What water tanks in Mexico can tell us about powerful particle accelerators in the universe

Henrike Fleischhack
CUA/NASA GSFC/CRESST II

June 22nd 2021

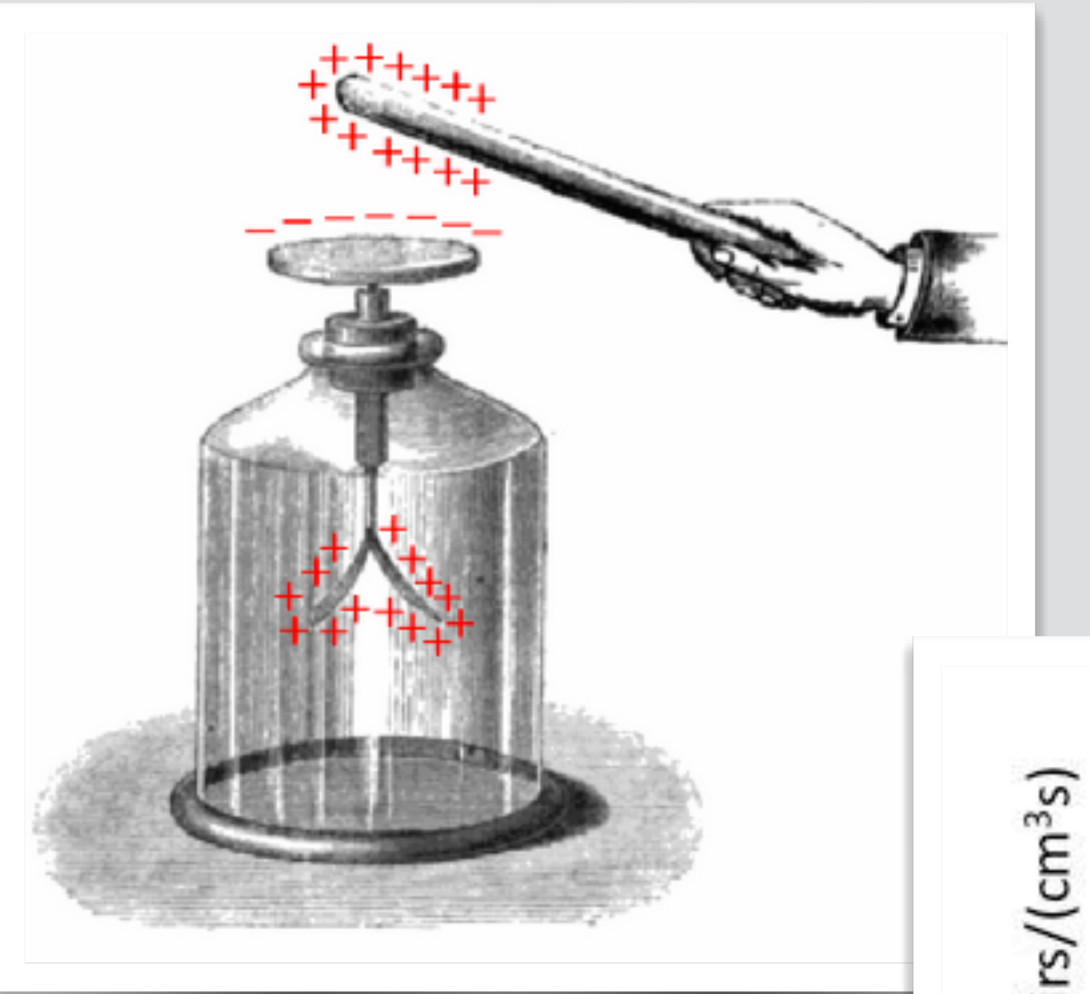
HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

THE CATHOLIC UNIVERSITY OF AMERICA

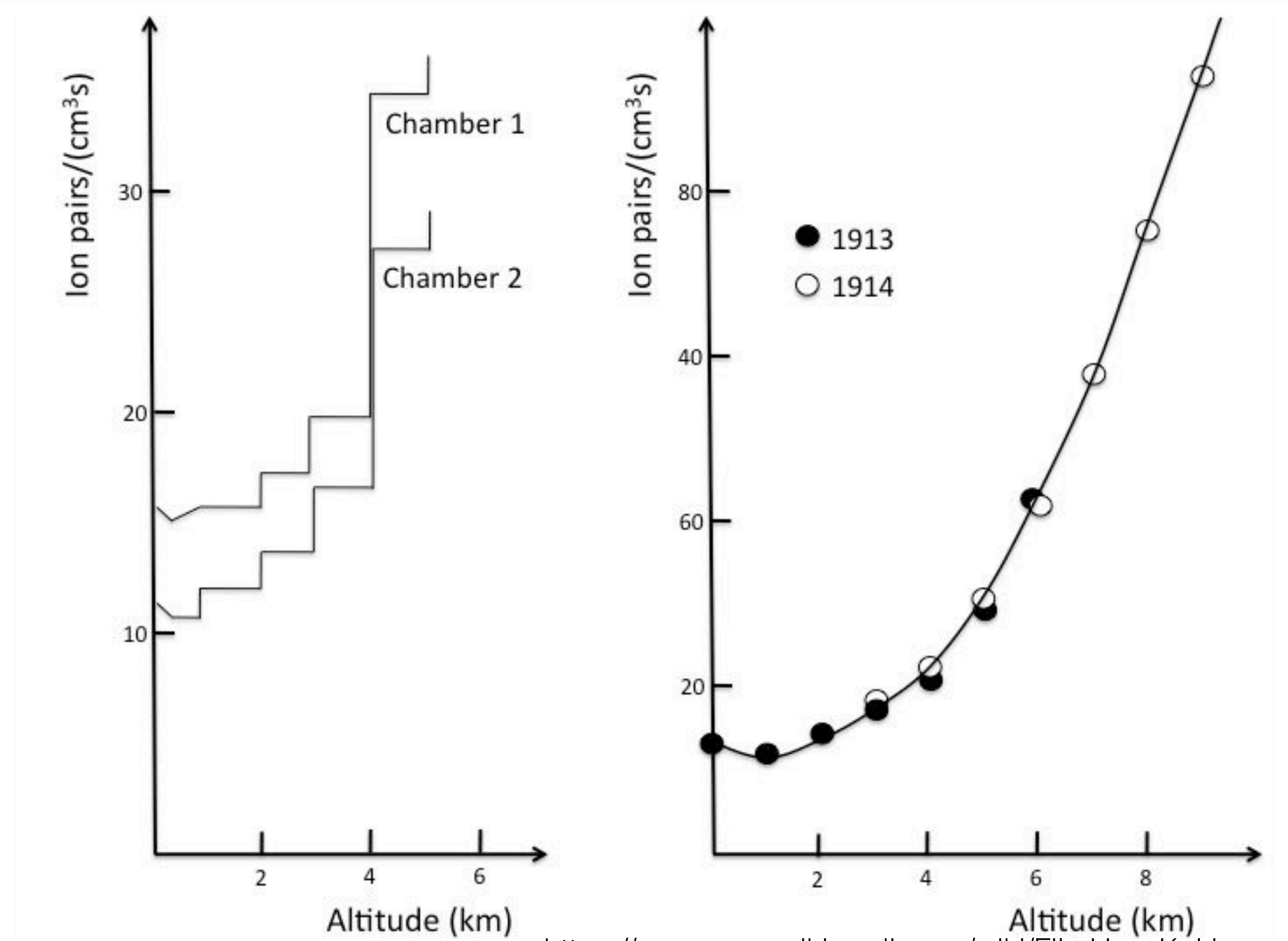
NASA Partner

Disclaimer: The material contained in this document is based upon work supported by a National Aeronautics and Space Administration (NASA) grant or cooperative agreement. Any opinions, findings, conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of NASA.
The material is based upon work supported by NASA under award number 80GSFC21M0002.

Hess & Kolhörster 1912



Ionizing radiation rate increases with altitude



https://commons.wikimedia.org/wiki/File:HessKol.jpg

Cosmic Rays and their Sources

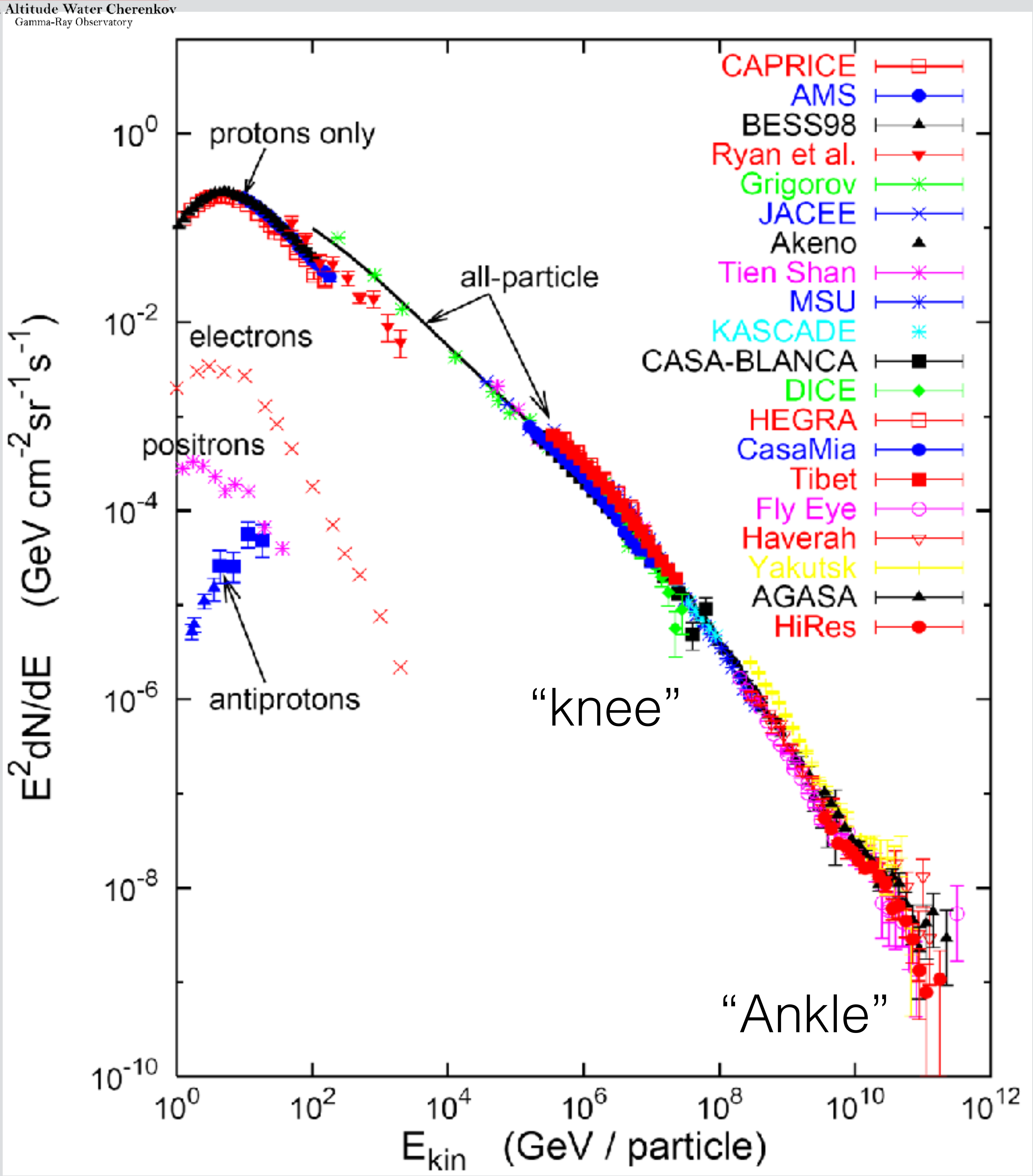
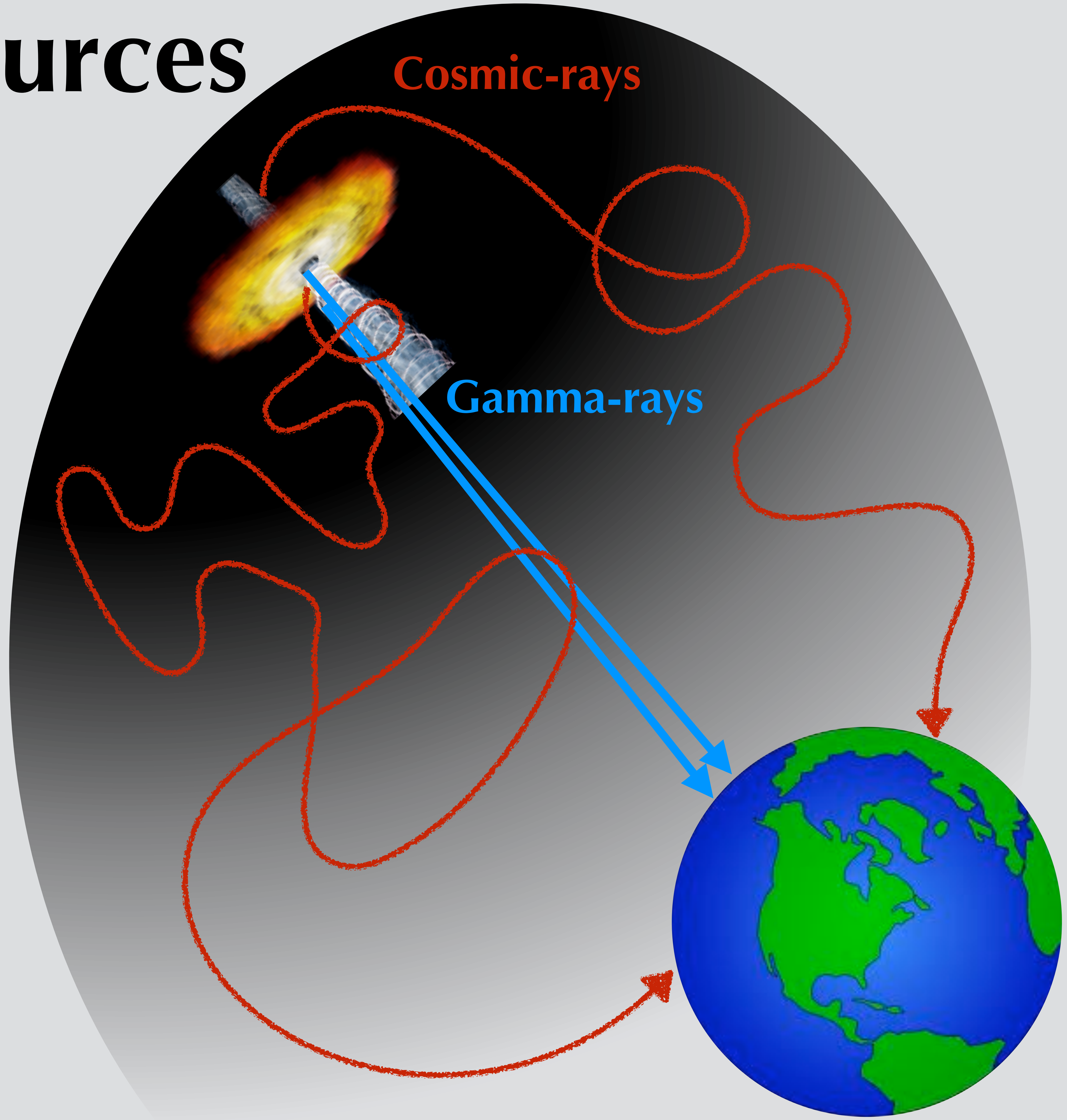


Image: http://w3.iihe.ac.be/~aguilar/PHYS-467/PA3.html



Energies up to $3 \cdot 10^{20}$ eV!

(~50 Joules)

Particle Accelerators

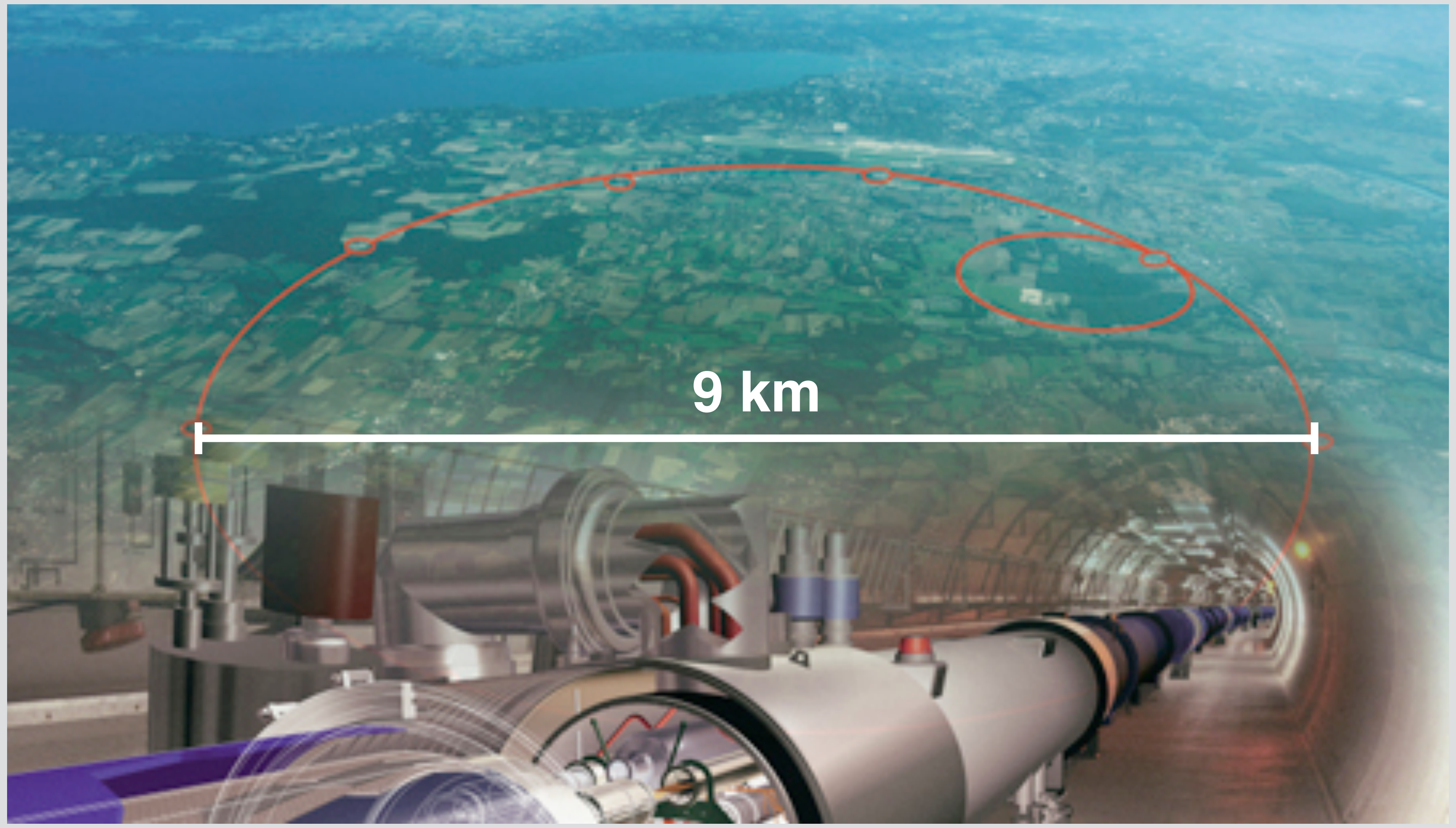
10^6: **M**ega
10^9: **G**iga
10^{12}: **T**era
10^{15}: **P**eta

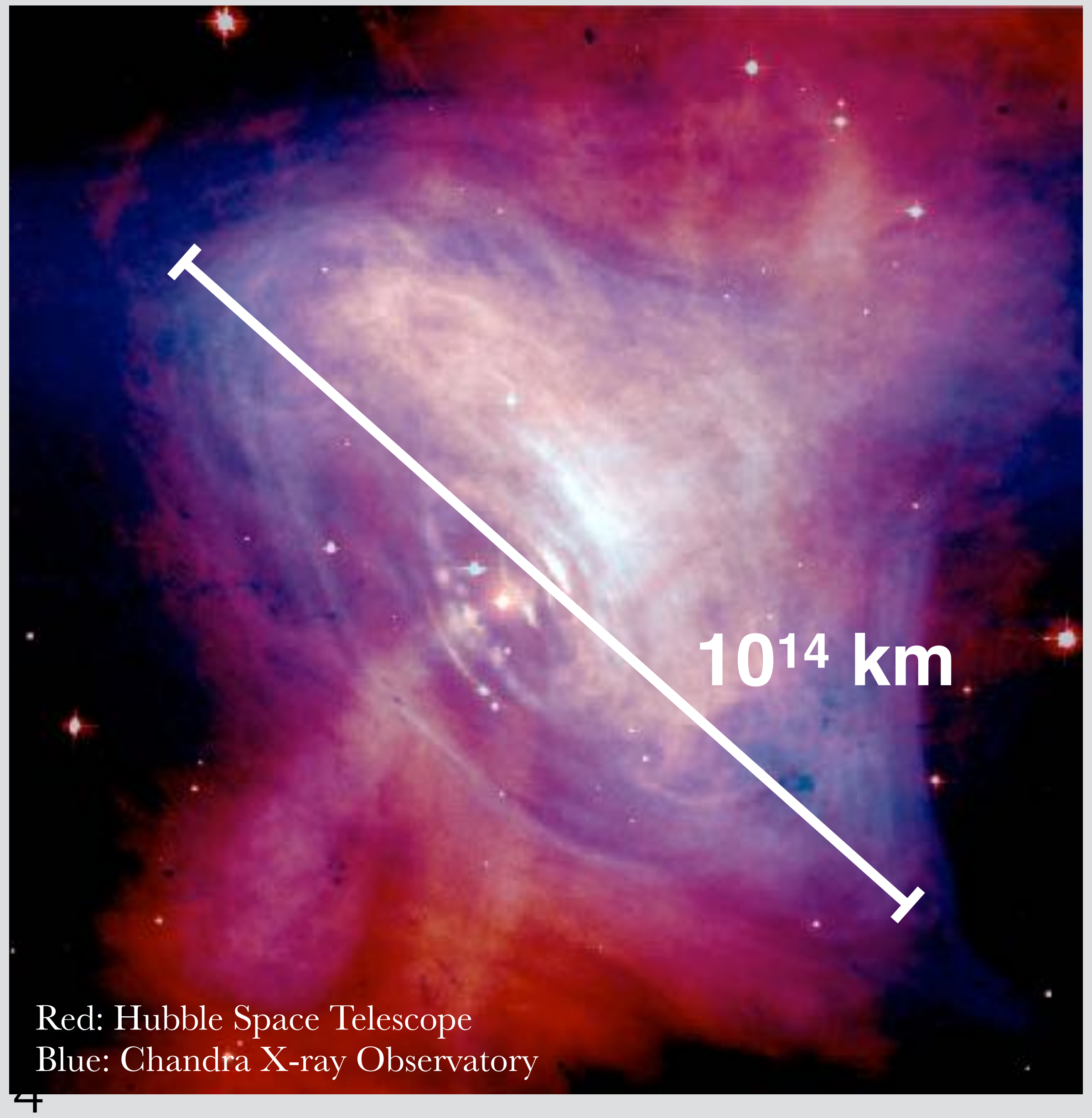
Terrestrial accelerators:

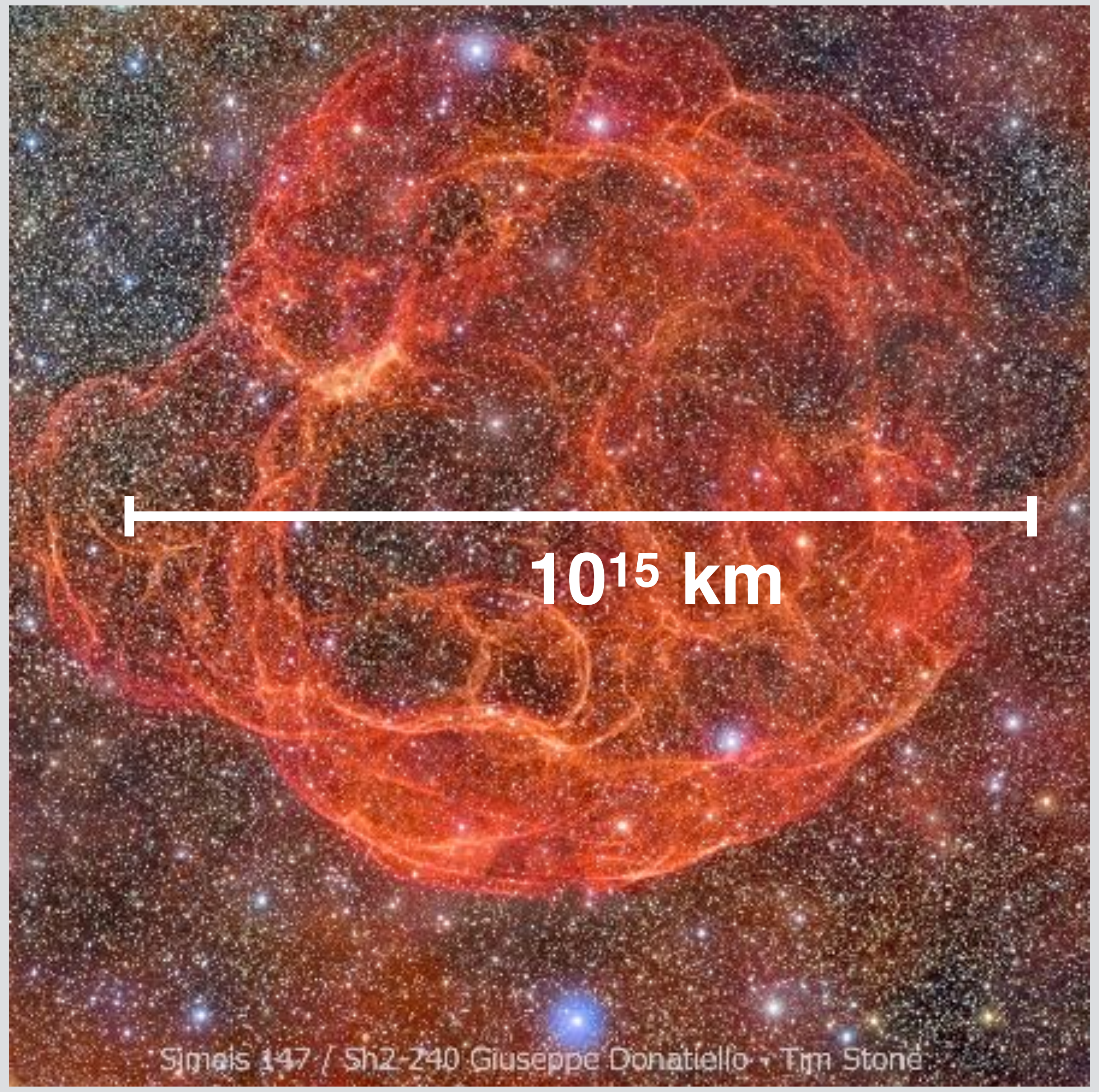
- LHC: protons ~ $7*10^{12}$ eV
- TeVatron: protons ~ 10^{12} eV
- Decades of planning.
- Thousands of engineers and scientists.
- Active for a few decades.

Cosmic accelerators:

- Galactic: protons ~10^{15} eV
- Extragalactic: protons ~ 10^{20} eV
- No engineers and scientists involved.
- Can be active for seconds to millions of years.







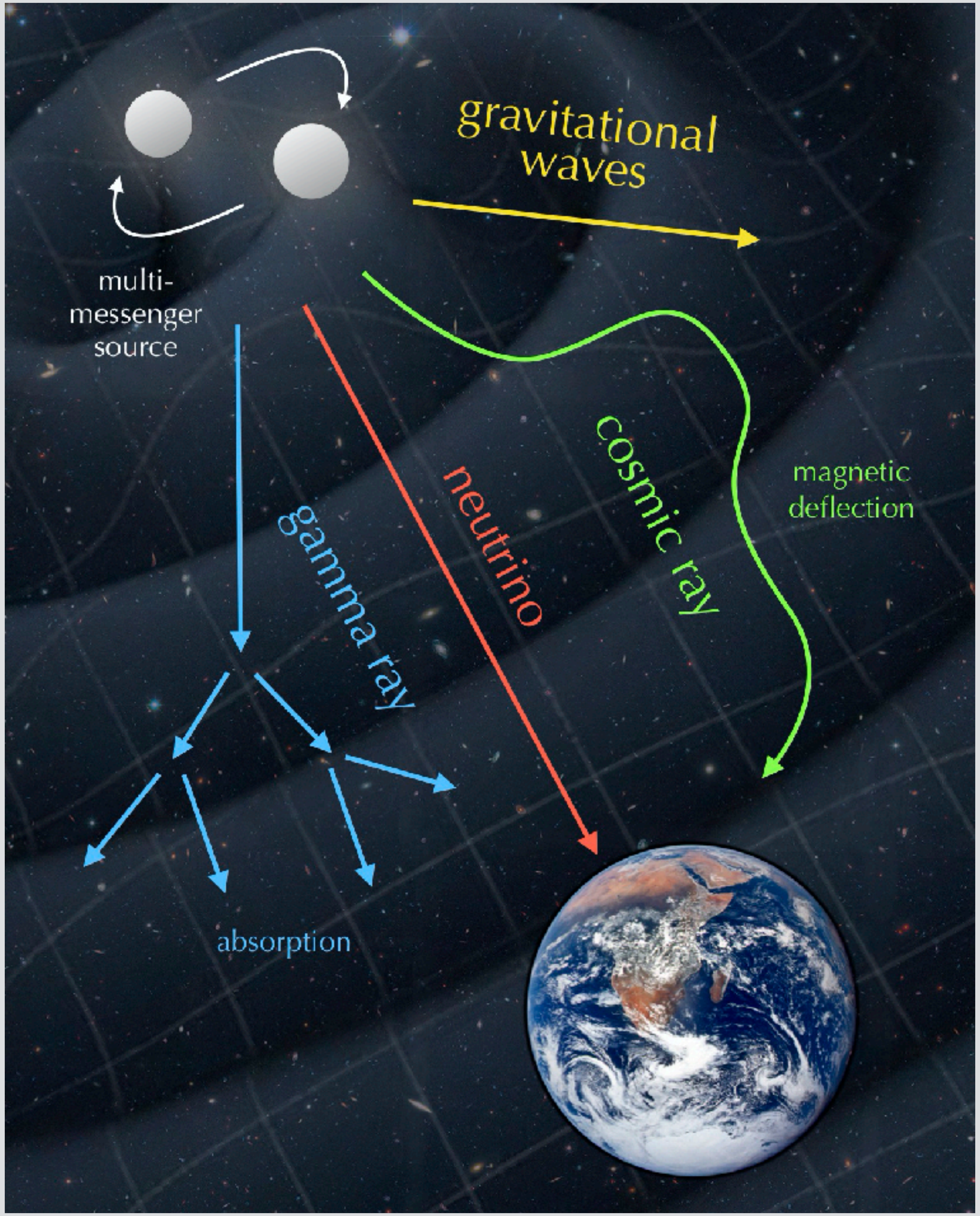
Observing Cosmic Ray Accelerators

Cosmic rays are deflected by magnetic fields.

Neutral "particles" point back to their sources:

- Photons (gamma rays)
- Neutrinos
- (Gravitational waves)

Not all cosmic ray accelerators emit all of these messengers!

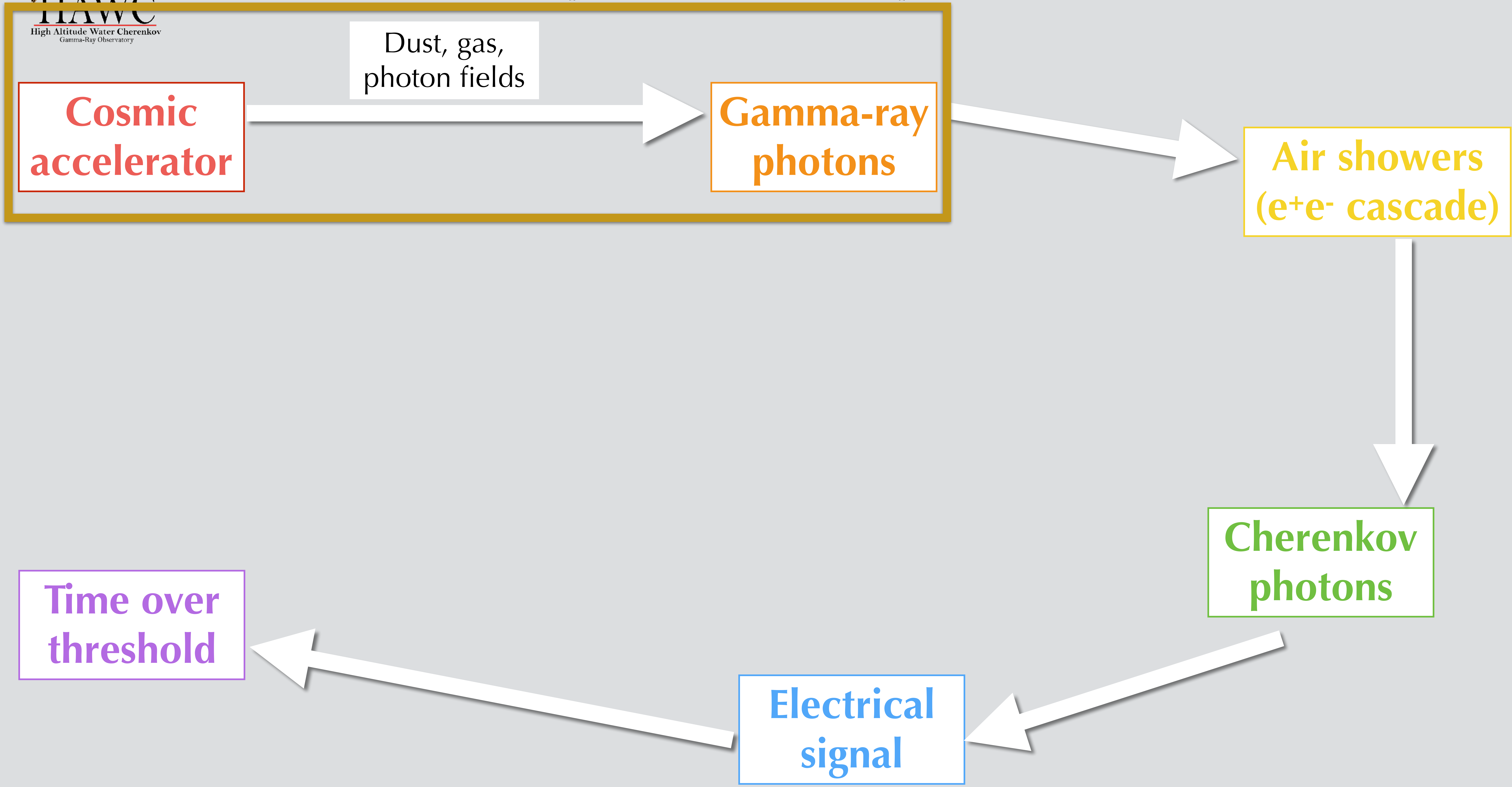


https://nbi.ku.dk/english/research/experimental-particle-physics/icecube/astroparticle-physics/

Gamma-Ray Astronomy with HAWC

Cosmic accelerator → Gamma-ray photons → Air showers (e^+e^- cascade) → Cherenkov photons → Electrical signal → Time over threshold

Gamma-Ray Astronomy with HAWC



Cosmic Rays and Gamma Rays

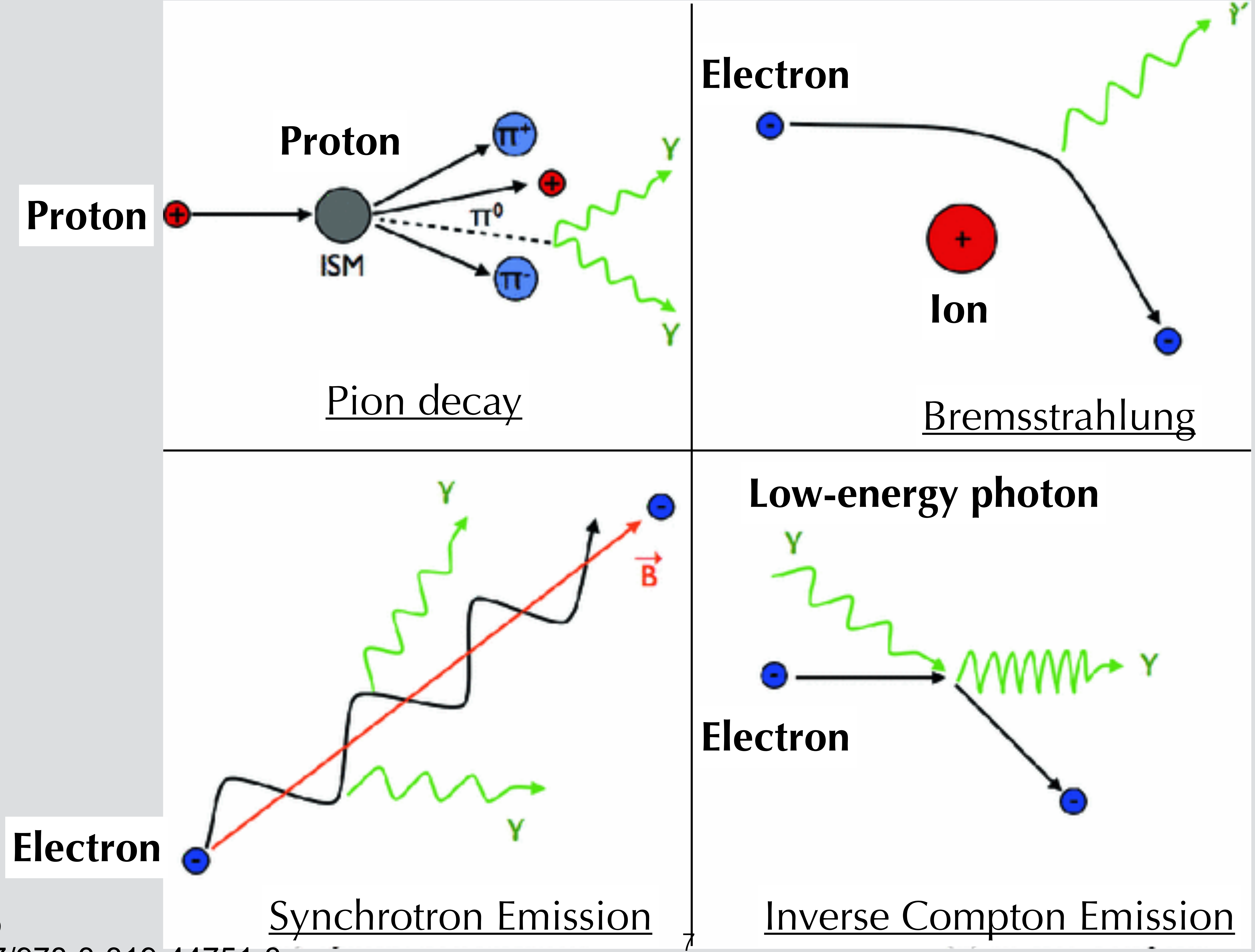


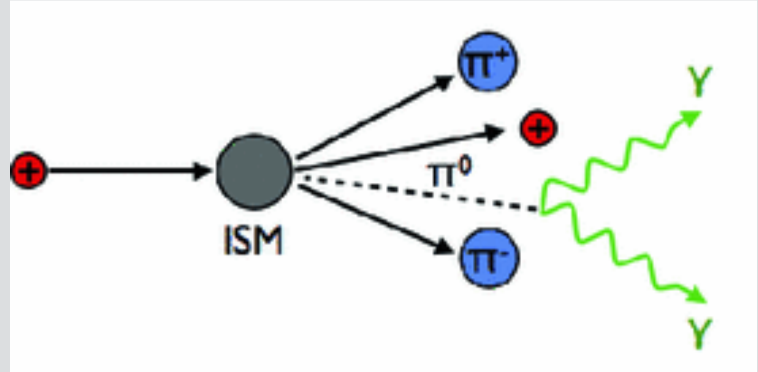
Image: R. Lopez-Coto
https://doi.org/10.1007/978-3-319-44751-3

Gamma-Ray Astronomy with HAWC

HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

Cosmic accelerator

Dust, gas, photon fields



Gamma-ray photons

Air showers (e^+e^- cascade)

Cherenkov photons

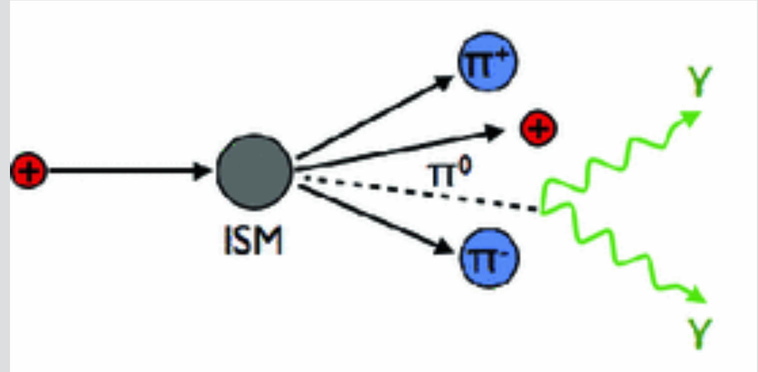
Electrical signal

Time over threshold

Gamma-Ray Astronomy with HAWC

Cosmic accelerator

Dust, gas, photon fields



Gamma-ray photons

Atmosphere

Air showers (e^+e^- cascade)

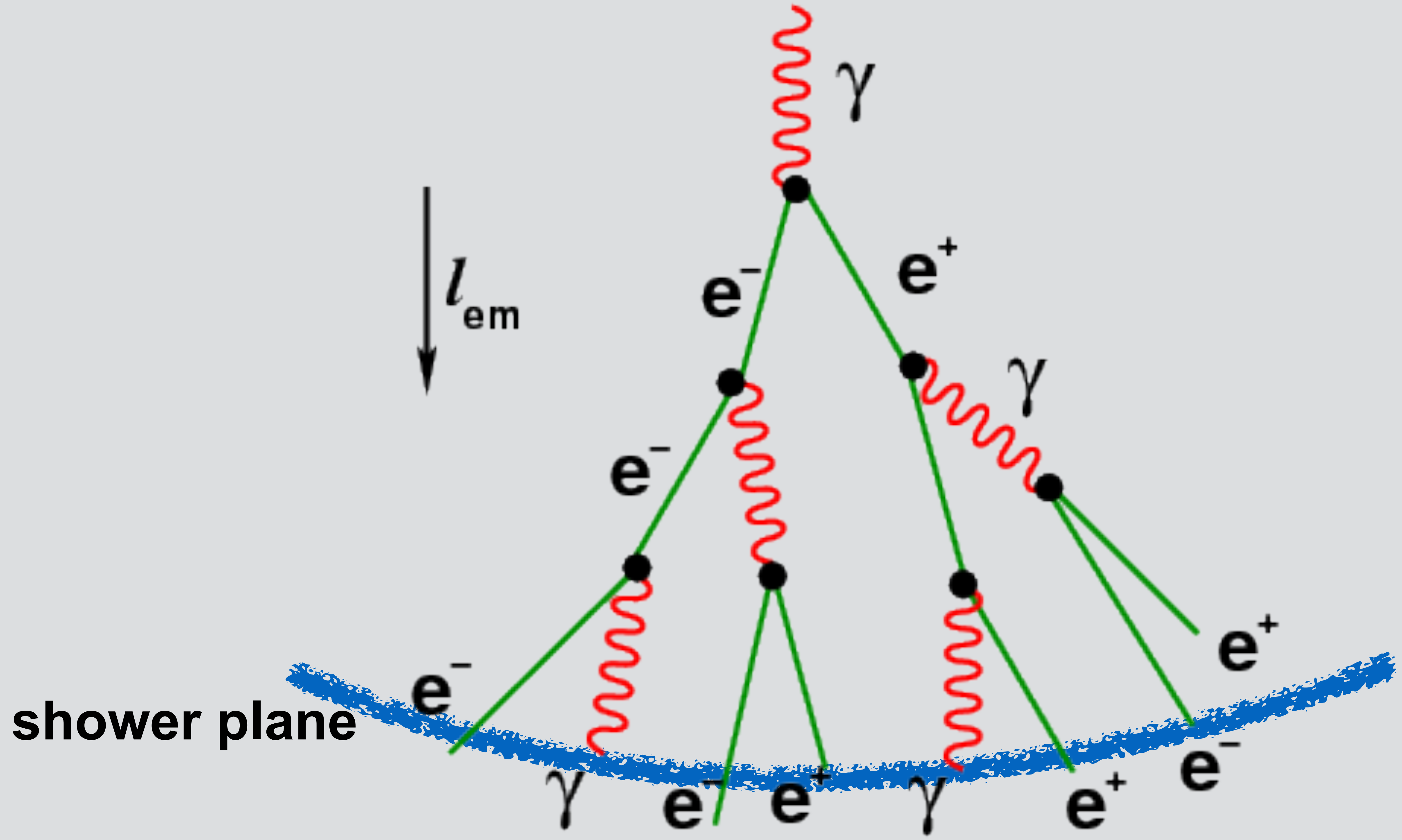
Cherenkov photons

Electrical signal

Time over threshold

Extensive Air Showers

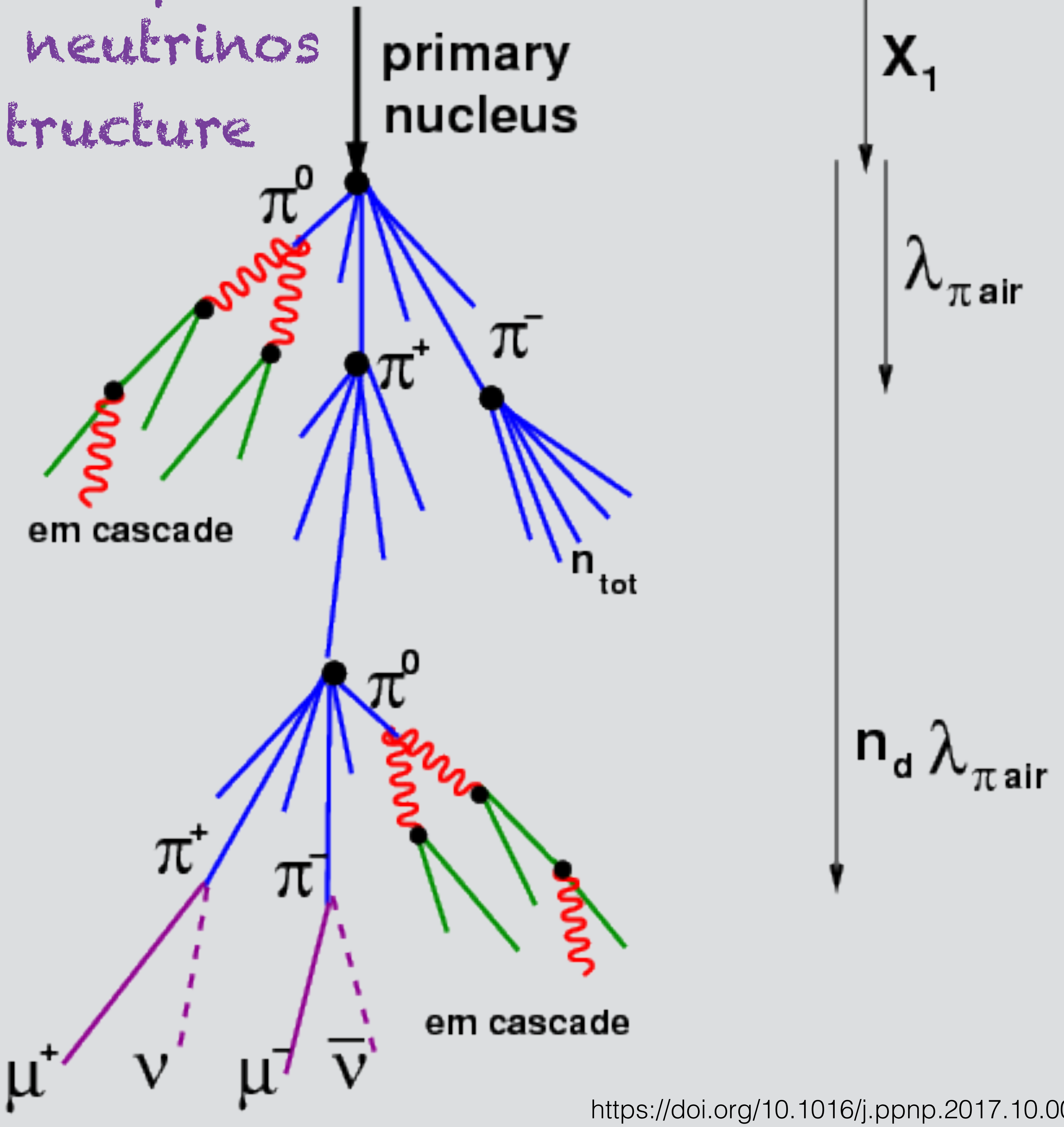
em cascade



- mainly electrons and photons
- tend to develop evenly.

hadronic cascade

- protons, pions, muons, and neutrinos
- substructure

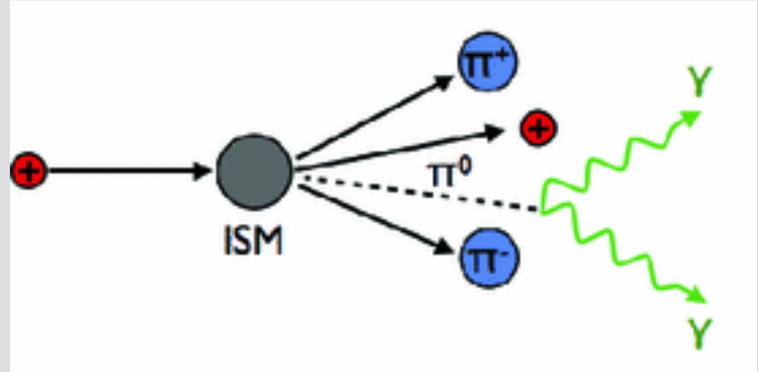


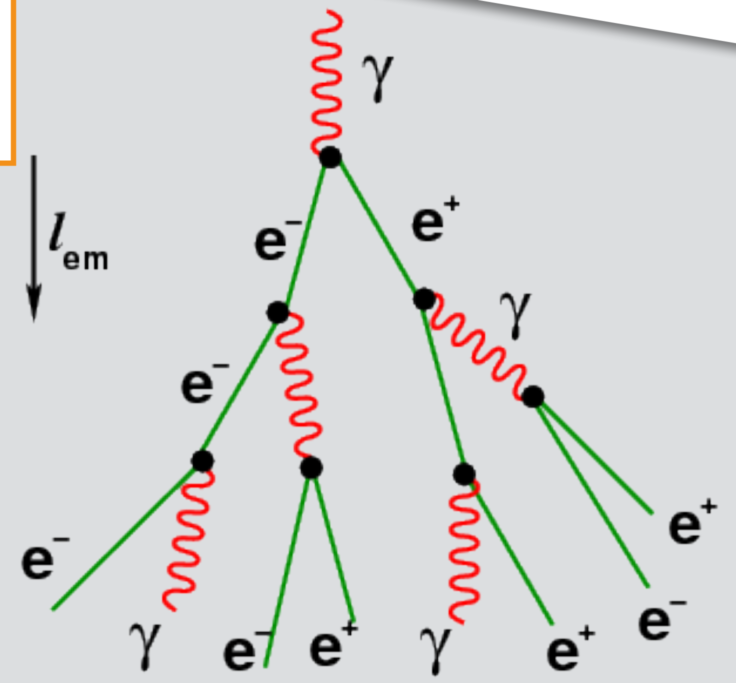
https://doi.org/10.1016/j.ppnp.2017.10.002

Gamma-Ray Astronomy with HAWC

High Altitude Water Cherenkov
Gamma-Ray Observatory

Cosmic accelerator → Dust, gas, photon fields → **Gamma-ray photons** → Atmosphere → **Air showers (e^+e^- cascade)** → **Cherenkov photons** → PMT → **Electrical signal** → DAQ electronics → **Time over threshold**



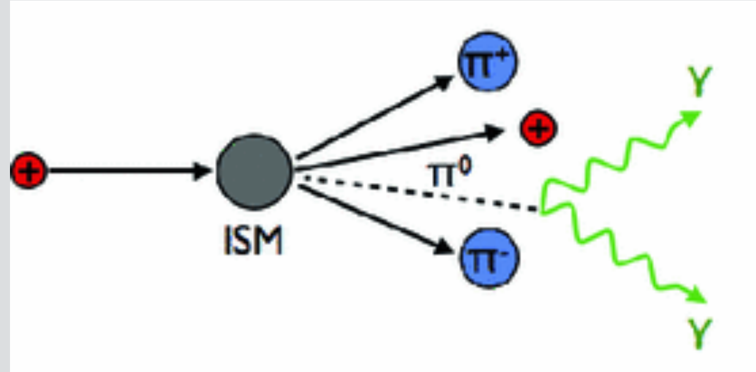


Gamma-Ray Astronomy with HAWC

HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

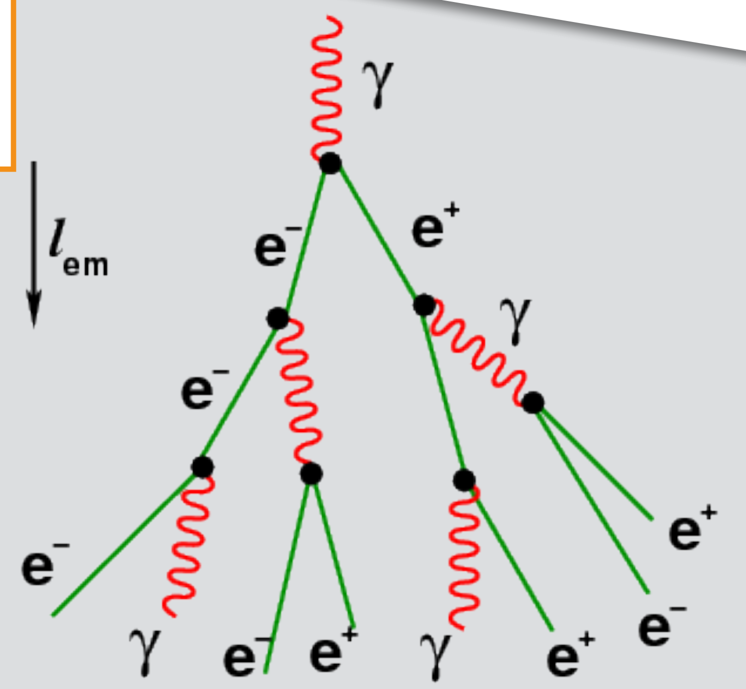
Cosmic accelerator

Dust, gas, photon fields



Gamma-ray photons

Atmosphere



Air showers (e^+e^- cascade)

Water tank

Cherenkov photons

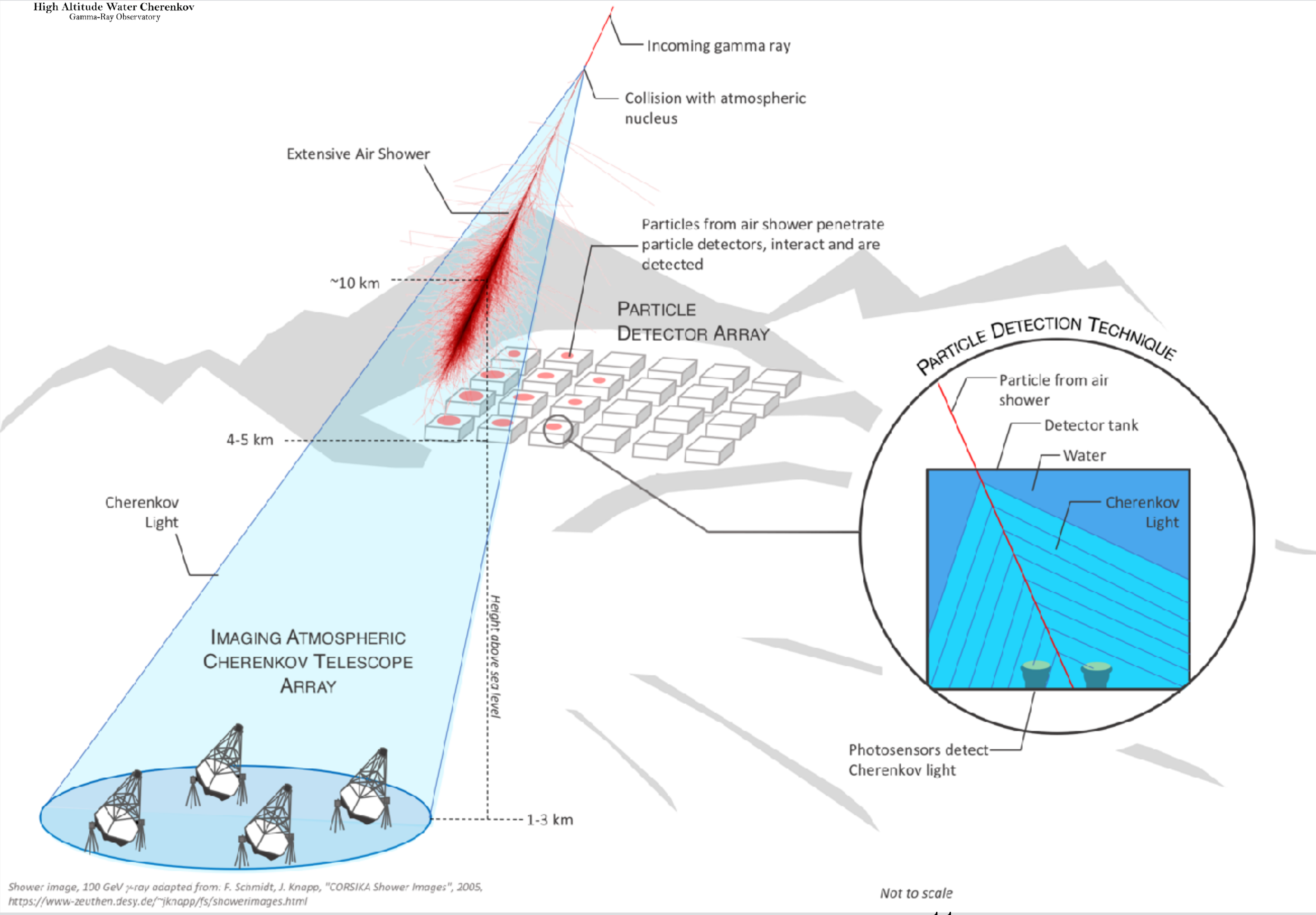
PMT

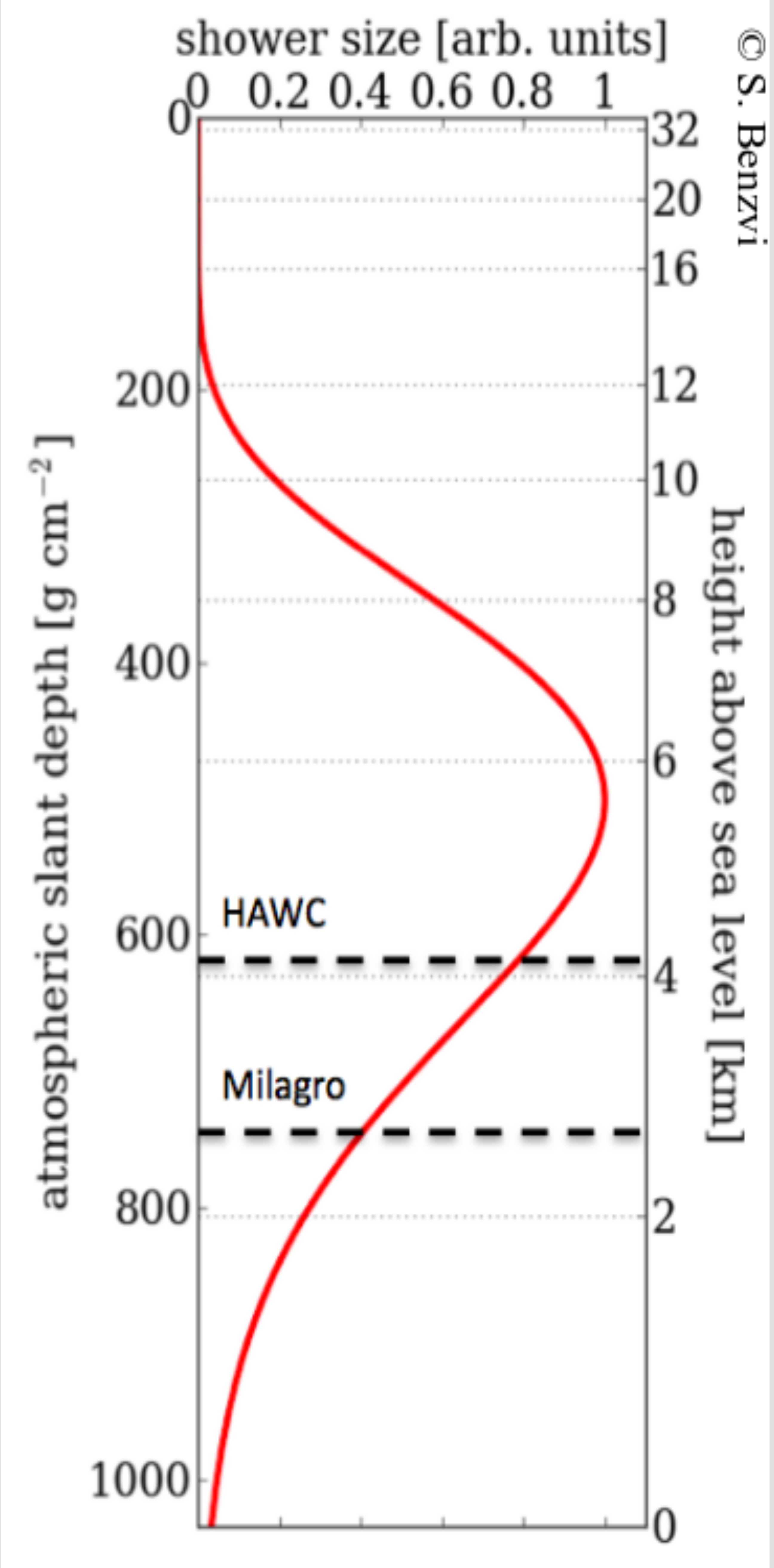
Electrical signal

DAQ electronics

Time over threshold

Extensive Air Showers

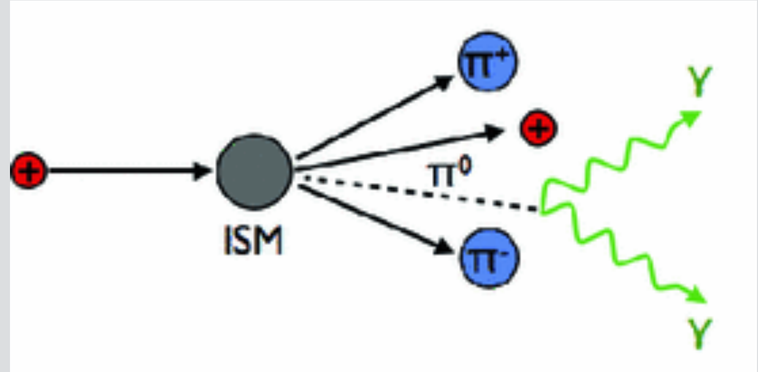




Gamma-Ray Astronomy with HAWC

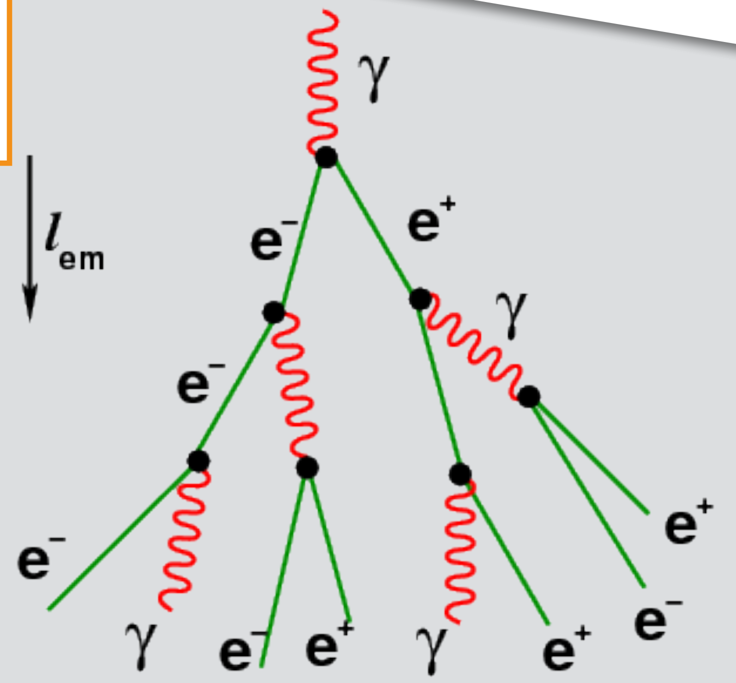
Cosmic accelerator

Dust, gas, photon fields



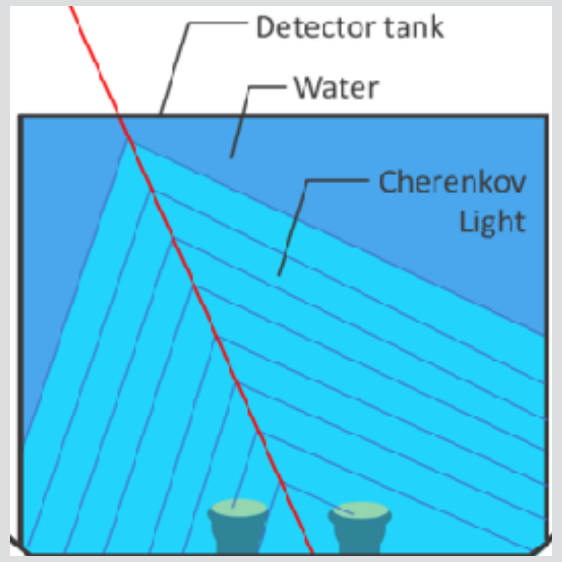
Gamma-ray photons

Atmosphere



Air showers (e^+e^- cascade)

Water tank



Cherenkov photons

PMT

Electrical signal

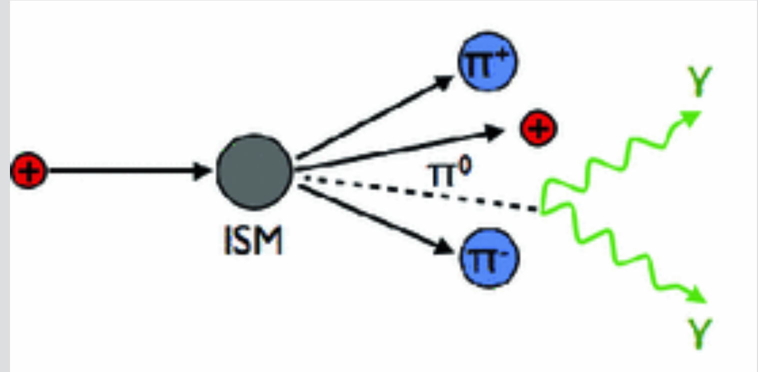
DAQ electronics

Time over threshold

Gamma-Ray Astronomy with HAWC

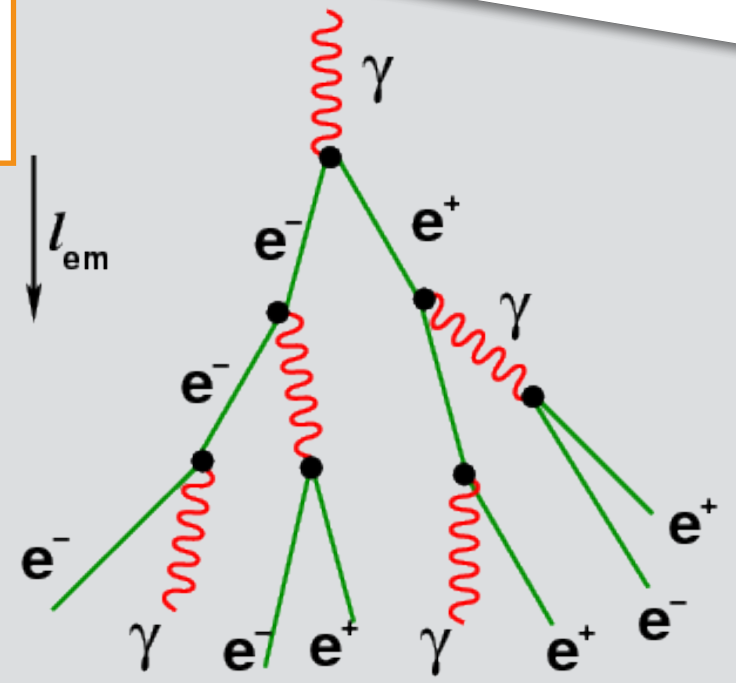
Cosmic accelerator

Dust, gas, photon fields

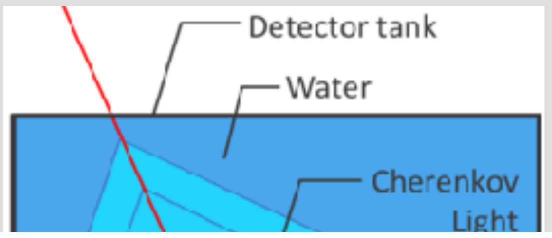


Gamma-ray photons

Atmosphere

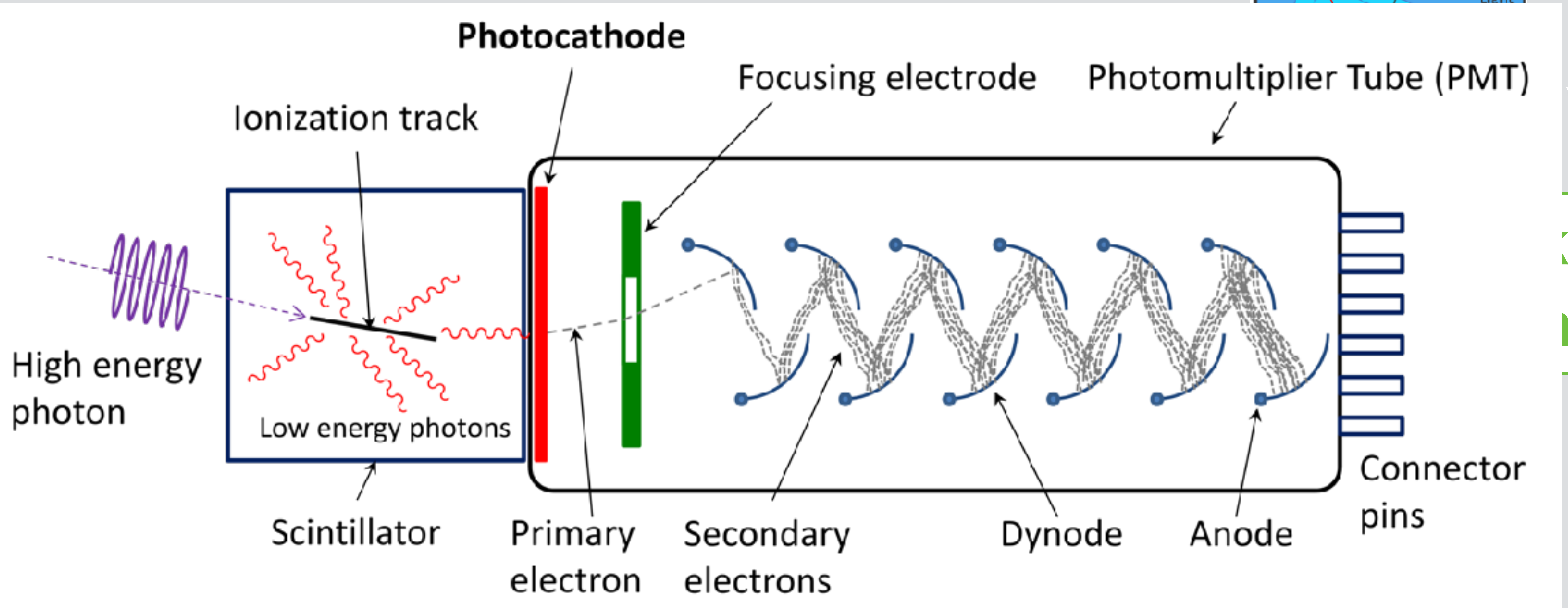


Air showers (e+e- cascade)



Water tank

kov
ns



signal

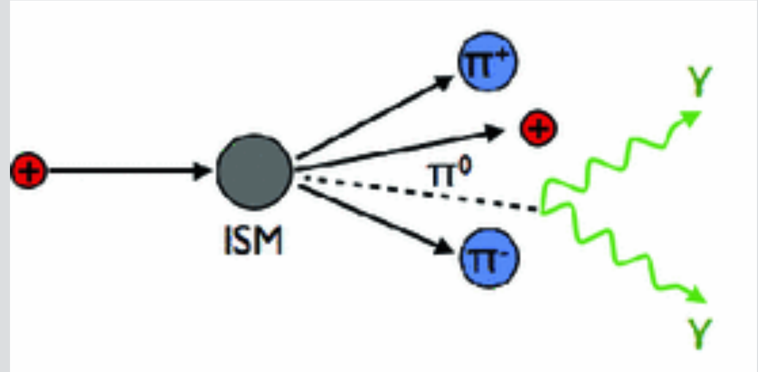
DA
electronics

Time over threshold

Gamma-Ray Astronomy with HAWC

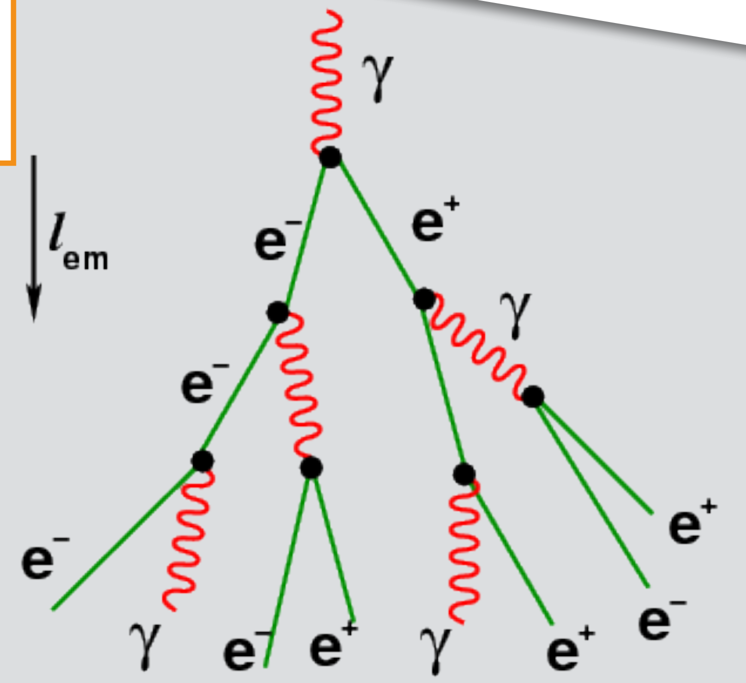
Cosmic accelerator

Dust, gas, photon fields



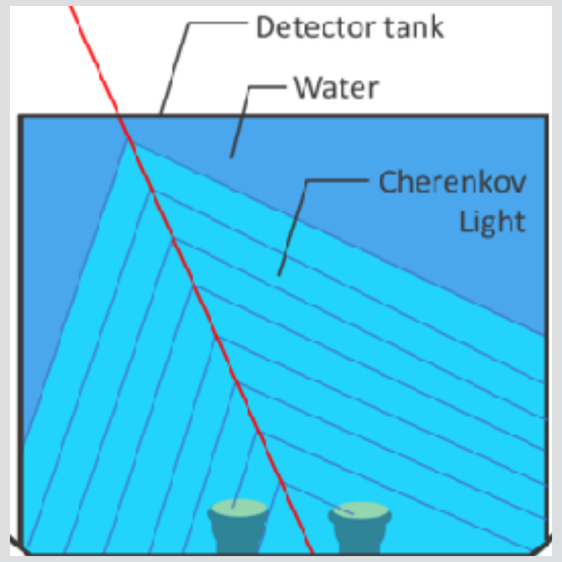
Gamma-ray photons

Atmosphere



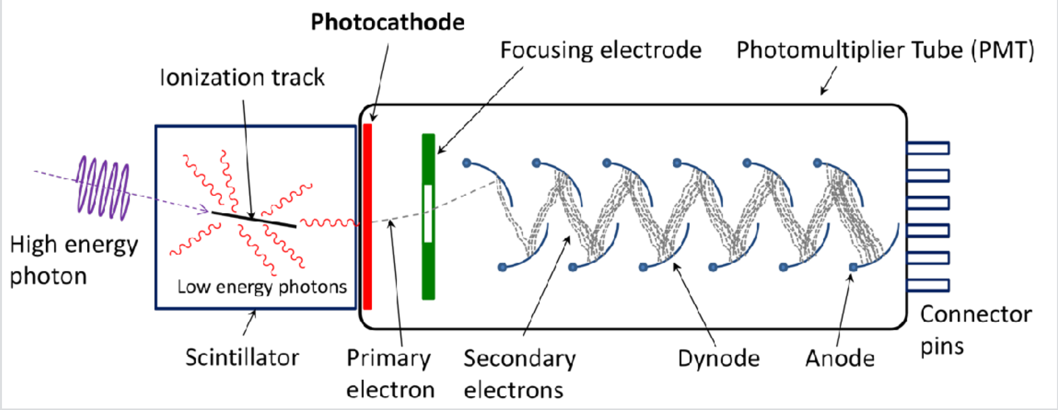
Air showers (e^+e^- cascade)

Water tank



Cherenkov photons

PMT



Electrical signal

DAQ electronics

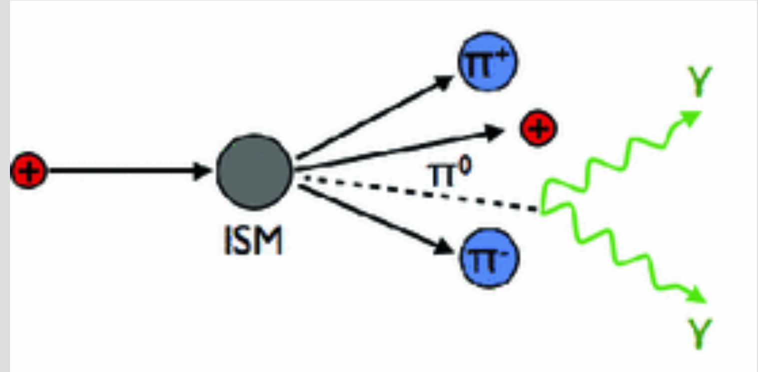
Time over threshold

Gamma-Ray Astronomy with HAWC

High Altitude Water Cherenkov
Gamma-Ray Observatory

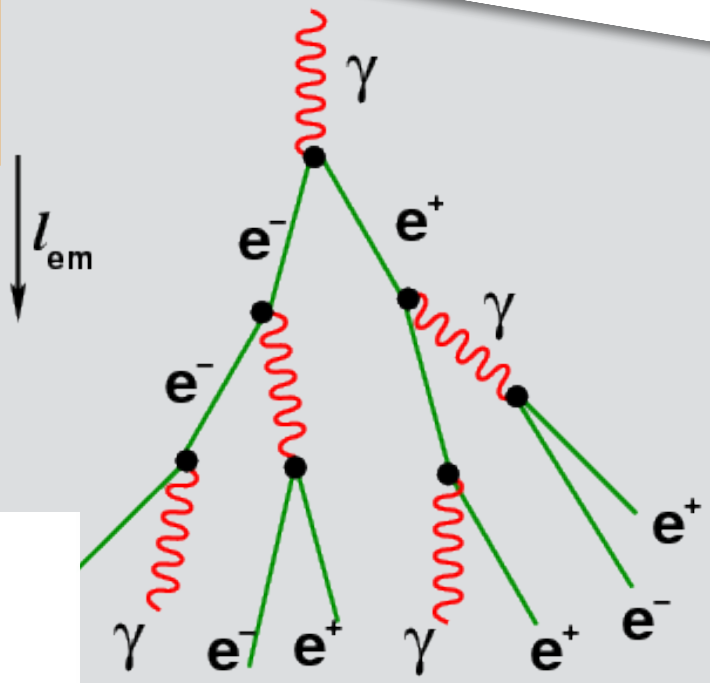
Cosmic accelerator

Dust, gas, photon fields



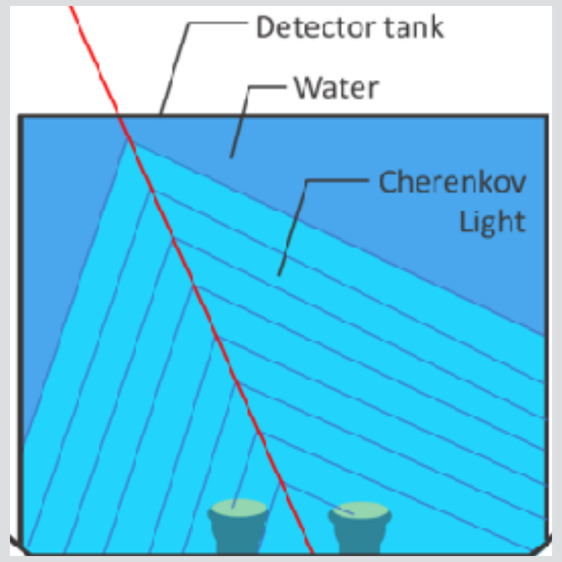
Gamma-ray photons

Atmosphere



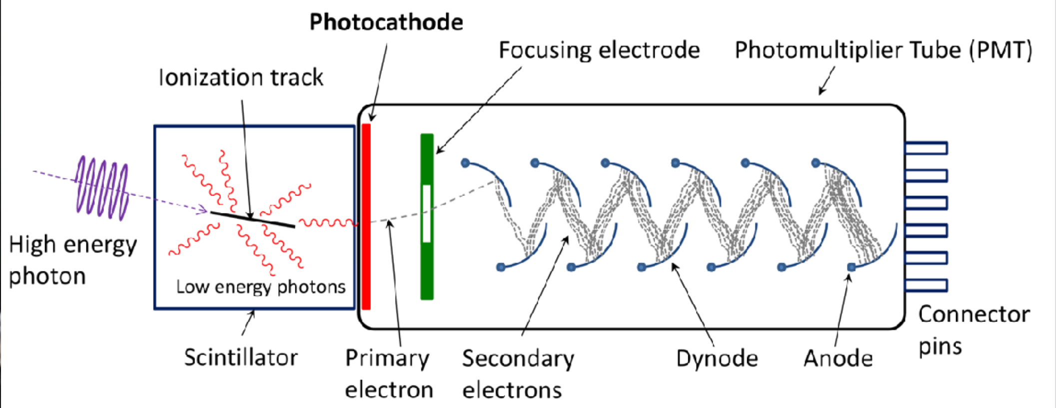
Air showers (e+e- cascade)

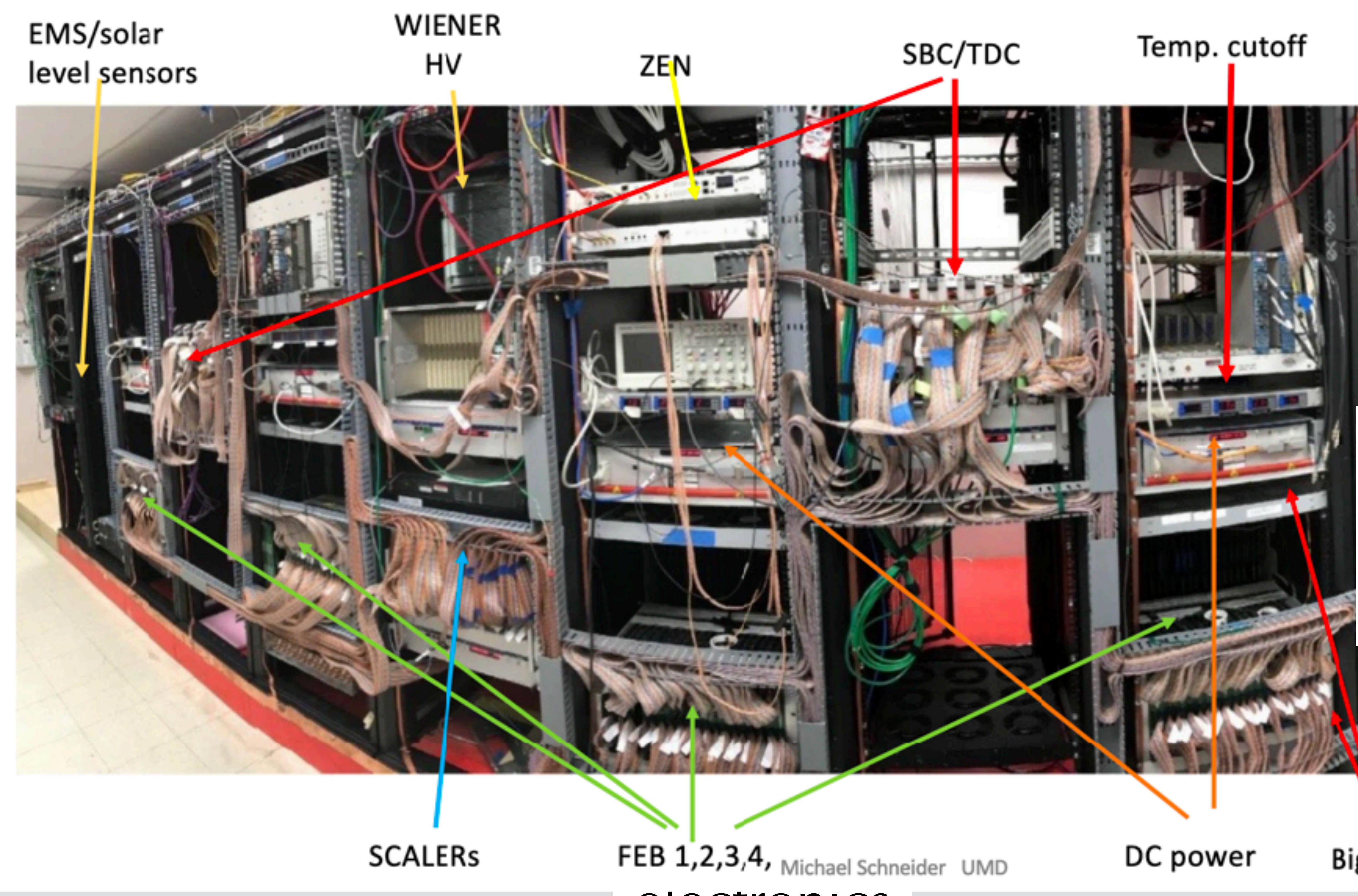
Water tank



Cherenkov photons

PMT





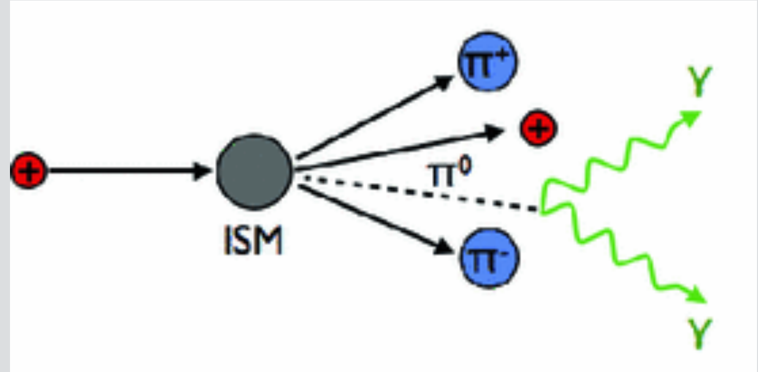
electronics

HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

Gamma-Ray Astronomy with HAWC

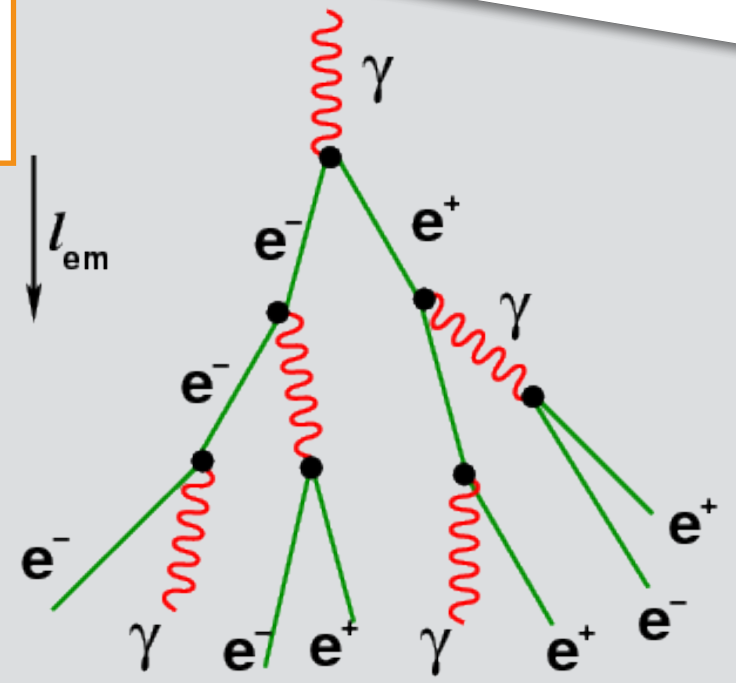
Cosmic accelerator

Dust, gas, photon fields



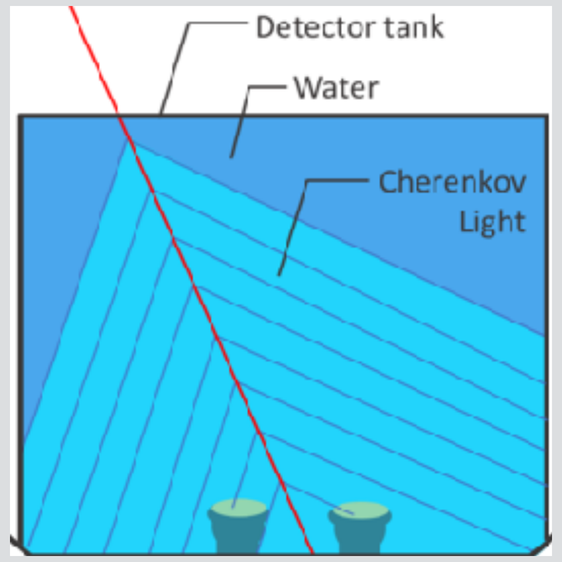
Gamma-ray photons

Atmosphere



Air showers (e^+e^- cascade)

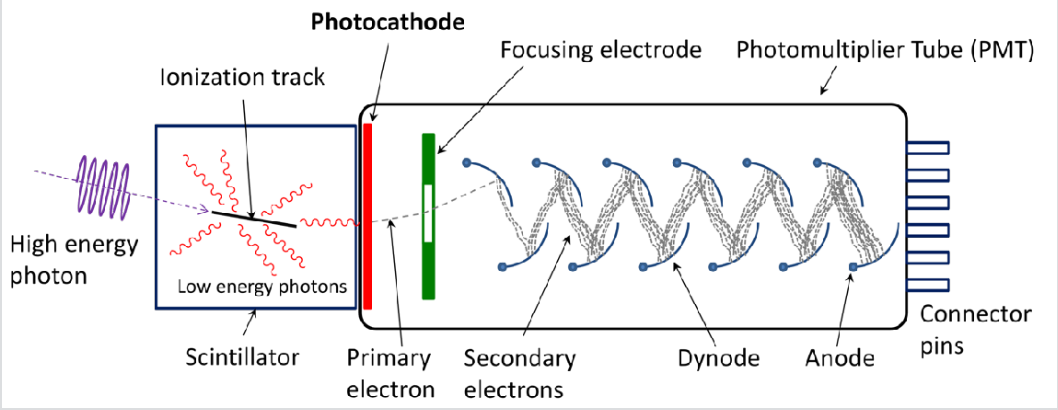
Water tank



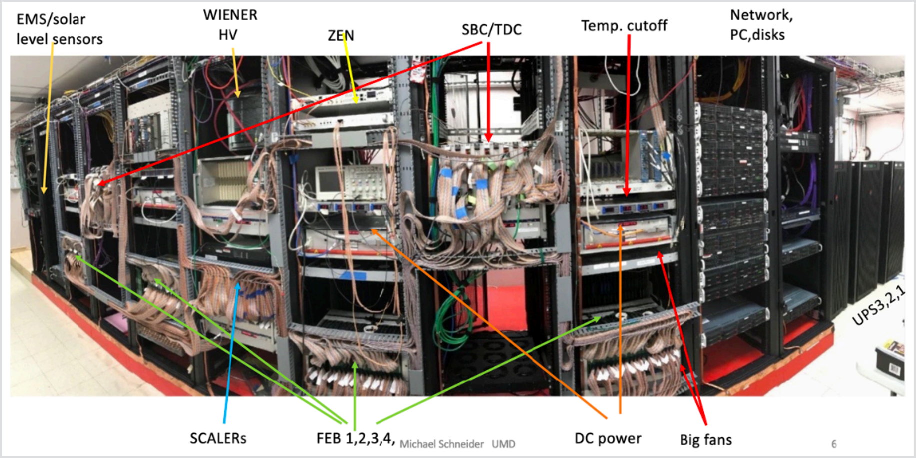
Cherenkov photons

PMT

Electrical signal



DAQ electronics

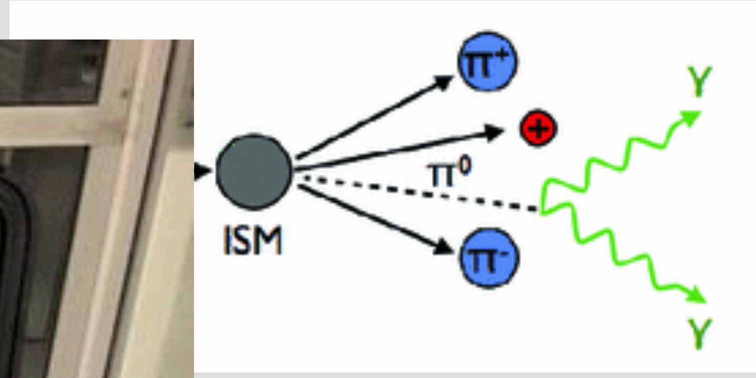


Time over threshold

Gamma-Ray Astronomy with HAWC

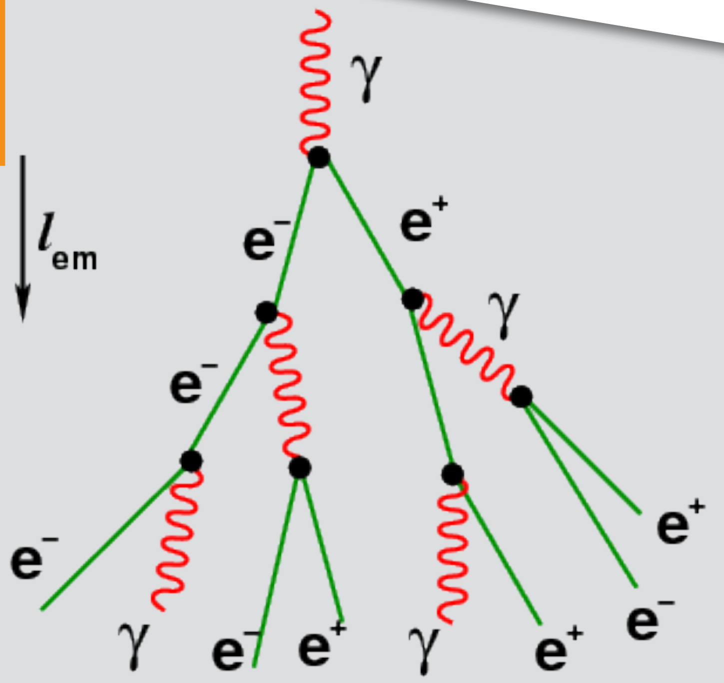
Cosmic

Dust, gas,
photon fields

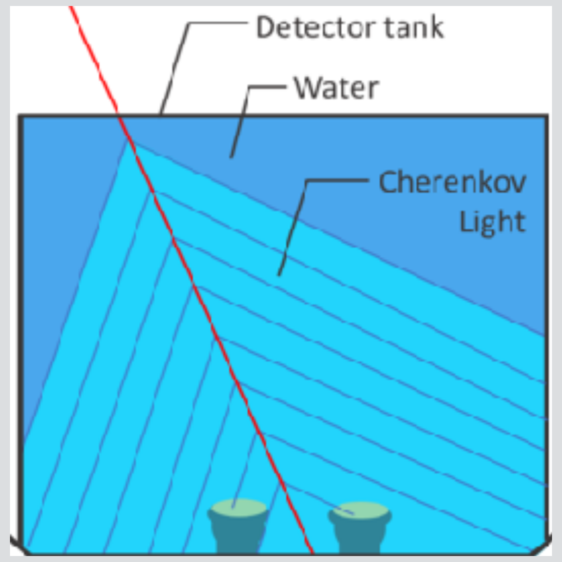


Gamma-ray photons

Atmosphere

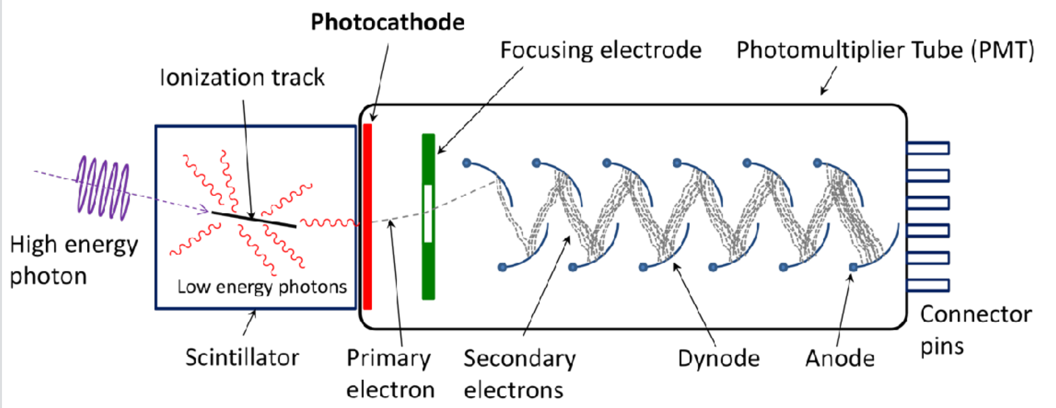


Air showers (e+e- cascade)



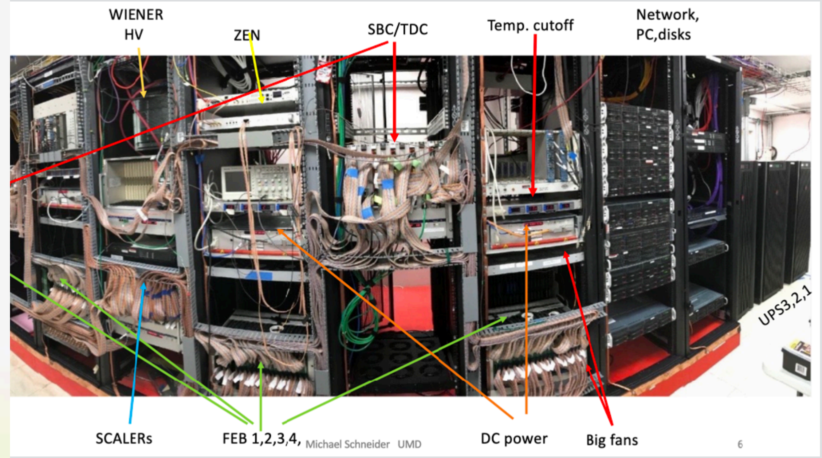
Water
tank

Cherenkov photons



PMT

Electrical signal

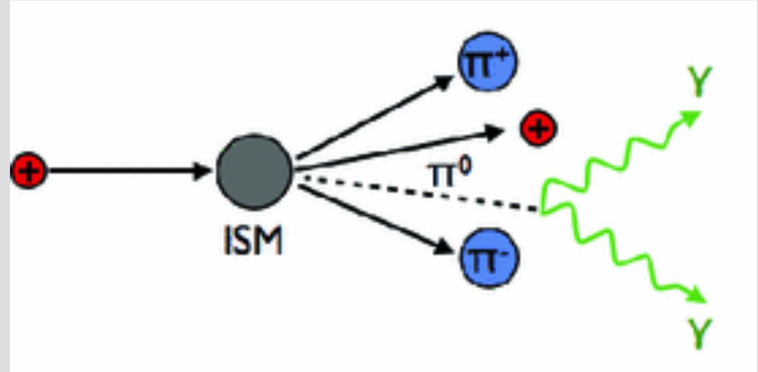


DAQ
electronics

Gamma-Ray Astronomy with HAWC

Cosmic accelerator

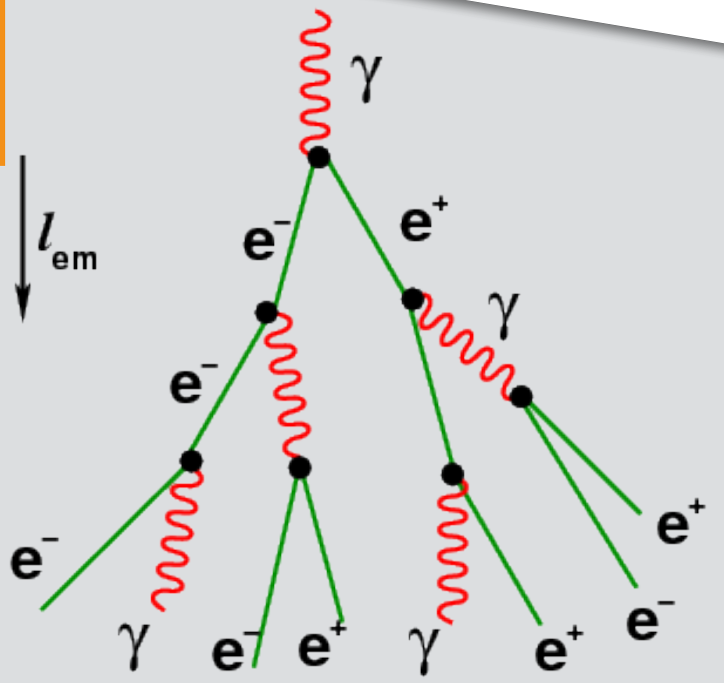
Dust, gas, photon fields

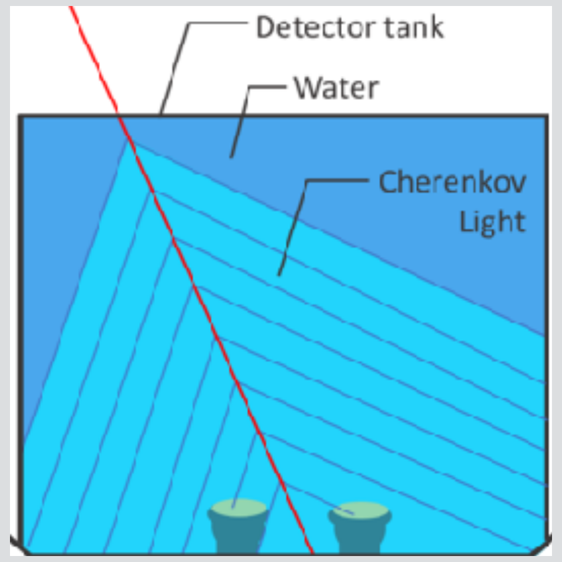


Gamma-ray photons

Atmosphere

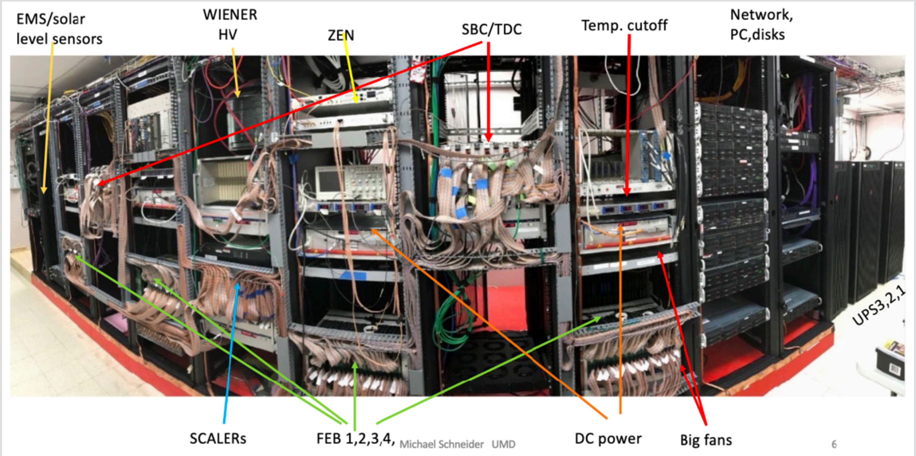
Air showers (e^+e^- cascade)

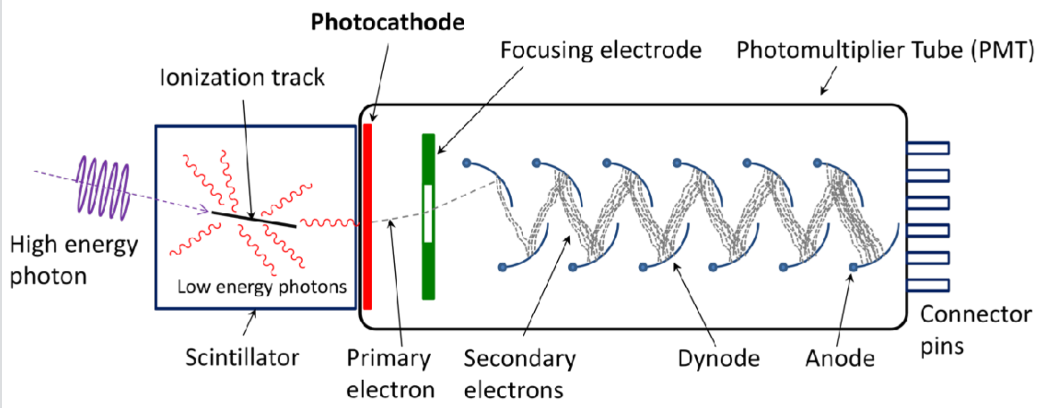




Water tank

Cherenkov photons





Time over threshold

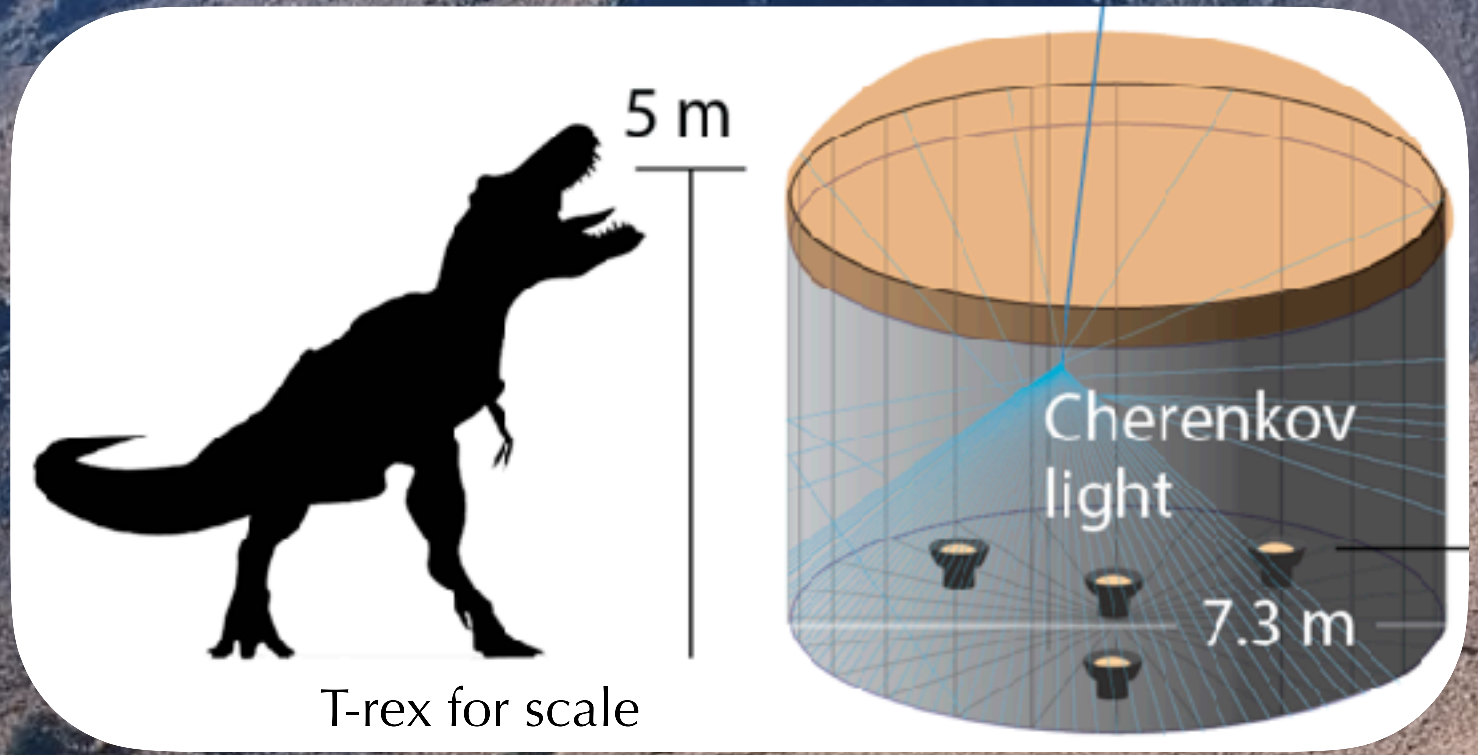
Electrical signal

PMT

DAQ electronics

High Altitude Water Cherenkov Observatory

HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory



Energy range: ~300 GeV — 100 TeV
Angular resolution: ~0.1°
Field of View: ~2 sr
>95% Uptime

10^6: **M**ega
10^9: **G**iga
10^{12}: **T**era
10^{15}: **P**eta

Main array completed March 2015
Outriggers deployed 2018

Gamma-Ray Astronomy with HAWC

Cosmic accelerator

Gamma-ray photons

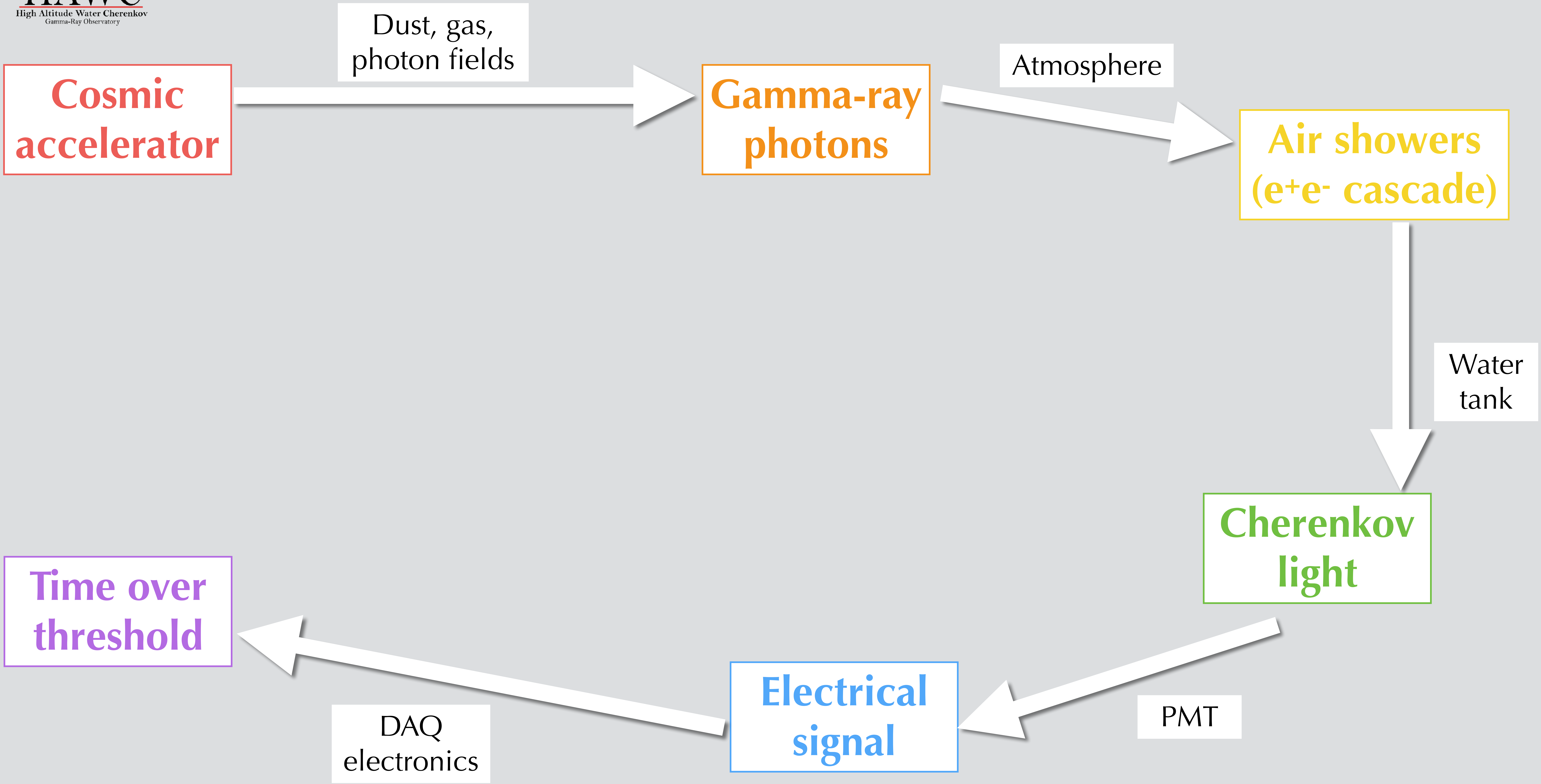
Air showers (e^+e^- cascade)

Cherenkov light

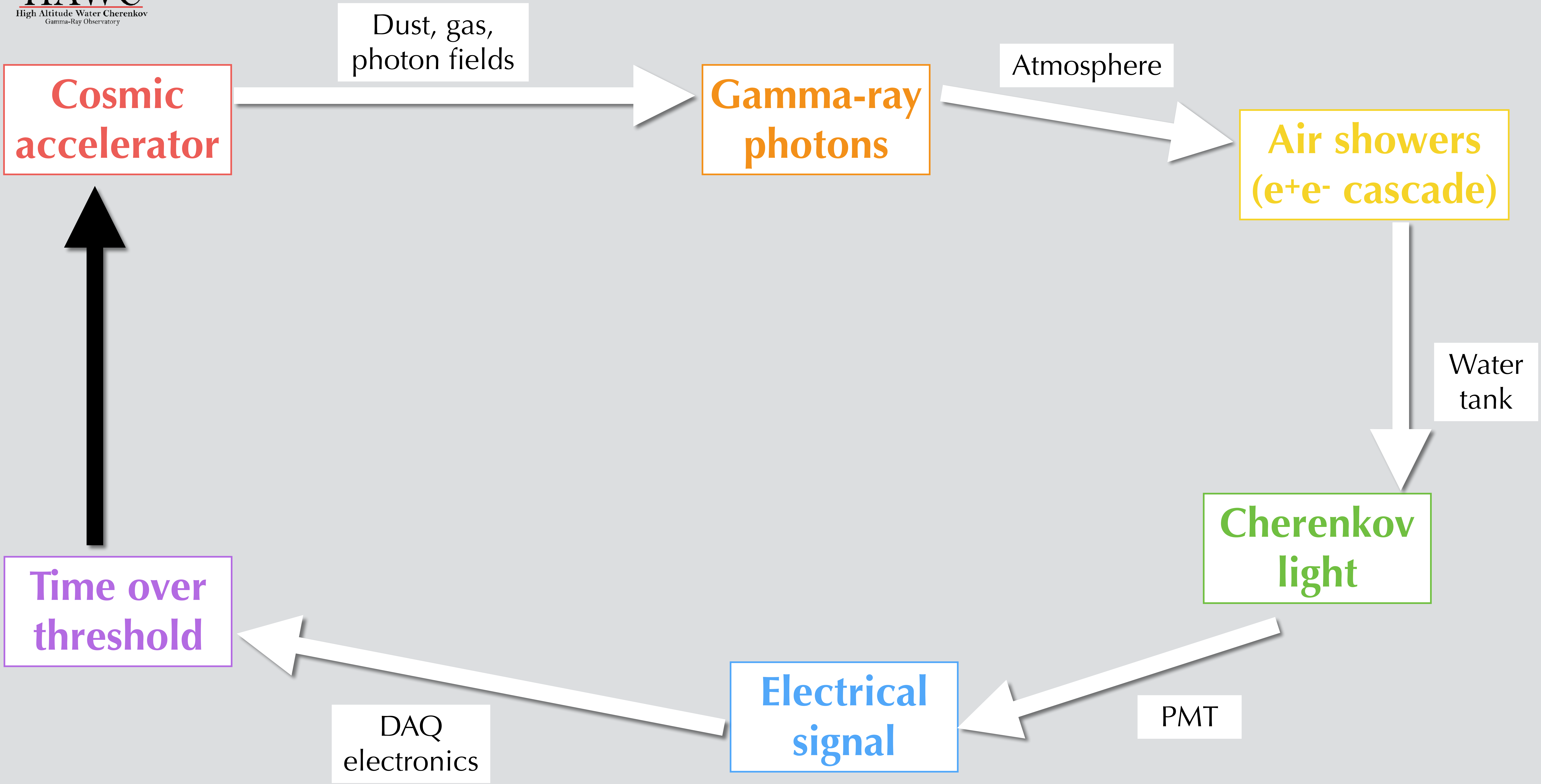
Time over threshold

Electrical signal

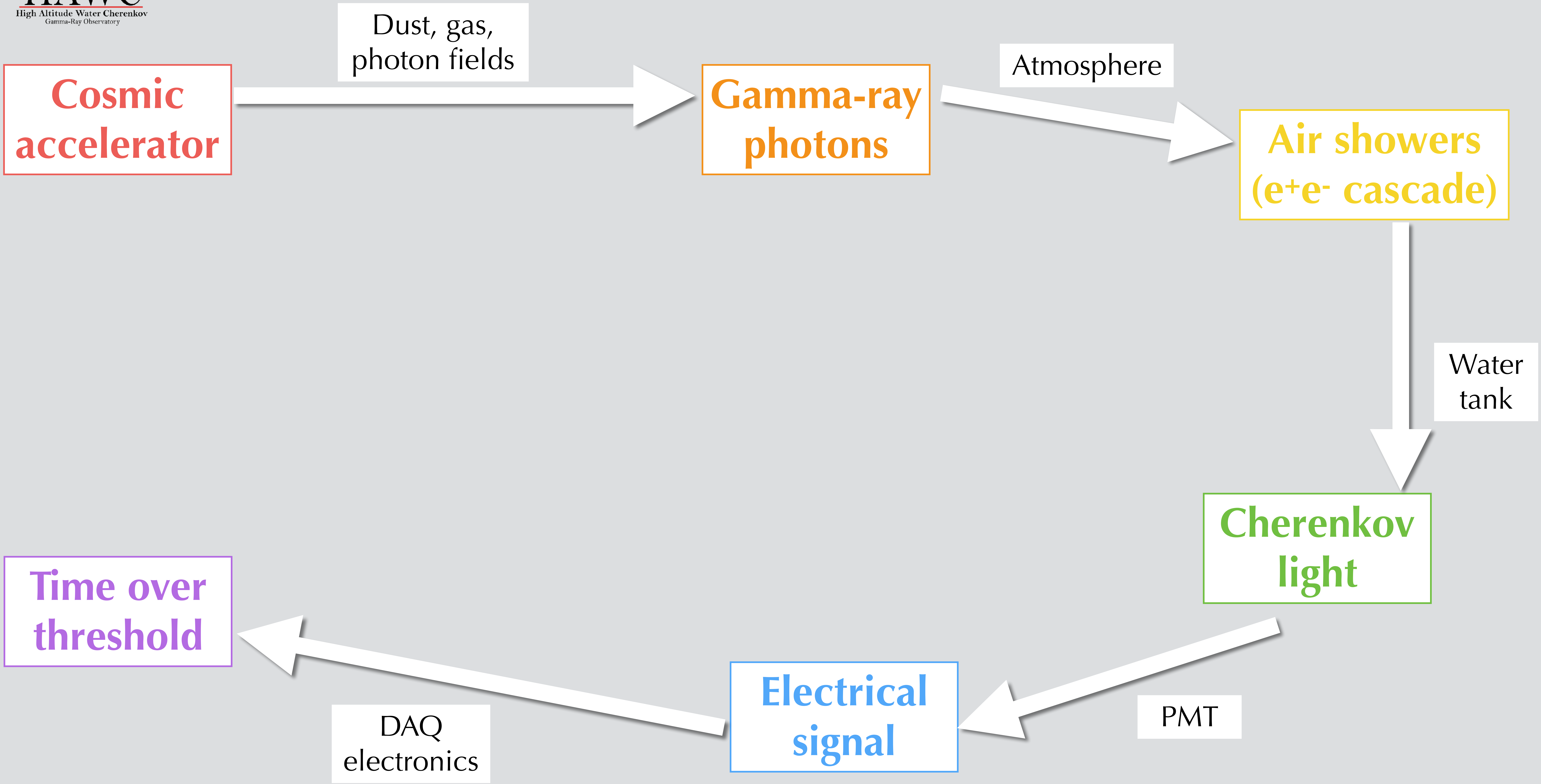
Gamma-Ray Astronomy with HAWC



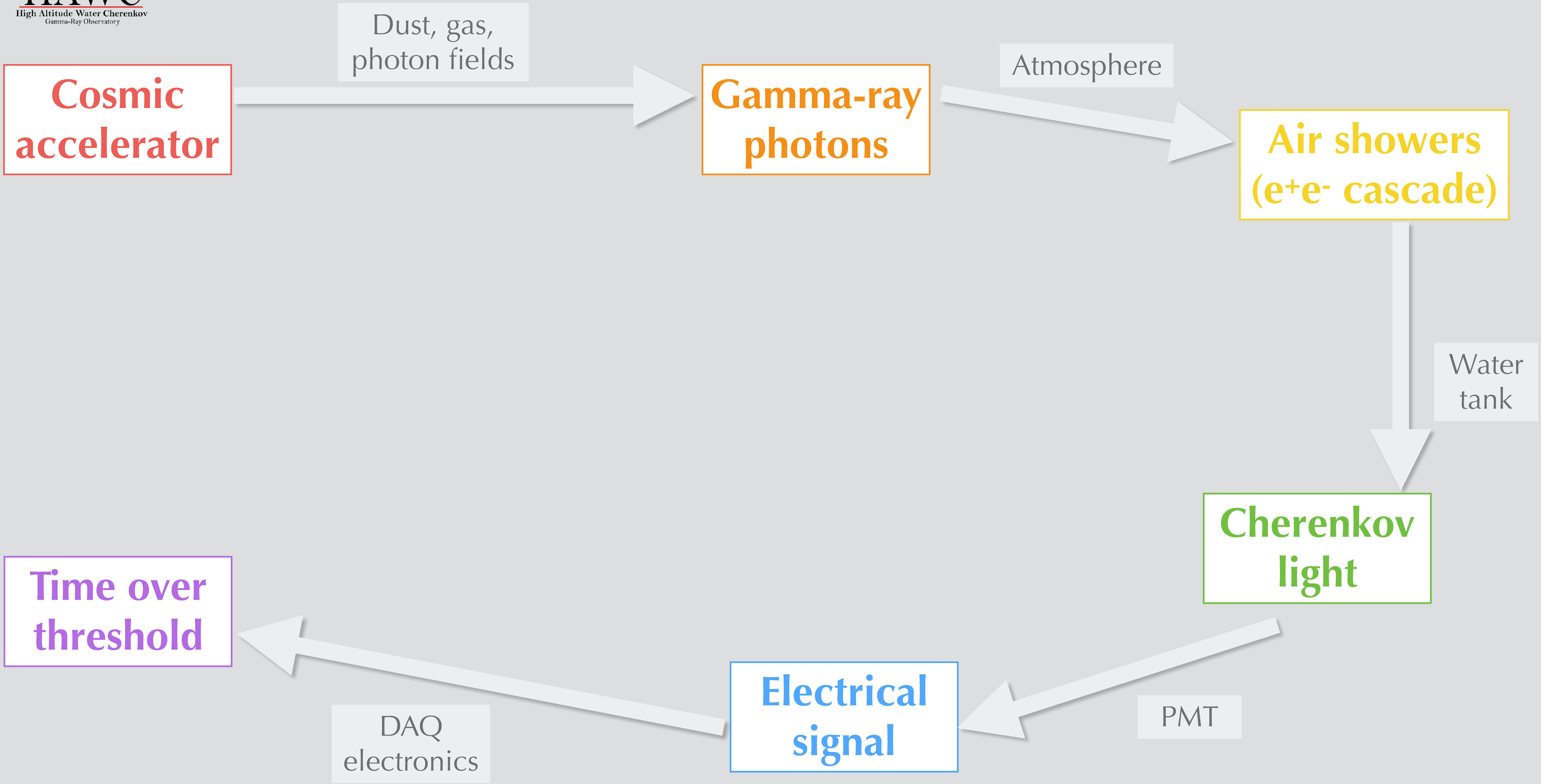
Gamma-Ray Astronomy with HAWC



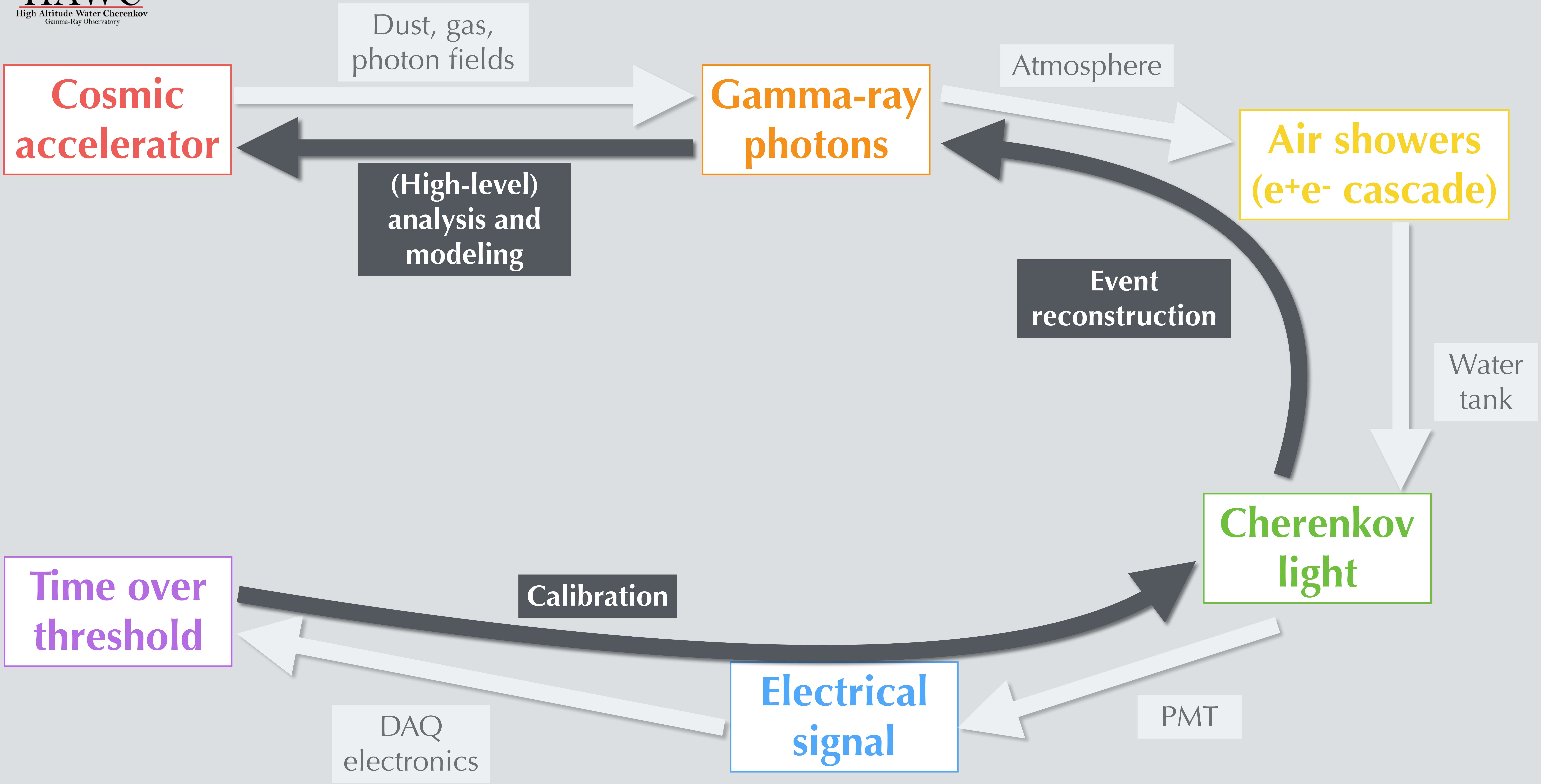
Gamma-Ray Astronomy with HAWC



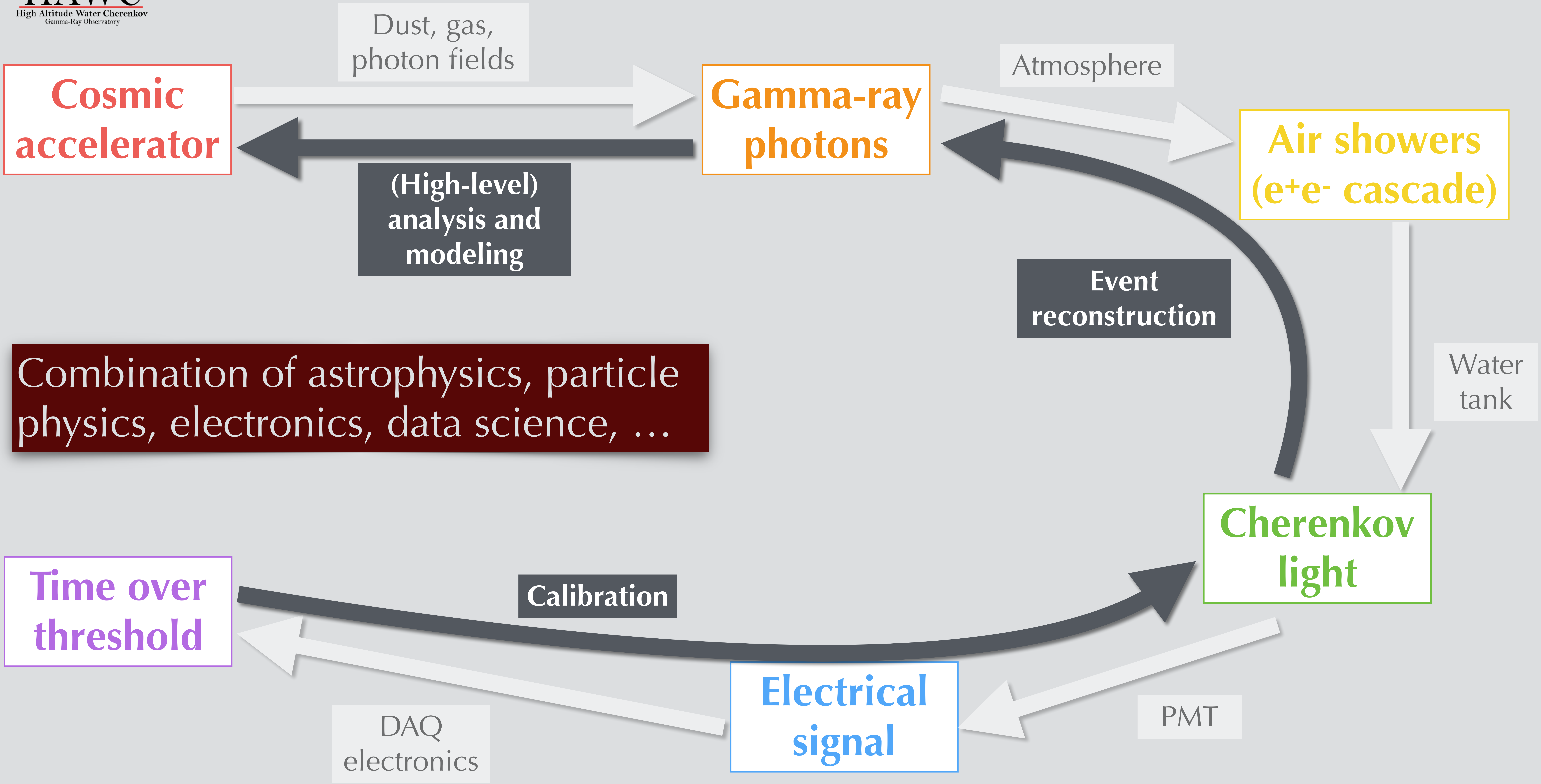
Gamma-Ray Astronomy with HAWC



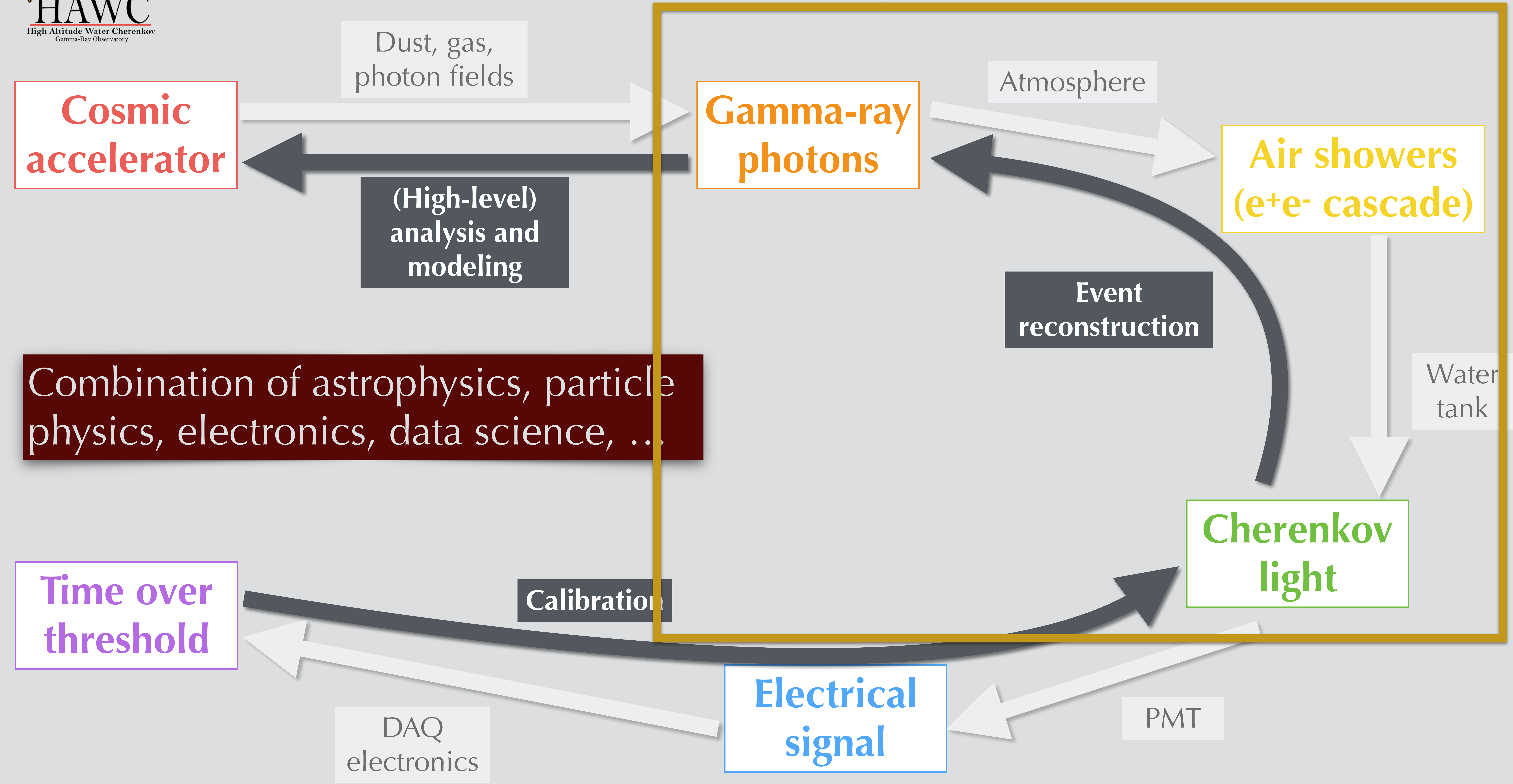
Gamma-Ray Astronomy with HAWC



Gamma-Ray Astronomy with HAWC

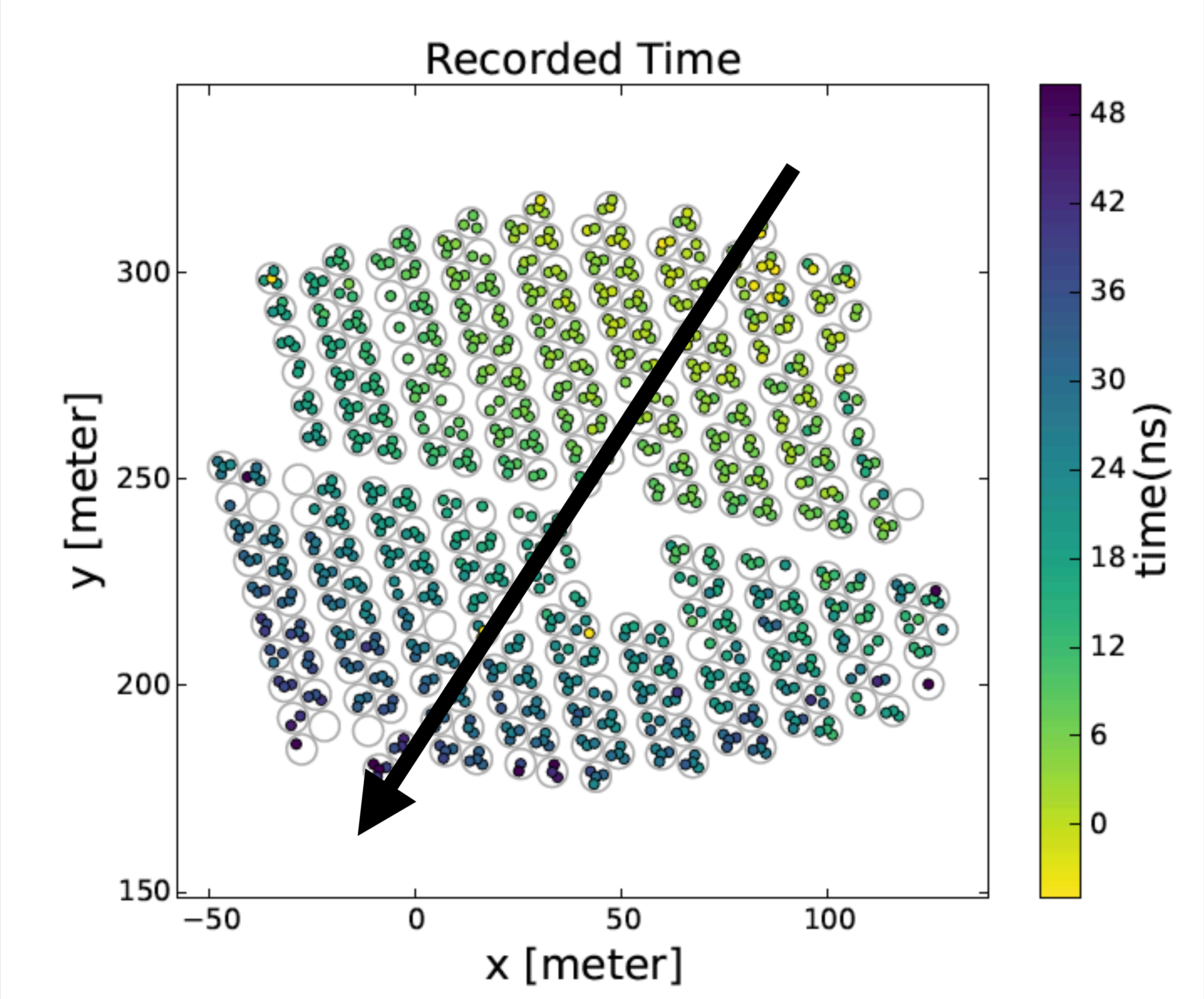


Gamma-Ray Astronomy with HAWC

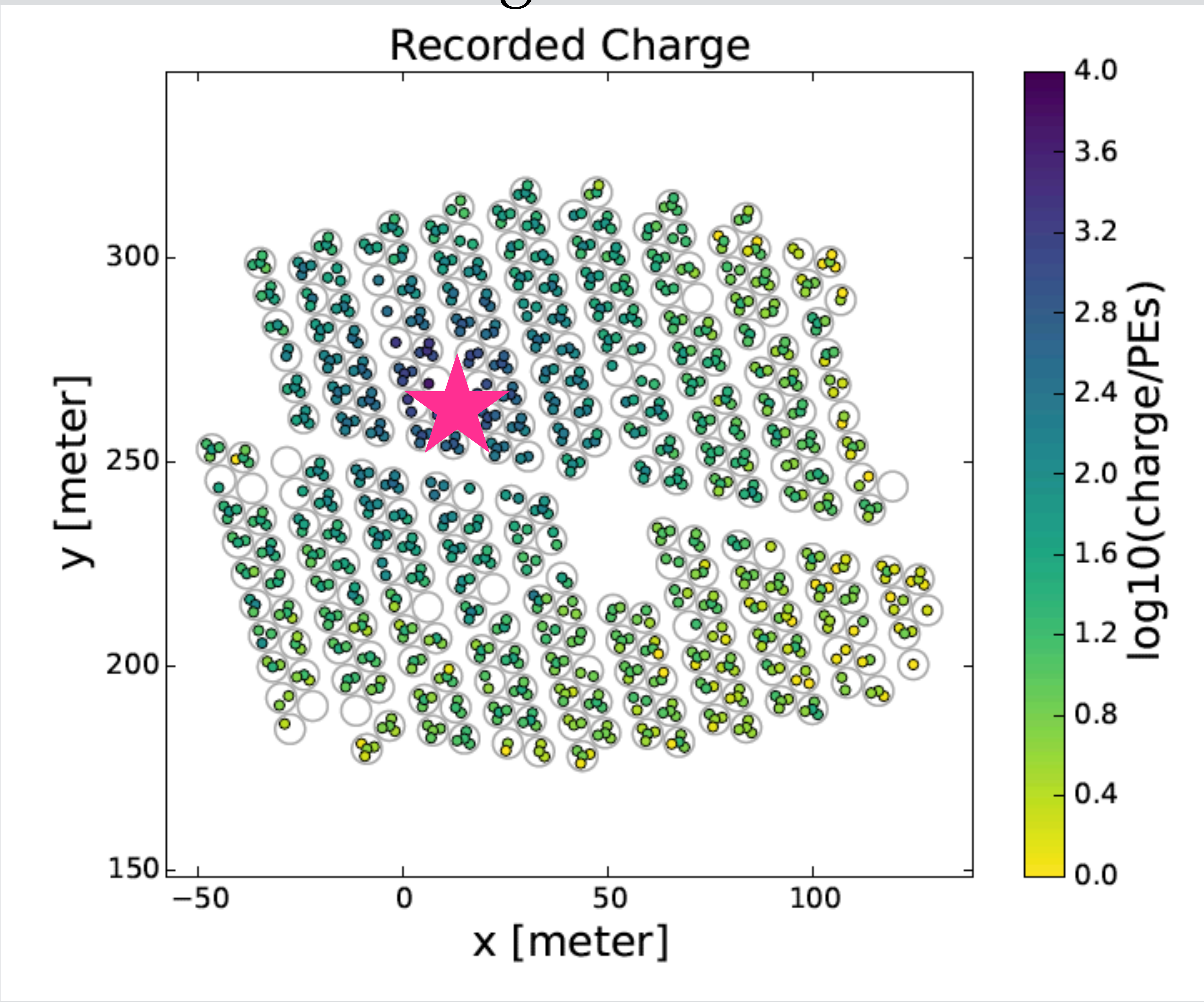


Event Reconstruction

Incident Direction
(Time Gradient)



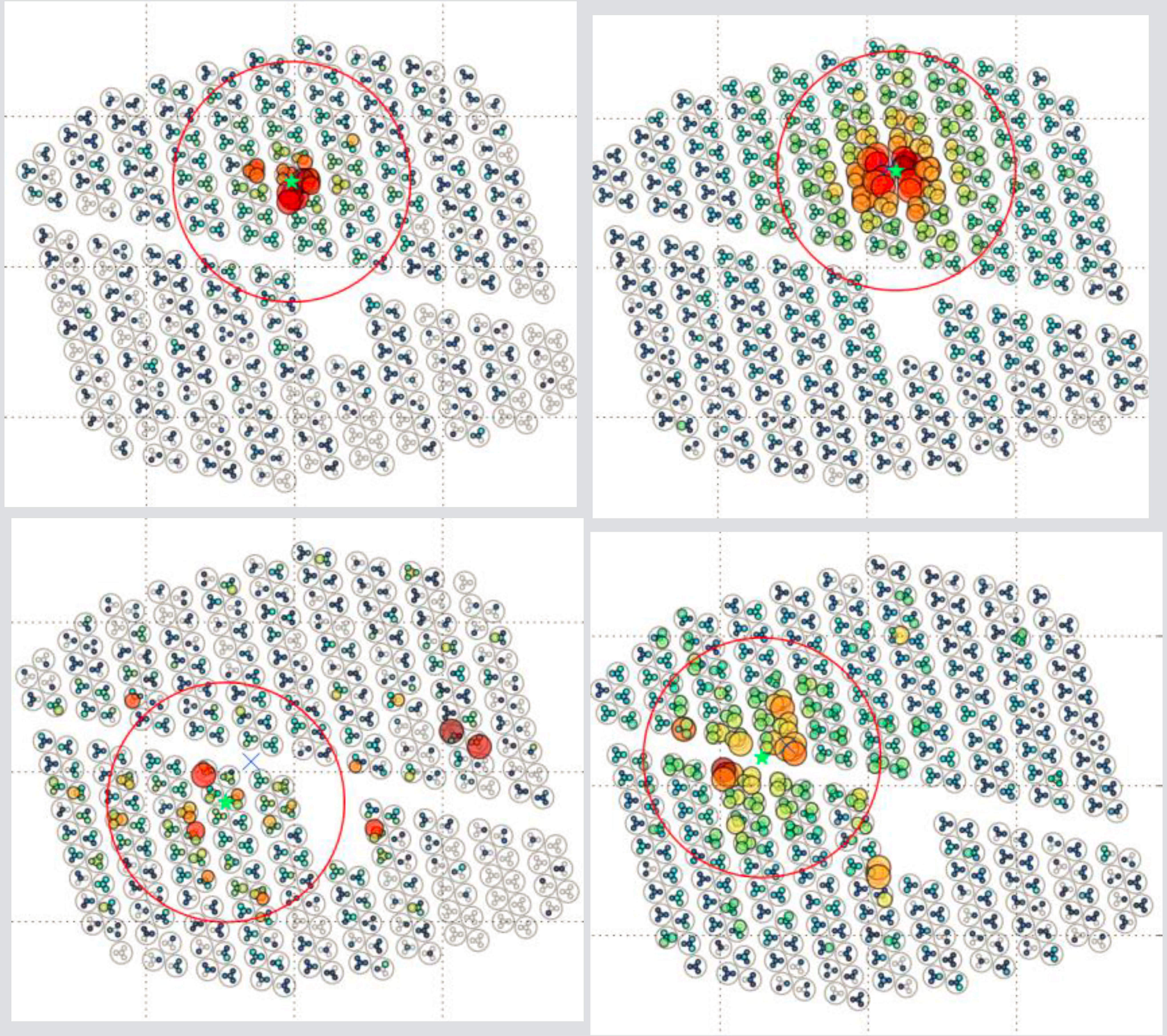
Core Location
(Light level)



Gamma/Hadron Separation

Gamma-ray event

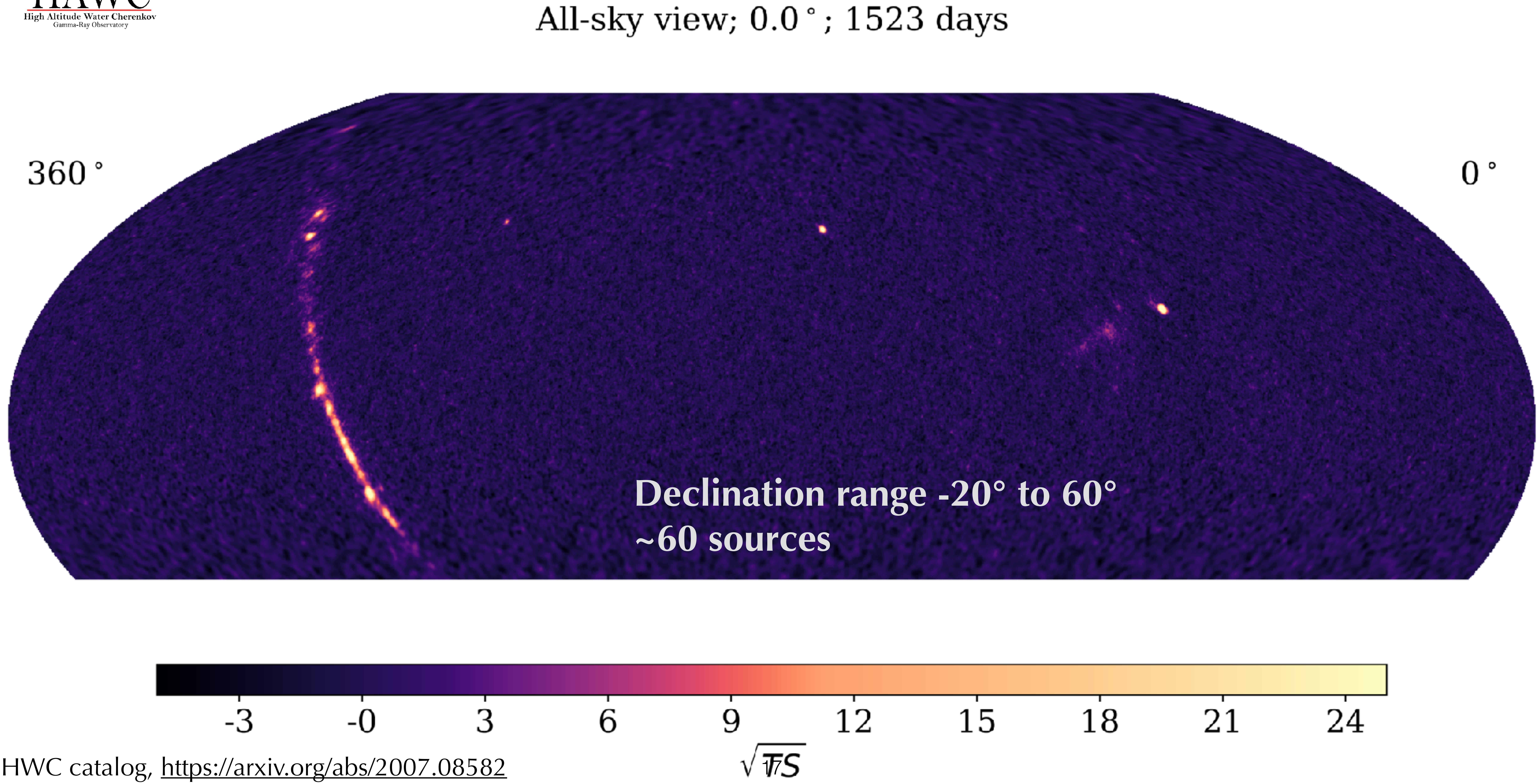
Cosmic-ray event



Axial symmetry

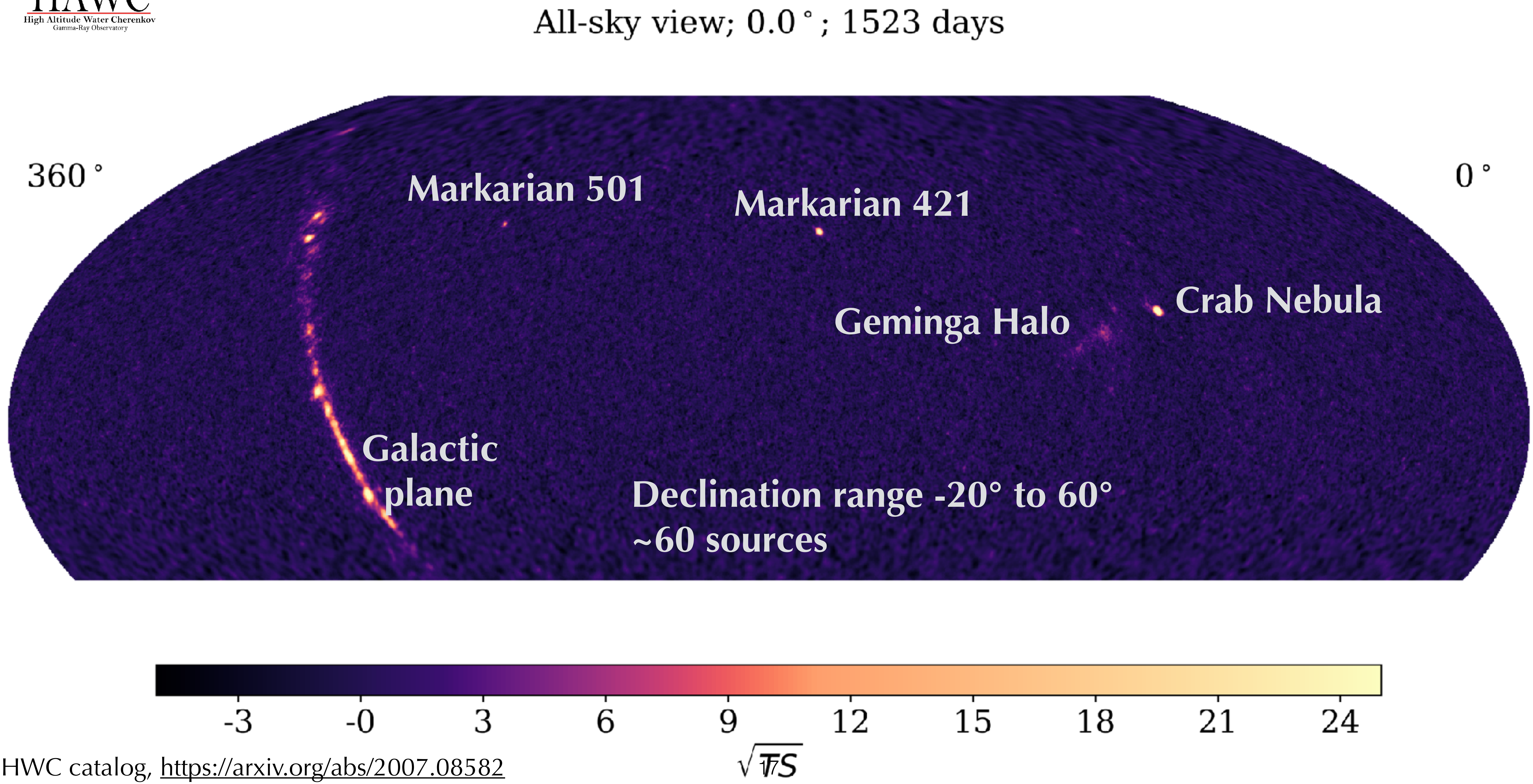
Asymmetric, high charge hits far from core

HAWC's Gamma-Ray Sky



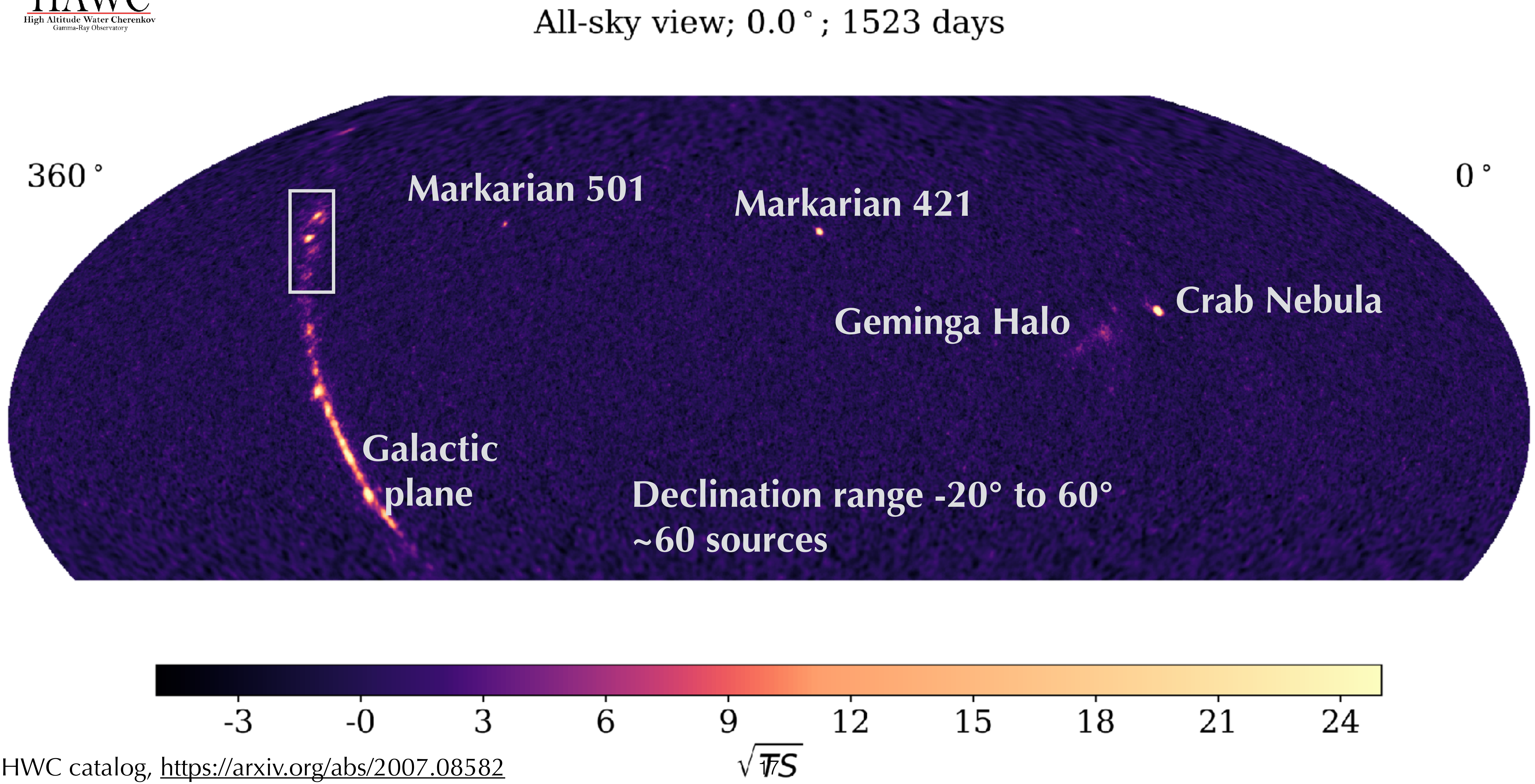
3HWC catalog, https://arxiv.org/abs/2007.08582

HAWC's Gamma-Ray Sky



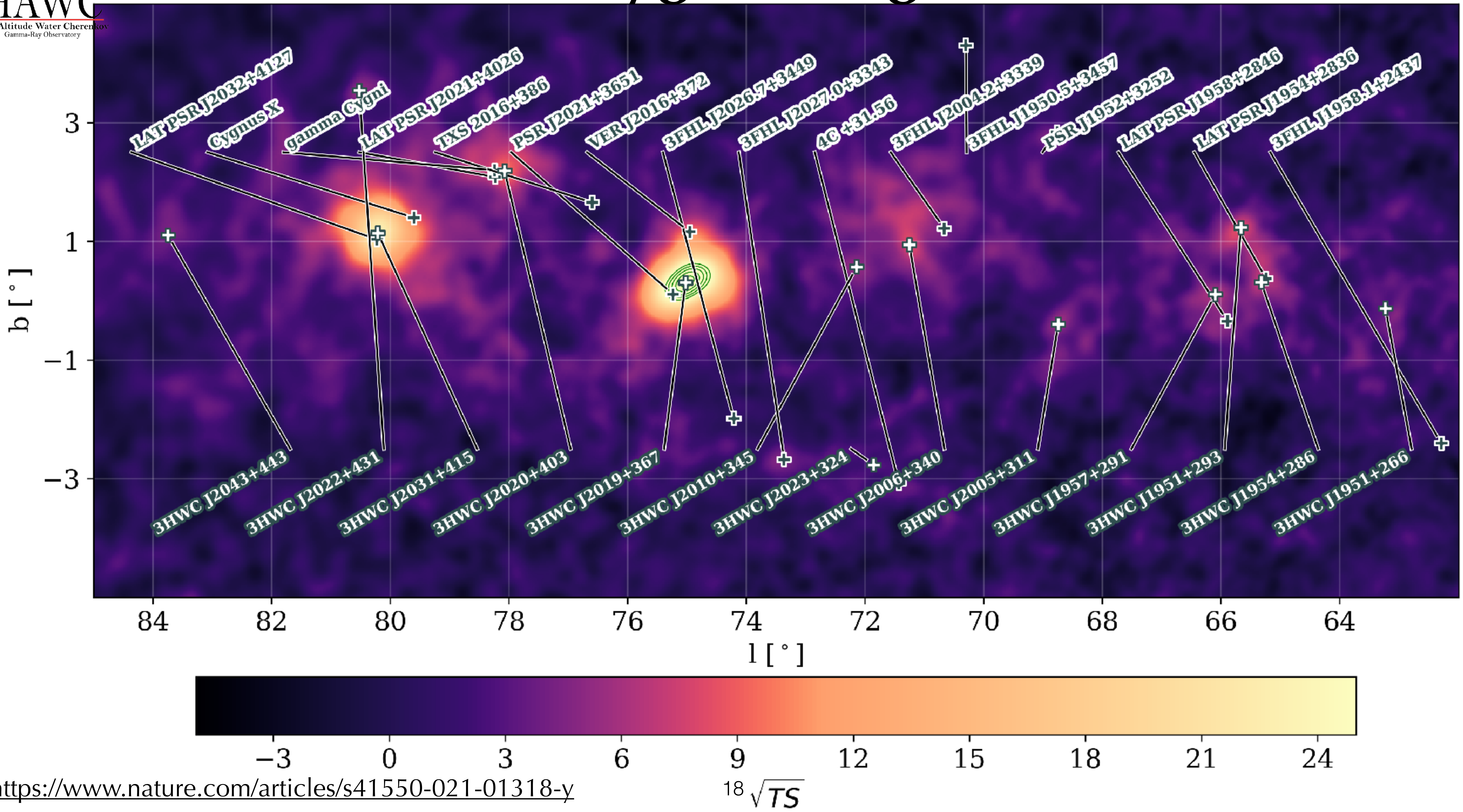
3HWC catalog, https://arxiv.org/abs/2007.08582

HAWC's Gamma-Ray Sky



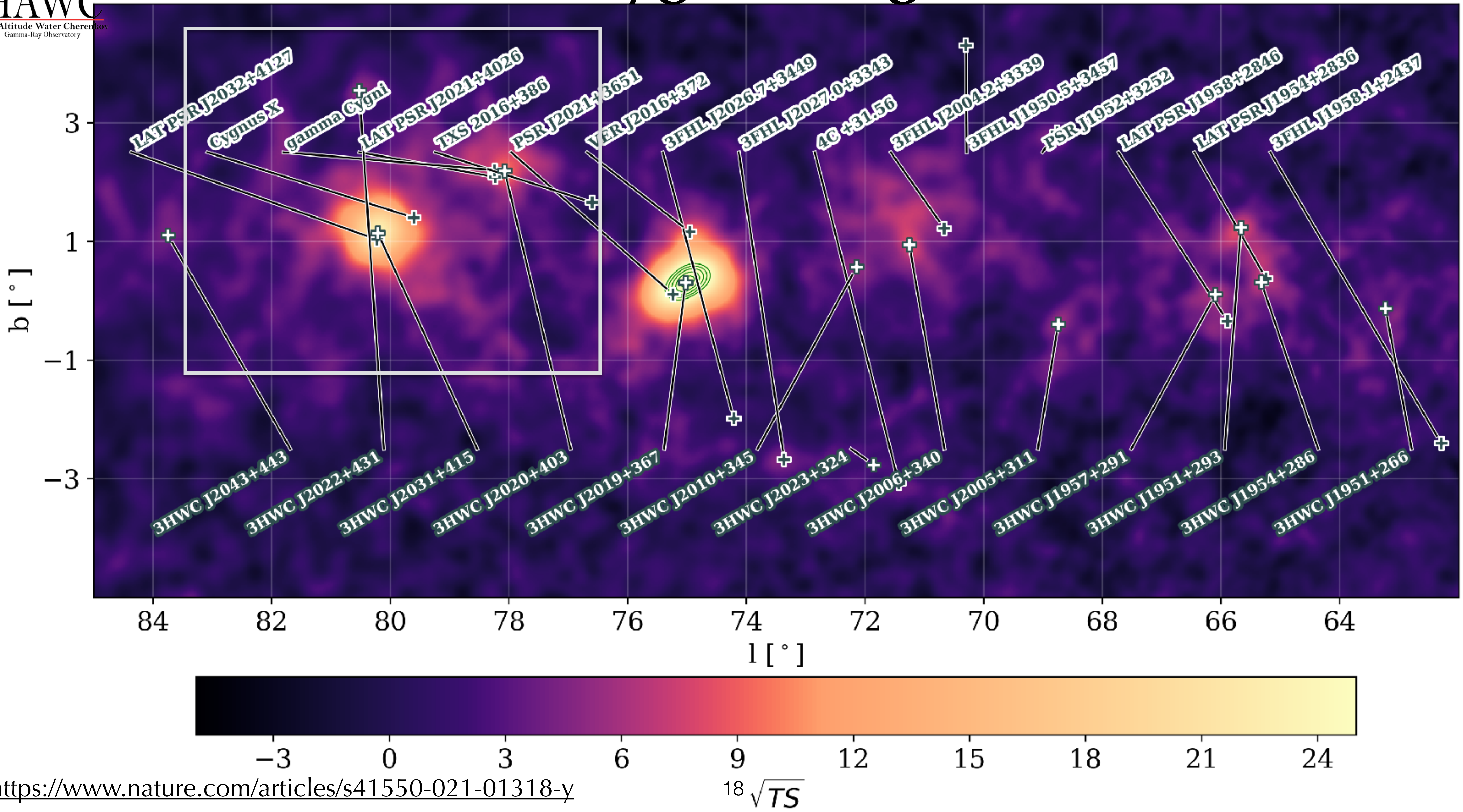
3HWC catalog, https://arxiv.org/abs/2007.08582

The Cygnus Region



https://www.nature.com/articles/s41550-021-01318-y

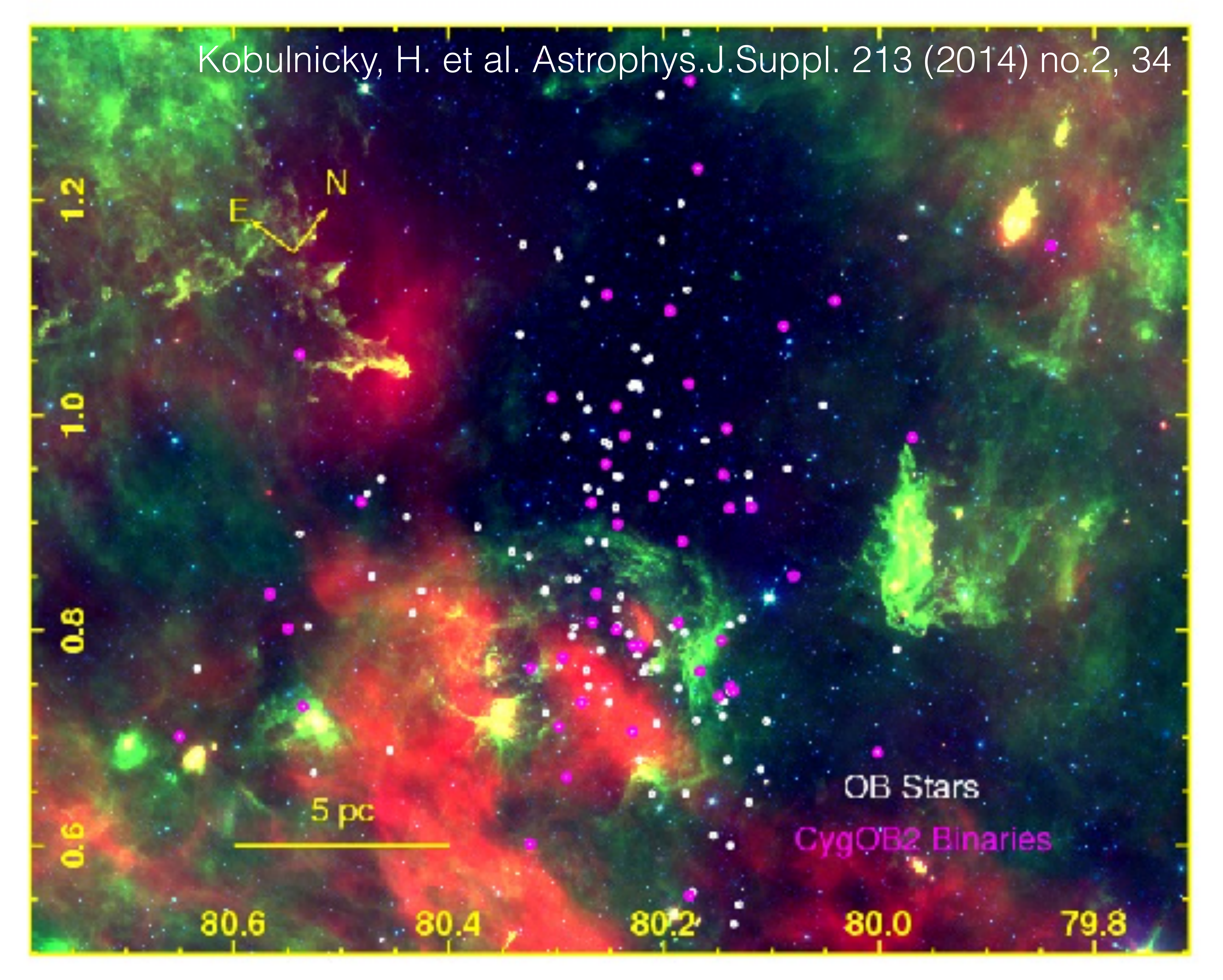
The Cygnus Region



https://www.nature.com/articles/s41550-021-01318-y

Cygnus OB2 Association

- OB association in the Cygnus region.
- 1400 pc from Earth.
- Few 10^6 years old.
- 50-100 O-type stars.
- ~50 binary systems.



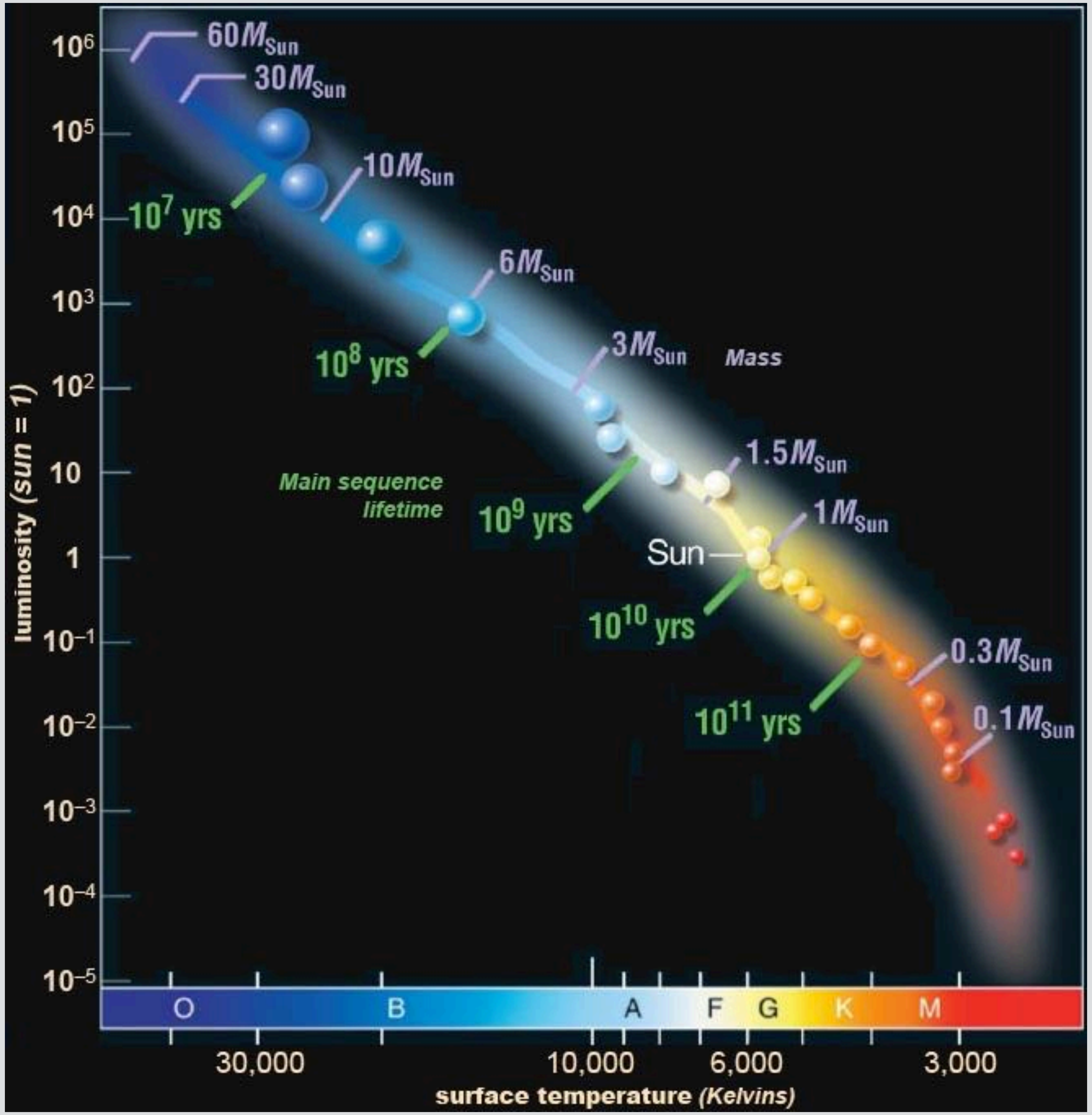
Particle Acceleration in Star-Forming Regions

Possible acceleration mechanisms:

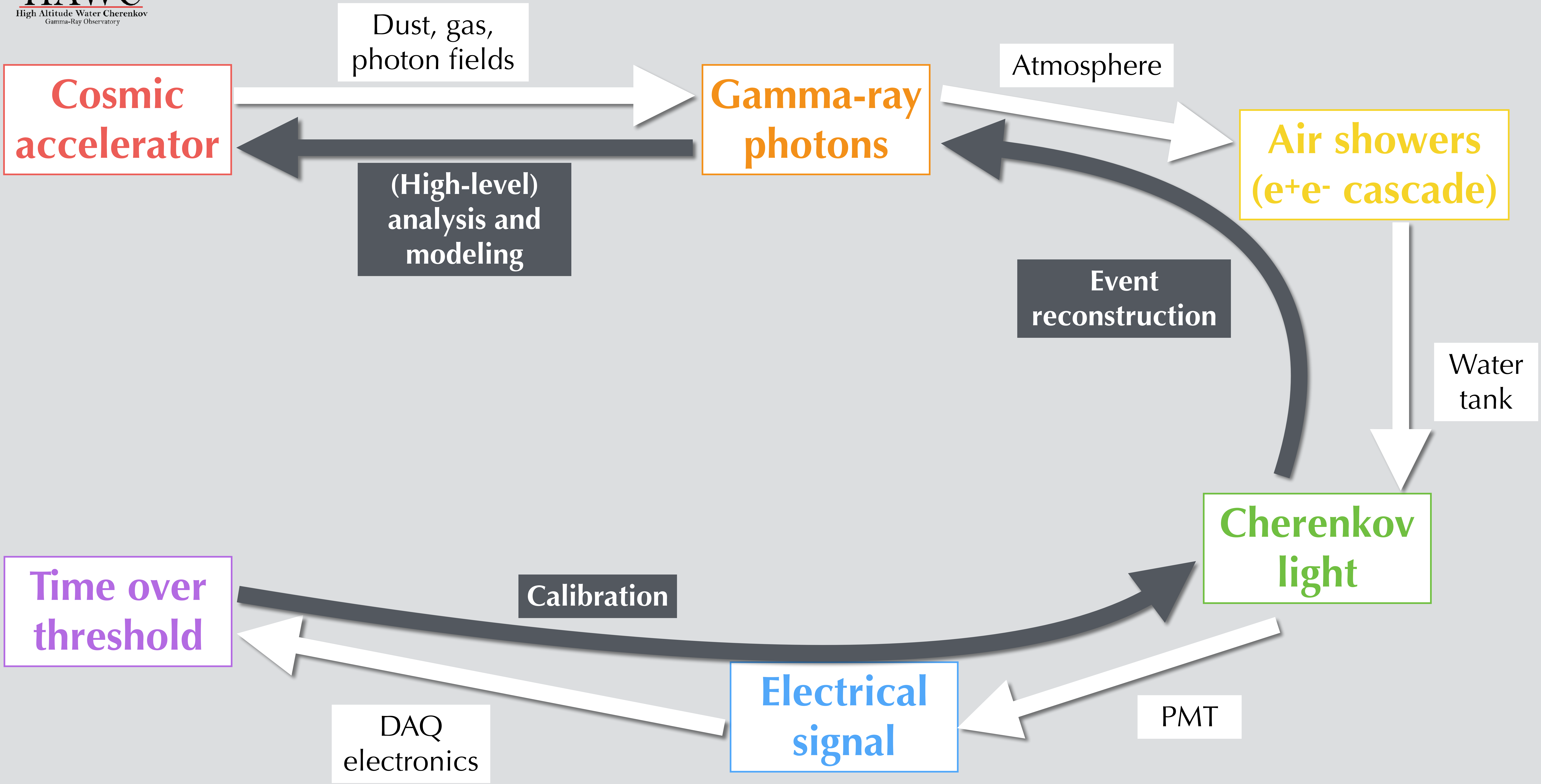
- Proto-planetary disks and their jets.
- **Collective effects of stellar winds.**
- **High-mass binary systems.**
- Supernova explosions/supernova remnants.

Significant sources of Galactic CRs?

Could they accelerate CRs up to the knee (PeV energies)?



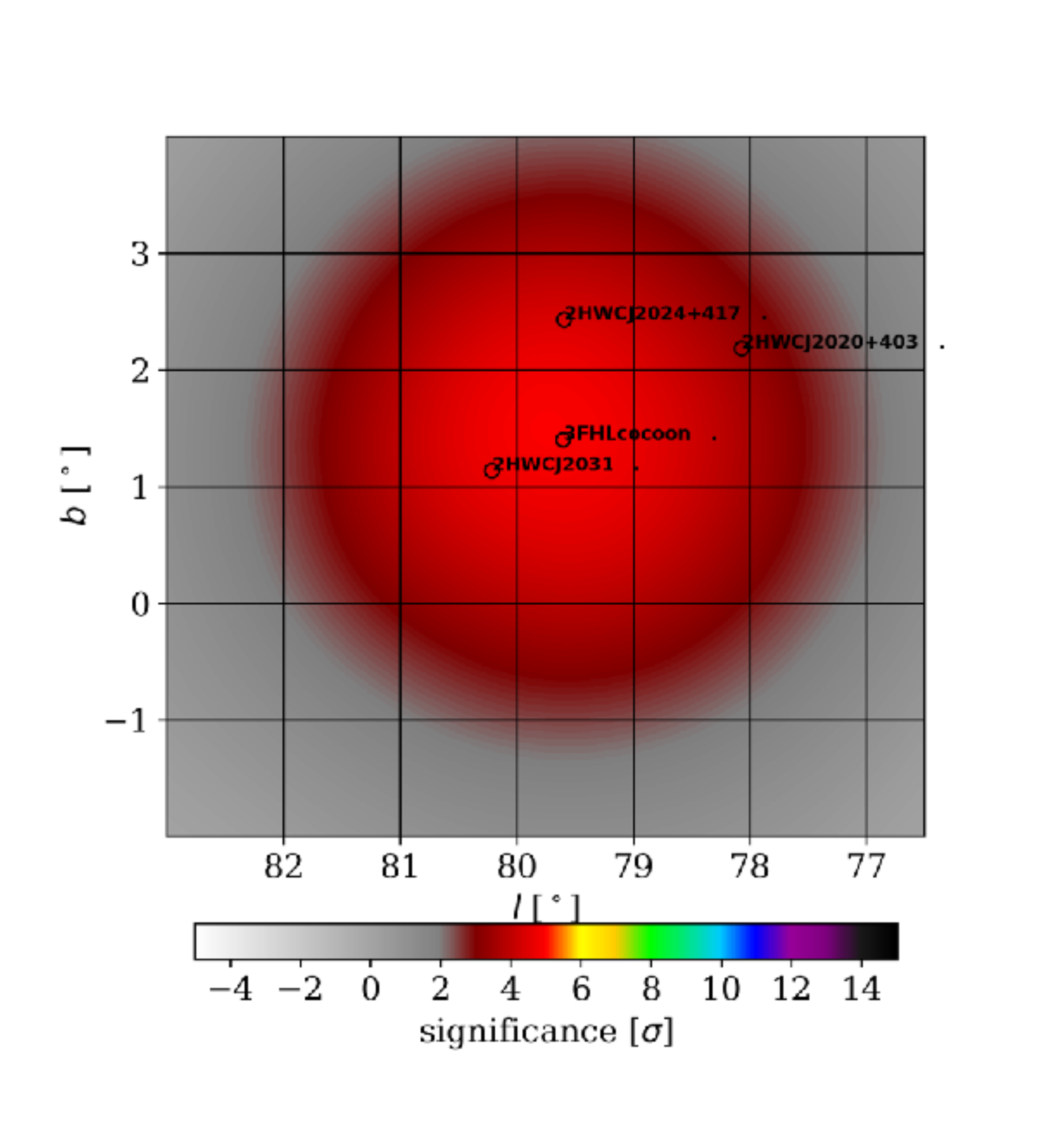
Gamma-Ray Astronomy with HAWC



Gamma-Ray Astronomy with HAWC

'Cygnus Cocoon'

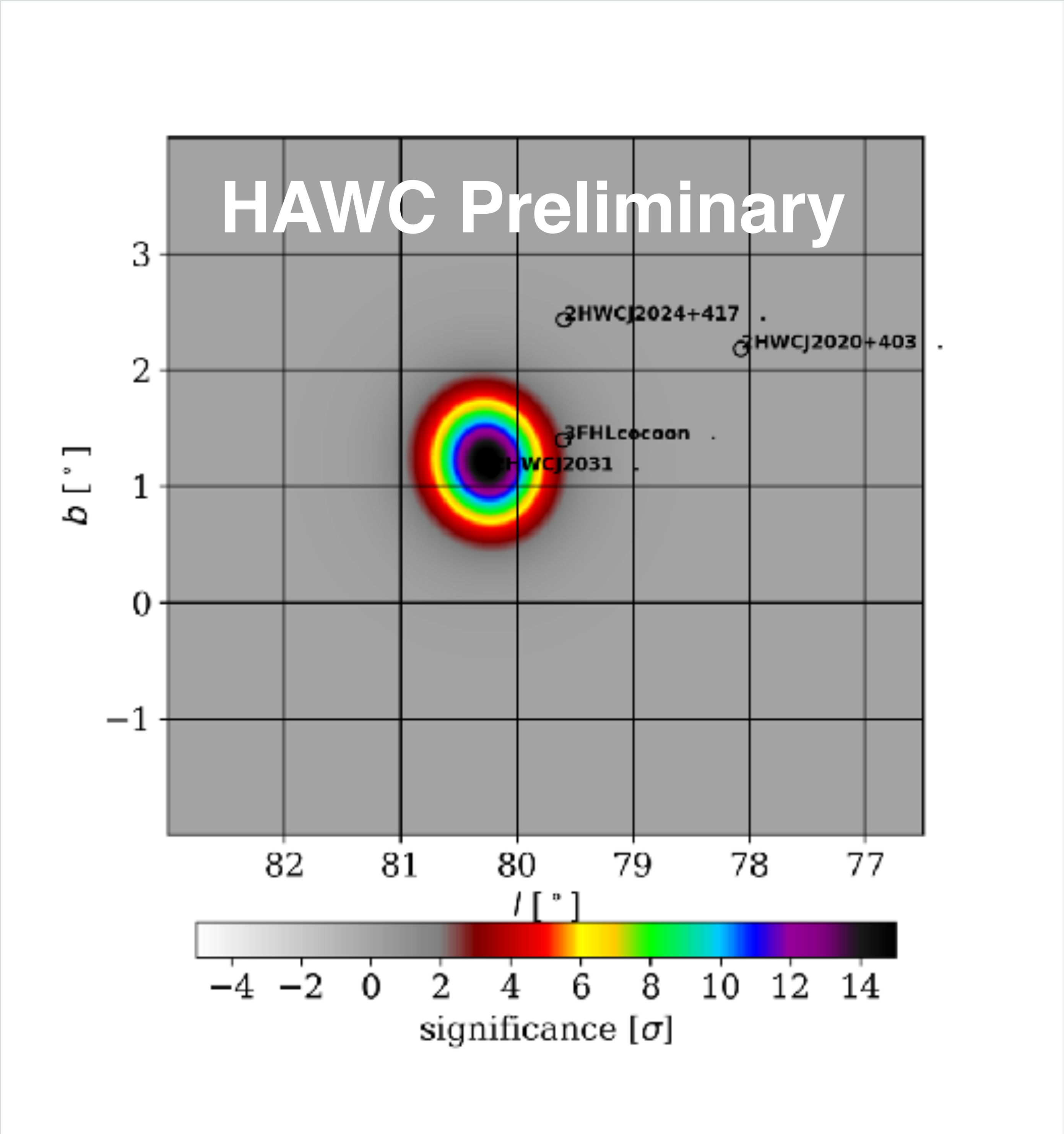
- Extended (50 pc) diffuse HE gamma-ray source (Ackermann et al., 2011, Science 334).
- 'Cocoon' of freshly accelerated CRs.
- Modeled as symmetric Gaussian source with power-law energy spectrum.



'TeV J2031+4130'

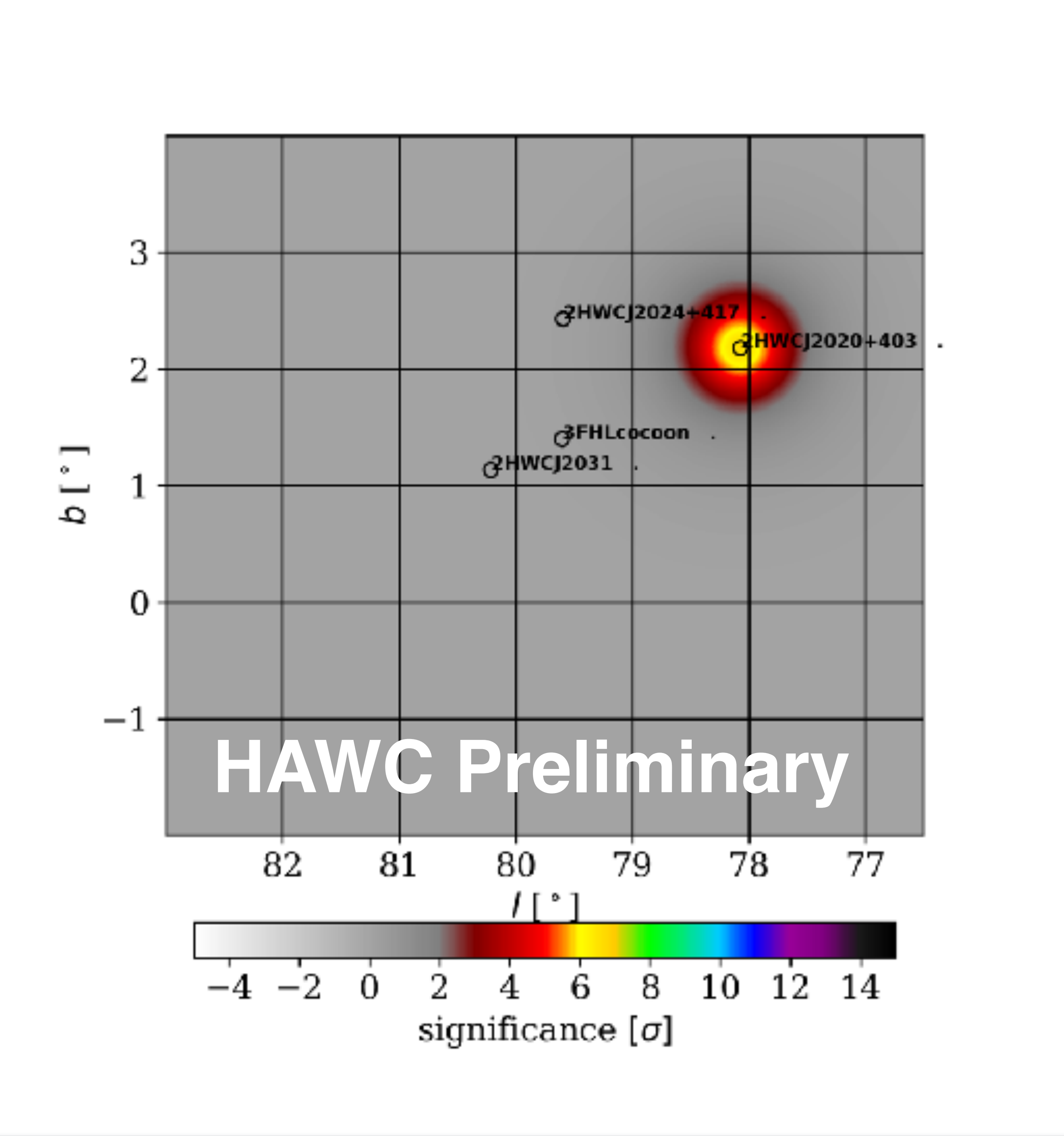
- Extended VHE gamma-ray source [E. Aliu et al. ApJ 783 (2014), R. Bird et at, ICRC 2017].
- Associated with PWN of PSR J2032+413
- Long-period binary system:
    - Period of 50 years (Ng et al, 2017).
    - Periastron in November 2017 [ICRC 2019/https://arxiv.org/abs/1908.04165].
- Modeled as Gaussian source, power-law energy spectrum with exponential cutoff.

HAWC not sensitive to periastron enhancement

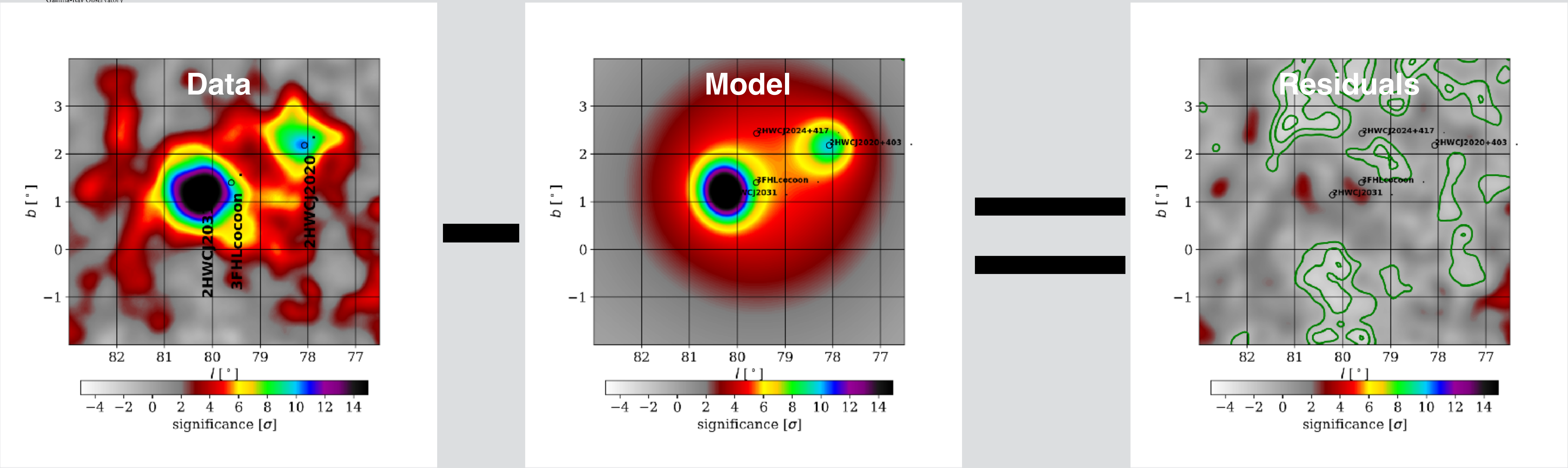


'Gamma Cygni SNR'

- Extended (0.1˚) VHE gamma-ray source [E. Aliu et al., ApJ 770 (2013) 93].
- Additional extended (0.6˚) disk component (Strysz et al., ICRC 2017).
- SNR G78.2+2.1 of PSR J2021+4026
- HAWC sees the extended disk detected by MAGIC.
- Modeled as disk, power-law energy spectrum.



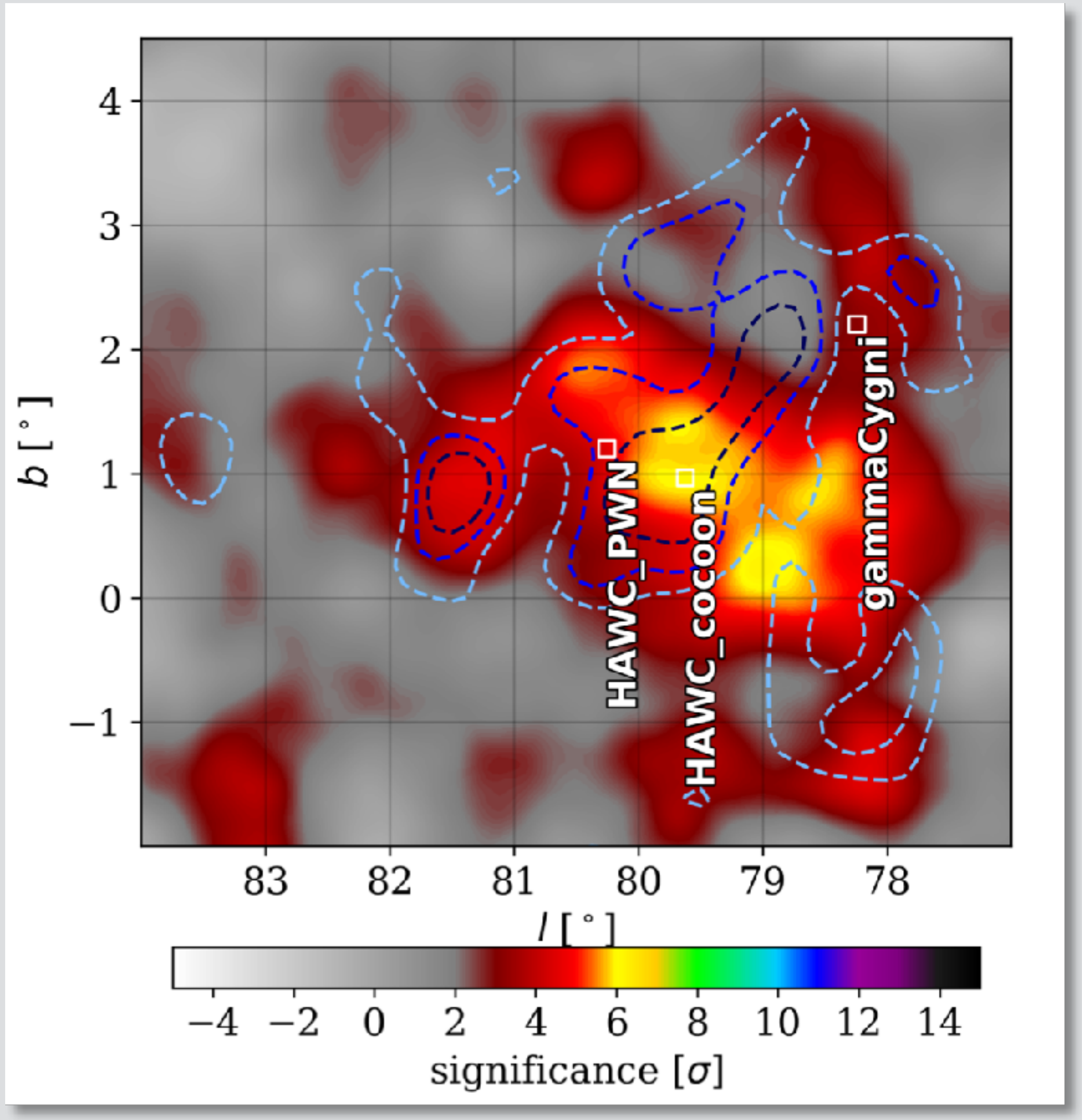
Combined Model



- Combined model describes region reasonably well.

Cocoon Morphology

- Map on the left has PWN and gamma Cygni subtracted.
- Blue contours are Fermi-LAT counts.
- HAWC Morphology matches what was seen at GeV energies.



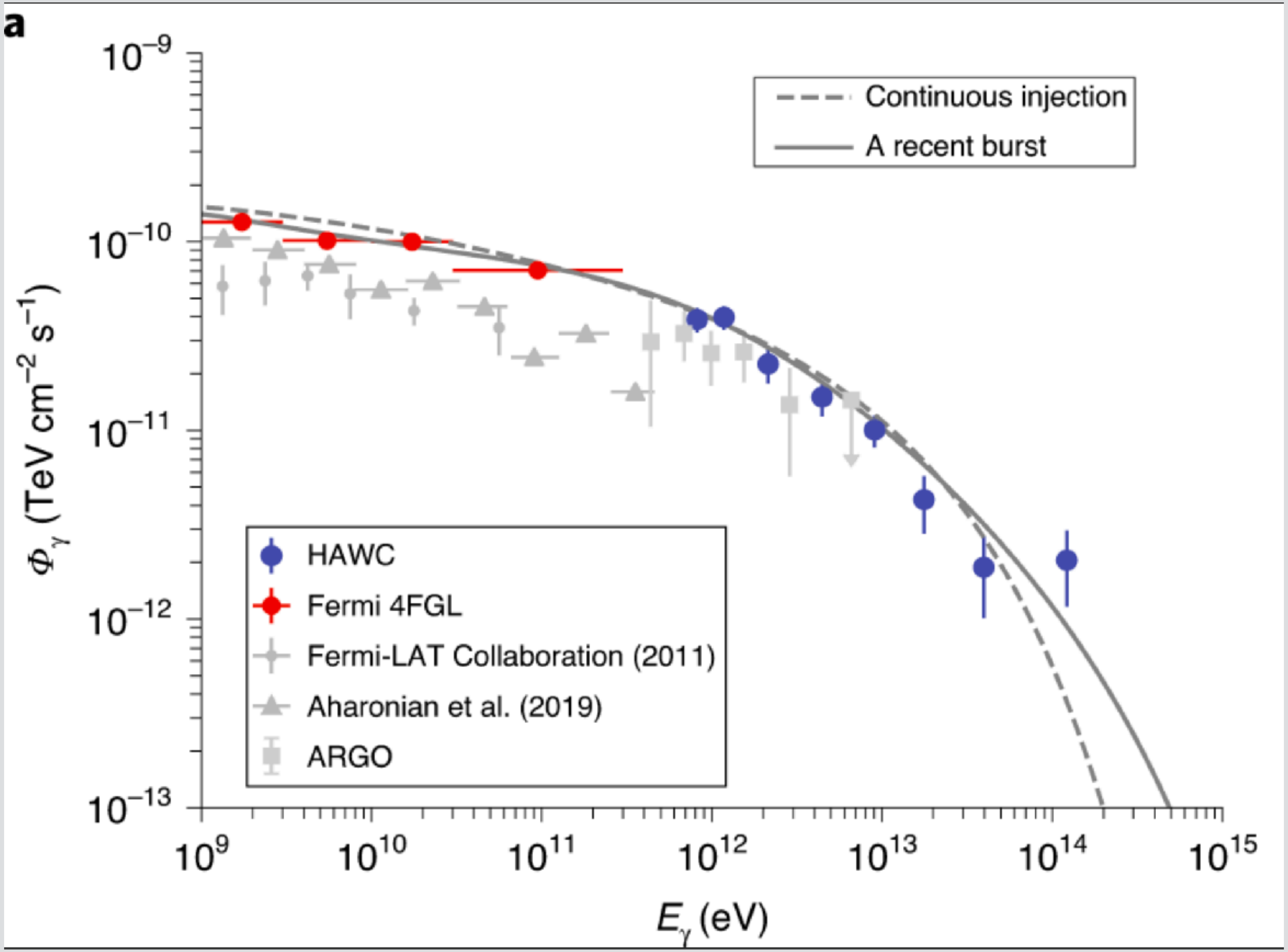
Energy Spectrum

Two hadronic models can explain gamma-ray emission:

- Continuous proton acceleration over a long time
- "Recent" enhancement in acceleration efficiency due to starburst activity.

Protons with energies of >100 TeV must be present to produce the observed gamma-ray emission.

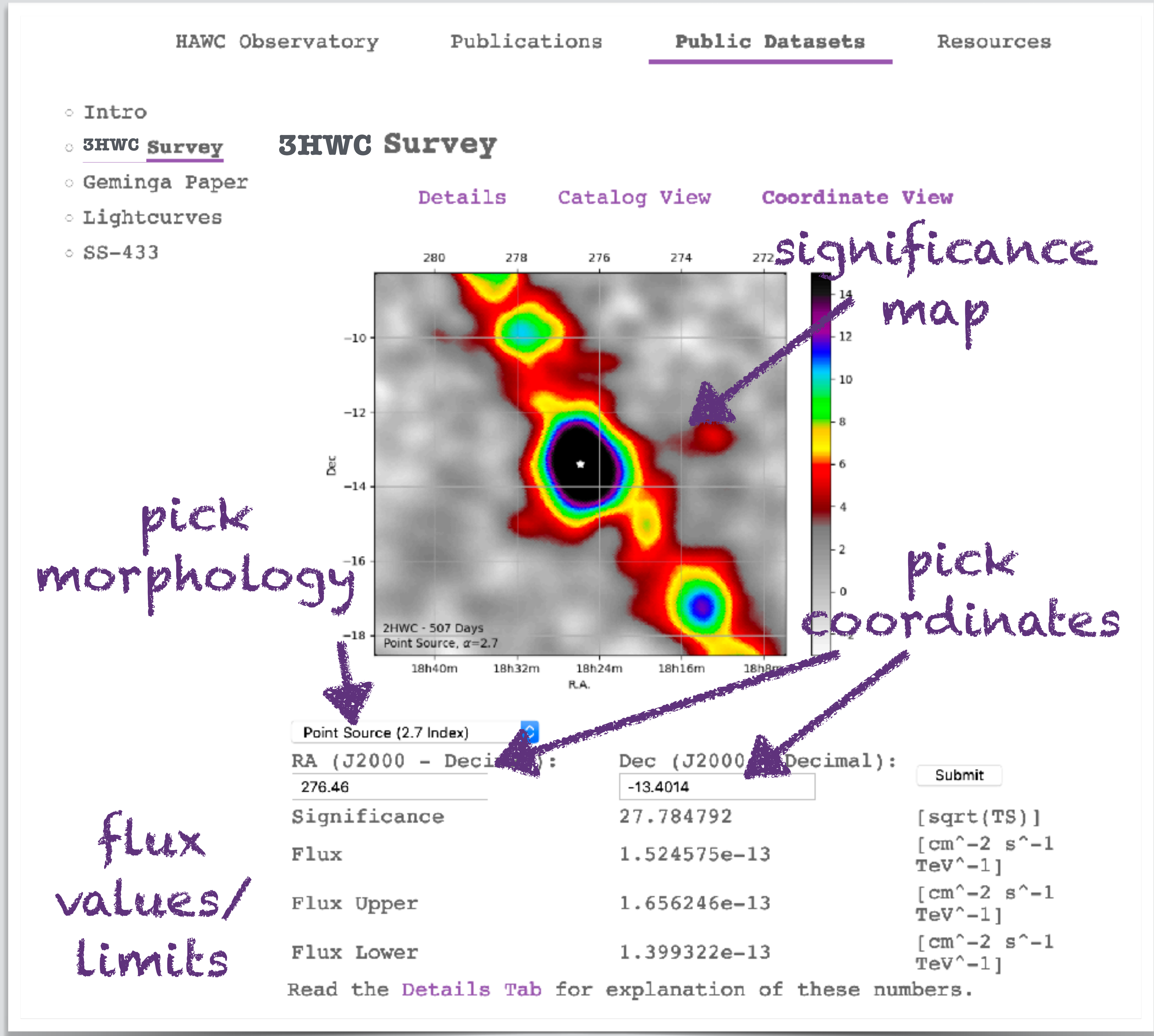
About **1% of the kinetic energy in stellar winds** is converted to relativistic protons.



HAWC Data Access

data.hawc-observatory.org

- High-level data:
  - 3HWC survey maps
  - Mrk 421/Mrk 501 light curves
- Intermediate-level data (count maps)
- Contact the spokespeople:
  - Petra Huentemeyer (petra@mtu.edu)
  - Andres Sandoval (asandoval@fisica.unam.mx)
- Self-triggered burst alerts in GCN/AMON

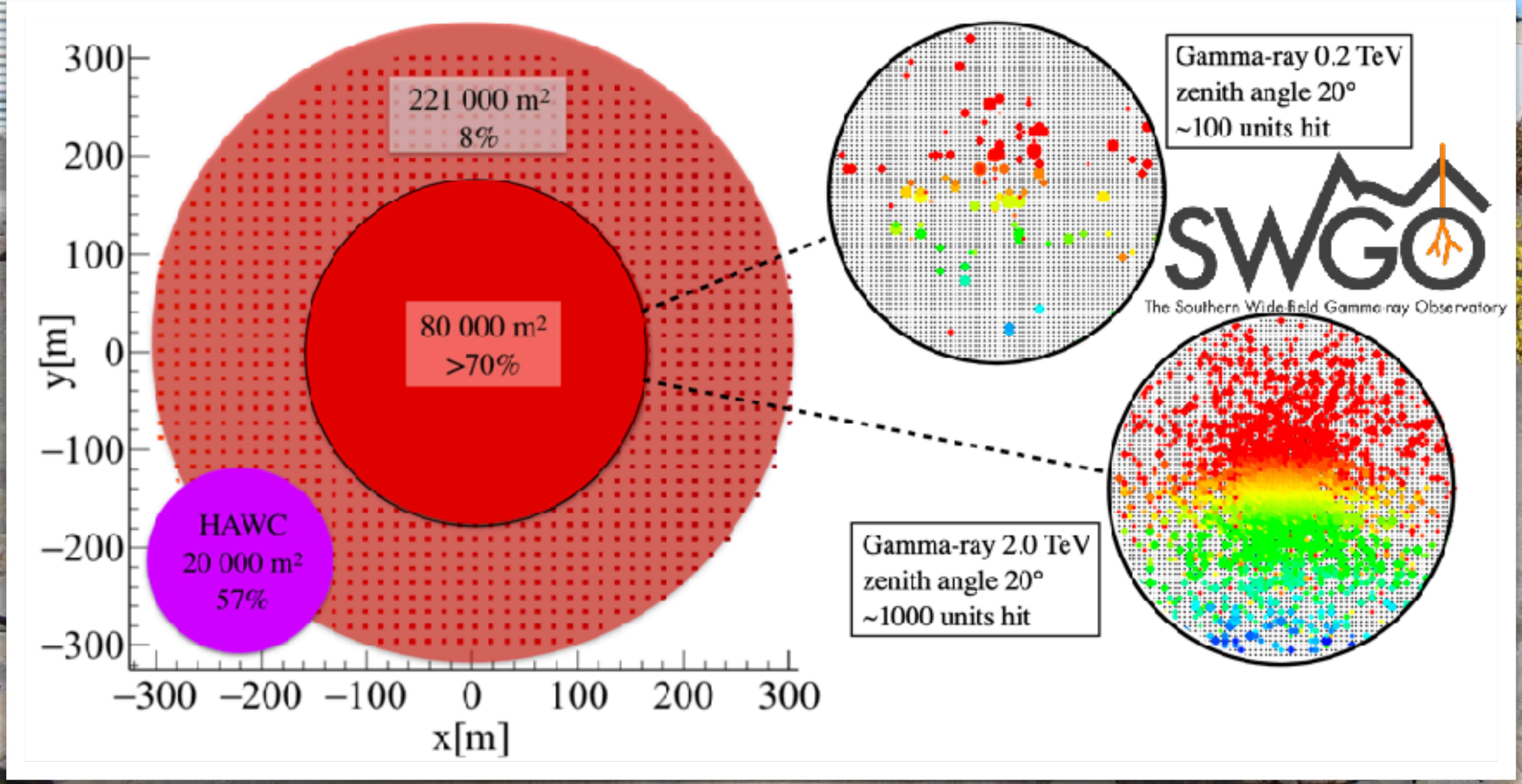


What's next?

- In ground-based gamma-ray astronomy?
- For me?

What's next?

- In ground-based gamma-ray astronomy?
- For me?



HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

What's next?

- In ground-based gamma-ray astronomy?
- For me?

What's next?

- In ground-based gamma-ray astronomy?
- For me?

The X-ray sky (~keV)

https://www.mpe.mpg.de/7461950/erass1-presskit

The ɣ-ray sky >1GeV

NASA GSFC/Fermi-LAT collaboration

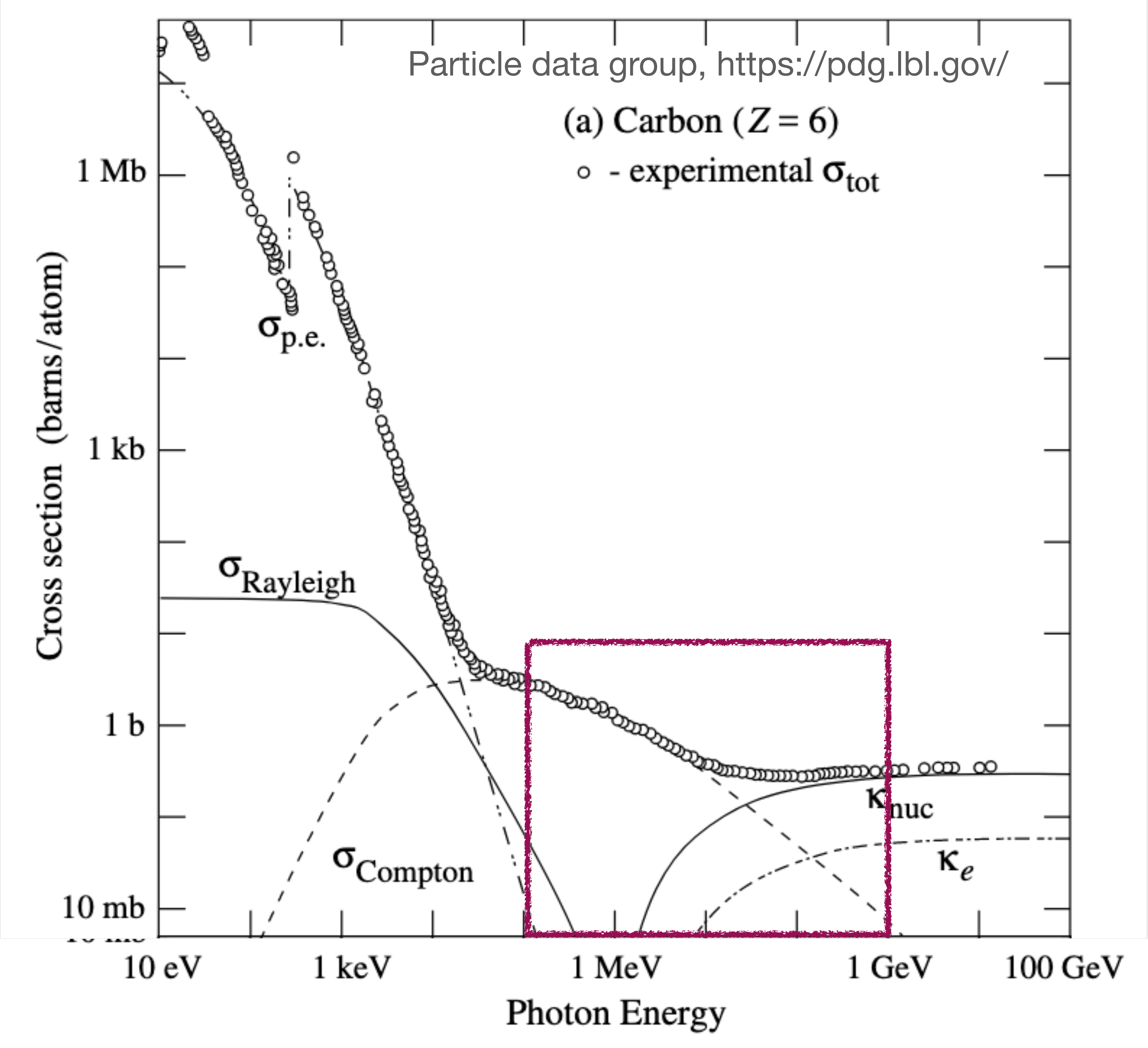
https://svs.gsfc.nasa.gov/vis/a010000/a011300/a011342/

The ɣ-ray sky (1-30 MeV)

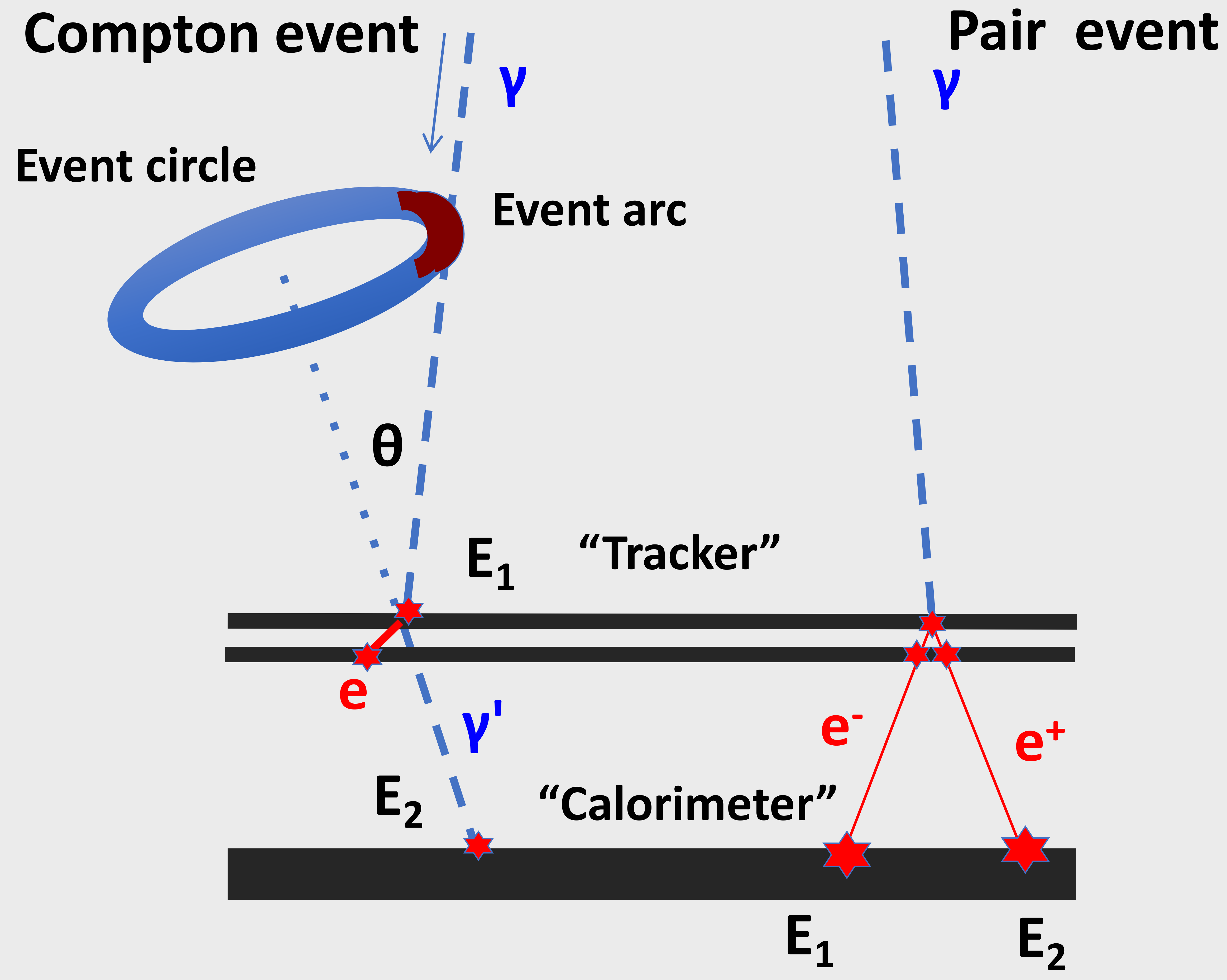
COMPTEL team/MPE, 2006

https://science.nasa.gov/science-news/science-at-nasa/compton_ast

MeV γ-ray Detection



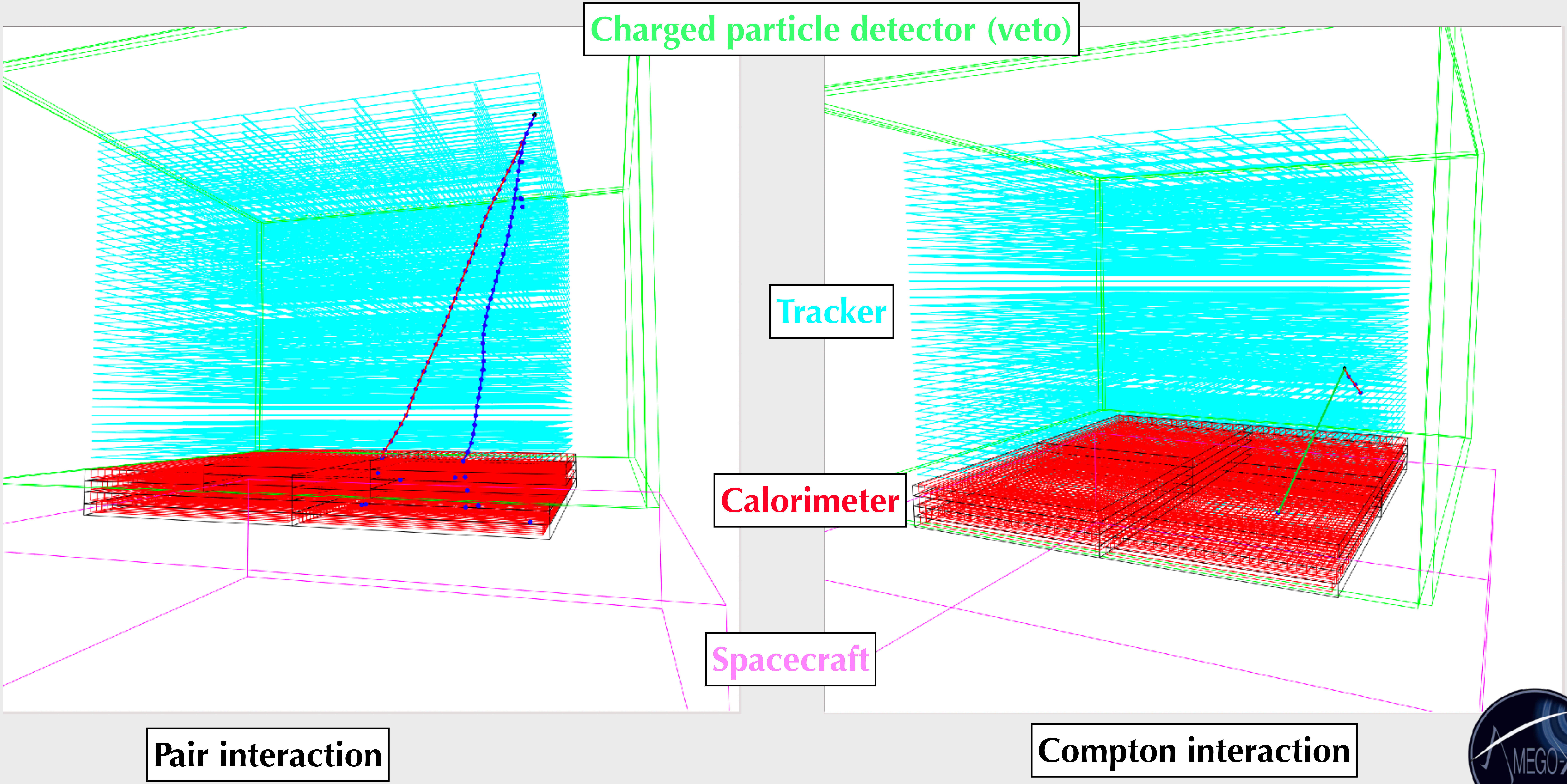
$\sigma_{p.e.}$ = Atomic photoelectric effect (electron ejection, photon absorption)
$\sigma_{Rayleigh}$ = Rayleigh (coherent) scattering–atom neither ionized nor excited
$\sigma_{Compton}$ = Incoherent scattering (Compton scattering off an electron)
κ_{nuc} = Pair production, nuclear field
κ_e = Pair production, electron field



Compton scattering angle:

$$\cos(\theta) = 1 - \frac{m_e c^2}{E_2} - \frac{m_e c^2}{E_1 + E_2}$$

The AMEGO-X Instrument



AMEGO-X: Our Eyes on the Gamma-Ray Sky

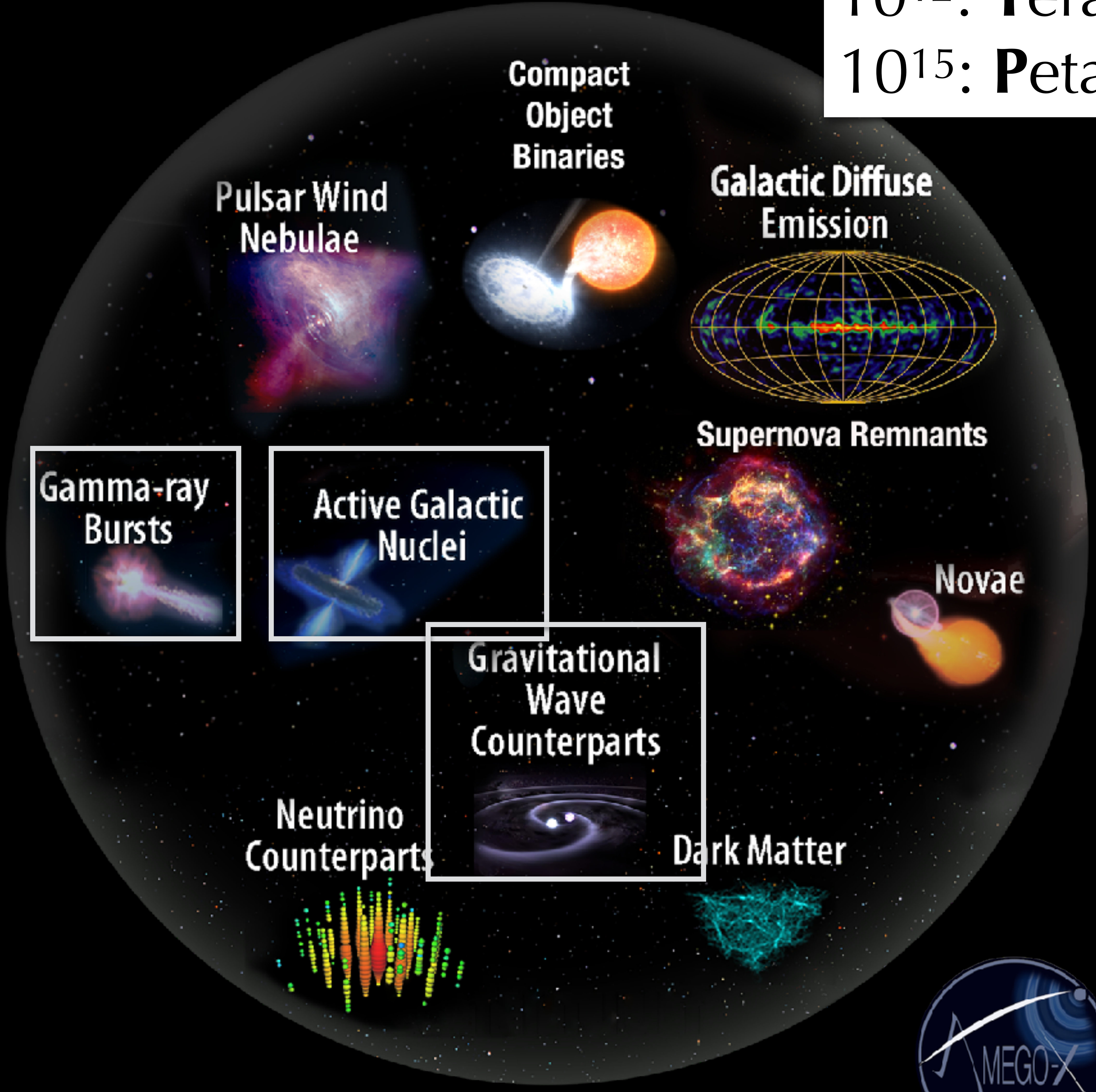
10^6: Mega
10^9: Giga
10^{12}: Tera
10^{15}: Peta

- MIDEX-sized mission concept.
- Silicon "pixel" tracker and CsI scintillator calorimeter.
- Energy range: 100 keV to 1 GeV.
- Multi-messenger astronomy.

AMEGO-X: Our Eyes on the Gamma-Ray Sky

10^6: **M**ega
10^9: **G**iga
10^{12}: **T**era
10^{15}: **P**eta

- MIDEX-sized mission concept.
- Silicon "pixel" tracker and CsI scintillator calorimeter.
- Energy range: 100 keV to 1 GeV.
- Multi-messenger astronomy.



Multi-Messenger Astronomy with AMEGO-X

Image: M. Negro