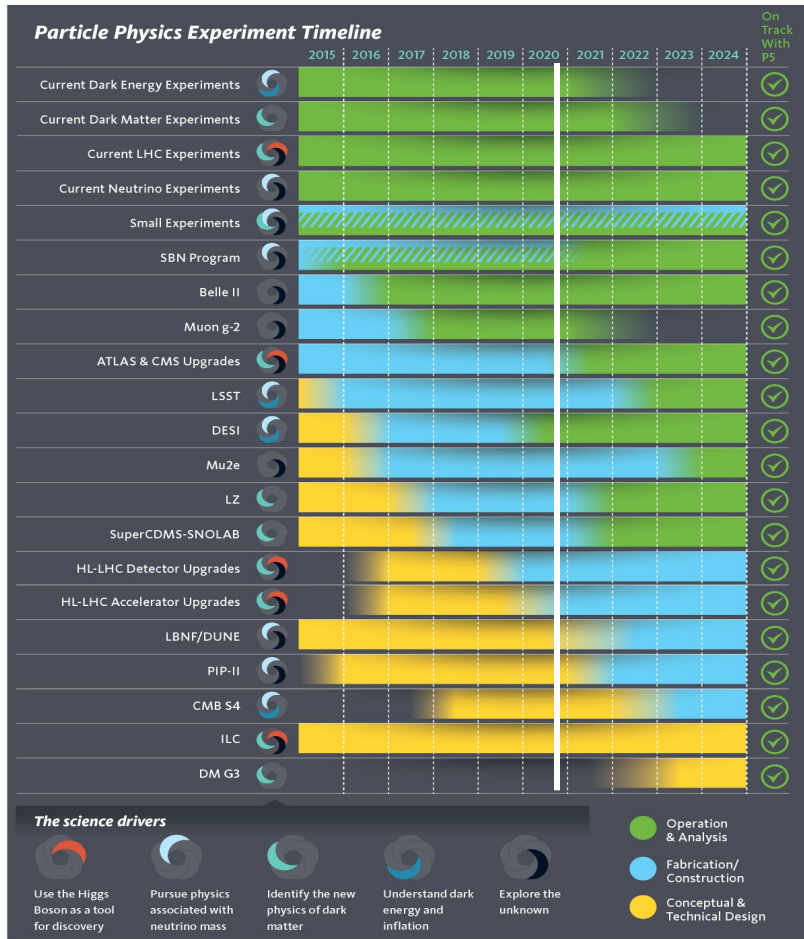


The Exciting Physics Before US!

JoAnne Hewett
Snowmass Community Planning Meeting
October 5, 2020

2014 P5 Report: Building for Discovery

SnowMass2021



- The P5 plan recommended construction of a suite of experiments across broad areas of particle physics
- Many have started or will be starting operations soon!
- The remainder will be operating by end of decade
- This talk will serve as a tour of the physics reaped over the next decade from the P5 projects

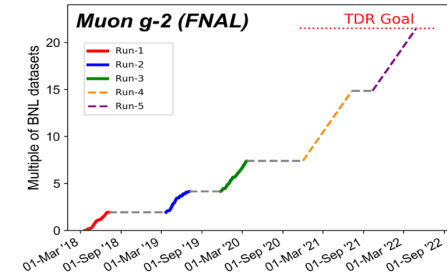
Precision SM Tests: Muon Anomalous Magnetic Moment

Long-standing discrepancy between exp't and the SM

- E821 @ BNL achieved 540 ppb sensitivity with 3.7σ discrepancy with SM

Muon g-2 Experiment @FNAL

- Target sensitivity is 140 ppb
- 3 physics runs completed



The world is holding its breath waiting for the results!!

Independent Exp't @JPARC with accelerated low emittance muon beam – operations planned 2024-2026

Muon g-2 Theory Initiative

- significant advances in determinations of HPV and HLbL contributions
- More improvements to come

Aoyama etal2006.04822

Contribution	Section	Equation	Value $\times 10^{11}$	References
Experiment (E821)		Eq. (8.13)	116 592 089(63)	Ref. [1]
HVP LO (e^+e^-)	Sec. 2.3.7	Eq. (2.33)	6931(40)	Refs. [2–7]
HVP NLO (e^+e^-)	Sec. 2.3.8	Eq. (2.34)	−98.3(7)	Ref. [7]
HVP NNLO (e^+e^-)	Sec. 2.3.8	Eq. (2.35)	12.4(1)	Ref. [8]
HVP LO (lattice, $udsc$)	Sec. 3.5.1	Eq. (3.49)	7116(184)	Refs. [9–17]
HLbL (phenomenology)	Sec. 4.9.4	Eq. (4.92)	92(19)	Refs. [18–30]
HLbL NLO (phenomenology)	Sec. 4.8	Eq. (4.91)	2(1)	Ref. [31]
HLbL (lattice, uds)	Sec. 5.7	Eq. (5.49)	79(35)	Ref. [32]
HLbL (phenomenology + lattice)	Sec. 8	Eq. (8.10)	90(17)	Refs. [18–30, 32]
QED	Sec. 6.5	Eq. (6.30)	116 584 718.931(104)	Refs. [33, 34]
Electroweak	Sec. 7.4	Eq. (7.16)	153.6(1.0)	Refs. [35, 36]
HVP (e^+e^- , LO + NLO + NNLO)	Sec. 8	Eq. (8.5)	6845(40)	Refs. [2–8]
HLbL (phenomenology + lattice + NLO)	Sec. 8	Eq. (8.11)	92(18)	Refs. [18–32]
Total SM Value	Sec. 8	Eq. (8.12)	116 591 810(43)	Refs. [2–8, 18–24, 31–36]
Difference: $\Delta a_\mu := a_\mu^{\text{exp}} - a_\mu^{\text{SM}}$	Sec. 8	Eq. (8.14)	279(76)	



LHC Run 3 and HL-LHC Physics Program

Much more data to come! Much more physics to come!

- LHC Run 2 delivered ~5% of anticipated 3 ab⁻¹ HL program

Higgs coupling measurements

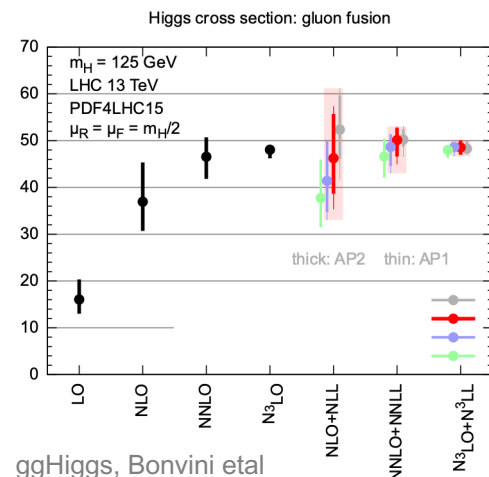
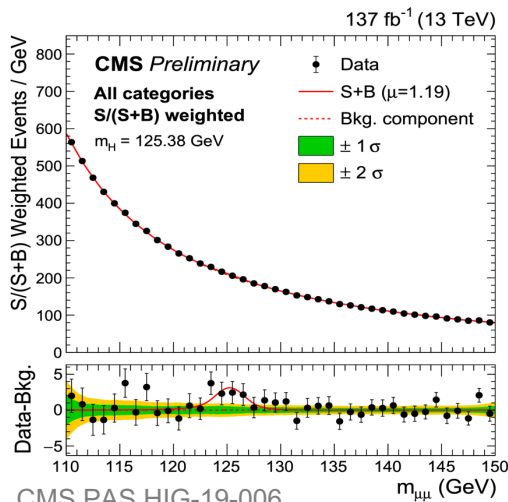
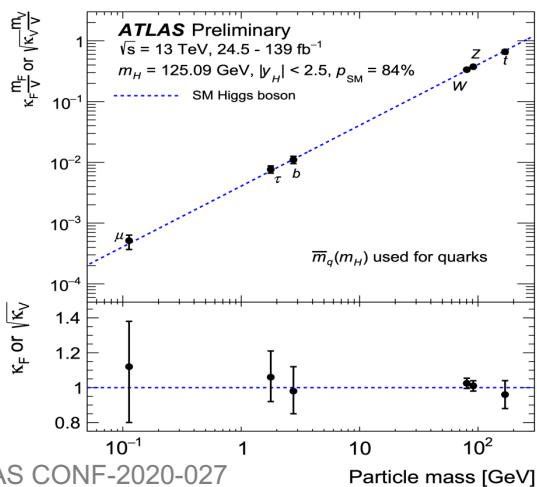
- Ever increasing precision for gauge boson & 3rd gen fermion decays
- Decays to 2nd gen fermions
- Rare and invisible decays
- Tri-linear & quartic self-coupling

Exploring the Unknown

- Precision tests of SM
- Search for New Physics & Dark Matter – many crucial channels need high-luminosity to tease signal from background

Precise interpretation of data made possible by theory

- Three-loop N³LO calculations now state of the art for SM processes



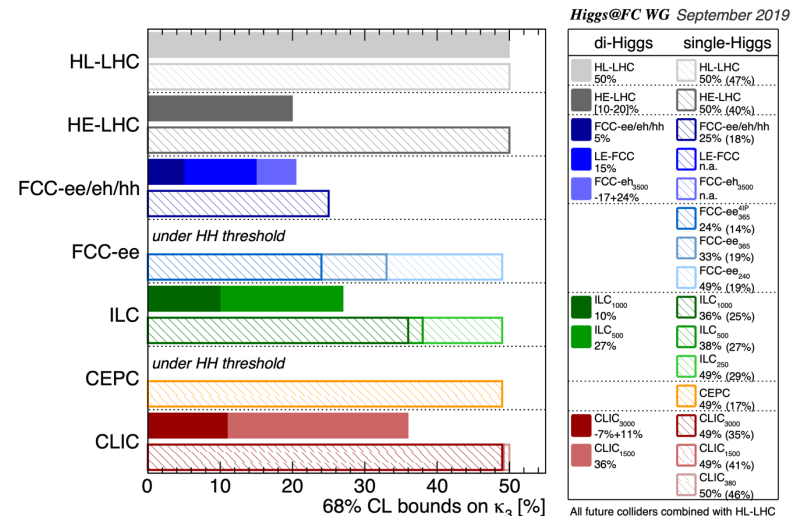
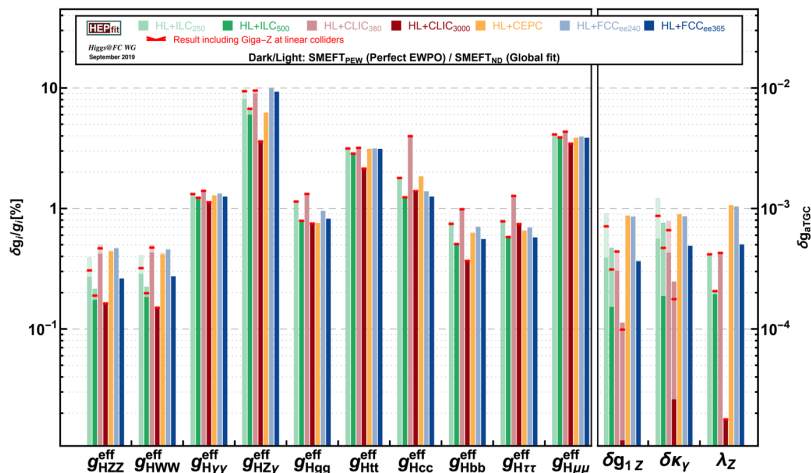
The Next Collider: A Higgs Factory?

The next collider will be subject of much discussion @ Snowmass2021

- Many collider options to study – some designs more mature than others with ILC most mature

2020 Update of European Particle Physics strategy recommendation: An electron-positron Higgs Factory is the highest-priority next collider

- Percent-level determinations of Higgs couplings to SM fields
- Tri-linear Higgs self-coupling is the next Holy Grail - provides study of Higgs potential
 - 50% precision at HL-LHC excludes absence at 95% CL
 - 20% precision establishes existence at 5σ
 - 5-10% precision begins to probe quantum level corrections

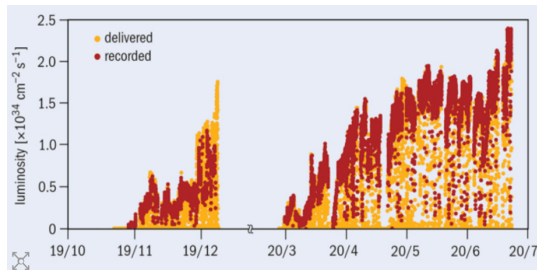


Exploring the Unknown: Rare Processes

Rare B Meson Decays

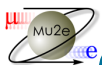
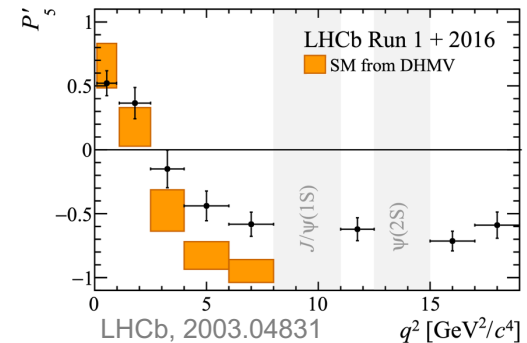
- Anomalies persist in $b \rightarrow sl^+l^-$ decays in various distributions and at various levels of σ
- Players are Belle-II (50 ab^{-1}), ATLAS/CMS (3 ab^{-1}), LHCb (300 fb^{-1})

Watch this space!!



KEK reclaims world luminosity record June 2020

Angular distribution in $B \rightarrow K^* \mu \mu$
 3σ discrepancy with SM



Charged Lepton Flavor Violation: Mu2e

- Tests of magnetic dipole and 4-fermion interactions
- Measures $R_{\mu e}$ to sensitivity of 3×10^{-17} $R_{\mu e} = \frac{\Gamma(\mu^- N \rightarrow e^- N)}{\Gamma(\mu^- N \rightarrow \text{All captures})}$
- Expect to start data taking 2024, reach full sensitivity by ~ 2030
- Probe new physics up to 10^4 TeV

Short Baseline Neutrino Program

Snowmass2021

MiniBooNE anomaly persists

- 4.8 σ excess summed over neutrino & anti-neutrino modes
- 6.1 σ including LSND results
- Timing information shows excess is timed with neutrinos interacting in detector volume

MicroBooNE

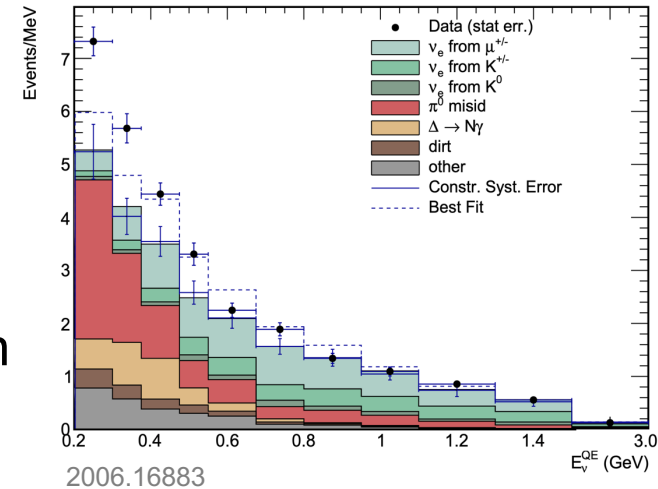
- Many pretty event displays
- Expect to unblind results soon

ICARUS

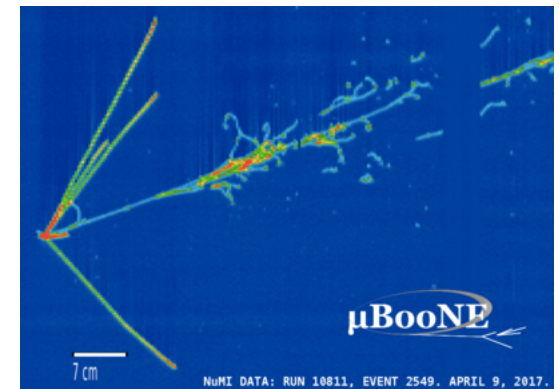
- Commissioning!

SBND

- Under construction



The world is holding its breath waiting for the results!!



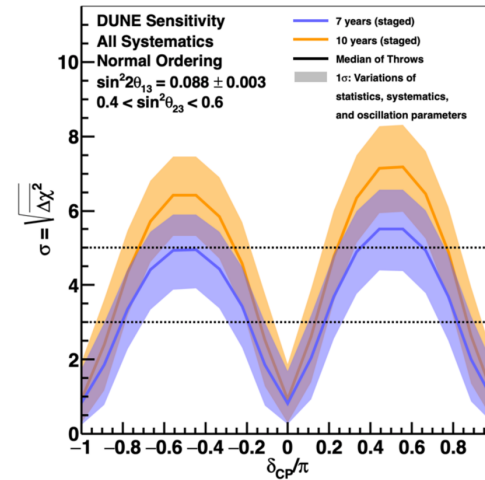
DUNE Scientific Program

- Neutrino Oscillation Program
- Atmospheric & Solar Neutrinos
- Nucleon Decay
- Supernova Neutrinos
- BSM Physics

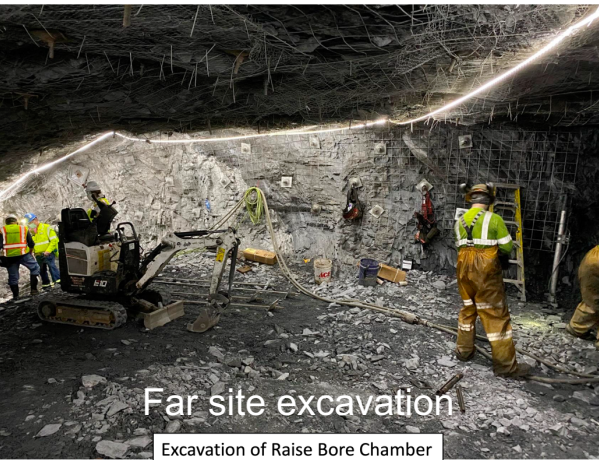
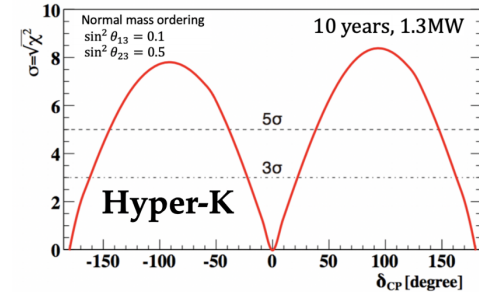
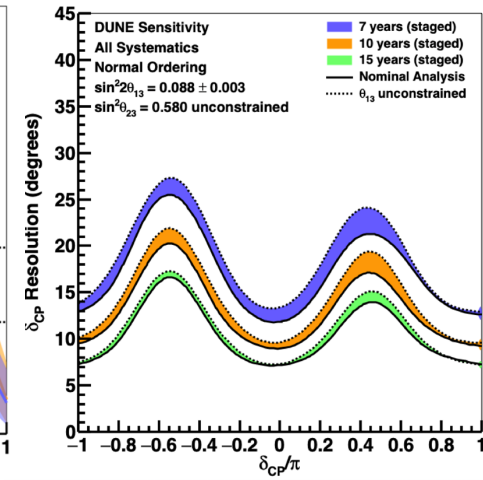
PIP-II

- 1.2 MW beam, upgradable to 2.4 MW
- Construction groundbreaking July 2020
- 1st MW beam to SURF in late 2020's

CP Violation Sensitivity



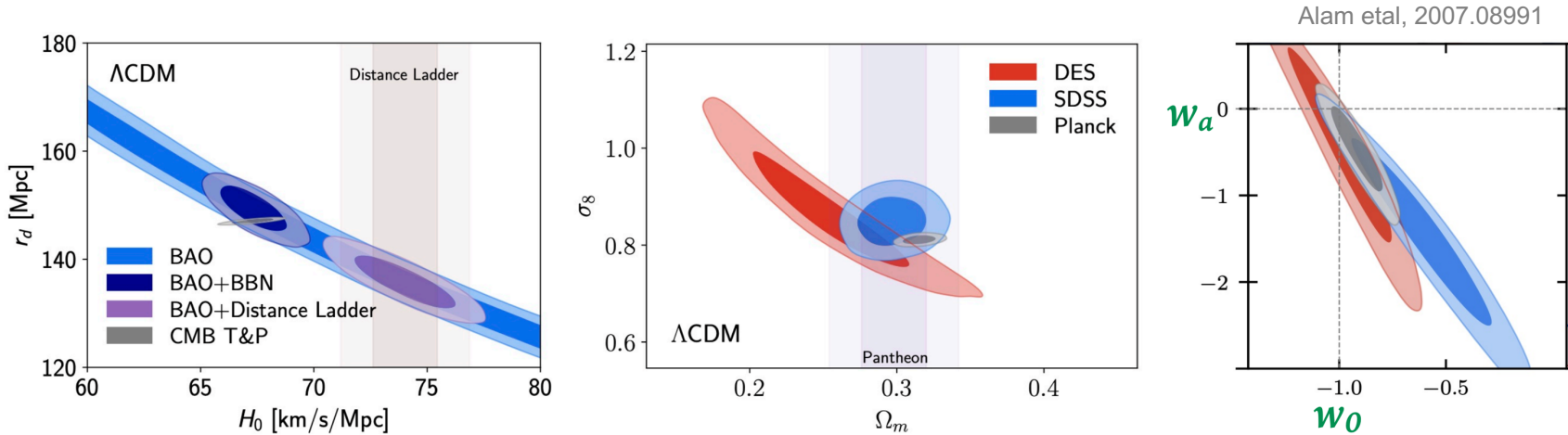
DUNE TDR, 2002.03005



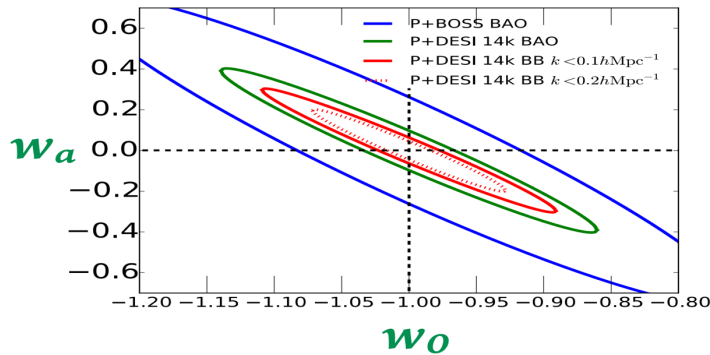
Dark Energy circa 2021

Tension in Λ CDM measurements persist @ 2-3 σ

- Complete SDSS-IV (eBOSS) Baryon oscillation spectroscopic survey

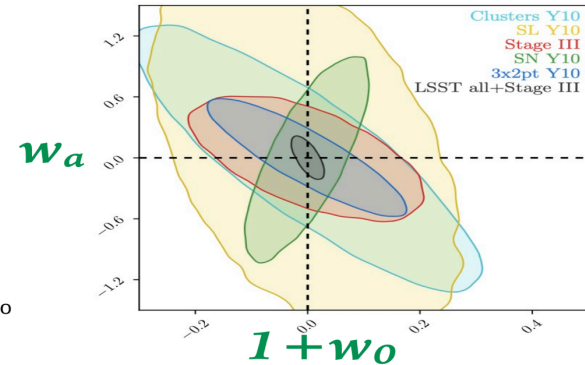


- DES 3-yr analysis to appear soon
- DESI has begun operations



DESI forecast

<https://arxiv.org/abs/1611.00036>



Vera Rubin Obs (DESC) forecast

<https://arxiv.org/abs/1809.01669>

From D. Kirkby, ICHEP2020

Watch this space!!

Dark Energy circa 2023/24

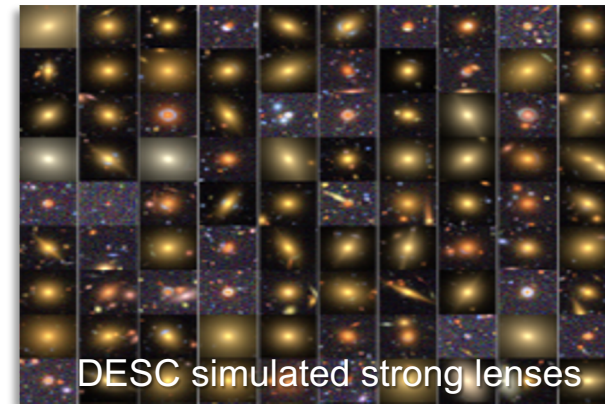
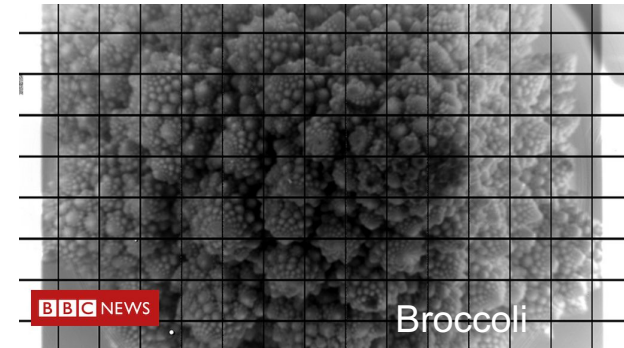
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Vera Rubin Observatory will conduct the Legacy Survey of Space and Time

- Will record deep images of 10B galaxies to observe the nature of Dark Energy
- 3.2 Gpixel camera is nearly complete and took world-famous photo of broccoli
- Commissioning and preparations for operations underway
- Data from the facility will serve 8 science collaborations for 10 yrs of operations!

Dark Energy Science Collaboration

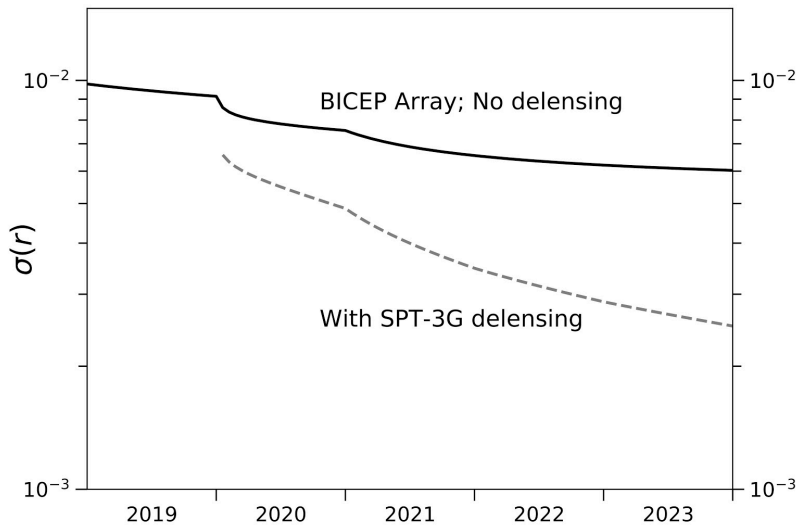
- Will perform the dark energy science
- Production of extragalactic catalogs and mock data challenges to sharpen tools in preparation for start of operations



South Pole CMB Observatories

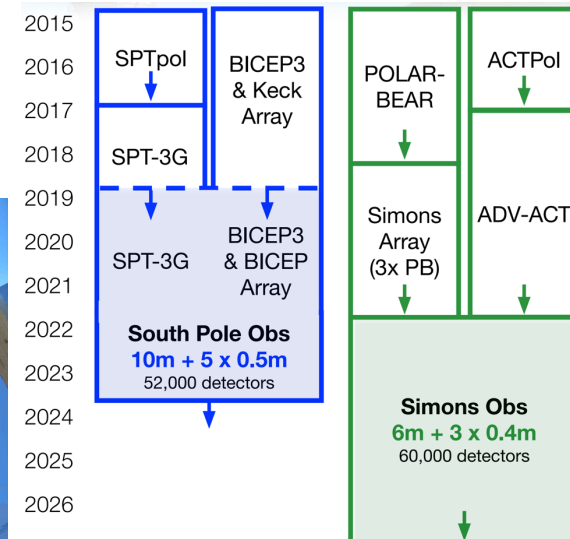
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BICEP/Keck Array and South Pole Telescope



BICEP/Keck + South Pole Telescope projected $\sigma(r) \lesssim 0.003$ with r being the tensor to scalar ratio

CMB Experiment Roadmap



First science result from SPT3G coming soon!



1st out of 4 BICEP Array receivers installed early 2020

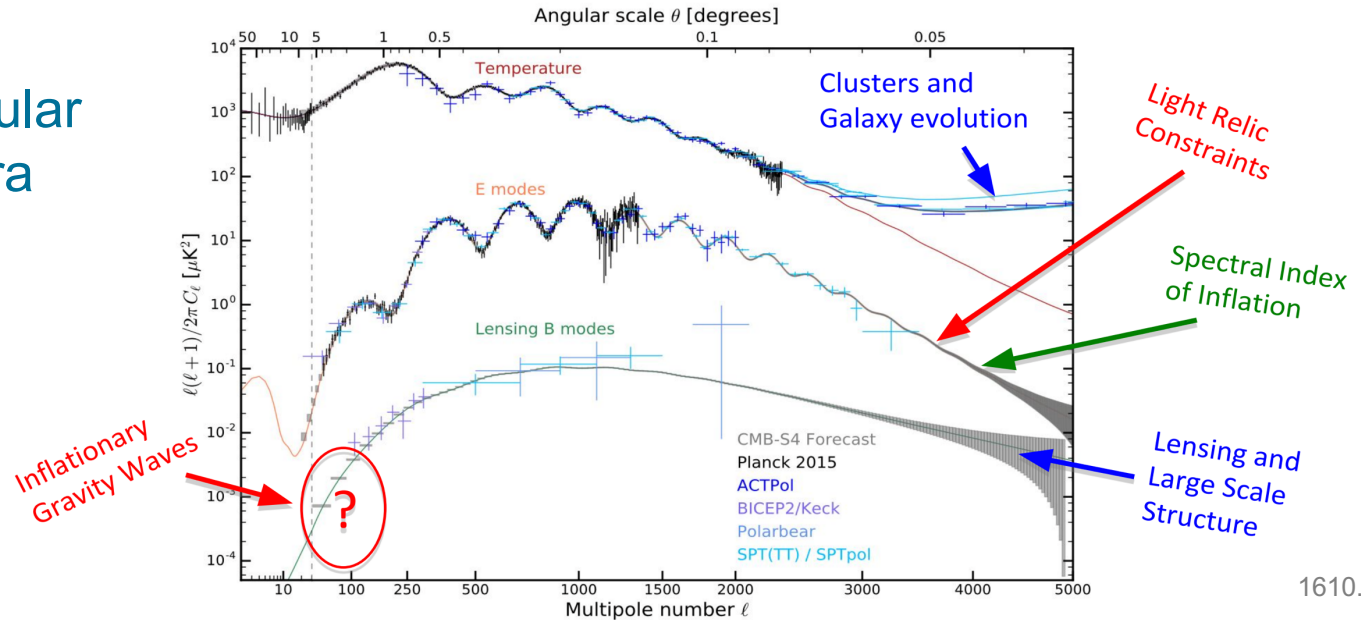
≥2027

CMB-S4 starts operations with 500,000 detectors

Science Drivers of CMB-Stage 4

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CMB-S4 Angular Power Spectra



1610.02743

Primary Science Drivers:

- **Inflation:** imprint of gravitational waves on CMB B-mode polarization
 - Sensitivity to figure of merit $r < 0.001$ (tensor to scalar ratio) [$\sigma(r)=0.0005$]
 - Determine energy scale of inflation
- **Light Relic Particles**
 - Limits on sum of neutrino masses
 - Determine $\Delta N_{\text{eff}} < 0.06$
 - Limits on ultra-light dark matter
 - Complementary to DUNE and $0\nu\beta\beta$
- **Legacy Sky Survey:** Λ CDM stress test of standard model of the universe; connect to optical surveys

Dark Matter Generation 2 Experiments

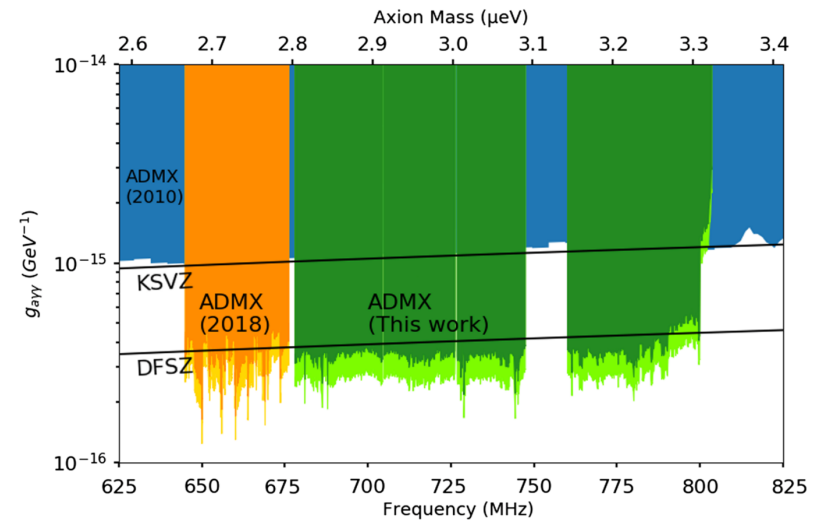
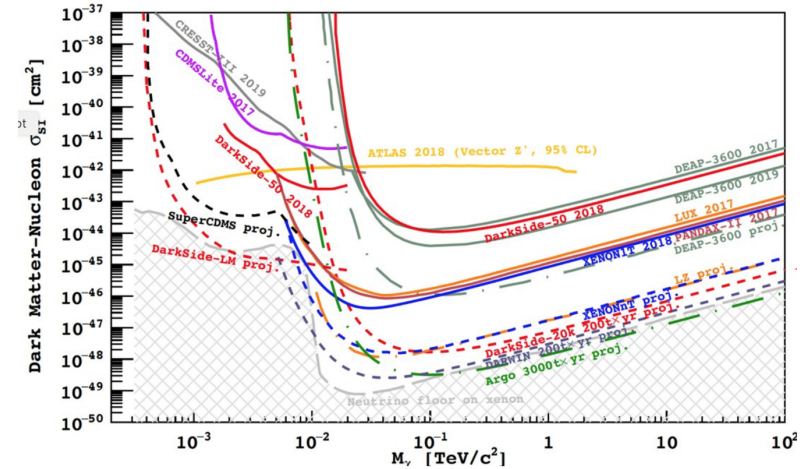
WIMP Searches

- LZ:
 - Probe 10 GeV – 10 TeV WIMPS
 - LXe TPC
 - Operations starting ~2021
- sCDMS:
 - Probe 0.5 – 5 GeV
 - Si/Ge detectors
 - operations starting ~2022

Watch this space!!

Searches for Axions

- AMDX
 - Probes ~3 μeV axions in strong CPV models
 - Cavity haloscope
 - Operating!



Braine et al, 1910.08638

What's New Since P5!

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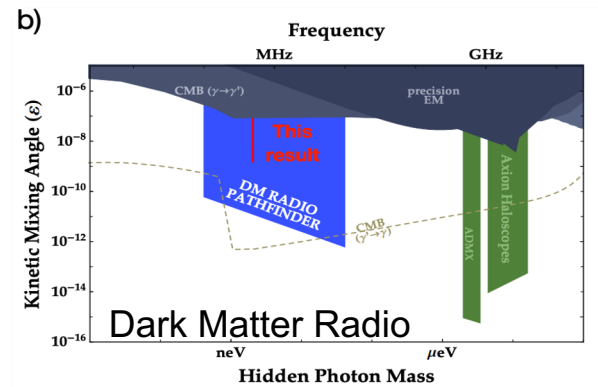
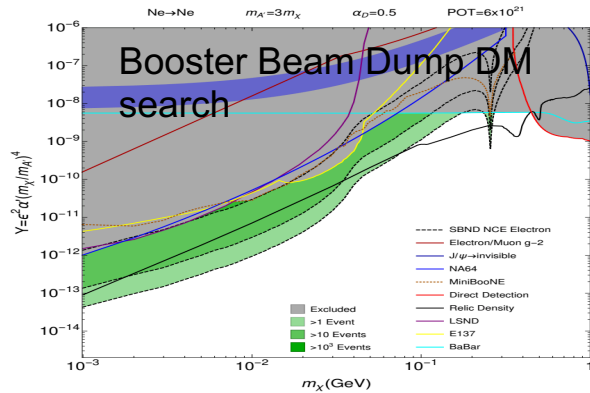
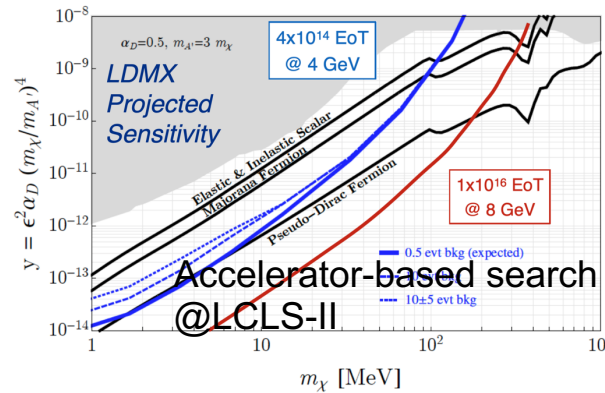
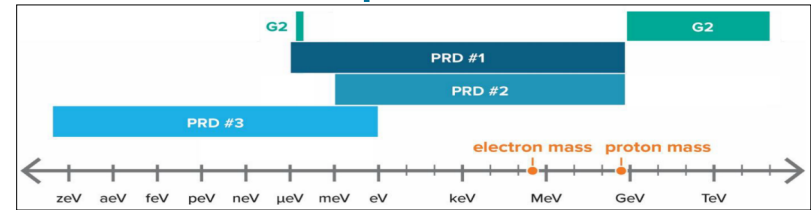
New Ideas!

Dark Matter New Initiatives

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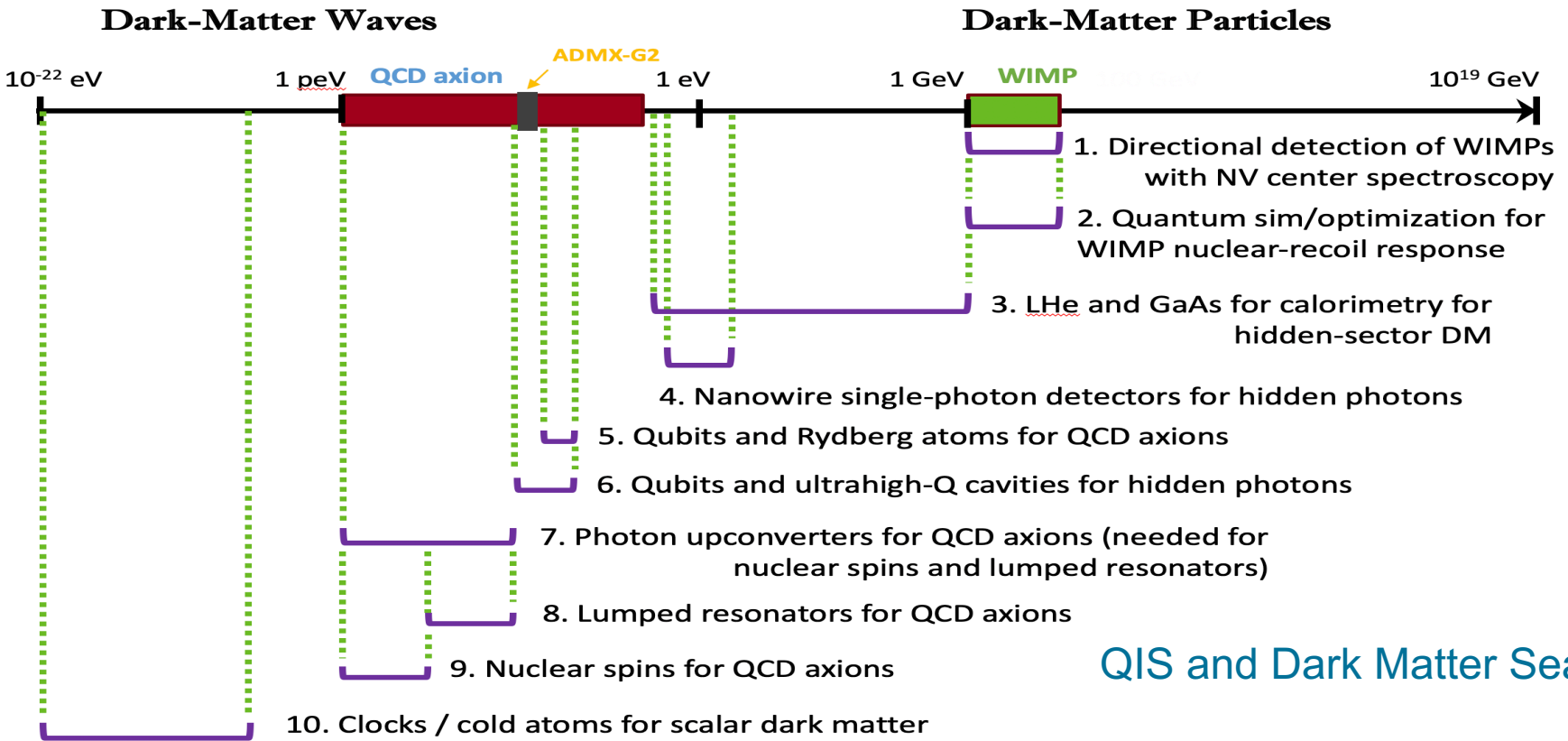
Explosion of ideas for new experiments to expand reach of dark matter searches

- Led by the theory community!!
- Basic Research Needs workshop held to determine priorities



Investments in HEP-related QIS with QuantISED program

- Application of quantum techniques to solve HEP problems
- Activities range from quantum algorithms for data analysis to table-top holographic atomic simulators

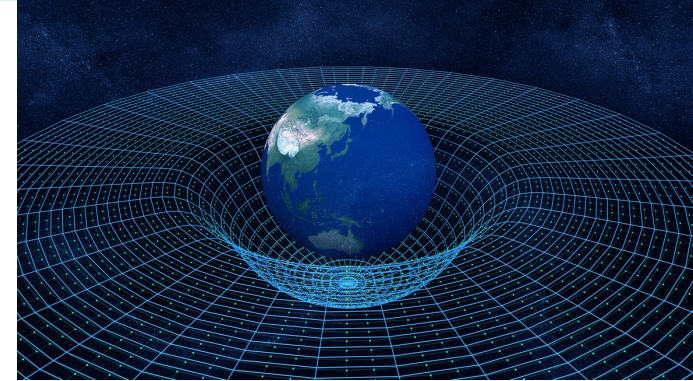


Gravitational Wave Science

Gravitational waves provide information on the early universe, back to inflation, that is difficult or impossible to access by other methods

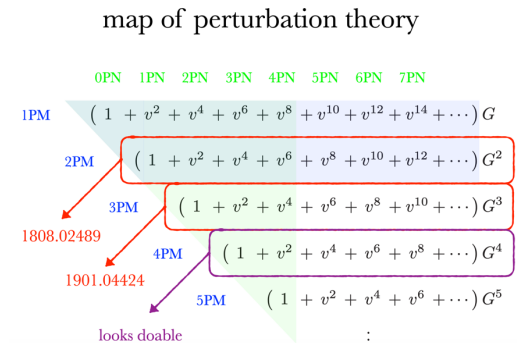
New way to explore the cosmos and probe fundamental physics!

- **Cosmology**
 - Tests of GR
 - Tests of cosmological parameters
 - Stochastic gravity wave from early universe probe phase transitions
 - Cosmic strings
- **Dark Matter**
 - Ultraligh wave dark matter
 - Blackholes produced from collapse of large primordial density fluctuations
- **Particle Astrophysics**
 - Black hole formation



Theory: Scattering amplitudes for massive scalar binary systems at 3rd post-Minkowskian order

- Higher order calculations in inspiral velocity and G_n



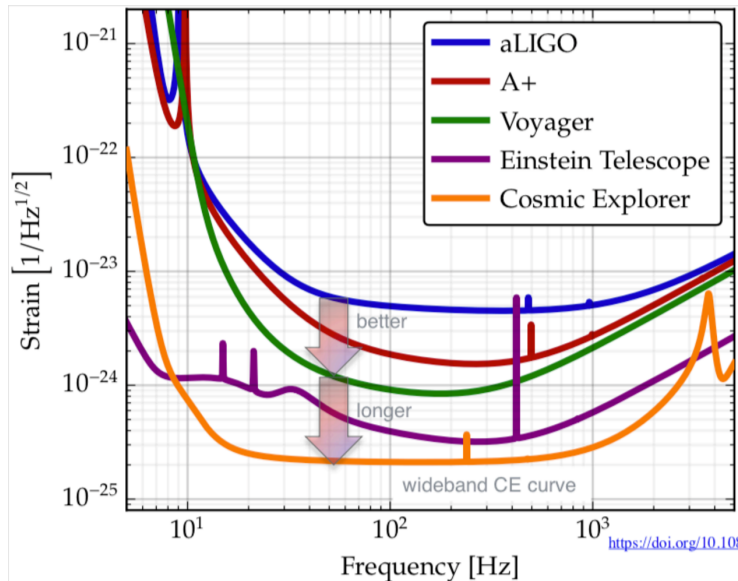
The Future of Gravitational Wave Measurements

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Gen-3 Laser Interferometers

Cosmic Explorer – 40 km arm interferometer on Earth surface

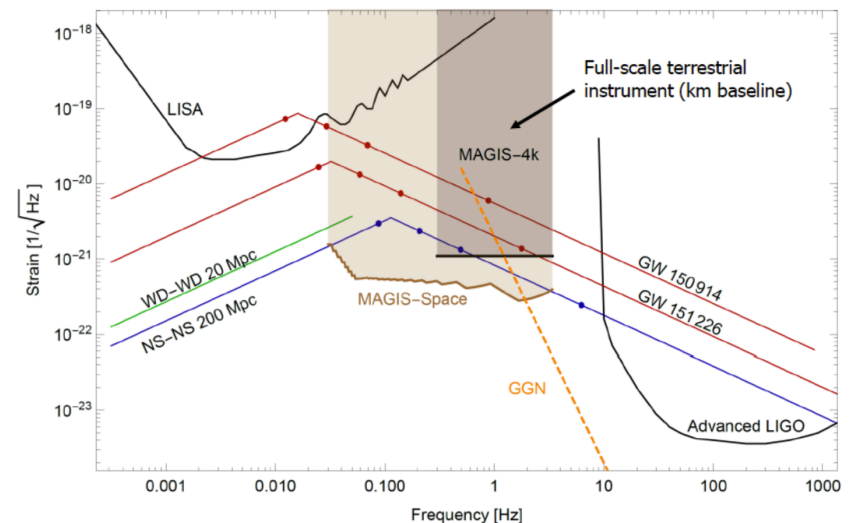
- Large & complex experiment that would benefit from particle physics expertise



Atom Interferometer

MAGIS - Lasers act as beam splitters for atomic de Broglie waves between 2 atom sources while they are in free-fall

- Ultralight dark matter induces frequency variations
- Gravitational waves change length of fall



Summary

Remarkable achievement by the community in building the suite of P5 experiments

- Over the next decade, the community will reap the rewards and do science with these experiments!
- Several outstanding anomalies waiting to be resolved!
- Discoveries of new properties and interactions waiting to be made!
- Theorists will be busy interpreting the data!

The 2020's will be an exciting decade for particle physics!