Cosmic Probes of Fundamental Physics
Dark Energy and Cosmic Acceleration

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Snowmass Community Summer Meeting | Seattle | July 21, 2022

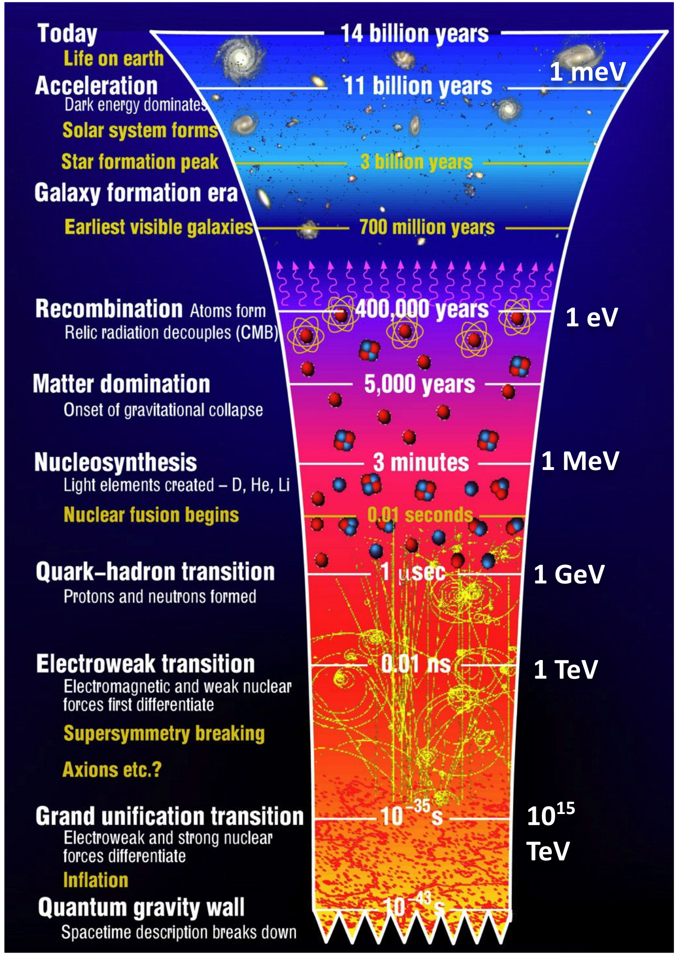
Background image: The Dark Energy Survey

Introduction

Particle physics aims to understand the fundamental constituents of matter and energy, revealing profound connections underlying everything we see, from the smallest to the largest structures in the Universe.

The cosmic frontier realizes this vision.

Dark energy and cosmic acceleration is a **discovery-driven, high-visibility, rigorous and bold** component of our program, which has matured and grown over the last two decades by both **leveraging and driving new developments across the entire community**.



High-impact science

HEP science drivers have been lines of inquiry recognized by multiple Nobel prizes.
Cosmic Frontier is key to four (out of five) of the 2014 P5 science drivers.

- **Dark Energy and Cosmic Acceleration** 2011, 2019
- **Dark Matter**
- Higgs 2013
- **Neutrinos** 2015
- **New Particles, Interactions and Principles**

New breakthroughs are within reach in the upcoming decade.

Our science also lends itself naturally to **powerful public engagement opportunities**.

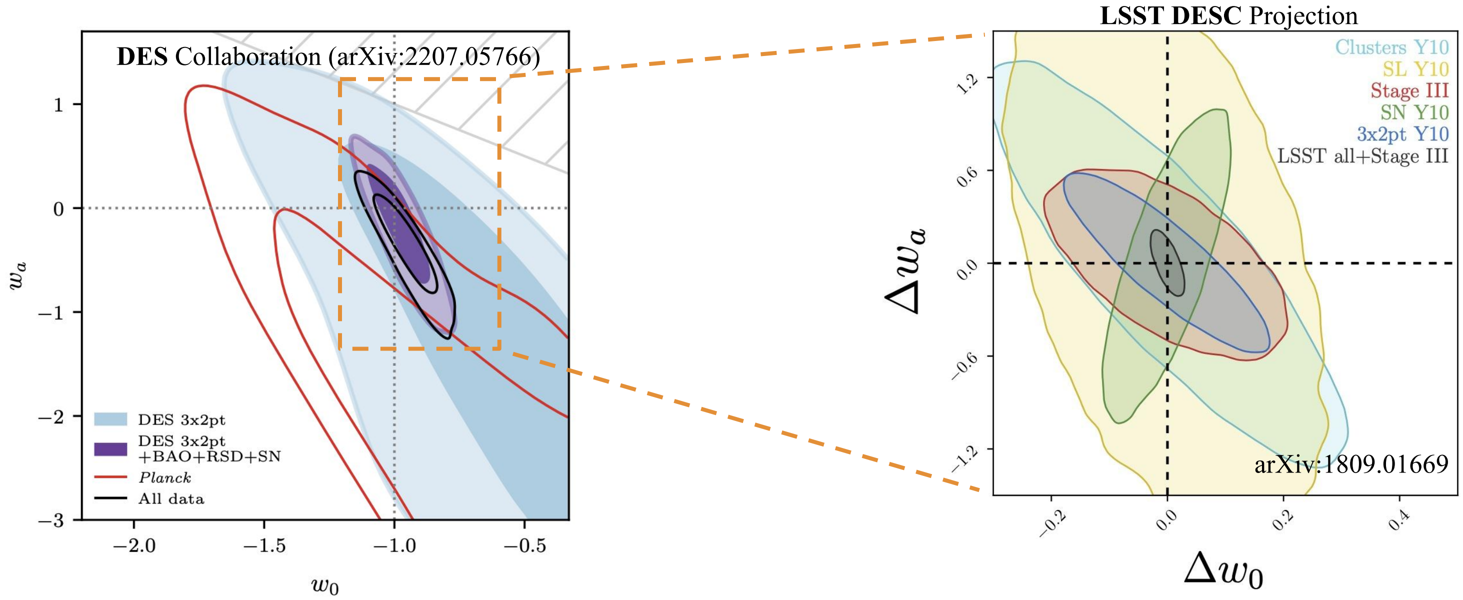
Fundamental questions

- **Is dark energy the cosmological constant?**
  - Or a new field?
  - Or the result of beyond General Relativity physics?
- **Did BSM degrees of freedom influence the thermal history of the universe?**
- **Is the inflation paradigm realized in nature?**
  - What is the energy scale of the inflaton field?
  - What are the dynamics of inflation?

Thanks to detector technology developments, new discovery windows have just opened up!

Precision cosmology

The discovery of **dark energy** led to a **precision measurement program** to understand its physics.



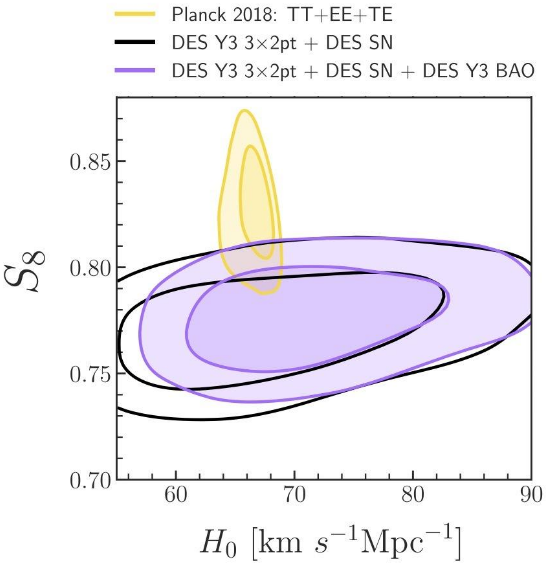
Precision cosmology

Tantalizing "anomalies" between early and late-universe probes of cosmology:

> **Overall, the universe seems to expand faster and be smoother than the cosmological constant prediction.** — Adam Riess, at the Snowmass Public Lecture, July 20.

We may be at the edge of a new discovery.

DES Collaboration, **PRD** 105, 043512 (2022)



Key observables

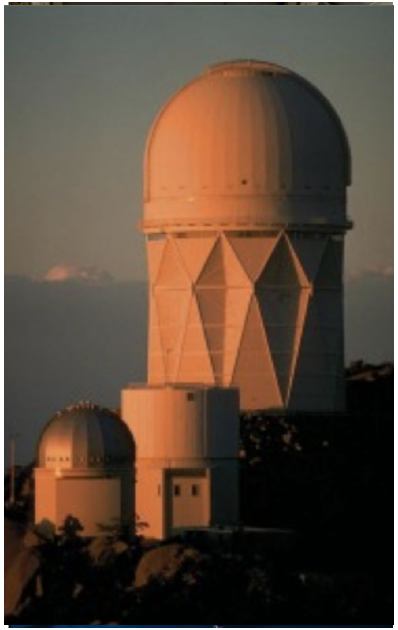
- Cosmic expansion history
- Cosmic microwave background
- Growth of structure
- Gravitational waves

Thanks to an integrated theory program that spans

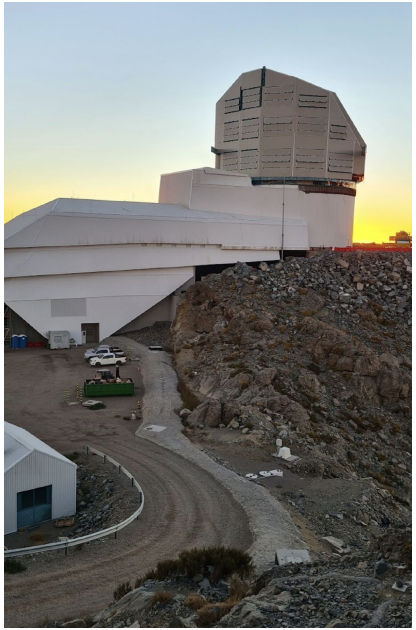
- New models
- New observables & algorithms
- Predictions & forecasting
- Simulations
- Pipeline development

the discovery potential of these key observables is fully realized.

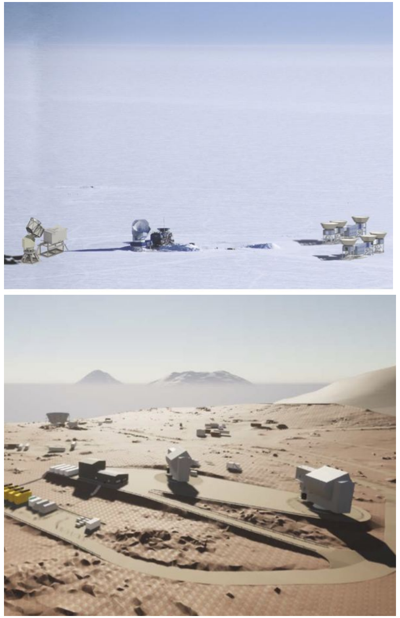
Key facilities



DESI



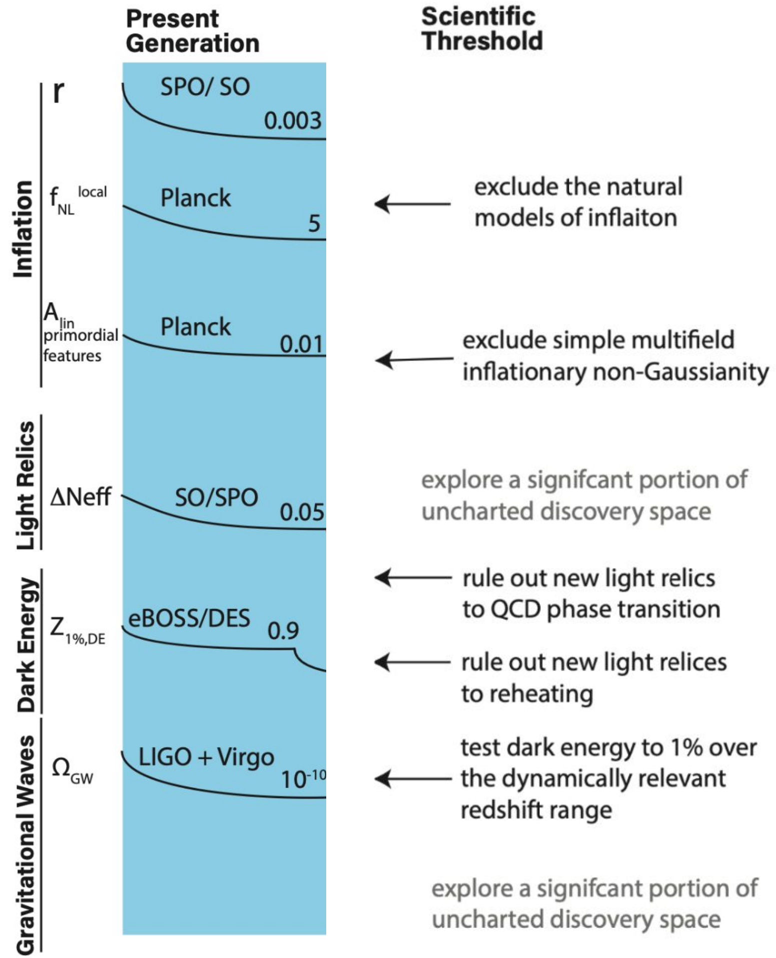
LSST



CMB-S4

GWO

The path to discovery



Present Generation
Scientific Threshold
Inflation
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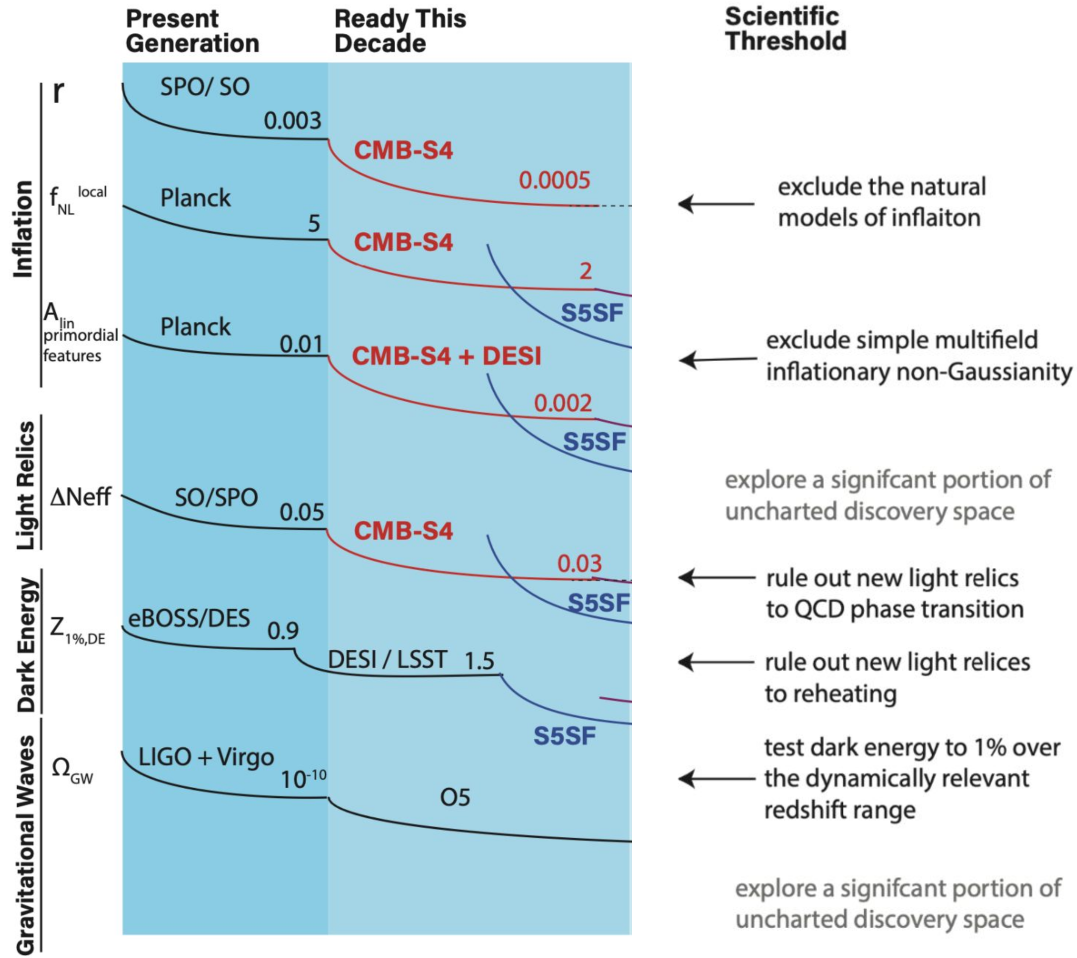
SPO/ SO
0.003
f_{NL}^{local}
Planck
5
exclude the natural models of inflaiton
A_{lin} primordial features
Planck
0.01
exclude simple multifield inflationary non-Gaussianity
Light Relics
ΔNeff
SO/SPO
0.05
explore a signifcant portion of uncharted discovery space
rule out new light relics to QCD phase transition
Dark Energy
$Z_{1\%,DE}$
eBOSS/DES
0.9
rule out new light relices to reheating
Gravitational Waves
Ω_{GW}
LIGO + Virgo
10^{-10}
test dark energy to 1% over the dynamically relevant redshift range
explore a signifcant portion of uncharted discovery space



Present Generation
Ready This Decade
Scientific Threshold
Inflation
Light Relics
Dark Energy
Gravitational Waves
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S5SF
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CMB-S4 + DESI
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S5SF
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DESI / LSST
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rule out new light relices to reheating
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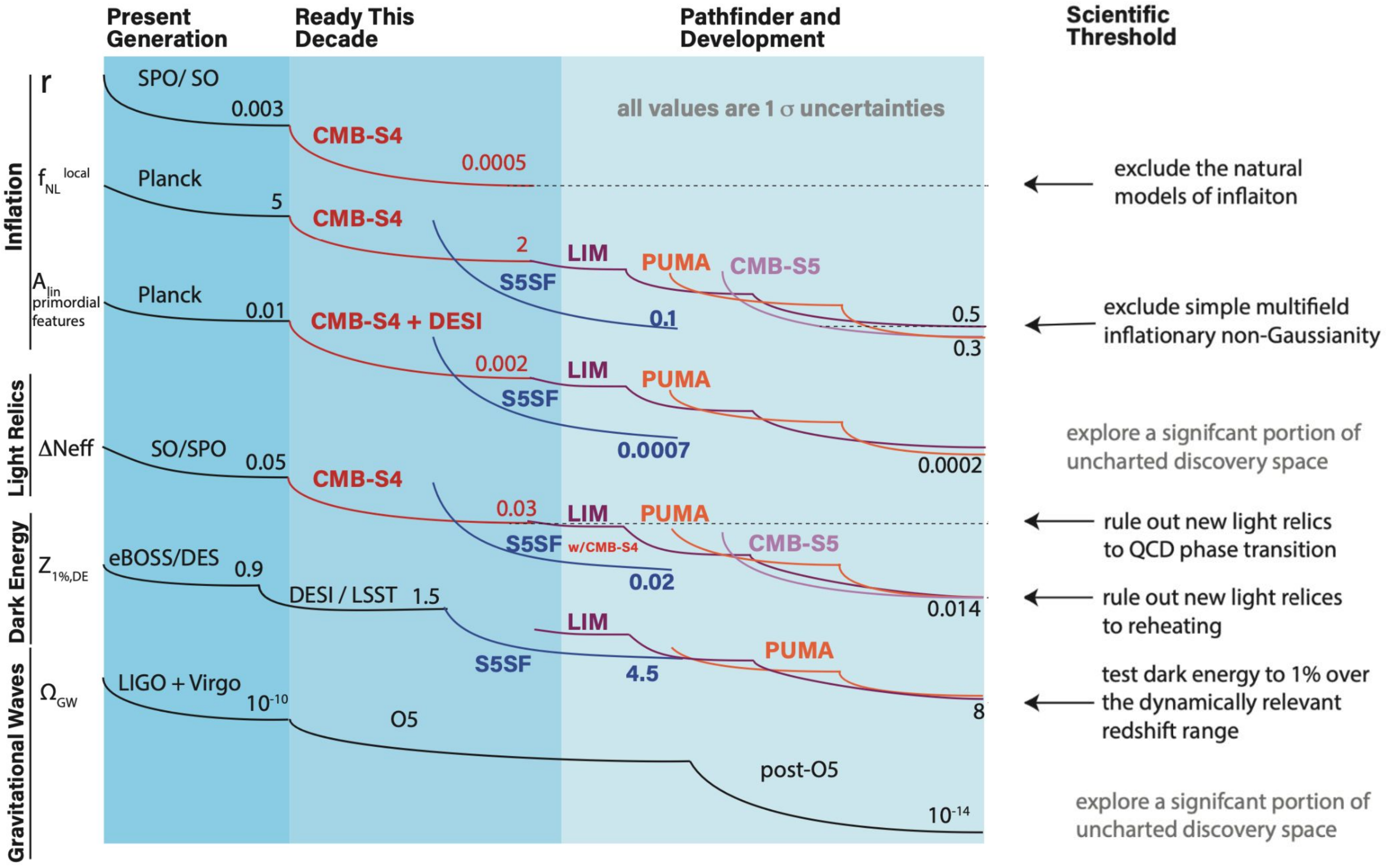
test dark energy to 1% over the dynamically relevant redshift range
Ω_{GW}
LIGO + Virgo
10^{-10}
O5
explore a signifcant portion of uncharted discovery space


Present Generation
Ready This Decade
Pathfinder and Development
Scientific Threshold
all values are 1 σ uncertainties
Inflation
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SPO/ SO
0.003
CMB-S4
0.0005
exclude the natural models of inflaiton
f NL local
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PUMA
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S5SF
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0.3
exclude simple multifield inflationary non-Gaussianity
A lin primordial features
Planck
0.01
CMB-S4 + DESI
0.002
LIM
PUMA
S5SF
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0.0002
explore a signifcant portion of uncharted discovery space
Light Relics
ΔNeff
SO/SPO
0.05
CMB-S4
0.03
LIM
PUMA
CMB-S5
S5SF w/CMB-S4
0.02
0.014
rule out new light relics to QCD phase transition
rule out new light relices to reheating
Dark Energy
Z 1%,DE
eBOSS/DES
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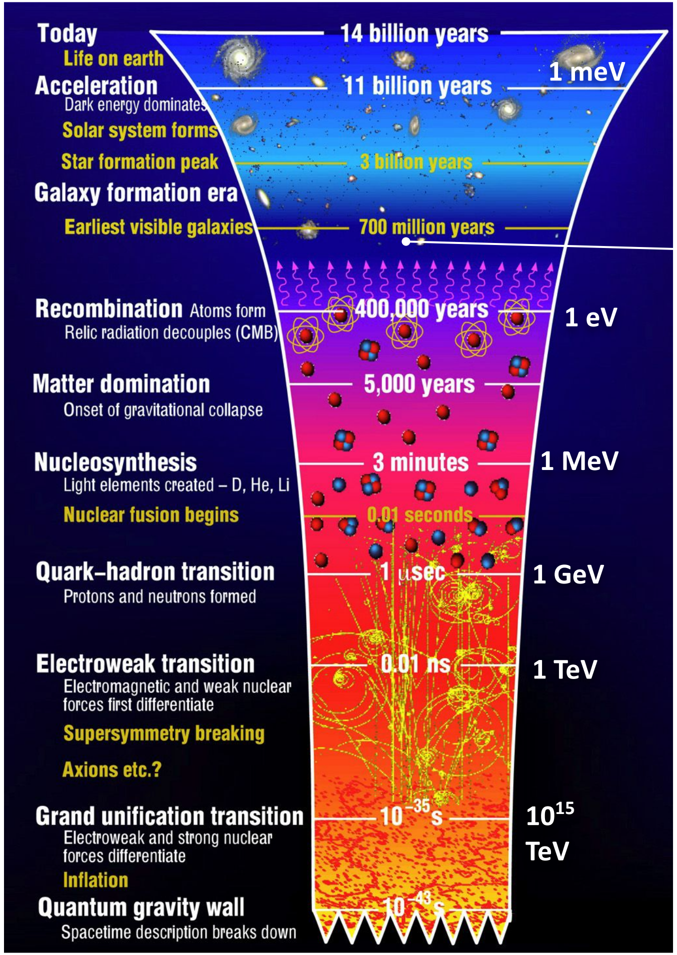
DESI / LSST
1.5
LIM
S5SF
PUMA
4.5
8
test dark energy to 1% over the dynamically relevant redshift range
Gravitational Waves
Ω GW
LIGO + Virgo
10-10
O5
post-O5
10-14
explore a signifcant portion of uncharted discovery space

Community consensus

In the dark energy and cosmic acceleration community, we are pursuing the vision outlined in the last P5 while fully engaged in a new vision for this upcoming decade and beyond.

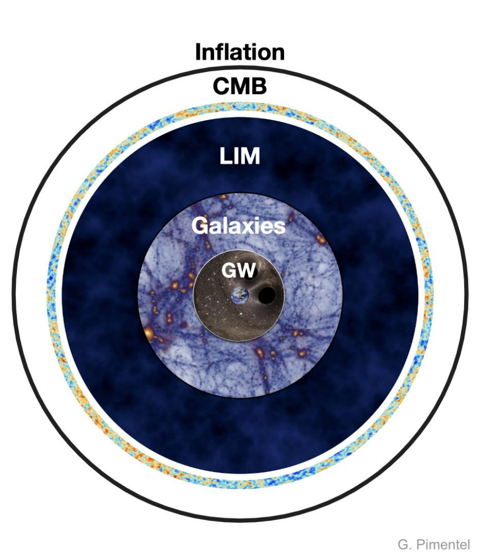
Specific areas with strong community consensus:

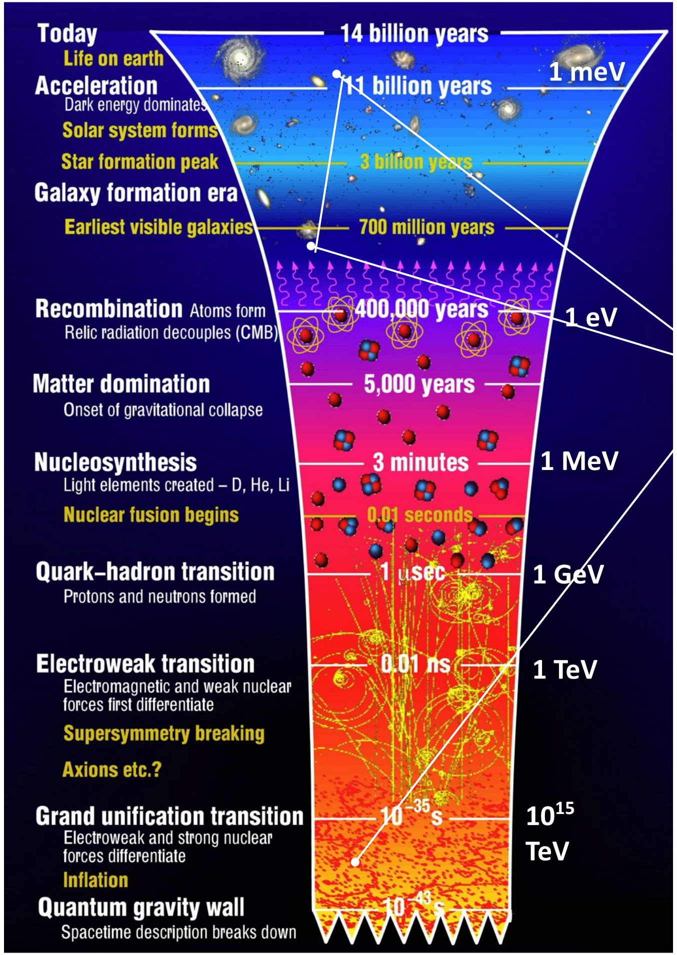
- Carry out cross-survey science and leverage DESI, LSST
- Completion of CMB-S4
- Roadmap to Stage 5 spectroscopy project
- Pathfinders for new opportunities: GW and 21cm/LIM



Line Intensity Mapping: an emerging technique

- Key observable: structure growth/clustering
  - **21cm** - CII line
  - **LIM** - CO line
- Connect early and late-Universe with a single probe

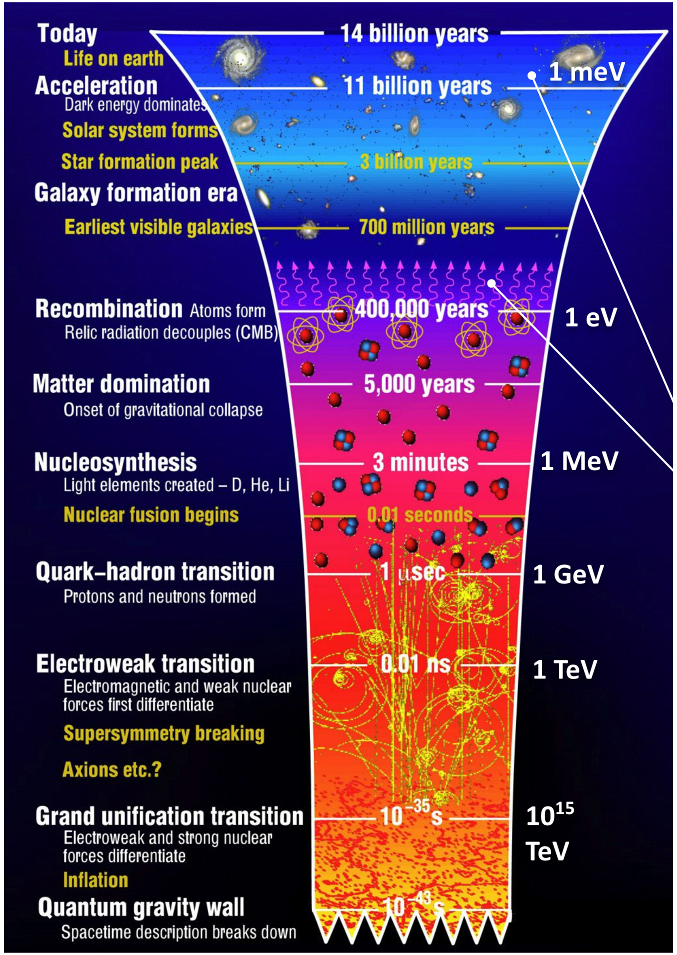




Role of gravitational waves (a 20 year vision)

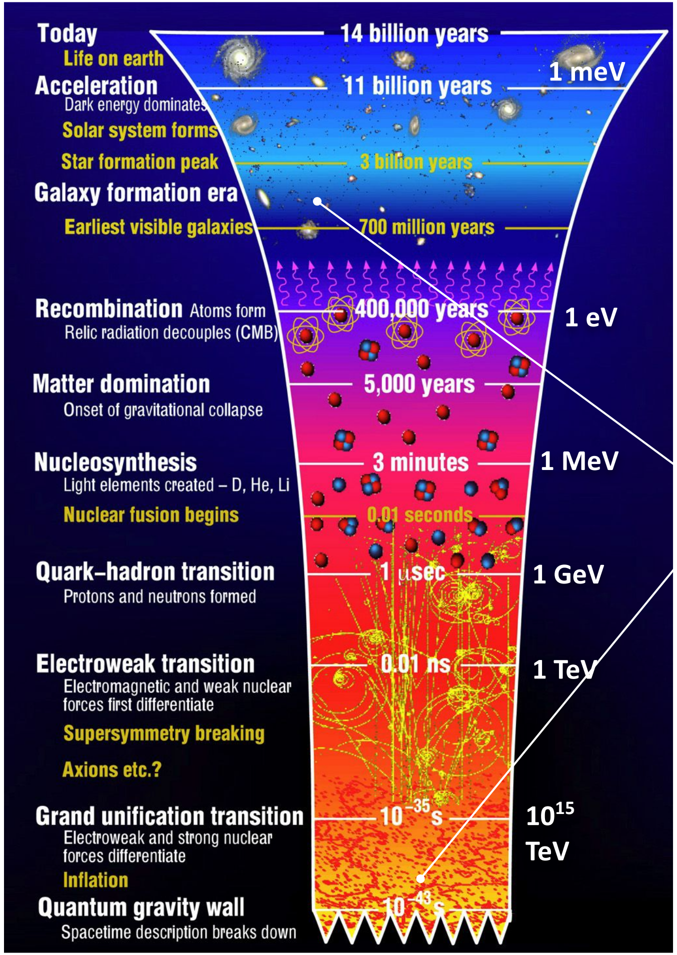
- **Standard sirens all the way up to z=10**
  - First probe of dark energy across the regime where it begins to dominate.
- **Sensitive to primordial gravitational waves direct detection**
  - Sensitivity at a different frequency than CMB-S4
  - Possilbe detection of the spectrum primordial GWs
- **First opportunity to bridge the gap between early and late time with a single facility!**

In order to fully realize the potential of this new opportunity, we need to start preparing now (identifying targeted R&D and community-building activities throughout this decade, so we can consider the possibility of such a big investment at Snowmass 2032.



Elements of the dark energy science program

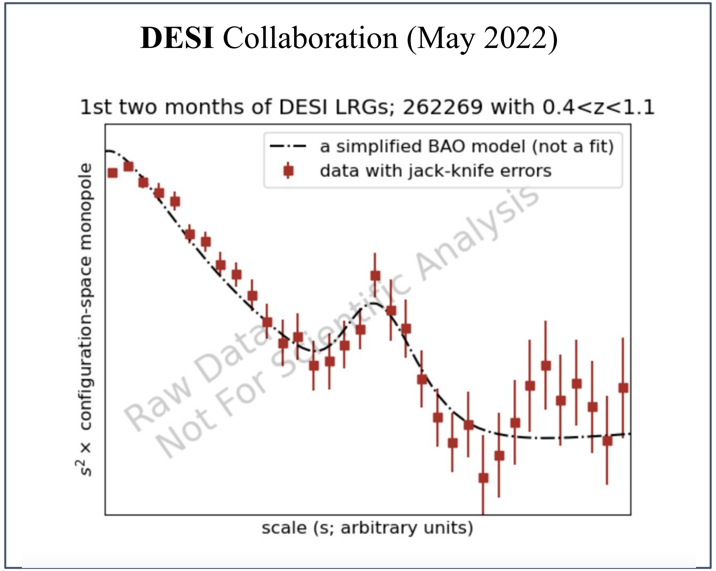
- **Key observables:** expansion history, structure growth/clustering
- **Parameters to measure, e.g.:**
  - Equation of state, $w = w_0 + w_a\, z/(1+z) + \ldots$
  - Amplitude of clustering of galaxies, S_8
  - Rate of expansion today, H_0
  - Energy density today, Ω_m
- **Test for consistency:**
  - Many classes of dark energy models can be ruled out because perturbations will grow differently.
  - Early universe analysis, under the assumption of the same dark energy model, should yield consistent results with modern universe analyses.
- **Data vector examples:**
  - Galaxies (flux, shapes, redshifts)
  - Supernovae (flux, redshifts)
  - Merging neutron stars/black holes (GW chirp, redshifts)
  - CMB (T power spectrum, SZ signal for galaxy clusters)

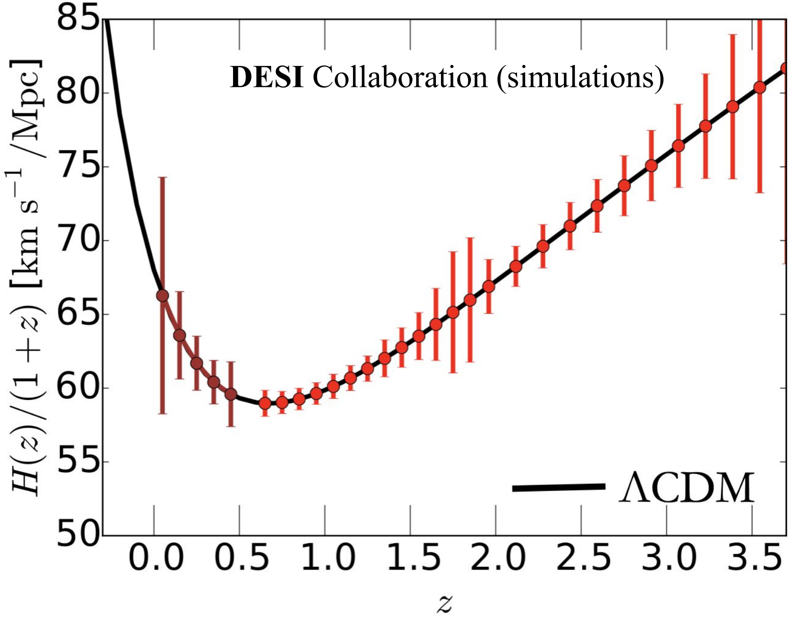


Elements of the inflation search program

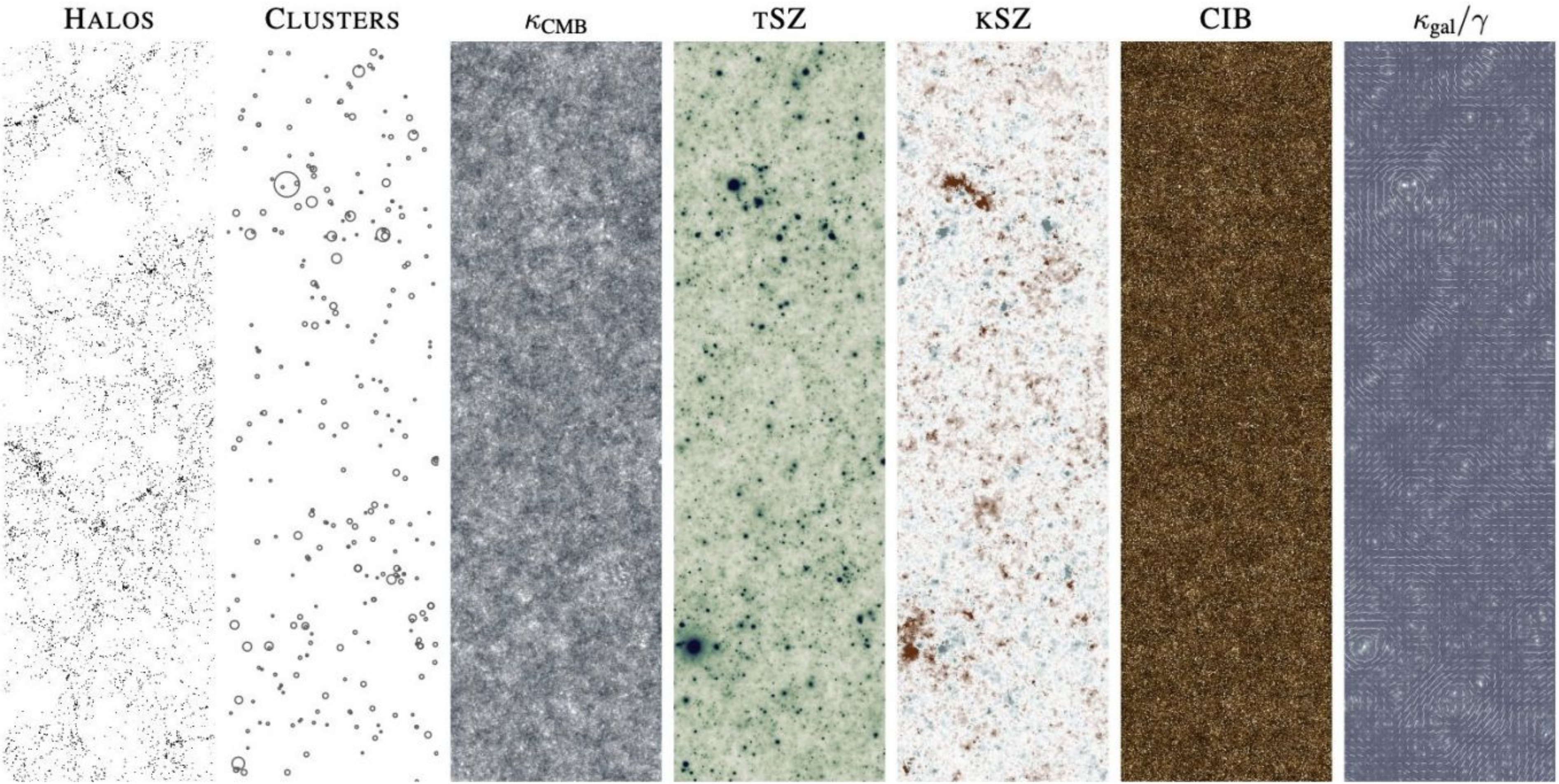
- **Key observables:** CMB, structure growth/clustering
- **Discovery channels:**
  - CMB B-mode polarization power spectrum
  - Bispectrum (3pt function)
- **Parameters to be measured:**
  - Energy scale of inflation, r
  - non-Gaussianity parameter, f_{NL} (dynamics)
- **Data vector examples:**
  - Galaxies (redshifts)
  - CMB (B-modes)
- **Need to combine datasets:**
  - DESI
  - LSST
  - CMB-S4
  - GW

DESI science



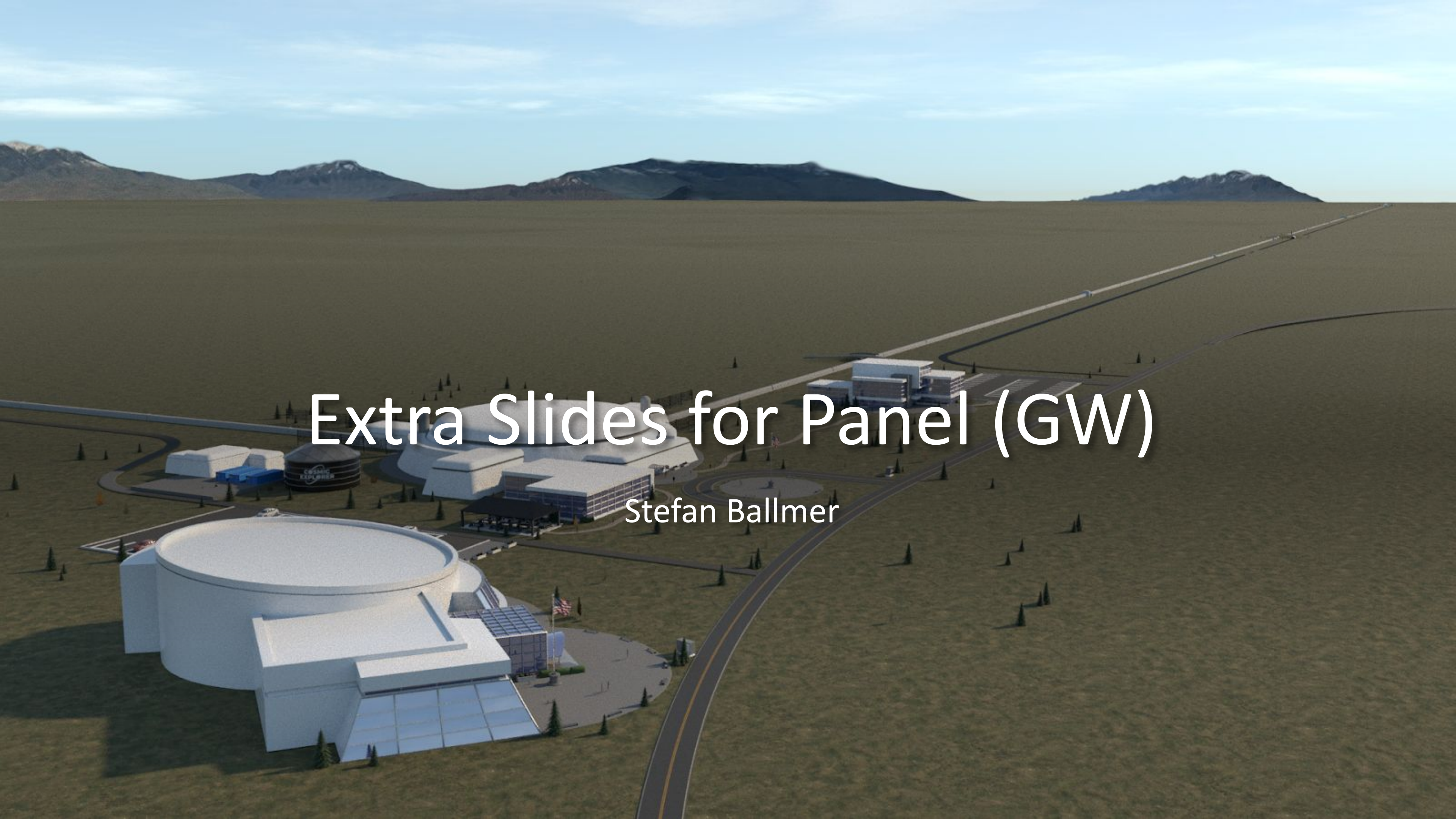



DECam Logbook
dbweb3.fnal.gov:8080/ECL/decam/E/index
the Astro2020 Program:
Pathways From Foundations to Frontiers
Explore the Cosmos
Worlds and Suns in Context
New Messengers and New Physics
Cosmic Ecosystems
Pathways to Habitable Worlds
New Windows on the Dynamic Universe
Unveiling the Drivers of Galaxy Growth
Forge the Frontiers
Enable U.S. community participation in ELT program
Develop and Implement Cosmic microwave Background S4 (joint DOE)
Begin ngVLA design, technical demonstration, construction
Upgrade IceCube to Gen2 (NSF/PHY)
Begin implementation of an Infrared/Optical/Ultraviolet large strategic mission for exoplanet exploration and general astrophysics after a successful maturation program
Enable Future Visions
Develop technology for future gravitational wave upgrades and observatories (NSF/PHY)
Commence Great Observatories Missions and Technology Maturation Program
First entrant: IR/O/UV missions
Second entrants: Far-IR and X-ray missions
Sustain and Balance the Science
Augment mid-scale programs, add strategic competitions
Implement time domain & multi-messenger program
Compete probe missions in strategic areas of Far-IR and X-ray Astrophysics
Build the Foundations
Expand grants to bring science and ideas to fruition
Develop and diversify the scientific workforce
Support data archives and curation
Bolster theory underpinnings
Advance crucial laboratory measurements
Expand support for early-stage and basic technology development
Promote scientific literacy and engage the public
Guiding Principles
Balance the portfolio
Broaden and optimize the science
Advance diversity and equity
Nurture sustainability
Ground-Based
Space-Based


HALOS
CLUSTERS
κ_{CMB}
tSZ
kSZ
CIB
κ_{gal}/γ

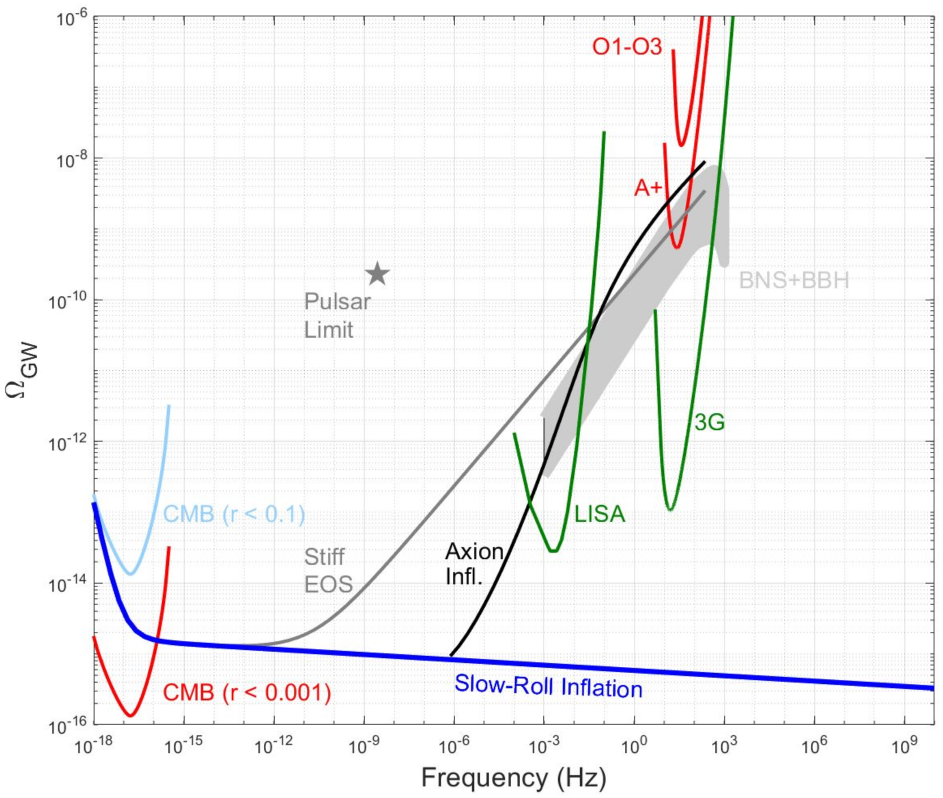
Extra Slides for Panel (GW)

Stefan Ballmer



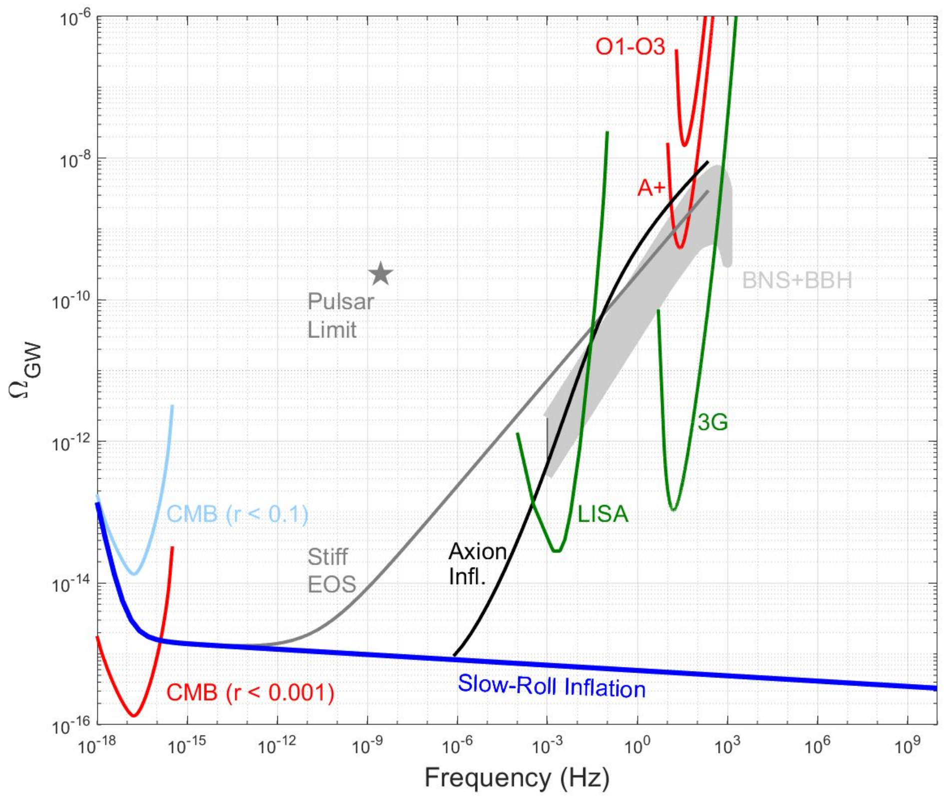
Primordial GW

- BNS+BBH foreground is **not** limiting observations
  - O(1e6) chirps per year (~every 30sec), well separated in frequency
  - Subtraction and “notching” techniques exist



Primordial GW

- **Complementary** to CMB GW signature
  - At the other end of the spectrum
- Vanilla Slow-Roll inflation produces lowest GW signature
  - Any other physics only **increases** signature
  - (TDE level is 1e-6)

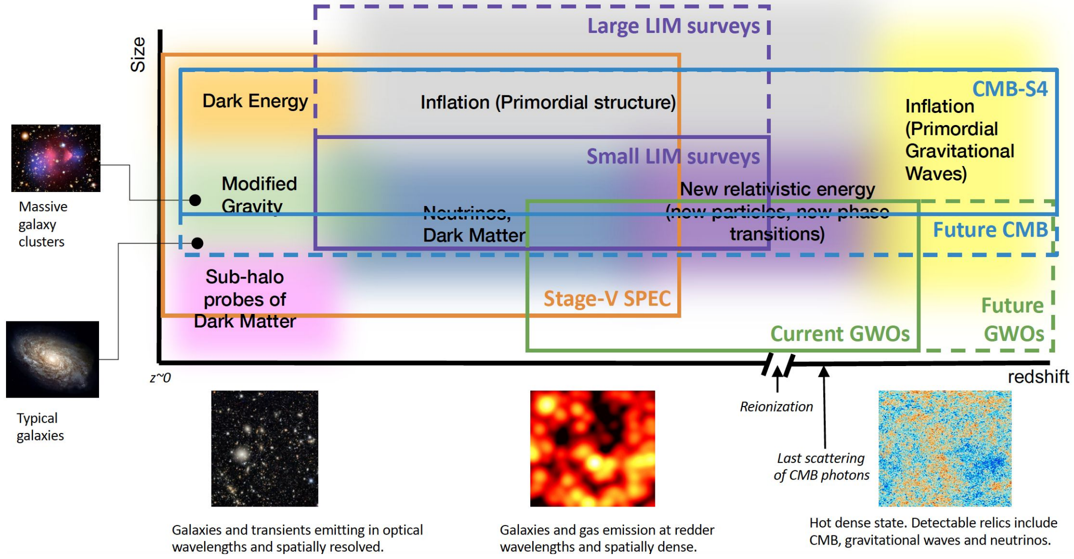


Primordial GW

Other early-universe GW fingerprints:

- Primordial BH
- DM signatures

- Terrestrial GWO can provide access to the smallest individual objects out to redshifts of z=O(10)



The Next-Generation: Cosmic Explorer

- Needed for the realization of Next Generation GWO:

  Take mature technology and
  apply it at large scale,
  to pursue otherwise inaccessible science

- This is what DOE labs do best!

Cosmic Explorer R&D

- Large-scale Vacuum System
  - Collaboration between High-Energy Particle and GW Community already exists in Europe (CERN - Einstein Telescope)

- Quantum Squeezing (application)
  - Large technology overlap with existing detector research at DOE labs

- Large Suspensions and Seismic Isolation Systems
- Large Optics manufacturing
- Coatings
- Experience operating large facilities (land questions, etc)

Cosmic Explorer R&D

- Technical expertise required for GWO very similar to the needs for EP detectors and accelerators
    - To this point: The GW community profited immensely from an influx of HEP expertise in the 90's…