Gamma-Ray Astronomy

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Plan

Why bother?

γ-ray sources

Detection techniques

Galactic & extra-galactic source

Galactic Cosmic Rays

Want

10^{33} Watt

Power law

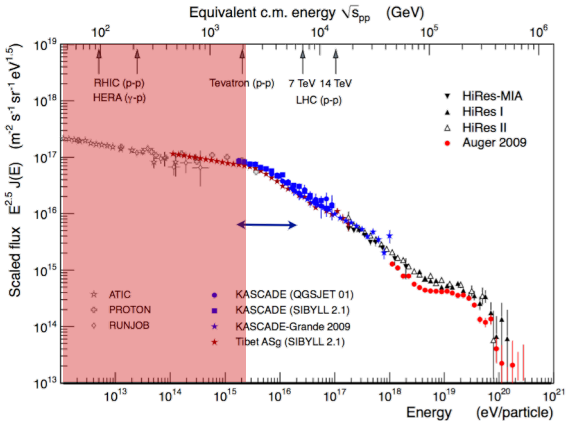
$10^{15} - 10^{16}$ eV

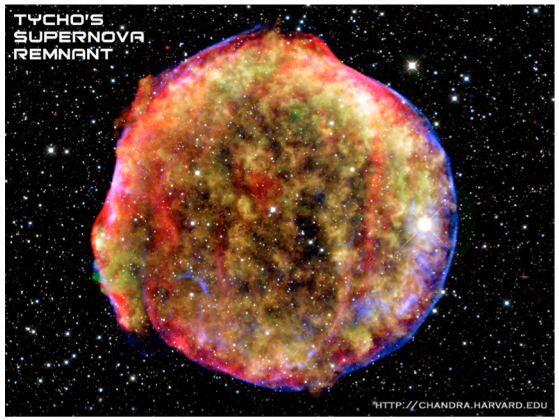
Have

SNRs

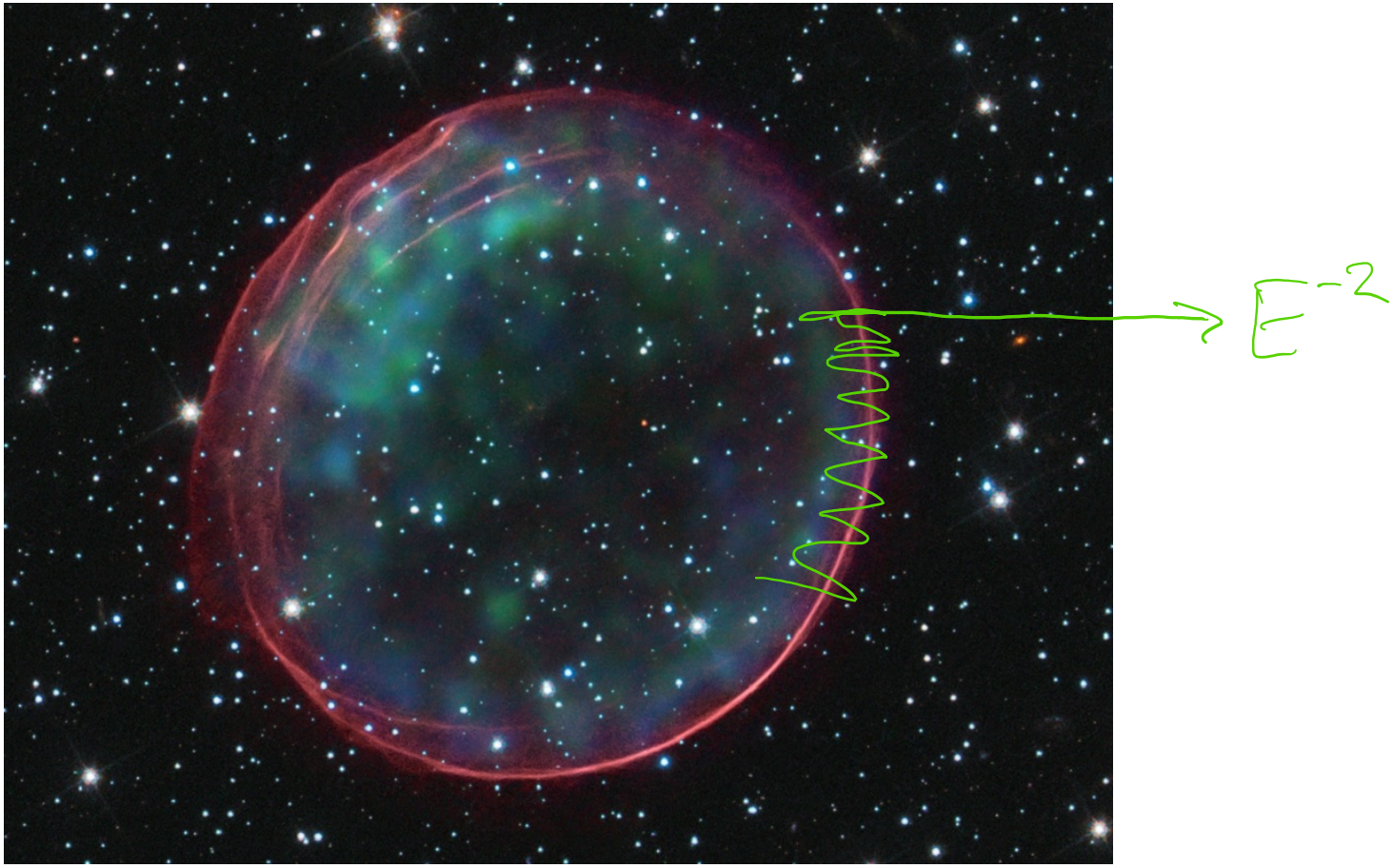
Energy

Shock acceleration



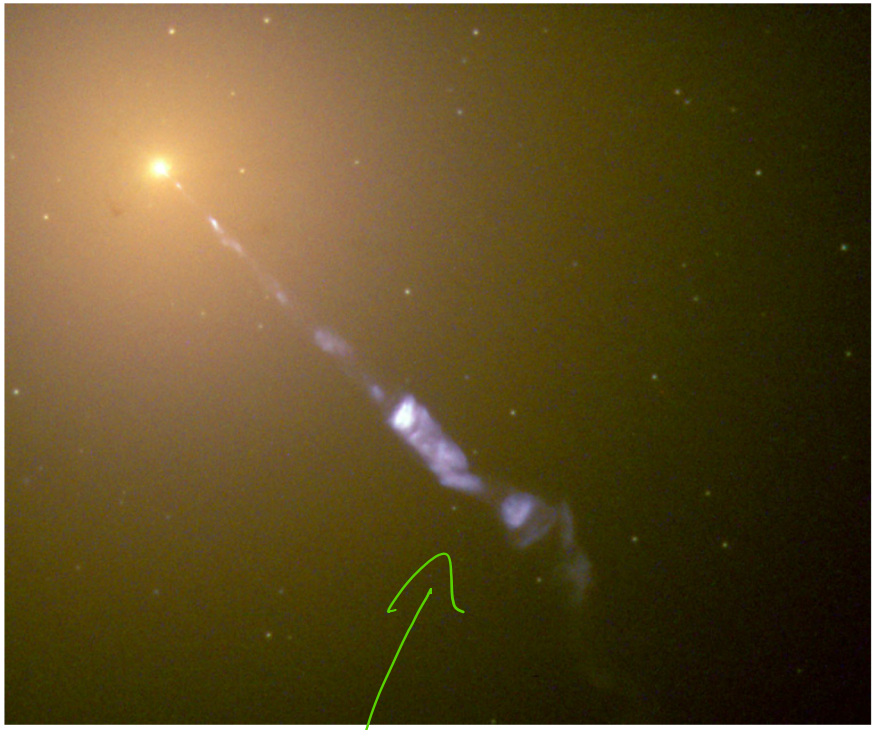


Supernova Remnants



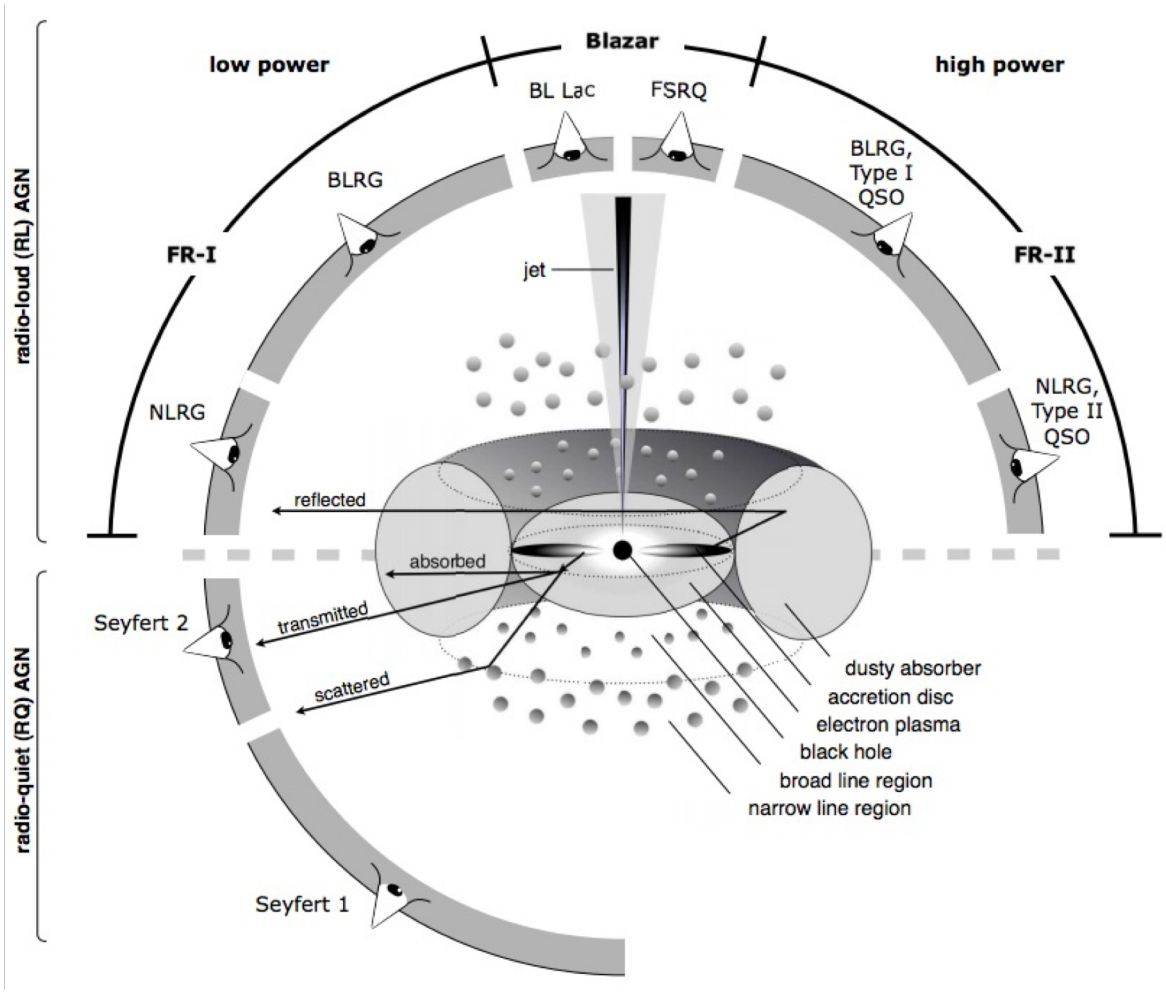
SNR 0509-67.5, Large Magellanic Cloud
X-ray: NASA/CXC/SAO/J.Hughes et al
Optical: NASA/ESA/Hubble Heritage Team (STScI/AURA)

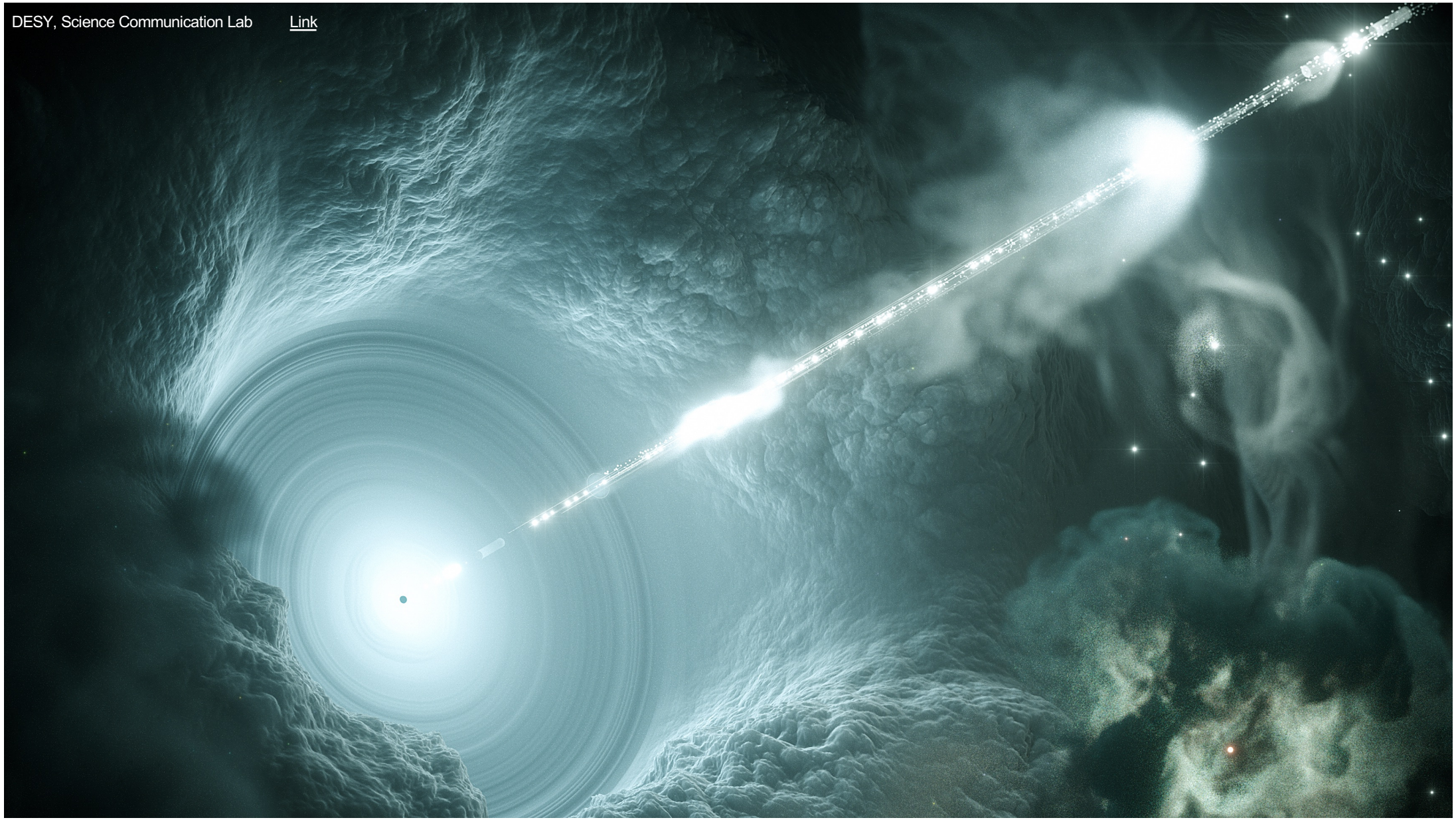
AGN



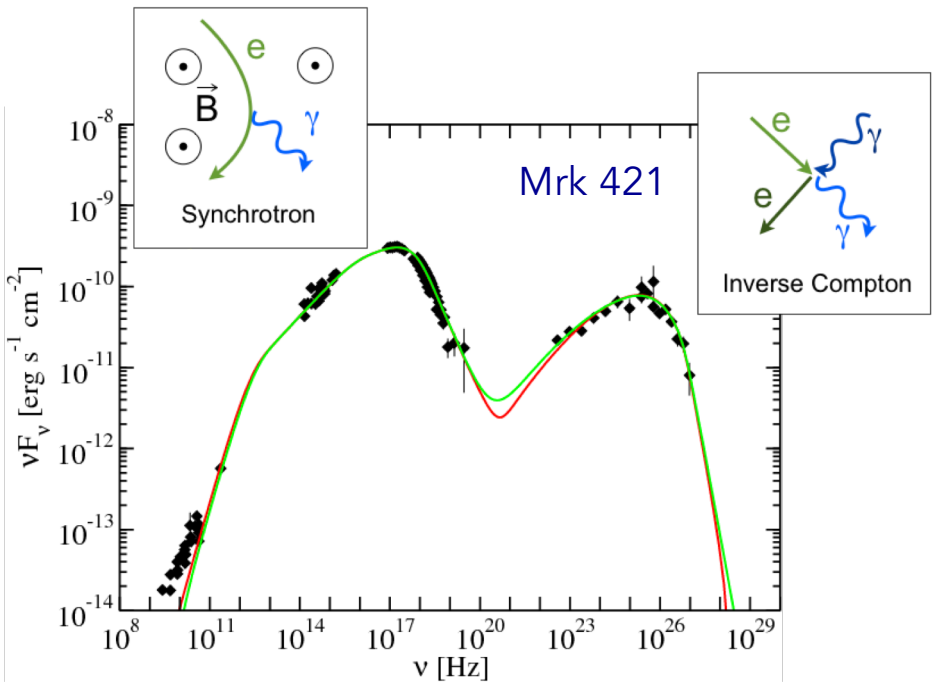
M87, Hubble

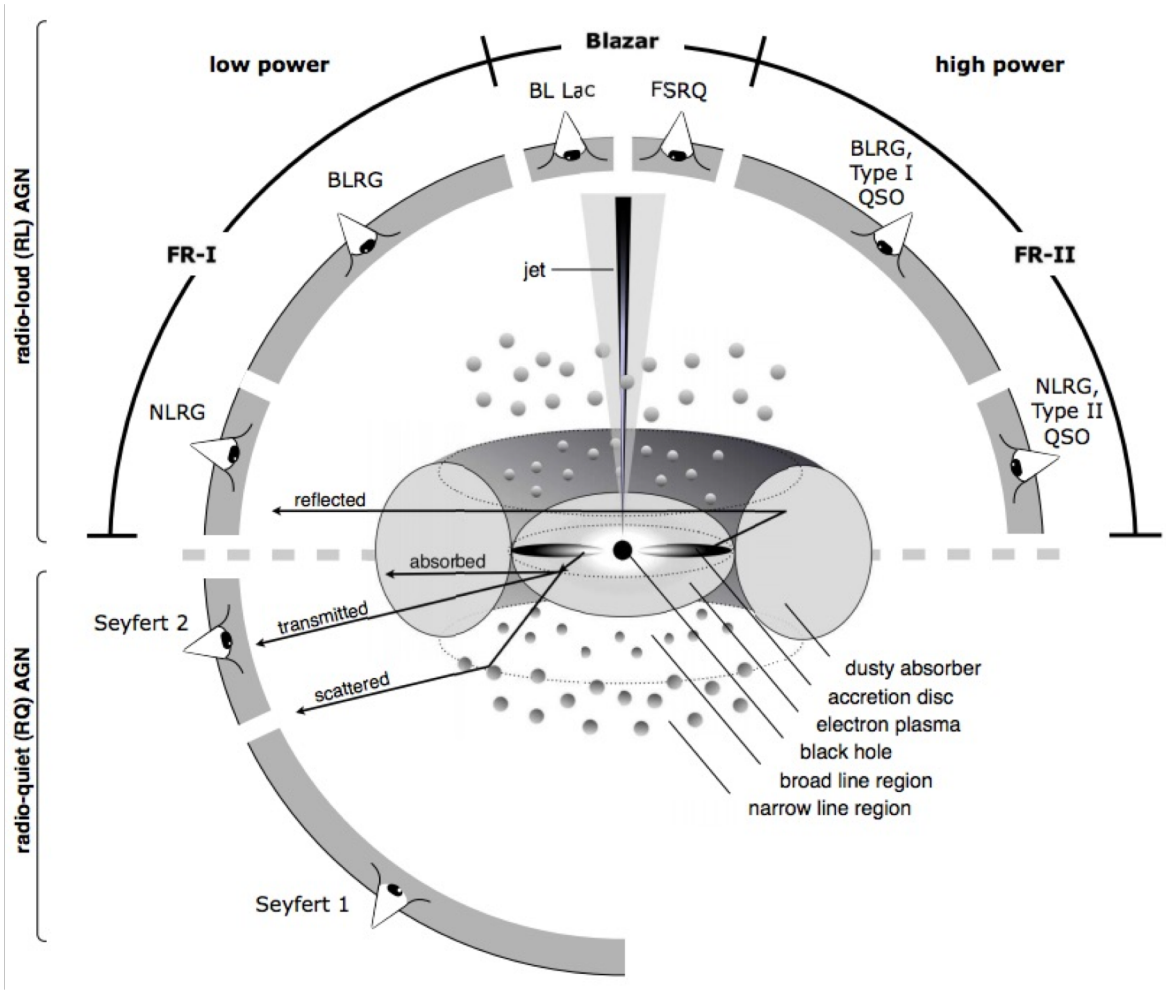
pc – 100's kpc



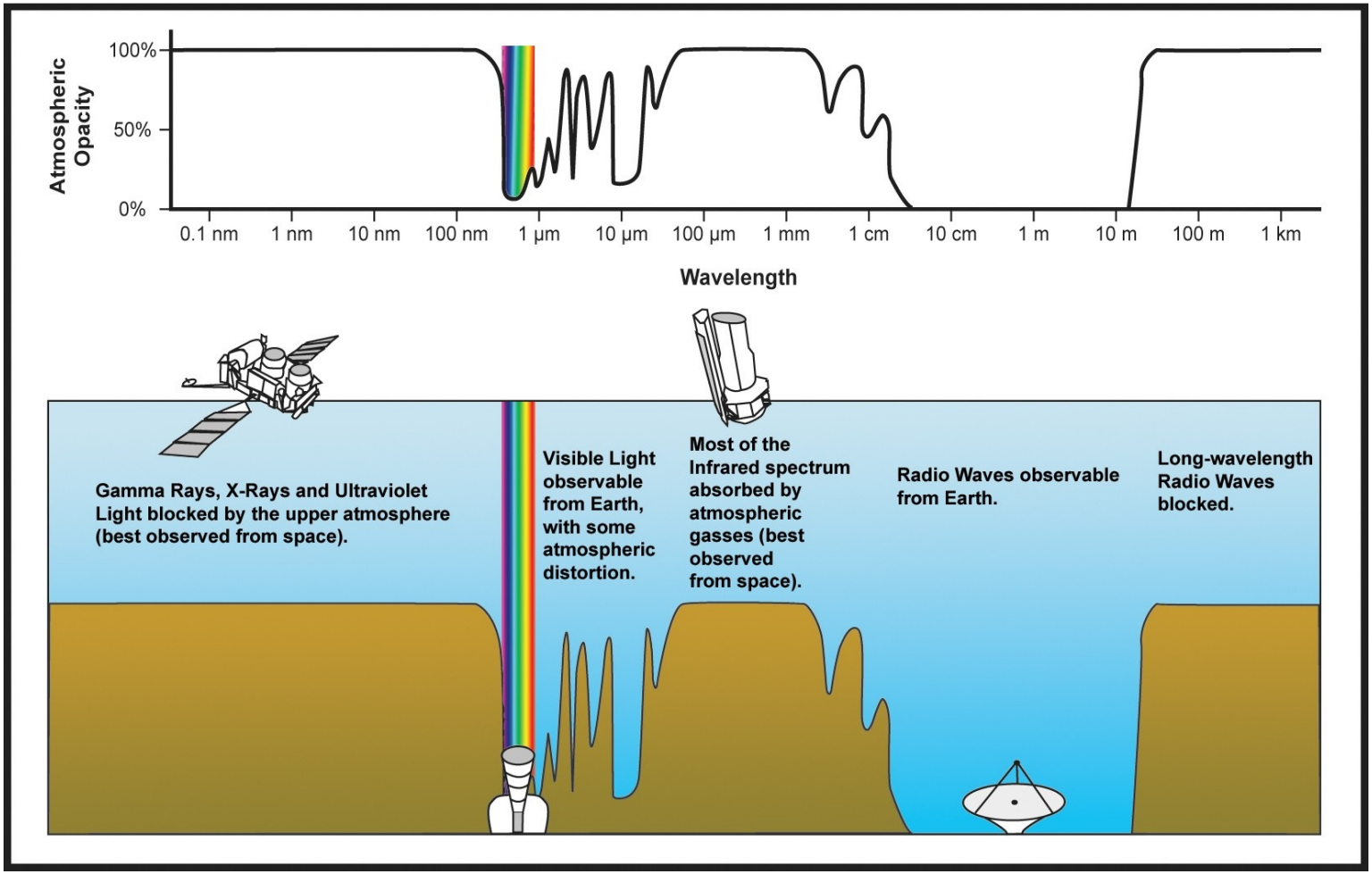

DESY, Science Communication Lab
Link

AGN

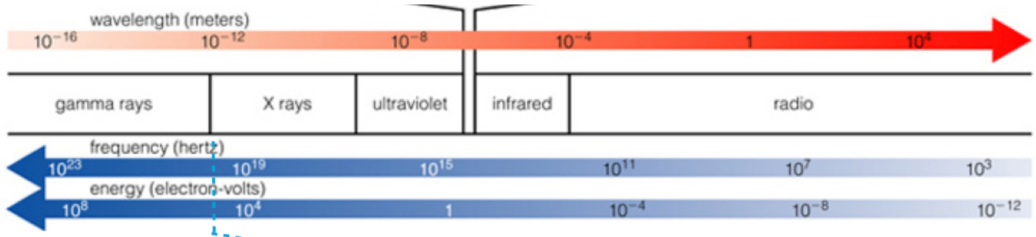

Mrk 421
Synchrotron
Inverse Compton
e
B
γ
νF_ν [erg s^{-1} cm^{-2}]
ν [Hz]


Blazar
low power
high power
BL Lac
FSRQ
BLRG
BLRG, Type I QSO
FR-I
FR-II
jet
NLRG
NLRG, Type II QSO
reflected
absorbed
transmitted
scattered
Seyfert 2
Seyfert 1
dusty absorber
accretion disc
electron plasma
black hole
broad line region
narrow line region
radio-loud (RL) AGN
radio-quiet (RQ) AGN

Detection of MeV-TeV Gamma Rays


Atmospheric Opacity
100%
50%
0%
0.1 nm
1 nm
10 nm
100 nm
1 µm
10 µm
100 µm
1 mm
1 cm
10 cm
1 m
10 m
100 m
1 km
Wavelength
Gamma Rays, X-Rays and Ultraviolet Light blocked by the upper atmosphere (best observed from space).
Visible Light observable from Earth, with some atmospheric distortion.
Most of the Infrared spectrum absorbed by atmospheric gasses (best observed from space).
Radio Waves observable from Earth.
Long-wavelength Radio Waves blocked.

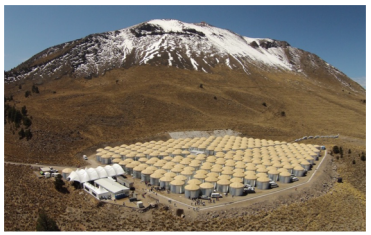
Today‘s gamma-ray telescopes



Indirect detection

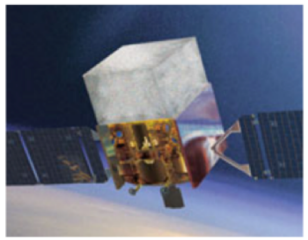
Direct detection

100 TeV | 100 GeV | 100 MeV | 100 keV

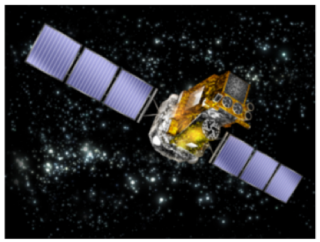


> Particle detector array
- 1-100 TeV
- HAWC (Mexico)

> Air-shower telescopes
- 50 GeV - 100 TeV
- H.E.S.S. (Namibia)
- MAGIC (La Palma)
- Veritas (Arizona)



> Satellite based pair-creation telescopes
- 30 MeV - 1 TeV
- Fermi LAT
- AGILE



> Integral mission
- SPI Spectrometer: 18 keV - 8 MeV
- IBIS Imager: 15 keV - 10 MeV

How to observe MeV-GeV gamma rays

Interactions of gamma rays with matter

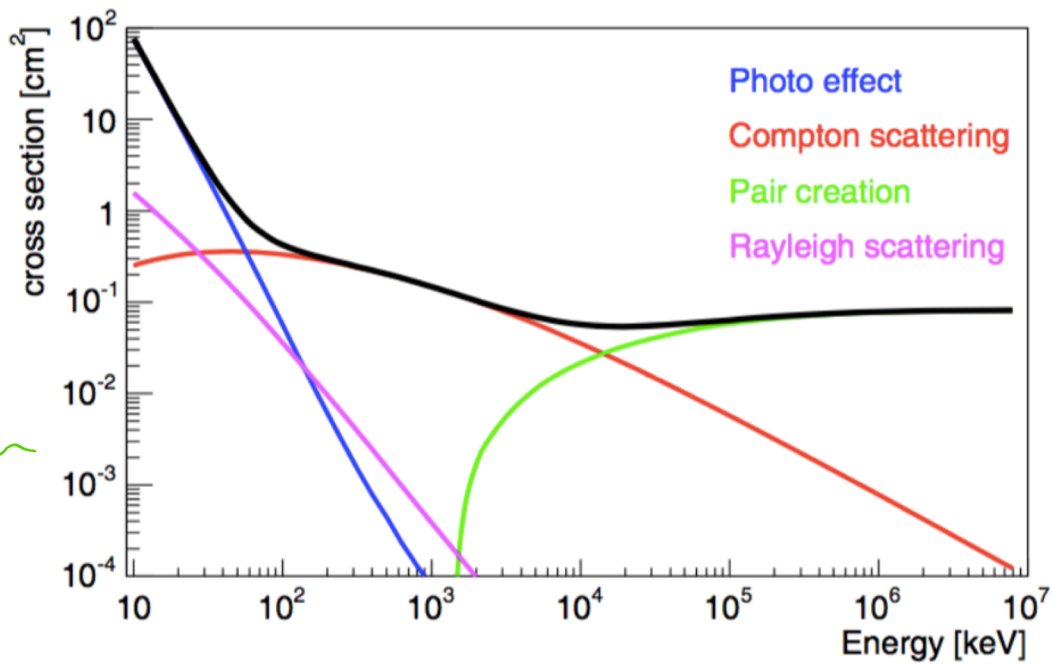
How to observe MeV-GeV gamma rays

Interactions of gamma rays with matter

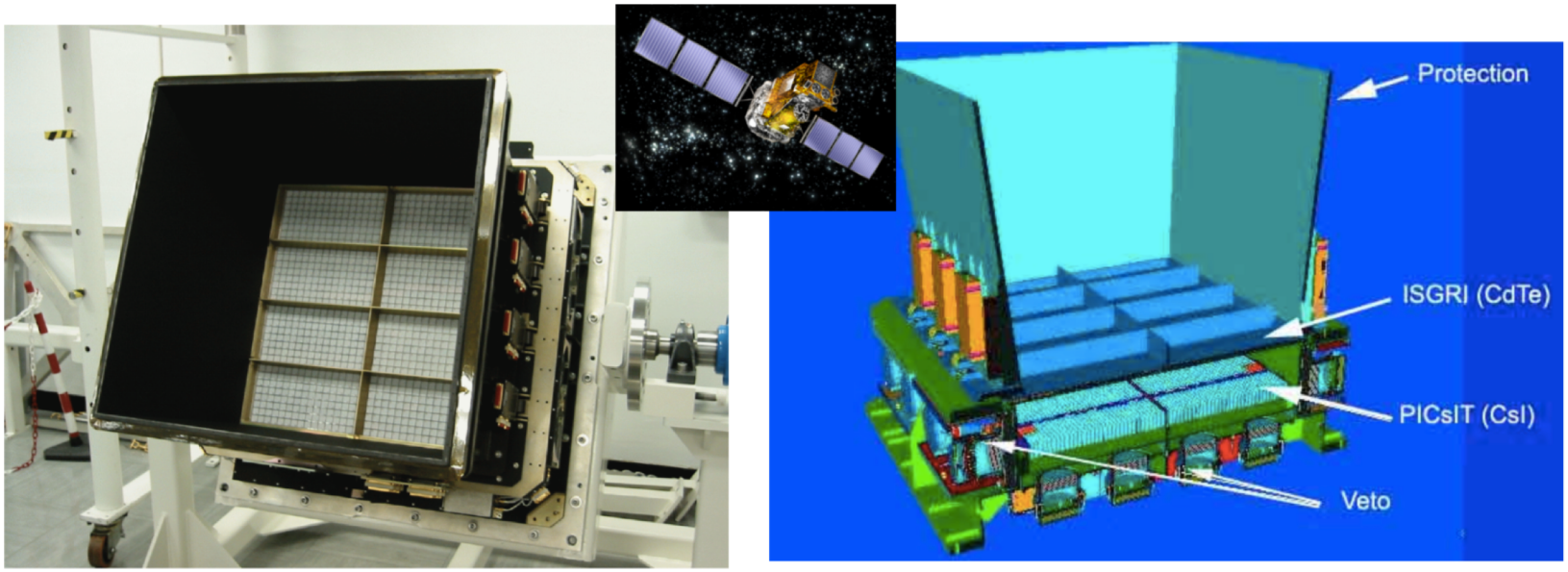
Low-E photo-elect. effect

Compton scattering

high-E pair creation

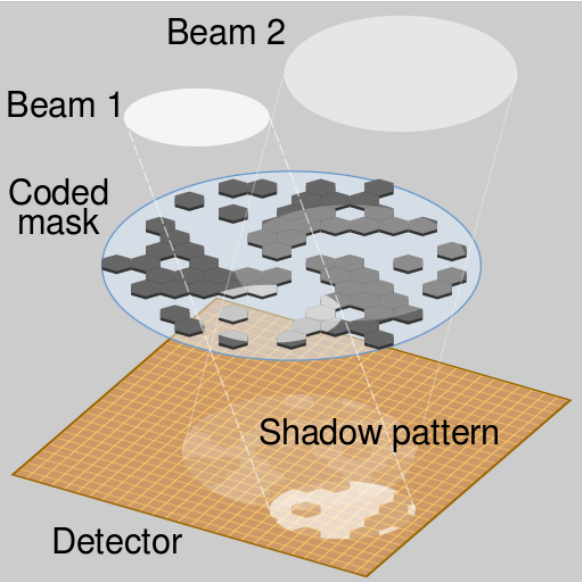


INTEGRAL IBIS

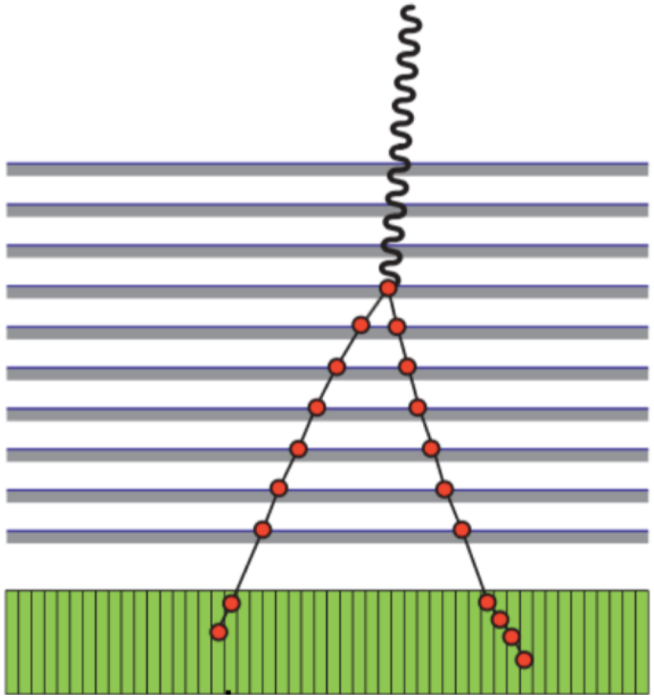


Energy range	15 keV - 10 MeV
Detector area	2600 cm^2 (CdTe - Cadmium Telluride) 3000 cm^2 (CsI - Caesium Iodide)
Spectral energy resolution (FWHM)	8% @ 100 keV 10% @ 1 MeV
Field of view	8.3° x 8.0° (fully coded) 29.1° x 29.4° (down to zero response)
Angular resolution	12' FWHM

INTEGRAL Coded Mask Imaging

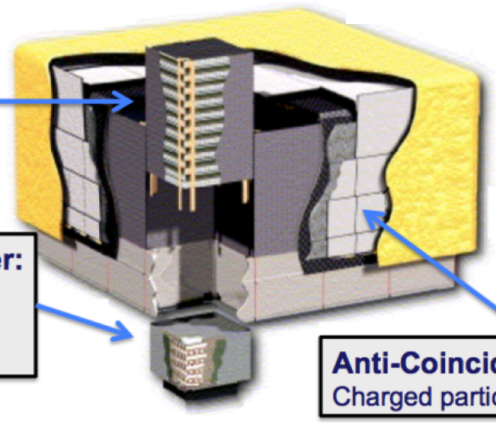


Pair Creation Telescope: Fermi LAT



Public Data Release:
All γ-ray data made public within 24 hours (usually less)

Si-Strip Tracker:
convert $\gamma \rightarrow e^+e^-$
reconstruct γ direction
EM v. hadron separation



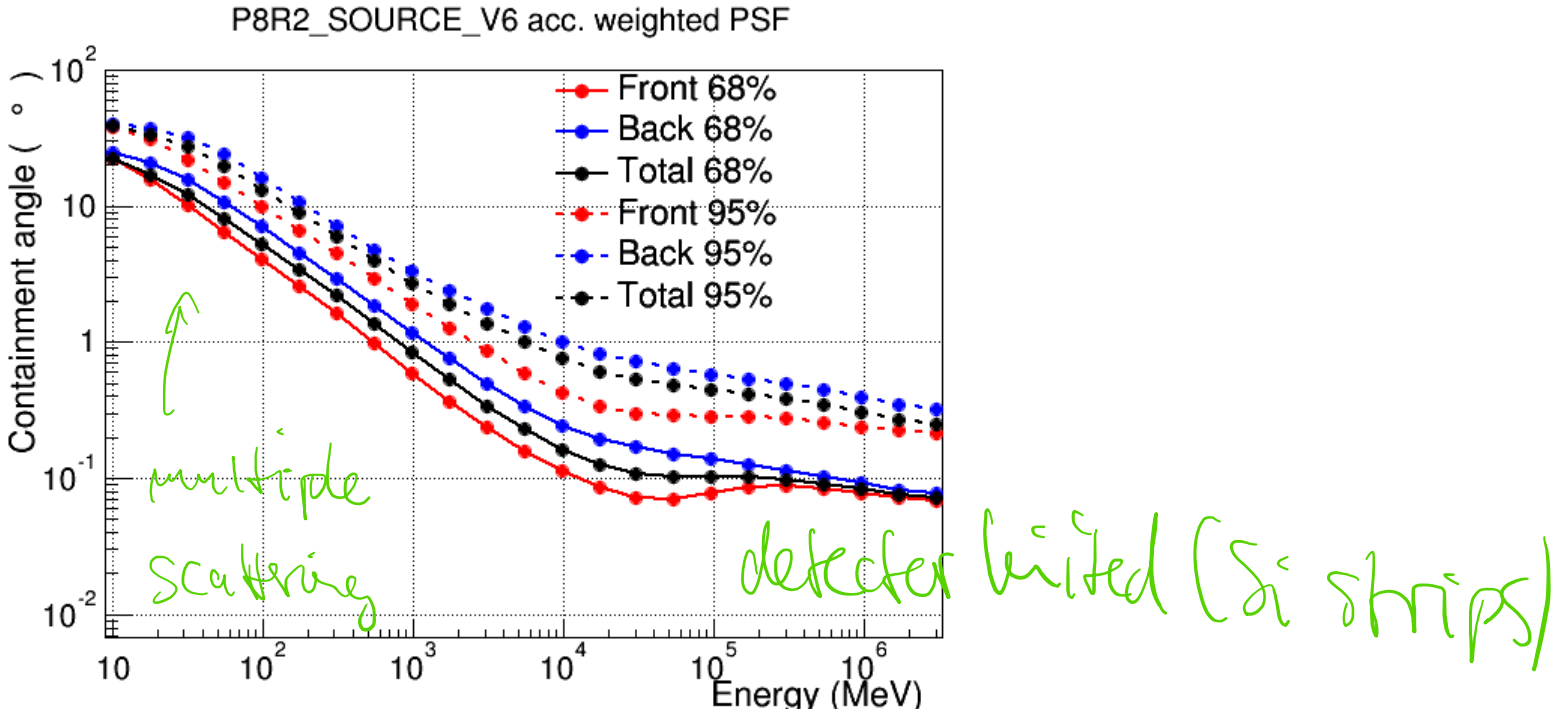
Hodoscopic CsI Calorimeter:
measure γ energy
image EM shower
EM v. hadron separation

Anti-Coincidence Detector:
Charged particle separation

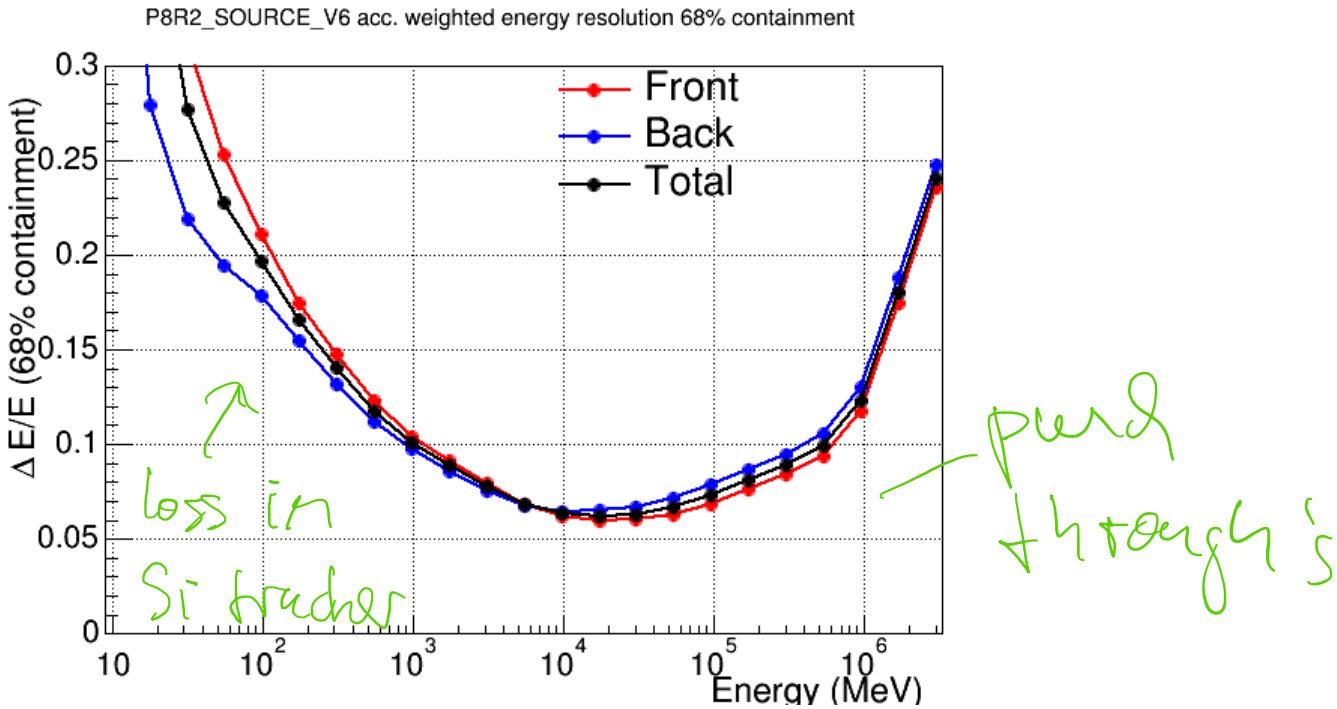
Sky Survey:
With 2.5 sr Field-of-view LAT sees whole sky every 3 hours

Trigger and Filter:
Reduce data rate from ~10kHz to 300-500 HZ

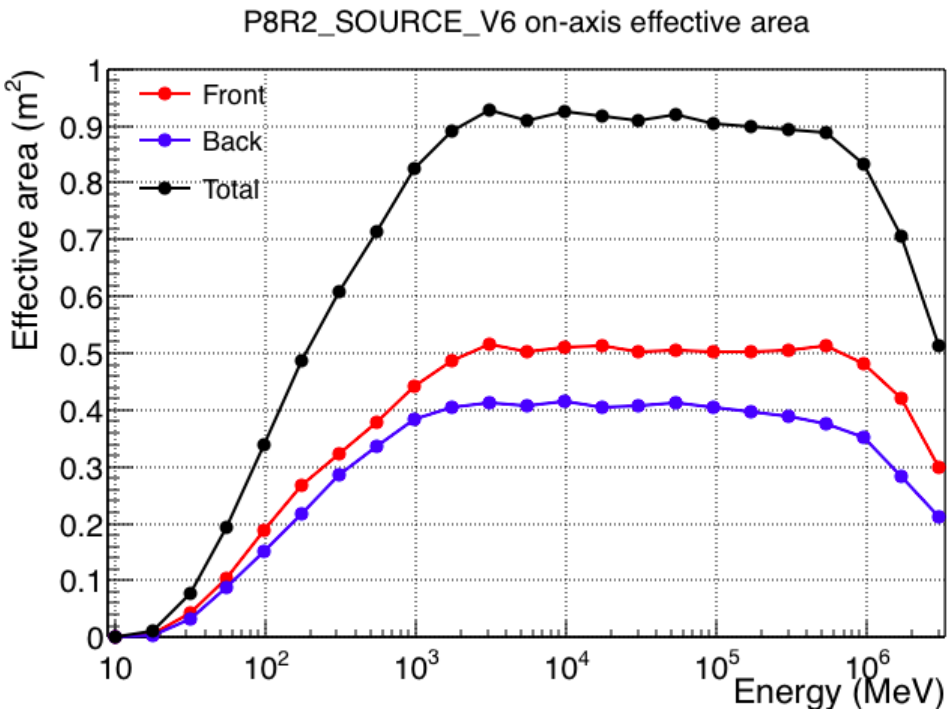
Fermi LAT Performance



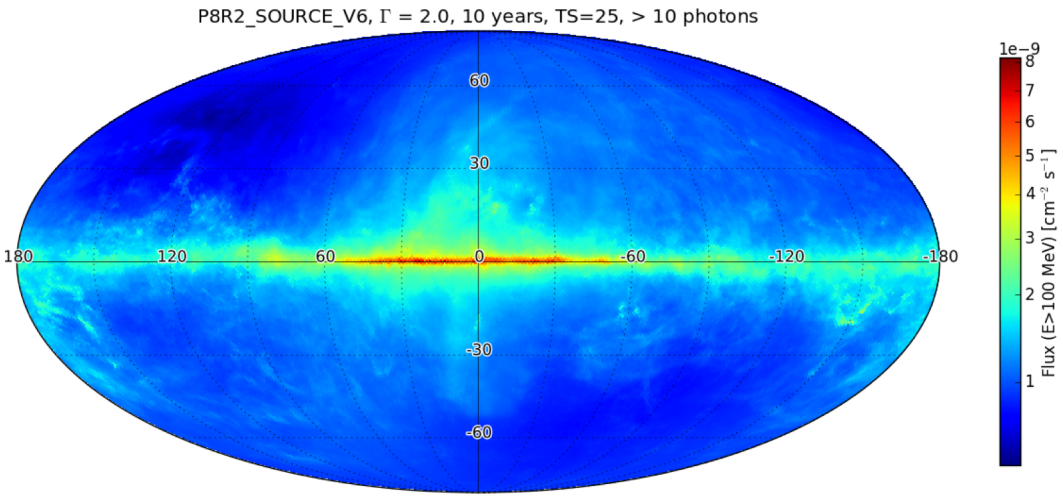
Fermi LAT Performance

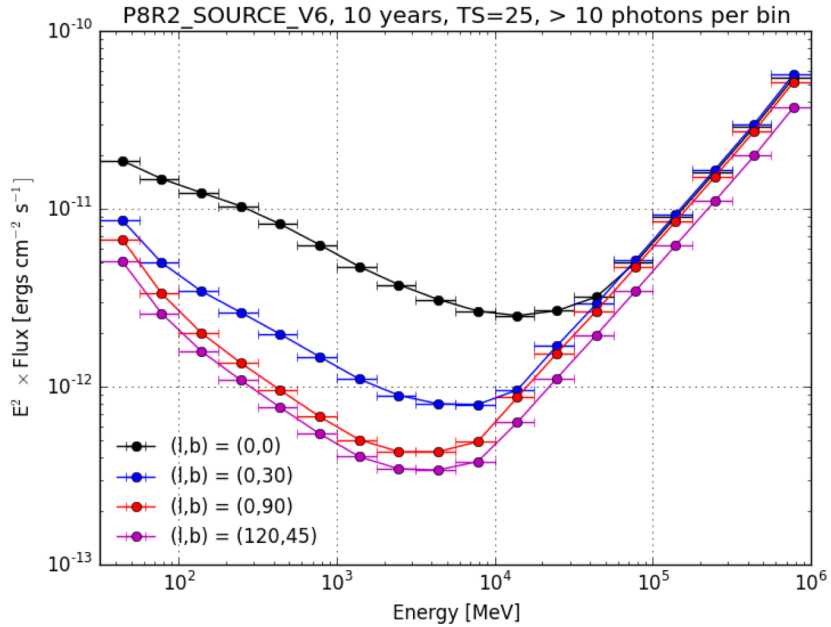


Fermi LAT Performance

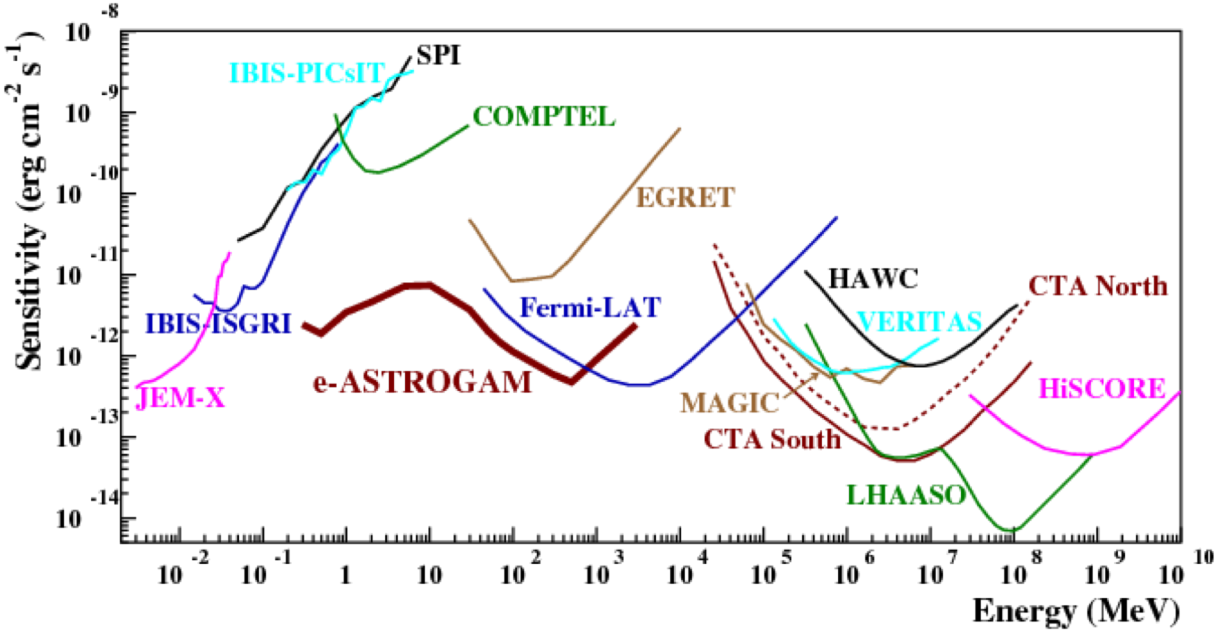


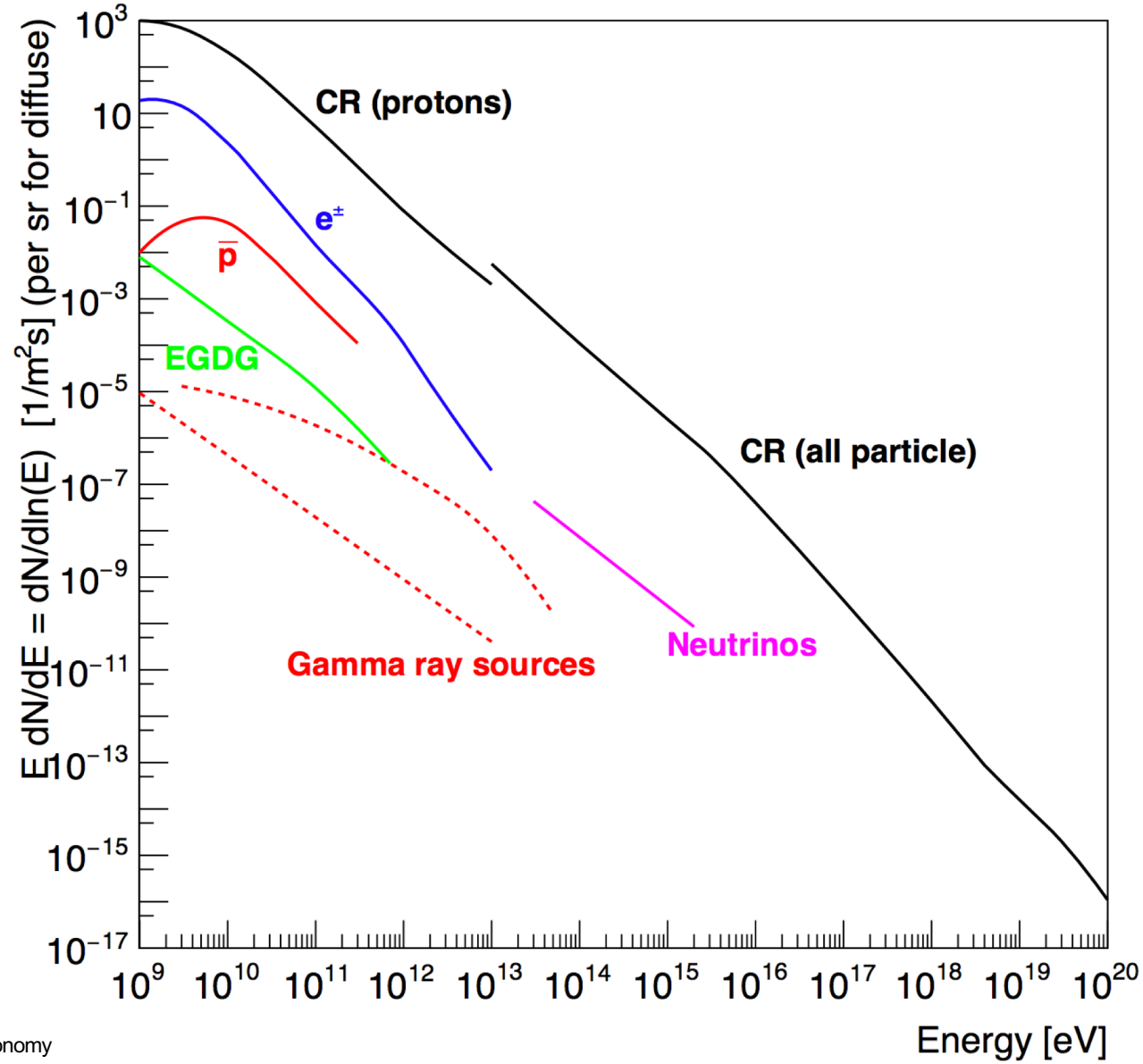
Fermi LAT Point Source Sensitivity

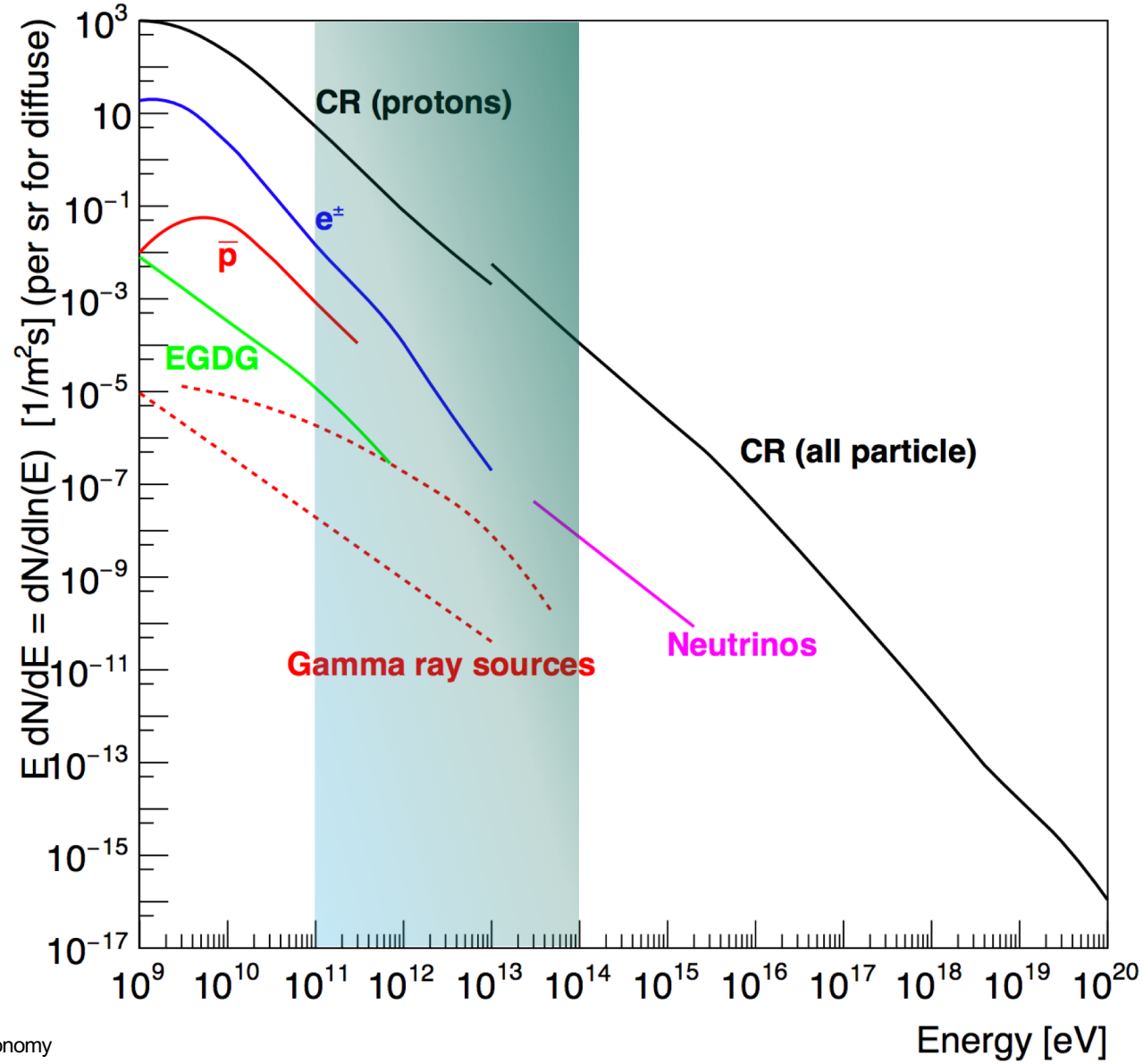




Sensitivities MeV – GeV




CR (protons)
e±
p̄
EGDG
CR (all particle)
Neutrinos
Gamma ray sources
E dN/dE = dN/dln(E) [1/m²s] (per sr for diffuse)
Energy [eV]


CR (protons)
e±
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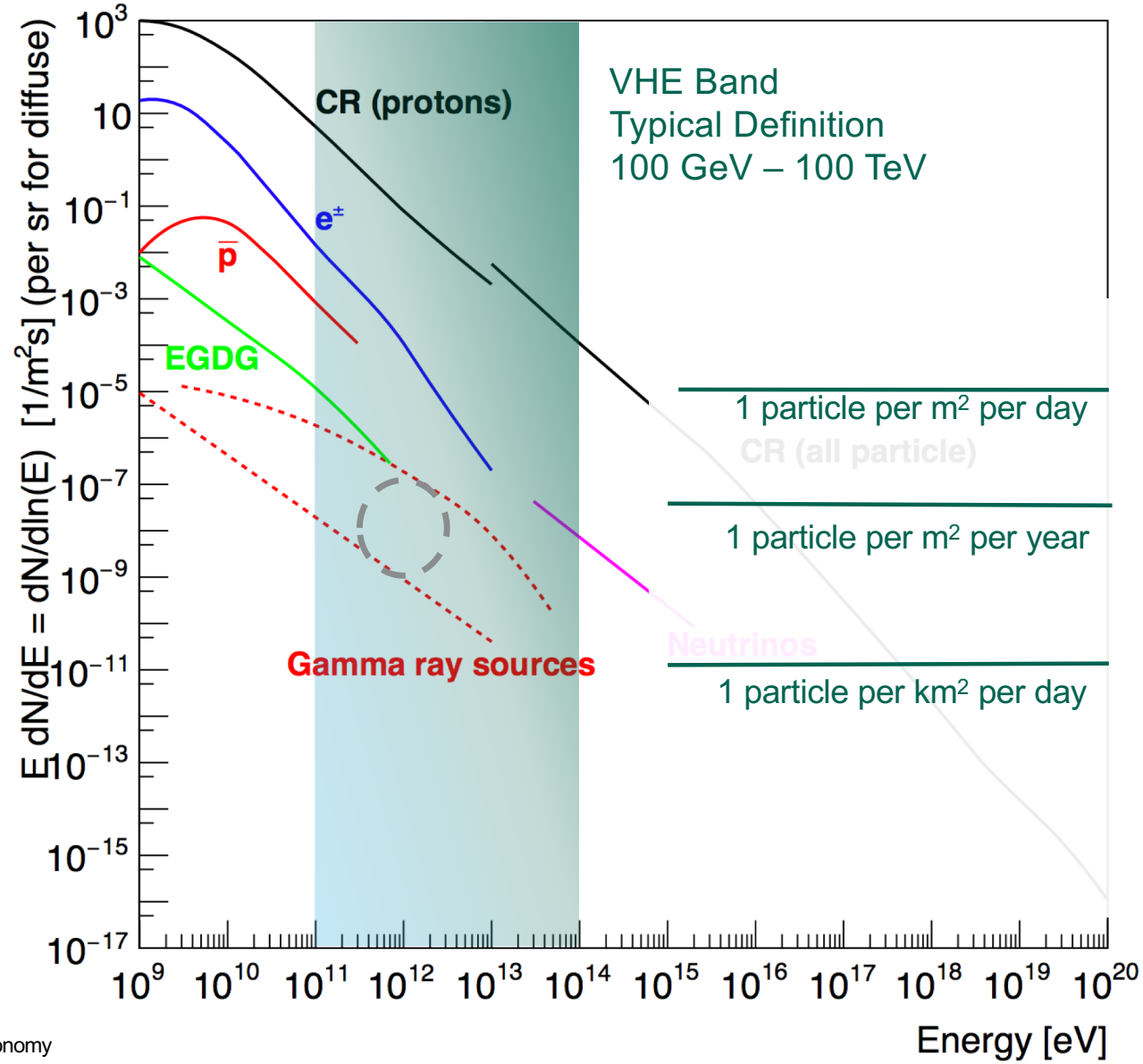
Energy [eV]

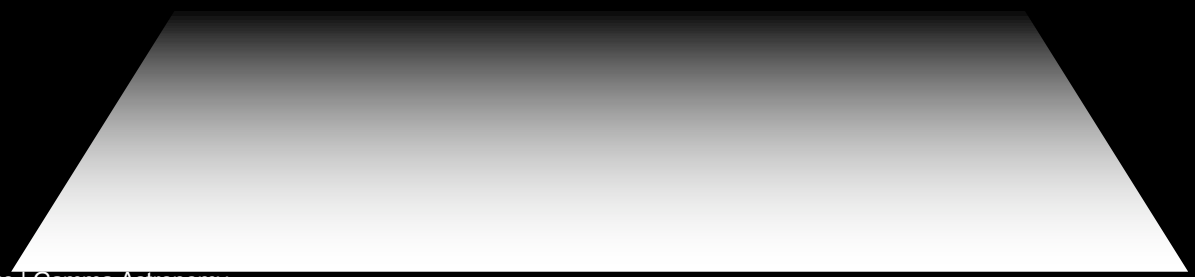

VHE Band
Typical Definition
100 GeV – 100 TeV
CR (protons)
e±
p̄
EGDG
Gamma ray sources
1 particle per m² per day
CR (all particle)
1 particle per m² per year
Neutrinos
1 particle per km² per day
E dN/dE = dN/dln(E) [1/m²s] (per sr for diffuse)
Energy [eV]

Air Showers

↓ 1 TeV γ-ray

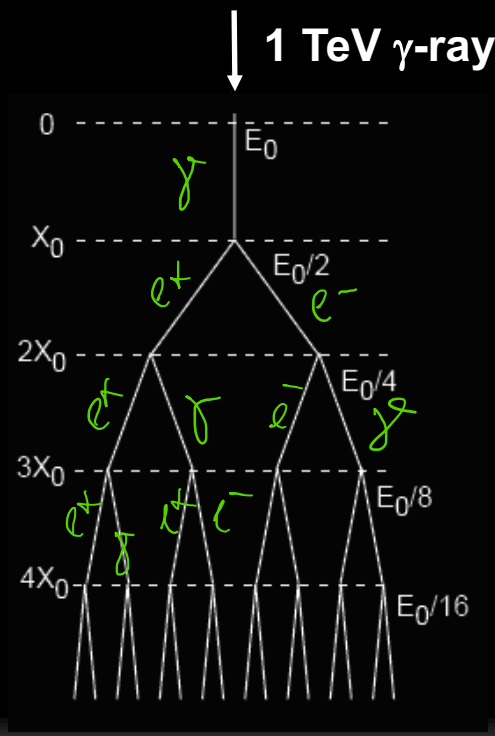
20 —
~30km

rad. length
$X_0 = 40\ g/cm^2$



Air Showers

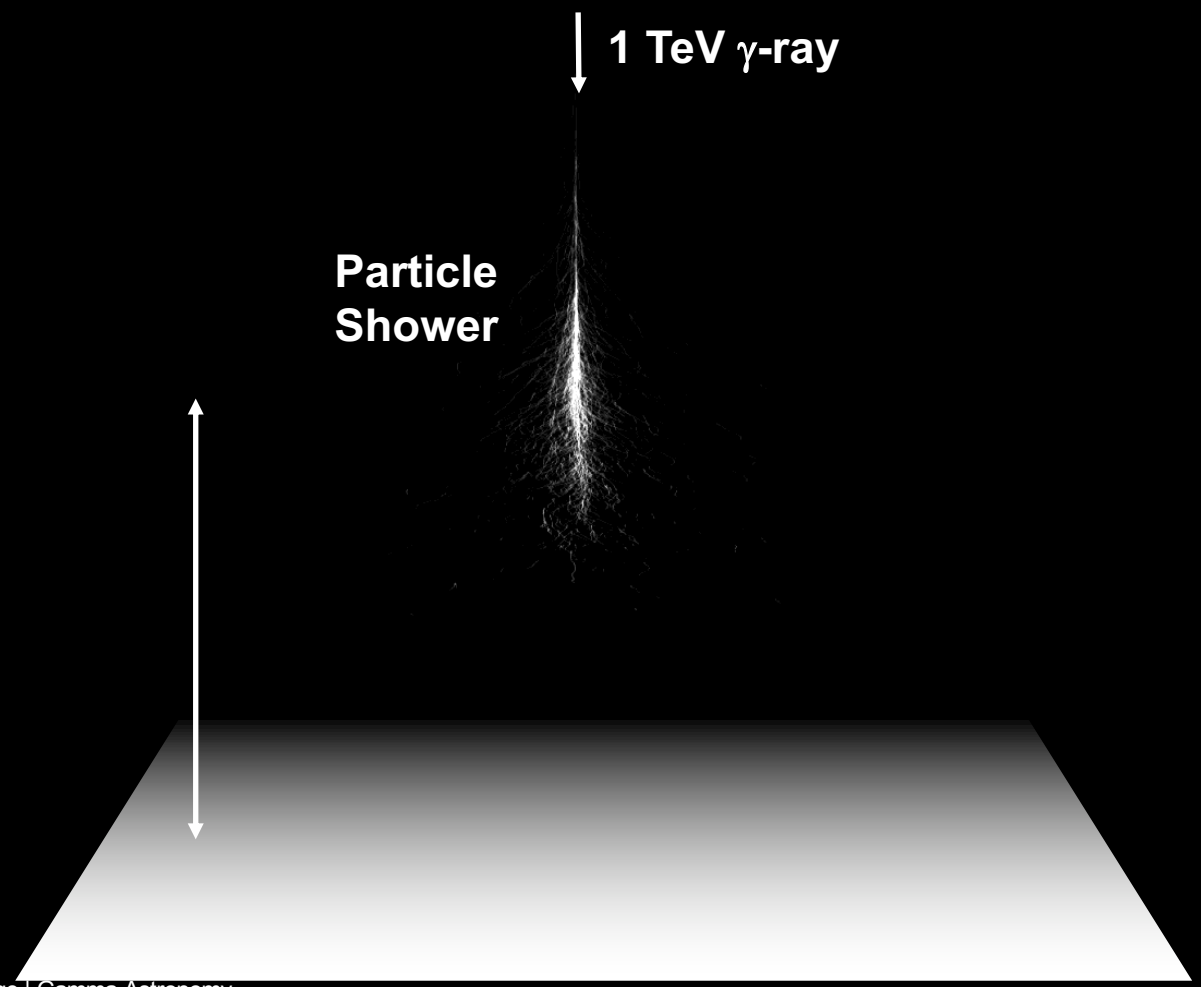
Particle Shower



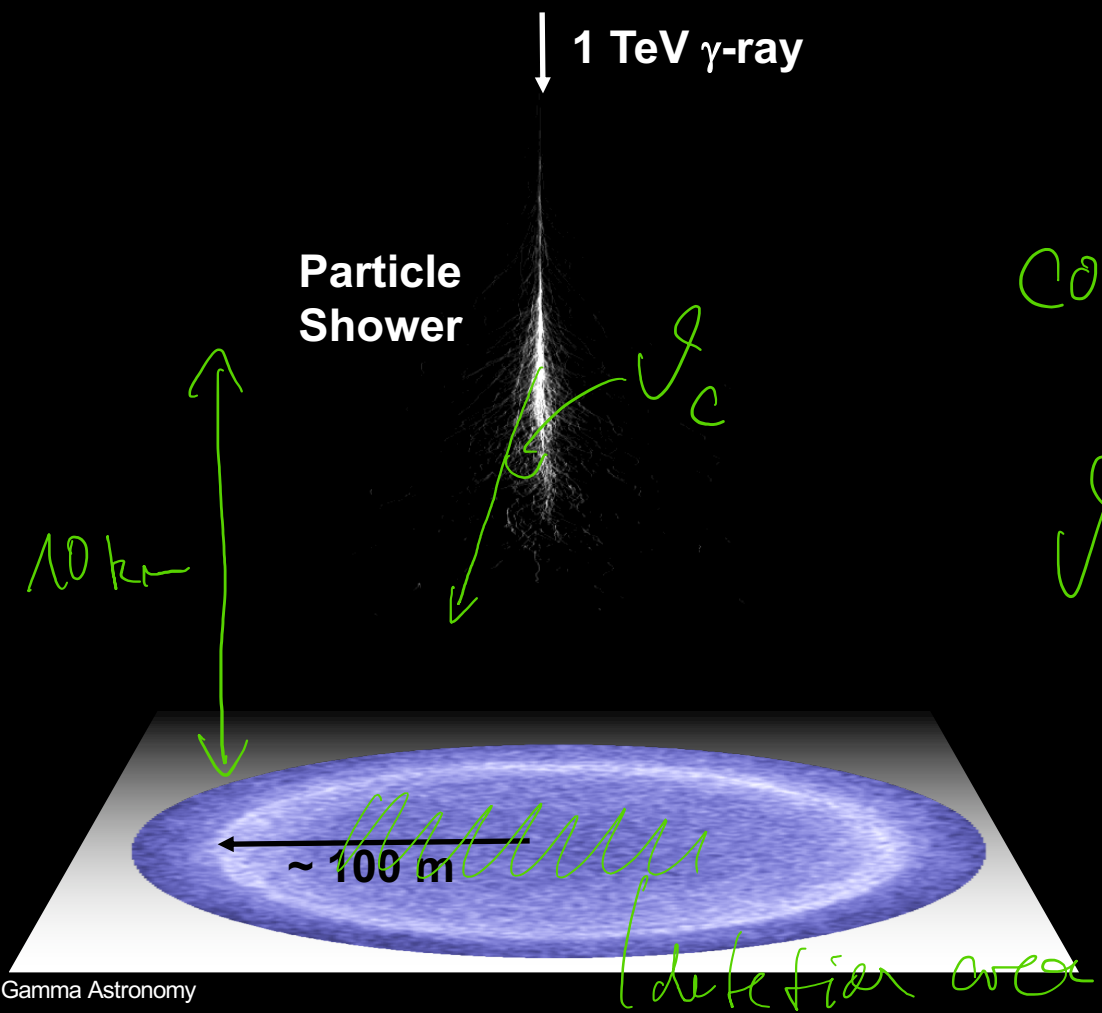
$N_{max} \propto E_0$

$X_{max} \propto \ln E_0$

Air Showers



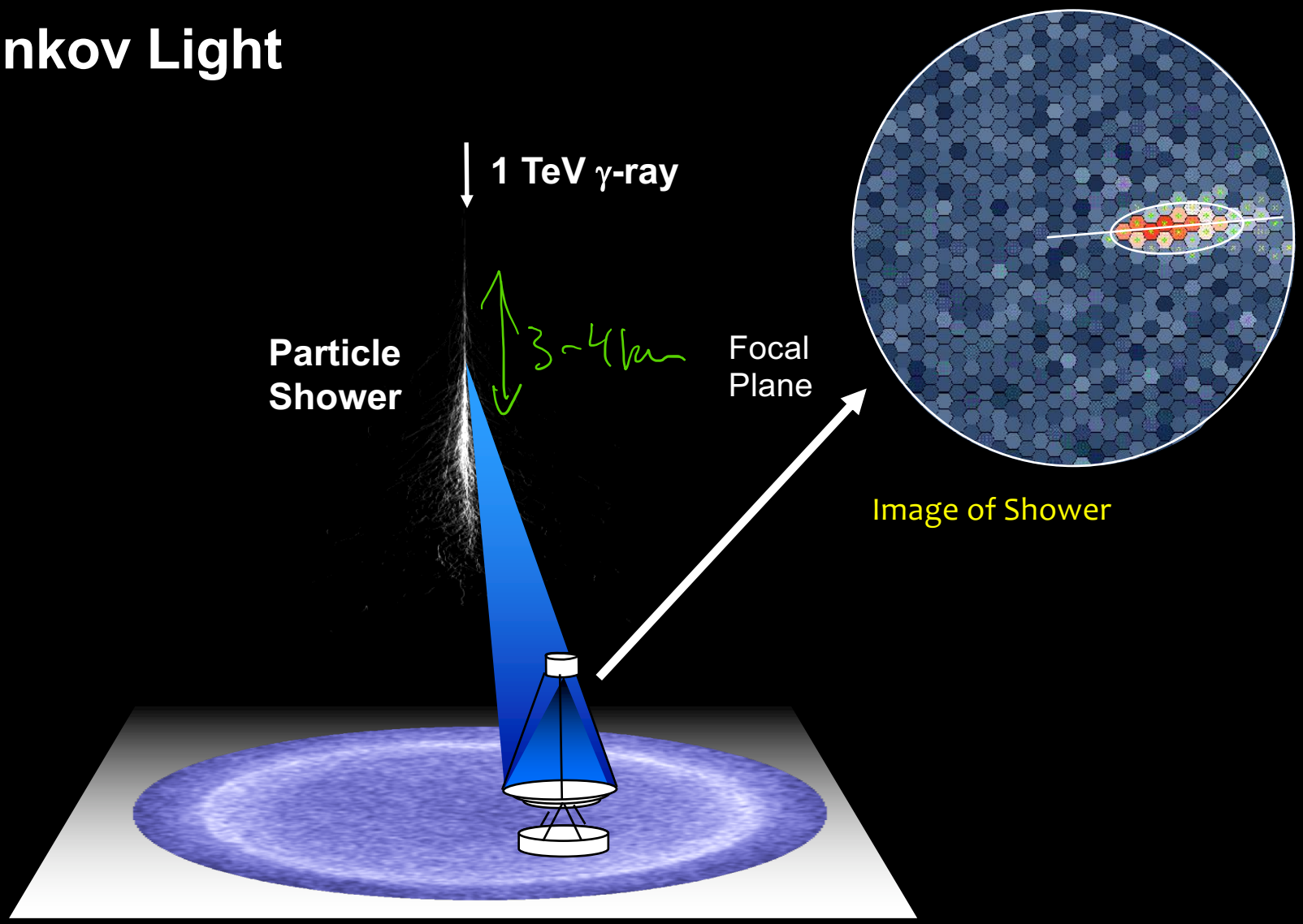
Cherenkov Light



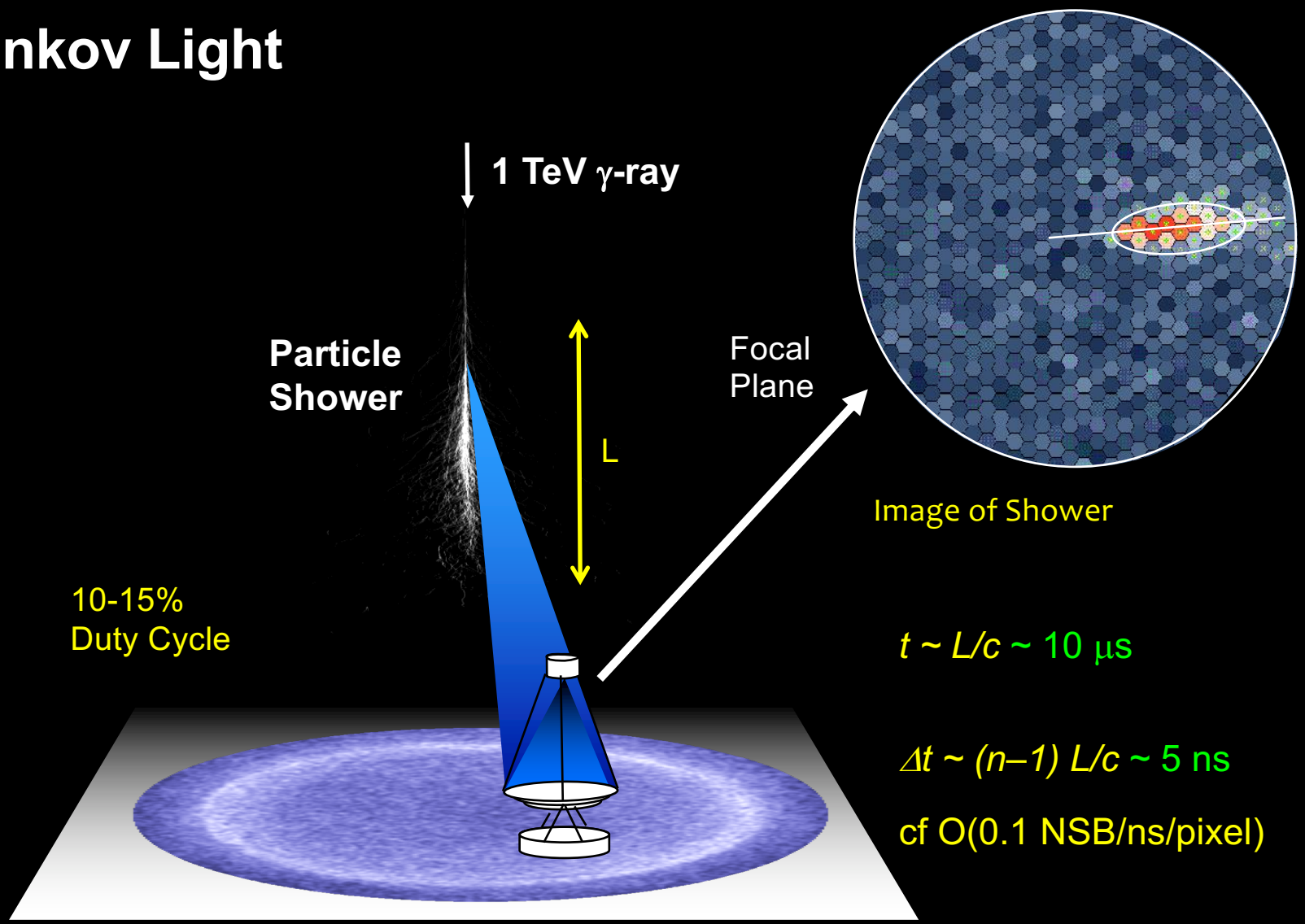
$$\cos\vartheta_c = \frac{1}{\beta n}$$

$$\vartheta_c \sim 0.7^\circ$$

Cherenkov Light



Cherenkov Light



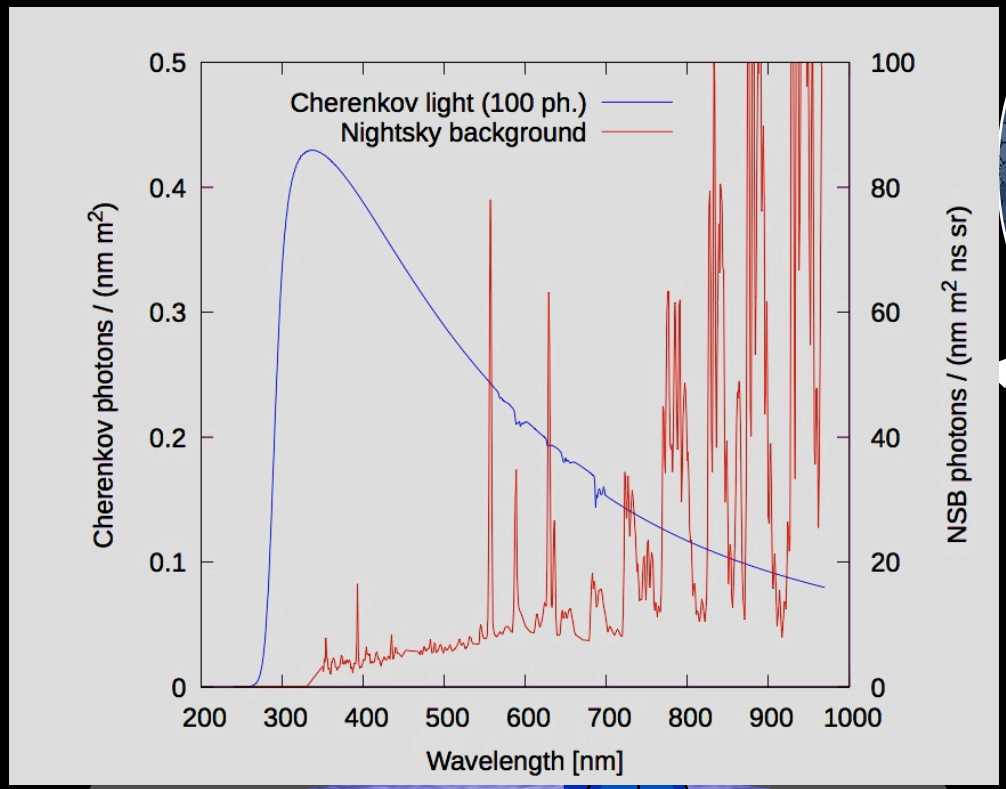
10-15% Duty Cycle

$t \sim L/c \sim 10\ \mu s$

$\Delta t \sim (n-1)\ L/c \sim 5$ ns

cf O(0.1 NSB/ns/pixel)

Cherenkov Light



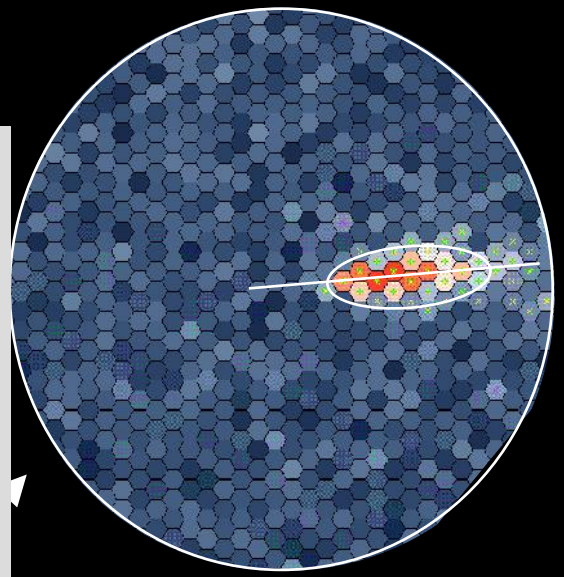
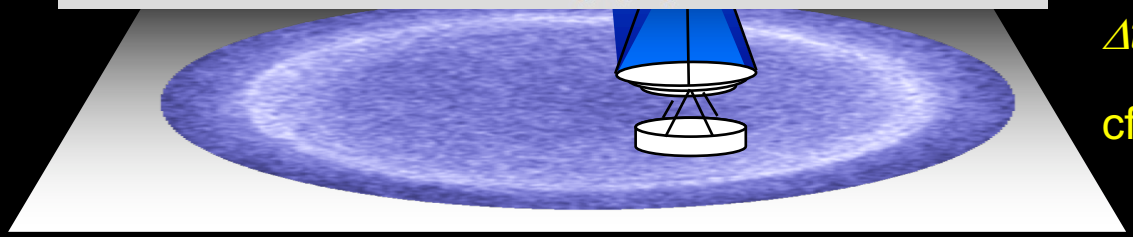


Image of Shower



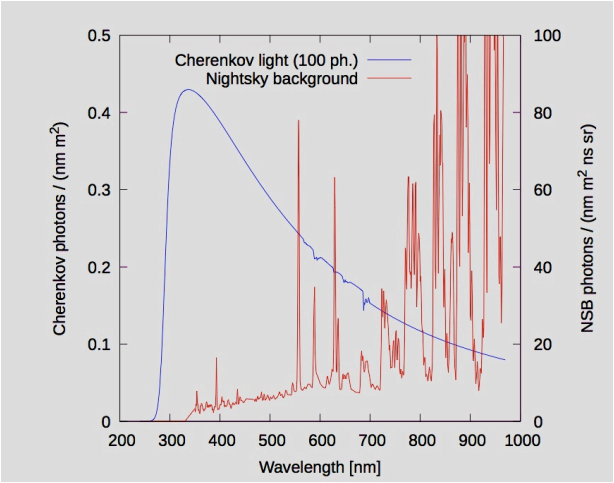
$t \sim L/c \sim 20\ \mu s$

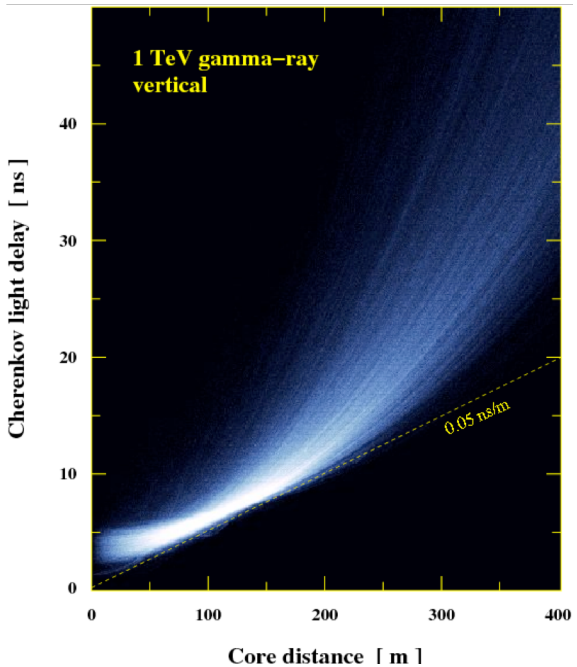
$\Delta t \sim (n-1)\ L/c \sim 5$ ns

cf O(0.1 NSB/ns/pixel)

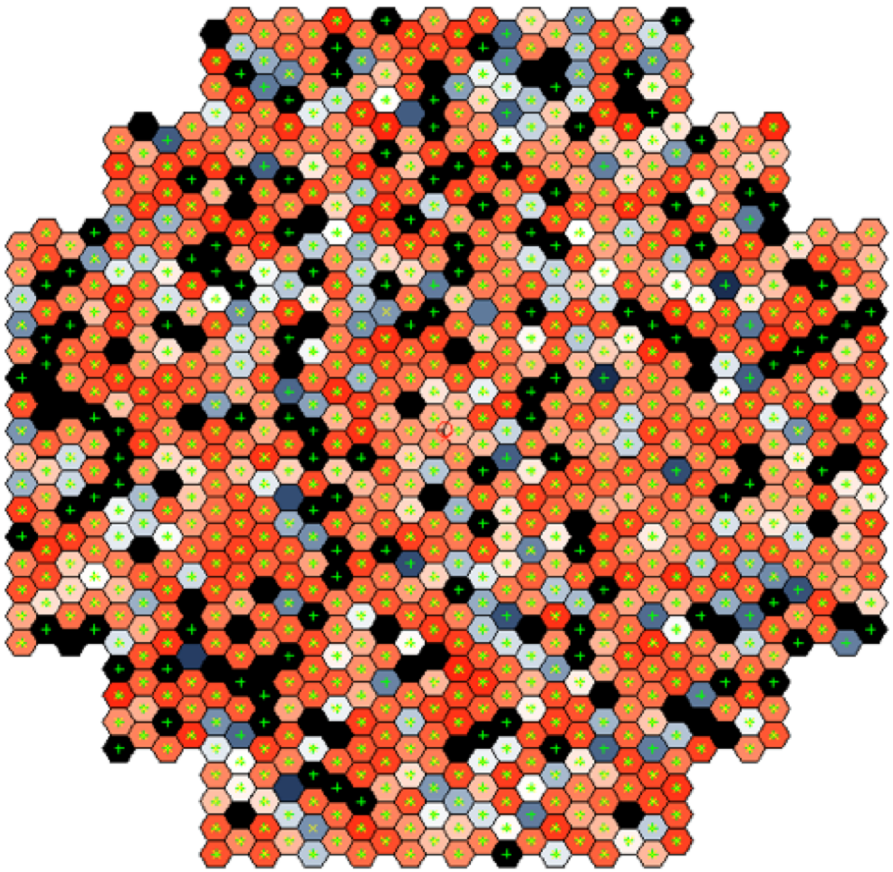
Imaging Detector

How can we take Cherenkov images of air showers?





Fast Cameras



1/10000 s
(100 μs)

1/100000 s
(10 μs)

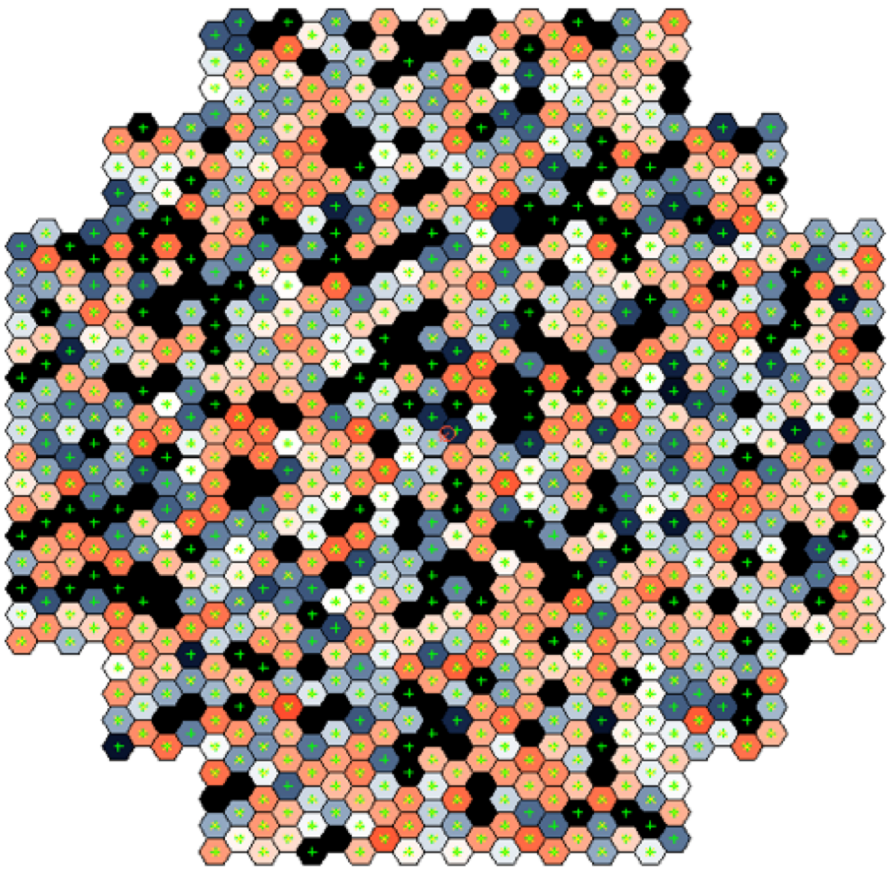
1/1000000 s
(1 μs)

1/10000000 s
(100 ns)

16/100000000 s
(16 ns)

O(1000) photo-sensors on O(1m^2) sampling O(10 ns) blue light flashes

Fast Cameras



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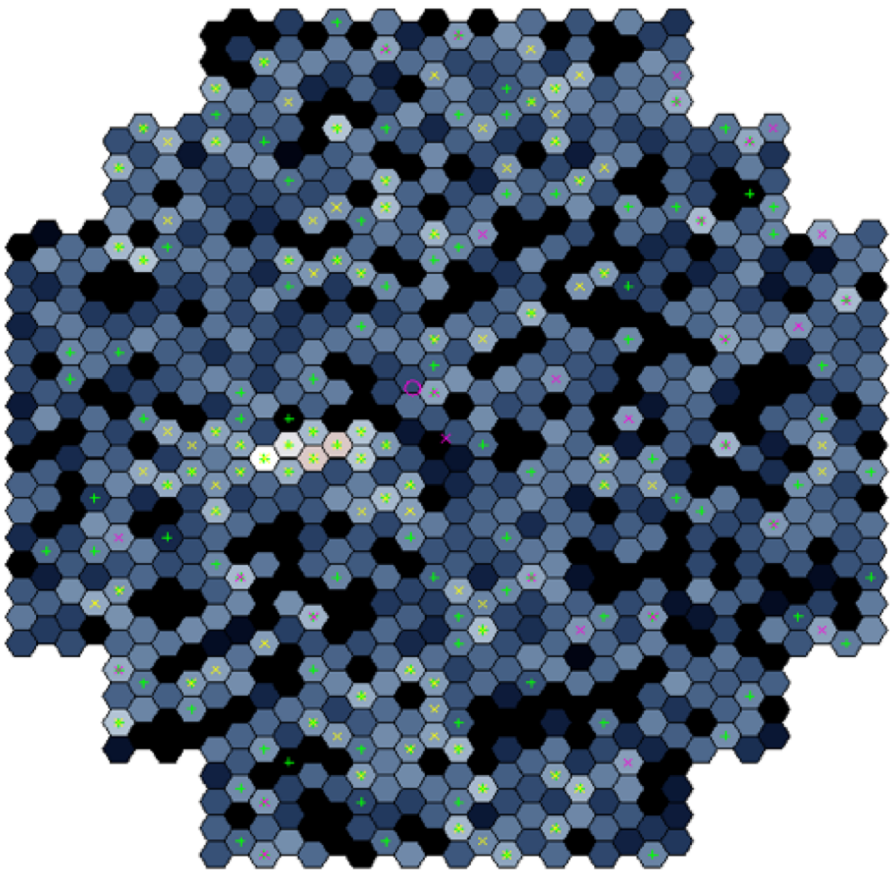
Fast Cameras



1/10000 s
(100 μs)

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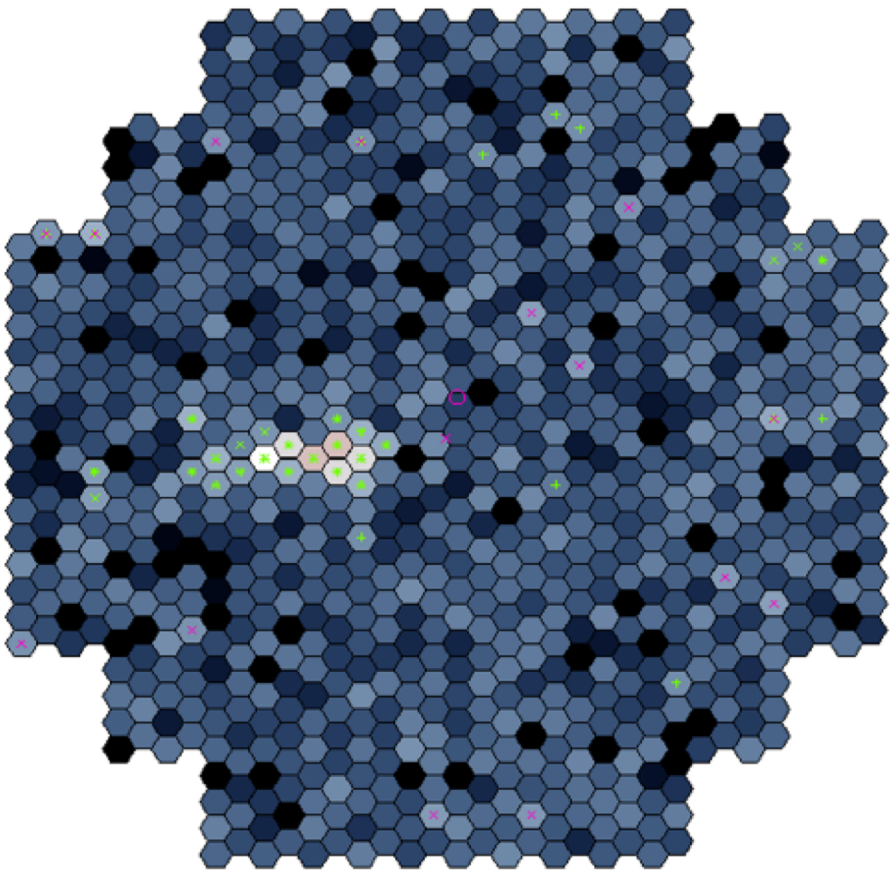

1/10000 s
(100 μs)

1/100000 s
(10 μs)

1/1000000 s
(1 μs)

1/10000000 s
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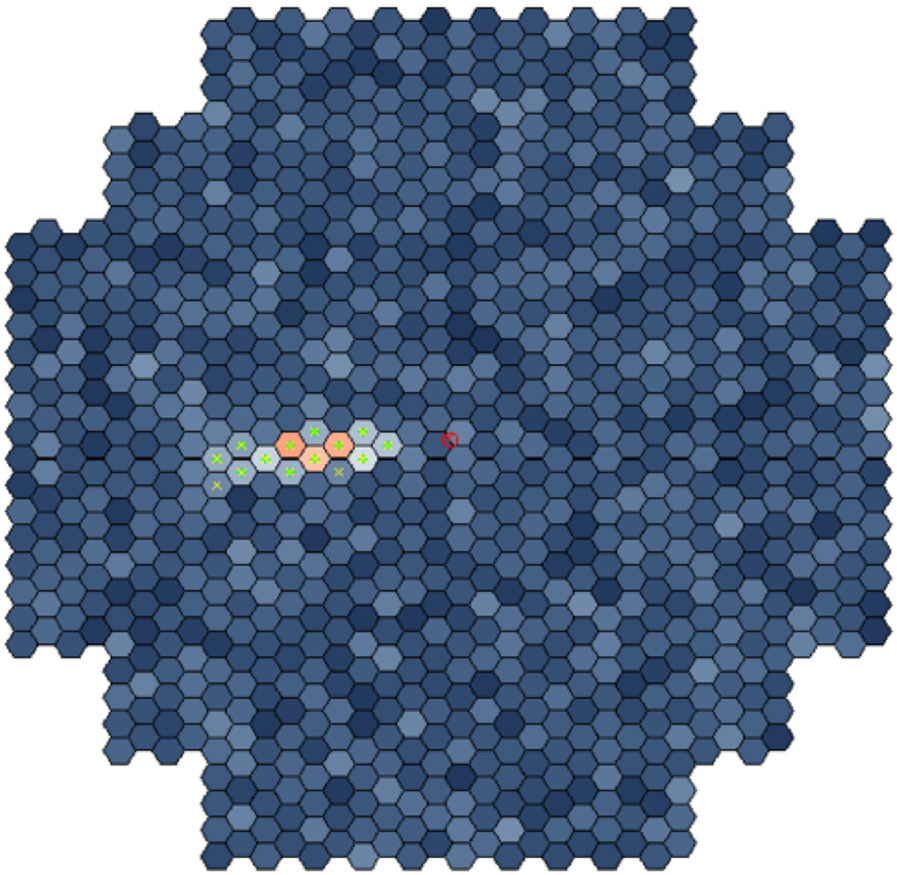
O(1000) photo-sensors on O(1m^2) sampling O(10 ns) blue light flashes

Fast Cameras



1/10000 s
(100 μs)

1/100000 s
(10 μs)

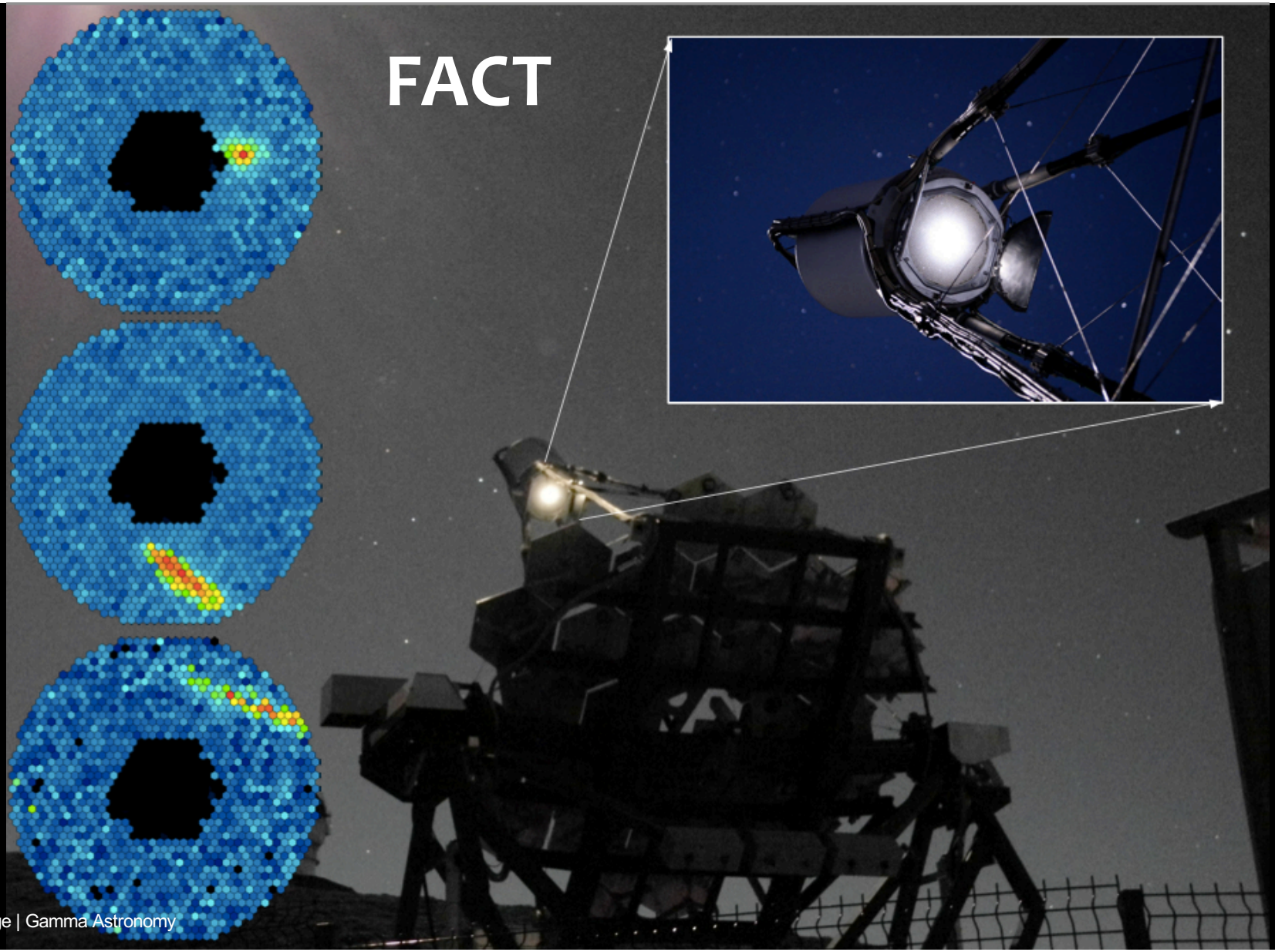
1/1000000 s
(1 μs)

1/10000000 s
(100 ns)

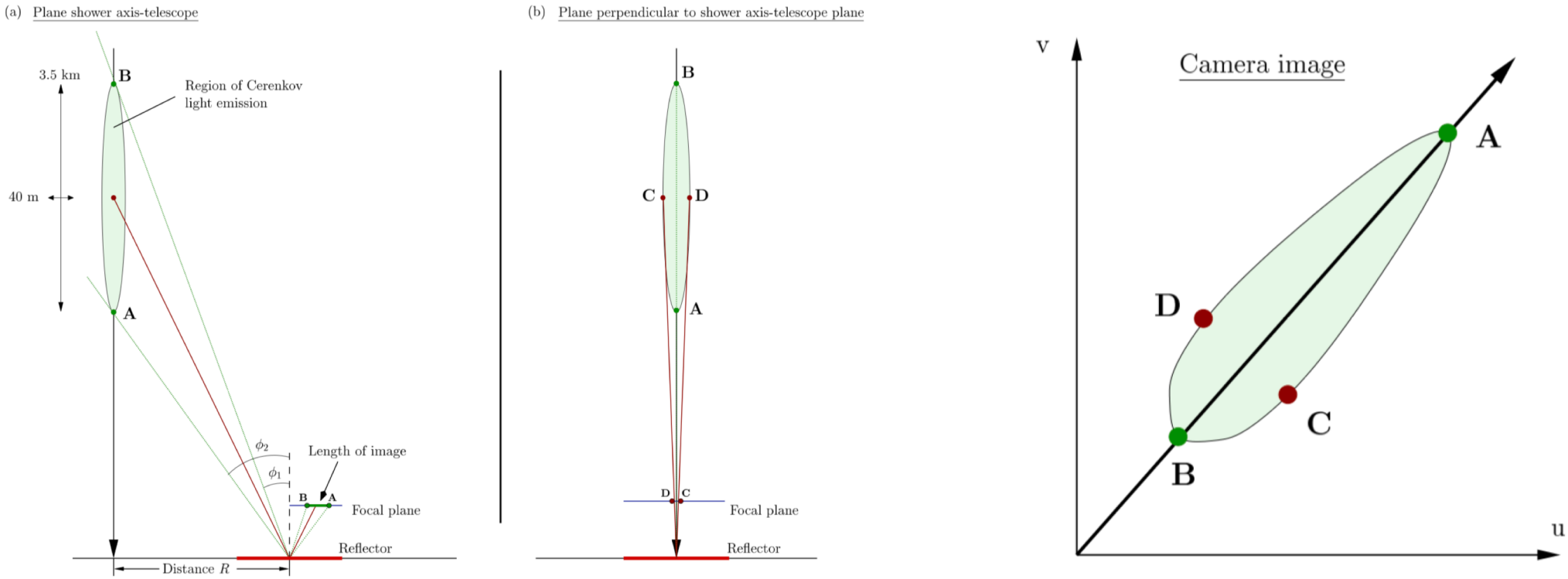
16/100000000 s
(16 ns)

O(1000) photo-sensors on O(1m^2) sampling O(10 ns) blue light flashes

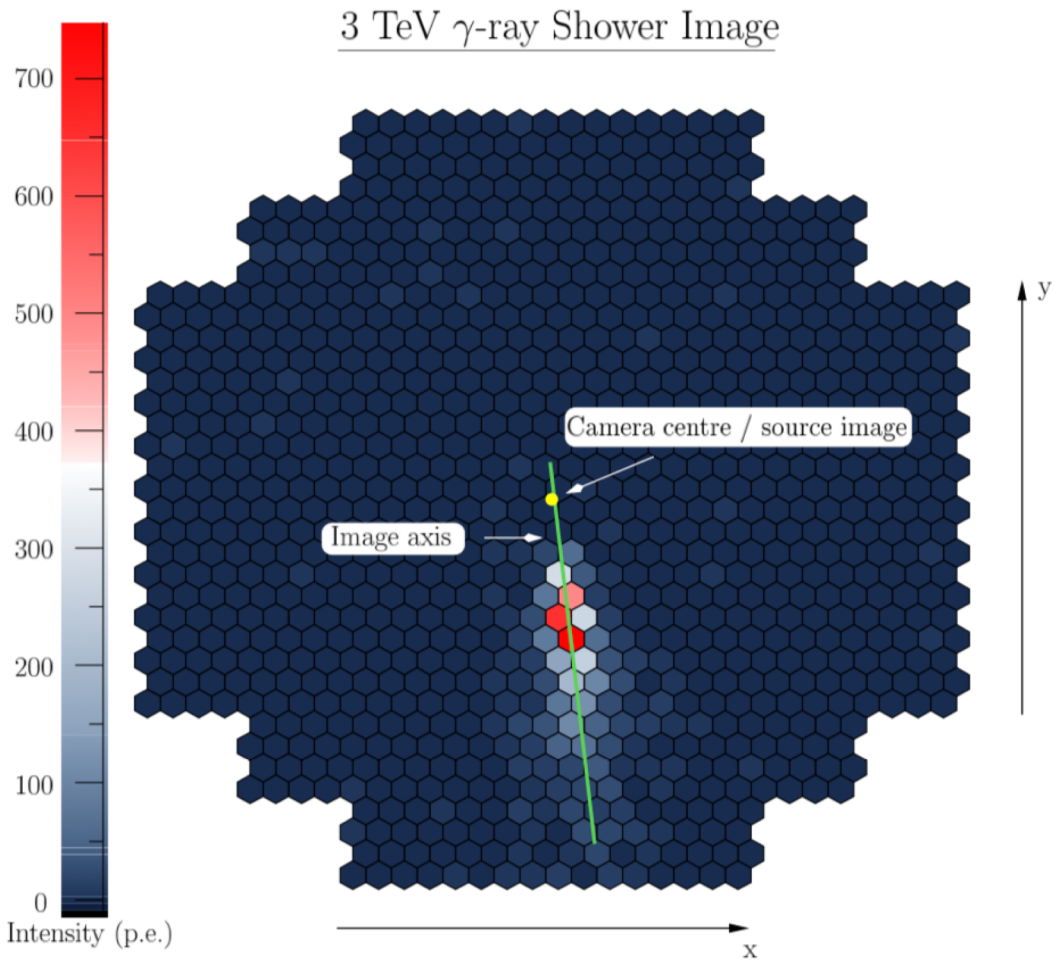
FACT



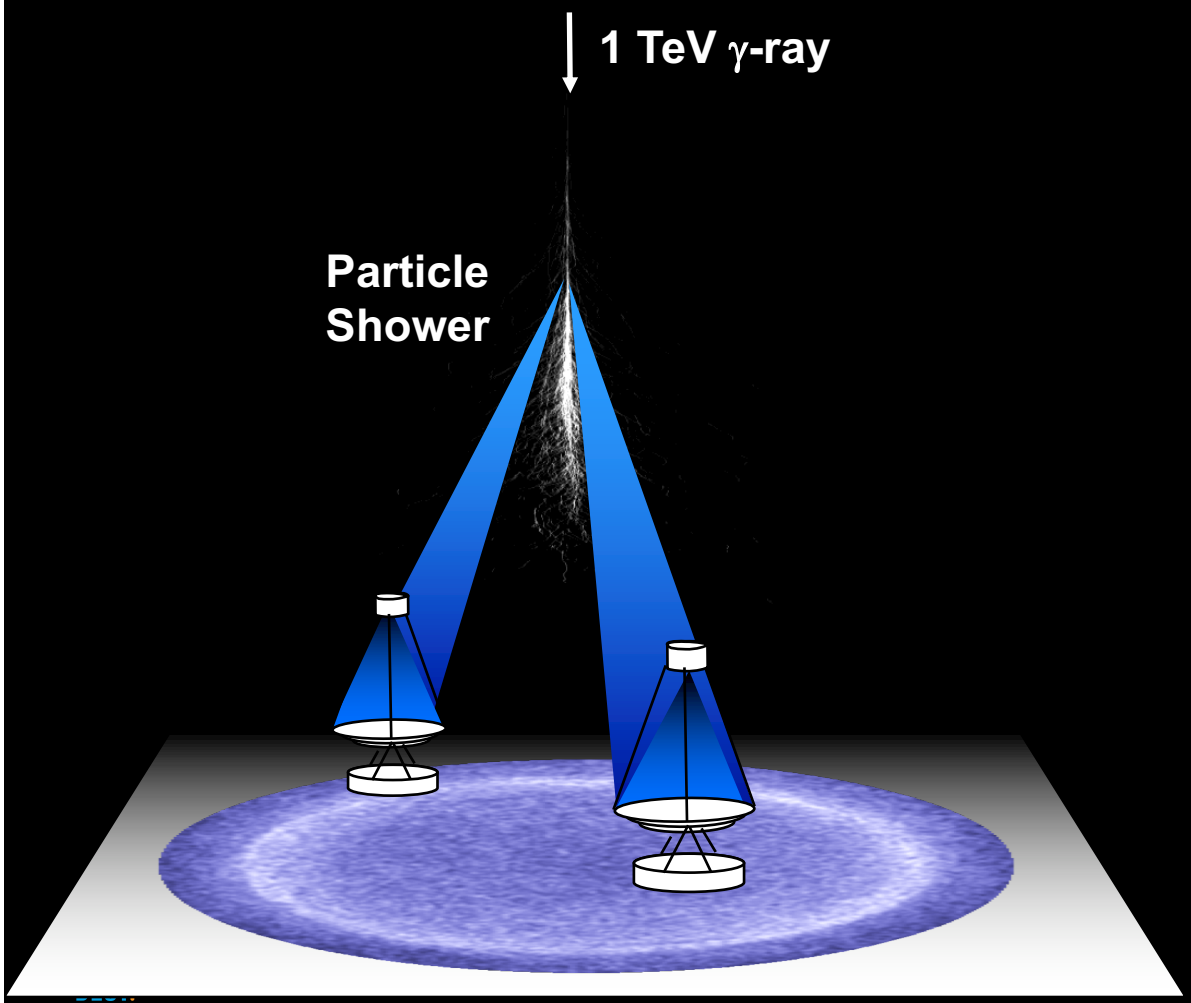
Geometry of Imaging Cherenkov Technique



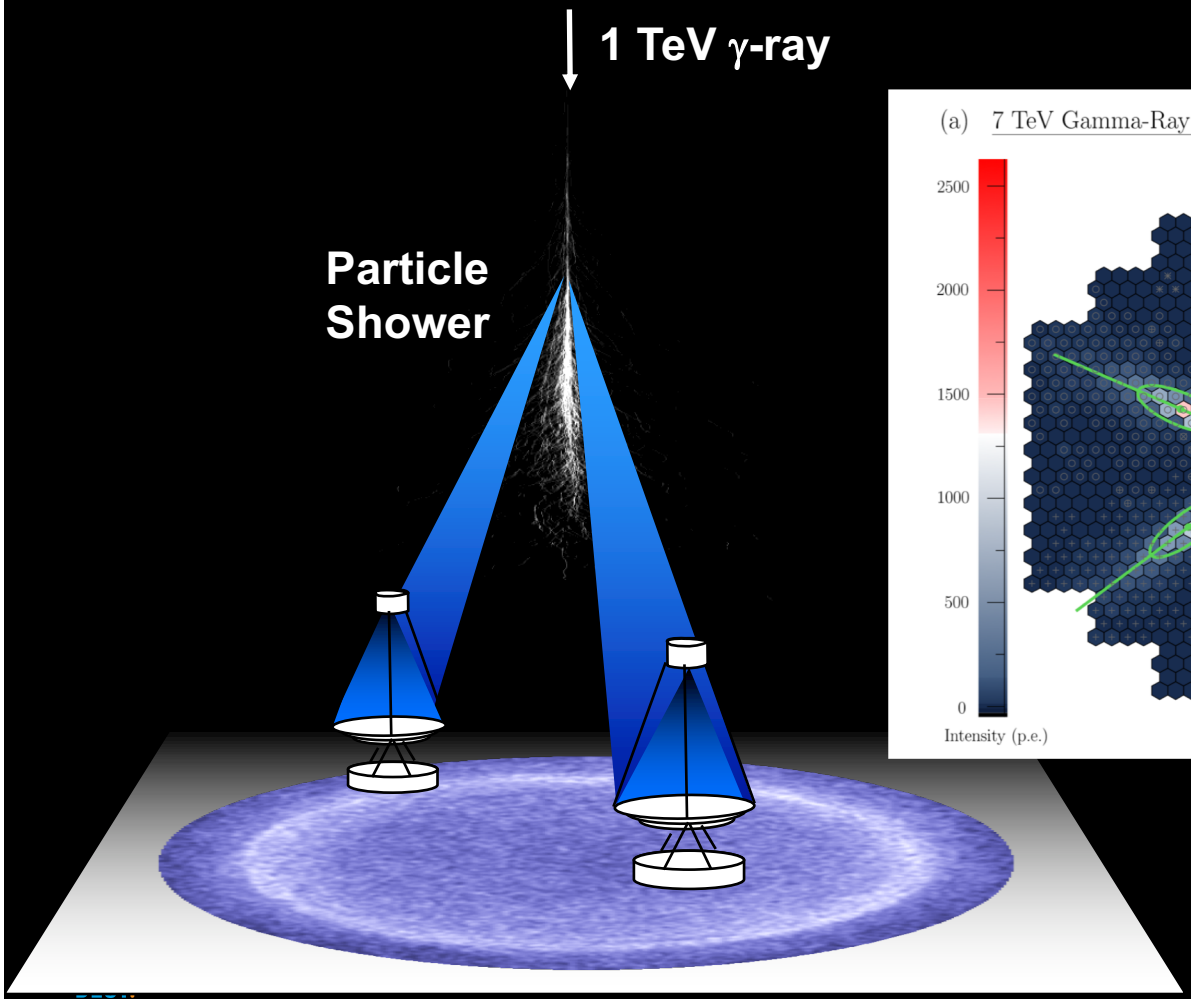
Cherenkov Camera Image

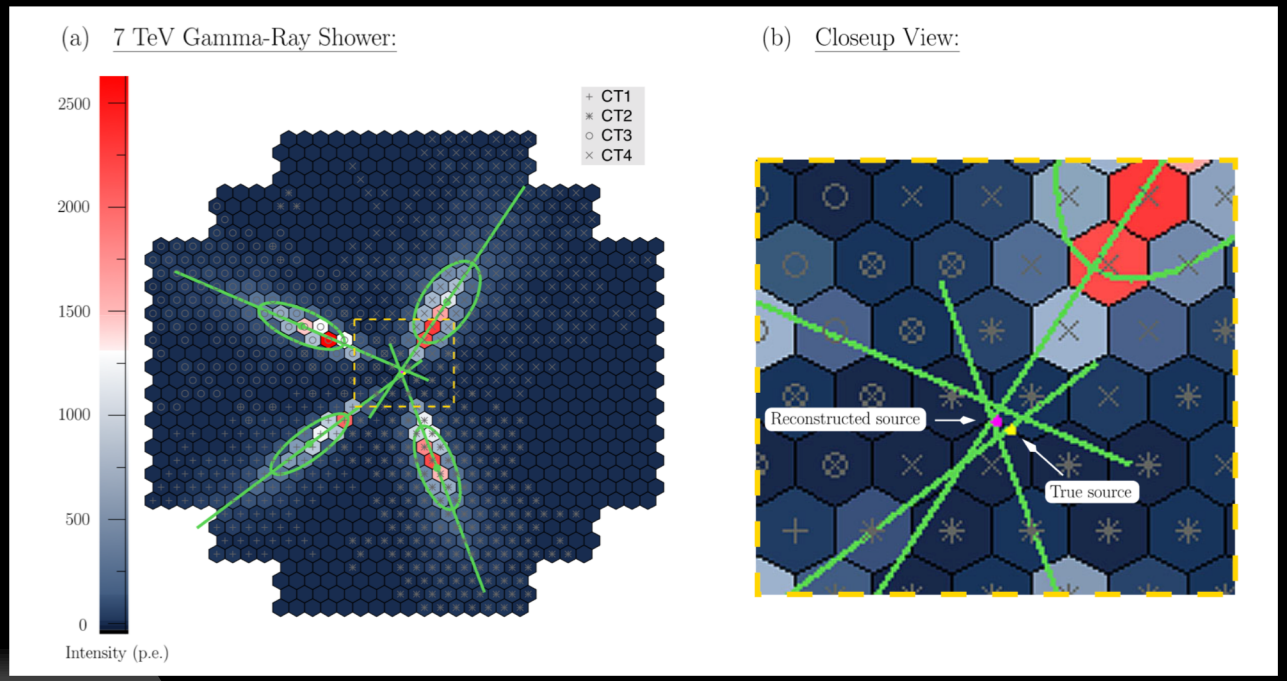


Geometry Reconstruction



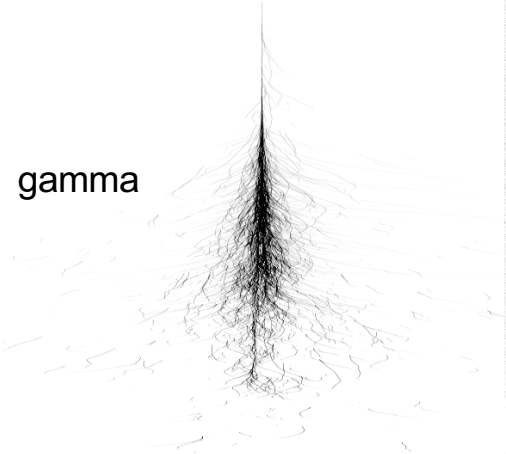
Geometry Reconstruction

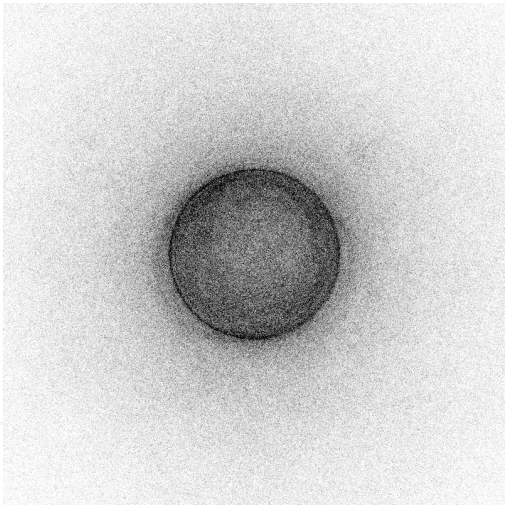


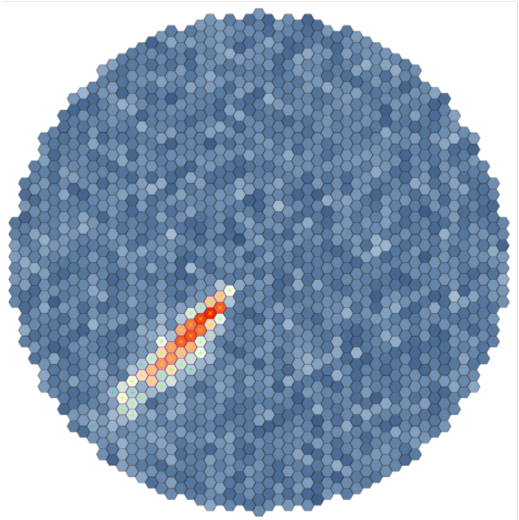


The Background Challenge

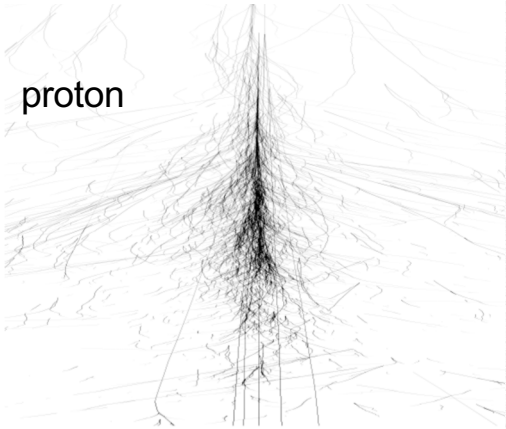
gamma

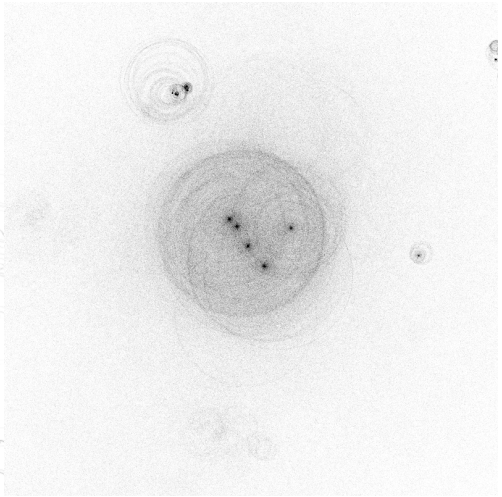


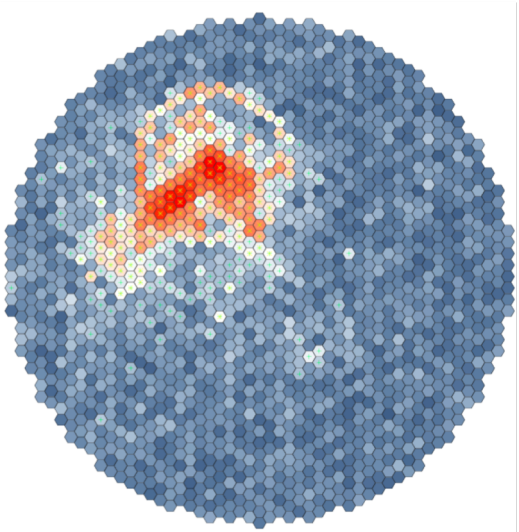




proton



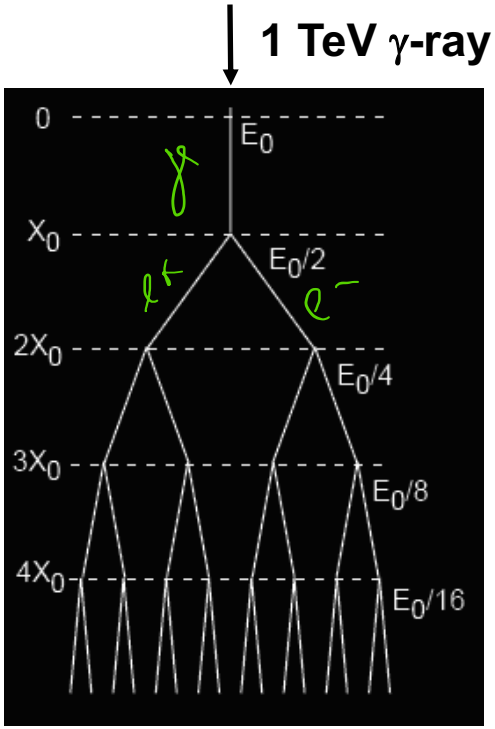


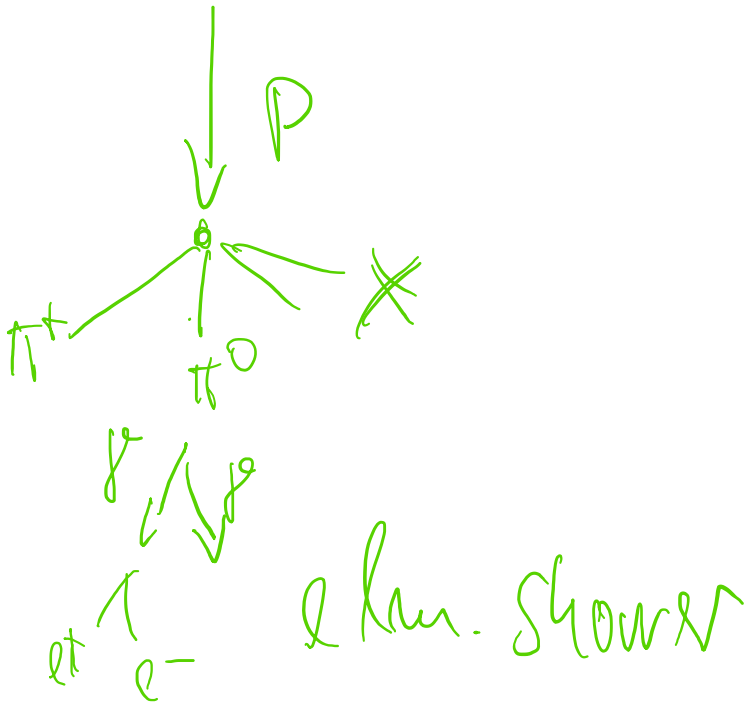


most protons do broad showers

The Background Challenge

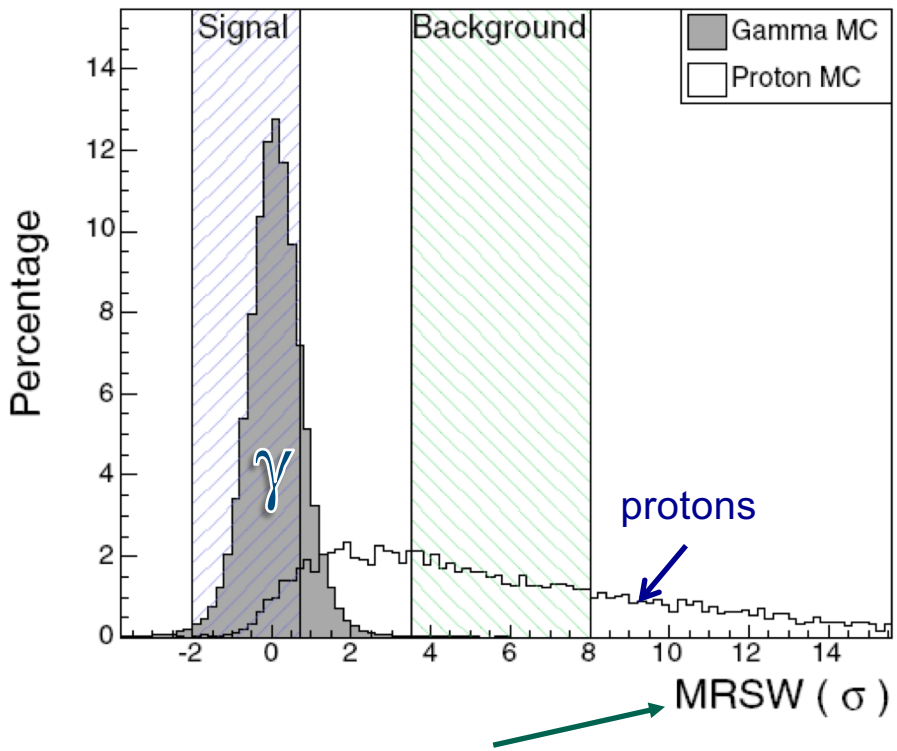
Irreducible backgrounds!





Background Suppression

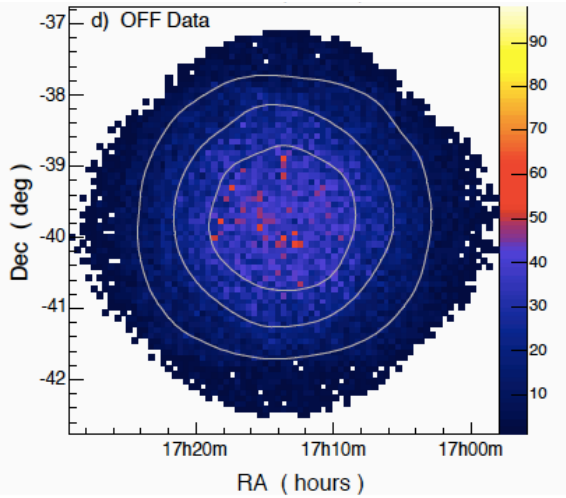
Berge, Hinton, Funk 2006

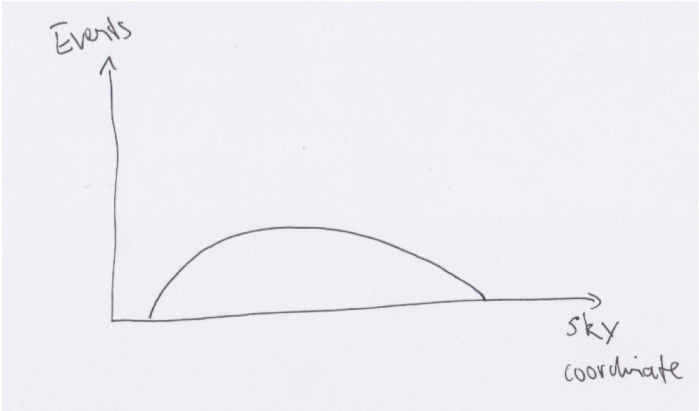


(Width - Expected Width) / (Expected Spread)

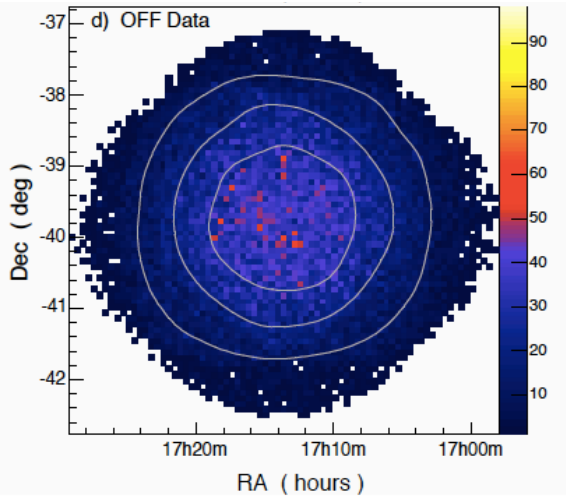
Functions of image size and impact distance

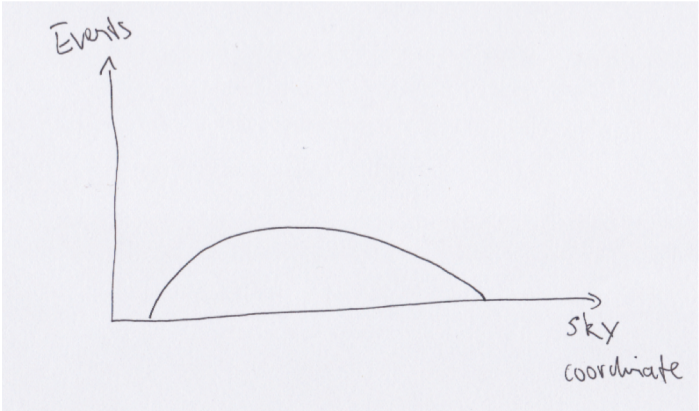
Background modeling



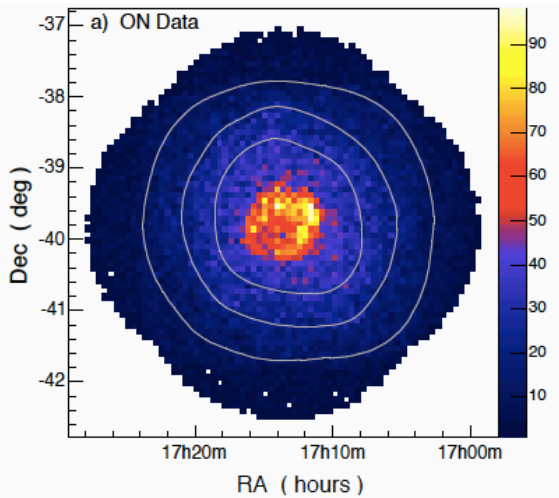


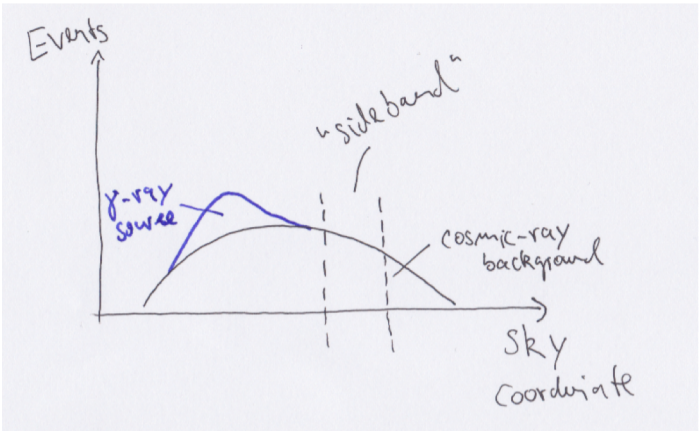
Background modeling



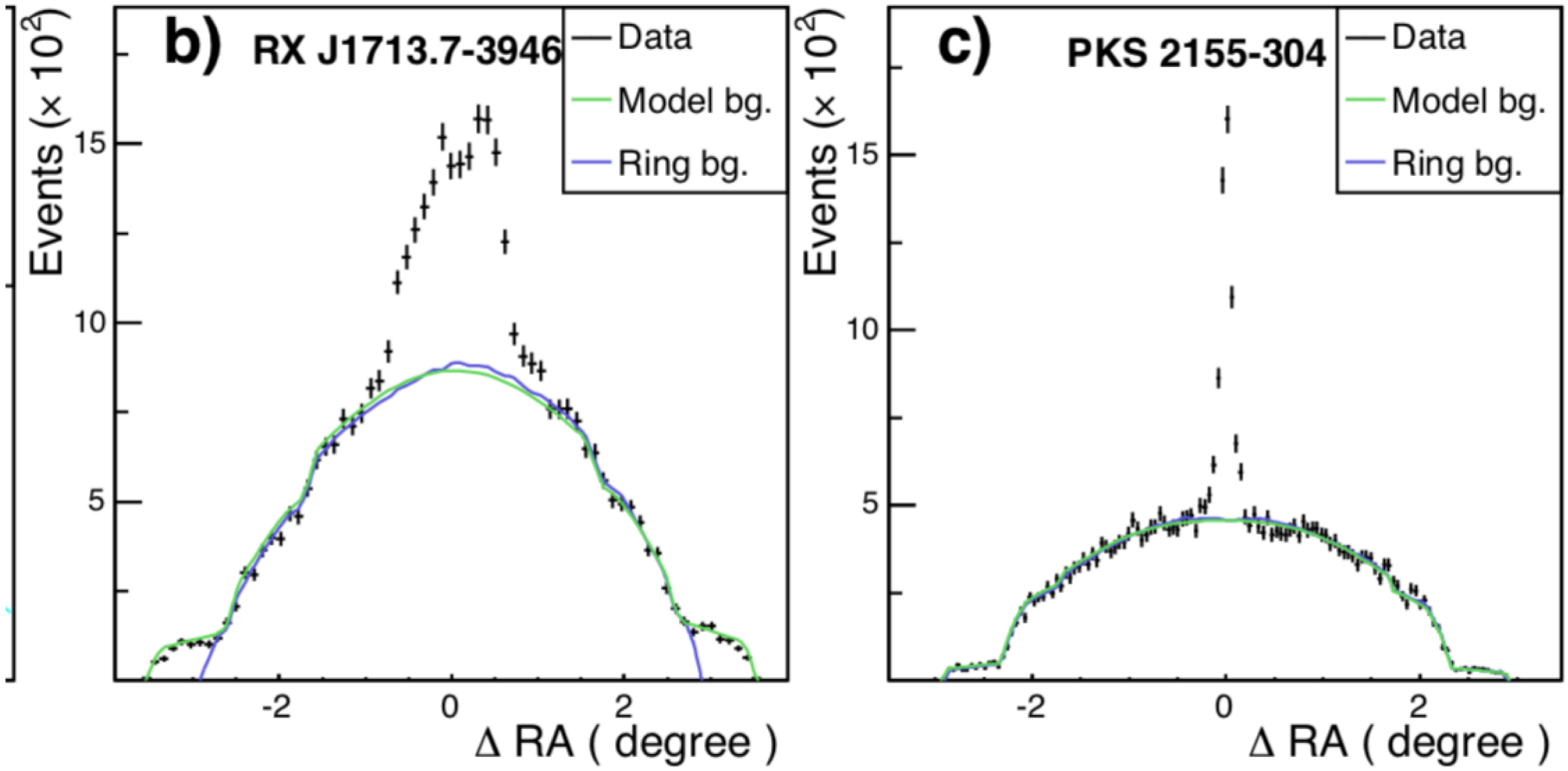


No MC, but measure from data!

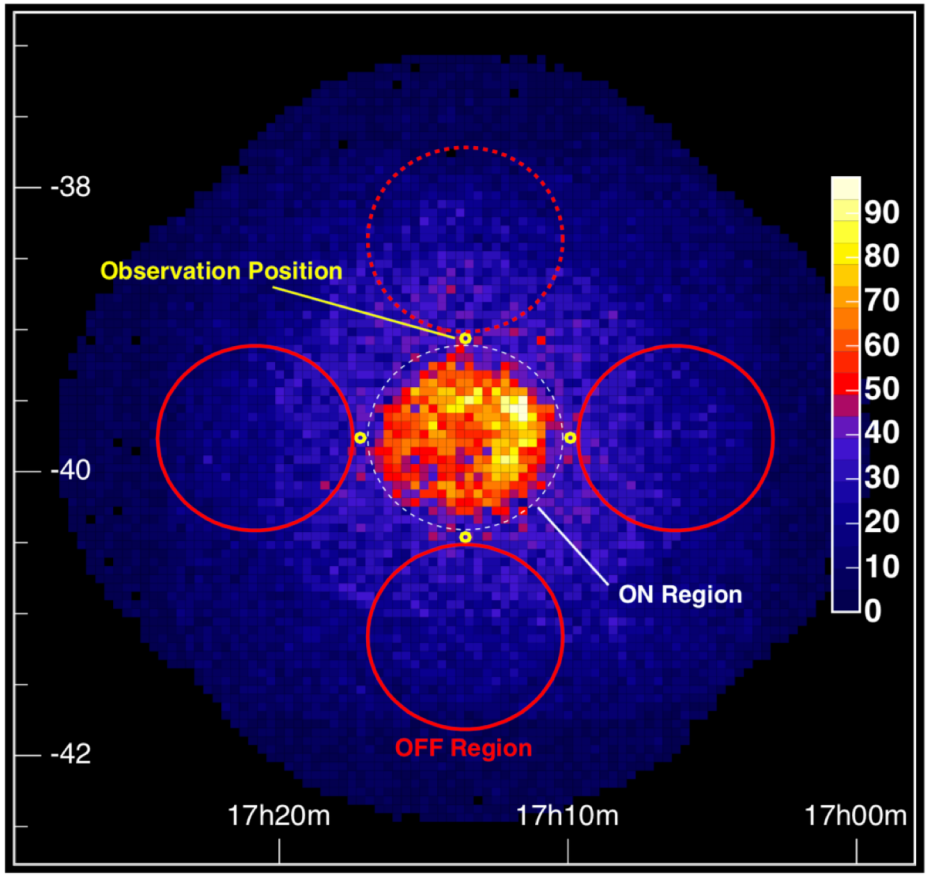


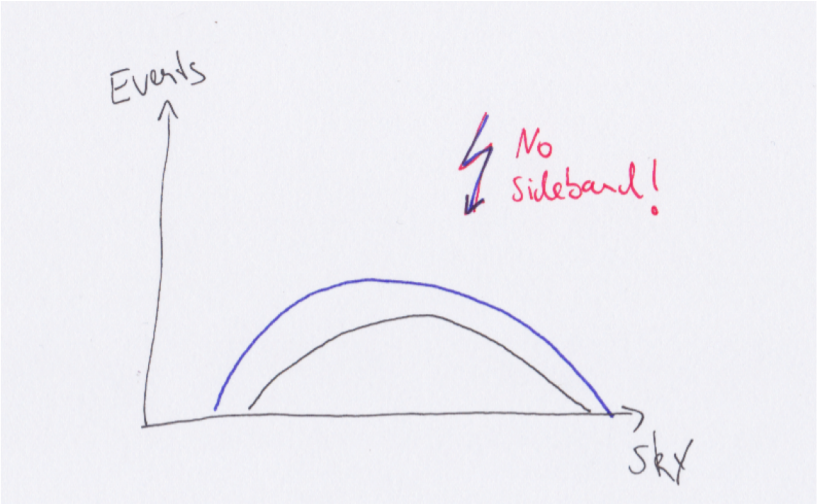


Background modeling in action

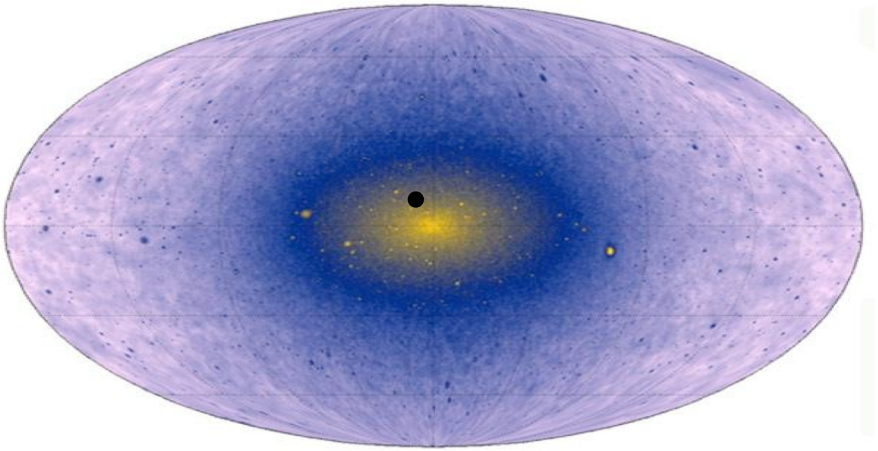


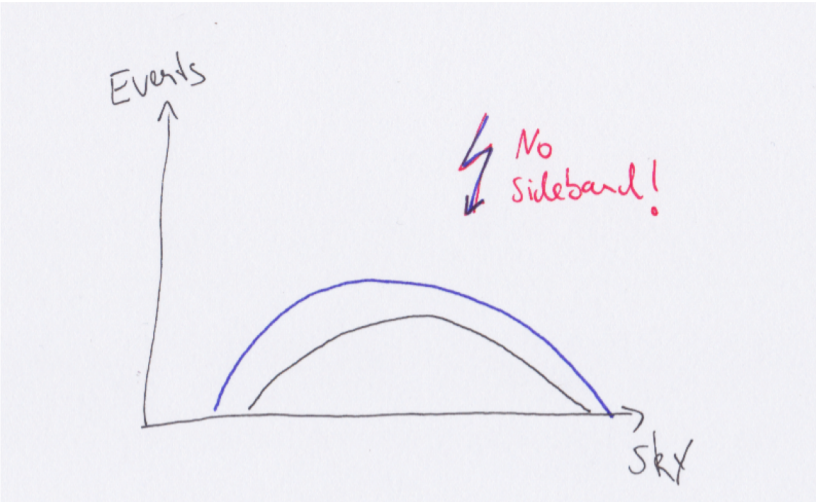
Background modeling techniques



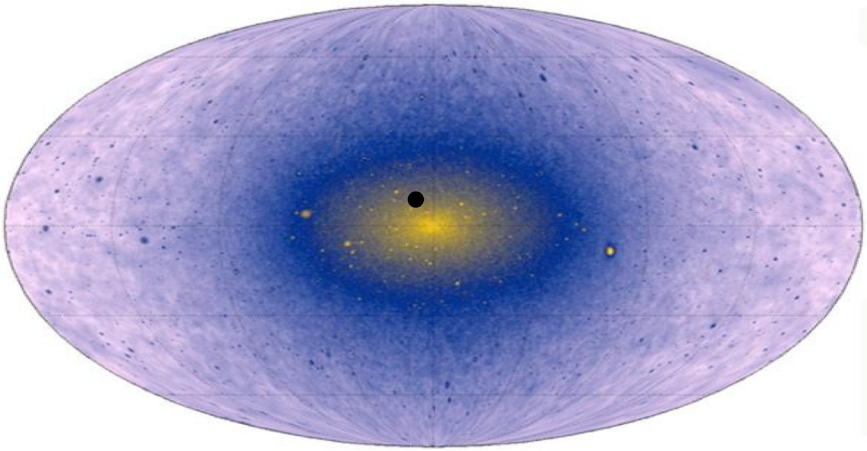


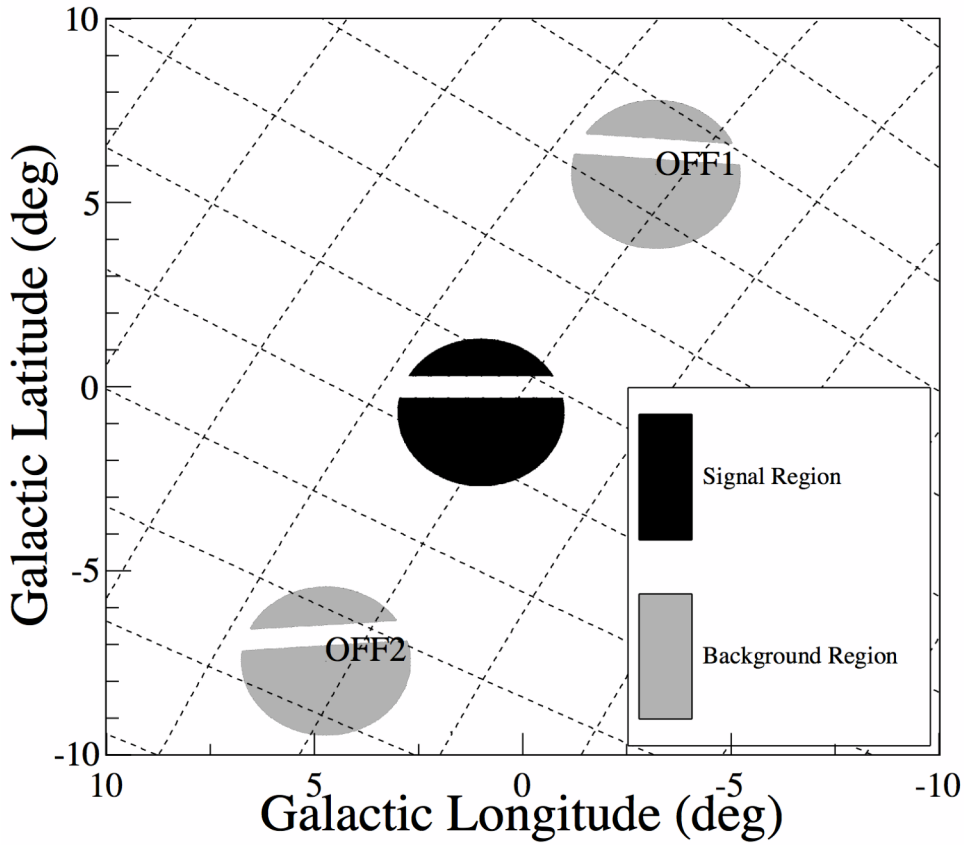
Major limitation: can only ever use fraction of FoV





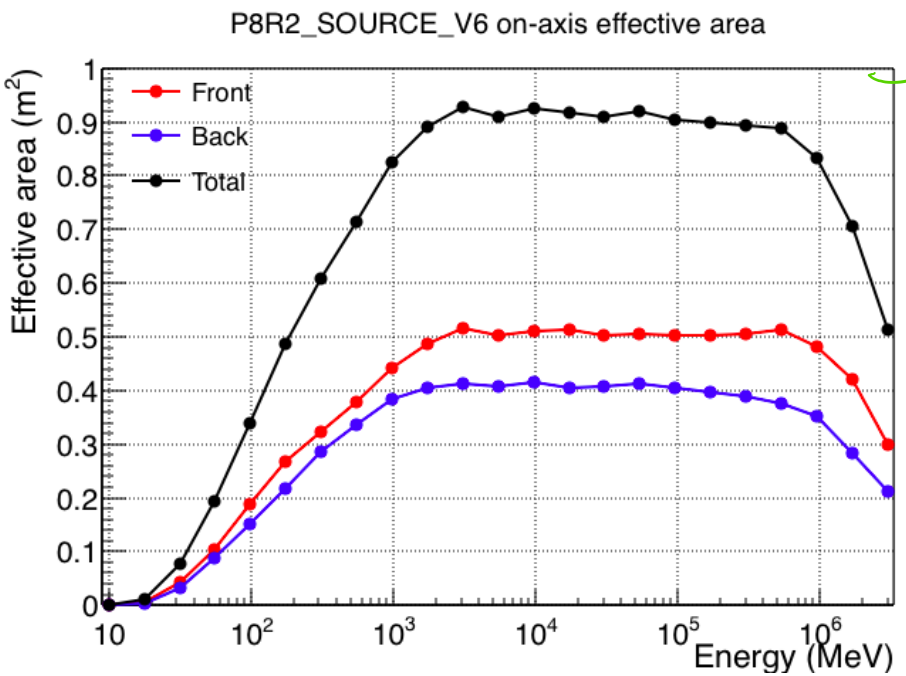
Major limitation: can only ever use fraction of FoV



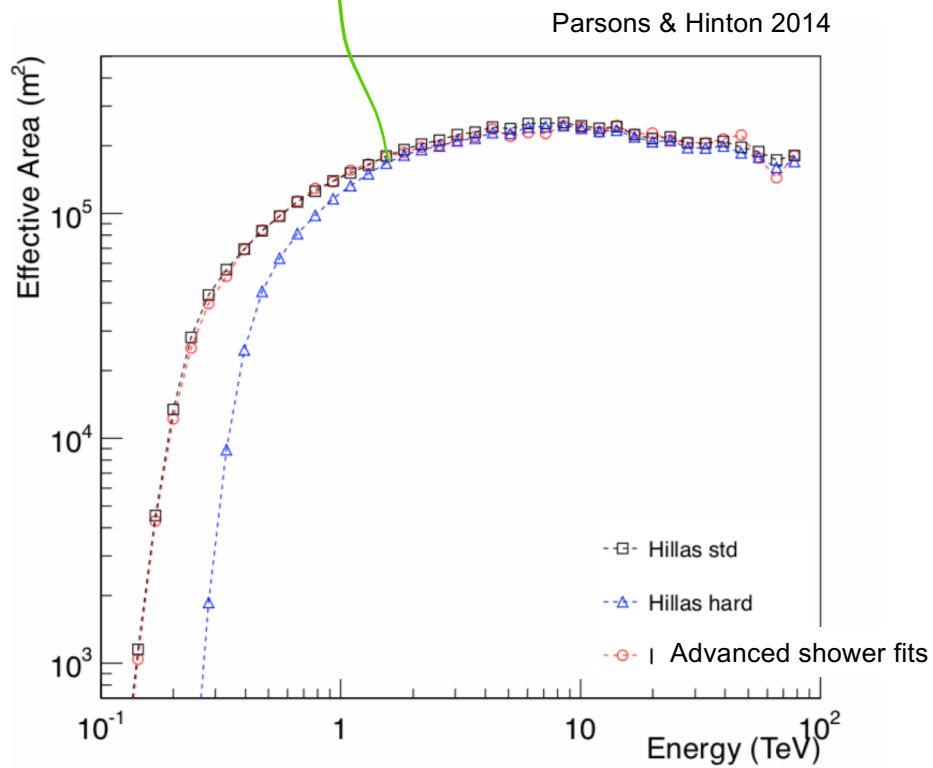


H.E.S.S. 2015 (PRL)

Effective Detection Areas

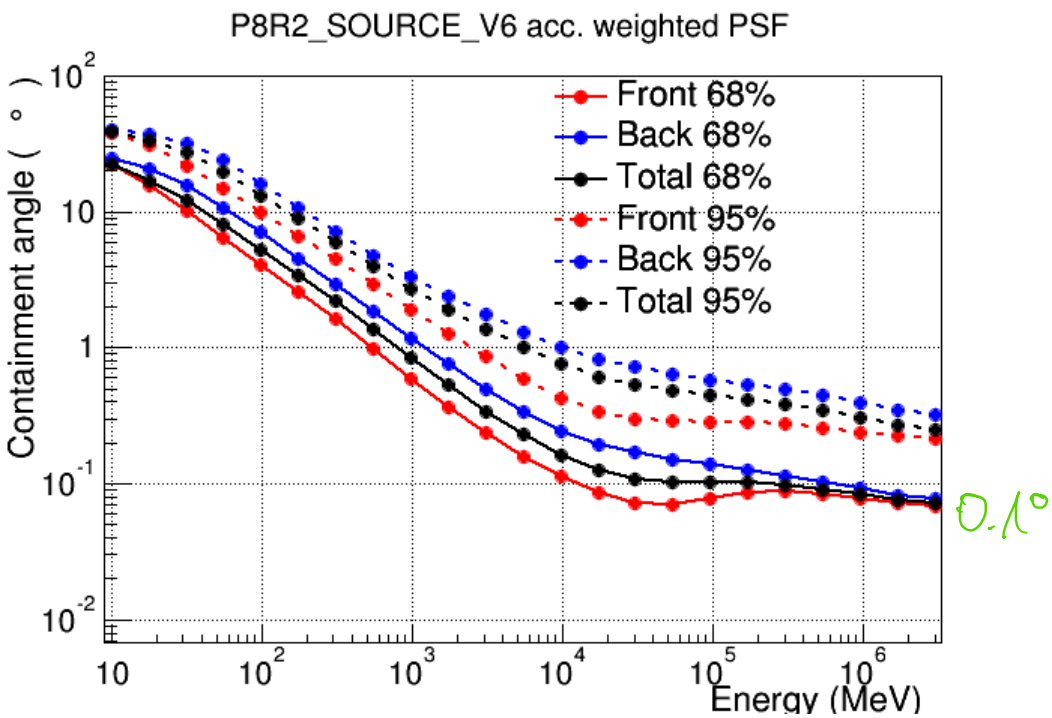


Fermi LAT



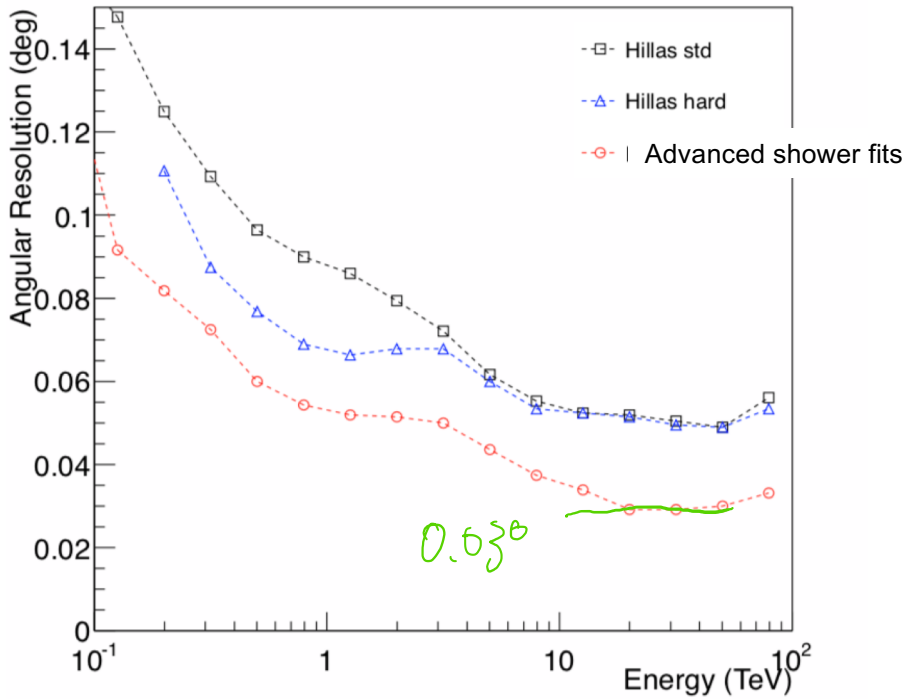
Cherenkov Telescopes

Angular Resolutions



Fermi LAT

Parsons & Hinton 2014

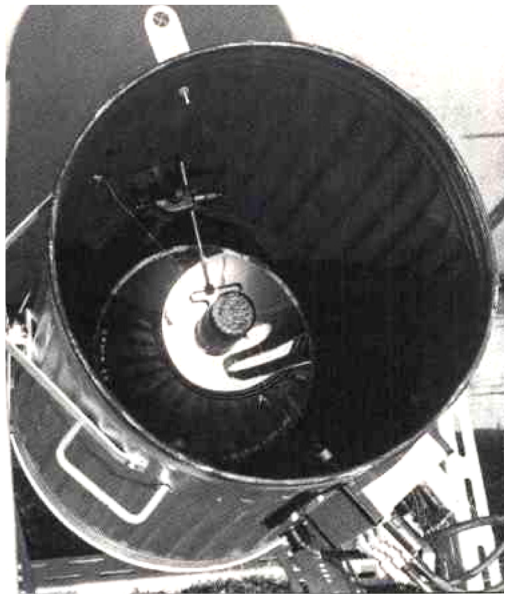


Cherenkov Telescopes

Imaging Atmospheric Cherenkov Telescopes (IACTs)

Super-brief History

Galbraith & Jelley, 1953



Discovery of Cherenkov Light from air-showers with a garbage can!

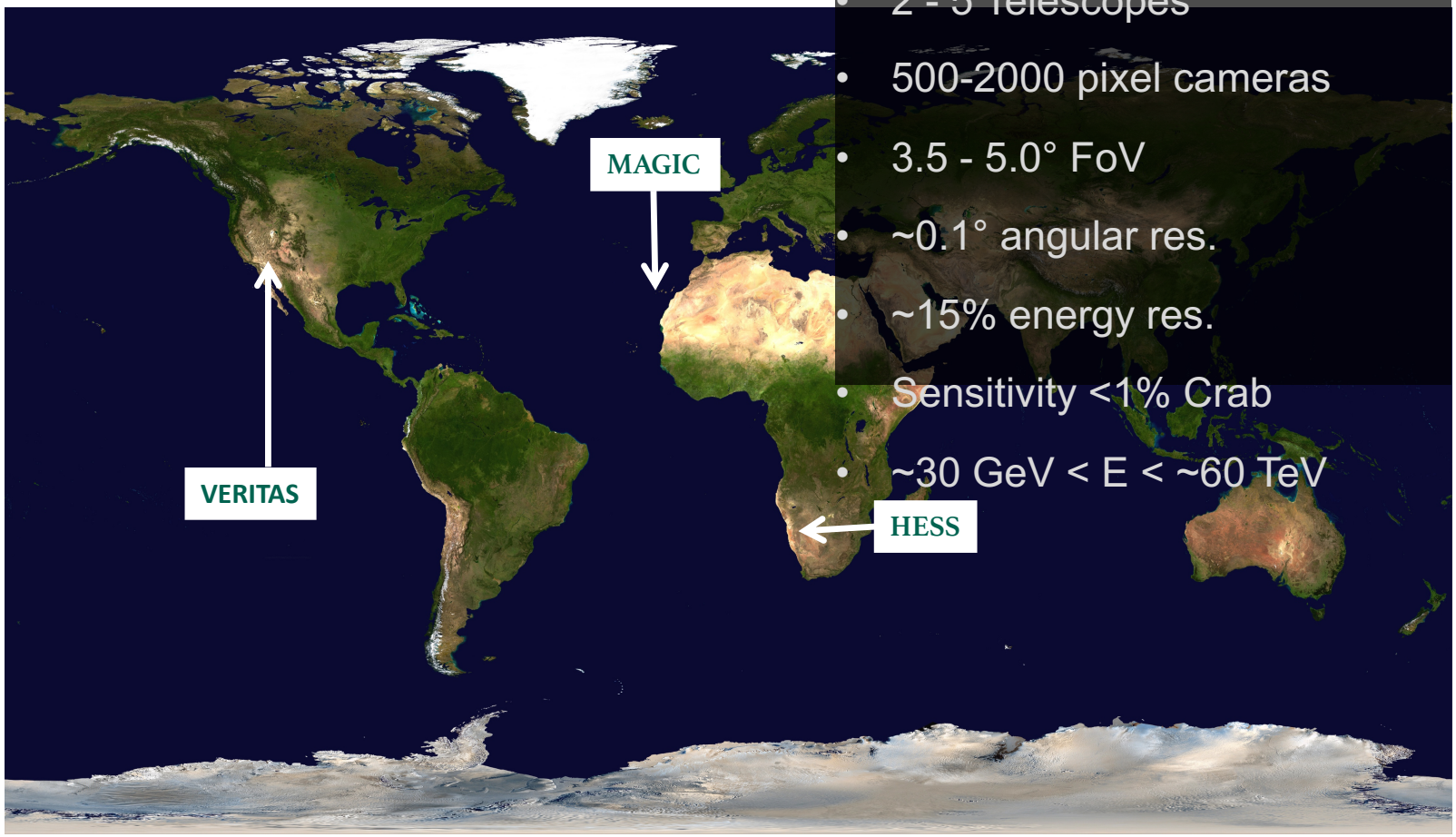
Weekes et al. 1989

1st TeV gamma-ray source (The Crab Nebula)

- 1990s

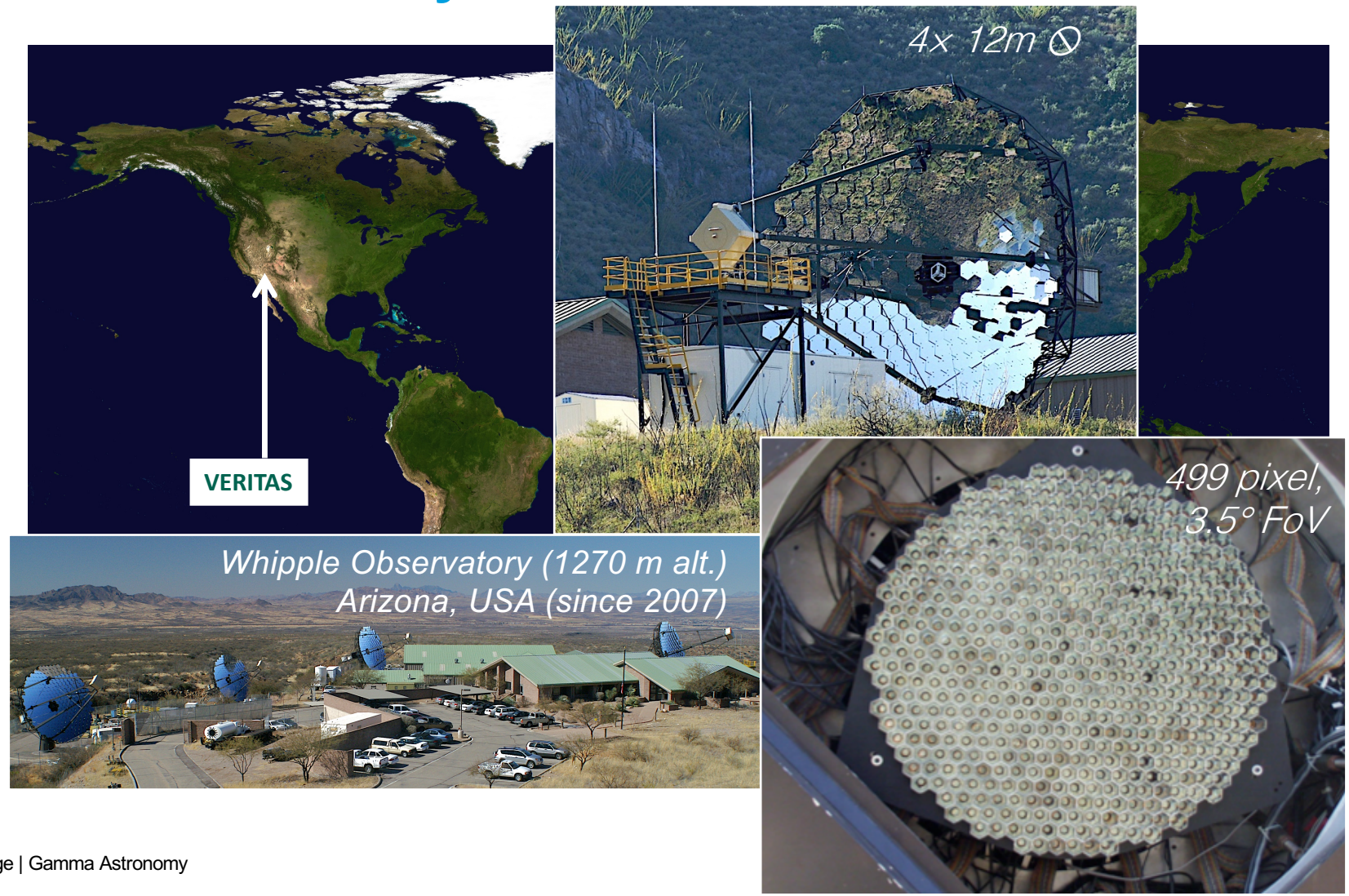
1st Telescope Arrays
Camera improvements
(Whipple, CAT, HEGRA, …)

The Current IACT Arrays

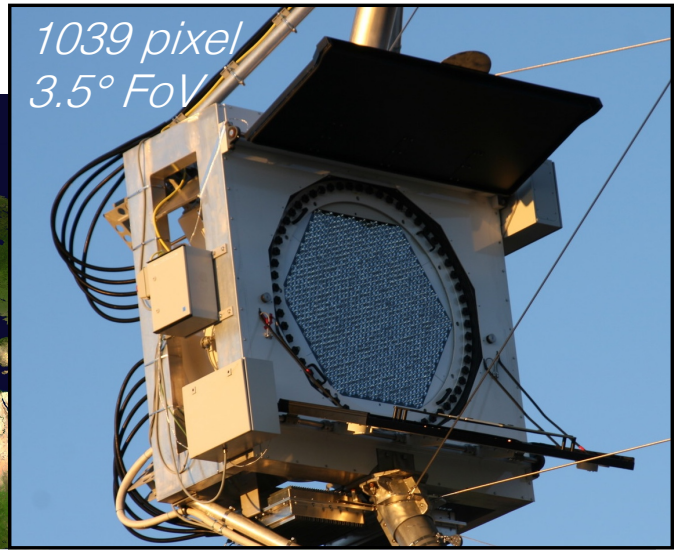


- 2 - 5 Telescopes
- 500-2000 pixel cameras
- 3.5 - 5.0° FoV
- ~0.1° angular res.
- ~15% energy res.
- Sensitivity <1% Crab
- ~30 GeV < E < ~60 TeV

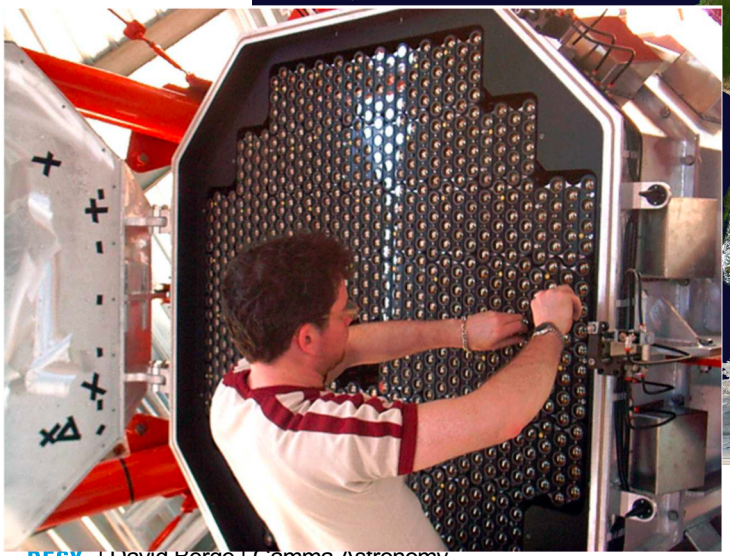
The Current IACT Arrays

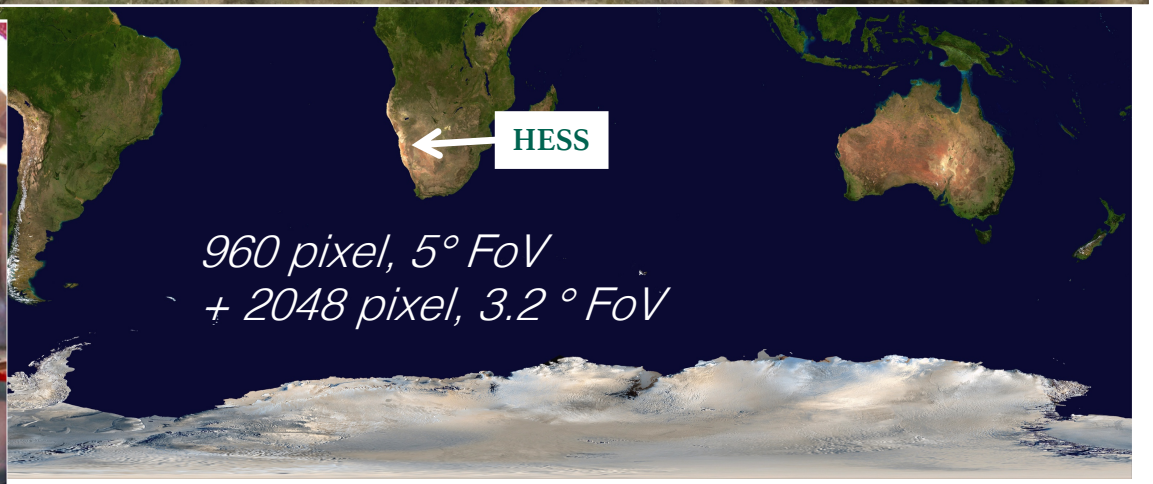


The Current IACT Arrays



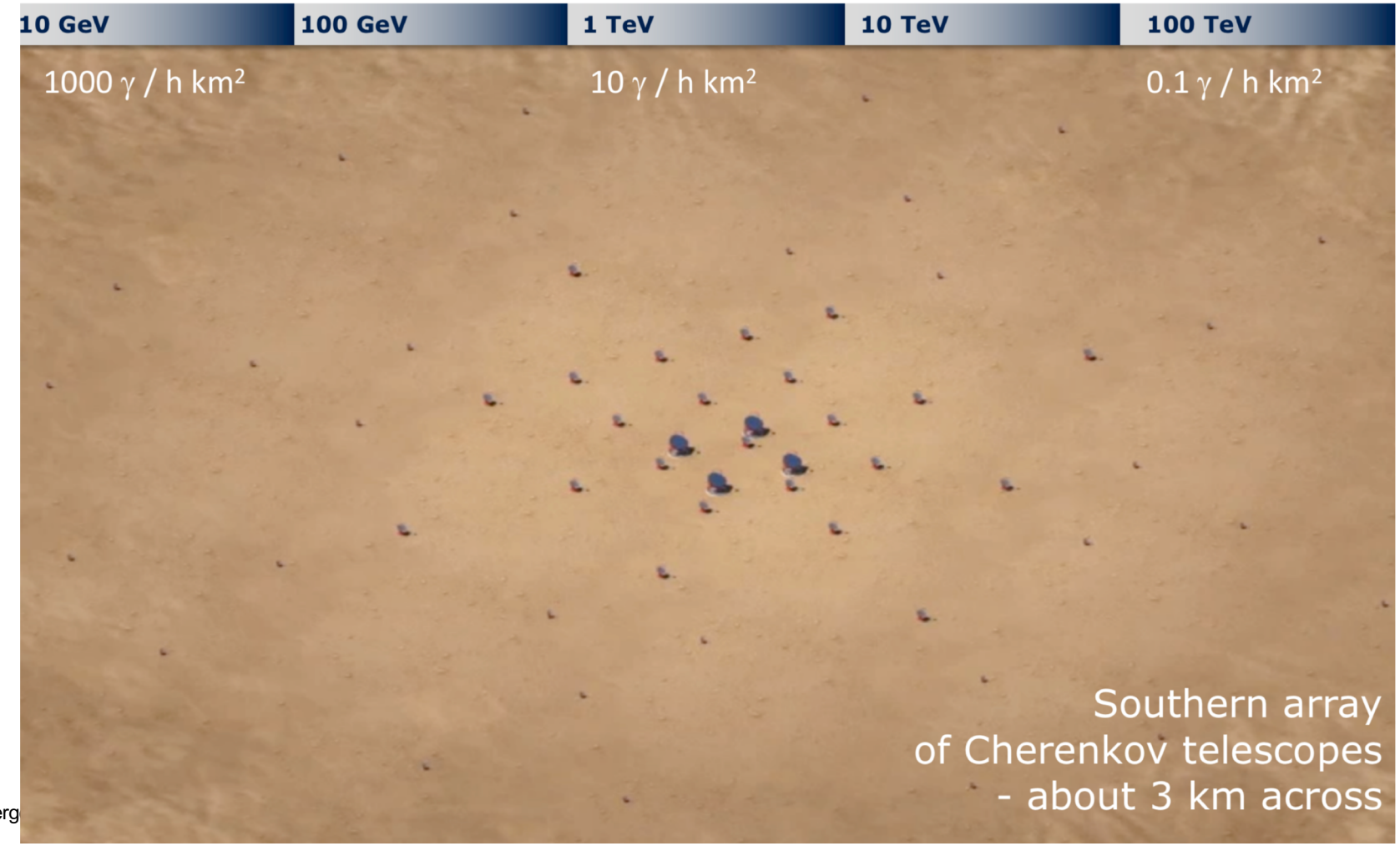
The Current IACT Arrays



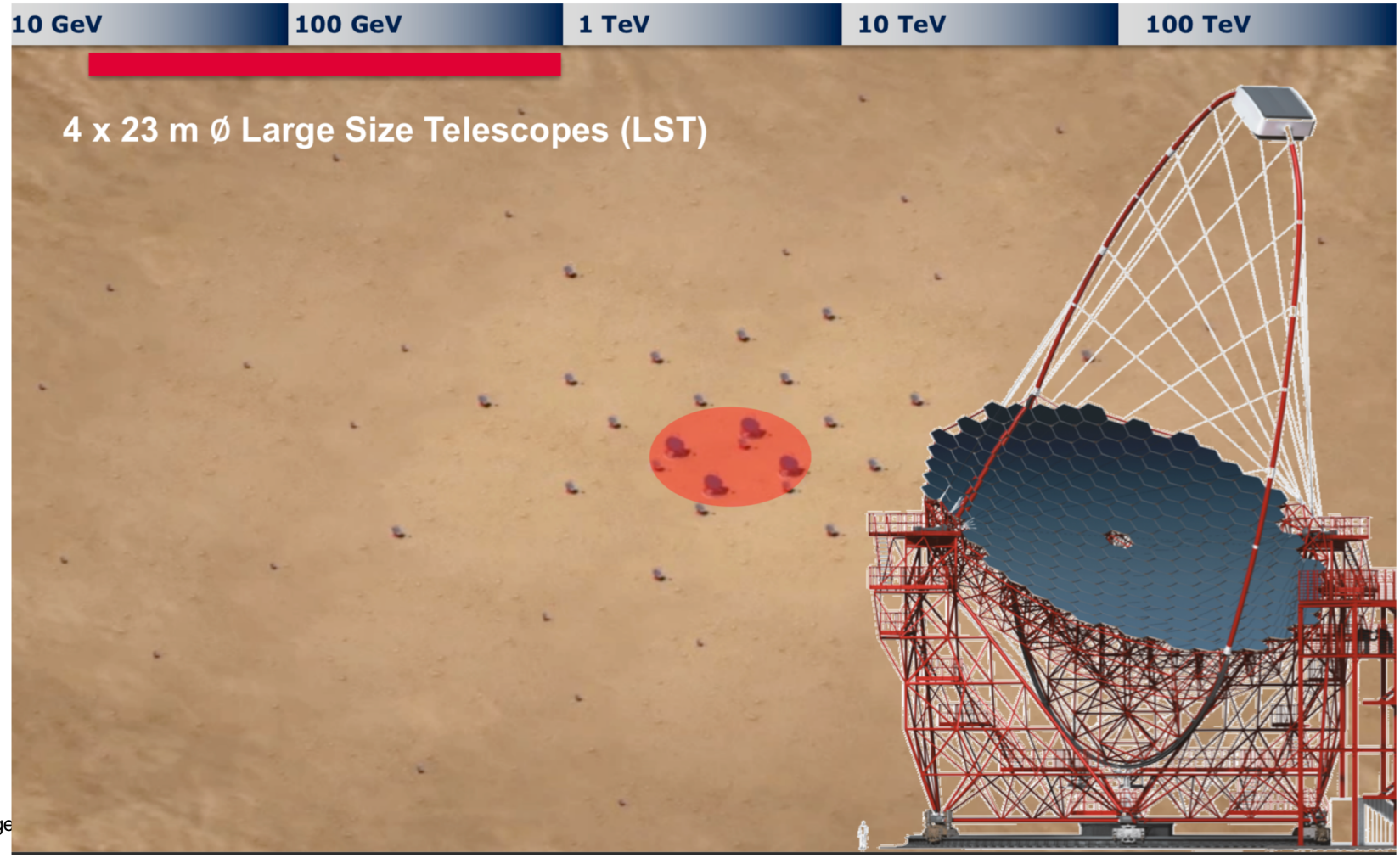


The Current IACT Arrays

CHERENKOV TELESCOPE ARRAY



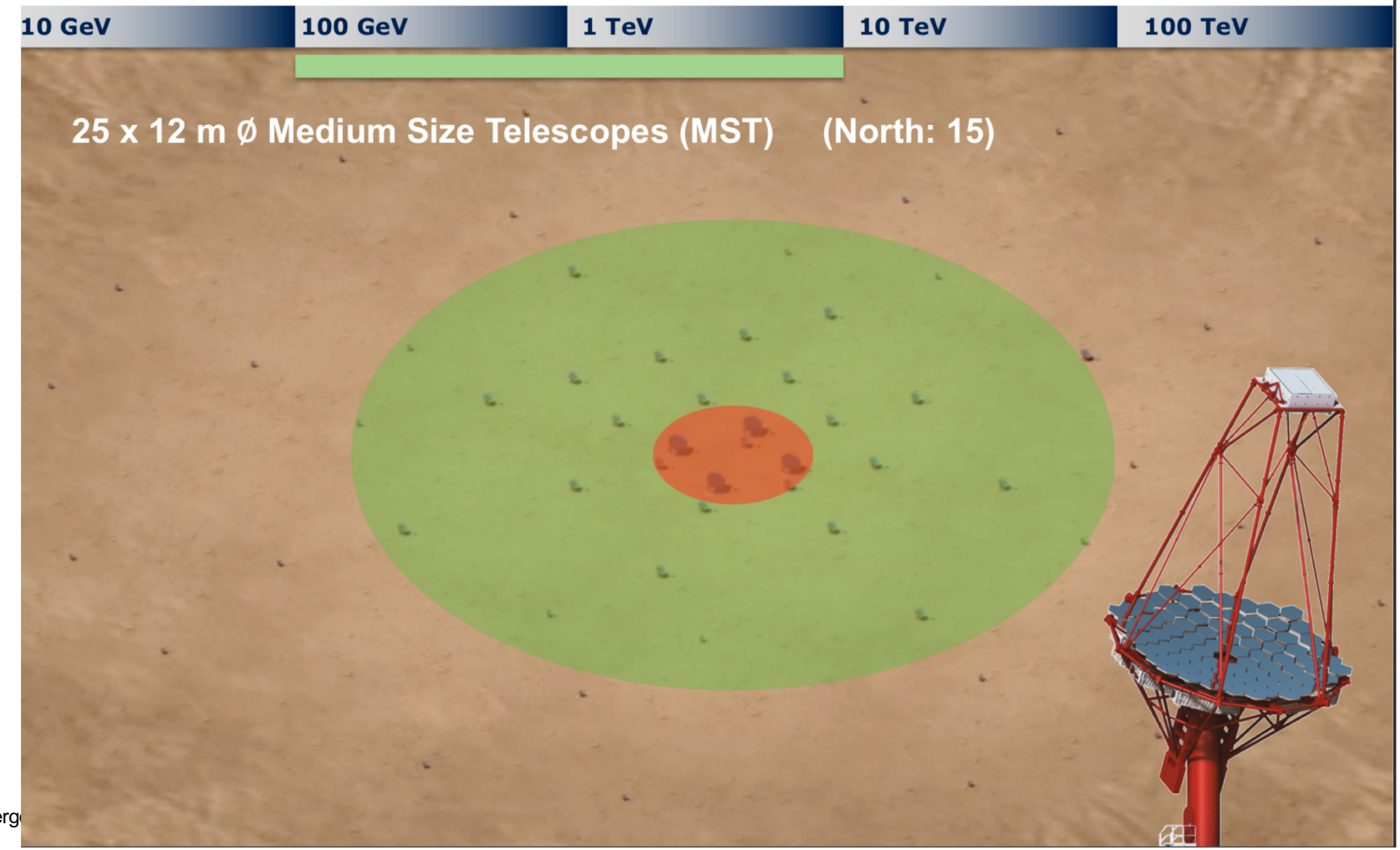
CHERENKOV TELESCOPE ARRAY



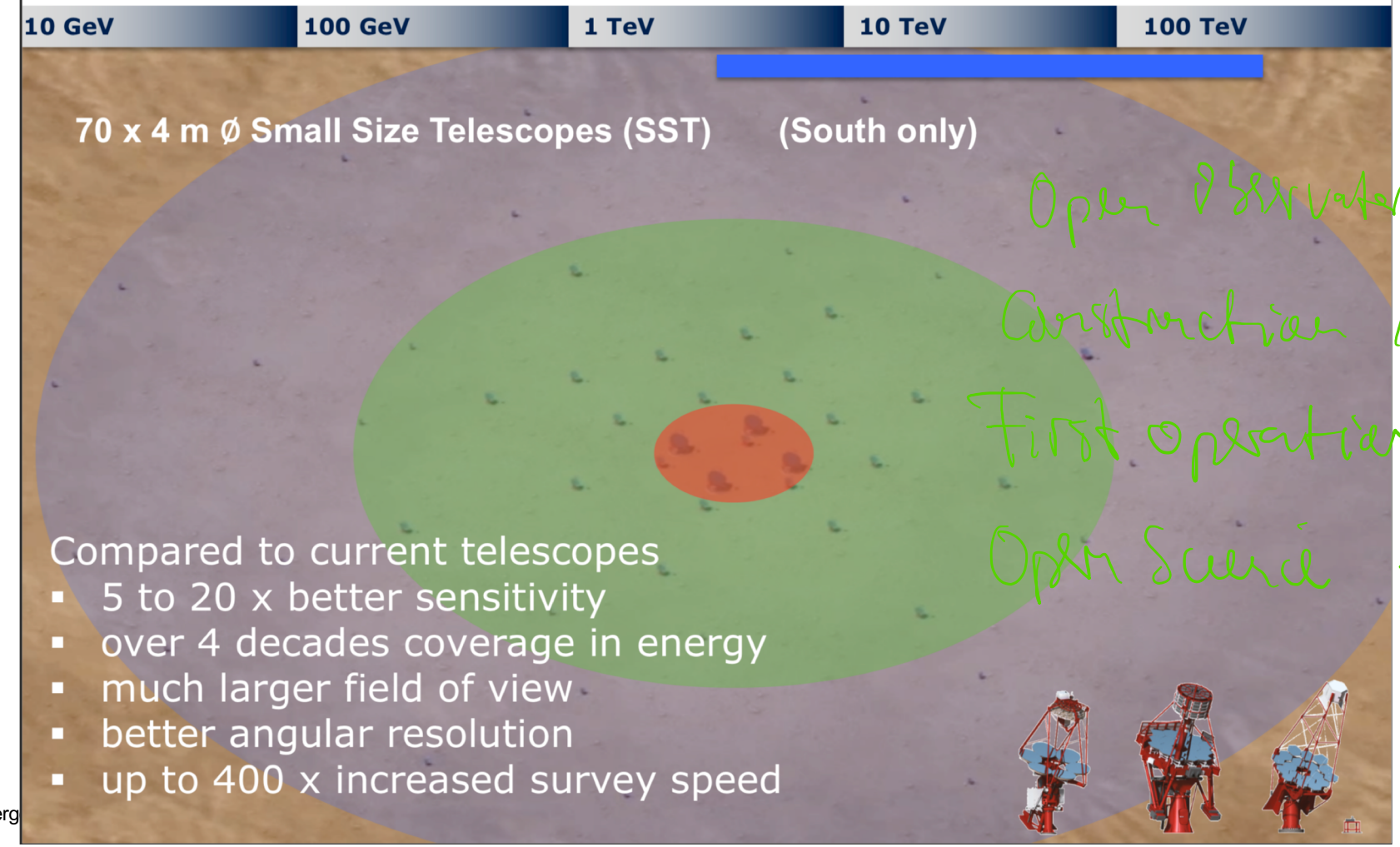
CHERENKOV TELESCOPE ARRAY

LST-1 inaugurated today!

CHERENKOV TELESCOPE ARRAY



CHERENKOV TELESCOPE ARRAY



Compared to current telescopes

- 5 to 20 x better sensitivity
- over 4 decades coverage in energy
- much larger field of view
- better angular resolution
- up to 400 x increased survey speed

Open Observatory!

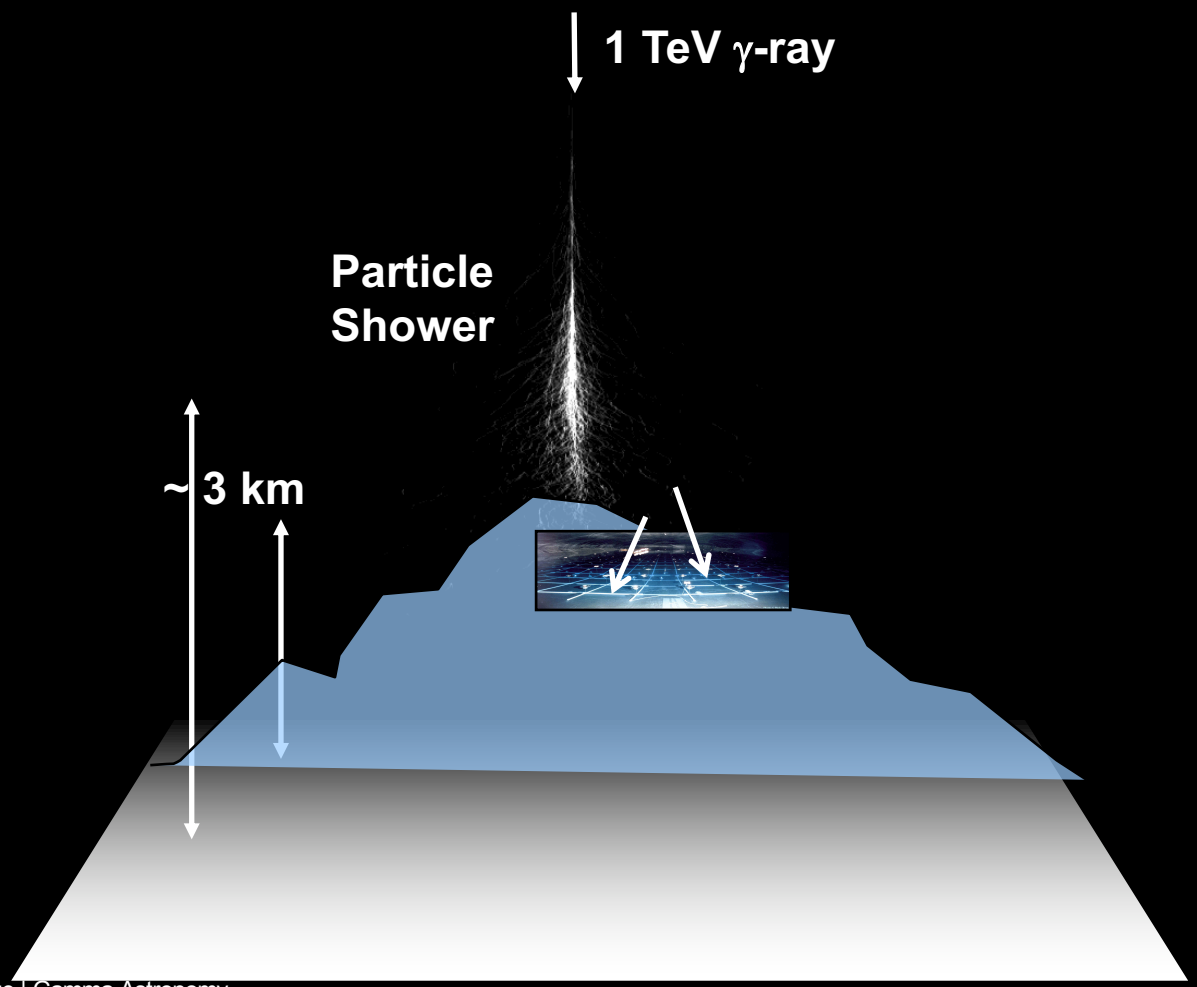
Construction ~2020

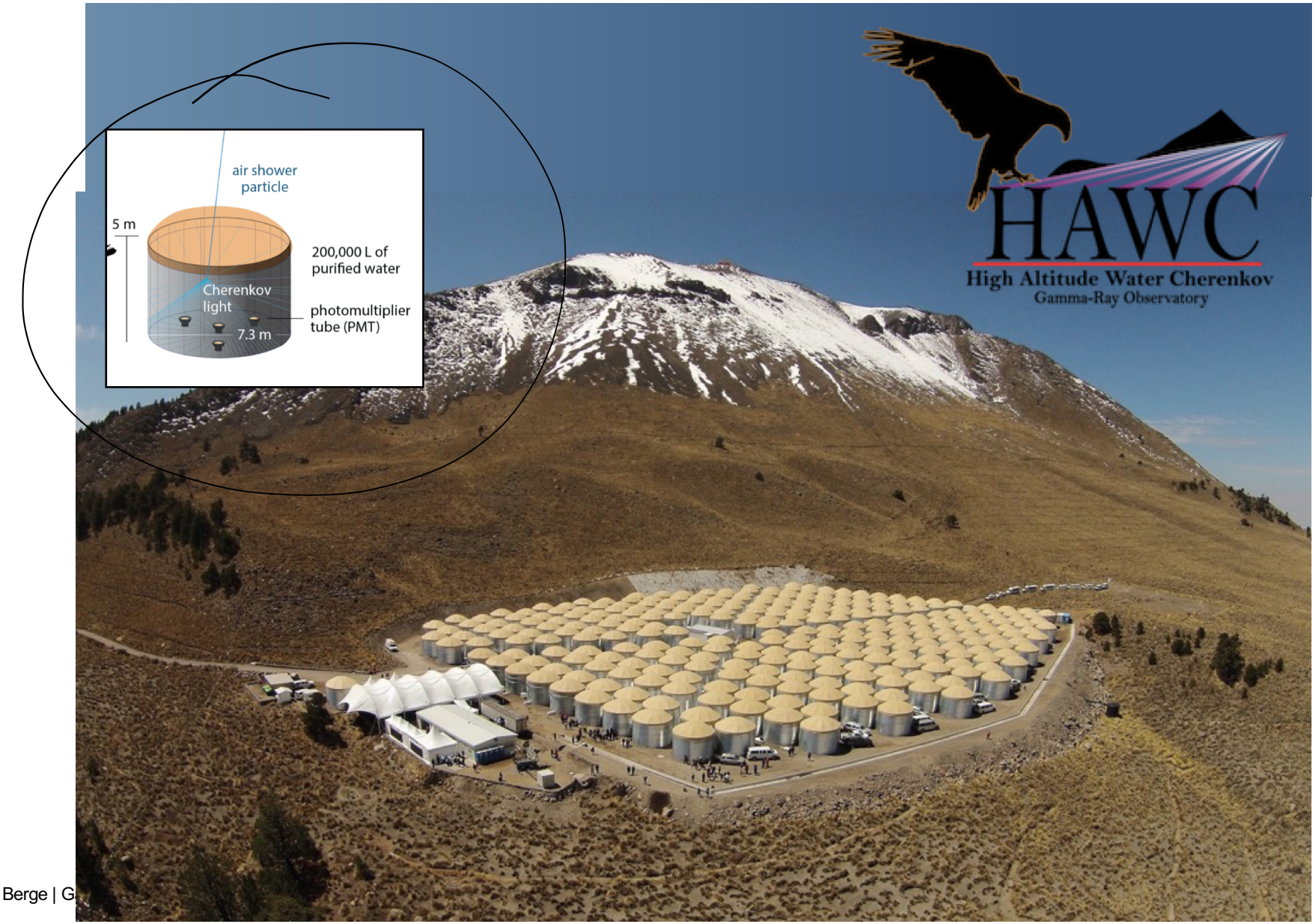
First operations ~2022

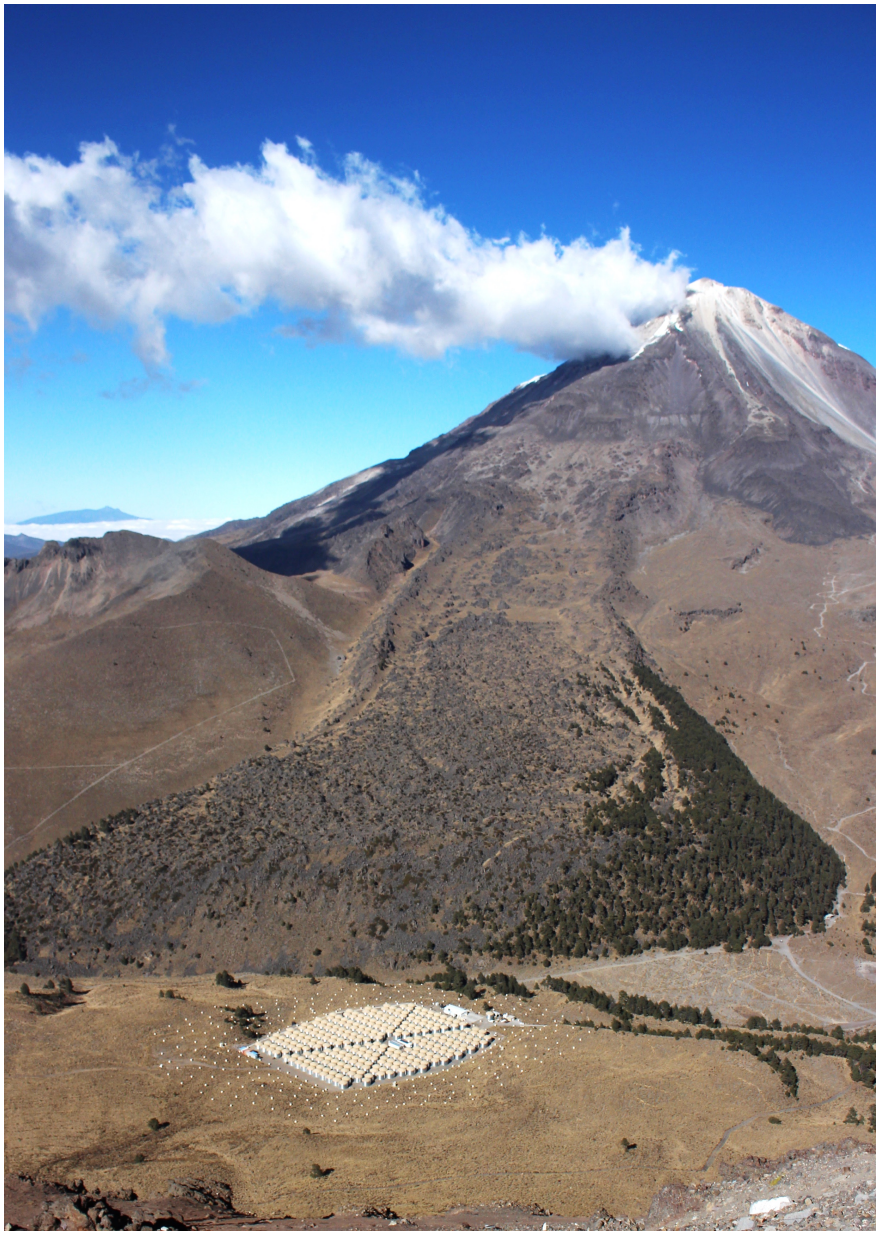
Open Source ~2025

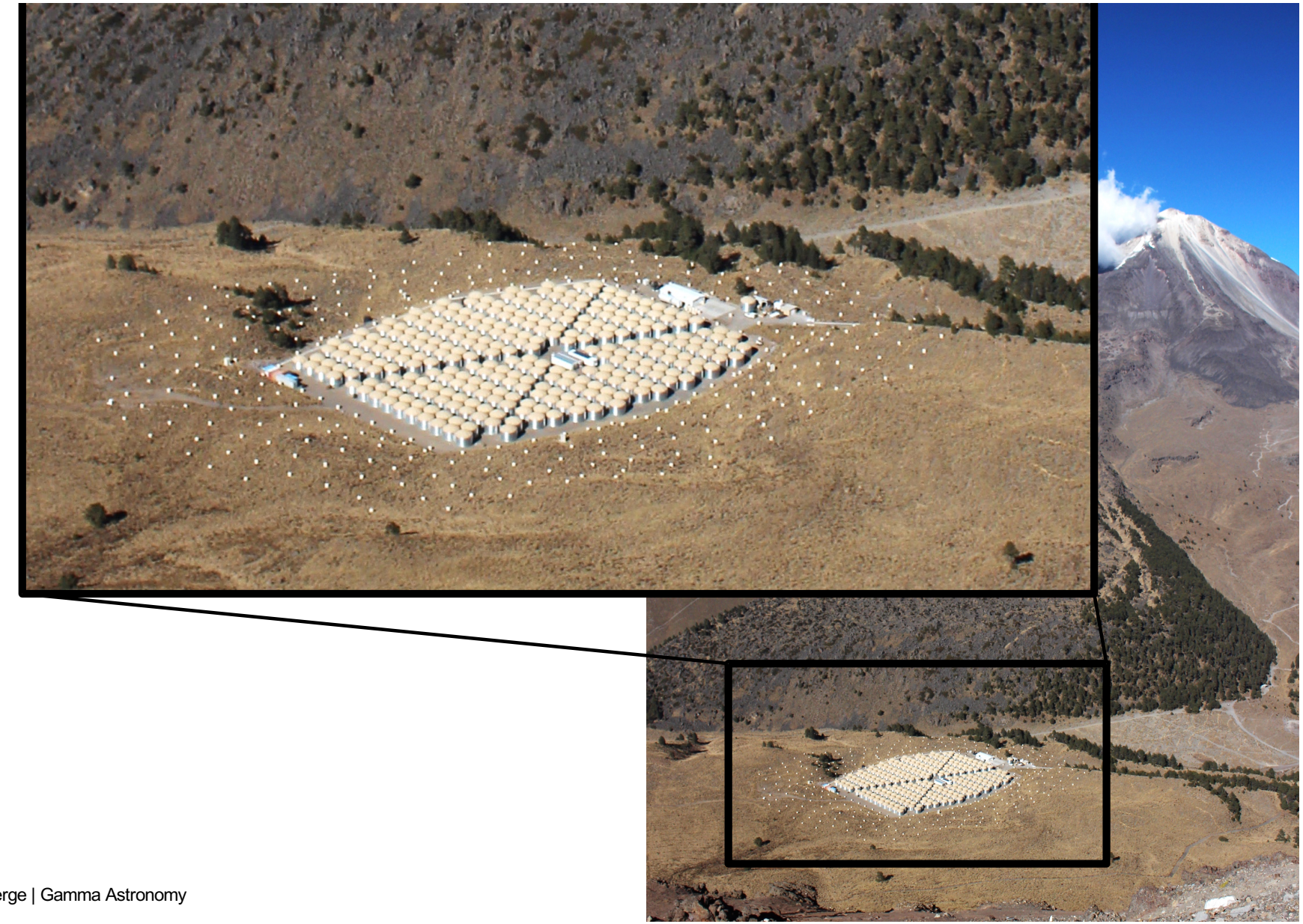
Shower Particle Detection

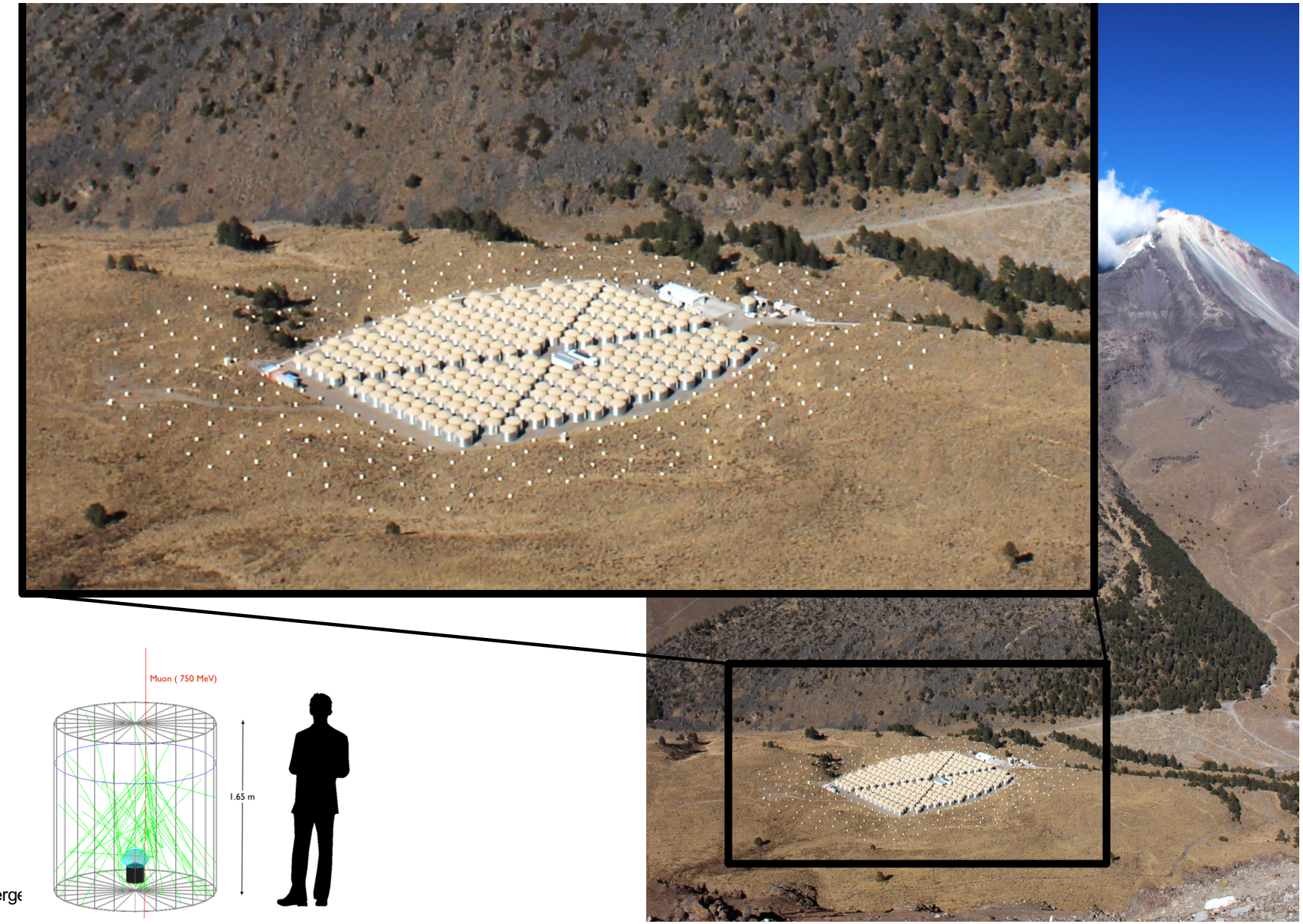
Air Showers



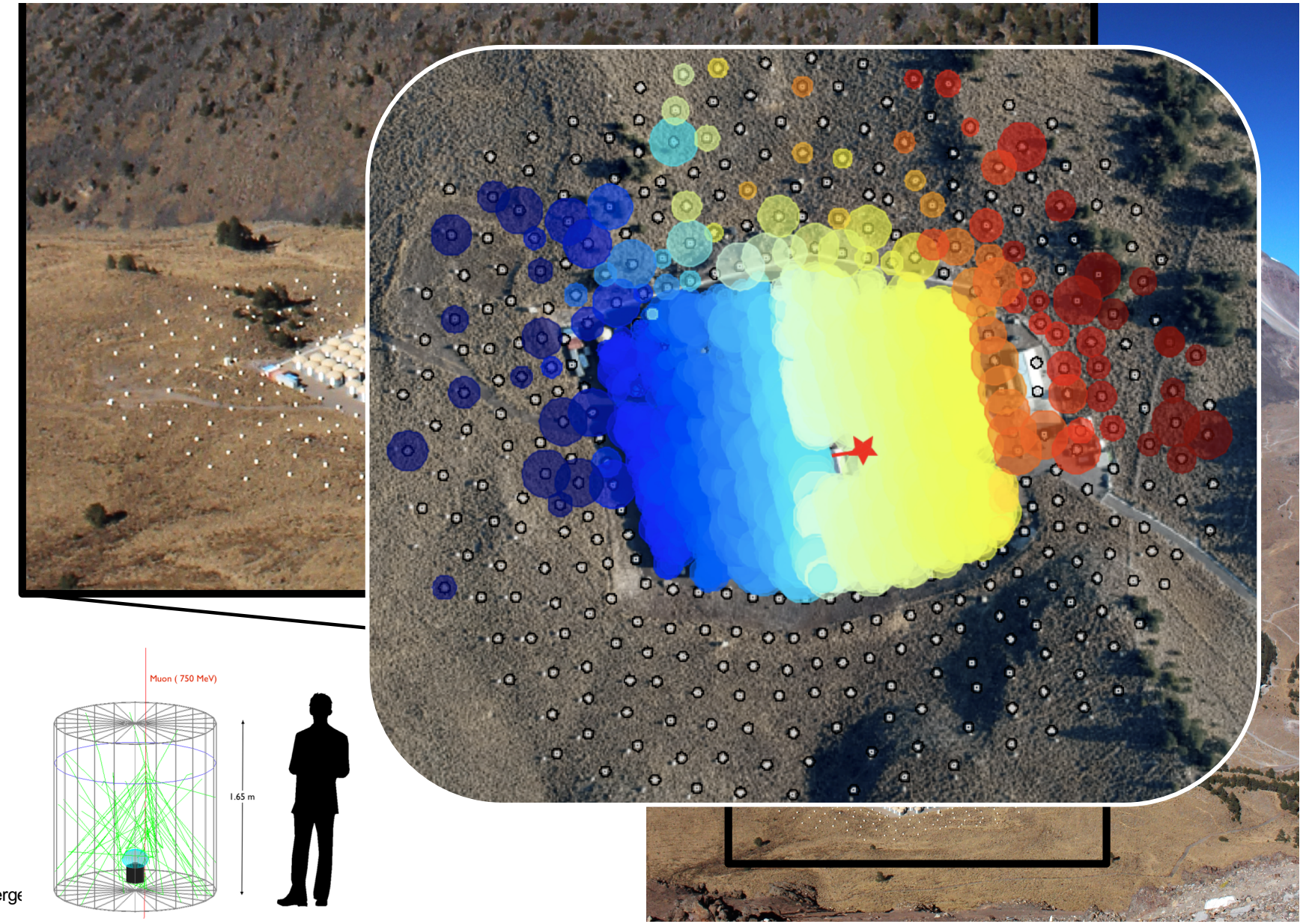

air shower
particle
5 m
200,000 L of
purified water
Cherenkov
light
photomultiplier
tube (PMT)
7.3 m
HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory





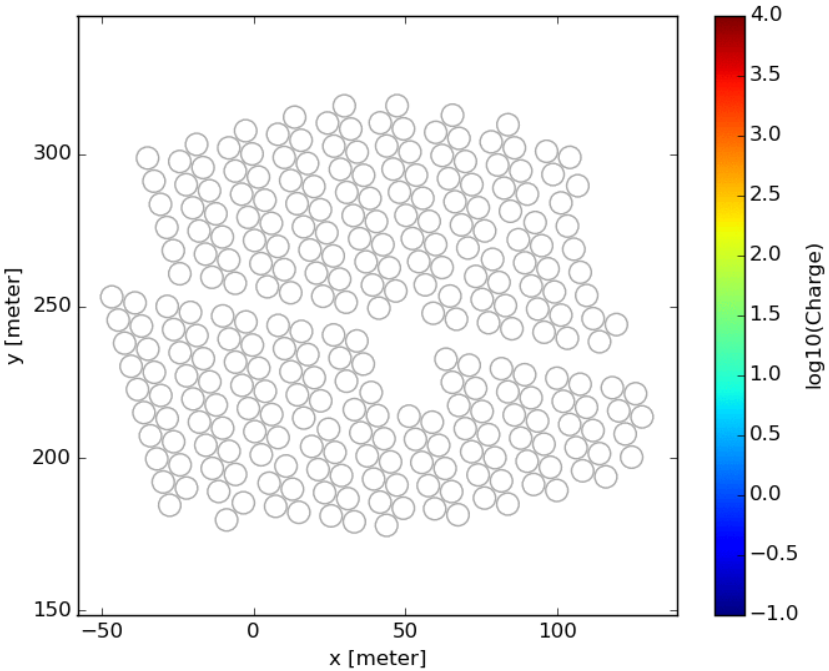


Muon (750 MeV)
1.65 m



Muon (750 MeV)
1.65 m

Events in HAWC



Direction from arrival times

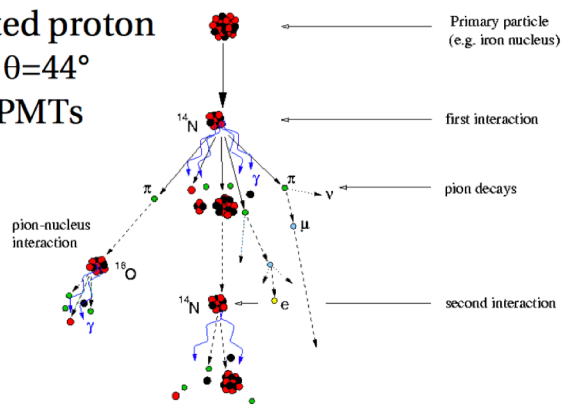
Energy from ground-level size

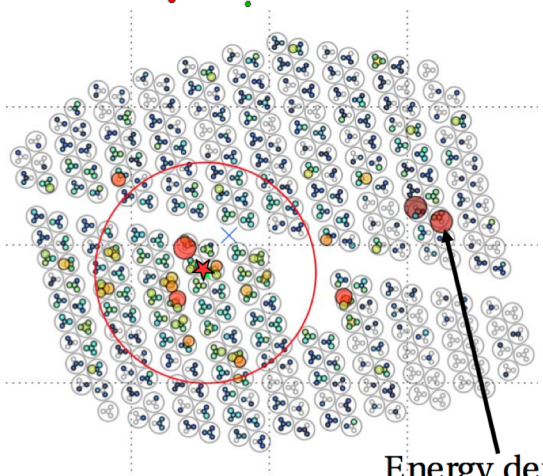
angular resolution

1ns * c/100m ~ 0.2°

Gamma / Hadron Separation

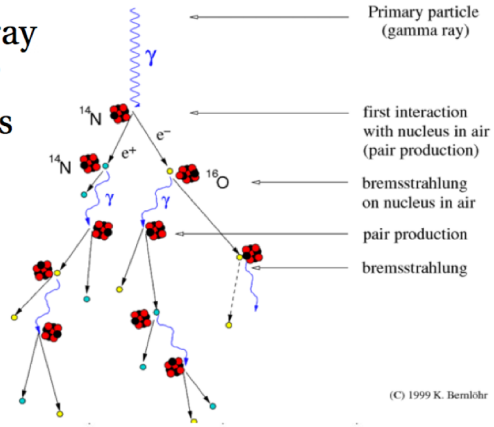
Simulated proton
24 TeV, θ=44°
837 hit PMTs

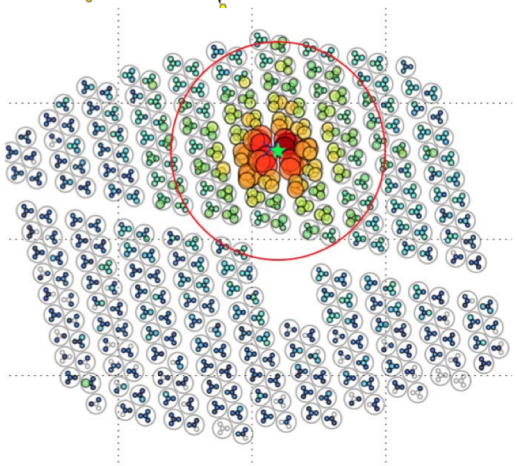




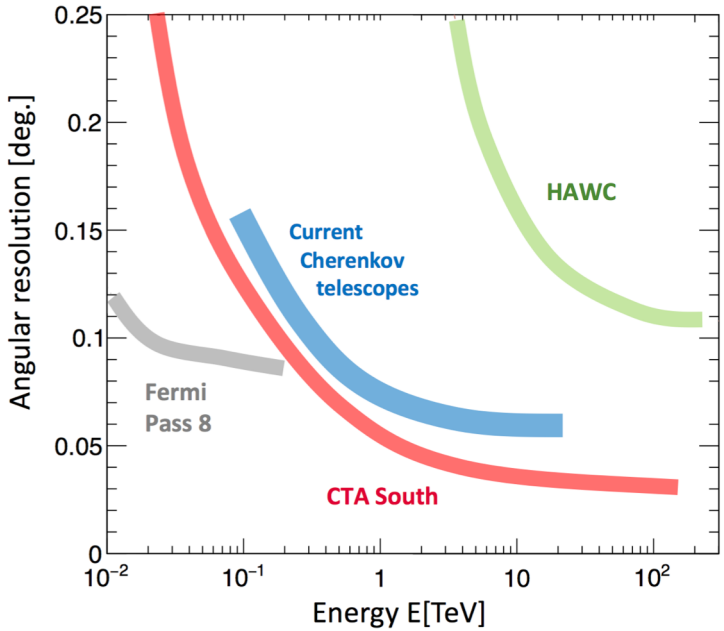
Energy deposited
away from the core

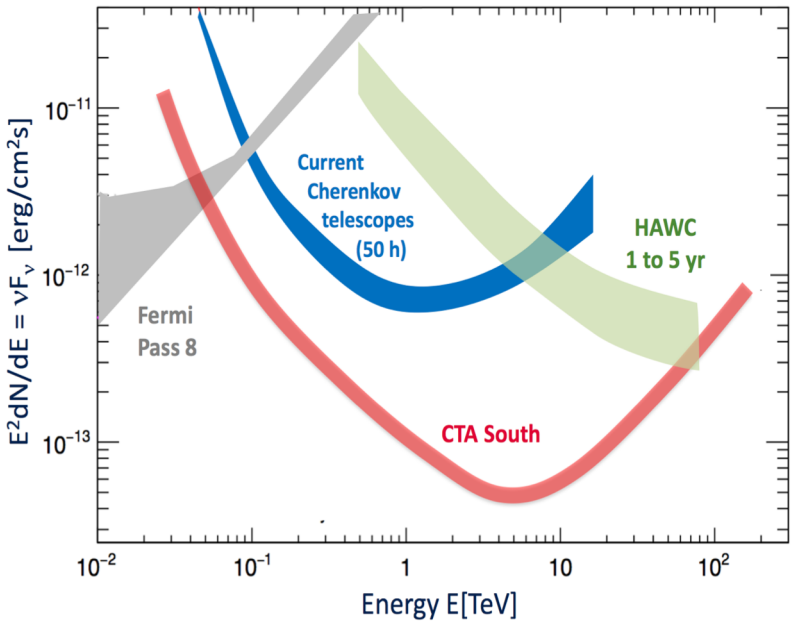
Simulated γ-ray
21 TeV, θ=21°
1131 hit PMTs



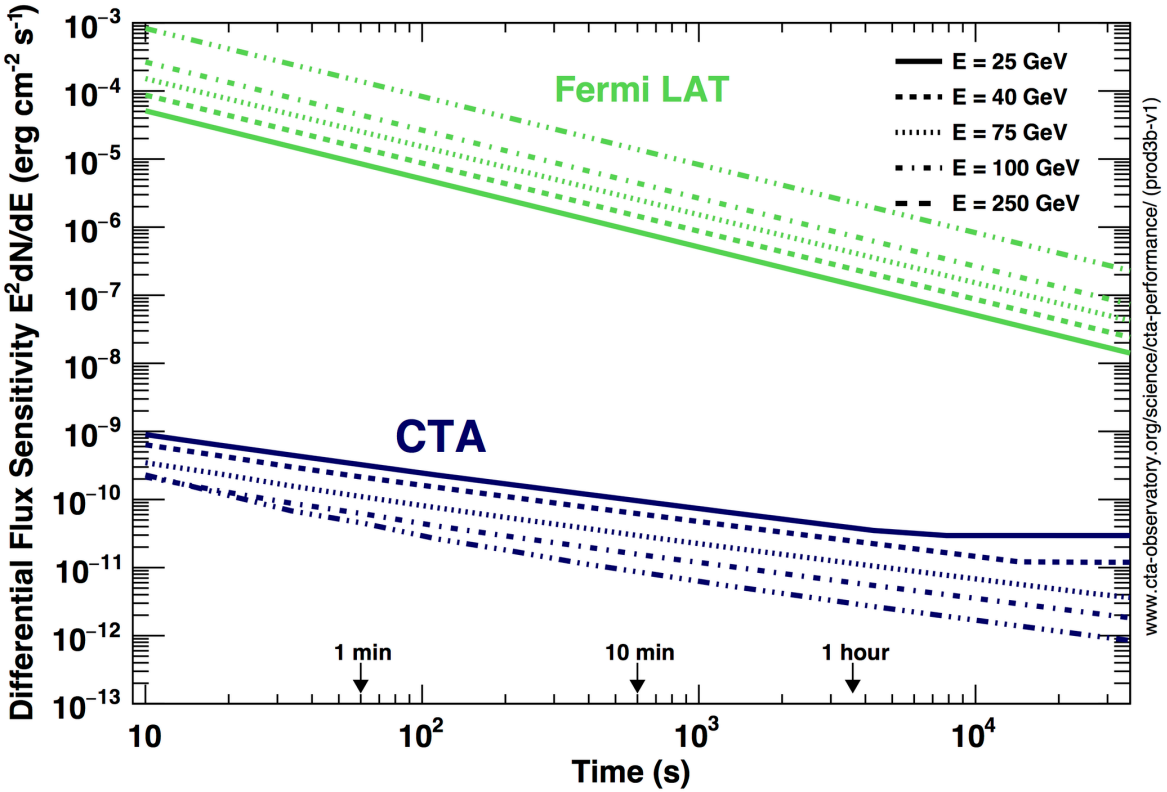


Performance





Performance



IACTs vs Ground Arrays

	IACT Arrays	Ground Arrays
Energy resolution	++	-
Angular resolution	++	-
Threshold	++	-
Transients	++(*)	++ (**)
V. extended sources	-	++
Full sky surveys	-	++

*But need a trigger and ~30 s to get there
**Only at higher energies, horizon closer

- Below 100 GeV – Fermi is better
- +long-term monitoring
- >1 degree