Fundamental Physics from Cosmology

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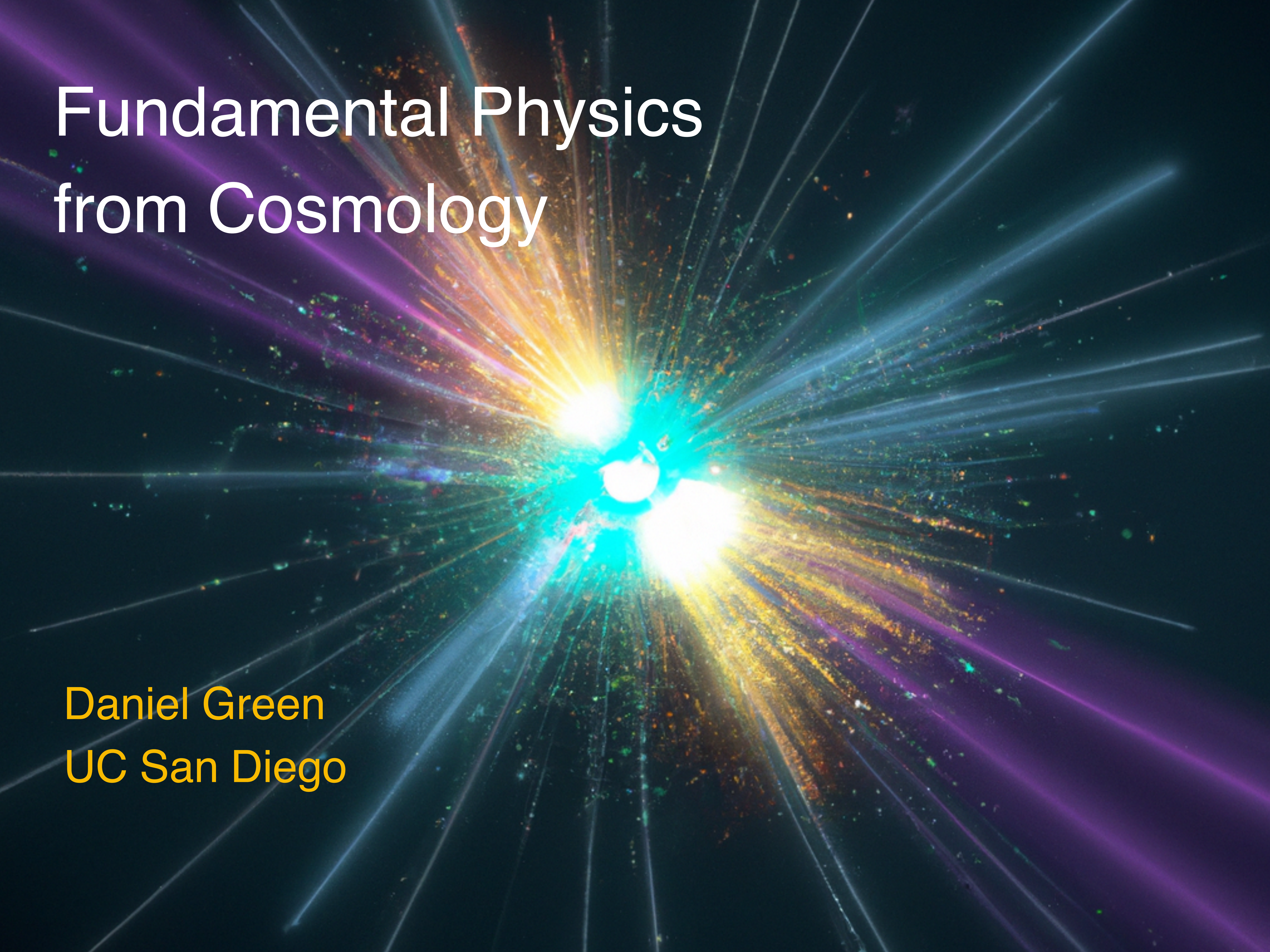
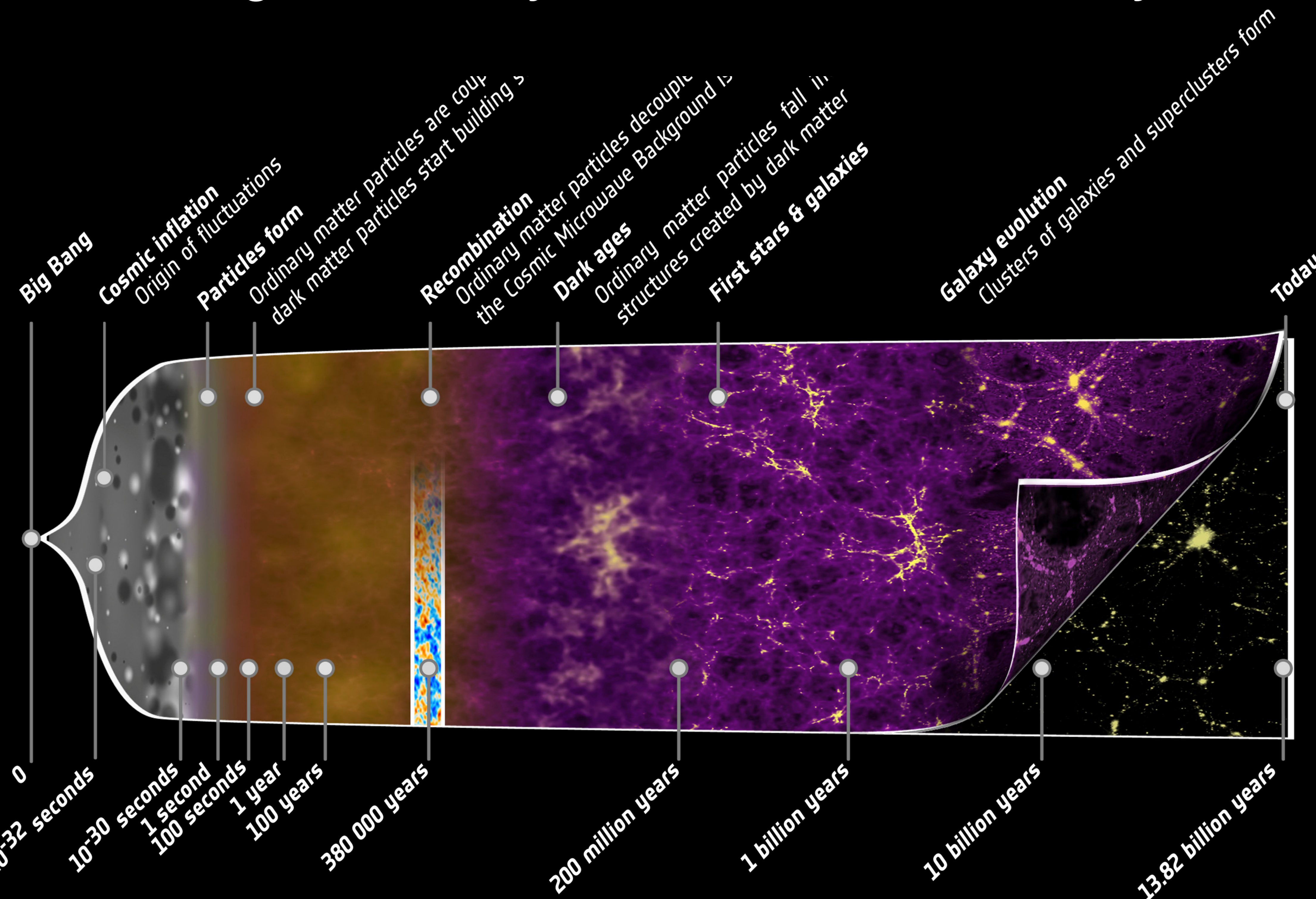
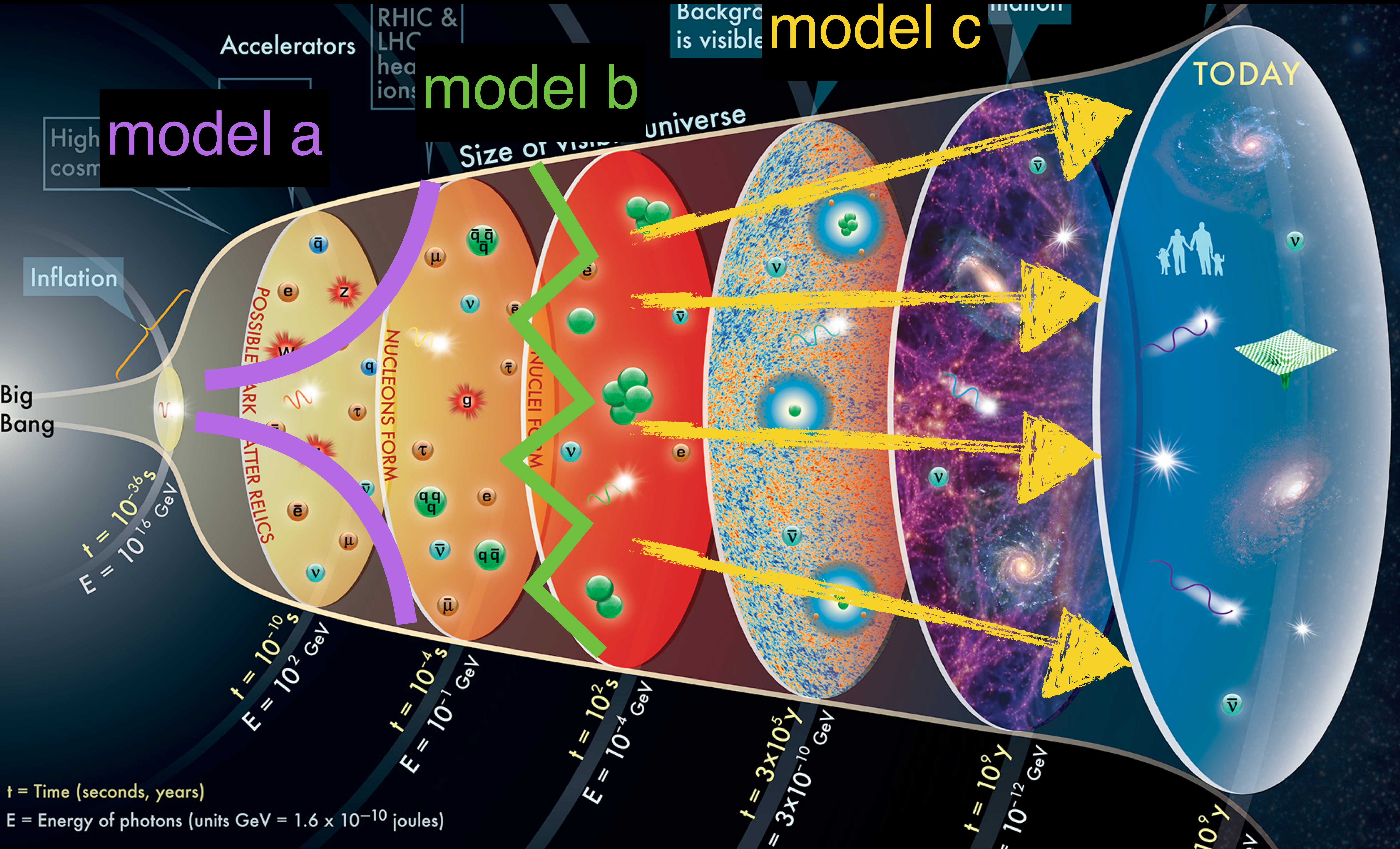


The cosmologists' history of the universe is always the same



Model builders have different ideas

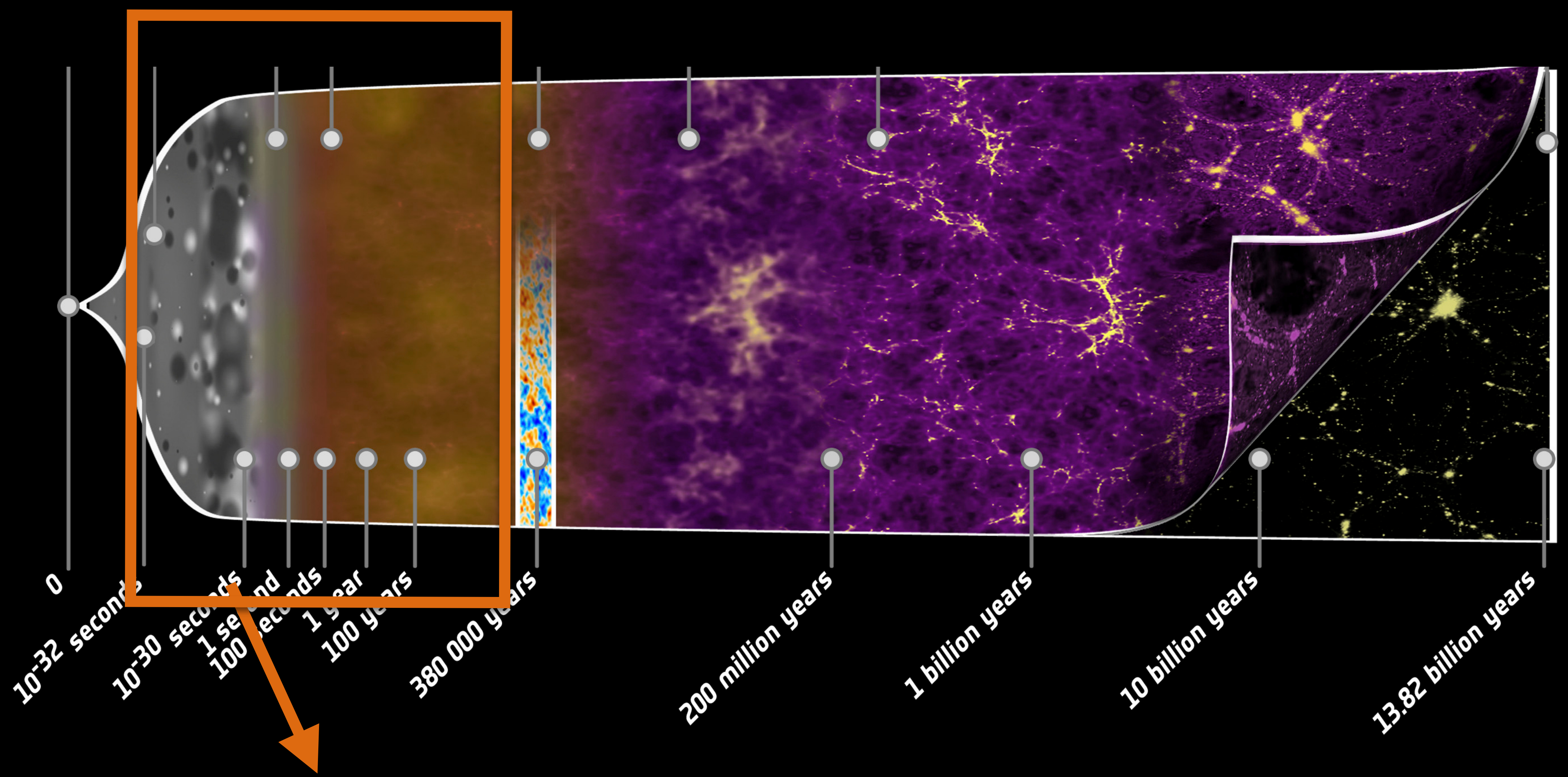


Model Building

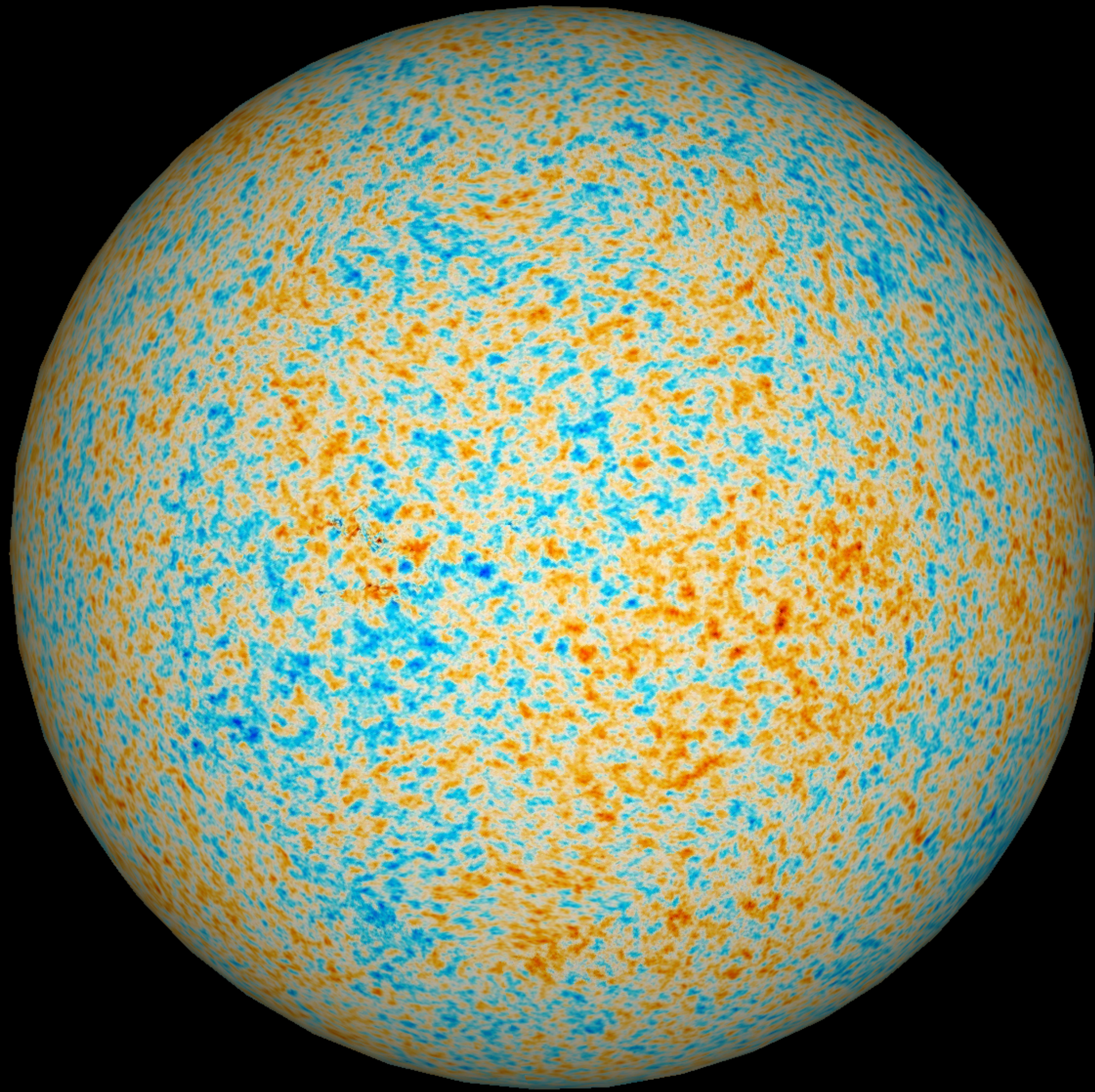
Cosmology fundamentally tied to model building

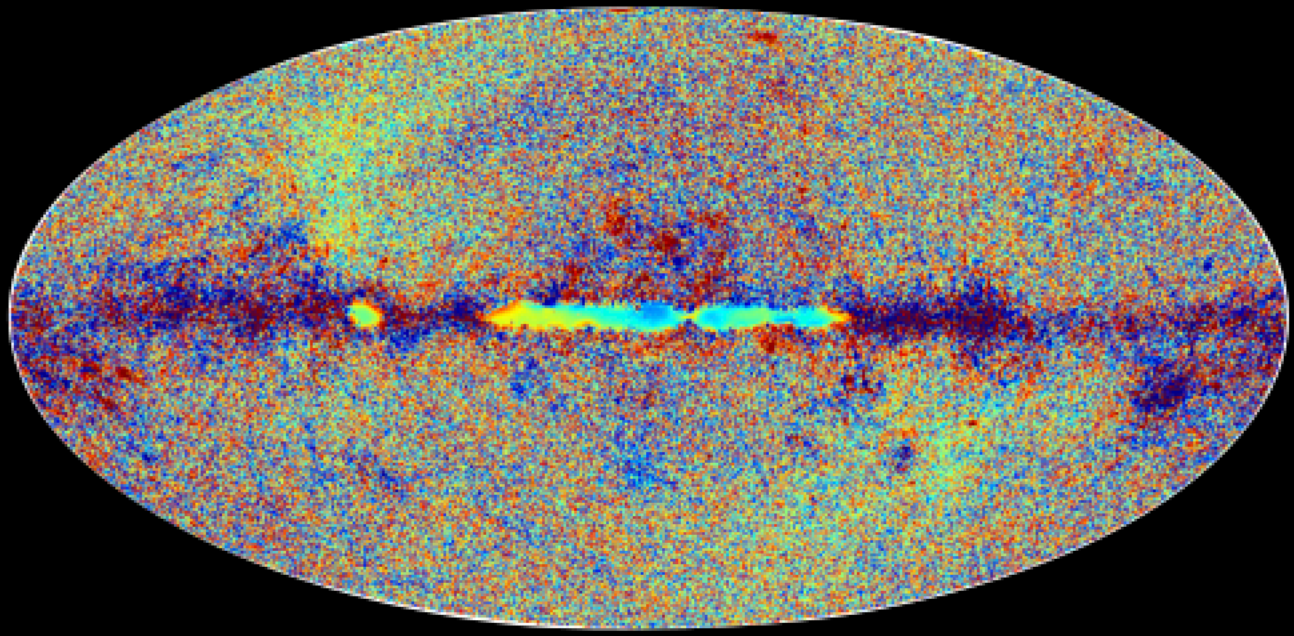
- Cosmological Constant
- Dark Matter / Dark Sectors
- Solution to strong CP problem (axion)
- Cosmological solutions to Hierarchy Problem
- Relics from new symmetries (e.g. gravitino)
- Origin of structure, baryogenesis, B-fields, …

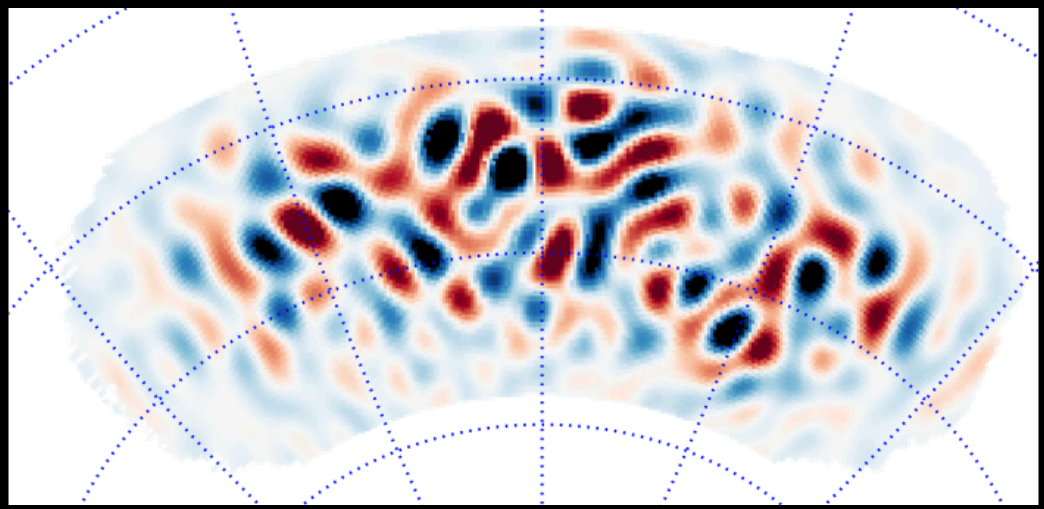
Answers live in the early universe

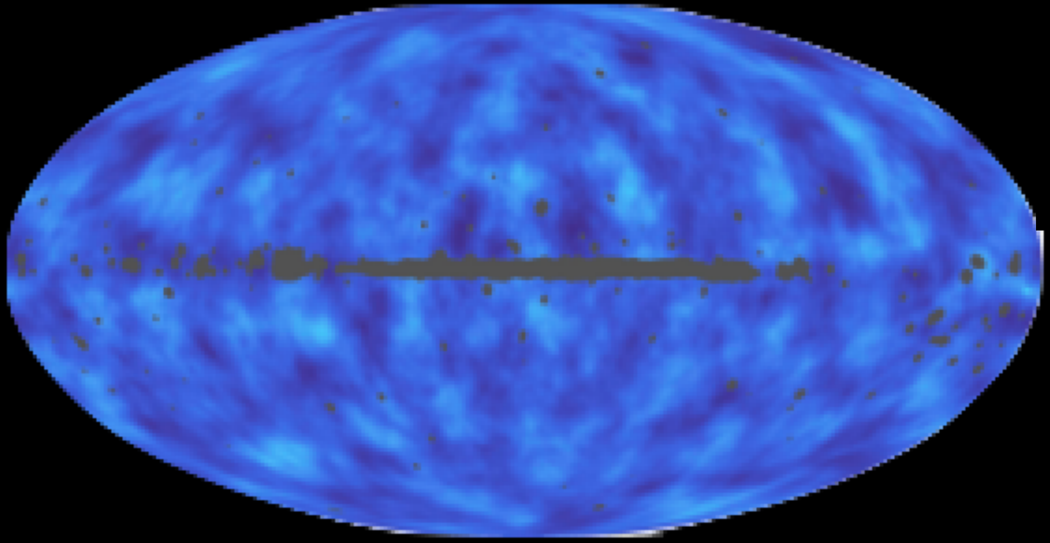


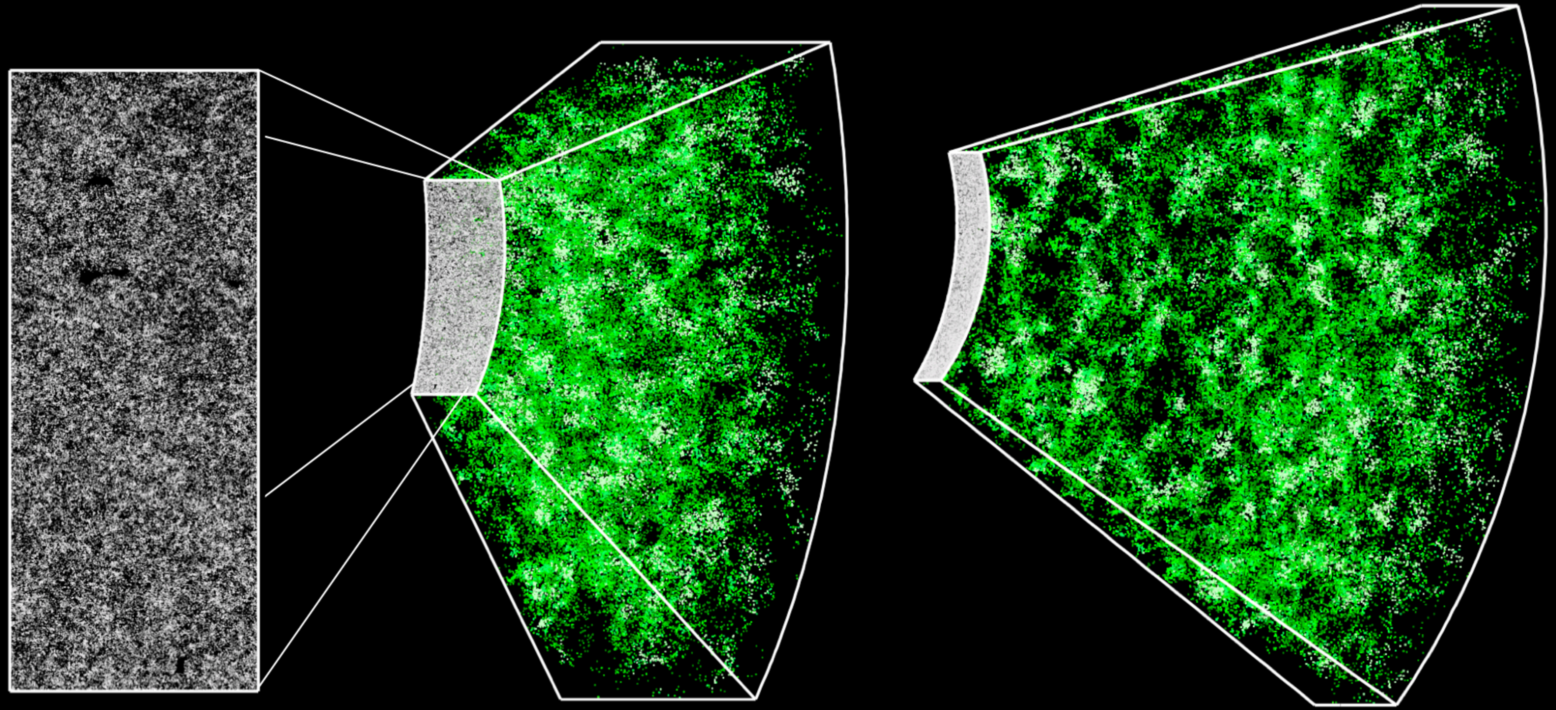
Unproven(?)



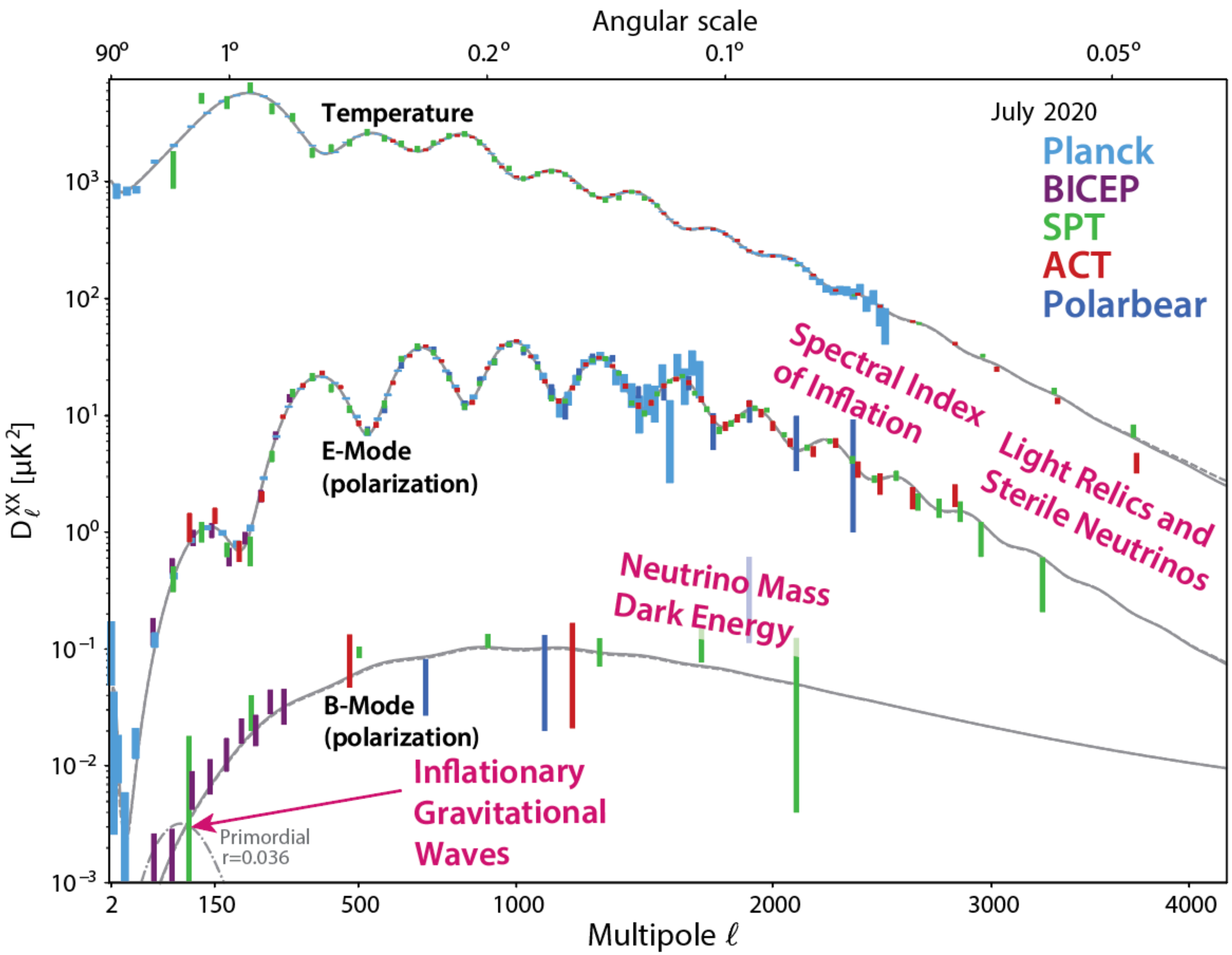








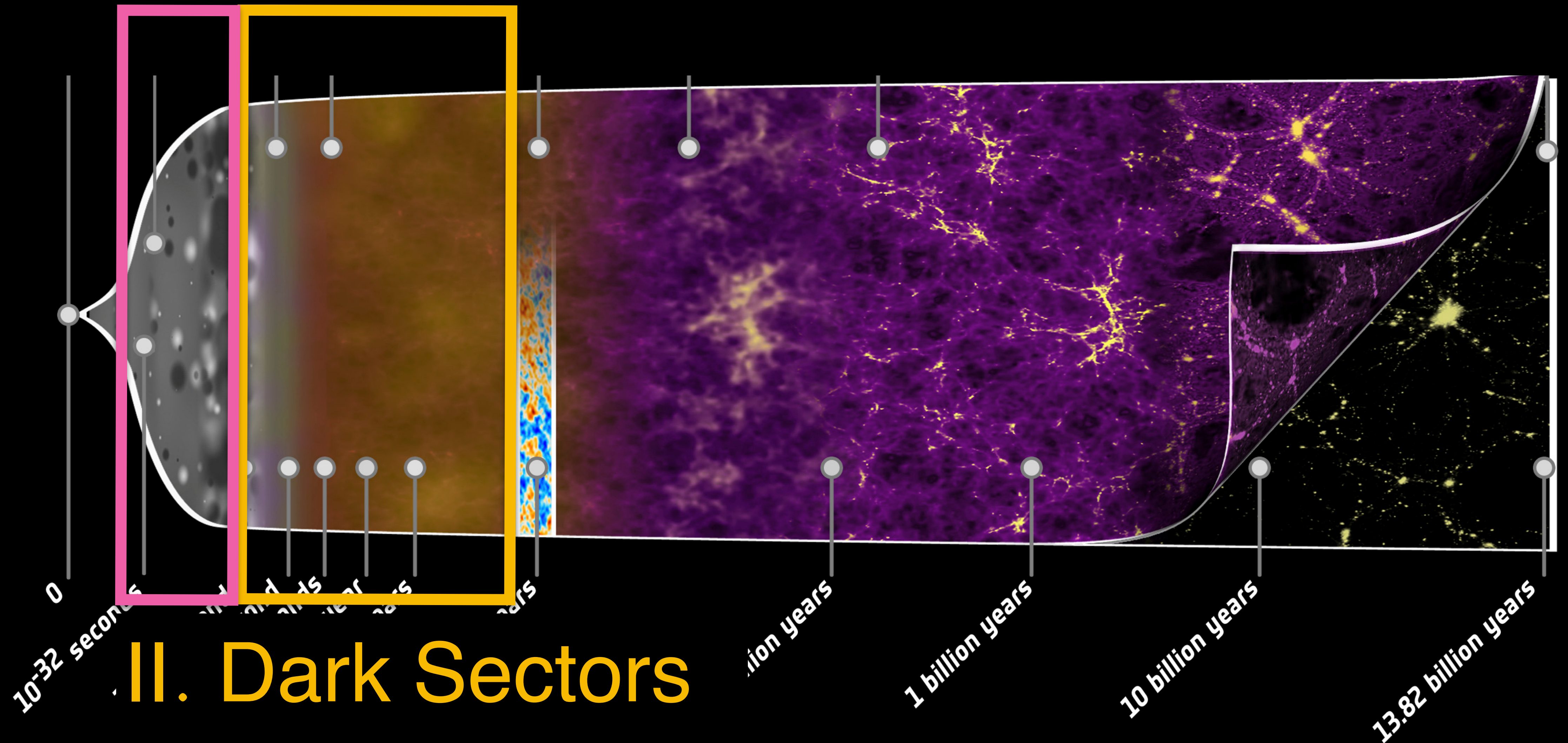
CMB observables



From B. Benson & J. McMahon

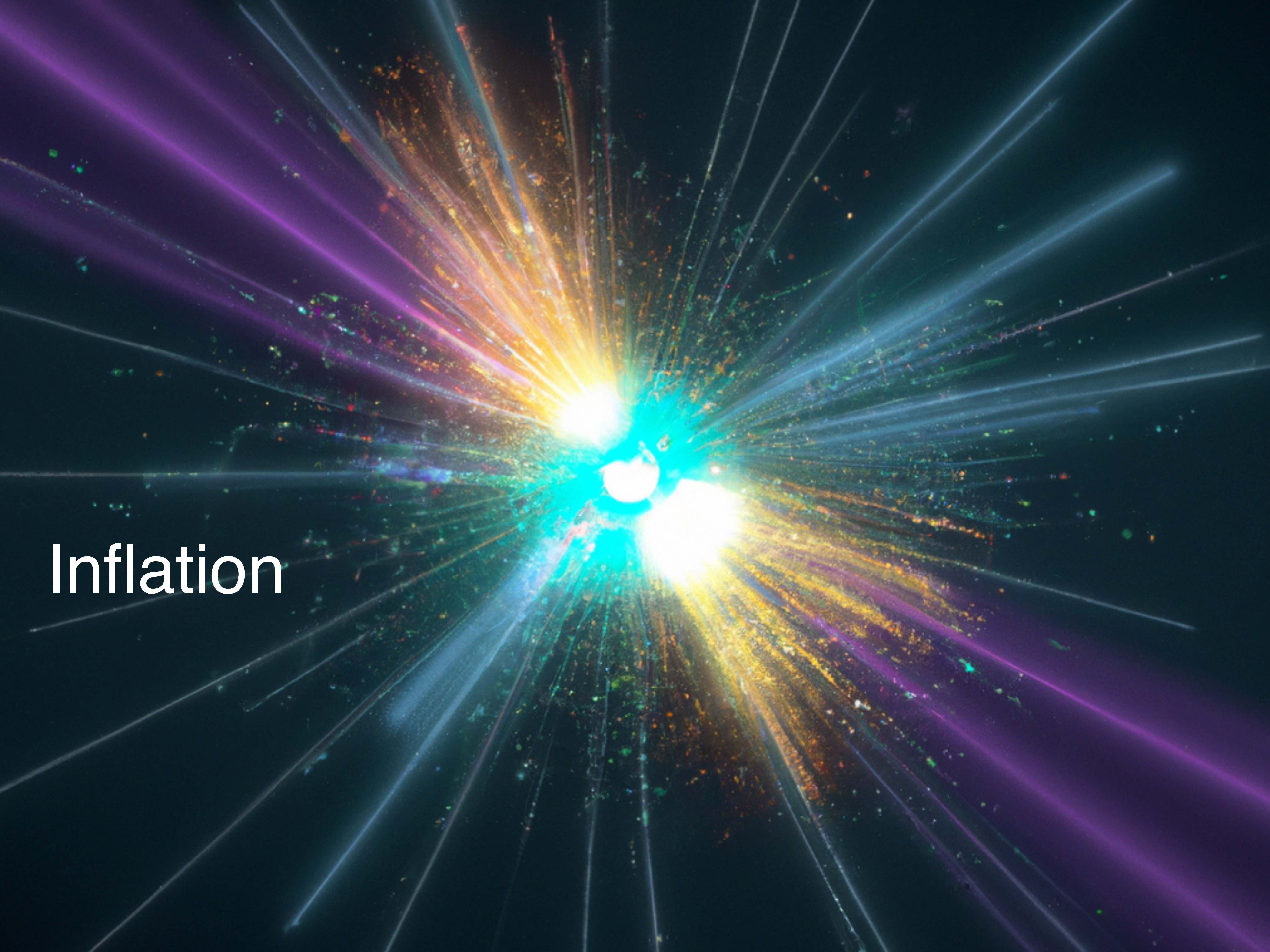
Plan for the talk:

I. Inflation

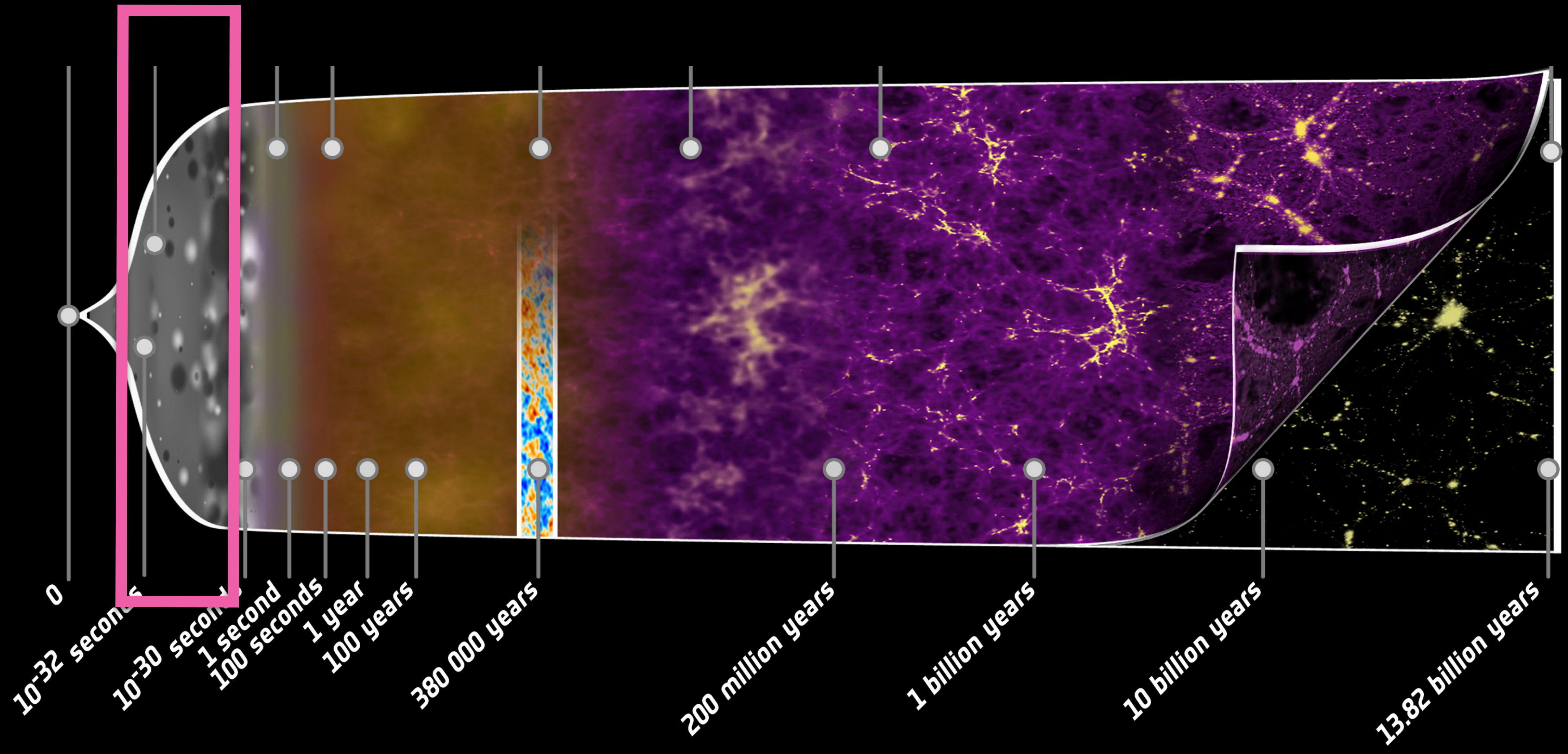


II. Dark Sectors

Inflation



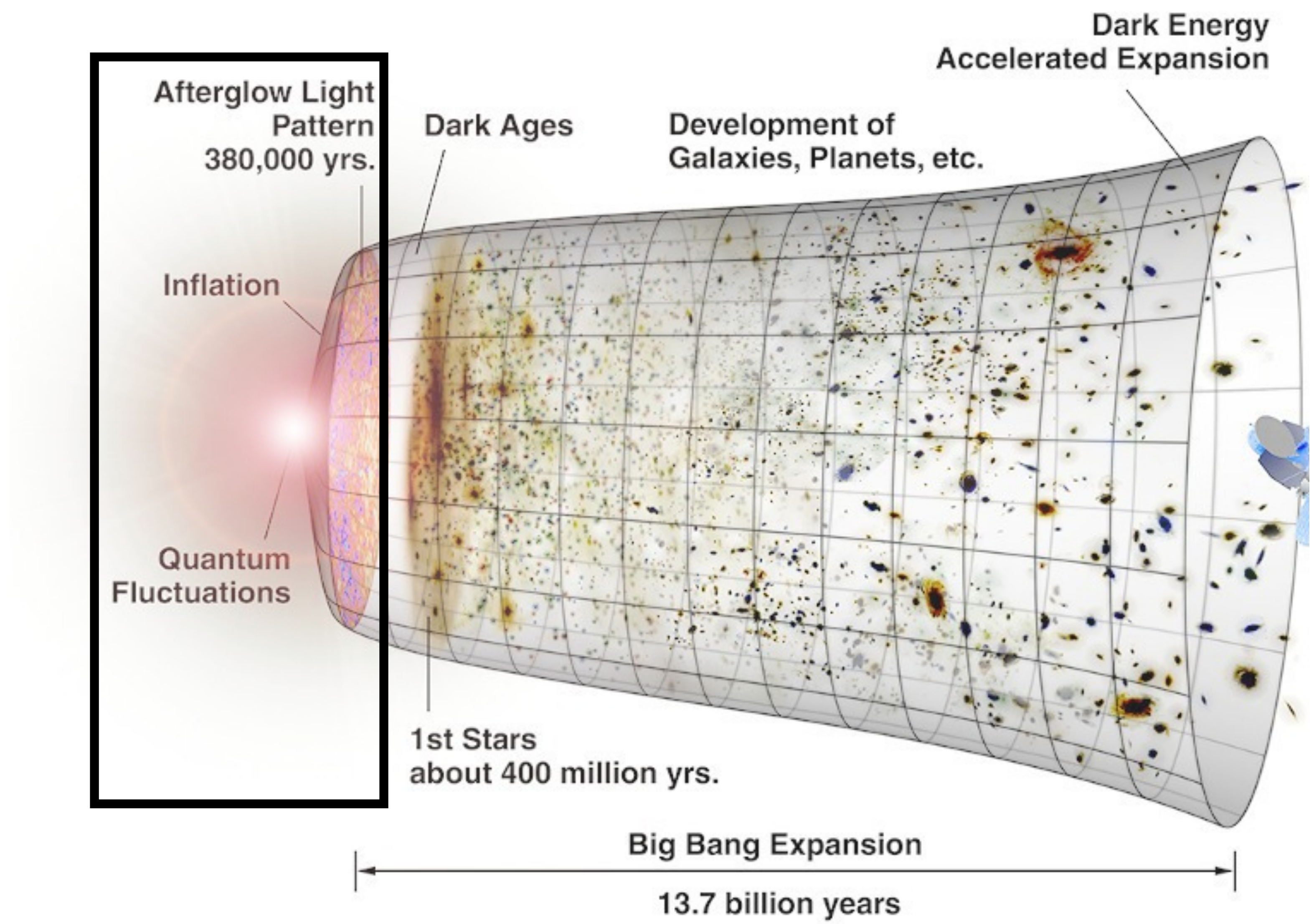
I. Inflation



0
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

The Nature of Inflation

The story of inflation is often told in one way

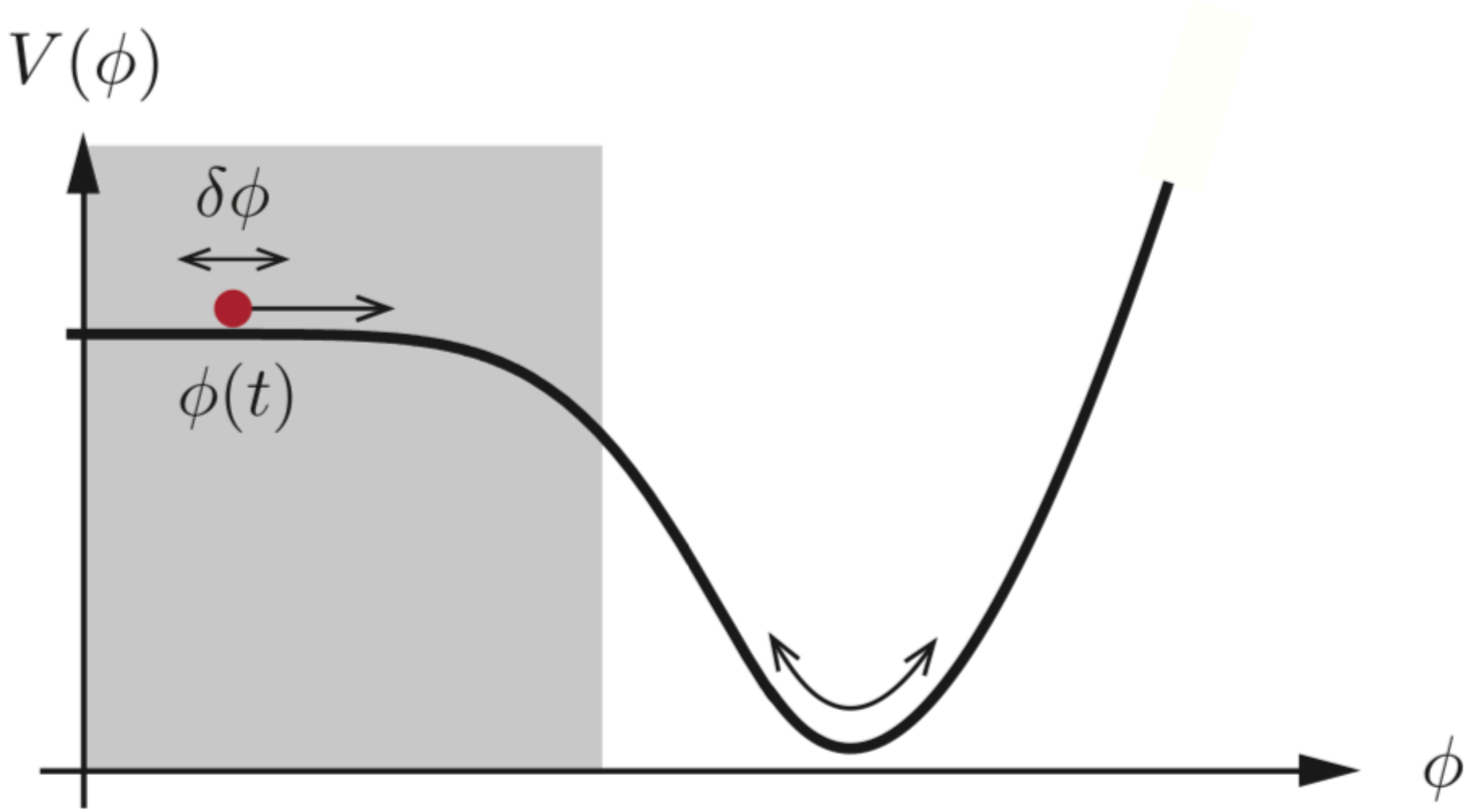


Period of exponential expansion

From WMAP

The Nature of Inflation

The story of inflation is often told in one way

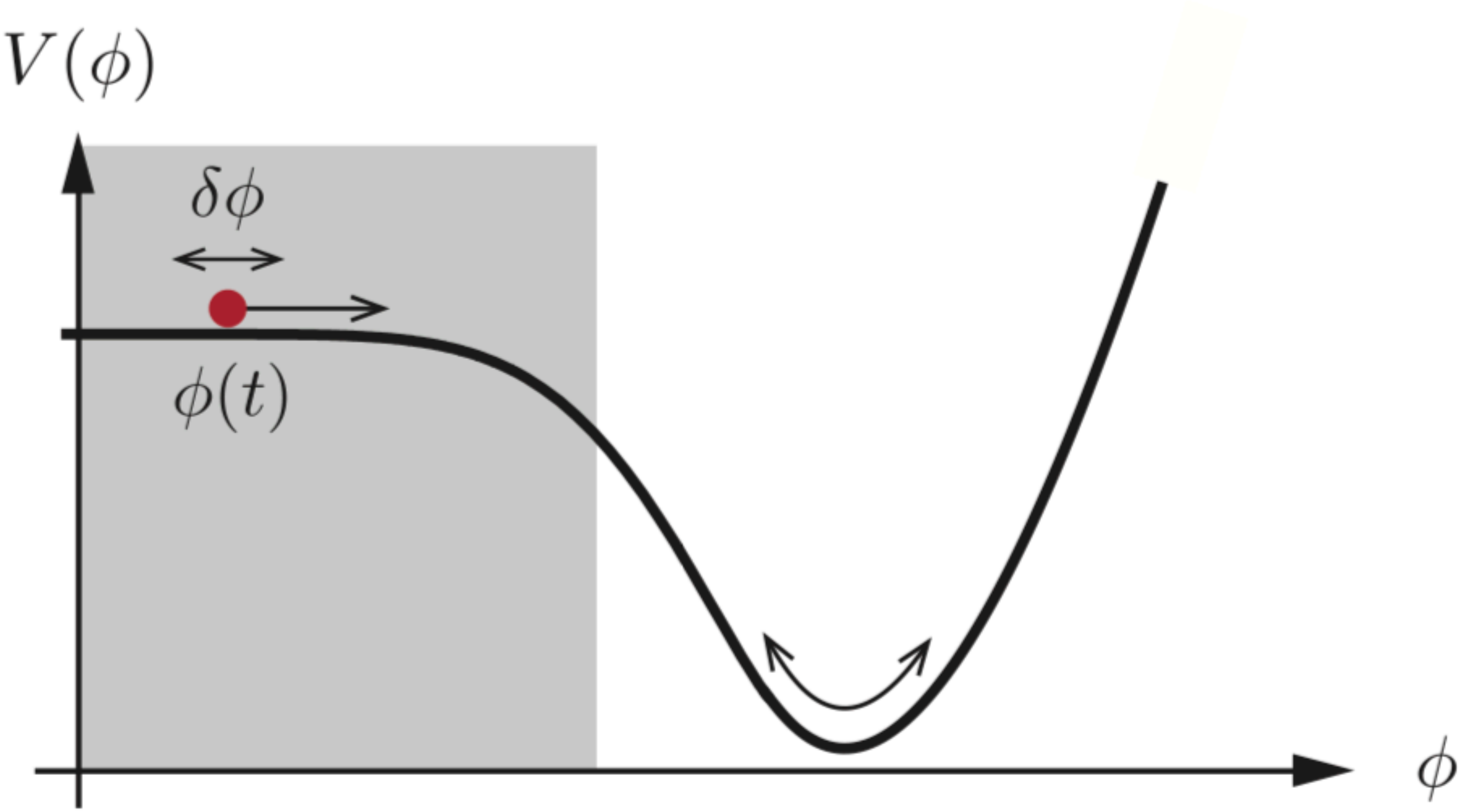


Driven by a slowly rolling scalar field

From Baumann & McAllister

The Nature of Inflation

The story of inflation is often told in one way

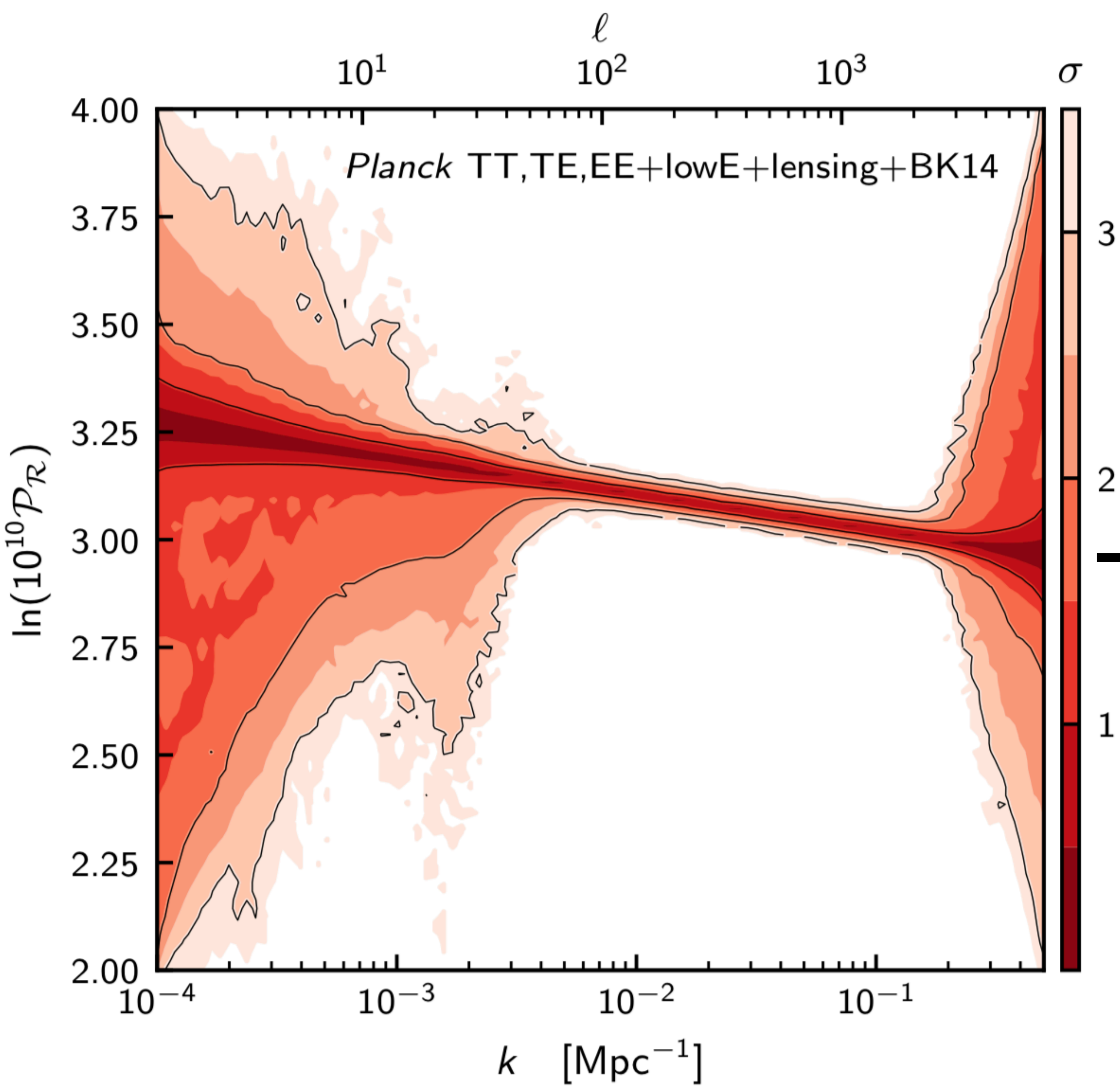


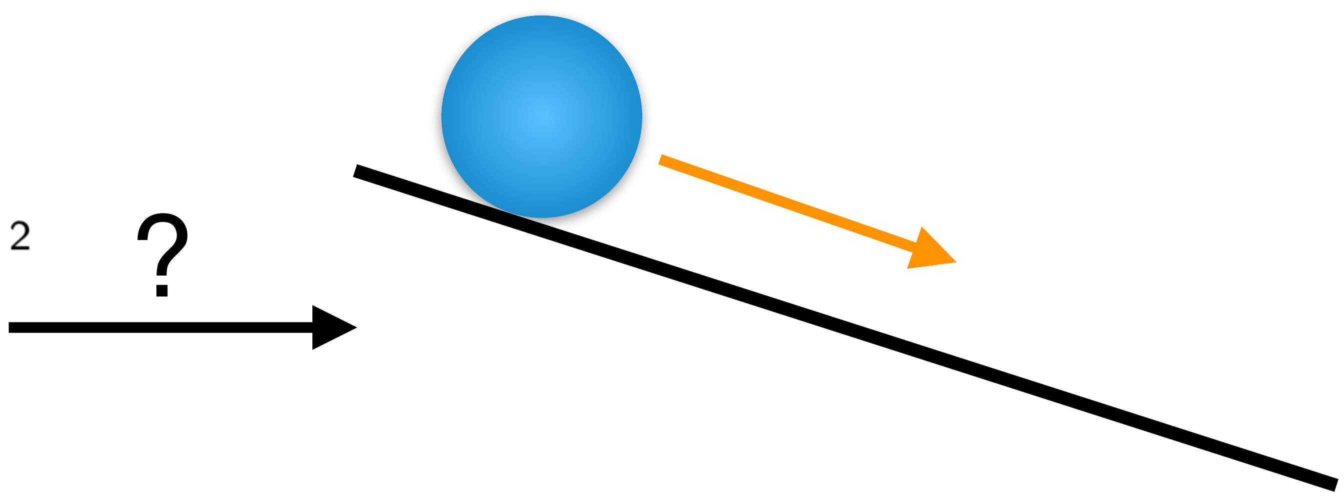
Quantum fluctuations of this field = initial conditions

From Baumann & McAllister

The Nature of Inflation

This pictures is consistent with observations

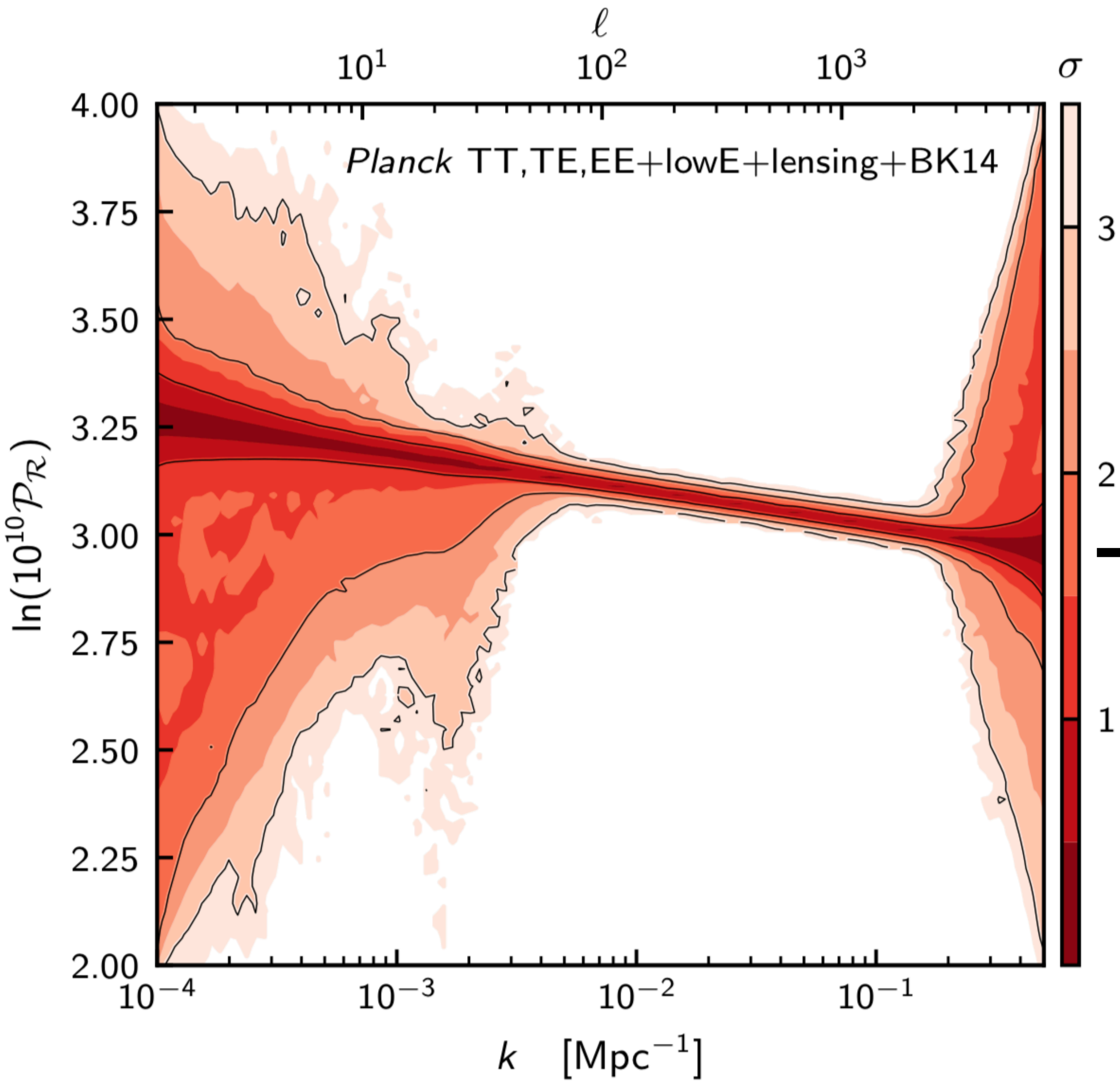




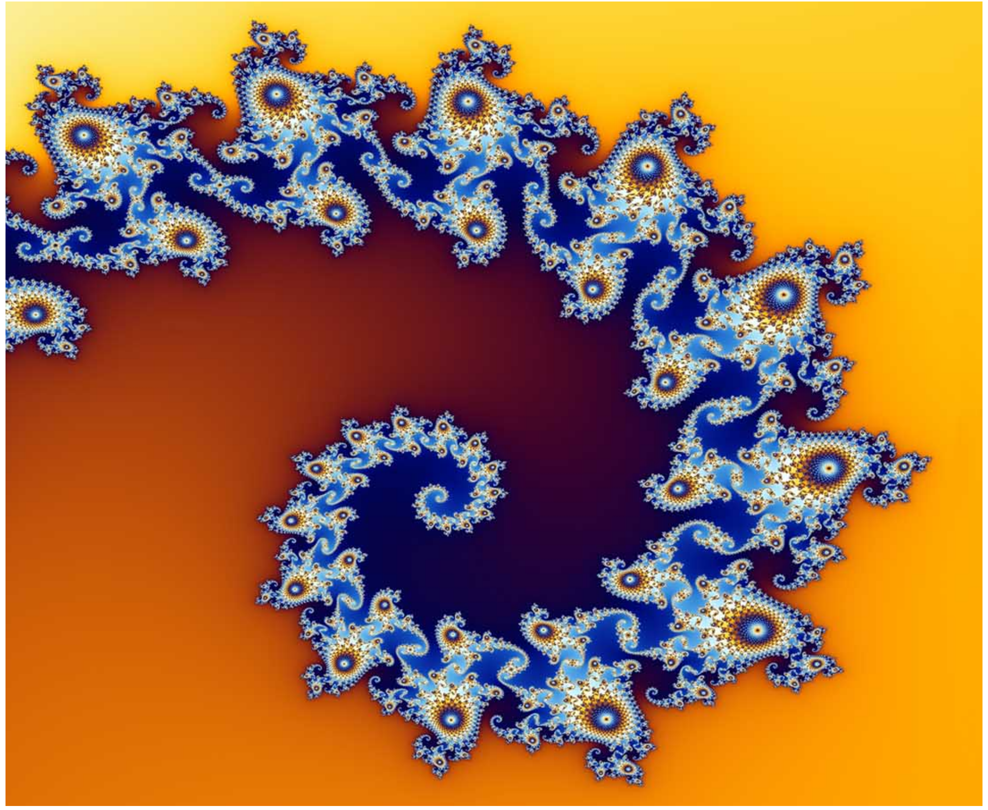
Planck 2018

The Nature of Inflation

But is it necessary ?



?



Planck 2018

The Nature of Inflation

Inflation：A definition

（1）A period of quasi-de Sitter expansion

$$H \equiv \frac{\dot{a}}{a} \qquad \dot{H}(t) \ll H^2 \qquad a(t) \approx e^{Ht}$$

（2）Inflation ends：requires a physical clock

In slow roll inflation – we set our clocks to $\phi(t) \approx \dot{\phi}\, t$

The Nature of Inflation

Defines two kinds of questions about inflation

（A）Do we know the geometry? Is it really inflation?

Strategy：primordial gravitational waves（CMB B-modes）

GW see the true geometry of spacetime

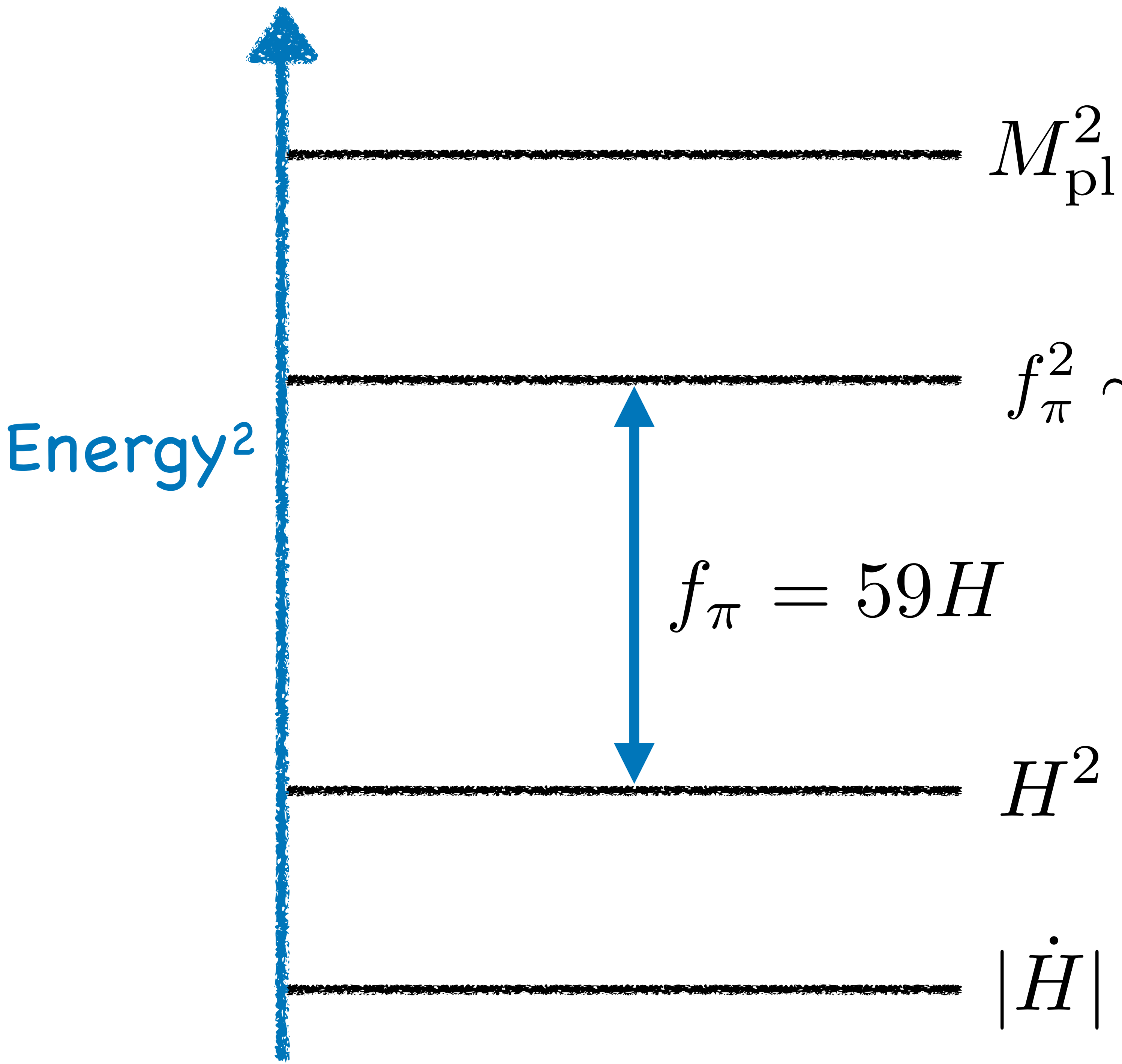
（B）What is the clock?

Real world clocks aren't fundamental scalars

Strategy：Non-trivial dynamics affects statistics

Scales

What do we know from data?

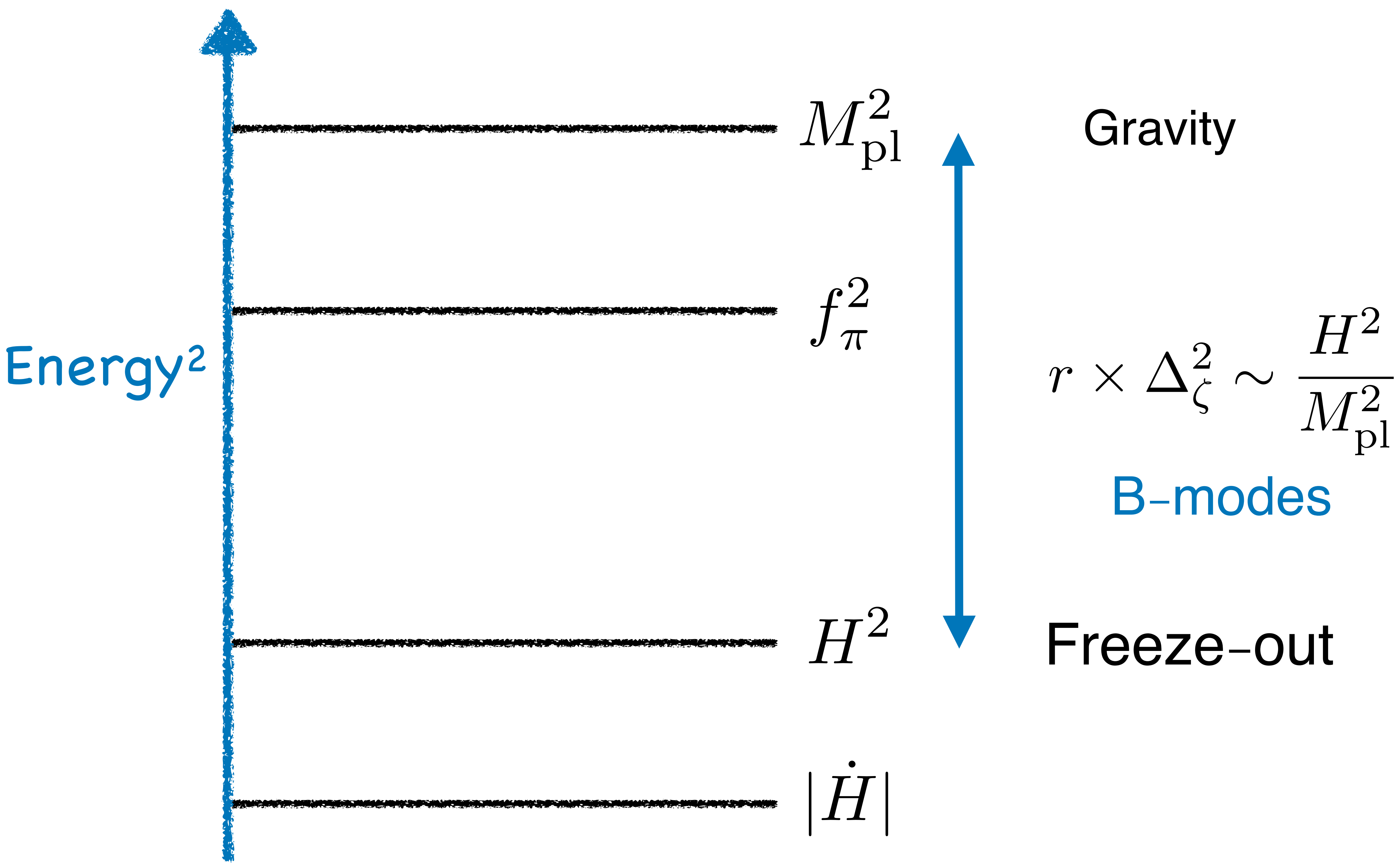


Resolution of the clock

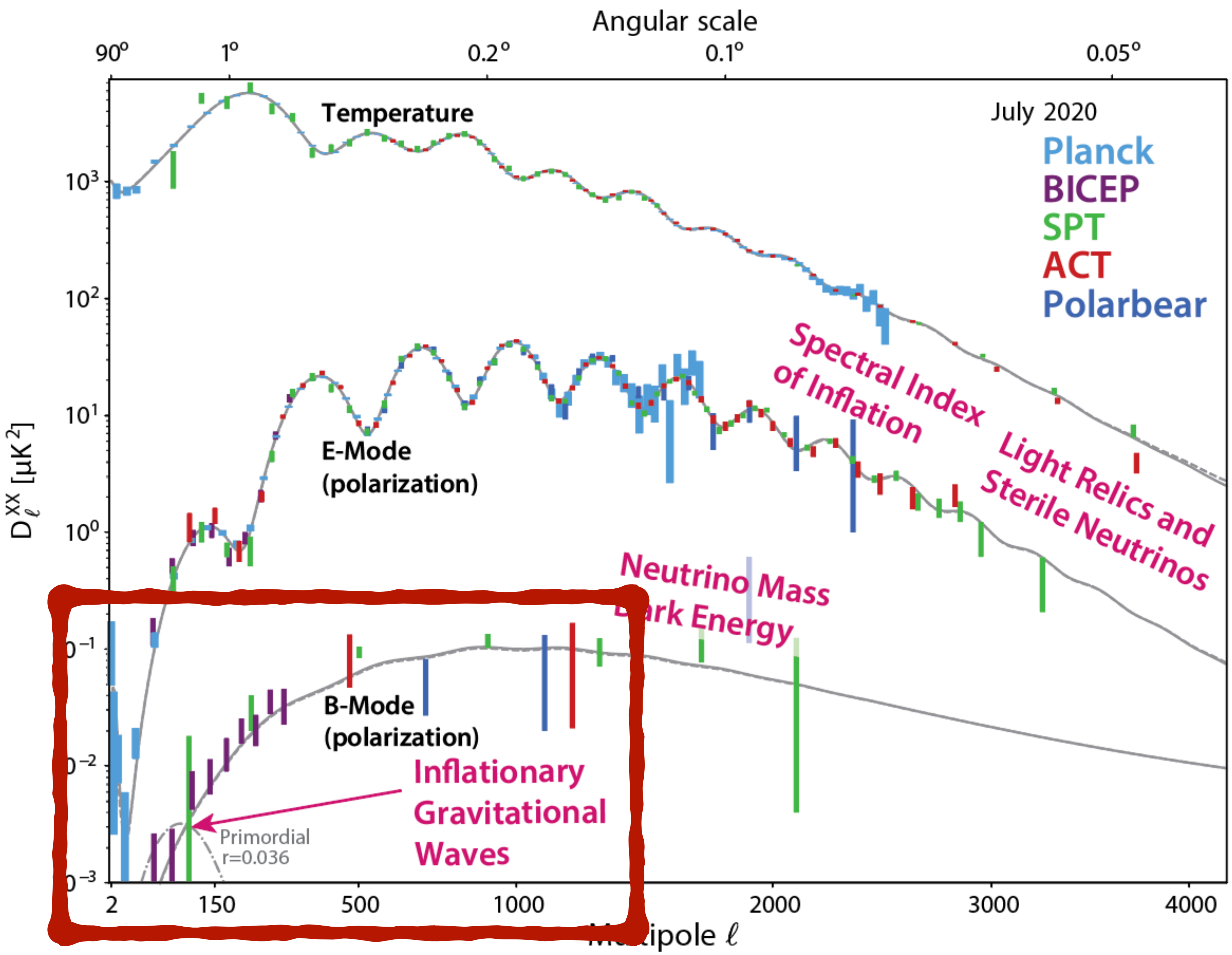
$$A_s = 2.1 \times 10^{-9}$$
$$= \frac{1}{4\pi^2}\left(\frac{H}{f_\pi}\right)^4$$

Scale of fluctuations

Gravitational Waves

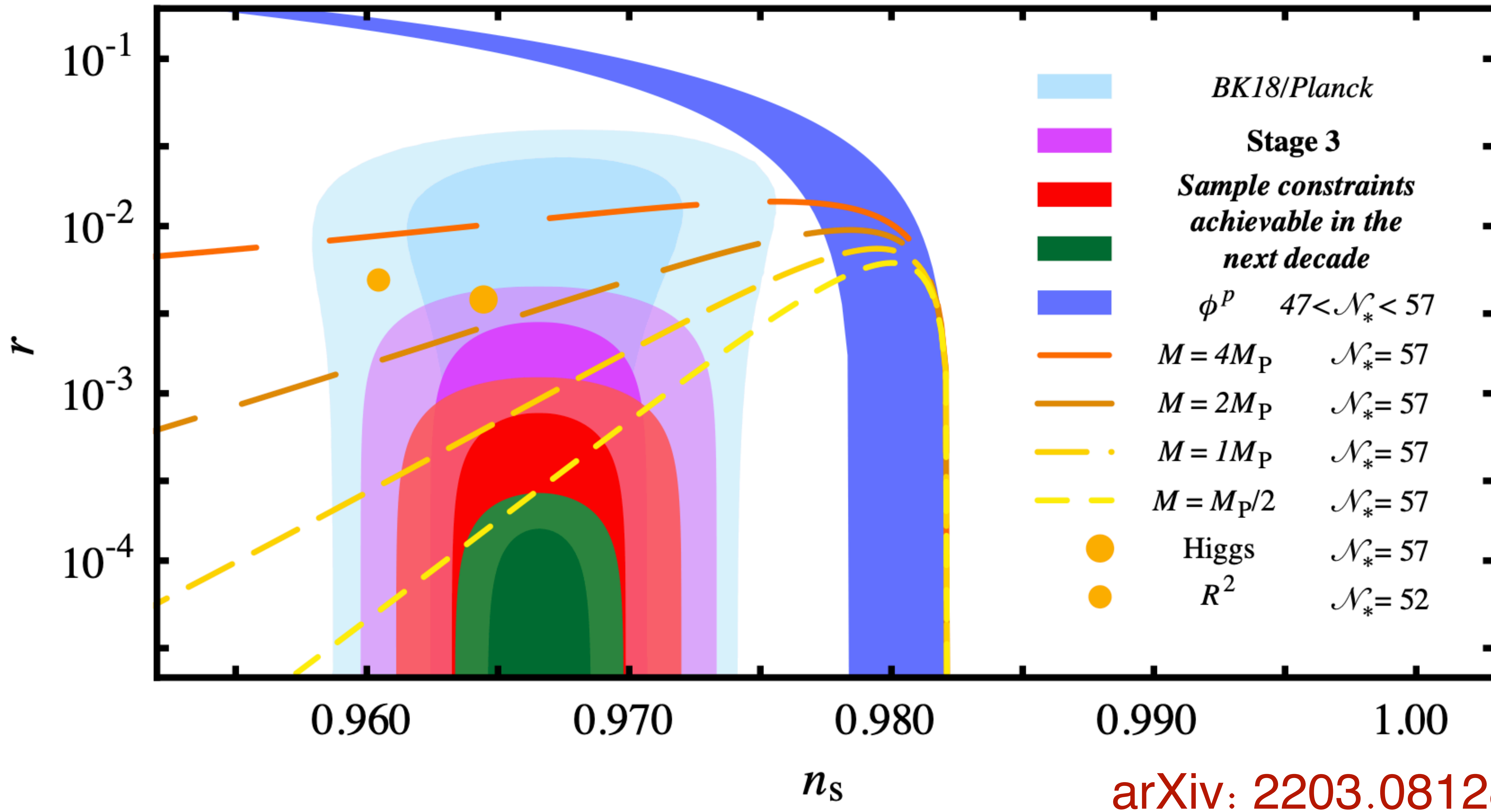


B-modes



From B. Benson & J. McMahon

B-modes



arXiv: 2203.08128

Gravitational Waves

Lots of reasons to prefer models that produce observable GW

Not seeing GWs would exclude entire classes of (good) ideas

Detection of primordial GW would be profoundly important

Is a direct window into the geometry of spacetime

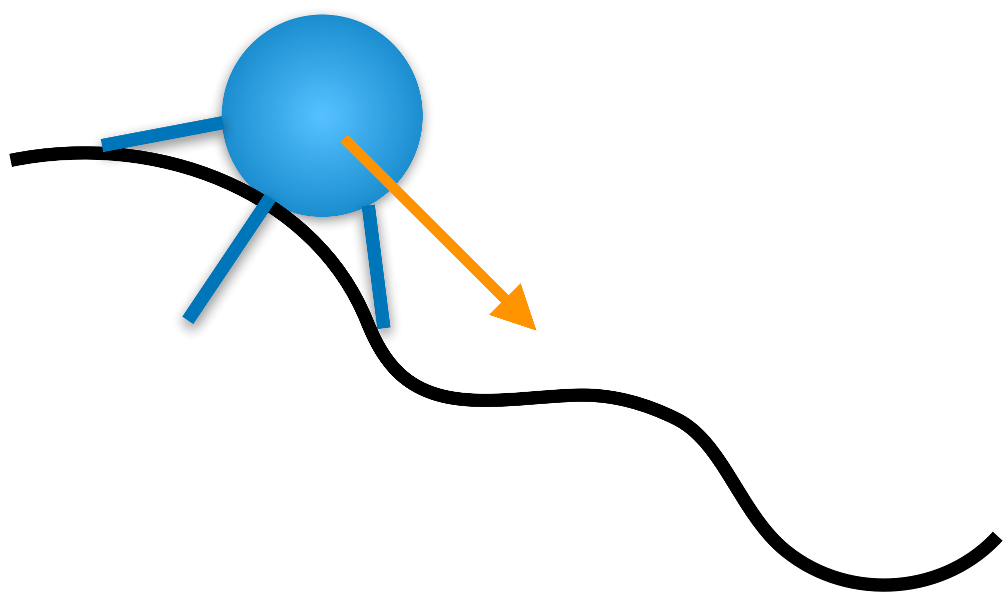
Determines the energy scale of inflation was very high

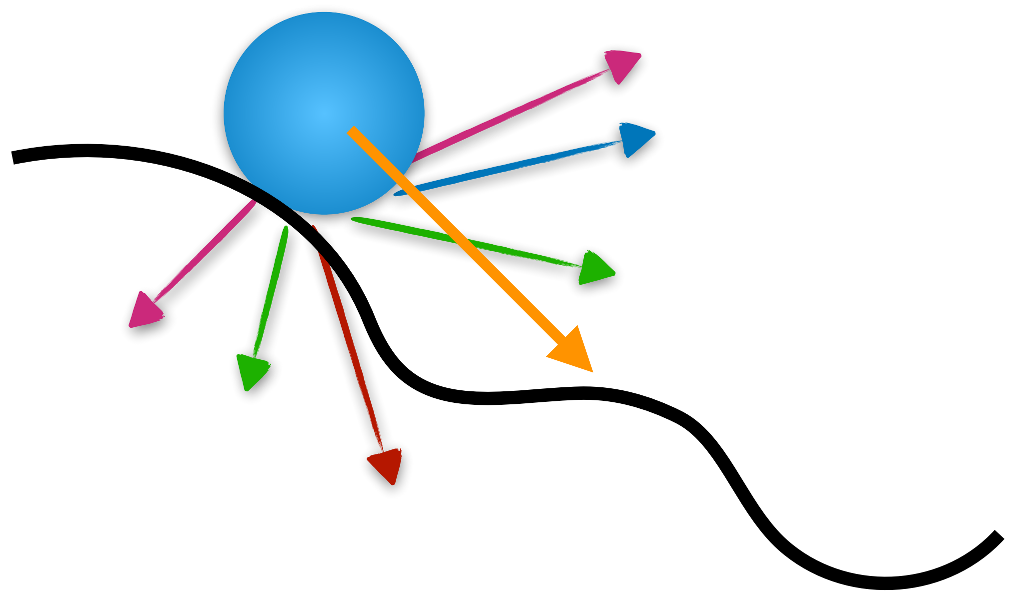
Implications for particle spectrum / interactions at GUT scale

What is the clock?

Theoretically, making a flat enough potential is hard

Dynamics may resolve a number of theoretical challenges



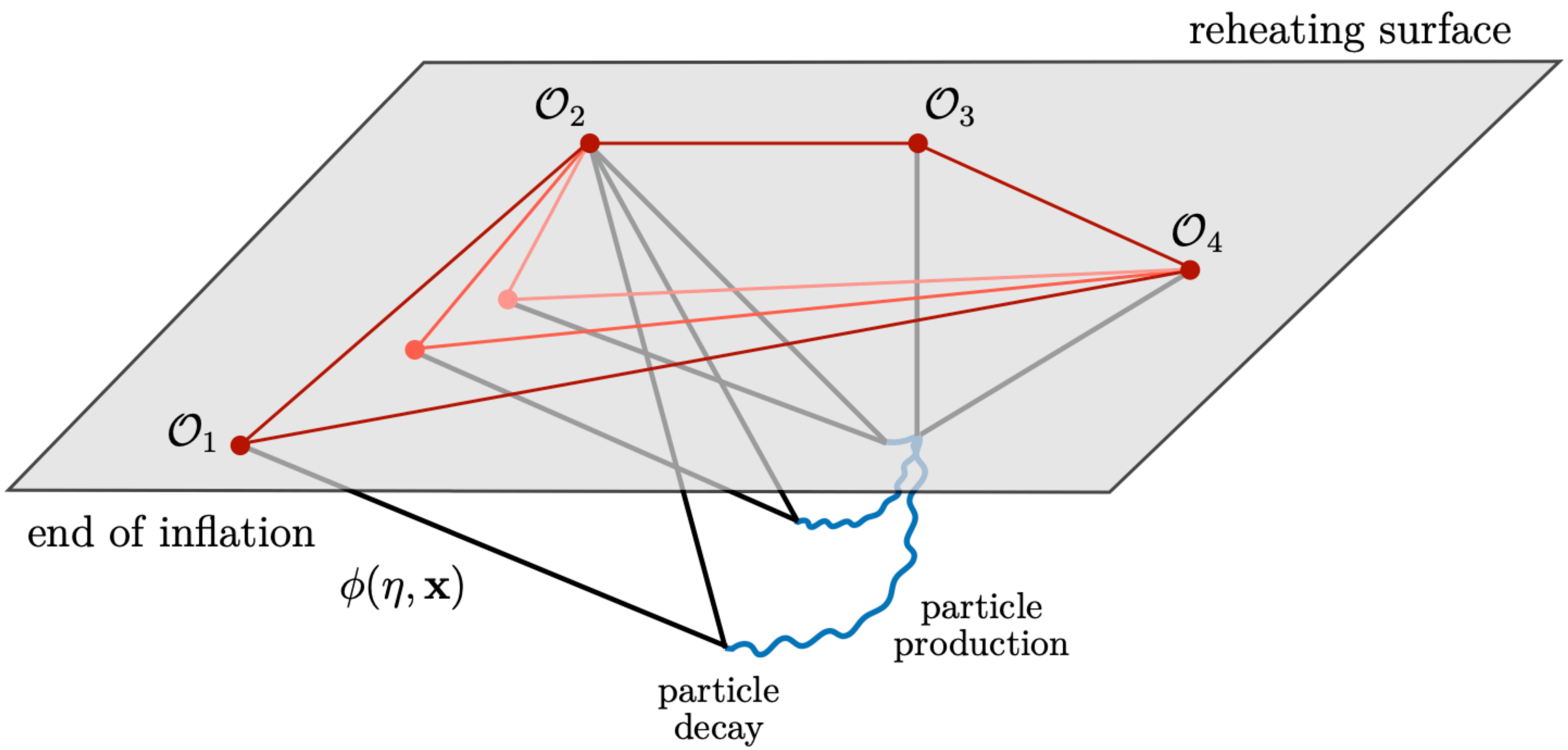


e.g. self-interactions or particle-production

Leads to measurable non-Gaussianity and/or features

The Cosmological Collider

Primordial Statistics is particle physics at the scale of inflation



Masses and spins of new states are observable

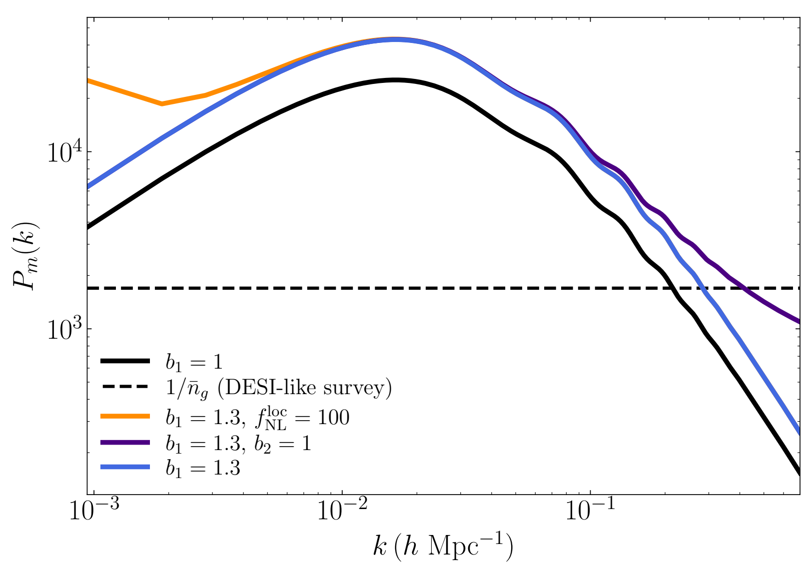
For high-scale inflation, probes Planck suppressed couplings

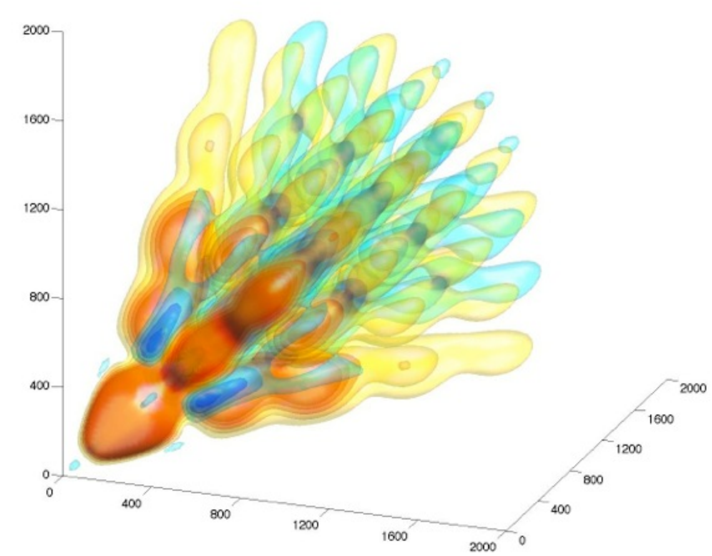
arXiv: 2203.08121

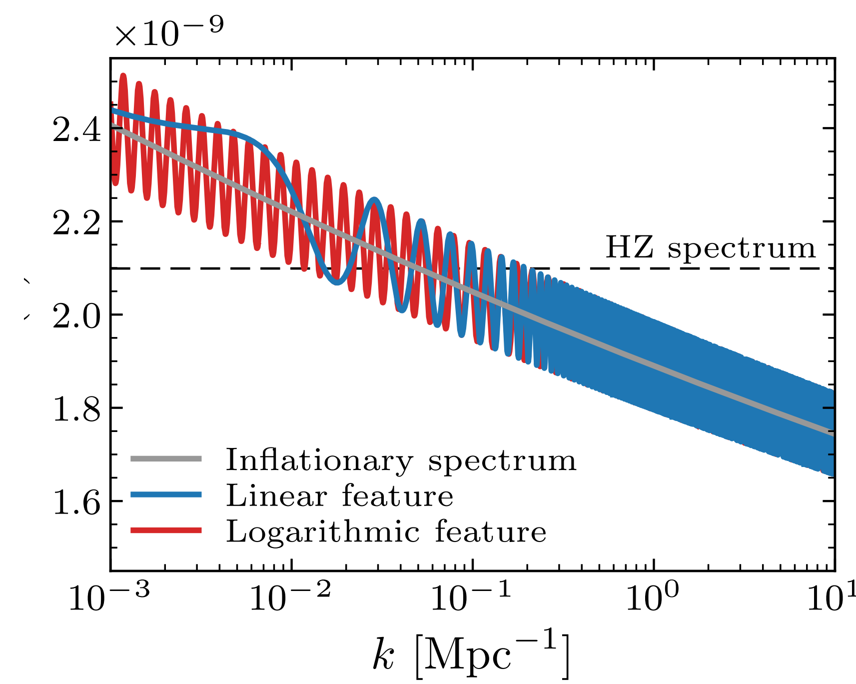
Cosmic Signals

	New Particles	Self-Interactions	Primordial Features
Parameter:	$f_{\mathrm{NL}}^{\mathrm{local}}$	$f_{\mathrm{NL}}^{\mathrm{equilateral}}$	A_{lin}
Observable:	CMB+LSS+ Cross-Correlation	CMB/LSS Bispectrum	CMB (frequency range) LSS (sensitivity)

Signal:

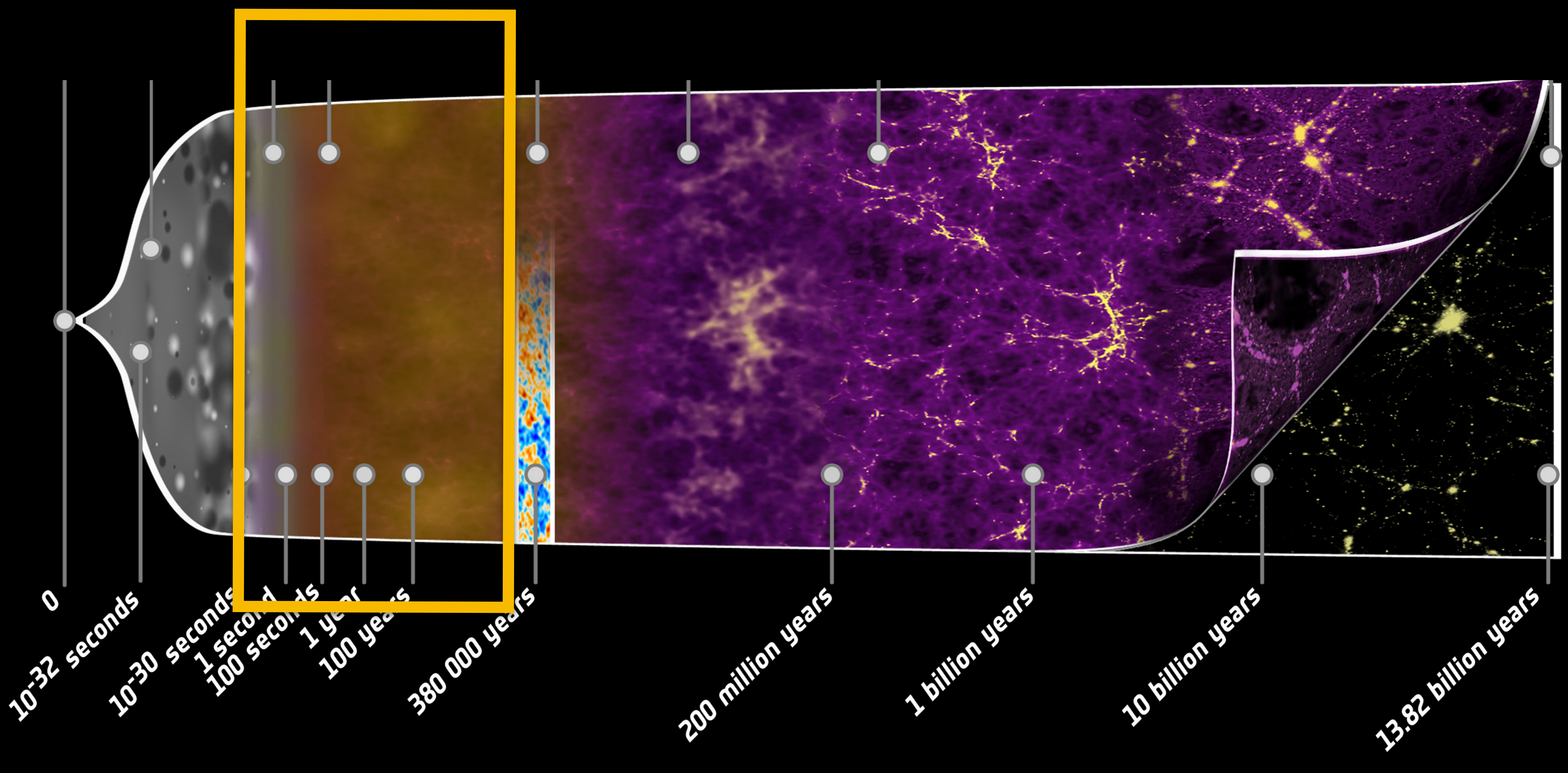




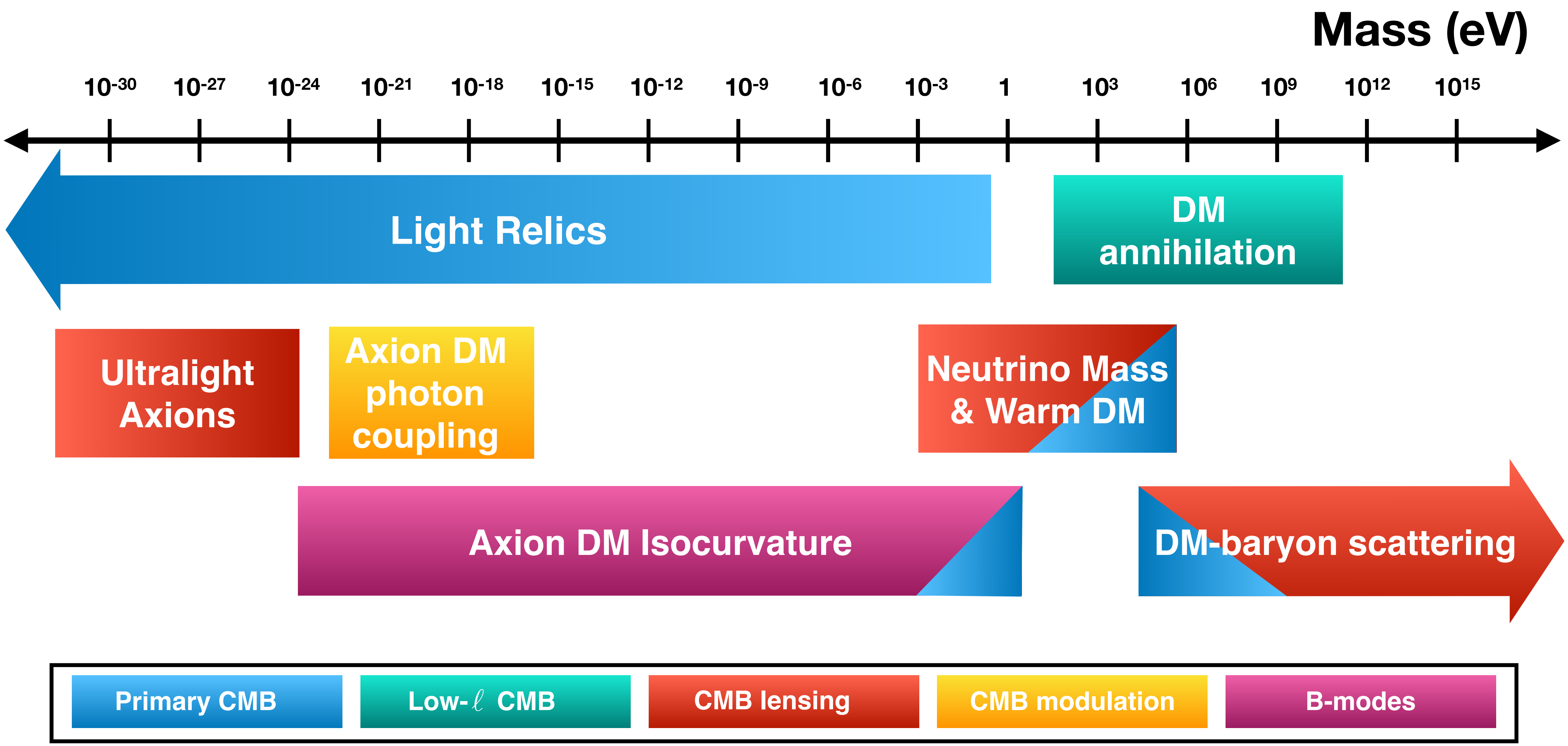


Dark Sectors

Dark Sectors

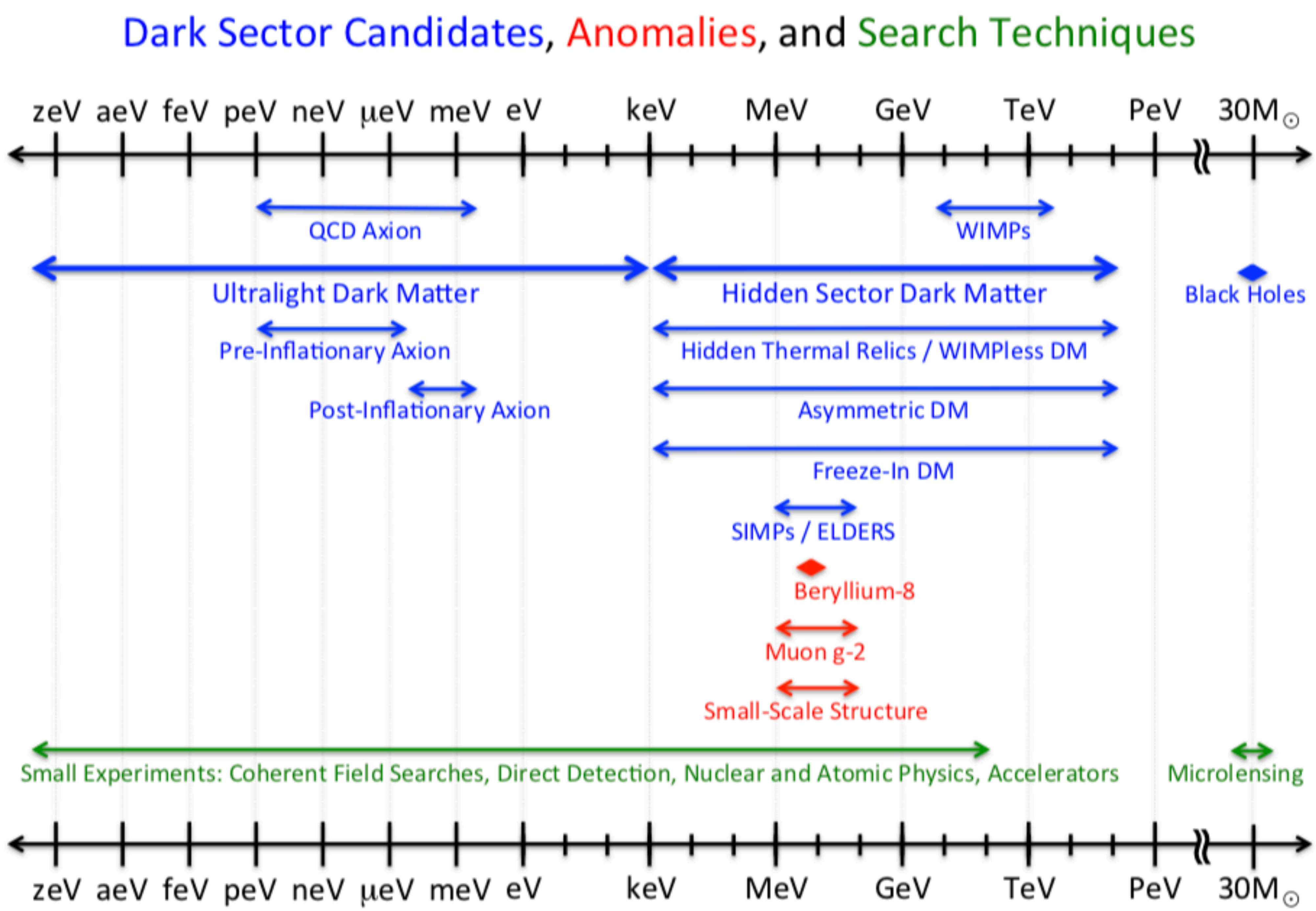


Dark Sectors & the CMB



arXiv: 1907.04473

Dark Sector Experiments



arXiv: 1707.04591

Dark Sectors

Cosmology competes head to head with the lab

- Detect dark matter at 120σ
- Detect cosmic neutrino background at 30σ

Neither has been seen in the lab

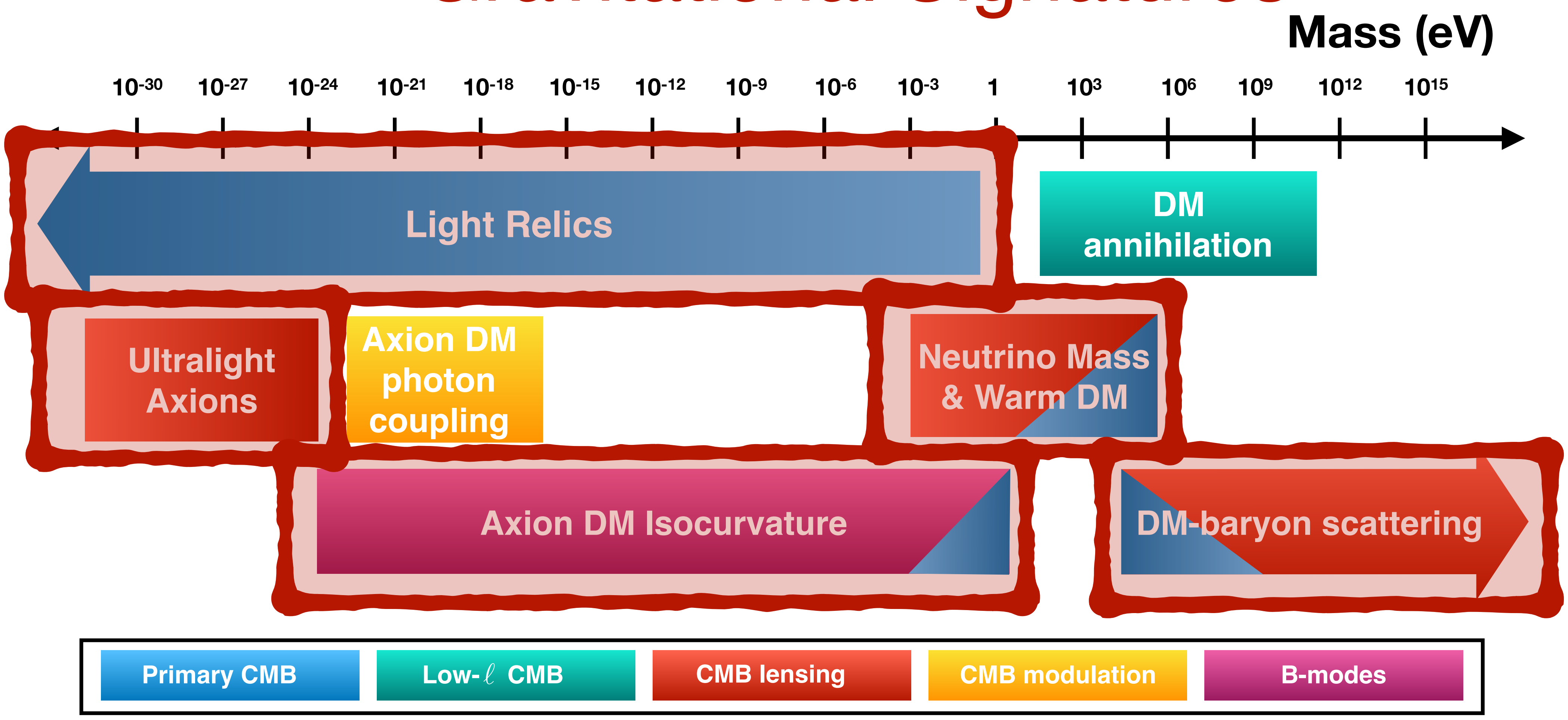
Superior sensitivity arises because of

(1) high T / number density in early universe

(2) large gravitational influence at recombination

Dark Sectors

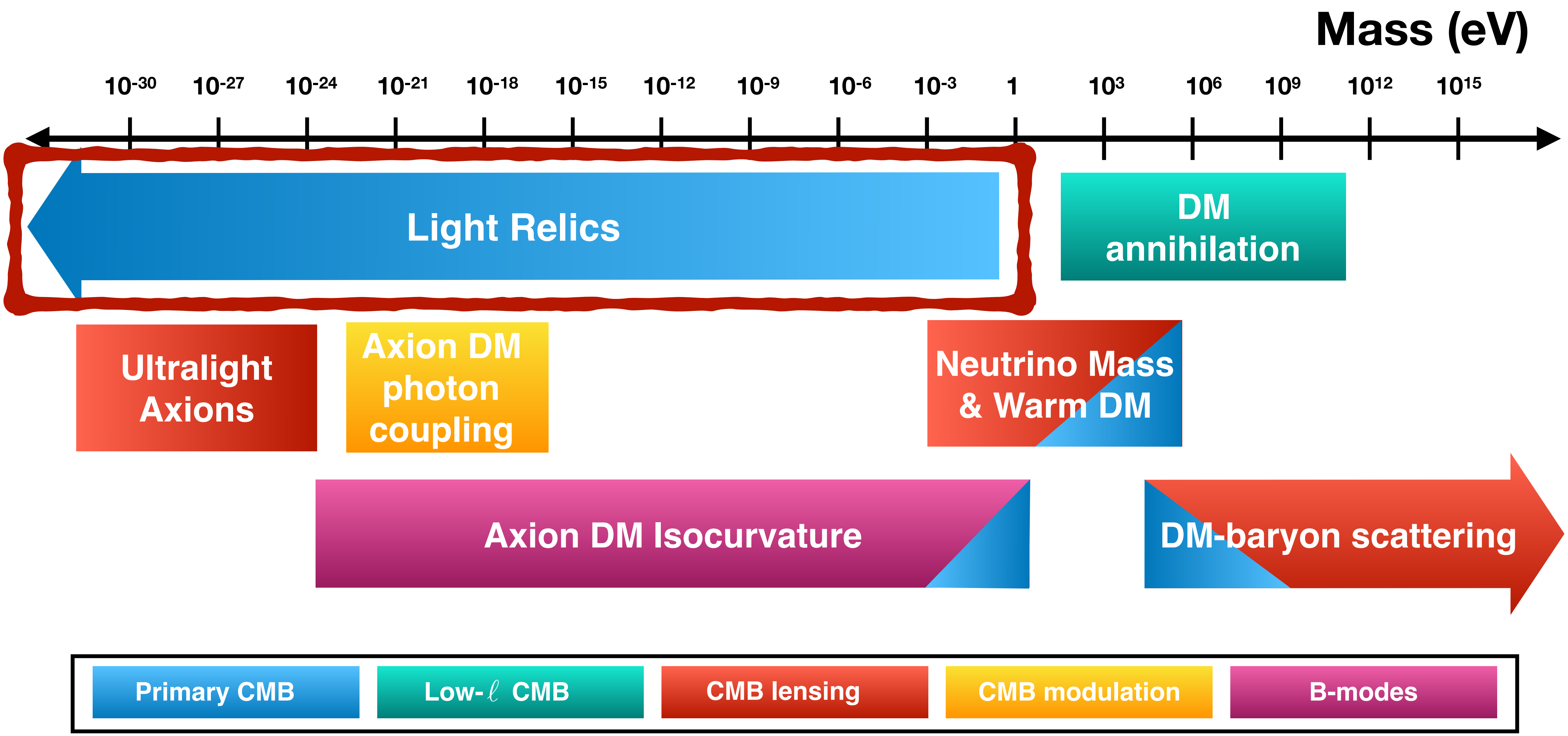
Gravitational Signatures



We see these dark sectors through gravity

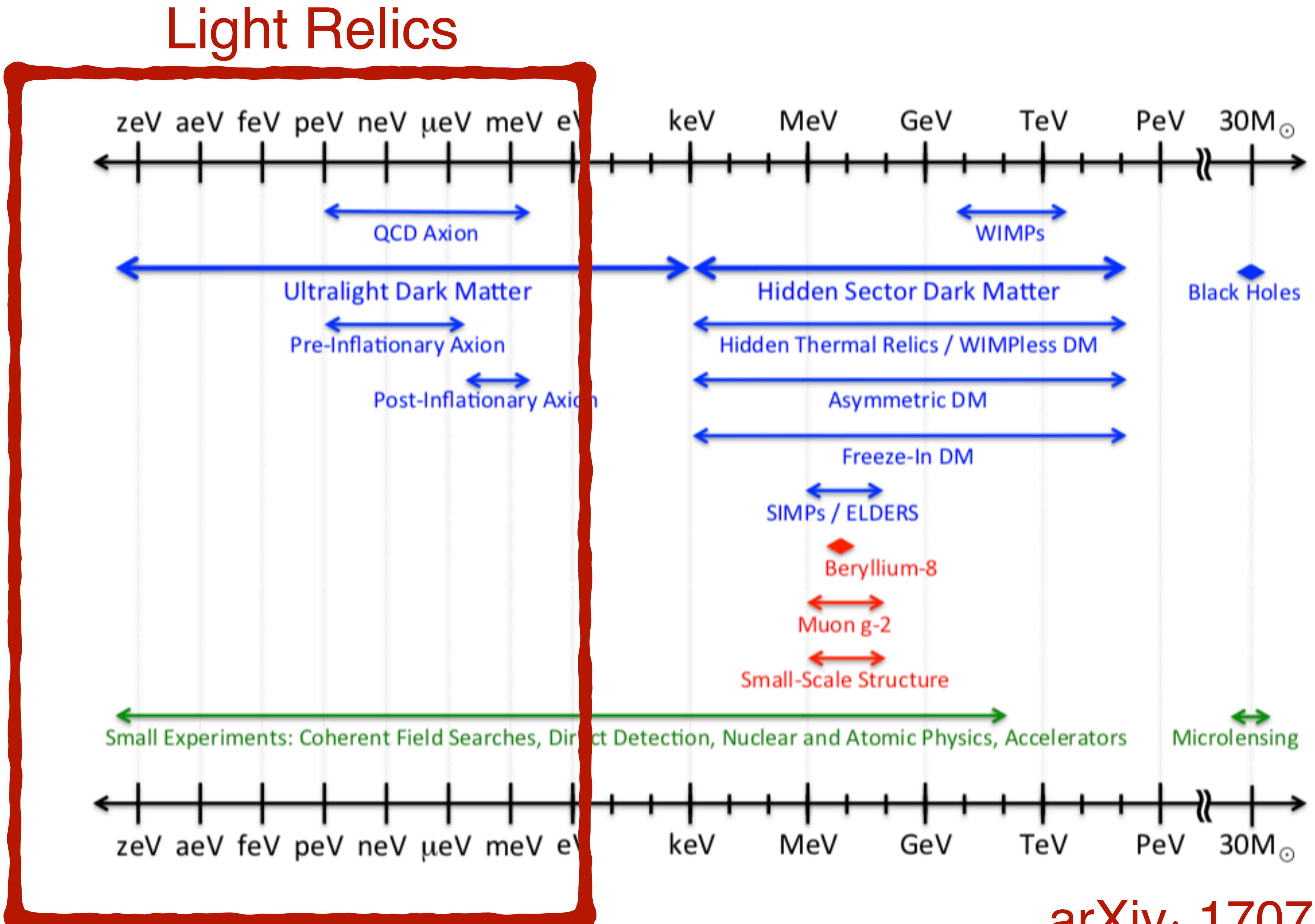
Can’t hide the signature by changing the coupling

Dark Sectors



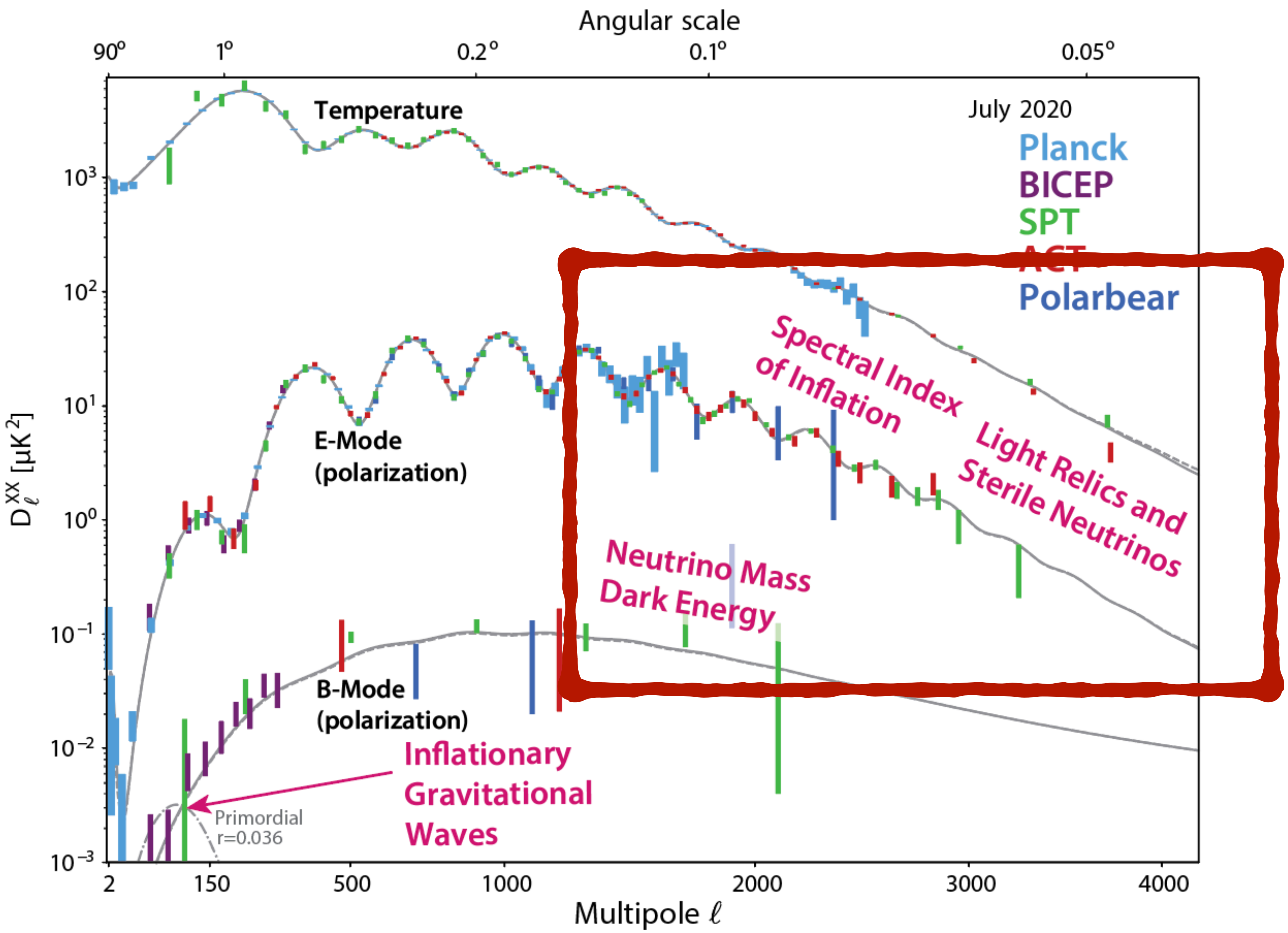
arXiv: 1907.04473

Light Relics

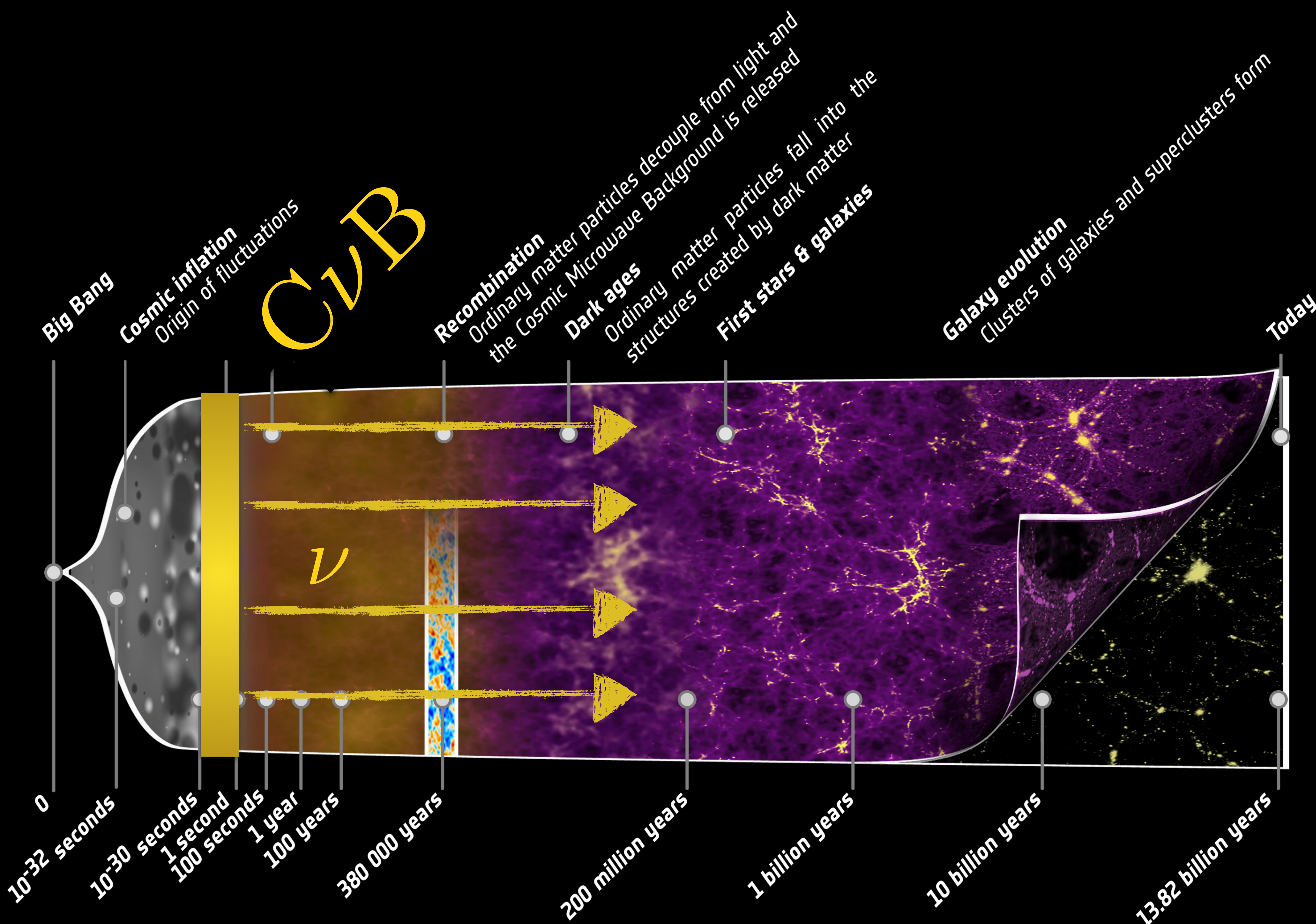


arXiv: 1707.04591

Damping Tail

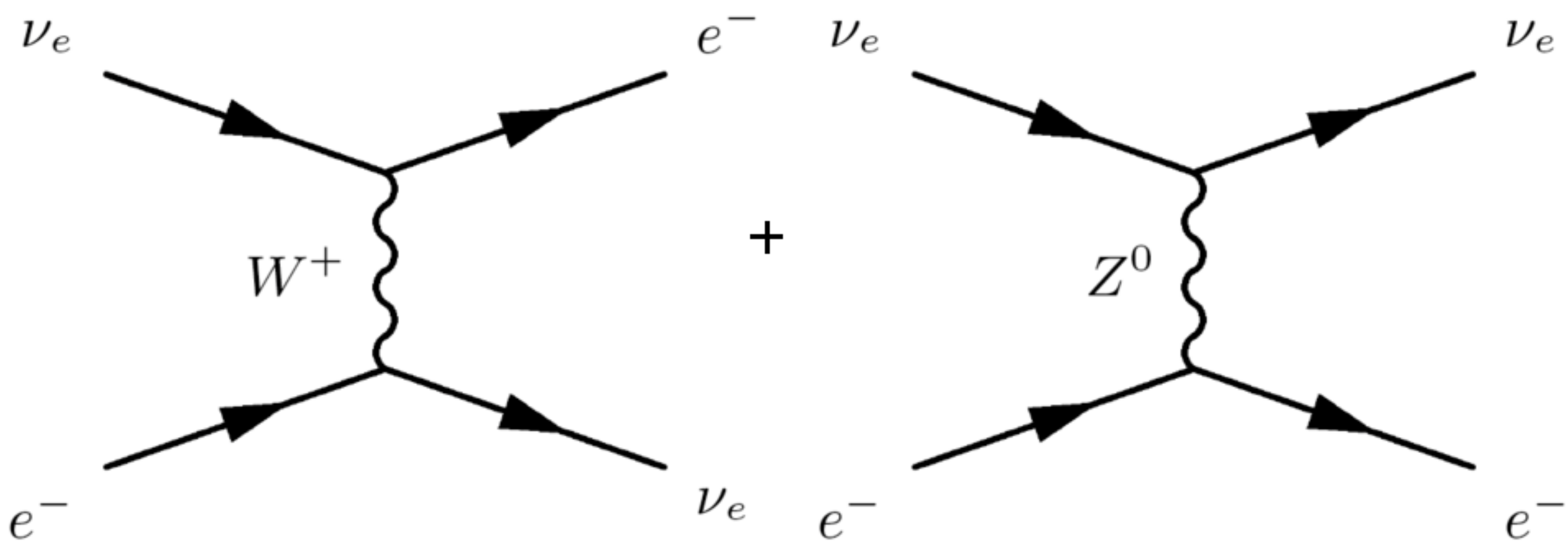


From B. Benson & J. McMahon



CνB
ν
Big Bang
Cosmic inflation
Origin of fluctuations
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
0
10-32 seconds
10-30 seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

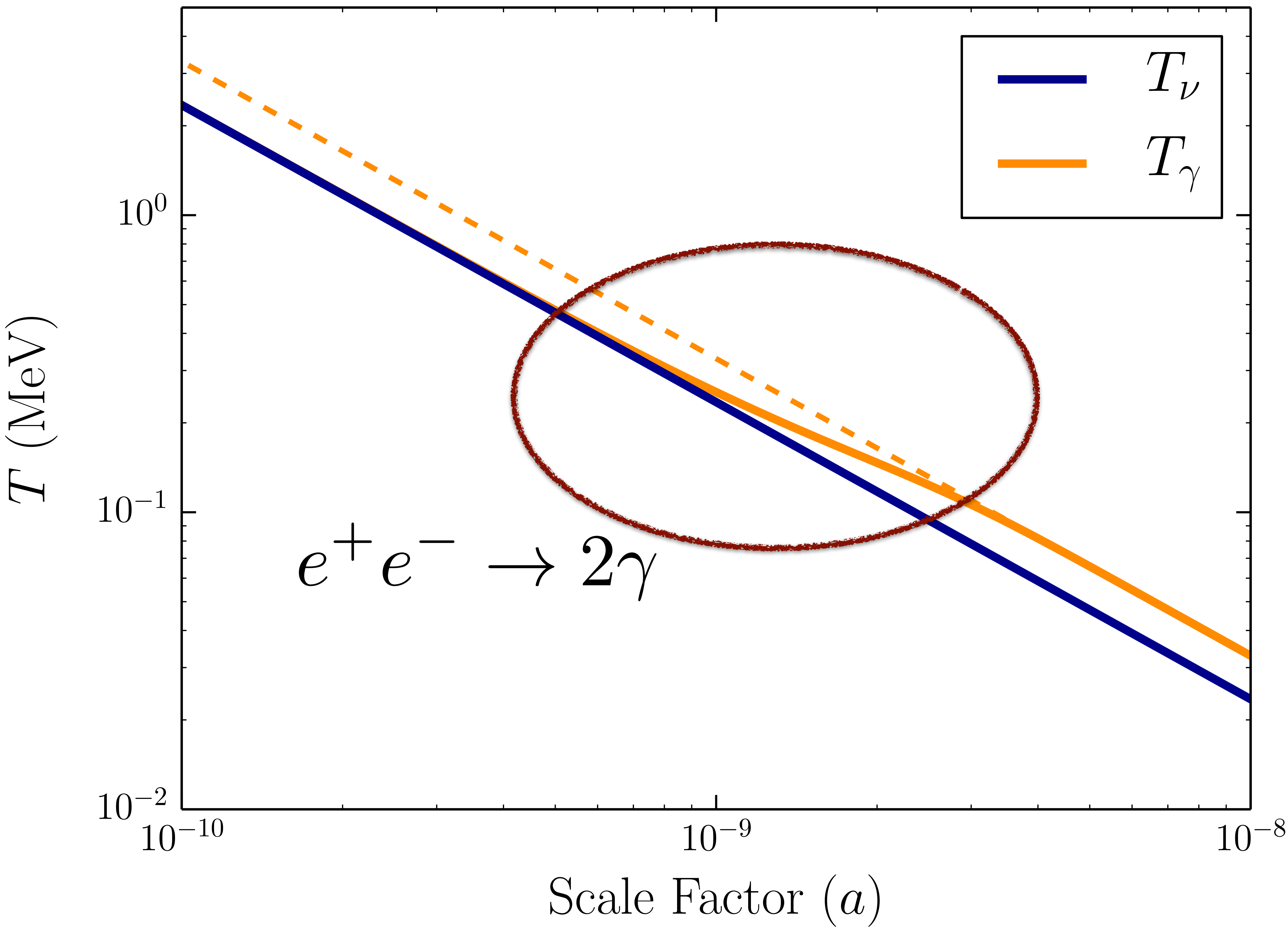
Cosmic Neutrino Background



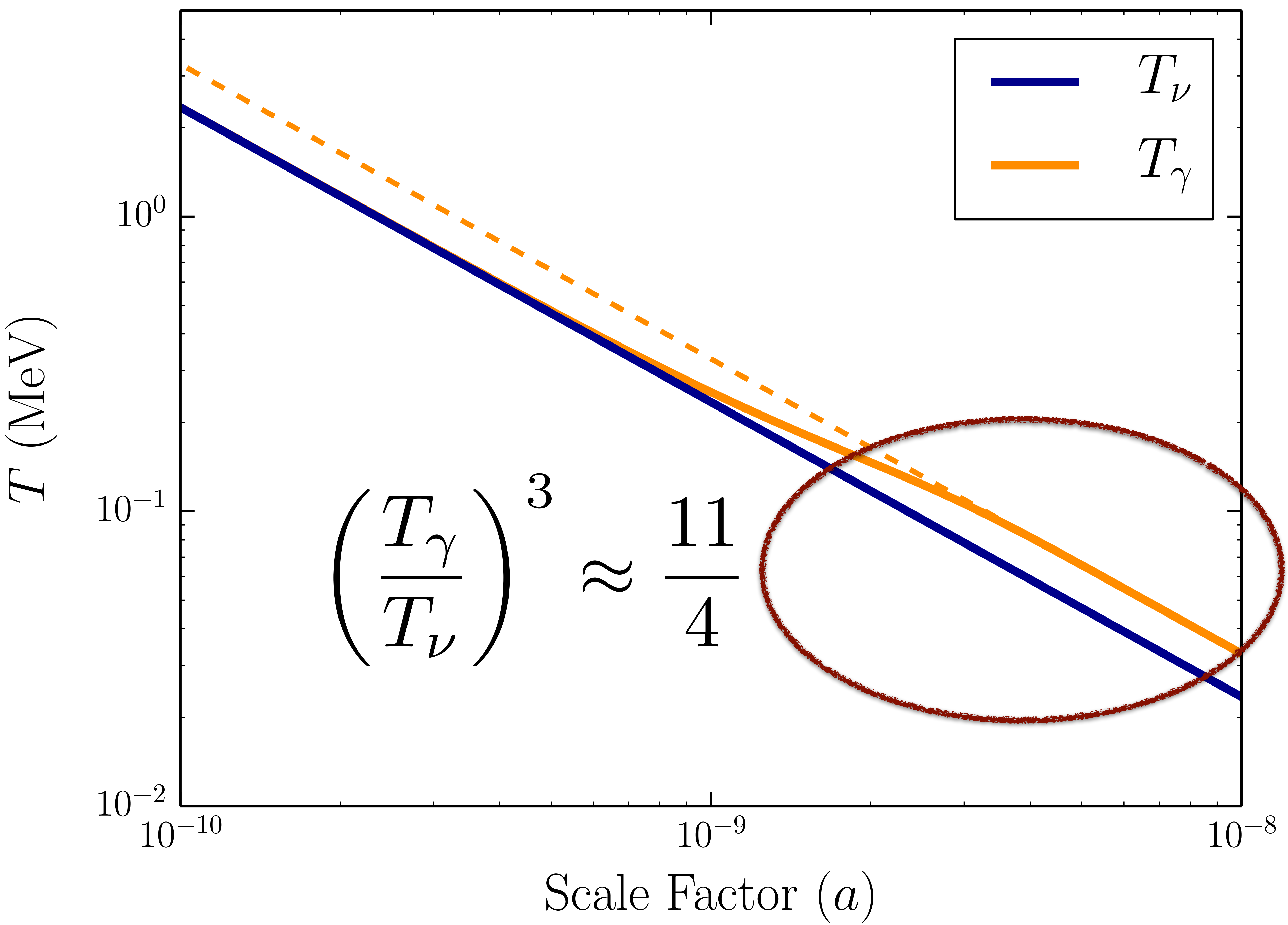
Equilibrium：

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

Decoupling: $T^3 \sim G_{\rm F}^{-2}/M_{\rm pl} = \mathcal{O}(1\,{\rm MeV})$



T_ν
T_γ
10^0
10^{-1}
10^{-2}
T (MeV)
$e^+e^- \to 2\gamma$
10^{-10}
10^{-9}
10^{-8}
Scale Factor (a)



T_ν
T_γ
10^0
10^{-1}
10^{-2}
T (MeV)
10^{-10}
10^{-9}
10^{-8}
Scale Factor (a)
$\left(\frac{T_\gamma}{T_\nu}\right)^3 \approx \frac{11}{4}$

Cosmic Neutrino Background

Cosmology sensitive to the neutrino energy density

Conventional to define

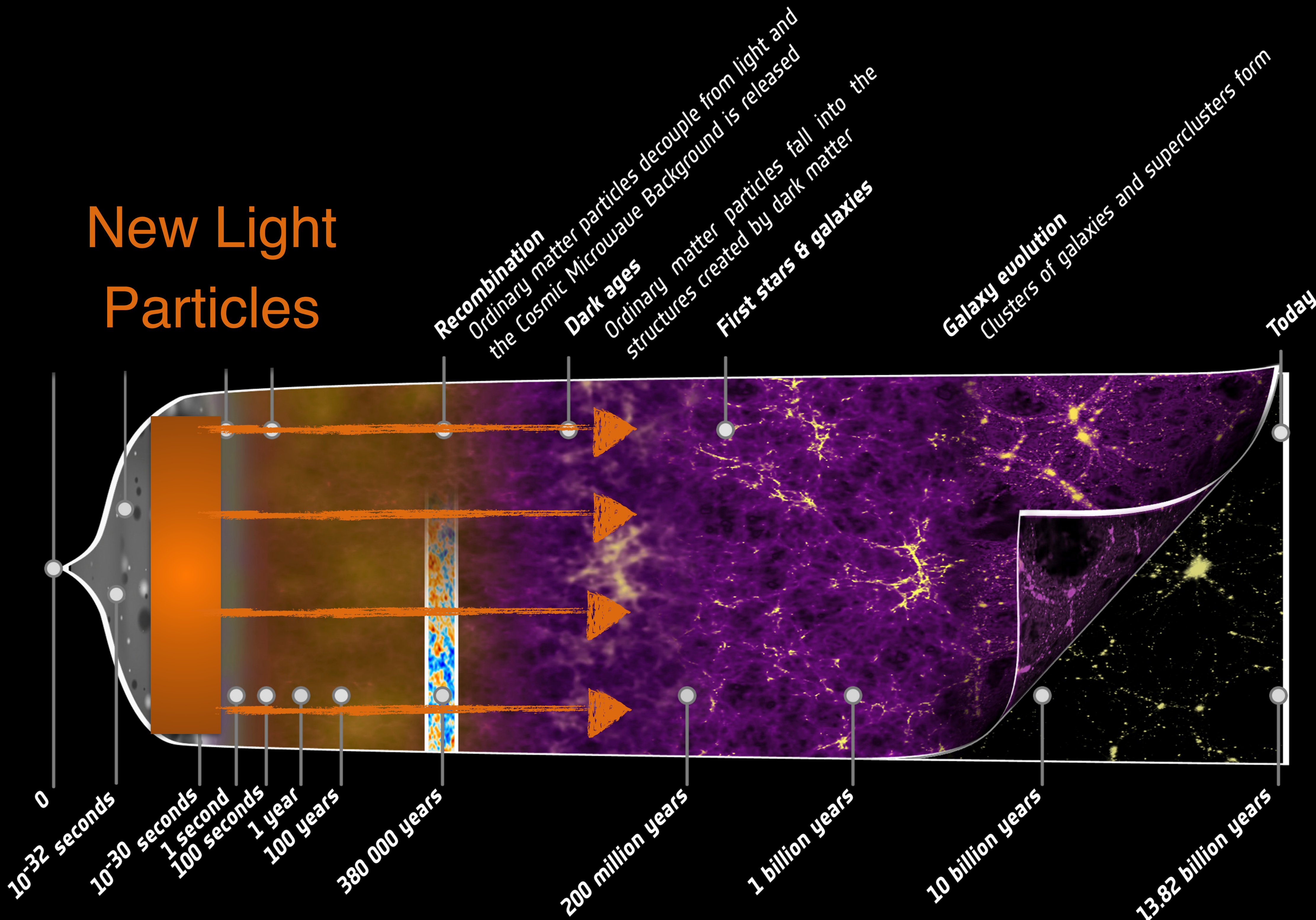
$$N_{\mathrm{eff}} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_\nu}{\rho_\gamma}$$

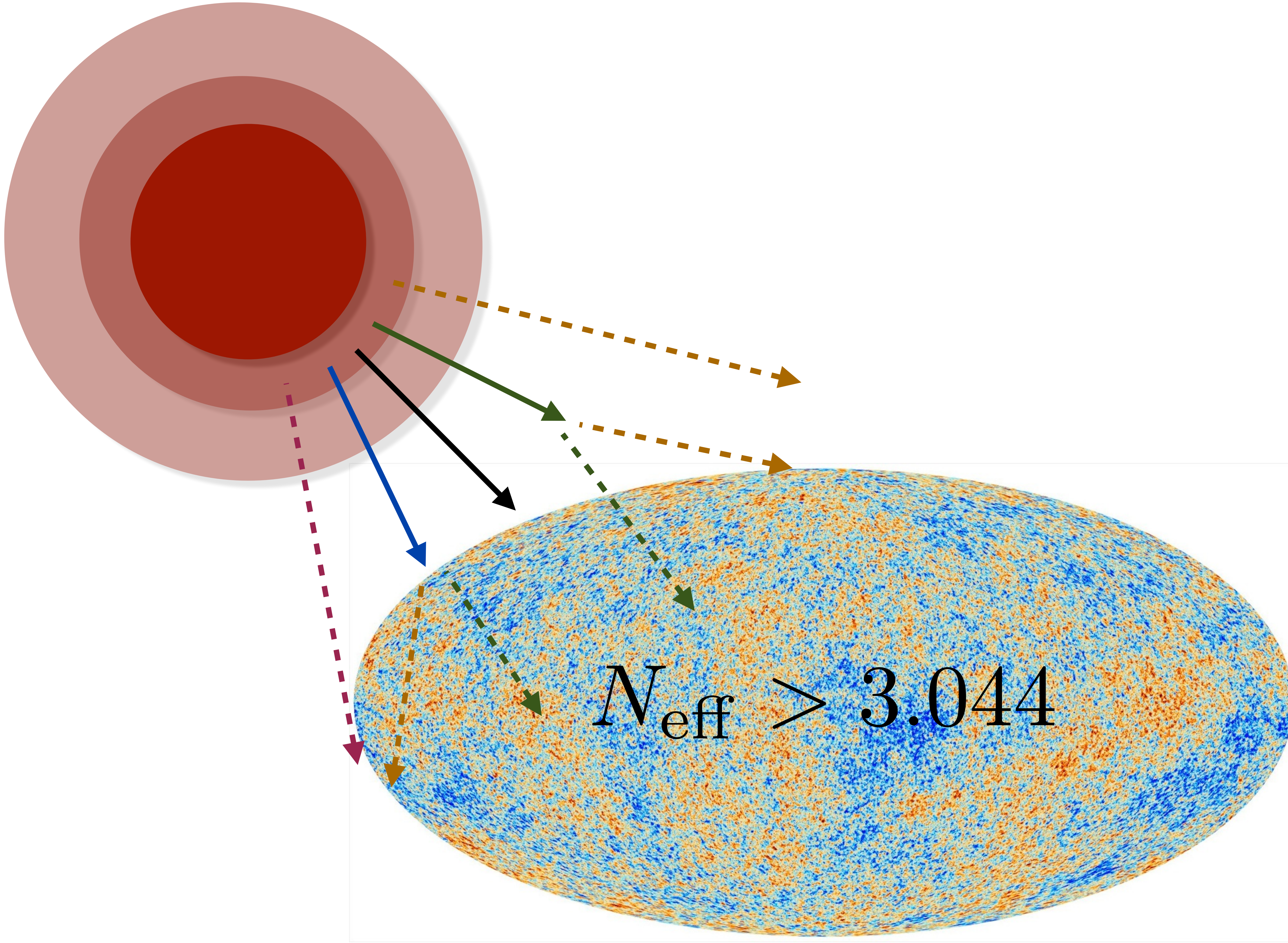
Perfect decoupling : $N_{\mathrm{eff}} = 3.$

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

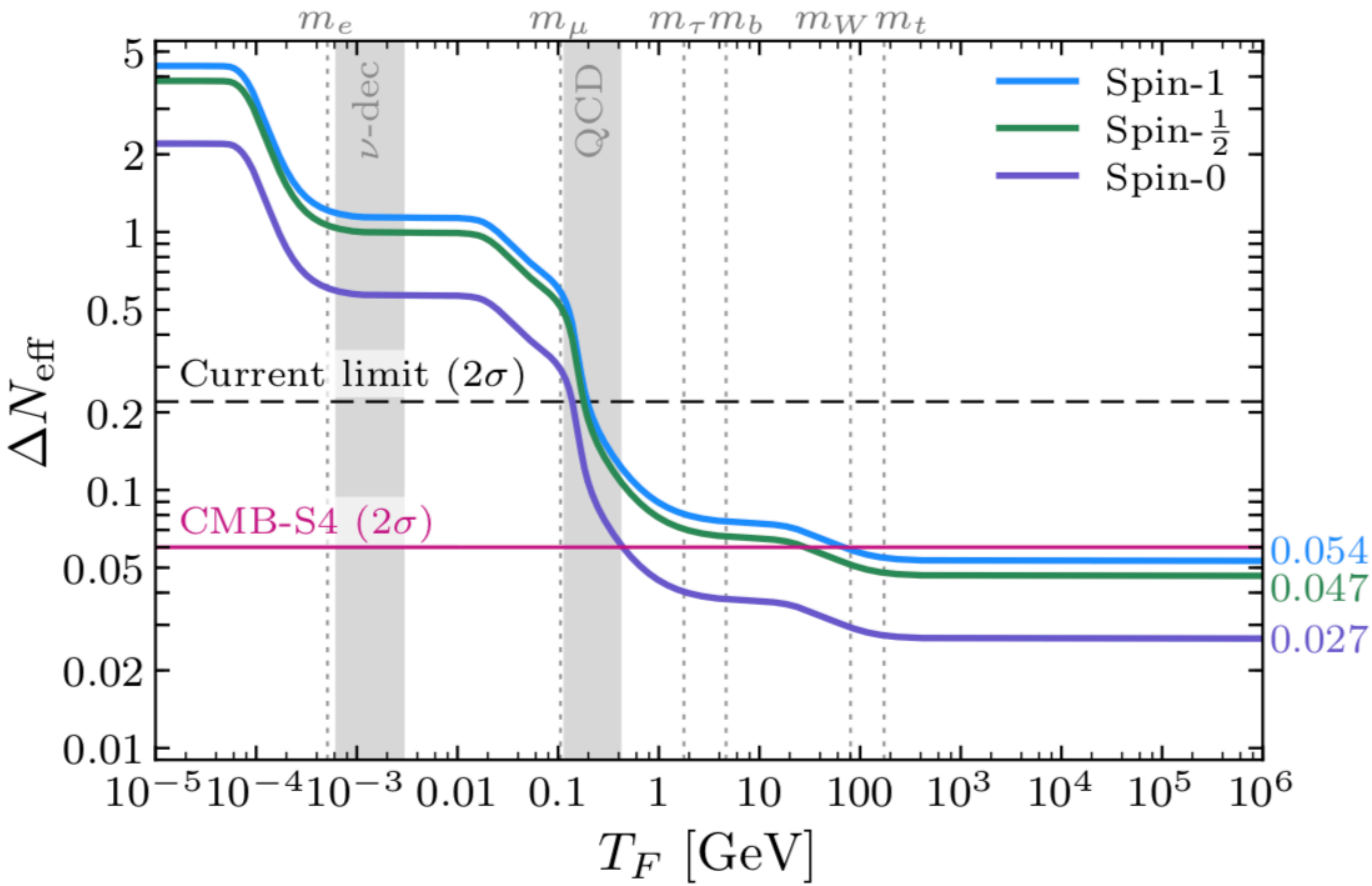
Bennett et al. (2020)

New Light Particles



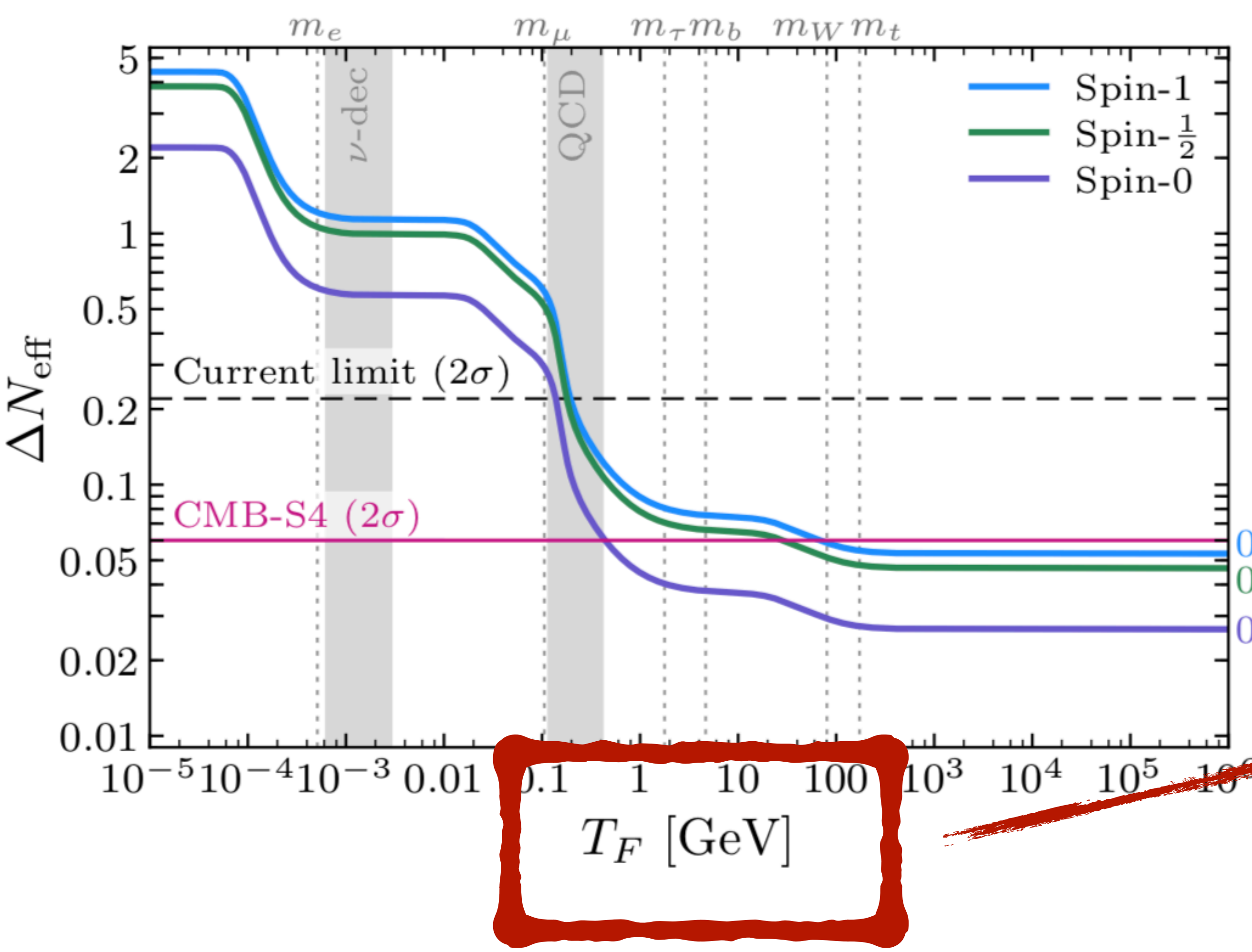

$N_{\rm eff} > 3.044$

Light Relics



arXiv:2203.07943.

Light Relics

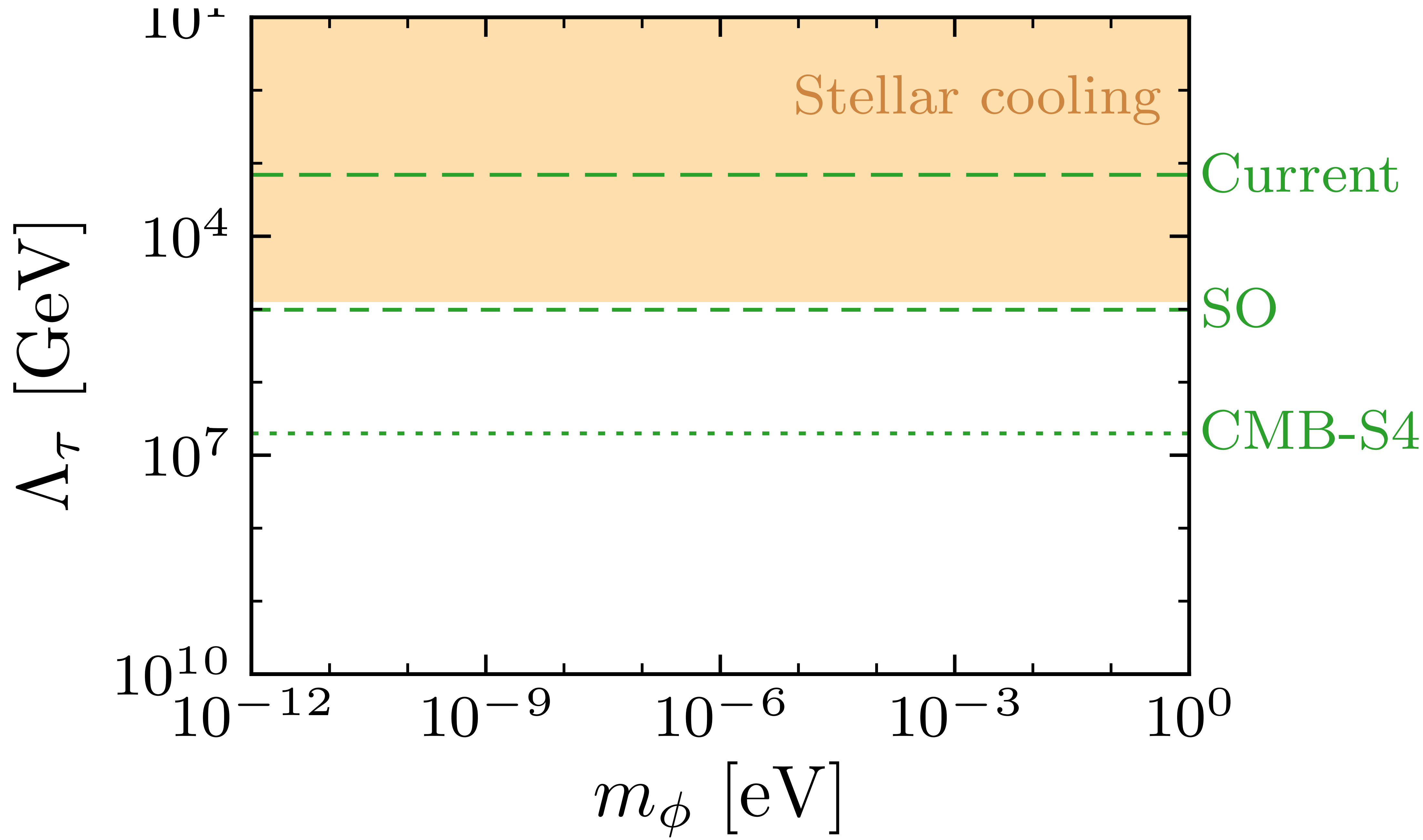


Coupling	Current Constraints: Bound [GeV]	Current Constraints: Origin	Future CMB Constraints: Freeze-Out [GeV]	Future CMB Constraints: Freeze-In [GeV]	$\Delta\tilde{N}_{\rm eff}$
Λ_{ee}	1.2×10^{10}	White dwarfs	6.0×10^{7}	2.7×10^{6}	1.3
$\Lambda_{\mu\mu}$	2.0×10^{6}	Stellar cooling	1.2×10^{10}	3.4×10^{7}	0.5
$\Lambda_{\tau\tau}$	2.5×10^{4}	Stellar cooling	2.1×10^{11}	9.5×10^{7}	0.05
Λ_{bb}	6.1×10^{5}	Stellar cooling	9.5×10^{11}	–	0.04
Λ_{tt}	1.2×10^{9}	Stellar cooling	3.5×10^{13}	–	0.03
$\Lambda^V_{\mu e}$	5.5×10^{9}	$\mu^+\to e^+\,\phi$	6.2×10^{9}	4.8×10^{7}	0.5
$\Lambda_{\mu e}$	3.1×10^{9}	$\mu^+\to e^+\,\phi\,\gamma$	6.2×10^{9}	4.8×10^{7}	0.5
$\Lambda_{\tau e}$	4.4×10^{6}	$\tau^-\to e^-\phi$	1.0×10^{11}	1.3×10^{8}	0.05
$\Lambda_{\tau\mu}$	3.2×10^{6}	$\tau^-\to \mu^-\phi$	1.0×10^{11}	1.3×10^{8}	0.05
Λ^A_{cu}	6.9×10^{5}	D^0-$\bar{D}^0$	1.3×10^{11}	2.0×10^{8}	0.05
Λ^A_{bd}	6.4×10^{5}	B^0-$\bar{B}^0$	4.8×10^{11}	3.7×10^{8}	0.04
Λ_{bs}	6.1×10^{7}	$b\to s\phi$	4.8×10^{11}	3.7×10^{8}	0.04
Λ_{td}	6.6×10^{9}	Mixing	1.8×10^{13}	2.1×10^{9}	0.03
Λ_{tc}	2.2×10^{9}	Mixing	1.8×10^{13}	2.1×10^{9}	0.03

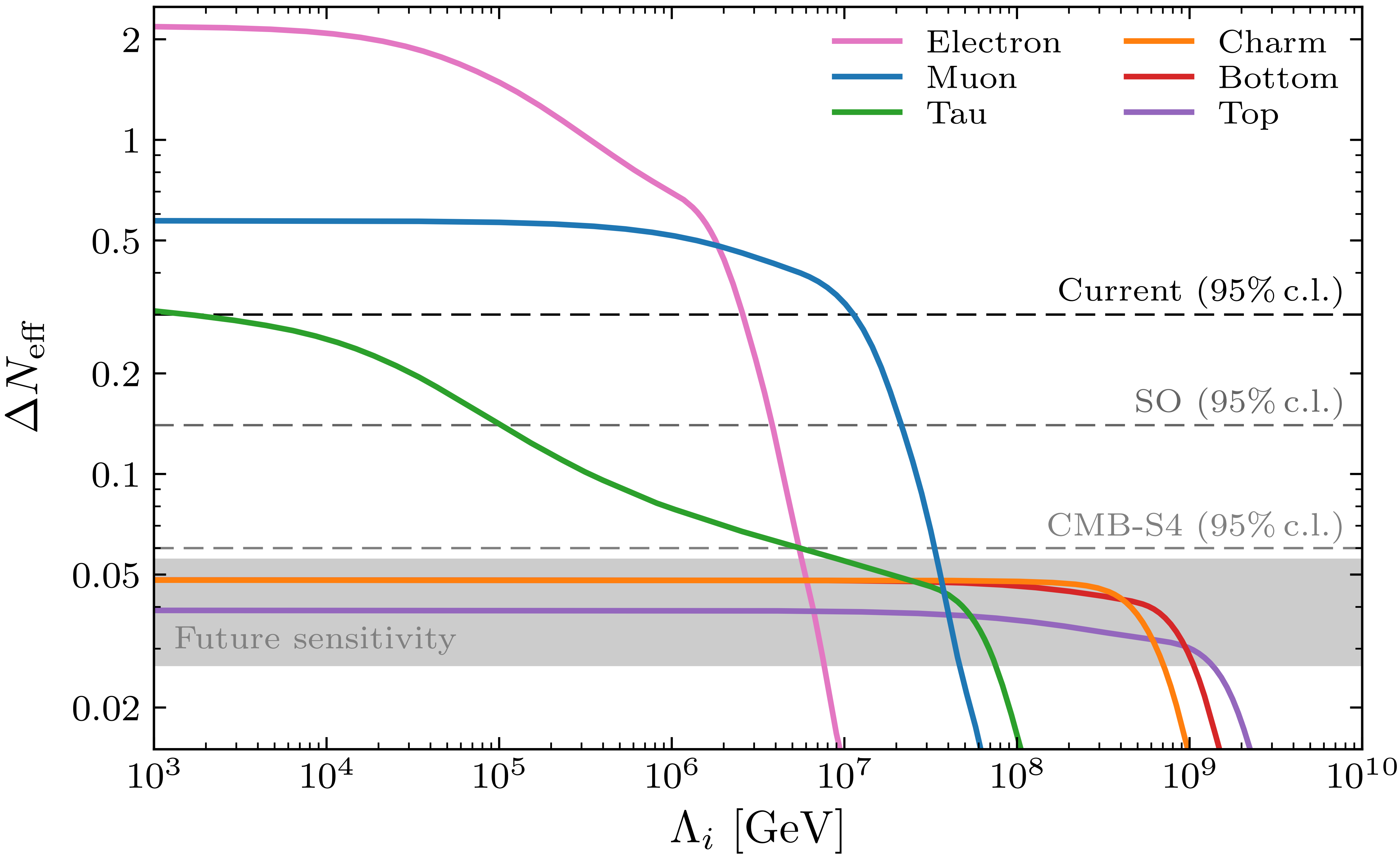
E.g. T_F is sensitive to any standard model coupling

$N_{\rm eff}$ constrains many couplings simultaneously

Axions Coupled to Matter

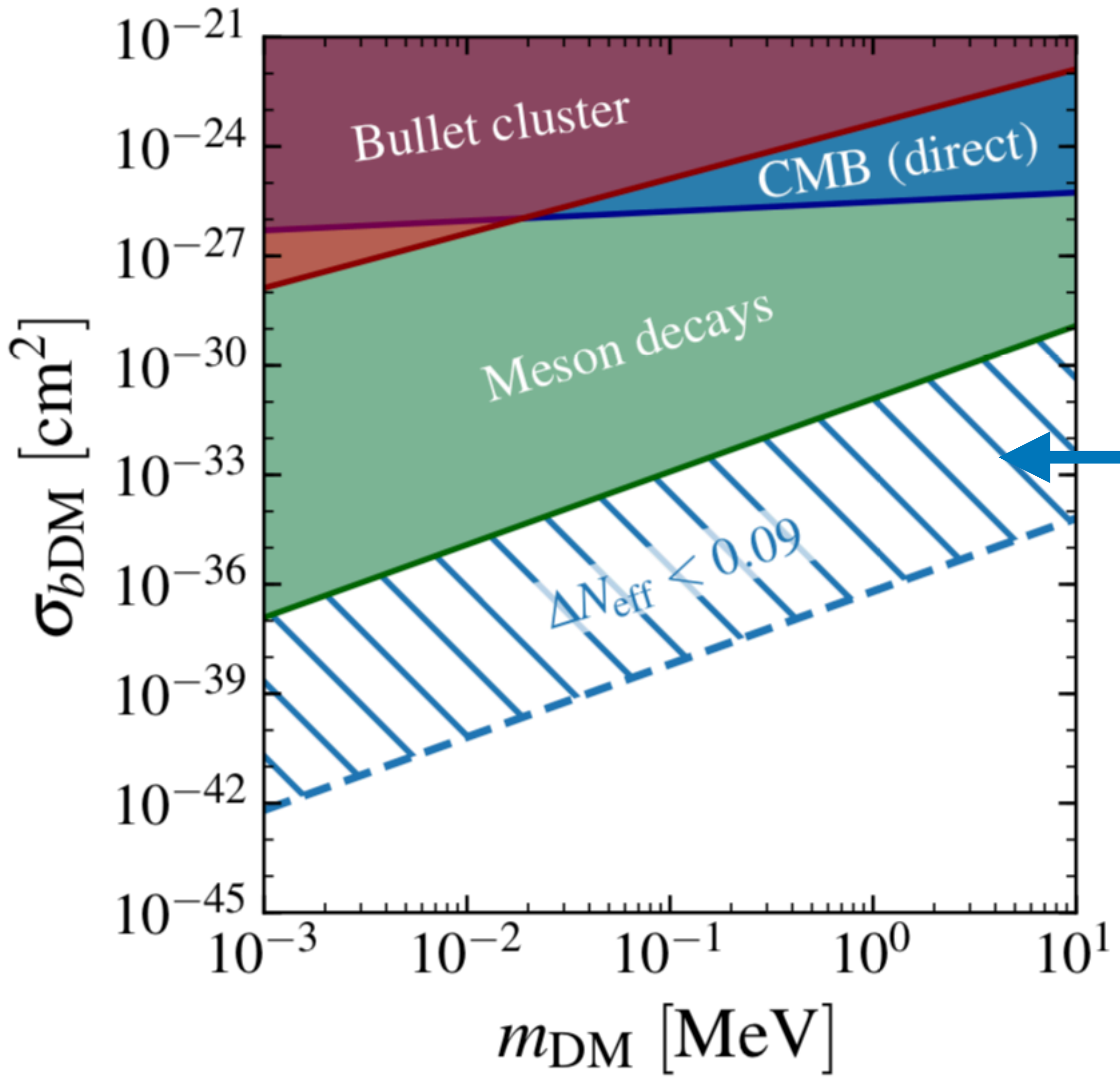


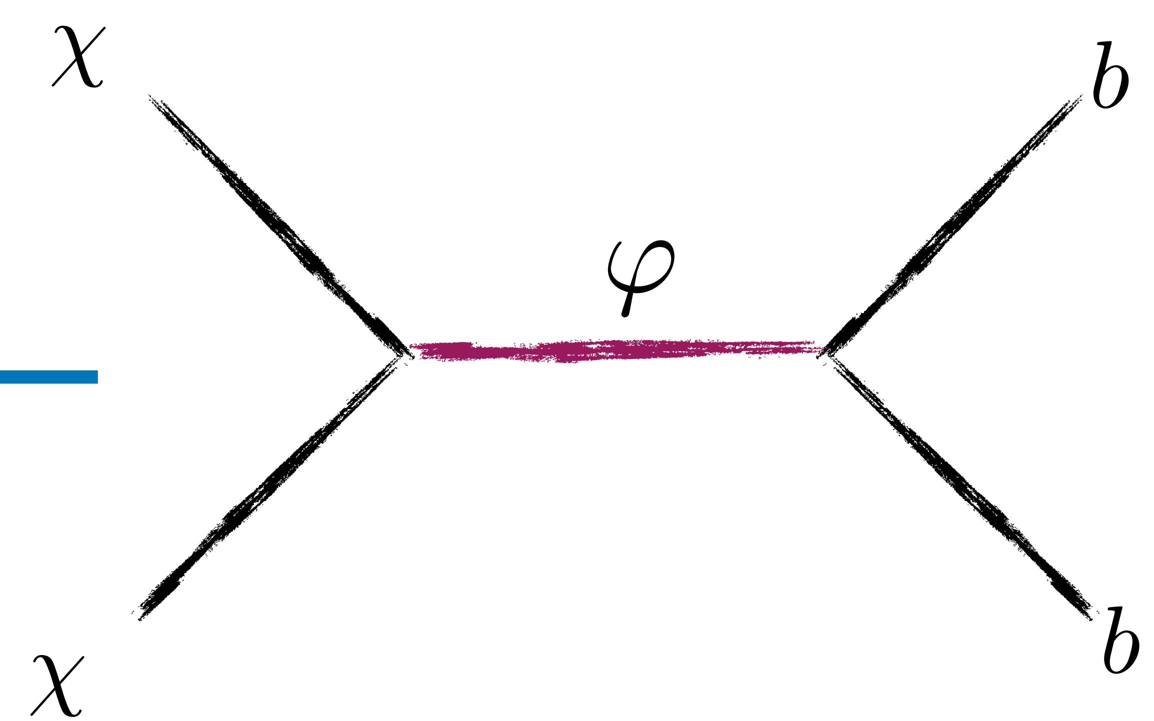
Axions Coupled to Matter



Dark–Matter Baryon Interactions

Mediators of dark forces = light relics





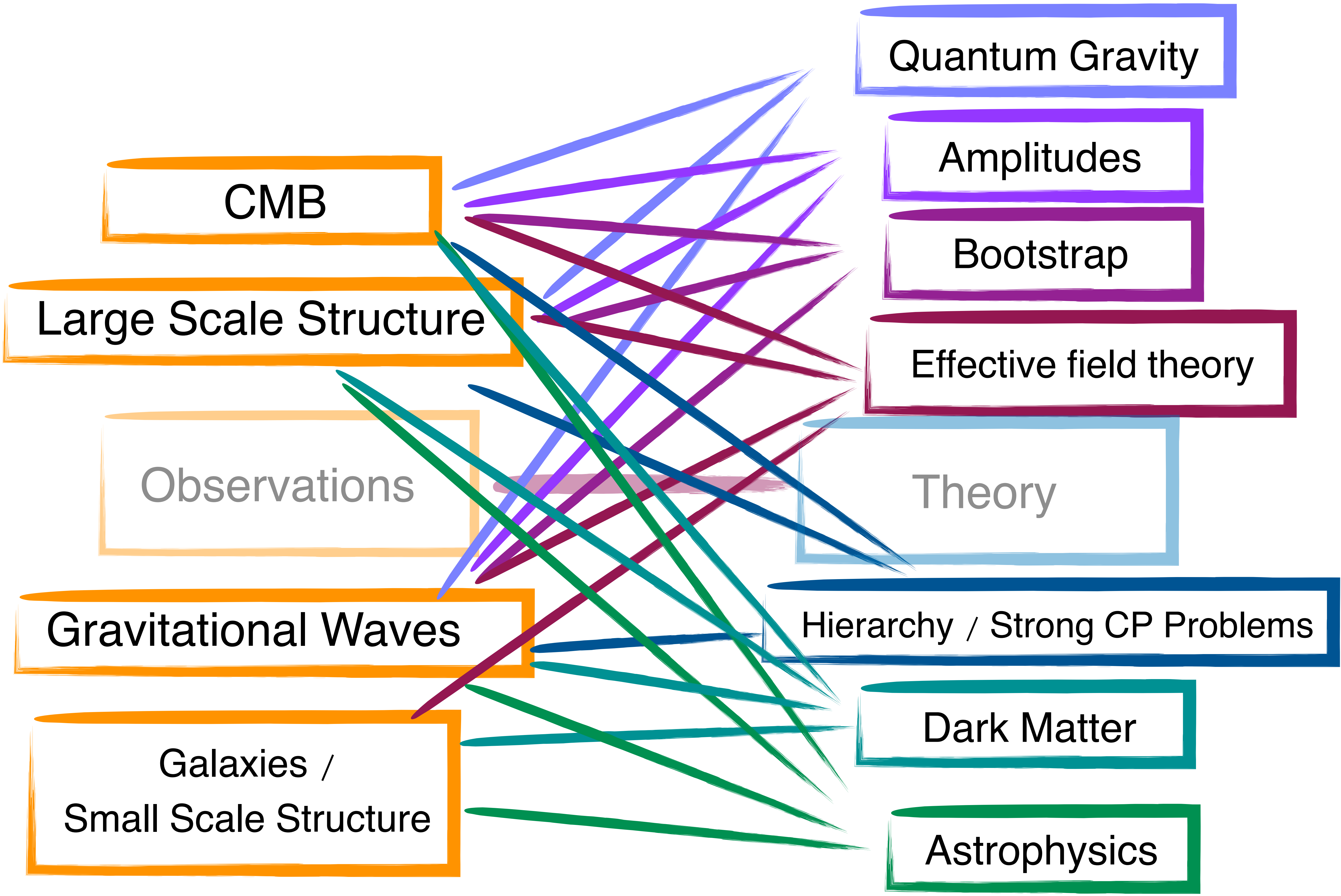
Constraint on mediator often stronger than direct limits

Theory Aside

Theory

Cosmology blurs the line between theory and experiment

Connections are essential for understanding data

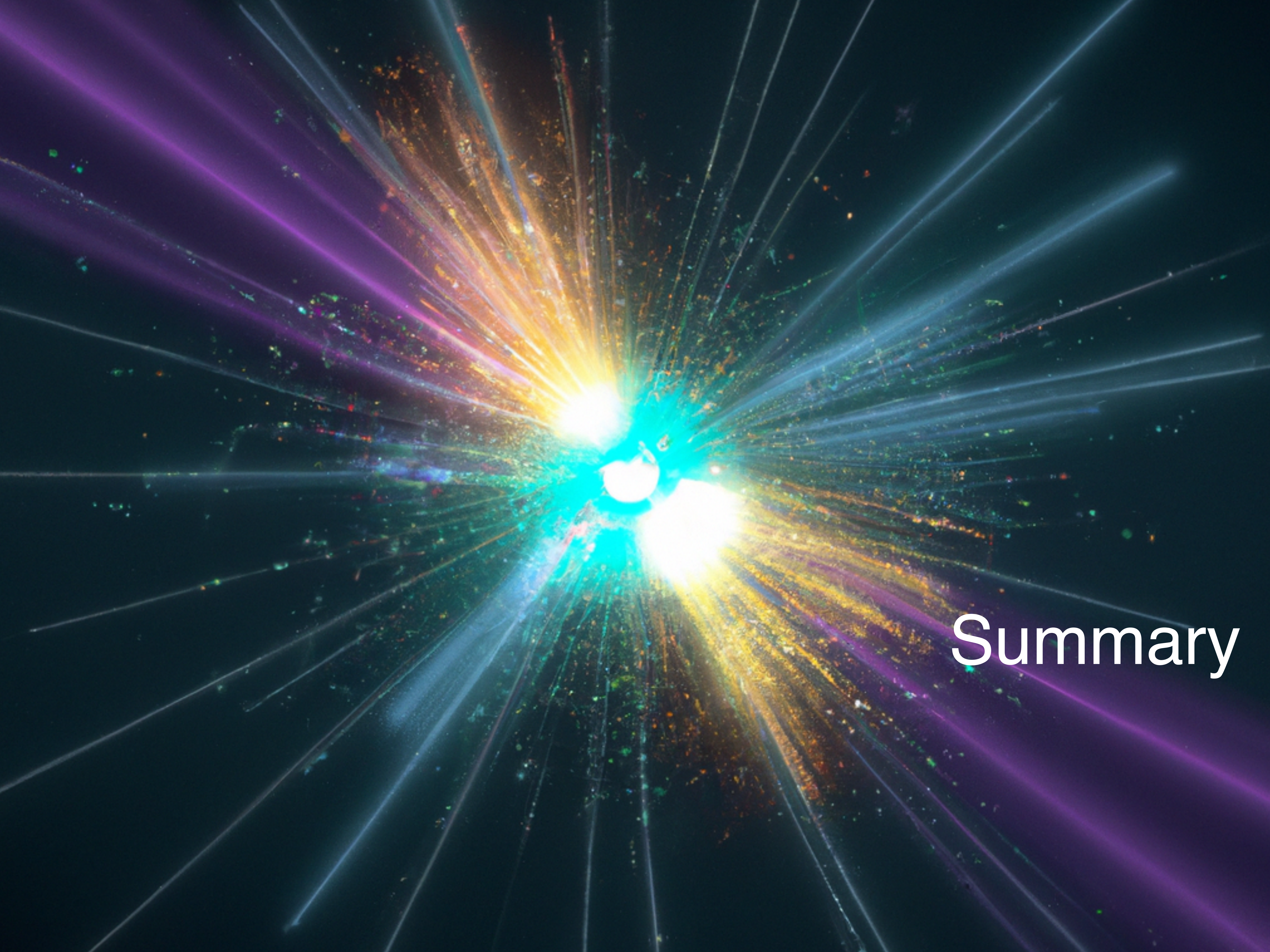

CMB
Large Scale Structure
Observations
Gravitational Waves
Galaxies /
Small Scale Structure
Quantum Gravity
Amplitudes
Bootstrap
Effective field theory
Theory
Hierarchy / Strong CP Problems
Dark Matter
Astrophysics

Theory

Theorists are essential to this progress

1. New analyses of existing and future data
2. Directly working on projects (likelihoods, pipeline)
3. Simulations / theory that impacts data analysis
4. Defining theoretically interesting targets
5. Pure theory (e.g. formal aspects of inflation)

ALL of this work needs to be supported



Summary

Summary

The early universe is the frontier

- Key targets for inflation are within reach
- Gravitational waves directly probe geometry
- Statistics are a window into particle physics of inflaton
- Cosmic probes of dark sectors competitive with lab
- Sensitivity to individual specifies produced at reheating


Thank you