Hunting for ultra-high energy photons

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Seminar Annecy
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HELMHOLTZ | GEMEINSCHAFT
Allianz für Astroteilchenphysik
RWTH AACHEN UNIVERSITY
bmb+f - Förderschwerpunkt
Astroteilchenphysik
Großgeräte der physikalischen Grundlagenforschung

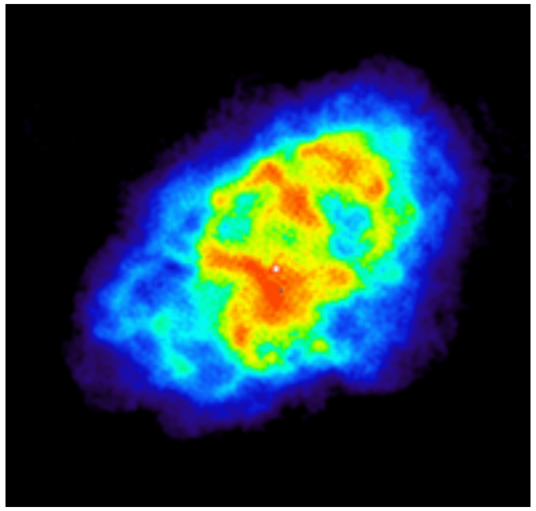
Cosmic Rays
influence our life!

- About 20% of natural radioactivity
- Increased exposure on aircraft
- Can induce massive blackouts
- Vivid discussion on impact on cloud formation
- Induce lightning?
- Impact on climate?
- ...




Photons from outer space

- **Radio astronomy** (wavelength above 1mm):
  Produced by synchrotron radiation and thermal emission
  Feature: Many objects in radio wavelength (e.g. interstellar gas, pulsars, 21cm line, …)

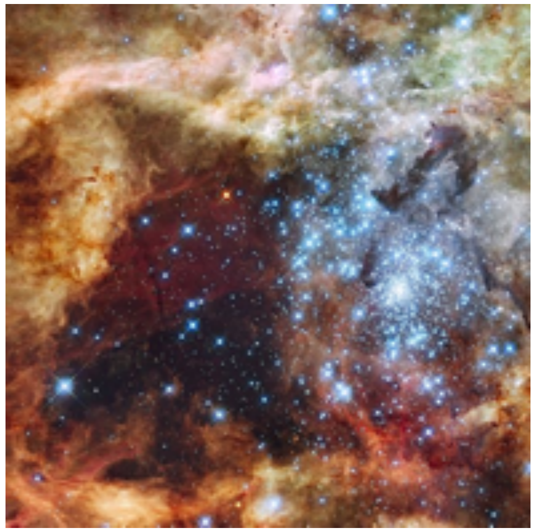


Crab nebula

- **Infrared astronomy** (wavelength 0.75 - 300 micrometer):
  Heavily absorbed by atmosphere
  Feature: Detect objects (e.g. planets, nebula) too cold for optical astronomy

Tarantula nebula

- **Optical astronomy** (wavelength 400 - 700 nm):
  Oldest form of astronomy
  Feature: Most discoveries in optical range. Visible by eye.



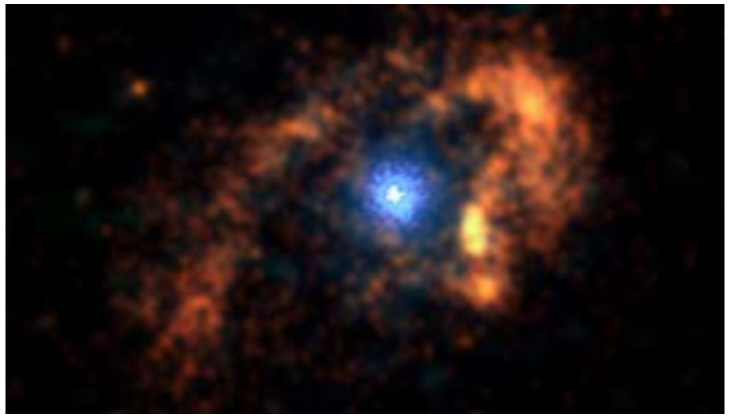
Star-forming region R136

Photons from outer space

- **Ultraviolet astronomy** (wavelength 10 - 320 nm):
  Also absorbed by atmosphere
  Feature: Study thermal radiation and spectral emission lines. Detect objects such as supernovae remnants or active galactic nuclei.

Spiral galaxy Messier 81

- **X-ray astronomy** (wavelength 8 pm - 8 nm):
  Observation at high altitudes or space. Typical production by synchrotron emission of electrons in magnetic fields.
  Feature: Detection of X-ray sources such as pulsars, X-ray binaries or clusters of galaxies



Star Eta Carinae

- **Gamma-ray astronomy** (wavelength 10 pm and below):
  Direct detection by satellites or indirect via secondary particles in atmosphere.
  Feature: Detection of new sources and phenomena such as neutron stars, gamma-ray bursts

Moon
(cosmic ray interacting on surface)

Photons from outer space

- **Ultraviolet astronomy** (wavelength 10 - 320 nm):
  Also absorbed by atmosphere
  Feature: Study thermal radiation

er 81

All observation windows have their own features and discovery potential

Current world record in measured photon energy: ~ 10^{14} eV

In this talk: Search for photons with energies ~10^{18} eV = 1 EeV

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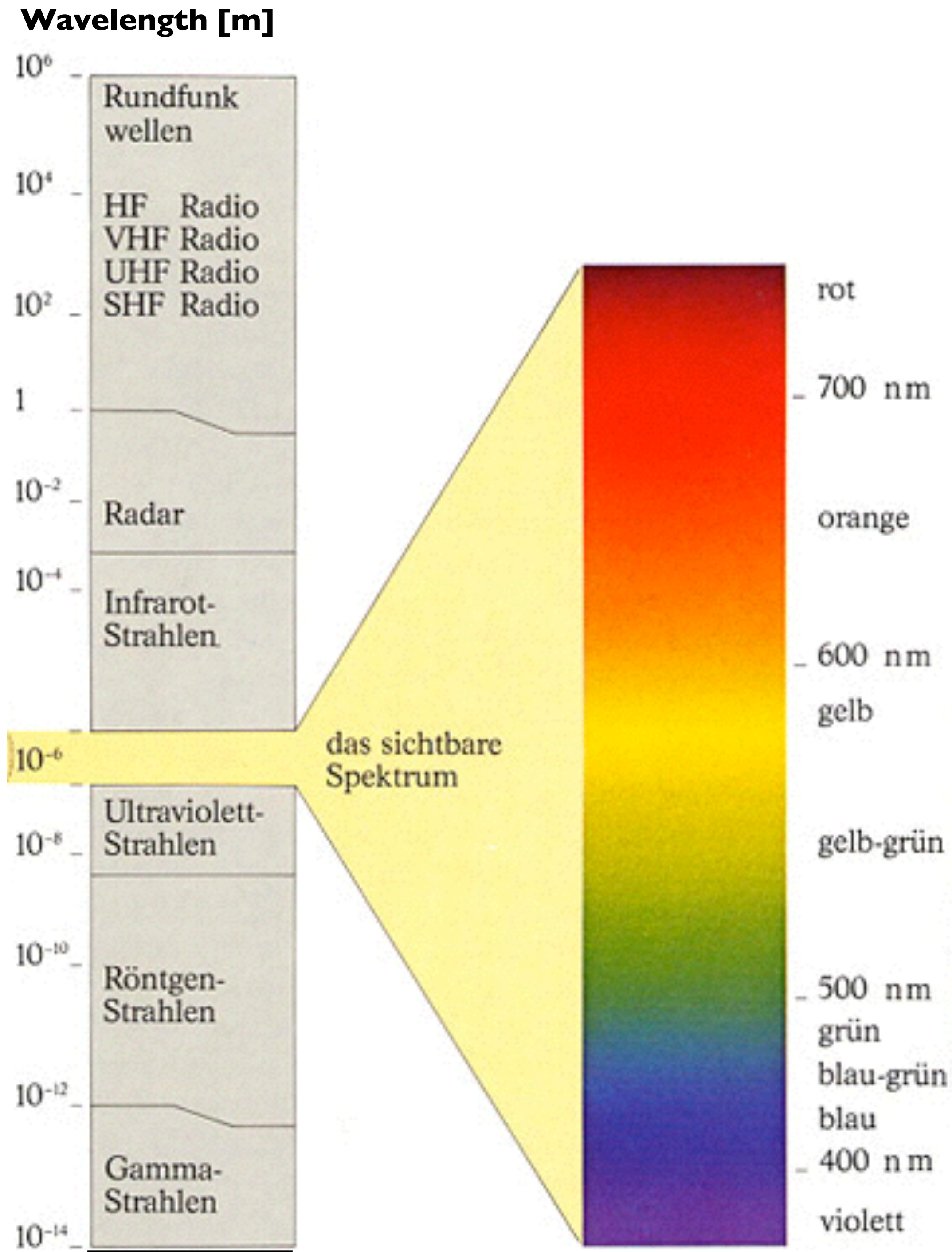
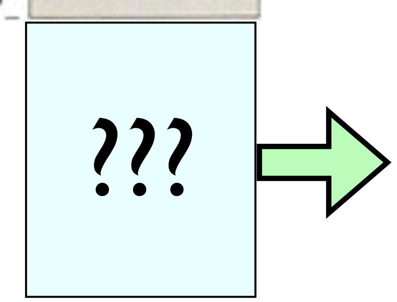
  Fea ... phenomena such as
  neu ..., gamma-ray bursts

Moon
(cosmic ray interacting on surface)

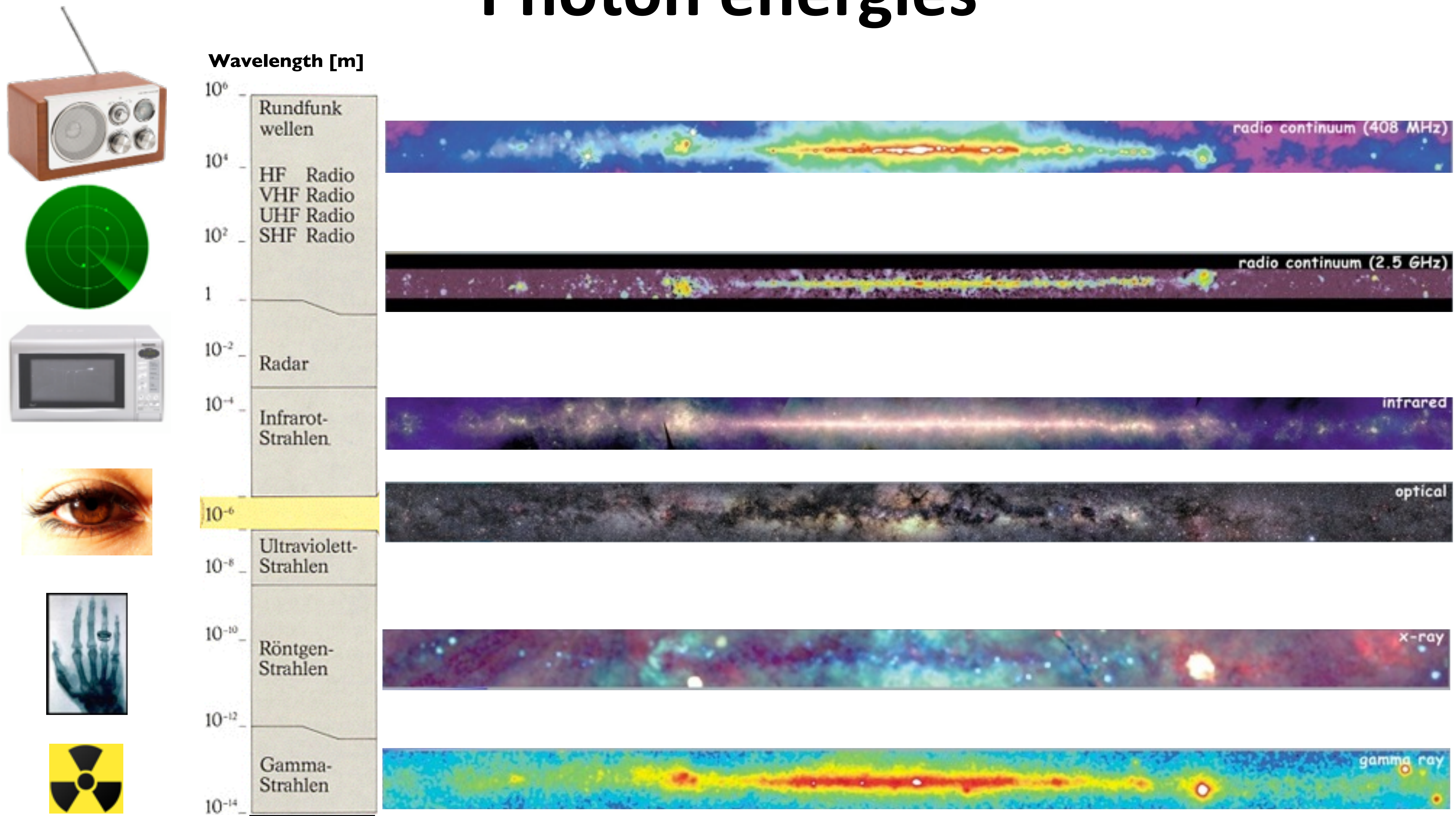
Photon energies





How far can we go?

Photon energies



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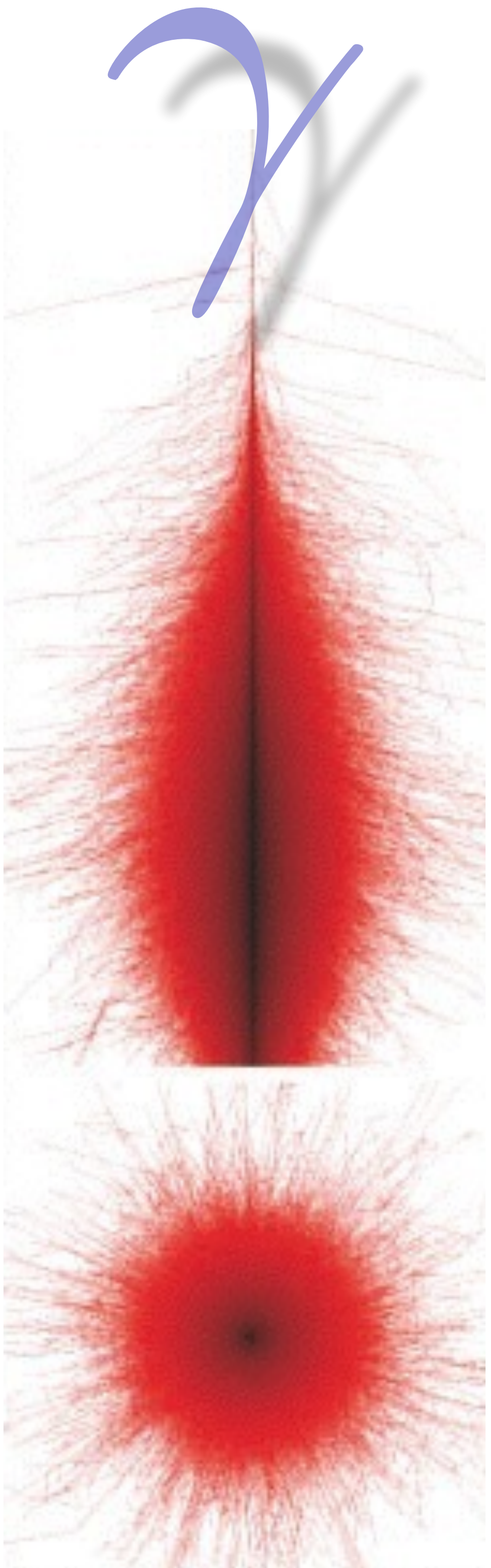
Milky Way in EeV energies?

Motivation



- Photons, as the gauge bosons of the EM force, at such enormous energy are unique messengers and probes of extreme and, possibly, new physics
- UHE photons are a *smoking gun* for non-acceleration models
- UHE photons are important when trying to constrain interaction parameters such as the proton-air-cross-section at energies far beyond LHC energies
- UHE photons point back to the location of their production. Arrival directions may correlate to possible sources
- UHE photons play a role in fundamental physics:
  E.g. they help to constrain Lorentz invariance violation (LIV)

$$\gamma_{\mathrm{UHE}} + \gamma_{\mathrm{b}} \not\rightarrow e^{+} + e^{-}$$ (more photons expected in LIV)

- *and more...*

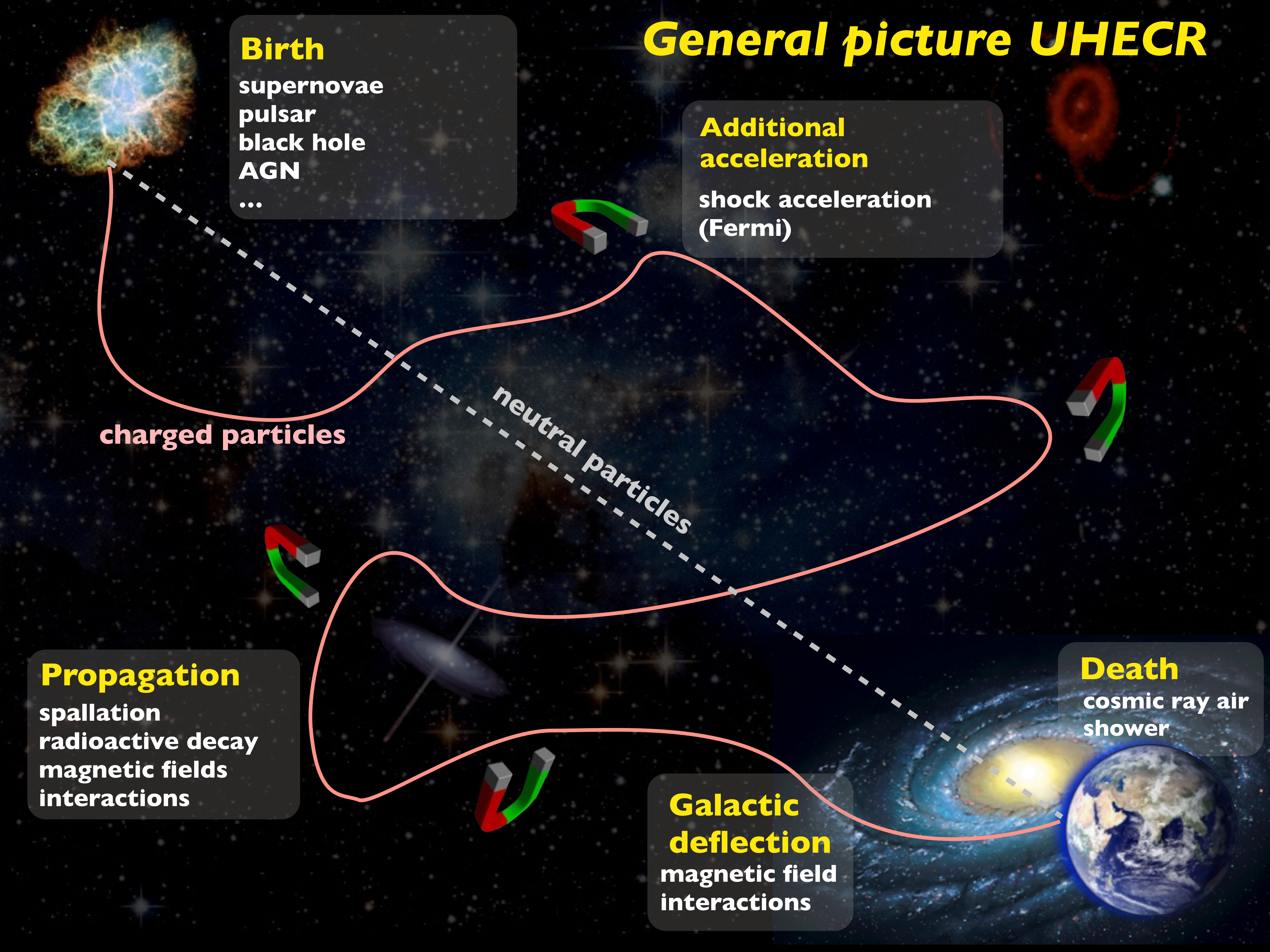
Ultra-high energy cosmic rays

$E > 10^{17}$ eV

Pressing questions:

1. Where do they come from?
2. What are they made of?
3. How are they accelerated?
4. What can they tell us about fundamental and particle physics?
5. Is there a maximal energy?

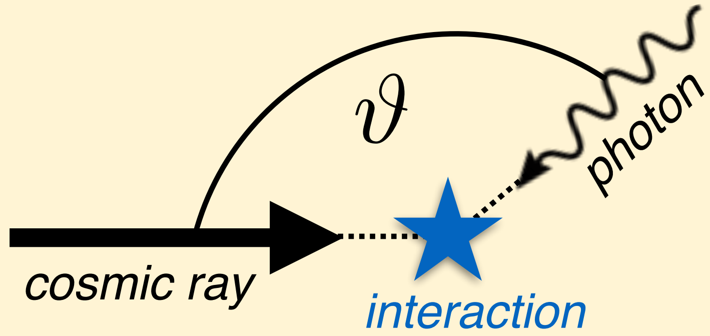
General picture UHECR



Extra-galactic energy density

- Cosmic rays can interact with background photons:

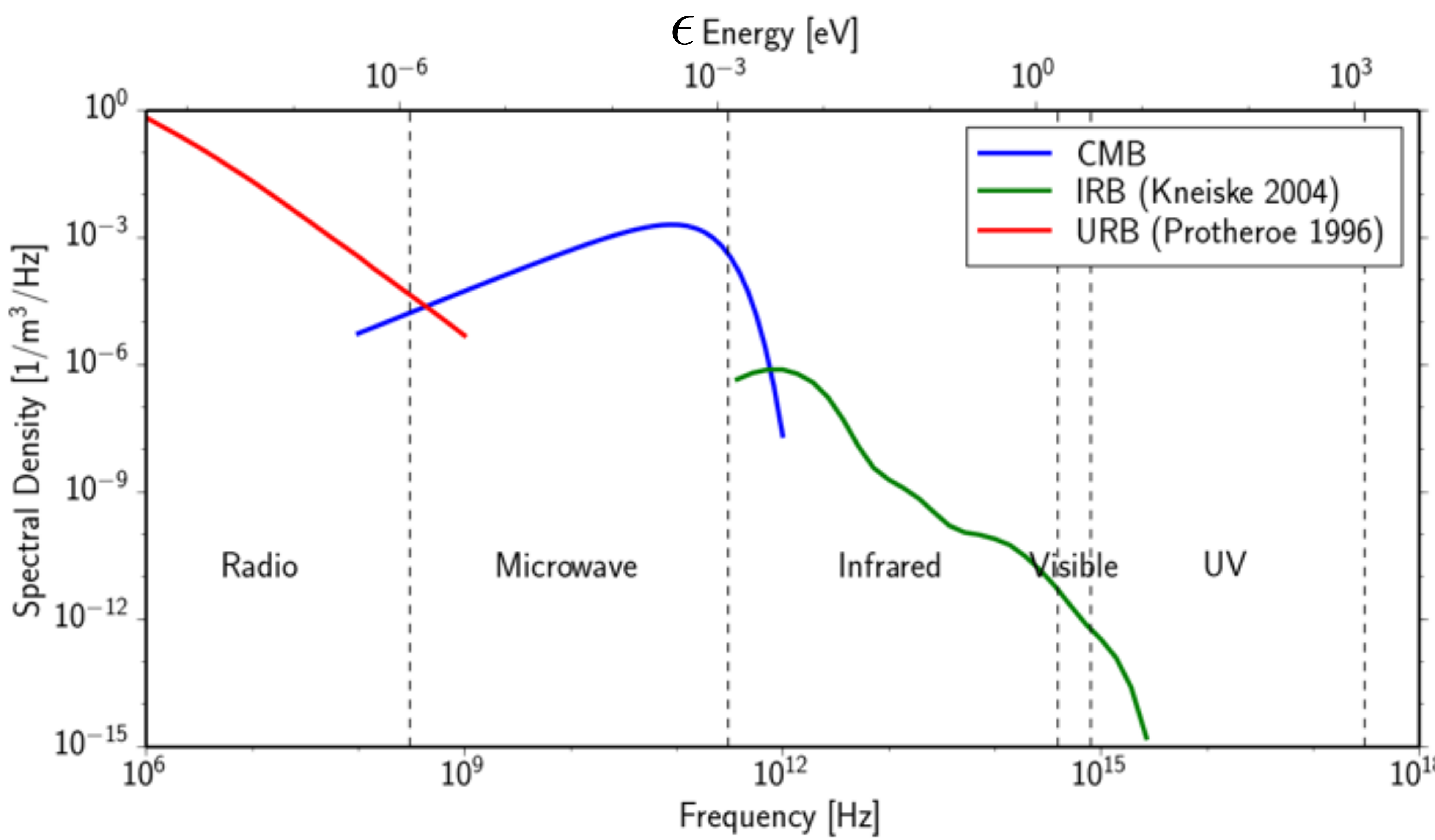
$$\Gamma = \frac{E}{m}$$



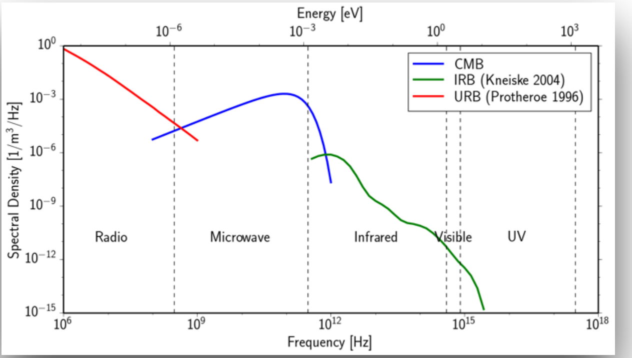
$$\epsilon' = \epsilon\Gamma(1 - \cos(\vartheta))$$

photon energy in nucleus rest frame

ϵ' is the relevant energy scale for interaction



Interactions



Pion production

Pion production for a head-on collision of a nucleon *N*:

$$N + \gamma \rightarrow N + \pi$$

with the threshold energy

$$E_{\text{thres}} = \frac{m_\pi (m_N + m_\pi/2)}{2\epsilon} \approx 6.8 \cdot 10^{19} \left(\frac{\epsilon}{10^{-3}\ \text{eV}}\right)^{-1} \text{eV}$$

where $\epsilon \sim 10^{-3}$ eV represents a typical target photon such as a CMB photon.
Both the electromagnetic and the strong interaction play a role.
Example: Pion production by protons via delta resonance:

EM interaction

strong interaction

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ & \text{with branching ratio } 1/3 \\ p + \pi_0 & \text{with branching ratio } 2/3 \end{cases}$$

$n + \pi^+$: $\rightarrow \mu^+ + \nu_\mu$ — main production channel of neutrinos by hadronic cosmic rays

$p + \pi_0$: $\rightarrow \gamma + \gamma$ — main channel of high energy photons by hadronic cosmic rays

After the discovery of the CMB (1965) people realized:

Universe gets opaque for cosmic rays at ultra-high energies: GZK-effect

first realized by Greisen, Zatsepin and Kuzmin in 1966

K. Greisen, PRL 16 748 (1966), G.T. Zatsepin and V.A. Kuzmin Sov. Phys. JETP Lett. 4 78 (1966)

Interactions

- **Pair production**

Pair production by a nucleus with mass number *A* and charge *Z* on a photon:

$$^A_Z + \gamma \rightarrow ^A_Z + e^+ + e^-$$

induces electromagnetic cascades via inverse Compton scattering

with the threshold energy

$$E_{\mathrm{thres}} = \frac{m_e(m+m_e)}{\epsilon} \approx 4.8 \cdot 10^{17}\ A\ \left(\frac{\epsilon}{10^{-3}\ \mathrm{eV}}\right)^{-1} \mathrm{eV}$$

where $\epsilon \sim 10^{-3}\ \mathrm{eV}$ represents a typical target photon such as a CMB photon.

Interactions

Pair production

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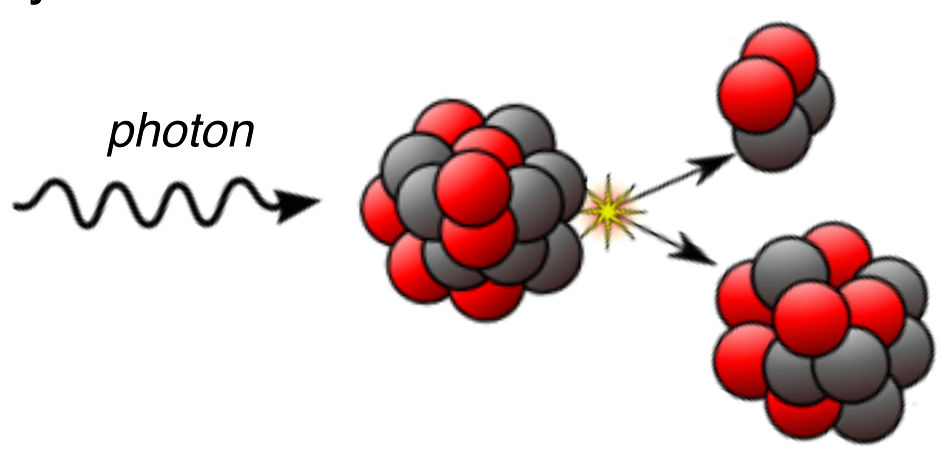
where $\epsilon \sim 10^{-3}\ {\rm eV}$ represents a typical target photon such as a CMB photon.

Photodisintegration of nuclei

Gamma ray is absorbed by nuclei and causes it to enter excited state before splitting in two parts.



Changes in energy ΔE, and atomic number ΔA, are related by $\Delta E/E = \Delta A/A$
Thus, effective energy loss rate is given by:

$$ \frac{1}{E}\frac{{\rm d}E}{{\rm d}t}\bigg|_{\rm eff} = \frac{1}{A}\frac{{\rm d}A}{{\rm d}t} = \sum_i \frac{i}{A} l_{A,i}(E) $$

rate for emission of *i* nucleons of mass *A*

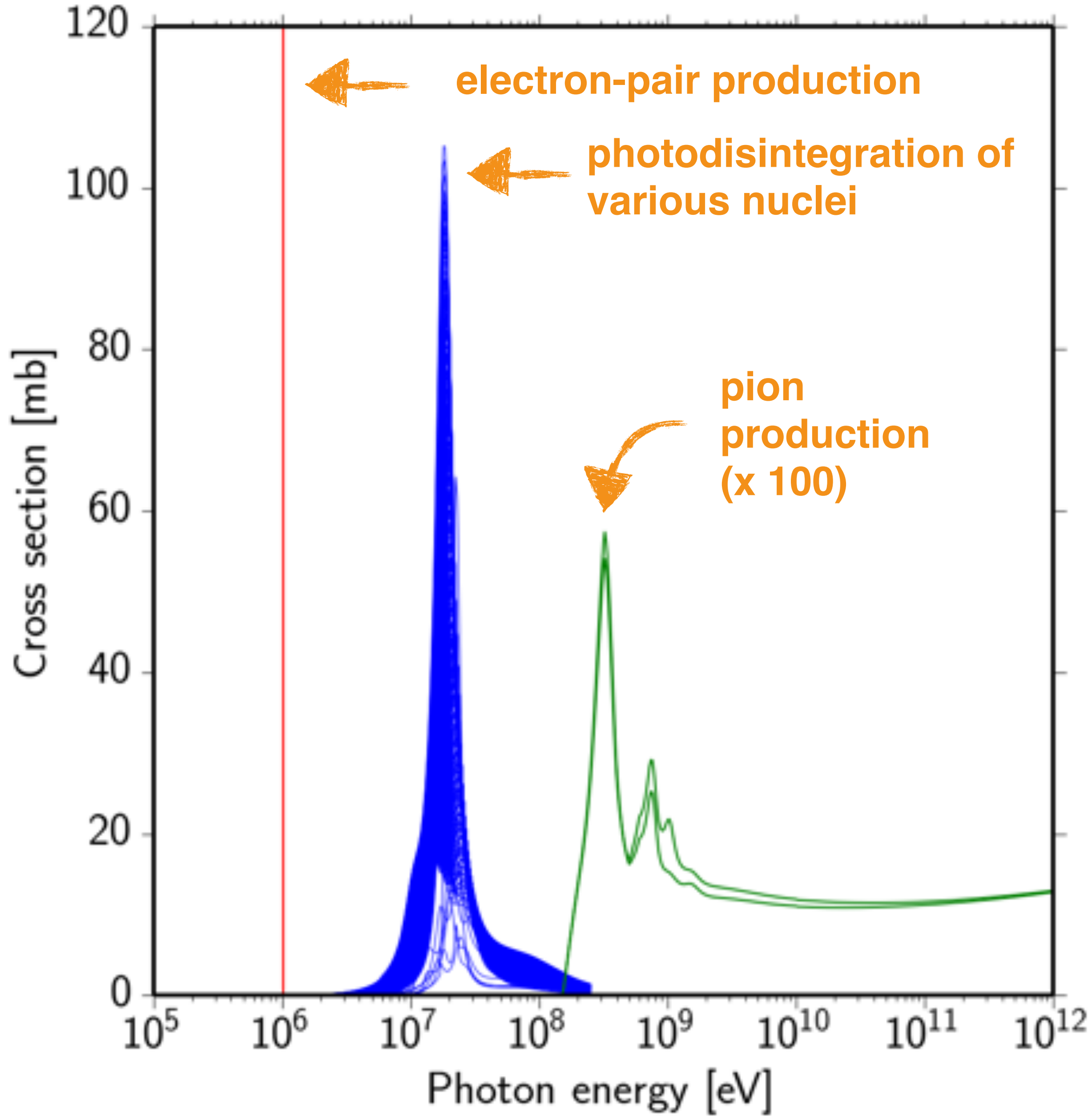
Interaction rate

Interaction rate can be calculated as

$$\lambda^{-1} = \int_0^\infty n(\epsilon)\sigma_{\text{avg}}(\epsilon)\ \mathrm{d}\epsilon$$

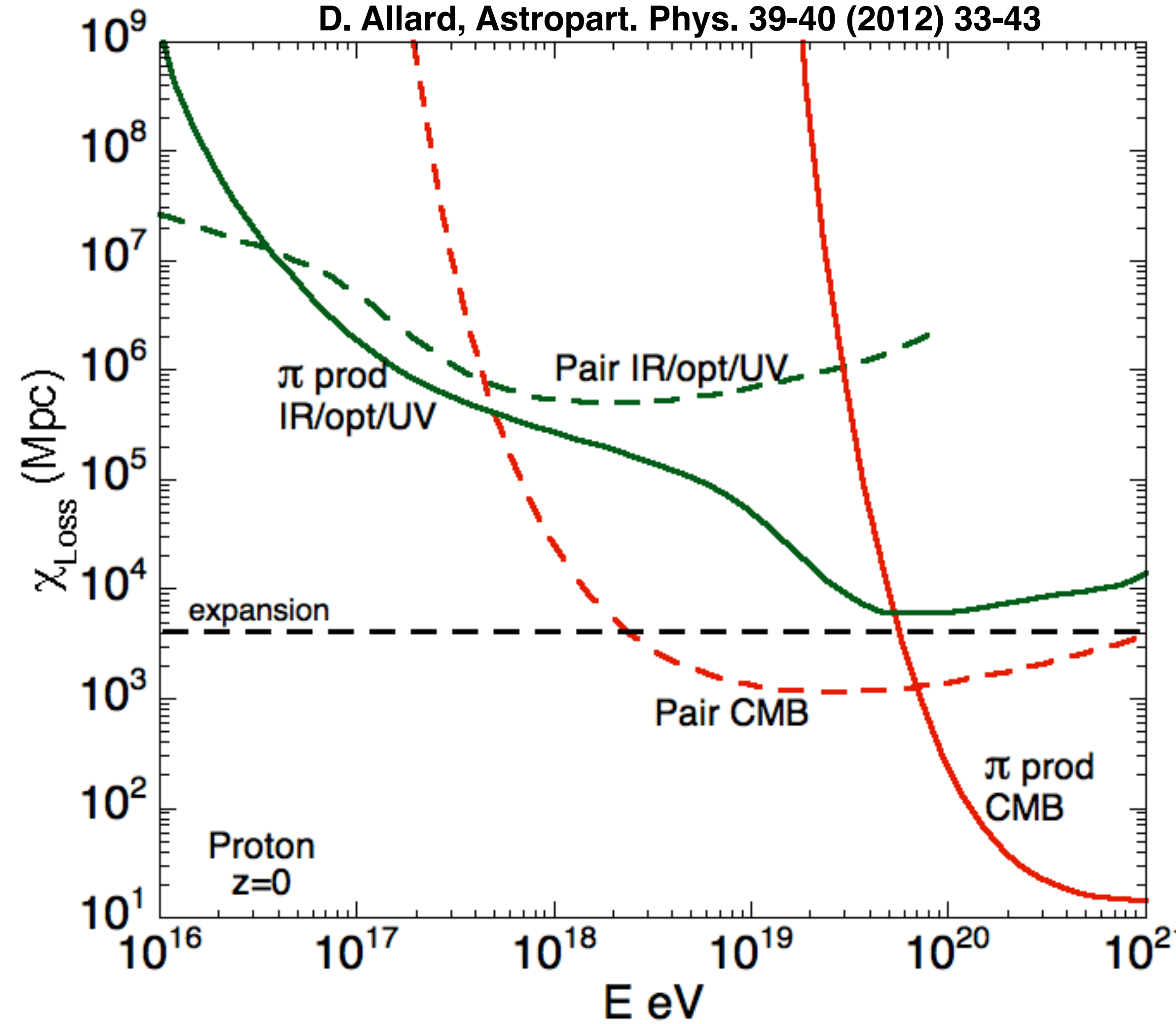
photon number density

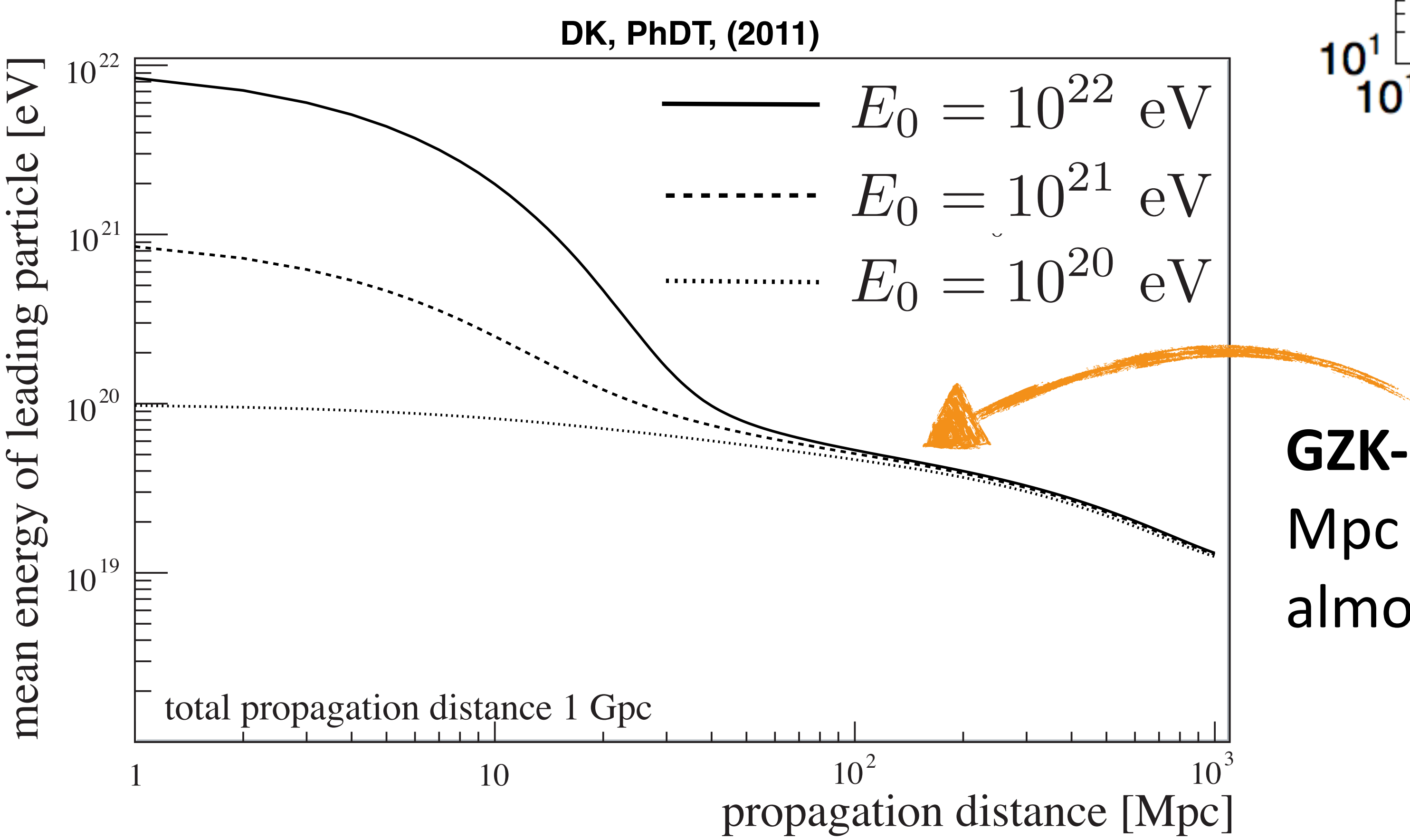
collision angle averaged cross section



Attenuation length for protons

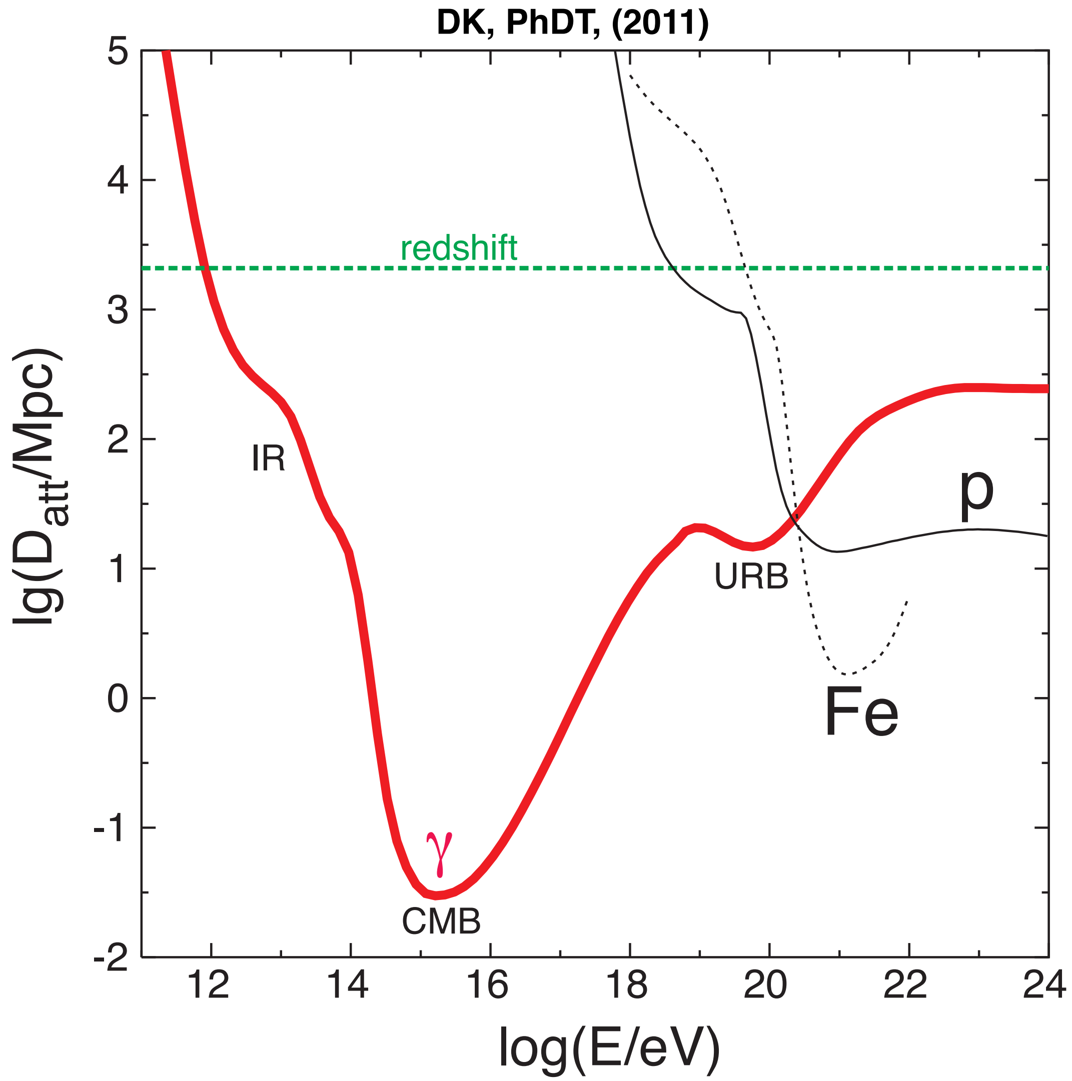
- **Low energies:**
  energy loss dominated by expansion of the universe
- **Intermediate energies:**
  Most important loss length is pair production on CMB
- **High energies:**
  Most important loss length is pion production on CMB





GZK-effect: For propagation distances > 100 Mpc the primary energy is attenuated to almost the same value

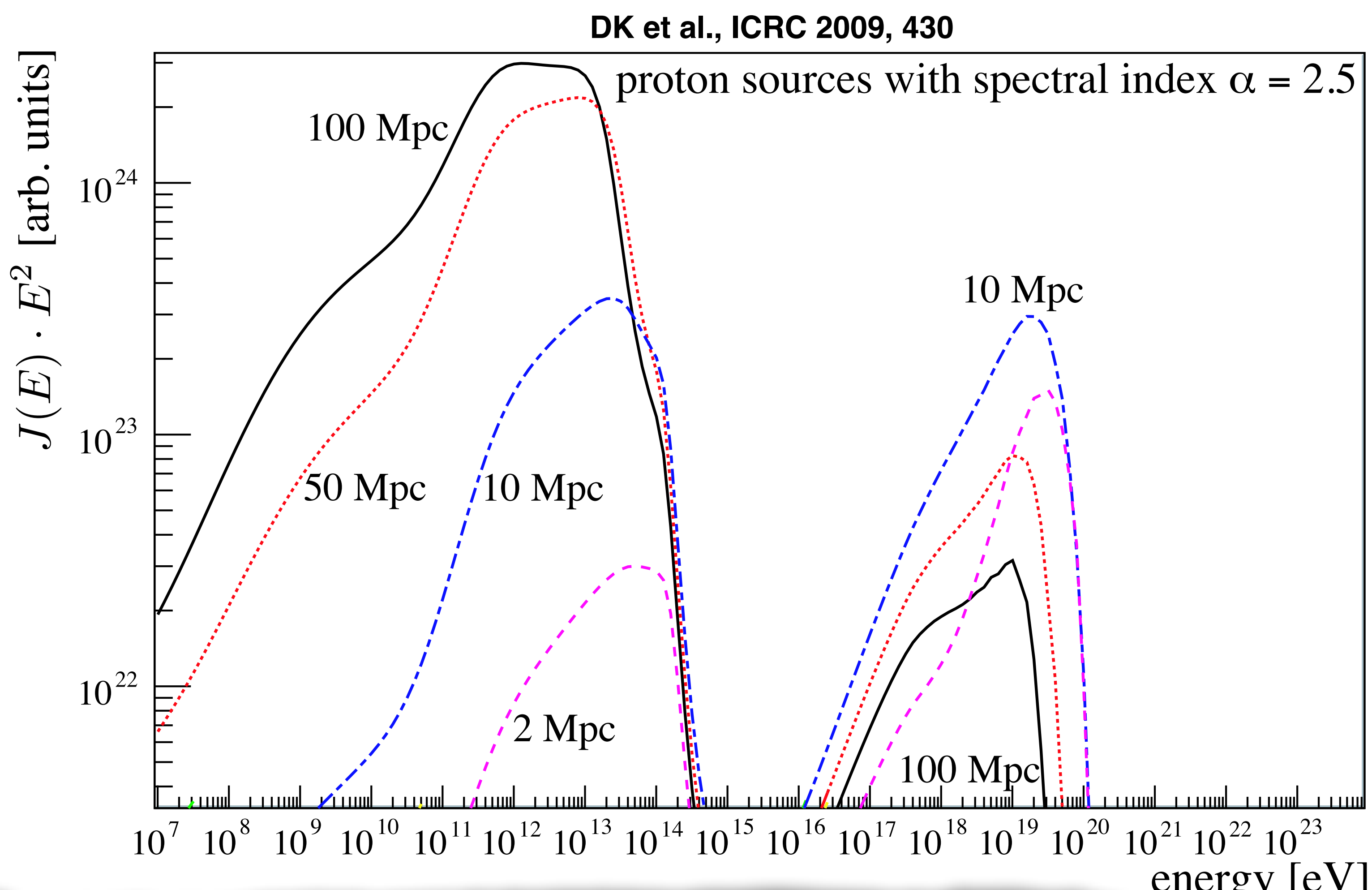
Secondary photons



- Dominant interaction process is pair production:

$$\gamma_{\mathrm{UHE}} + \gamma_b \rightarrow e^+ + e^-$$

- Strong attenuation in PeV regime by CMB photons



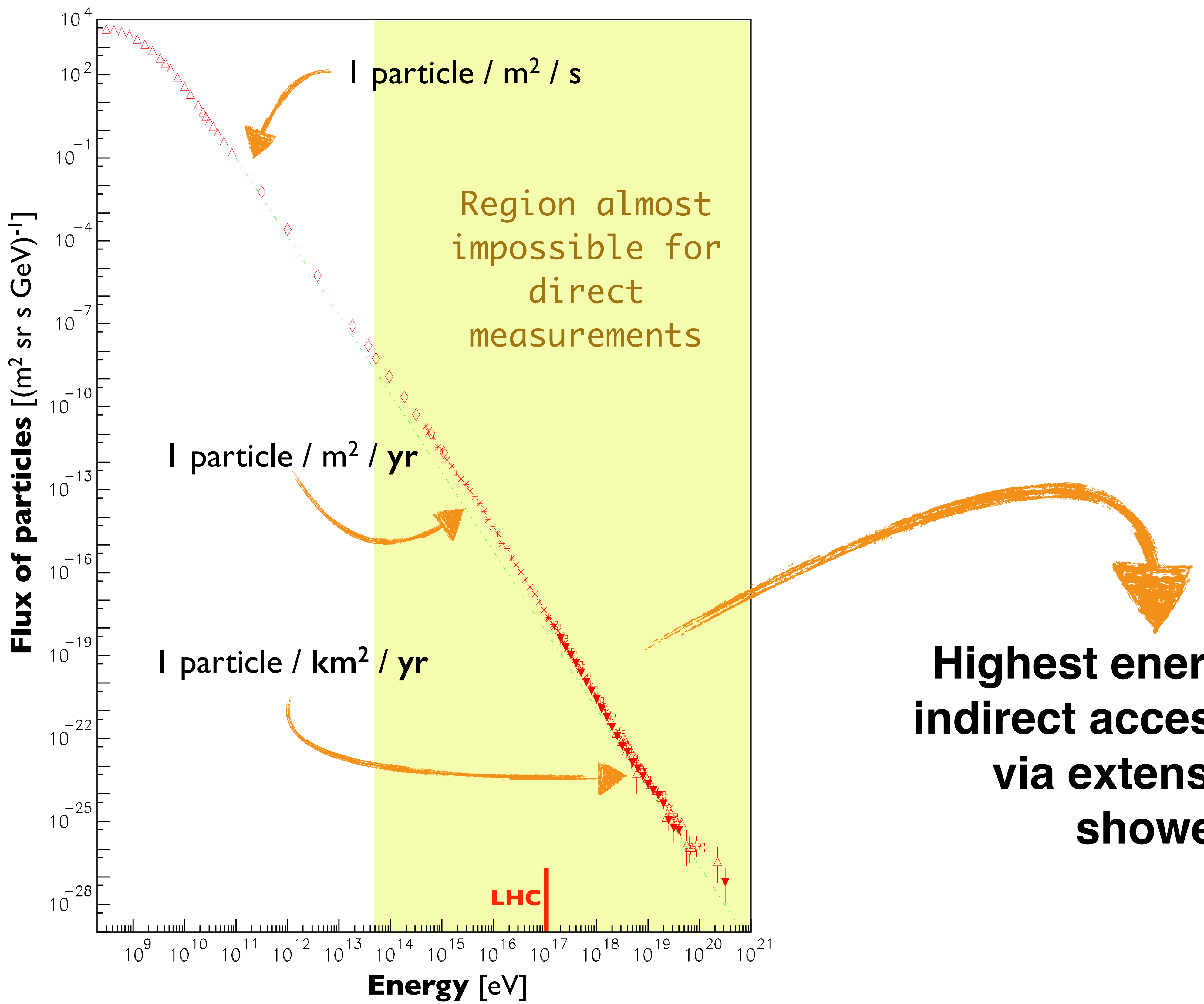
- Typical energy loss length:
  - 7-15 Mpc at 10^{19} eV
  - 5-30 Mpc at 10^{20} eV

observation of galactic and nearby extragalactic sources may be possible

Current status: No photons above ~TeV energies observed

Detection

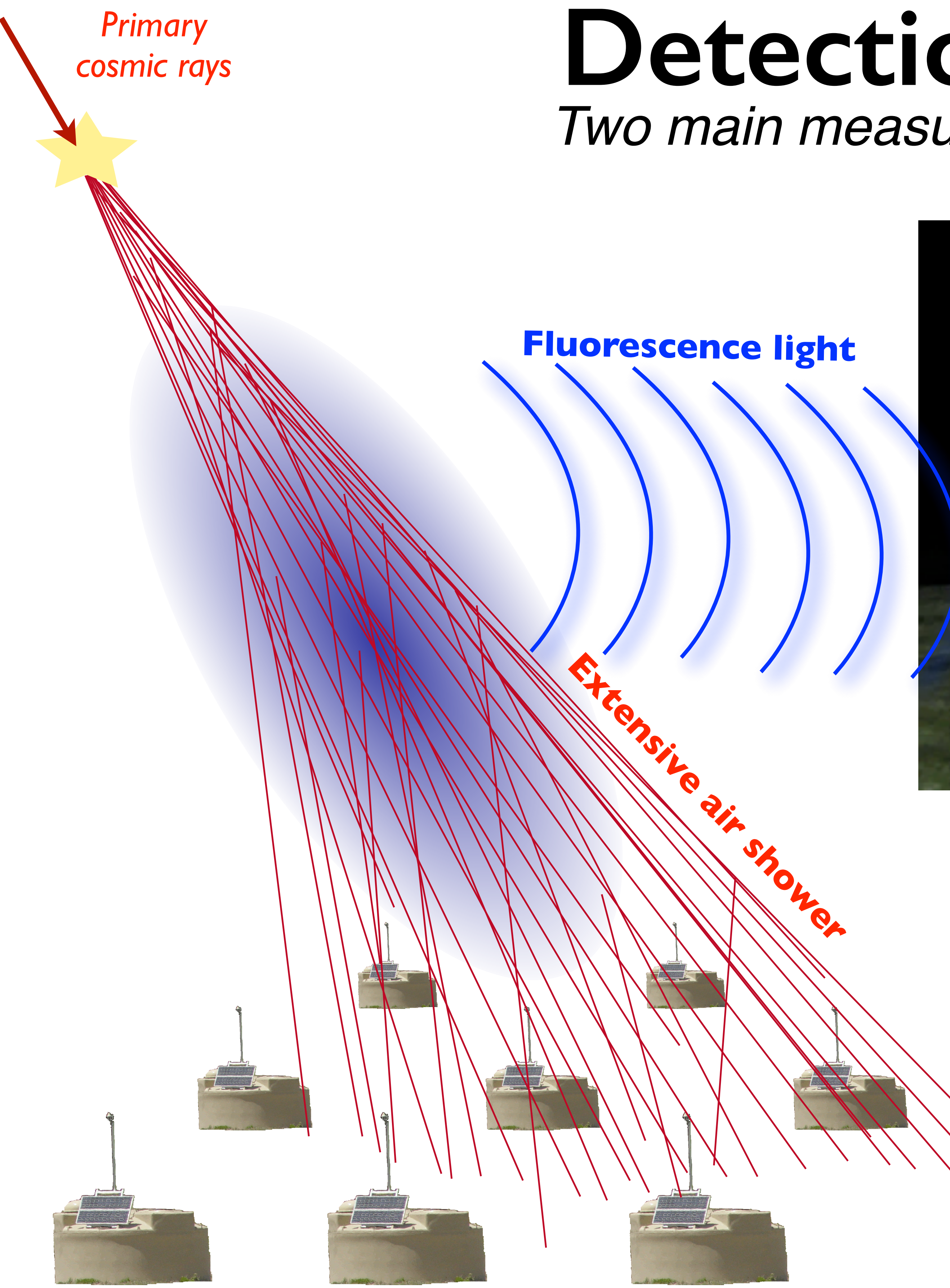
Detection via secondary particles



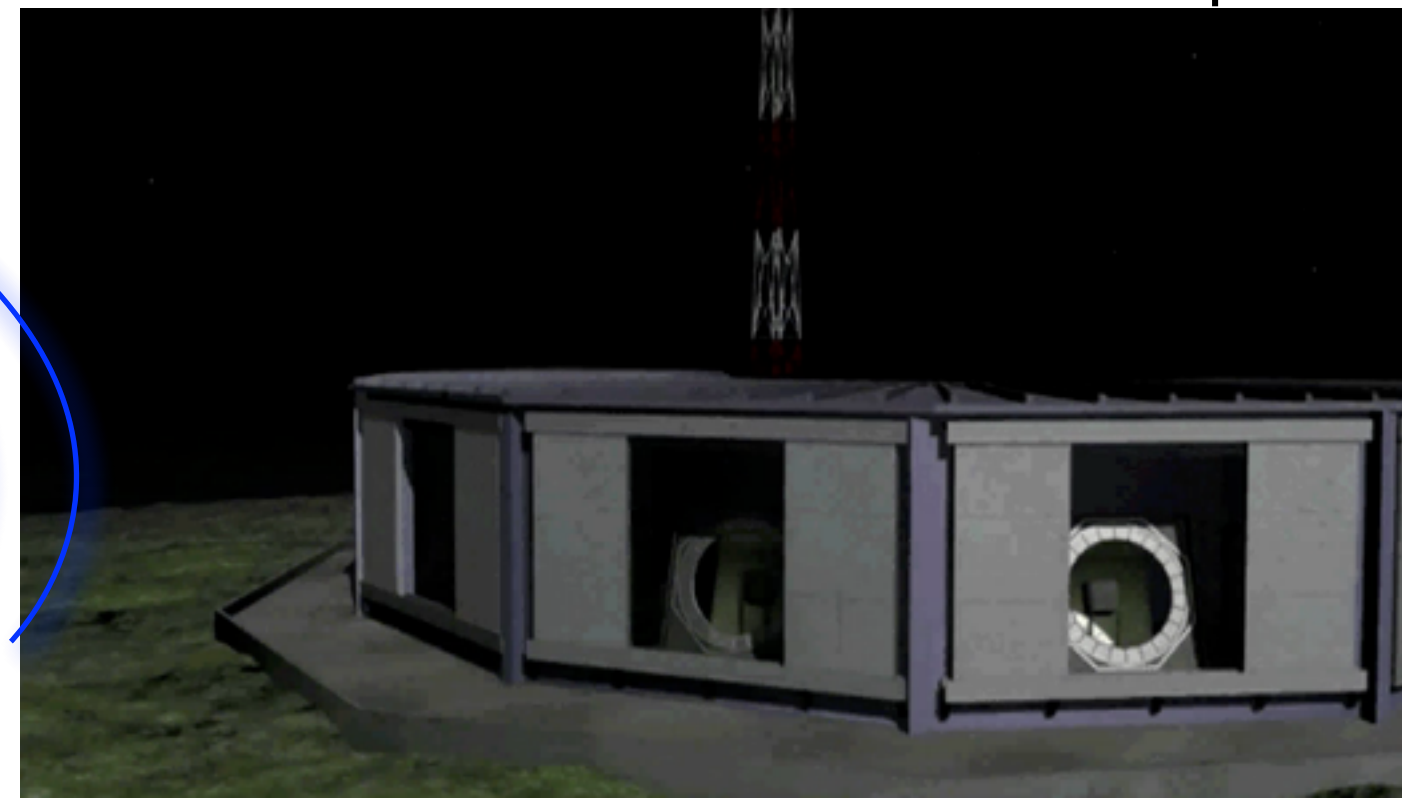
Highest energies only indirect accessible, e.g. via extensive air showers

Detection of EAS

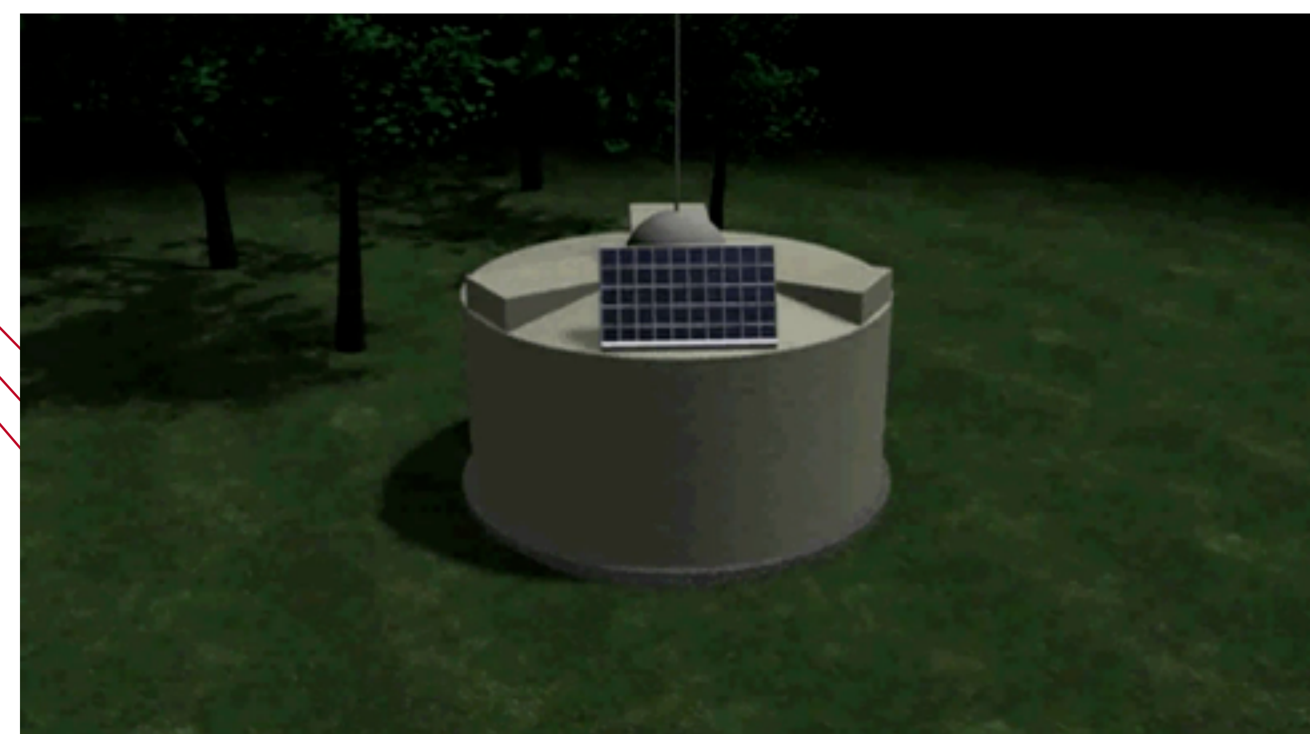
Two main measurement techniques:



Fluorescence telescope



Water-Cherenkov detector



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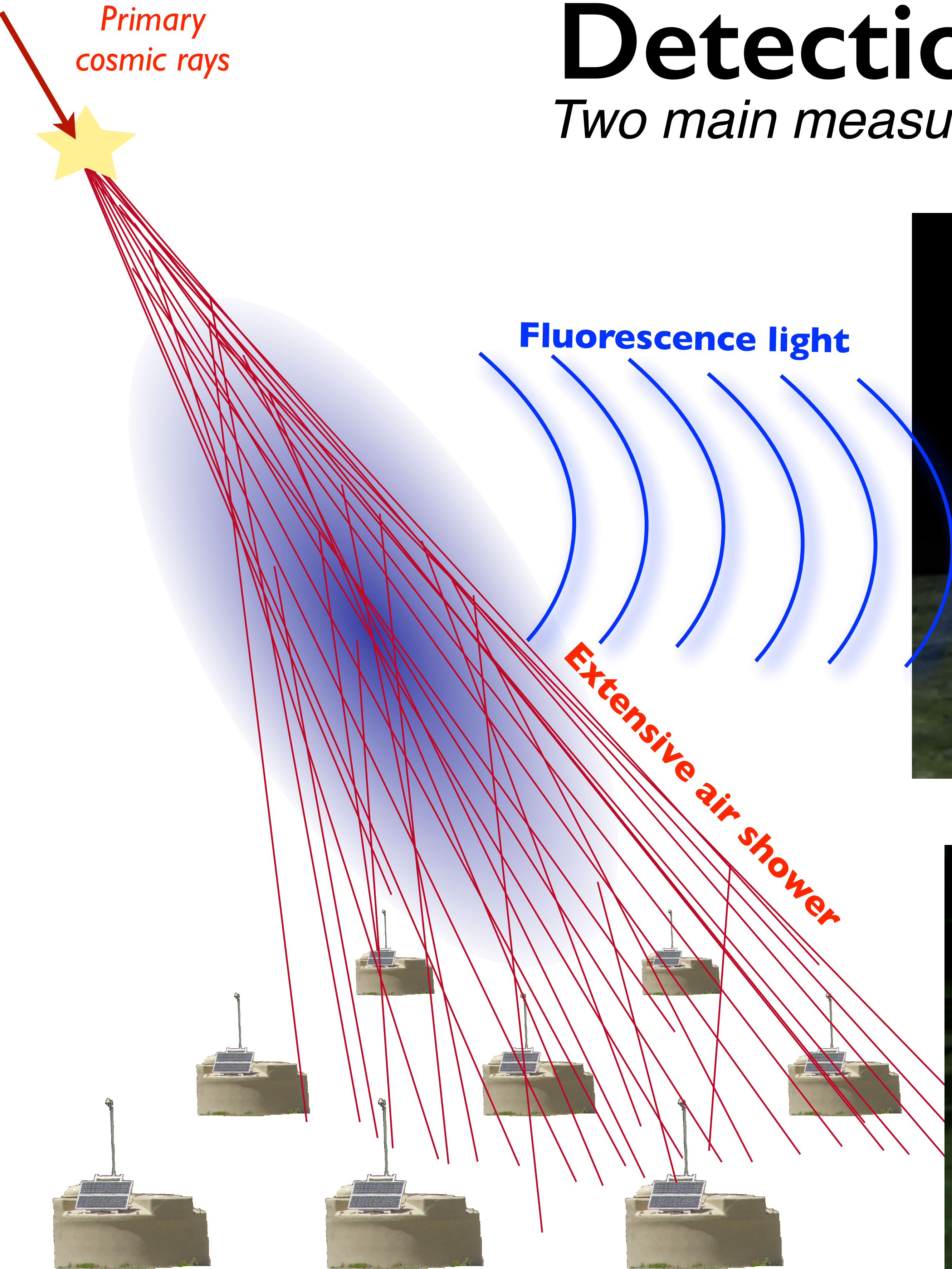

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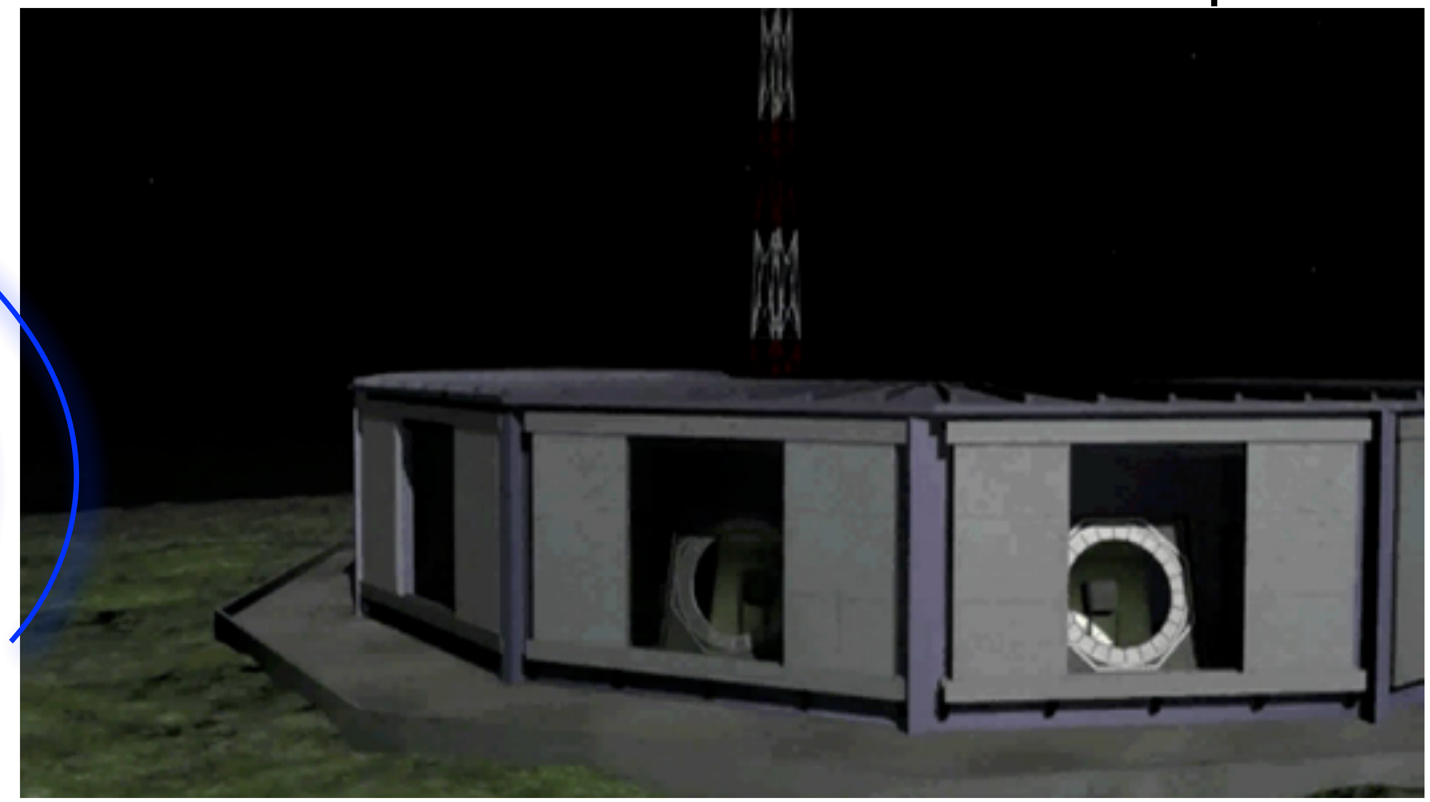

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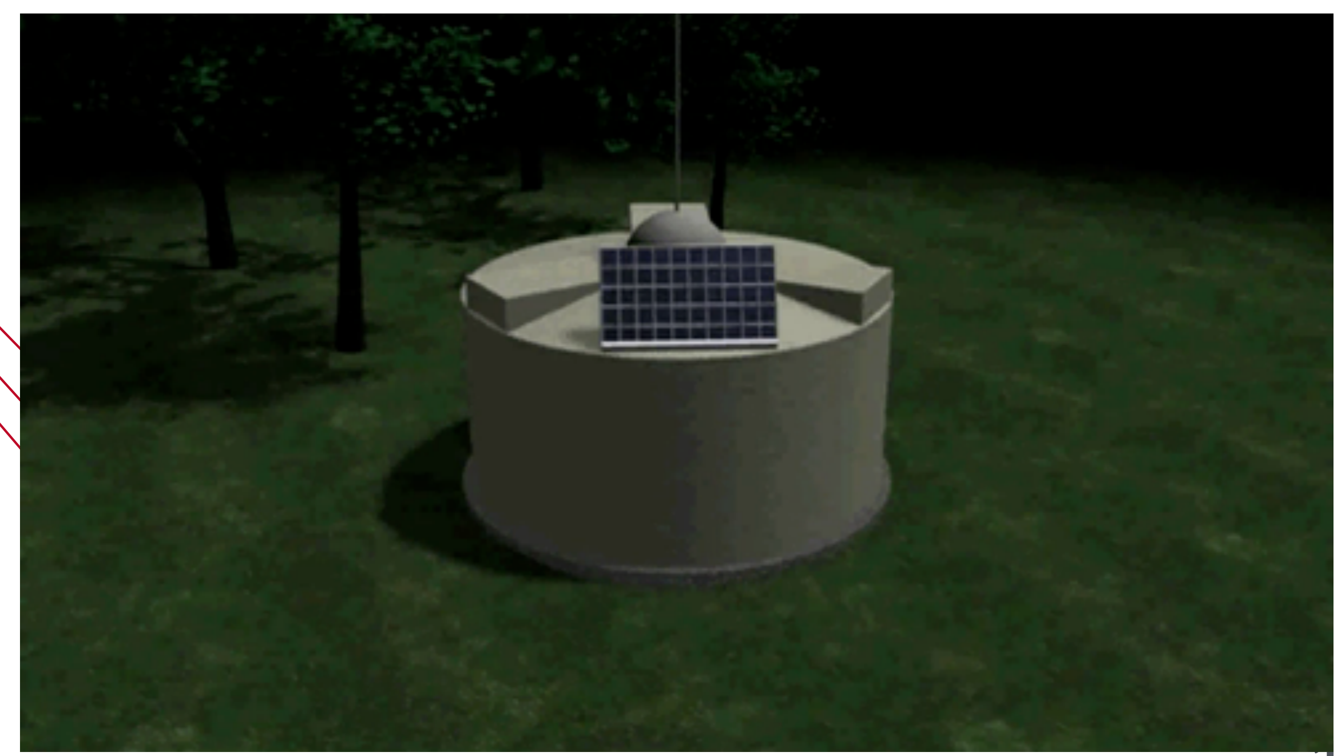
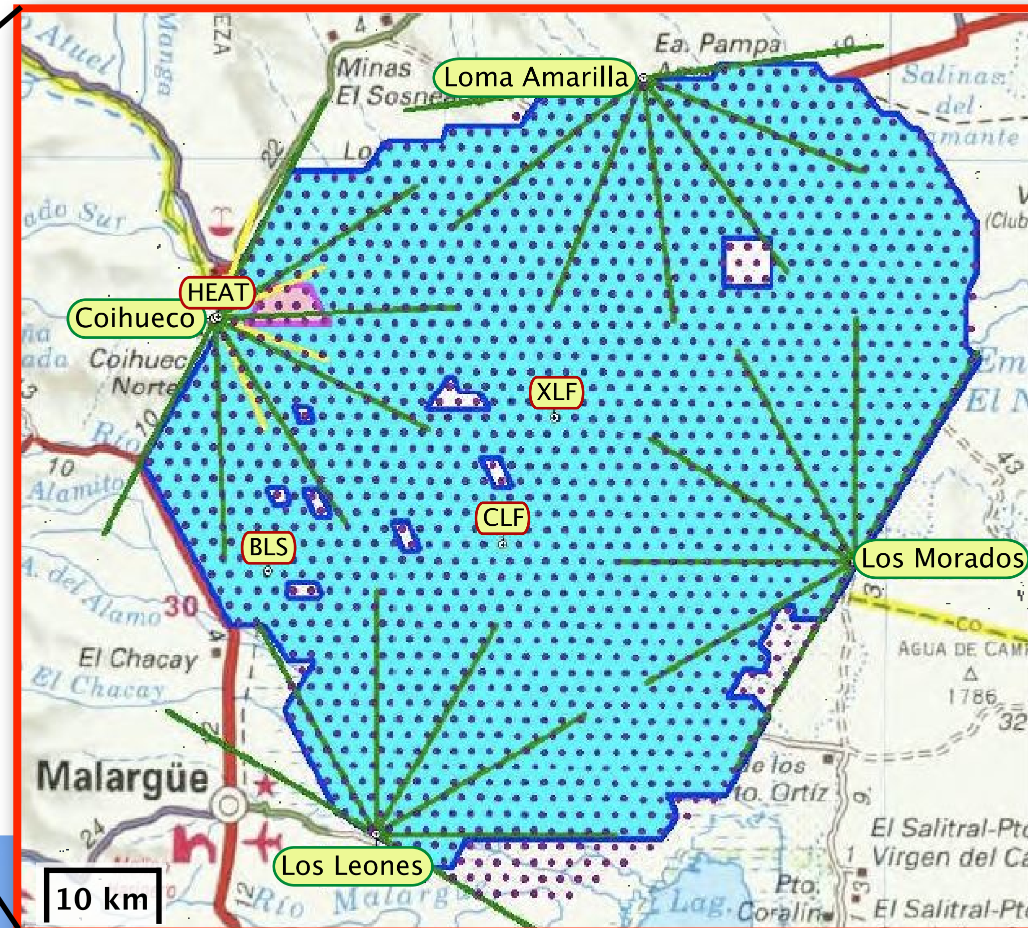


Pierre Auger Observatory

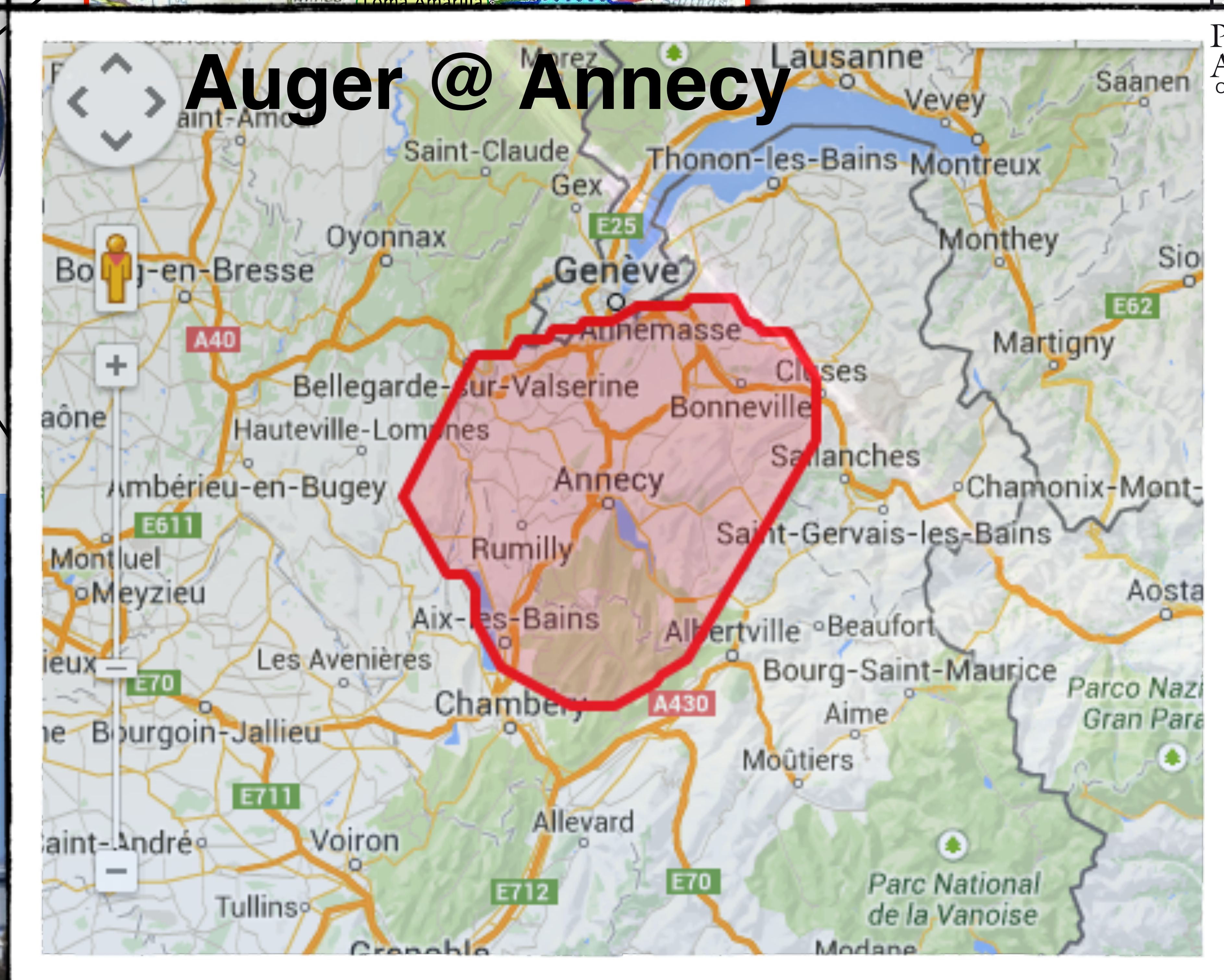
PIERRE AUGER OBSERVATORY



- About **500 collaborators** from **18 countries**
- **~ 3000 km²** area
- **1660** water-Cherenkov tanks
- **27** fluorescence telescopes

Additional R&D antennas

Pierre Auger Observatory



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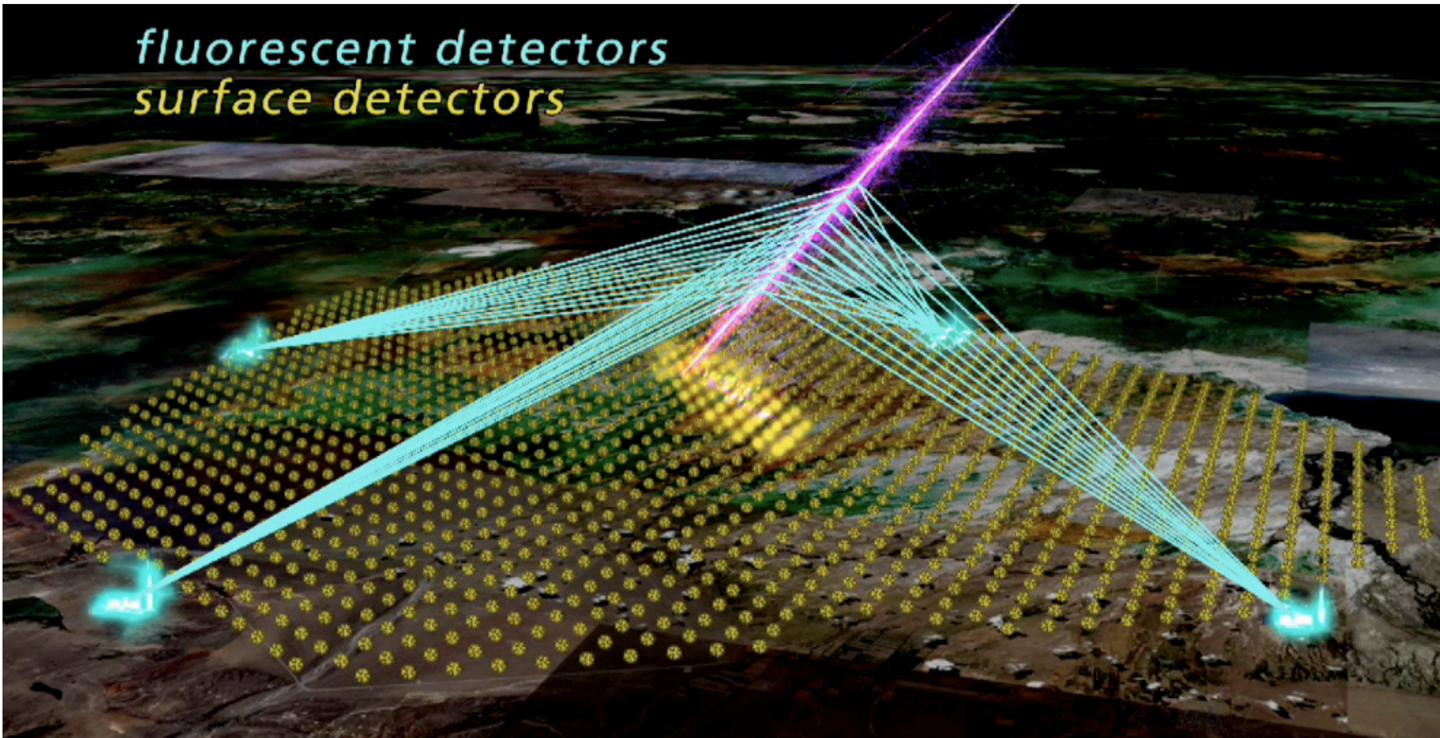
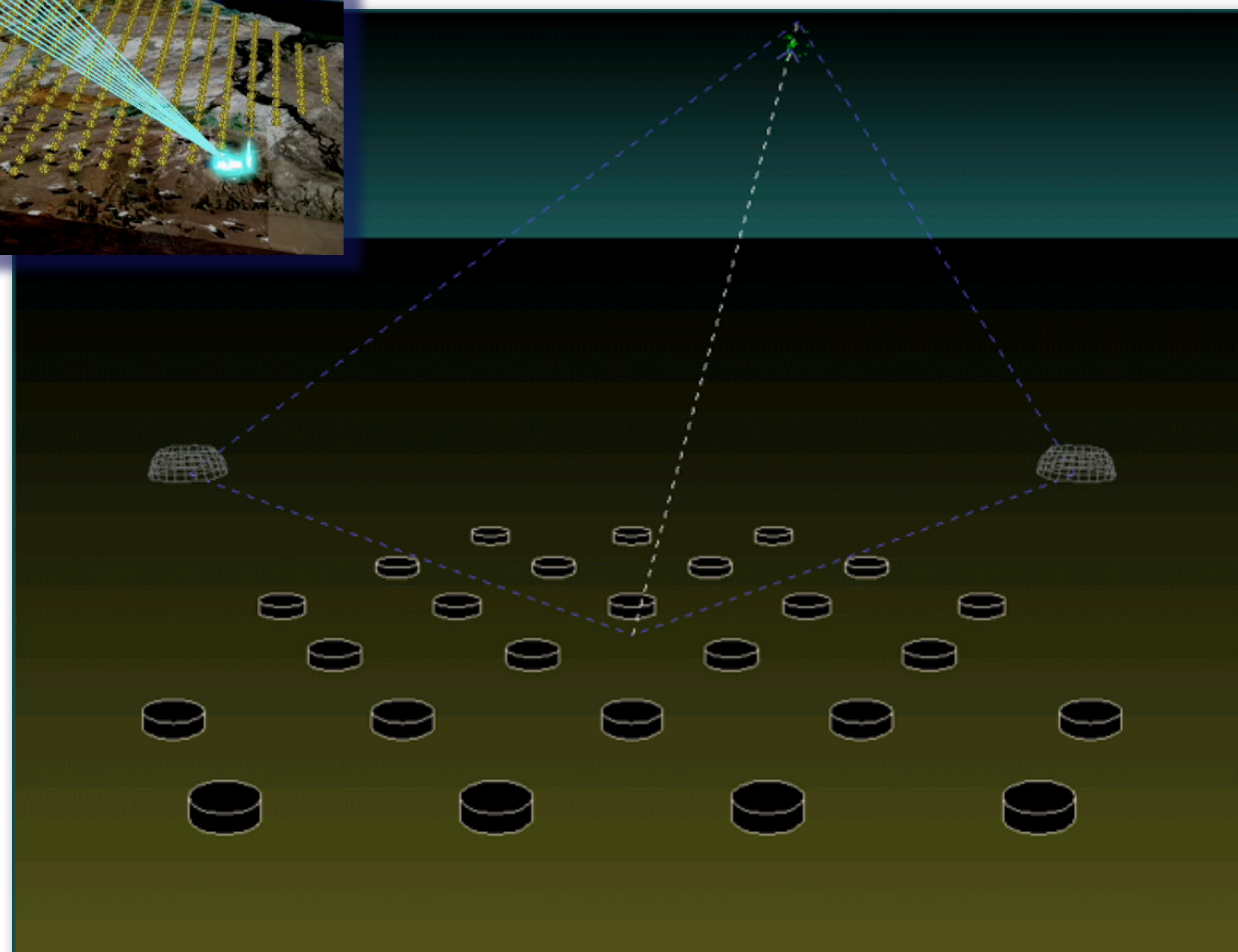


Hybrid technique



Advantage:

- More accurate energy and directional information
- Lower energy threshold
- Small dependence on interaction models

Disadvantage:

- Only 10-15% duty cycle

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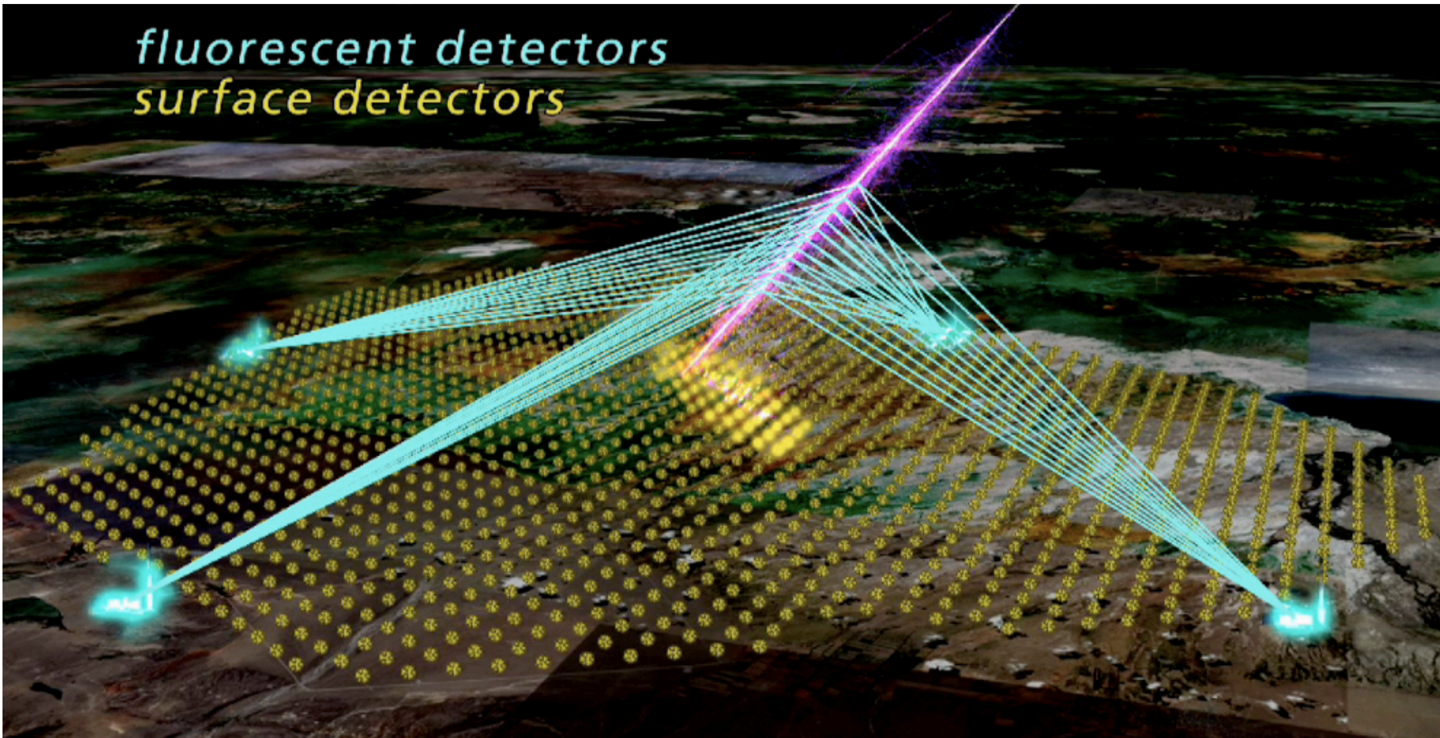

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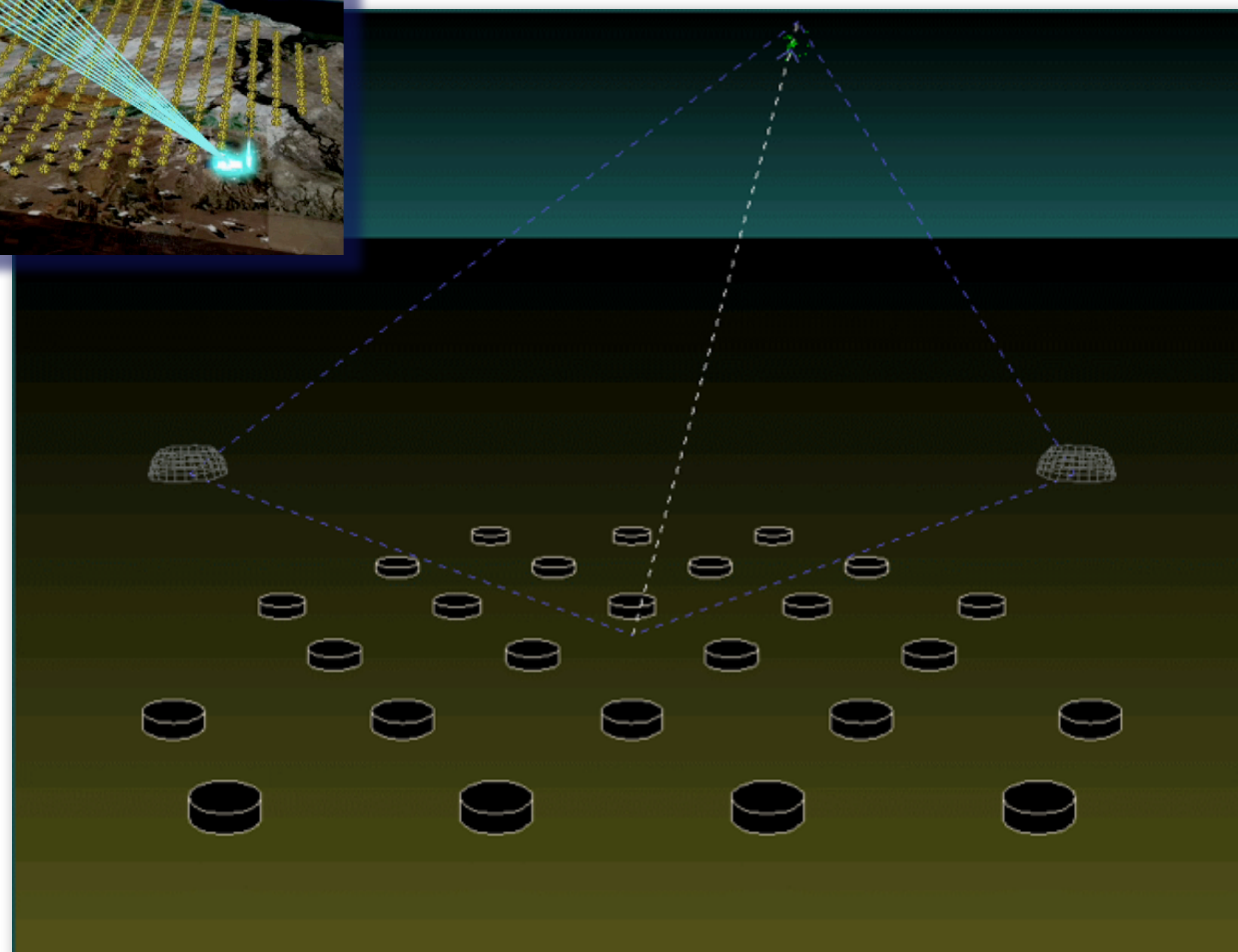

Advantage:

- More accurate energy and directional information
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Disadvantage:

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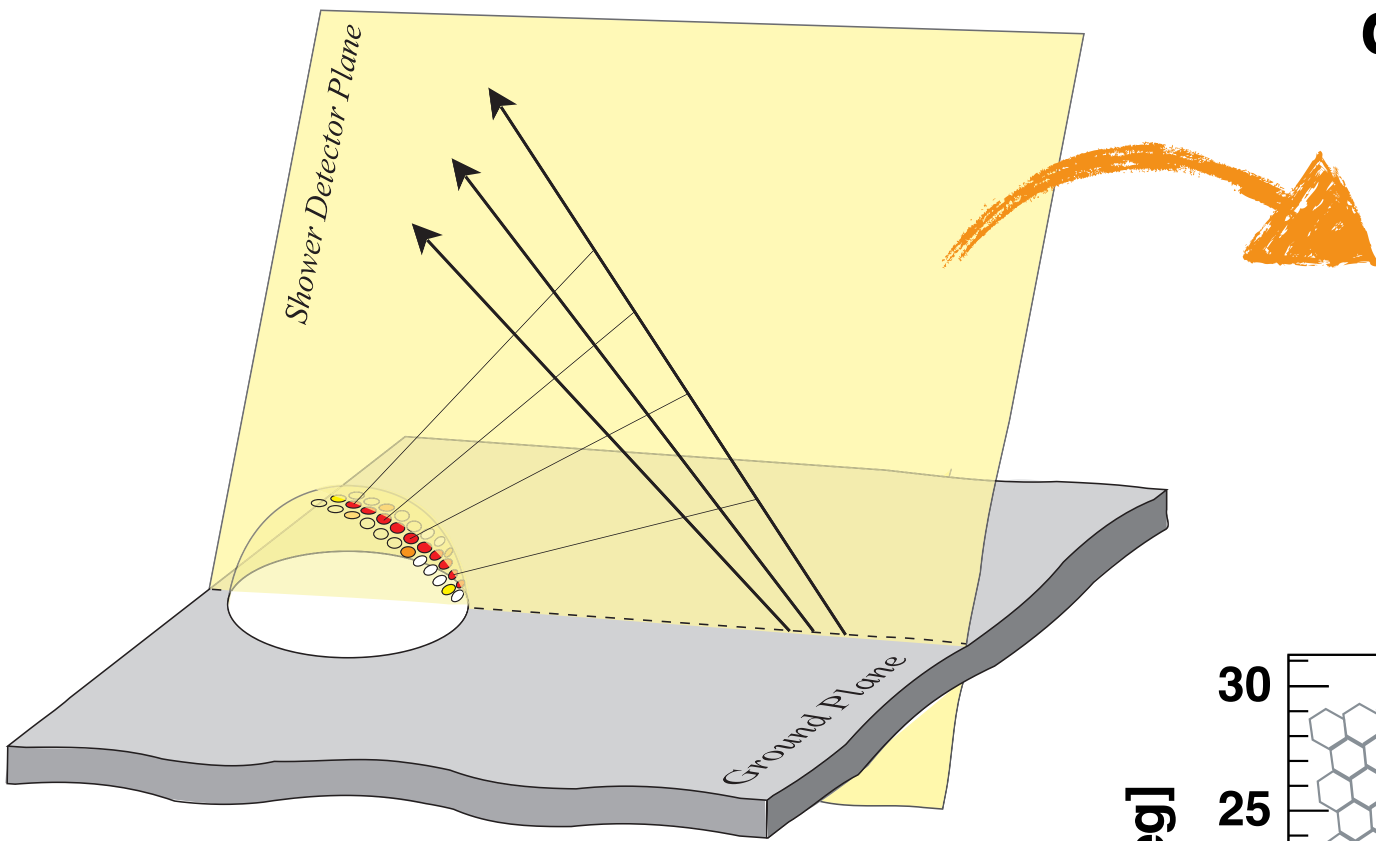
Geometry reconstruction

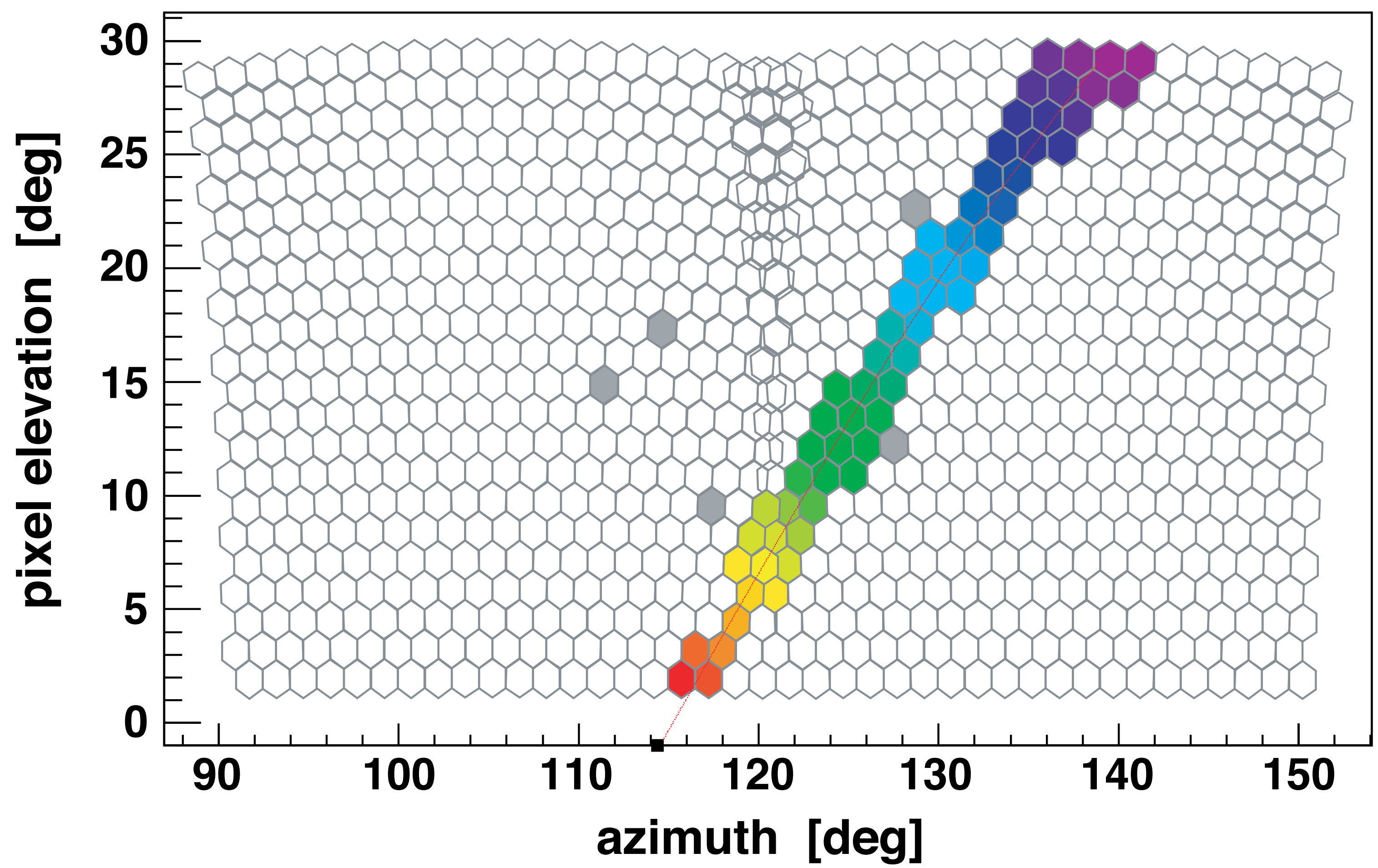
Two step process:

1. Determination of the shower detector plane (SDP)



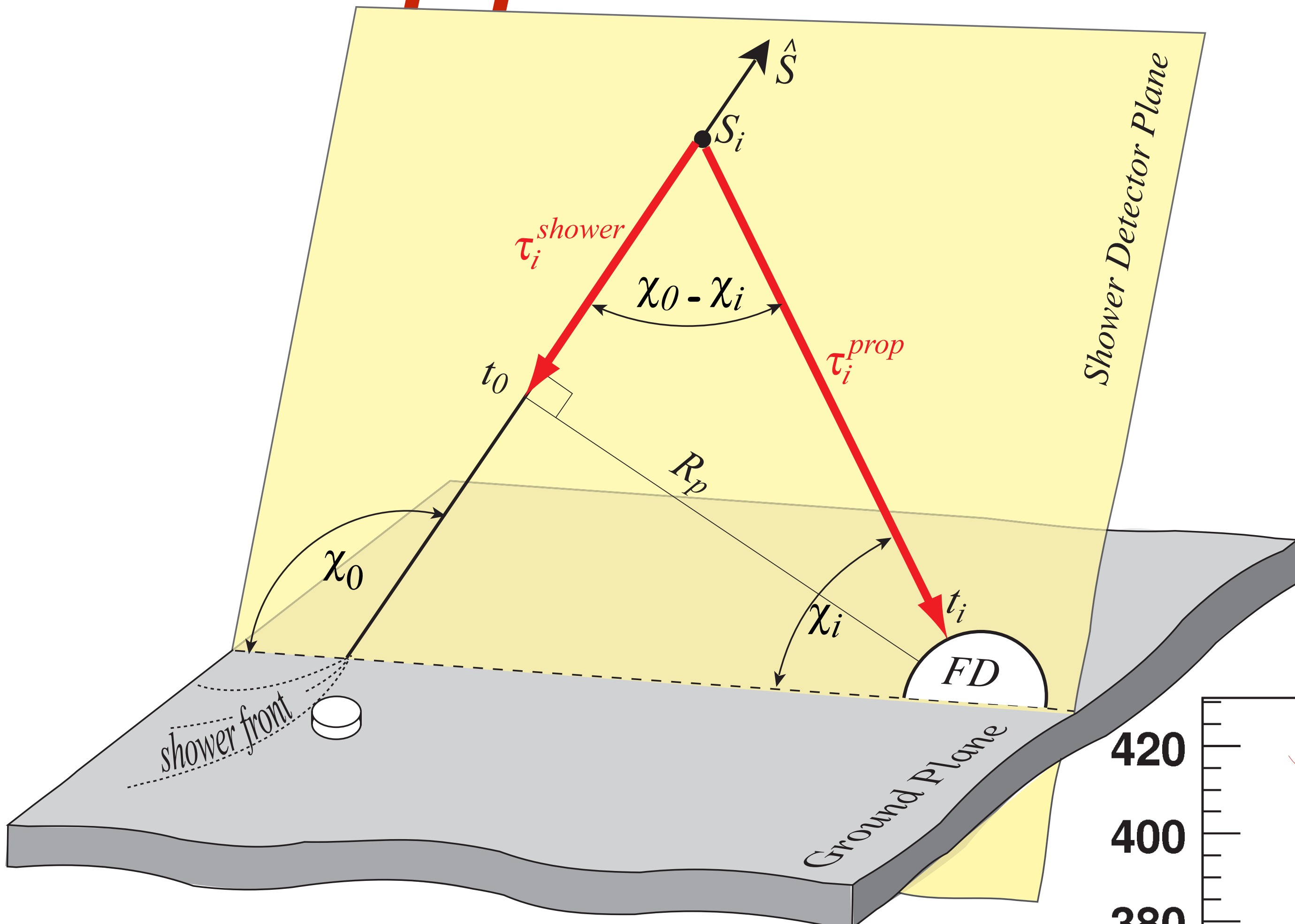
Plane spanned by the (signal-weighted) viewing directions of the triggered camera

Direction within this plane still unclear…



Geometry reconstruction

Two step process:



Fit R_p, t_0 and *chi_0 to determine geometry*

Angular resolution typically less than 1°

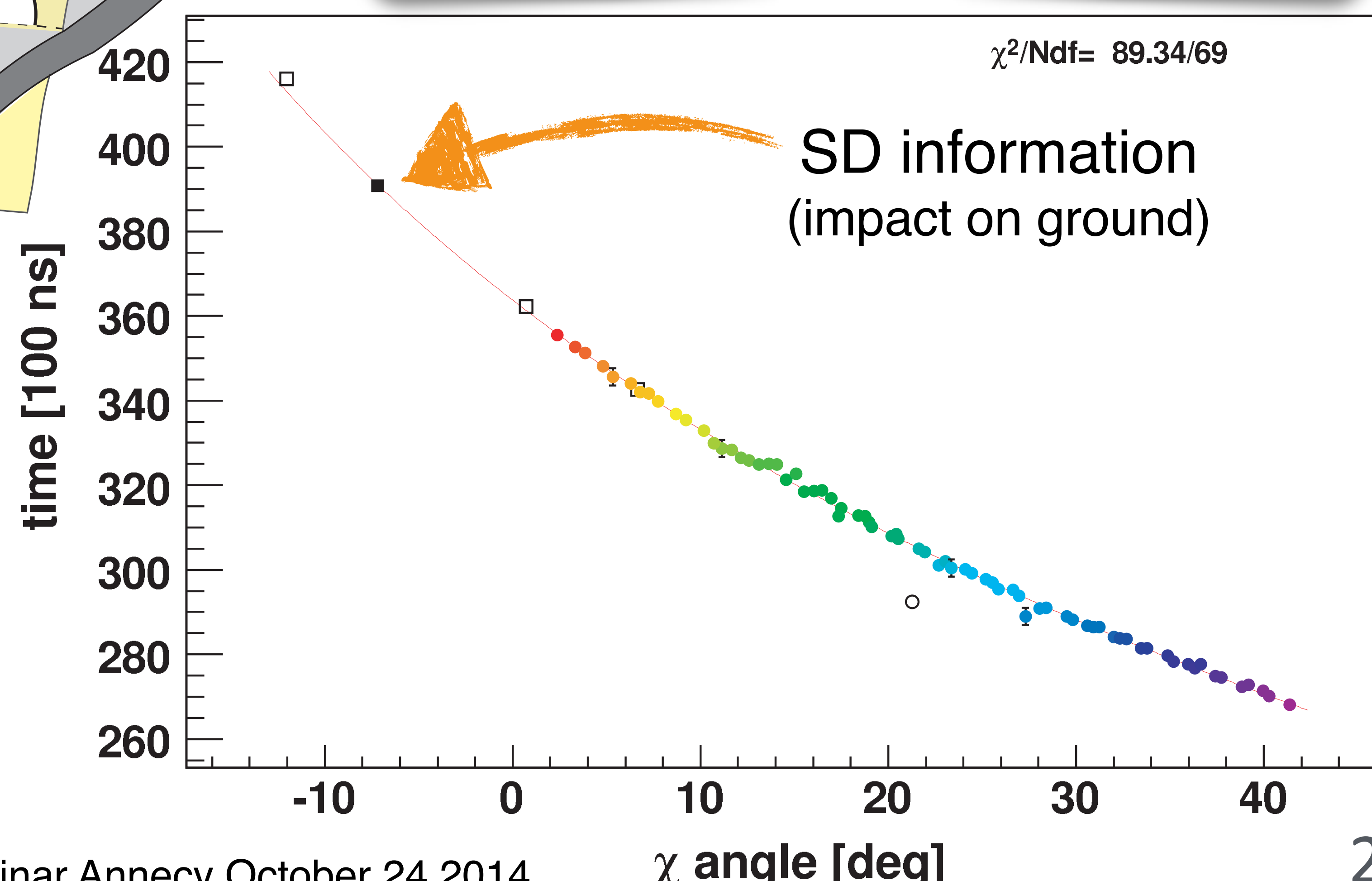
2.Determine geometry within SDP

Use timing information of pixel!

Express expected arrival time t_i at telescope as function of R_p, t_0 and chi_0 :

$$t_i = t_0 - \tau_i^{\text{shower}} + \tau_i^{\text{prop}}$$

$$t_i = t_0 + \frac{R_p}{c} \tan\left(\frac{\chi_0 - \chi_i}{2}\right)$$



Geometry reconstruction

Two step process:

2.Determine geometry within SDP

...ation of pixel!

...val time t_i at

...R_p, t_0 and chi_0 :

$$\ldots + \tau_i^{\text{prop}}$$

$$\left(\frac{\chi_0 - \chi_i}{2}\right)$$

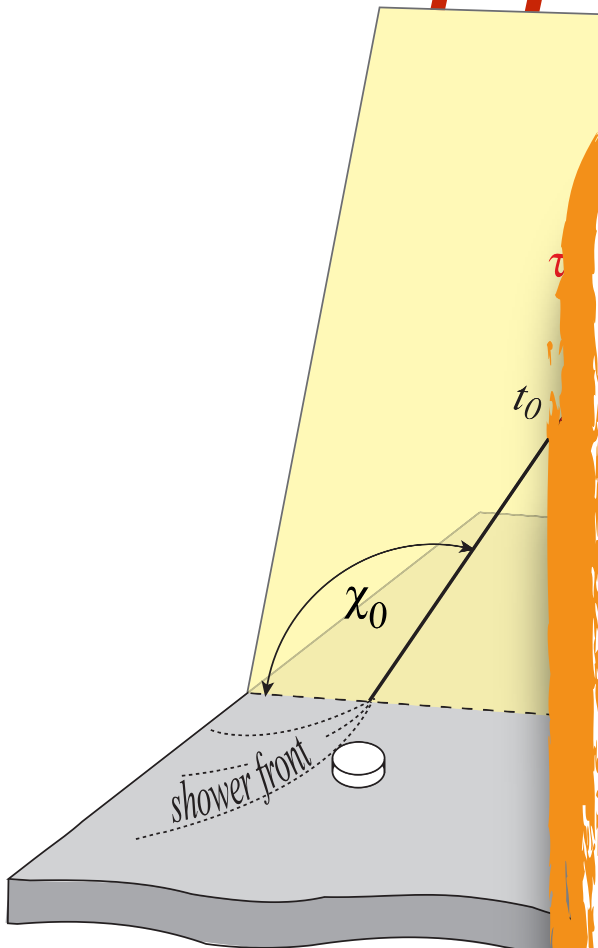
...formation

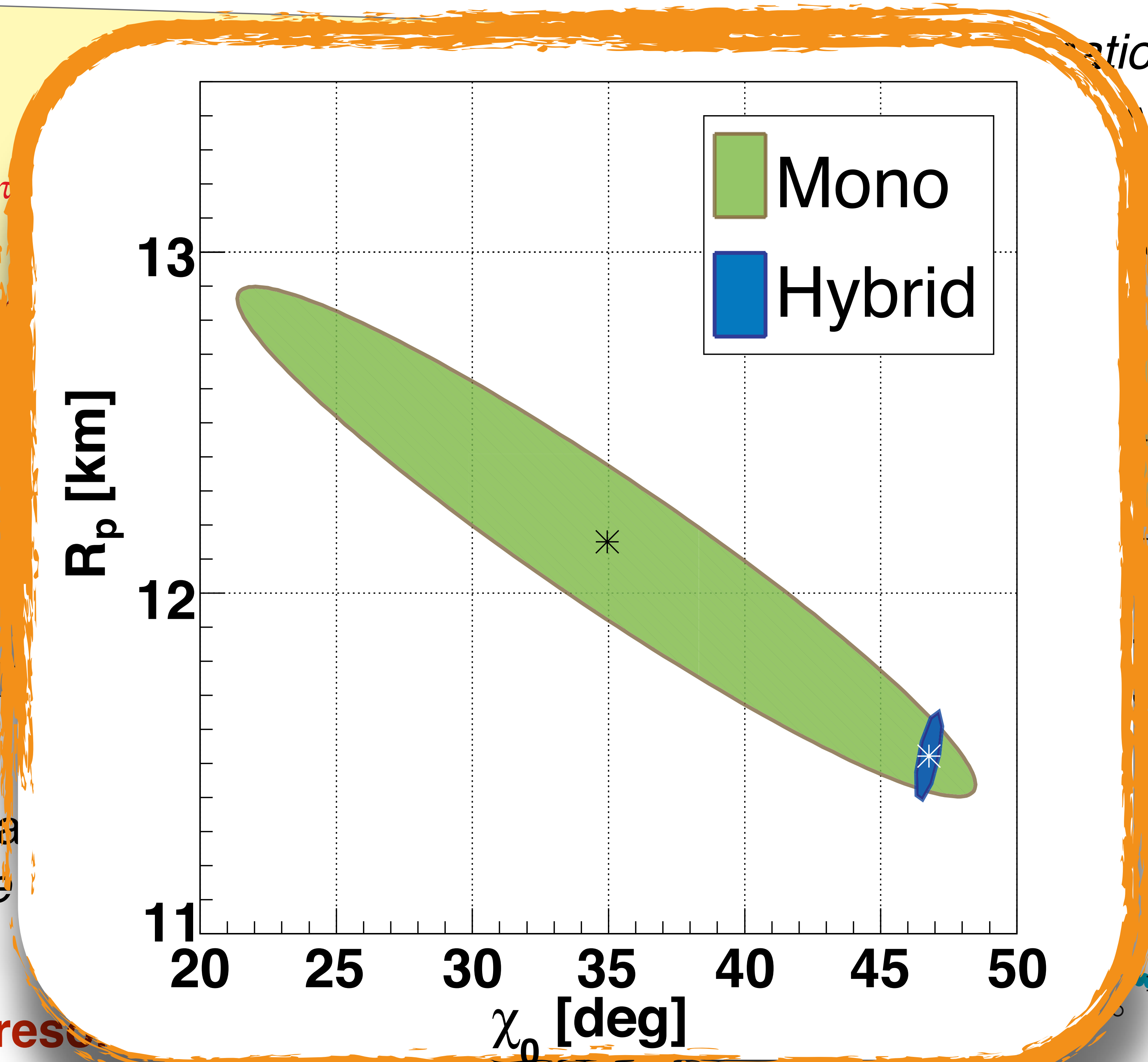
...on ground)

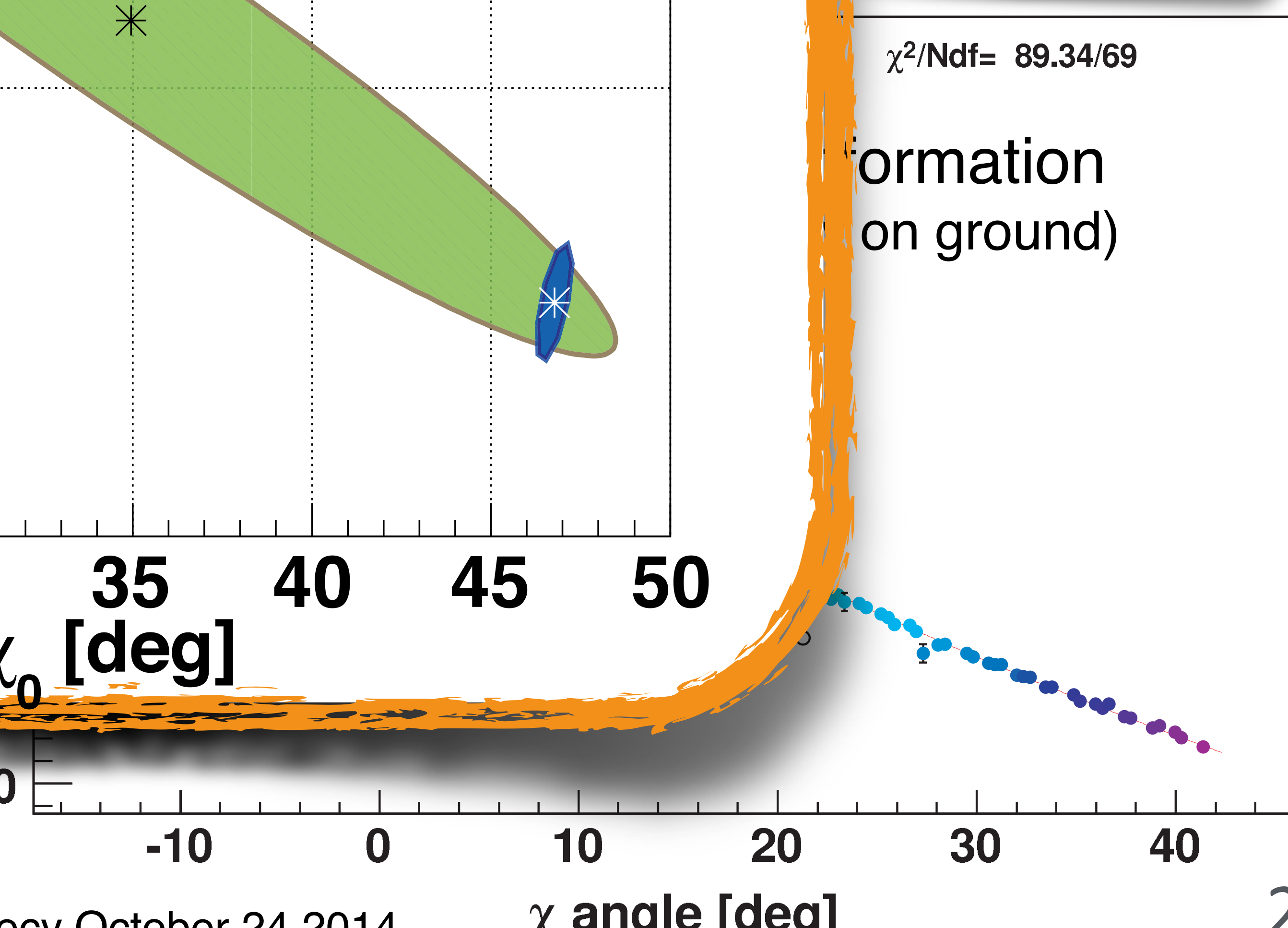
Fit R_p, t_0 a...

determine...

Angular res... typically less than 1°

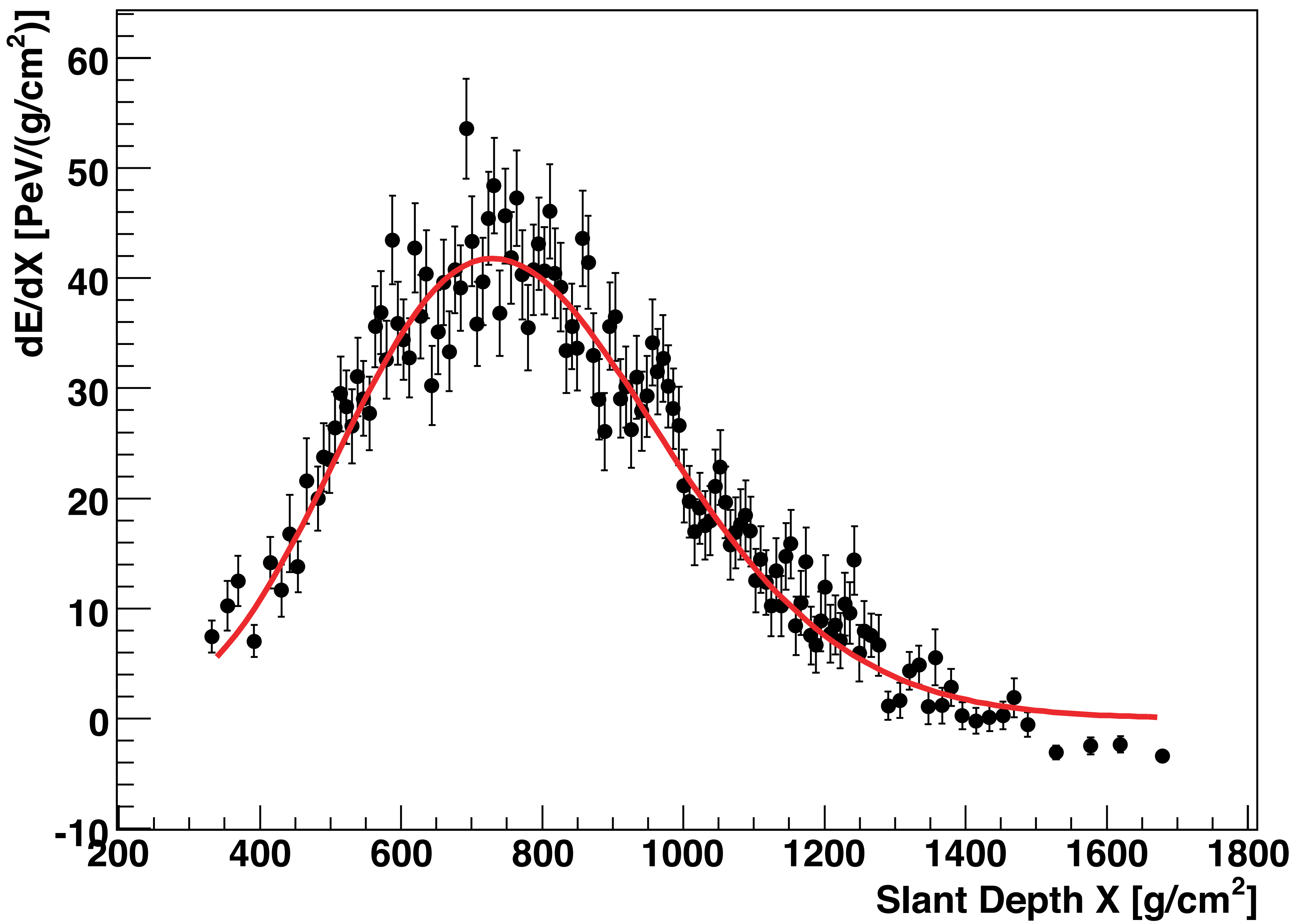






Energy reconstruction

Energy determination from profile fit



$$\int \frac{dE}{dX}\, dX \sim E$$

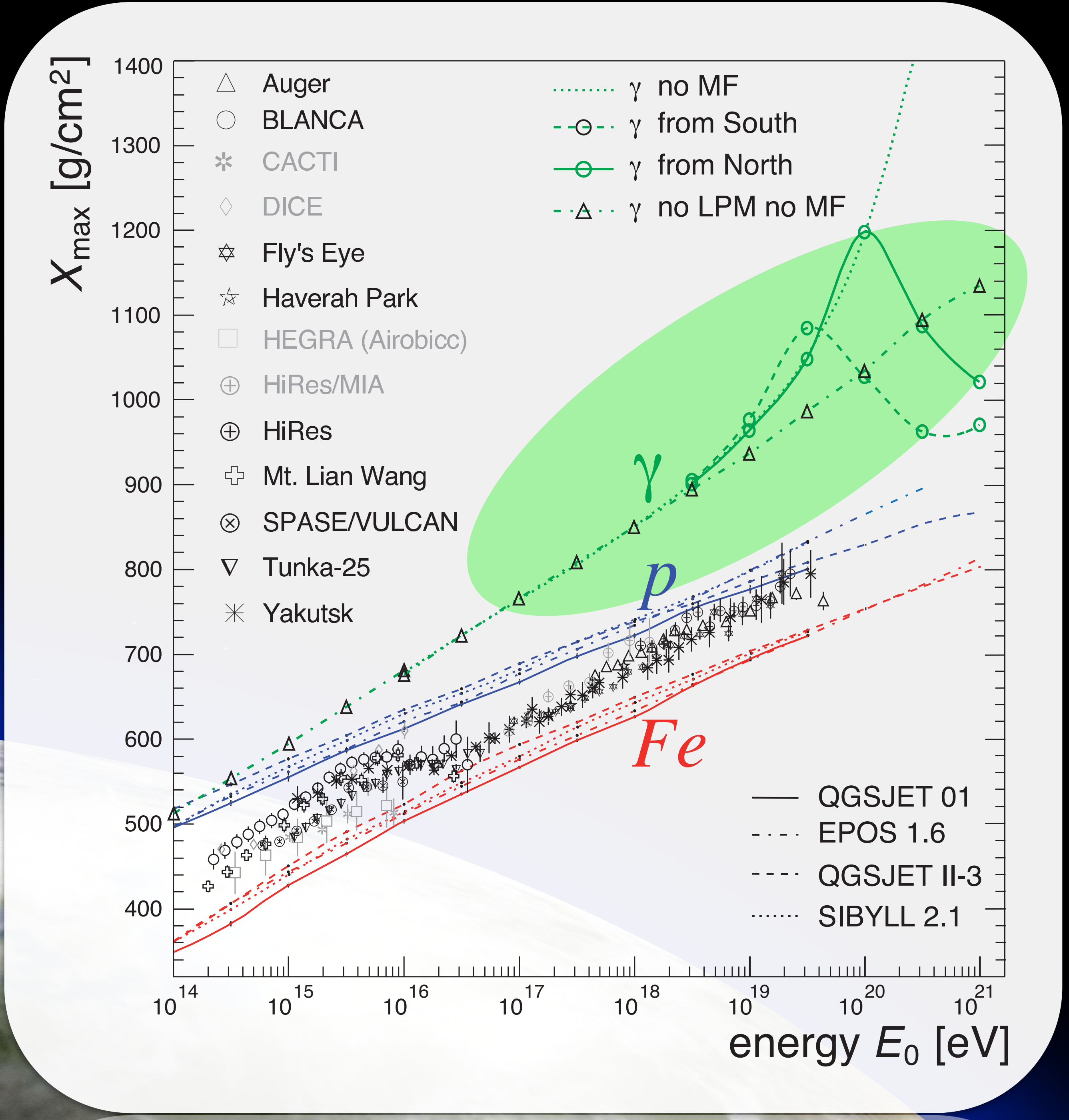
Largest uncertainty from fluorescence yield

Systematic uncertainty ~14%

Photon induced air showers:

Two main characteristics:

1. Delayed shower development (larger X_{max})
2. Lack of muons due to smaller photo-nuclear cross-section



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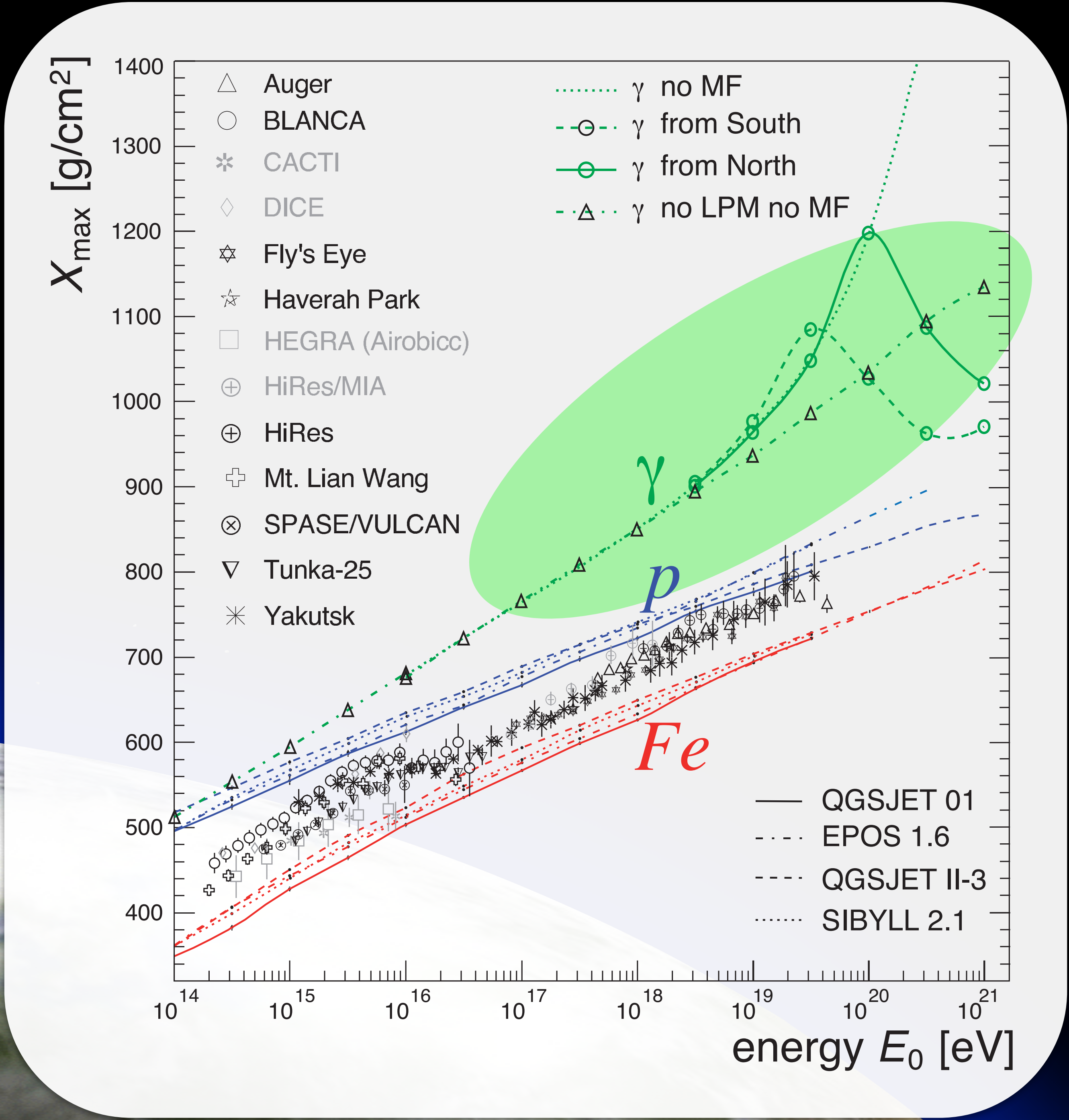
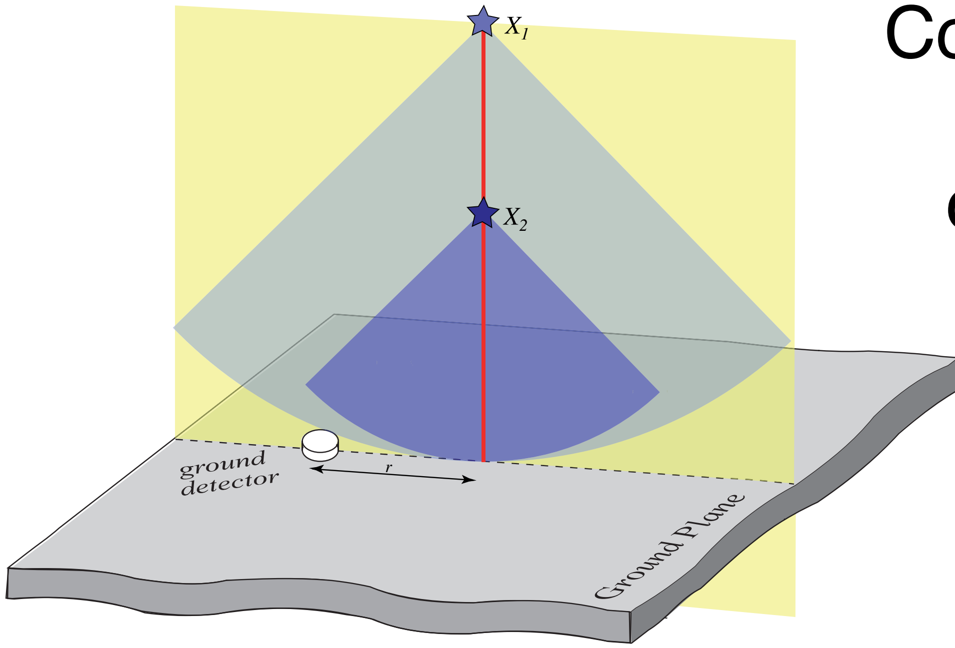


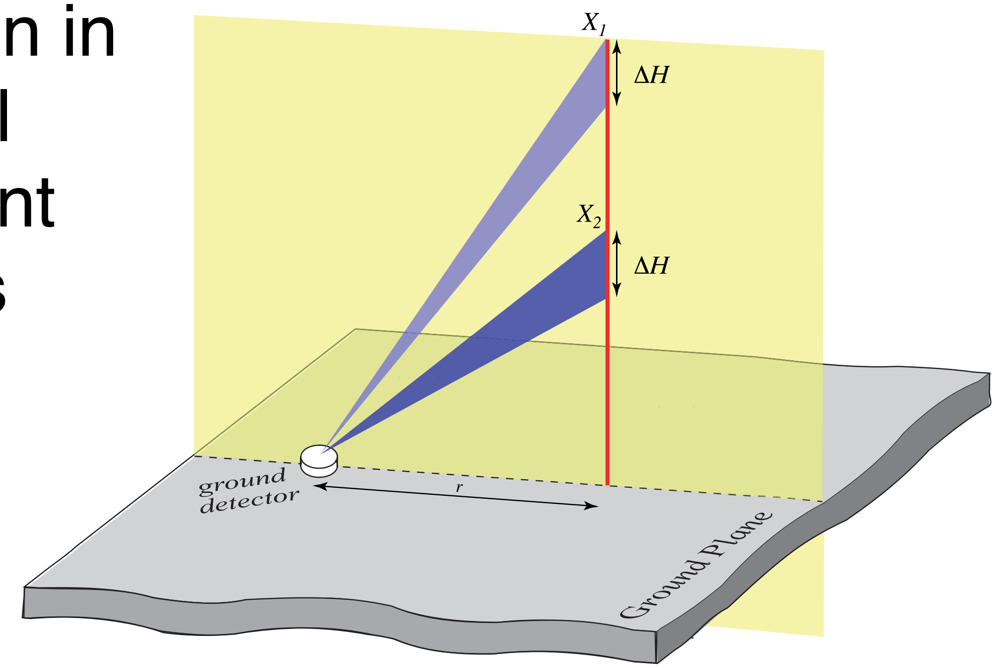
Diffuse photon search

Radius of curvature

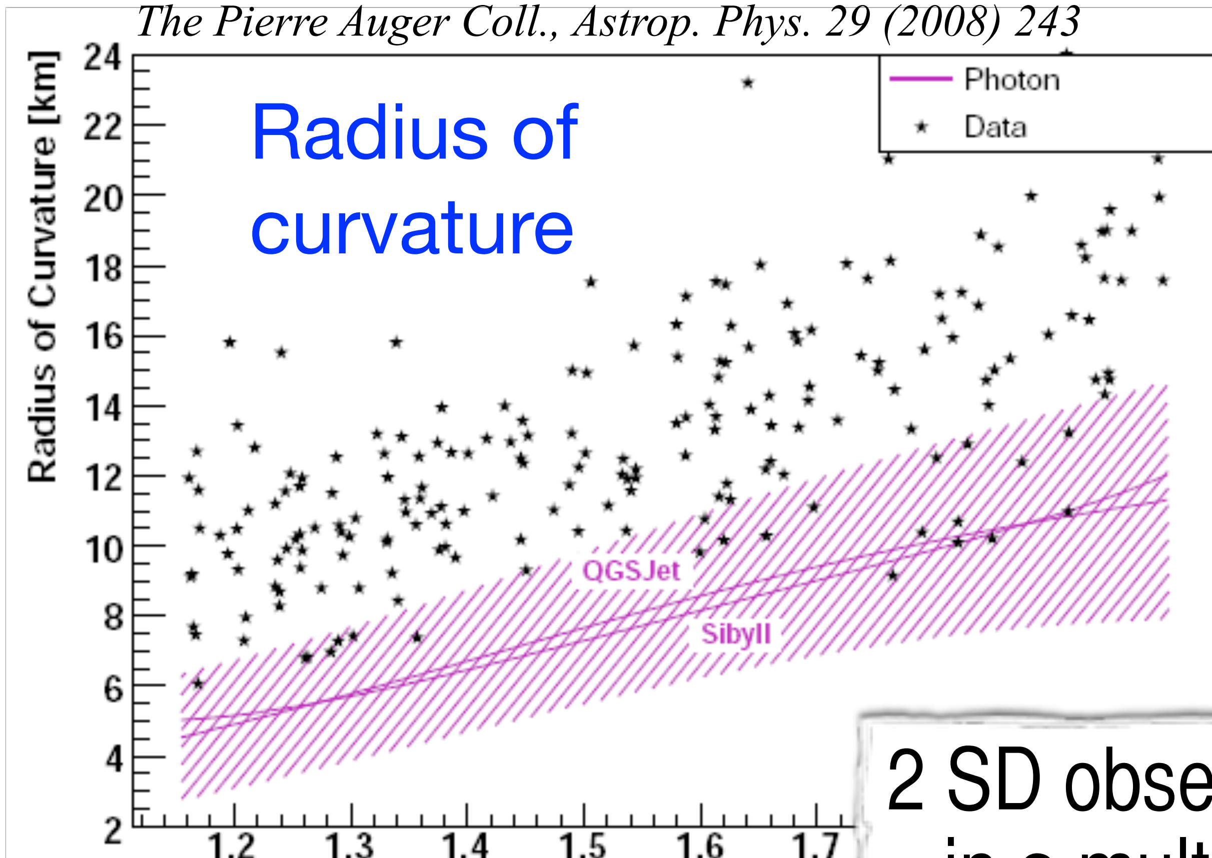


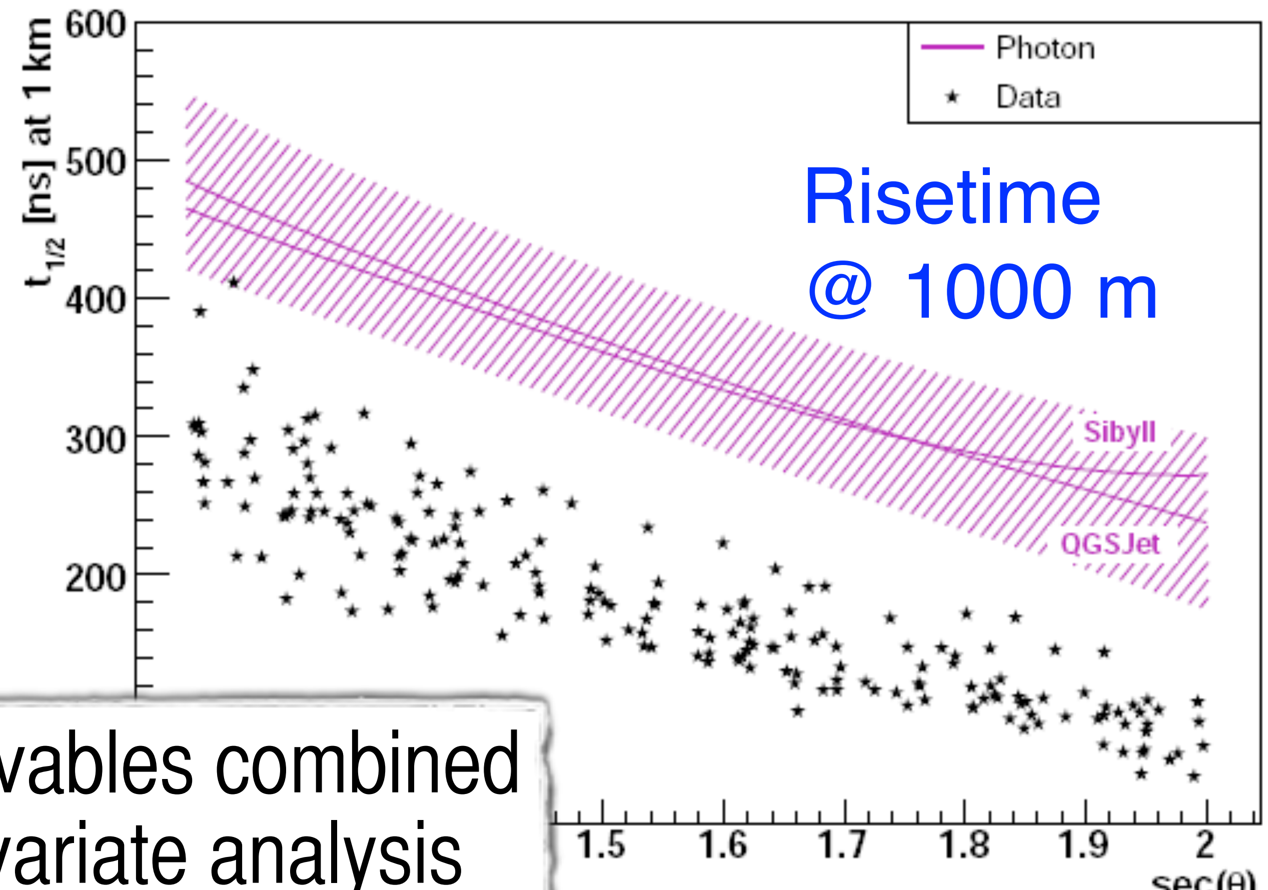
Combination in principal component analysis

Risetime



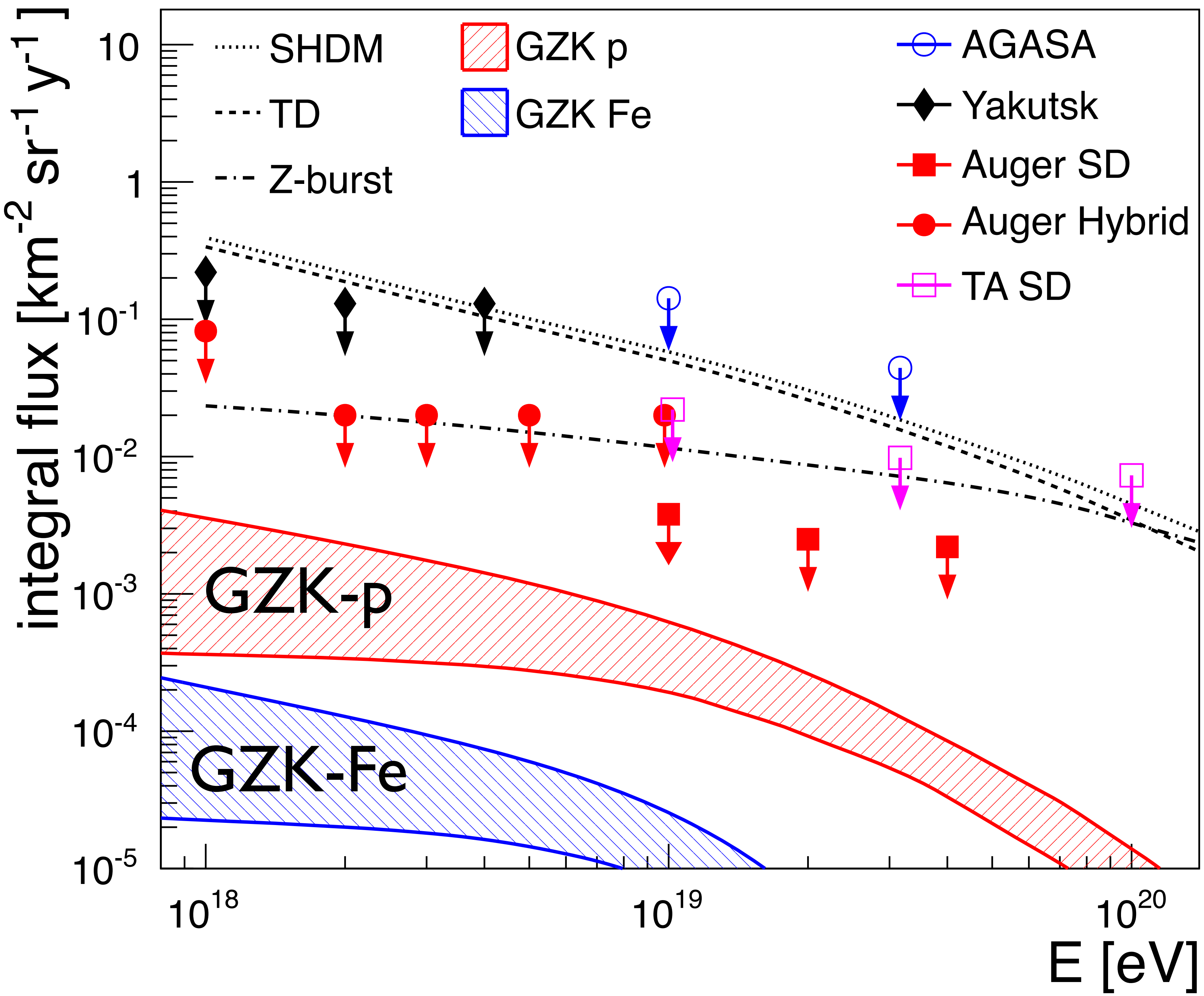
The Pierre Auger Coll., Astrop. Phys. 29 (2008) 243





2 SD observables combined in a multivariate analysis

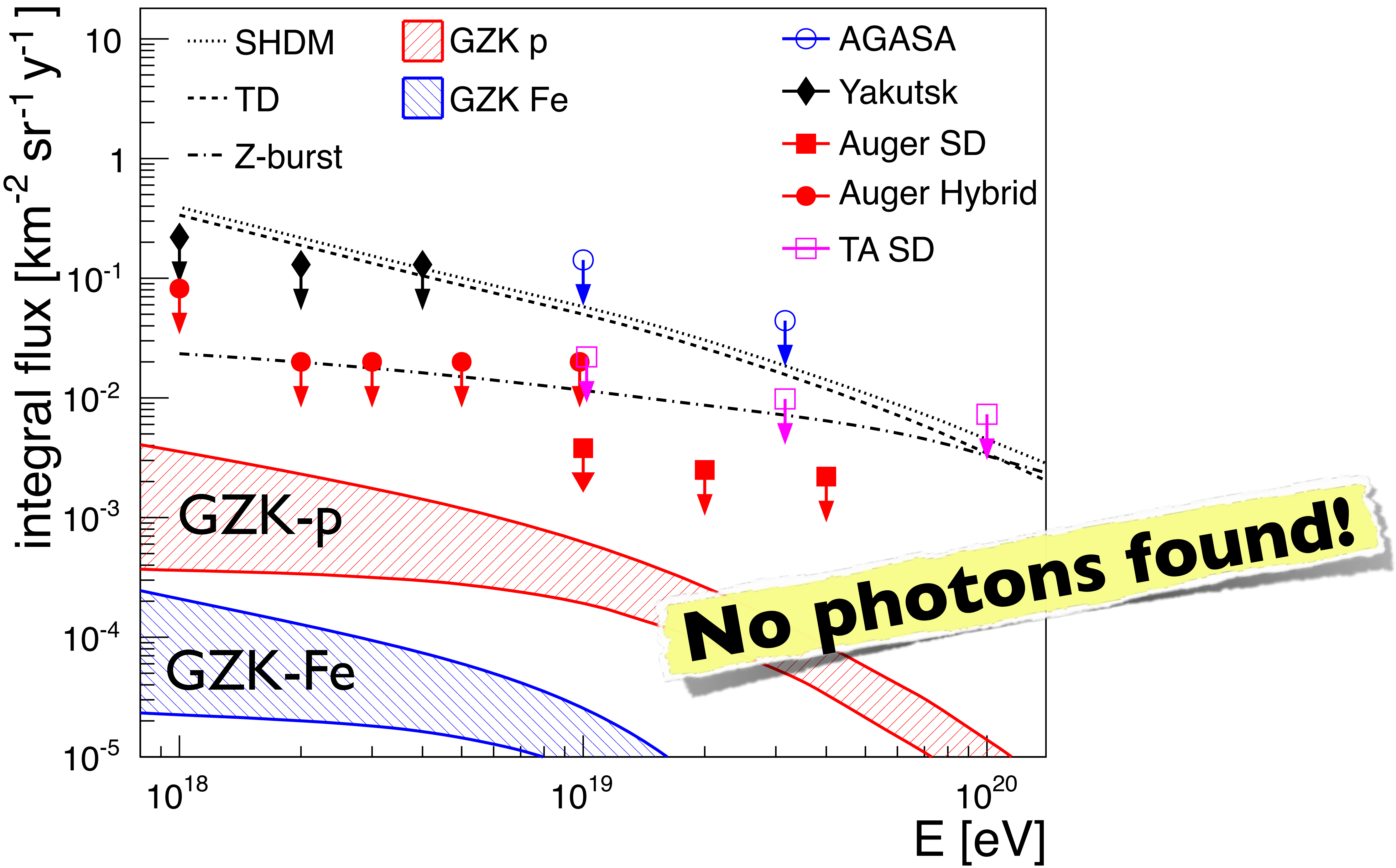
Status of diffuse searches



▶ **Top-down** models **severely constrained**

Remember: *Limits are diffuse, i.e. not using pointing information*

Status of diffuse searches



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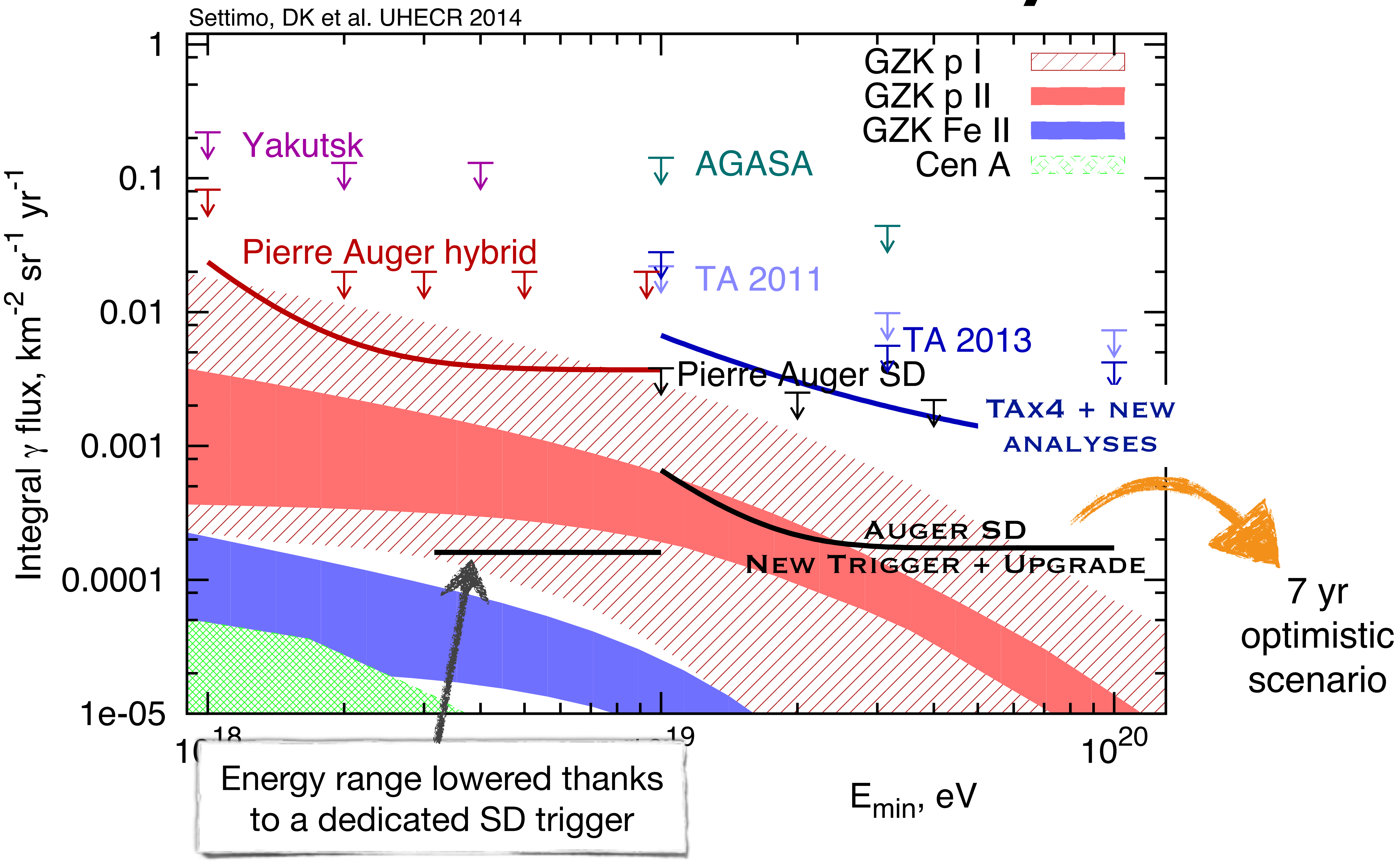
Photon sensitivity



▸ Optimistic **GZK-predictions in reach**

Pierre Auger Coll. ApJ 789 (2014) 160

Idea directional information

Measure extensive air showers

- Arrival direction
- Shower characteristics

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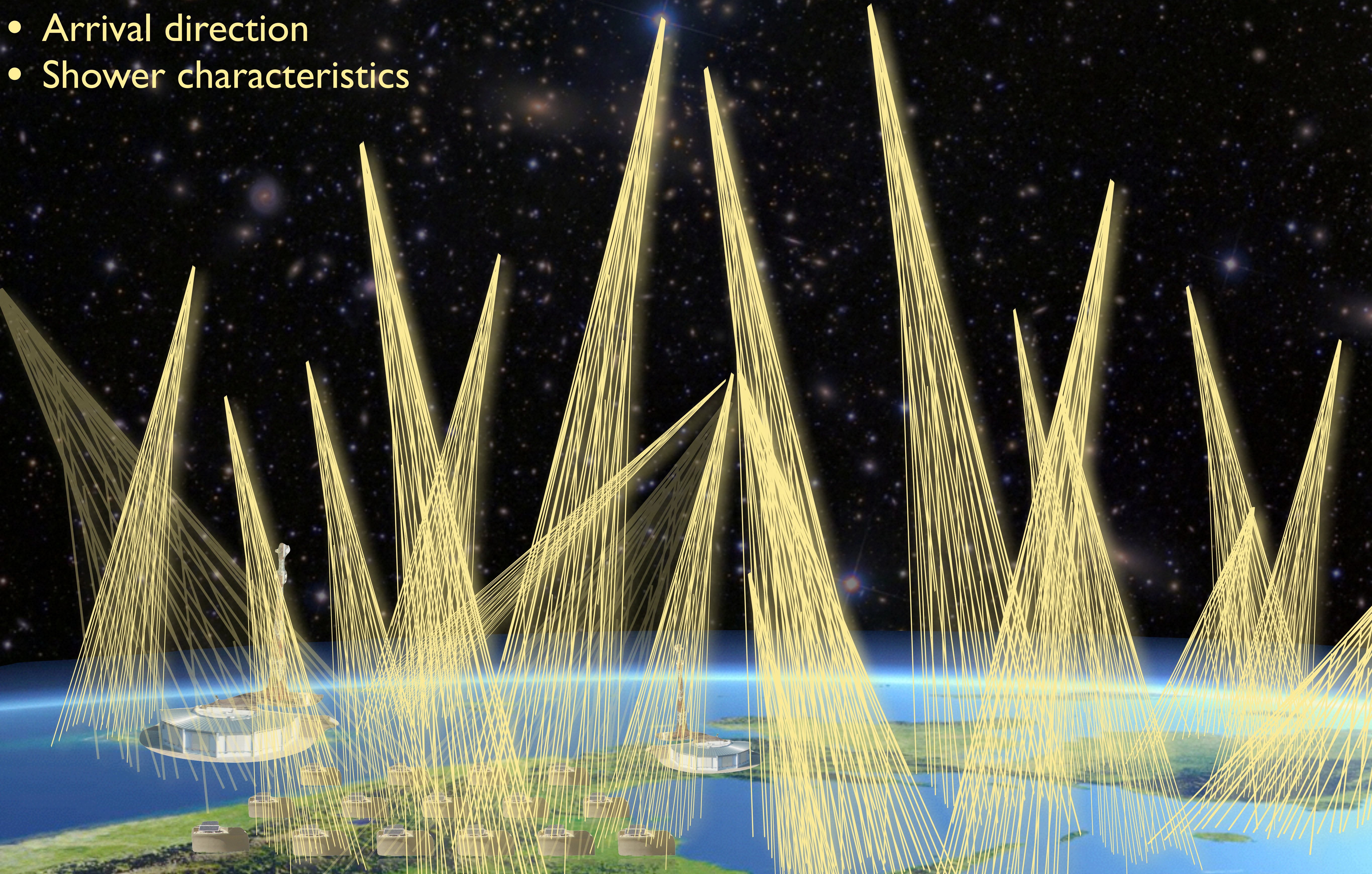
Idea directional information

Any point sources visible?

Measure extensive air showers

- Arrival direction
- Shower characteristics



Pierre Auger Coll. ApJ 789 (2014) 160

Idea directional information

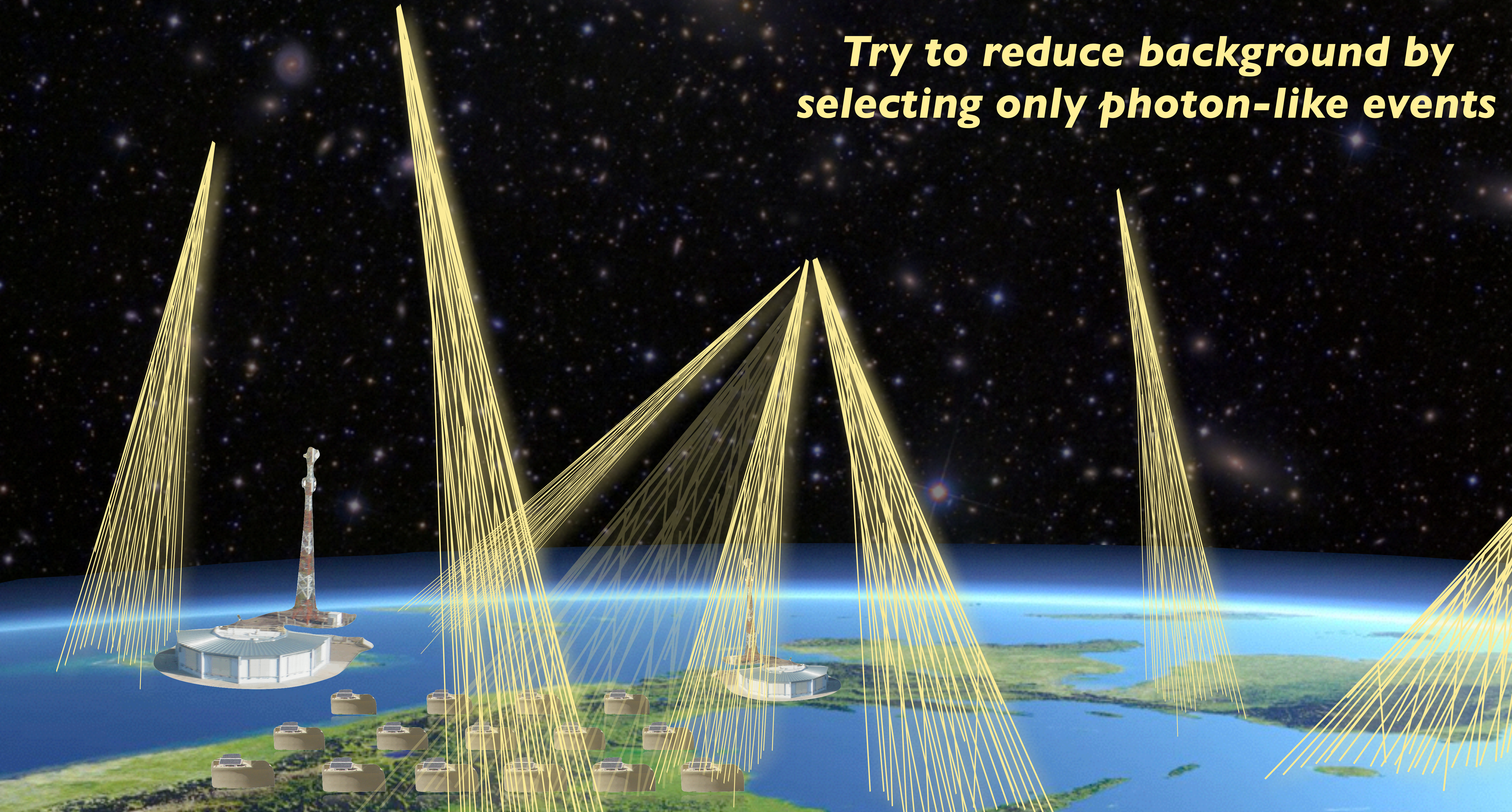
Measure extensive air showers

- Arrival direction
- Shower characteristics

Any point sources visible?

No!?

Try to reduce background by selecting only photon-like events



Observables

1. **Depth of shower maximum X_{max}** (FD related)

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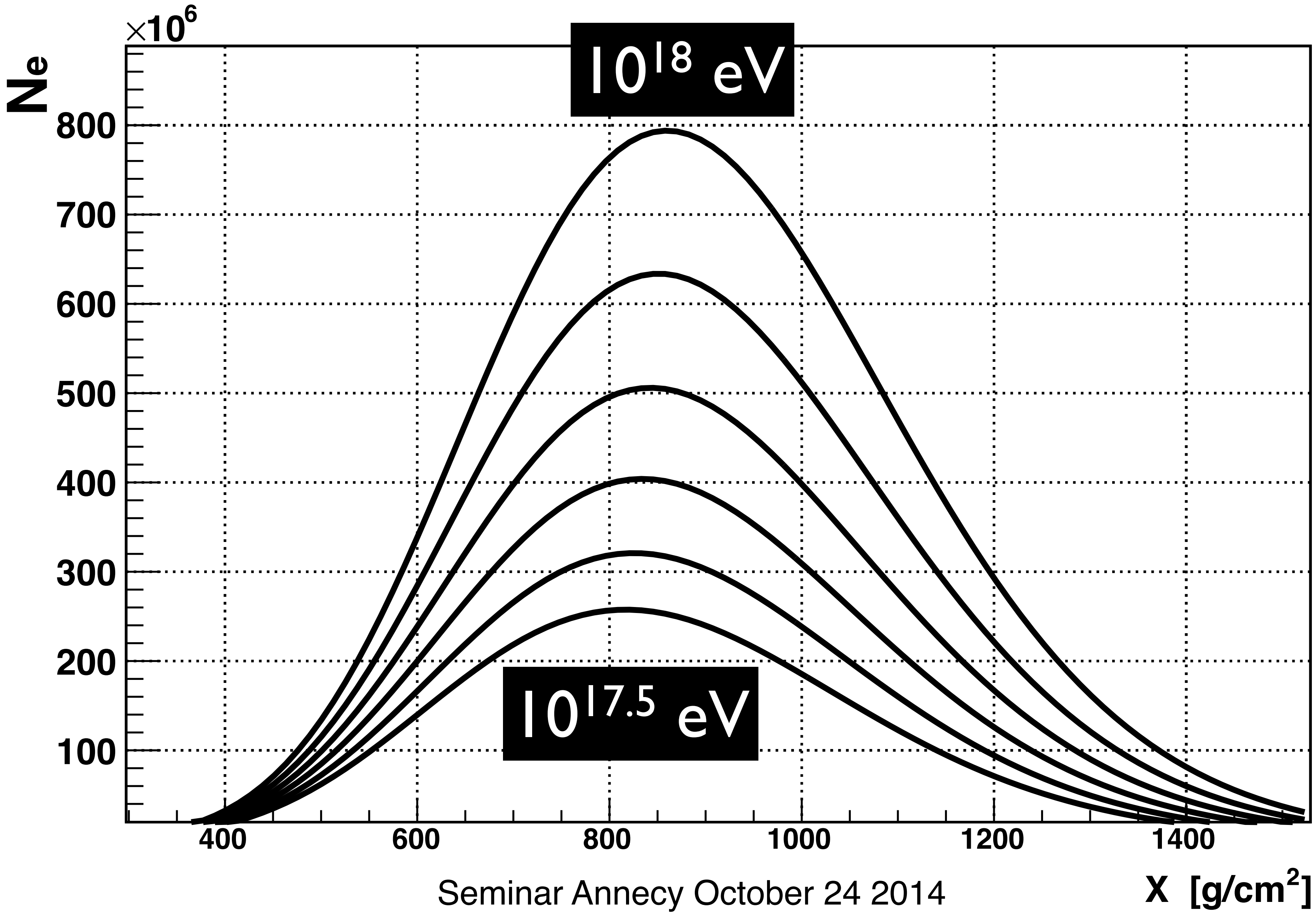
2. **Fit of Greisen function** (FD related)

$$N_{\rm ch}(X,E) = \frac{0.31}{\sqrt{\ln(E/E_c)}} e^{\frac{X}{X_r}} \left(\frac{3X}{X + 2X_r \ln(E/E_c)} \right)^{-\frac{3X}{2X_r}}$$

„parametrization of the longitudinal shower development based on electromagnetic cascade equations"

critical energy

radiation length



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3. **Energy ratio of Greisen energy and standard energy** (FD related)

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critical energy — *radiation length*

„parametrization of the longitudinal shower development based on electromagnetic cascade equations"

3. **Energy ratio of Greisen energy and standard energy** (FD related)
4. **Sb parameter** (SD related)

$$S_b = \sum_{i=1}^{N} \left[S_i \cdot \left(\frac{r_i}{1000\ \mathrm{m}} \right)^b \right]$$

distance station - shower axis

Signal in station i

b=3 for photon separation

„sensitive to different lateral distribution functions (presence/absence of muon component)"

Observables

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critical energy (E_c) — *radiation length* (X_r)

„parametrization of the longitudinal shower development based on electromagnetic cascade equations“

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4. **Sb parameter** (SD related)

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Signal in station i (S_i) — *distance station - shower axis* (r_i) — *b=3 for photon separation*

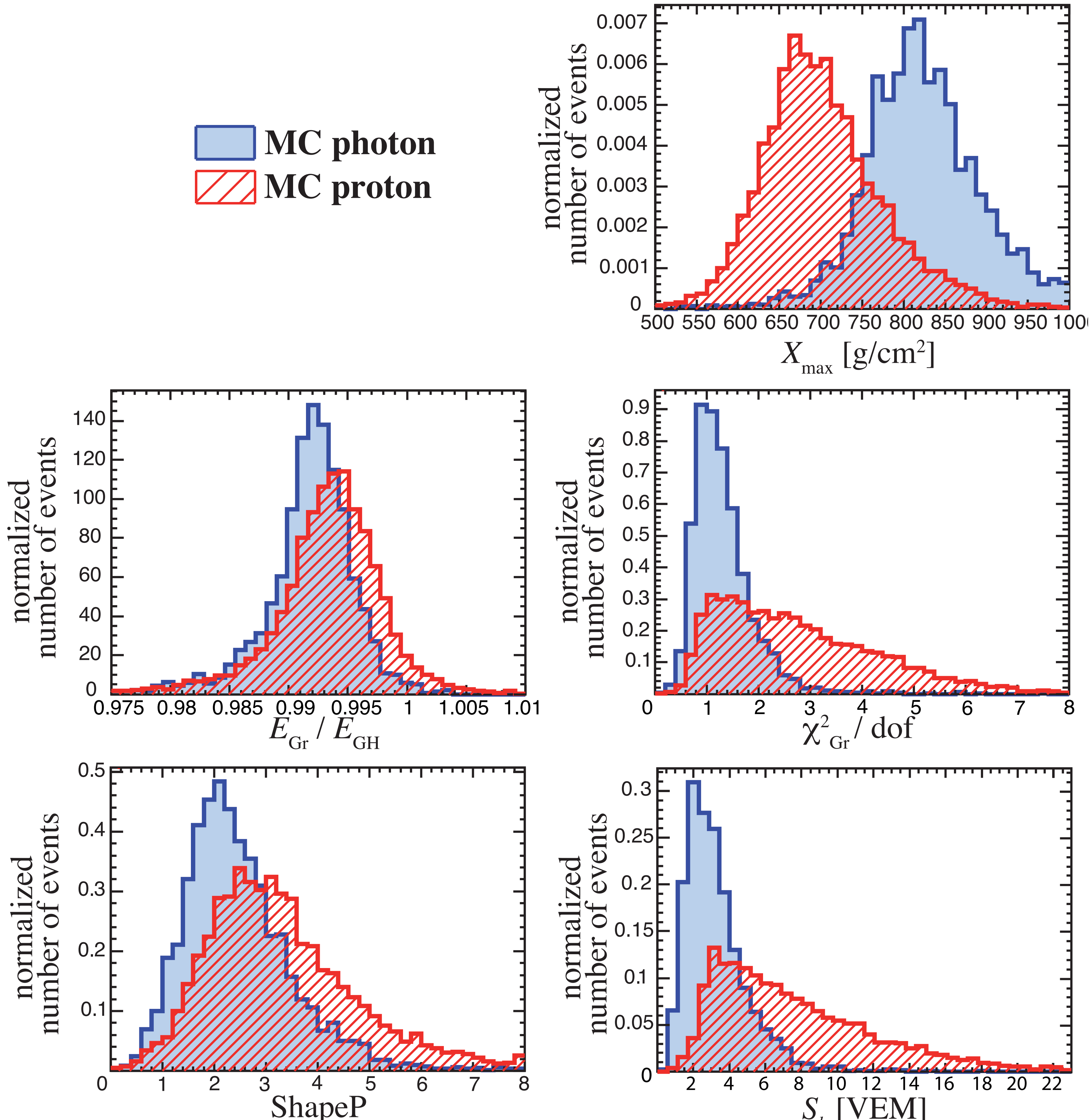
„sensitive to different lateral distribution functions (presence/absence of muon component)“

5. **Shape parameter** (SD related)

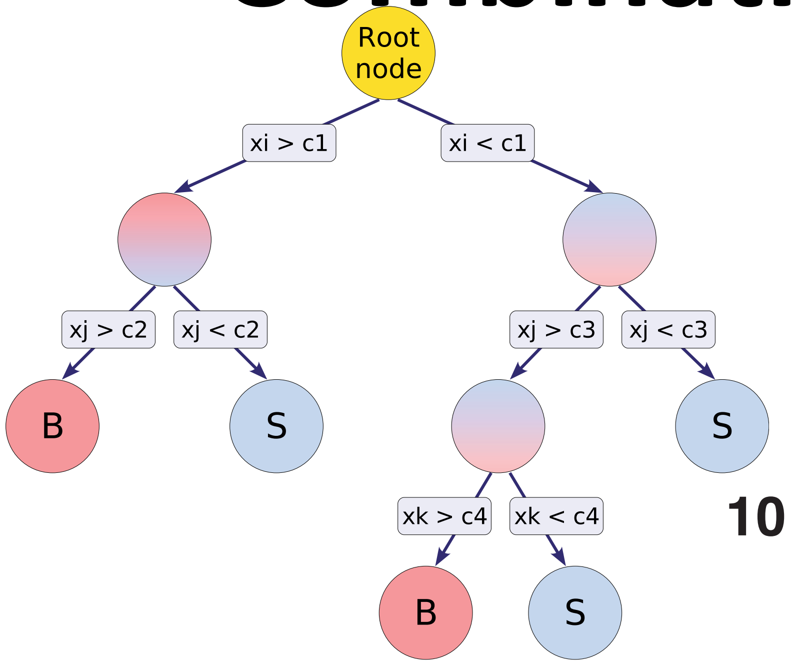
$$\mathrm{ShapeP}(r,\theta) = \frac{S_{\mathrm{early}}(r,\theta)}{S_{\mathrm{late}}(r,\theta)}$$

„For primary photons a larger spread of particles in arrival time is expected, i.e. deep developing particles“

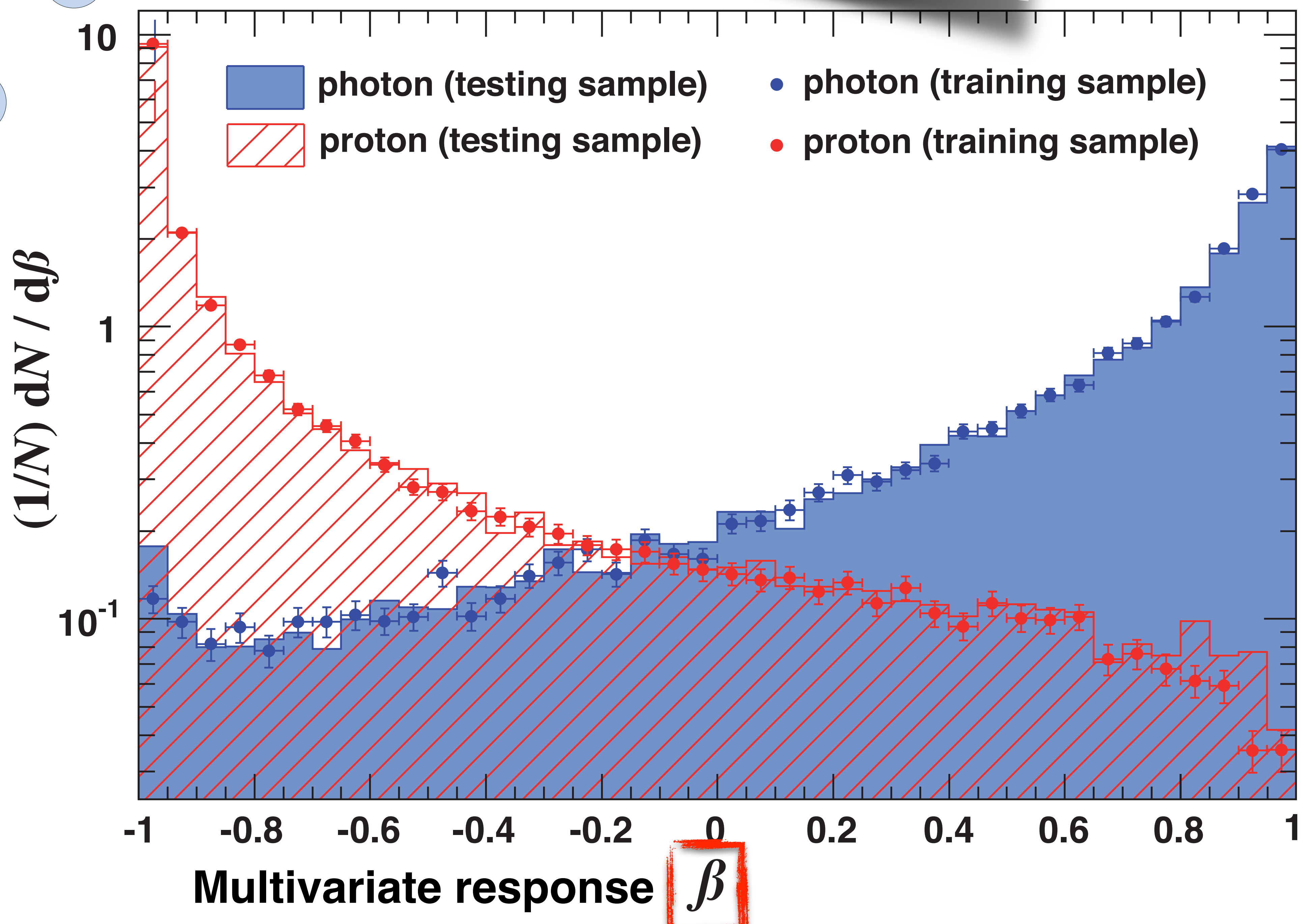
Observables



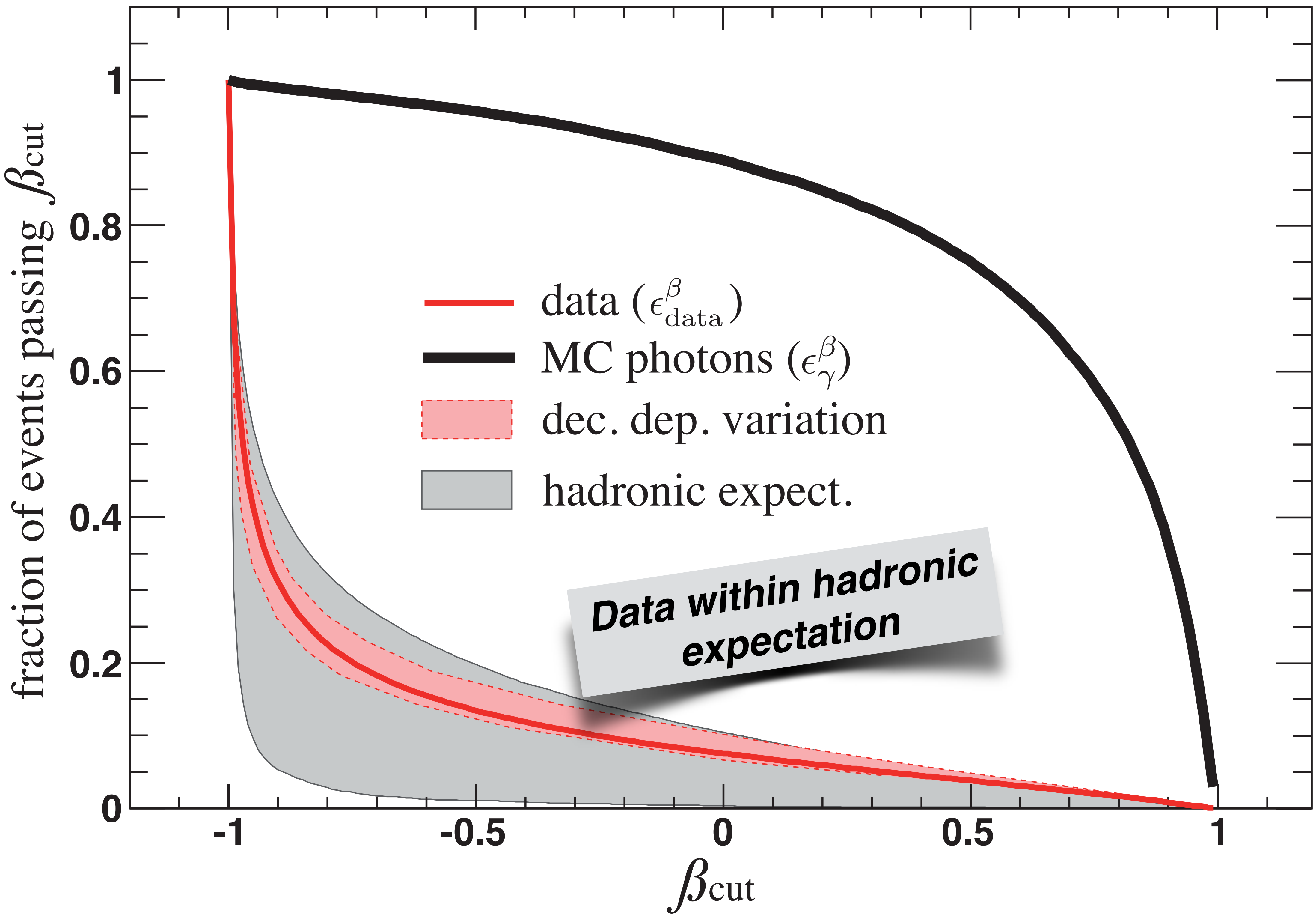
Combination via boosted decision trees



Select photon-like events by cut in β-distribution



Fraction of events passing β_{cut}



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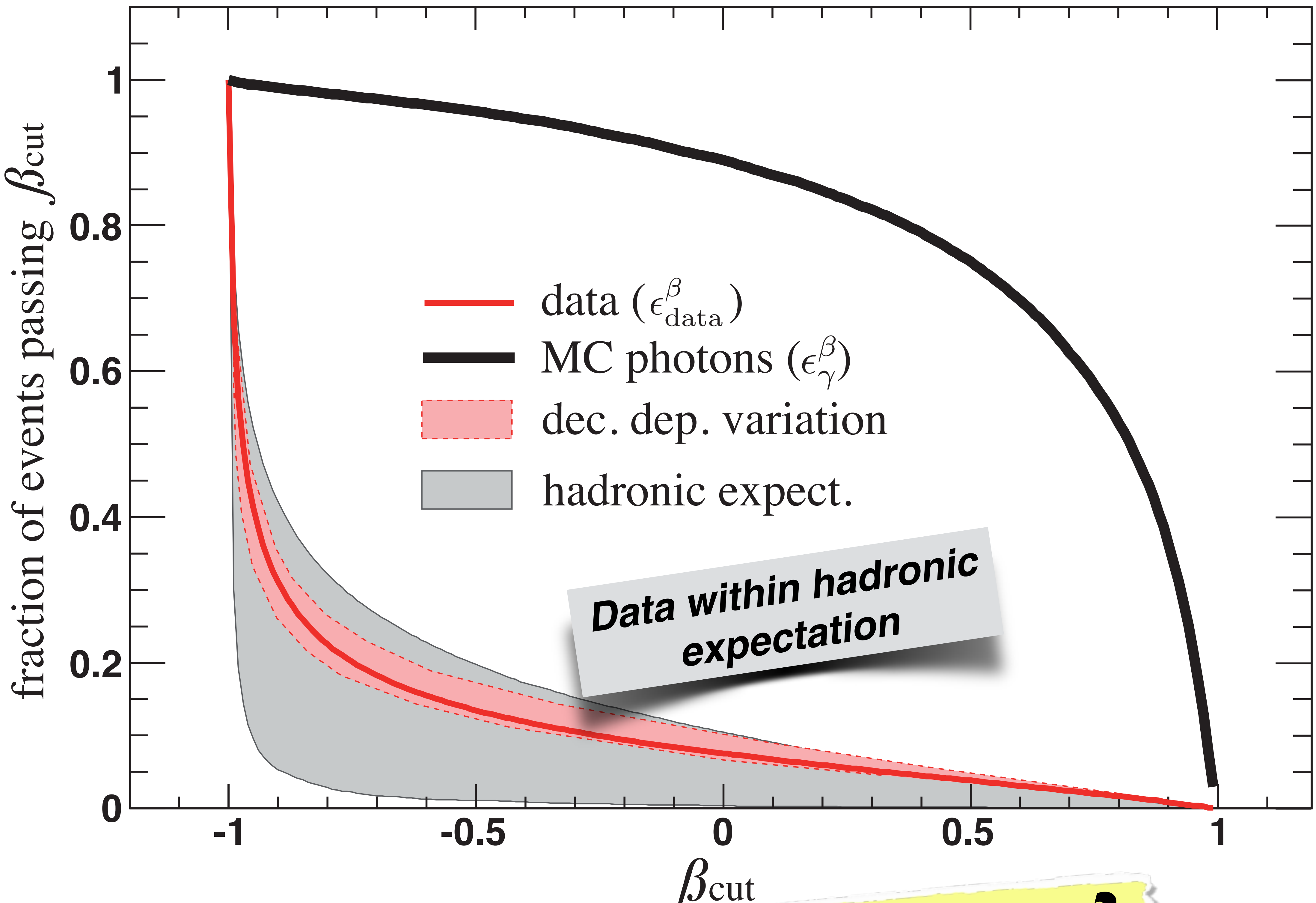
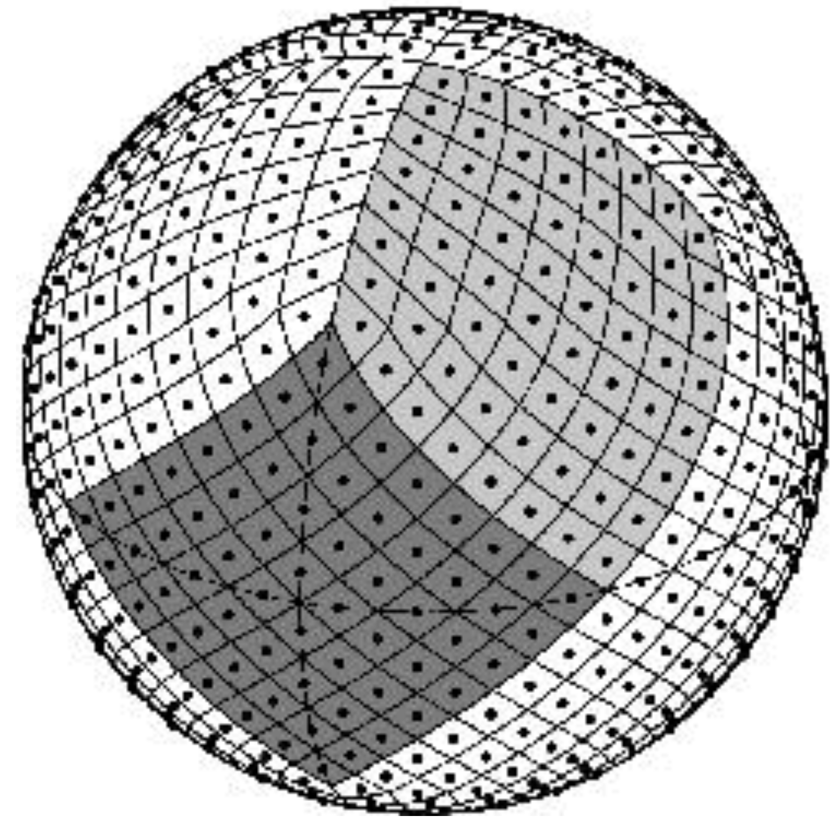


What cut should we use?

Analysis strategy



- **Blind search:** Sky maps are pixelized with 526200 target directions between declination -85° and +20°. Target separation about 0.3°
- Top-hat counting with radius 1°
  (choice will be explained later)

- Consider each target direction **individually**

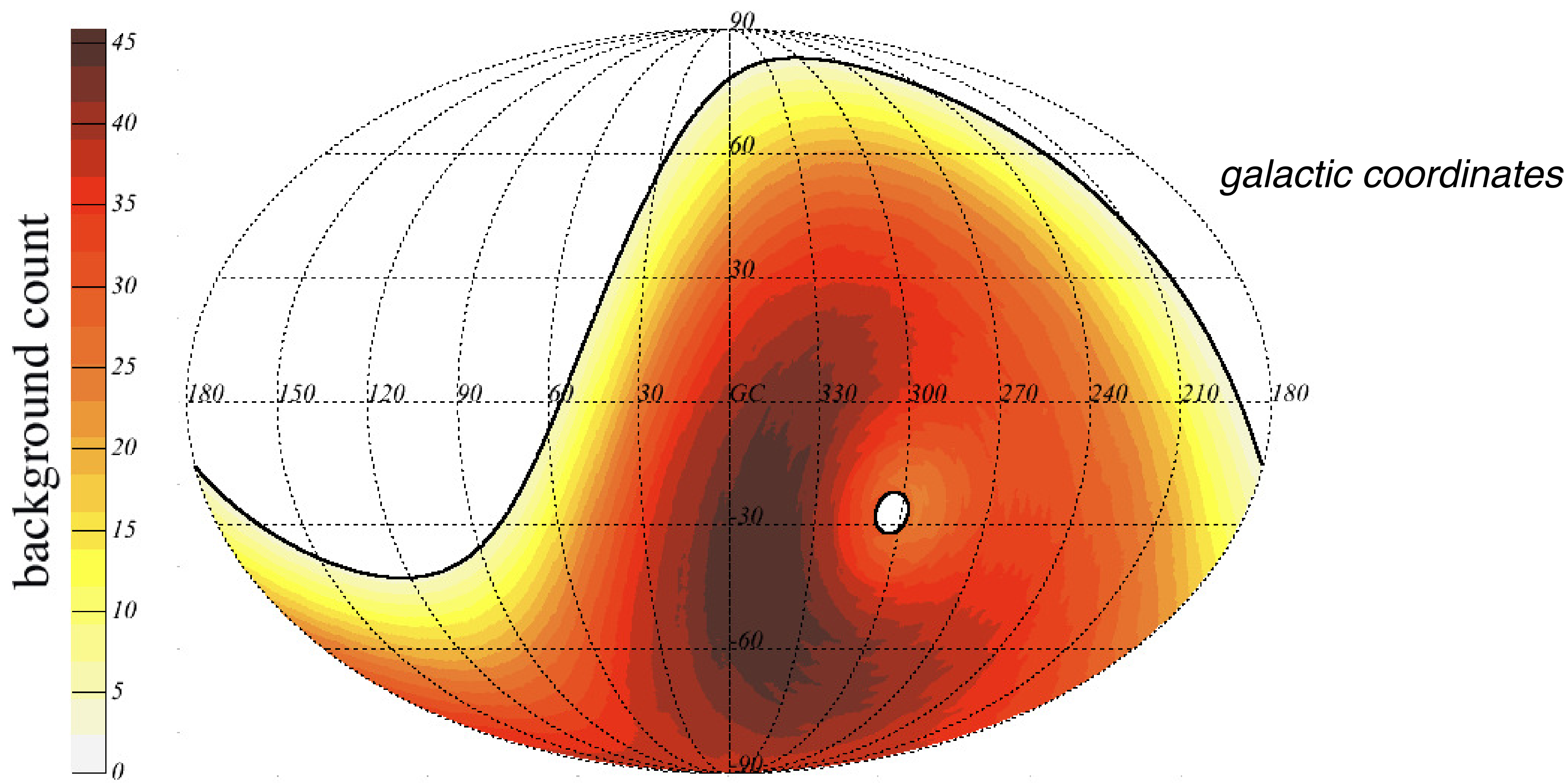
- *For each direction:*
  Optimized β_{cut} is determined by **minimizing upper limit** using Zech's method assuming that the expected background is equal to the observed number (G. Zech, NIM A277, 608-610 (1989)):

$$P(\leq n_b^\beta | n_b^\beta + n_s) = \alpha_{\text{CL}} \cdot P(\leq n_b^\beta | n_b^\beta)$$

expected background — **upper limit photon events** — **1 - confidence level (95%)**

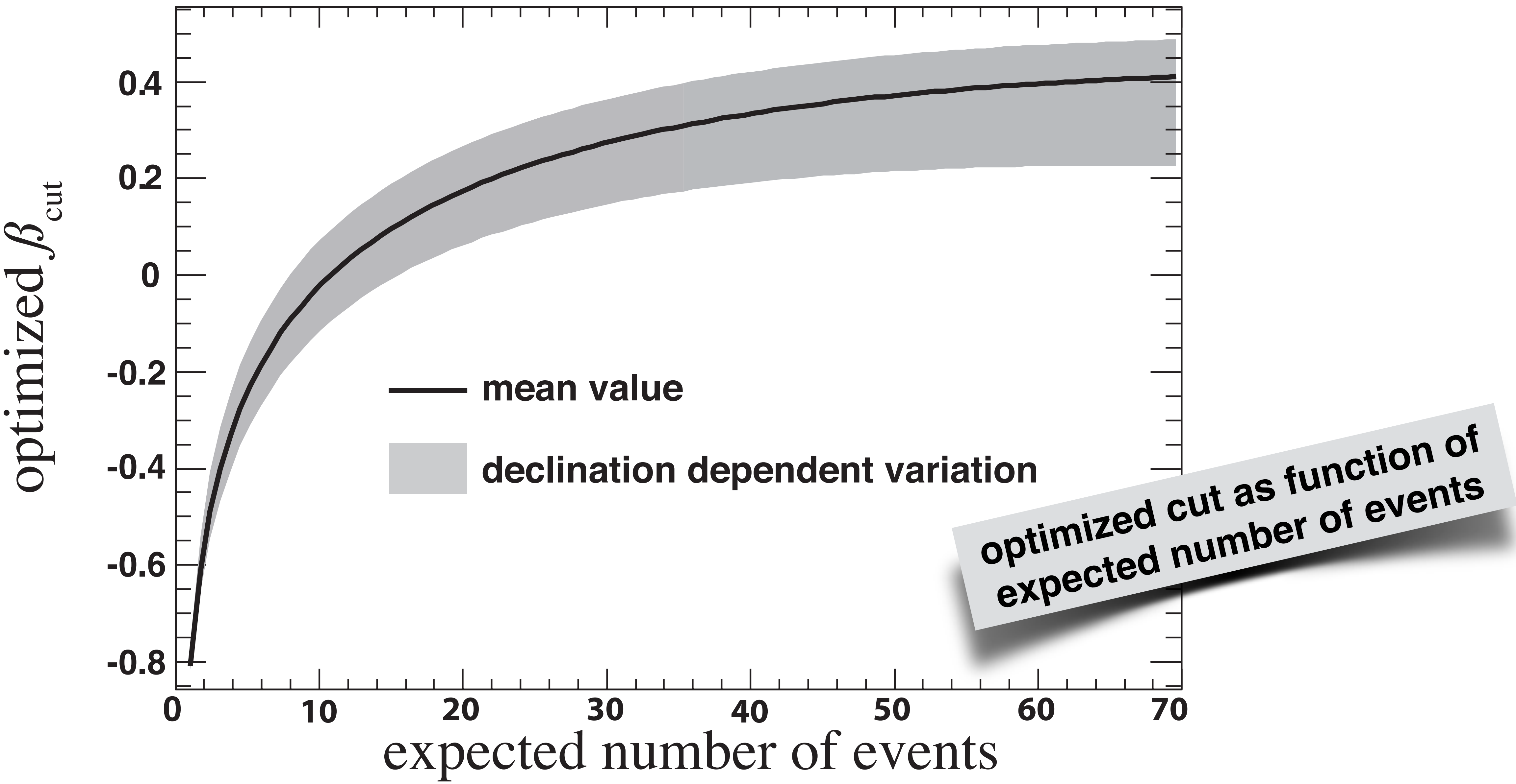
Background expectation

- **Question:** What is the sky map of arrival directions from the Pierre Auger Observatory if all cosmic rays arrive isotropically at Earth?
- **Answer:** Calculate isotropic map using scrambling (or shuffling) method
- **Idea:**
  - Split arrival time (UTC) and direction (in local coordinates) and combine randomly to obtain one (isotropic) sky map
  - Repeat step several times (5000 sky maps) and take the average



Obtained using scrambling method
Cassiday et al. Nucl. Phys. Proc. Suppl. **14A**, 291 (1990)

Optimized cut in β distribution

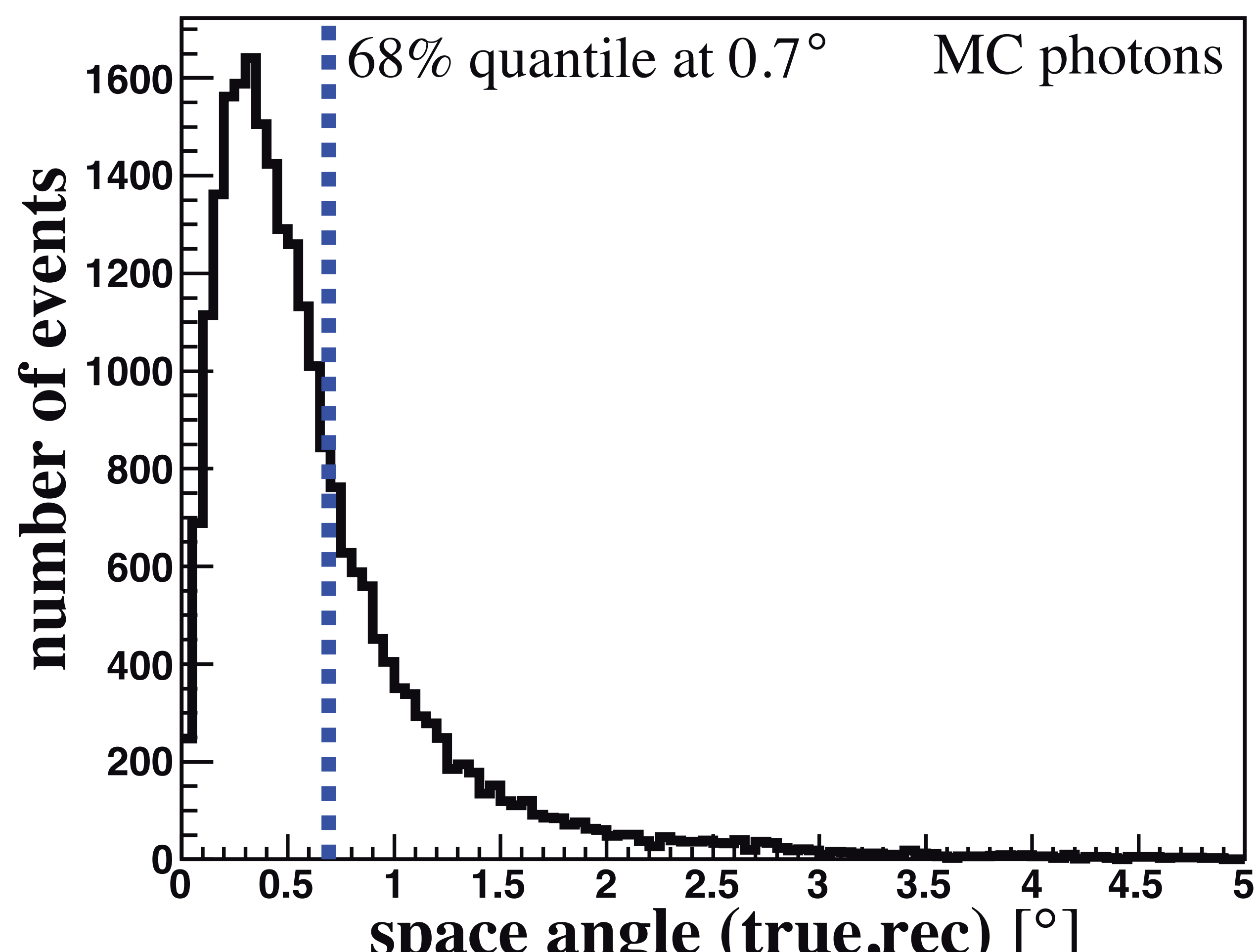


- **Typical β cut value:** 0.22
- **Photon efficiency:** 85%
- **Background efficiency:** 8%
- **Typical background expectation after cut:** 1,48 events

Application to data

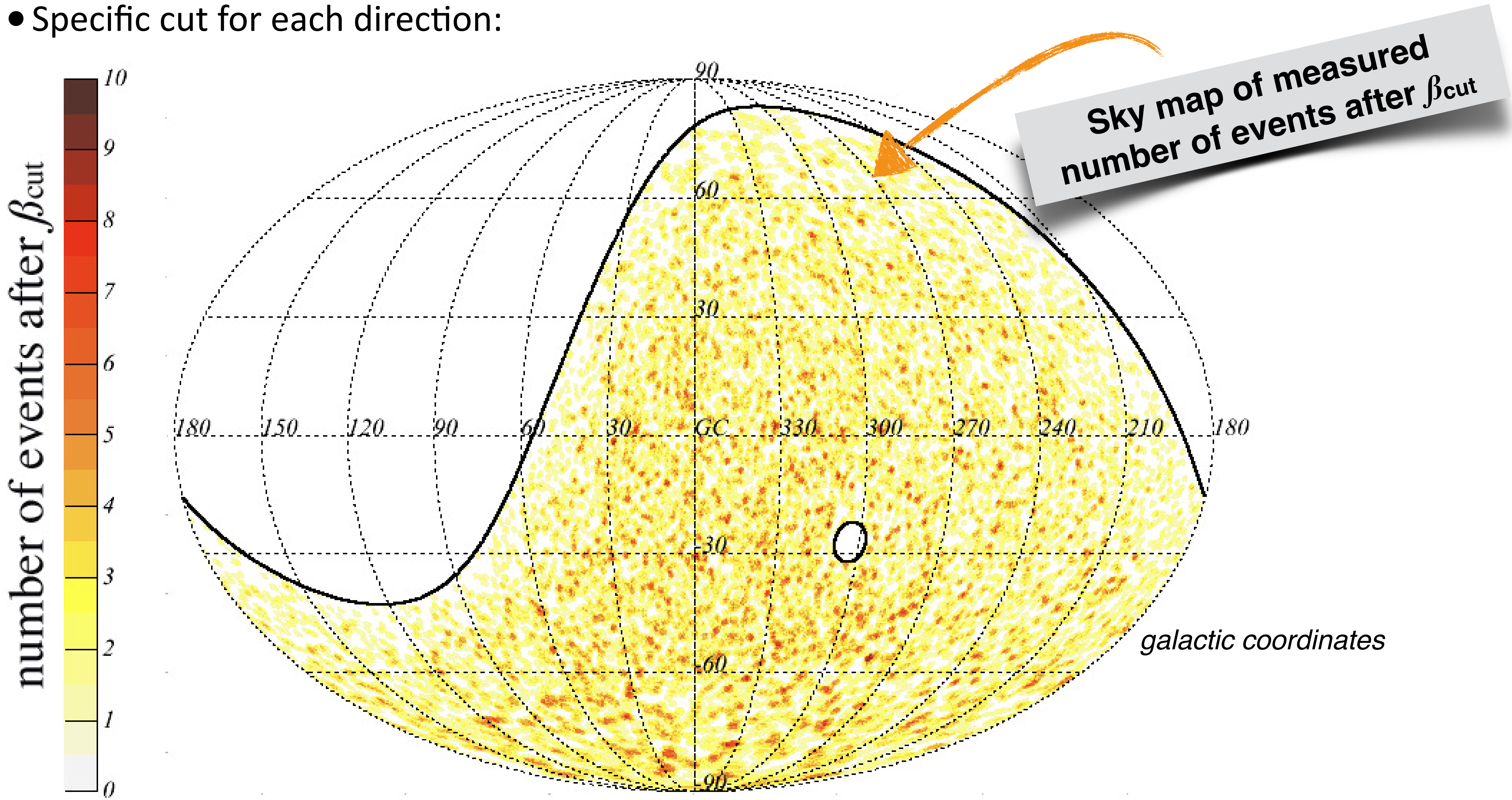
from the Pierre Auger Observatory

- **Data**:
  - Air showers recoded at the Pierre Auger Observatory by fluorescence and surface detector (**hybrid data**) between Jan. 2005 and Sep. 2011
  - **Energy range**: 17.3 < log(E/eV) < 18.5
  - **Zenith range**: 0° < theta < 60°
  - **Angular resolution:** 0.7° → use top-hat counting with radius 1°
    (90% containment of possible point source)
  - Apply additional quality cuts



Photon like events

- Specific cut for each direction:



Photon like events

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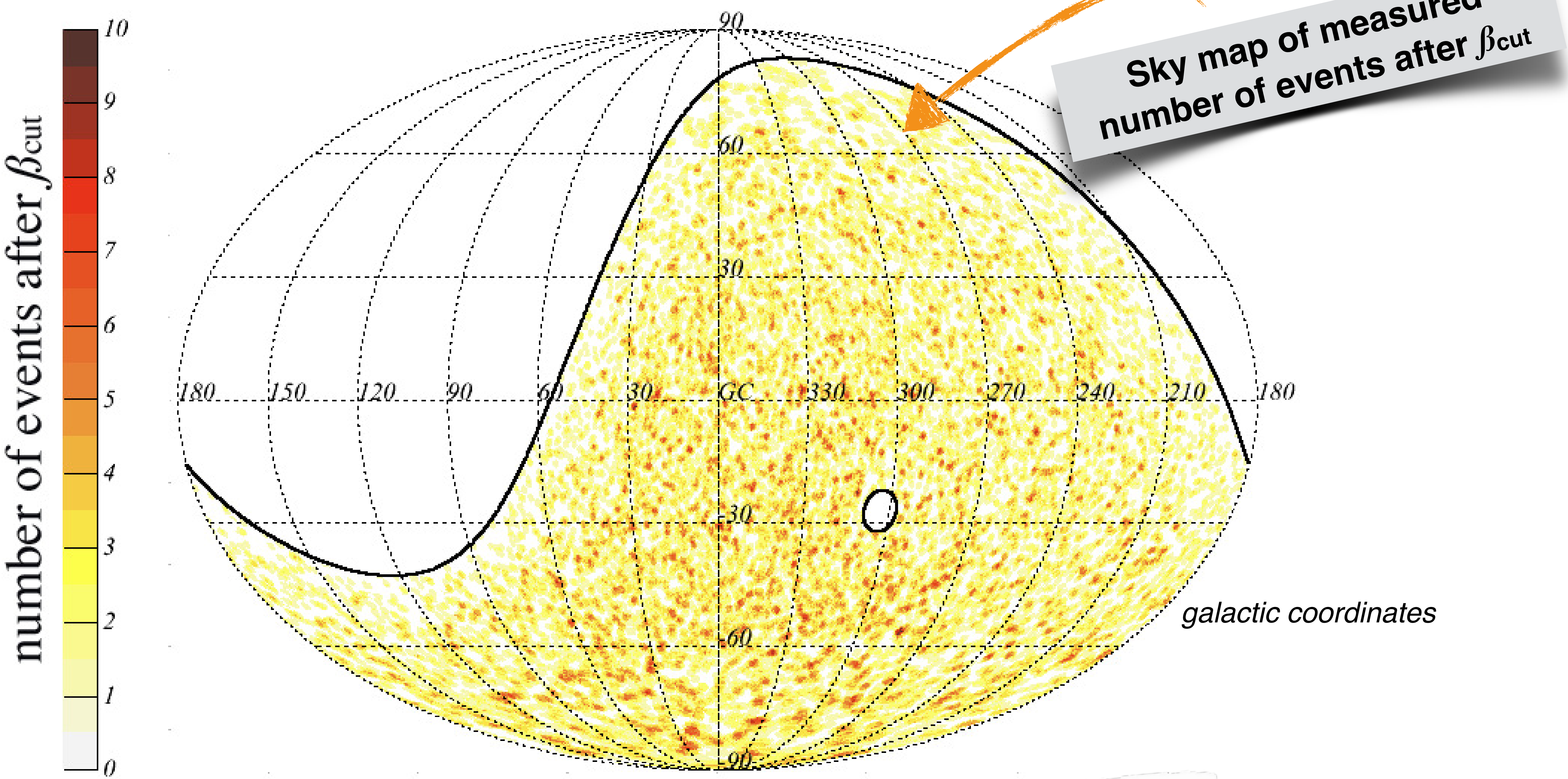


Any significant direction?

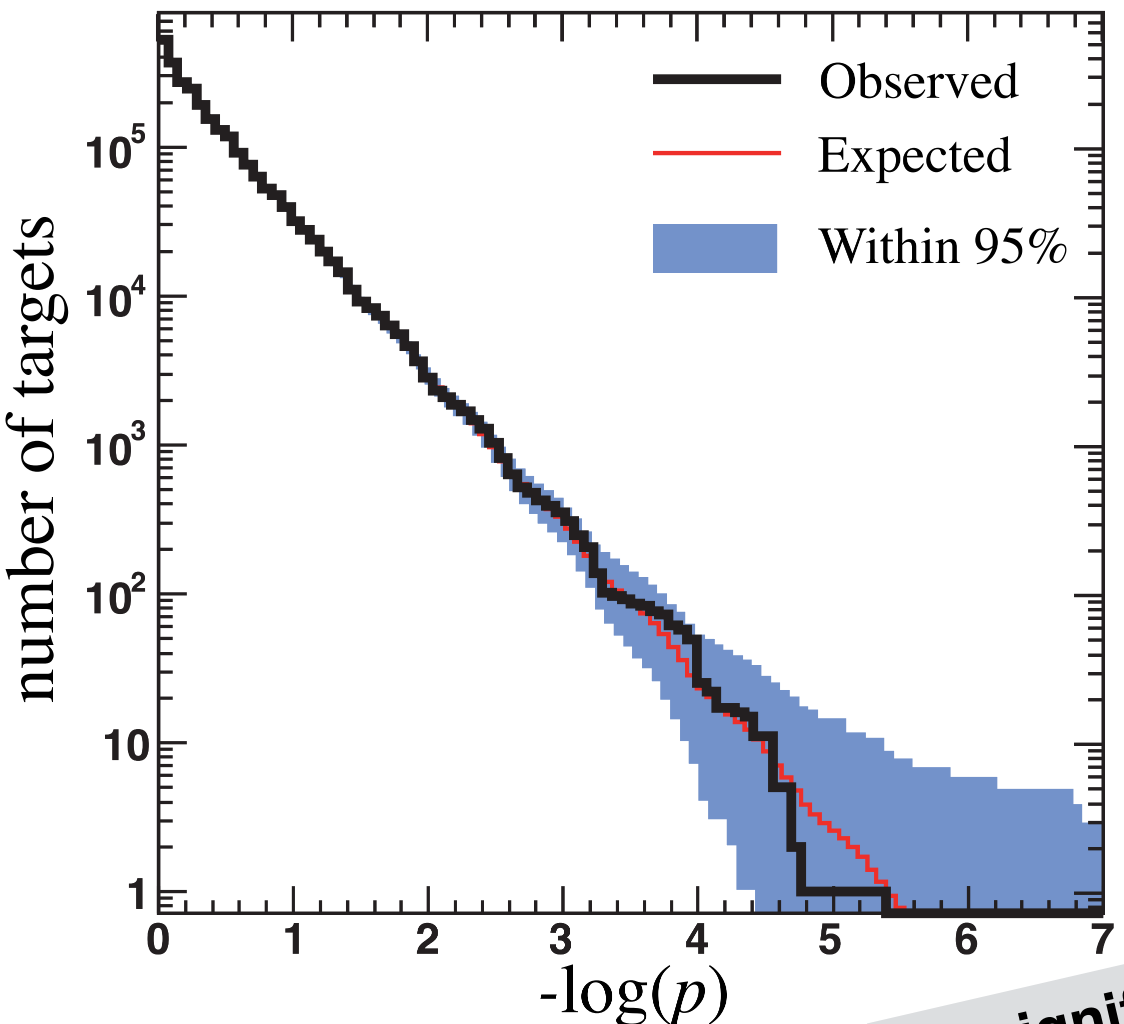
Results: Direct search for point sources

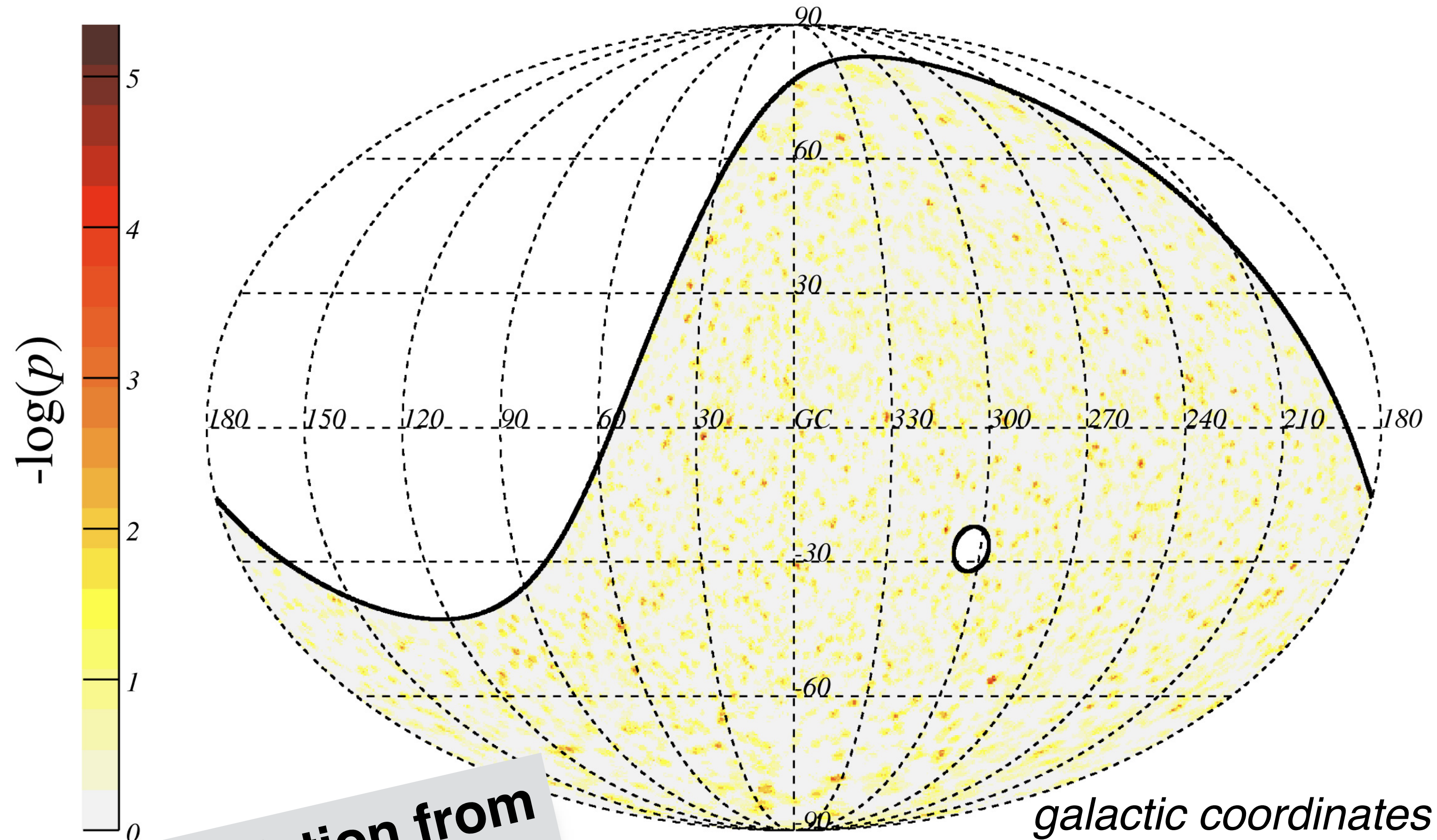
- **Ask for the p-value of this observation:**

$$p = \text{Poiss}(\geq n^{\beta}_{\text{data}} | n^{\beta}_{b})$$

expected number

observed number





No significant deviation from isotropic expectation!

Chance probability that p_{min} is observed anywhere in the sky: 36%

Upper limit for photon point sources

- **Calculate flux upper limit f^{UL} using Zech's method again:**

$$f^{\mathrm{UL}} = \frac{n_s^{\mathrm{Zech}}}{n_{\mathrm{inc}} \cdot \mathcal{E}_\beta}$$

particle upper limit

photon exposure (from time-dependent detector simulations)

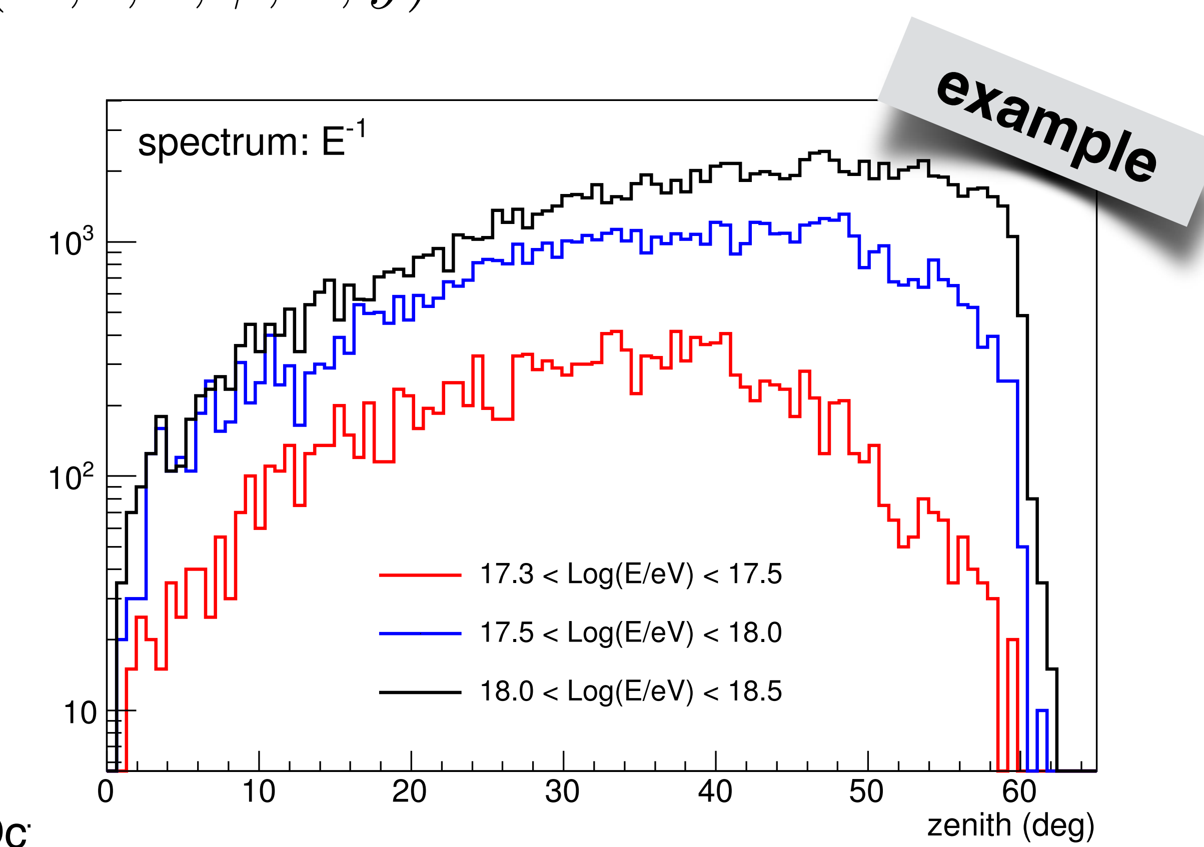
correction factor for top-hat choice (=0.9)

- **Exposure as a function of celestial coordinates:**

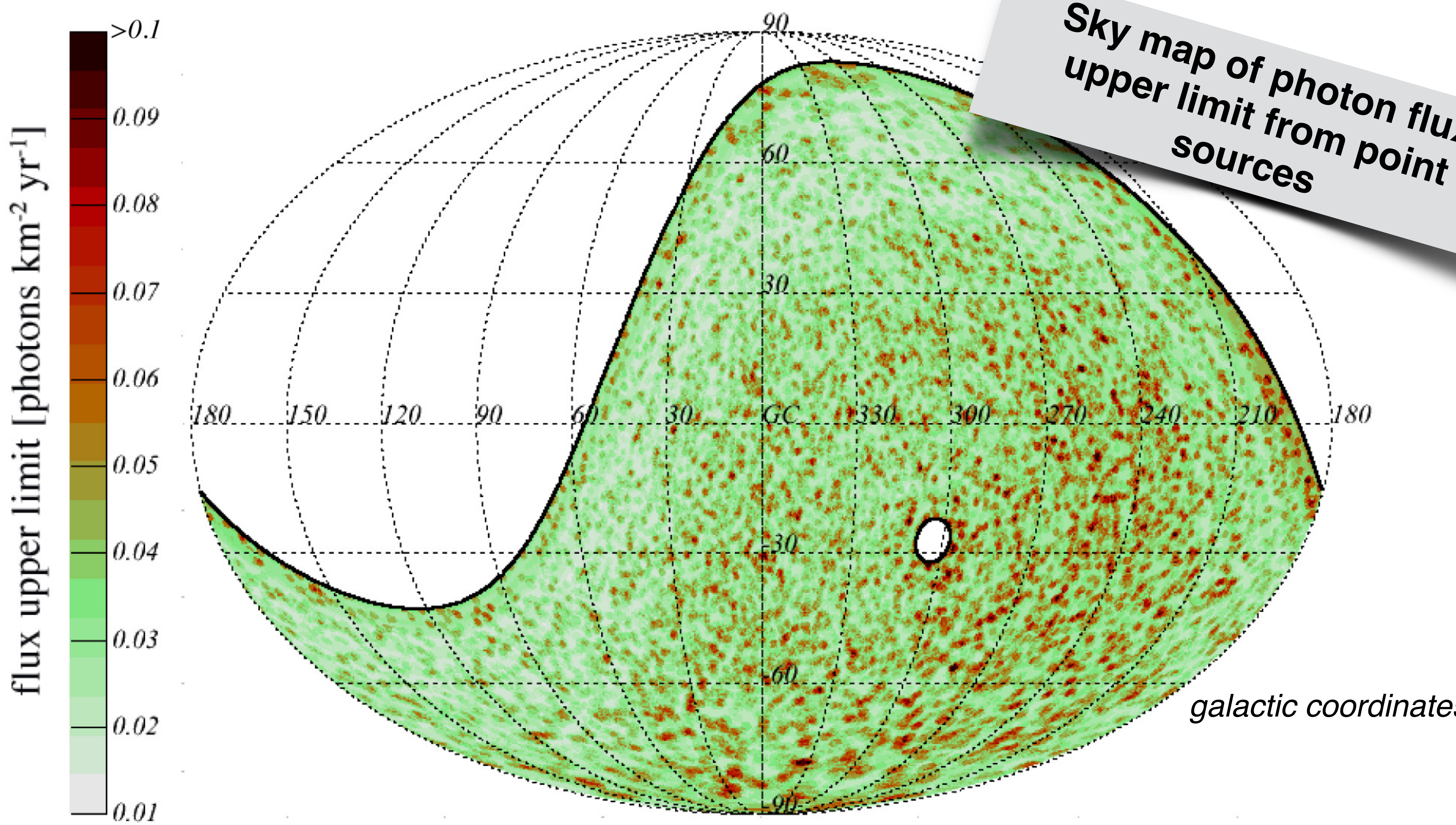
$$\mathcal{E}(\alpha,\delta) = \frac{1}{c_E}\int_E \int_T \int_S E^{\zeta}\ \varepsilon(E,t,\theta,\phi,x,y)\ \mathrm{d}S\ \mathrm{d}t\ \mathrm{d}E$$

Exposure not constant with energy and not uniform in right ascension.

Detailed simulations that take into account the status of detector and dependence in energy and direction.



Results: Upper limit for photon point sources

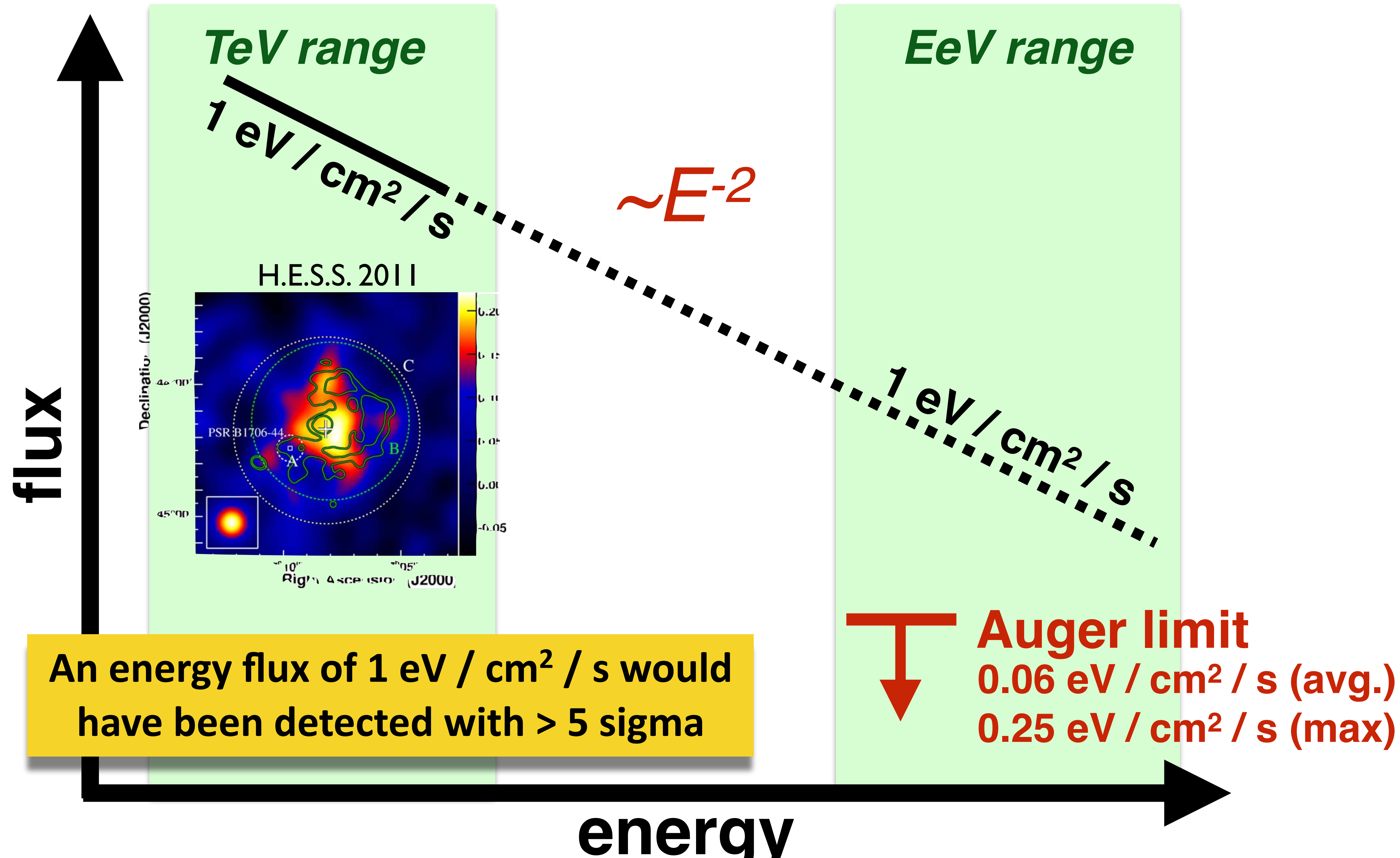


Sky map of photon flux upper limit from point sources

Average particle flux upper limit: 0.035 photons / km^2 / yr
Average energy flux upper limit: 0.06 eV / cm^2 / s (energy spectral index -2)

Interpretation of results

Exclude extrapolation of TeV sources



- **Absense** of point source photons does **not mean** that **sources are extragalactic:**
  - Maybe produced in **transient sources** (e.g. GRB or SN)
  - Maybe **emitting in jets** not pointing to Earth
  - Maybe EeV protons from sources with much **lower optical depth** *(comp. to TeV sources)*

Summary

- Search for ultra-high energy photons is an interesting field with high discovery potential
- No photons in EeV range observed so far
- First directional search and energy flux upper limits for photon point sources

- *It's just a matter of time until*
  A) EeV photons are detected.
     That would **open a new window of astronomy**
  B) Existence of EeV photons is disproved
     That would **role up** the current understanding of **physical principles**

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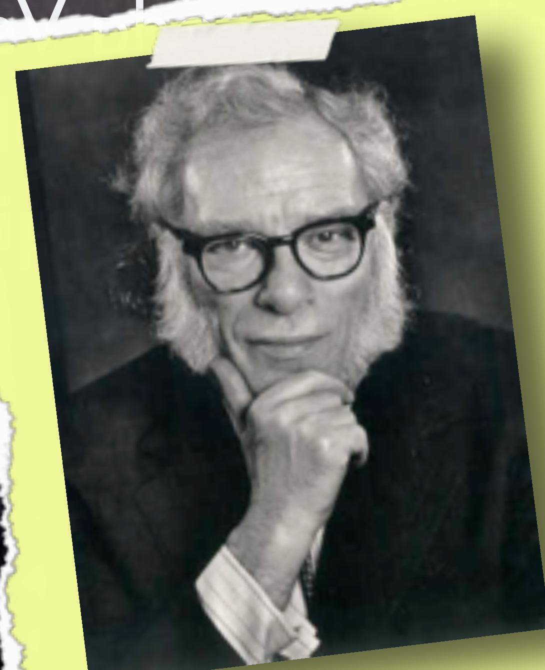

Isaac Asimov

The most exciting phrase to hear in science, the one that heralds the most discoveries, is not "Eureka!" (I found it!) but "That's funny…".