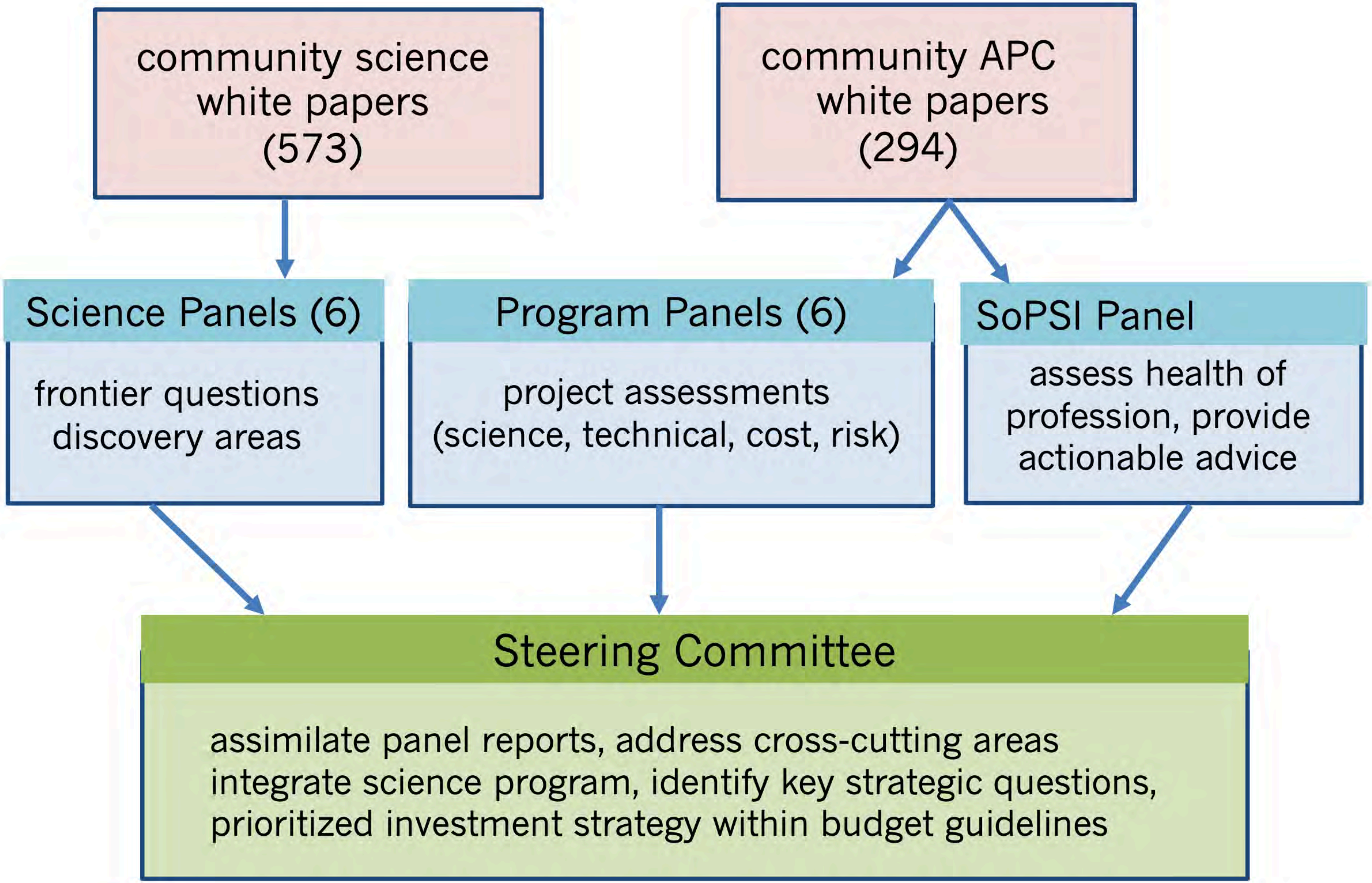
The National Academies of
SCIENCES · ENGINEERING · MEDICINE

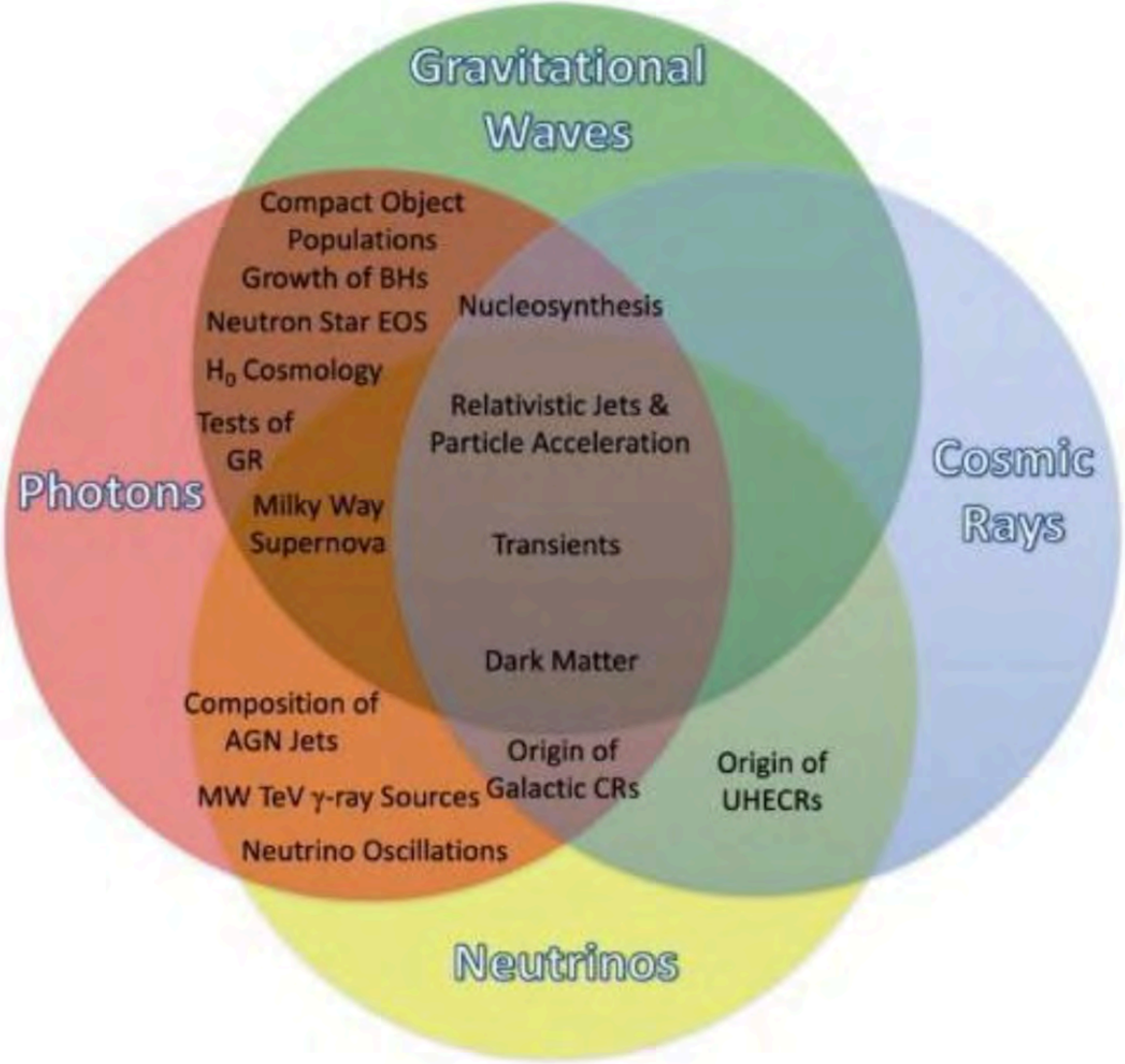
Pathways to Discovery in Astronomy and Astrophysics for the 2020s

Astro 2020

- The Charge:
  - Generate consensus recommendations to implement a comprehensive strategy and vision for a decade of transformative science at the frontiers of astronomy and astrophysics
- Sponsors - NASA, NSF, DOE
- How do these agencies respond to Astro 2020
  - NASA - basically uses this a roadmap
  - NSF - influences panels and program calls (Windows on the Universe, etc)
  - DOE - input to Snowmass/P5

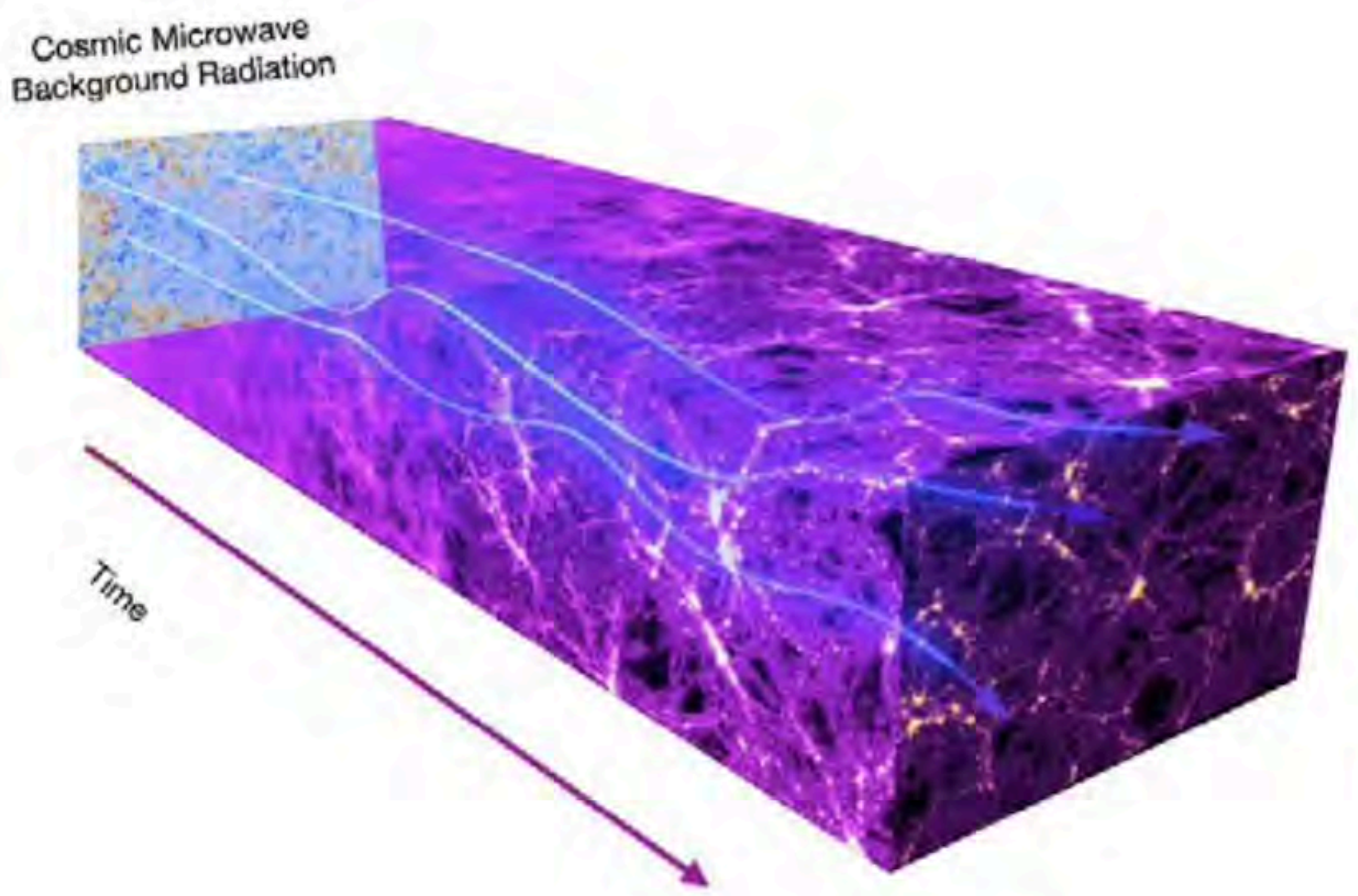

community science white papers (573)
community APC white papers (294)
Science Panels (6)
frontier questions discovery areas
Program Panels (6)
project assessments (science, technical, cost, risk)
SoPSI Panel
assess health of profession, provide actionable advice
Steering Committee
assimilate panel reports, address cross-cutting areas
integrate science program, identify key strategic questions,
prioritized investment strategy within budget guidelines

Multi-Messenger Astronomy



Science Theme: New Messengers and New Physics

New Messengers and New Physics captures the scientific questions associated with inquiries ranging from astronomical constraints on the nature of dark matter and dark energy, to the new astrophysics enabled by combined observations with particles, neutrinos, gravitational waves, and light.



This theme is forefront this decade because of:

- The tremendous progress in observations of the Cosmic Microwave Background
- Time domain surveys in optical and radio that have uncovered an astounding array of transient phenomena
- The discovery of black hole-black hole mergers and neutron star – neutron star mergers with LIGO, and the detection of electromagnetic counterparts
- Ice Cube's detection of high energy neutrinos of astrophysical origin

Bottom Line for PA

- Main Report
  - IceCube Gen 2 - endorsed but not explicitly recommended because it's NSF Physics not Astro
  - CMB S-4 recommended
  - Tech development for next Gen Gravitational Wave Detectors
  - Recommended enhancement of Mid-scale funding
- PAG panel report
  - SWGO recommended (~$20M)
  - US participation in CTA recommended (~$40M)
  - Continued support for current generation detectors (HAWC, IceCube, LIGO (A+), Fermi)

Ground

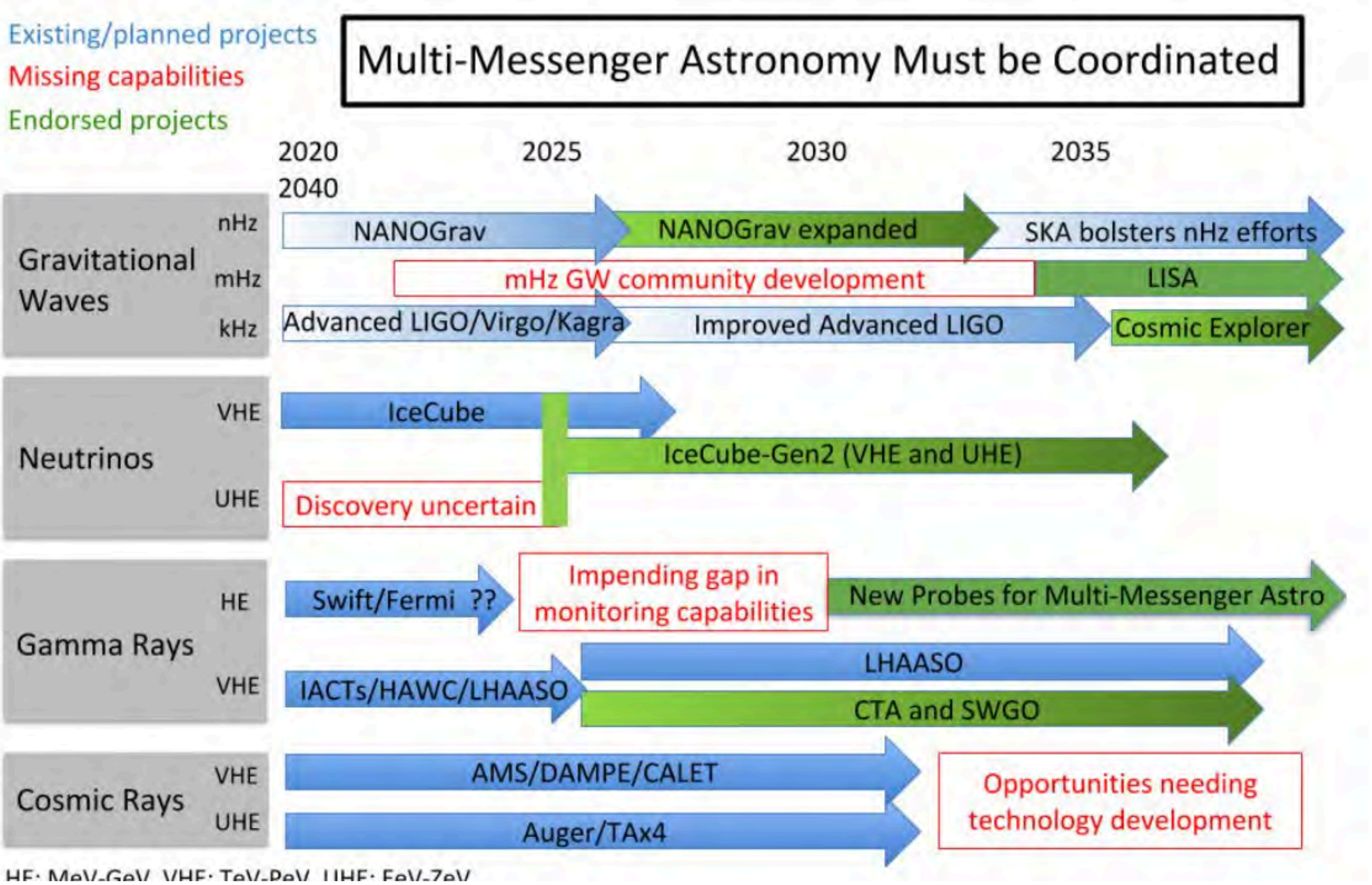
Ground Medium/Large Program Overview

Endorsements for Programs in NSF/PHYS

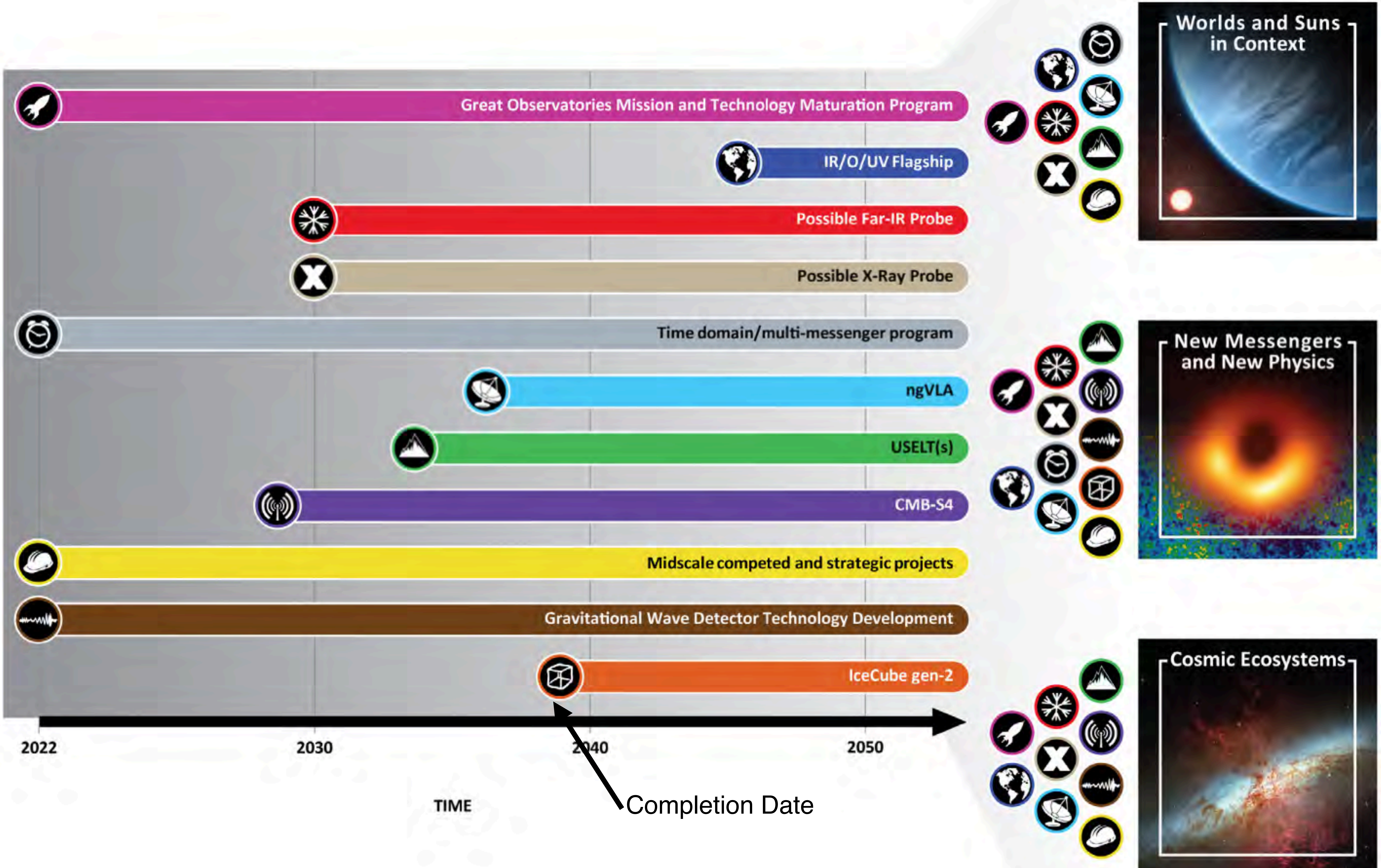
Technology Development for Future Gravitational Wave Observatories
Upgrades to LIGO and preparation for future generation facilities

The IceCube-Generation 2 High Energy Neutrino Observatory
Upgrades to IceCube Antarctic neutrino observatory

PAG Report



Existing/planned projects
Missing capabilities
Endorsed projects
Multi-Messenger Astronomy Must be Coordinated
2020
2025
2030
2035
2040
Gravitational Waves
nHz
mHz
kHz
NANOGrav
NANOGrav expanded
SKA bolsters nHz efforts
mHz GW community development
LISA
Advanced LIGO/Virgo/Kagra
Improved Advanced LIGO
Cosmic Explorer
Neutrinos
VHE
UHE
IceCube
IceCube-Gen2 (VHE and UHE)
Discovery uncertain
Gamma Rays
HE
VHE
Swift/Fermi ??
Impending gap in monitoring capabilities
New Probes for Multi-Messenger Astro
IACTs/HAWC/LHAASO
LHAASO
CTA and SWGO
Cosmic Rays
VHE
UHE
AMS/DAMPE/CALET
Auger/TAx4
Opportunities needing technology development
HE: MeV-GeV, VHE: TeV-PeV, UHE: EeV-ZeV


Great Observatories Mission and Technology Maturation Program
IR/O/UV Flagship
Possible Far-IR Probe
Possible X-Ray Probe
Time domain/multi-messenger program
ngVLA
USELT(s)
CMB-S4
Midscale competed and strategic projects
Gravitational Wave Detector Technology Development
IceCube gen-2
2022
2030
2040
2050
TIME
Completion Date
Worlds and Suns in Context
New Messengers and New Physics
Cosmic Ecosystems

Some Big Particle Physics Questions

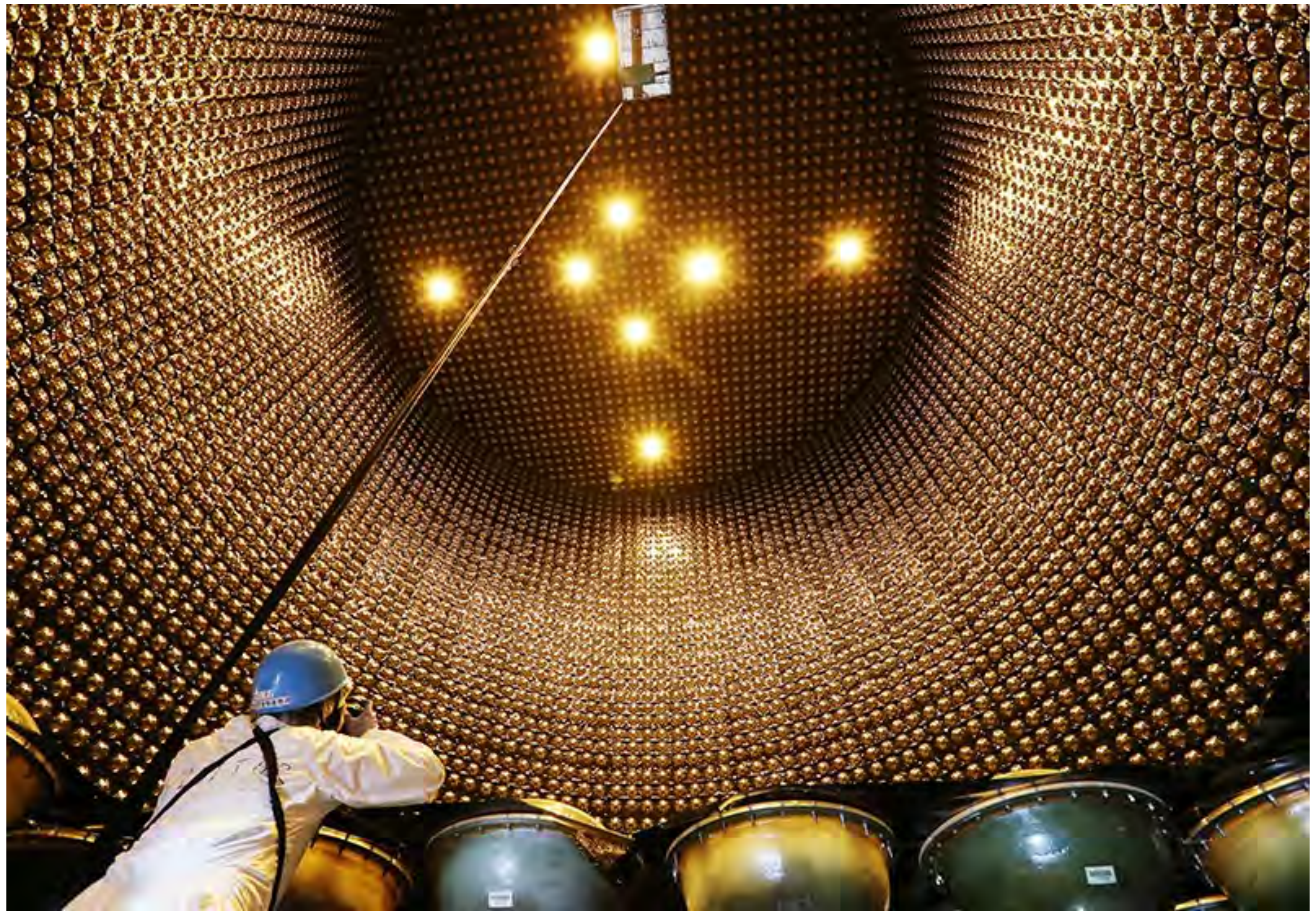
- Extreme Accelerators
- Dark Matter / Dark Energy (Both discovered in Astronomy)
- Neutrino mass/ Hierarchy
- Extreme interactions
- Axion-Like Particles (ALP)
- Lorentz Invariance Violation (LIV)
- Gamma Ray Bursts (GRBs)
- Primordial Black Holes
- Merging Black Holes & Neutron Stars
- Tension in the Hubble Constant

A Little History (from an old cosmic ray guy)

- Prehistory (before me)
  - discovery of anti-particles in cosmic rays
  - discovery of hyperons, pions and kaons
  - Rising cross sections
- Neutrino/Proton Decay Experiments (pre 1990's)
  - Davis - Solar neutrino deficit
  - IMB, Kamiokande
    - SN 1987a ~20 neutrinos - 774 papers
    - Missing muon neutrinos
  - Not seeing Proton Decay ruled out:
    - Minimal SU(5)/Minimal SUSY SU(5)
    - SUGRA SU(5)

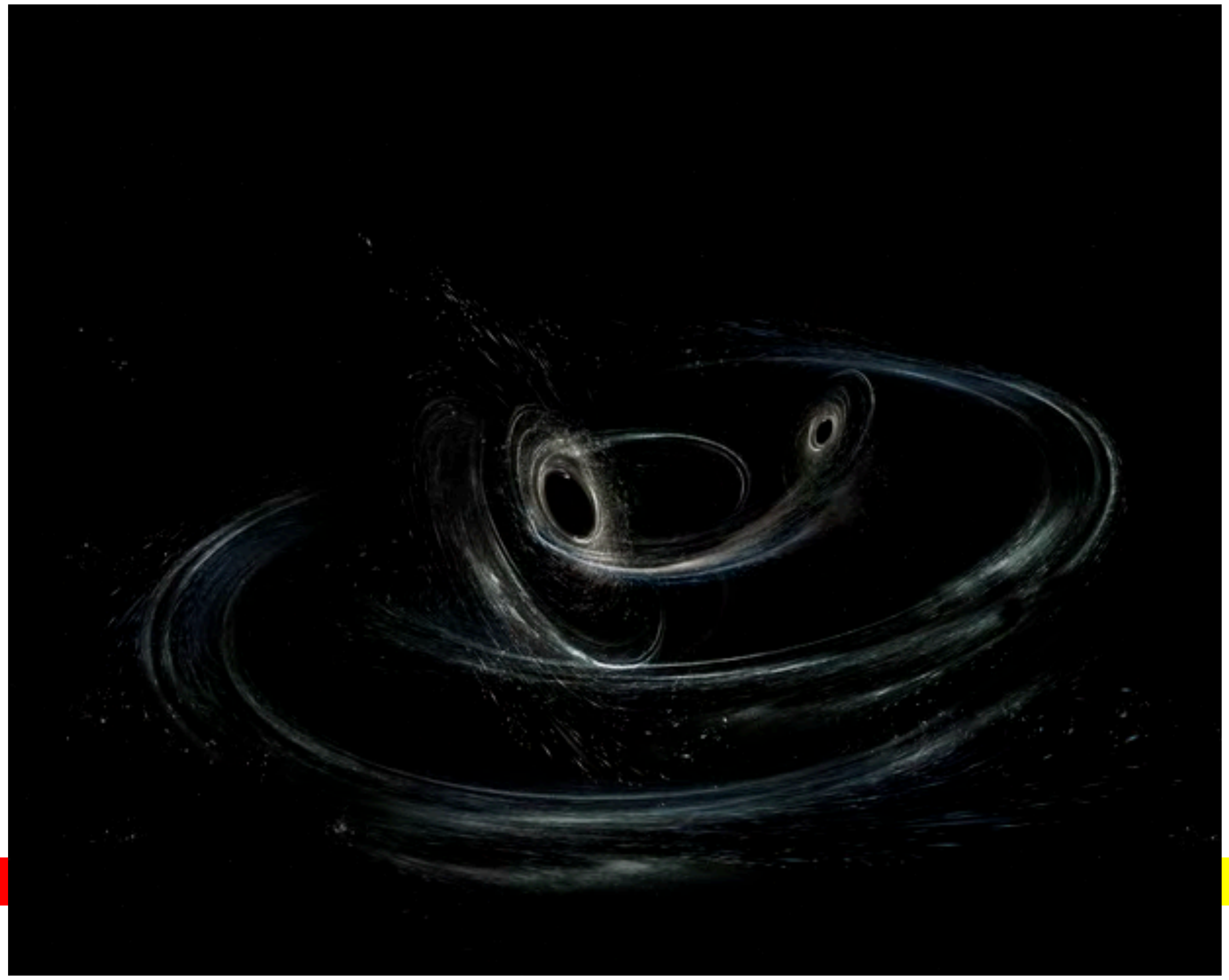
A Little History (from an cosmic ray old guy)

- The next generation neutrino detectors (~ order of magnitude bigger)
  - Super-K (water)
    - Solar neutrinos, atmospheric neutrinos, supernova
    - DOE supported (but originally only for Proton Decay)
  - SNO (Canada) D_2O
    - Solar neutrinos (sensitive to all flavors)
  - Together they show neutrino flavor oscillation
  - First real BSM physics confirmed - neutrino mass
    - 2015 Nobel prize in physics
  - DUNE is an outgrowth of this work
- Future detectors
  - GADZOOKS - gadolinium loading in Super-K
  - Hyper-k



A Little History (from an cosmic ray old guy)

- LIGO



August 17, 2017: binary neutron star merger!

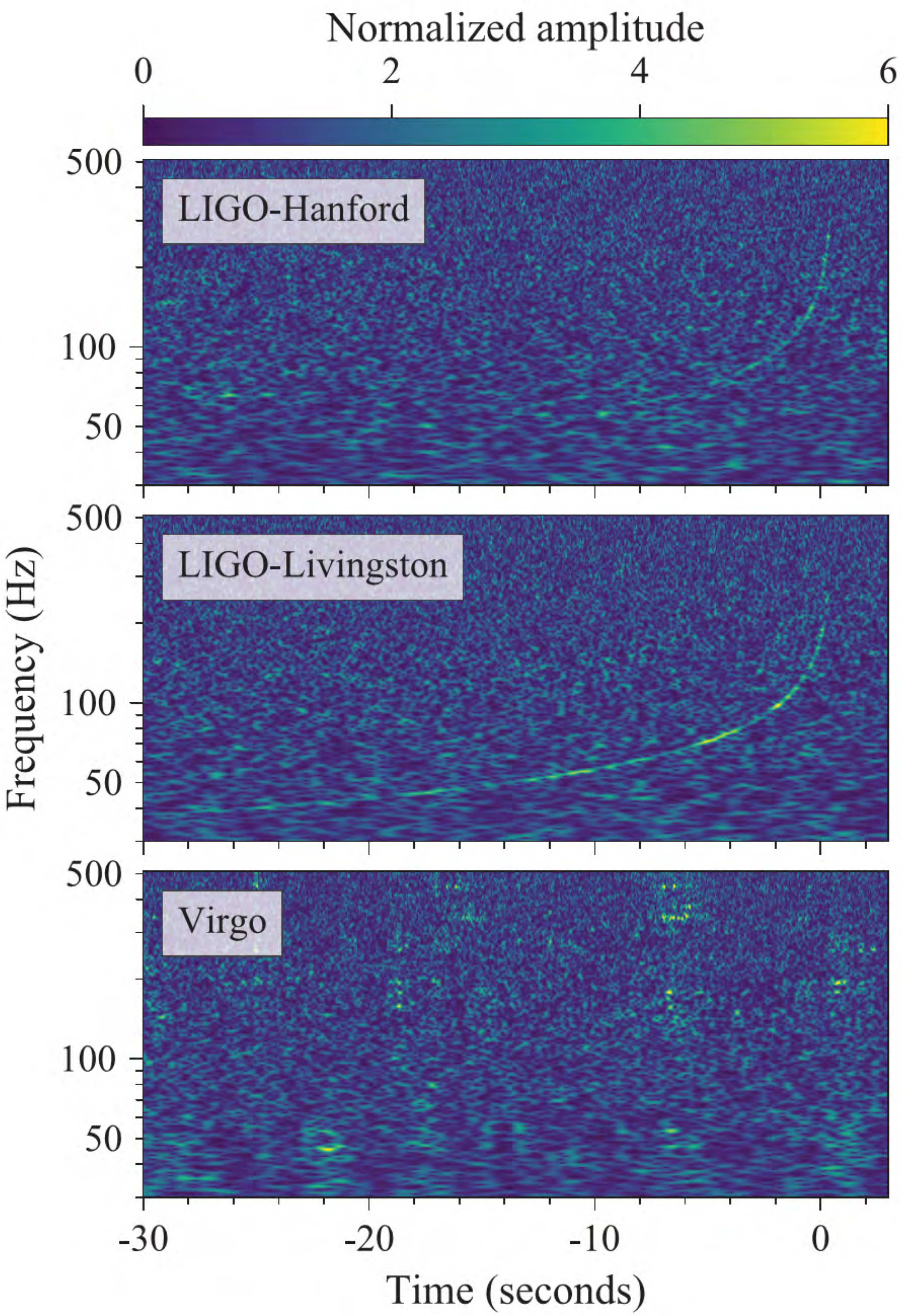
GW170817

Initially found using a template with masses and

Coincident
(within ~2 sec)
with a short gamma-ray burst (GRB) detected by the GBM instrument on the Fermi satellite!

Visible in LIGO spectrograms!

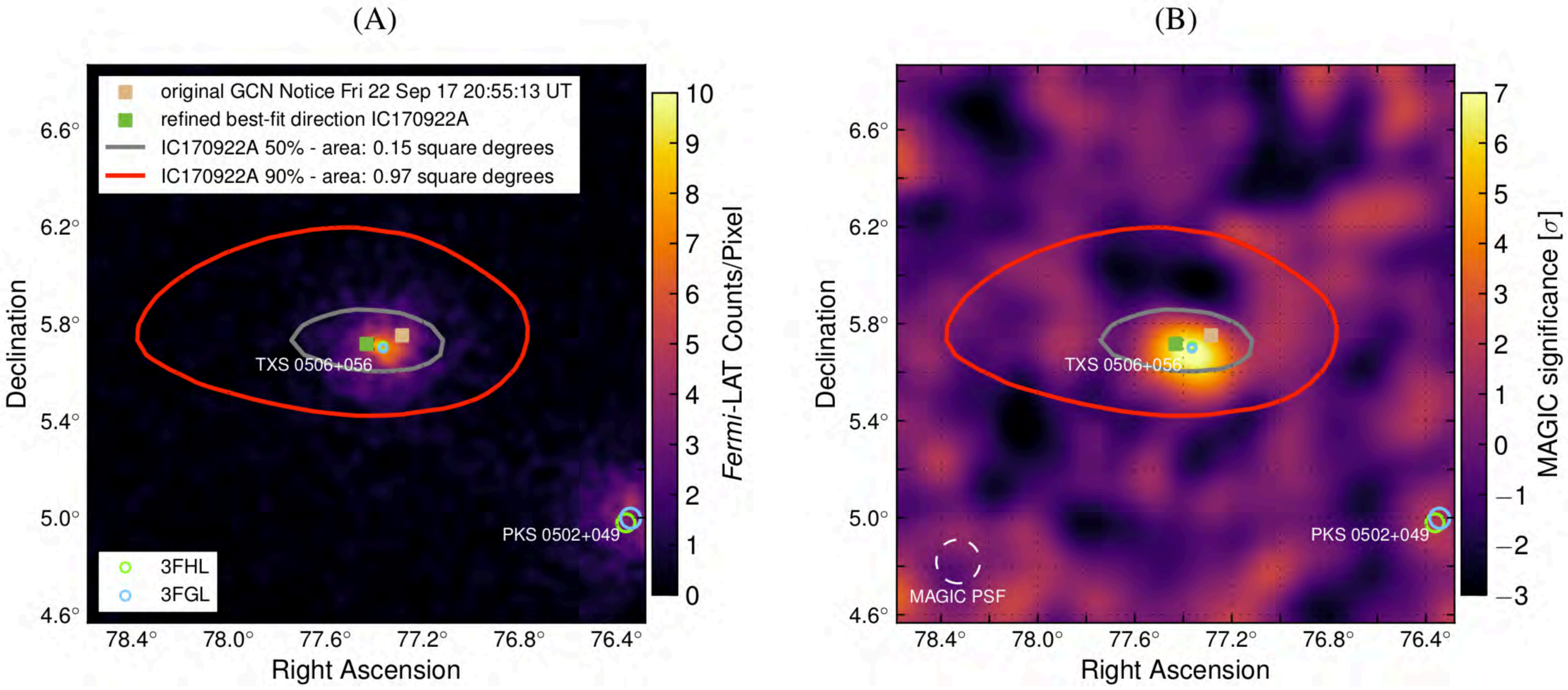
A glitch in LIGO-Livingston data prevented rapid localization, but later was gated / subtracted



Multi-messenger Astroonmy

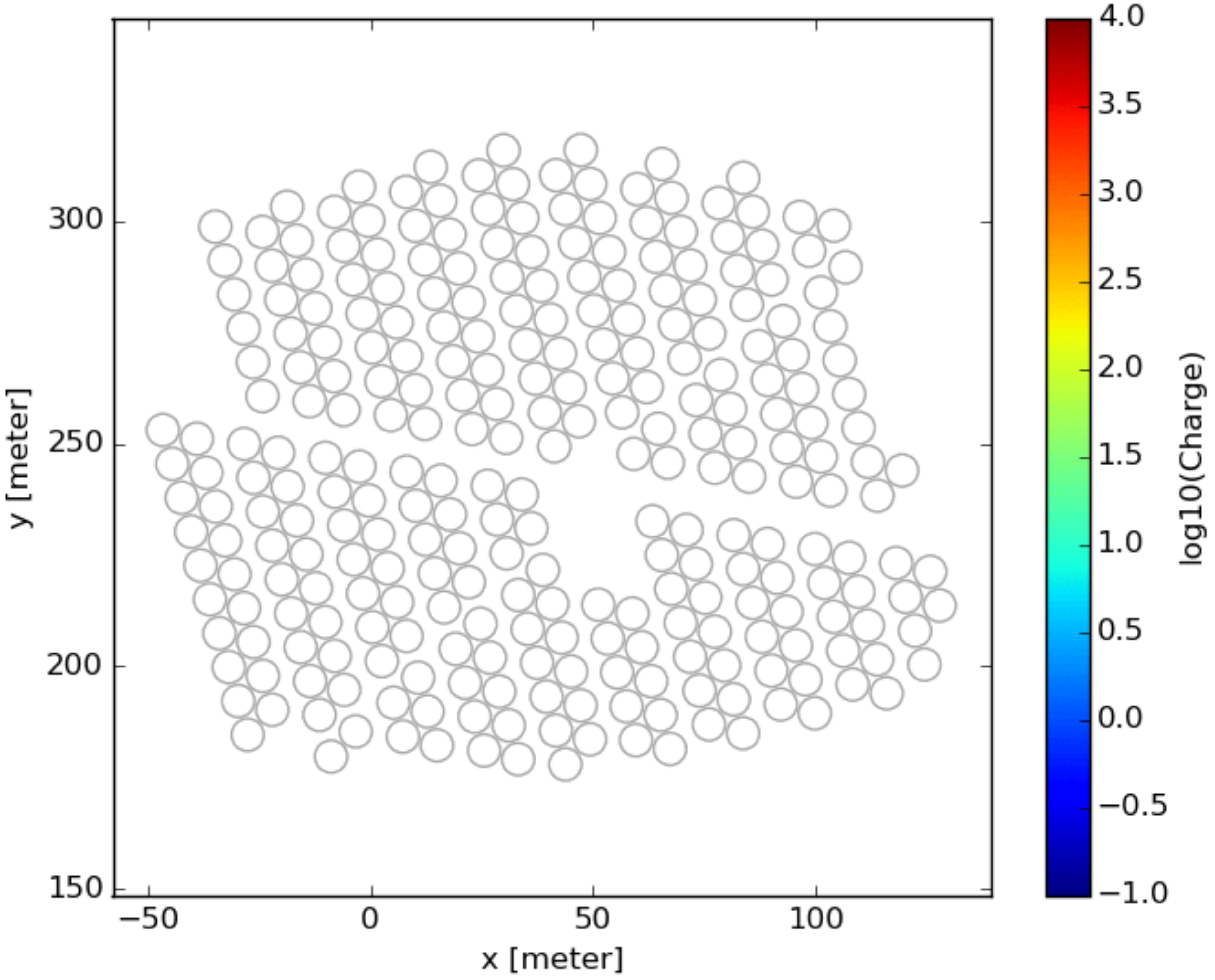
[Abbott et al. 2017, PRL 119, 161101]

IceCube 170922A - TXS0506+056



High Altitude Water Cherenkov
HAWC

Angle Reconstruction



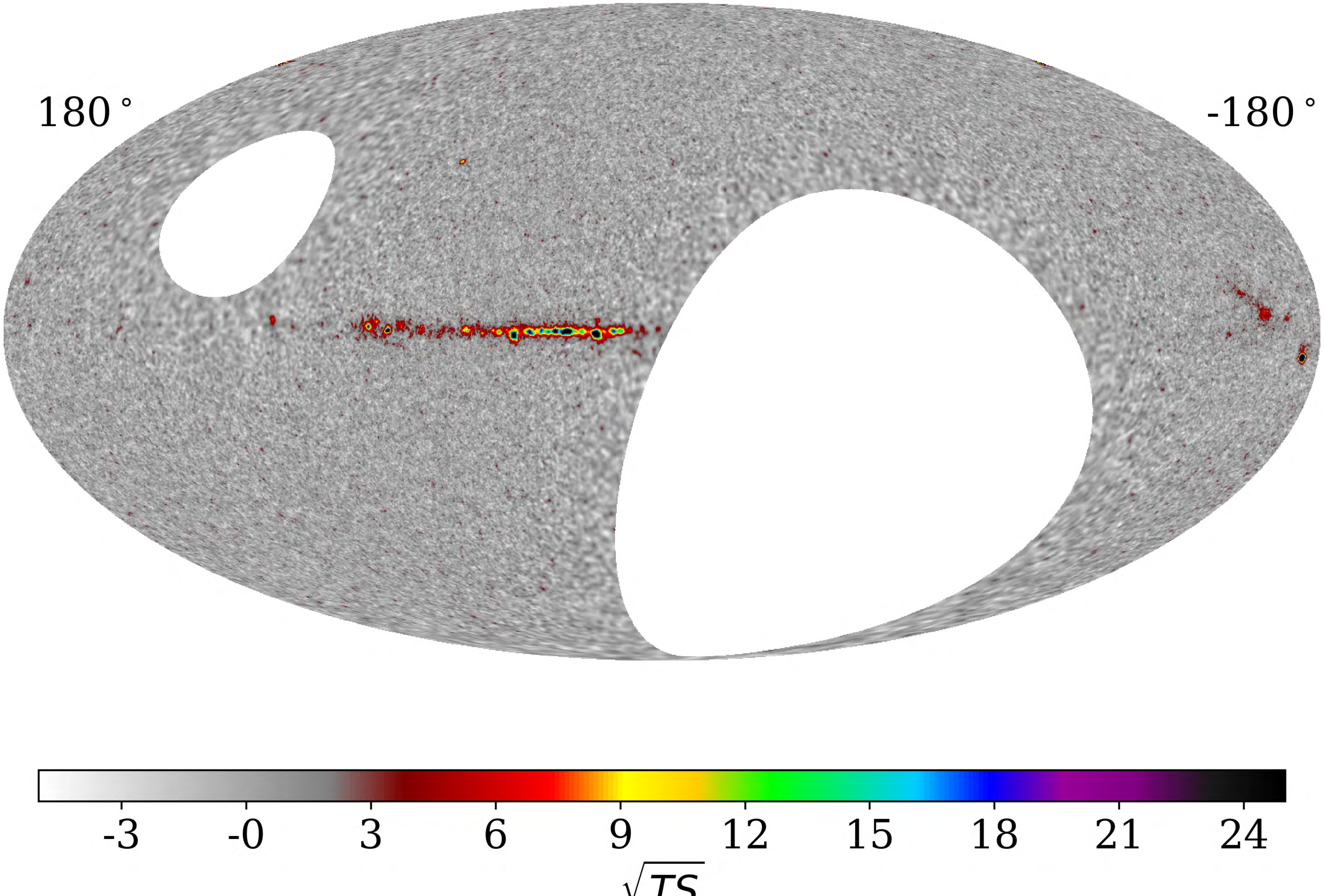
HAWC

- NSF, DOE, Mexico, MPIK
  - DoE funding enabled Los Alamos Participation
  - It also allowed LANL LDRD funding of HAWC (~$2M)
- Follow on to Milagro
  - Also supported by DoE
- Endorsed by PASAG (HEPAP sub panel)
- Total Cost ~$15M (DOE contributed about $4M)

HAWC

- Wide-field γ-ray survey of the Northern Sky at energies from 1-200 TeV
- Discovery of many new TeV sources (13 sources > 100 TeV)
- Discovery of many new source classes
  – TeV Halos
  – Micro-quasars
  – Star forming regions
- Best high-mass dark matter limits
- Limits on:
  – Lorentz Invariance Violation
  – Primordial Black Holes
  – Axion-Like Particles

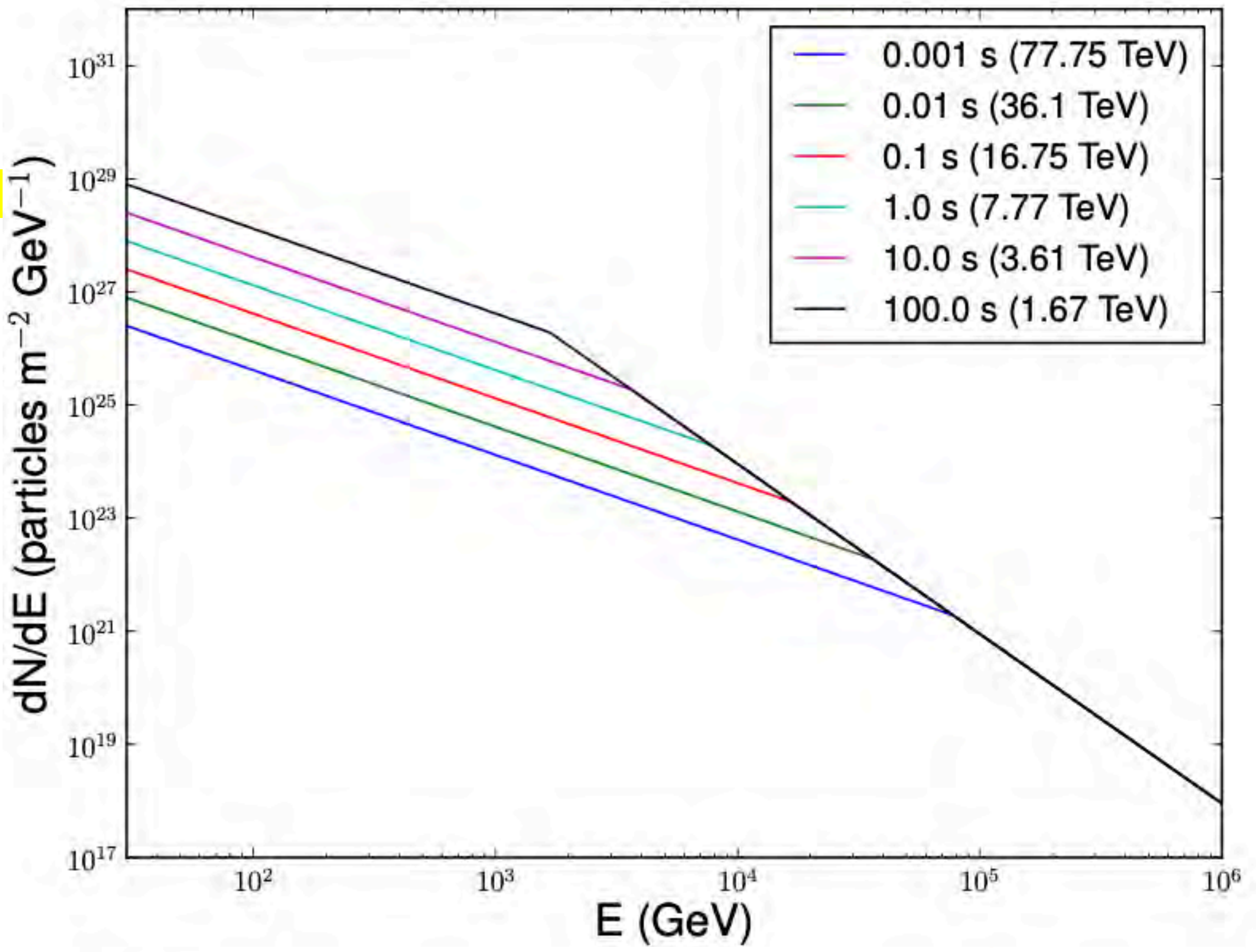
Galactic view

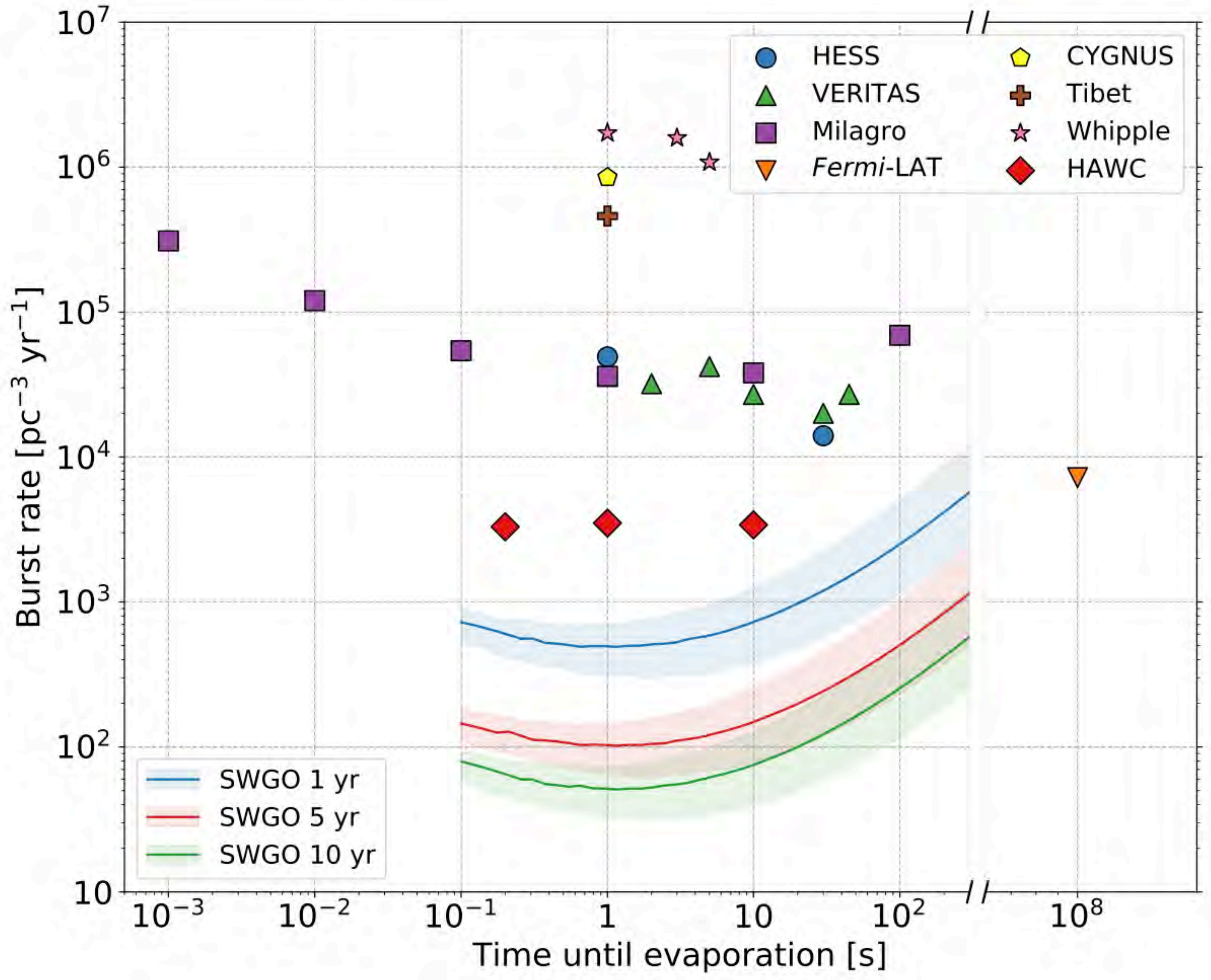



Galactic plane I; 0.0 °; 2090 days
Preliminary
Galactic plane II; 0.0 °; 2090 days
Preliminary
Galactic plane III; 0.0 °; 2090 days
Preliminary
Galactic plane IV; 0.0 °; 2090 days
l [°]
l [°]
√TS

Primordial Black Holes

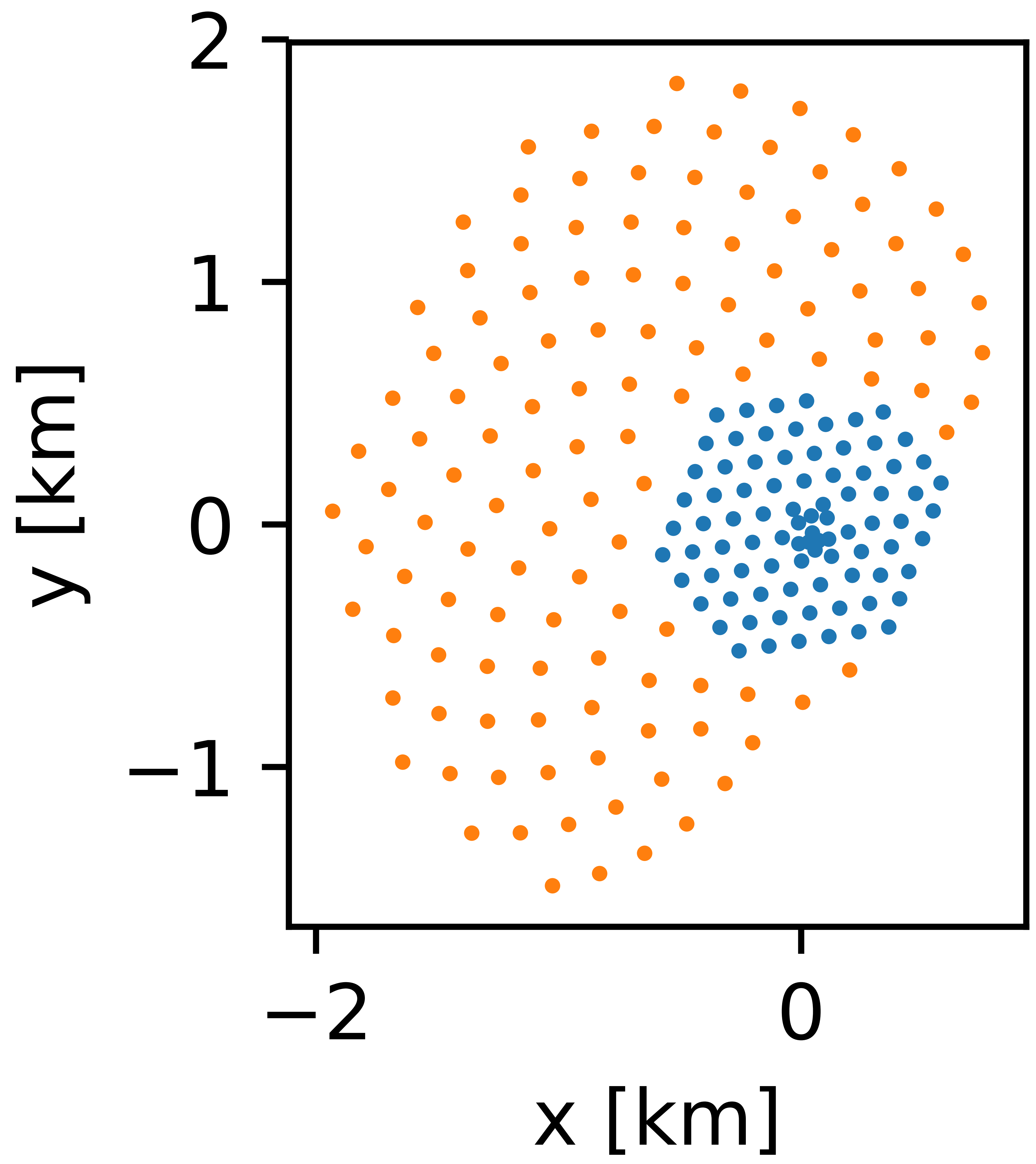
- As a black hole evaporates it loses mass and hence its temperature increases and the number of particle species that it emits increase until the end of its evaporation lifetime
- A PBH should directly radiate those fundamental particles whose Compton wavelengths are on the order of the size of the black hole
- Gamma flux like a GRB but spectrum getting harder and then disappearing
- As the BH evaporates all fundamental particles will be emitted and DoF can be counted
- Enormous particle physics discovery potential

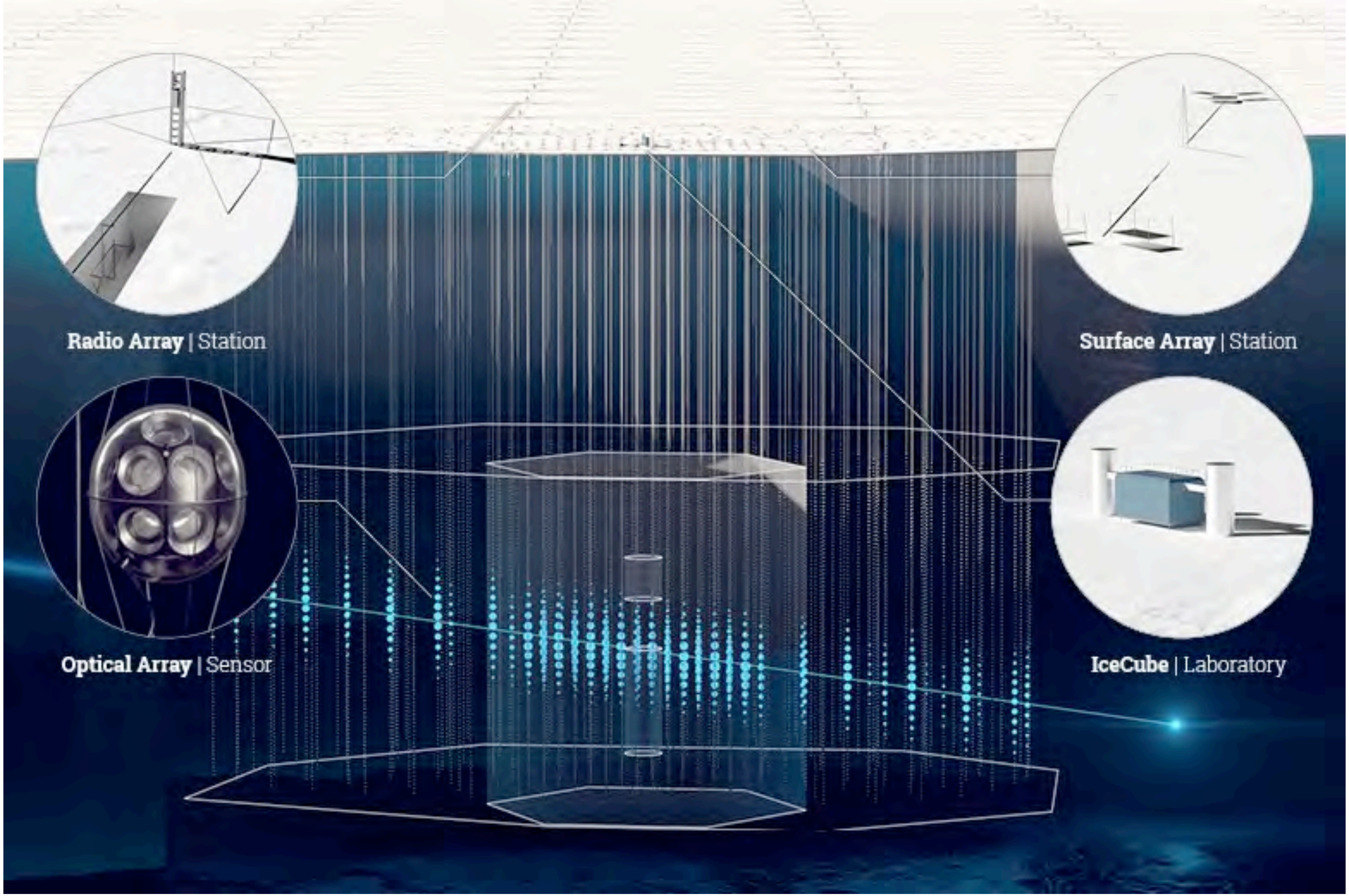




Future Detectors

- IceCube Gen 2 =10 Km^3
  - 8-10 x larger optical Cherenkov detector
  - Neutrino astronomy and multi-messenger astrophysics
  - 120 strings with spacing of 240 m -> ~10k new mDOM-like modules
  - Askaryan radio detector array
  - Probe neutrinos beyond EeV energies
- US led effort (with European support)




Radio Array | Station
Surface Array | Station
Optical Array | Sensor
IceCube | Laboratory

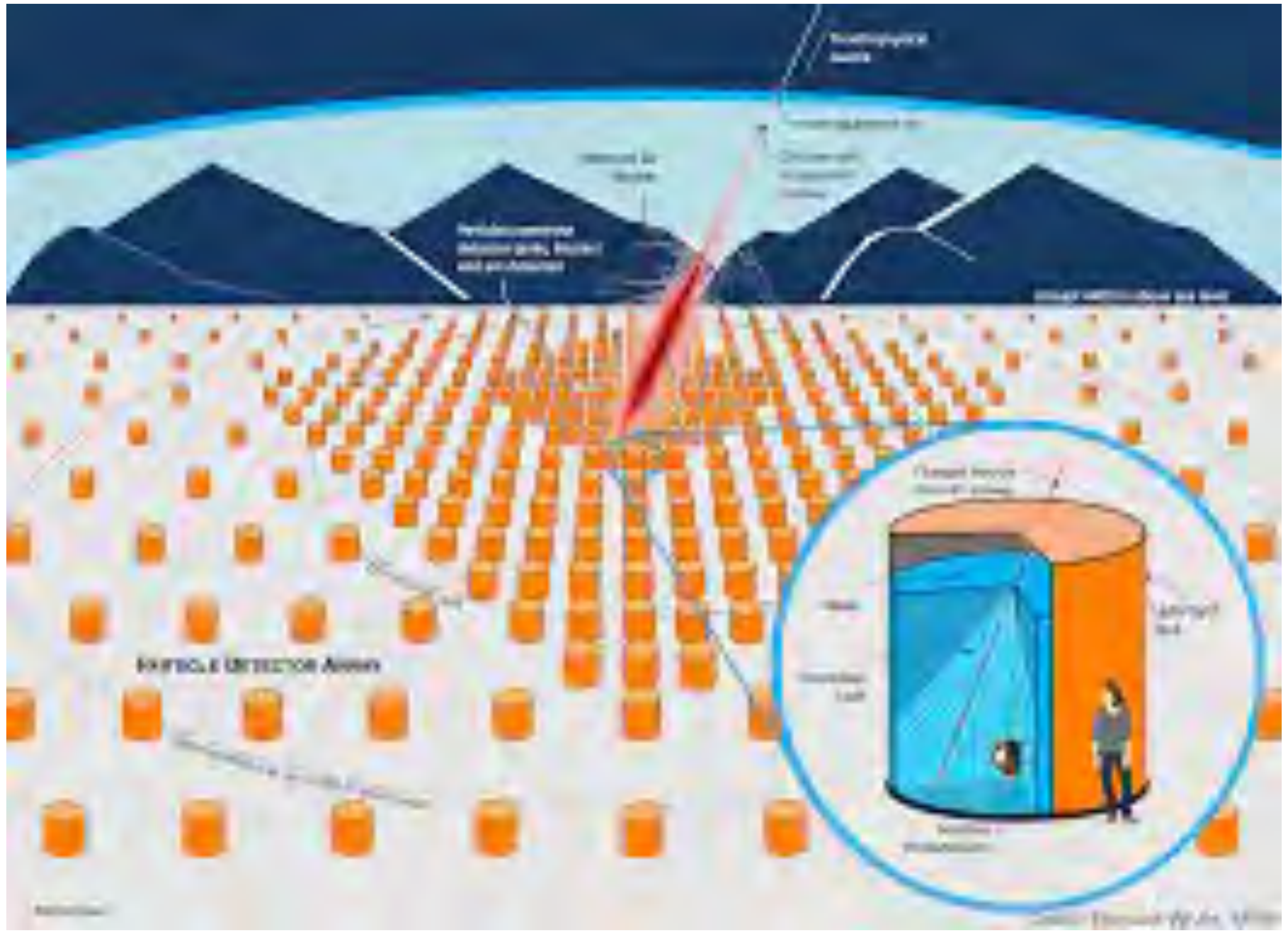
Future Dectetors

- Cherenkov Telescope Array - CTA
  – Energy from 20 GeV to 300 TeV
  – Wider field of view and improved sensitivity will enable CTA to survey hundreds of times faster than previous TeV IACTs.
  – A one to two order-of-magnitude collection area improvement makes CTA a powerful instrument for time-domain astrophysics, three orders of magnitude more sensitive on hour timescales than Fermi-LAT at 30 GeV

- Enormous physics reach
- About to begin construction (Europe led)
  – US Participation needs support

Future Dectetors

- Southern Wide-Field Gamma Ray Observatory - SWGO
  – Complimentary to HAWC/LHAASO/CTA in the Southern Hemisphere.
  – Higher altitude (lower threshold)
  – Much larger area
  – Higher density
  – Ideal for transients
- Joint US, Europe, South America



DOE Lab Involvement

- SLAC - Fermi, DECam, Vera Rubin Observatory (LSST)
- FNAL - Auger, Sloan, DES
- LANL - Milagro, HAWC, SWGO
- Argonne - VERITAS, SPT, CMBS-4
- LBNL - IceCube, DESI, CMBS-4

US Innovation

- IACTs
  - First IACT - Whipple (US - DOE, NSF, CFA supported)
  - VERITAS (US - DOE, NSF, CFA supported)
    - H.E.S.S. based on VERITAS design got built first (MPIK)
- Neutrinos (PDK)
  - IMB - (US - DOE)
    - Kamiokande - Japan
  - Amanda (NSF)
  - IceCube (NSF)
    - KM3NET - Baikal (Europe, Russia), P-ONE (Canada)
- Wide-field Gamma Rays
  - HAWC (US - DOE, NSF, LANL - Mexico, MPIK)
    - LHAASO - China

The Importance of Snowmass

- Proposals must always compete on scientific merit
  - but with DOE they don't have a chance unless the science is endorsed by Snowmass and P5
- DOE and DOE labs provide leverage with other agencies
- Opportunities for lab scientists
  - developments from the lab can be used for astrophysics
- You need to tell DOE the importance of astrophysics to particle physics