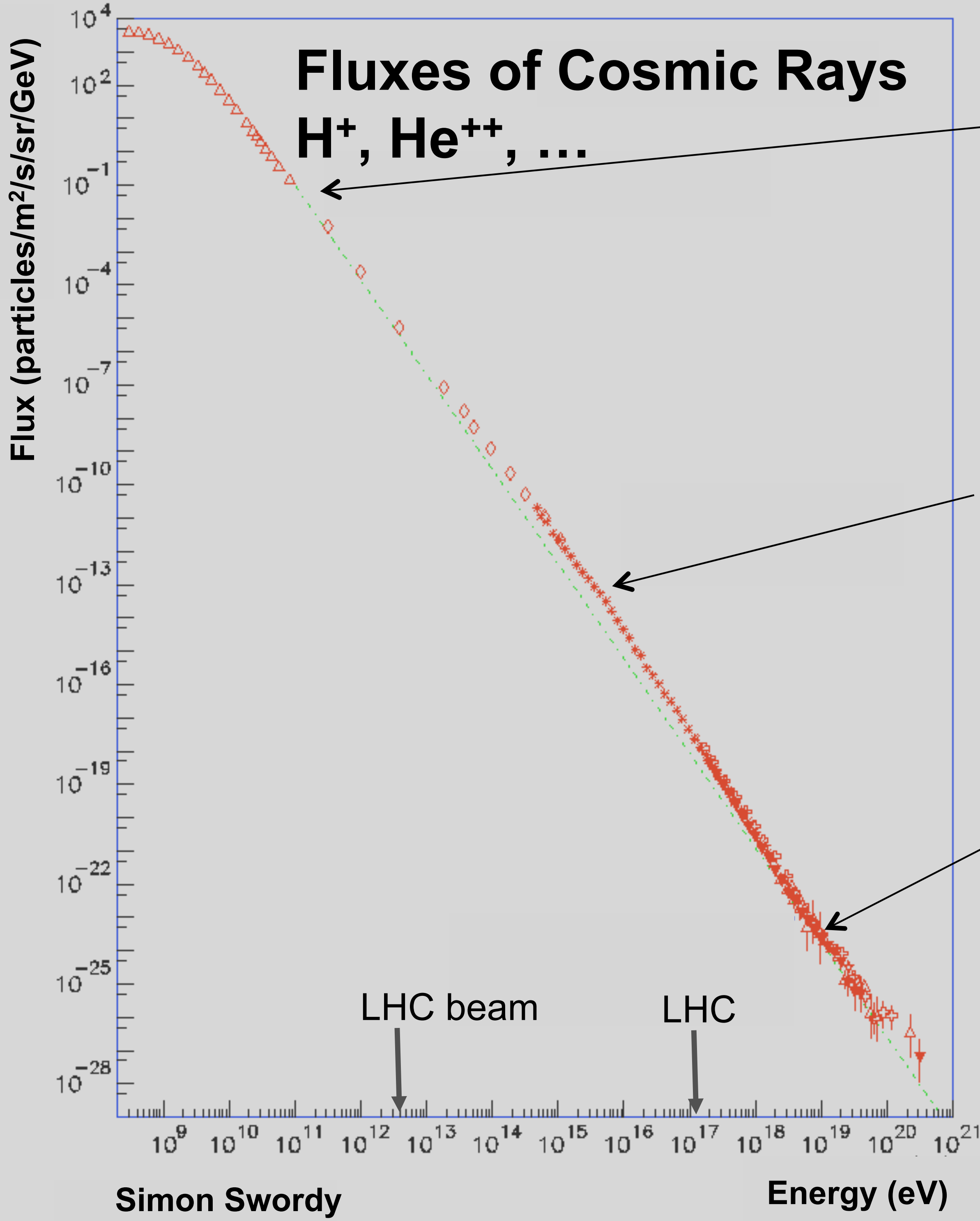
Detection of Cosmic Particles

Frank Krennrich, Iowa State University

Detection of Cosmic Particles

- **Experimental challenges & Science Drivers**
- **Detectors & Instrumentation.**
- **Discoveries with current Experiments.**
- **Next Generation Observatories.**

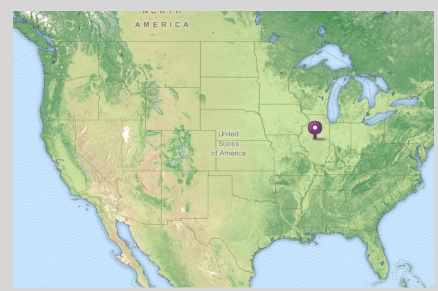
Experimental Challenges

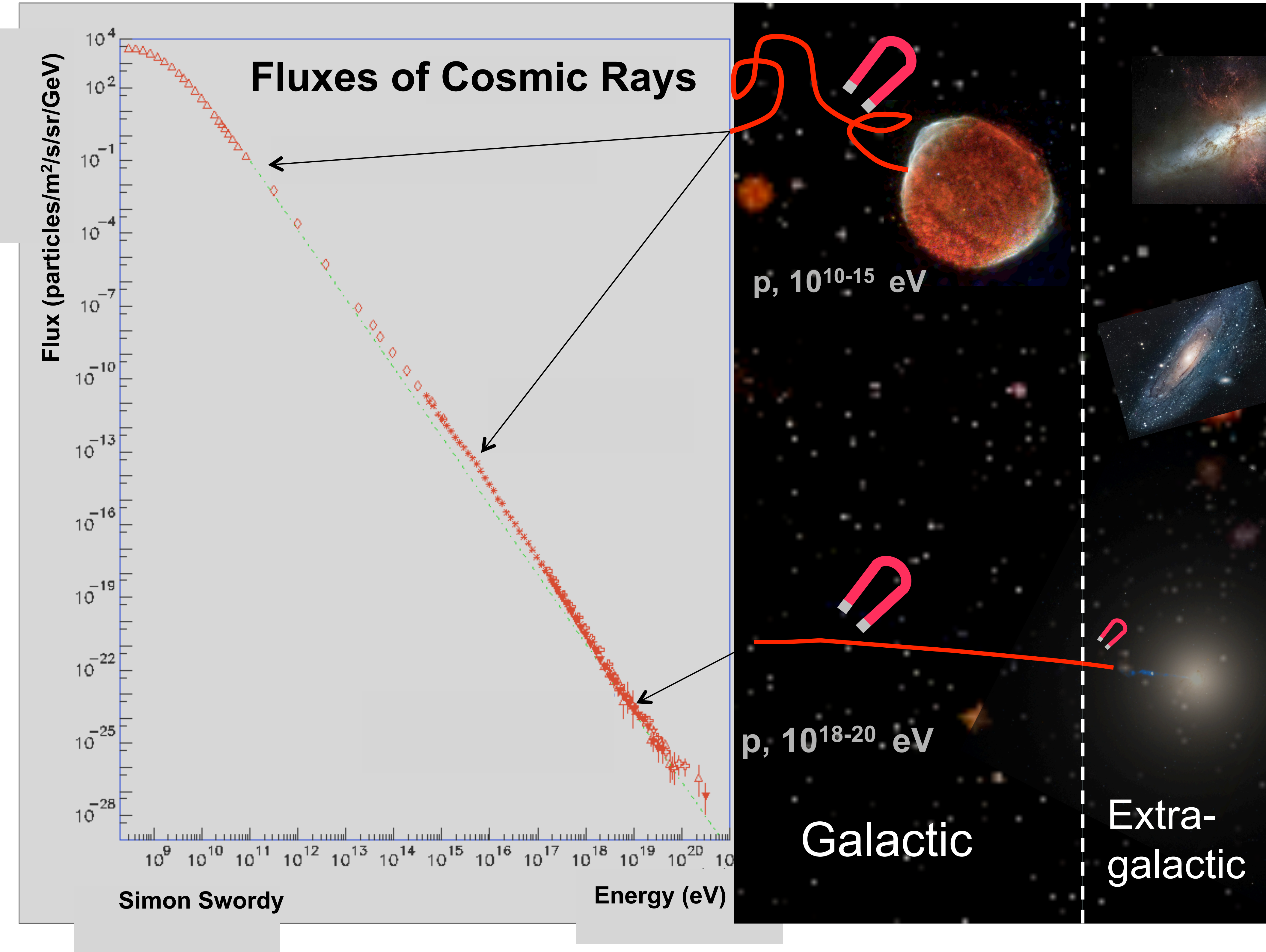


1 particle per m^2 - second

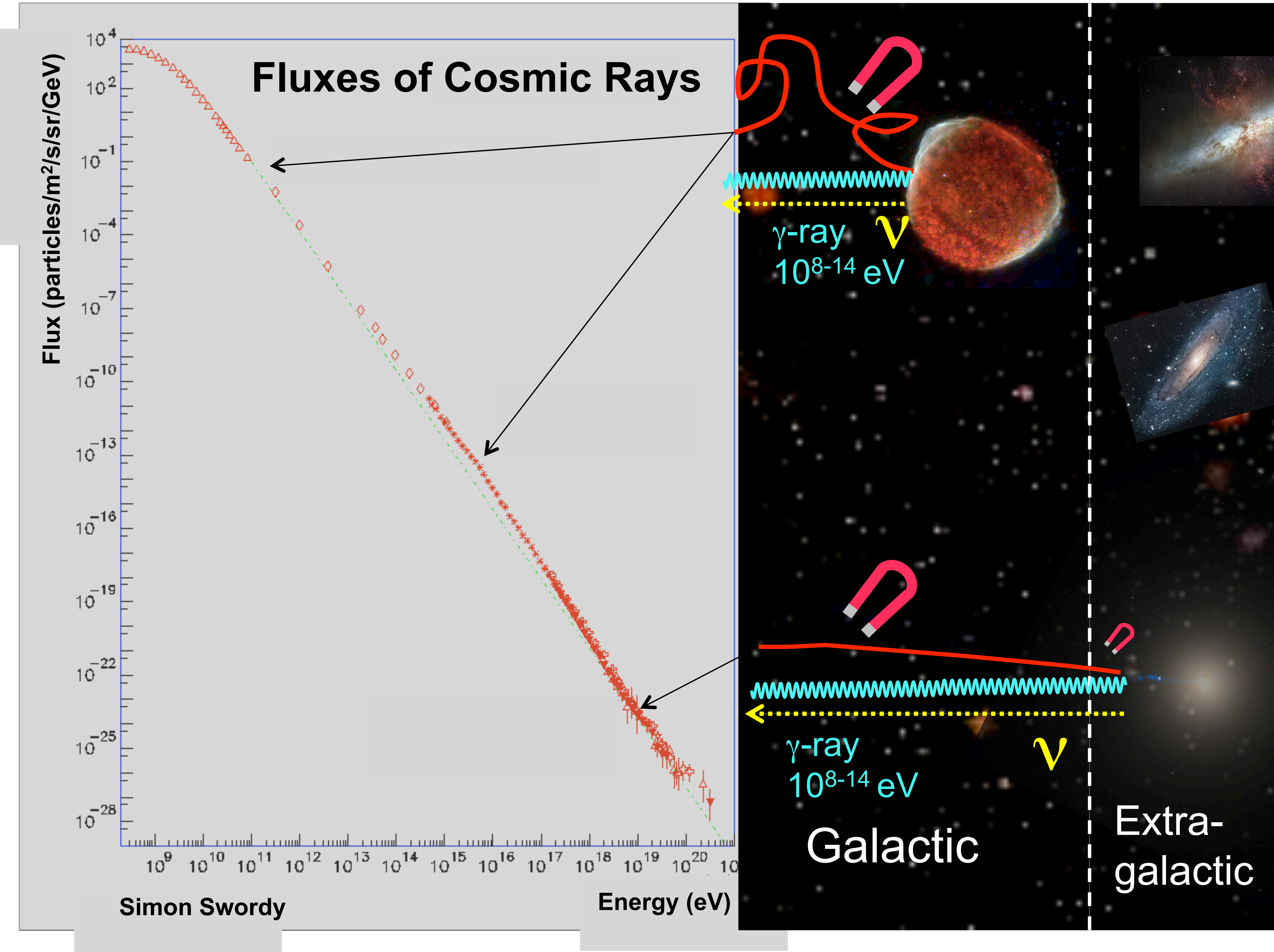
1 particle per m^2 - year

1 particle per km^2 - year





Fluxes of Cosmic Rays
Flux (particles/m²/s/sr/GeV)
Energy (eV)
Simon Swordy
p, 10^10-15 eV
p, 10^18-20 eV
Galactic
Extra-
galactic



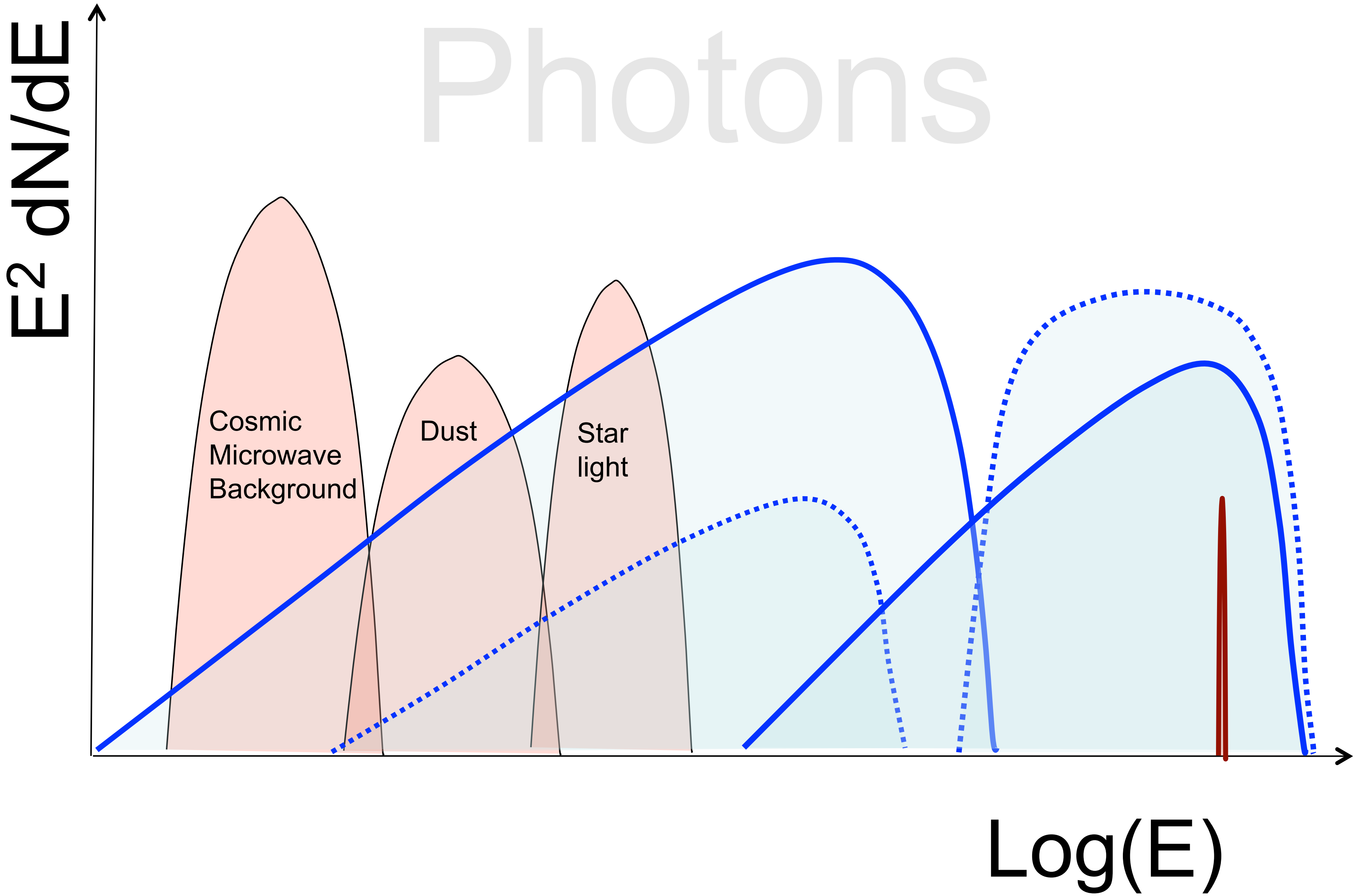
Fluxes of Cosmic Rays
Flux (particles/m²/s/sr/GeV)
10⁴
10²
10⁻¹
10⁻⁴
10⁻⁷
10⁻¹⁰
10⁻¹³
10⁻¹⁶
10⁻¹⁹
10⁻²²
10⁻²⁵
10⁻²⁸
10⁹ 10¹⁰ 10¹¹ 10¹² 10¹³ 10¹⁴ 10¹⁵ 10¹⁶ 10¹⁷ 10¹⁸ 10¹⁹ 10²⁰
Energy (eV)
Simon Swordy
γ-ray
ν
10⁸⁻¹⁴ eV
γ-ray
10⁸⁻¹⁴ eV
ν
Galactic
Extra-
galactic

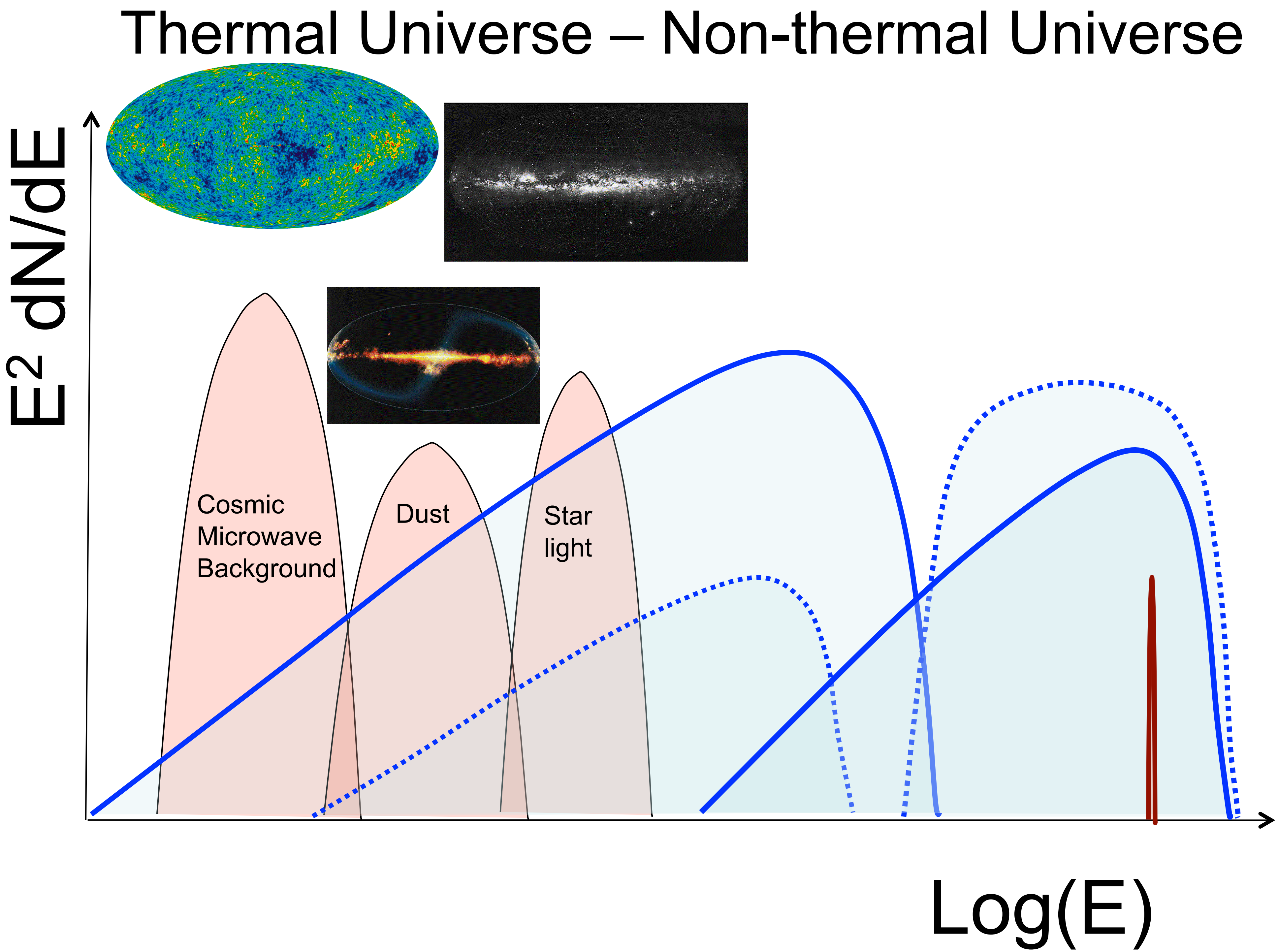
Why do we care?

Up to the 20th century, **‘reality’ was everything humans could touch, smell, see, and hear**. Since the (discovery of) the **electromagnetic spectrum** ... humans have learned that what they can touch, smell, see, and hear is **less than one millionth of reality**. Ninety-nine percent of all that is going to affect our tomorrows is being developed by humans using instruments and working in ranges of reality that are non-humanly sensible.

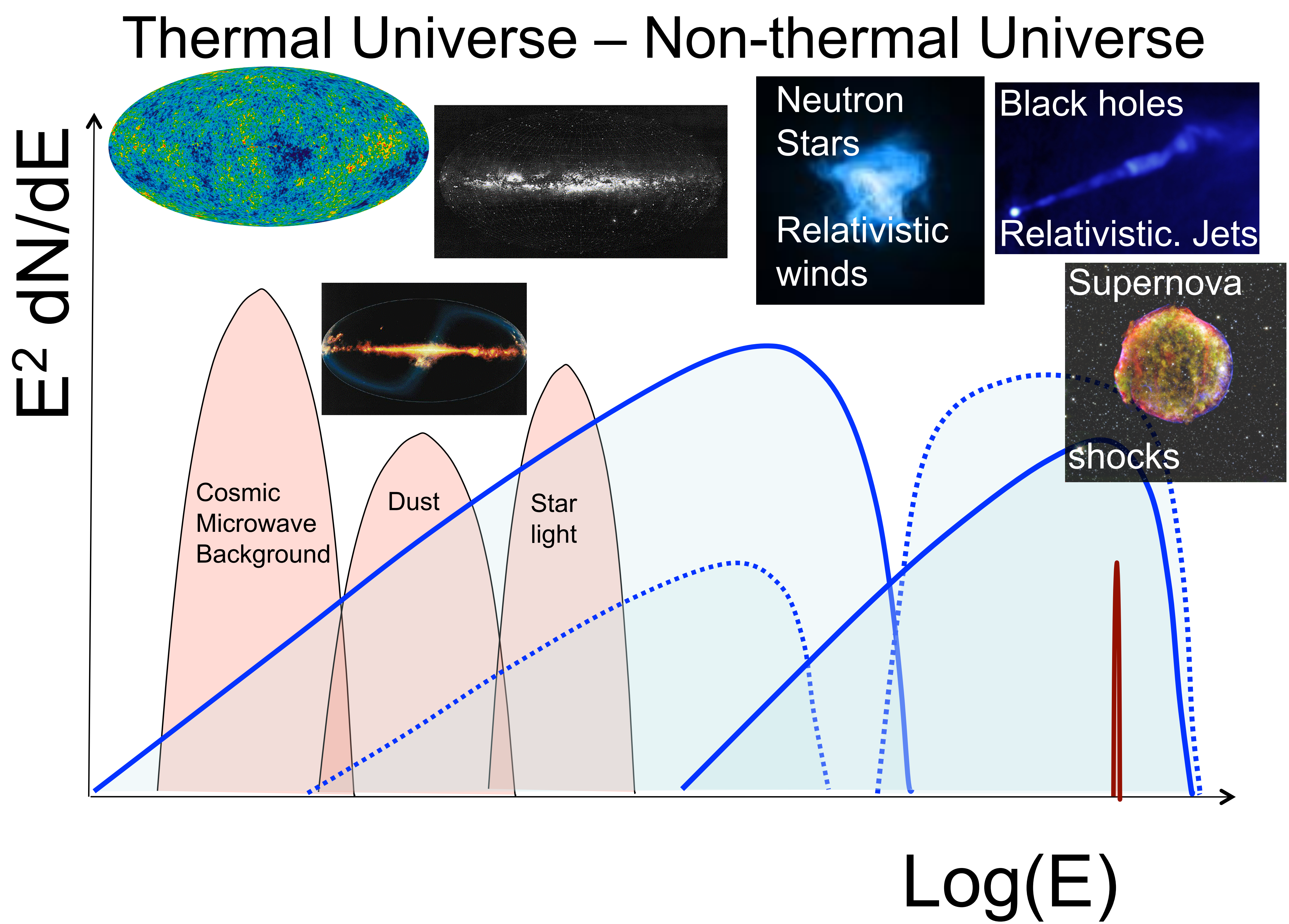
- R. Buckminster Fuller

Thermal Universe – Non-thermal Universe



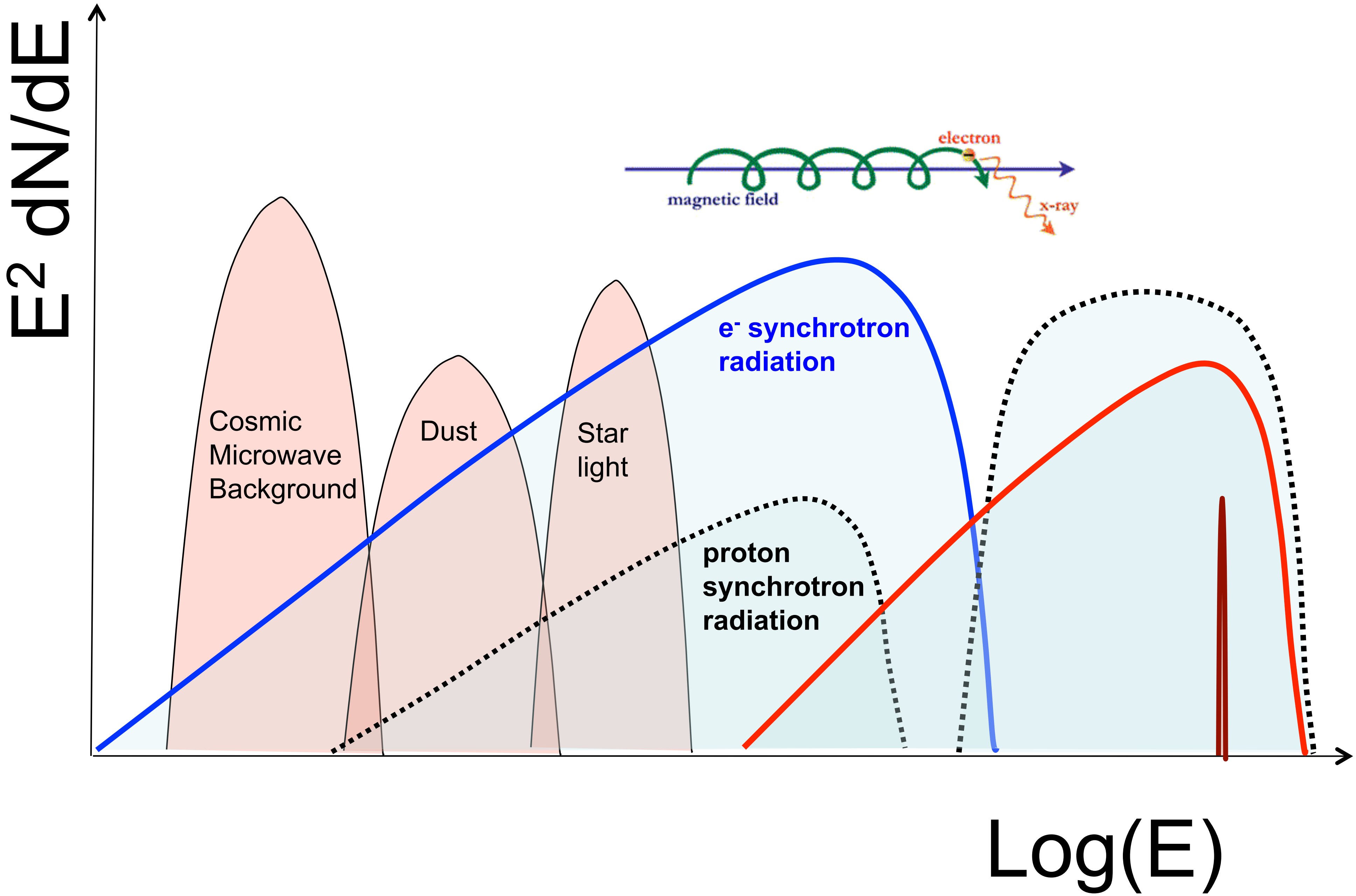


Thermal Universe – Non-thermal Universe
E2 dN/dE
Cosmic
Microwave
Background
Dust
Star
light
Log(E)

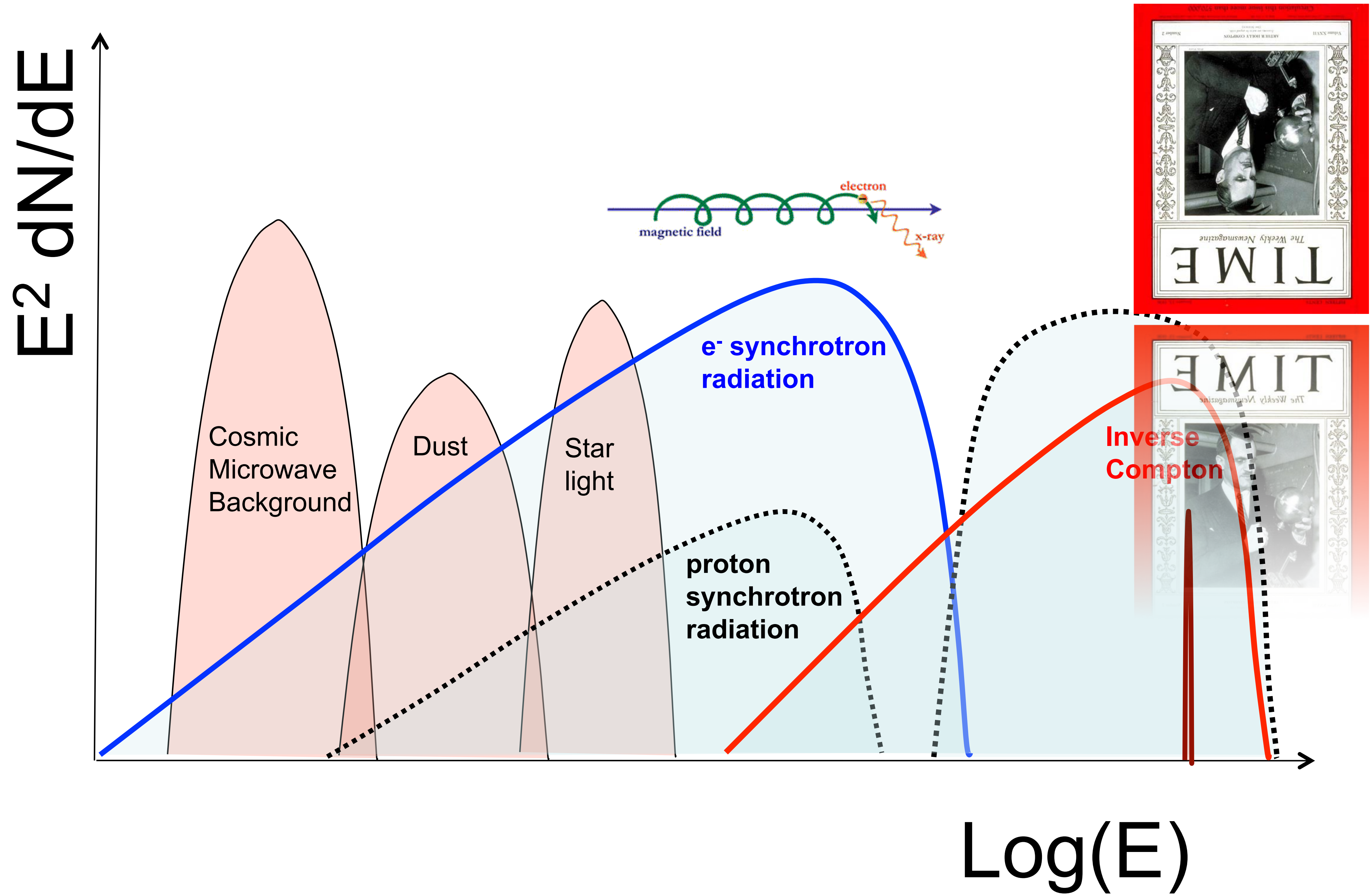


Thermal Universe – Non-thermal Universe
E² dN/dE
Neutron Stars
Relativistic winds
Black holes
Relativistic. Jets
Supernova
shocks
Cosmic Microwave Background
Dust
Star light
Log(E)

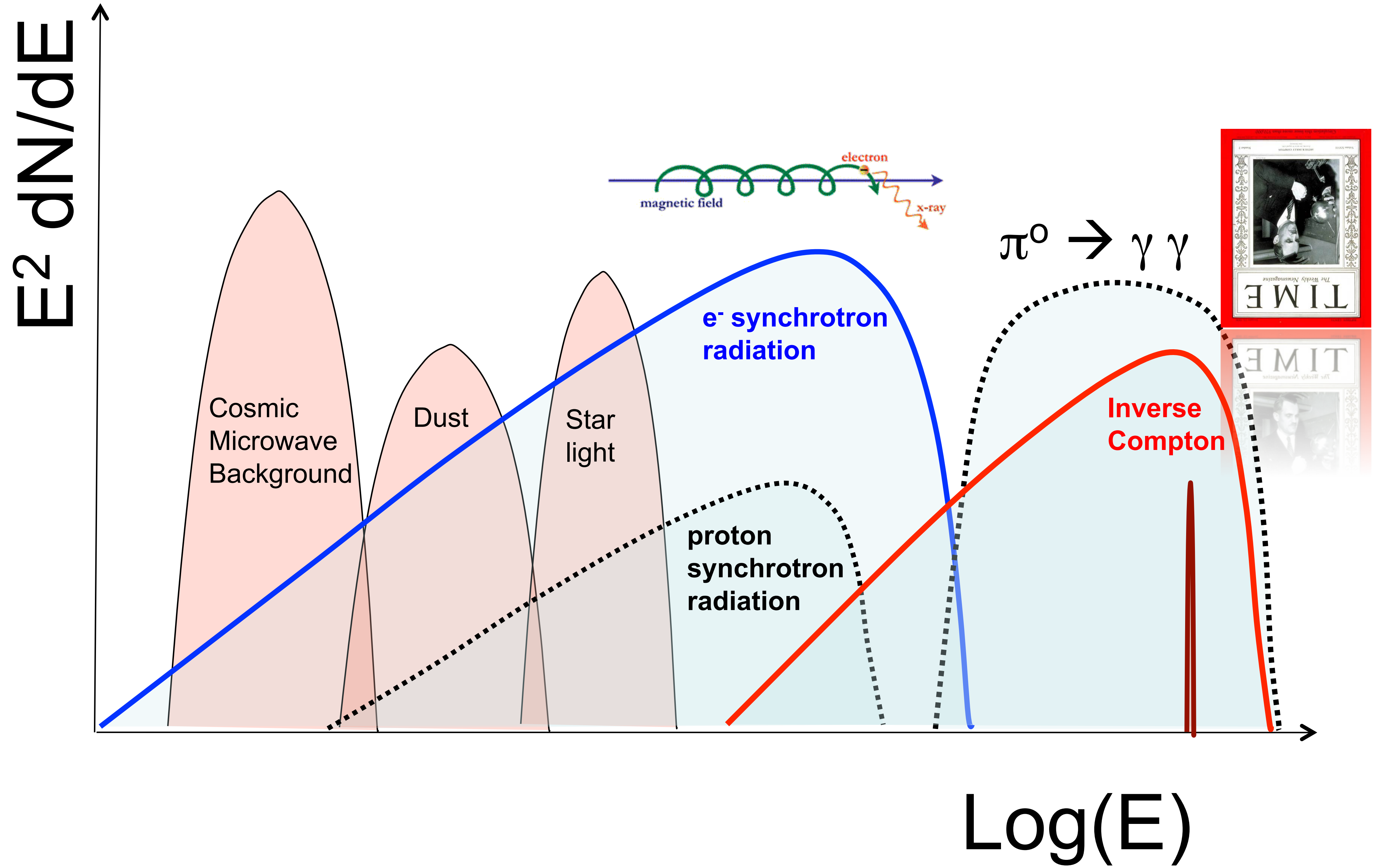
Thermal Universe – Non-thermal Universe



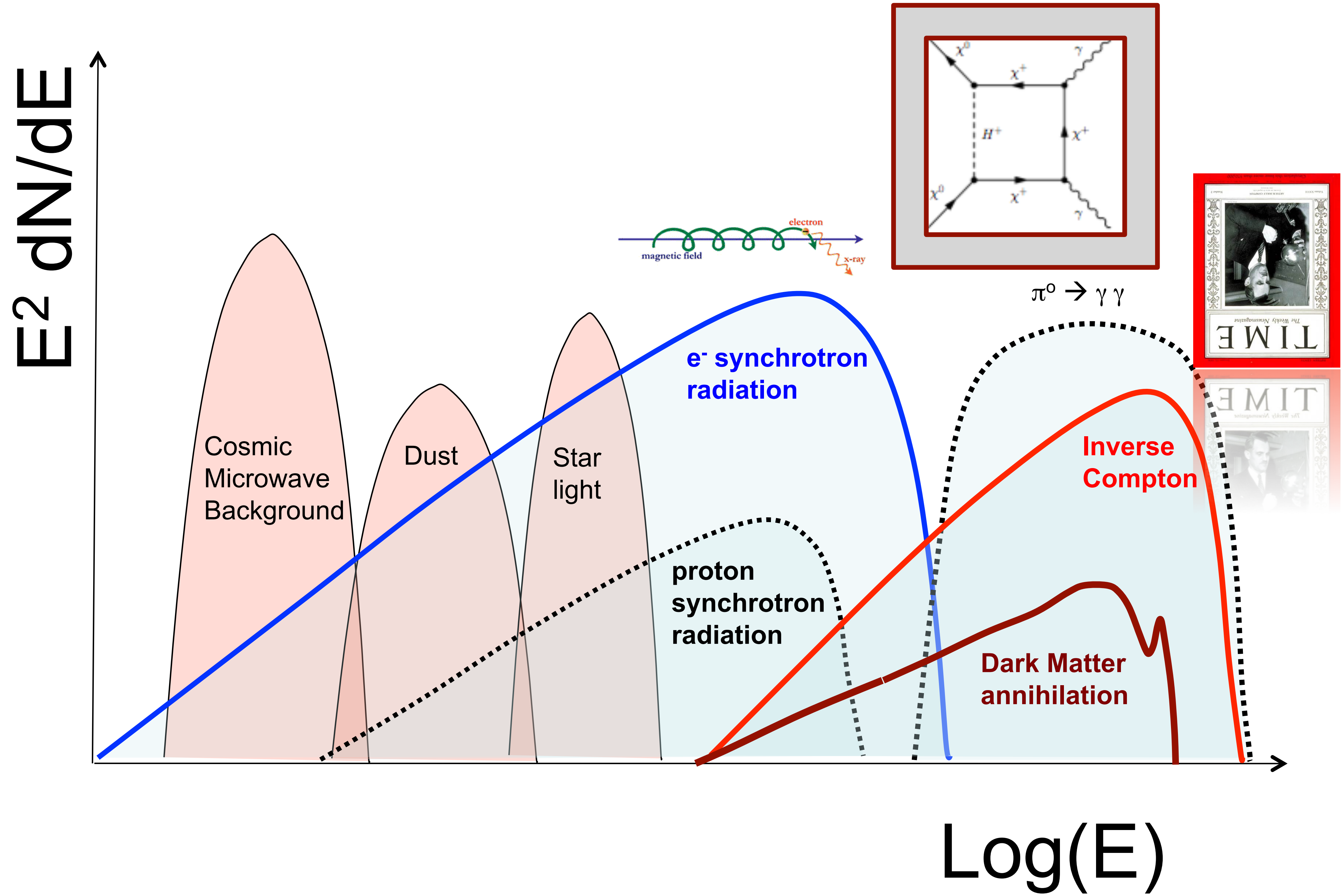
Thermal Universe – Non-thermal Universe



Thermal Universe – Non-thermal Universe

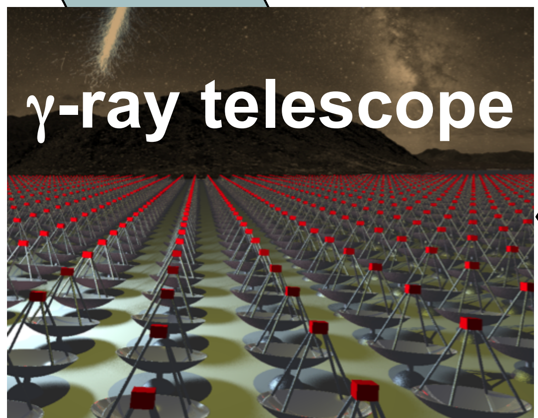


Thermal Universe – Non-thermal Universe



Cosmic Particles from Dark Matter Annihilation

WIMP mass



DM spatial distribution

$\chi\,\chi \rightarrow$ … + γ

Particle Physics
WIMP ~ 10 GeV – few TeV

Cosmology
Galaxy formation ✓
CMB ✓
Nucleosynthesis ✓

Cold DM

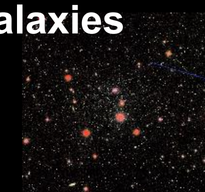
Astrophysical Theory & Simulations

N-body simulation:
gravit. interactions of WIMPs
Diemand et al. 0805.1244

Boost Factor?

Dark Matter Sites ✓

Dwarf Galaxies



Local group
M31

Cosmic Particles from Dark Matter Annihilation

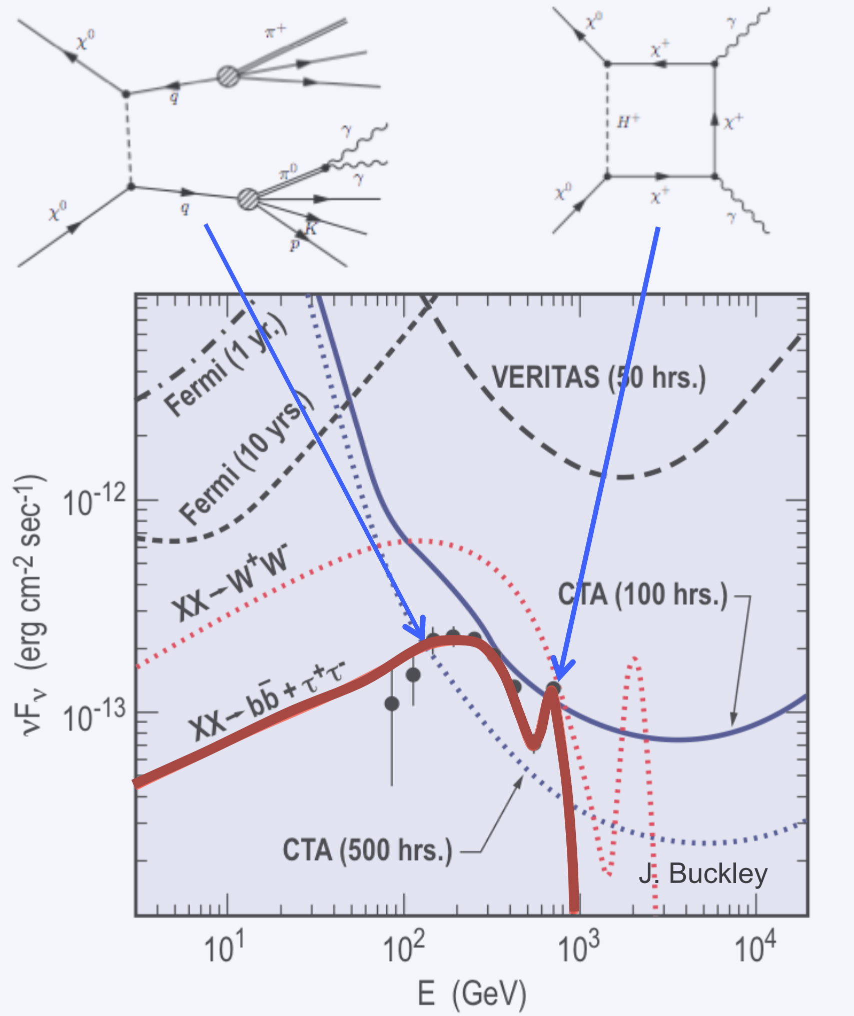
Unique Dark Matter Annihilation γ-ray signal

- Future γ-ray detectors will reach **critical flux sensitivity** to probe large fraction of cosmologically motivated SUSY neutralino models.

- those studies will study nature & properties of **DM particles in a cosmic context**, e.g., in dwarf galaxies, the galactic center, halo and clusters of galaxies.

- **"smoking gun" spectral signature** is common to all DM dominated sources.

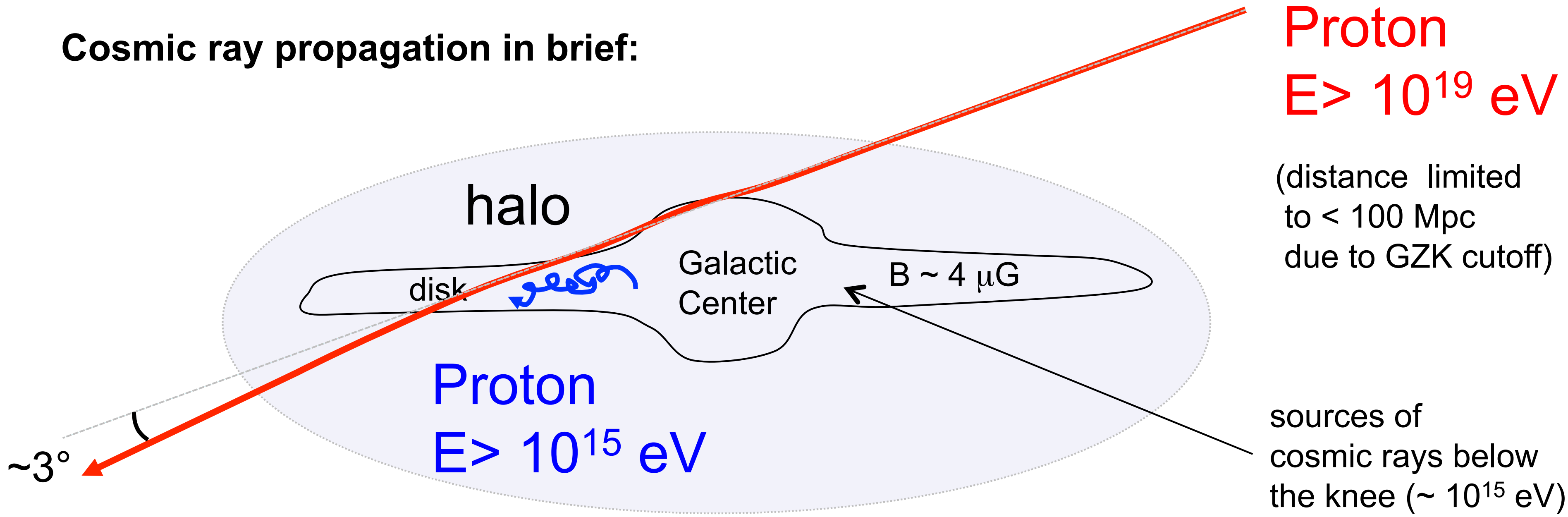
- **complementary** to DM searches at **LHC & nuclear recoil experiments,** especially for large mass



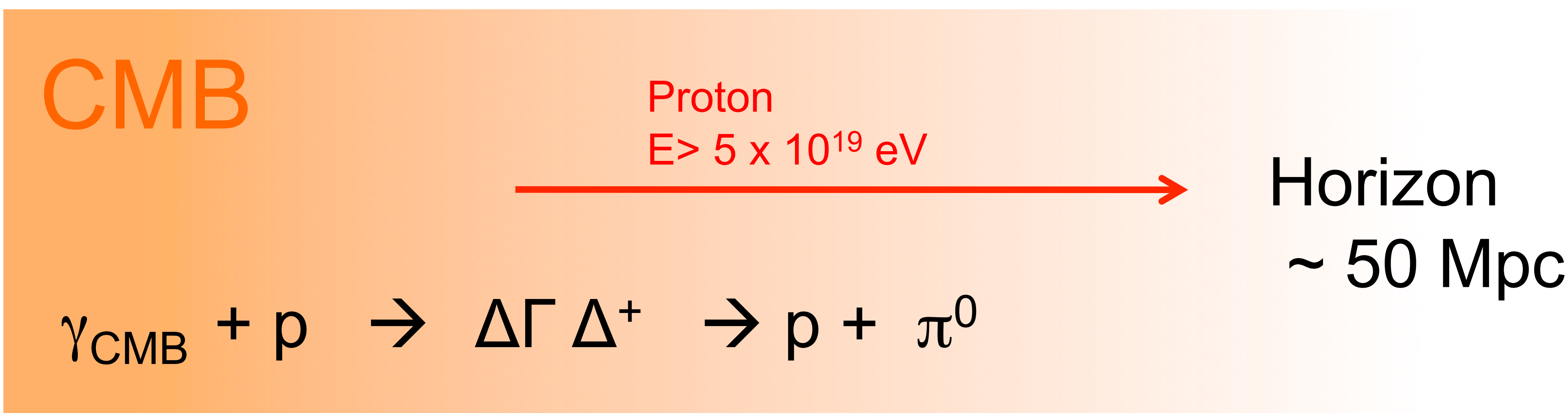
Model predictions for the spectrum from dark matter annihilation from the Sagittarius dwarf galaxy together with simulated CTA (includes US proposed US contribution) data points for one of the models.

Propagation of Cosmic Particles

Cosmic ray propagation in brief:



Opacity of Universe to cosmic ray propagation (extragalactic scales):



$$\gamma_{CMB} + p \rightarrow \Delta\Gamma\,\Delta^{+} \rightarrow p + \pi^{0}$$

Detectors & Instrumentation

Early Experiments

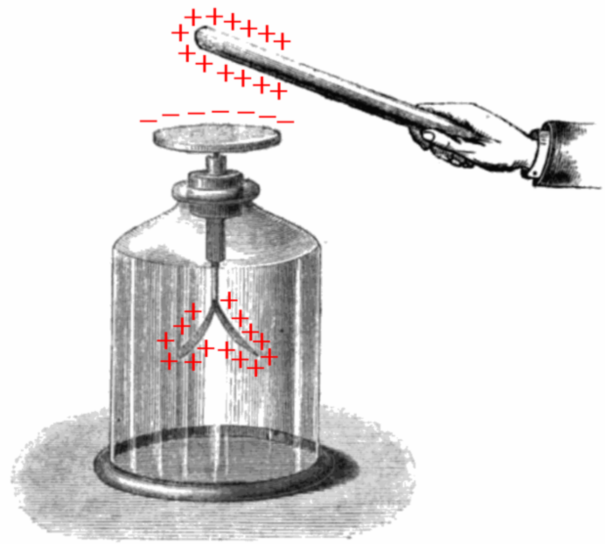
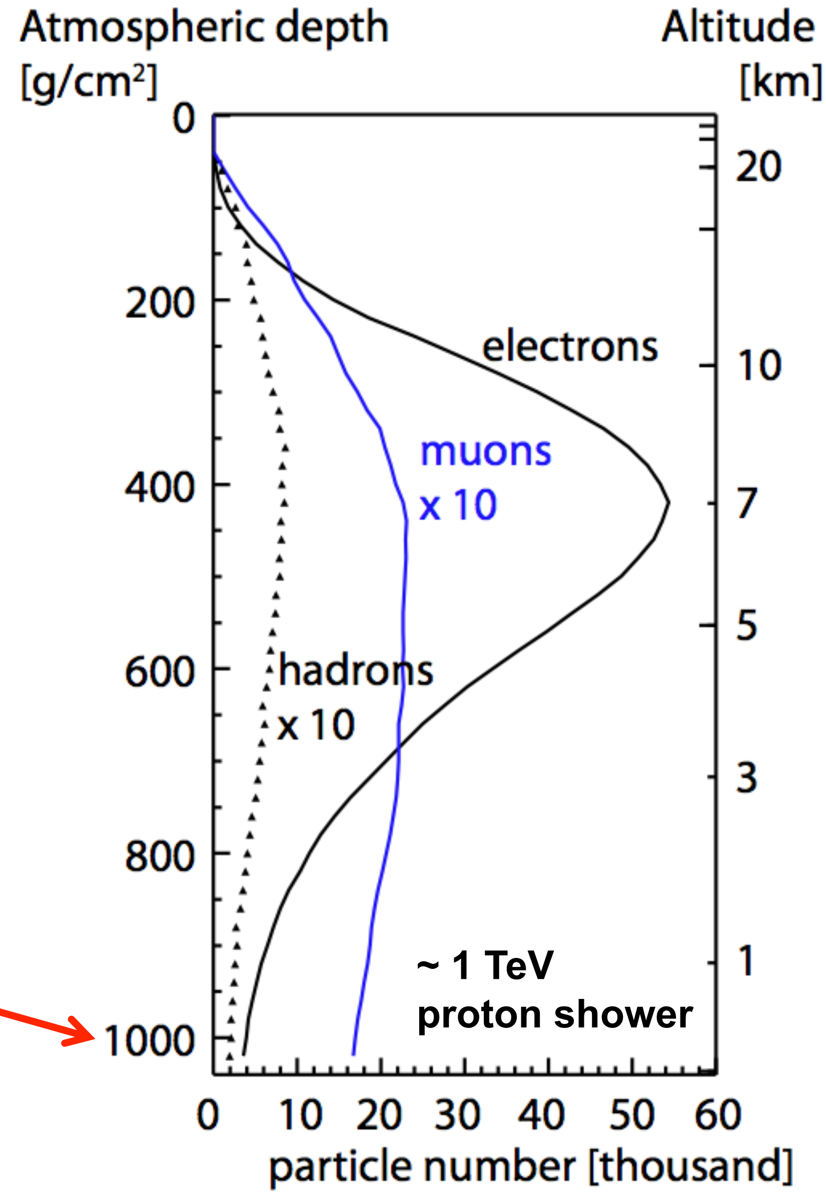
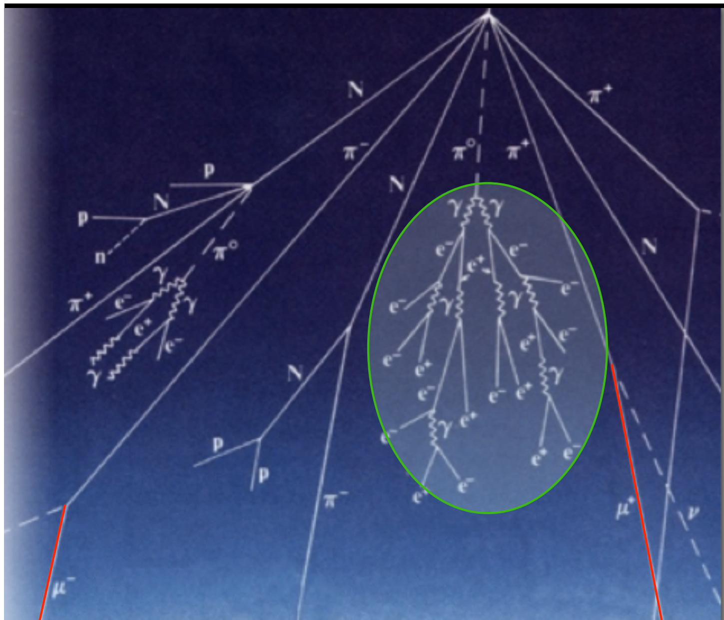


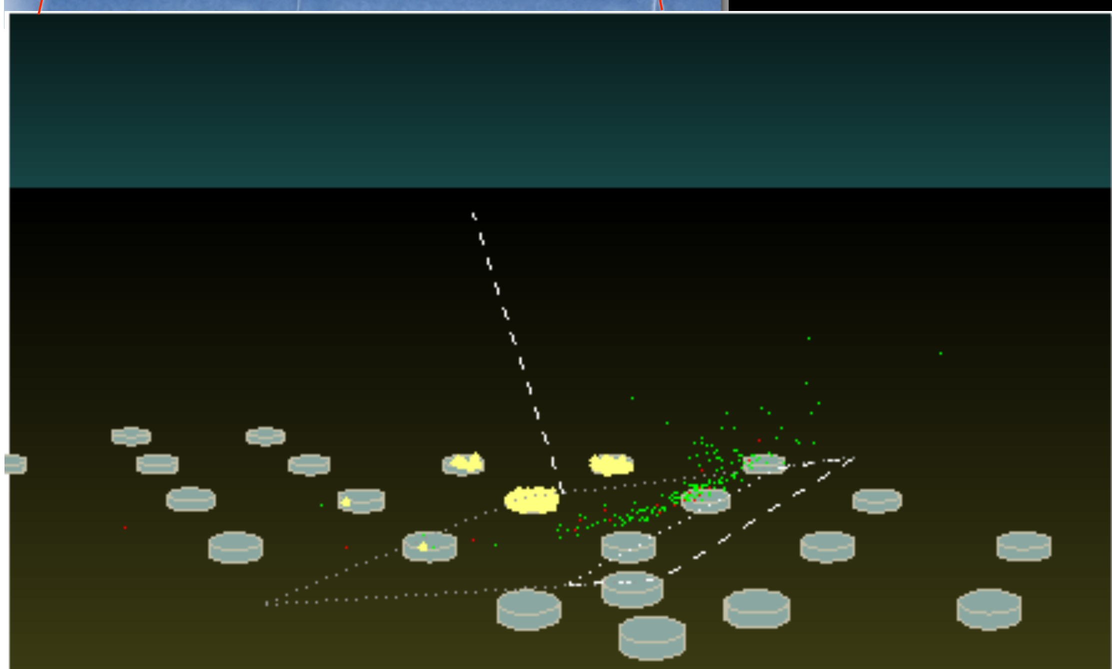
Table 7.1. *The variation of ionisation with altitude from the observations of Kolhörster (1913)*

Altitude (km)	Difference between observed ionisation and that at sea-level ($\times 10^6$ ions m^{-3})
0	0
1	−1.5
2	+1.2
3	+4.2
4	+8.8
5	+16.9
6	+28.7
7	+44.2
8	+61.3
9	+80.4

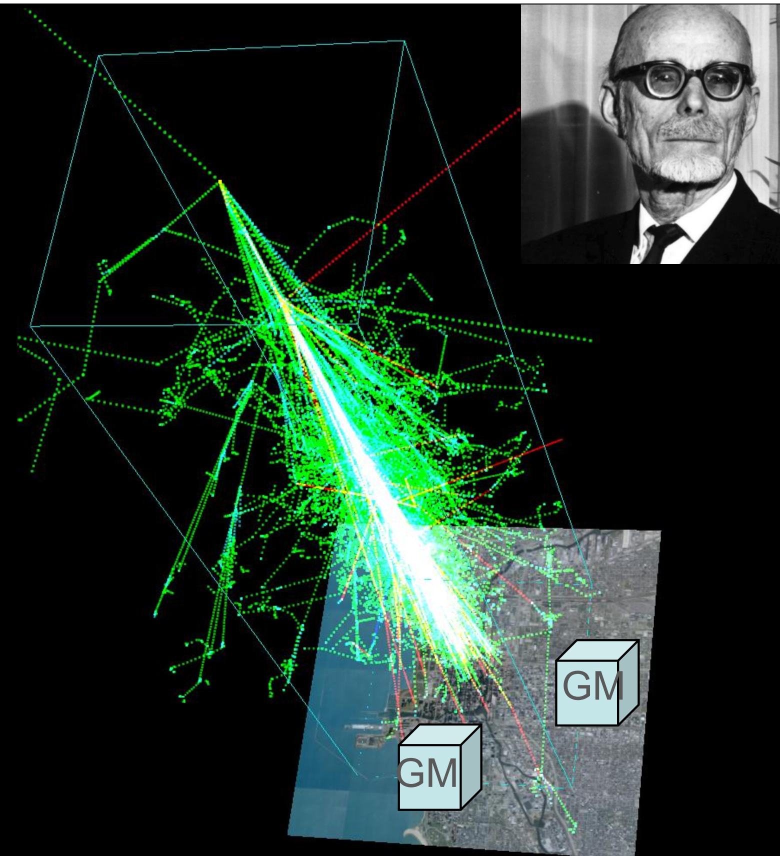


Early Experiments





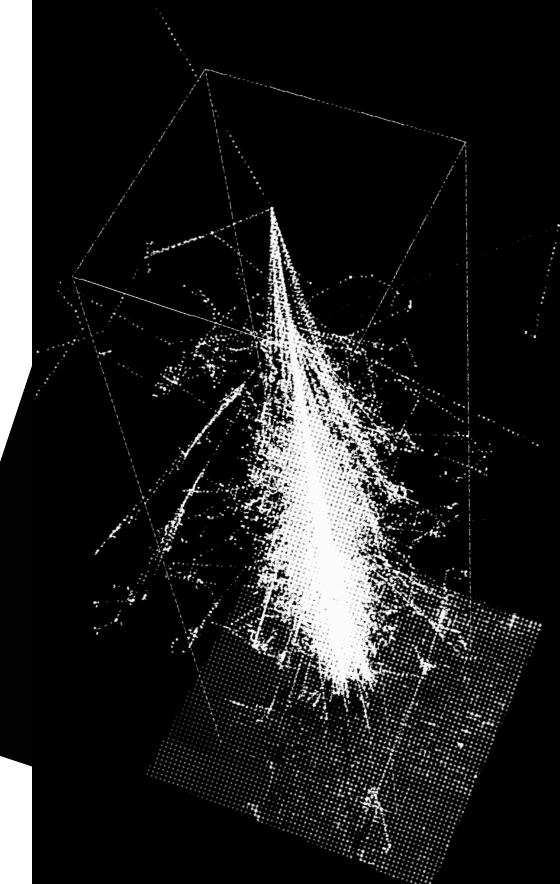
Credit: AUGER Collaboration

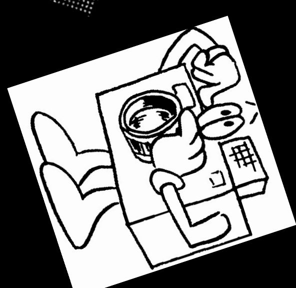


Credit: AIRES by Sergio Sciutto

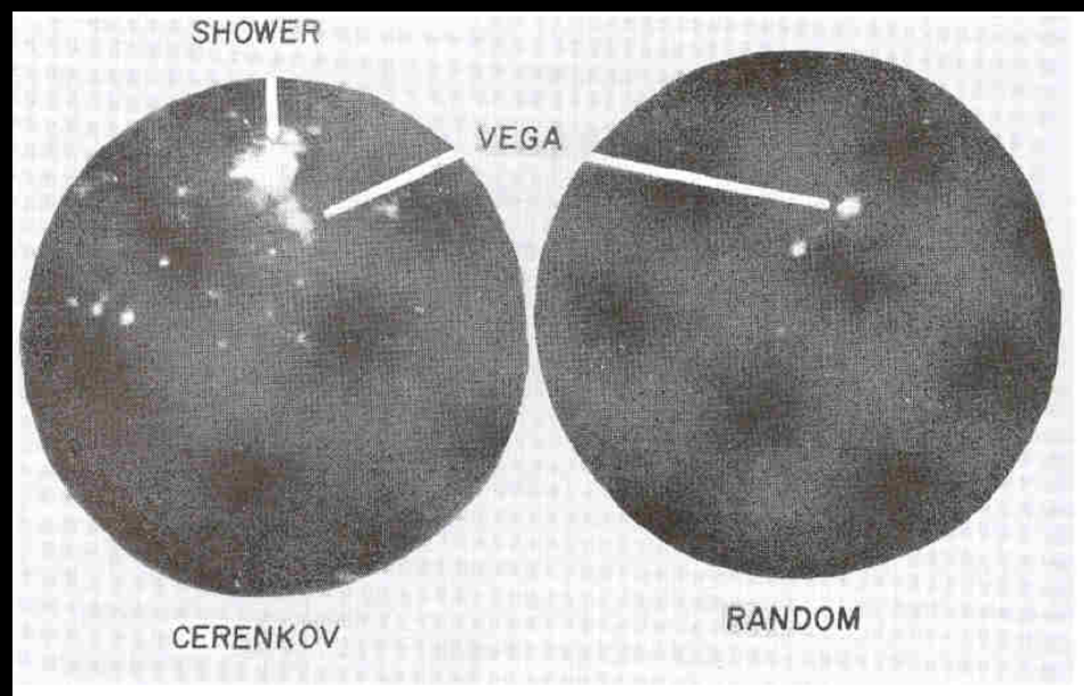
Pierre Auger 1938

Early Experiments





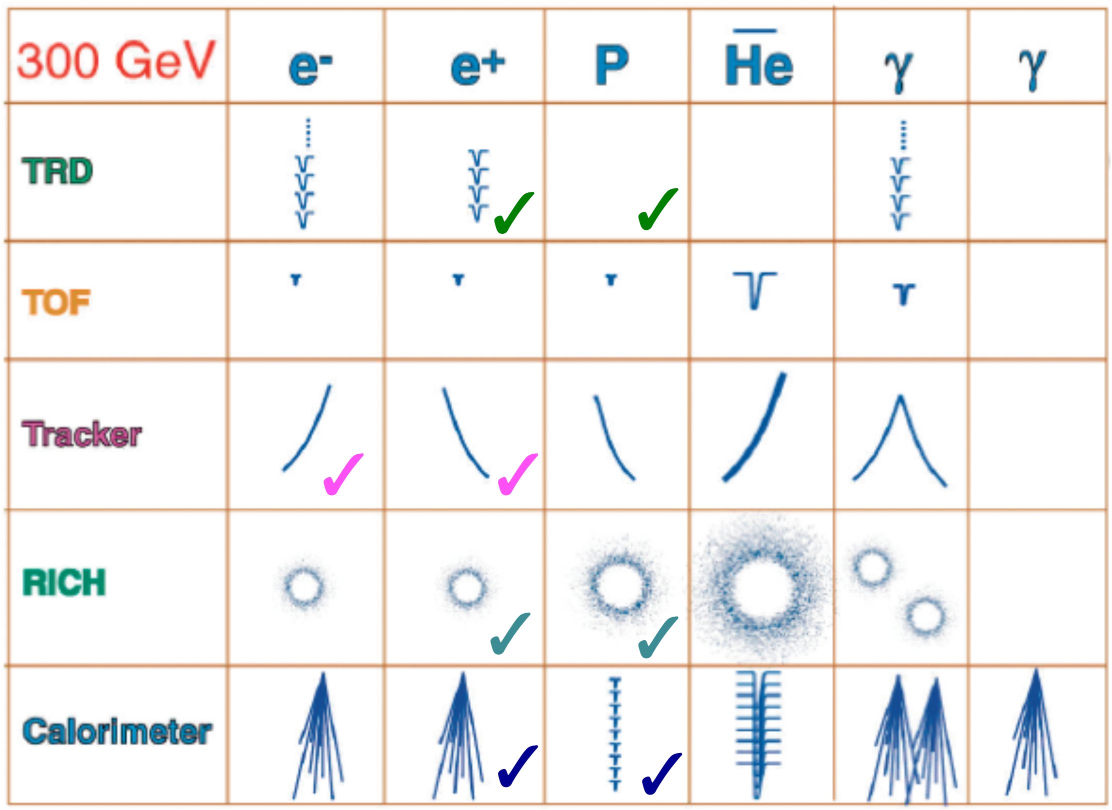
Cherenkov light images of air showers for gamma ray astronomy
proposed by G. Zatsepin & A. Chudakov

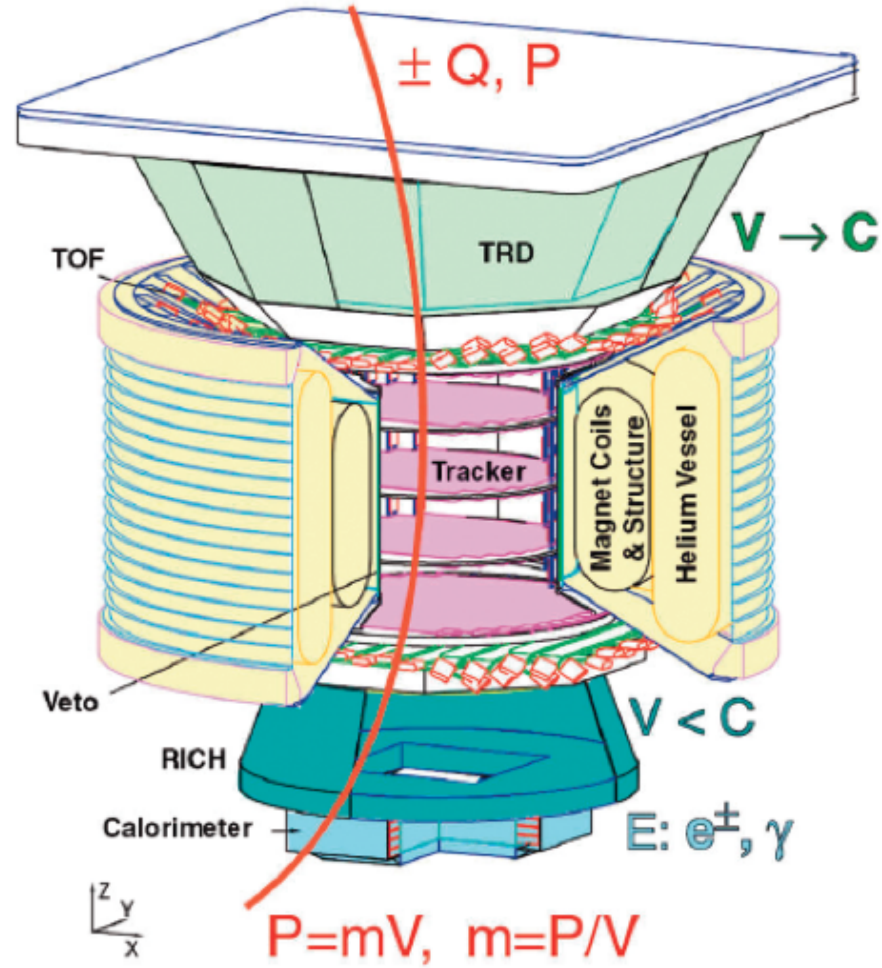


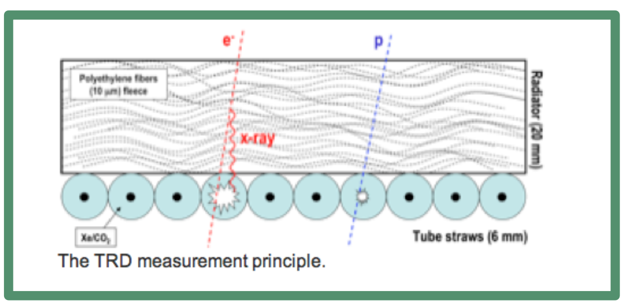
Credit: N. Porter & D. Hill 1960

Cosmic Ray Detectors

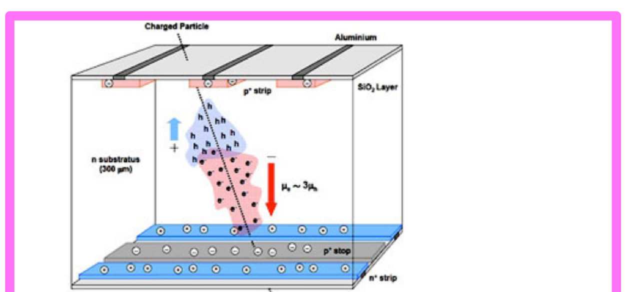
In Space: AMS on the ISS

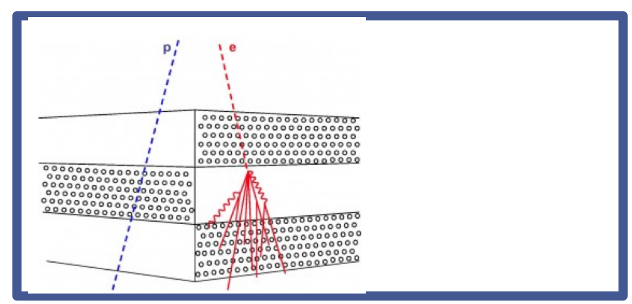




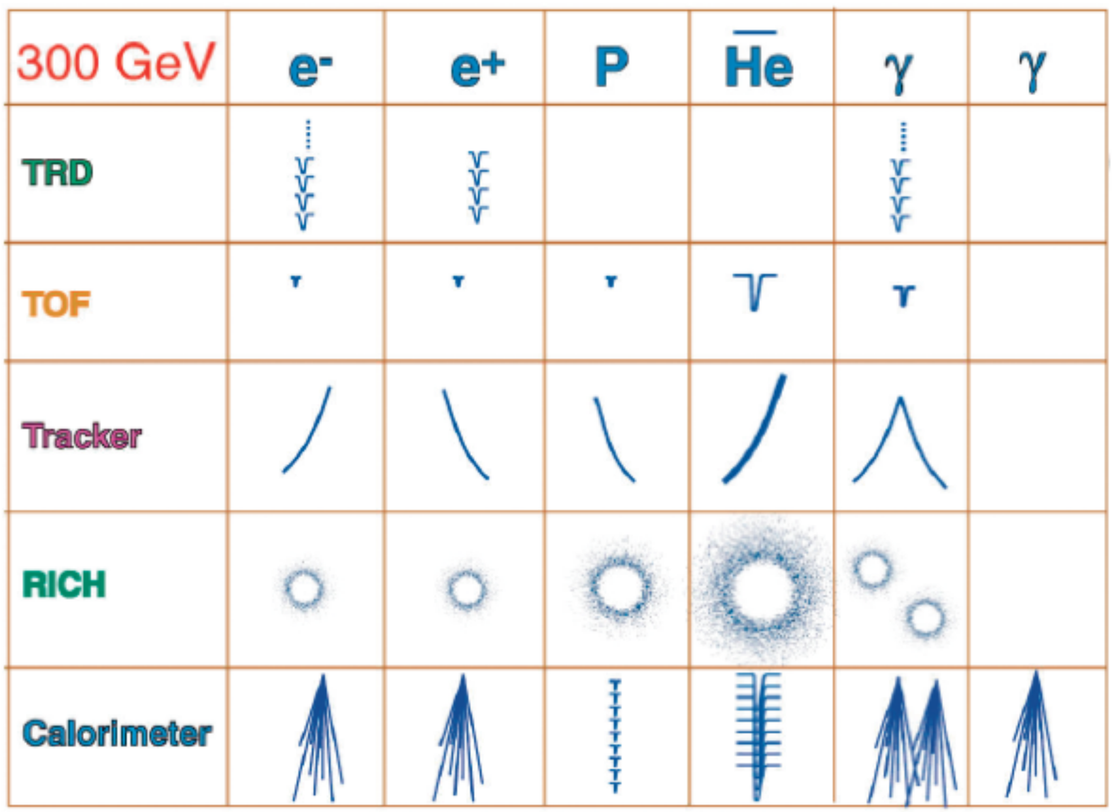


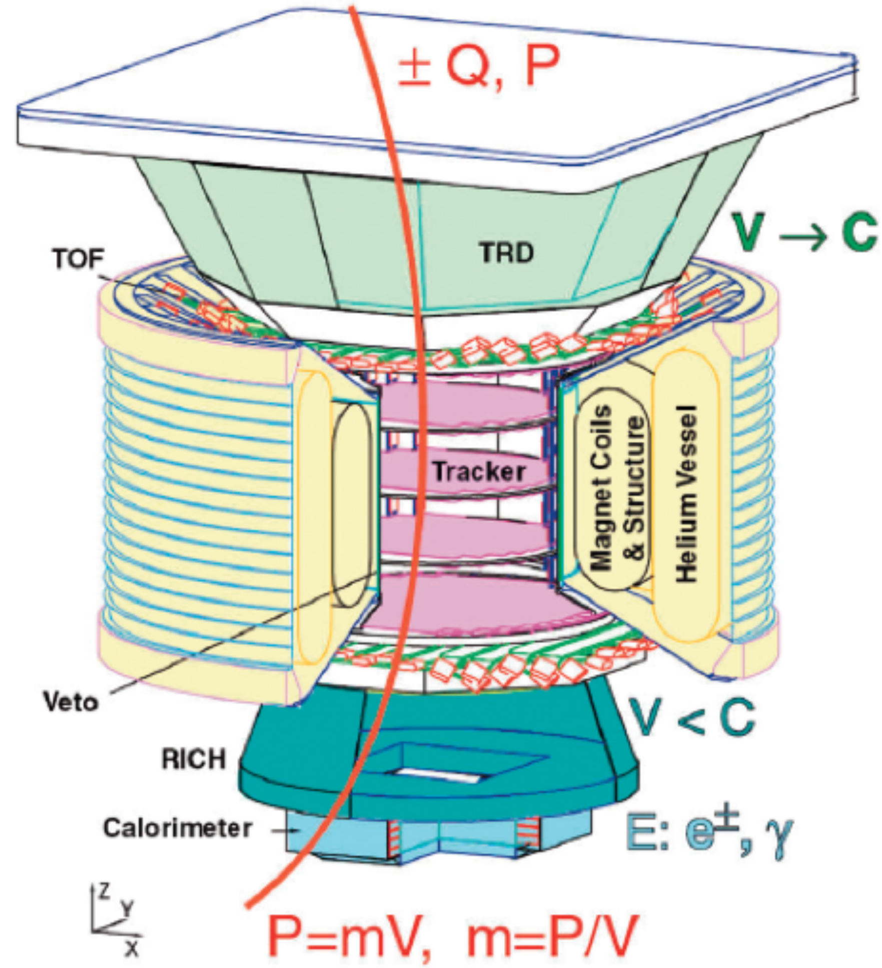
The TRD measurement principle.





In Space: AMS on the ISS



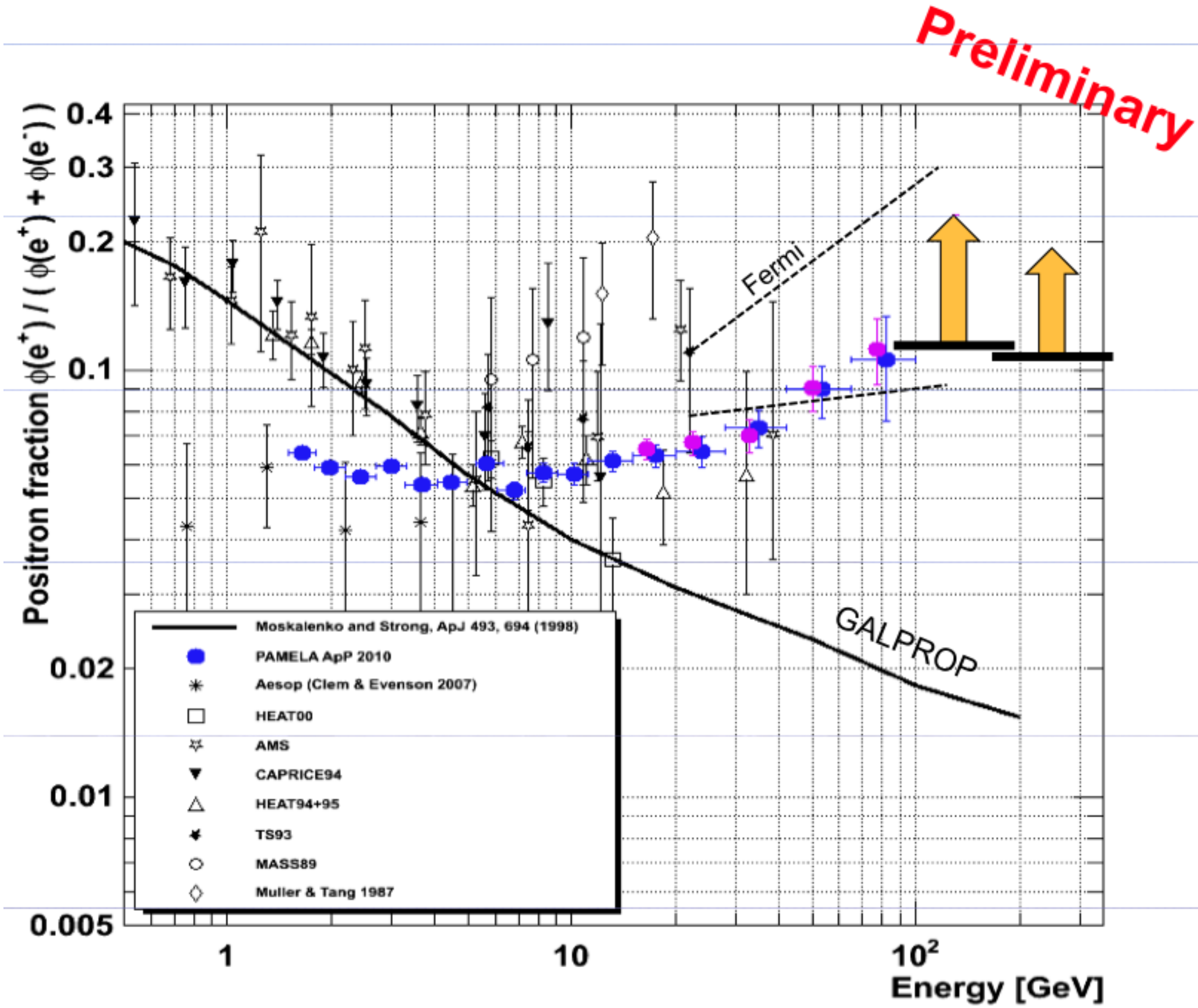


- A antihelium/helium flux ratio of 10^{-9} could be measured!

Galaxies made from antimatter?

- Excellent separation power between positrons and protons!

Cosmic Ray e^+ Spectrum



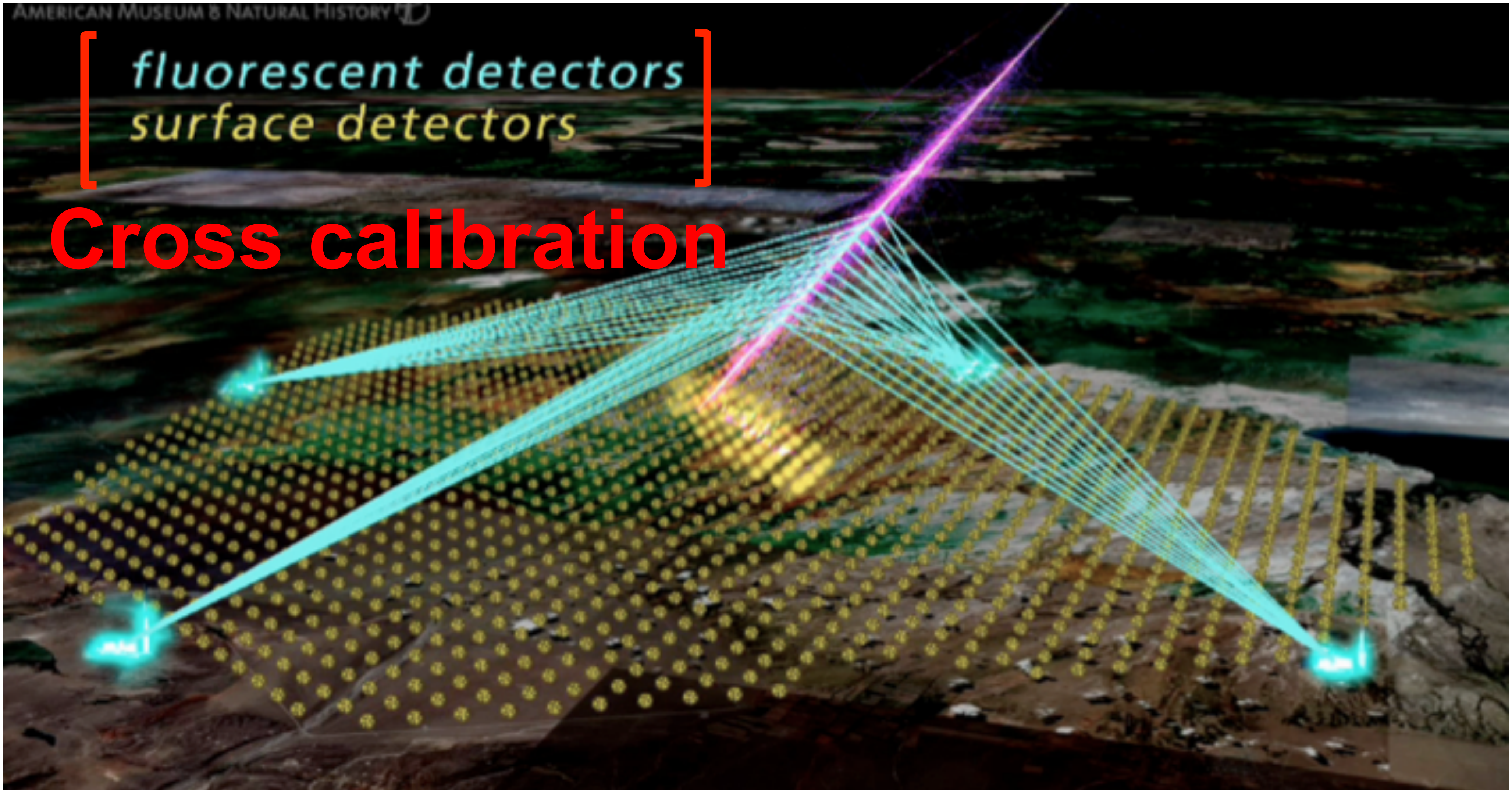
<u>Primary e^-:</u>
e^- from acceleration in Supernova remnants

<u>Secondary e^- & e^+:</u>
Interactions of C.R.s with *ISM in our galaxy*

Additional <u>component</u> above 1 GeV of mostly e^+:

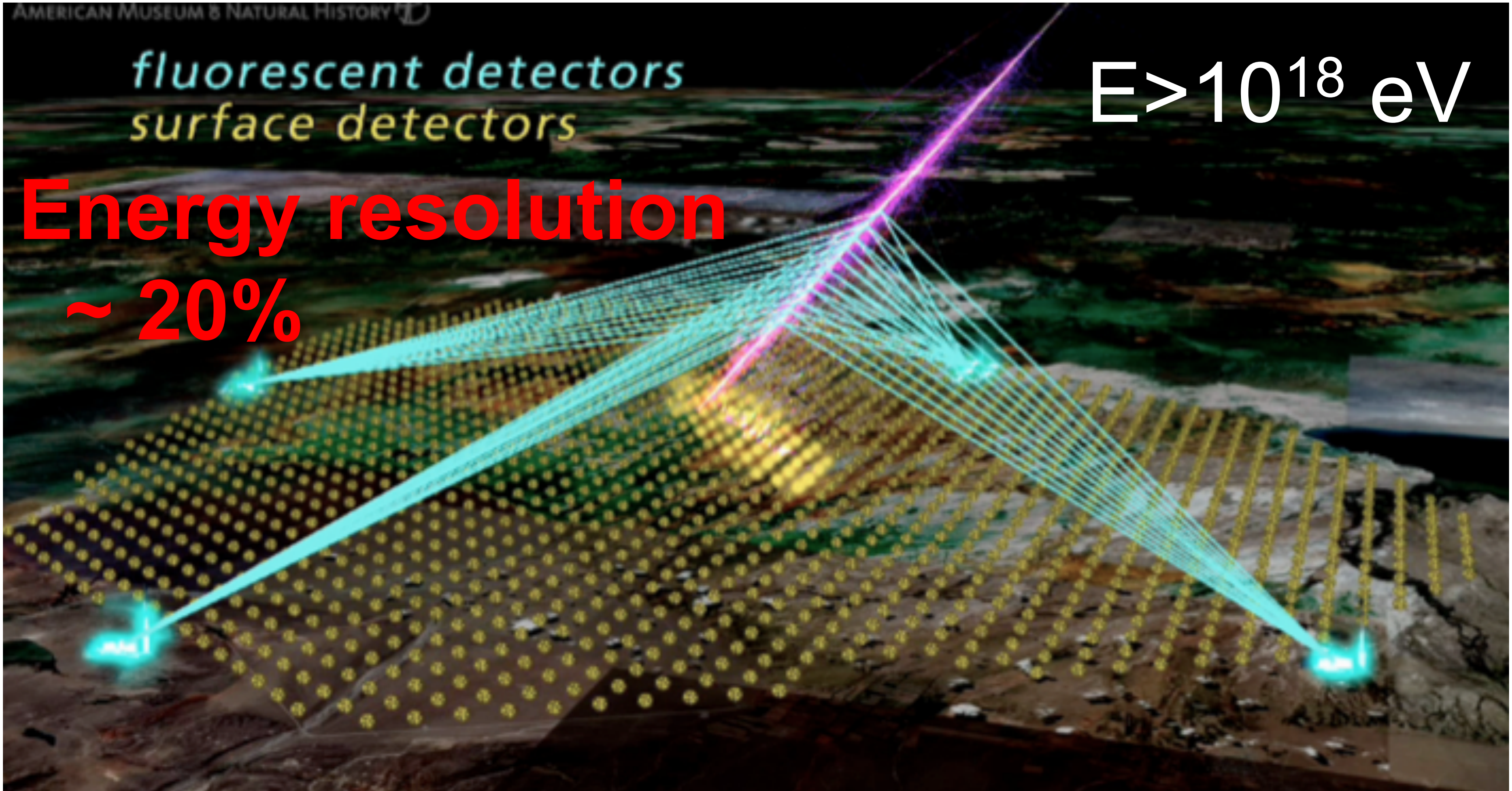
→ nearby SNR, pulsar or dark matter annihilation?

Air Shower Arrays: AUGER



Effective area: ~ 3,000 km^2

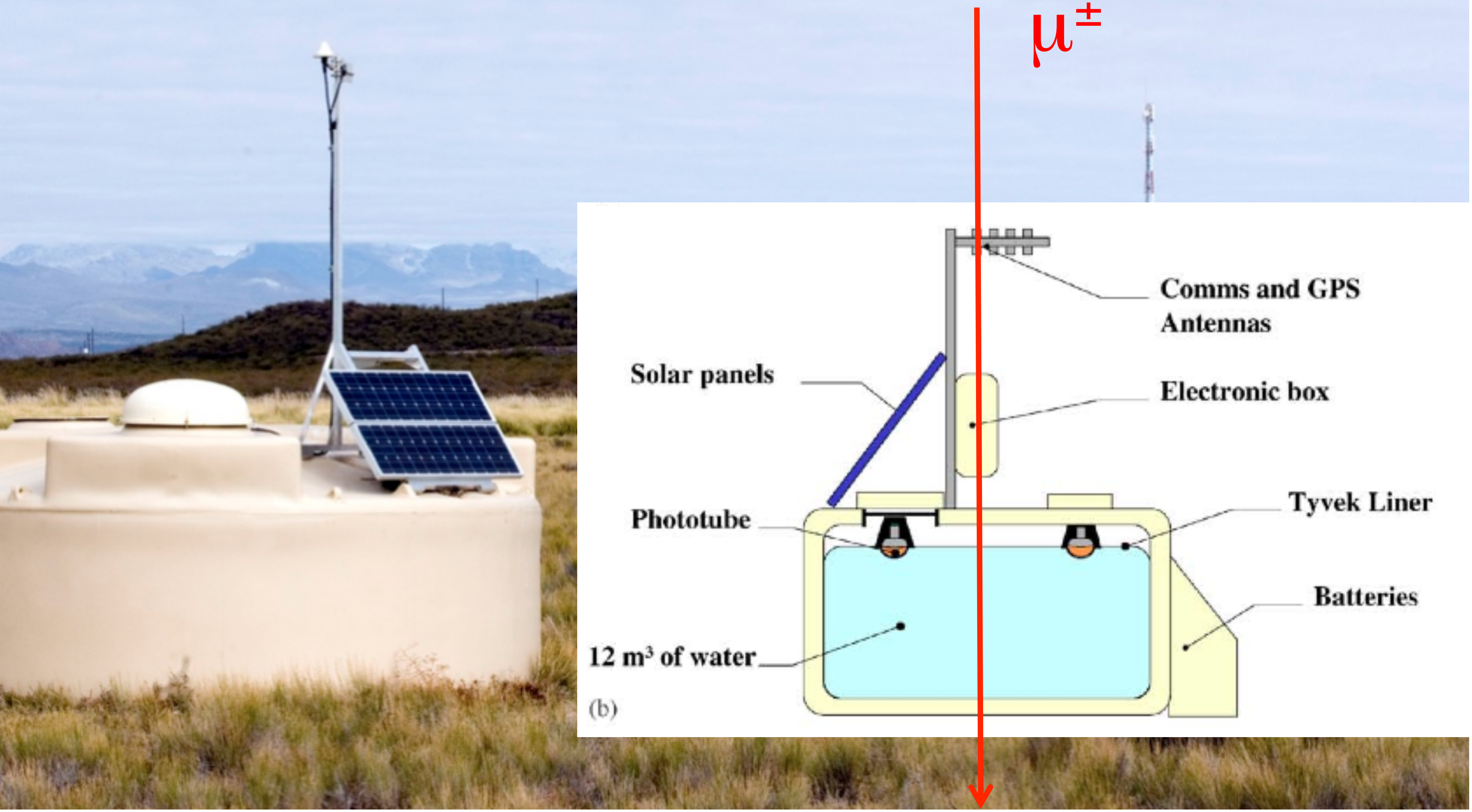
Air Shower Arrays: AUGER



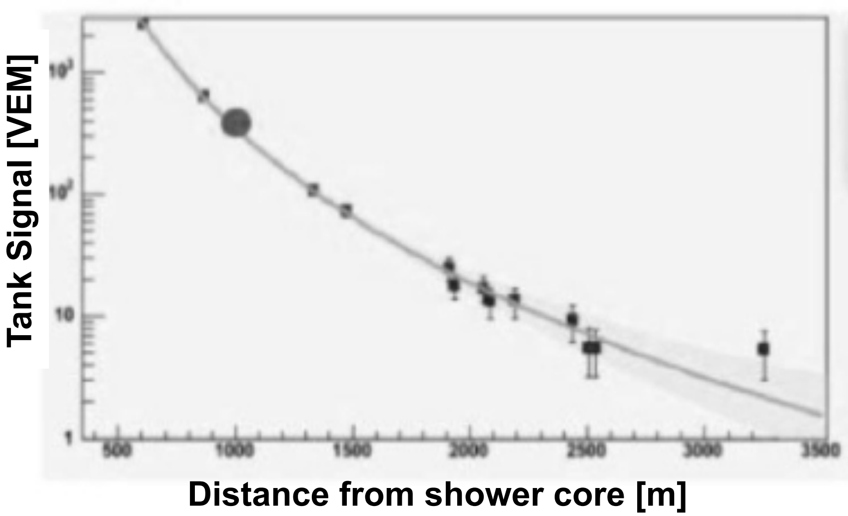
Air Shower Arrays: AUGER

Air Shower Arrays: AUGER

surface detector calibration



AUGER: Events (young shower)

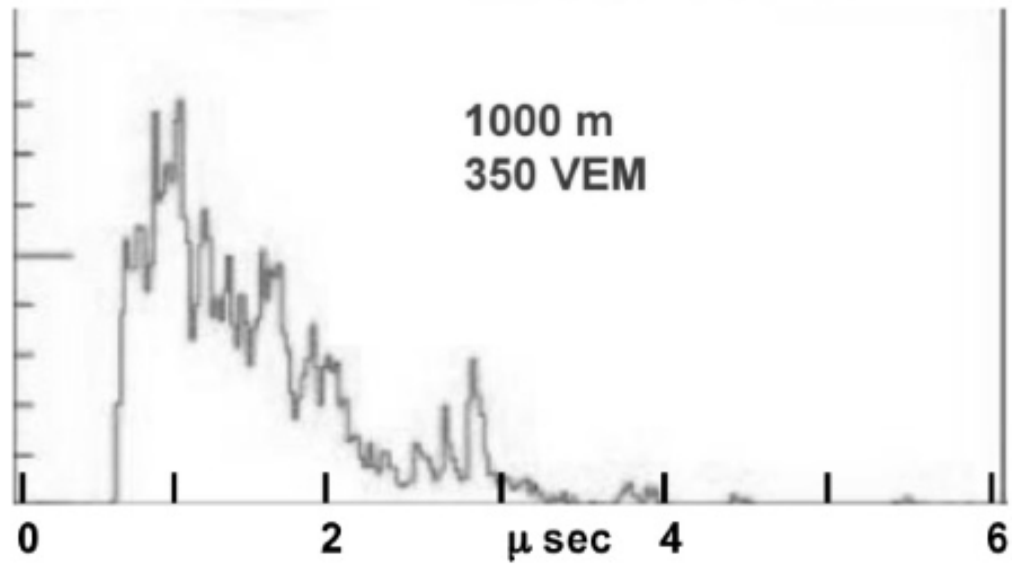


Mon Dec 29 09:23:45 2003
Easting = 470343 ± 21 m
Northing = 6095432 ± 25 m
dt = 126.8 ns

Theta = 34.4 ± 0.3 deg
Phi = 140.1 ± 0.3/sin(Theta) deg

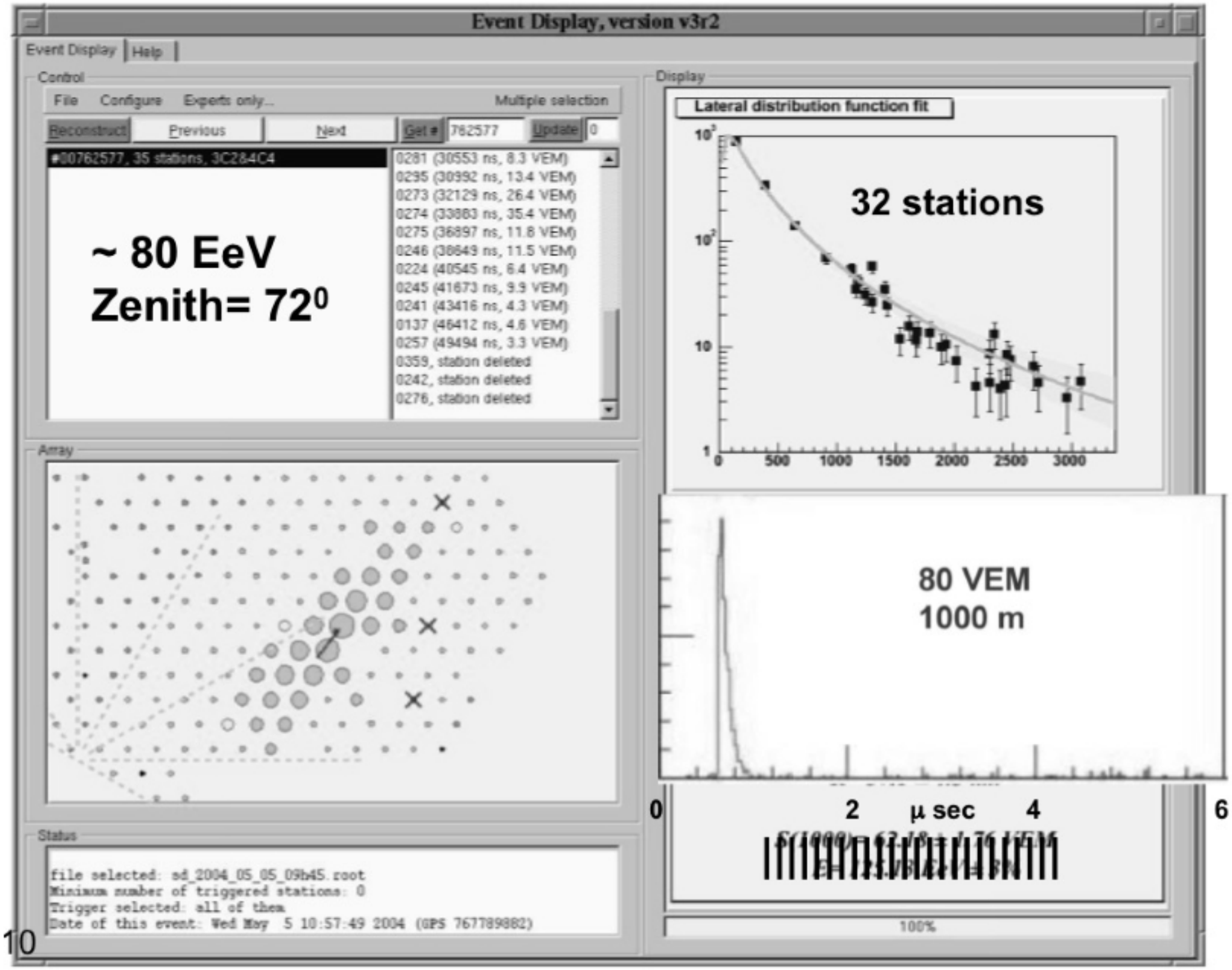
R = 12.5 ± 0.8 km

S(1000) = 347.8 ± 8.43 VEM
E = 75.2 EeV ± 3%



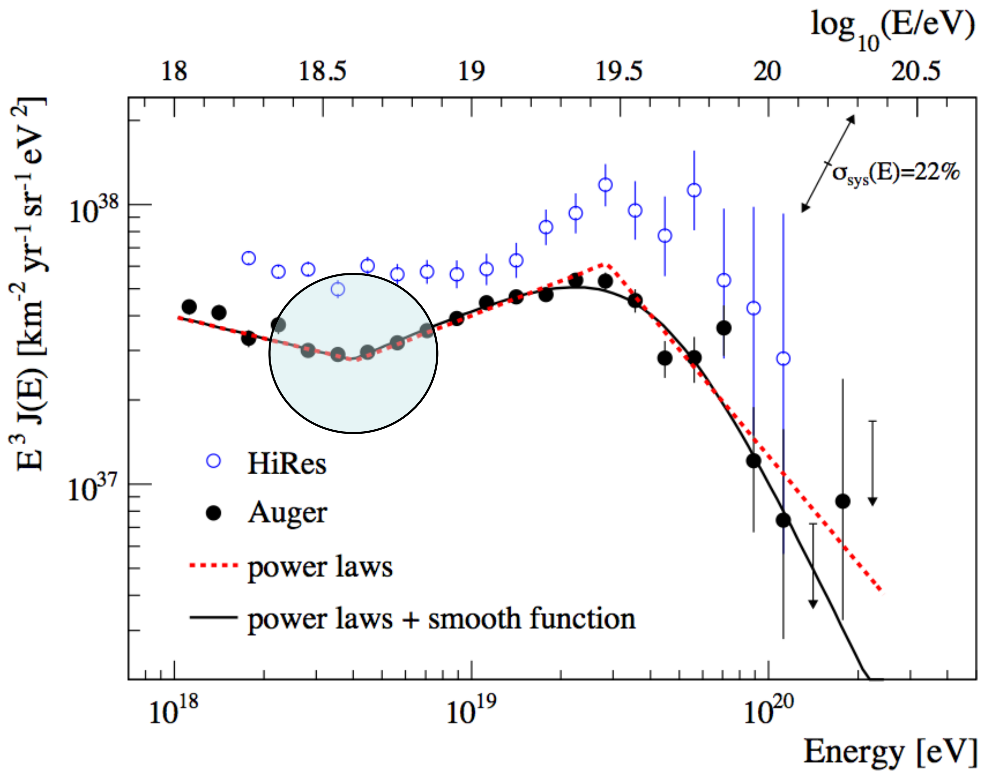
Cronin et al. 2009, arXiv:0911.4714v1

AUGER: Events (old shower)



Cronin et al. 2009, arXiv:0911.4714v1

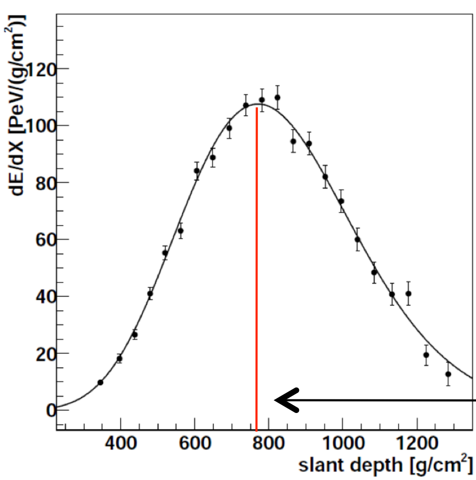
AUGER: Key Measurements



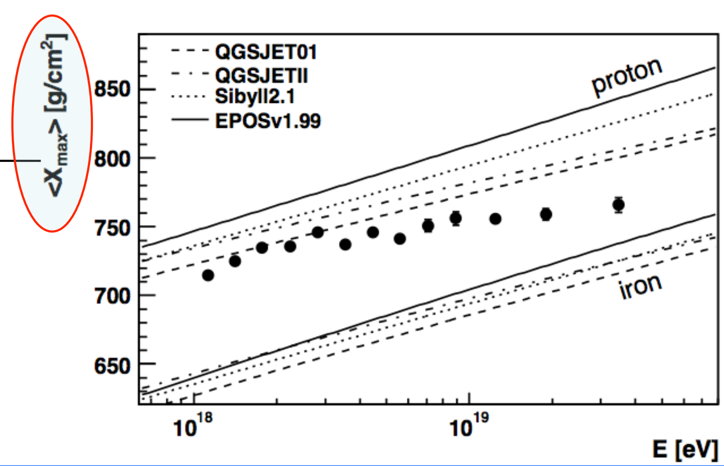
ankle

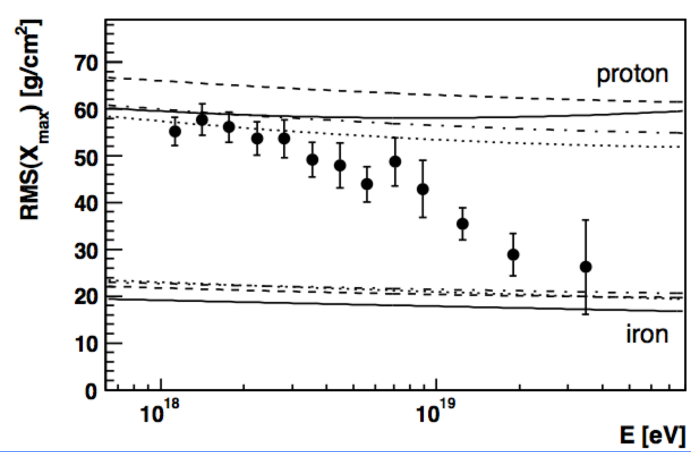
GZK

cutoff …



X[g/cm^2]





Gamma Ray Detectors

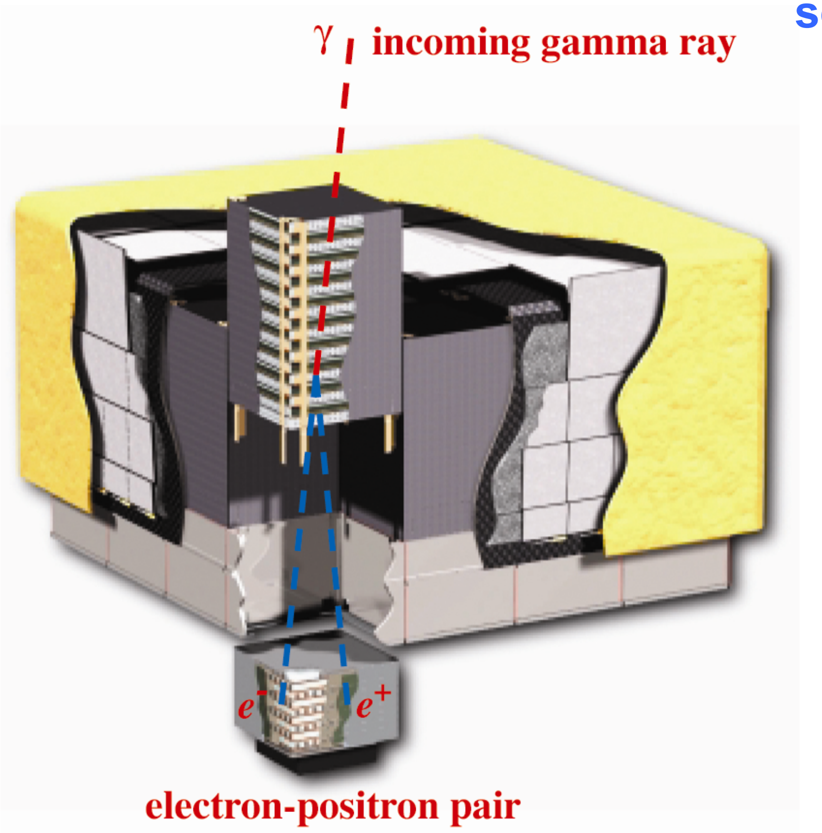
Gamma Ray Detectors Basic Properties

Instruments	Energy Range	Effective Collection Area	Angular Resolution	Field of View	Duty Cycle
Space Fermi-LAT (AGILE)	0.1 – 300 GeV	~ 1 m^2	0.6° (1 GeV) 0.15° (10 GeV)	~2.4 sr	~ 100%
Air Shower Surface detectors ARGO-YBJ, Milagro, …	~ 1 TeV – 100 TeV	~ 5,000 m^2	~0.5° - 1° (3 TeV)	~1 sr	~100%
Air Cherenkov MAGIC H.E.S.S. VERITAS	30 GeV – 100 TeV	~ 10^5 m^2	0.2° (50 GeV) 0.1° (E>200 GeV)	~10^{-2} sr	~ 10%

In Space: Fermi-LAT

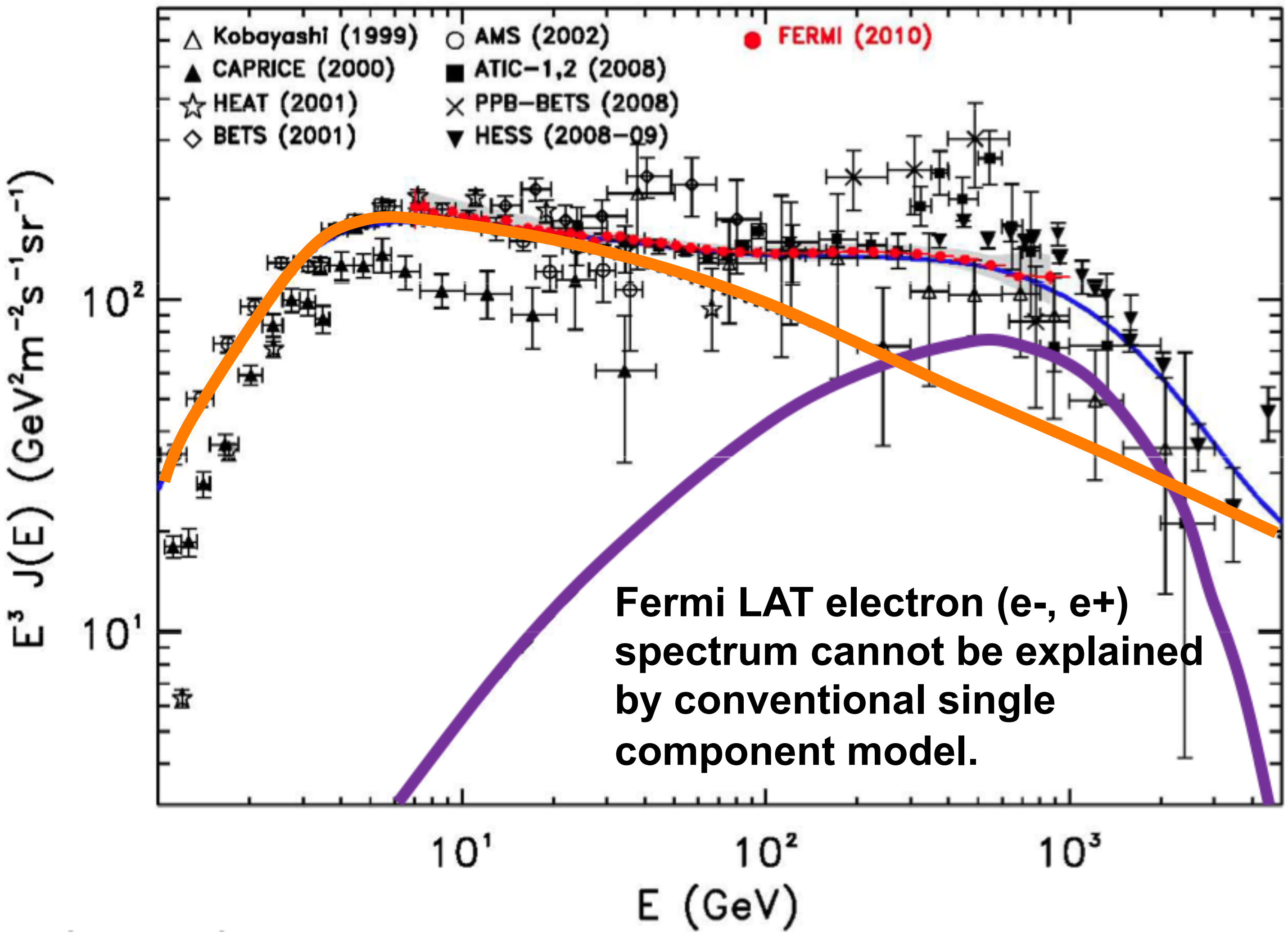
ACD
segmented scintillator tiles

Si Tracker
pitch = 228 μm
8.8 x 10^5 channels
18 planes



CsI Calorimeter
hodoscopic array (8 layers)
6.1 x 10^3 channels

Cosmic Ray e^- Spectrum by Fermi



possible explanation

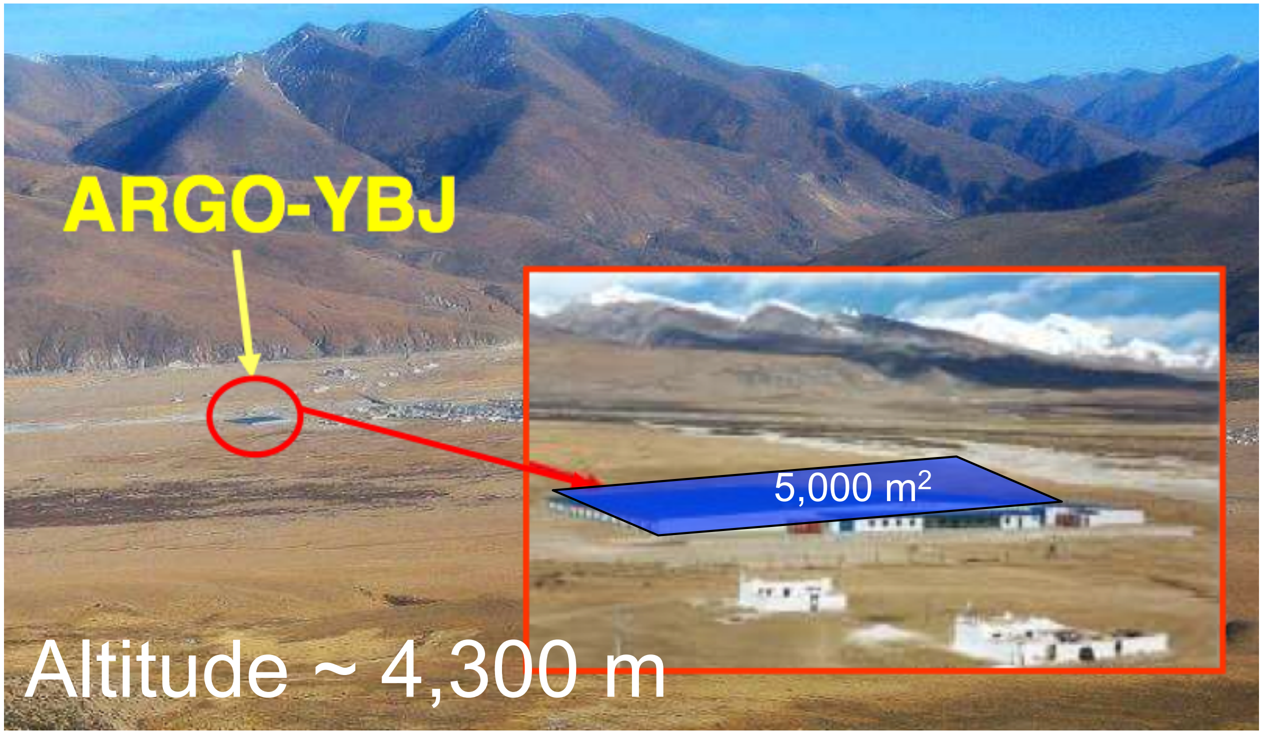
Primary e^-:
e^- from acceleration in Supernova remnants

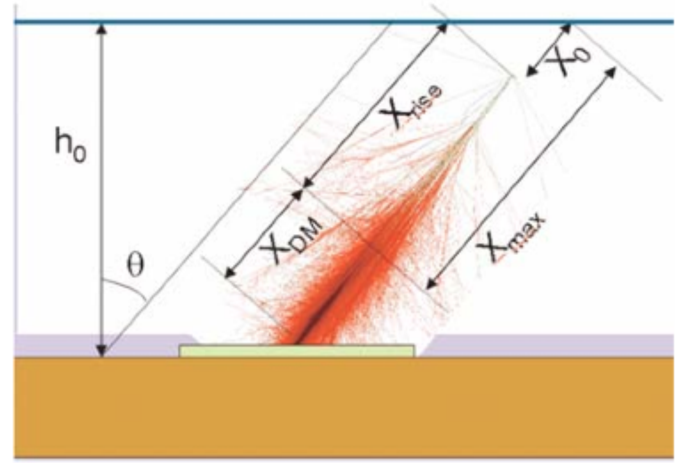
Secondary e^- & e^+:
Interactions of C.R.s with *ISM in our galaxy*.

Secondary e^- & e^+:
produced during acceleration of C.R.s in Supernova remnants

see also Mertsch & Sarkar 2011, arXiV:1108.1753v1

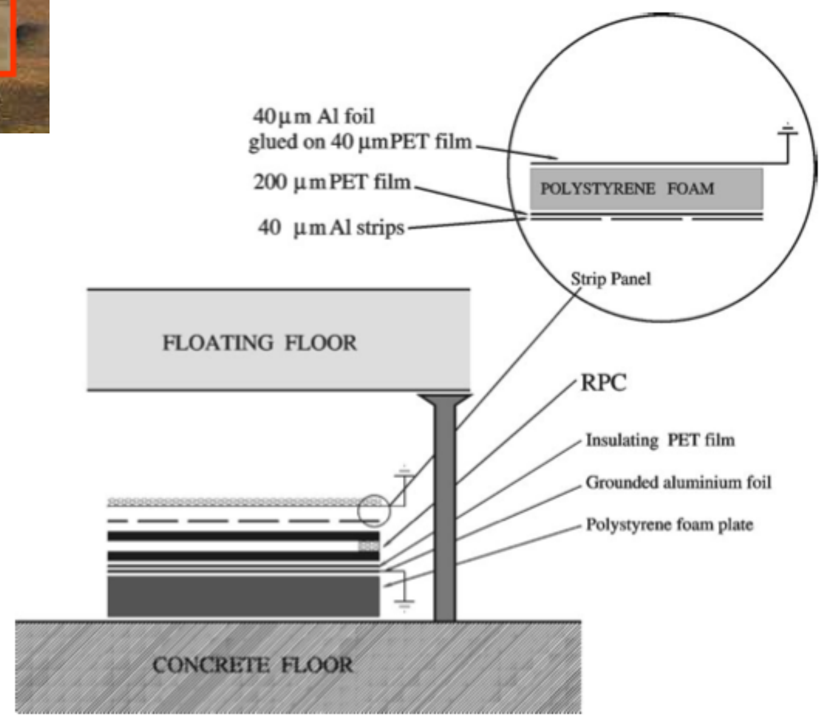
Air Shower γ-ray Detector: ARGO-YBJ



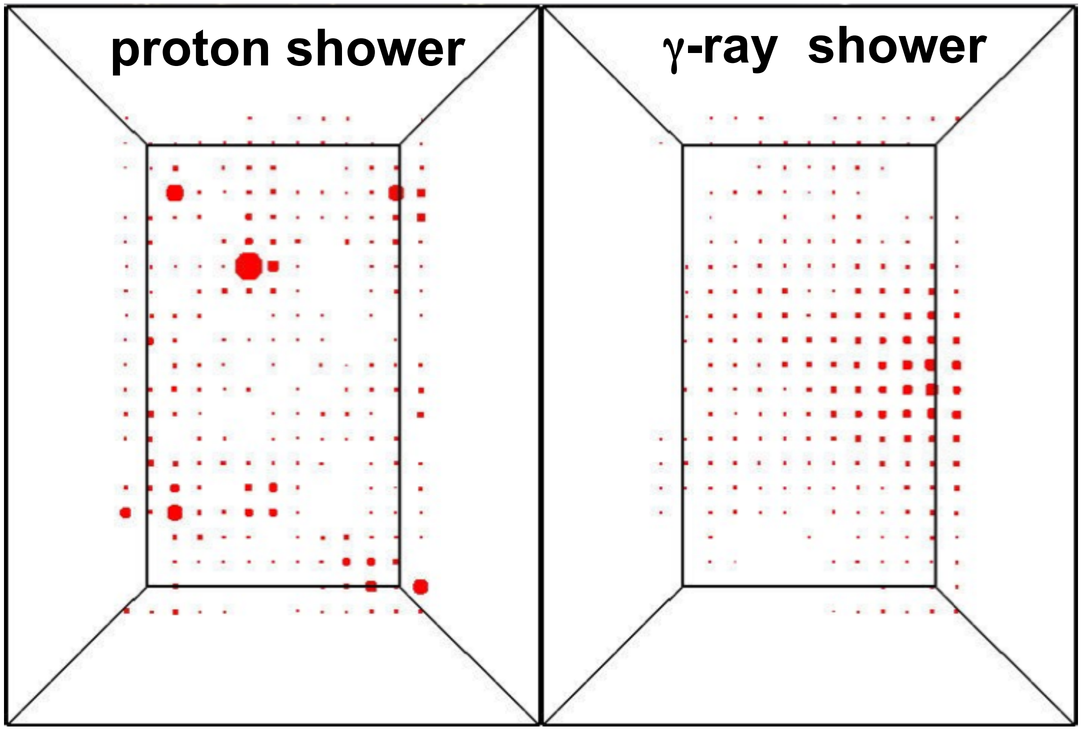


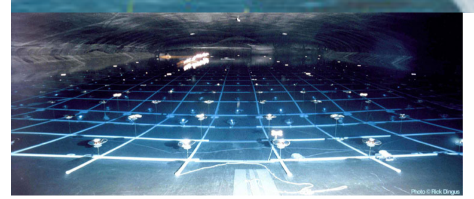
Resistive Plate Chambers (RPCs)

- large active area covered
- ns timing accuracy – shower reconstruction
- energy threshold E_T ~ 1 TeV
- Angular resolution ~ 1^{o}
-Effective area ~ 5,000 m^2
- wide FOV



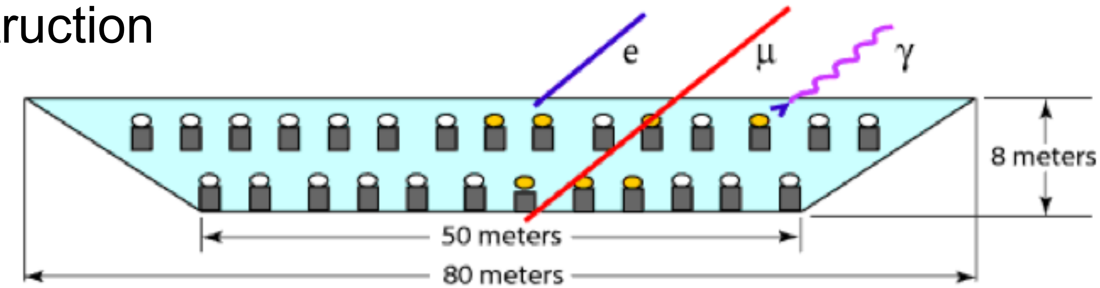
Air Shower γ-ray Detector: Milagro



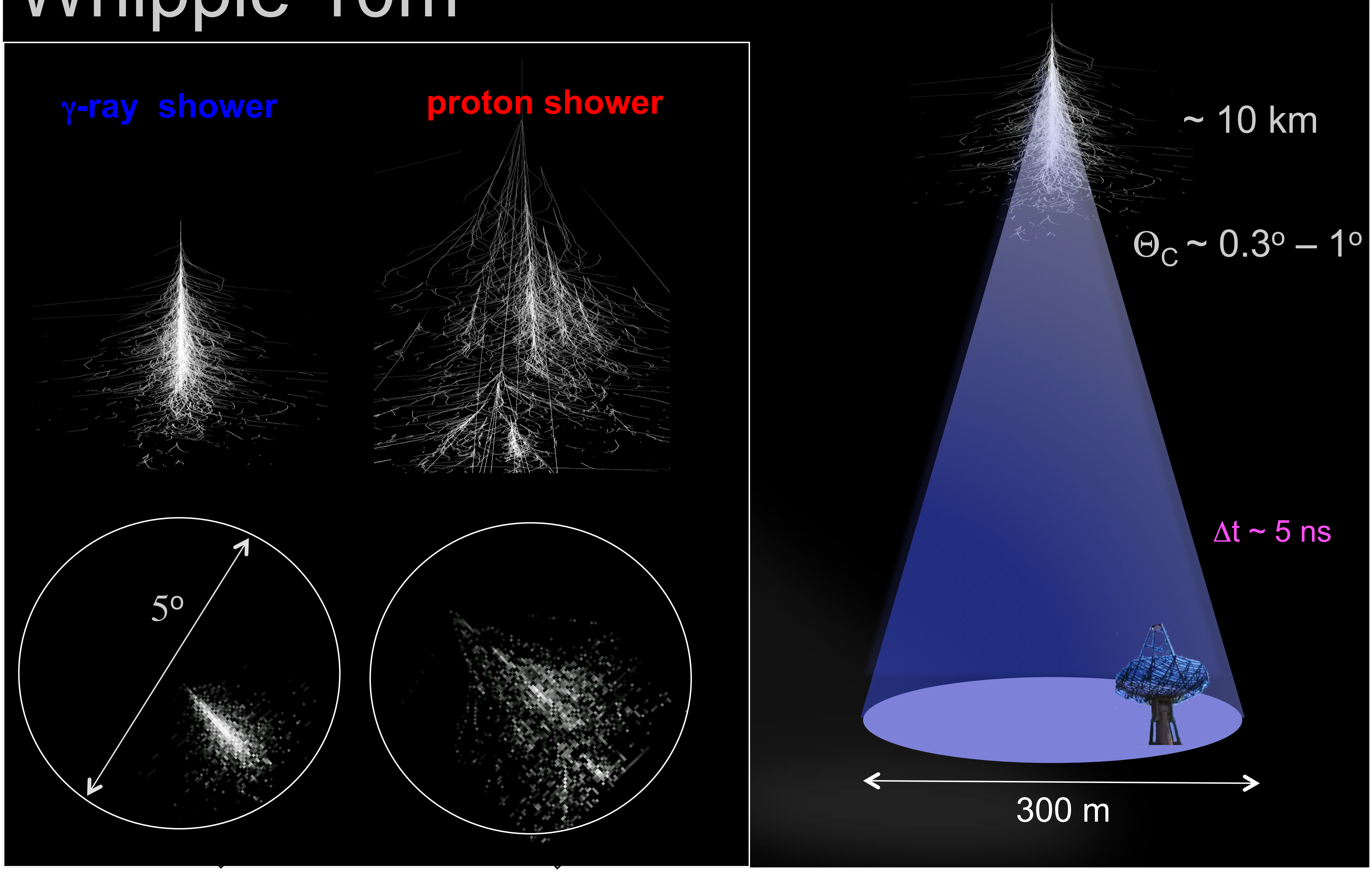


Water Cherenkov Technique

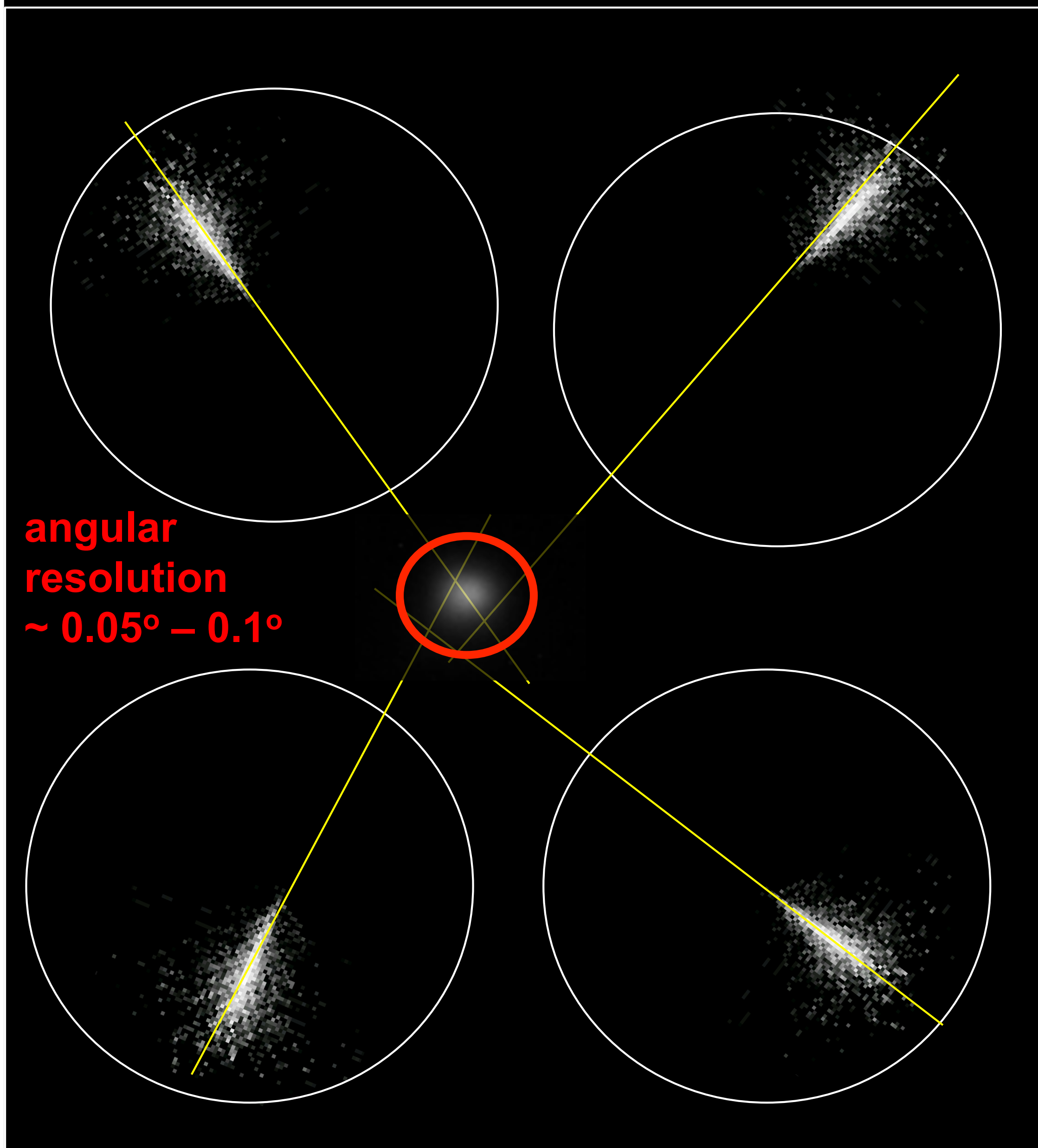
- wide FOV
- ns timing accuracy – shower reconstruction
- energy threshold E_T ~ few TeV
- Angular resolution ~ 0.5^o - 1^o
- Area of pond ~ 4,000 m^2

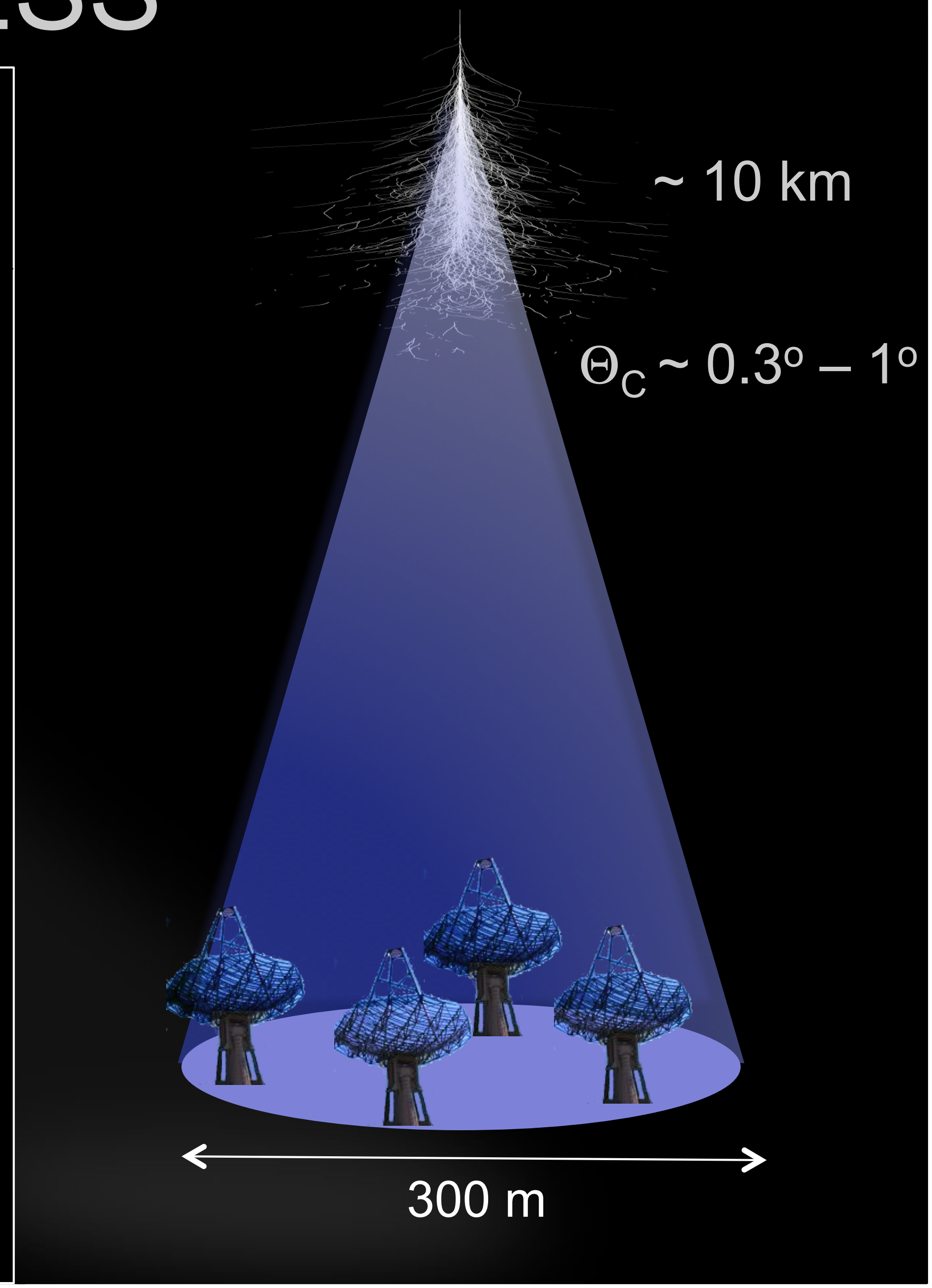


Air Cherenkov Technique: Whipple 10m

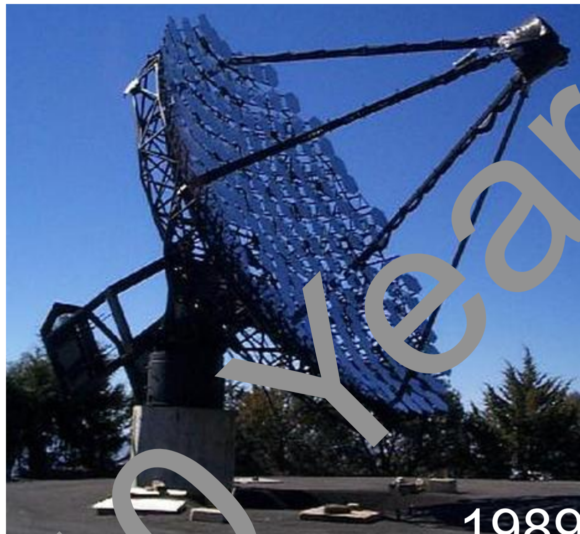


Air Cherenkov Technique: Stereo: VERITAS, HESS

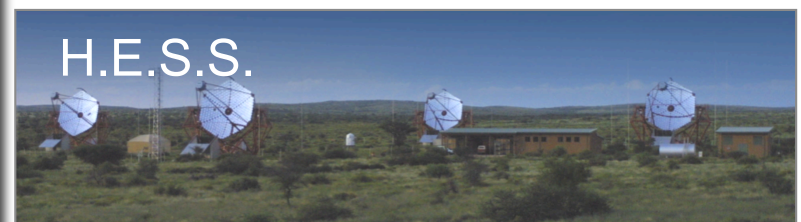




Air Cerenkov Technique:



40 Years!



Camera ~ 1 PMT
- Sensitivity ~ 10 Crab
- No 5 σ detection

Camera ~ 37 PMTs
- Sensitivity ~ 1 Crab
- 9 σ detection

Cameras ~ 500-1000 PMTs
- Sensitivity ~ 1% of Crab
- 5 σ detection of 1 Crab in 30 s

Whipple: Weekes et al. 1989, ApJ, 342, 379

Air CerenkovTechnique: Arrays

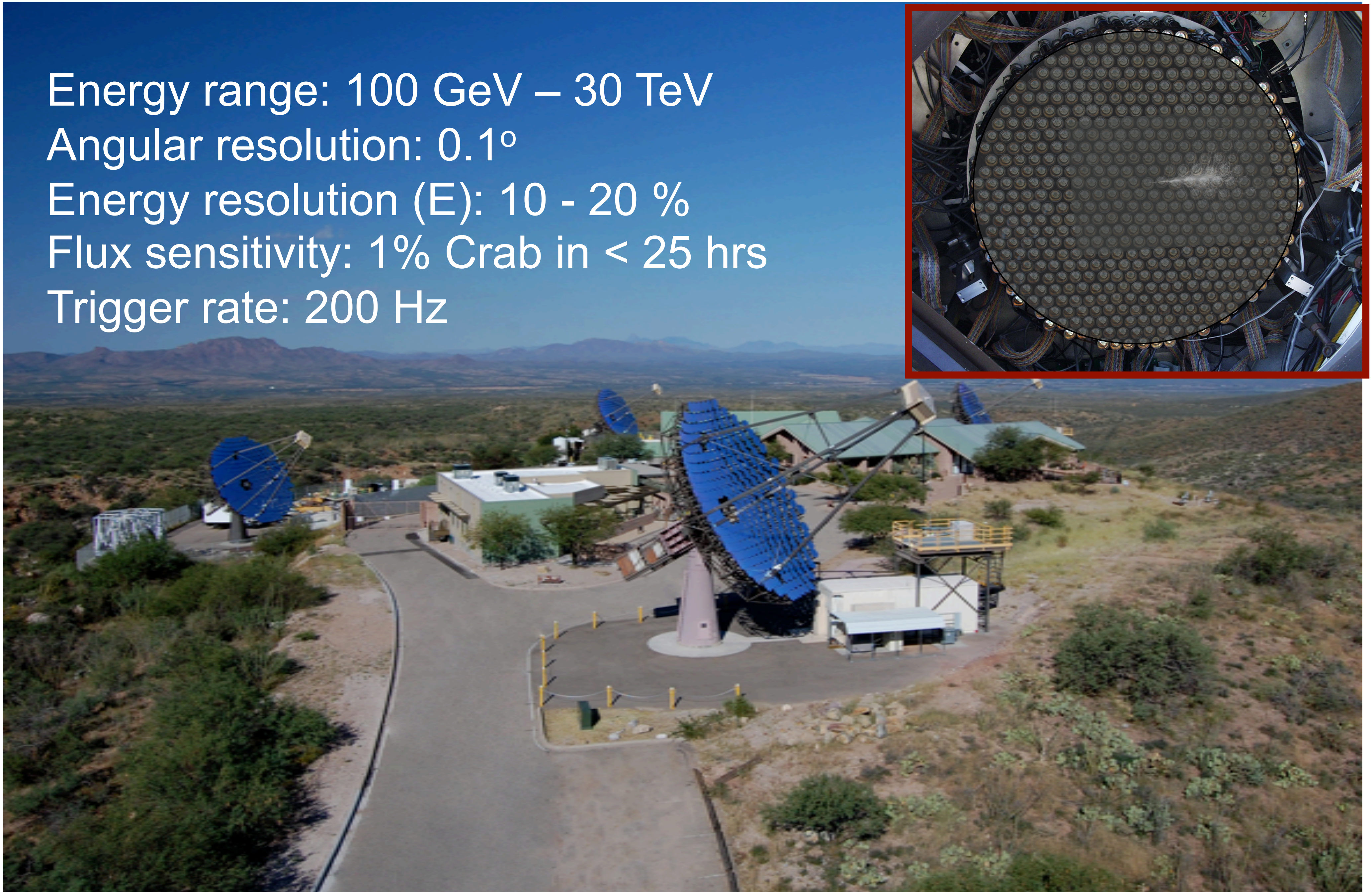
Air CerenkovTechnique: Arrays

Air Cerenkov Technique: Arrays

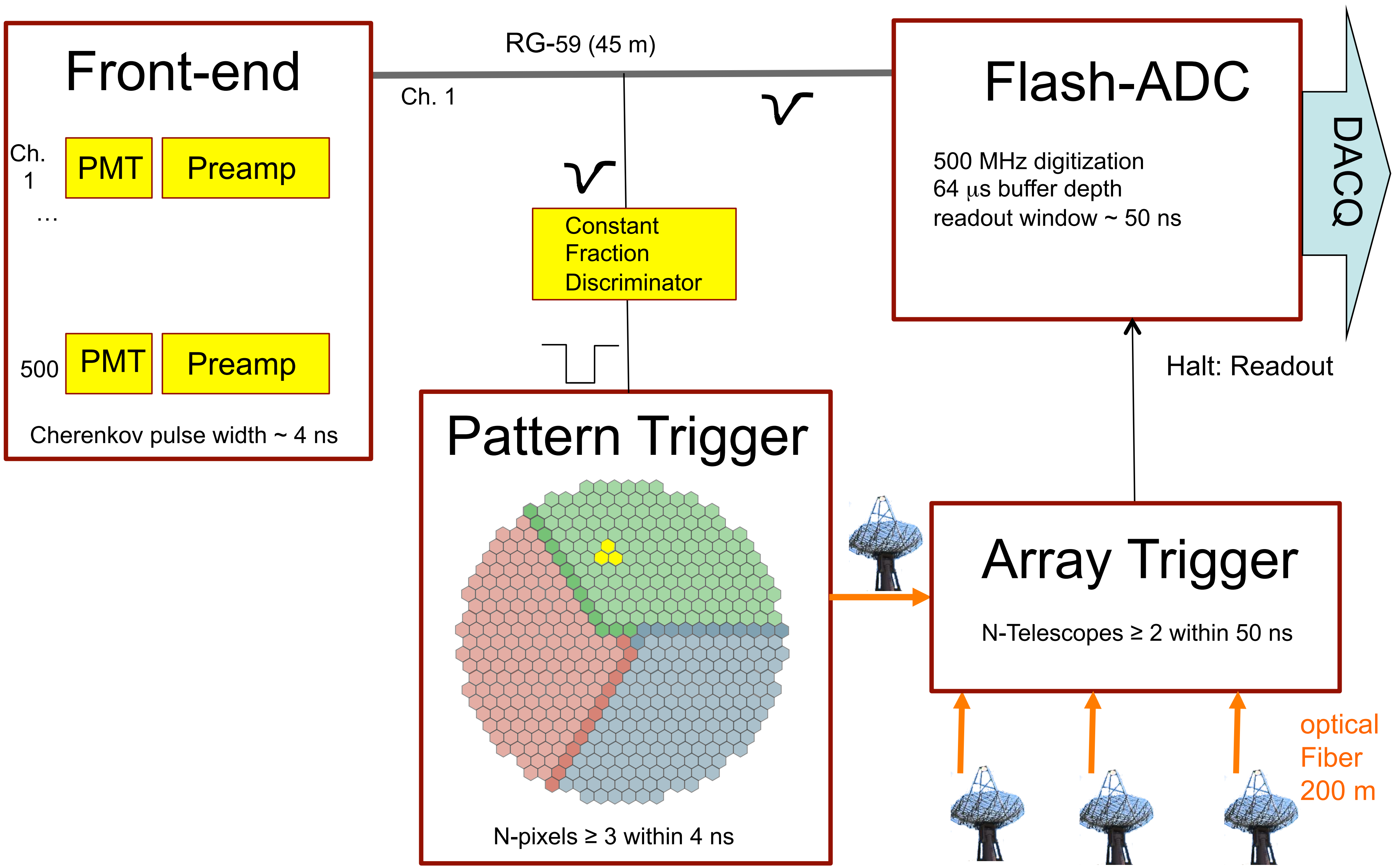
Air Cerenkov Technique: Arrays

Air Cerenkov Technique: Arrays

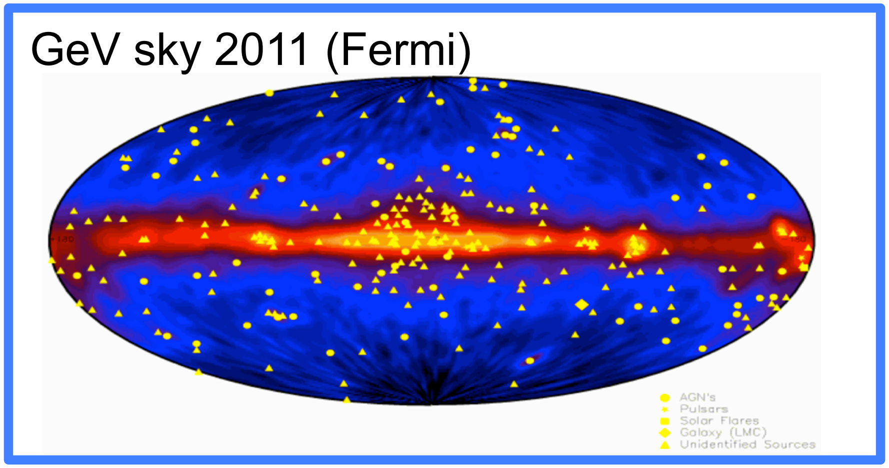
Energy range: 100 GeV – 30 TeV
Angular resolution: 0.1°
Energy resolution (E): 10 - 20 %
Flux sensitivity: 1% Crab in < 25 hrs
Trigger rate: 200 Hz

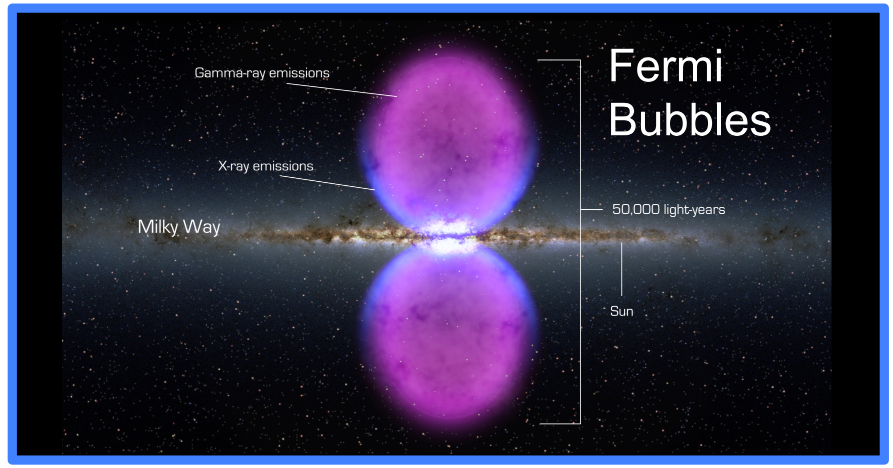


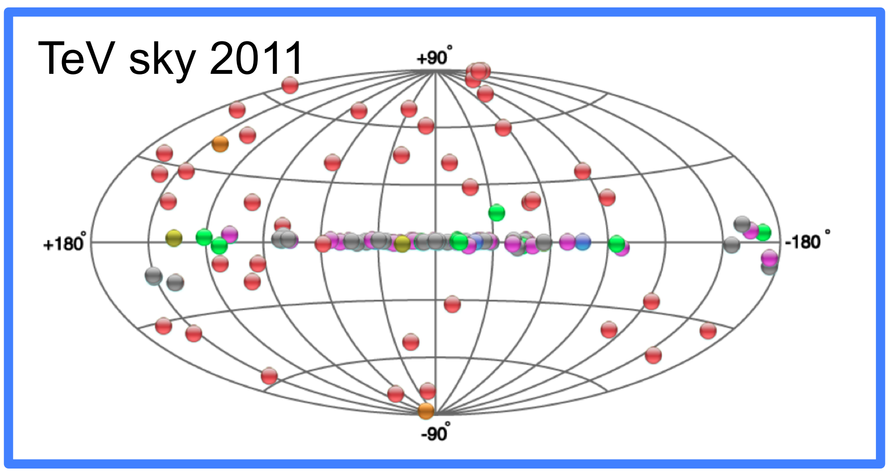
VERITAS Electronics

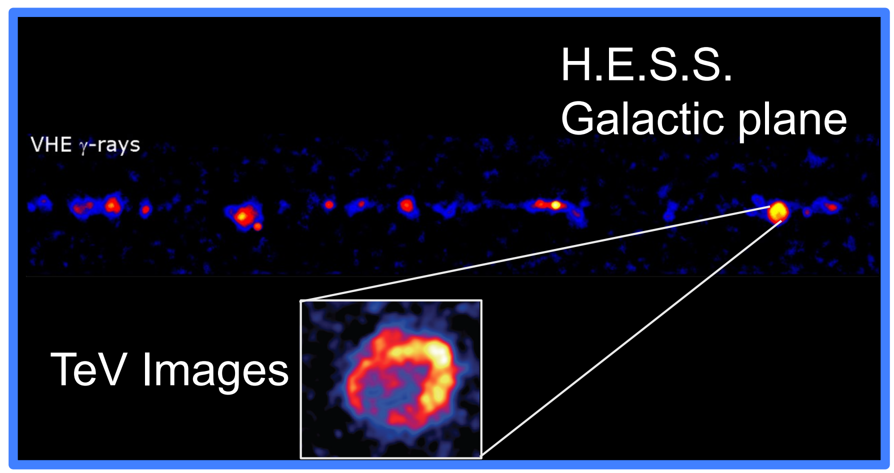


Surprising Discoveries with Current Generation Gamma Ray Telescopes

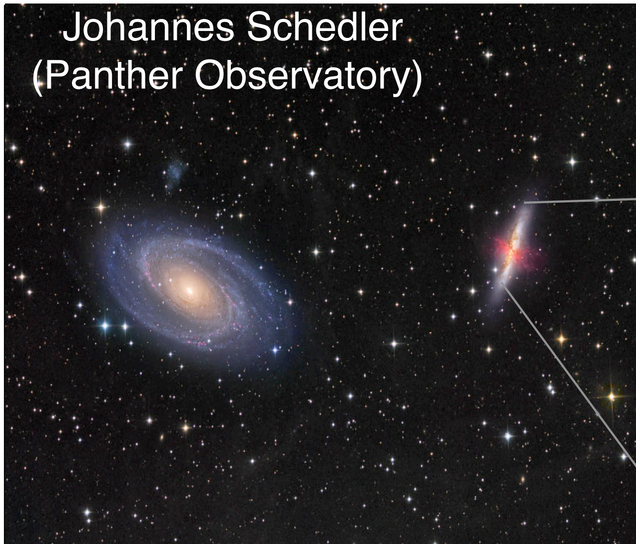




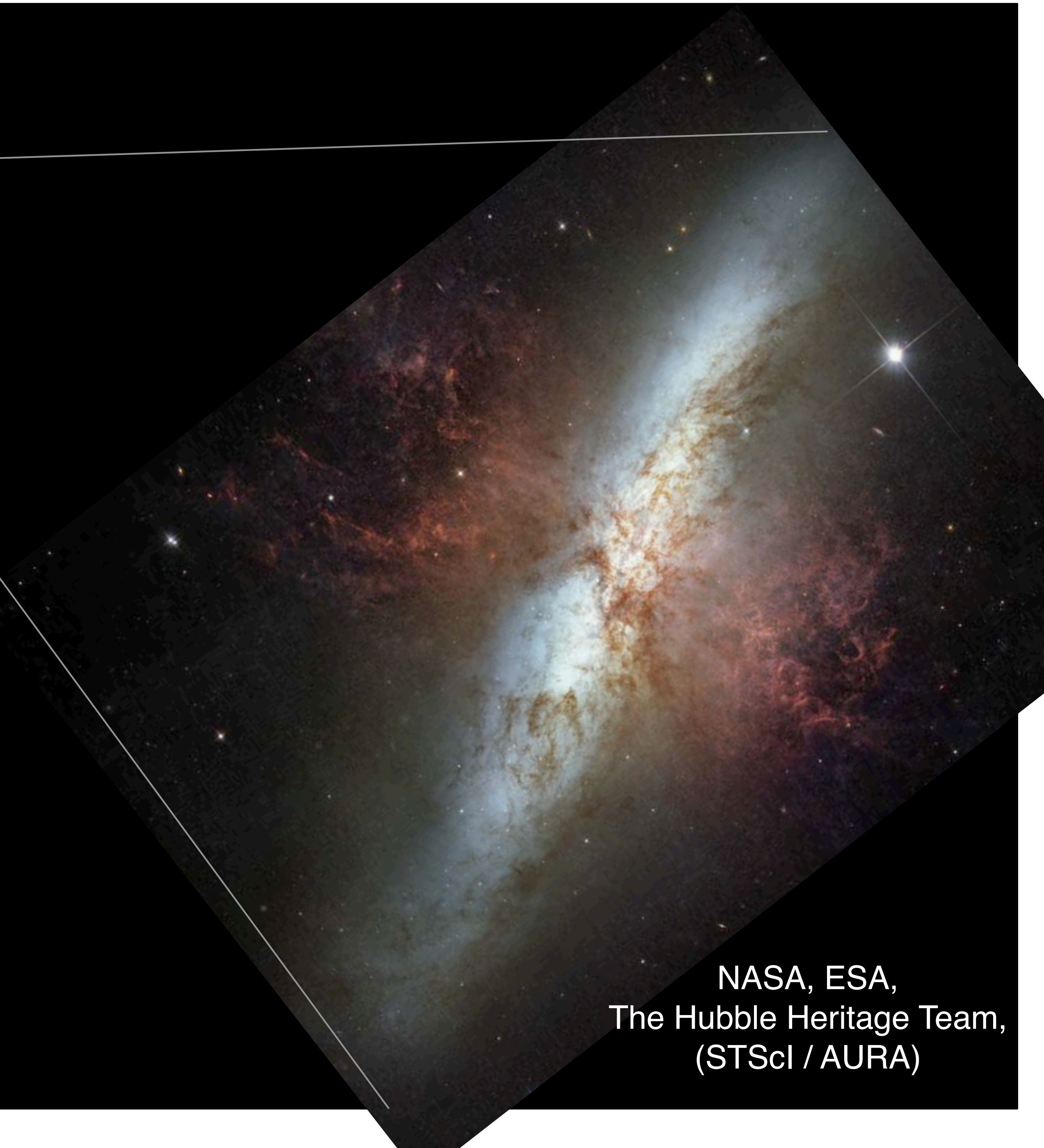




Viewing Cosmic Accelerators in Bulk – Starburst Galaxies

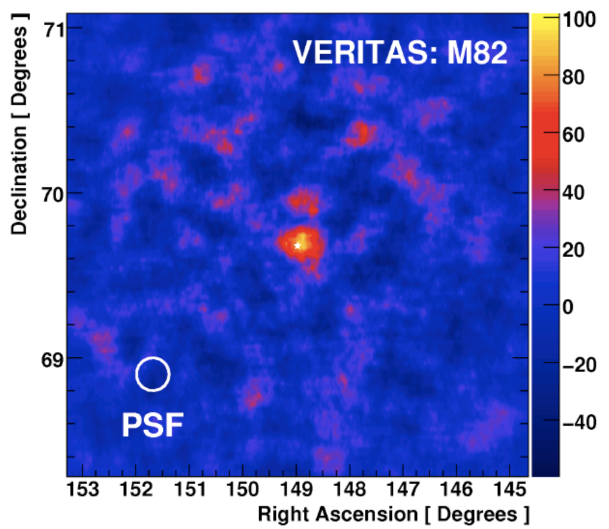


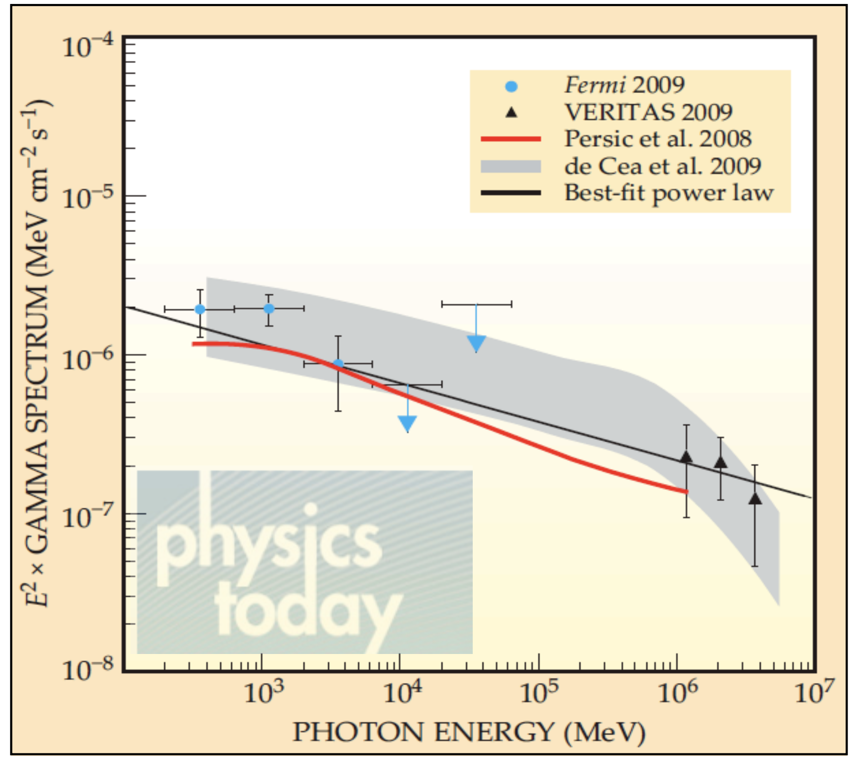
Galaxy collision
→ tidal wave
→ starbursts
→ supernovae



Origin of Cosmic Particles: in Bulk – Starburst Galaxies

Connection between star formation & acceleration of hadronic cosmic particles



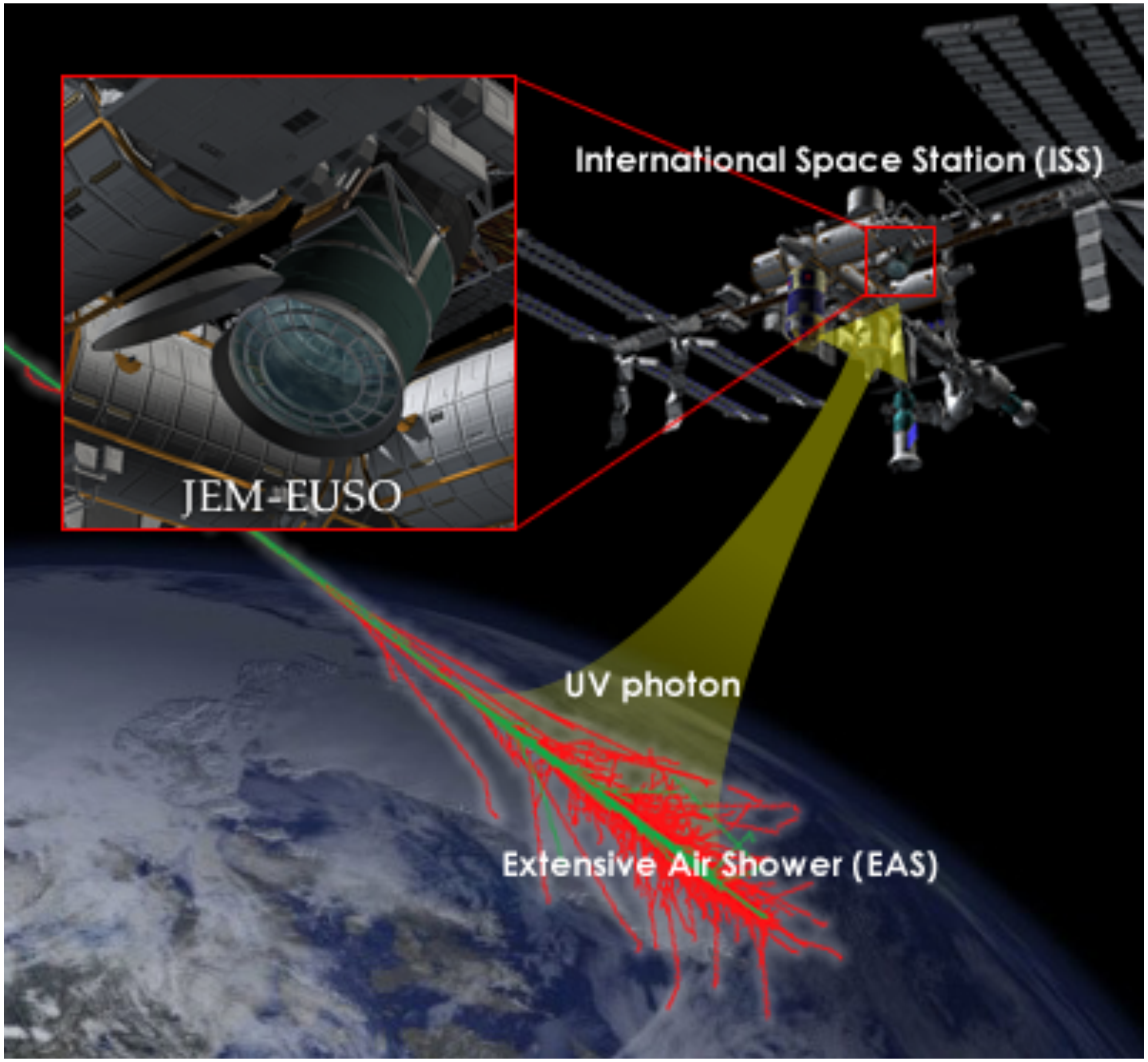


Acciari et al. (VERITAS Collab.), Nature, 462, 770 (2009)
Abdo et al. (Fermi Collab.), arXiv:0911.5327
B. Schwarzschild, Physics Today, vol. 63, p 13 (2010)

- Starburst galaxy M82 (nearby Milky Way) exhibits a glut of **supernova** remnants (**accelerator providing beam …**)!
- Combined with high **gas** density (**… on target**).
- M82 provides the "perfect storm" for a high yield of GeV – TeV emission.
- Strong evidence that **supernova remnants** accelerate **protons (100 year old mystery)**!

Next Generation Observatories

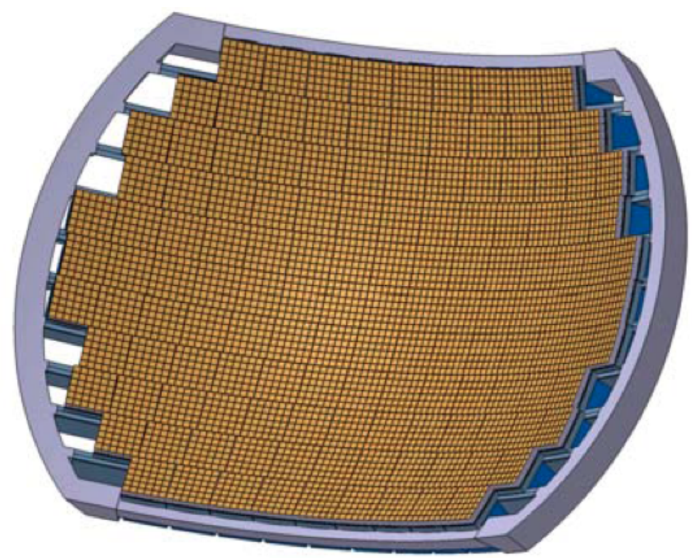
Cosmic Rays from Space:



Extreme Universe Space Observatory

- Fresnel lense for the detection of fluorescence light from E> 10^{19} eV showers

- Aperture
 ~ 125,000 km^2 sr
 (AUGER ~ 7,000 km^2 sr)



Water Cherenkov Technique: HAWC

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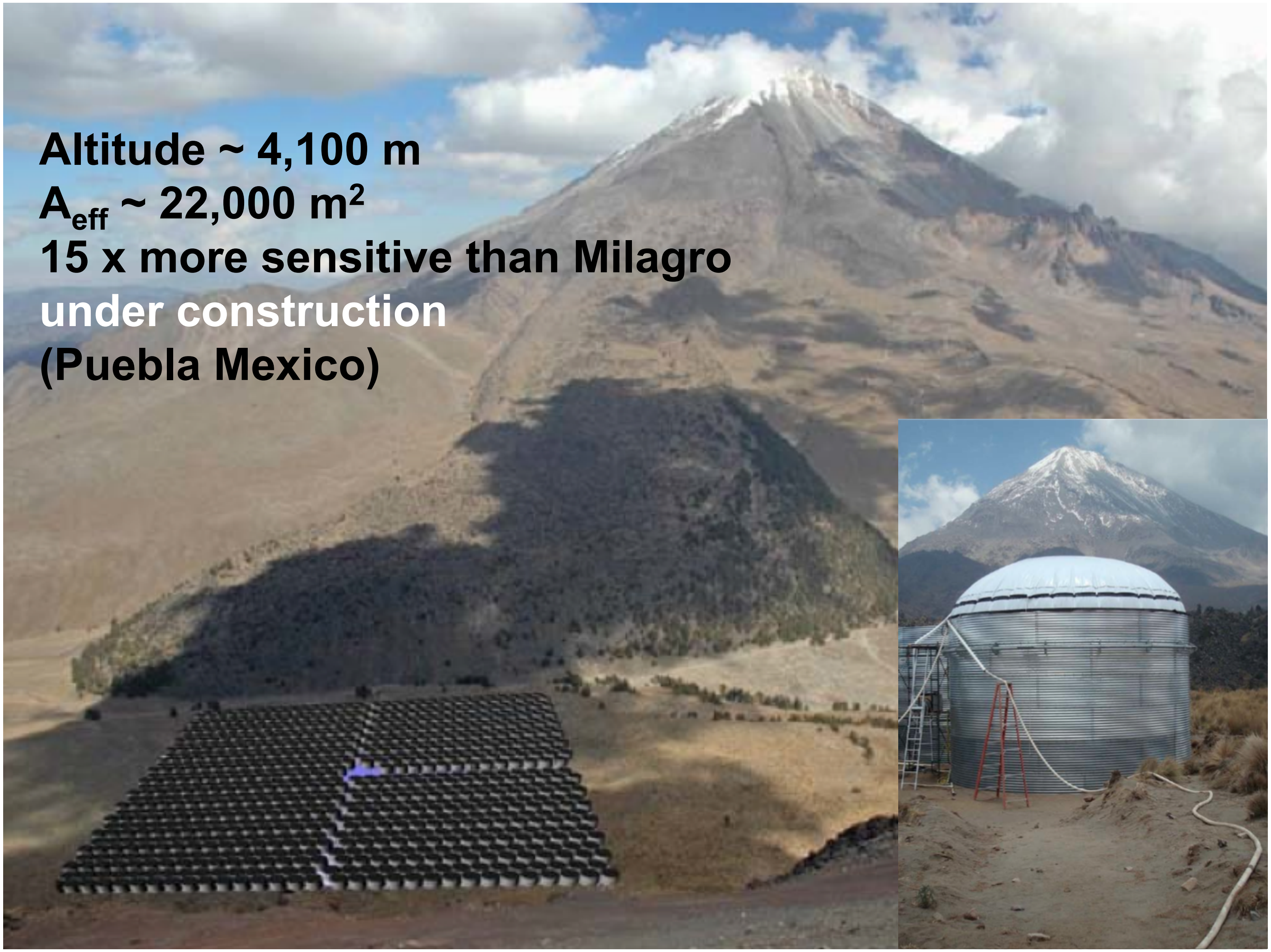
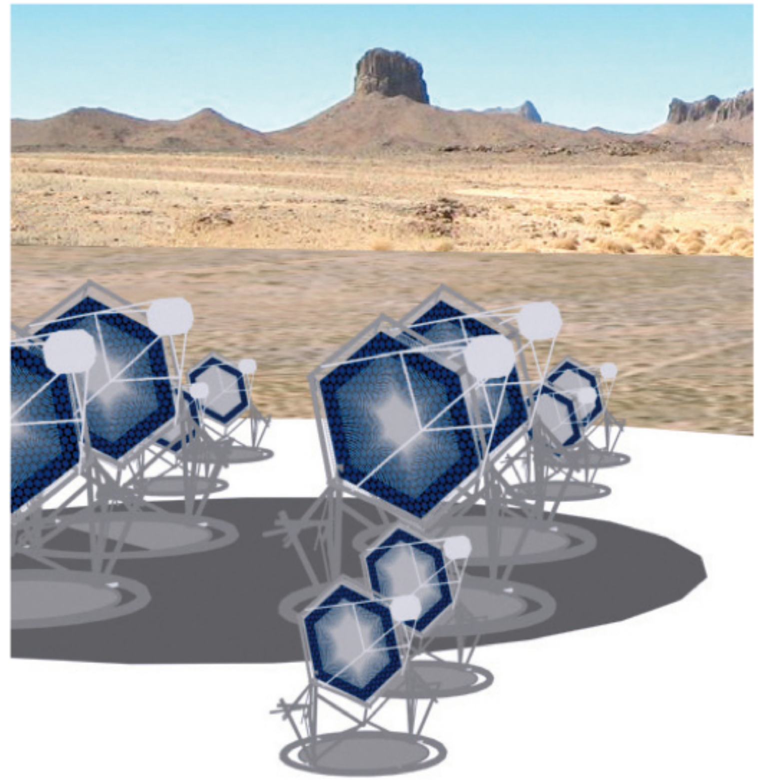


Cherenkov Telescope Array (CTA)

- **What is CTA?**

  - **ground-based successor** to **MAGIC**, **VERITAS, HESS & Fermi** will revolutionize VHE γ-ray science
  - 10 GeV – 100 TeV with **ten times better sensitivity**
  - worldwide VHE science community coalesced around a single project: 1 km^2 array of Cherenkov telescopes
  - **3 different telescope sizes**: Small Size Telescopes, **Medium Size Telescopes**, Large Size Telescopes



- **What will CTA do?**

Particle Physics

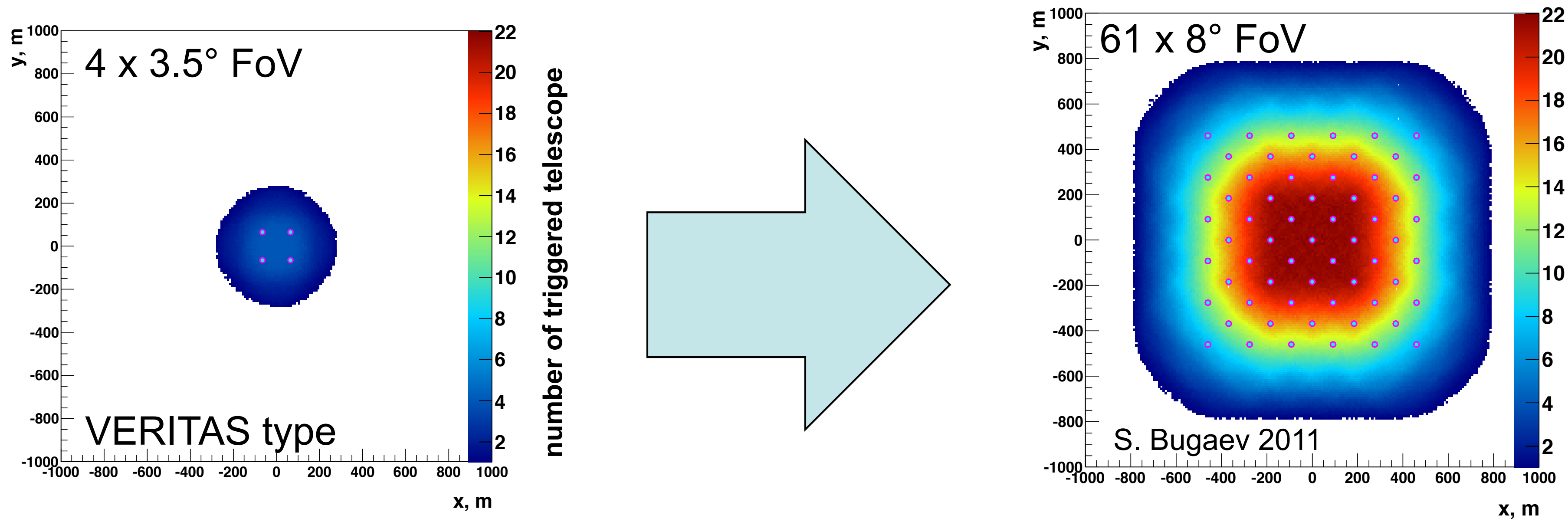
- Dark Matter annihilation
- Lorentz invariance violation
- EBL; axion-like pseudoscalar bosons

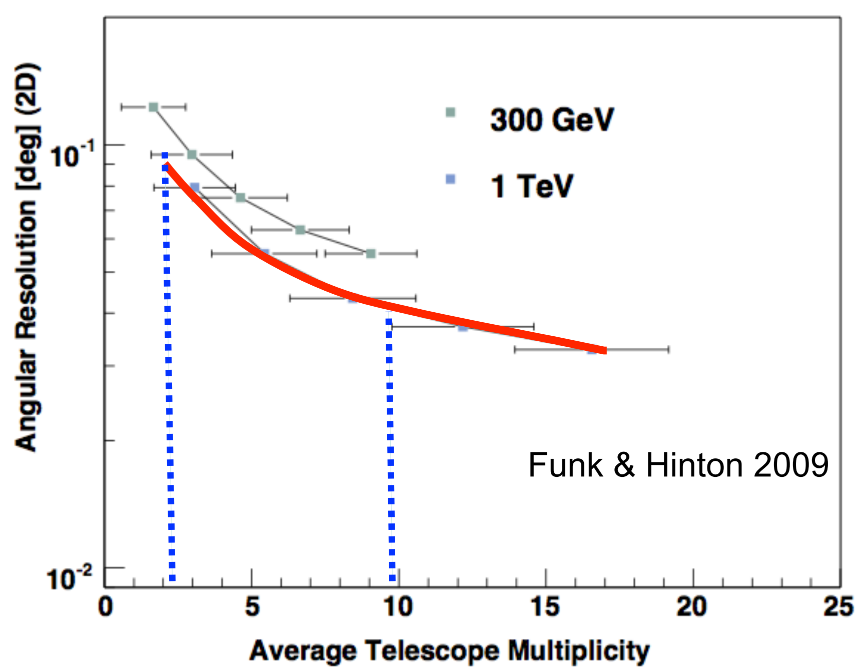
Astrophysics & Cosmology

- Galactic/extragalactic particle acceleration
- Origin of intergalactic/cosmological B-fields
- Black holes & relativistic jets

"Discovery machine" for particle astrophysics & astronomy at the TeV scale

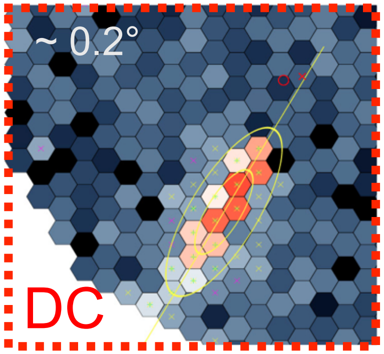
Medium Size T. Array – Effective Area

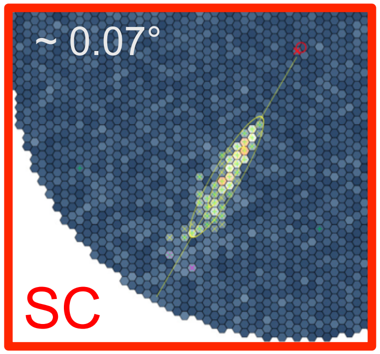


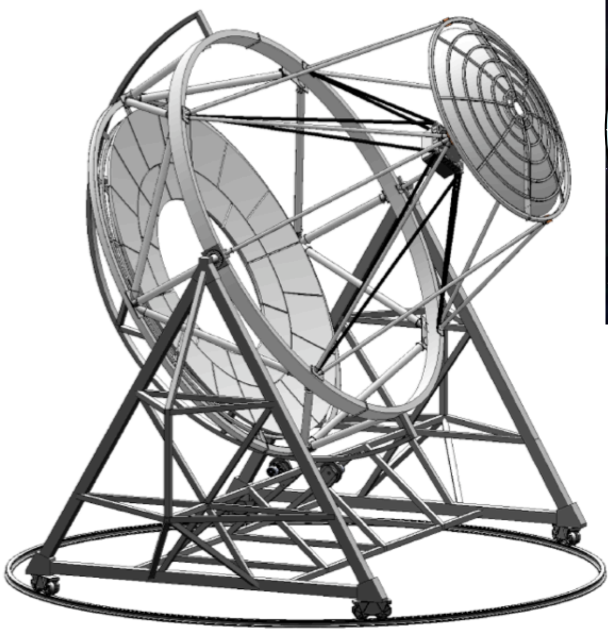


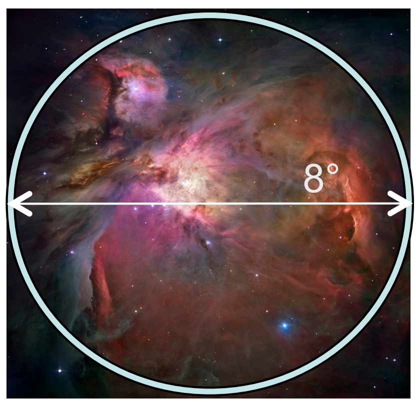
- 1 km^2 array with nearly **optimal angular resolution**
- **better C.R. rejection**
- **10 x better sensitivity**

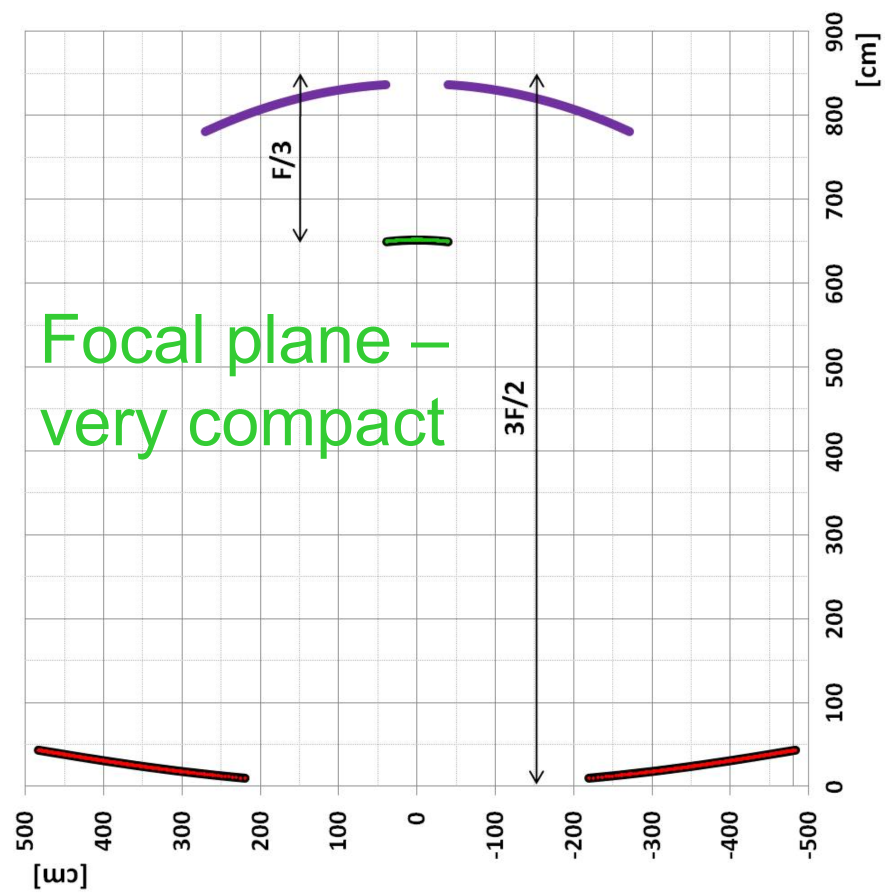
US: High resolution 2-mirror telescope



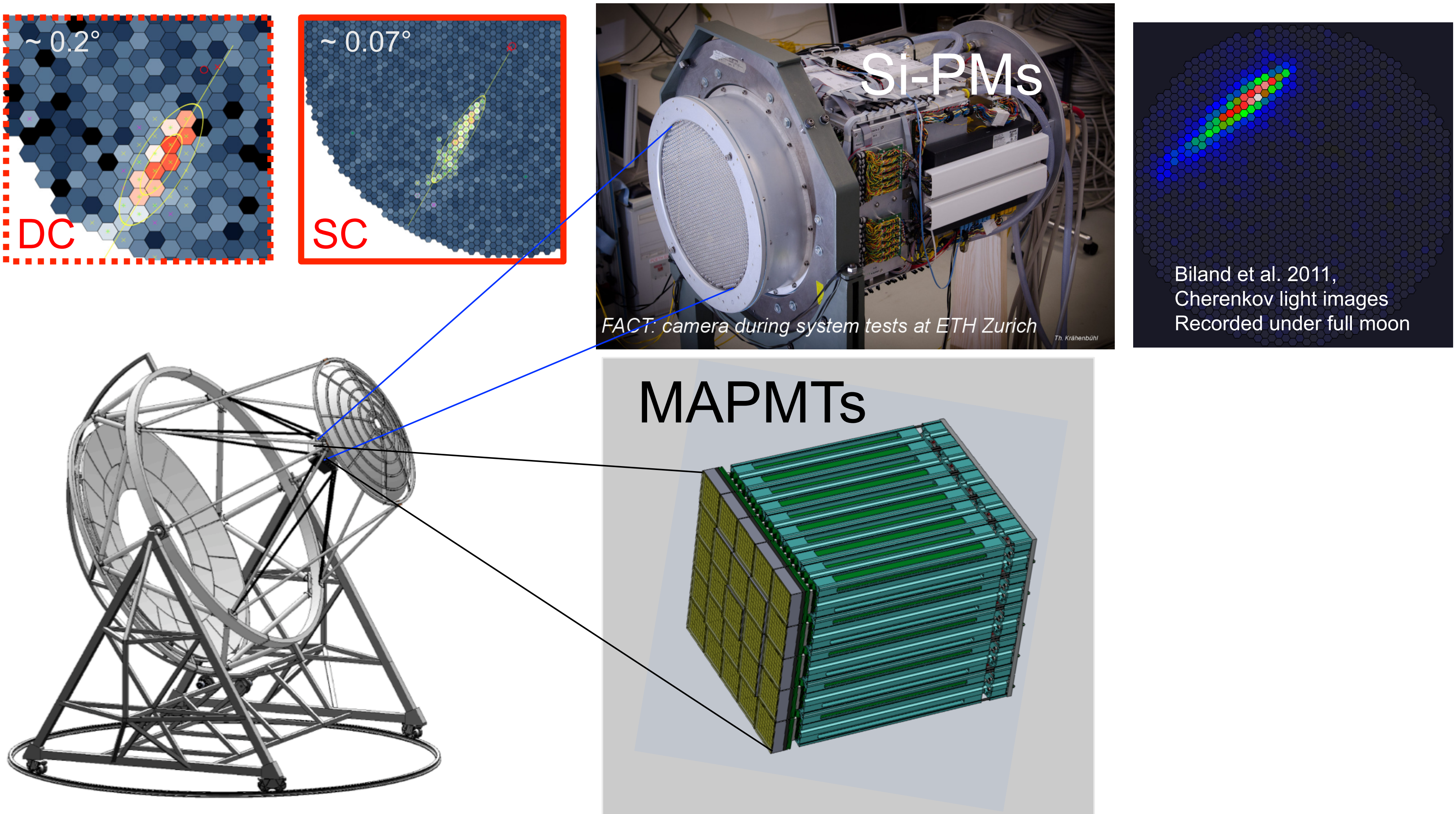




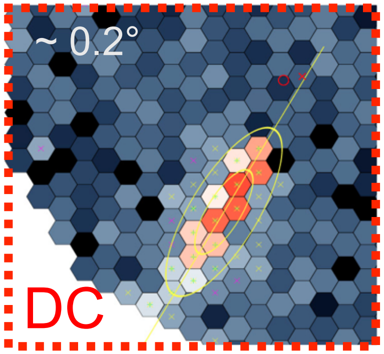


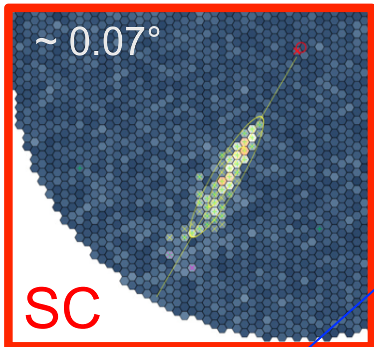


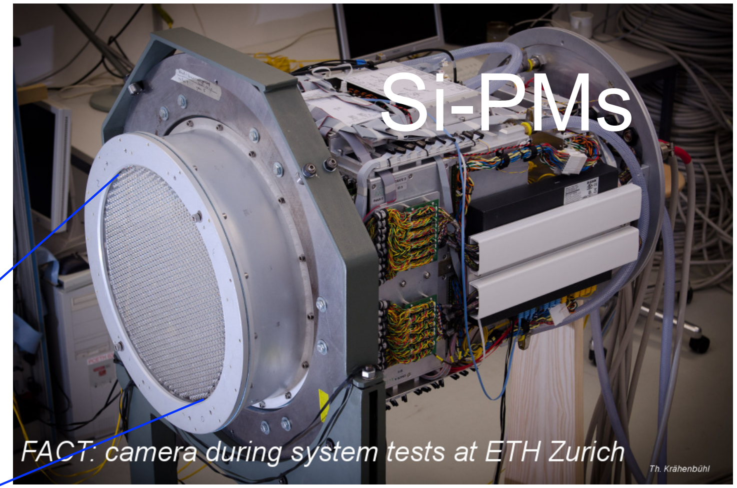
High resolution – Compact Camera

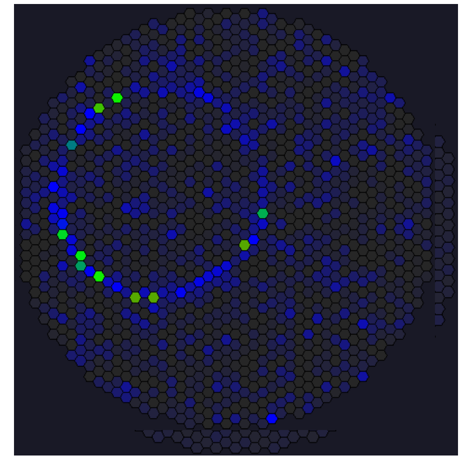


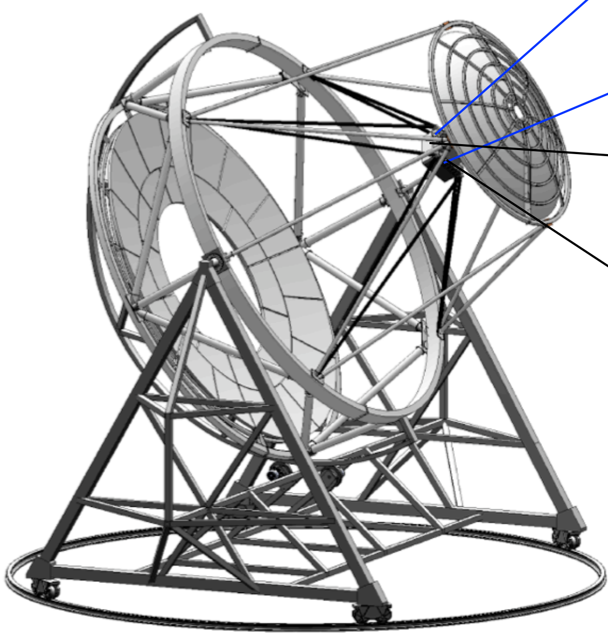
High resolution – Compact Camera

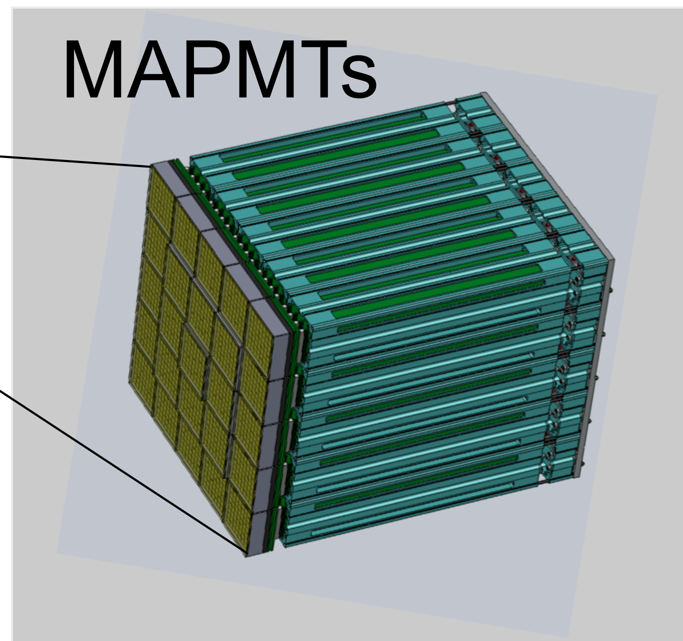












- <u>reduced plate scale</u> allows the use of Si-PMs & MAPMTs

- potential **cost savings** through high QE, lower cost pixel and compact camera design.

Summary:

• **Cosmic-ray** and **gamma-ray** detectors are providing insights into the non-thermal universe and continue to provide **unexpected discoveries.**

• They shed light on the **origin of relativistic particles** in cosmic environments and **underlying particle physics processes**.

• **New technologies** (MAPMTs, SiPMs,novel mirror designs, …) are playing a major role in the development of better **instruments**.

• **Next generation observatories** are in the planning stages and will provide much improved instrument capabilities, such as angular resolution, background rejection, and much increased collection areas.

• These are exciting times!