ALL CF WORKSHOP

CF5. DARK ENERGY AND COSMIC ACCELERATION: COSMIC DAWN AND BEFORE

Snowmass 2021

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April 5, 2022

UPCOMING WORKSHOPS

- This is only an overview of major drivers and general themes
- Three upcoming workshops
  - CF5 Projects:
    - April 13, 9-10:00am Central
    - https://indico.fnal.gov/event/54021/
  - CF5 Theory:
    - April 14, 3-5:00pm Central
    - https://indico.fnal.gov/event/54010/
  - CF5 Technology R&D:
    - May 6, 2-4:30pm Central
    - https://indico.fnal.gov/event/54015/

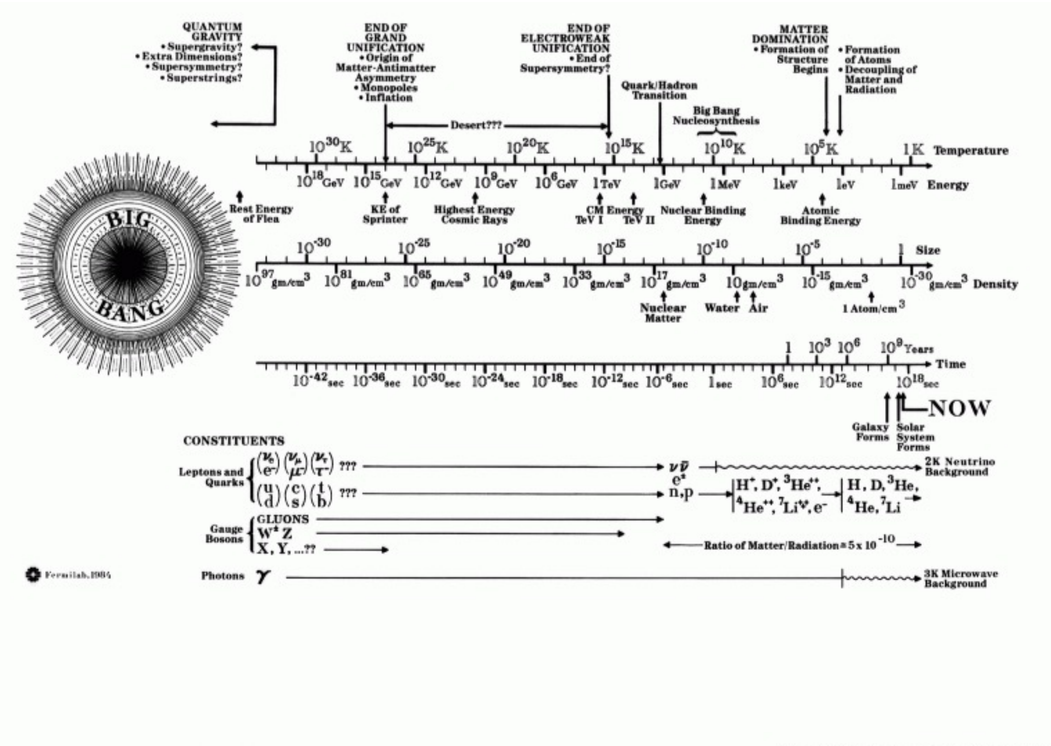
CF5. DARK ENERGY AND COSMIC ACCELERATION

Cosmic Dawn and Before

- This group covers cosmic probes of cosmology in the early Universe from Inflation Era through the Cosmic Dawn.
- Subtopics include:
  - growth of structure probes (e.g. 21cm power spectrum in the dark ages),
  - probes of expansion history (e.g. BAO with black hole mergers, CMB),
  - primordial non-gaussianity and inflation.
- Experiments include:
  - High-z gravitational wave observatories
  - 21cm
  - CMB

WHY STUDY THE EARLY UNIVERSE?

Hot Big bang -> unique access to fundamental physics

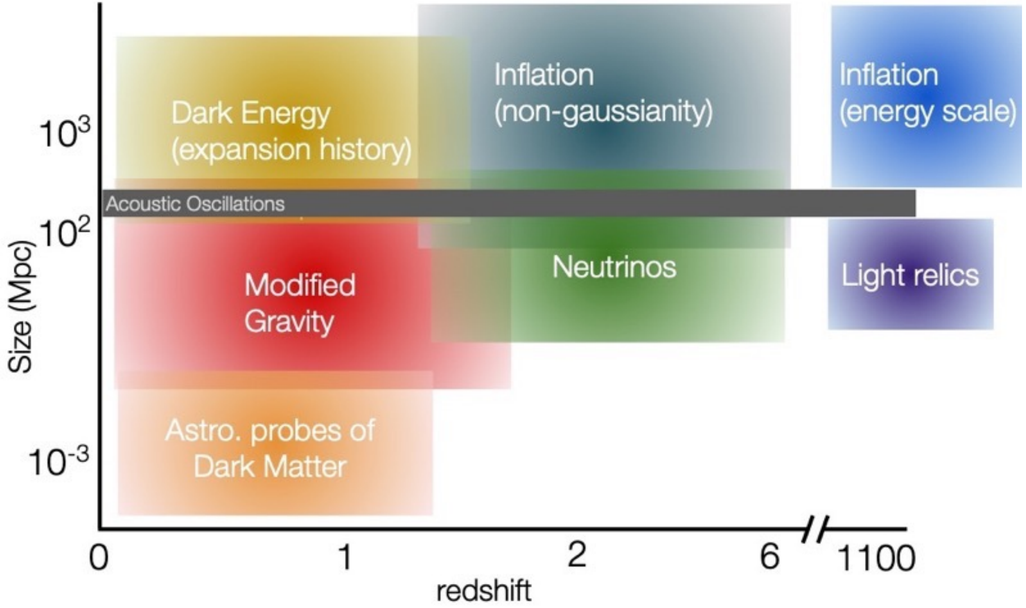


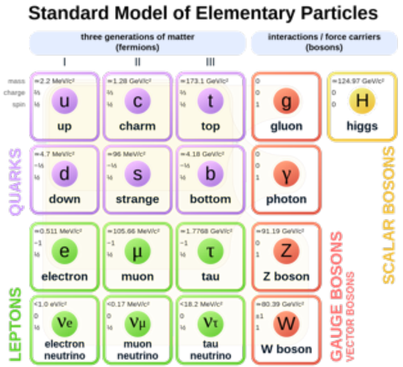
Fermilab Photograph 85-138CN

- The early universe is a high energy universe.
- Our understanding of high energy physics is also the story of our cosmic origin

COSMOLOGICAL SURVEYS

Measure the distribution and evolution of our universe





- “Baryons/astrophysics” are the tracer
- Initial/early conditions
- Dark Matter
- Dark Energy

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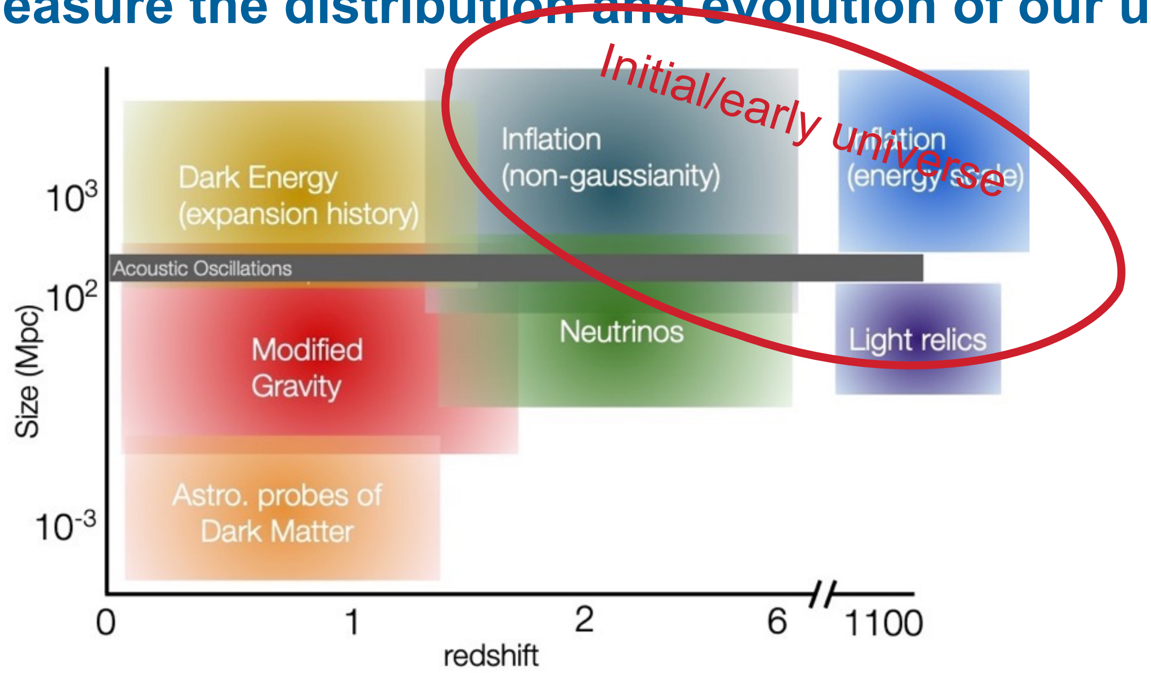

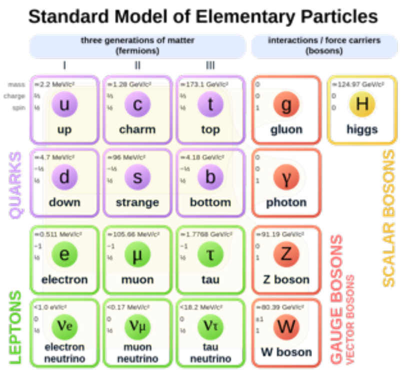

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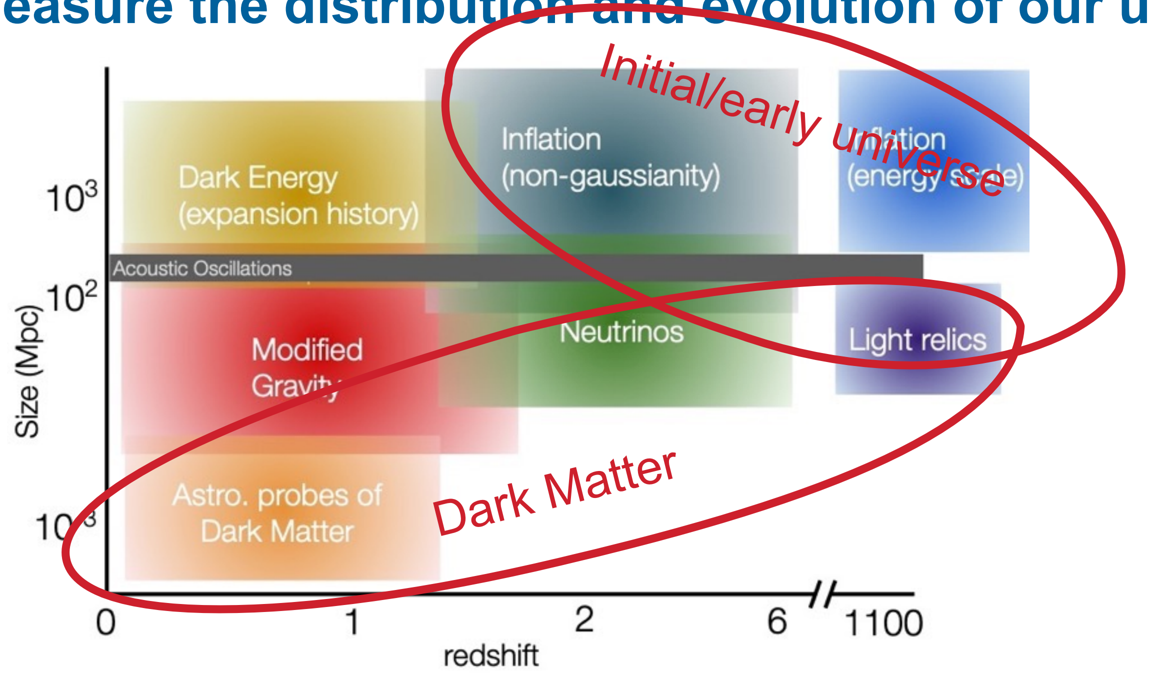

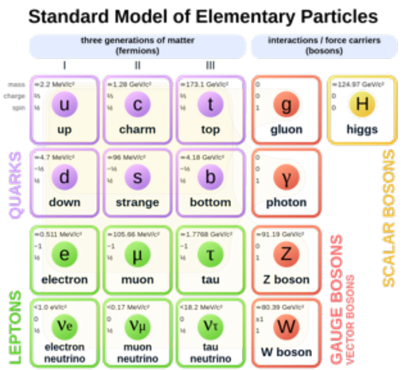

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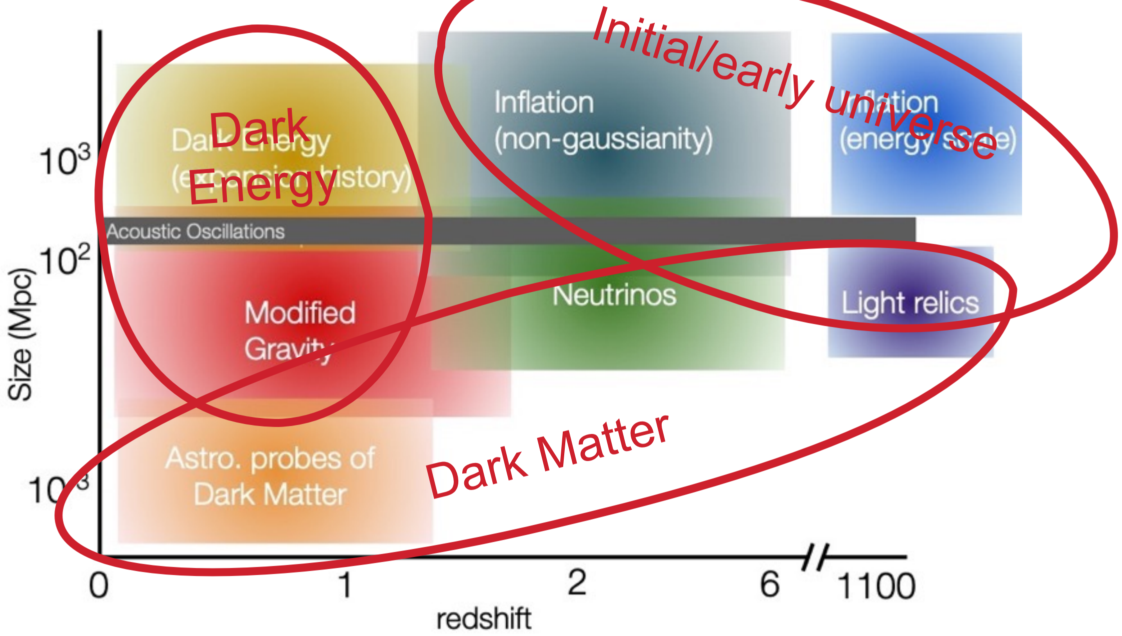

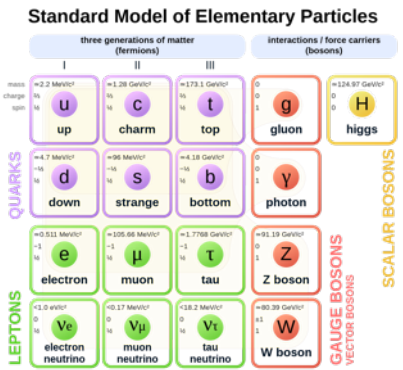

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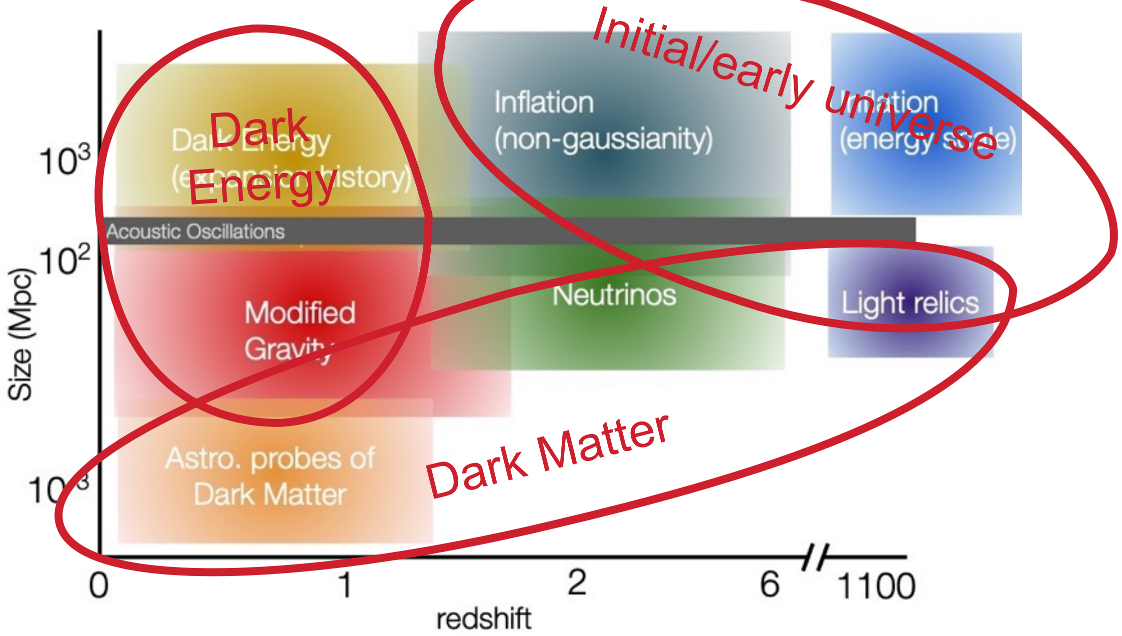
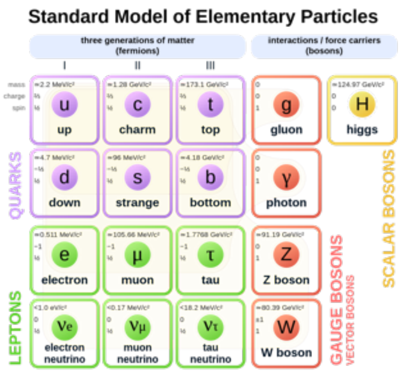


Current knowledge anchored by measurements at large scale at low & high z.

Future is to fill out the space between



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THE GOAL IS TO TEST THE "SIMPLE MODEL"

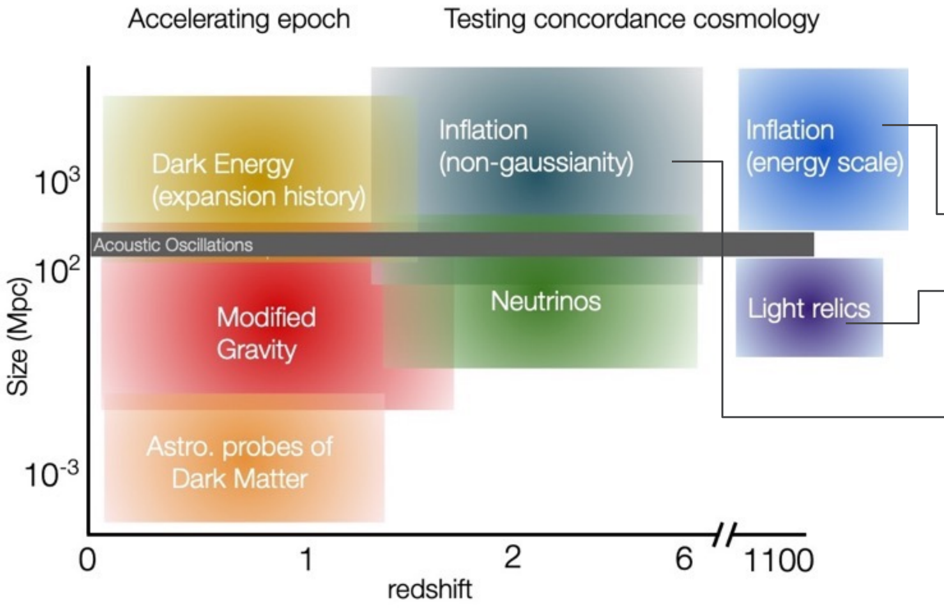
- Standard Model + CDM + simplest inflation model
  - single field
  - super-Planckian excursion
  - naturally explain the measured nearly scale invariant spectrum, n_s

Is this simple model true? or naïve?

- The "simple model" makes concrete predictions for signals that we should (and should not) observe
- Search for and measure these predicted signals
  - Develop the technologies and facilities to make these measurements
  - Develop the theoretical machinery to predict and interpret the data

THE NEXT 10-20 YEARS

Observe & interpret new phenomena in the early universe

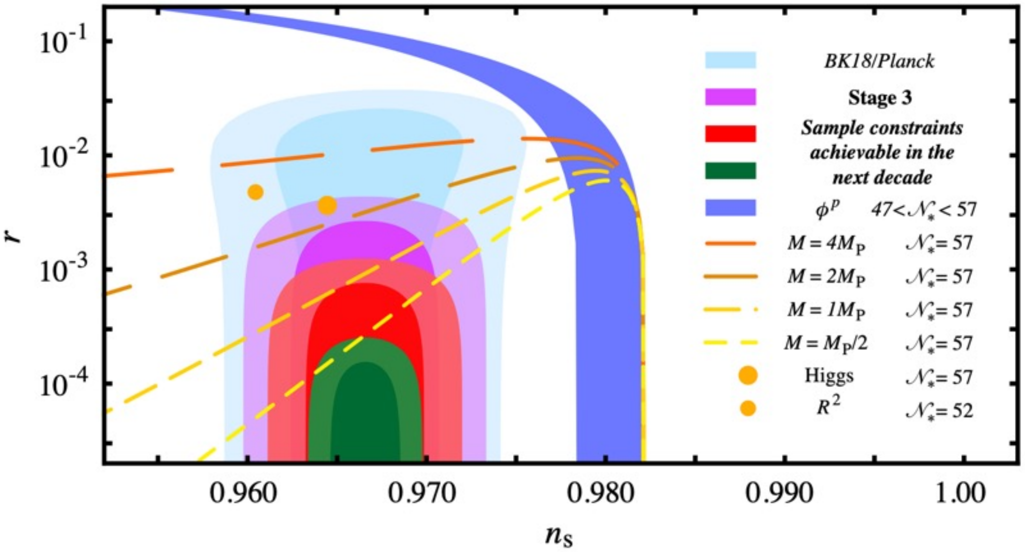


- Inflationary metric perturbations
- Non-SM energy in the early universe
- Inflationary scalar perturbations

INFLATIONARY METRIC PERTURBATIONS

Horizon scale

- "Smoking gun" signature of inflation
- Amplitude is related to inflationary energy scale (~GUT scale)
- Indirect observation of quantum fluctuations in the spacetime metric
- Next 10-20 years targets excluding (all) single-field models with a characteristic scale that exceeds the Planck scale.



Inflation: Theory and Observations, arXiv:2203.08128

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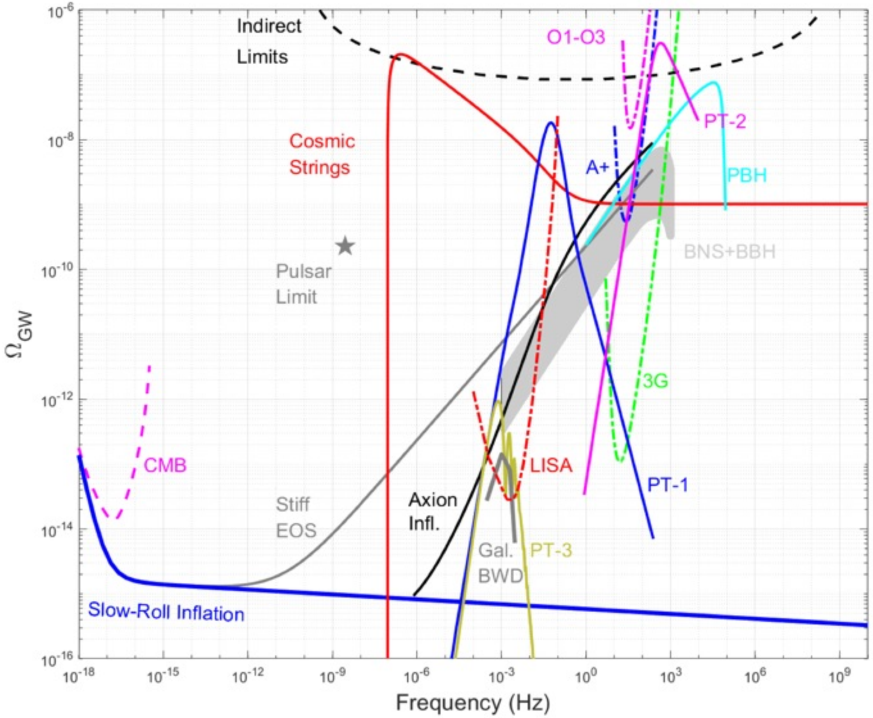
INFLATIONARY METRIC PERTURBATIONS

Sub-horizon scale

- GWs from “simple” slow roll model redshift
- More sophisticated models can predict a different GW spectrum
- GW observations in the next 10-20 years can search for these GWs. Constrain n_T



- Detection of Early-Universe Gravitational Wave Signatures and Fundamental Physics, arXiv:2203.07972
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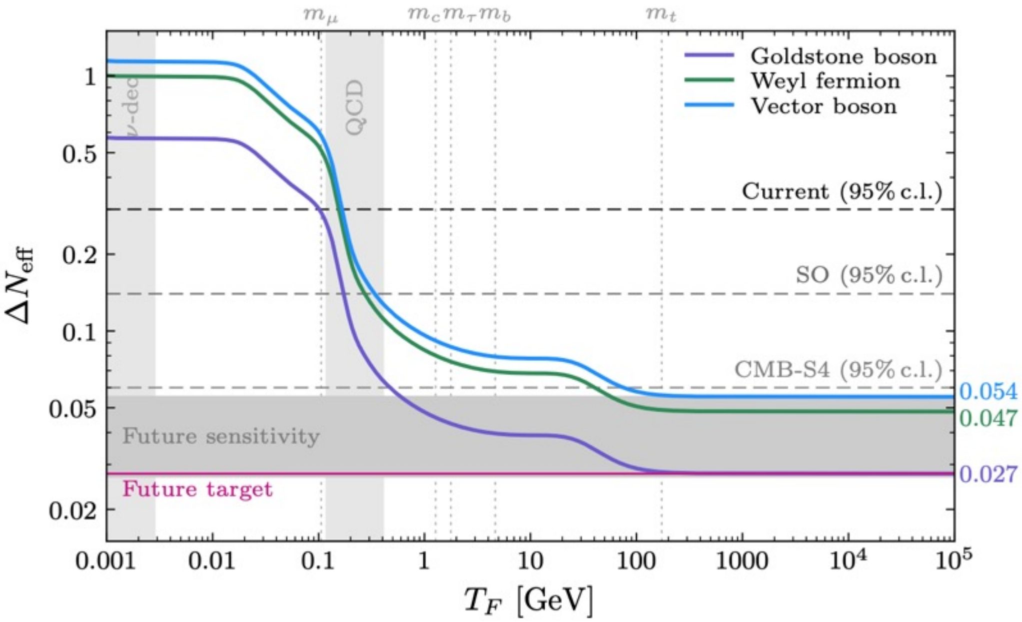
NON-SM ENERGY IN THE EARLY UNIVERSE

Relic particles

- Thermal relics
  - Free streaming vs fluid can probe interactions
- Light & massive
  - Also have late universe effect (like neutrino mass) measured via LSS signals
- Dark sector complexity
- Neutrino physics
  - Can shift $\Delta N_{eff} < 0$



The Physics of Light Relics”, arXiv:2203.07943

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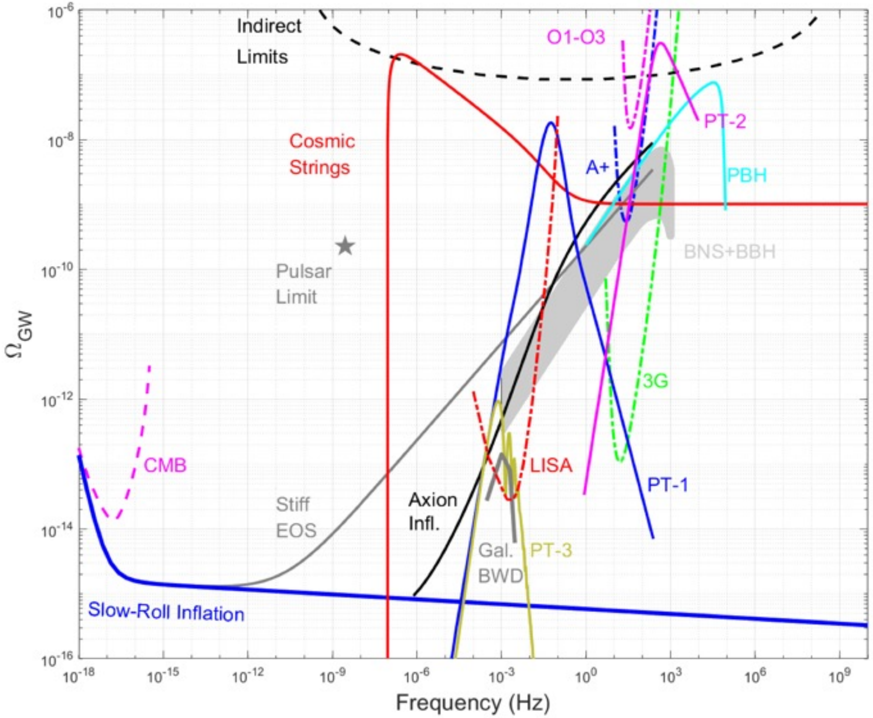
NON-SM ENERGY IN THE EARLY UNIVERSE

Gravitational waves

- 1st order phase transitions
- Cosmic strings
- More complex inflationary mechanisms (and non-inflationary alternatives)



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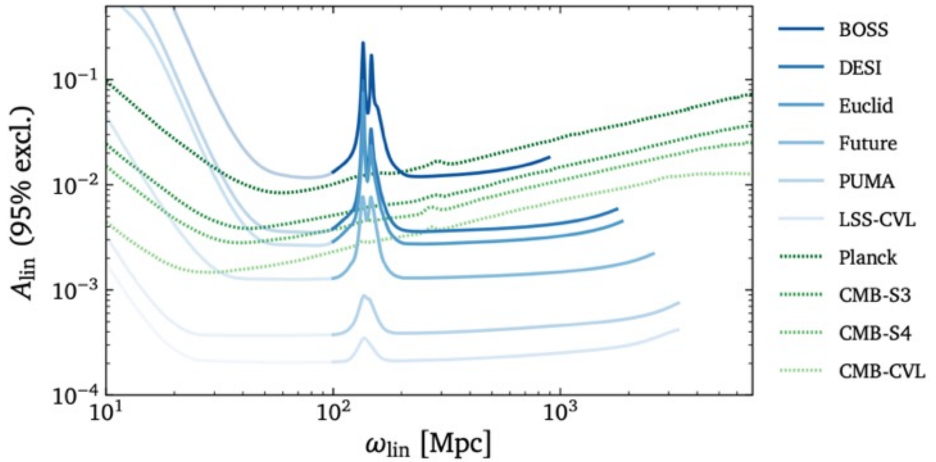
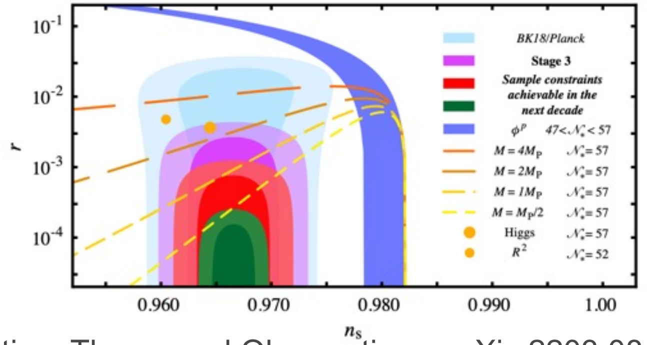
INFLATIONARY SCALAR PERTURBATIONS

Primordial features

- Primordial spectrum of scalar perturbations is connected to details of inflationary physics
- “Simple” inflation model predict nearly scale-invariant spectrum
  - Measurements of n_s are constraining models
- Many non-simple models, including those that attempt to connect to fundamental physics, predict new features in the primordial spectrum

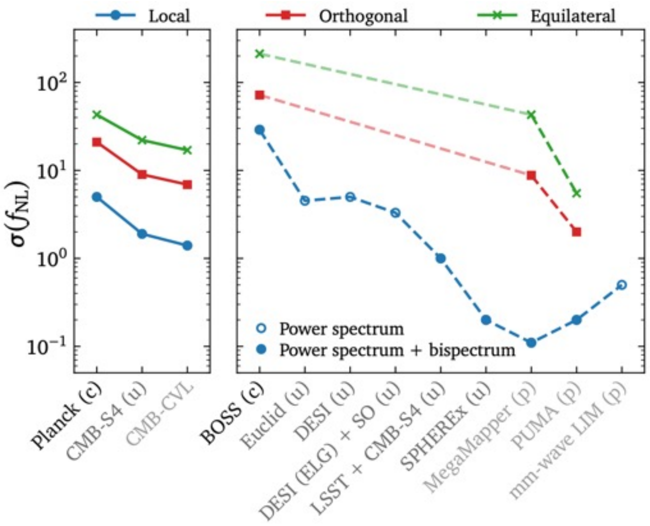




Inflation: Theory and Observations, arXiv:2203.08128

INFLATIONARY SCALAR PERTURBATIONS

Higher order statistics (non-gaussianity)



- “Non-simple” inflation models can predict non-zero higher order statistics related to
  - How many scalar degrees of freedom were light during inflation?
  - Were there degrees of freedom with masses comparable to the Hubble scale of inflation? What were their mass and spin spectra?
  - What were the initial states of these quantum fluctuations? What were their interactions and how fast were they propagating?
  - Was the background spacetime of the primordial universe quasi-de Sitter?
- CMB will be best measurement in the near term, but is Cosmic Variance limited (2-D sampling of modes)
- LSS will eventually go further (3-D sampling of modes), especially going out to high z
- Multi-tracer LSS can cancel Cosmic Variance

Inflation: Theory and Observations, arXiv:2203.08128

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OBSERVATORIES

- CMB
  - Cosmic Microwave Background Measurements White Paper, arXiv:2203.07638
  - CMB-S4 White Paper, arXiv:2203.08024
  - CMB-HD White Paper, arXiv:2203.05728
- GW
  - Future Gravitational-Wave Detector Facilities, arXiv:2203.08228
- 21-cm LIM
  - 21cm Radiation as a Probe of Physics Across Cosmic Ages, arXiv:2203.07864
- Mm-wave LIM
  - Cosmology with Millimeter-Wave Line Intensity Mapping, arXiv:2203.07258

OBSERVATORIES

- All observatories need to be major facilities to achieve science goals for studies of the early universe

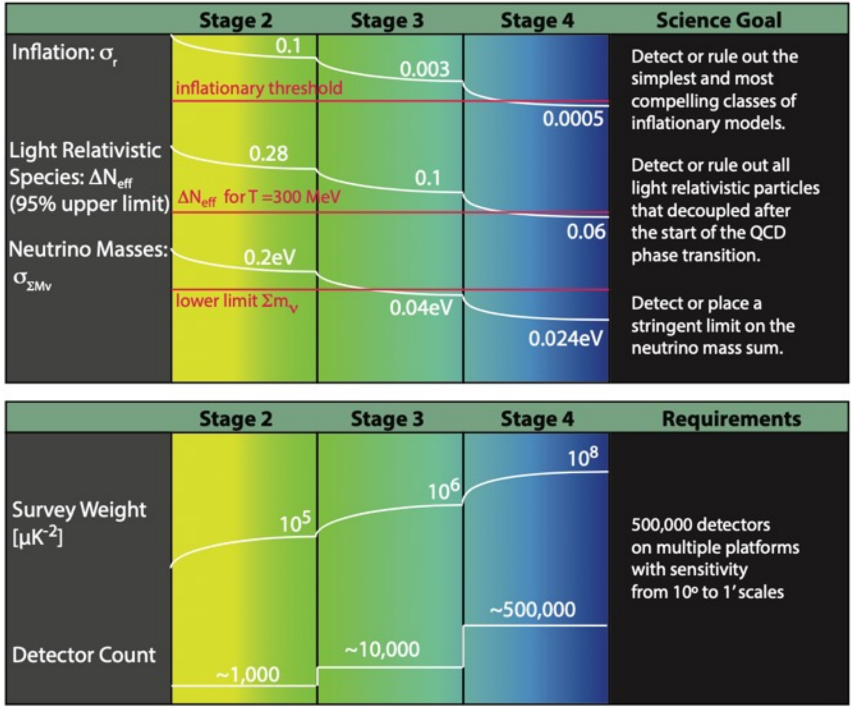
Small		Large
30	# scientists	300
PI led	governance	By-laws & elections
Few year proposals	funding	DOE MIE, NSF MREFC, line item in Fed. budget
PI managed	management	Institution Project Office
Proposal peer review	review	Major panel recommendations, agency reviews
novel	technology	demonstrated

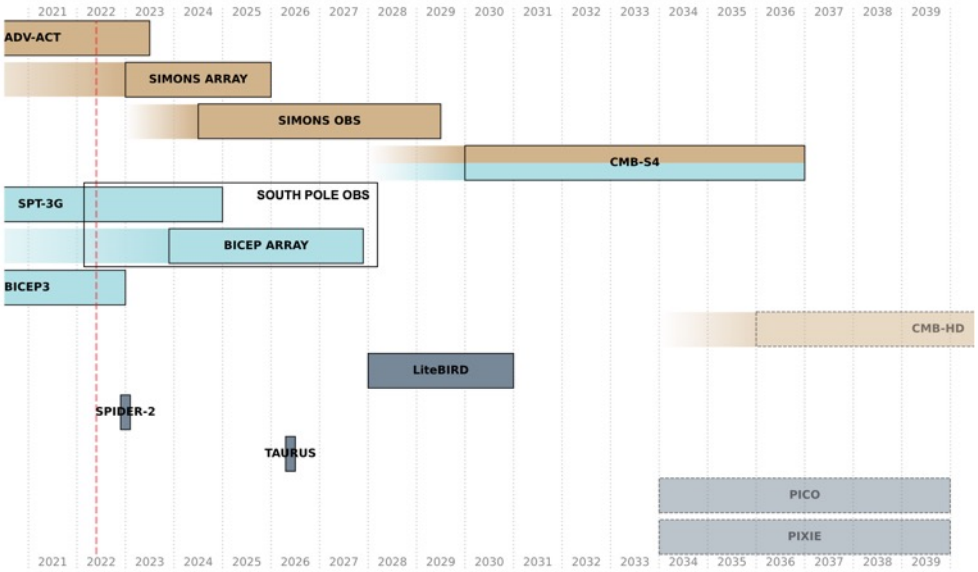
OBSERVATORIES

Towards large facilities

- Technology is not conventional
  - Superconducting detectors
  - Quantum enhanced interferometry
  - Large-scale radio technology
- Develop projects through a series of staged smaller projects
  - develop technology
  - control instrument and astrophysical systematics
  - build up the team, engage the community, coordinate w/ stakeholders
  - Build the facility

E.G. STAGED DEVELOPMENT FOR CMB EXP.





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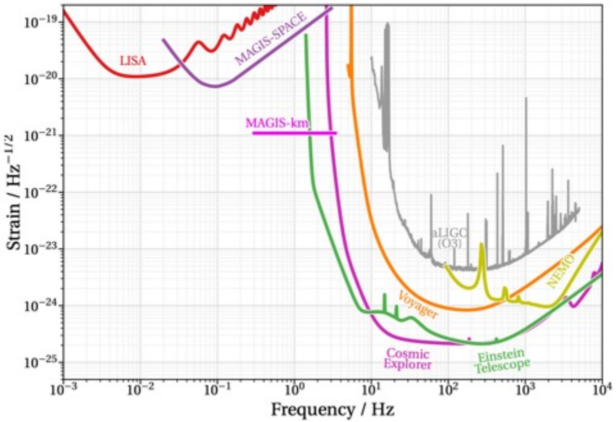
PROPOSED STAGED APPROACHES

- 21-cm
  - CHIME/HIRAX, PUMA-5k, PUMA-32k
- GW
  - A+LIGO, LIGO-Voyager, Cosmic Explorer/Einstein Telescope
  - MAGIS-100/AION, MAGIS-km, MAGIS-space

Experiment	(Proposed) Site	Baseline L (m)	LMT Atom Optics n	Atom Sources	Phase Noise $\delta\phi$ (rad/$\sqrt{\text{Hz}}$)
Sr prototype tower	Stanford	10	10^2	2	10^{-3}
MAGIS-100 (initial)	Fermilab (MINOS shaft)	100	10^2	3	10^{-3}
MAGIS-100 (final)	Fermilab (MINOS shaft)	100	4×10^4	3	10^{-5}
MAGIS-km	Homestake mine (SURF)	2000	4×10^4	40	10^{-5}
MAGIS-Space	Medium Earth orbit (MEO)	4×10^7	10^3	2	10^{-4}



- MM-wave LIM

Spec-hrs	Example	Time-scale	$\sigma(f_{\mathrm{NL}})$	$\sigma(M_\nu)$ (meV)	$\sigma(N_{\mathrm{eff}})$	$\sigma(w_0) \times 10^2$	$\sigma(w_a) \times 10^2$
10^5	TIME, CCAT-p, SPT-SLIM	2022	5.1 (5.1)	61 (65)	0.1 (0.11)	13 (14)	51 (52)
10^6	TIME-EXT	2025	4.7 (5)	43 (47)	0.082 (0.087)	5.3 (6.3)	21 (26)
10^7	SPT-like 1 tube	2028	3.1 (4.2)	23 (28)	0.043 (0.051)	2 (2.2)	8.5 (9.7)
10^8	SPT-like 7 tubes	2031	1.2 (3)	9.7 (13)	0.02 (0.023)	0.93 (1)	3.8 (4.3)
10^9	CMB-S4-like 85 tubes	2037	0.48 (2.4)	4.1 (6.8)	0.013 (0.016)	0.61 (0.73)	2.1 (2.8)
Planck			5.1	83	0.187	41	100

- Future Gravitational-Wave Detector Facilities, arXiv:2203.08228
- 21cm Radiation as a Probe of Physics Across Cosmic Ages, arXiv:2203.07864
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BIG & SMALL PROJECTS

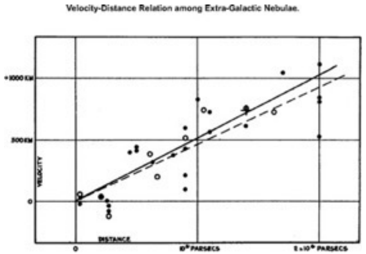
- Different CMB, GW, LSS/LIM experiments are at varying degrees of readiness.
- Motivates a mixture of small and large investments that evolves over the next two decades
  - Construct larger projects where the experiments are mature
  - Smaller investments to advance the readiness of newer techniques
  - Over time, large projects will complete construction and transition to operations. Small projects evolve into larger projects.

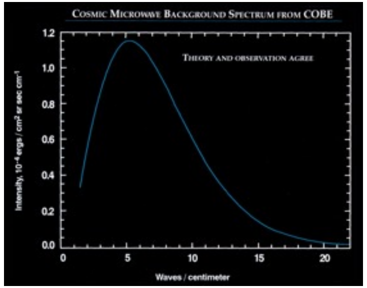
THEORY

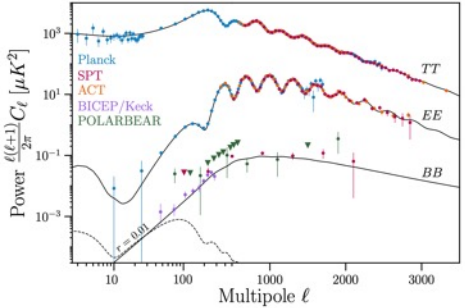
- History shows that contemporaneous development of theory is important
  - Expanding cosmology, BBN, acoustic oscillations
- Invest in developing broad suite of theoretical tools for understanding the data
  - Simulations, model building, forecasting, tools & analysis techniques, astrophysics

The Cosmological Bootstrap", arXiv:2203.08121 and TF09

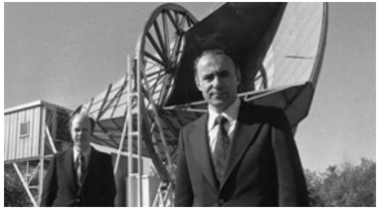
THE NEXT TWO DECADES WILL BE EXCITING

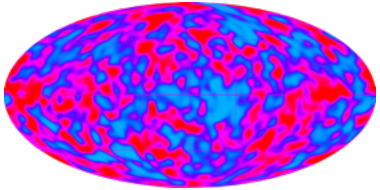






- CMB
- GW
- LSS





- Primordial abundances
- LSS
- SNe

H_0, Ω_γ + $T_{CMB}, \delta T(n)$ + $\tau, \Omega_b, \Omega_{CDM}, A_s, n_s, N_{eff}, \Lambda$ + **r, n_T "A_{lin}", f_{NL} ΔN_{eff}**

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THANK YOU

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