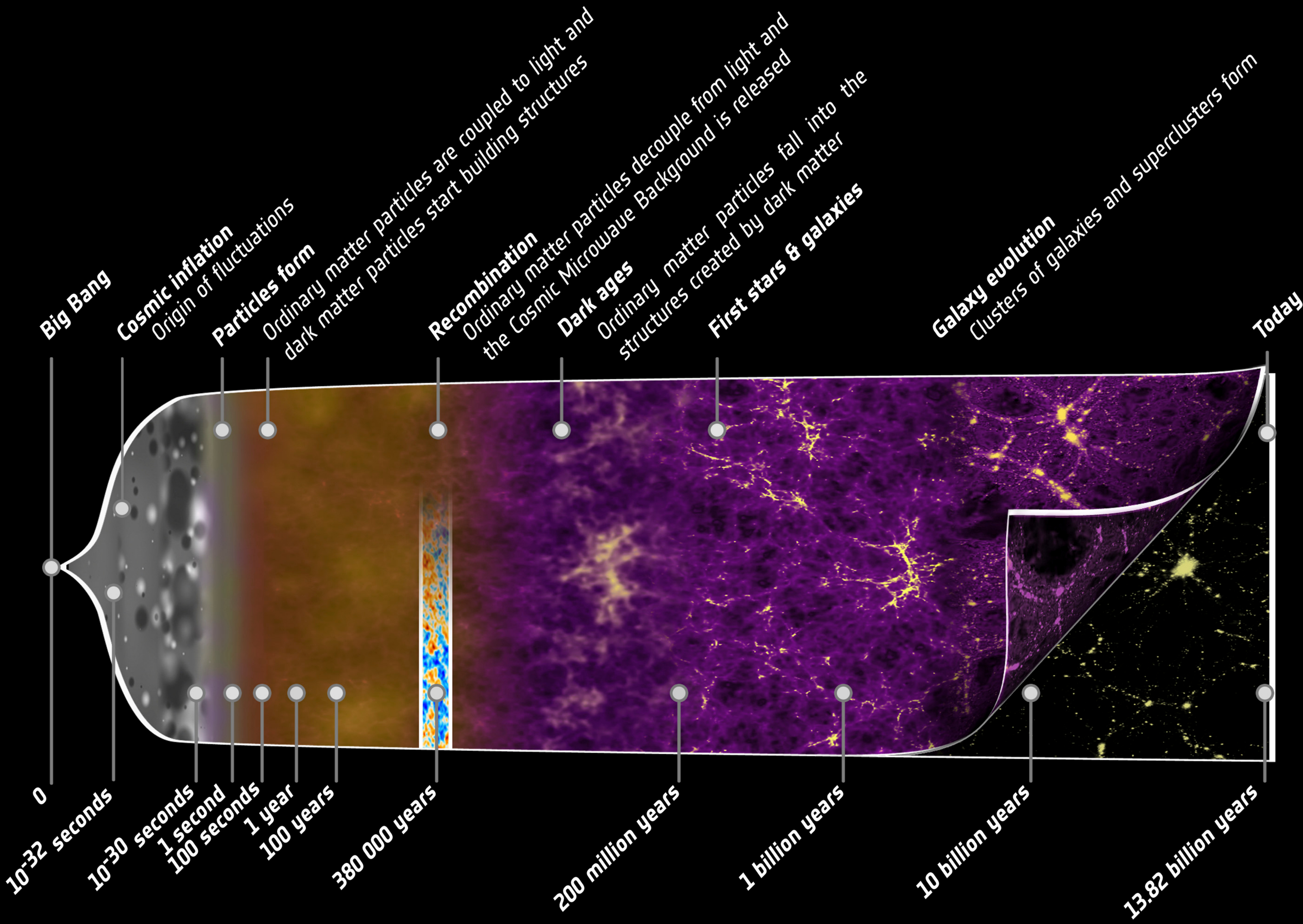
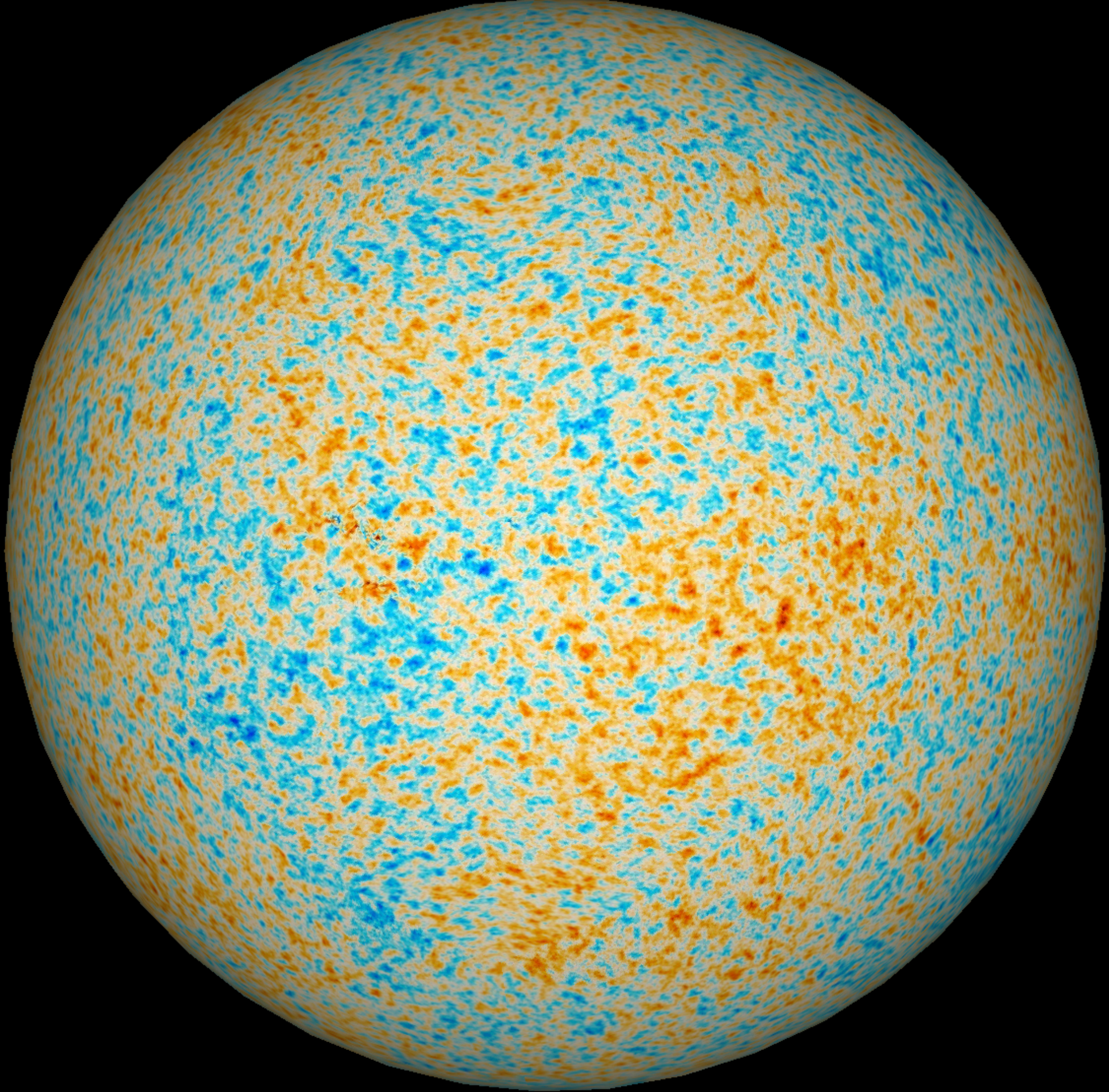
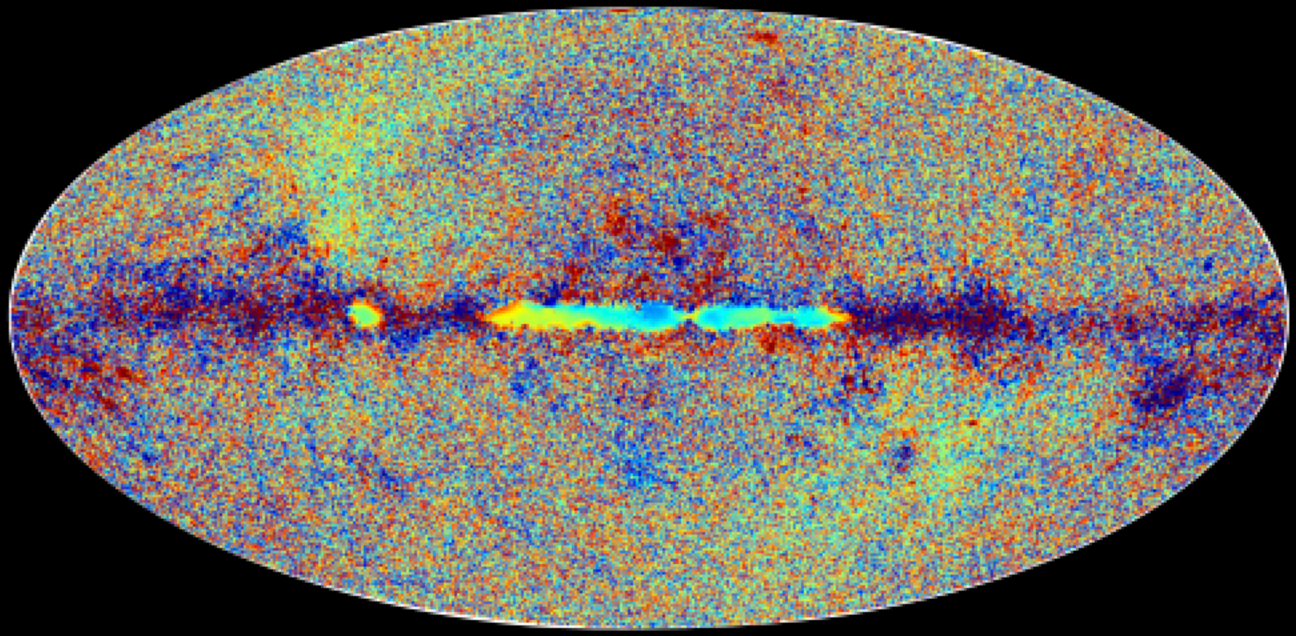
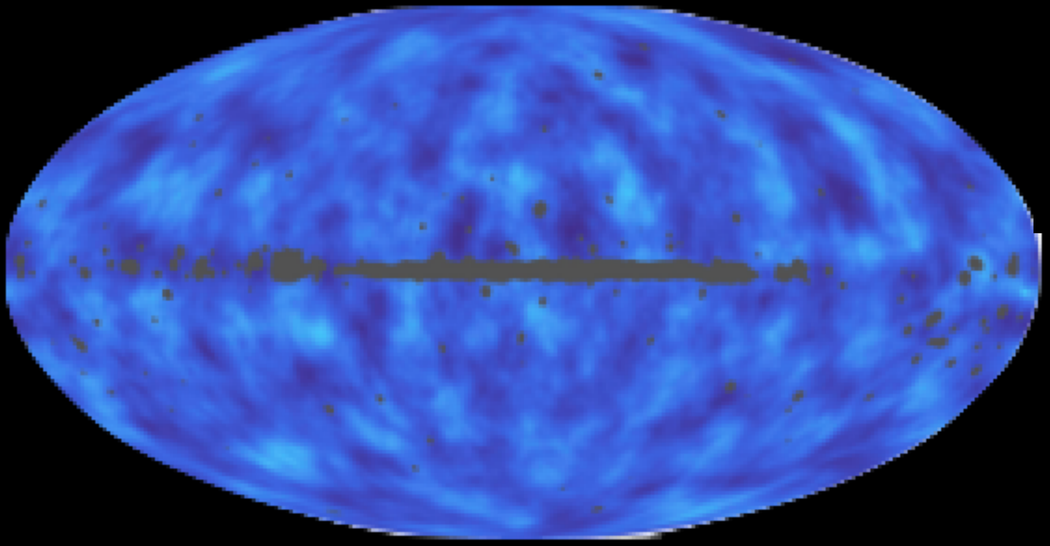
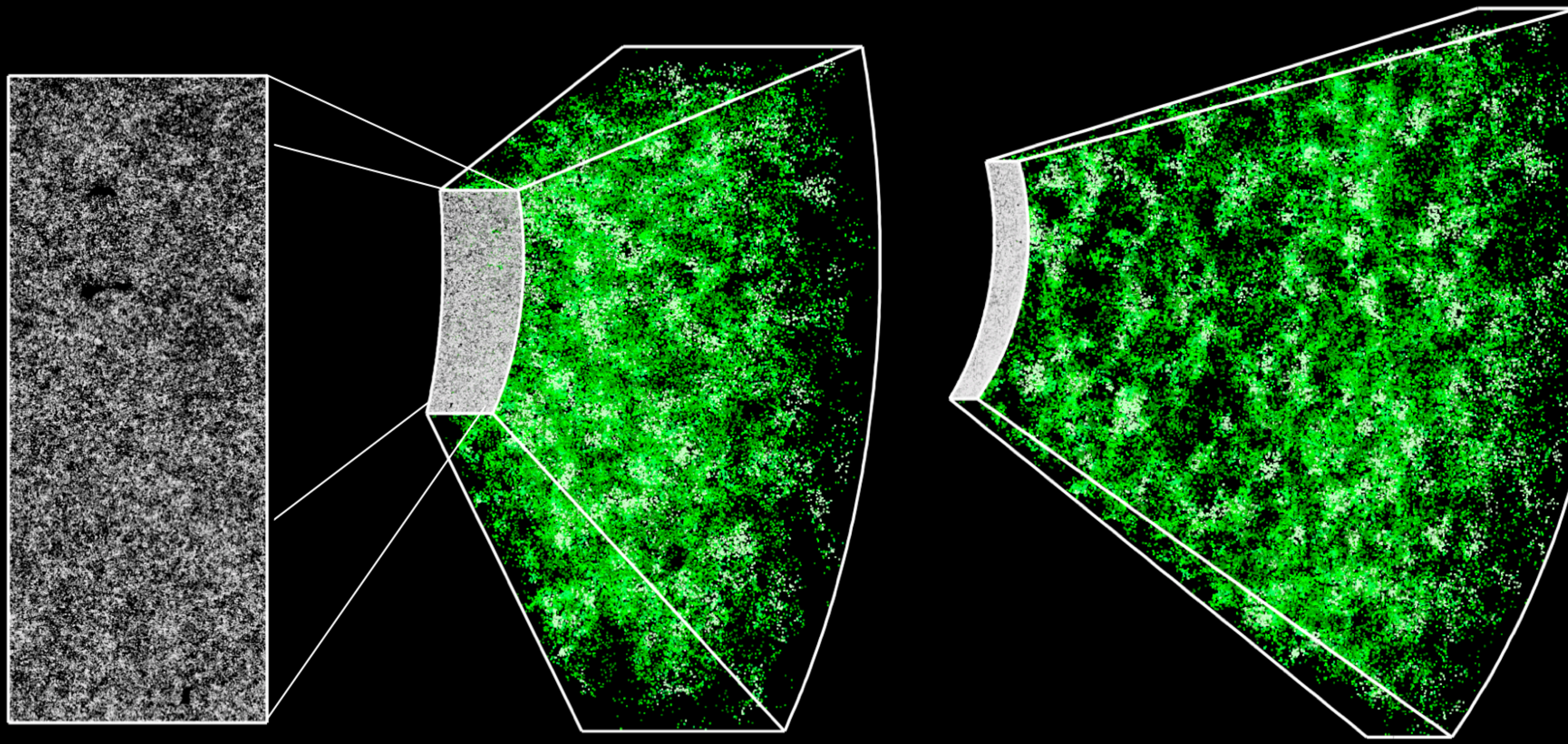
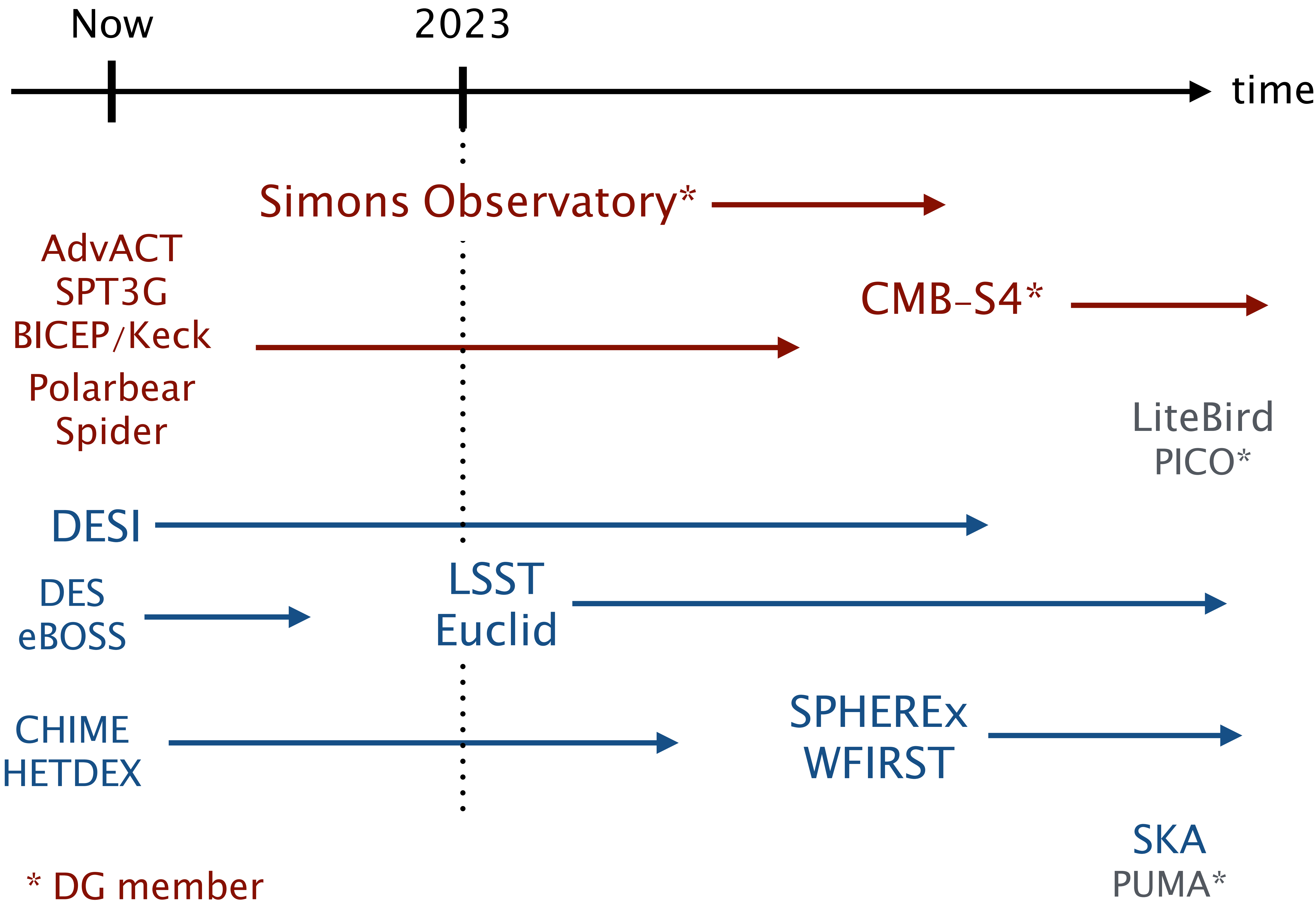
Fundamental Physics & Cosmological Data

Daniel Green
UC San Diego



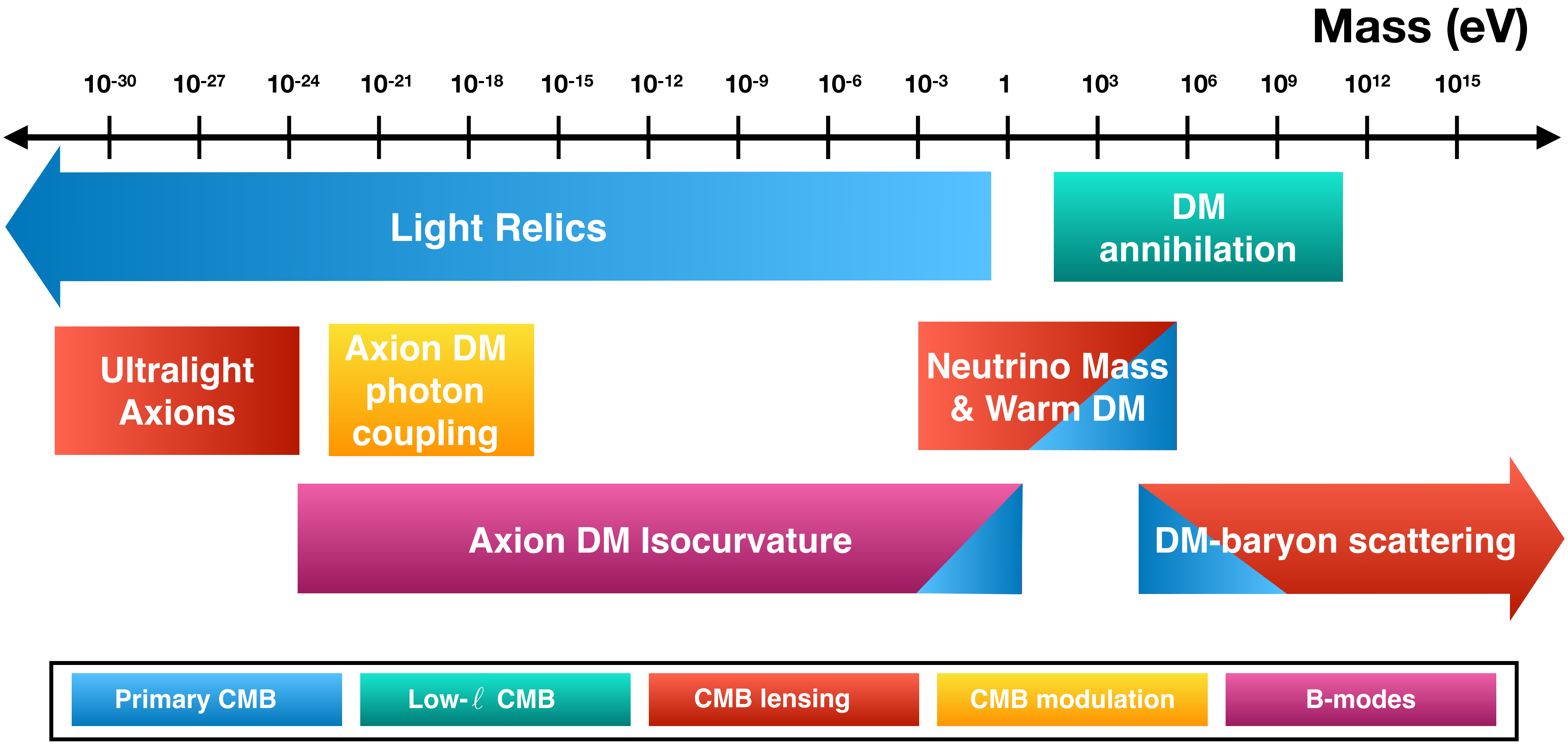
Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles 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



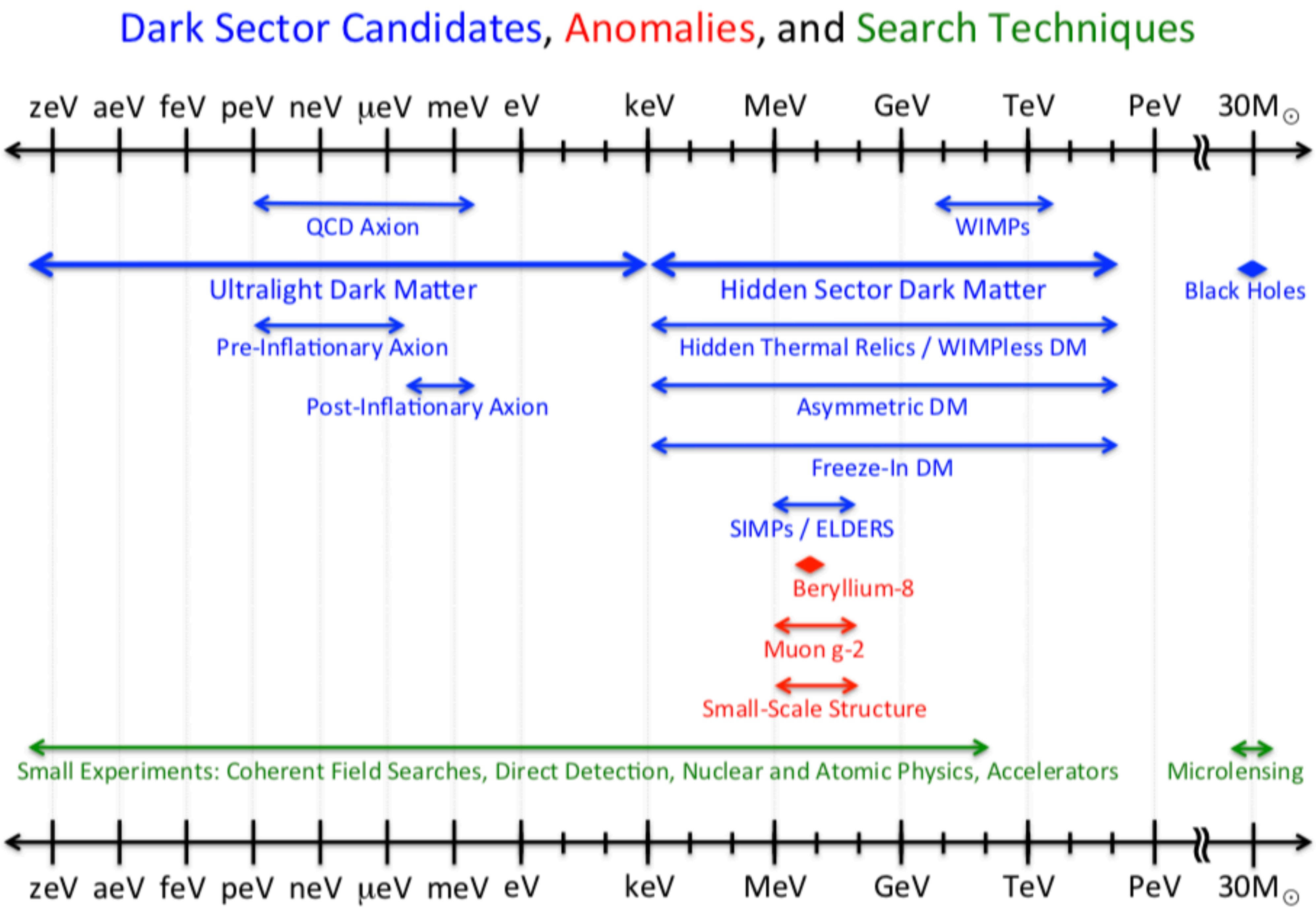
Now
2023
time
Simons Observatory*
AdvACT
SPT3G
BICEP/Keck
Polarbear
Spider
CMB-S4*
LiteBird
PICO*
DESI
DES
eBOSS
LSST
Euclid
CHIME
HETDEX
SPHEREx
WFIRST
SKA
PUMA*
* DG member

Cosmology and Particle Physics



arXiv: 1907.04473

Cosmology and Particle Physics



arXiv: 1707.04591

Cosmology and Particle Physics

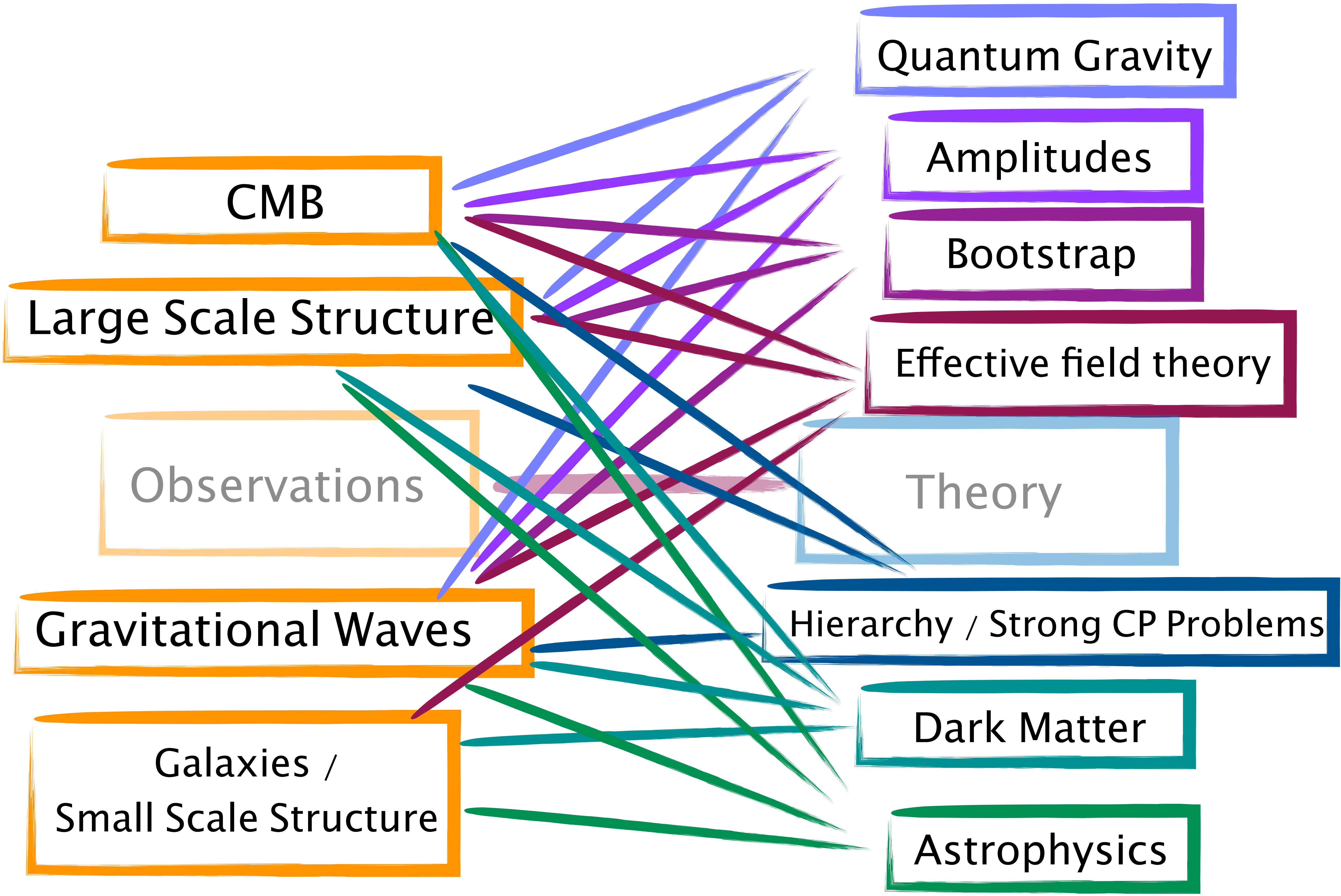
Cosmology tied to many basic problems

- 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, …

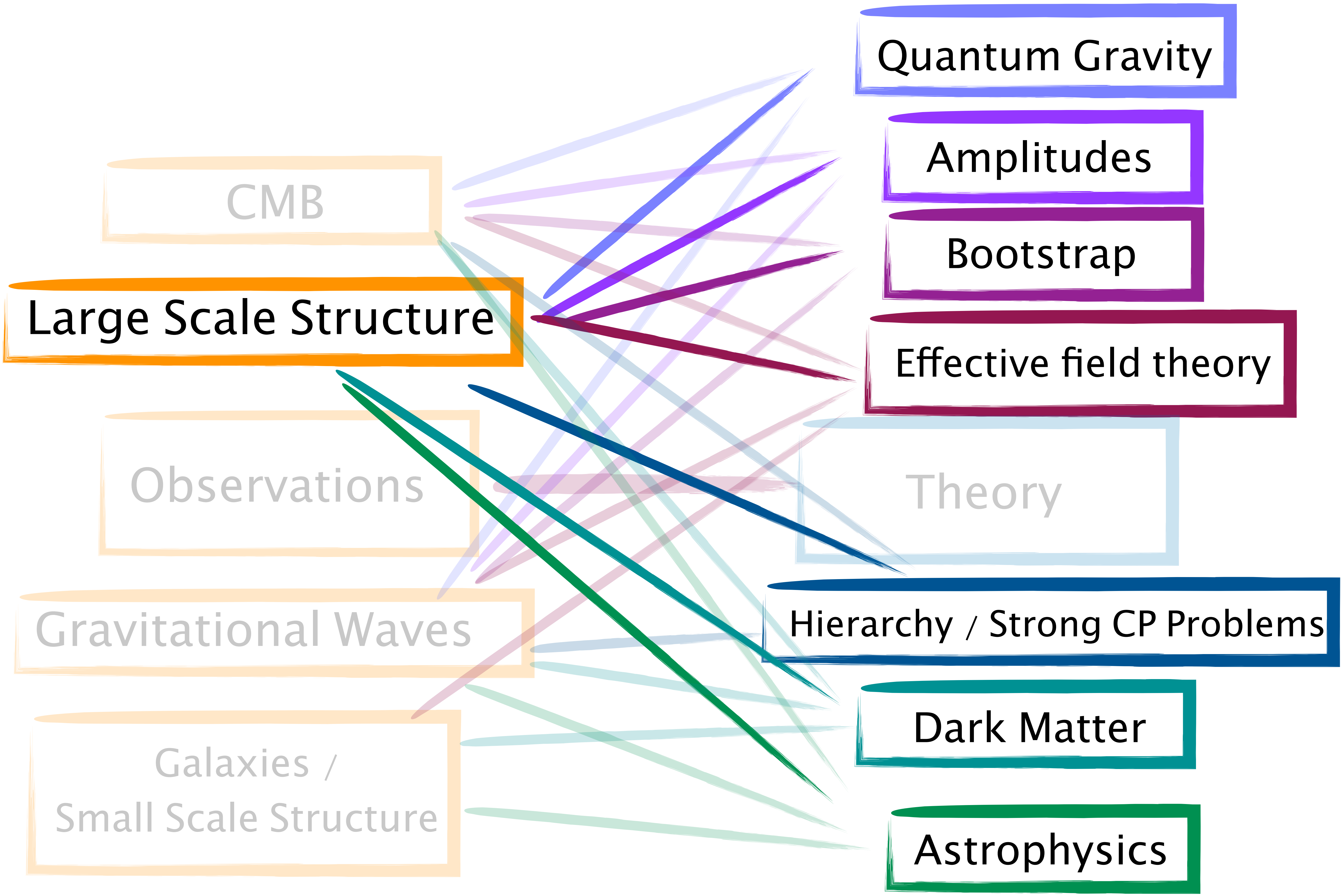
Cosmology and Fun(damental) Physics

Cosmology is interconnected across theory frontier

Connections are essential for understanding data



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

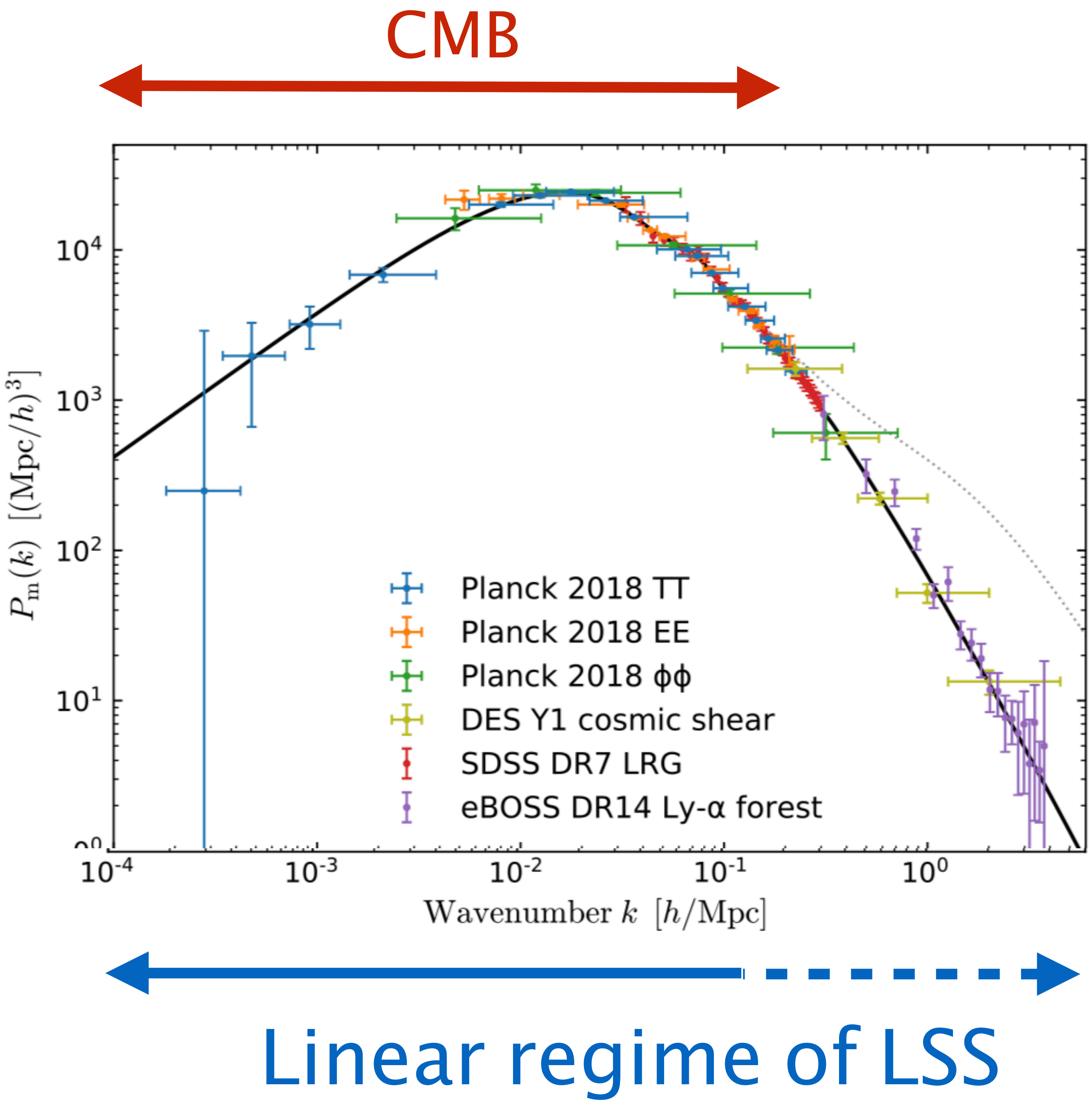


Quantum Gravity
Amplitudes
Bootstrap
Effective field theory
Theory
Hierarchy / Strong CP Problems
Dark Matter
Astrophysics
CMB
Large Scale Structure
Observations
Gravitational Waves
Galaxies /
Small Scale Structure


Inflation &
Large Scale Structure

Large Scale Structure

LSS is a key to our to understanding inflation



$$N_{\rm modes}^{\rm CMB} \sim \left(\frac{k_{\rm max}}{k_{\rm min}}\right)^2$$

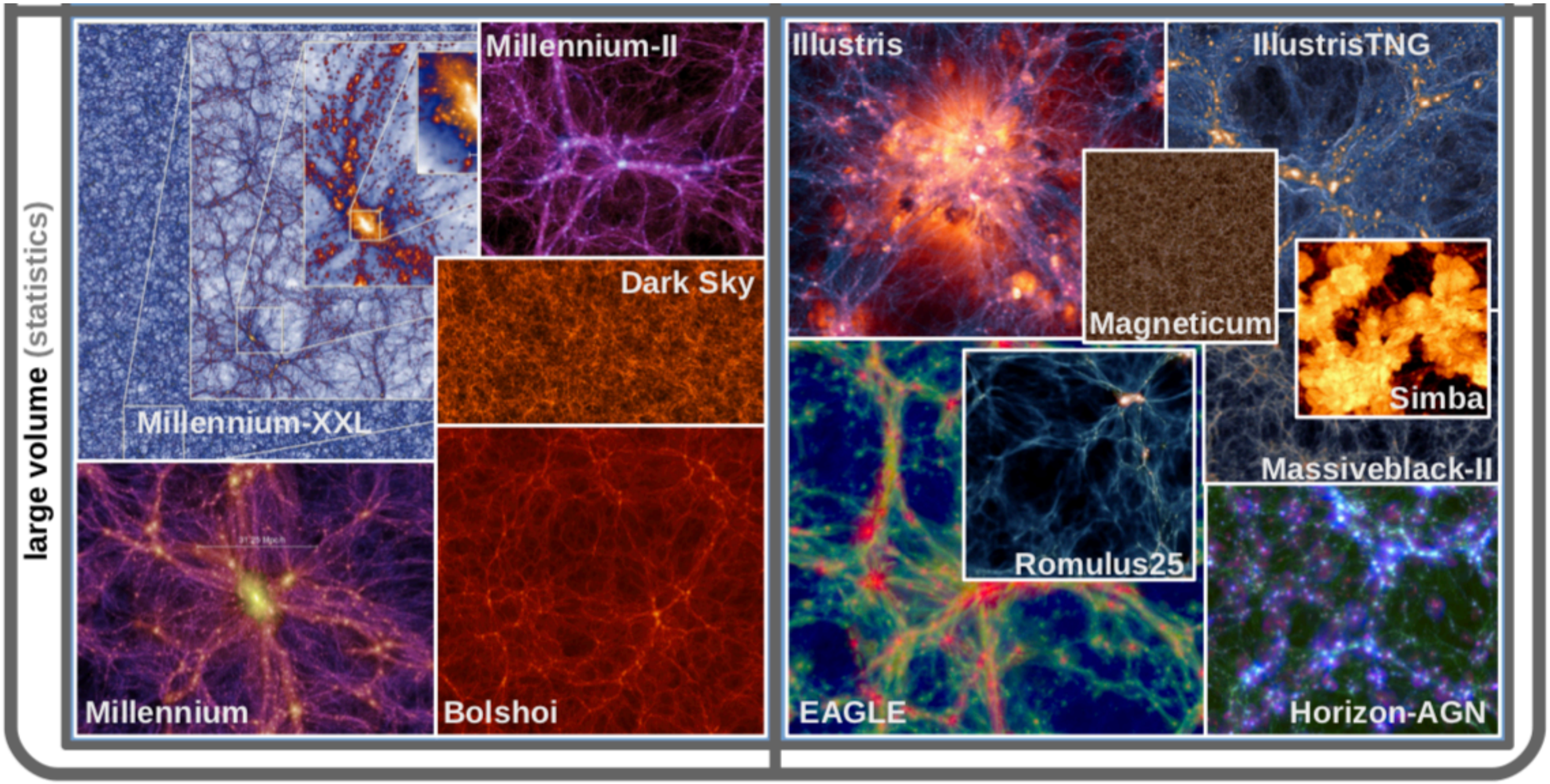
$$N_{\rm modes}^{\rm LSS} \sim \left(\frac{k_{\rm max}}{k_{\rm min}}\right)^3$$

Figure from Chabanier et al.

Large Scale Structure

Problem: low redshift universe is hard to model

DM-only DM + Baryons



Vogelsberger et al. (2019)

Strategies

Inflation

Look for novel signals:

Top down (QG)

EFT/symmetries

New fields

New mechanisms

LSS Modeling

Improve accuracy:

N-body

Sims with baryons

Machine learning

EFT / perturbative

Principles

Protected quantities

Locality

Causality

Symmetries

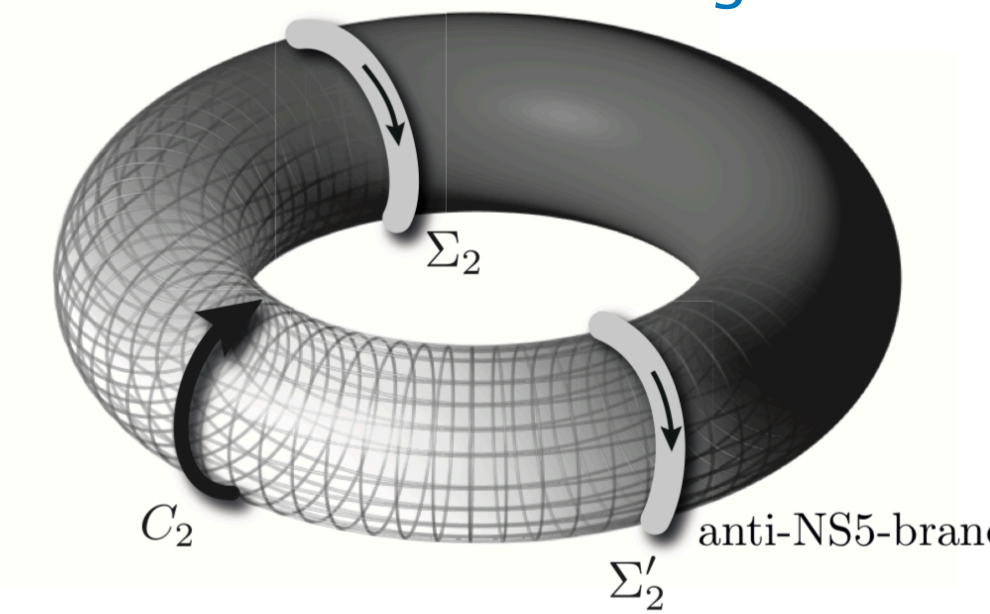
Bootstrap

Top Down Model Building

E.g. axion monodromy inspires features searches

$$V(\phi) = \mu^3\phi + \boxed{\Lambda^4 \cos\left(\frac{\phi}{f}\right)} = \mu^3\left[\phi + \boxed{bf\cos\left(\frac{\phi}{f}\right)}\right]$$

Flauger et al. (2009)



Originated from string models

Silverstein & Westphal (2008)

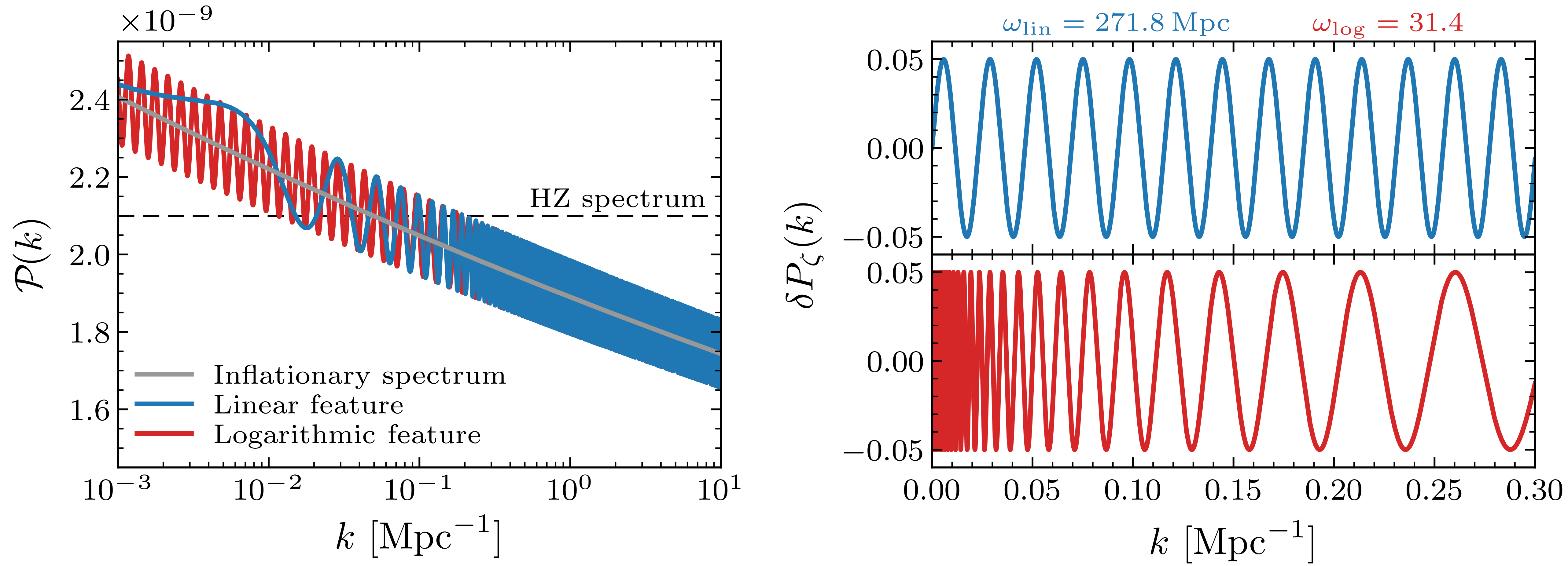
McAllister, Silverstein, & Westphal (2008)

Logarithmic oscillations tied to non-perturbative effects

Figure from Baumann & McAllister

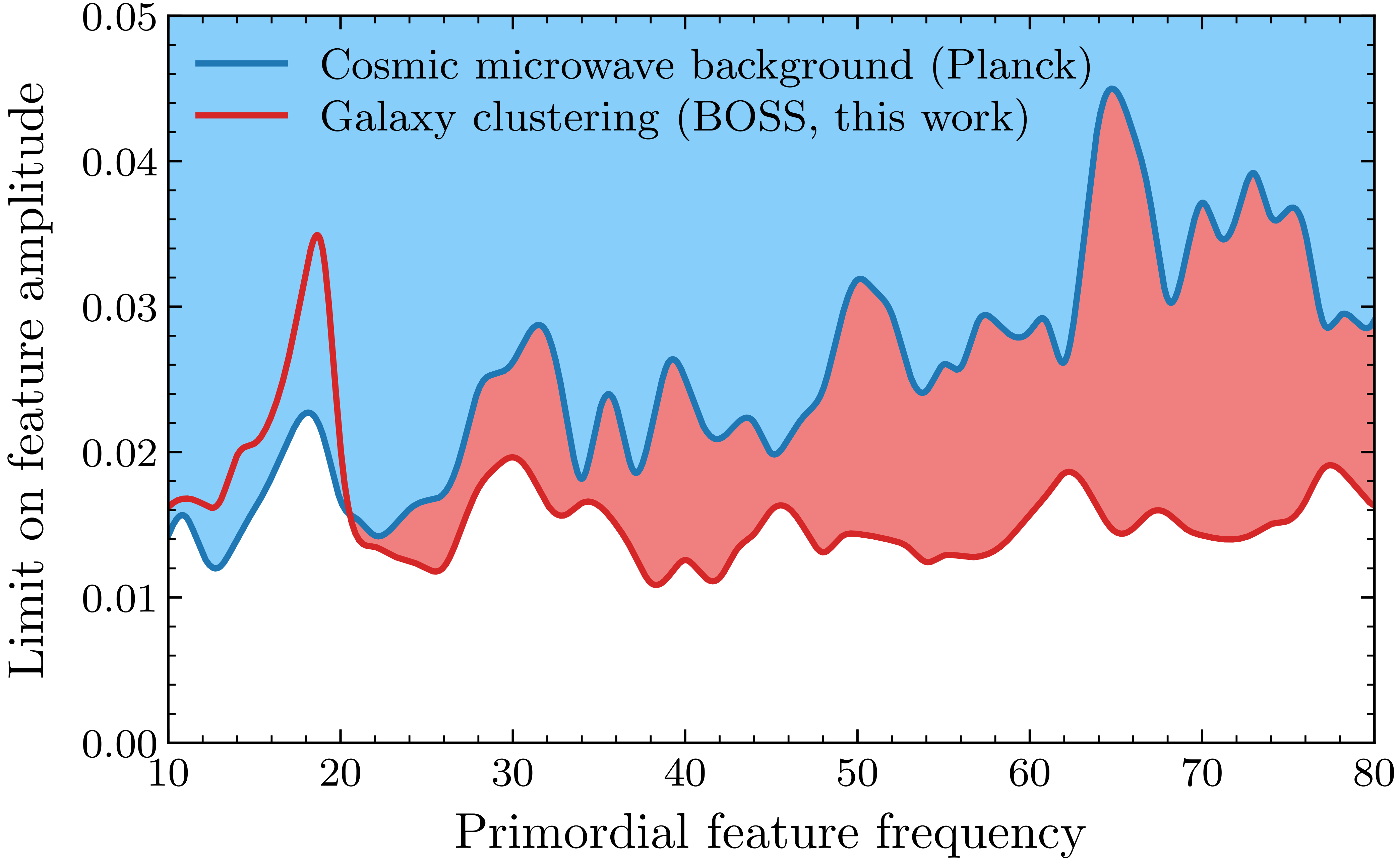
Top Down Model Building

Oscillatory features in correlators



Top Down Model Building

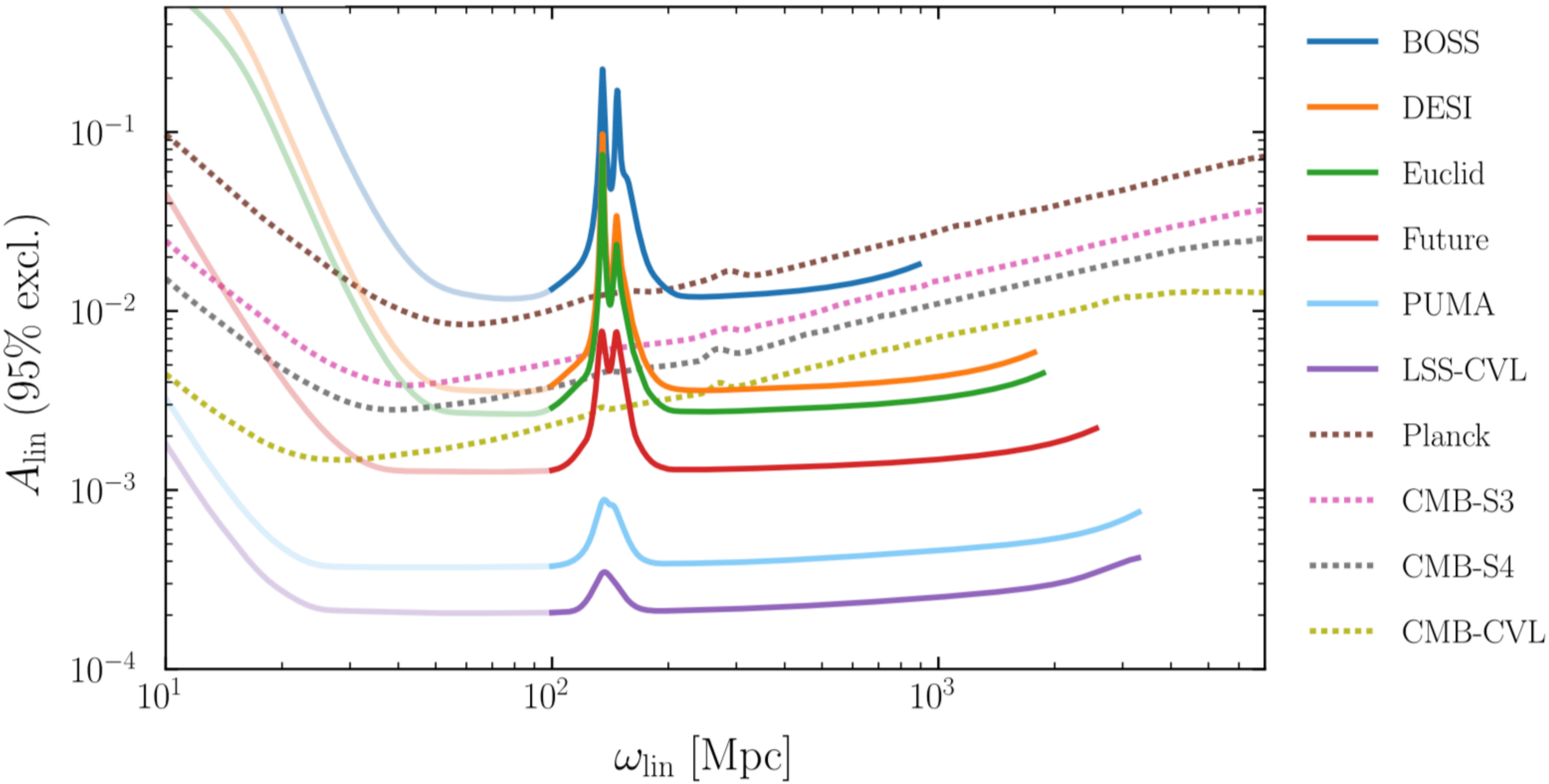
Oscillatory signals in LSS are distinct from nonlinearity



Beutler, Biagetti, DG, Slosar, & Wallisch (2019)

Top Down Model Building

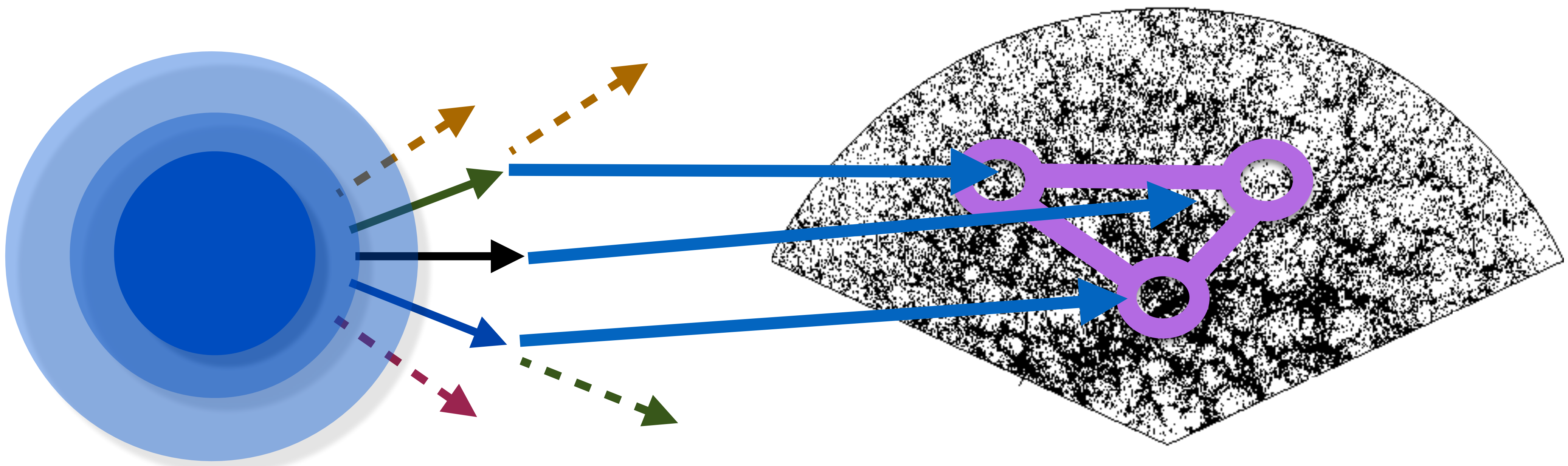
Oscillatory signals in LSS are distinct from nonlinearity



Beutler, Biagetti, DG, Slosar, & Wallisch (2019)

Cosmological Collider

Light(ish) particles are detectable via non-Gaussianity



Leaves unique signatures in the soft limits

Chen & Wang (2009); DG & Baumann (2011); Chen & Wang (2012); Noumi et al. (2012); Arkani-Hamed & Maldacena (2015); Lee et al. (2016); + many many more

Violates the single-field consistency conditions

Maldacena (2002); Creminelli & Zaldarriaga (2004)

Cosmological Collider

Single field consistency can be applied directly to LSS

Creminelli et al. (2013 x 3)

Breaking of consistency–scale dependent bias, e.g.

Dalal et al. (2007)

Galaxies Matter

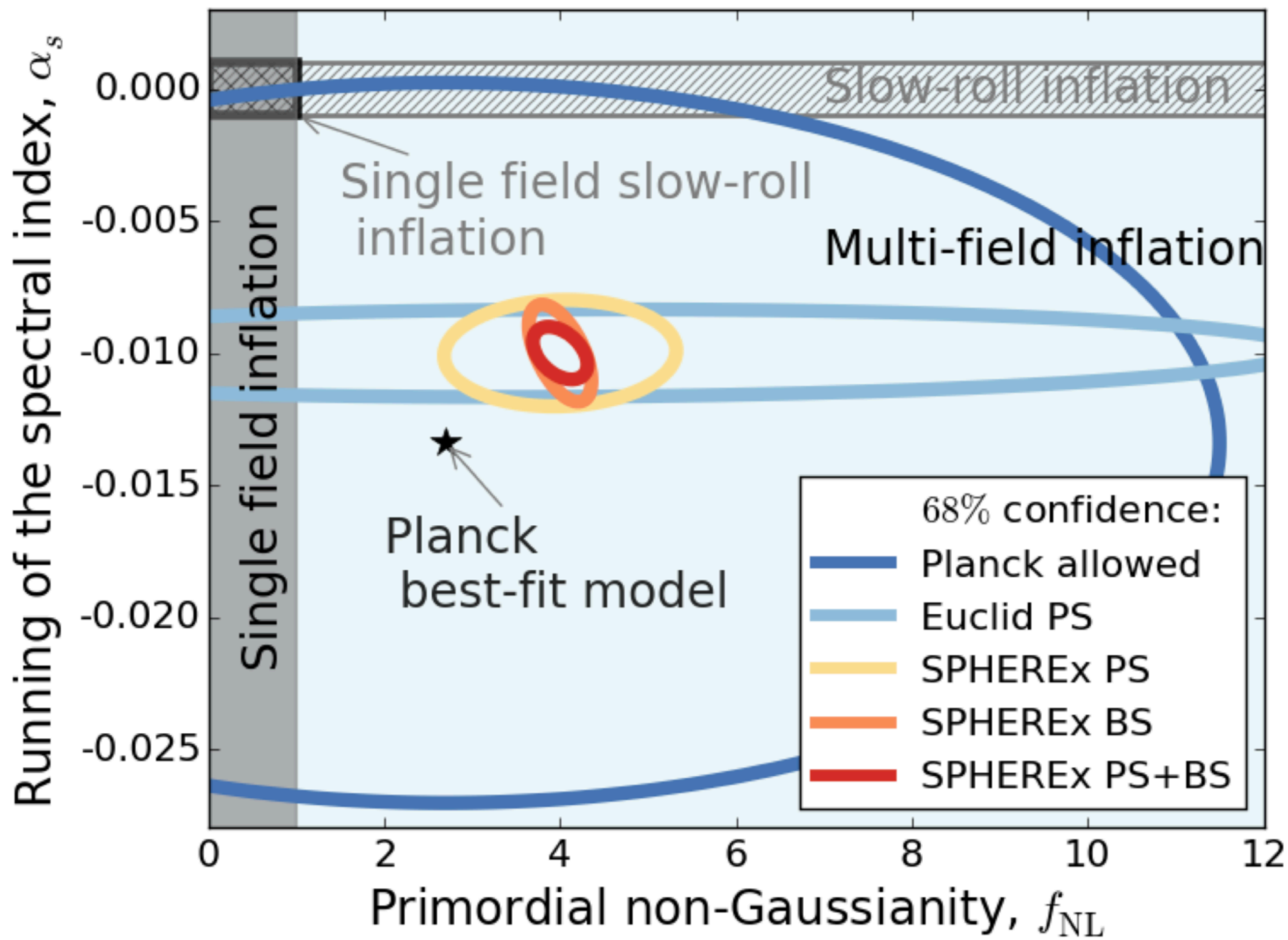
$$\delta_g(\vec{k}) \approx \frac{1}{k^{1/2+\nu}}\delta_m(\vec{k}) \qquad \nu \equiv \sqrt{\frac{9}{4} - \frac{m^2}{H^2}}$$

Looks like a violation of equivalence principle

Does not arise from nonlinear dynamics

Cosmological Collider

For extra light fields, LSS will make large improvement



Doré et al. (2014) [SPHEREx]

The Nature of Inflation

Inflation is a pattern of symmetry breaking Cheung et al. (2007)

$$\frac{d}{dt}\langle\mathcal{O}(x,t)\rangle \neq 0$$

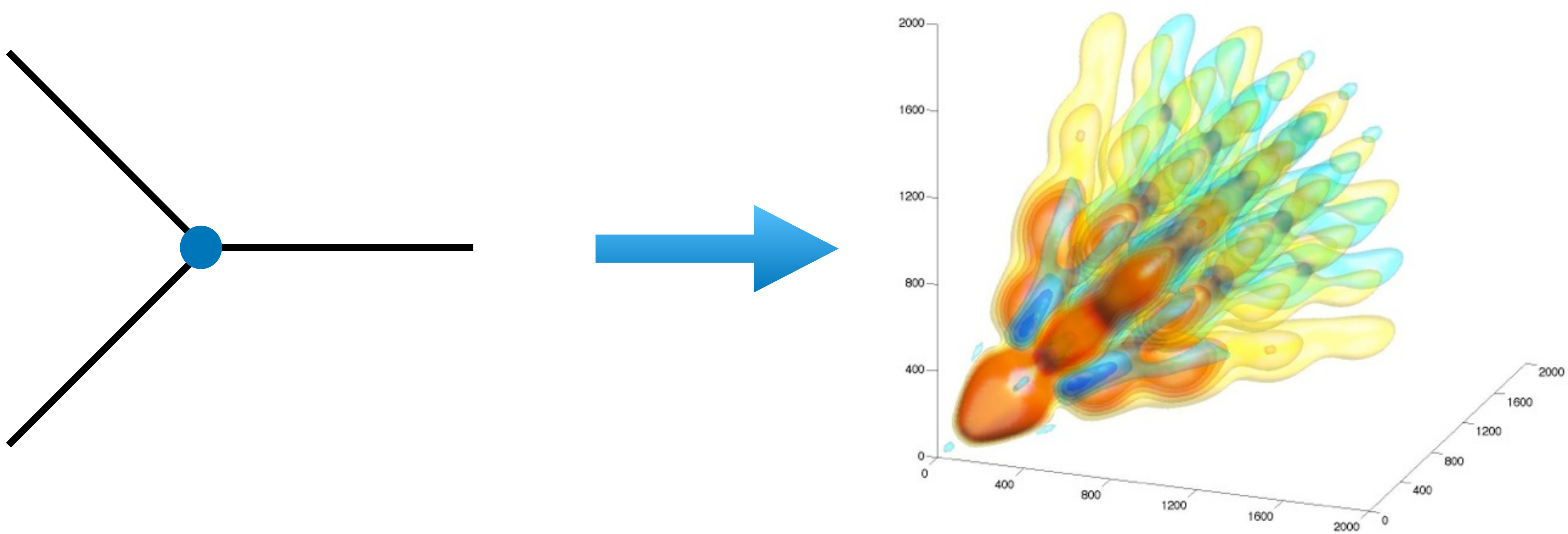
It is also a period of quasi-de Sitter expansion

Inflation ends: requires a physical clock

e.g. $\phi(t) \approx \dot{\phi}\, t$ sets time in slow-roll inflation

No reason the clock must be a weakly coupled scalar

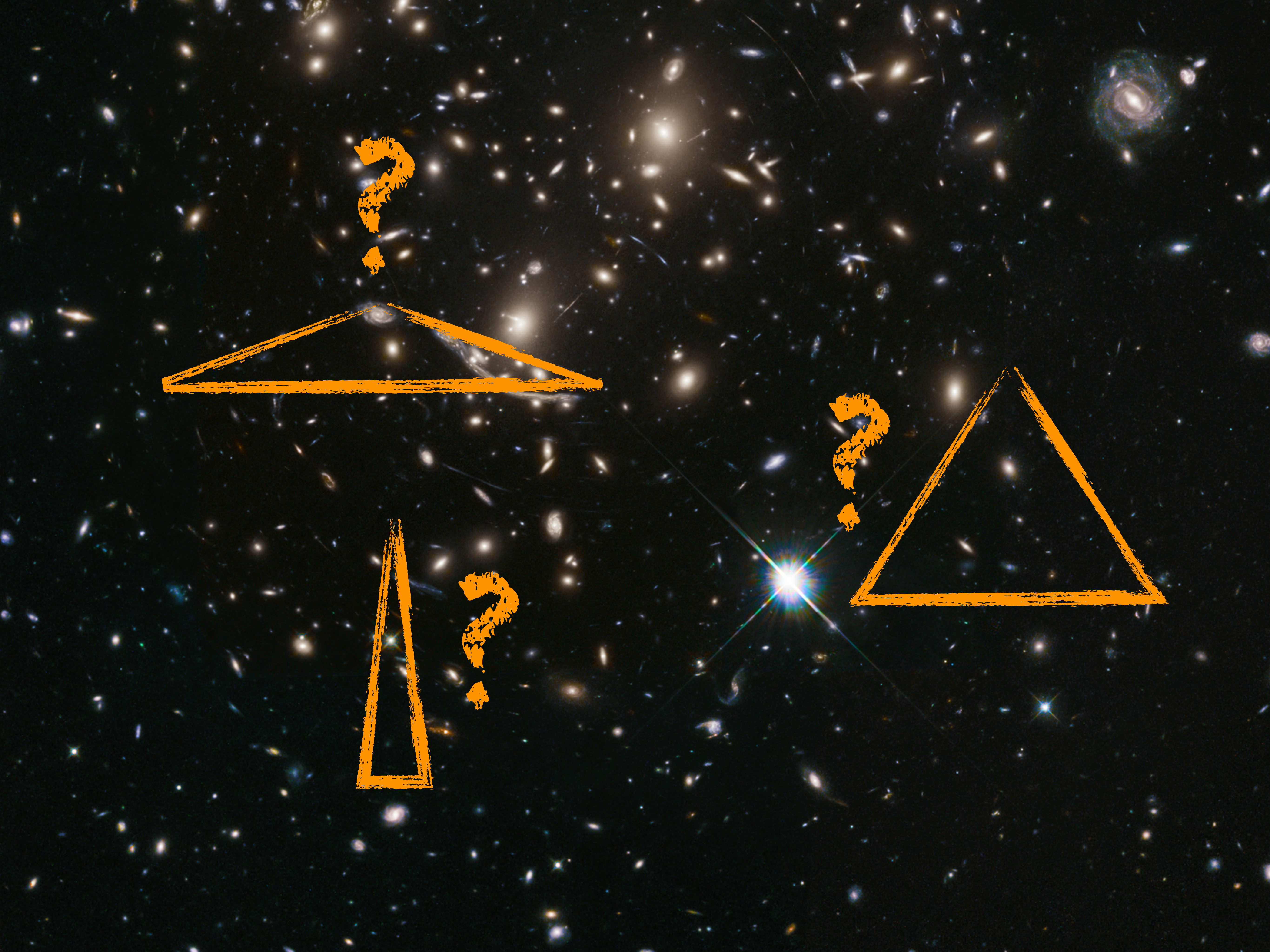
Interactions = primordial Non-Gaussianity



$$\mathcal{L}_{\rm int} \supset \frac{1}{\Lambda^2}\dot{\zeta}_c \nabla_\mu \zeta_c \nabla^\mu \zeta_c$$

$$\Delta_\zeta^{-1}\frac{H^2}{\Lambda^2} \approx f_{\rm NL}^{\rm eq} = -26 \pm 94\,(95\%)$$

Courtesy of Fergusson & Shellard

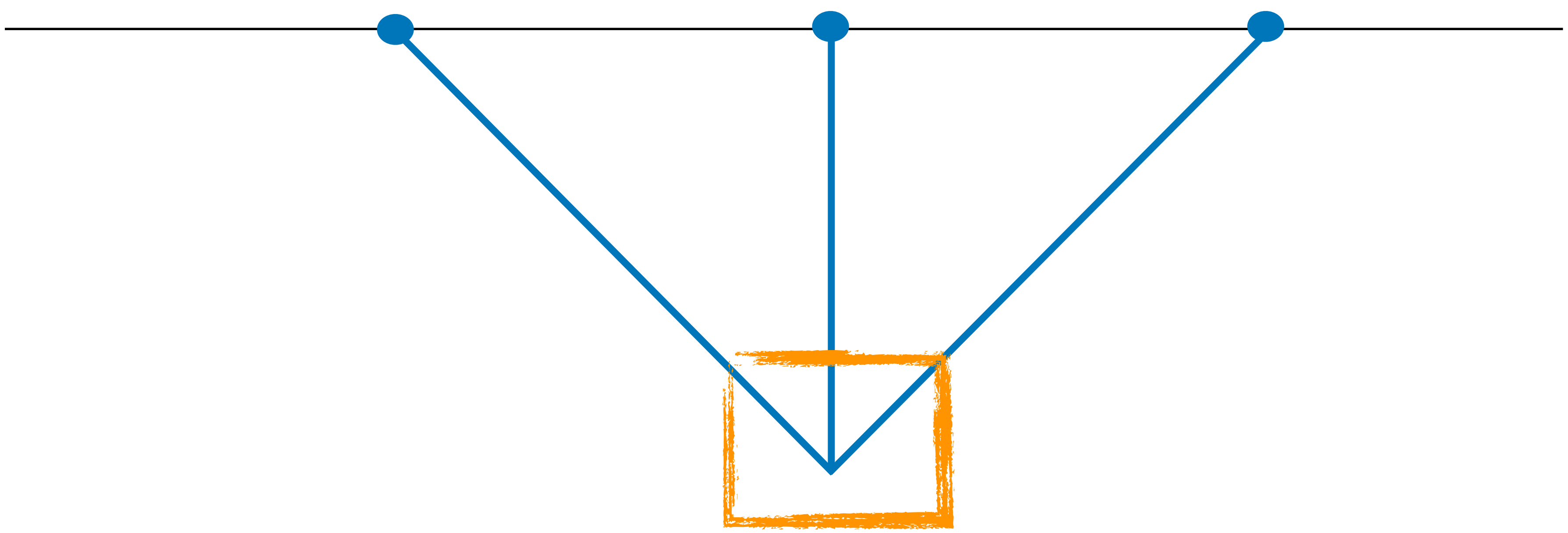


Locality

The inflationary signal is nonlocal in space

Created at the past intersection of the light cones

DG & Porto (2020)

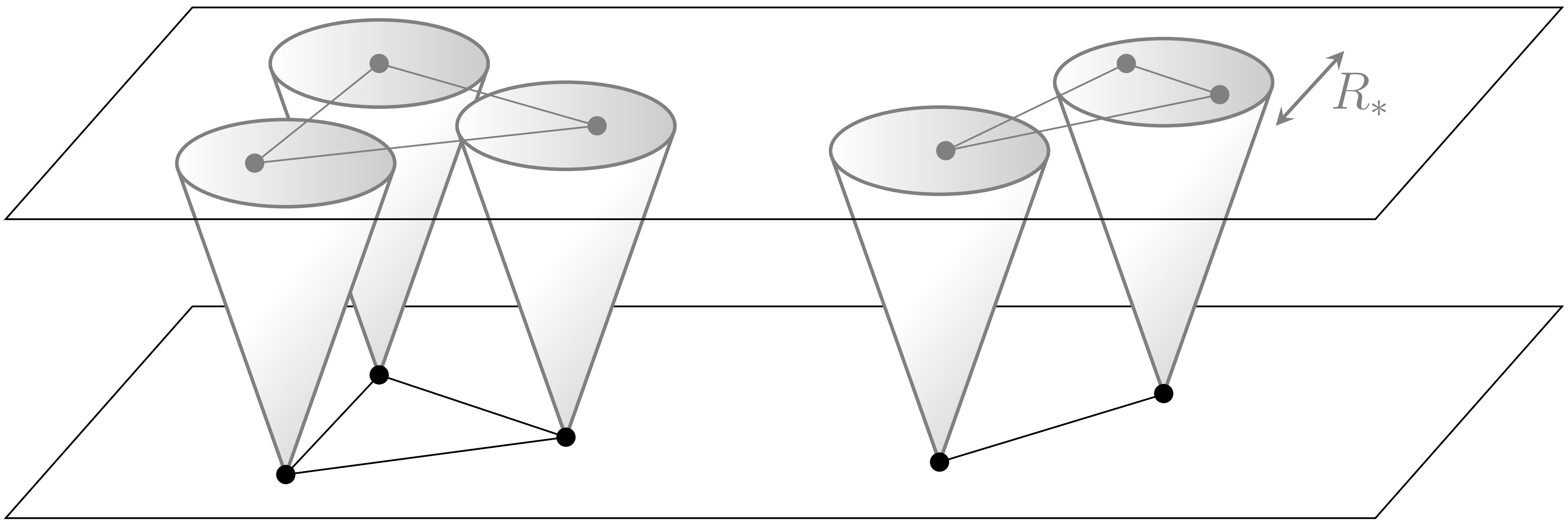


$$B_{\rm eq} = 162\, f_{\rm NL}^{\rm eq}\, \frac{\mathcal{T}(k_1)\mathcal{T}(k_2)\mathcal{T}(k_3)\Delta_\Phi^2}{k_1 k_2 k_3 (k_1+k_2+k_3)^3}$$

Proportional to 3 commutators: uniquely quantum!

Locality

Dark matter is slow: late-time evolution is ultra-local*



Primordial NG

Late-time NG

Nonlinearity can never completely mimic the signal

Differences seen at map-level

DG & Baumann (2021)

Locality

This is deeply connected to AdS/bootstrap/amplitudes

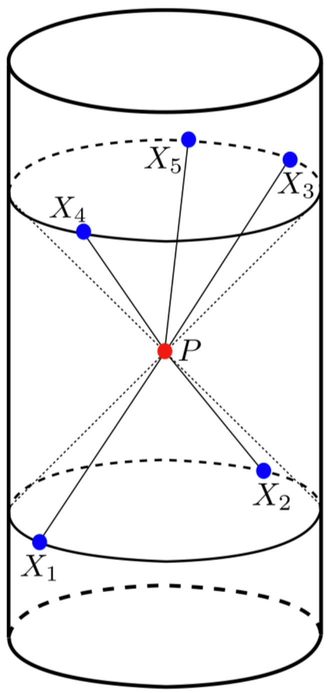


Figure from Simmons-Duffin et al.

AdS/Conformal Bootstrap

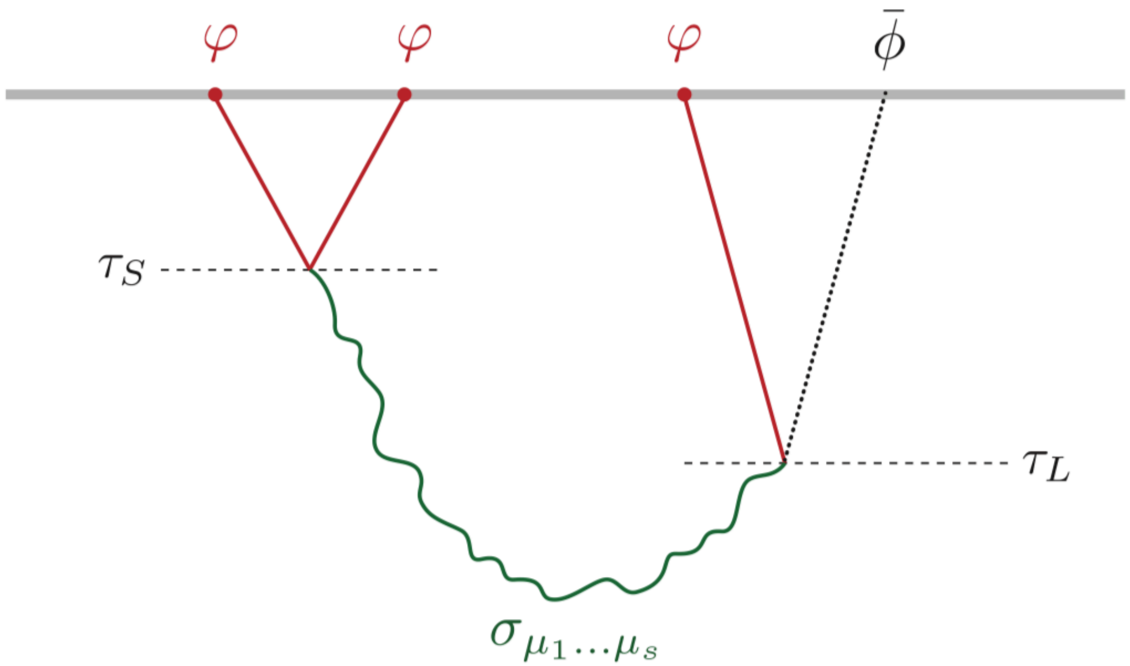


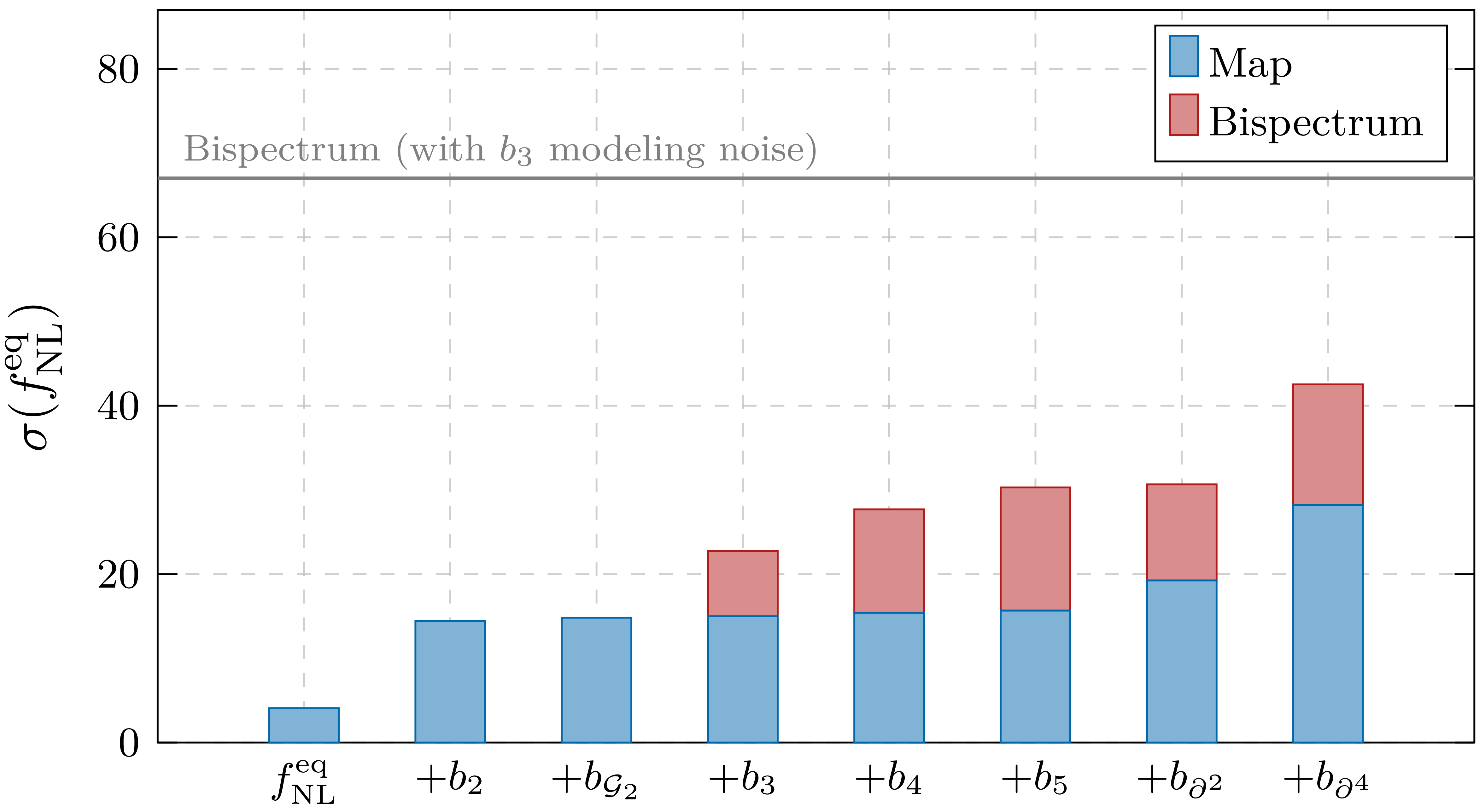
Figure from Baumann

Cosmological bootstrap

Analytic structure tied to causality/locality

Error correction in AdS $\approx$ Protection of pNG in LSS

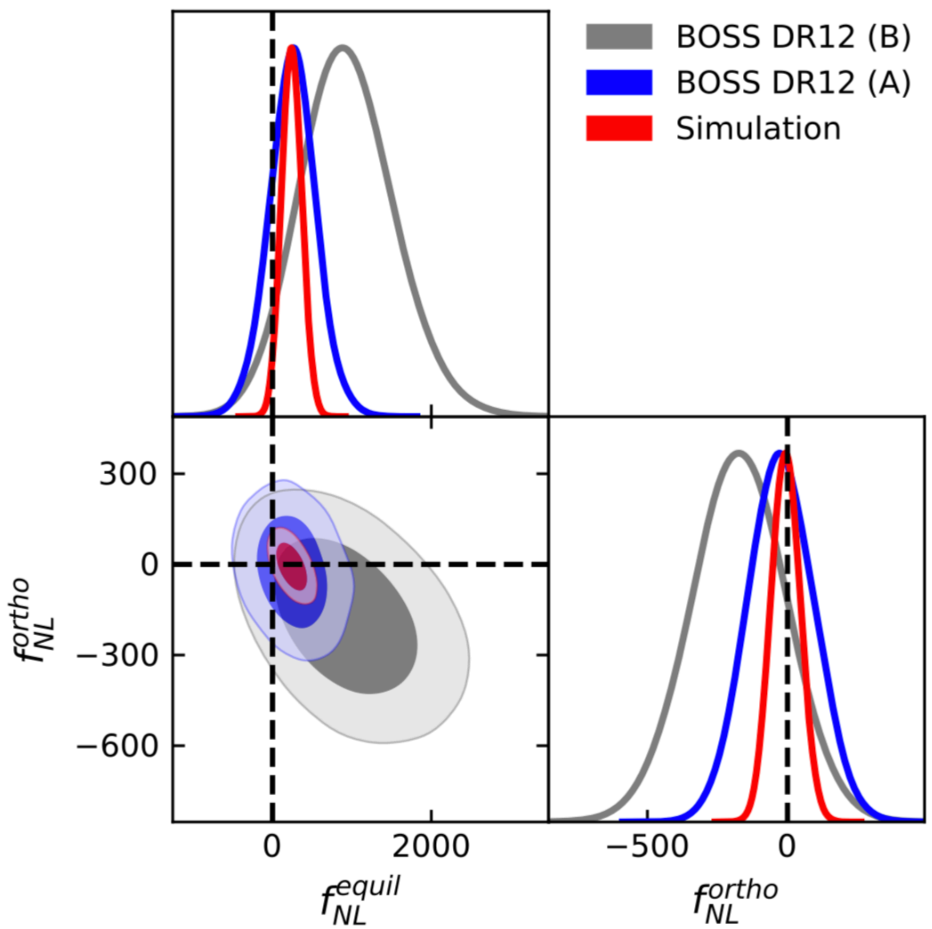
Forecasts



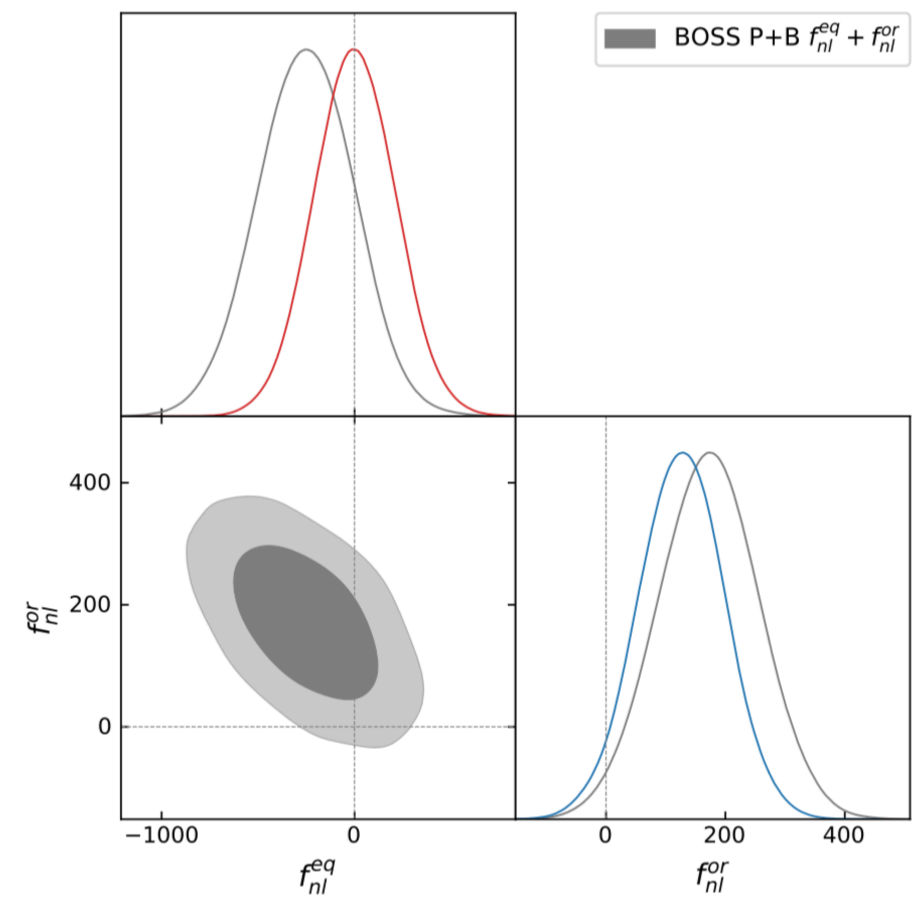
DG & Baumann (2021)

Status

First ever LSS constraints on pNG from the bispectrum



Cabass et al. (2022)



D'Amico et al. (2022)

Far from competitive now; proof of principle

Status

Forecasts for future surveys

Euclid: $\sigma(f_{\rm NL}^{\rm eq}) = 7.5$ $k_{\rm max} = 0.15\, h\, {\rm Mpc}^{-1}/D(z)$

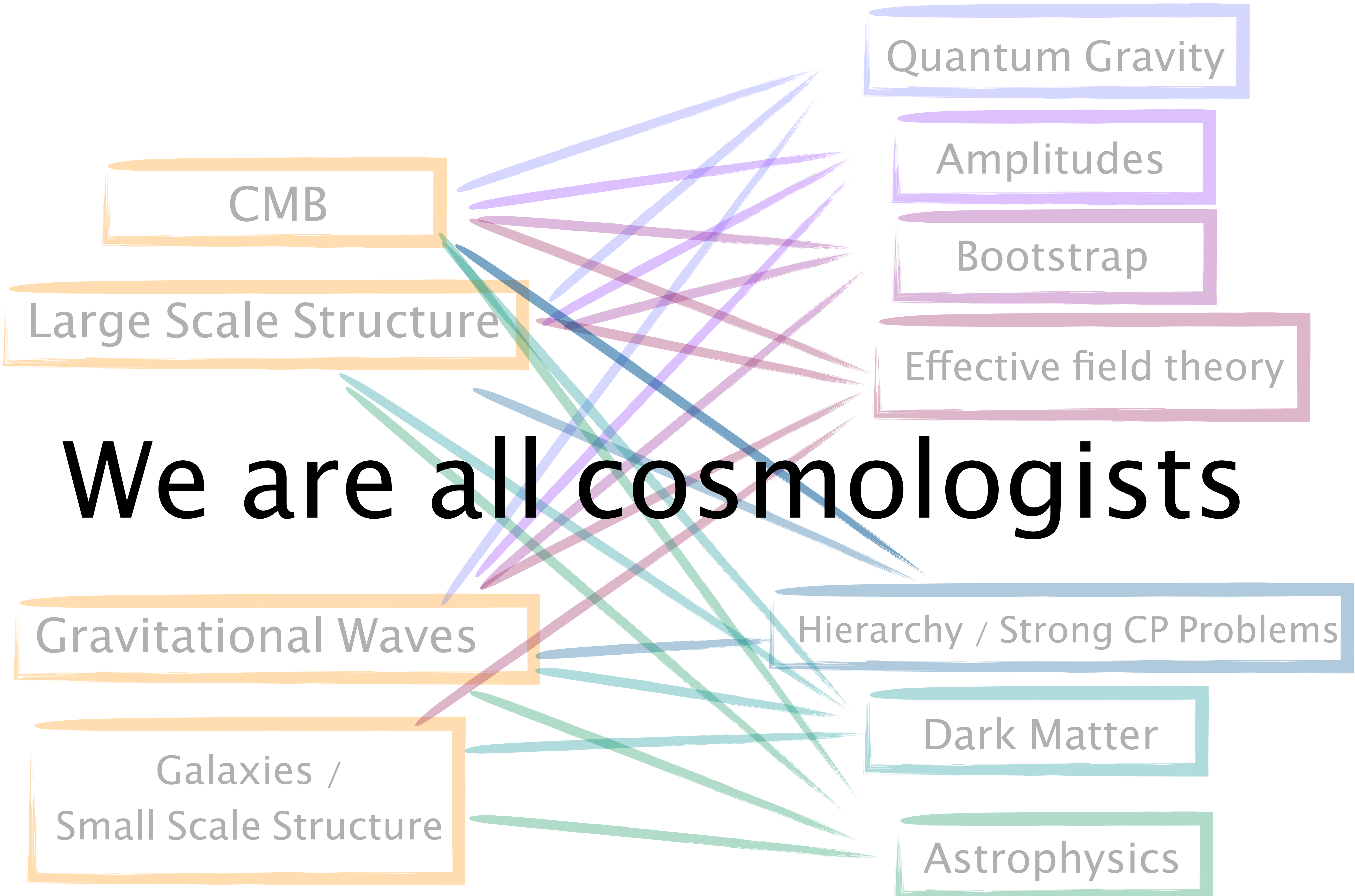
Euclid: $\sigma(f_{\rm NL}^{\rm eq}) = 16$ $k_{\rm max} = 0.1\, h\, {\rm Mpc}^{-1}/D(z)$

21cm intensity mapping (e.g. PUMA)

$$\sigma(f_{\rm NL}^{\rm eq}) = 4.5 \qquad k_{\rm max} = 0.1\, h\, {\rm Mpc}^{-1}/D(z)$$

Summary

We are all cosmologists




Thank You