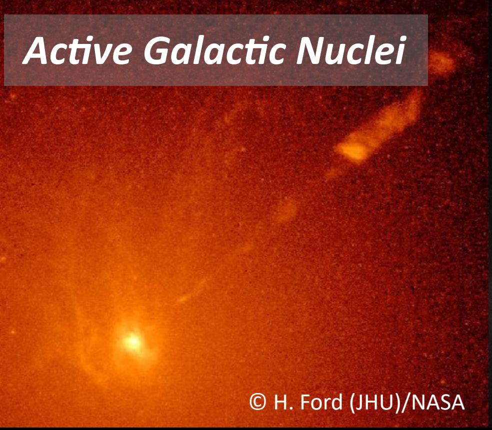
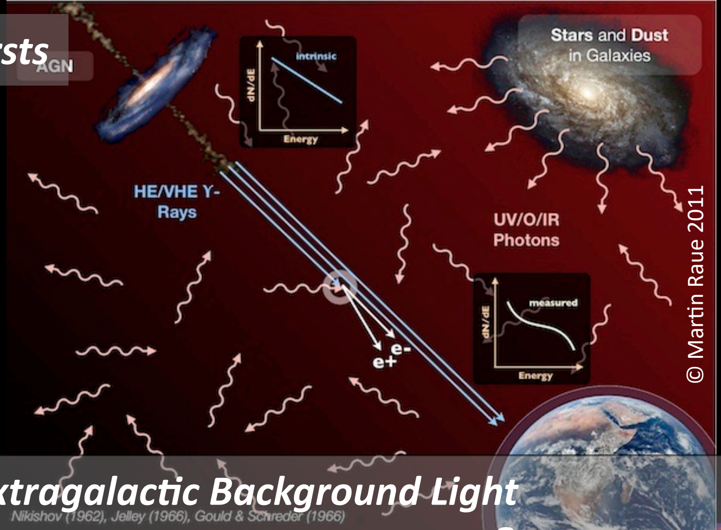

Active Galactic Nuclei
© H. Ford (JHU)/NASA

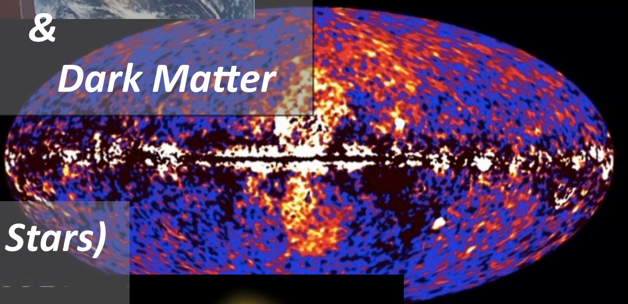

Starburst Galaxies
© NASA/STScI


"Naked Eye" Gamma-Ray Bursts
© NASA/SWIFT



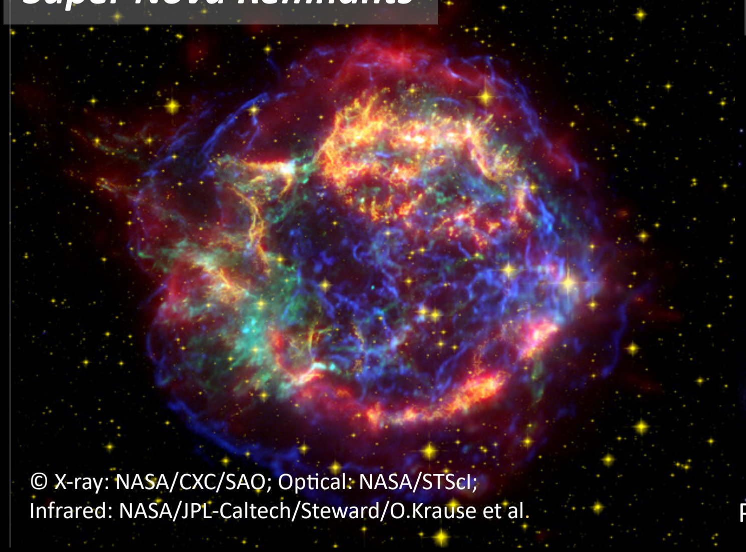
© Martin Raue 2011
Extragalactic Background Light

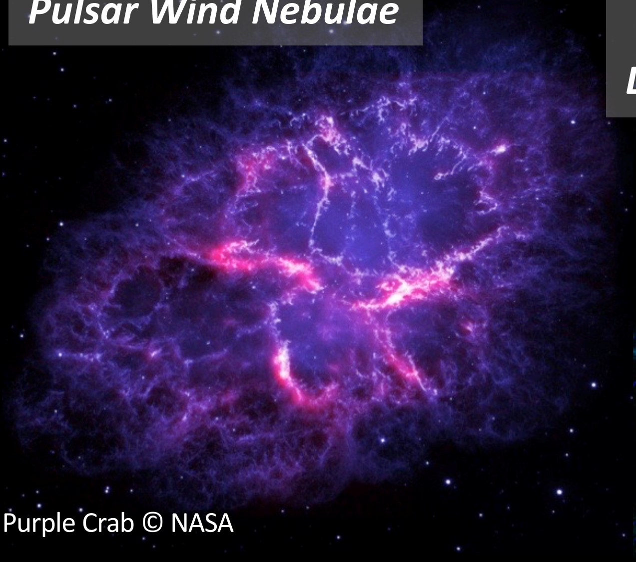
&


Dark Matter
Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.

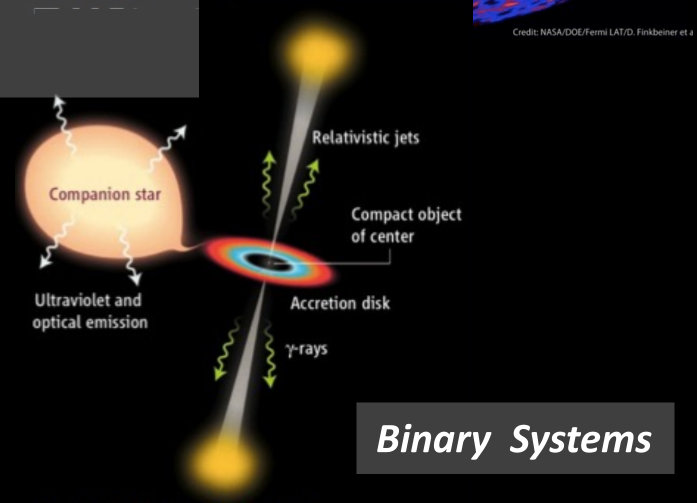
Gamma-Ray Astronomy

Window Into the Non-Thermal Universe


Super Nova Remnants
© X-ray: NASA/CXC/SAO; Optical: NASA/STScI;
Infrared: NASA/JPL-Caltech/Steward/O.Krause et al.


Pulsar Wind Nebulae
Purple Crab © NASA


Pulsars (Fast Spinning Neutron Stars)
&
Lorentz Invariance
© NASA/Fermi



Binary Systems
Mirabel, Science, 312, 1759

Petra Huentemeyer – petra@mtu.edu
Michigan Tech

γ-Ray Observatories

γ-Ray Observatories

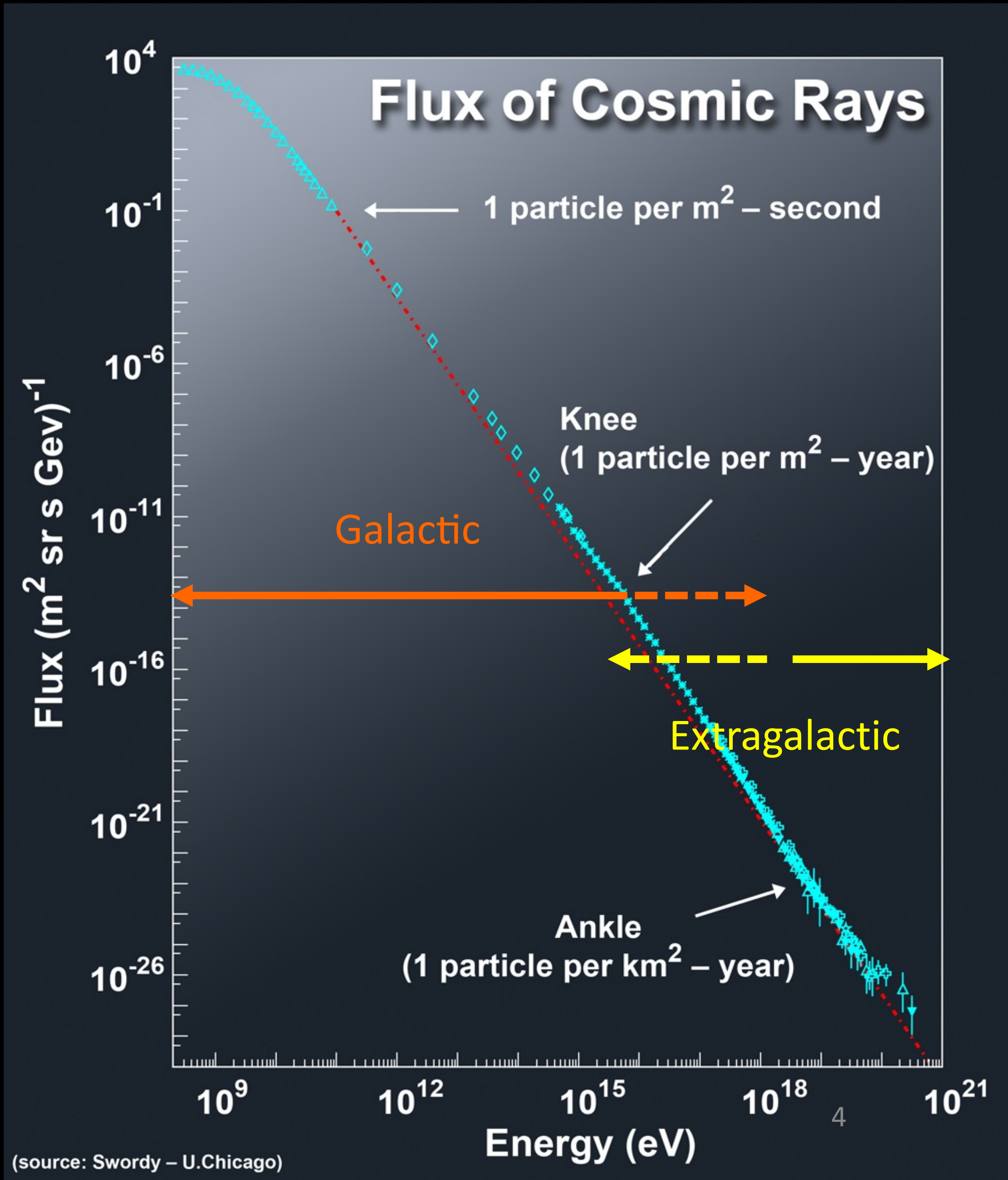
Gamma-Rays are Probing the Non-Thermal Universe

1. **Cosmic rays are pervasive in galaxies.**
   - In Milky Way-like galaxies, the energy density in cosmic rays is ~ 1eV/cm^3 and in equipartition with the magnetic and turbulent energy densities
   - The Role of cosmic rays in the dynamics and energy balance of interstellar gas is of considerable interest, e.g. through the aspects of galaxy evolution such as star formation, change of chemical composition, and growth and maintenance of galactic magnetic fields.

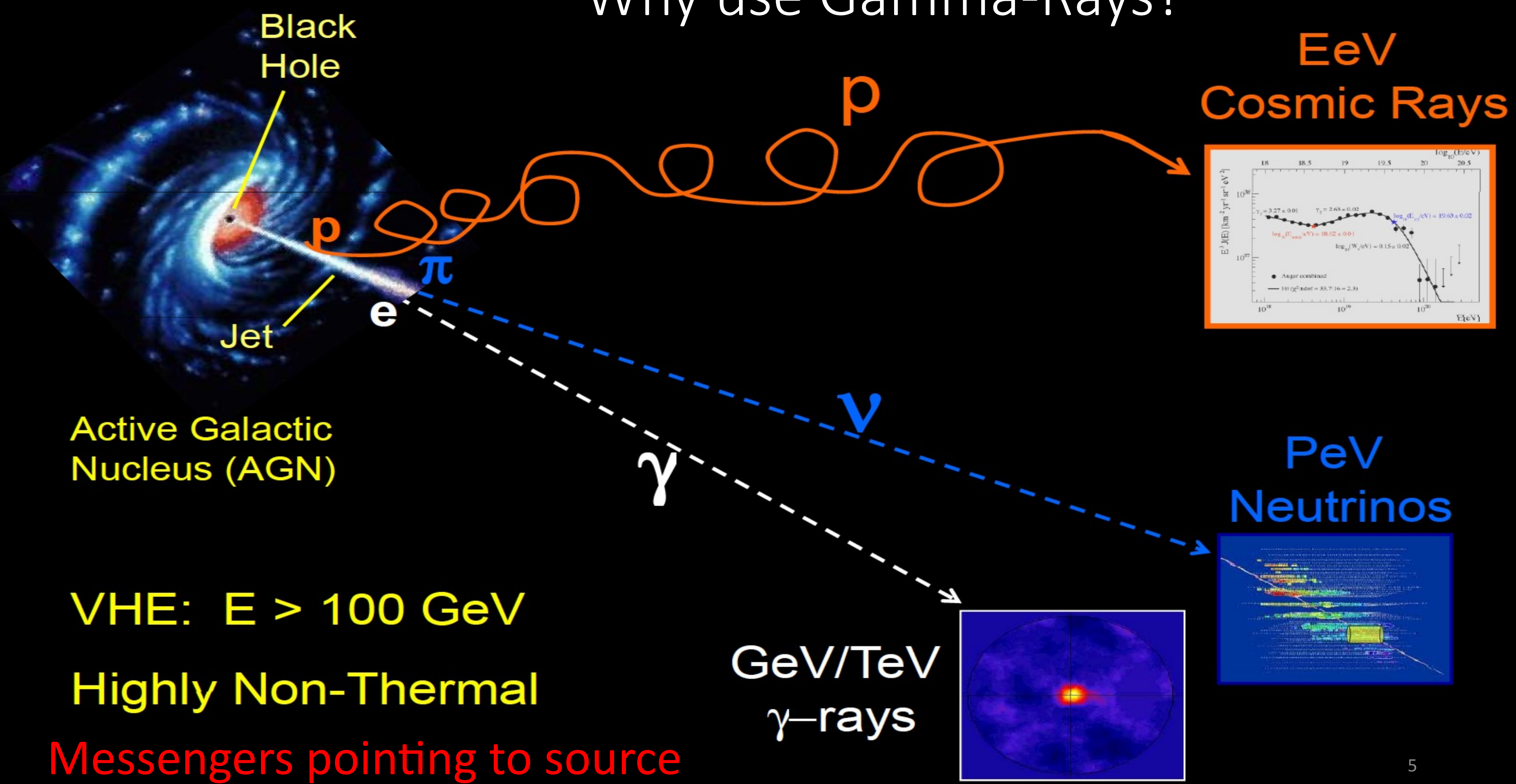
2. **Nature accelerates protons to >10^{20} eV, and to >10^{15} eV within our Galaxy** compared to ~ 10^{12} eV reached by terrestrial accelerators

So we are studying:

1. Which astrophysical sources accelerate particles?
2. How do these astrophysical sources accelerate particles?
3. What new high energy and fundamental physics can we learn from astrophysics?



Why use Gamma-Rays?

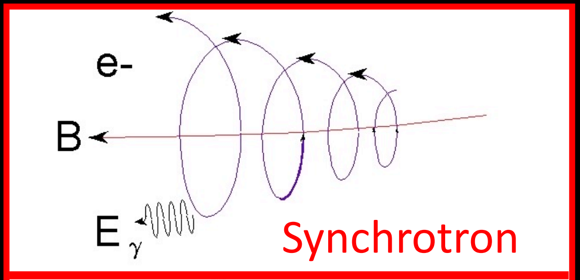


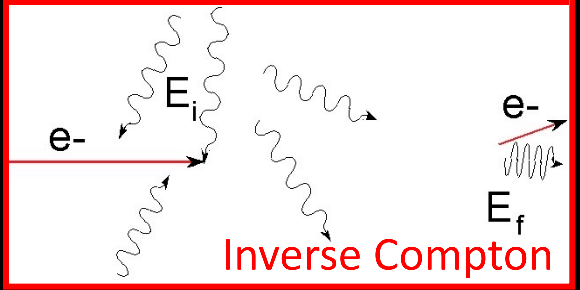
VHE: E > 100 GeV

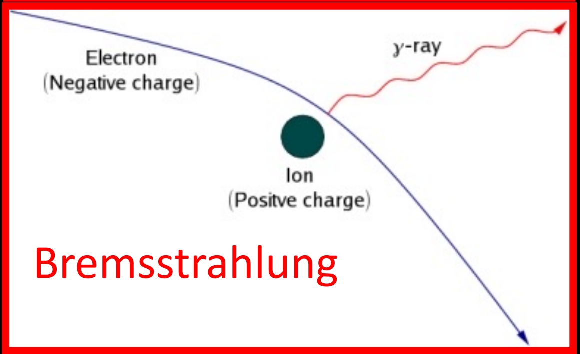
Highly Non-Thermal

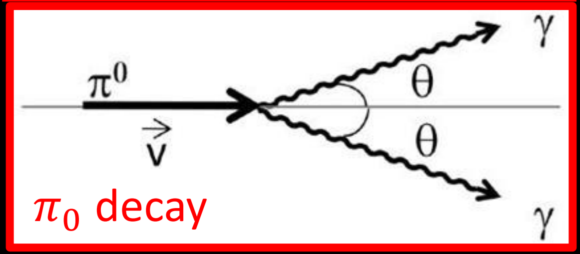
Messengers pointing to source

Gamma-Rays Probe Accelerated Particles









Electrons:

Synchrotron Emission

- Probes Magnetic Field, Electron Energy

Inverse Compton Scattering

- Probes Photon Field, Electron Energy

Synchrotron Self Compton

- If photon field is synchrotron, then Electron Energies & Magnetic Field are determined
- Quadratic relation between variability of TeV (IC) and X-rays (synch)

Bremsstrahlung (@ MeV energies)

- Probes gas/matter distributions

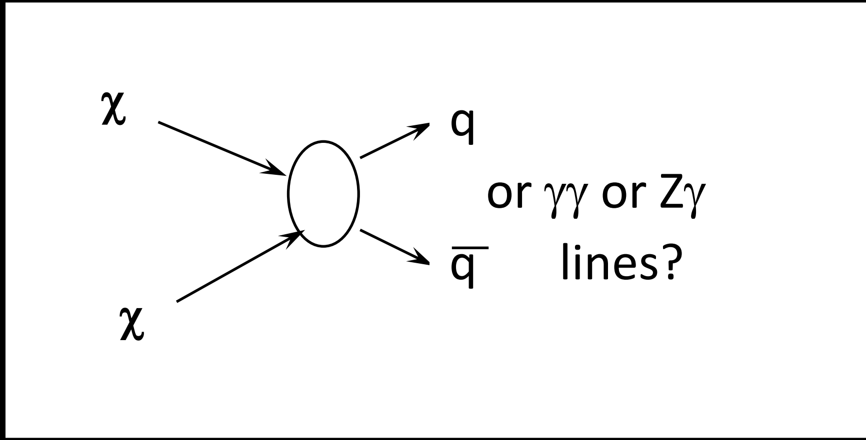
Hadrons:

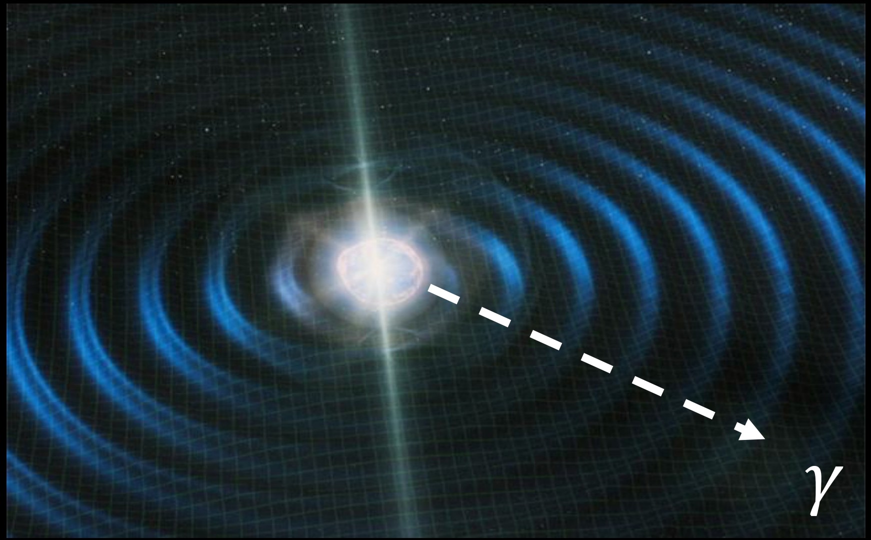
$p + p \rightarrow \pi^{+} + \pi^{o} + \ldots \rightarrow e + \nu + \gamma + \ldots$

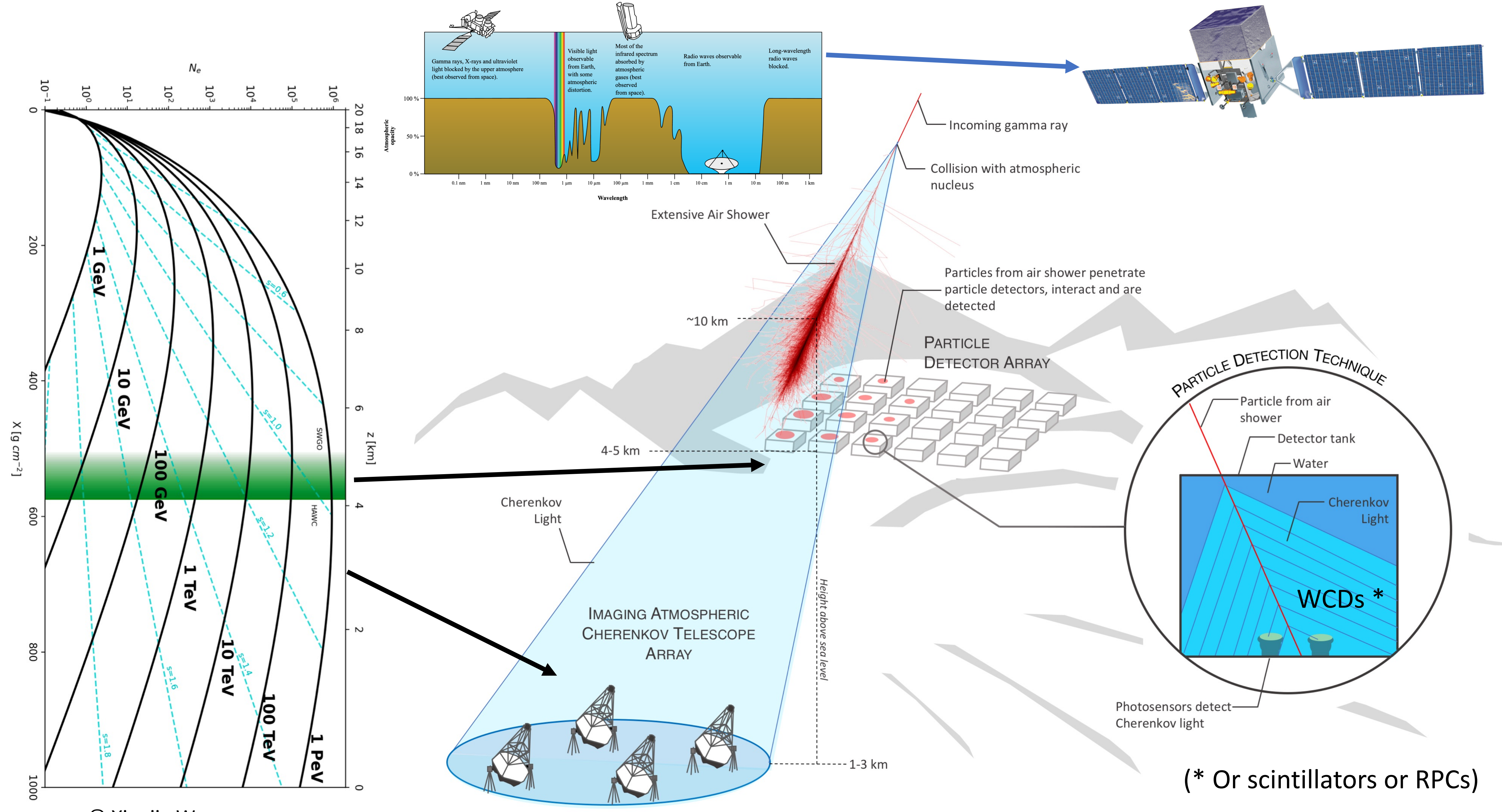
$p + \gamma \rightarrow \pi^{+} + \pi^{o} + \ldots \rightarrow e + \nu + \gamma + \ldots$

What About New Fundamental Physics?

- **Dark Matter**
  - Is the dark matter composed of WIMPs that annihilate or decay into gamma-rays?
- **Lorentz Invariance**
  - Do photons of different energy travel at different speeds from distant astrophysical transients?
- **Gravitational Waves**
  - Are there sources of both gamma-ray and gravitational waves in addition to neutron star mergers?
- **Cosmology**
  - What does the measurement of the attenuation of gamma-rays by infrared photons tell us about the evolution of the universe?



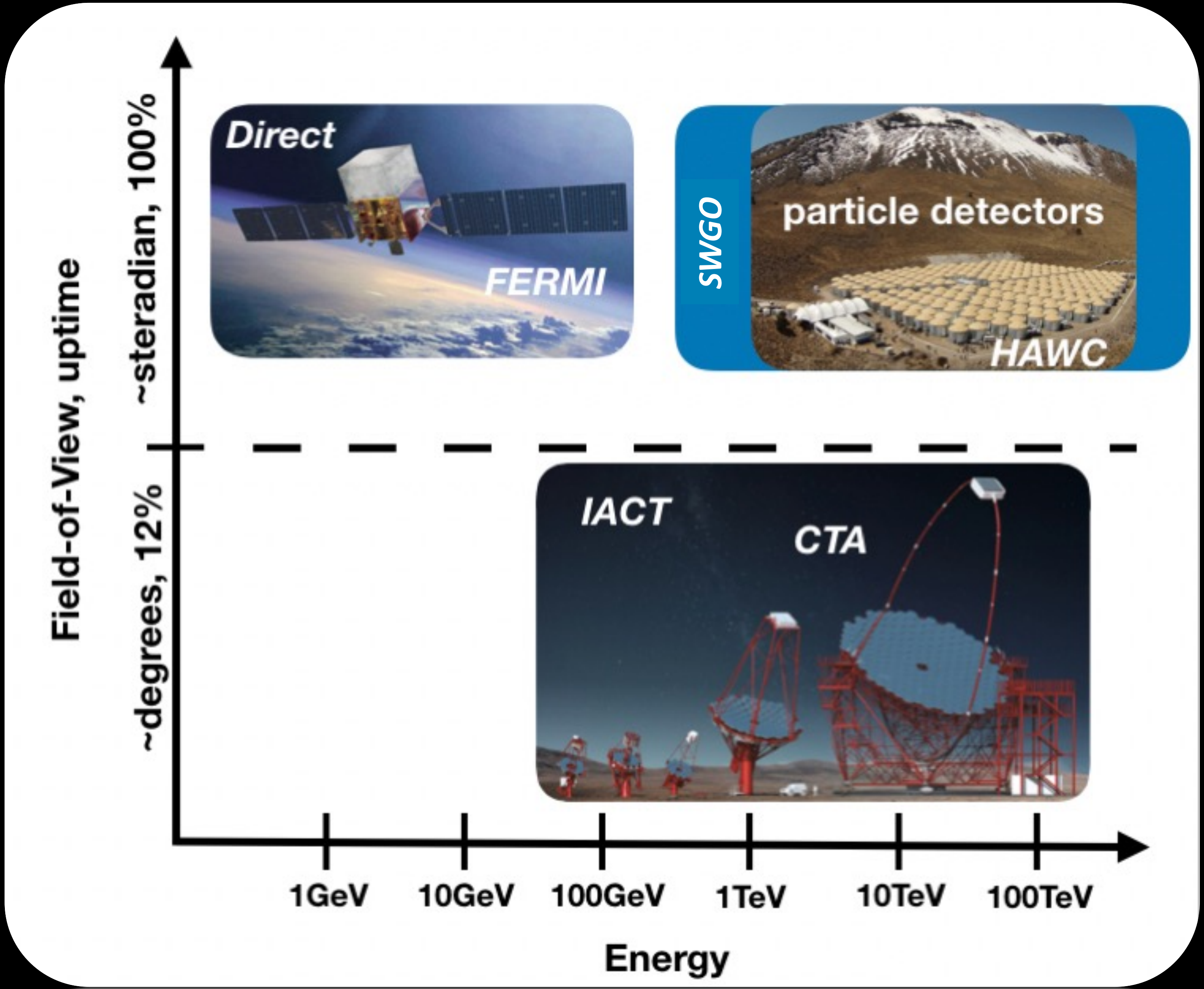




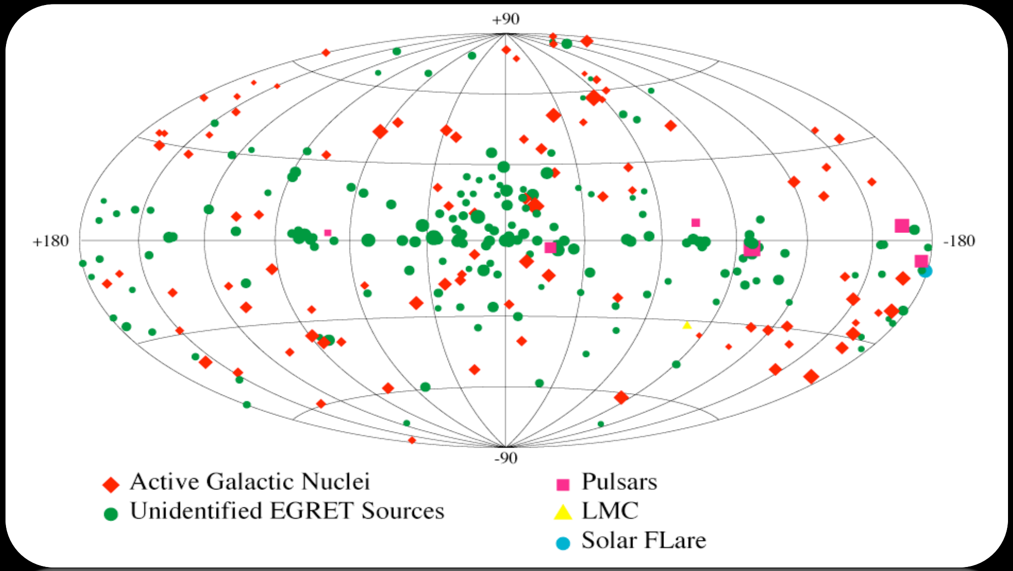
© Xiaojie Wang

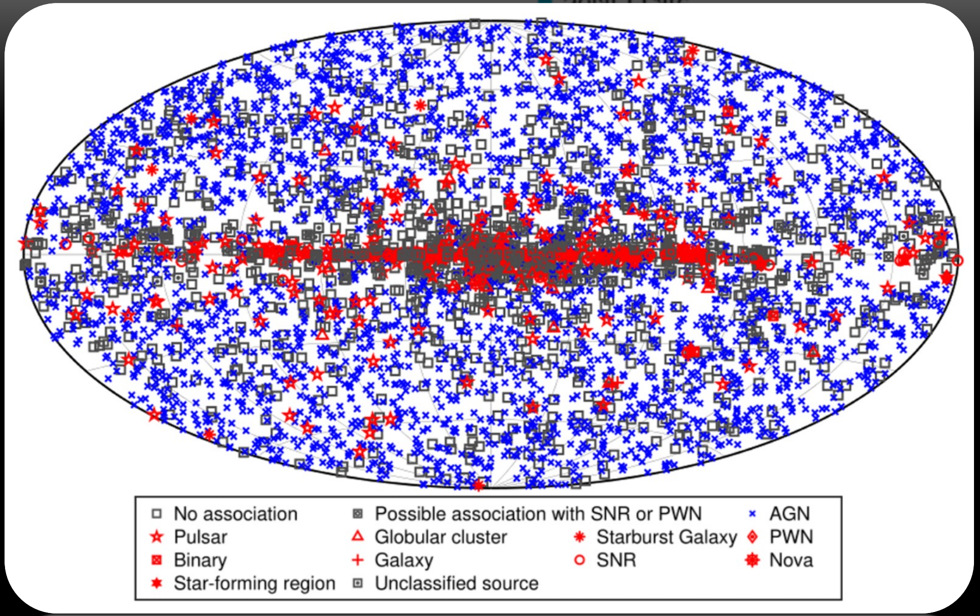
Shower image, 100 GeV γ-ray adapted from: F. Schmidt, J. Knapp, "CORSIKA Shower Images", 2005, https://www-zeuthen.desy.de/~jknapp/fs/showerimages.html

Gamma-Ray Detectors: A Comparison



Gamma-Ray Sources – Space Based

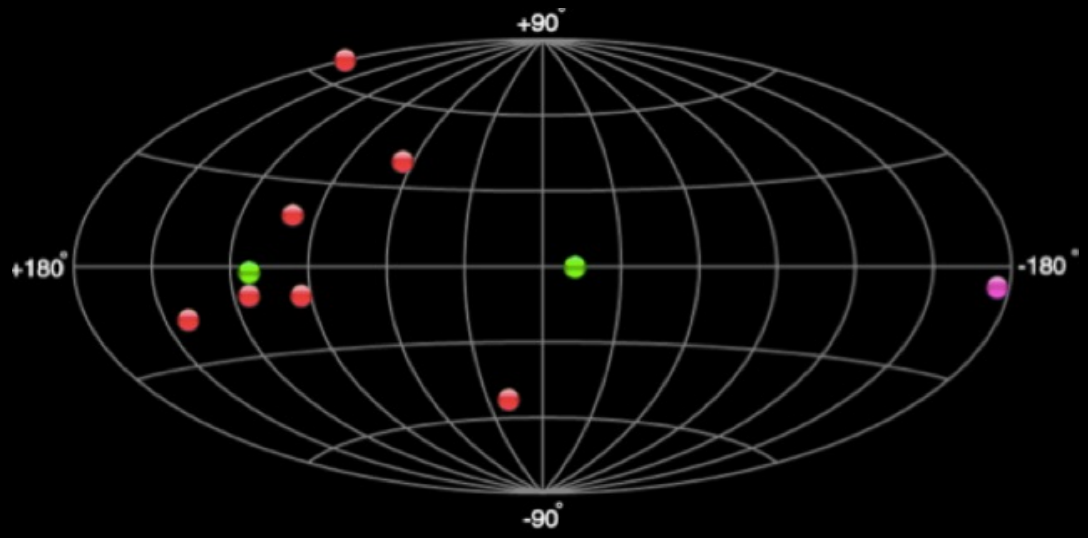


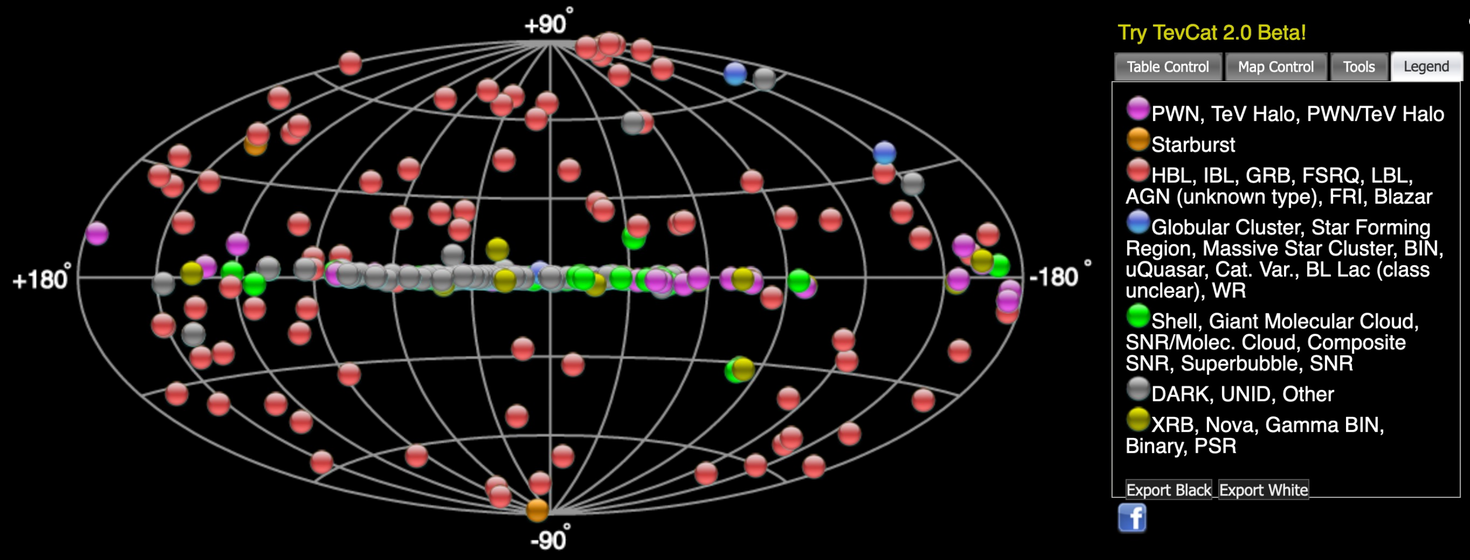


- **3rd EGRET Catalog (1999):**
  - E > 100 MeV
  - 271 sources
  - 170 unassociated

- **4th Fermi Catalog (2019):**
  - 50 MeV<E<1 TeV
  - 5098 sources
  - 1500 no plausible counterparts
  - 3100 of the identified blazars and other AGN
  - Pulsars largest Galactic source class (241)

Gamma-Ray Sources – Ground Based



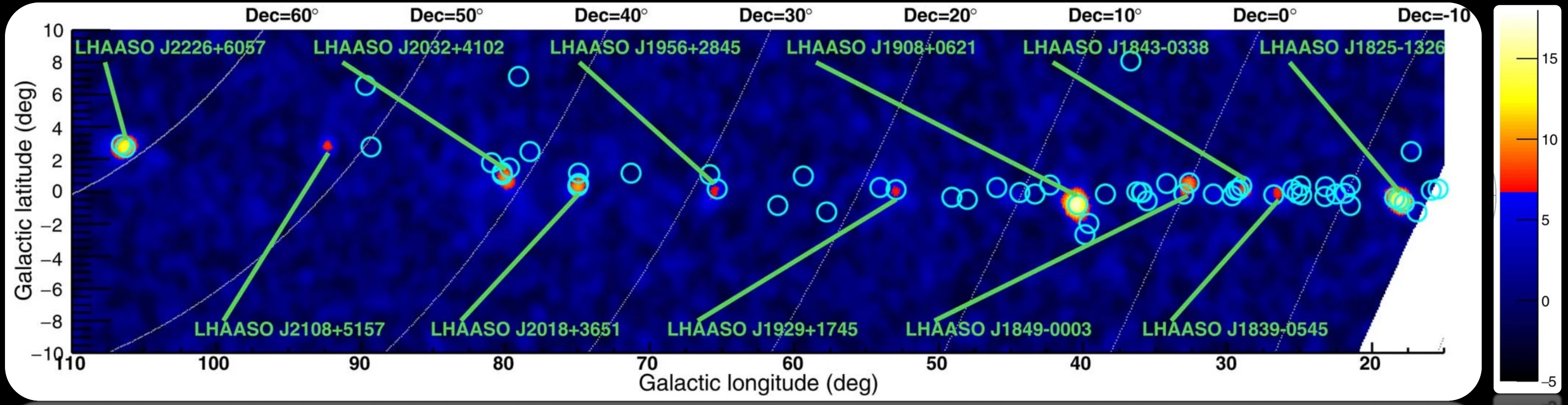


<u>TeVCat (http://tevcat.uchicago.edu):</u>

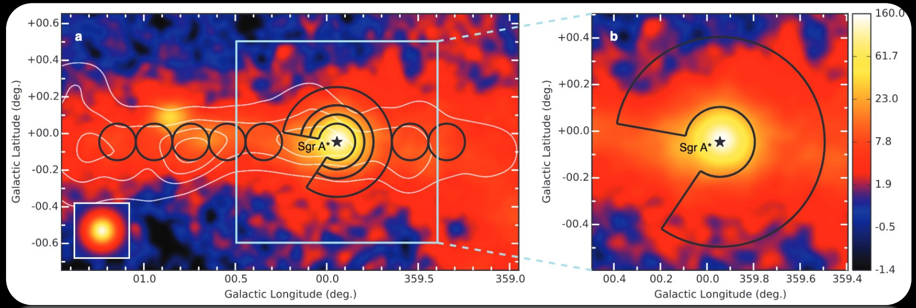
- **Sources >100 GeV as of 2001: 10**
  - 7 blazars,
  - 2 SNR
  - 1 PWN

- **Sources as of 2022: 223**
  - Also: new classes:
    - pulsars
    - binary systems
    - globular clusters
    - star-forming regions
    - starburst galaxies

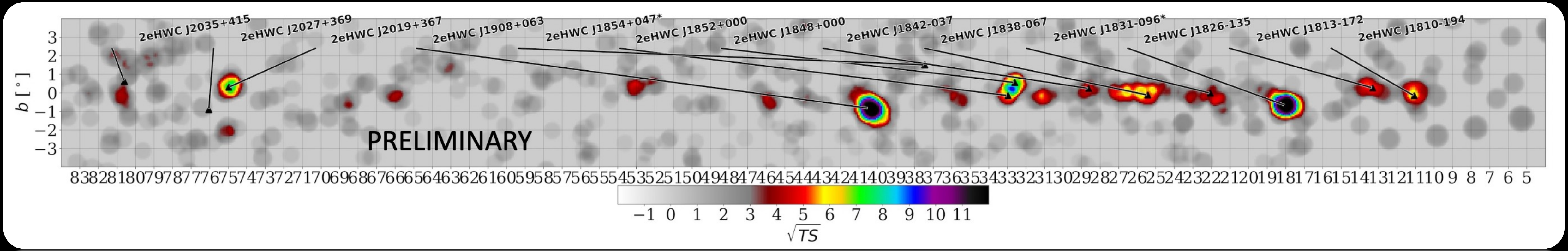
In Addition we now have 14 PeVatron candidates



LHAASO *Nature* **594**, 33 (2021)



H.E.S.S. *Nature* **531**, Is. 7595, 476 (2016)



HAWC *HEAD 19* (2022)

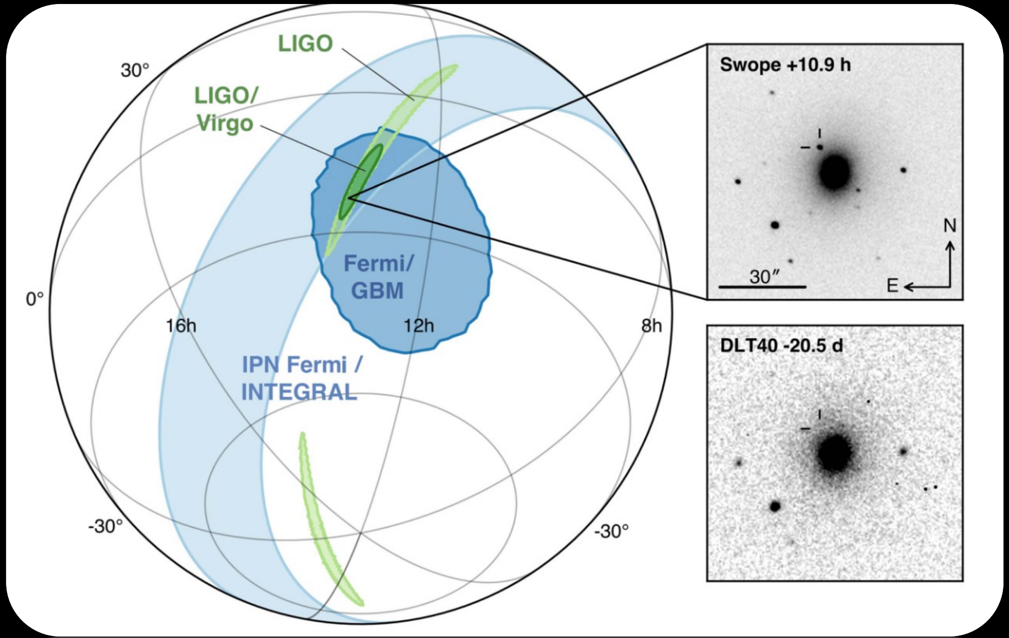
Why does this matter?

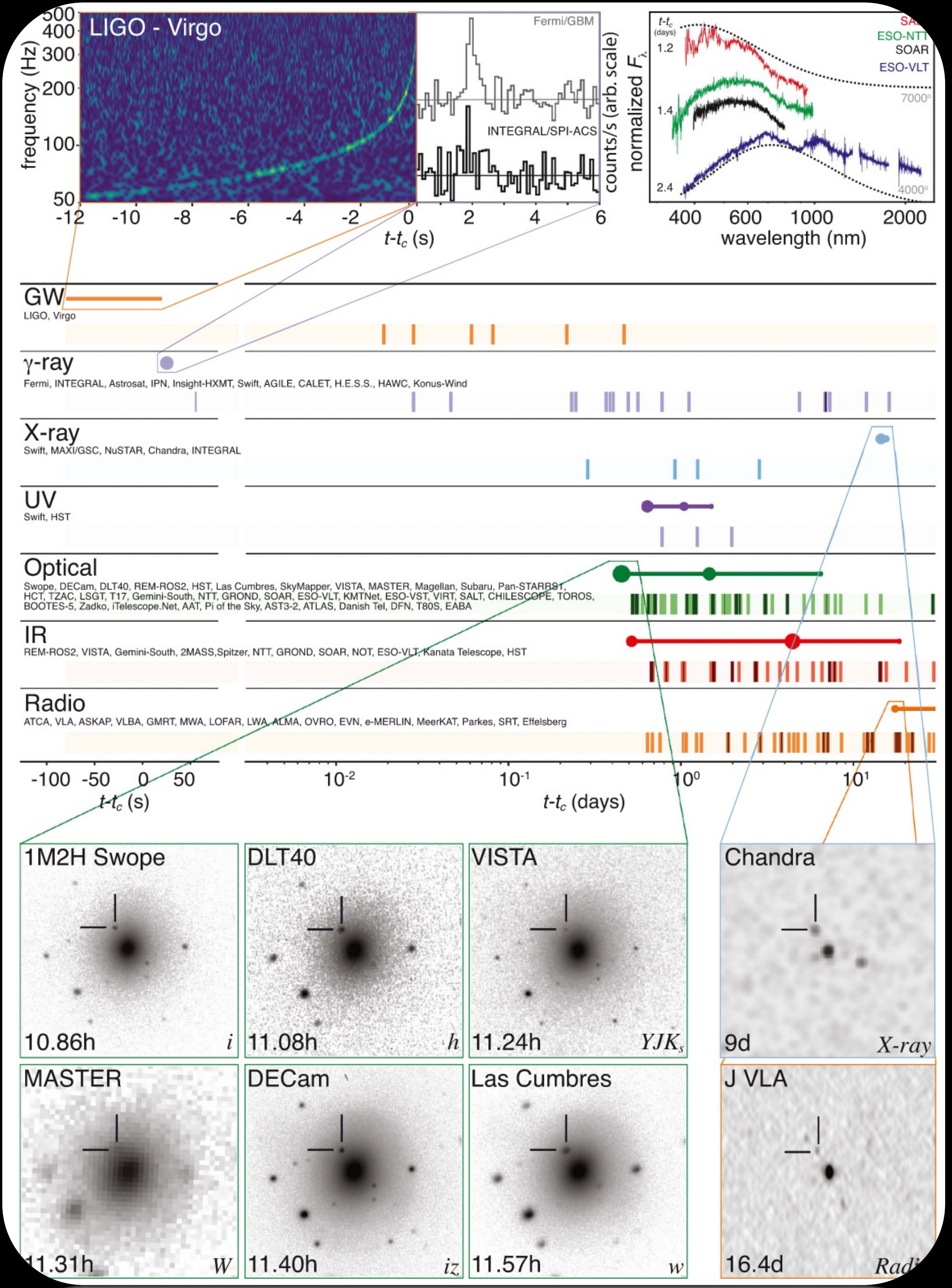
- Increase of sources allows for source class studies
- Increase in the diversity of sources allows to study and understand the “traditional” astrophysical processes better
- Increase in the sensitivity of instruments allows to study production and acceleration of cosmic particles more precisely
- Finally, all of the above allow for unprecedented insights into fundamental physics at VHE, highly non-thermal scales
- Some examples:

Fundamental Physics: Gravitational Wave

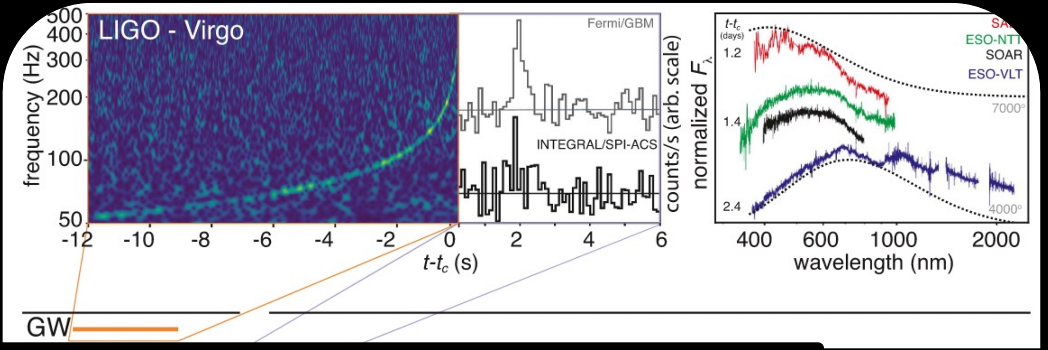
In 2017, the Fermi GBM on board flight software triggered on, classified, and localized GRB 170817A six minutes before the LIGO from the same region.

ApJ Letters, 848, L12 (2017)



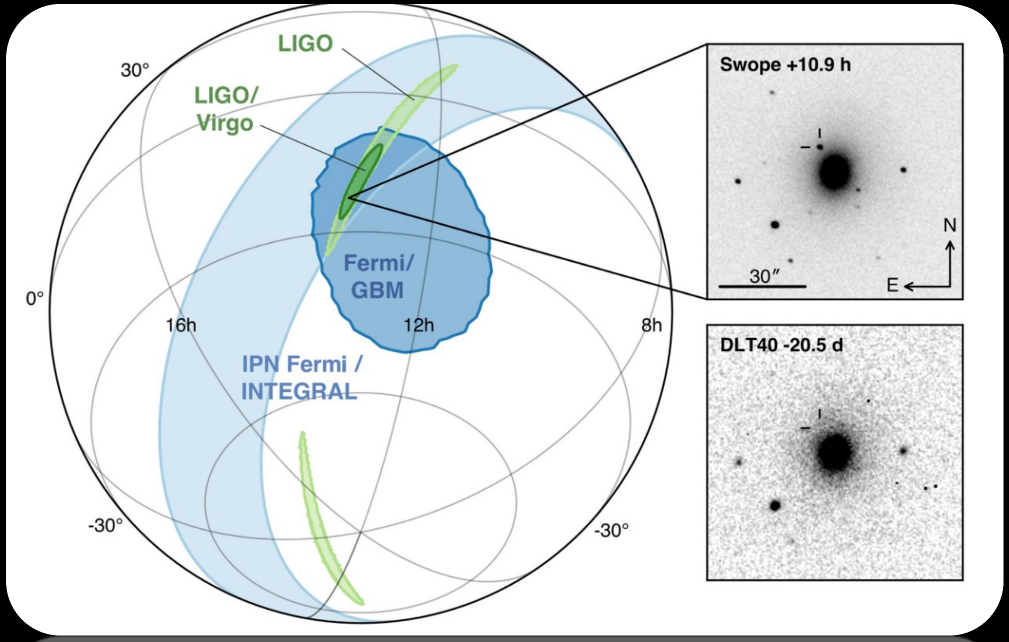


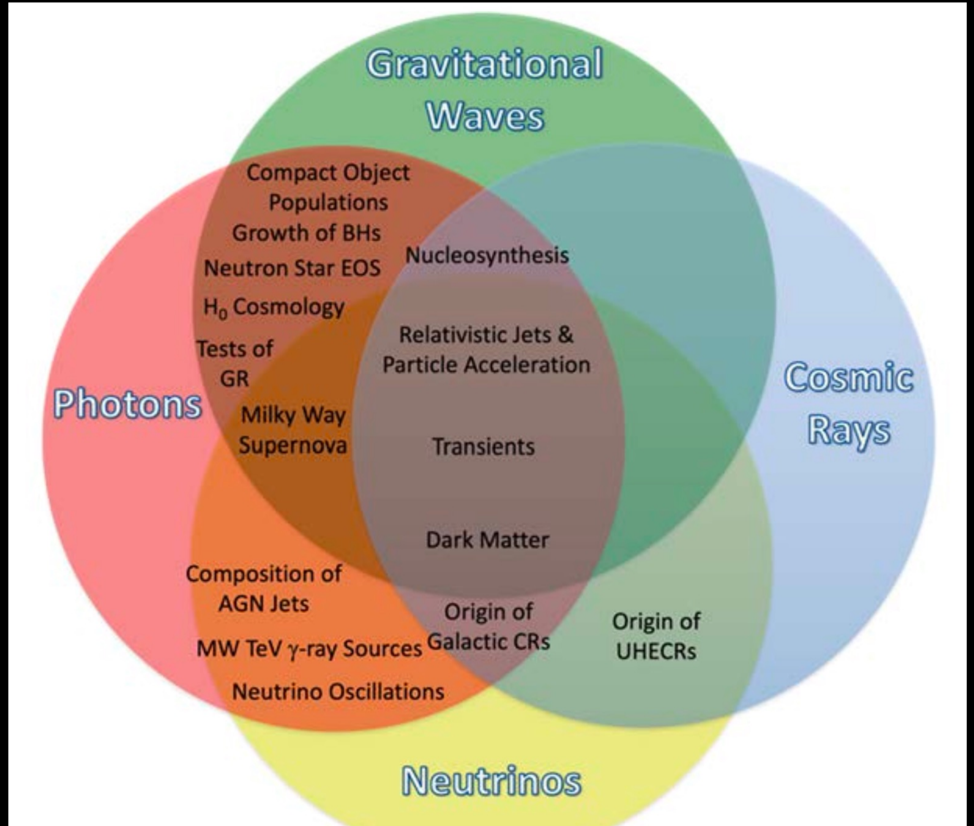
Fundamental Physics: Gravitational Wave



⇒ ***Perfect case study of Multi Messenger Astronomy***

ApJ Letters, 848, L12 (2017)

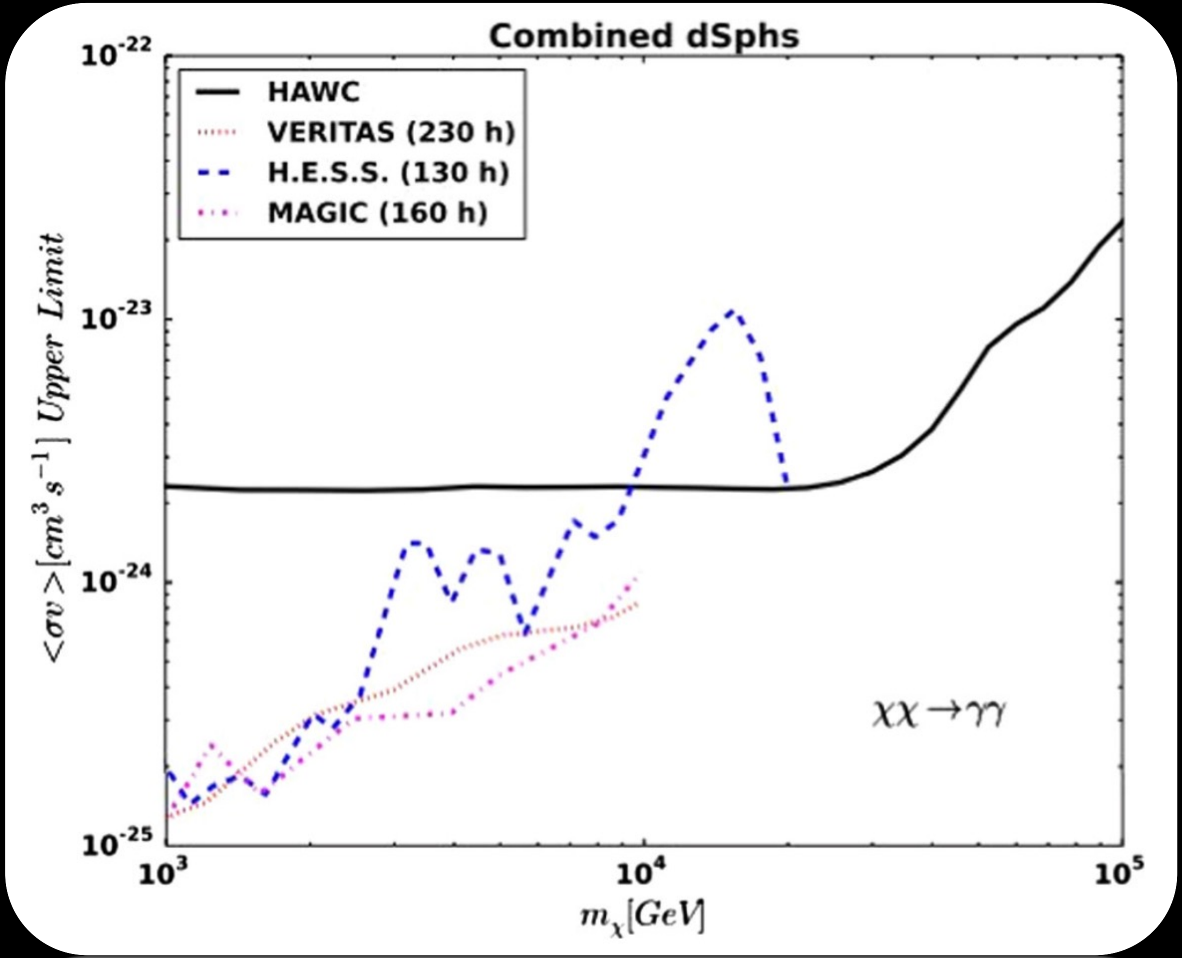




Astro 2020 (2021) (https://doi.org/10.17226/26141)

Fundamental Physics: Dark Matter

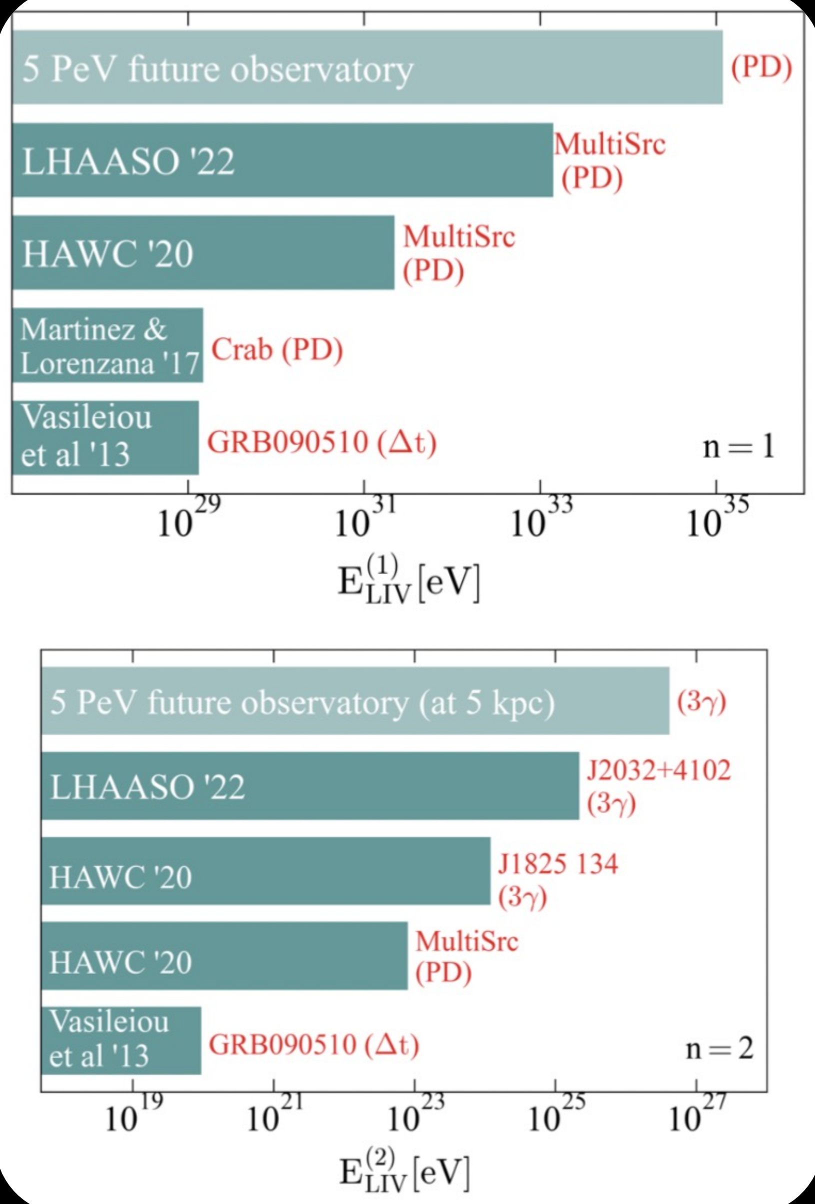
- Local dwarf spheroidal galaxies (dSphs) are nearby dark-matter dominated systems, making them excellent targets for searching for gamma rays from particle dark matter interactions.
- If dark matter annihilates or decays directly into two gamma rays (or a gamma ray and a neutral particle), a monochromatic spectral line is created.
- At TeV energies, no other processes are expected to produce spectral lines, making this a very clean indirect dark matter search channel.



PRD, 101, Is. 10, article id.10300 (2020)

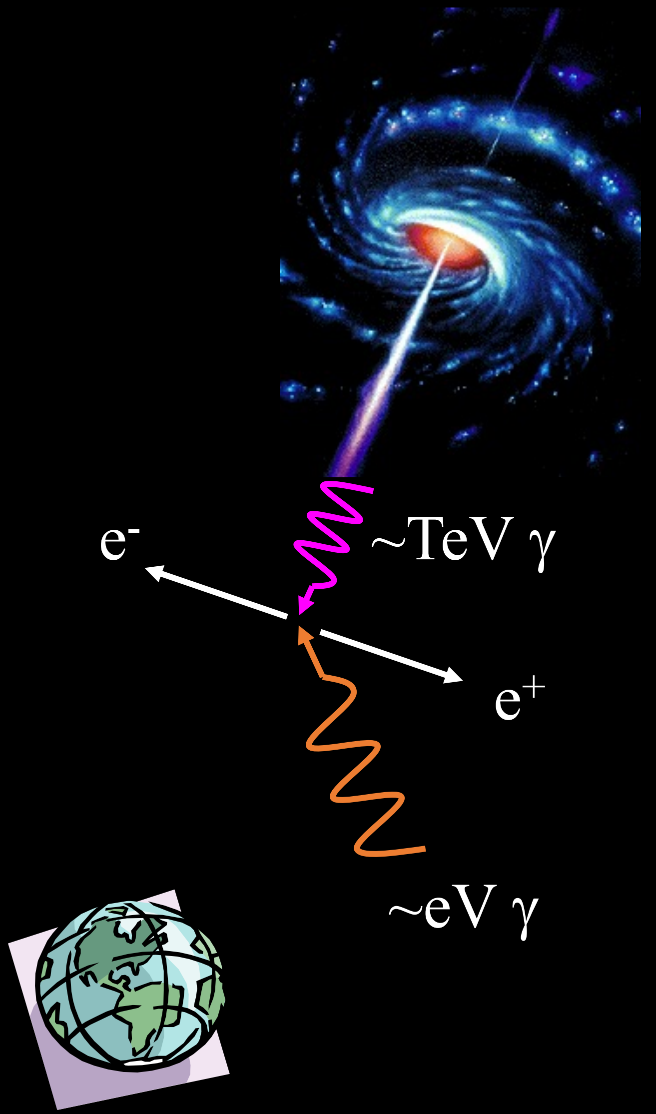
Fundamental Physics: Lorentz Invariance

- LI is a fundamental symmetry in the SM.
- GUTs/ST/QG can motivate some LIV
    - Photons of sufficient energy are unstable and decay over short timescales.
        - Photon decay (PD)
        - Photons splitting (3γ)
        - …
- **High energy photons will improve LIV limits**



Credit: H. Martínez-Huerta

Fundamental Physics: Cosmological Infrared Extragalactic Background Light (EBL)



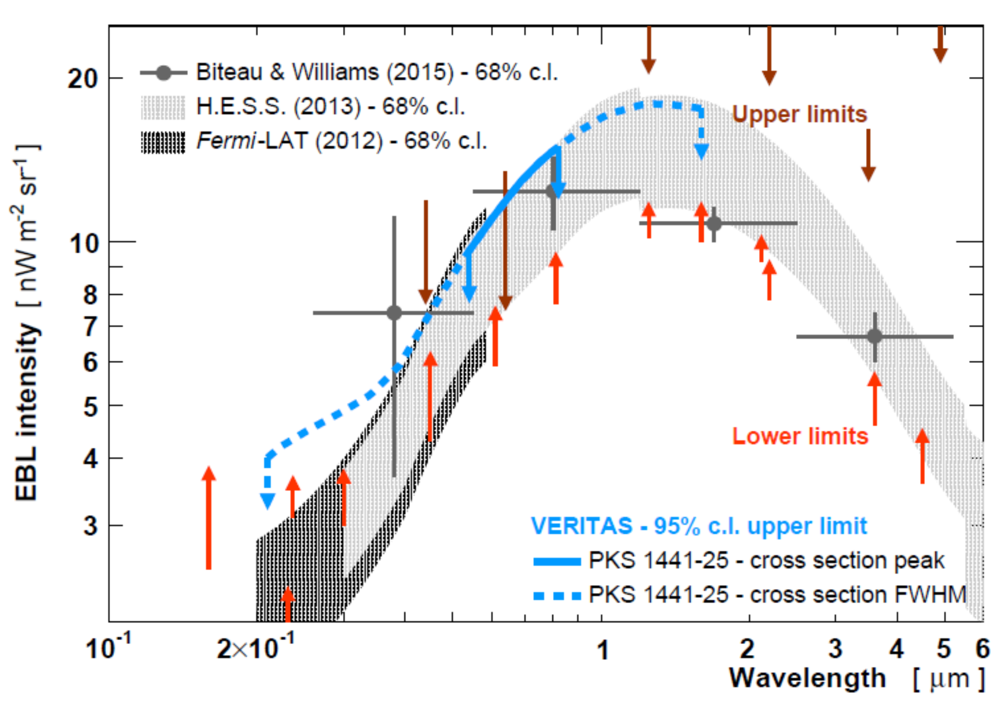
- EBL constrains galaxy and star formation history
- High energy gamma rays pair produce with the infrared extragalactic background light (EBL)
- EBL not well constrained by direct measurements due to zodiacal light

Fundamental Physics:
Cosmological Infrared Extragalactic Background Light (EBL)

- One of the most distant AGN detected in VHE (z=0.939)
- Triggered by Fermi/MAGIC alerts
- 15 hours of observations with VERITAS– Apr 15, ‘15
- ~400 gamma rays, 8σ
- 5% Crab above 80 GeV
- Very soft spectral index Γ=5.3±0.5

VERITAS Results on Blazar PKS 1441+25

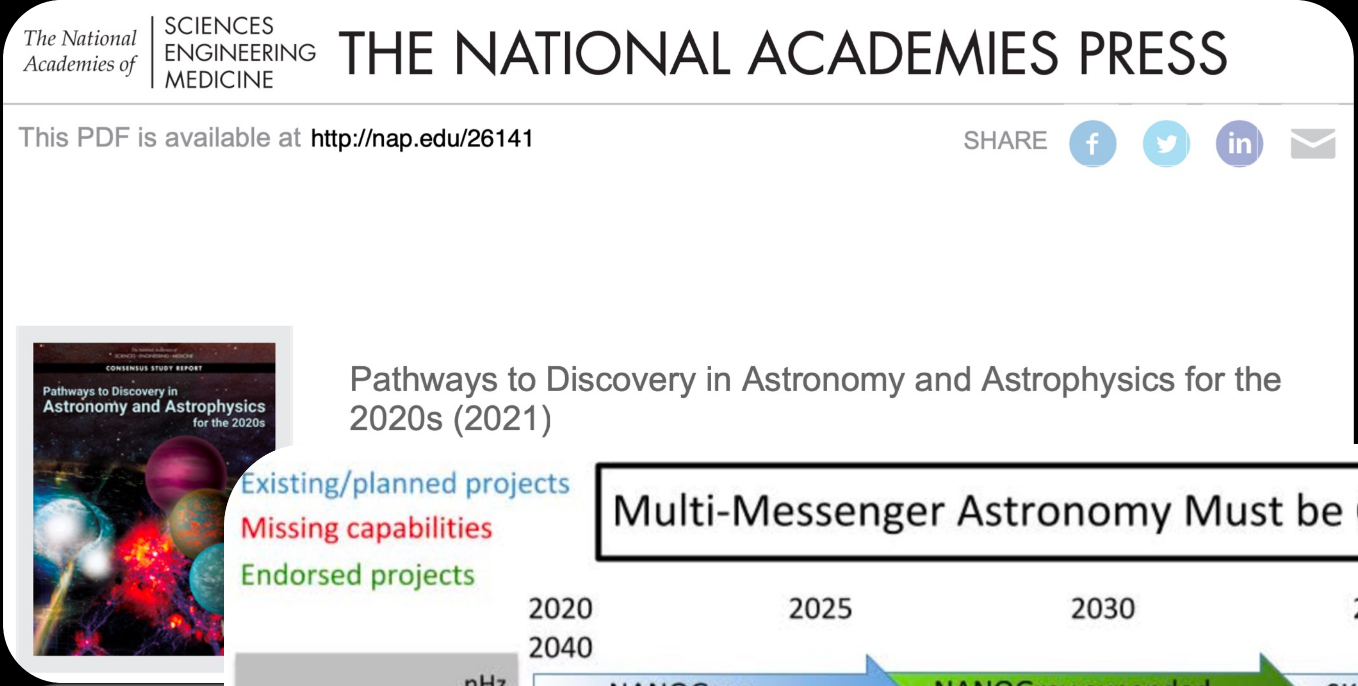
Abeysekaraet al. (2015), ApJL, 815, L22

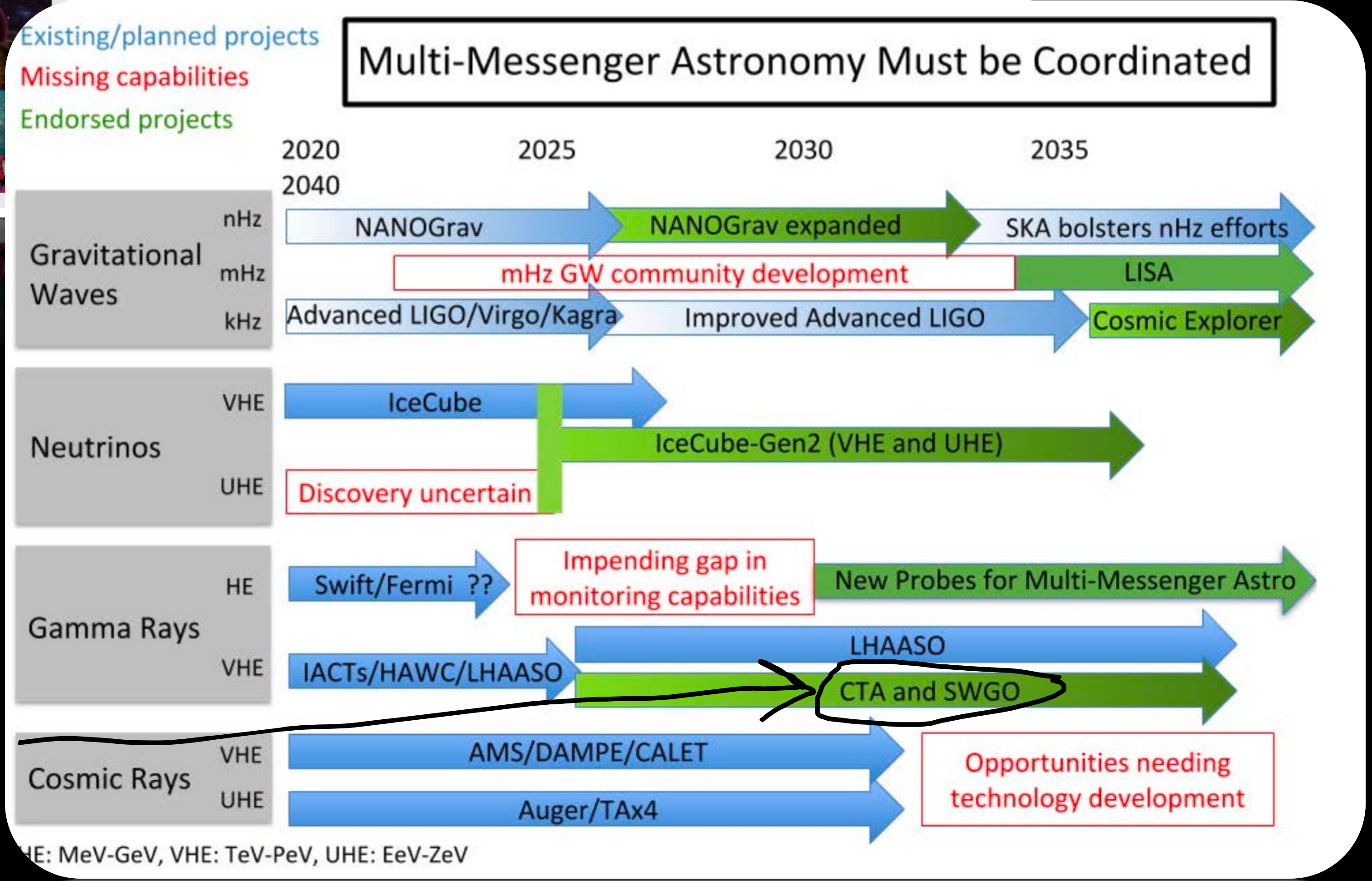


First time that one single source constrains a large fraction of the EBL spectrum.

What's Next?

- Imaging Atmospheric Cherenkov Telescopes
  - **Cherenkov Telescope Array**
- Extensive Air Shower Detectors
  - **Southern Wide Field Gamma-Ray Observatory**



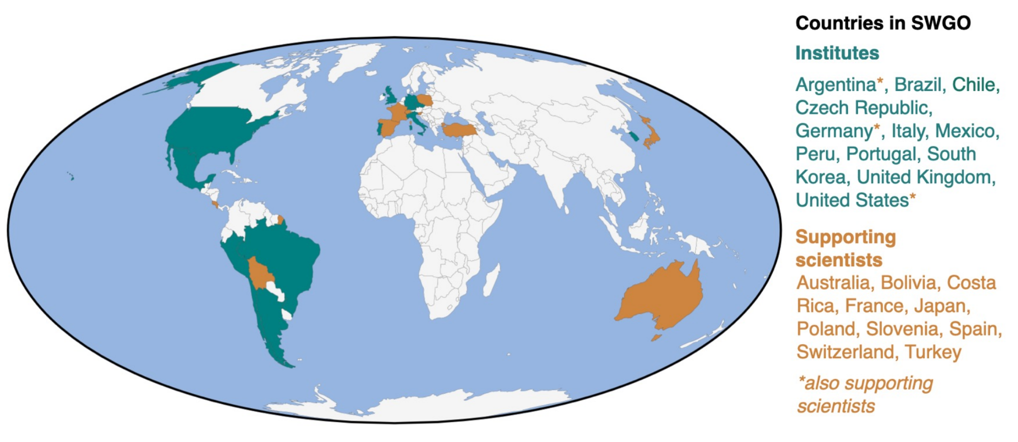


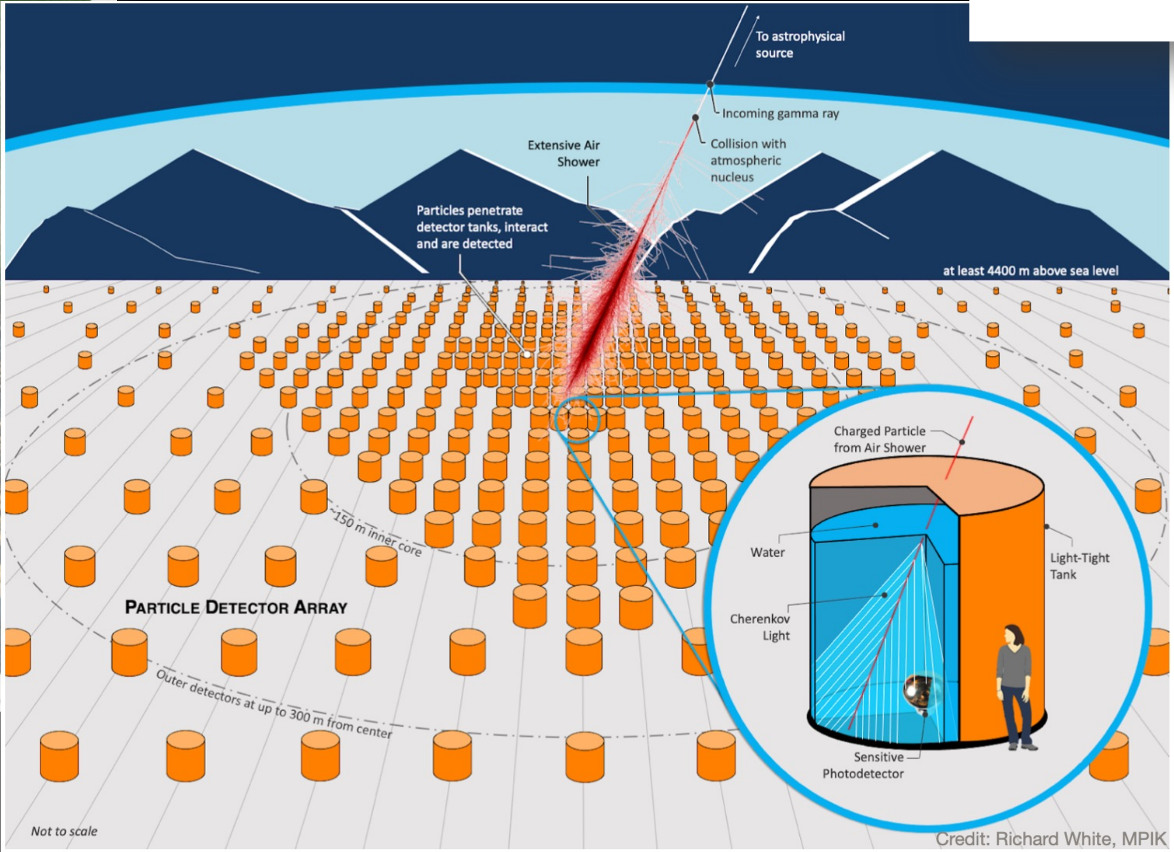
Panel on Particle Astrophysics and Gravitation recommends contributions by the U.S. to

- SWGO at the level of ~$20M
- CTA at the level of ~$70M

The Future: Southern Wide Field Gamma-Ray Observatory

54 research institutions from 12 countries have signed an agreement for R&D on a gamma-ray observatory in the southern hemisphere. The aim of the collaboration is to develop a detailed proposal for the implementation of such an observatory, incl. site selection and technology choices.





Spokespersons

Spokesperson: Jim Hinton

Vice-spokespersons: Petra Huentemeyer, Ulisses Barres

Steering Committee

Countries in which institutes have signed the "Statement of Interest" in SWGO are asked to appoint a national representative to sit on the SWGO Steering Committee. The current membership of the steering committee is:

- Adrian Rovero (Argentina)
- Ronald Shellard (Brazil)
- Claudio Dib (Chile)
- Jakub Vicha (Czech Republic)
- Christopher Van Eldik (Germany)
- Alessandro de Angelis (Italy, INFN)
- Marco Tavani (Italy, INAF)
- Andres Sandoval (Mexico)
- Jose Bellido Caceres (Peru)
- Mário Pimenta (Portugal)
- Jason Lee (South Korea)
- Jon Lapington (UK)
- Pat Harding (USA)

swgo.org

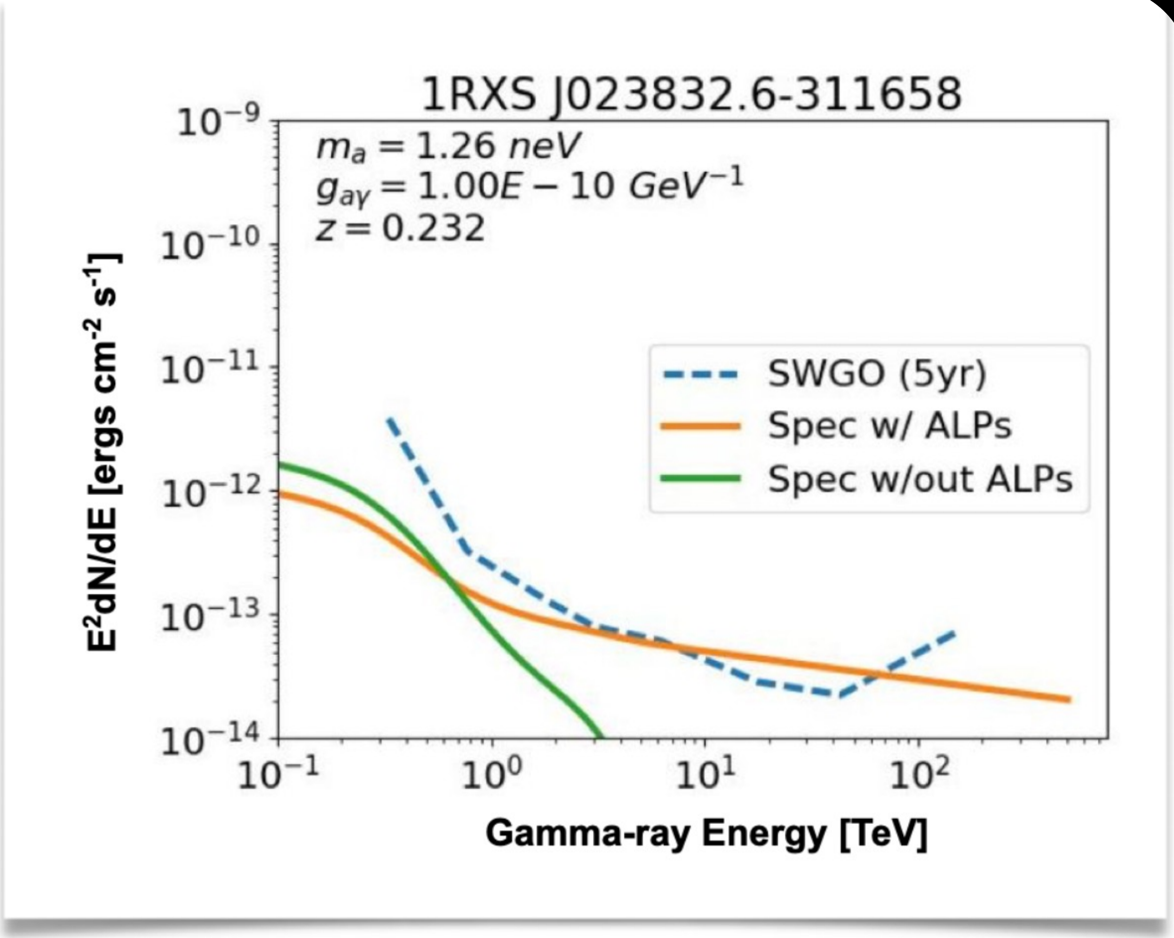
The Spokesperson and Vice-spokespersons are ex-officio members of the steering committee.

SWGO
The Southern Wide-field Gamma-ray Observatory

- Four host country candidates
- Exploratory Site visits planned for this fall

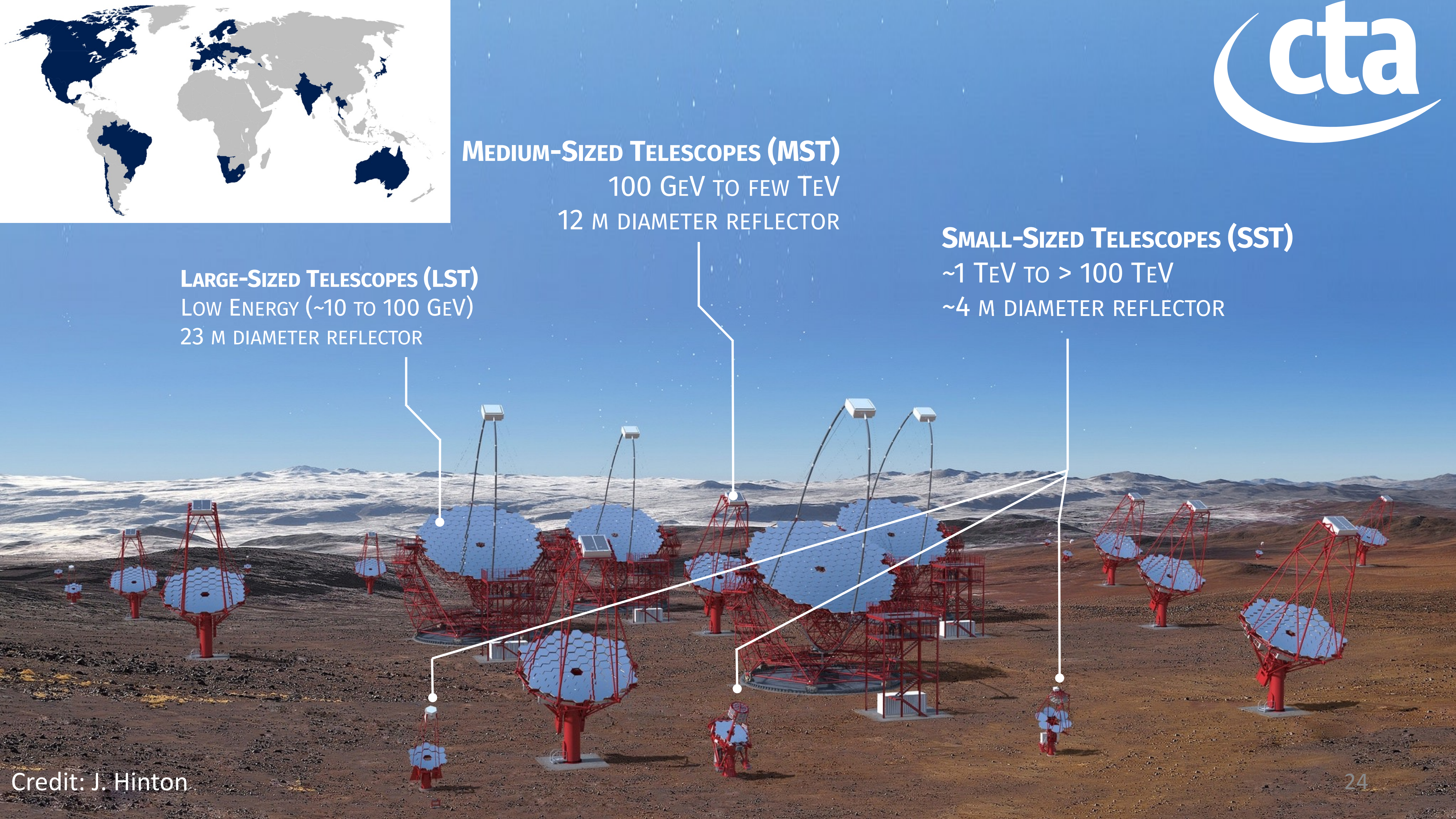
SWGO will for example search for ALPS

- **Axions are pseudo-scalar particles**
  - They are motivated by Peccei-Quinn (1977) to solve the strong CP problem.
- ALPs are like axions but with different couplings and masses
  - Couple to photons, but they can avoid attenuation at long distances.
- **Good sensitivity at high energies will improve axion-like particles' sensitivity**
  - High energy tail in AGN spectra



https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF2_CF7_Andrea_Albert-186.pdf

Credit: H. Martínez-Huerta/A. Albert


cta
Medium-Sized Telescopes (MST)
100 GeV to few TeV
12 m diameter reflector
Large-Sized Telescopes (LST)
Low Energy (~10 to 100 GeV)
23 m diameter reflector
Small-Sized Telescopes (SST)
~1 TeV to > 100 TeV
~4 m diameter reflector
Credit: J. Hinton

CTA-North

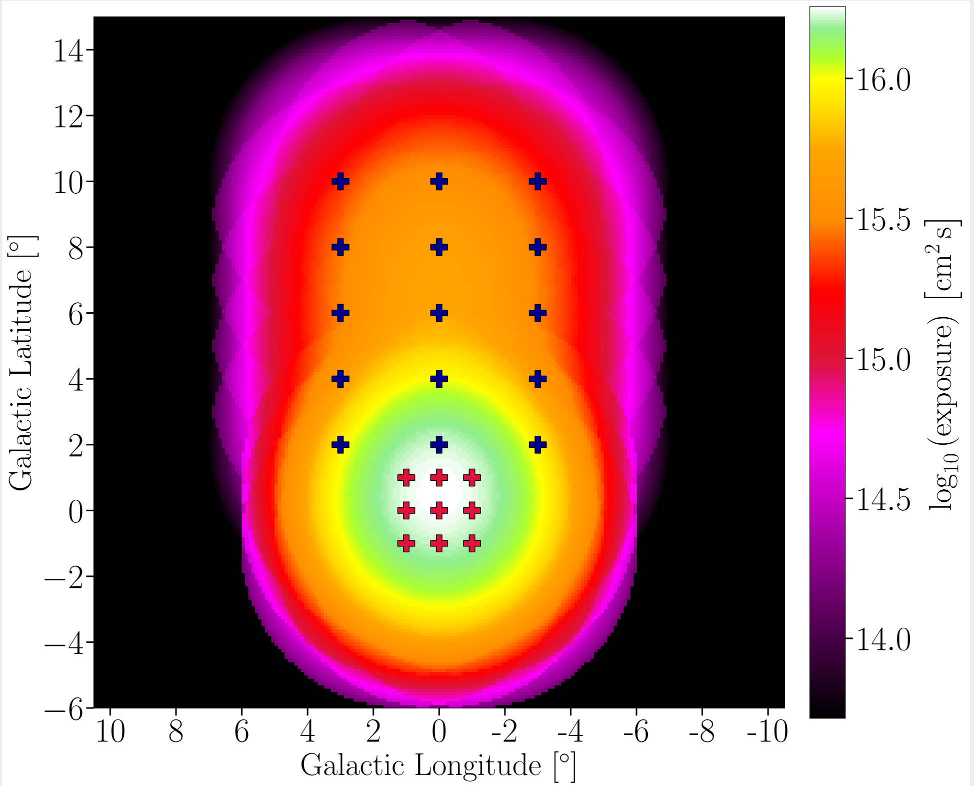
Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias (IAC) at 2200 m

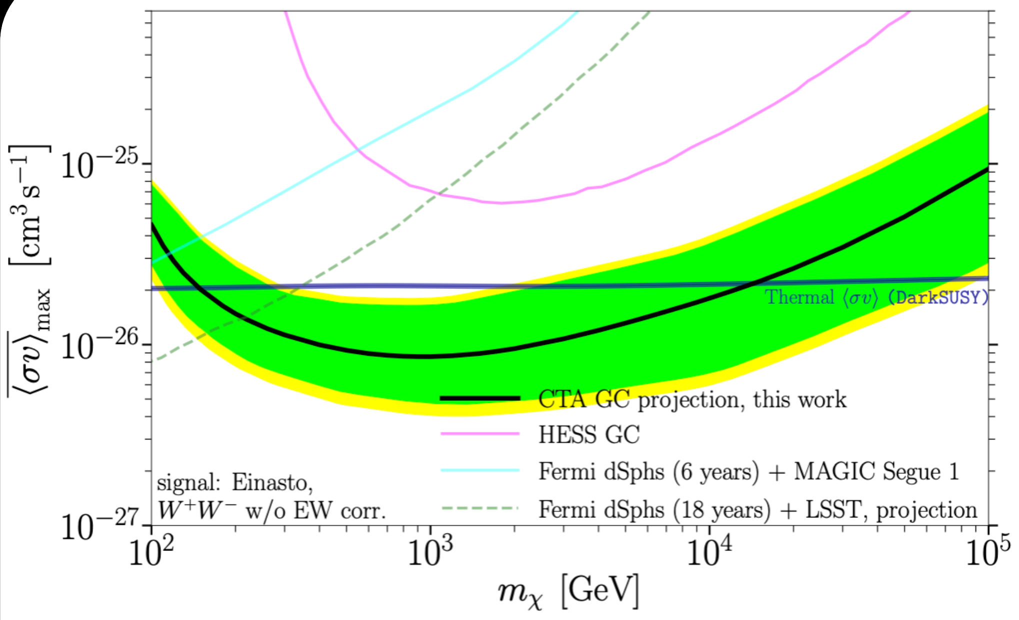
CTA-South

European Southern Observatory (ESO) site at 2100 m

Credit: J. Hinton

CTA will for example perform deep observations of the Galactic Center Region and searches for Dark Matter





GC observations can set DM constraints below the thermal relic cross-section in the 0.2-20 TeV mass range.

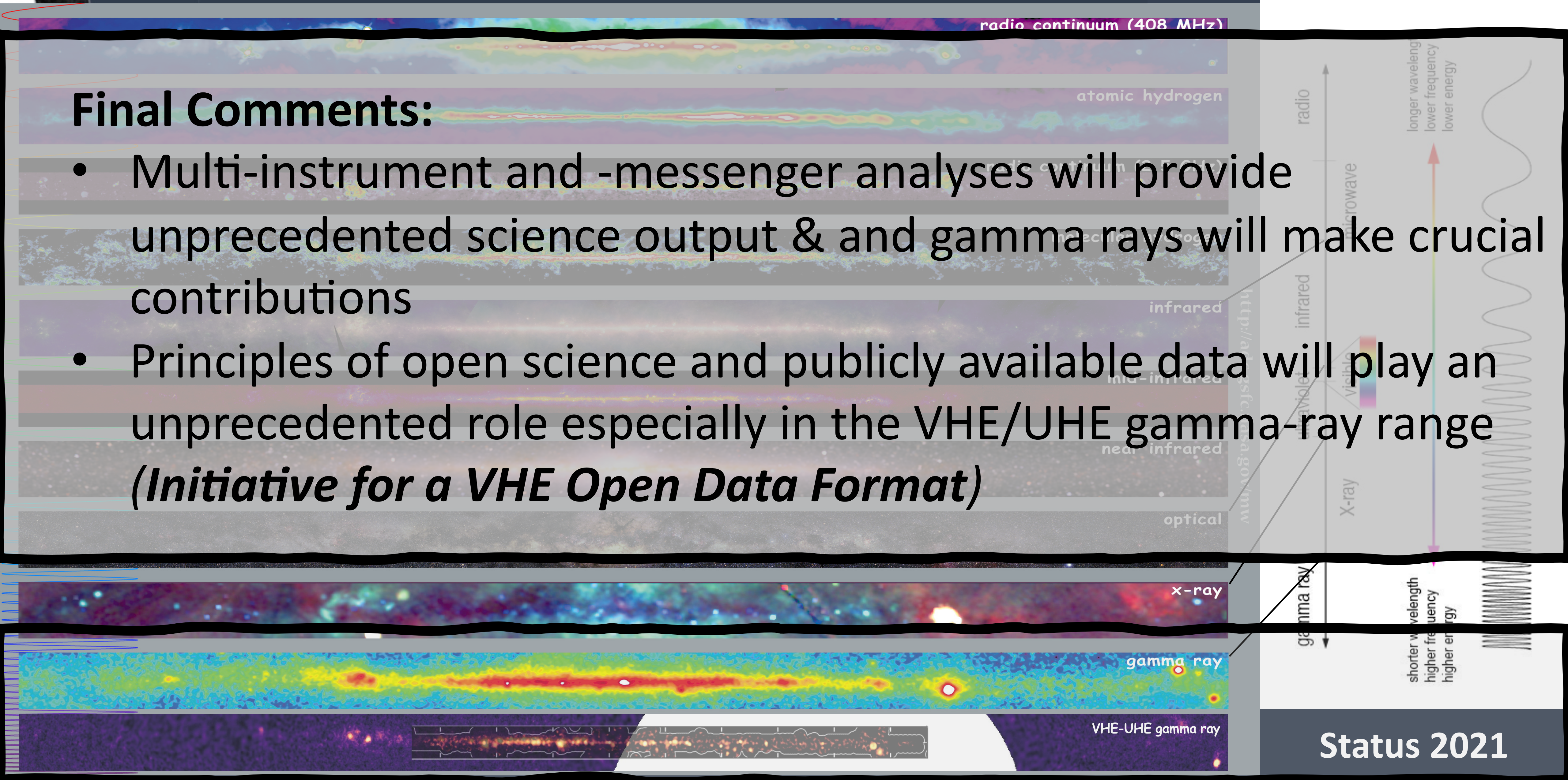
Credit: M. Santander

N S F ' S 10 B I G I D E A S

Windows on the Universe

Final Comments:

- Multi-instrument and -messenger analyses will provide unprecedented science output & and gamma rays will make crucial contributions
- Principles of open science and publicly available data will play an unprecedented role especially in the VHE/UHE gamma-ray range ***(Initiative for a VHE Open Data Format)***



Status 2021