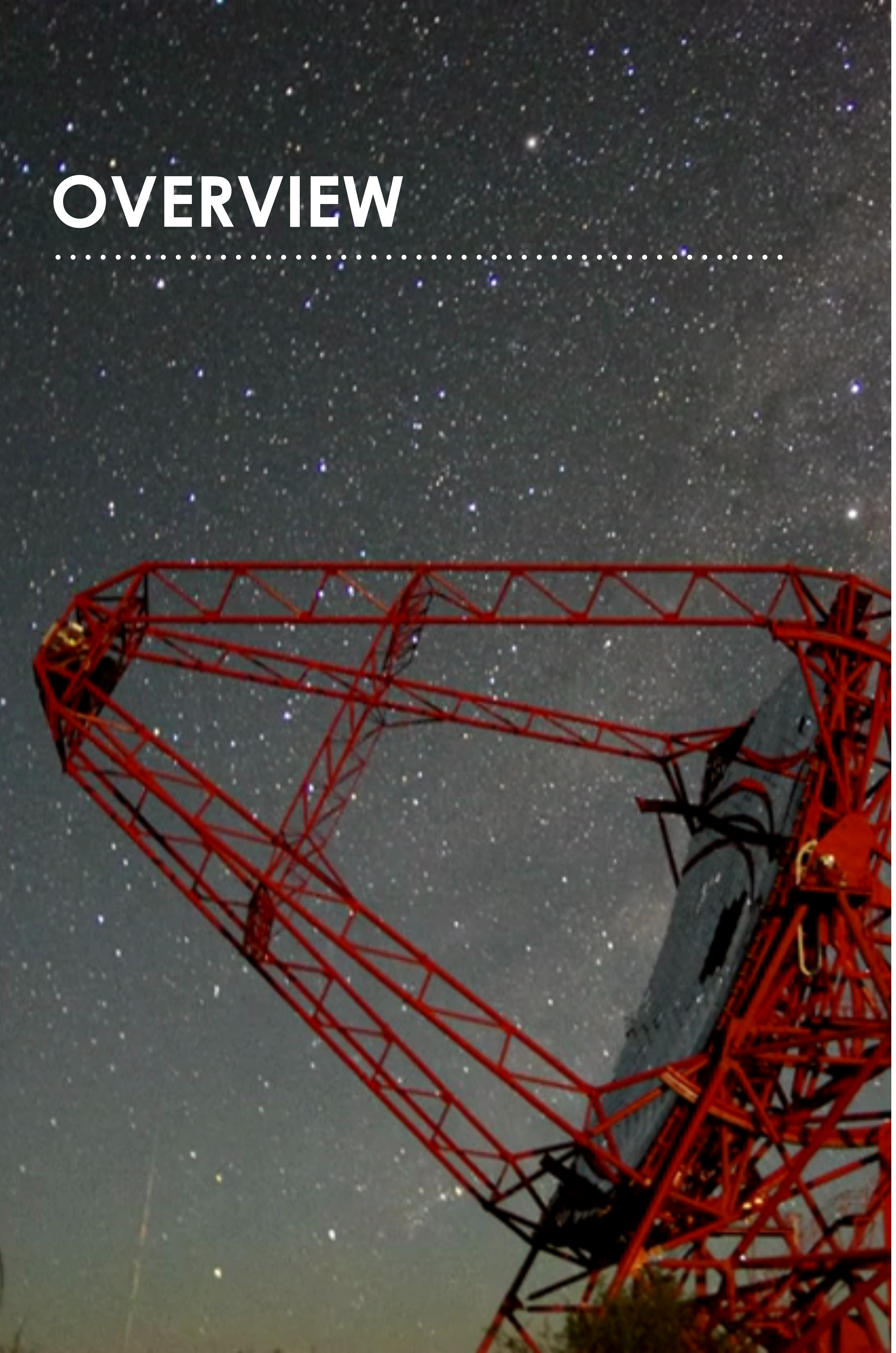
Gamma Rays
(and Cosmic Explosions)

Karl Kosack
CEA Saclay / CTA Observatory

Cosmic Explosions 2019 - Cargèse



Introduction

Medium Energy Gamma Rays

- detection
- science
- future

High-Energy Gamma Rays

- detection
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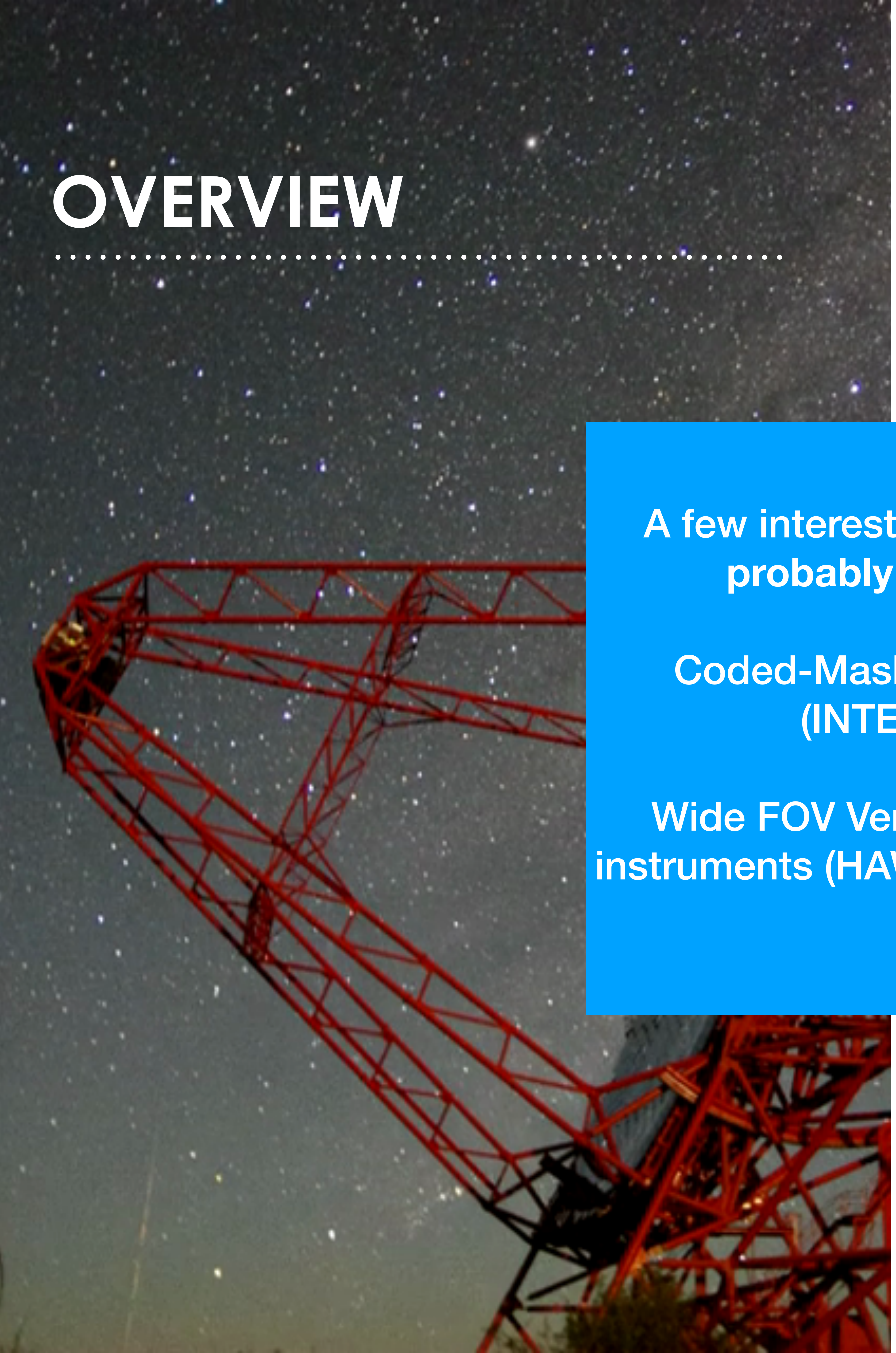
Very High Energy Gamma Rays

- detection
- science
- future

Summary and Outlook

OVERVIEW



A few interesting things I will **probably not cover:**

Coded-Mask Instruments (INTEGRAL)

Wide FOV Very High-Energy instruments (HAWC/ARGO/SGSO)

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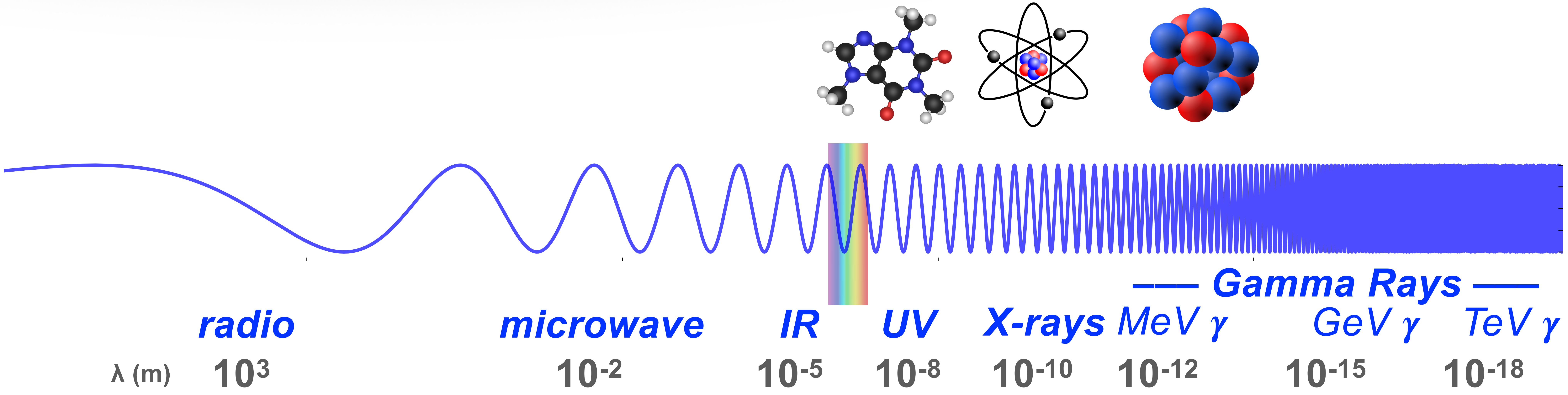
Gamma Rays: definitions



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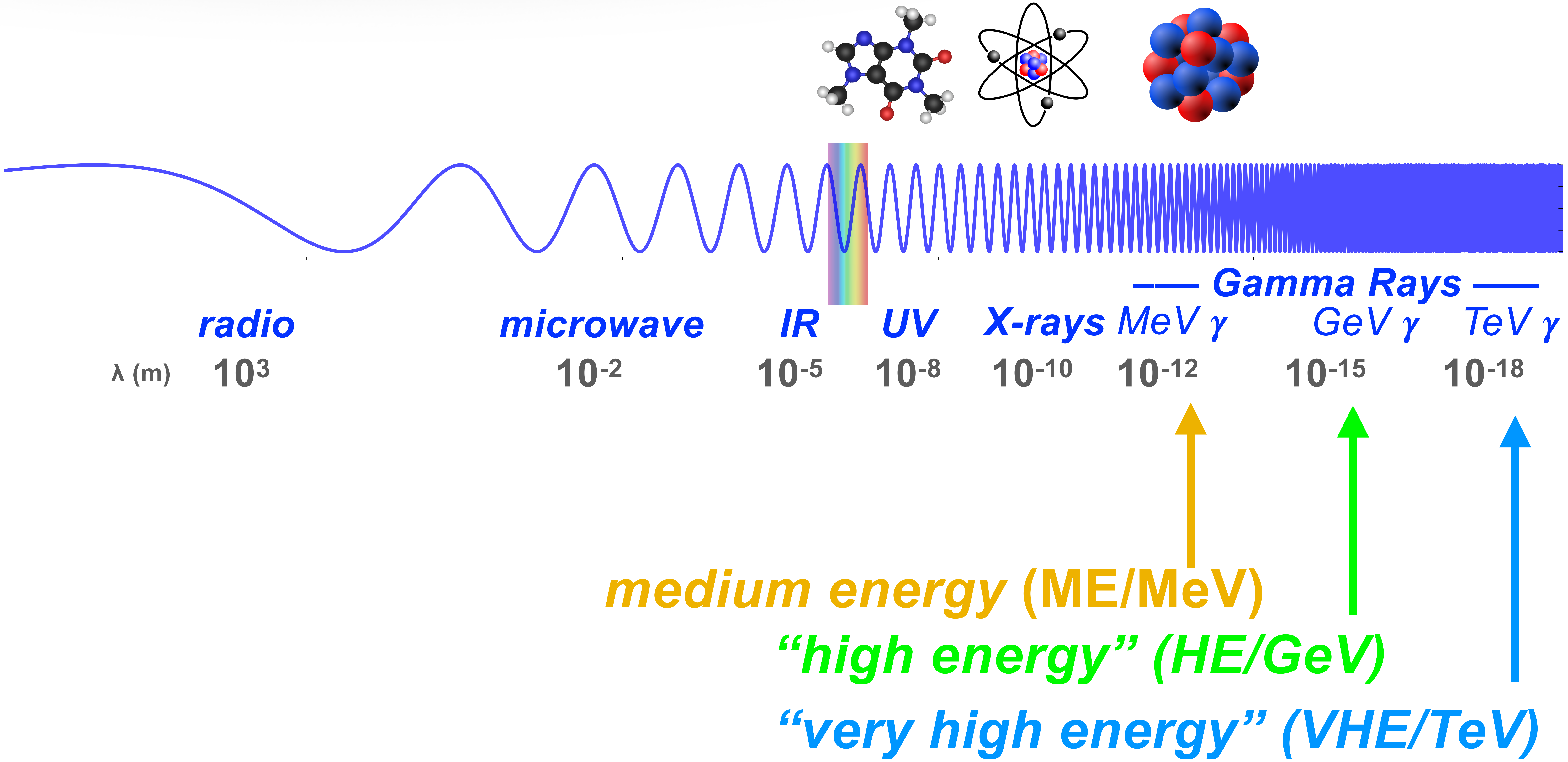
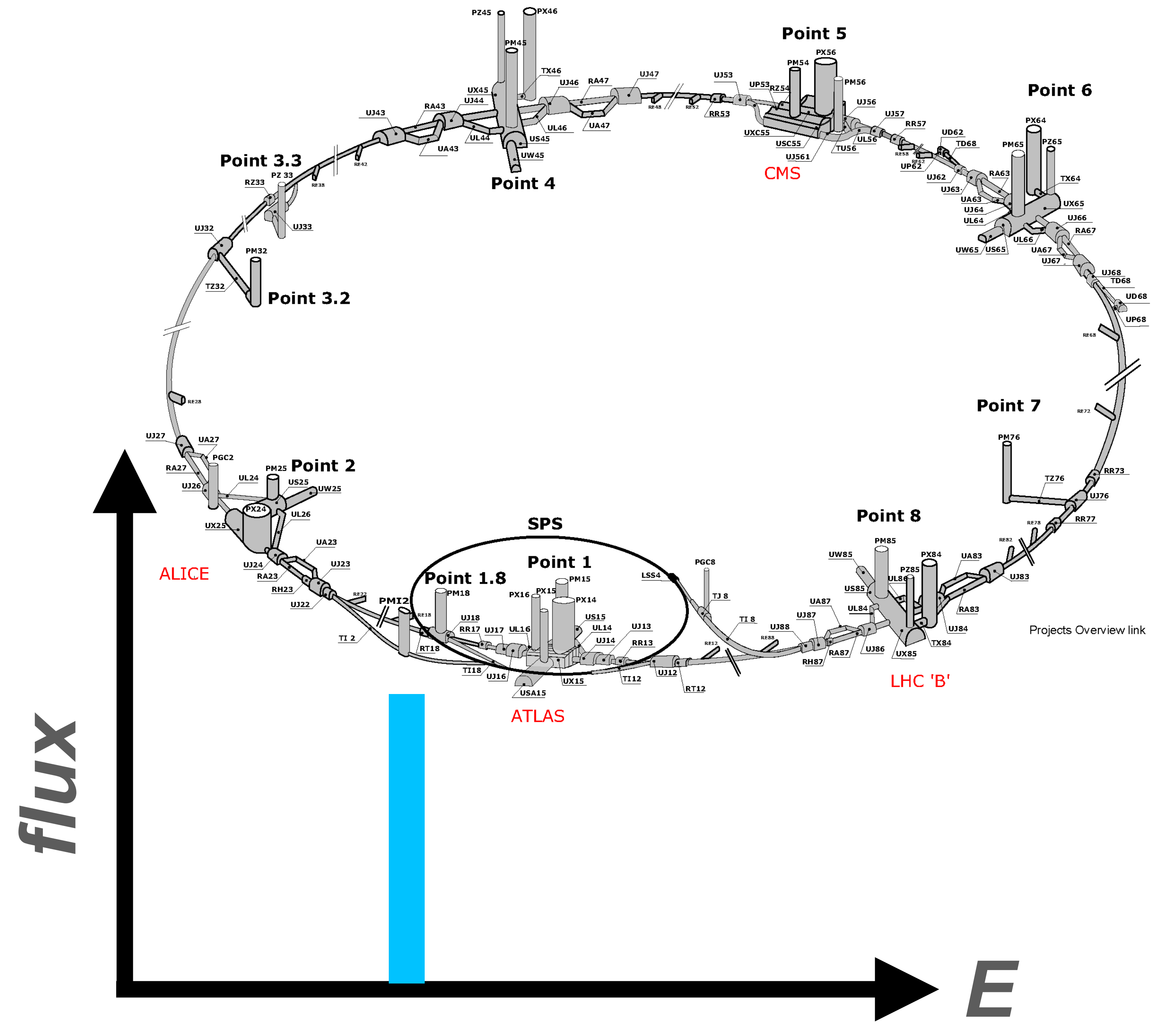


Gamma-rays come from Non-Thermal Emission

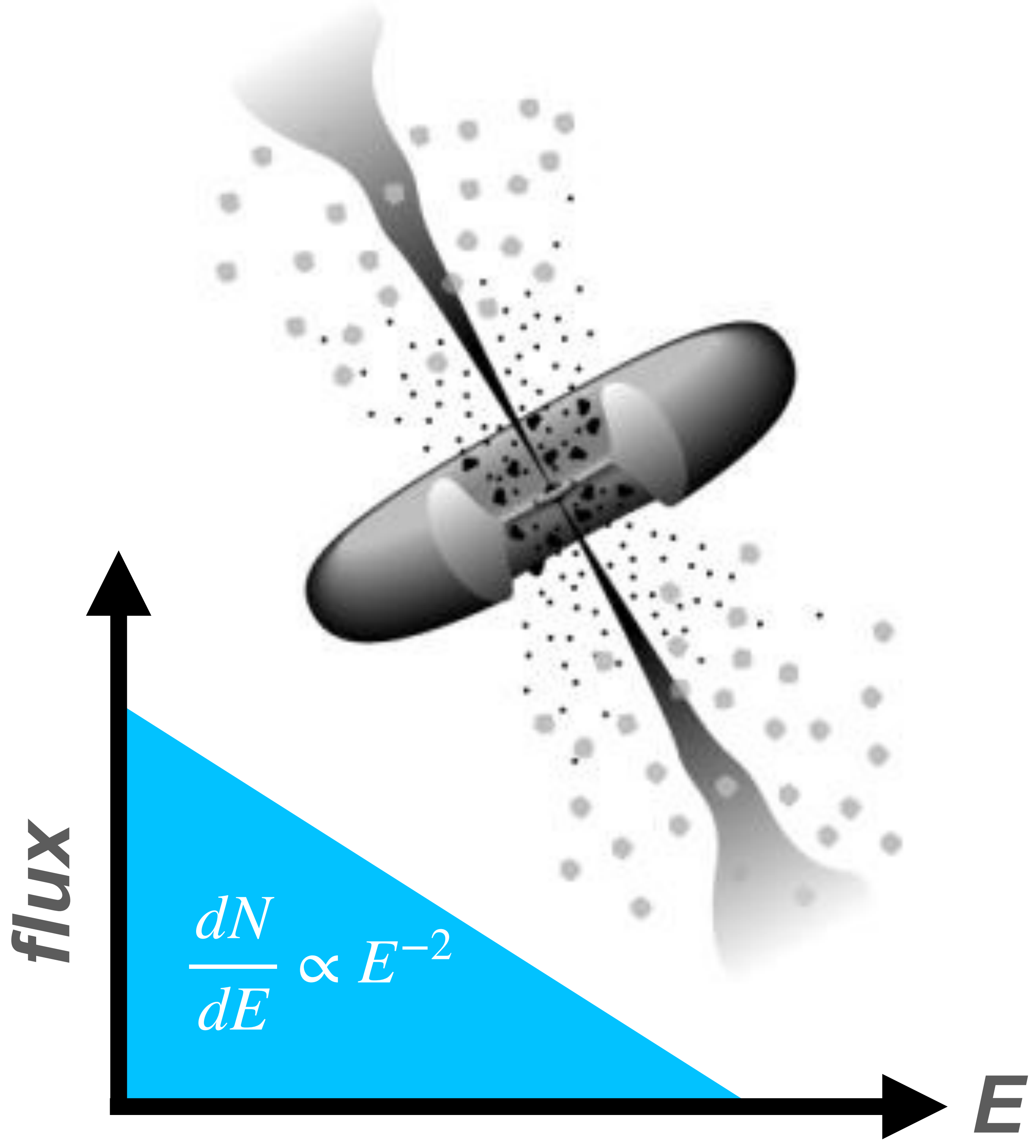
Particle Acceleration

Human-made Particle Accelerators



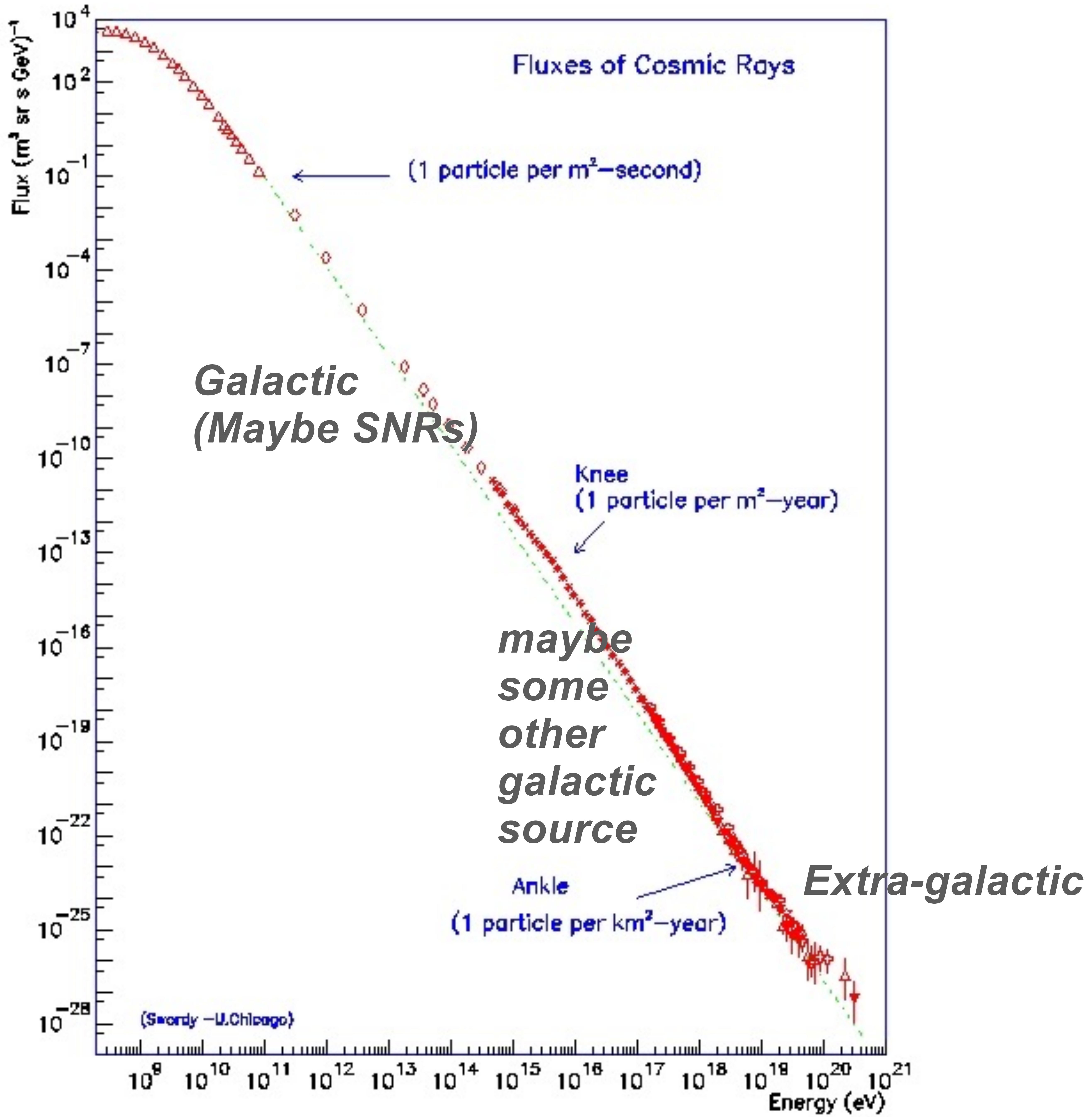
series of radio-frequency cavities

Astrophysical Particle Accelerators



diffusive shock acceleration

Gamma-rays show the *sites* of cosmic-ray acceleration

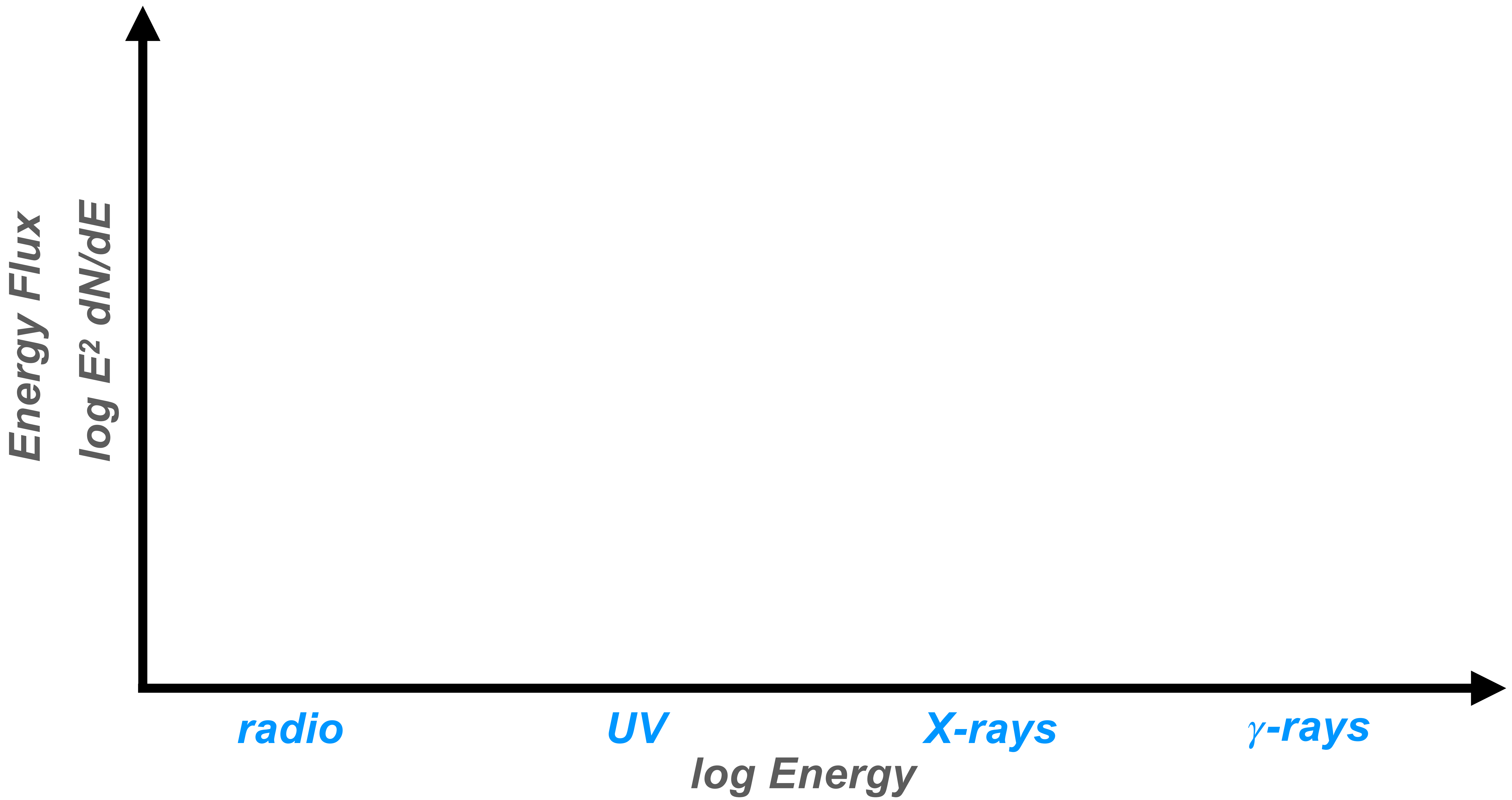


Non-Thermal Emission

What radiation do you get from a power-law of particles?

Spectral Energy Distribution for various processes:

Electron population **Hadron Population**



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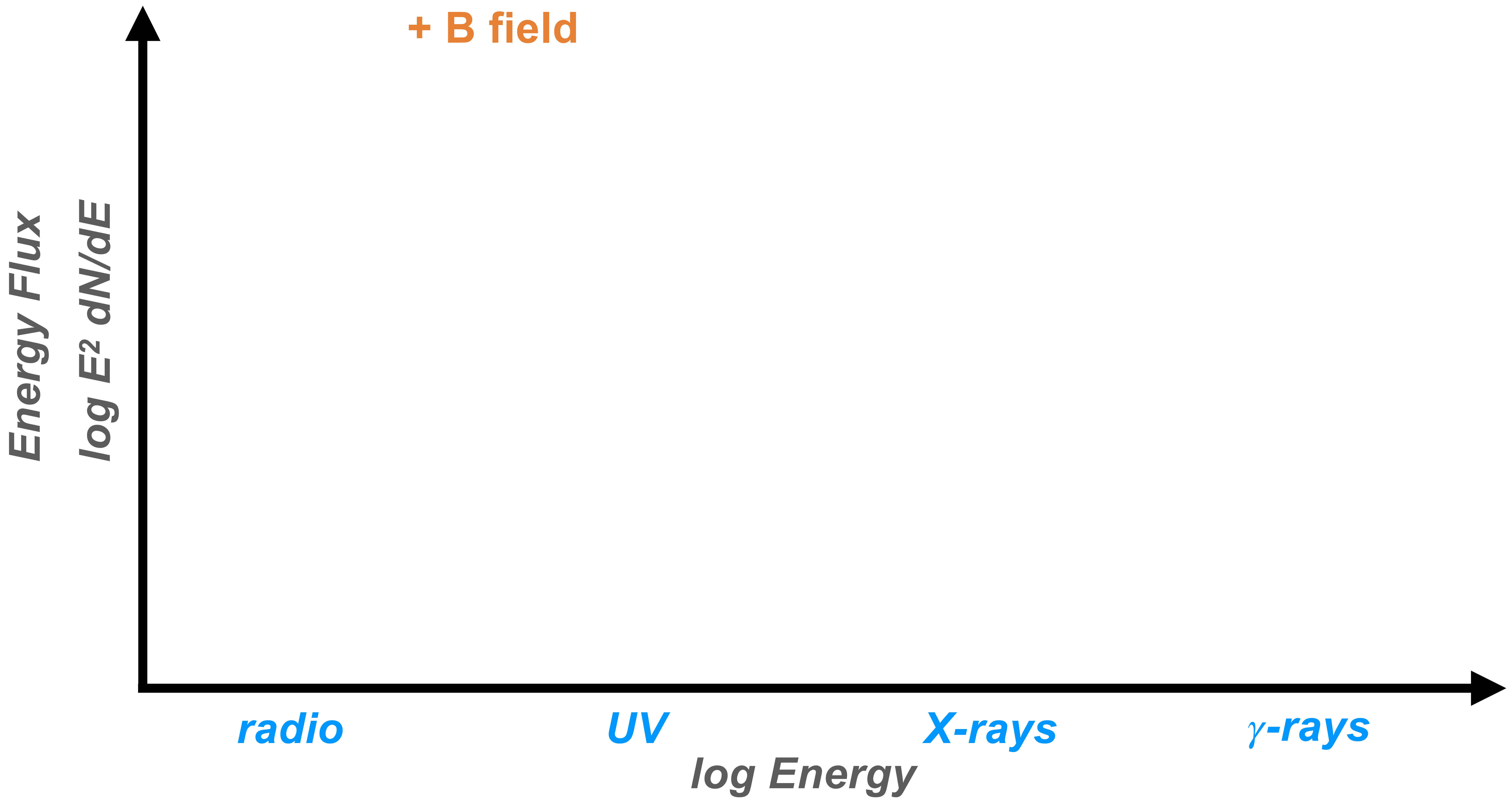

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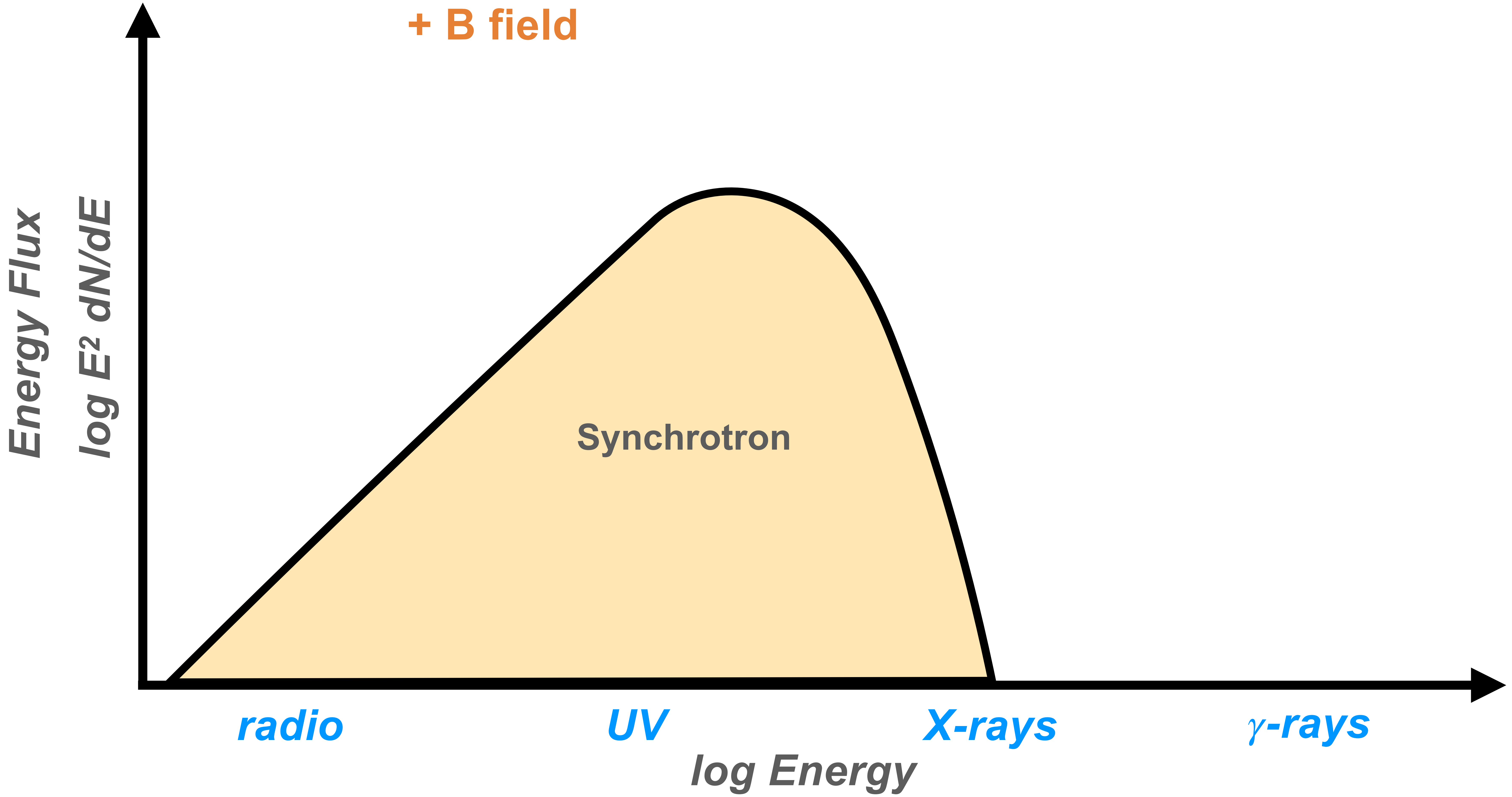

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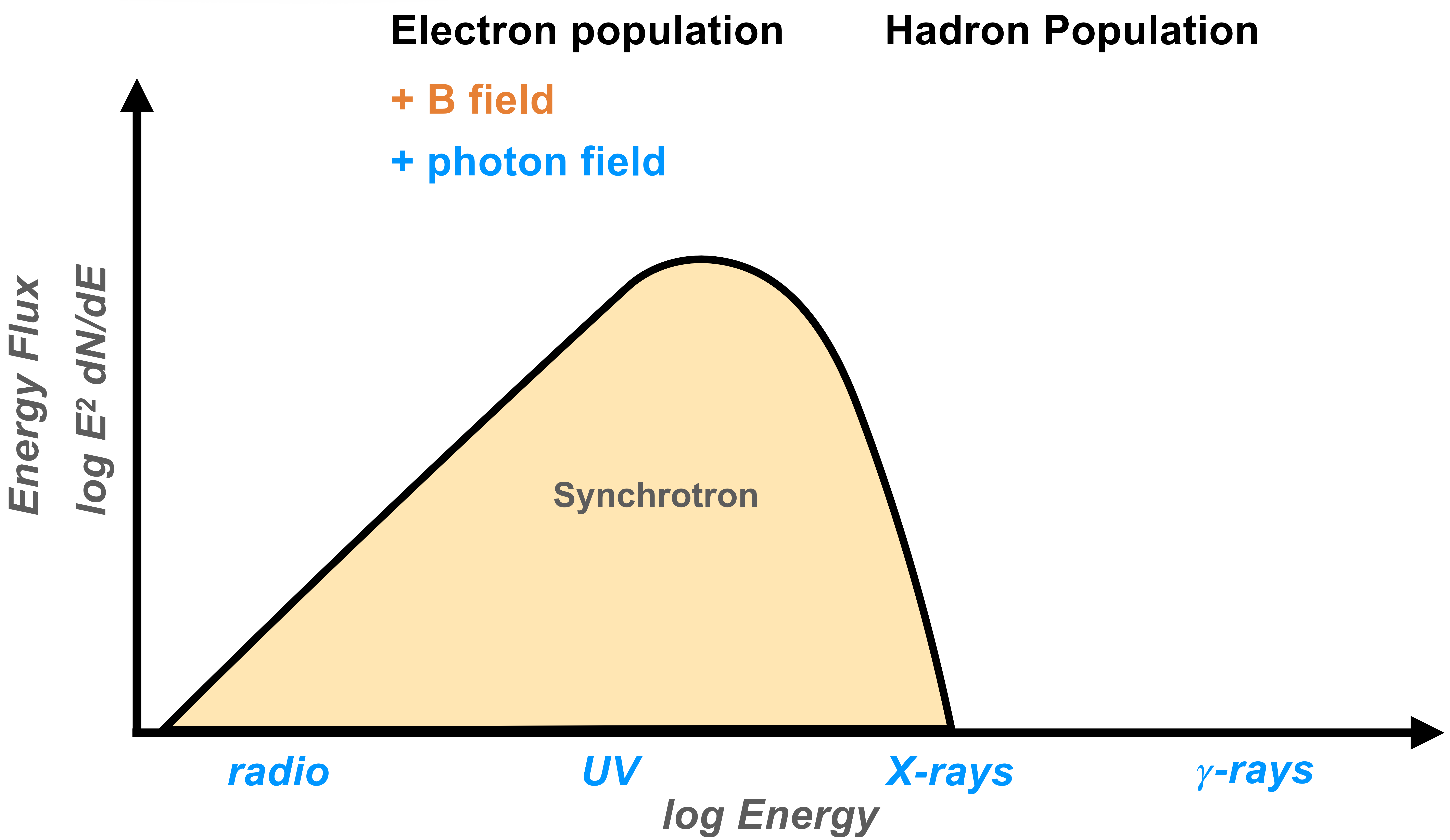

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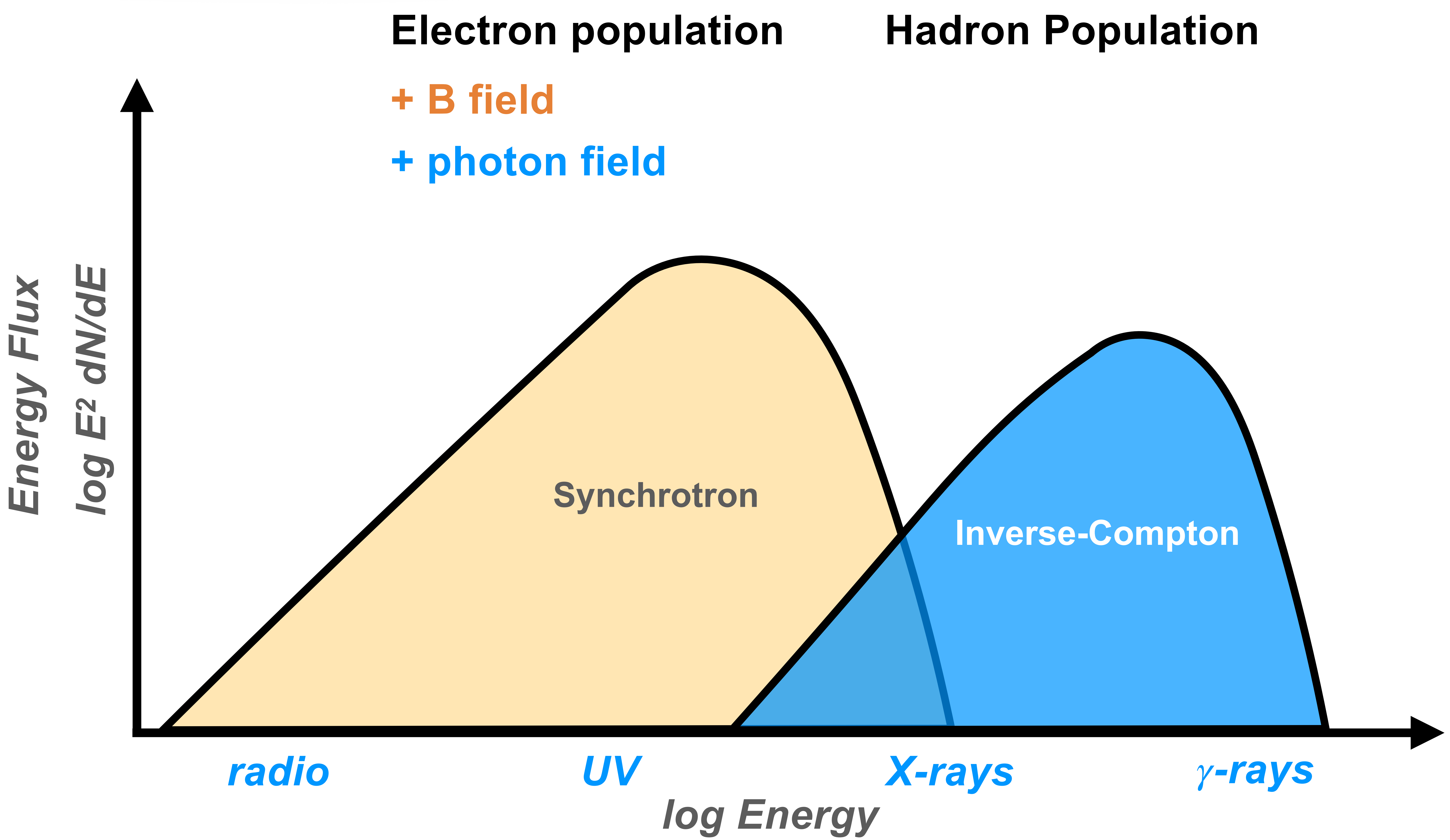

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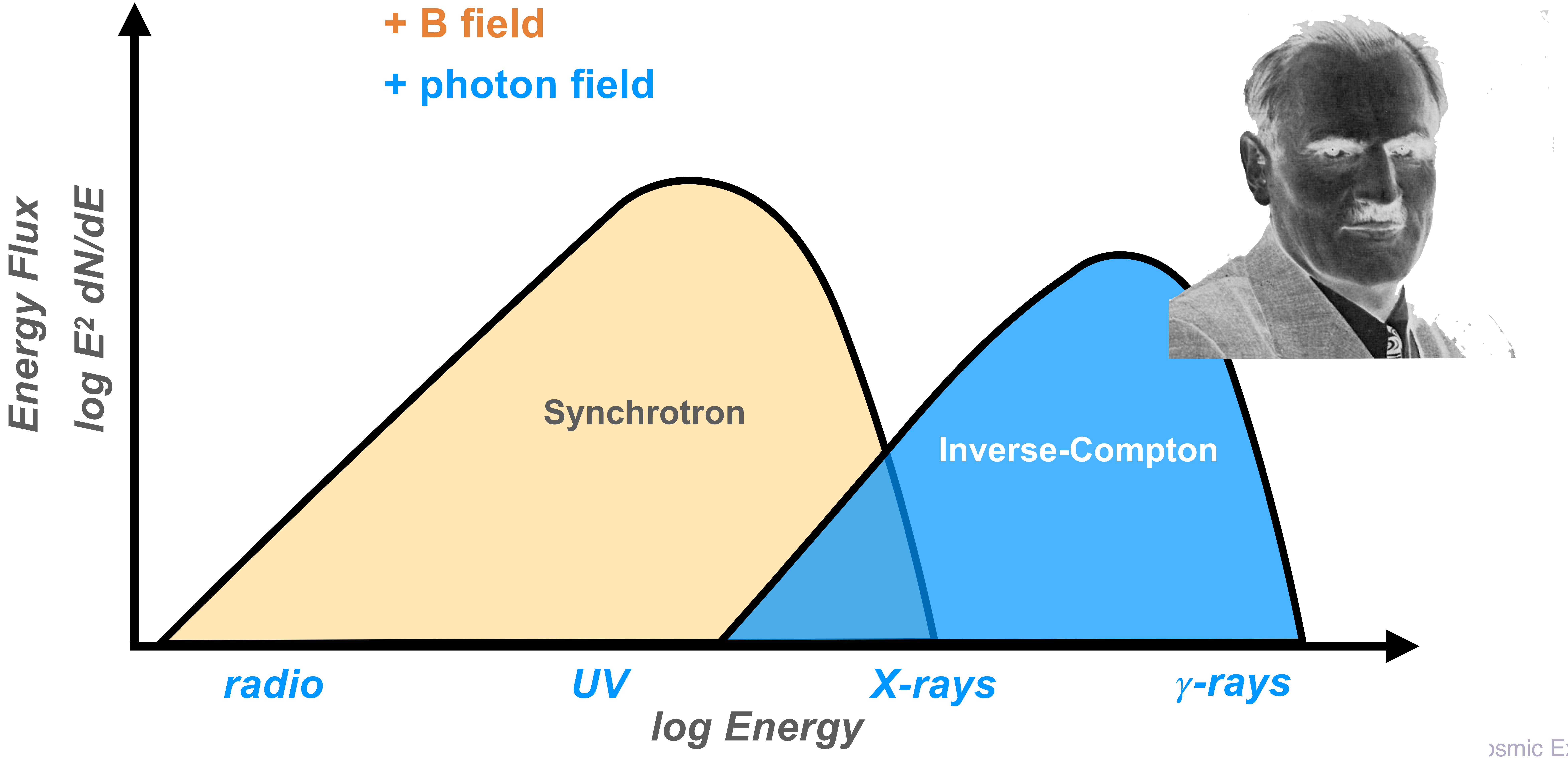

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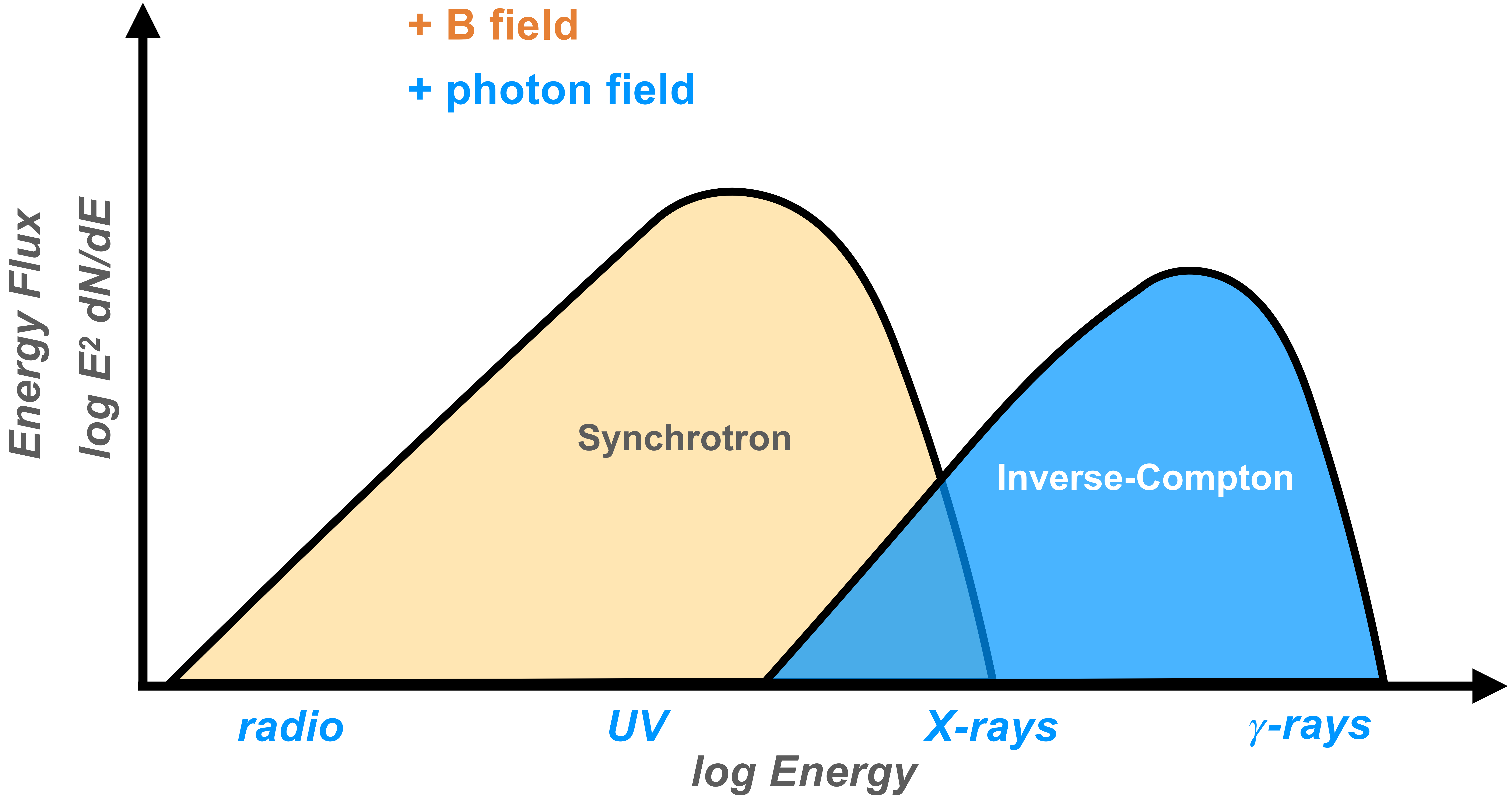

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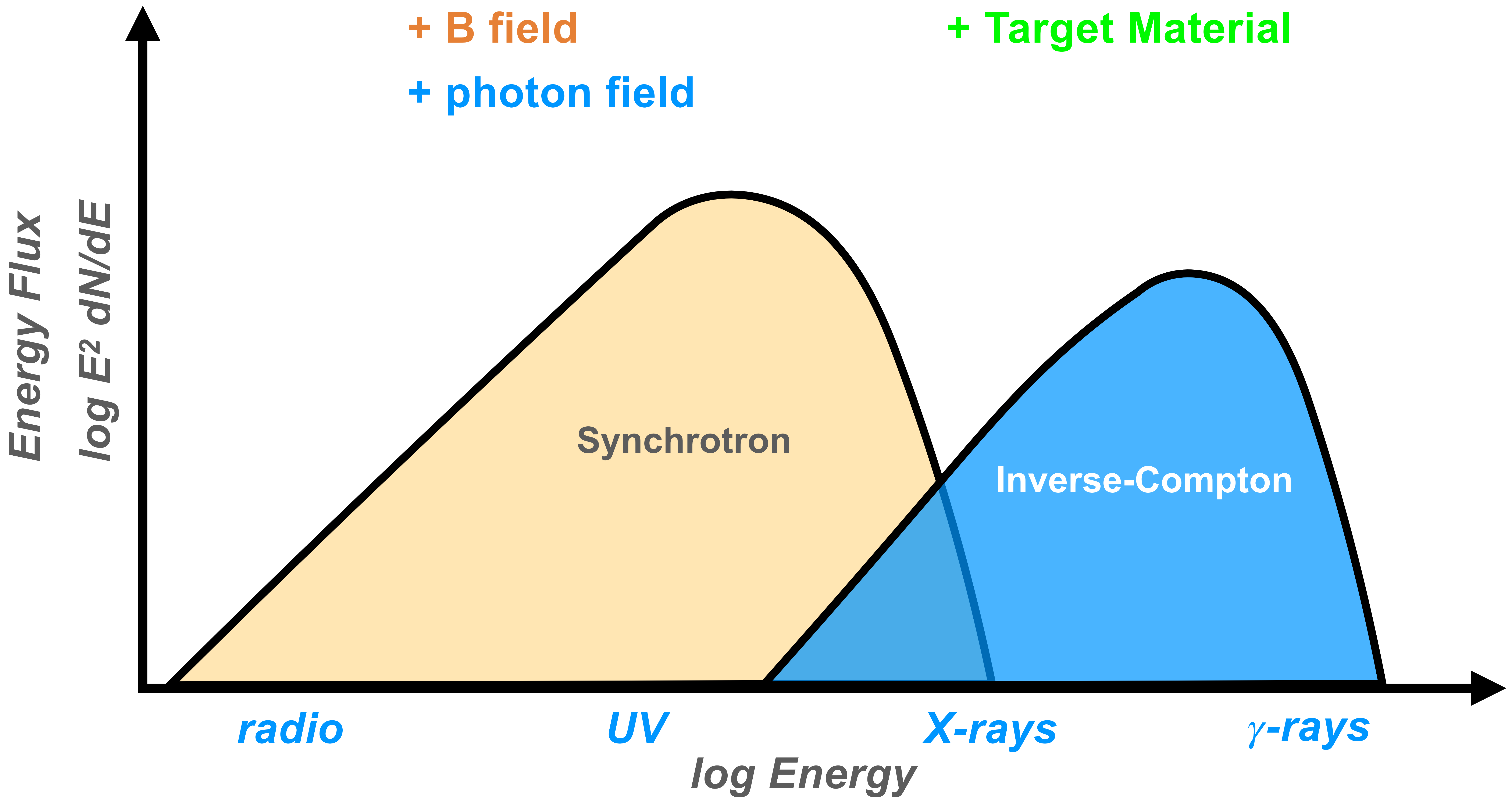
Hadron Population

+ Target Material



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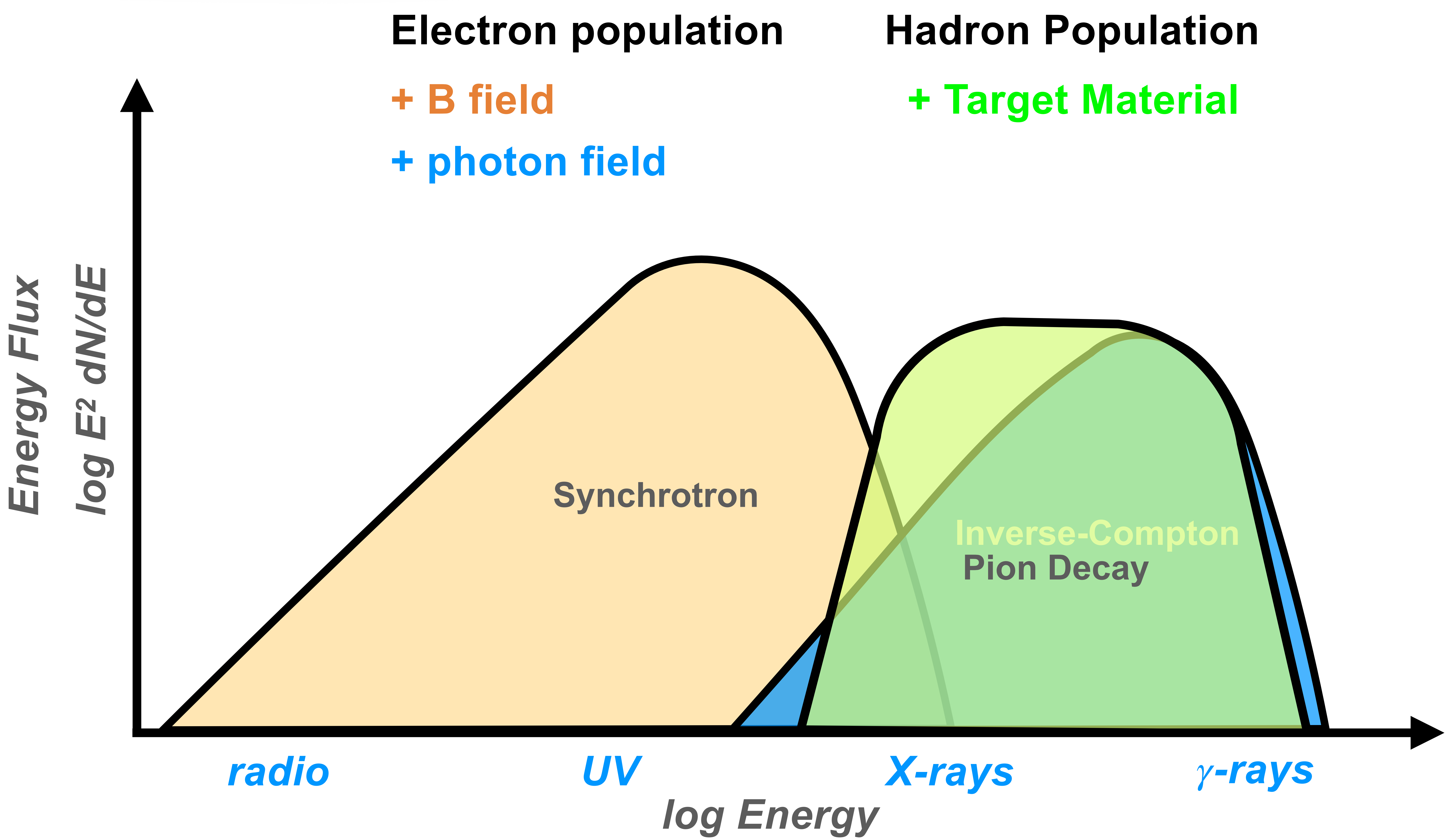

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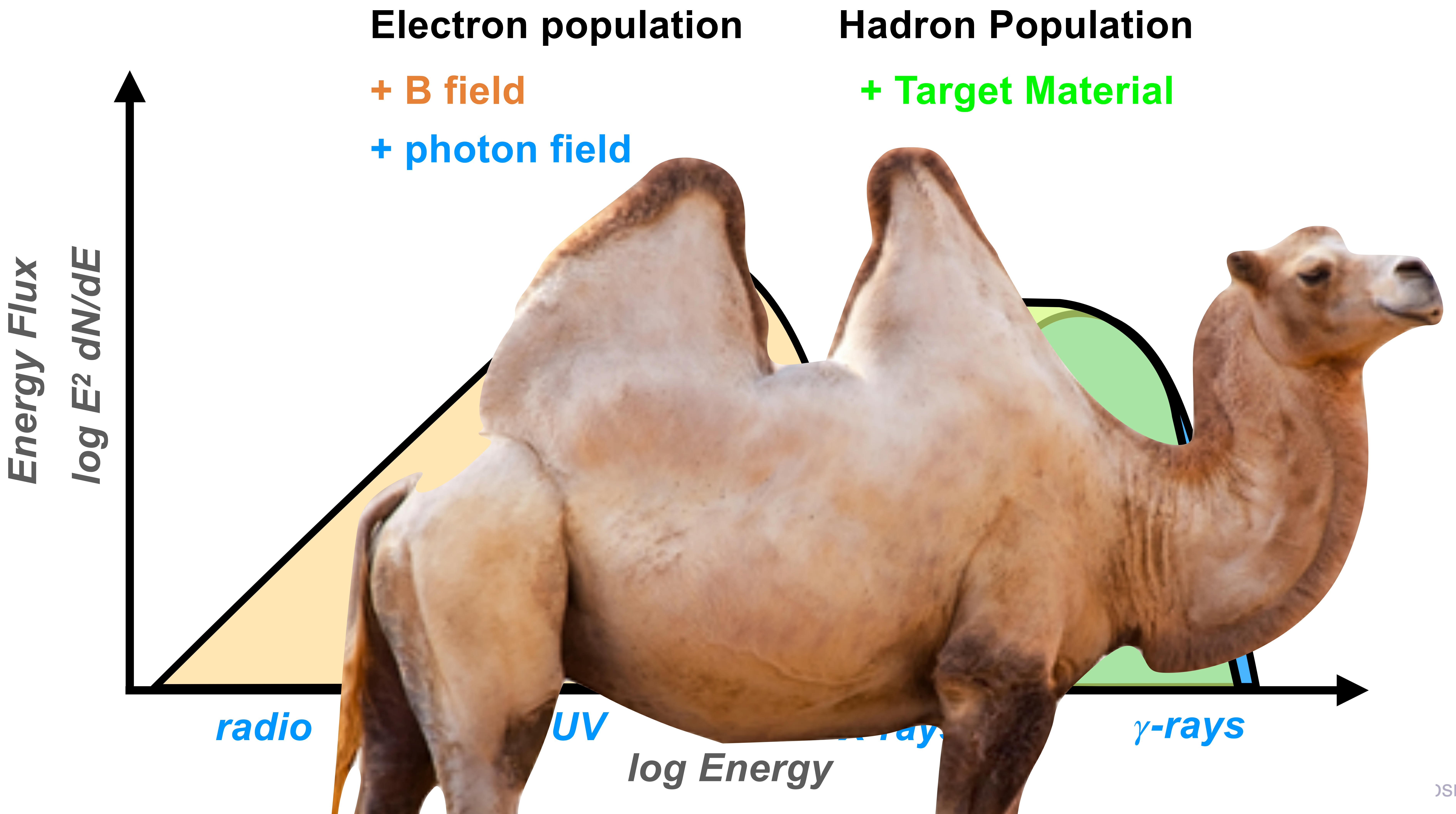

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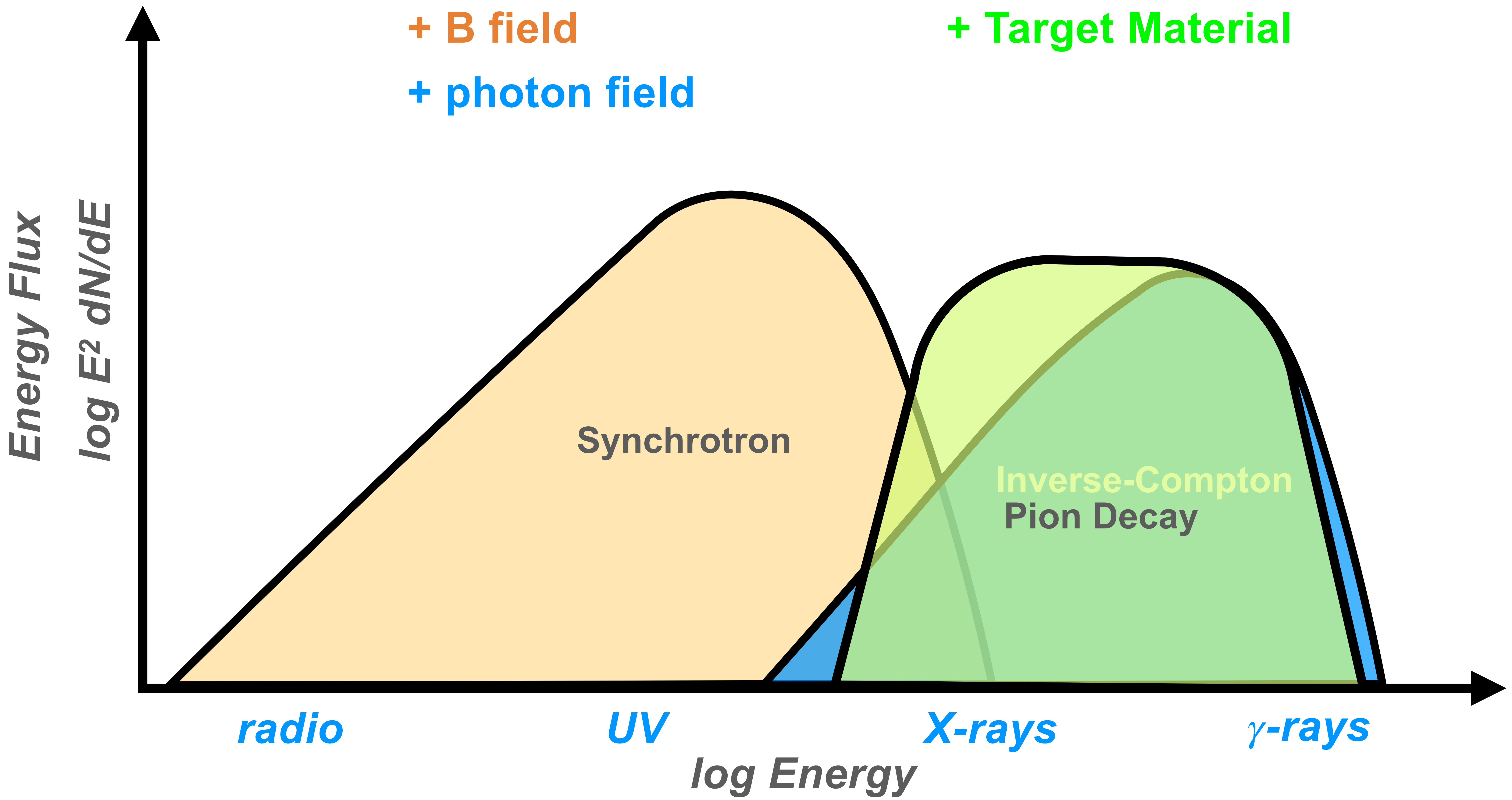

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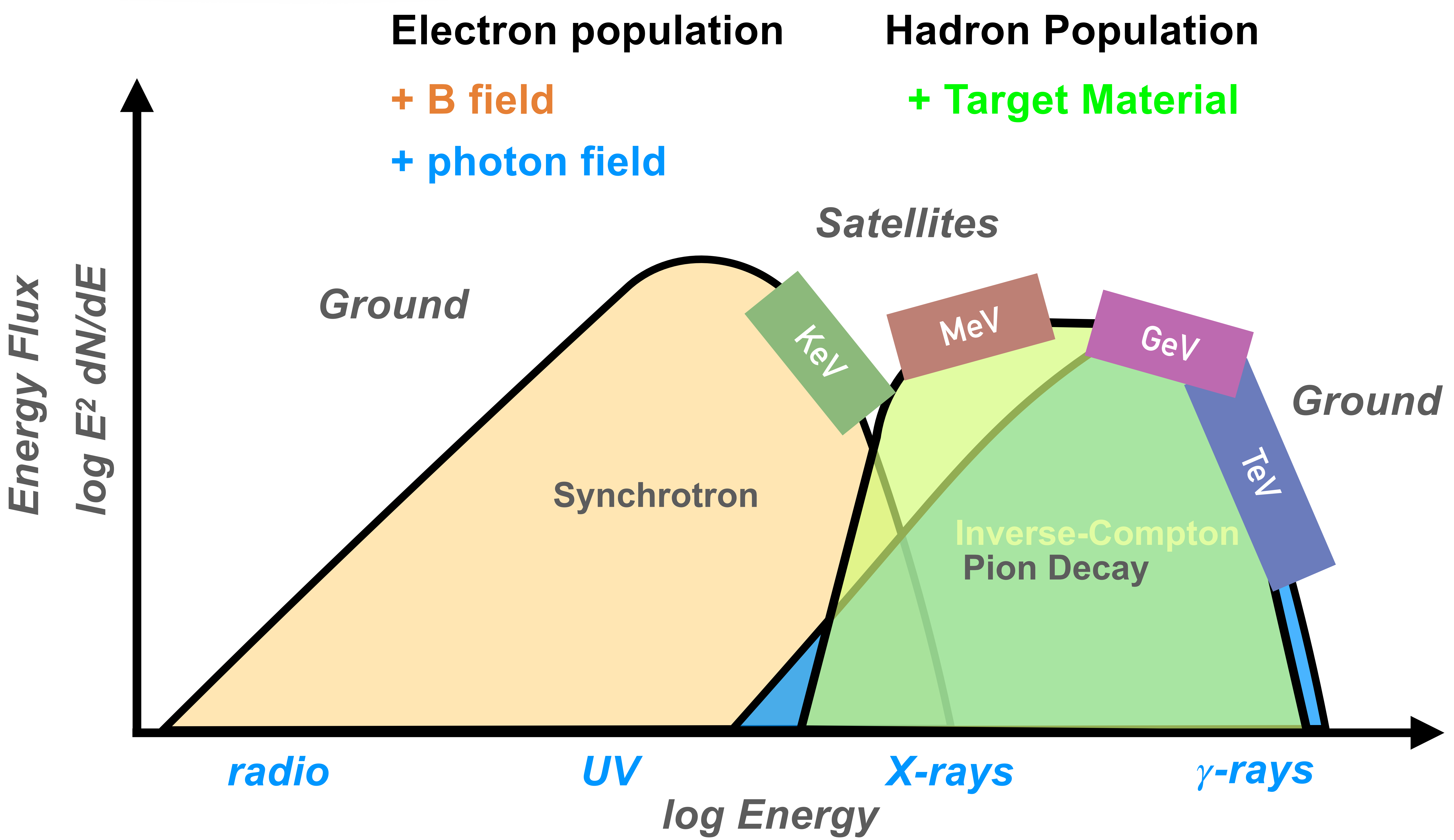
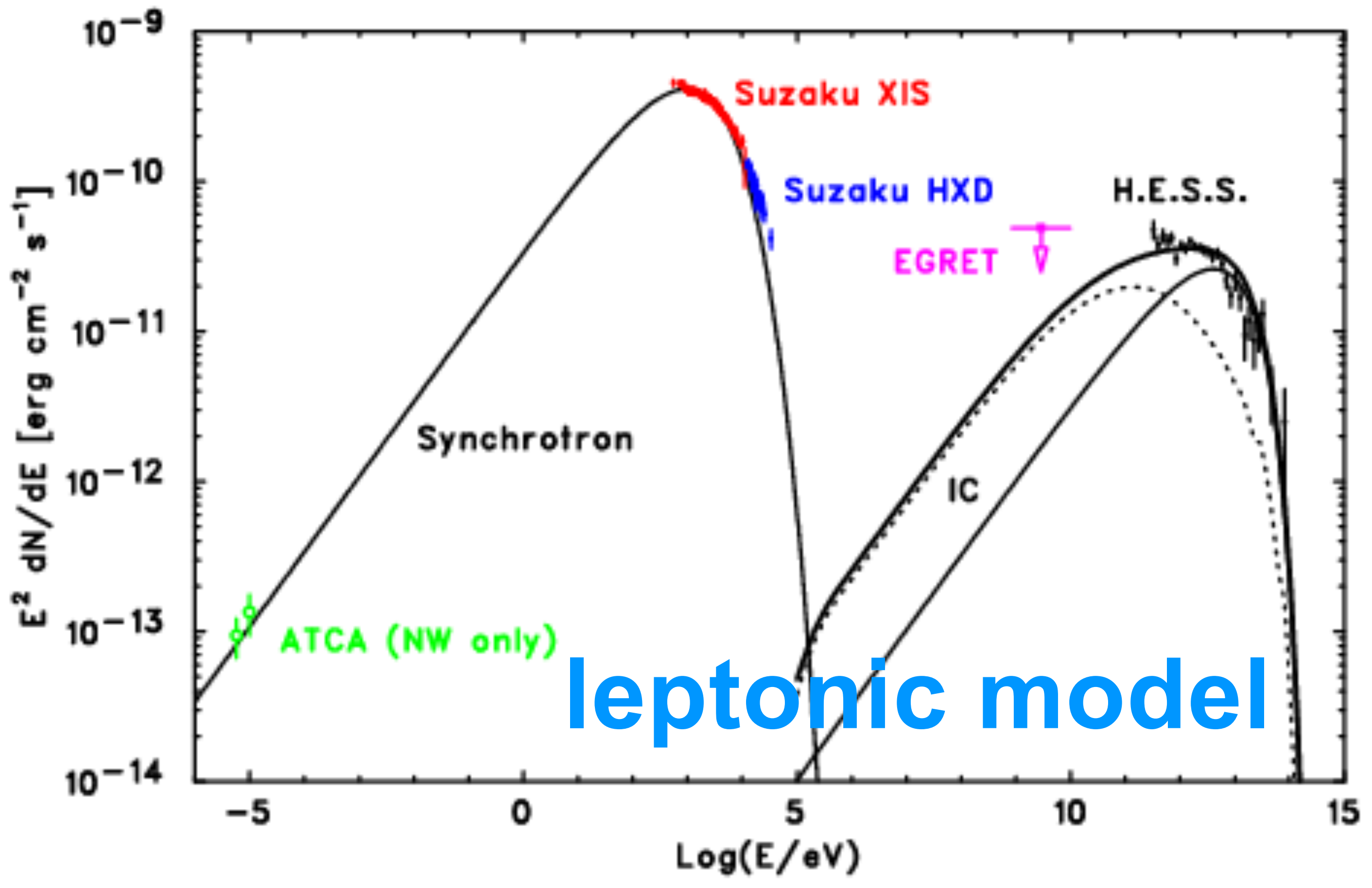
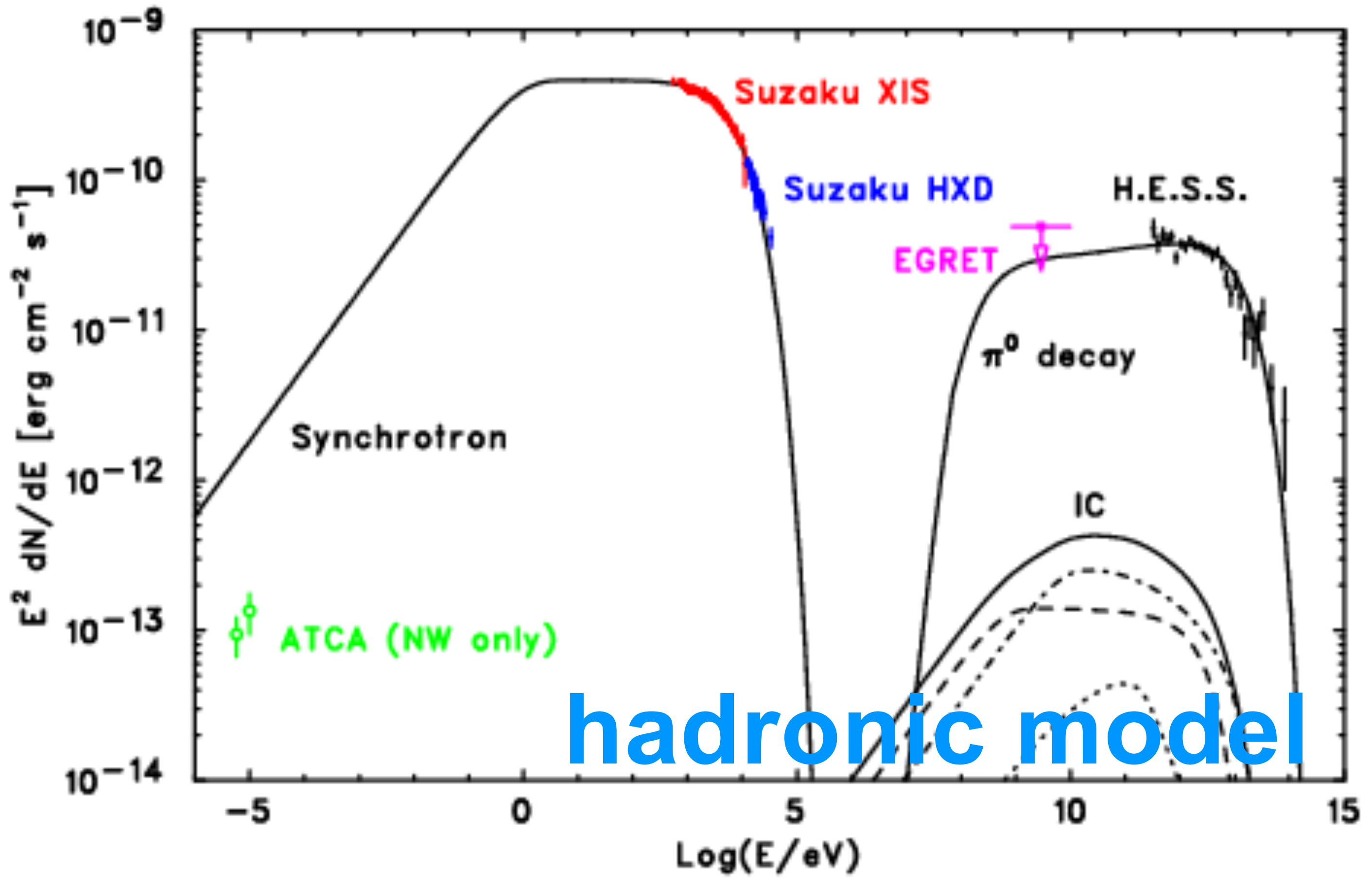


Non-Thermal Emission

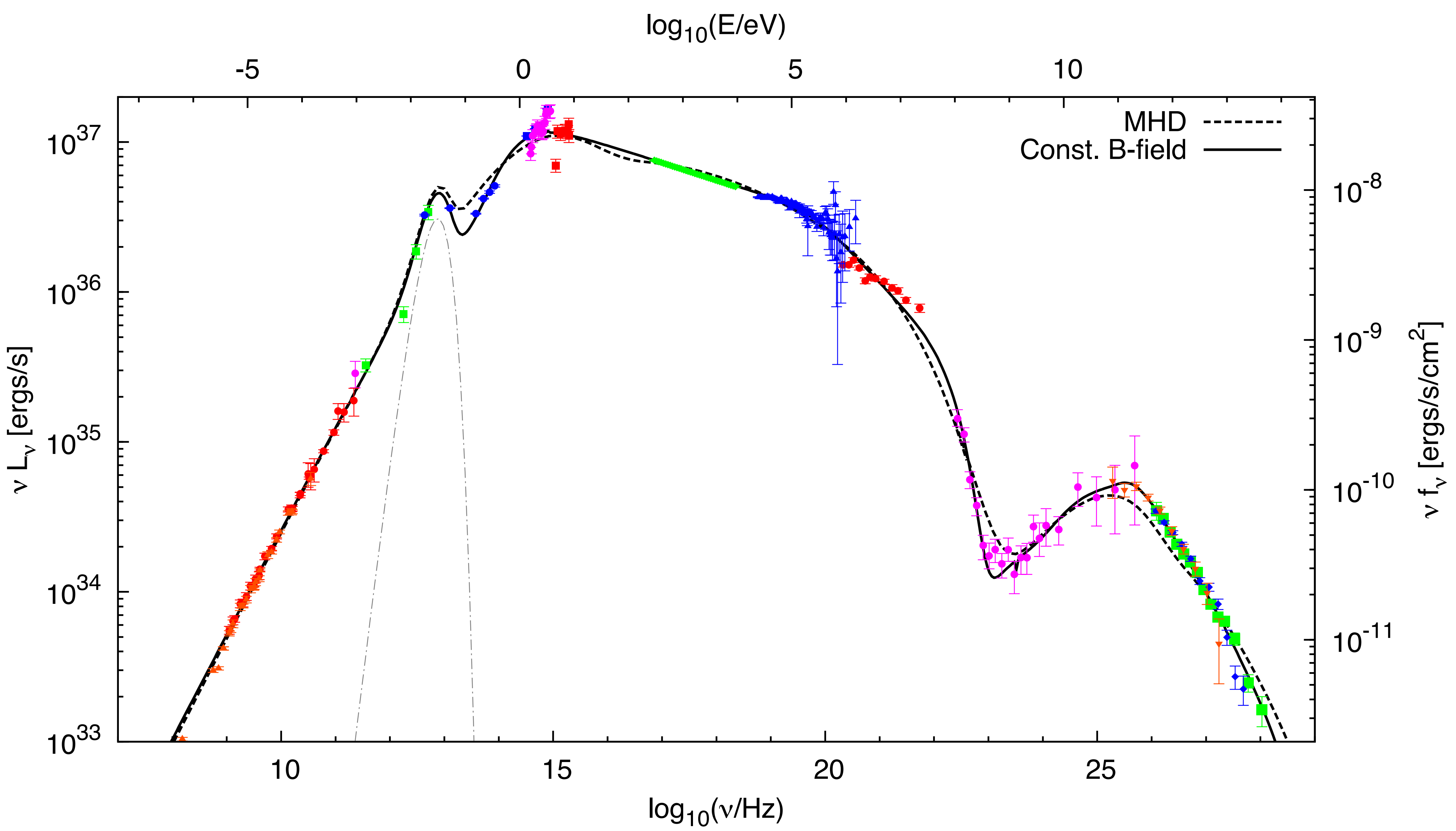
Some real examples

RX J1713.7-3946 (Supernova Remnant)



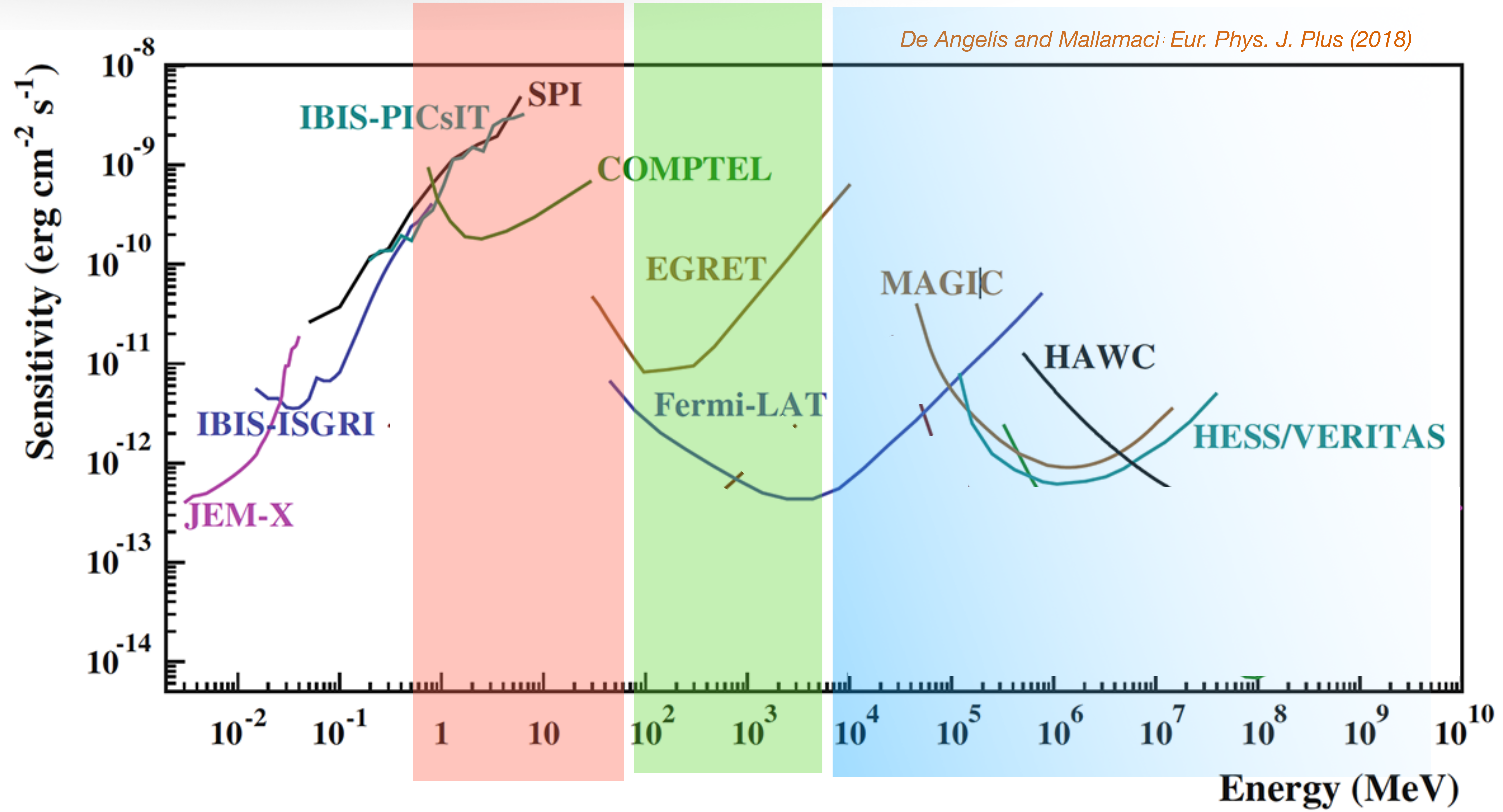


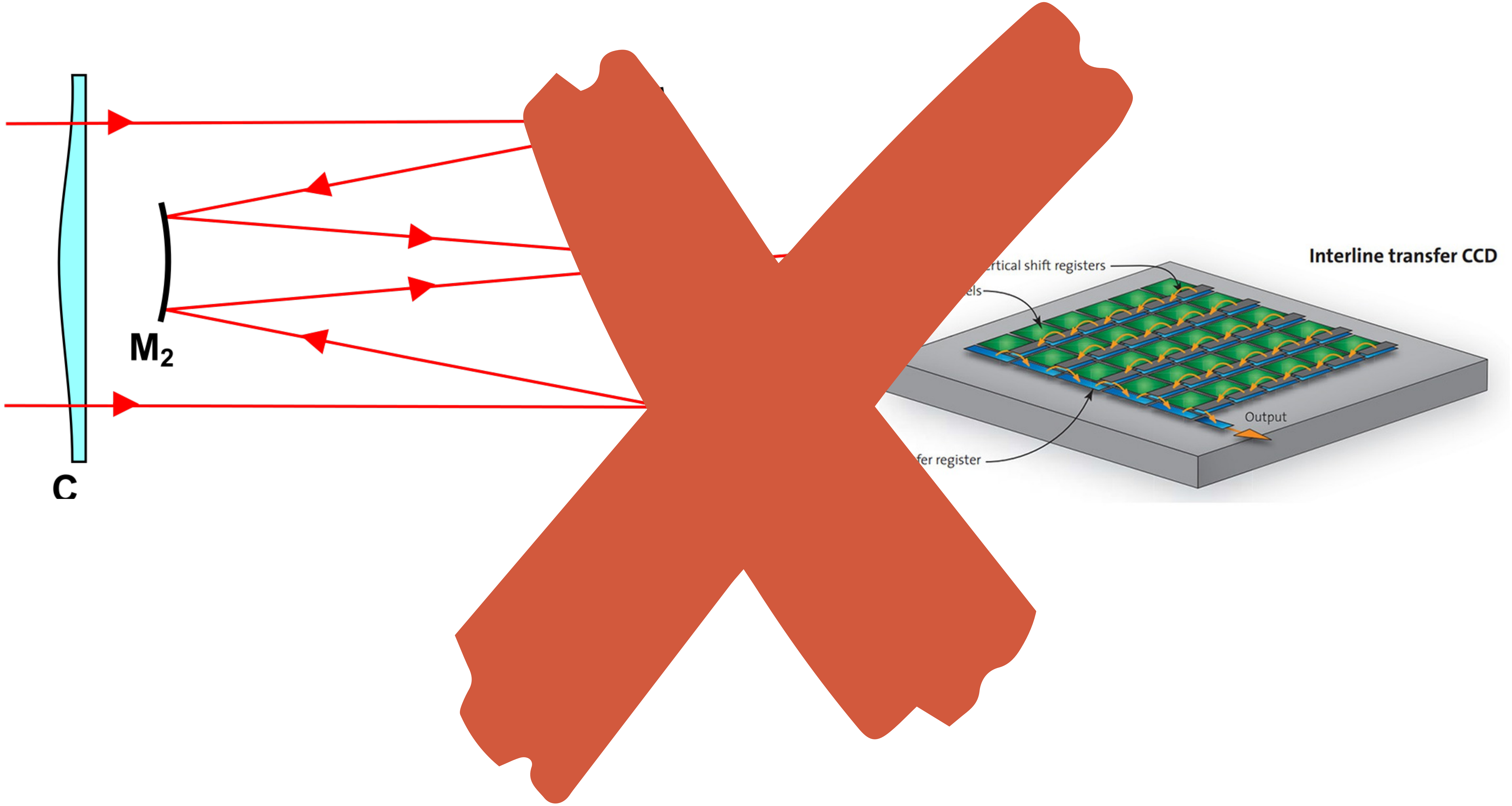
Crab Nebula (Pulsar Wind Nebula)



Mayer+ (http://dx.doi.org/10.1051/0004-6361/201014108)
Tanaka+ (http://dx.doi.org/10.1086/591020)

Gamma-ray Instrument Sensitivities





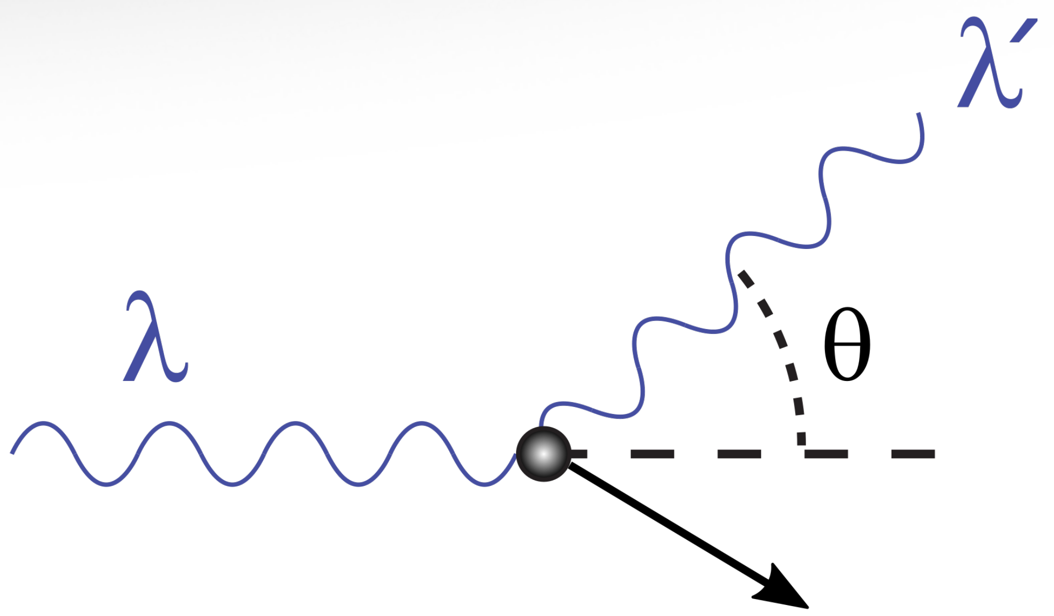
No focusing optics

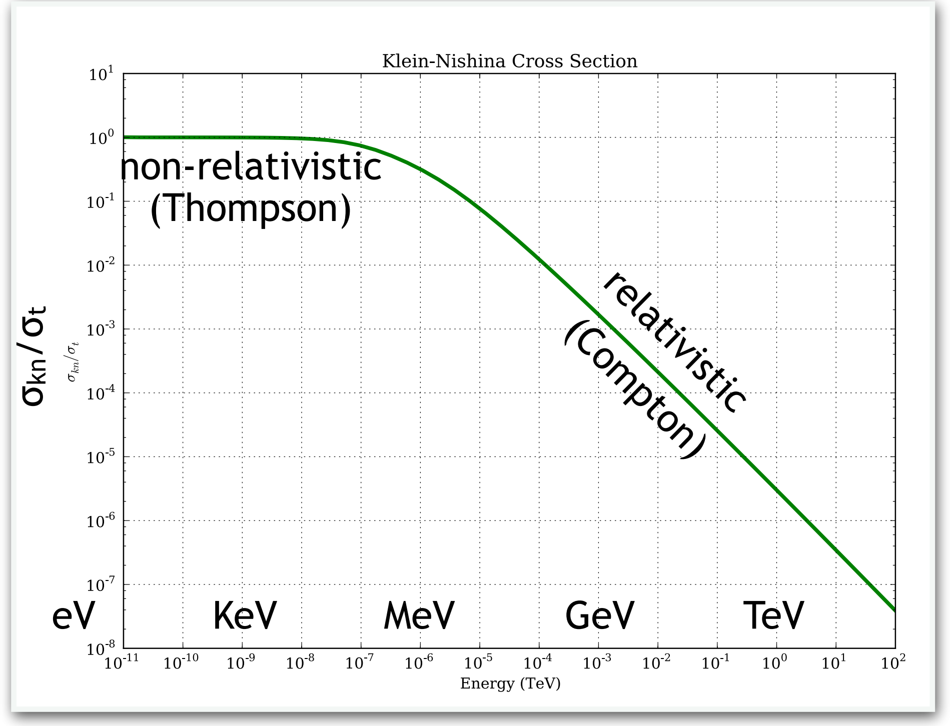
No CCDs

Single Photon Counting

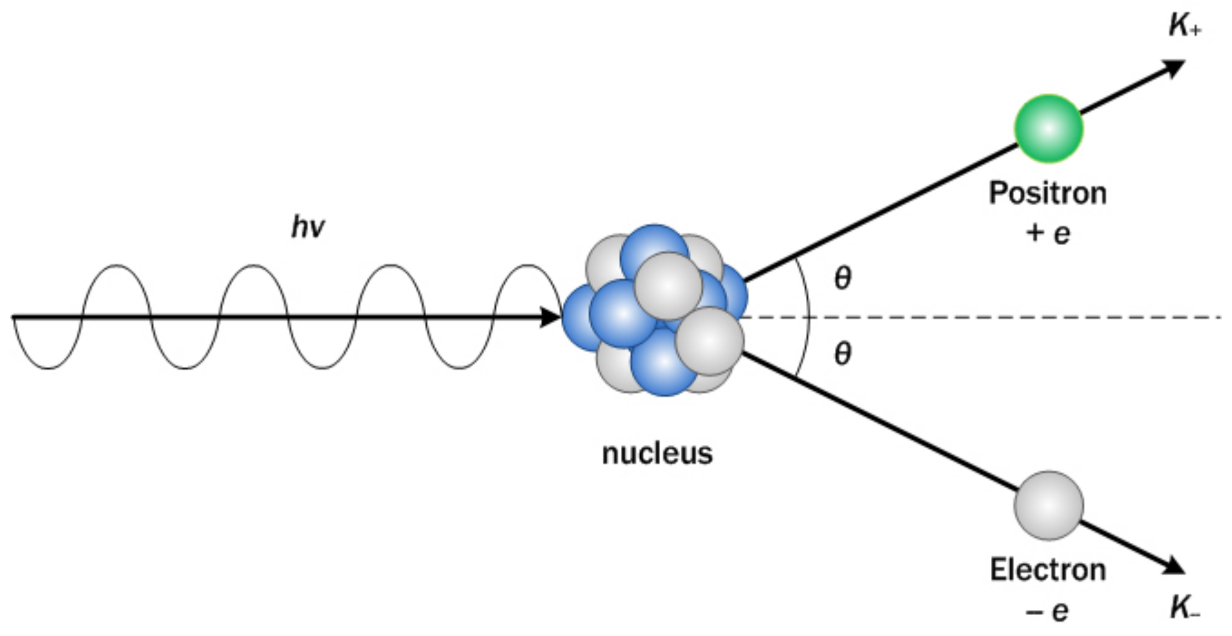
Particle Interactions beyond the Photoelectric Effect…

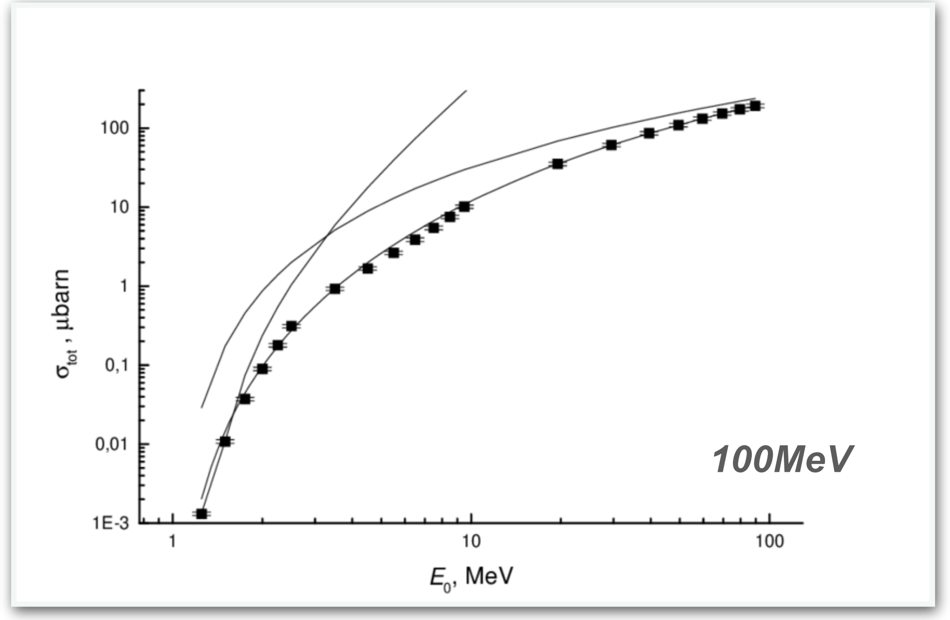
- Compton Scattering



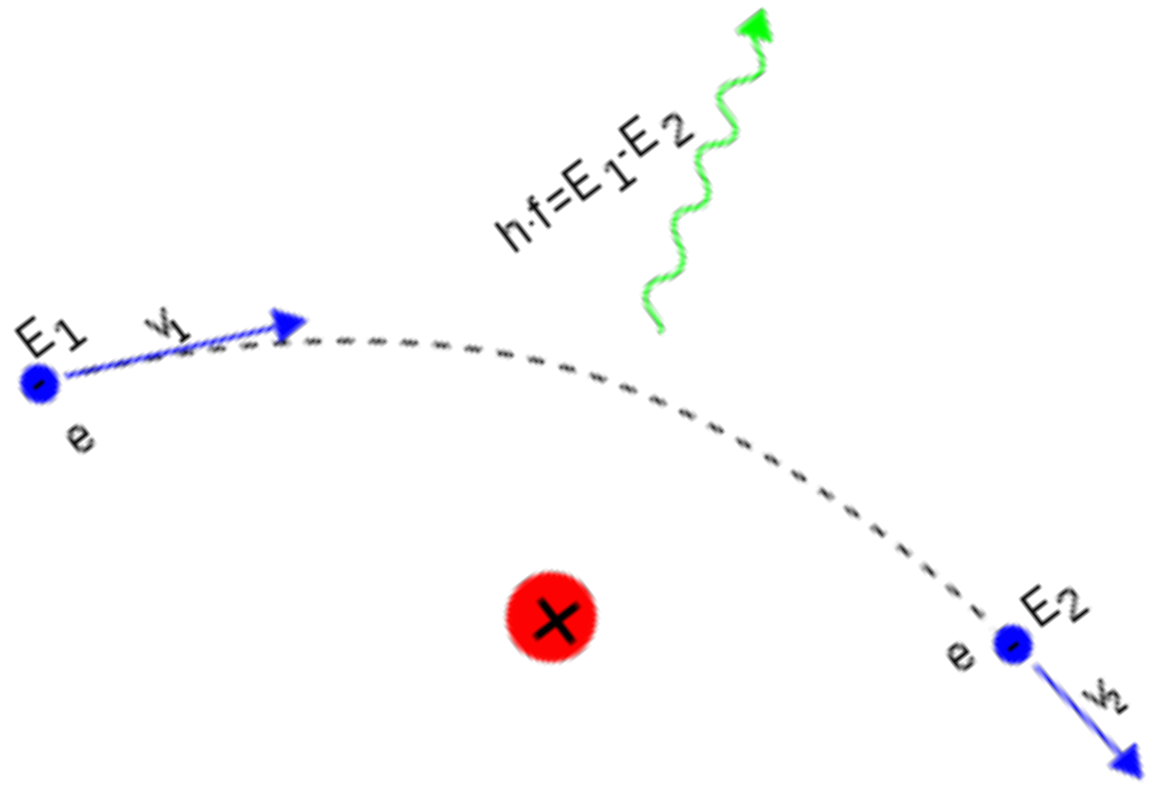


- Pair Production





- Bremsstrahlung



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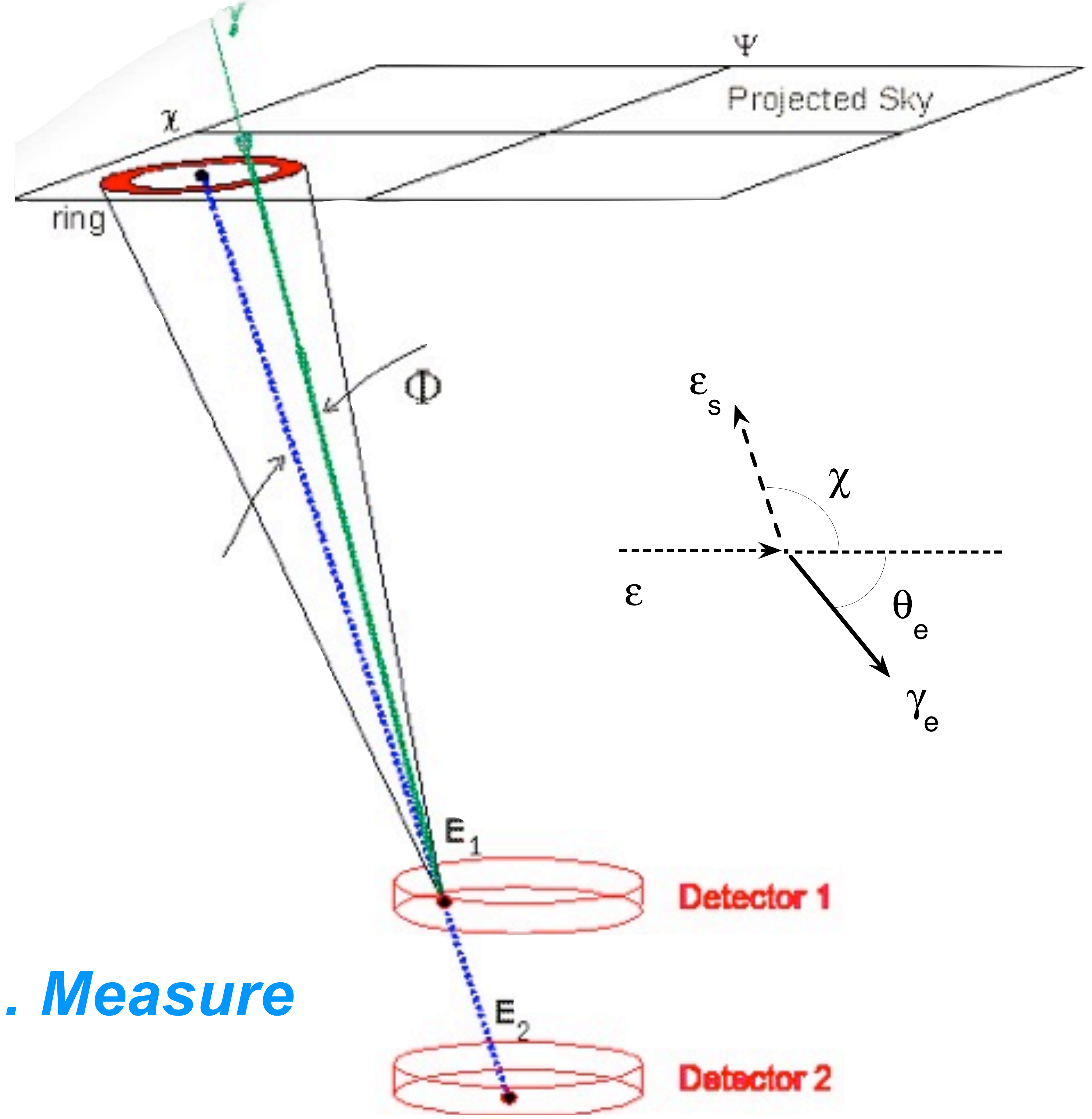
Detection: *Compton Scattering*

10s of MeV to few GeV

2. Reconstruct



1. Measure

★ χ

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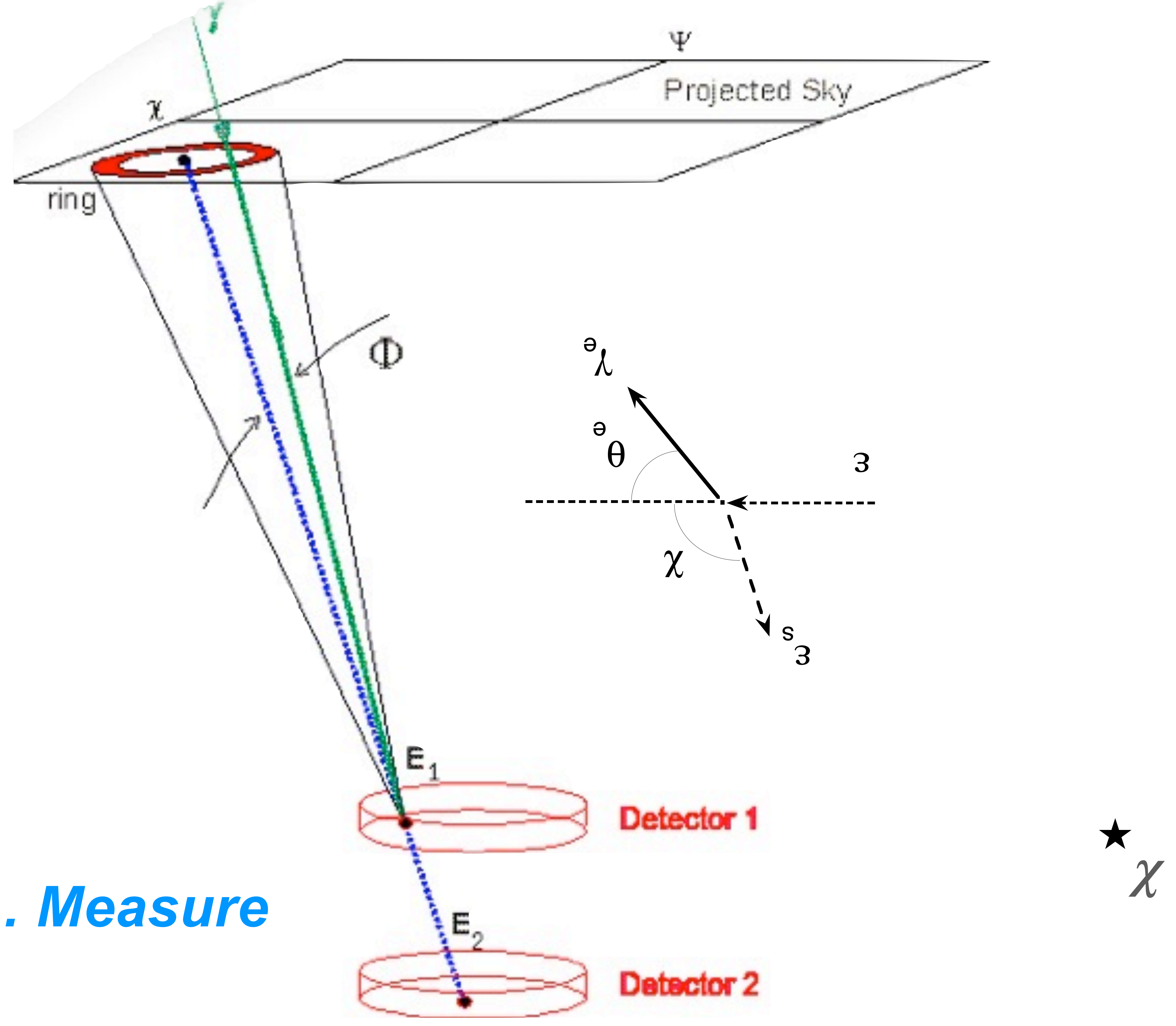

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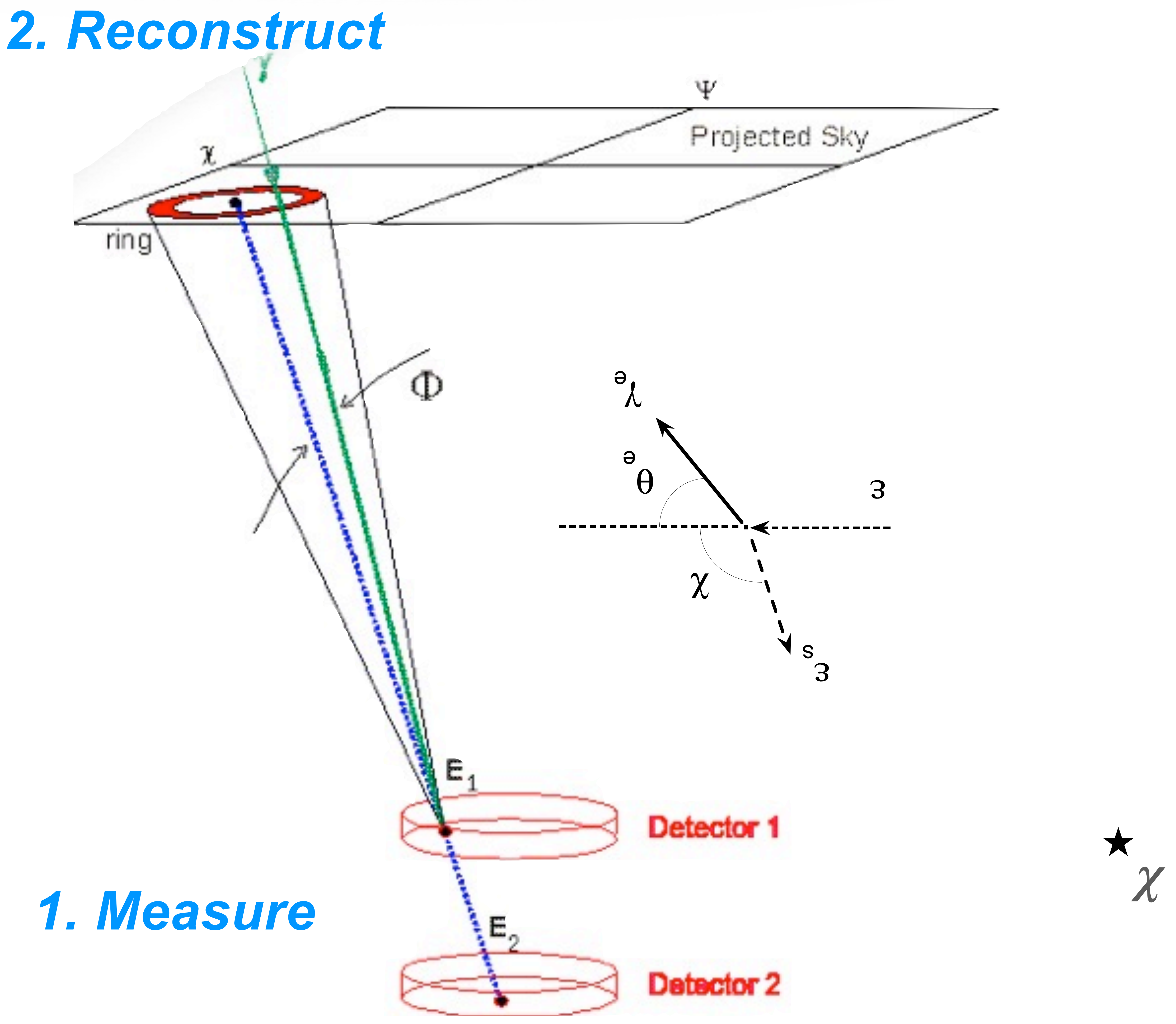

- Gamma-ray Scatters off electron in detector 1
  - ➤ measure E1 and position P1
- Scattered photon seen in Detector 2
  - ➤ measure E2, P2
- Calculate scattering angle
  - ➤ χ_{reco} = cone on sky for gamma-ray positional origin
  - ➤ $E_{gamma} = E1 + E2$

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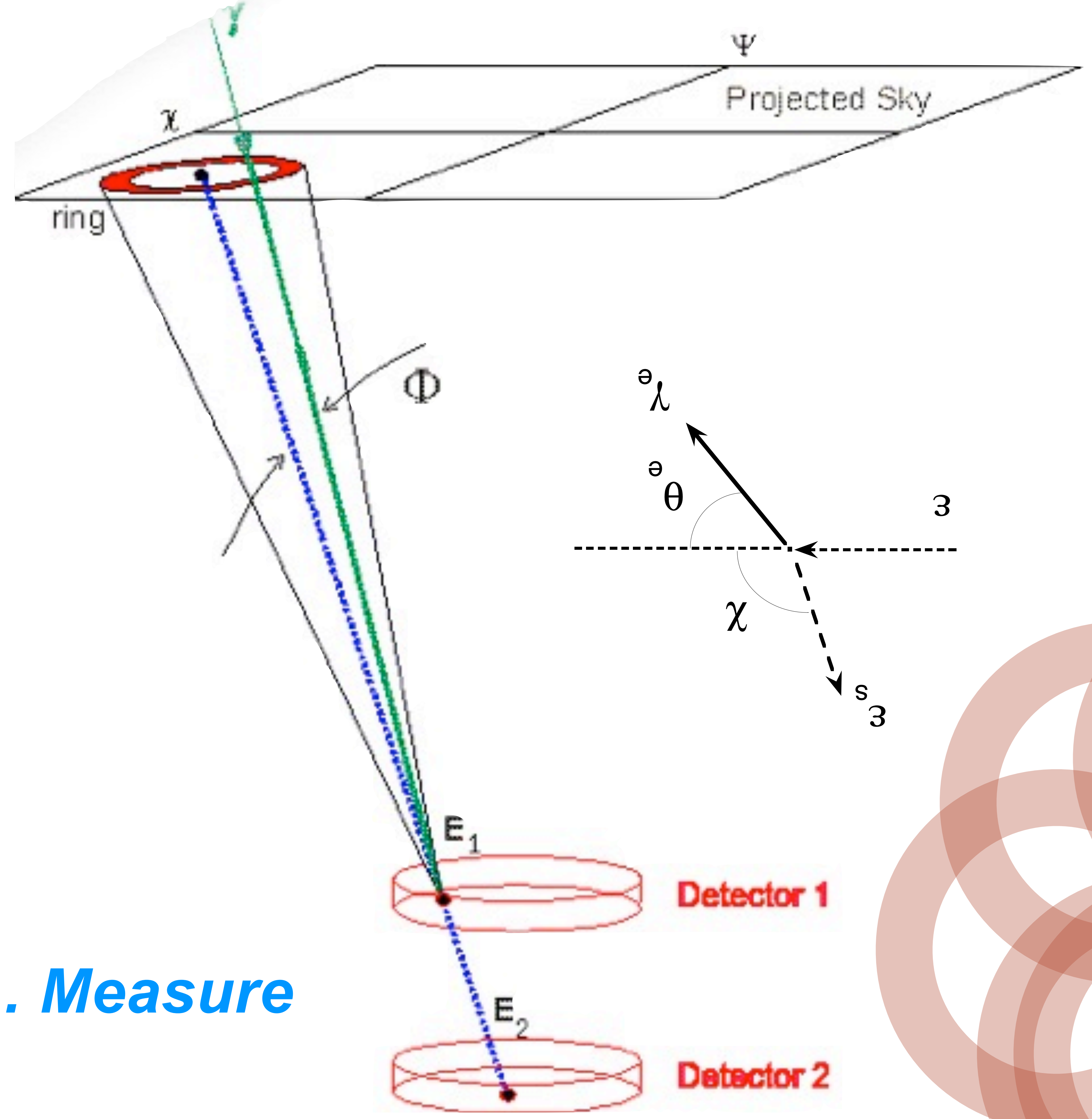

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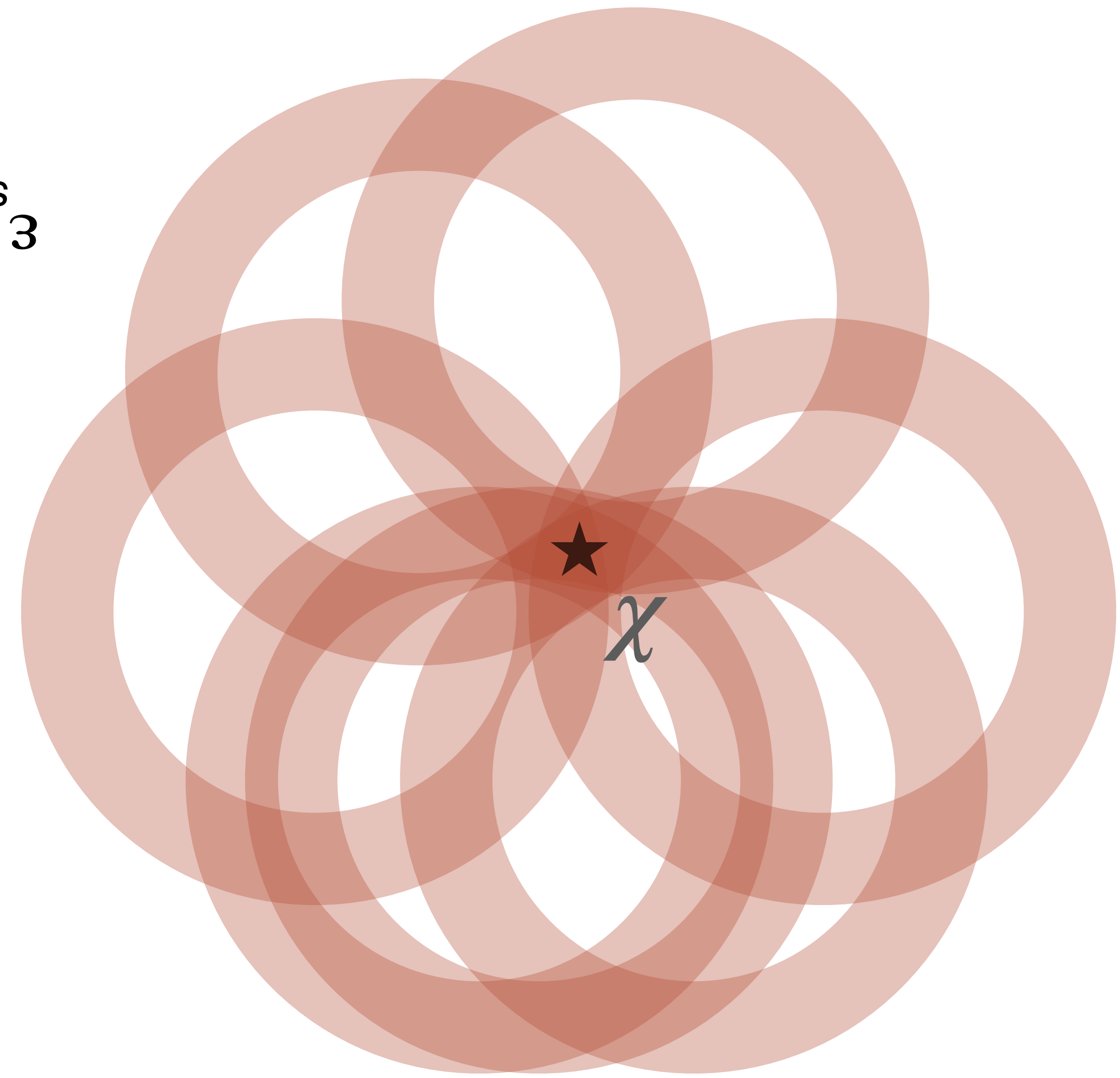

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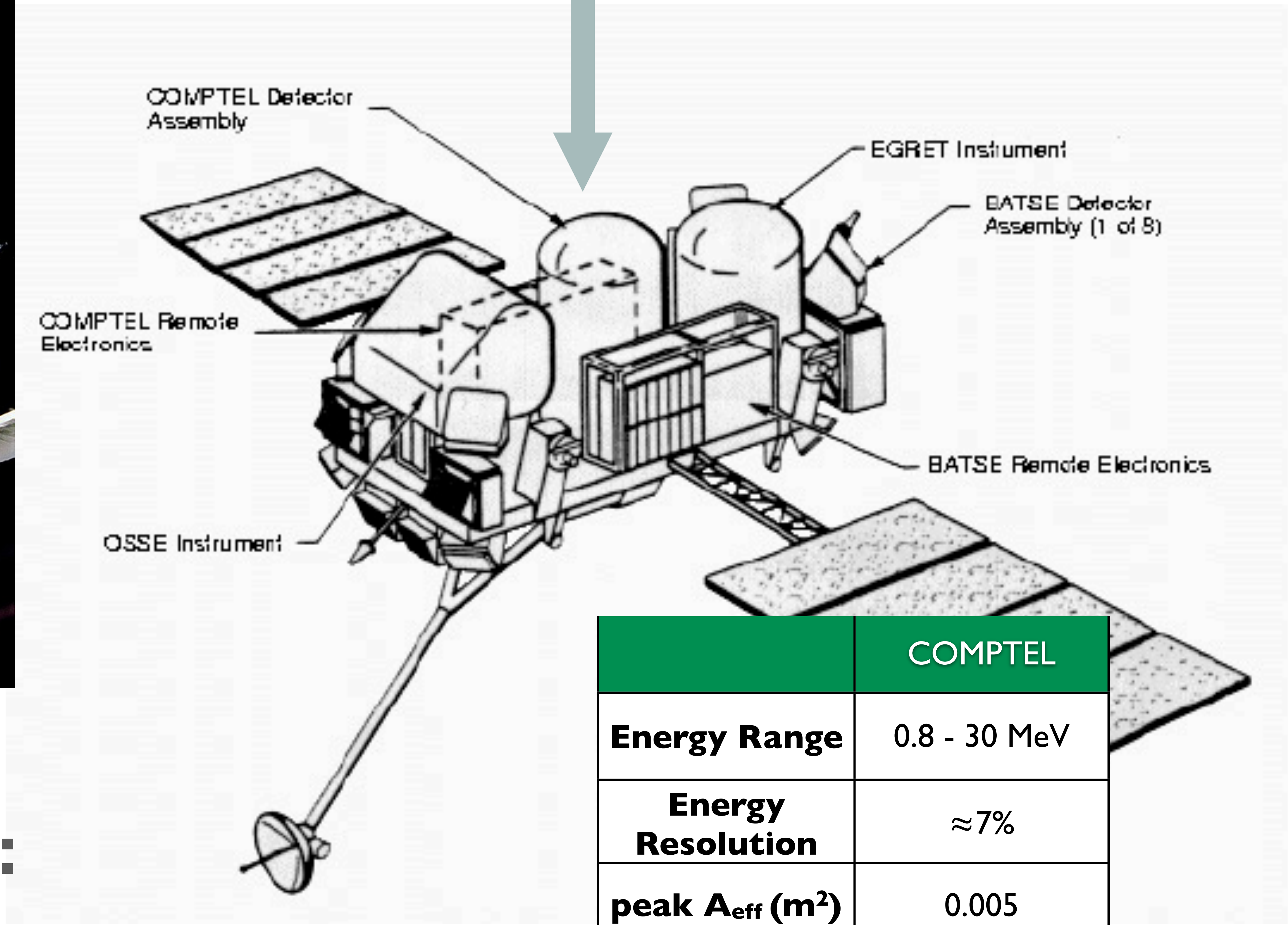
Compton Gamma-ray Observatory

Arthur Holly Compton

NASA "Great Observatory":

- 1991-2000

COMPTEL instrument:



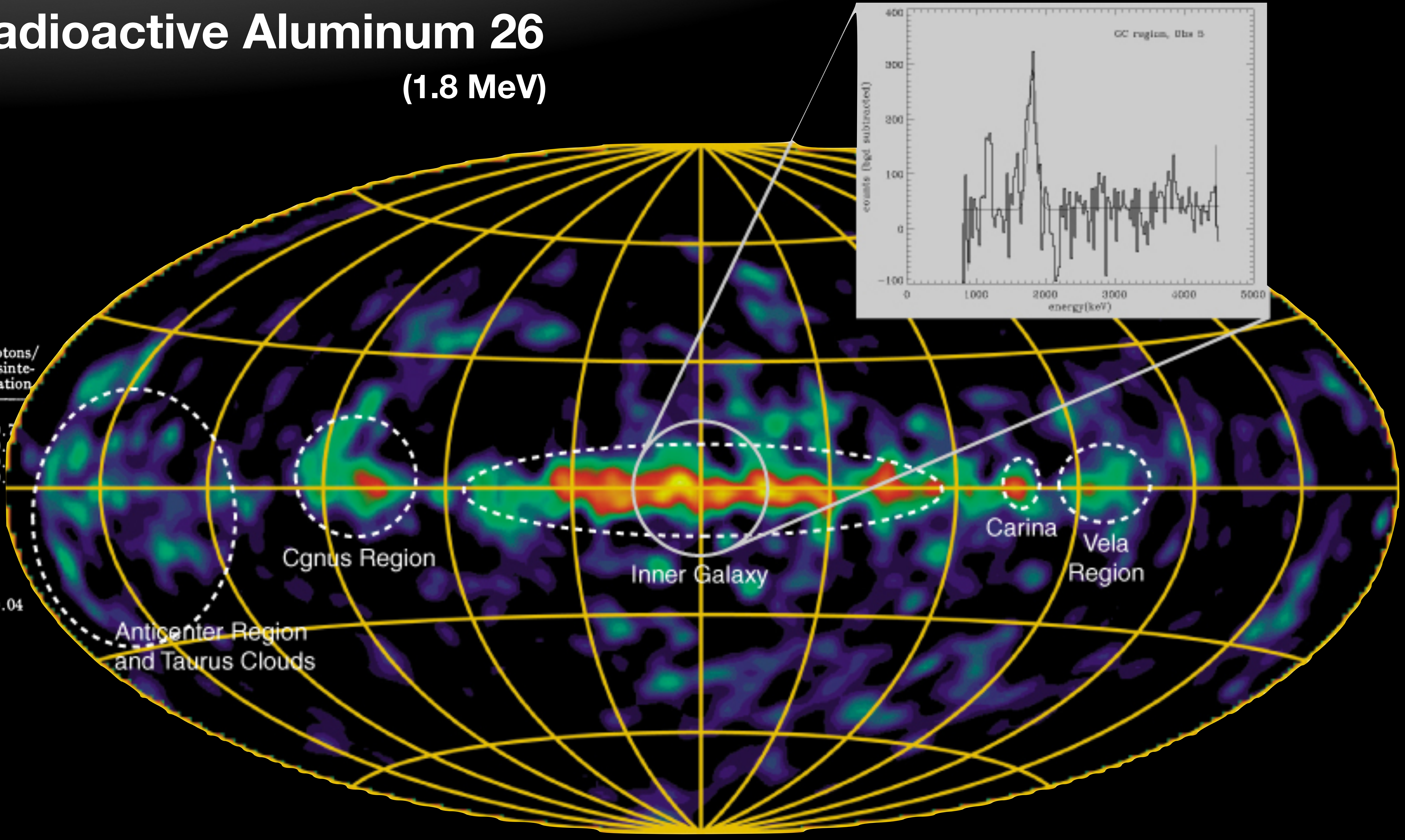
	COMPTEL
Energy Range	0.8 - 30 MeV
Energy Resolution	≈7%
peak A_{eff} (m^2)	0.005
FOV	1 sr
PSF	1°

Nuclear Line Emission at MeV

The galaxy in Radioactive Aluminum 26

(1.8 MeV)

Decay Chain	Half-Life	Nuclei/ Supernova	Photon Energy (MeV)	Photons/ Disinte- gration
$^{56}Ni \rightarrow ^{56}Co \rightarrow ^{56}Fe$........	77.3 d	3×10^{54}	0.847	1
			1.238	0.7
			2.598	0.
			1.771	0.
			1.038	0.
$^{44}Ti \rightarrow ^{44}Sc \rightarrow ^{44}Ca$.........	47 yr	6×10^{51}	0.068	1
			0.078	1
			1.156	1
$^{60}Fe \rightarrow ^{60}Co \rightarrow ^{60}Ni$........	3×10^{5} yr	5×10^{50}	0.059	1
			1.173	1
			1.332	1
$^{26}Al \rightarrow ^{26}Mg$..............	7.4×10^{5} yr	4×10^{50}	1.809	1
			1.130	0.04

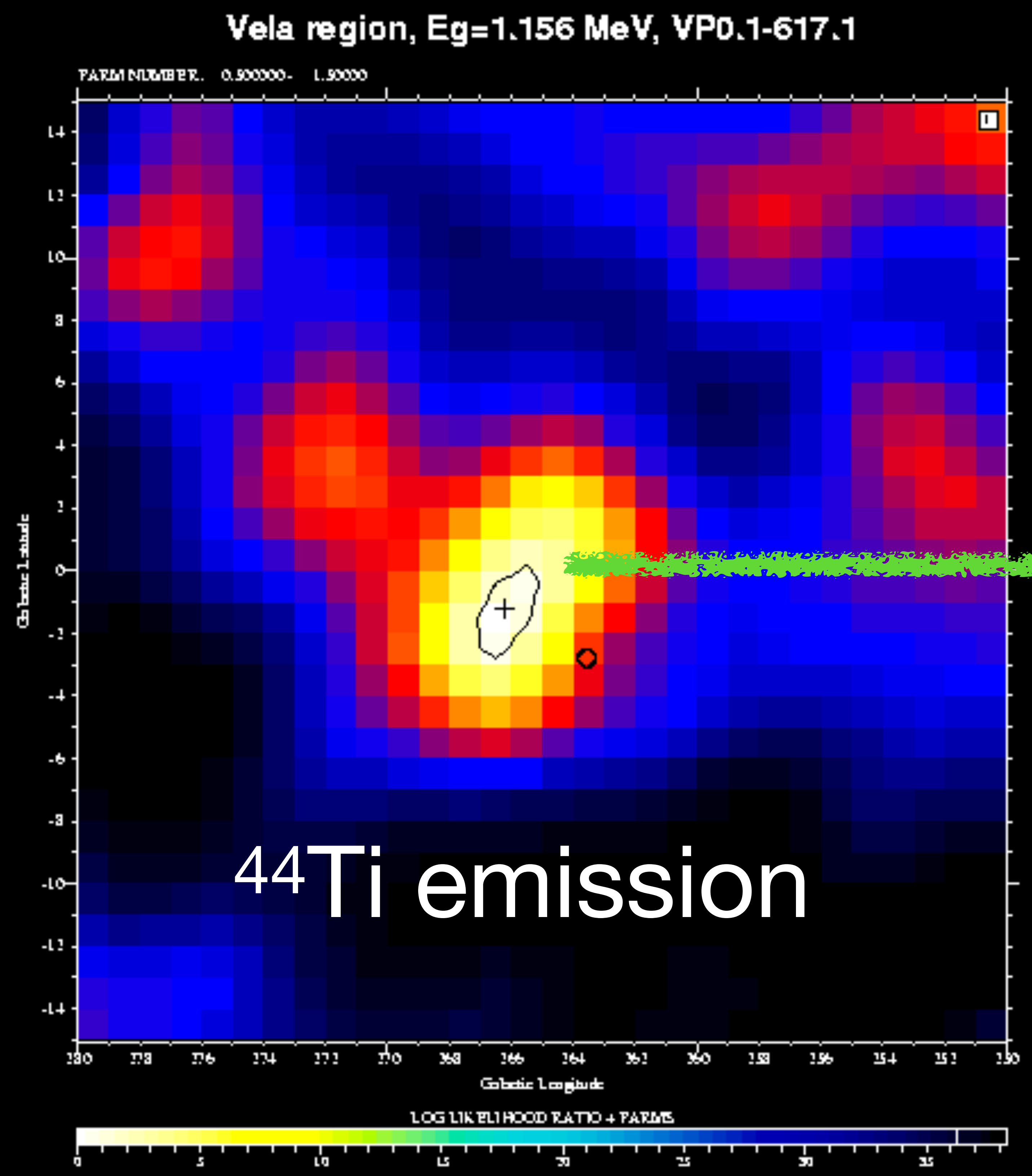


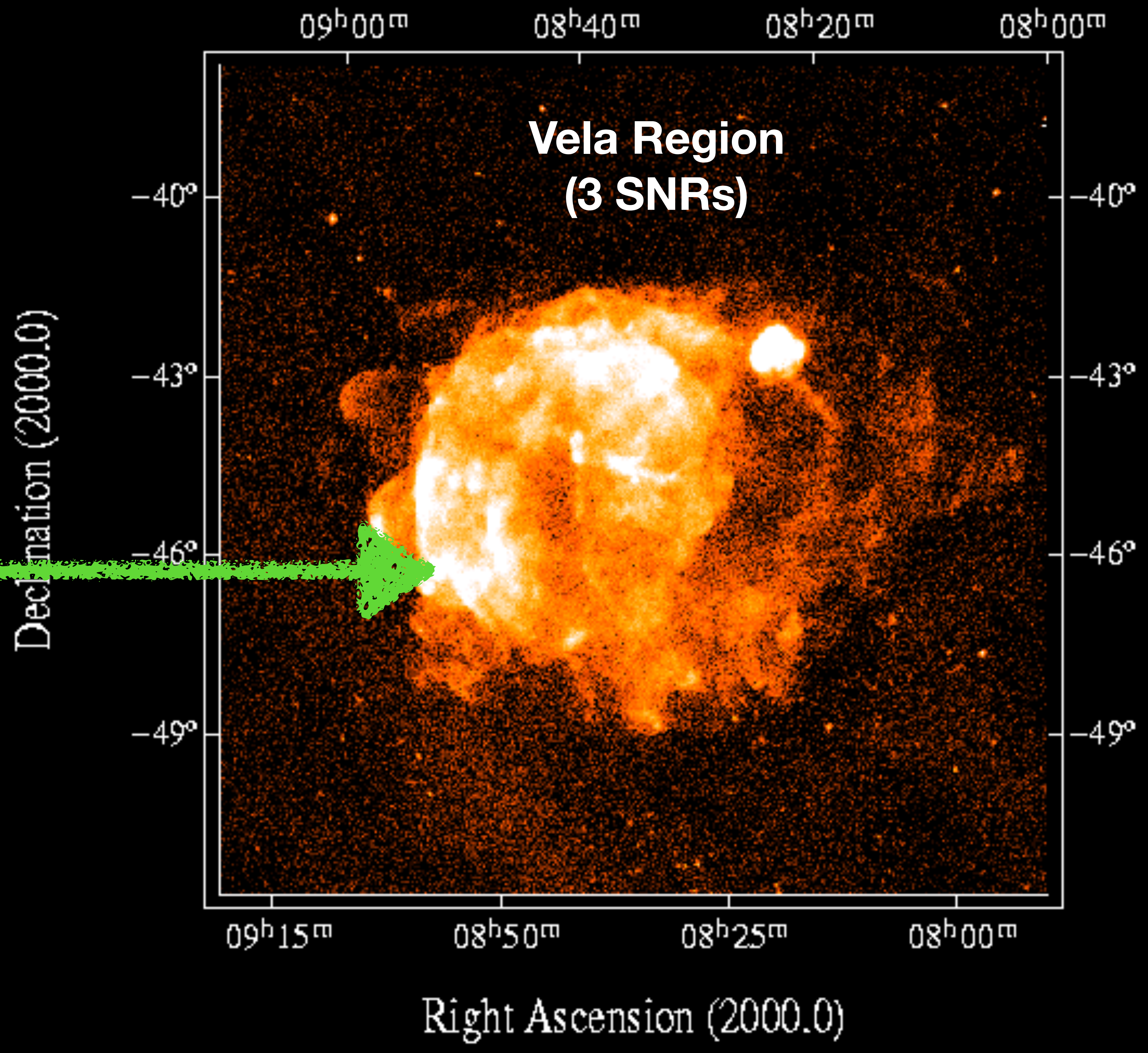
http://articles.adsabs.harvard.edu//full/1977ApJ...213L...5R/L000005.000.html

https://heasarc.gsfc.nasa.gov/docs/cgro/cgro/comptel_al26.html

Supernova Detection with Comptel

Look at where nucleosynthesis is happening → Find SNRs!





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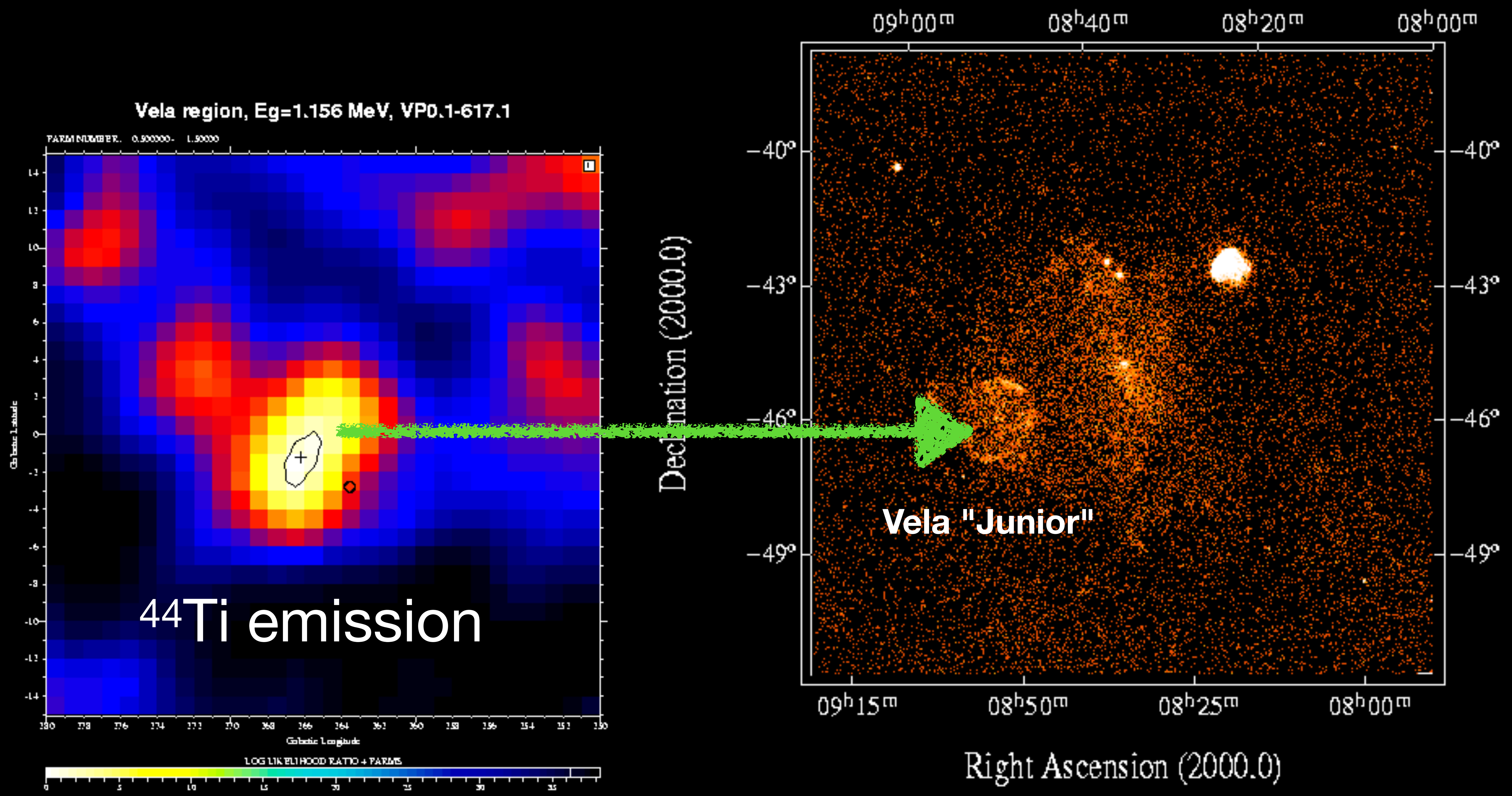

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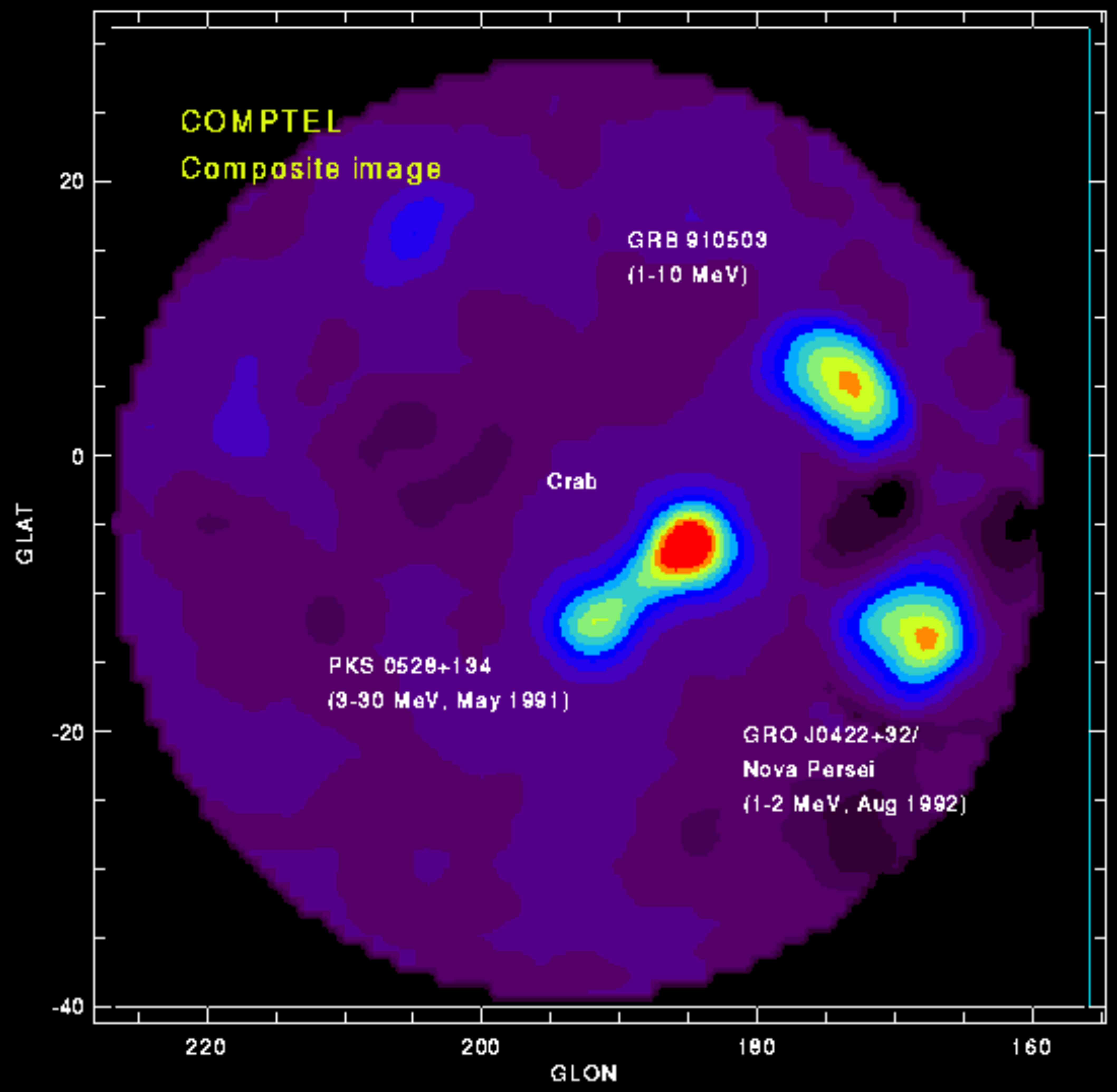
Comptel: Crab Nebula



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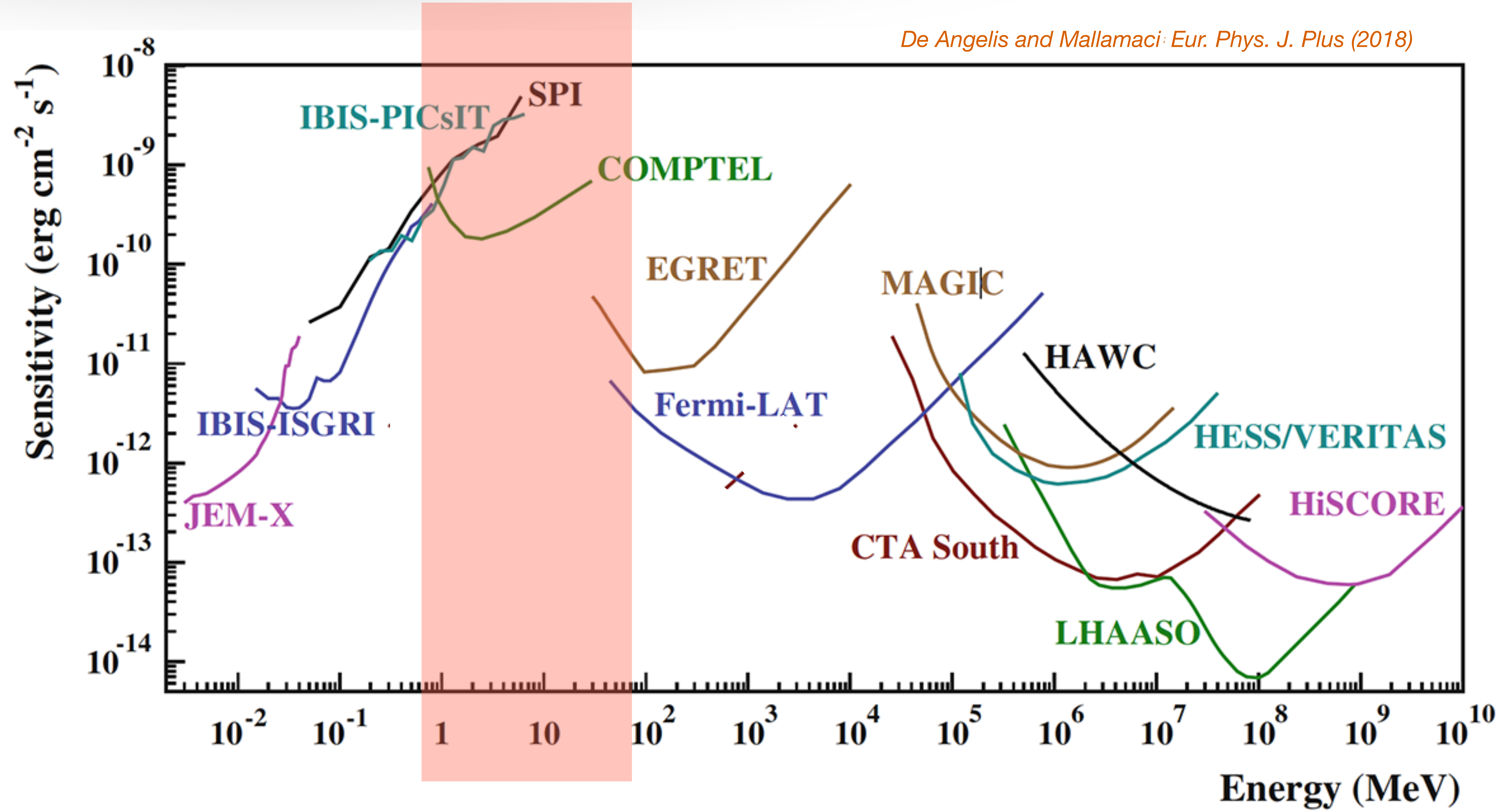

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- Important energy band for Gravitational Wave and multi-messenger astrophysics!

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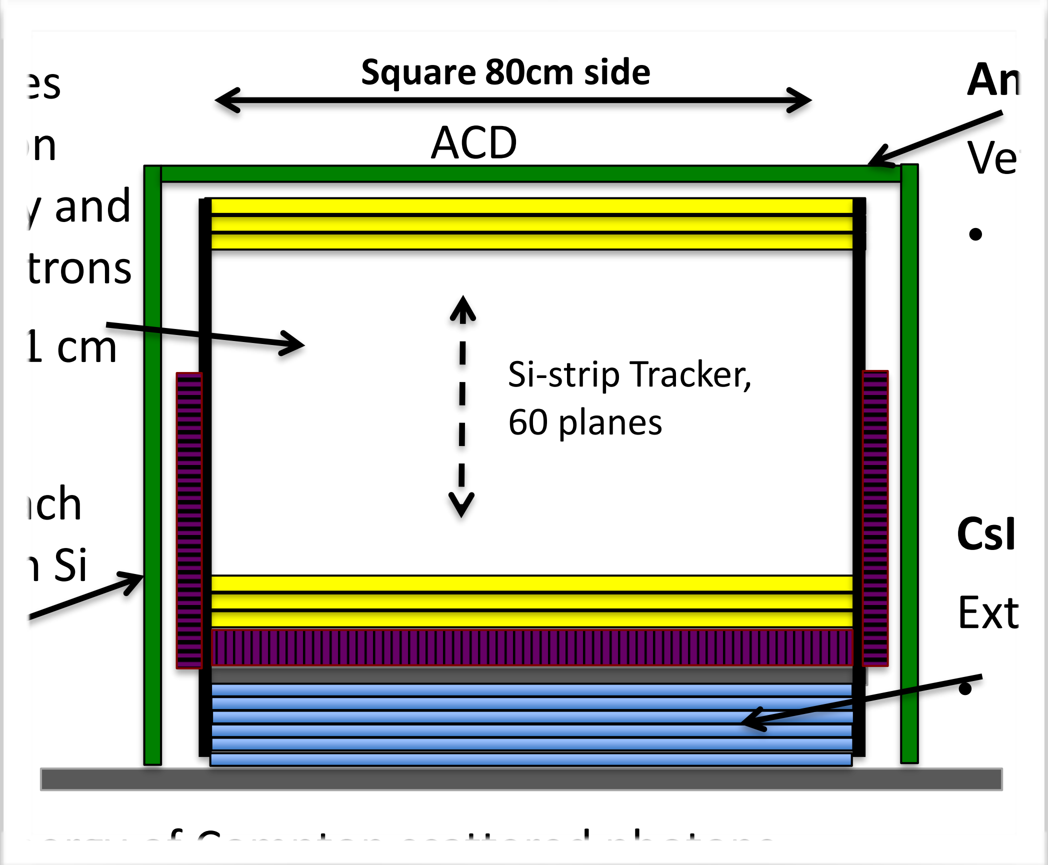
Future Proposed Missions:

- AMEGO:
  - ➤ https://asd.gsfc.nasa.gov/amego/
  - ➤ **NASA probe-class call**
  - ➤ Prototype Instrument:
    - ➤ Beam-test 2019
    - ➤ Balloon Flight 2021



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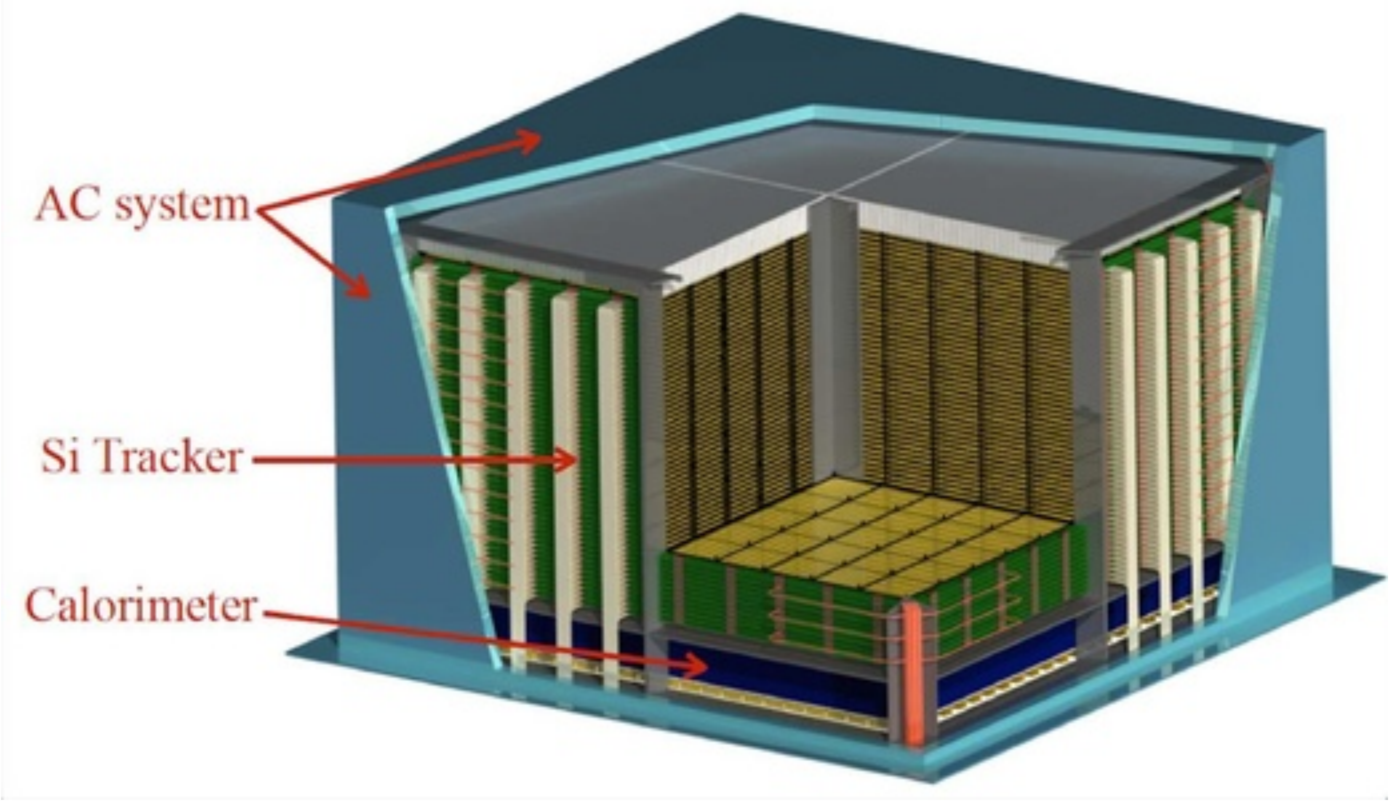
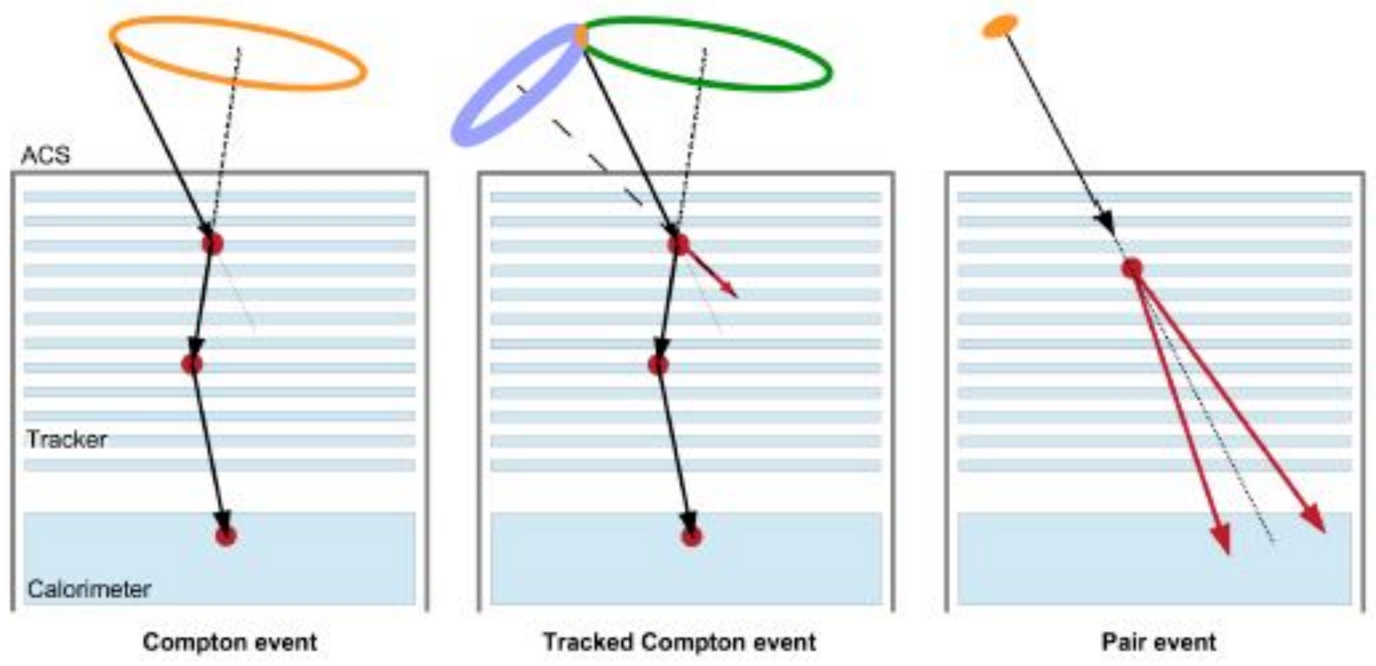
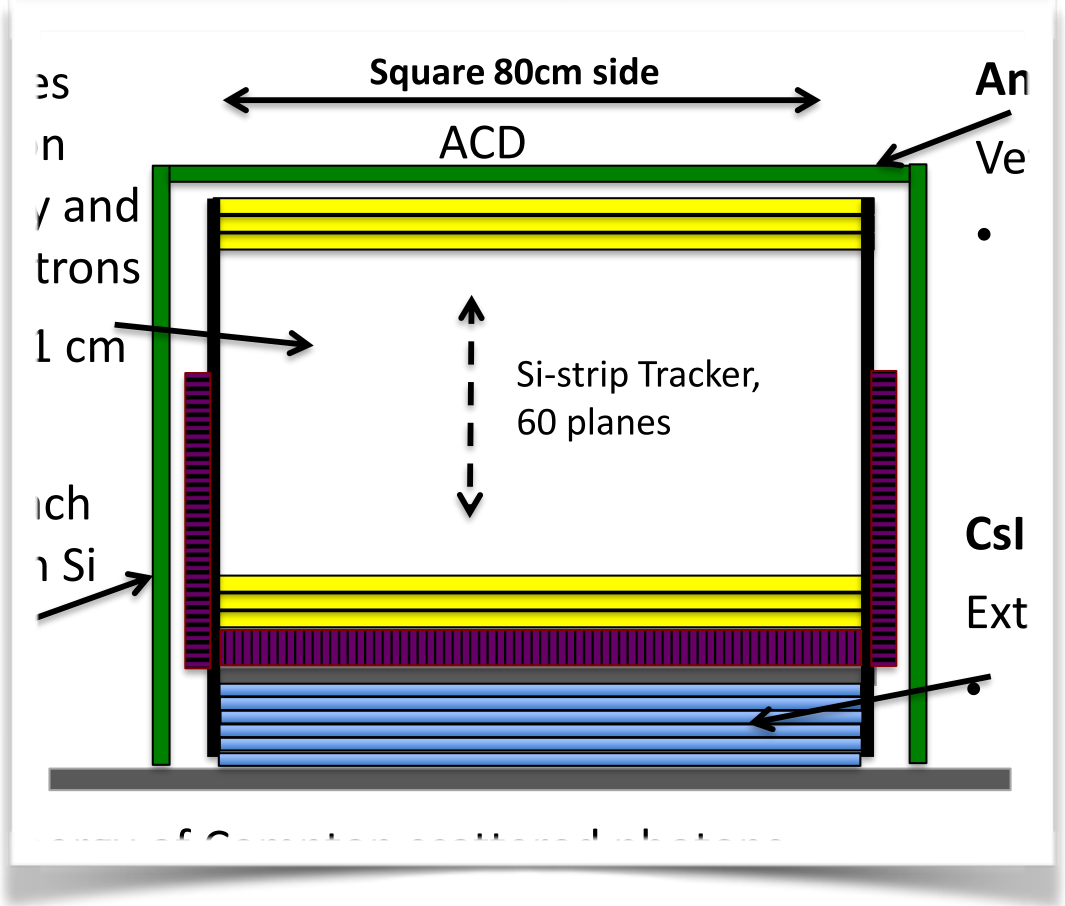
- e-ASTROGAM
  - ➤ http://eastrogam.iaps.inaf.it/
  - ➤ **ESA M5 call**







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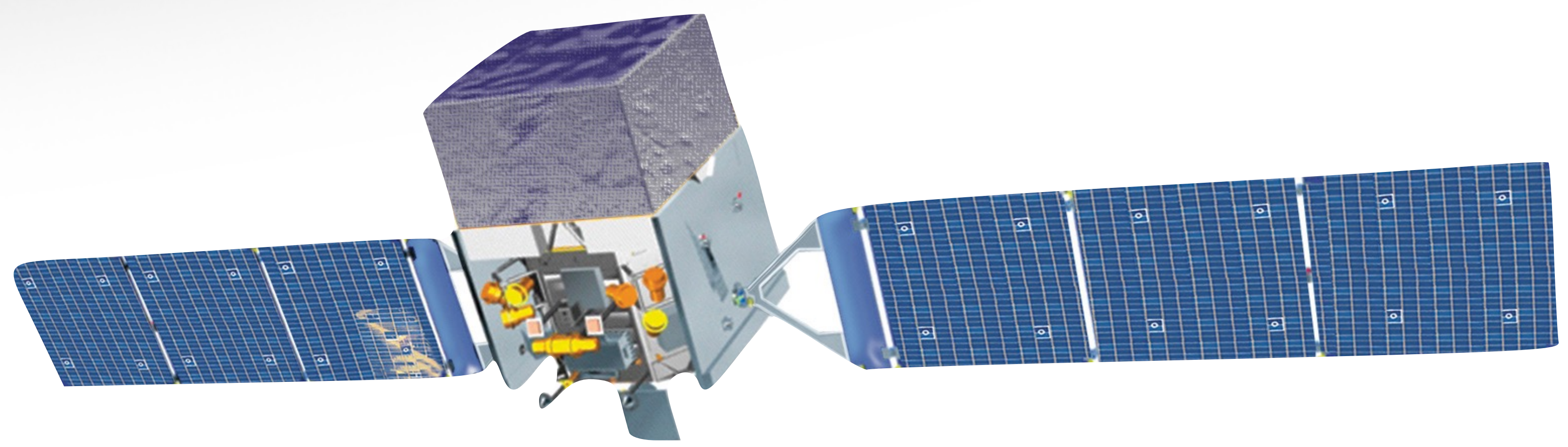
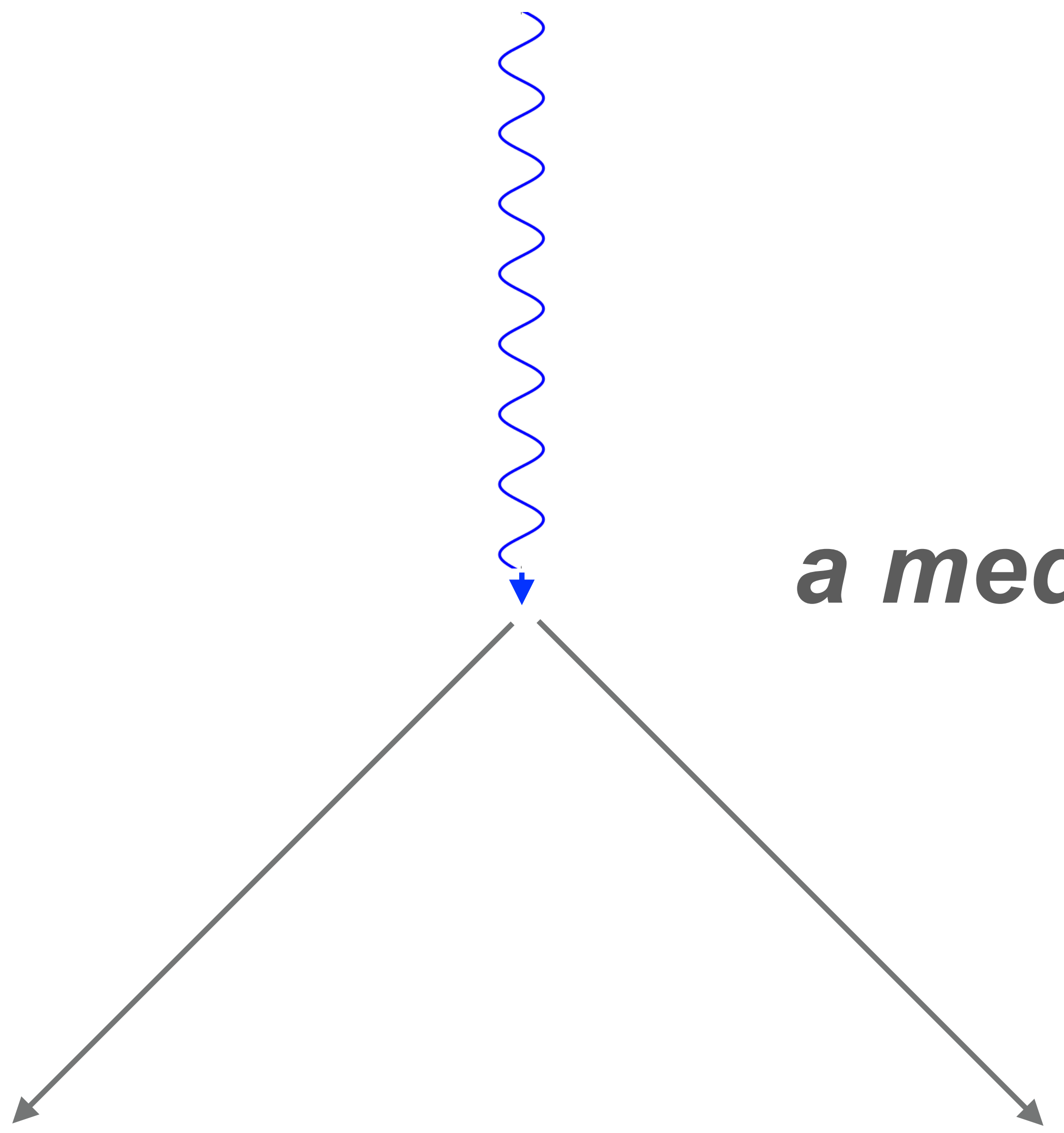
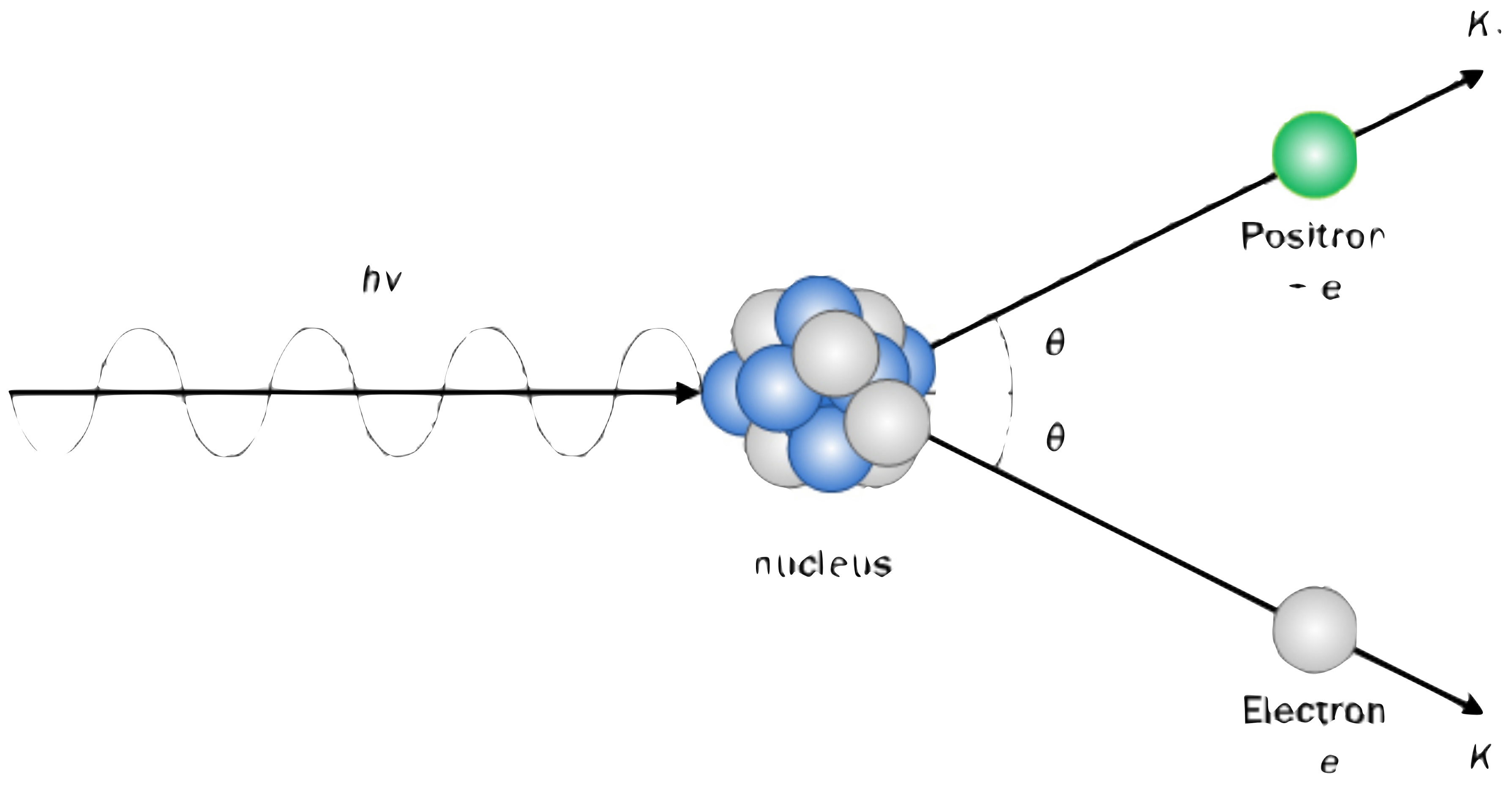




a medium



Pair-conversion Telescopes

Detection: *High Energy Gamma Rays*

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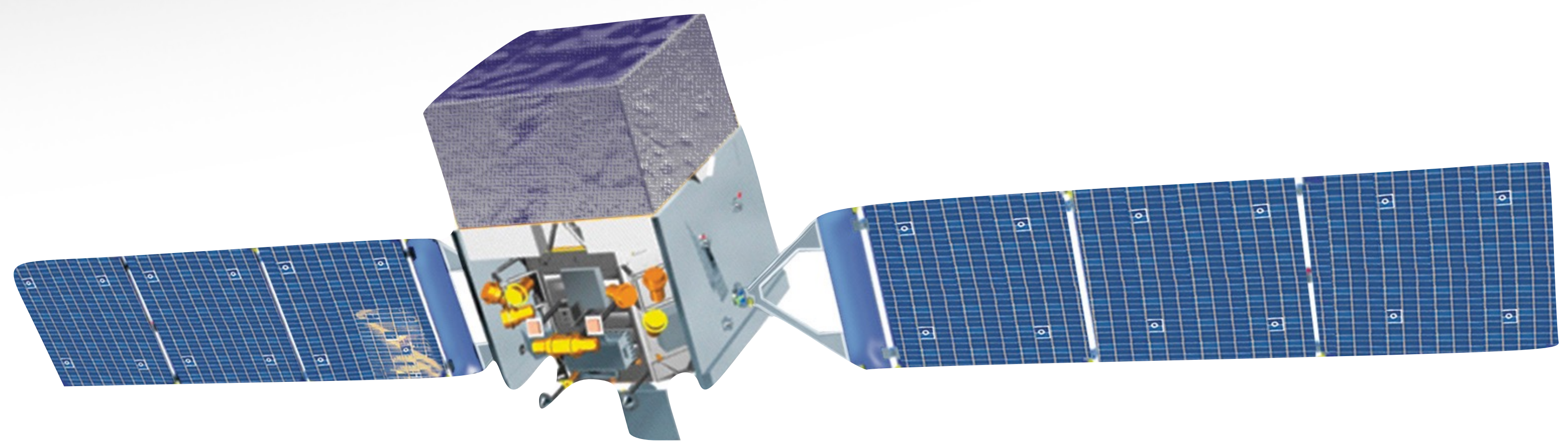

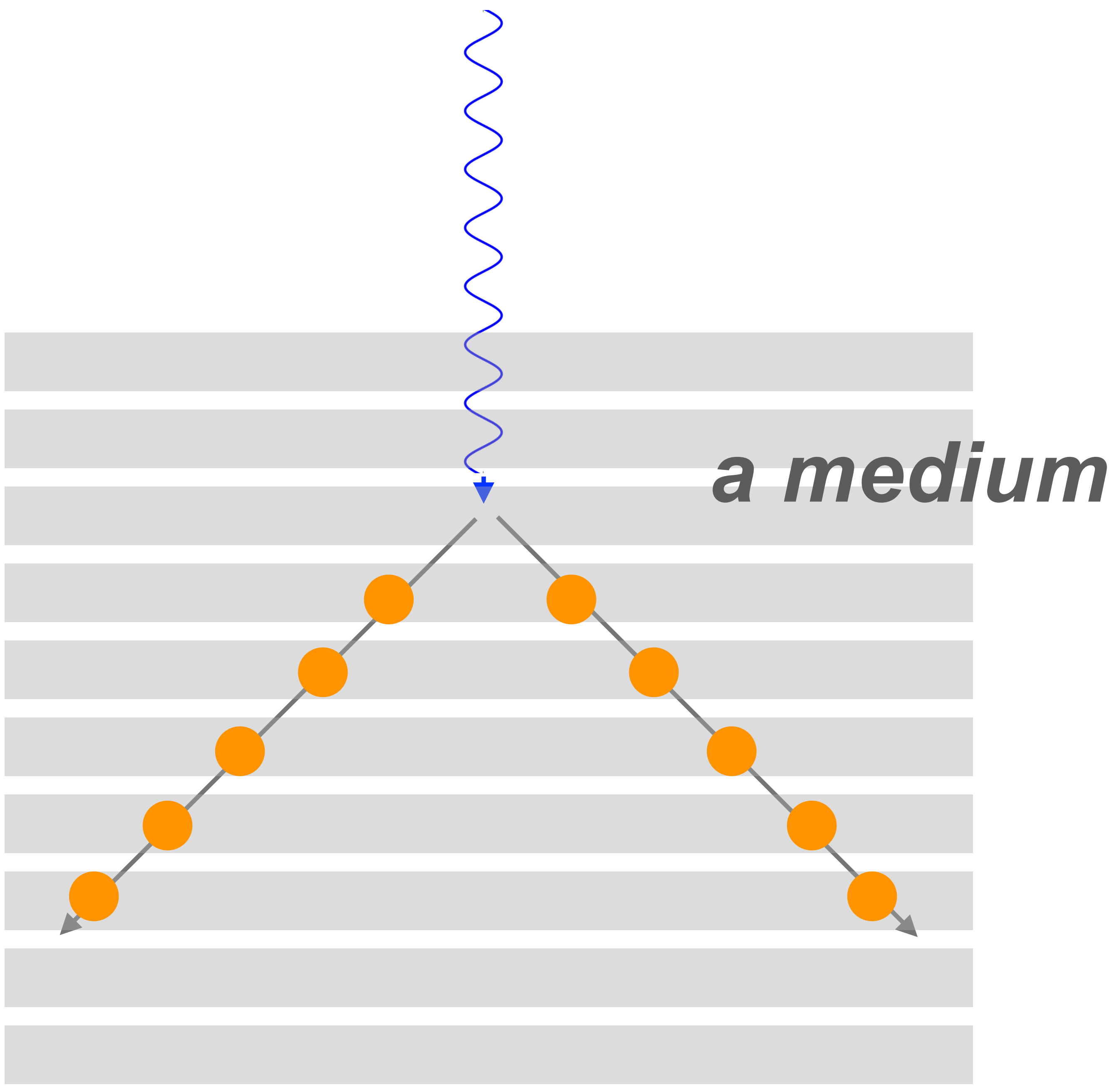

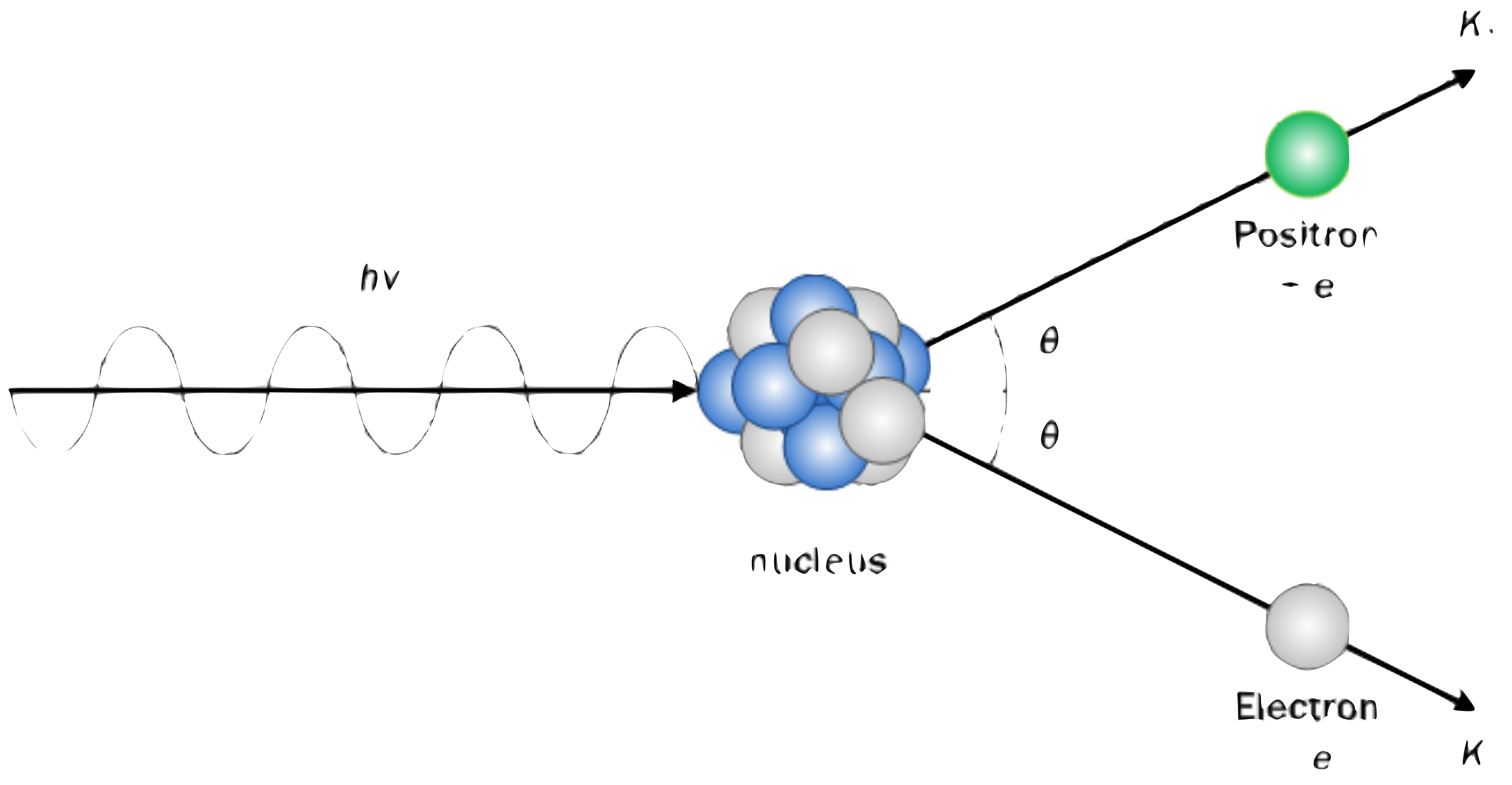

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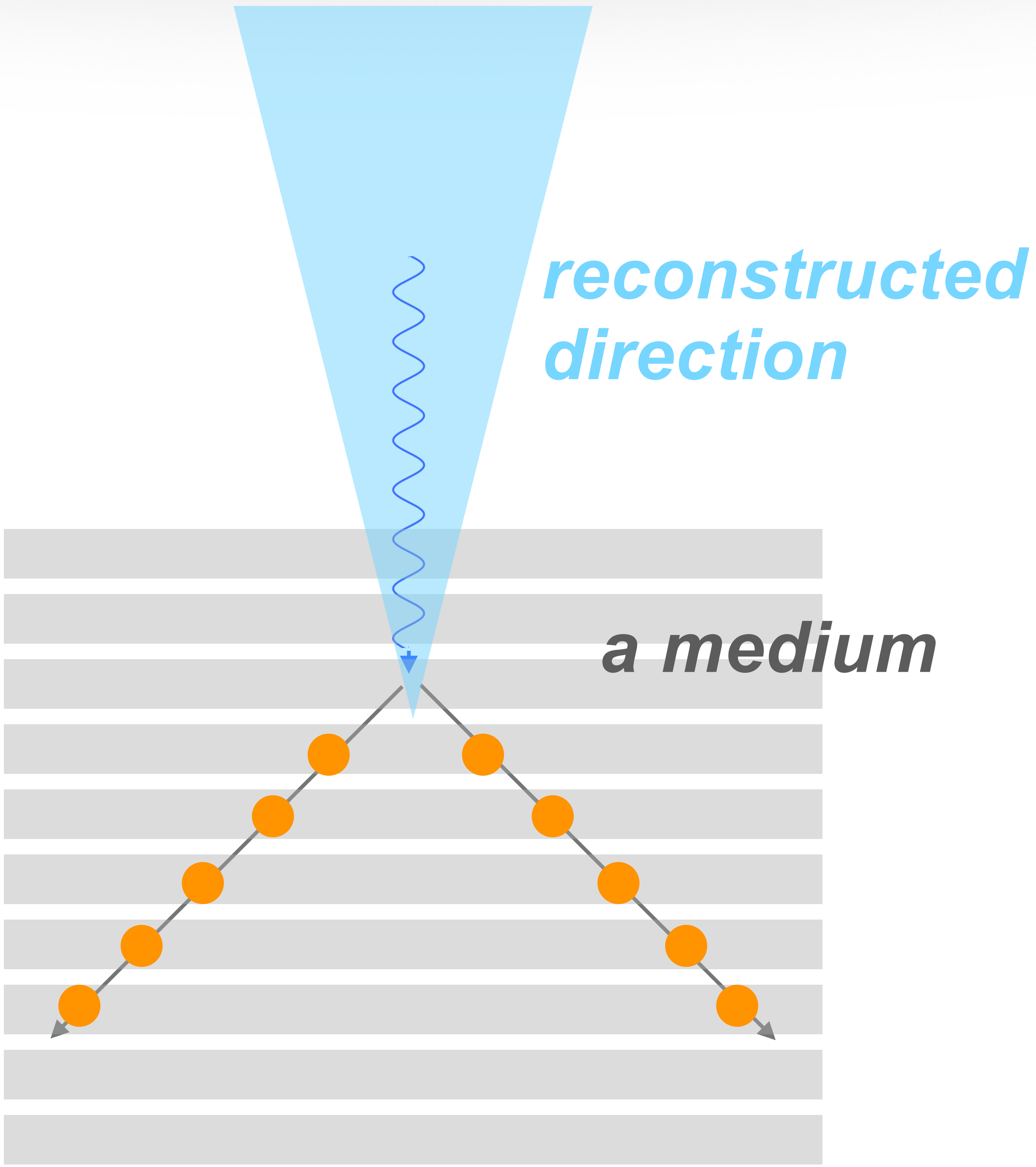

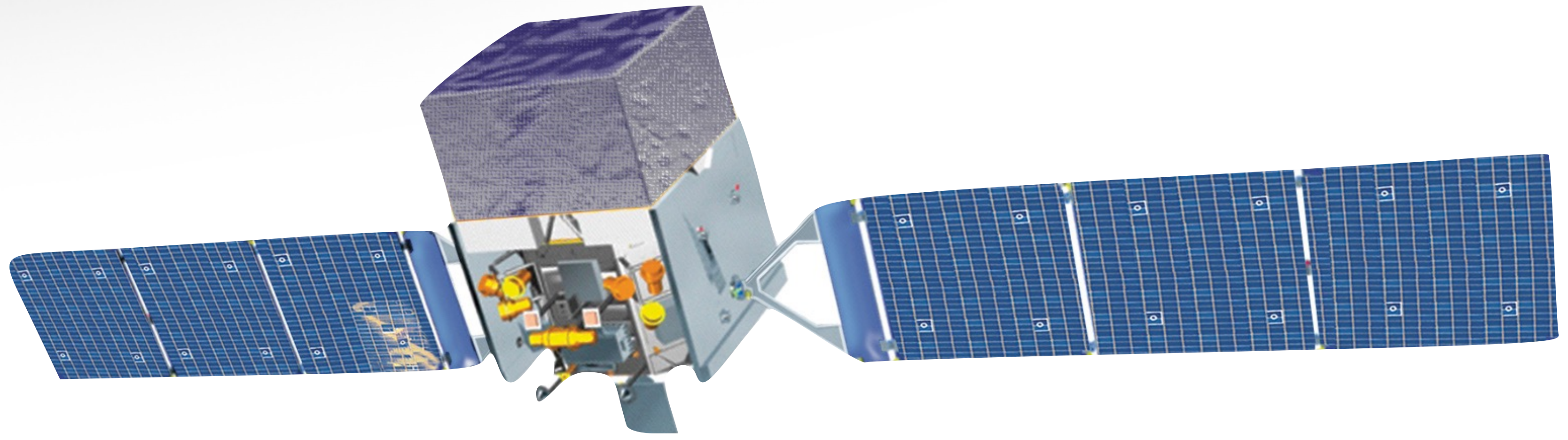

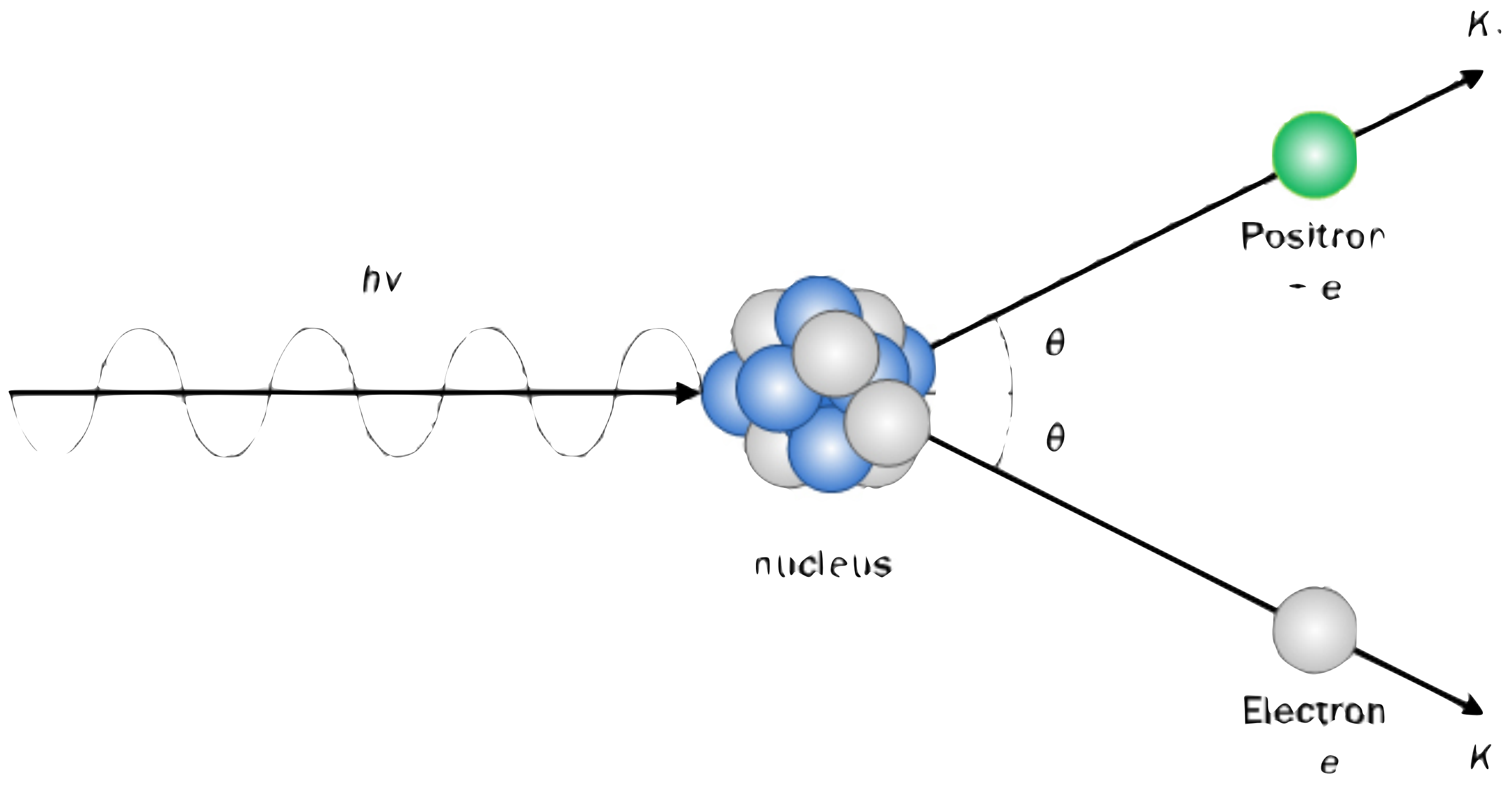

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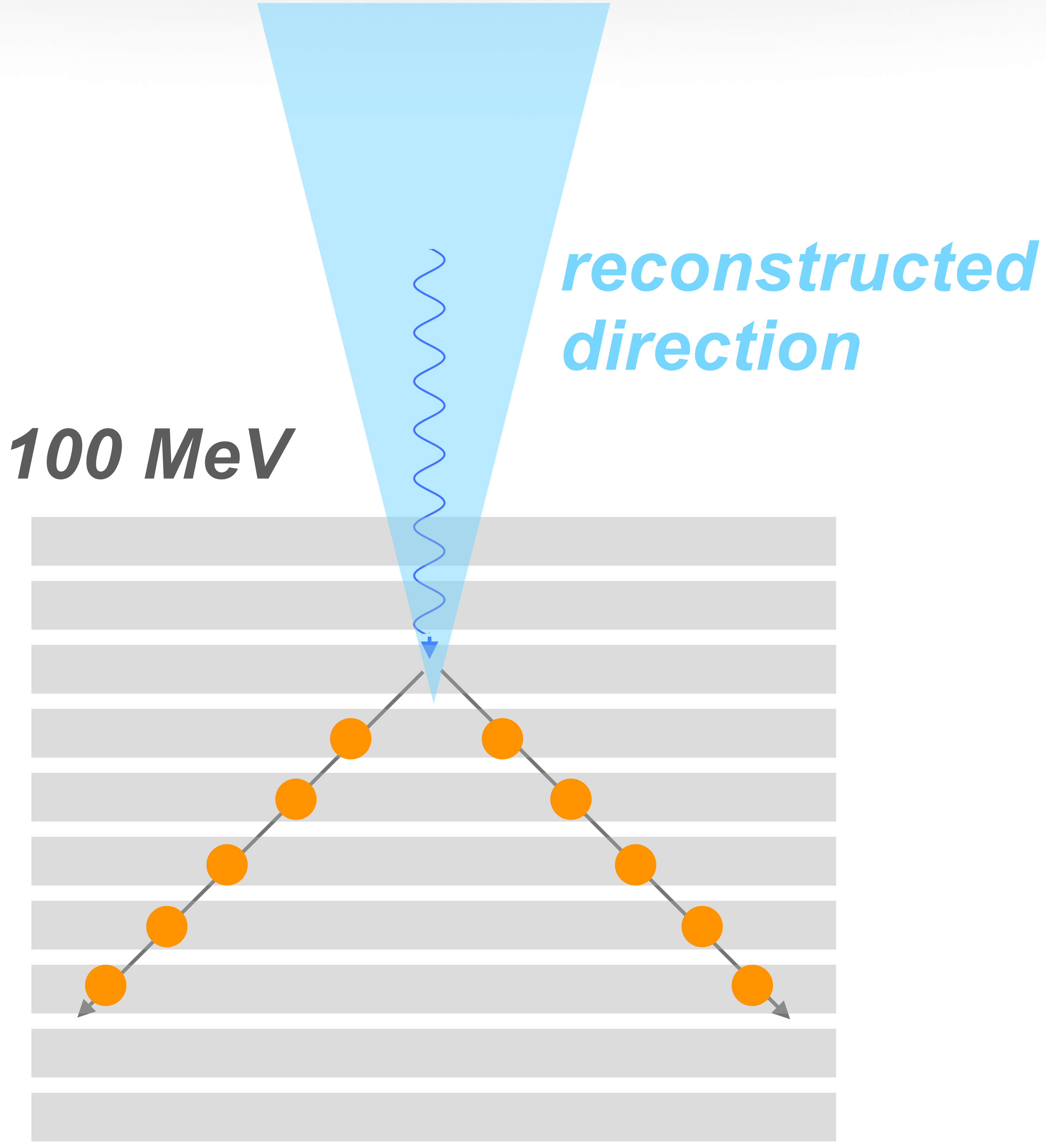
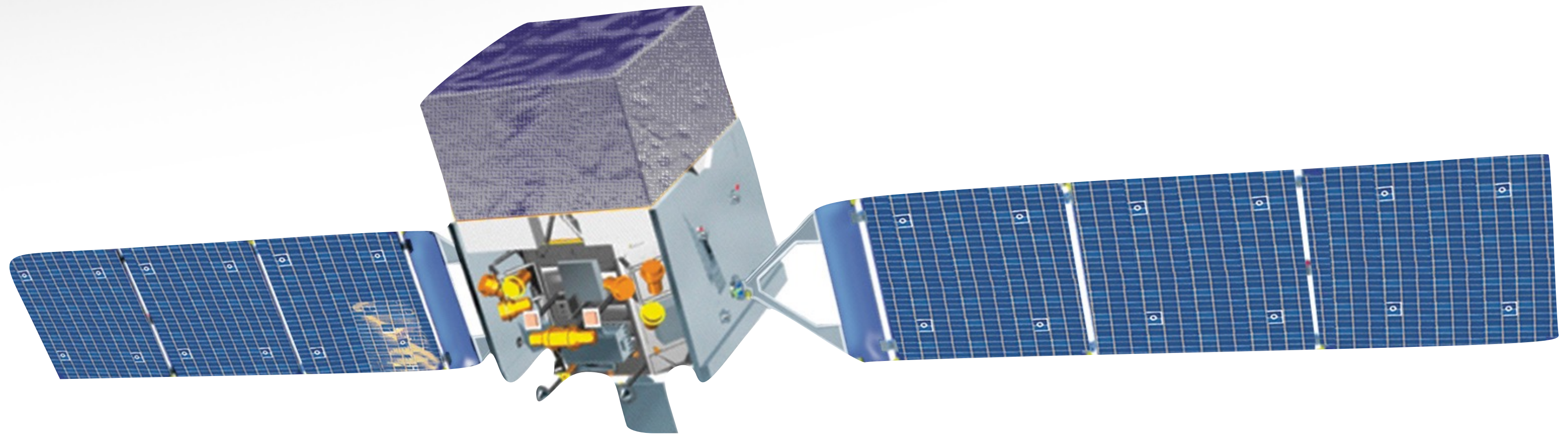
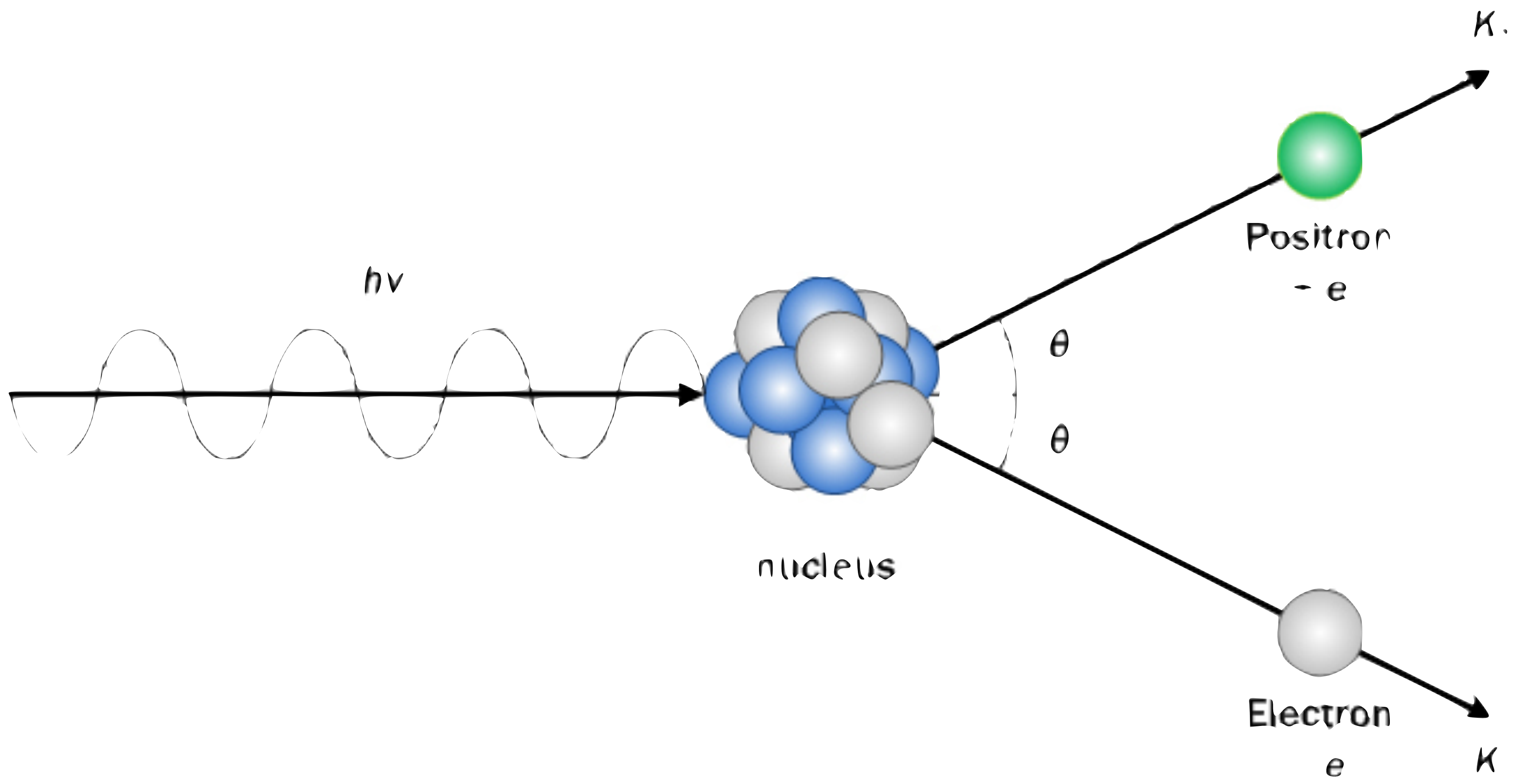
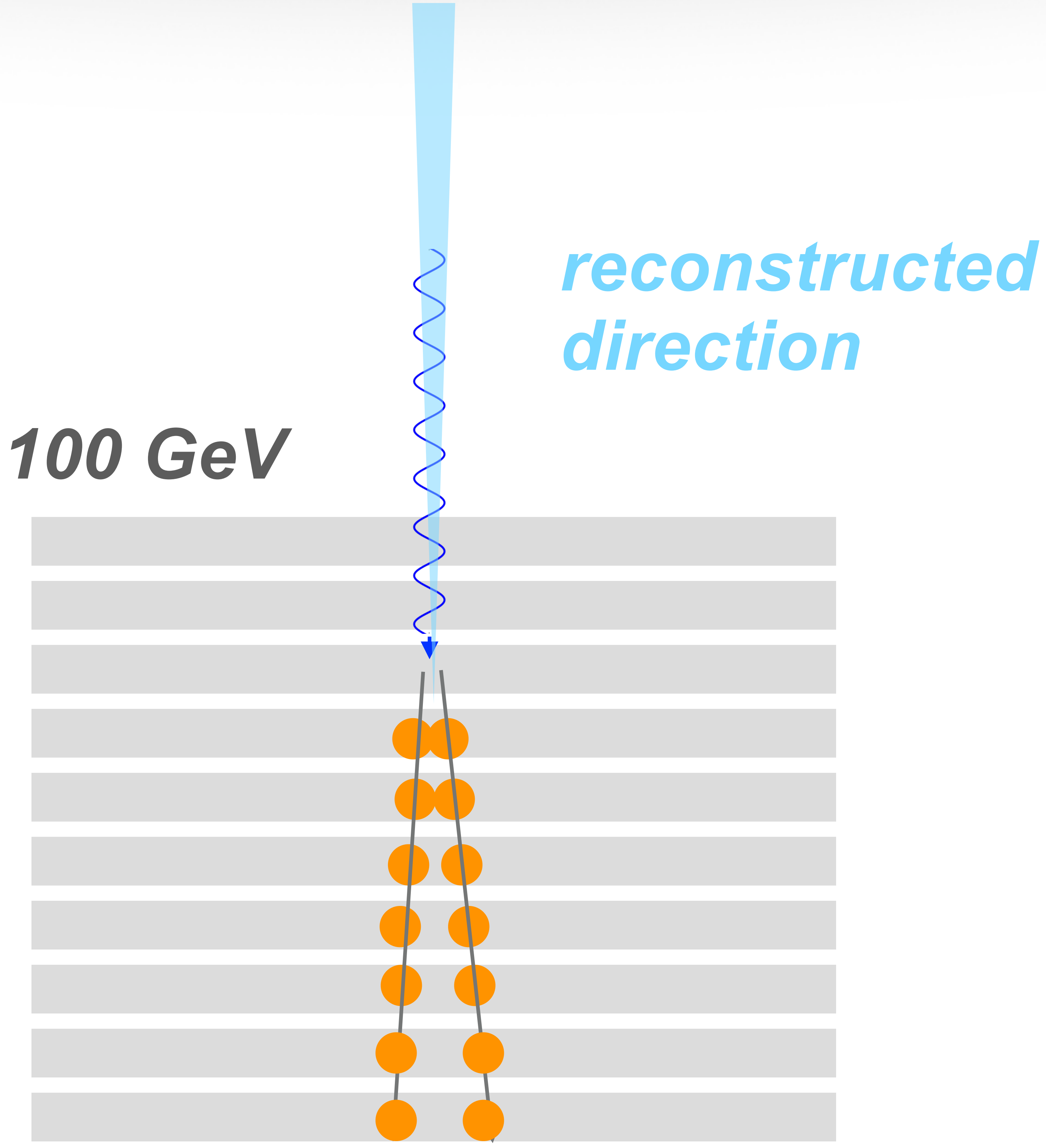


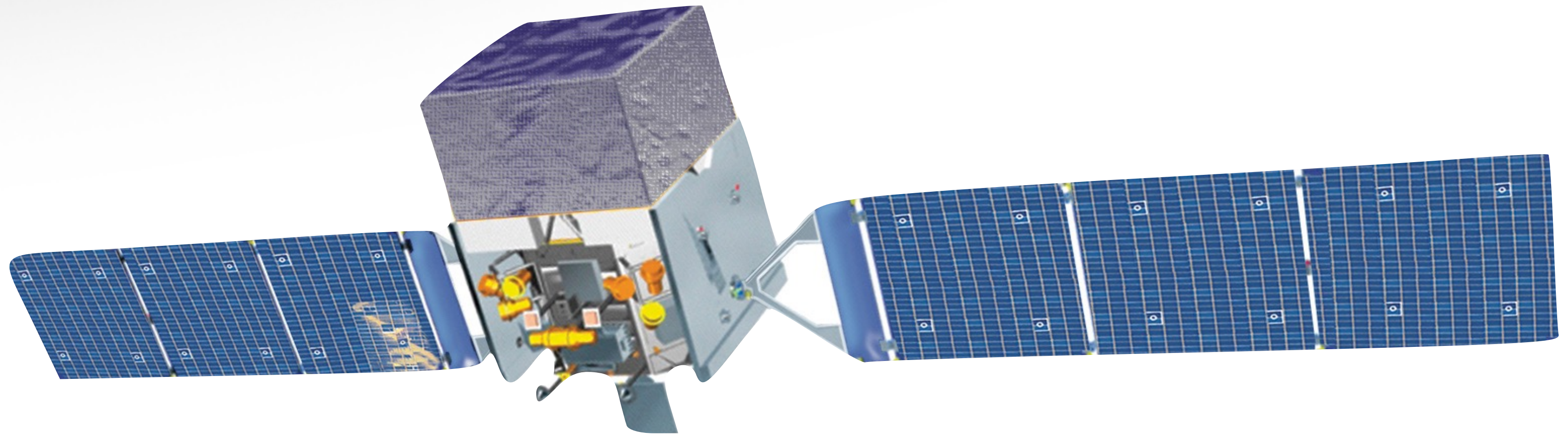




Pair-conversion Telescopes

Detection: *High Energy Gamma Rays*





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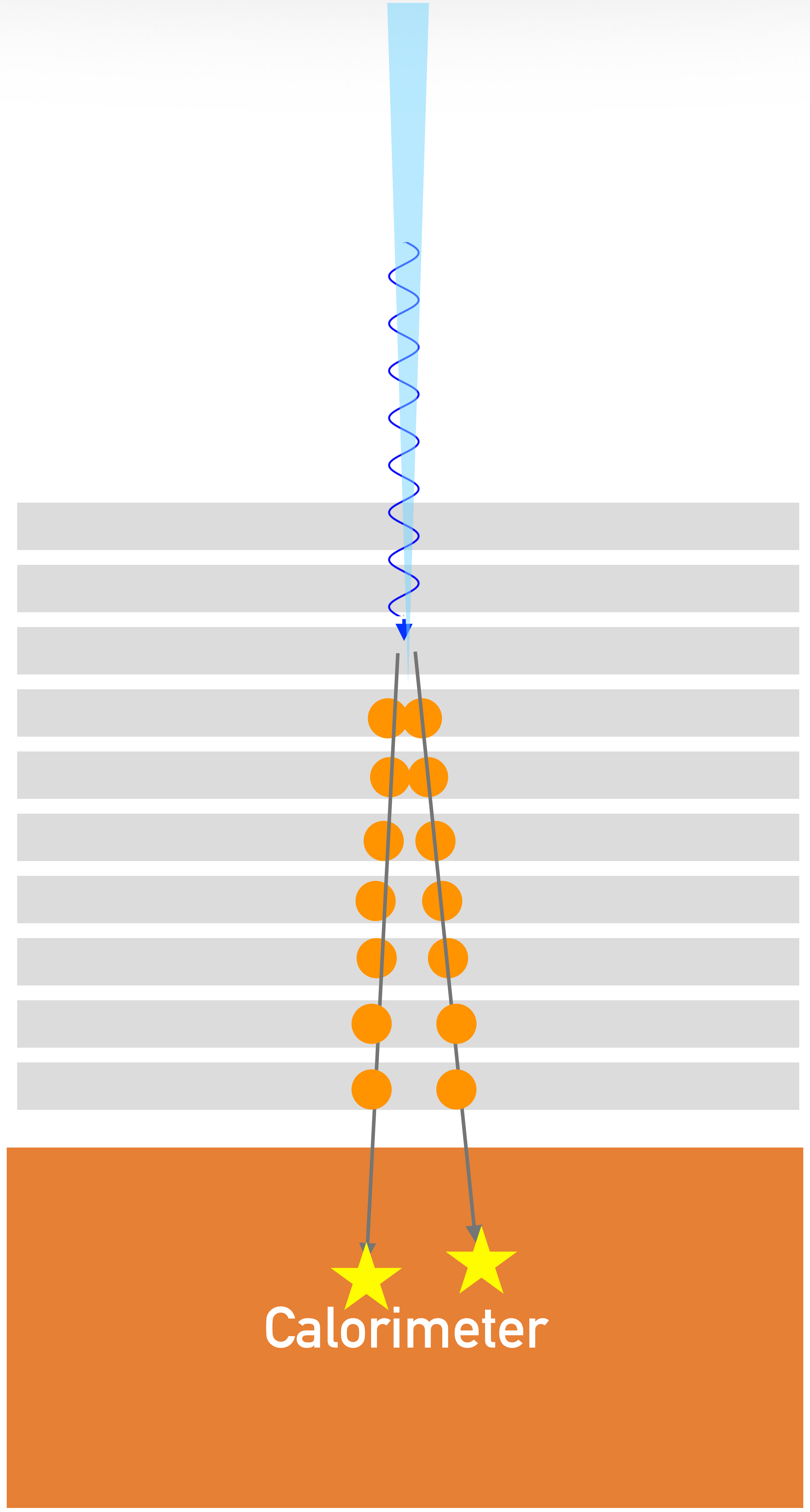

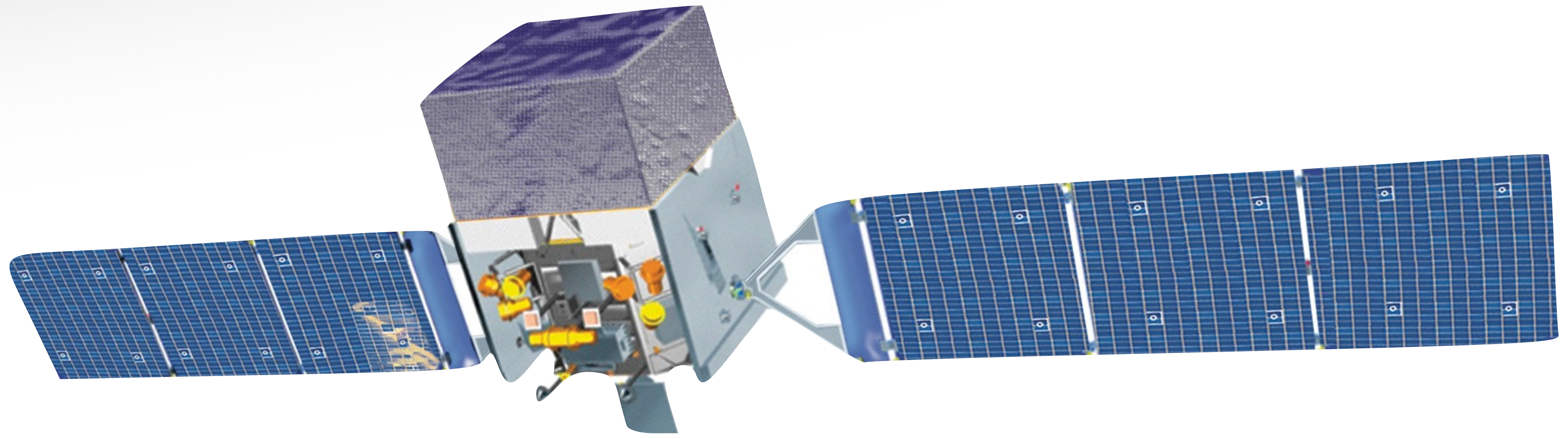

- At low energy, poorer reconstruction
- Direction reconstruction (PSF) gets better at higher energies
- Measure energy with a calorimeter
- Reject background with an anti-coincidence shield

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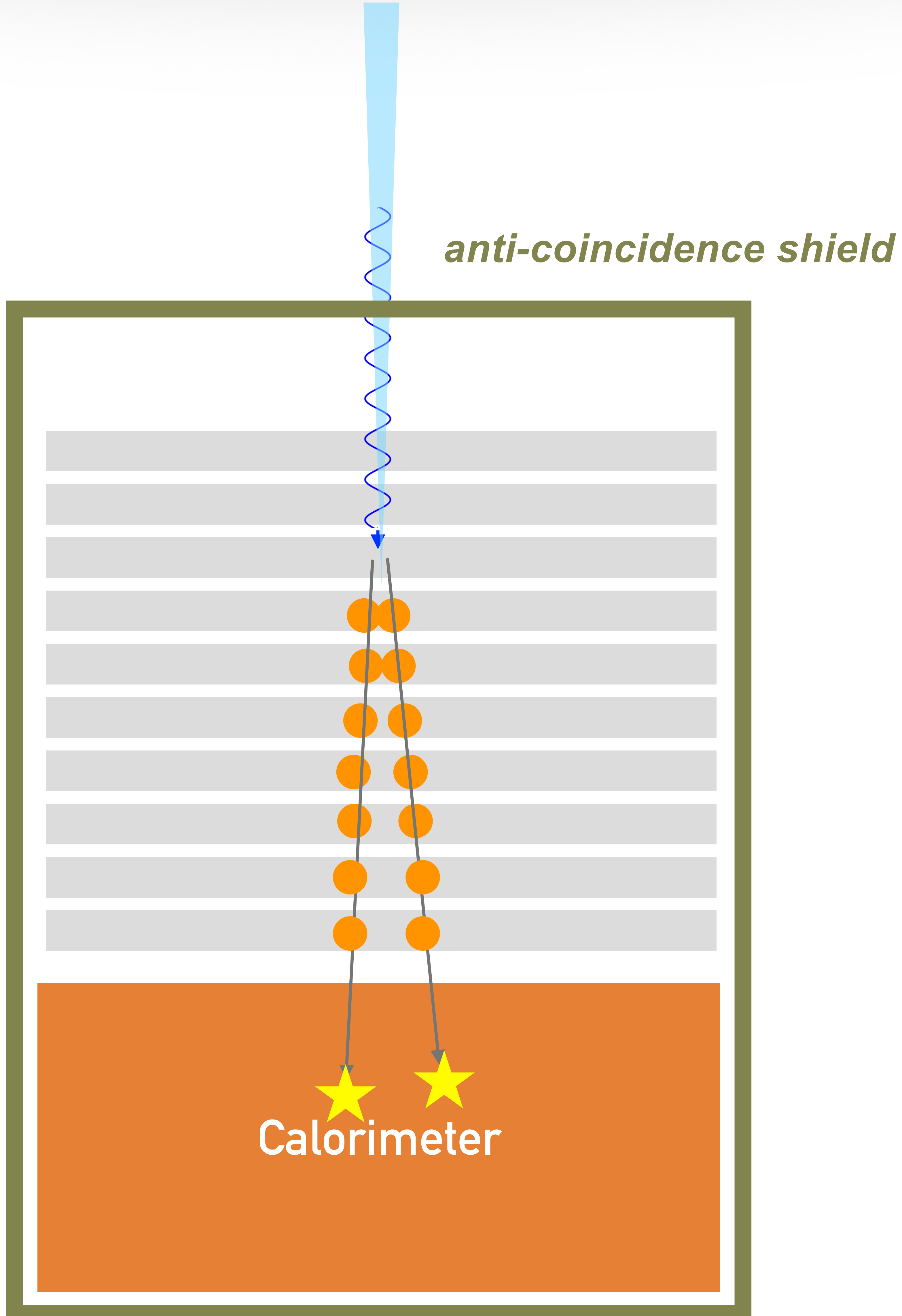

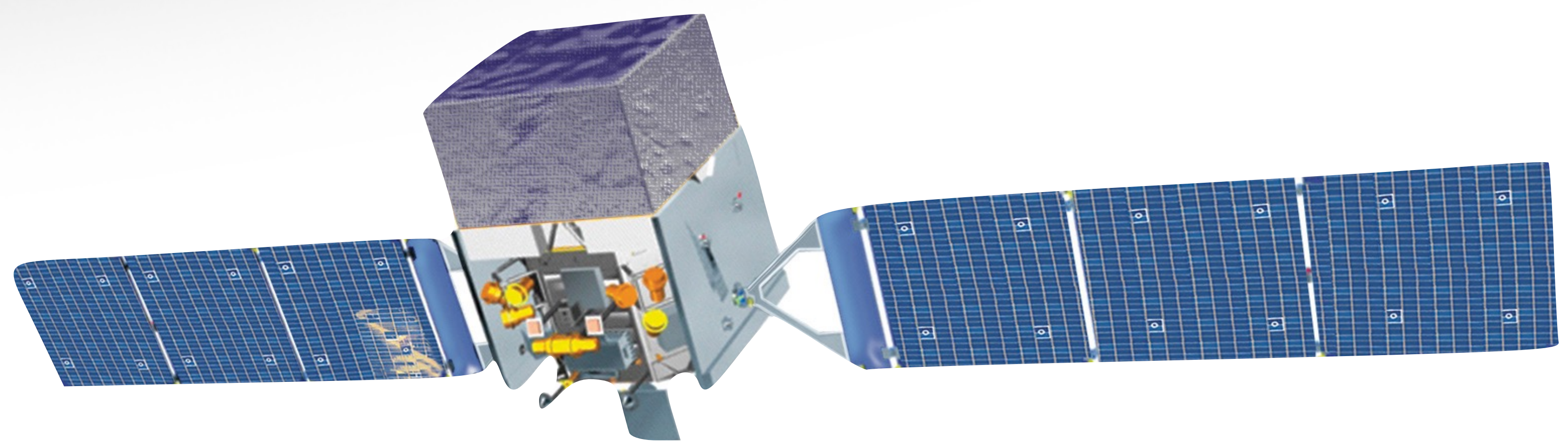

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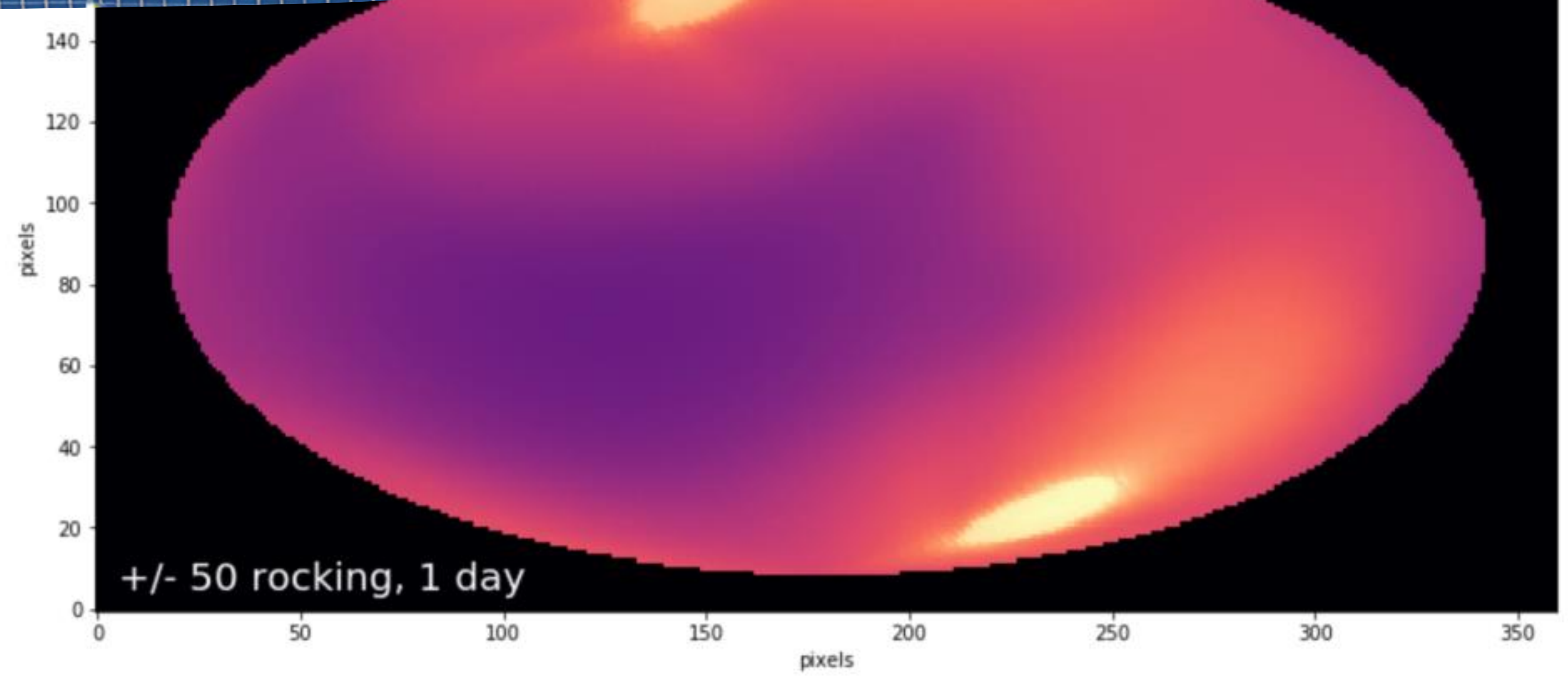
Fermi Gamma-ray Space Telescope

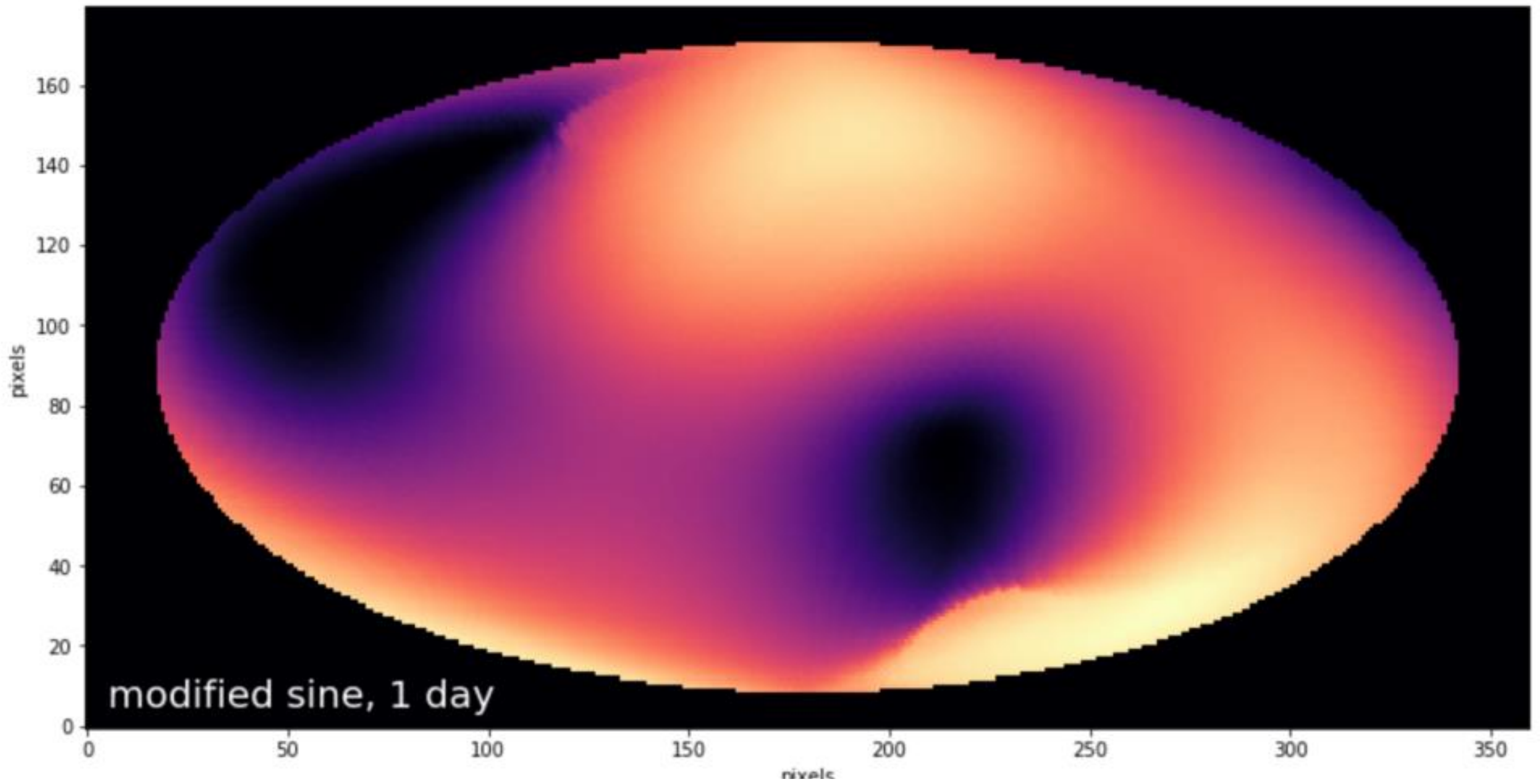
Instruments:

- LAT: "Large Area Telescope" (GeV)
- GBM "Gamma-ray Burst Monitor" (KeV -MeV)

LAT:

- FoV: > 2 steradians
- Energy Range: 20 MeV - 300 GeV
- Coverage:
  - ➤ all sky (normally once per day, but now 1/3 per day due to failed solar array drive)
- Angular Resolution:
  - ➤ < 3.5° (100 MeV)
  - ➤ < 0.15° (>10 GeV)
  - ➤ point-source localization: < 0.5'

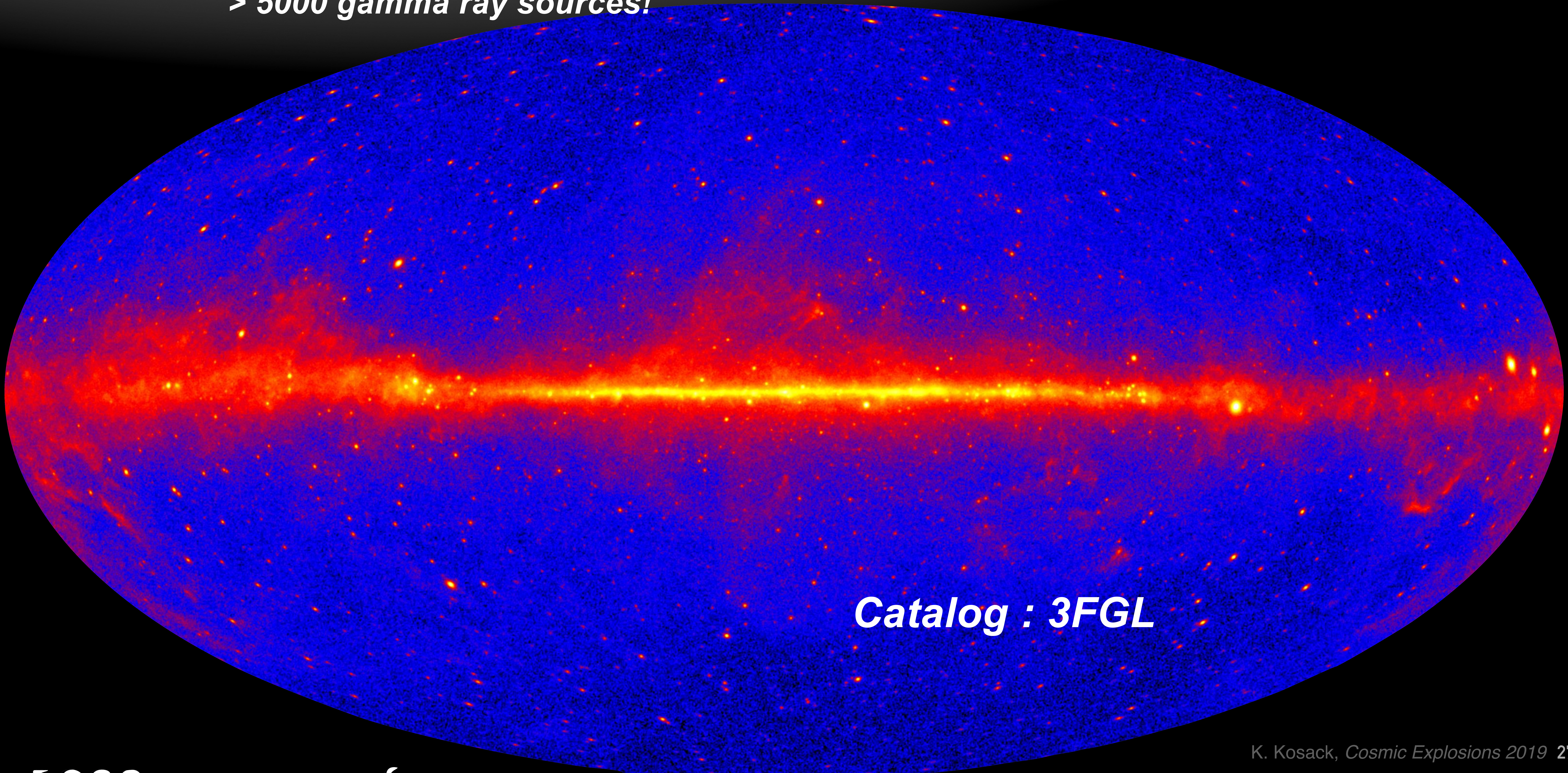




See Also: AGILE Space Telescope

The GeV Sky

> 5000 gamma ray sources!



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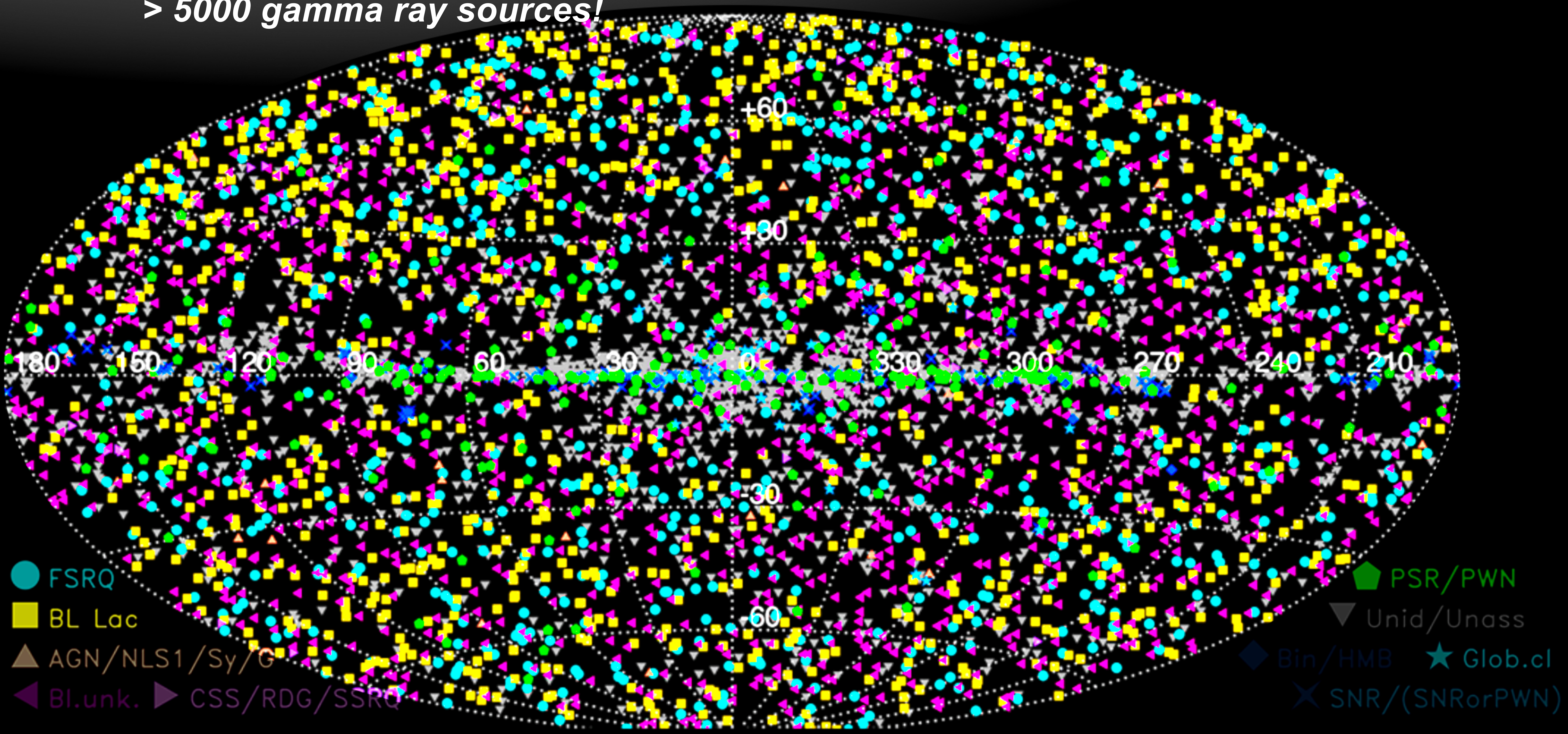
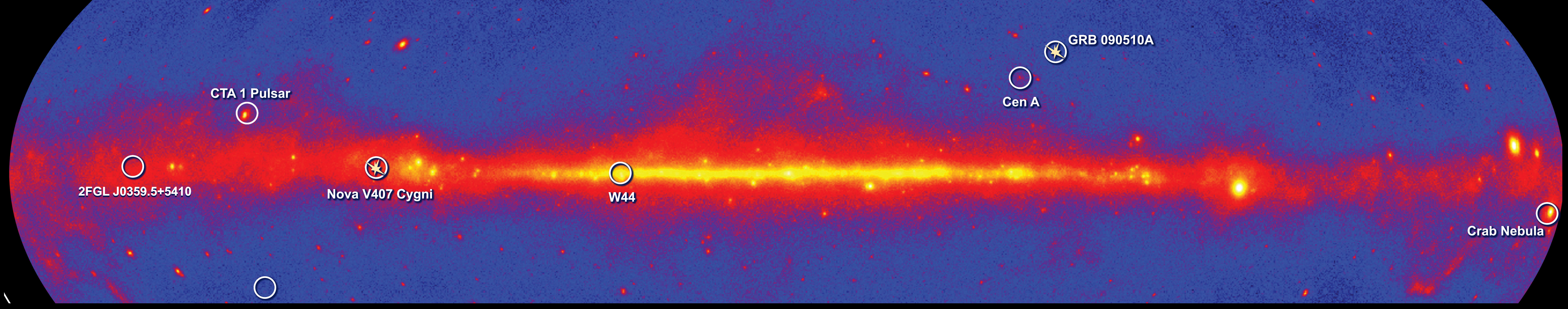
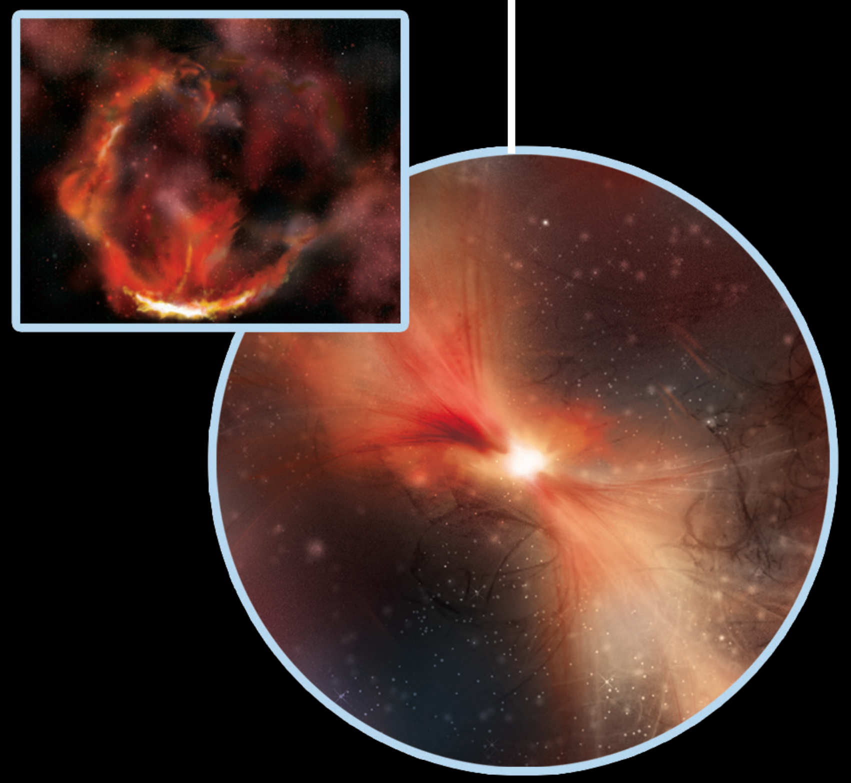
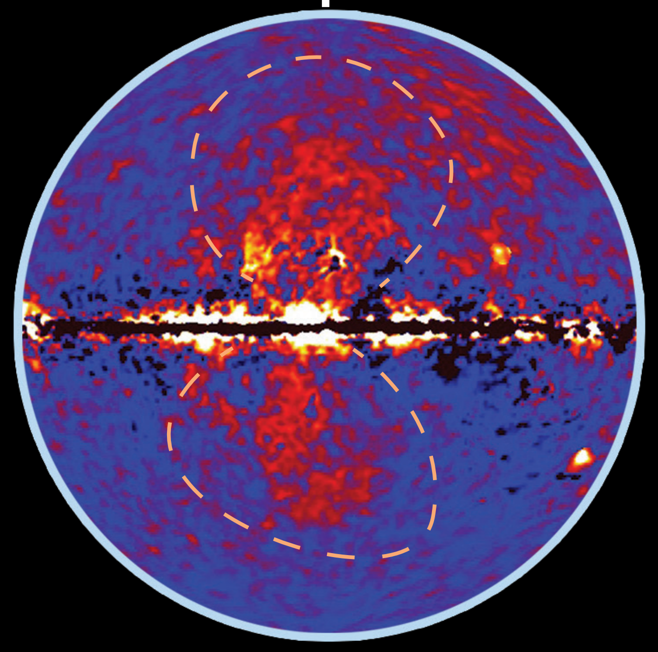


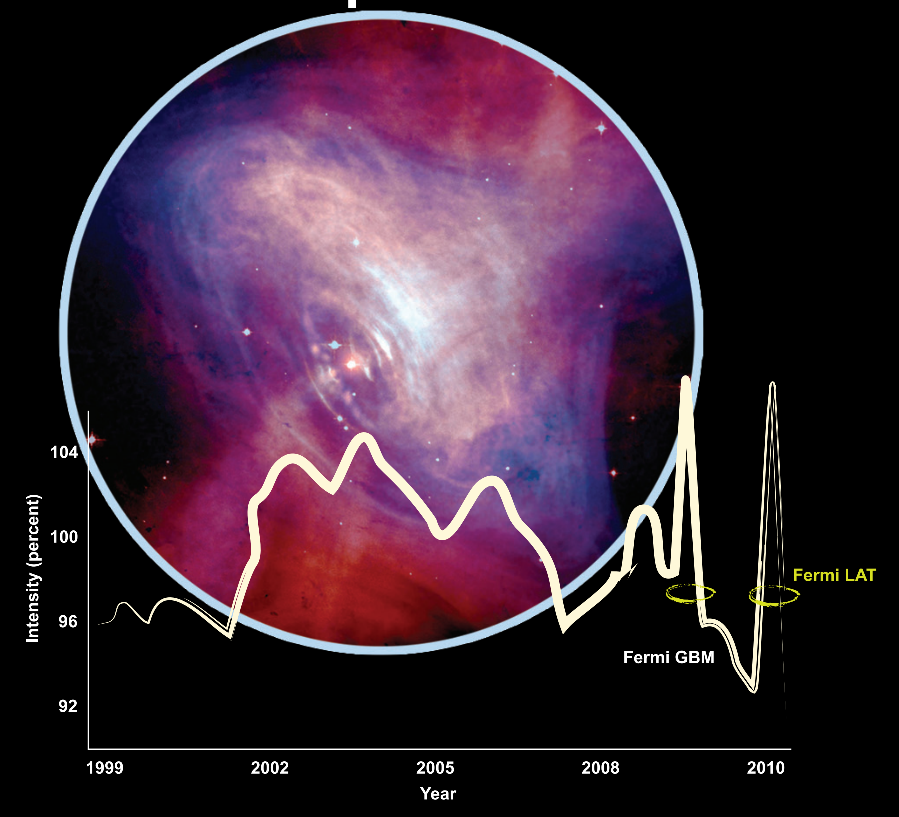




CTA 1 Pulsar: The first of many pulsars discovered by LAT scientists using only gamma-ray data was the one in supernova remnant CTA 1. A pulsar is a neutron star whose rapid rotation powers beams of radio, X-ray and gamma radiation. Although 10,000 years old, the CTA 1 pulsar still emits a thousand times more energy than our sun. *Illustration: NASA SSU E/PO, Simonnet.*

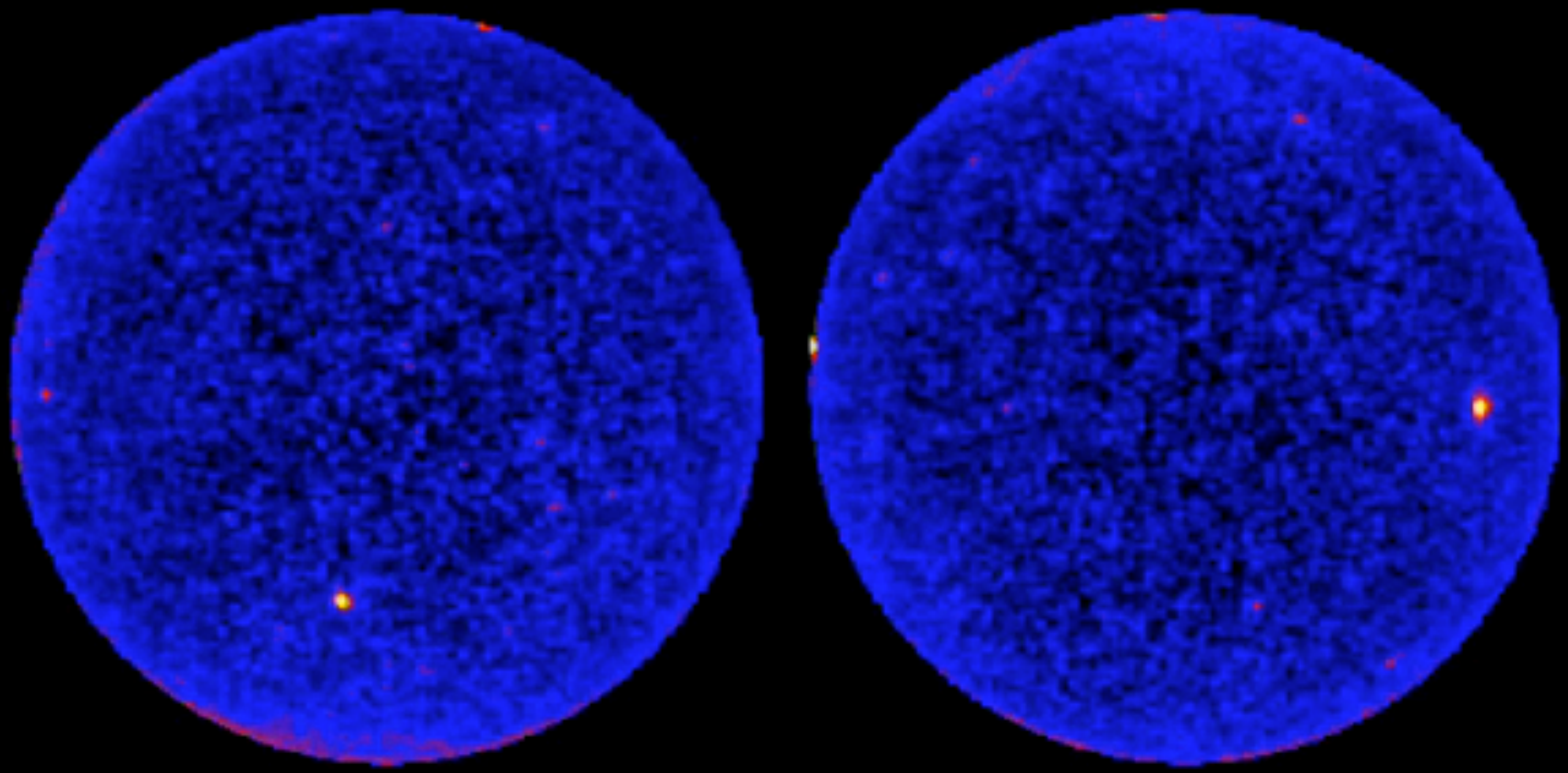


Giant Gamma-ray Bubbles: Another Fermi surprise: In late 2010, scientists uncovered a giant gamma-ray-emitting structure (dashed lines) extending 25,000 light-years north and south of the Milky Way's central plane. These gamma-ray "bubbles" may have formed from a past eruption of our galaxy's supermassive black hole. *NASA/DOE/Fermi LAT/D. Finkbeiner et al.*



Crab Nebula: Fermi observations of the Crab Nebula, a young supernova remnant containing a pulsar, reveal gamma-ray flares set off by the most energetic particles ever traced to a specific astronomical object. To account for the days-long flares, scientists say that electrons near the pulsar must be accelerated to energies a thousand trillion (10^{15}) times greater than that of visible light. Above is a composite of the nebula in visible light and X-rays. *NASA/CXC/HST/ASU/J. Hester et al.*

The Variable Sky at GeV energies



Fermi-LAT 2008

https://svs.gsfc.nasa.gov/10407

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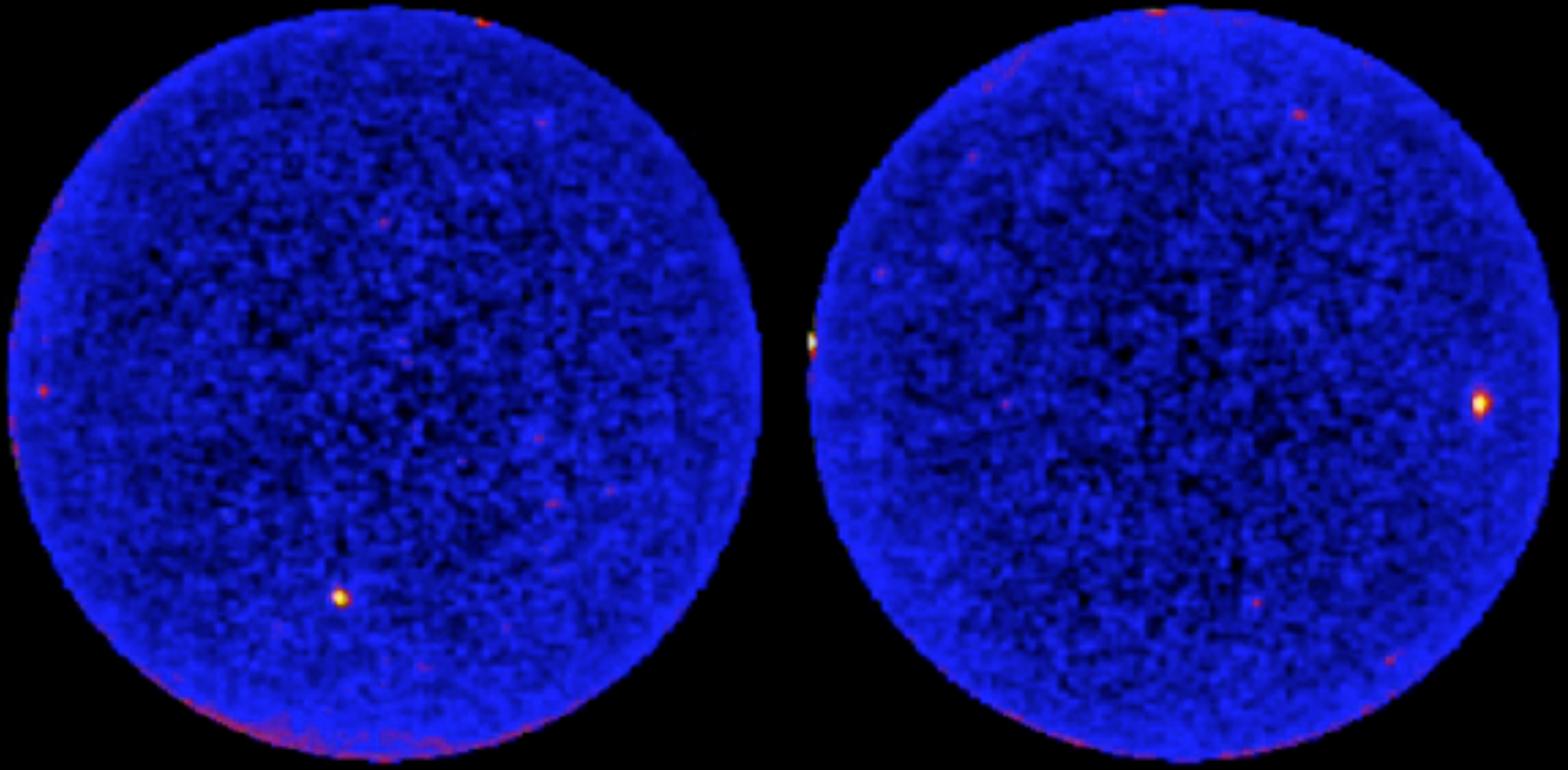


Fermi-LAT 2008

https://svs.gsfc.nasa.gov/10407

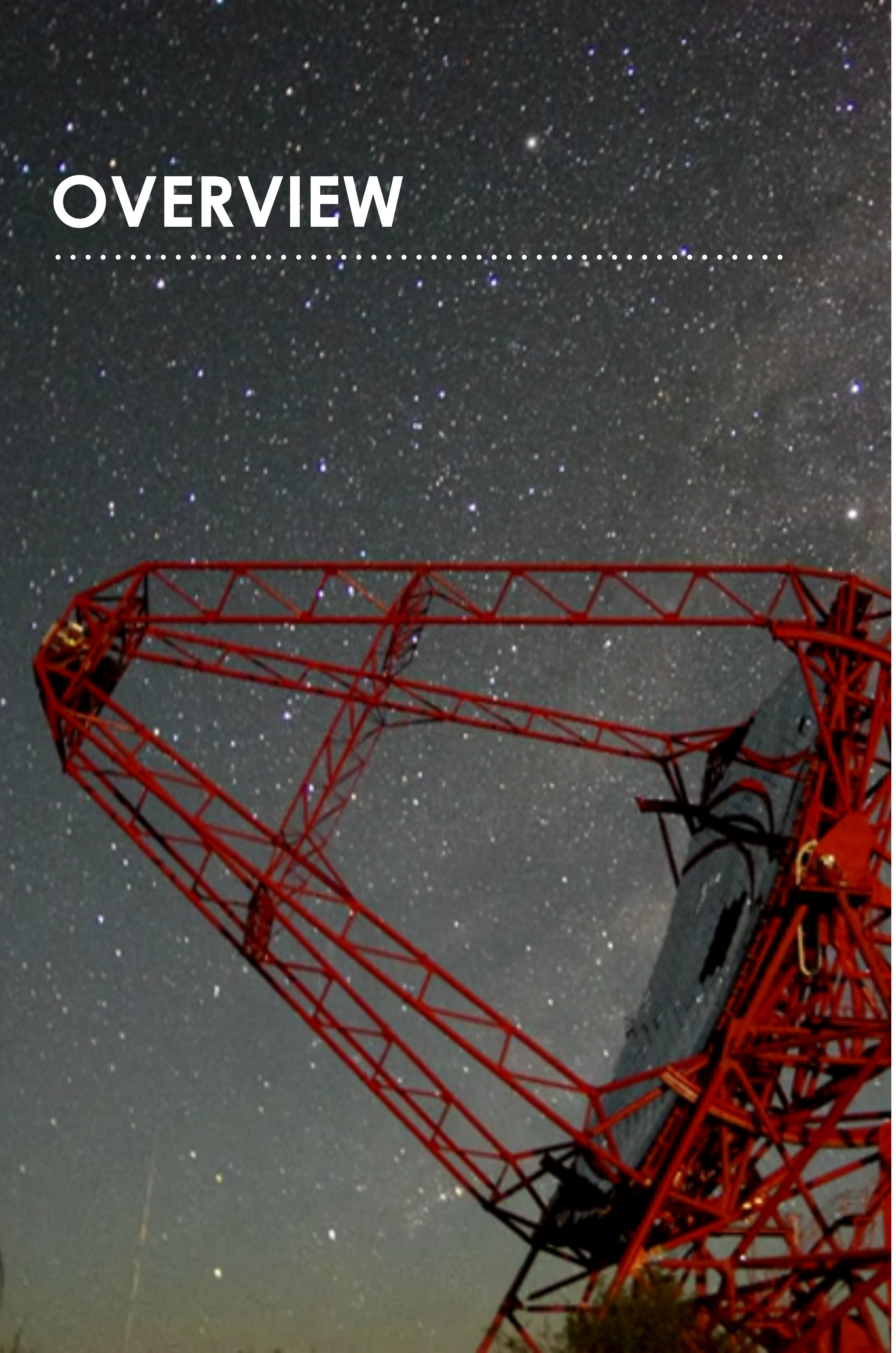
High-Energy Resources

Fermi Catalogs:

- 3FGL: 3rd Fermi-Lat Gamma-Ray catalog
- 3FHL: Highest energy catalog (subset of sources)
- 1SC: First Fermi-LAT supernova catalog

Fermi-Lat Data:

- all publicly available online
- need Fermi Science Tools to analyze
  - ➤ spatial-spectral likelihood minimization



Introduction

Medium Energy Gamma Rays

- detection
- science
- future

High-Energy Gamma Rays

- detection
- science
- future

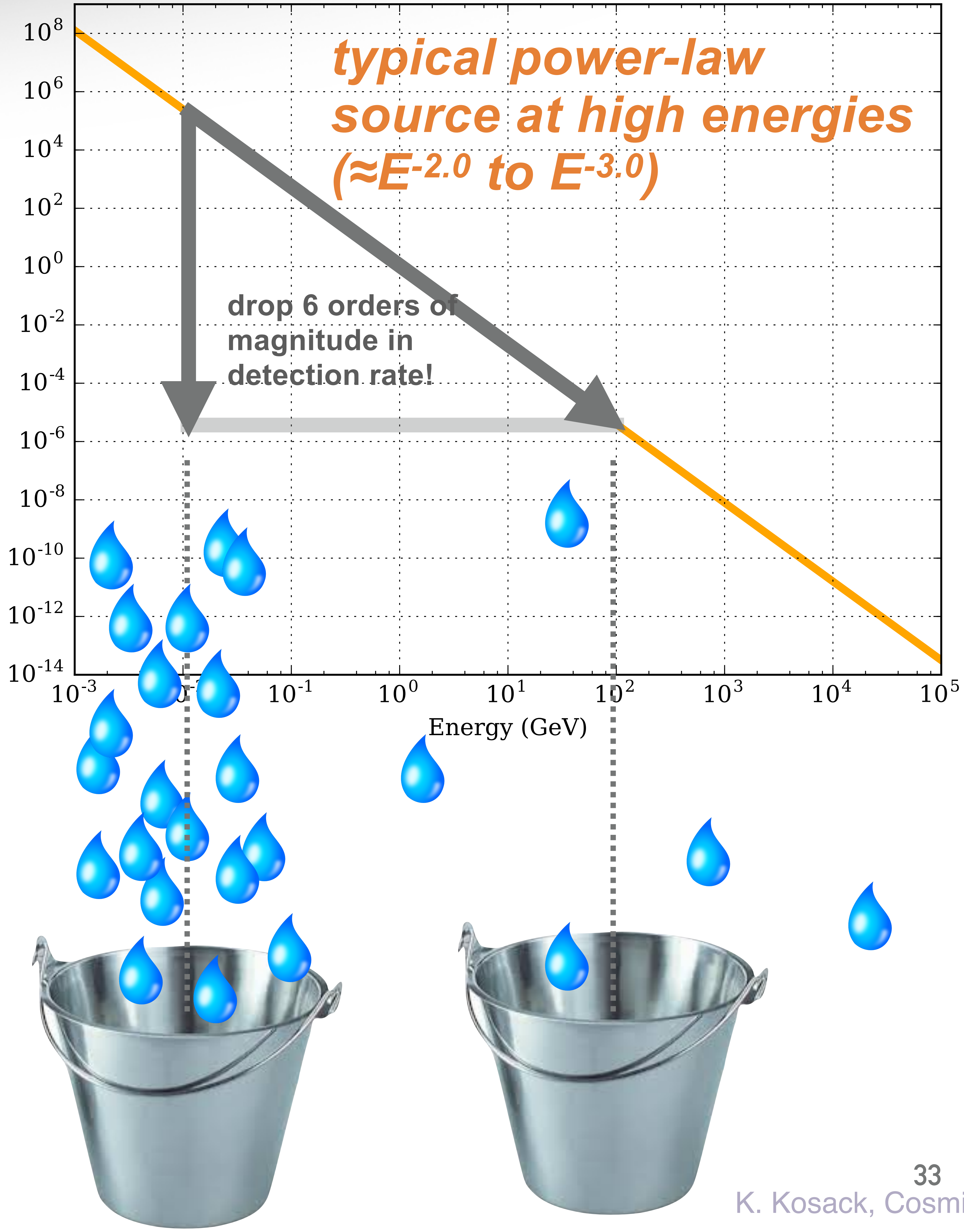
Very High Energy Gamma Rays

- detection
- science
- future

Summary and Outlook

Limiting effect: the spectrum!

- Effective collection area of Fermi-Lat is 1 m²
- Count-rate of brightest gamma-ray source (Crab Nebula) :
  10^{-7} Hz above **1 TeV**
  - ➤ a *photon* every few months!
- **beyond a few hundred GeV: want at least 100,000x bigger!**



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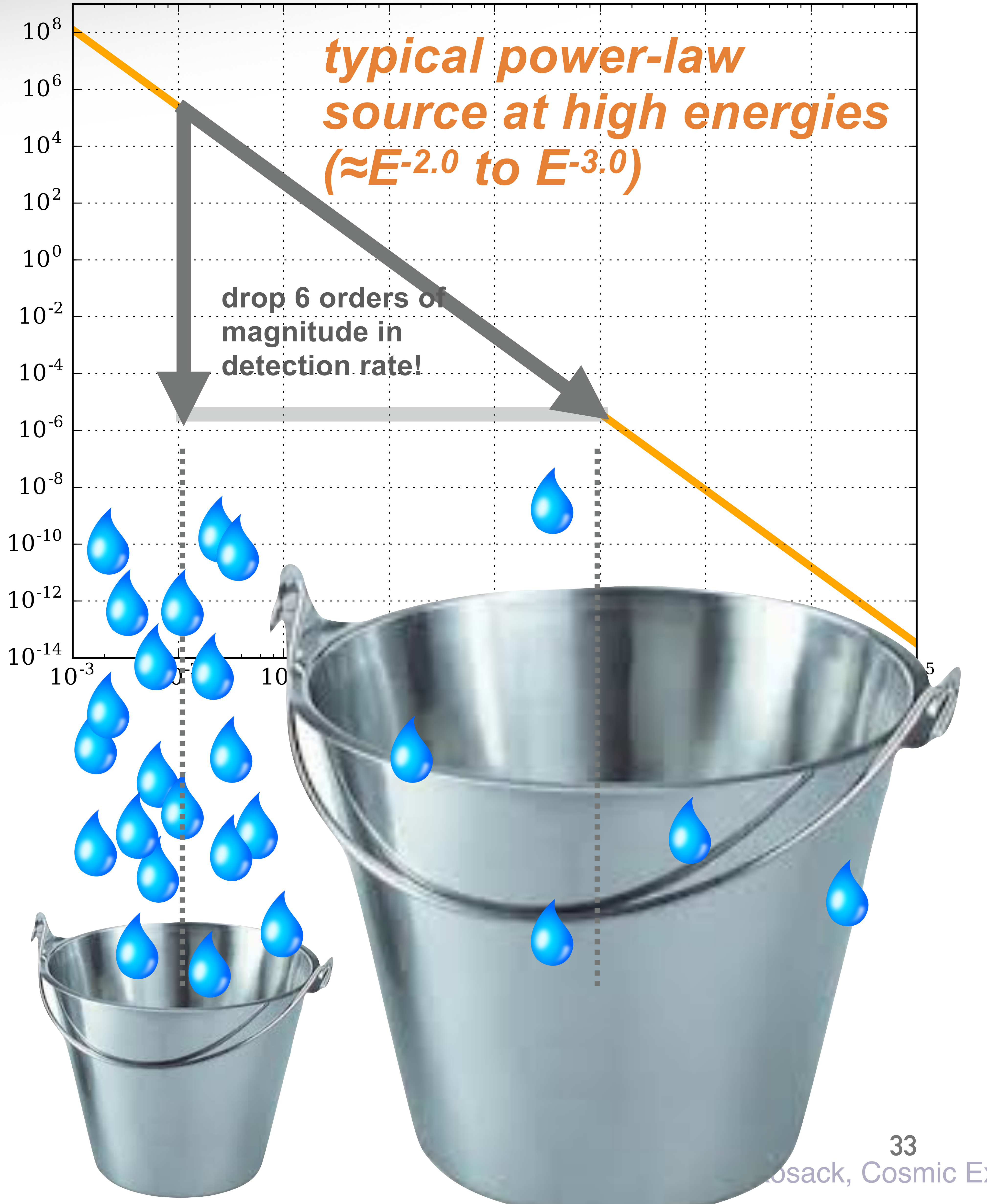
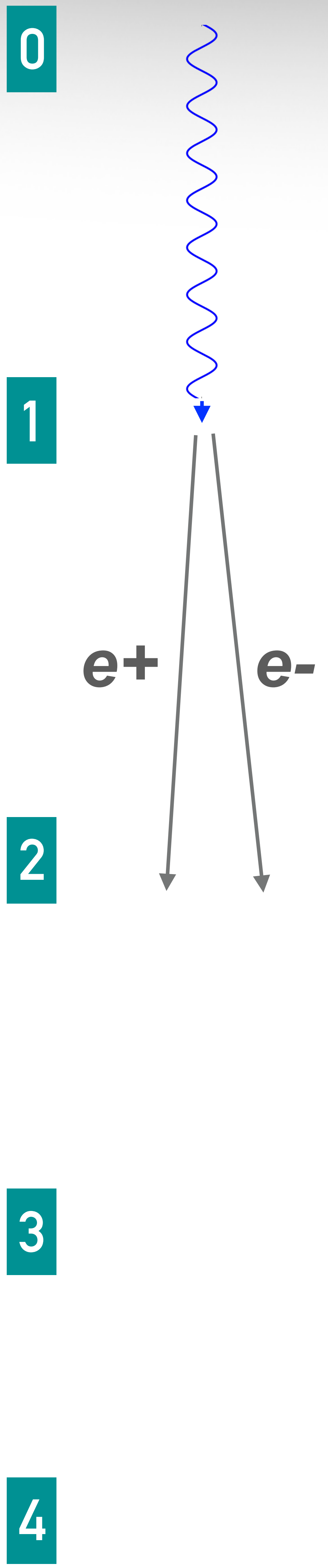


Pair production → Shower



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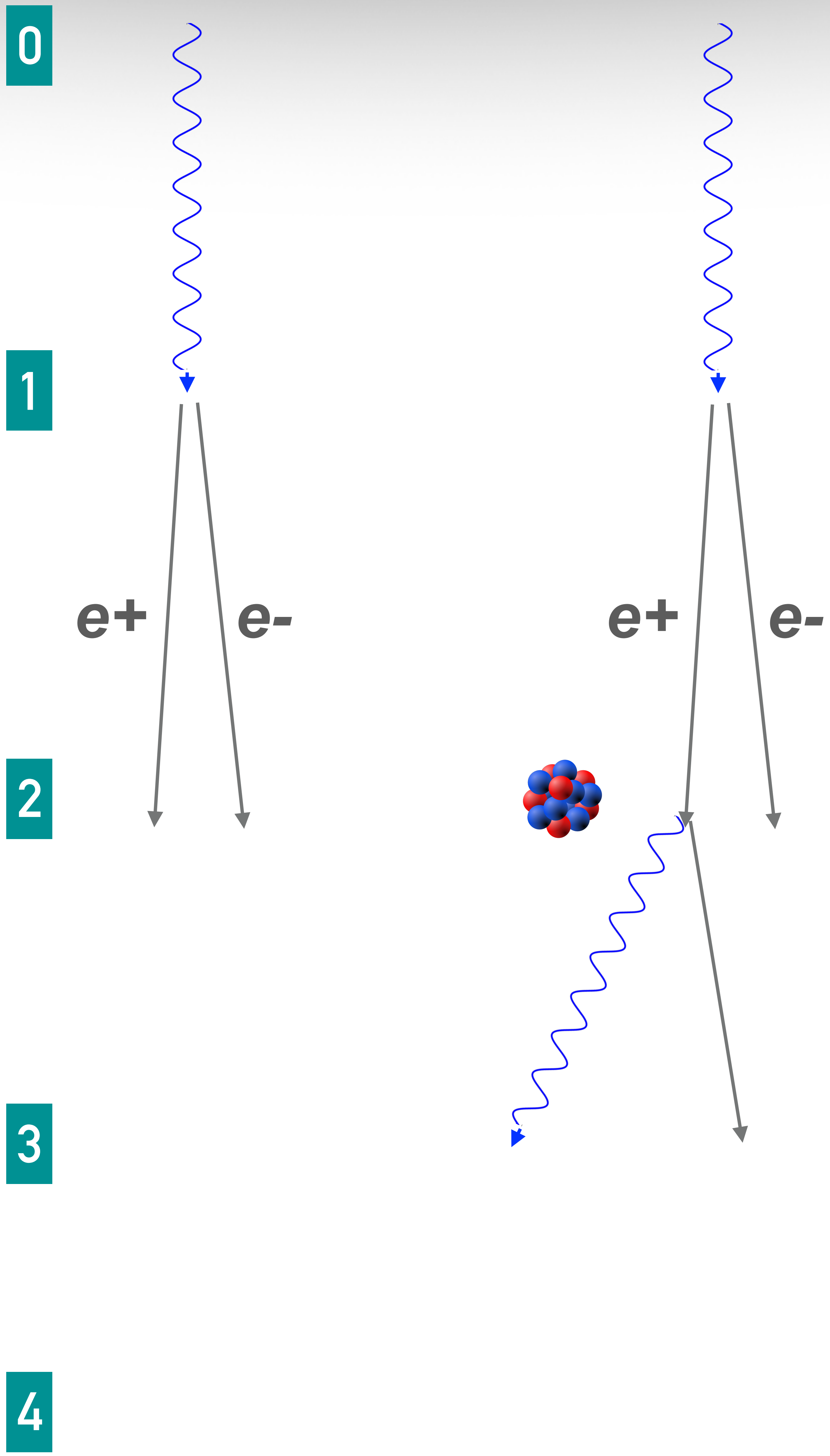

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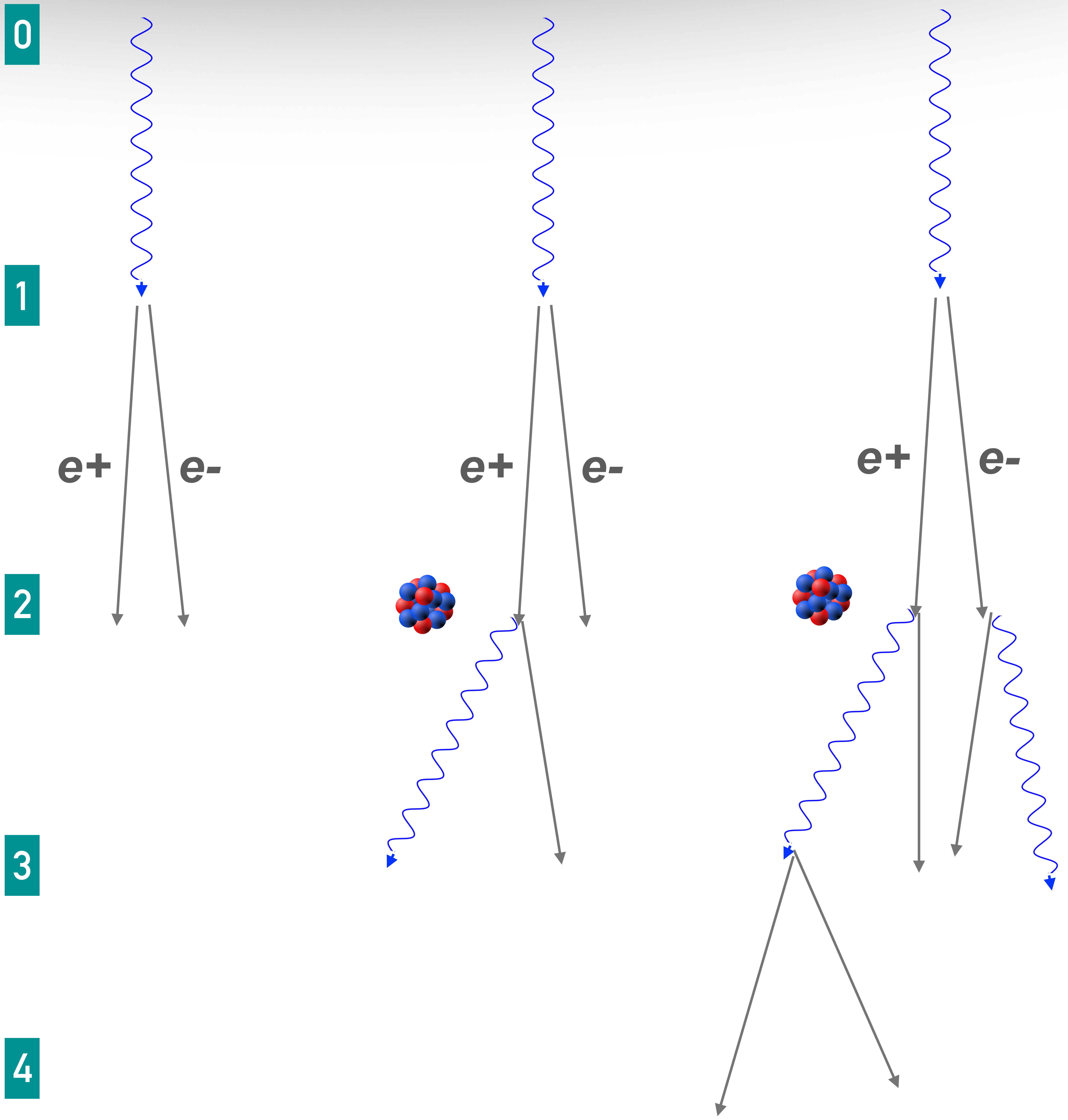

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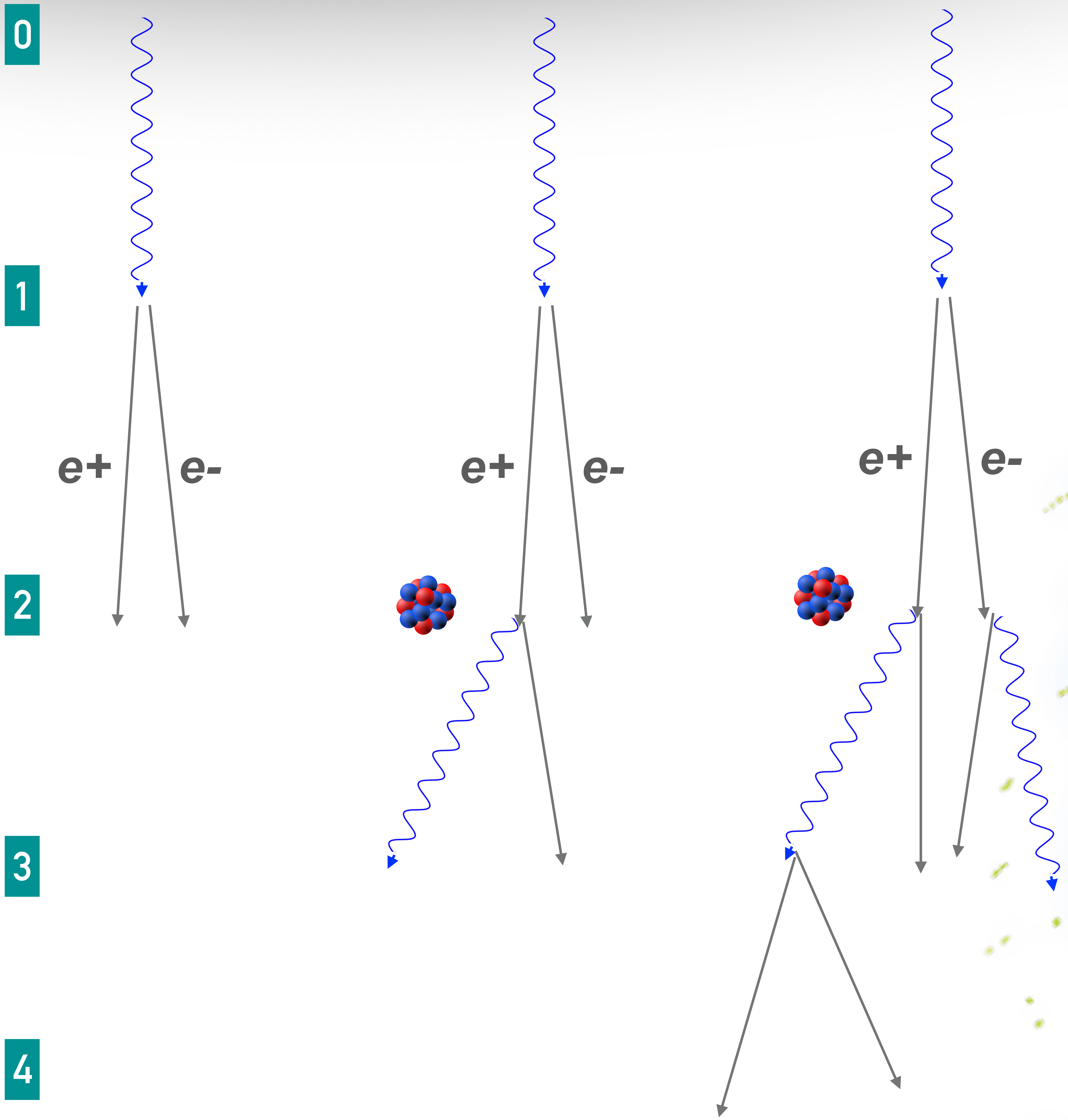

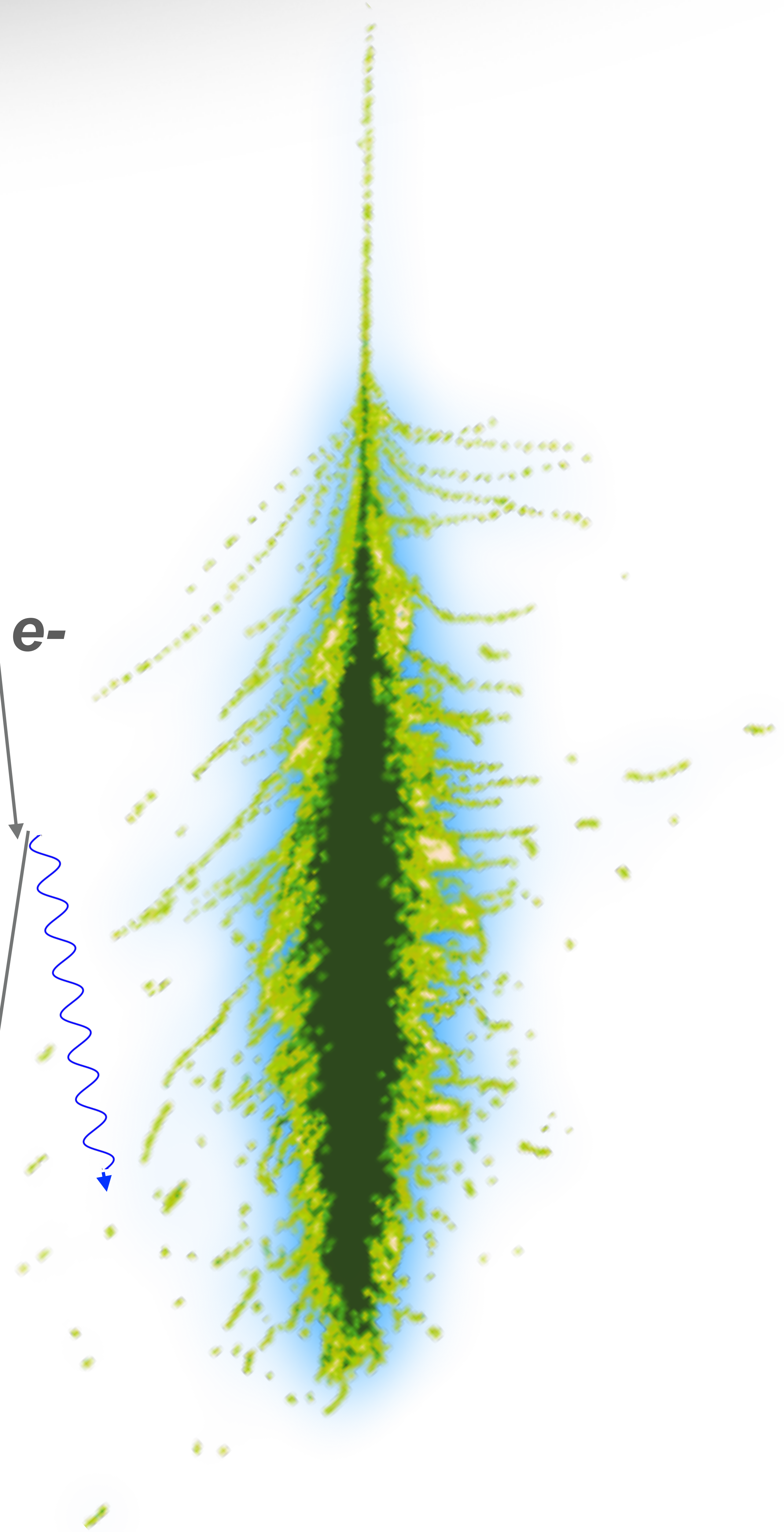

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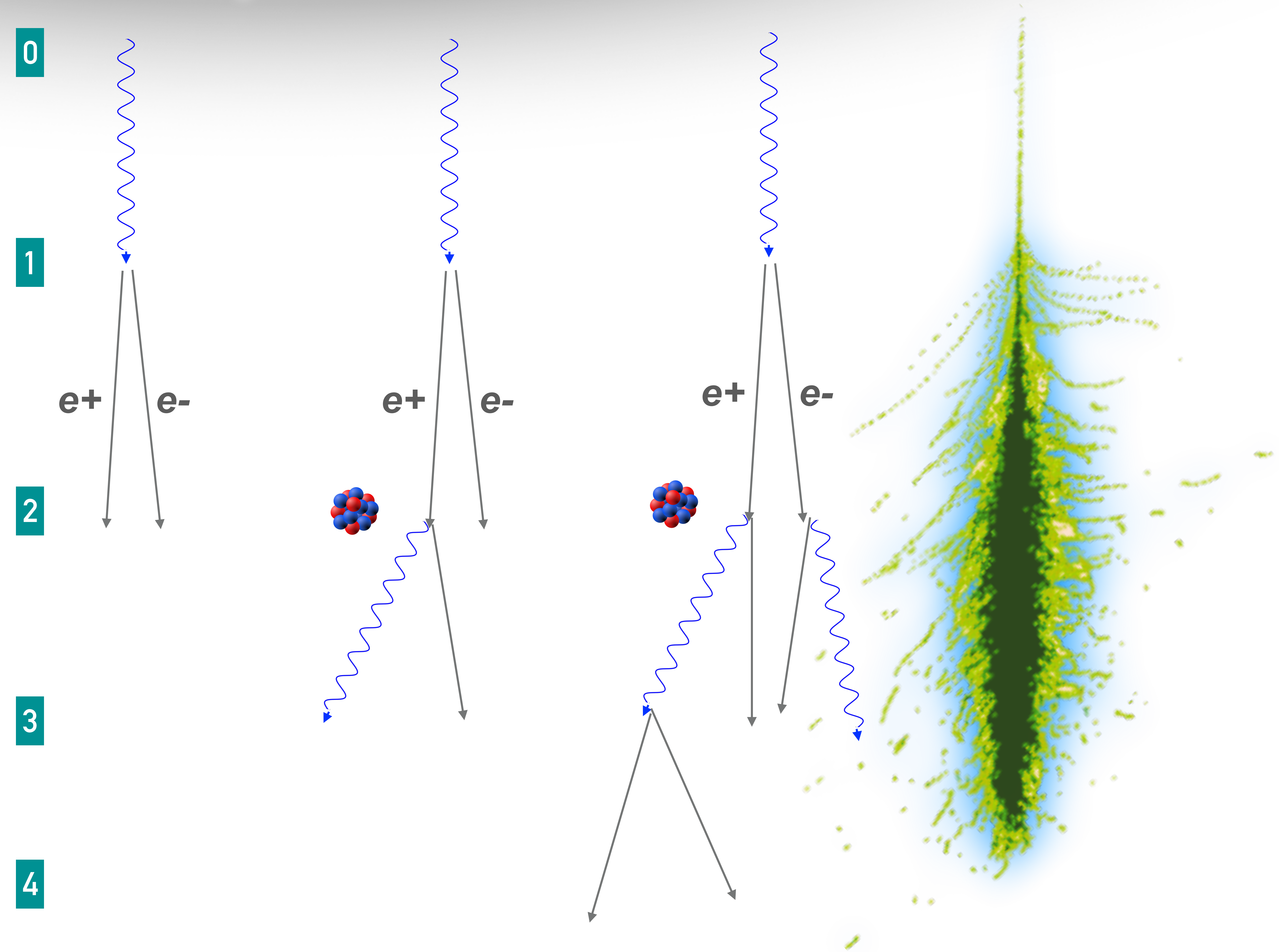

- With enough distance into a medium (1 interaction length), the secondaries will emit Bremsstrahlung radiation when they encounter a nucleus
- If high enough energy, the Bremsstrahlung photon can pair-produce
- and so on…

This becomes an electromagnetic *shower*

- *number of particles doubles, energy divided by 2 at each step*
- *eventually shower stops when energy too low*

Atmospheric Cherenkov Technique

Showers can be produced in many media, but we want a large detection volume (100,000+ m^2 needed!):

- Earth's atmosphere is ideal!
- Radiation and interaction length ≈ 37 g/cm^2
- showers form and complete before hitting ground

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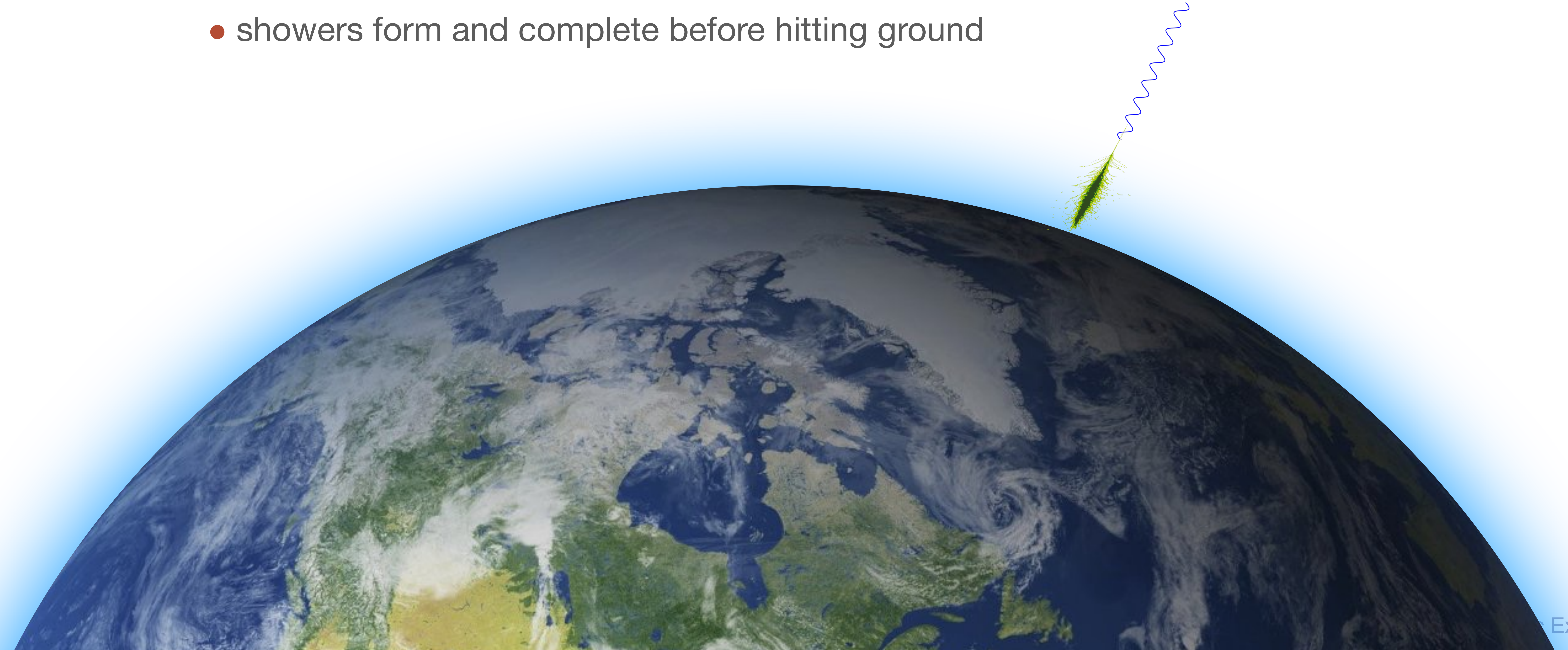
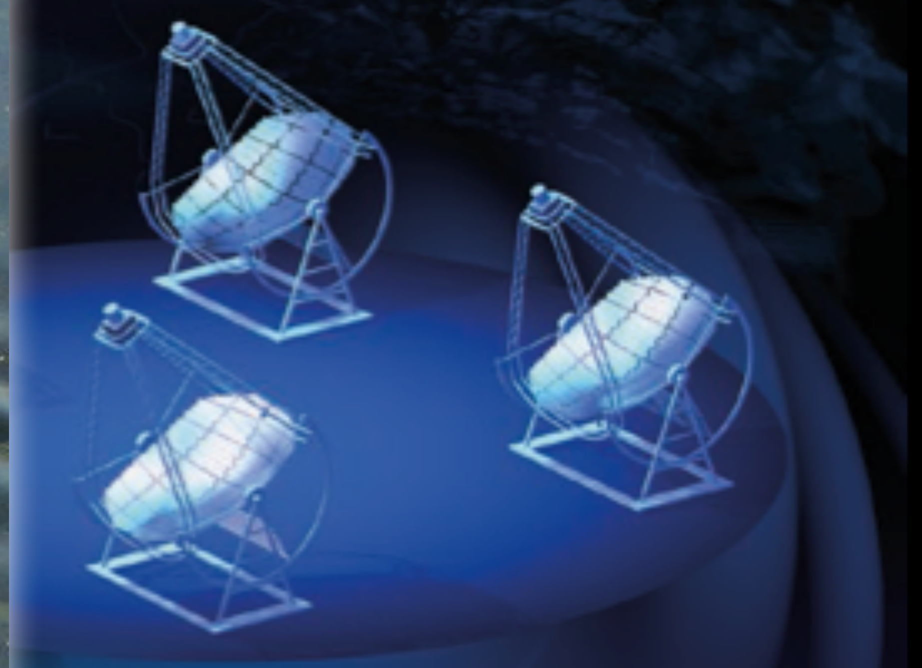


Osiris reactor, CEA Saclay



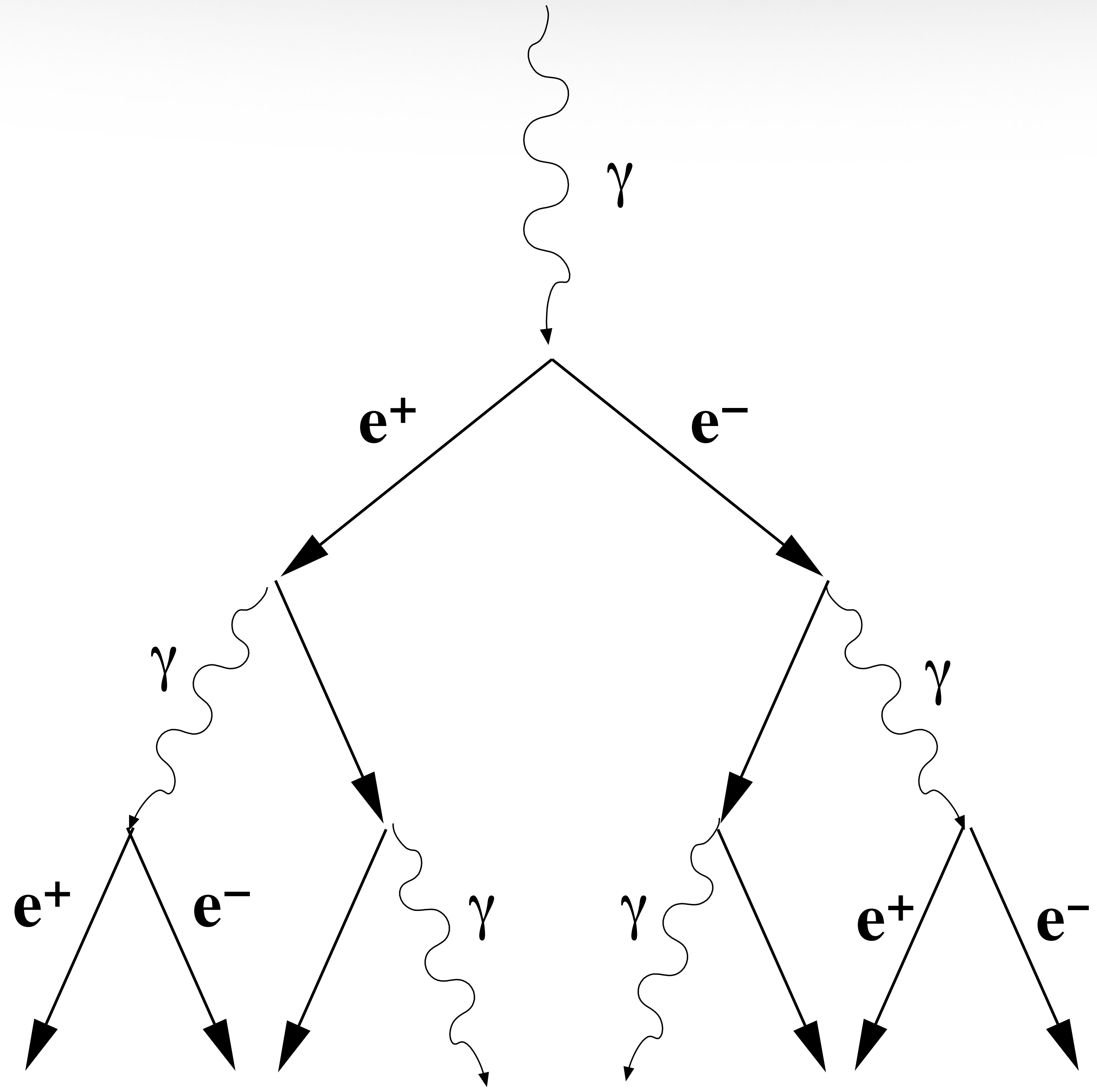
Saclay

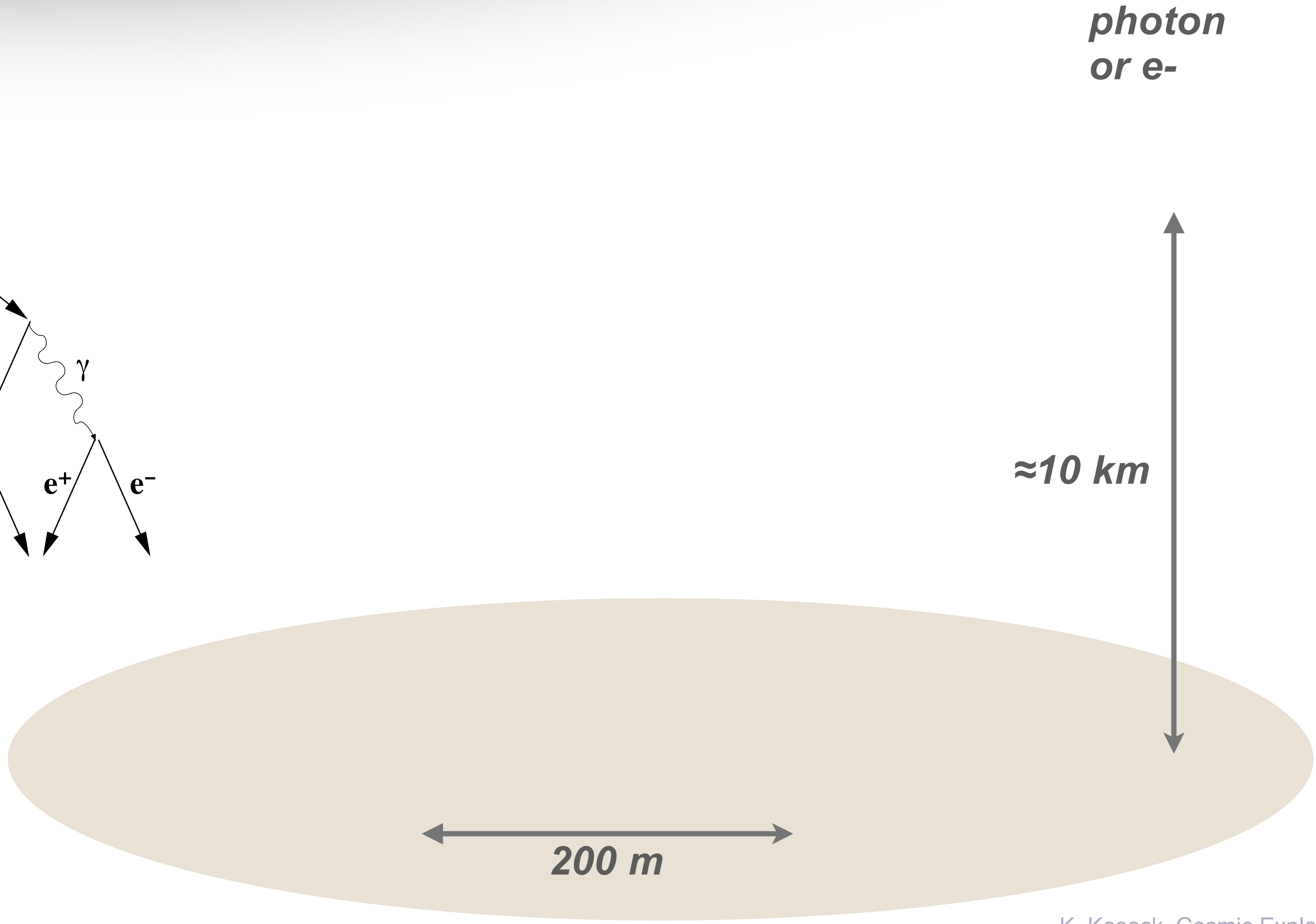
Credit: Les Défis du CEA, N°197 , March 2015- ©CEA/ Fabrice Mathé

Osiris reactor, CEA Saclay

Credit: Les Défis du CEA, N°197 , March 2015- ©CEA/ Fabrice Mathé

Electromagnetic Showers





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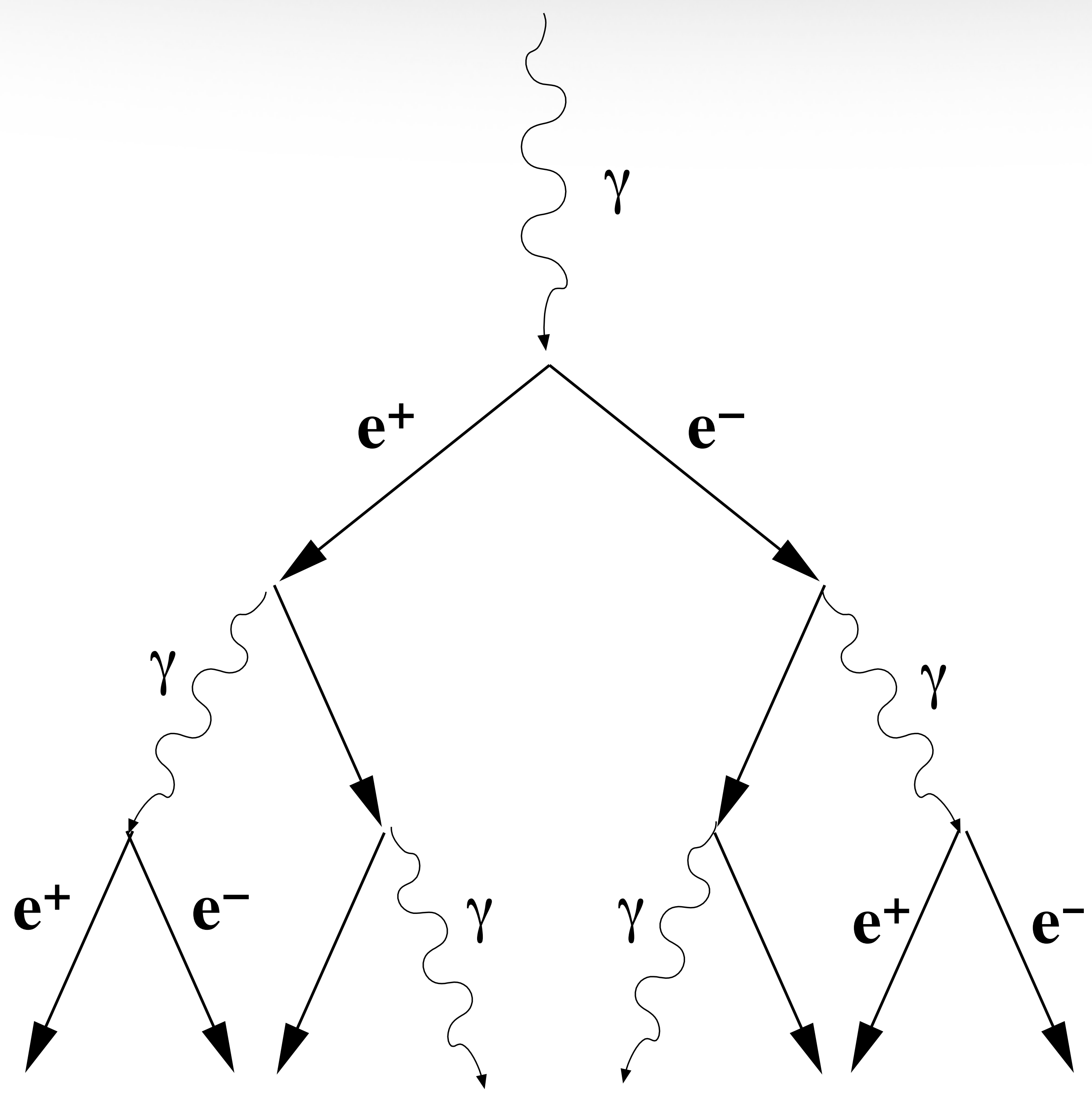

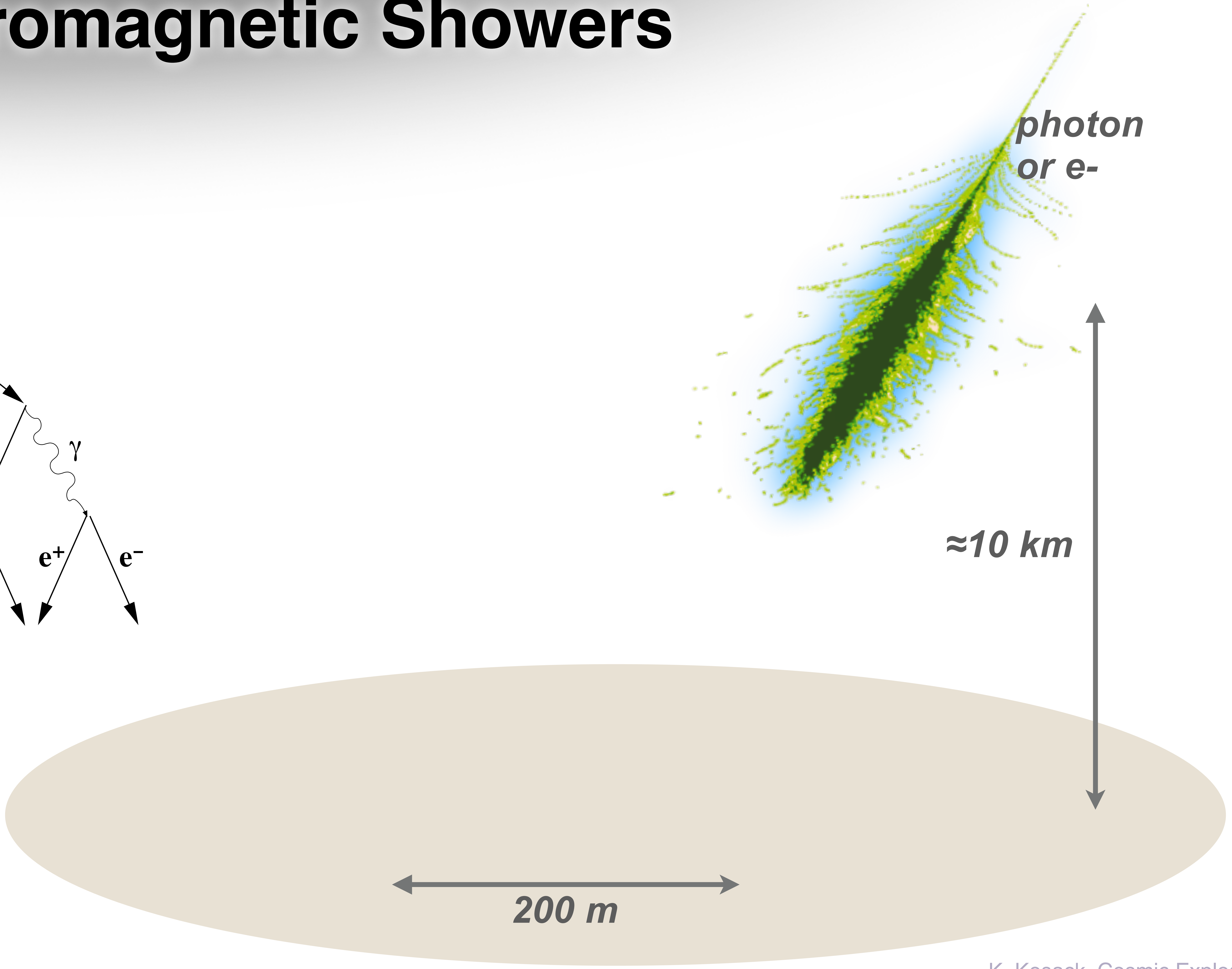

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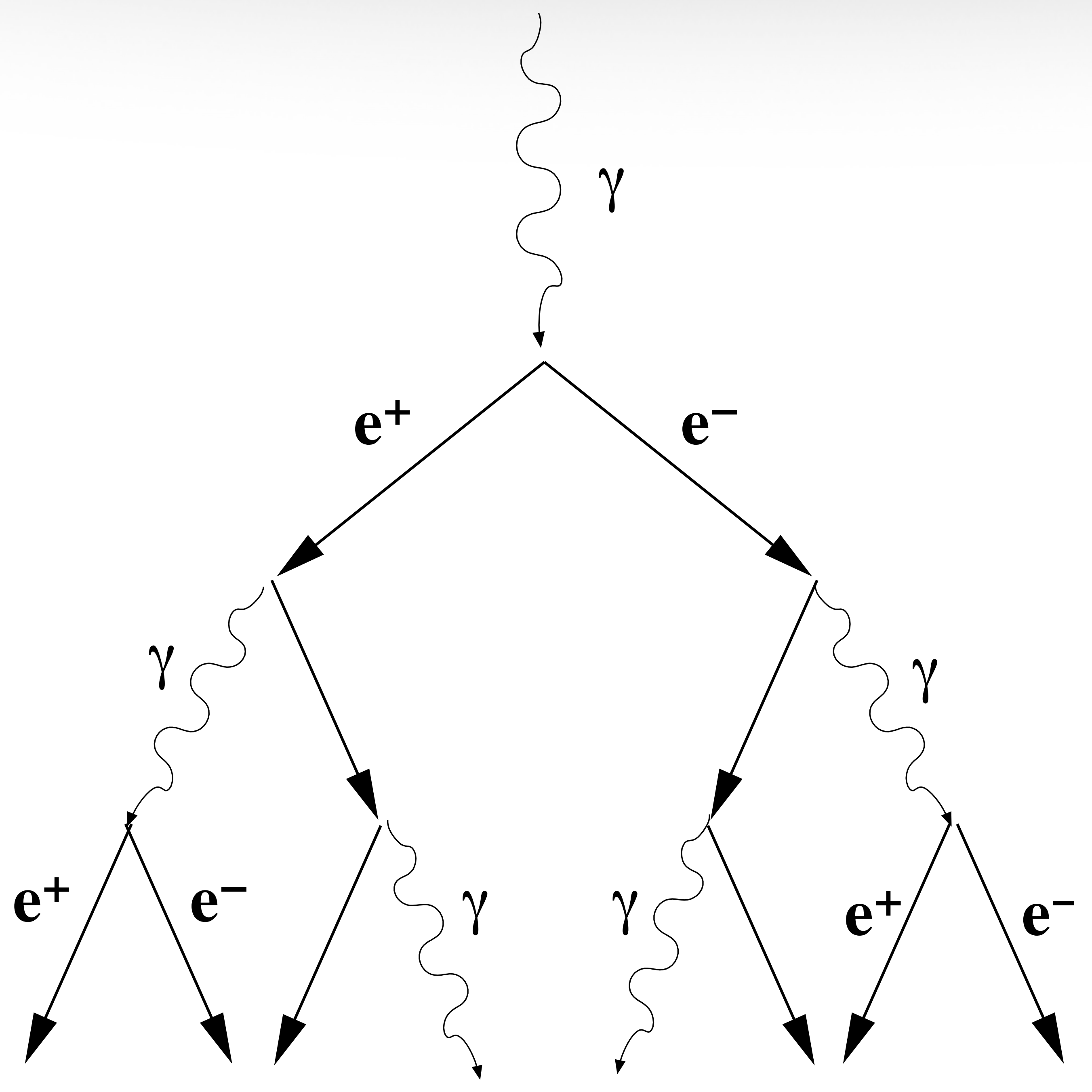

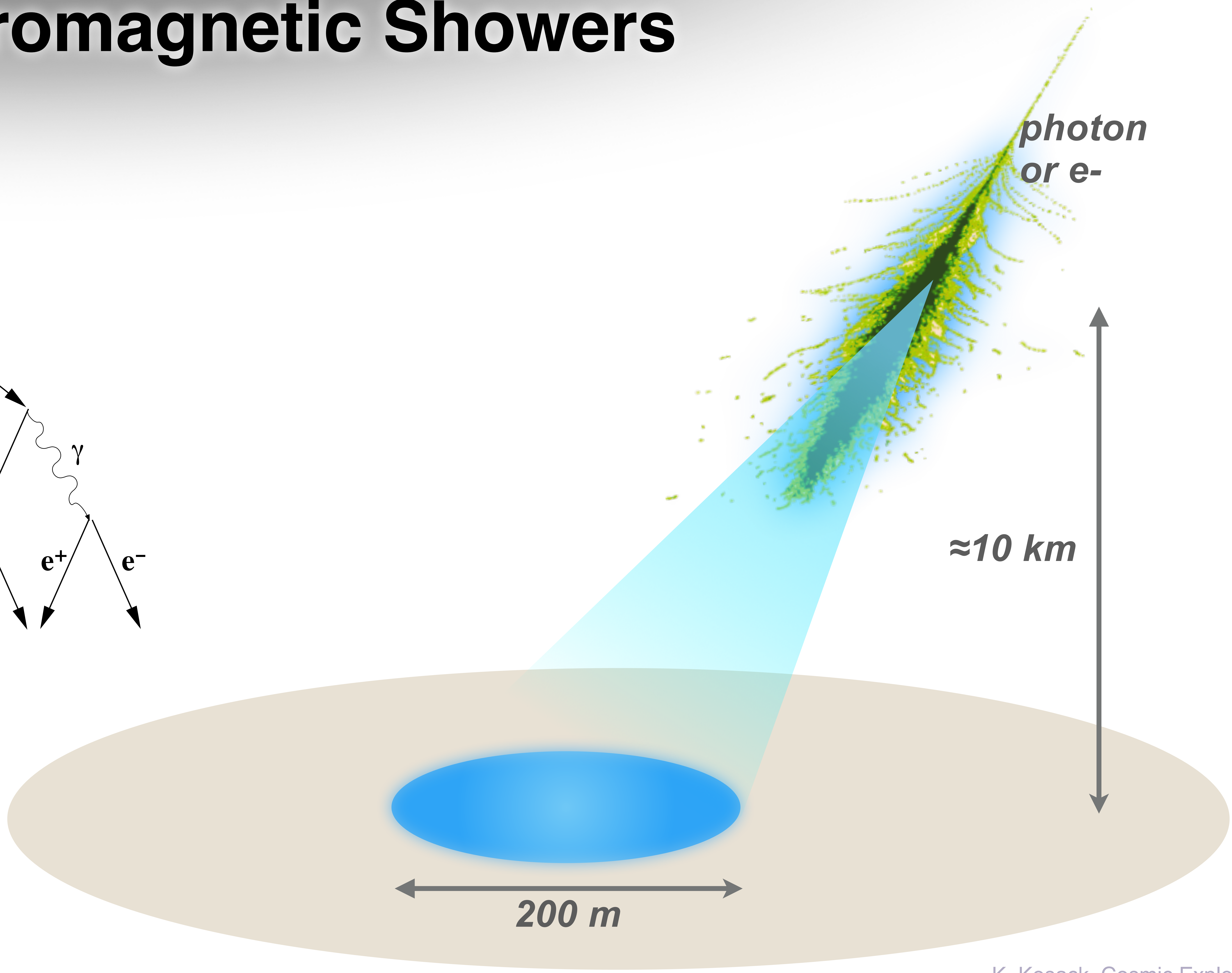

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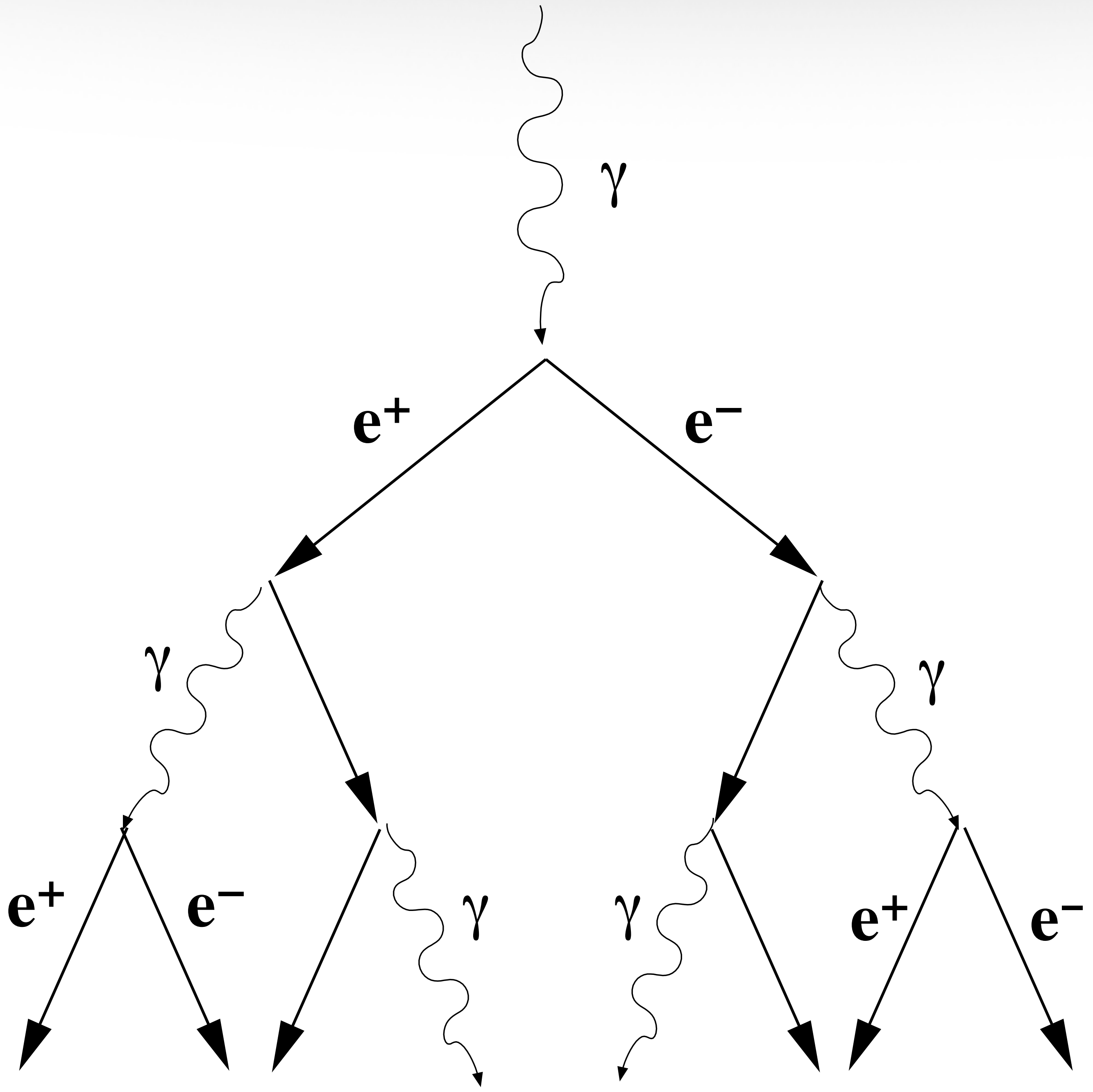

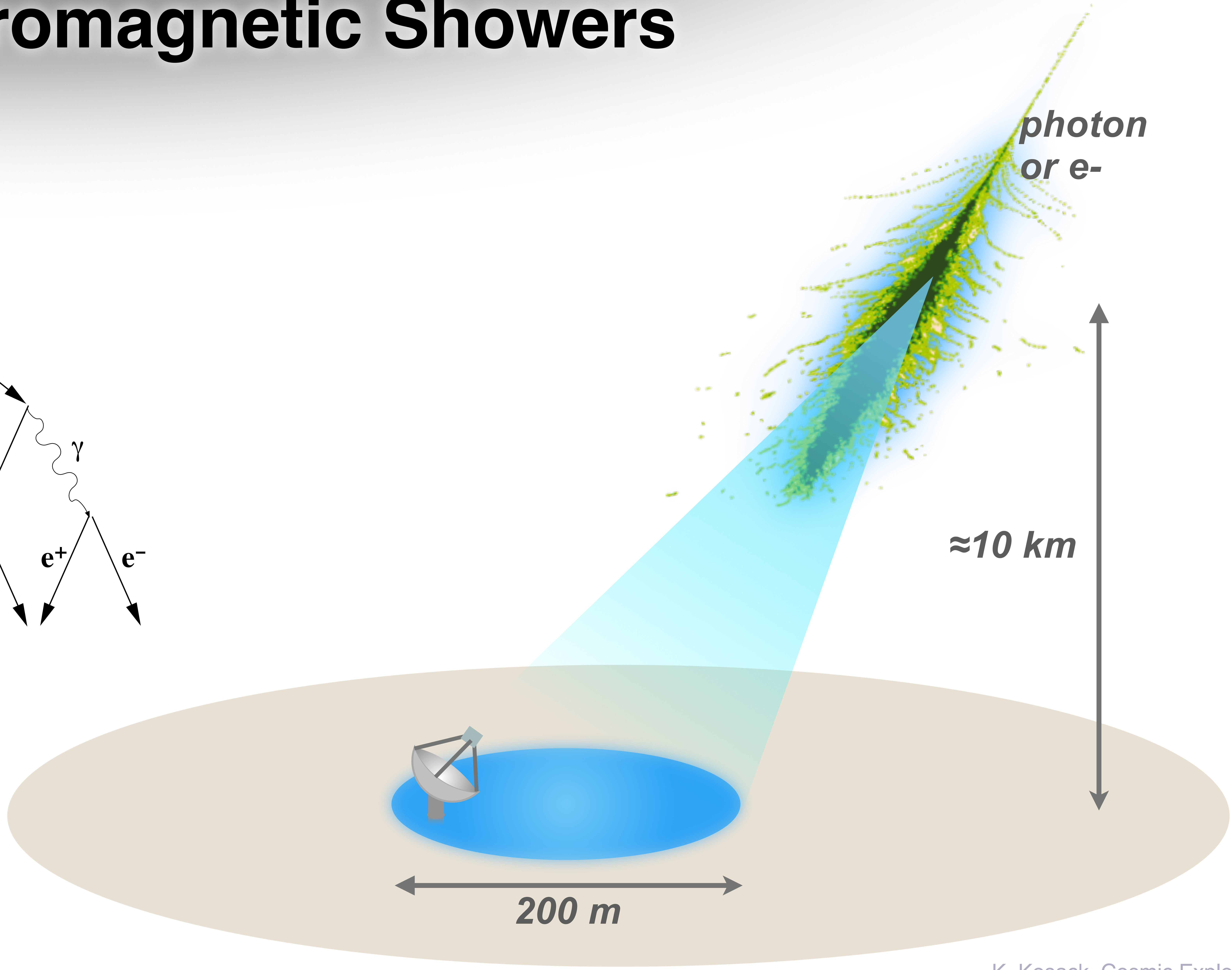

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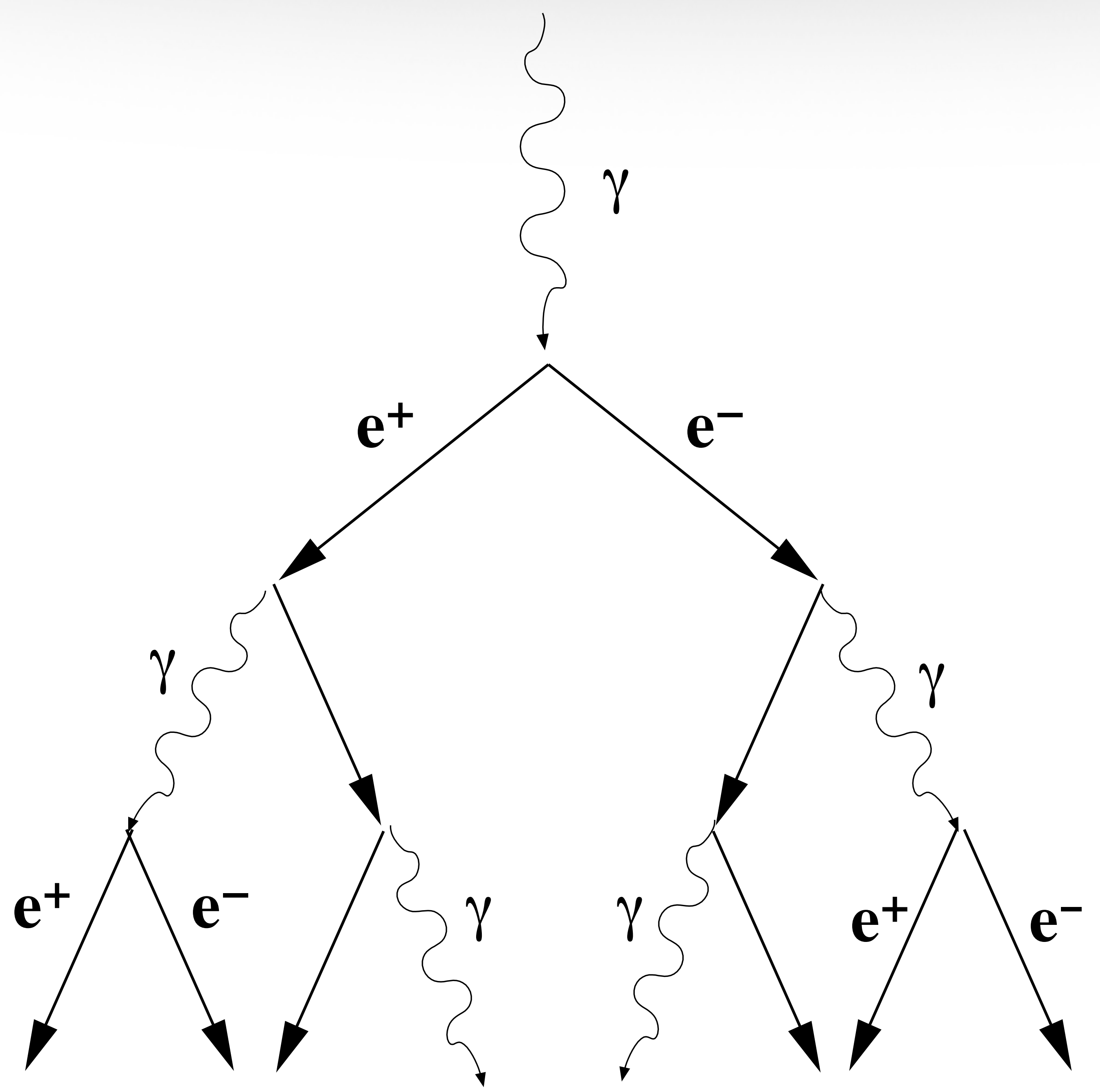

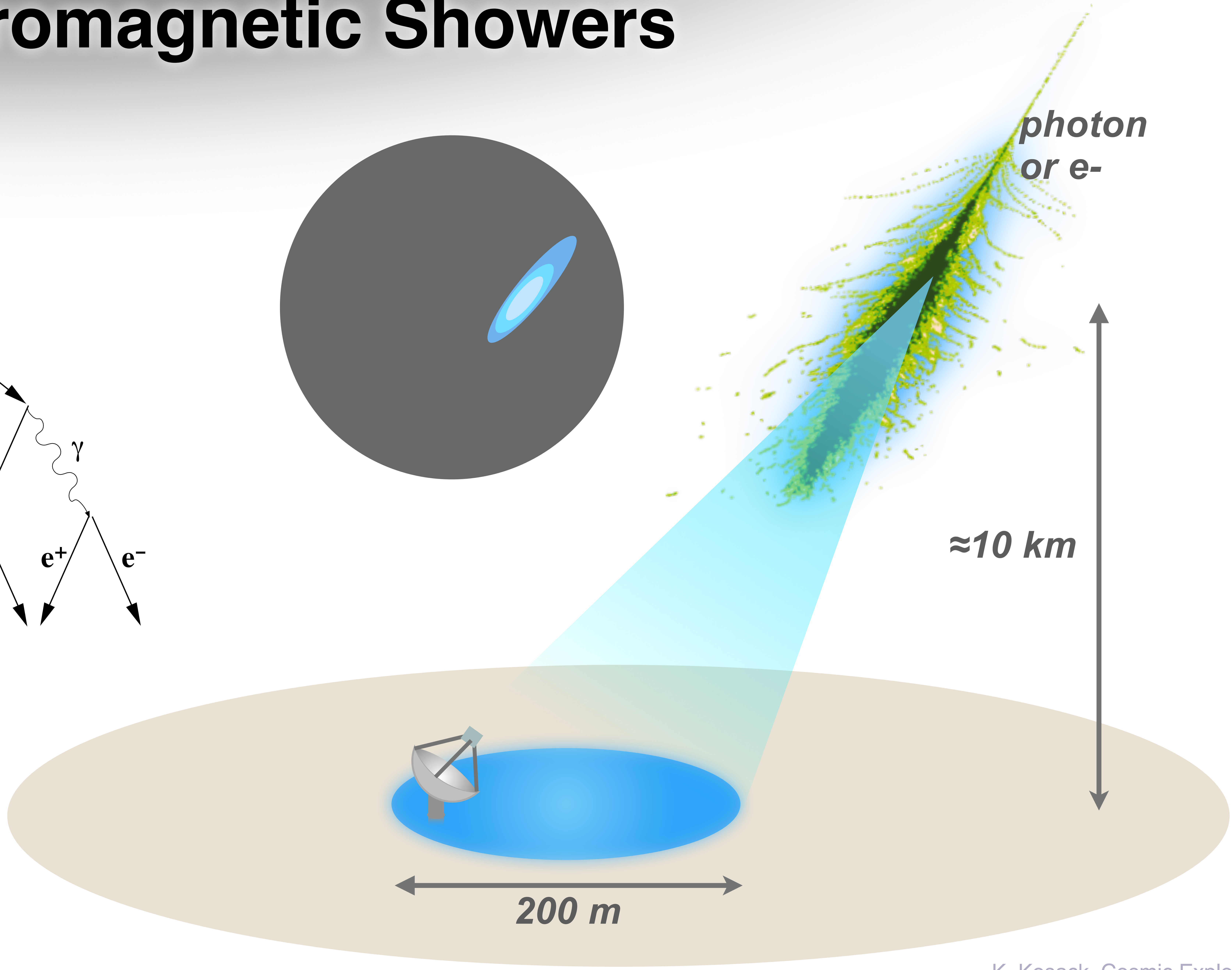

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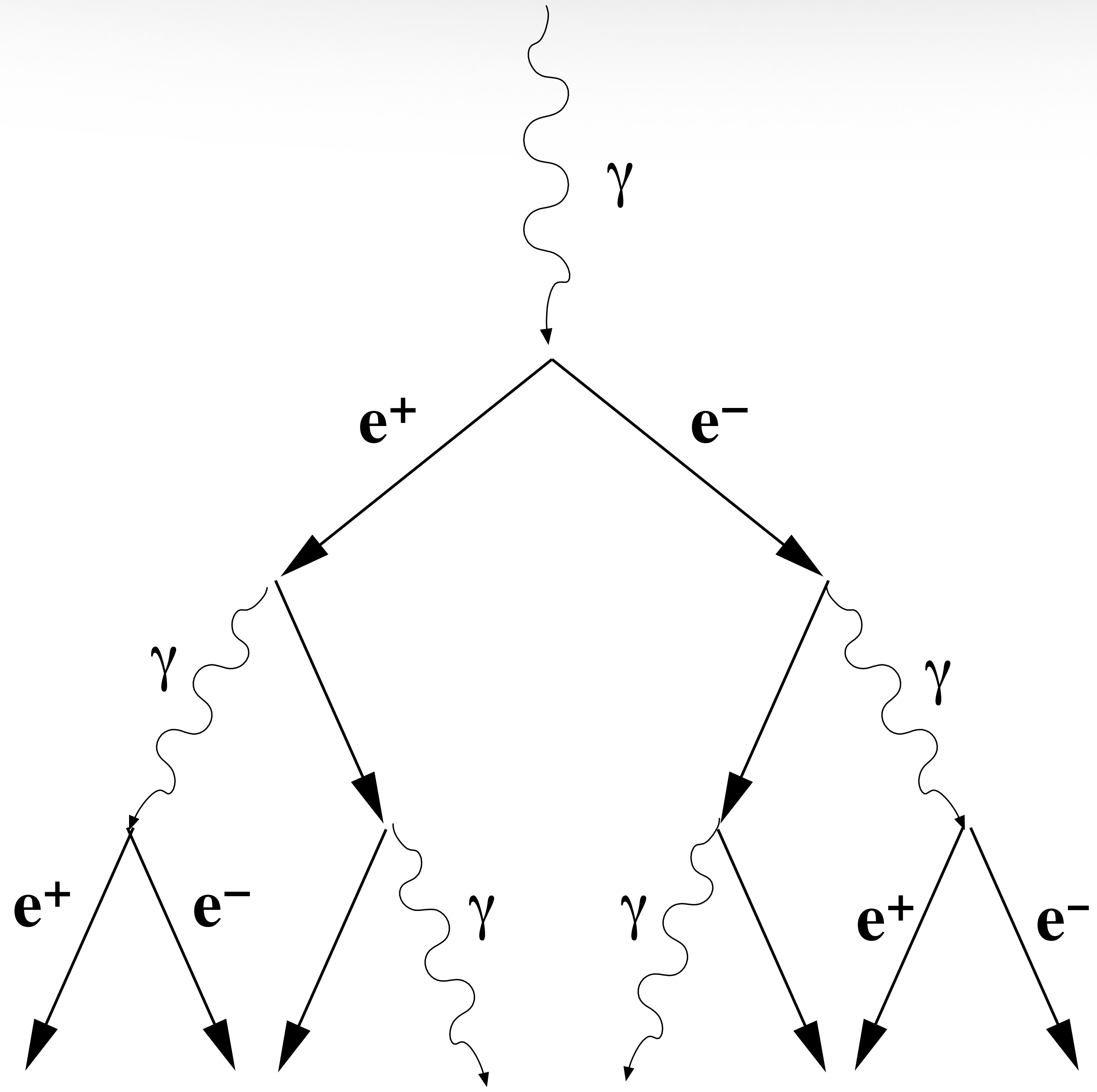

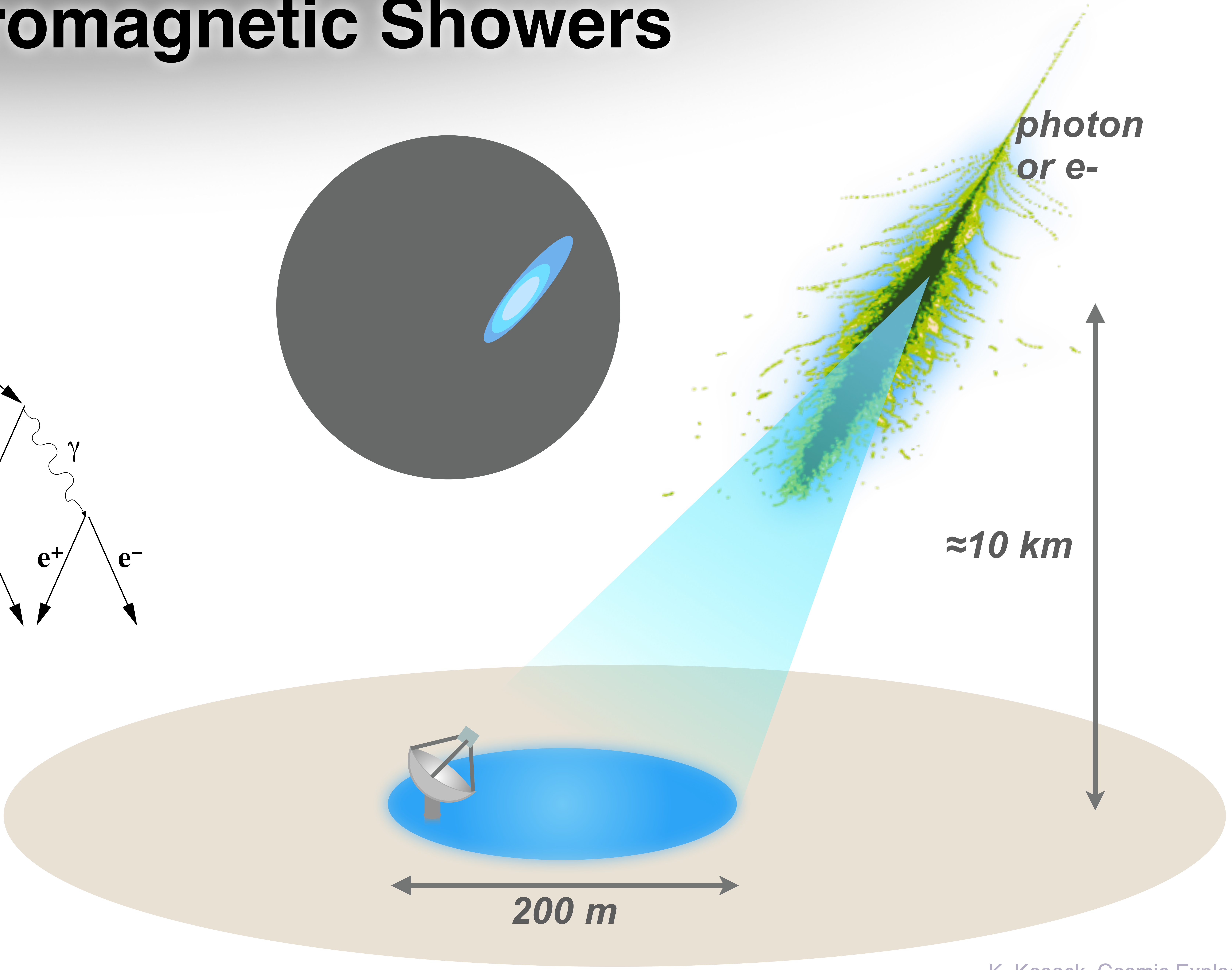

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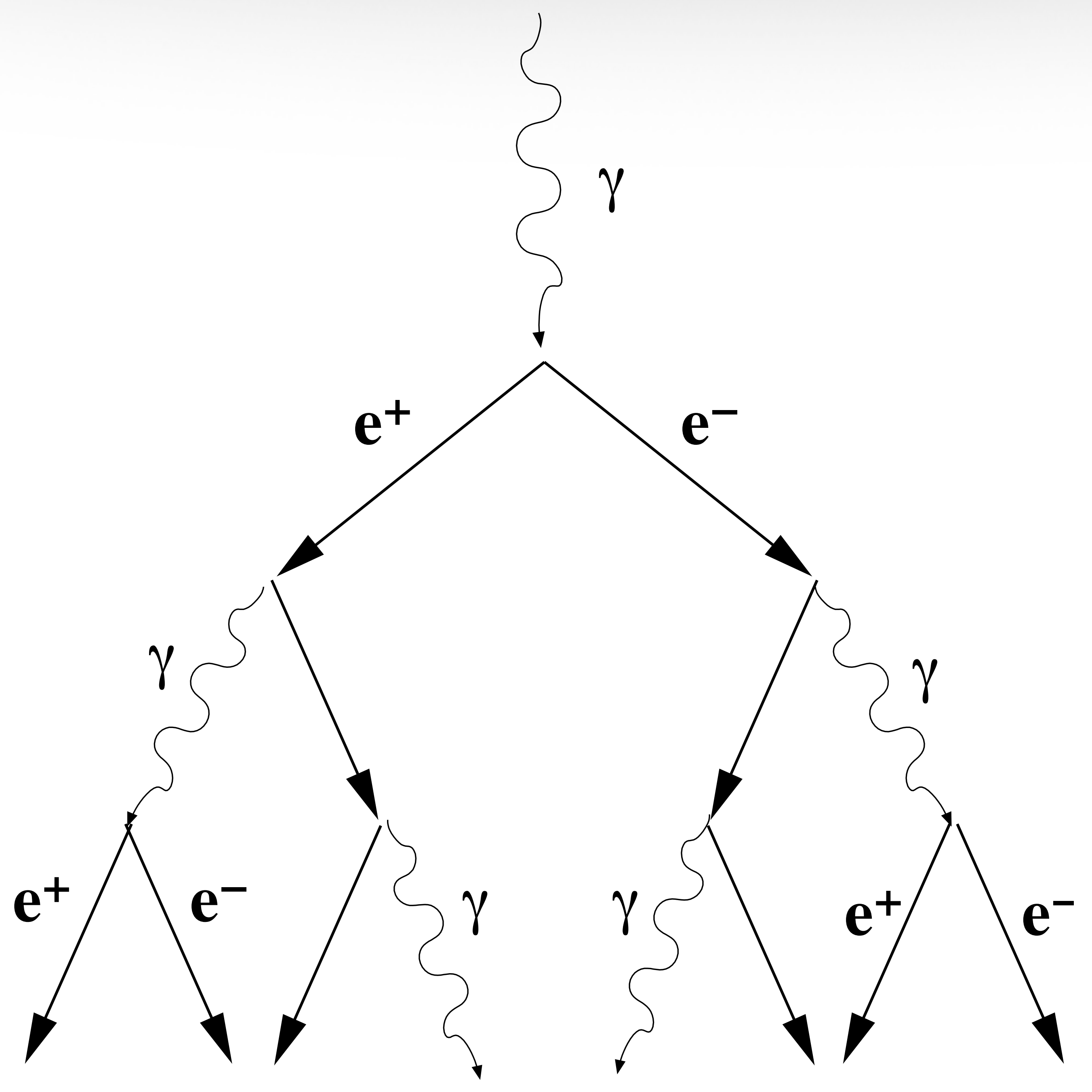

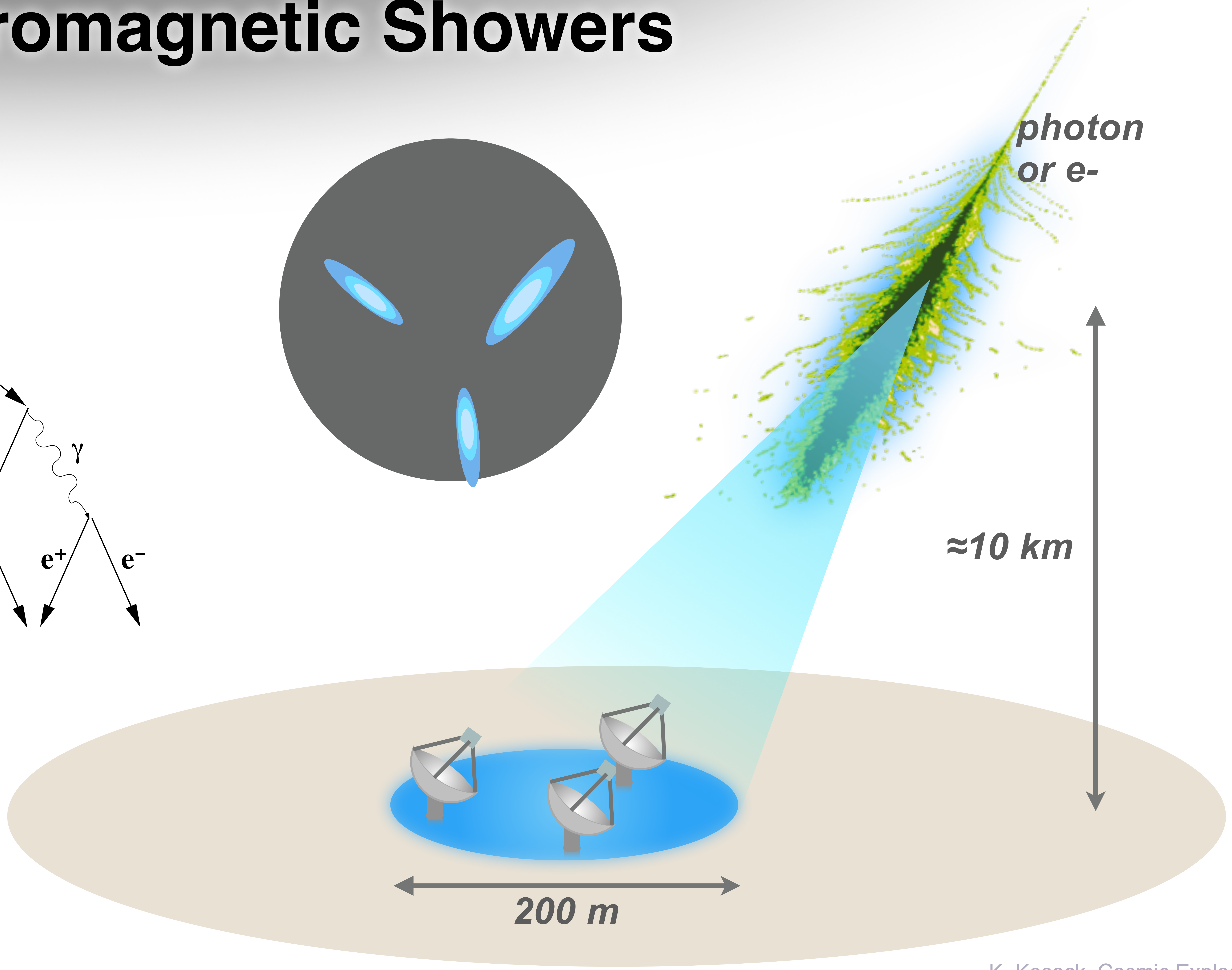

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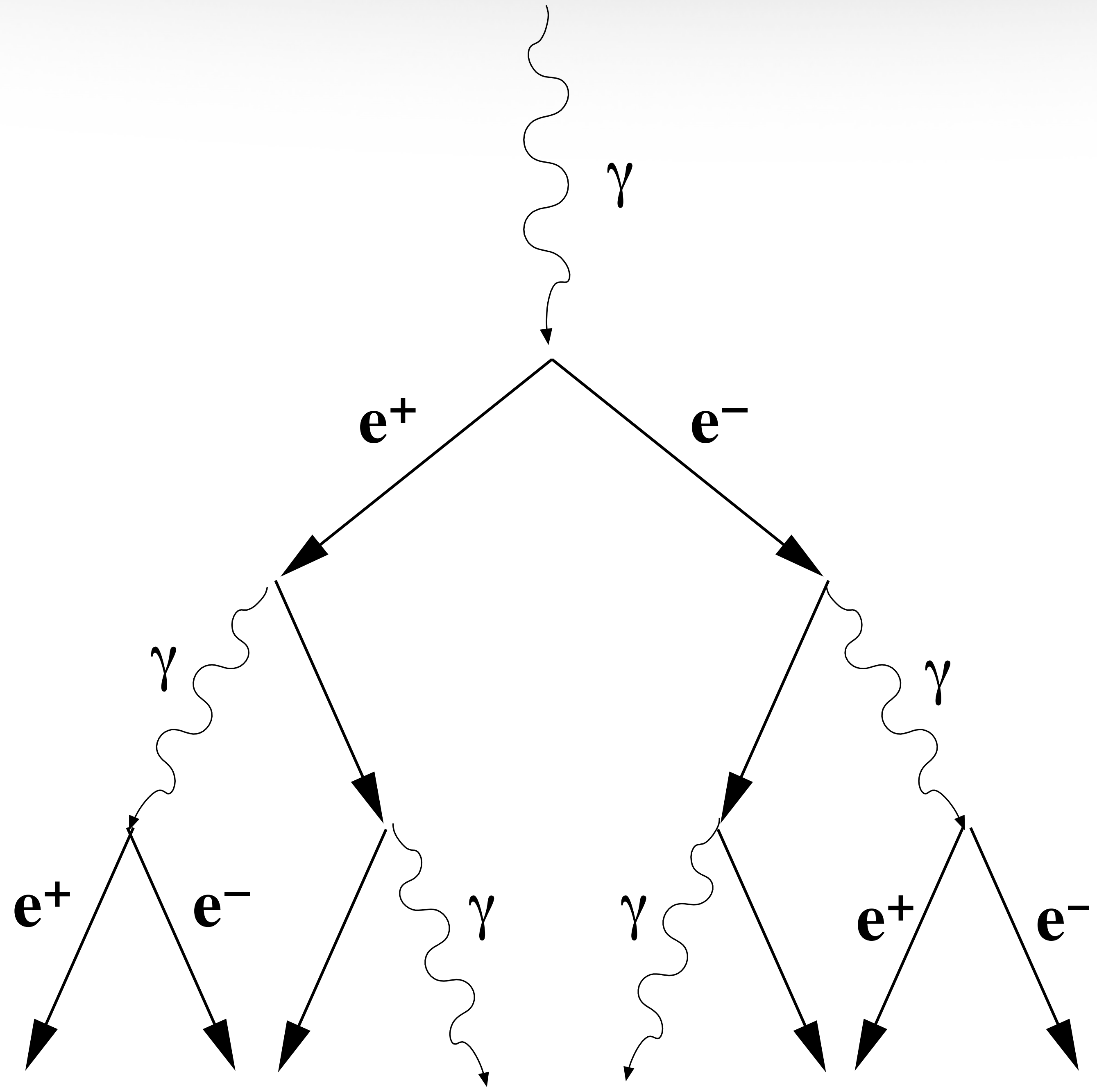
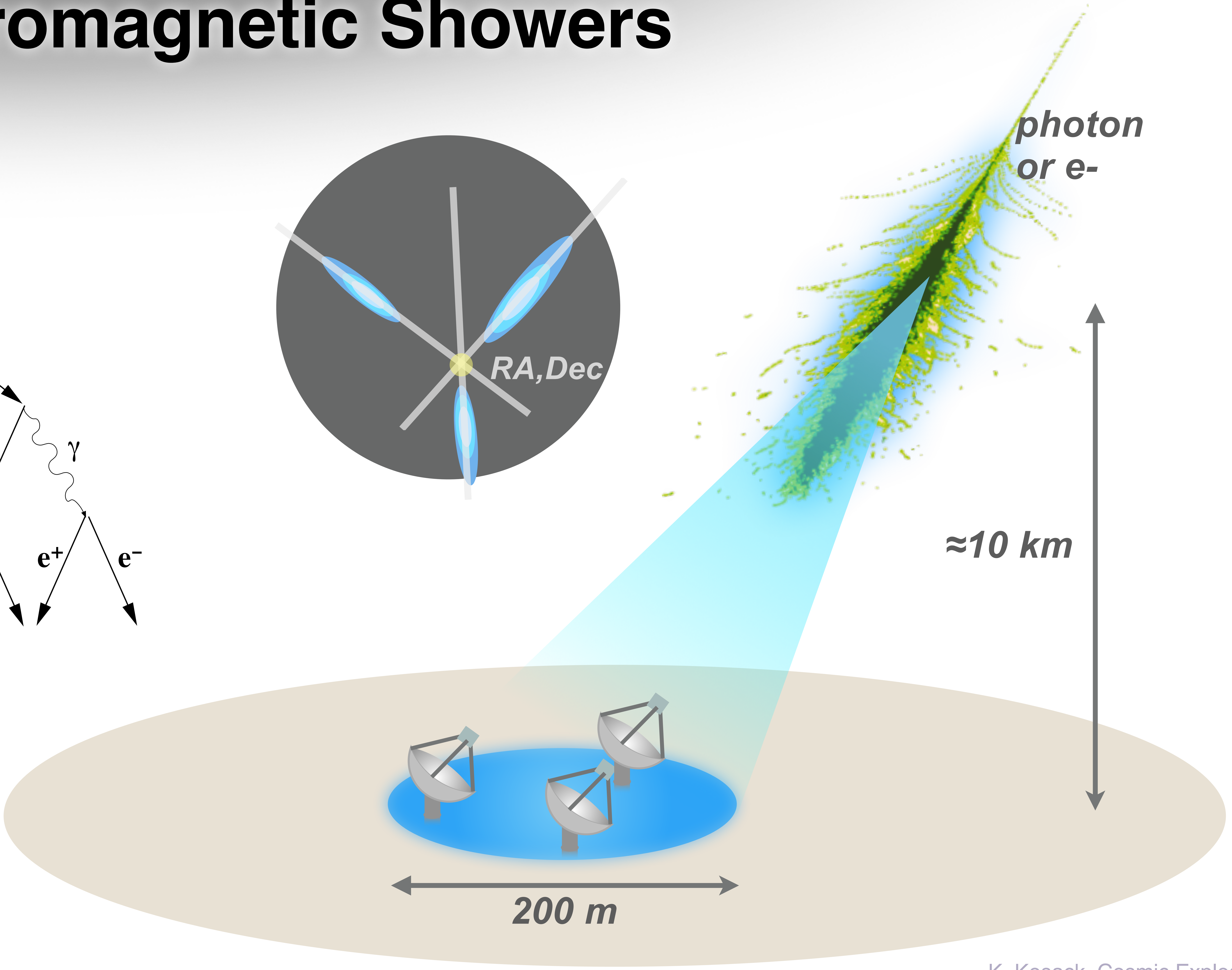
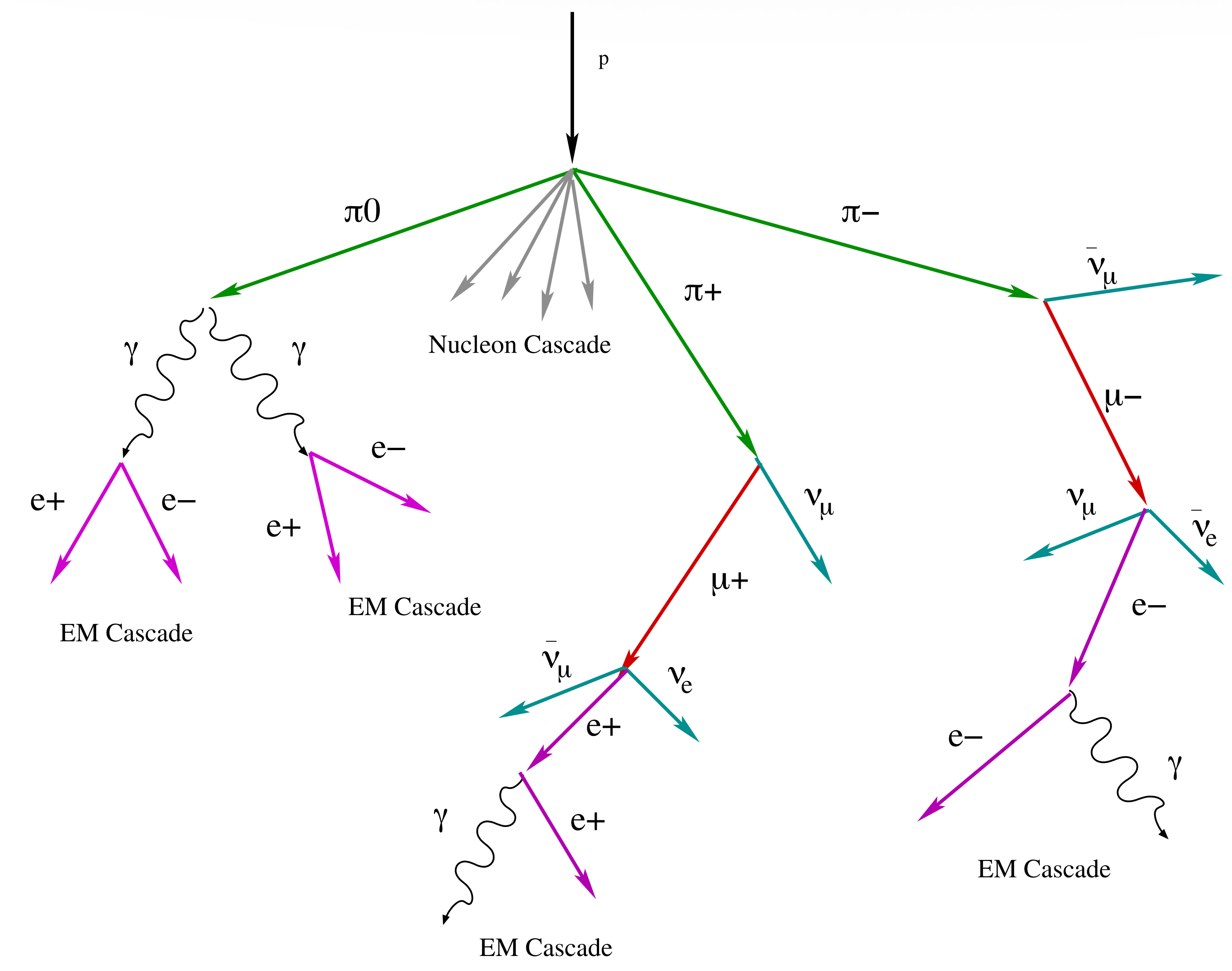




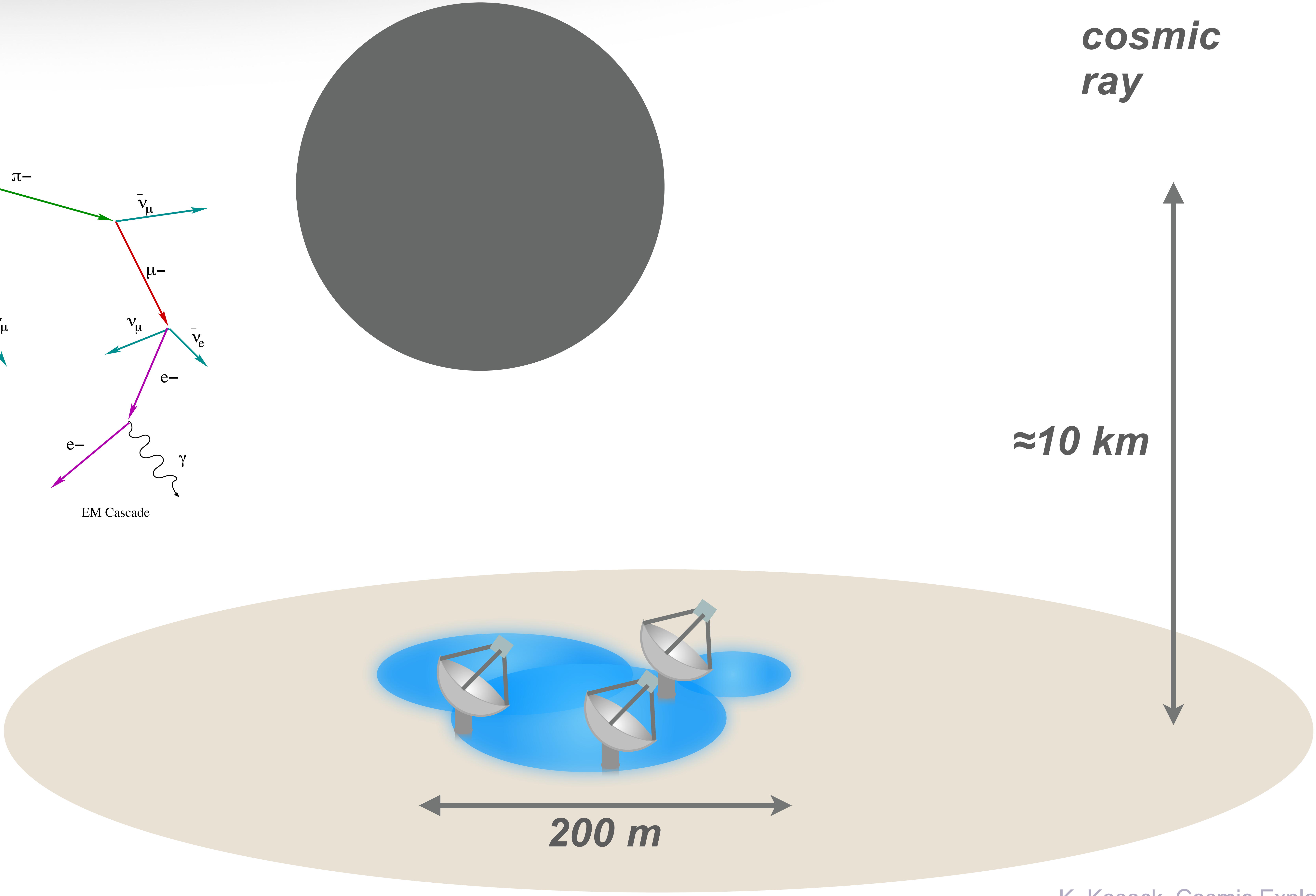
Hadronic Showers

cosmic ray



EM sub-showers

cosmic ray



Hadronic Showers

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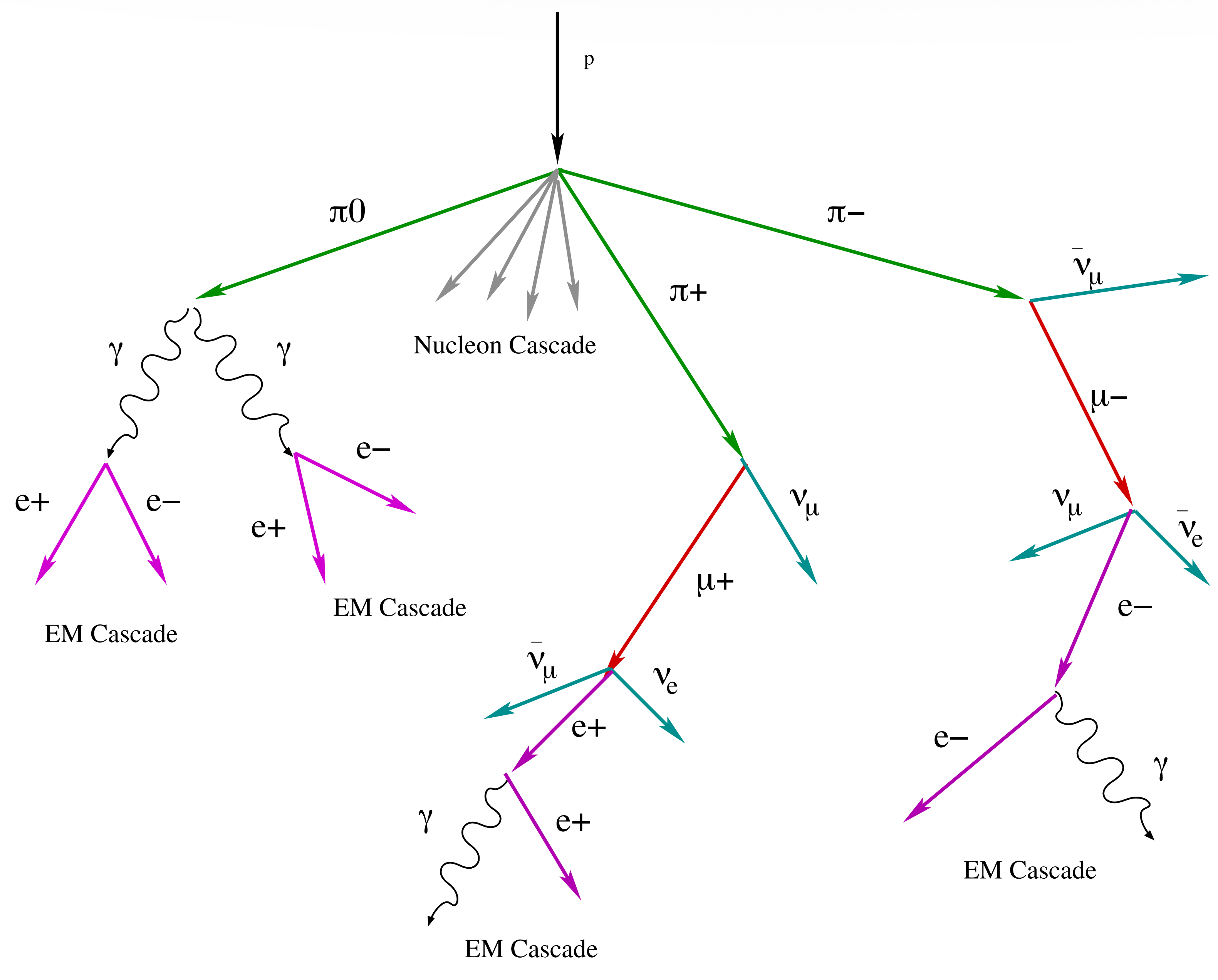

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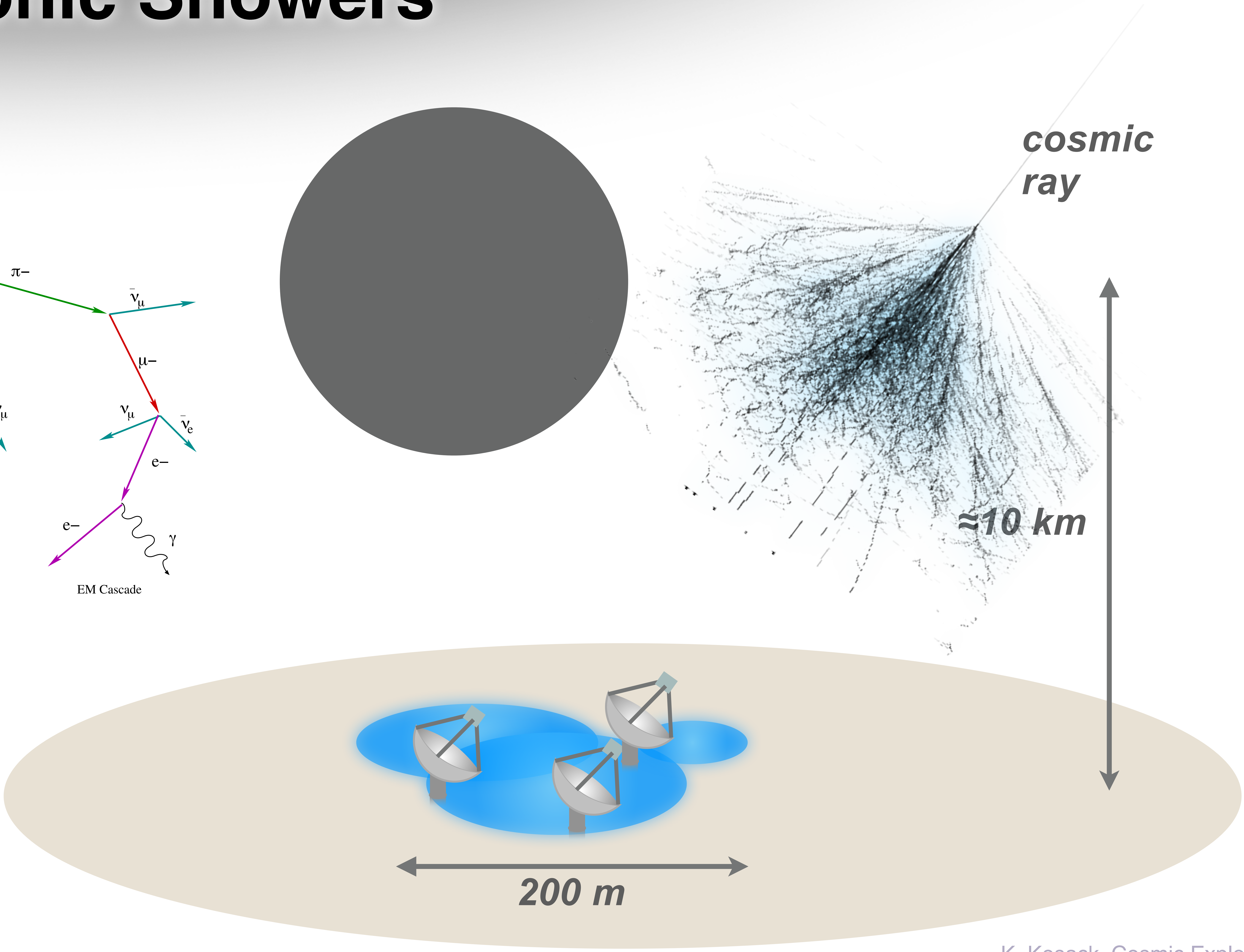

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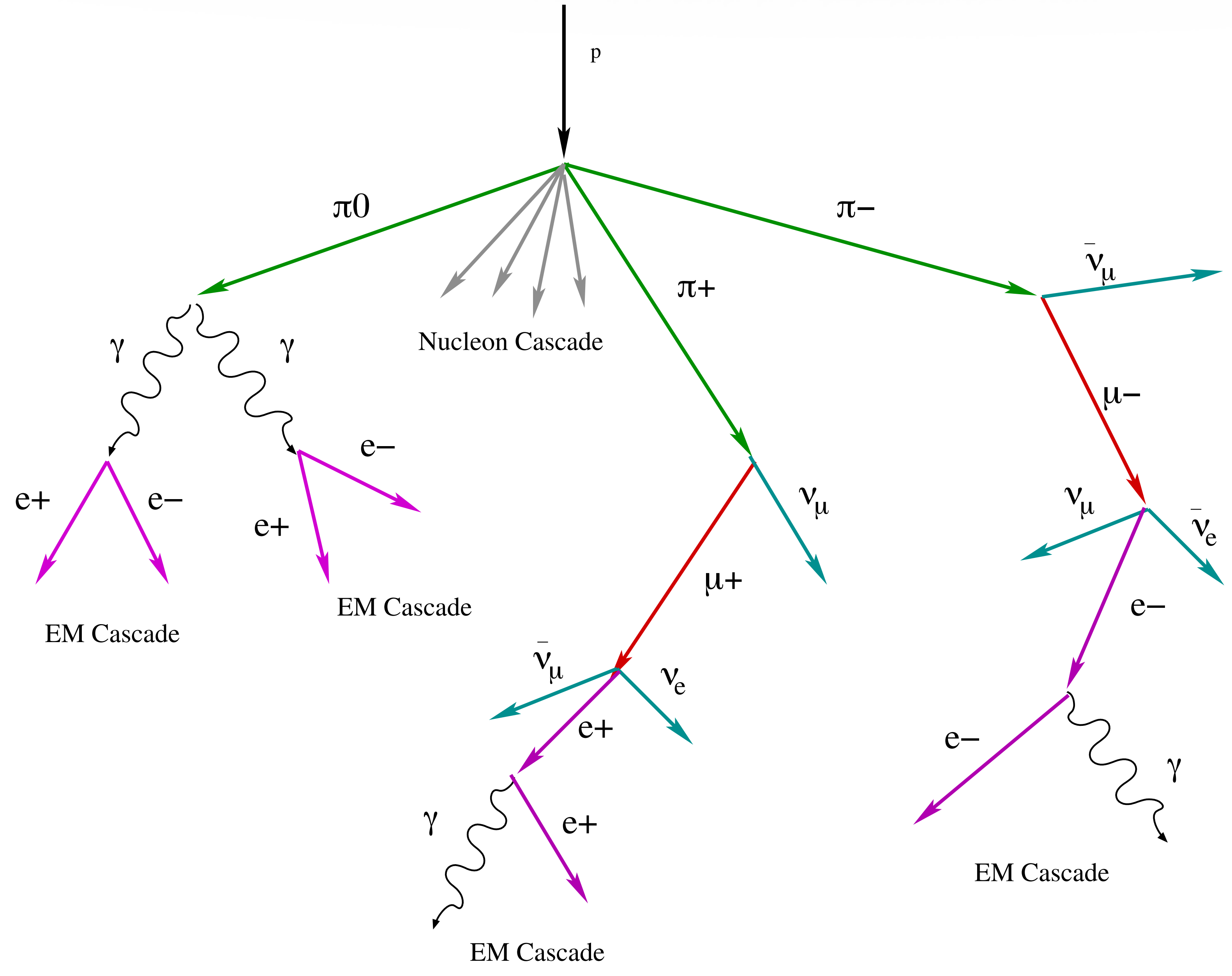

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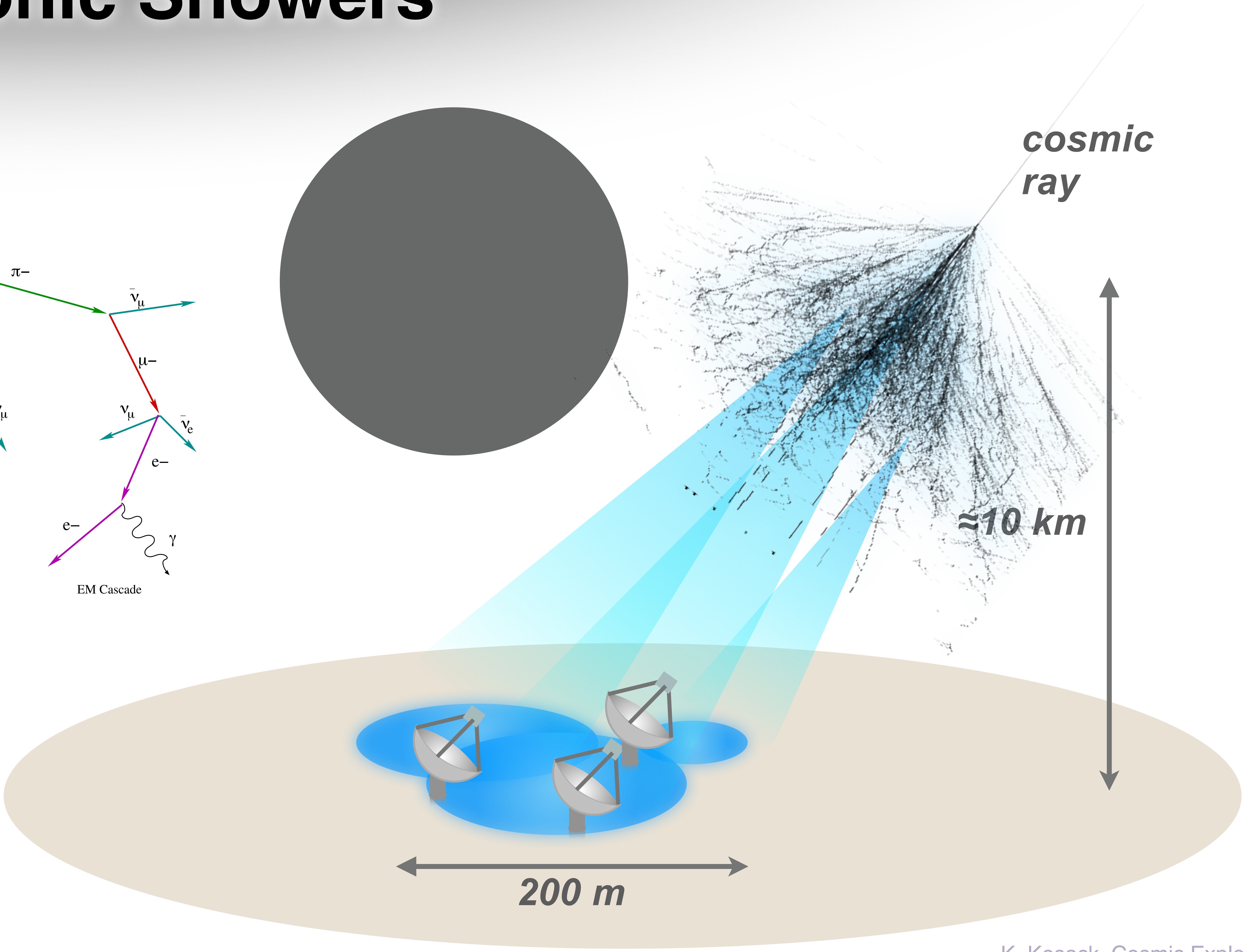

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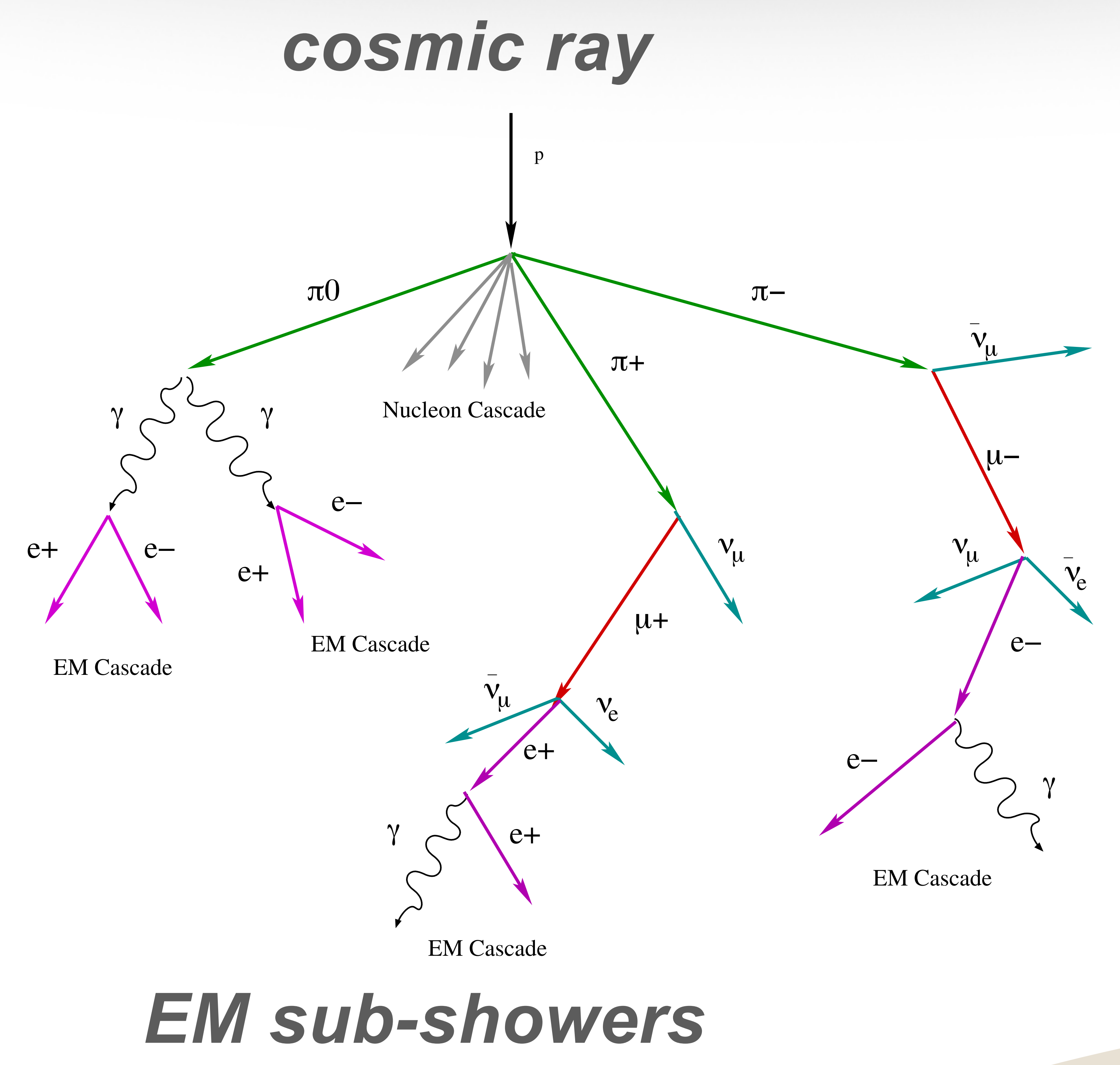
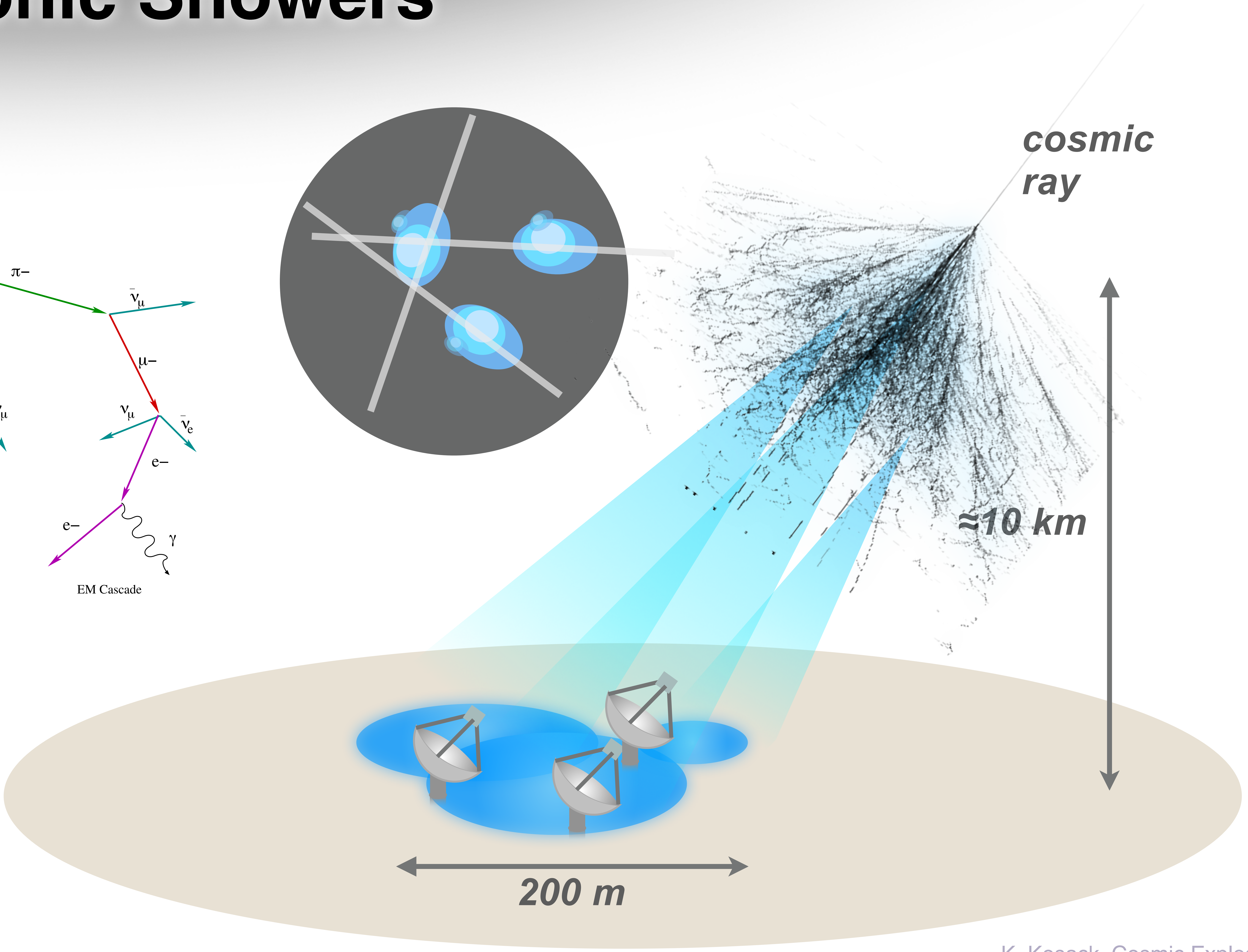




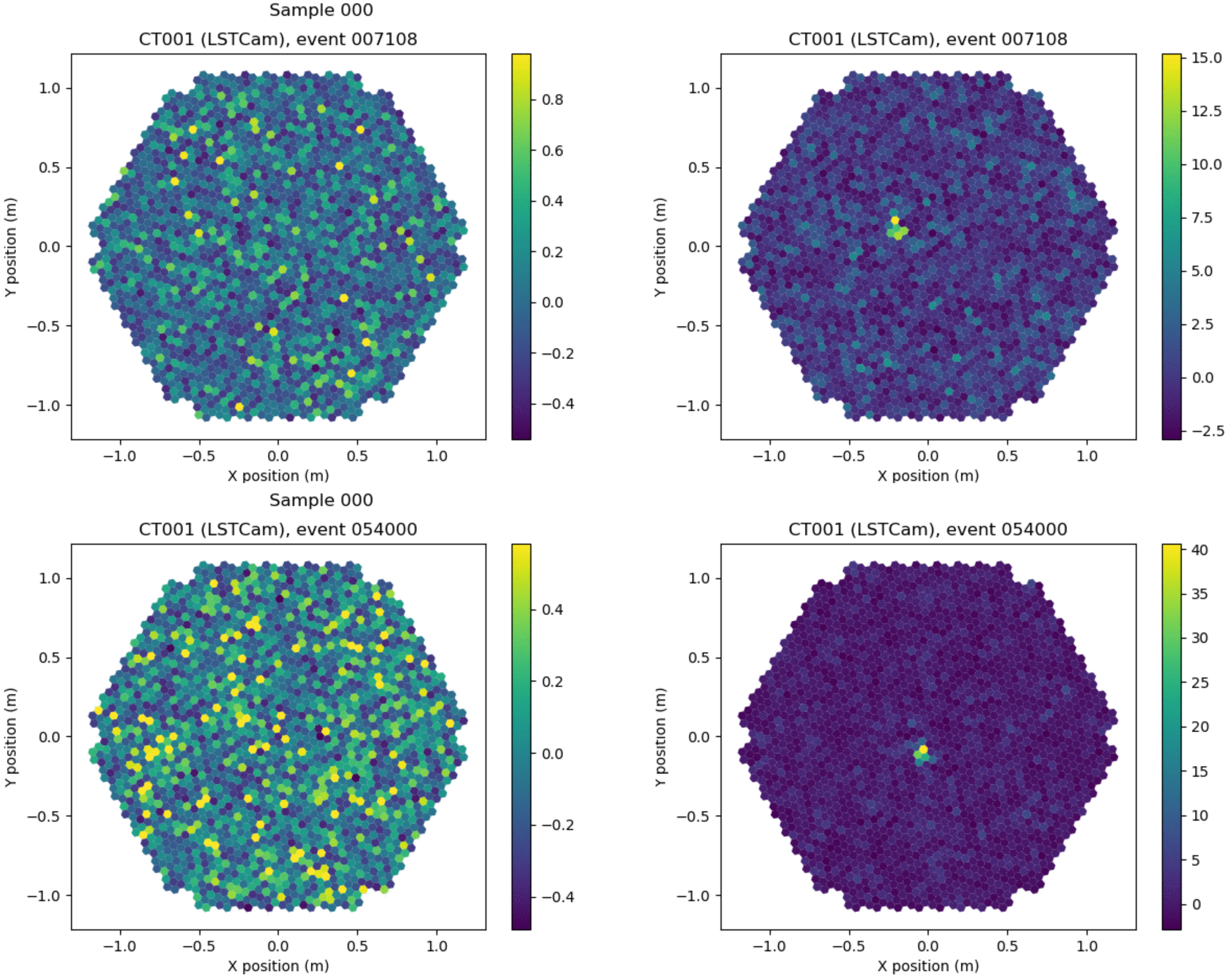
Single Telescope View

nanosecond samples ***time-integrated***

gamma ray

cosmic ray

(background)



Single Telescope View

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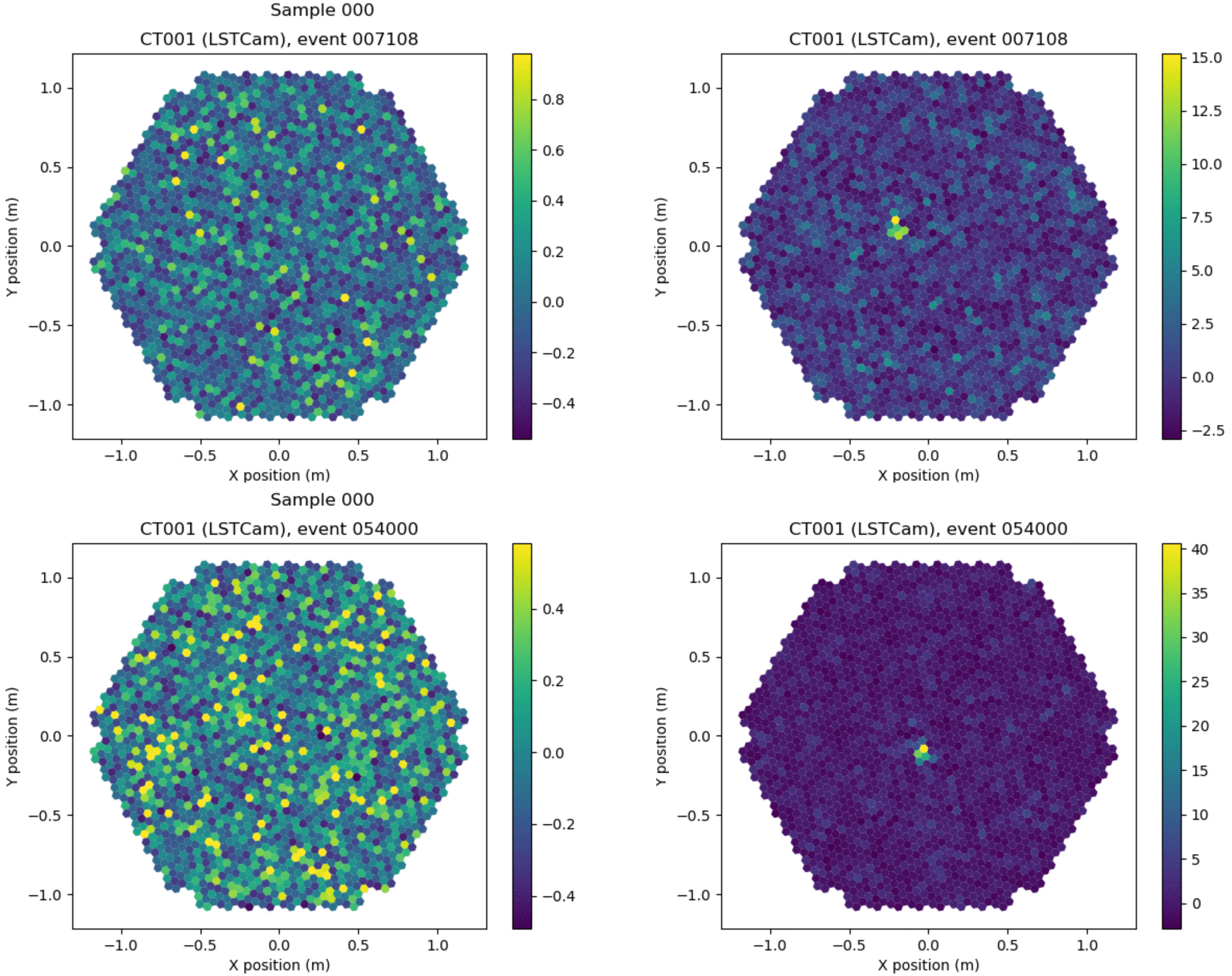


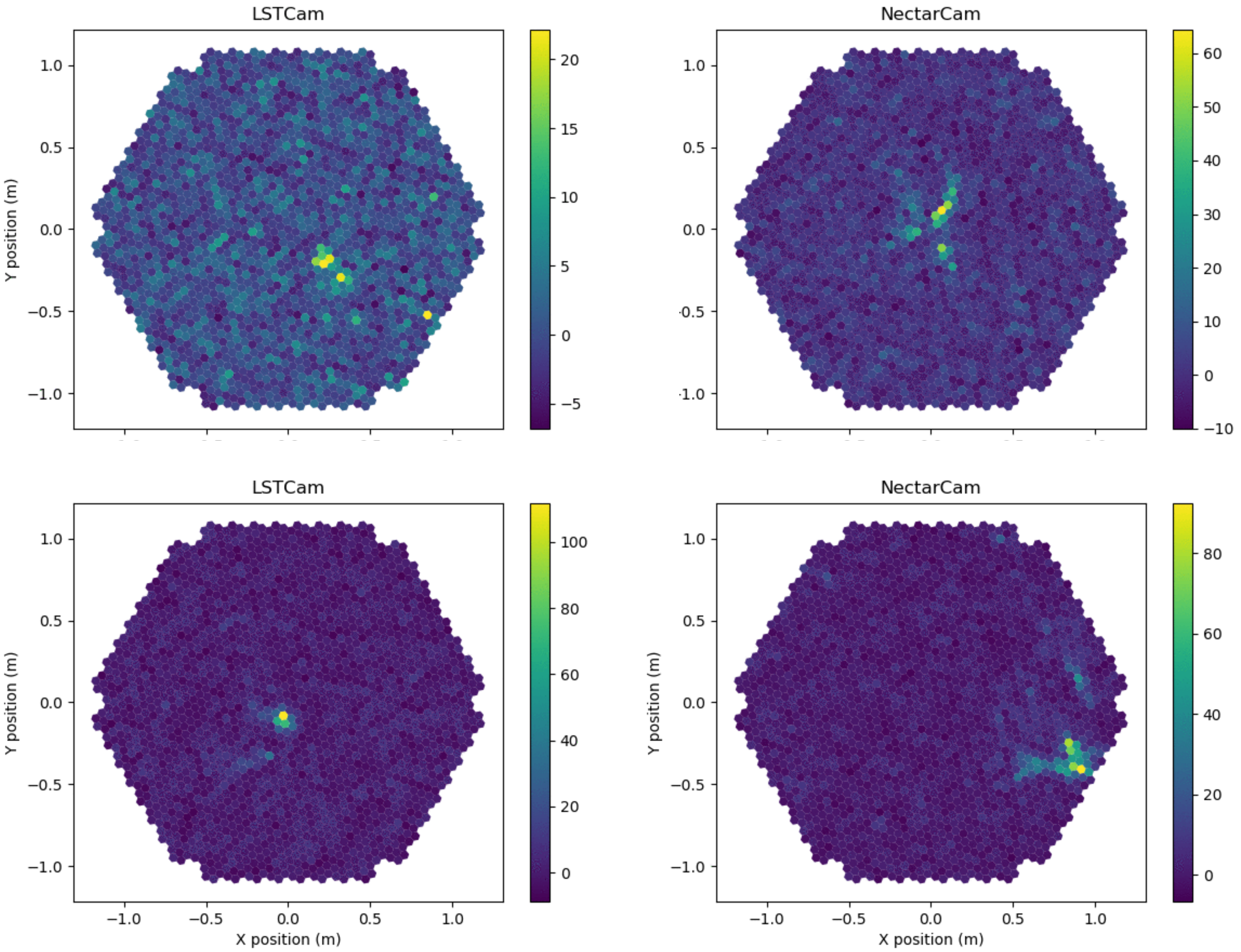
Stereo View

Large-Telescope Subarray — *Medium Telescope Subarray*

gamma ray

cosmic ray

(background)



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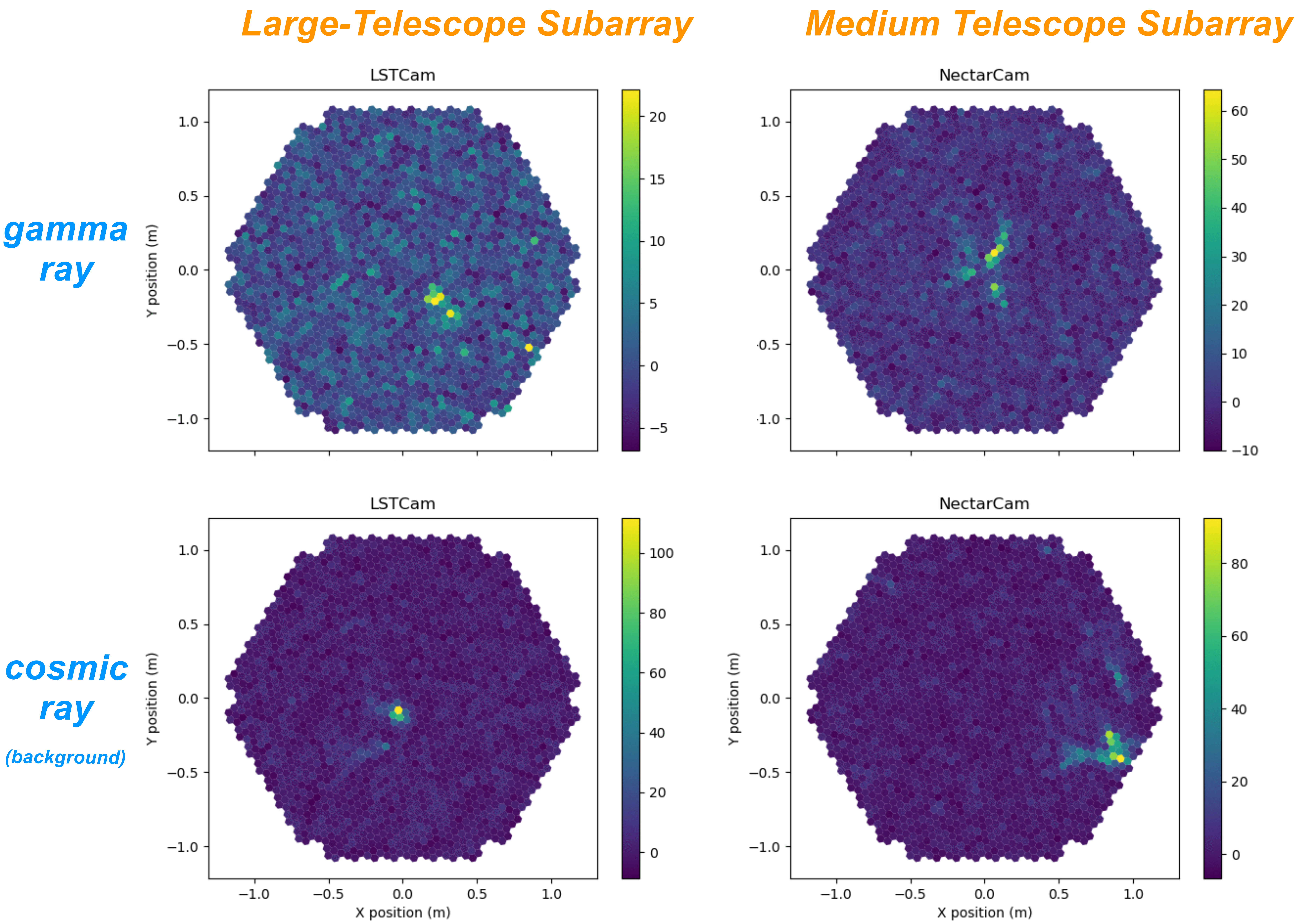
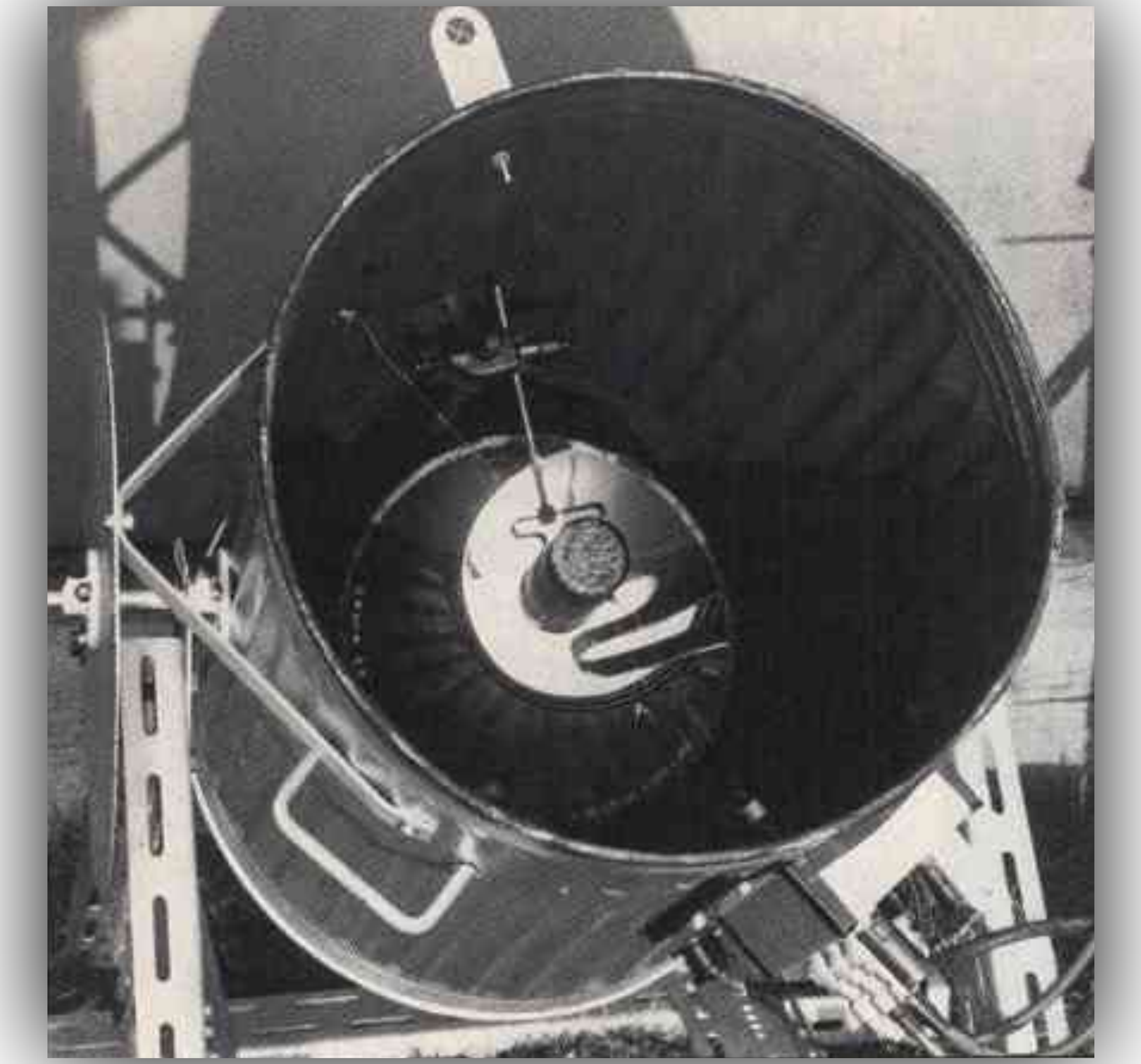


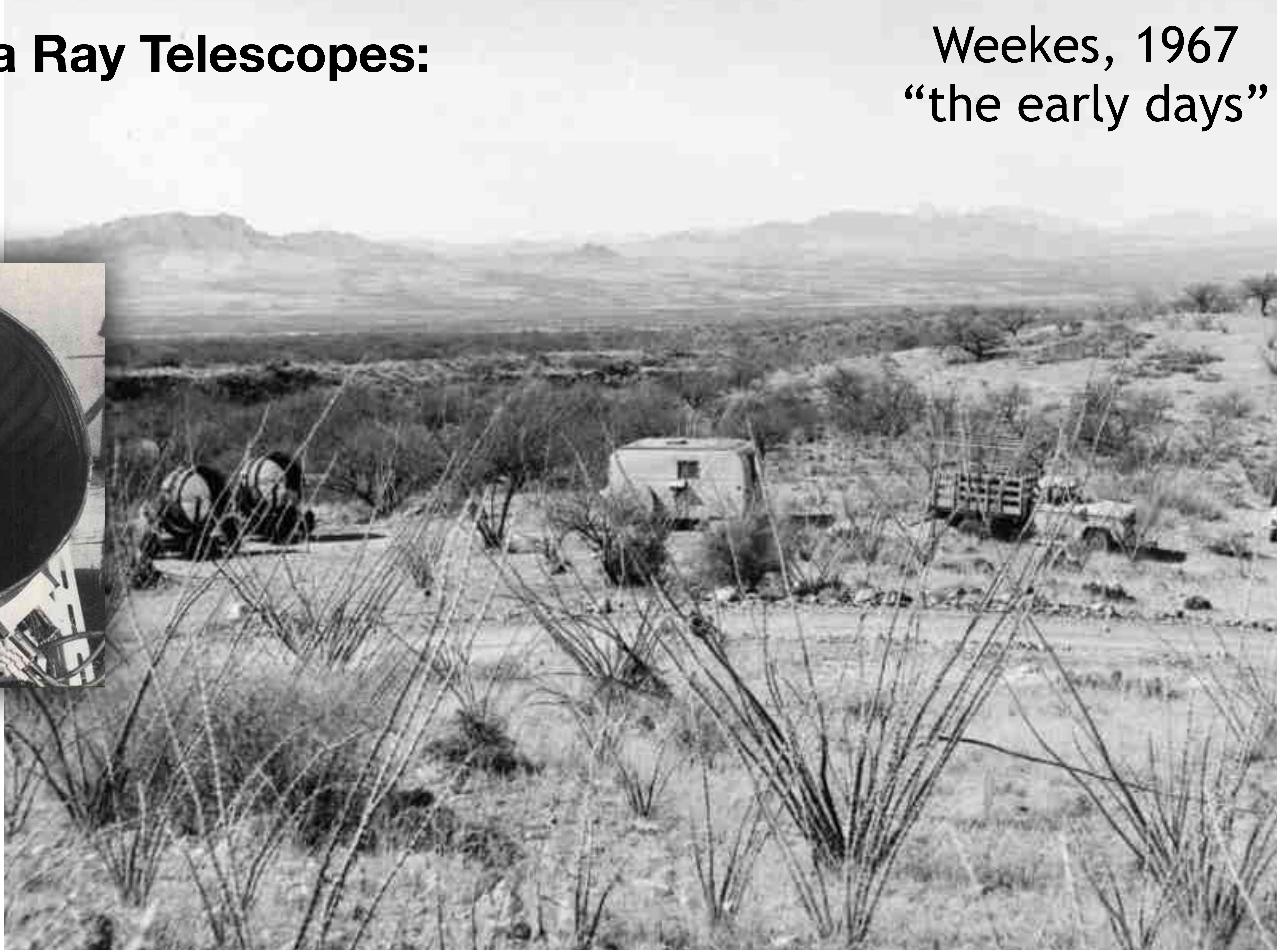
Large-Telescope Subarray
Medium Telescope Subarray
gamma ray
cosmic ray
(background)
LSTCam
NectarCam
Y position (m)
X position (m)

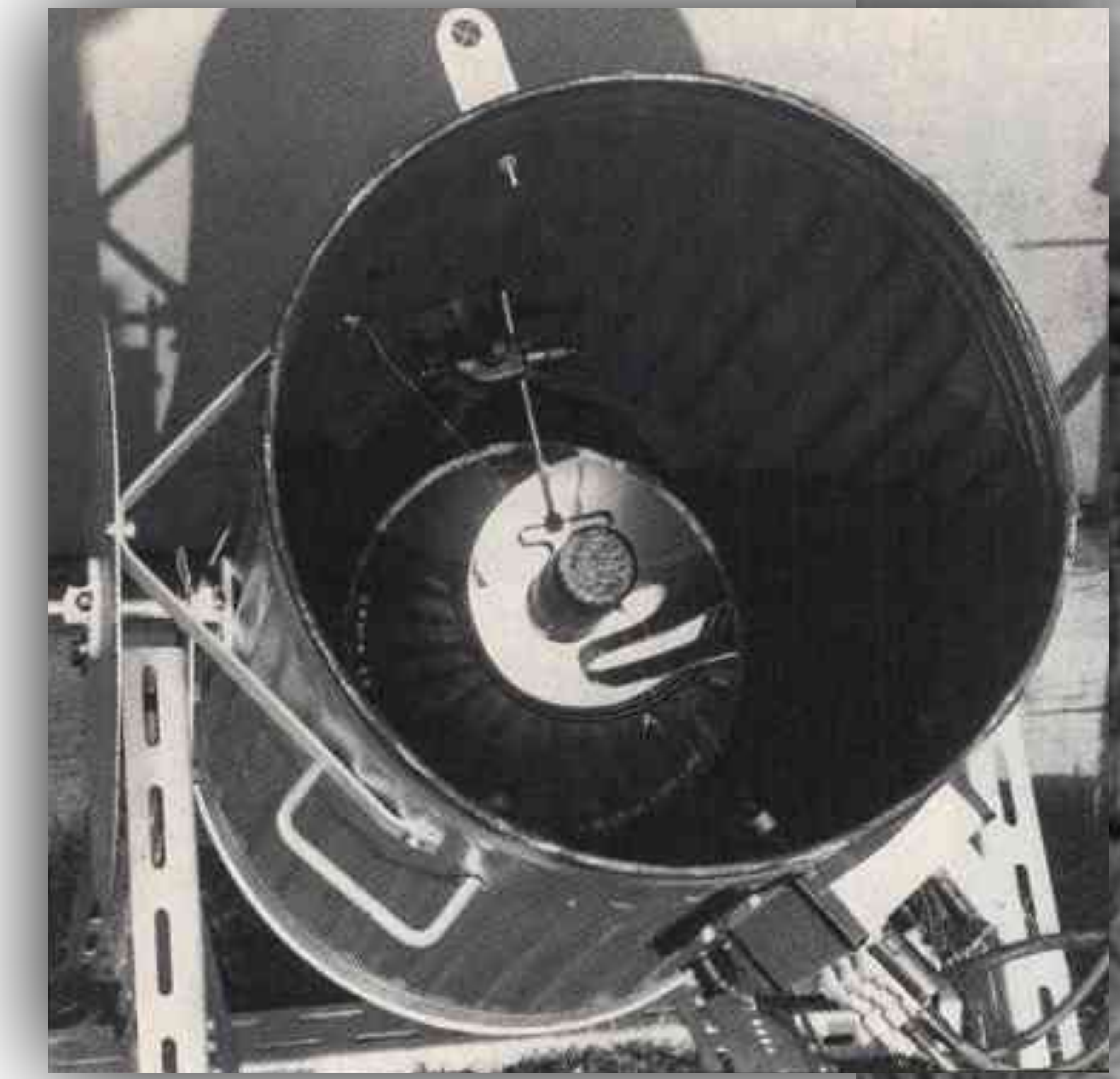
Early Gamma Ray Telescopes:
a look back



Early Gamma Ray Telescopes:
a look back

Weekes, 1967
"the early days"





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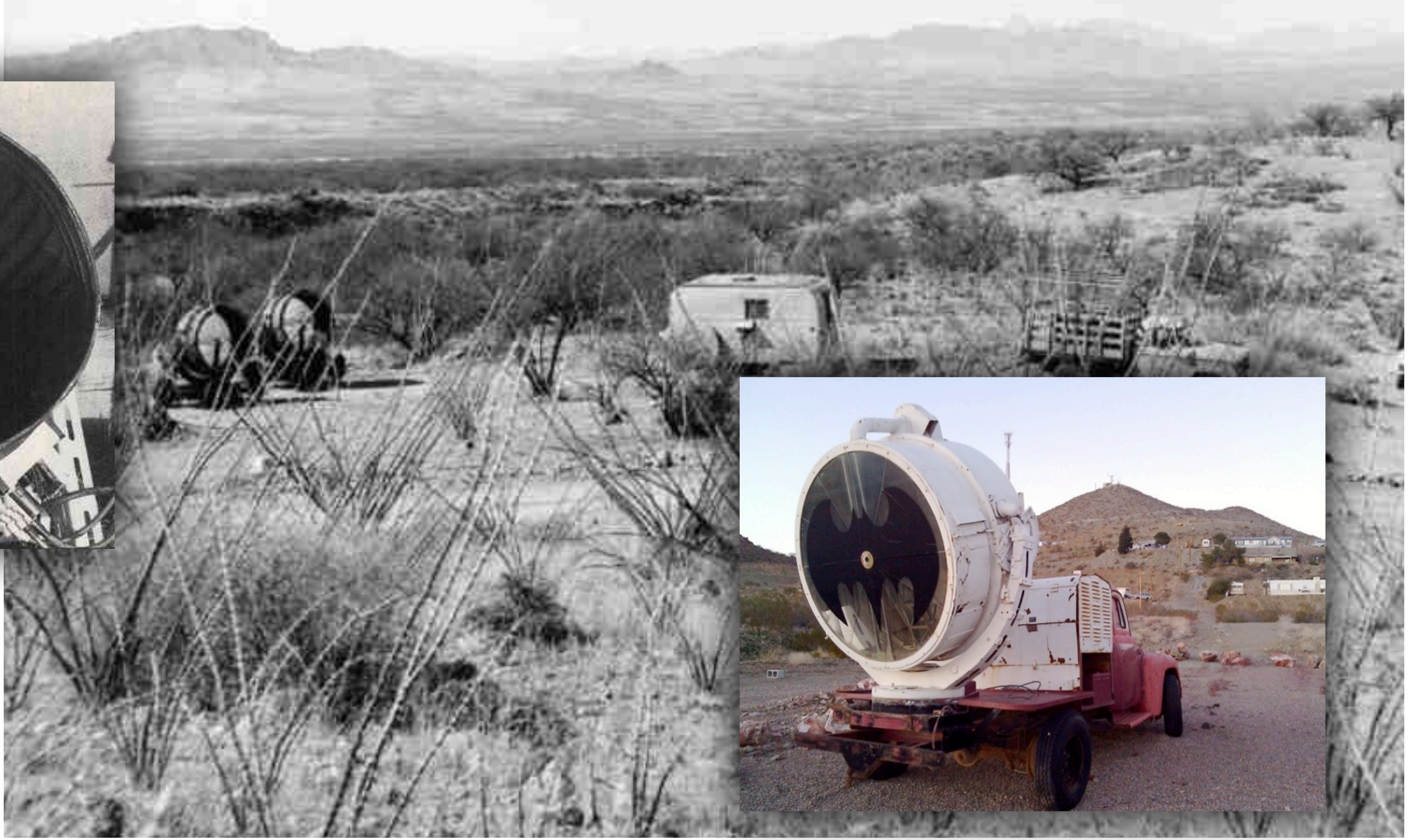
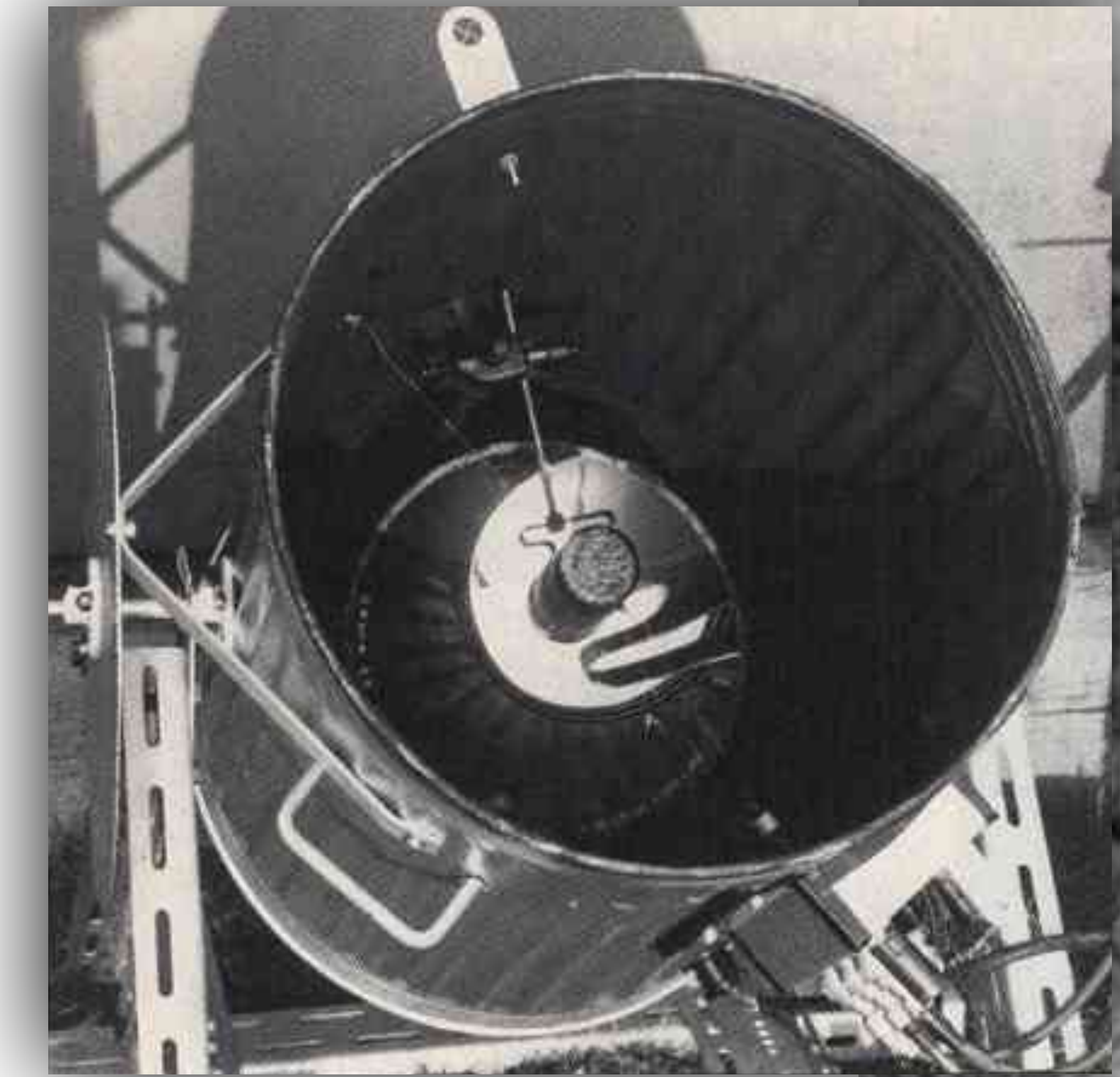
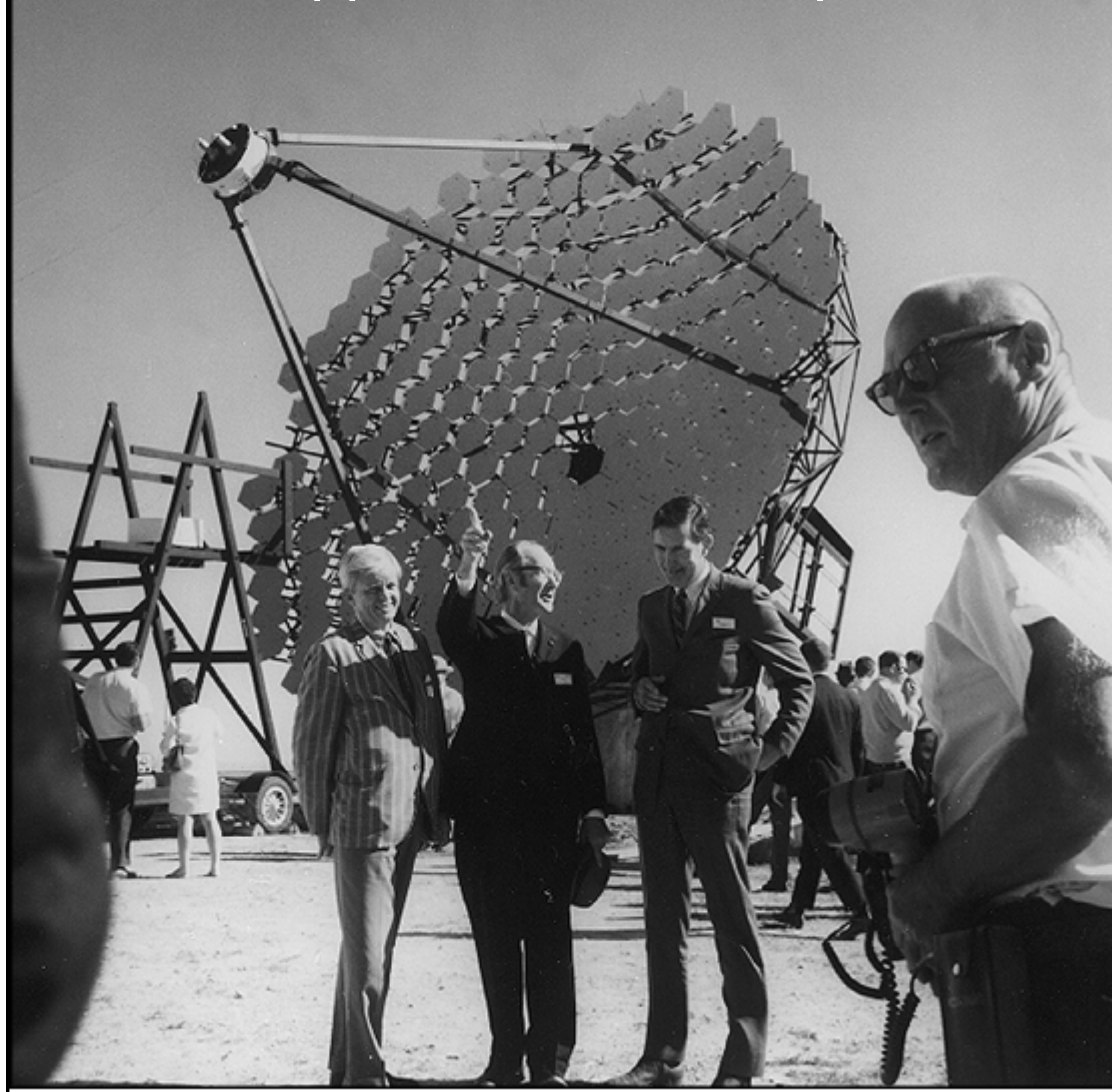
Weekes, 1967
“the early days”





Some VHE History

The Whipple 10 m Telescope, 1968



Whipple 10m teleescope

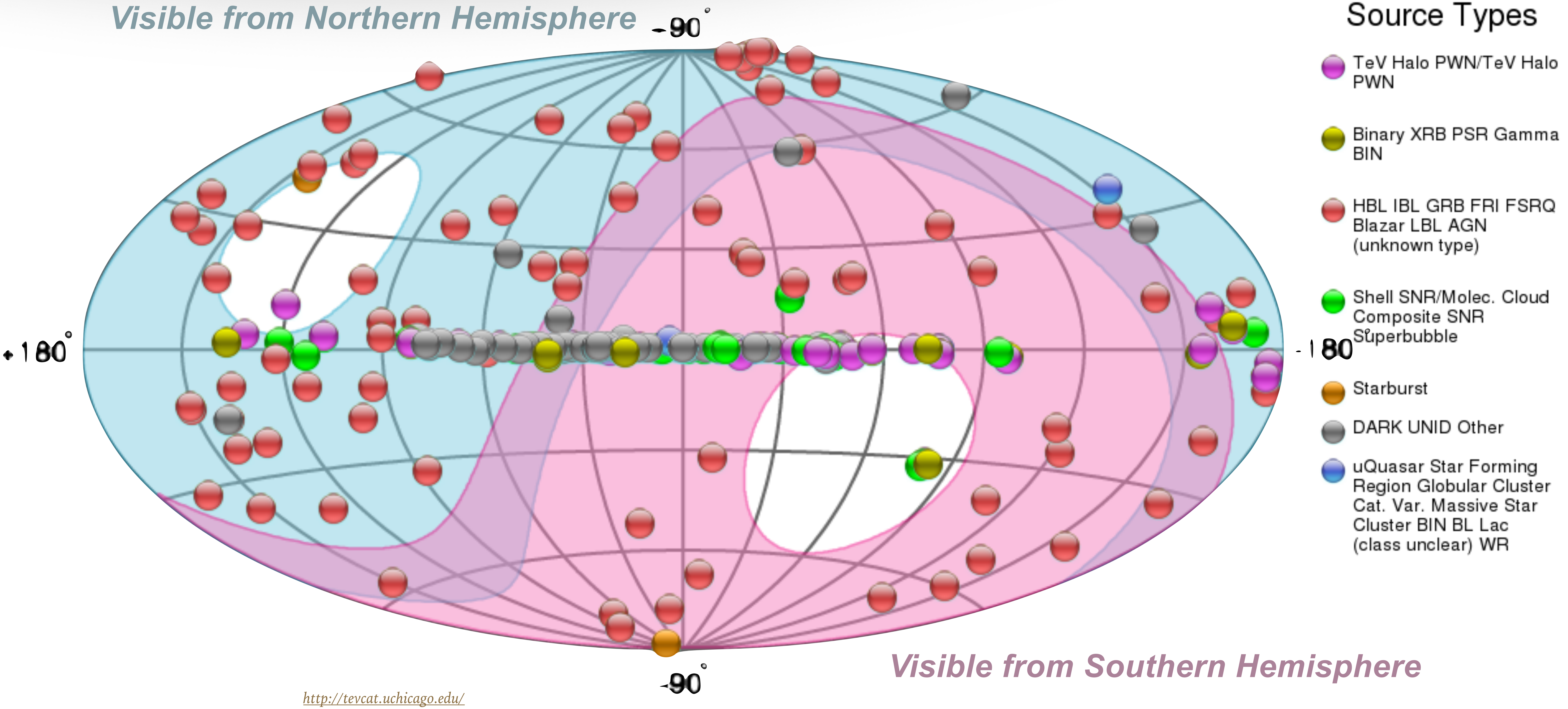
- **1968:** Built, Single-pixel camera
- **Breakthrough**: multi-pixel camera: **Shower Imaging**
- **1989:** First detection of Crab Nebula (at 5 σ)

Many came in between:

- CAT (Pyrenees),
- Durham (Australia)
- HEGRA (Canaries)
- Grace (India)
- CANGAROO (Australia)

Current Atmospheric Cherenkov Telescopes

Ground-based Telescopes: **Visibility**



http://tevcat.uchicago.edu/

Atmospheric Cherenkov Telescopes

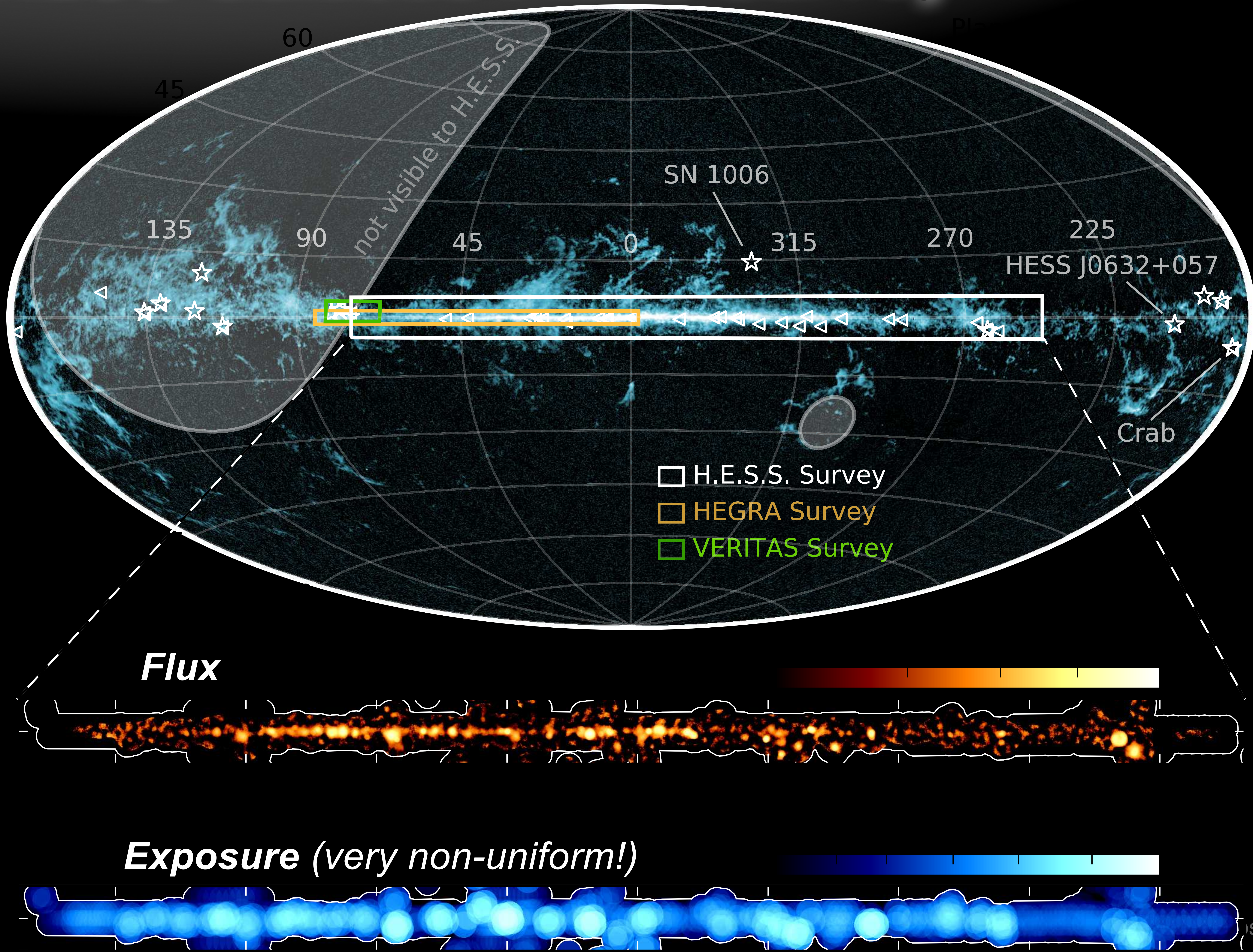
Advantages:

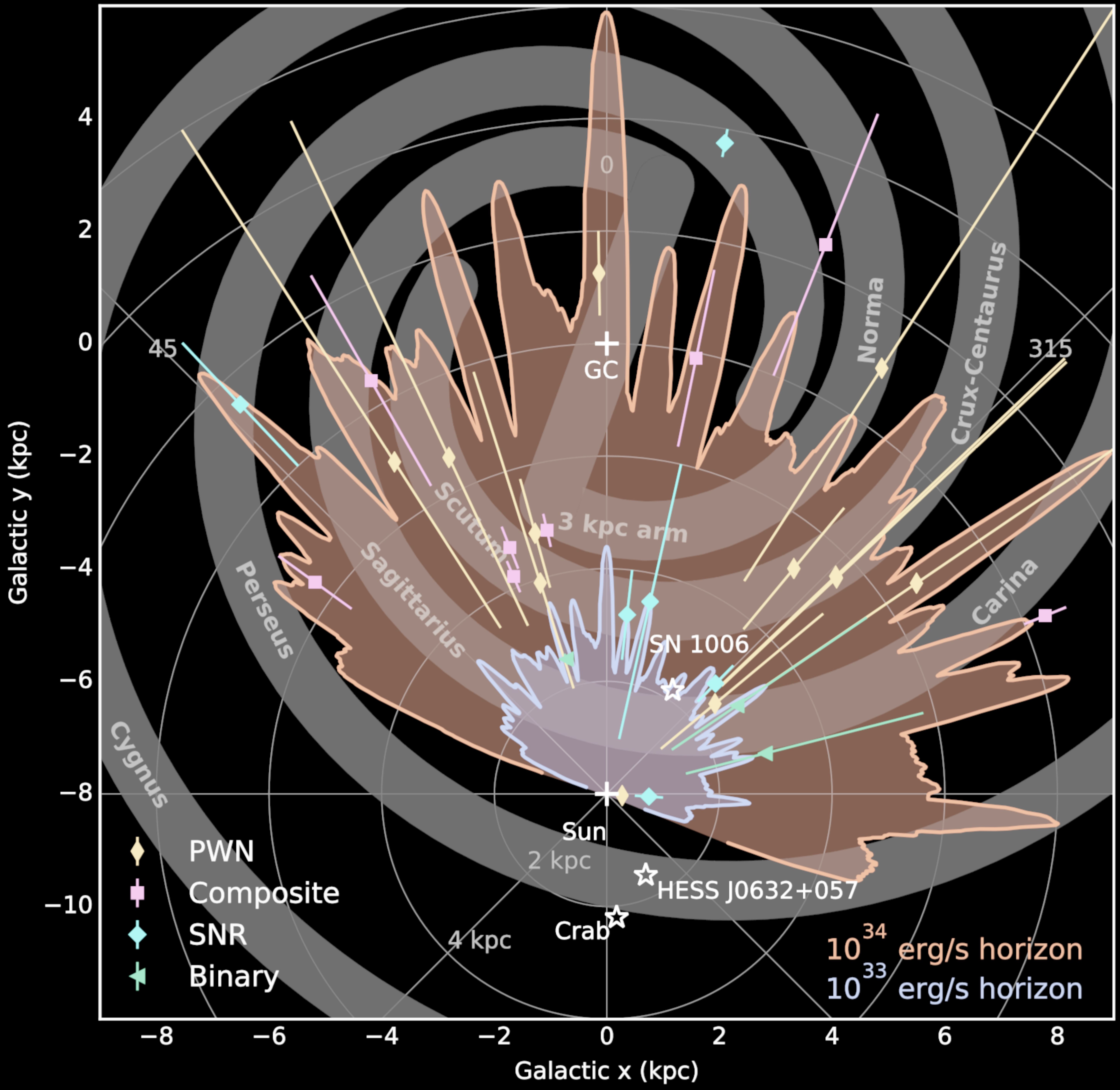
- high angular (<0.1°) and energy (<15%) resolution
- very good sensitivity
  - many orders of magnitude better than Fermi-Lat in overlapping energy range!
  - great for short-term variability
- Cheap! (ground-based)
- Upgradable!
  - e.g. add more telescopes to get larger effective area

Disadvantages

- Small(ish) Field-Of-View (3°-10°) → non uniform exposure, must know where to look
- Small duty cycle
  - can't observe in day or with bright moon!
  - ≈1000-1400 hours/year
- No full-sky coverage for single instrument
  - limitation of being on Earth
- Limited by atmosphere quality

HESS Galactic Plane Survey

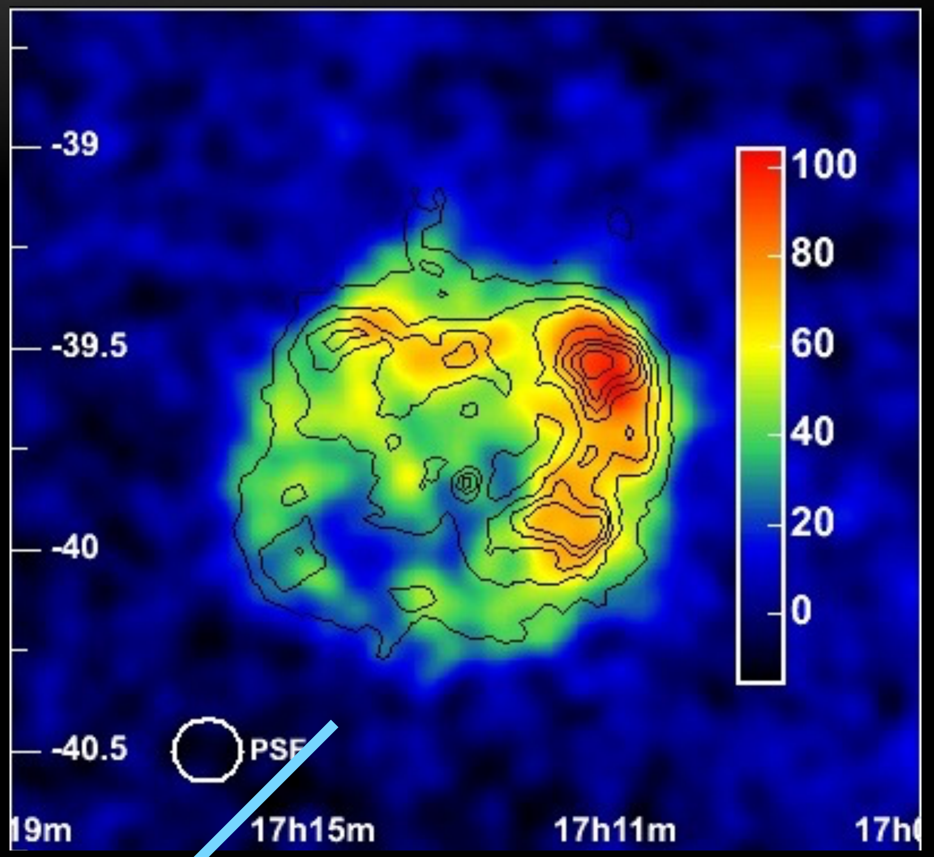


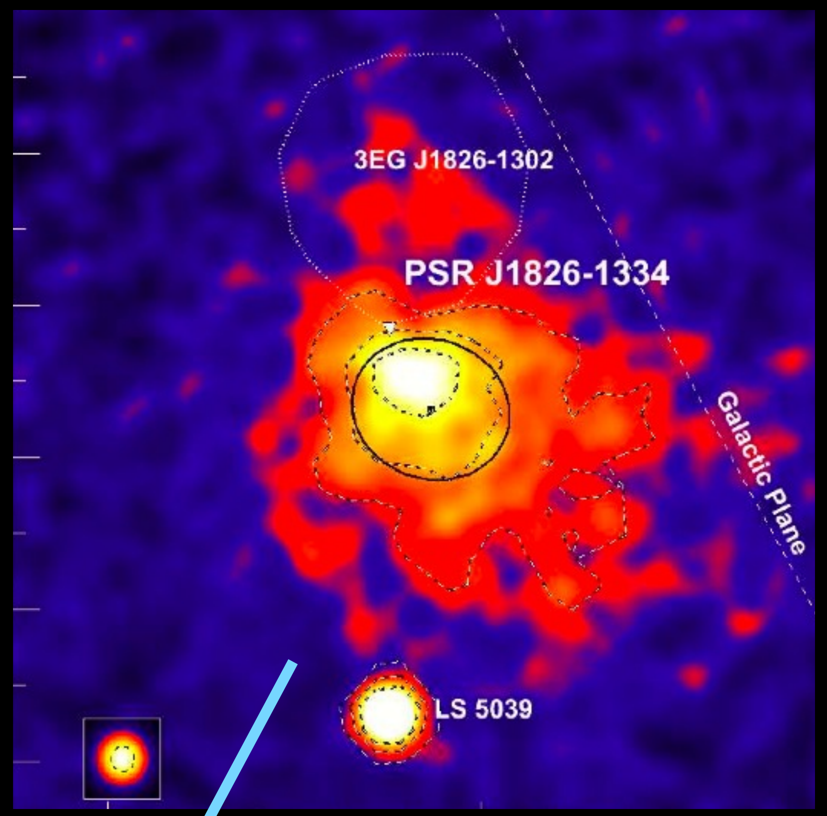


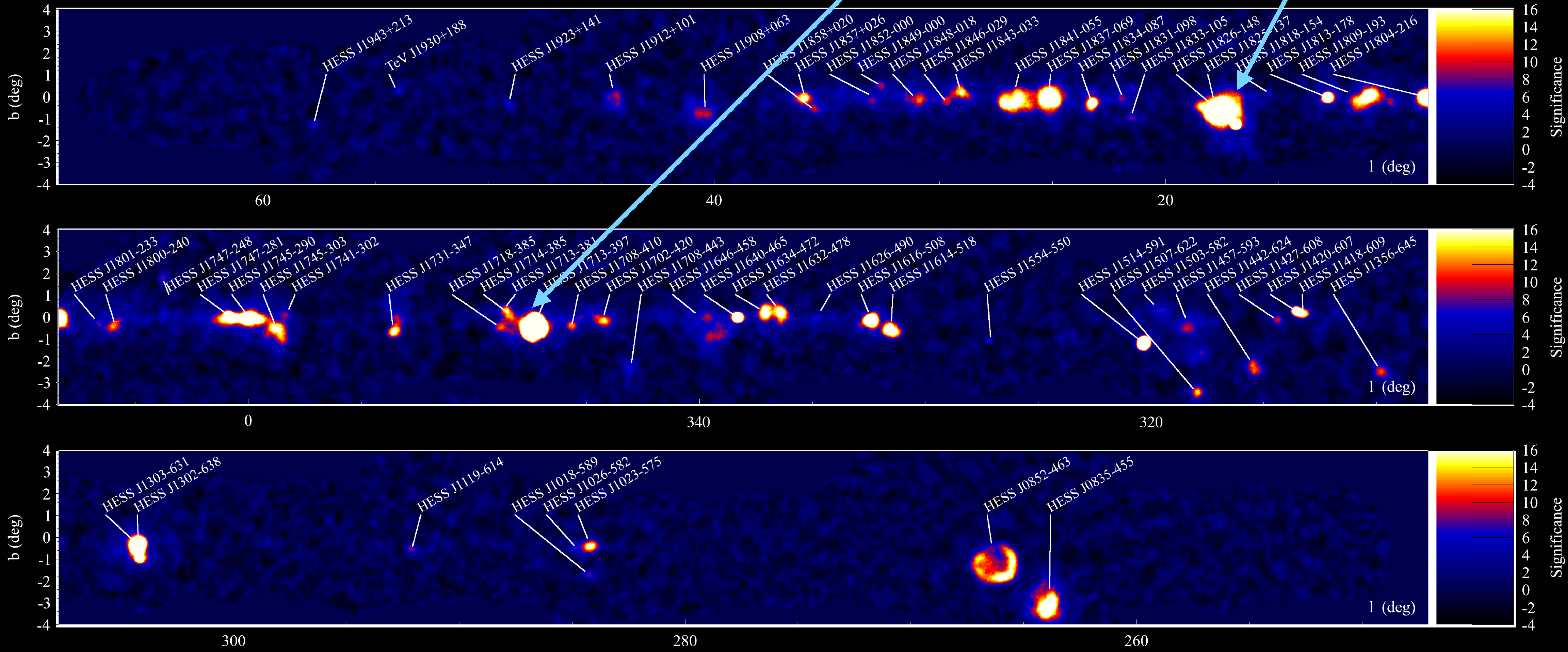
GC
Sun
SN 1006
HESS J0632+057
Crab
0
45
315
2 kpc
4 kpc
3 kpc arm
Scutum
Sagittarius
Perseus
Cygnus
Norma
Crux-Centaurus
Carina
PWN
Composite
SNR
Binary
10^{34} erg/s horizon
10^{33} erg/s horizon
Galactic x (kpc)
Galactic y (kpc)

The Very-high-energy sky

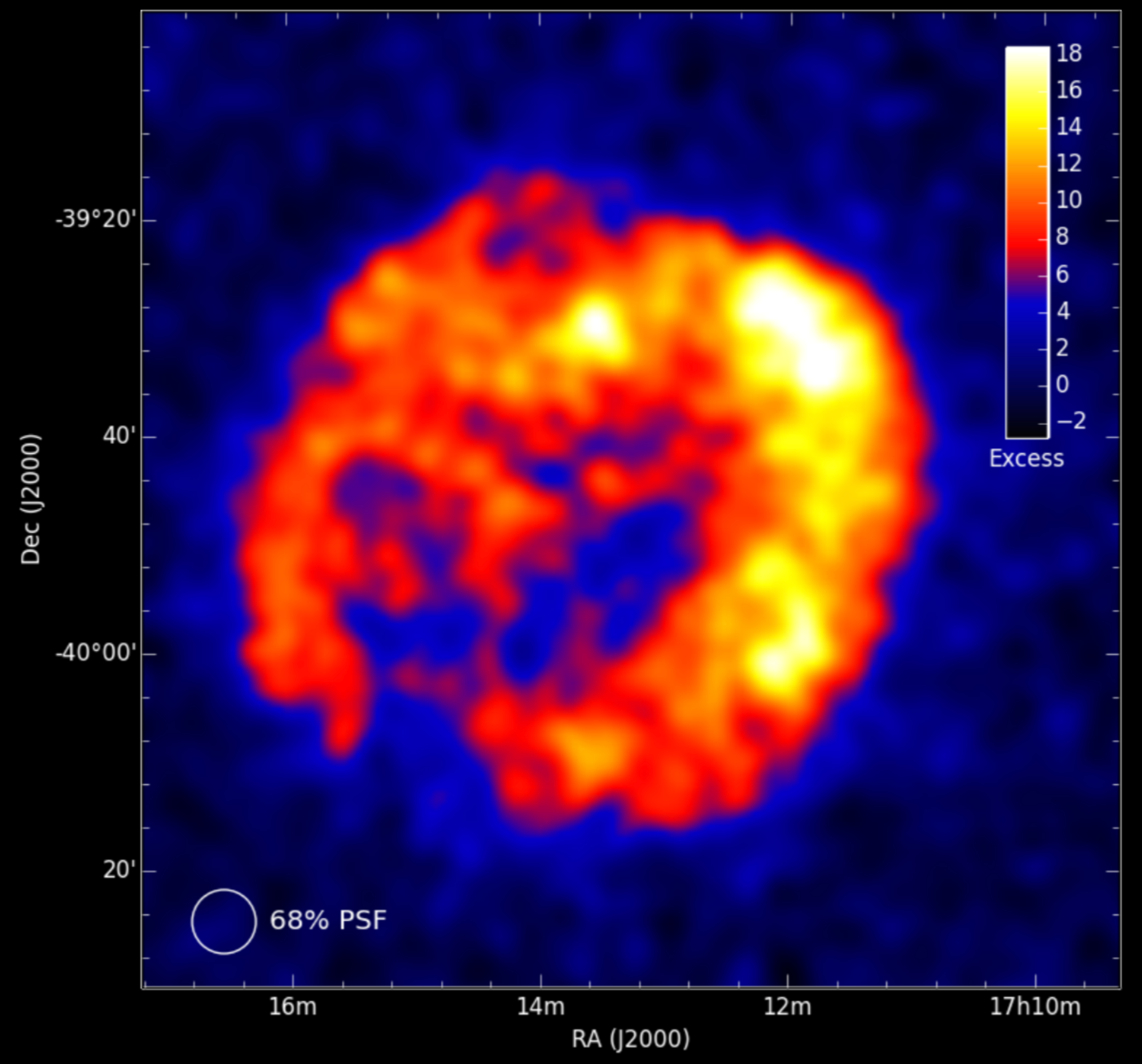
in the plane ,mostly extended sources (pulsar wind nebulae, supernova remnants)

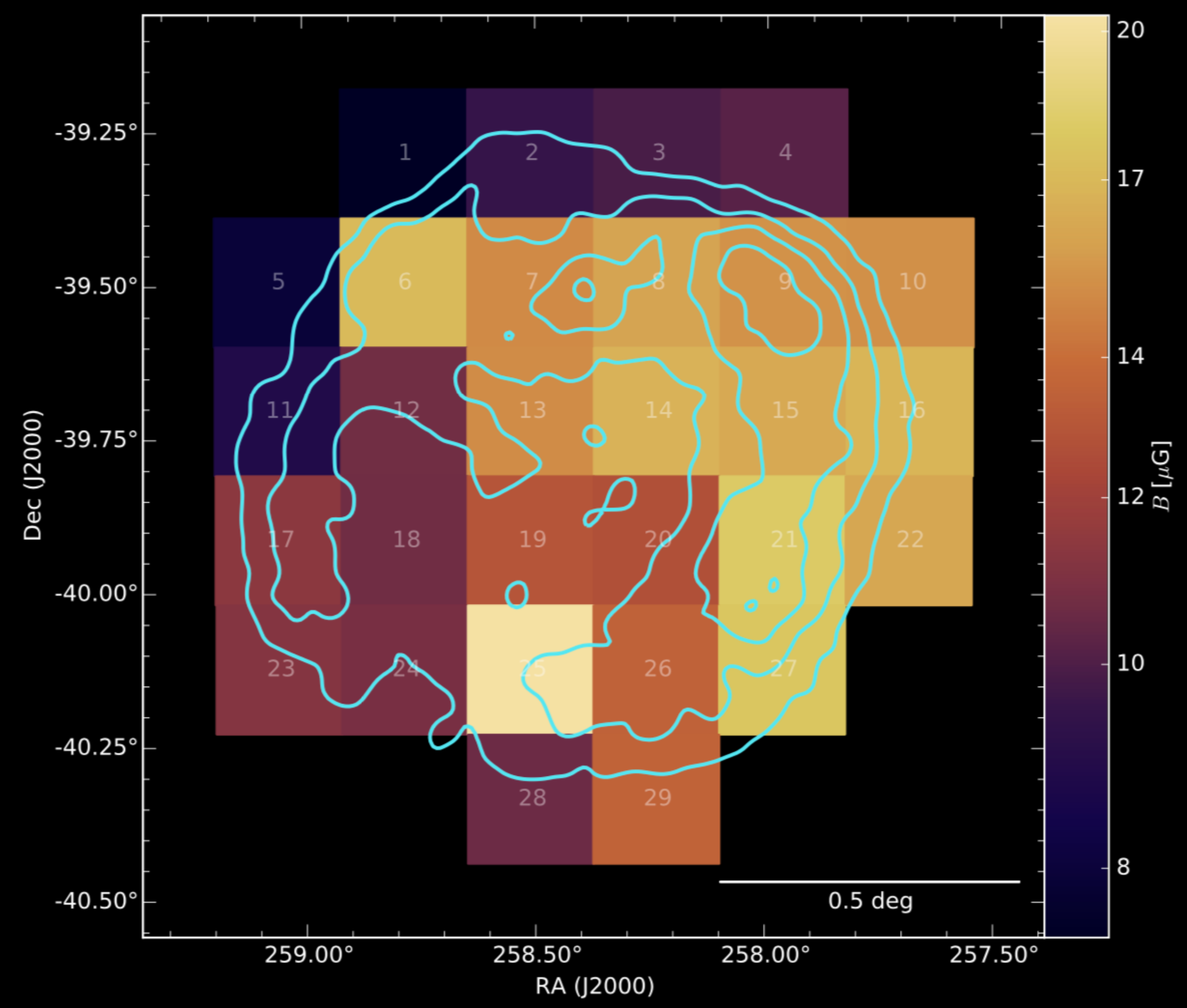




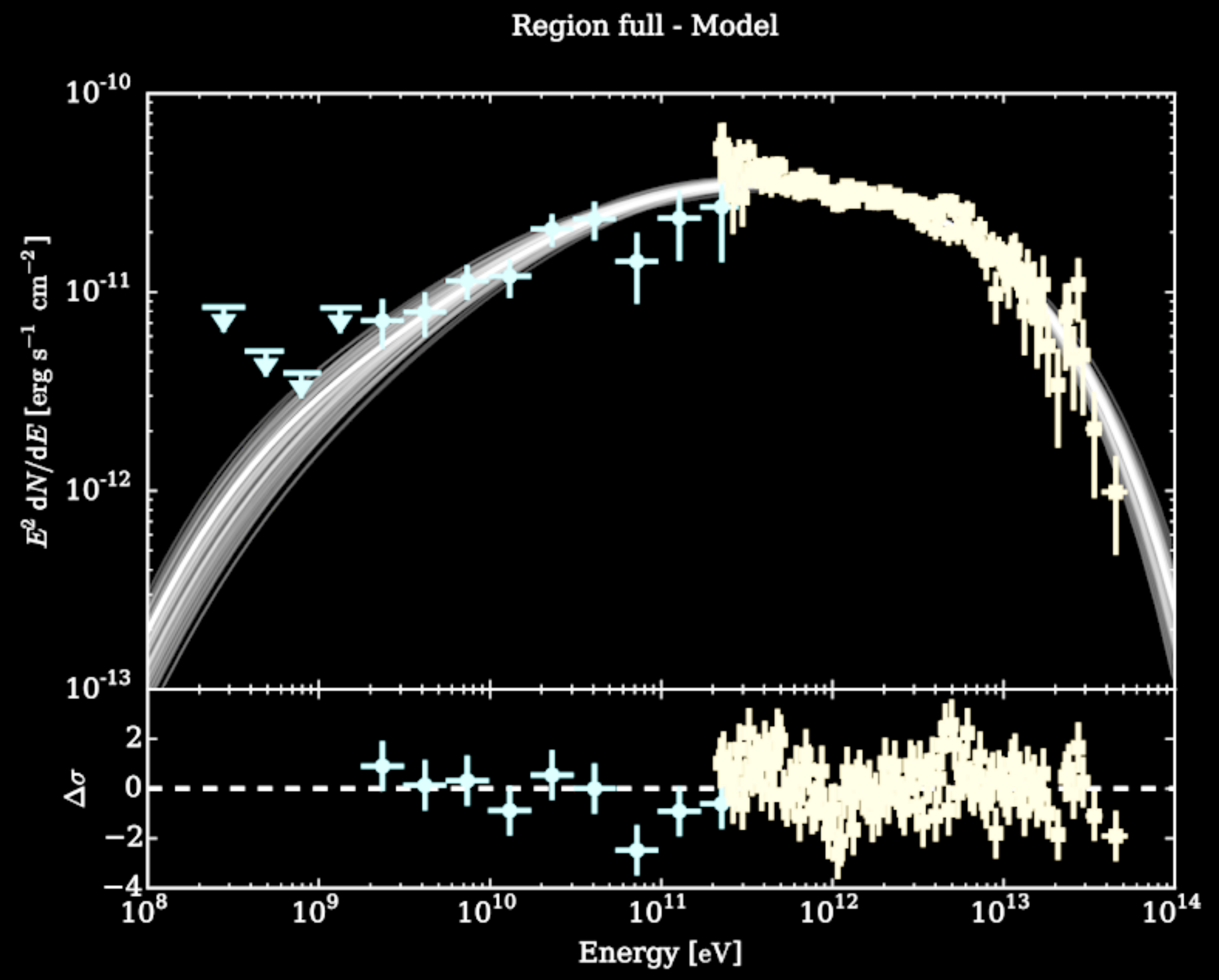


Supernova Remnants



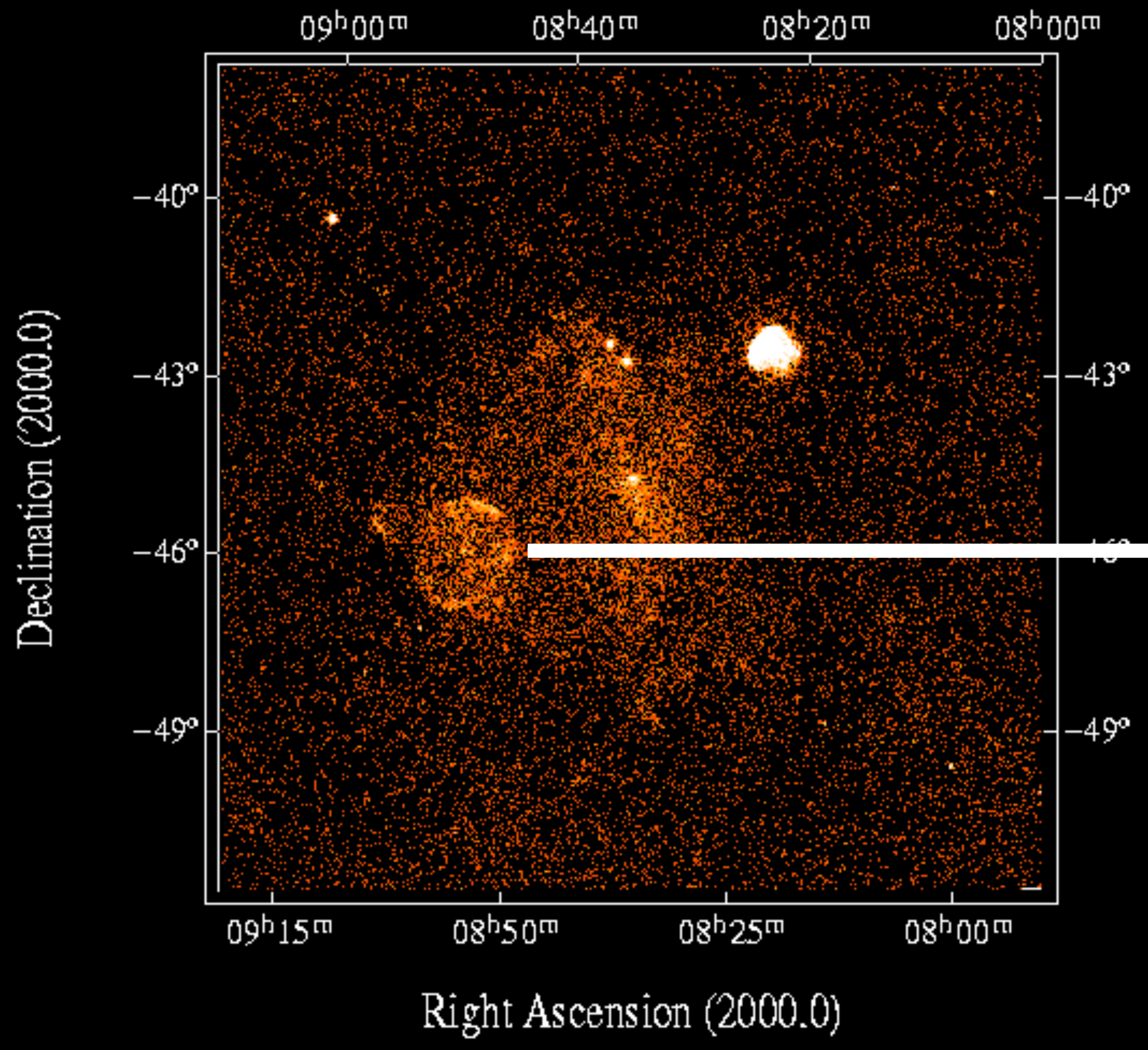


B-field strength map under leptonic scenario



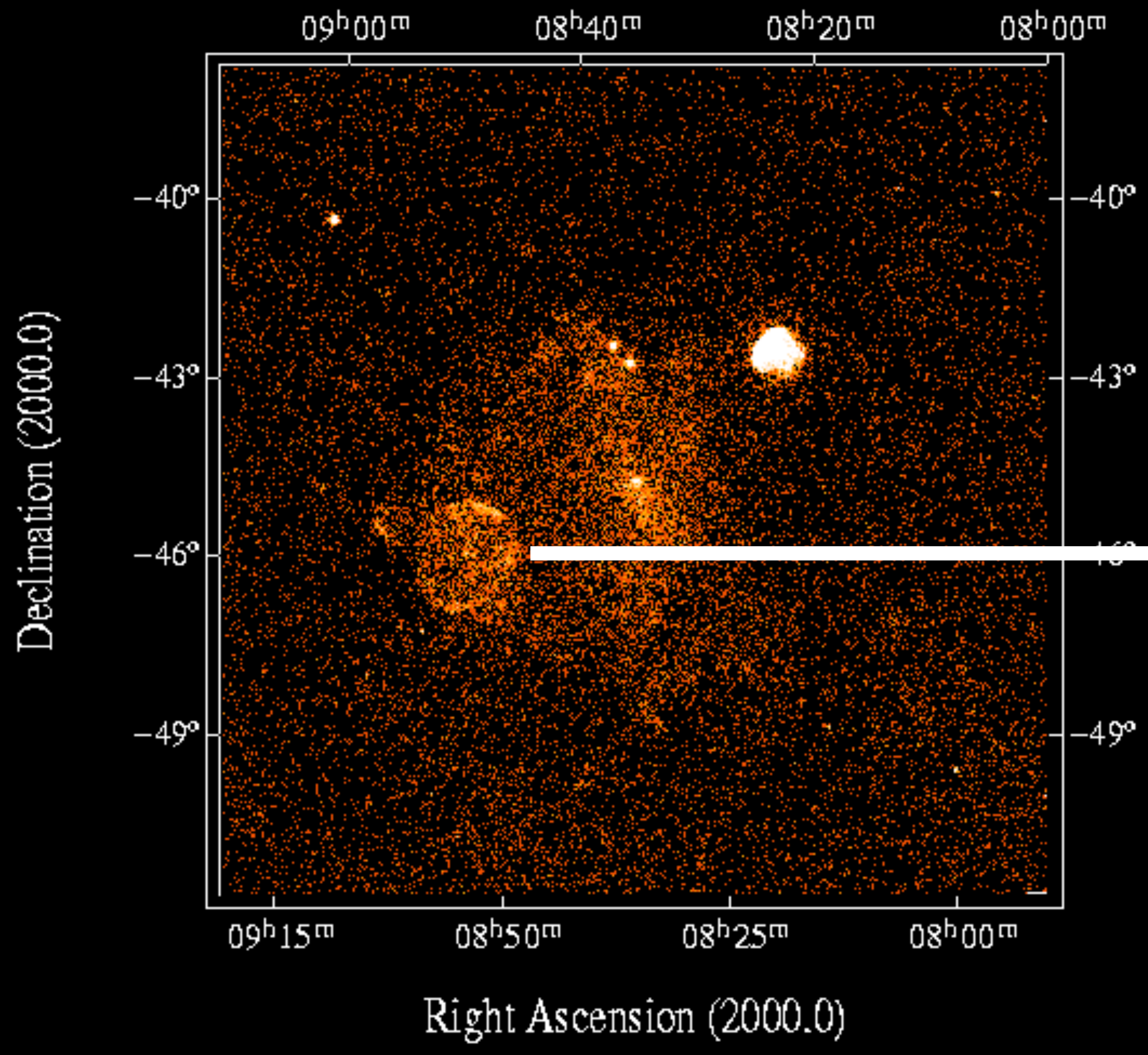
(See Jacco's SNR Talk yesterday)

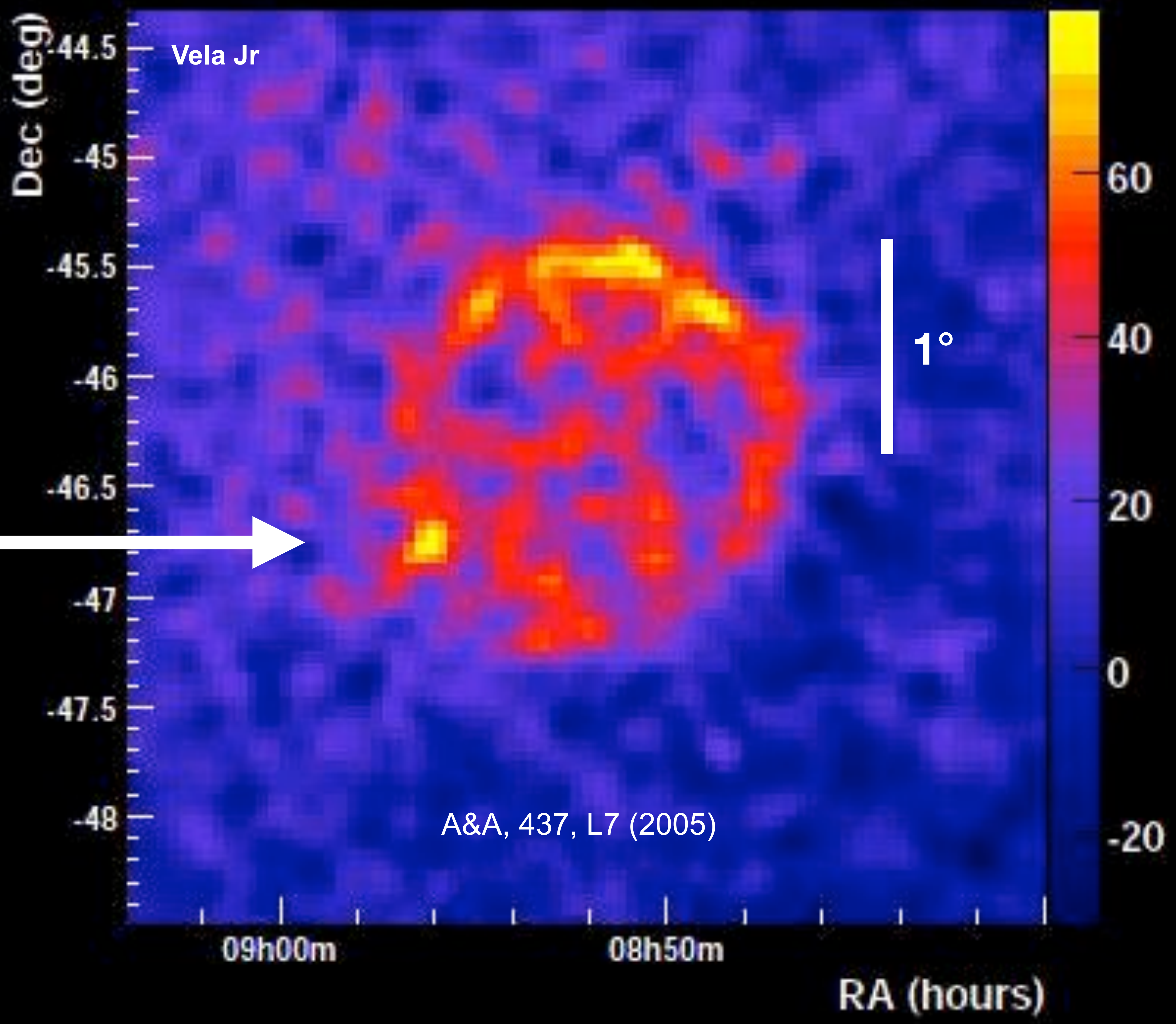
Remember Vela Jr from COMPTEL?



1°

Remember Vela Jr from COMPTEL?





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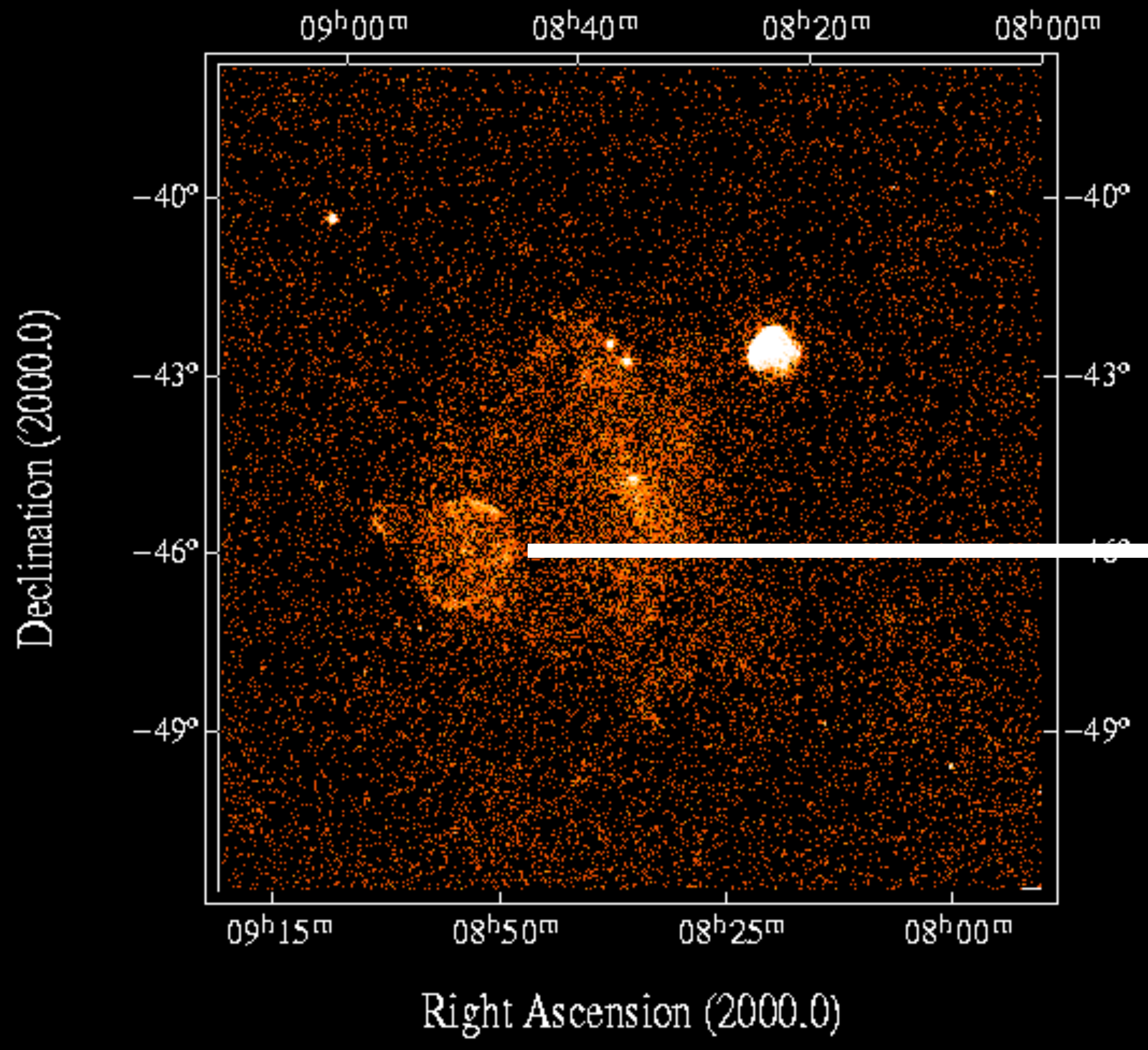
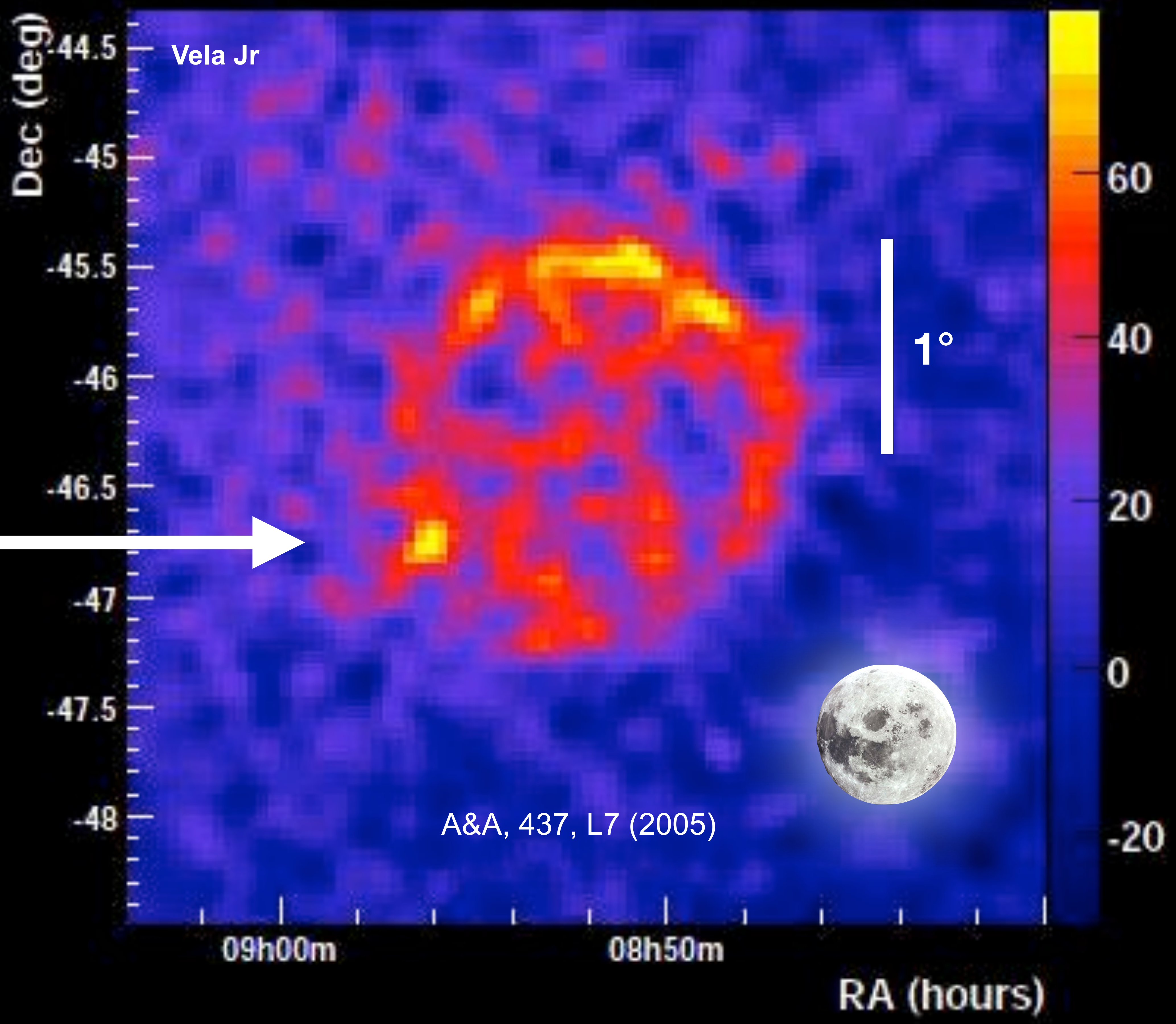
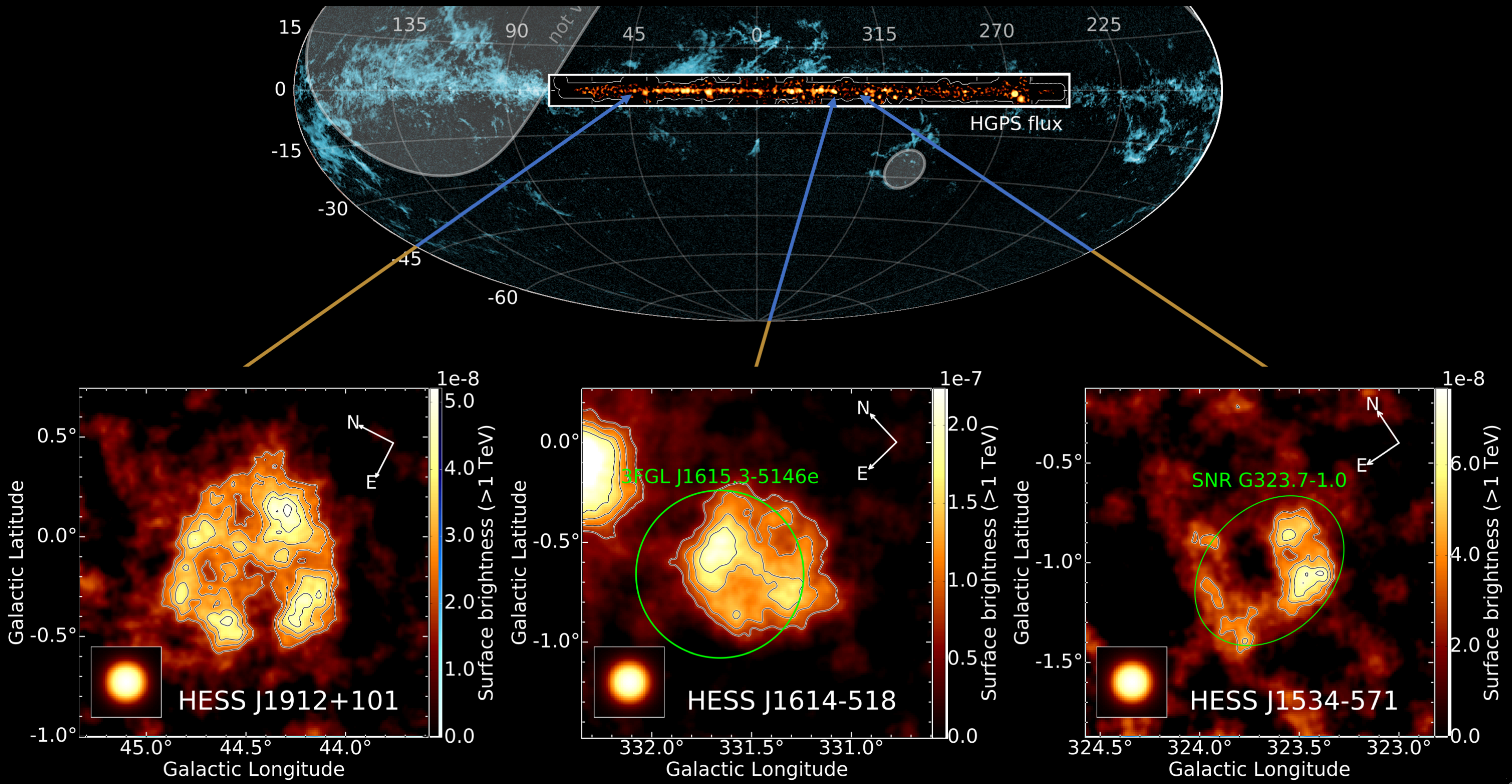




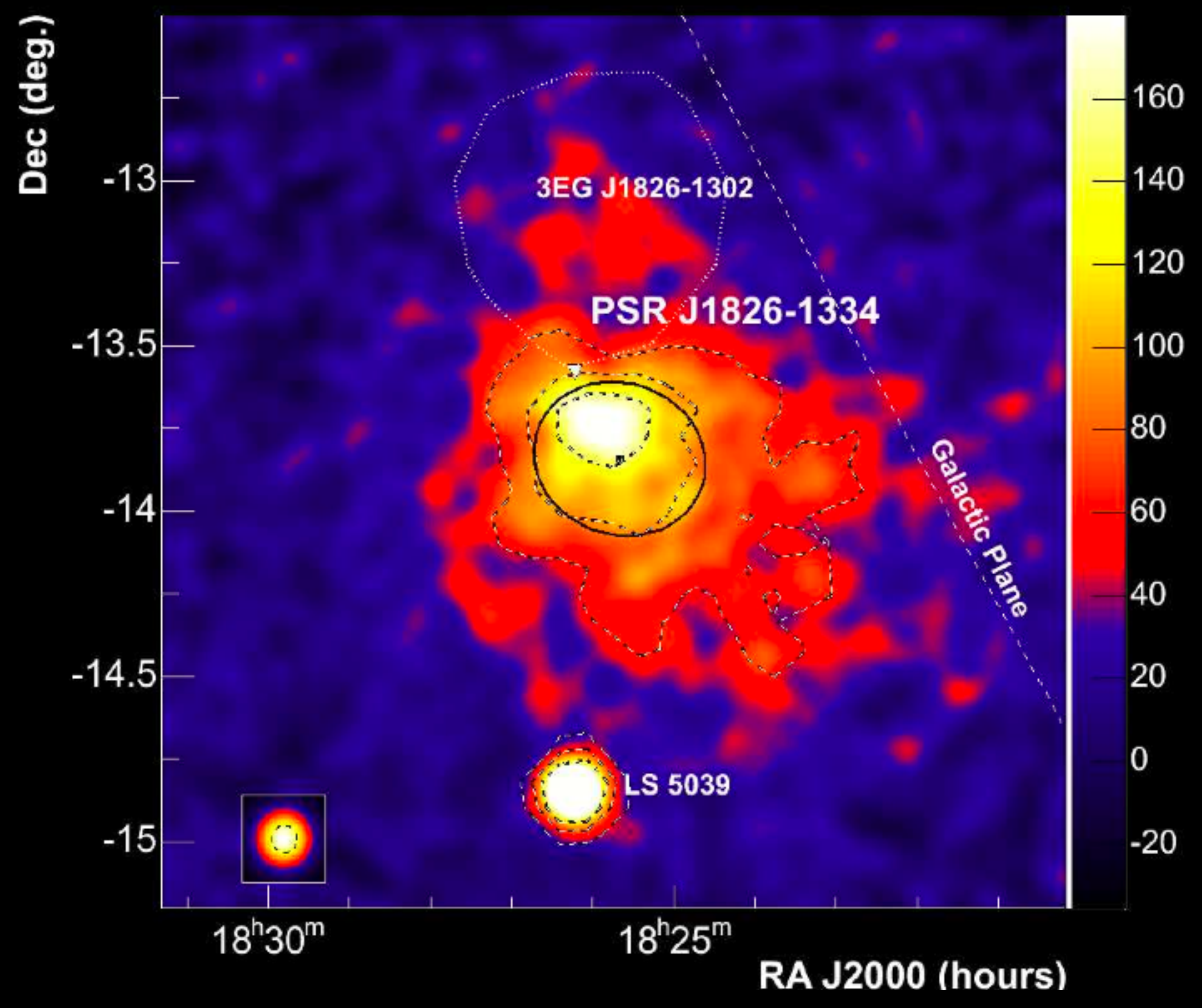
Discovering new Supernova Remnants

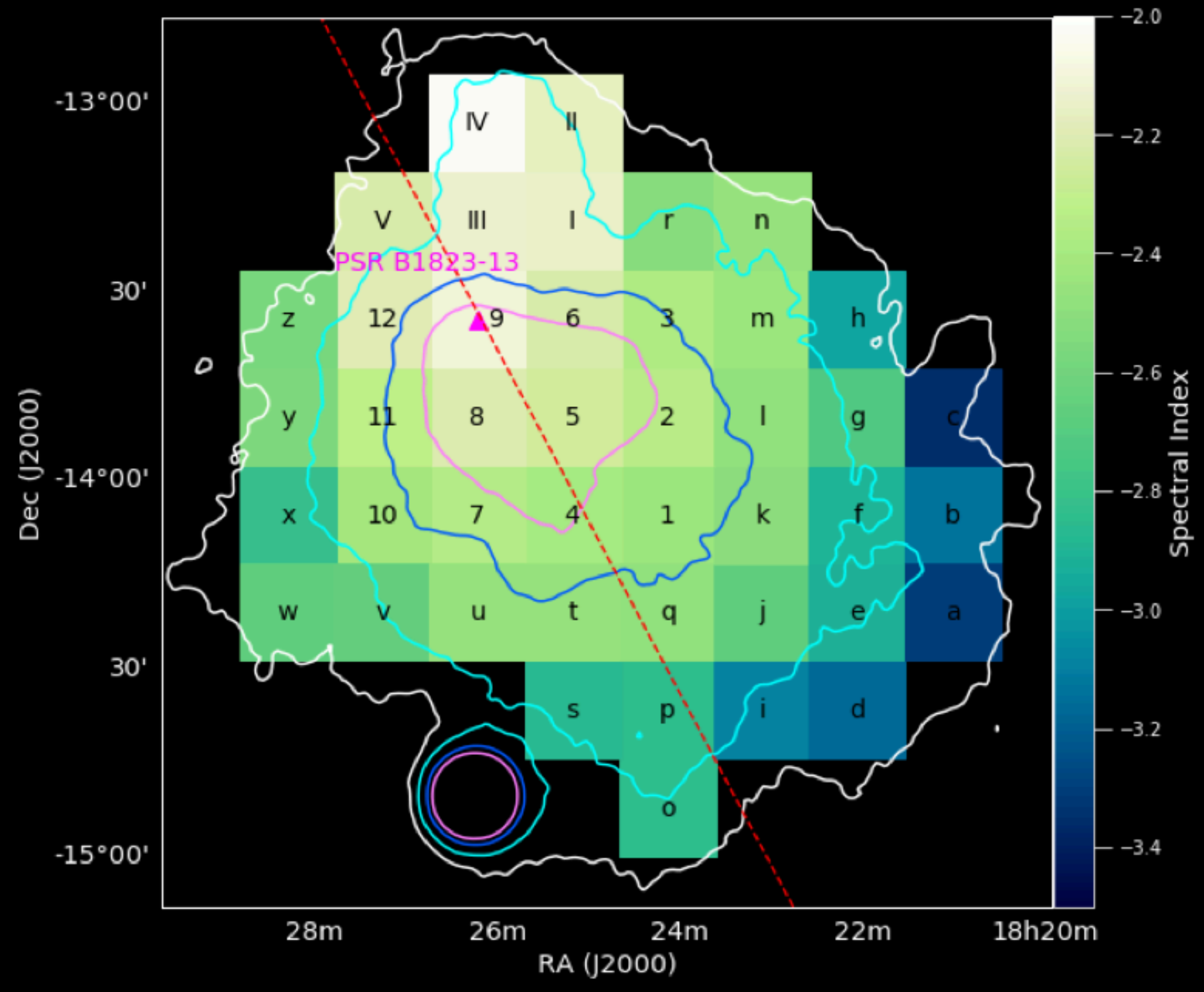


https://www.mpi-hd.mpg.de/hfm/HESS/pages/home/som/2018/03/

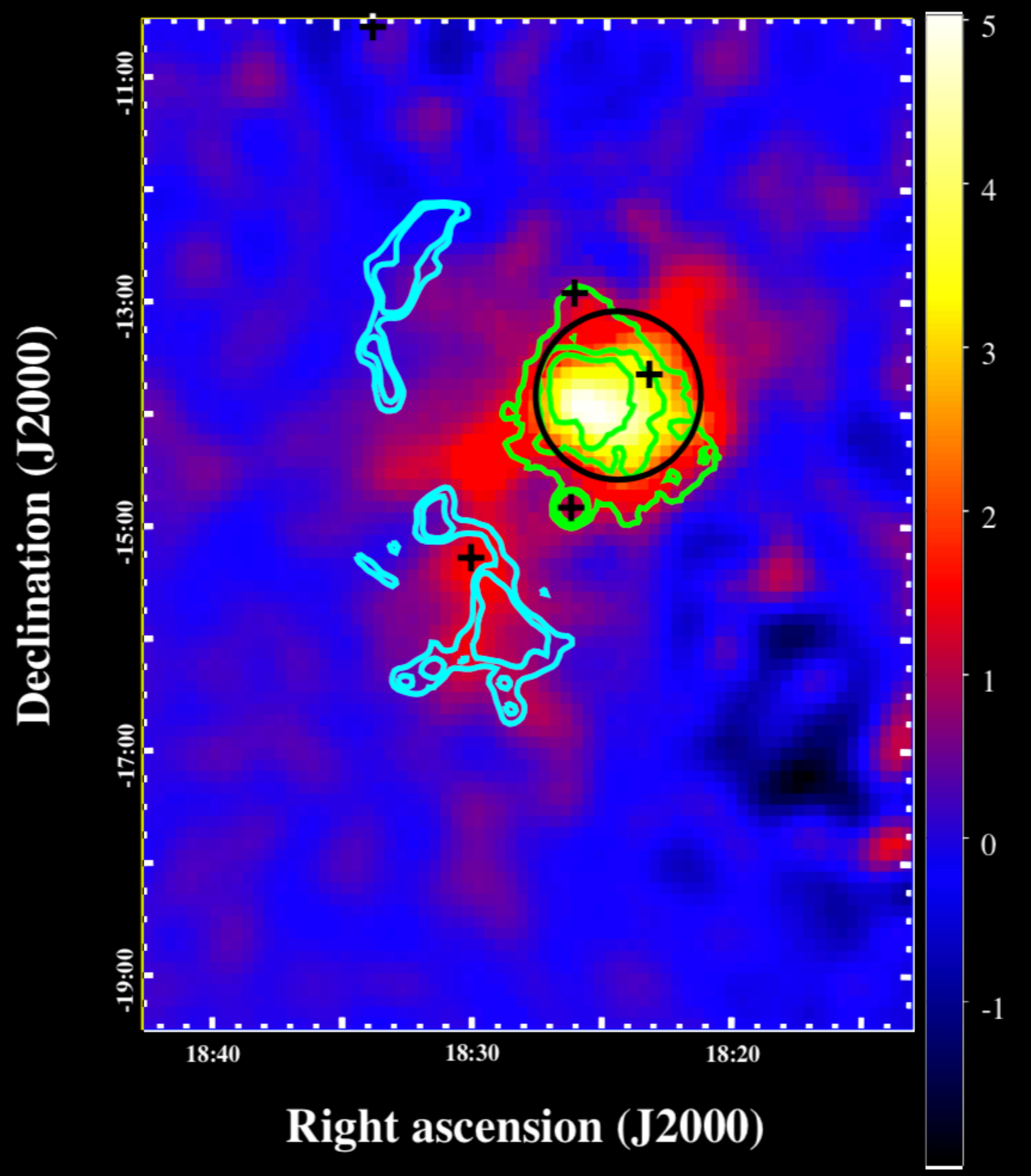
Pulsar Wind Nebula: HESS J1825-137

HESS





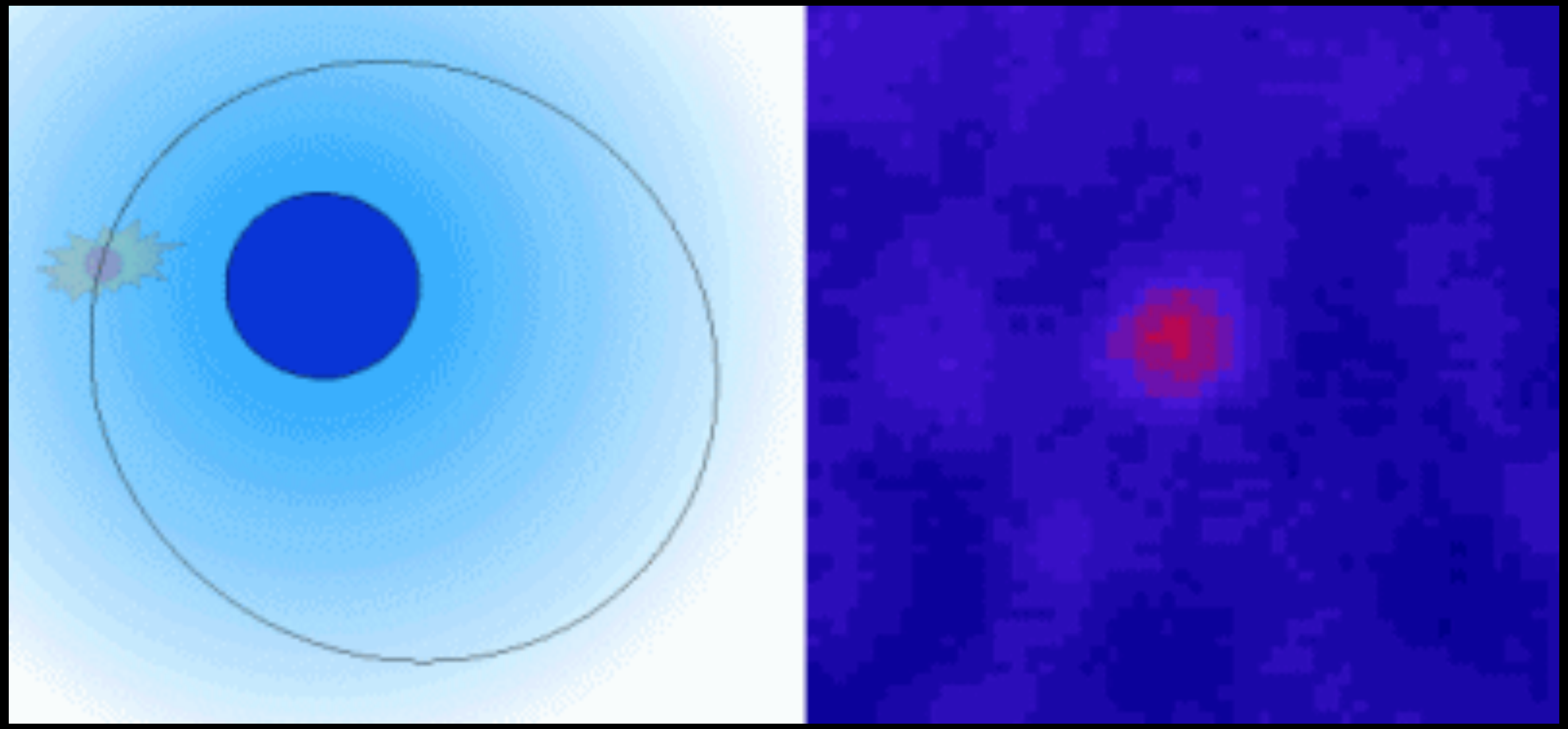
Fermi-LAT

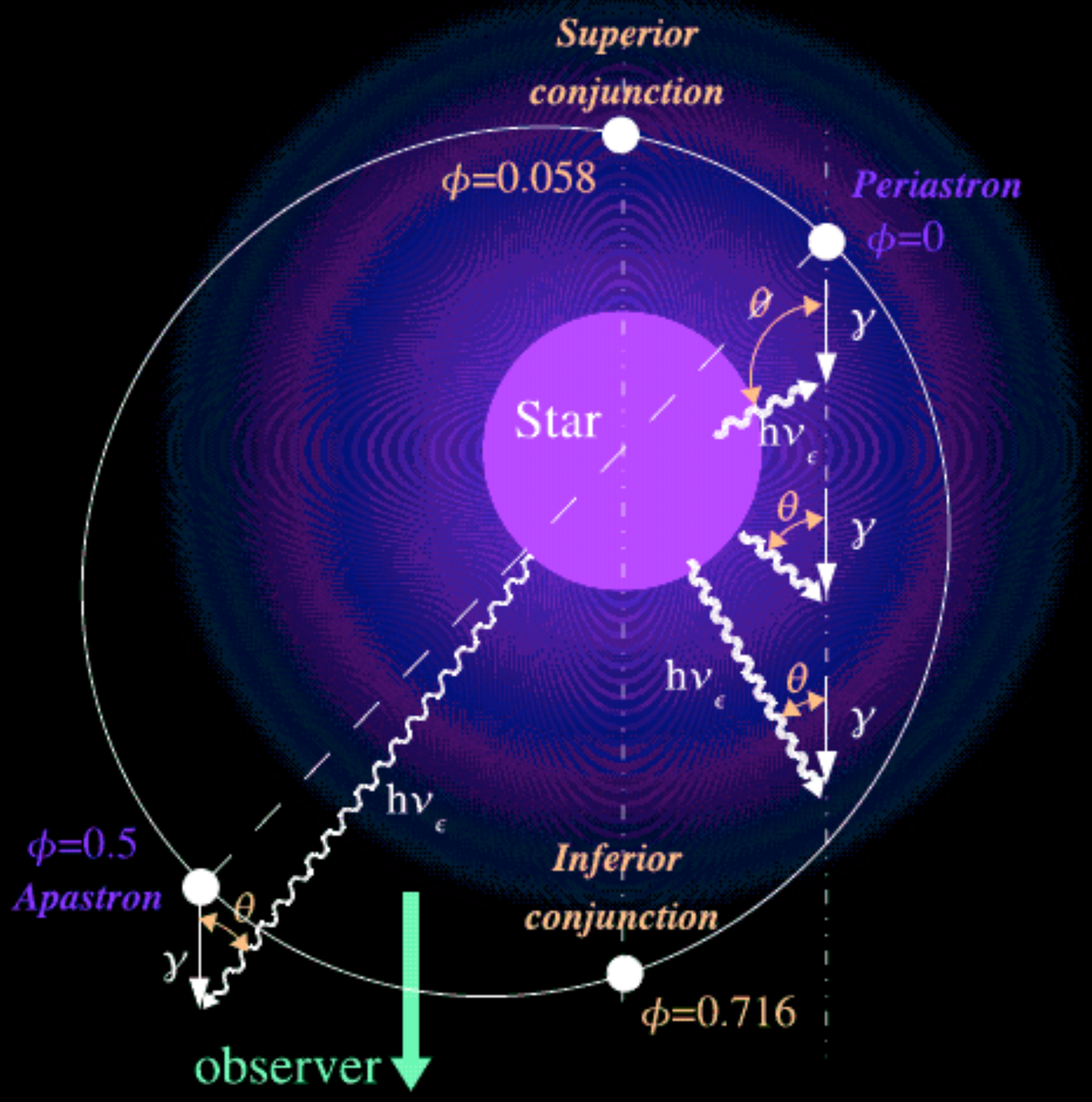


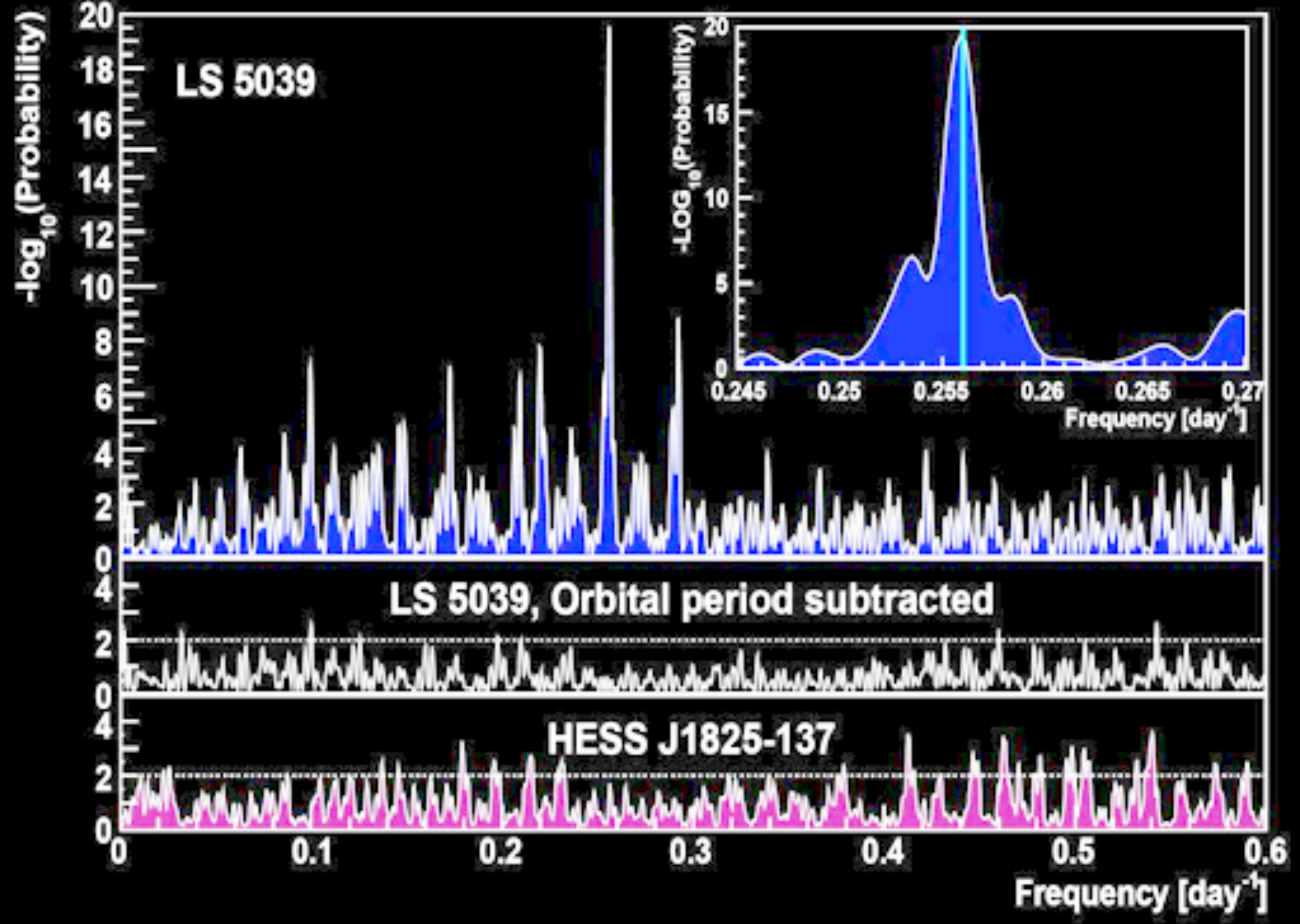
Araya et al., MNRAS 2009

HESS Collaboration, Astron. Astrophys. 621 (2019) A116

LS 5039: A Gamma-ray Binary



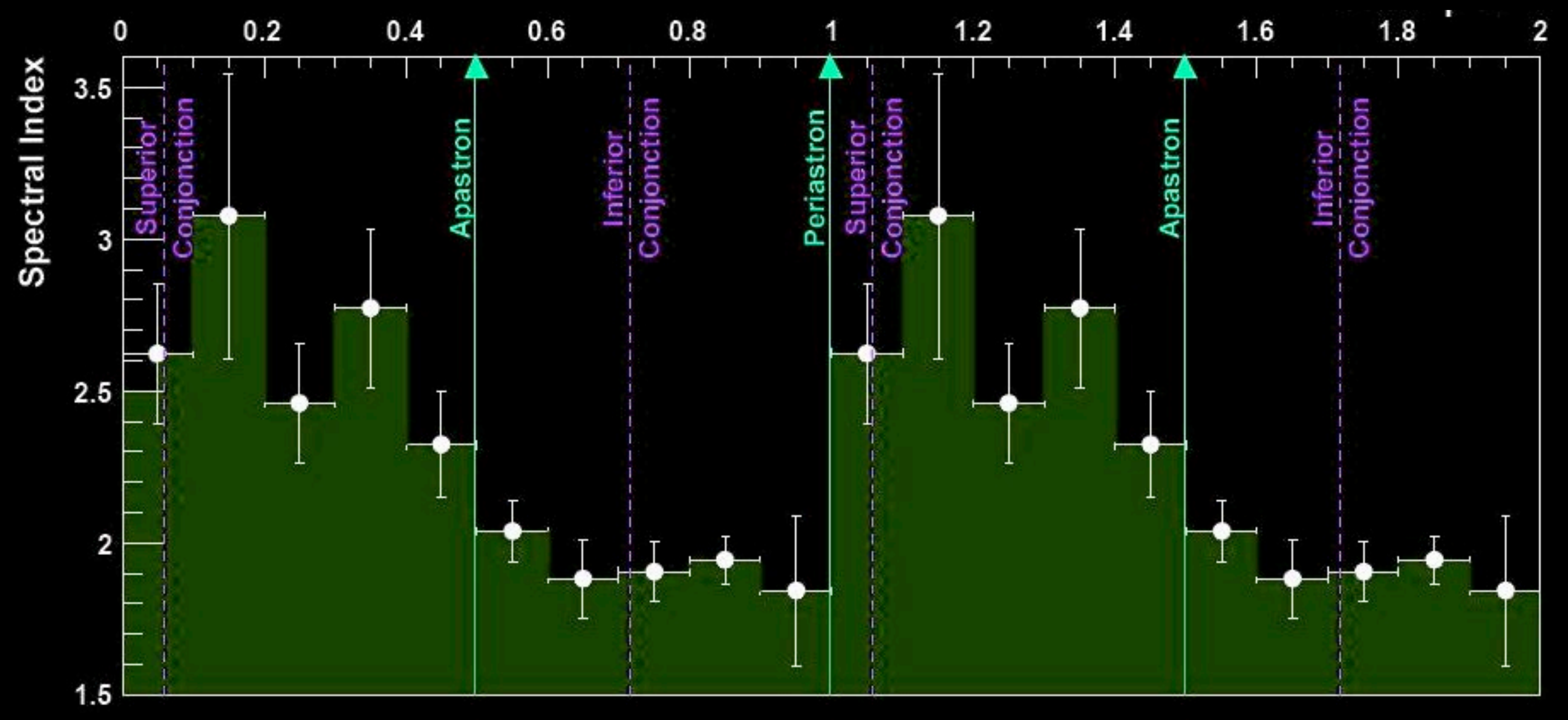




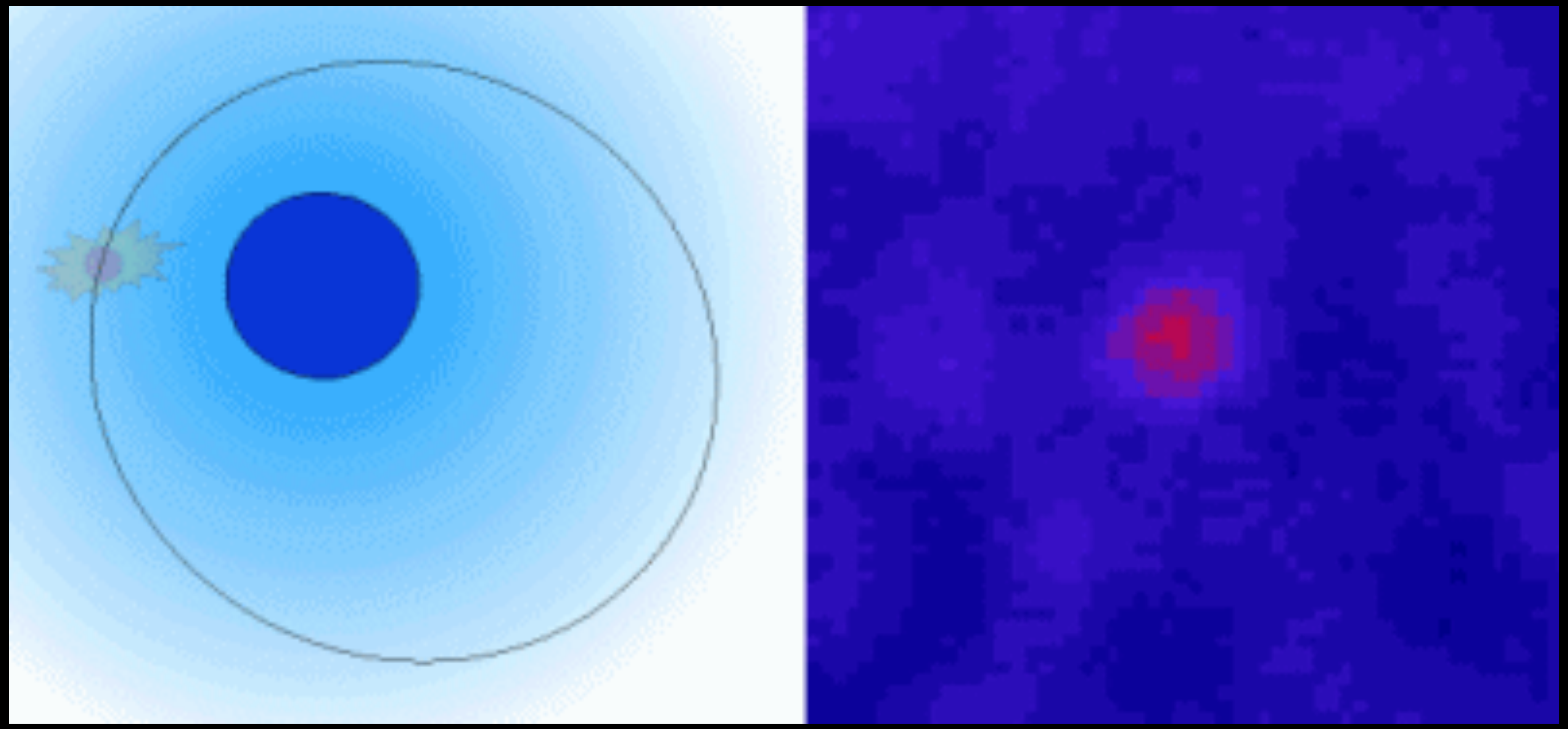
Period:

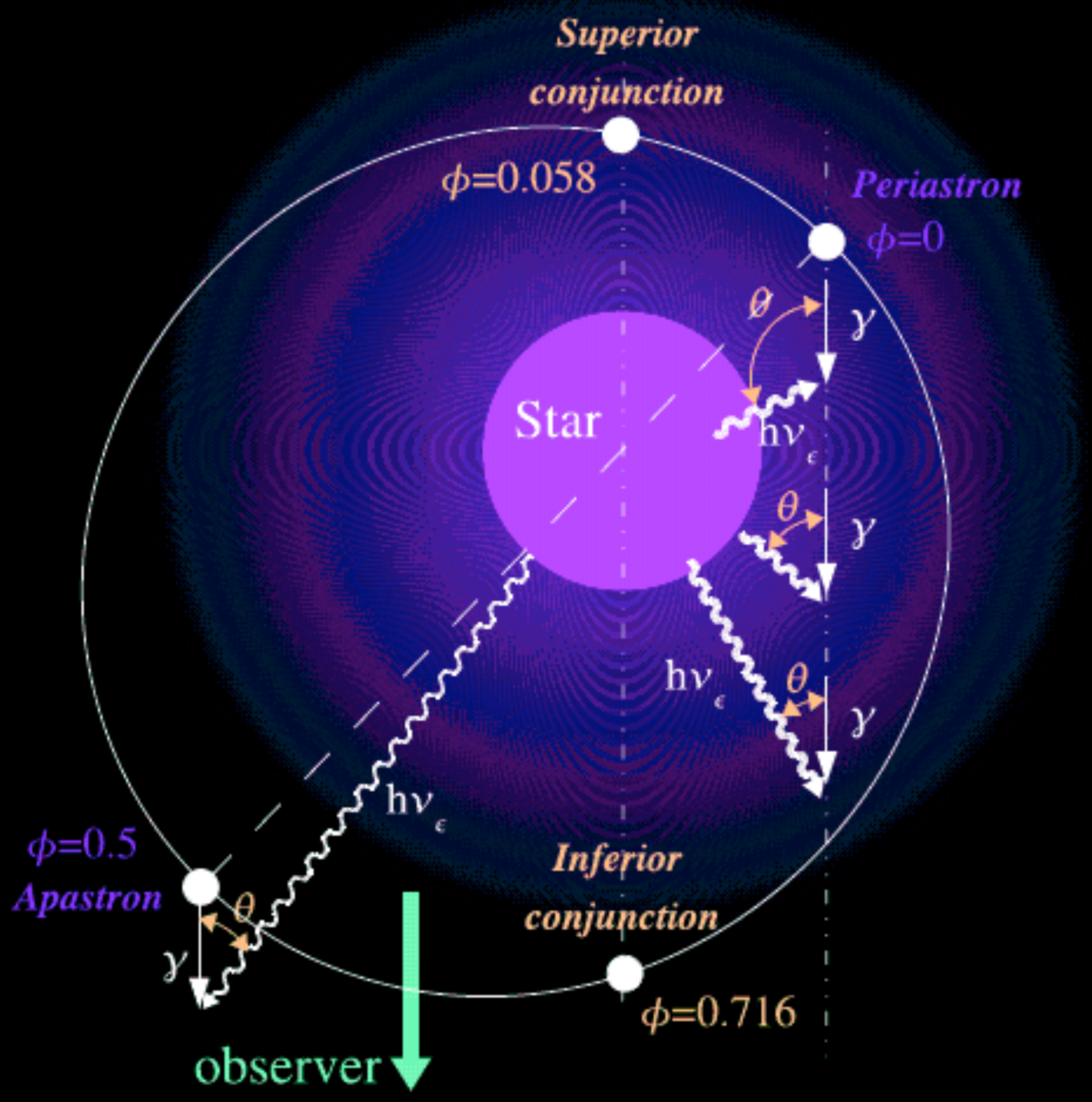
<u>HESS</u>: 3.908(2)d

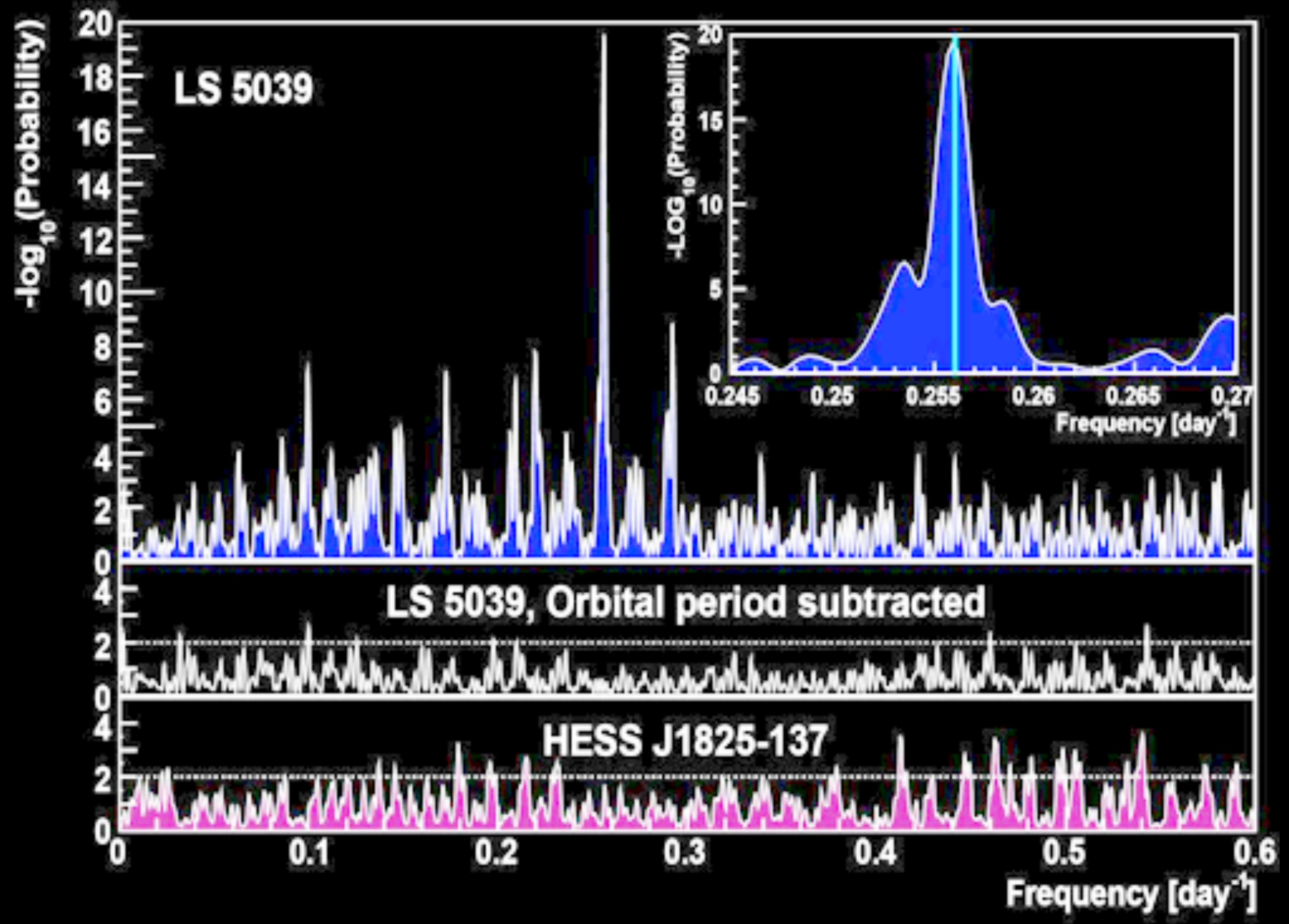
<u>Optical</u>: 3.9060 d



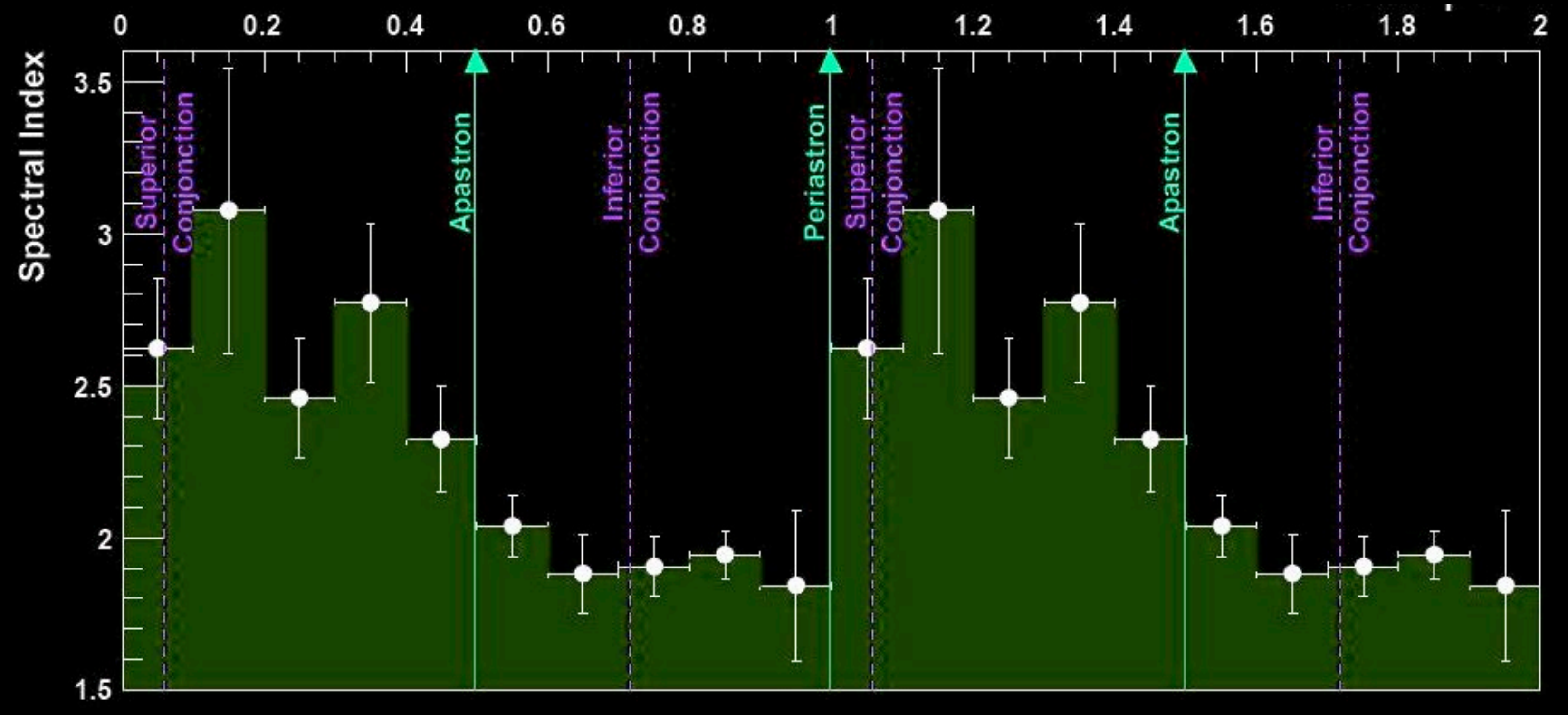
LS 5039: A Gamma-ray Binary





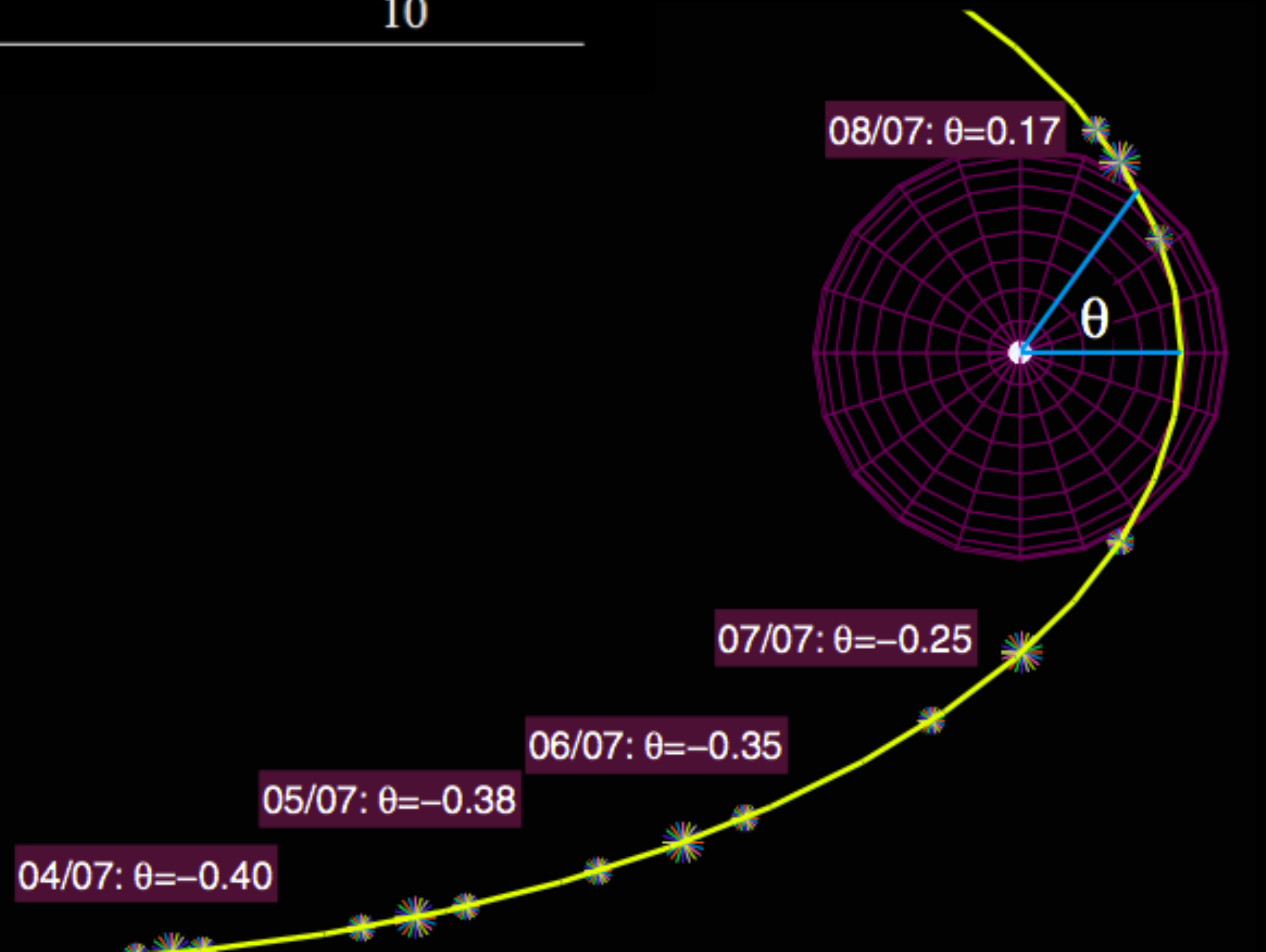


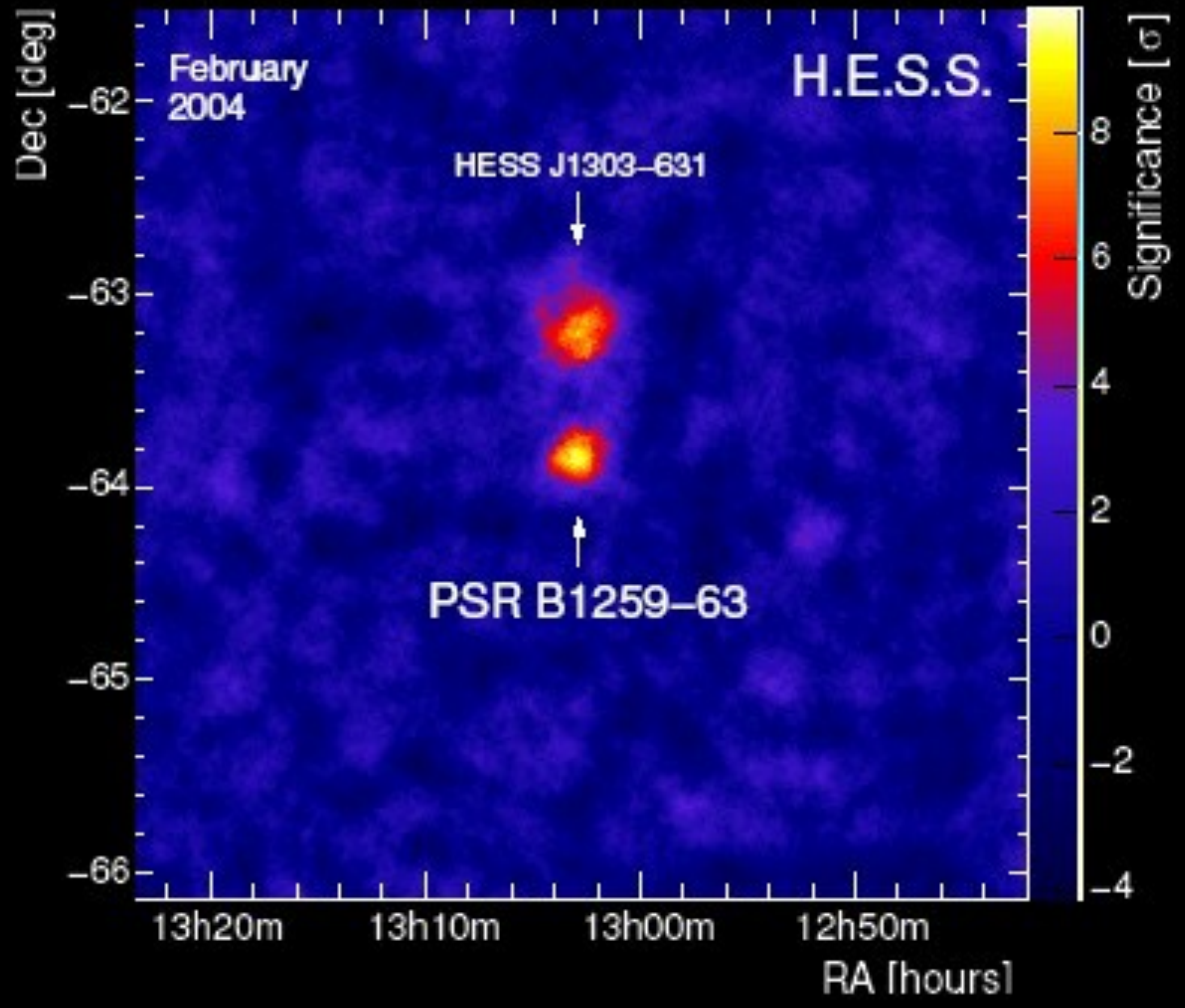
Period:
HESS: 3.908(2)d
Optical: 3.9060 d



PSR B1259-63

Parameter	Value
Distance, D [kpc]	1.5
Eccentricity, e	0.87
Orbital Period, $P_{\rm orb}$[d]	1273
Last Periastron Passage	2007-07-27
Compact Object	
Pulsar Period, P [ms]	47.7
$\dot{P} = \frac{dP}{dt}\left[\frac{s}{s}\right]$	2.27579×10^{-15}
Spin-down age, τ [yr]	3×10^5
Spin-down luminosity, $L_p\left[\text{erg s}^{-1}\right]$	8×10^{35}
Magnetic field, B [G]	3×10^{11}
Companion Star (B2Ve)	
Temperature [K]	10^4
Mass [$M_\odot$]	10





Breaking News: **Prompt VHE Emission from a GRB**

GRB 190114C:

MAGIC Detection!

- First VHE GRB!
- 50s after burst
- > 20 sigma
- very large zenith angle
  - > 300 GeV

First time detection of a GRB at sub-TeV energies; MAGIC detects the GRB 190114C

ATel #12390; *Razmik Mirzoyan on behalf of the MAGIC Collaboration*
on ***15 Jan 2019; 01:03 UT***
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Gamma Ray, >GeV, TeV, VHE, Request for Observations, Gamma-Ray Burst

Referred to by ATel #: 12395, 12475

Tweet

The MAGIC telescopes performed a rapid follow-up observation of GRB 190114C (Gropp et al., GCN 23688; Tyurina et al., GCN 23690, de Ugarte Postigo et al., GCN 23692, Lipunov et al. GCN 23693, Selsing et al. GCN 23695). This observation was triggered by the Swift-BAT alert; we started observing at about 50s after Swift T0: 20:57:03.19. The MAGIC real-time analysis shows a significance >20 sigma in the first 20 min of observations (starting at T0+50s) for energies >300GeV. The relatively high detection threshold is due to the large zenith angle of observations (>60 degrees) and the presence of partial Moon. Given the brightness of the event, MAGIC will continue the observation of GRB 190114C until it is observable tonight and also in the next days. We strongly encourage follow-up observations by other instruments. The MAGIC contact persons for these observations are R. Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de) and K. Noda (nodak@icrr.u-tokyo.ac.jp). MAGIC is a system of two 17m-diameter Imaging Atmospheric Cherenkov Telescopes located at the Observatory Roque de los Muchachos on the Canary island La Palma, Spain, and designed to perform gamma-ray astronomy in the energy range from 50 GeV to greater than 50 TeV.

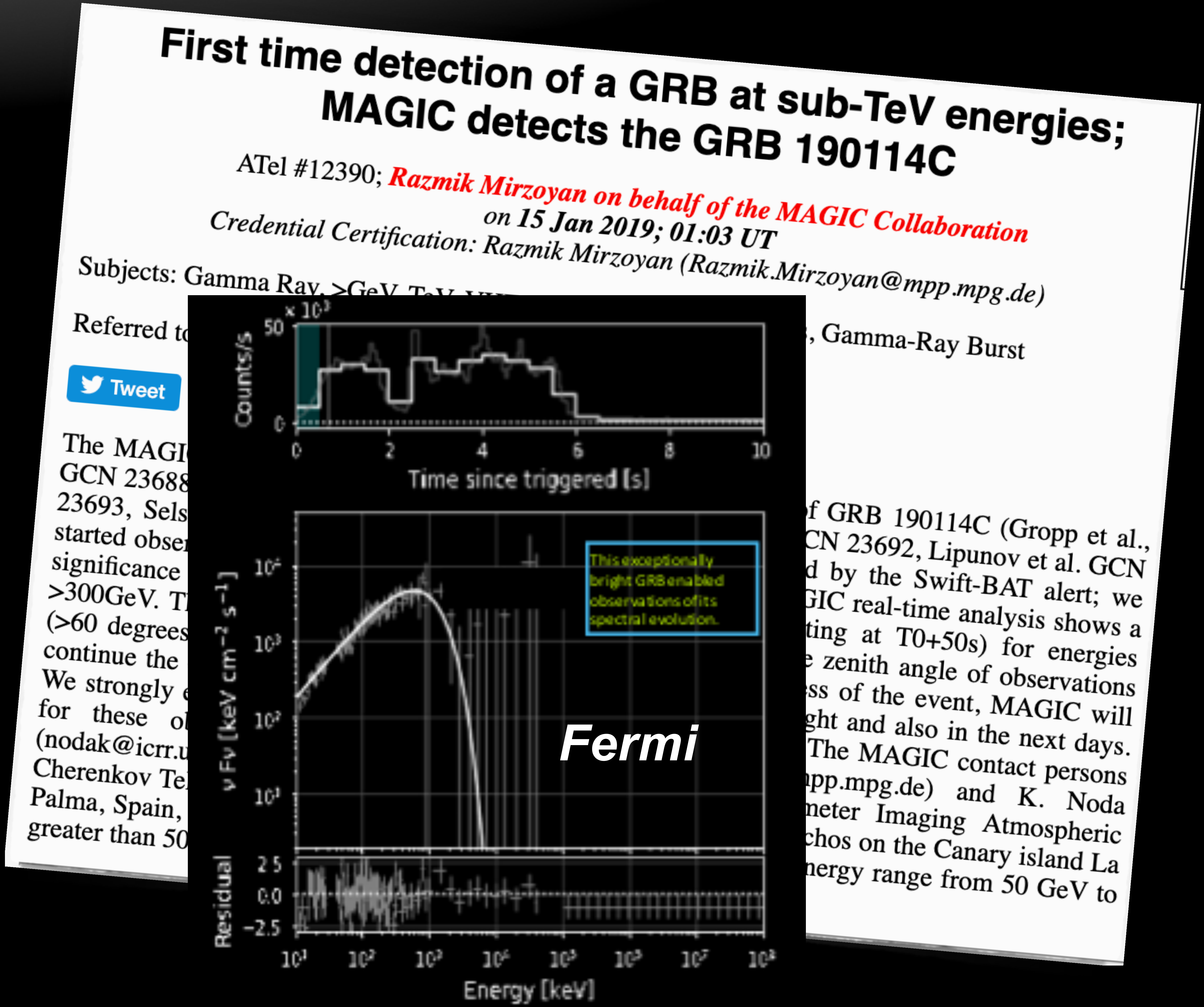
Look for details soon!

Breaking News: **Prompt VHE Emission from a GRB**

GRB 190114C:

MAGIC Detection!

- First VHE GRB!
- 50s after burst
- > 20 sigma
- very large zenith angle
    - ➤ > 300 GeV

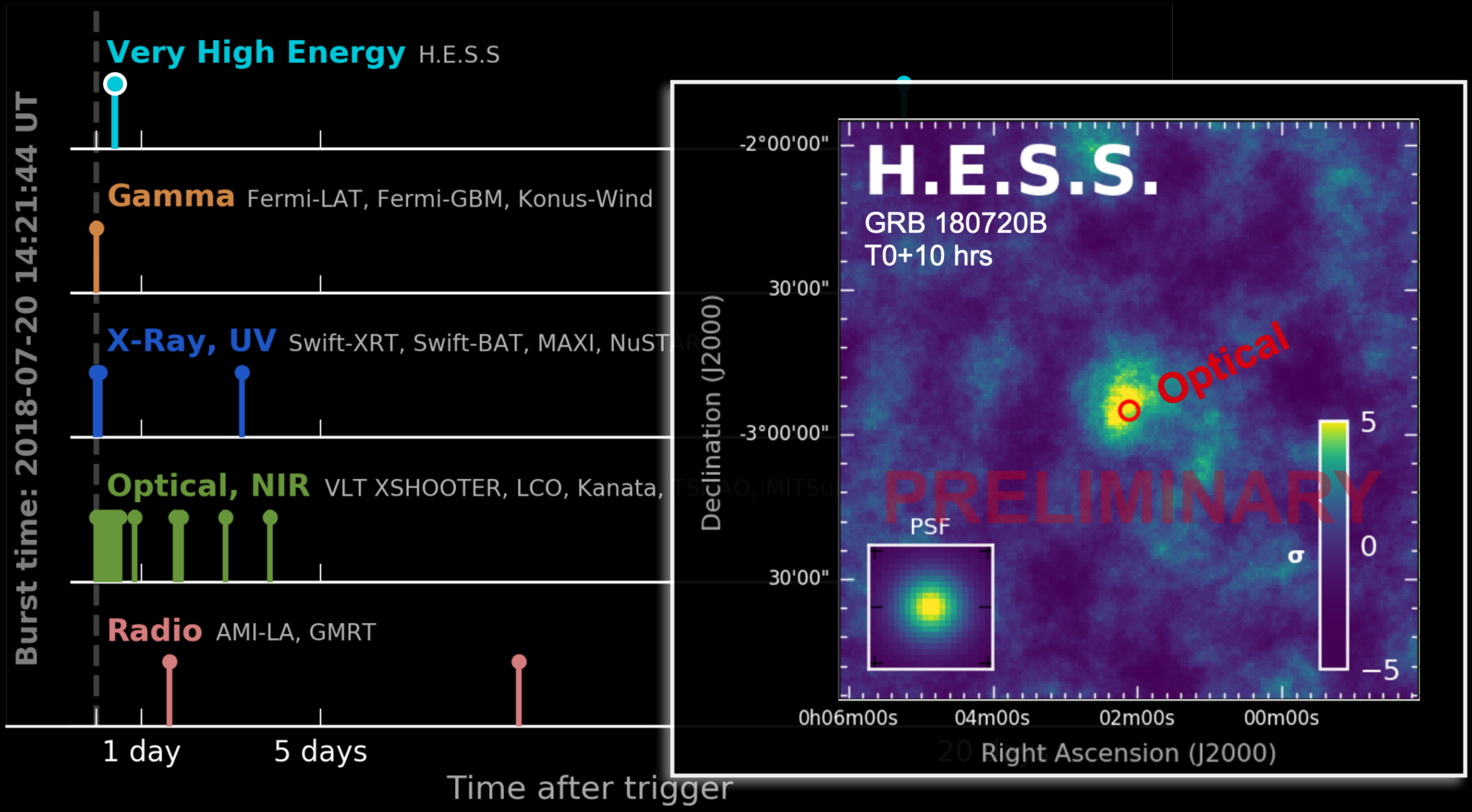


Look for details soon!

Breaking News: **GRB Afterglow in VHE γ's**

HESS detection of GRB 180720B

- 10 hours after burst, 5 sigma > 100 GeV.
- observation 18 days later, no signal
- One of Fermi-GBM highest fluence GRBs

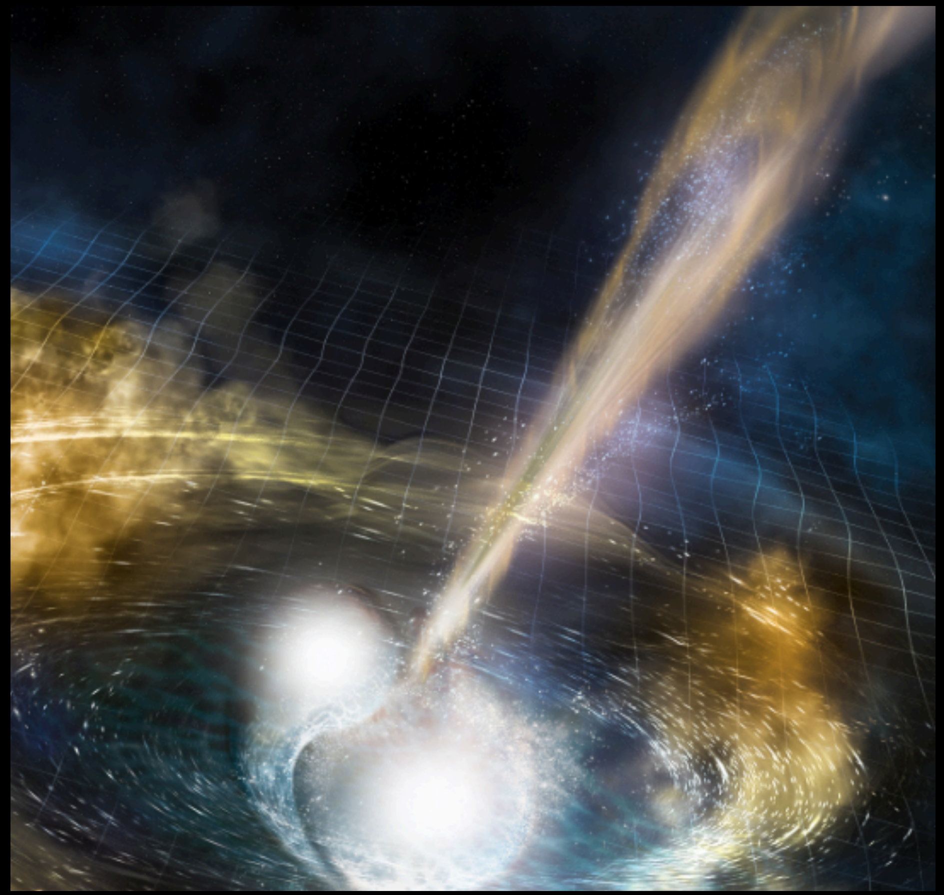


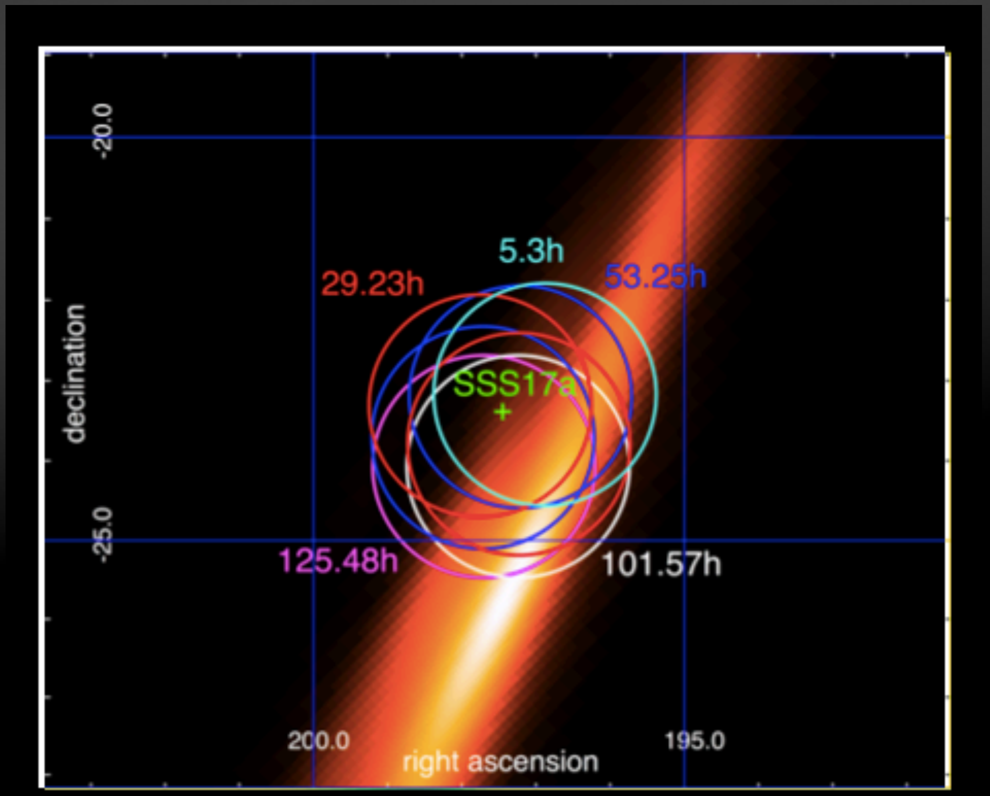
Look for details soon!

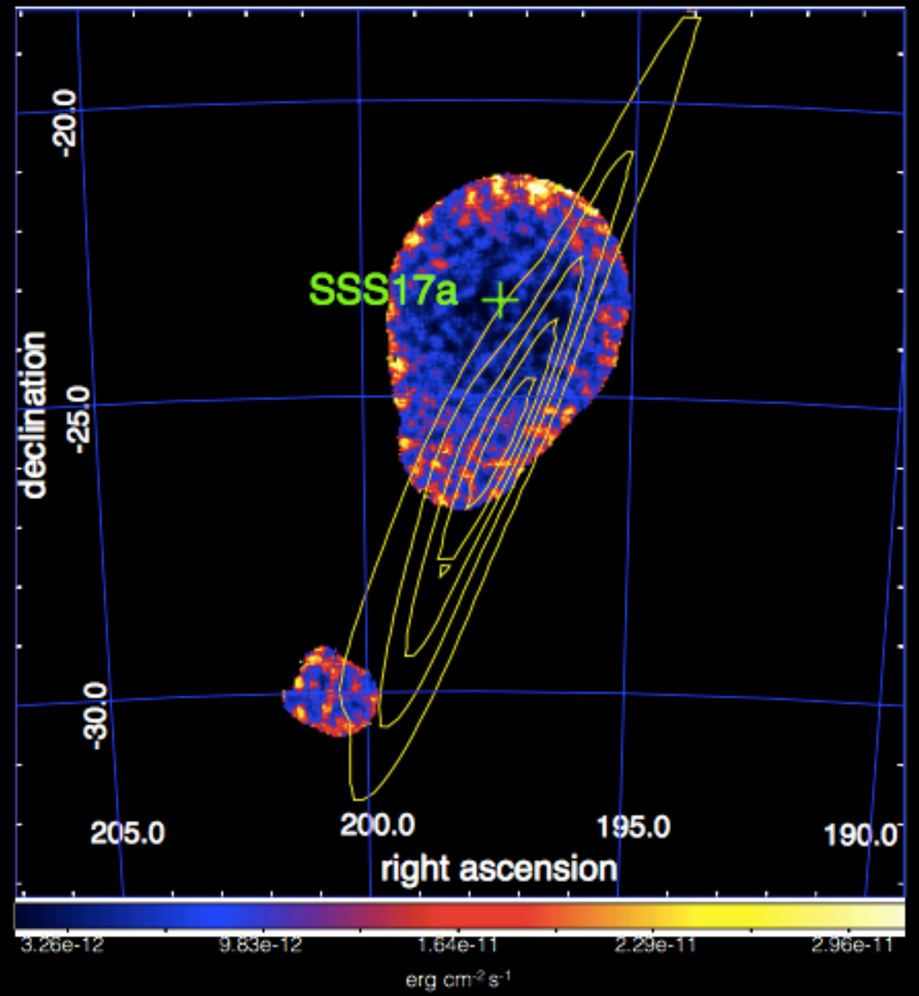
source: CTA Symposium 2019, Bologna, Italy https://www.cta-symposium.com/

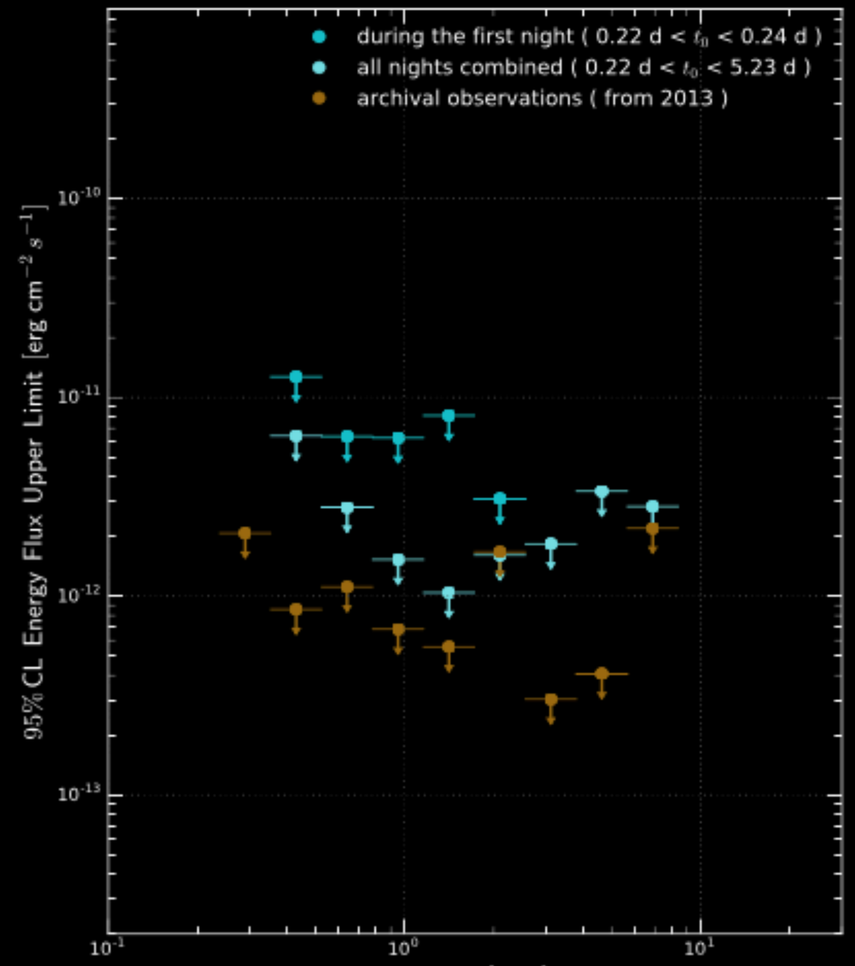
Kilonovas?

GW170817



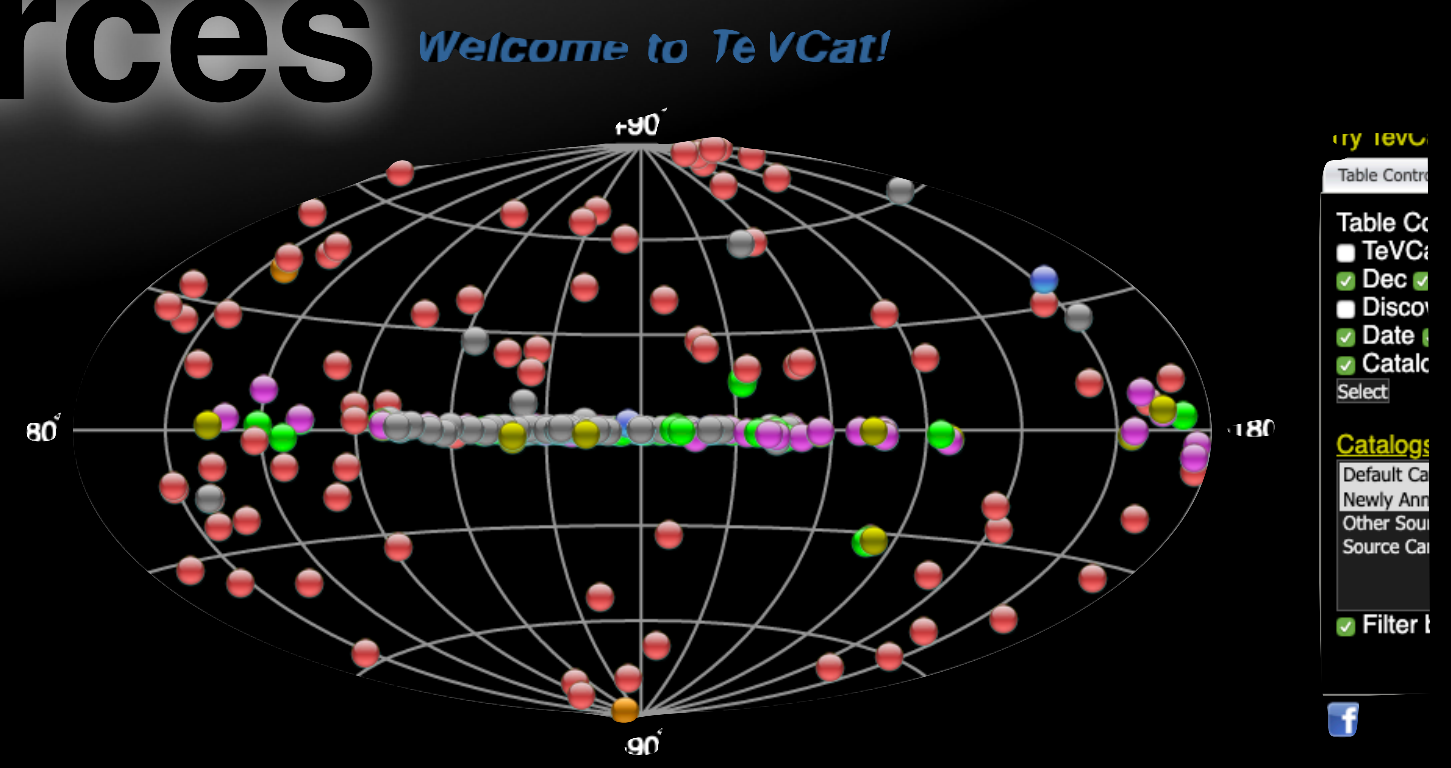






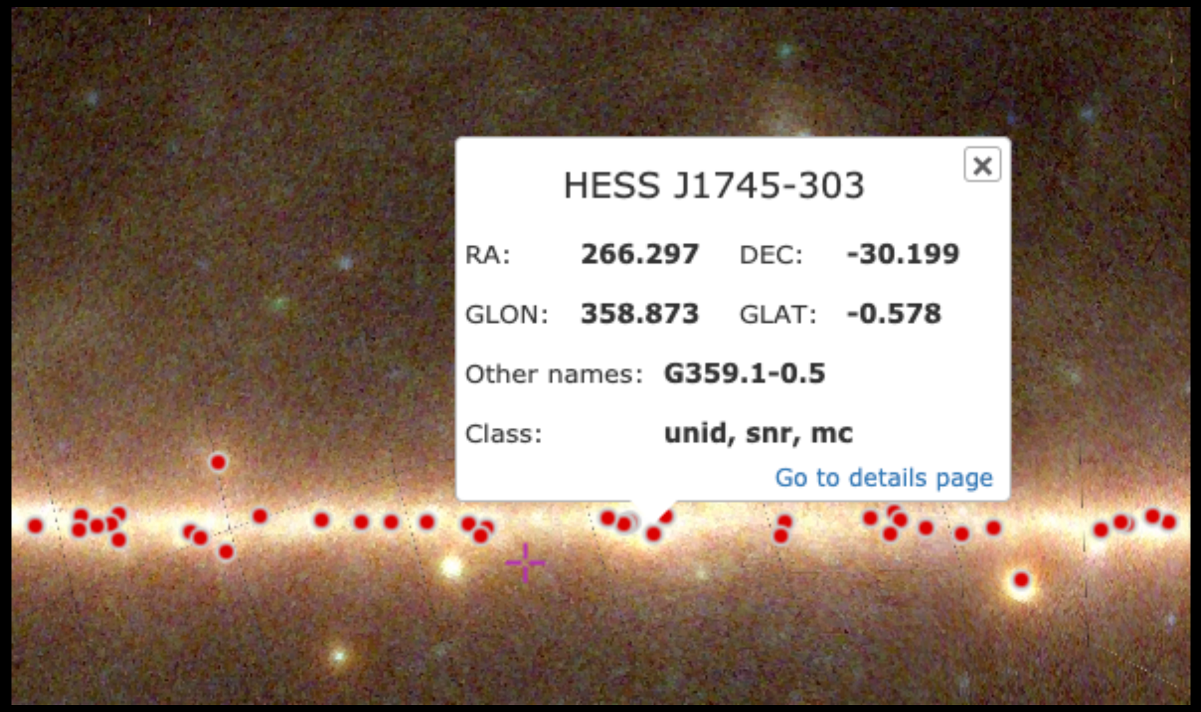
See also talk by Skyler Scott (tuesday)

Very-High-Energy Resources



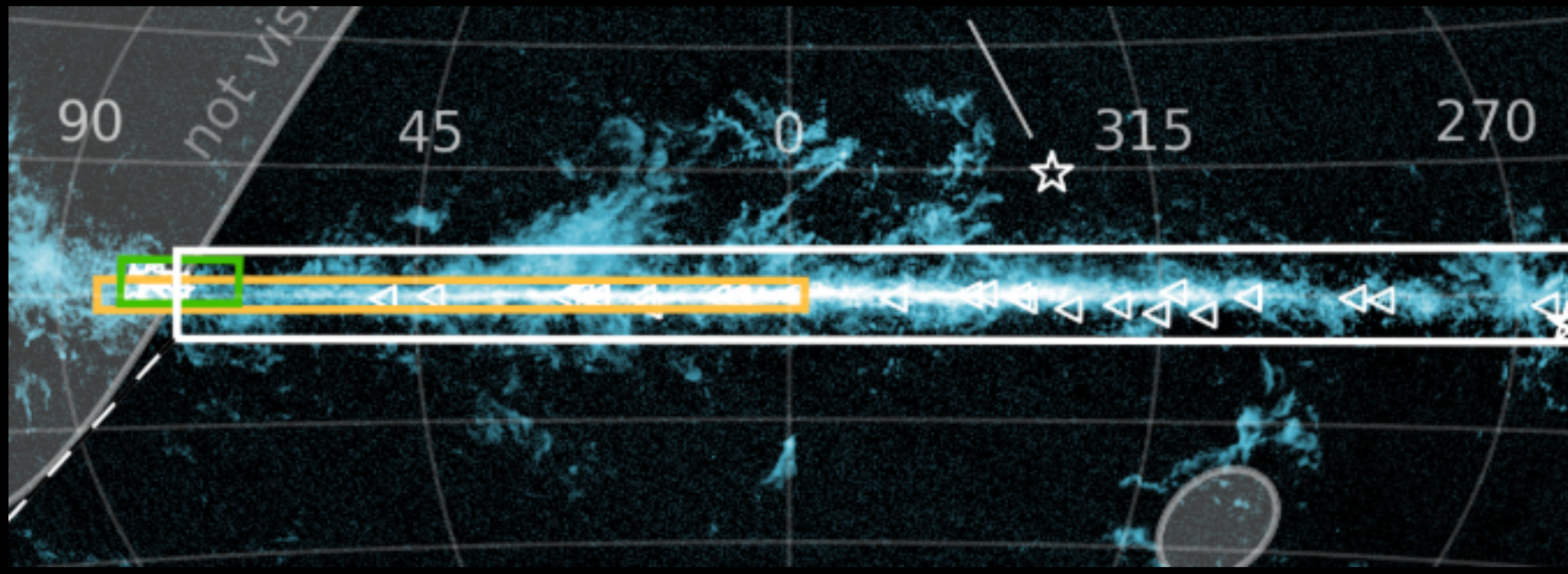
TeVCat

- tevcat.uchicago.edu, tevcat2.uchicago.edu
- All published sources from all Cherenkov Telescopes
- lots of detail about each source, including links to all subsequent publications



GammaCat / GammaSky

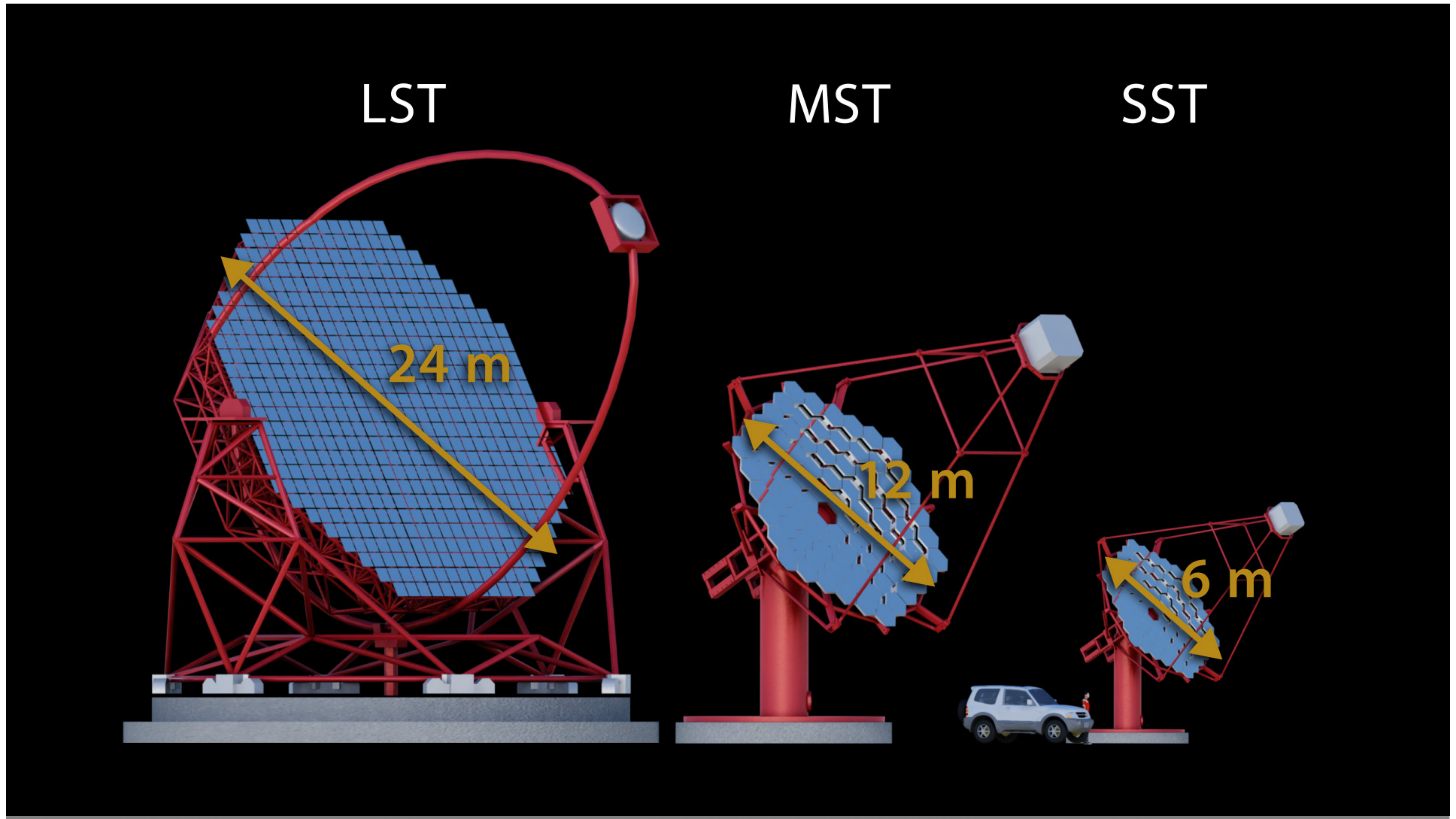
- gamma-sky.net/
- similar to TeVCat, but open-source catalog available (much less detail than TeVCat, however)



HESS Galactic Plane Survey

- www.mpi-hd.mpg.de/hfm/HESS/hgps/
- Catalog as FITS table (includes spectra for each source)
- the only "true" catalog (all identical analysis methodology, single publication), so only exposure bias
- Image data (flux, etc) as FITS images

VHE/TeV gamma rays: the Future!



More Telescopes = larger effective area

Densely Packed Telescopes = higher angular resolution

Multiple Dish Sizes = wider energy coverage for cheaper

- large: 50 GeV - 100 GeV
  - ➤ fast repointing for GRBs and transients
  - ➤ expensive
- medium = 100 GeV - 30 TeV
  - ➤ core science
- small = 5 TeV - 100 TeV:
  - ➤ new frontiers
  - ➤ cheap, easy to make many of them

cherenkov telescope array

the observatory for ground-based gamma-ray astronomy

≈10 PB of gamma-ray data/year processed down to small, standard products

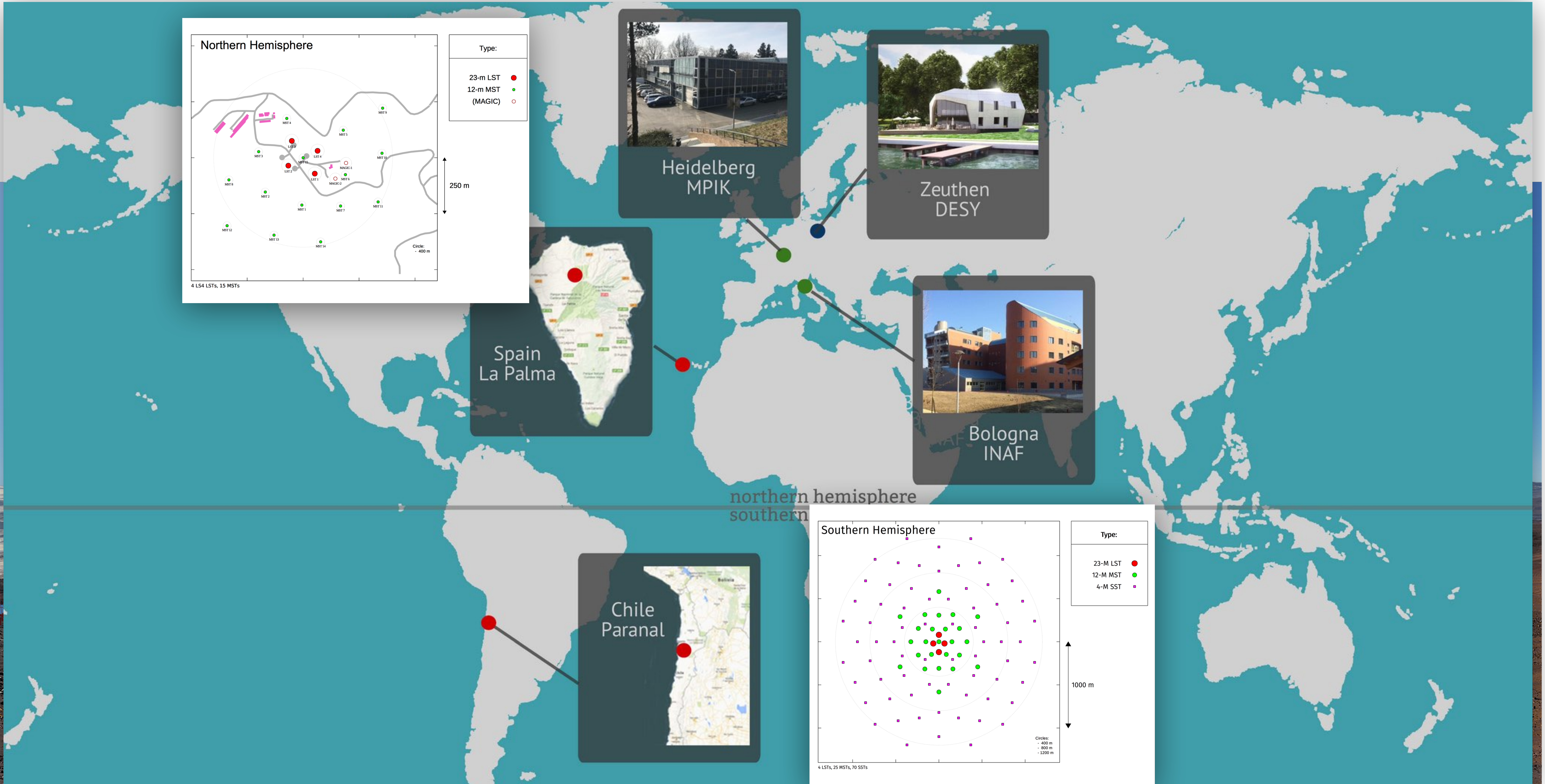
largest telescope array ever

open observatory: you can be a PI!

https://www.cta-observatory.org/

cherenkov
telescope
array

the observatory for
ground-based
gamma-ray astronomy

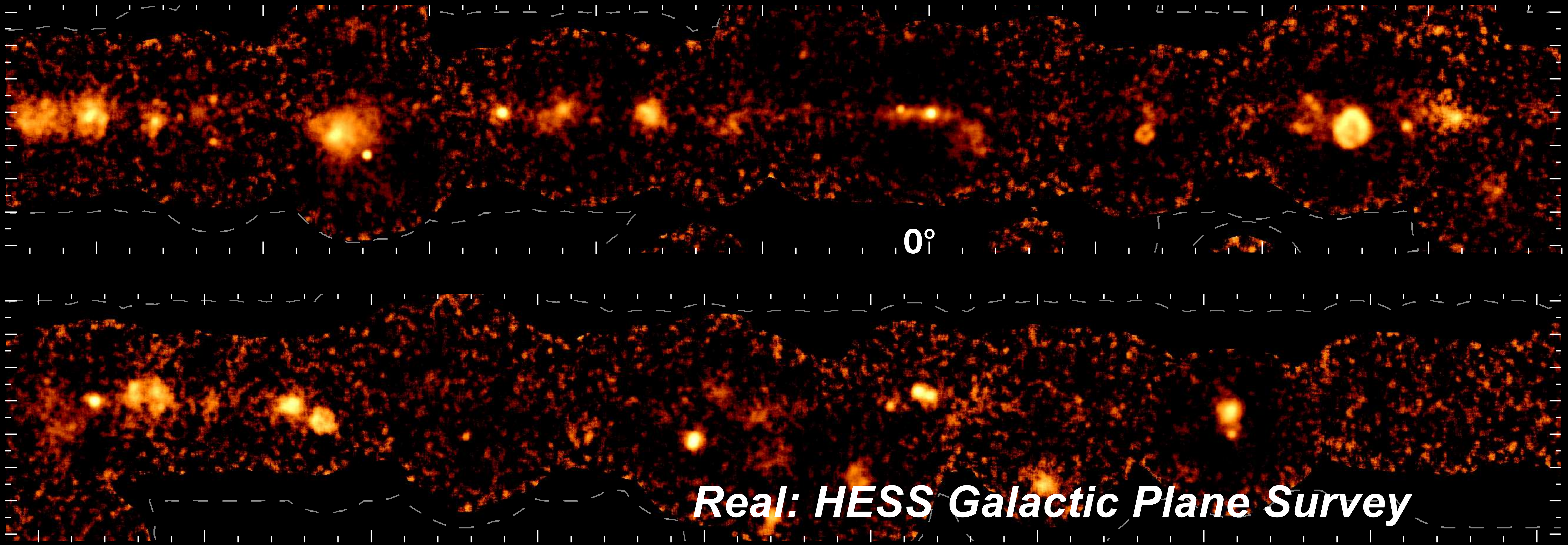


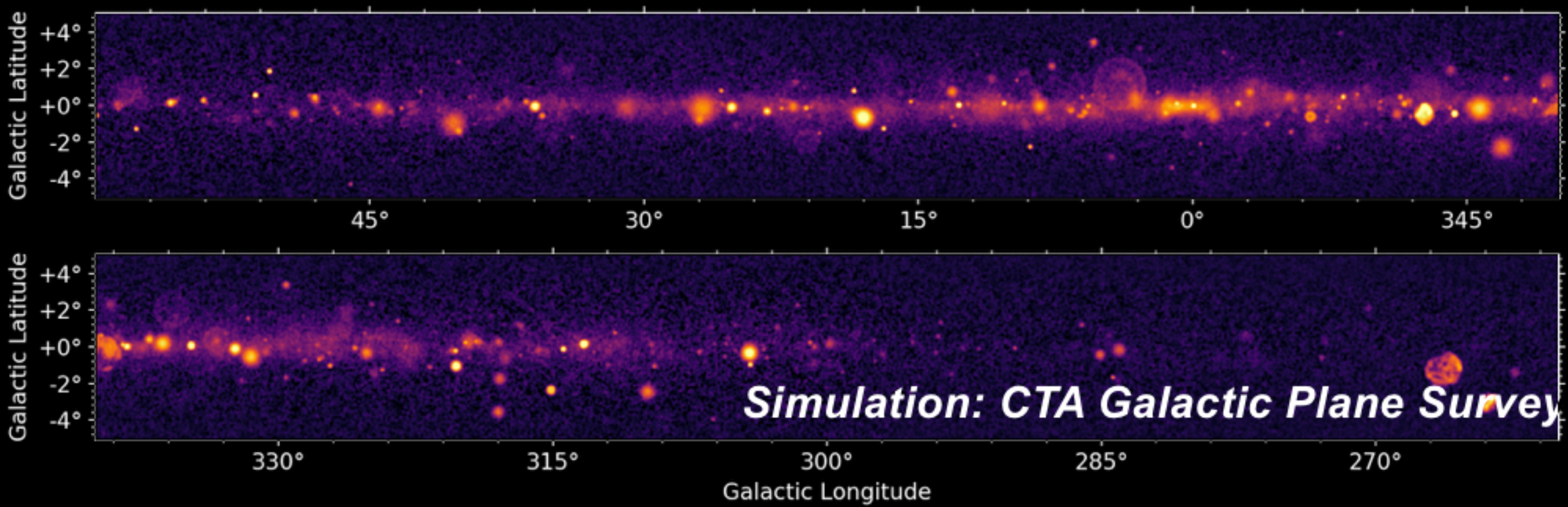
CTA Consortium consists of over **1,420 members** working in **200 institutes** from **31 countries**:

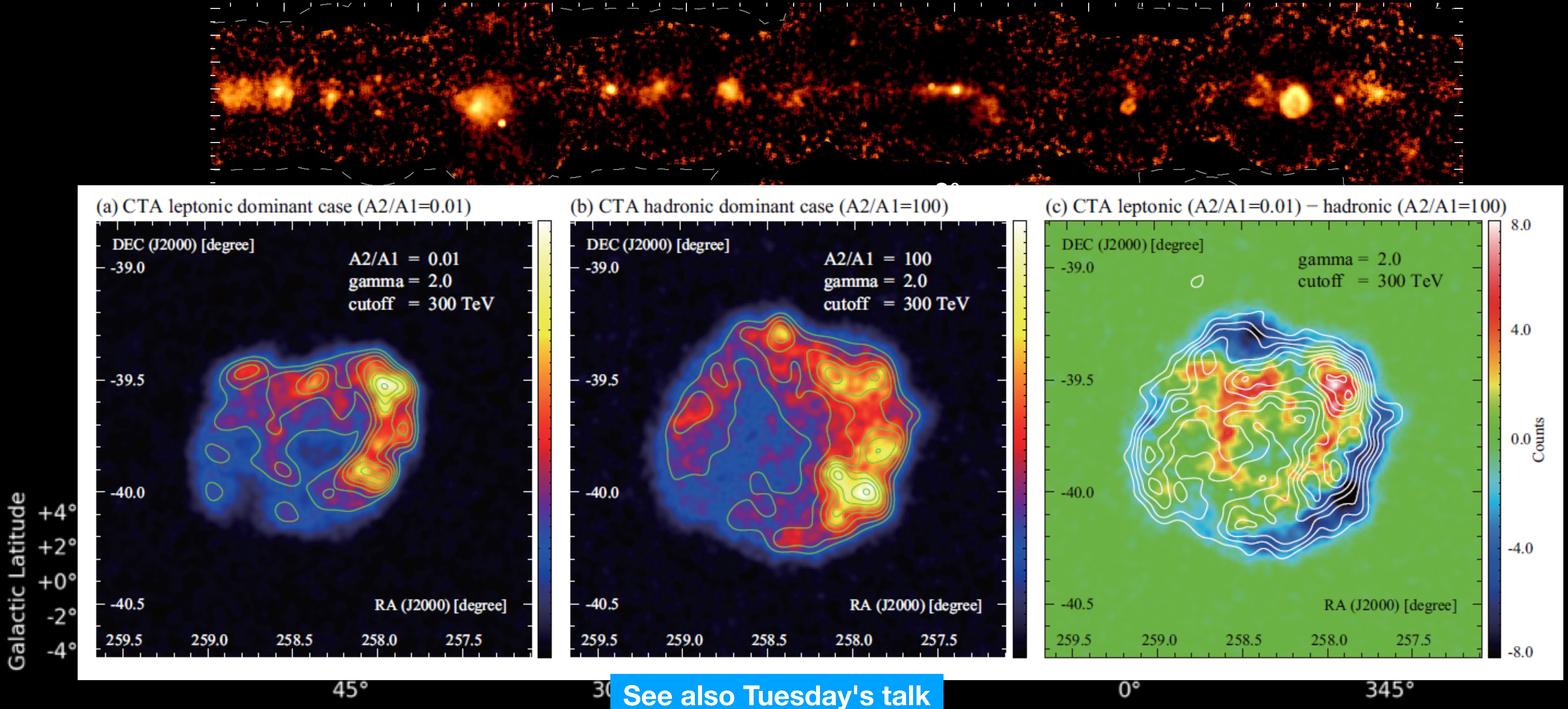
cta
cherenkov telescope array

Armenia, Australia, Austria, Brazil, Bulgaria, Canada, Chile, Croatia, Czech Republic, Finland, **France, Germany**, Greece, India, Ireland, **Italy**, Japan, Mexico, Namibia, Netherlands, Norway, Poland, Slovenia, South Africa, **Spain**, Sweden, Switzerland, Thailand, the UK, Ukraine and the USA.

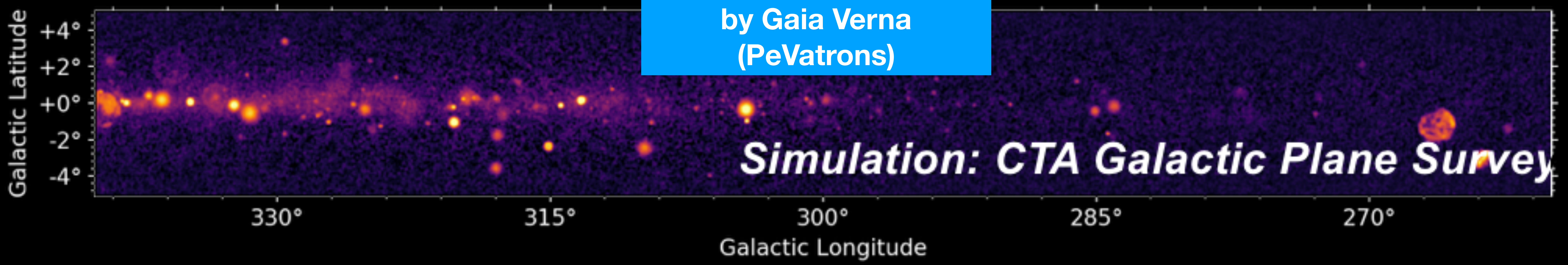
credit: DESY/Milde Science Comm./Exozet


0°
Real: HESS Galactic Plane Survey


Galactic Latitude
+4°
+2°
+0°
-2°
-4°
45°
30°
15°
0°
345°
330°
315°
300°
285°
270°
Galactic Longitude
Simulation: CTA Galactic Plane Survey



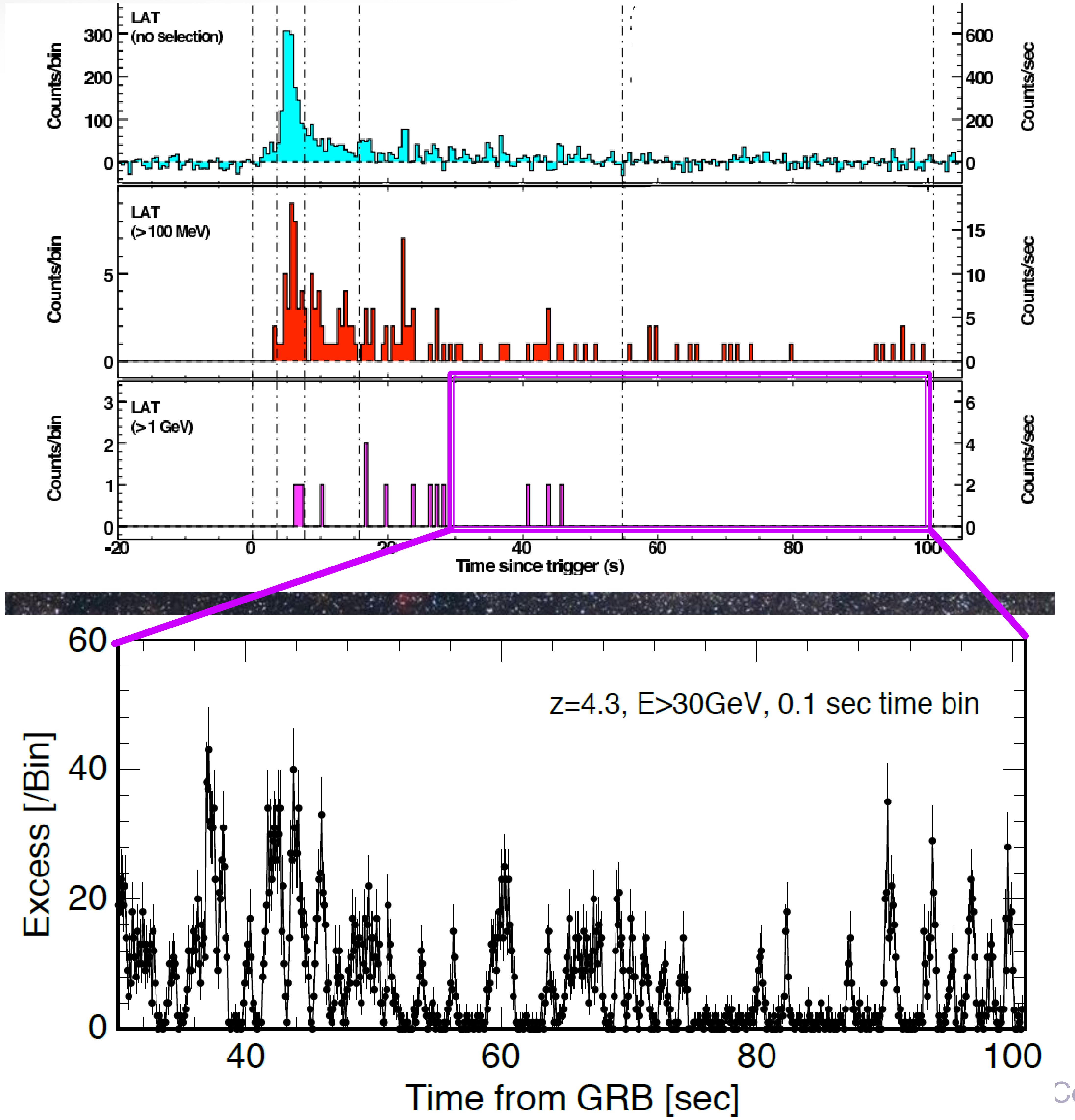
See also Tuesday's talk by Gaia Verna (PeVatrons)



GRBs with CTA

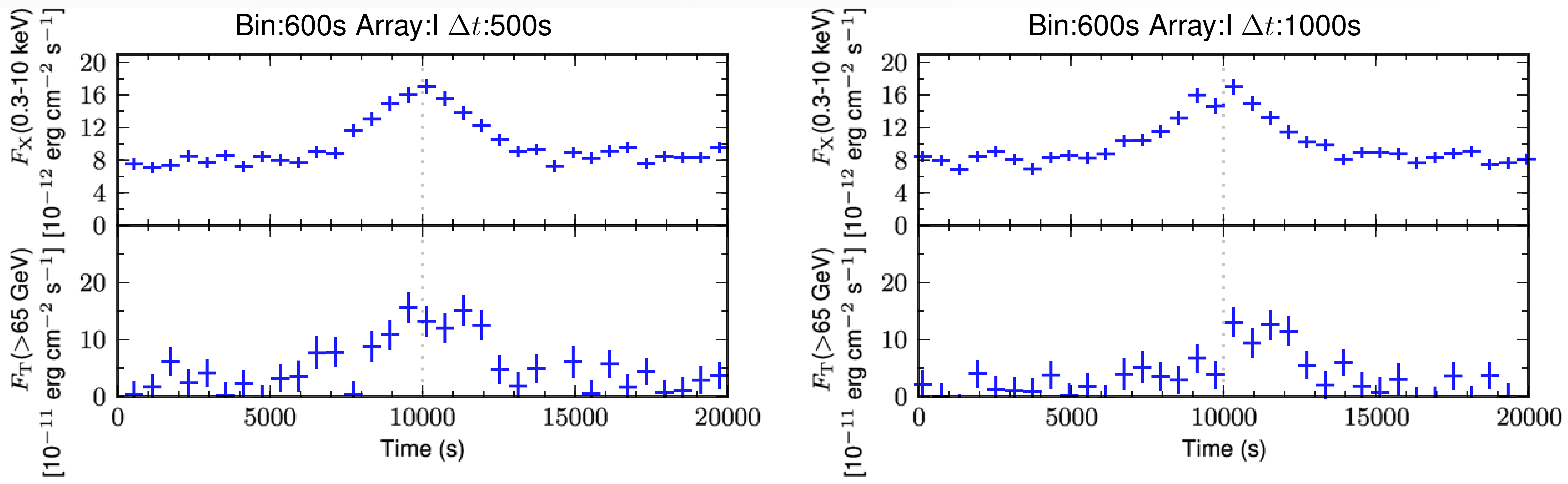
Fermi-LAT

CTA (simulated)

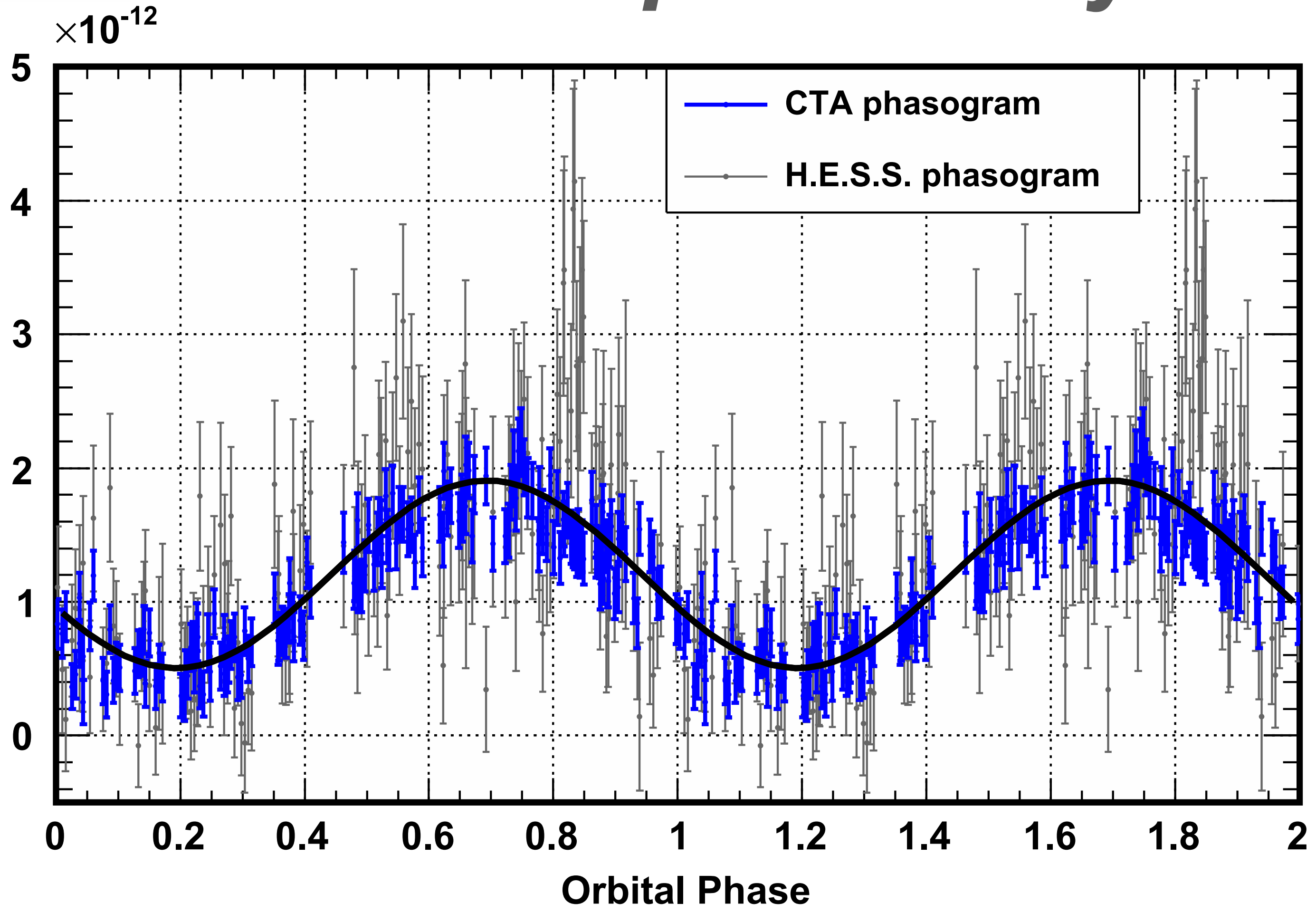


Binaries with CTA

Gaussian Flare (LSI +61 303)

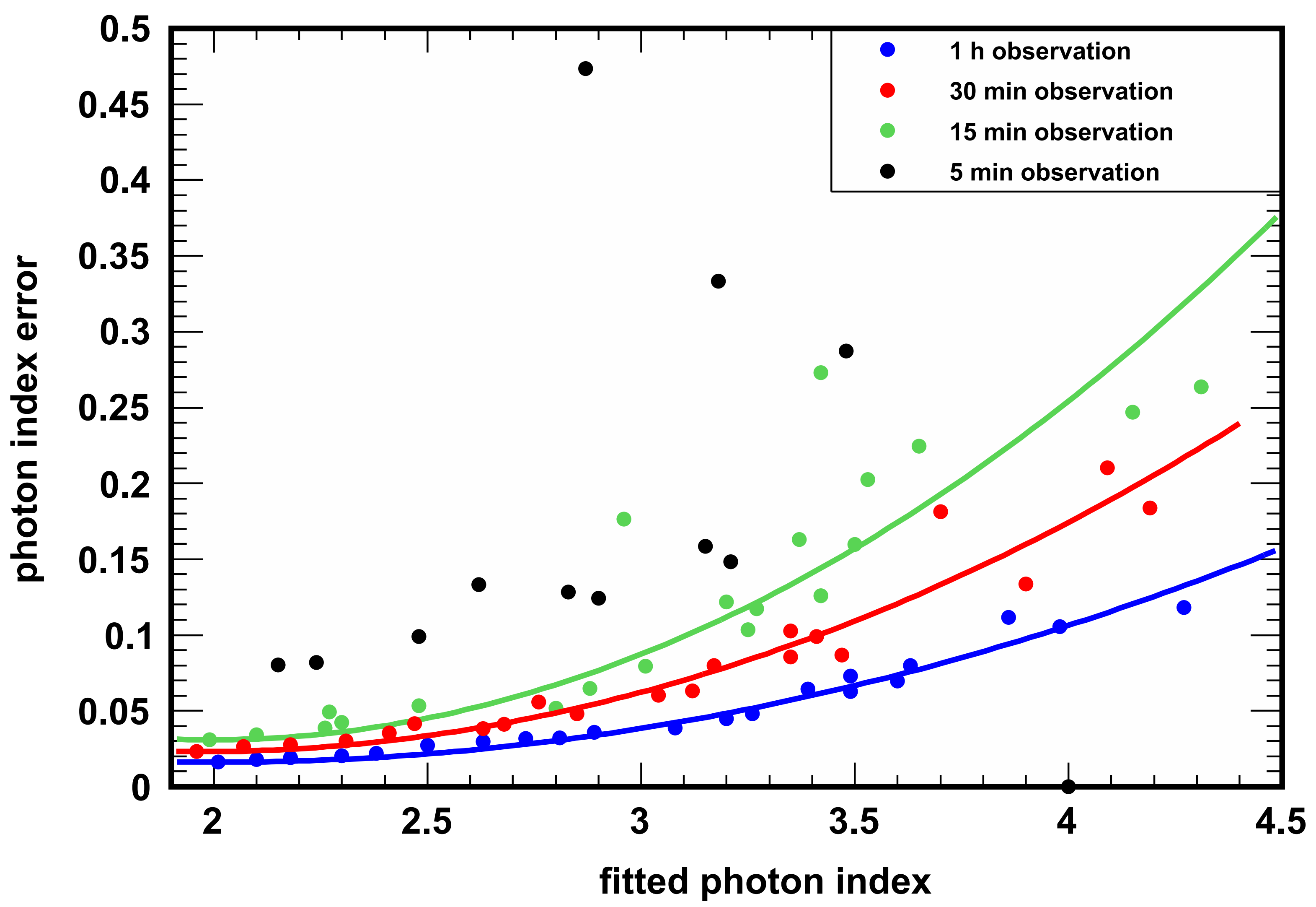


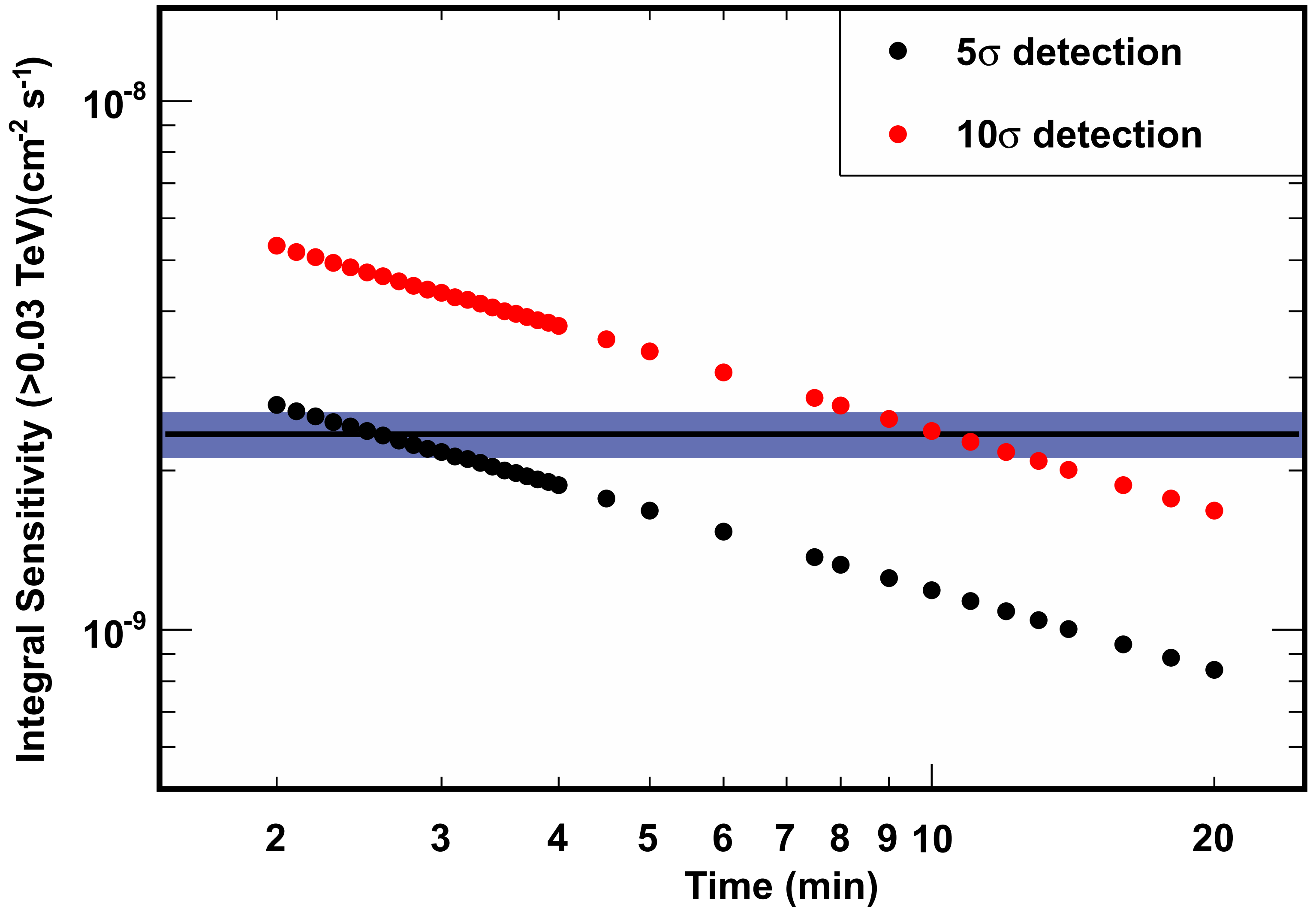
LS 5039 periodicity:

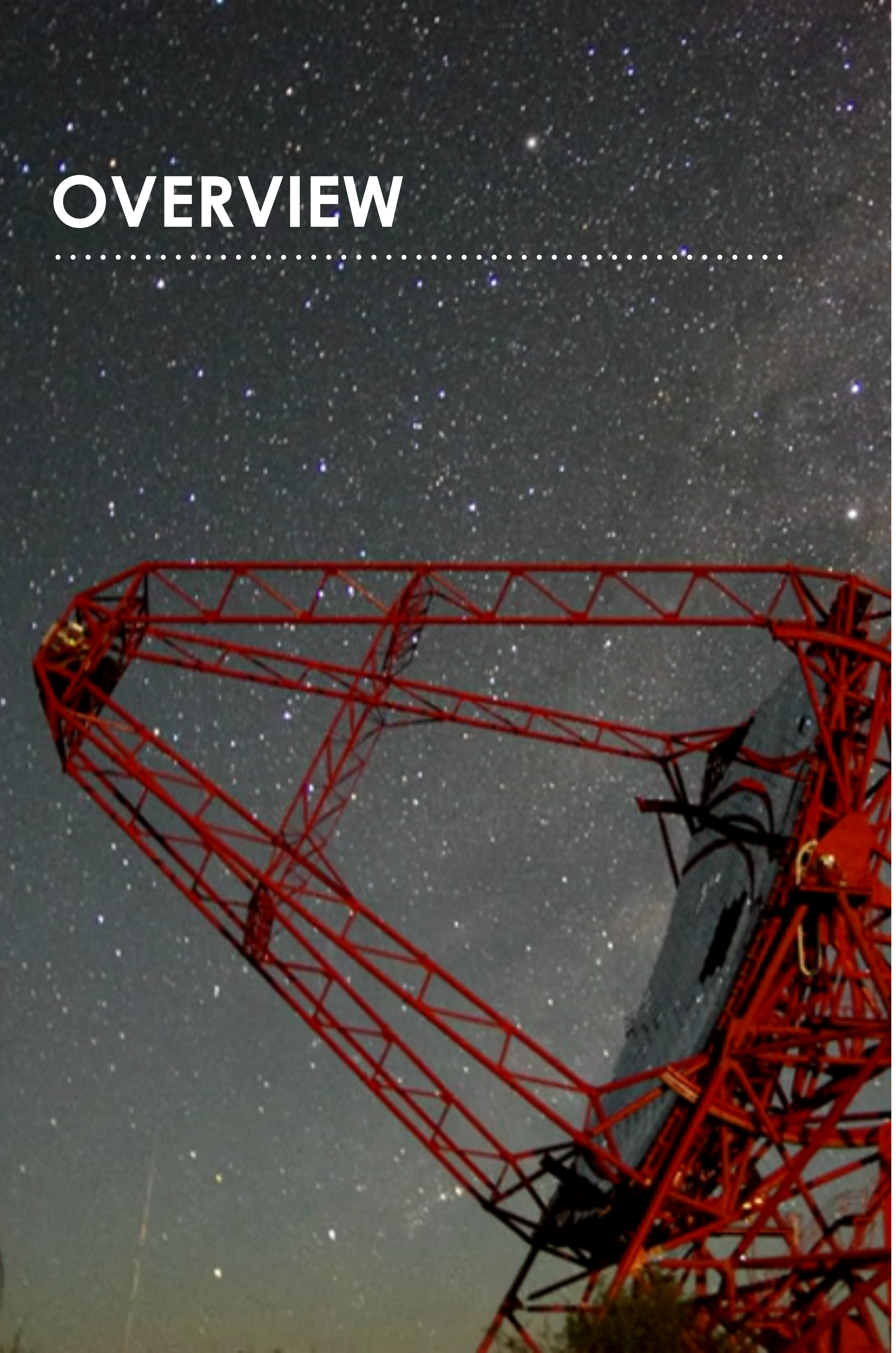


Paredes et al, 2013
A&A CTA Special Issue

Cyg X-1 Outburst







OVERVIEW

Introduction

Medium Energy Gamma Rays

- detection
- science
- future

High-Energy Gamma Rays

- detection
- science
- future

Very High Energy Gamma Rays

- detection
- science
- future

Summary and Outlook

gamma-ray detection in context

keV **X-ray**	**20 KeV** - ≈**1** MeV	**0.2** MeV - **10** MeV	**10** MeV - **100** GeV	**100** GeV - **100**TeV

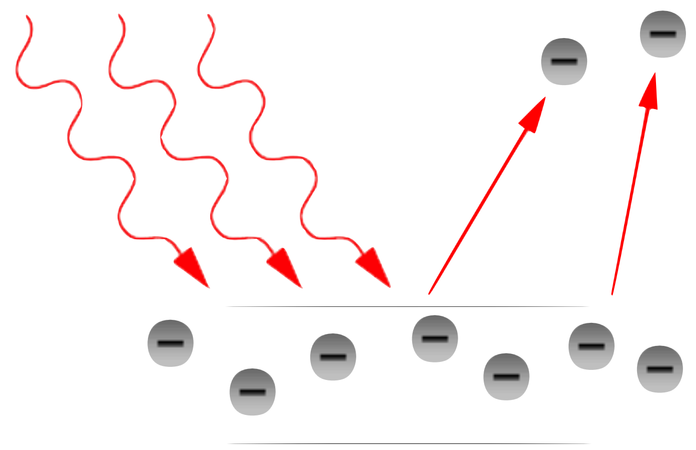
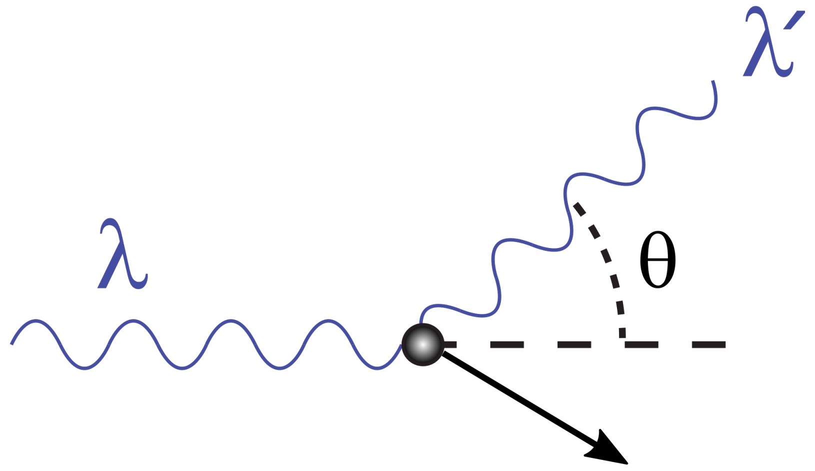
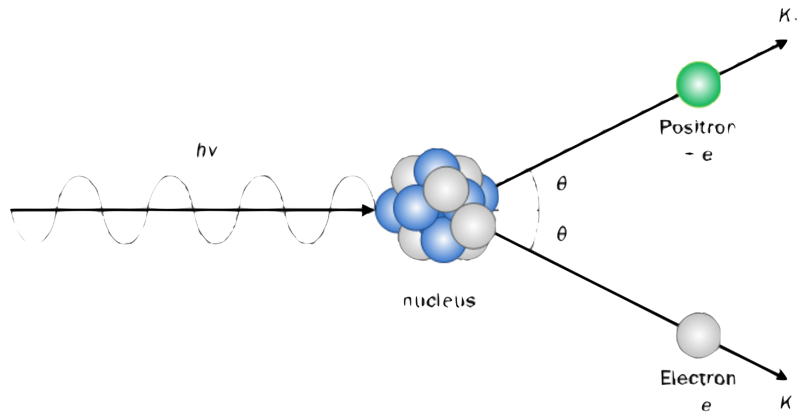


photo-electric effect
400 cm² @ 5keV

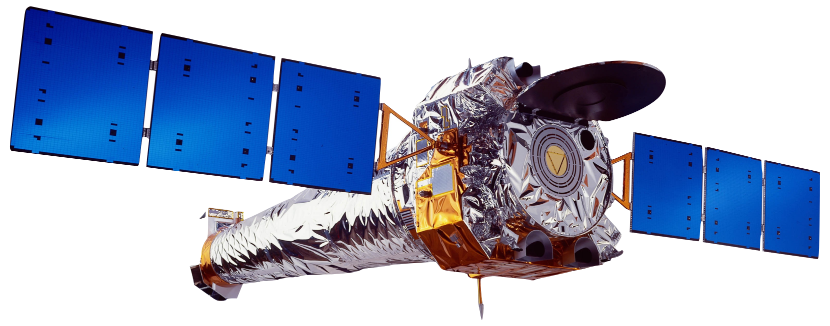


Compton Effect
50 cm² @ 5 MeV

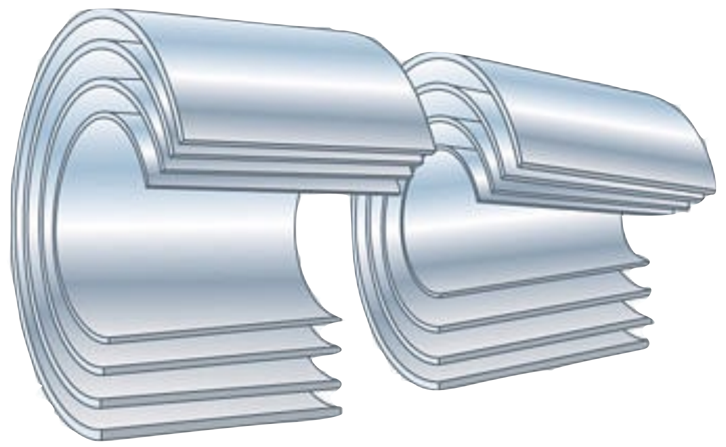


Pair Conversion
1m² @ 1 GeV

Extensive Air Shower
> 10^5 - 10^6 m² @ 1 TeV

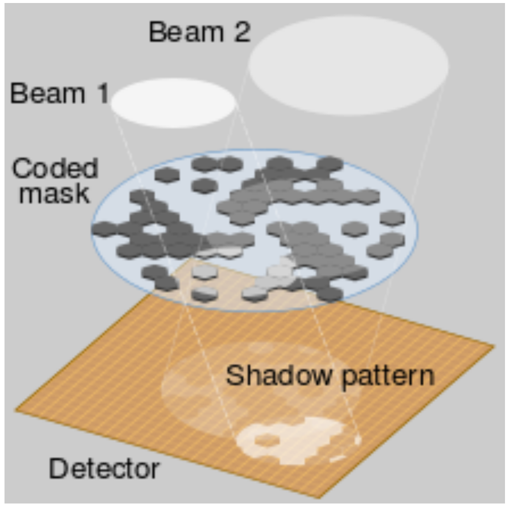


Chandra, XMM

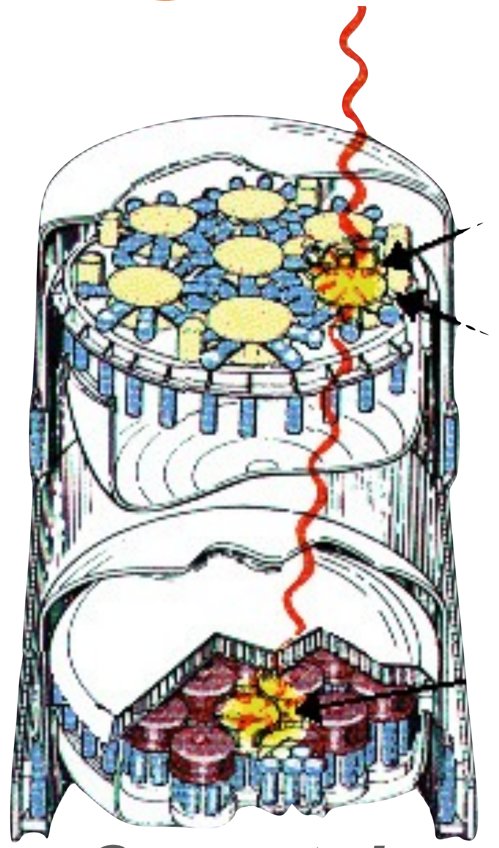


grazing-incidence mirror

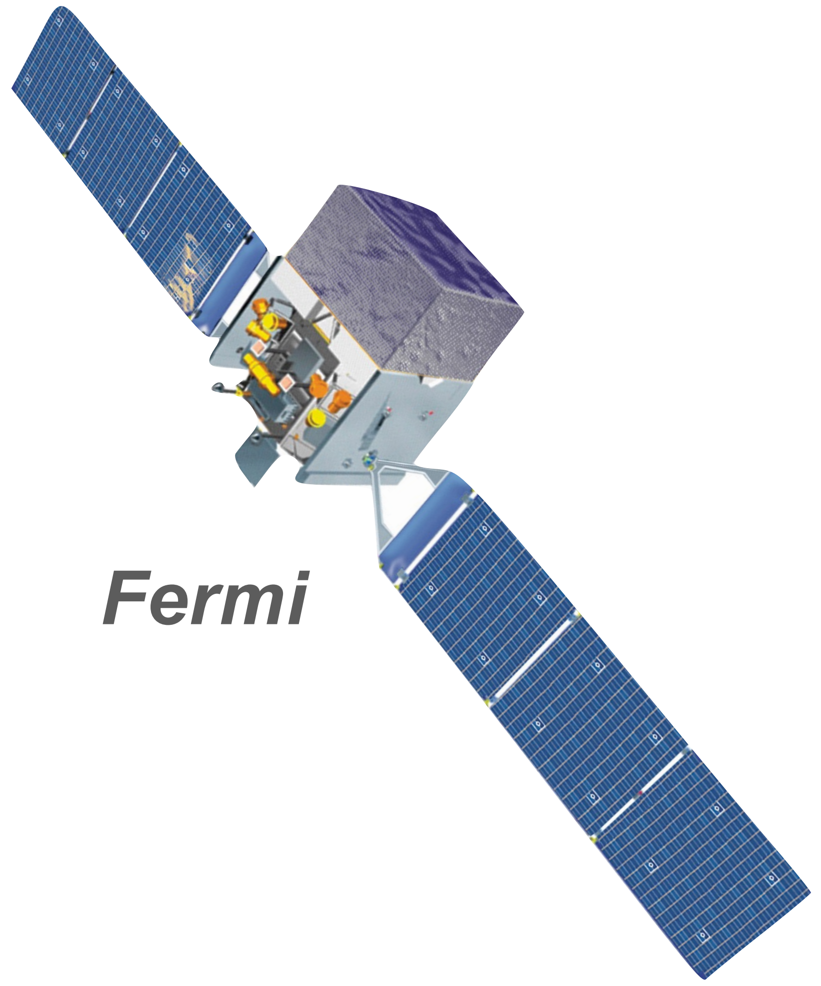
INTEGRAL



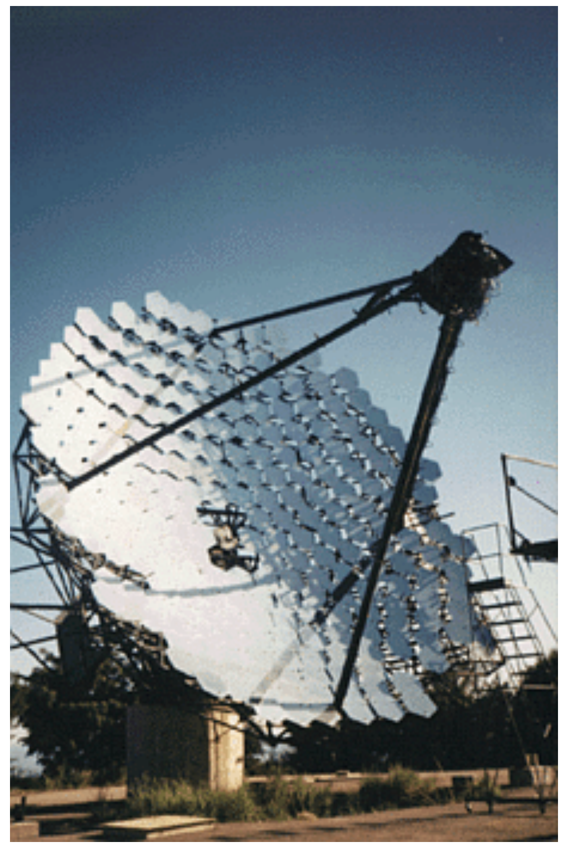
coded-mask



Comptel
(no longer flying)



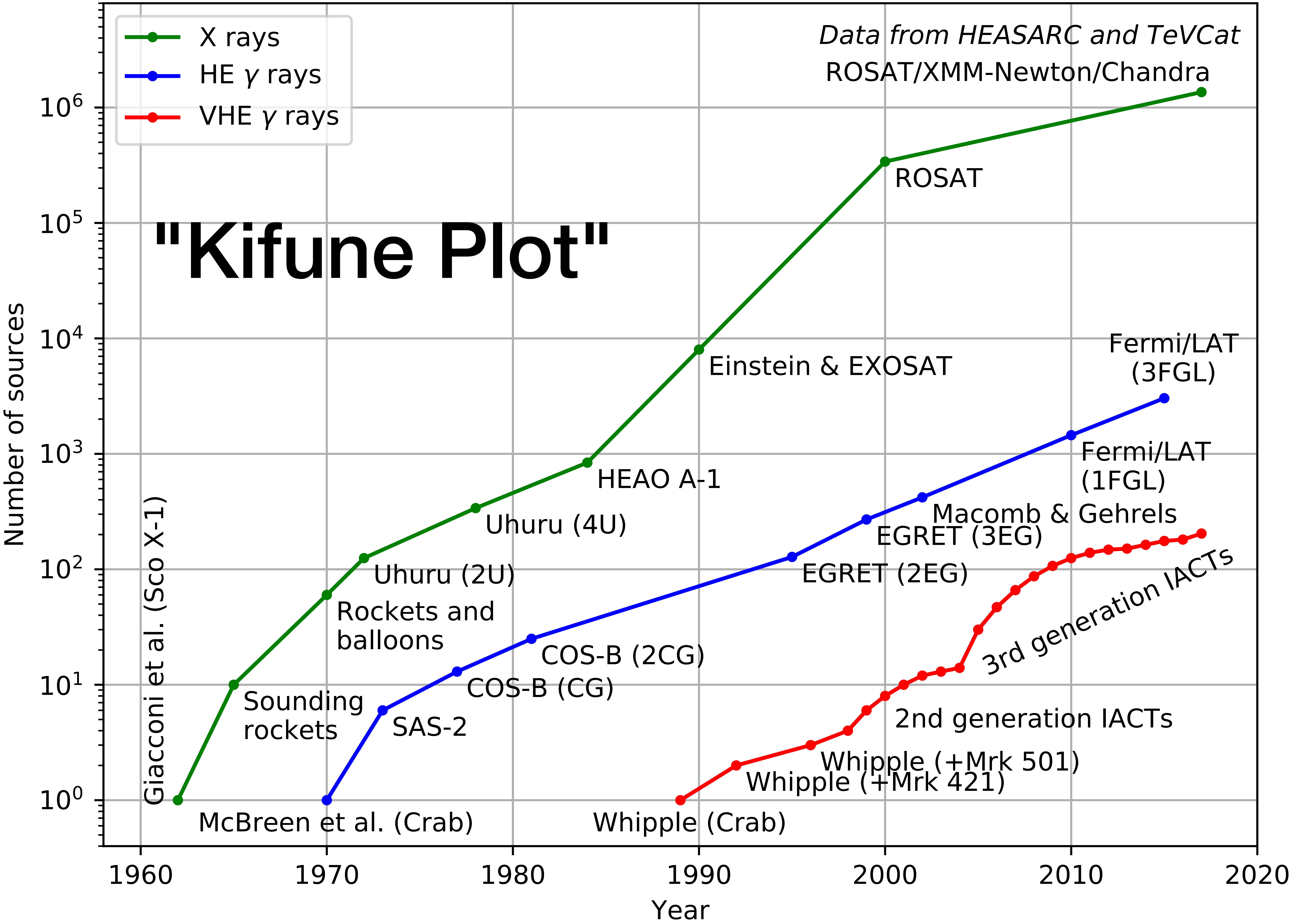
Fermi



Whipple 10m

Comparison

	Compton Telescopes	Fermi-LAT	IACTs (e.g. HESS)	WCTs (HAWC)
Energy Range	Medium-energy Gamma	High-Energy Gamma	Very-High-Energy Gamma	Very-High-Energy Gamma
Field of view	**Large**	**Effectively All-Sky**	Small	Half-Sky
PSF (E-dependant)	fair ≈1°	**good 0.1-1.0°**	**good 0.01-0.1°**	fair 0.3-0.5°
Energy Resolution	**good ≈10%**	**good ≈10%**	**good ≈10%**	poor 50%-100%
Duty Cycle	**very good**	**very good**	poor	**very good**
Sky Coverage	**full**	**full**	half	half
Short-Term Sensitivity	good	good (GeV) poor (>100GeV)	good (>100GeV)	poor

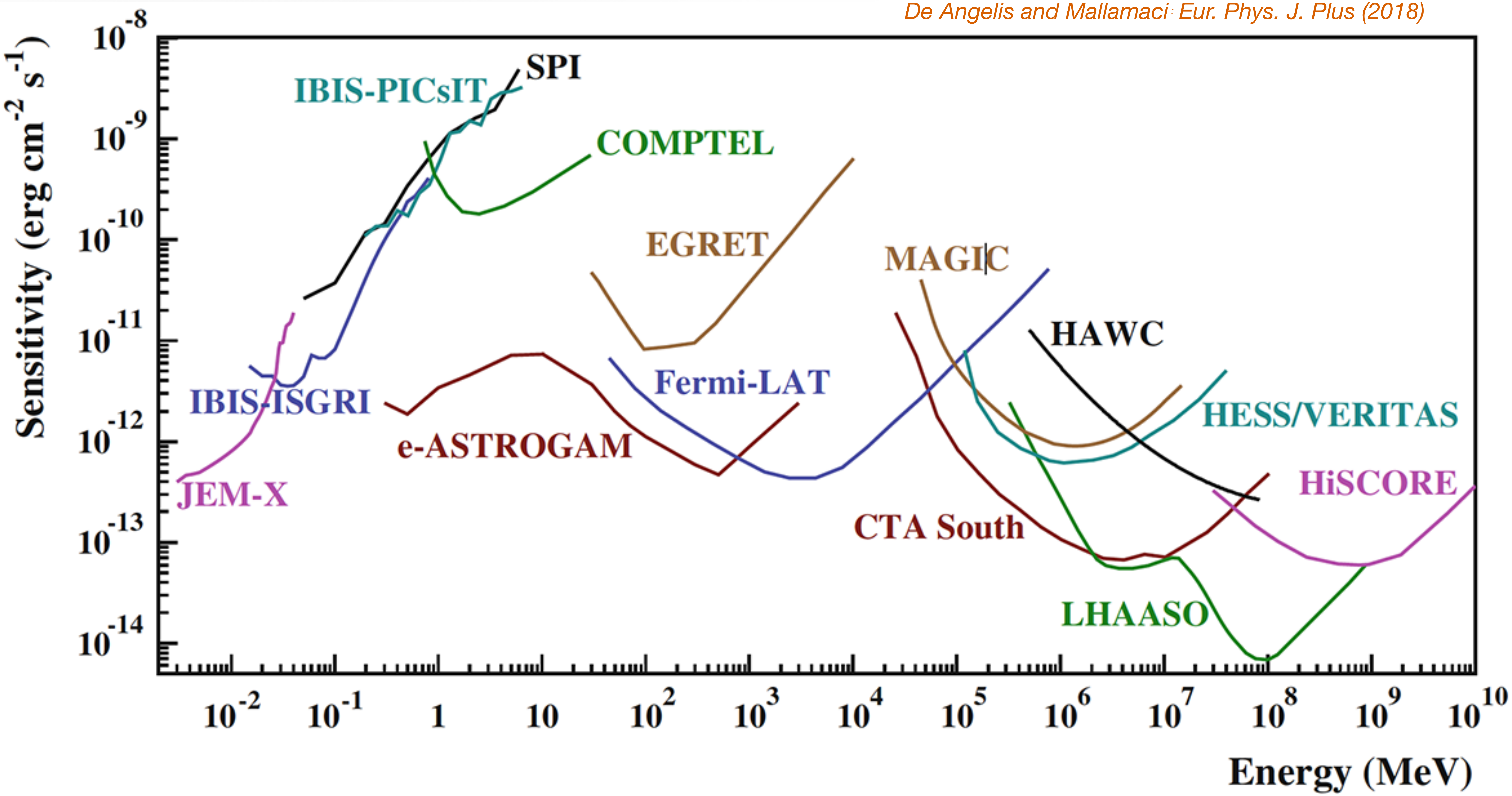


S. Fegan,
https://github.com/sfegan/kifune-plot ,

original by Tadashi Kifune 1996

Gamma-ray Instrument Sensitivities

De Angelis and Mallamaci Eur. Phys. J. Plus (2018)

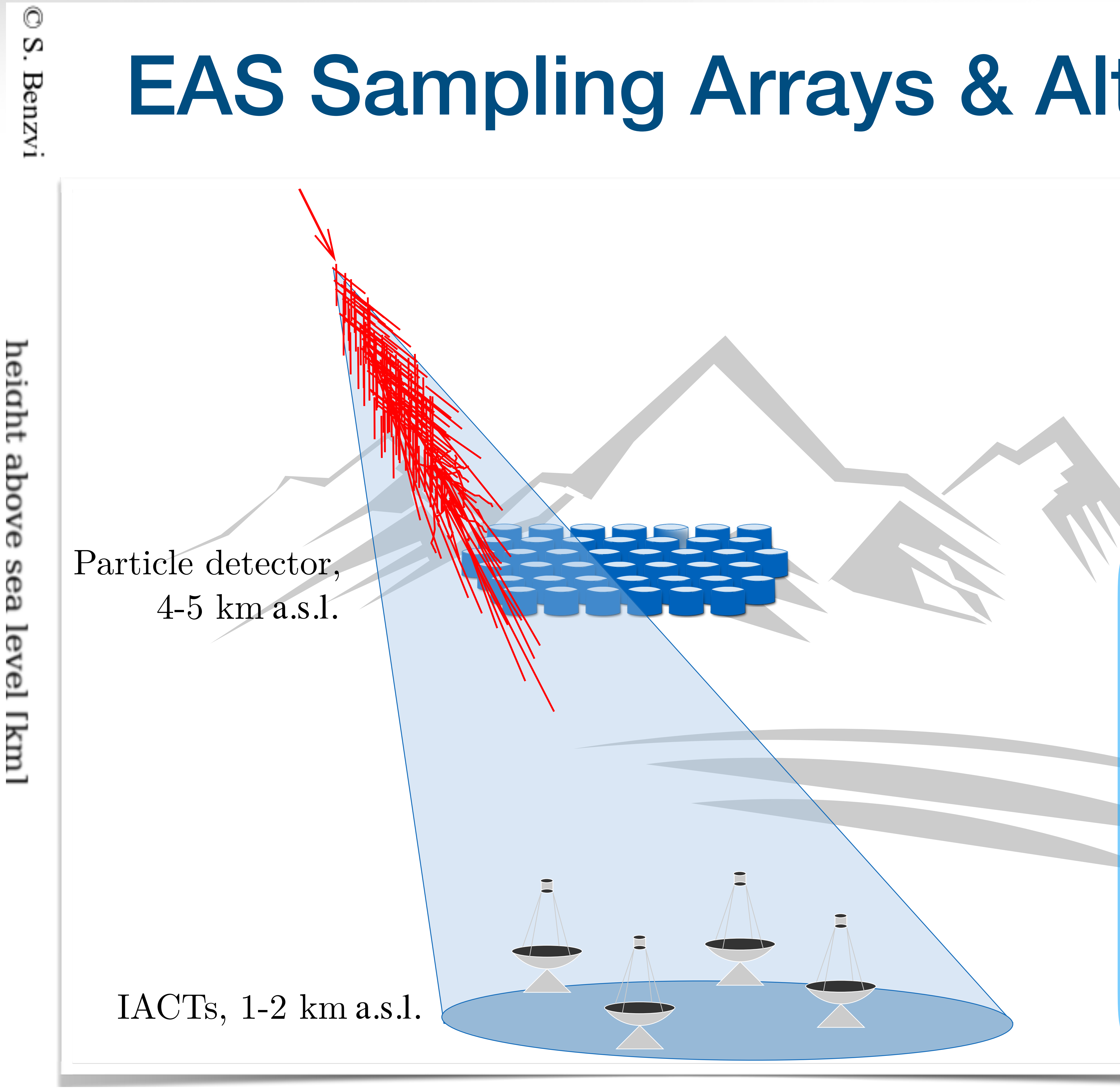


Thank-you!

backup

Detection: All Sky VHE gammas

See talk by

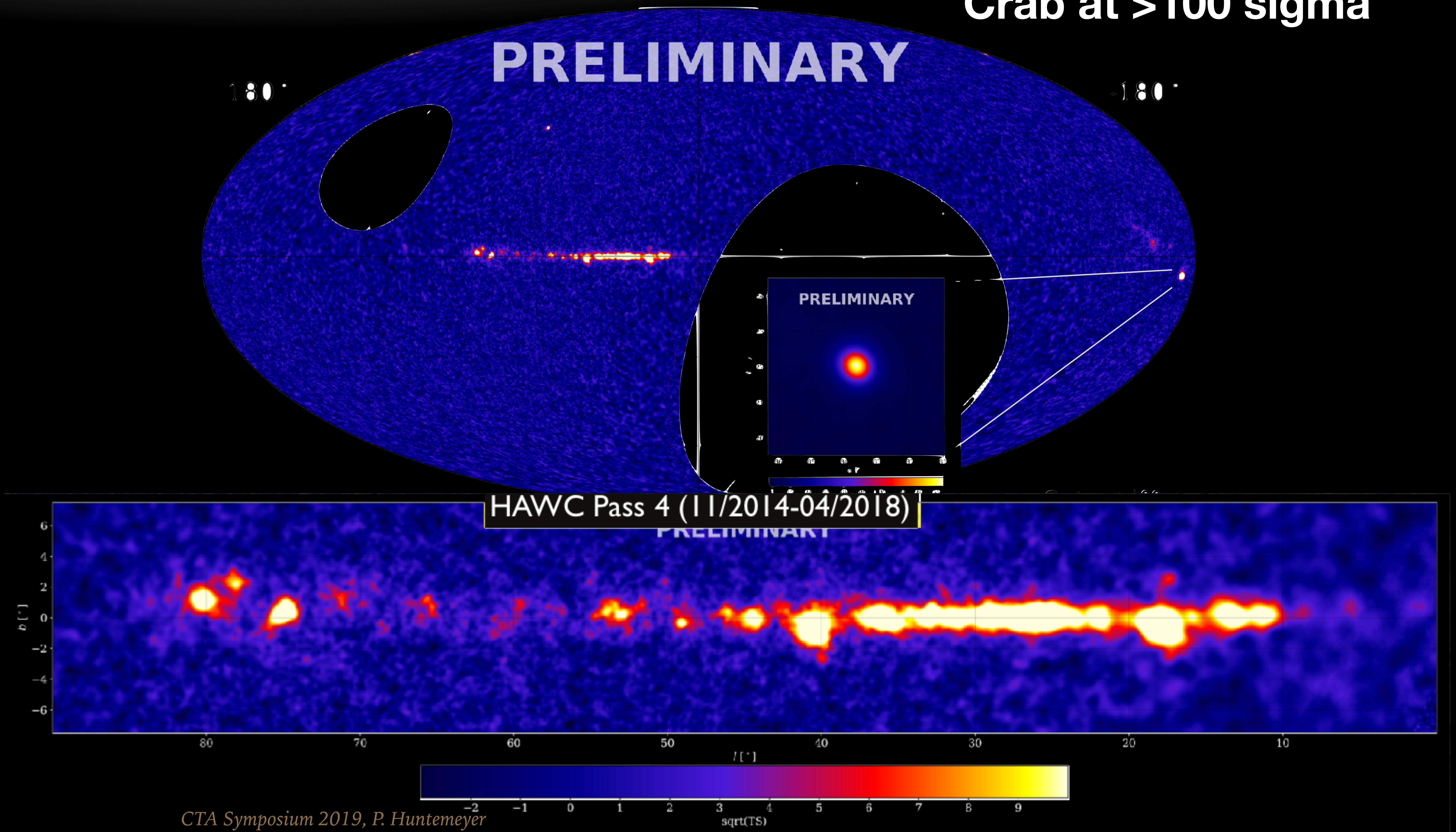


HAWC

High Altitude Water-Cherenkov observatory

HAWC Survey 2014-2018

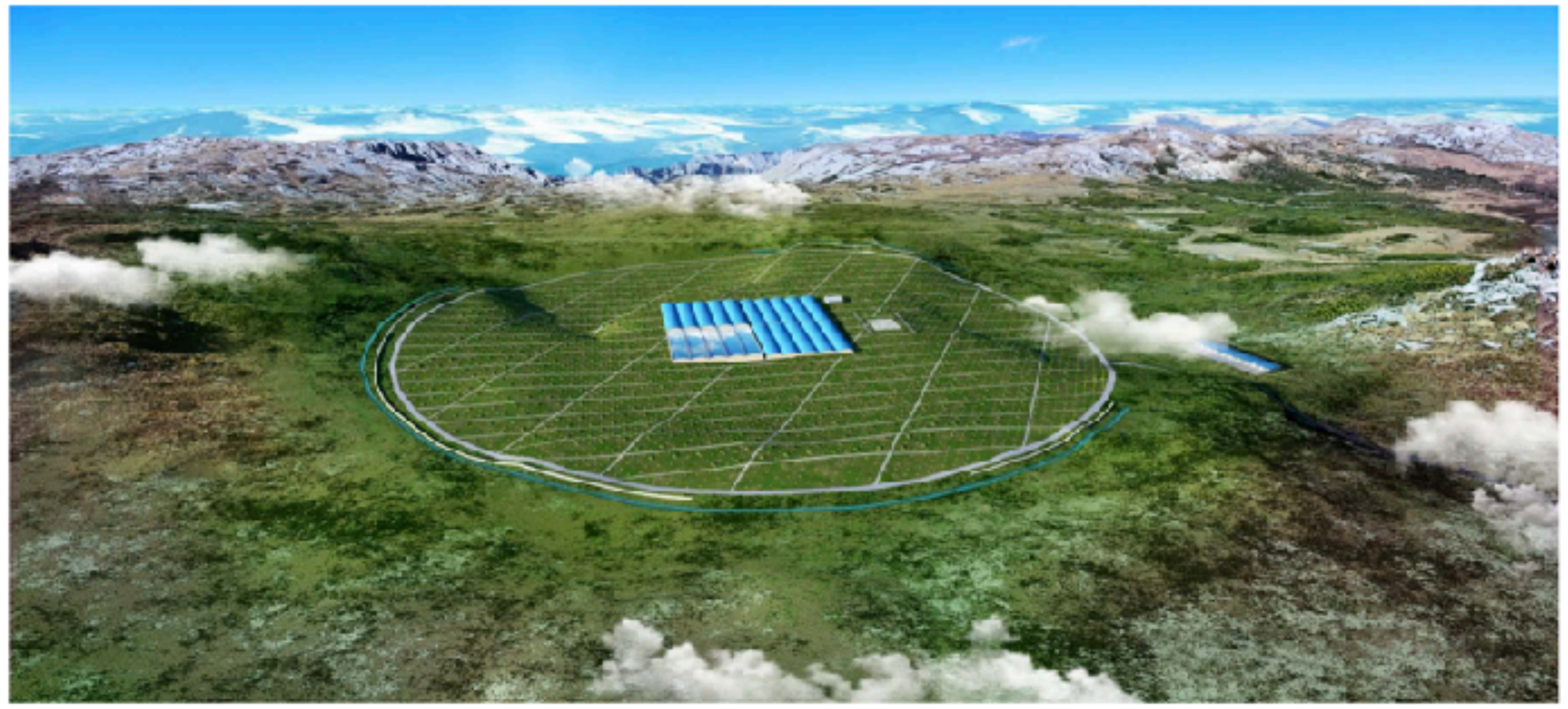
Crab at >100 sigma



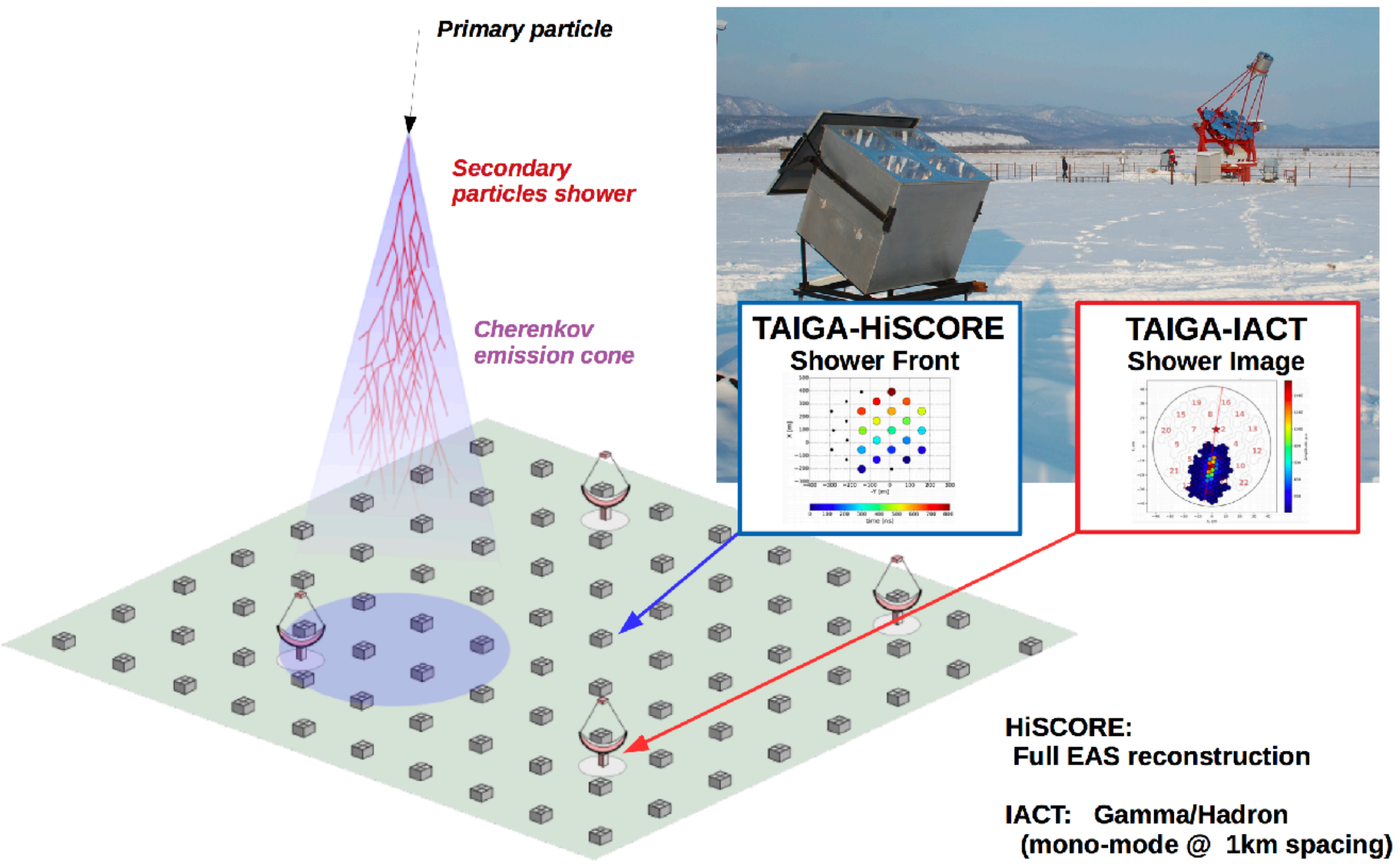
CTA Symposium 2019, P. Huntemeyer

Other VHE large-FOV instruments:

Sichuan province
4400 m a.s.l.



The TAIGA Hybrid Detector: Imaging and Non-Imaging Techniques



Future All-Sky: SGSO