Fundamental Physics from Cosmic Surveys

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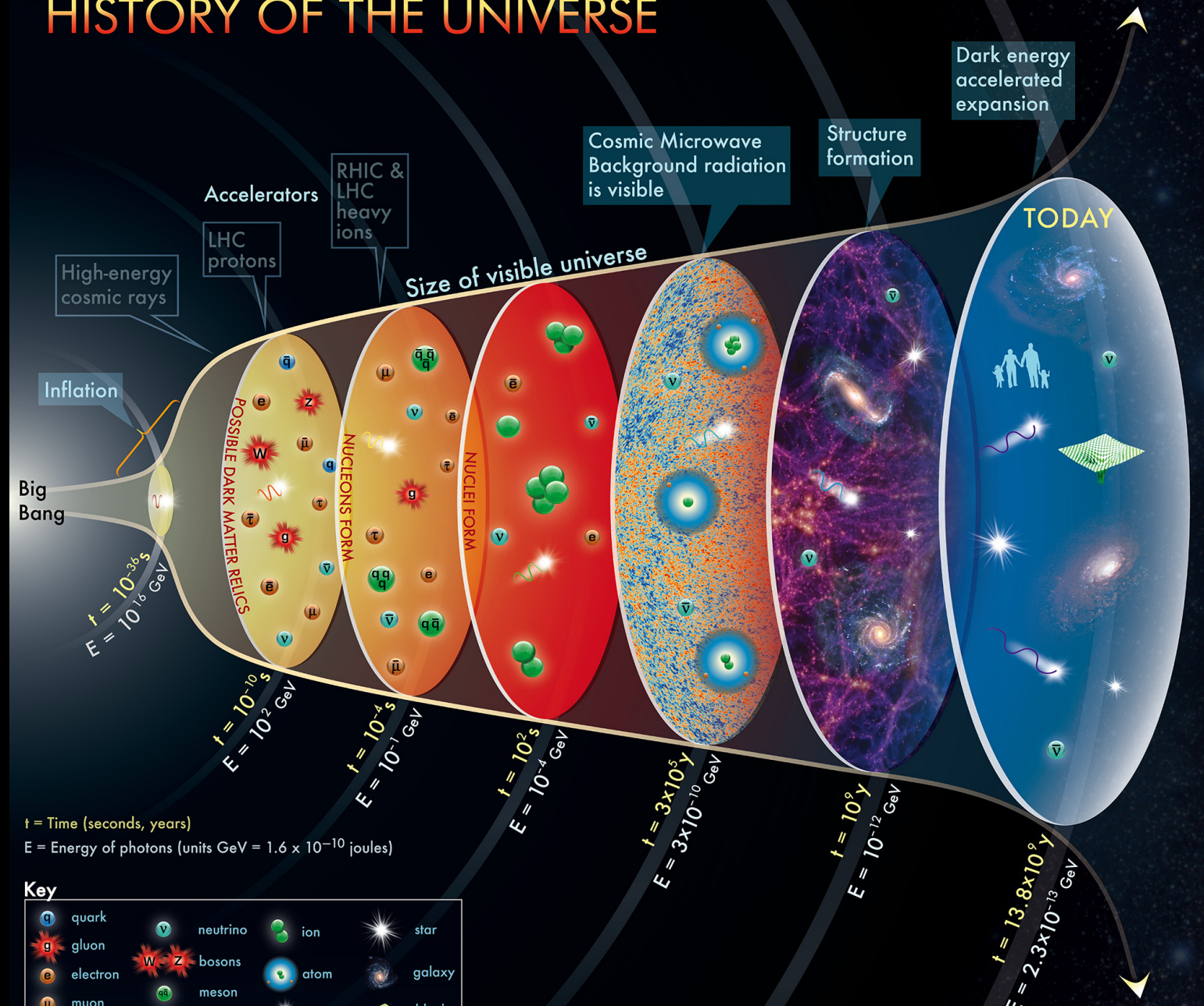
For references:
CF5/TF09 reports
and white papers

HISTORY OF THE UNIVERSE



t = Time (seconds, years)

E = Energy of photons (units GeV = 1.6 x 10^{-10} joules)

Key

quark, gluon, electron, muon, tau, neutrino, bosons, meson, baryon, ion, atom, photon, star, galaxy, black hole

The concept for the above figure originated in a 1986 paper by Michael Turner.

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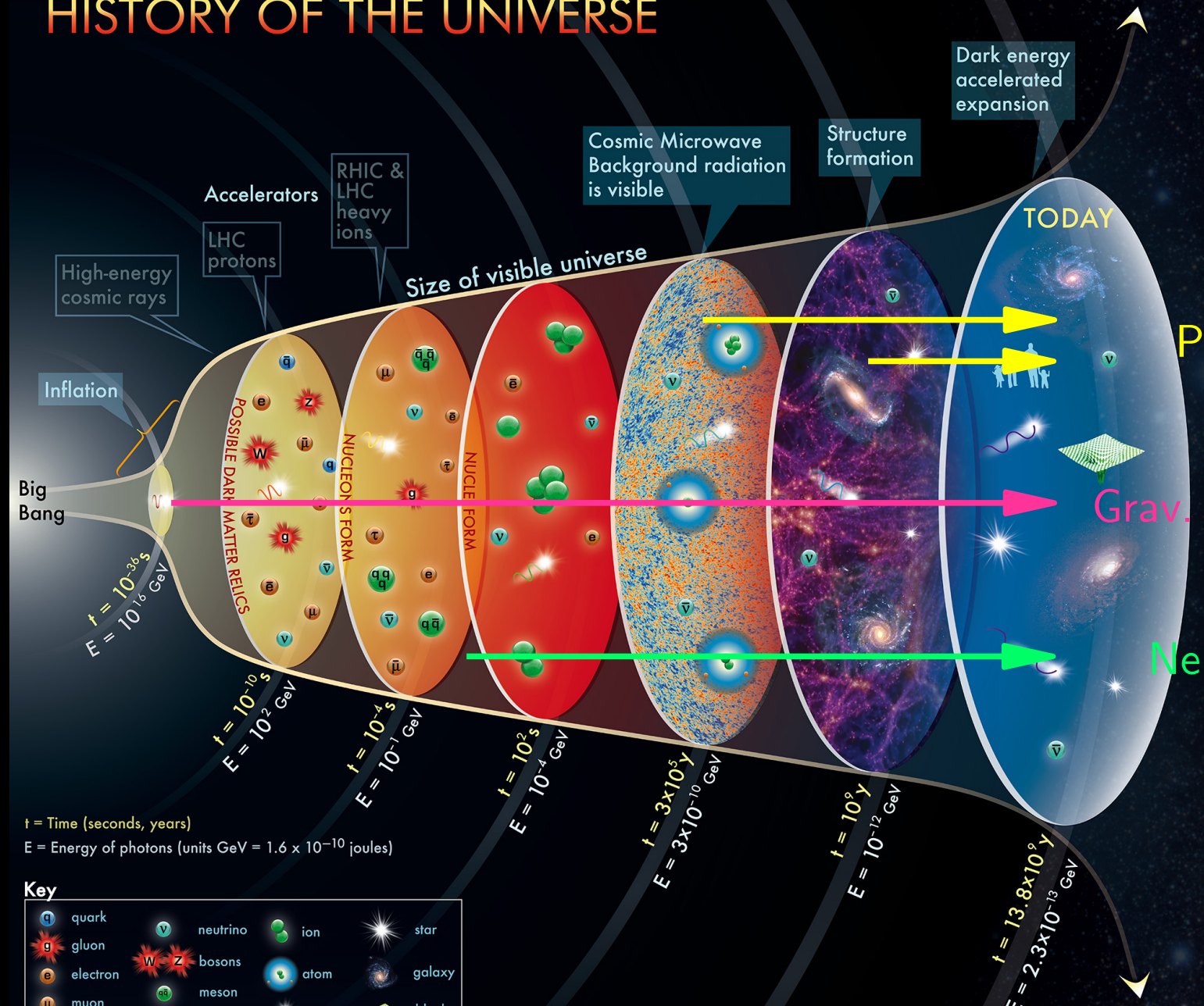

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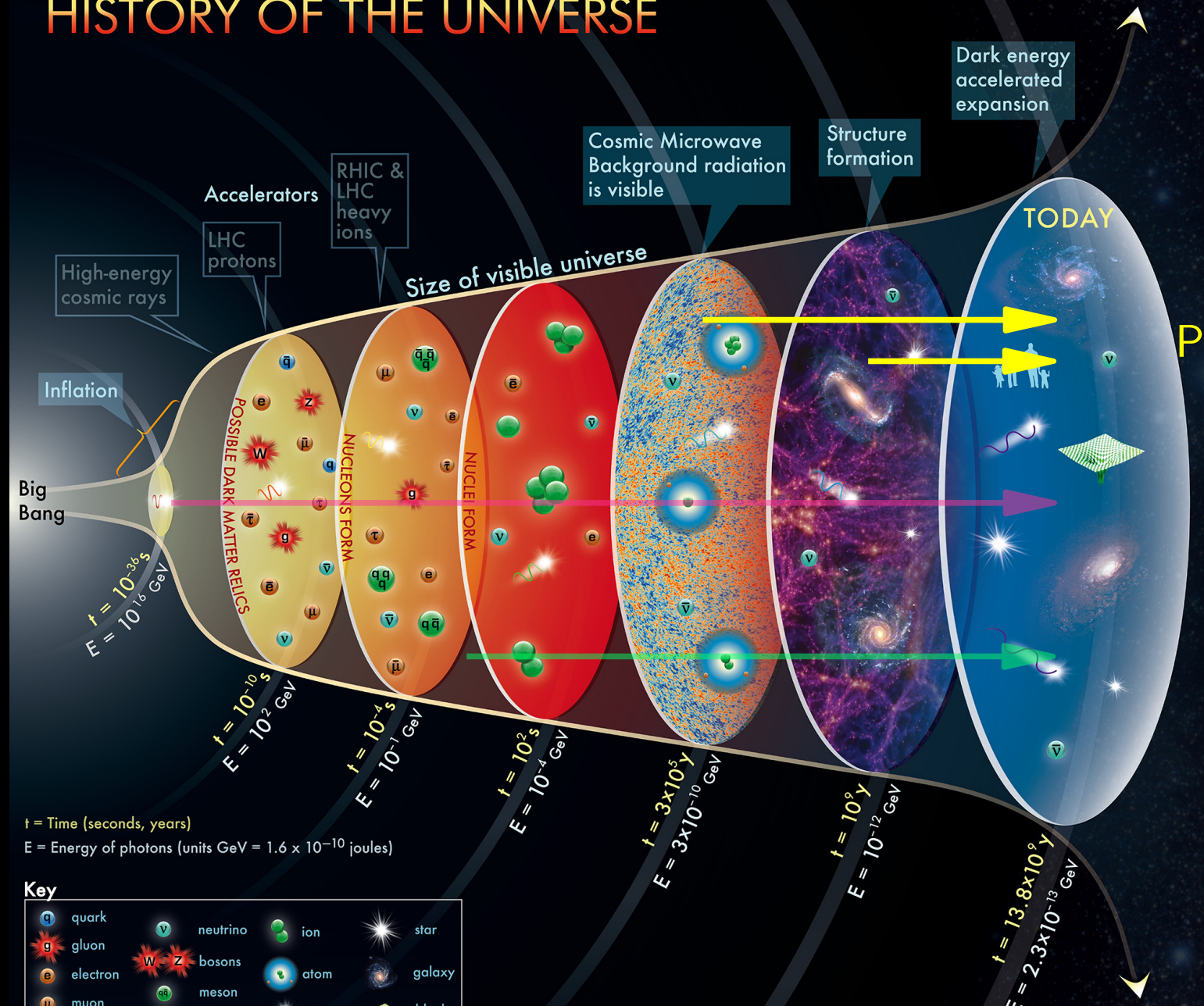

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Key

quark	neutrino	ion	star		
gluon	bosons	atom	galaxy		
electron	meson	photon	black hole		
muon	baryon				
tau					

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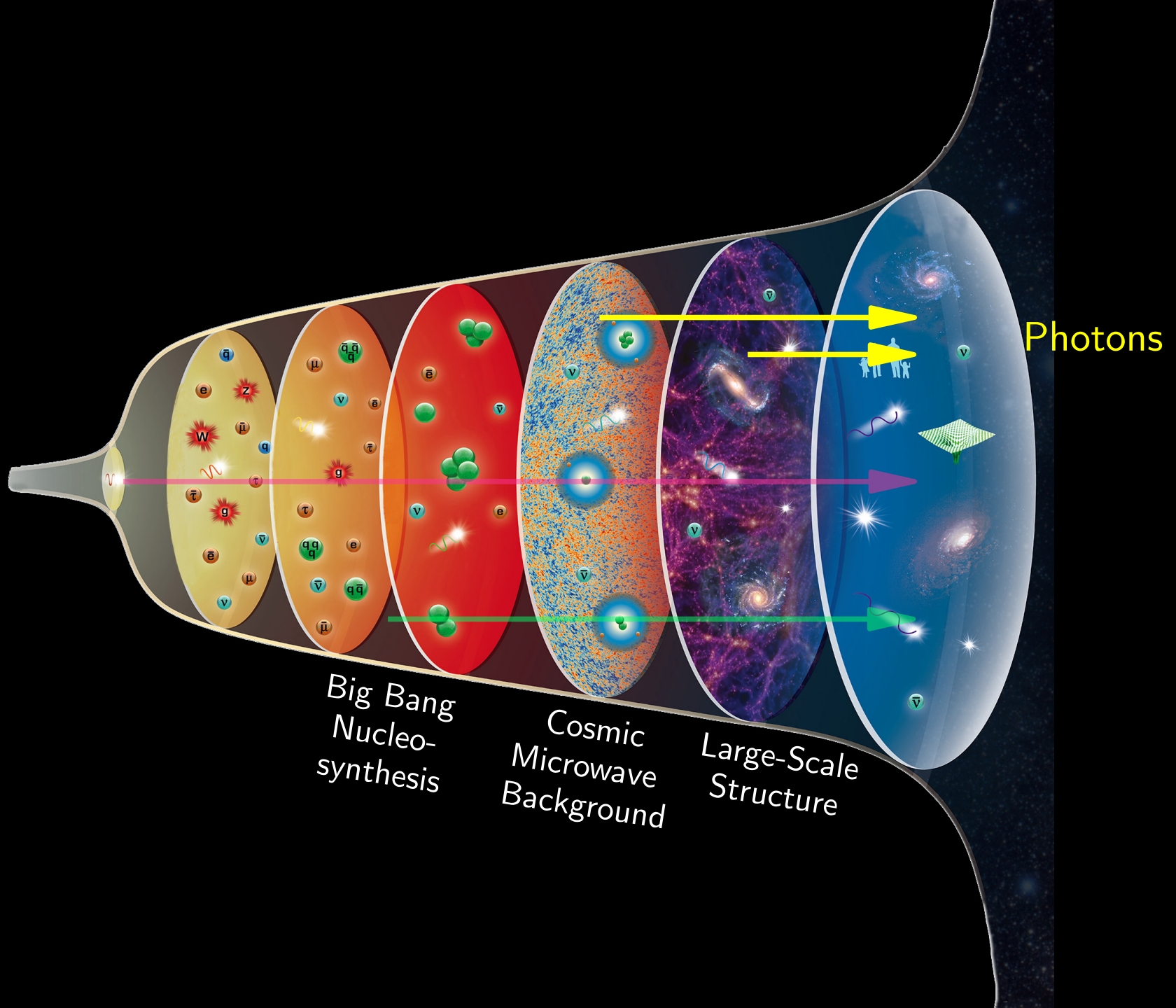
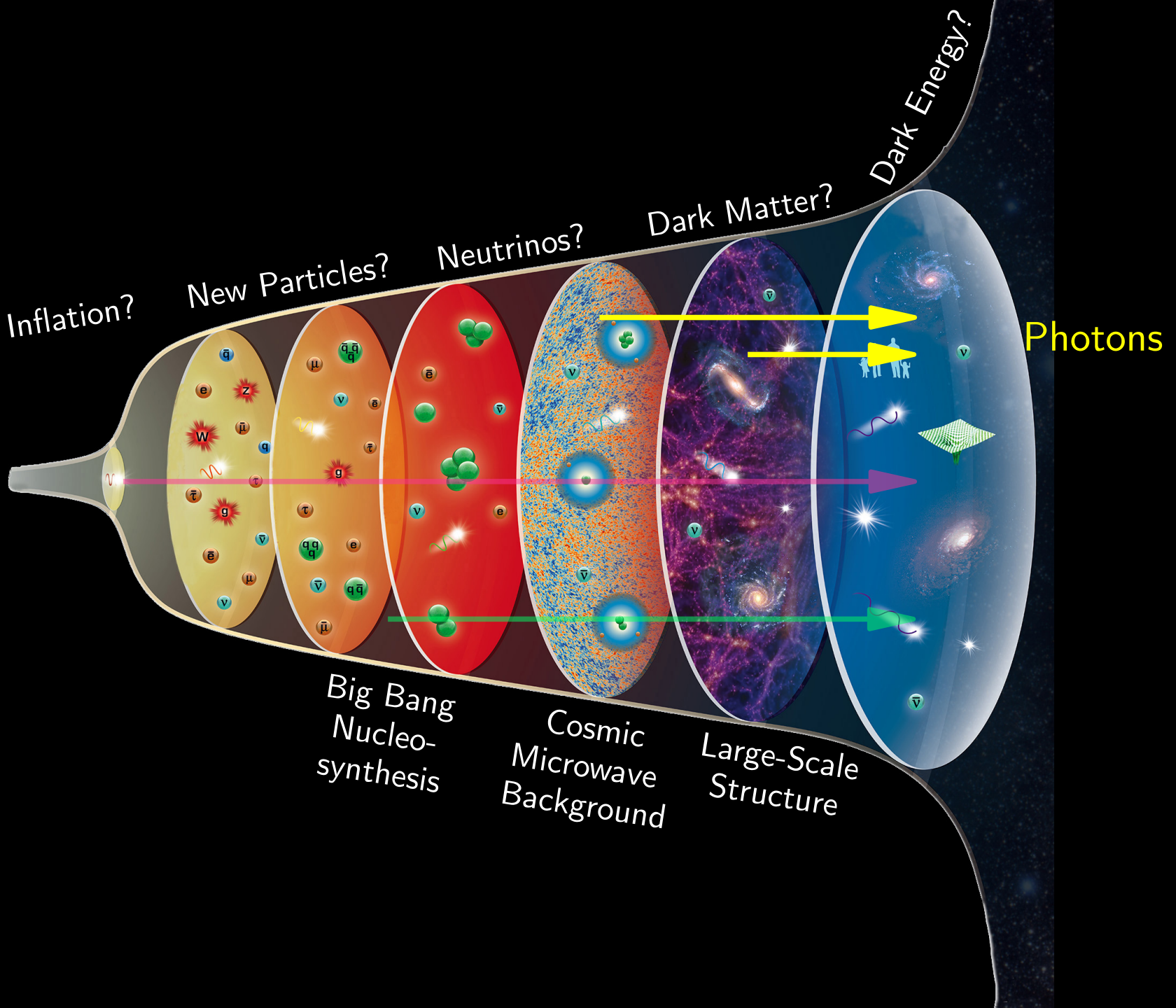
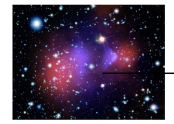
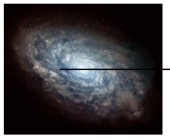

Photons
Big Bang Nucleo-synthesis
Cosmic Microwave Background
Large-Scale Structure


Inflation?
New Particles?
Neutrinos?
Dark Matter?
Dark Energy?
Photons
Big Bang Nucleo-synthesis
Cosmic Microwave Background
Large-Scale Structure



Massive galaxy clusters



Typical galaxies

Size

Dark Energy

Modified Gravity

Sub-halo probes of Dark Matter

Inflation (Primordial structure)

Neutrinos, Dark Matter

New relativistic energy (new particles, new phase transitions)

Inflation (Primordial Gravitational Waves)

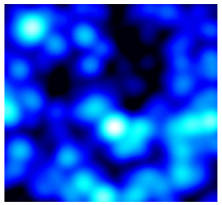
z~0

redshift

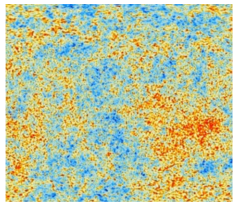
Reionization

Last scattering of CMB photons

Galaxies and transients emitting in optical wavelengths and spatially resolved.



Galaxies and gas emission at redder wavelengths and spatially dense.



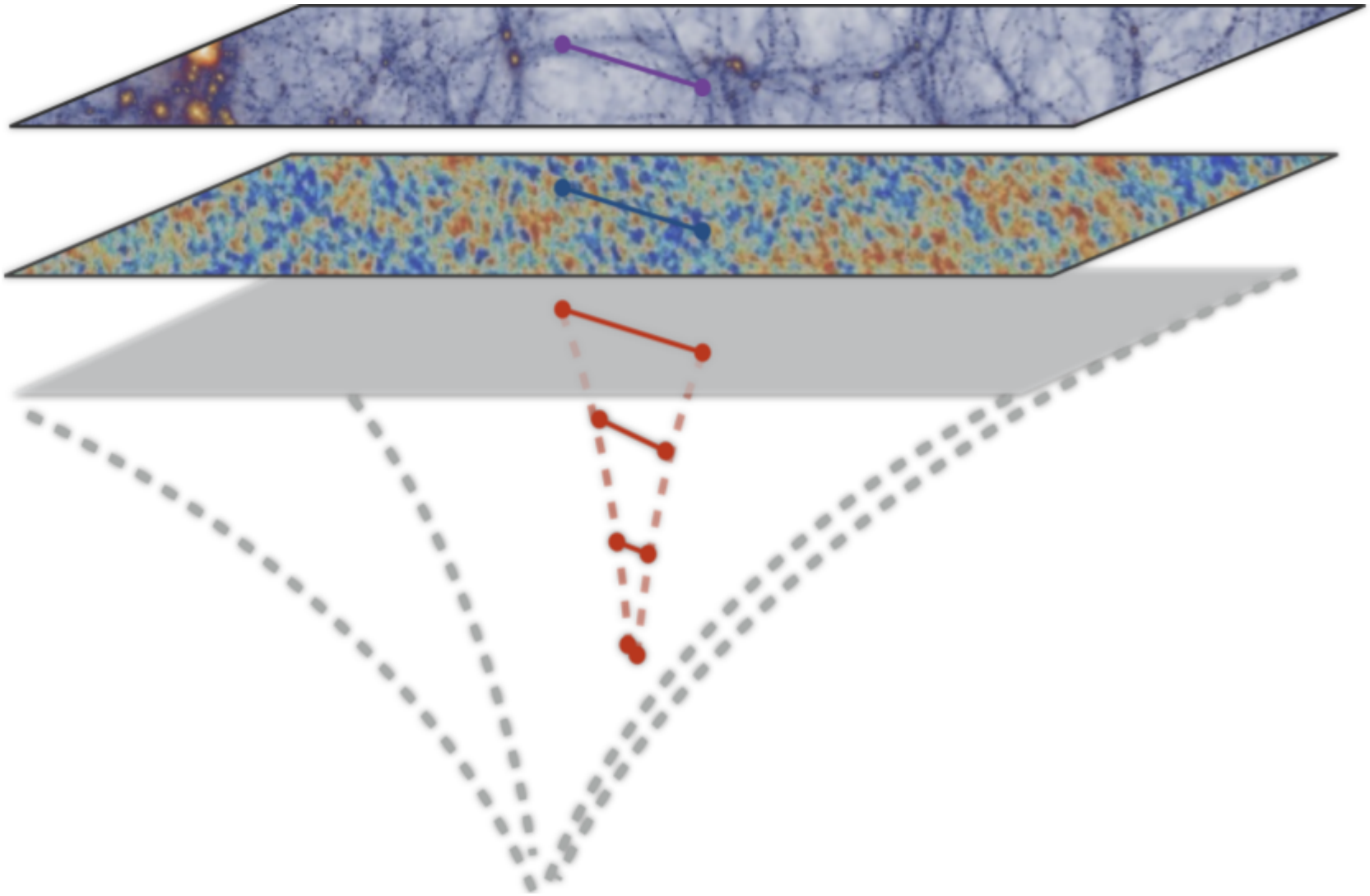
Hot dense state. Detectable relics include CMB, gravitational waves and neutrinos.

Galaxy Surveys

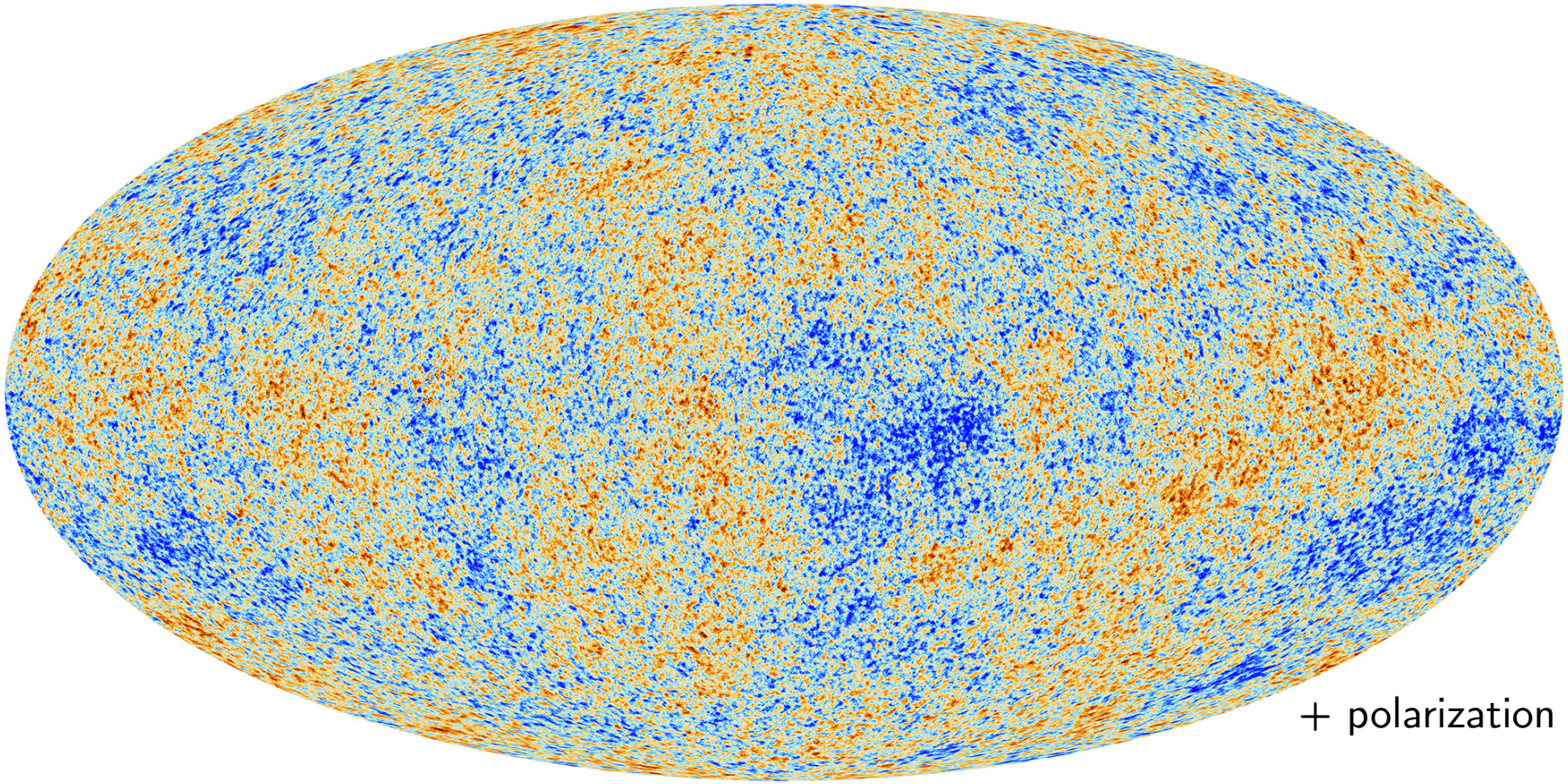
Line Intensity Mapping

CMB Surveys

Imprinting Primordial Information



Cosmic Microwave Background (CMB)



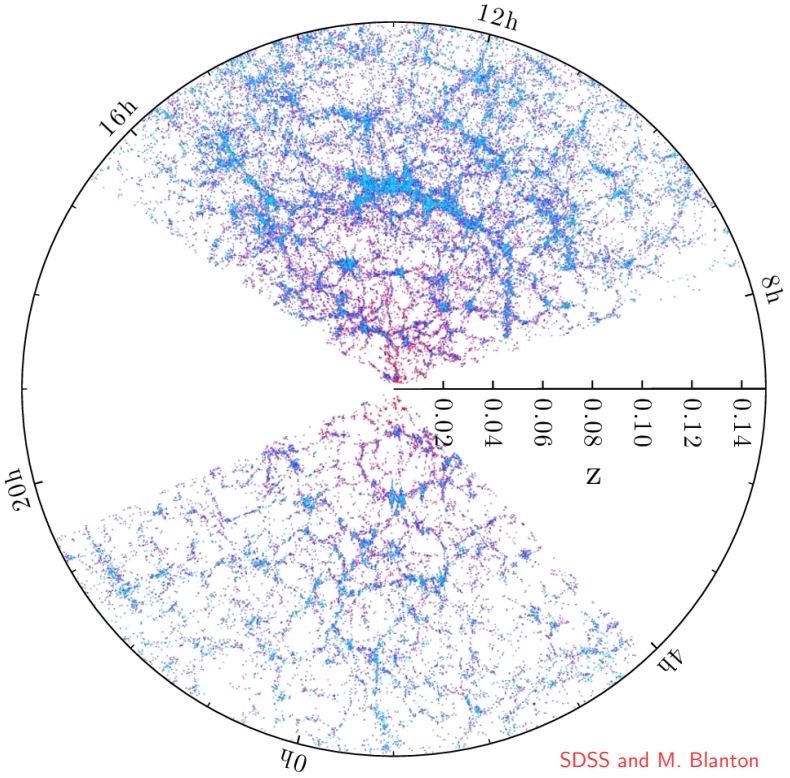
+ polarization

Cf. electron-positron collider.

Planck (2018)

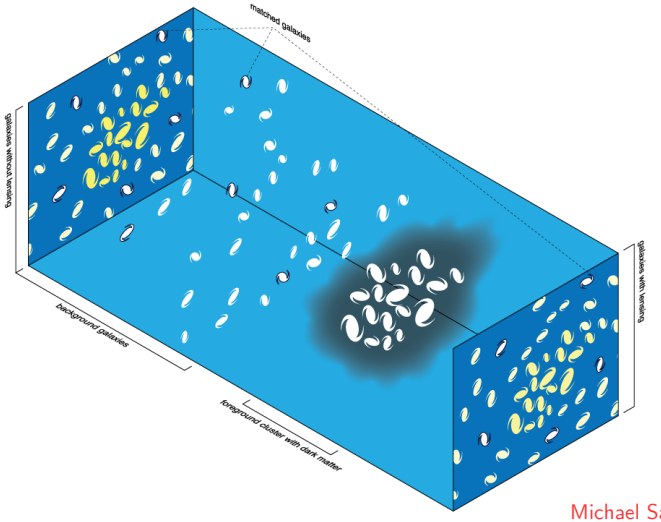
Large-Scale Structure (LSS)

Galaxy Clustering



SDSS and M. Blanton

Weak Gravitational Lensing



Michael Sachs

+ Lyman-α forest,
galaxy clusters,
...

Cf. proton-proton collider.

Recent Examples

- Free-Streaming Neutrinos in the CMB & LSS
- Dark Radiation and Axion-Like Particles
- Cosmological Parameters from LSS
- Primordial Non-Gaussianity from LSS
- Primordial Features in LSS
- ...

Free-Streaming Neutrinos

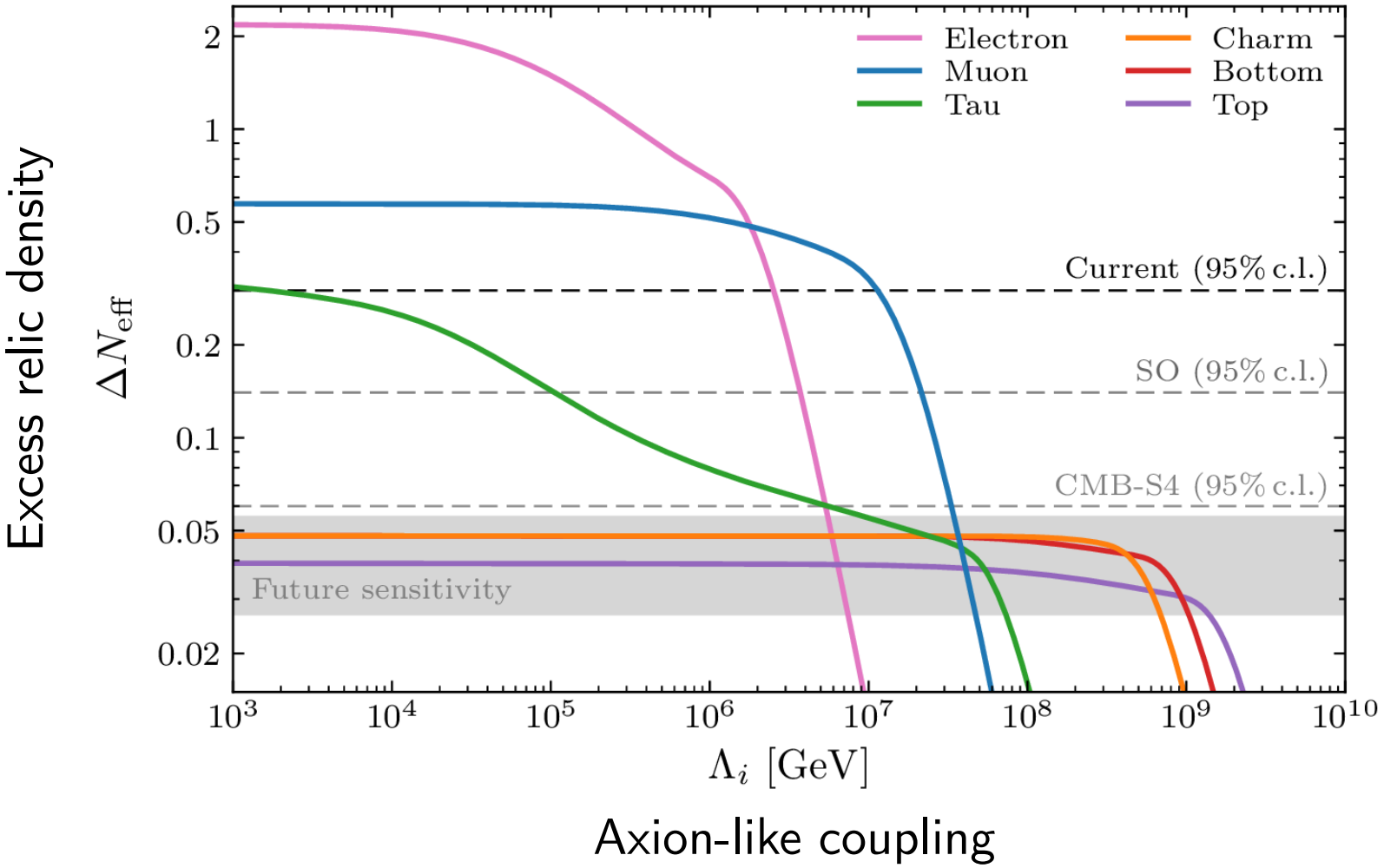
- 41% of the radiation density in the universe:
  - $\rightarrow$ Leave gravitational imprint,
  - $\rightarrow$ Can detect their energy density.
- In the Standard Model: free-streaming since $T \sim 1\,\mathrm{MeV}$.
- Free-streaming neutrinos overtake the photons and pull them ahead of the sound horizon.
- New theoretical insights & modeling + precise observational data:
  - $\rightarrow$ Extraction from CMB (2015) and LSS (2018) data!
  - $\rightarrow$ Constraints on neutrino interactions.

Dark Radiation and Axion-Like Particles

- Cosmological surveys can precisely measure the radiation density.

- Neutrino energy density theoretically computed to high precision.
  - Deviation means physics beyond the Standard Model!
  - No deviation implies constraints on potential new physics, e.g.
    $\rightarrow$ on couplings of new particles to the Standard Model,
    $\rightarrow$ on changes to thermal history, e.g. phase transitions,
    $\rightarrow$ ...

SM Couplings of Axion-Like Particles



Cosmological Parameters from LSS

- Theoretical development of the effective field theory of large-scale structure (EFTofLSS).

- Powerful description of structure formation into the mildly nonlinear regime.

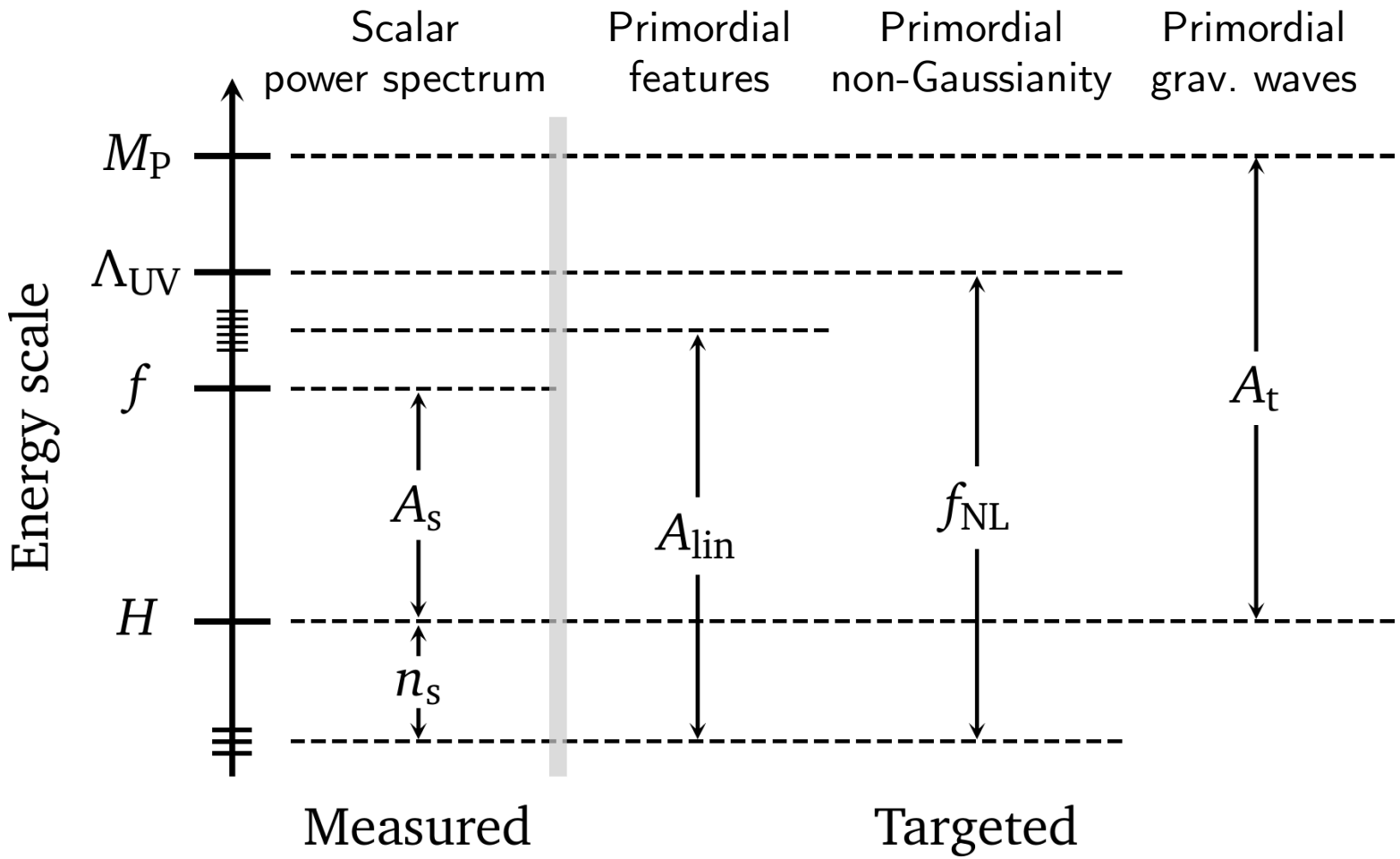
  $\rightarrow$ Analyses can use more information.

- Additional theoretical advances for computational tractability.

  $\rightarrow$ Cosmological analyses of the full power spectrum (2019),

  $\rightarrow$ Independent of the CMB.

Inflation and Fundamental Physics

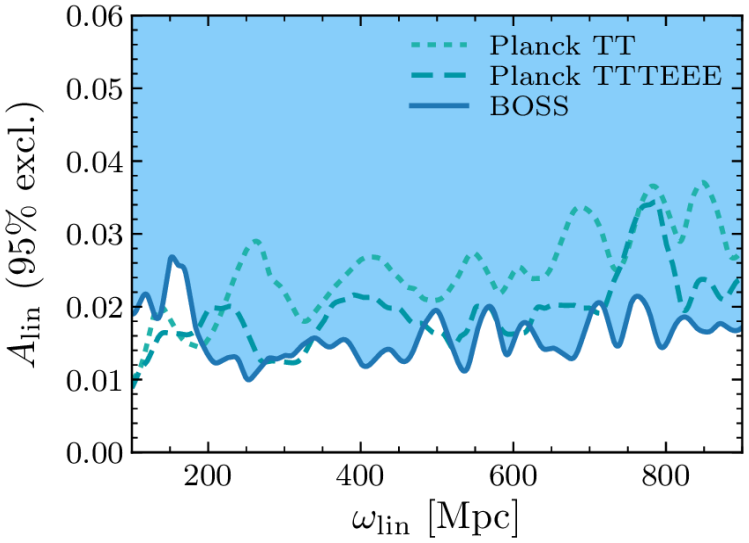


Primordial Features from LSS

- Primordial features:
  - Observational signature of departure from scale invariance, i.e. new inflationary energy scale(s) and phenomena.
  - Oscillatory imprint in CMB and LSS observations.

- Theoretical insights allow separation from late-time effects.

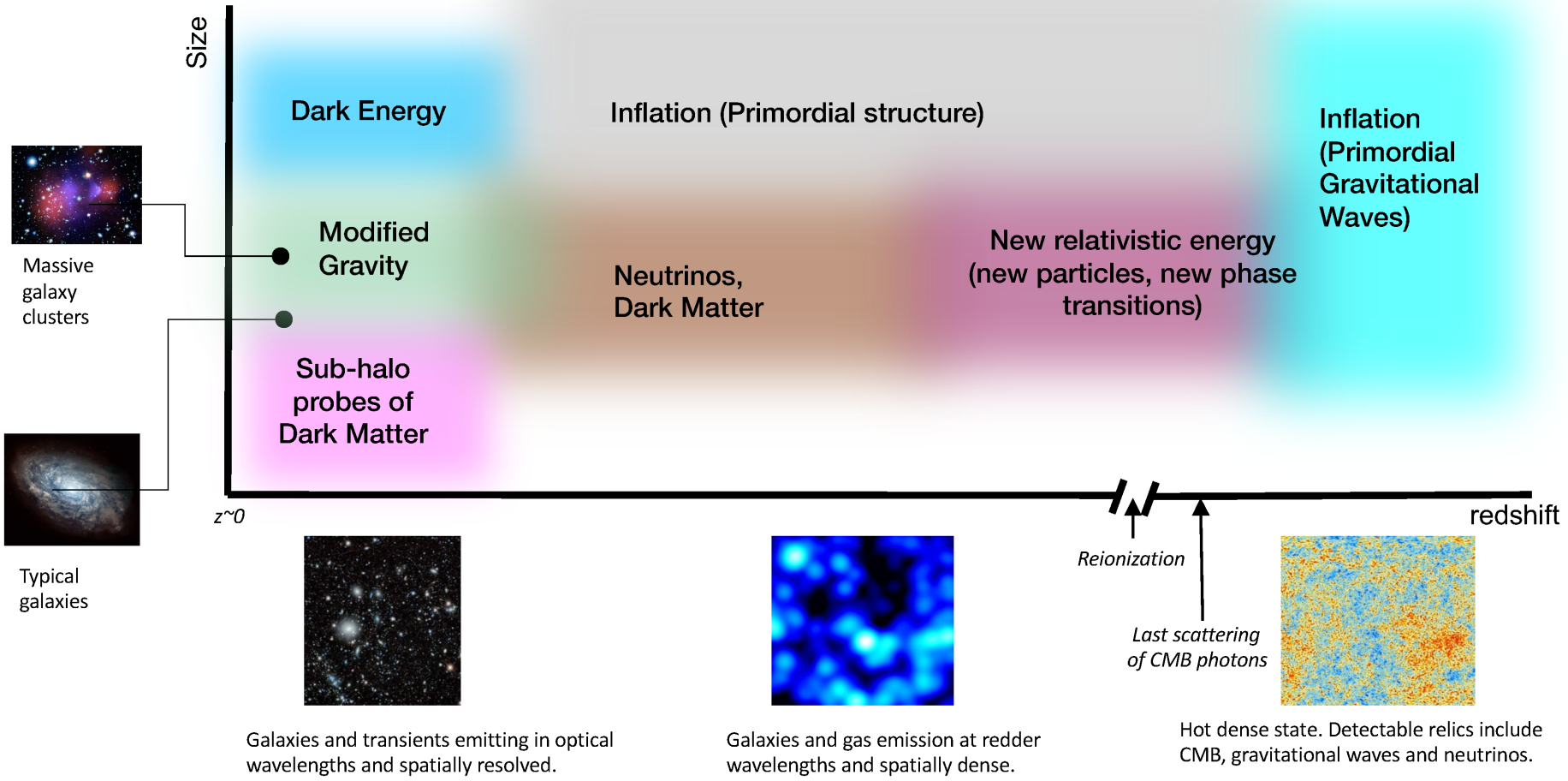
  $\rightarrow$ Use full statistical power of LSS surveys (2019).



Primordial Non-Gaussianity from LSS

- Primordial non-Gaussianity:
  - Observational signature of inflationary dynamics, e.g. number of light fields and inflaton self-interactions.
- Non-Gaussianity also induced by gravitational evolution in the late universe.
- EFTofLSS allows first constraint on equilateral primordial non-Gaussianity, similar to WMAP (2022).
- A lot of ongoing theoretical work, including map-based analyses, simulation-based inference, machine learning, ...

Thank you!



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