CF7. Cosmic Probes of Fundamental Physics

Conveners: Rana X Adhikari, Luis A. Anchordoqui, Ke Fang, Bangalore Sathyaprakash, Kirsten Tollefson

Early Career Representatives: Kristi Engel and Tiffany Lewis

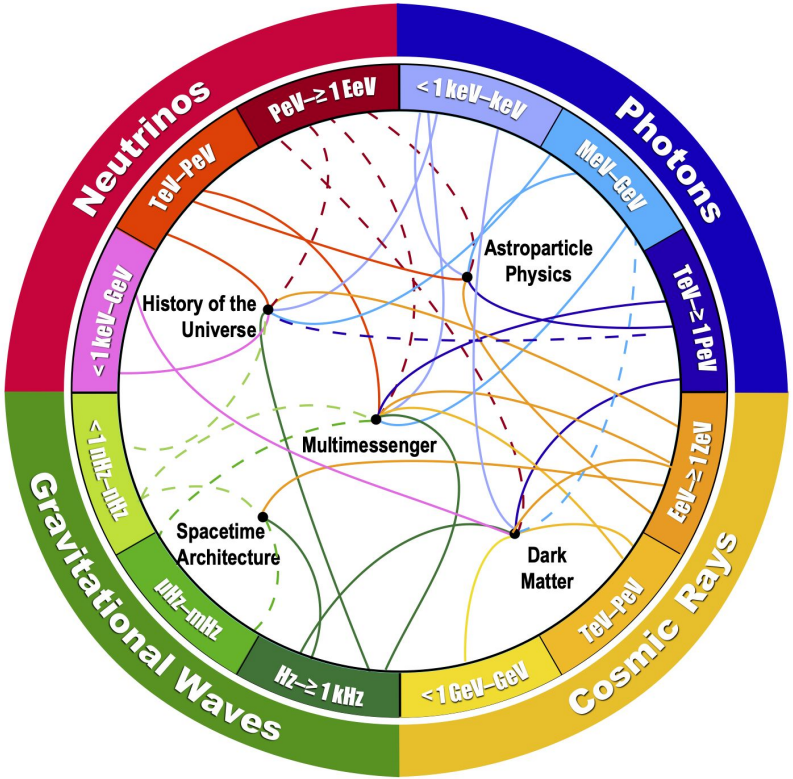
137 Letters of Intent; 12 white papers

Link to CF7 Report:
https://www.dropbox.com/s/7aaxxlmtcjvxyqb/CF7-report.pdf?dl=0

Feedback form:
https://forms.gle/kKuWWPgRaohQ8YqN7

Five main topical areas drived by big science questions with cosmic probes over the next decade:

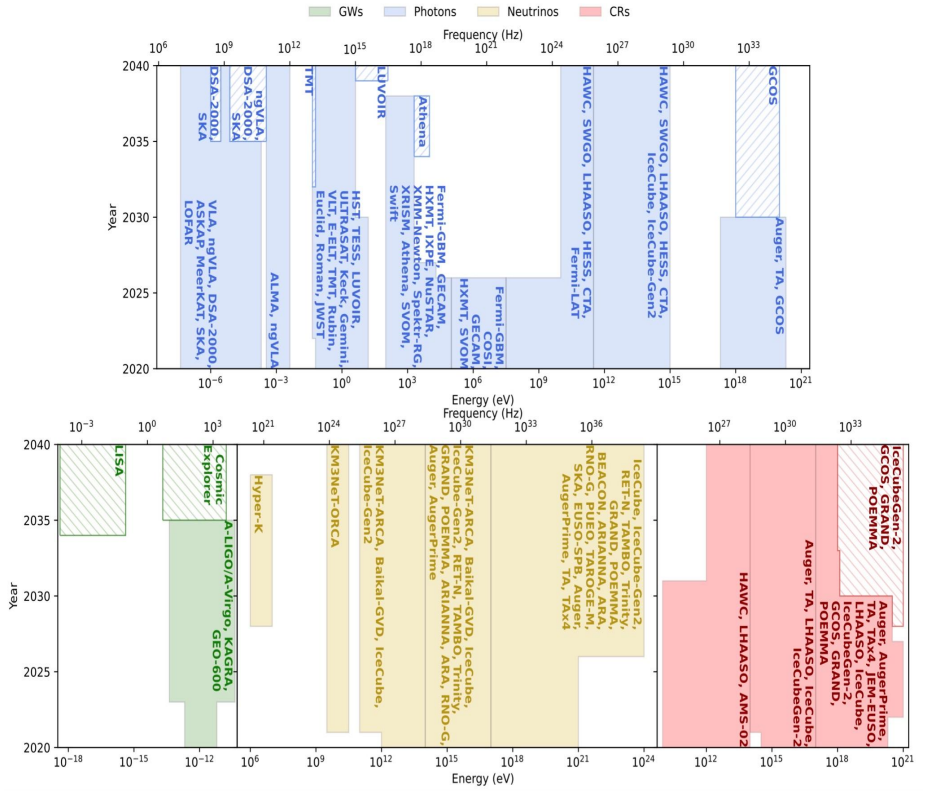
- History of Universe and Cosmology
- Cosmic Probes of Dark Matter
- Astroparticle Physics
- Multimessenger Synergies in Particle Astrophysics
- Architecture of Spacetime



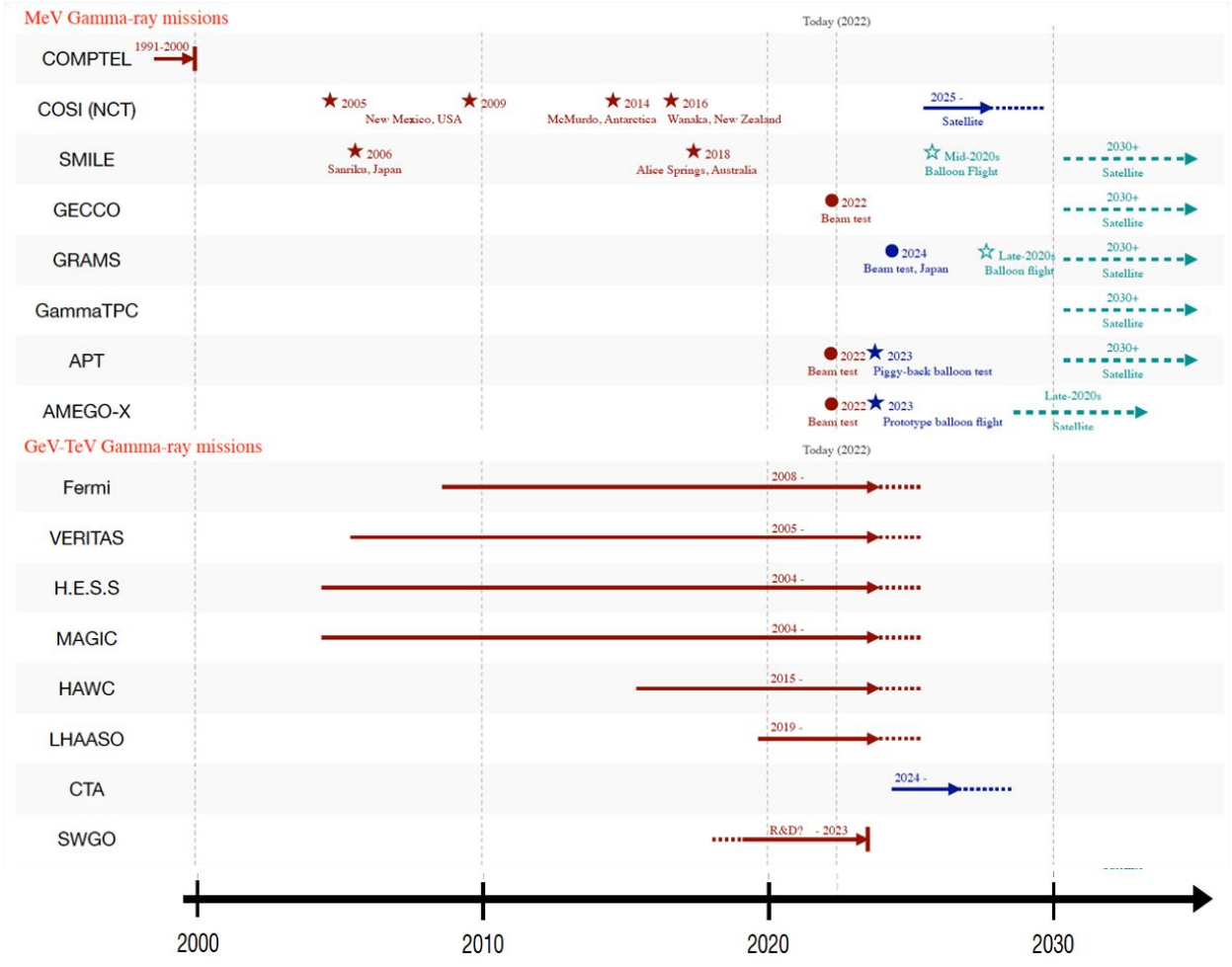
Solid curve: current existing facilities
Dashed curve: future experiments

Multimessenger Synergies in Particle Astrophysics

- **Sources of Cosmic Particles**
- **Extreme-energy particle acceleration and interaction**
- **Diffuse backgrounds:** gamma-ray, supernova neutrino, astrophysical diffuse neutrino, cosmogenic neutrino backgrounds, and Galactic diffuse emission
- **Galactic TeVatrons and PeVatrons**
- **Production of heavy elements**



Gamma-Ray Instrumentation Roadmap



Current/previous, Near-term, Future

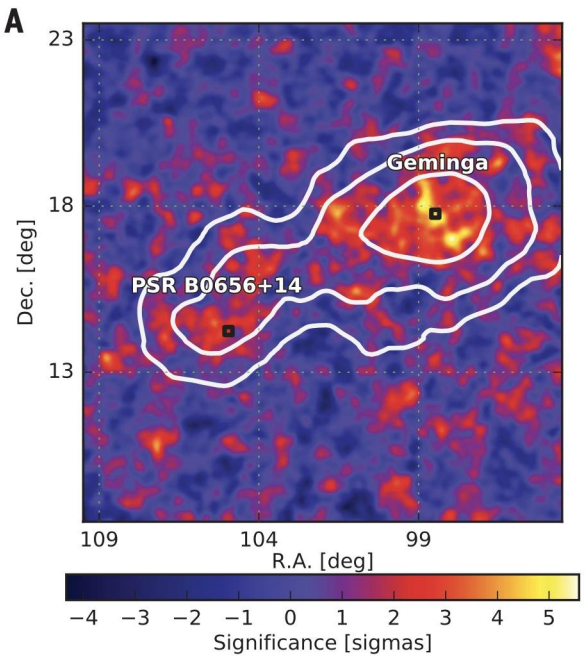
Satellite: funded/proposed

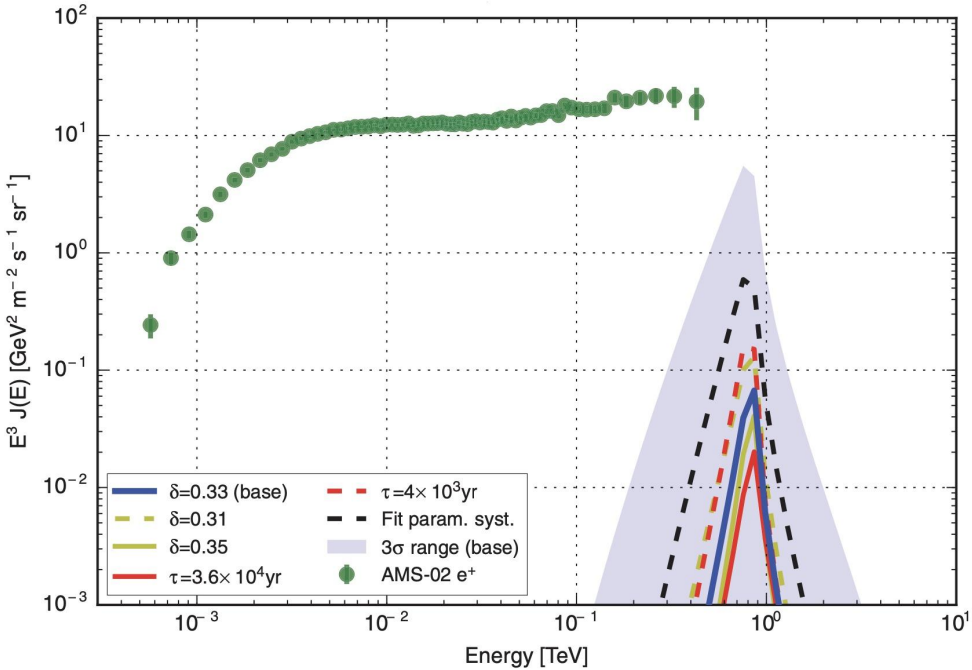
Balloon: funded/proposed

Beam test: funded/proposed

Particle Astrophysics example - TeV halos vs AMS-02 Positron Excess

HAWC Coll. *Science* (2017)

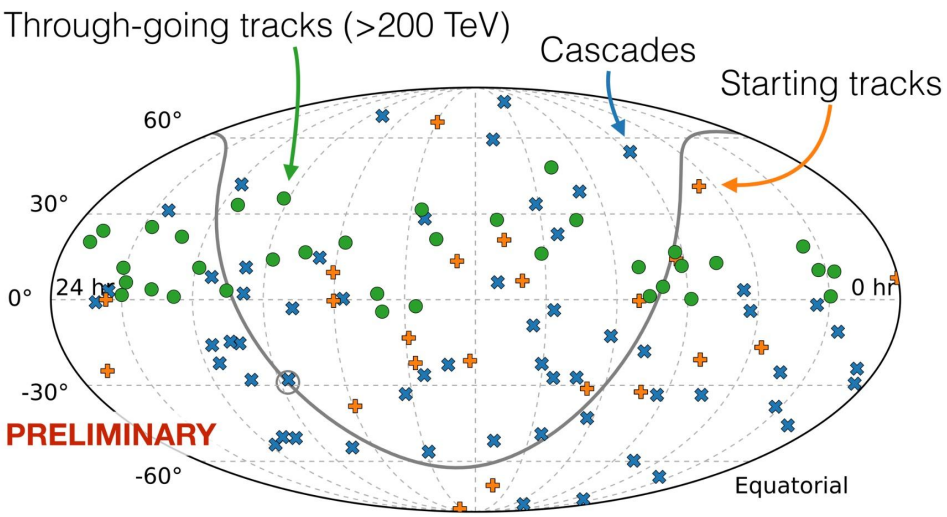




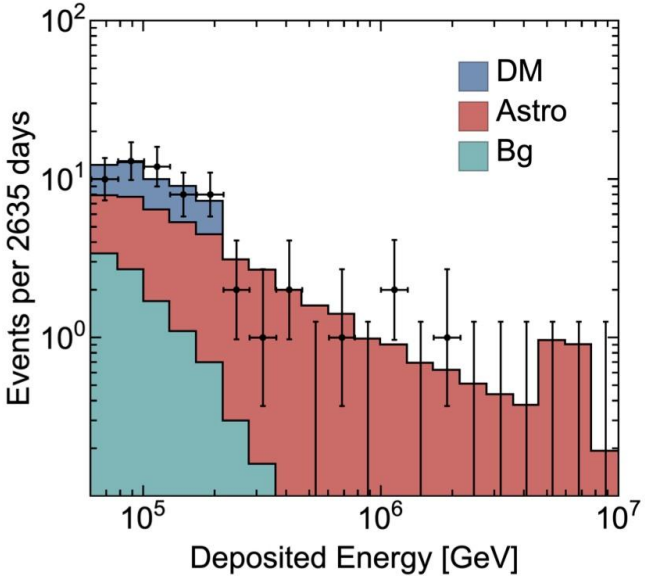
Understanding the astrophysical contribution is crucial to indirect dark matter searches

Particle Astrophysics example - Diffuse High-energy Neutrino Background

IceCube Coll. (2020, 2021, 2022); Reimann, *galaxies* (2017)



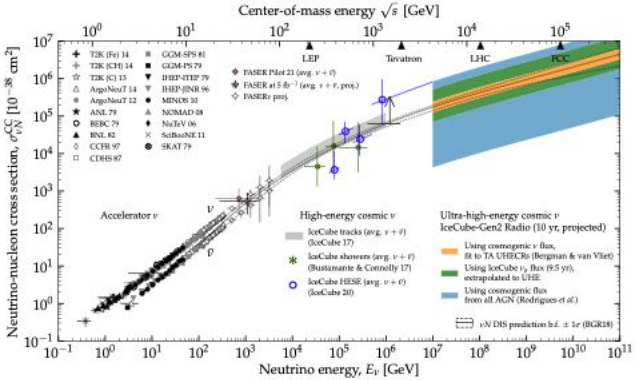
Chianes et al *JCAP* (2019)



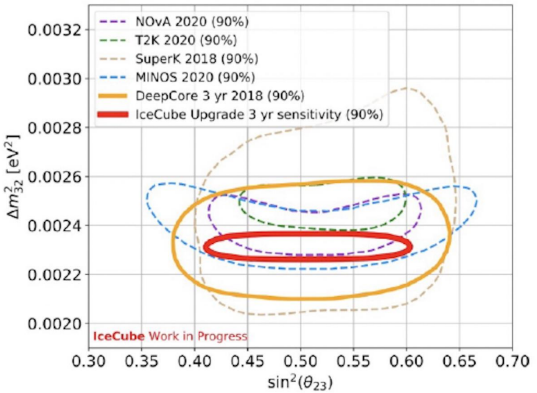
Precise measurements of diffuse emission backgrounds are important to indirect searches

Astroparticle Physics

- **Standard Model particles and their interactions**
- **Beyond-Standard-Model (BSM) neutrino physics:** BSM neutrino interaction with DM, sterile neutrinos, secret neutrino interactions, neutrino flavors
- **Muon puzzle of UHECRs**
- **Nature of matter in neutron star interiors**
- **Test of Lorentz and CPT invariance**
- **Exotic particles in QED domain**

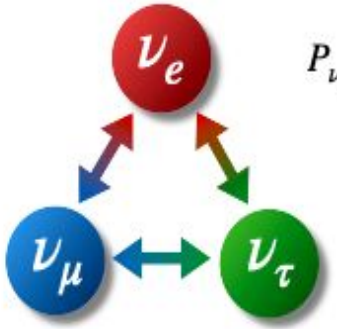


Ackermann et al., *HE and UHE neutrino whitepaper* 2203.08096



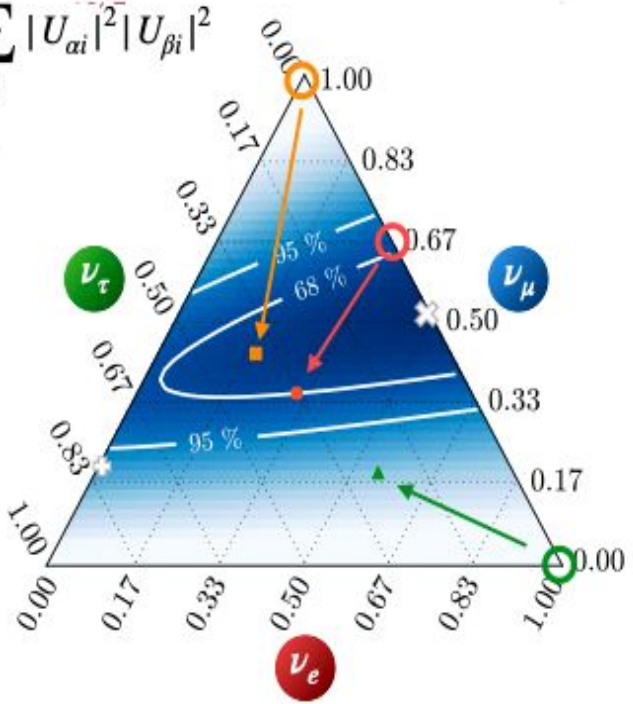
Updated from IceCube Coll. 1908.09441

Astroparticle Physics
in synergy with Neutrino Frontier



$$P_{\nu_\alpha \to \nu_\beta} = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$

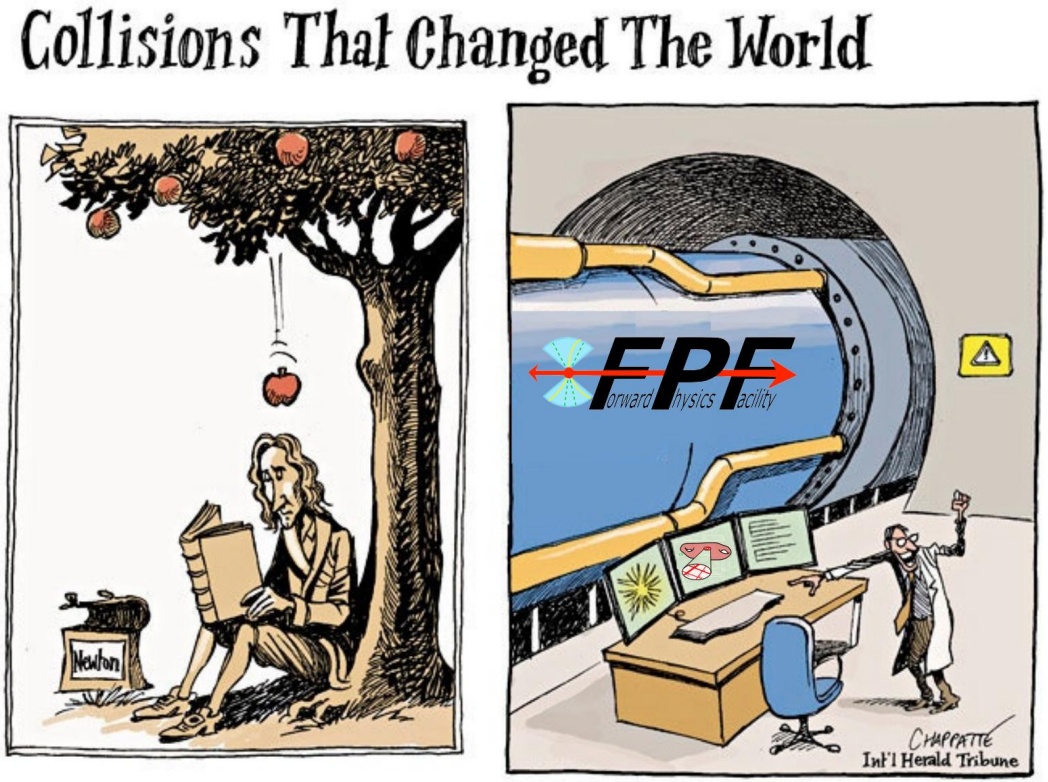
- initial composition: $\nu_e : \nu_\mu : \nu_\tau$
  - *pion & muon decay:* 1 : 2 : 0
  - *muon-damped decay:* 0 : 1 : 0
  - *neutron decay:* 1 : 0 : 0



Galactic sources of UHECR neutrons + electron antineutrinos
unique beam to determine neutrino oscillations parameters

Astroparticle Physics

in synergy with Energy, Accelerator, and Computational Frontiers

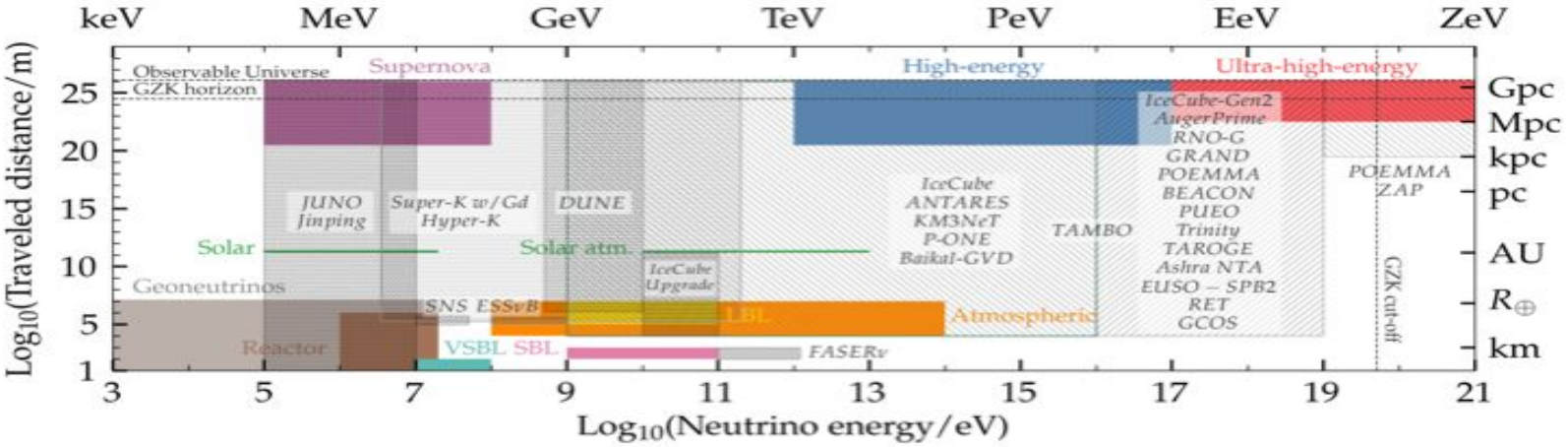


Test of strangeness production: Solving the "muon puzzle" with AugerPrime + CERN's FPF

Instrumentation Roadmap

Experiment	Feature	Cosmic Ray Science	Timeline
Pierre Auger Observatory	Hybrid array: fluorescence, surface e/μ + radio, 3000 km^2	Hadronic interactions, search for BSM, UHECR source populations, $\sigma_{\text{p-Air}}$	AugerPrime upgrade
Telescope Array (TA)	Hybrid array: fluorescence, surface scintillators, up to 3000 km^2	UHECR source populations, $\sigma_{\text{p-Air}}$	TAx4 upgrade
IceCube / IceCube-Gen2	Hybrid array: surface + deep, up to 6 km^2	Hadronic interactions, prompt decays	Upgrade + surface enhancement; IceCube-Gen2 deployment; IceCube-Gen2 operation
GRAND	Radio array for inclined events, up to 200,000 km^2	UHECR sources via huge exposure, search for ZeV particles, $\sigma_{\text{p-Air}}$	GRANDProto 300; GRAND 10k; GRAND 200k multiple sites, step by step
POEMMA	Space fluorescence and Cherenkov detector	UHECR sources via huge exposure, search for ZeV particles, $\sigma_{\text{p-Air}}$	EUSO program; POEMMA
GCOS	Hybrid array with $X_{\max}$ + e/μ over 40,000 km^2	UHECR sources via event-by-event rigidity, forward particle physics, search for BSM, $\sigma_{\text{p-Air}}$	GCOS R&D + first site; GCOS further sites

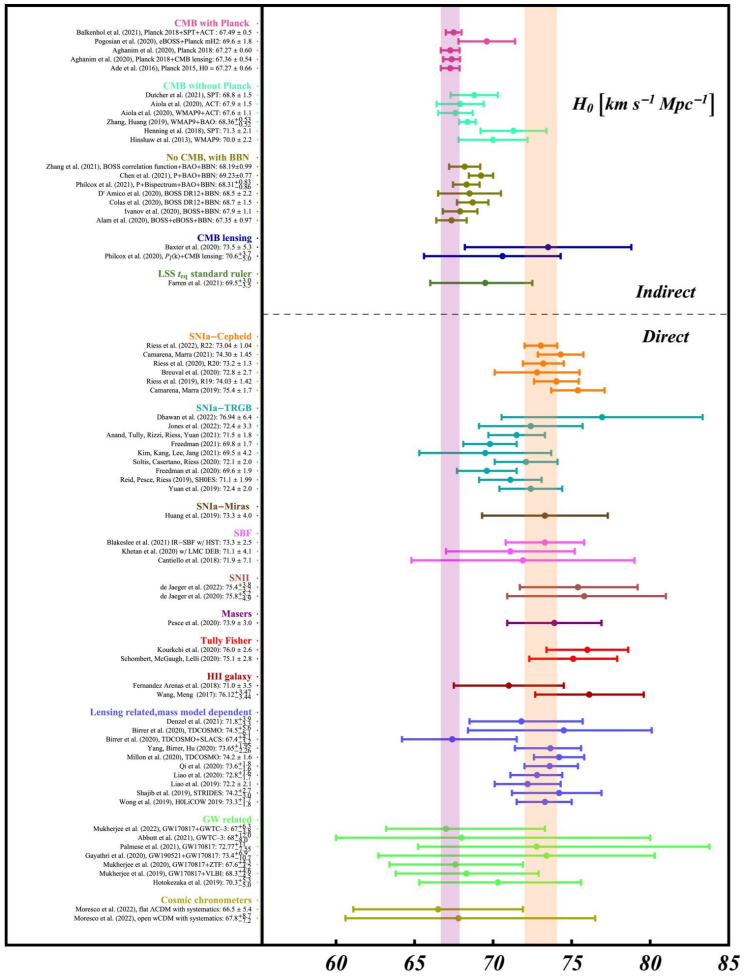
2025 2030 2035 2040



History of the Universe and Cosmology

- **Hubble constant (H_0) tension** (in synergy with CF4-6)
- **Imprints from early universe:** cosmic strings, primordial GW from inflation, GW from phase transitions
- **Super-have dark matter particles produced at the end of inflation**: ultrahigh-energy cosmic rays, photons, and neutrinos
- **Inferring the Neutrino Mass from Cosmological Probes**

  NF5-CF7 cross-frontier discussion session in HUB 307 (July 22 8:00 to 12:00)

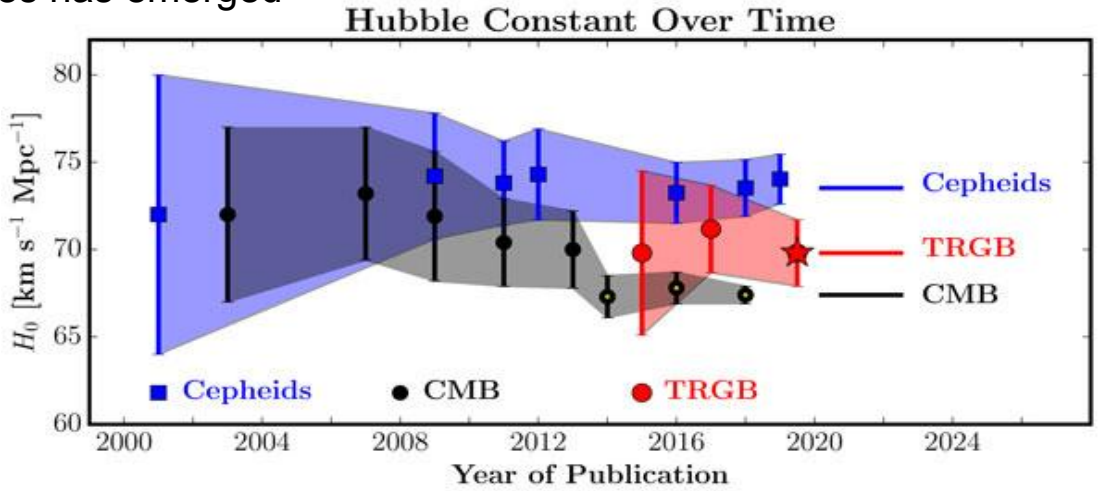


Abdalla et al., *Cosmology Intertwined whitepaper* 2203.0614

Hubble constant tension

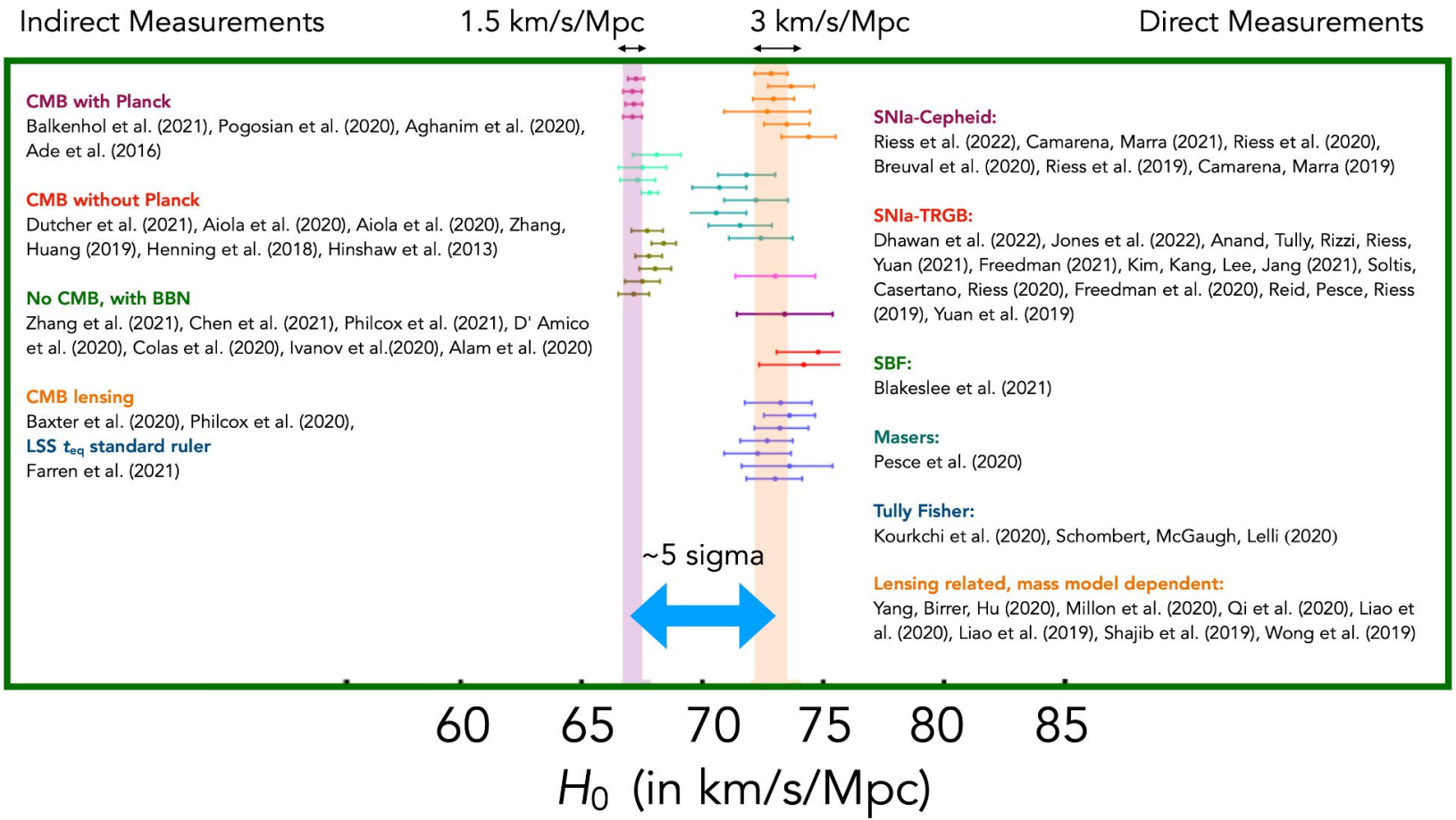
- After last Snowmass an intriguing inconsistency between measurements of the cosmic expansion rate based on early- and late-Universe probes has emerged

- This inconsistency shows up as a discrepancy in the value of H_0 as inferred from measurements of CMB anisotropies and as measured from a series of distance indicators in the local Universe

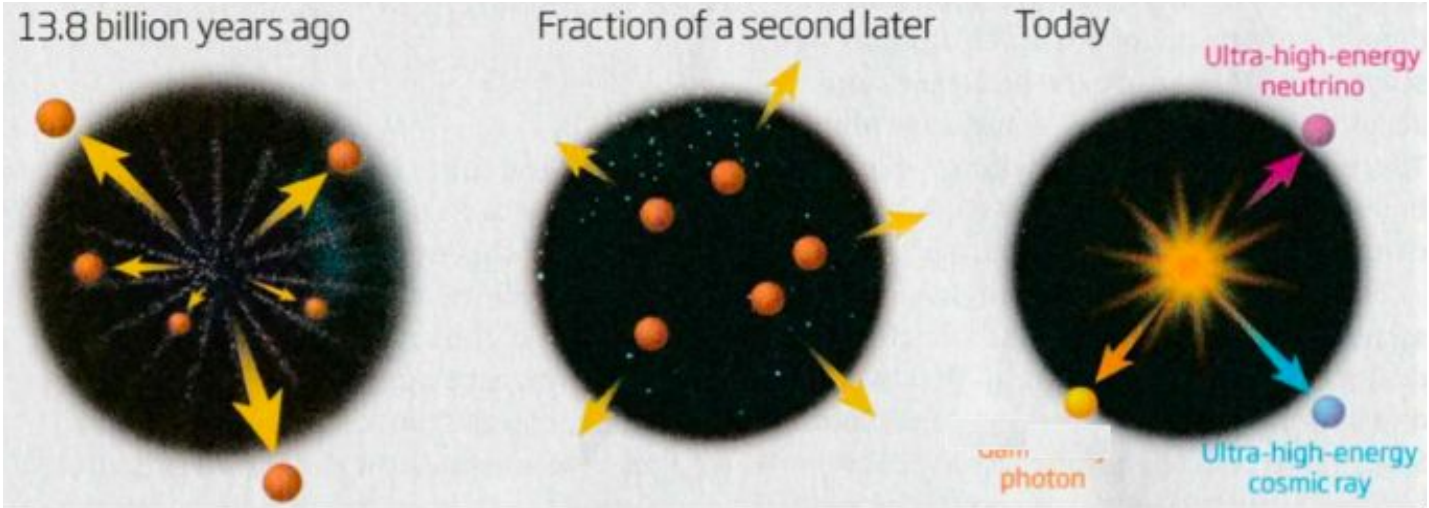


- Depending on which set of measurements one combines ➤ tension between model-dependent and independent estimates of H_0 sits between 4.5σ to 6.3σ
- The H_0 tension has become new cornerstone of modern cosmology and many new-physics setups are rising to the challenge
- Is the H_0 tension a footprint of BSM physics?
- Roughly 50 GWSS with EM counterparts would be needed to measure H_0 to 1% precision

High Precision Measurements of the Hubble Constant



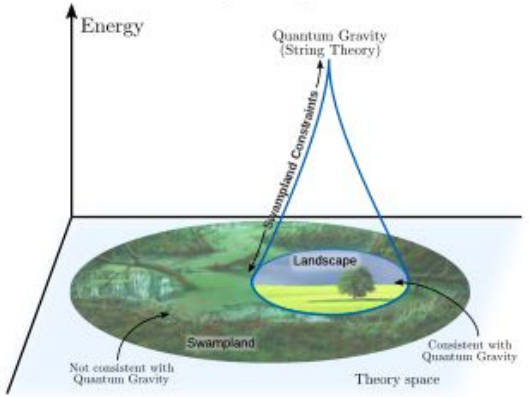
Birth and death of superheavy X-particles



- Intense fluctuating gravitational fields gave birth to superheavy X-particles just after the big bang
- The expansion of space during inflation distributed the X-particles through the cosmos
- After billions of years the X-particles decay producing a range of detectable particles
  particle physics factor (solving DGLAP numerically)
- To estimate the flux of detectable particles we need to evaluate:
  astrophysical factor (with roughly 10% uncertainty)
- X-particle have GUT scale masses ➽ background free dark matter indirect detection experiments!
- *A clear detection of an extreme energy photon would be momentous discovery*

Quantum Gravity Constraints on Low Energy Dynamics
in synergy with Theory Frontier

Swampland: IR consistent QFTs that cannot be embedded into a UV complete QGT

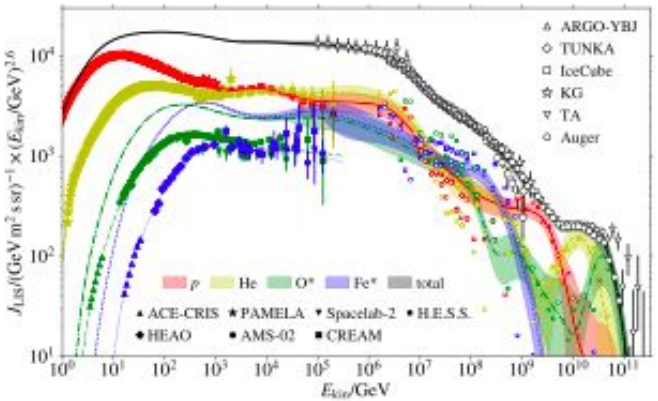


- **This sorting of QFTs by their consistency with gravity has become an unexpectedly powerful theoretical tool offering potential solutions to the problems of fine-tuning**
- **E.g. Cosmological Hierarchy Problem** $\Lambda \sim 10^{-122}\ M_{\rm Pl}^4$
- **Local EFT breakdown at higher-dim Planck scale:**

$$M_{\rm UV} \sim \lambda^{-1/3} \Lambda^{1/12} M_{\rm Pl}^{2/3} \sim 10^{10}\ {\rm GeV}$$

- **Is the cutoff of the CR spectrum driven by** $M_{\rm UV}$ **?**
- **Connection to the** H_0 **tension?**

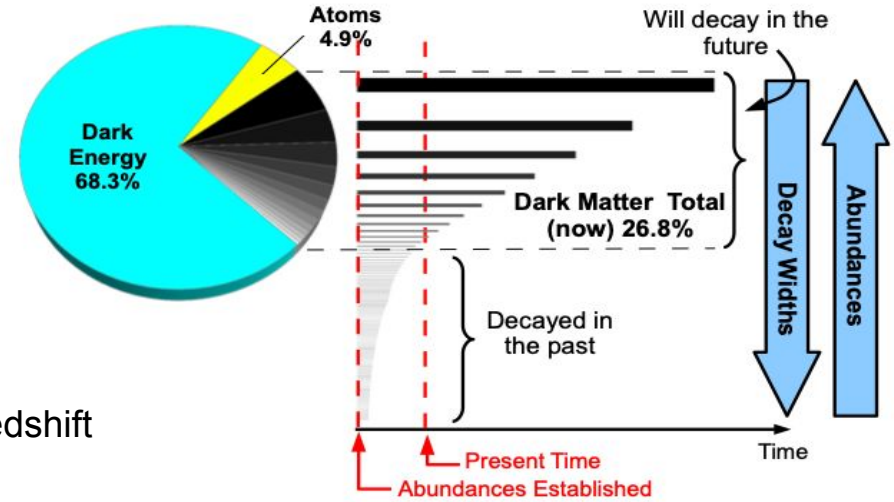
See Montero-Vafa-Valenzuela arXiv:2205.12293



Cosmology of non-minimal dark sectors

- Dynamical Dark Matter (DDM) is a framework for non-minimal dark sectors which posits that the dark matter in the Universe comprises a vast ensemble of interacting fields with a variety of different masses, lifetimes, and cosmological abundances

- Distinctive probe of secluded dark sectors



- Dark-to-dark decays modify the way in which the expansion rate of the Universe evolves with redshift

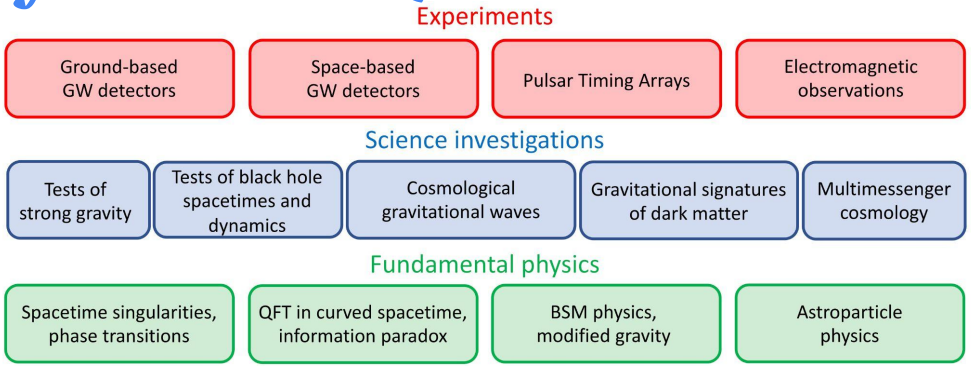
- E.g. dark-to-dark decays of a DDM ensemble alter the dependence of H(z) on z and so DDM framework can potentially provide a way of addressing the H_0 tension

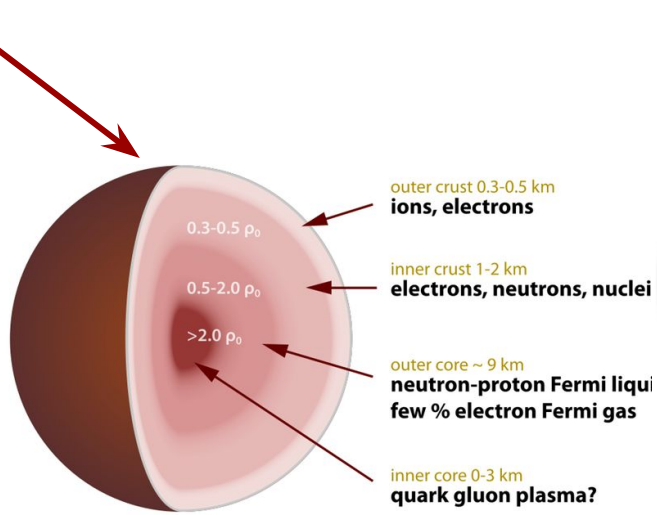
- 13 “take-away lessons” for Snowmass 2021

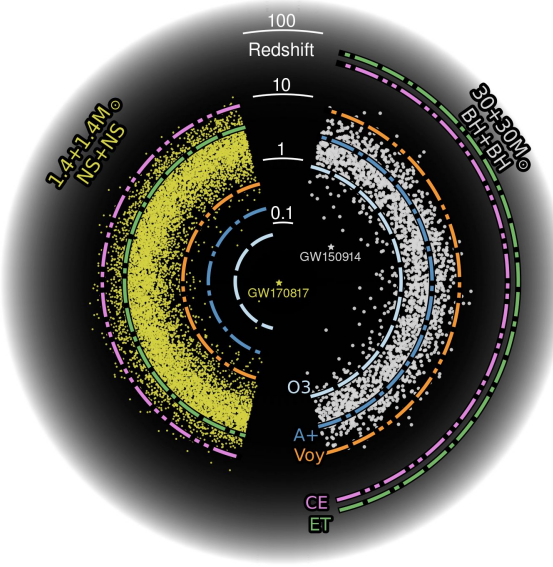
see Dienes and Thomas arXiv2203.17258:

Gravitational Waves: Key Science Questions

- Black holes and neutron stars throughout the Universe
  - Axion clouds around black holes
  - Primordial black holes
- Dynamics of dense nuclear matter
  - Equation of state ($p > 10^{17}$ kg/m^3)
  - QCD phase diagram
  - Synthesis of heavy elements in the Universe
  - Synergies w Rare Isotope studies (e.g. FRIB)
- Physics beyond the standard model
  - Dark matter in neutron stars
  - Modified gravity; spacetime structure
  - What is the nature of BH Horizons?
  - Boson stars and other exotic objects
  - Precision cosmology for H_0 and dark energy

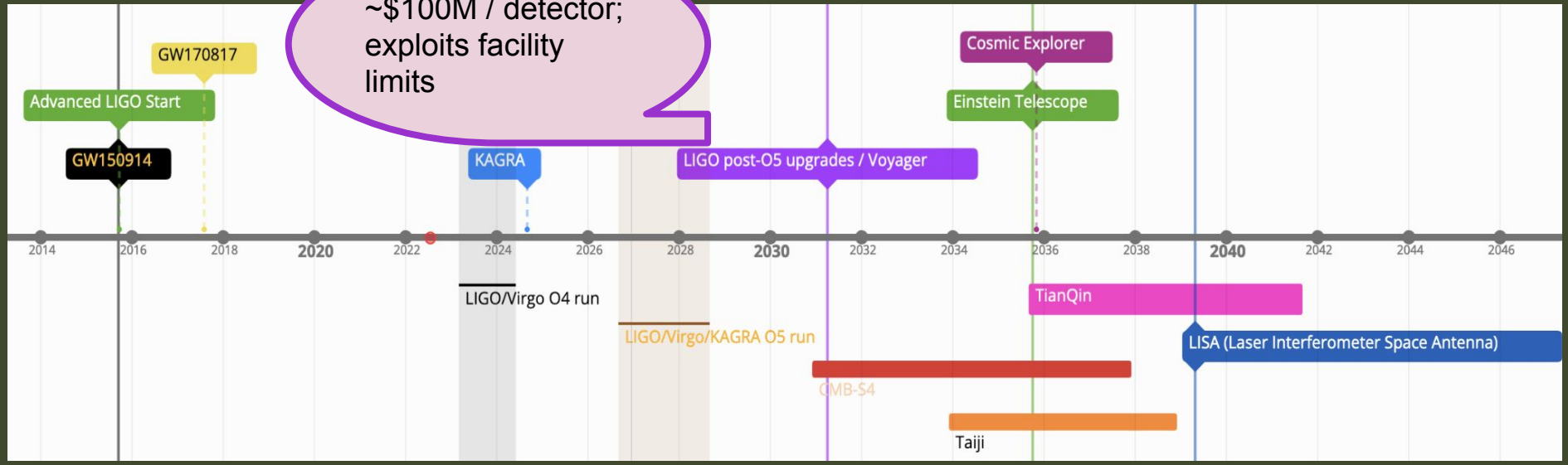


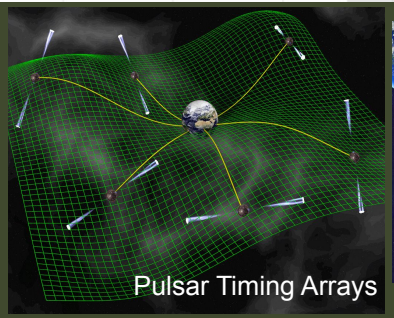


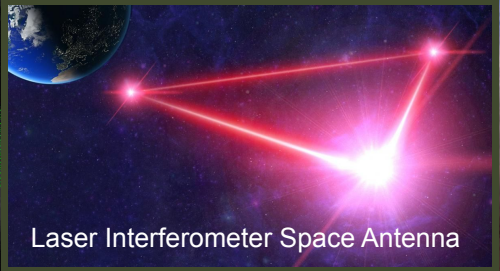


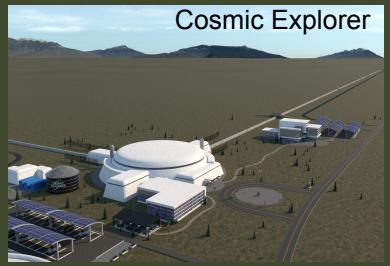
Gravitational Waves: Facilities and Timeline

~$100M / detector; exploits facility limits

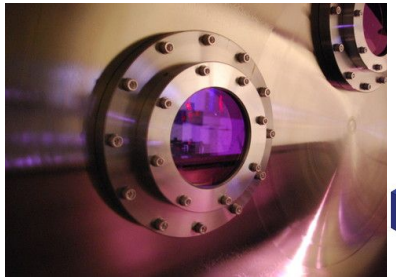


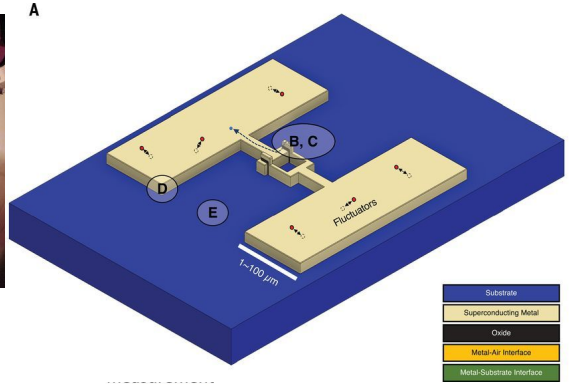


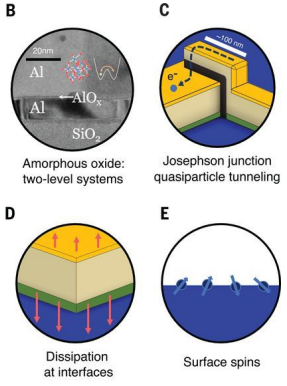




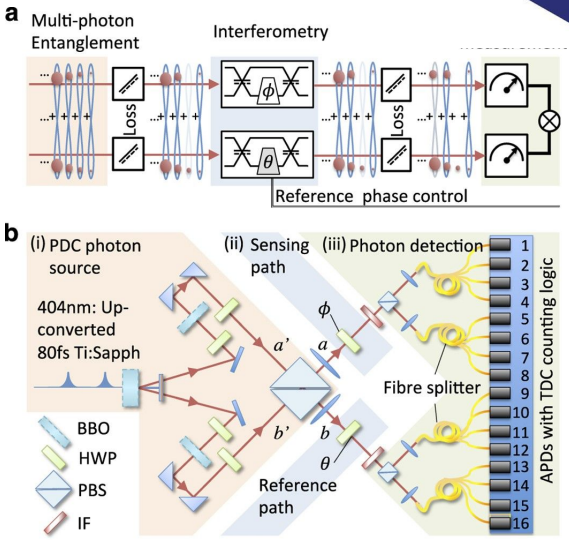
GW Instrumentation Roadmap*

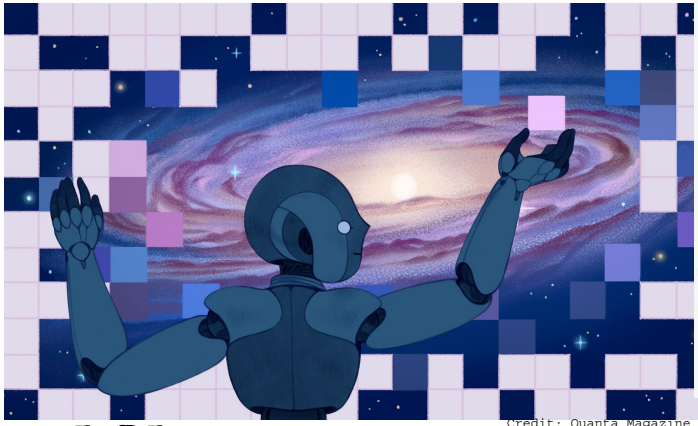






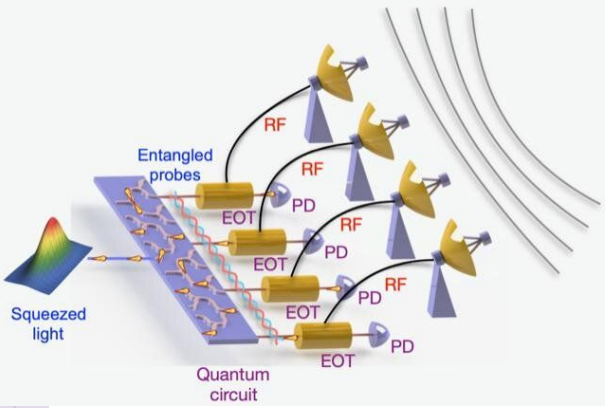
UHV tubes ~ 10-40 km





Credit: Quanta Magazine

ML: RL control systems



*many synergies with existing HEP expertise/goals

Link to CF7 Report:
https://www.dropbox.com/s/7aaxxlmtcjvxyqb/CF7-report.pdf?dl=0

Feedback form:
https://forms.gle/kKuWWPgRaohQ8YqN7

Conclusion:
Great Opportunities for Discoveries

- Several Science Objectives from Multi-Messenger Probes (EM, UHECR, GW)
- Cosmic Probes of Dark Matter: Particle, wave, or modified gravity
-