Opportunities at the Intersection of Theory and Observations

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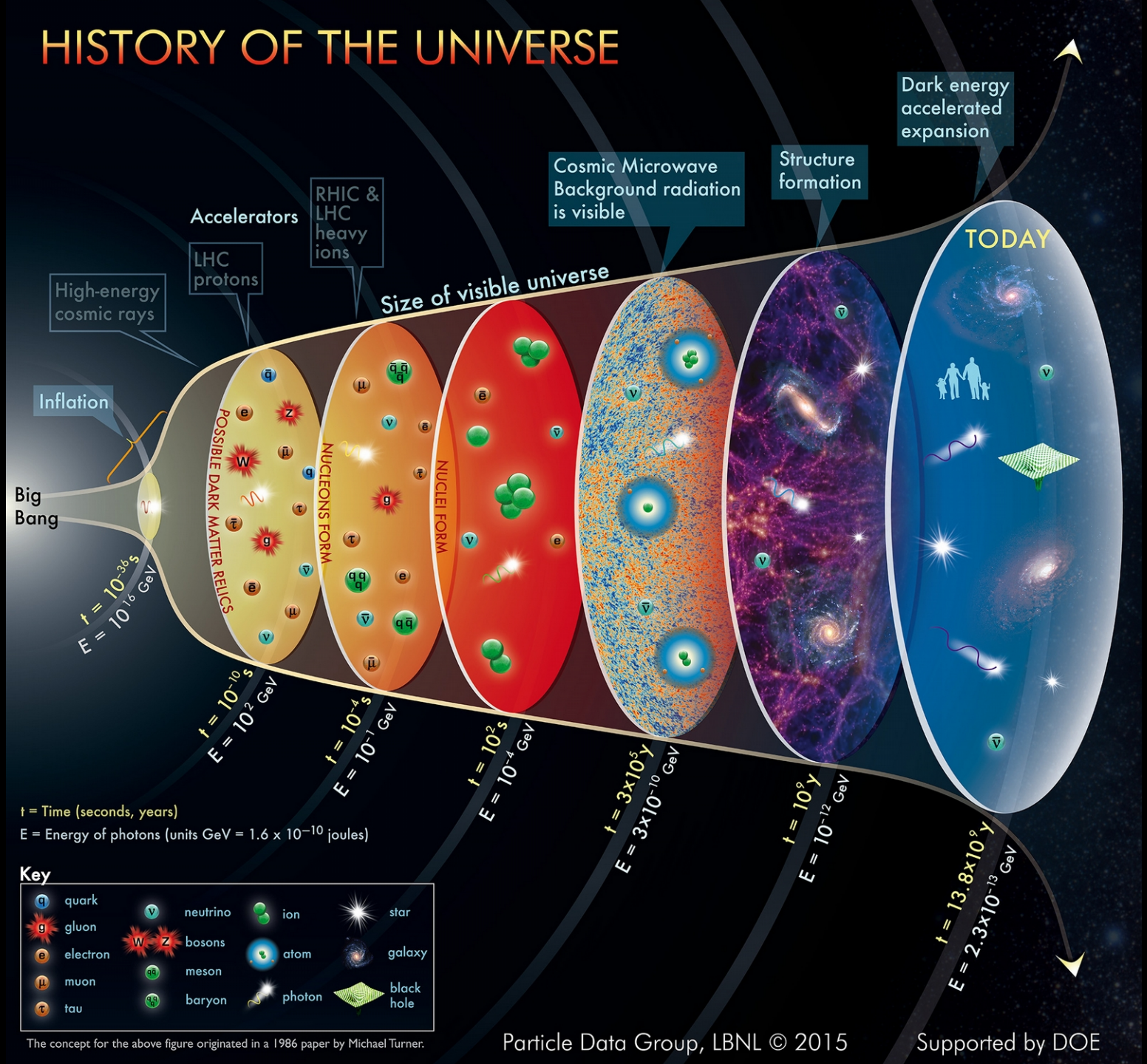
For references:
CF5/TF09 reports
and white papers


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Cosmic Microwave Background radiation is visible
Structure formation
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
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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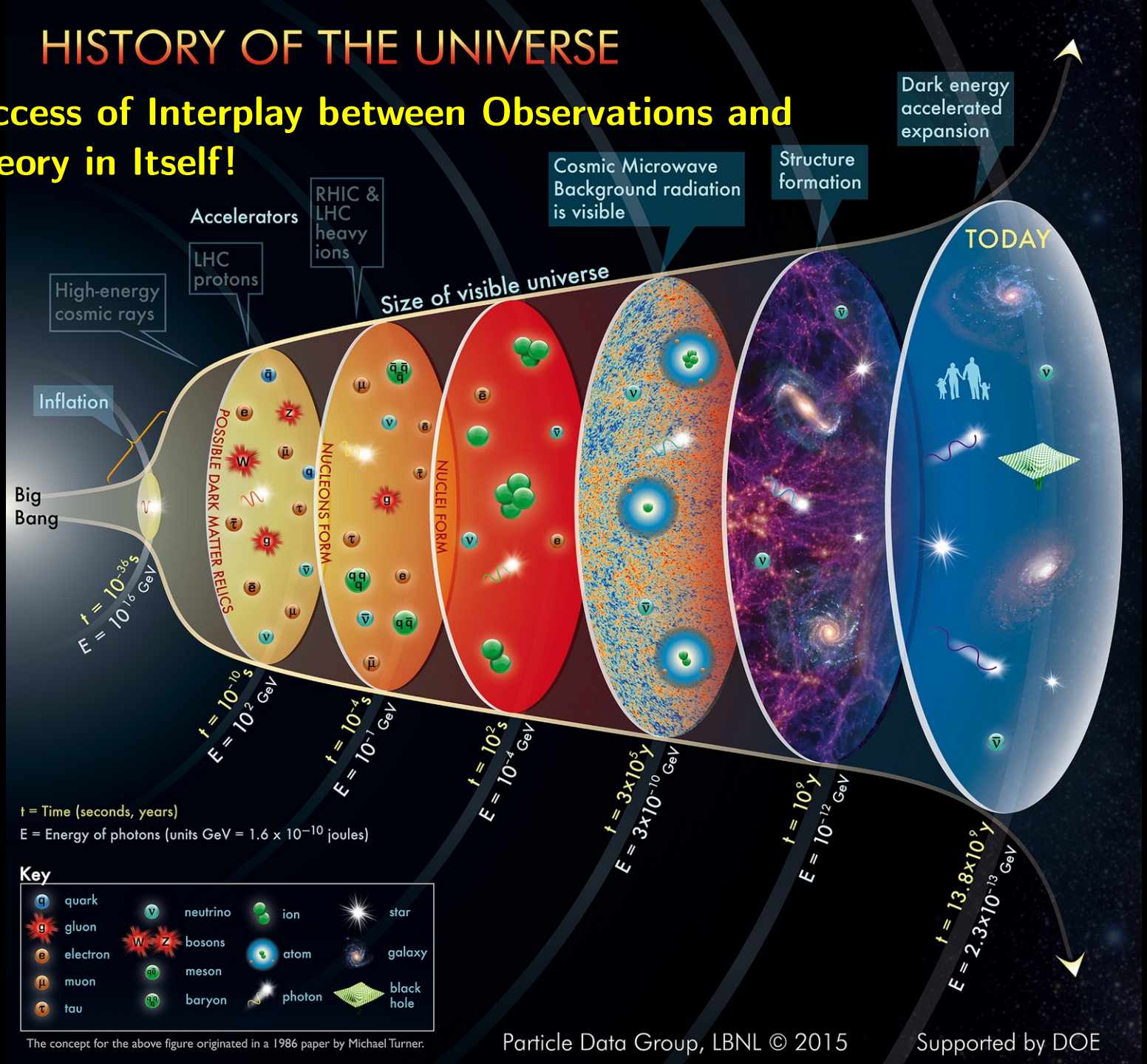
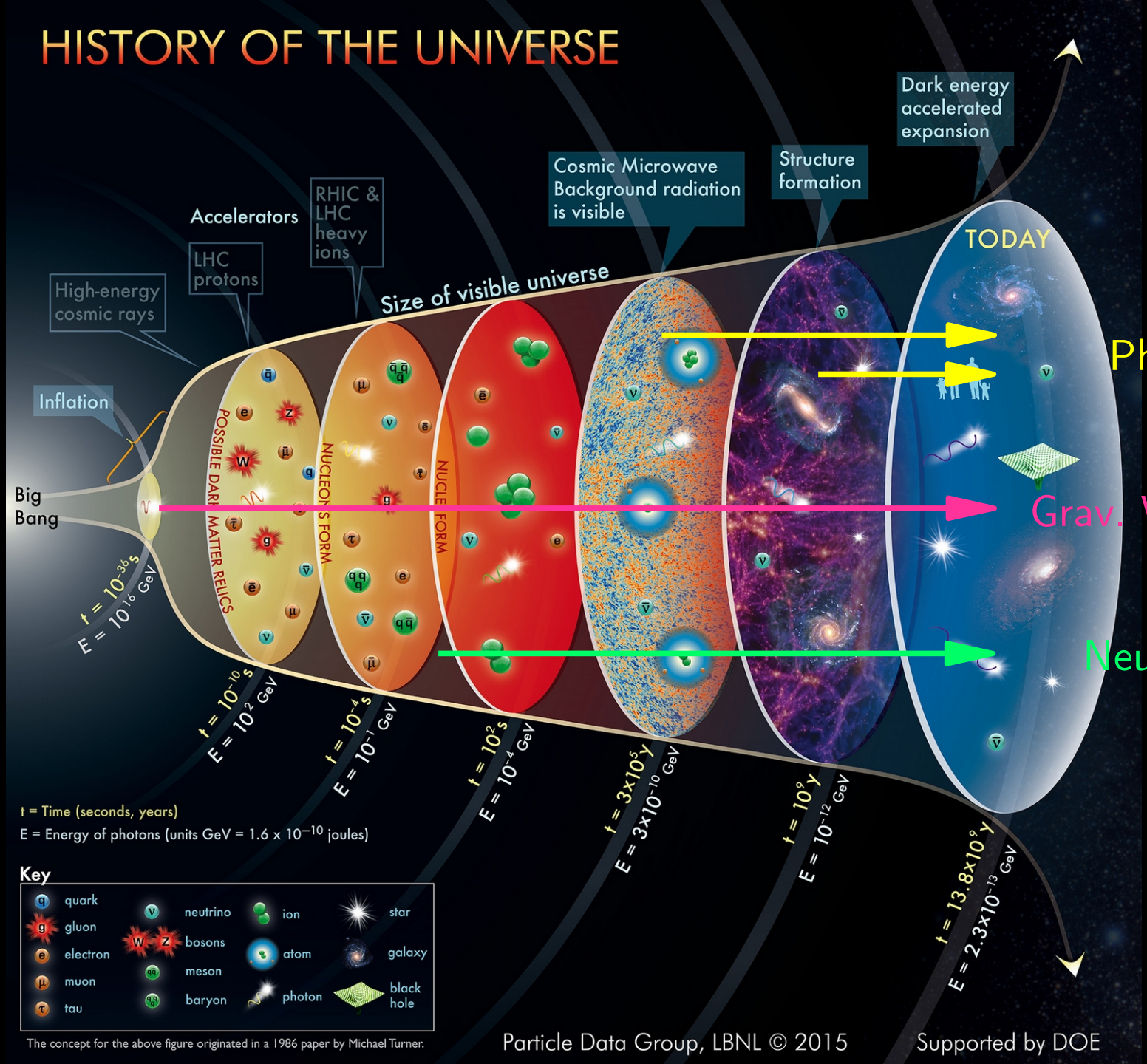
Success of Interplay between Observations and Theory in Itself!

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POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
Photons
Grav. Waves
Neutrinos
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
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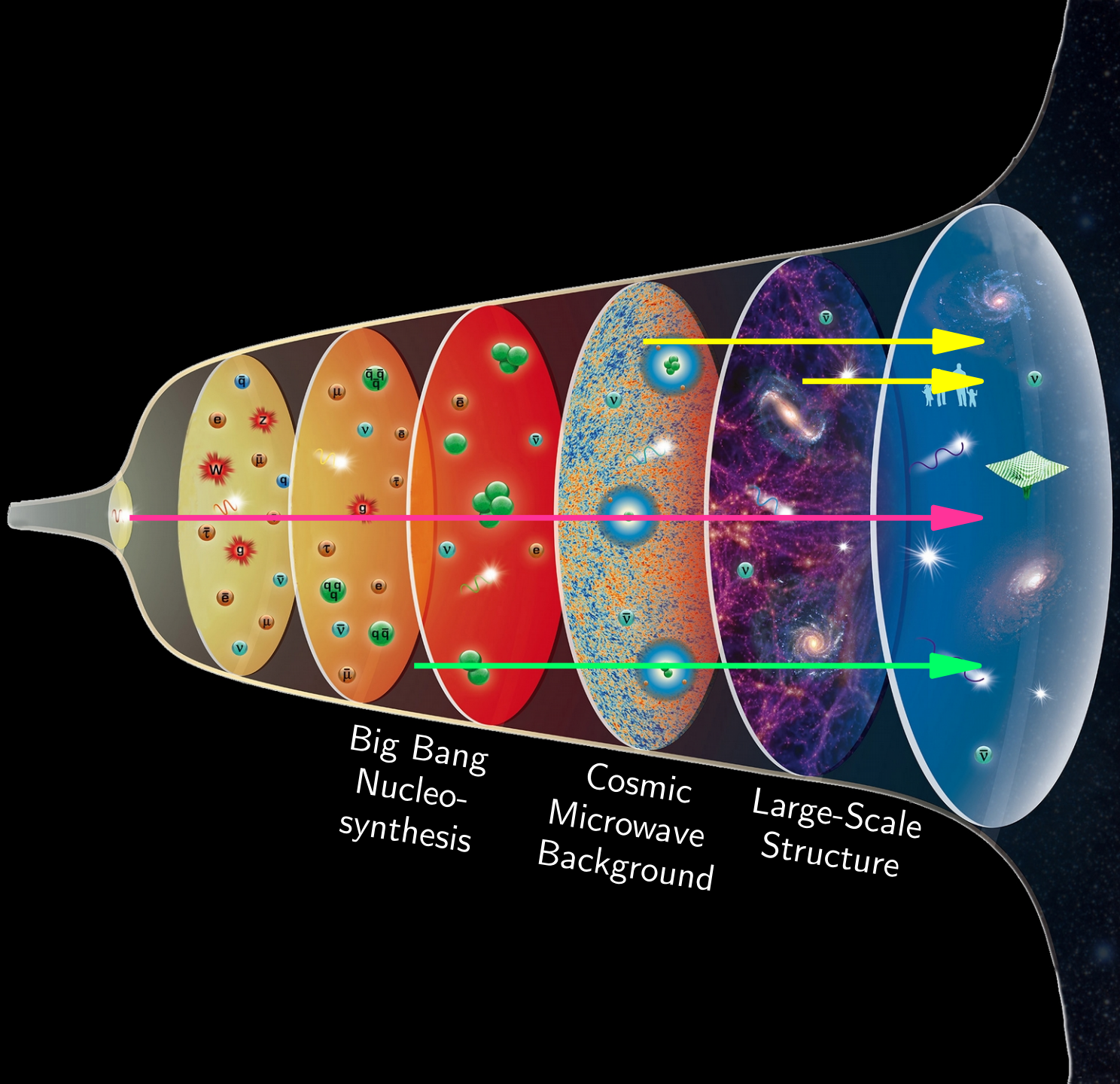
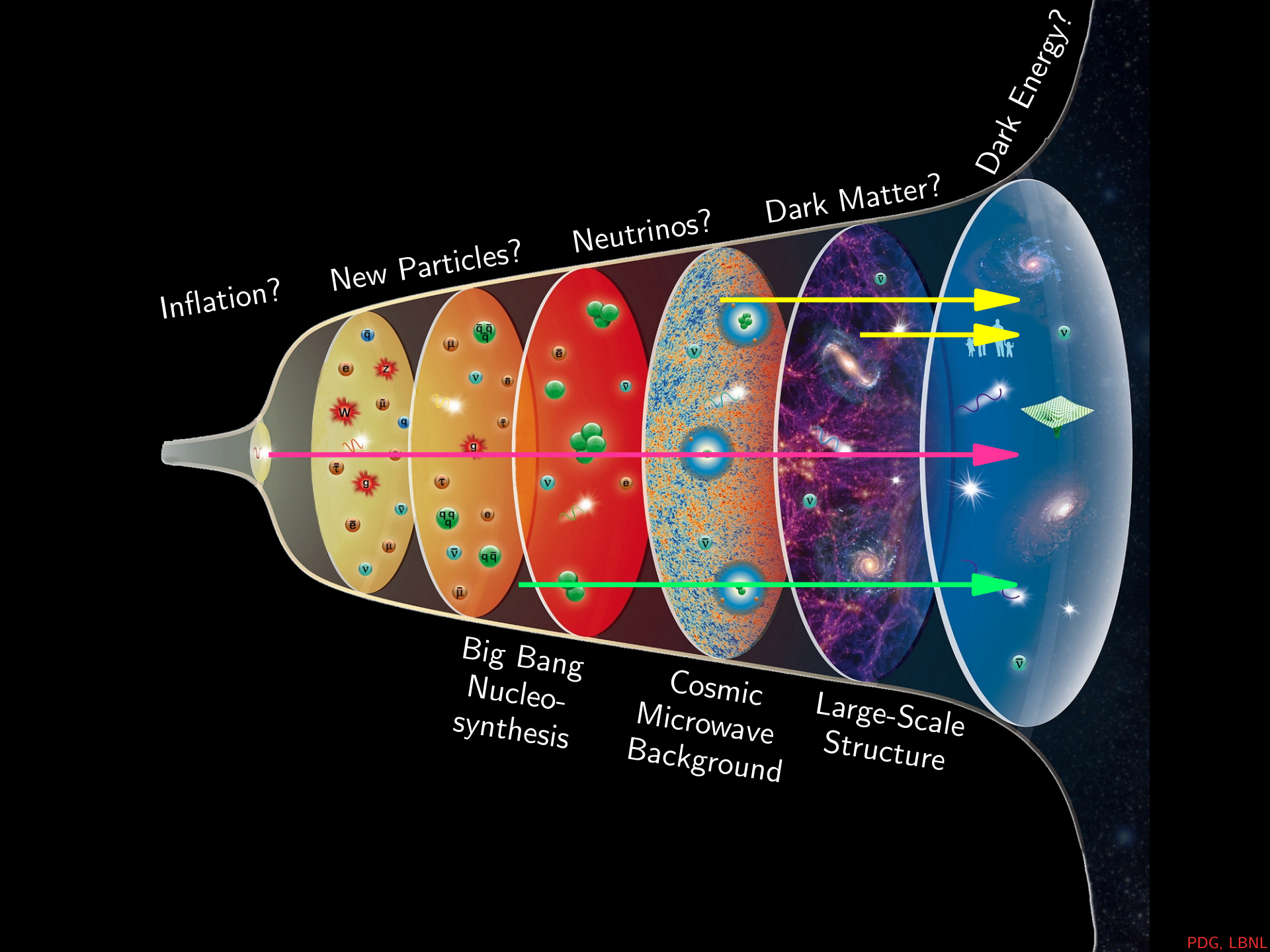
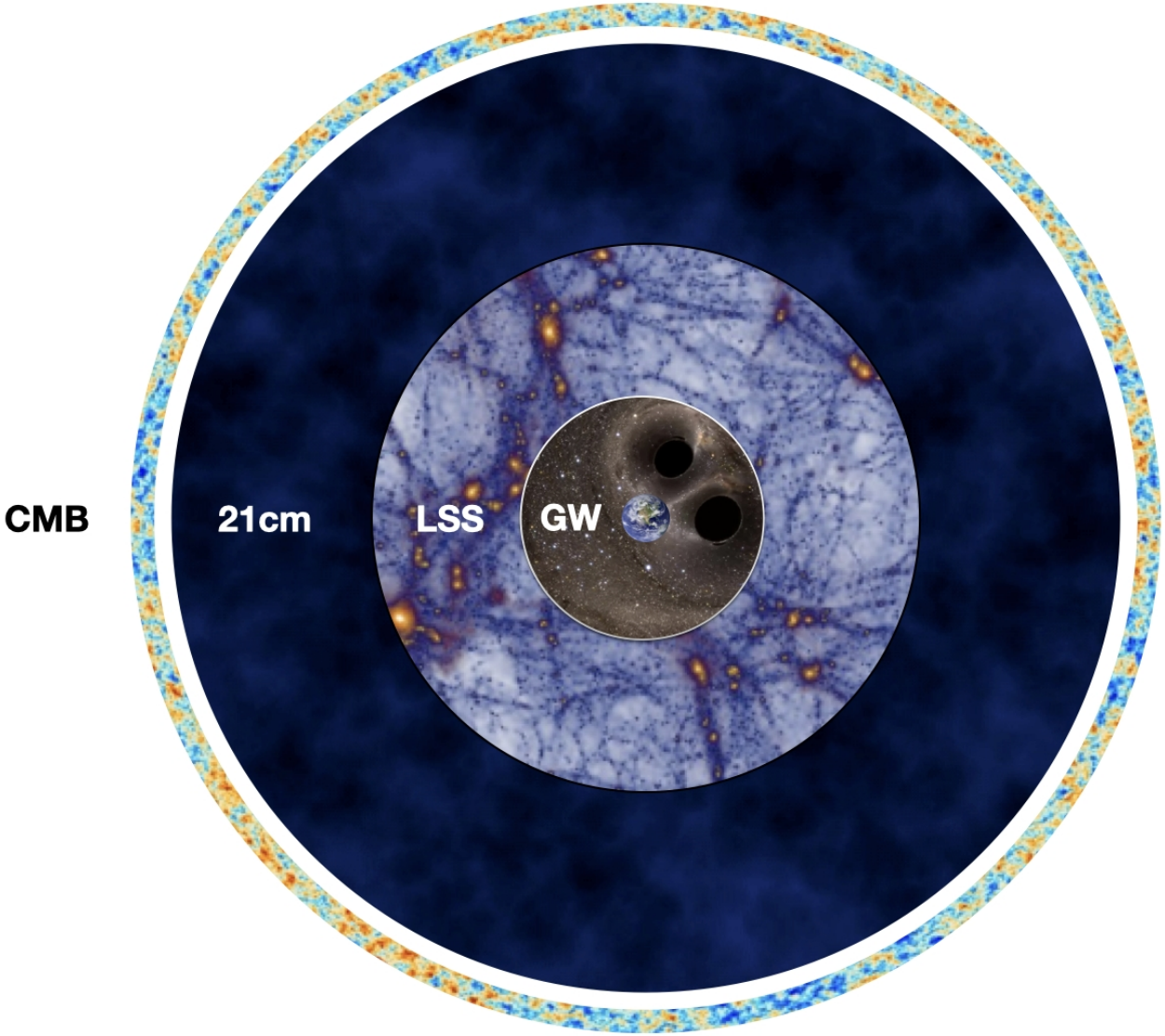

Big Bang
Nucleo-
synthesis
Cosmic
Microwave
Background
Large-Scale
Structure

PDG, LBNL


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

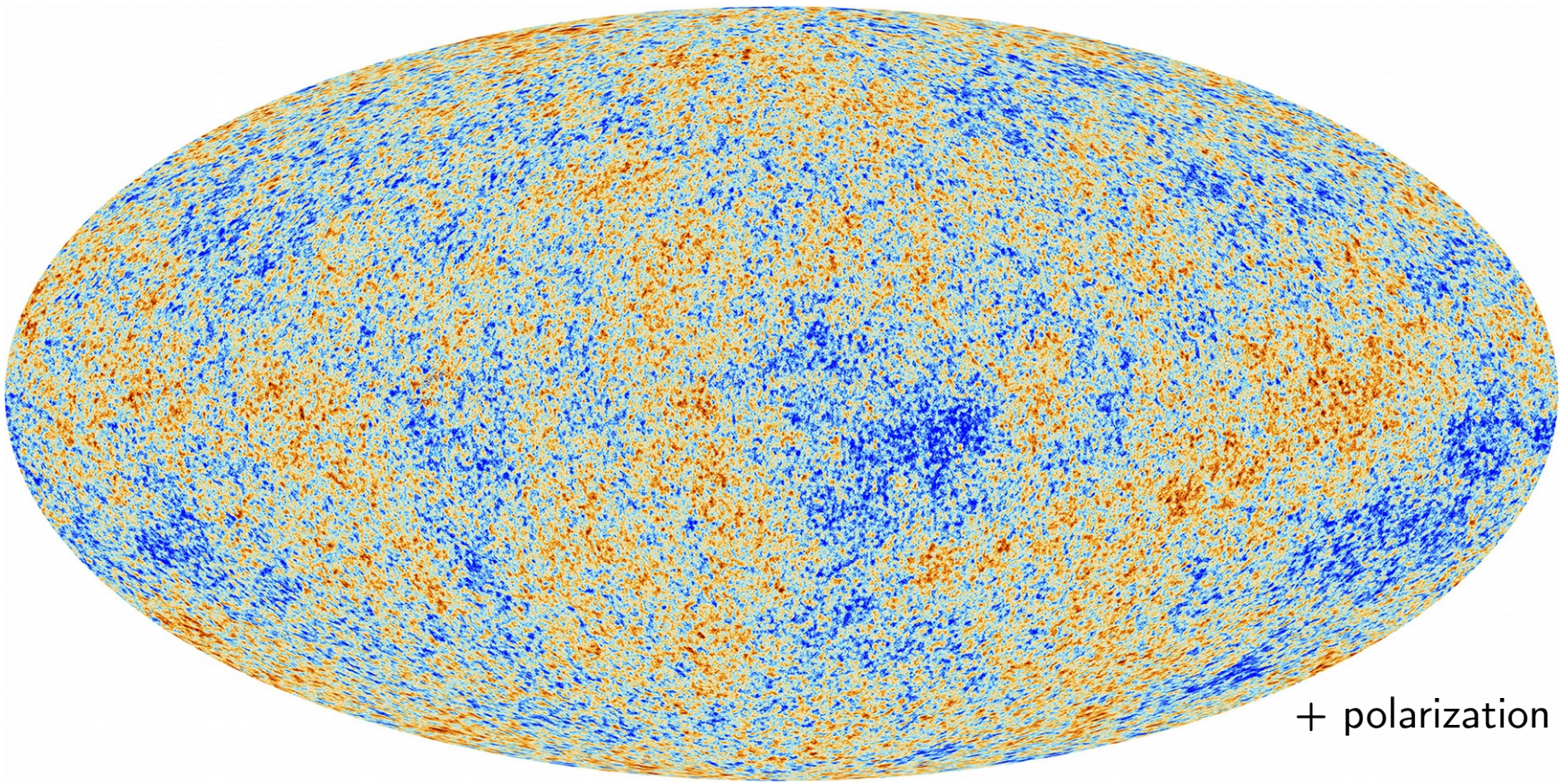
PDG, LBNL

Cosmological Observations



G. Pimentel

Cosmic Microwave Background (CMB)

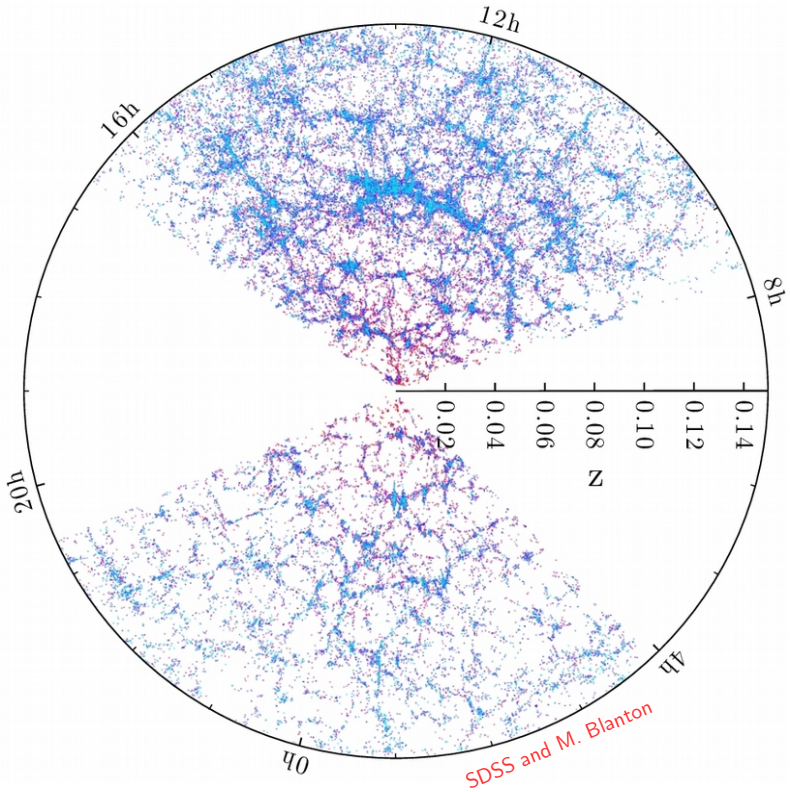


Cf. electron-positron collider.

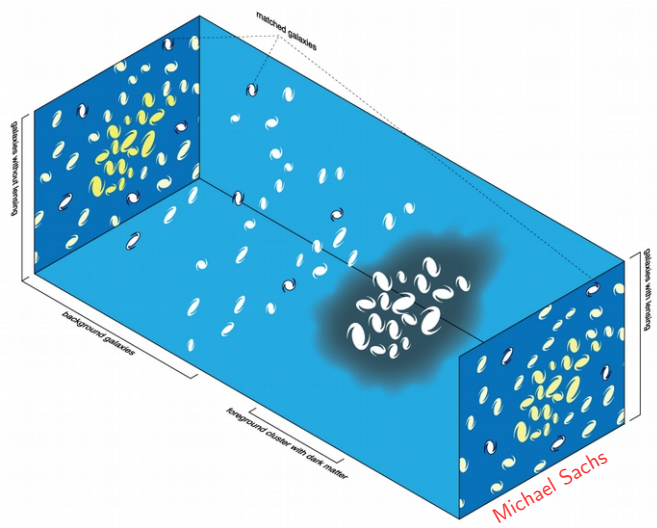
Planck (2018)

Large-Scale Structure (LSS)

Galaxy Clustering

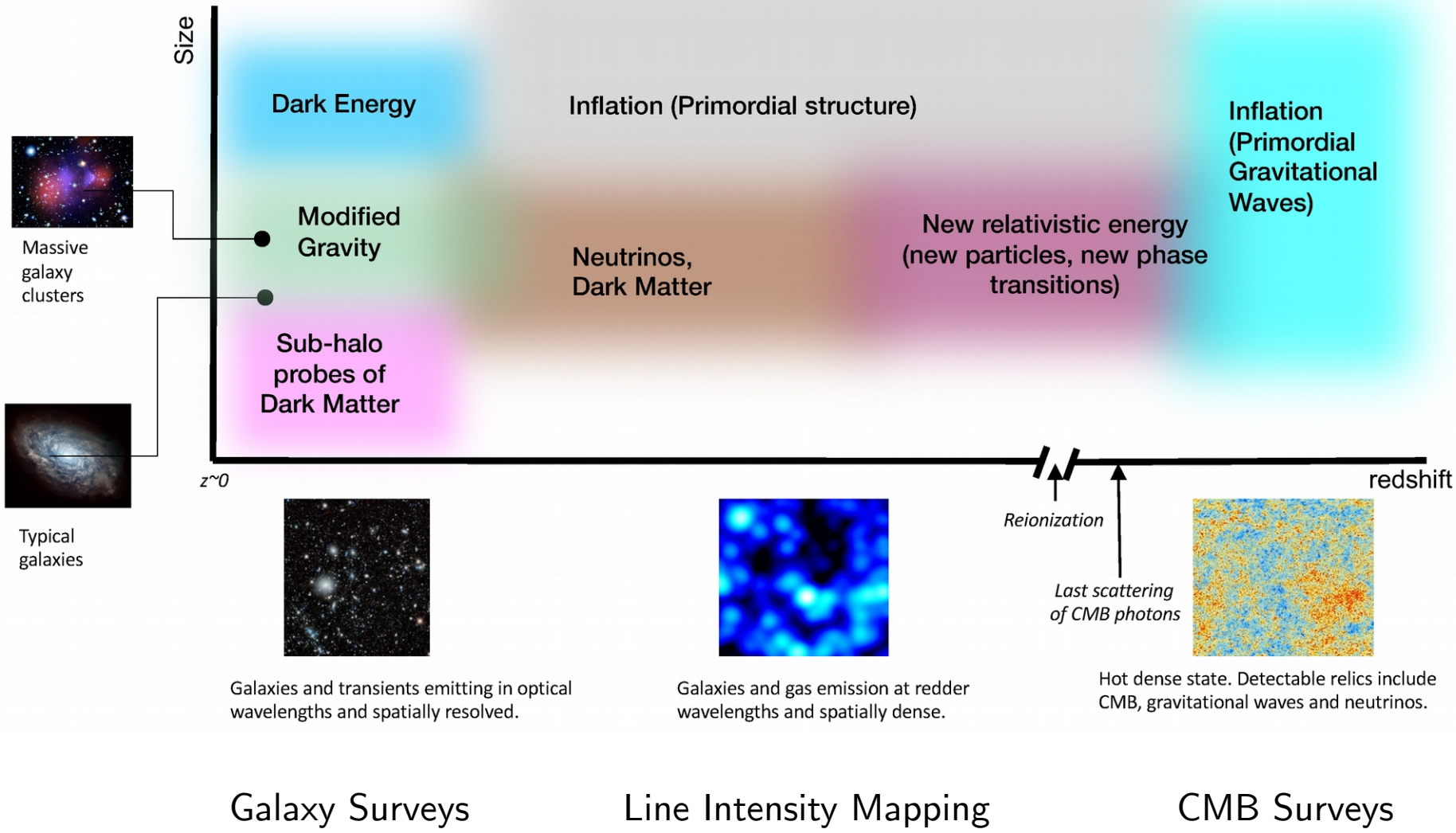


Weak Gravitational Lensing



+ CMB secondaries, Lyman-α forest, galaxy clusters, 21cm, ...

Cf. proton-proton collider.



Galaxy Surveys Line Intensity Mapping CMB Surveys

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

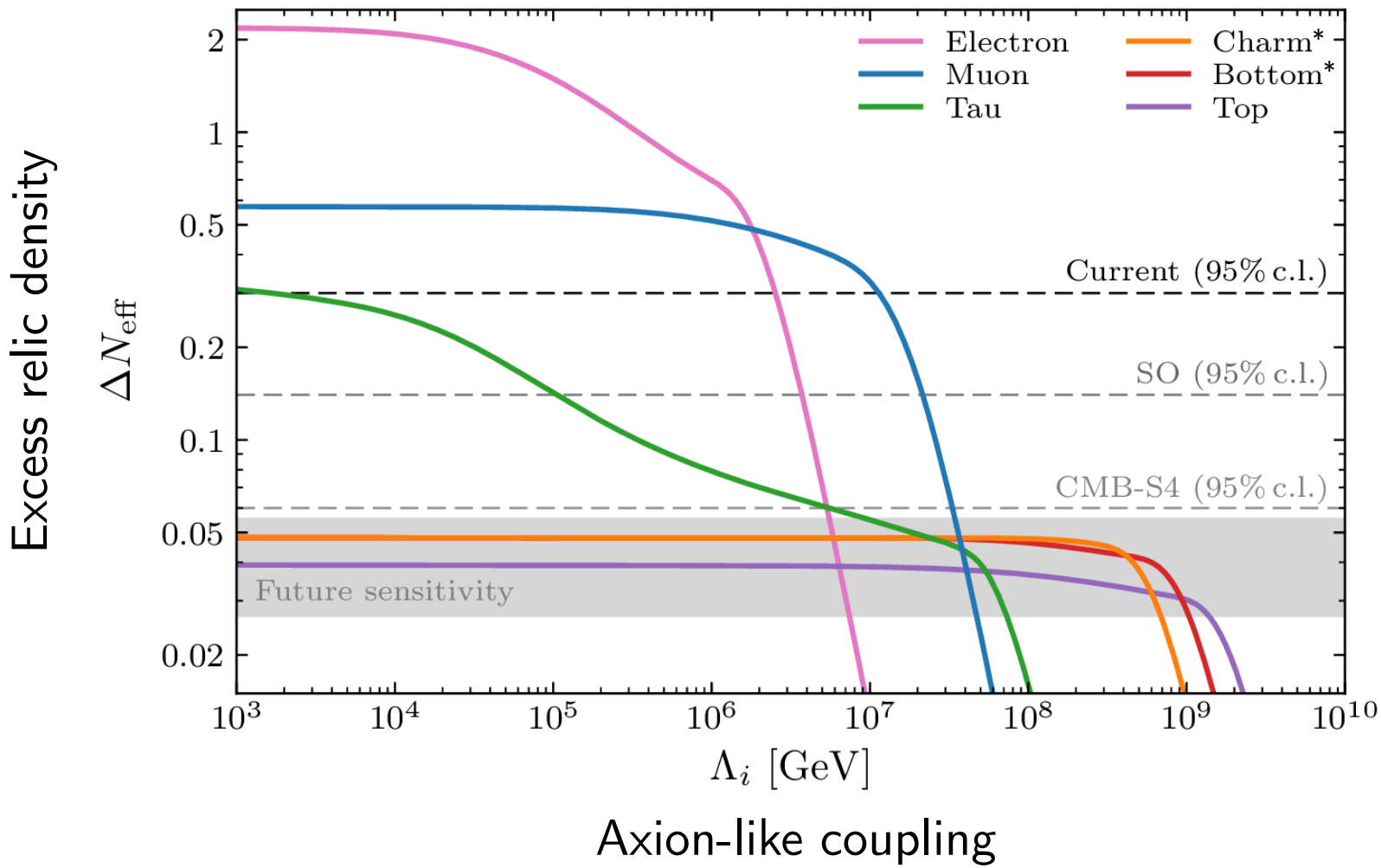
- 41% of the radiation density in the universe:
  - $\rightarrow$ Leave gravitational imprint,
  - $\rightarrow$ Can detect their energy density.
- In the Standard Model: free-streaming since $T \sim 1\,\mathrm{MeV}$.
- Free-streaming neutrinos overtake the photons and pull them ahead of the sound horizon.
- 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



* Calculations for charm and bottom couplings are impacted by the QCD phase transition. Here: conservative estimate, might be larger.

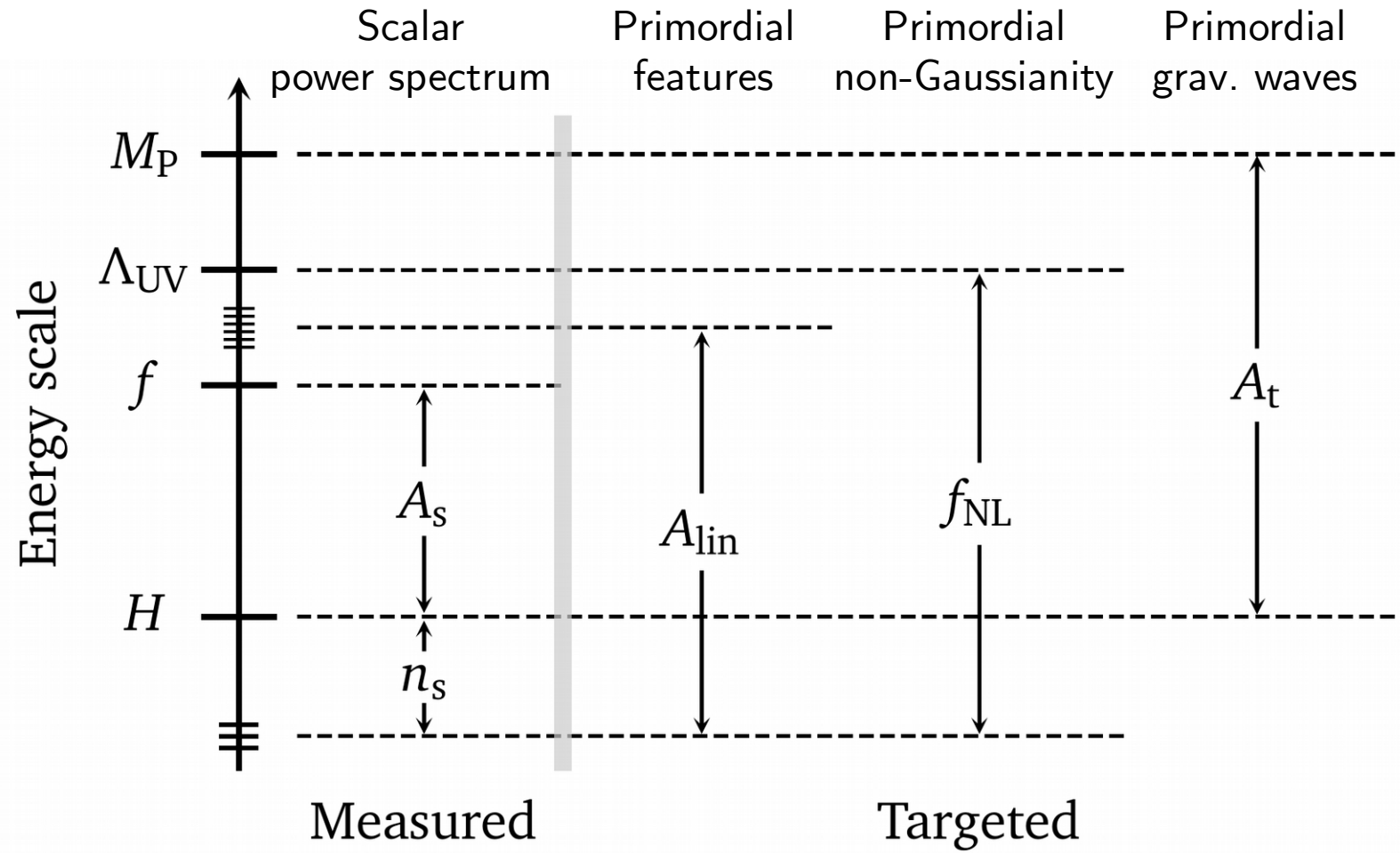
Cosmological Parameters from LSS

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

- Powerful description of structure formation into the mildly nonlinear regime.
  - $\rightarrow$ Remember: $N_{\mathrm{modes}} \sim V k_{\mathrm{max}}^3$
  - $\rightarrow$ Analyses can extract more information from same survey.

- Additional theoretical advances for computational tractability.
  - $\rightarrow$ Cosmological analyses of the full power spectrum (2019),
  - $\rightarrow$ Independent of the CMB.

Inflation and Fundamental Physics

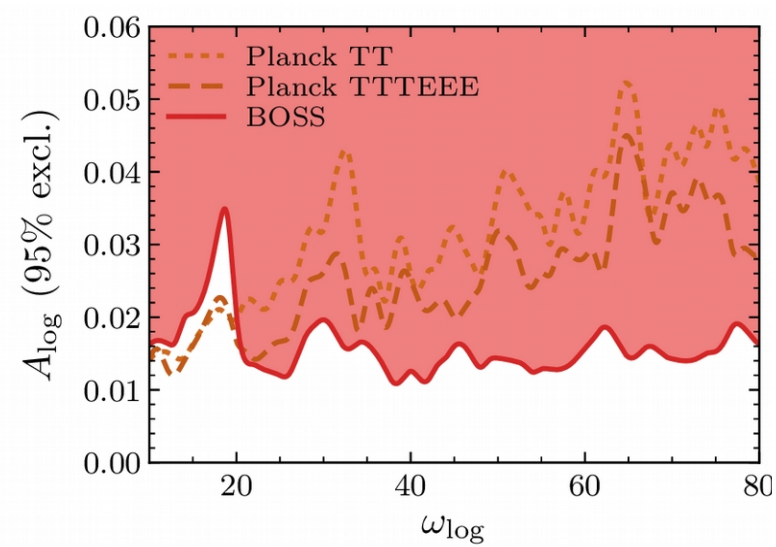


Primordial Features from LSS

- 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, ...

Conclusions

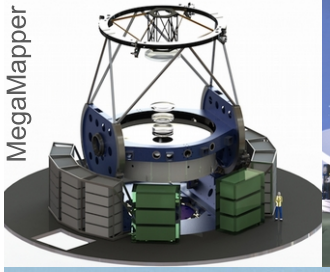
- Theory impacts observational cosmology in many ways:
  - Fundamental insights,
  - Motivating targets,
  - Understanding observables,
  - Crucial modeling,
  - Demonstrating analyses,
  - ...

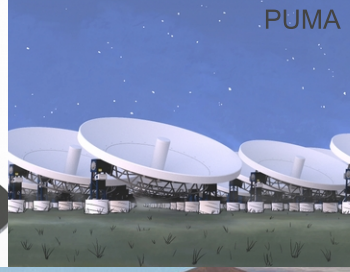
- Ongoing dialog between theory and observations is required to untangle the laws of physics of our universe.

$\rightarrow$ Let's map the universe and find out!

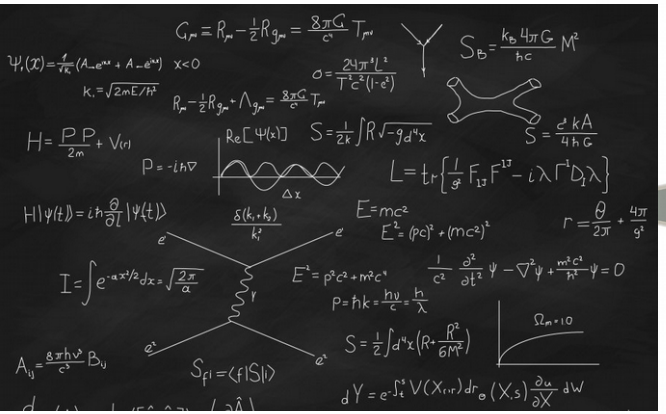
Thank you!

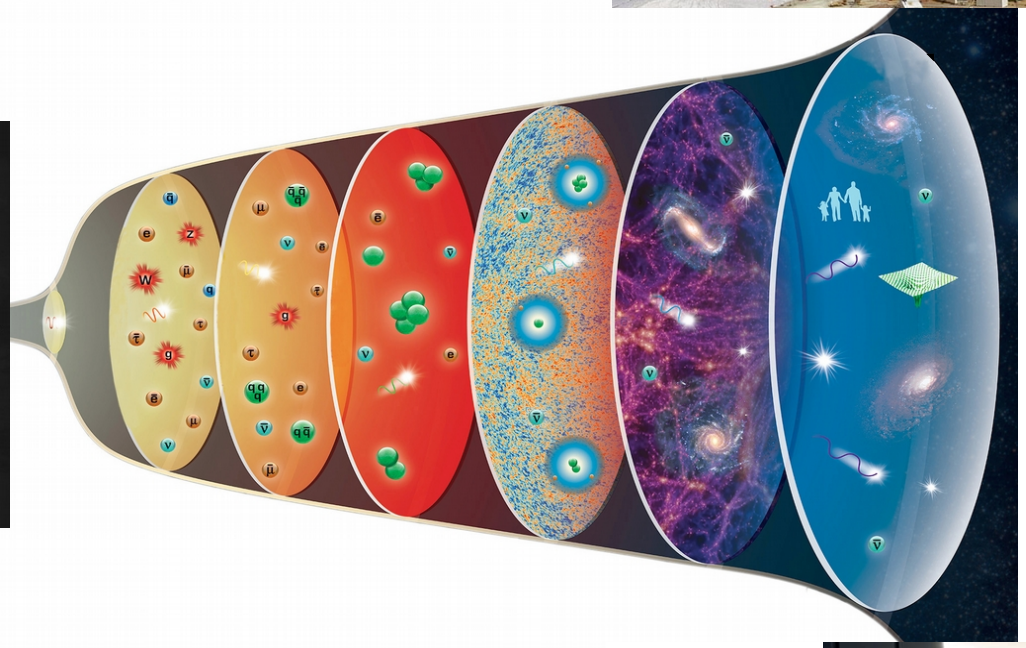
Observations



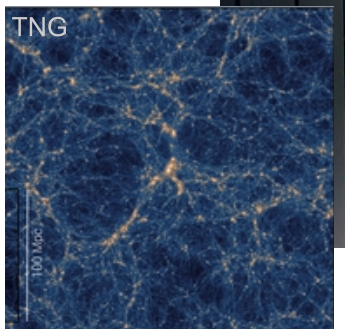


Theory





Simulations/Modeling/Analysis



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