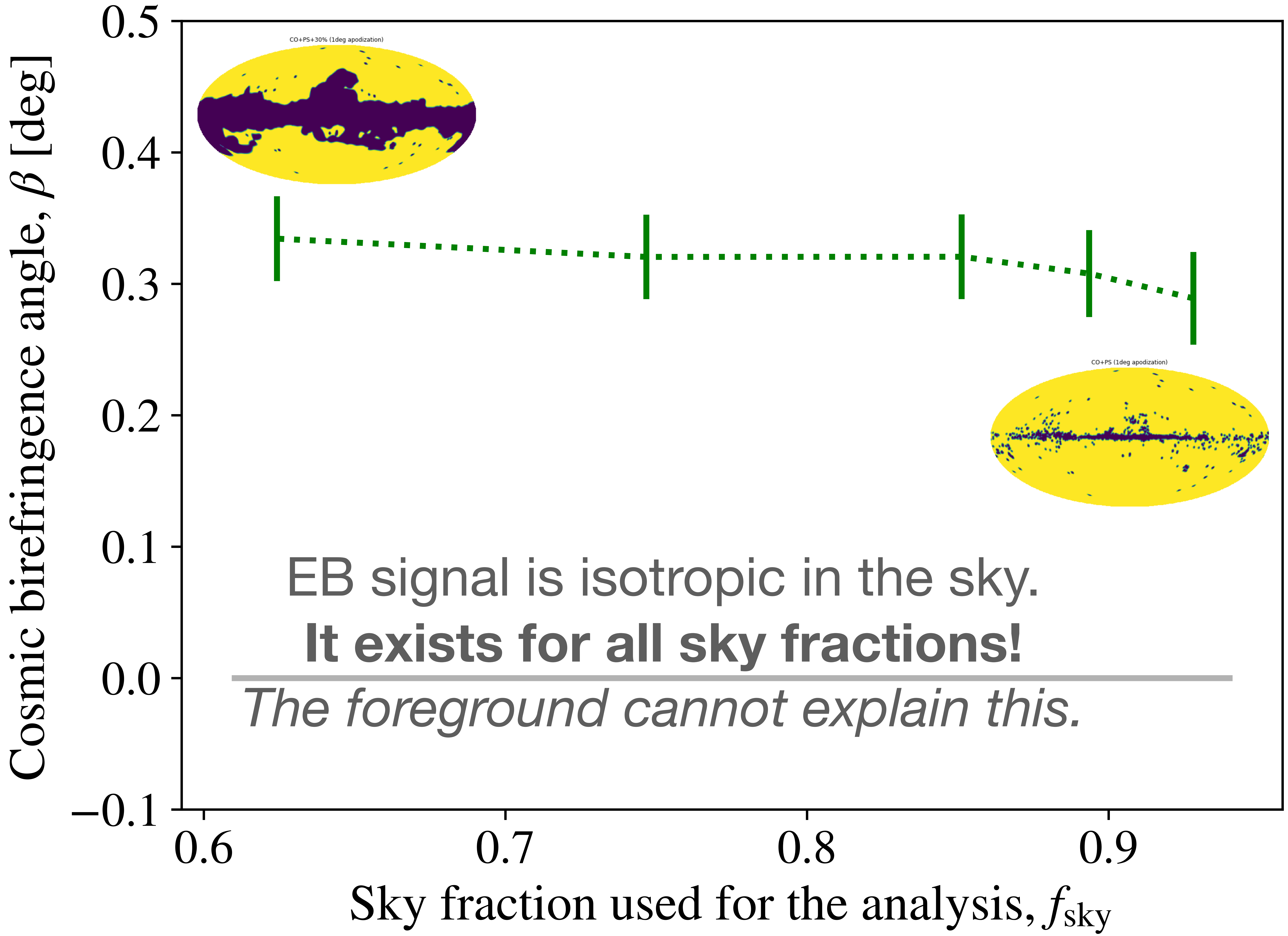




f_{sky} = 0.75



f_{sky} = 0.63

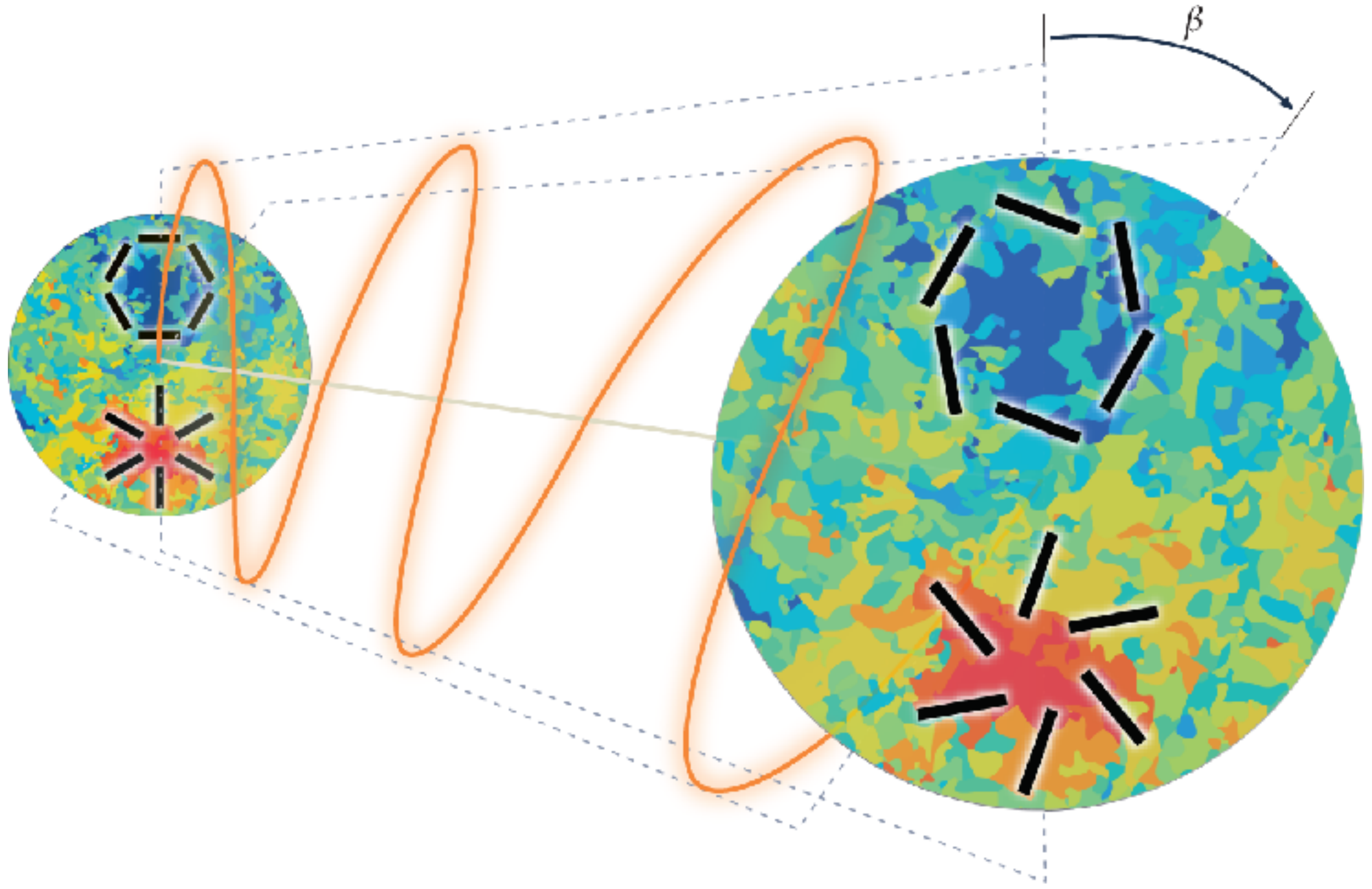

CO+PS+30% (1deg apodization)
CO+PS (1deg apodization)
EB signal is isotropic in the sky.
It exists for all sky fractions!
The foreground cannot explain this.
Cosmic birefringence angle, β [deg]
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
0.6
0.7
0.8
0.9
Sky fraction used for the analysis, $f_{\rm sky}$

The Biggest Problem: Miscalibration of detectors

Wu et al. (2009); Komatsu et al. (2011); Keating, Shimon & Yadav (2012)

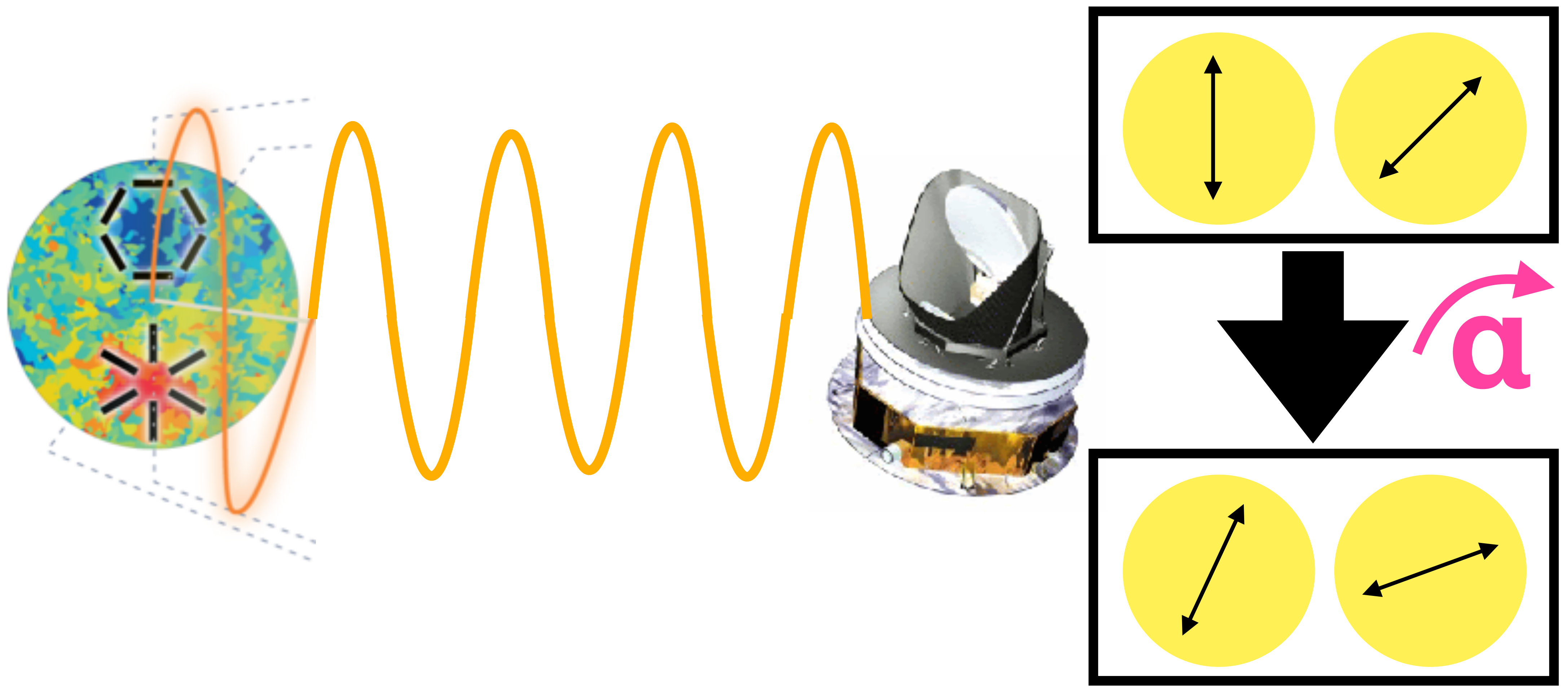
Impact of miscalibration of polarisation angles

Cosmic or Instrumental?



OR

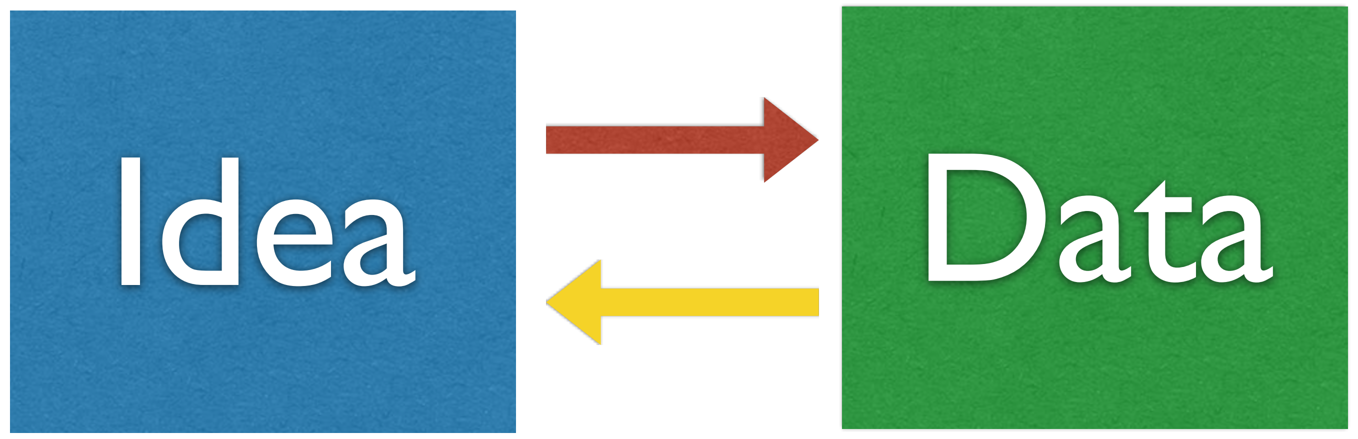
Polarisation-sensitive
detectors on the focal plane



rotated by an angle “α”
(but we do not know it)

- Is the plane of linear polarisation rotated by the genuine cosmic birefringence effect, or simply because the polarisation-sensitive directions of detectors are rotated with respect to the sky coordinates (and we did not know it)?

- If the detectors are rotated by α, it seems that we can measure only the **sum α+β**.



The Key Idea: The polarised Galactic foreground emission as a calibrator

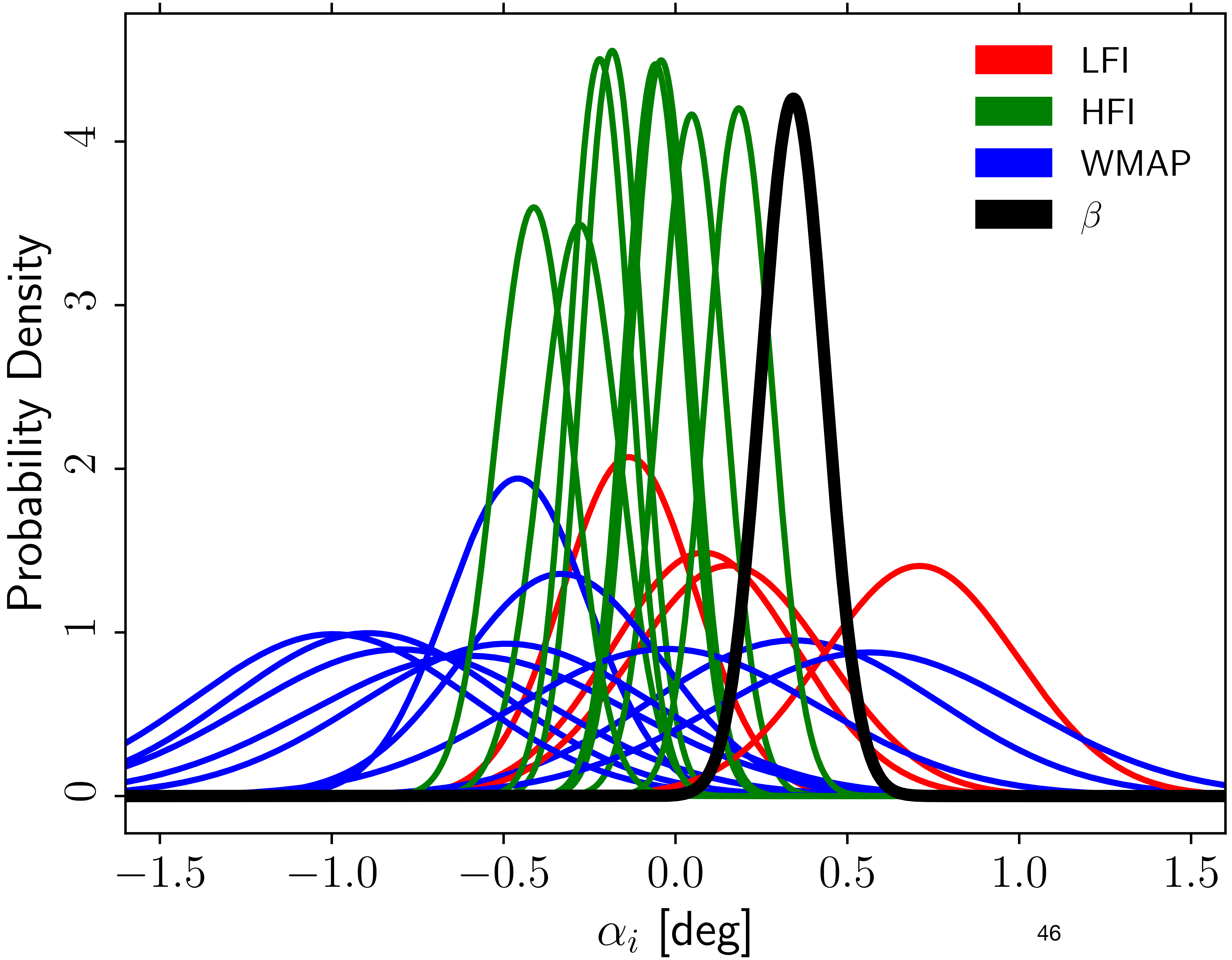
ESA’s Planck

Credit: ESA

Directions of the magnetic field inferred from polarisation of the thermal dust emission in the Milky Way

Miscalibration angles (WMAP and Planck)

Nearly full-sky data (92% of the sky)

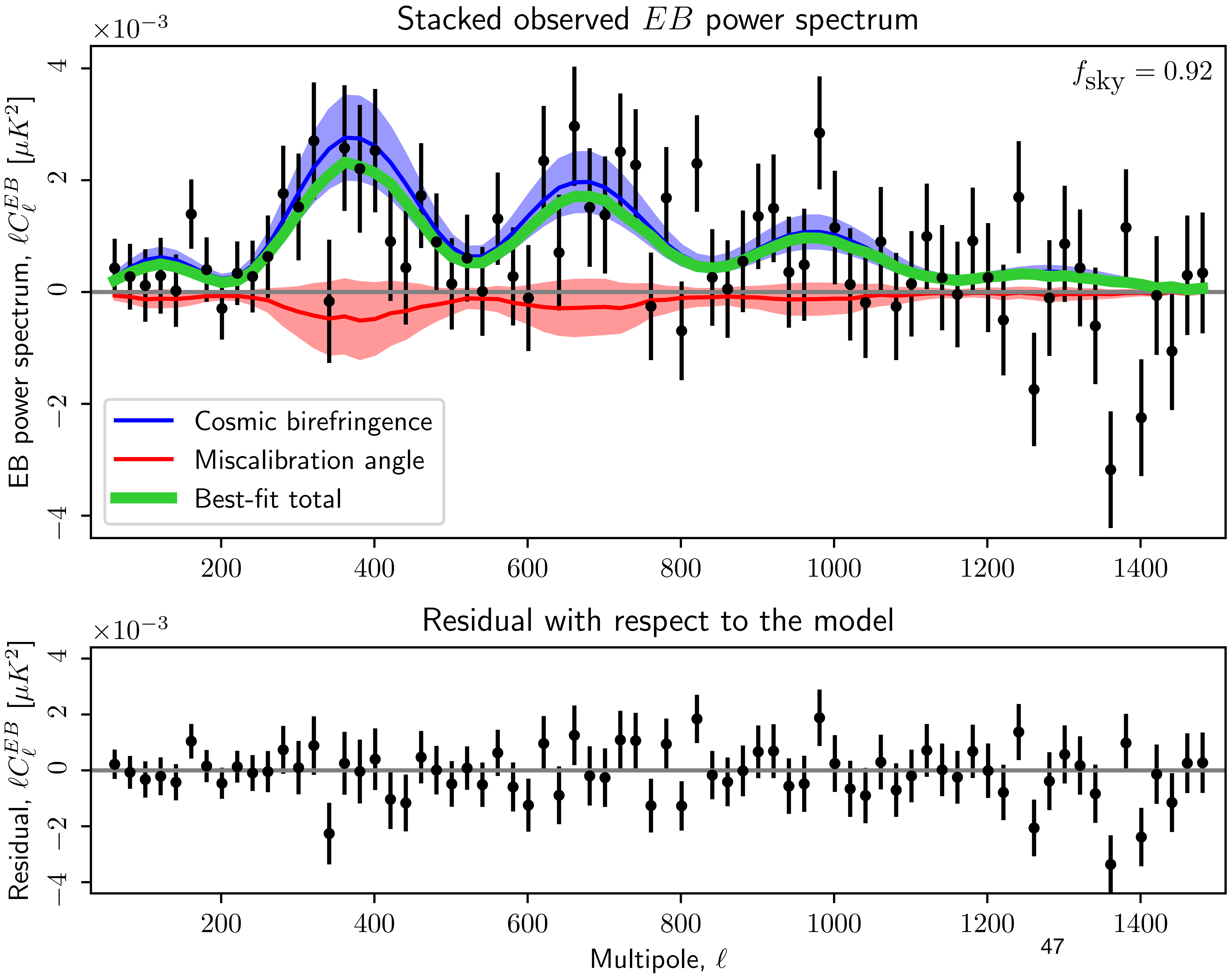


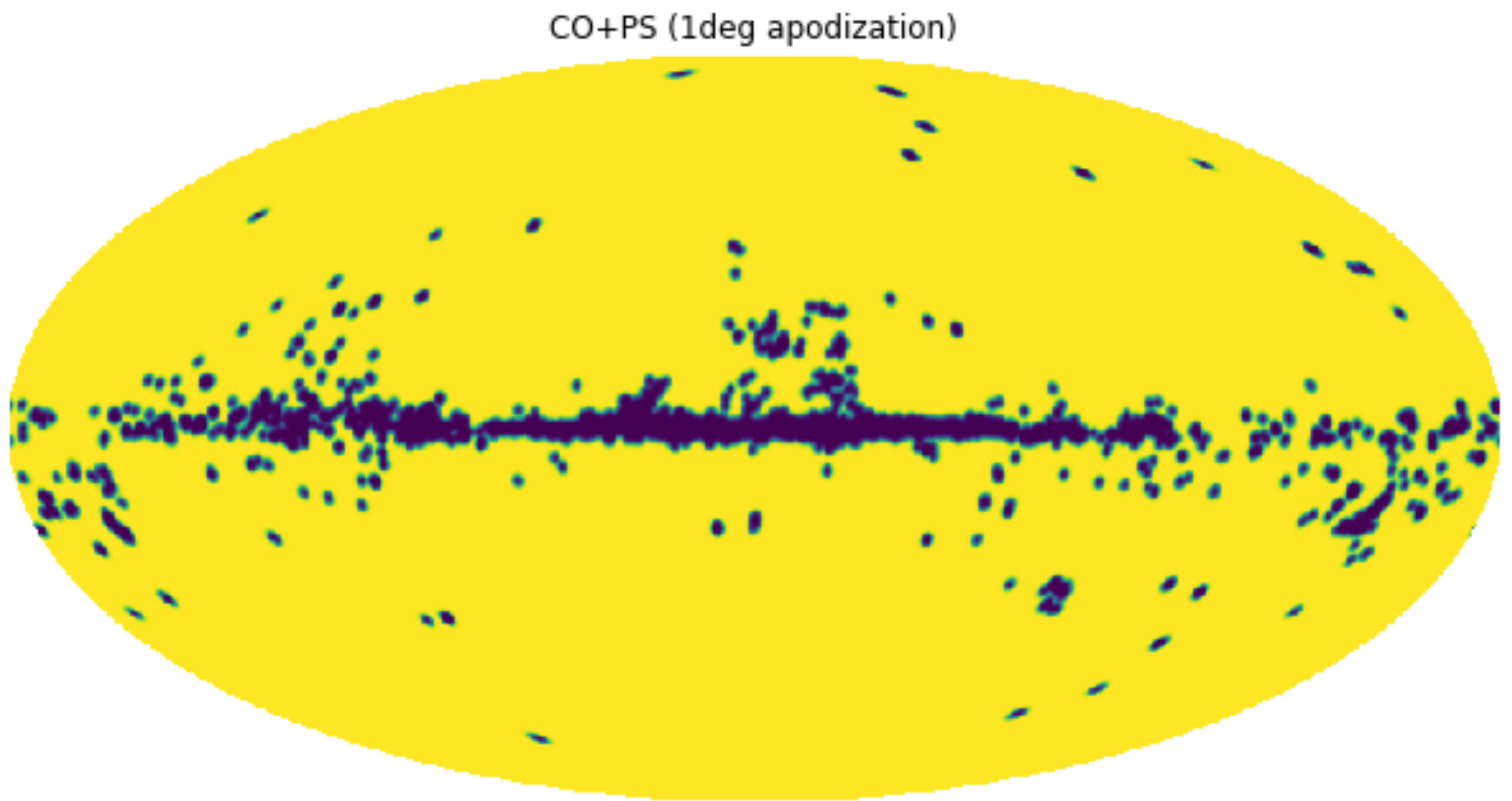
- The angles are all over the place, and are well within the quoted calibration uncertainty of instruments.
  - 1.5 deg for WMAP
  - 1 deg for Planck
- They cancel!
  - The power of adding independent datasets.

Eskilt & EK (2022)

Cosmic Birefringence fits well (WMAP+Planck)

Nearly full-sky data (92% of the sky)



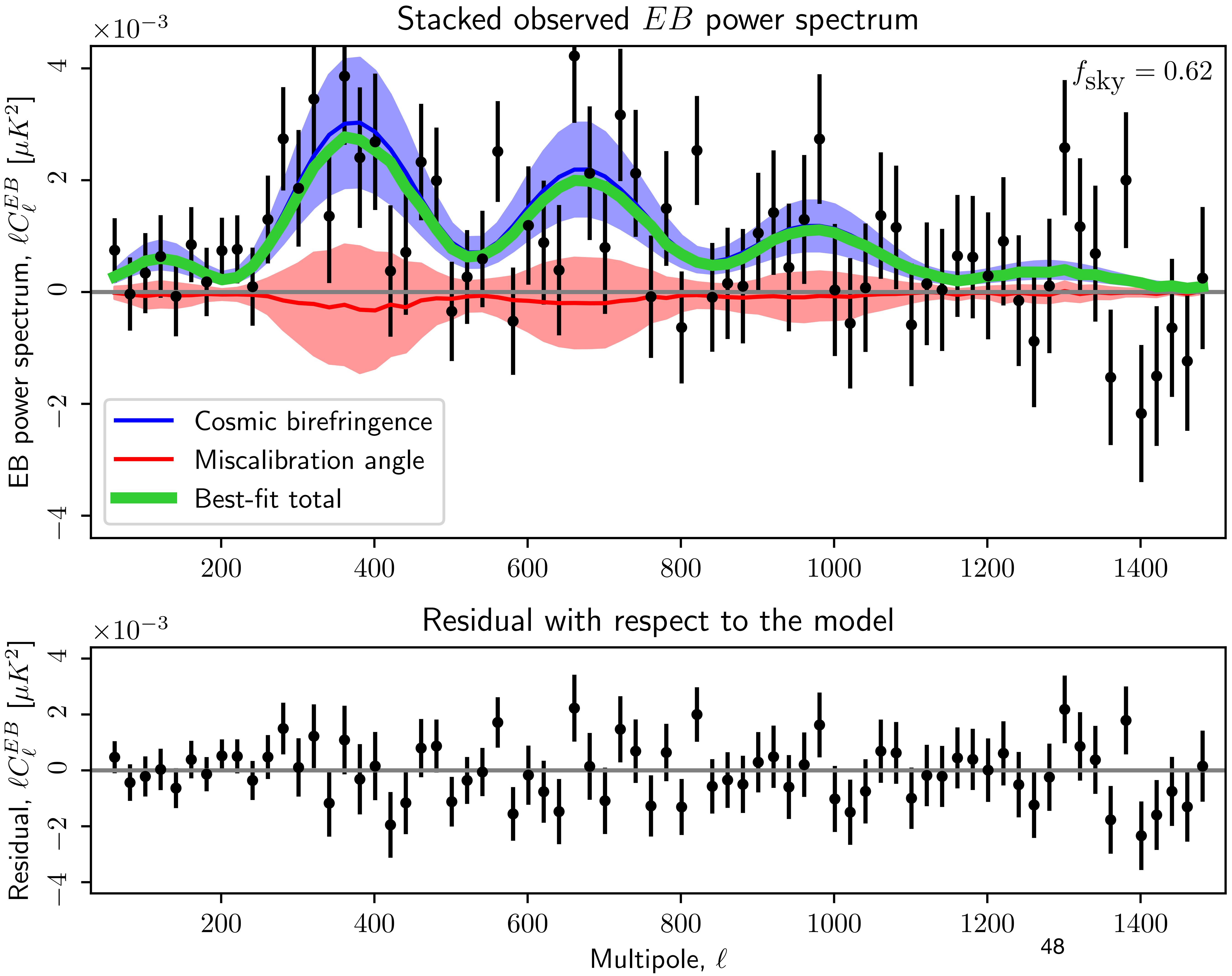


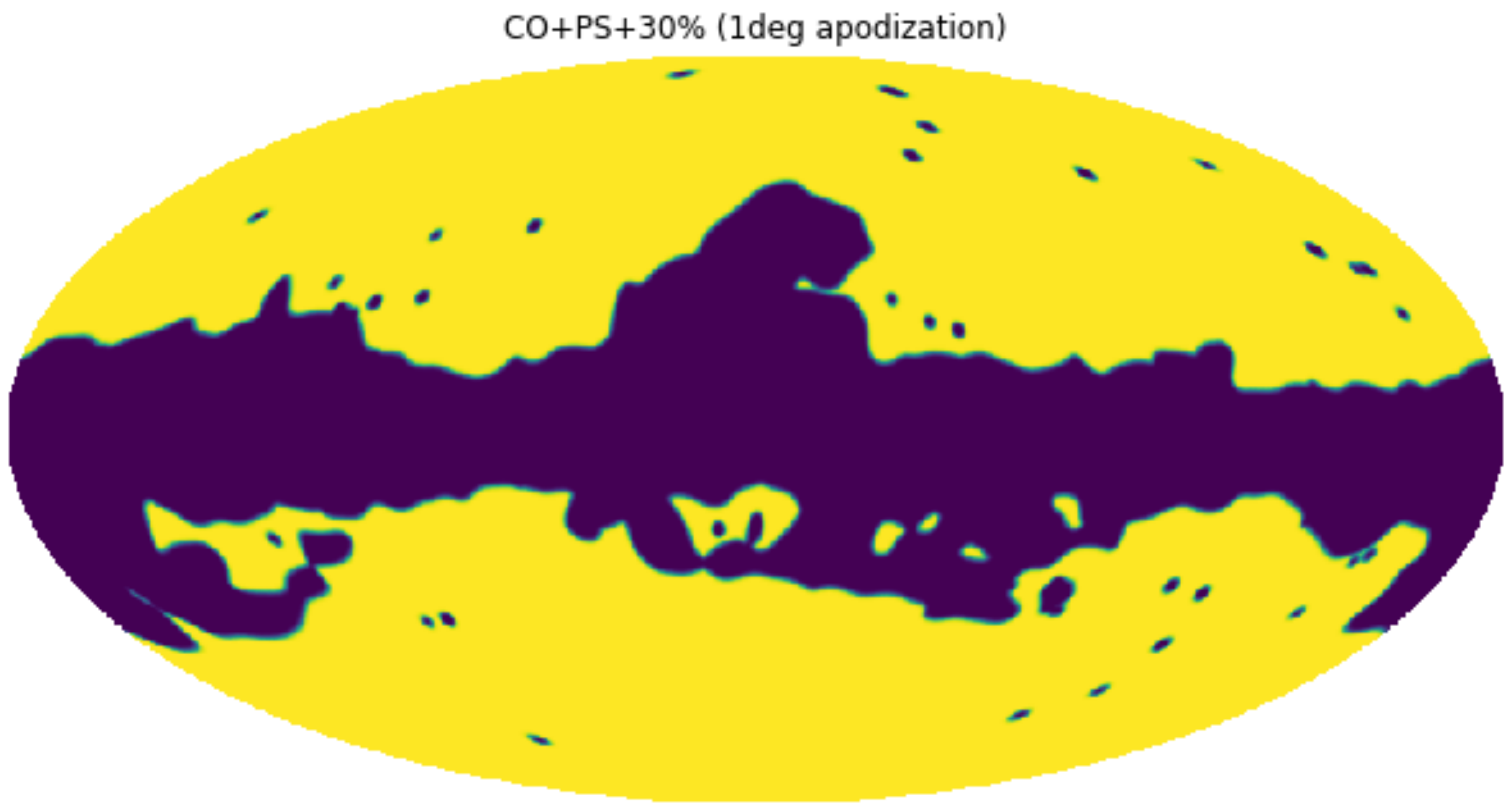
- **Miscalibration angles** make only small contributions thanks to the cancellation.
- **β = 0.34 ± 0.09 deg**
- χ^2 = 65.3 for DOF=72

Eskilt & EK (2022)

Cosmic Birefringence fits well (WMAP+Planck)

Robust against the Galactic mask (62% of the sky)

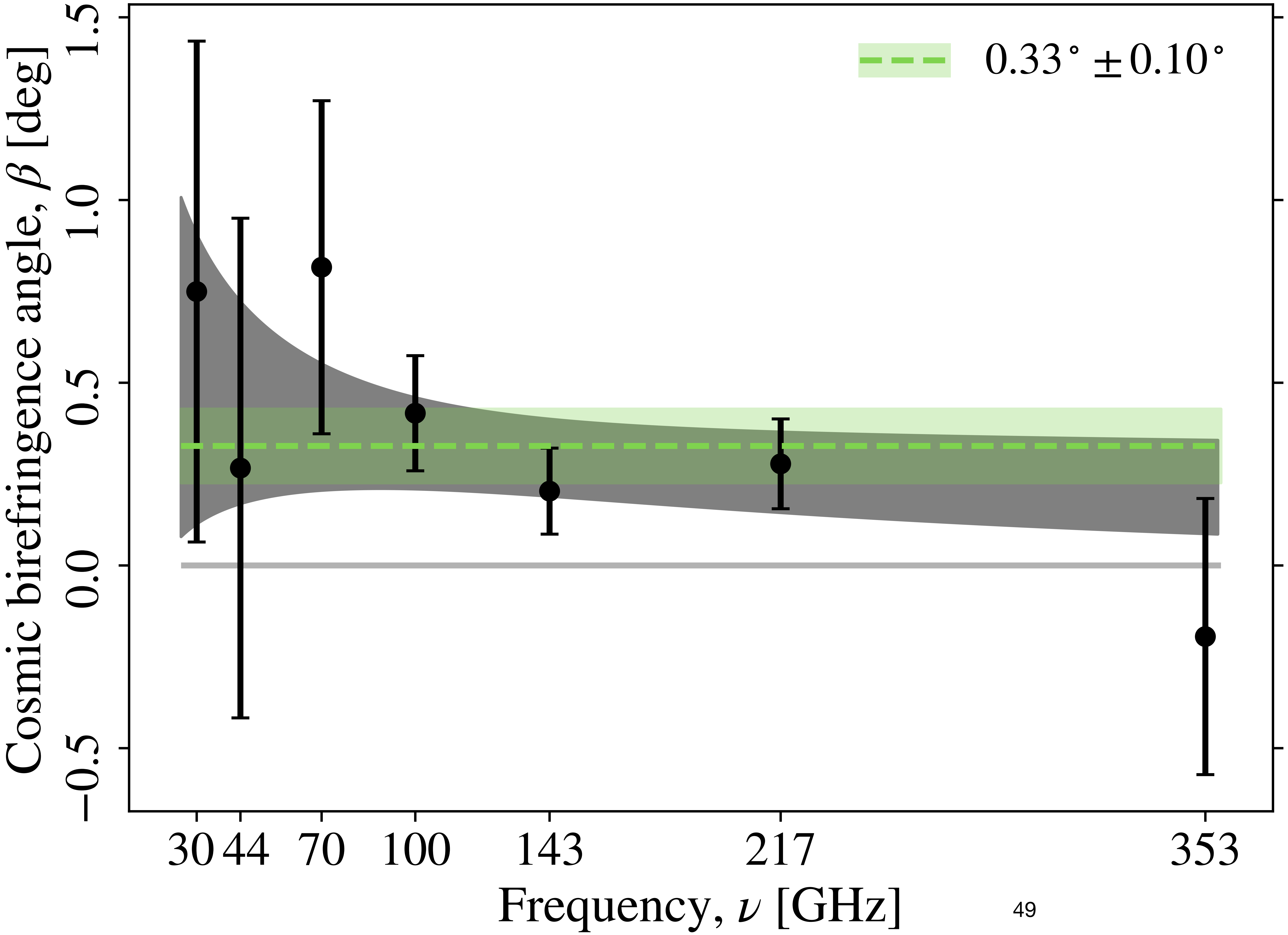




- **Miscalibration angles** make only small contributions thanks to the cancellation.
- **β = 0.37 ± 0.14 deg**
- χ^2 = 65.8 for DOF=72

No frequency dependence is found

Consistent with the expectation from cosmic birefringence



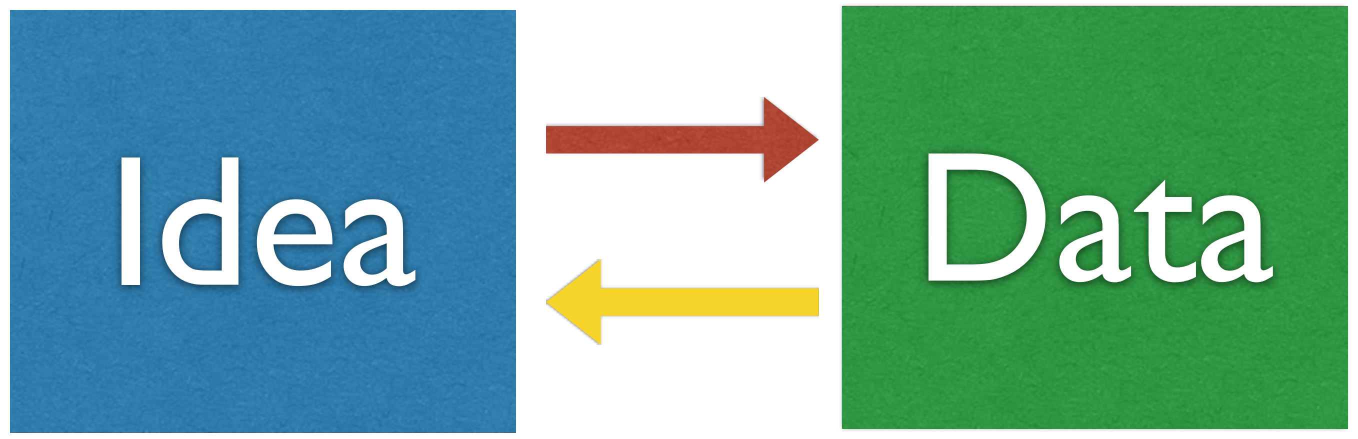
Johannes R. Eskilt
(Univ. Oslo)

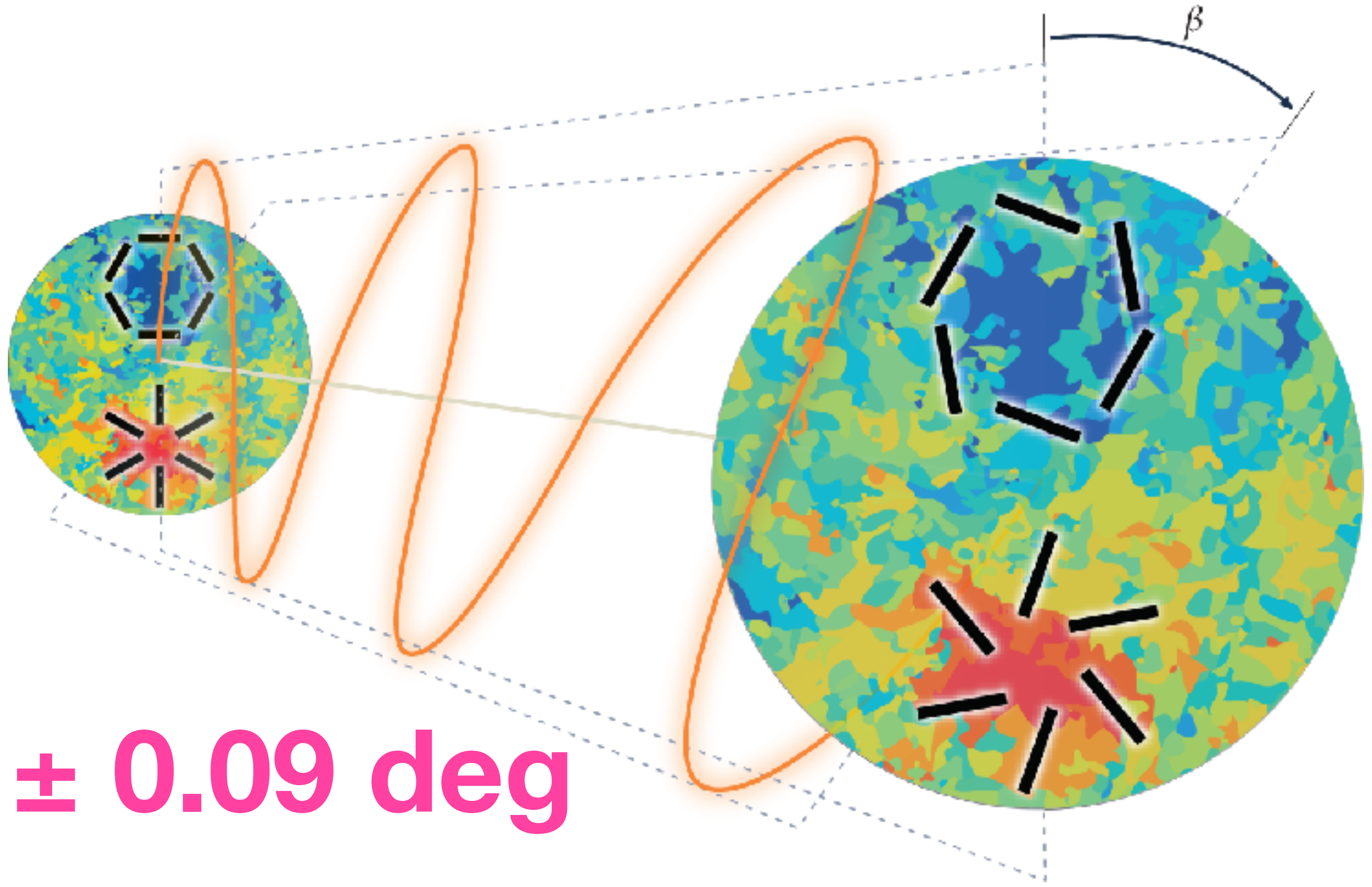
- No evidence for frequency dependence:
  - For $\beta \sim (\nu/150\text{GHz})^n$, **$n = -0.20^{+0.41}_{-0.39}$** (68% CL)
  - Faraday rotation (n=–2) is disfavoured.

Have we found new physics?

$\beta = 0.34 \pm 0.09$ deg (68%CL; nearly full sky)

- I am old enough to know that **3.6σ can disappear**.
- But, if confirmed in the future, it would be a breakthrough in cosmology and fundamental physics.
  - It is possible that we will know the origin of this signal (cosmological or otherwise) before the next Fachbeirat…





$\beta = 0.34 \pm 0.09$ deg

Credit: WMAP Science Team
The surface of "last scattering" by electrons
(Scattering generates ***polarisation***!)
What powered the Big Bang?

Parity violation in the initial fluctuations

Primordial parity violation during inflation!

- The parity-violating interaction could also exist during inflation.
- This will be imprinted in the initial density fluctuations and gravitational waves!

$$F\tilde{F} = -4\mathbf{B}\cdot\mathbf{E}$$

$$I_{\rm CS} = \int d^4x\sqrt{-g}\left(-\frac{\alpha}{4f}\chi F\tilde{F}\right)$$

→

$$\Box\chi - \partial V/\partial\chi = -(\alpha/f)\mathbf{E}\cdot\mathbf{B}$$

- initial density fluctuations

↓

- gravitational waves

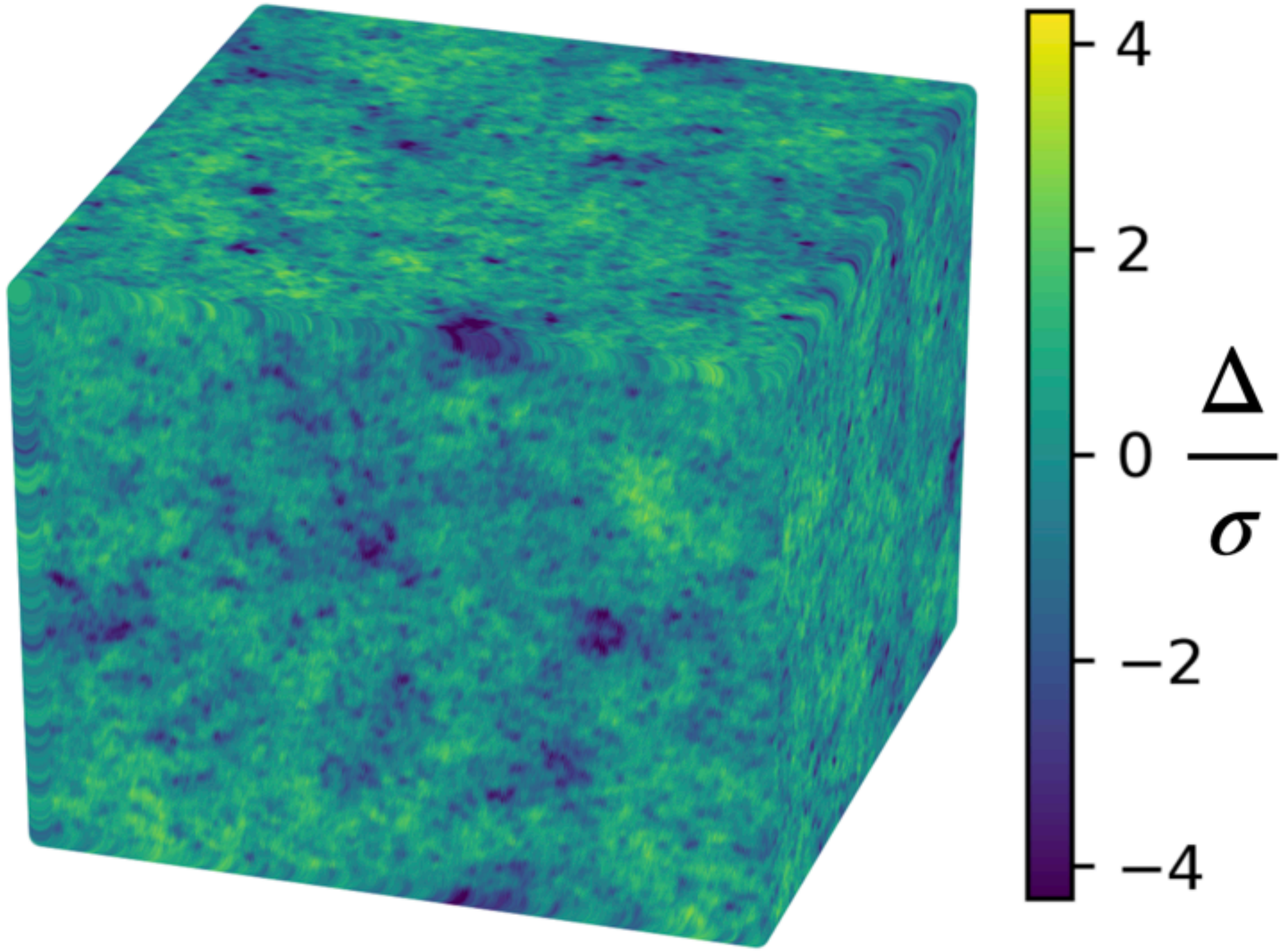
$$\Box h_{ij}(t,\mathbf{x}) = -16\pi G a^{-2}(t) T^{\rm t}_{ij}(t,\mathbf{x})$$
$$= 16\pi G(E_iE_j + B_iB_j)^{\rm TT}$$

Caravano, EK, et al. (2021; 2022a; 2022b)

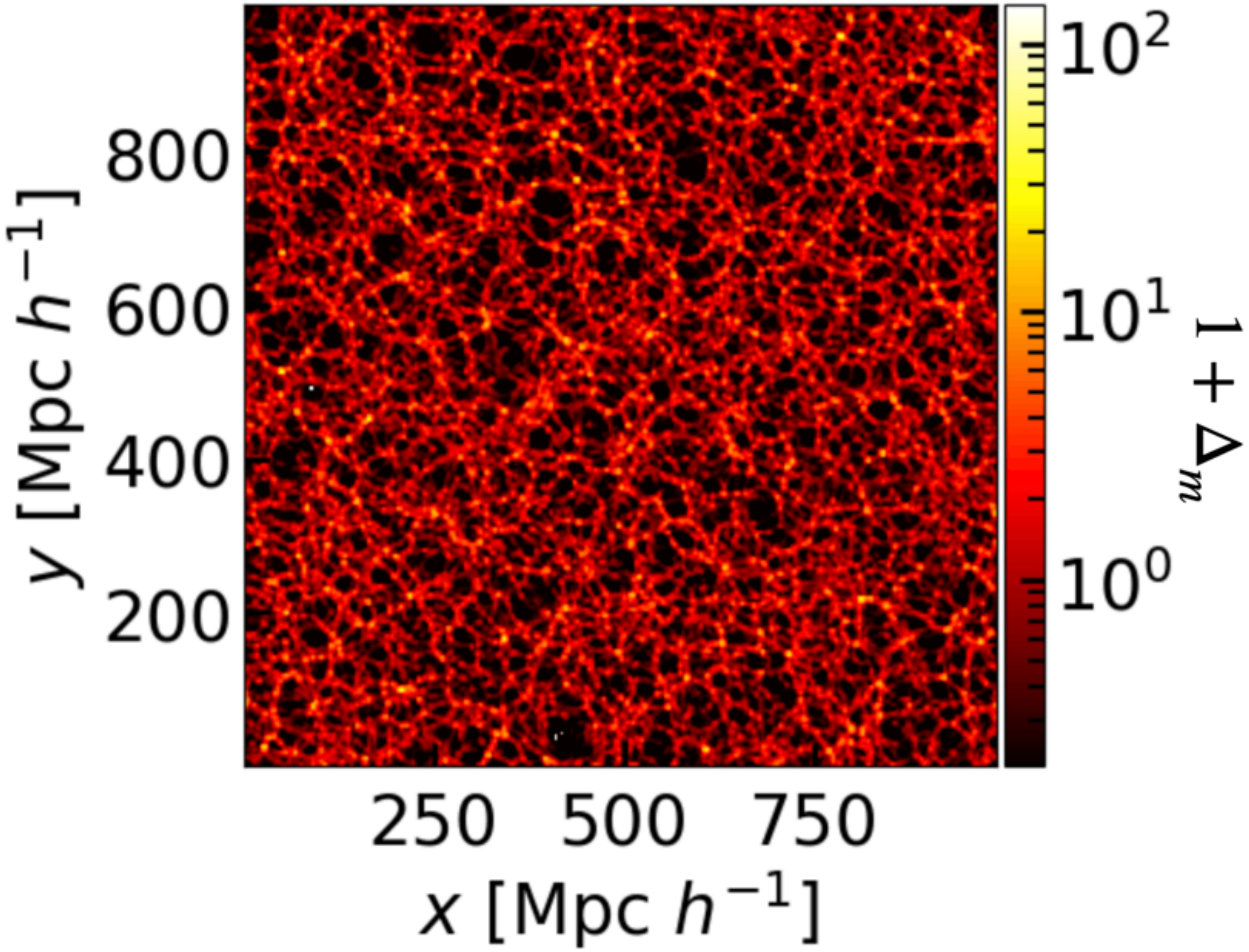
Truly *ab initio* simulation!

World's first lattice simulation of inflation

Angelo Caravano

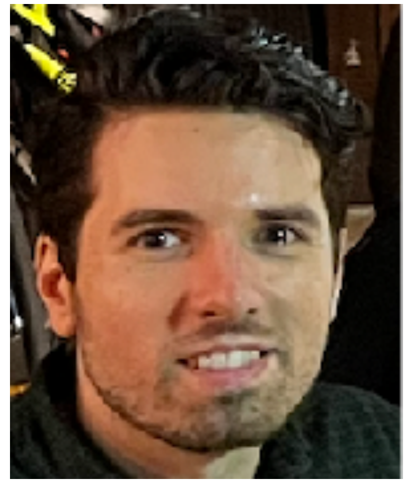


Drew Jamieson



- (Left) Parity-violating and non-Gaussian density fluctuation during inflation.
- (Right) Outcome of N-body simulation at z=0, using the left panel as the initial condition.

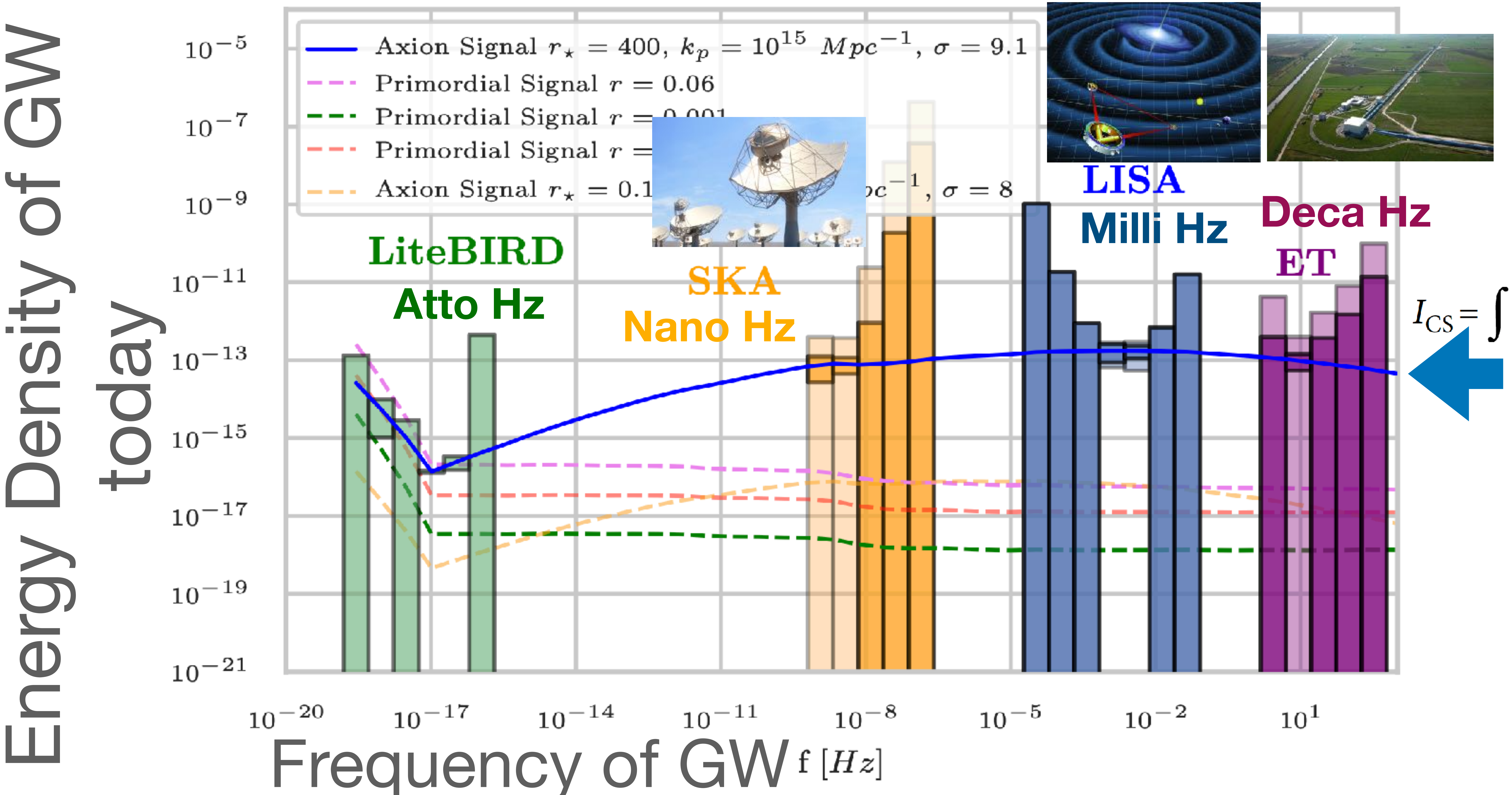
Not just CMB!



Campeti, EK, Poletti, Baccigalupi (2021)

Paolo Campeti

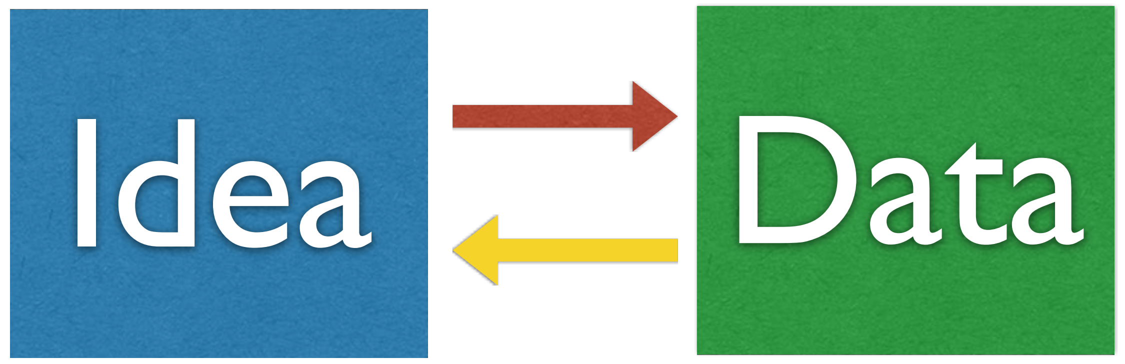
We can measure GW across 21 orders of magnitude in the frequency

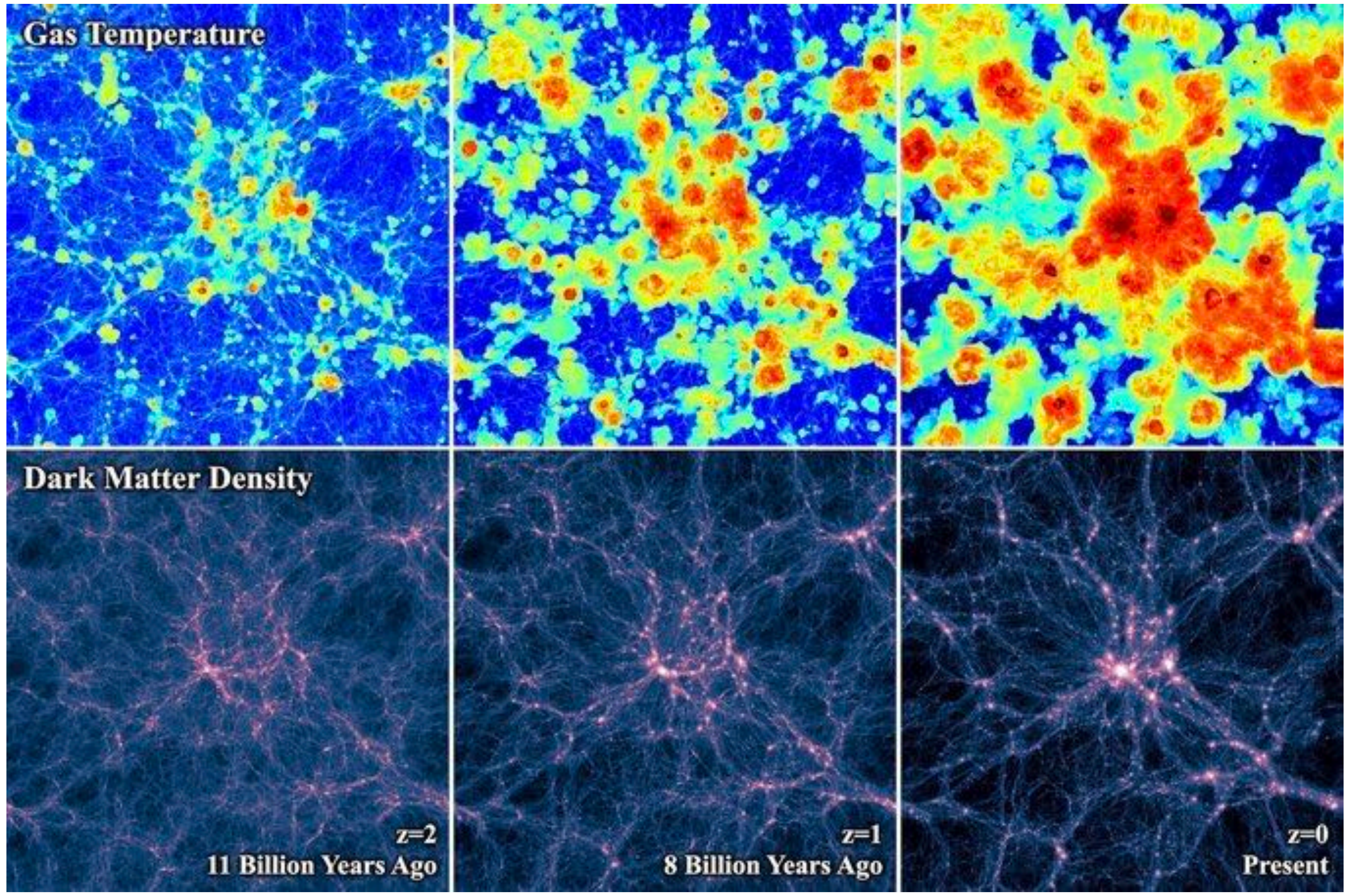


$$I_{\rm CS} = \int d^4x \sqrt{-g}\left(-\frac{\alpha}{4f}\chi F\tilde{F}\right)$$

How hot is the Universe?

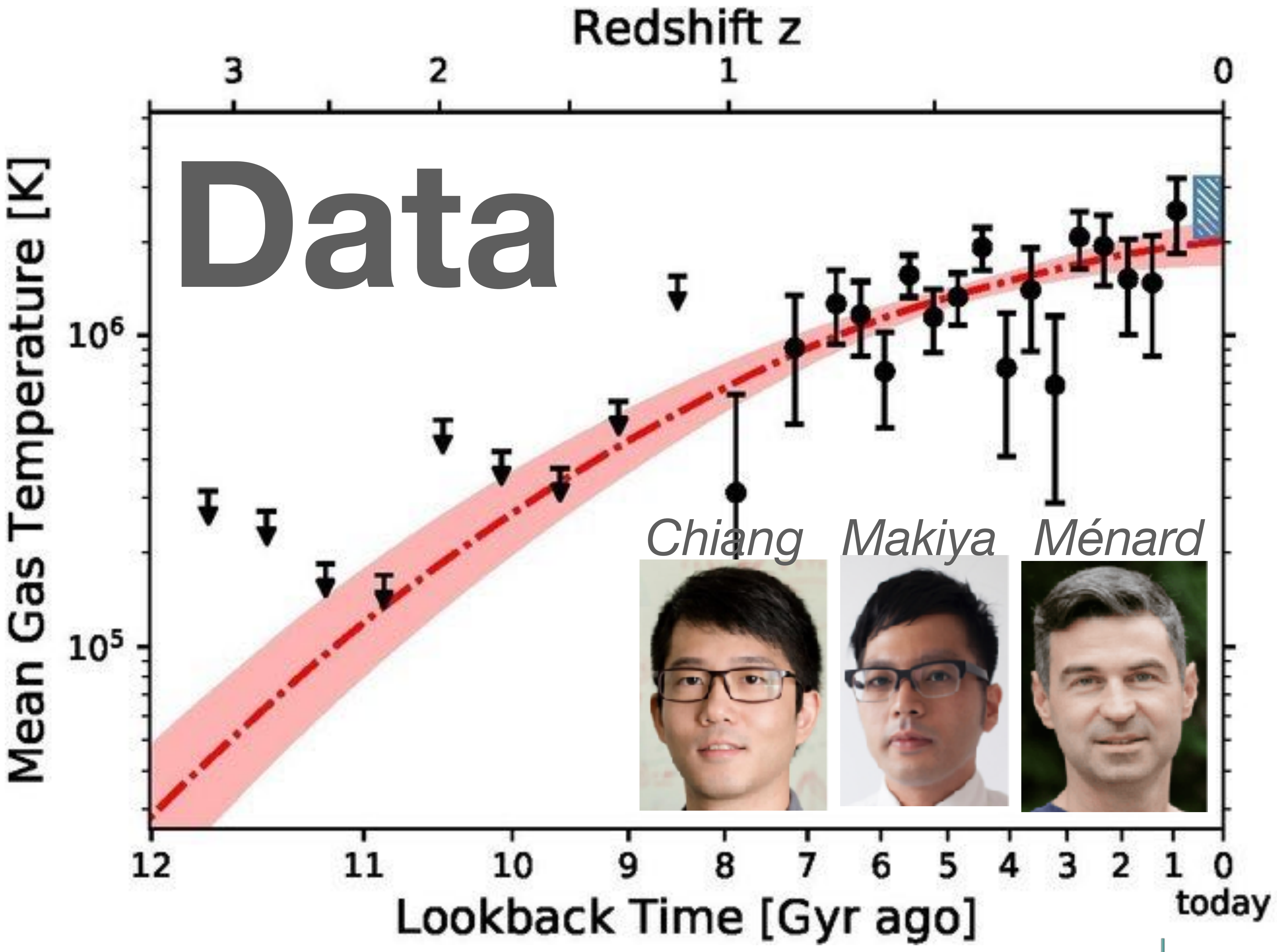
Taking the temperature of hot gas in the Universe over the last 8 billion years





Simulation

Credit: Dylan Nelson, Illustris Collaboration



- *Chiang, Makiya, Ménard, EK, ApJ, 902, 56 (2020)*
- *Chiang, Makiya, EK,. Ménard, ApJ, 910, 32 (2021)*
- *Young, EK, Dolag, PRD, 104, 083538 (2021)*

MAX-PLANCK-INSTITUT FÜR ASTROPHYSIK

MPA Press Release, November 10, 2020

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komatsu@...

Original publication

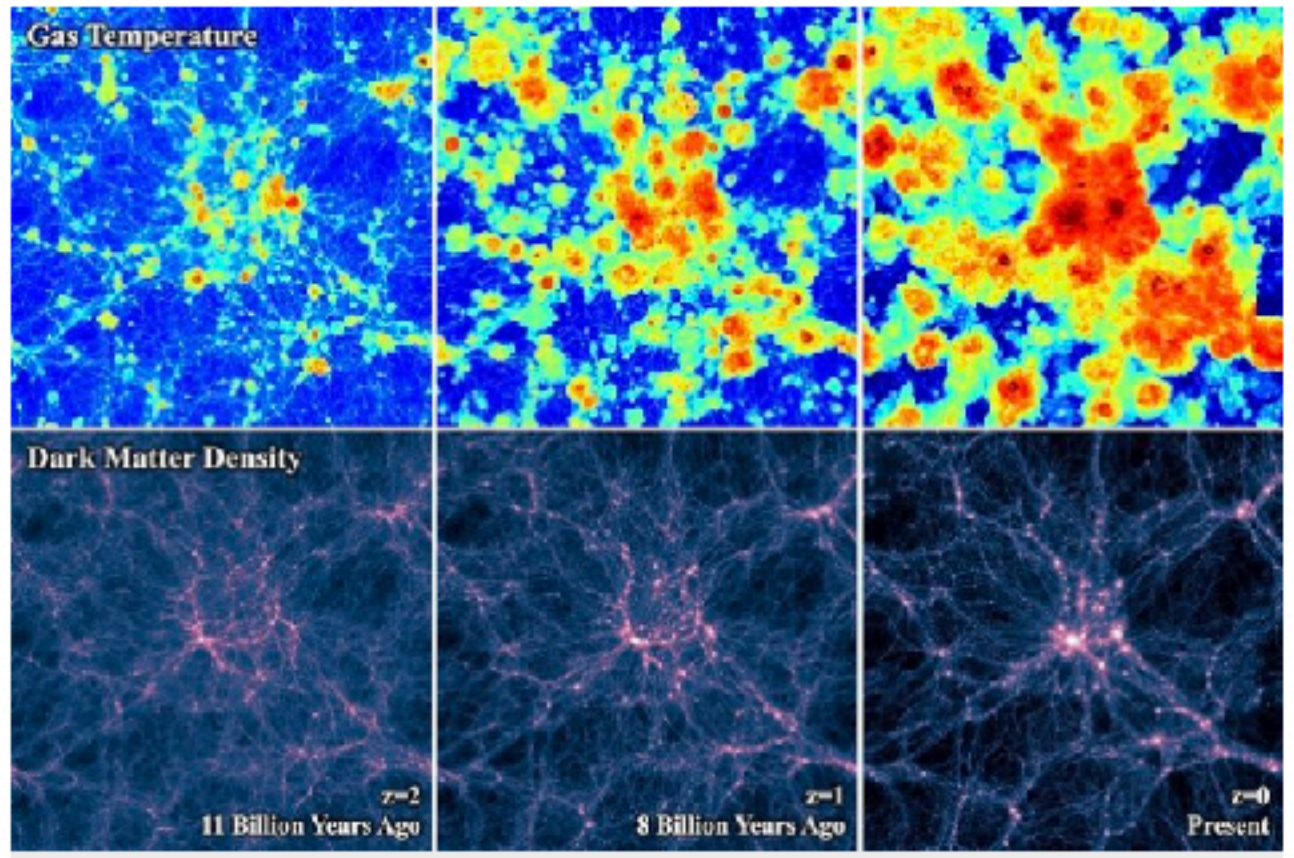
1. *Chiang, Makiya, Ménard and Komatsu*
The Cosmic Thermal History Probed by Sunyaev-Zeldovich Effect Tomography
Astrophysical Journal, 902, 56 (2020)

Taking the temperature of the Universe

NOVEMBER 10, 2020

How hot is the Universe today? How hot was it before? A new study, which has been published in the Astrophysical Journal, suggests that the mean temperature of gas in large structures of the Universe has increased ten times over the last 10 billion years, to reach about 2 million Kelvin today.

The large-scale structure of the Universe refers to the global pattern of how galaxies and galaxy clusters are distributed in space. This cosmic net formed from tiny irregularities in the matter distribution in the early Universe, which were amplified through gravitational attraction. "As the Universe evolves, gravity pulls dark matter and gas in space together into galaxies and clusters of galaxies," said Yi-Kuan Chiang, the lead author of the study and a research fellow at the Ohio State University Center for Cosmology and AstroParticle Physics. "The drag is violent - so violent that more and more gas is shocked and heated up."



Computer simulation of the evolution of the large-scale structure (bottom) and the temperature (top) of the Universe. The time flows from the left to the right panels, with the rightmost panel showing the present-day epoch.

This heated gas can then be used to measure the mean temperature of the Universe over cosmic time. In particular, the researchers used the so-called "Sunyaev-Zeldovich" effect, named after Rashid Sunyaev, director emeritus at the Max Planck Institute for Astrophysics, who first predicted this phenomenon theoretically. This effect arises when low-energy photons of the cosmic microwave background radiation are scattered by hot electrons in the large-scale structure of the Universe. The scattering transfers energy from electrons to photons, making the hot electron gas visible. The intensity of the Sunyaev-Zeldovich effect is proportional to the thermal pressure of the gas, which, in turn, is proportional to the temperature of electrons.

While this measurement is straightforward in principle, collecting the

The cosmic energy inventory

Fukugita & Peebles (2004)

- We know the mean total mass density of the Universe: $\mathbf{\Omega_m \sim 0.3}$.
- We also know the mean baryonic mass density of the Universe: $\mathbf{\Omega_B \sim 0.05}$.
- We also have estimates for many other energy densities in the Universe:

THE COSMIC ENERGY INVENTORY

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Institute for Advanced Study, Einstein Drive, Princeton, NJ 08540; and Institute for Cosmic Ray Research,
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AND

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Received 2004 June 3; accepted 2004 August 9

ABSTRACT

We present an inventory of the cosmic mean densities of energy associated with all the known states of matter and radiation at the present epoch. The observational and theoretical bases for the inventory have become rich enough to allow estimates with observational support for the densities of energy in some 40 forms. The result is a global portrait of the effects of the physical processes of cosmic evolution.

Fukugita & Peebles (2004)

TABLE 1

The Cosmic Energy Inventory

Category	Parameter		Components[a]	Totals[a]
1	Dark sector:			0.954 ± 0.003
1.1	Dark energy		0.72 ± 0.03	
1.2	Dark matter		0.23 ± 0.03	
1.3	Primeval gravitational waves		$\lesssim 10^{-10}$	
2	Primeval thermal remnants:			0.0010 ± 0.0005
2.1	Electromagnetic radiation		$10^{-4.3 \pm 0.0}$	
2.2	Neutrinos		$10^{-2.9 \pm 0.1}$	
2.3	Prestellar nuclear binding energy		$-10^{-4.1 \pm 0.0}$	
3	Baryon rest mass:			0.045 ± 0.003
3.1	Warm intergalactic plasma		0.040 ± 0.003	
3.1a	Virialized regions of galaxies	0.024 ± 0.005		
3.1b	Intergalactic	0.016 ± 0.005		
3.2	Intracluster plasma		0.0018 ± 0.0007	
3.3	Main-sequence stars: spheroids and bulges		0.0015 ± 0.0004	
3.4	Main-sequence stars: disks and irregulars		0.00055 ± 0.00014	
3.5	White dwarfs		0.00036 ± 0.00008	
3.6	Neutron stars		0.00005 ± 0.00002	
3.7	Black holes		0.00007 ± 0.00002	
3.8	Substellar objects		0.00014 ± 0.00007	
3.9	H I + He I		0.00062 ± 0.00010	
3.10	Molecular gas		0.00016 ± 0.00006	
3.11	Planets		10^{-6}	
3.12	Condensed matter		$10^{-5.6 \pm 0.3}$	
3.13	Sequestered in massive black holes		$10^{-5.4}(1 + \epsilon_n)$	
4	Primeval gravitational binding energy:			$-10^{-6.1 \pm 0.1}$
4.1	Virialized halos of galaxies		$-10^{-7.2}$	
4.2	Clusters		$-10^{-6.9}$	
4.3	Large-scale structure		$-10^{-6.2}$	
5	Binding energy from dissipative gravitational settling:			$-10^{-4.9}$
5.1	Baryon-dominated parts of galaxies		$-10^{-8.8 \pm 0.3}$	
5.2	Main-sequence stars and substellar objects		$-10^{-8.1}$	

Fukugita & Peebles (2004)

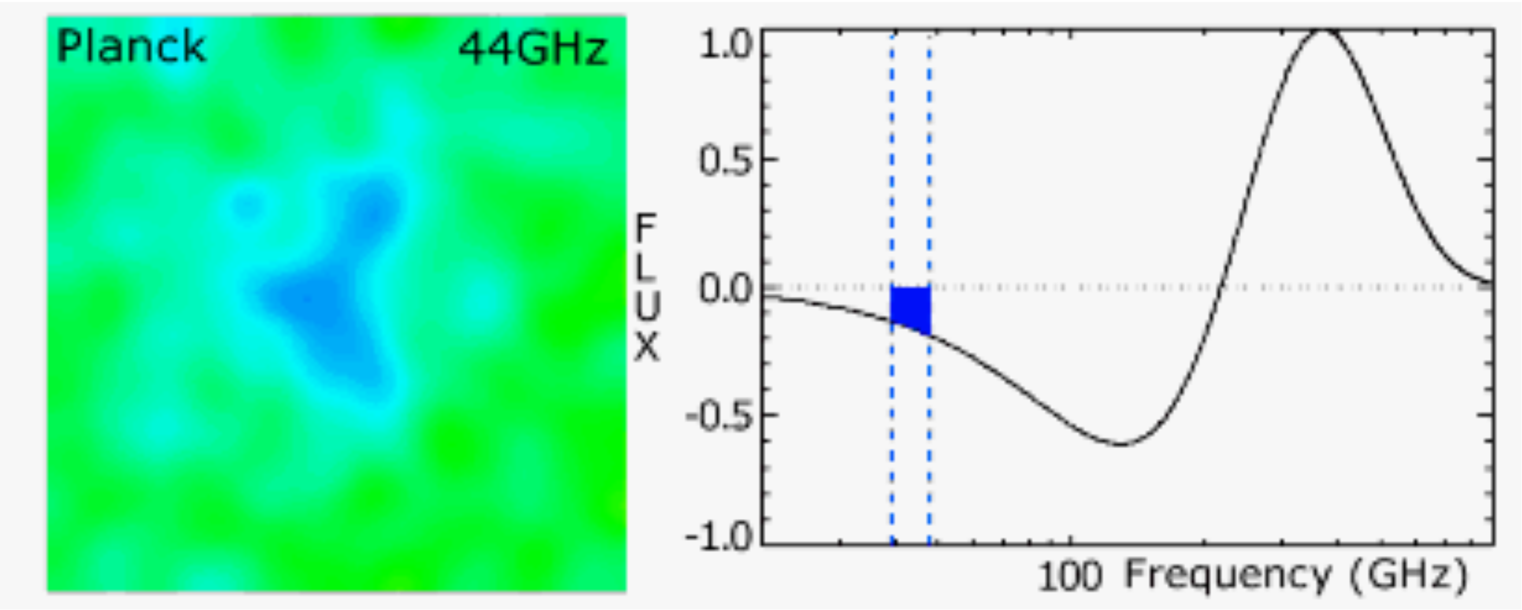
Category	Parameter	Components[a]	Totals[a]
5.3.	White dwarfs	$-10^{-7.4}$	
5.4.	Neutron stars	$-10^{-5.2}$	
5.5.	Stellar mass black holes	$-10^{-4.2}\epsilon_s$	
5.6.	Galactic nuclei: early type	$-10^{-5.6}\epsilon_n$	
5.7.	Galactic nuclei: late type	$-10^{-5.8}\epsilon_n$	
6.	Poststellar nuclear binding energy:		$-10^{-5.2}$
6.1.	Main-sequence stars and substellar objects	$-10^{-5.8}$	
6.2.	Diffuse material in galaxies	$-10^{-6.5}$	
6.3.	White dwarfs	$-10^{-5.6}$	
6.4.	Clusters	$-10^{-6.5}$	
6.5.	Intergalactic	$-10^{-6.2 \pm 0.5}$	
7.	Poststellar radiation:		$10^{-5.7 \pm 0.1}$
7.1.	Resolved radio-microwave	$10^{-10.3 \pm 0.3}$	
7.2.	FIR	$10^{-6.1}$	
7.3.	Optical	$10^{-5.8 \pm 0.2}$	
7.4.	X-ray–γ-ray	$10^{-7.9 \pm 0.2}$	
7.5.	Gravitational radiation: stellar mass binaries	$10^{-9 \pm 1}$	
7.6.	Gravitational radiation: massive black holes	$10^{-7.5 \pm 0.5}$	
8.	Stellar neutrinos:		$10^{-5.5}$
8.1.	Nuclear burning	$10^{-6.8}$	
8.2.	White dwarf formation	$10^{-7.7}$	
8.3.	Core collapse	$10^{-5.5}$	
9.	Cosmic rays and magnetic fields		$10^{-8.3^{+0.6}_{-0.3}}$
10.	Kinetic energy in the IGM		$10^{-8.0 \pm 0.3}$

- But we did not know the mean thermal energy density of the Universe, Ω_{th}
  - Let's measure this!

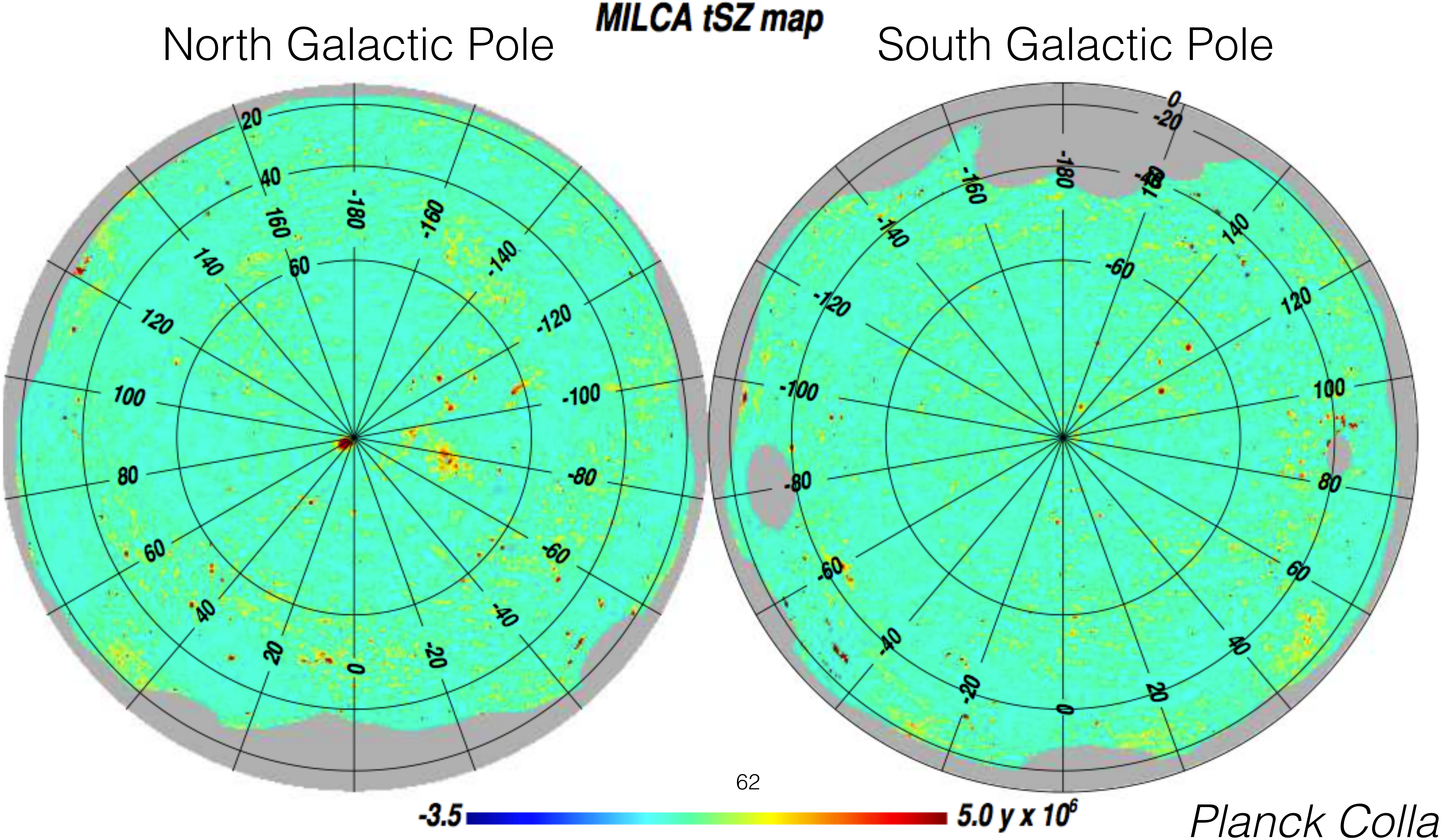
Chiang, Makiya, Ménard, EK, ApJ, 902, 56 (2020)

Q1: How hot is the large-scale structure of the Universe?

Create a full-sky map of the thermal Sunyaev-Zeldovich effect using the multi-frequency data!



Full-sky Electron Pressure Map



Planck Collaboration

Makiya, Ando & EK (2018)

The Limitation of the SZ data

The need for "Tomography"

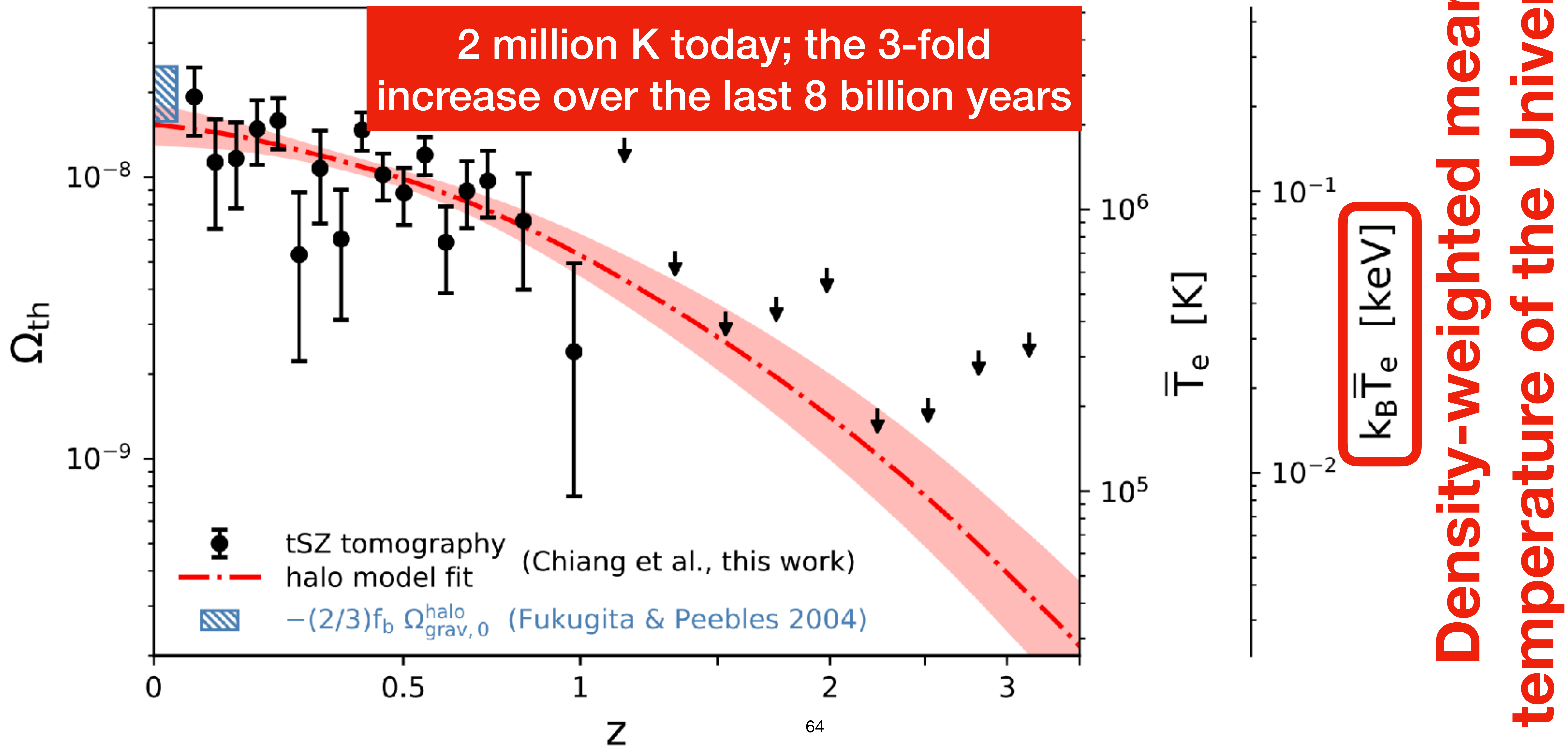
- This map gives us all the hot electron pressure **in projection**.
    - No redshift information.
- We can overcome this limitation by cross-correlating the SZ map with the locations of galaxies with the known redshifts => **the SZ tomography**.

Chiang et al. (2020)

$$\Omega_{\rm th}(z) = 1.78 \times 10^{-8}\ \frac{k_{\rm B}\bar{T}_\rho(z)}{0.2\ {\rm keV}}\frac{\Omega_{\rm b}}{0.049}$$

The main result

The mean thermal energy density of the Universe!



Chiang, Makiya, EK, Ménard, ApJ, 910, 32 (2021)

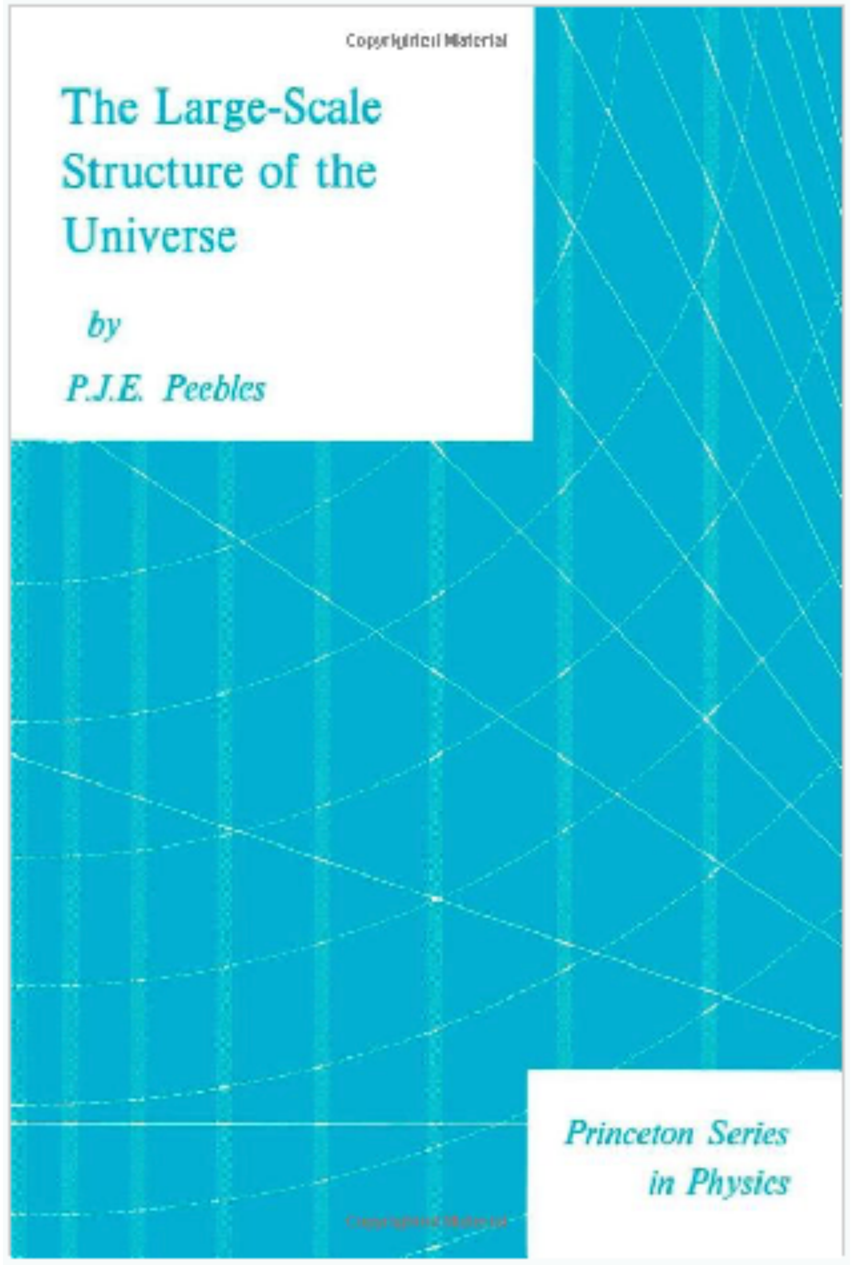
Q2: Where did the thermal energy come from?

Of course you know the answer.

Open any textbook!

- You can find a statement like, "*As the large-scale structure forms and the matter density fluctuation collapses, the gravitational energy is converted into the thermal energy via a shock.*"
  - Yes, of course this picture is correct. However, how much do we know about this energy conversion **quantitatively**?
  - To my knowledge, no quantitative assessment of this statement has been made before.
- Our approach: We have measured Ω_{th}. We can calculate Ω_{grav} using theory of the structure formation. Let's compare the two and see if they make sense.

The "W": Gravitational potential energy per unit mass



Considering a system of mass M consisting of particles with mass m_i, such that $M = \sum_i m_i$,

$$MW = -\frac{1}{2}a^3\rho_{\rm m}(a)\int d^3x\ \delta(\mathbf{x},a)\phi(\mathbf{x},a)$$

$$= -\frac{1}{2}Ga^5\rho_{\rm m}^2(a)\int d^3x\int d^3x'\ \frac{\delta(\mathbf{x},a)\delta(\mathbf{x}',a)}{|\mathbf{x}-\mathbf{x}'|}$$

- The ensemble average is given by the density-potential cross power spectrum:

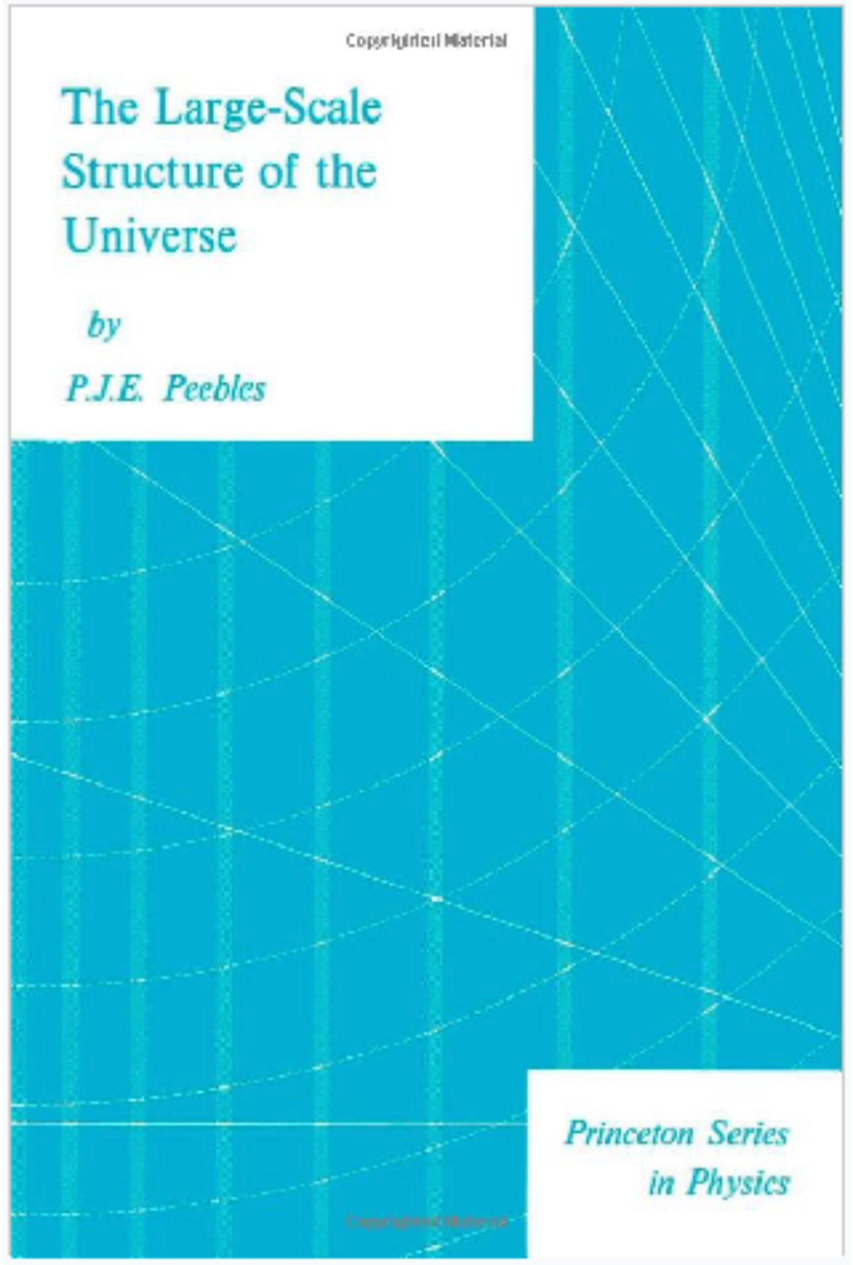
$$MW = -\frac{1}{2}\rho_{\rm m0}\left(\int d^3x\right)\int\frac{d^3k}{(2\pi)^3}P_{\phi\delta}(k,a)$$

$$M = \rho_{\rm m0}\int d^3x$$

With the Poisson equation:

$$P_{\phi\delta}(k,a) = -4\pi G\frac{\rho_{\rm m0}}{a}\frac{P(k,a)}{k^2}$$

The "W": Gravitational potential energy per unit mass



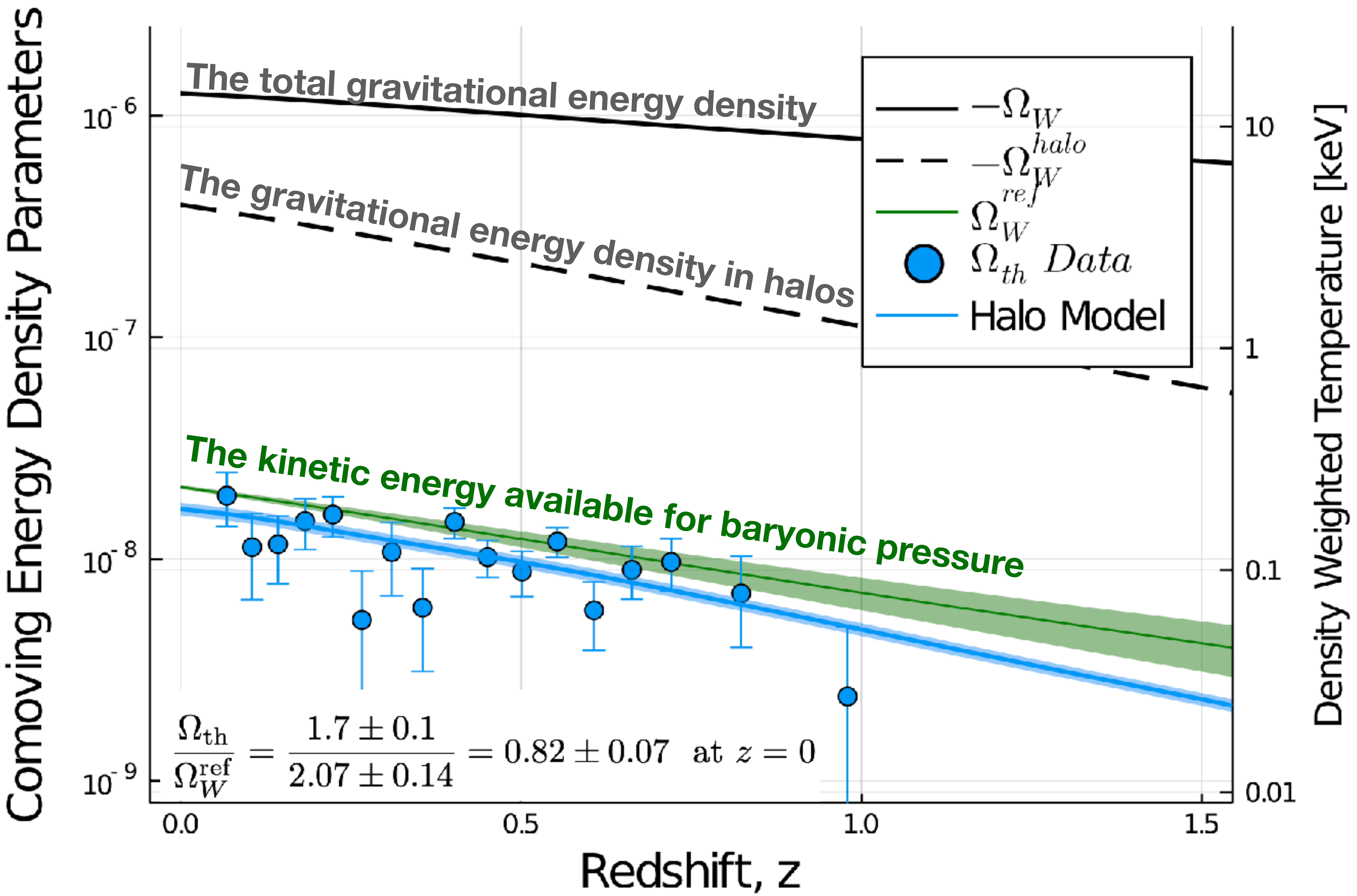
Considering a system of mass M consisting of particles with mass m_i, such that $M = \sum_i m_i$,

$$MW = -\frac{1}{2}a^3\rho_{\rm m}(a)\int d^3x\ \delta(\mathbf{x},a)\phi(\mathbf{x},a)$$

$$W = -\frac{3\Omega_{\rm m}H_0^2}{8\pi^2 a}\int_0^\infty {\rm d}k\ P(k,a)$$

This is the exact formula for W (in the Newtonian limit).

The Energy Balance in the Large-scale Structure



The energy density parameter for W:

$$\Omega_W = \frac{\Omega_{\rm m}}{c^2} W$$

The halo contribution:

$$\frac{\Omega_W^{\rm halo}}{\Omega_W^{\rm tot}} \simeq 0.3 \quad \text{at } z = 0$$

Pressure available for baryons

$$\Omega_W^{\rm ref} = -\frac{1}{3} f_{\rm b}\, \Omega_W^{\rm halo}$$

Conclusion from the second part

The energy balance does work, but where is the rest of the K.E.?

- We can now make the following statement:
  - The measured thermal energy density accounts for ~80% of the gravitational potential energy available for kinetic energy of collapsed baryons.
  - **This is the first quantitative assessment** of the textbook statement on gravitational -> thermal energy conversion in the large-scale structure formation (using the observational data).
- **What is the rest (~20%)?** => Non-thermal pressure due to the mass accretion! [Shi and EK (2014); Shi et al. (2015; 2016)]
- There is a lot more (x3) kinetic energy available in the LSS beyond collapsed baryons. **Where/how can we find it?** Kinetic SZ effect?

Young, EK, Dolag, PRD, 104, 038538 (2021)

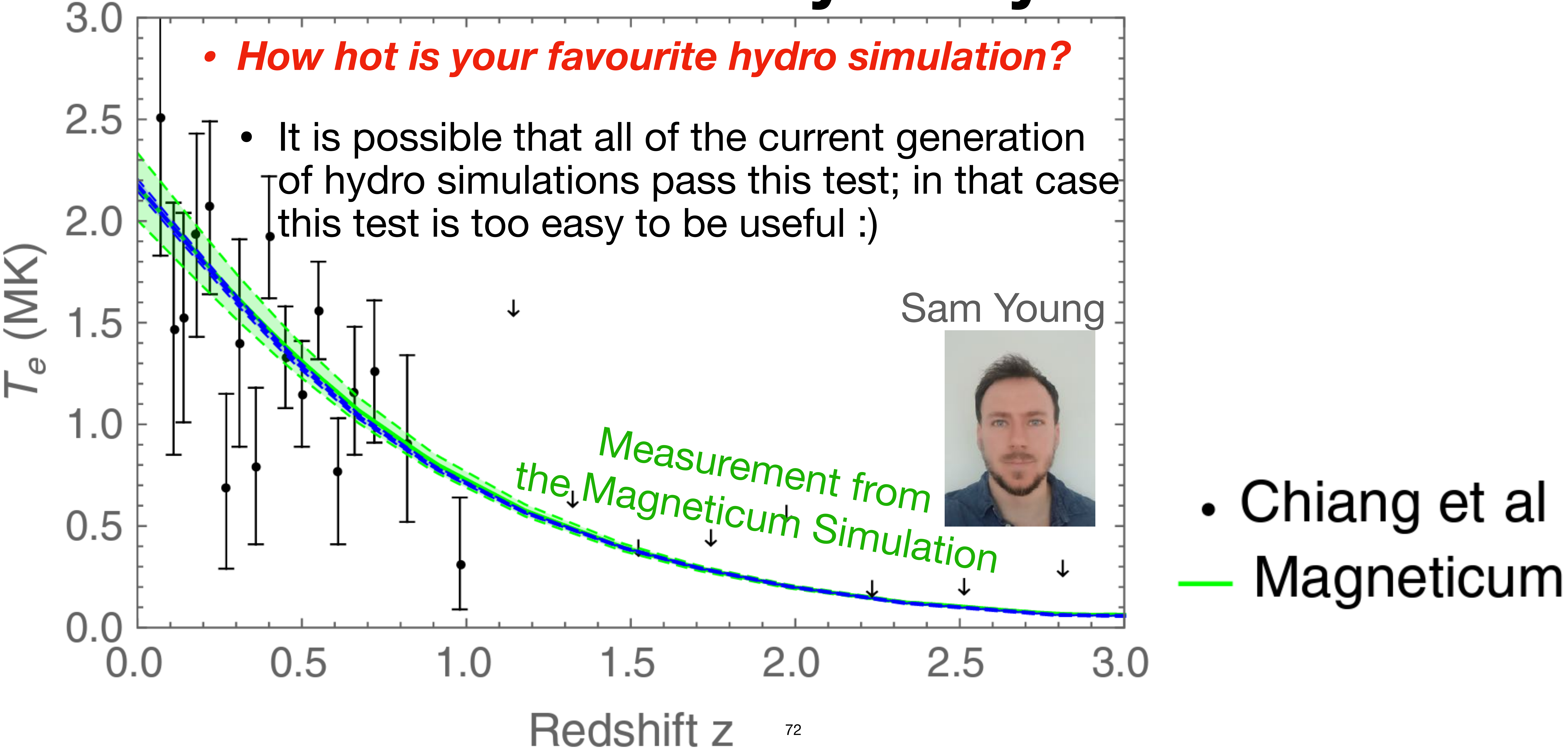
Q3: Is this good for anything?

Is this just beautiful physics, or actually useful for anyone?

Young, EK, Dolag, PRD, 104, 038538 (2021)

"Thermometer" test of your hydro simulation

- ***How hot is your favourite hydro simulation?***
- It is possible that all of the current generation of hydro simulations pass this test; in that case this test is too easy to be useful :)



HETDEX has arrived.

HETDEX: On the origin of extended Lyα halos

Idea → Data

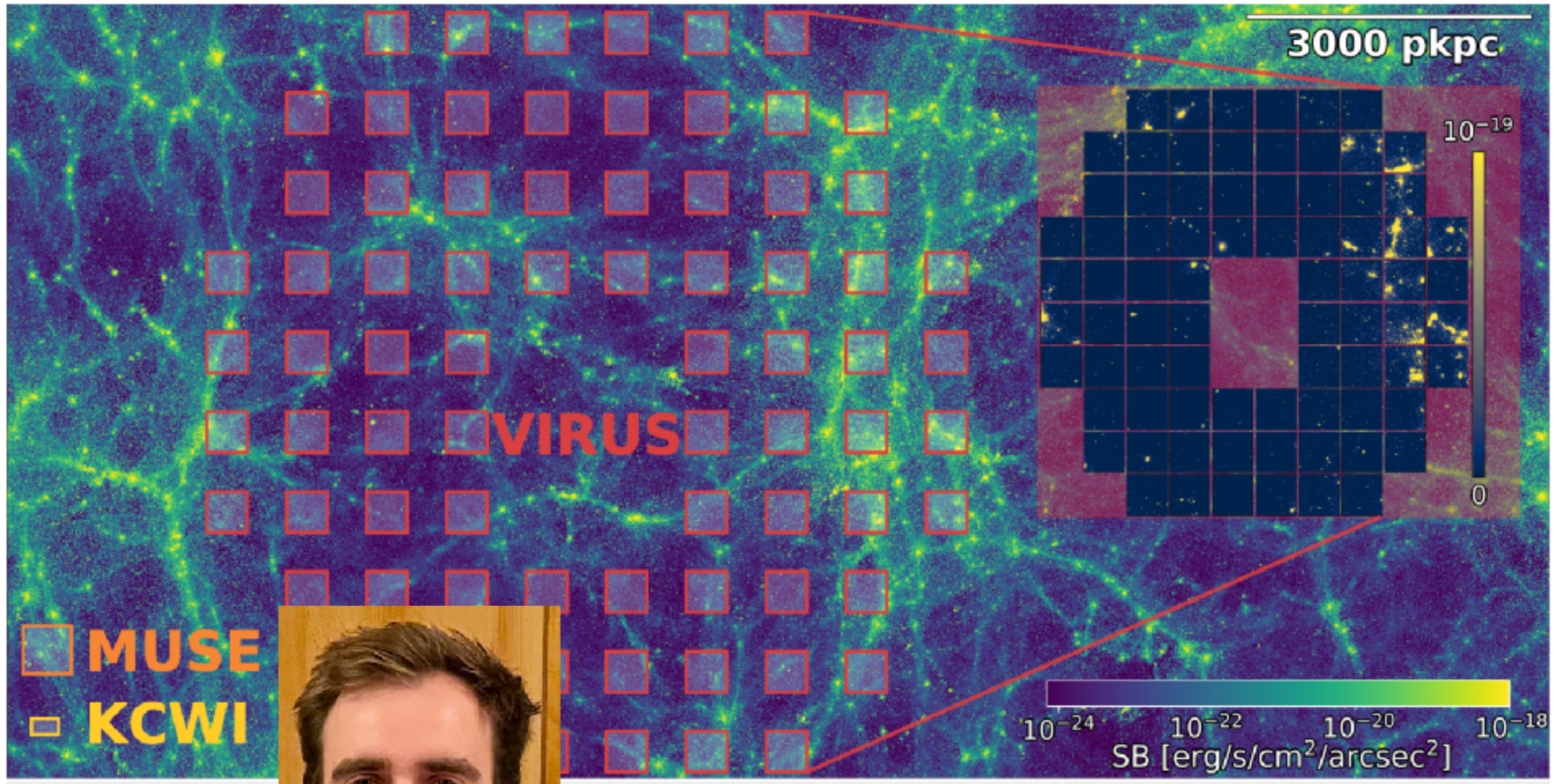
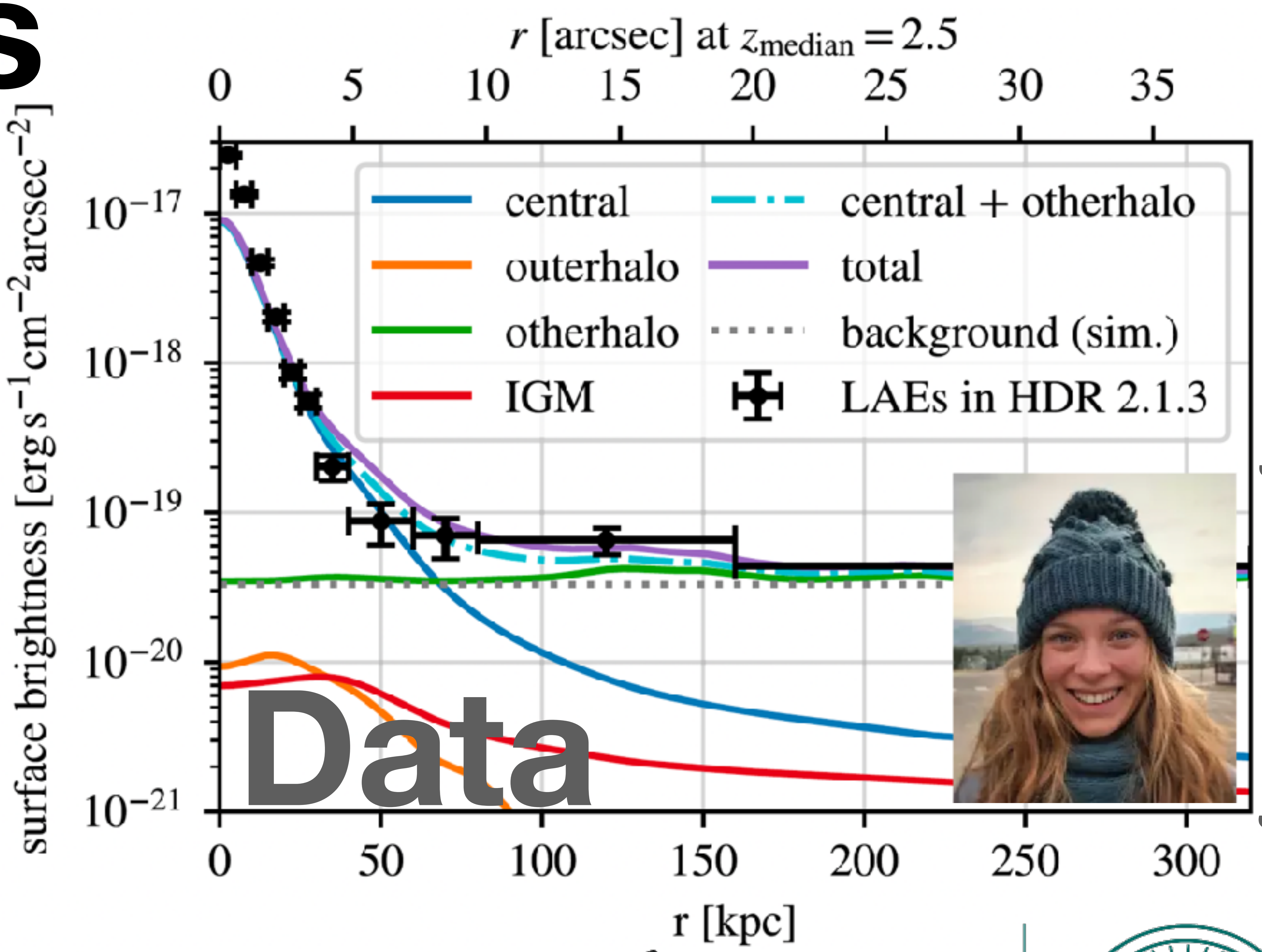


Figure 1: Simulated Lyα … at z=2.0 for a slice depth of 5.7Å in the observed frame with the footprints of VIRUS,

Chris Byrohl

Simulation



Data

Maja L. Niemeyer

- *Byrohl, et al., MNRAS, 506, 5129 (2021)*
- *Niemeyer, EK, Byrohl, et al., ApJ, 929, 90 (2022)*
- *Niemeyer, et al., ApJ Letters, 934, L26 (2022)*

MAX-PLANCK-INSTITUT FÜR ASTROPHYSIK

Monthly Highlight Oct. 2022

Galaxies light up hydrogen halos around neighbouring galaxies

OCTOBER 01, 2022

Galaxies are embedded in large reservoirs of gas - mostly hydrogen and helium. This hydrogen gas has been found to glow faintly in a specific ultraviolet wavelength, or color, called Lyman-alpha. Scientists at the MPA have discovered that these Lyman-alpha halos are larger than previously thought, spanning several 100,000 light years. The inferred size and shape of the halos suggest that the light in the outer parts of the halos comes from surrounding galaxies or the gas in their environments rather than from the central galaxy itself.

Stars only account for 10% of the visible matter in the universe. The rest is mostly comprised of hydrogen and helium gas distributed in, around, and in between galaxies, called *interstellar*, *circumgalactic* and *intergalactic media*, respectively. The *circumgalactic* gas (CGM) is in close interaction with the galaxies. Cold gas streaming into galaxies enables star formation, while supernovae and actively accreting supermassive black holes heat up the gas and push it out of the galaxy. This complex interplay between the galaxies and the CGM is crucial for the evolution of the galaxies. Hence scientists are highly interested in the composition and dynamics of the CGM.

However, the gas outside of galaxies is dark and difficult to observe. Through long-exposure observations and statistical averaging, scientists have discovered a faint ultraviolet glow of the hydrogen gas around galaxies around the so-called cosmic noon, the epoch of peak star formation (roughly 11 billion years ago). More precisely, the gas is lit up in one specific wavelength, the so-called Lyman-alpha wavelength. These Lyman-alpha halos appear around different kinds of galaxies, including both Lyman-alpha bright and Lyman-alpha faint galaxies.

Author

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Large-scale structure survey with HETDEX

Simple: We tile the sky with lots of pointings with no-preselection

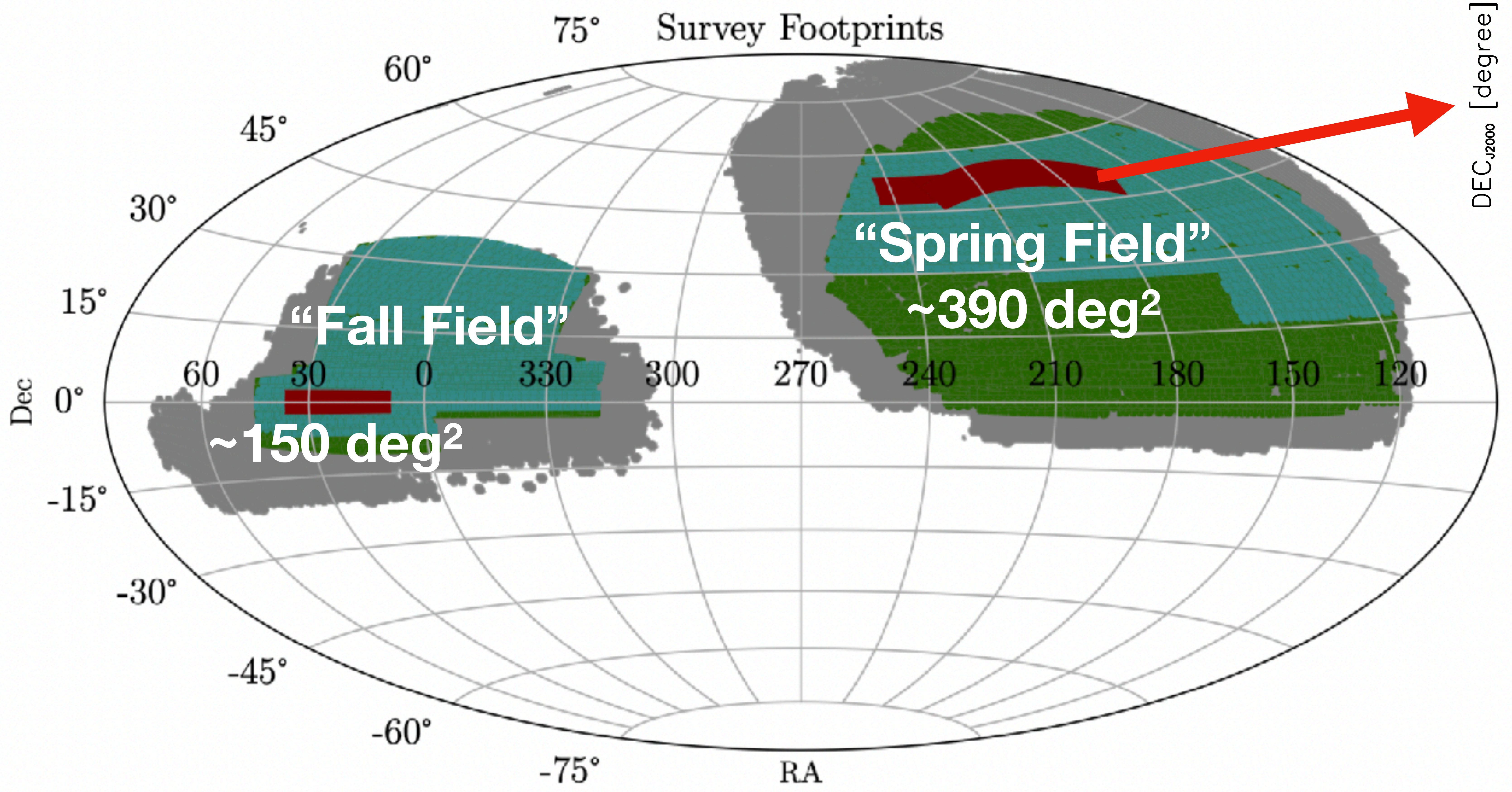
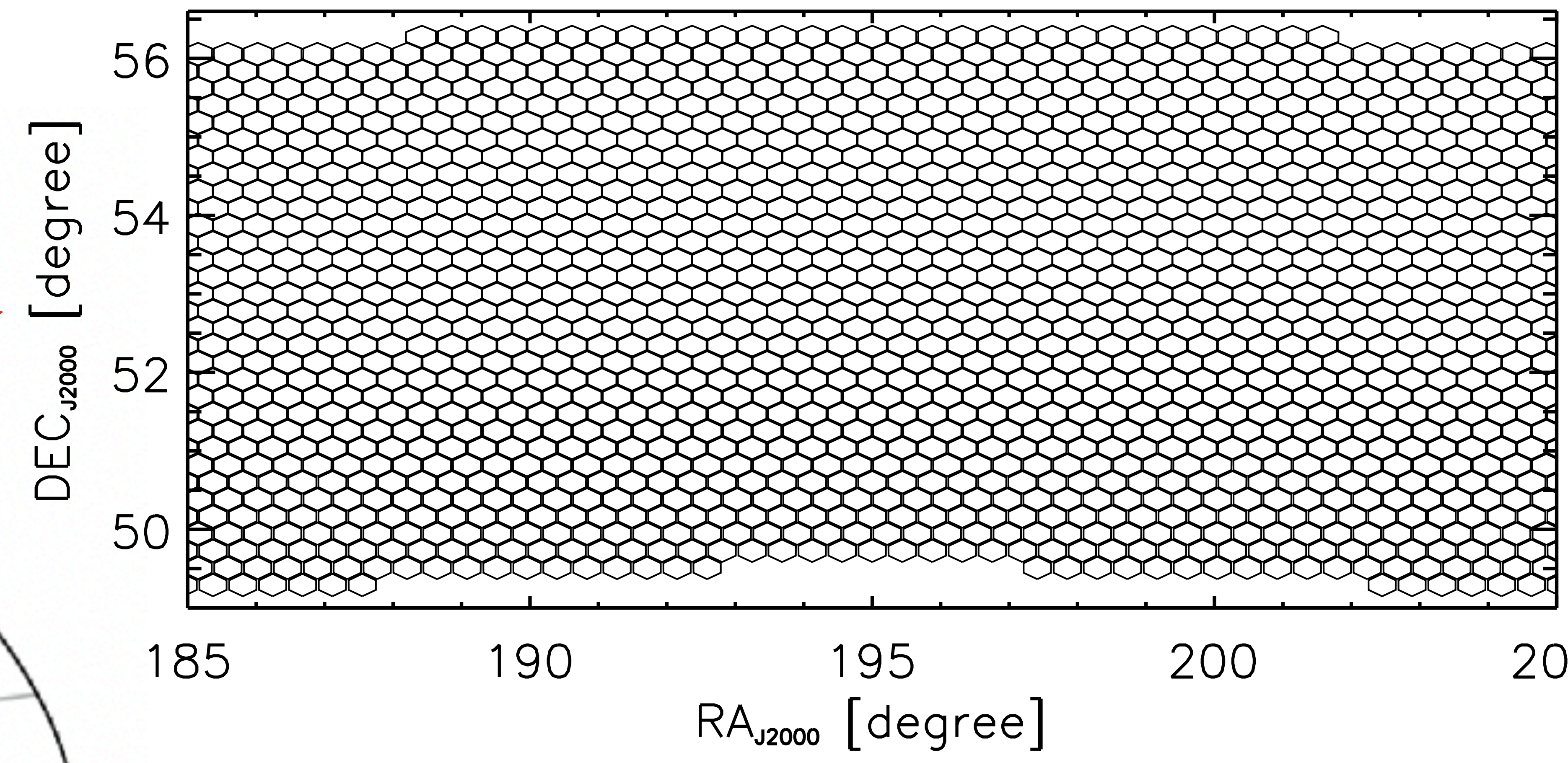


Figure 1. The HETDEX field compared to overlapping large-area surveys. The red regions display the 540 deg^2 baseline fields of HETDEX. The Green, Cyan and Gray areas show, respectively, the BOSS (Dawson et al. 2013), eBOSS (Dawson et al. 2016), and DESI (DESI Collaboration et al. 2016) footprints.



- *As of June 2022:*
  - 271K IFU observations x 448 fibers/IFU x 3 dithers = **364M spectra**
- **Goal:** 468K IFUs and **629M spectra.** Big data!

We take spectra of a lot of objects without pre-selection

Maja Lujan Niemeyer, EK, et al. (2022)

Stacking analysis of (a subset of) LAEs

HETDEX is ideal for this type of analysis

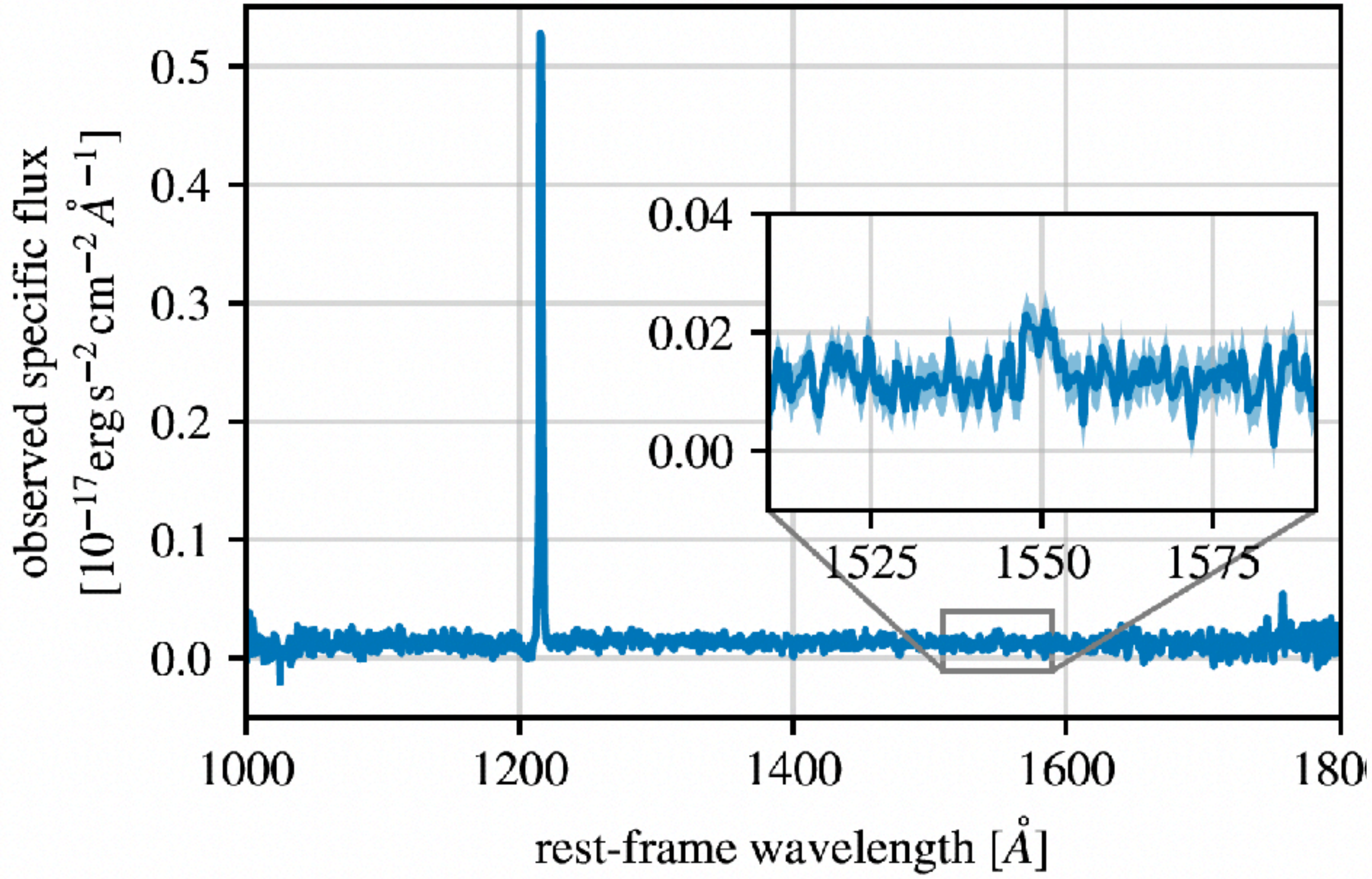


Figure 2. Median spectrum of the 968 LAEs

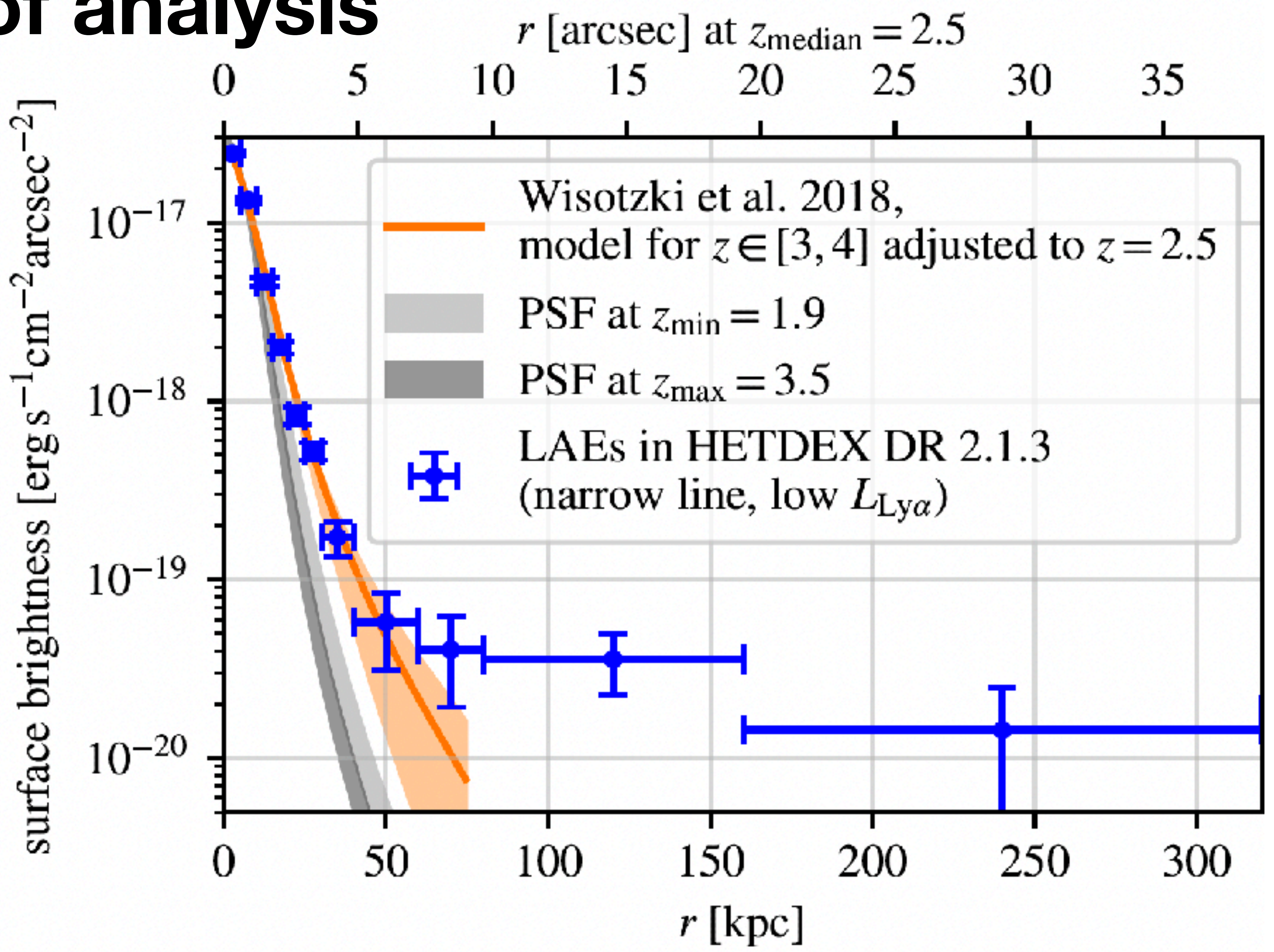


Figure 4. Left: Average Lyman-α surface brightness profile

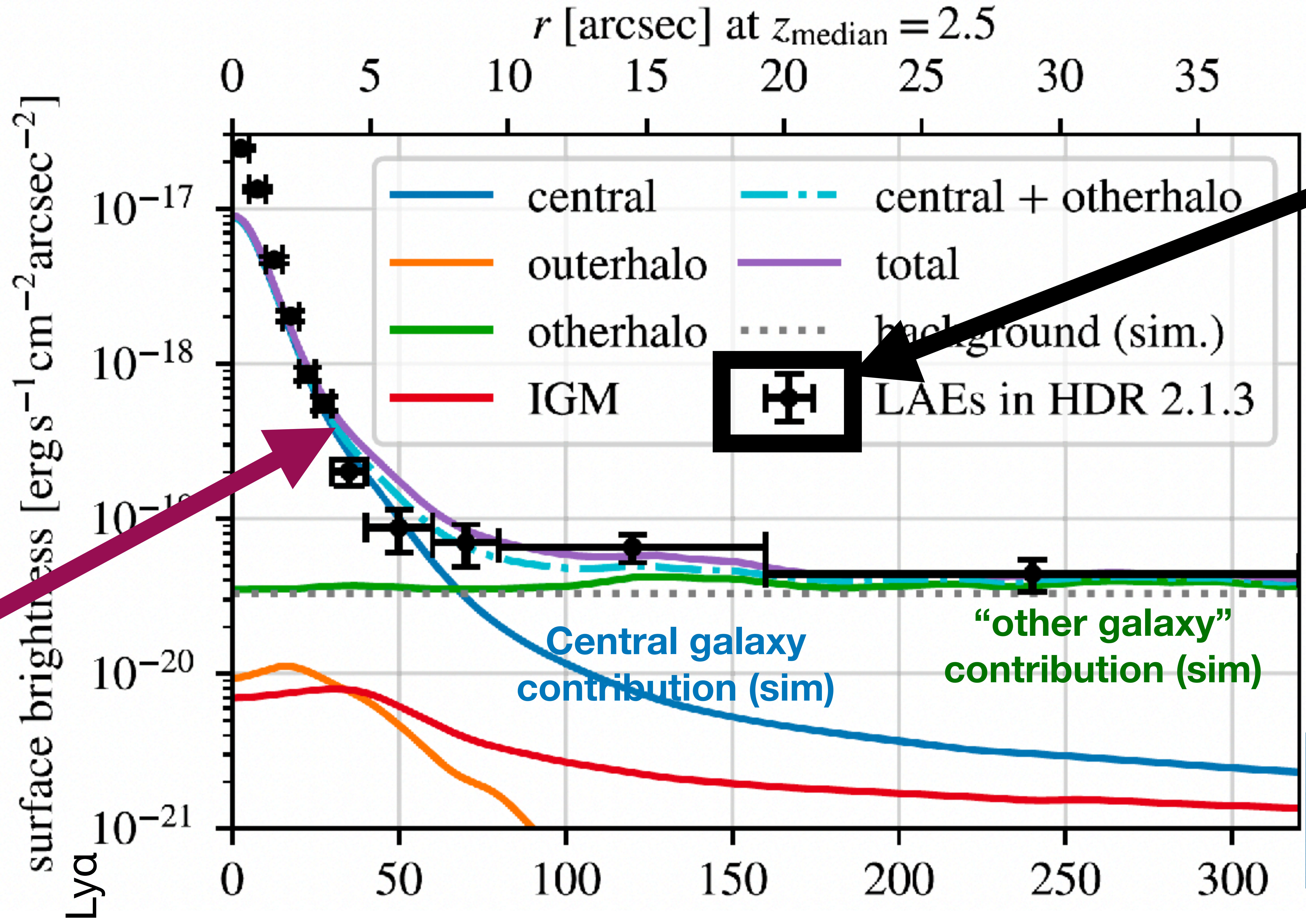
In the end we expect to detect one million LAEs!

Clear detection of very extended Lyman-alpha emission out to 160 kpc!

Maja Lujan Niemeyer, EK, et al. (2022)

The main origin of extended Lyman-alpha halo?

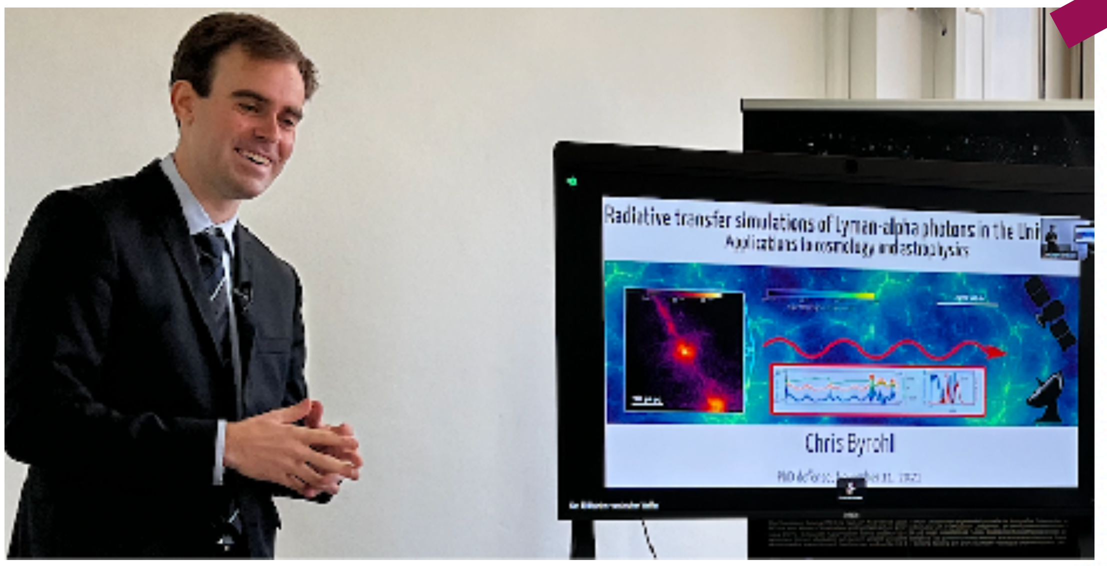
- *The answer depends on radii from the central galaxy!*

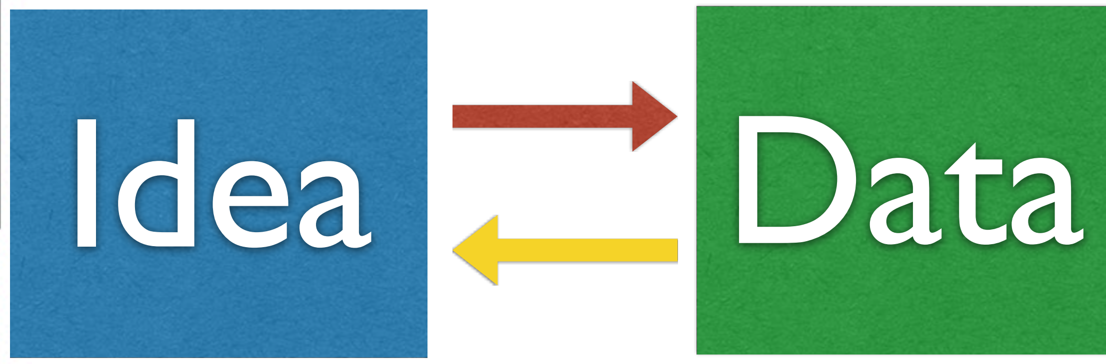


Physical distance in kpc from the center of stacked galaxies

Maja Lujan Niemeyer

Chris Byrohl
(Former PhD student;
Postdoc@Heidelberg)



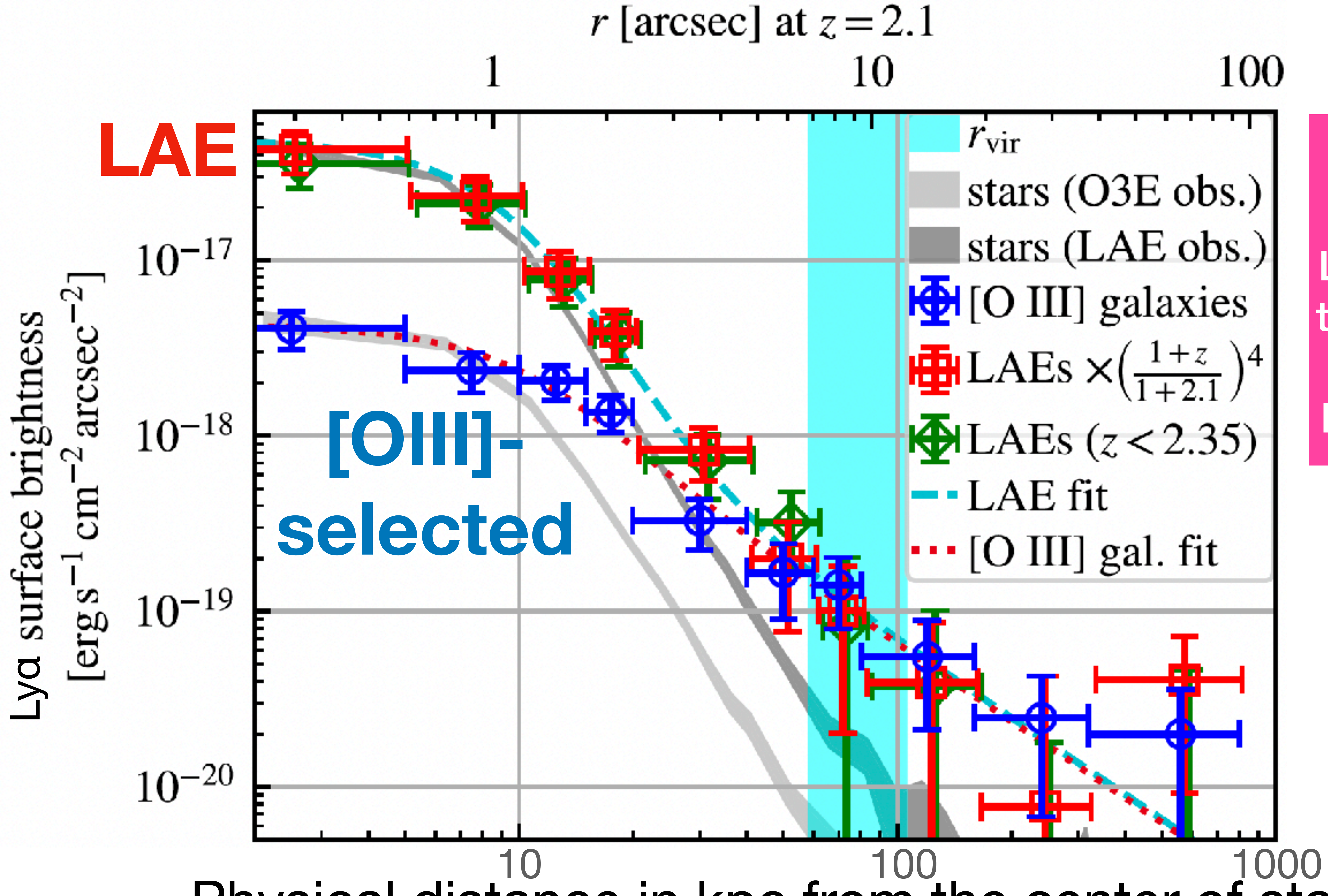


THE ASTROPHYSICAL JOURNAL LETTERS, 934:L26 (6pp), 2022 August 1 https://doi.org/

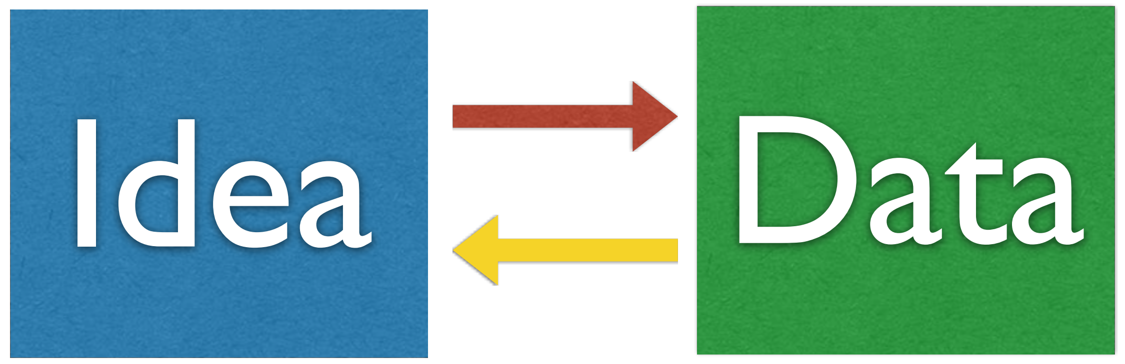
A Proof?

Lyα Halos around [O III]-selected Galaxies in HETDEX

Maja Lujan Niemeyer[1], William P. Bowman[2,3], Robin Ciardullo[2,3], Max Gronke[1], Eiichiro



LAEs and [OIII]-selected galaxies have very different Lyman-alpha brightness near the center, but the same level of the Lyman-alpha brightness in the outer parts.



Idea → Data

Resolving the Hubble Tension with Early Dark Energy

- *Herold, Ferreira, EK, ApJ Letters, 929, L16 (2022)*
- *Herold, Ferreira, submitted to PRL, arXiv:2210.16296*

Laura Herold

Elisa Ferreira

MAX-PLANCK-INSTITUT
FÜR ASTROPHYSIK

Relieving the Hubble tension with Early Dark Energy

AUGUST 01, 2022

Different measurements of the Hubble constant, the current expansion rate of our universe, show a discrepancy known as the Hubble tension. This could hint towards new physics beyond the standard model of cosmology. Using a complementary statistical method, researchers at MPA now narrow down possible new physics in the early universe and constrain the fraction of a proposed new component: early dark energy.

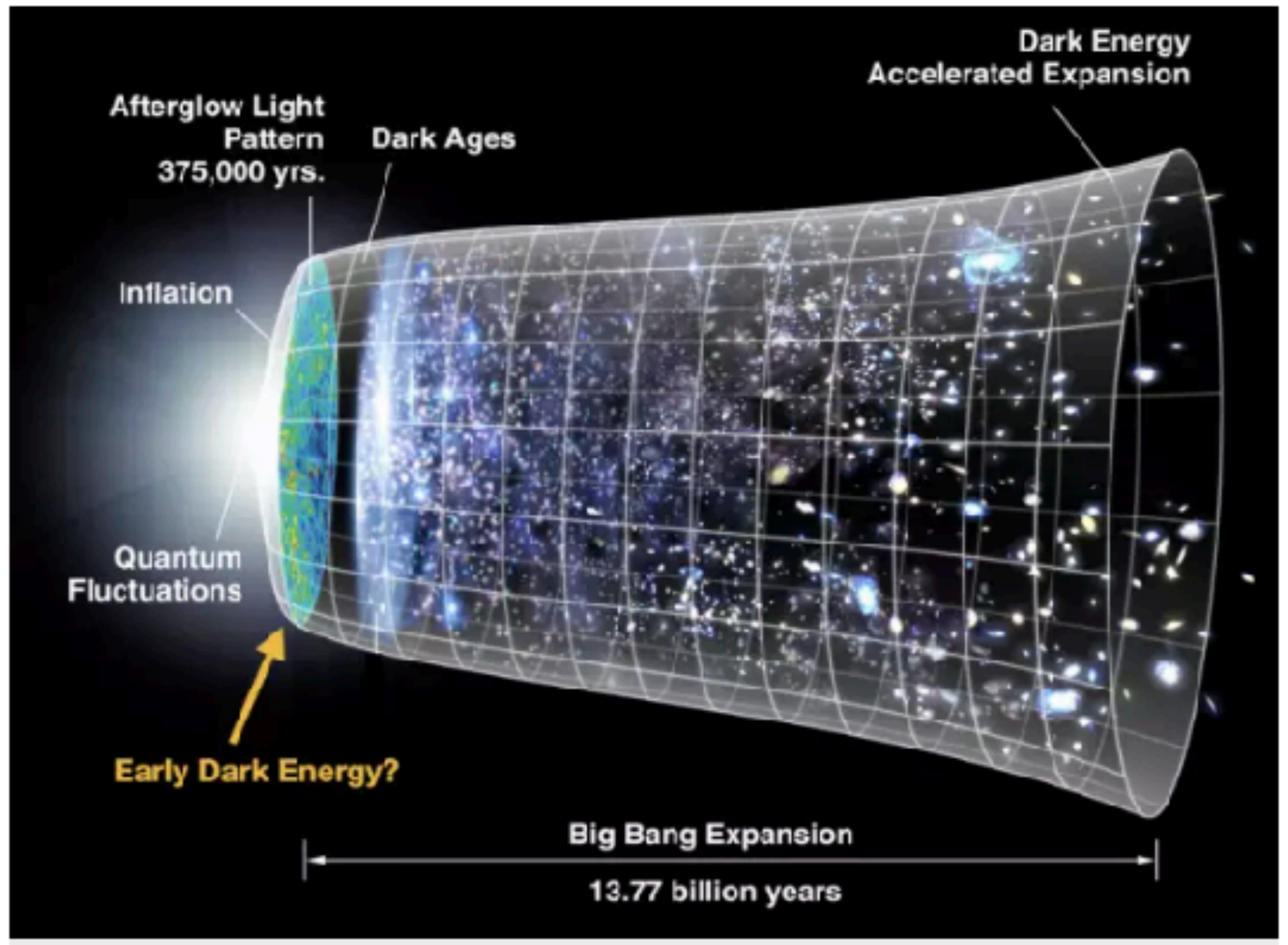


Fig 1: History of the universe: early dark energy could influence the expansion history in the early universe.
Credit: NASA/WMAP Science Team (modified)

The universe is 13.8 billion years old – or is it really? The age of the universe is closely related to the so-called Hubble constant, which measures the current expansion rate of the universe. A higher Hubble constant means the universe expands faster and is therefore younger, while a more slowly expanding universe is older. Measurements of the Hubble constant have become more and more precise in recent years and revealed a puzzling observation: different experiments gave slightly different values of the Hubble constant and consequently different answers about how old our universe is. Could this discrepancy be a hint towards new physics beyond the standard model of cosmology?

If one measures the velocity of galaxies around us, one finds that the vast majority of galaxies observed on the night sky move away from our galaxy, the Milky Way – this is known as the Hubble-Lemaître law and it is direct evidence for the expansion of the universe: the space between all galaxies increases.

Author

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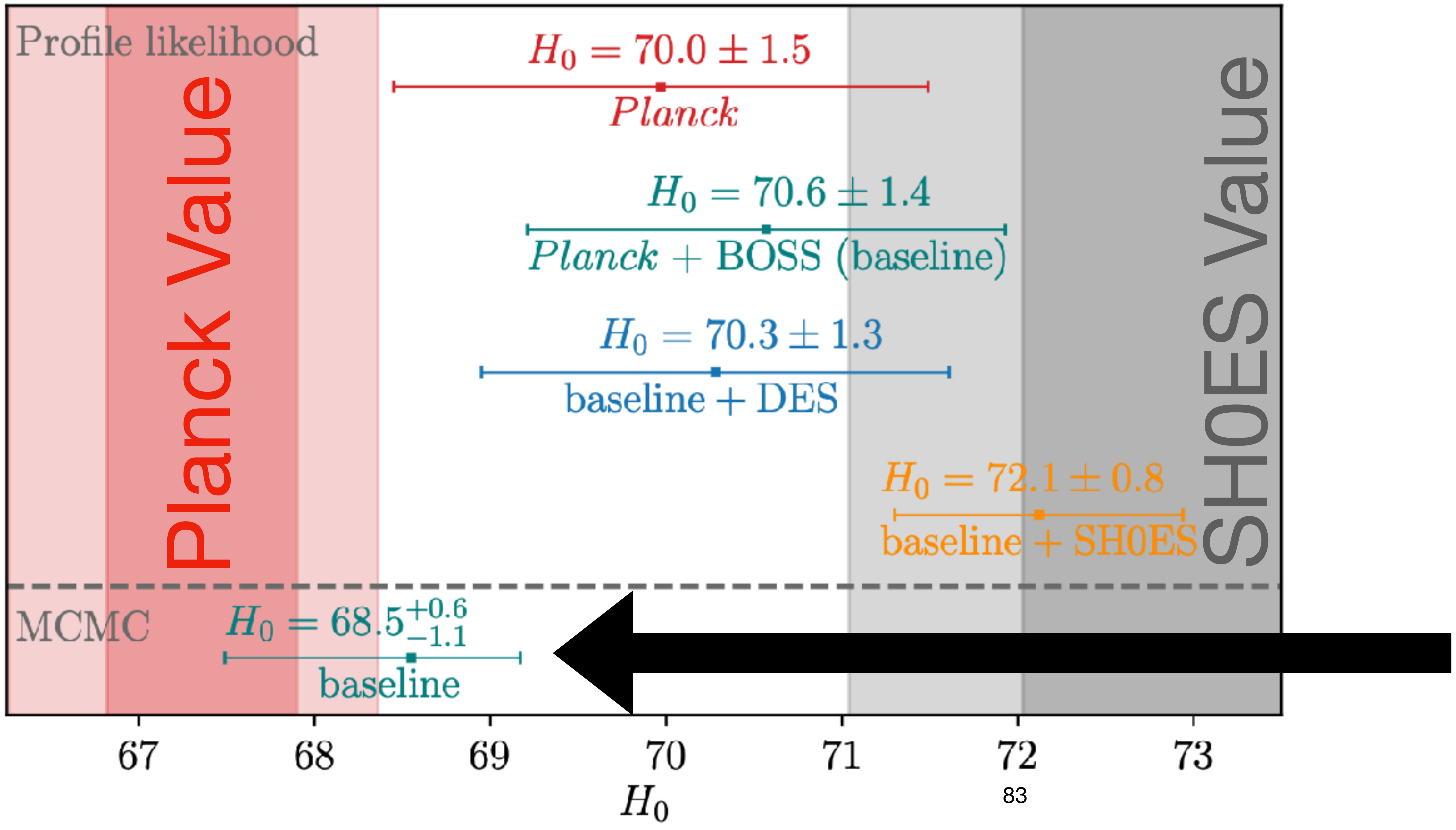
for the team: Elisa G. M. Ferreira, Eiichiro Komatsu

Long story short…

Laura and Elisa have settled the debate in the community.

- **Yes, Early Dark Energy can resolve the Hubble tension.**

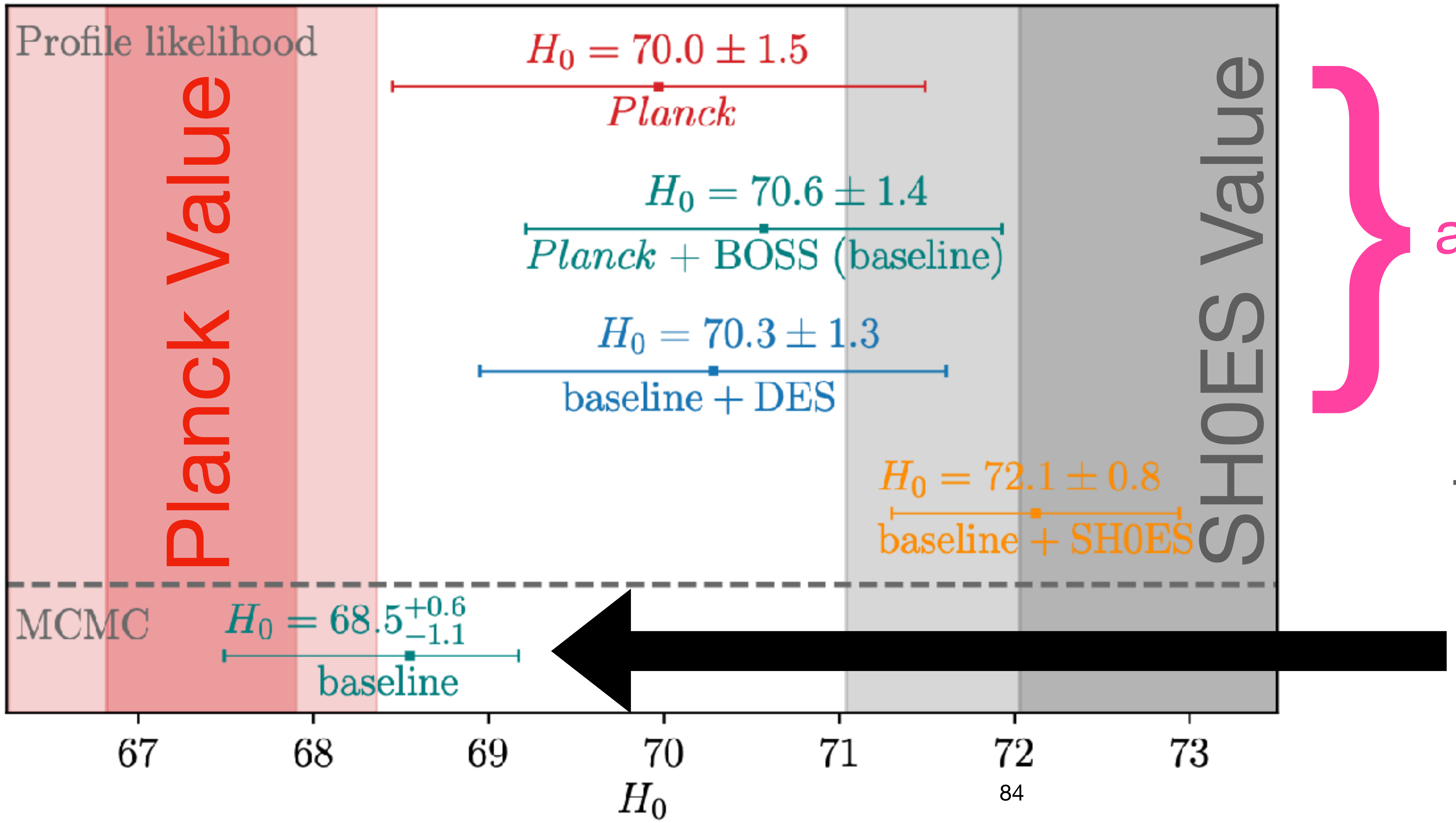


The standard Markov Chain Monte Carlo (MCMC) analysis suffers from the effect known as "prior volume effect".

Long story short…

Laura and Elisa have settled the debate in the community.

- **Yes, Early Dark Energy can resolve the Hubble tension.**

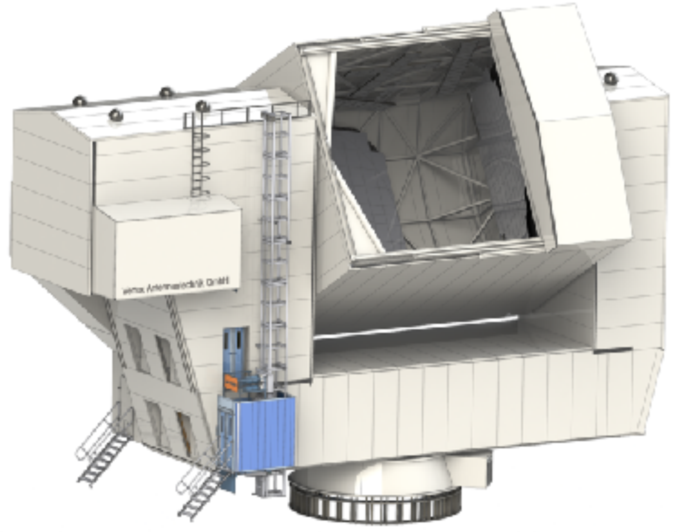


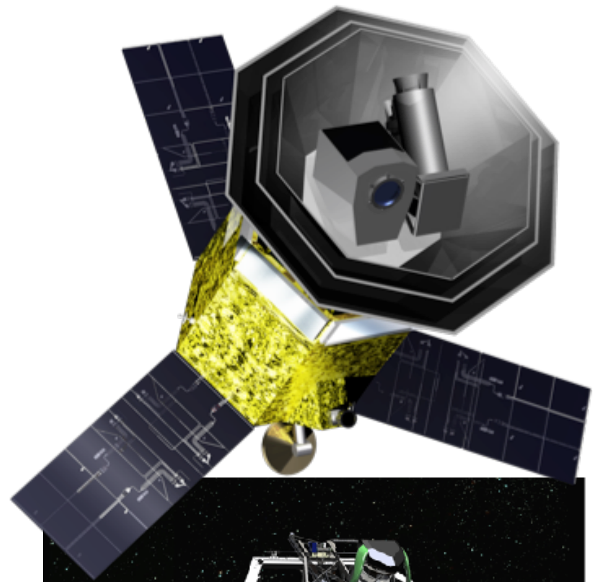
The "profile likelihood" analysis avoids the volume effect in MCMC.

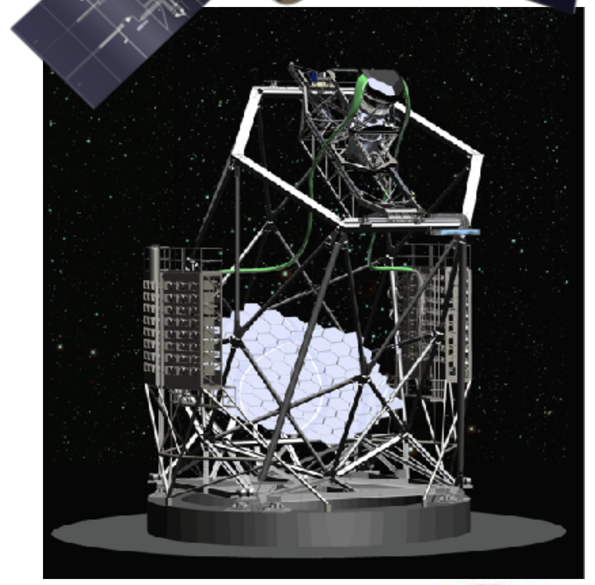
The standard Markov Chain Monte Carlo (MCMC) analysis suffers from the effect known as "prior volume effect".

Vision: Summary

Let's find new physics!







- Over the next decade, I wish to make significant contributions to the search for new physics.

CMB

- Discovery of new parity-violating physics
- Discovery of (parity-violating) primordial gravitational waves

- Rule out ΛCDM!

LSS

- Cosmological tension is already a hint?
- Determination of the neutrino mass

- "*Doing whatever we find interesting at the time*" has been effective, which was made possible by stable funding of the Max Planck Society.

Back up slides

The past measurements

The quoted uncertainties are all statistical only (68%CL)

- $\alpha+\beta = -6.0 \pm 4.0$ deg (Feng et al. 2006) first measurement
- $\alpha+\beta = -1.1 \pm 1.4$ deg (WMAP Collaboration, Komatsu et al. 2009; 2011)
- $\alpha+\beta = 0.55 \pm 0.82$ deg (QUaD Collaboration, Wu et al. 2009)
- …
- $\alpha+\beta = 0.31 \pm 0.05$ deg (Planck Collaboration 2016)
- $\alpha+\beta = -0.61 \pm 0.22$ deg (POLARBEAR Collaboration 2020)
- $\alpha+\beta = 0.63 \pm 0.04$ deg (SPT Collaboration, Bianchini et al. 2020)
- $\alpha+\beta = 0.12 \pm 0.06$ deg (ACT Collaboration, Namikawa et al. 2020)
- $\alpha+\beta = 0.07 \pm 0.09$ deg (ACT Collaboration, Choi et al. 2020)

Why not yet discovered?

The past measurements

Now including the estimated systematic errors on α

- $\beta = -6.0 \pm 4.0 \pm$ **??** deg (Feng et al. 2006)
- $\beta = -1.1 \pm 1.4 \pm$ **1.5** deg (WMAP Collaboration, Komatsu et al. 2009; 2011)
- $\beta = 0.55 \pm 0.82 \pm$ **0.5** deg (QUaD Collaboration, Wu et al. 2009)
- …
- $\beta = 0.31 \pm 0.05 \pm$ **0.28** deg (Planck Collaboration 2016)
- $\beta = -0.61 \pm 0.22 \pm$ **??** deg (POLARBEAR Collaboration 2020)
- $\beta = 0.63 \pm 0.04 \pm$ **??** deg (SPT Collaboration, Bianchini et al. 2020)
- $\beta = 0.12 \pm 0.06 \pm$ **??** deg (ACT Collaboration, Namikawa et al. 2020)
- $\beta = 0.07 \pm 0.09 \pm$ **??** deg (ACT Collaboration, Choi et al. 2020)

Uncertainty in the calibration of α has been the major limitation

The basic methodology: A heuristic description

Vikram, Lids & Jain (2017)

- We focus on the clustering signal at large scales (the so-called “2-halo term” of clustering).
    - Ignore non-linear clustering inside dark matter halos, but focus only on clustering between distinct halos.
- In this limit, we can write $P_e = \langle P_e \rangle (1 + b_y \delta_{matter})$ and $n_{gal} = \langle n_{gal} \rangle (1 + b_{gal} \delta_{matter})$. Thus, the cross-correlation yields

$$\frac{\langle P_\mathrm{e} n_\mathrm{gal} \rangle}{b_\mathrm{gal} \langle n_\mathrm{gal} \rangle \langle \delta_\mathrm{matter} \delta_\mathrm{matter} \rangle} = b_y \langle P_\mathrm{e} \rangle$$

What we measure from the cross-correlation

What we want in the end

Measured from the auto galaxy correlation

From the ΛCDM model

The first key deliverable

How the measurements look

To show that we are in the "linear" regime

- The data within the grey band are used for the analysis, where the ratio is a constant, justifying the extraction of the single constant amplitude in each z bin.