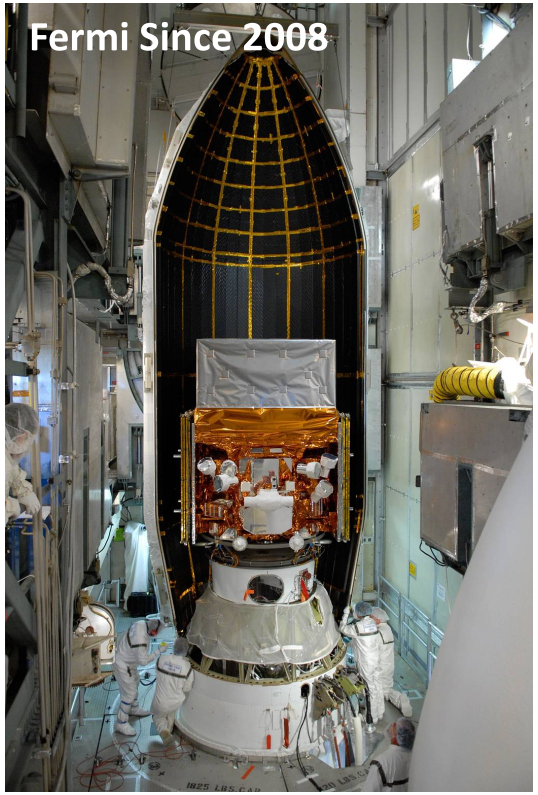
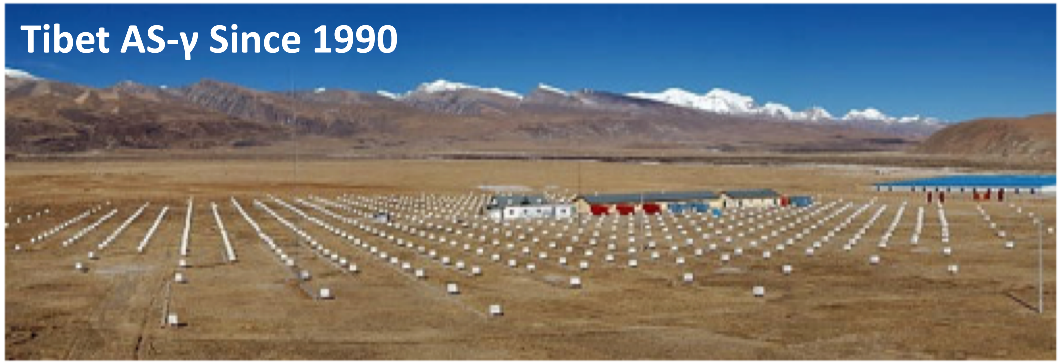


Probing High Energy Physics with Astrophysical Gamma Rays

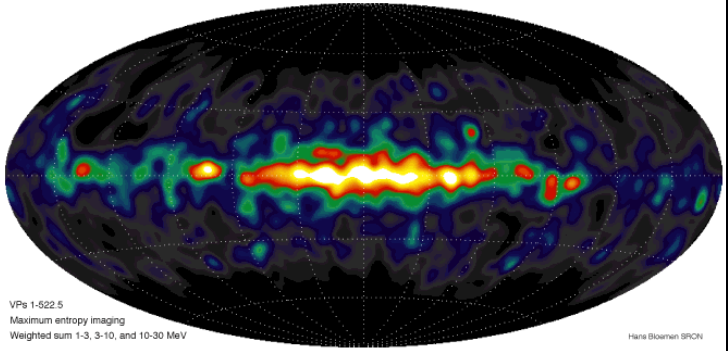
Brenda Dingus (UMD/LANL) and Pat Harding (LANL)

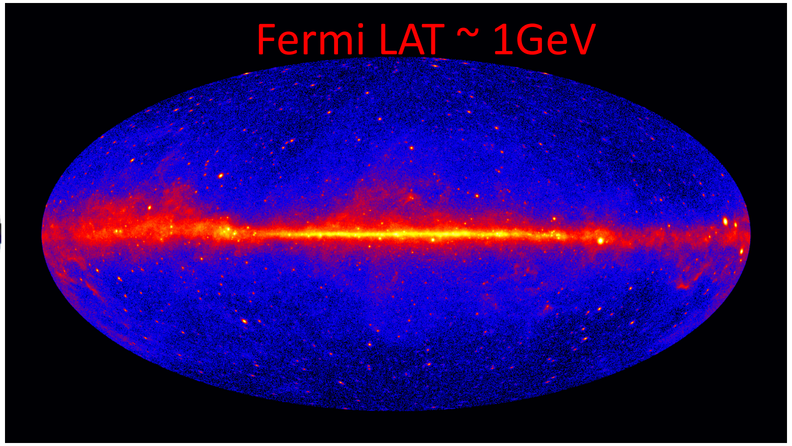


Detecting Gamma Rays < 1 MeV to > 1 PeV

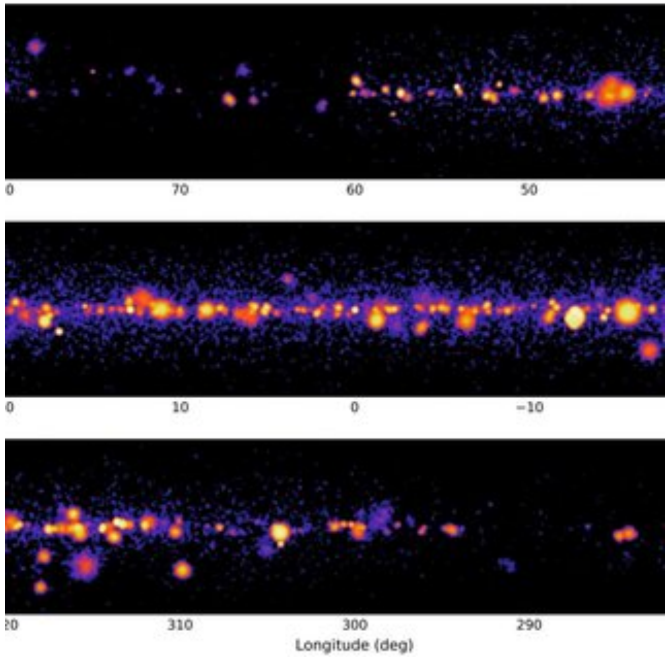
- > 9 orders of magnitude (i.e. the difference between radio and optical) with different detection techniques
  - Space based (low E) and Ground Based (high E) due to limited size of space based observatories and decreasing flux of gamma rays with energy
- Multiple classes of gamma-ray sources have been observed
  - Galactic: Pulsars, Novae, Supernova Remnants, X-ray Binaries, Pulsar Wind Nebulae, TeV Halos, Microquasars
  - Extragalactic: Active Galactic Nuclei, Starburst Galaxies, Radio Galaxies, Gamma-Ray Bursts
  - Unidentified
- Mature technologies exist with multiple approaches to increase sensitivity for future observatories
  - Current observatories are 2nd + generation designs

COMPTEL 1-30 MeV

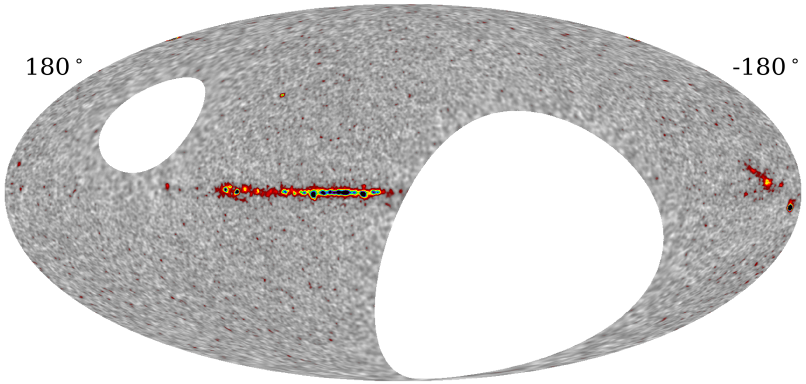




HESS Galactic Plane Survey ~ 1 TeV

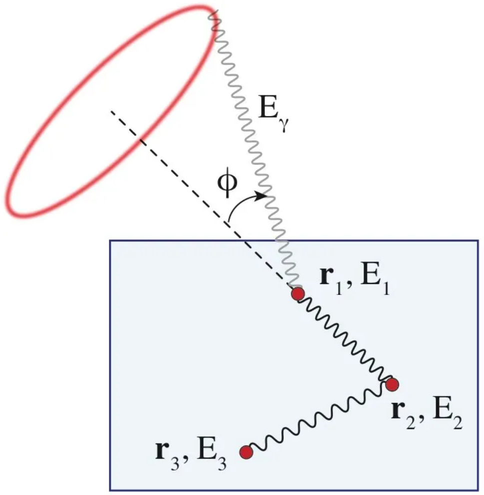


HAWC ~ 10 TeV

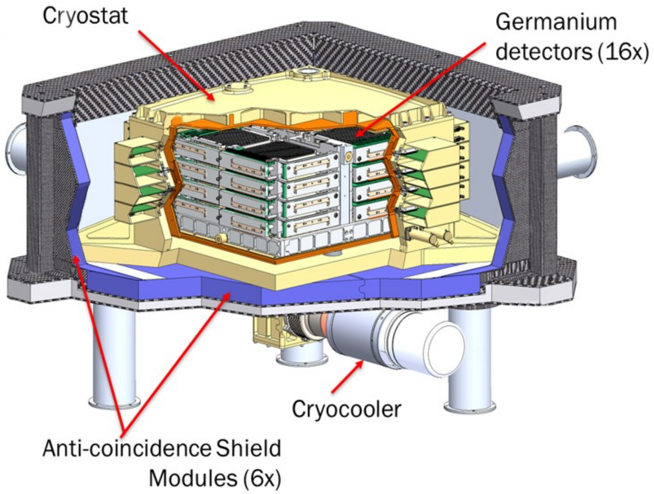


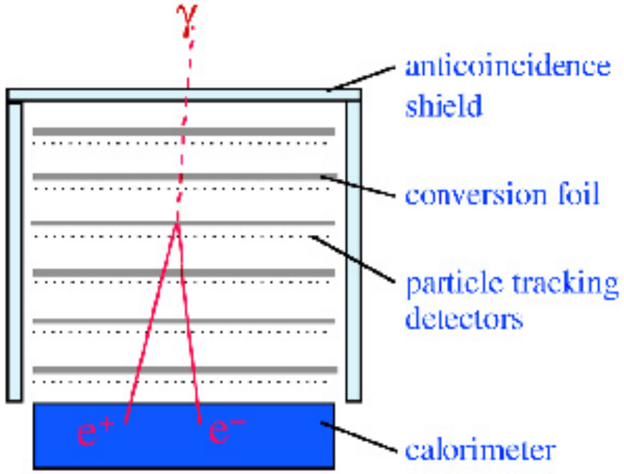
Detecting Gamma Rays from Space

- < ~ MeV gamma rays are detected with collimated detectors, coded masks, or comparative area and timing techniques (INTEGRAL, SWIFT/BAT, Fermi GBM)
- < ~ 10 MeV gamma rays require 2 Compton scatters within the detector to locate sources to annulus on the sky (COMPTEL, COSI)
- > ~ 10 MeV gamma rays pair produce and electron positron tracking gives fraction of a degree angular resolution (EGRET, Fermi LAT)

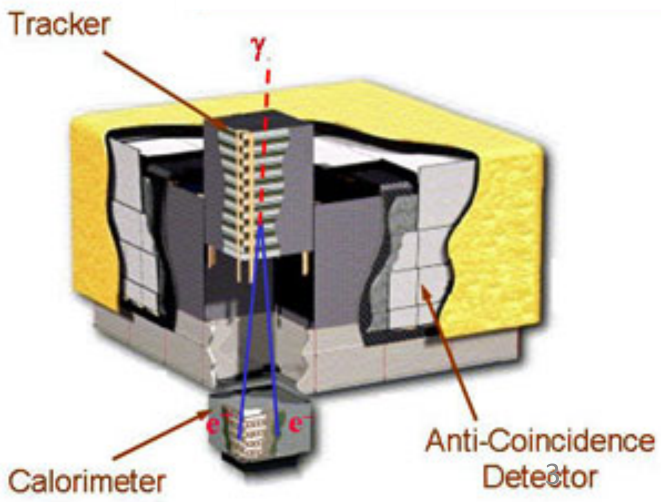


COSI (2025-2027+)



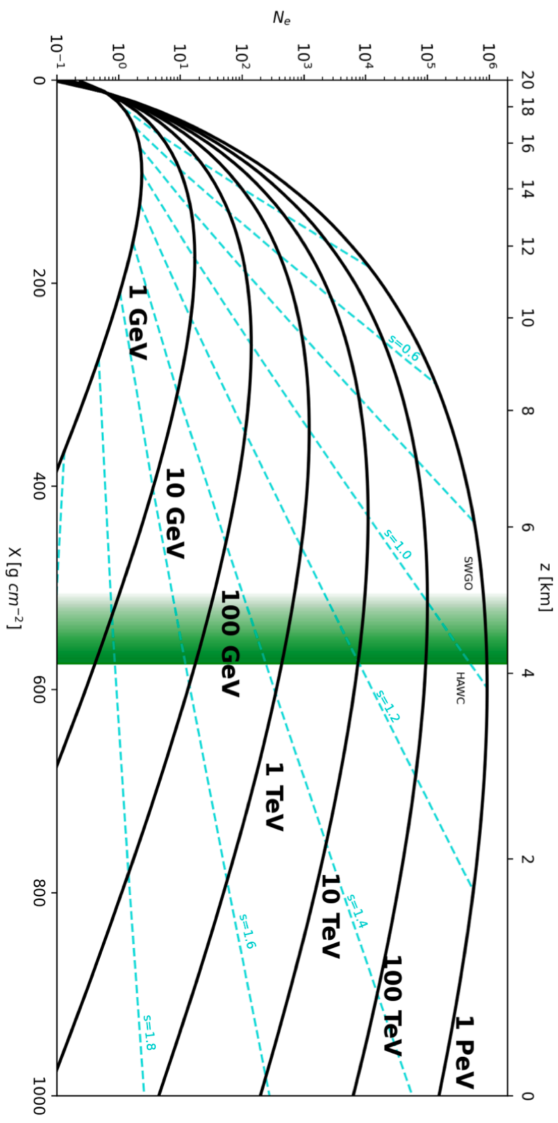


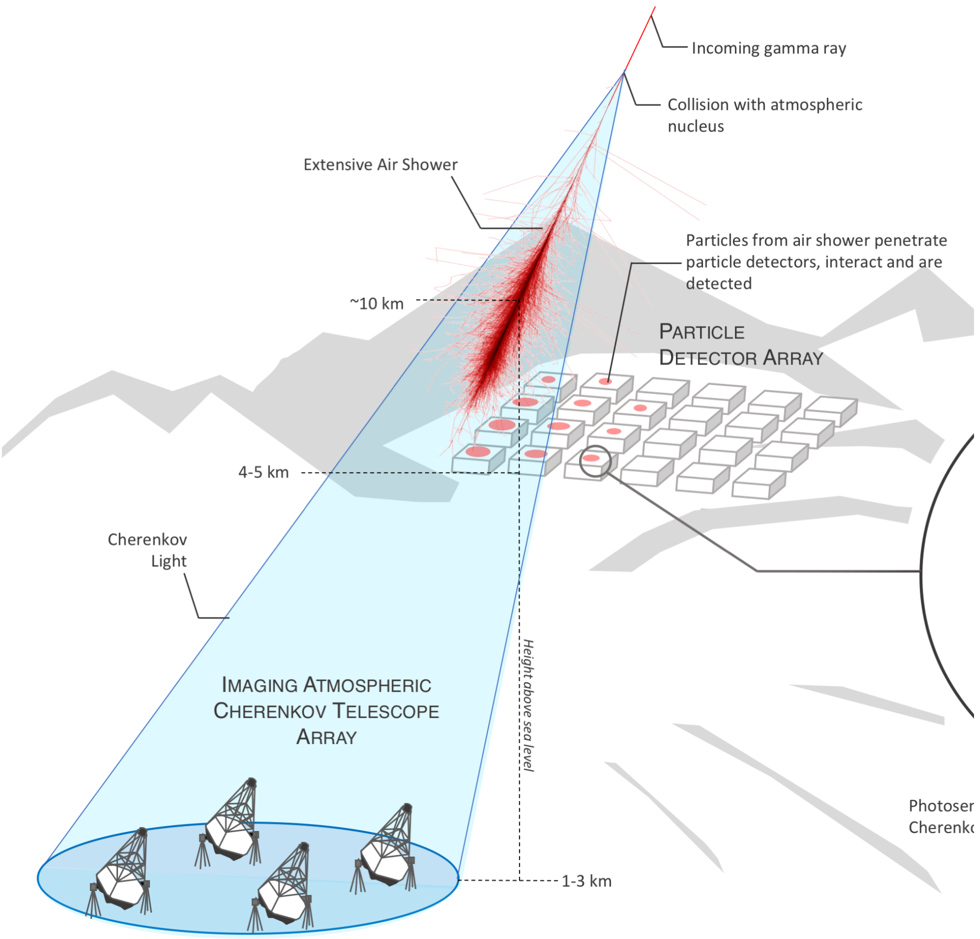
Fermi LAT (2008-now)



Detecting Gamma Rays from the Ground

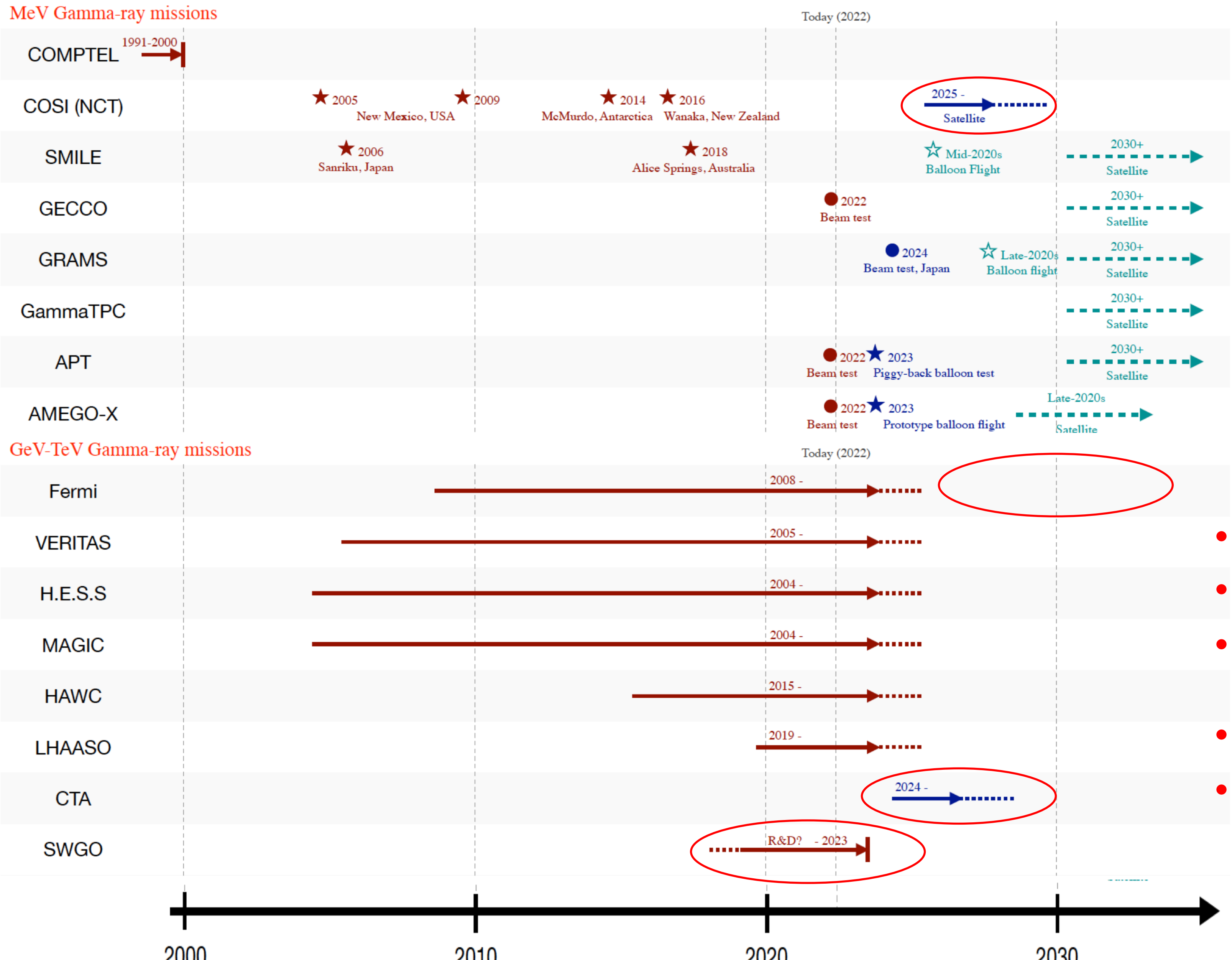
- Imaging Atmospheric Cherenkov Telescopes (IACTs) point large mirrors and pixelated cameras (HESS, VERITAS, MAGIC, CTA) to detect the Cherenkov light in the atmosphere
  - Point at known or postulated sources
  - Operate with 10-20% duty cycle due to dark conditions required
- Extensive Air Shower (EAS) particle detectors use water Cherenkov detectors located at high elevations to observe more than half the sky each day (HAWC, LHAASO, SWGO)
  - Higher energy threshold
  - Worse energy resolution

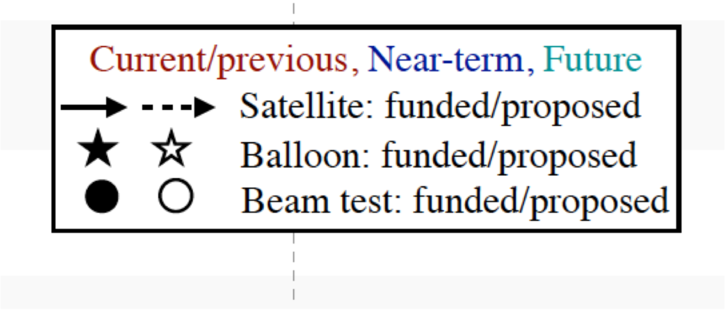




Shower image, 100 GeV γ-ray adapted from: F. Schmidt, J. Knapp, "CORSIKA Shower Images", 2005, https://www-zeuthen.desy.de/~jknapp/fs/showerimages.html

Current, upcoming and proposed observatories





- COSI (< few MeV) 2025-2027+
- No next generation Fermi (> GeV)
- Despite many ideas for MeV-GeV, no selected mission to fill gap
- CTA (TeV) ~ 2024
- SWGO (TeV) new wide field of view is in R&D phase

Gamma-Ray Detector Technologies Overlap High Energy Physics Technologies

- Space Based
  - Trackers: Silicon, Germanium, GEMs, Scintillating Fibers
  - Calorimeters: Ge, CZT, 31BGO, CsI
  - Photon Detectors: PMTs, SiPMs
  - Electronics: Low Power ASICs
- Ground Based
  - Pixelated Cameras: Multi-anode PMTs, SiPMs
  - Large Area Photodectors: PMTs, SiPMs, wavelength shifters
  - Multi Pbyte per year data streams

Gamma rays from Space are unique probes of Fundamental High Energy Physics Phenomena

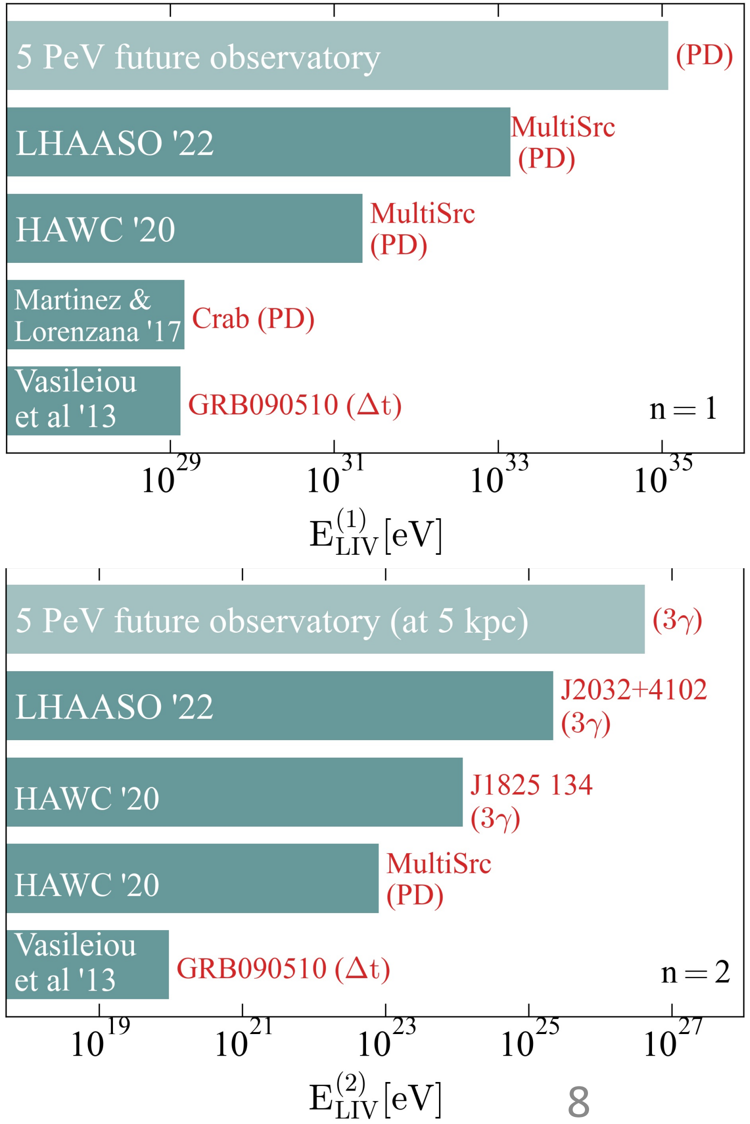
For example (Outline of the rest of this talk)

- Lorentz Invariance Tests
- Primordial Black Holes
- Axion Like Particles
- WIMPs
- Multimessenger Observations

PeV Probes Quantum Gravity at Planck Scale

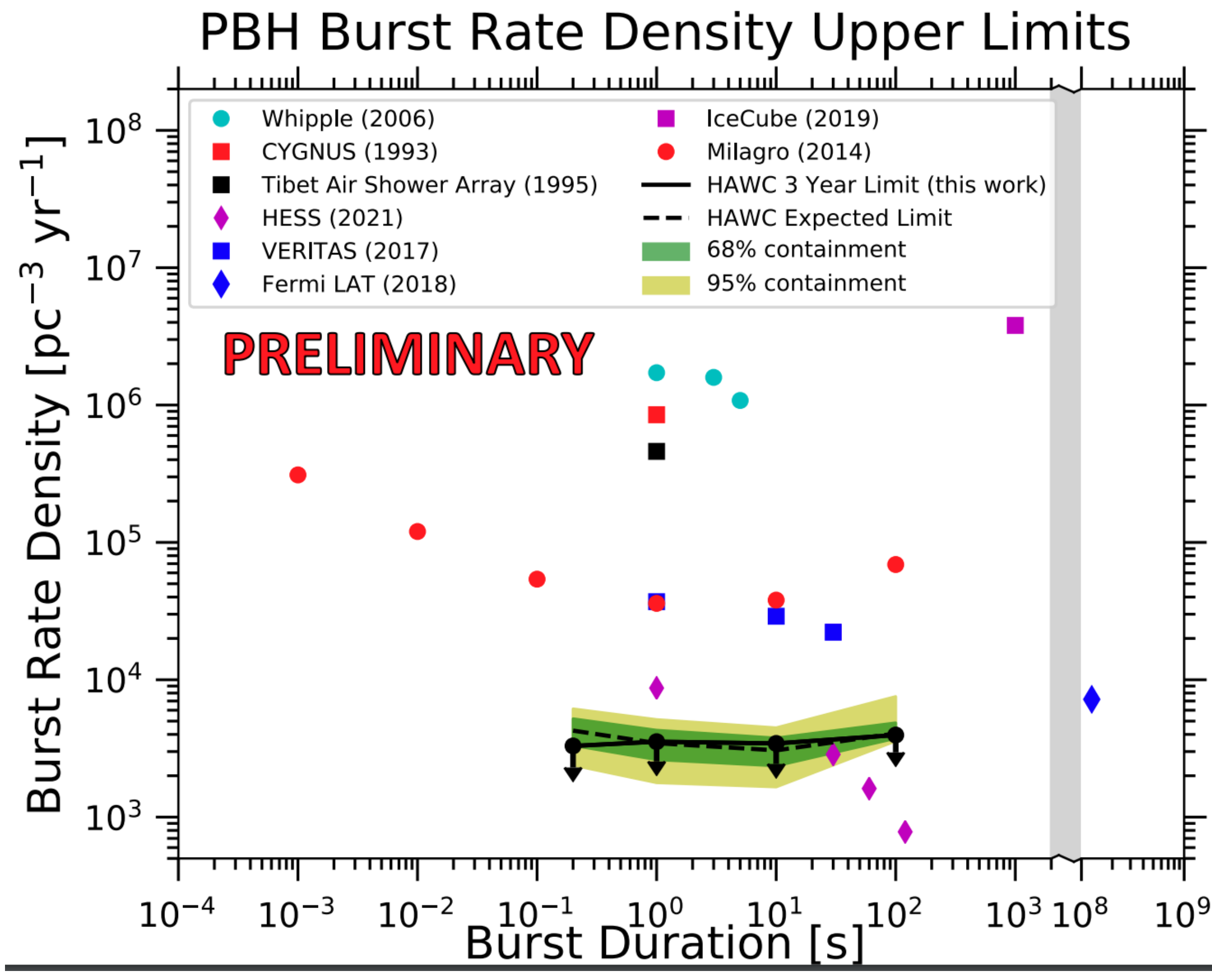
- Lorentz Invariance Violation (LIV) is required by many theories of quantum gravity
- Time of arrival of different energy gamma rays from distant transients tests LIV
- Even tighter constraints from the existence of PeV gamma rays that would have decayed if LIV were present
- Can probe energies beyond the Planck mass (=1.22e28 eV) for n=1

$$E_\gamma^2 - p_\gamma^2 = \pm \frac{E_\gamma^{n+2}}{(E_{LIV}^{(n)})^n}$$



Transient gamma-rays probe evaporating Primordial Black Holes

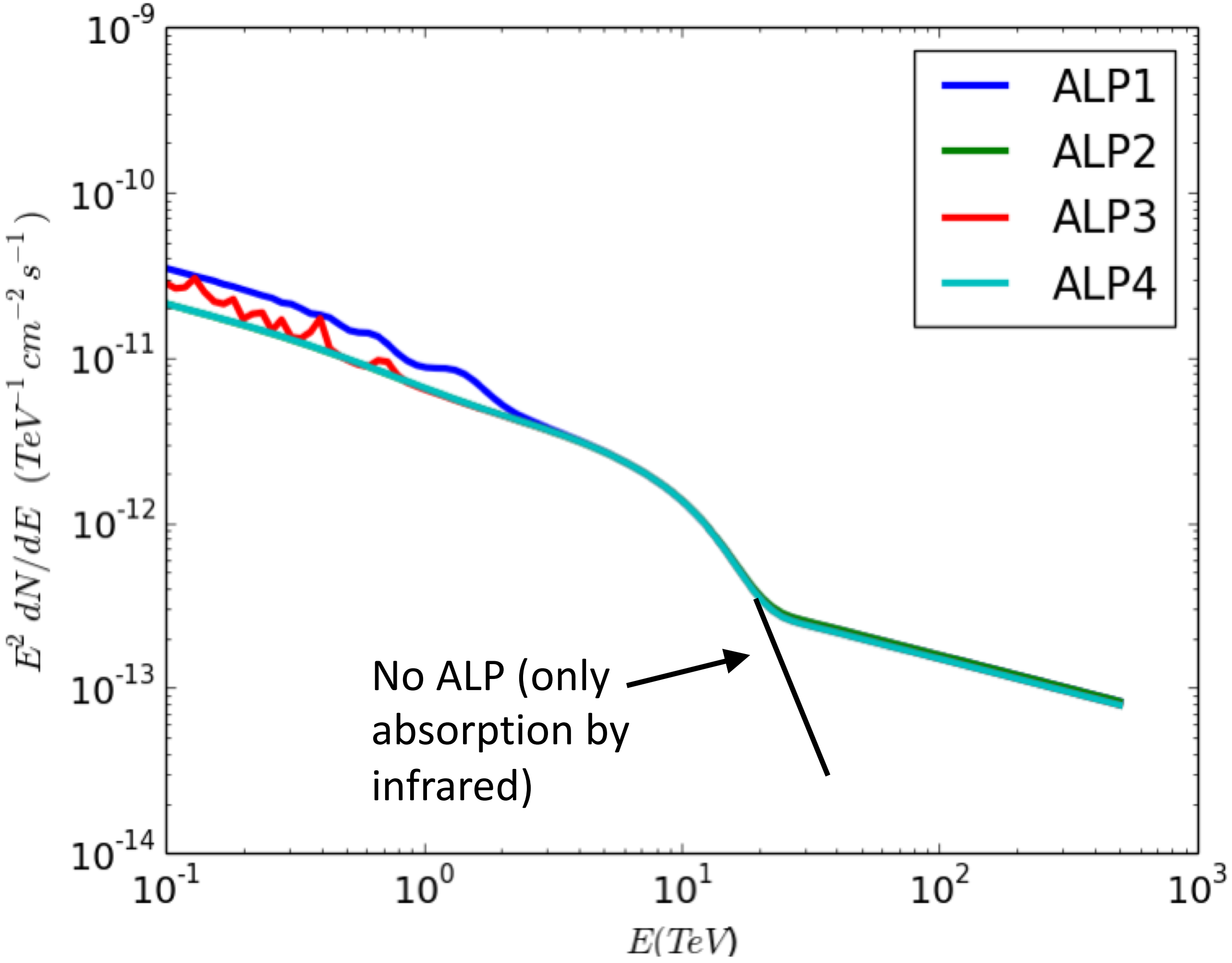
- Temperature of BH is inversely proportional to mass
- PBH evaporating now had mass of 5e14 grams in early universe
- Lifetime at GeV energies is days and at TeV energies is seconds
    - Spectrum and Lightcurve probe number of species of neutrinos, quarks, …
- Limits on PBHs from isotropic diffuse GeV gamma-rays
- Limits on local PBHs from gamma-ray transient searches



Adapted from *JCAP* 04 (2020) 026

Distant Gamma-Rays Probe Axion Like Particles (ALP)

- Gamma rays from distant sources travel billions of years interacting with magnetic fields which can produce ALPs
- ALPS can cause GeV gamma-ray spectrum wiggles
- ALPS can produce >>TeV gamma rays that otherwise would have been attenuated by pair production with infrared background photons
- Effect on gamma-ray spectrum depends on ALP mass and coupling constant and magnetic fields



ALP 1
m_a = 100 neV
$G_{a\gamma}$ = 5e-11 GeV^{-1}

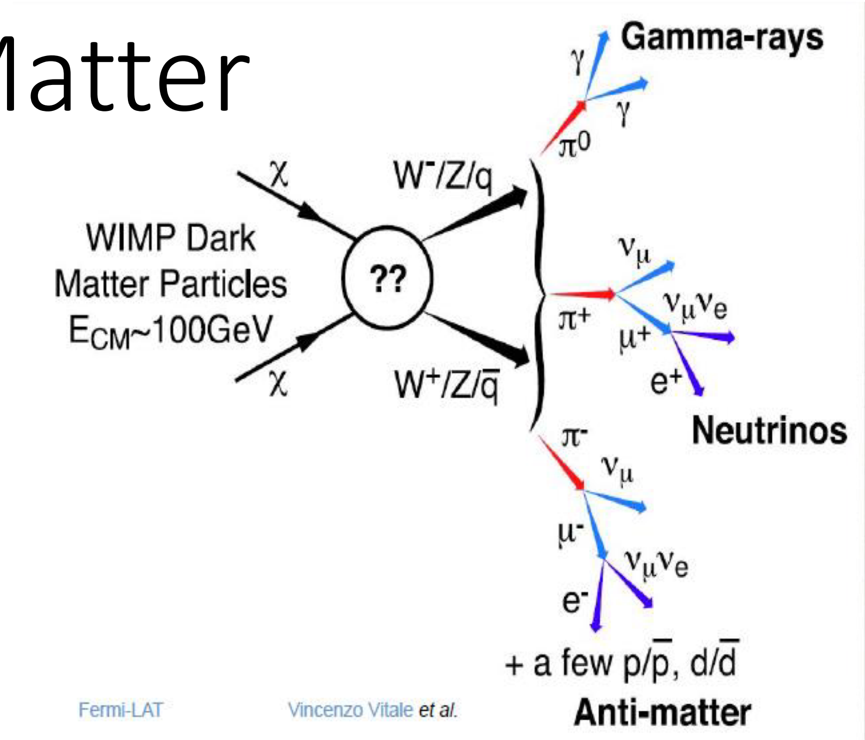
ALP 2
m_a = 10 neV
$G_{a\gamma}$ = 5e-11 GeV^{-1}

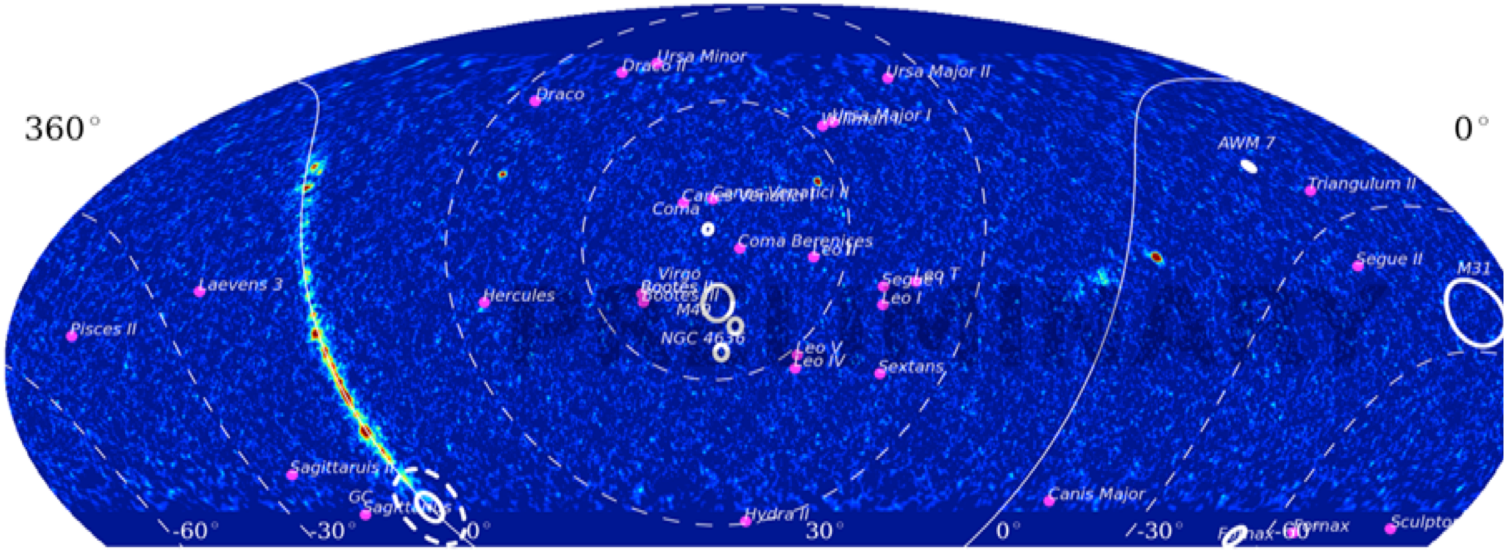
ALP 3
m_a = 100 neV
$G_{a\gamma}$ = 5e-10 GeV^{-1}

ALP 4
m_a = 10 neV
$G_{a\gamma}$ = 5e-10 GeV^{-1}

Gamma Rays Probe WIMP Dark Matter from Dark Matter Rich Locations

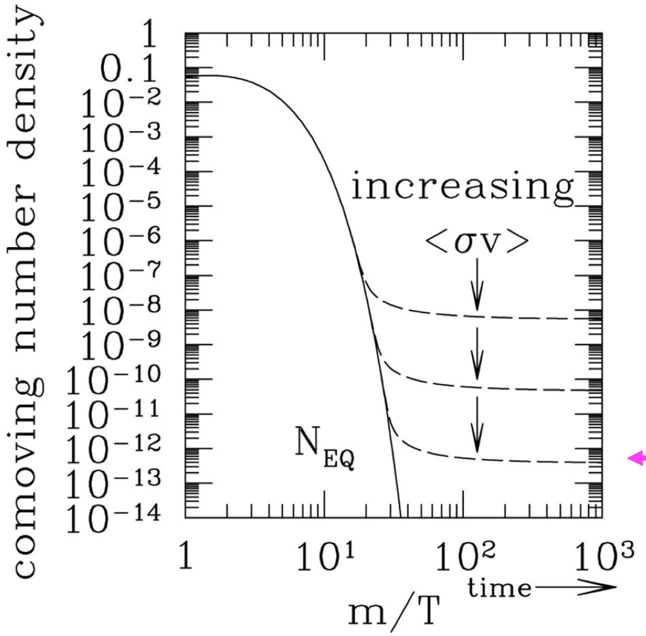
- Galactic Center, Galactic Clusters
  - Observationally known to have lots of DM
- Dwarf Galaxies
  - Clean searches with few astrophysical backgrounds
  - Optical Searches discovering more
- Gamma ray detection would measure annihilation cross section and dark matter mass (important for particle physics and cosmology)
- Even if collider or direct detection discovers WIMP, gamma-ray observations prove that WIMPs are where the DM is observed





DM Self Annihilation Produces Gamma Rays

- Thermal production of dark matter particles in the early universe predicts a testable annihilation cross section
- Gamma-ray flux depends on standard model particles into which the dark matter annihilates or decays as well as the dark matter spatial distribution



time in early Universe when amount of DM freezes out

Particle Physics

$$\frac{d\Phi}{dE}_{annihilation} = \frac{J}{8\pi}\frac{\langle\sigma v\rangle}{M^2}\frac{dN(M, channel)}{dE}$$

$$J = \int\int \rho^2_{dm}(l,\Omega)dld\Omega$$

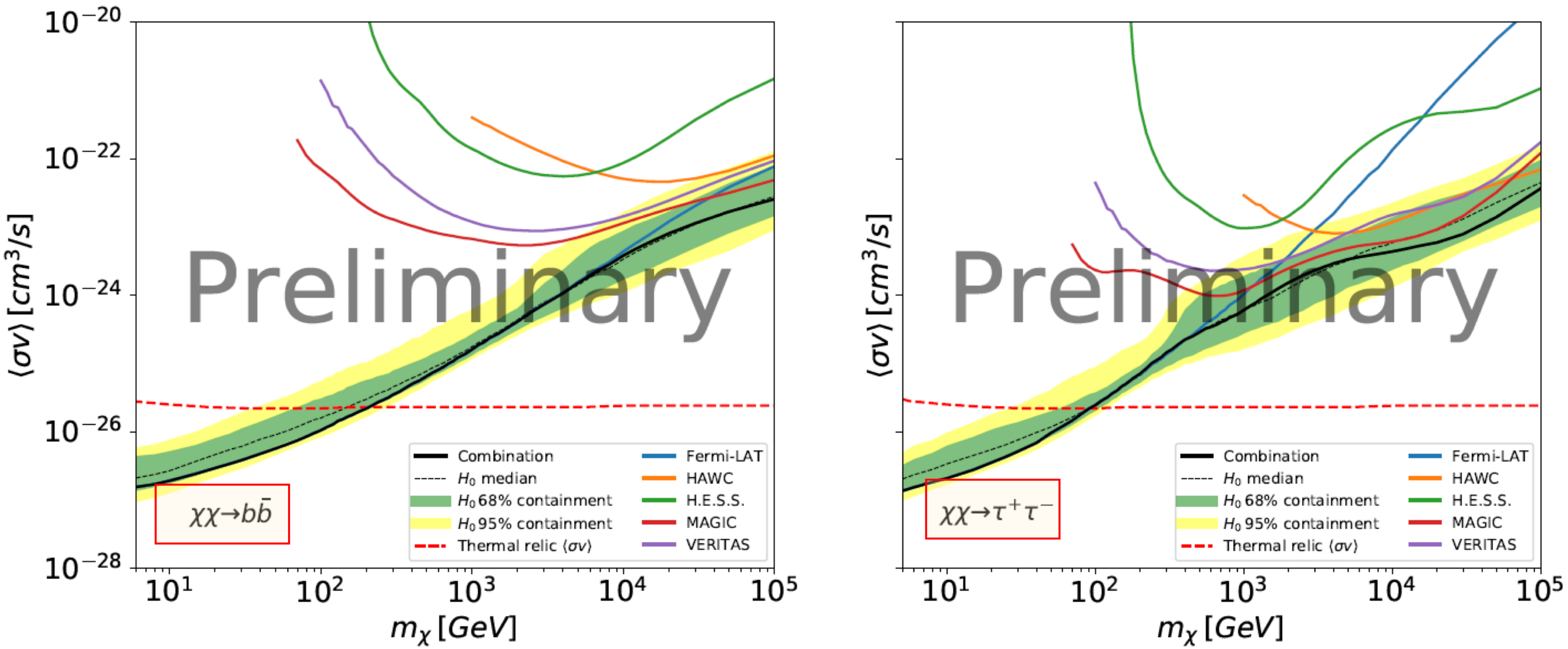
$$\frac{d\Phi}{dE}_{decay} = \frac{D}{4\pi}\frac{1}{\tau M}\frac{dN(M, channel)}{dE}$$

$$D = \int\int \rho_{dm}(l,\Omega)dld\Omega$$

Astrophysics

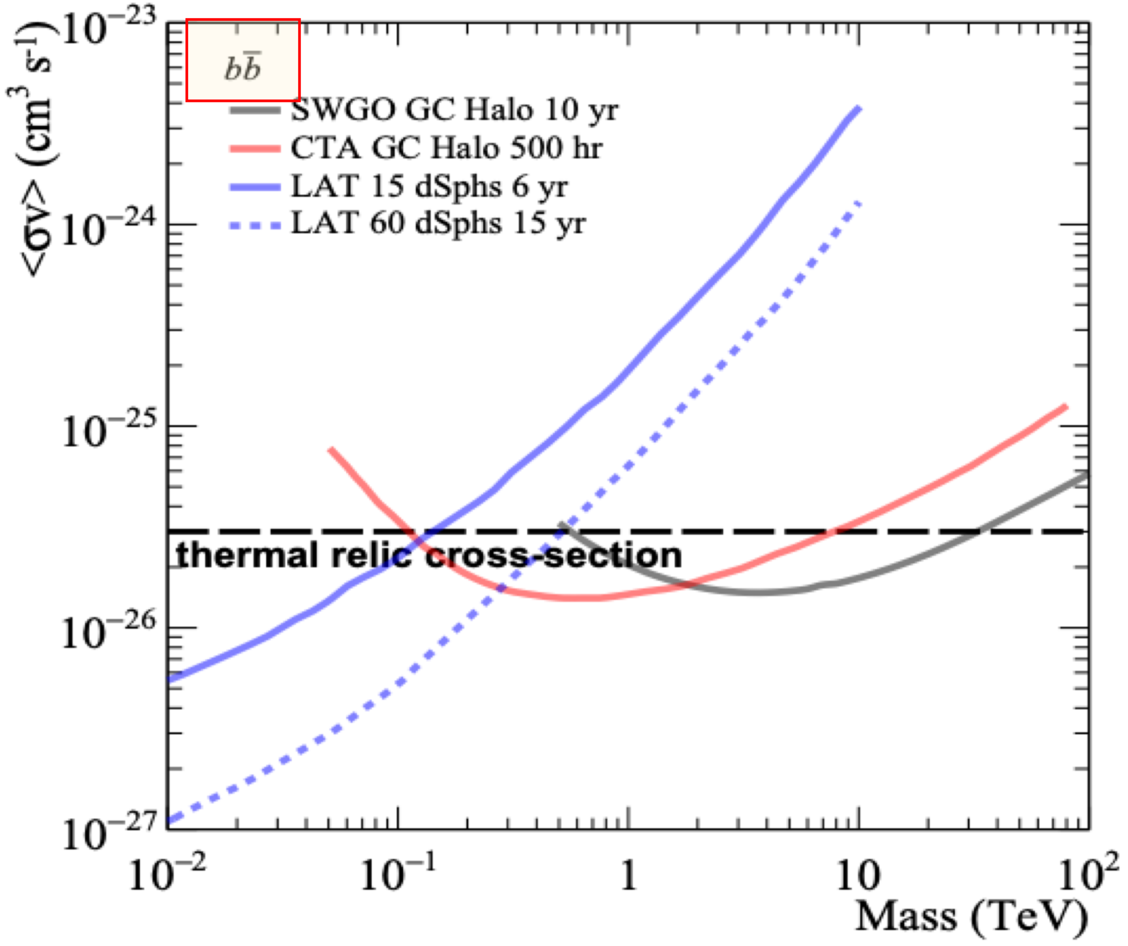
Gamma Ray Searches Probe Thermal Relic Limit

- Combined Limit from multiple observatories for emission from dwarf spheroidals places limit on annihilation cross section for dark matter masses from 5 GeV to 100 TeV

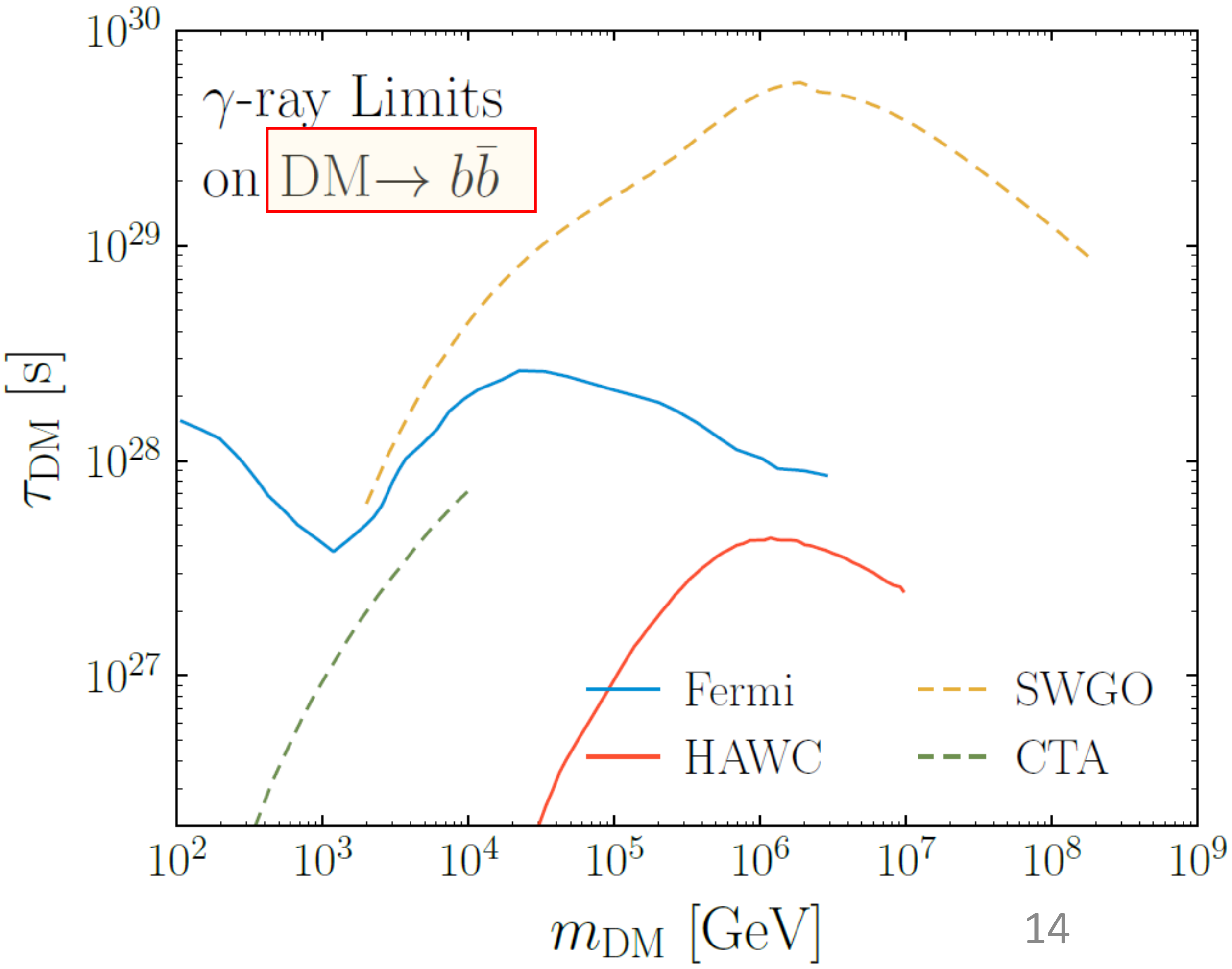


Future Expected Limits from Galactic Center DM

Cross Section Upper Limits

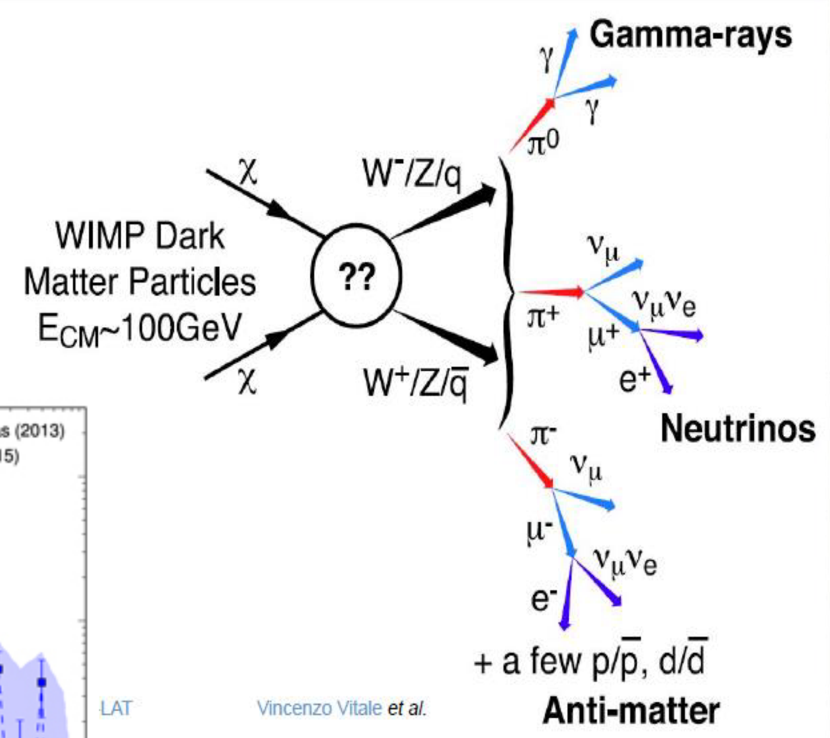


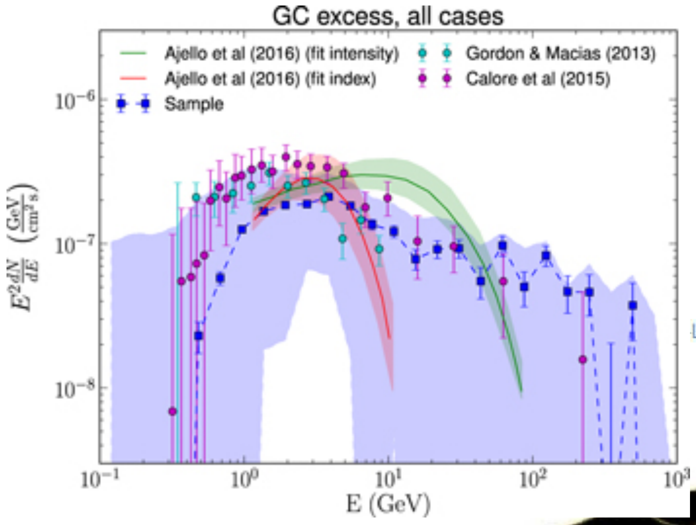
Decay Lower Limits



Excess GeV and 511 keV gamma rays around Galactic Center

- Excess of 511 keV gamma rays is seen from the Galactic center
- Excess of GeV gamma rays also seen in Galactic center
  - May be due to Diffuse Model uncertainties or unresolved sources,
  - If DM, must be consistent with cross section limits from dwarf spheroidals
- COSI (2025-2027+) will better resolve the angular distribution of 511 keV gamma-rays and compare with dark matter expectations and GeV emission





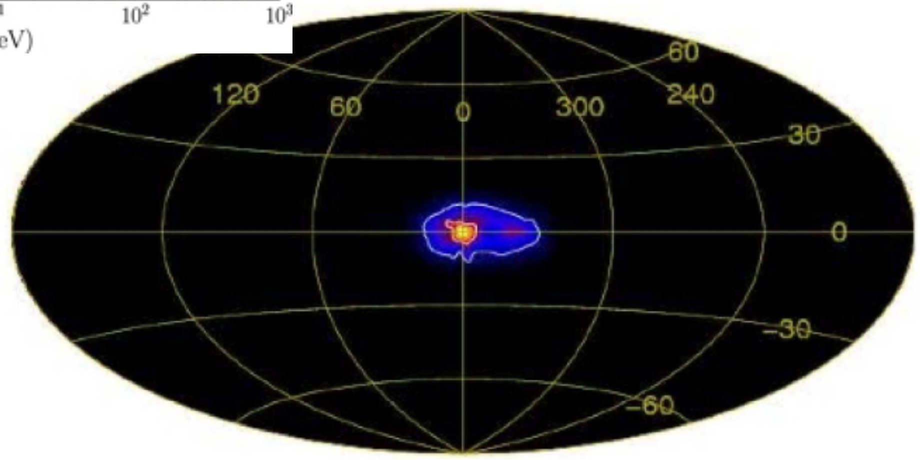
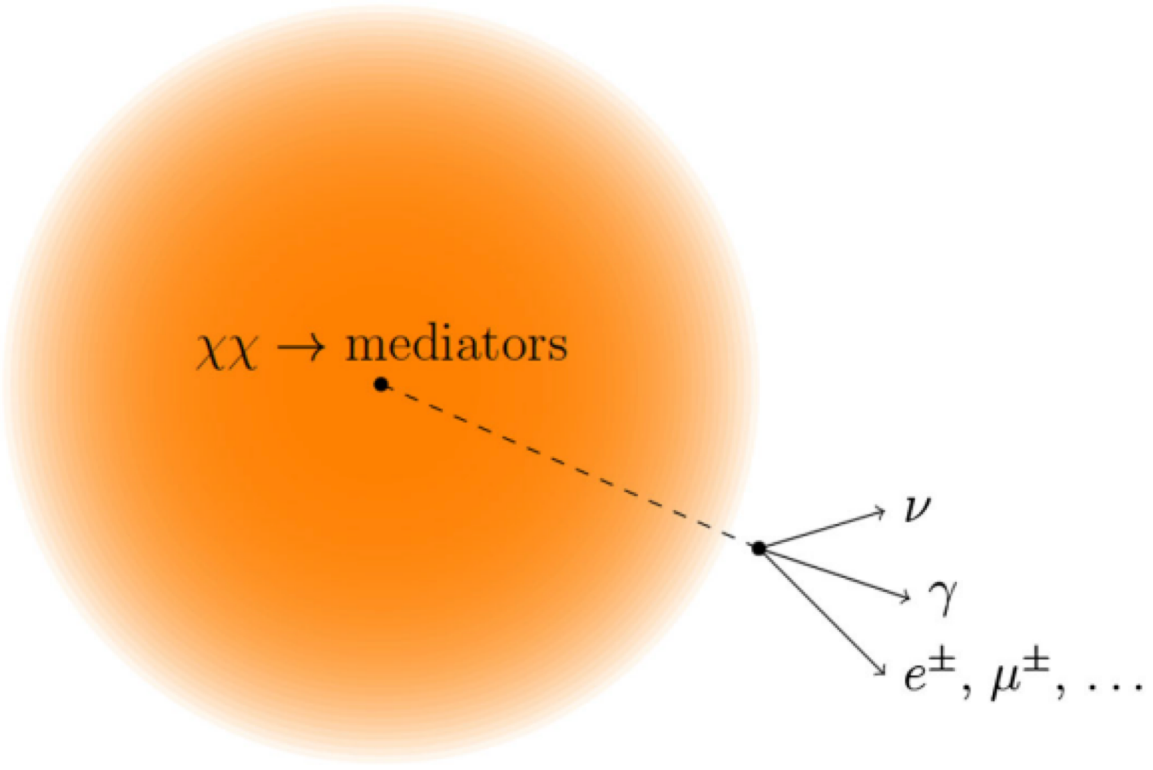


FIG. 4 511 keV line map derived from 5 years of INTEGRAL/SPI data (from Weidenspointner *et al.*, 2008a).

DM Trapped by the Sun



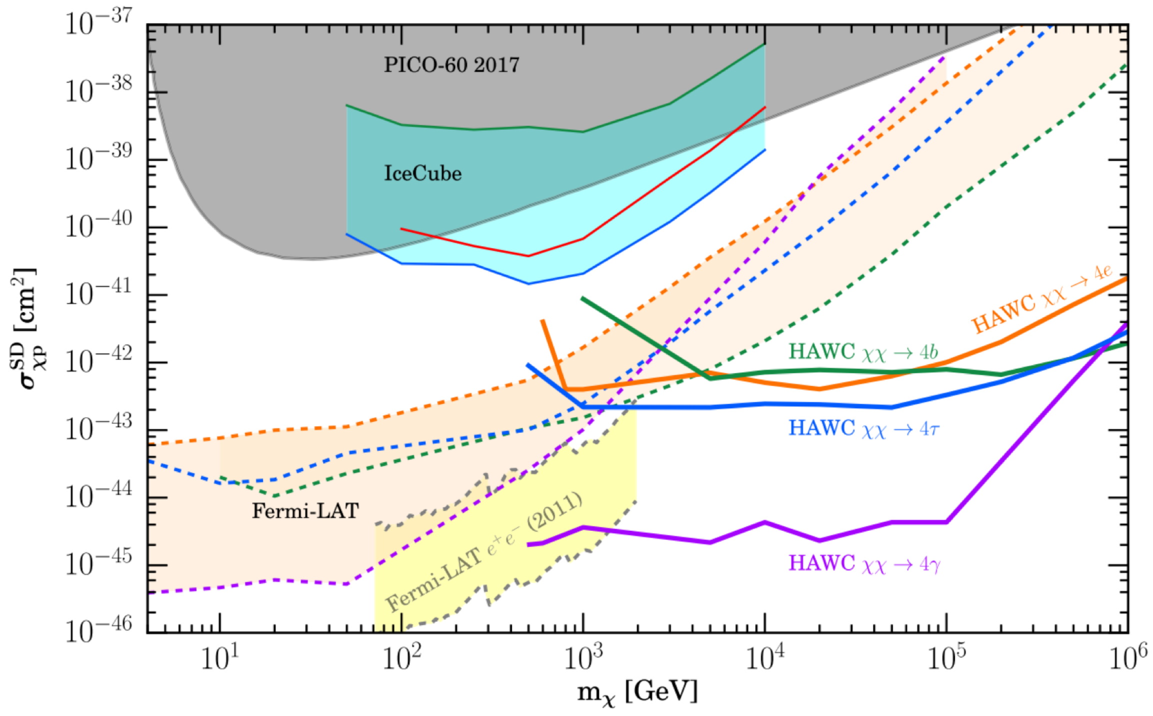


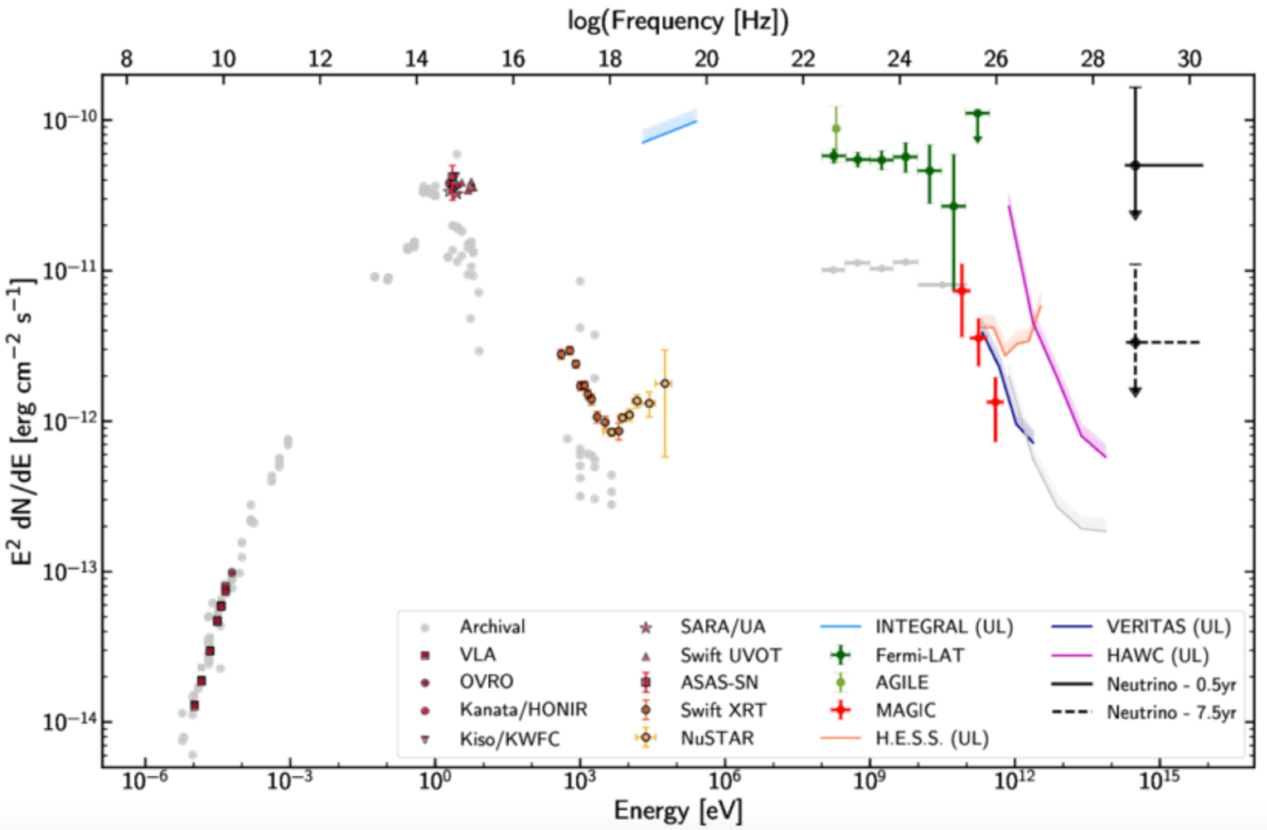
FIG. 4. Upper limits on the spin-dependent dark matter–proton scattering cross section $\sigma^{\rm SD}$, from various gamma-ray and neutrino experiments. The thick solid lines show the limits obtained from HAWC in this work for the $\bar{b}b$, e^+e, $\tau^+\tau^-$, and $\gamma\gamma$ channels. The dashed lines following the same channelwise color scheme show the limits from Fermi-LAT for $\bar{b}b$, e^+e, $\tau^+\tau^-$, and $\gamma\gamma$, updated from Ref. [37]. The HAWC and Fermi-LAT limits in this work are for scenarios where the mediator has a decay length $L = R_\odot$ and can be scaled for more conservative cases as discussed in Sec. IV A. The 2011 Fermi-LAT results are for mediators decaying into electrons, with decay lengths between 0.1 and 5 AU [56]. The thin solid lines show the results from IceCube for the $\bar{b}b$, W^+W^-, and $\tau^+\tau^-$ channels [31] and are for scenarios with short-lived mediators (results for long-lived mediators would be better [16,37], but IceCube results are not yet available). The grey region indicates the parameter space excluded by PICO-60 [24].

Albert, A. et al. PRD 98, 123012 (2018)

- Note IceCube limits don't require long lived mediator because neutrinos can escape the Sun.
- Also HAWC's reanalysis with much improved sensitivity will be out soon.

Gamma Rays are Key to Multi-Messenger Observations

- Gamma Rays are likely produced by same sources as neutrinos and gravitational waves.
- The most compelling counterparts for these sources have been identified with gamma-ray observations.
- Counterparts provide unique probes of fundamental physics
    - Neutrino constraints from gamma-ray/neutrino detections
    - Cosmology constraints from gamma-ray/gravitational wave detections
- Several small GRB satellites are planned to locate GRBs, but other observatories are needed to fill in the higher energy gamma-ray spectrum



Spectral Energy Distribution of Neutrino Source TXS 0506+056. Association with the active galactic nuclei was made by flaring at GeV and TeV gamma-ray energies coincident with the neutrino.

Summary

- Gamma-ray observatories exist that have already placed unique constraints on dark matter, Lorentz Invariance, primordial black holes.
- New observatories are planned with > order of magnitude improvements in sensitivity
- Collaborative efforts between astrophysicists and high energy physicists have been essential to the past success of this field.
  - DOE labs' contributions have been critical to the success of many projects (e.g. SLAC and Fermi, Argonne and VERITAS, LANL and HAWC, Fermilab and Auger). These smaller projects complement bigger projects led by labs and aid in recruitment.
- Future investments by high energy physics in this field will continue to expand our knowledge of fundamental physics.