

# Cosmic Probes of Fundamental Physics (CF7)

An overview of the draft report and community discussion

Tiffany Lewis - NASA Goddard Space Flight Center  
B Sathyaprakash - Pennsylvania State University

# Discussion Outline

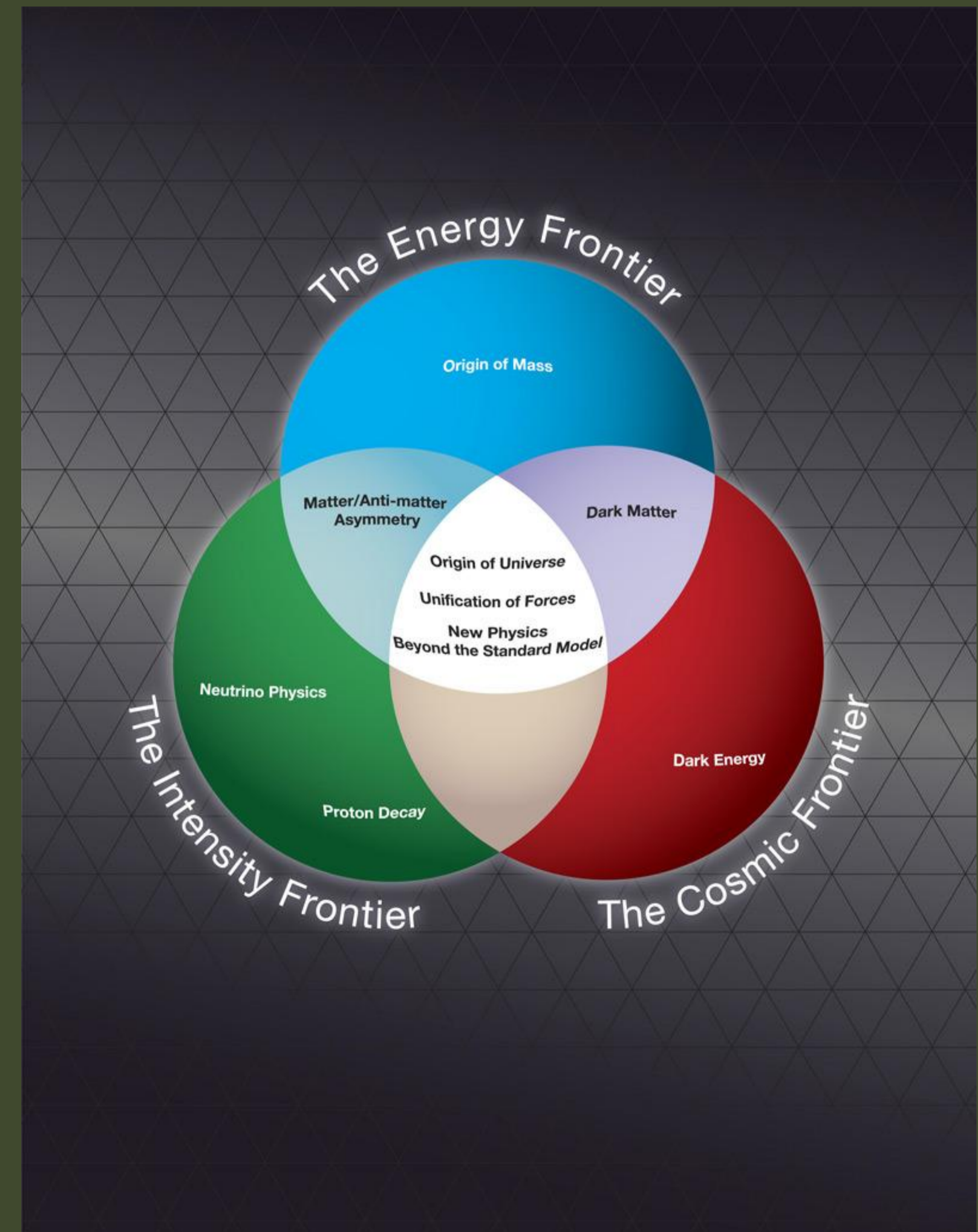
- Overview Presentation of Report
  - 15-20 min
- Open Discussion
  - Q&A
  - Suggestions
  - 40-45 min

CF7 Report:

<https://www.dropbox.com/s/7aaxxlmtcjvxyqb/CF7-report.pdf?dl=0>

Feedback form:

<https://forms.gle/kKuWWPqRaohQ8YqN7>



# Report Outline

- Big Questions & Goals for the Next Decade
  - History of the Universe & Cosmology
  - Cosmic Probes of Dark Matter
  - Astroparticle Physics
  - Multimessenger Synergies in Particle Astrophysics
  - Architecture of Spacetime
- Current & Future Experiments
- Connections to Other Snowmass Frontiers
- Diversity, Equity, Inclusion & Accessibility

The Standard Model is inherently incomplete. It does not explain all physical phenomena. One of the most challenging problems in High-Energy Physics is to elucidate the complete theory underlying the SM.

# Diversity Equity Inclusion Accessibility

DEIA support means providing educational and career development opportunities to potential scientists whose background did not provide them.

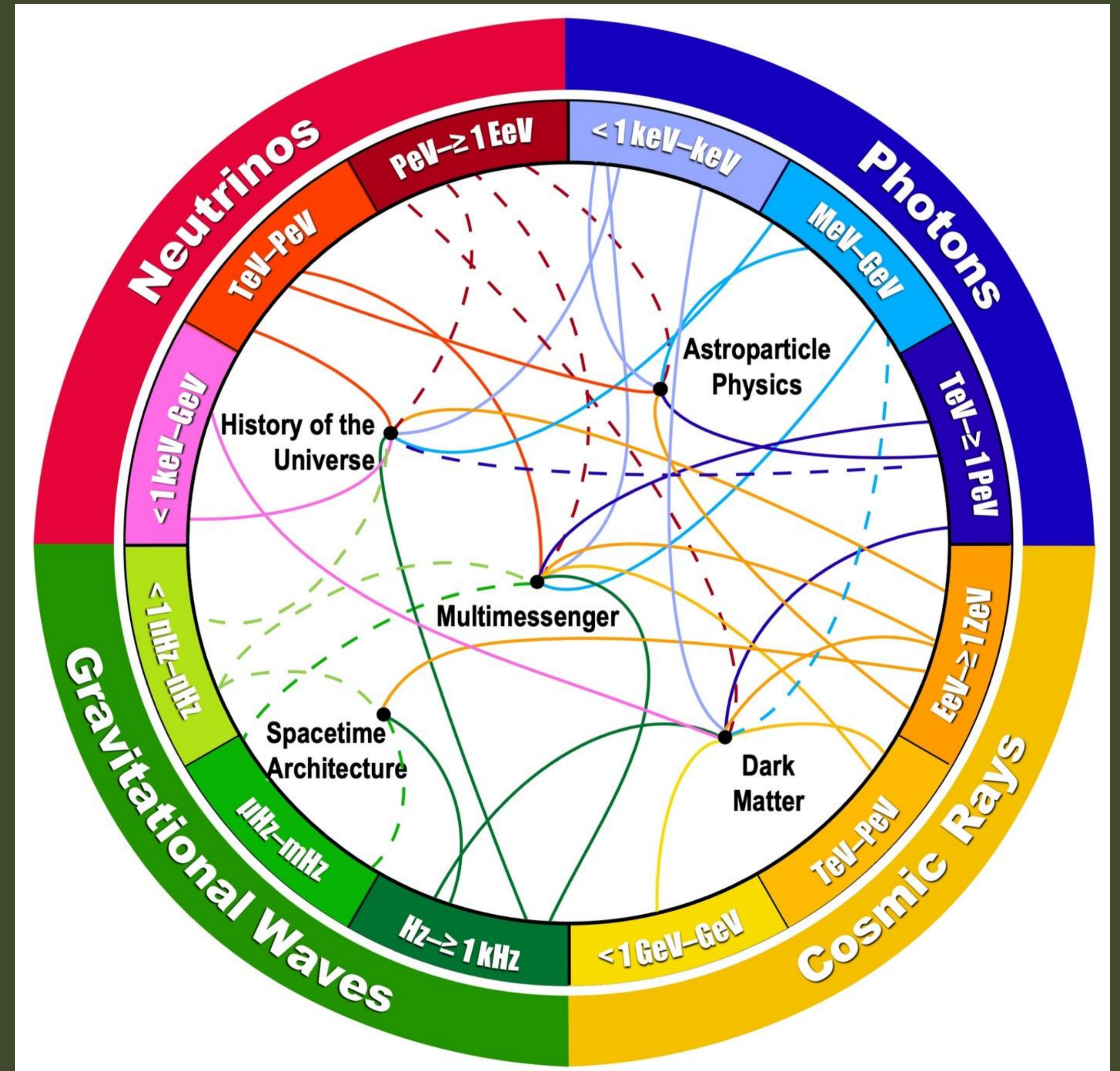
It means examining our decisions about admissions, hiring, teaching and mentoring to support excellence in the whole community, by making sure each individual achieves their full potential.

Recommendations:

- Track demographic information for collaborations
  - Especially PIs
  - Include at a min: gender & ethnicity
  - Release aggregate data publicly
- Where money goes, so does demographic record keeping
- Consider DEIA service in hiring & evaluation in a similar fashion as other service work (e.g. refereeing papers, review panels, mentoring, etc)

# Big Science Questions

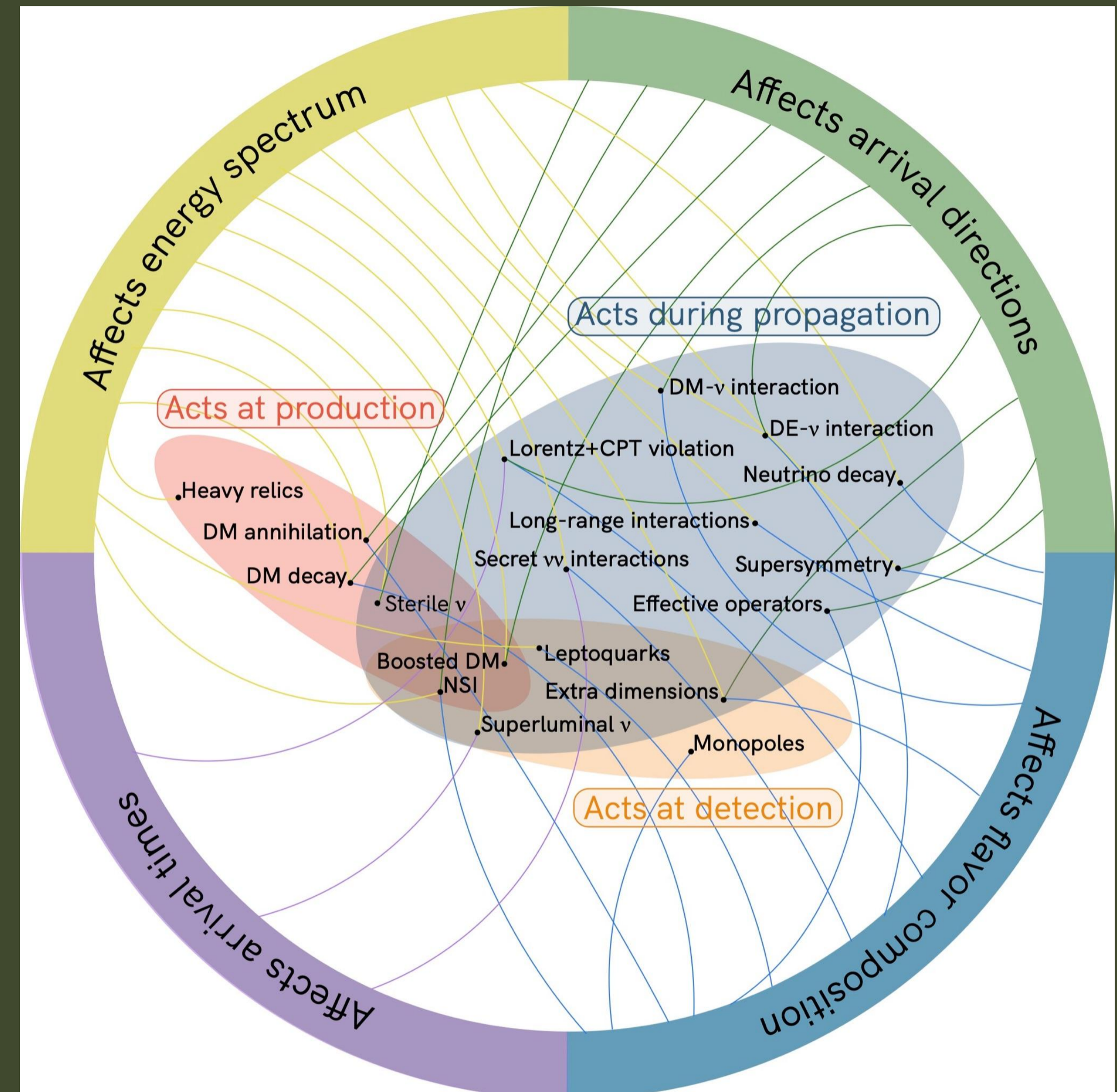
- 5 categories of Big Science Questions over the next decade
- Solid lines: established connections; dashed lines: anticipated connections
- Coordination between energies and messengers is imperative to rapid progress in the study of most important questions.



# Cosmic Neutrinos as BSM Probes

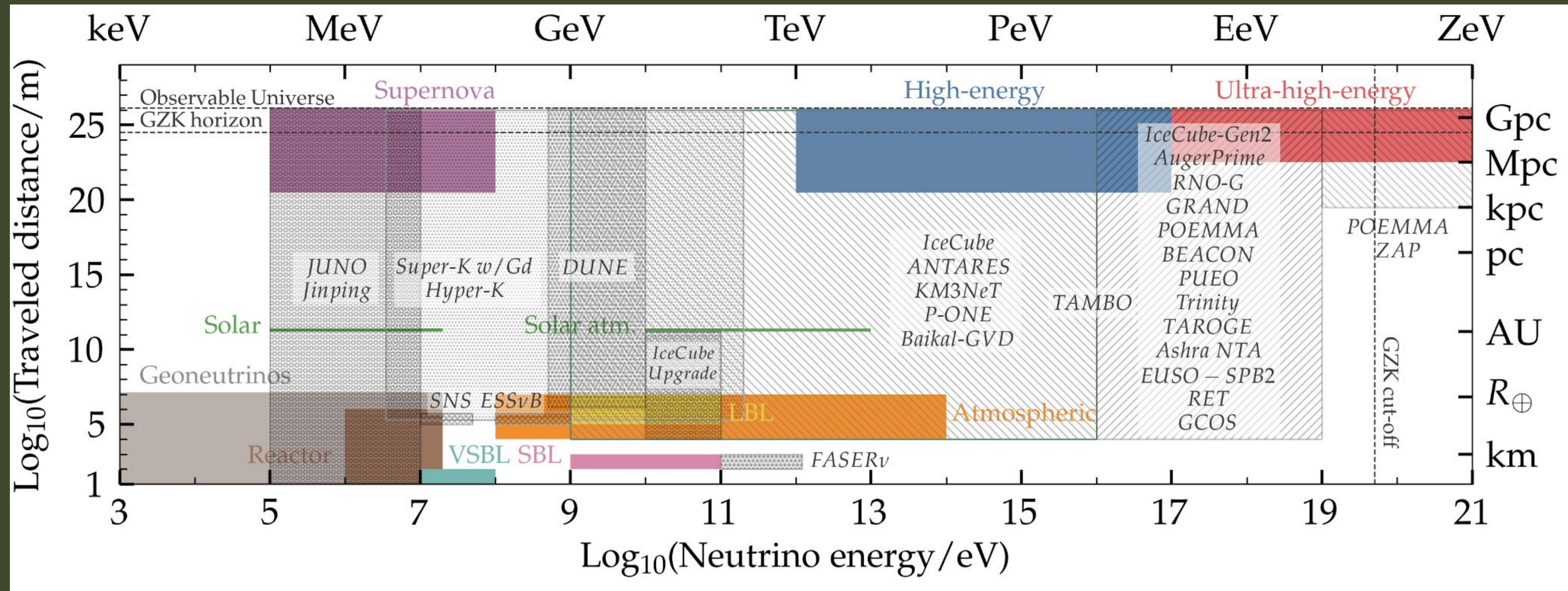
Models of new neutrino physics classified according to the stage at which they act, and what feature they affect. Ref. Arguelles et al. (2020)

Since neutrinos travel the longest distance unscathed, even tiny effects can accumulate into observable phenomena.



Credit: Neutrino WP

# Neutrino Discovery Space



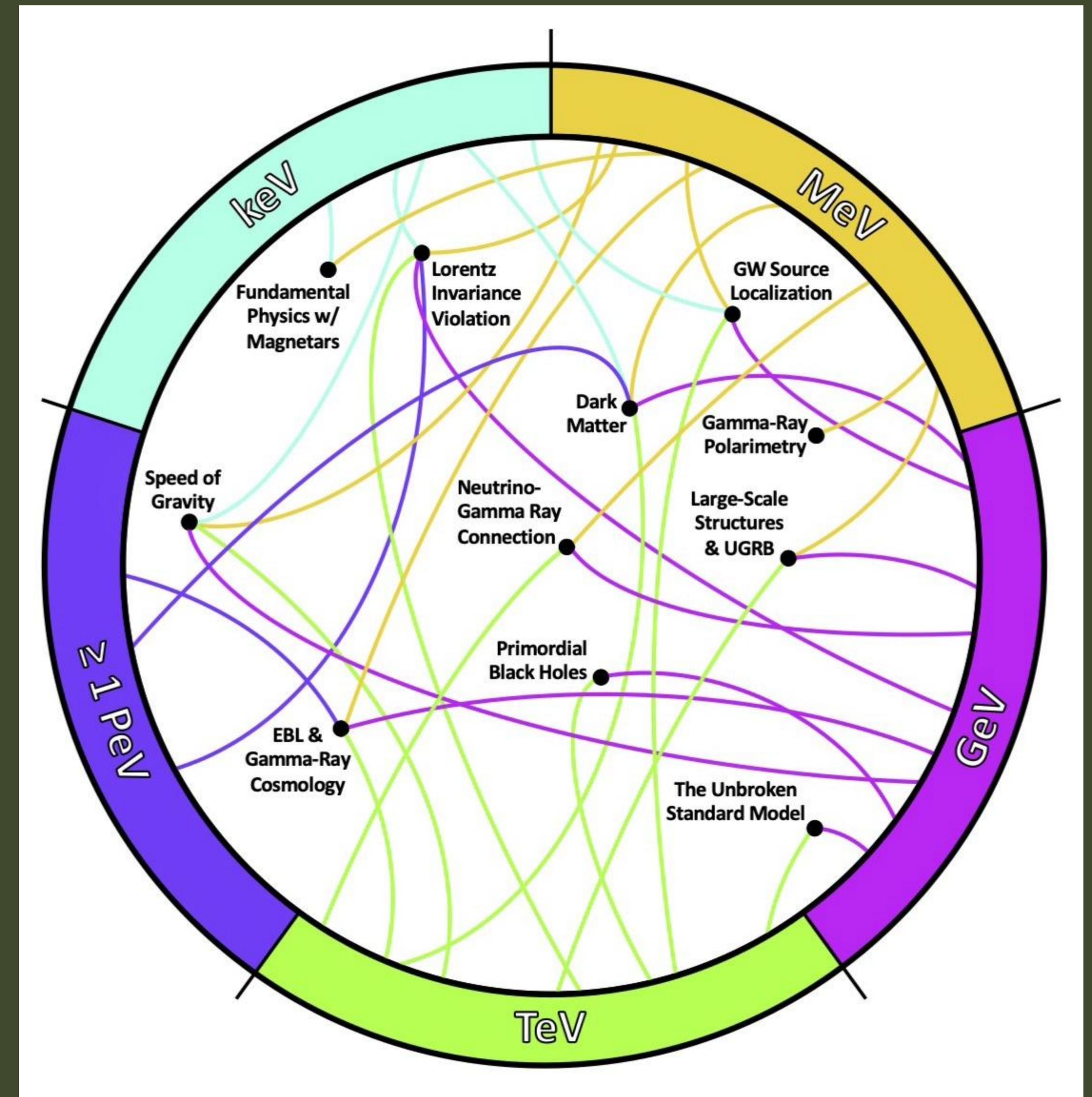
Future work will build on IceCube's discoveries to probe:

- Nature of Dark Matter
- New particles and interactions
- New fundamental symmetries

HE and UHE neutrinos can probe physics at energy scales inaccessible in the lab. Illustration of phenomena and experiments by neutrino energy and distance.

# Key Gamma-Ray Science

- Gamma rays provide a unique view of extreme environments
  - Magnetars, Active Galaxies, Cosmology, etc
- Crucial to Multimessenger Studies
  - GRB 170817 GeV with GW
  - TXS 0506+056 GeV with neutrinos
- To probe fundamental physics beyond earth, we have to understand the Universe's laboratories through Astrophysics.

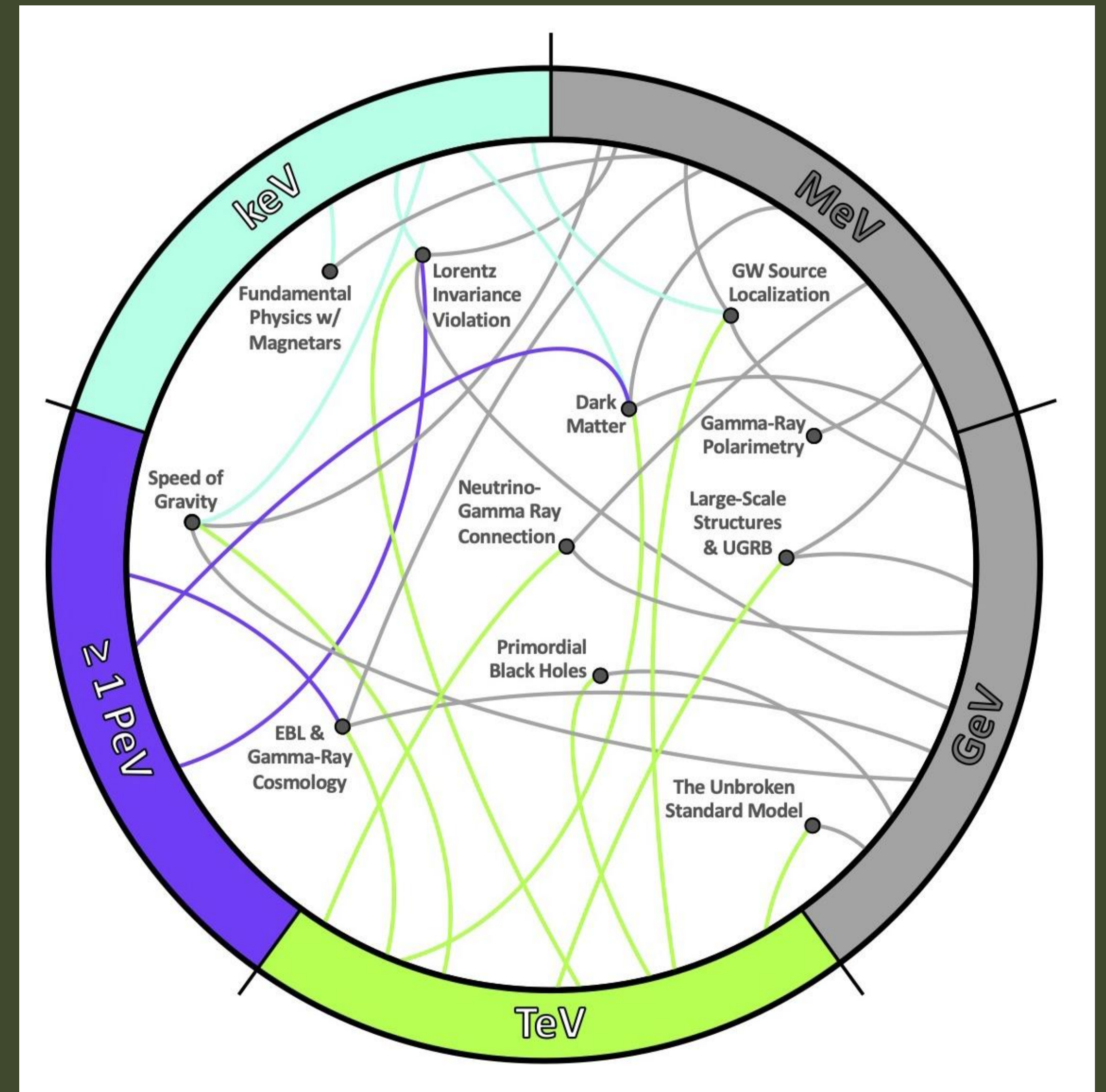


Credit: Kristi Engel; Gamma Ray WP



# Key Gamma-Ray Science

- Gamma rays provide a unique view of extreme environments
  - Magnetars, Active Galaxies, Cosmology, etc
- Crucial to Multimessenger Studies
  - GRB 170817 GeV with GW
  - TXS 0506+056 GeV with neutrinos
- To probe fundamental physics beyond earth, we have to understand the Universe's laboratories through Astrophysics.

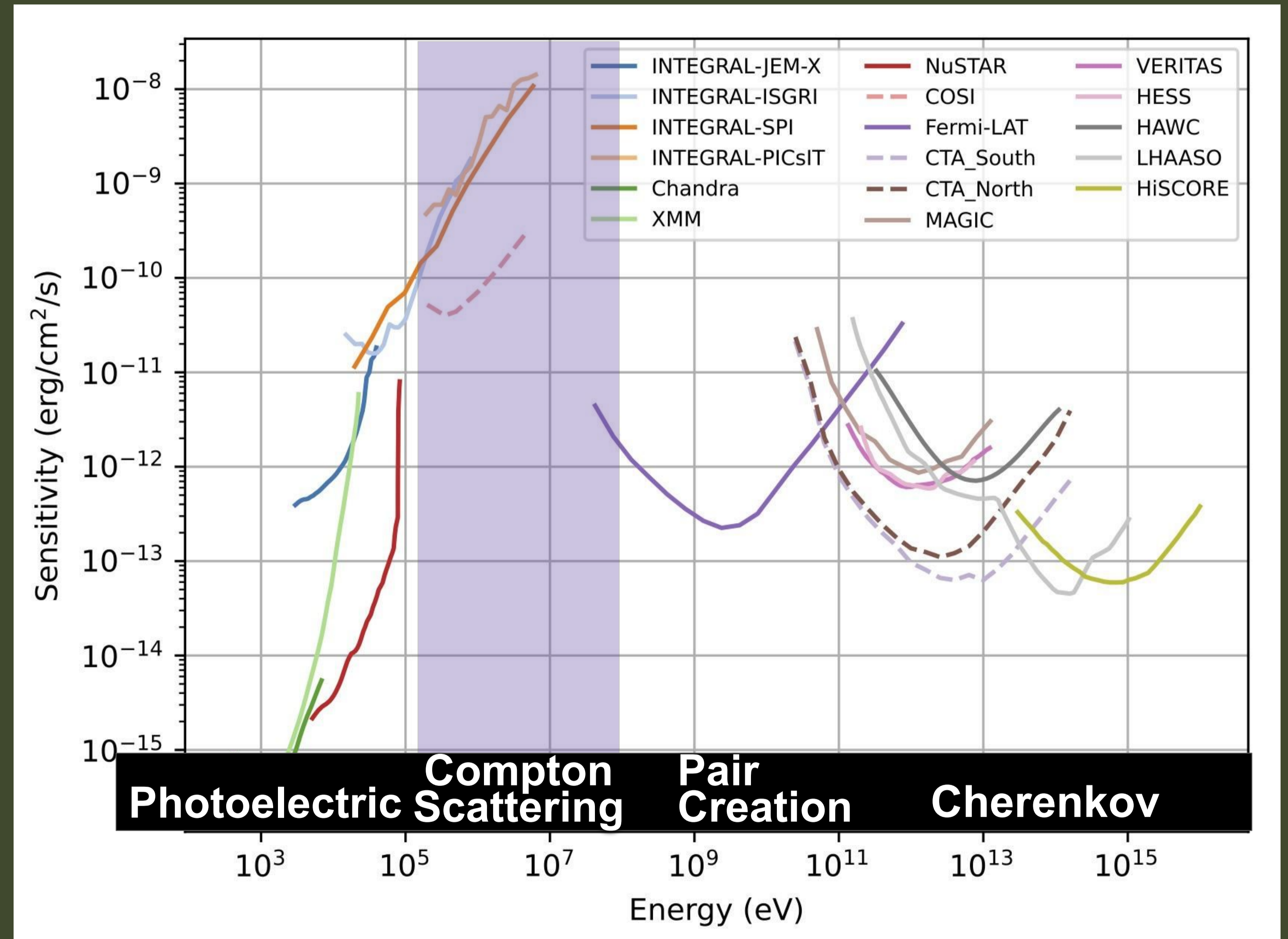


Credit: Kristi Engel; Gamma Ray WP

# Gamma-Ray Detector Development

A key opportunity in the next decade is in MeV gamma-ray detector development.

- Unprobed astrophysics - DM, Diffuse, AGN, Pulsars,
- Key space to Multimessenger
- Relevant to collider detector development



Credit: Henrike Fleischhack; Gamma Ray WP

# Particle Physics with Ultra-High-Energy Cosmic Rays

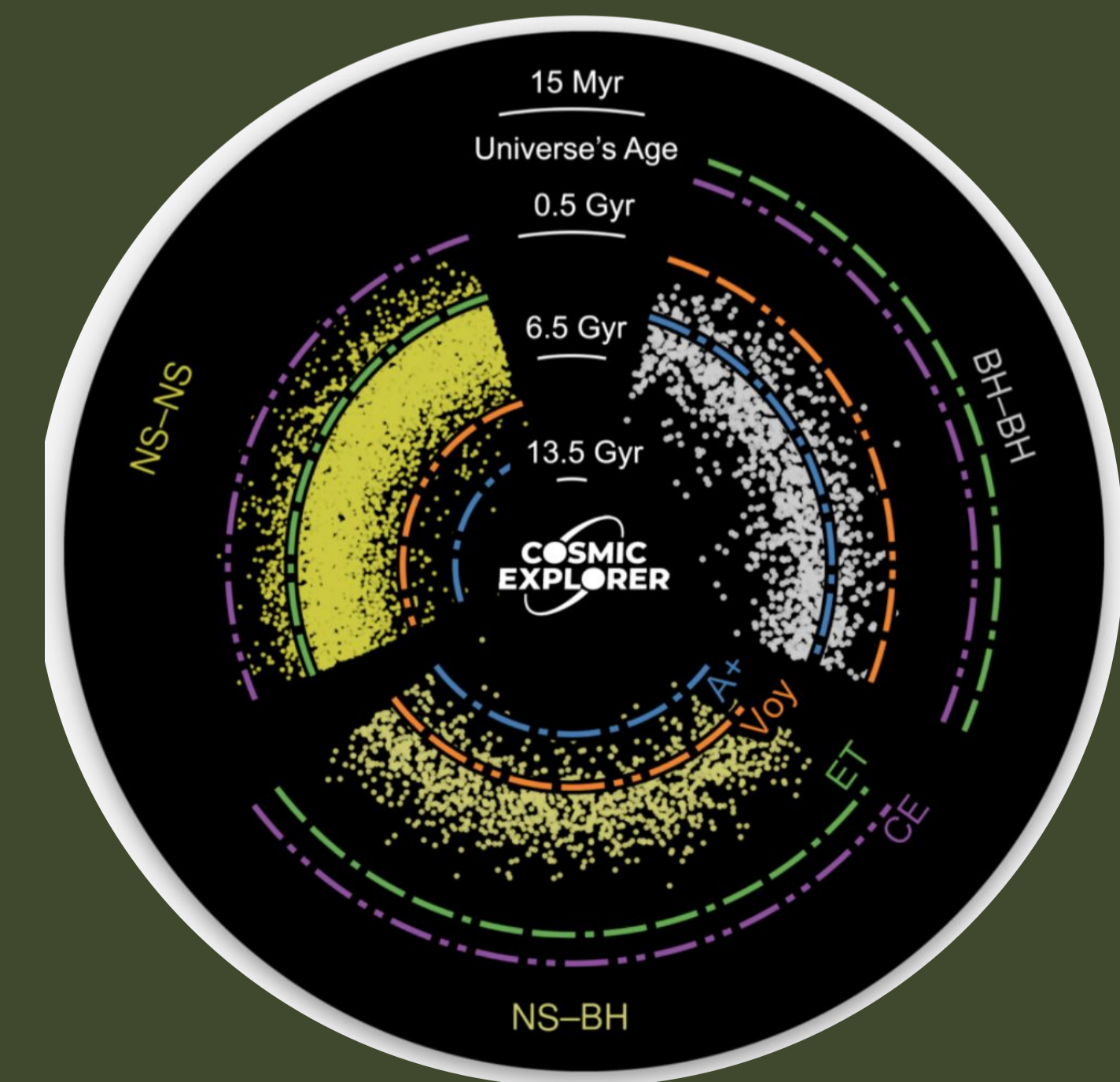
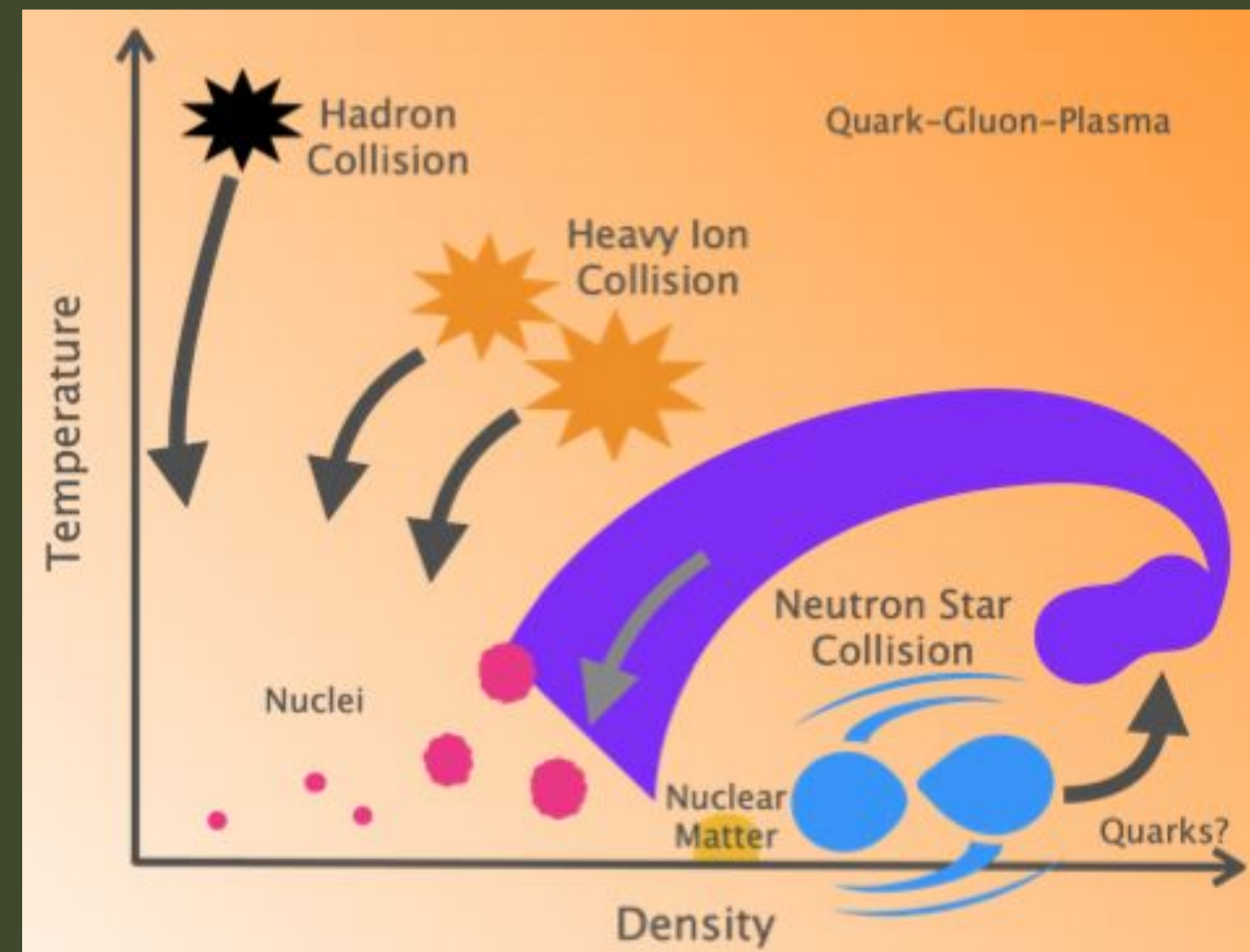
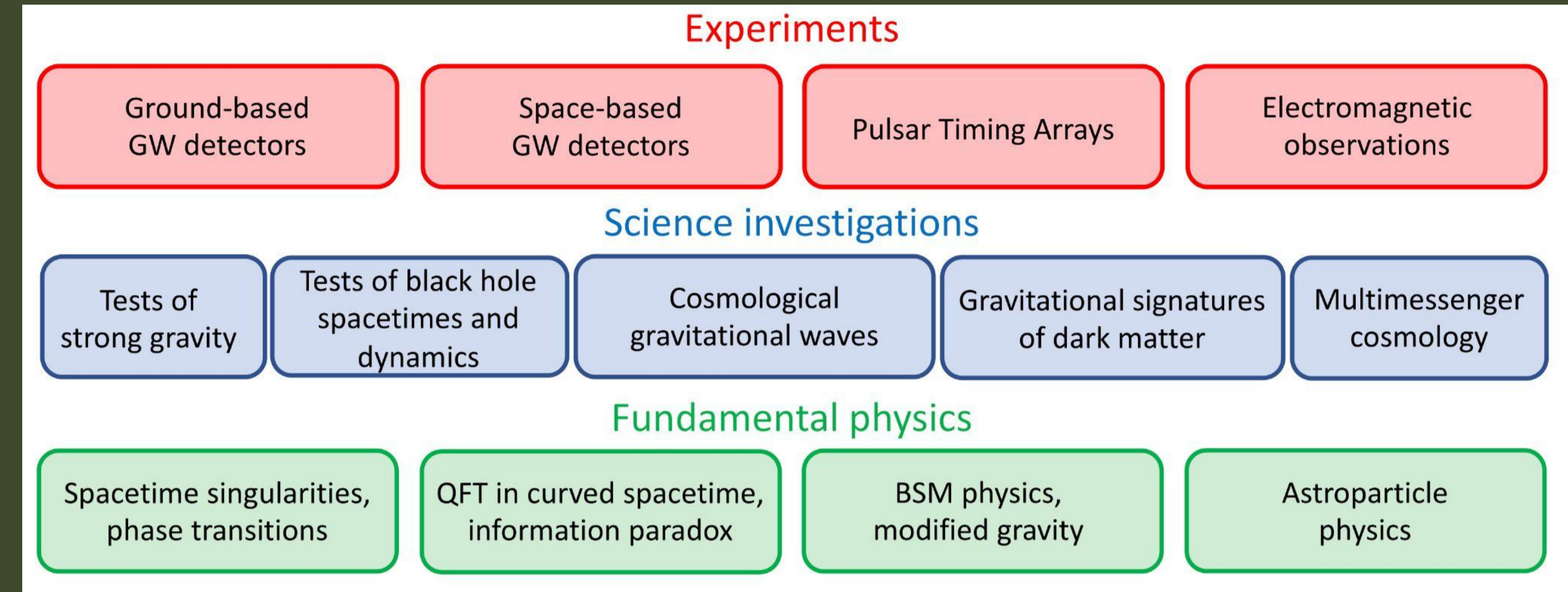
- Test of hadronic interaction models at c.m. energies and kinematic regimes not accessible at colliders
- Test of strangeness production answering the muon puzzle with AugerPrime and the CERN's Forward Physics Facility
- Test of Lorentz invariance during both cosmic ray propagation and air shower evolution
- Only background free dark matter indirect detection experiments!
- Highest energy cosmic rays are an incisive probe of UV physics

# Instrumentation Roadmap

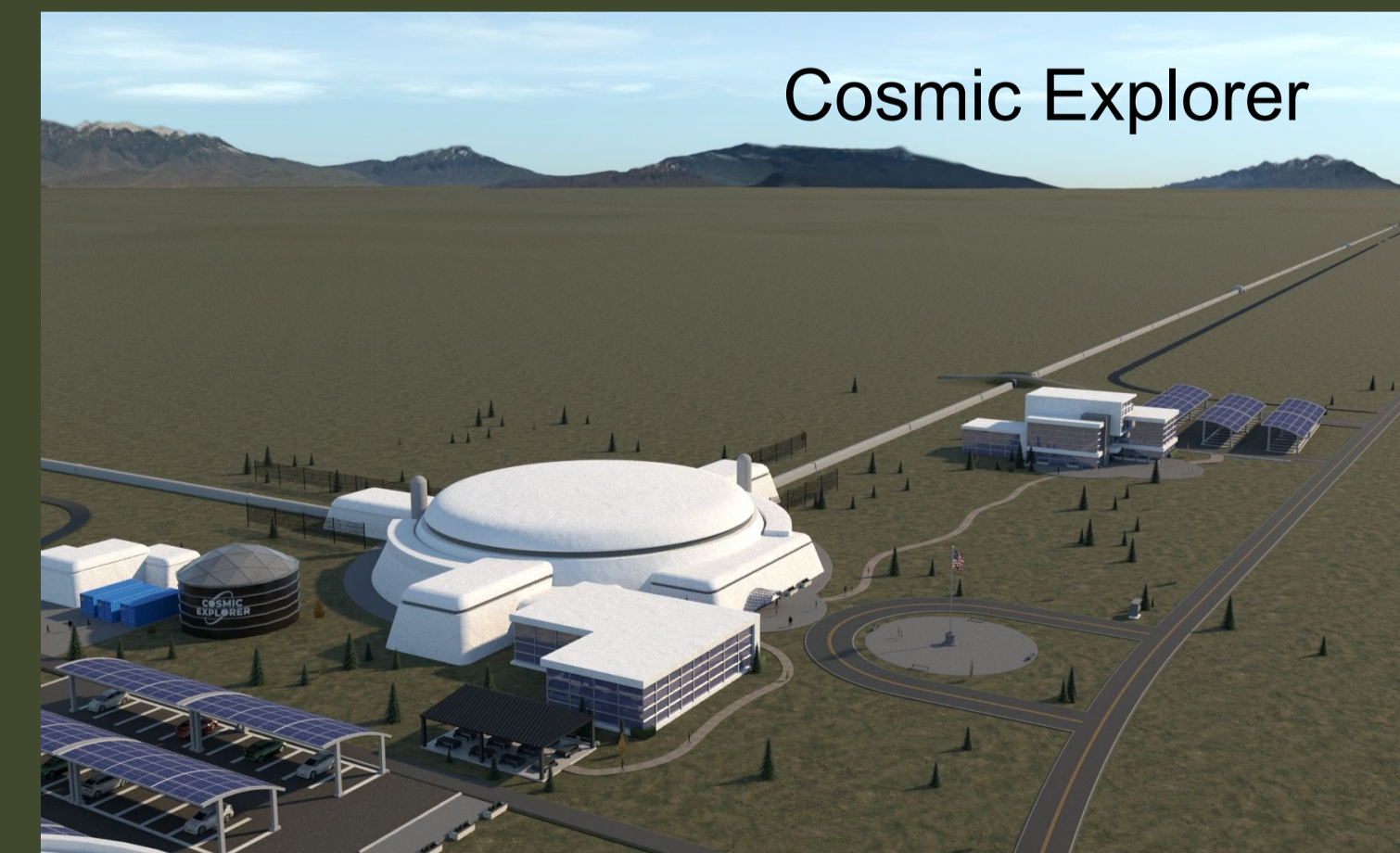
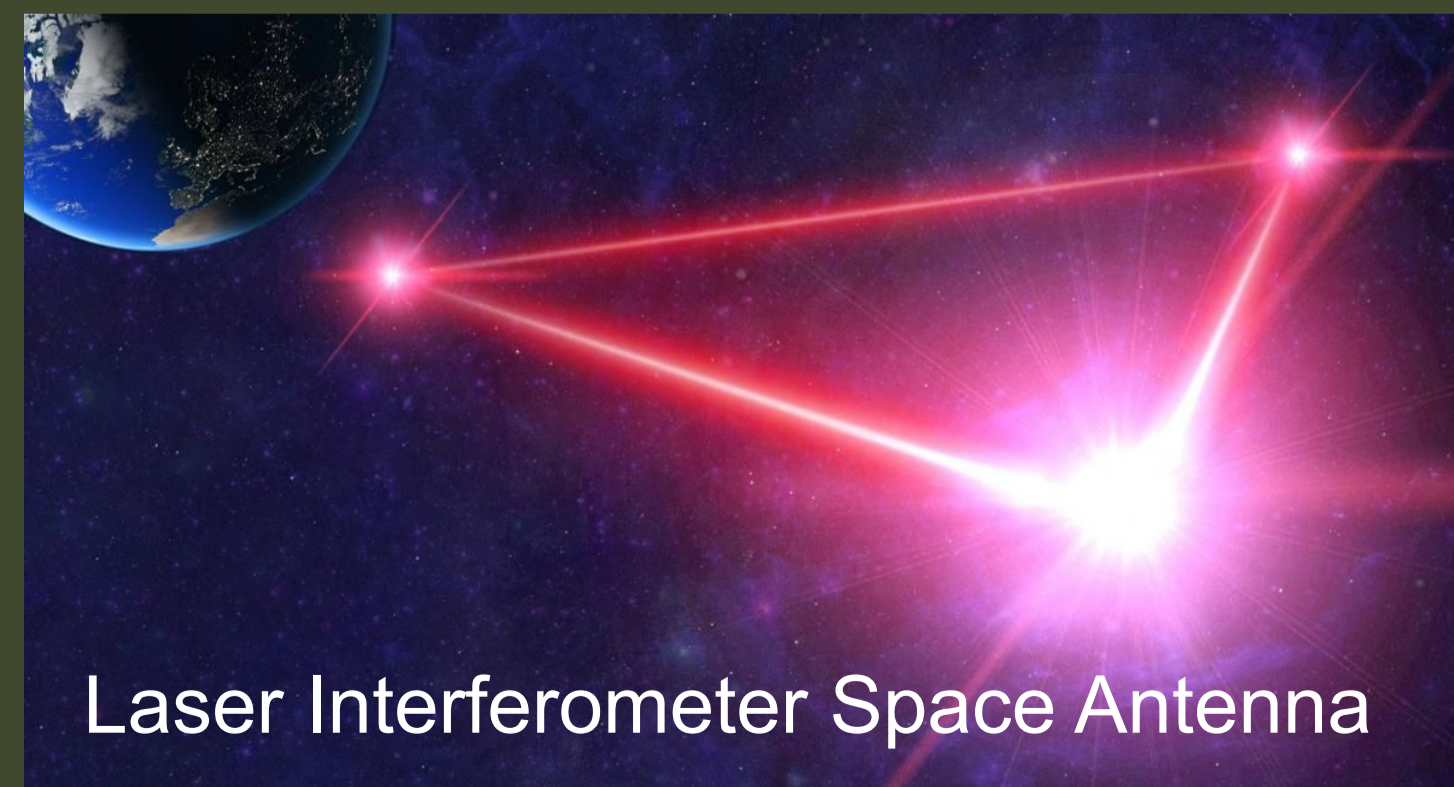
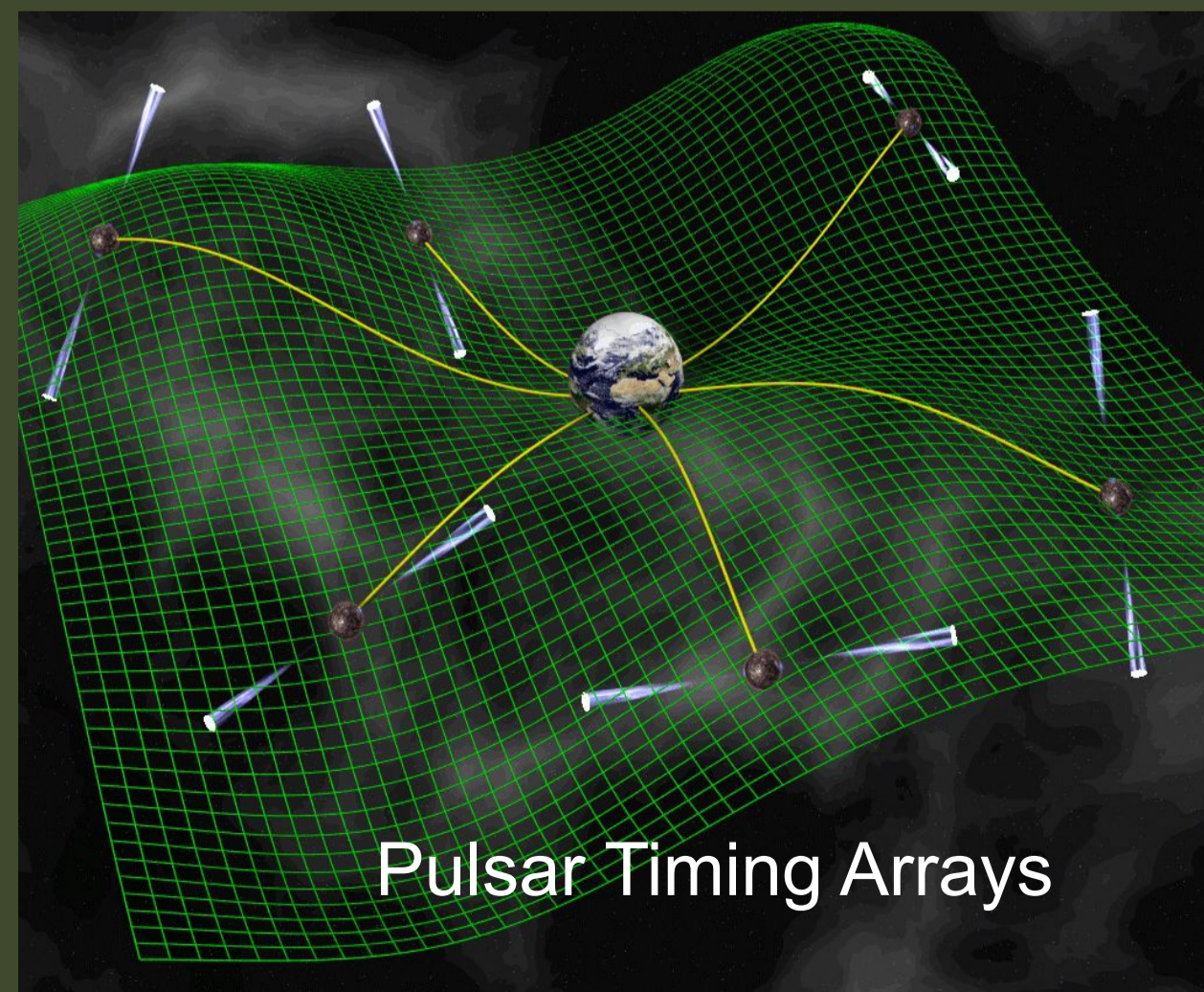
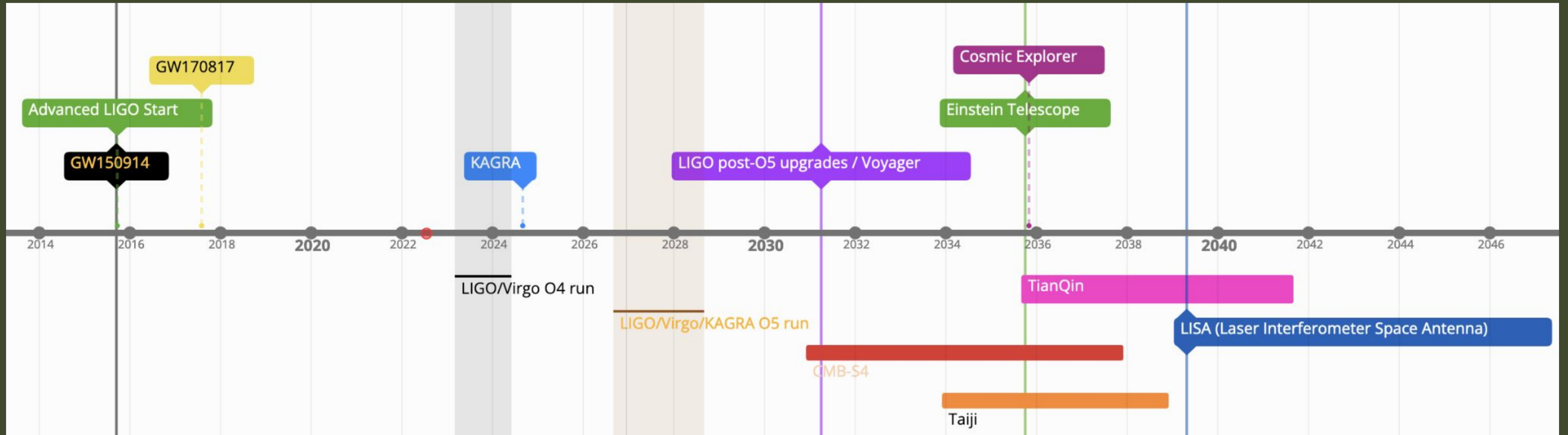
Experiment	Feature	Cosmic Ray Science	Timeline
Pierre Auger Observatory	Hybrid array: fluorescence, surface $e/\mu$ + radio, 3000 km <sup>2</sup>	Hadronic interactions, search for BSM, UHECR source populations, $\sigma_{p-Air}$	AugerPrime upgrade
Telescope Array (TA)	Hybrid array: fluorescence, surface scintillators, up to 3000 km <sup>2</sup>	UHECR source populations, $\sigma_{p-Air}$	TAx4 upgrade
IceCube / IceCube-Gen2	Hybrid array: surface + deep, up to 6 km <sup>2</sup>	Hadronic interactions, prompt decays	Upgrade + surface enhancement → IceCube-Gen2 deployment → IceCube-Gen2 operation
GRAND	Radio array for inclined events, up to 200,000 km <sup>2</sup>	UHECR sources via huge exposure, search for ZeV particles, $\sigma_{p-Air}$	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, $\sigma_{p-Air}$	EUSO program → POEMMA
GCOS	Hybrid array with $X_{max}$ + $e/\mu$ over 40,000 km <sup>2</sup>	UHECR sources via event-by-event rigidity, forward particle physics, search for BSM, $\sigma_{p-Air}$	GCOS R&D + first site → GCOS further sites
			2025                      2030                      2035                      2040

# Gravitational Waves: Key Science Questions

- Black holes and neutron stars throughout the Universe
  - Axion clouds around black holes
  - Black hole seeds and galaxy formation
  - Primordial black holes
- Dynamics of dense matter
  - Equation of state of dense nuclear matter
  - QCD phase diagram
  - Synthesis of heavy elements in the Universe
- Physics beyond the standard model
  - Dark matter in neutron stars
  - Modified gravity theories
  - Boson stars and other exotic objects
  - Precision cosmology for  $H_0$  and dark energy

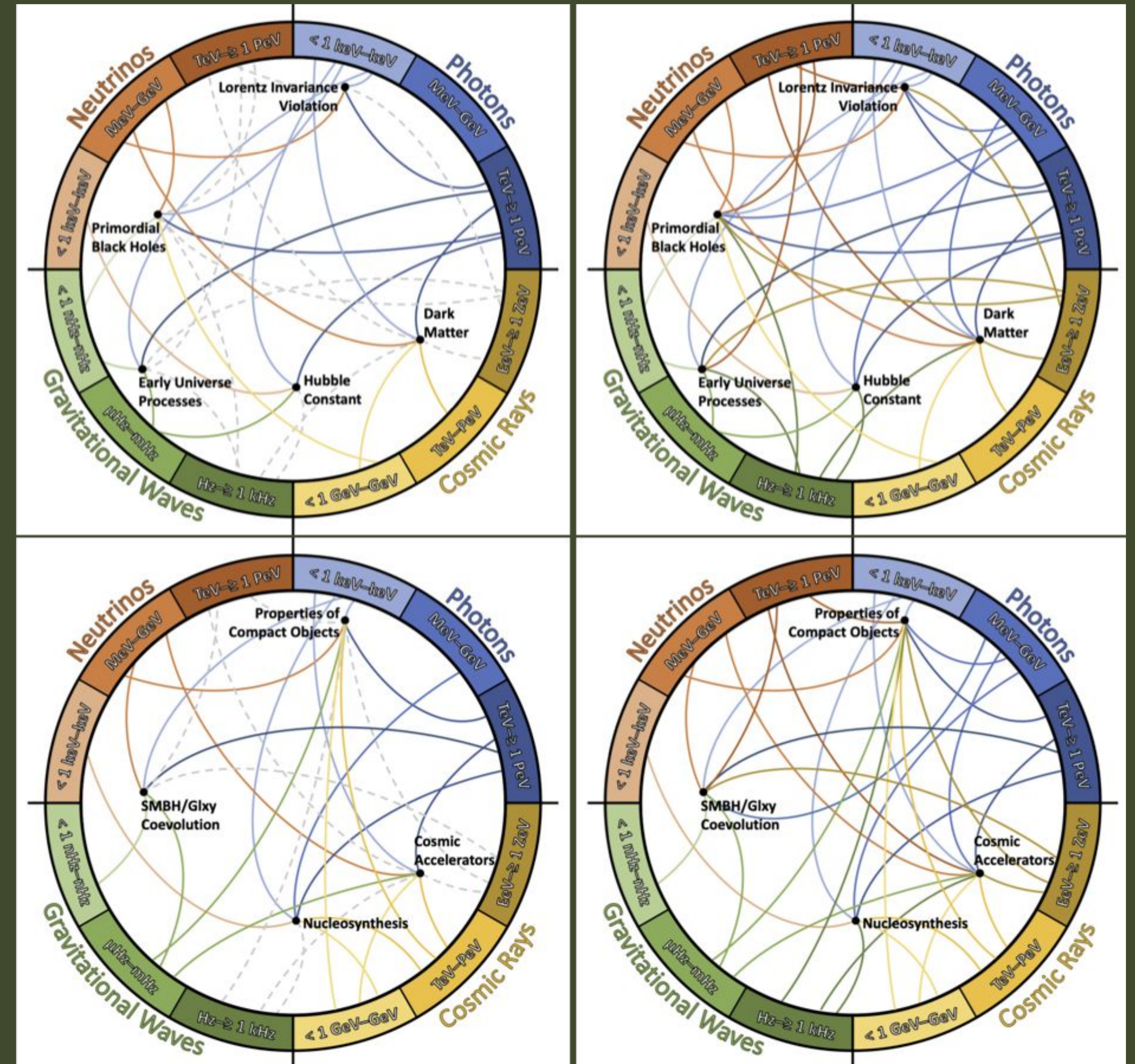


# Gravitational Waves: Facilities and Timeline



# Multimessenger Synergies in Particle Astrophysics

- Top Right: Probes of Cosmic Physics with a fully funded, balanced program
- Top Left: Probes of Cosmic Physics with a limited program
- Bottom Right: Fundamental Astrophysics with a fully funded, balanced program
- Bottom Left: Fundamental Astrophysics with a limited program
- Each solid line represents our best chance to solve major questions in the pointed topic over the next decade, and fewer lines give us fewer discovery opportunities. The potential loss is greater than linear since a single co-detection between messengers can provide more constraint than a decade of repeated observations with only one messenger.



Credit: Kristi Engel; Multimessenger WP





Gamma Rays

Neutrinos

Gravitational Waves

Cosmic Rays

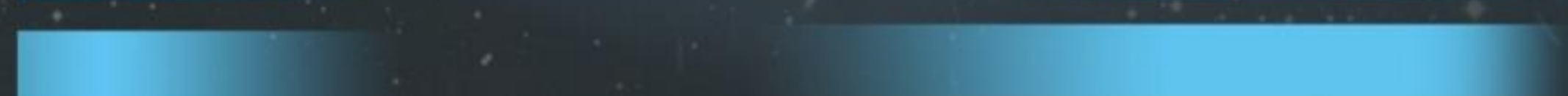
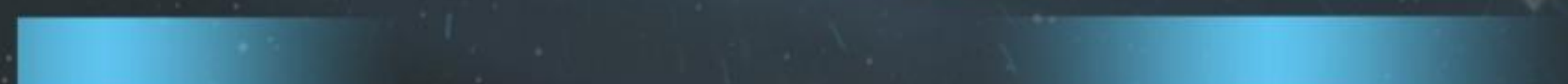
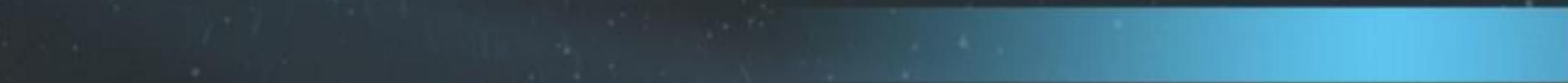
# Extra Slides

Gamma-ray Bursts

Blazars, TDEs

Pulsars/SN remnants

Radiation Type:

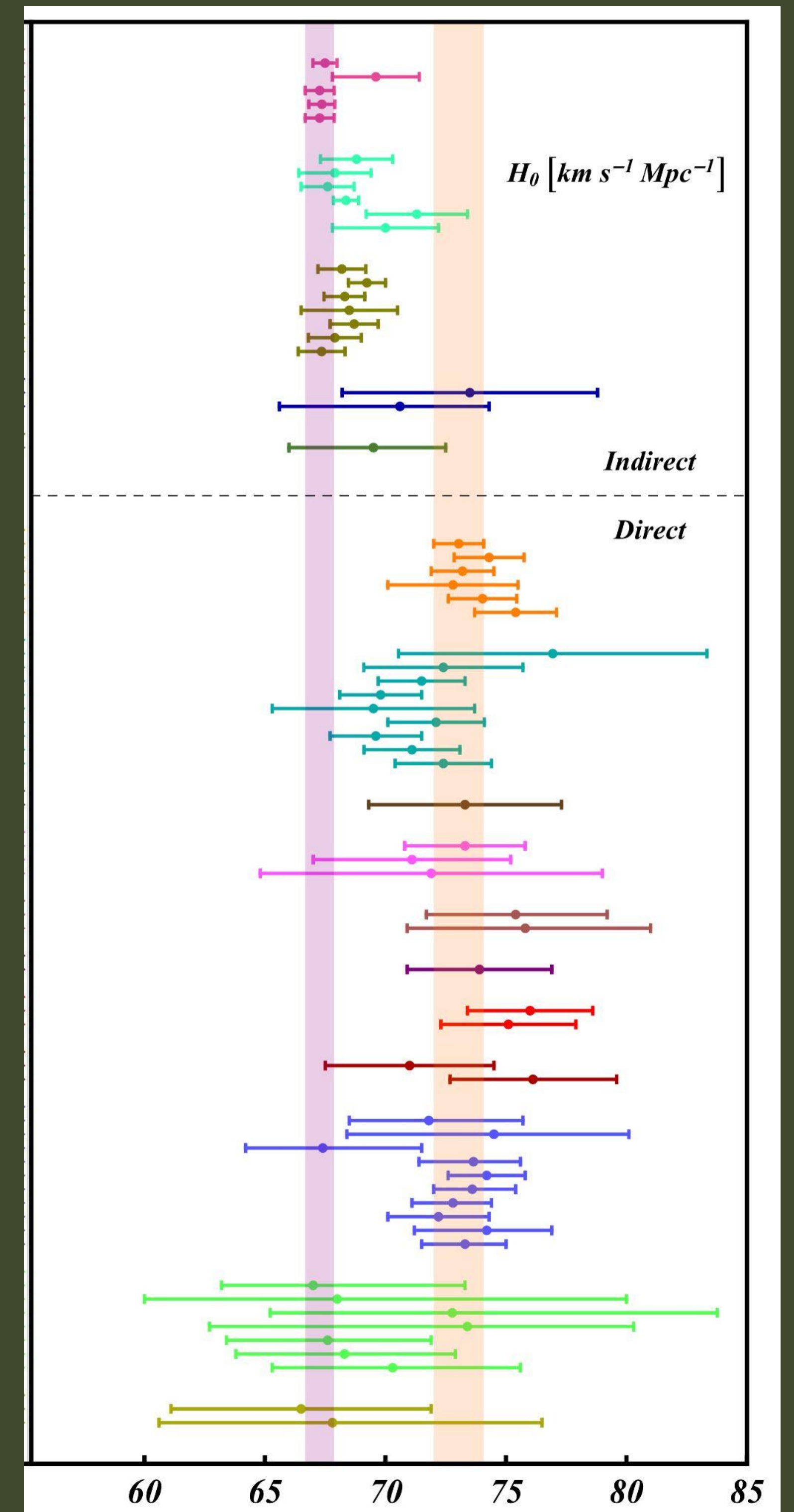


Radio - Microwave - Infrared - Visible - Ultraviolet - X-ray - Gamma ray



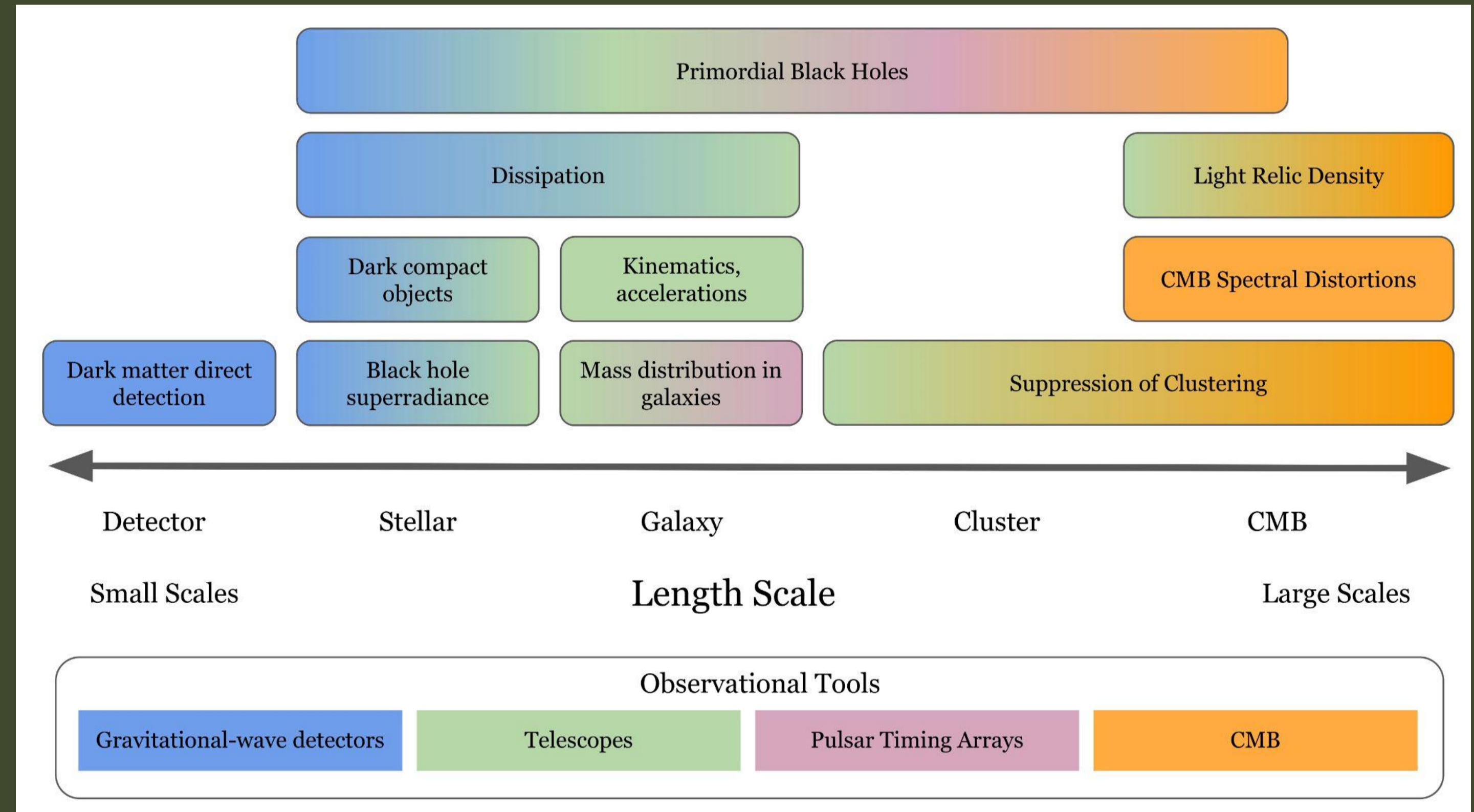
# History of the Universe and Cosmology

- Is the Hubble constant measured with low redshift probes different from the value inferred with  $\Lambda$ CDM normalized to the cosmic microwave background data?
- Is the Hubble tension a footprint of physics beyond the Standard Model?
- What are the imprints of early Universe phase transitions and inflation in the stochastic gravitational-wave backgrounds?
- What role do ultra-high-energy cosmic rays and advances in constraint-based modelling of Grand Unified Theories play in early Universe model building?



# Cosmic Probes of Dark Matter

- Is there a portal connecting the dark and visible sectors?
- What fraction of dark matter is held in primordial black holes and are there currently evaporating primordial black holes?
- Does the dark sector consist of a vast ensemble of particle species whose decay widths are balanced against their cosmological abundances?
- What is the gravitational-wave signature of dark matter?
- What are the gravitational-wave signatures of dilute dark matter distributions?

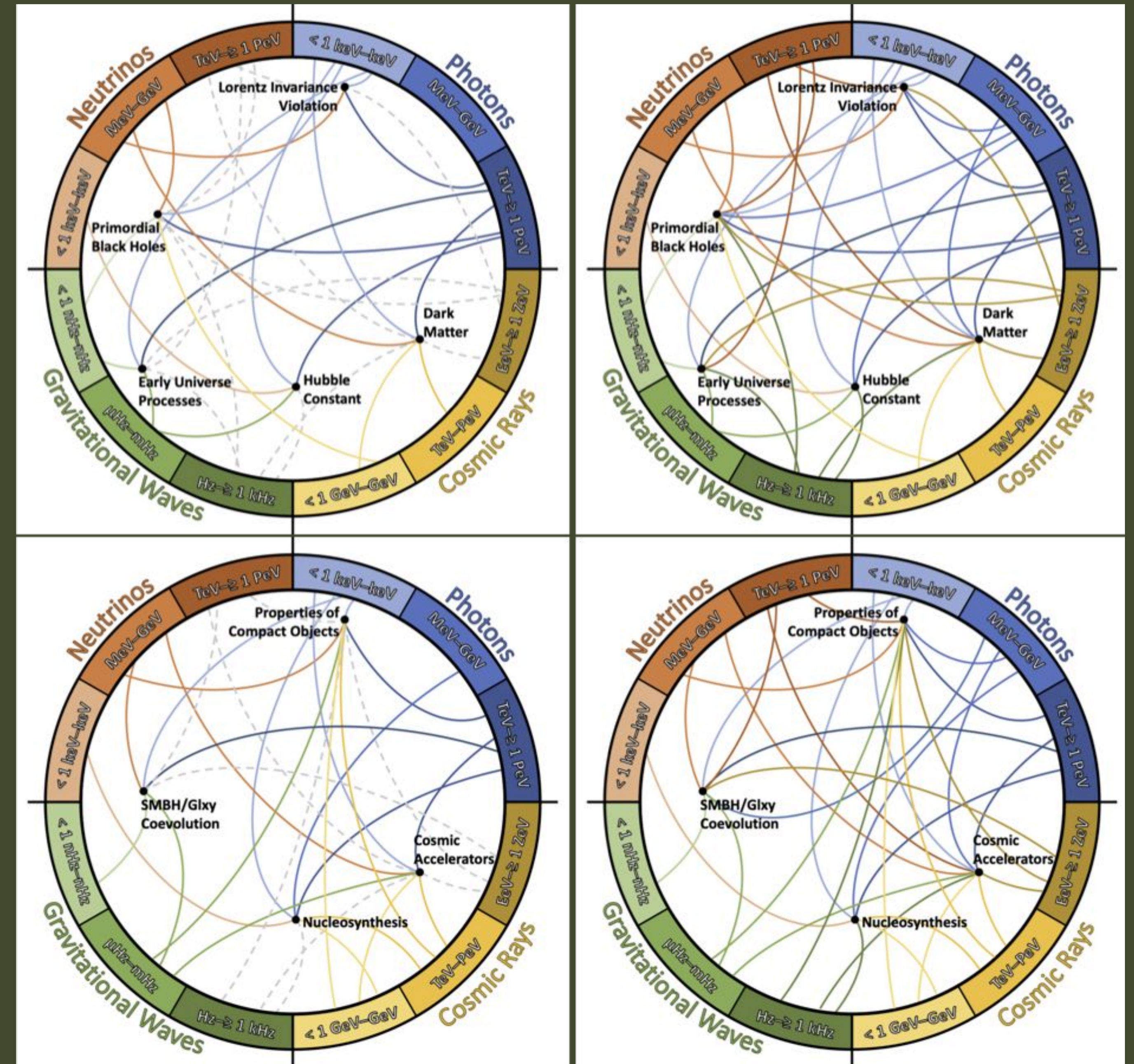


# Astroparticle Physics

- What are the properties of Standard Model particles and their interactions beyond the reach of terrestrial accelerators?
- How do neutrino flavors mix at high energies? Are neutrinos stable, are there hidden neutrino interactions with cosmic backgrounds?
- Could an enhancement of strangeness production in hadronic collisions be the carrier of the observed muon deficit in air-shower simulations when compared to ultra-high energy cosmic-ray data? Do new particles and interactions exist at the highest energies?
- How does matter behave in the center of neutron stars? What are the physical properties of matter at ultra-high density, large proton/neutron number asymmetry, and low temperature?
- Do the Lorentz and CPT symmetries that underpin the Standard Model break down in extreme cosmic environments?
- Does the QED domain (extreme magnetic fields) produce exotic particles or dark matter?

# Multimessenger Synergies in Particle Astrophysics

- How are particles accelerated in the cosmos to ultra-high energies? Is the cosmic ray maximum energy a fingerprint of physics beyond the Standard Model?
- What role do hadrons play in the extreme-energy Universe?
- How does diffuse emission from different messengers and energies contribute to cosmic evolution?
- How are Galactic TeVatrons and PeVatrons produced? Are gamma-ray halos a signal of physics beyond the Standard Model?
- How are heavy elements formed?



# Architecture of Spacetime

- What are the true degrees of freedom in gravitational-wave polarizations, how are gravitational waves produced and how do they propagate?
- Is there a modification of general relativity that successfully takes into account the effects ascribed to dark matter and dark energy?
- Does the graviton have a mass, what is the speed of gravity, is local Lorentz invariance a fundamental symmetry of nature?
- What is the space of low energy Effective Field Theories that admit an UV completion?
- What are the phenomenological implications of the Swampland conjectures?
- Does general relativity apply to EM and GW signals from black hole environments without modification?
- What are the “ab initio” models of nonsingular, horizonless alternatives to black holes, and self-consistent predictions of the ringdown and echo signals they produce?

