DUNLAP INSTITUTE *for* ASTRONOMY & ASTROPHYSICS

Cosmology in 2025(6)

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Dunlap Institute for Astronomy and Astrophysics

David. A Dunlap Department of Astronomy and Astrophysics

HNAUTS

Dunlap Institute for Astronomy & Astrophysics
UNIVERSITY OF TORONTO

How did the Universe begin?

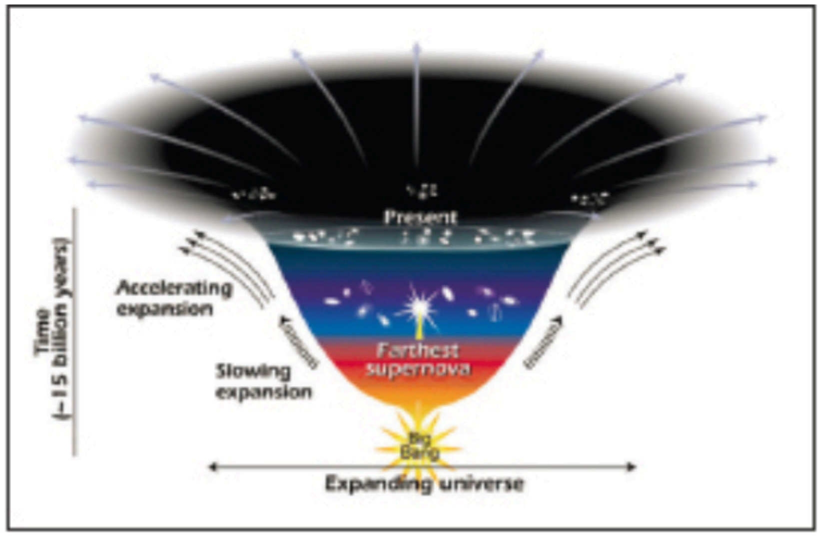
What is the Universe made of?

What sets how much dark matter there is in galaxies?

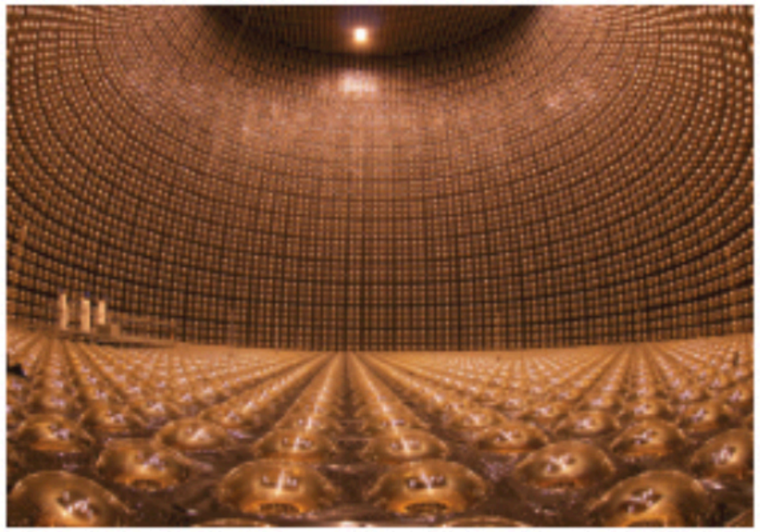
(What is dark matter anyway?)

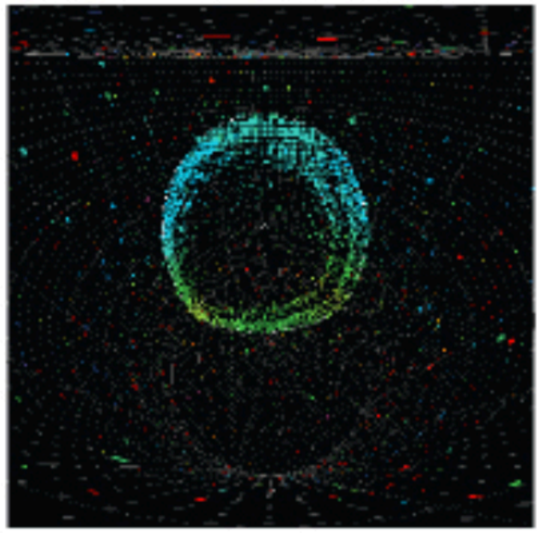
How is the Universe evolving and expanding?

2011

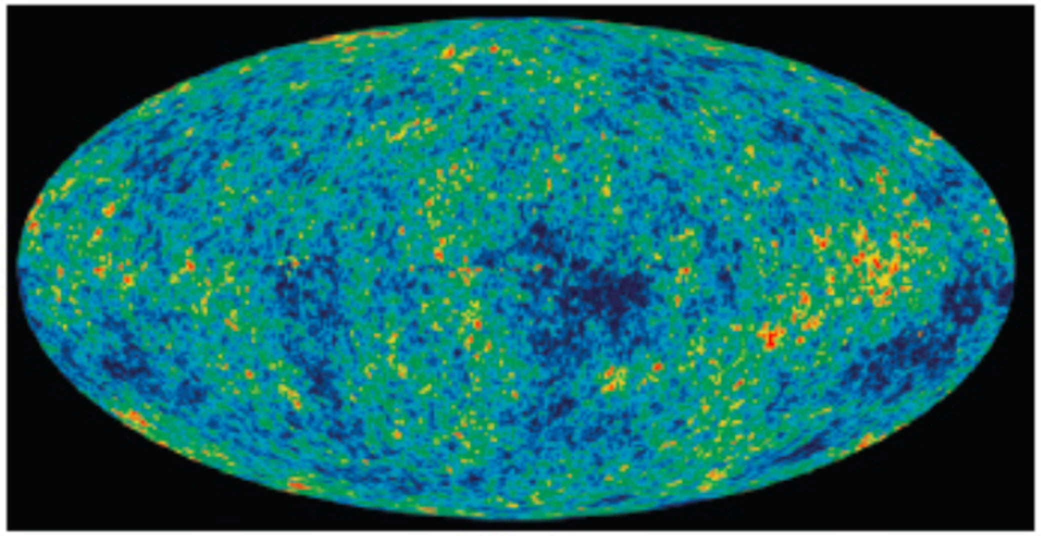


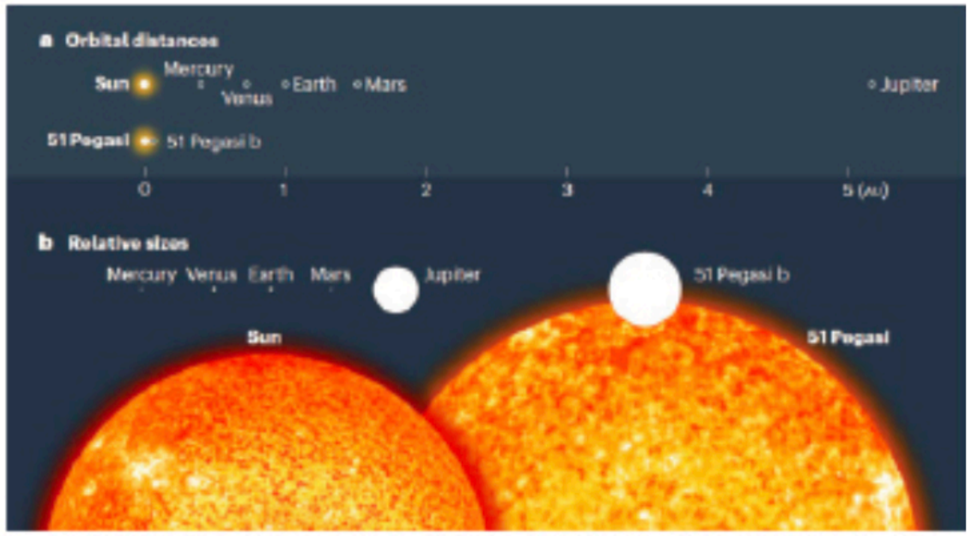
2015



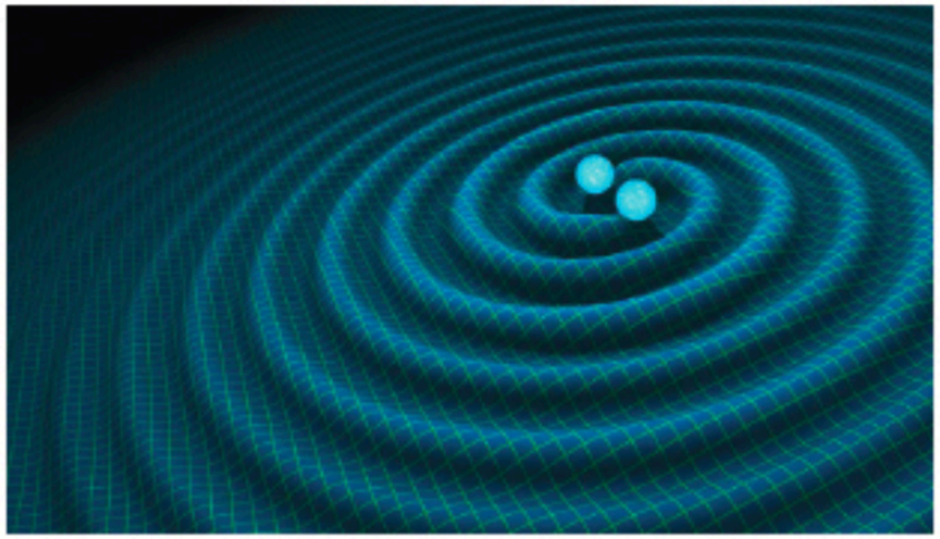


2019

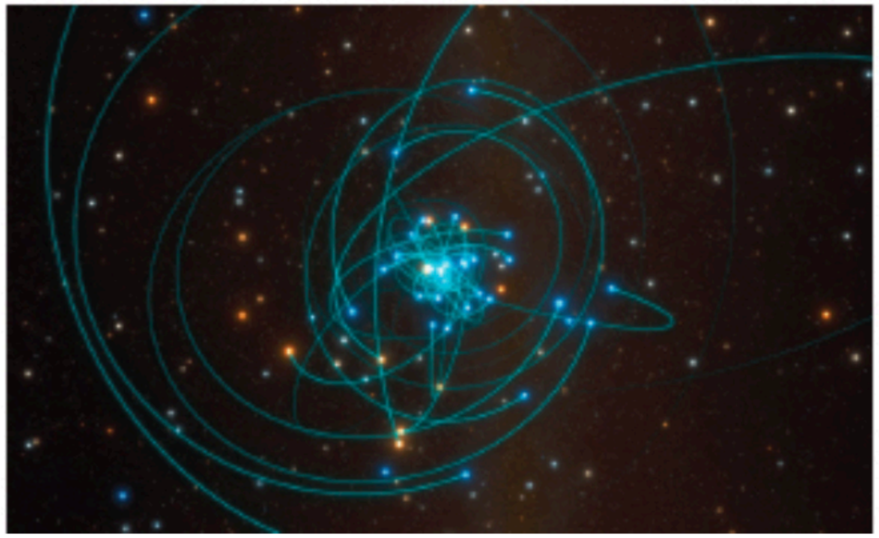




2017



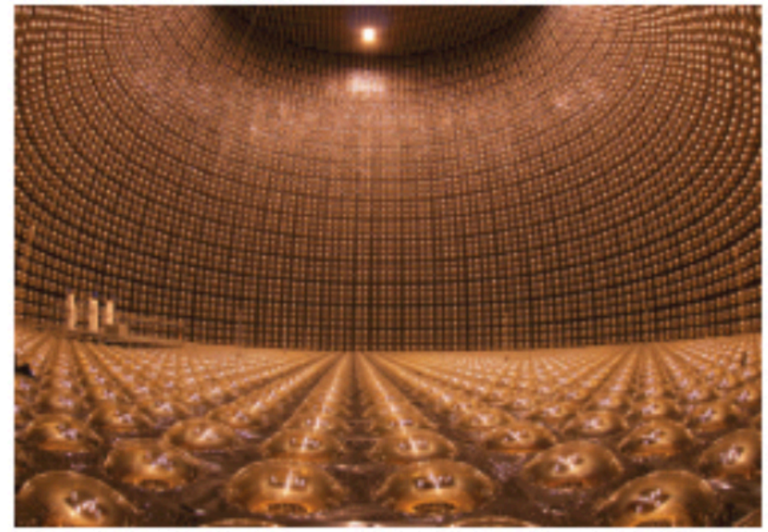
2020

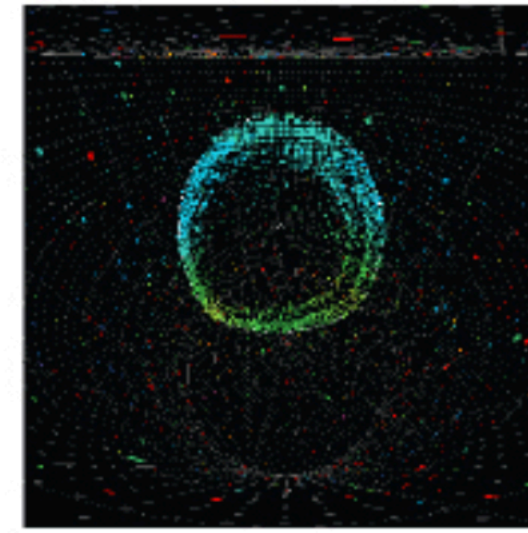


2011

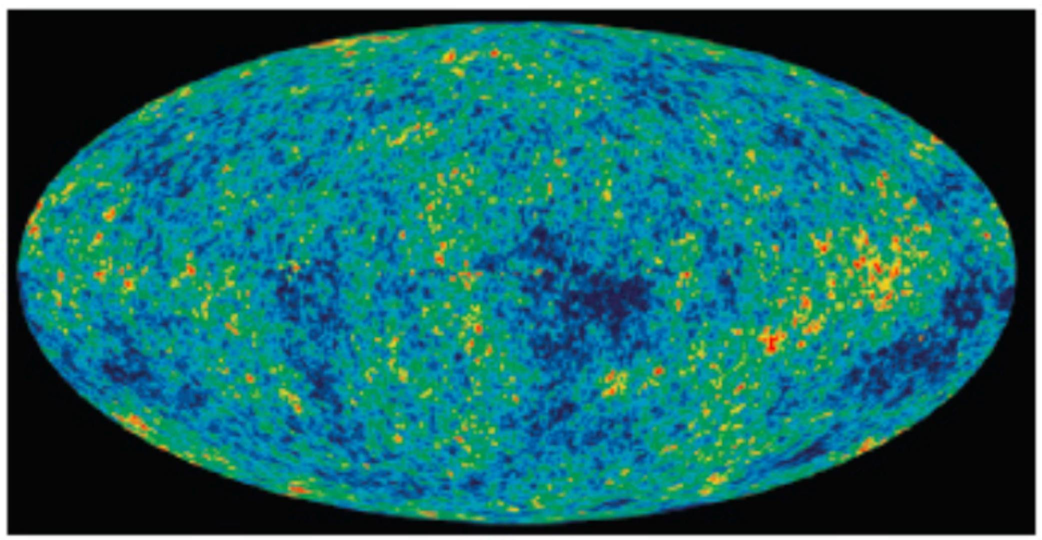
Cosmic Acceleration

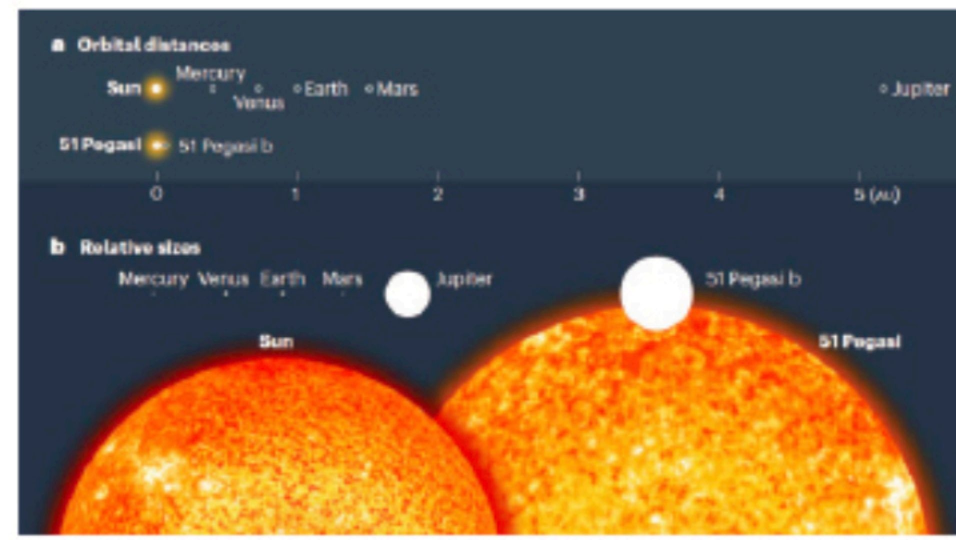
2015





2019





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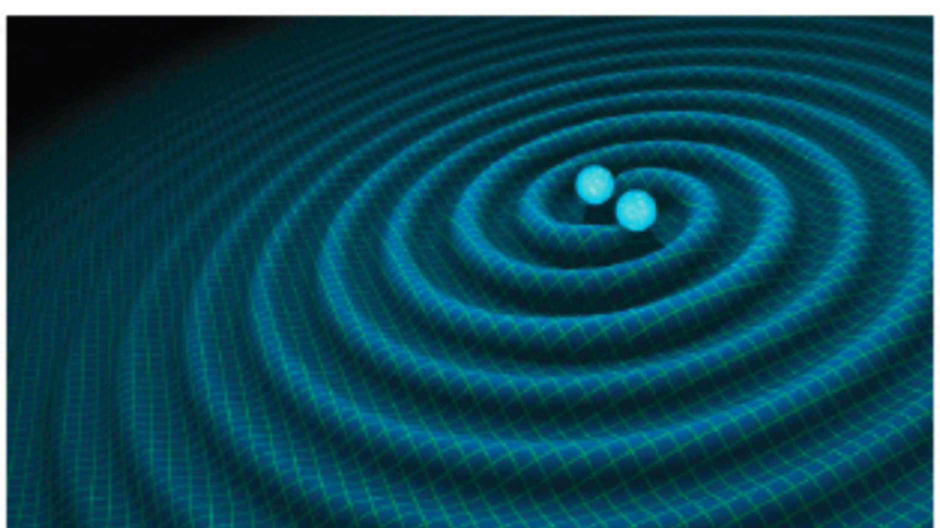
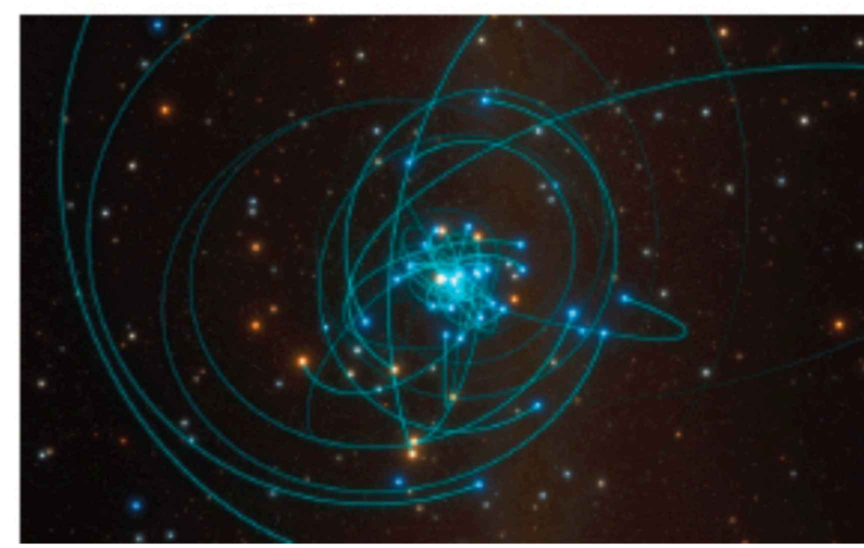


2020



2011

Cosmic Acceleration

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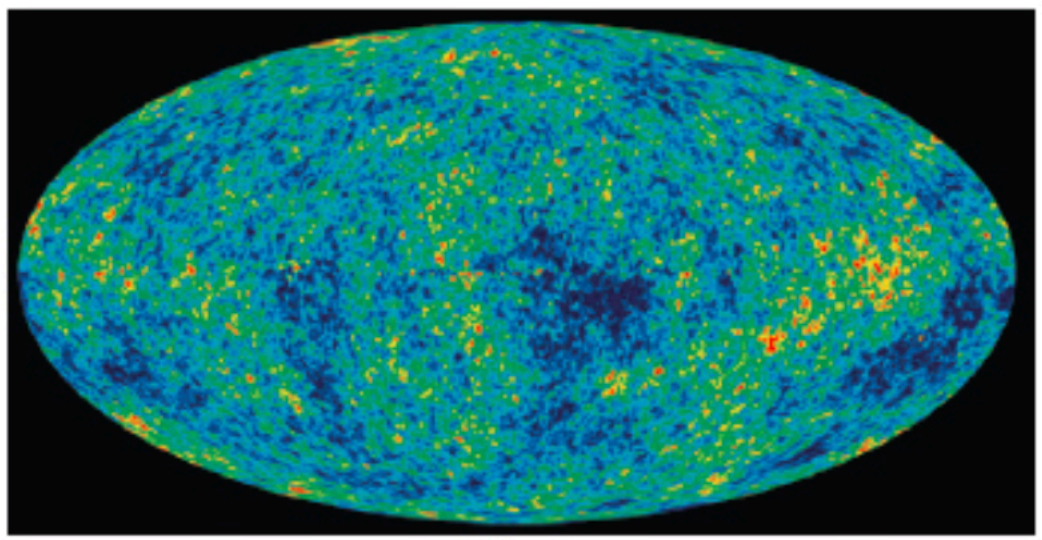
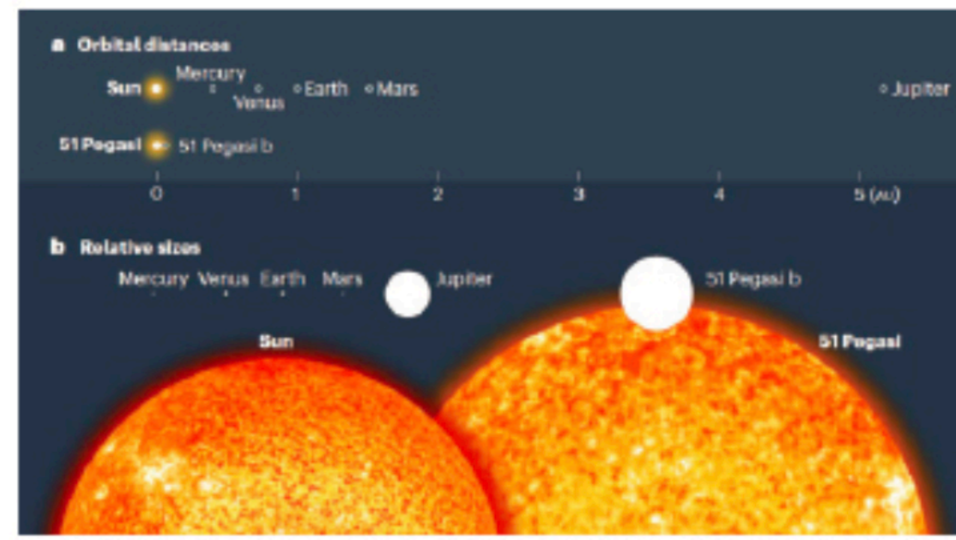
Neutrino Oscillations

2019





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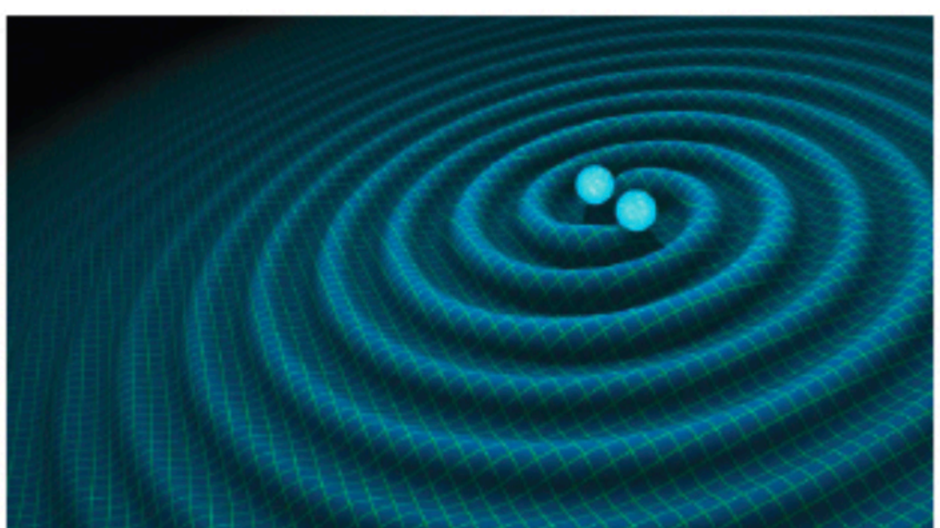
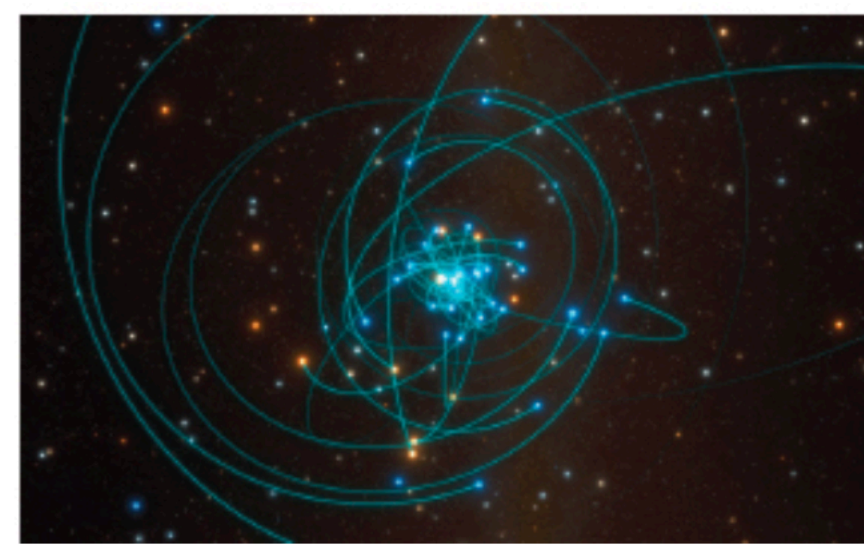


2020



2011

Cosmic Acceleration

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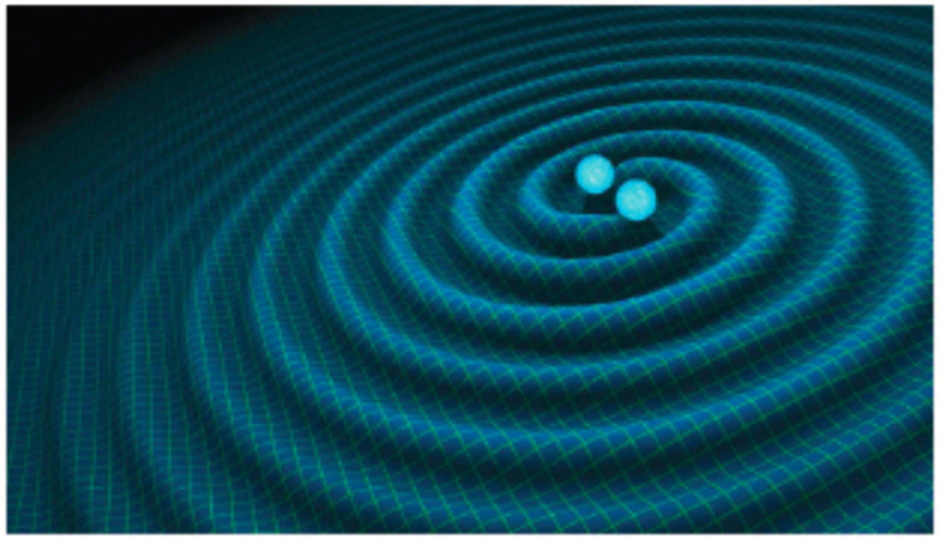
Neutrino Oscillations

2019

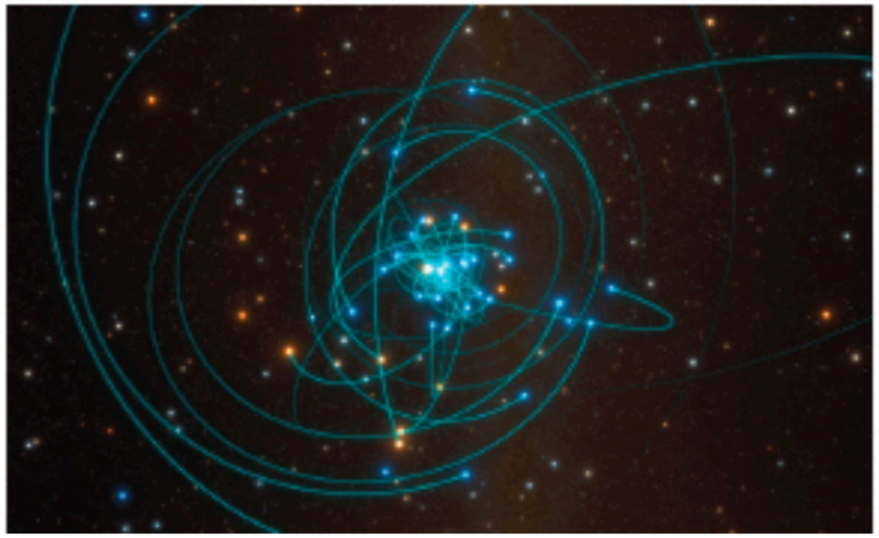
Theory of Physical Cosmology

(and exoplanets around solar-type star)

2017



2020



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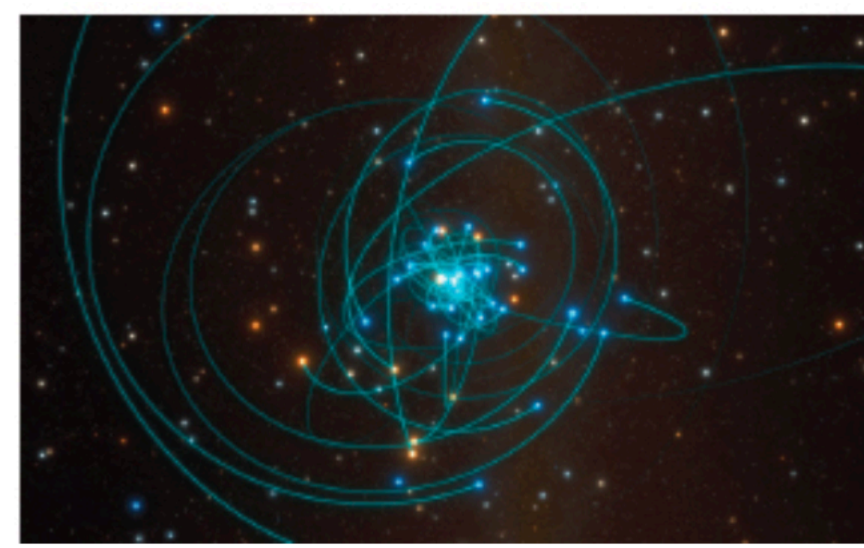
Gravitational Waves

2020



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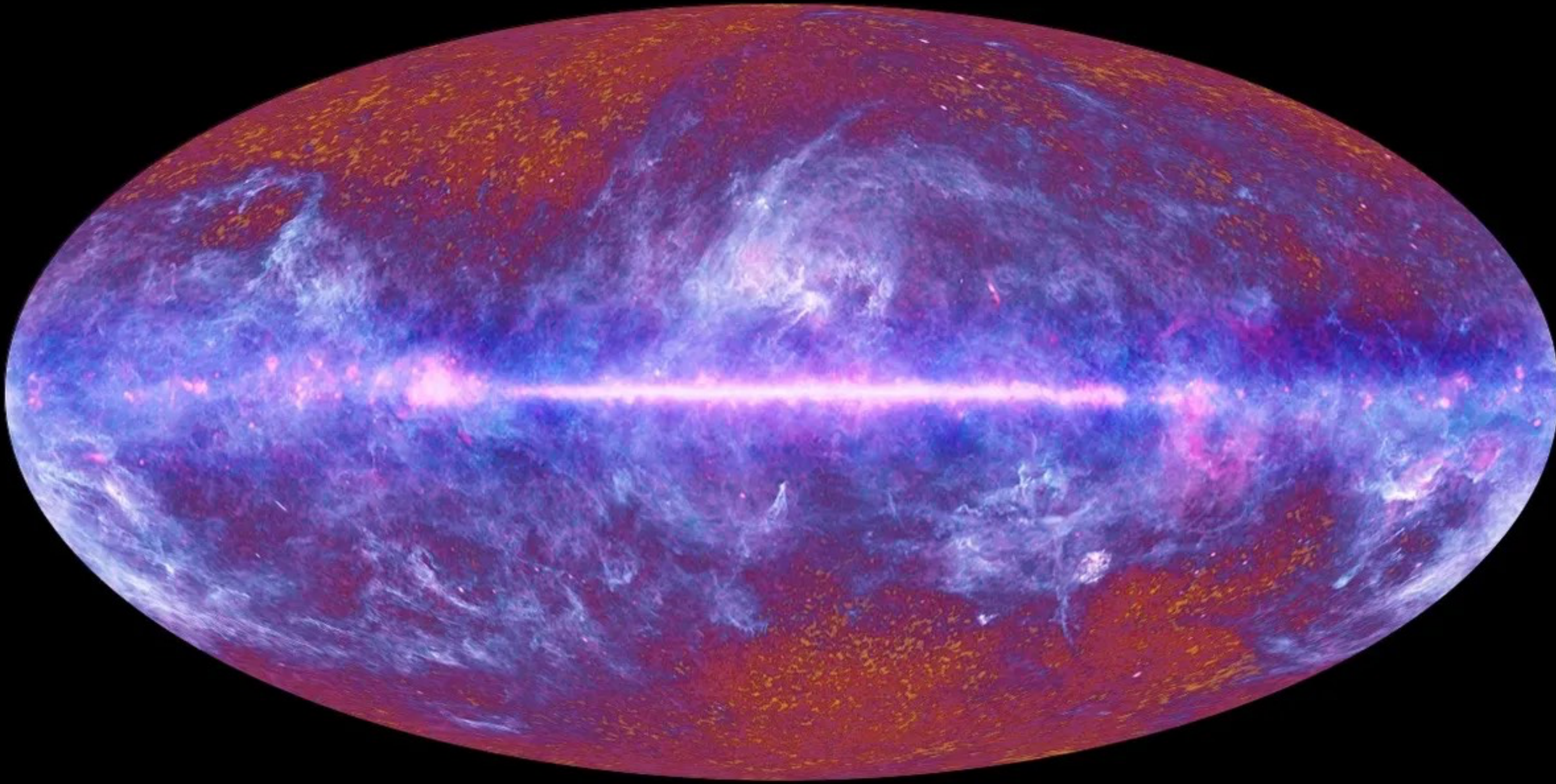
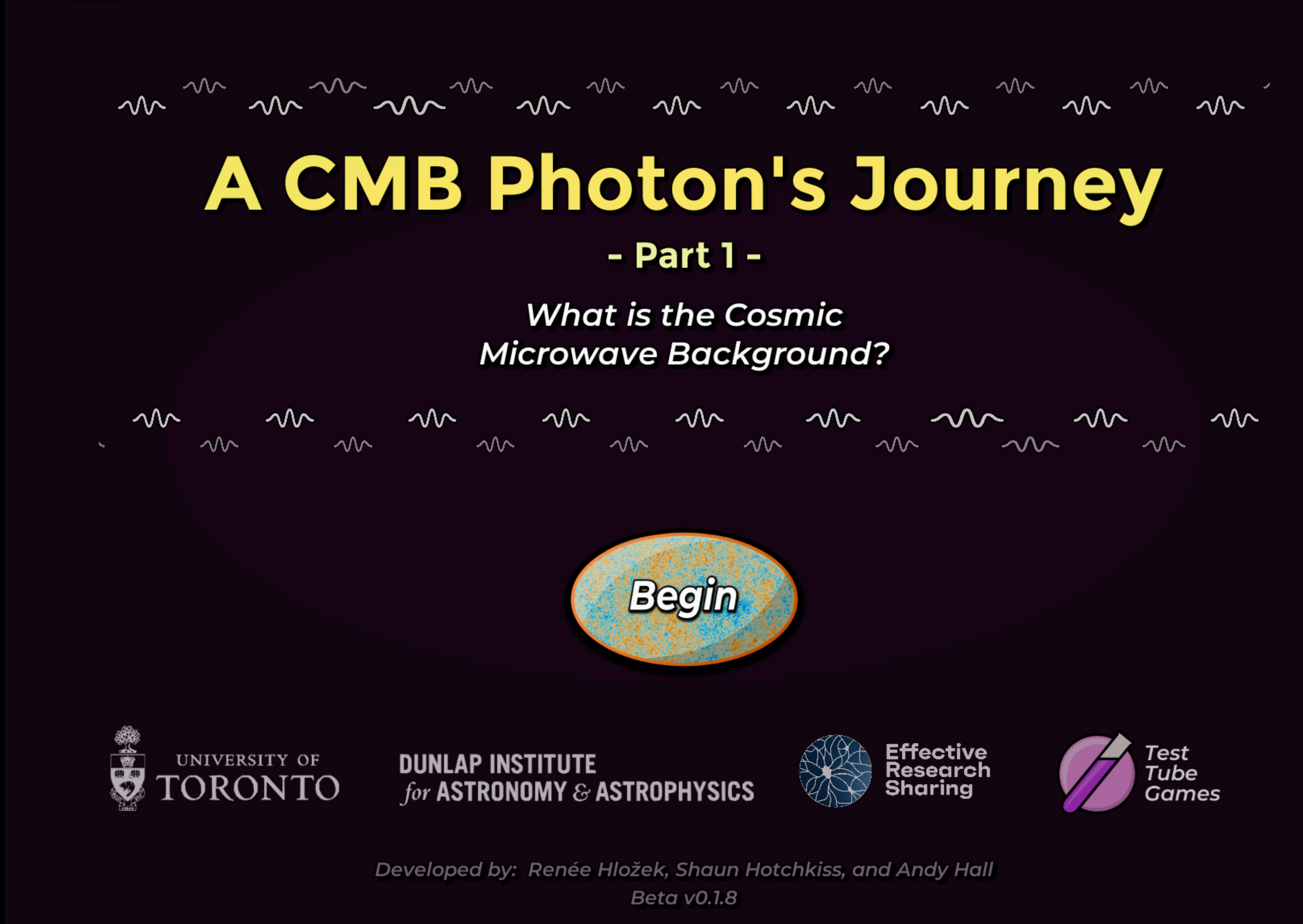
Black hole formation from General Relativity

What are our cosmological measurements

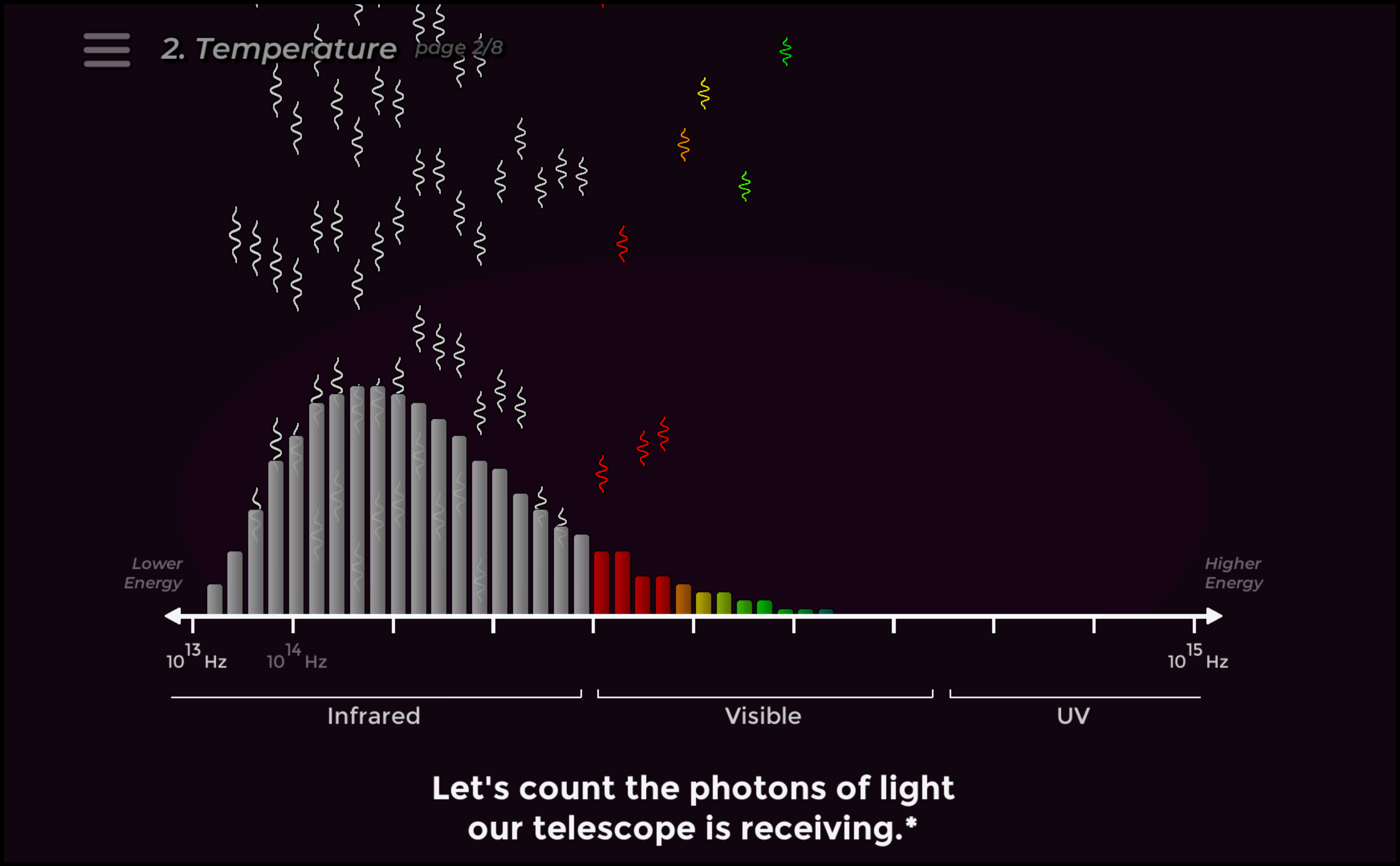
Thermal emission



A quick aside/shameless plug…



https://testtubegames.com/cmbjourney.html

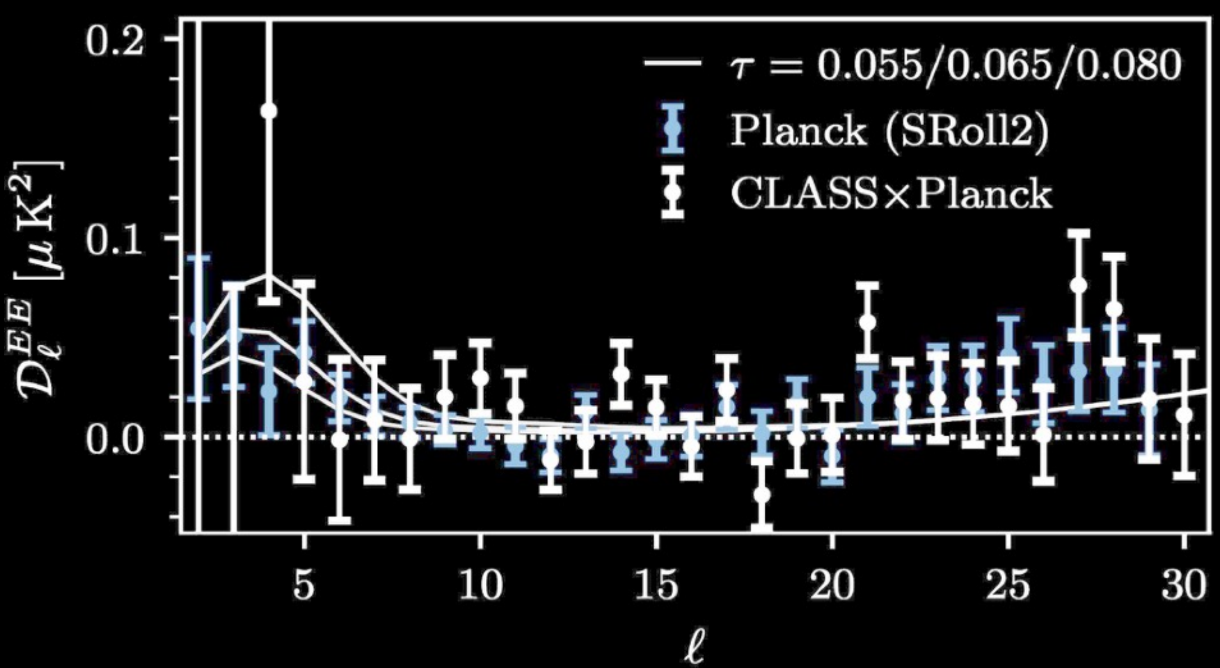


https://testtubegames.com/cmbjourney.html

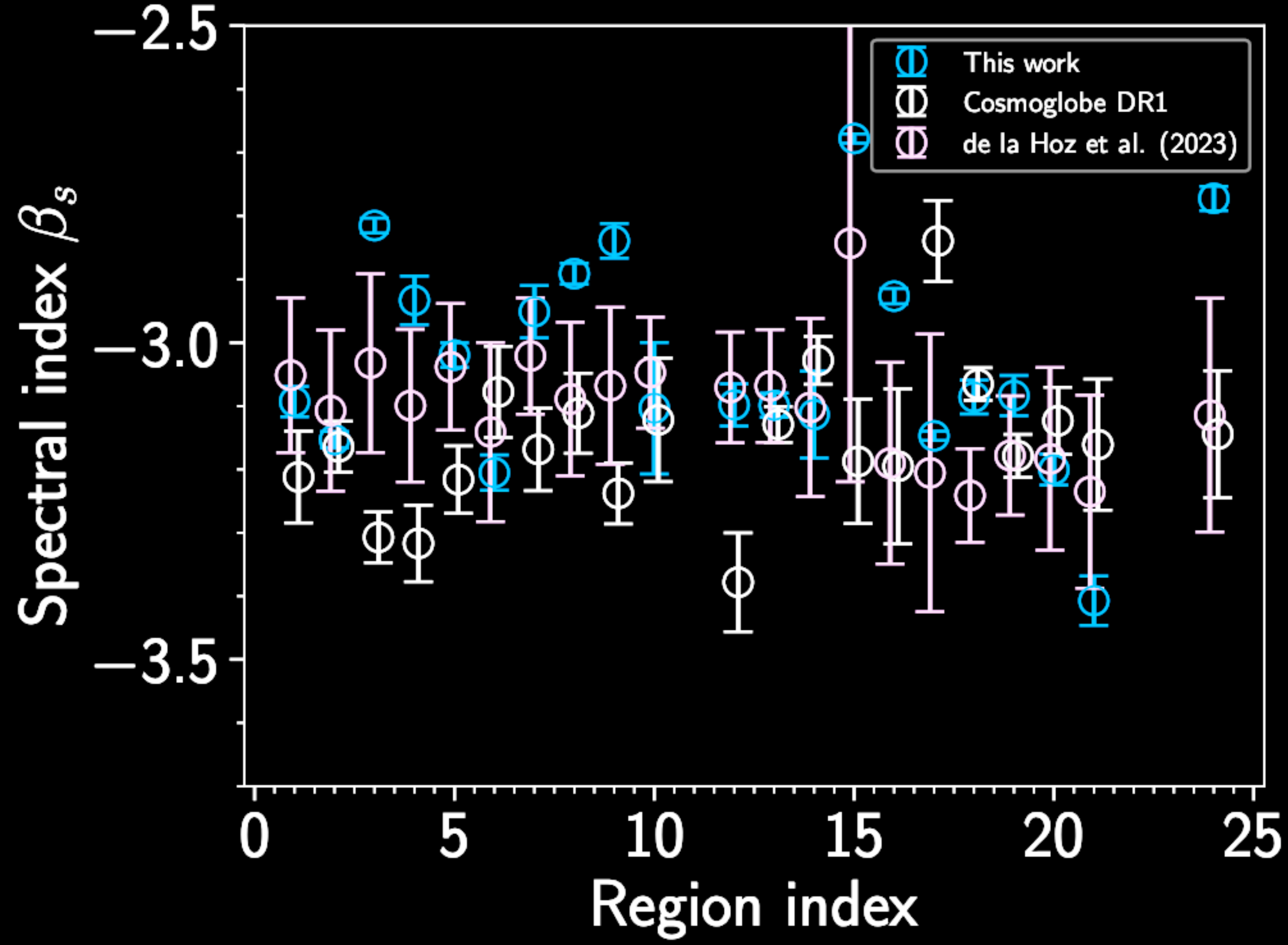
Thermal emission

Planck (space 2< ℓ<2500): all sky measurements — best measurements of largest modes on the sky

ABS, CLASS, QUIJOTE, GroundBIRD (2< ℓ<300): ground-based control of systematics, measurement of optical depth, search for primordial signal



Li et al. 2501.11904



Adak et al. 2510.17761

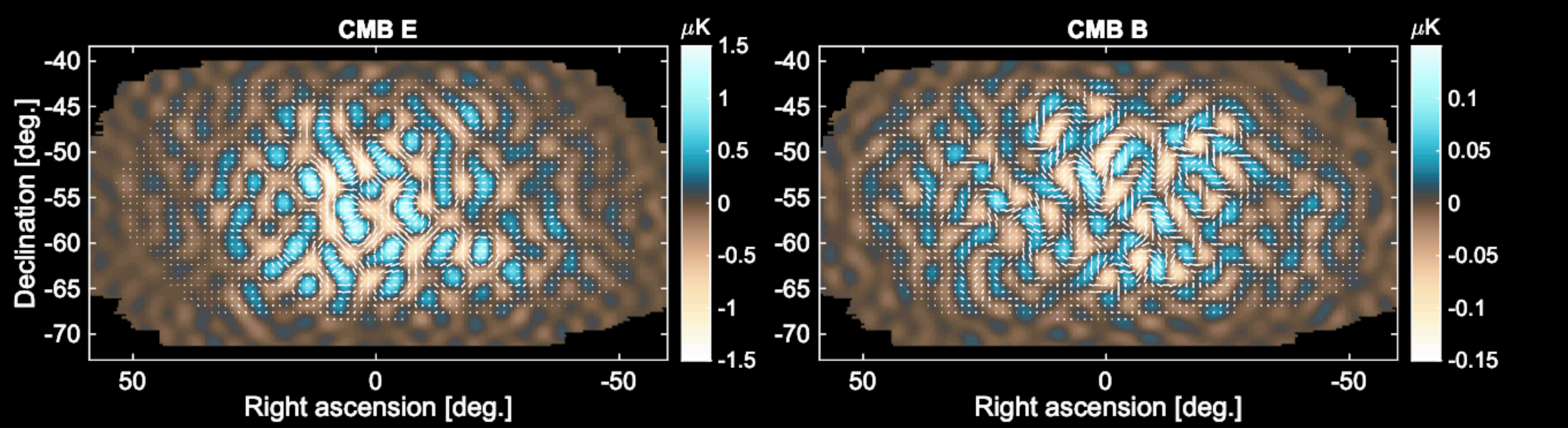
Thermal emission

Planck (space $2< \ell<2500$): all sky measurements — best measurements of largest modes on the sky

ABS, CLASS, QUIJOTE, GroundBIRD ($2< \ell<300$): ground-based control of systematics, measurement of optical depth, search for primordial signal

SPIDER/EBEX/LSPE (balloon $30<\ell < 300$): deep balloon measurements of smaller field, foreground constraints and limits on primordial signal

BICEP, Keck (ground $30<\ell < 300$): ongoing ground-based measurements of smaller field, foreground constraints and limits on primordial signal, combinations with SPT



Ade et al. 2509.21648

Thermal emission

Planck (space $2< \ell<2500$): all sky measurements — best measurements of largest modes on the sky
ABS, CLASS, QUIJOTE, GroundBIRD ($2< \ell<300$): ground-based control of systematics, measurement of optical depth, search for primordial signal

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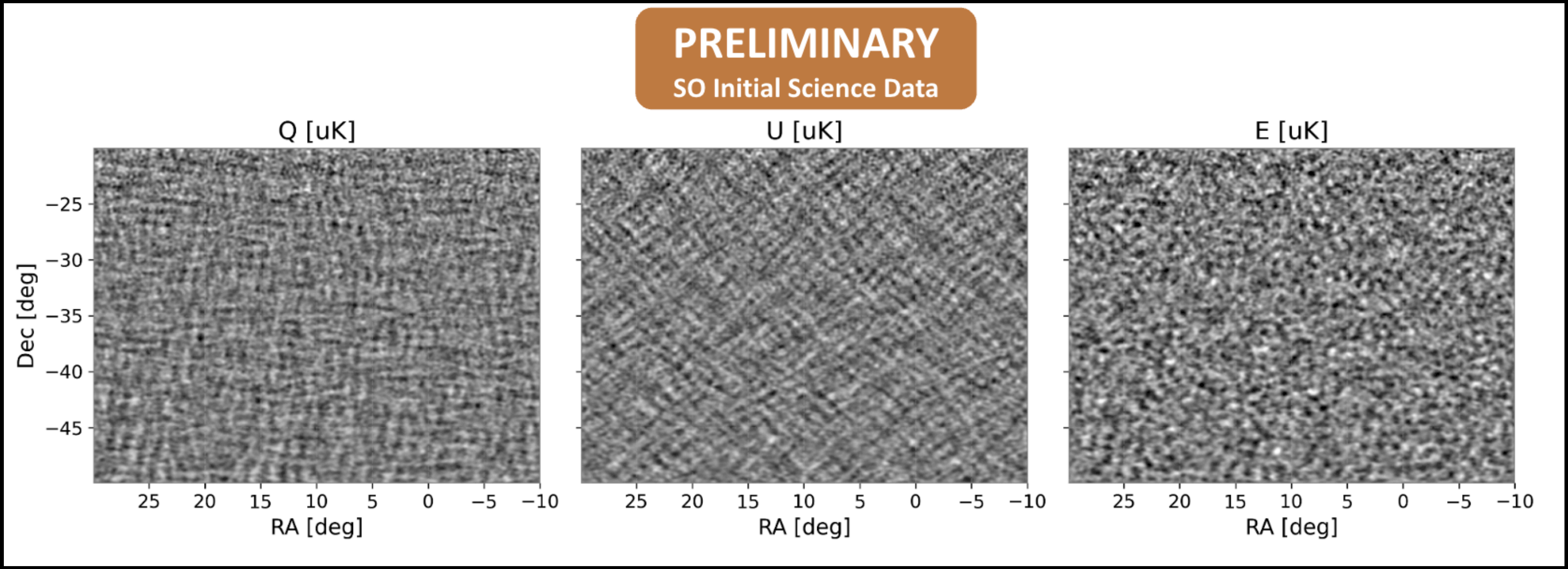
BICEP, Keck (ground $30<\ell < 300$): ongoing ground-based measurements of smaller field, foreground constraints and limits on primordial signal, combinations with SPT

ACT, SPT (ground, $300< \ell<5000$): ground-based small-scale measurements, damping tail constraints. Combination or contrast with Planck on cosmology constraints
POLARBEAR/Simons Array (ground, $500<\ell < 3000$): polarisation maps of, lensing from B-modes

Thermal emission (next-generation)

LiteBIRD (space $2< \ell<200$): improved large-scale polarisation for primordial search
Simons Observatory (ground, $30< \ell<5000$): ground-based now including larger scales, improved sensitivity on small scales



preliminary: Simons Observatory

Small-scale measurements also enable estimates of lensing of CMB light

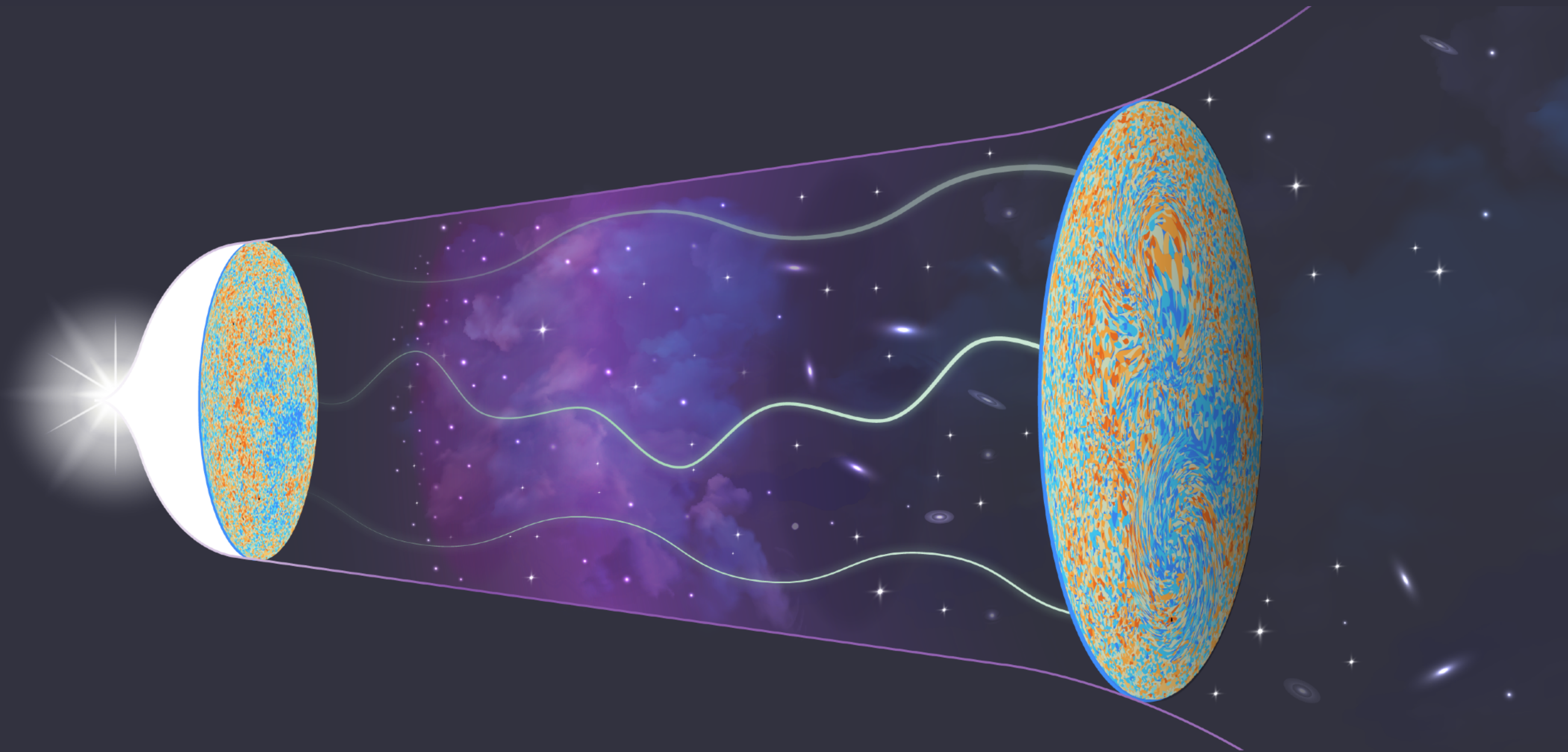


image: Lucy Reading-Ikkanda/Simons Foundation

Galaxy surveys

SDSS/BOSS (ground, spectroscopic+imaging, 14 000 deg^2, r~22): clustering, imagine, multiple upgrades

CFHTLens, COSMOS (ground, photometric < 200 deg^2, r~25): lensing, characterising fields/ preparation for future experiments

DES (ground, photometric, 5000 deg^2, r~25): galaxy lensing, clustering, supernova science

HSC, KiDS (ground, photometric, deep ~1300 deg^2, r~25/26): main focus on weak lensing and clustering

DESI (ground, spectroscopic, 14000 deg^2): galaxy clustering, BAO focus

Galaxy surveys

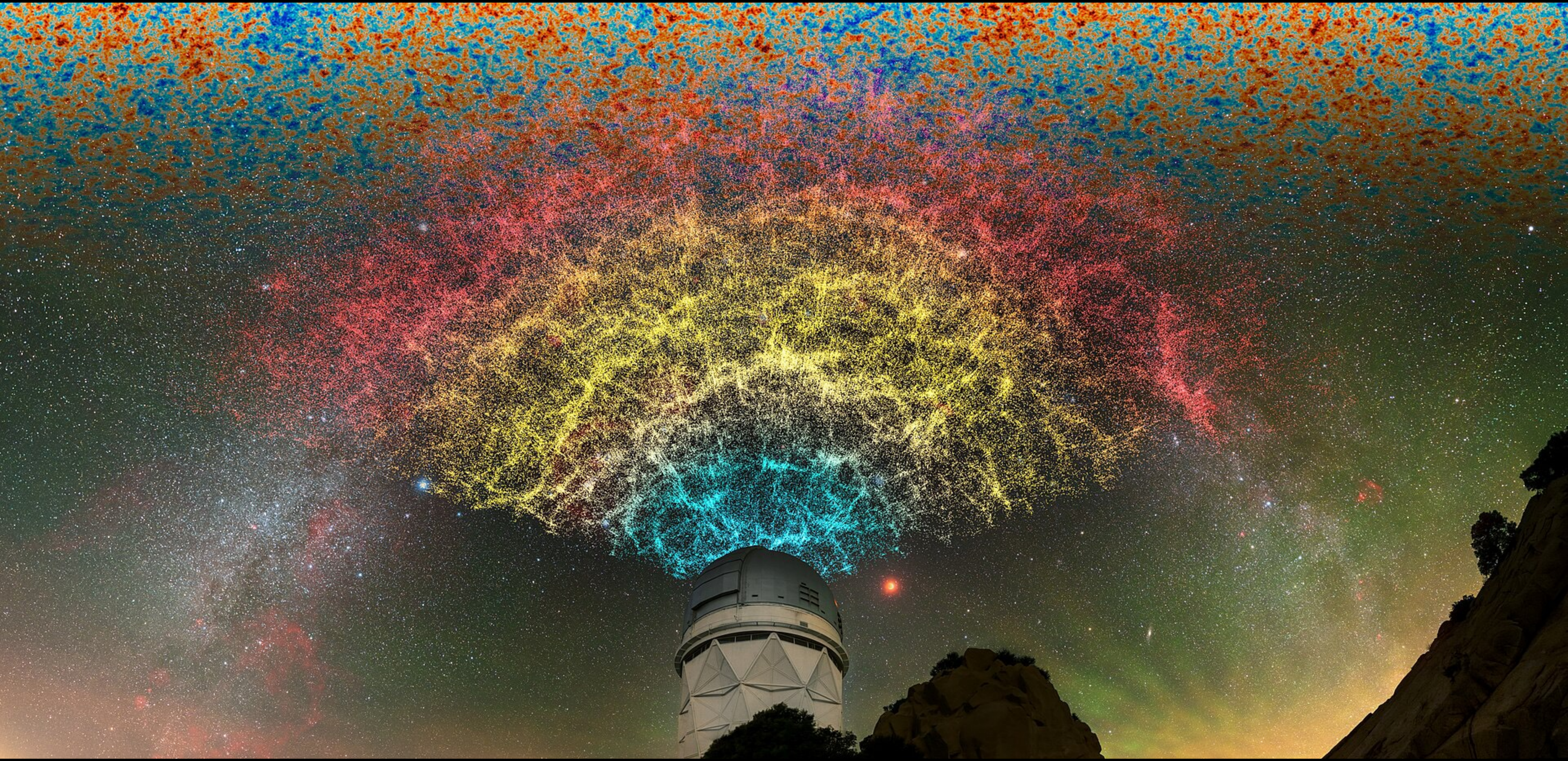


image Dark Energy Spectroscopic Imager

Galaxy surveys

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DESI (ground, spectroscopic, 14000 deg^2): galaxy clustering, BAO focus

Euclid (space, imaging+spectro, 15000 deg^2, VIS~25): Optical/NIR photometry, lensing, clustering

Roman (space, imaging 2700 deg^2, H~26.5): weak lensing, clustering, supernovae

Rubin Observatory (ground, imaging 14000 deg^2, r~27 co-add): strong and weak lensing, clustering, supernova

Galaxy surveys

image: Euclid ESA

Galaxy surveys

Image: Rubin/NOIRLab

Cosmic microwave background

large scale B-modes
→ tensor-to-scalar ratio (BB)
damping tail
→ primordial power on small scales (TE, TT, EE)
→ N_{eff} (TE, TT, EE)

reionization

from CMB+21cm
→ duration of reionization (kSZ)
→ mean free path of photons (kSZ)

neutrino mass

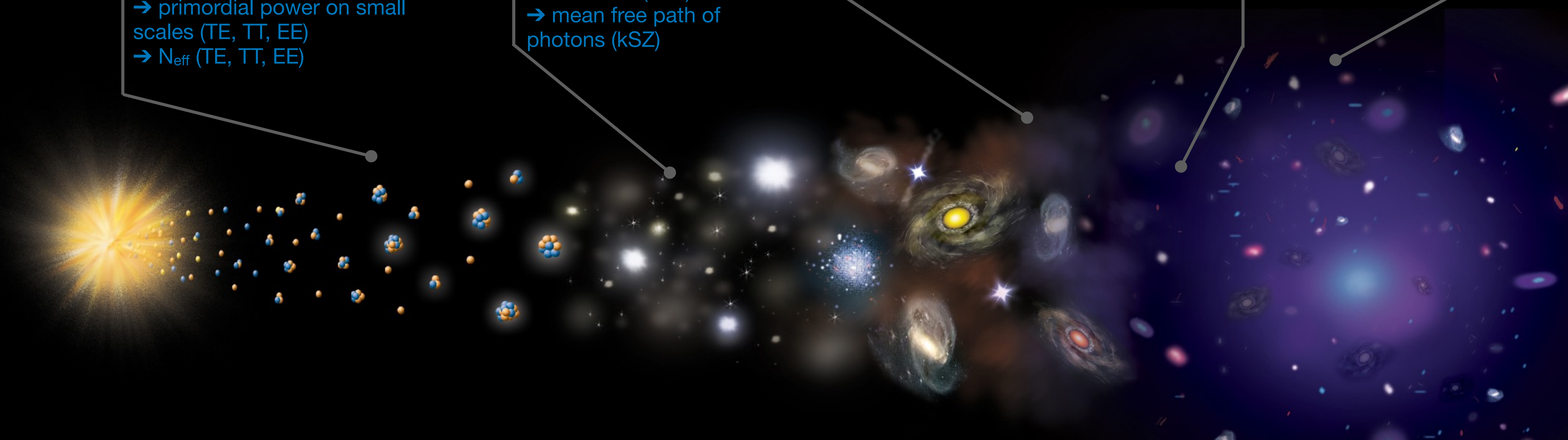
CMB lensing, 3x2pt lensing, P(k)/BAO
→ Σm_ν growth of structure

galaxy evolution

tSZ, kSZ
galaxy surveys

dark energy

CMB lensing
supernova
optical strong lensing



400,000 yrs	~0.5 billion yrs	4 billion yrs	10 billion yrs
z=1000	z=10	z=2	z=0

slide adapted from Colin Hill

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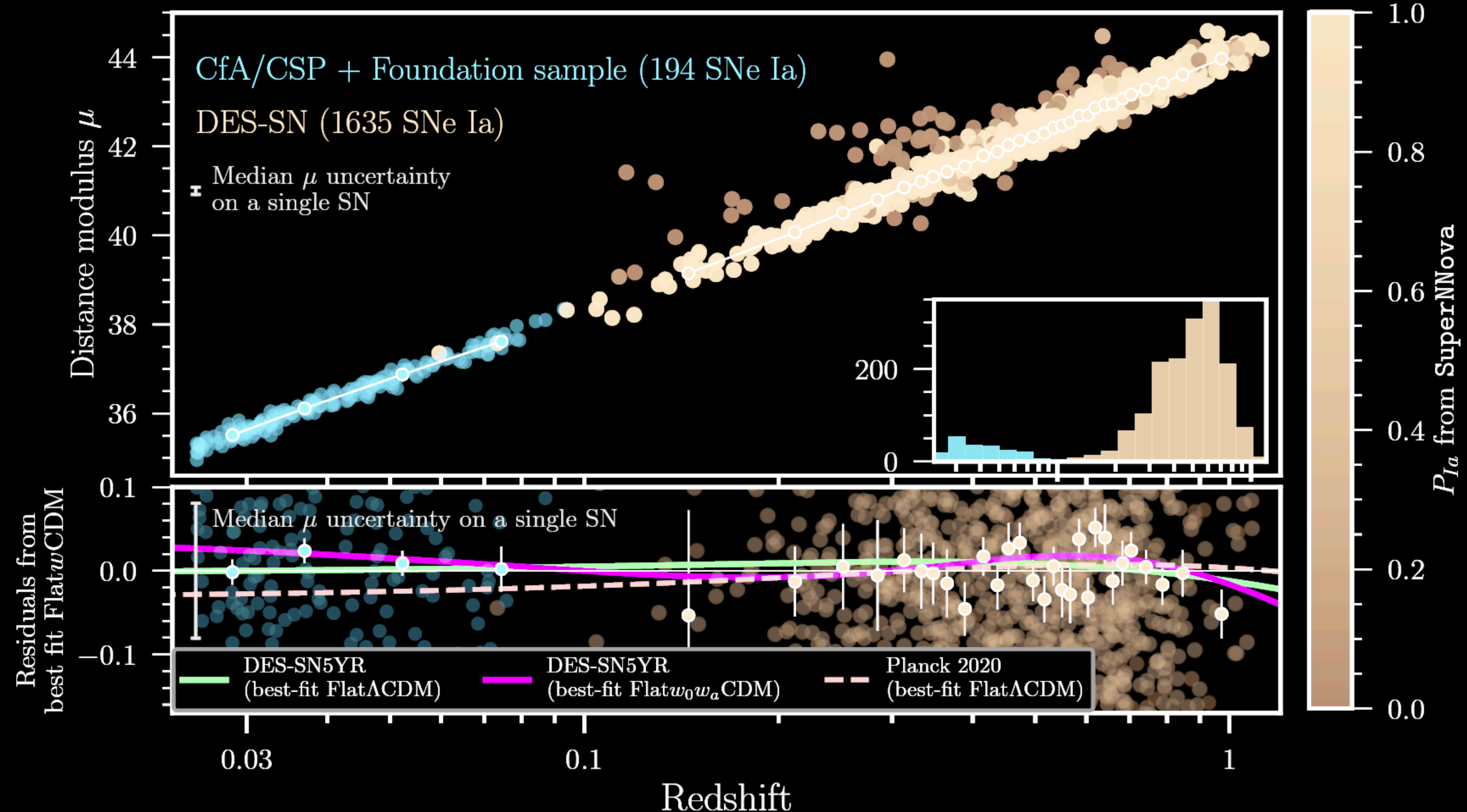
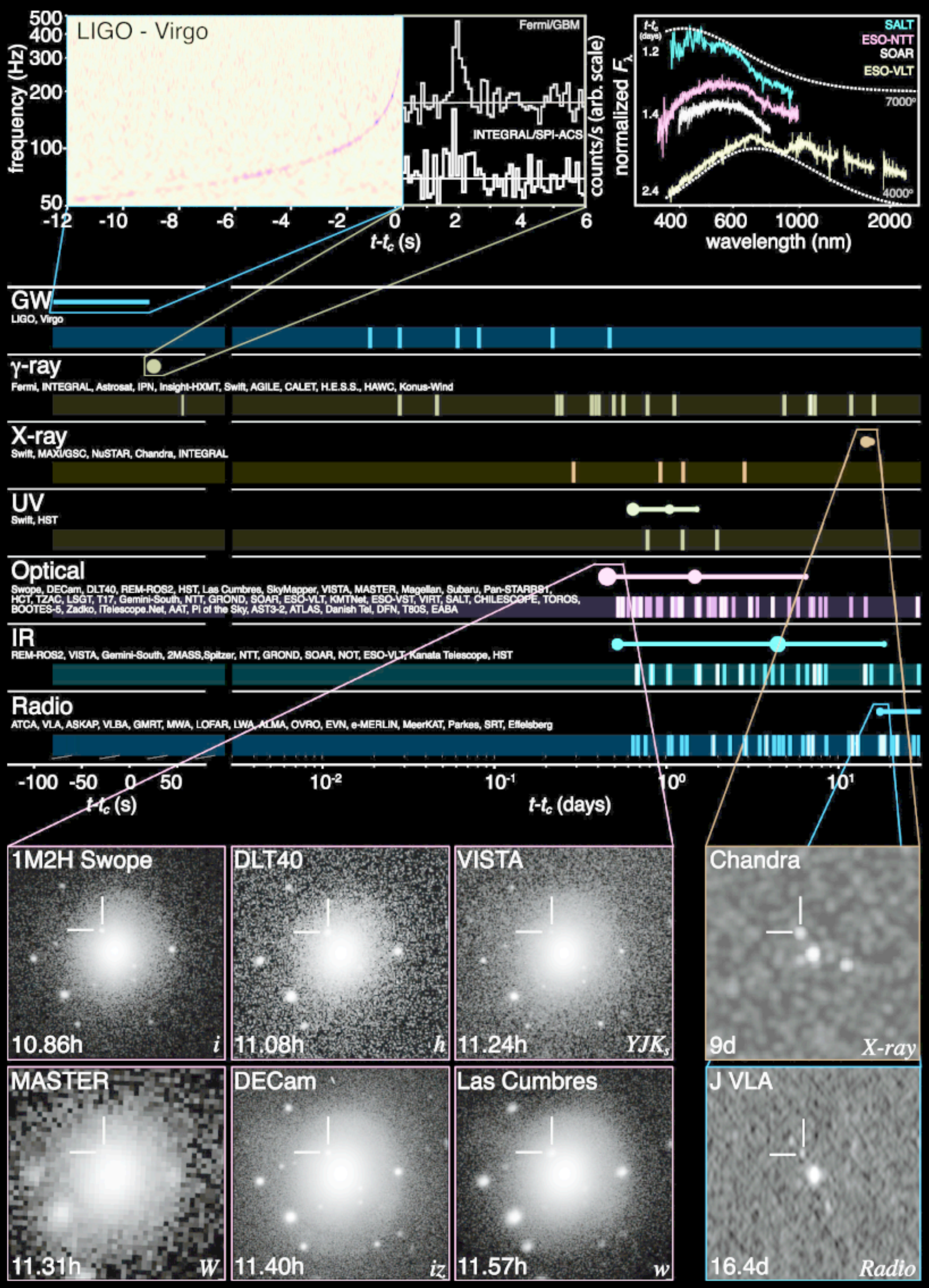
Other cosmological probes: supernovae



Abbot et al. 2401.02929

Other cosmological probes: standard sirens



Abbot et al. 1710.05833

Where did we come from?

Where did we come from?

[Submitted on 16 May 1995]

Cosmic Concordance

J. P. Ostriker, Paul J. Steinhardt

Observational constraints guide one forcefully to examine models in which the matter density is substantially less than critical density. Particularly noteworthy are those which are consistent with inflation. For these models, microwave background anisotropy, large-scale structure measurements, direct measurements of the Hubble constant, H_0, and the closure parameter, Ω_{Matter}, ages of stars and a host of more minor facts are all consistent with a spatially flat model having significant cosmological constant $\Omega_\Lambda = 0.65 \pm 0.1$, $\Omega_{\mathrm{Matter}} = 1 - \Omega_\Lambda$ (in the form of ``cold dark matter") and a small tilt: $0.8 < n < 1.2$. (Read comments at top of file to find out how to obtain figures.)

Remarkably simple model

$$G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu} + g_{\mu\nu}\Lambda$$

$$\mathcal{P}(k) = A_s(k_0)\left(\frac{k}{k_0}\right)^{n_s - 1}$$

$$\Omega_b h^2 \quad \Omega_c h^2 \quad \Omega_\Lambda$$

Densities of the universe

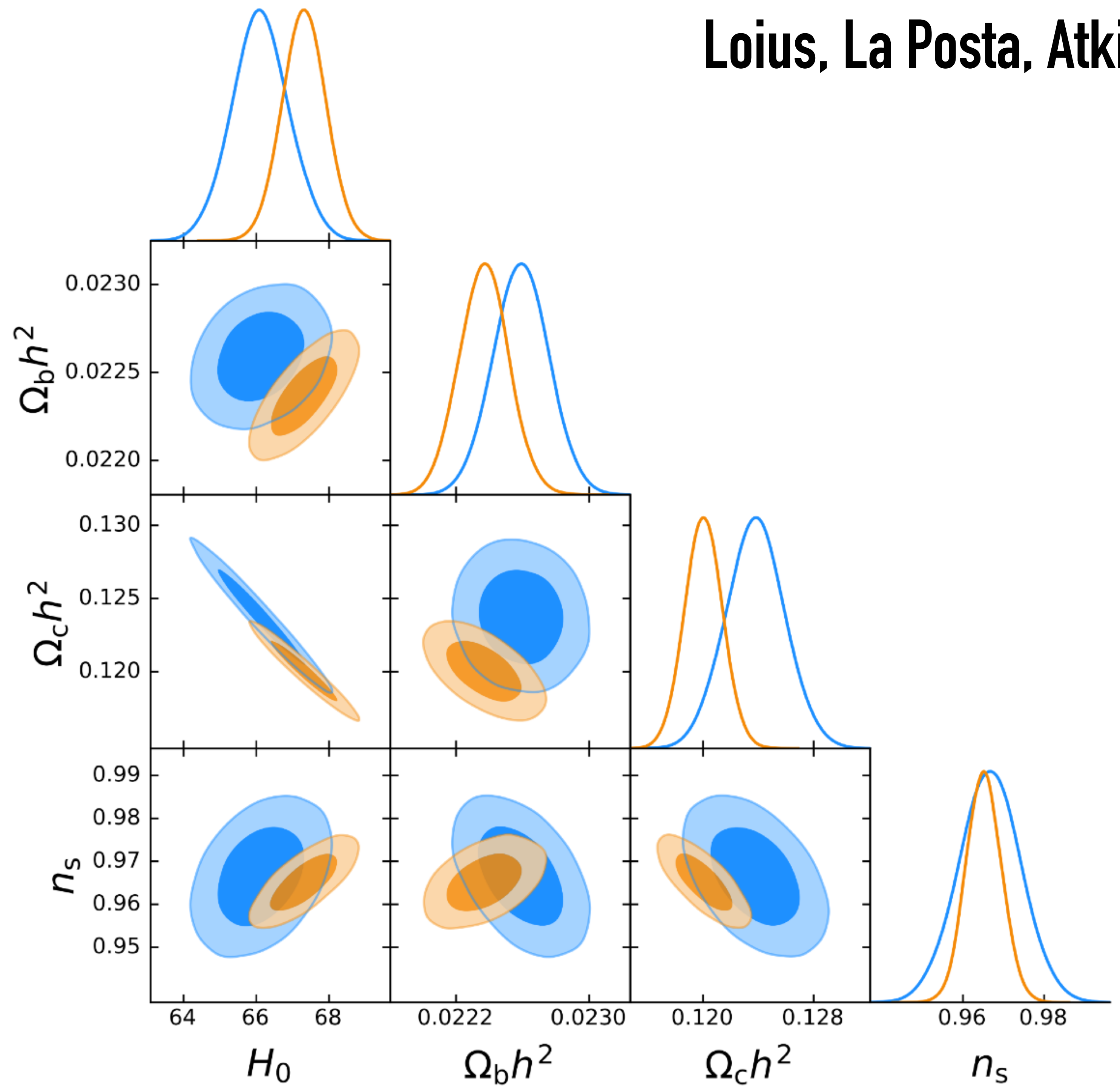
$$A_s \quad n_s$$

Initial conditions

τ Reionization physics

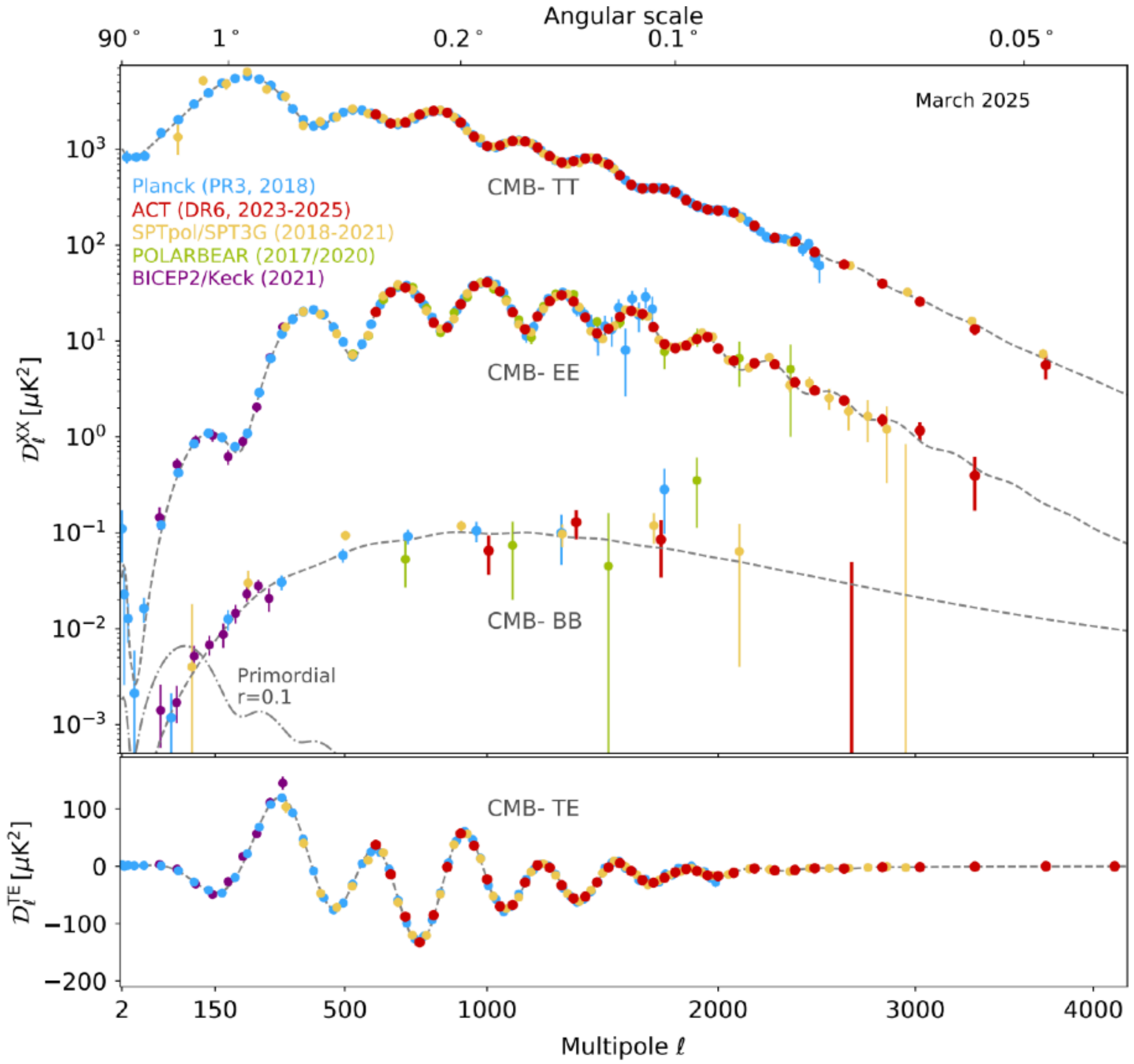
Where are we now?

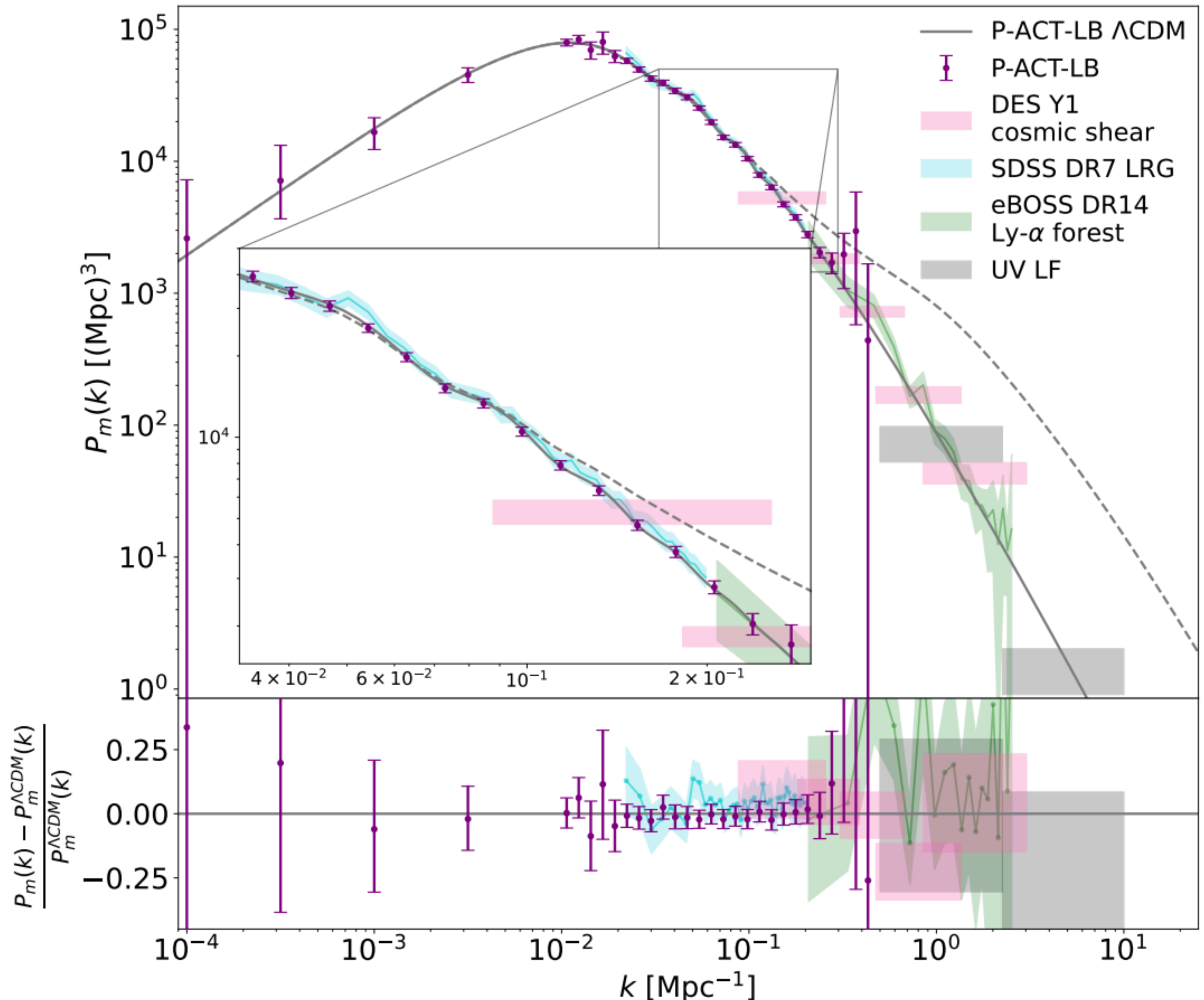
Loius, La Posta, Atkins, Jense et al. 2503.14452



When combined with CMB lensing from ACT and *Planck*, and baryon acoustic oscillation data from the Dark Energy Spectroscopic Instrument (DESI Y1), we measure a baryon density of $\Omega_b h^2 = 0.0226 \pm 0.0001$, a cold dark matter density of $\Omega_c h^2 = 0.118 \pm 0.001$, a Hubble constant of $H_0 = 68.22 \pm 0.36$ km/s/Mpc, a spectral index of $n_s = 0.974 \pm 0.003$, and an amplitude of density fluctuations of $\sigma_8 = 0.813 \pm 0.005$.

Where are we now?





Calabrese, Hill, Jense, La Posta et al. 2503.14454

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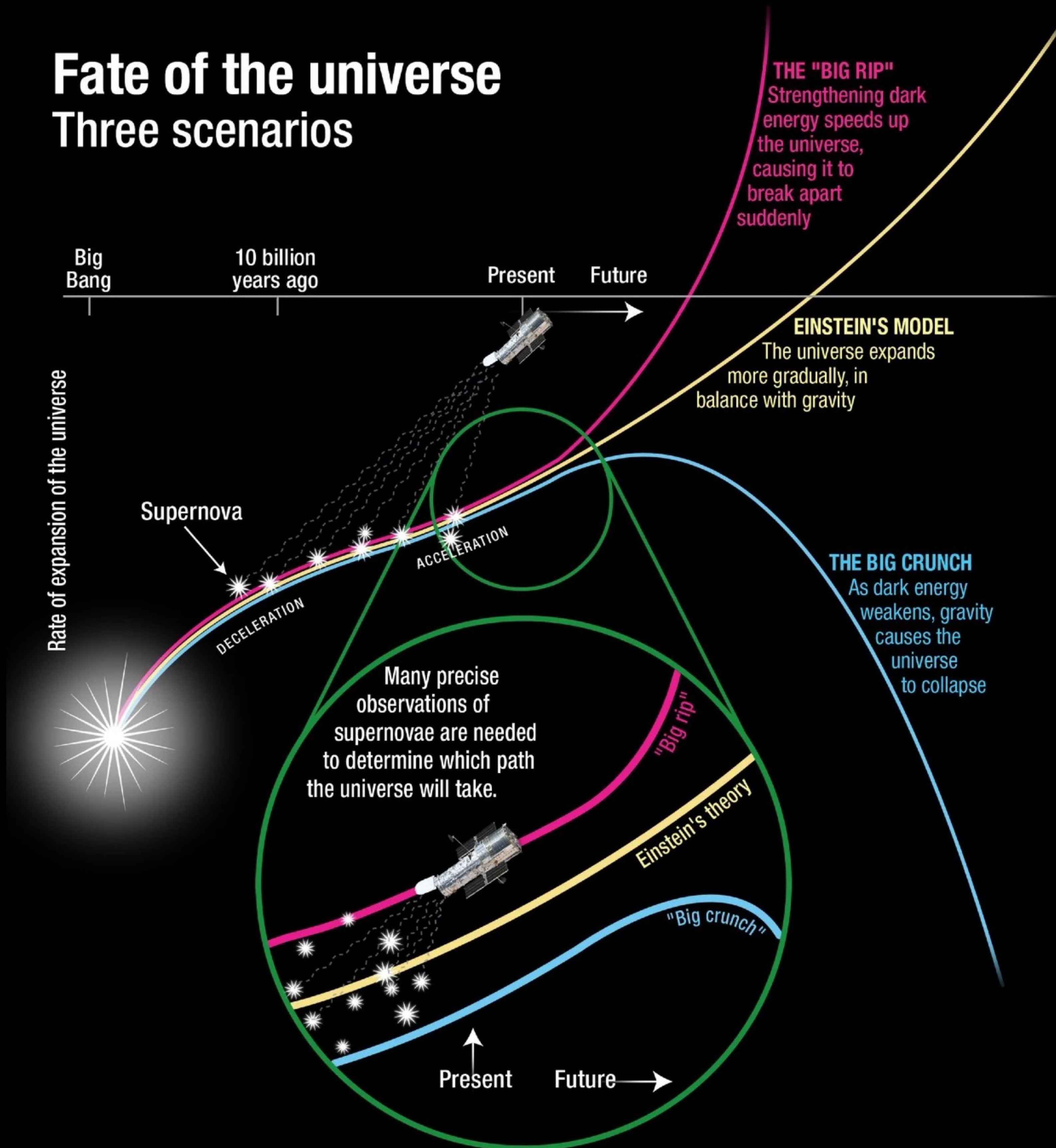
One of the big questions



Universe today

The dance of systematics vs new physics

Natalie Wolchover

Columnist

March 17, 2014

VIEW PDF/PRINT MODE

BICEP2 | Big Bang | cosmology | gravitational waves | inflation | physics | quantum gravity | theoretical physics

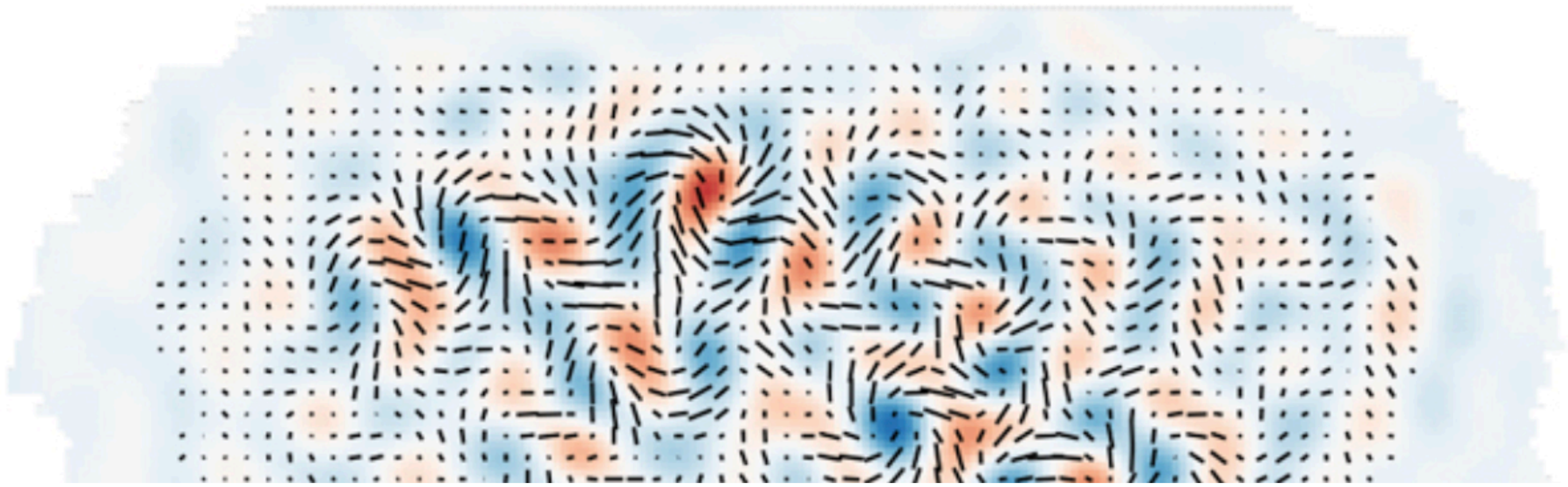
All topics →

COSMOLOGY

Possible Echo of Big Bang Detected

Scientists report the possible discovery of primordial gravitational waves, ripples in space-time that carry a record of how the universe began.

5



The dance of systematics vs new physics

Natalie Wolchover

Columnist

January 30, 2015

VIEW PDF/PRINT MODE

astrophysics | BICEP2 | Big Bang | cosmology | gravitational waves | inflation | physics

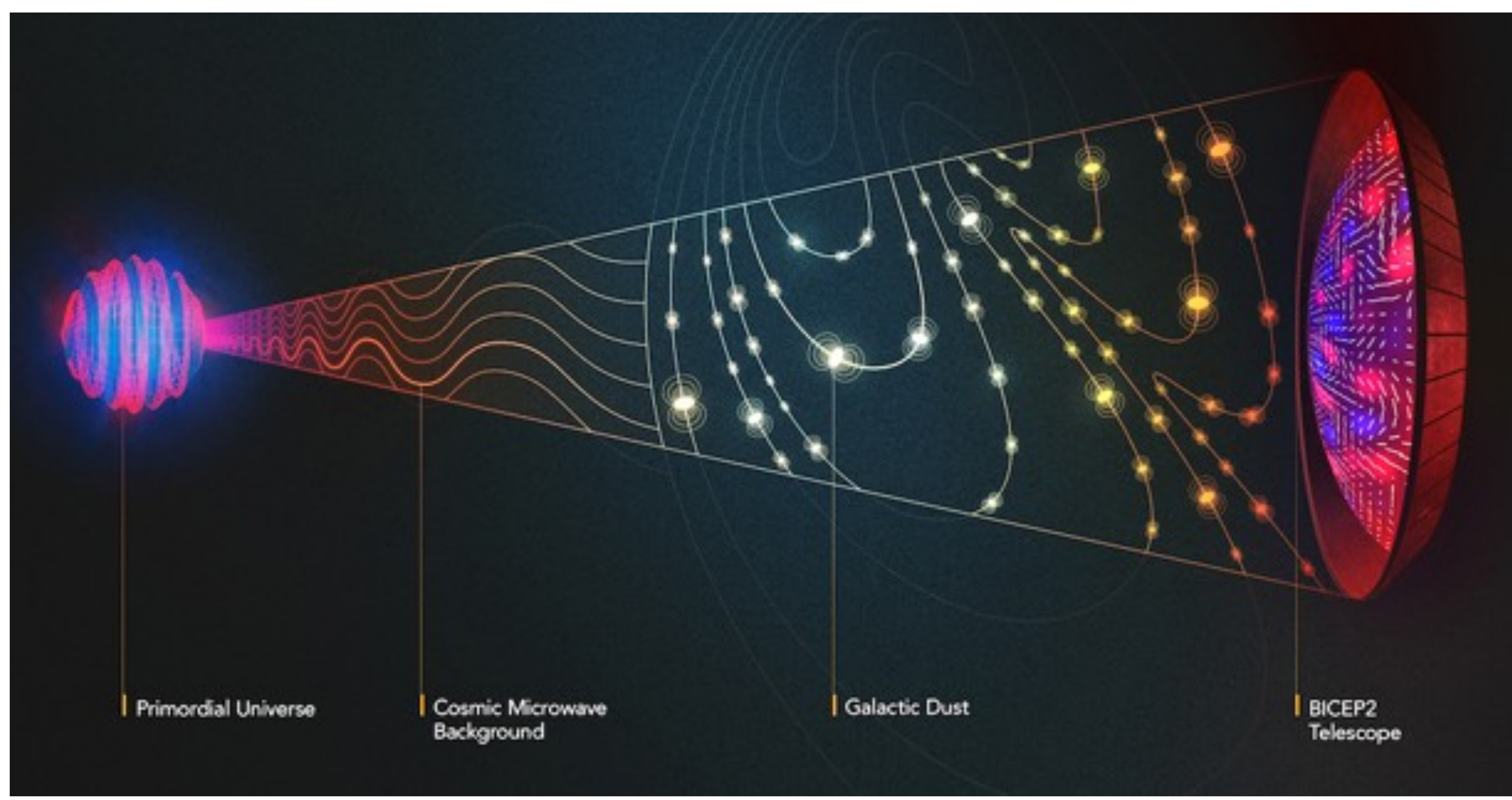
All topics →

COSMOLOGY

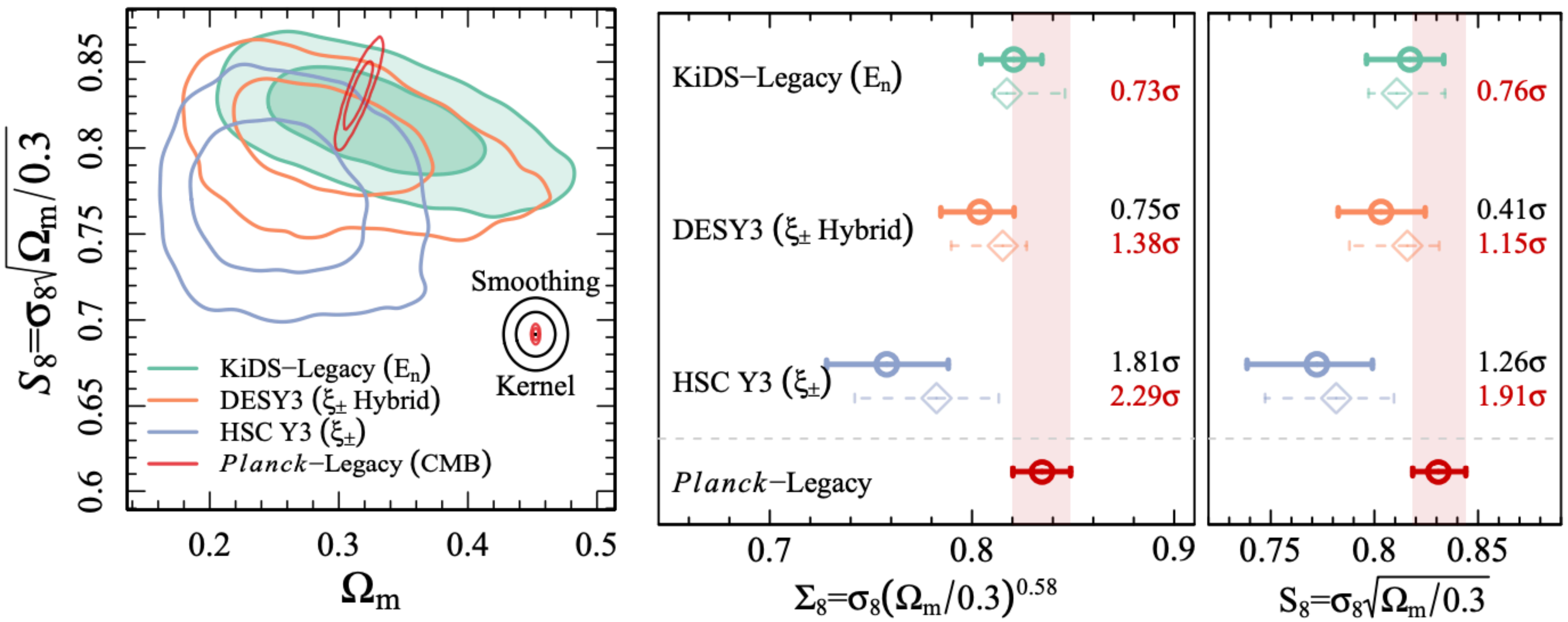
Joint Dust Analysis Deflates Big Bang Signal

No definitive evidence for cosmic inflation is found, but support remains strong for the theory even as critics highlight its shortcomings as an explanation for how and why the universe began.

9



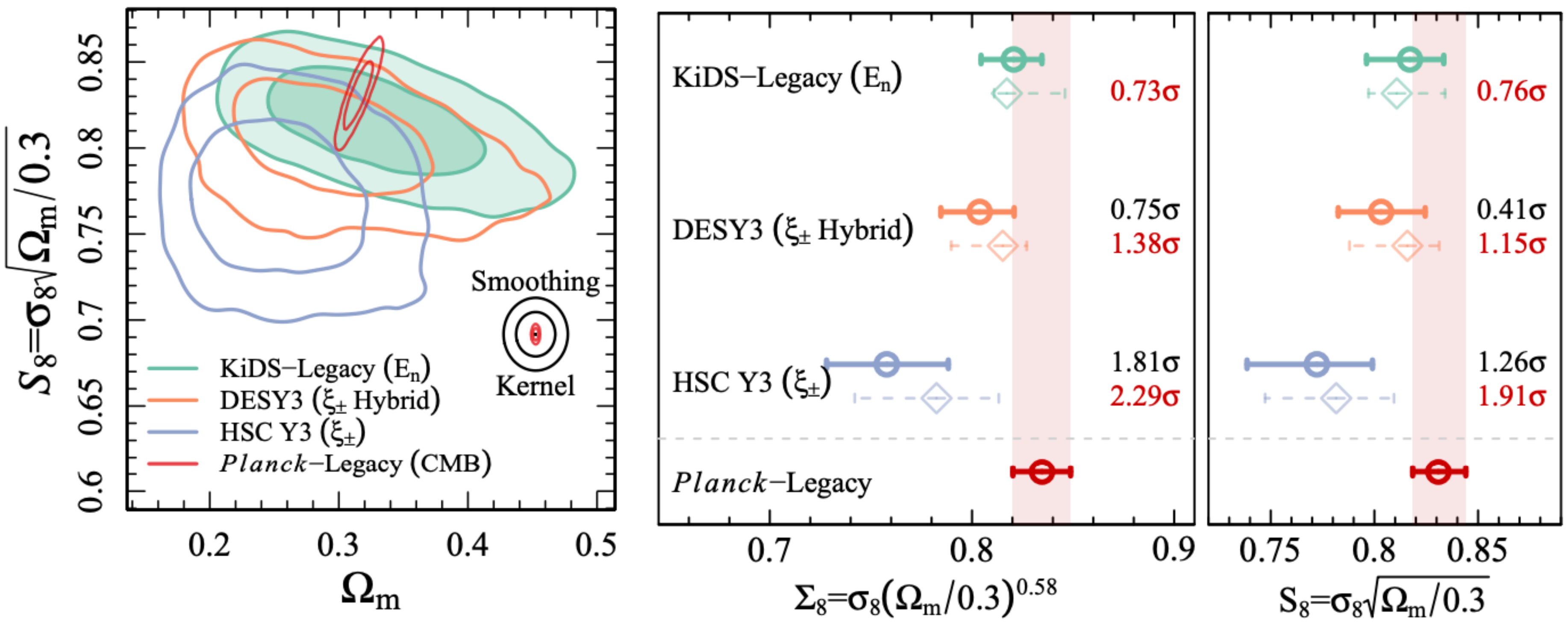
The dance of systematics vs new physics: s8



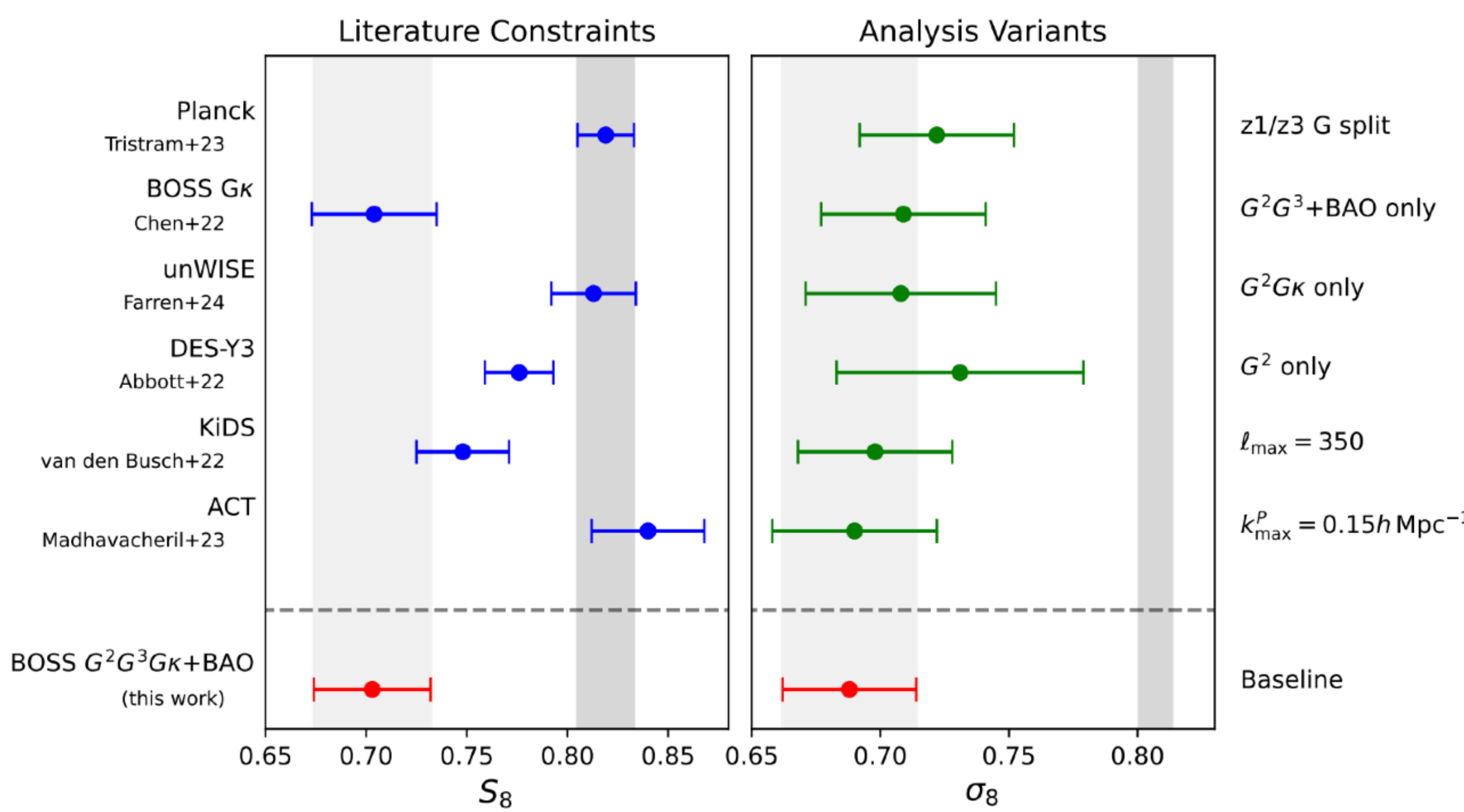
KiDS:

Wright et al. 2503.19441

The dance of systematics vs new physics: S8

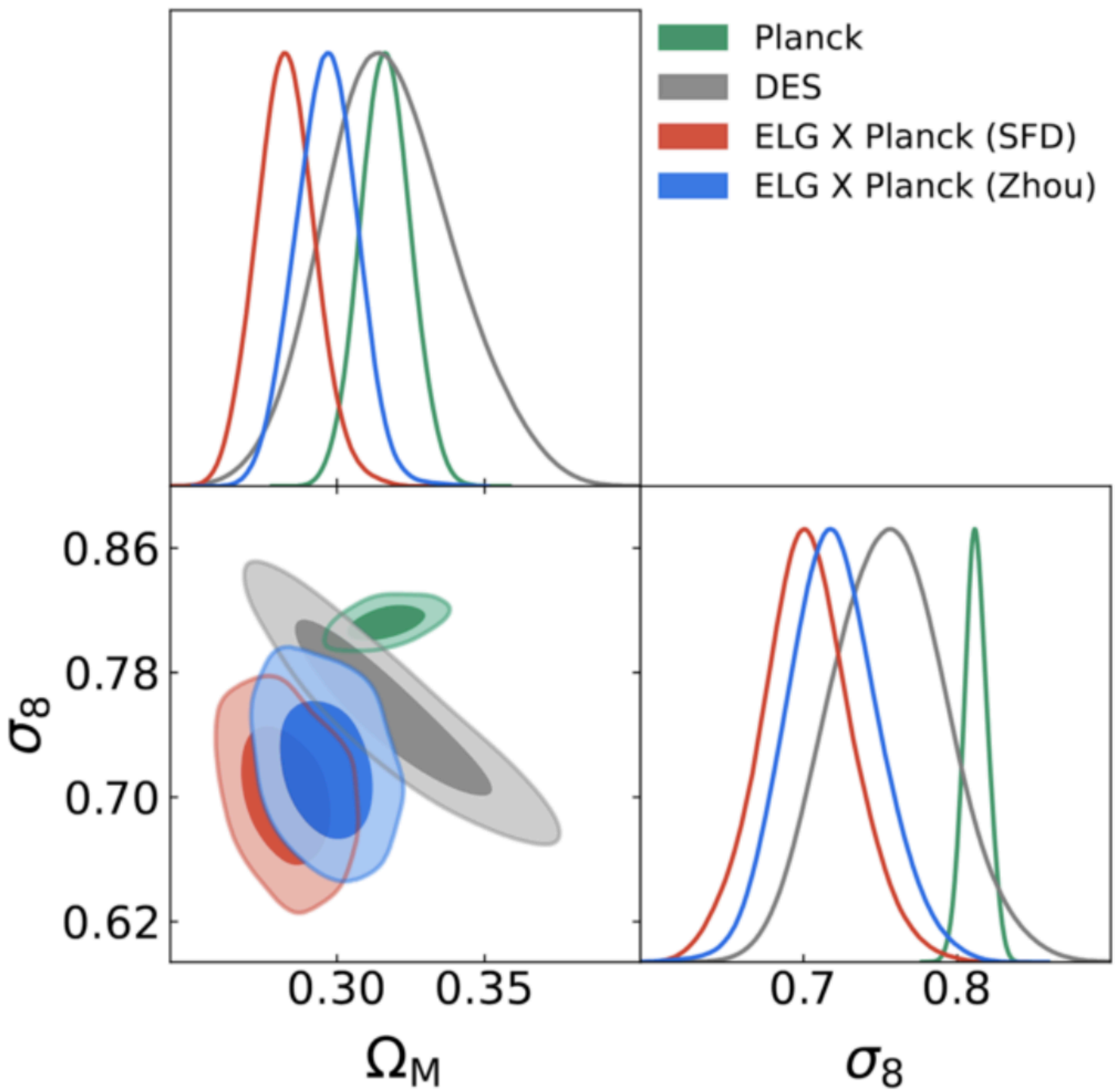


KiDS:
Wright et al. 2503.19441



BOSS:
Shen et al. 2406.13388

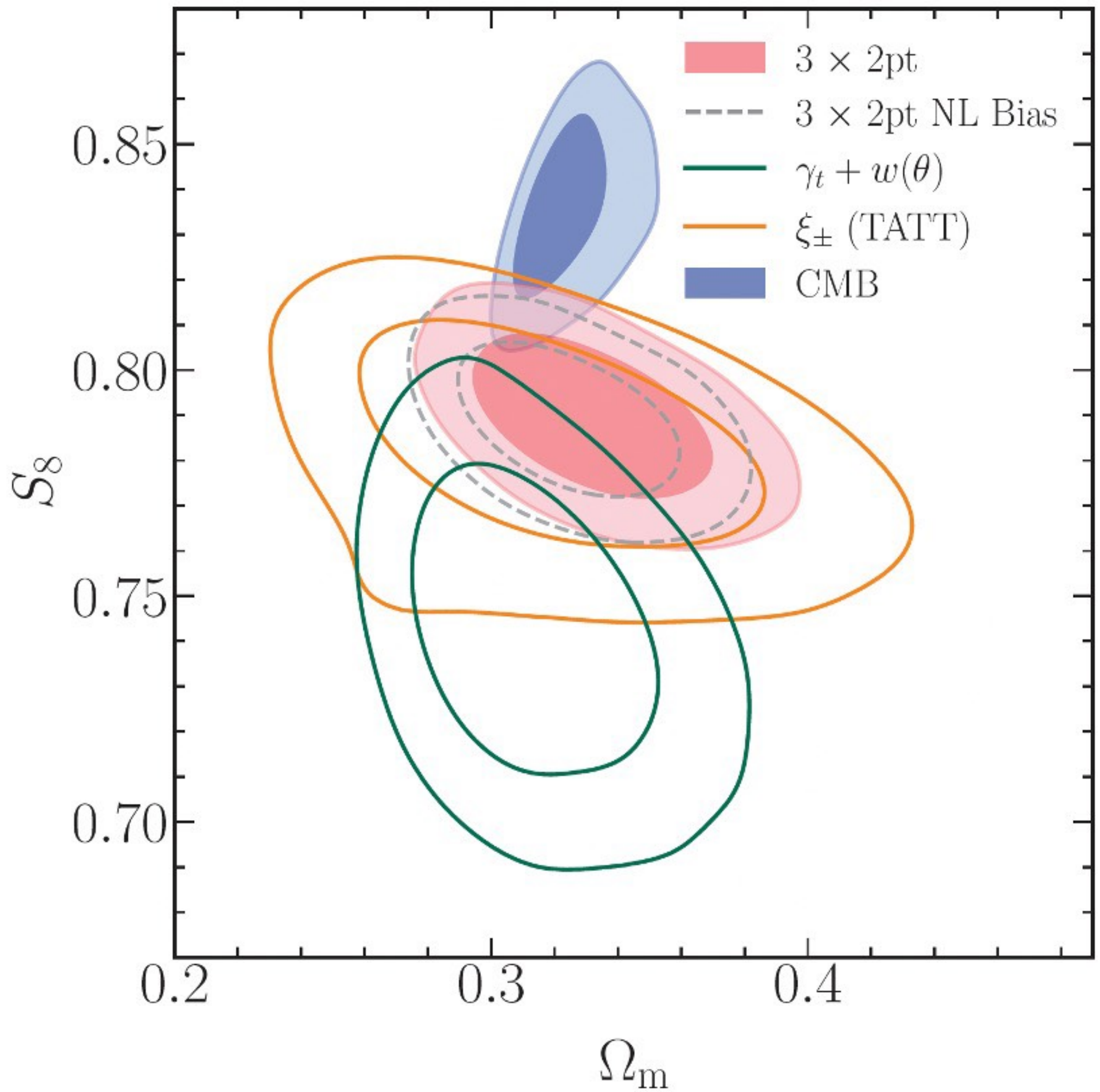
The dance of systematics vs new physics: S8



DESI:

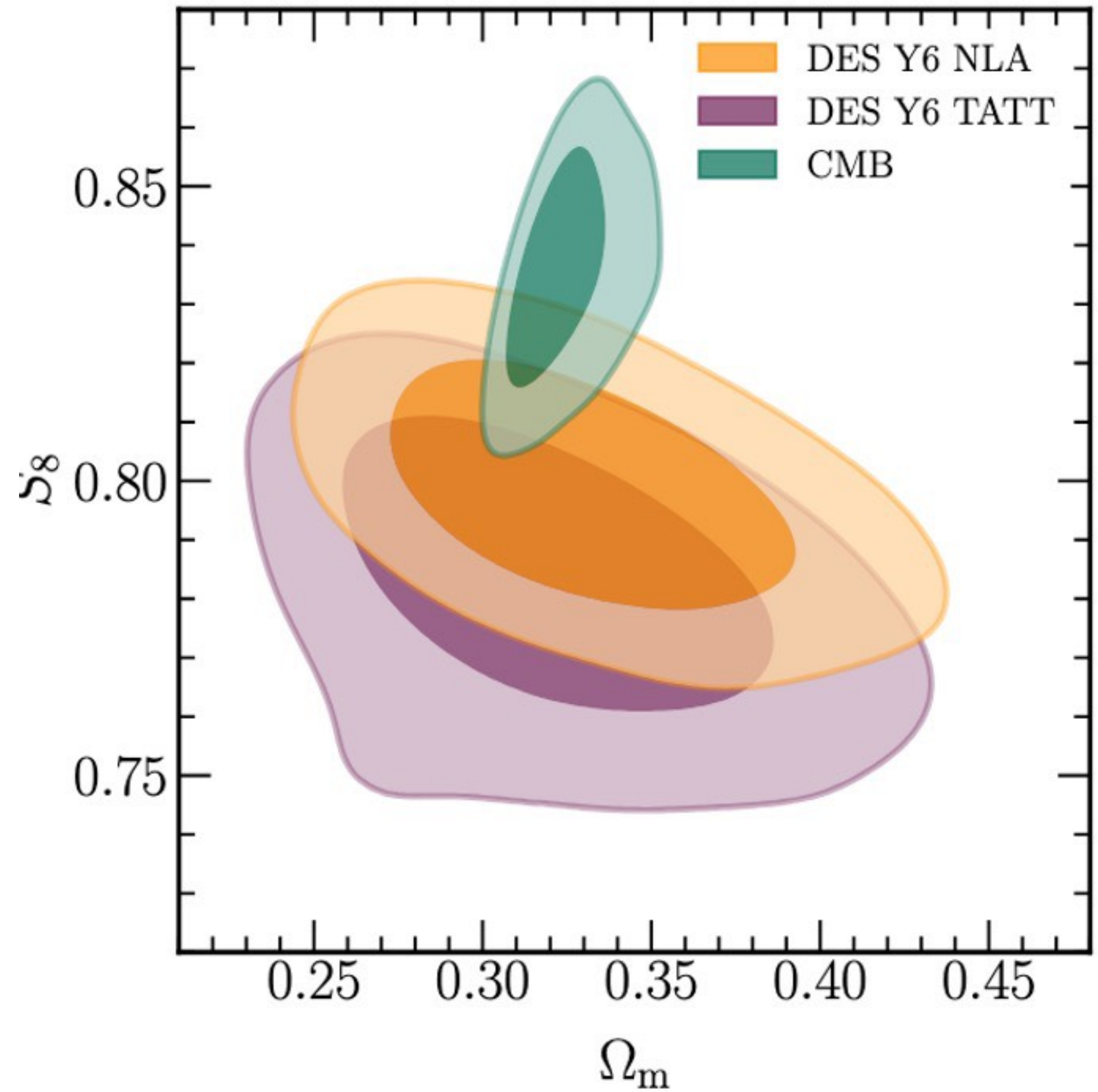
Kareem et al. 2408.15909

The dance of systematics vs new physics: S8

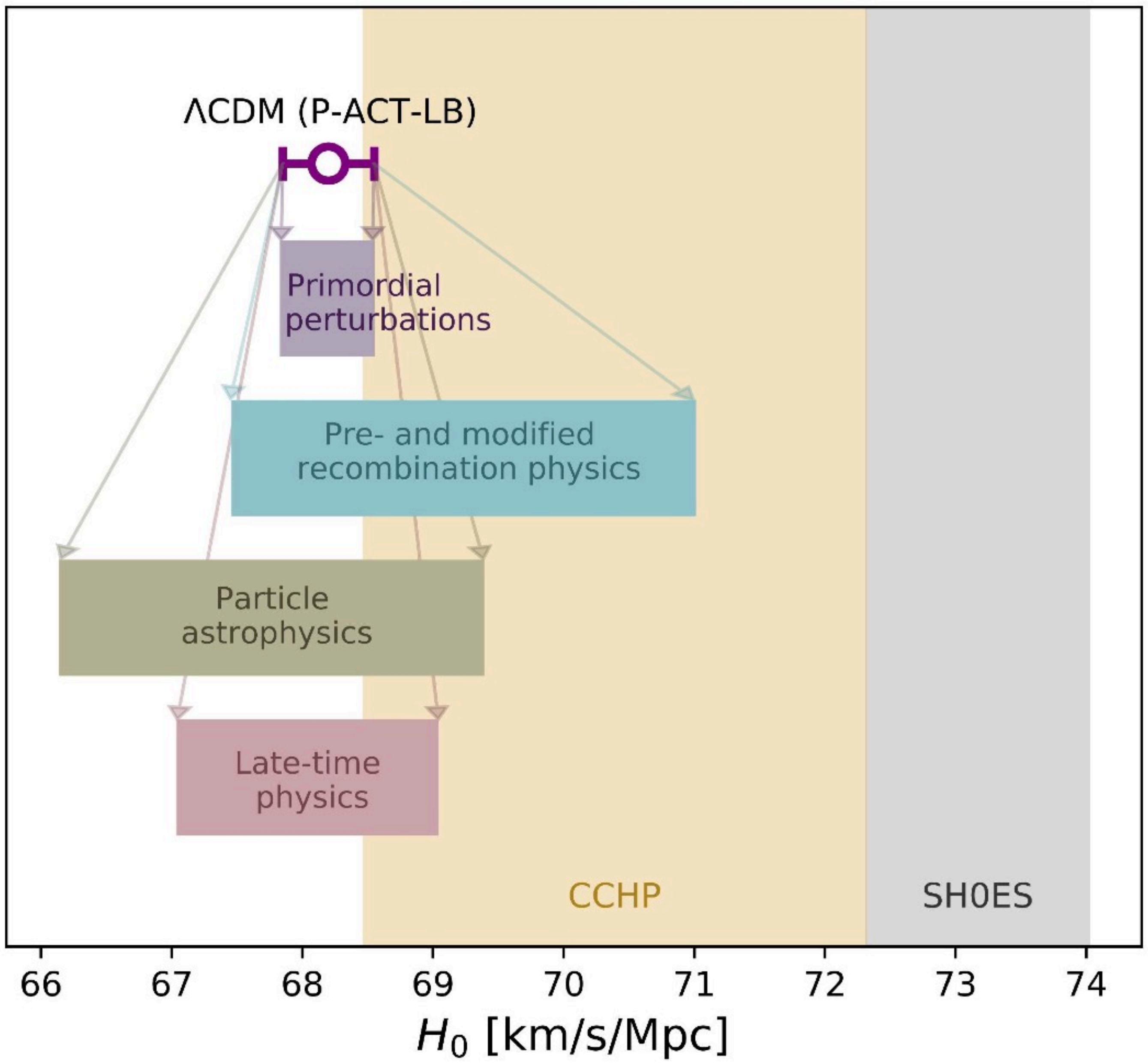


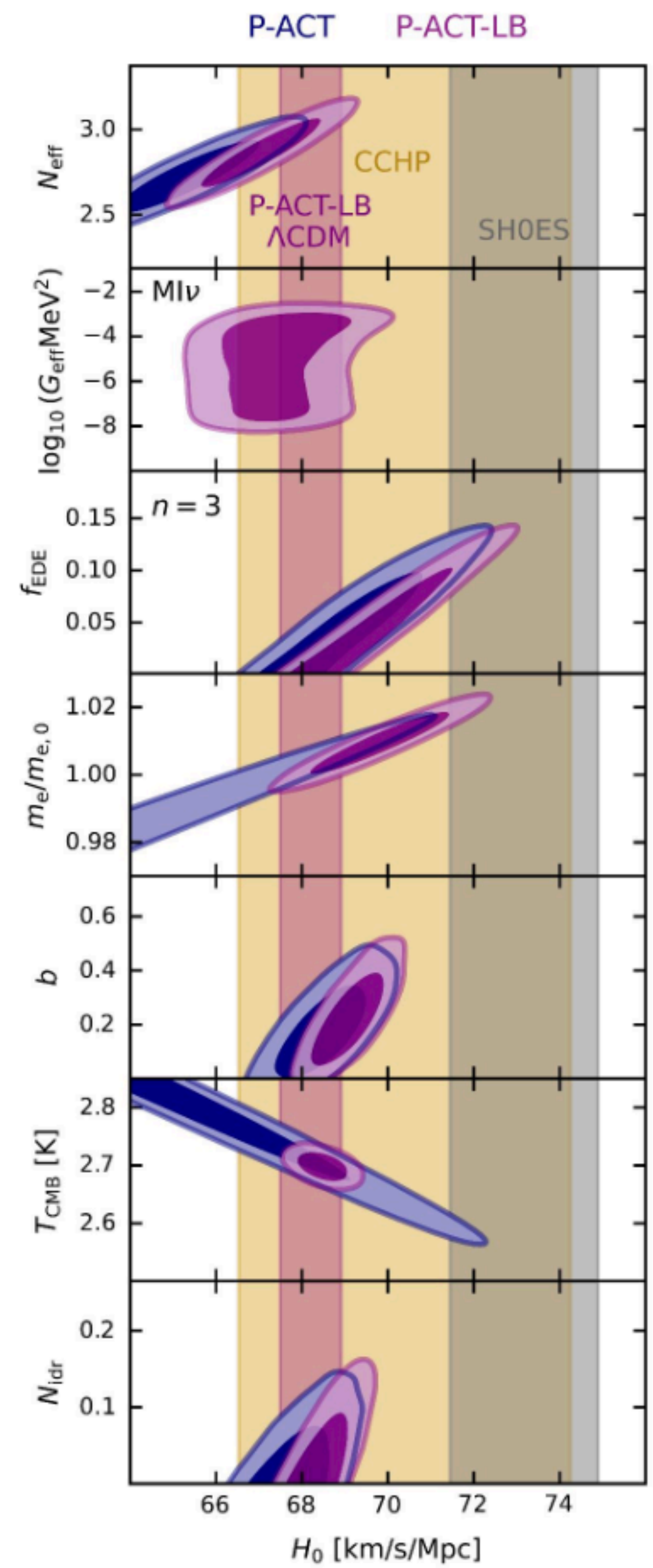
DES Y6 shear

DES Y6 3x2pt:
2601.14559



The dance of systematics vs new physics: H0





N_{eff}

Interacting neutrinos

Early dark energy

Varying m_e

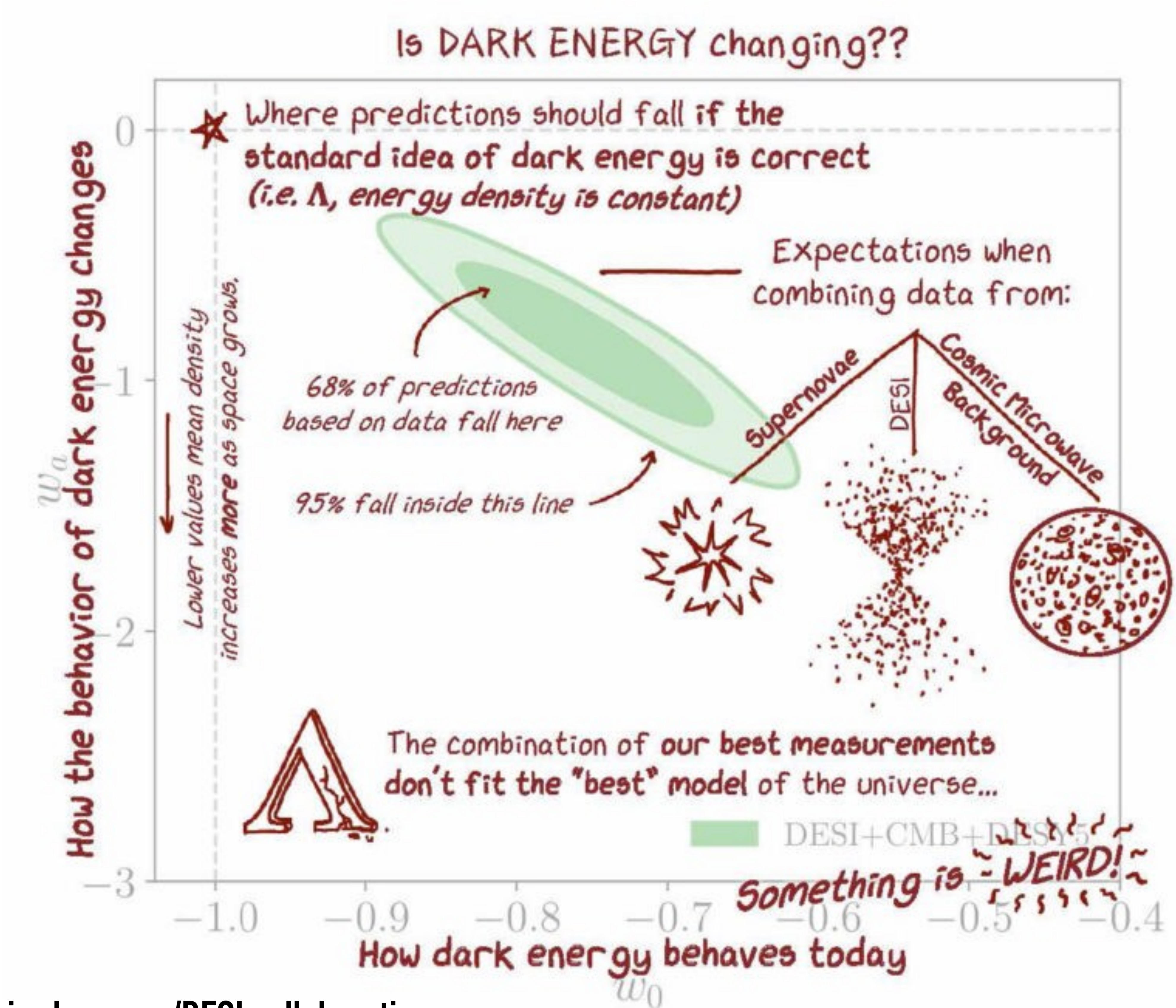
Primordial magnetic fields

CMB monopole temp.

SIDR

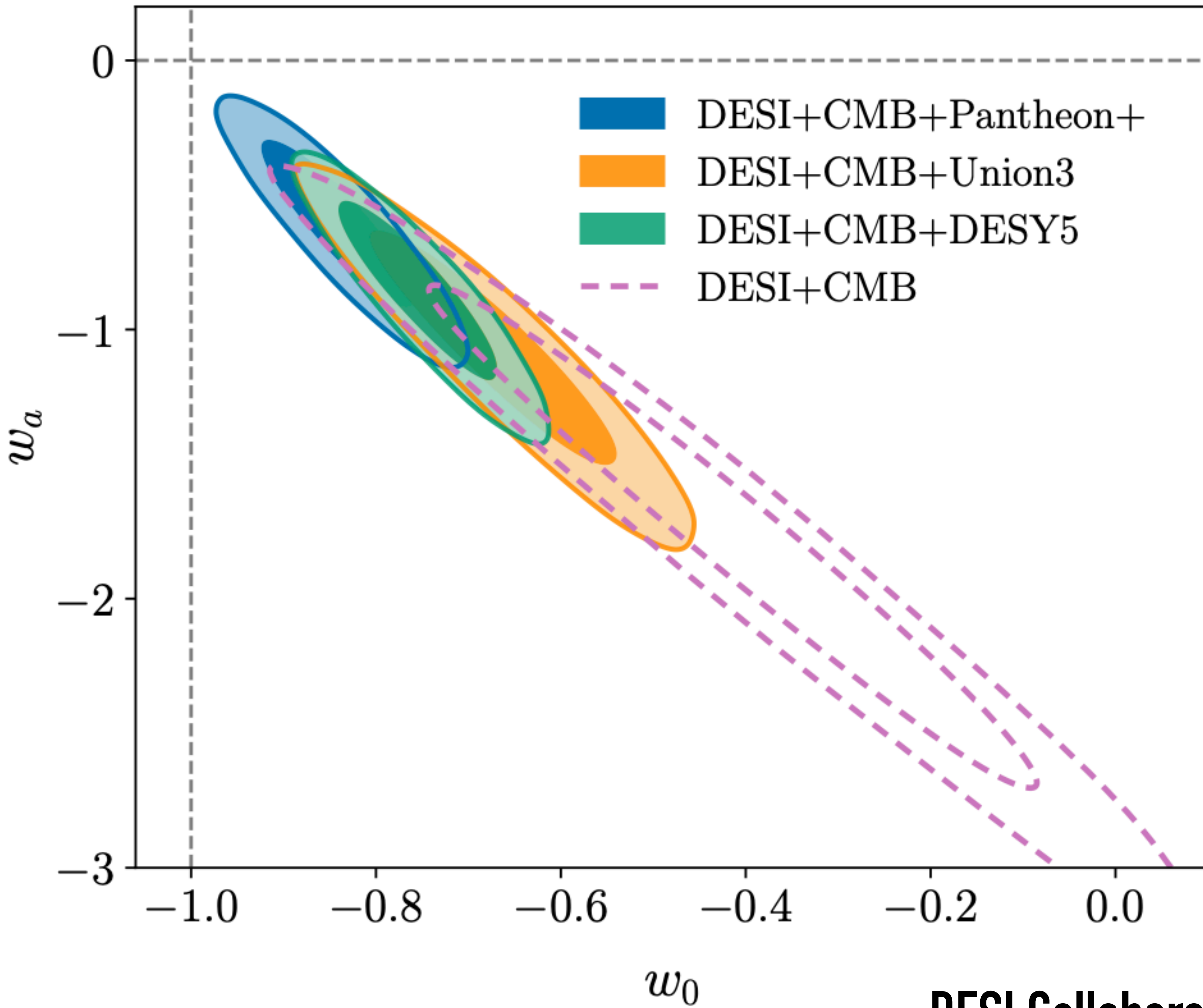
Calabrese, Hill, Jense, La Posta et al. 2503.14454

The dance of systematics vs new physics: dark energy



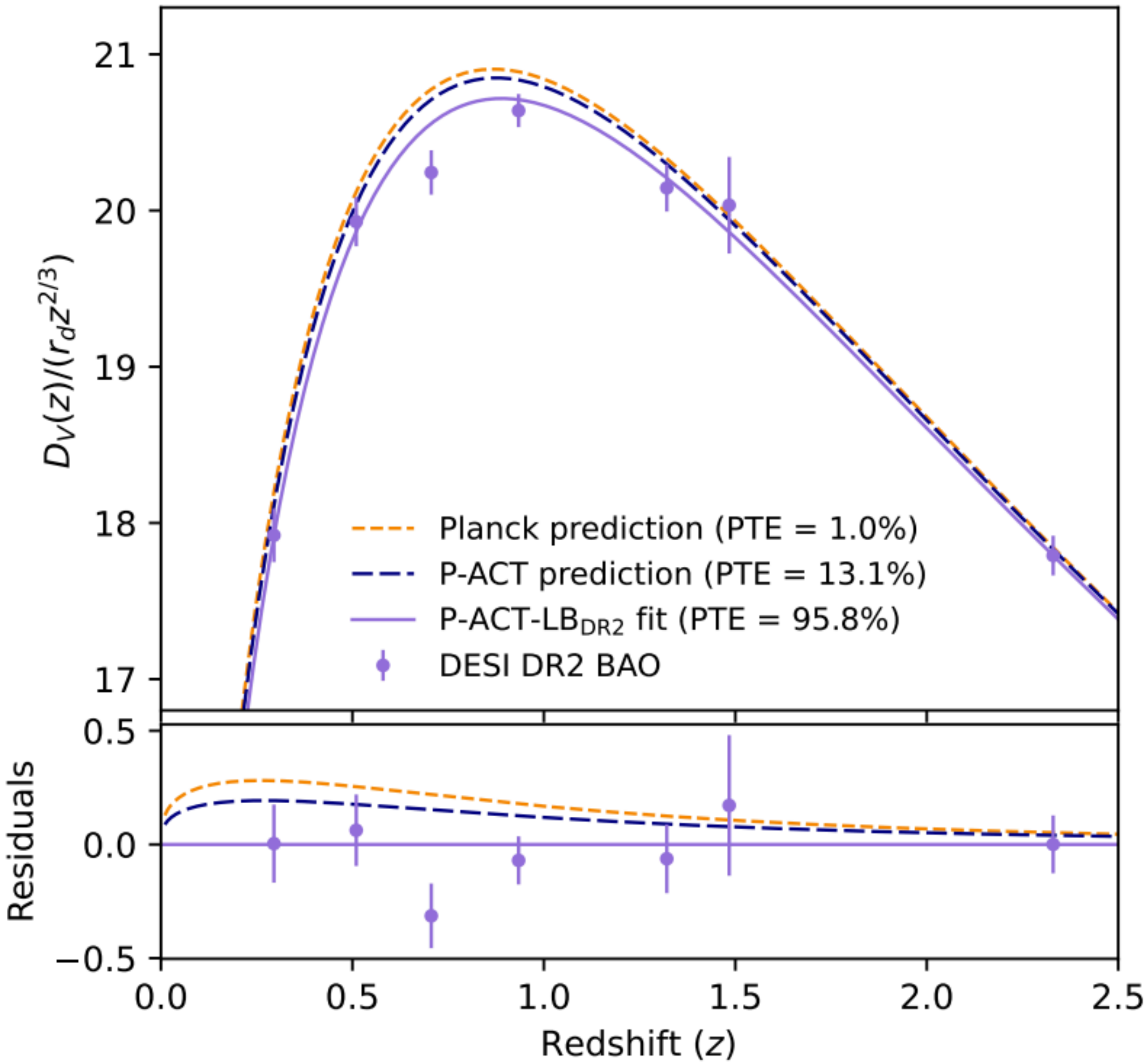
Credit: Claire Lamman/DESI collaboration

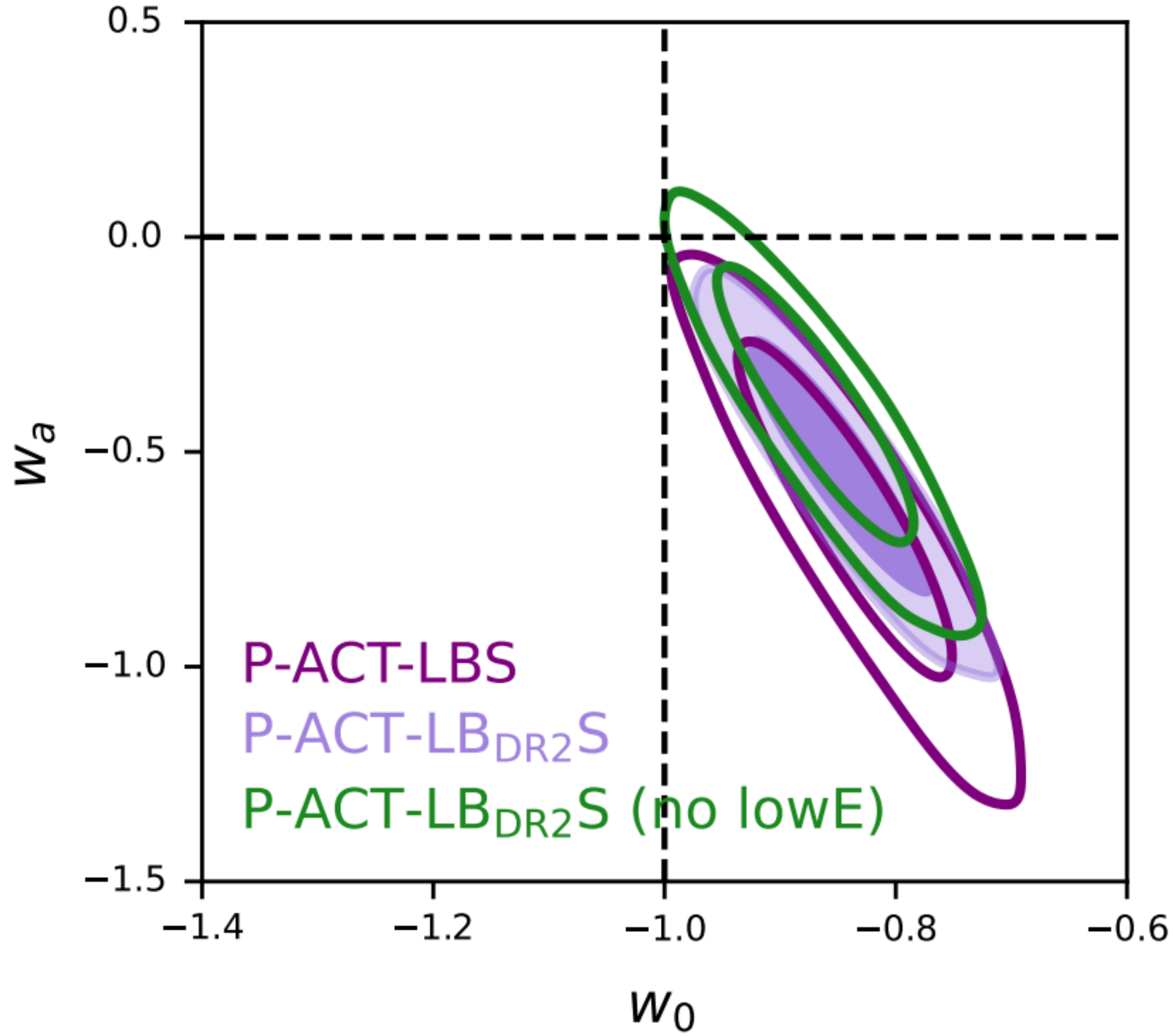
The dance of systematics vs new physics: dark energy



DESI Collaboration 2503.14738

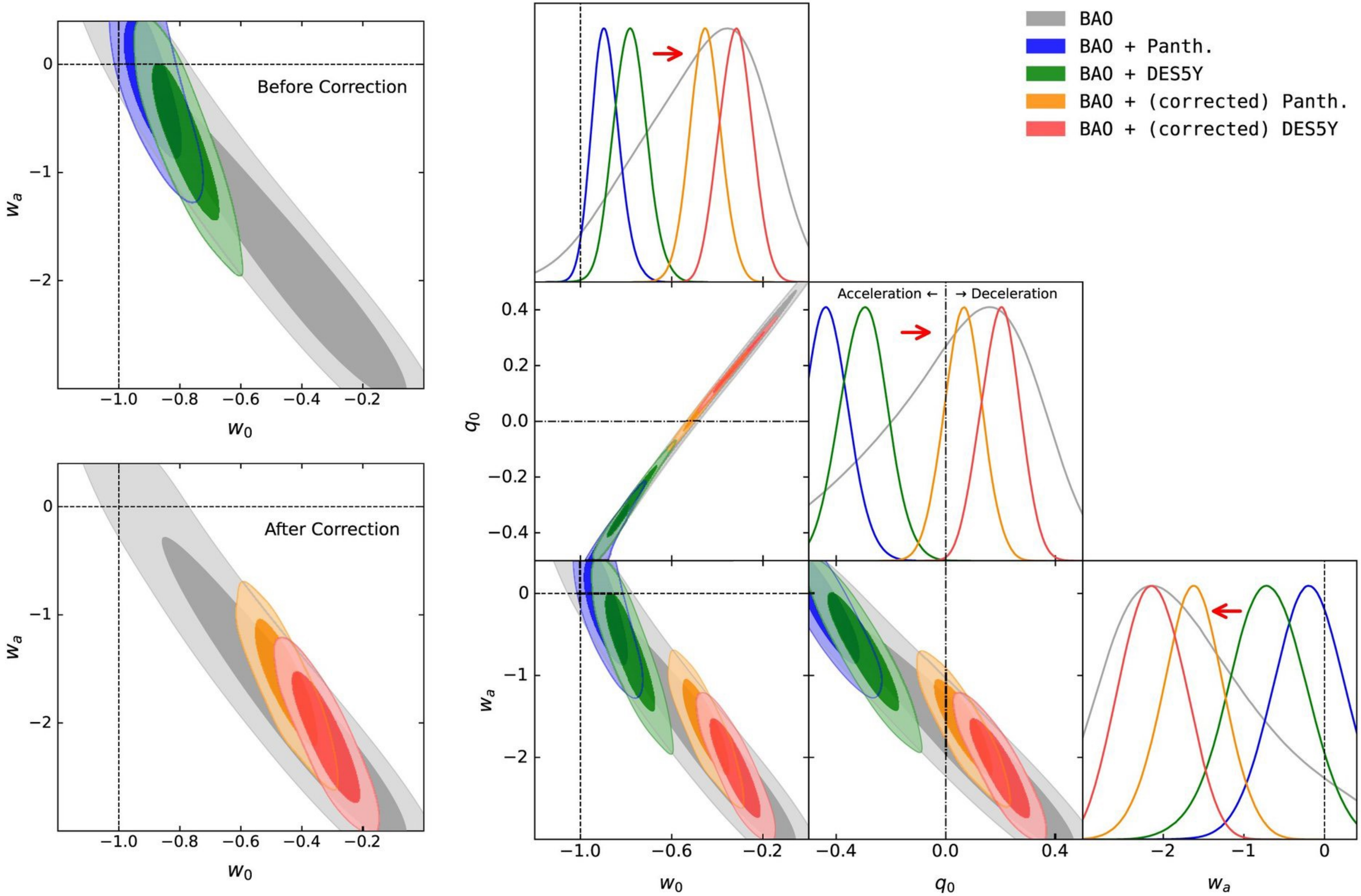
The dance of systematics vs new physics: dark energy





Calabrese, Hill, Jense, La Posta et al. 2503.14454

The dance of systematics vs new physics: dark energy

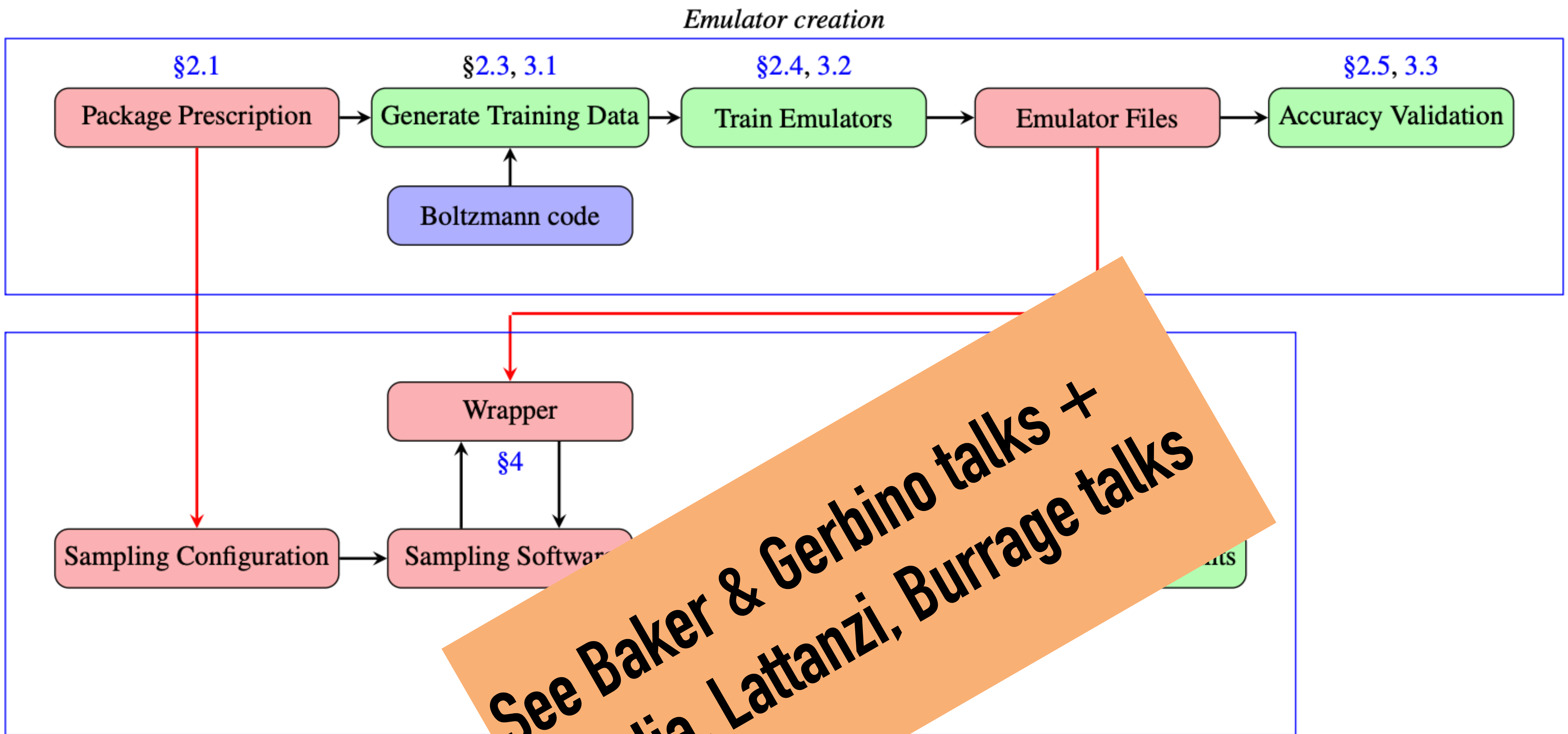


Son et al. 2510.13121

Big cosmological question for the 2020s (Canadian Long Range Plan 2020)

	ALMA	CASTOR	CFHT	CHORD	CMB-S4	Computation	Cooled infrared space telescope	Gemini	HabEx[11]	JWST	LiteBIRD	LSST	LUVOIR[11]	Lynx[11]	MSE	ngVLA[11]	Origins[11]	POEP	SKA1	Theory	VLOT	XRISM
How did the Universe begin and what is it made of?		✓		✓	✓	✓				✓	✓	✓			✓				✓	✓	✓	
What are the extreme conditions of the Universe?	✓	✓		✓		✓		✓		✓		✓		✓	✓	✓			✓	✓	✓	✓

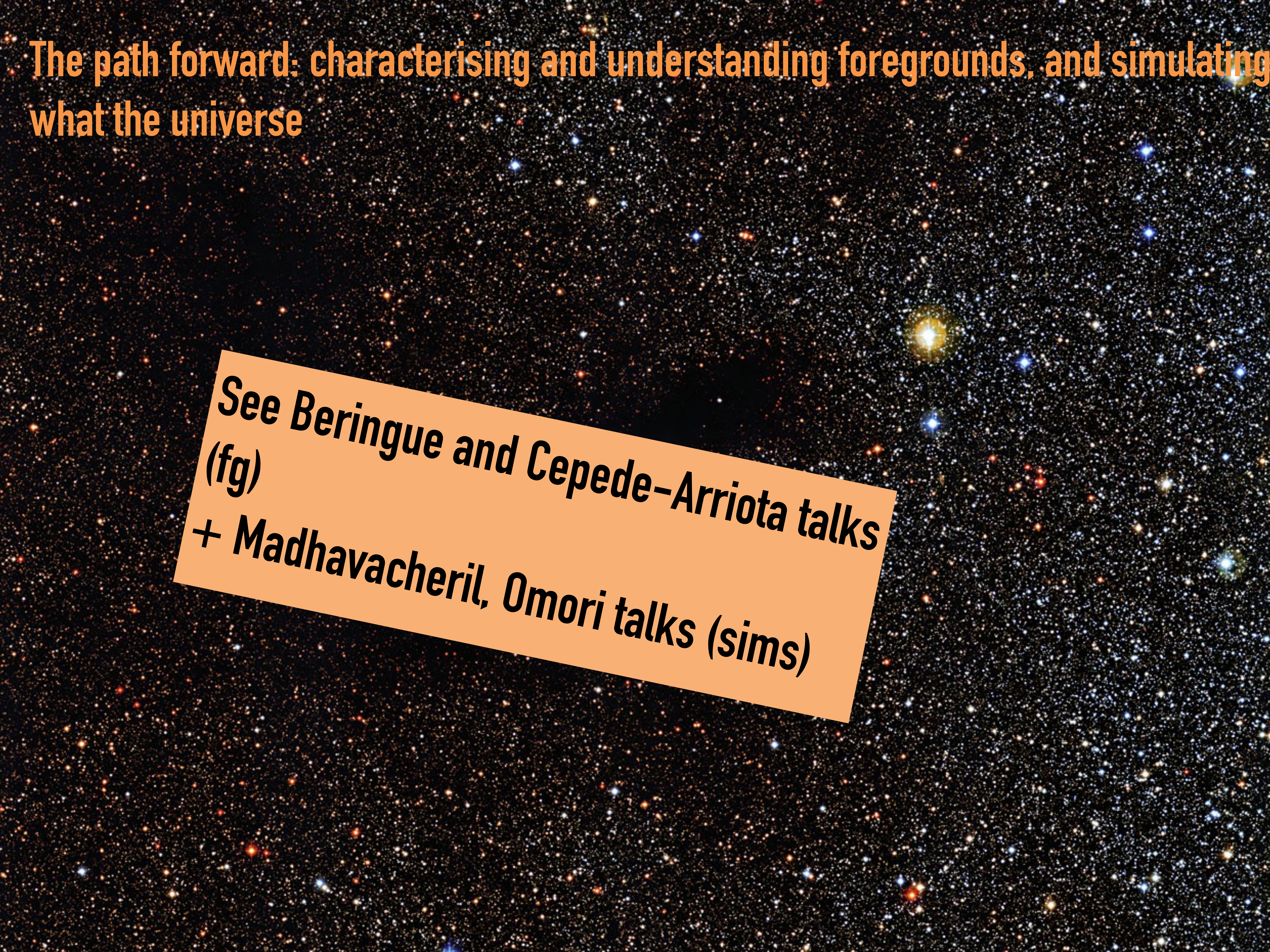
The path forward: understanding of theory and modelling uncertainties



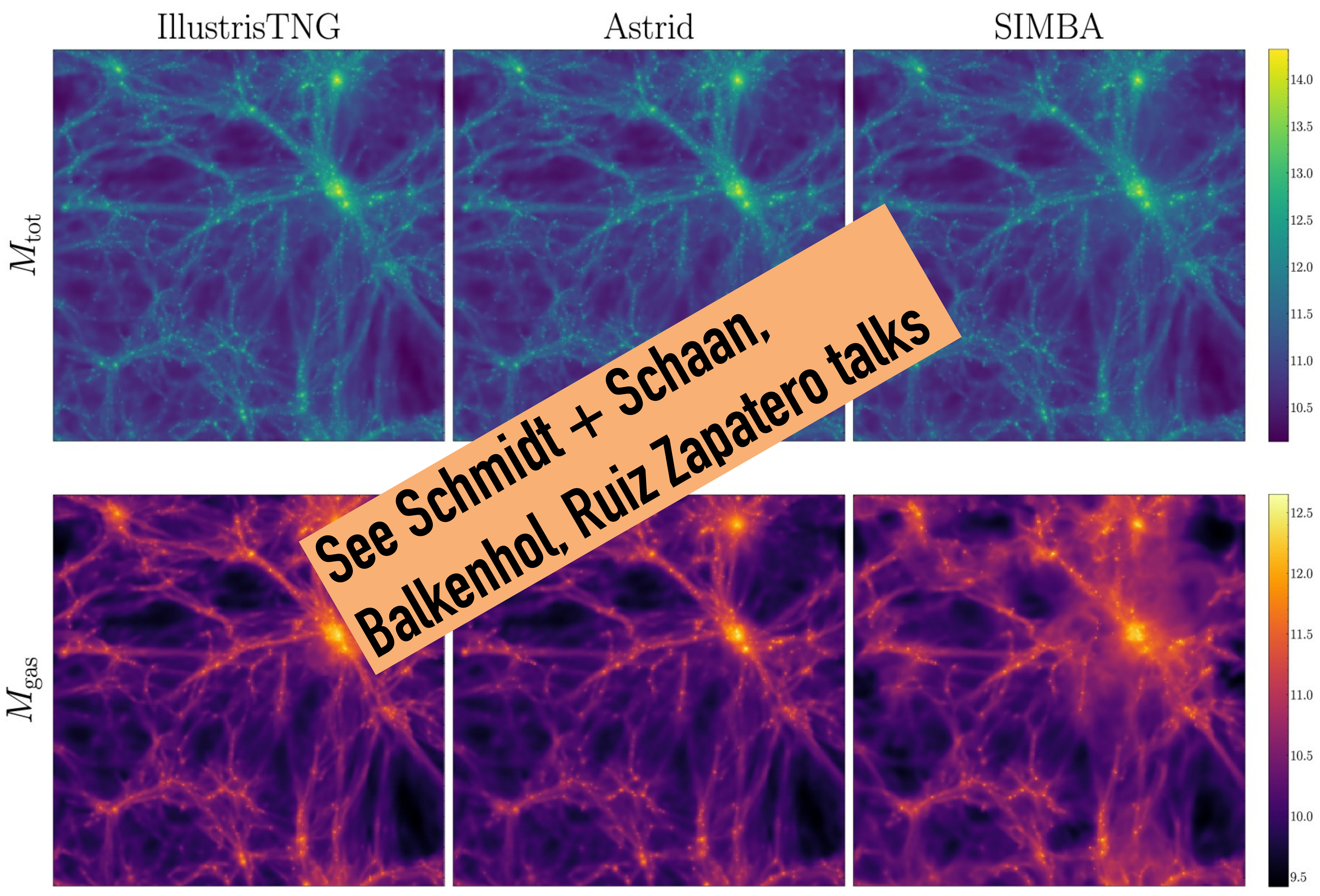
See Baker & Gerbino talks + Braglia, Lattanzi, Burrage talks

Jense et al. 2405.07903

The path forward: characterising and understanding foregrounds, and simulating what the universe



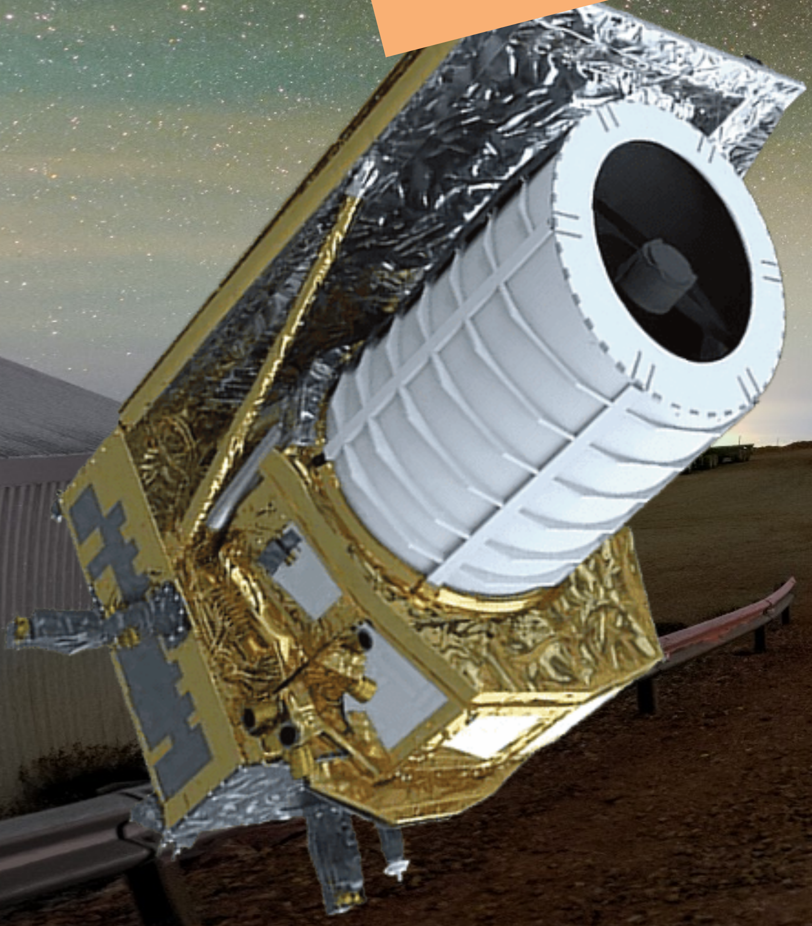
The path forward: adding just enough flexibility to our models



Akhmetzhanova et al 2508.05744

The path forward: deep (and iterative) knowledge of our data and likelihoods

See Duivenvoorden, Atkins talks +
Harrison, Nicola, Martinelli, Fabbian



Looking forward to a great meeting!