Ground-Based Gamma Ray Detection

How we detect the highest energy gamma-rays
and do science with them

Karl Kosack
CEA Paris-Saclay Astrophysics Department

Photon detection in context

keV **X-ray**

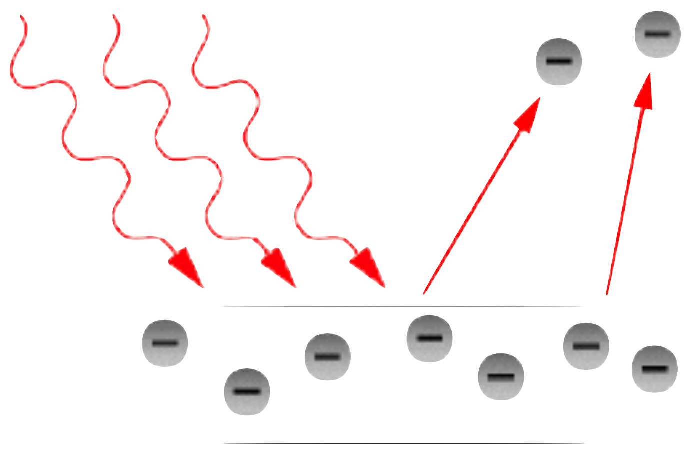
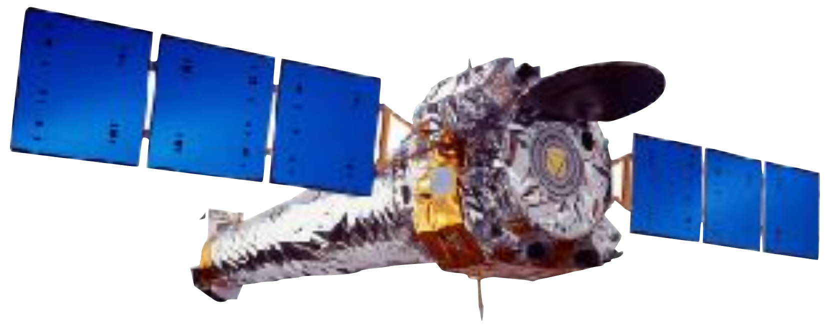
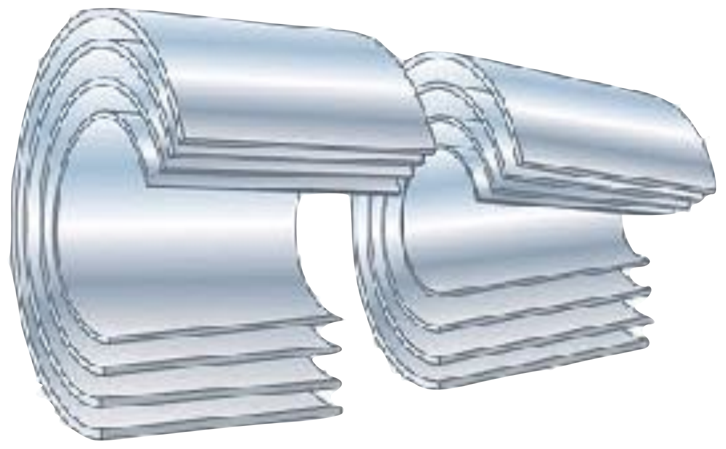


photo-electric effect

400 cm^2 @ 5keV



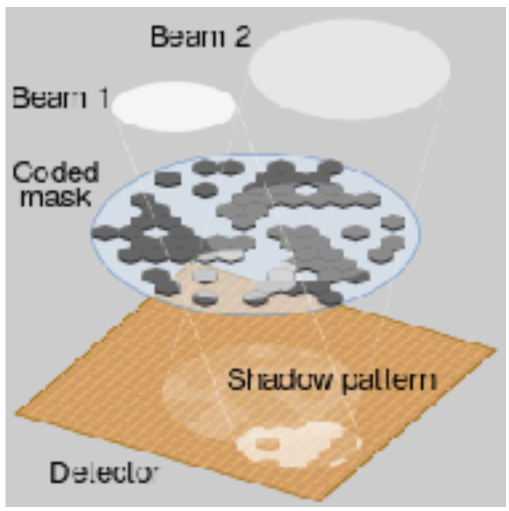
Chandra, XMM



grazing-incidence mirror

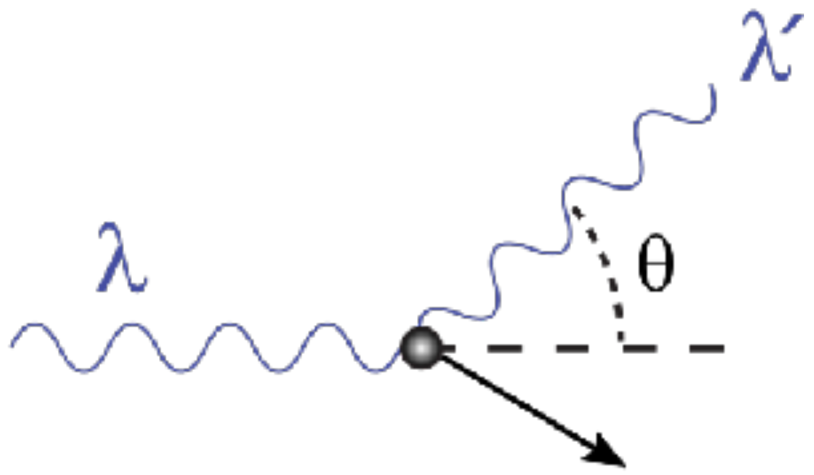
20 KeV -
≈1 MeV

INTEGRAL



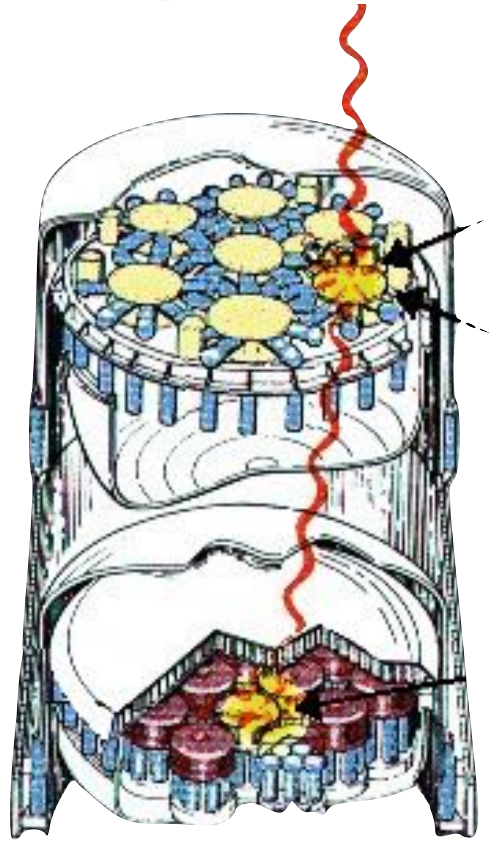
coded-mask

***0.2** MeV -*
***10** MeV*



Compton Effect

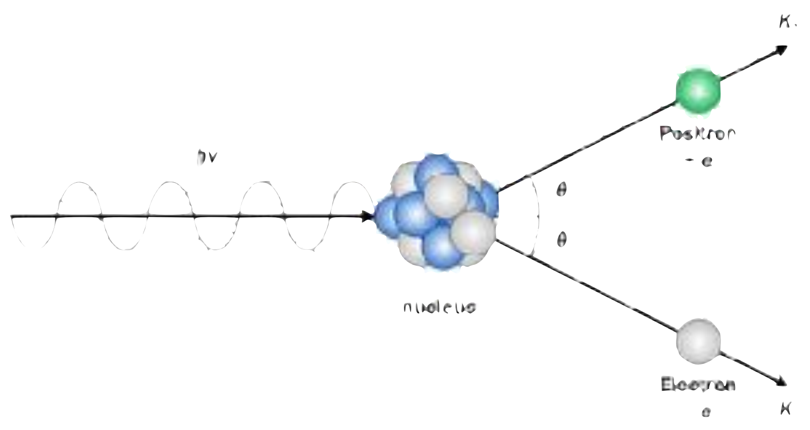
50 cm^2 @ 5 MeV



Comptel

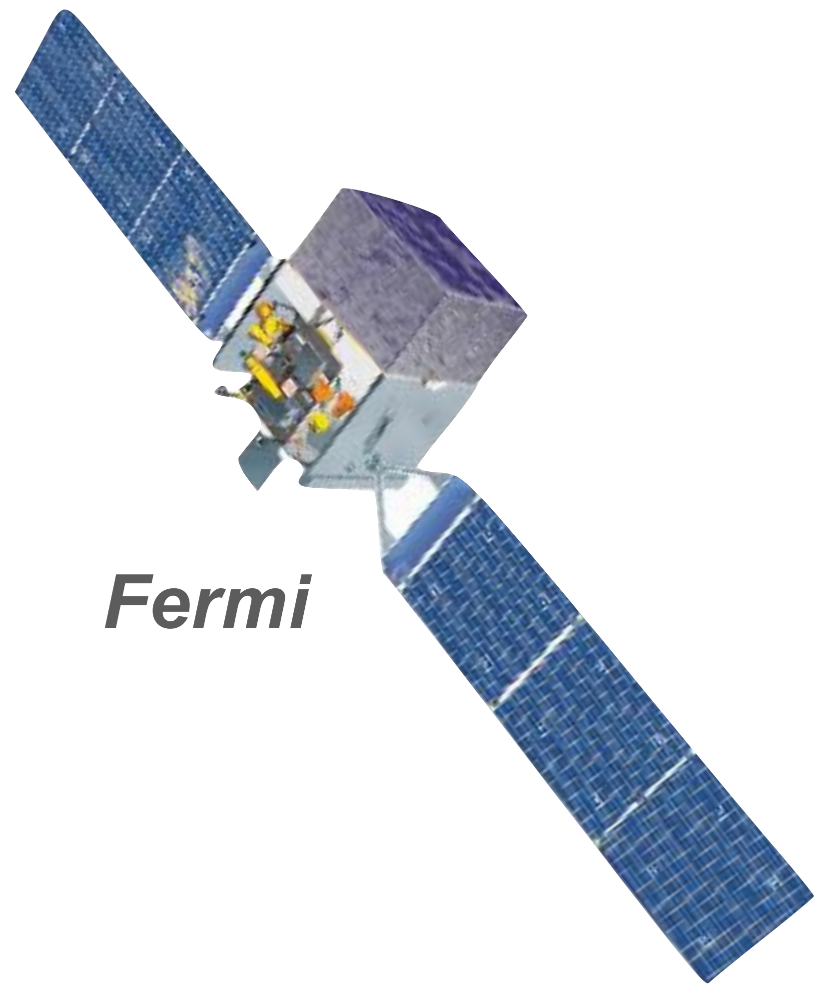
(no longer flying)

***10** MeV -*
***100** GeV*



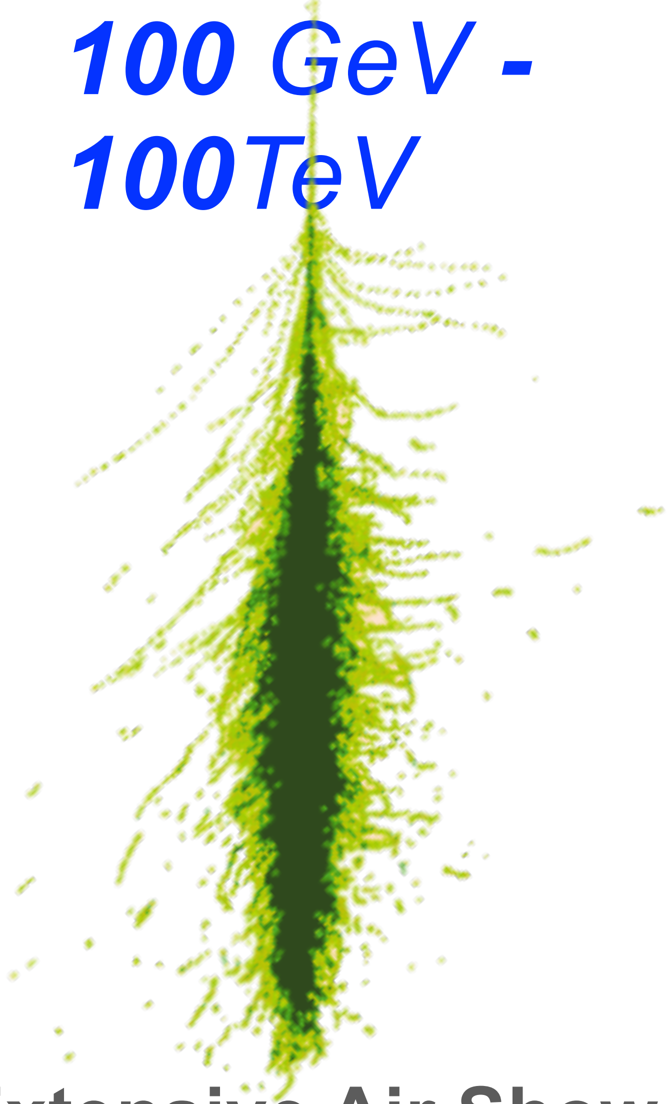
Pair Conversion

1m^2 @ 1 GeV



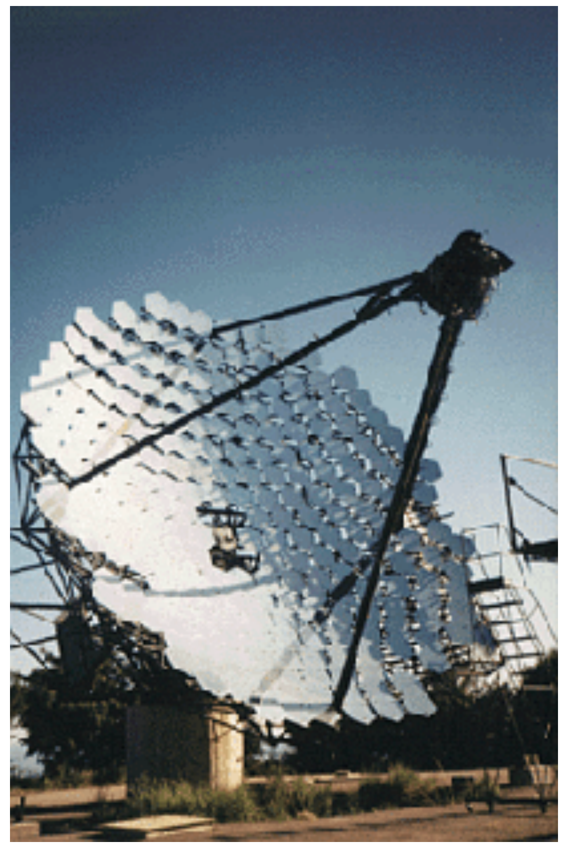
Fermi

***100** GeV -*
***100**TeV*

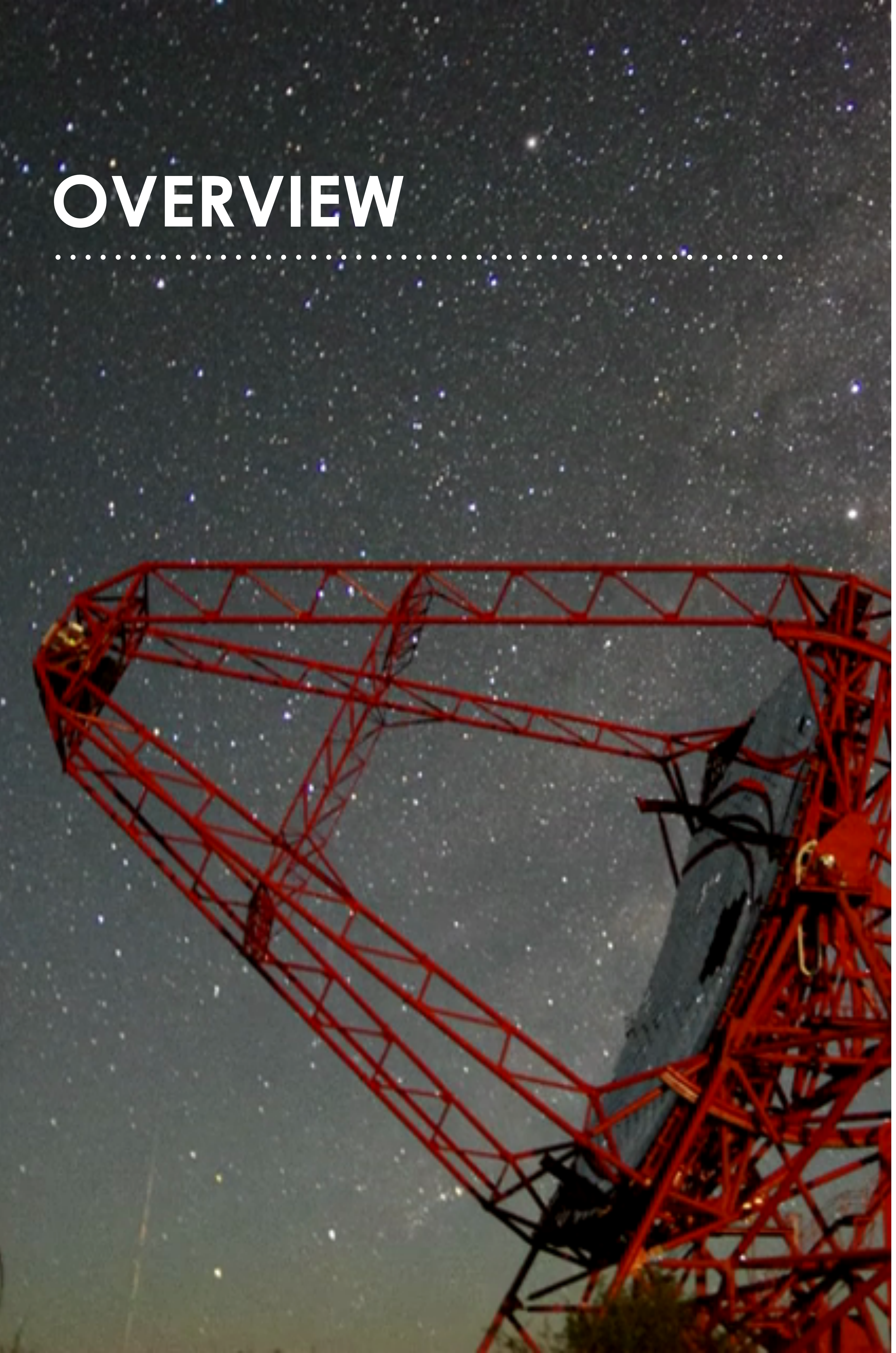


Extensive Air Shower

> 10^5 - 10^6 m^2 @ 1 TeV



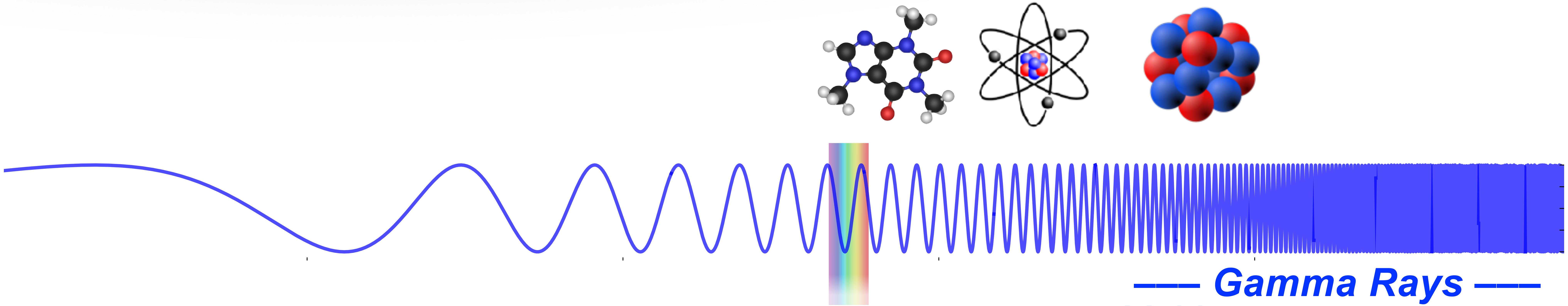
Whipple 10m



OVERVIEW

- **VHE Gamma Rays**
- **Gamma-ray Interactions in the Atmosphere**
- **Imaging Atmospheric Cherenkov Telescopes**
- **Water Cherenkov Telescopes**
- **Science with VHE Gamma rays**

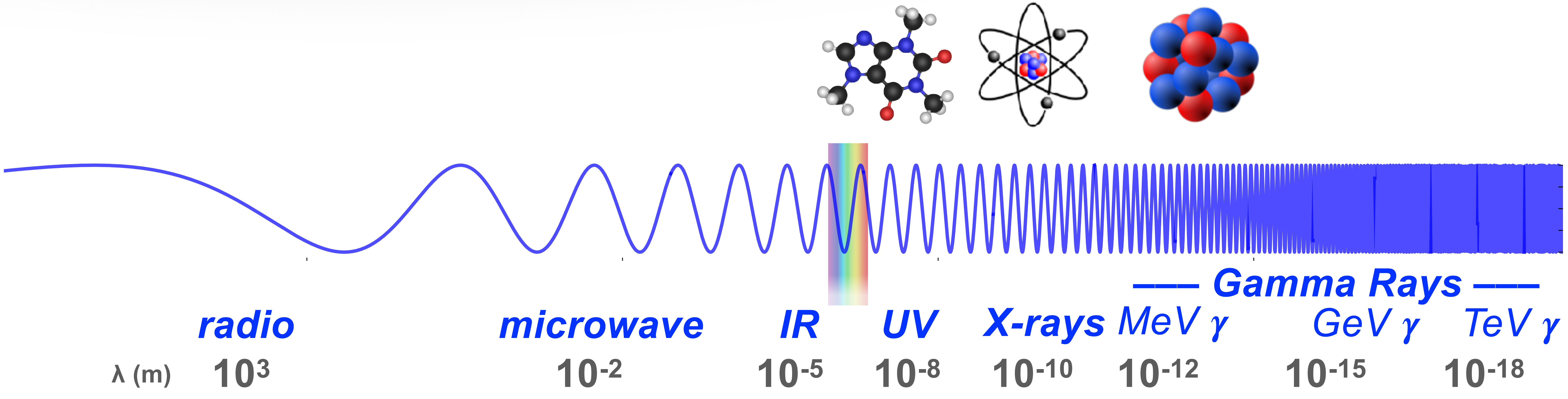
Gamma Rays: definitions



—— Gamma Rays ——

	radio	*microwave*	*IR*	*UV*	*X-rays*	MeV γ	GeV γ	TeV γ
λ (m)	10^{3}	10^{-2}	10^{-5}	10^{-8}	10^{-10}	10^{-12}	10^{-15}	10^{-18}

Gamma Rays: definitions



medium energy **(ME/MeV)**

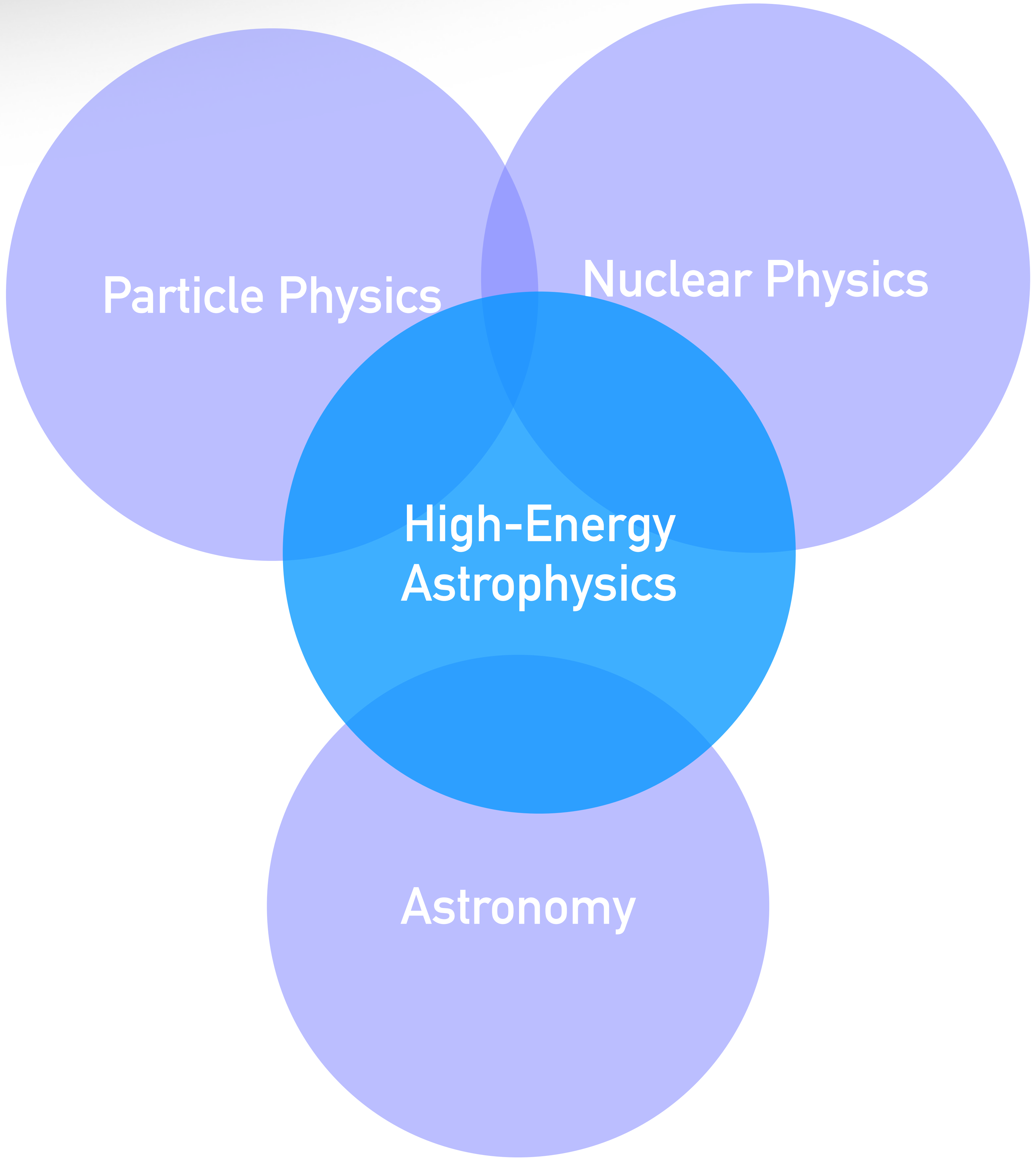
"high energy" (HE/GeV)

"very high energy" (VHE/TeV)

High Energy Astrophysics

Gamma rays allow us to:

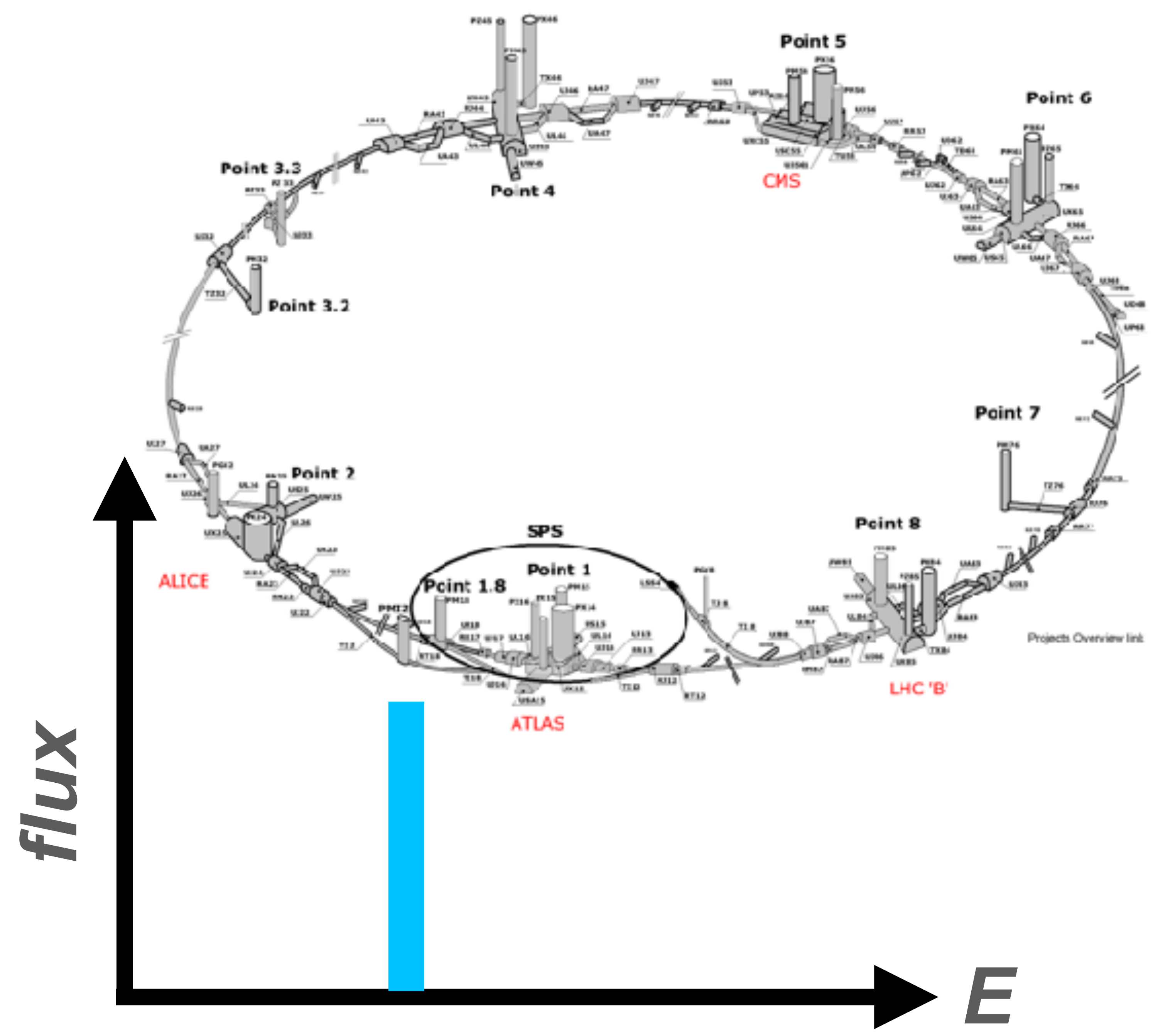
- study the sources of acceleration of cosmic rays
- understand the physics of jets
- understand the physics of accretion
- provide direct view: cosmic rays bend in B-fields and do not trace back to their origin spatially or temporally)



Gamma-rays come from Non-Thermal Emission

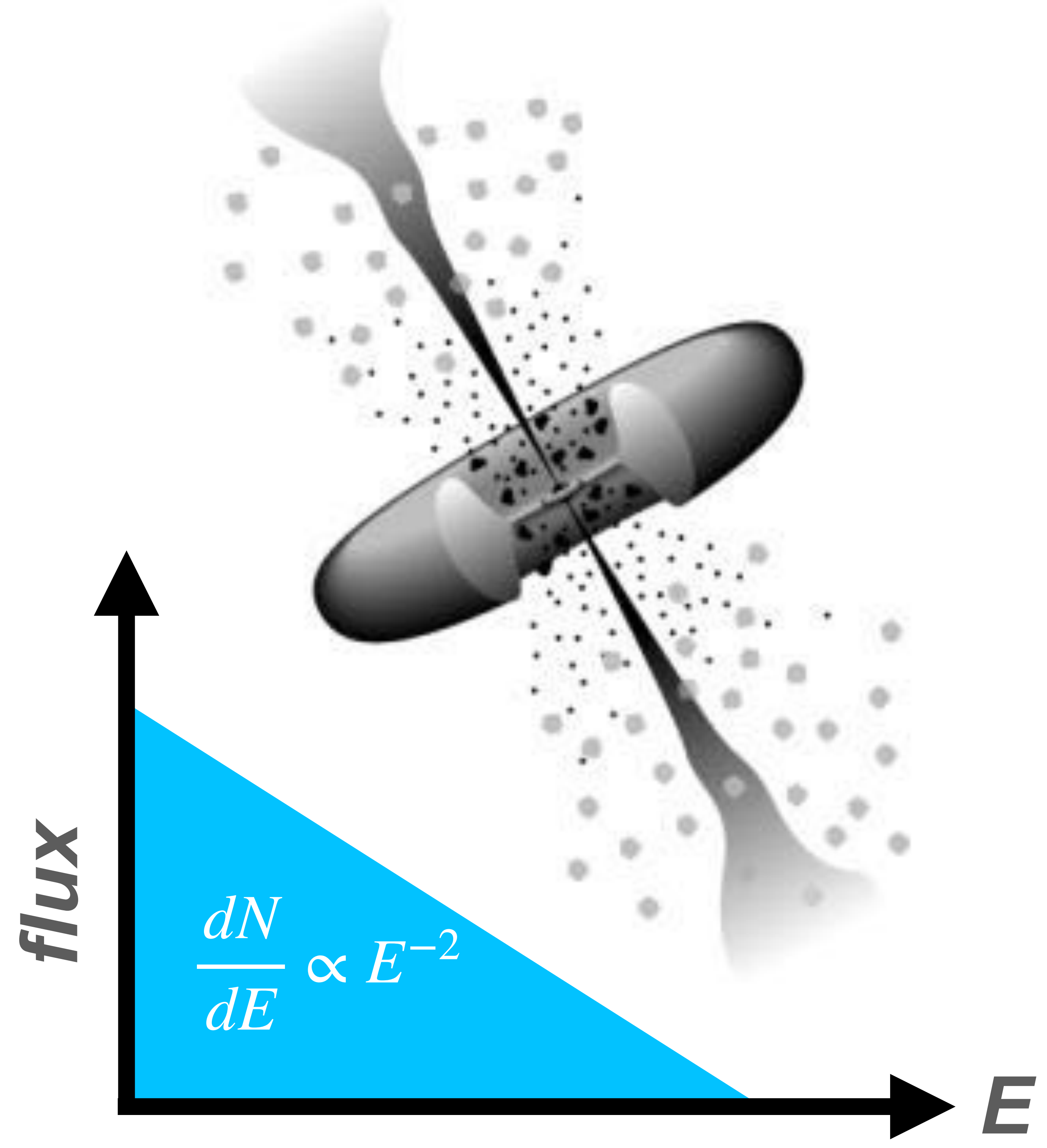
Particle Acceleration

Human-made Particle Accelerators



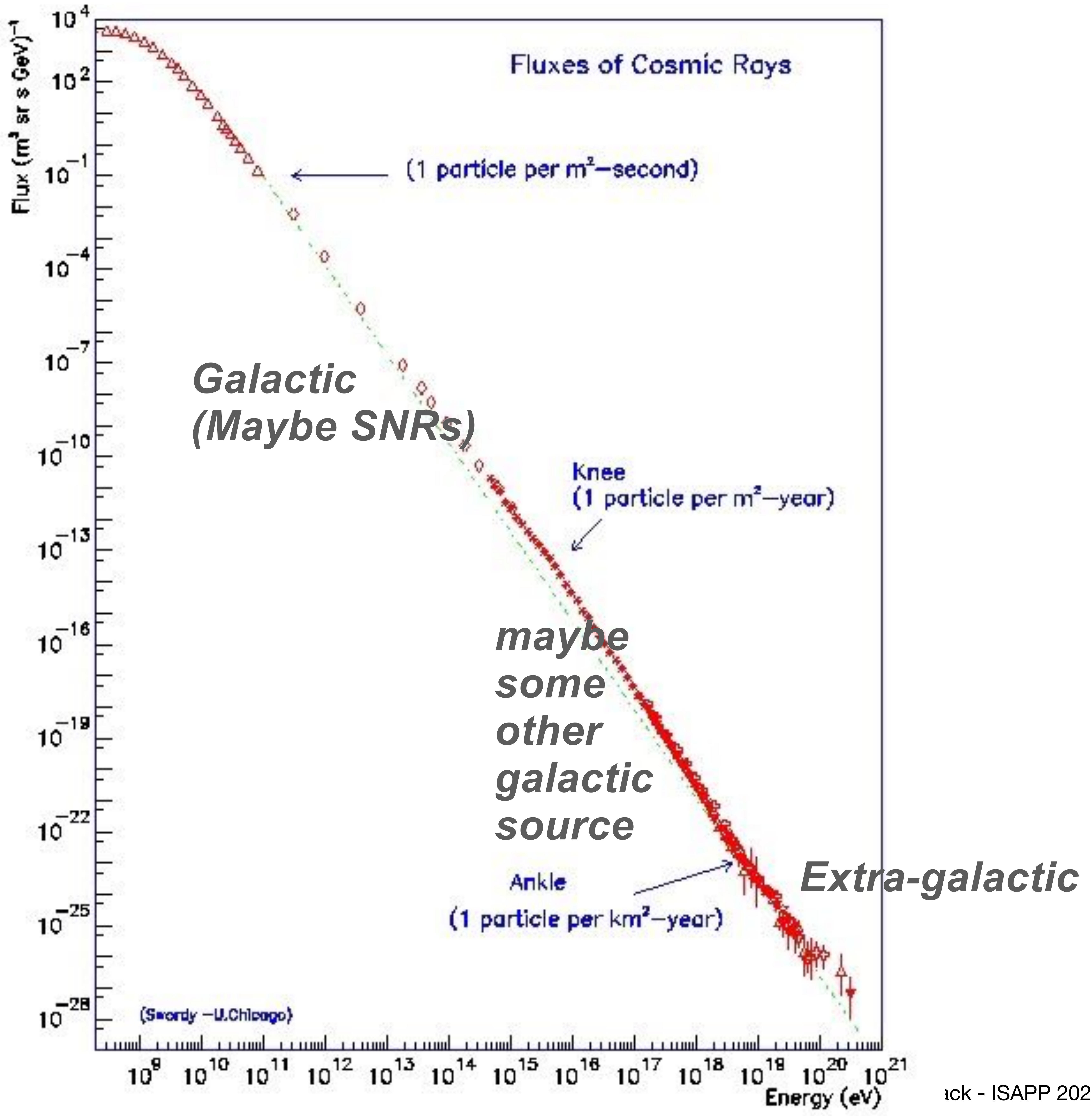
series of radio-frequency cavities

Astrophysical Particle Accelerators



diffusive shock acceleration

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

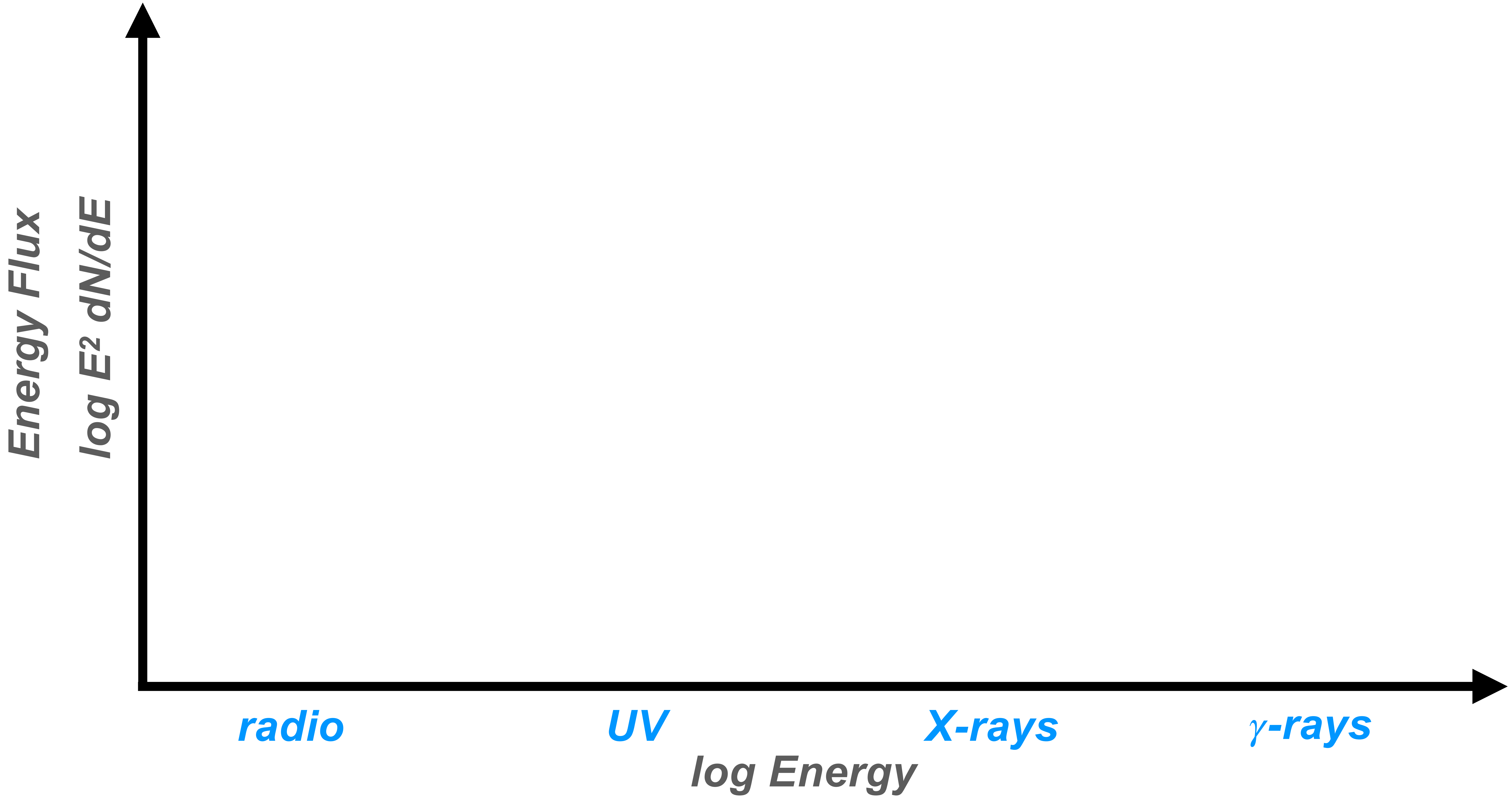


Non-Thermal Emission

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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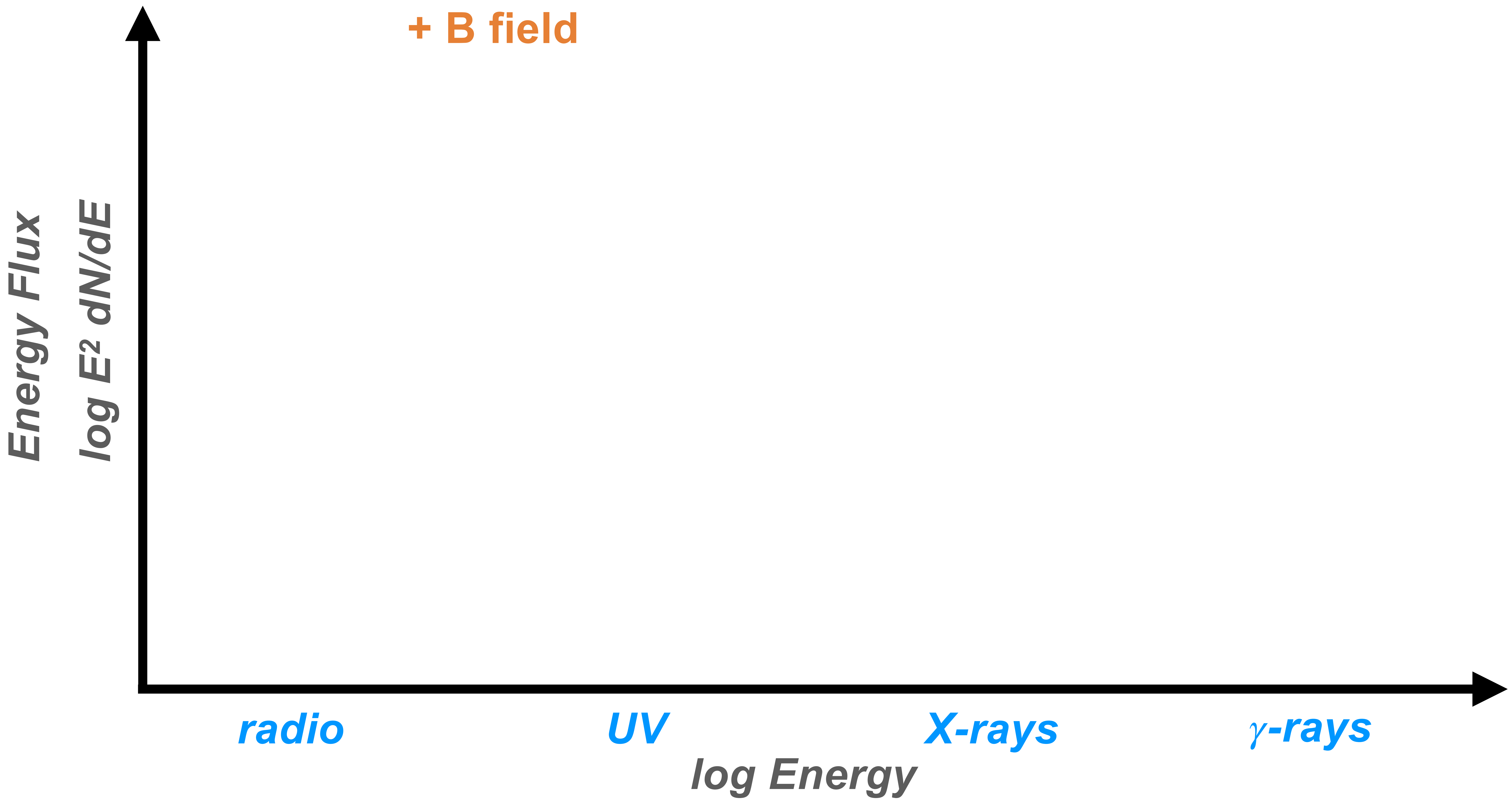

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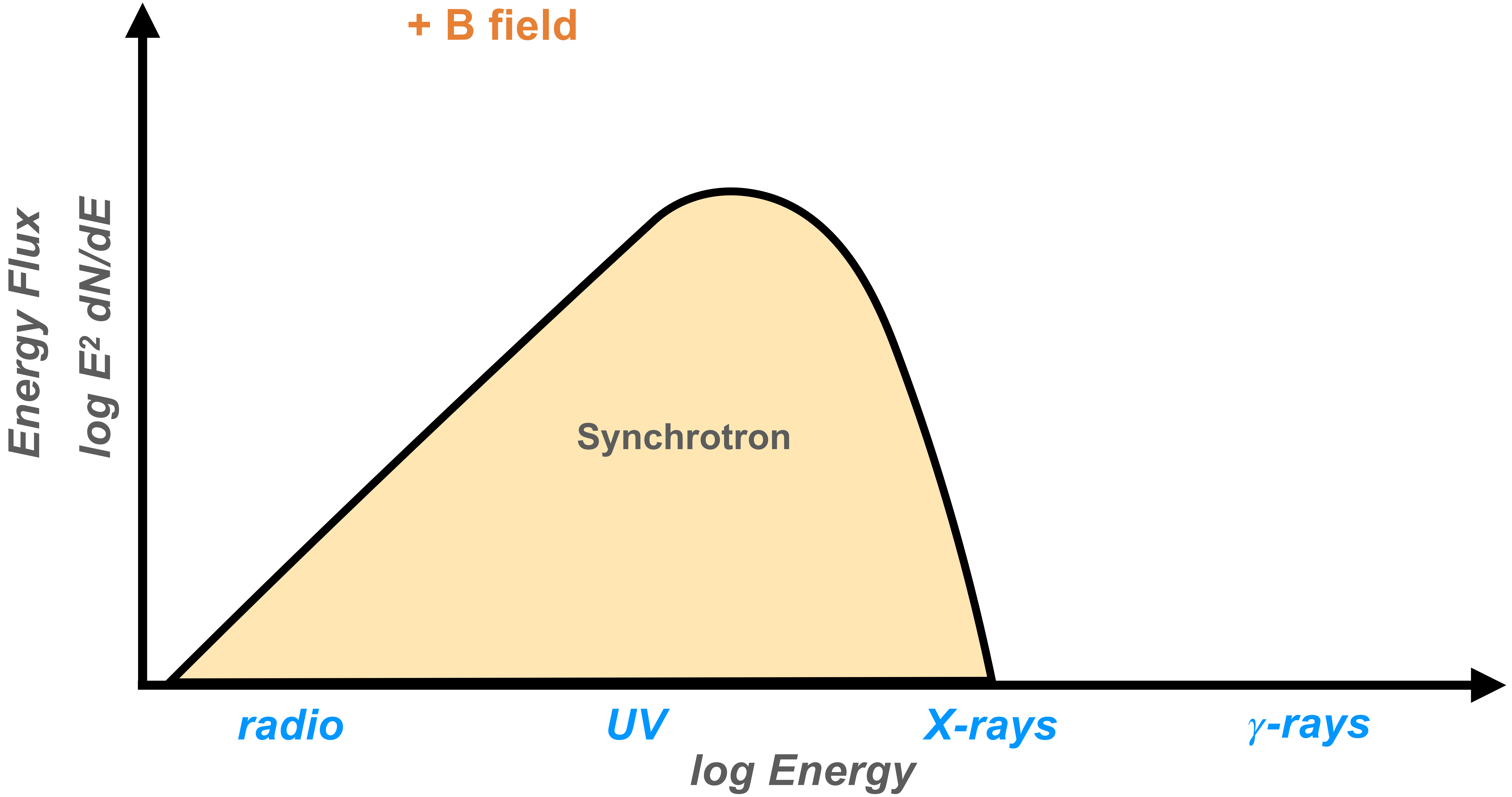

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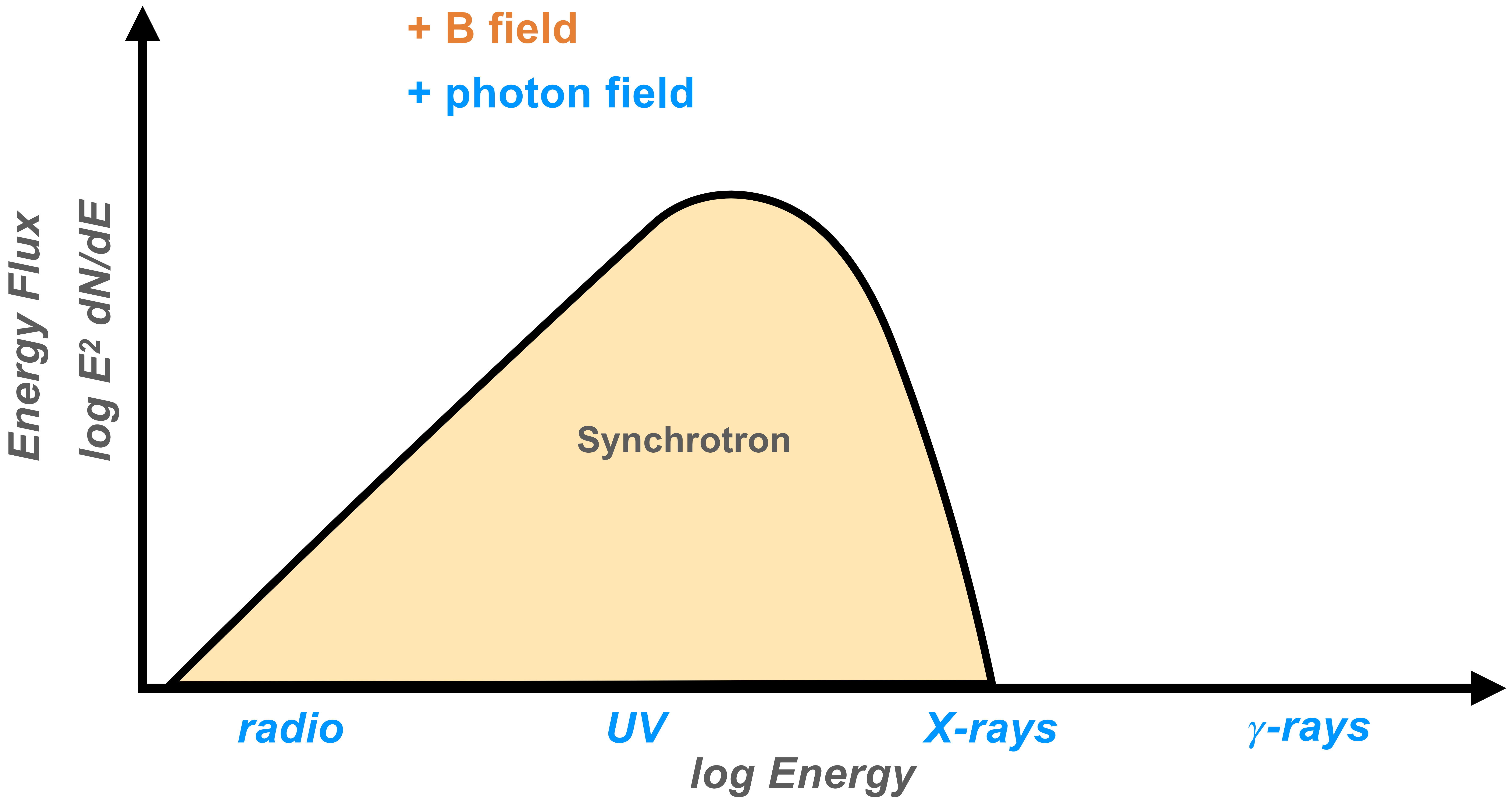

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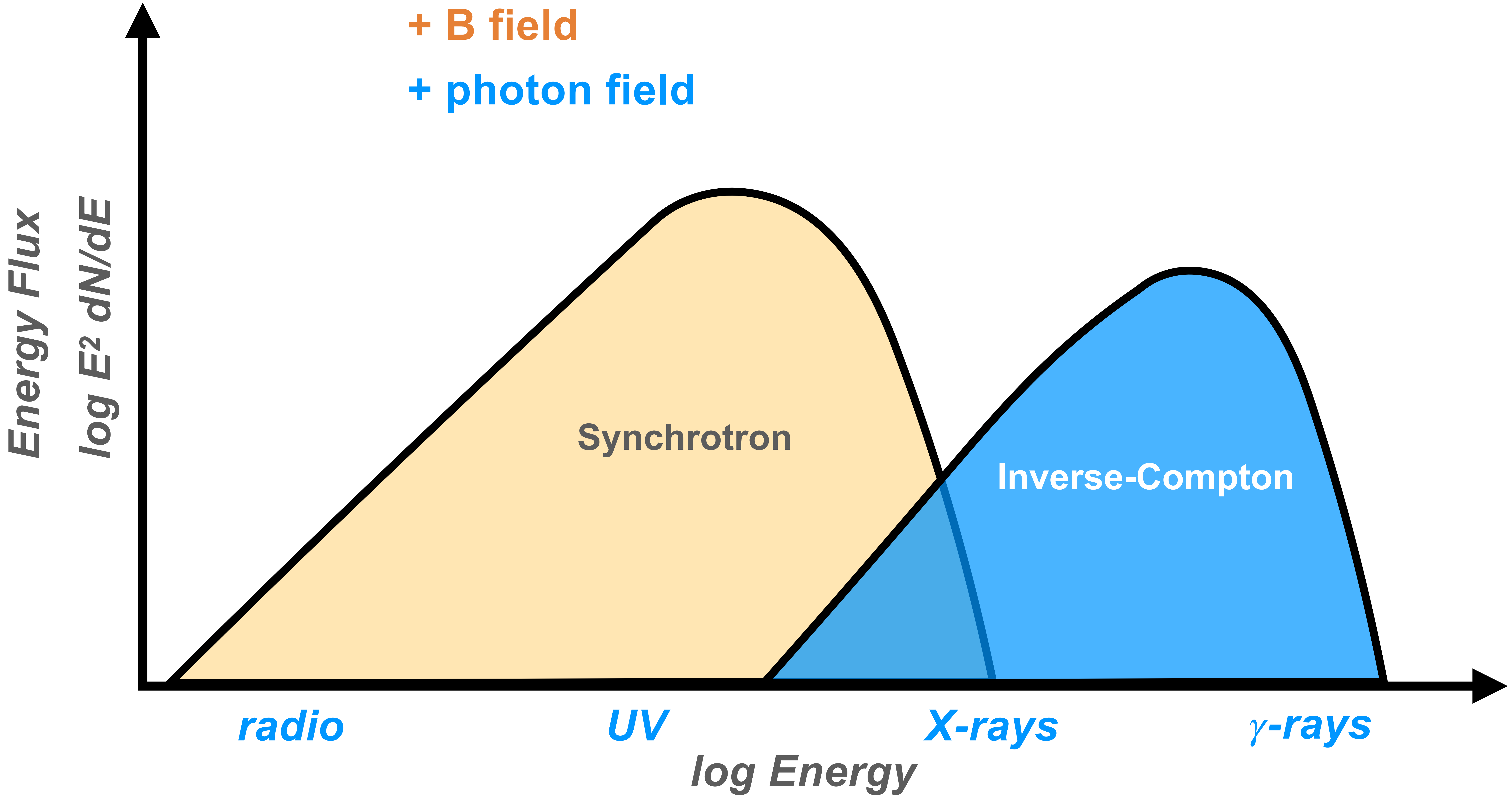

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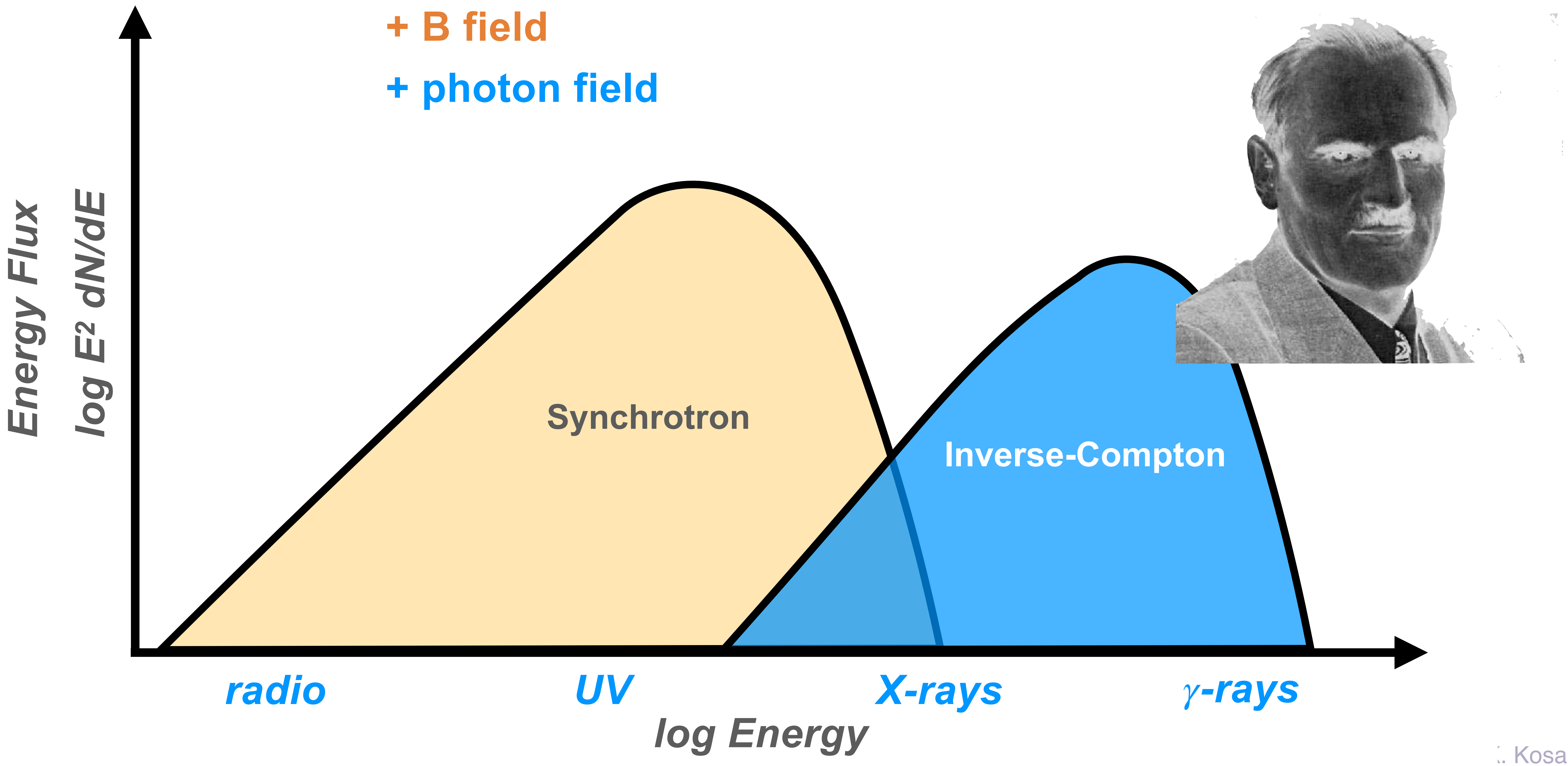

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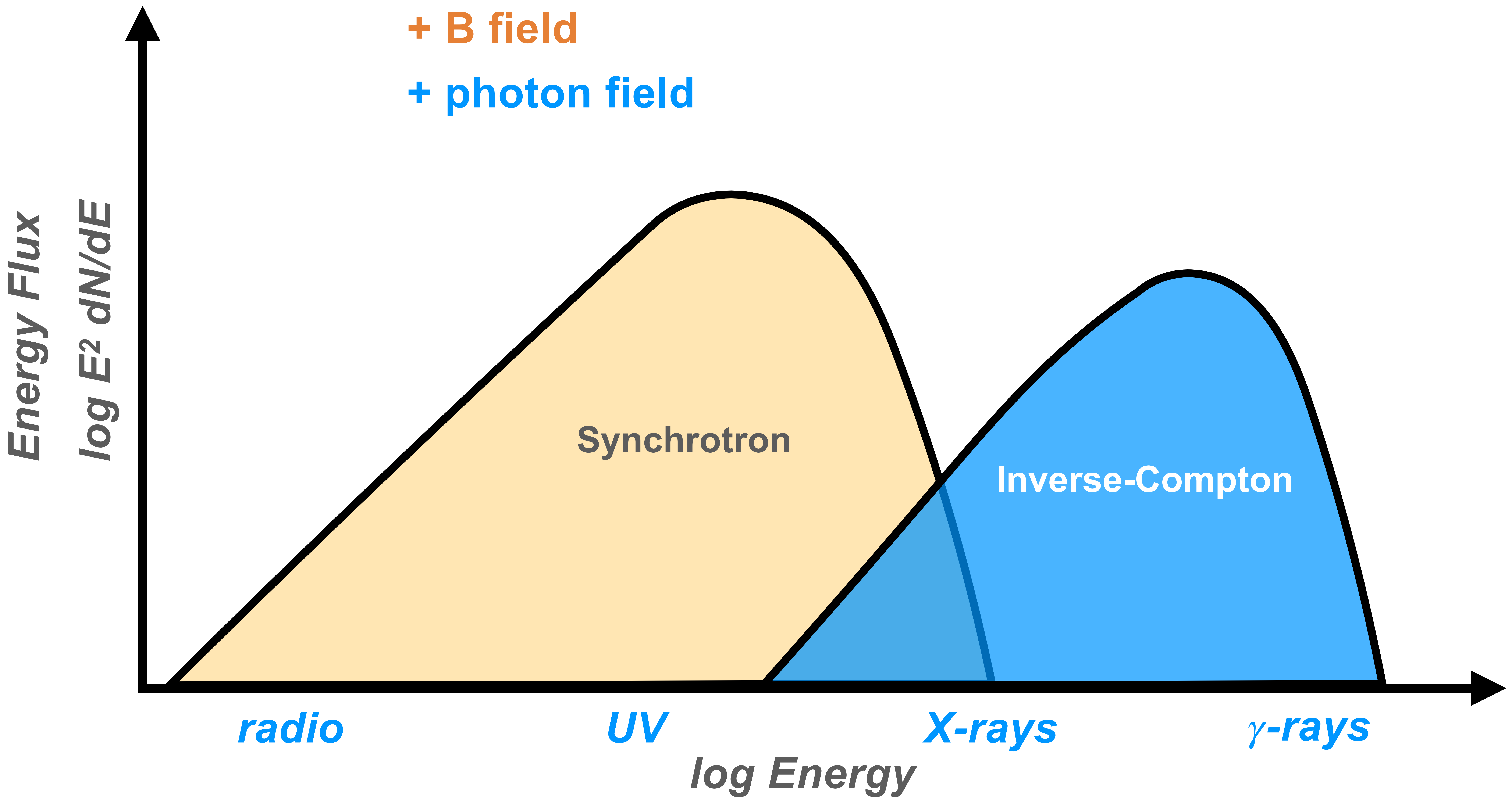

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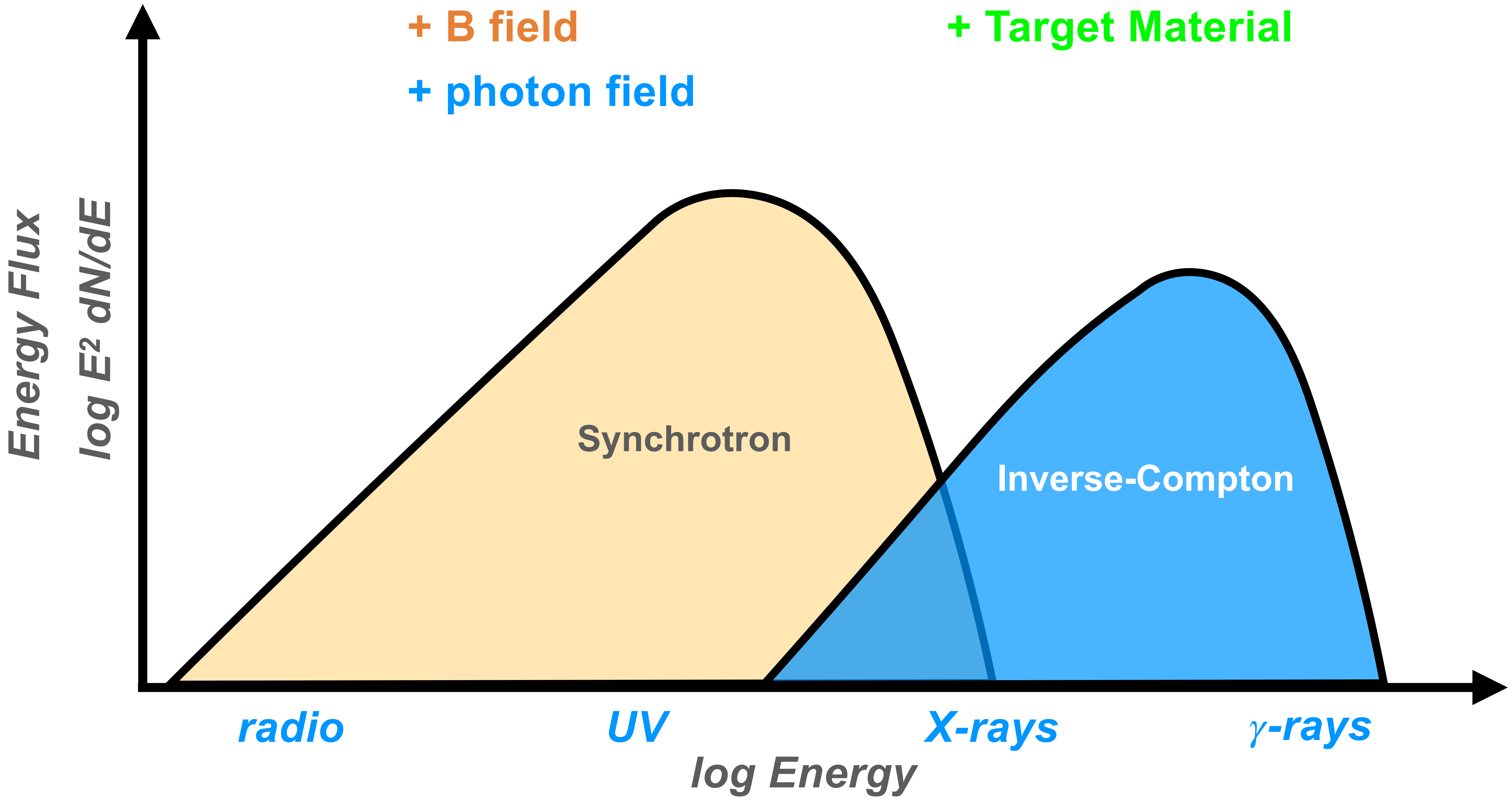

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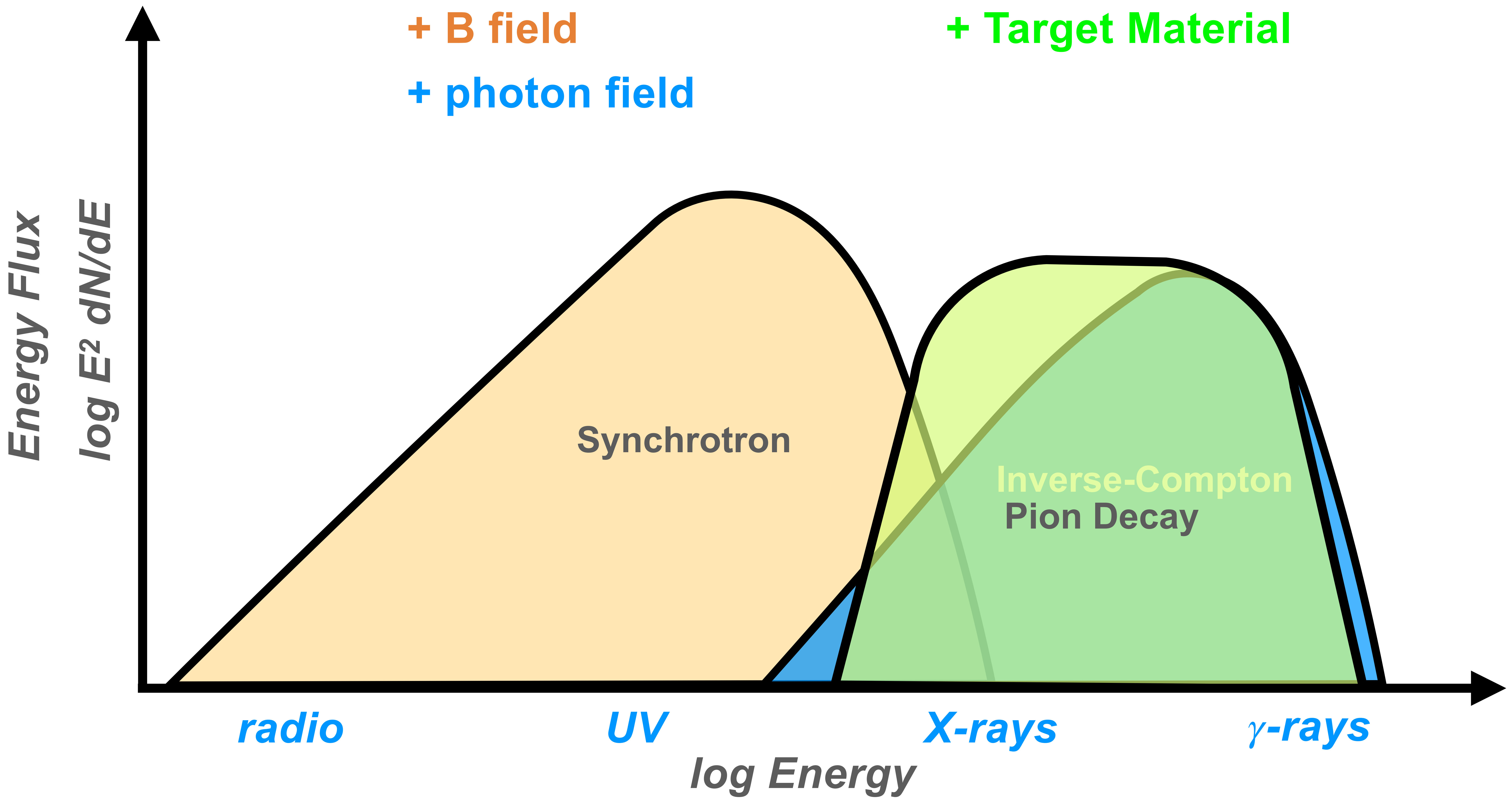

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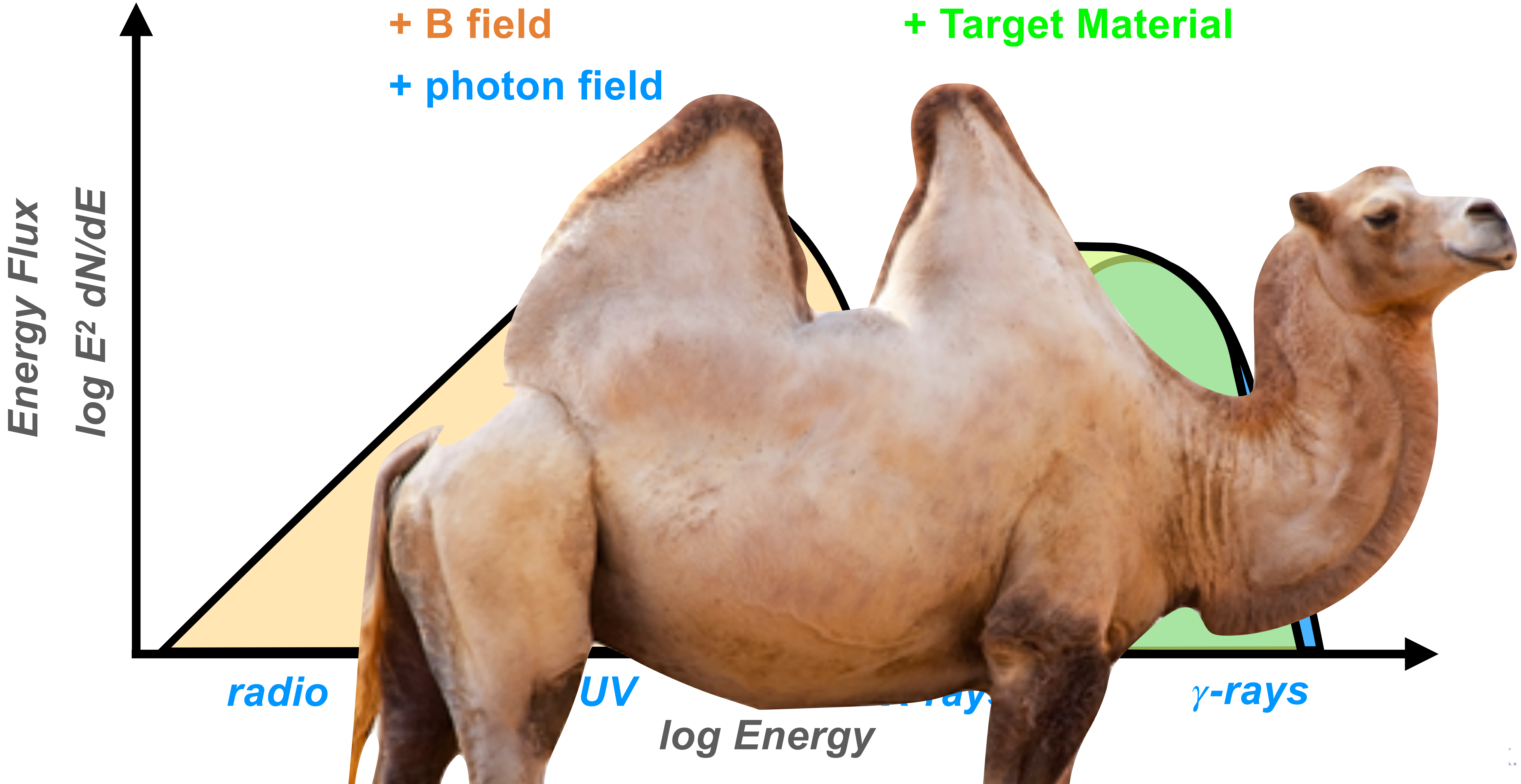

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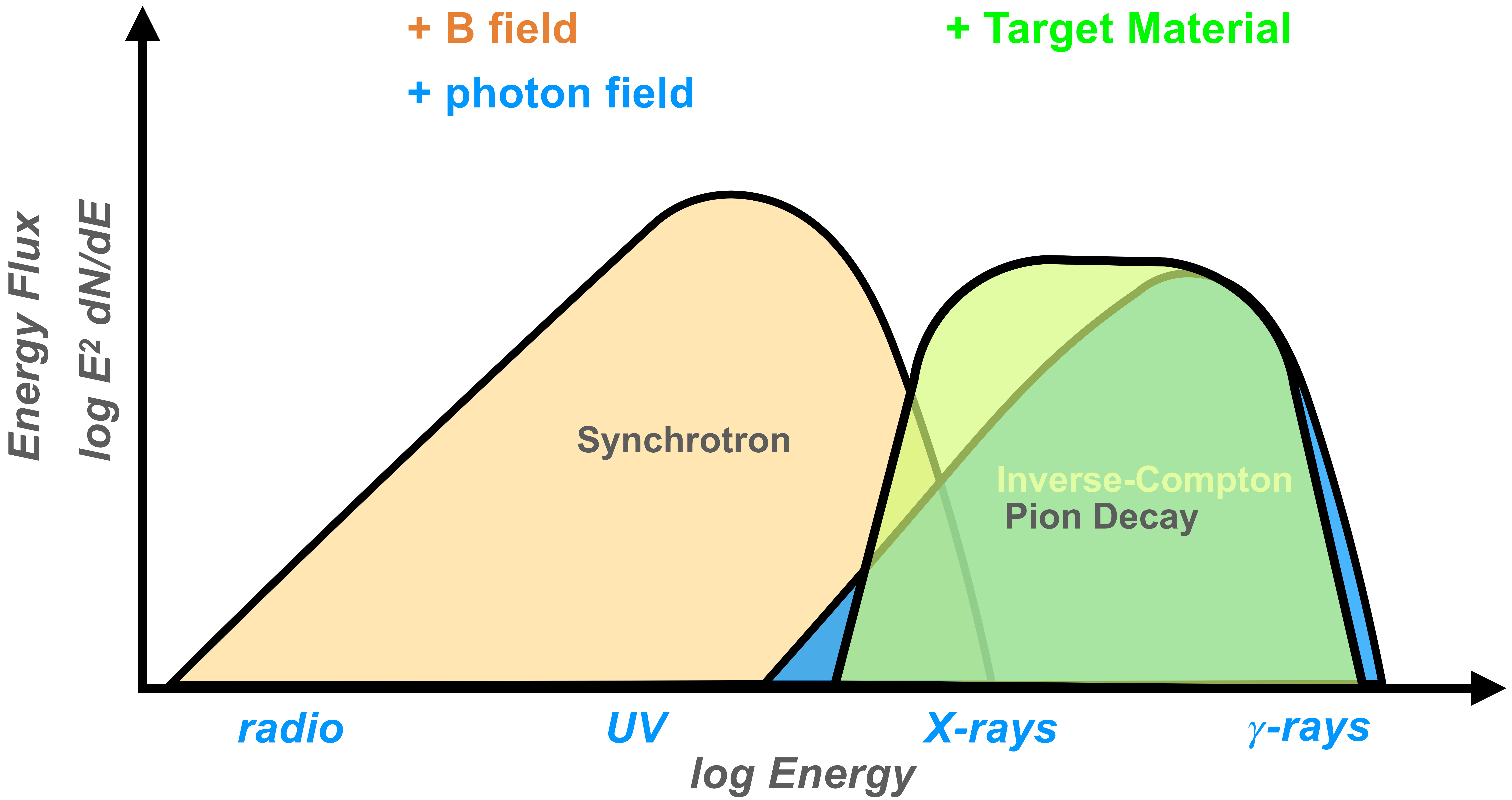

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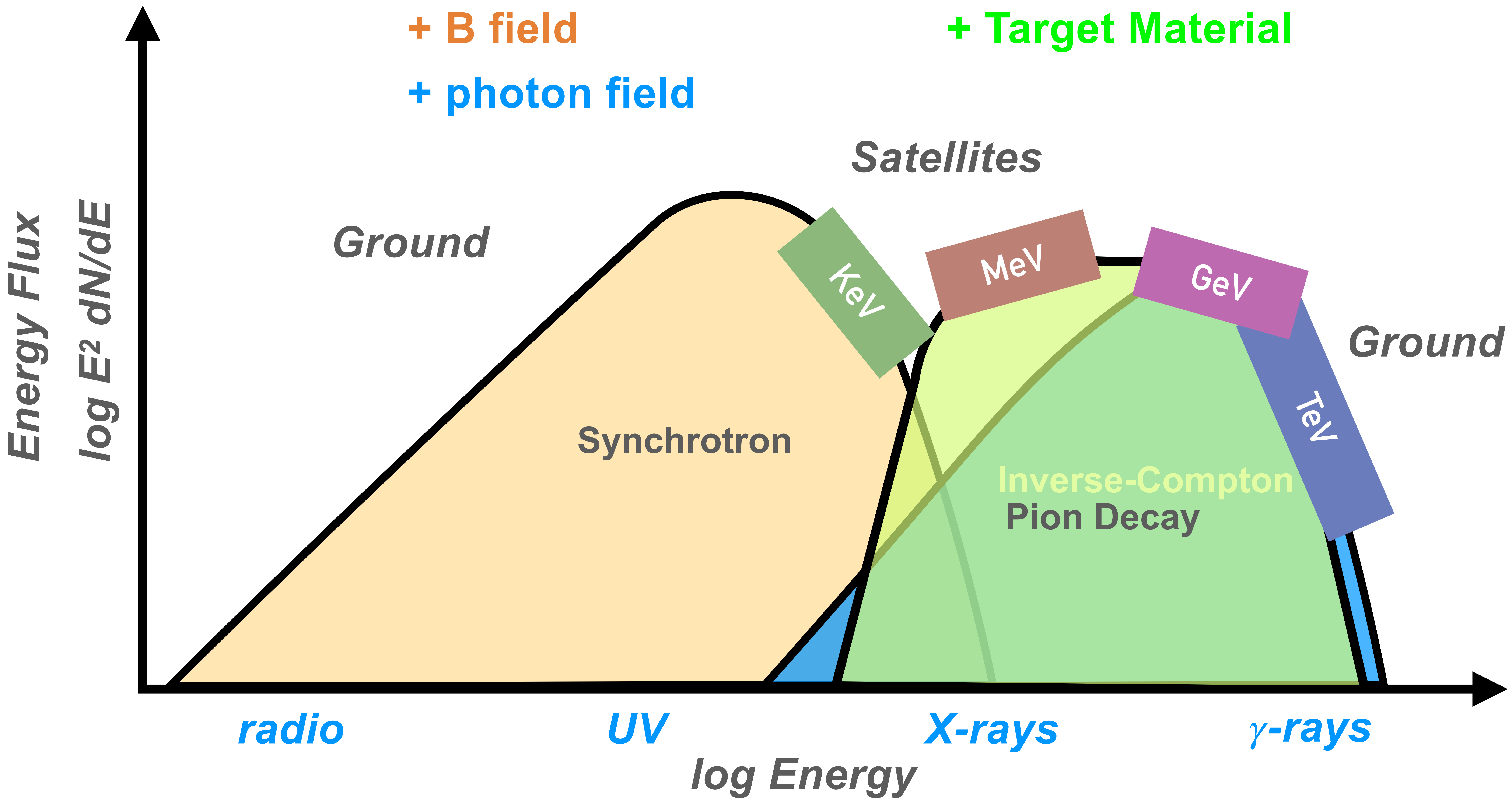
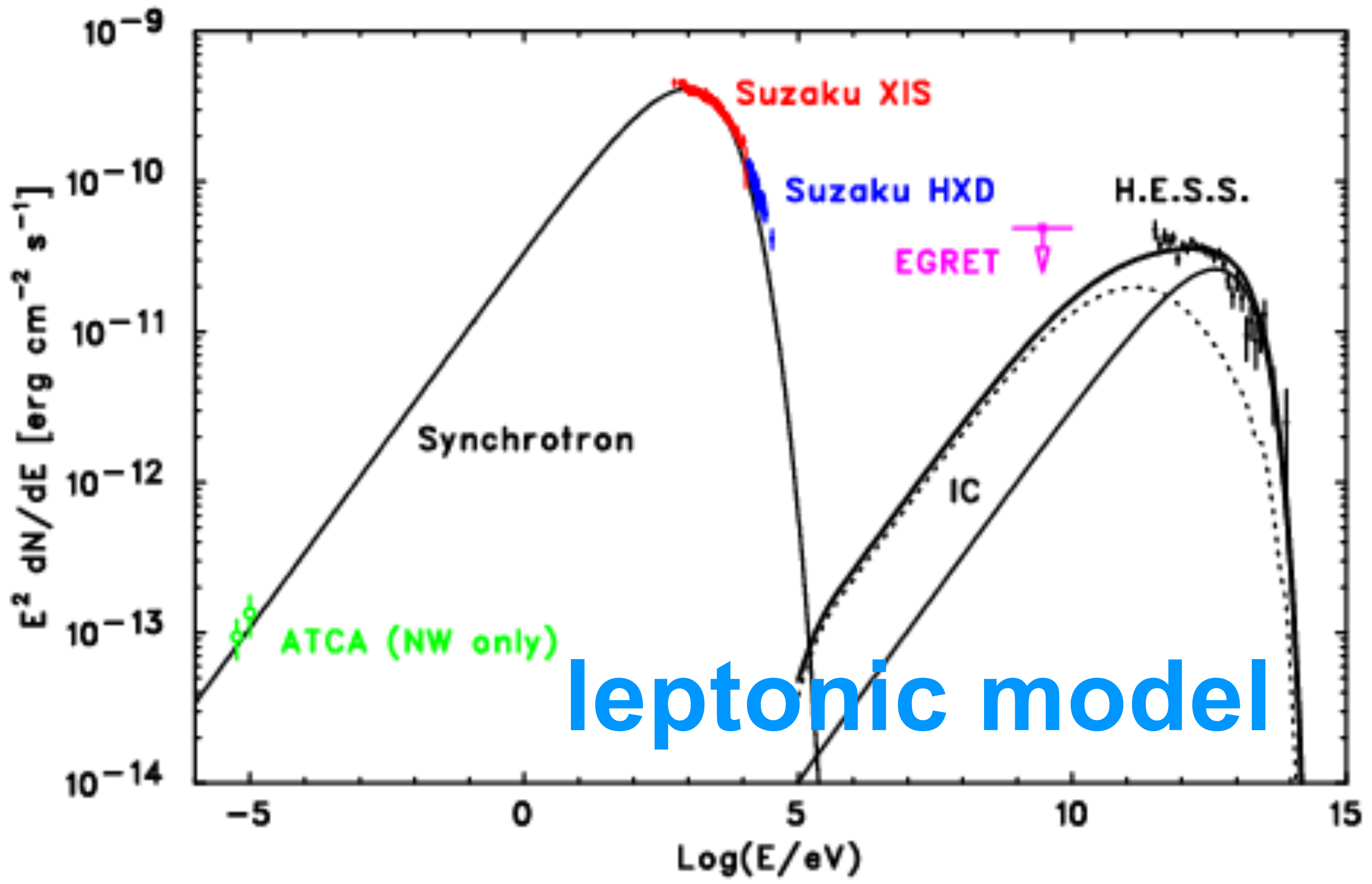


Non-Thermal Emission

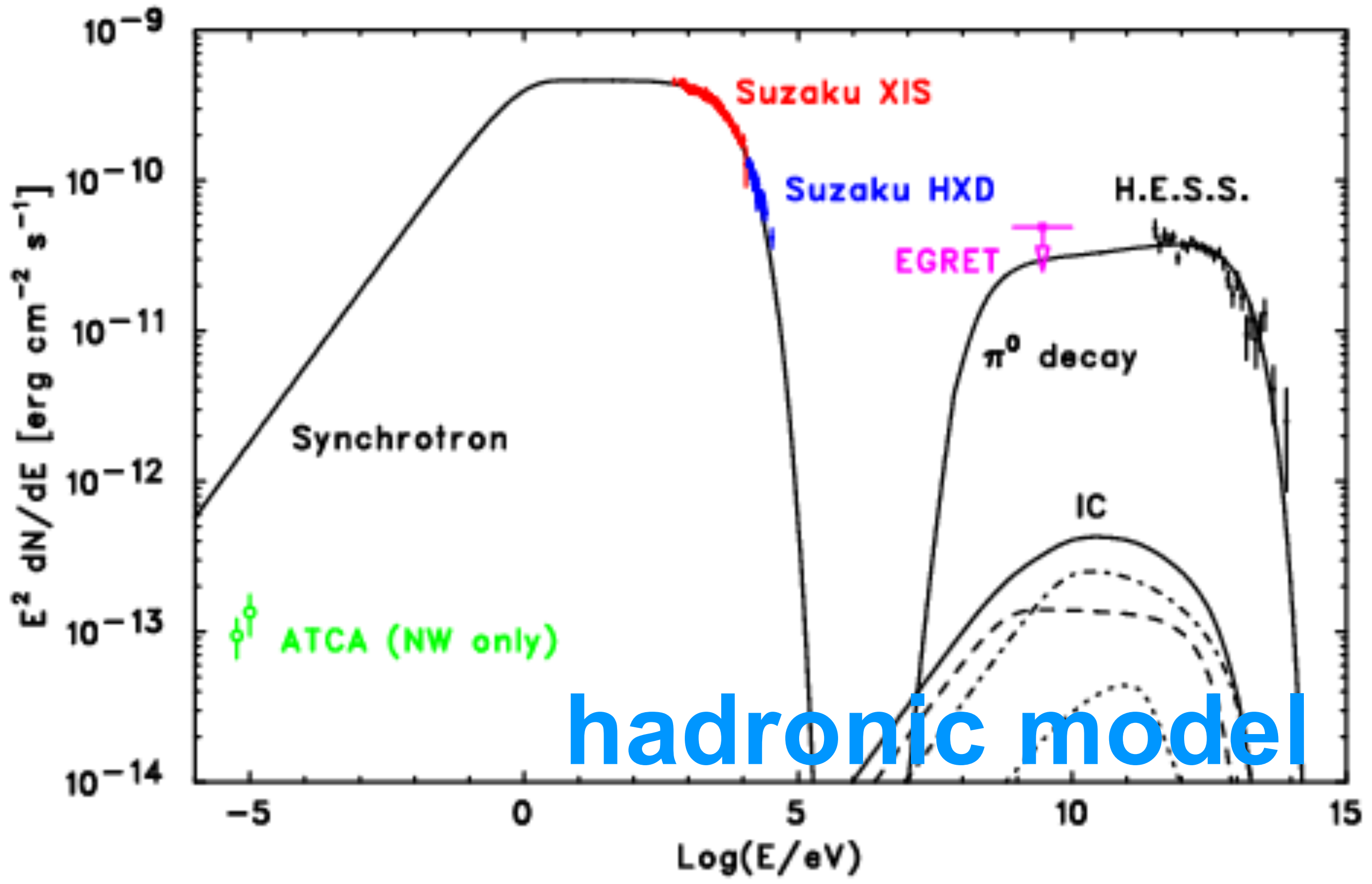
Some real examples

RX J1713.7-3946
(Supernova Remnant)

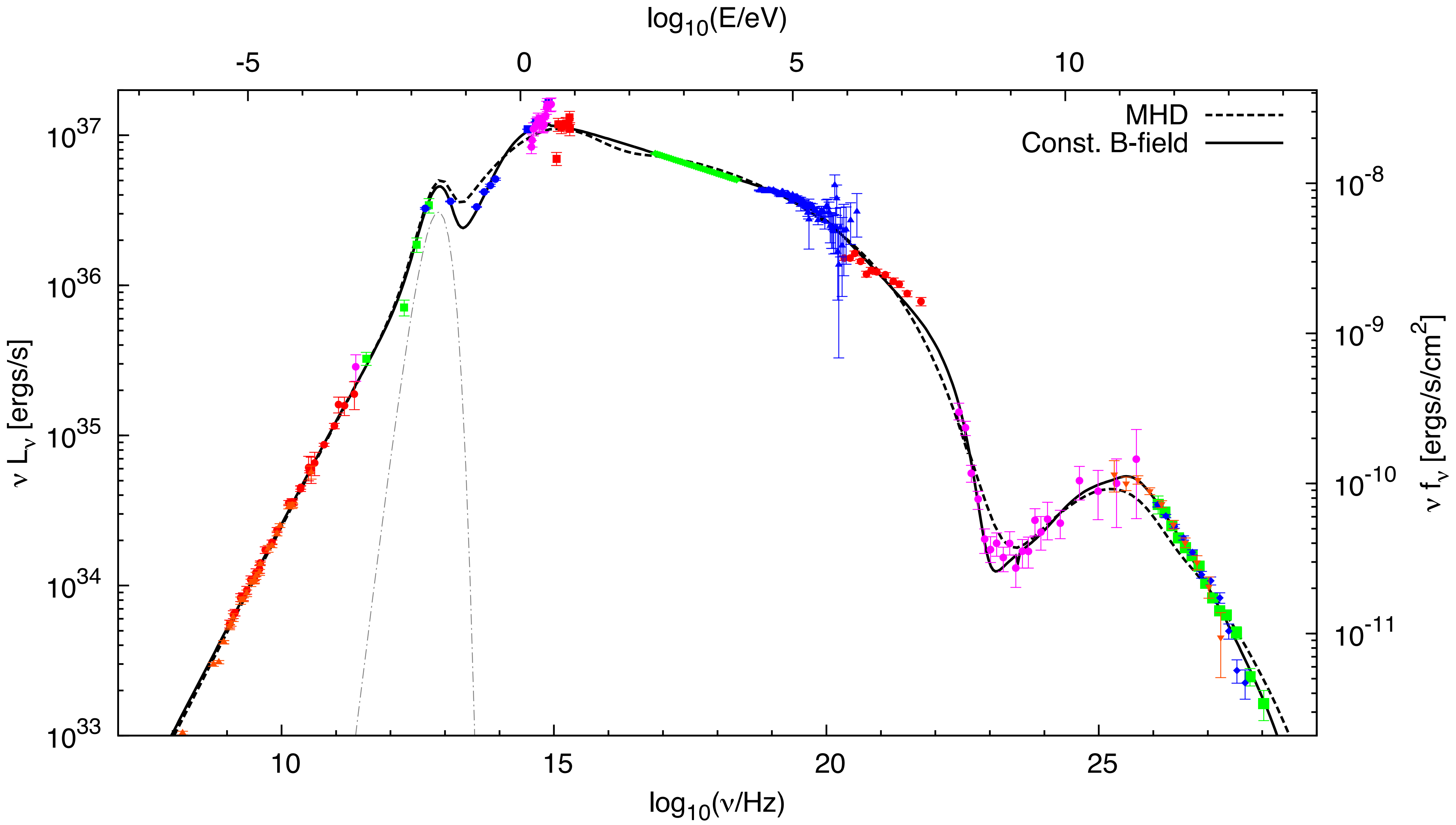
Crab Nebula
(Pulsar Wind Nebula)



leptonic model

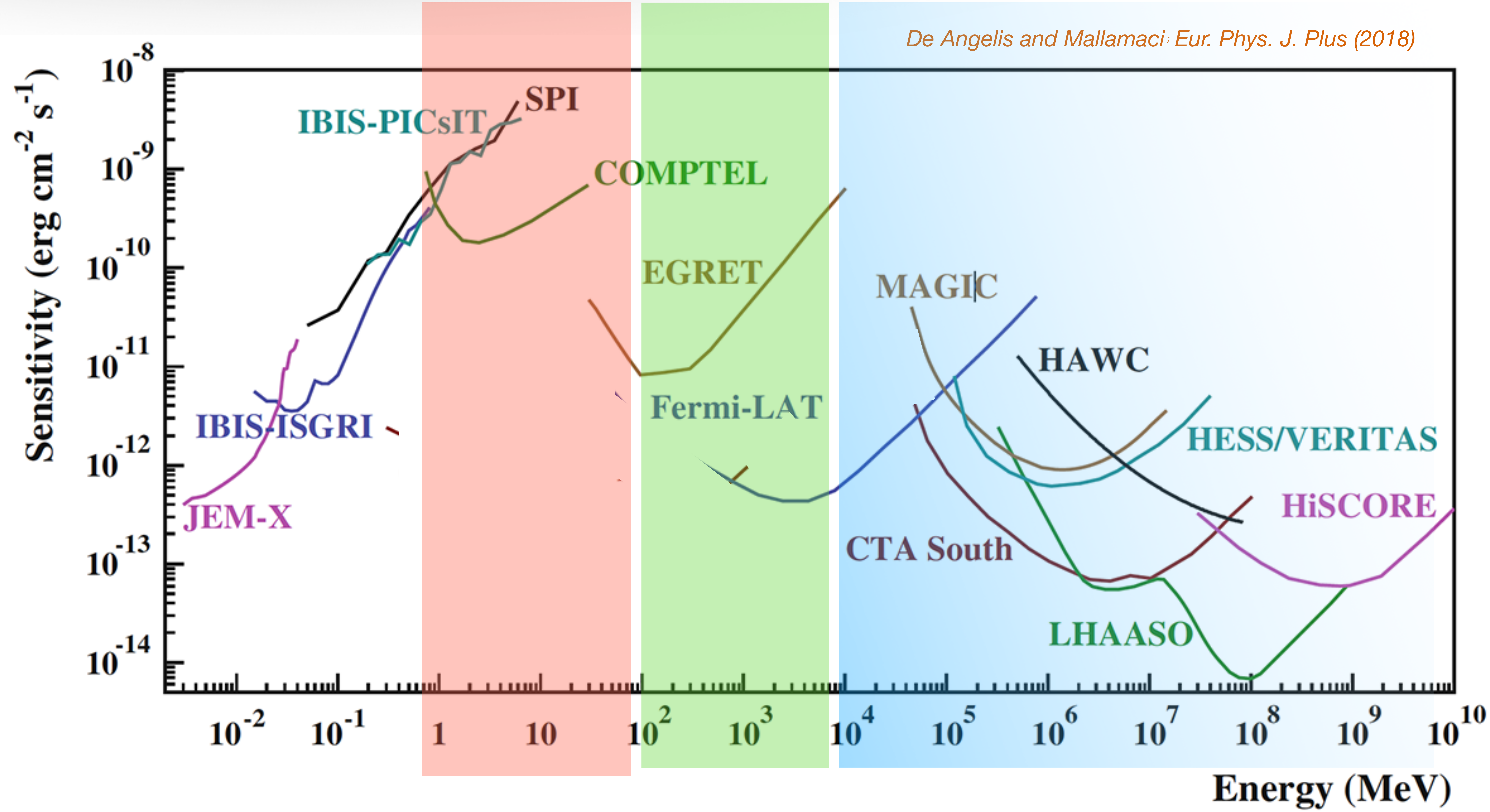


hadronic model

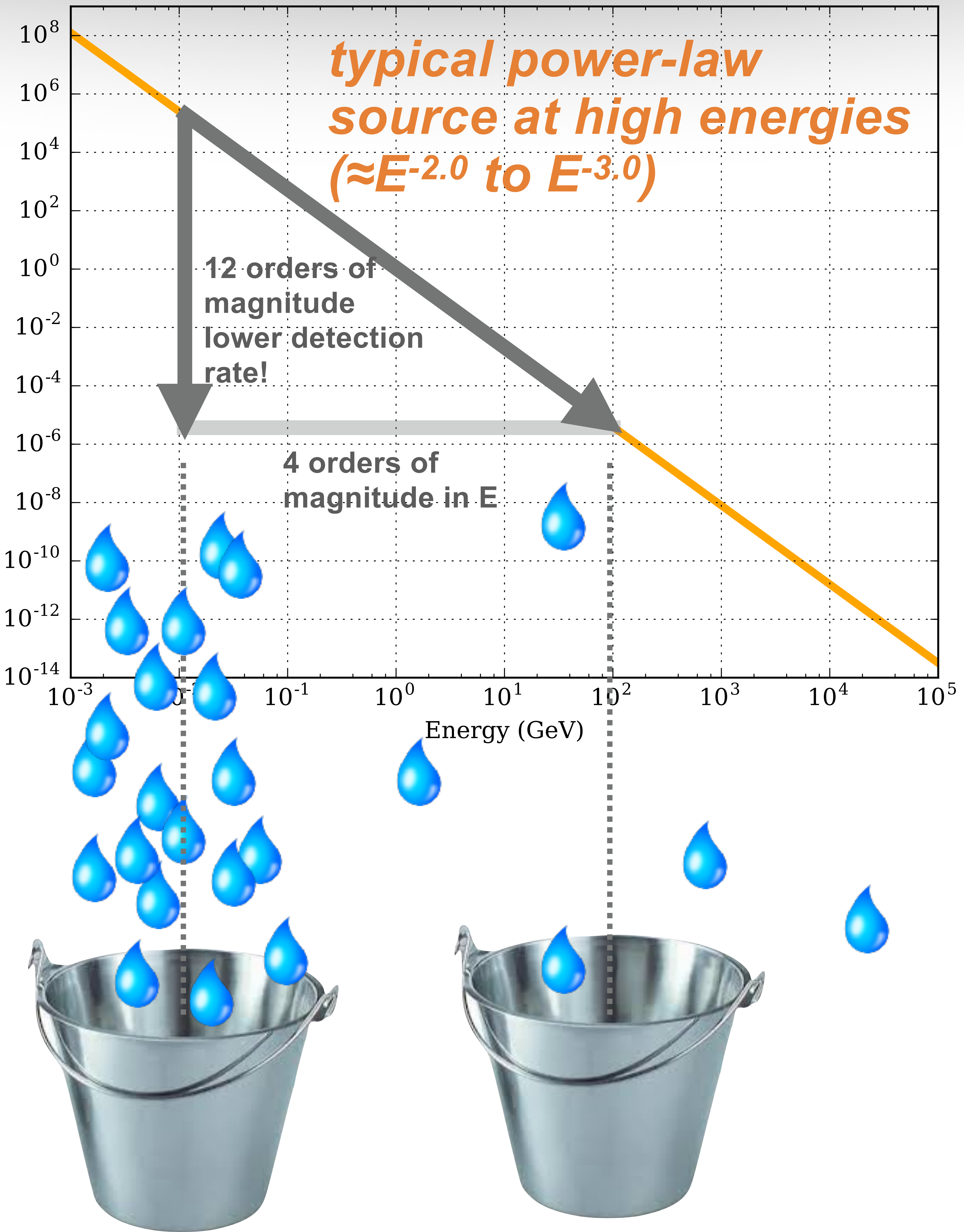


Mayer+ (http://dx.doi.org/10.1051/0004-6361/201014108)
Tanaka+ (http://dx.doi.org/10.1086/591020)

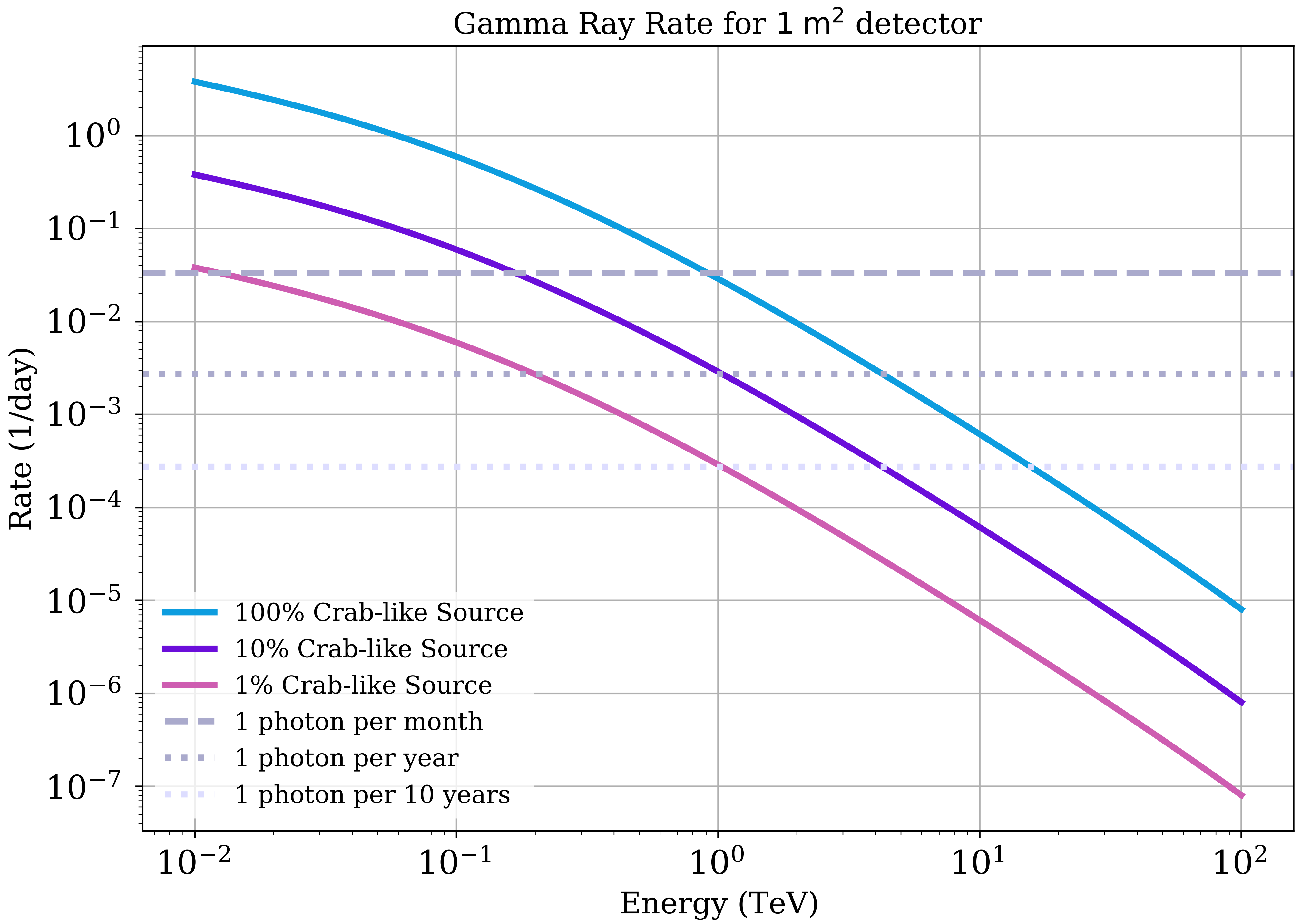
Gamma-ray Instrument Sensitivities



Limiting effect: the spectrum!



- Effective collection area of Fermi-Lat is ≈1 m²



- **beyond a few hundred GeV: want at least 100,000x bigger than Fermi-LAT!**

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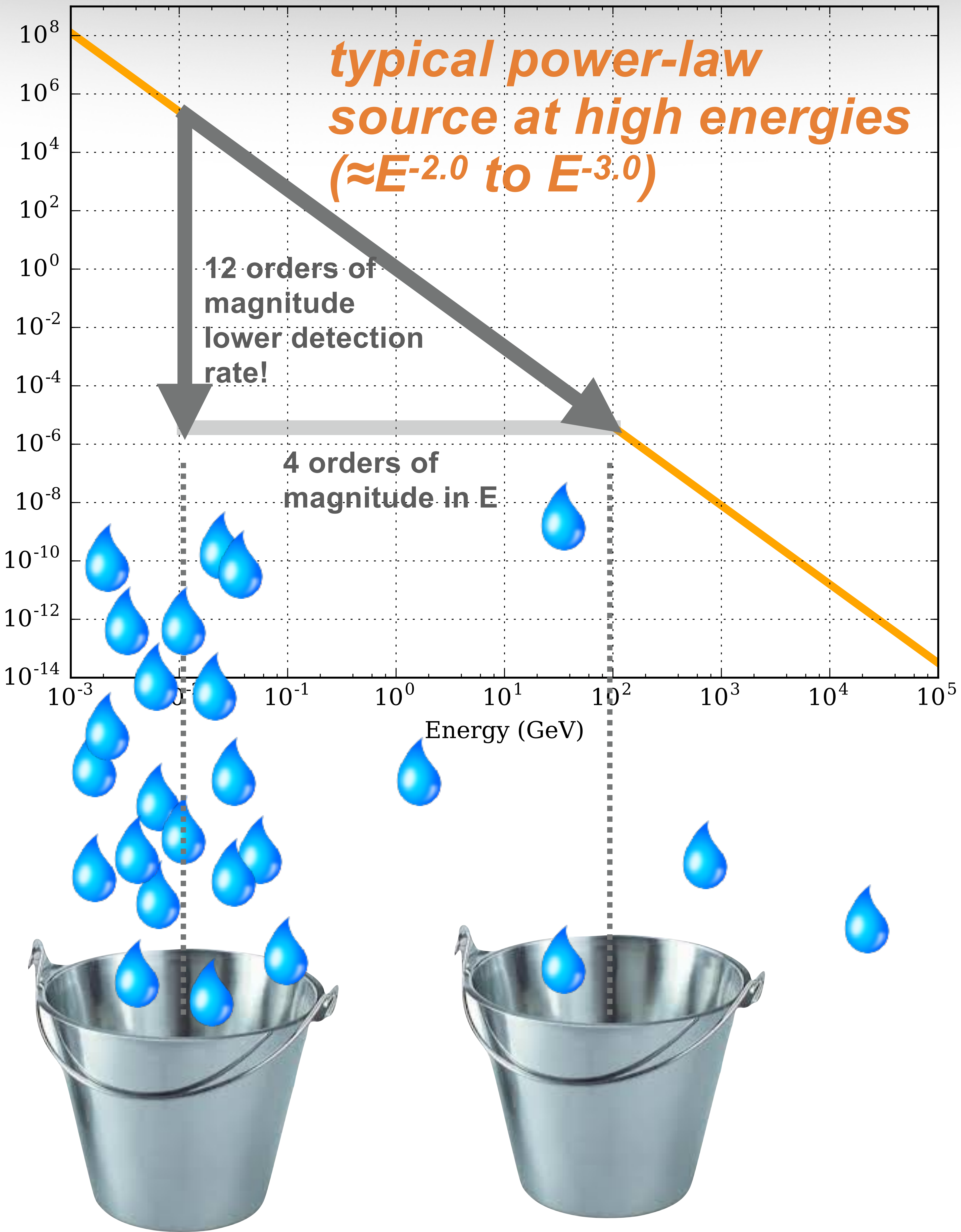

typical power-law source at high energies (≈$E^{-2.0}$ to $E^{-3.0}$)

12 orders of magnitude lower detection rate!

4 orders of magnitude in E

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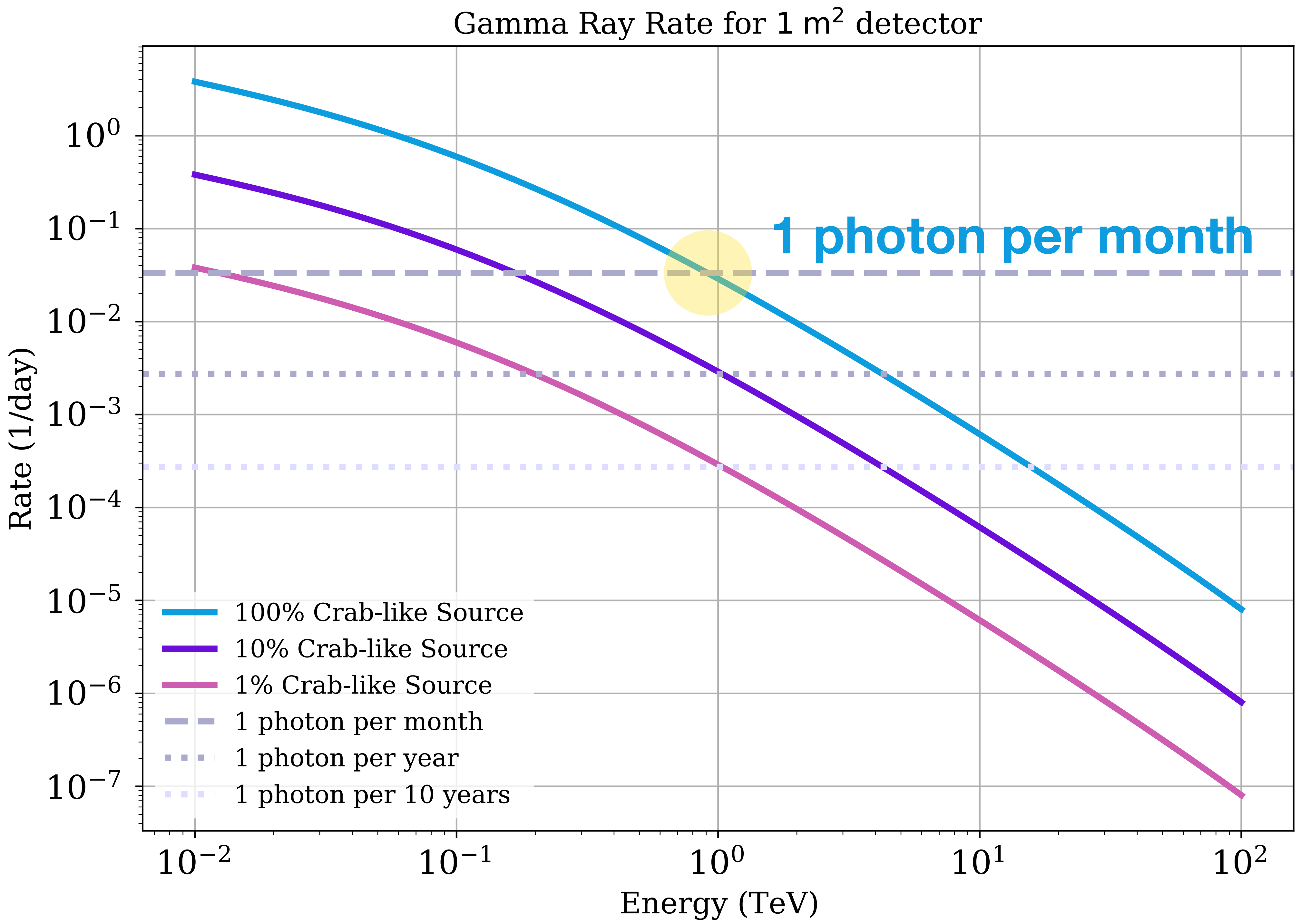
Gamma Ray Rate for 1 m² detector

1 photon per month

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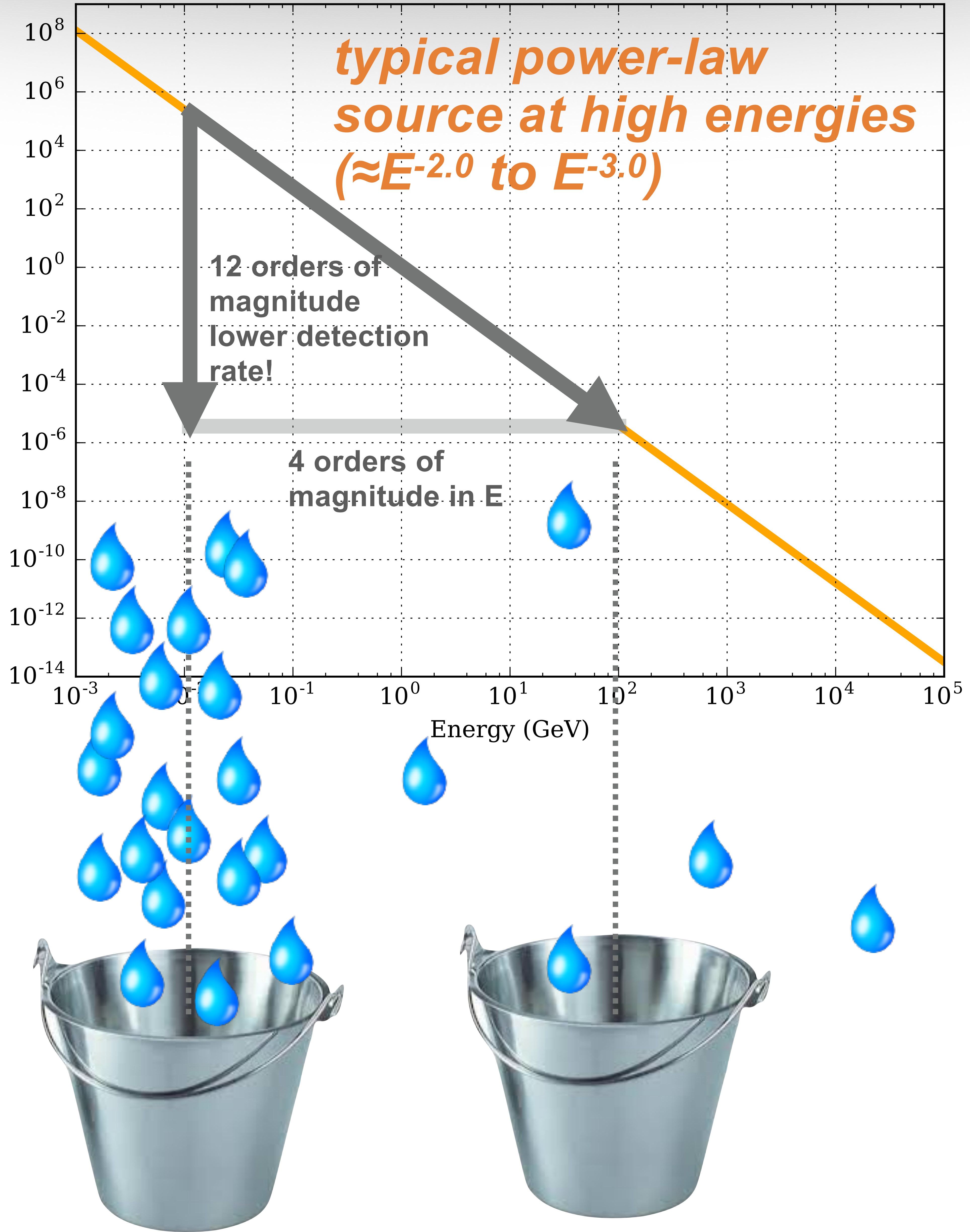

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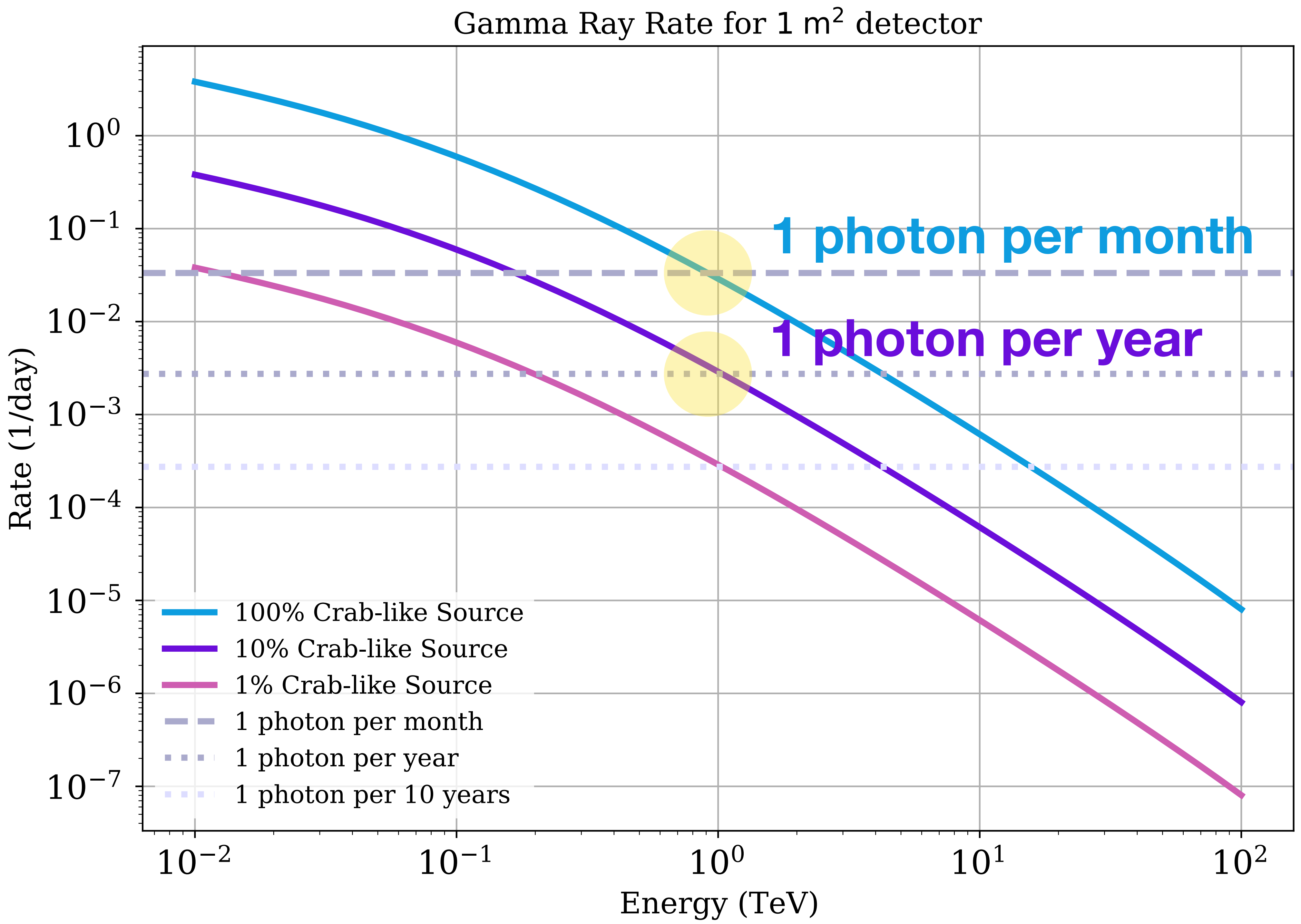
Gamma Ray Rate for 1 m^2 detector

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1 photon per year

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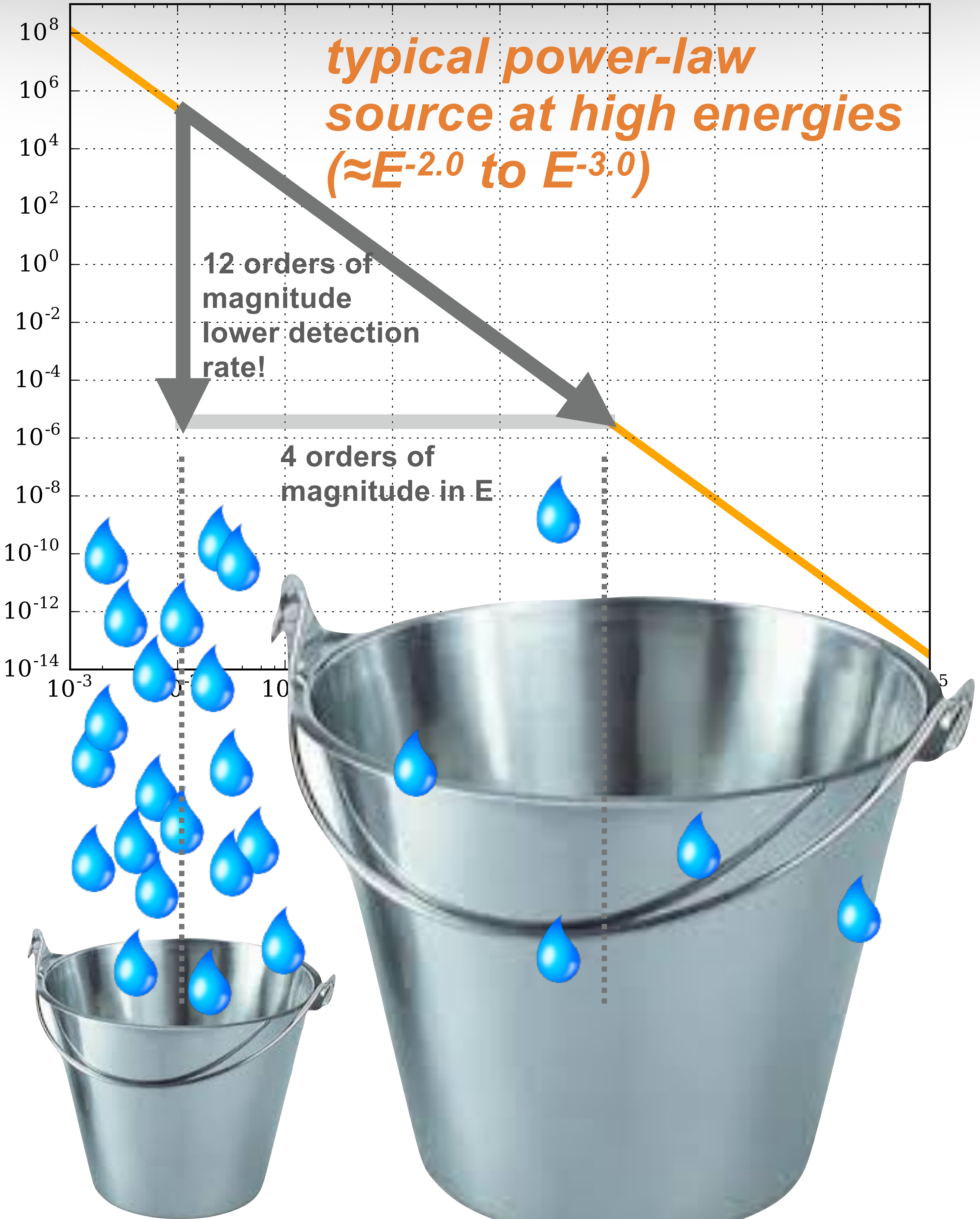

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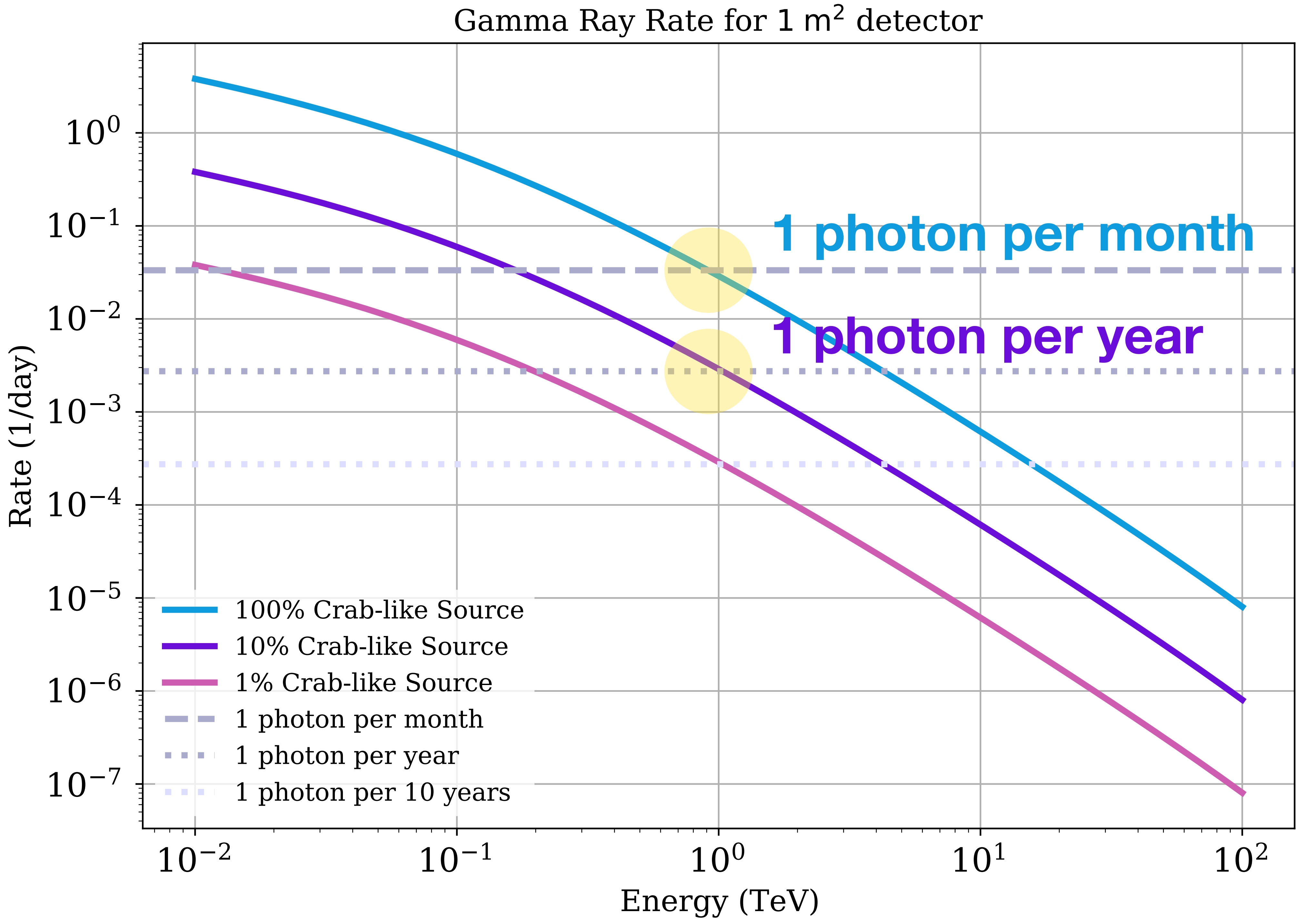

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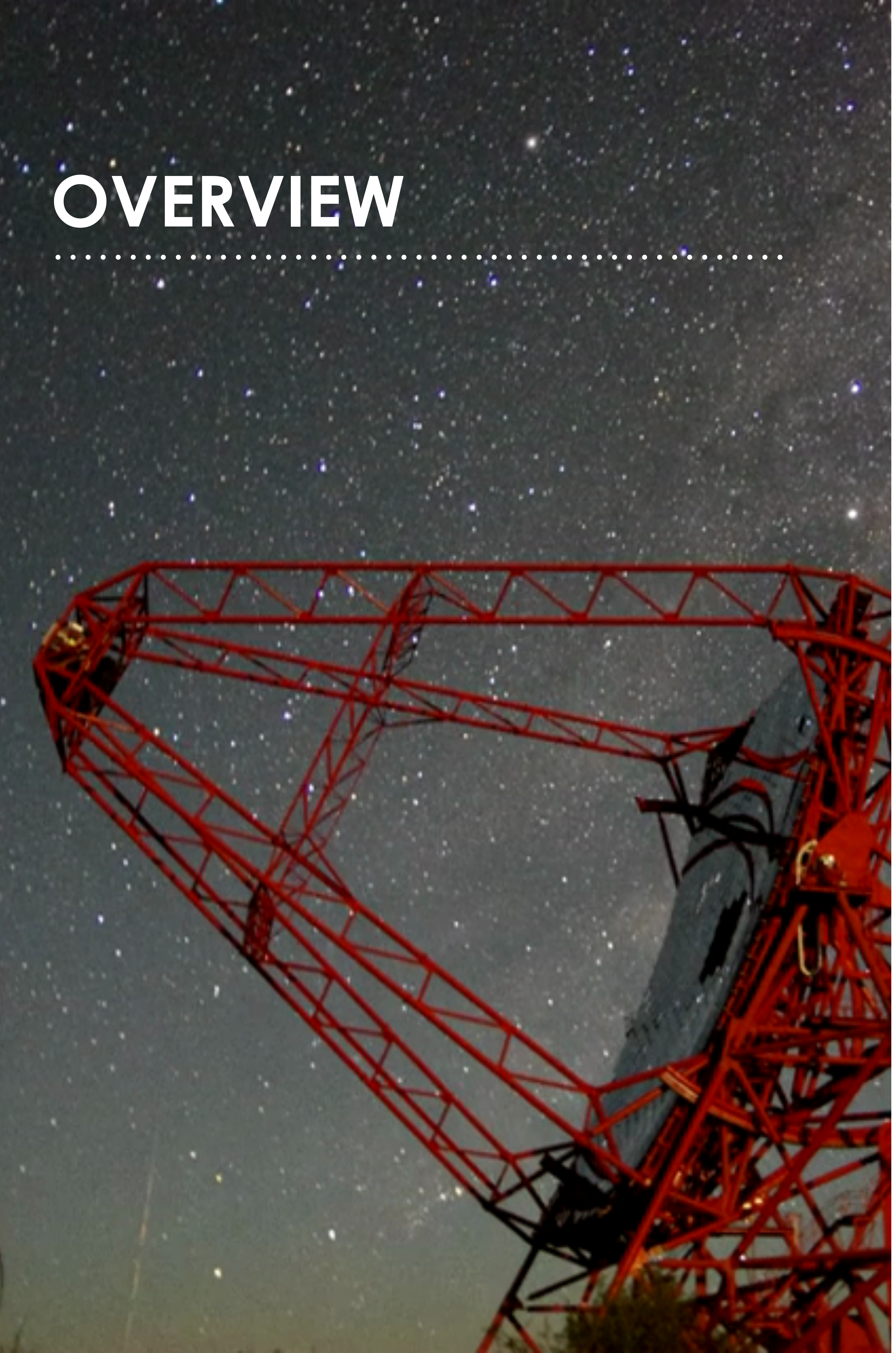
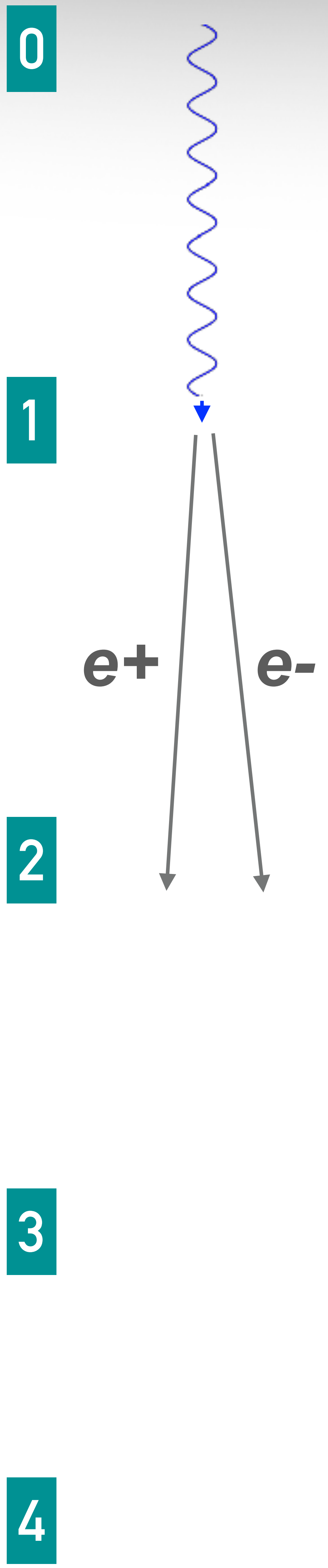


OVERVIEW

- VHE Gamma Rays
- Gamma-ray Interactions in the Atmosphere
- Imaging Atmospheric Cherenkov Telescopes
- Water Cherenkov Telescopes
- Science with VHE Gamma rays

Pair production → Shower



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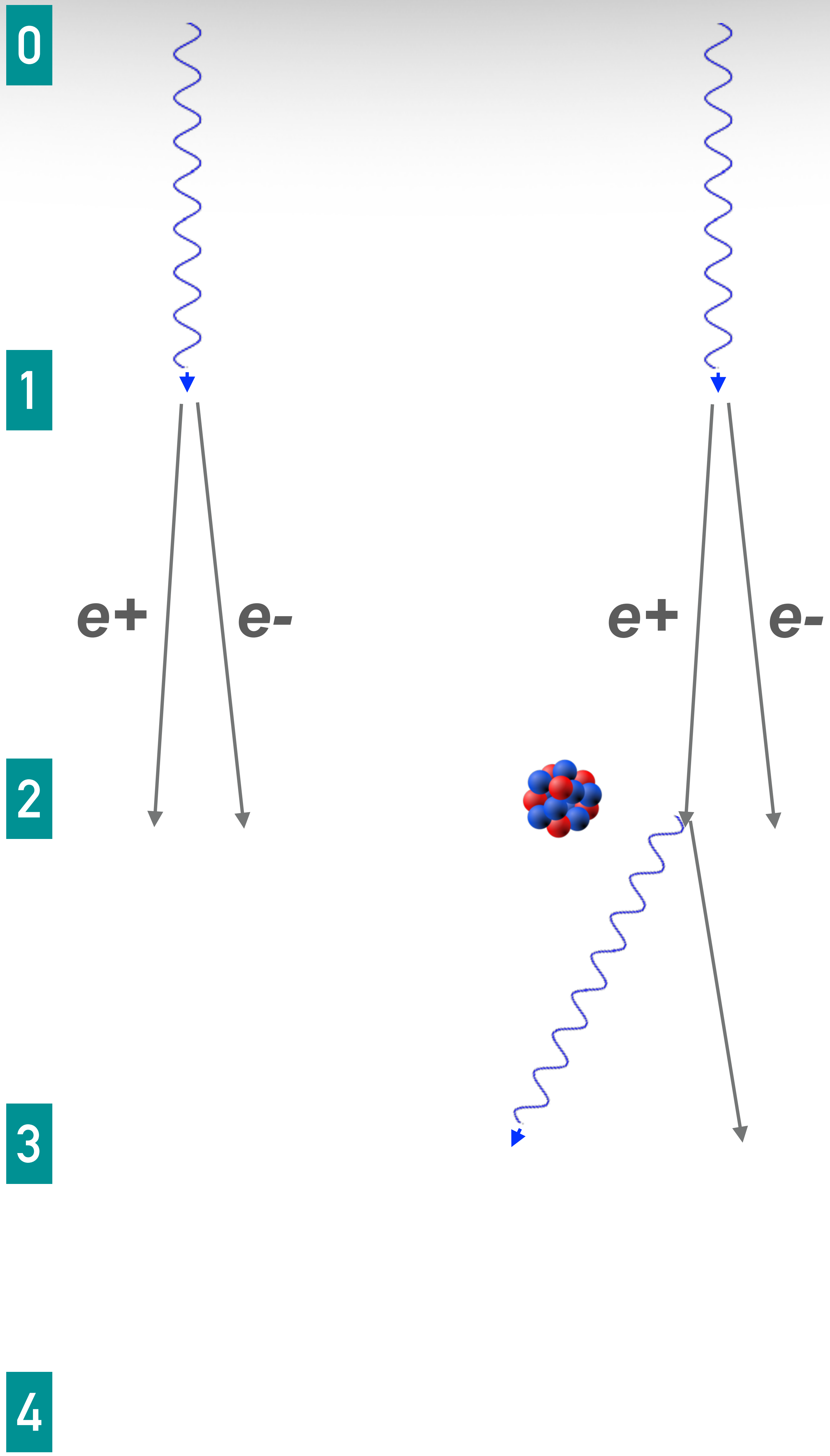

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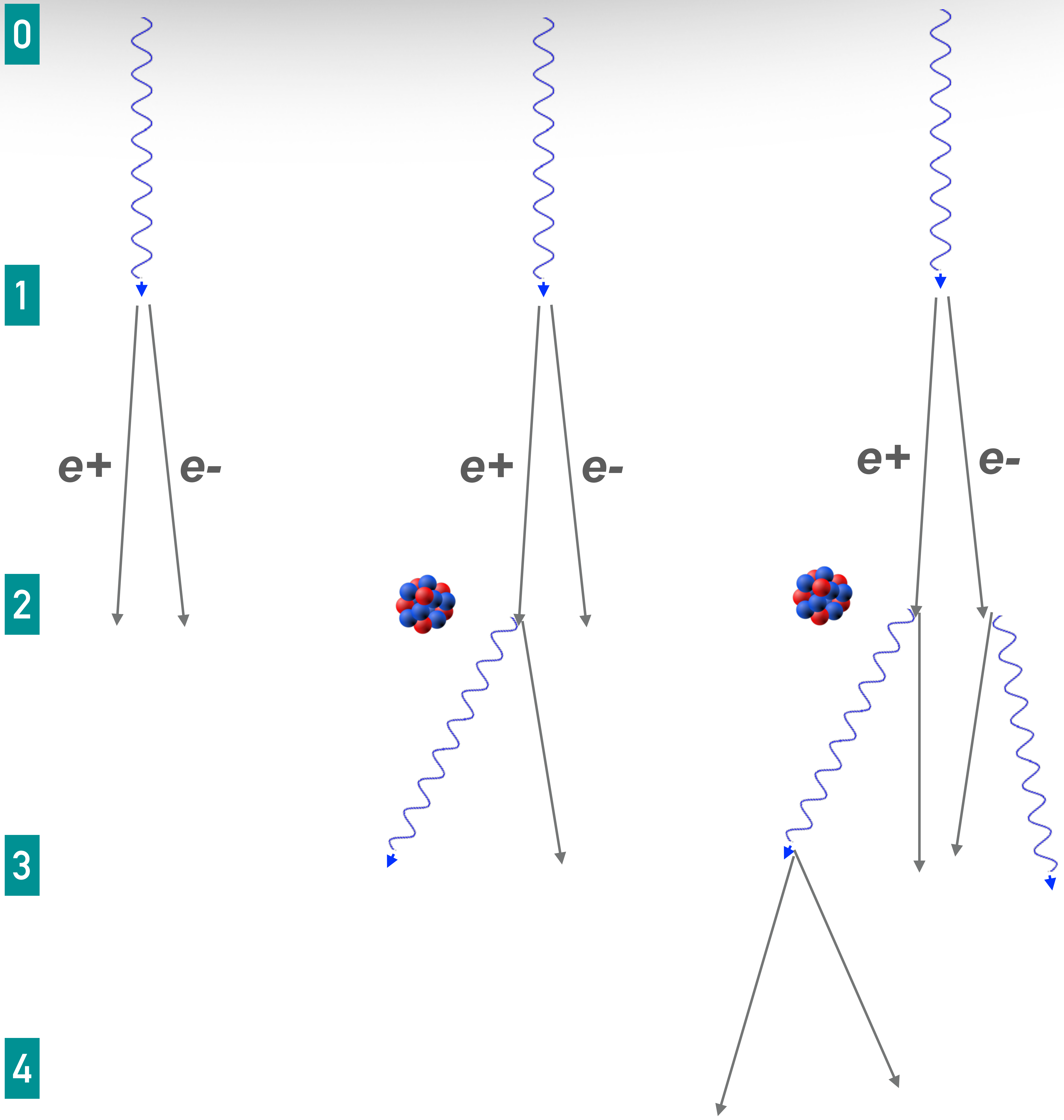

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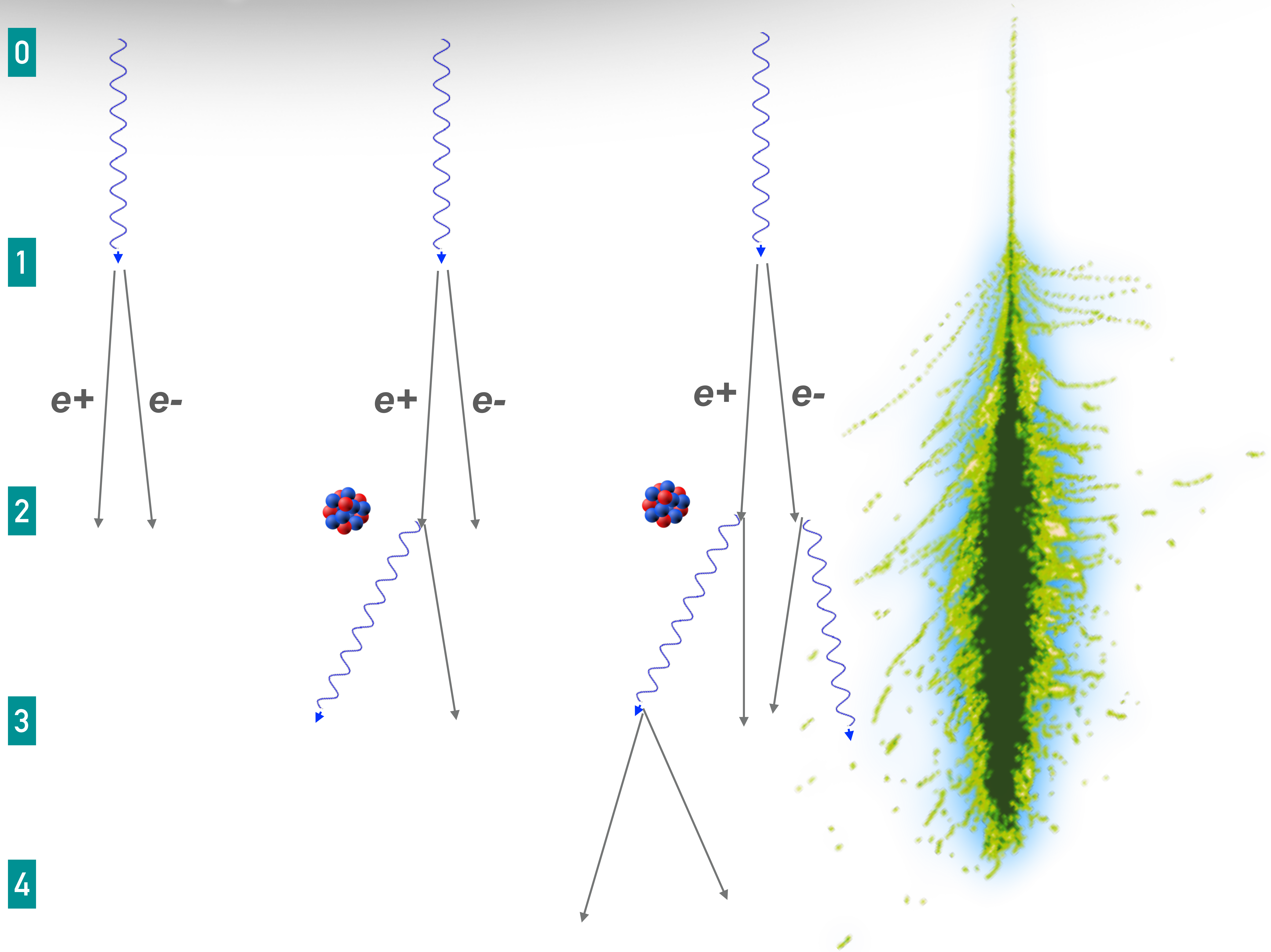

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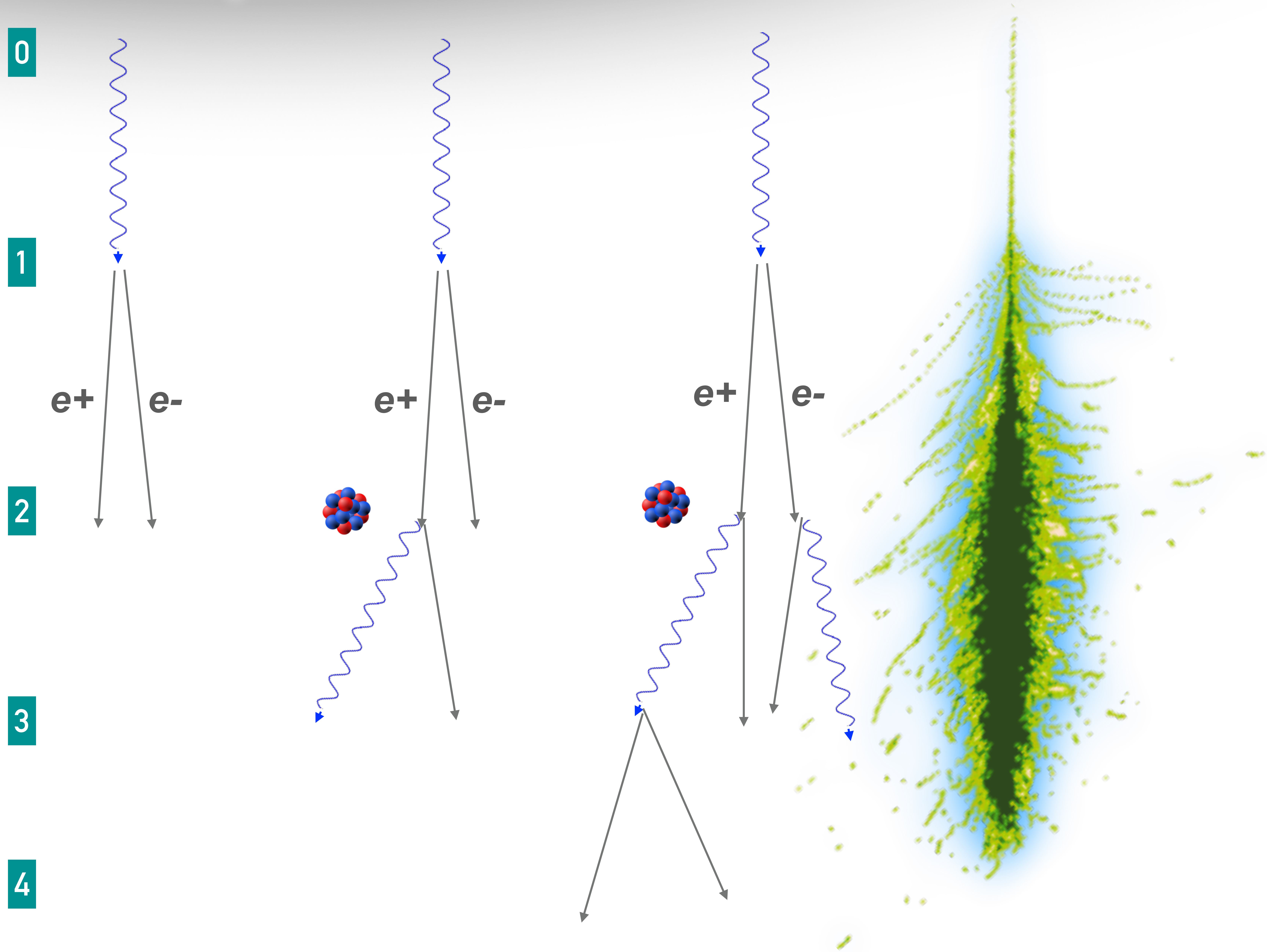
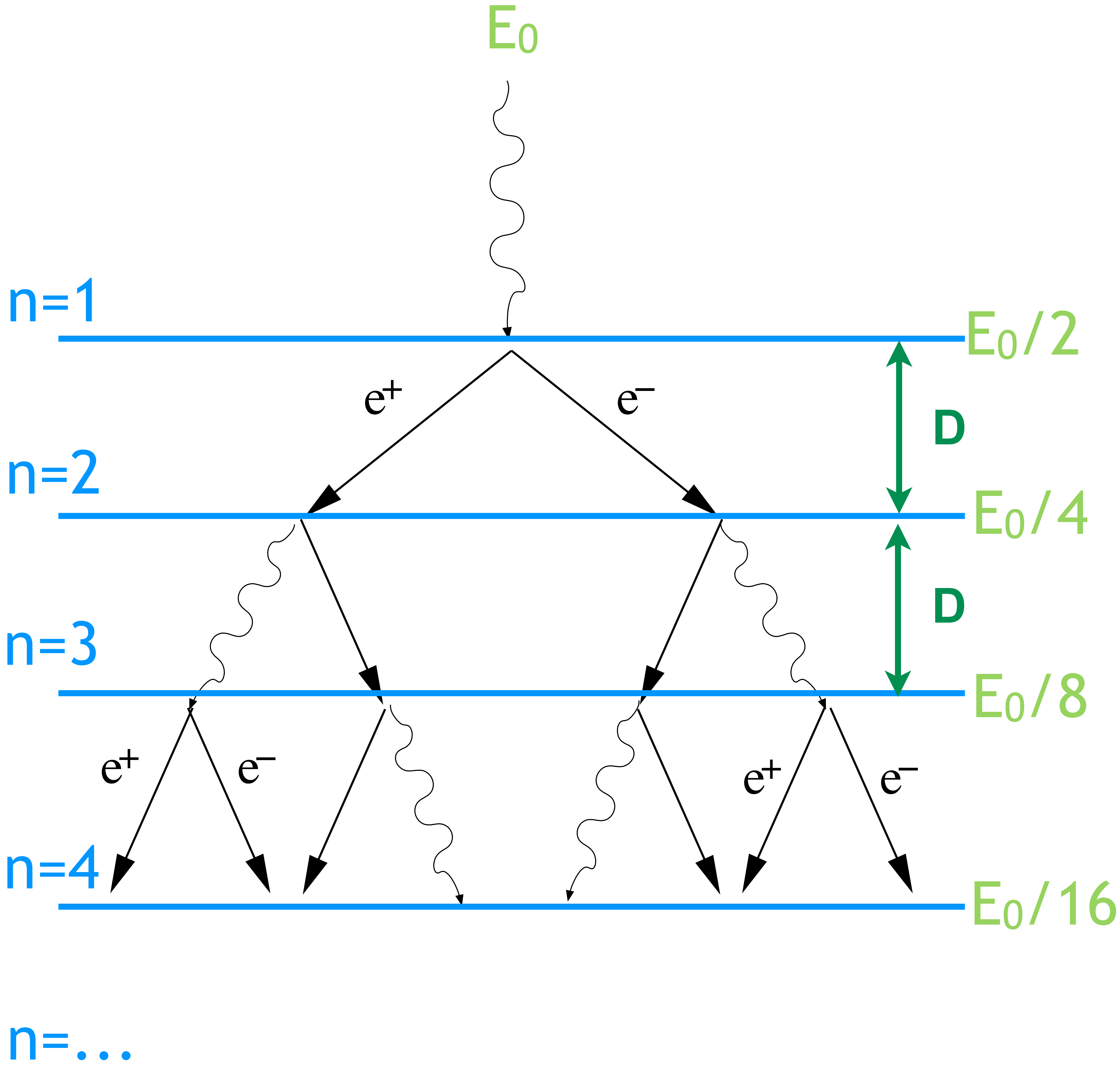


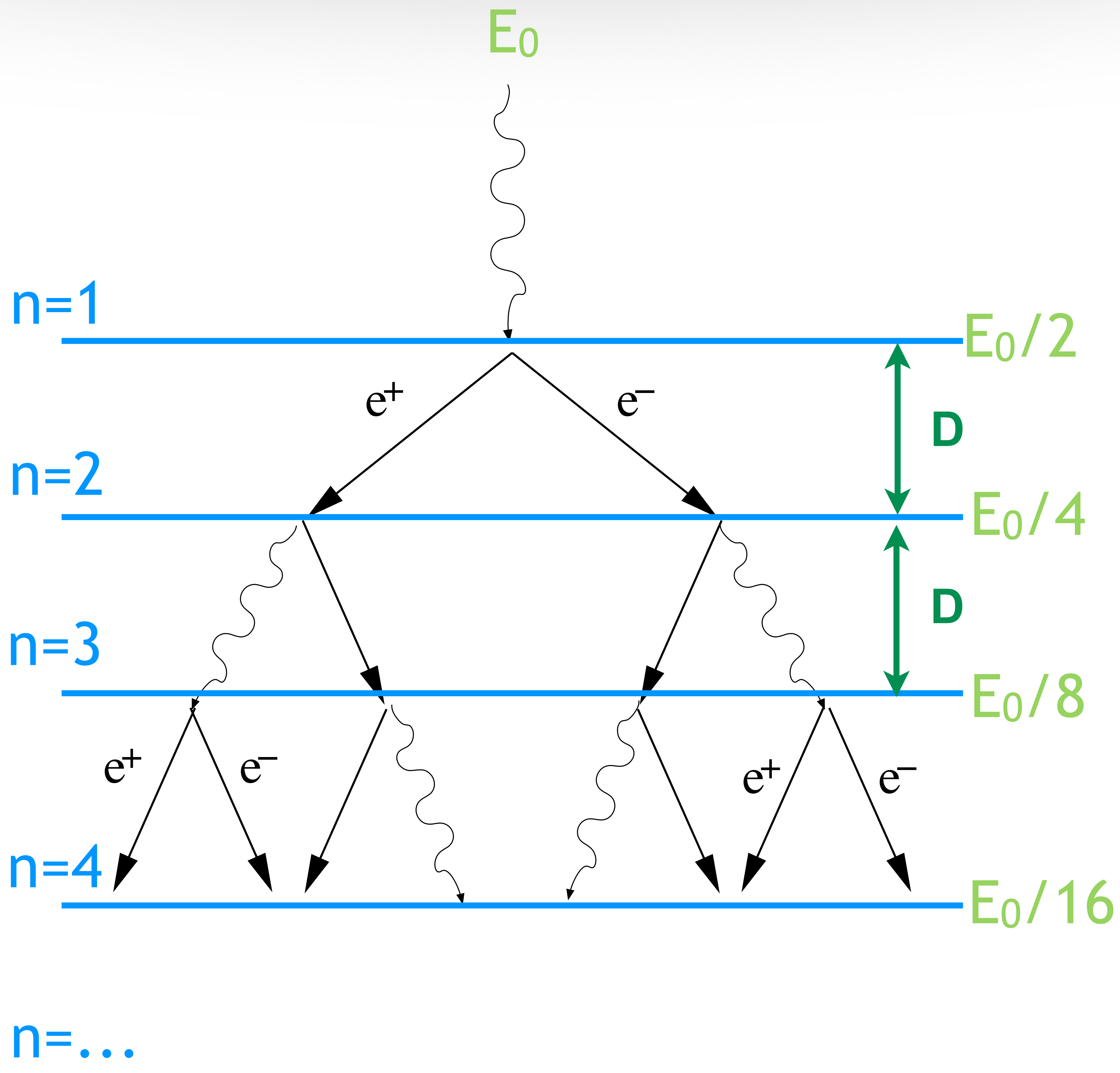
- With enough distance into a medium (1 interaction length), the secondaries will emit Bremsstrahlung radiation when they encounter a nucleus
- If high enough energy, the Bremsstrahlung photon can pair-produce
- and so on…

This becomes an electromagnetic *shower*

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


E_0
n=1
$E_0/2$
e^+
e^-
D
n=2
$E_0/4$
D
n=3
$E_0/8$
e^+
e^-
e^+
e^-
n=4
$E_0/16$
n=...

Simplistic Model:

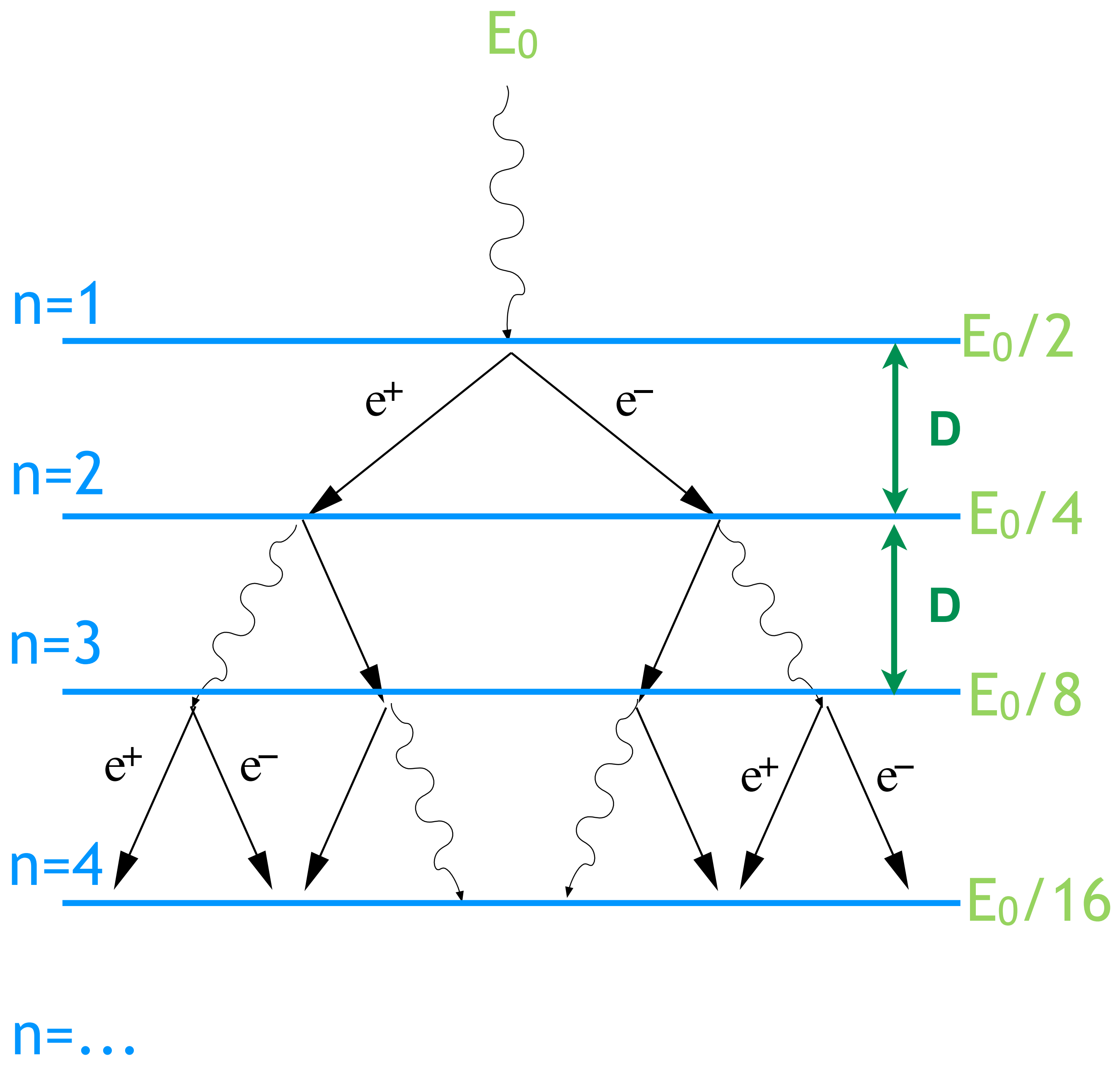


Assumptions:

- Atmosphere is purely exponential $\rho(h) = \rho_0 e^{-h/h_0}$
- Energy loss only via pair-production and bremsstrahlung
  - ➤ each interaction is a single splitting
  - ➤ Energy shared equally
- The radiation length and interaction length are equal: λ_r
- The critical energy E_{crit} equal for pair production and bremsstrahlung
- Below this energy, shower stops abruptly

Heitler, W. (1936). The quantum theory of radiation, volume 5 of Inter- national Series of Monographs on Physics. Oxford University Press, Oxford

Quantities you can estimate from this model



Quantities:

- **Column density**:
$$x(h) \equiv \int_{\infty}^{h} \rho(h')dh' = \rho_0 h_0 e^{-h/h_0}$$
- **Splitting depth**: $D = \lambda_r ln(2)$
- **Total particles** $N = 2^n$
- **Particle energy** $E = E_0/(2^n)$
- **Depth of shower** at step n:
$$x = n\,D = n\,\lambda\sqrt{2}$$
- At ***shower max***, $E_n = E_{crit}$, so
$$x_{max} = \lambda_r \ln(E_0/E_{crit})$$

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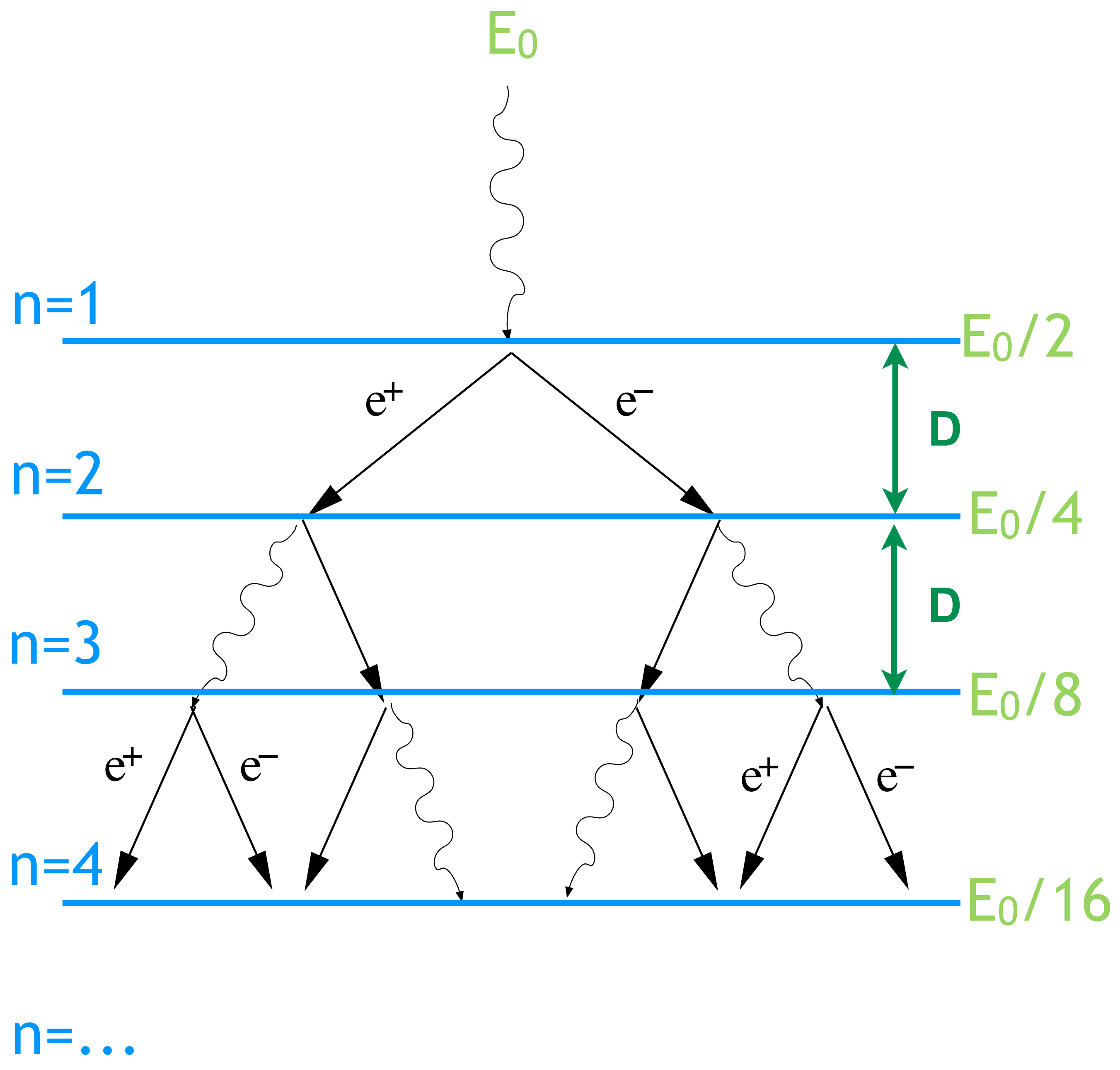

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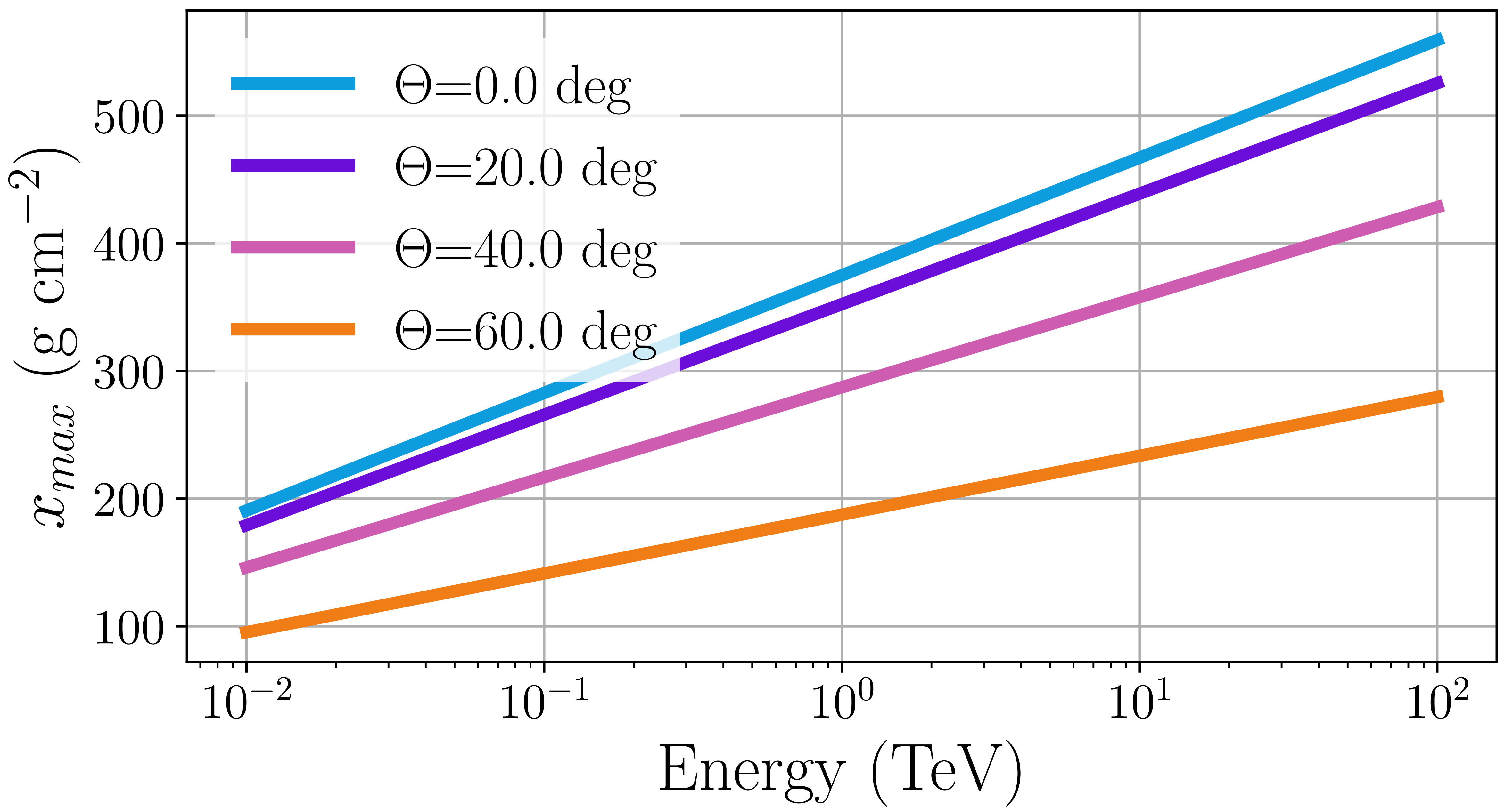
For Earth's Atmosphere:

$\lambda_r = 40 \text{ g cm}^{-2}$
$E_{crit} = 85\,\text{MeV}$
$h_0 = 8\,\text{km}$
$x_{tot} = 1000\,\text{g cm}^{-2}$

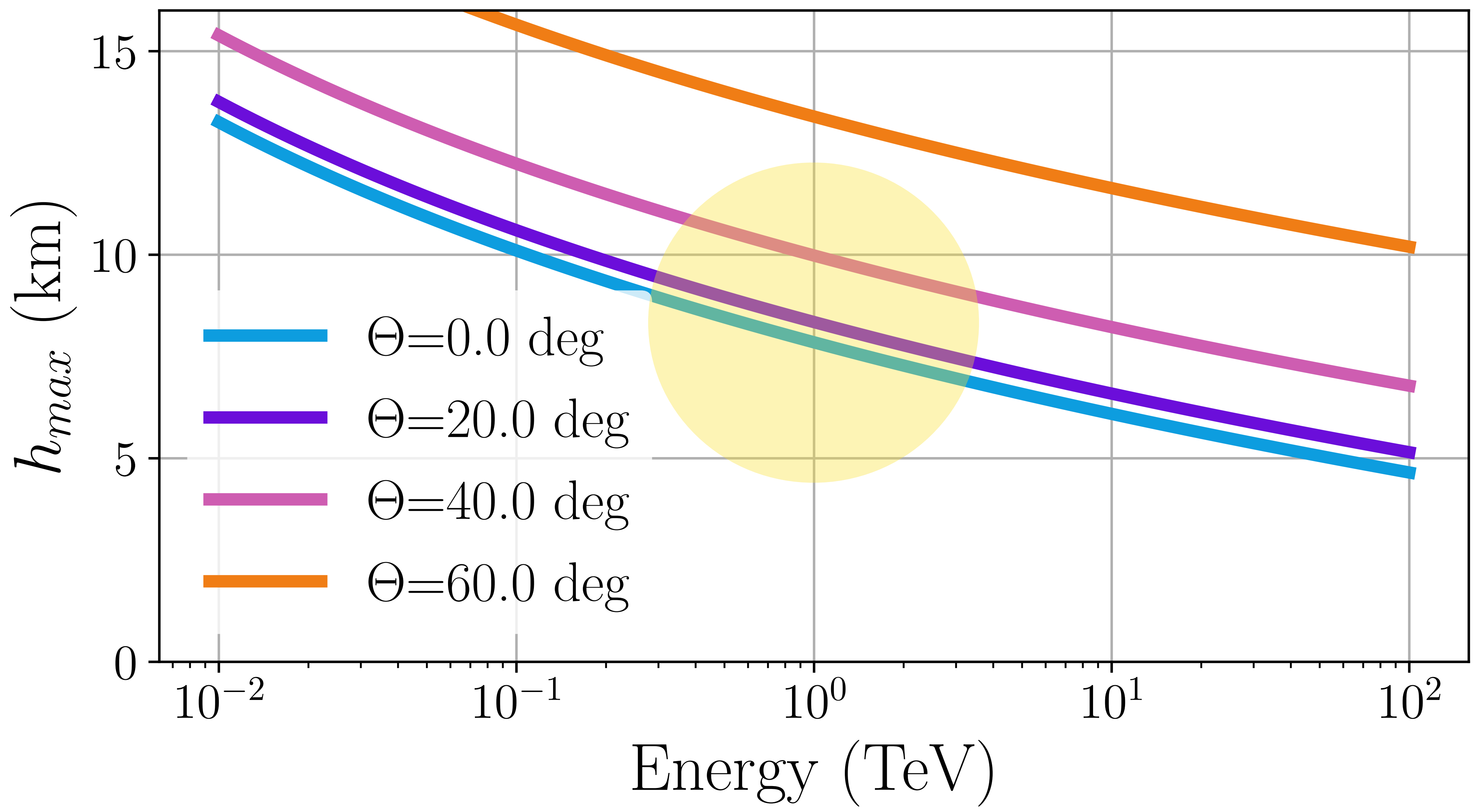
Can derive therefore

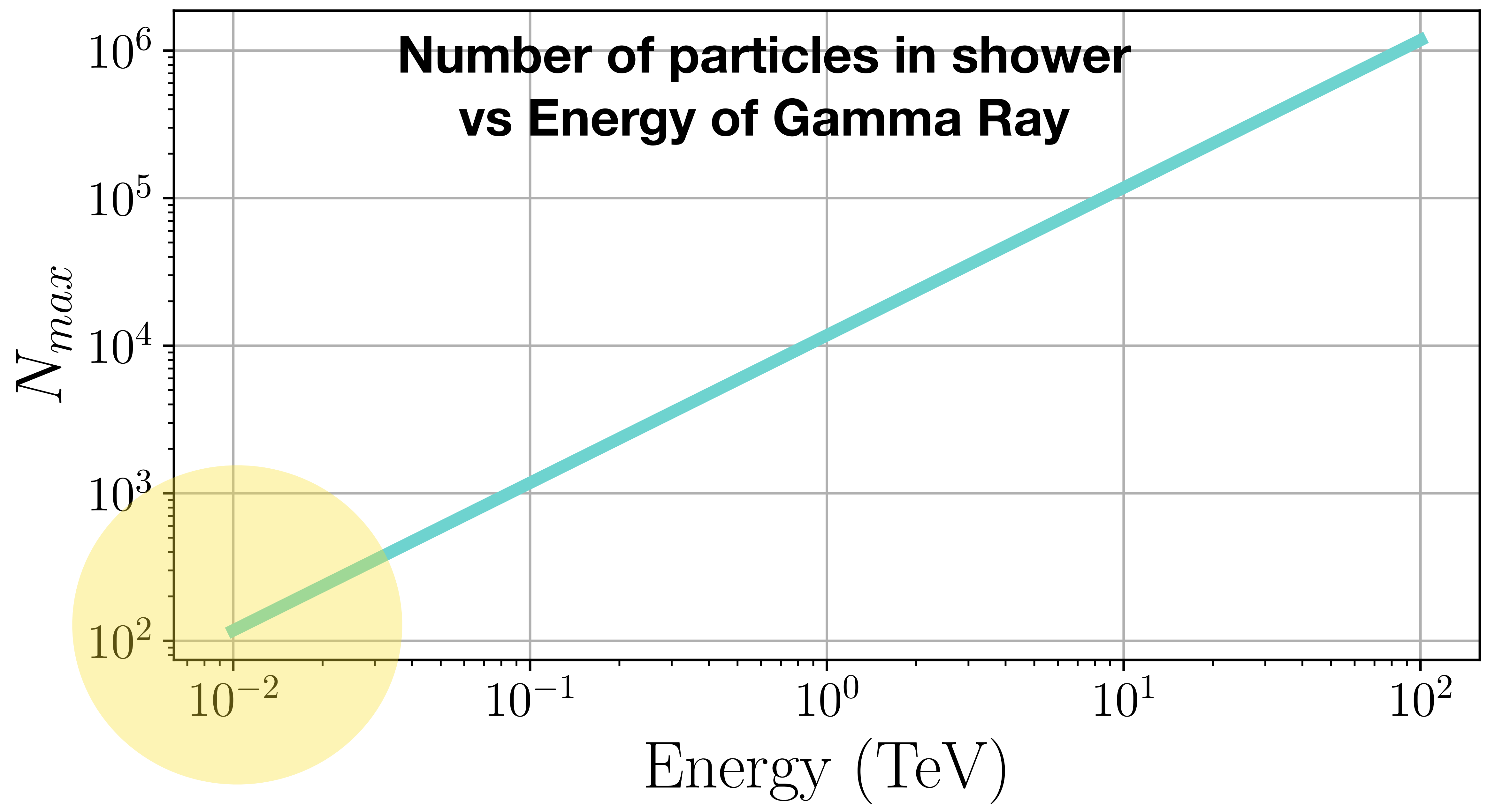
$\rho_0 = 1.25 \times 10^{-3}\,\text{g cm}^3$
$h_1 \simeq 29\,\text{km}$
$h_{max}(1\text{TeV}) \simeq 8\,\text{km}$
$N_{max}(1\text{TeV}) \simeq 1 \times 10^4$

Shower Maximum Height (in g/cm2)

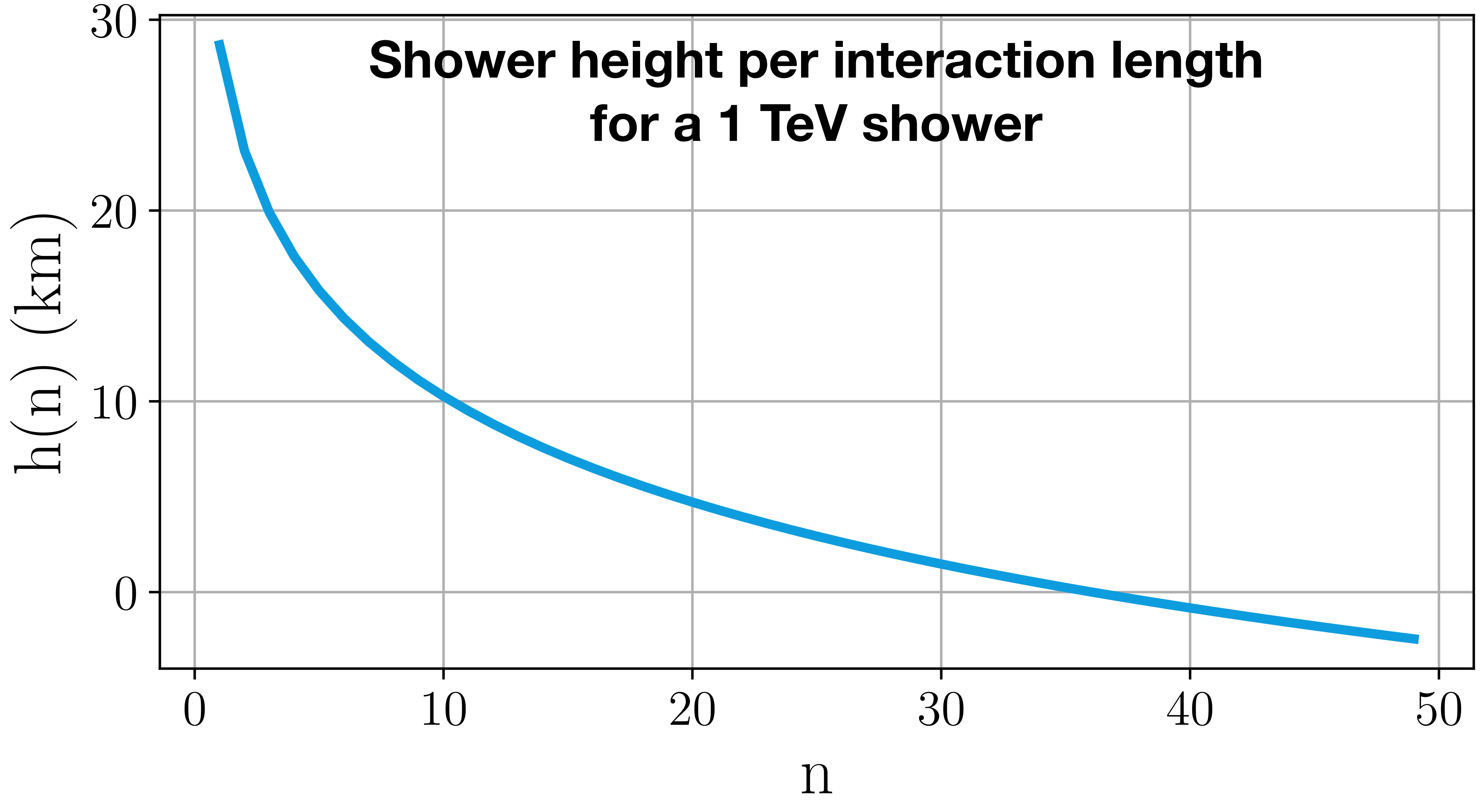


Shower Maximum Height (in km)





Number of particles in shower vs Energy of Gamma Ray



Shower height per interaction length for a 1 TeV shower

Karl Kosack - ISAPP 2022

Extensive Air Showers in our Atmosphere

- Earth’s atmosphere is ideal for making a "big" detector!
- Radiation and interaction length ≈ 37 g/cm^2
- showers **form and complete before hitting ground**

Not to scale

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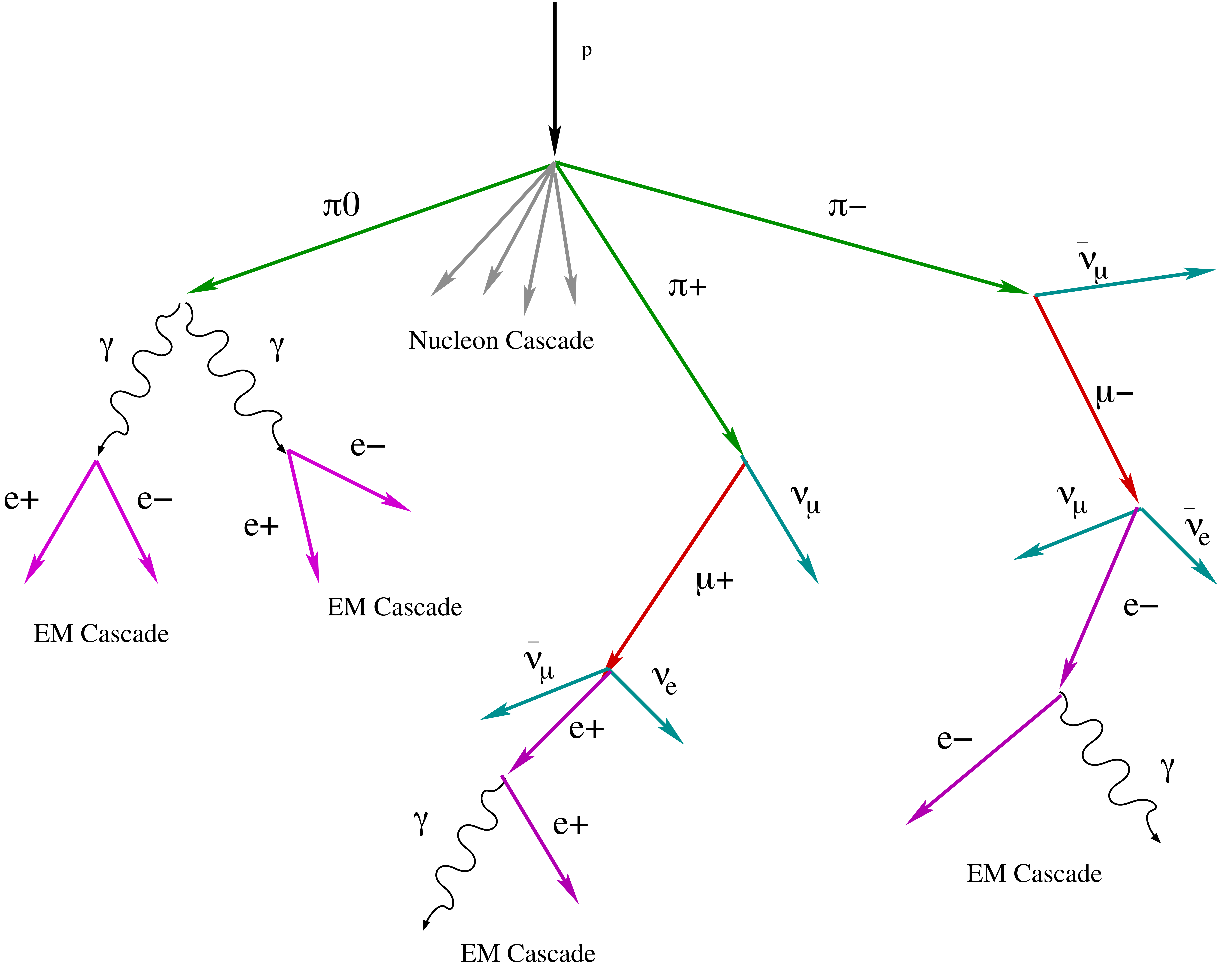
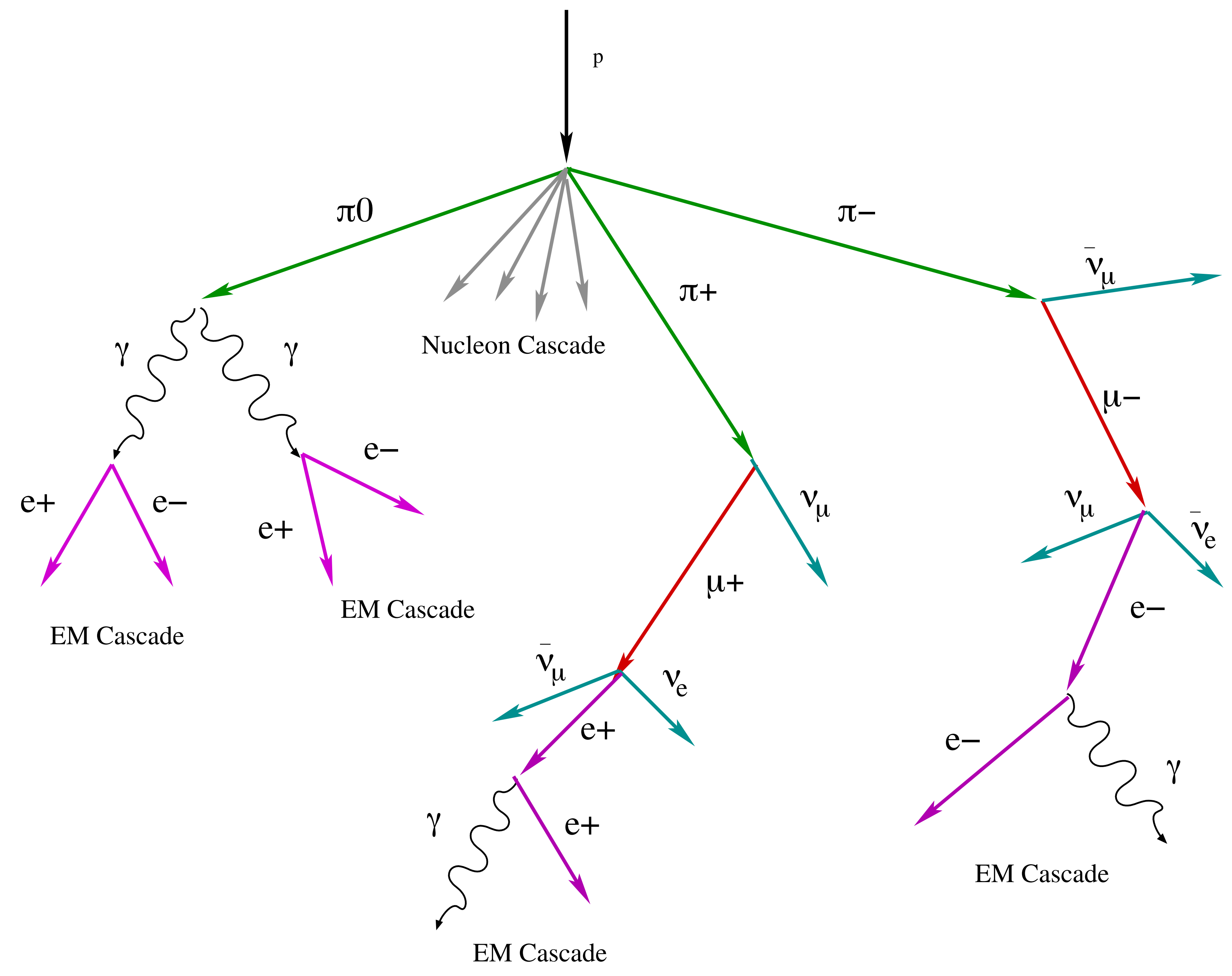
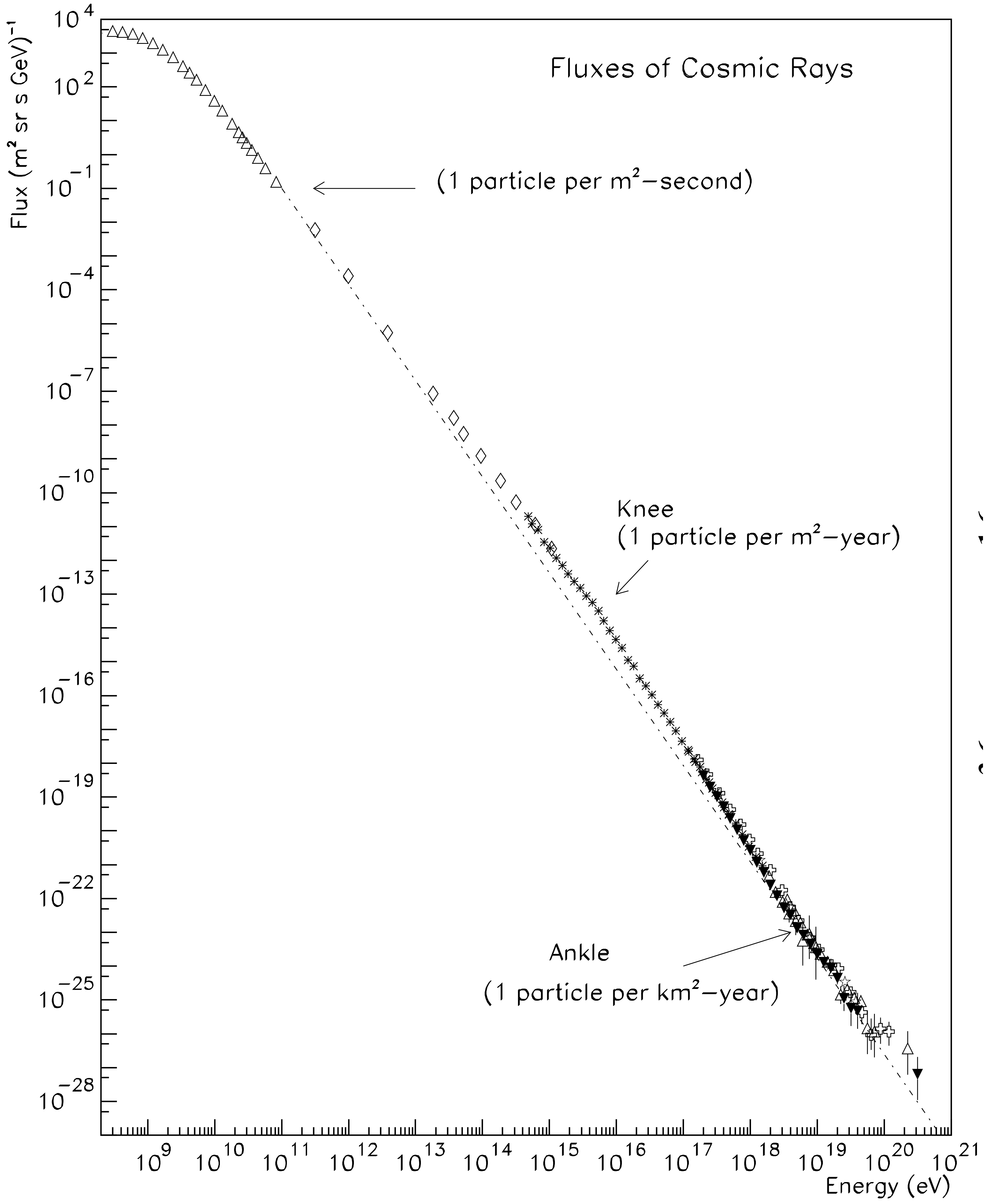


Karl Kosack - ISAPP 2022

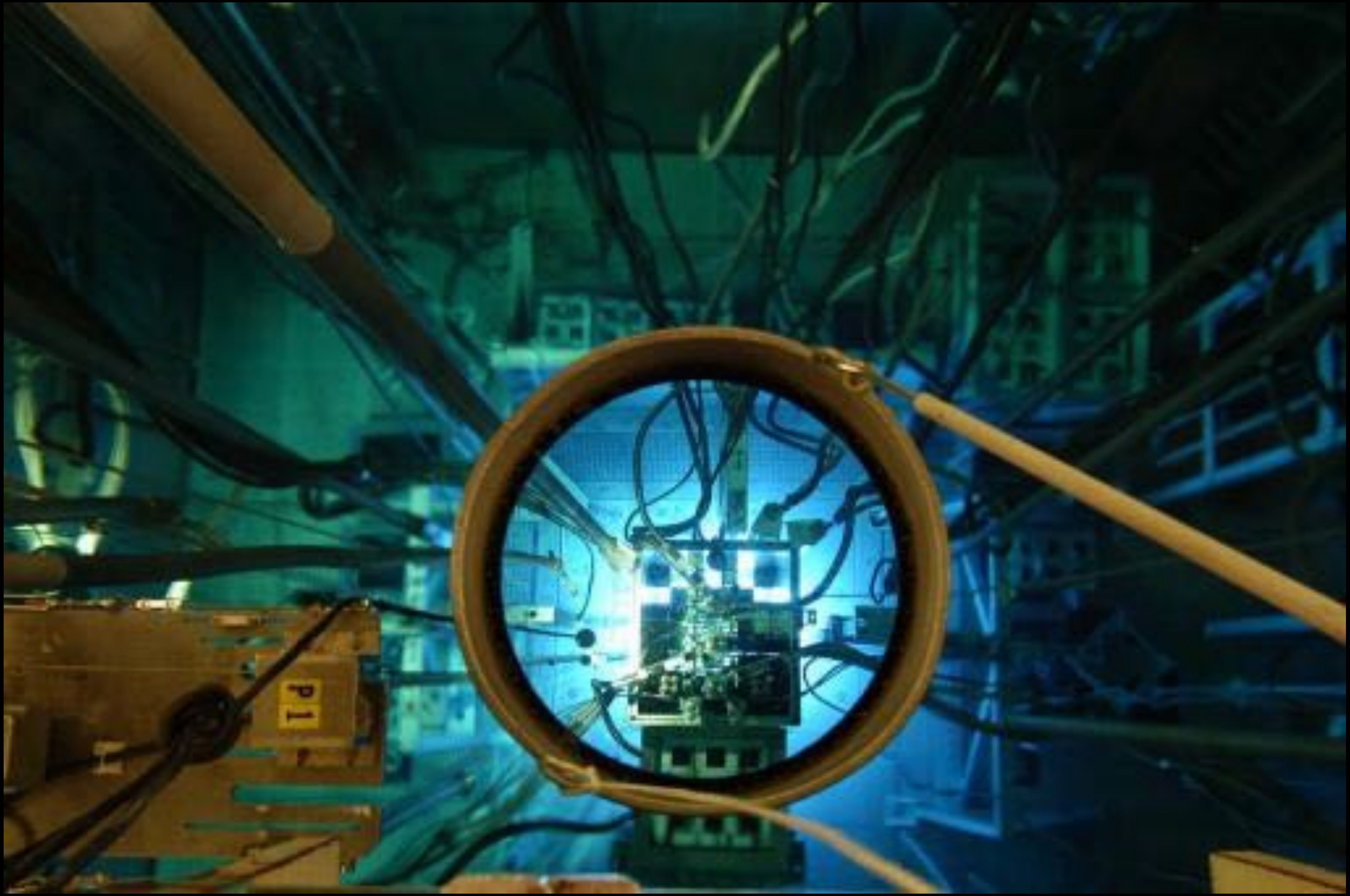
Cosmic Ray Background





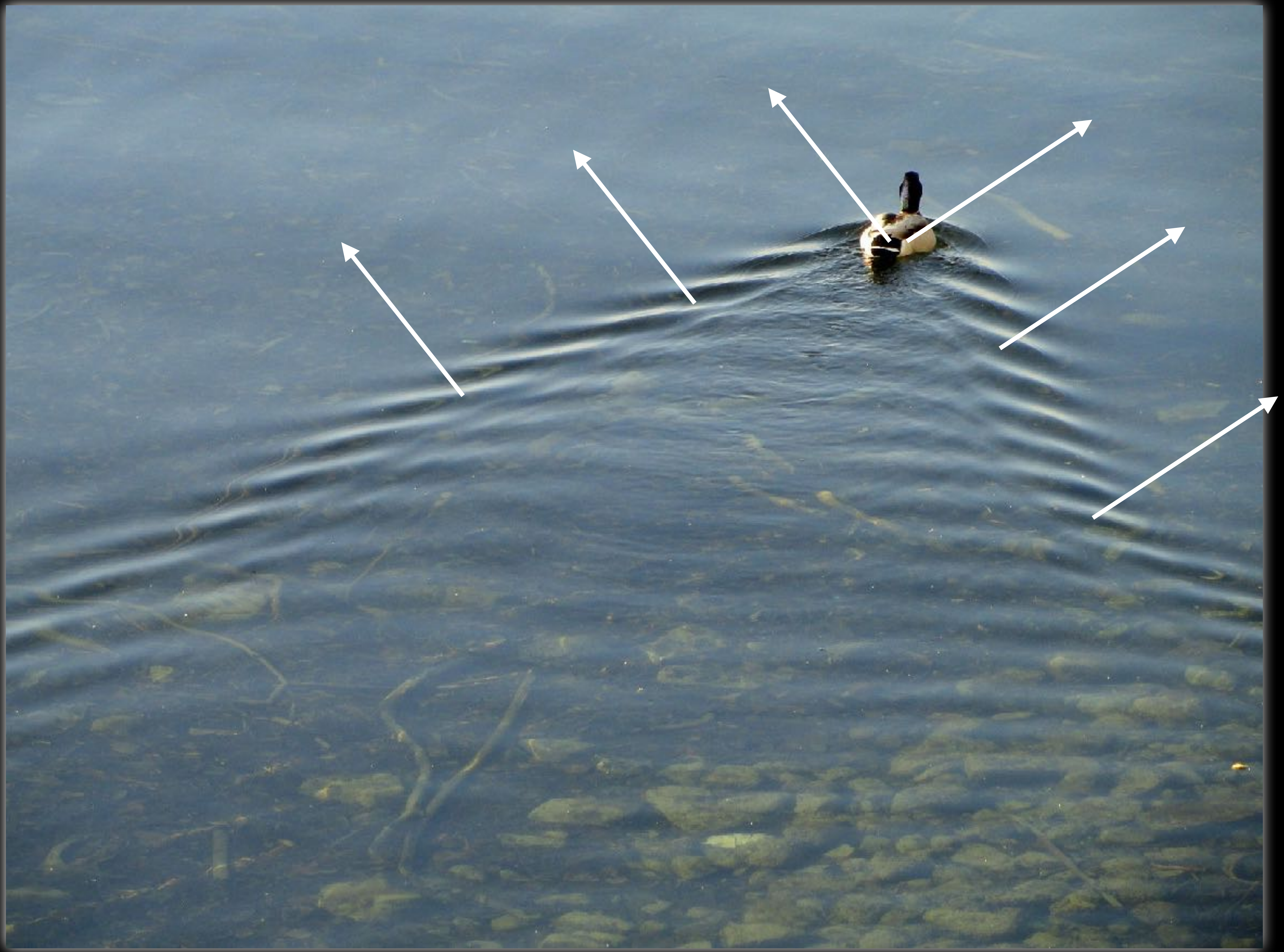
The number of cosmic ray showers in a given region of the sky is typically **orders of magnitude more** than for gamma rays

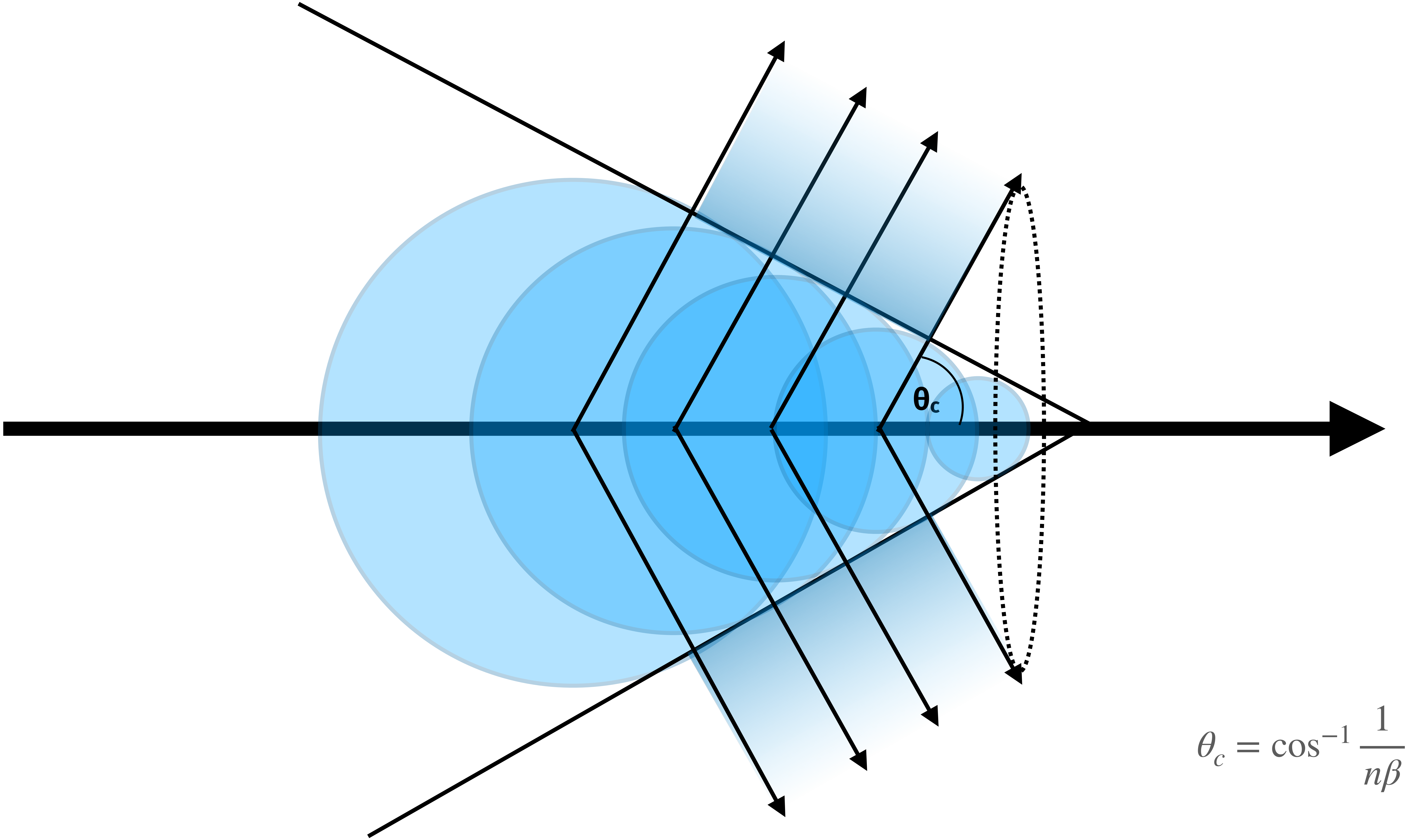
Rejecting them is critical.



Osiris reactor, CEA Saclay

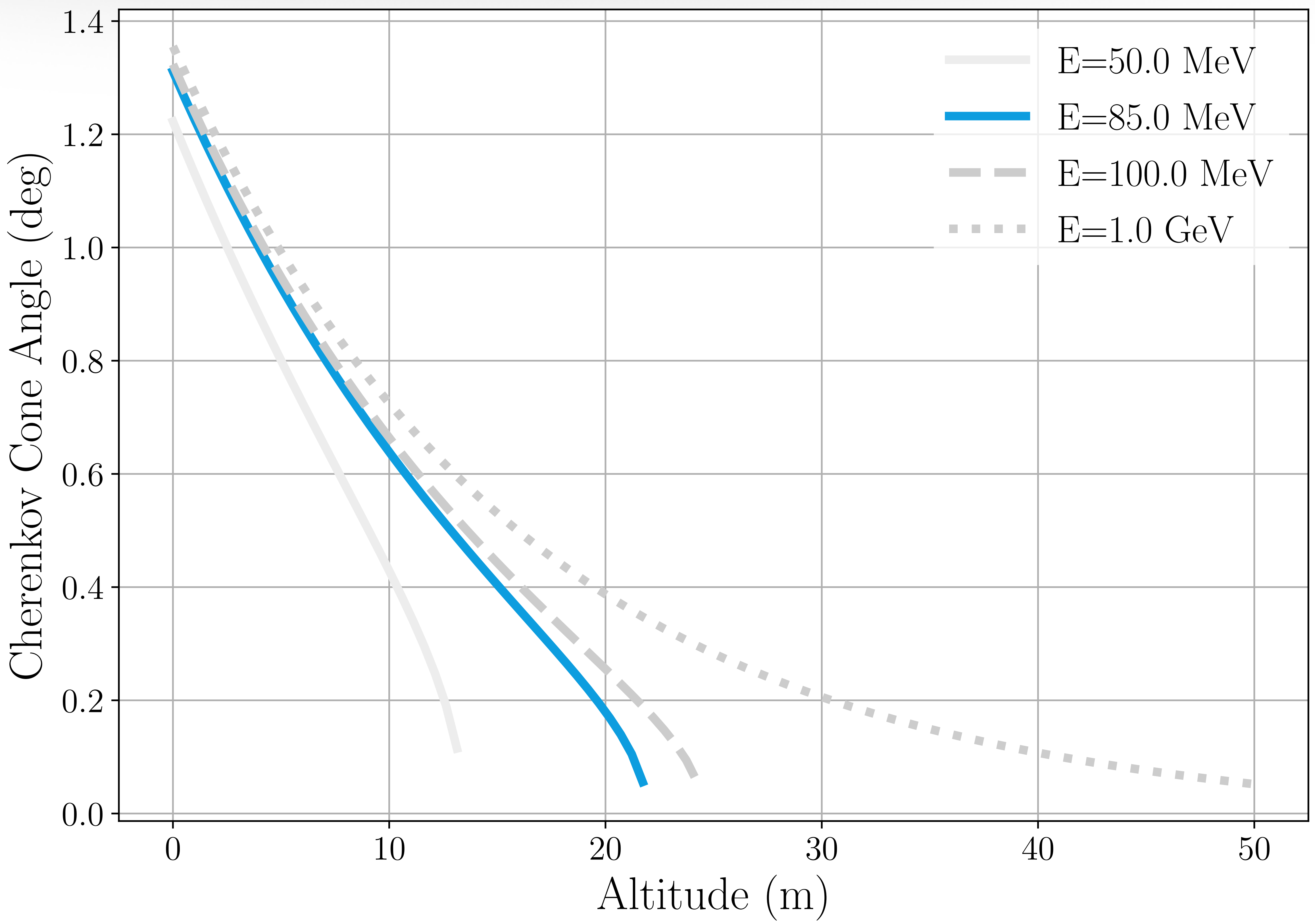
Credit: Les Défis du CEA, N°197 , March 2015- ©CEA/ Fabrice Mathé

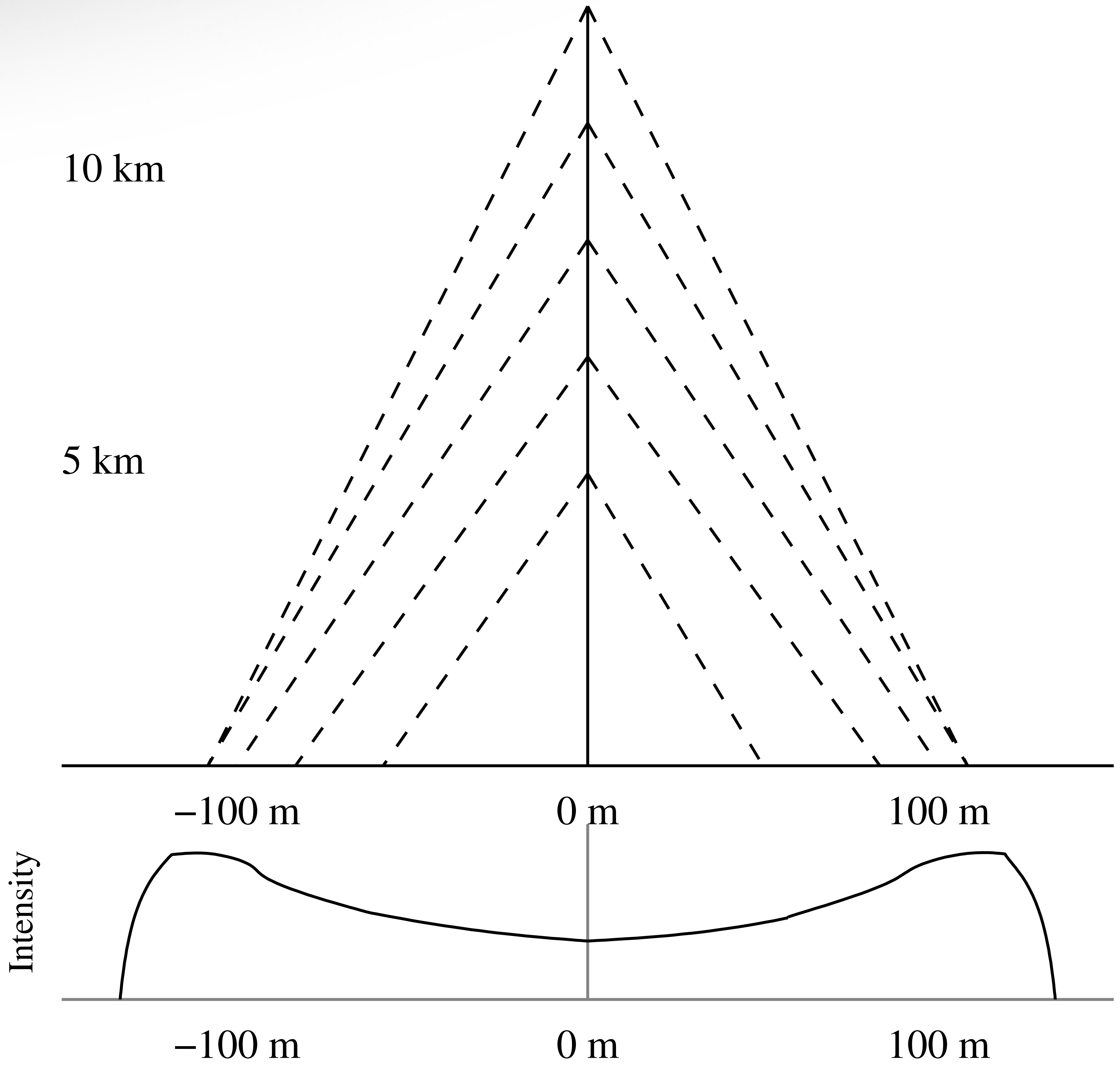




$$\theta_c = \cos^{-1}\frac{1}{n\beta}$$

Cherenkov Light From a Shower





"Footprint" On the ground from a single shower

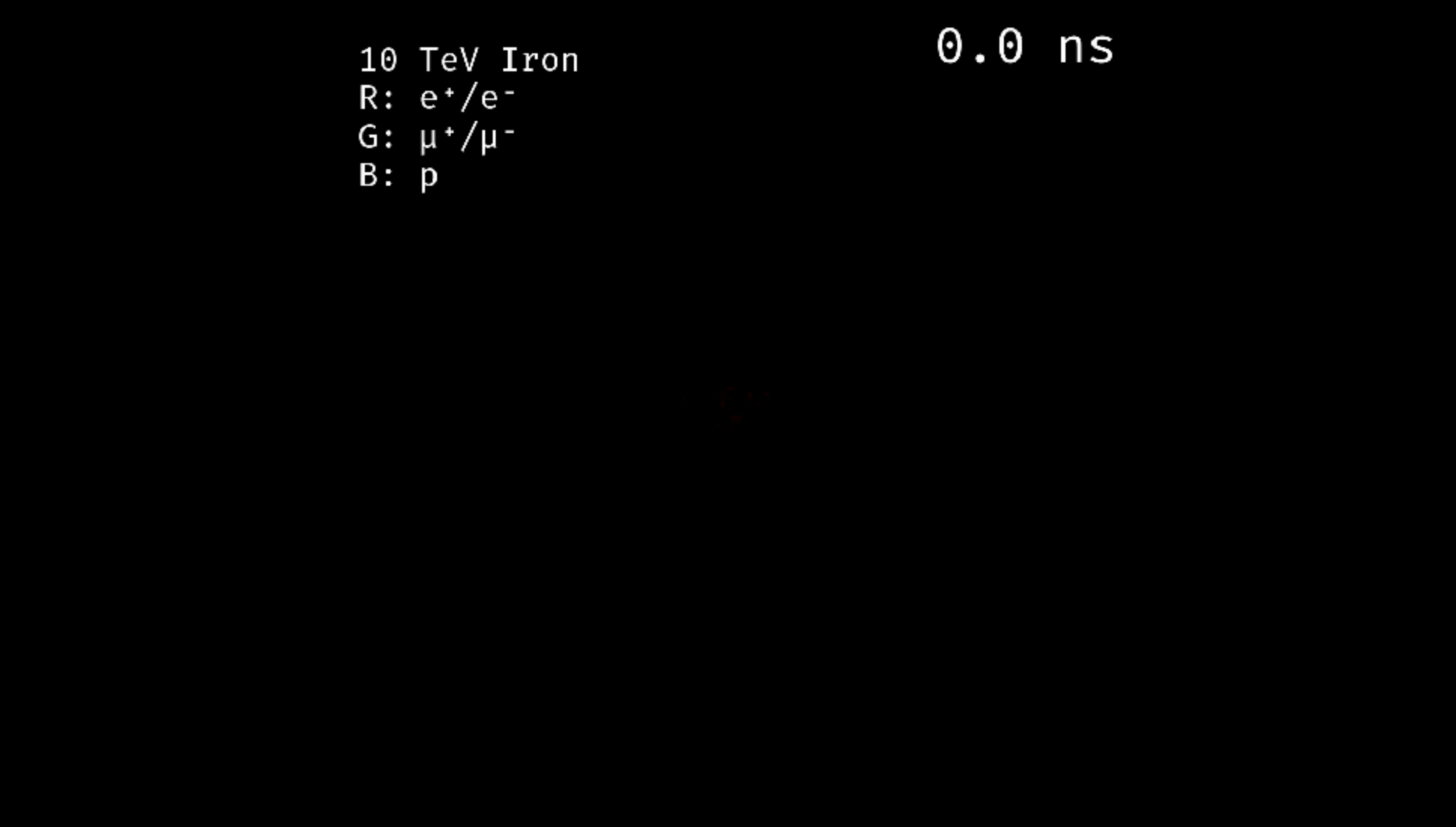
Cherenkov cone angle $\theta_c = \cos^{-1} \frac{1}{n\beta}$

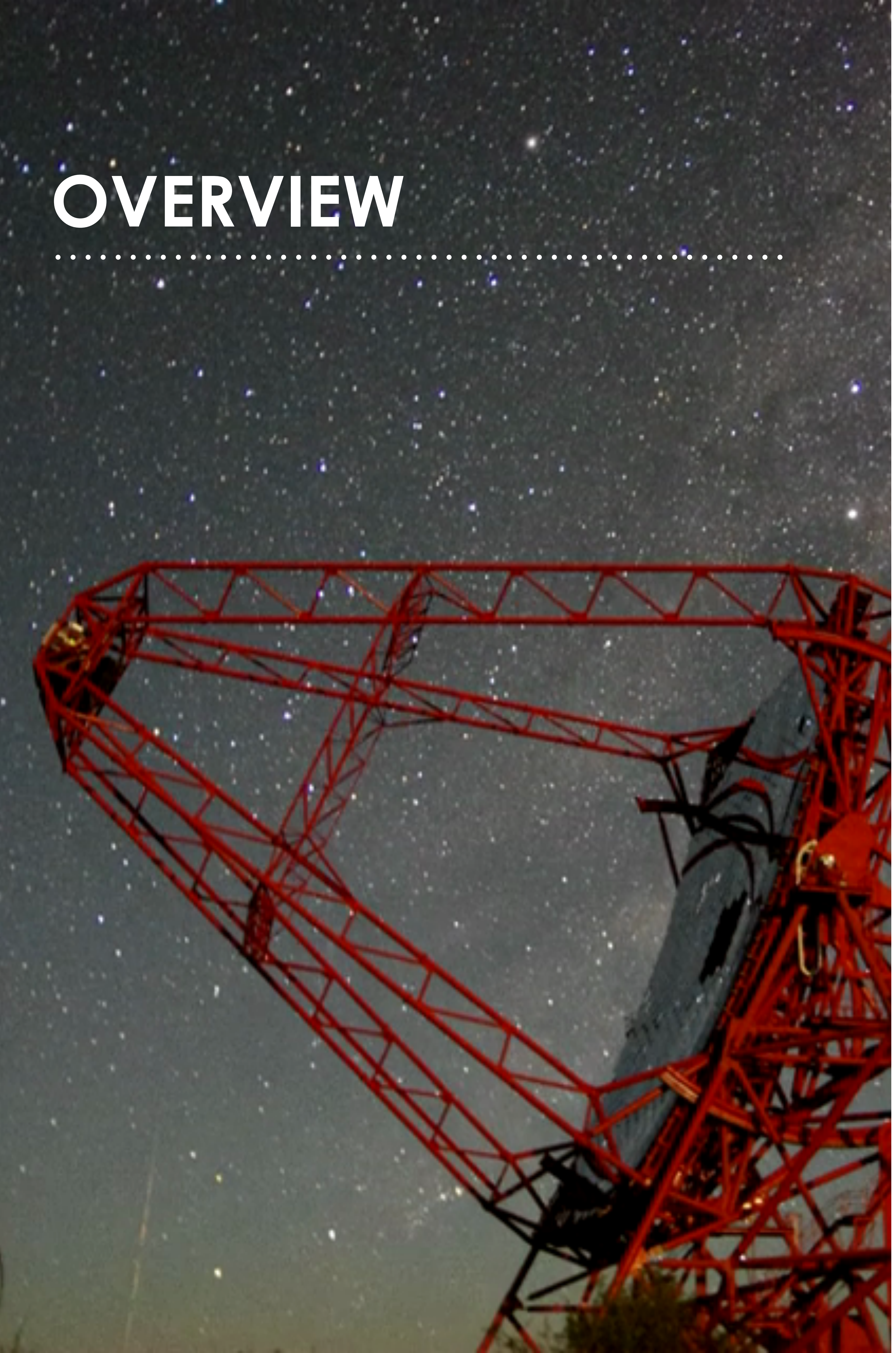
[M. Nöthe]

[M. Nöthe]


1 TeV Gamma
R: e⁺/e⁻
G: μ⁺/μ⁻
B: other
0.0 ns
100 m
[M. Nöthe]


1 TeV Proton
R: e⁺/e⁻
G: μ⁺/μ⁻
B: other
0.1 ns
100 m
[M. Nöthe]


10 TeV Iron
R: e⁺/e⁻
G: μ⁺/μ⁻
B: p
0.0 ns



OVERVIEW

VHE Gamma Rays

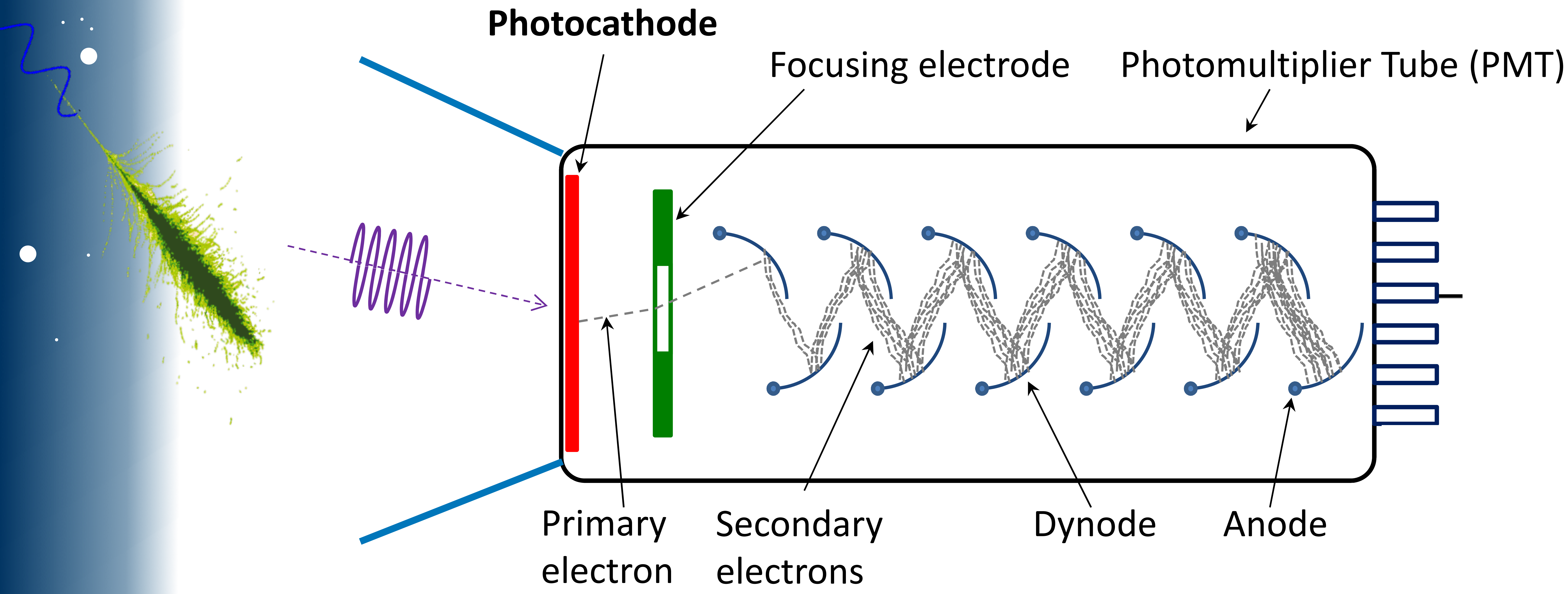
Gamma-ray Interactions in the Atmosphere

Imaging Atmospheric Cherenkov Telescopes

Water Cherenkov Telescopes

Science with VHE Gamma rays

How would one detect the Cherenkov light from extensive air shower?


Photocathode
Focusing electrode
Photomultiplier Tube (PMT)
Primary electron
Secondary electrons
Dynode
Anode

Photocathode

Focusing electrode

Photomultiplier Tube (PMT)

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Photocathode

Focusing electrode

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Primary electron

Secondary electrons

Dynode

Anode

Cherenkov Light

Night-Sky-Background Light

Photocathode

Focusing electrode

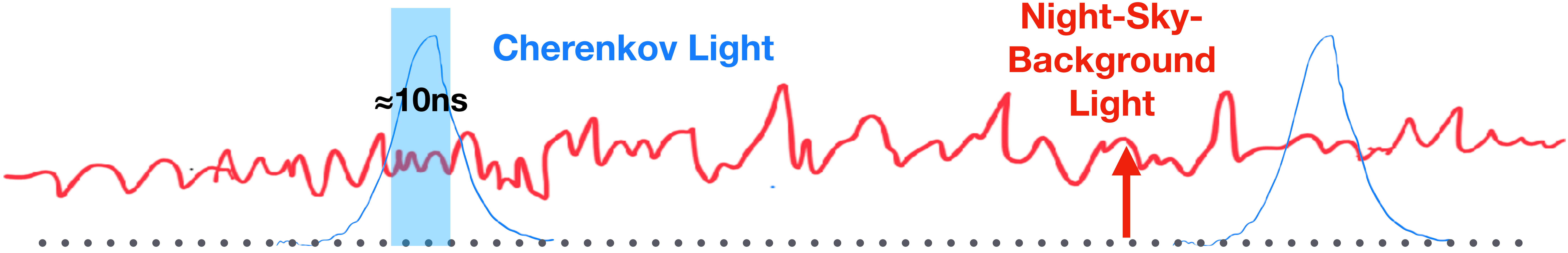
Photomultiplier Tube (PMT)

Primary electron

Secondary electrons

Dynode

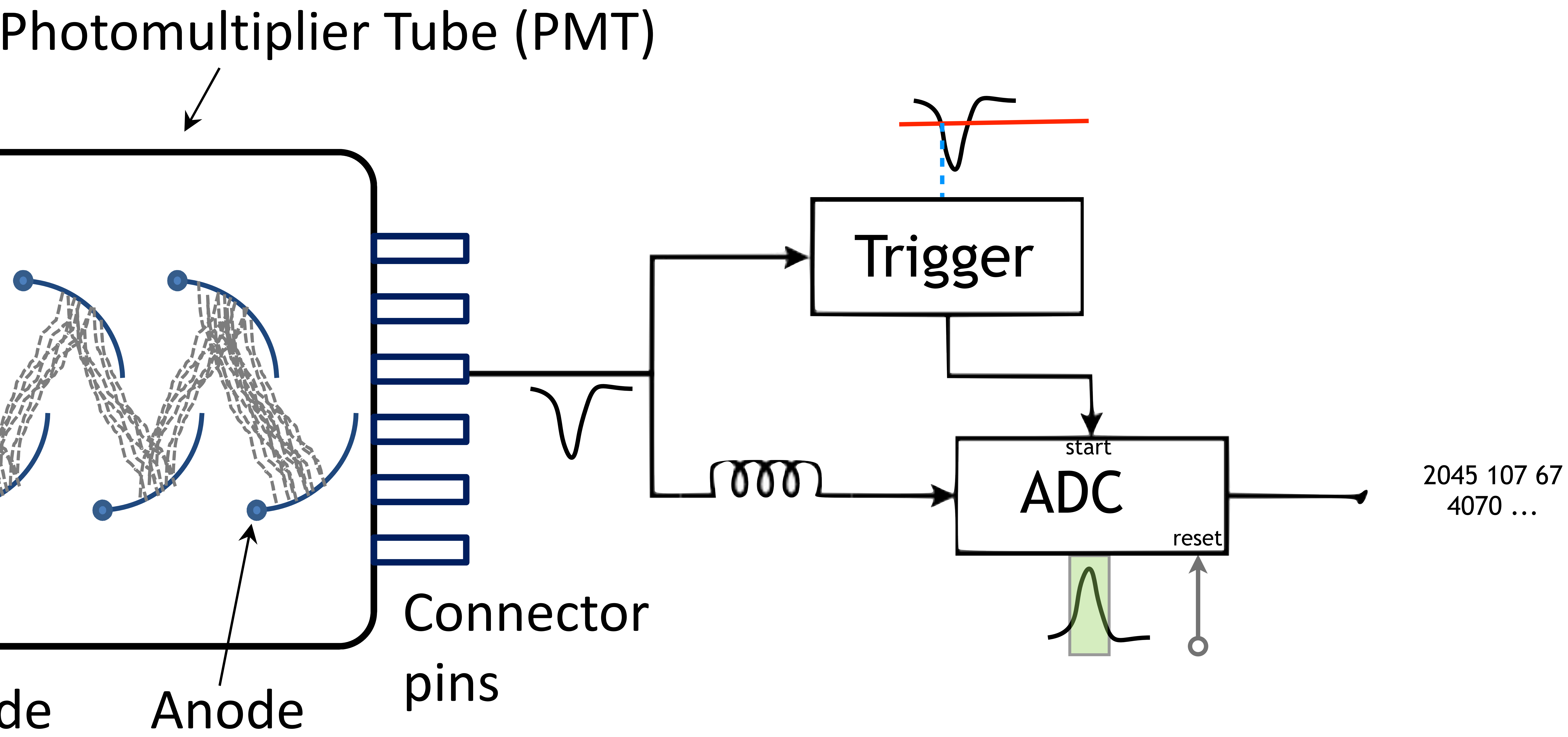
Anode



Cherenkov Light

≈10ns

Night-Sky-Background Light



Photomultiplier Tube (PMT)

Trigger

start

ADC

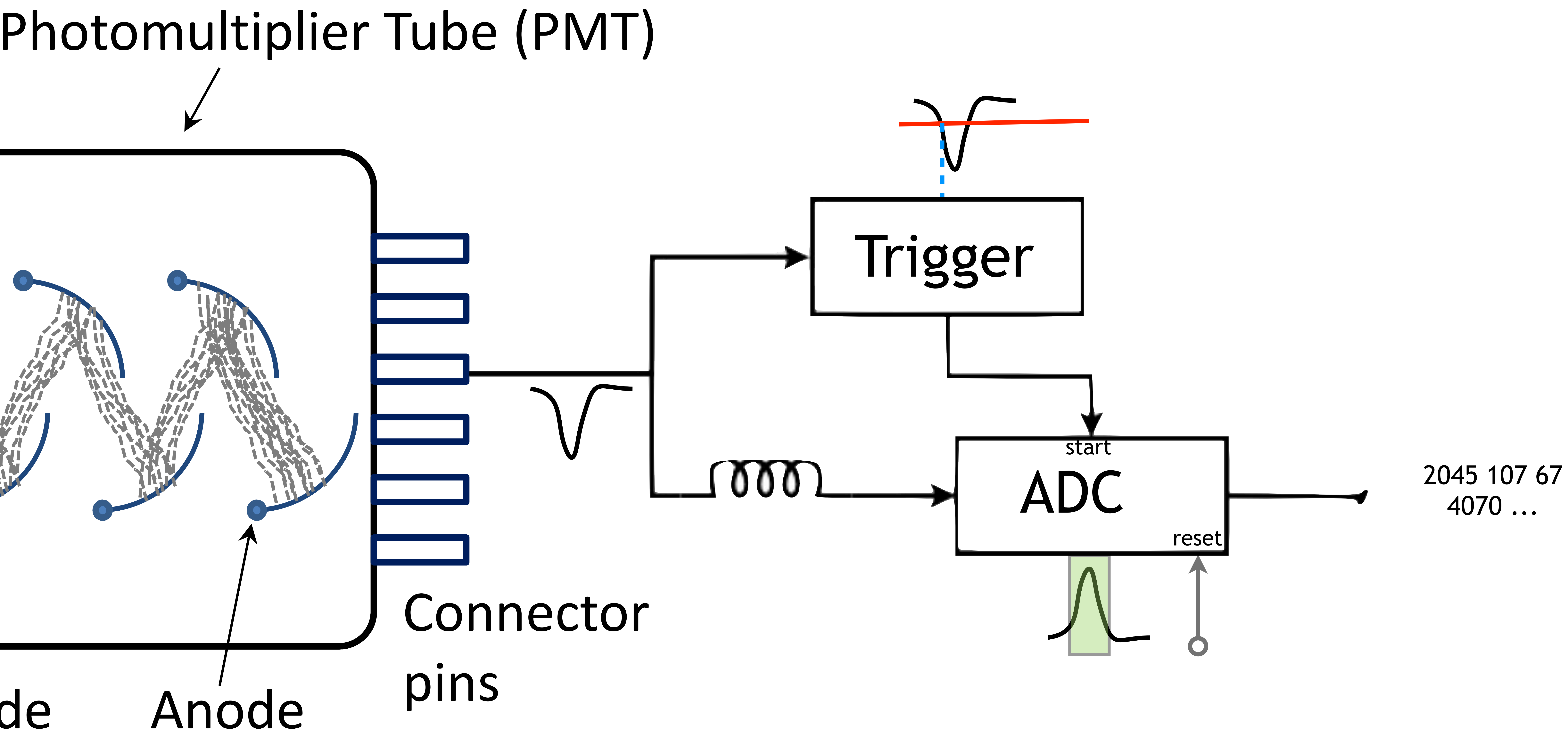
reset

2045 107 67
4070 …

de

Anode

Connector pins



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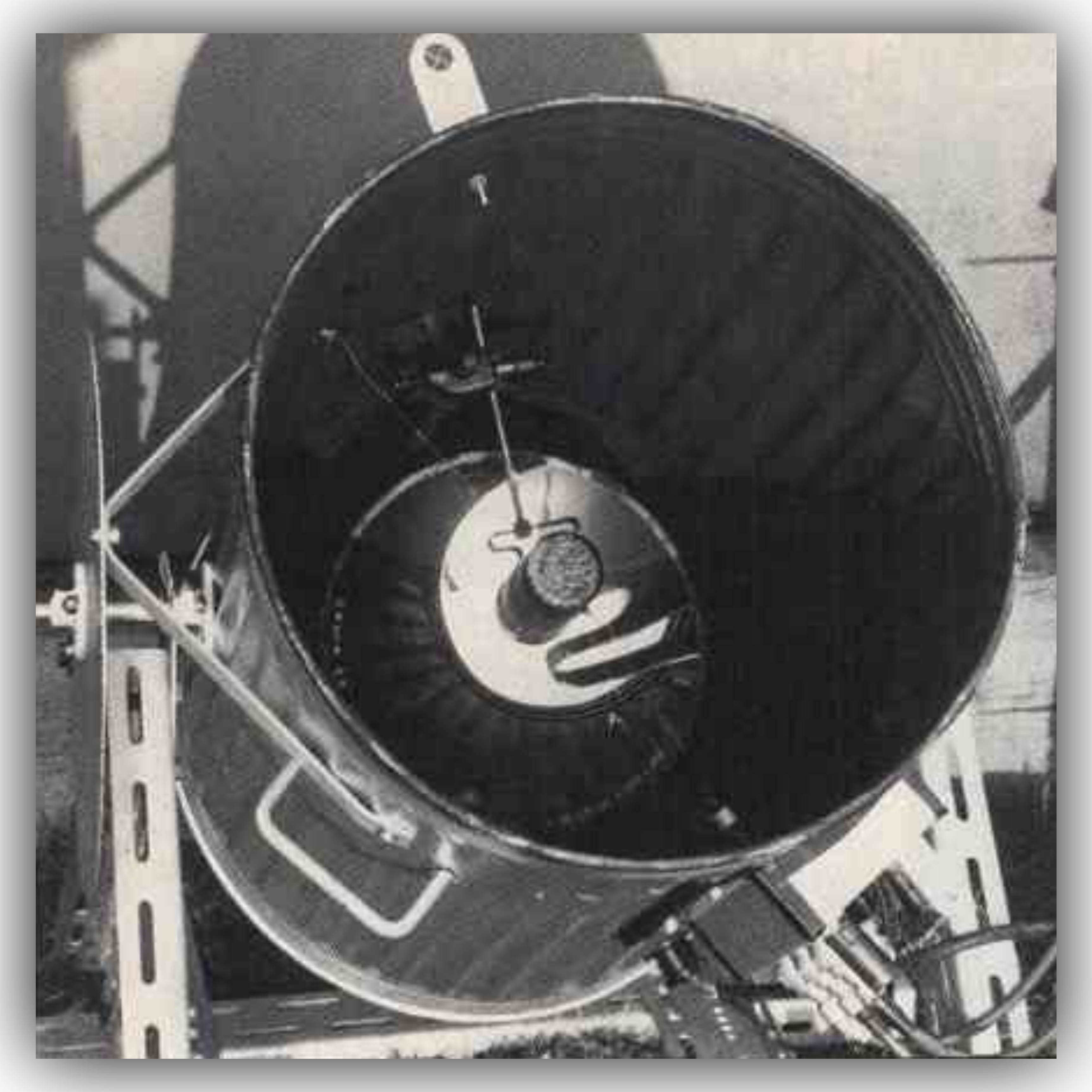
Early Gamma Ray Telescopes:
a look back



Galbraith & Jelley 1953

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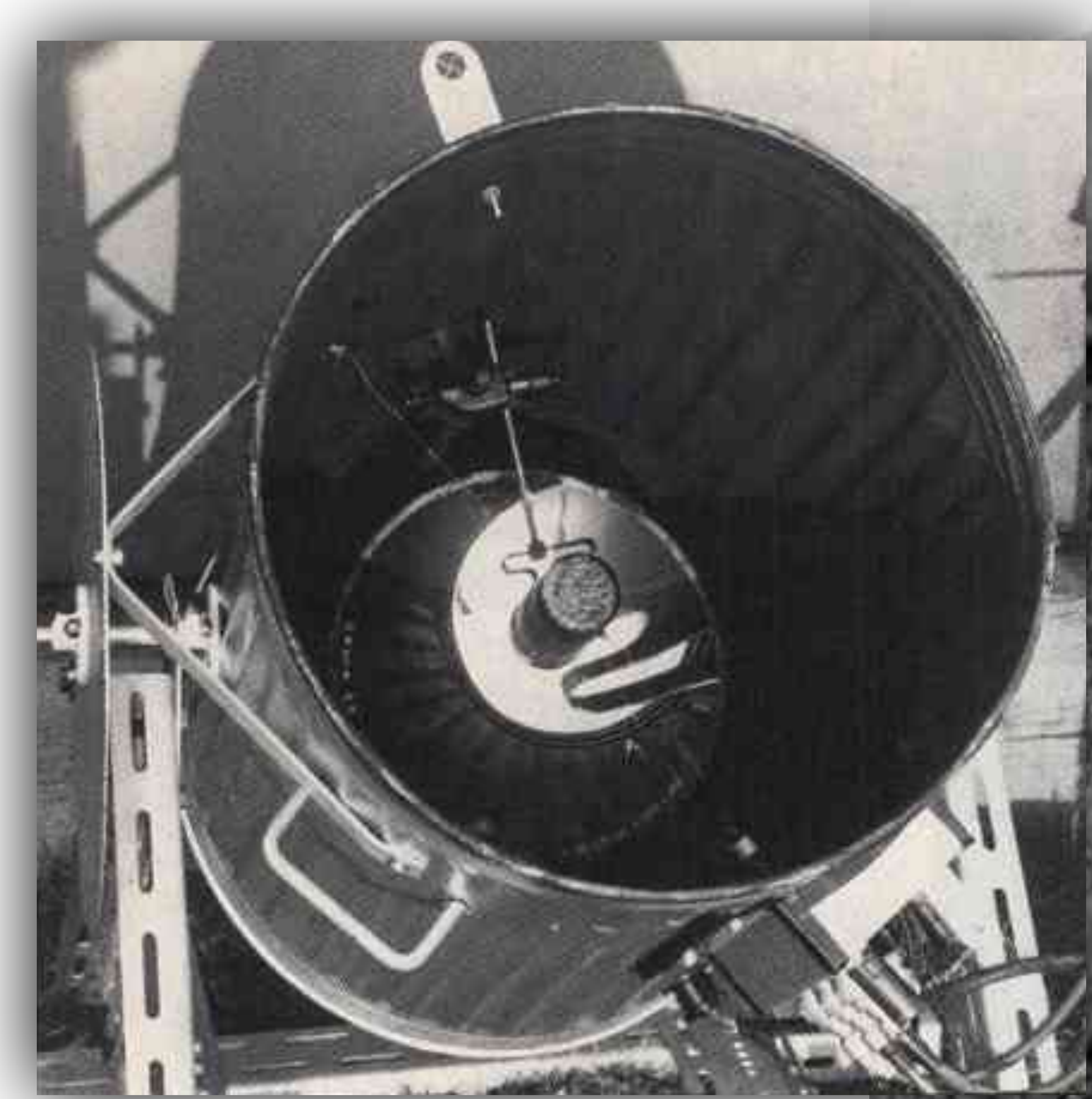
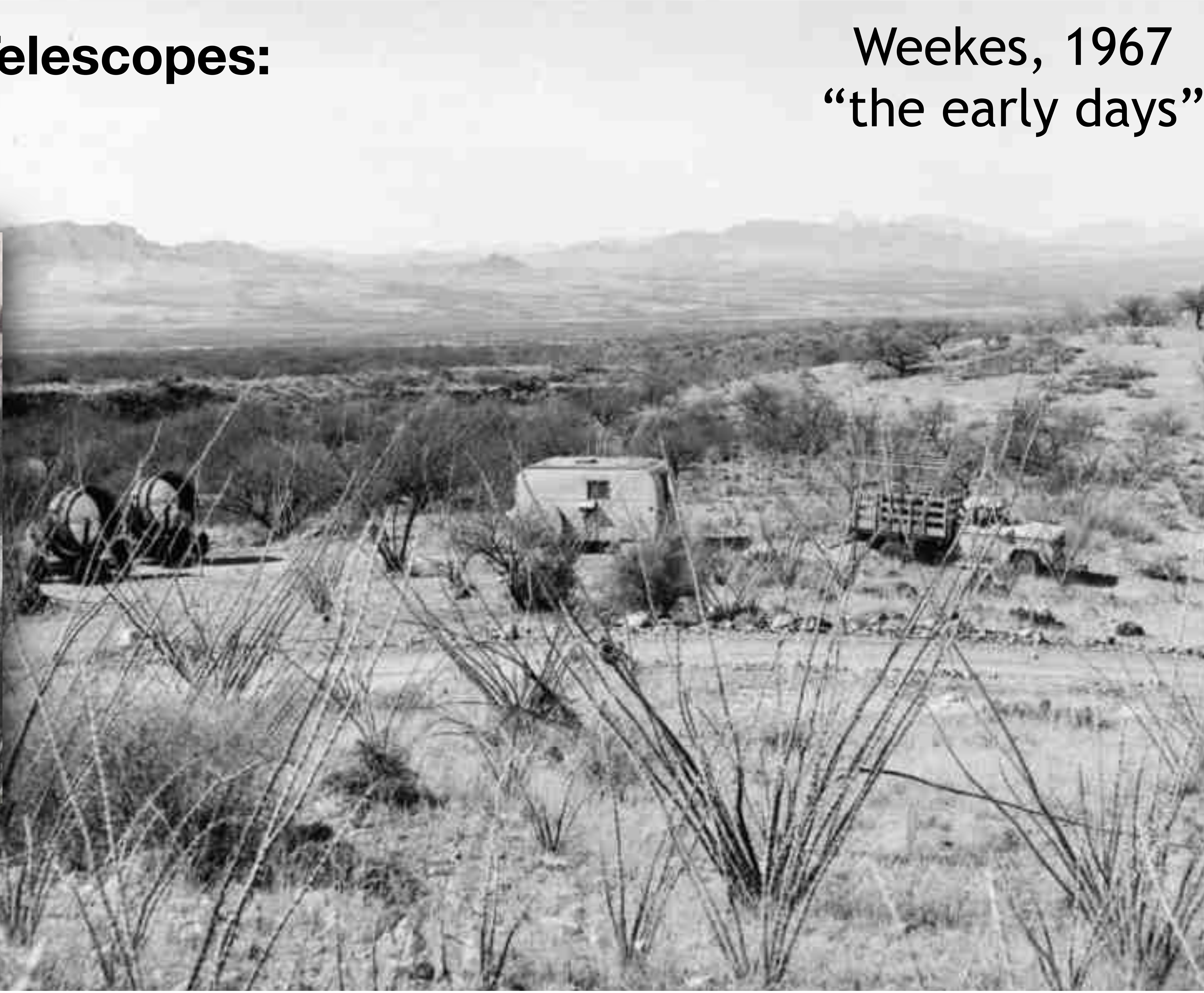
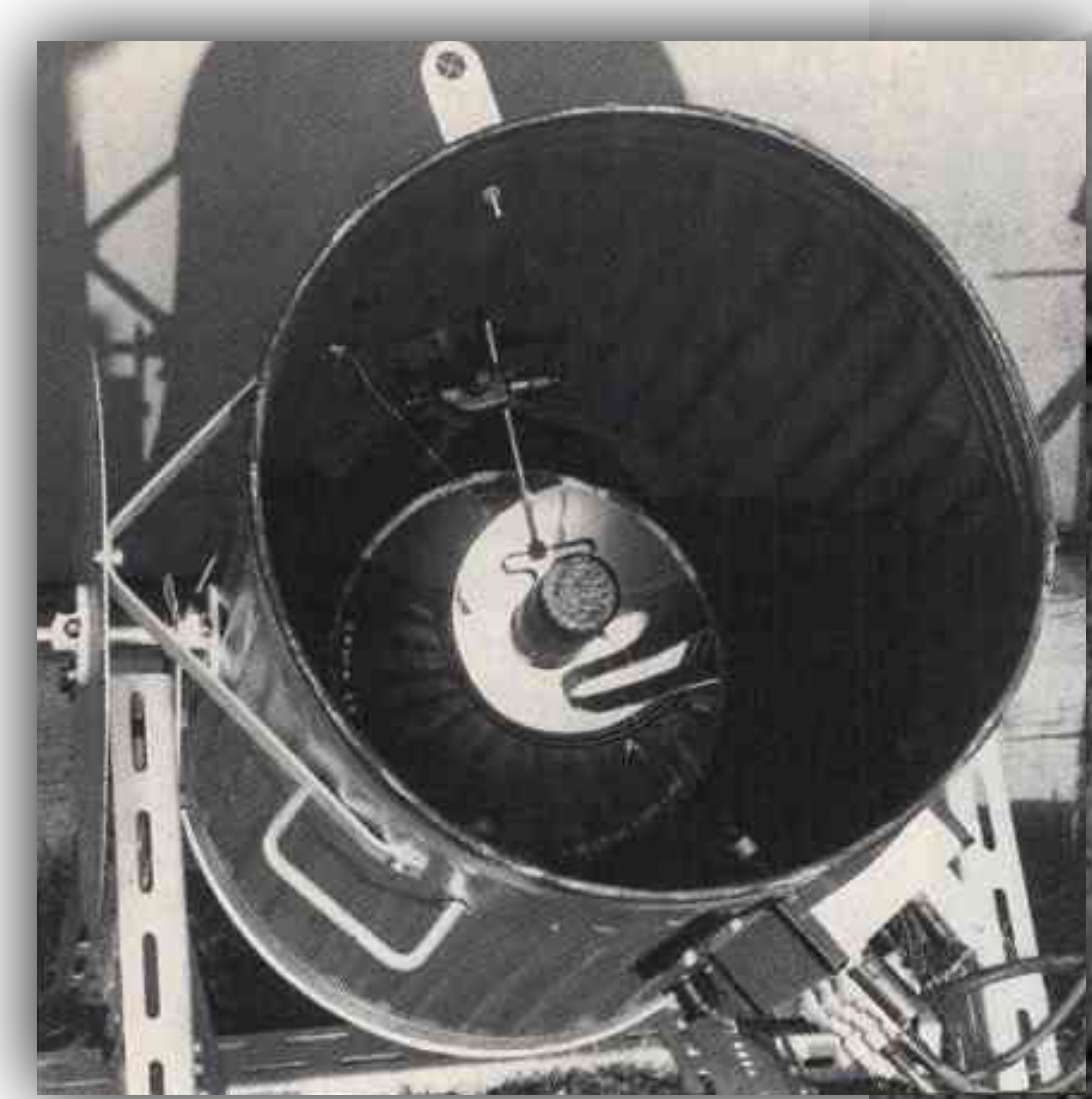


Galbraith & Jelley 1953



Weekes, 1967
“the early days”

Early Gamma Ray Telescopes: a look back



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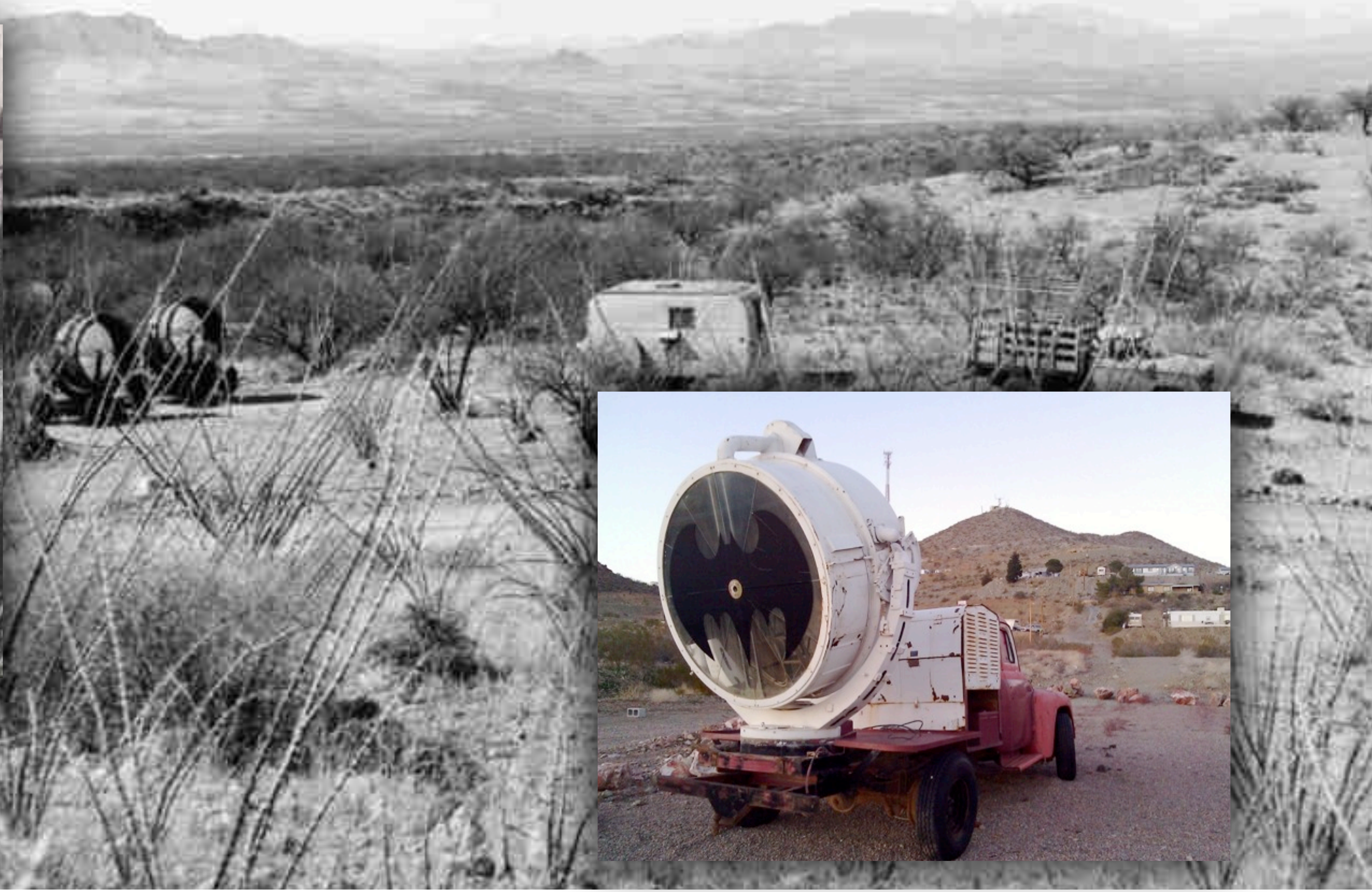
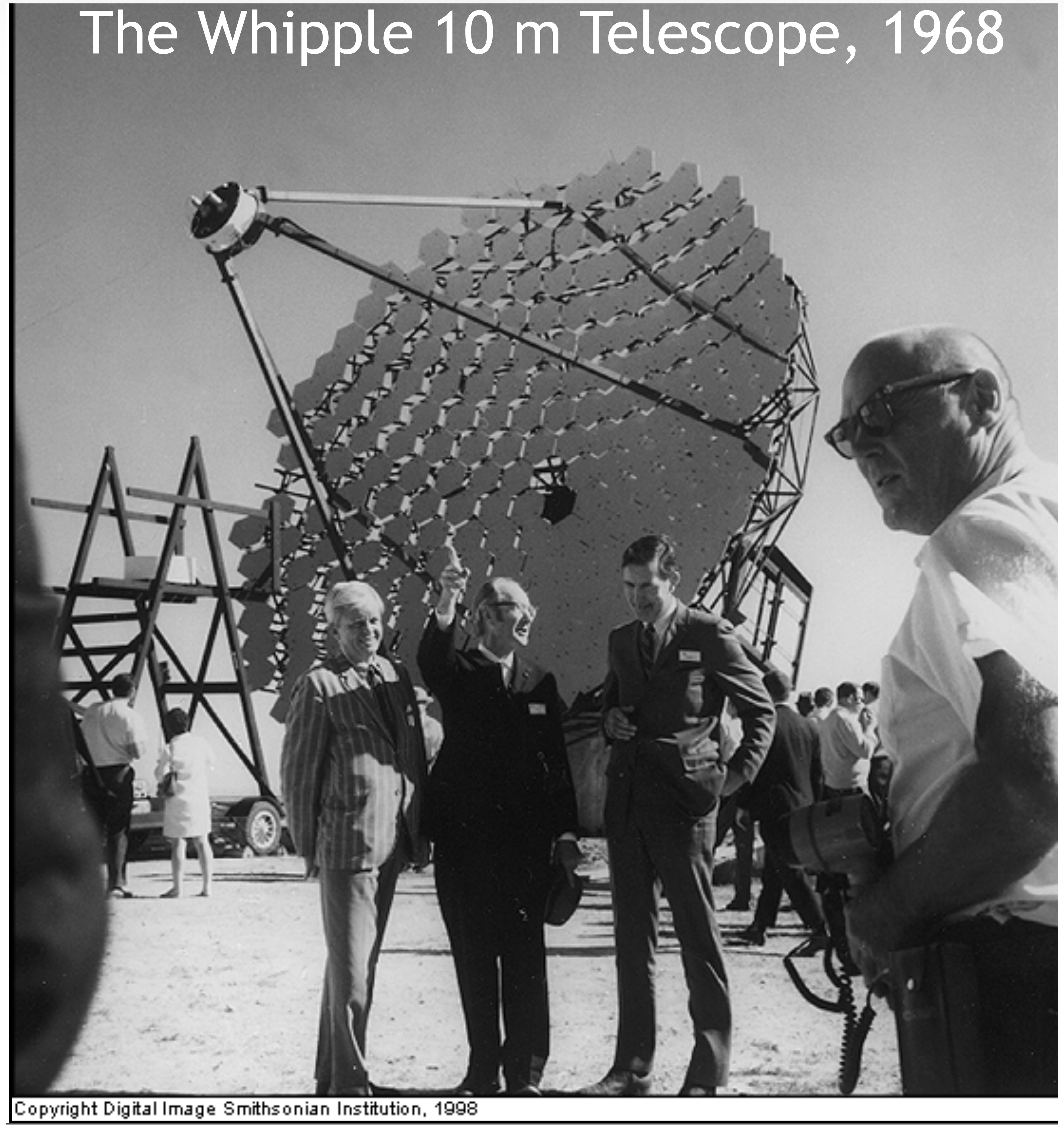


Some VHE Gamma-Ray History

The Whipple 10 m Telescope, 1968



Copyright Digital Image Smithsonian Institution, 1998

Whipple 10m teleescope

- **1968:** Built, Single-pixel camera
- **1972**: *3σ evidence* for Crab detection in 150 hours (3+ years of data)

……

- **Breakthrough!** *Hillas et al 1985*
- **1989:** First detection of Crab Nebula (5 σ) *Weeks et al, 1989*

Many came in between:

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

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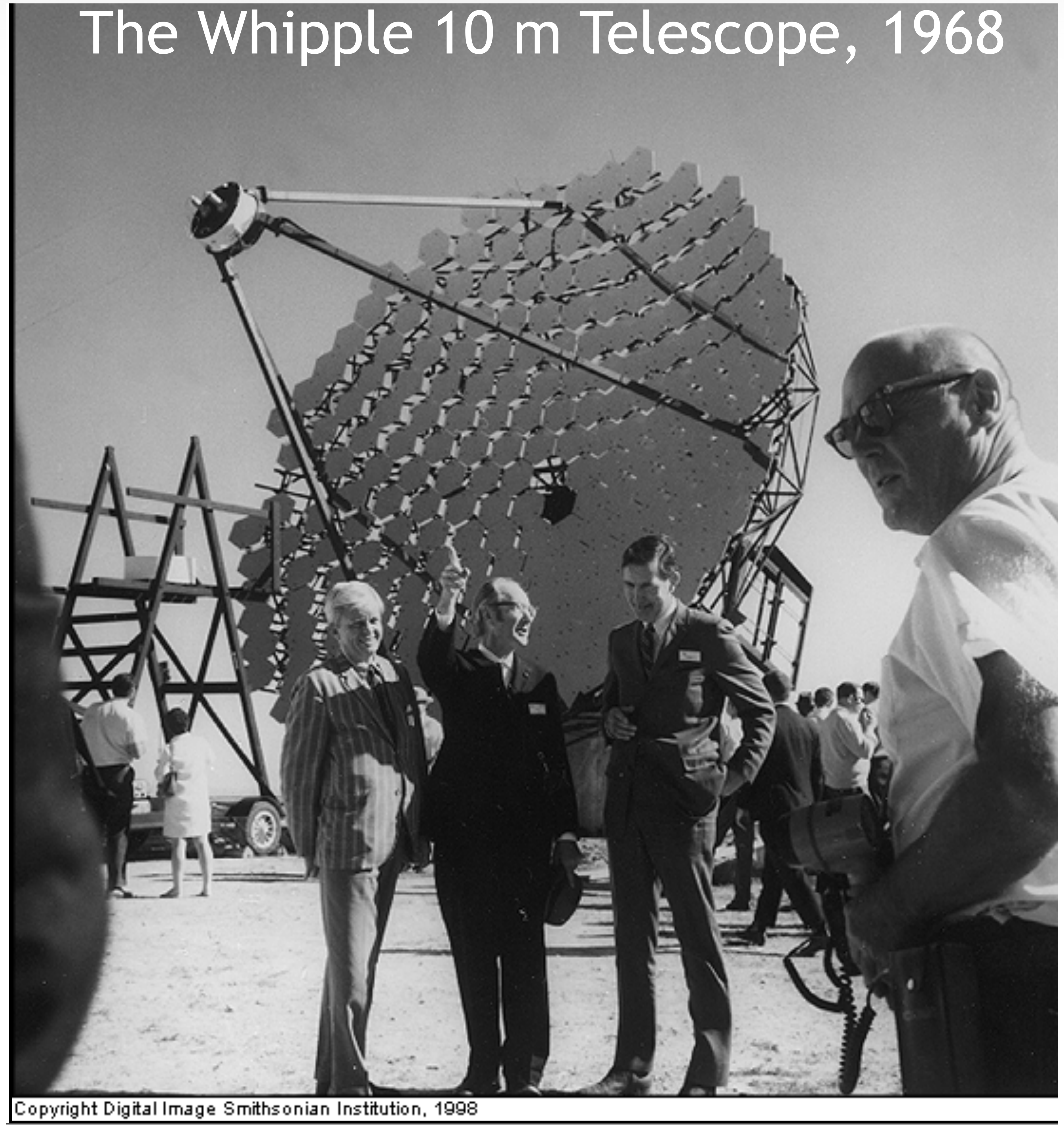

The Whipple 10 m Telescope, 1968

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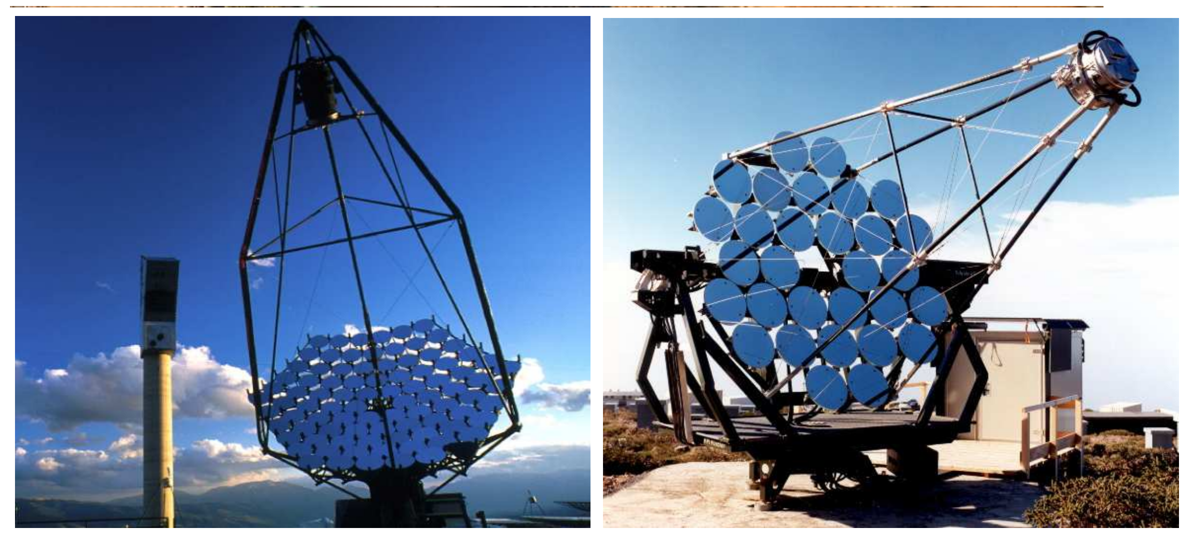


The problem

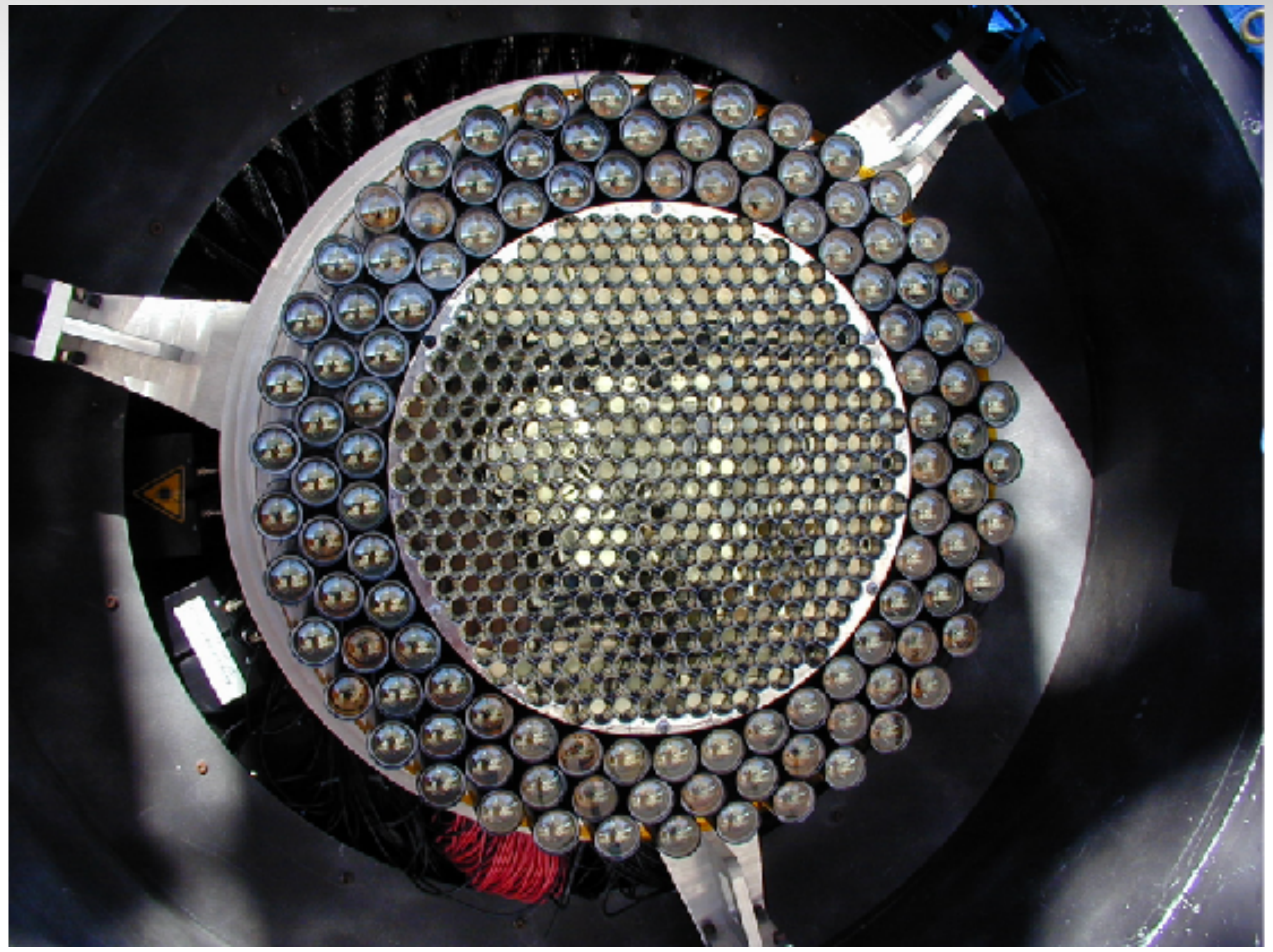
***Background to shower detection*:**
Night-Sky-Backgound (NSB) Light

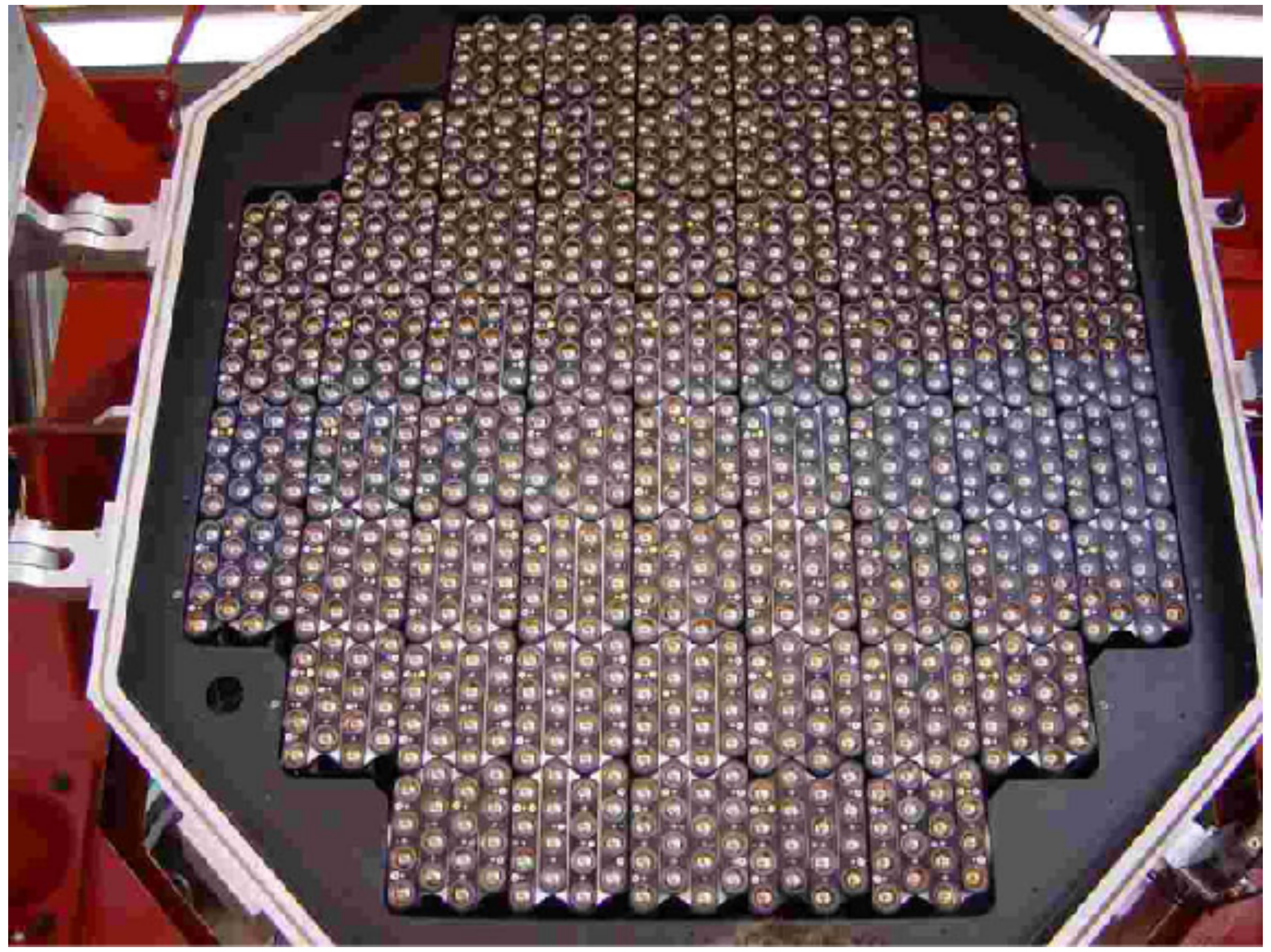
- Time helps here, but is not fully efficient → many NSB fluctuations still remain

***Background to gamma-ray detection*:**
Cosmic Ray showers

- Even if you reject all NSB, you still have vastly more cosmic ray-induced showers than gamma-ray showers!
- Need to discriminate!

Breakthrough #1: Shower *imaging*





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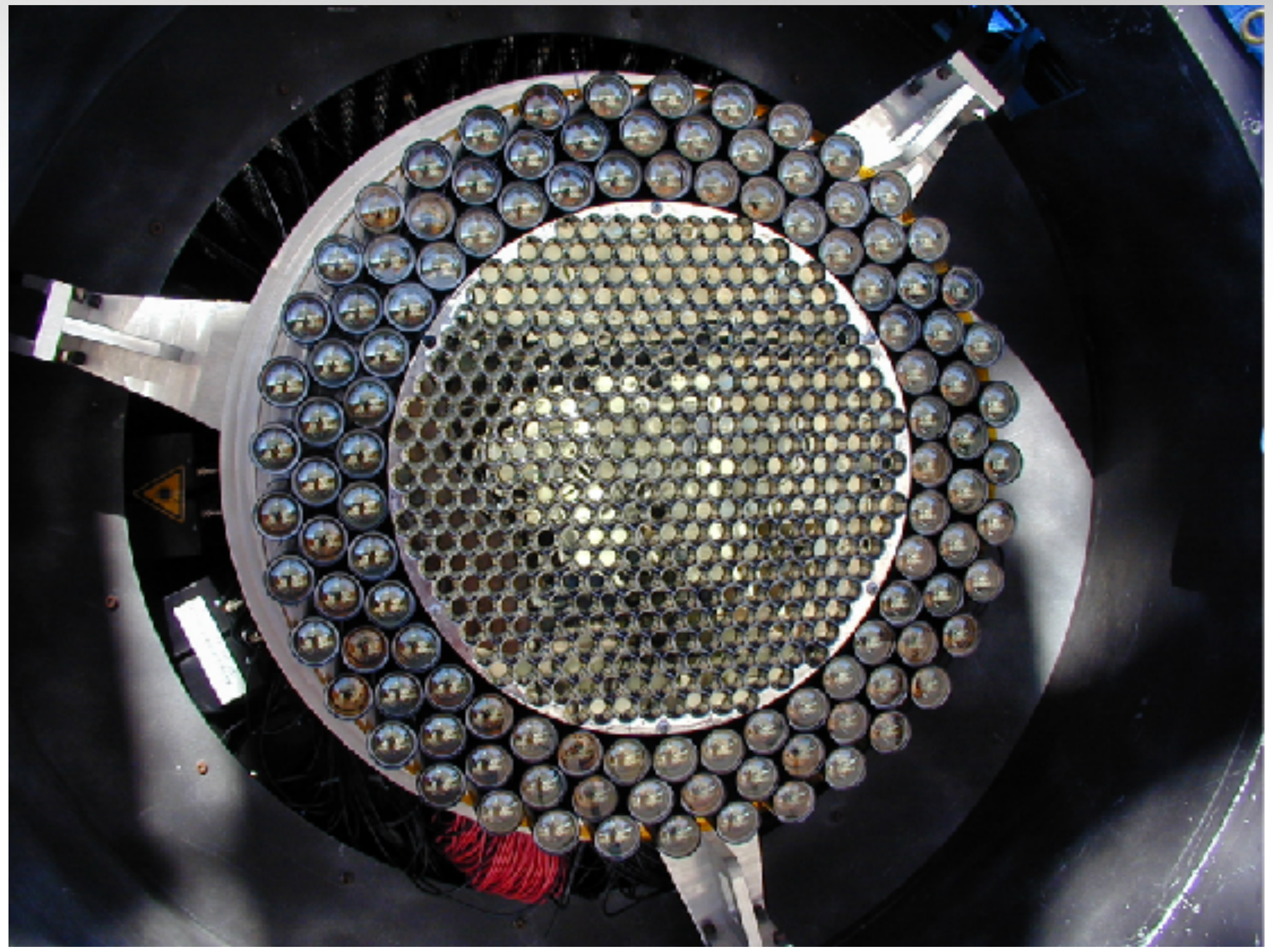

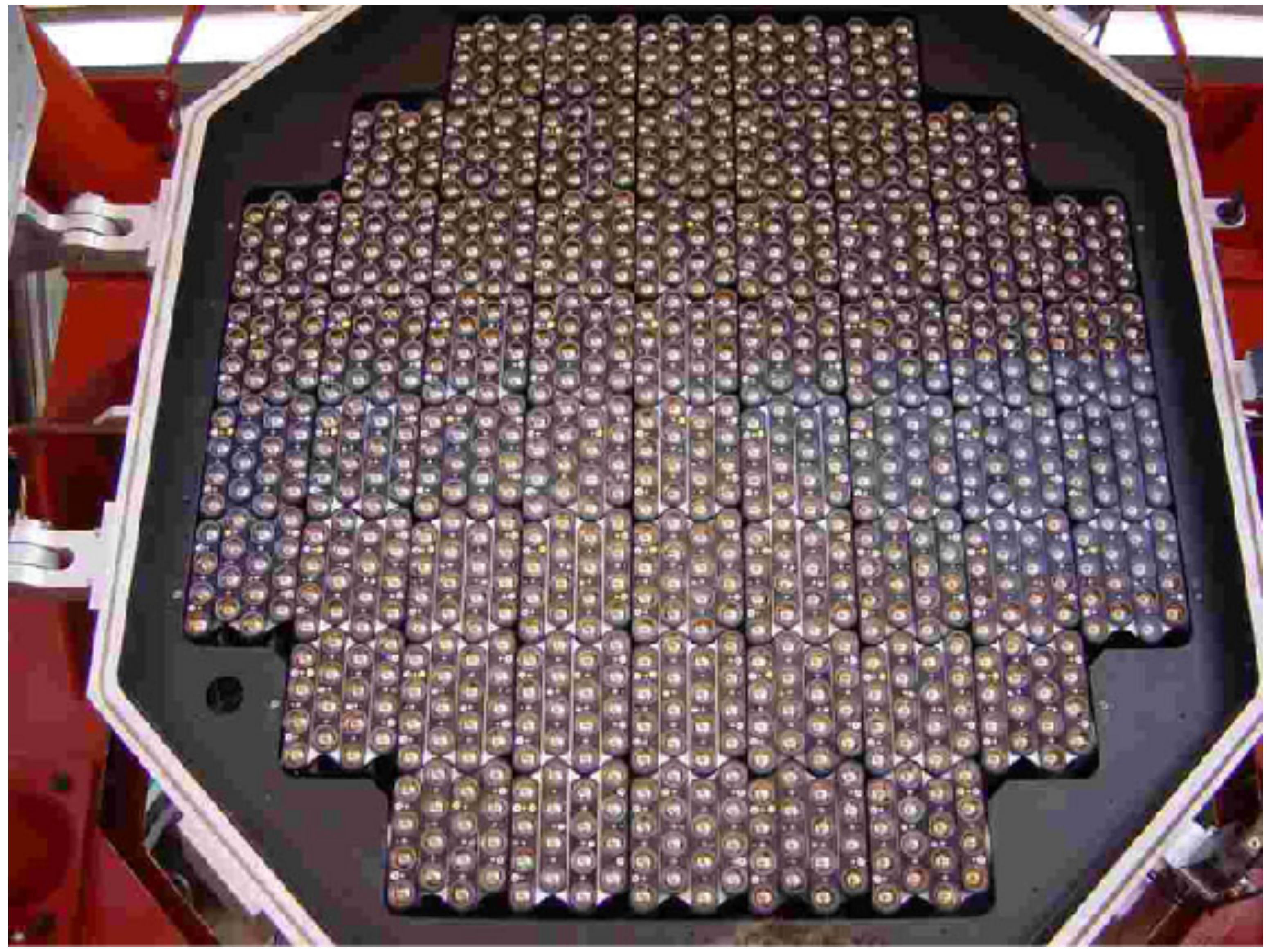

Build cameras out of *multiple photomultiplier pixels*!

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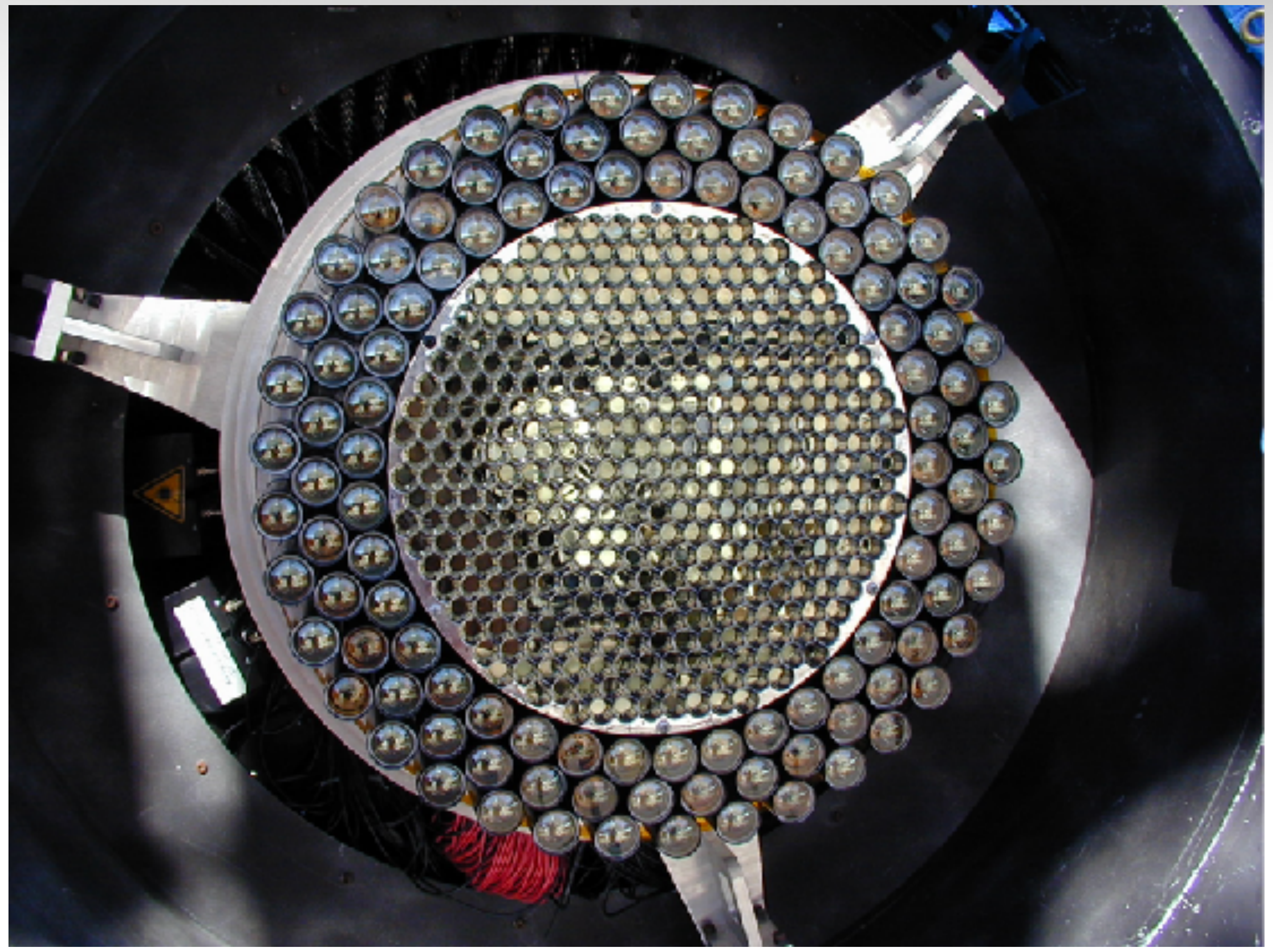

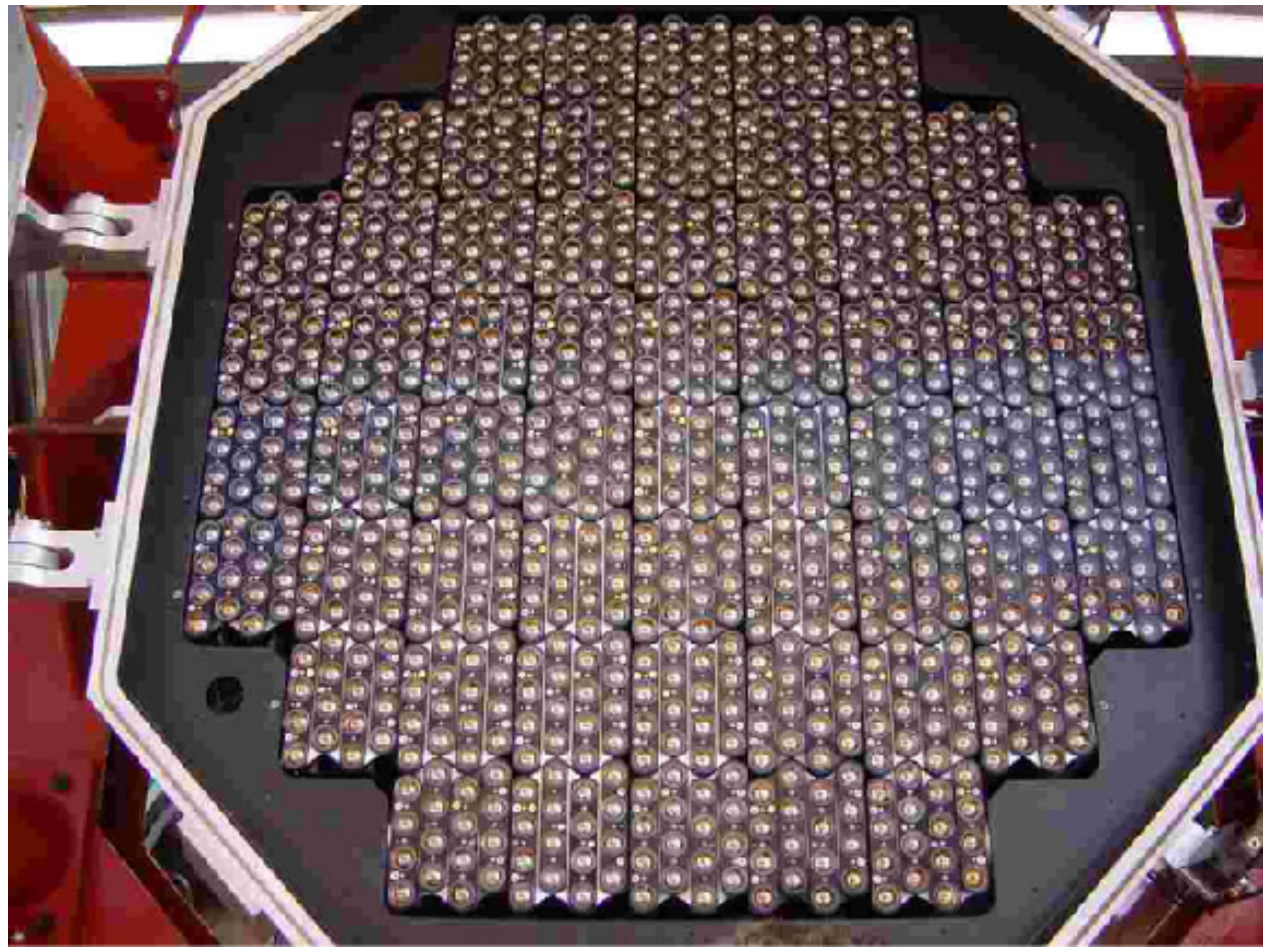

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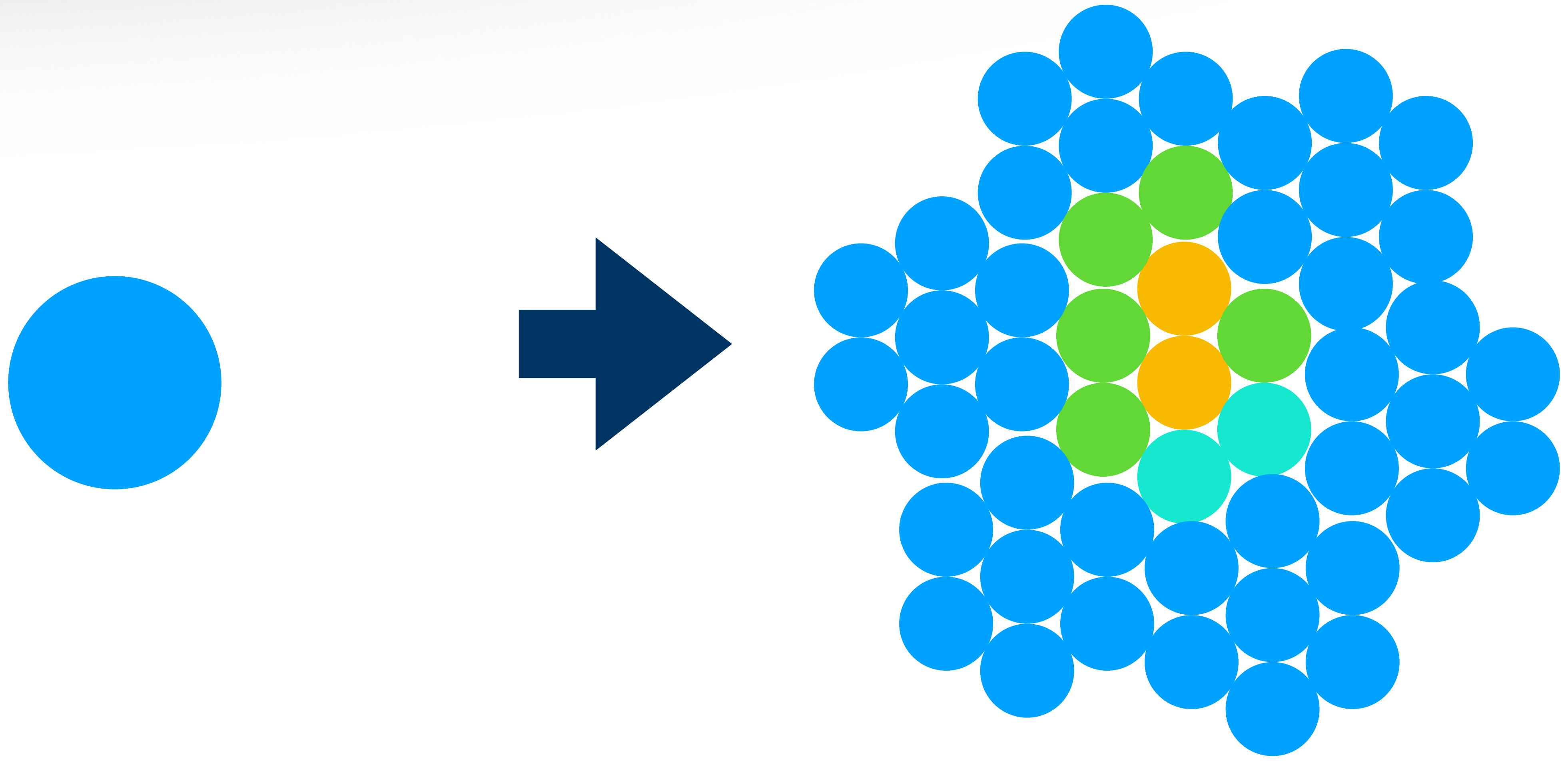

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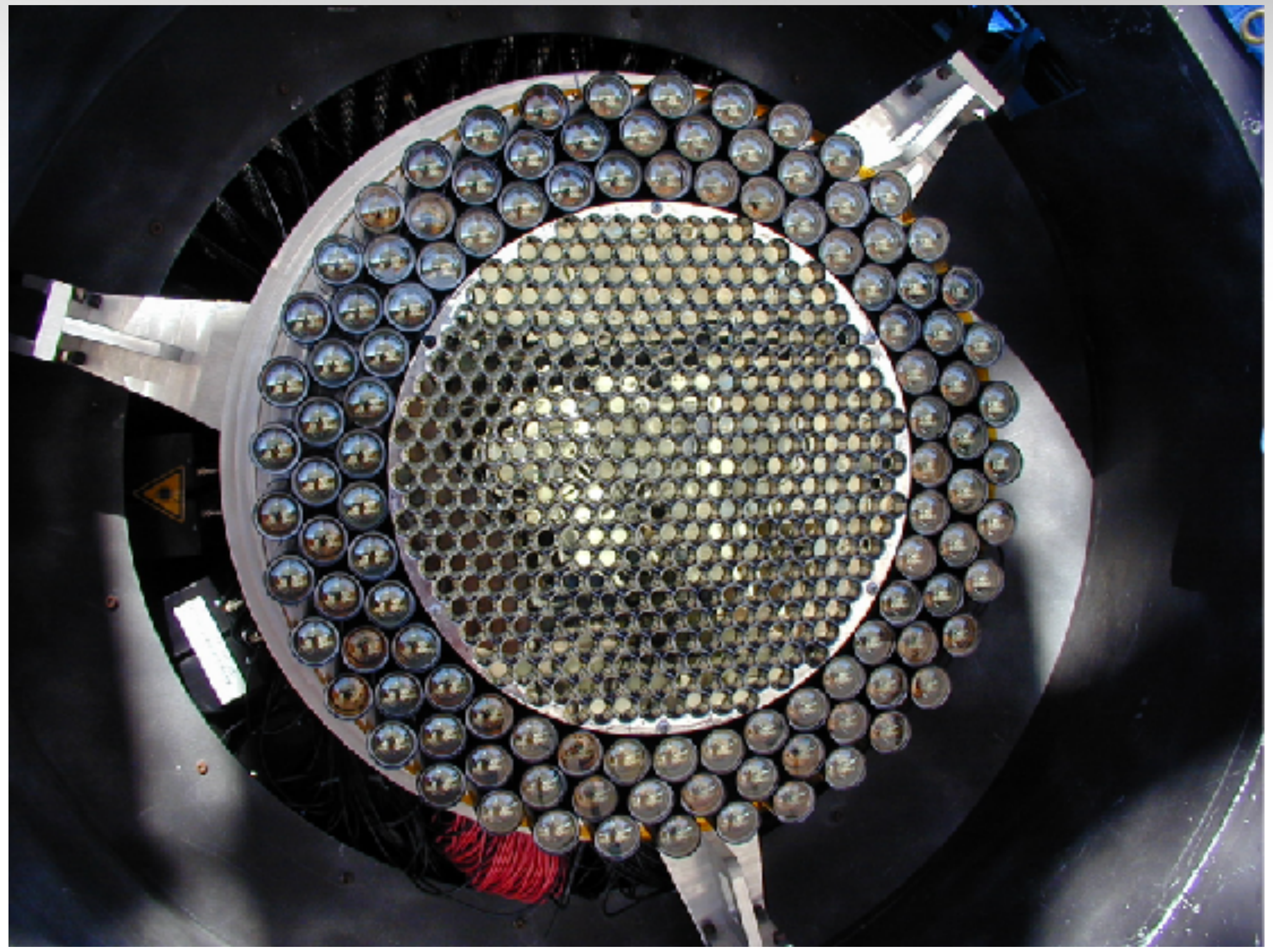

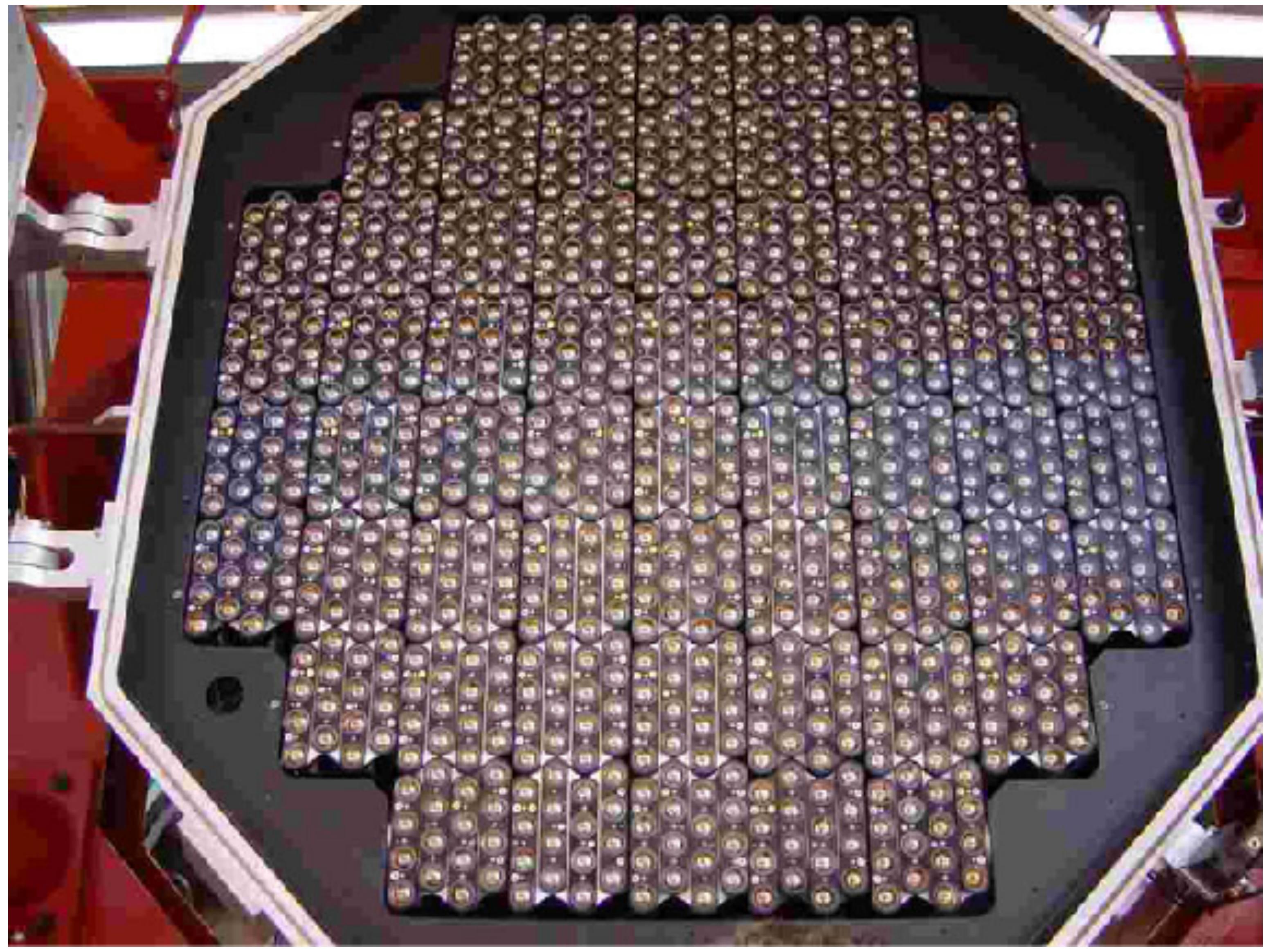

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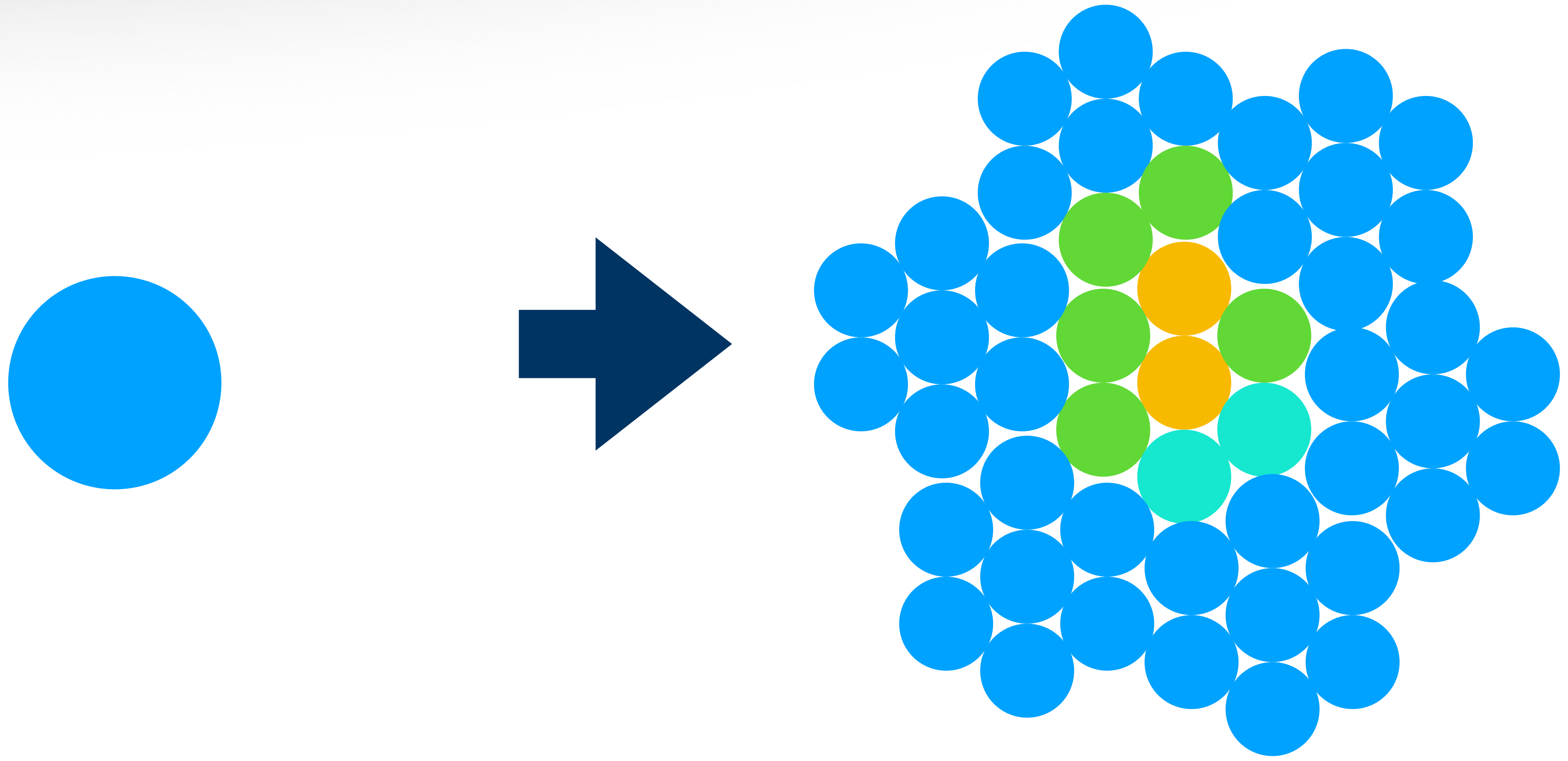

NSB Light Rejection :

- Require multiple neighbor pixels to have a signal in them → removes most fluctuations from NSB

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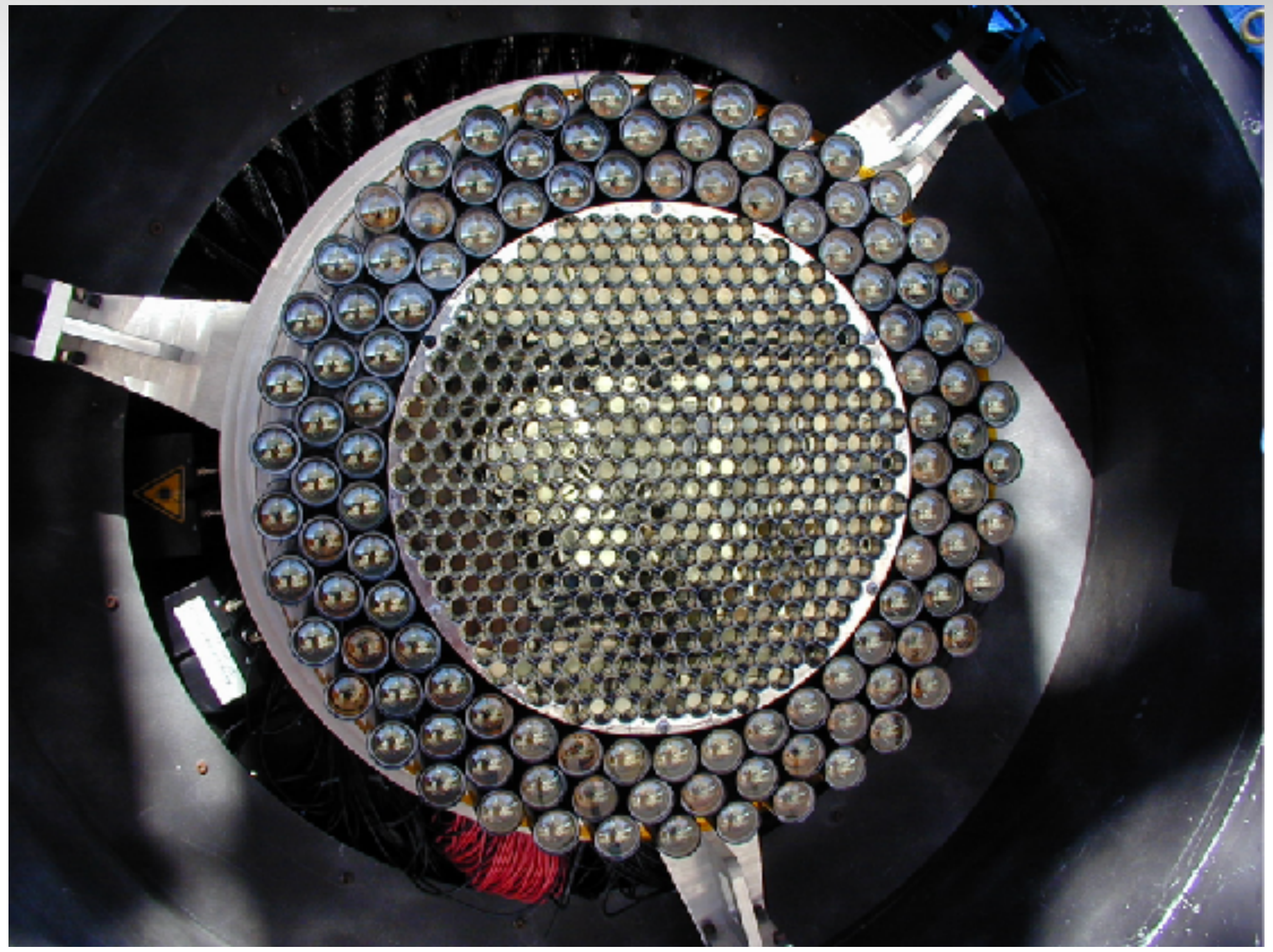

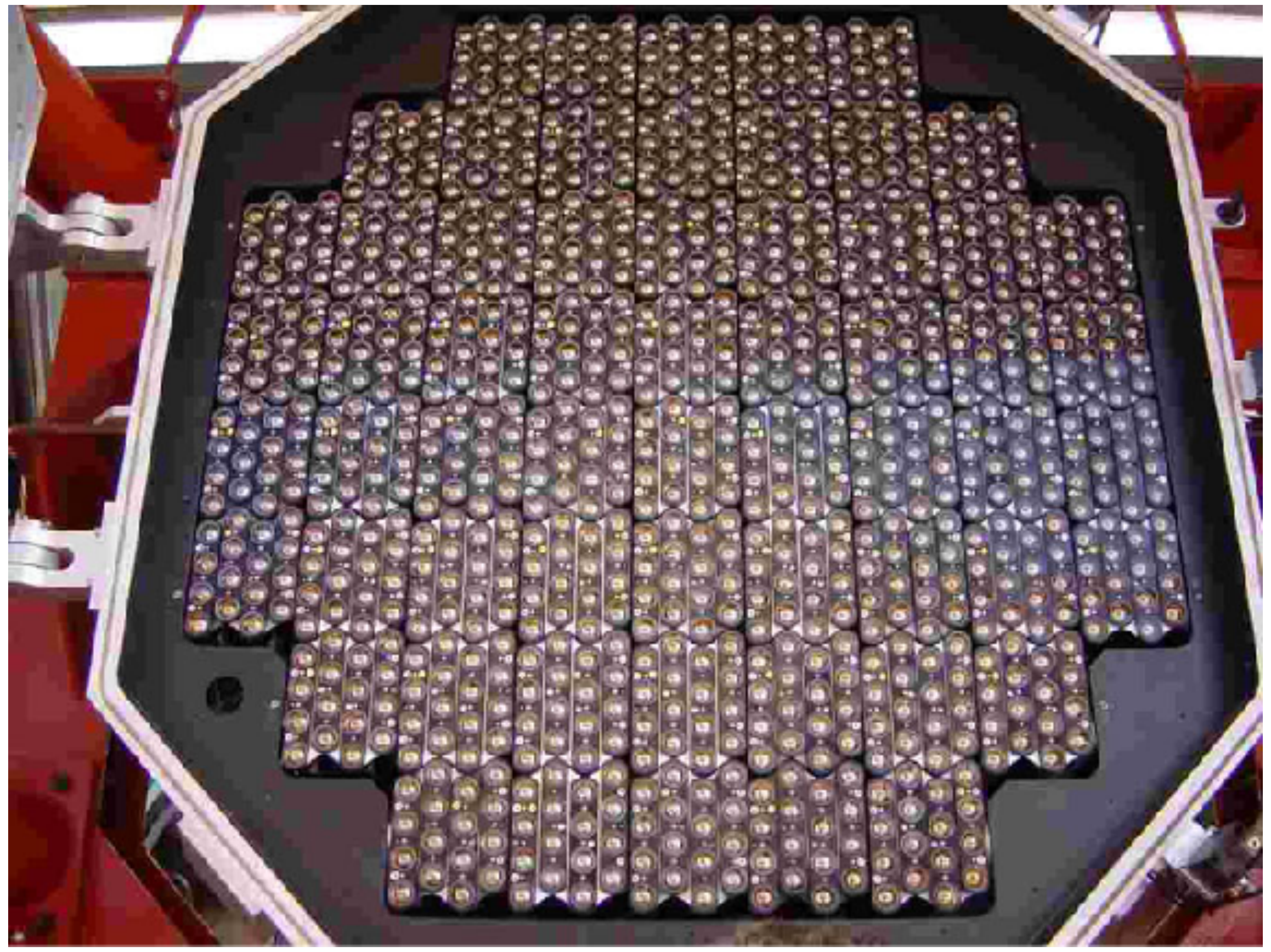

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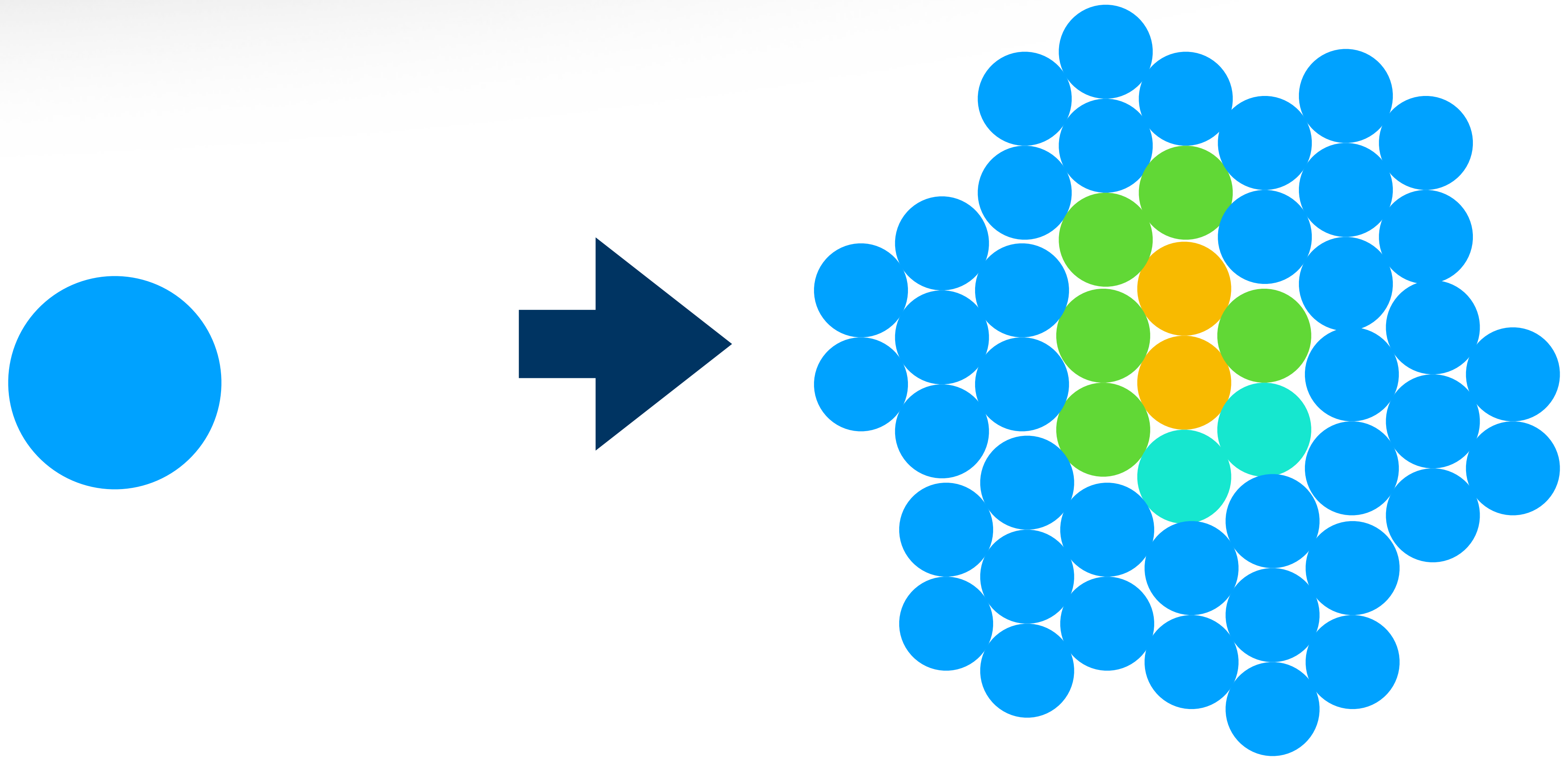

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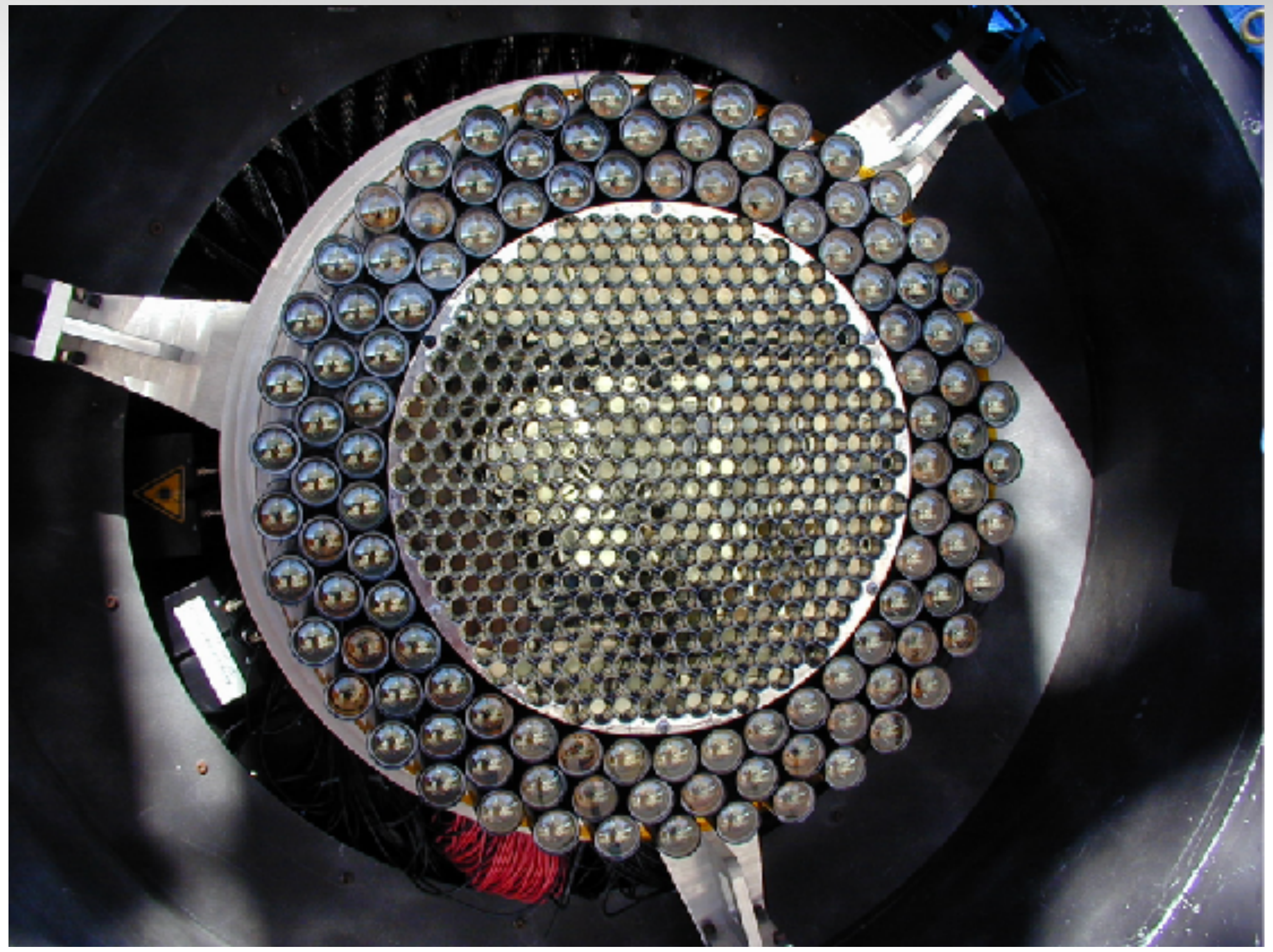
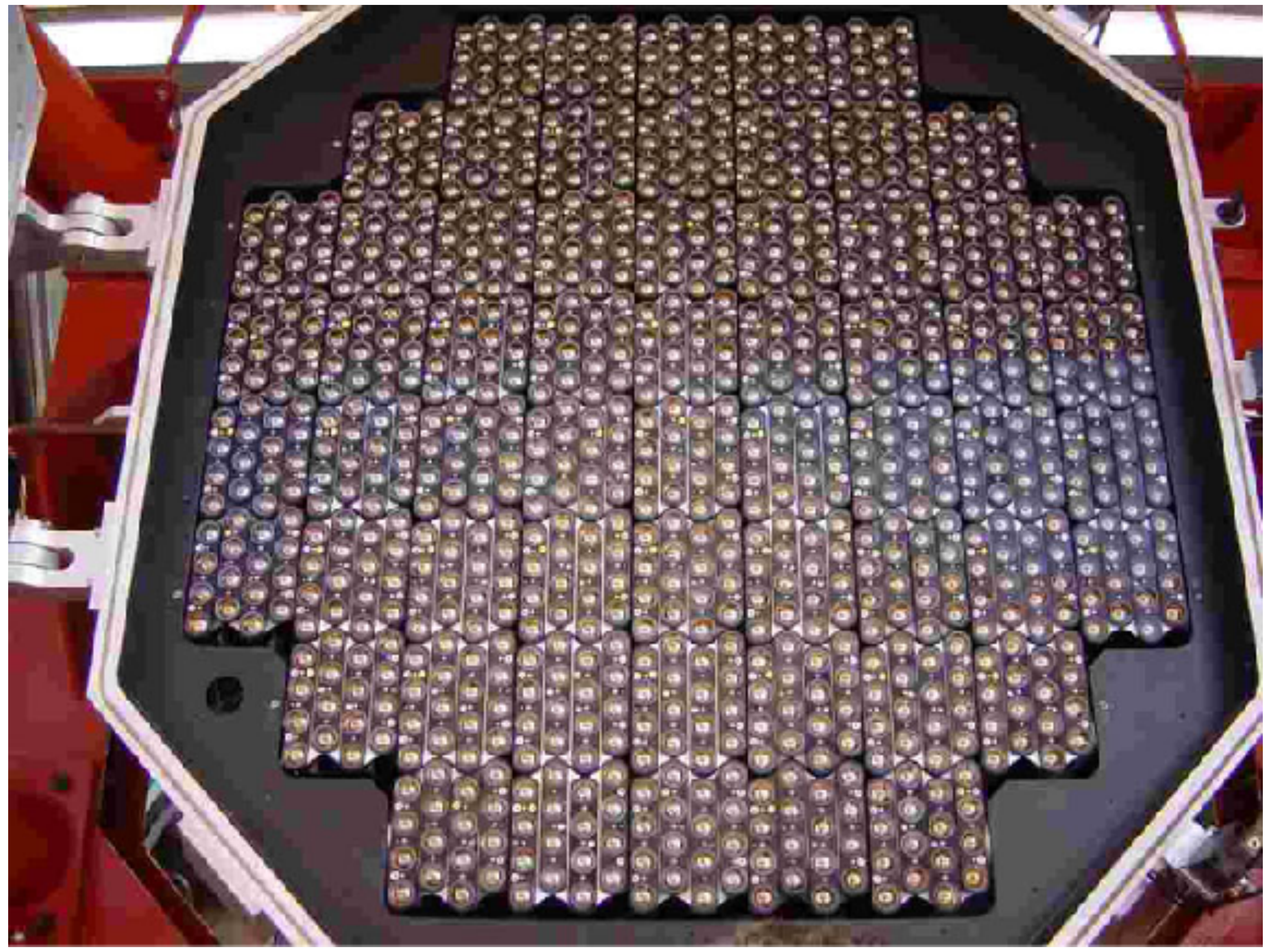
Cosmic Ray Background Rejection:

- Shape of shower, in particular its **width** tells you about the lateral shower size:
- wider = **more likely a cosmic ray** (transverse momentum from pion production + multiple sub-showers)

Breakthrough #1: Shower *imaging*





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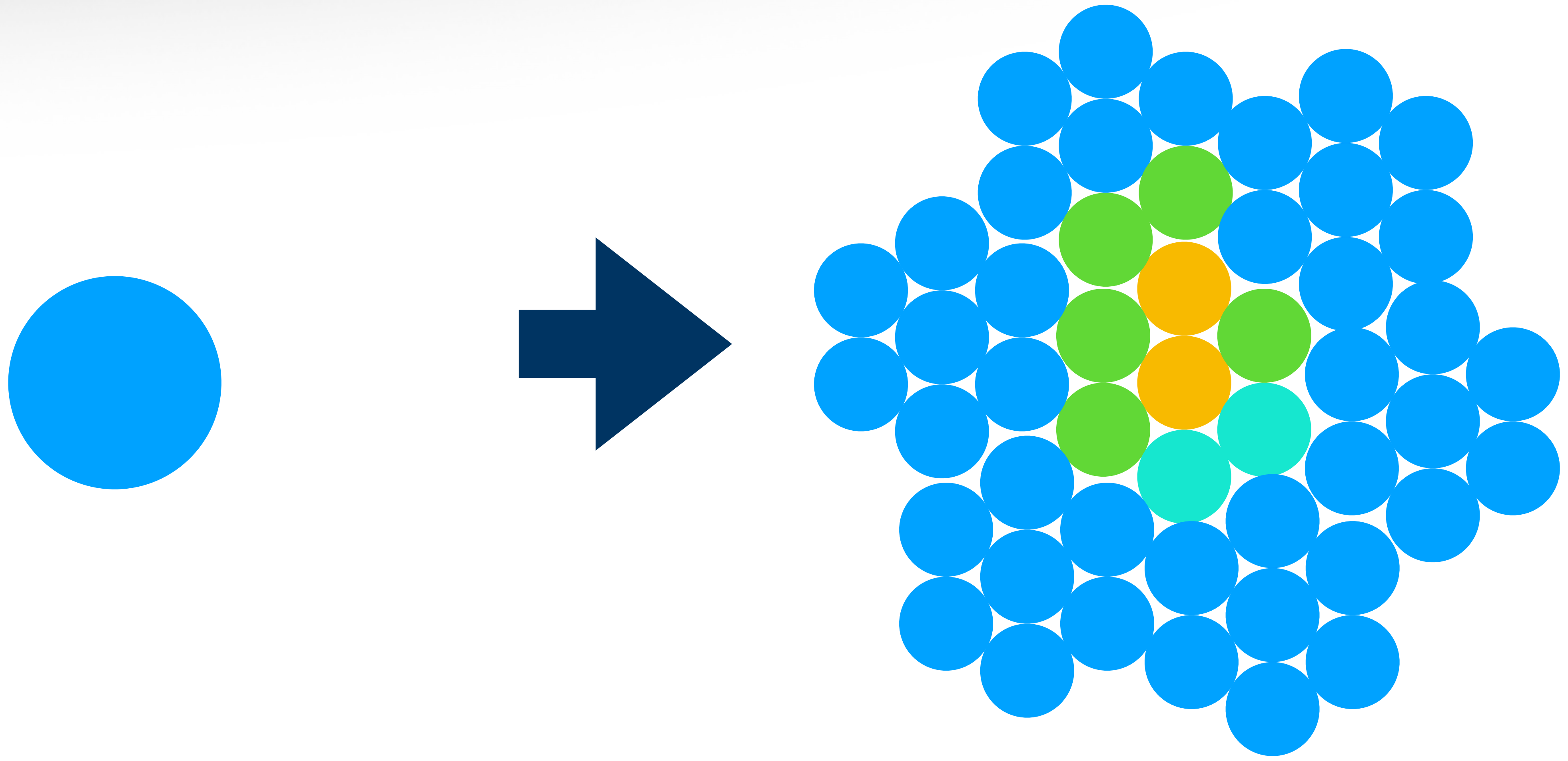

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Energy measurement:

- $E \propto \sum_{pixels} I_{pix}$

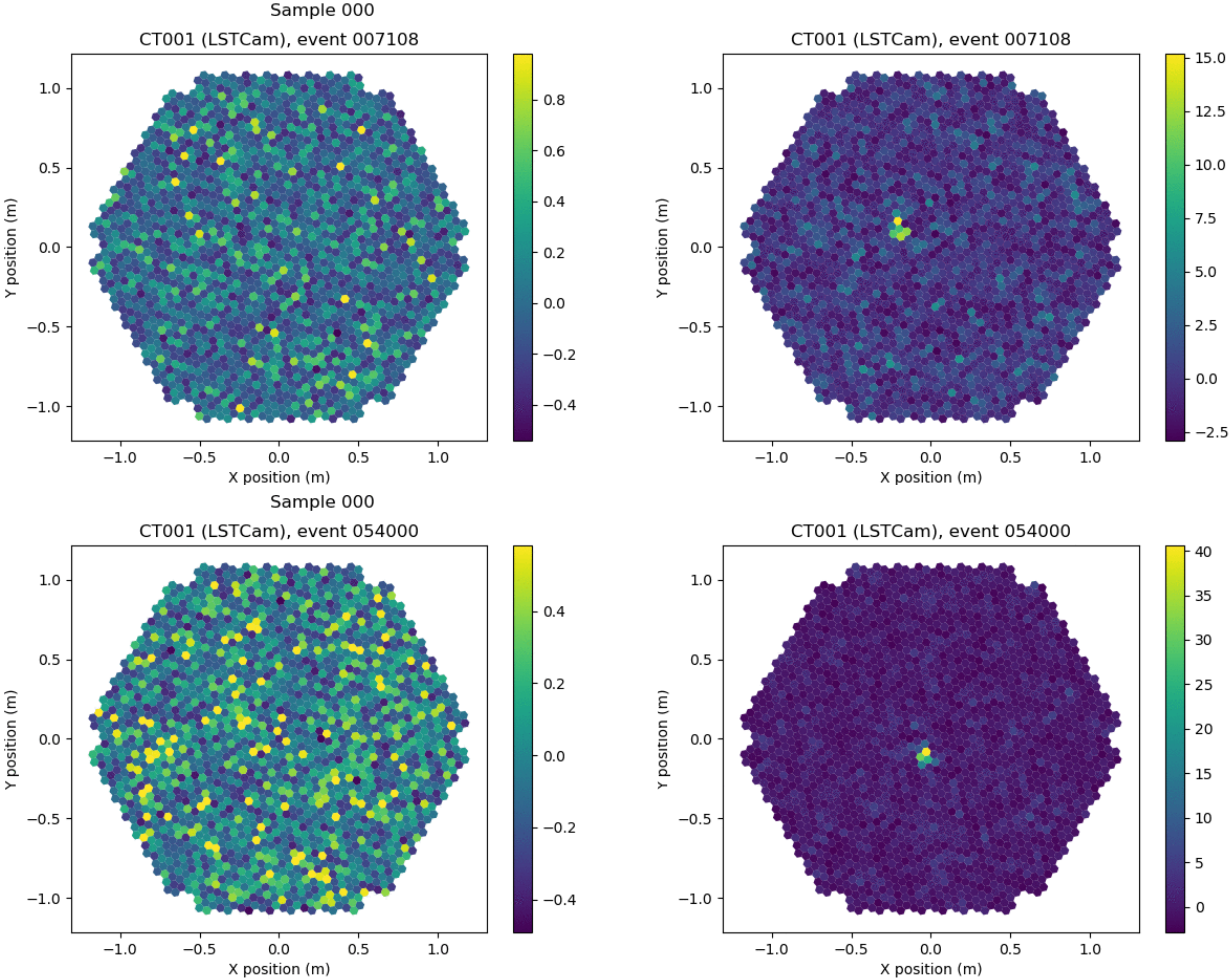
Single Telescope View

nanosecond samples ***time-integrated***

gamma ray

cosmic ray

(background)



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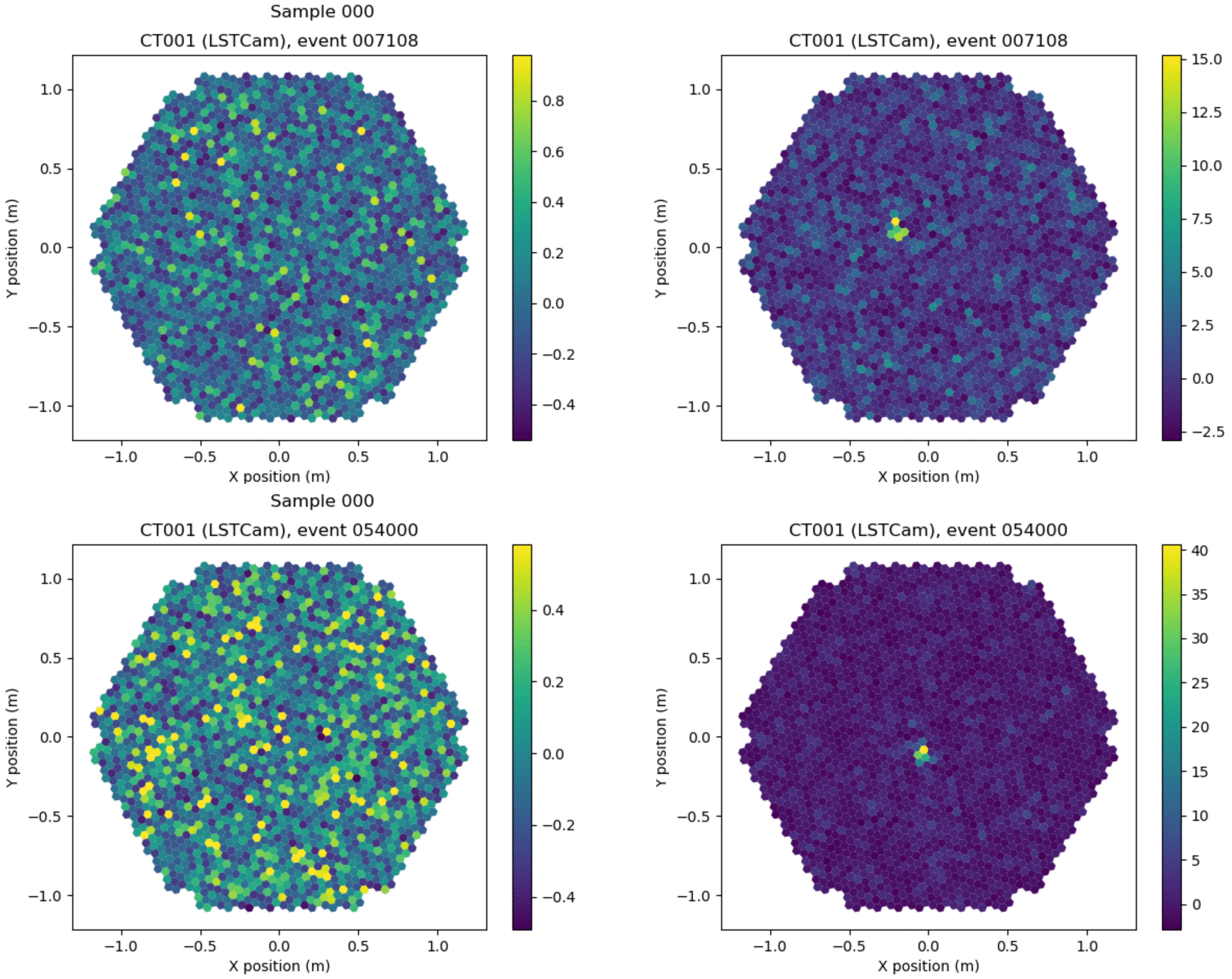
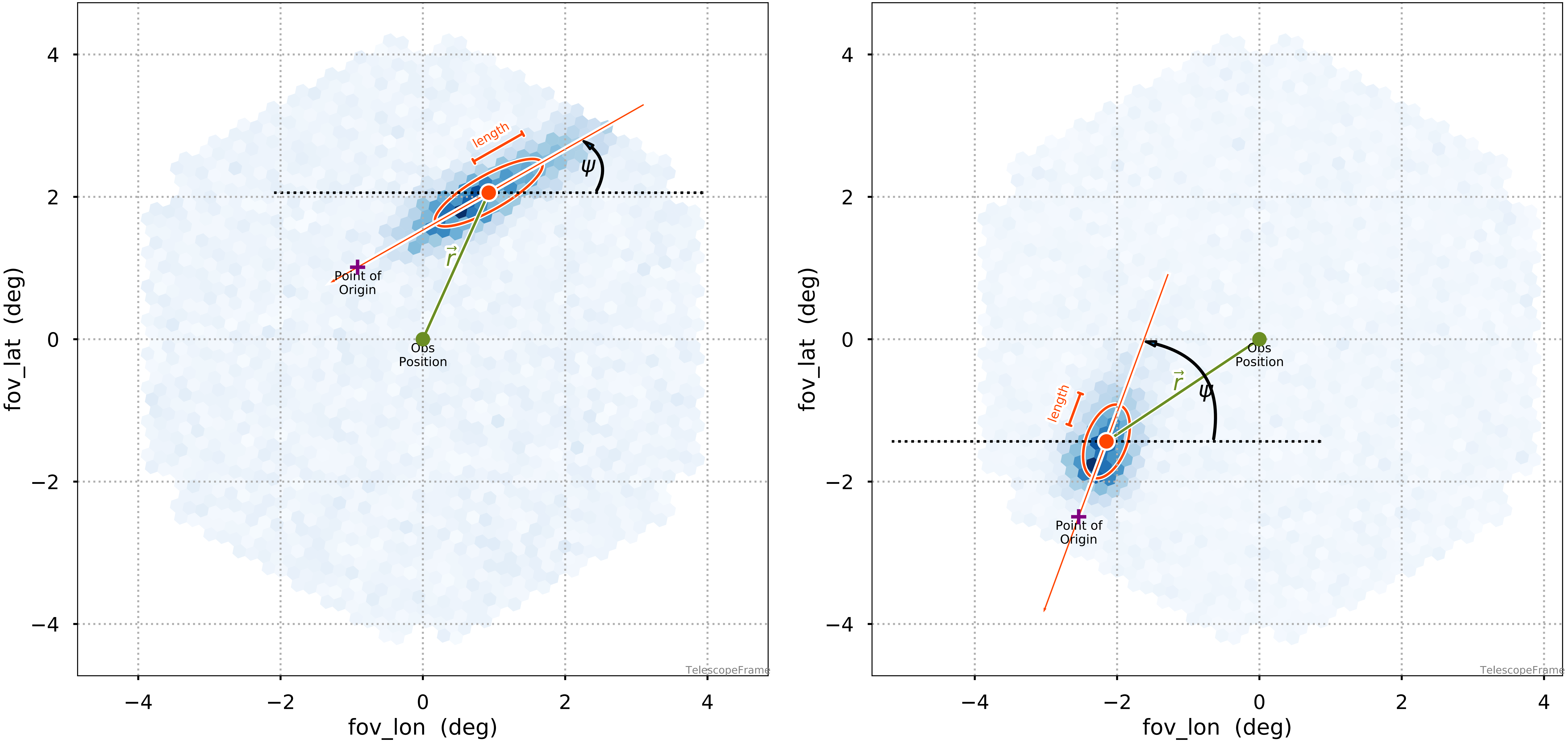


Determine shower energy and origin on sky

- Shower origin must be along the image axis.
- Related to ratio of width/length and energy/intensit



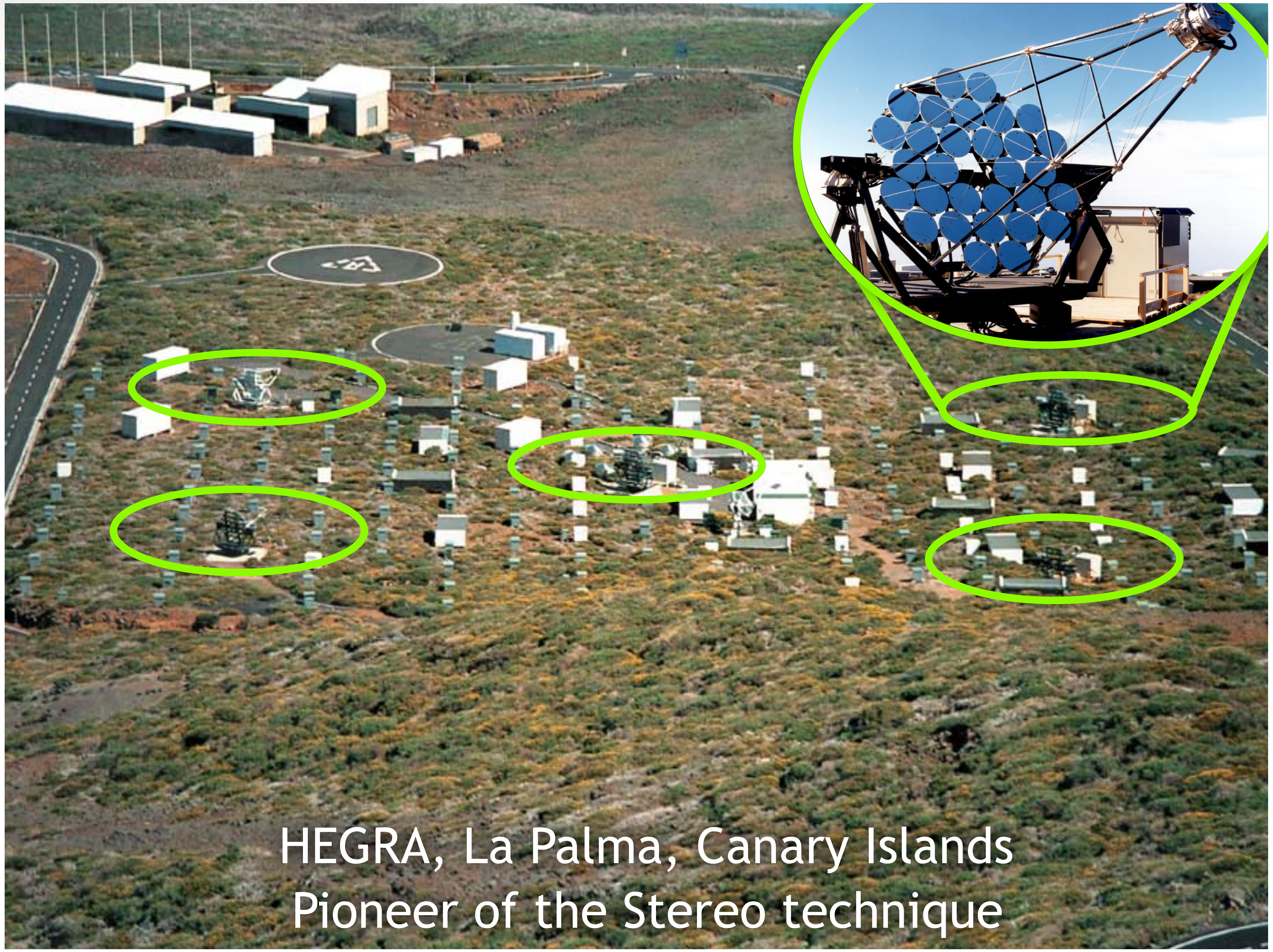
Breakthrough #2: Stereo Imaging

For a single telescope:

- Collection area ≈ Light pool size (100m radius)
- Only rough direction reconstruction → large PSF
- No easy reconstruction of impact distance from telescope
- Energy resolution poor

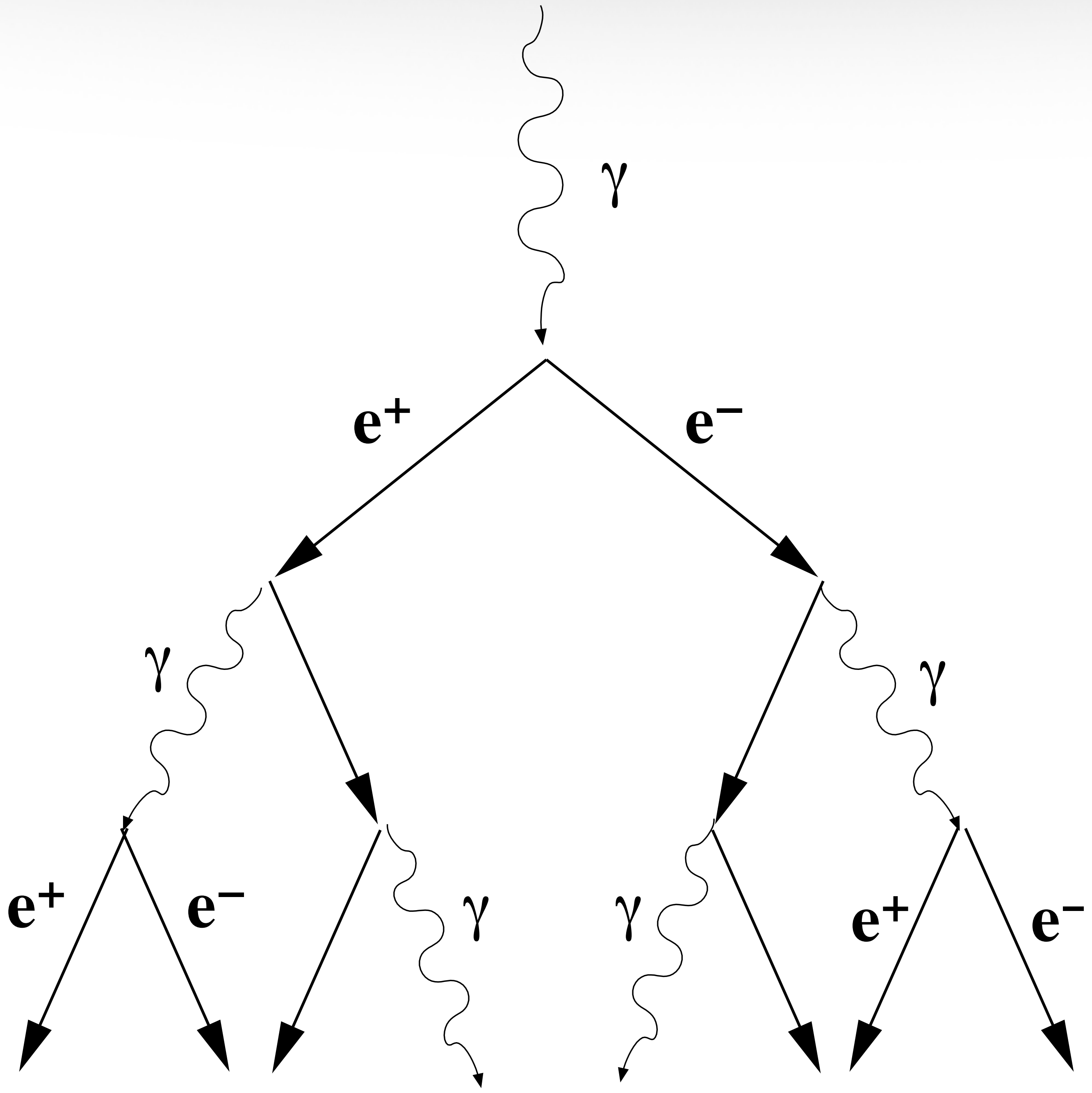
Adding multiple telescopes:

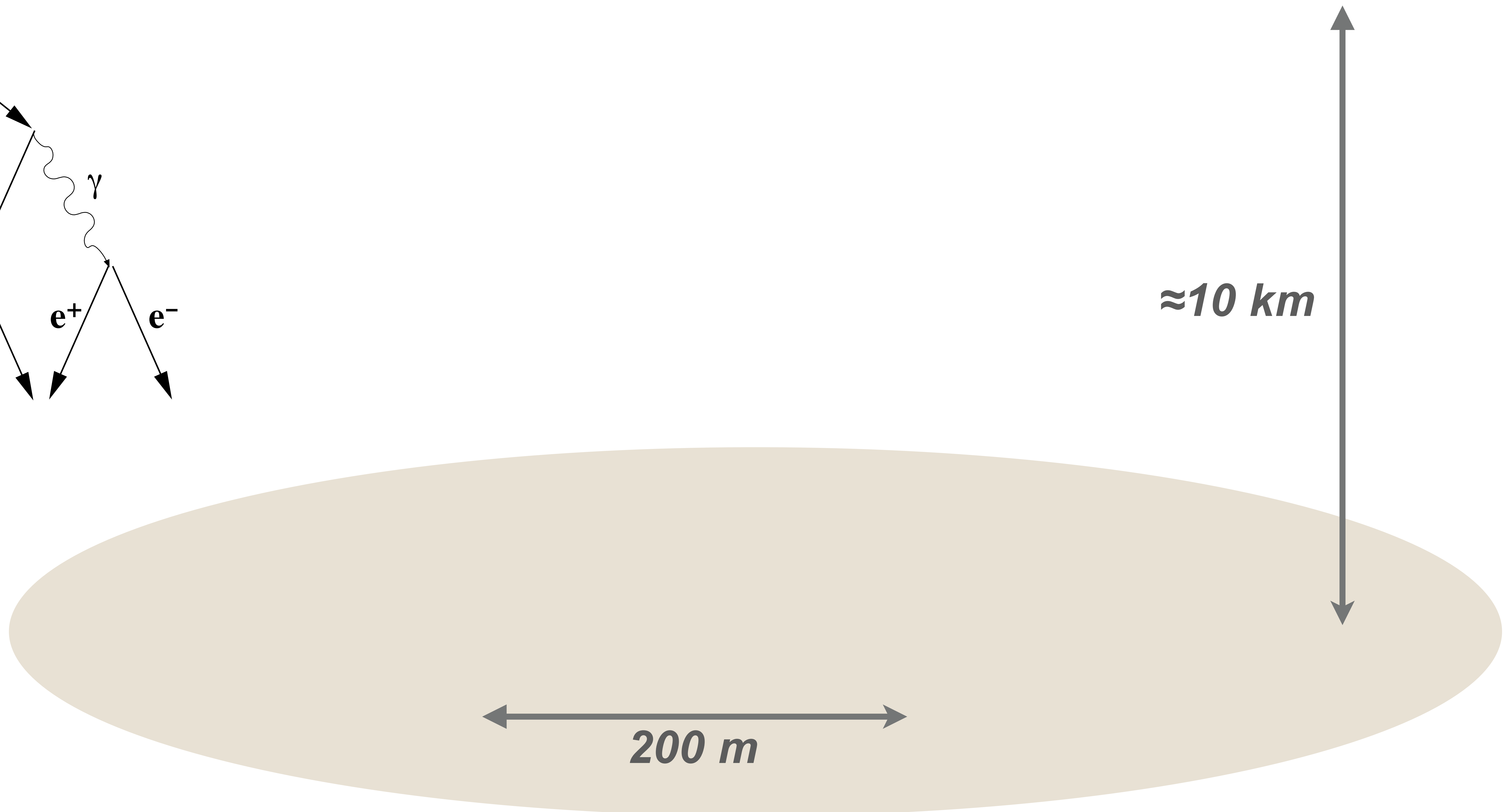
- Effective area increases by size of array
- More accurate direction reconstruction
- More accurate energy reconstruction
- Better Cosmic-Ray discrimination



HEGRA, La Palma, Canary Islands
Pioneer of the Stereo technique

Mono Imaging



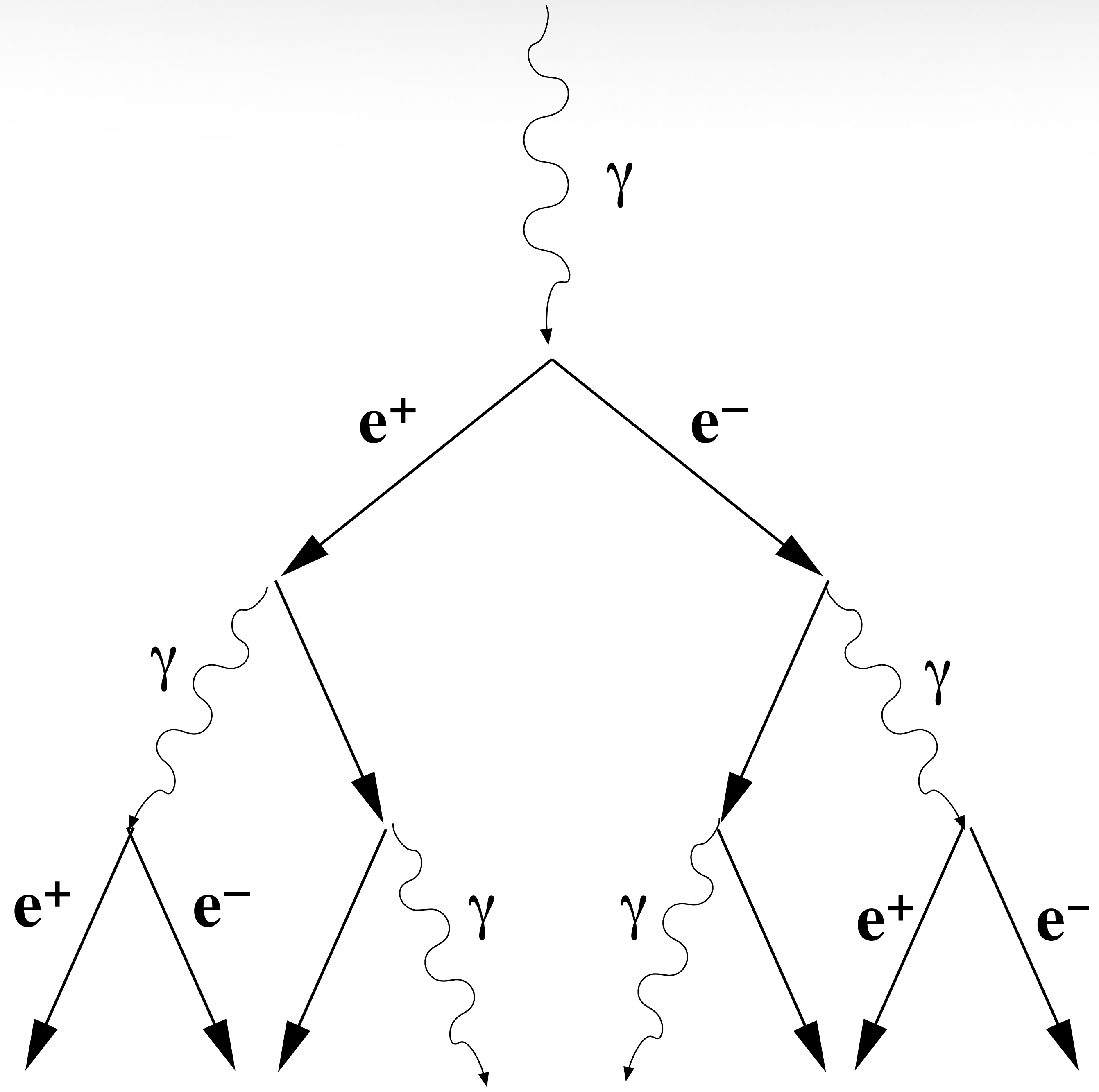


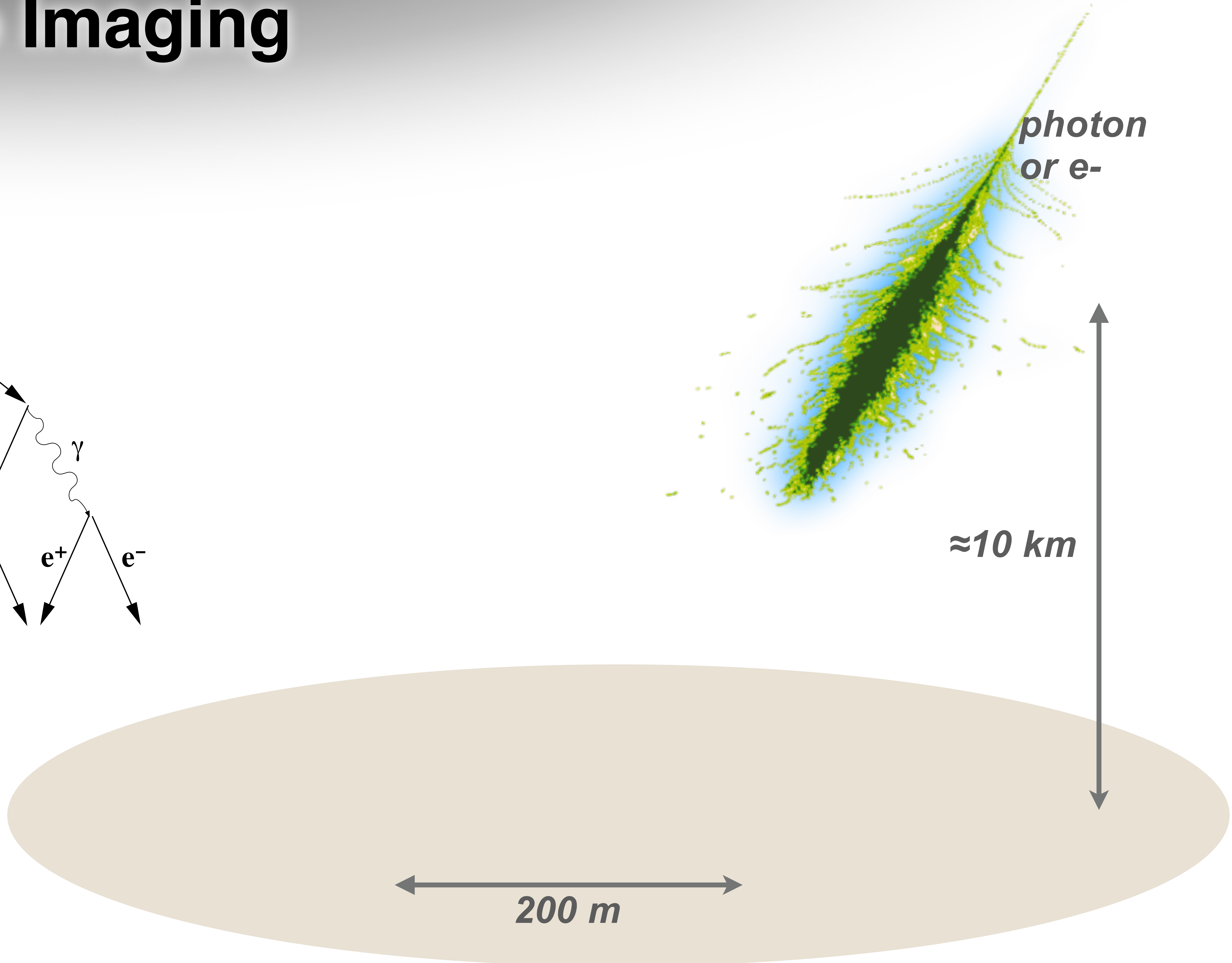
photon
or e-

≈10 km

200 m

Mono Imaging





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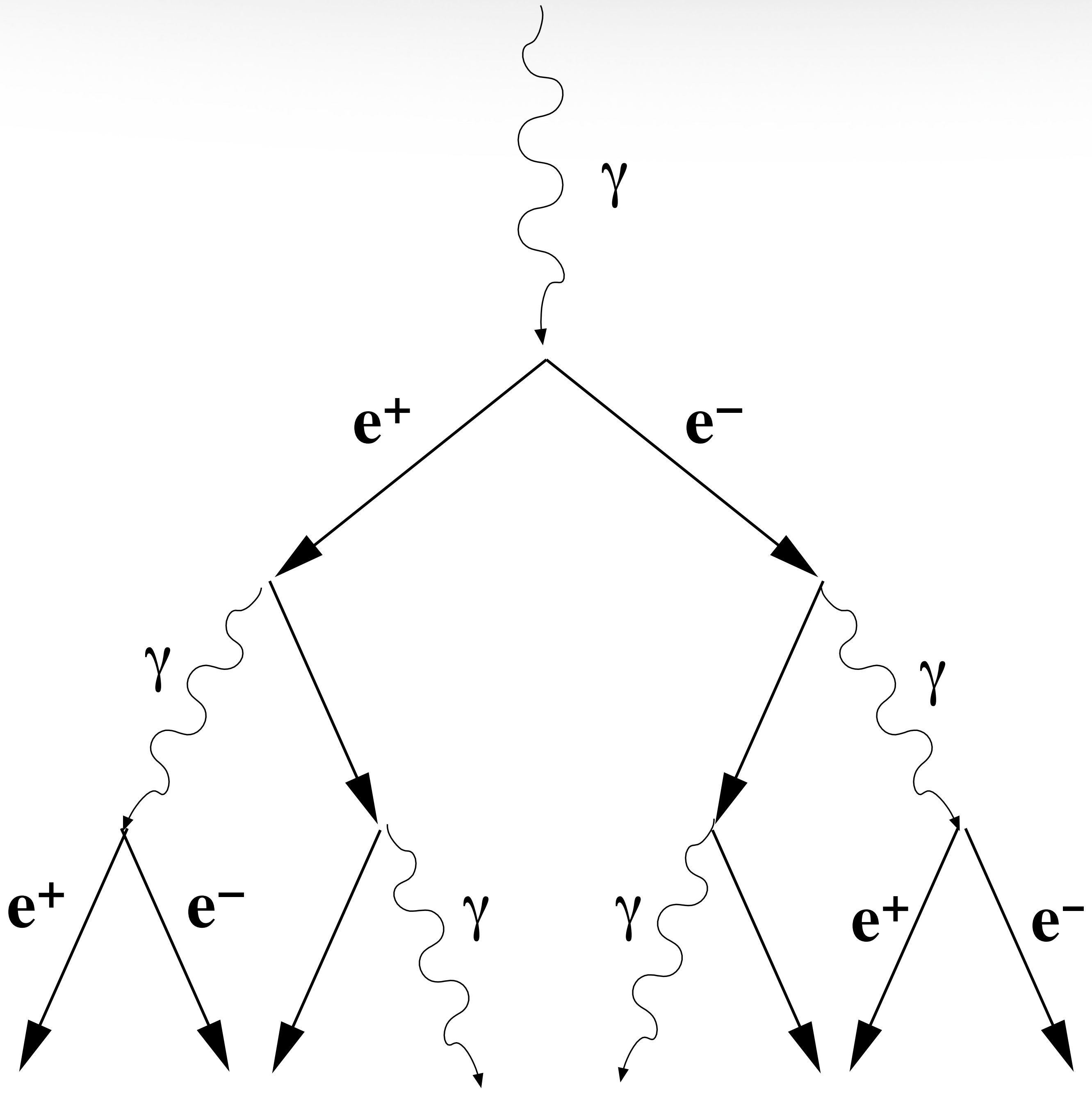

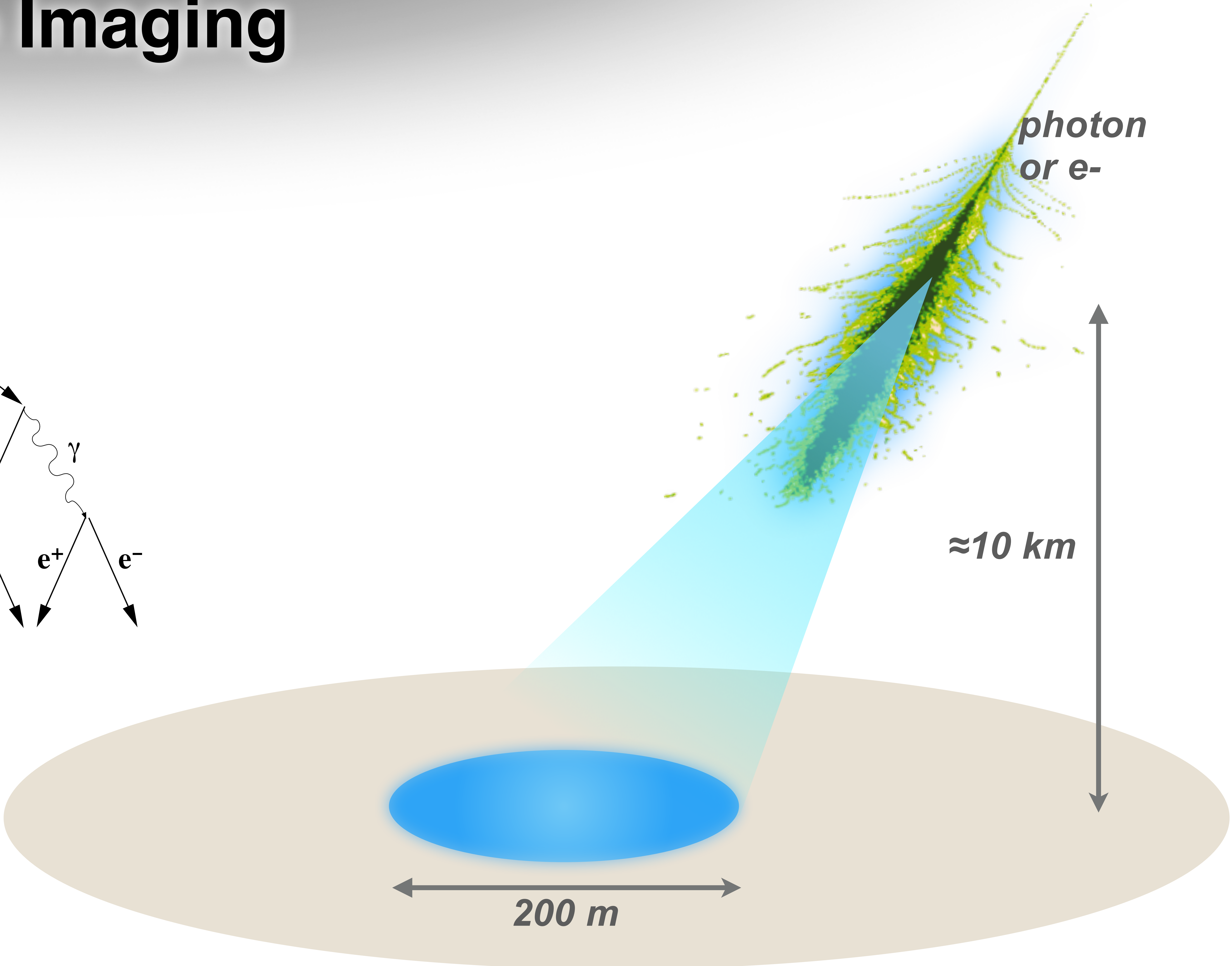

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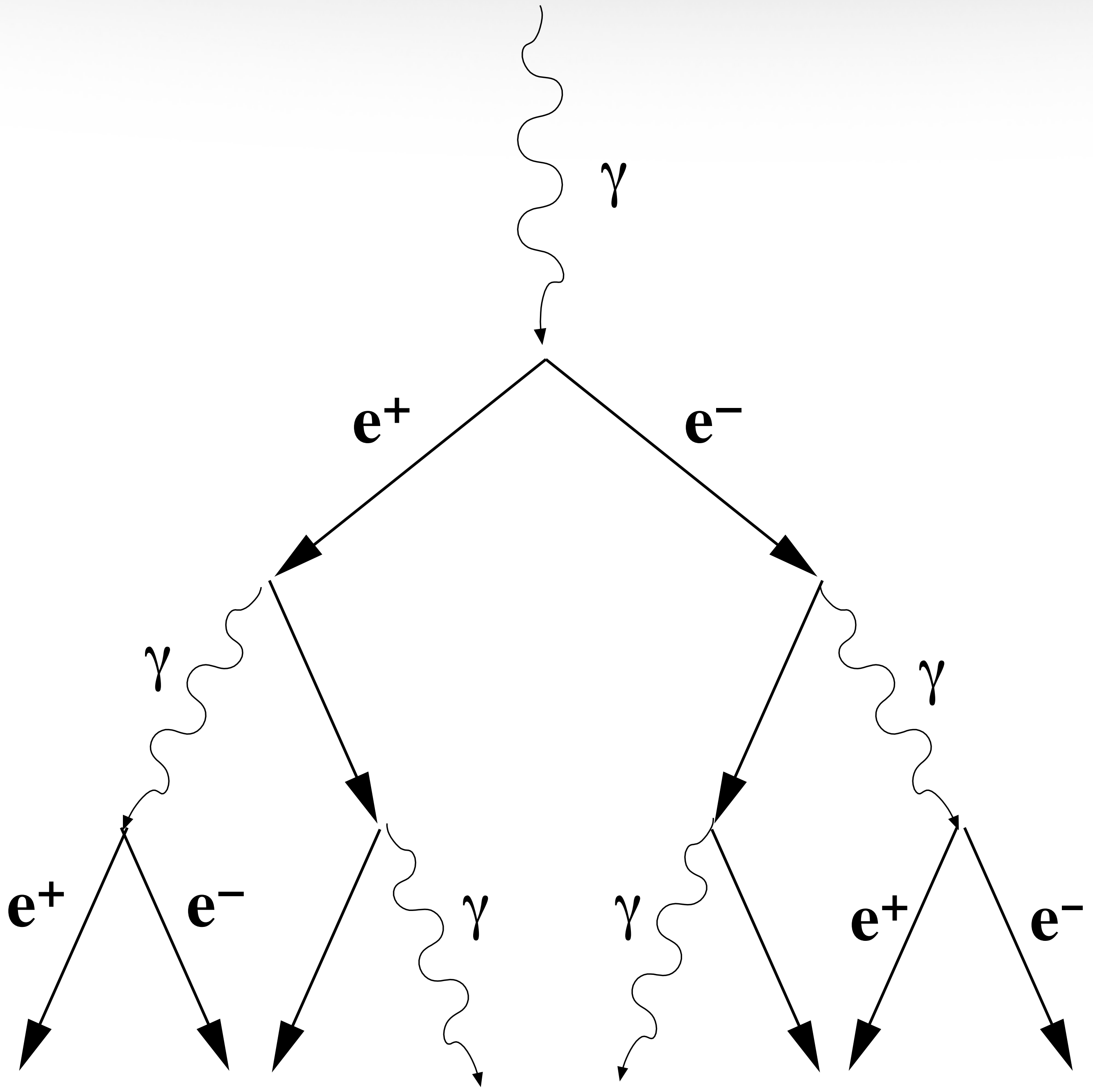

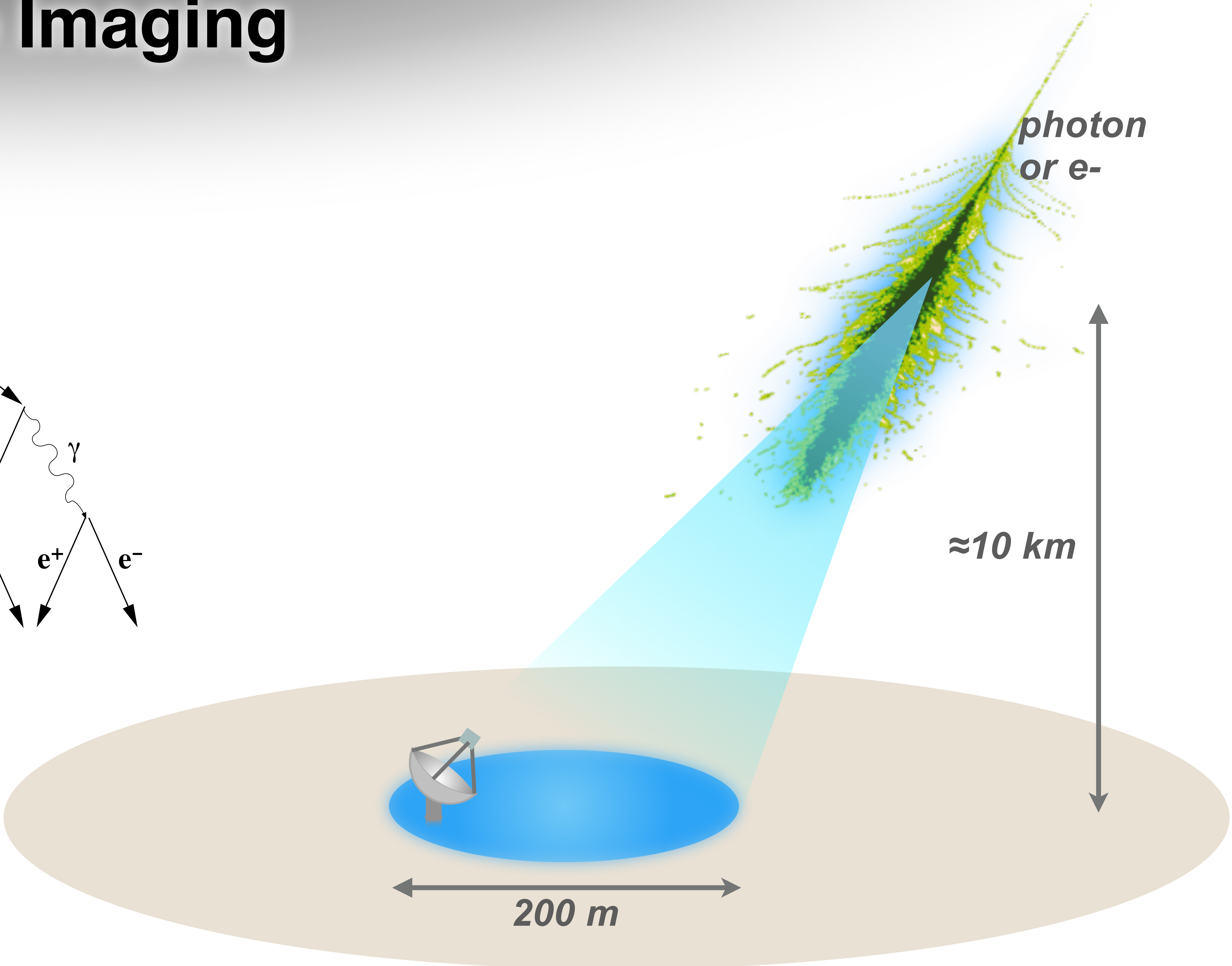

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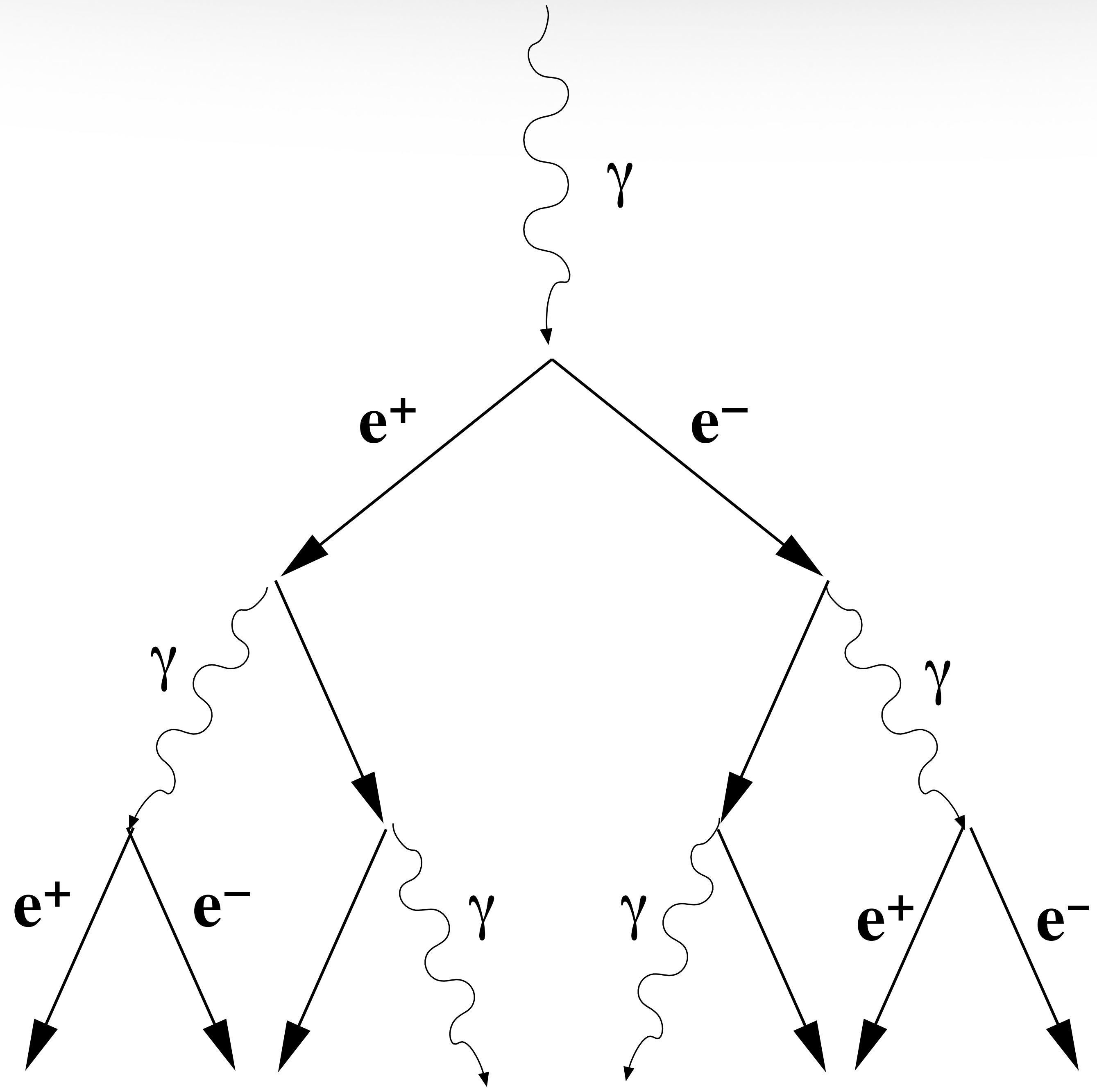
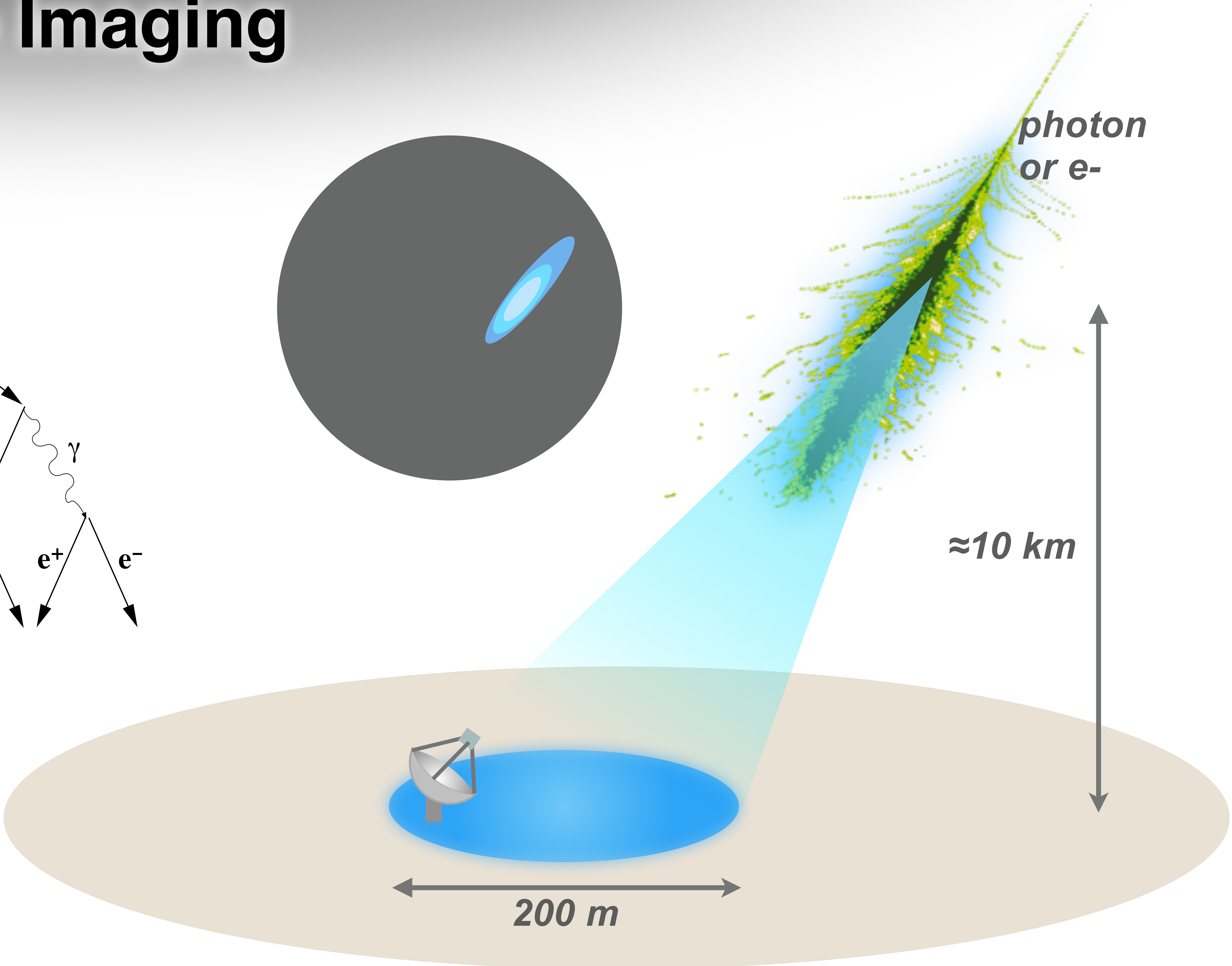
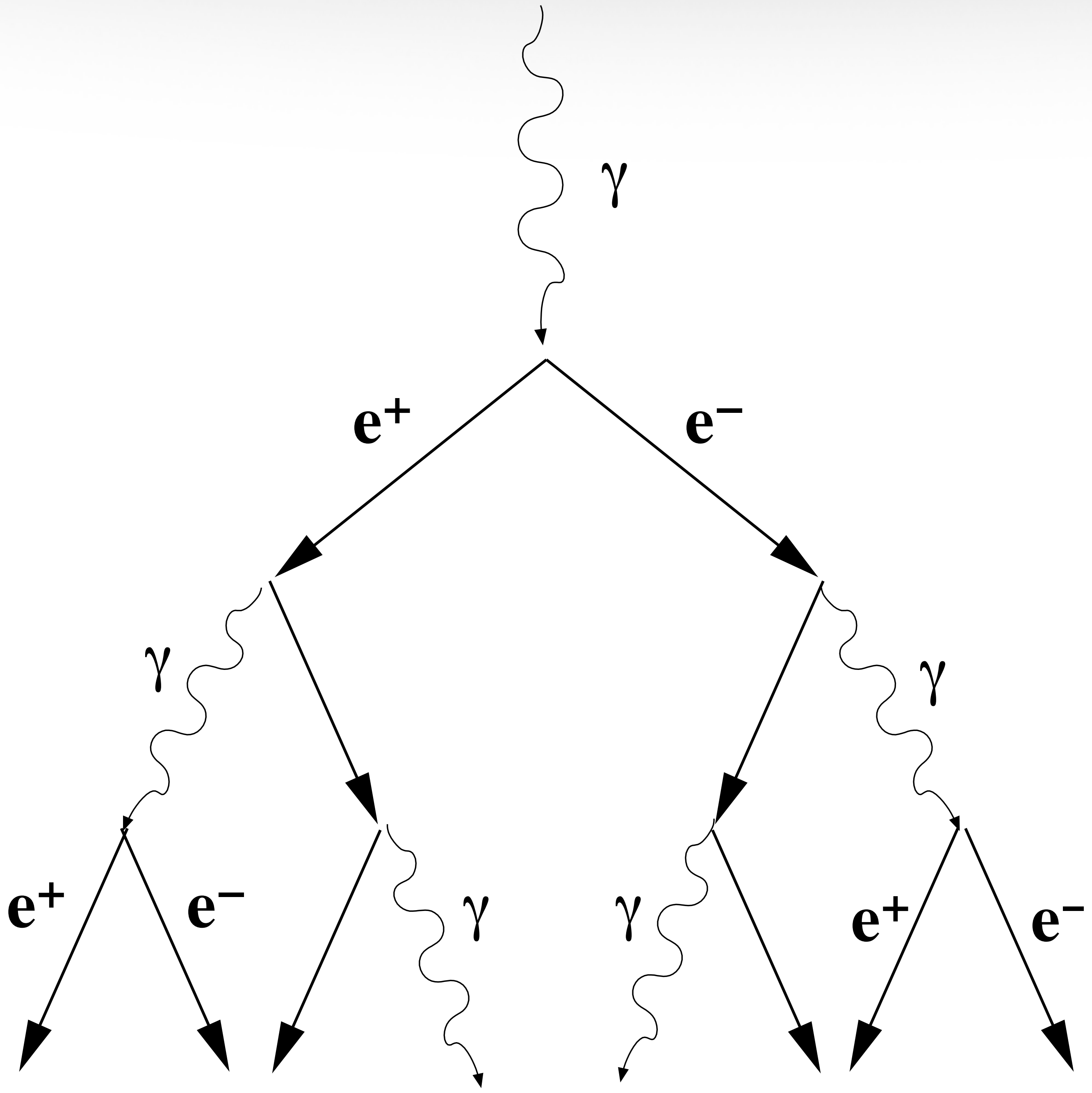
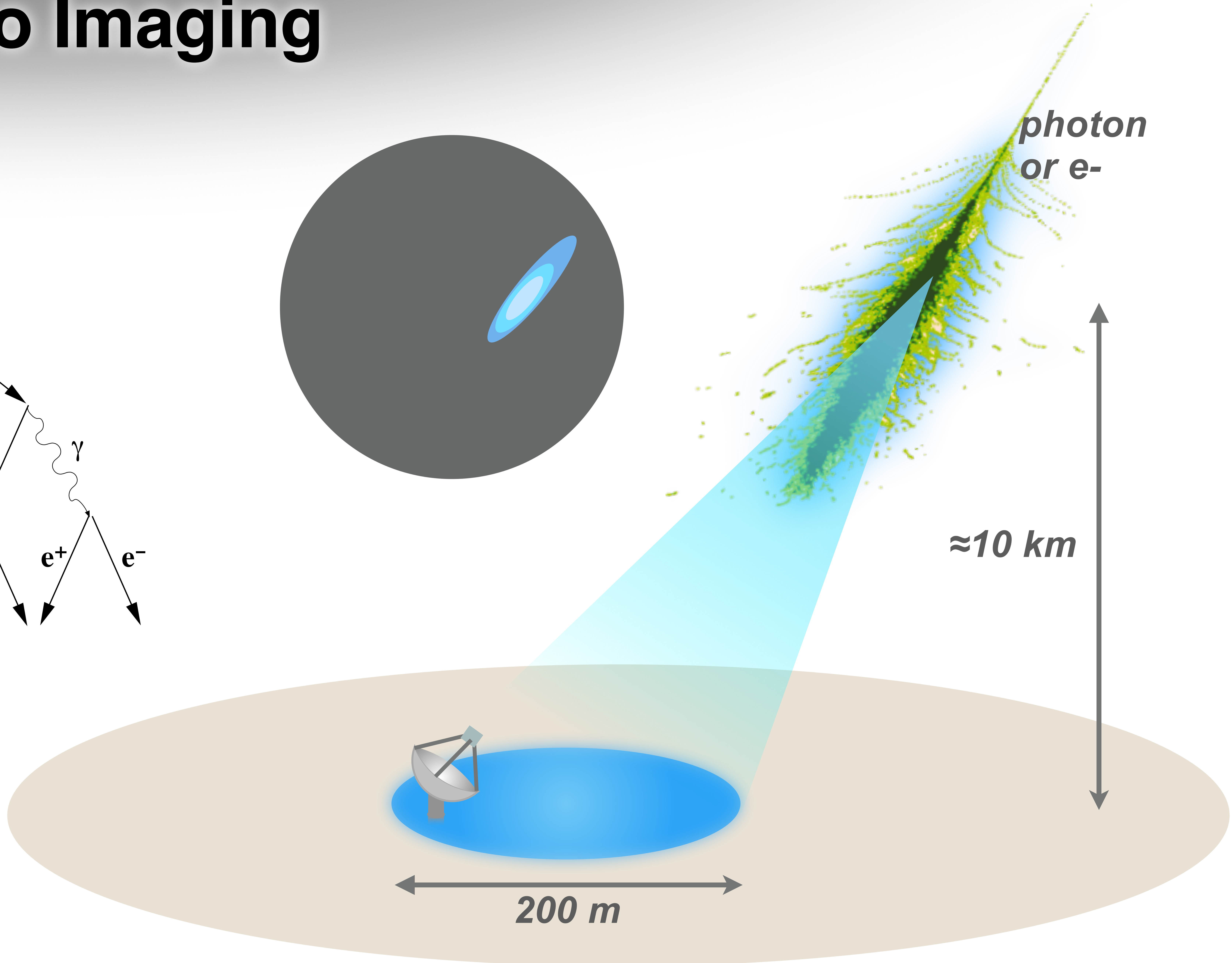


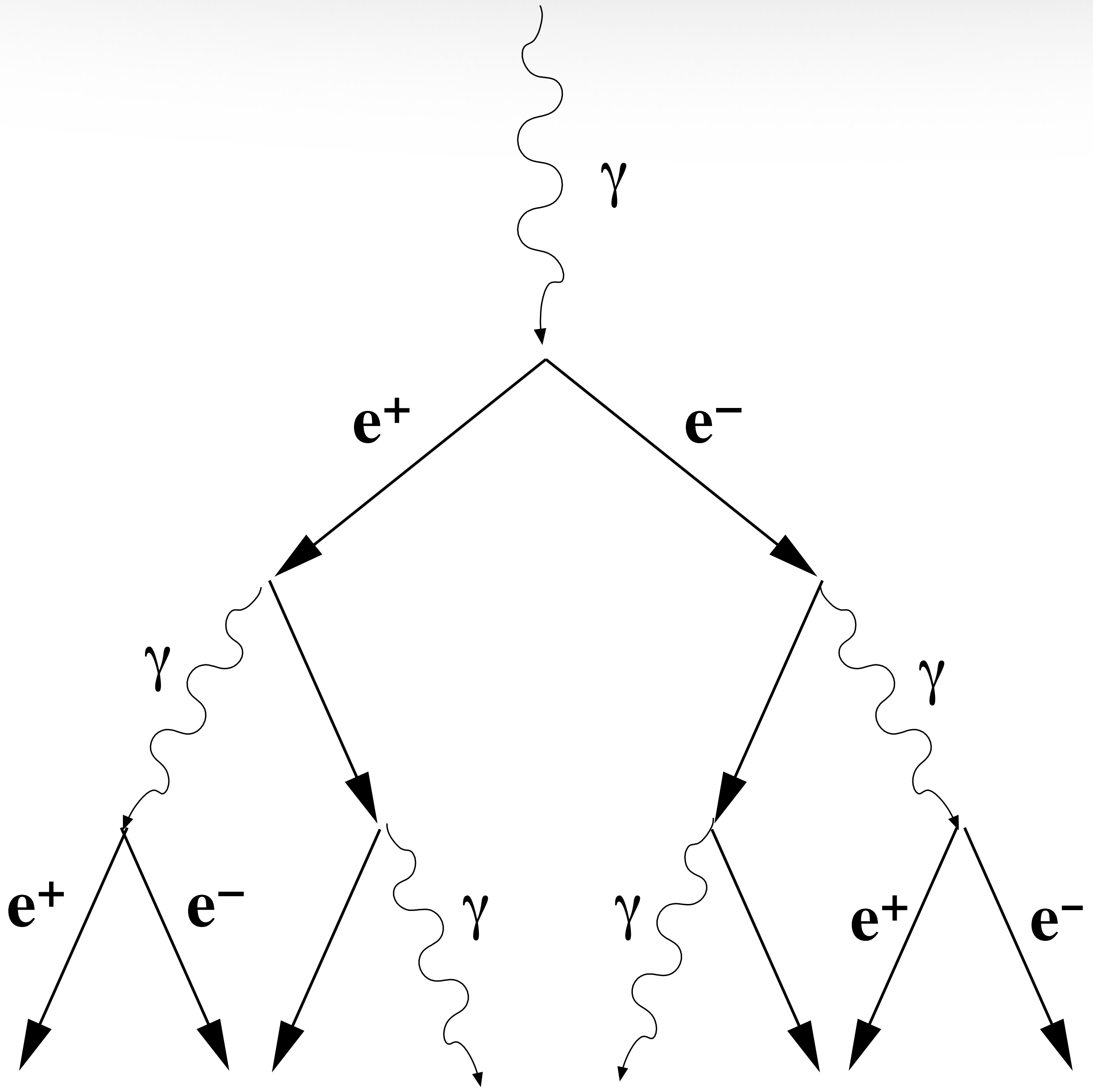


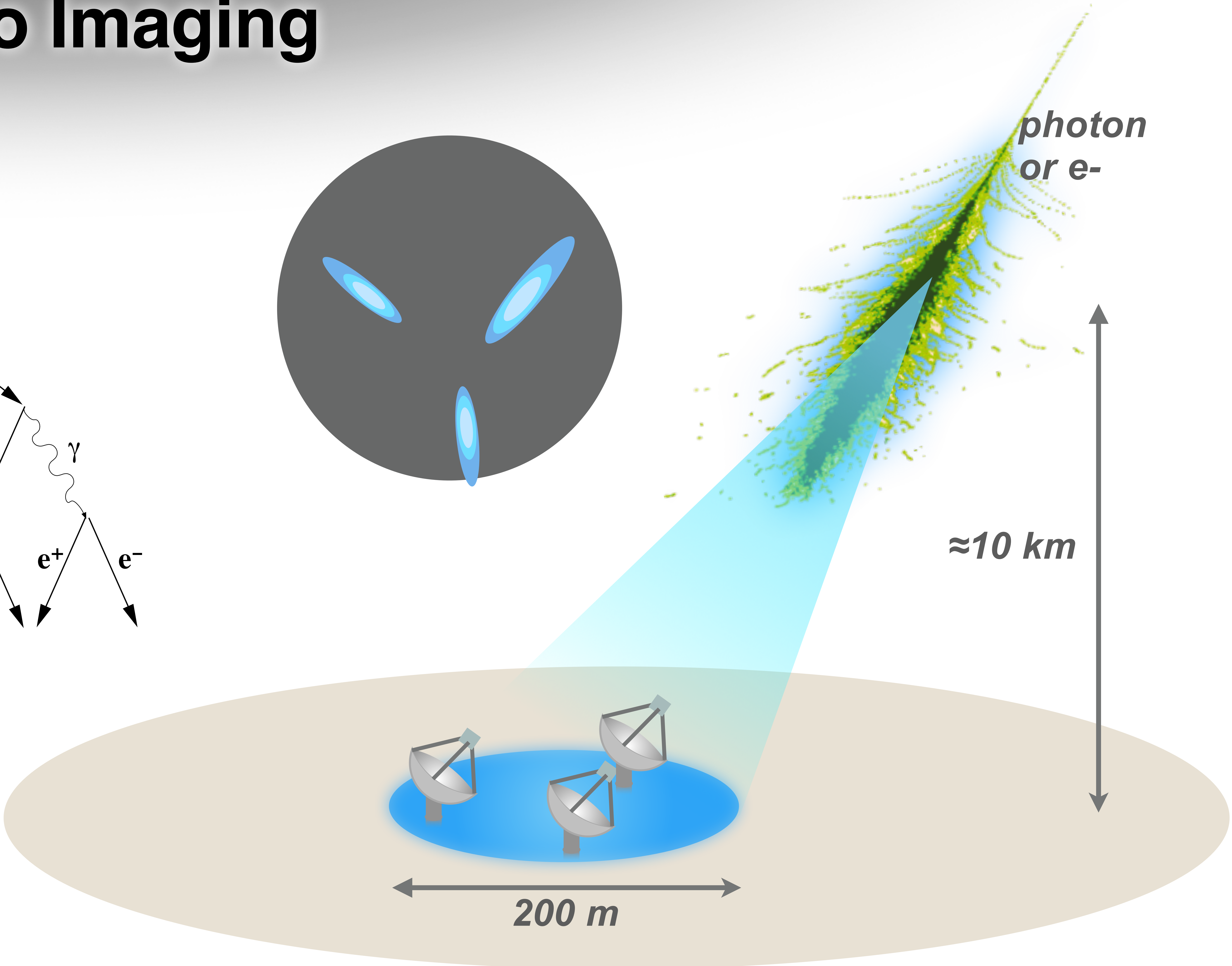
Stereo Imaging



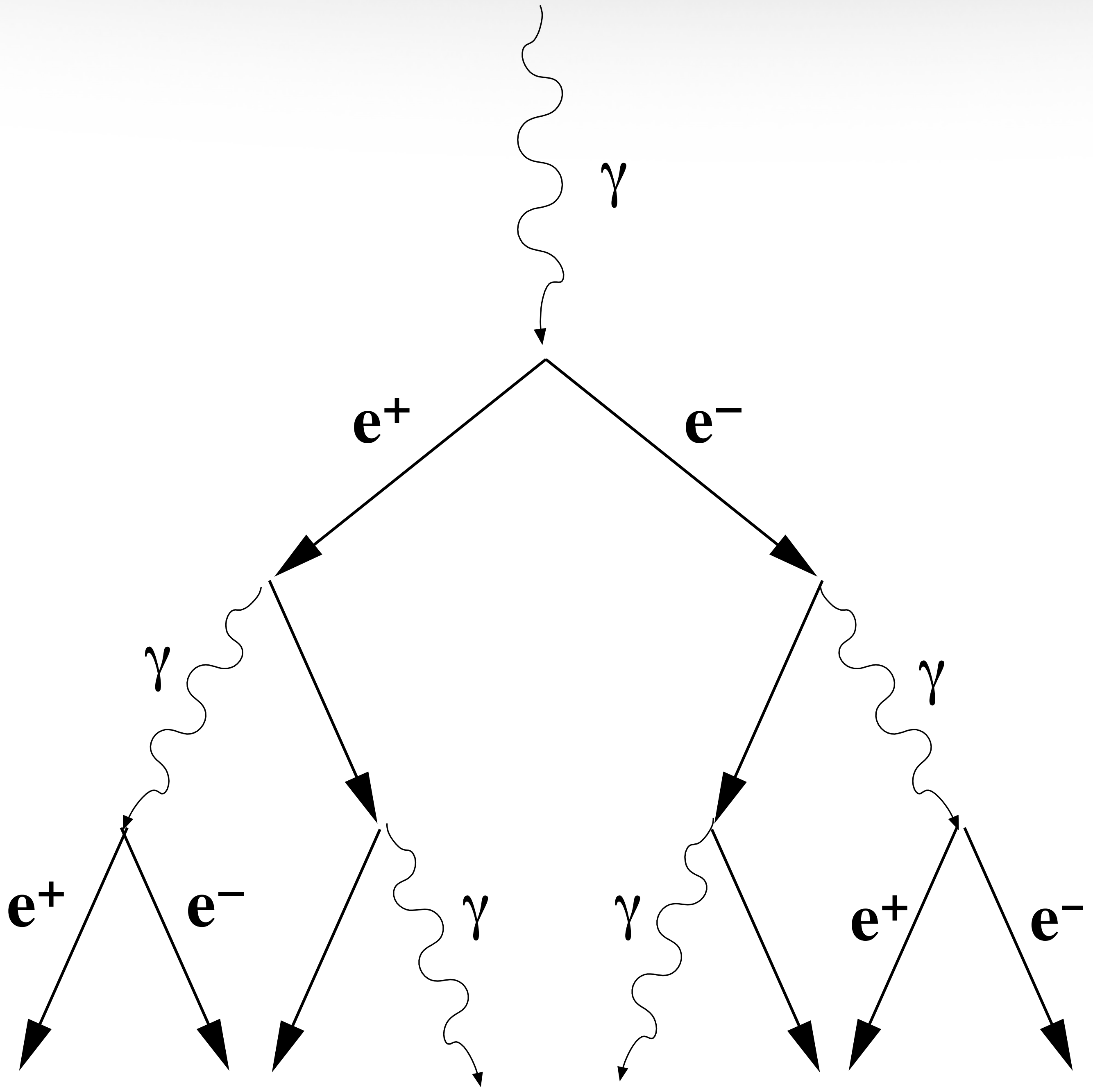


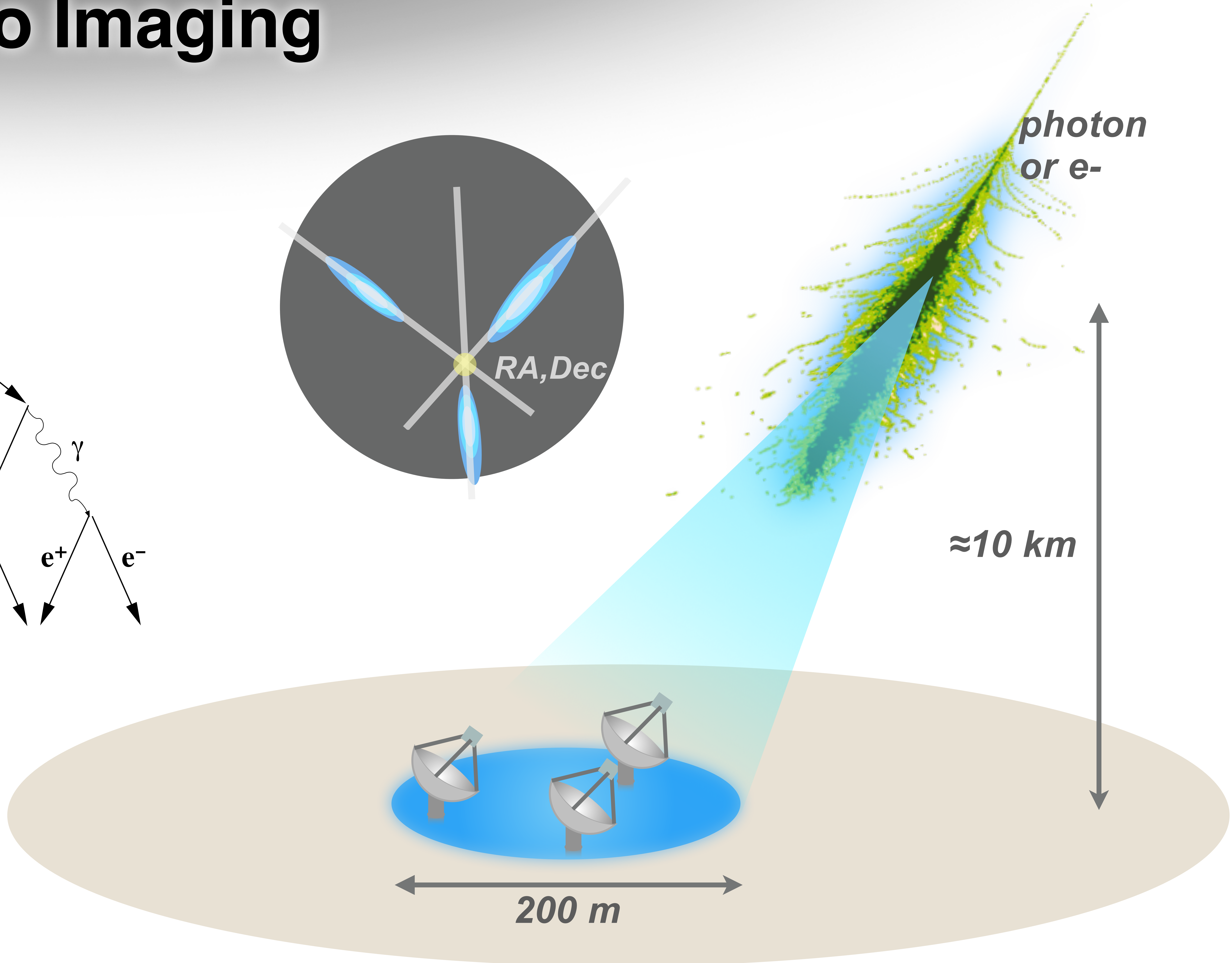
Stereo Imaging



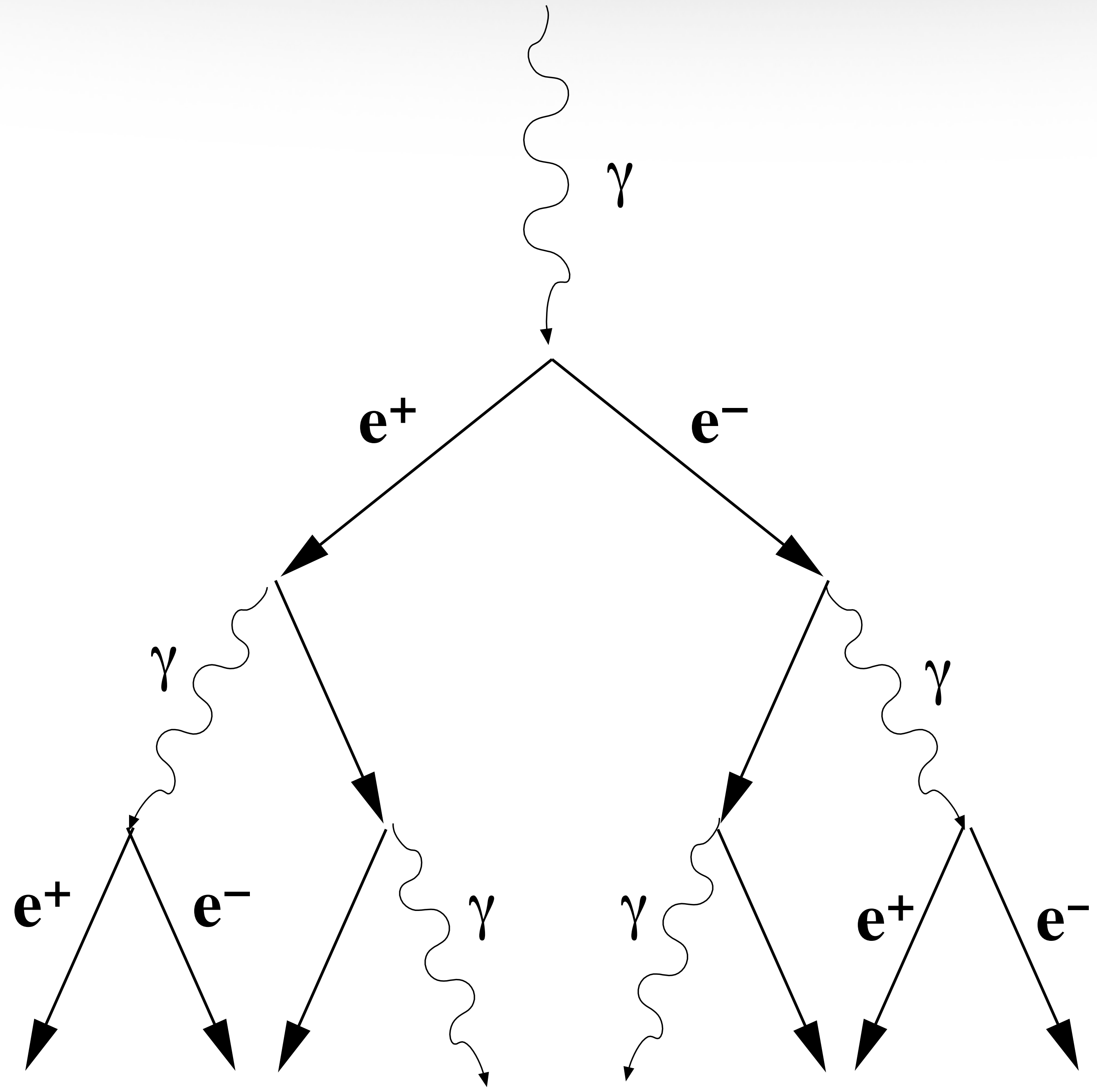


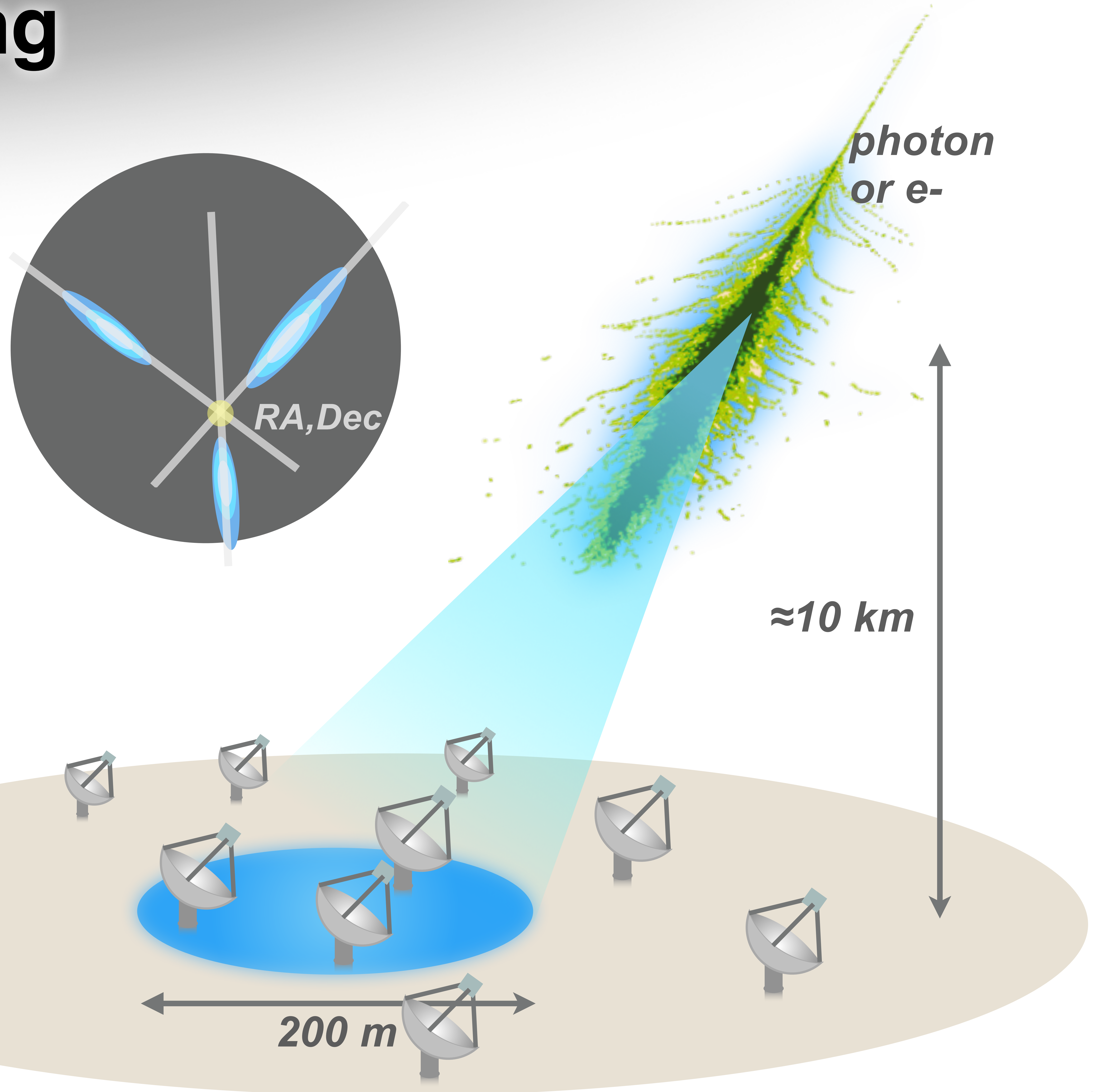
Stereo Imaging



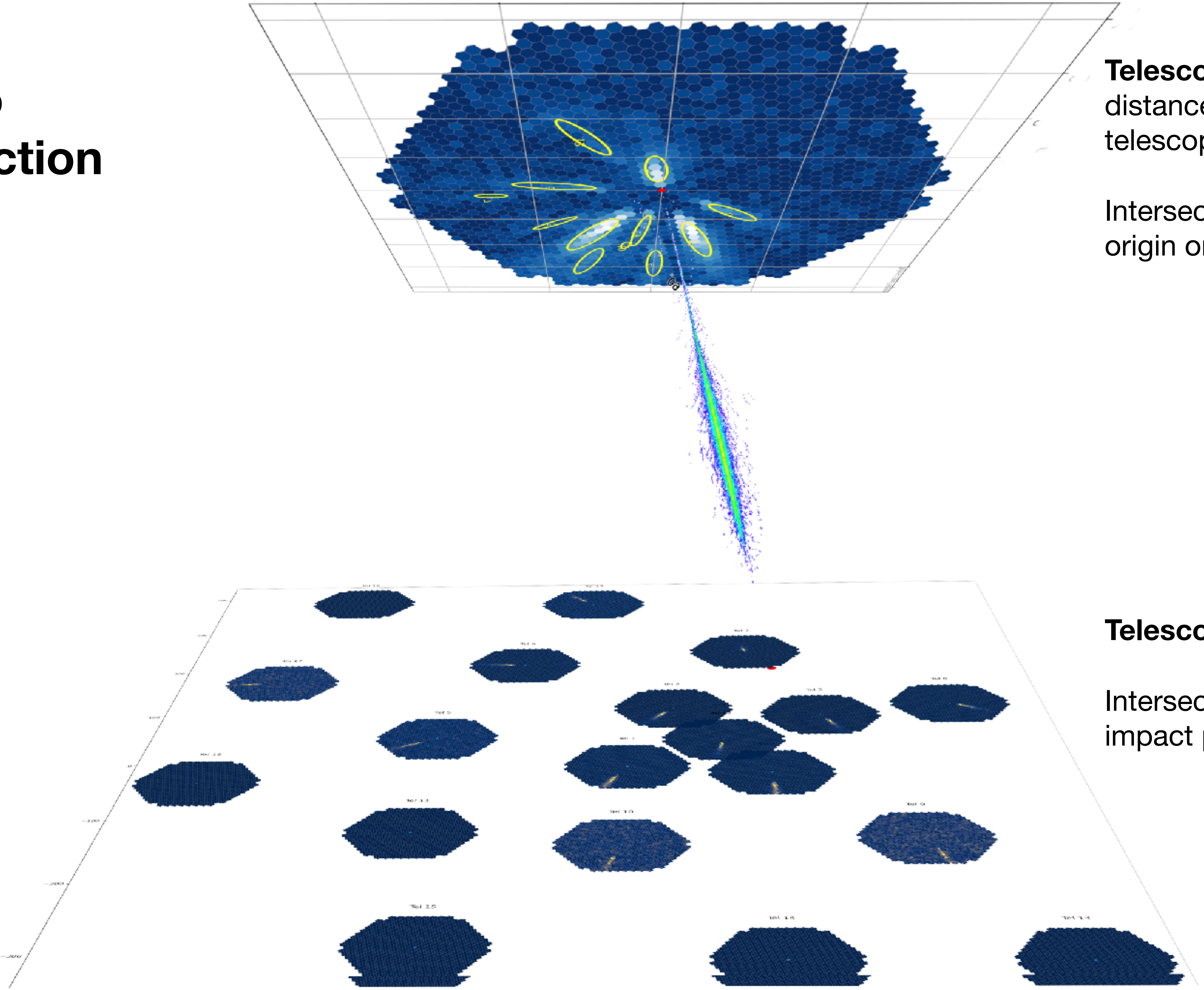


Stereo Imaging





Stereo Reconstruction



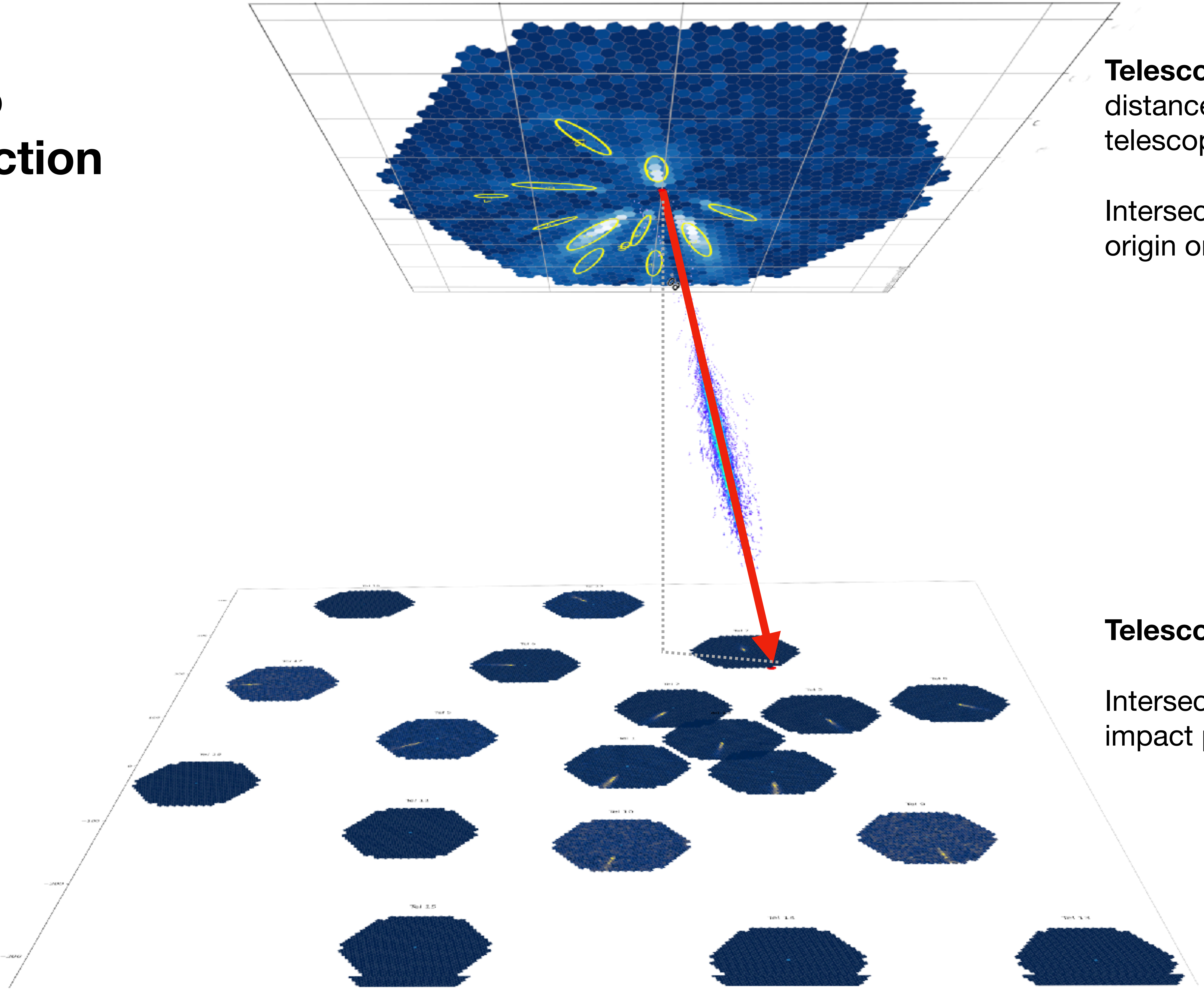
Telescopes "at infinity"
distance between telescopes → 0

Intersection = point-of-origin on sky

Telescopes "on ground"

Intersection = shower impact position on ground

Stereo Reconstruction



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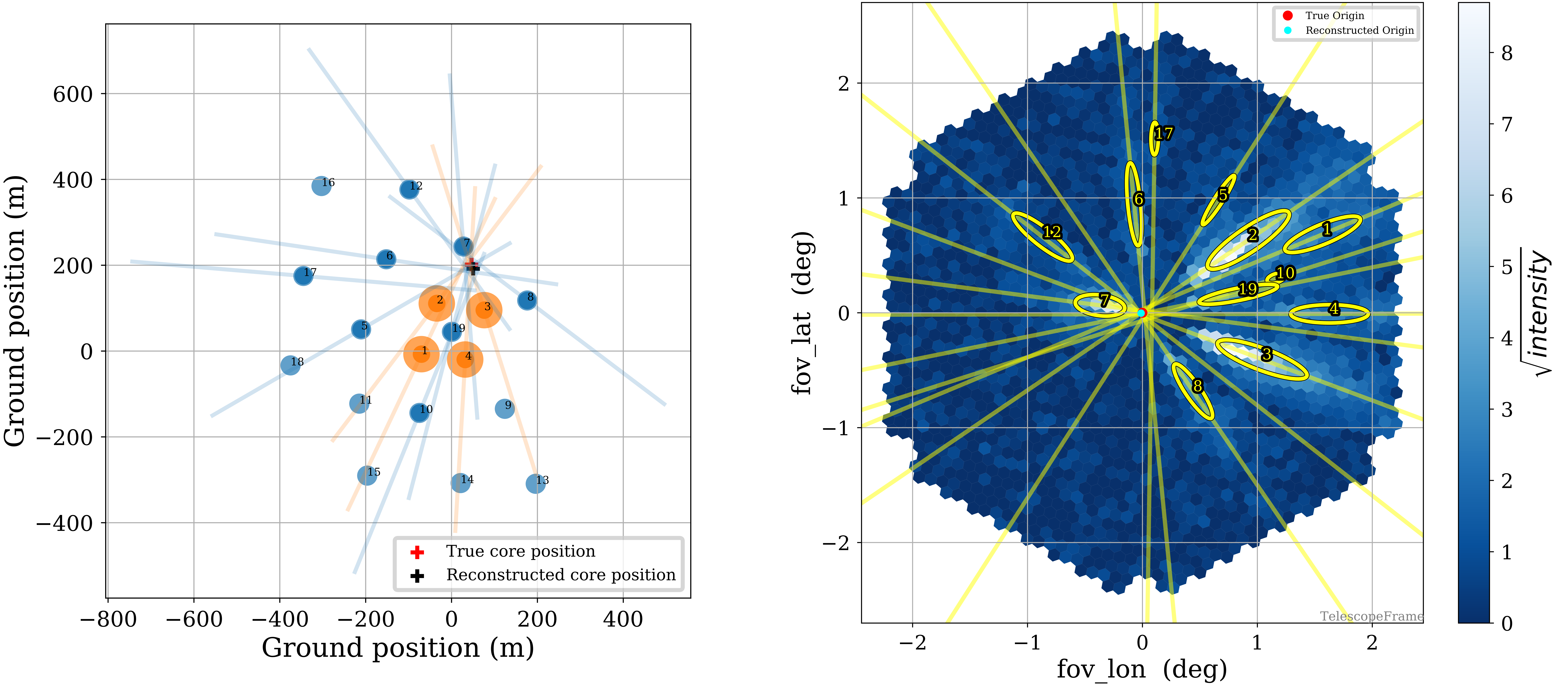
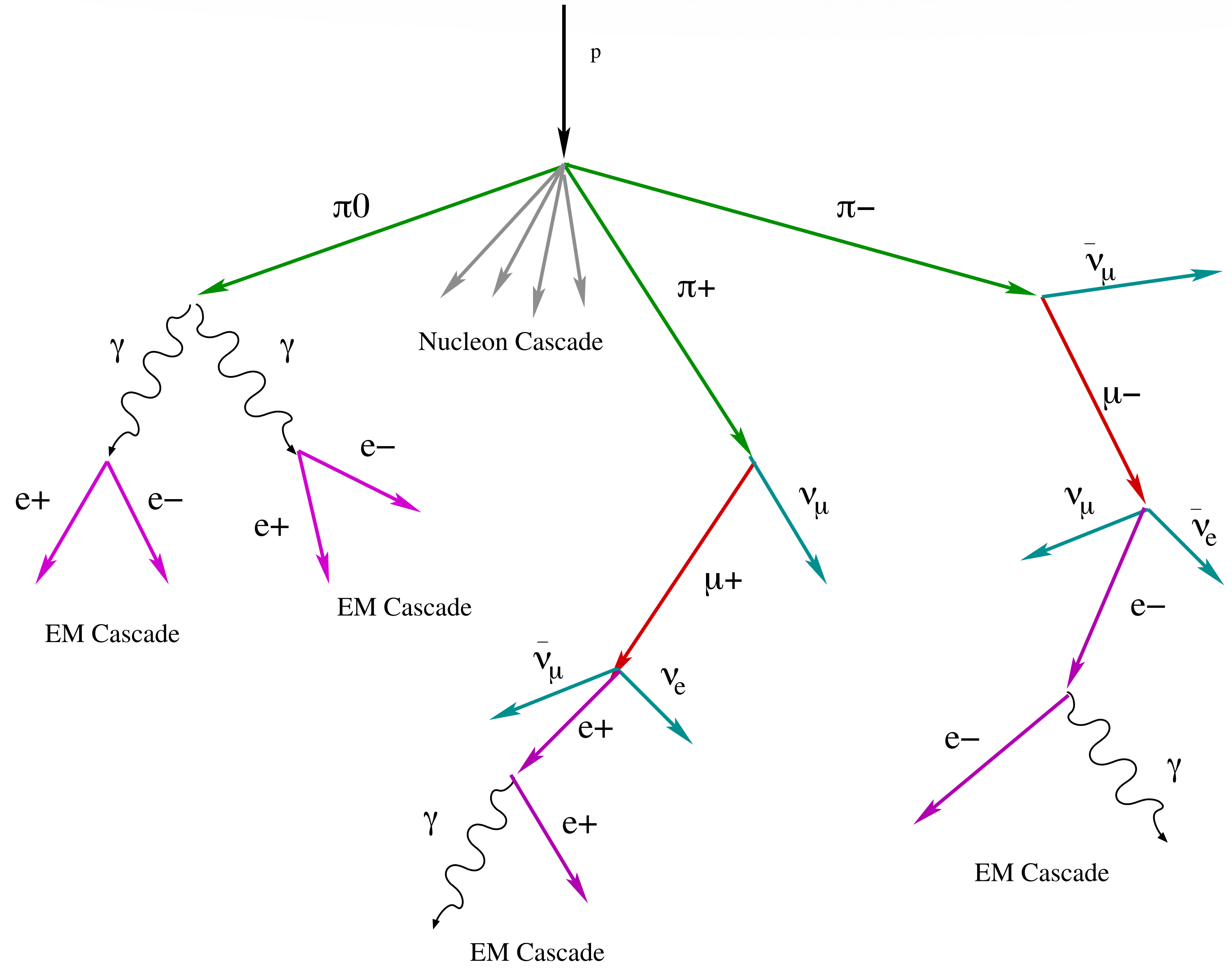


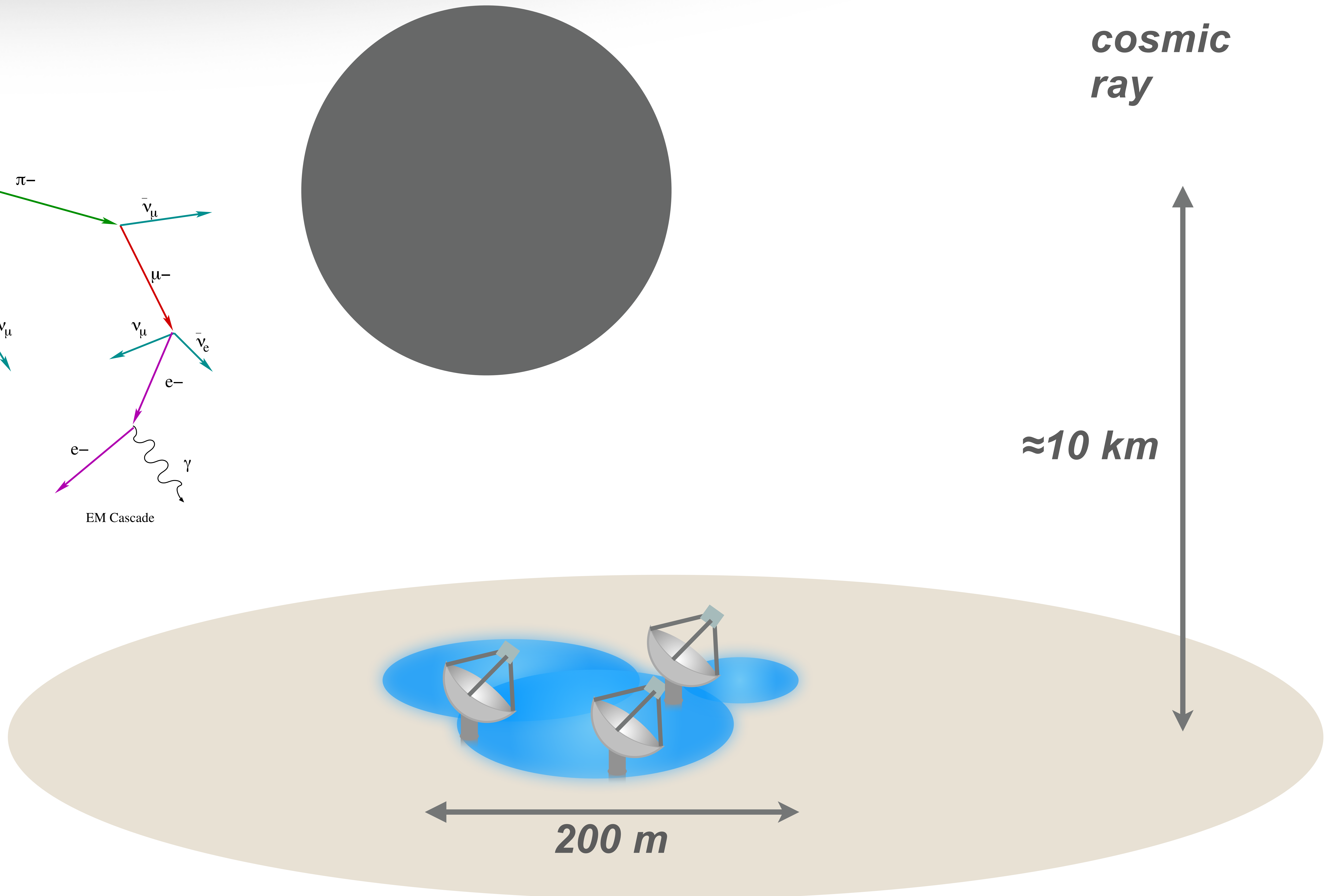
Karl Kosack - ISAPP 2022

Hadronic Showers

cosmic ray



EM sub-showers



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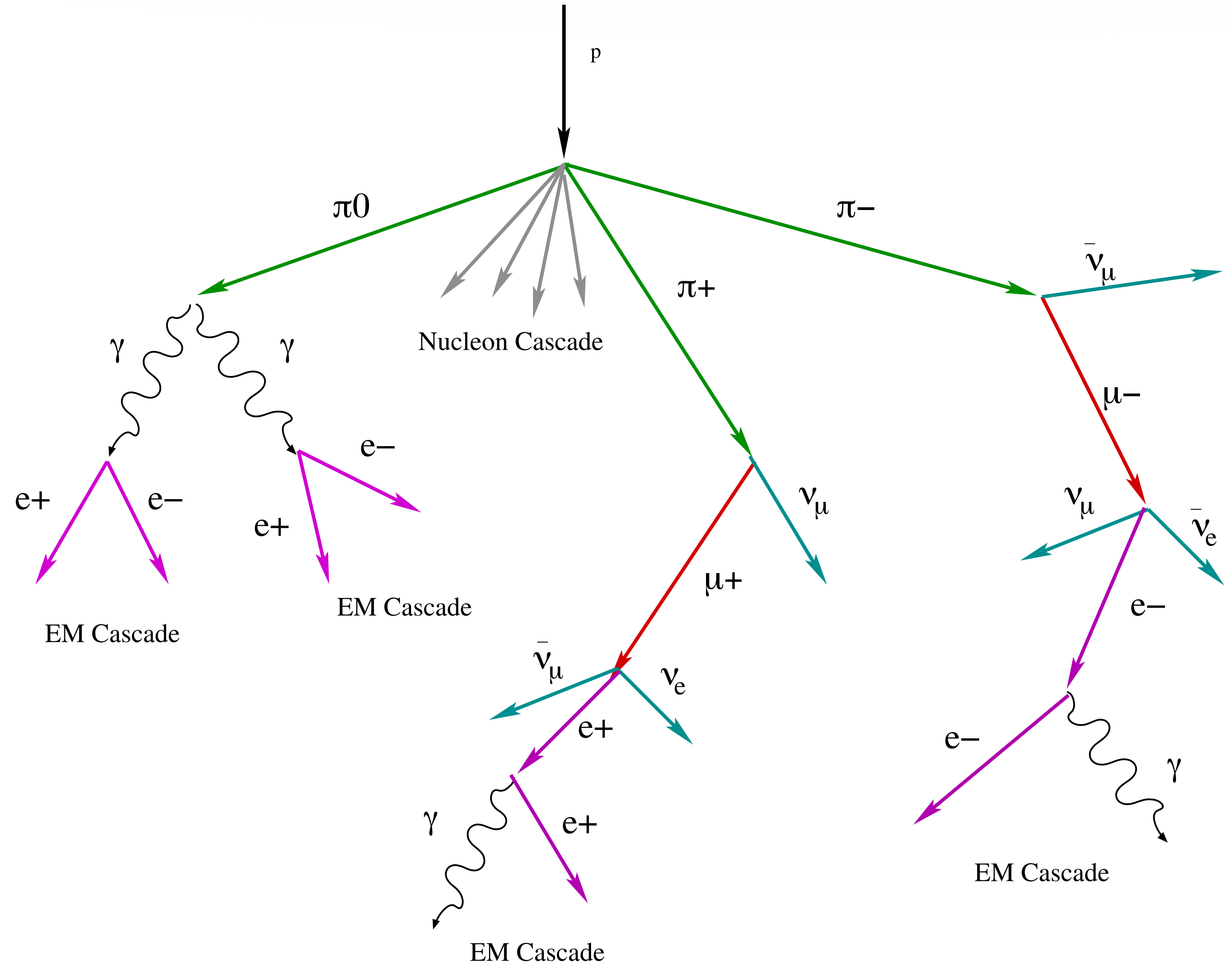

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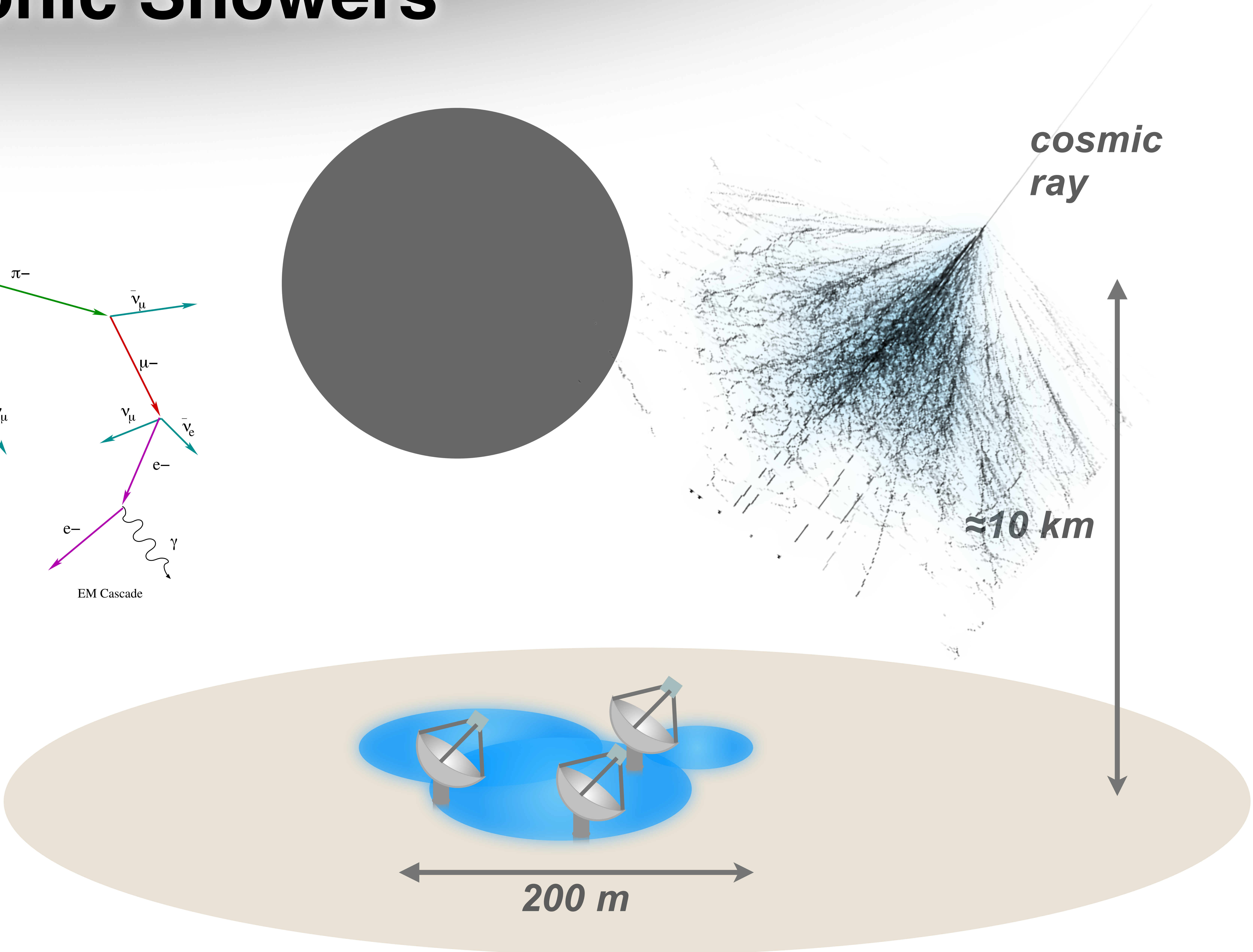


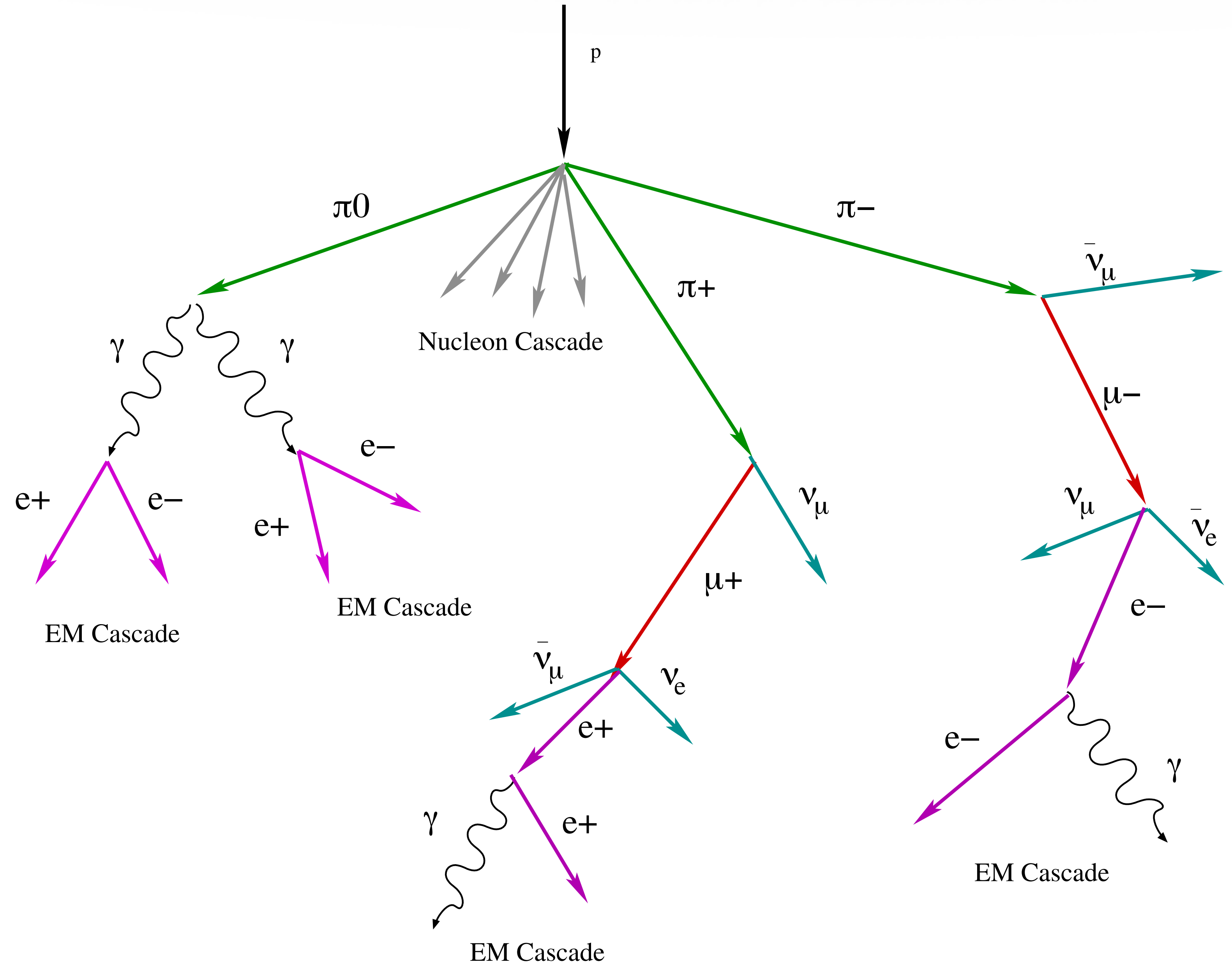
cosmic ray

≈10 km

200 m

Hadronic Showers

cosmic ray



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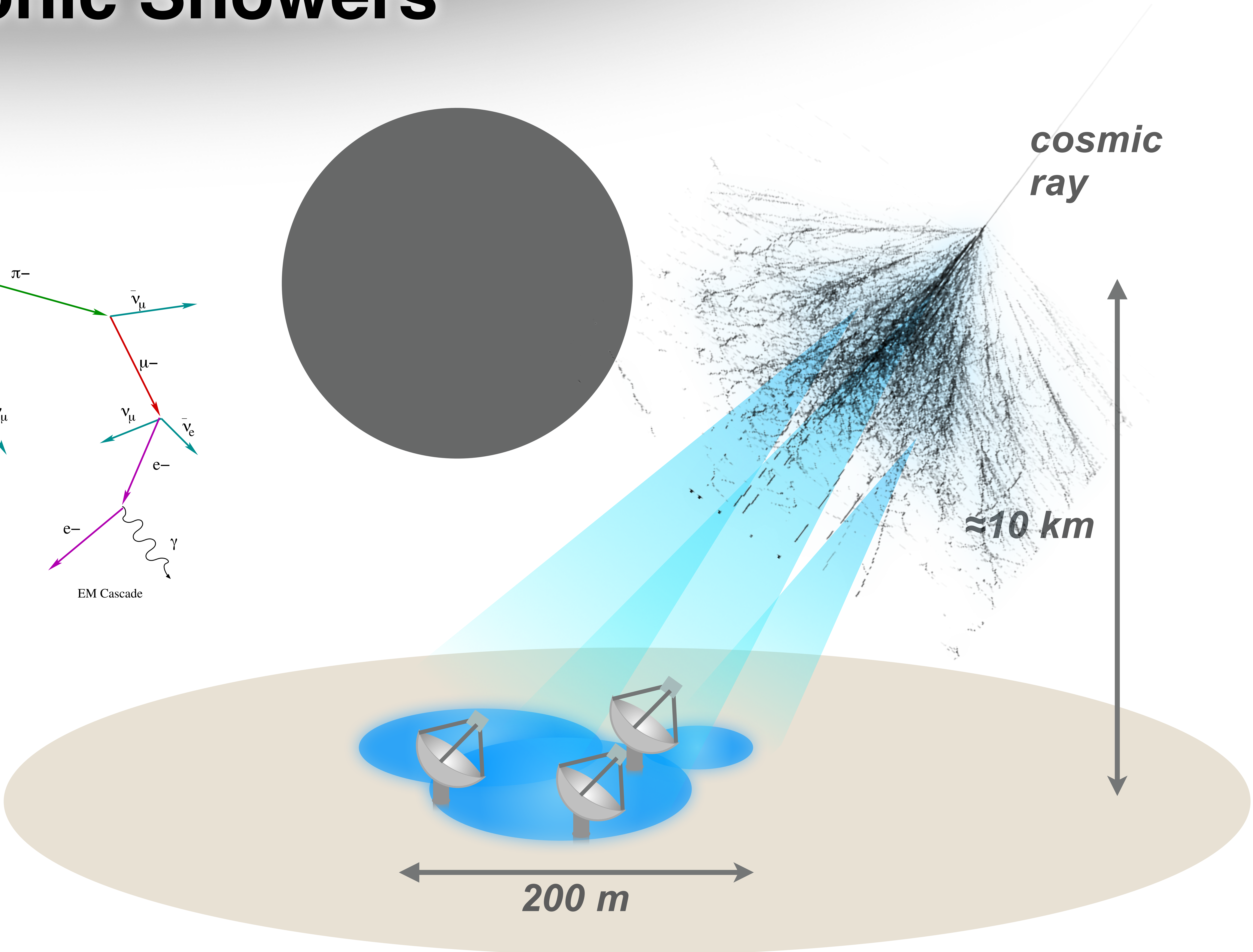

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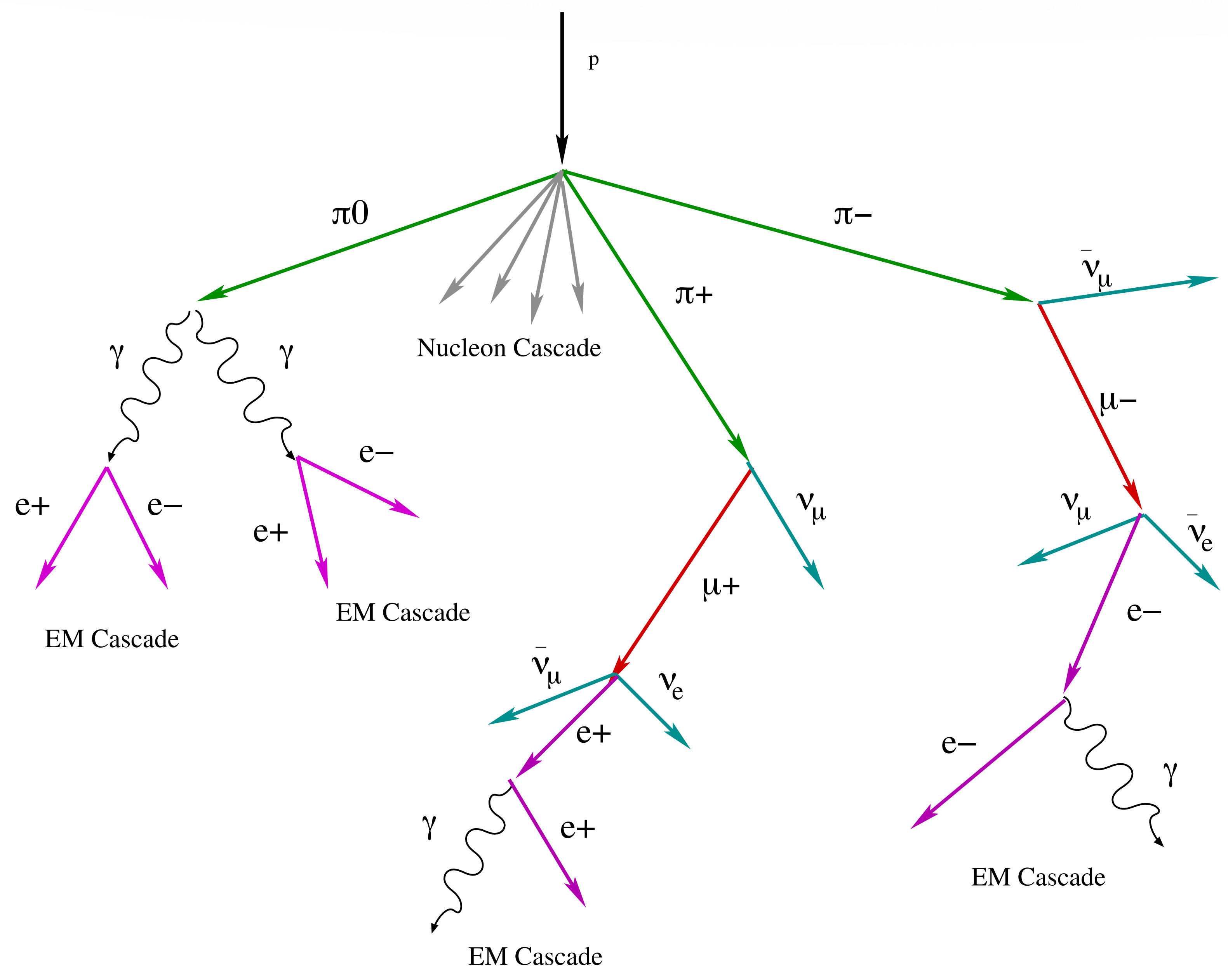
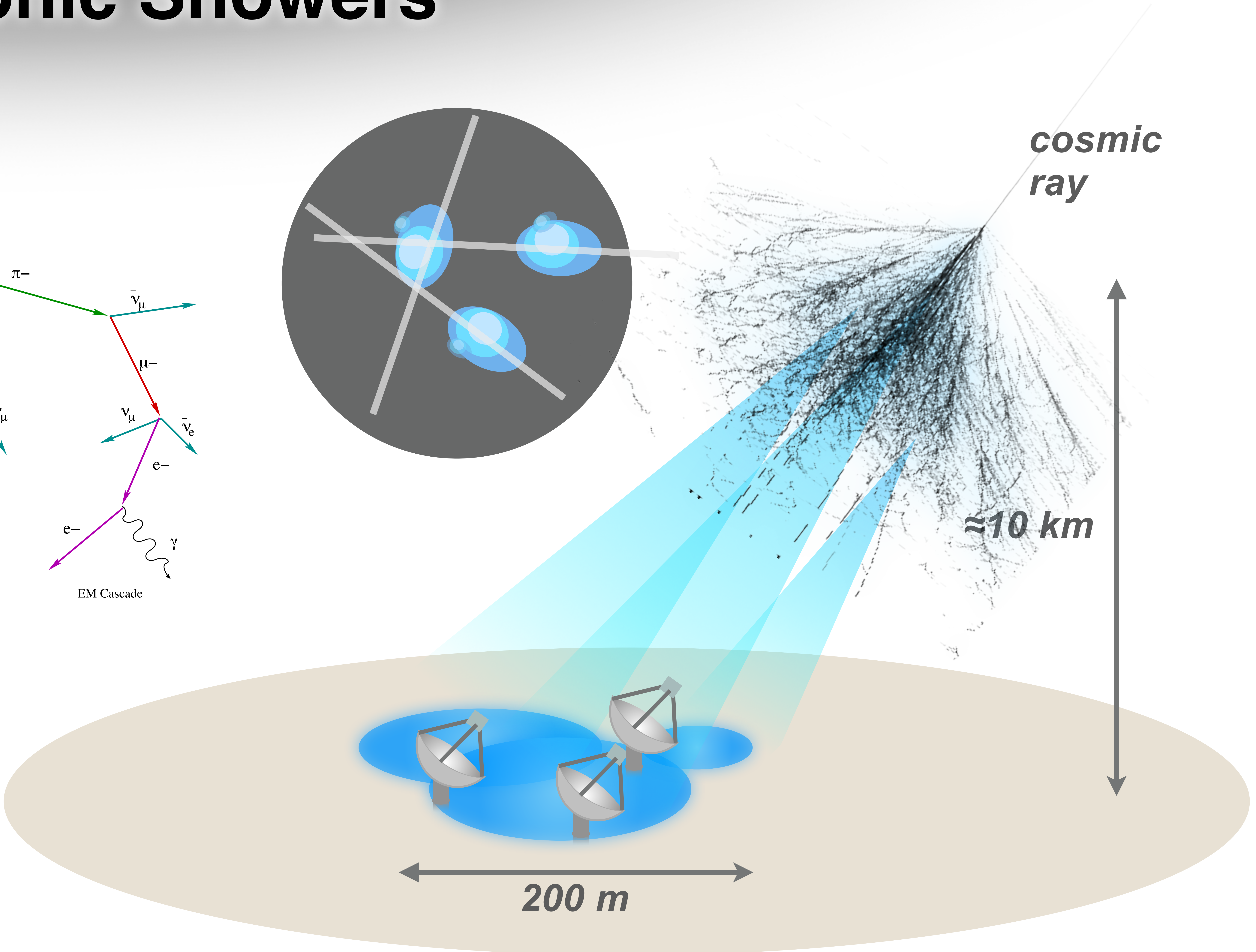
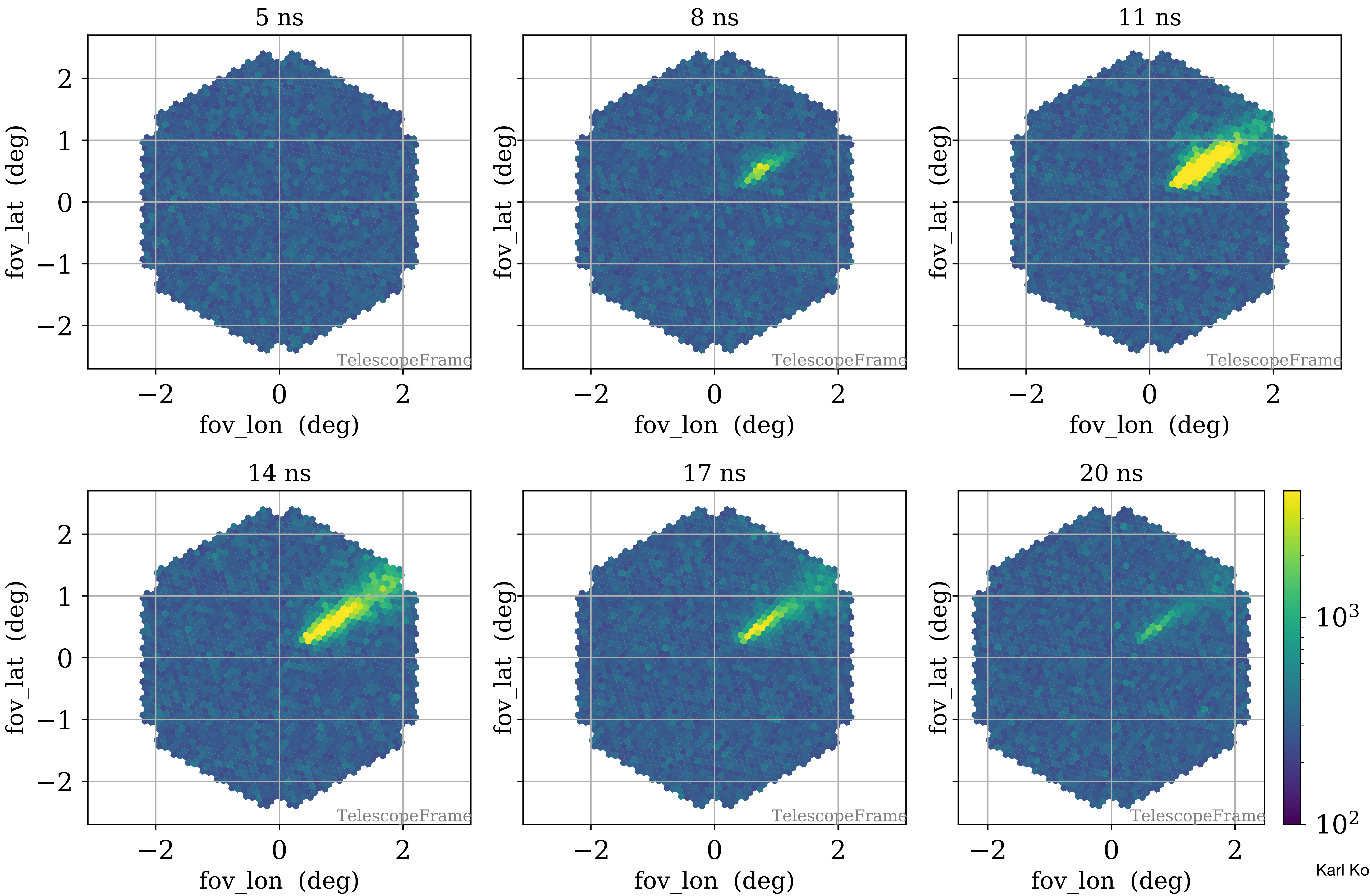
Hadronic Showers

cosmic ray



EM sub-showers





Karl Kosack - ISAPP 2022

Stereo View

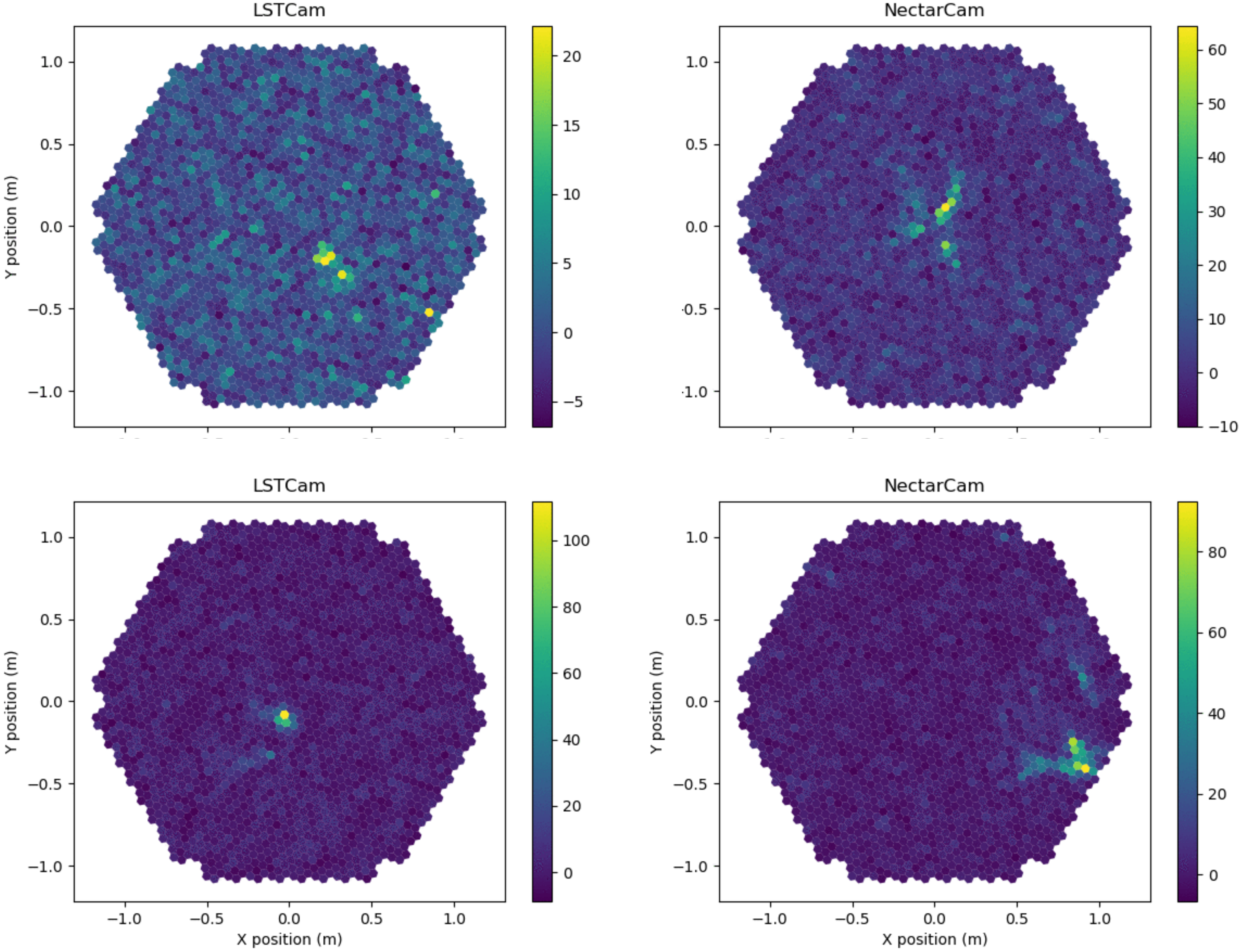
Large-Telescope Subarray

Medium Telescope Subarray

gamma ray

cosmic ray

(background)



Stereo View

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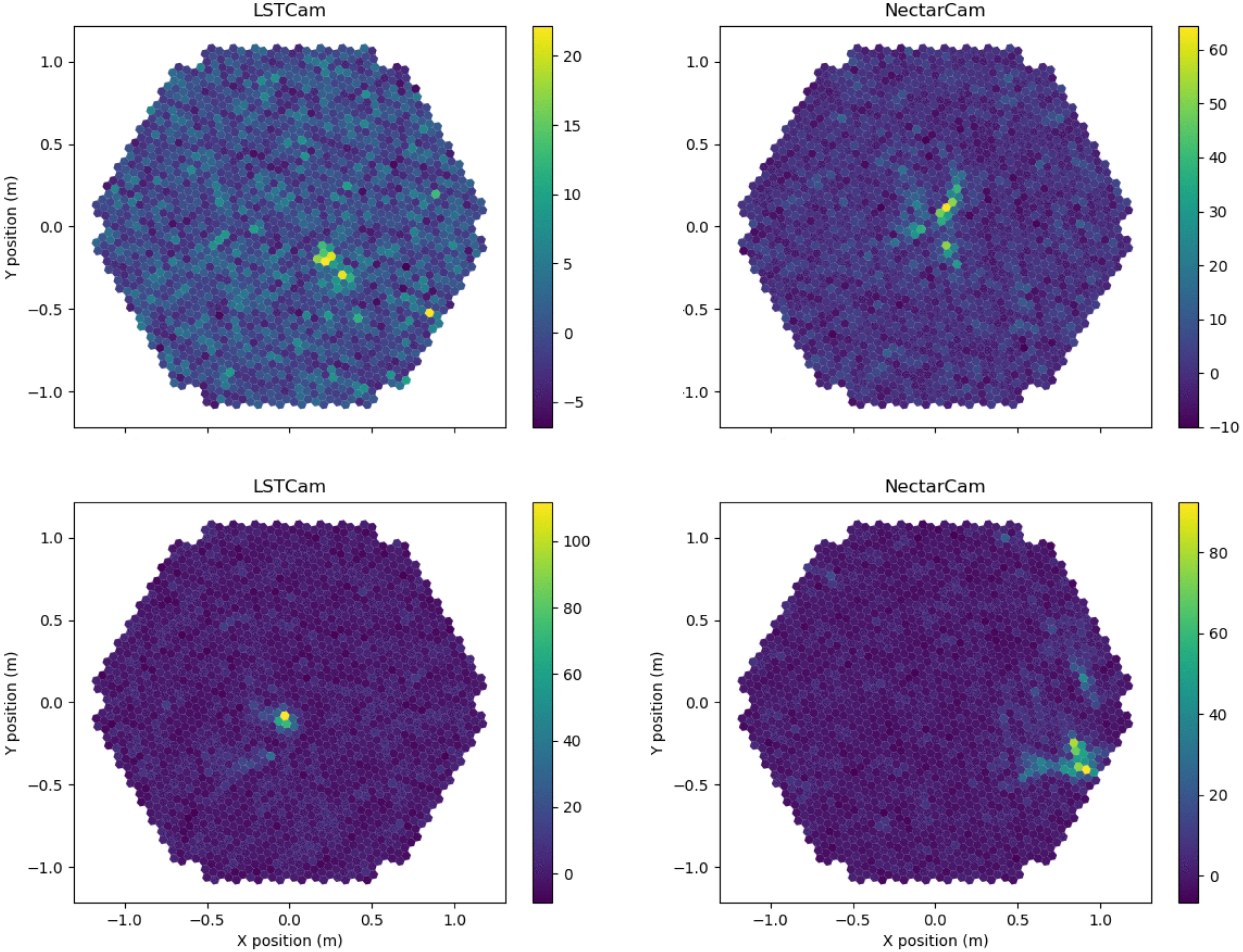
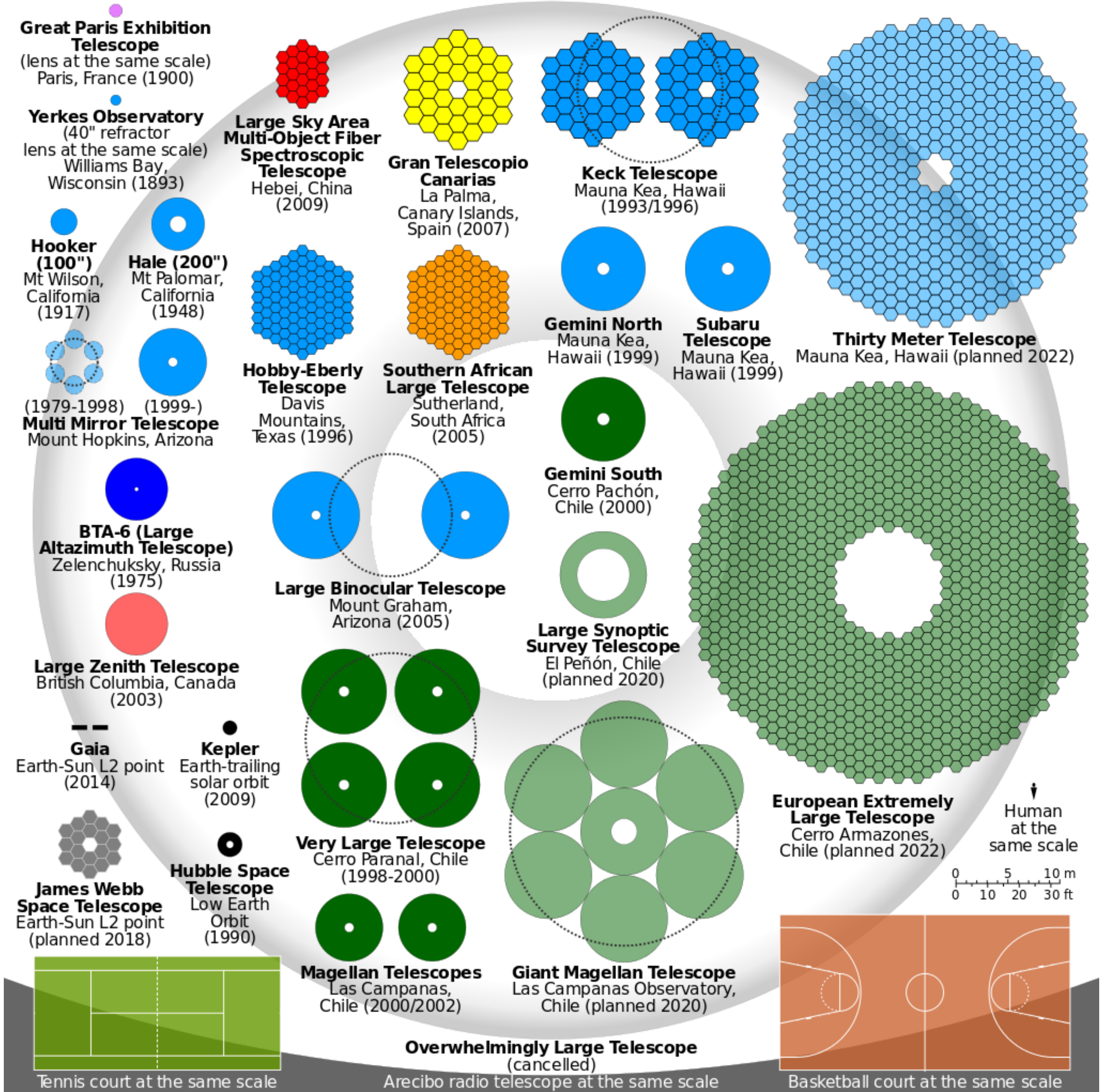


Currently Operating IACTs

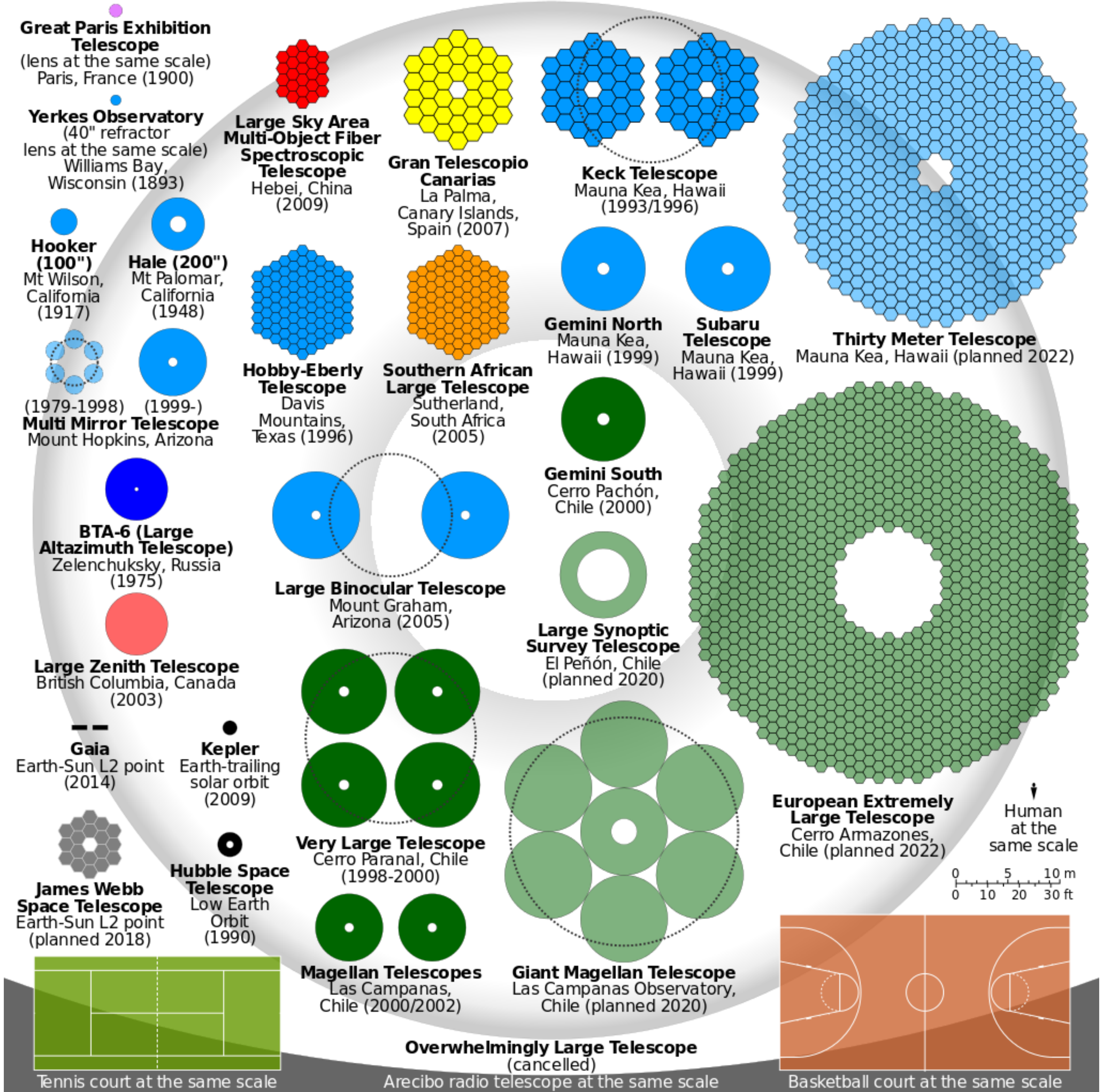
VERITAS: Arizona, USA
4x 12m. (Northern Hemisphere)

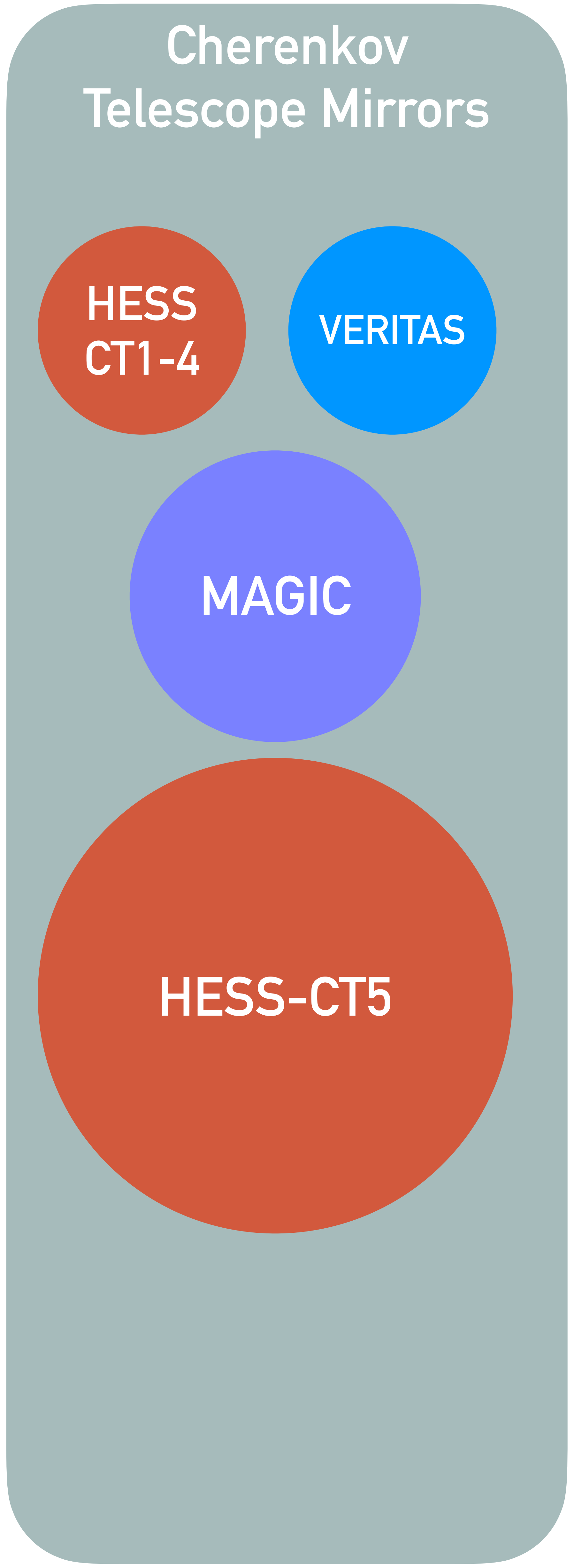
MAGIC: Canary Islands
2x 17 m (Northern Hemisphere)

HESS: Namibia
4x 12m, *1x* 28m (Southern Hemisphere)



Karl Kosack - ISAPP 2022





Karl Kosack - ISAPP 2022

cherenkov telescope array

the observatory for
ground-based
gamma-ray astronomy

See talk by W. Hofmann last Friday

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

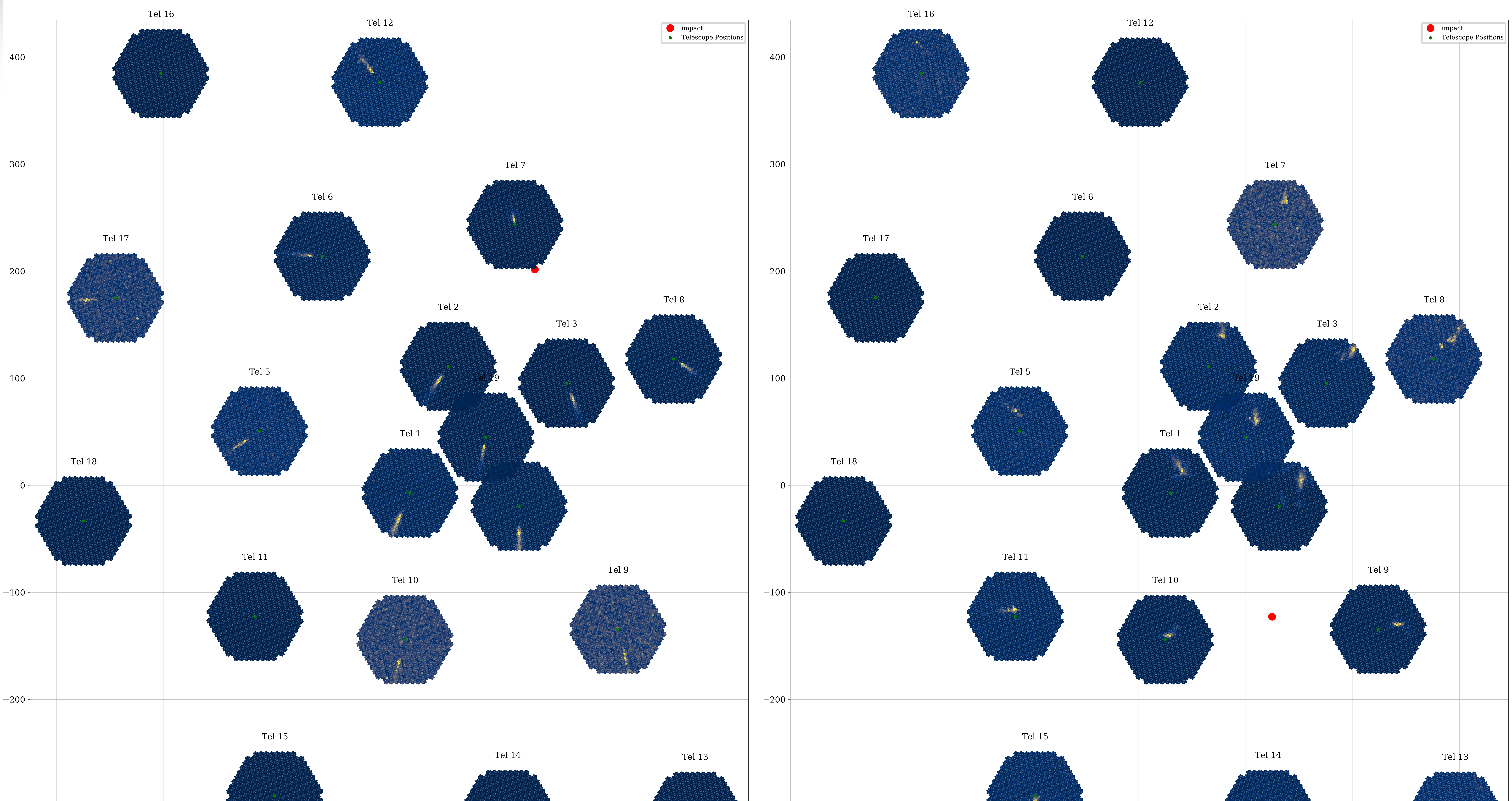
largest gamma ray telescope array ever

open observatory: you can be a PI!

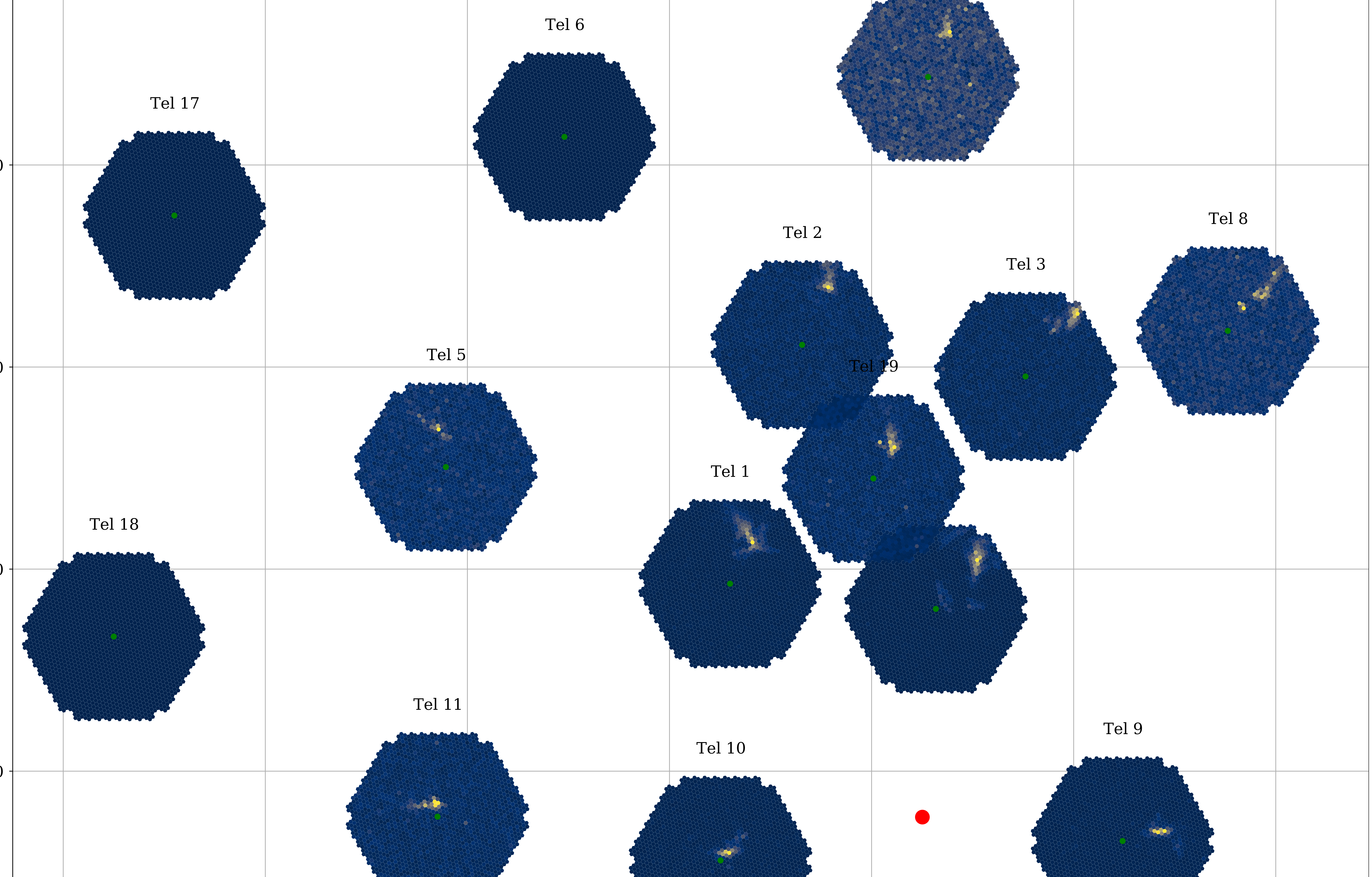
https://www.cta-observatory.org/

Discrimination

Example: CTA-North Full array




Tel 6
Tel 17
Tel 2
Tel 3
Tel 8
Tel 5
Tel 19
Tel 1
Tel 18
Tel 11
Tel 10
Tel 9
Tel 1
200
100
0
−100


Tel 6
Tel 17
Tel 2
Tel 8
Tel 3
Tel 19
Tel 5
Tel 1
Tel 18
Tel 11
Tel 10
Tel 9

Particle Discrimination: Machine Learning

Simulated Image Features

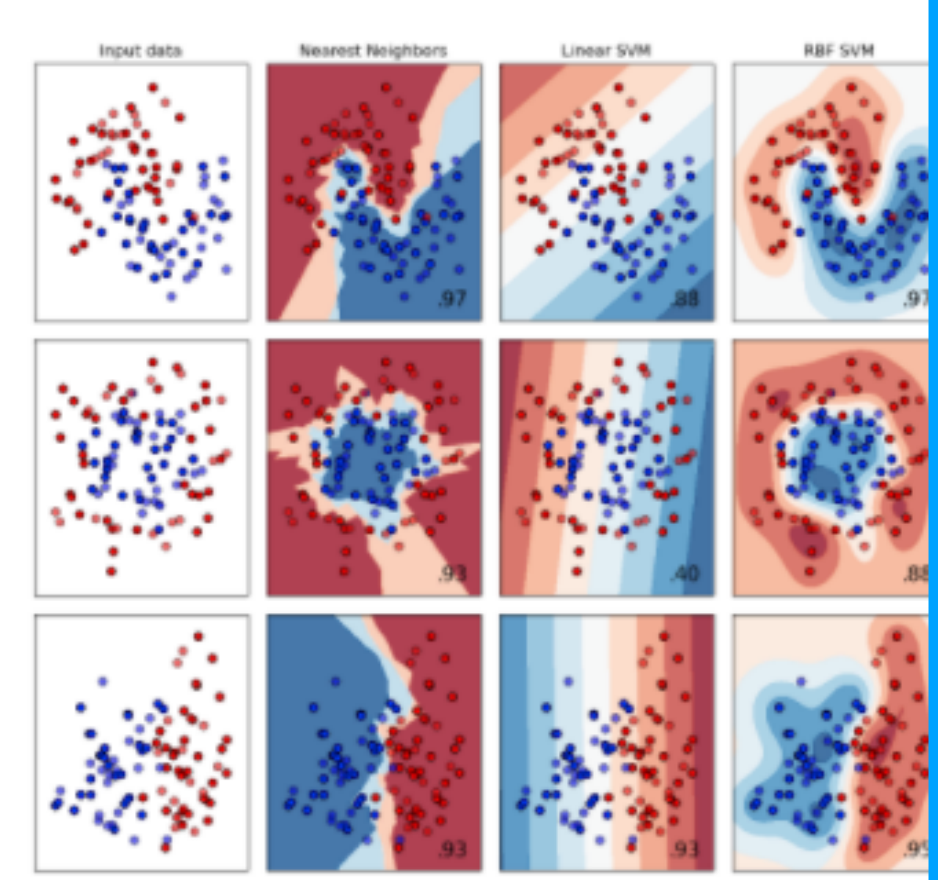
+ True Particle Type

Train

Test

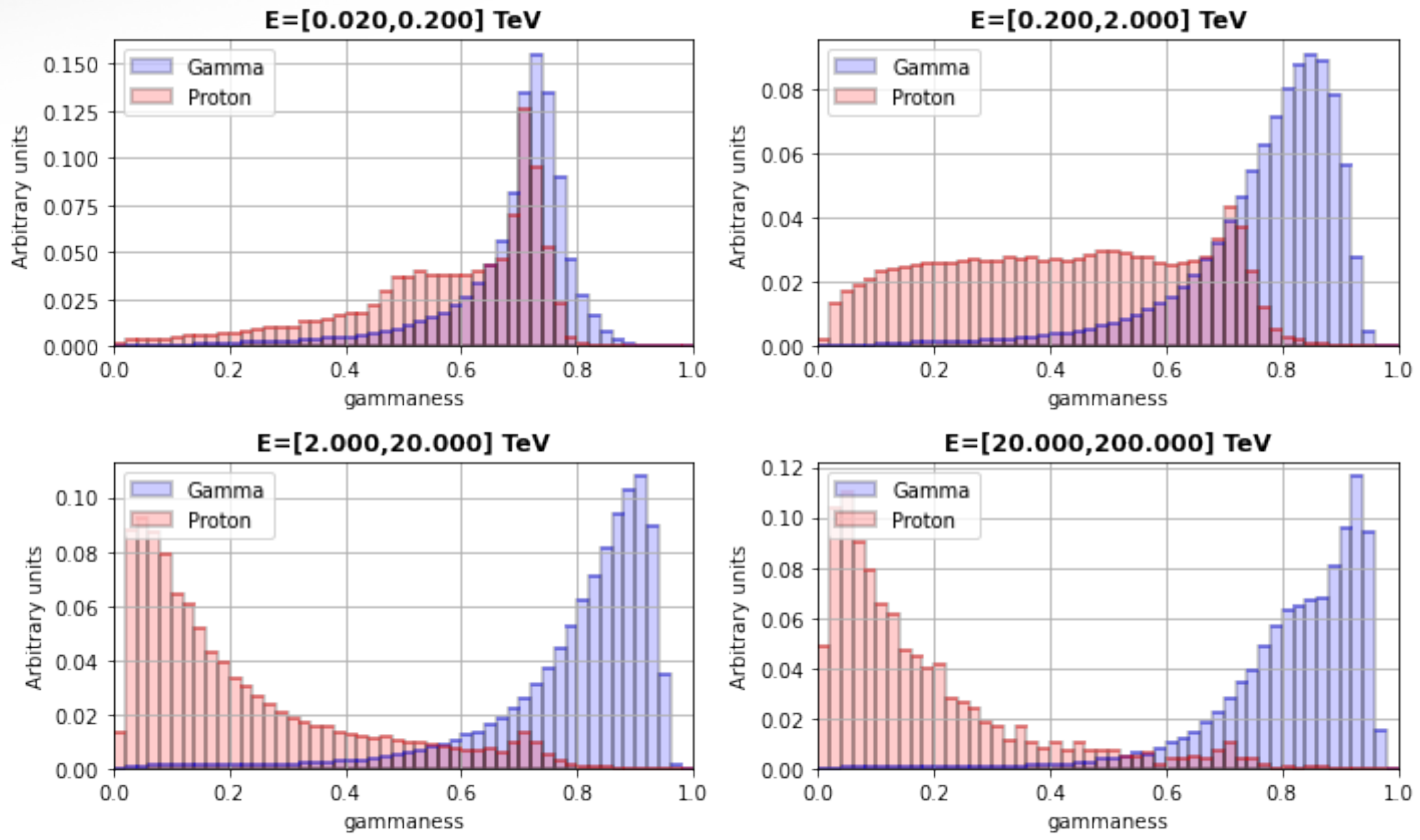
Observed Image Features

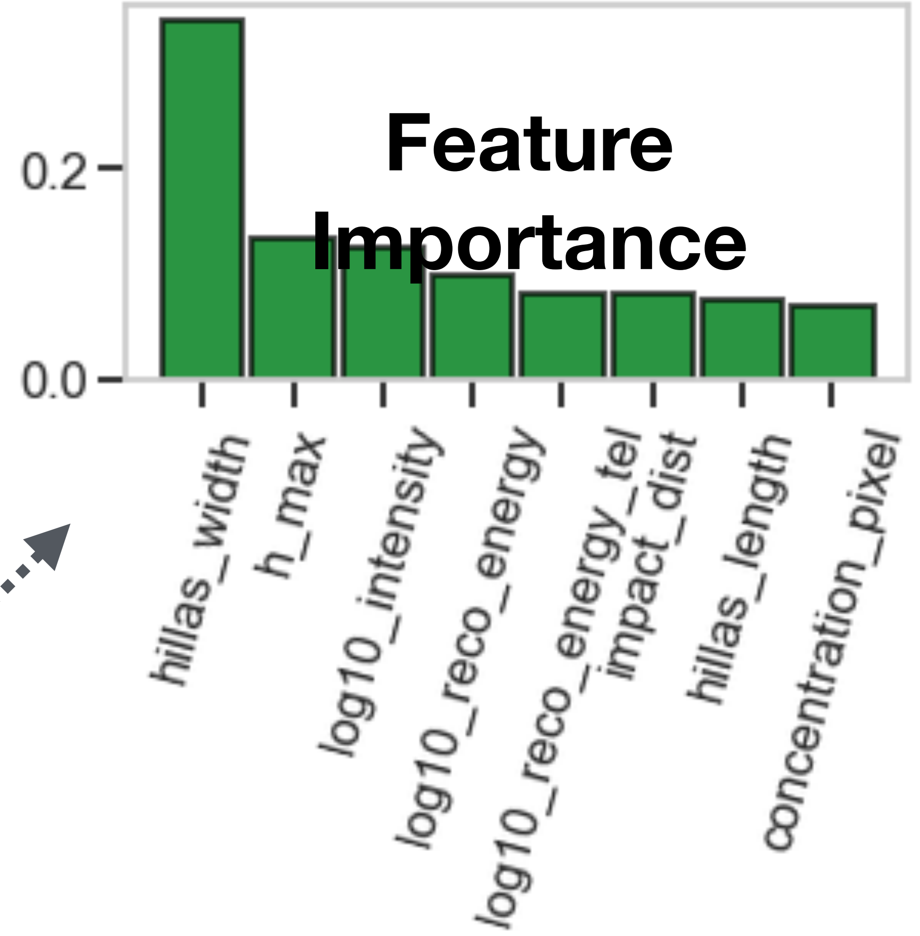
Machine Learning Model
(e.g. Random Forest)



Predict

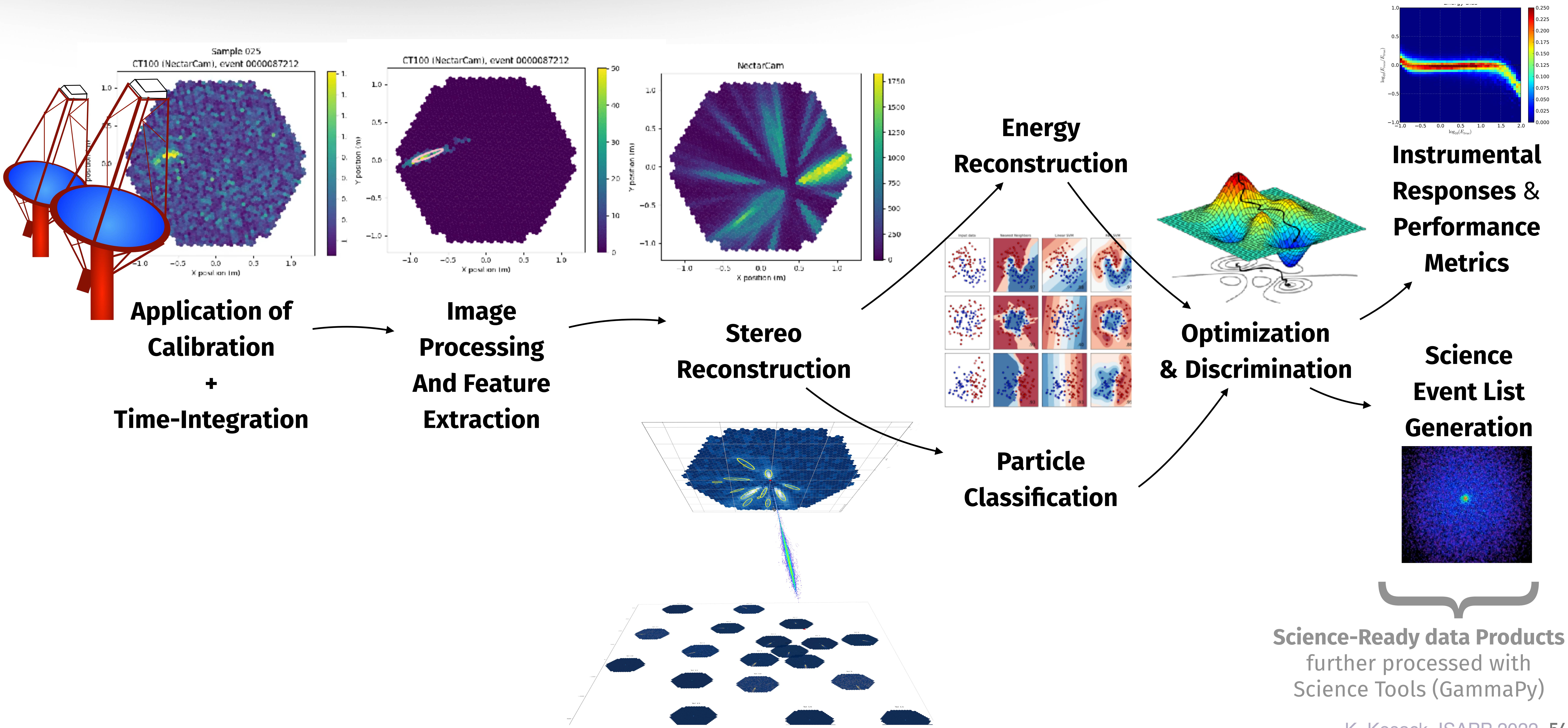
Gamma or Hadron





Note: To first order, the width of an image is a good discriminant!

Summary of Data Procesing



Application of Calibration
+
Time-Integration

Image Processing And Feature Extraction

Stereo Reconstruction

Energy Reconstruction

Particle Classification

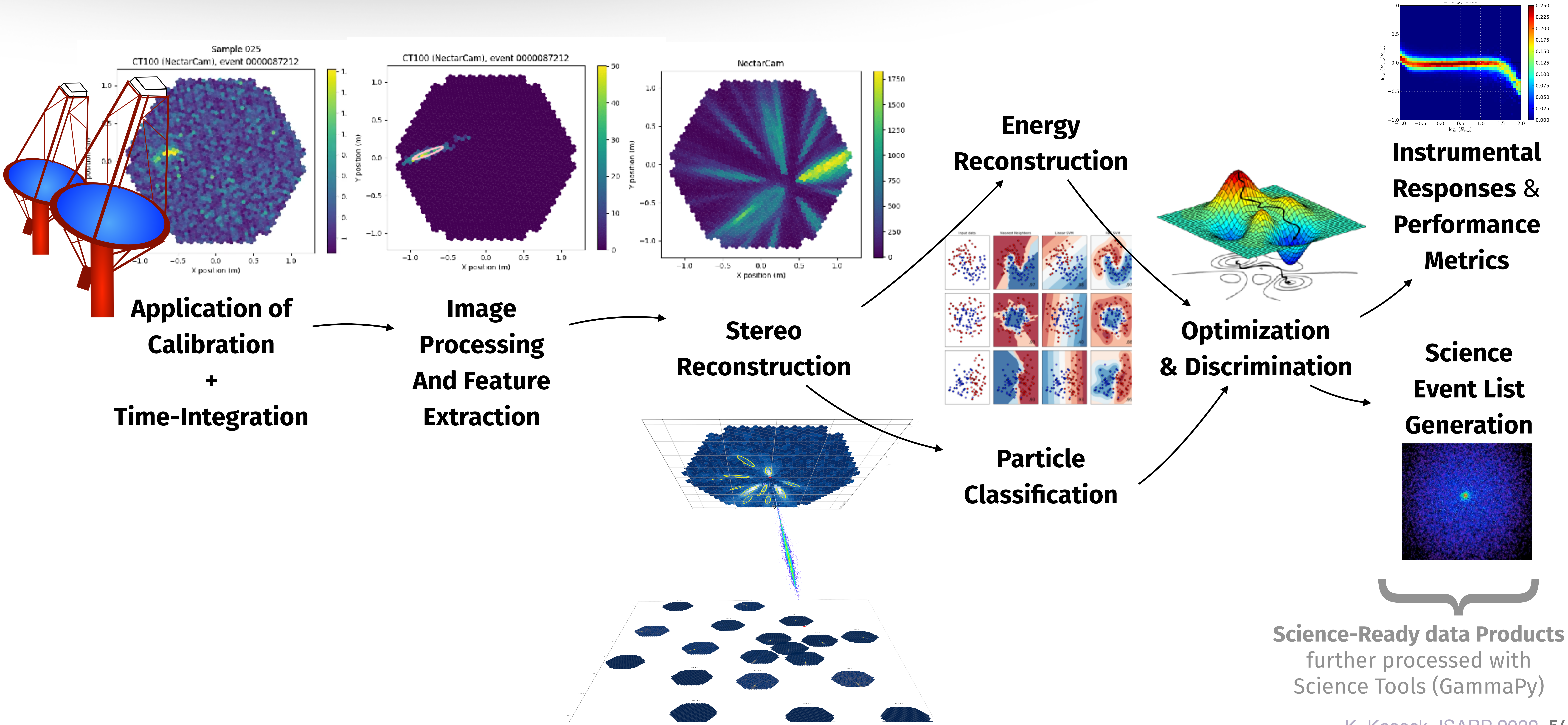
Optimization & Discrimination

Instrumental Responses & Performance Metrics

Science Event List Generation

Science-Ready data Products
further processed with
Science Tools (GammaPy)

Summary of Data Procesing



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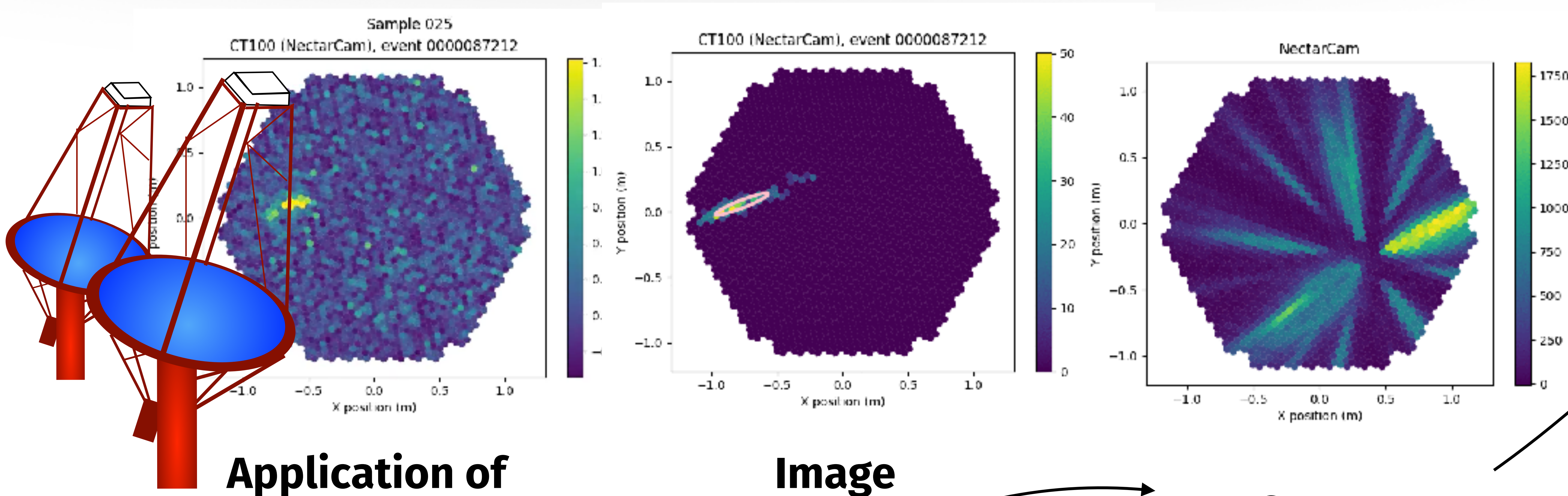

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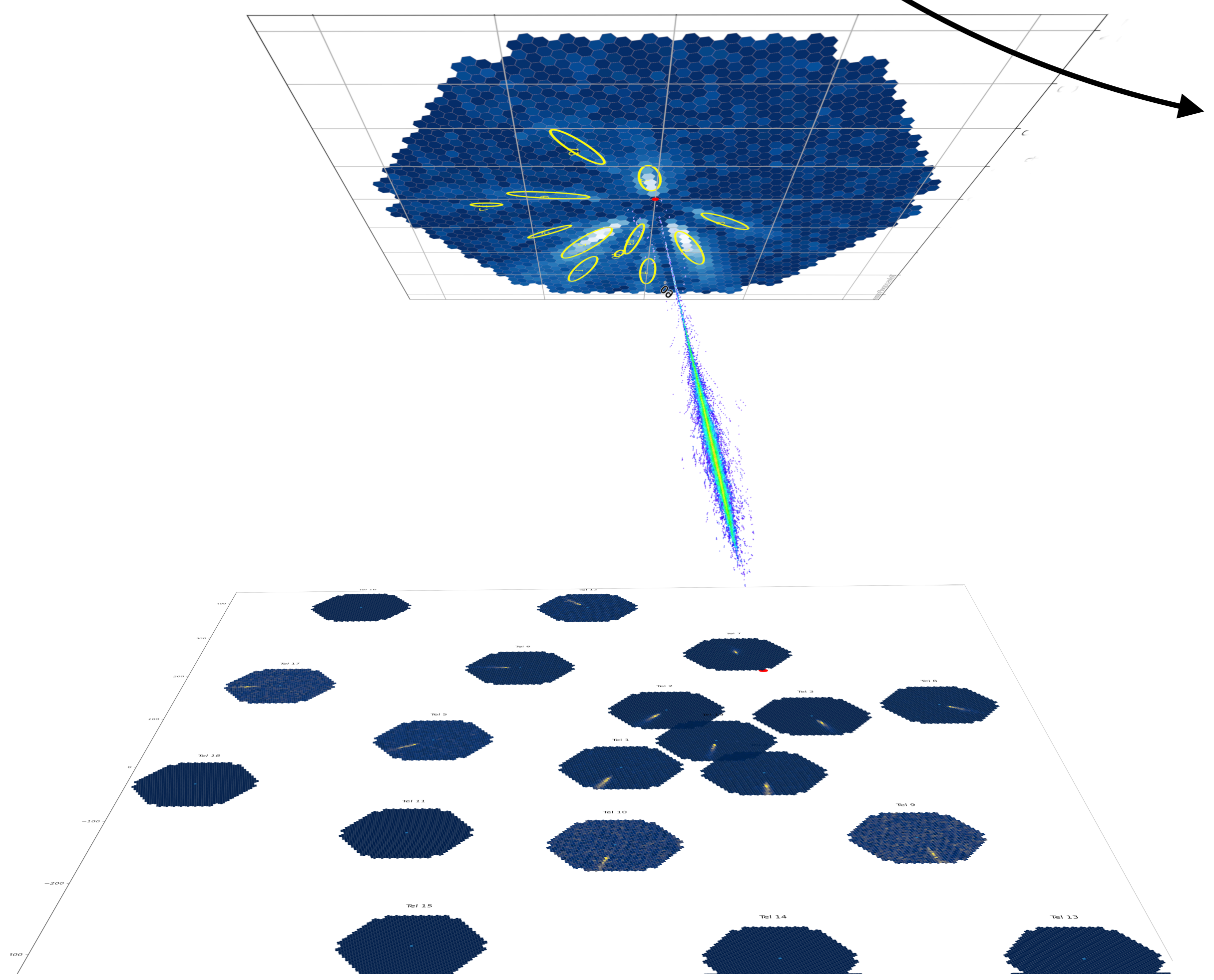
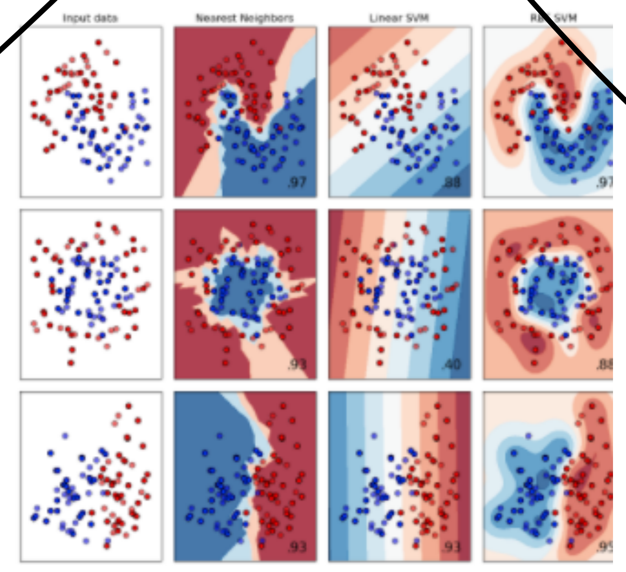
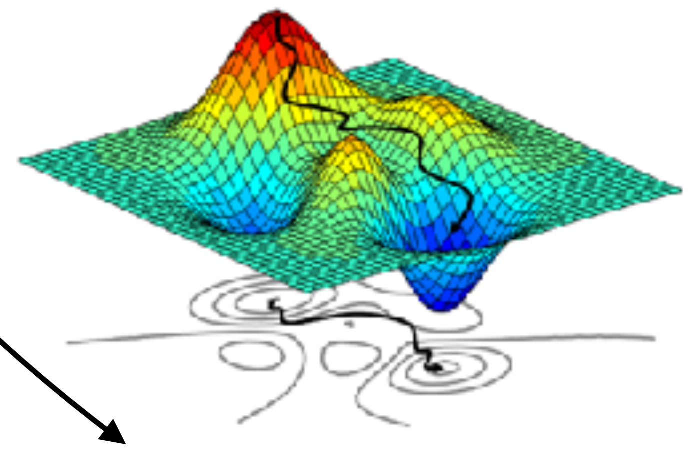


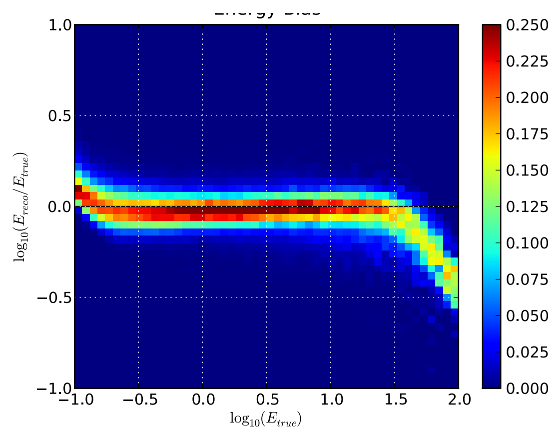
Energy Reconstruction

Particle Classification



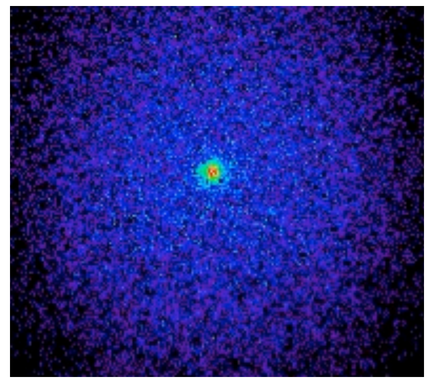


Optimization & Discrimination



Instrumental Responses & Performance Metrics

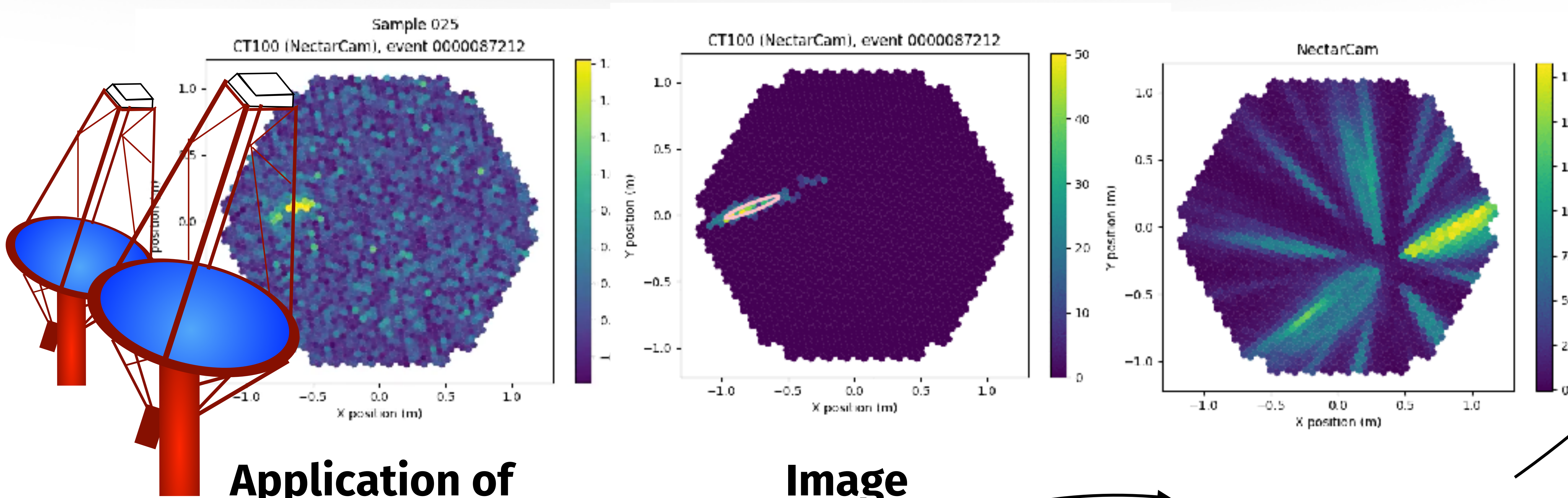
Science Event List Generation



Big Data

Science-Ready data Products
further processed with
Science Tools (GammaPy)

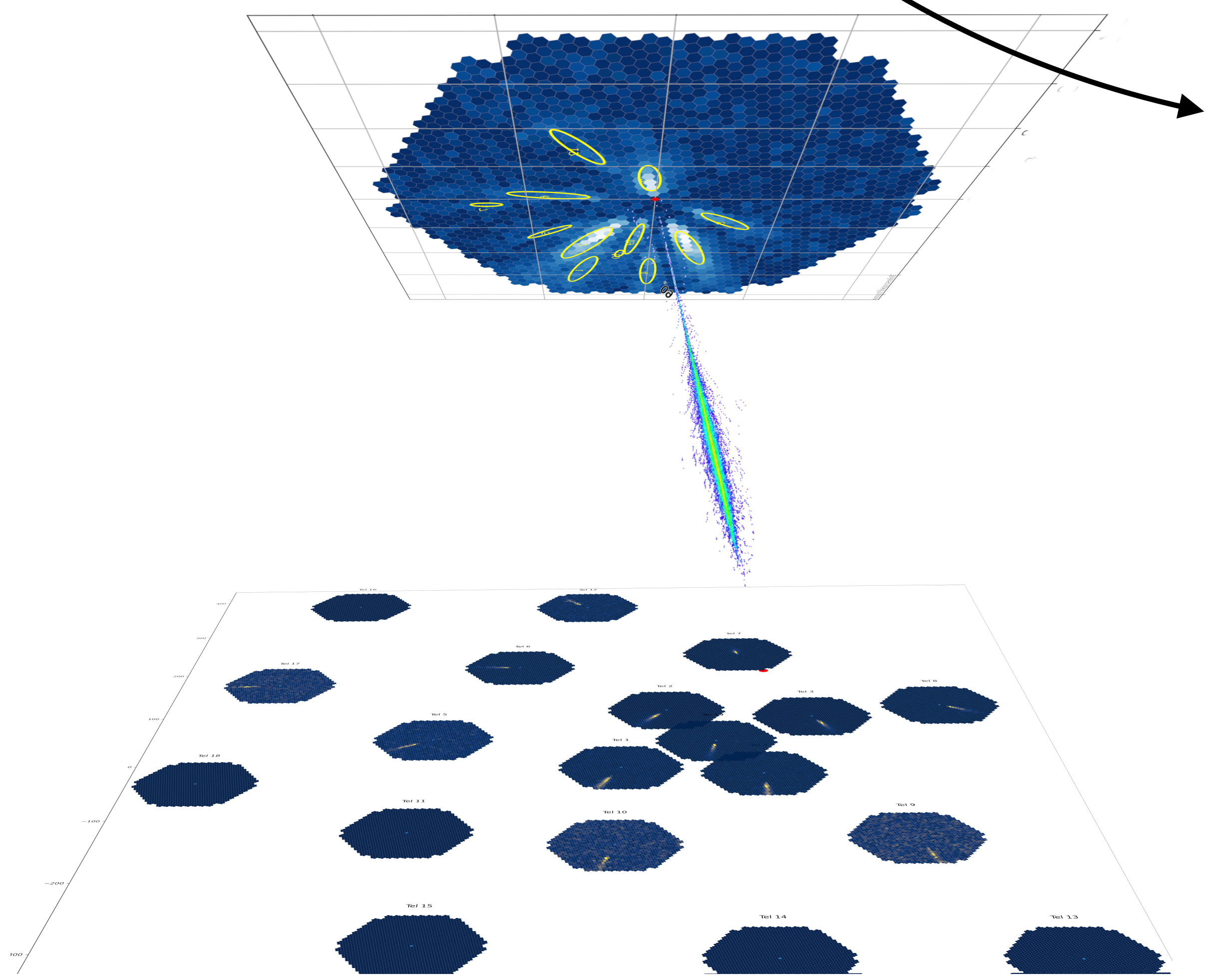
Summary of Data Procesing



Application of Calibration + Time-Integration

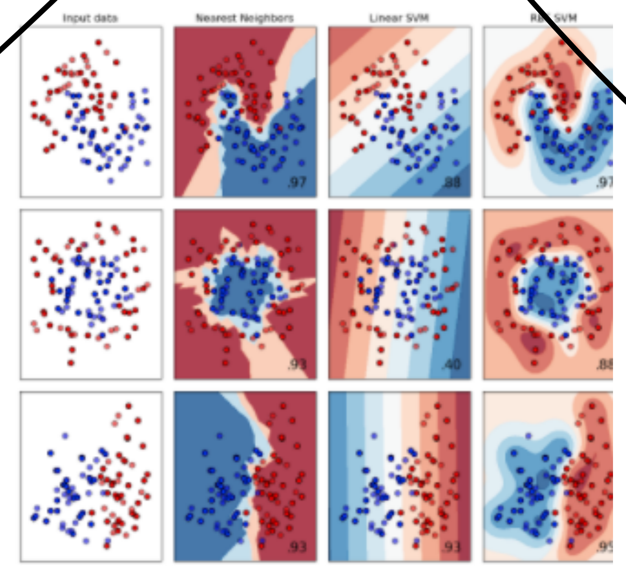
Image Processing And Feature Extraction

Stereo Reconstruction

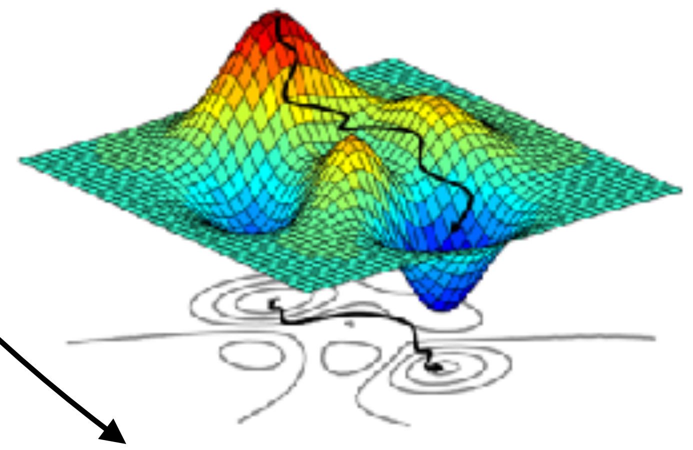


Machine Learning

Energy Reconstruction



Particle Classification



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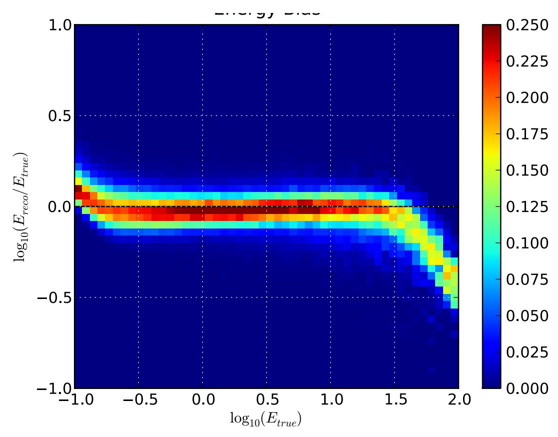
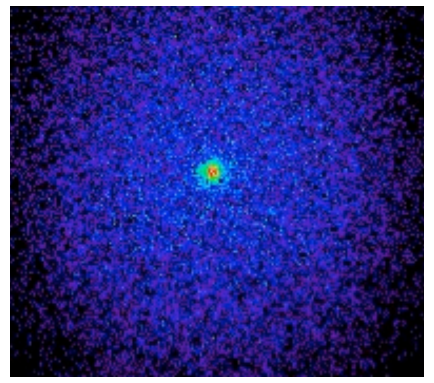


Instrumental Responses & Performance Metrics

Science Event List Generation



Big Data

Science-Ready data Products
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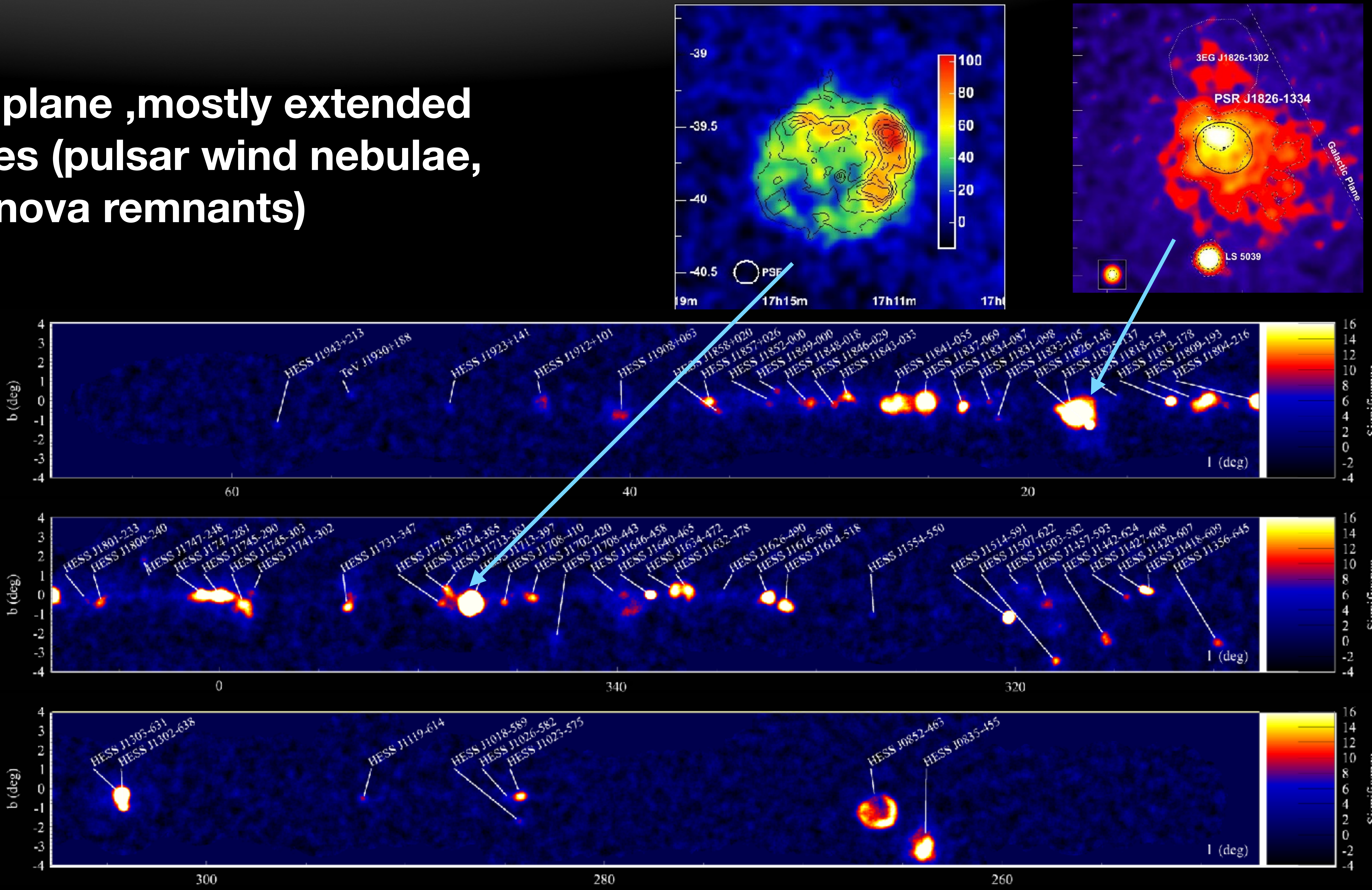
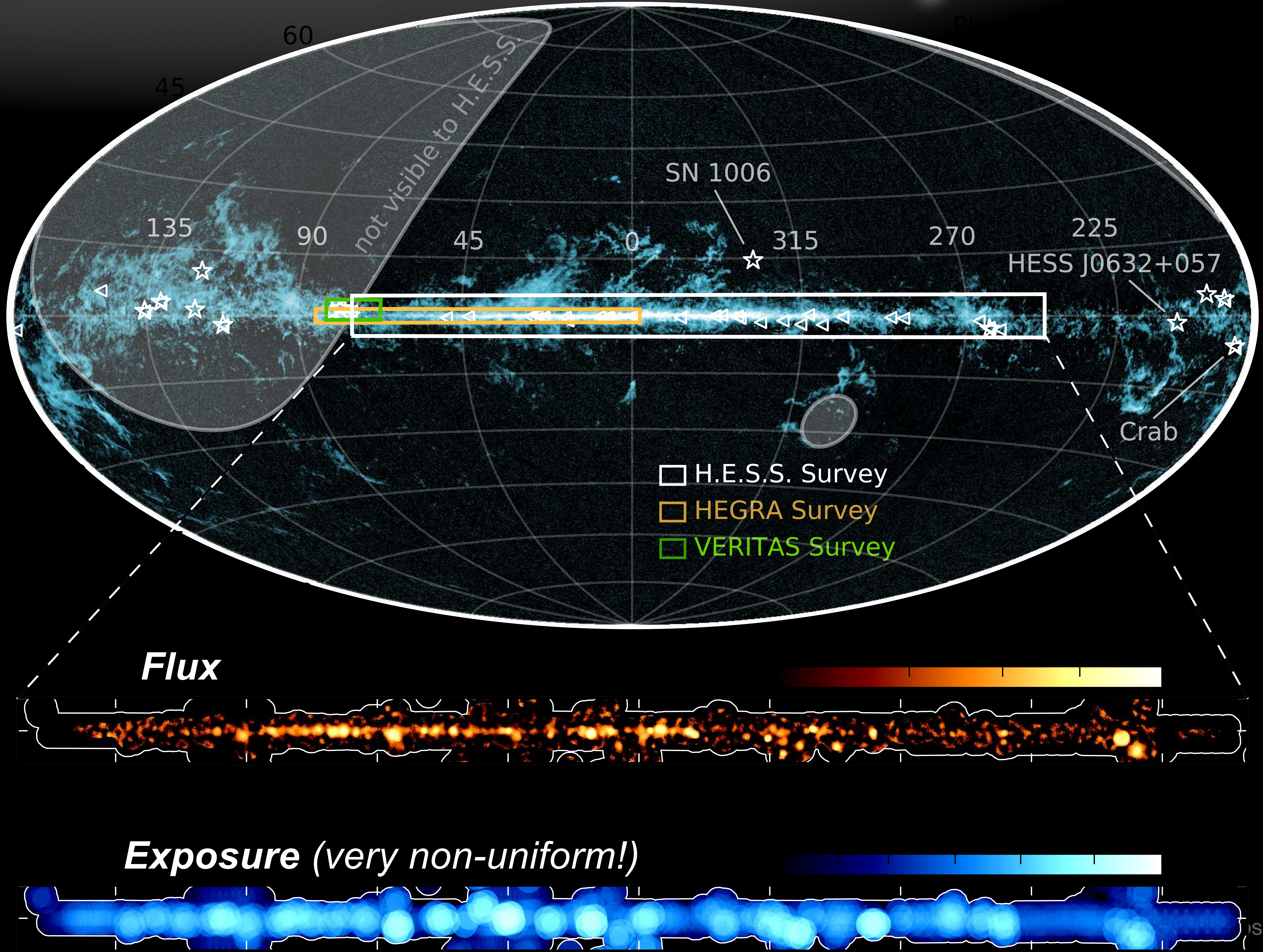
The Very-high-energy sky (HESS)

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



HESS Galactic Plane Survey



Flux

Exposure *(very non-uniform!)*

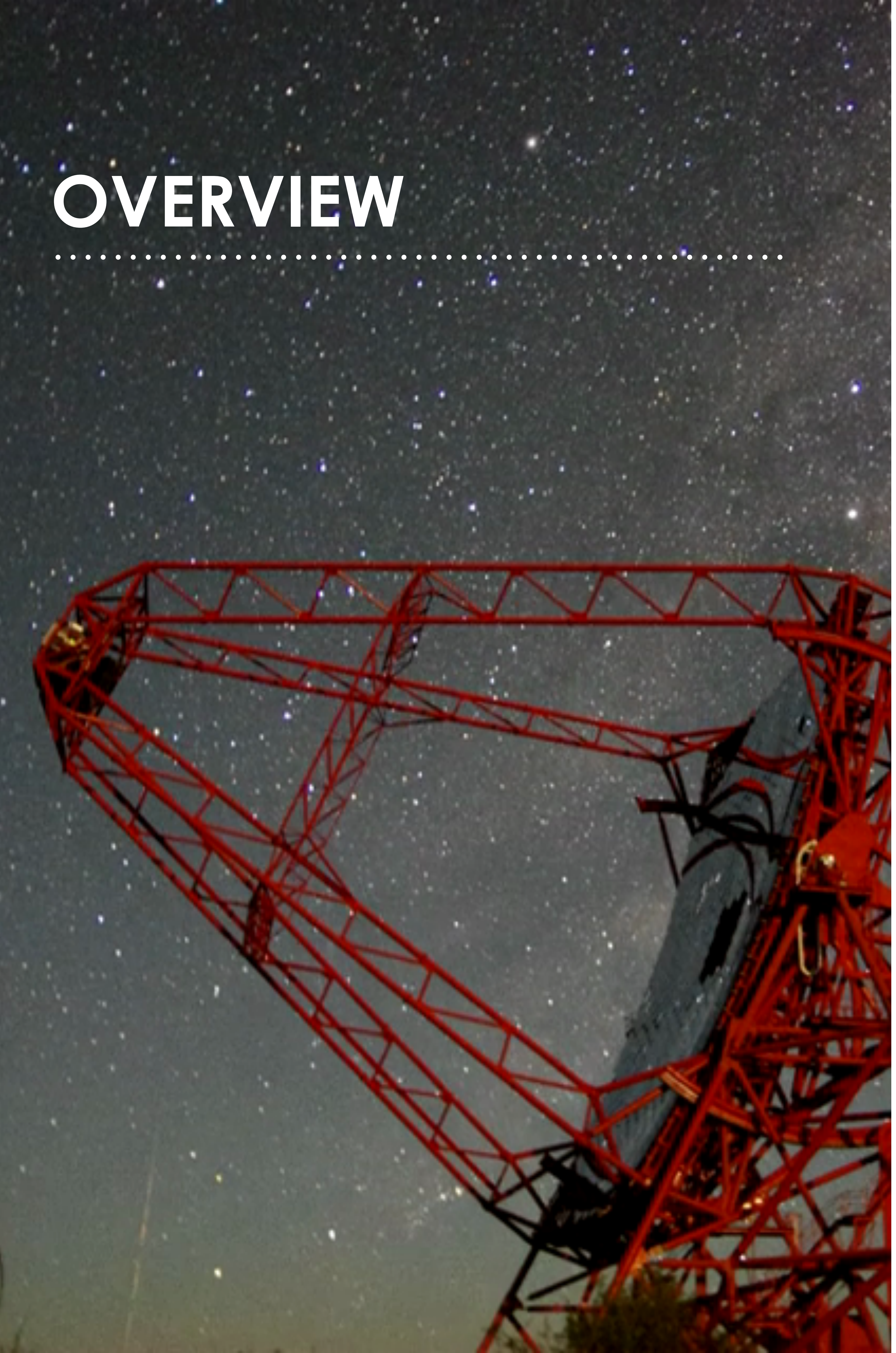
Atmospheric Cherenkov Telescopes

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 and ambient light conditions



OVERVIEW

VHE Gamma Rays

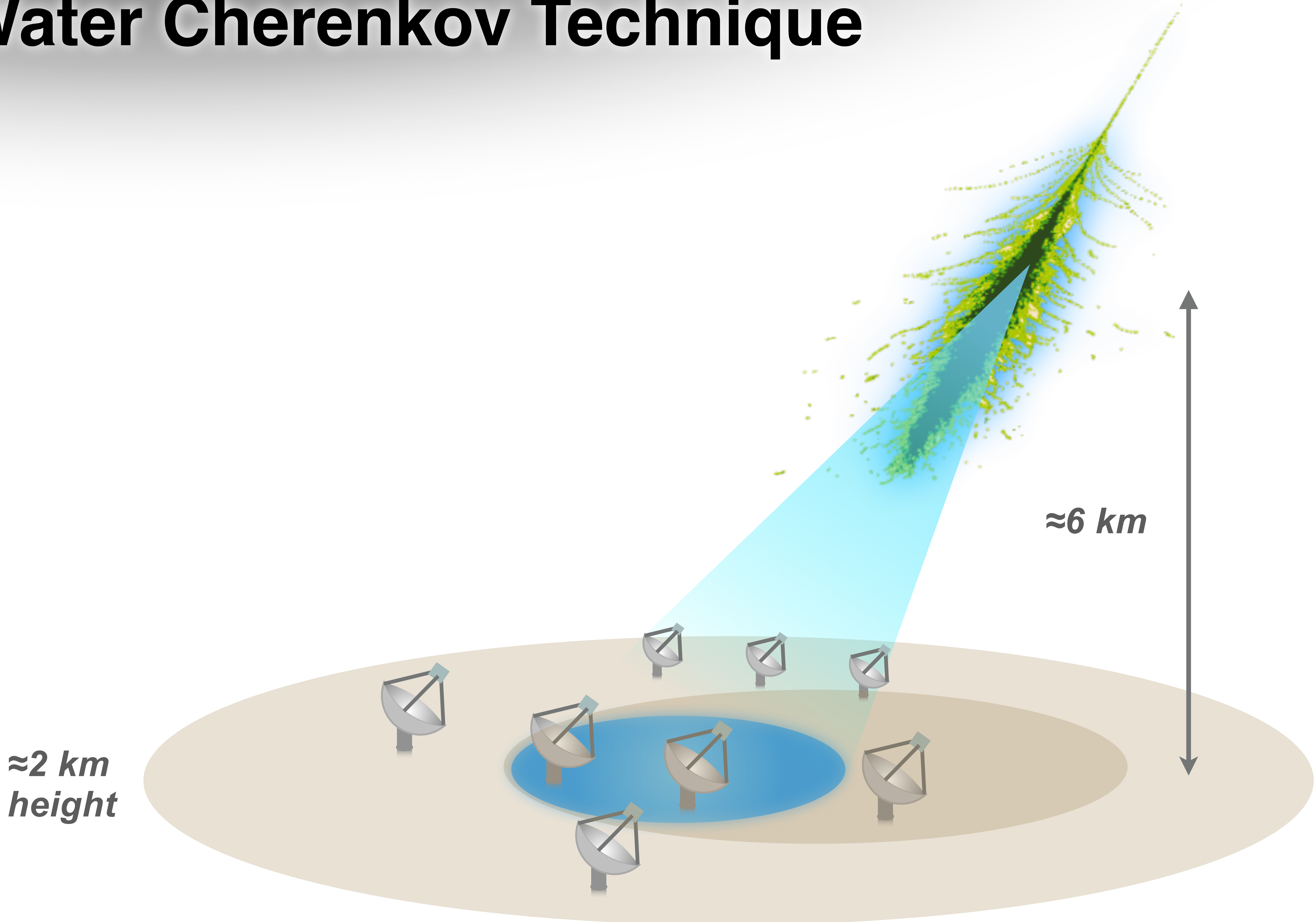
Gamma-ray Interactions in the Atmosphere

Imaging Atmospheric Cherenkov Telescopes

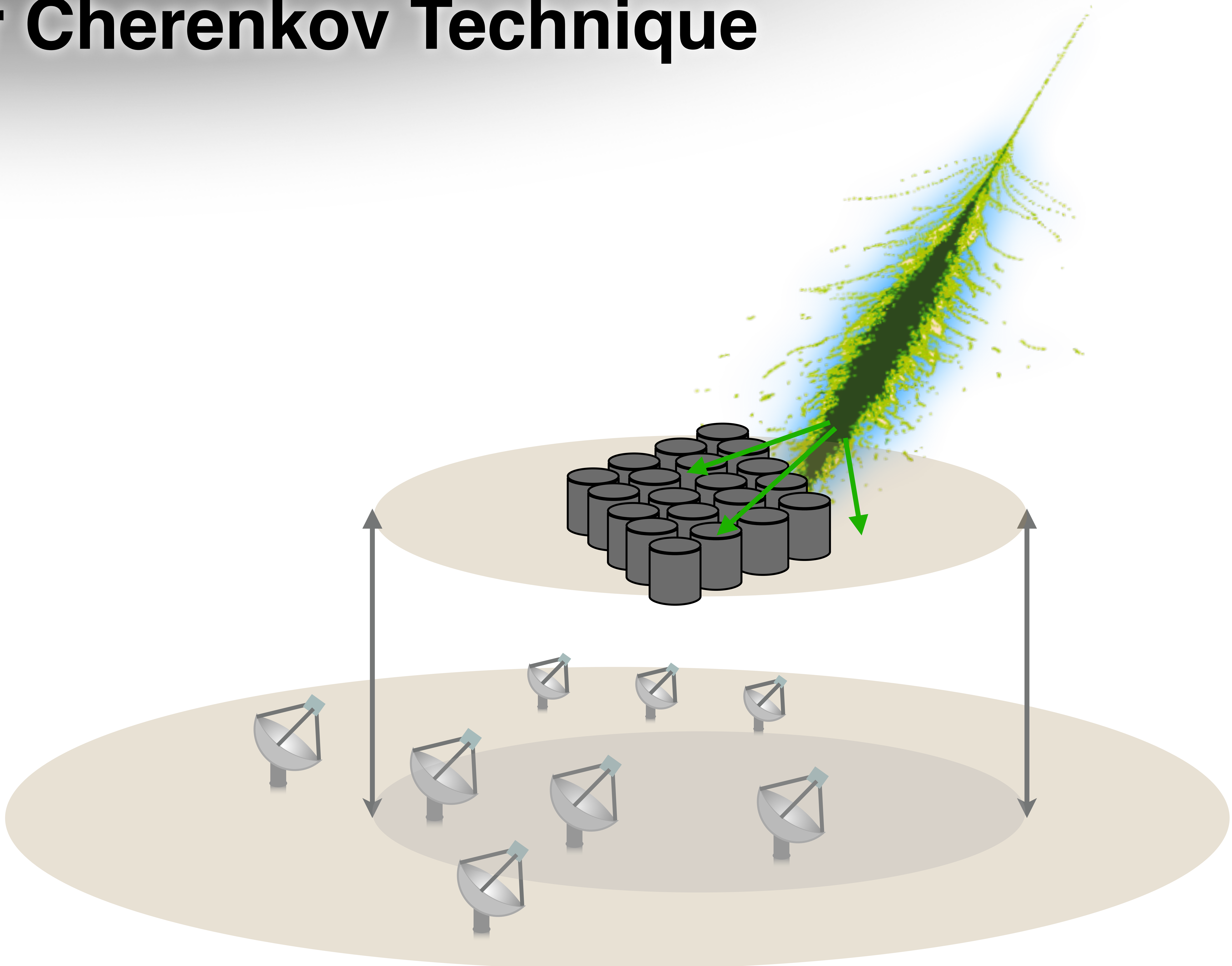
Water Cherenkov Telescopes

Science with VHE Gamma rays

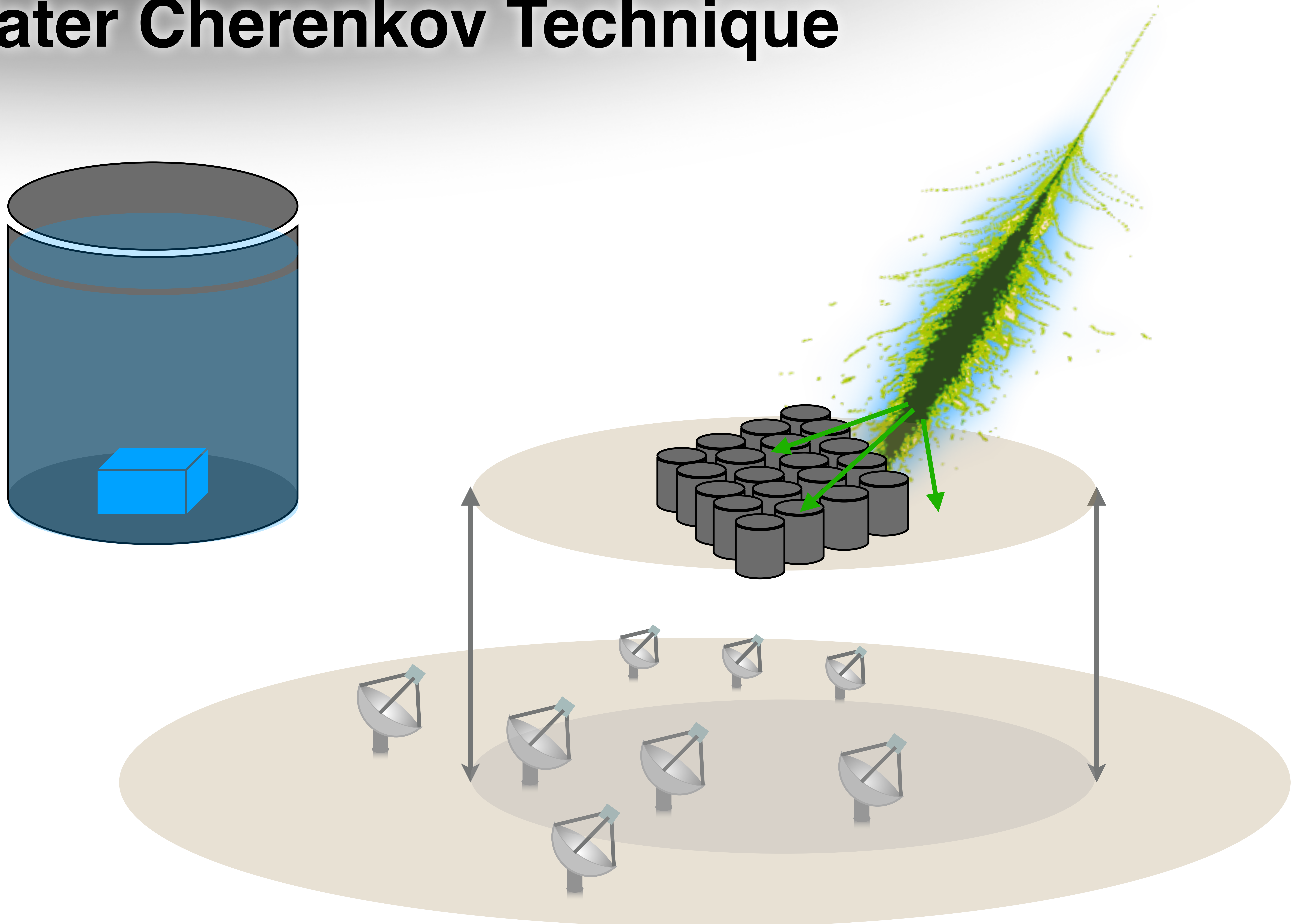
Water Cherenkov Technique



Water Cherenkov Technique



Water Cherenkov Technique



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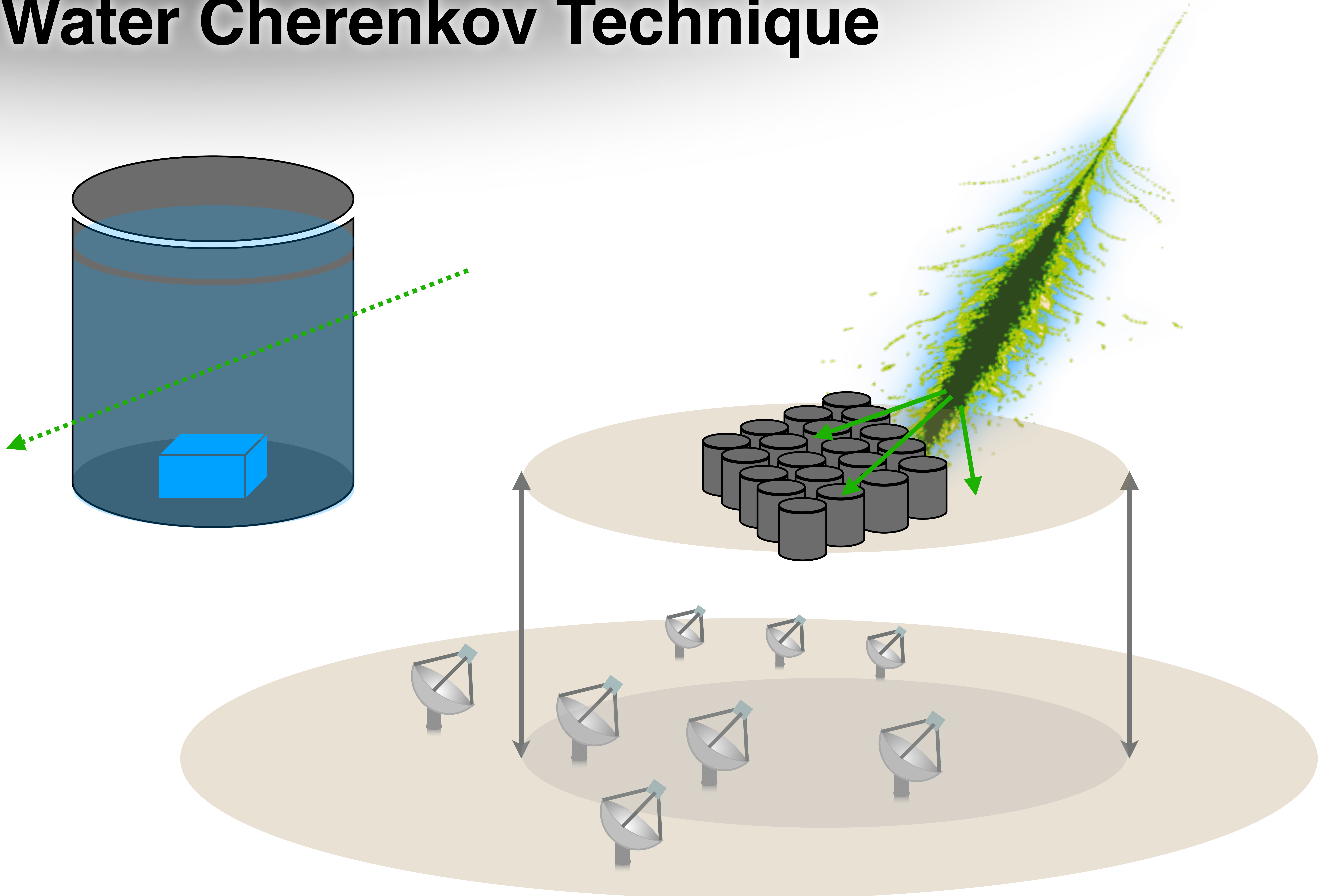

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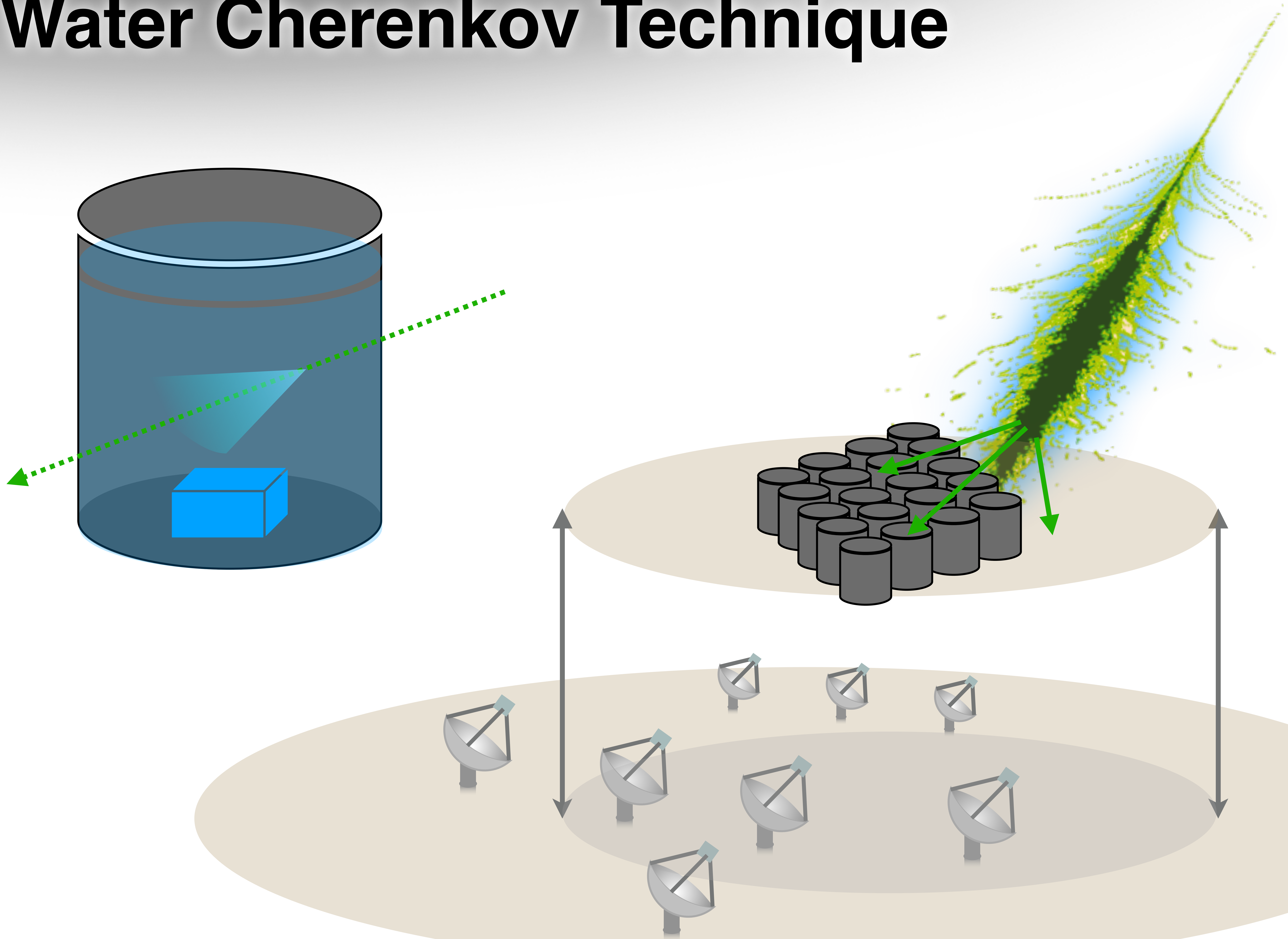
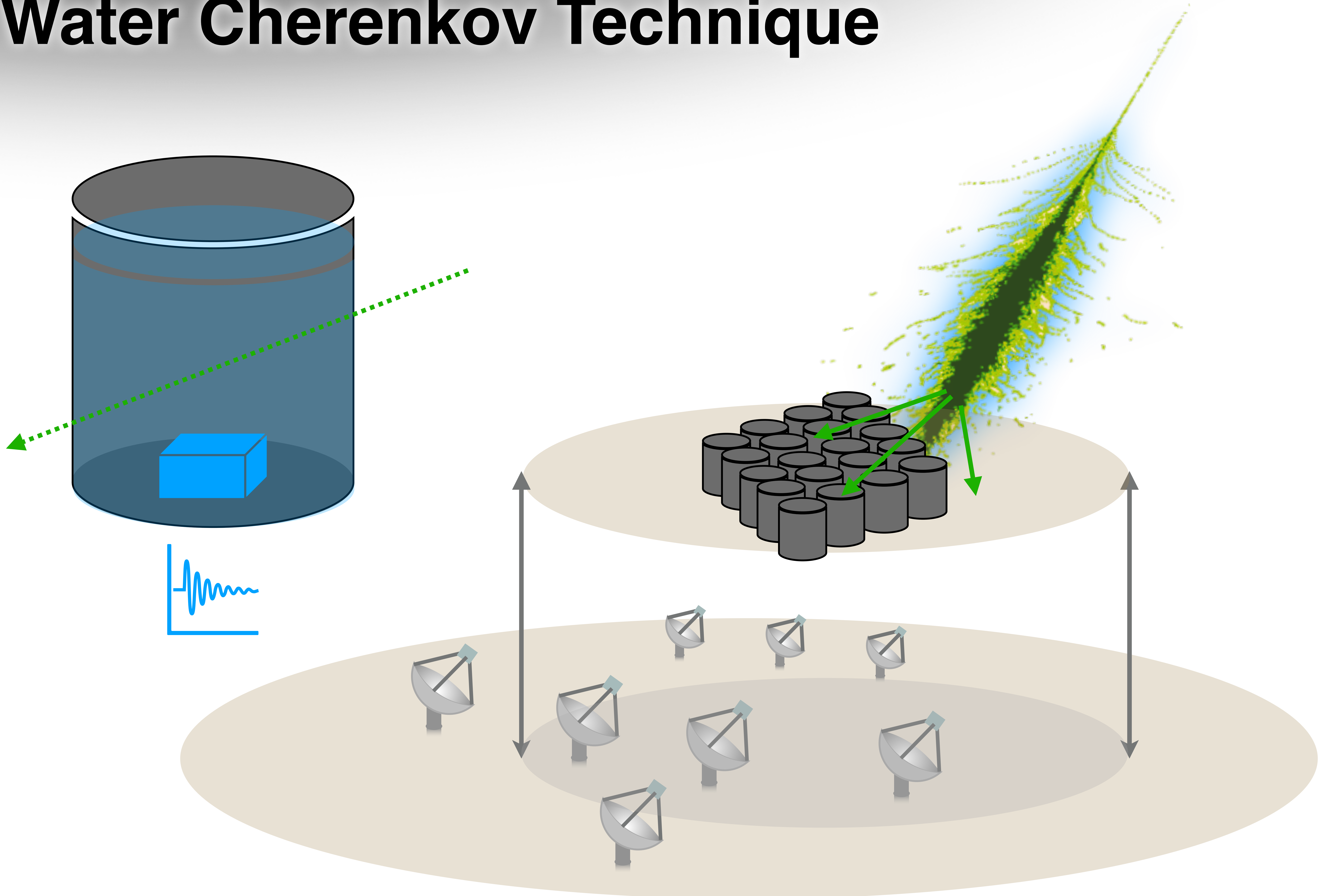


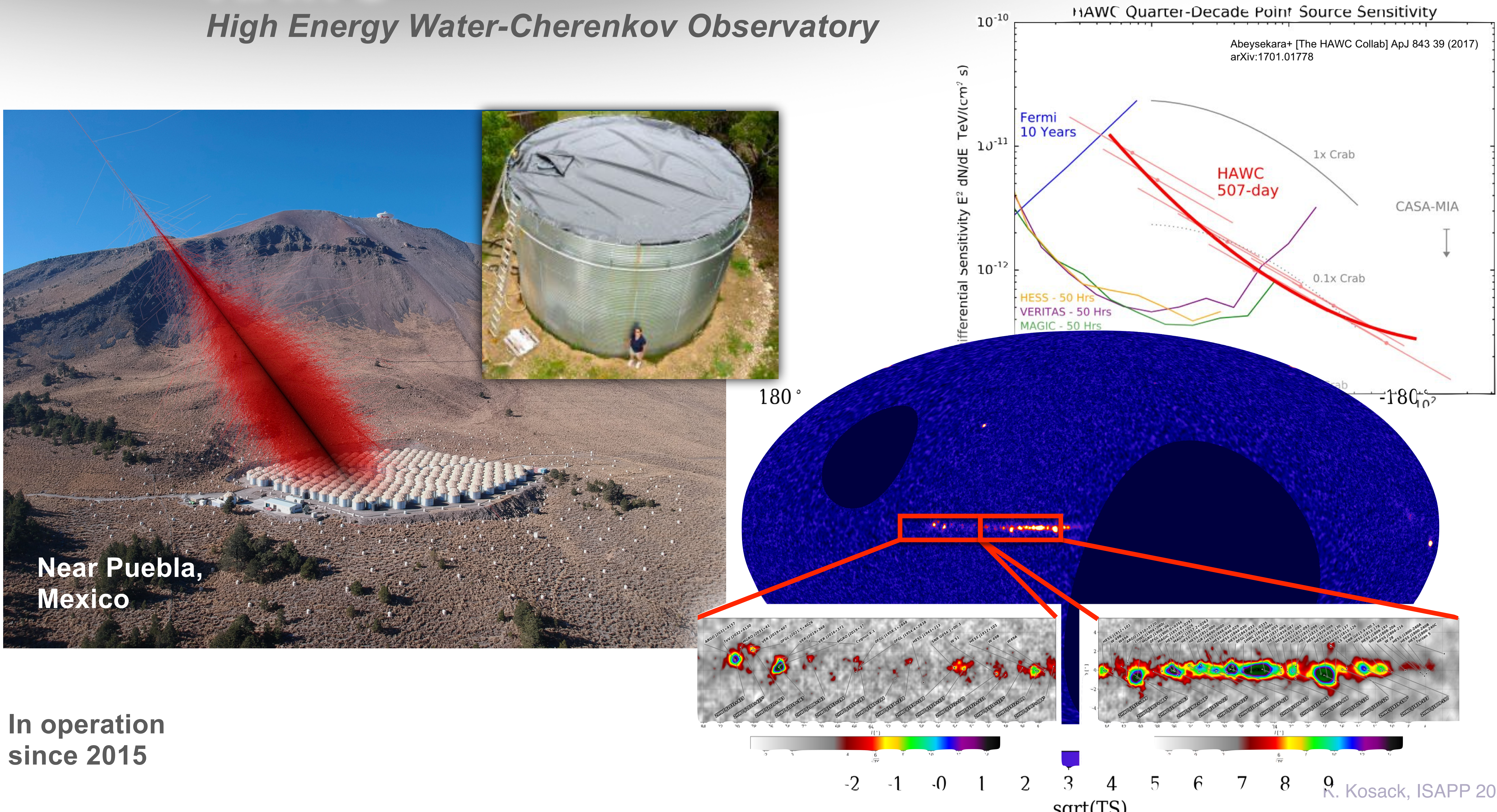
Water Cherenkov Technique



The HAWC Observatory (J. Goodman, Nov. 2016).

HAWC

High Energy Water-Cherenkov Observatory

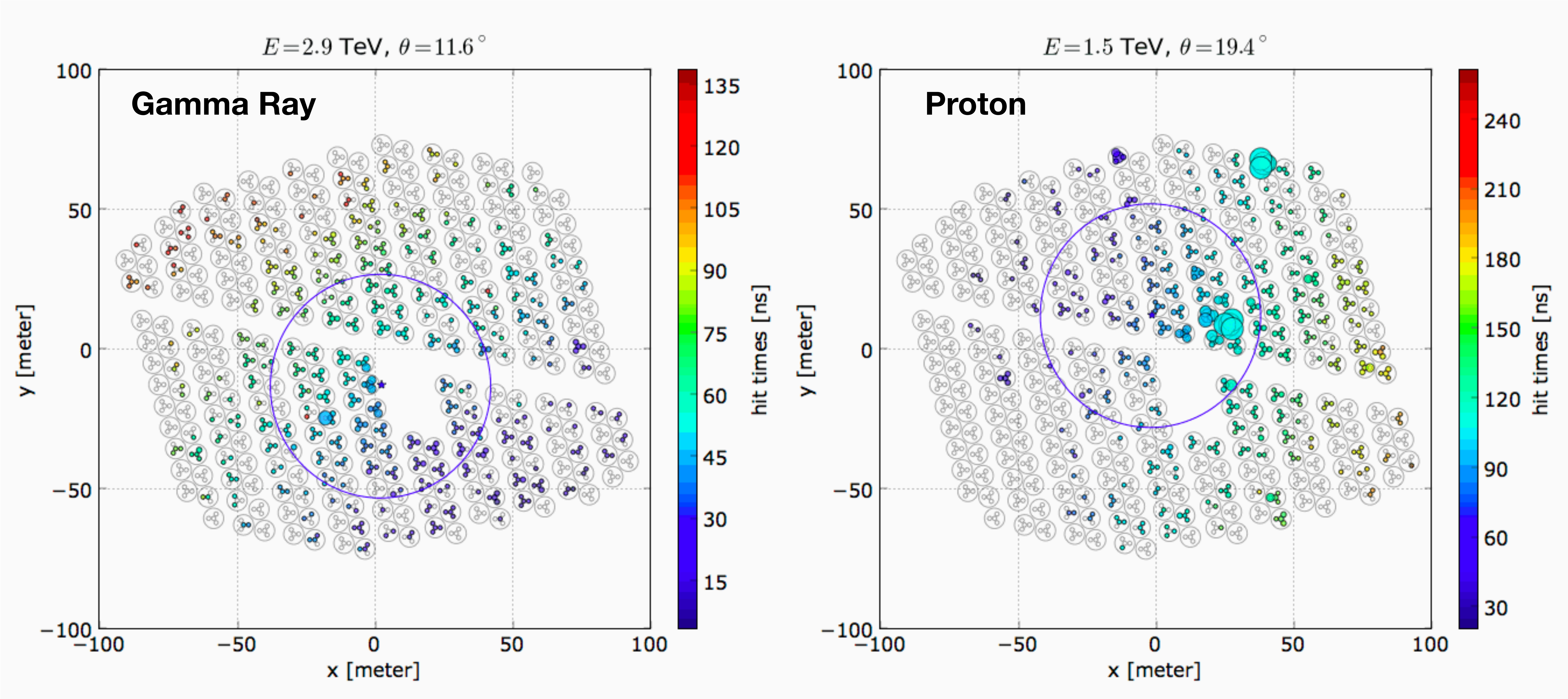


In operation since 2015

WCT Reconstruction

- Time gradient and center of gravity used for direction
- Uniformity for gamma/hadron separation
- Energy ≈ total signal (careful of partially contained showers however)

Large ground coverage critical!



Comparison With IACTs:

Advantages:

- High Duty Cycle : Operate during the day! Always looking!
- Wide Field-of-View: XXX deg (but no control over pointing)
- Relatively Cheap! No moving parts.

Disadvantages:

- Poorer PSF and Energy Resolution
- High energy threshold (no overlap with e.g. Fermi-LAT)
- Lower short-term sensitivity (need long integration times)

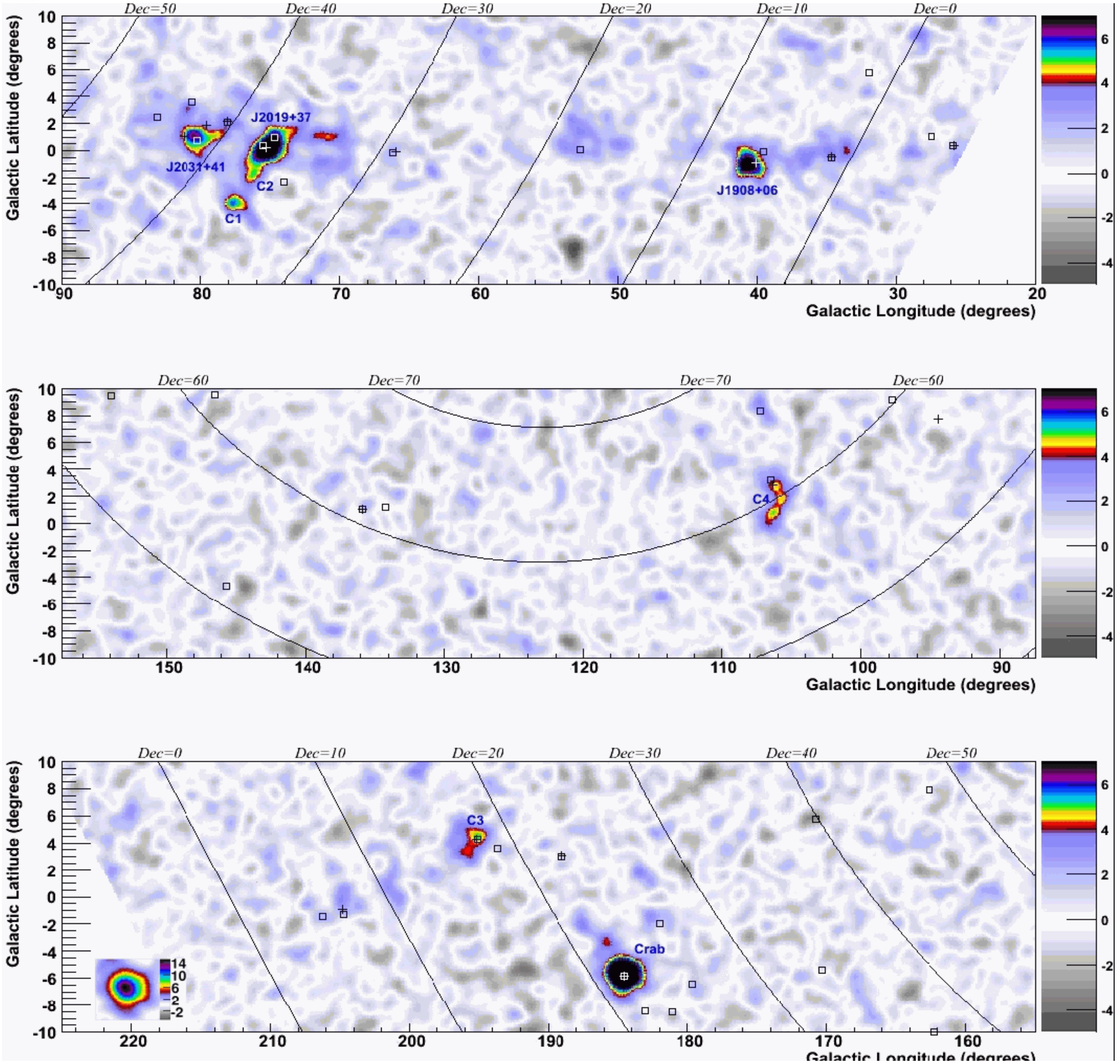
WCTs + IACTS are Quite Complimentary!

Milagro

Let's first take a step back to the original...

Milagro

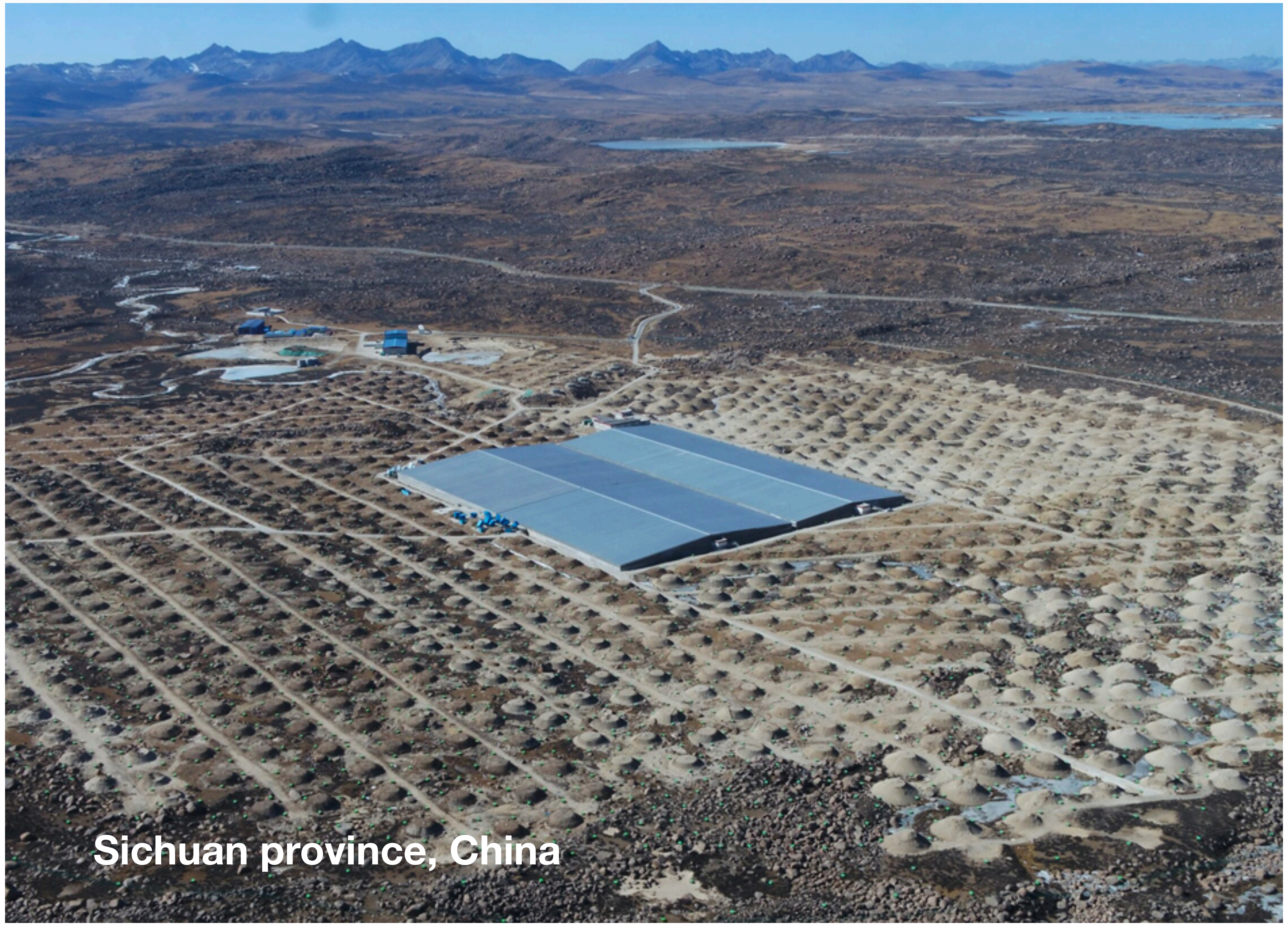
Let's first take a step back to the original...



6.4 years of data

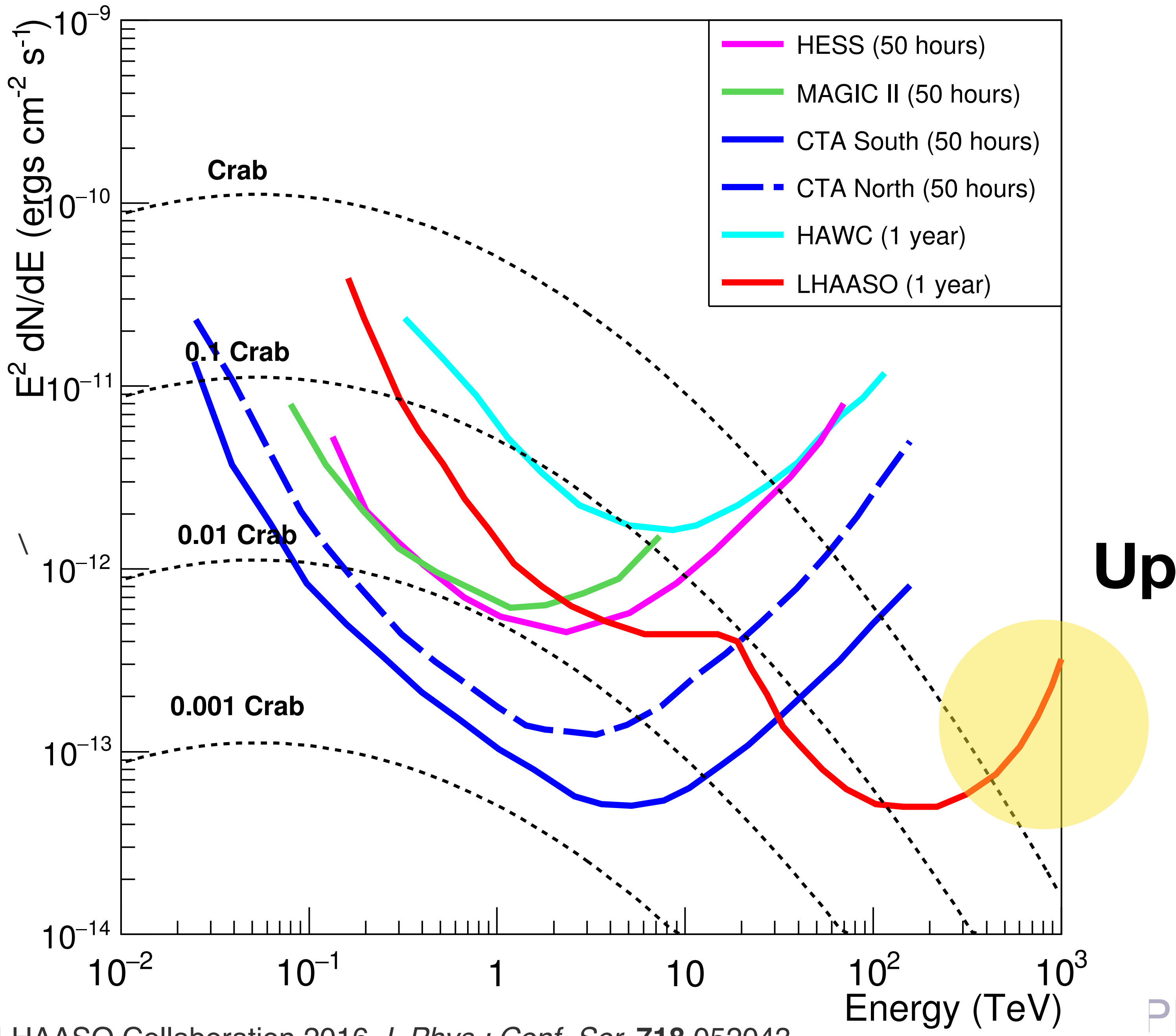
LHASSO

Large High Altitude Air Shower Observatory



Sichuan province, China

- Combines a less-dense water tank array with a Milagro-like central pools
  - ➤ Divided into cells by curtains for isolation

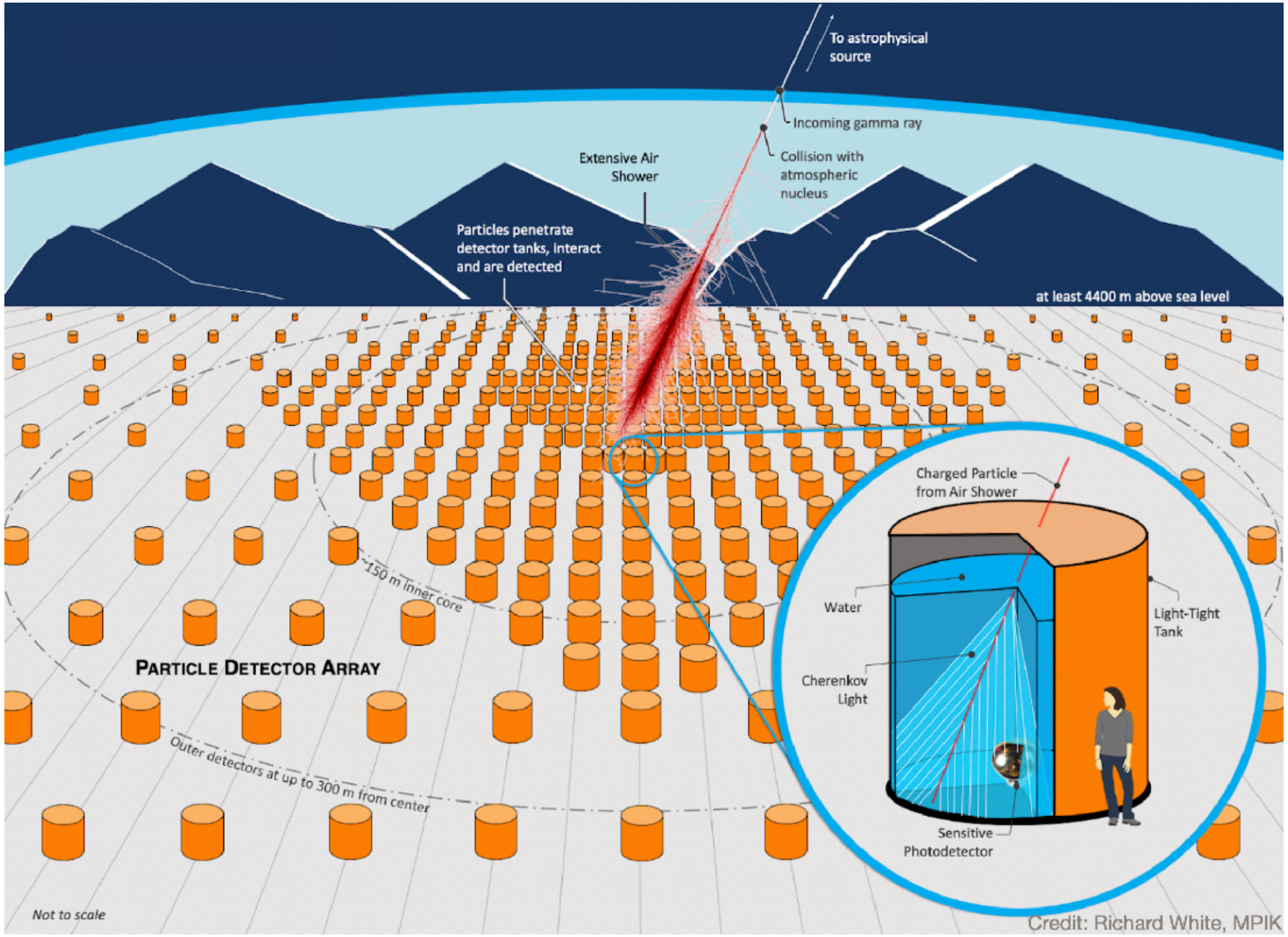


Up to EeV

S Vernetto and for the LHAASO Collaboration 2016 *J. Phys.: Conf. Ser.* **718** 052043

SWGO: The Future

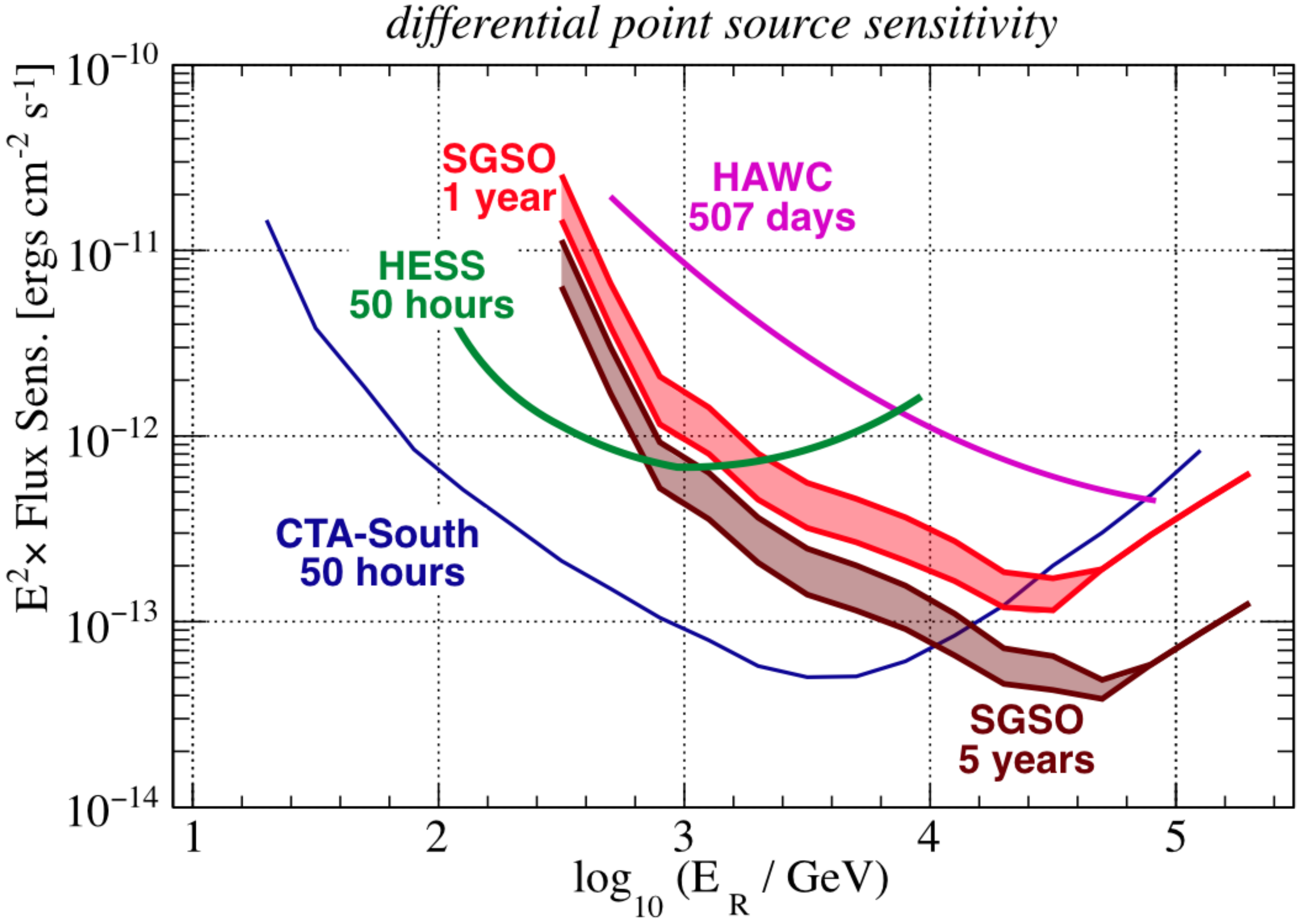
Southern Wide-field Gamma-ray Observatory



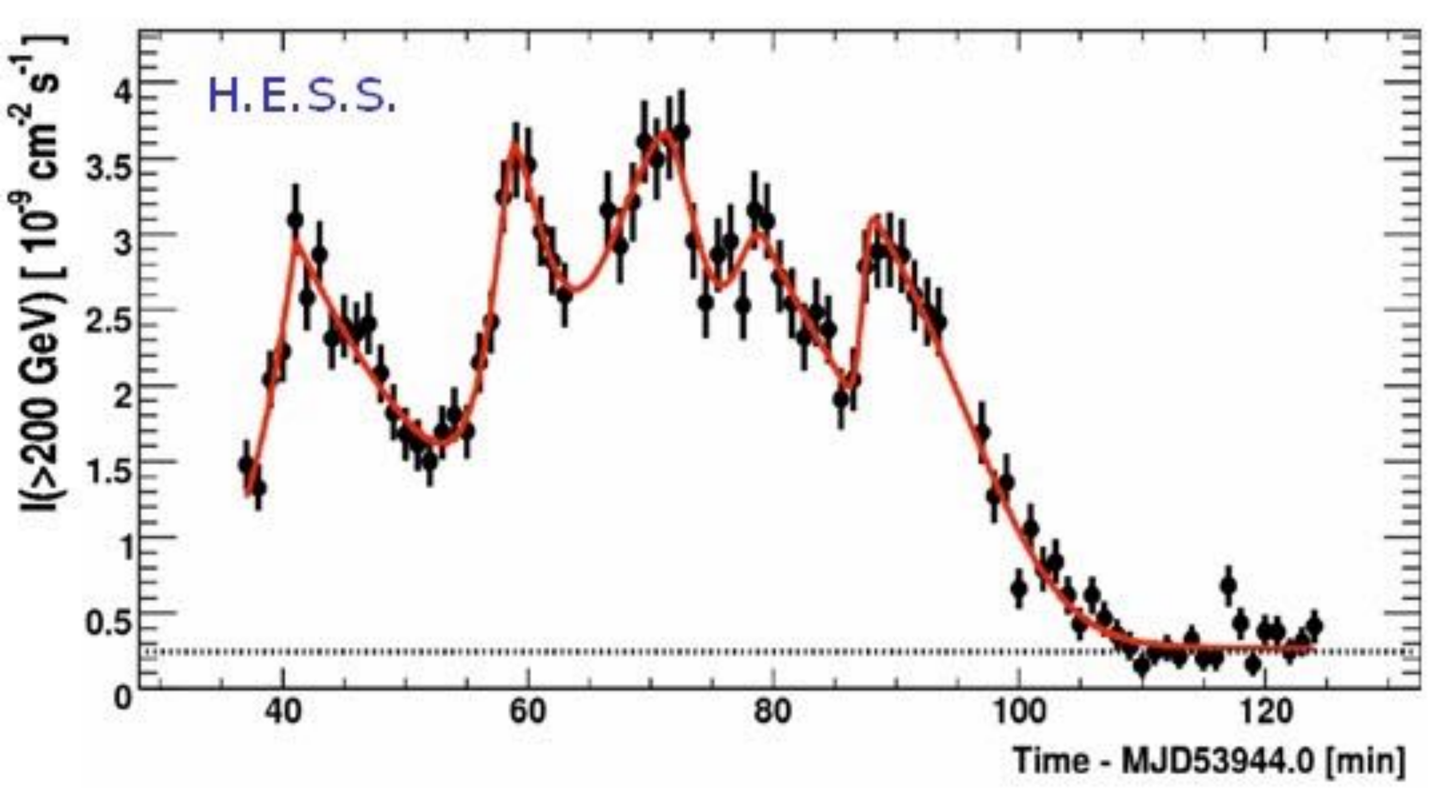
A. Albert et al, 2019, *Science Case for a Wide Field-of-View Very-High-Energy Gamma-Ray Observatory in the Southern Hemisphere*

Solves a big problem with WCTs:

- There are *none in the Southern hemisphere*!
- Most of the highest-energy sources are in the Galactic Plane!



Science Cases: Observation Time

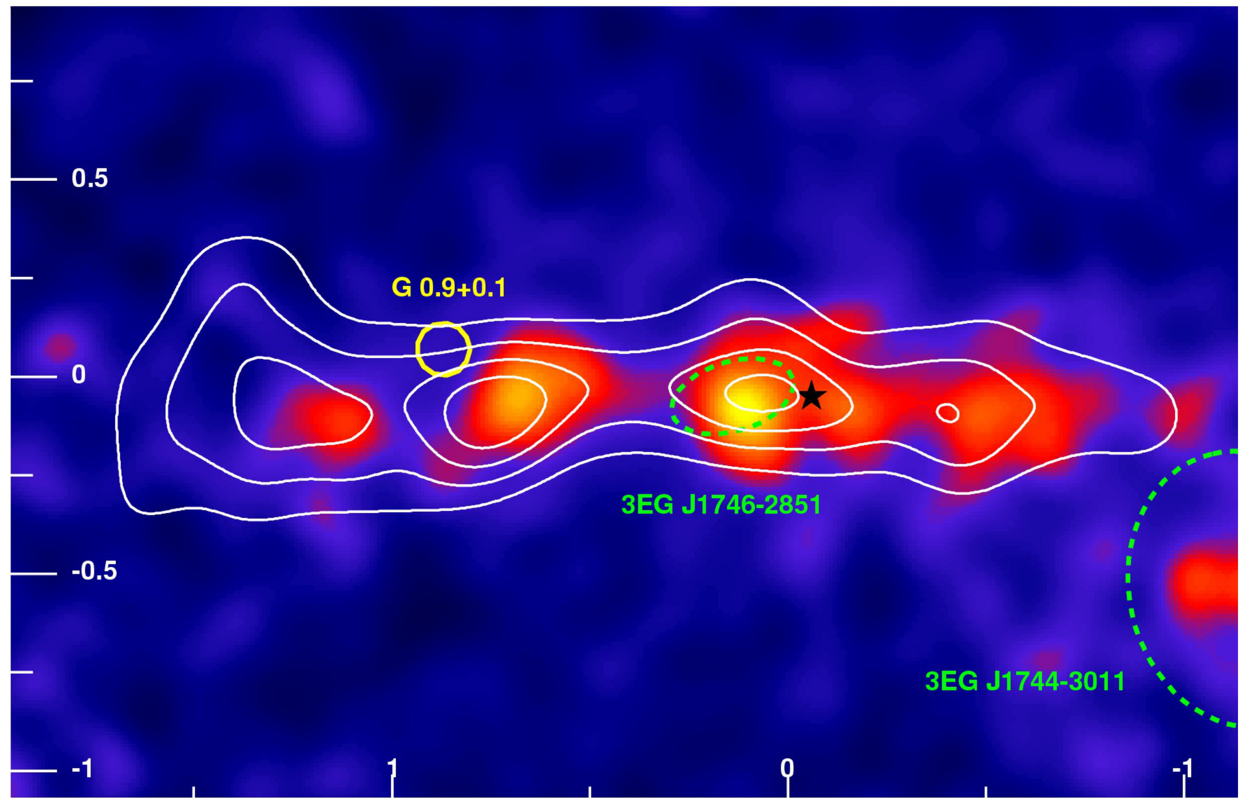


Transient and Periodic Sources

- Flares of Active Galactic Nuclei
- Black-Hole / Neutron-Star merger events
  (gravitational waves)
- Microquasars (Star - Compact Object binaries)
- Gamma Ray Bursts
- ...

IACTS with high short-term sensitivity and lower E threshold usually win

... if you know where to look!
(need multiwavelength alerts!)



Steady or Periodic Sources:

- Pulsar Wind Nebulae
- Supernova Remnants
- AGN Quiescent states, Radio Galaxies
- Gamma-ray Binary Systems
- Dark Matter
- Illuminated Molecular Clouds
- ...

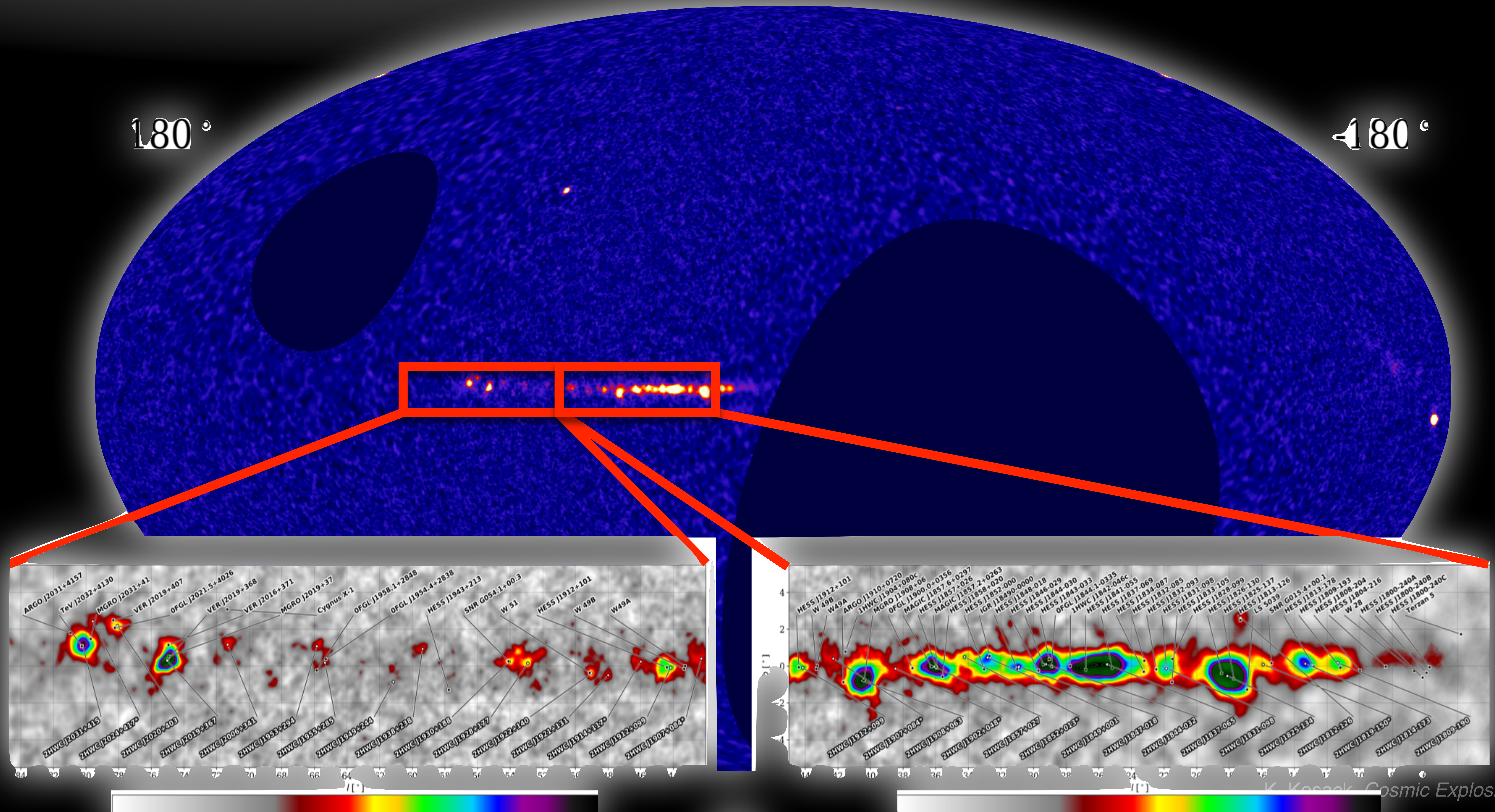
After a few years, WCTs become competitive

Advantage for IACTs is still angular and energy resolution in overlapping energy range

Comparison

	Fermi-LAT	IACTs (e.g. HESS)	WCTs (HAWC)
Energy Range	High-Energy Gamma	Very-High-Energy Gamma (30 GeV - >100 TeV)	Very-High-Energy Gamma (1 TeV - >100 TeV)
-100	**Effectively All-Sky**	Small (2-8°)	**Large (90°)**
PSF (E-dependant)	**good 0.1-1.0°**	**good 0.01-0.1°**	fair 0.1-0.3°
Energy Resolution	**good ≈10%**	**good ≈10%**	poor 20%-60%
Duty Cycle	**very good**	poor	**very good**
Sky Coverage	**full**	half	half
Short-Term Sensitivity	good (GeV) poor (>100GeV)	**good (>100GeV)**	poor

HAWC Survey



180 °
-180 °
ARGO J2031+4157
TeV J2032+4130
MGRO J2031+41
VER J2019+407
0FGL J2021.5+4026
VER J2019+368
VER J2016+371
MGRO J2019+37
Cygnus X-1
0FGL J1958.1+2848
0FGL J1954.4+2838
HESS J1943+213
SNR G054.1+00.3
W 51
HESS J1912+101
W 49B
W49A
2HWC J2031+415
2HWC J2024+417*
2HWC J2020+403
2HWC J2019+367
2HWC J2006+341
2HWC J1953+294
2HWC J1955+285
2HWC J1949+244
2HWC J1938+238
2HWC J1930+188
2HWC J1928+177
2HWC J1922+140
2HWC J1921+131
2HWC J1914+117*
2HWC J1912+099
2HWC J1907+084*
l [°]
HESS J1912+101
W 49B
W49A
ARGO J1910+0720
1HWC J1904+080c
MGRO J1908+06
0FGL J1900.0+0356
MAGIC J1857.6+0297
HESS J1857+026
MAGIC J1857.2+0263
HESS J1858+020
HESS J1852-000
IGR J18490-0000
HESS J1848-018
HESS J1846-029
HESS J1844-030
HESS J1843-033
0FGL J1844.1-0335
1HWC J1842-046c
HESS J1841-055
HESS J1837-069
HESS J1834-087
HESS J1832-085
HESS J1832-093
HESS J1831-098
HESS J1833-105
HESS J1828-099
HESS J1826-130
HESS J1825-137
HESS J1813-126
LS 5039
SNR G015.4+00.1
HESS J1813-178
HESS J1809-193
HESS J1808-204
HESS J1804-216
W 28
HESS J1800-240A
HESS J1800-240B
HESS J1800-240C
Terzan 5
2HWC J1912+099
2HWC J1907+084*
2HWC J1908+063
2HWC J1902+048*
2HWC J1857+027
2HWC J1852+013*
2HWC J1849+001
2HWC J1847-018
2HWC J1844-032
2HWC J1837-065
2HWC J1831-098
2HWC J1825-134
2HWC J1812-126
2HWC J1819-150*
2HWC J1814-173
2HWC J1809-190
b [°]
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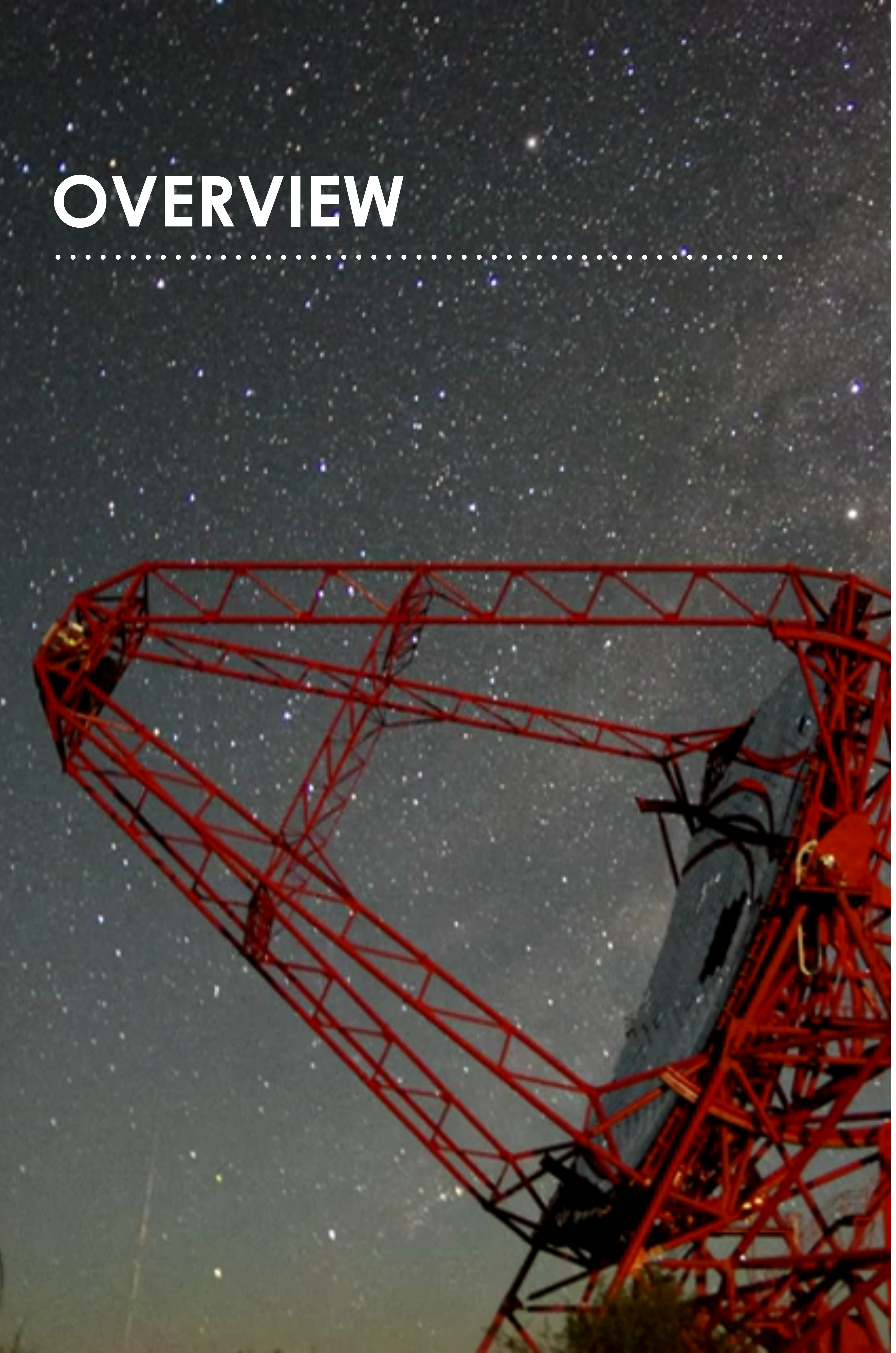
-4
l [°]



OVERVIEW

VHE Gamma Rays

Gamma-ray Interactions in the Atmosphere

Imaging Atmospheric Cherenkov Telescopes

Water Cherenkov Telescopes

Science with VHE Gamma rays

How to go from events to science?

What do we have?

- **Gamma-like Events**: points in space, time, and estimated energy that may be *gamma rays* or may be *mis-reconstructed cosmic rays*.

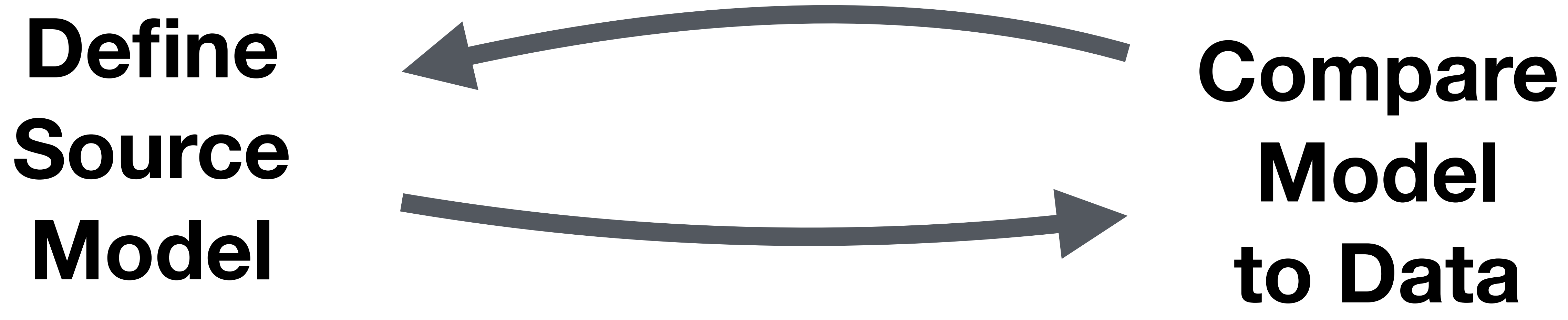
event id	time	ra	dec	E_{reco}
1	12	87.6	-23.7	5.6
2	150	87.2	-22.1	0.32
3	190	86.5	-23.4	0.45
4	2000	82.0	-23.2	0.57
5	7029	88.6	-24.1	2.4

What do we want? Fluxes!

- **Images**: Flux of gamma rays as a function of *spatial coordinates*
- **Spectra**: Flux of gamma rays from a region as a function of *energy*
- **Light Curves**: Flux of gamma rays from a region as a function of *time*
- *Or combinations thereof (data cubes)*

What we *really* want:

To make a hypothesis about the gamma-ray emission in a region of the sky and to test that hypothesis.



Define Source Model

Compare Model to Data

Physical Quantities

$$F(E_\text{true}, \overrightarrow{p}_\text{true}, t_\text{true})$$

Flux

Reconstructed Quantities

$$N_\text{events}(E_\text{reco}, \overrightarrow{p}_\text{reco}, t_\text{reco})$$

Counts

We are missing one piece of information:

how to go between true and measured (reconstructed) quantities?

Instrumental Response Functions

Generated from detailed air-shower simulations where you know both *true* and *reconstructed* quantities!

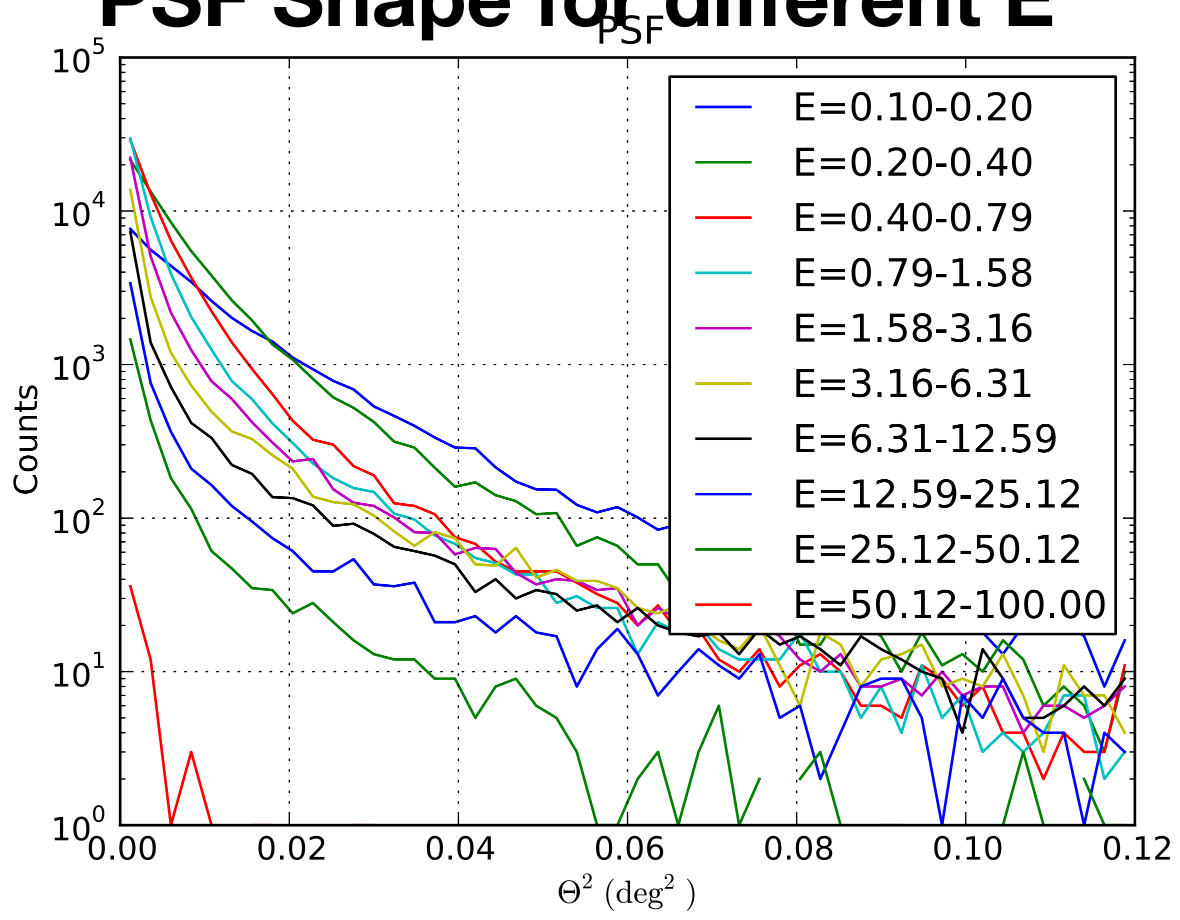
Instrumental Response Functions

Generated from detailed air-shower simulations where you know both *true* and *reconstructed* quantities!

Point-Spread Function (PSF)

- System Response to perfect point in **space**
  $P(\overrightarrow{p}_{\mathrm{reco}} \mid \overrightarrow{p}_{\mathrm{true}})$
- Usually assume no translation, only dispersion

PSF Shape for different E



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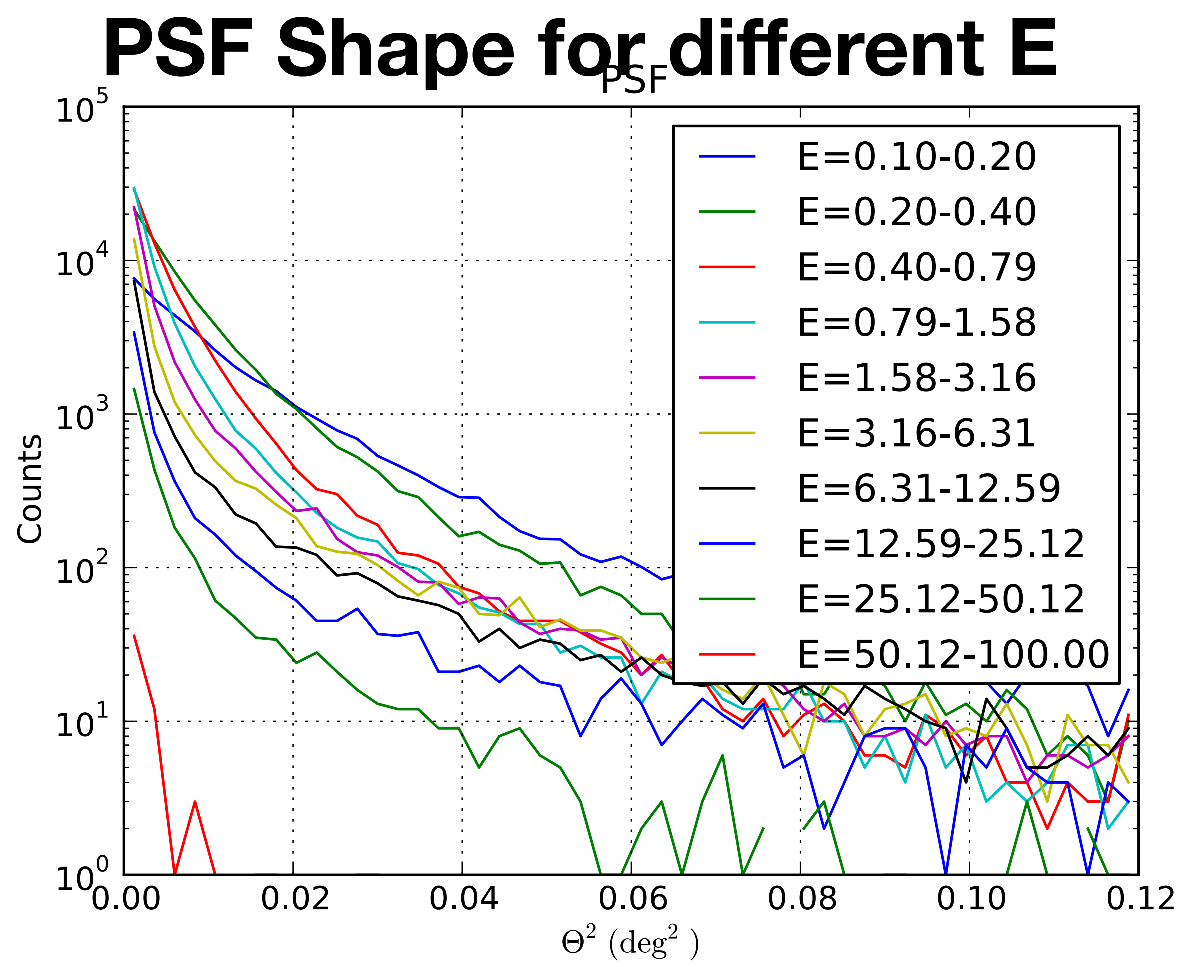
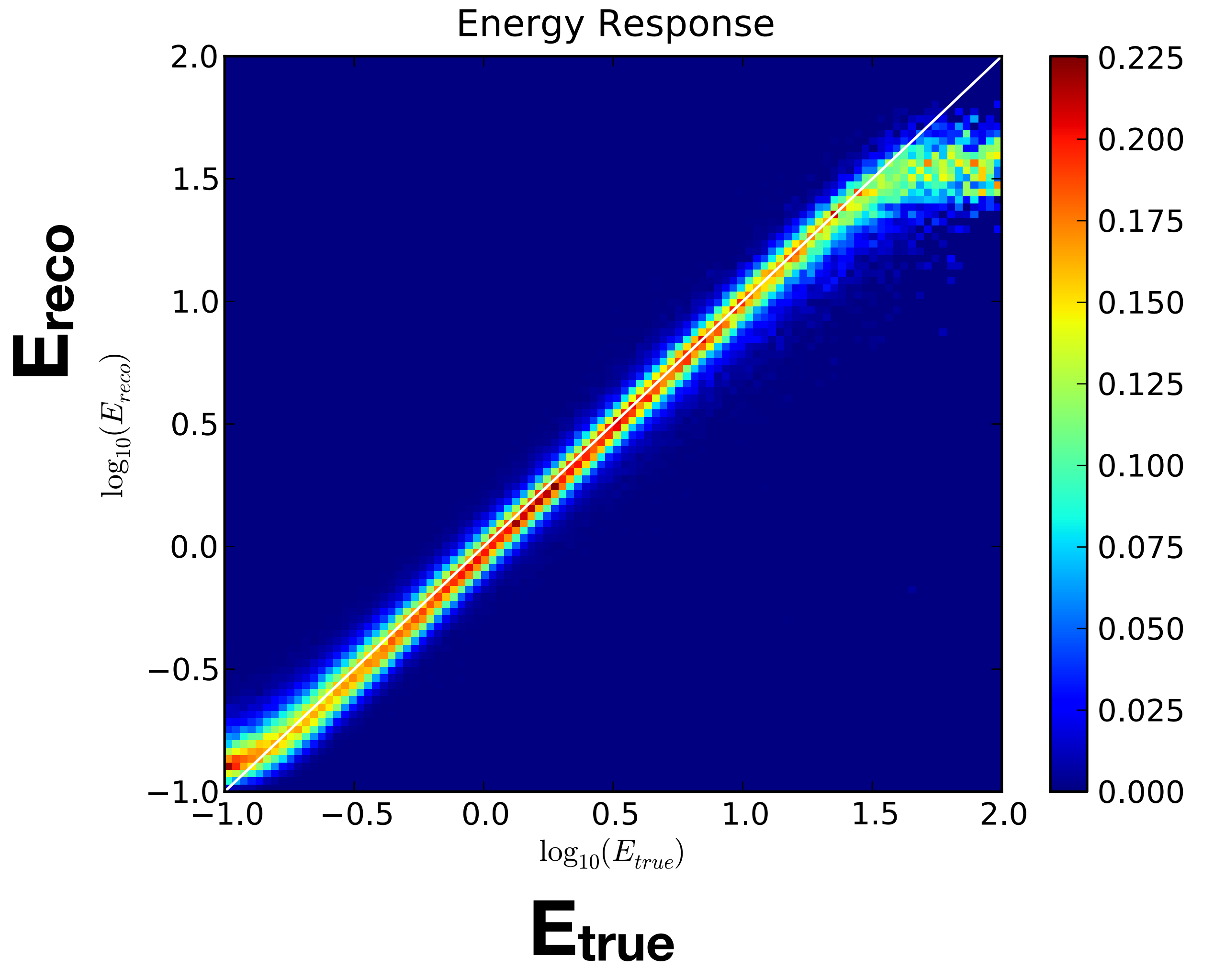
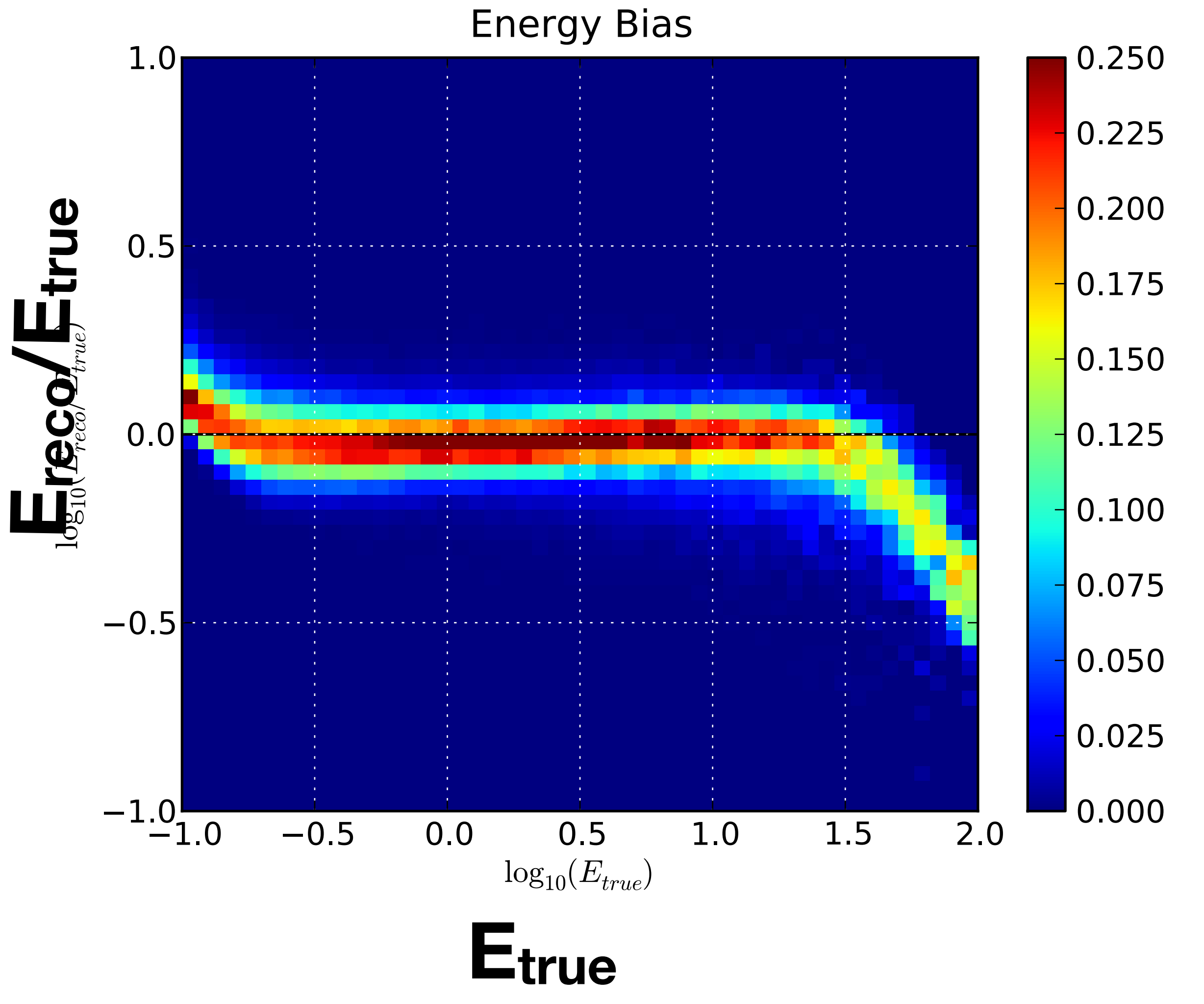
Energy-Migration Matrix:

- System Response to a **mono-energetic** source $P(E_{\text{reco}} \,|\, E_{\text{true}})$
- Takes into account both energy **resolution** and energy **bias**







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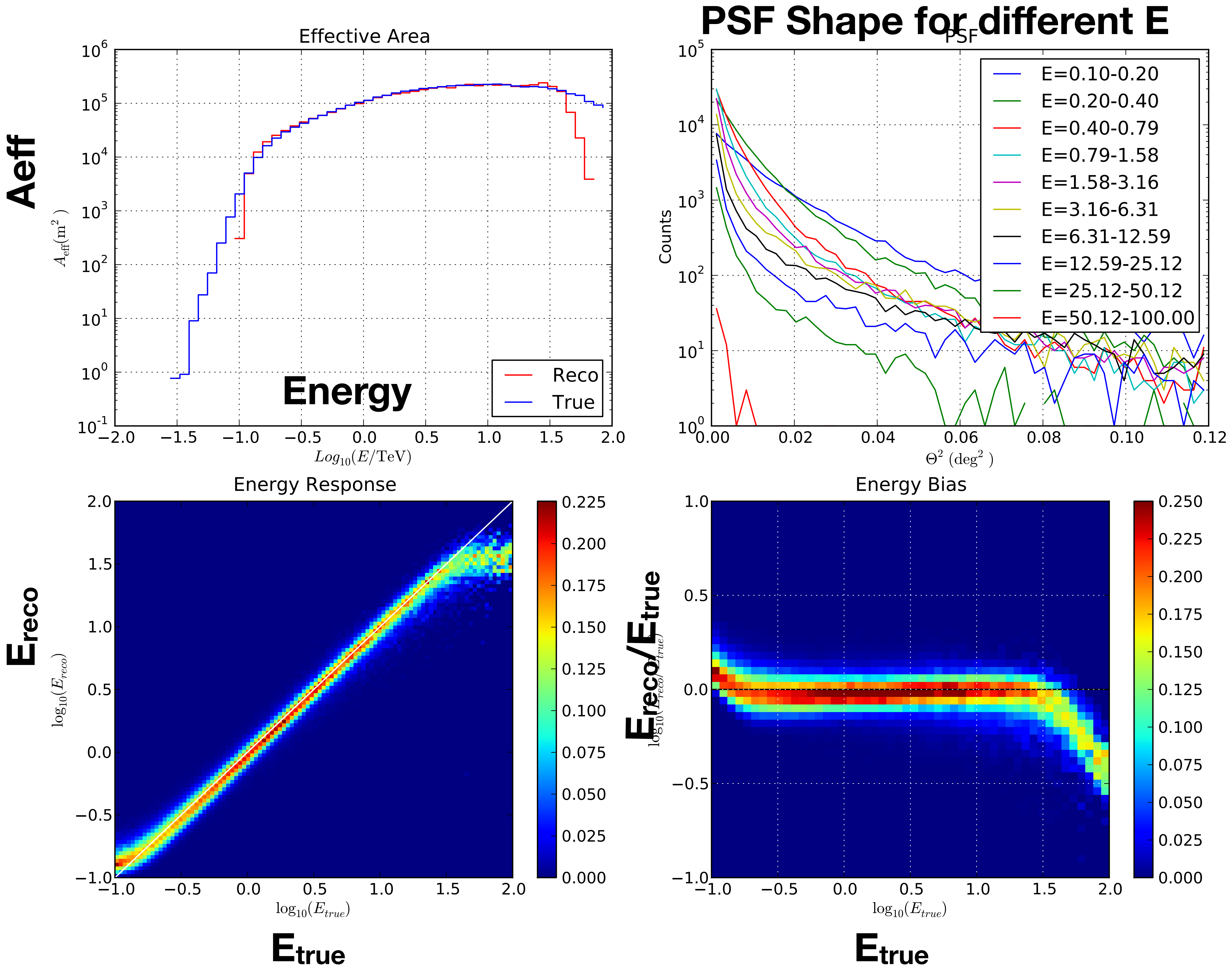
Effective Collection Area (A_{eff}):

- How likely it is to detect a gamma ray shower with respect to the number of true showers times the true area simulated on the ground
- $P(N_{\text{reco}} \,|\, N_{\text{true}}) \cdot A_{\text{true}}$



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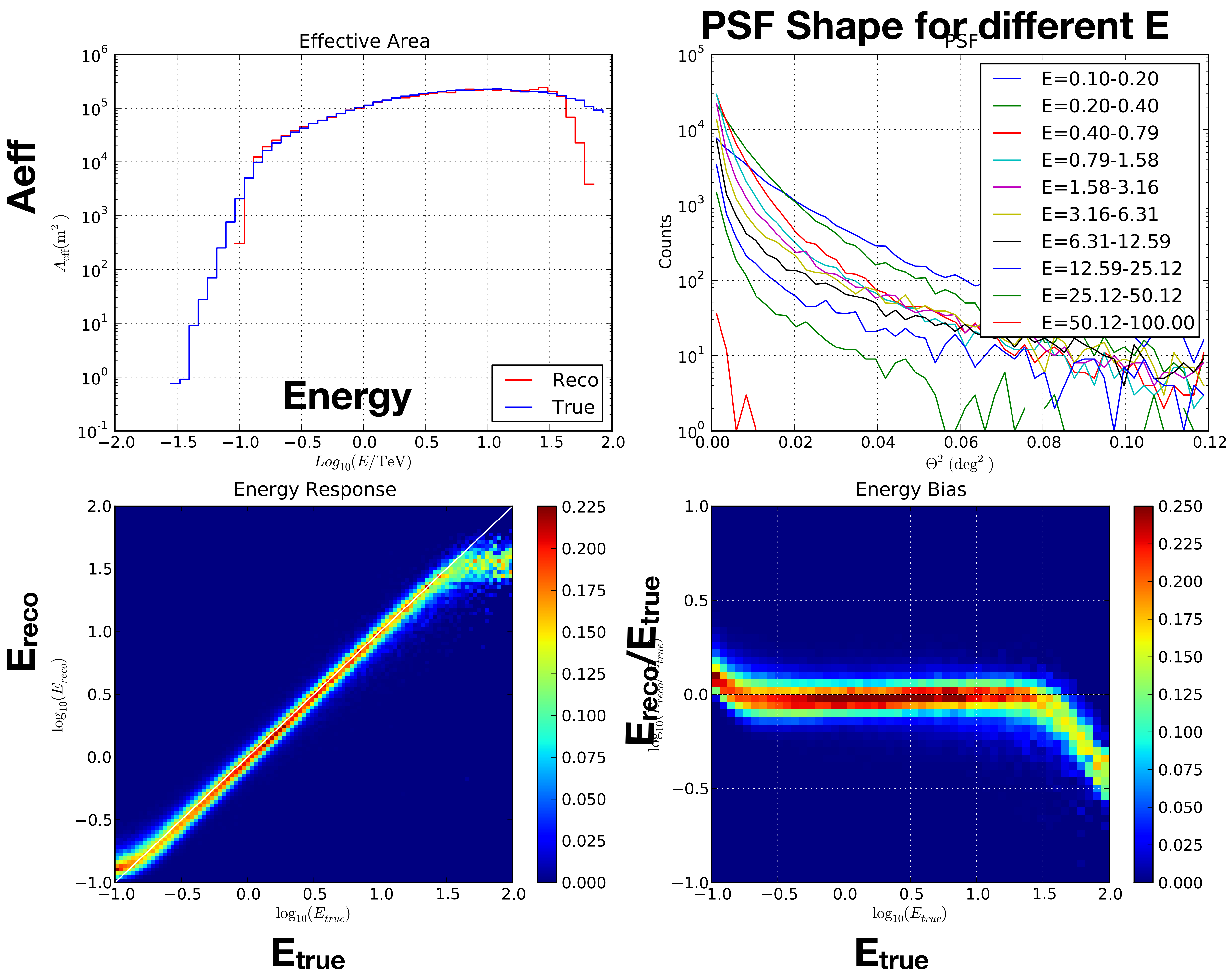

These vary with: time, direction on sky, direction relative to Earth (alt/az), energy, sky brightness, ...

Instrumental Response Functions

Generated from detailed air-shower simulations where you know both *true* and *reconstructed* quantities!

Point-Spread Function (PSF)

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Energy-Migration Matrix:

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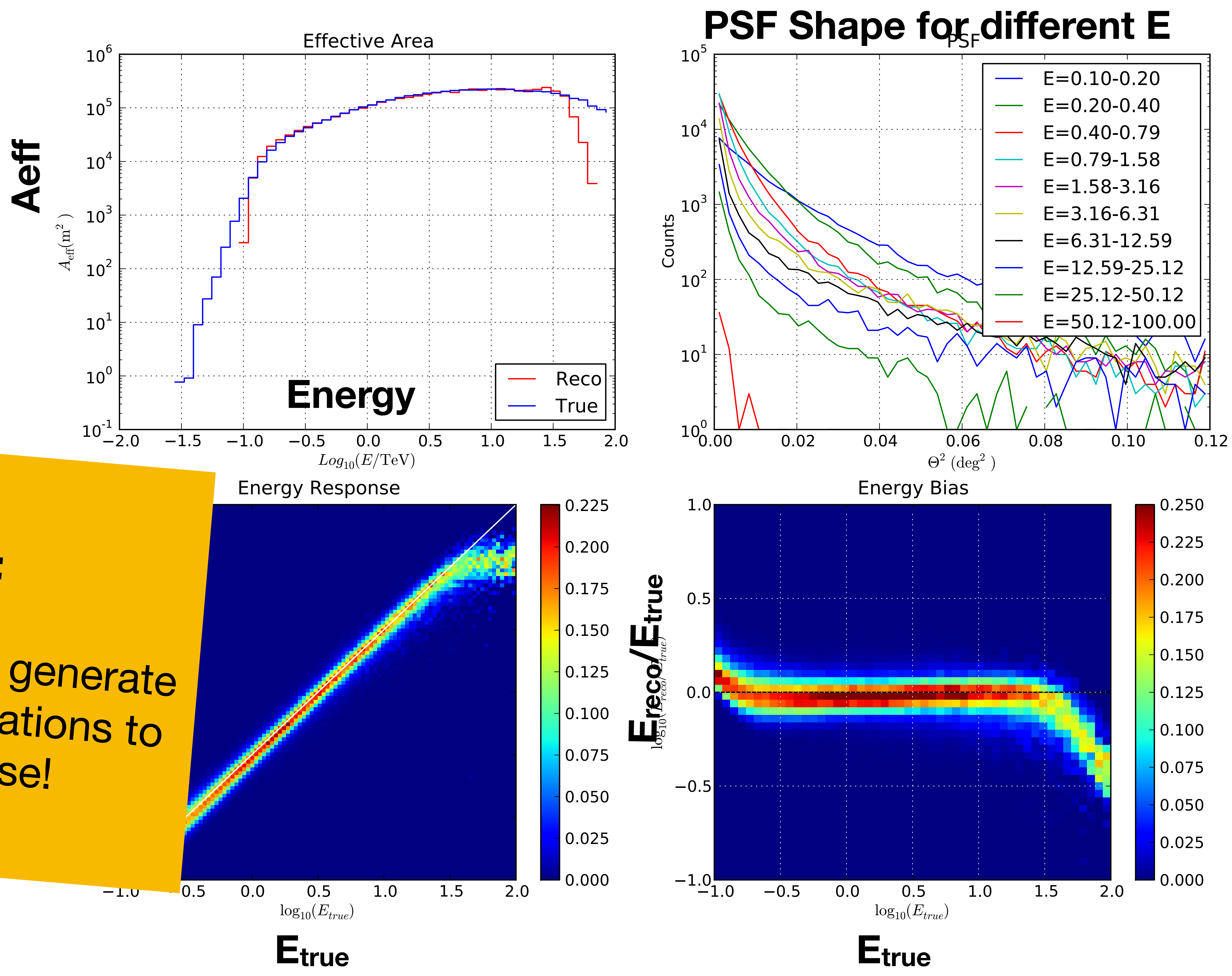
- Takes into account both energy and energy **bias**

Effective Collection Area (A_{eff}):

- How likely it is to detect a gam with respect to the number of times the true area simulated
- $P(N_{\mathrm{reco}} \,|\, N_{\mathrm{true}}) \cdot A_{\mathrm{true}}$



Fun Fact:

In CTA we currently generate ***Petabytes*** of simulations to determine these!

These vary with: time, direction on sky, direction relative to Earth (alt/az), energy, sky brightness, ...

From True Flux to Predicted counts

Assume: IRFs are independent factors (no cross-terms)

Given: ***flux model F*** that is a function of true energy, time, space:

- $N^{signal}_{\text{predicted}} = \mathbf{F}_{\text{true}} \circledast \left(A_{\text{eff}} \cdot PSF \cdot E_{\text{mig}} \right)$

But that's not all:

- $N^{observed}_{\text{predicted}} = N^{signal}_{\text{predicted}} + N^{background}_{\text{predicted}}$

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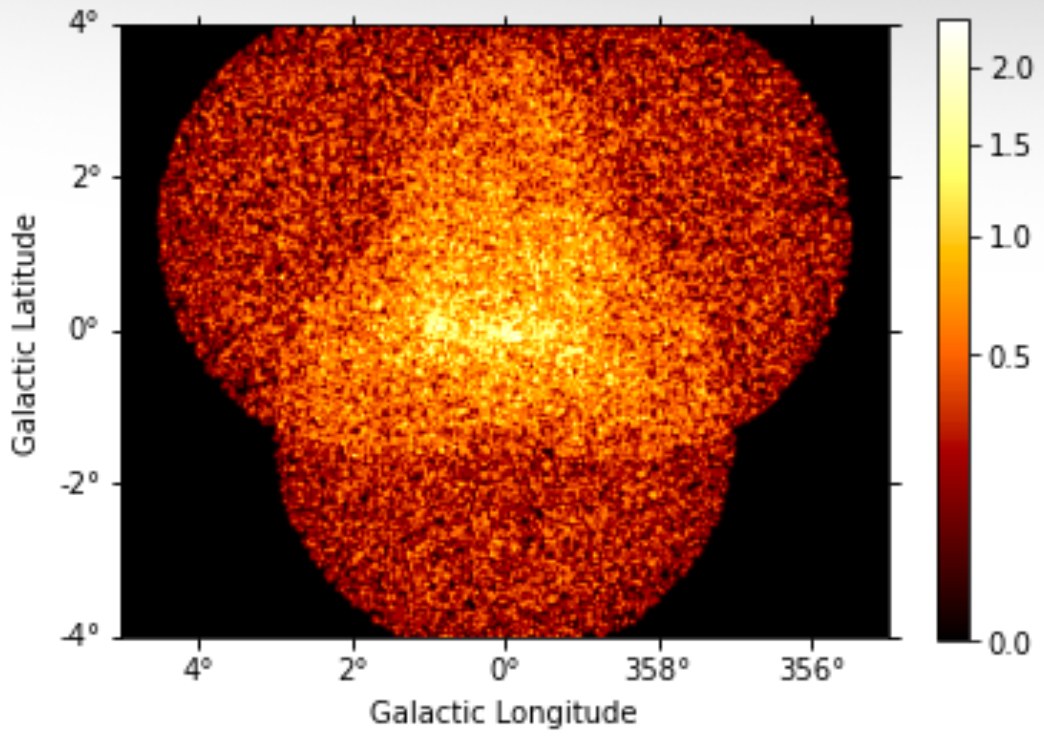
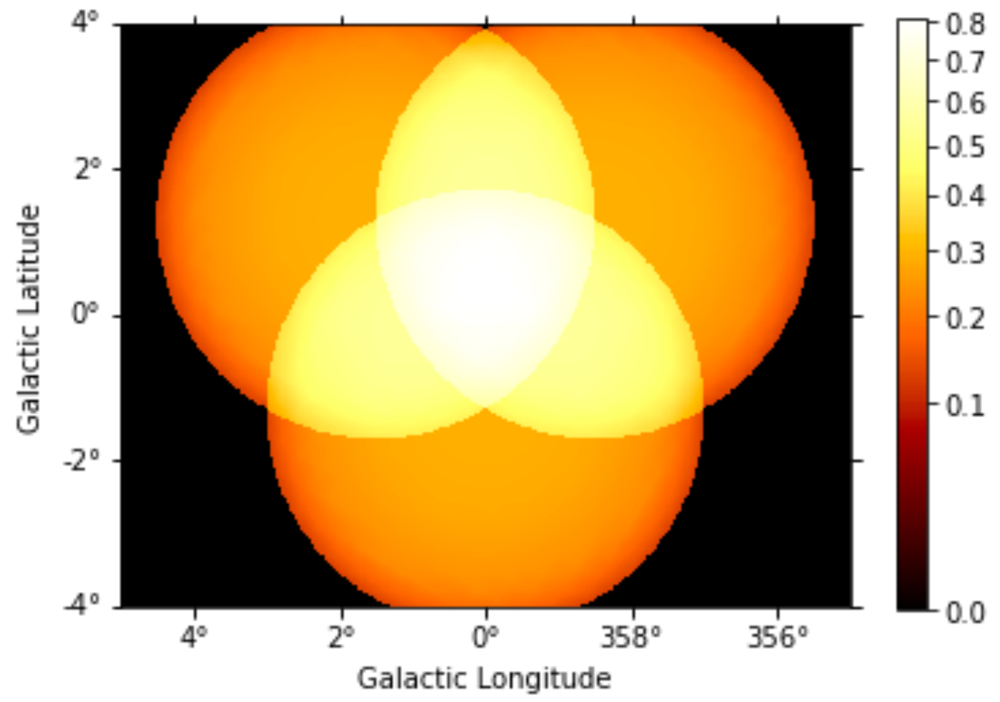
But that's not all:

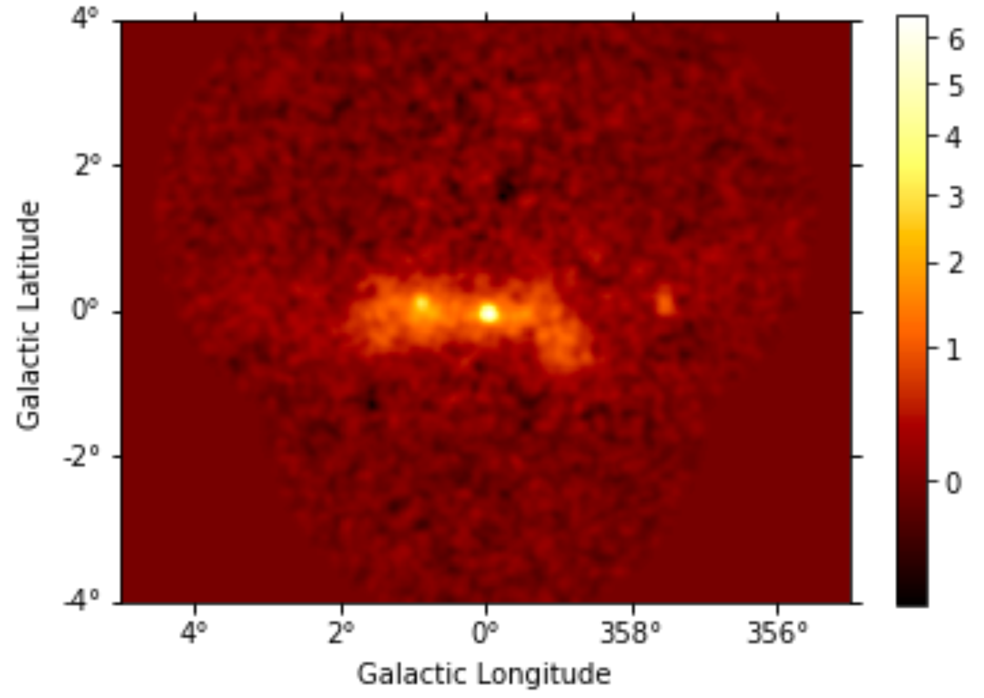
- $N^{observed}_{\mathrm{predicted}} = N^{signal}_{\mathrm{predicted}} \boxed{+ N^{background}_{\mathrm{predicted}}}$

In a residual-background-dominated instruments like IACTs and WCTs, this term is very important!

Background Model







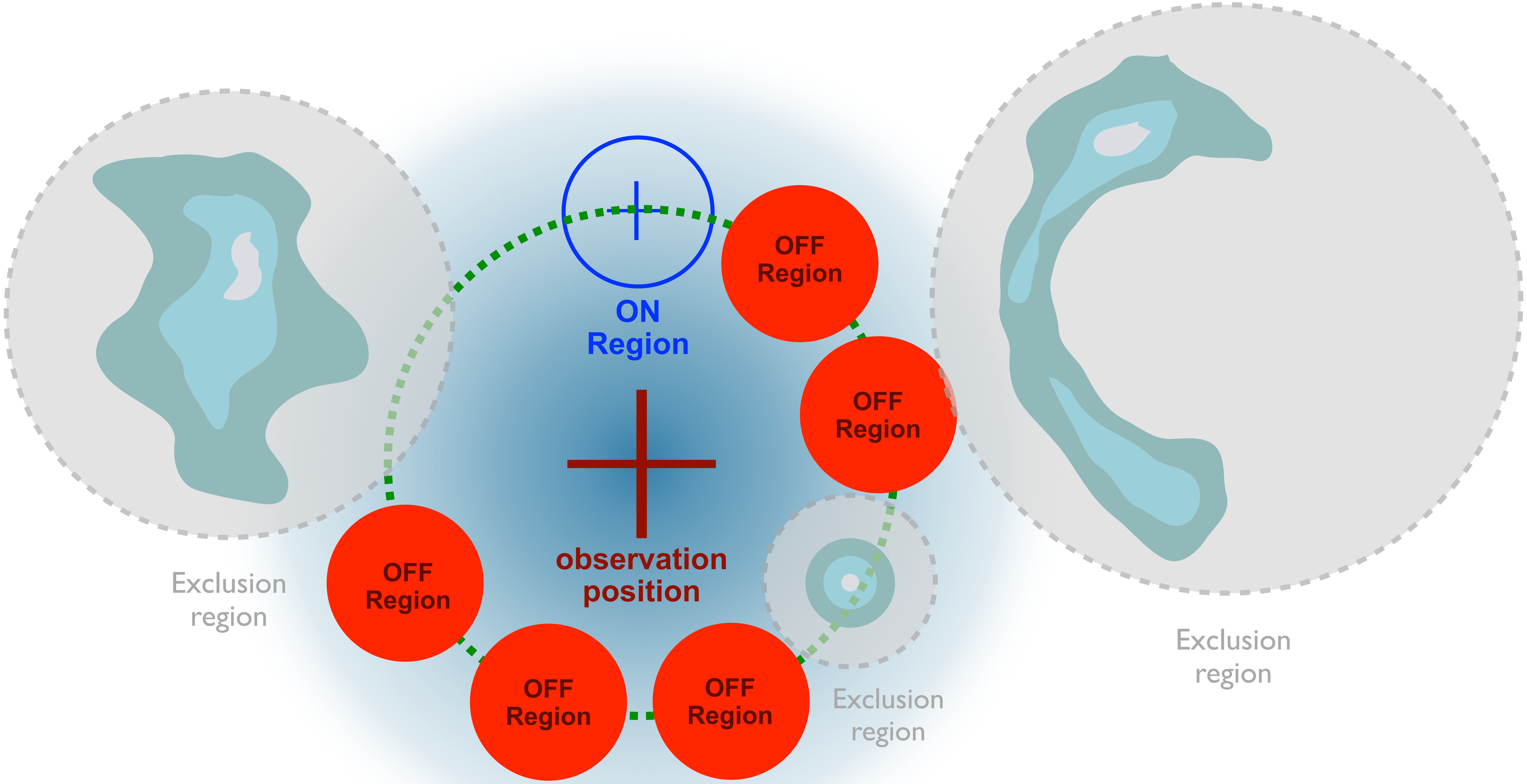
We are still missing something! How to account for the residual background?

- Measure $N_{\text{events}} = N_{\text{signal}} + \mathbf{N_{background}}$

Background Estimation:

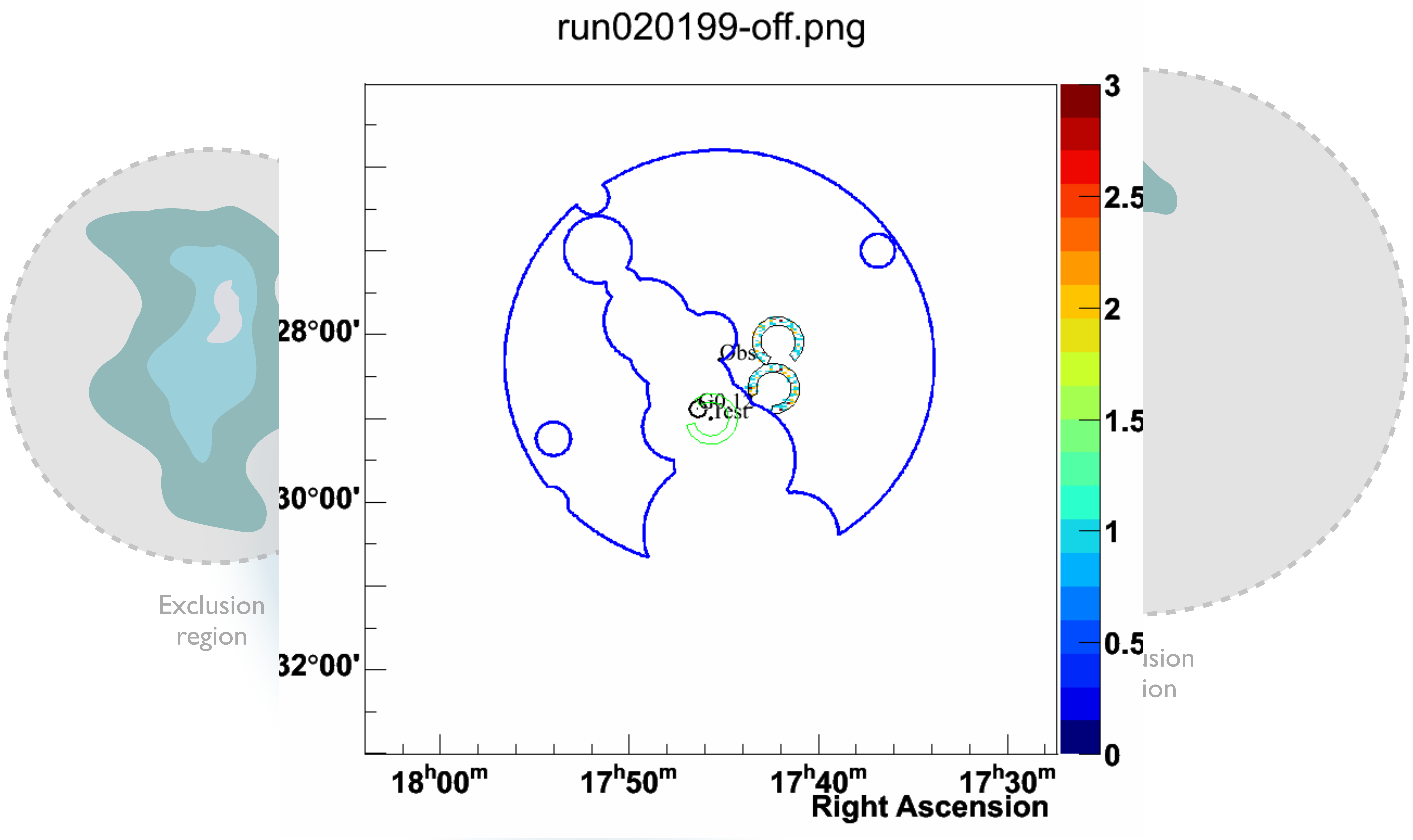
- Simulate it?
  - ➤ Not so easy, uncertainties in hadronic physics + huge computational burden!
- Measure it!
  - ➤ Most of the sky is free of gamma-rays.
  - ➤ *Assume* **emission-free zones**, and measure background counts from them
    - ➤ In the *same field-of-view*, or from ensemble of *other observations*

https://docs.gammapy.org/0.18.2/tutorials/analysis_3d.html



Only works for 1 region in space: good for spectra and light-curves, but not images

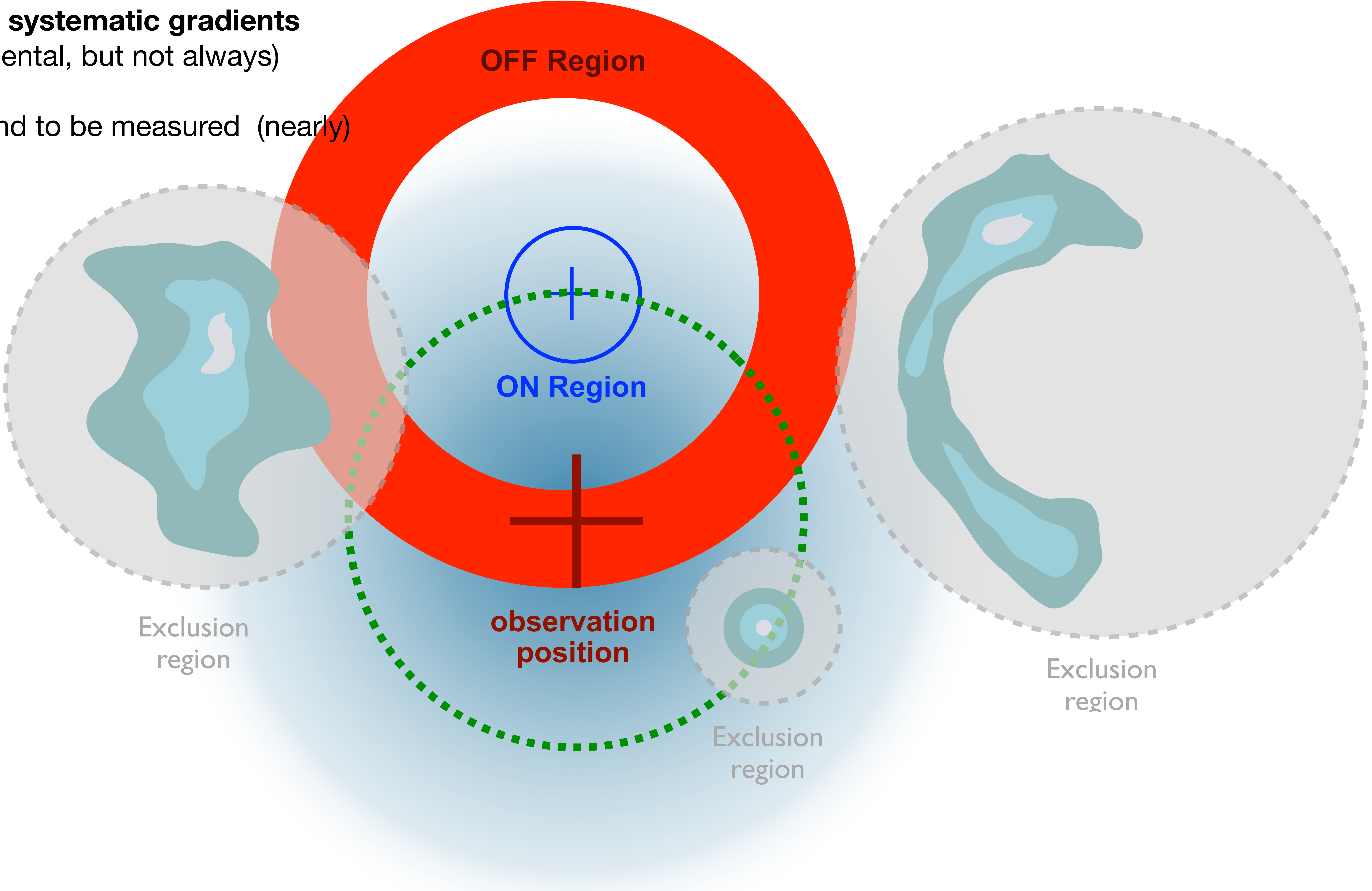
Karl Kosack - ISAPP 2022



Only works for 1 region in space: good for spectra and light-curves, but not images

Integrating over a ring region has the effect of removing any systematic gradients
(normally instrumental, but not always)

Allows background to be measured (nearly) everywhere



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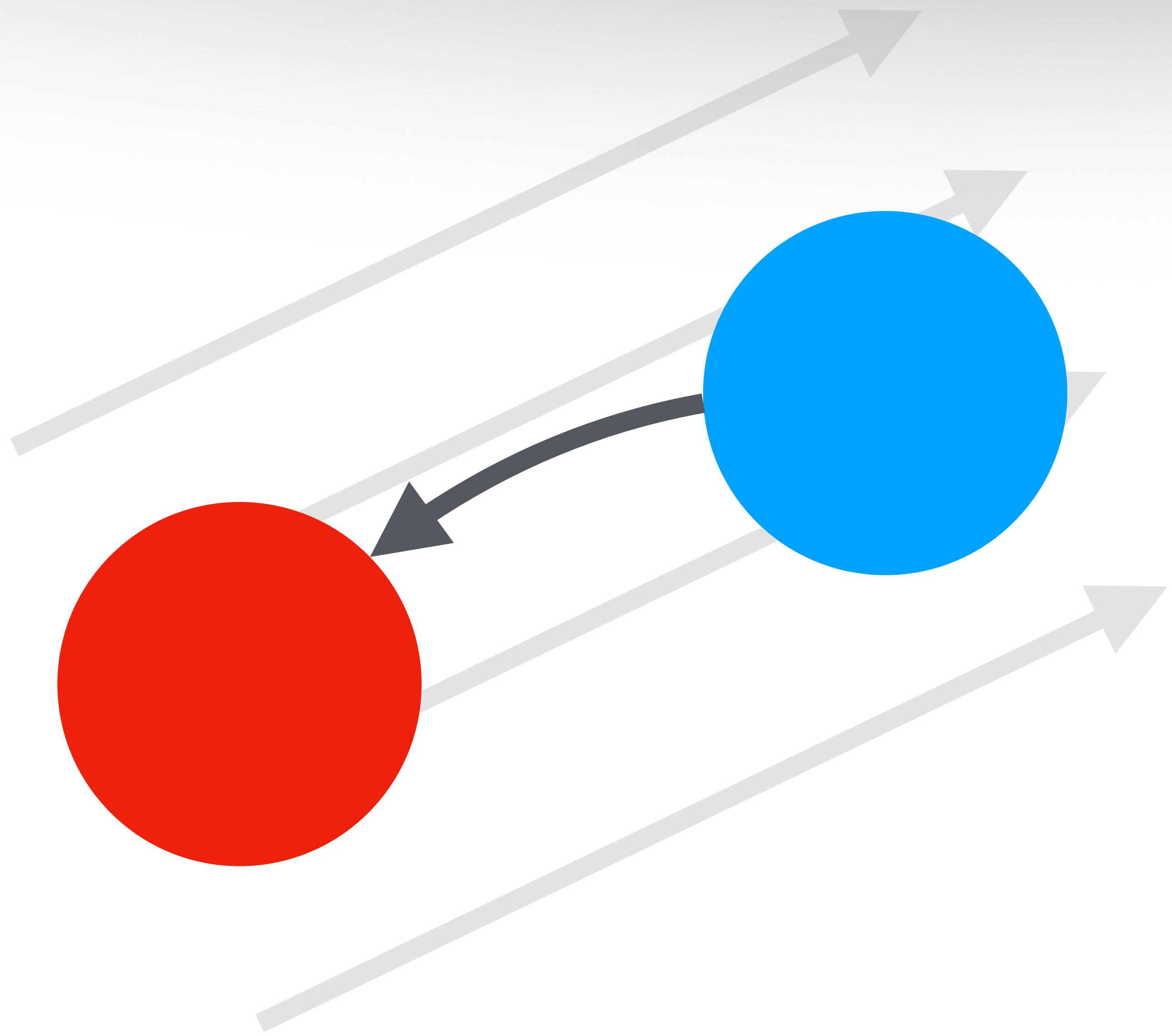
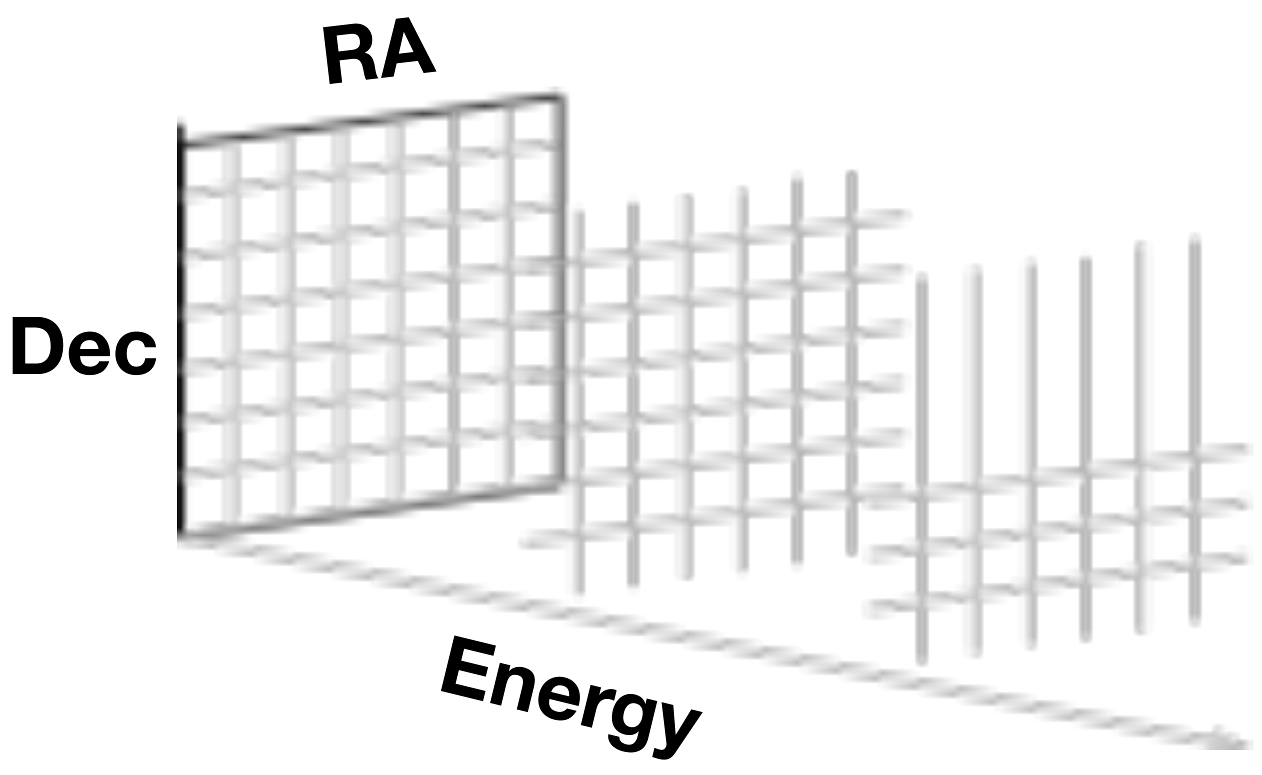
On-Off observations → 3D background models



In the old days:

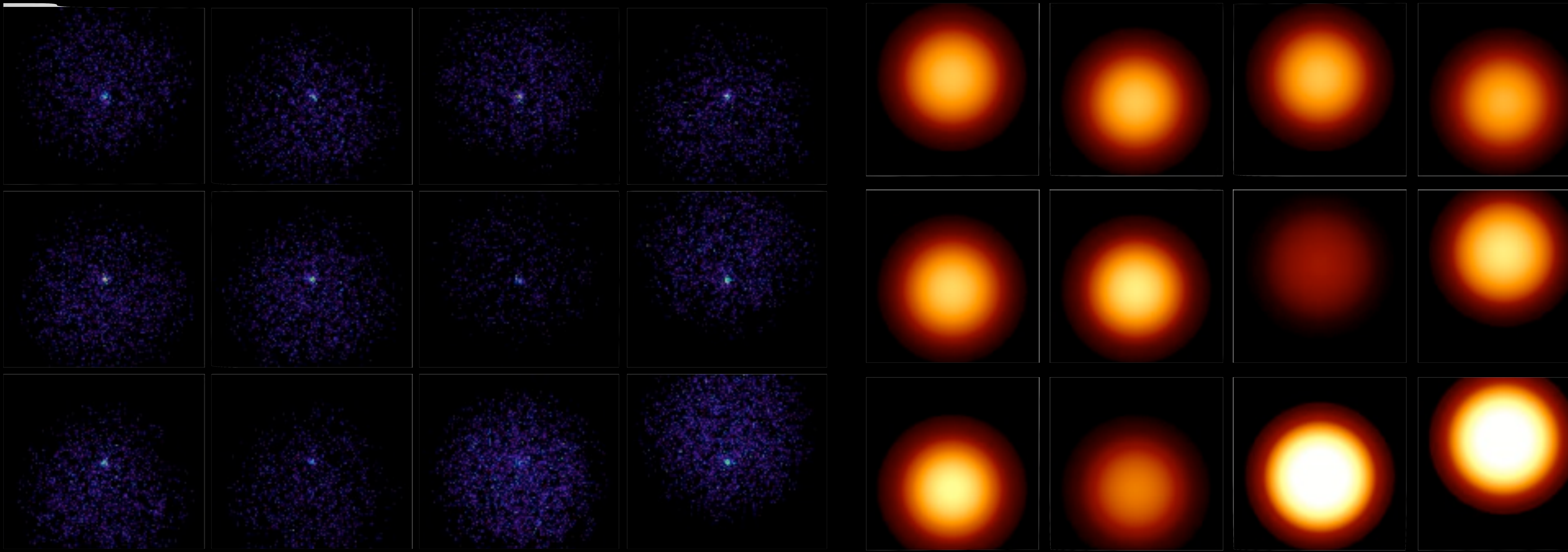
- Take a 28 minute **ON-source** exposure
- take 2 minutes to **Slew 30' minutes back** in Right Ascension
- Take a 28 minute **OFF exposure** (which you assume has no source)
- Tracks the **same column of air** in the atmosphere (with 30' delay)



Now:

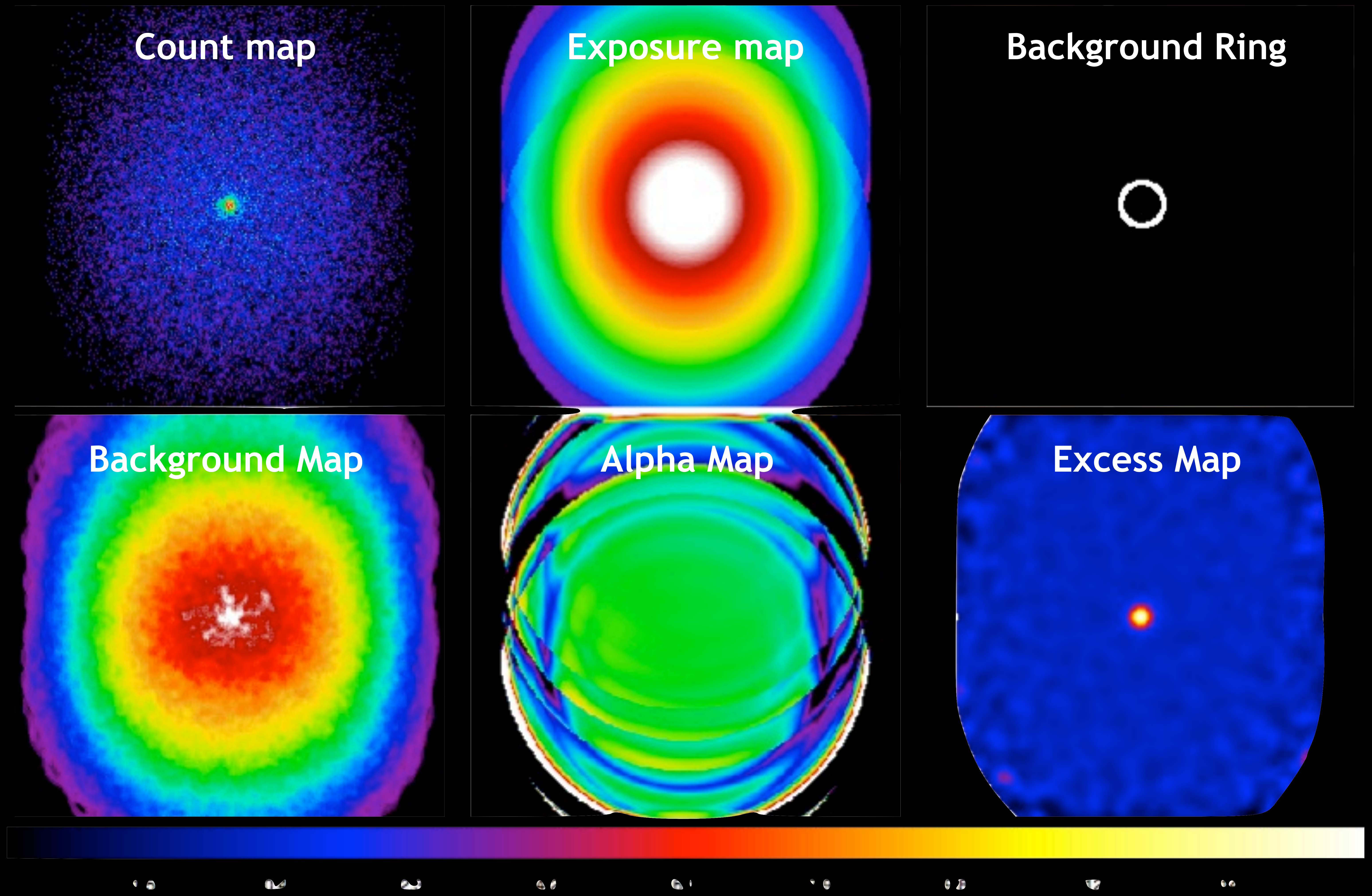
- Can use **historic observations** with few or no sources in the FOV to generate a background model, use **atmosphere calibration info**, plus a **control-region in the FOV** to match ON to OFF
- This is often used to build multi-dimensional **binned background models**: averaging many blank fields to provide enough statistics to make a background **cube** (space + energy).

Counts and Background Models



Observations of the Crab Nebula with HESS: each frame is 30 minutes exposure
The differences are due to zenith angle, time of year, etc.

Basic Aperture Photometry



$$N_{\text{excess}} = N_{on} - \alpha N_{off}$$

α corrects for ON/OFF exposure differences (depends on how you build background model)

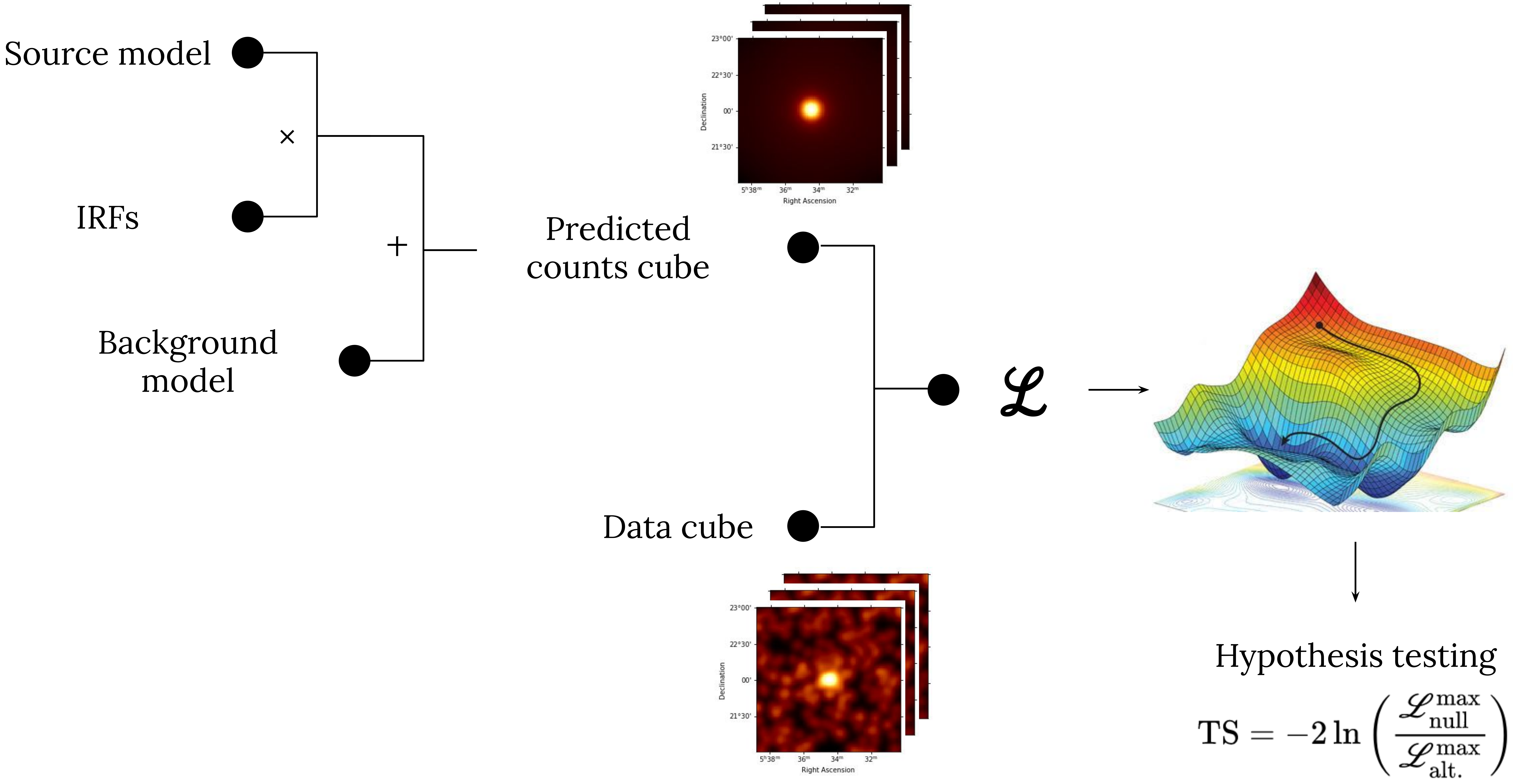
Significance can be computed using the Li and Ma formula (likelihood derived from Poisson statistics)

$$\ln\lambda = -N_{\text{on}}\ln\left[\left(\frac{1+\alpha}{\alpha}\right)\frac{N_{\text{on}}}{N_{\text{on}}+N_{\text{off}}}\right] - N_{\text{off}}\ln\left[(1+\alpha)\frac{Non}{N_{\text{on}}+N_{\text{off}}}\right]$$

$$S = \sqrt{-2\ln\lambda}$$

Useful for testing "is there a source"

Forward Folding Likelihood Minimization



$$\mathrm{TS} = -2\ln\left(\frac{\mathscr{L}^{\max}_{\text{null}}}{\mathscr{L}^{\max}_{\text{alt.}}}\right)$$

Luca Giunti, thesis presentation 2021

Forward Folding: Likelihood

Poisson likelihood: Depends on the method you are using

- Poisson data + modeled background:

$$\begin{aligned}\mathscr{L} &= \mathcal{P}(N_{\rm ON}|\mu_{\rm sig}+\mu_{\rm bkg}) \\ &= \frac{(\mu_{\rm sig}+\mu_{\rm bkg})^{N_{\rm ON}}}{N_{\rm ON}!} e^{-(\mu_{\rm sig}+\mu_{\rm bkg})}\end{aligned}$$

- Poisson data + Poisson background (from an OFF region)

$$\begin{aligned}\mathscr{L} &= \mathcal{P}(N_{\rm ON}|\mu_{\rm sig}+\mu_{\rm bkg}) \times \mathcal{P}(N_{\rm OFF}|\mu_{\rm bkg}/\alpha) \\ &= \frac{(\mu_{\rm sig}+\mu_{\rm bkg})^{N_{\rm ON}}}{N_{\rm ON}!} e^{-(\mu_{\rm sig}+\mu_{\rm bkg})} \times \frac{(\mu_{\rm bkg}/\alpha)^{N_{\rm OFF}}}{N_{\rm OFF}!} e^{-\mu_{\rm bkg}/\alpha}\end{aligned}$$

Advantage: can do any sort of modeling in the same way, just divide into bins:

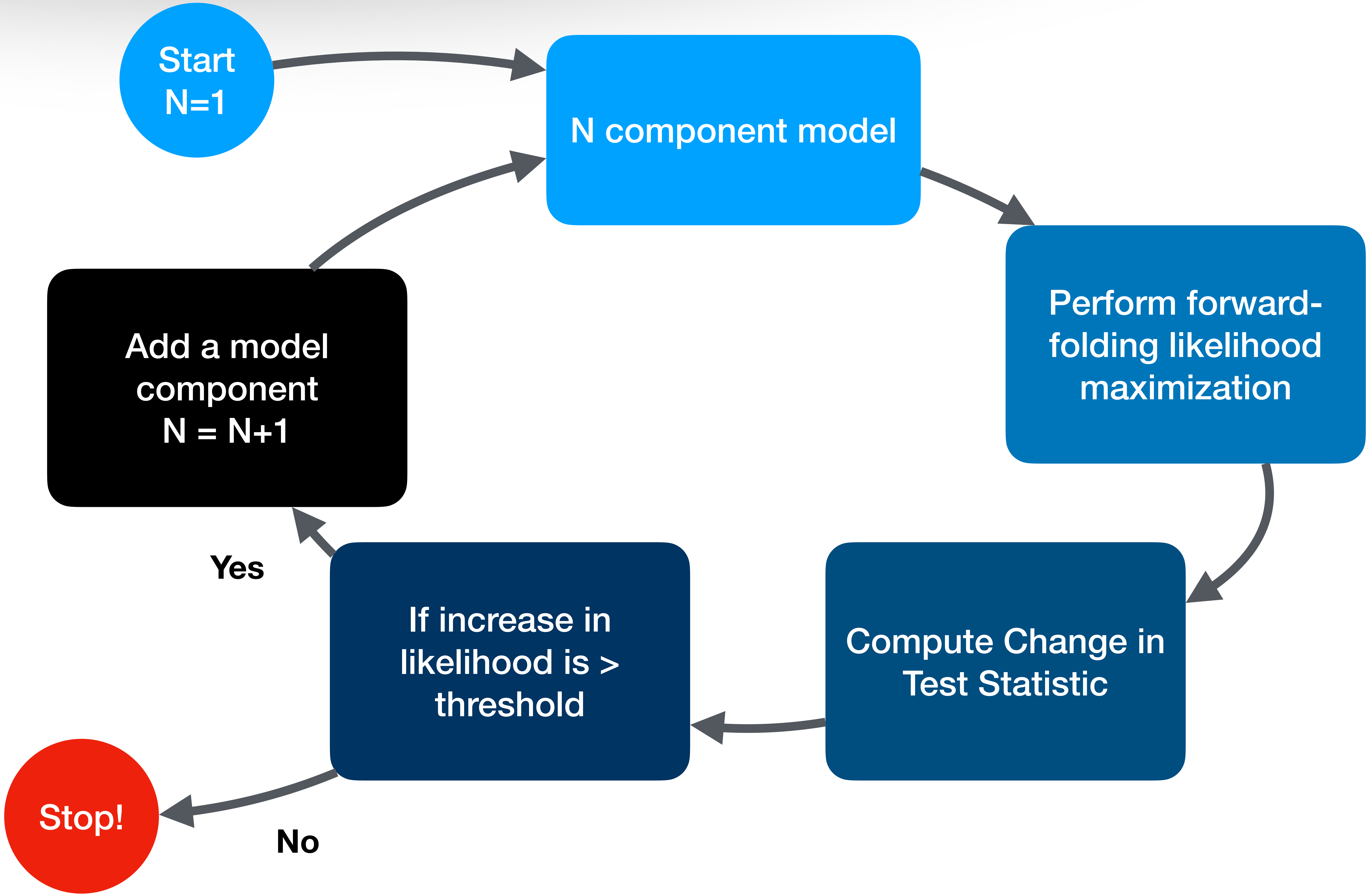
- 1D (energy ≈*spectrum*), (time≈*light-curve*)
- 2D (space ≈*image*) or (energy+time)
- 3D (energy+space) or (space+time),
- 4D (energy+space+time)

Likelihoods can be summed over all bins (log likelihoods can be multiplied)

Dimensionality **Limited by *statistics* and your physics model**

The output is a source model in physical units!

Iterative Modeling



Start
N=1

N component model

Perform forward-folding likelihood maximization

Compute Change in Test Statistic

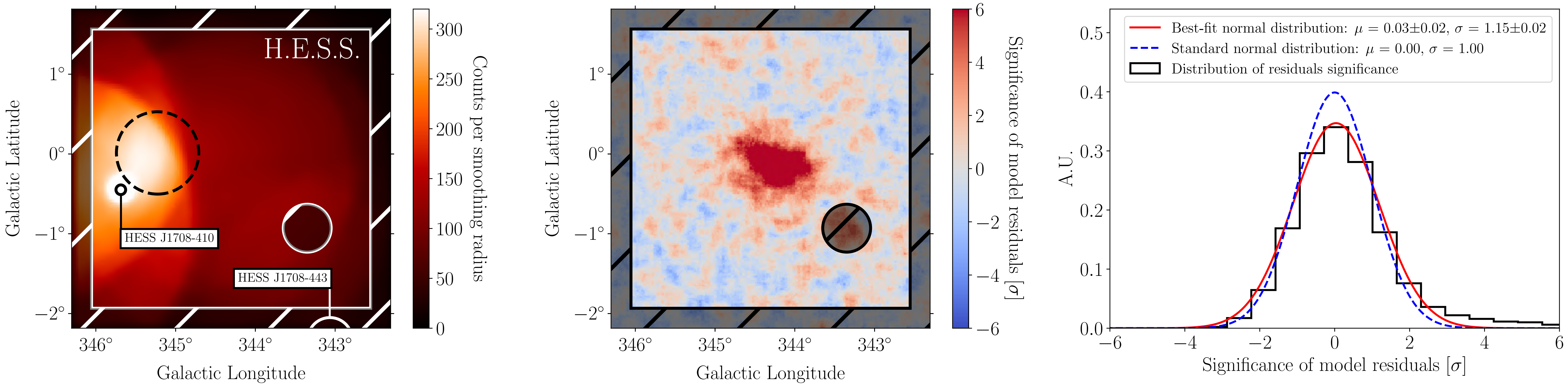
If increase in likelihood is > threshold

Yes

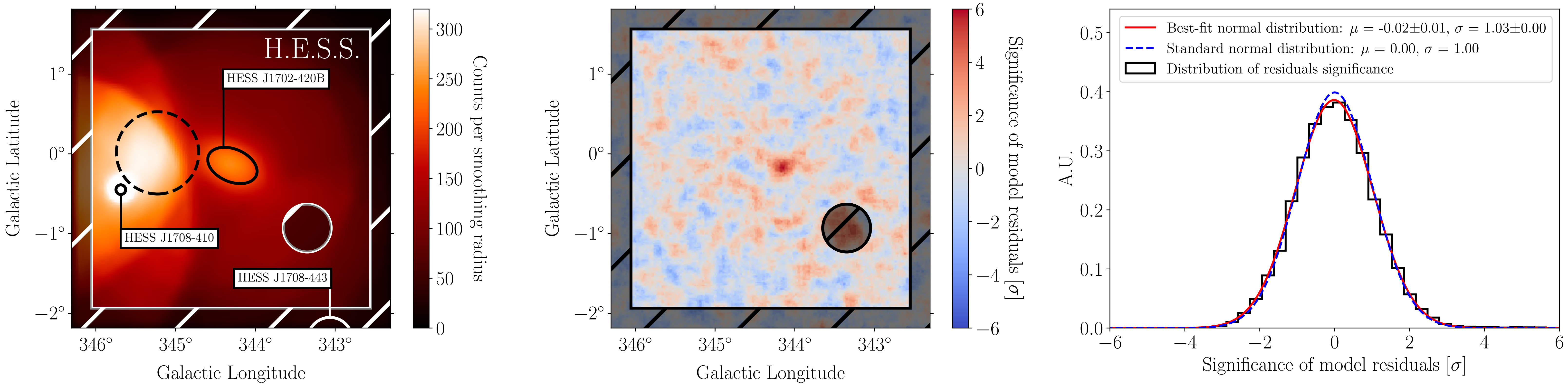
Add a model component
N = N+1

No

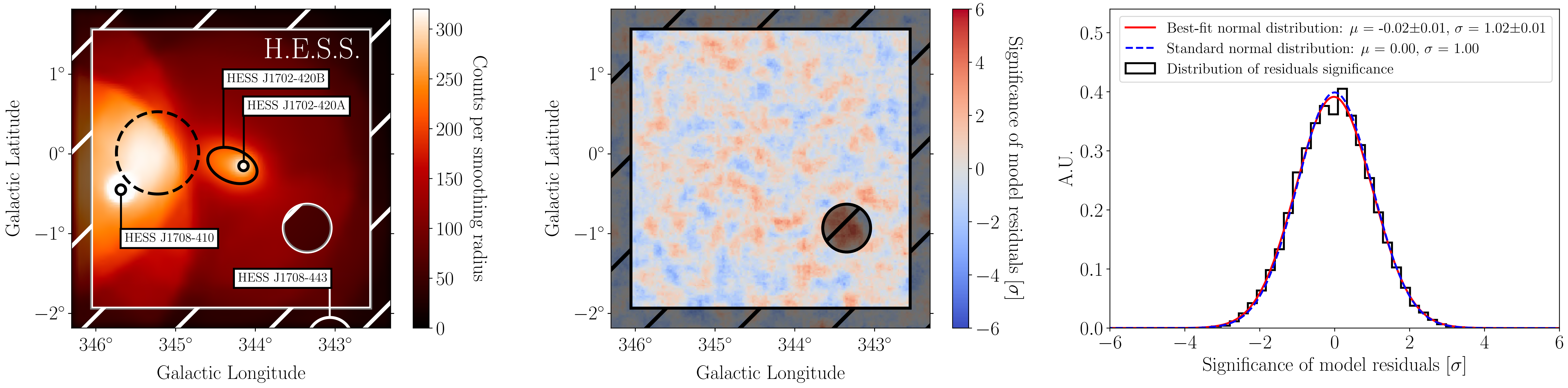
Stop!



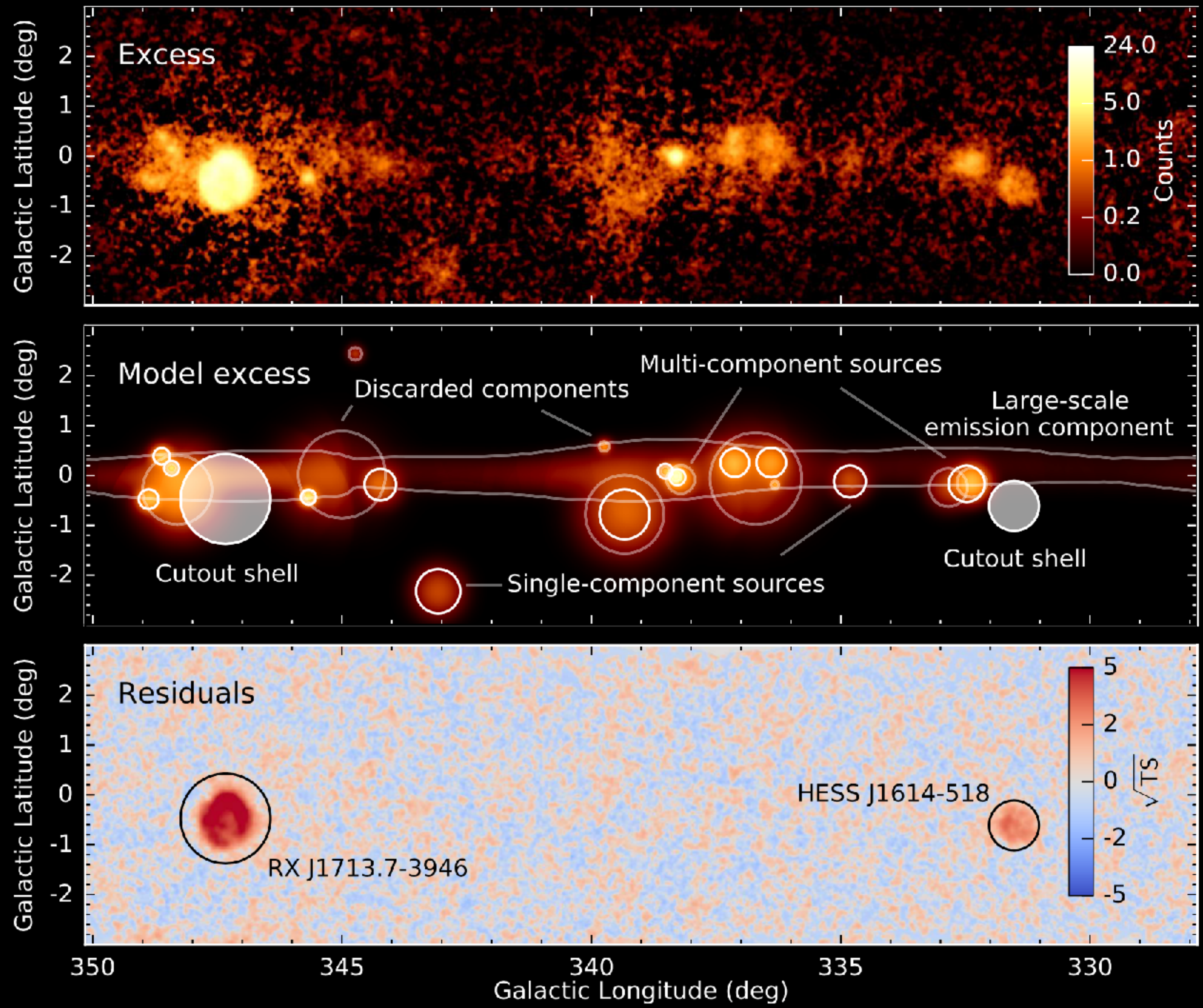
(c)



(d)



L. Giunti, Thesis 2021



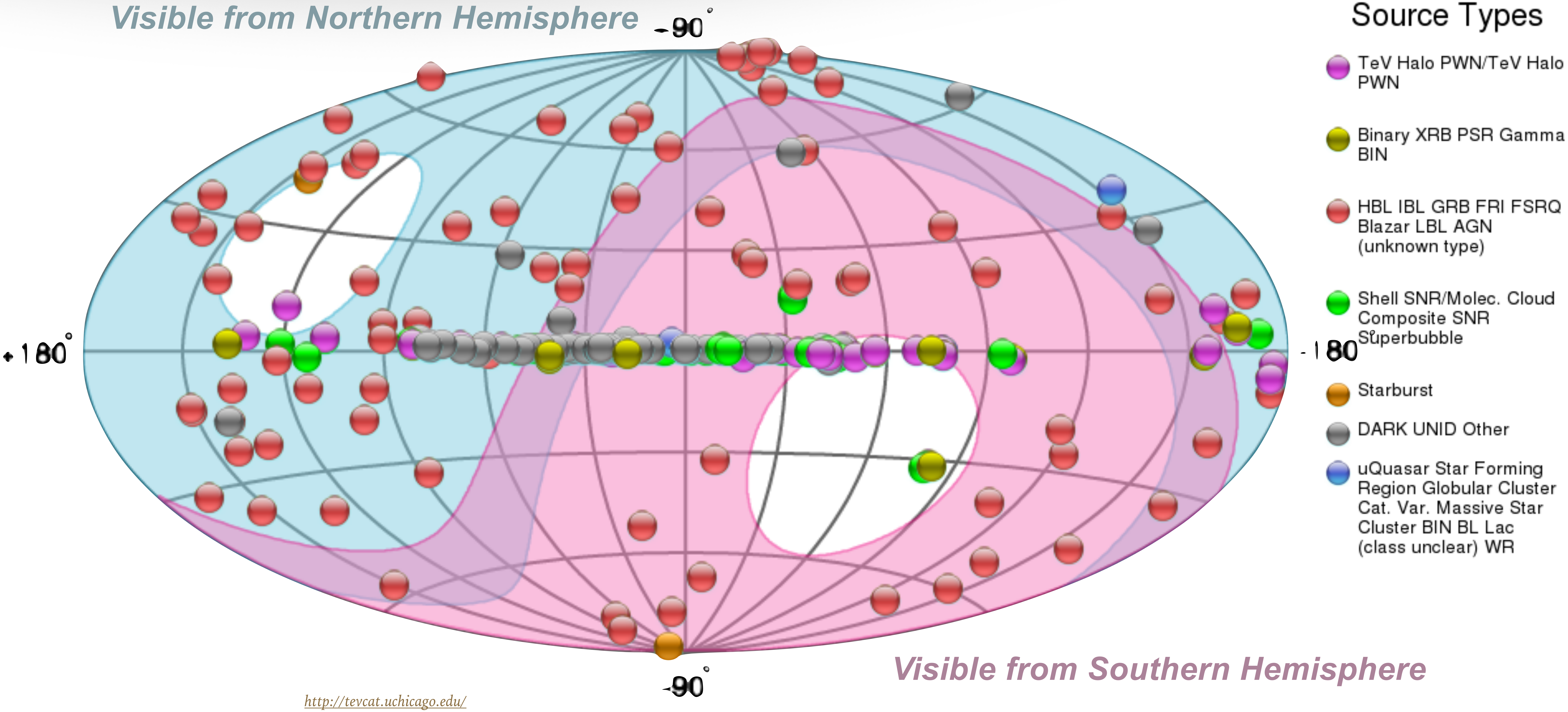
A&A 612, A1 (2018)

End

In the next session: you try!

Backup Material

Ground-based Telescopes: **Visibility**



Visible from Northern Hemisphere

Visible from Southern Hemisphere

http://tevcat.uchicago.edu/