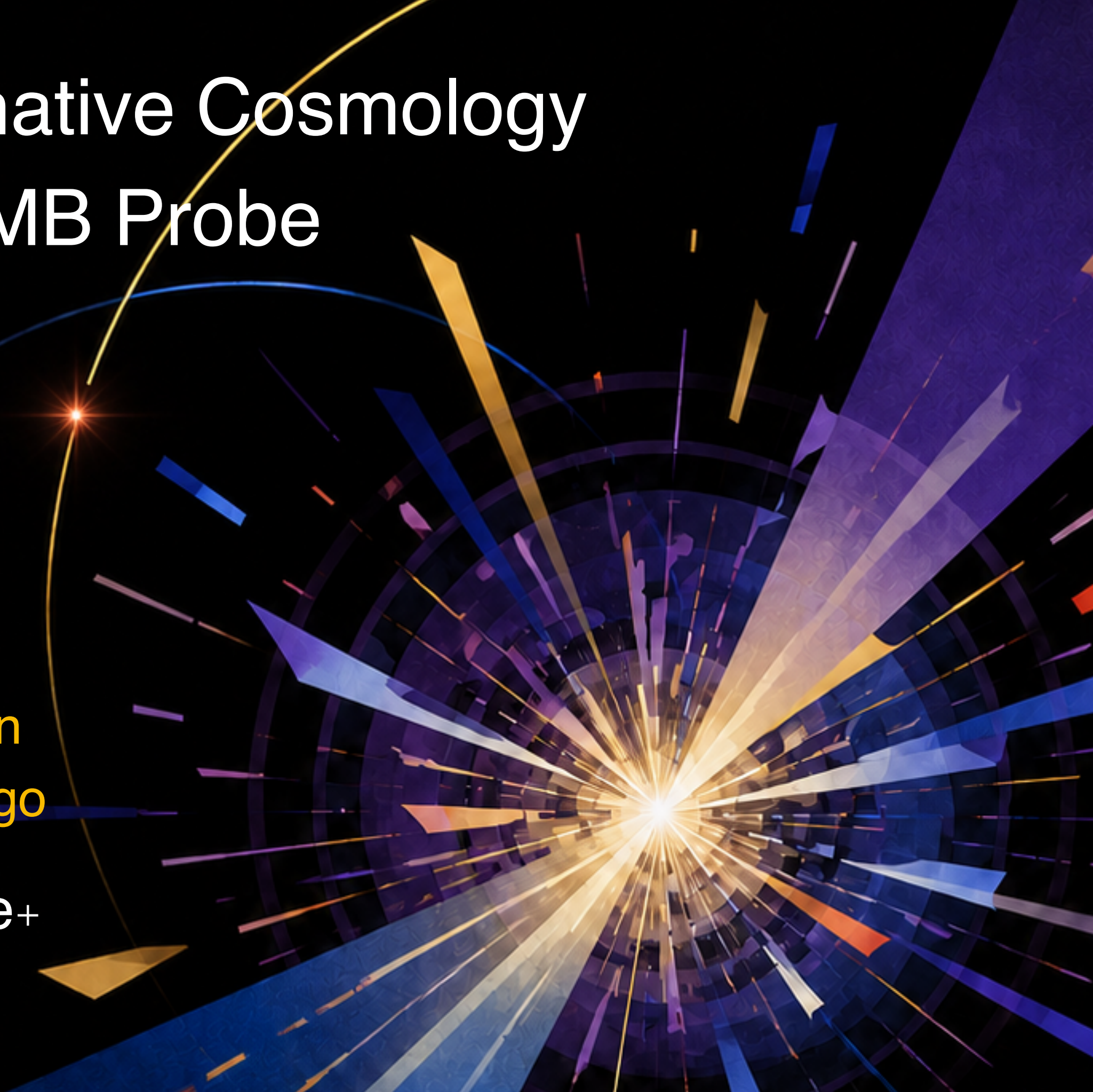


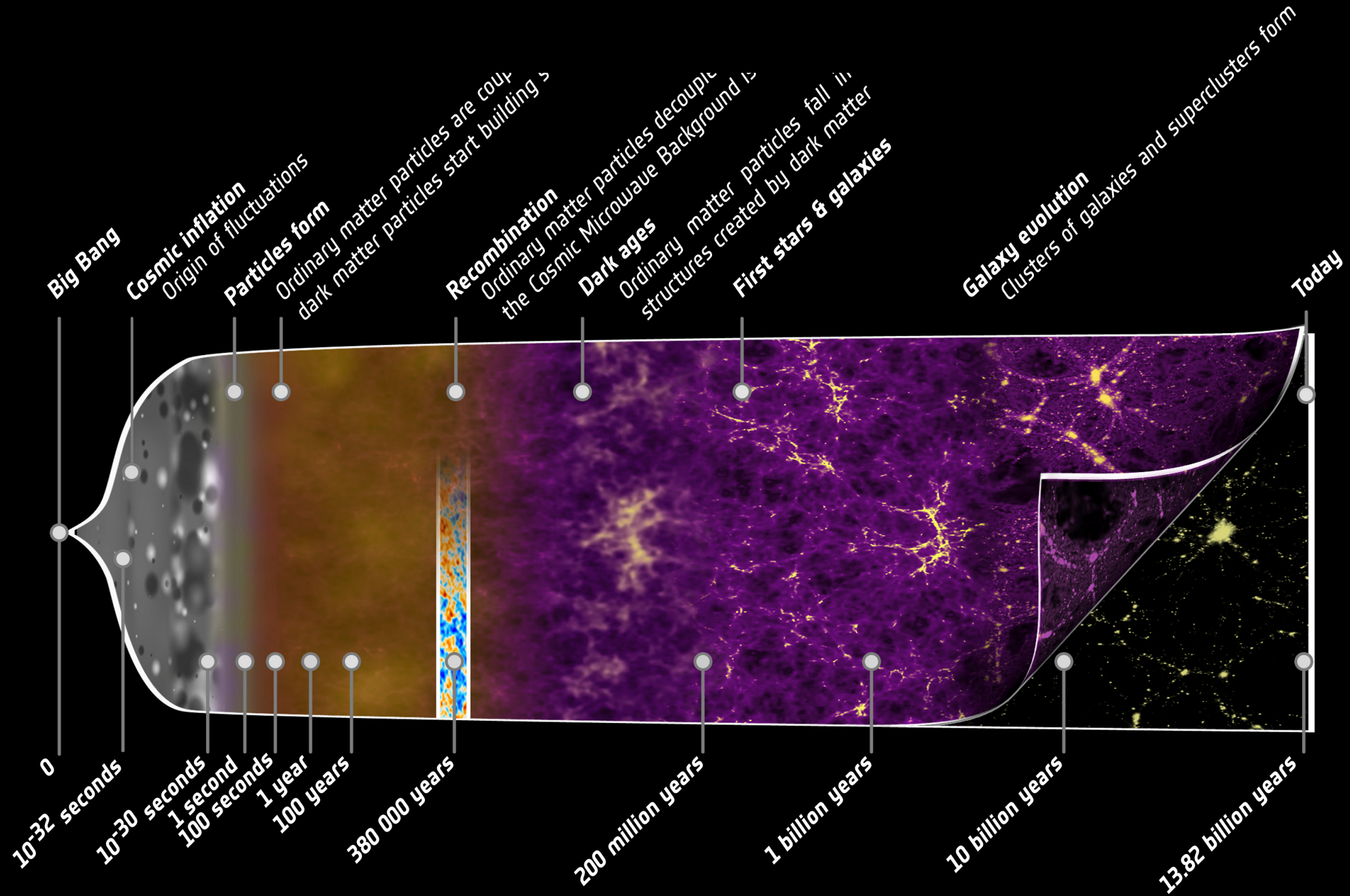
Transformative Cosmology with a CMB Probe

Daniel Green
UC San Diego

CMB Probe+

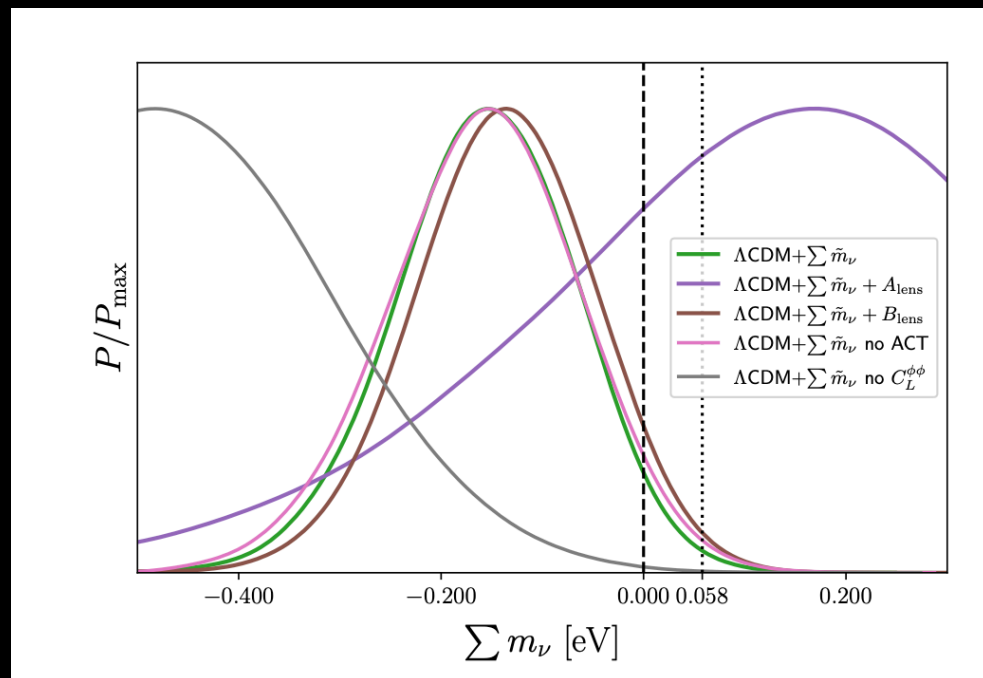


Cosmology is often presented as a complete story...

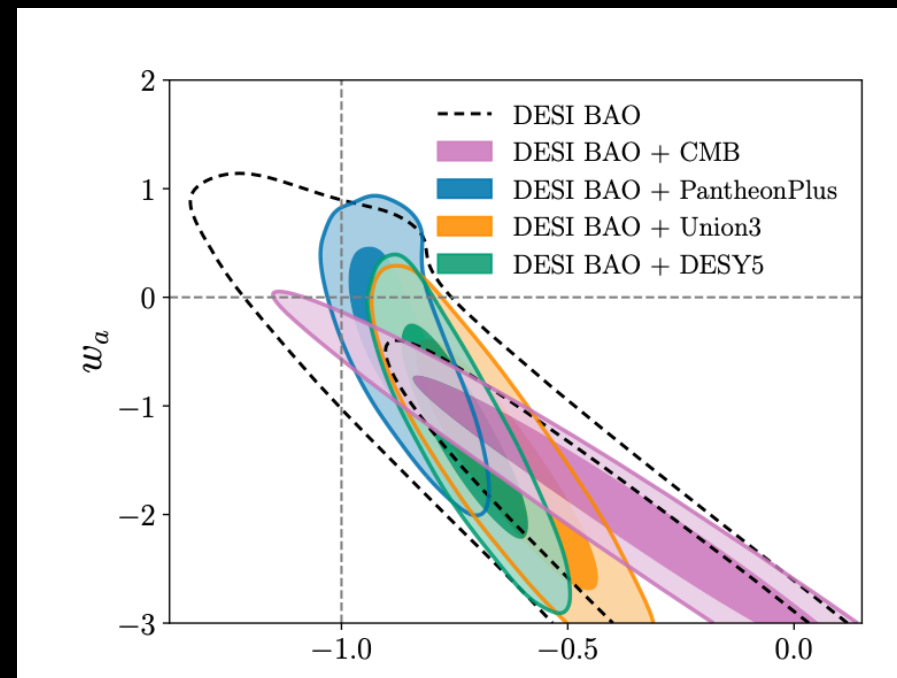


What current data tells us is not so simple...

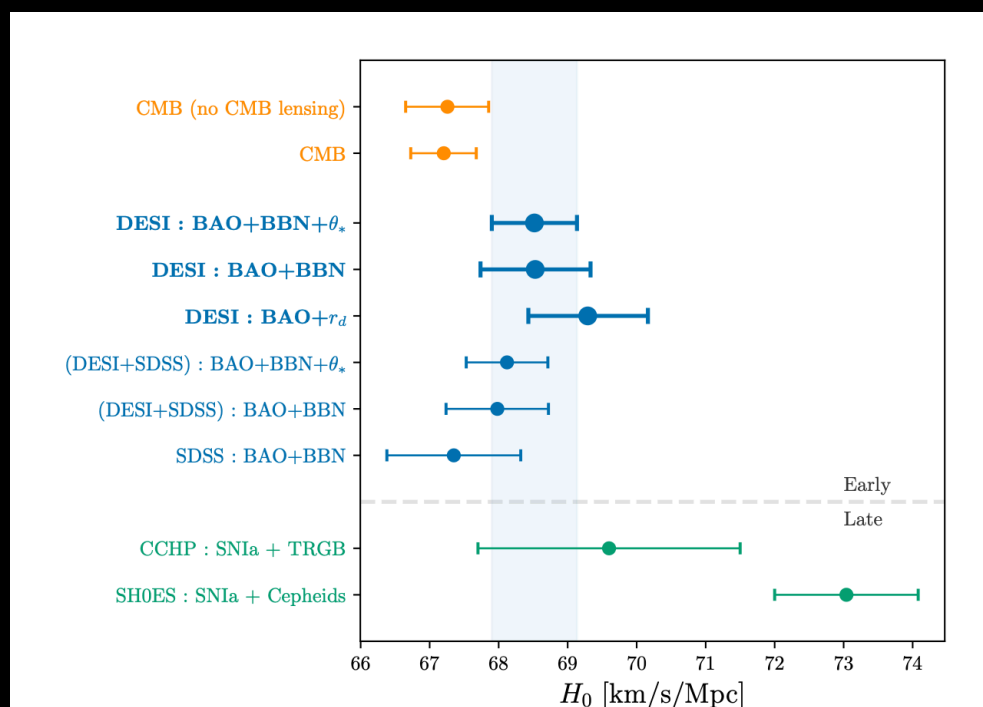
Neutrino Mass



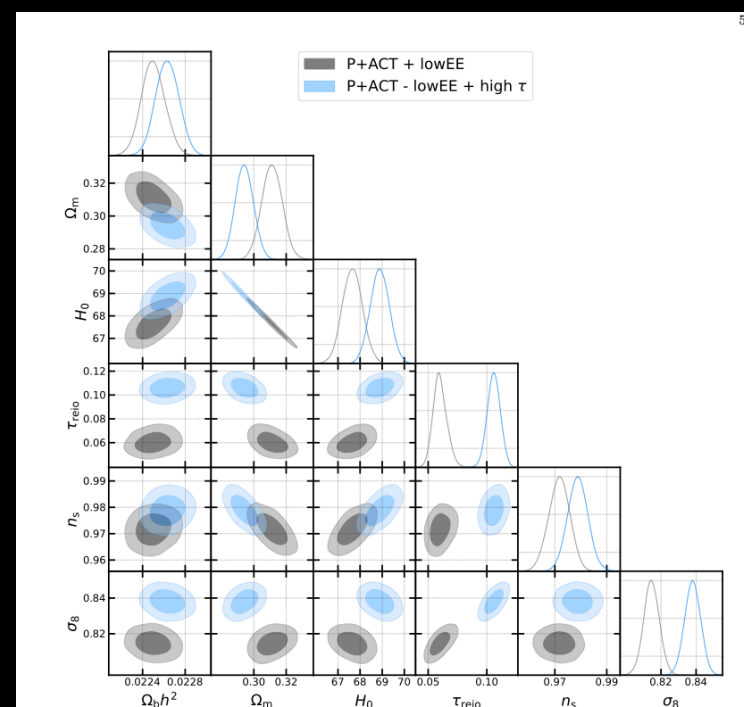
Dark Energy



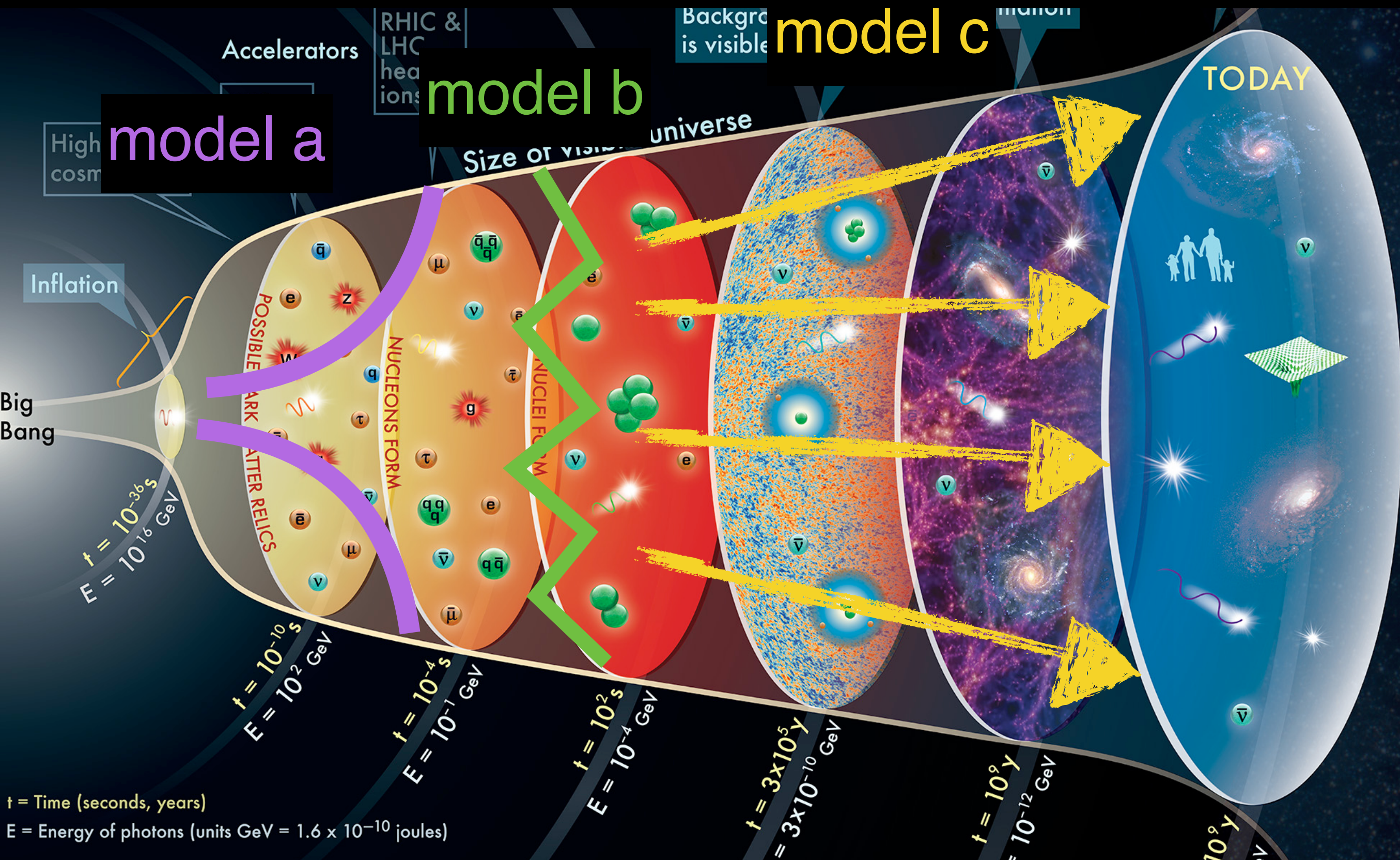
Hubble Parameter



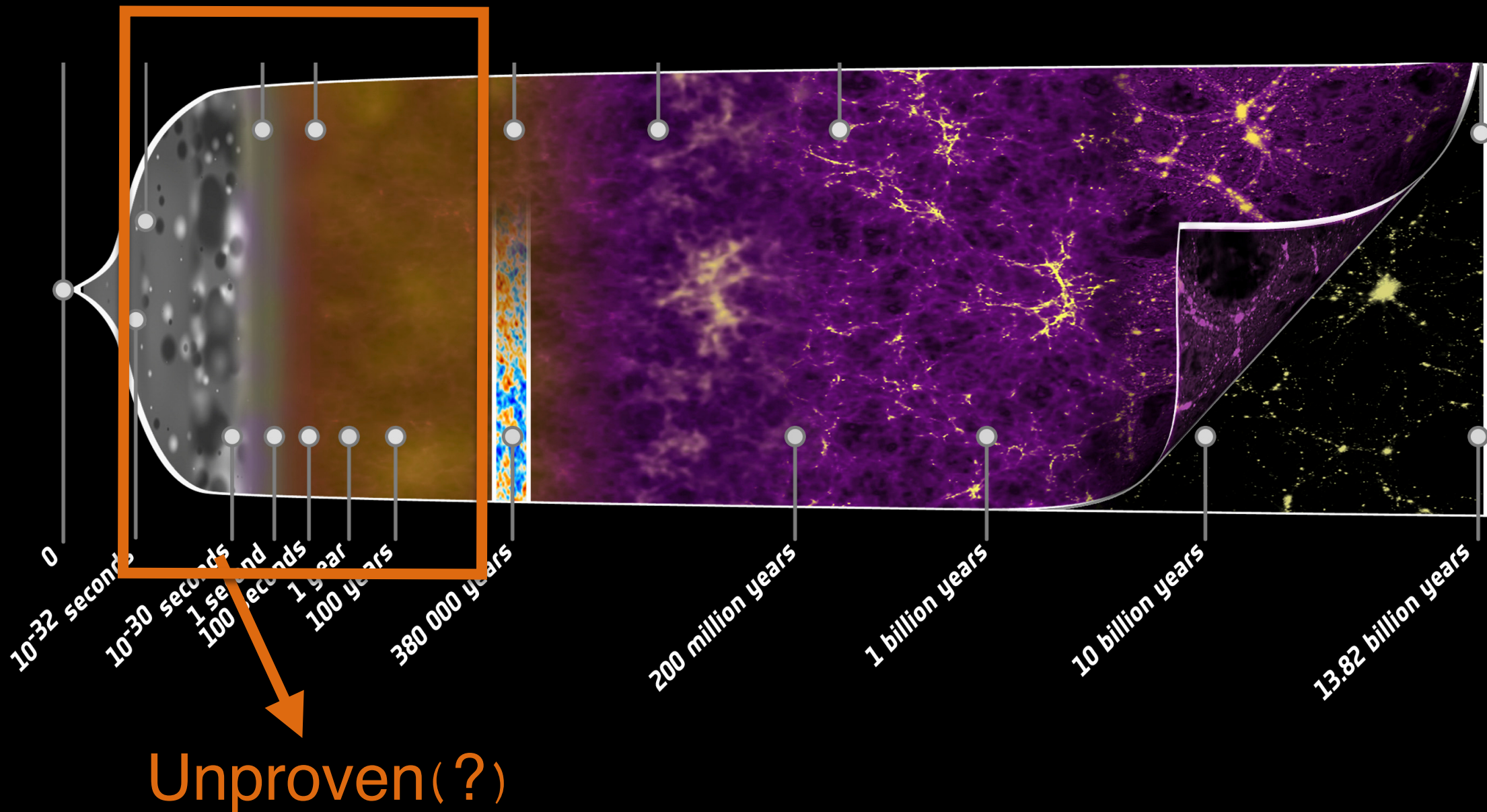
Optical Depth



Attempts to explain the data change the picture



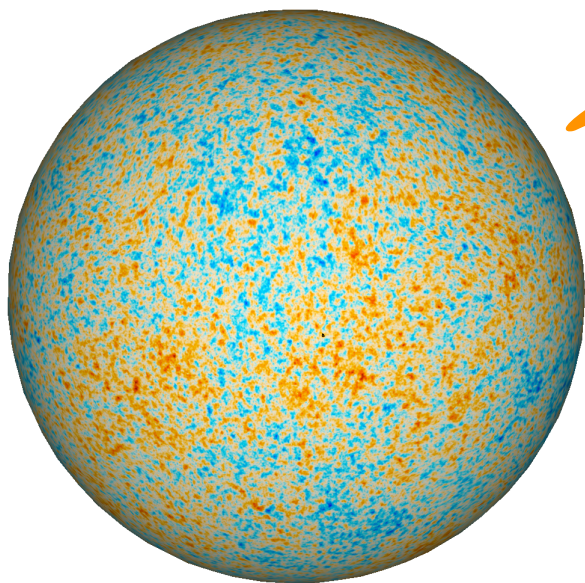
These models are viable because we don't know what happened in the early universe



CMB observables

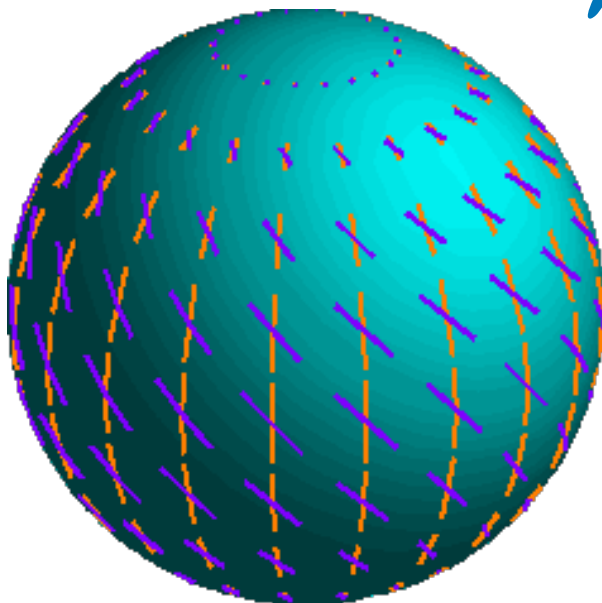
CMB Temperature

T

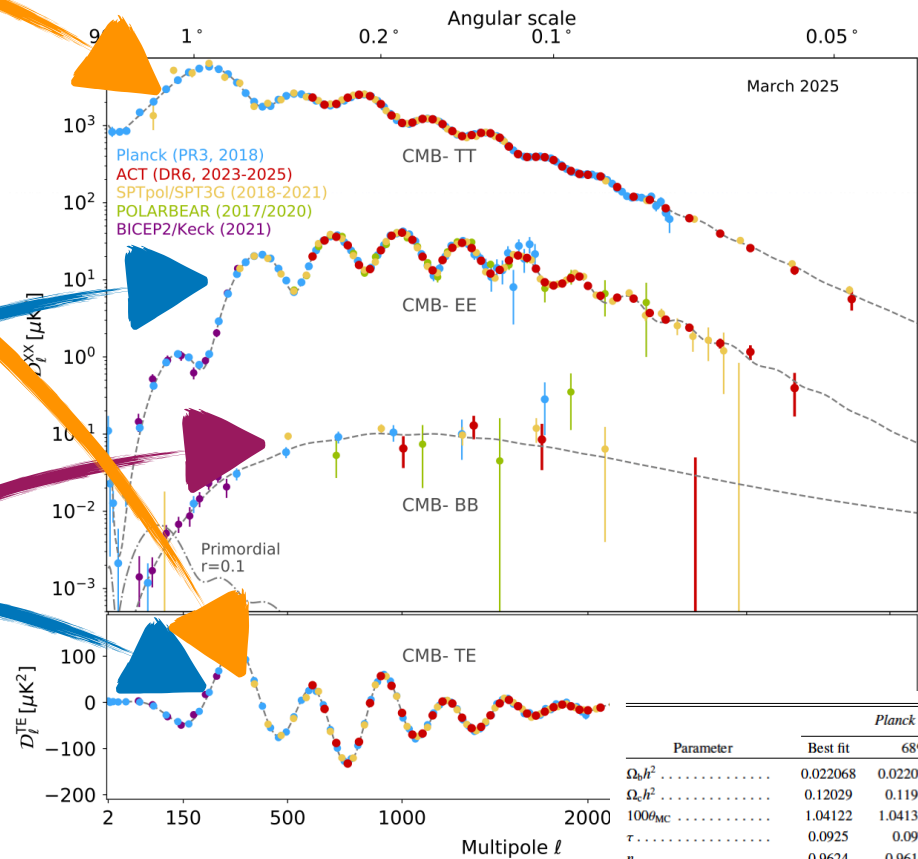


E

CMB Polarization



B



Analysis

Parameter	Planck		Planck+lensing		Planck+WP	
	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04150	1.04141 ± 0.00067	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0949	0.089 ± 0.032	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9675	0.9635 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.098	3.085 ± 0.057	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6825	0.686 ± 0.020	0.6964	0.693 ± 0.019	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314 ± 0.020	0.3036	0.307 ± 0.019	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8344	0.834 ± 0.027	0.8285	0.823 ± 0.018	0.8347	0.829 ± 0.012
z_{dr}	11.35	$11.4^{+4.0}_{-2.8}$	11.45	$10.8^{+3.1}_{-2.5}$	11.37	11.1 ± 1.1
H_0	67.11	67.4 ± 1.4	68.14	67.9 ± 1.5	67.04	67.3 ± 1.2
$10^9 A_s$	2.215	2.23 ± 0.16	2.215	$2.19^{+0.12}_{-0.14}$	2.215	$2.196^{+0.051}_{-0.060}$
$\Omega_m h^2$	0.14300	0.1423 ± 0.0029	0.14094	0.1414 ± 0.0029	0.14305	0.1426 ± 0.0025
$\Omega_b h^2$	0.09597	0.09590 ± 0.00059	0.09603	0.09593 ± 0.00058	0.09591	0.09589 ± 0.00057
Y_p	0.247710	0.24771 ± 0.00014	0.247785	0.24775 ± 0.00014	0.247695	0.24770 ± 0.00012
Age/Gyr	13.819	13.813 ± 0.058	13.784	13.796 ± 0.058	13.8242	13.817 ± 0.048
z_{*}	1090.43	1090.37 ± 0.65	1090.01	1090.16 ± 0.65	1090.48	1090.43 ± 0.54
r_{*}	144.58	144.75 ± 0.66	145.02	144.96 ± 0.66	144.58	144.71 ± 0.60
$100\theta_{*}$	1.04139	1.04148 ± 0.00066	1.04164	1.04156 ± 0.00066	1.04136	1.04147 ± 0.00062
z_{drag}	1059.32	1059.29 ± 0.65	1059.59	1059.43 ± 0.64	1059.25	1059.25 ± 0.58
r_{drag}	147.34	147.53 ± 0.64	147.74	147.70 ± 0.63	147.36	147.49 ± 0.59
k_D	0.14026	0.14007 ± 0.00064	0.13998	0.13996 ± 0.00062	0.14022	0.14009 ± 0.00063
$100\theta_D$	0.161332	0.16137 ± 0.00037	0.161196	0.16129 ± 0.00036	0.161375	0.16140 ± 0.00034
z_{eq}	3402	3386 ± 69	3352	3362 ± 69	3403	3391 ± 60
$100\theta_{eq}$	0.8128	0.816 ± 0.013	0.8224	0.821 ± 0.013	0.8125	0.815 ± 0.011
$r_{drag}/D_V(0.57)$	0.07130	0.0716 ± 0.0011	0.07207	0.0719 ± 0.0011	0.07126	0.07147 ± 0.00091

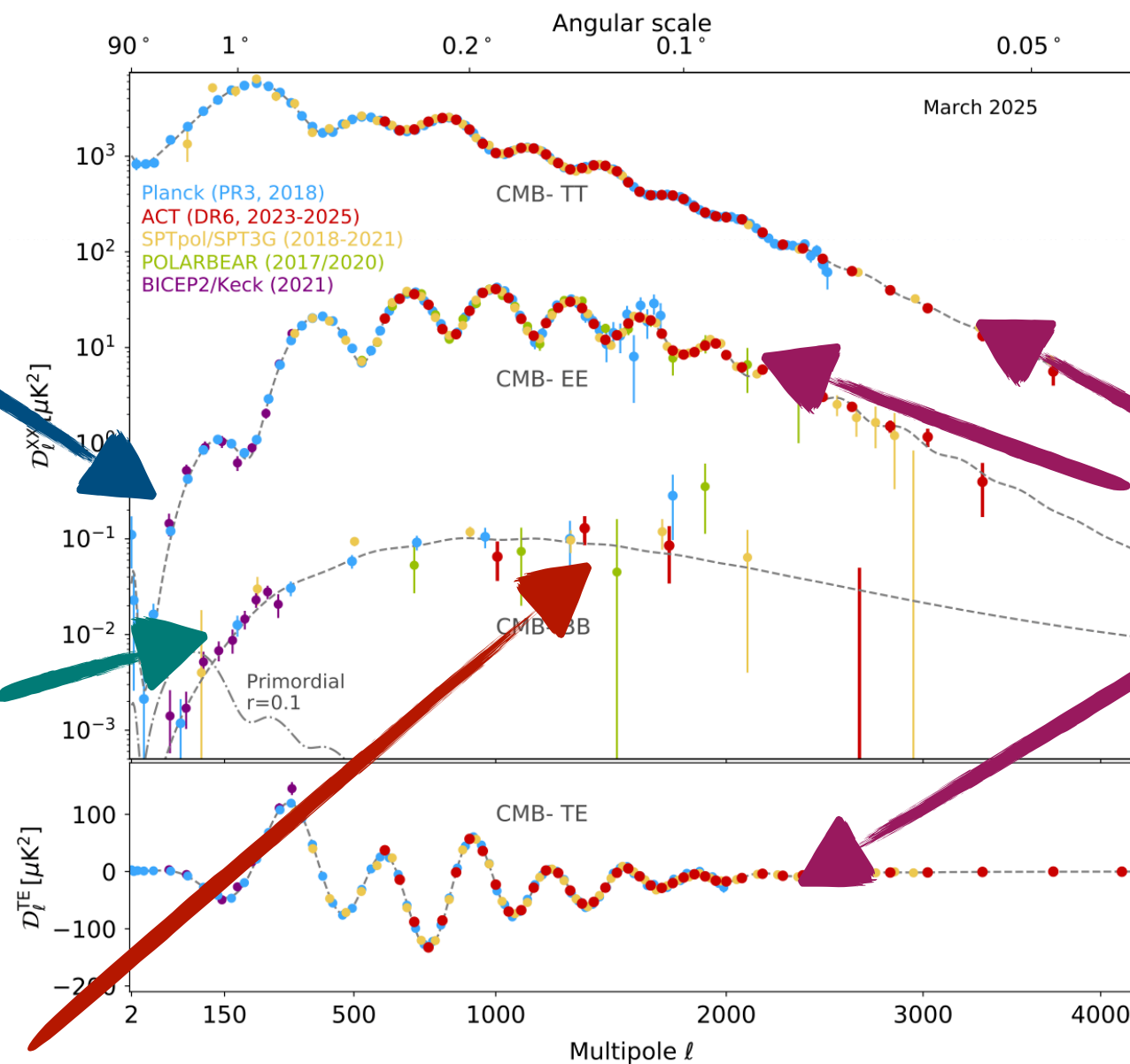
Cosmic Parameters

CMB observables

Optical Depth (τ)

Primordial GWs (r)

Neutrino Mass (M_ν)

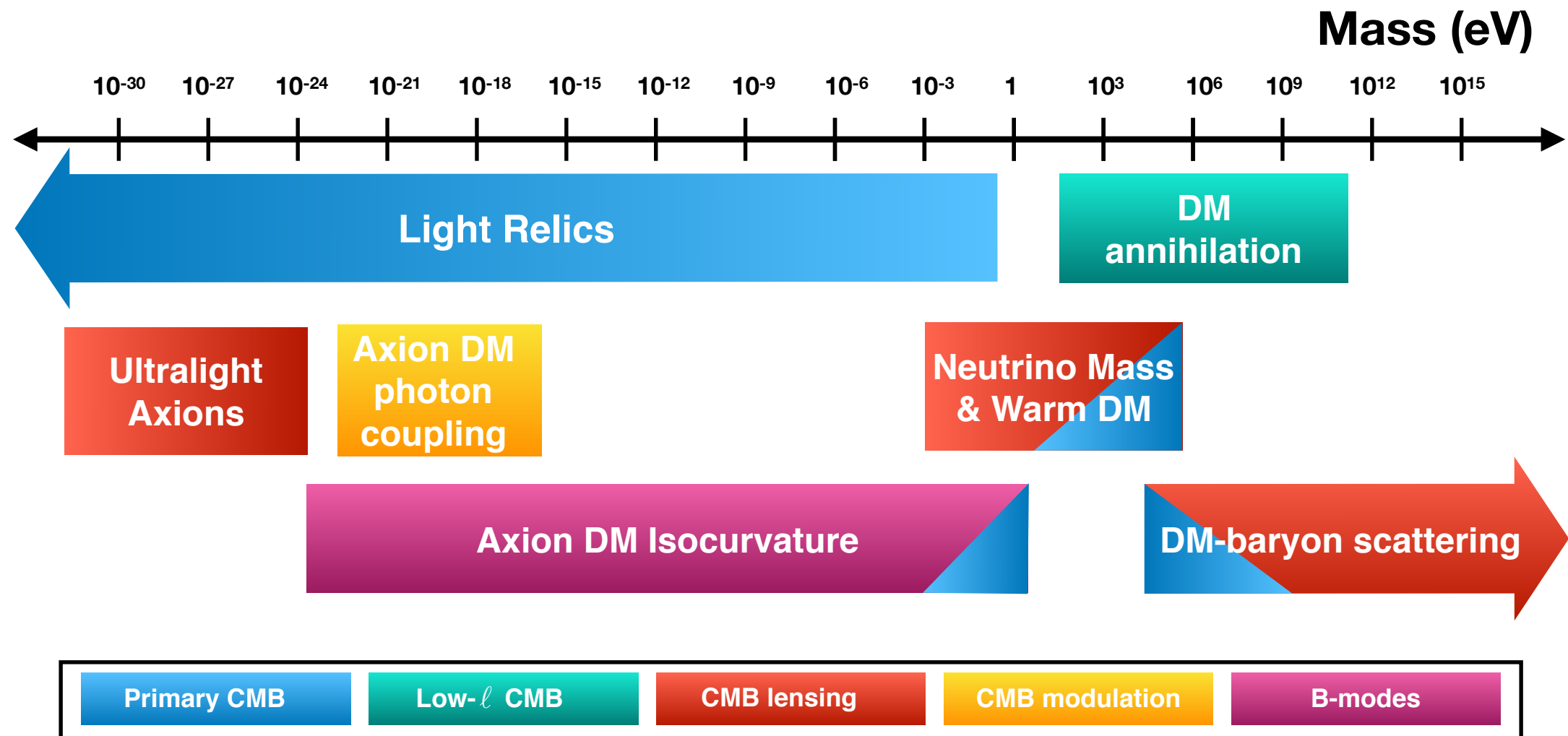


Dark Sectors (N_{eff})

CMB observables

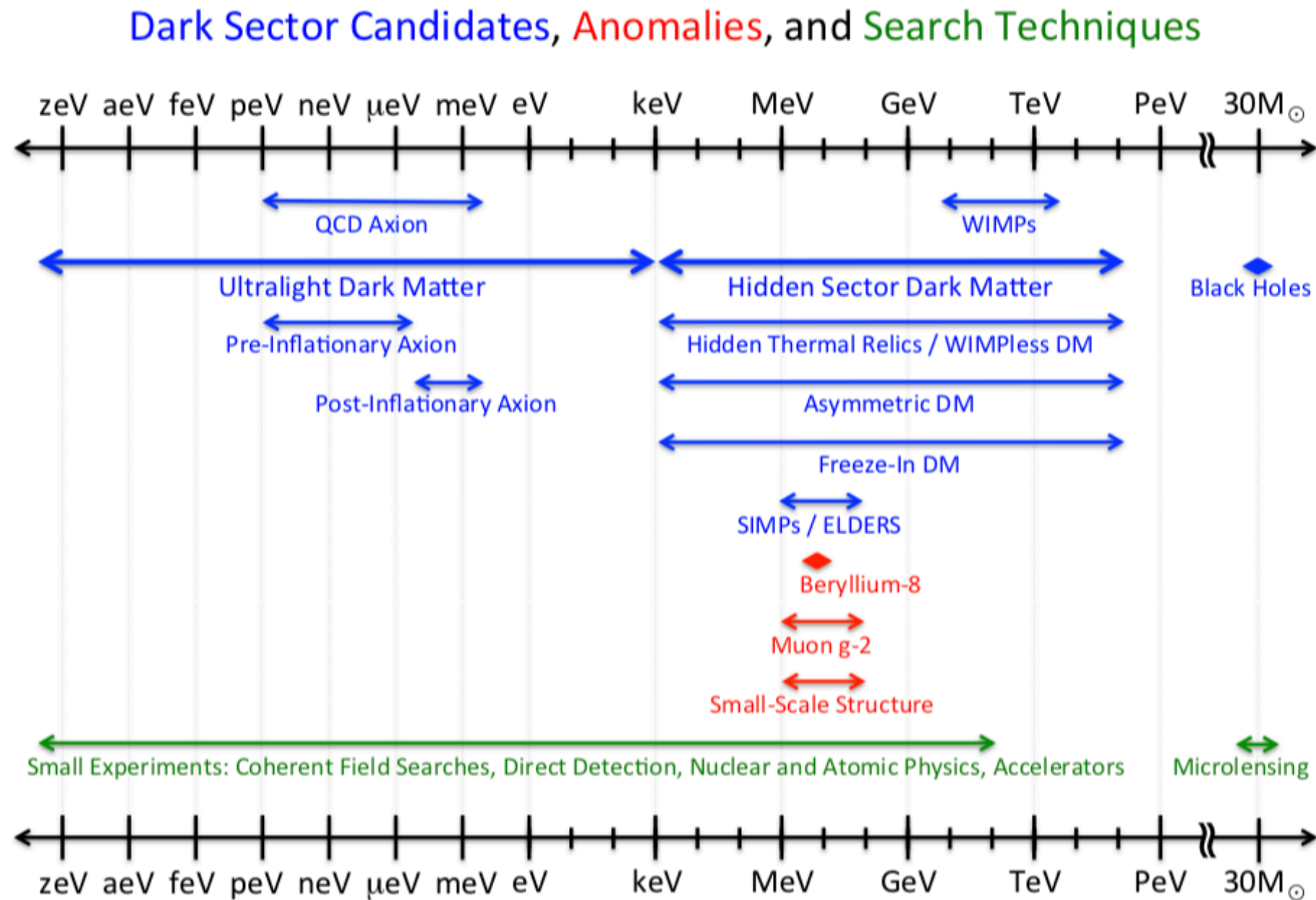
A single CMB (Probe+) survey = many experiments

E.g. One survey probes dark sectors in many ways



CMB observables

Compare to CMB + list of all dark matter experiments



arXiv: 1707.04591

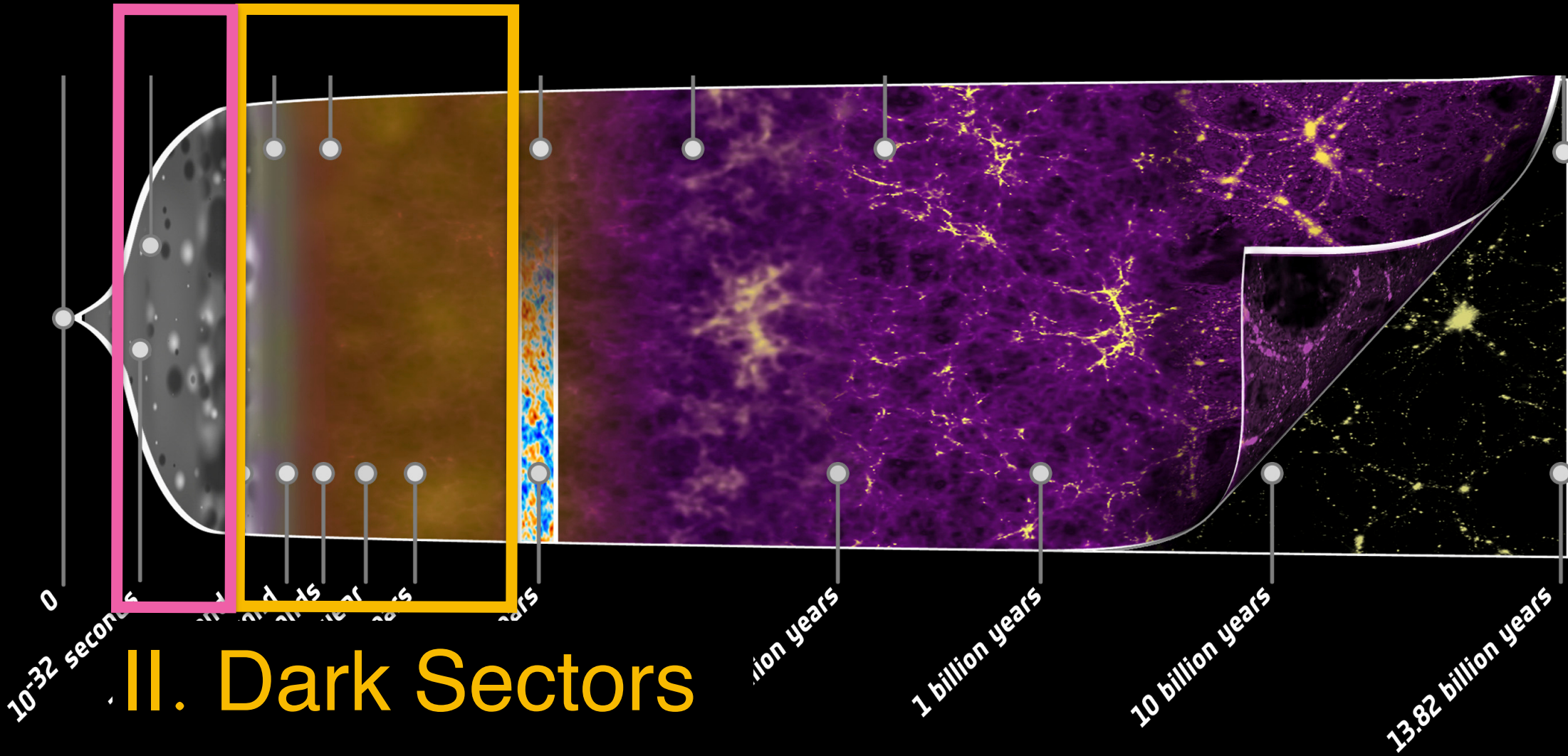
Cosmology via CMB Probe+

A CMB Probe+ survey can address a lot of critical questions:

- Pin down cosmic parameters
- Explore fundamentally new territory for the early universe
- Determine the neutrino mass (and how they affect structure)
- Reionization (Optical Depth, Duration, patchy)
- High redshift clusters, structure formation
- ... and we keep finding new applications

Let's focus on two key areas:

I. Inflation

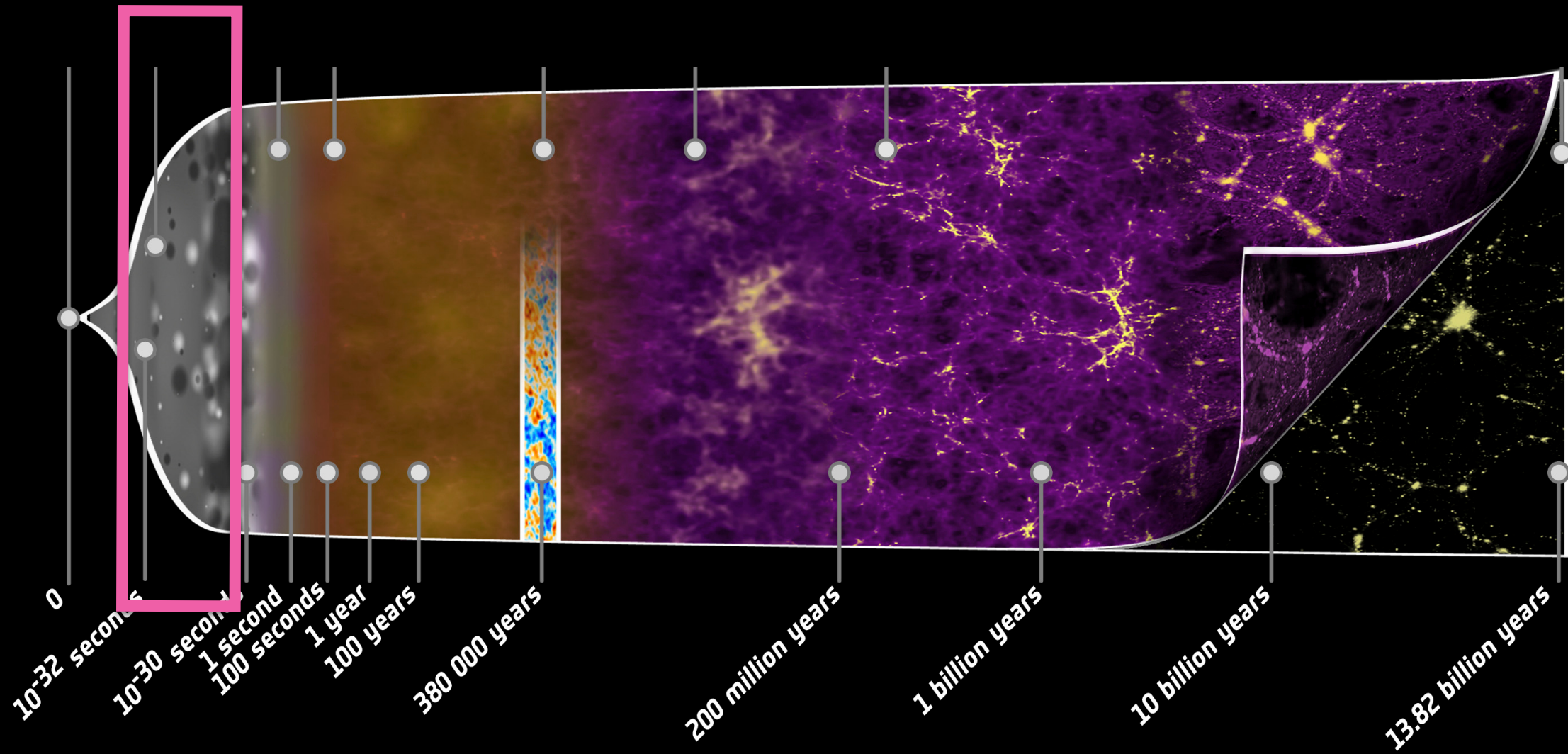


II. Dark Sectors

Inflation

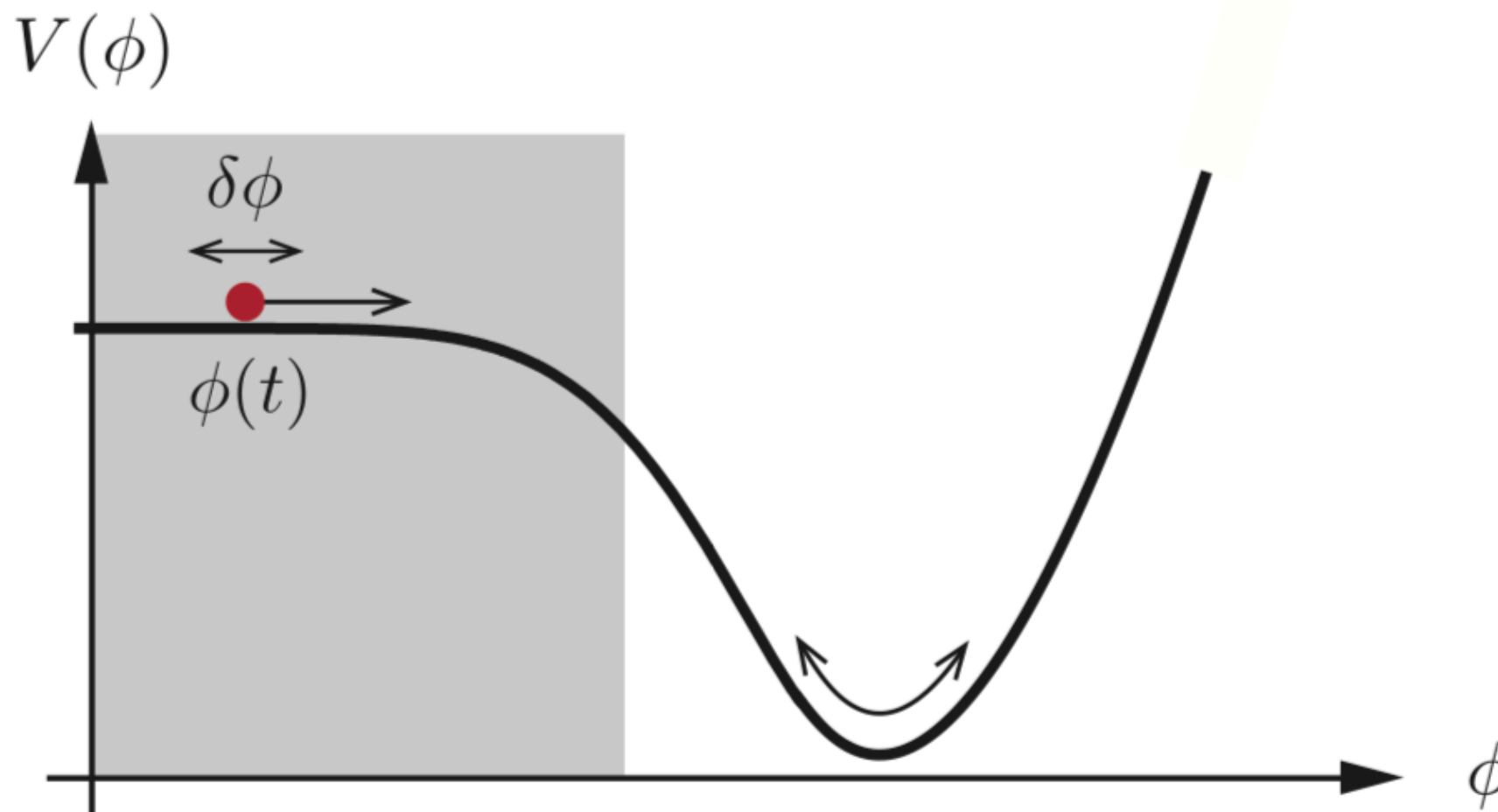


I. Inflation



The Nature of Inflation

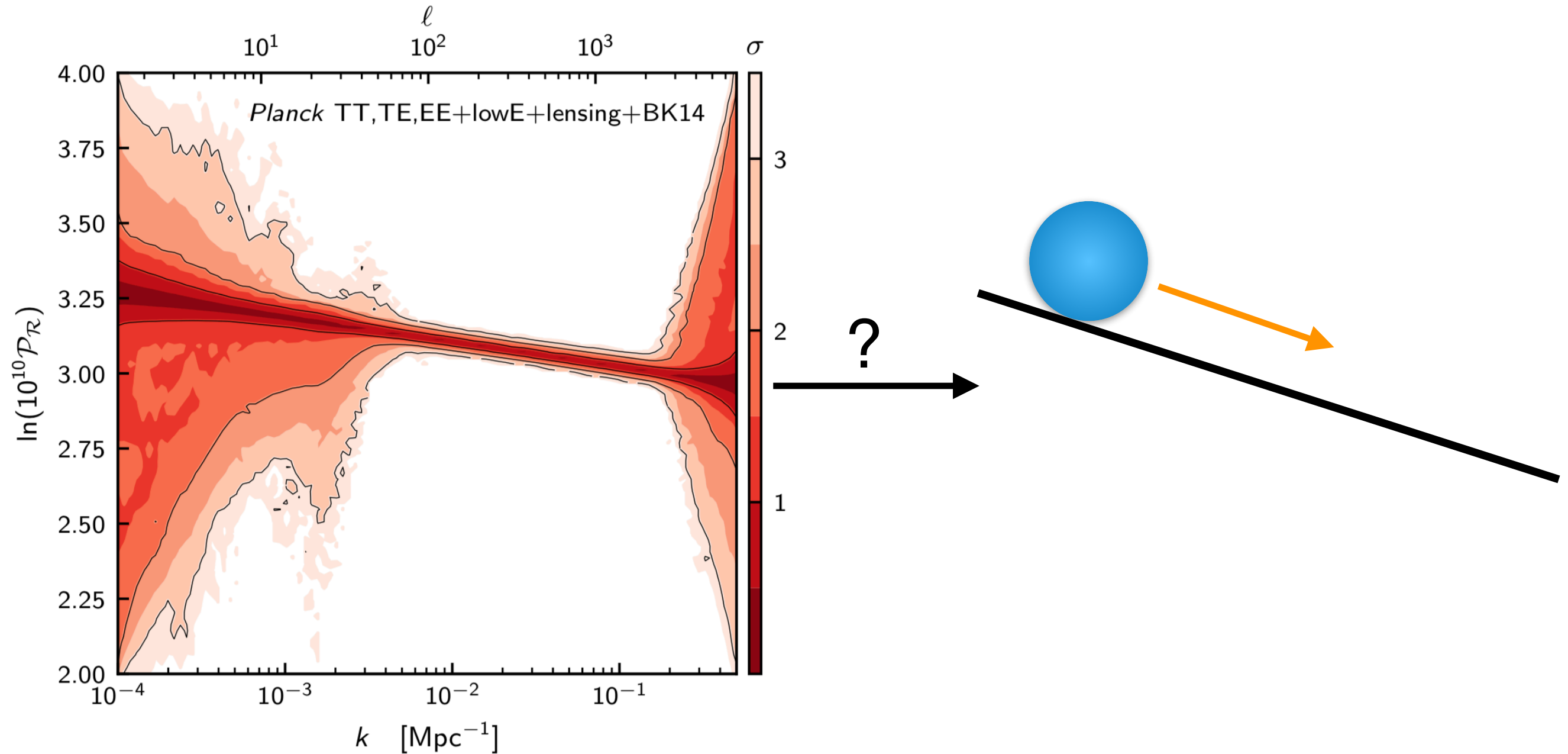
Inflation is often described in a single picture



Exponential expansion arises from potential energy

The Nature of Inflation

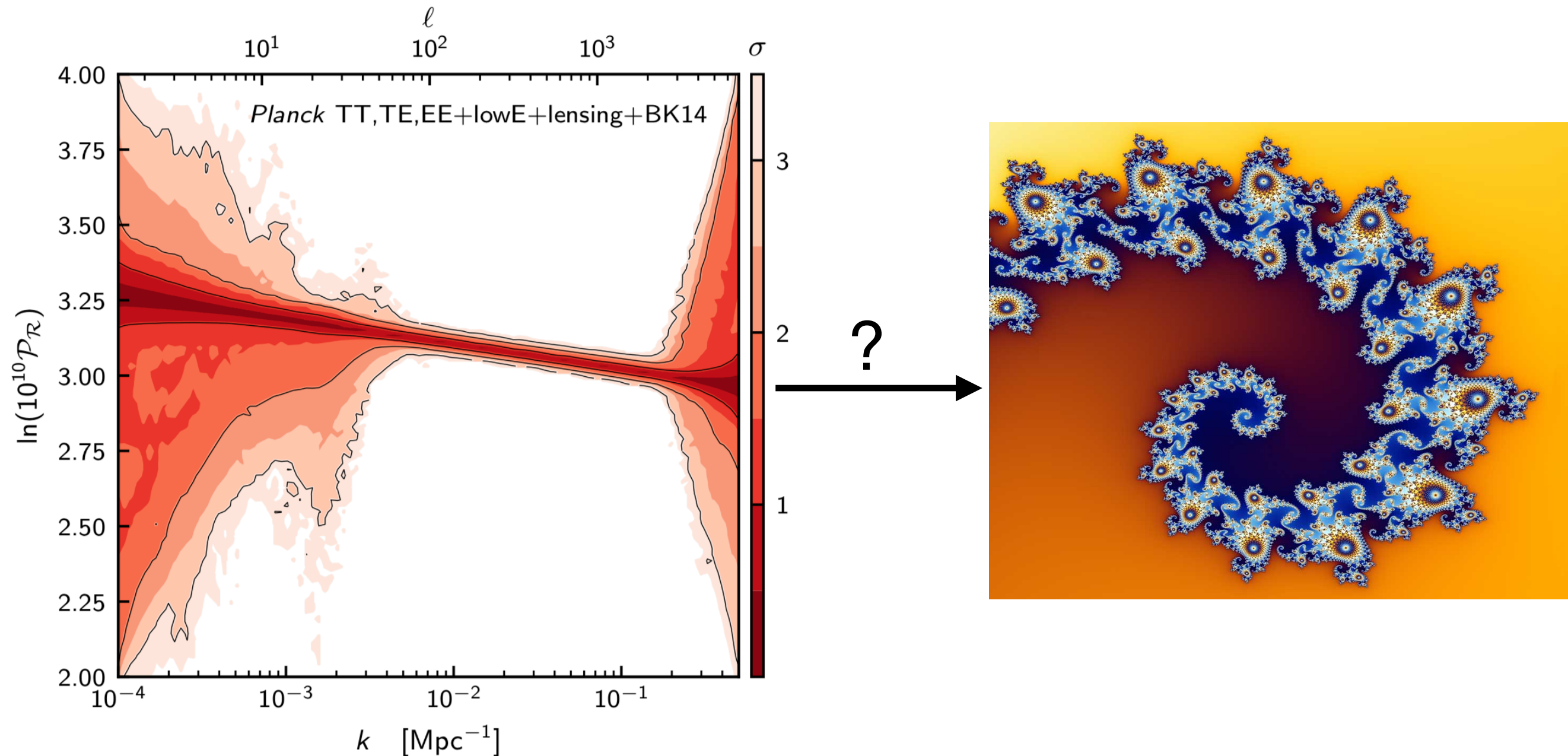
This picture is consistent with observations



Planck 2018

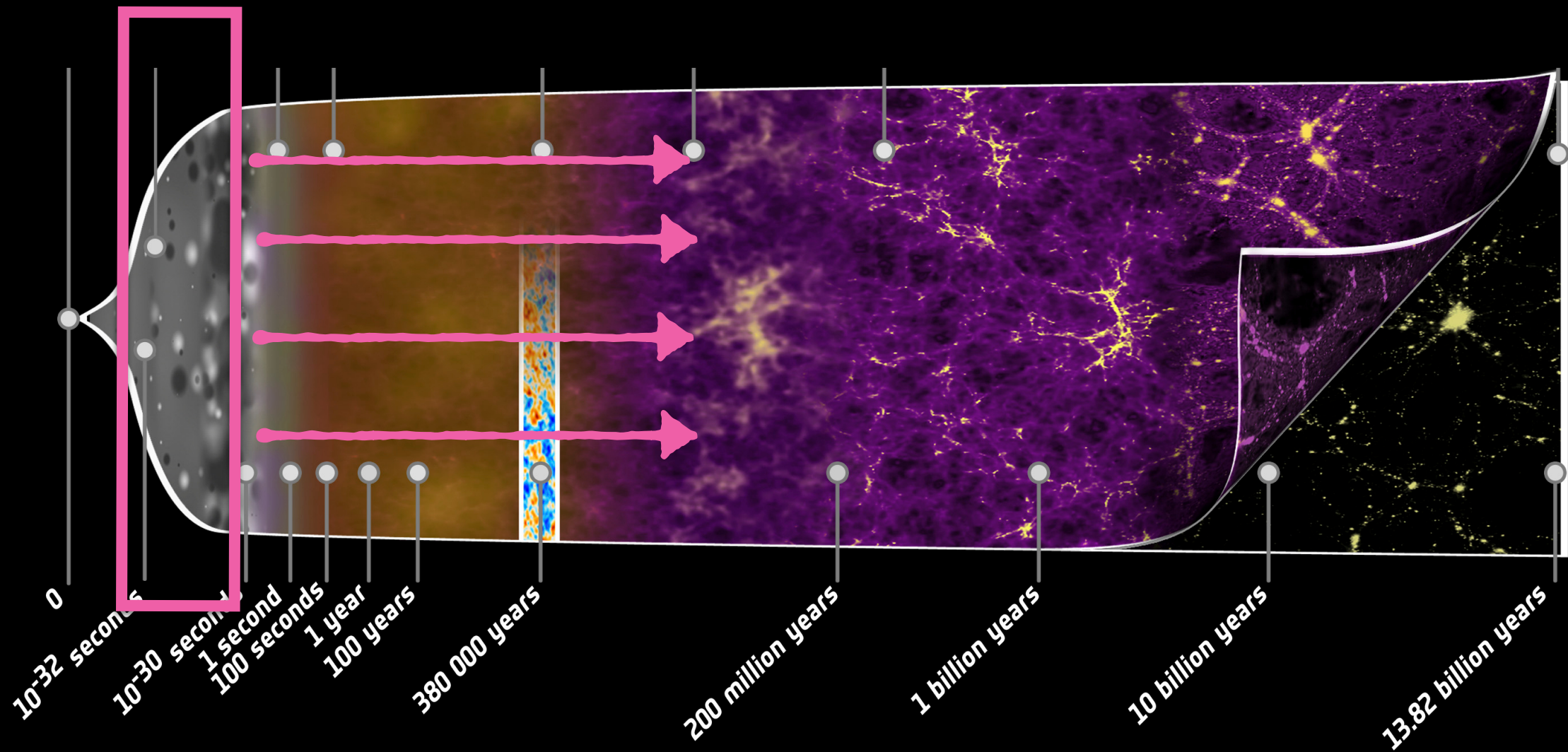
The Nature of Inflation

But current data doesn't require this is the story either

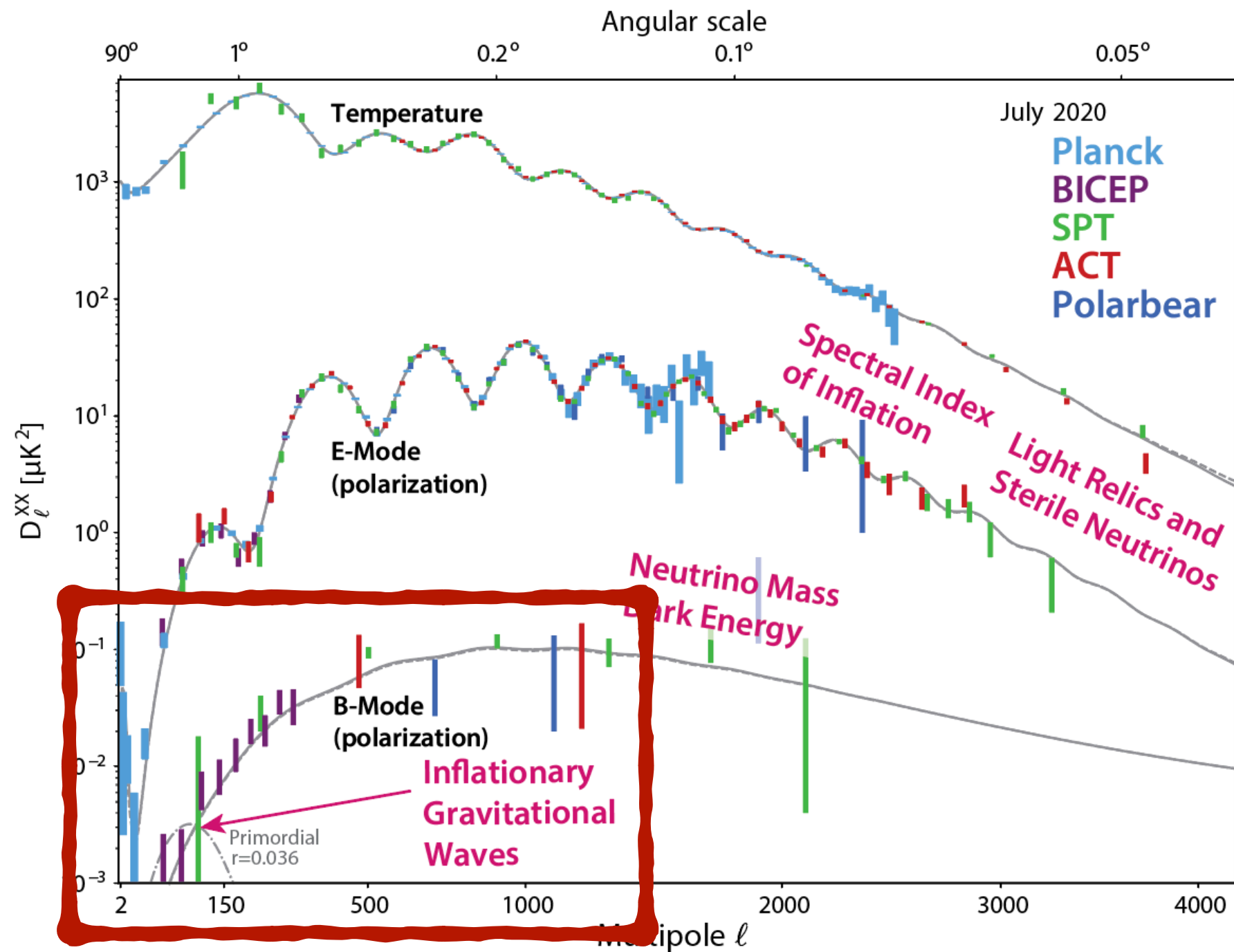


Planck 2018

Gravitational Waves from Inflation



B-modes



From B. Benson & J. McMahon

Gravitational Waves & Inflation

GWs provide a unique probe of the early universe:

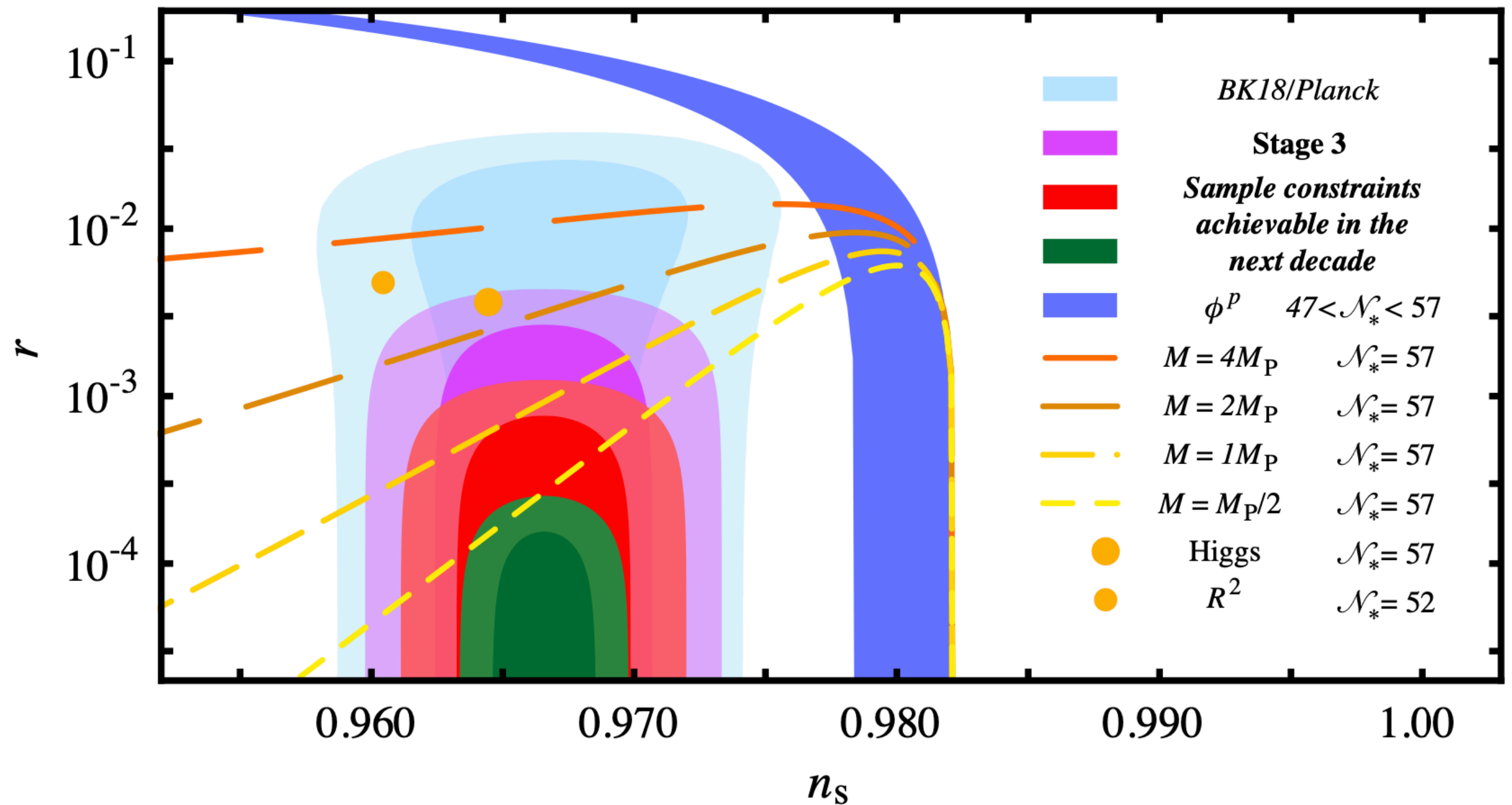
- They are a direct measure of the spacetime geometry
- They determine the energy scale of inflation

$$r \approx 9.65 \times 10^7 \left(\frac{H}{M_{\text{pl}}} \right)^2$$

- Higher scales are very sensitive to quantum gravity
- We distinguish high and low scale models if we reach

$$\sigma(r) \leq 5 \times 10^{-4}$$

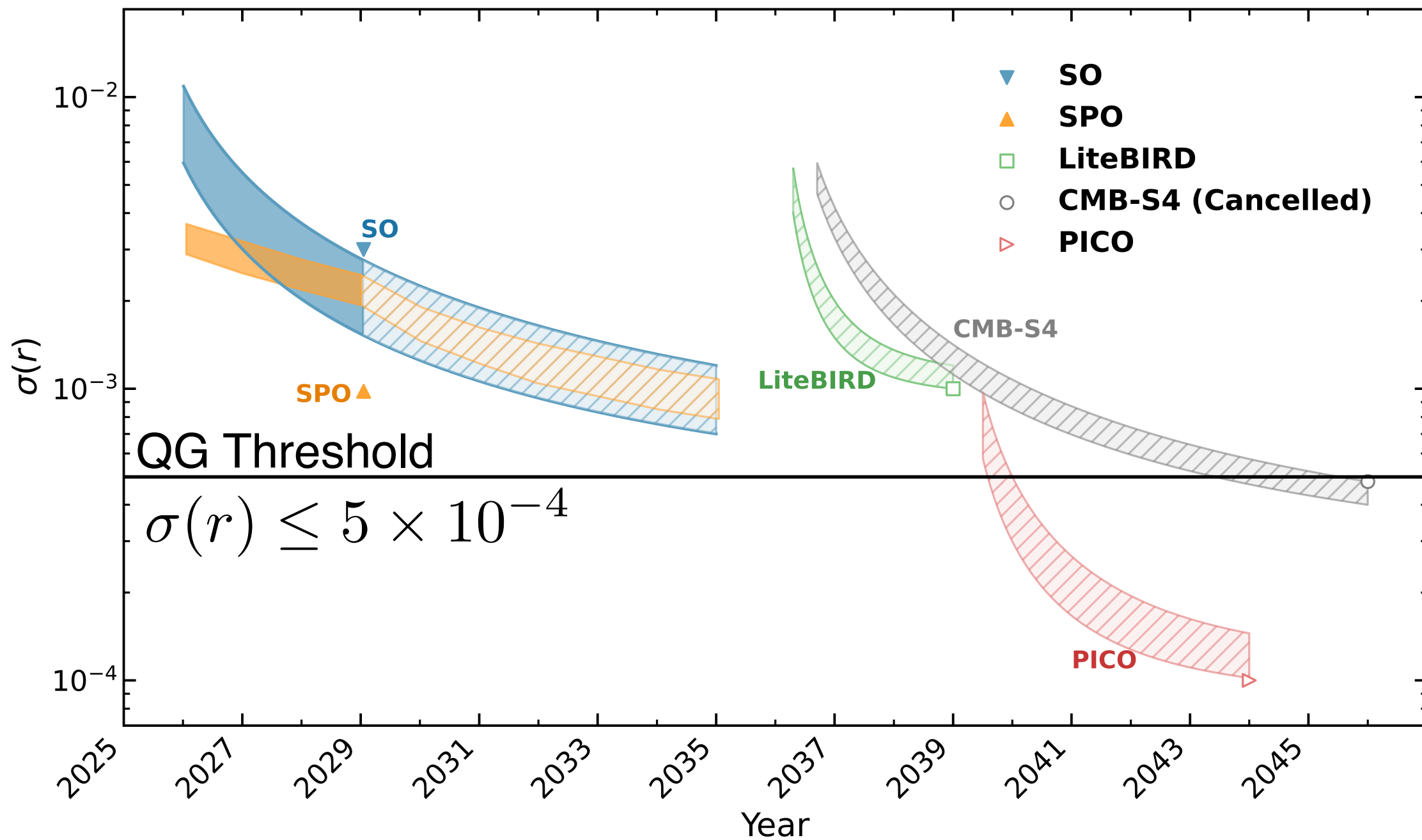
B-modes



arXiv: 2203.08128

CMB Probe+

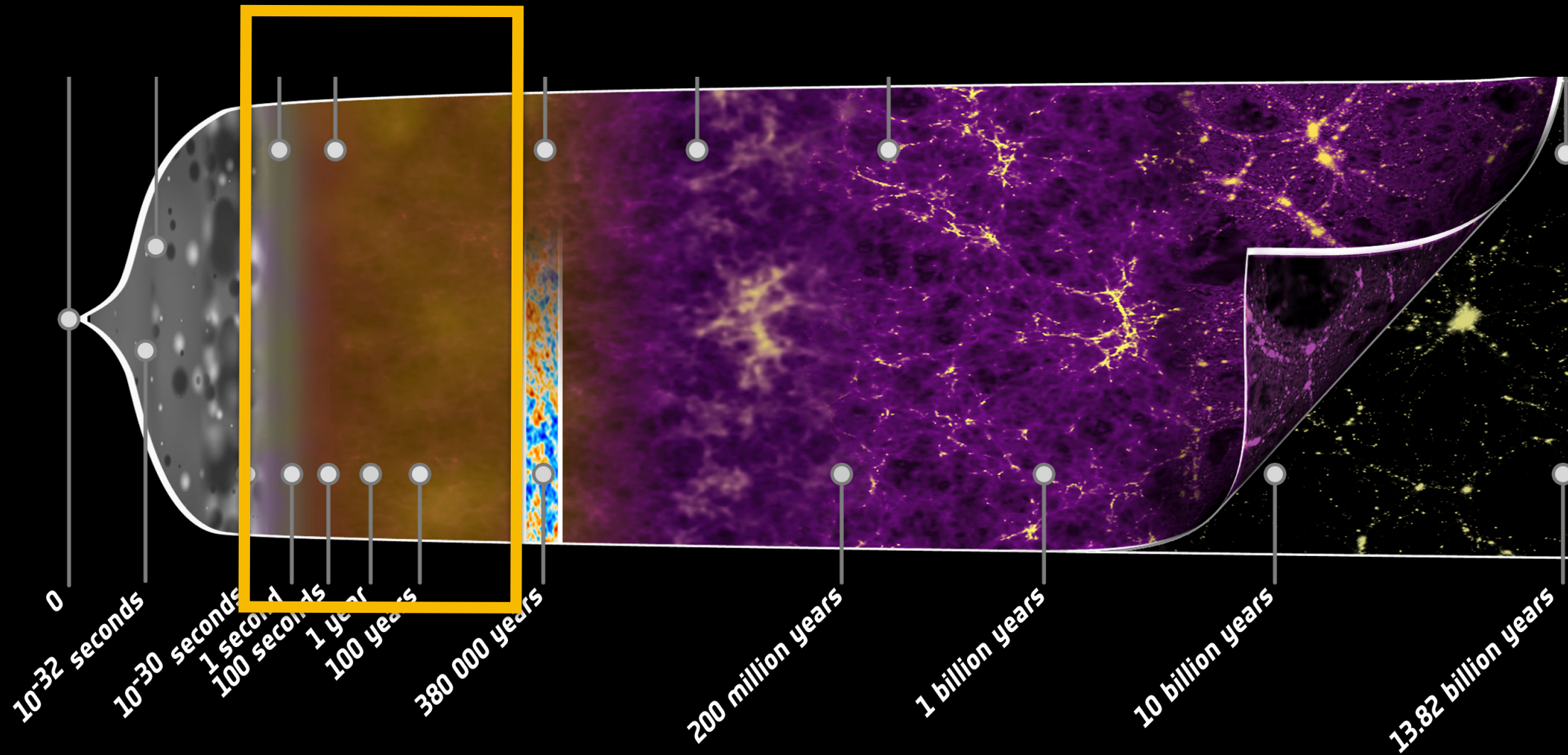
B-modes

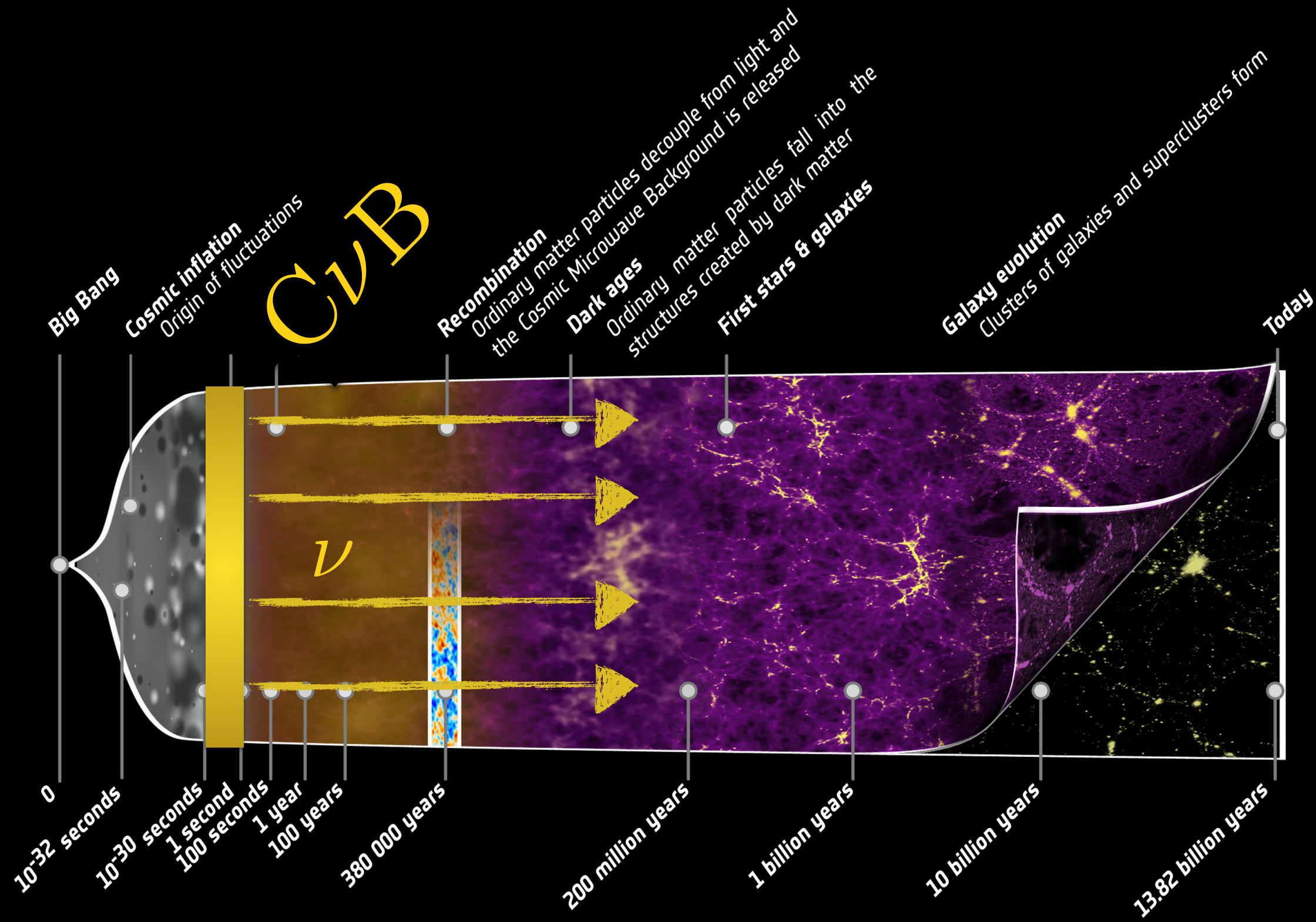


Dark Sectors

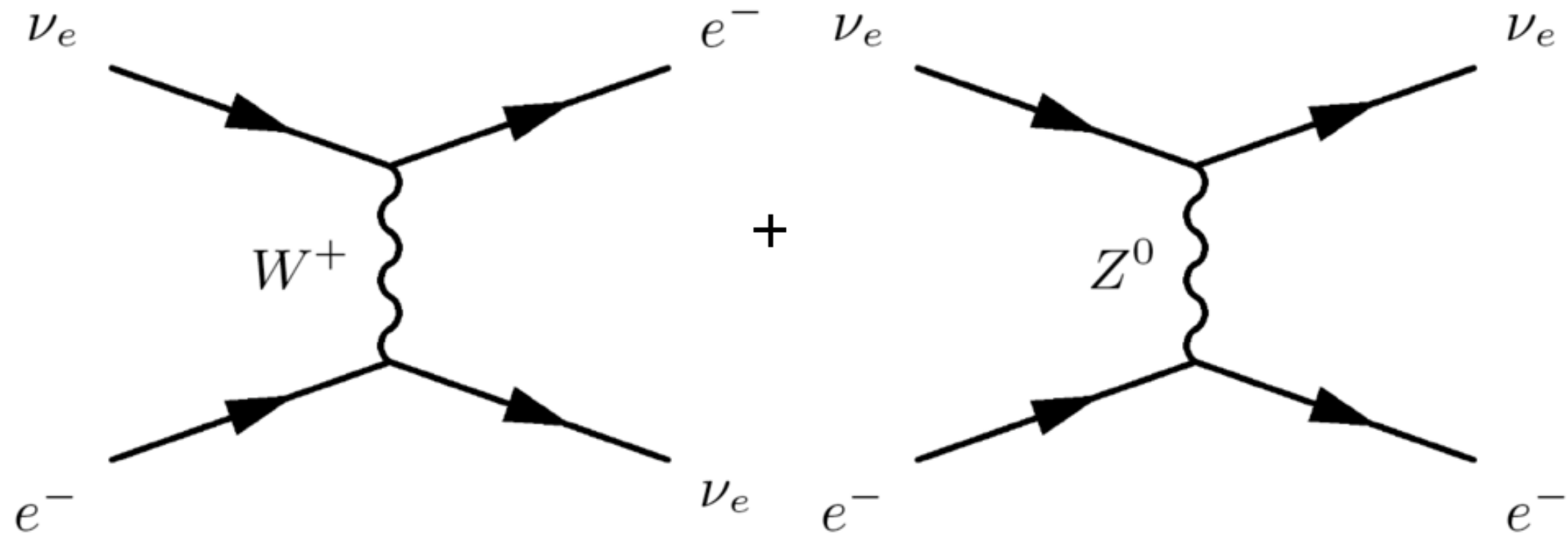


Dark Sectors





Cosmic Neutrino Background



Equilibrium :

$$\Gamma \sim G_F^2 T^5 > H \sim \frac{T^2}{M_{\text{pl}}}$$

Decoupling:

$$T^3 \sim G_F^{-2} / M_{\text{pl}} = \mathcal{O}(1 \text{ MeV})$$

Cosmic Neutrino Background

Cosmology sensitive to the neutrino energy density

Conventional to define

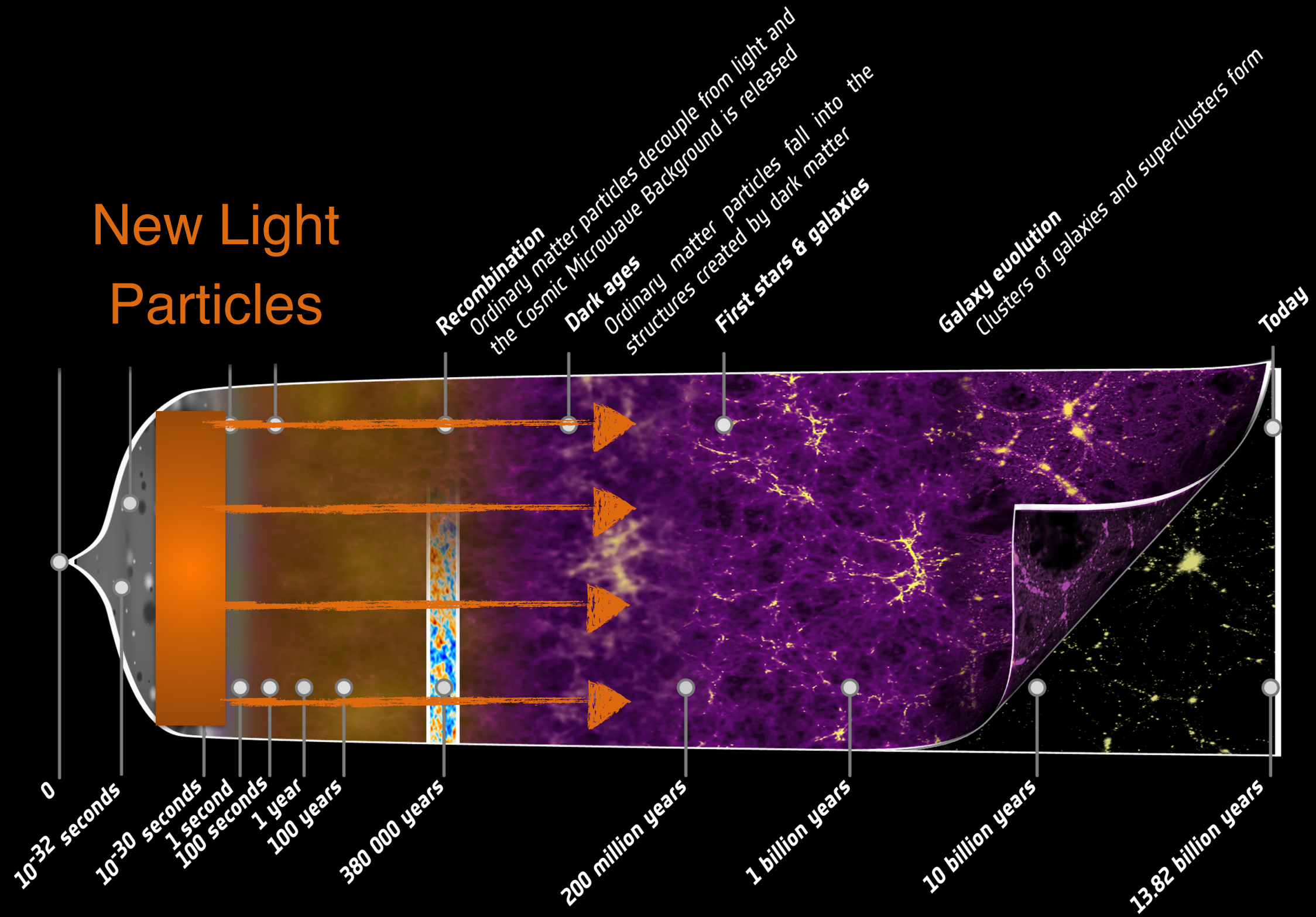
$$N_{\text{eff}} \equiv \frac{8}{7} \left(\frac{11}{4} \right)^{4/3} \frac{\rho_\nu}{\rho_\gamma}$$

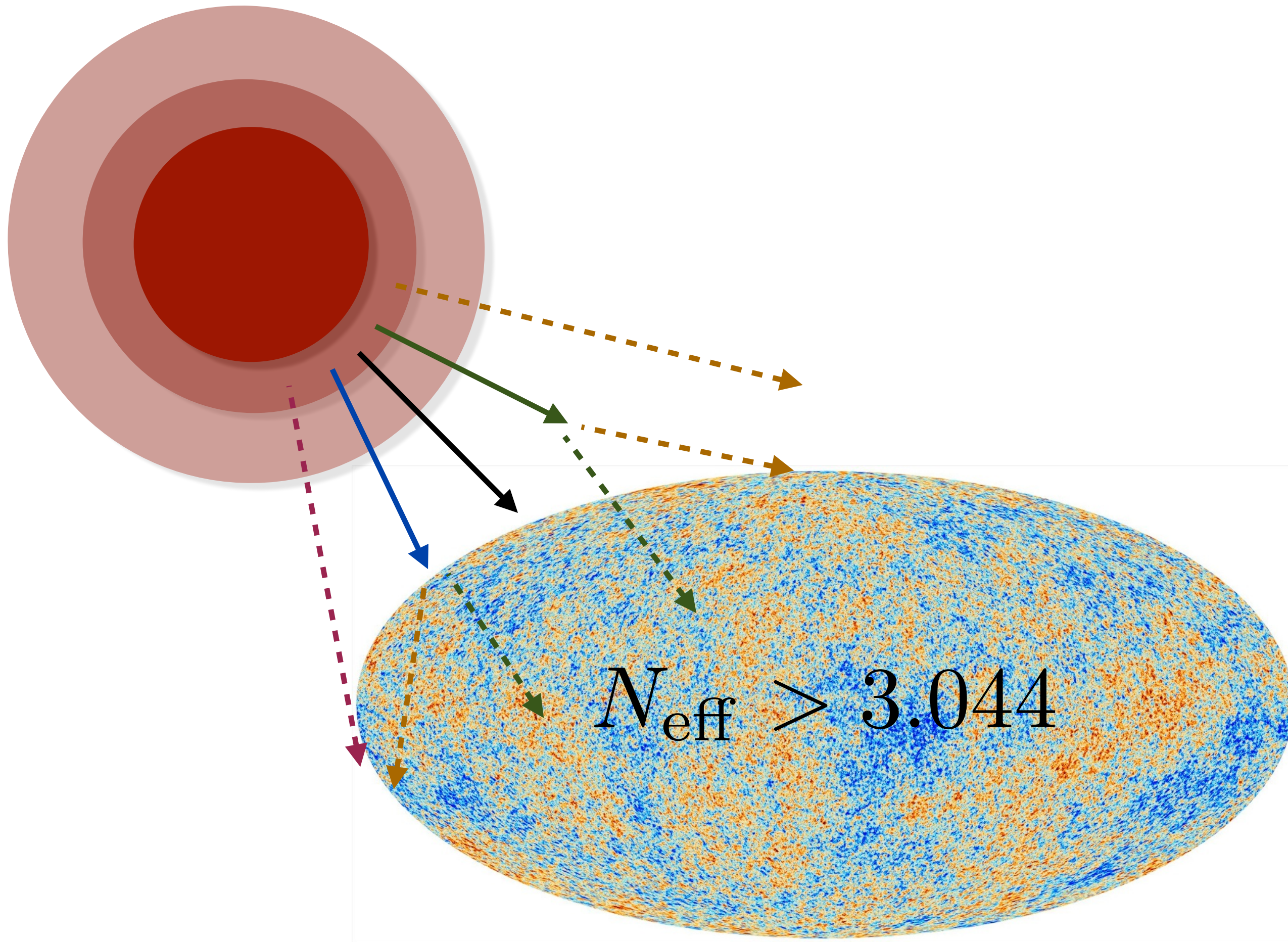
Perfect decoupling : $N_{\text{eff}} = 3.$

Imperfect decoupling + QED : $N_{\text{eff}} = 3.0440 \pm 0.0002$

Bennett et al. (2020)

New Light Particles

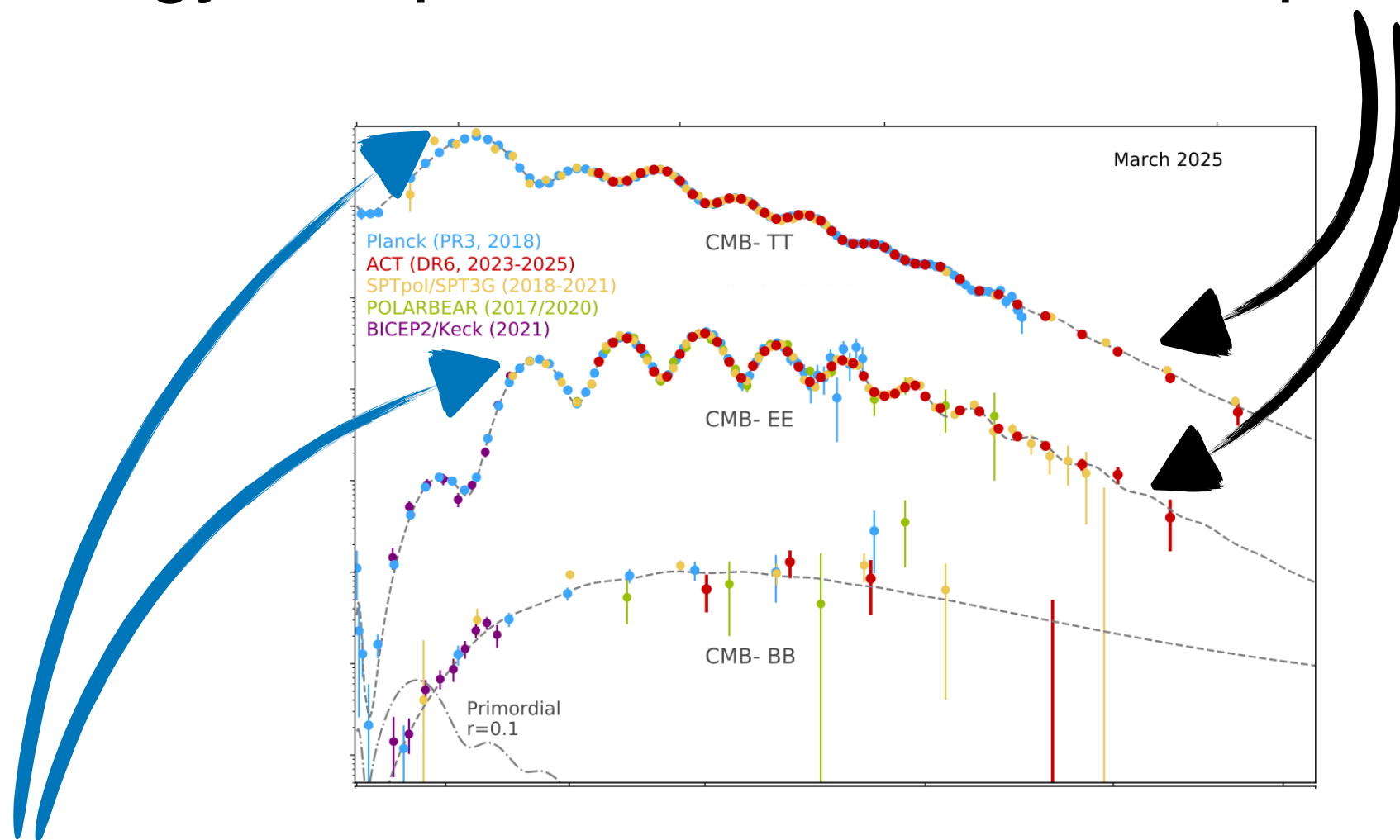




Light Relics

The peak locations + damping determine N_{eff} :

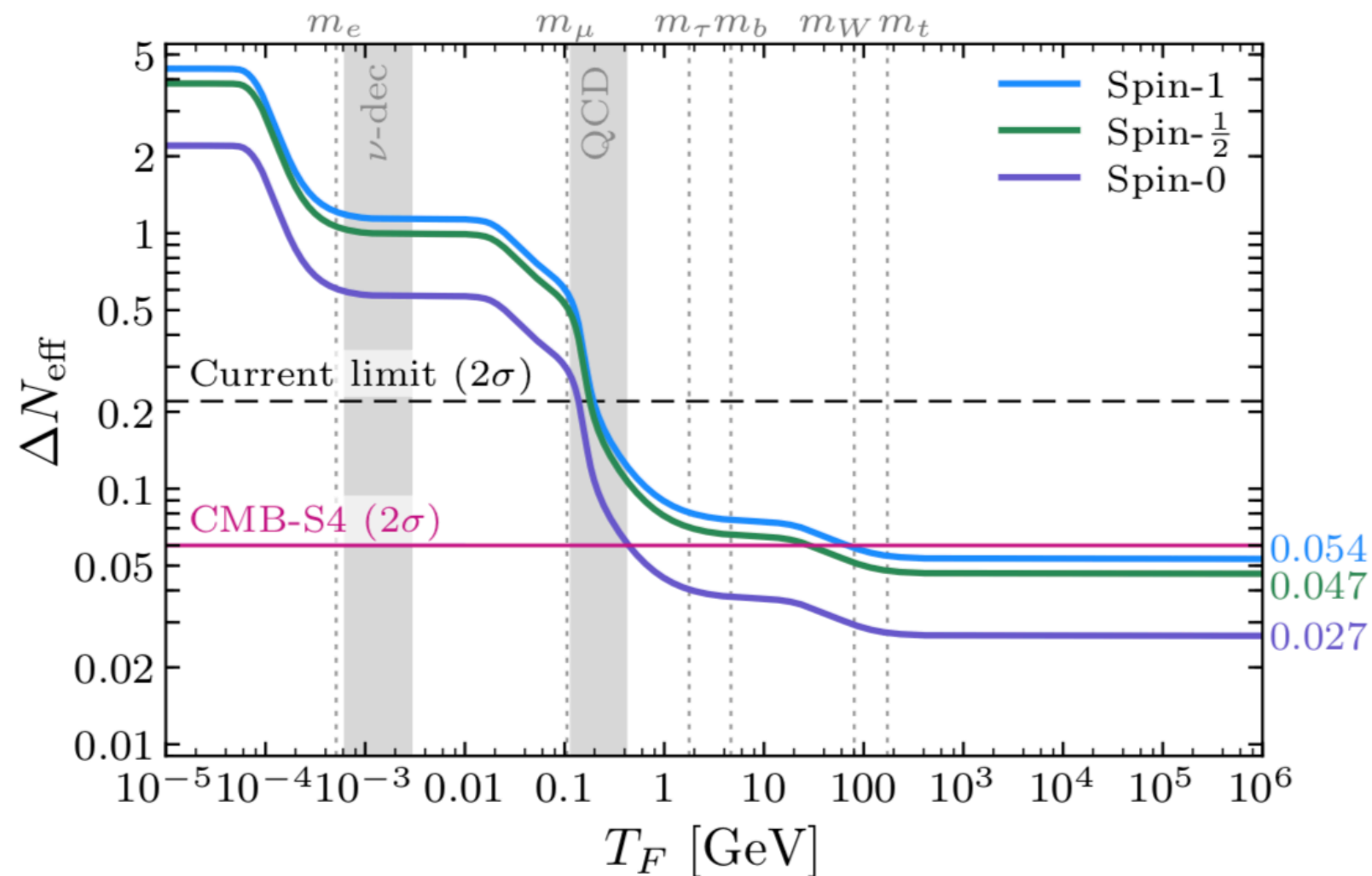
- Energy dissipation determines the expansion rate



- Peak locations measure neutrino perturbations

Light Relics

ΔN_{eff} depends only on degrees of freedom at freeze-out

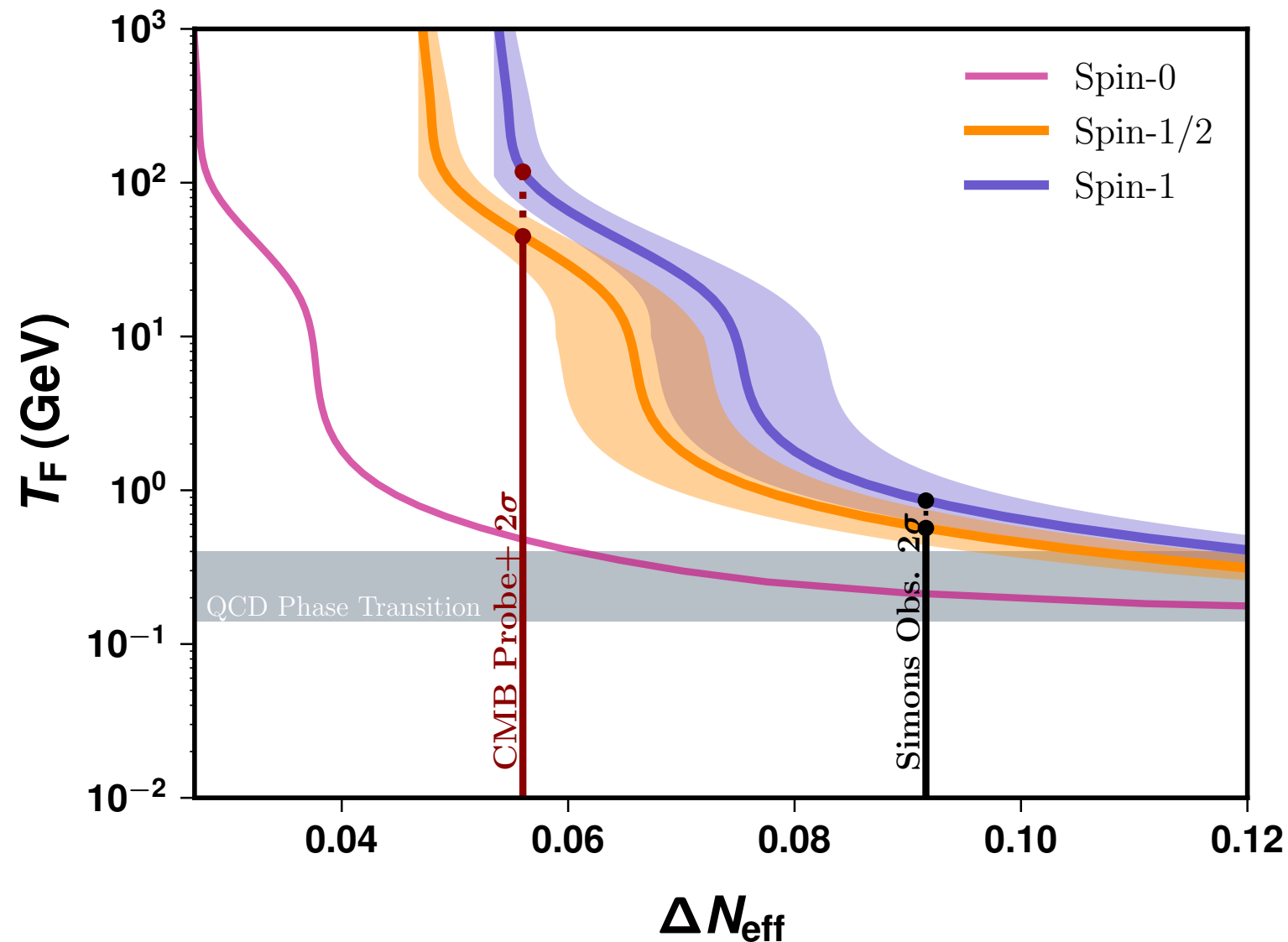


Robust determination of the universe at very high T

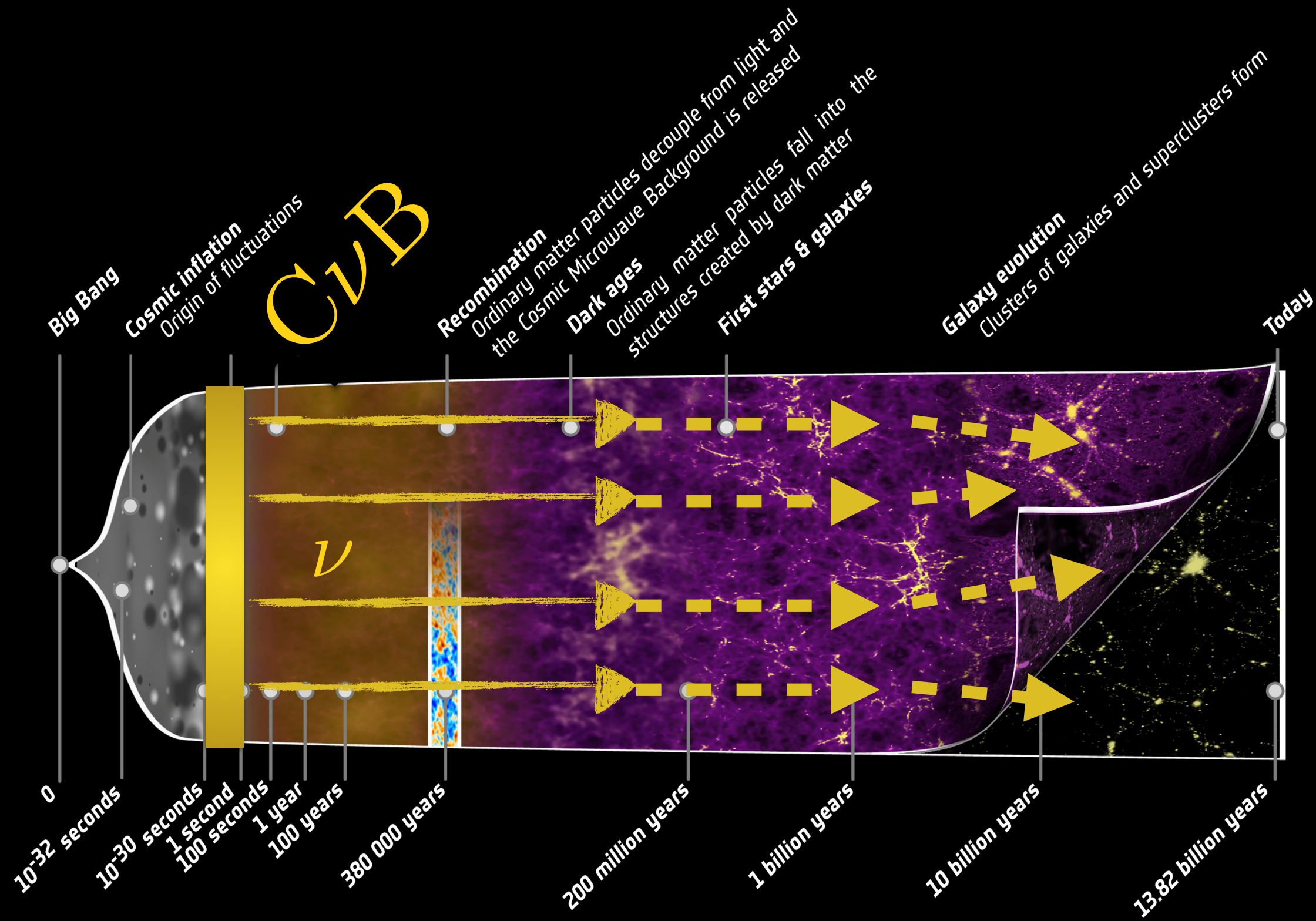
arXiv:2203.07943

Light Relics

The freeze-out temperature is the physical quantity

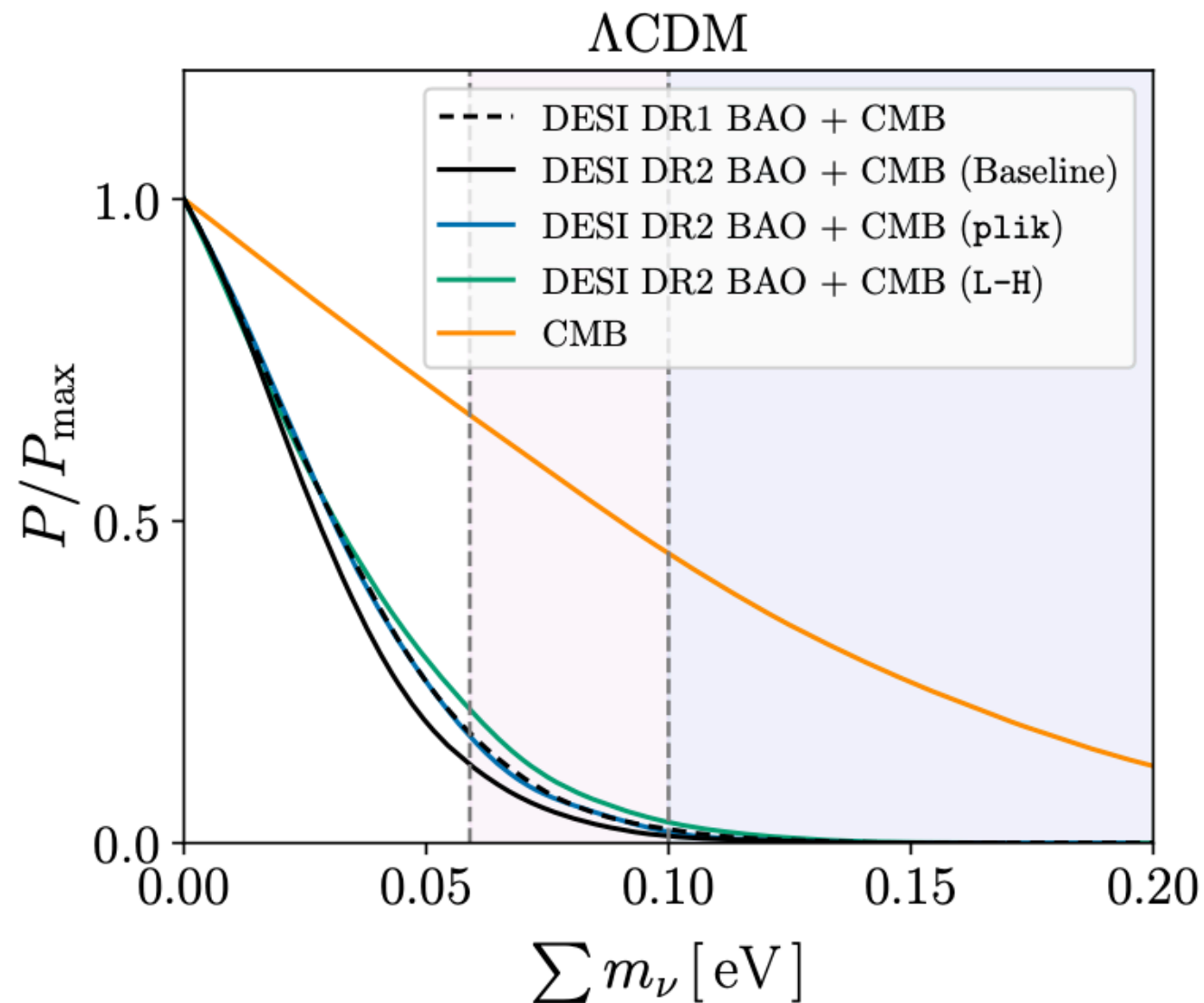


CMB Probe+ can improve on SO by a factor of 100



Neutrino Mass

Cosmological measurements are inconsistent with the lab



$M_{\nu} < 60 \text{ meV}$ Cosmology

$M_{\nu} \geq 60 \text{ meV}$ Oscillations

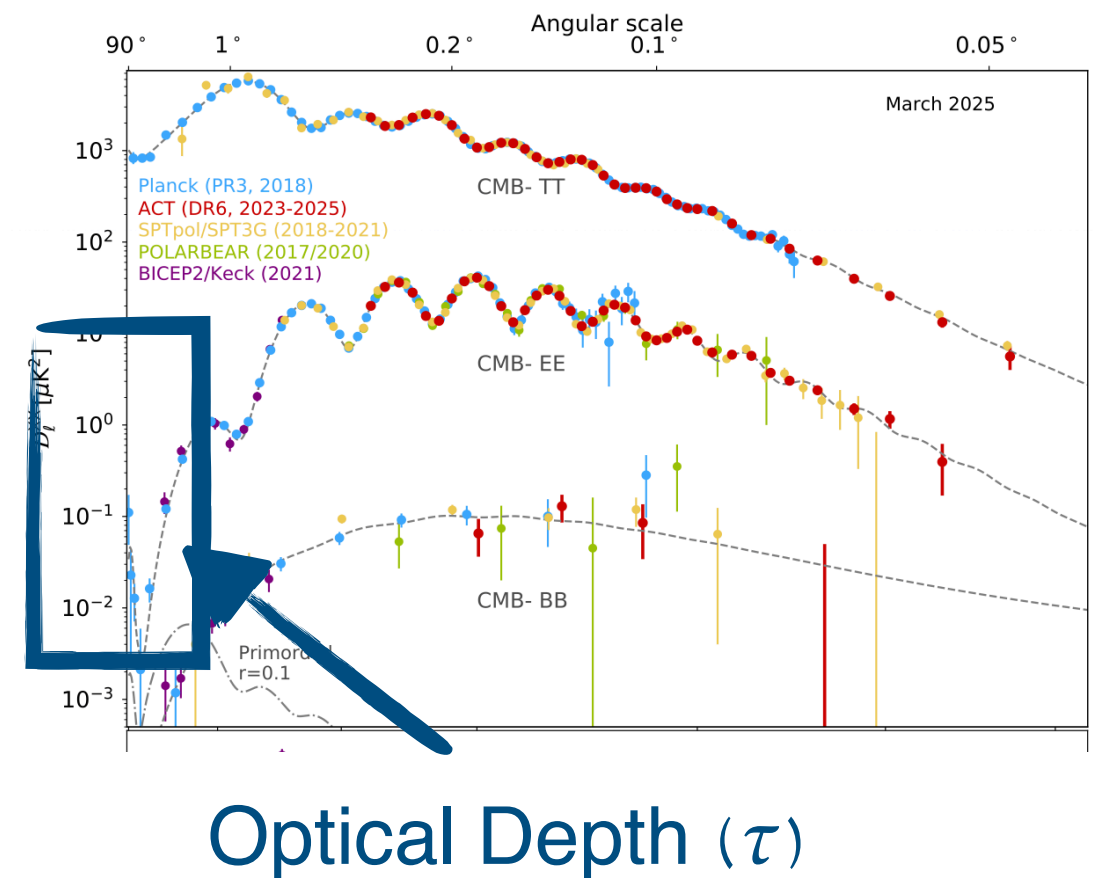
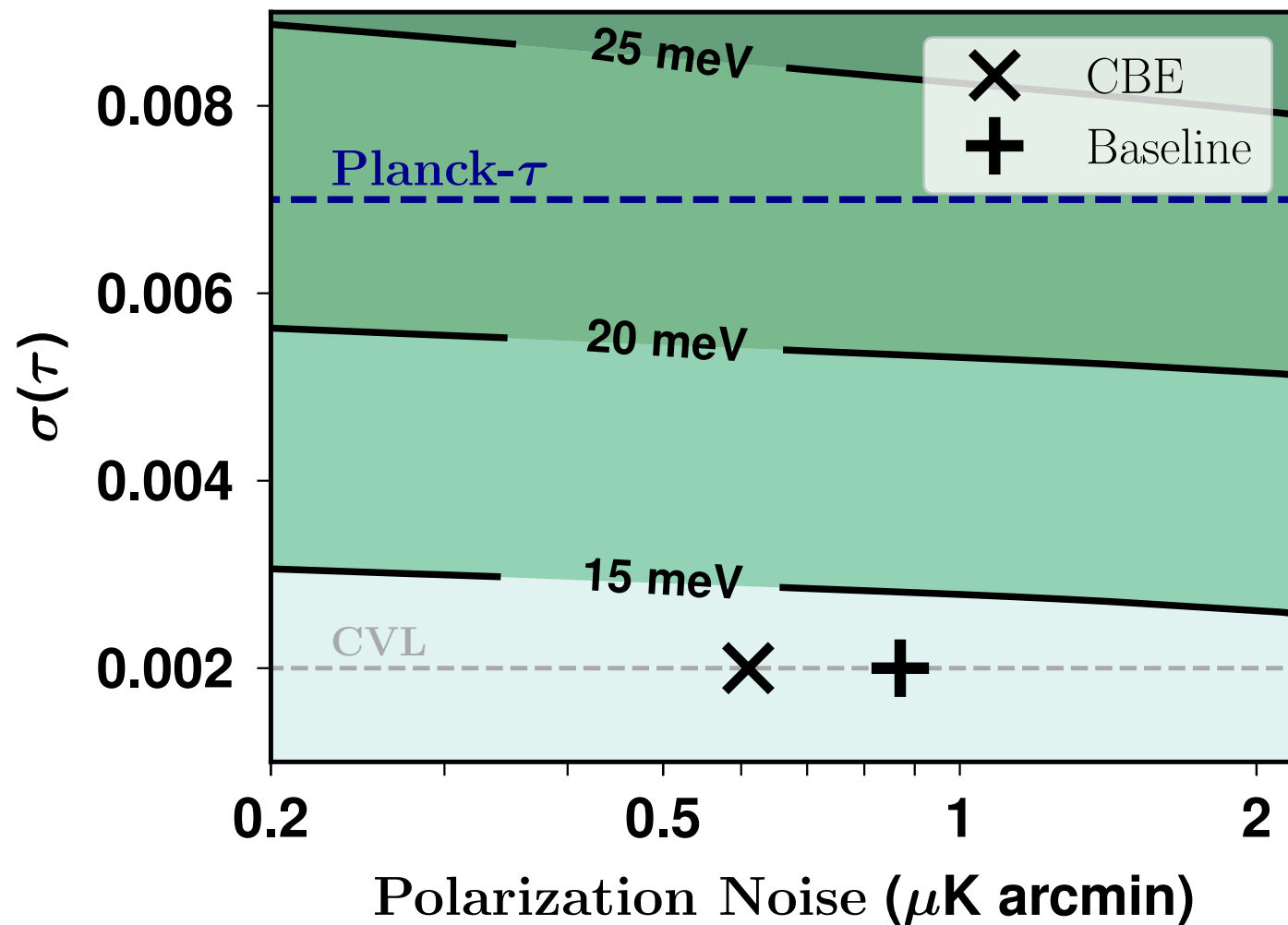
Likelihood actually peaks at large negative values

DESI (2025)

Neutrino Mass

The optical depth is central to our understand of neutrinos

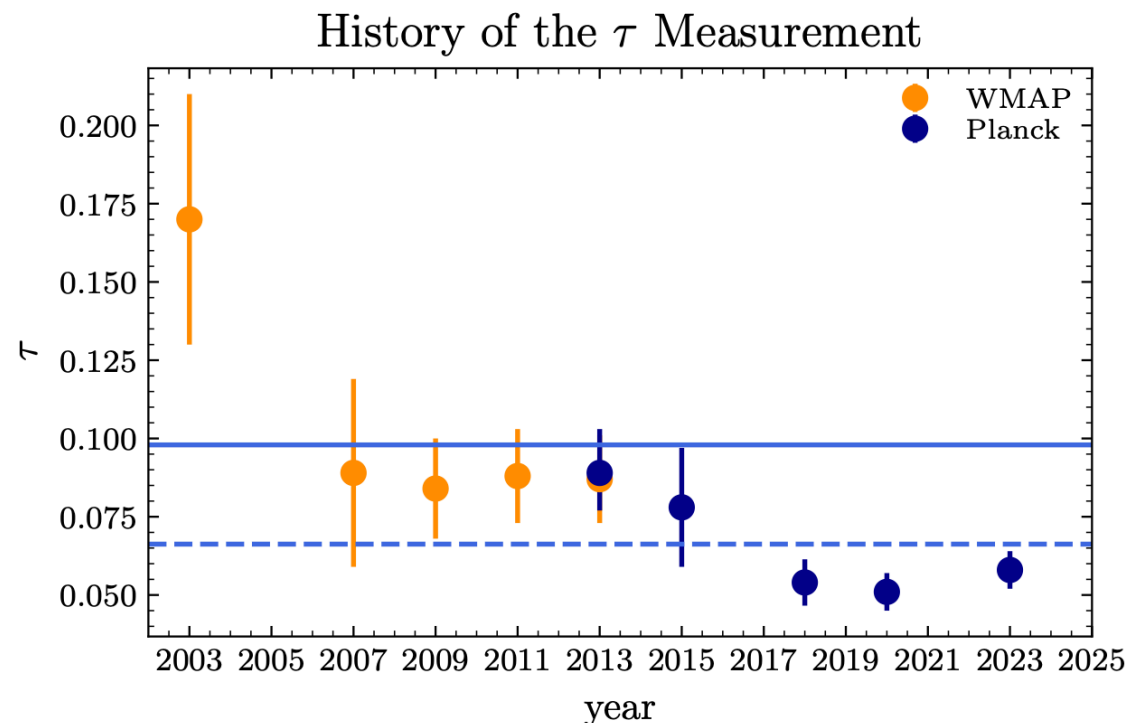
$\sigma(\sum m_\nu)$ -with DESI BAO



A CMB satellite is needed to reach the cosmic variance limit

Neutrino Mass

Evidence is that optical depth could explain a lot of tensions



Craig et al. (2025)
DG & Meyers (2025)

Consistent with?	$\tau = 0.06$	$\tau = 0.09$
<i>Planck</i> low- ℓ polarization	✓	✗✗ [72]
WMAP low- ℓ polarization	✓	✓
BAO within Λ CDM	✗	✓
$\sum m_\nu \geq 0.06$ eV	✗	✓
Cosmological constant Λ	✗	✓

Sailer et al. (2025)
Jhaveri et al. (2025)

High results are in tension with duration of reionization

Cain et al. (2025)

We need a better measurement

Summary



Summary

CMB Probe+ can answer many key cosmic questions

- It can determine the scale and geometry of inflation
- It would reach a critical threshold for r
- It would reach a critical threshold of N_{eff}
- It could determine the absolute mass of neutrinos
- It could resolve a number of tensions
- It would provide a CVL measurements of reionization

Thank You

