HELMHOLTZ GEMEINSCHAFT

Allianz für Astroteilchenphysik

RWTH AACHEN UNIVERSITY

bmb+f - Förderschwerpunkt

Astroteilchenphysik

Großgeräte der physikalischen Grundlagenforschung

Photon searches with the Pierre Auger Observatory and the connection to TeV gamma-ray observations

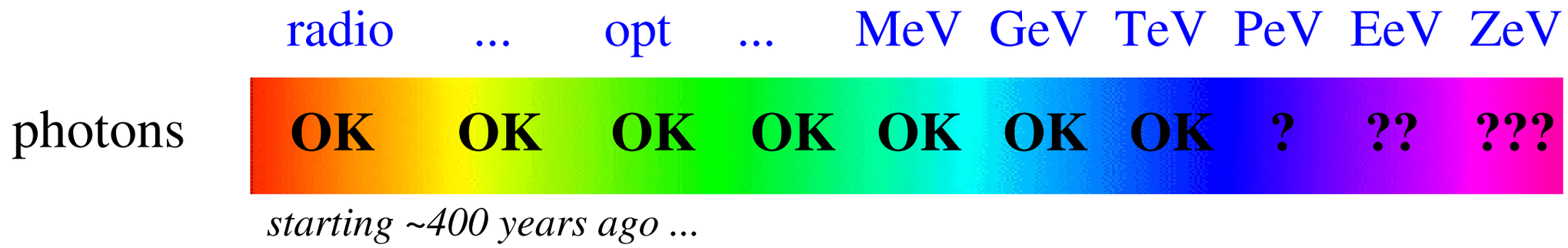
PIERRE AUGER OBSERVATORY

Daniel Kuempel

RWTH Aachen University

HAP Workshop *Cochem December 2016*

Search for photons at ultra-high energies



- 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)

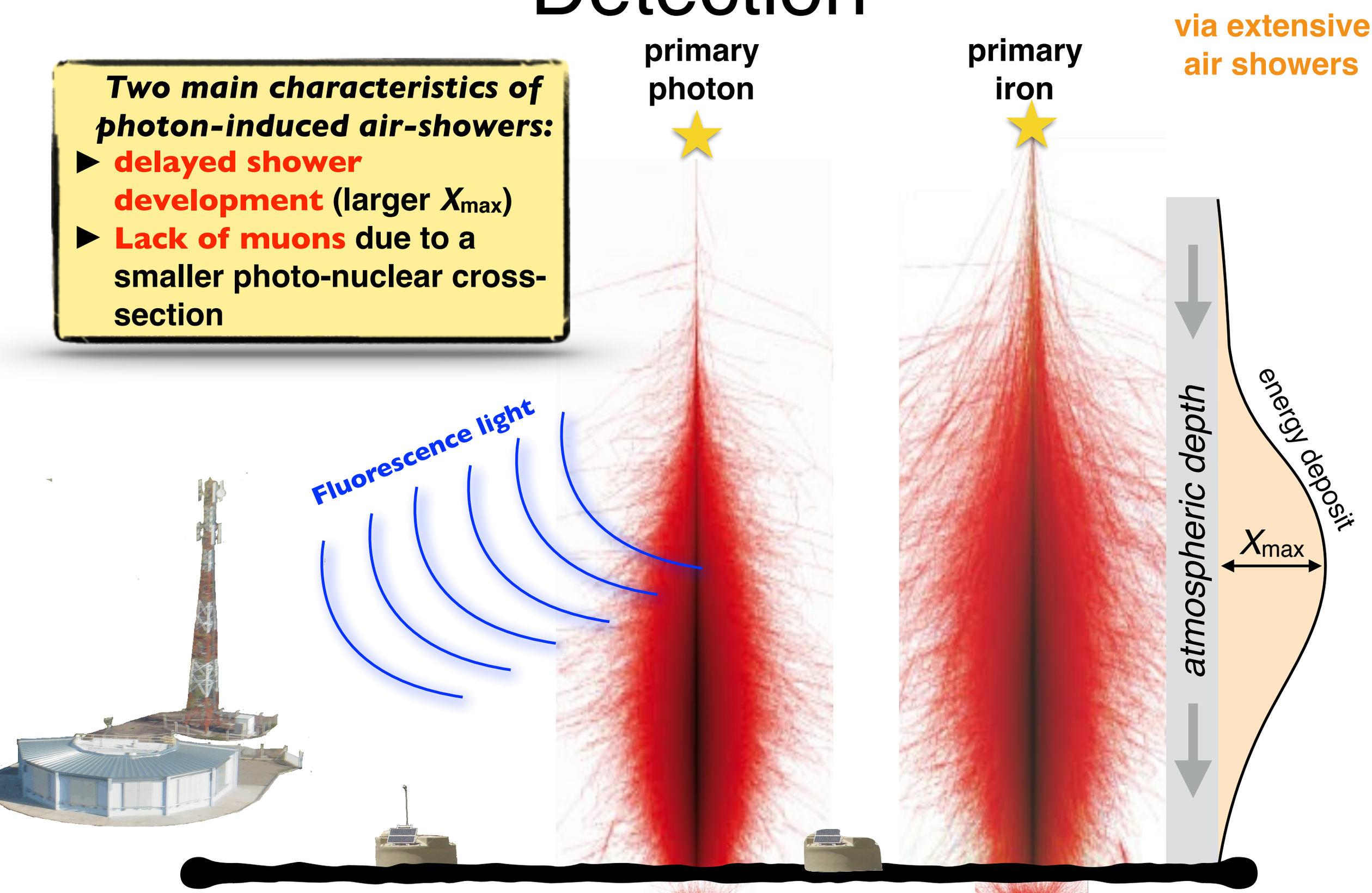
- UHE photons may help to interpret TeV observations

Detection

Measurement via extensive air showers

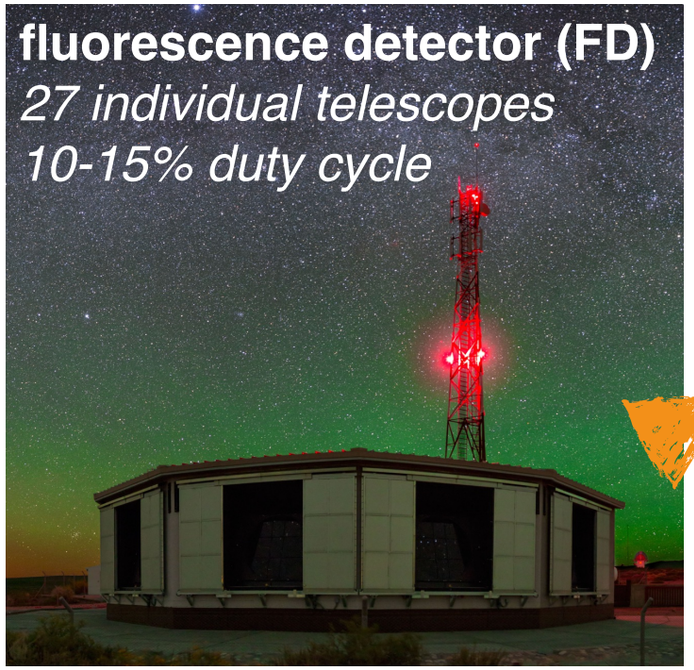
Two main characteristics of photon-induced air-showers:

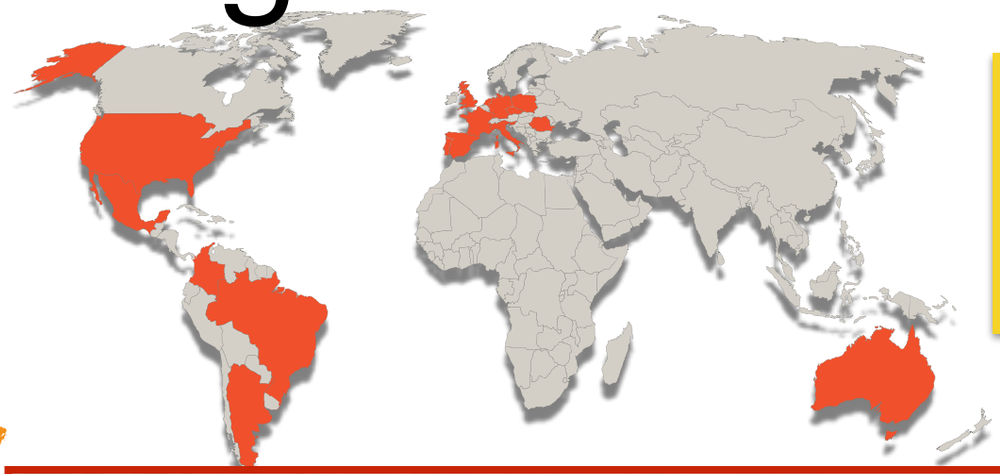
- **delayed shower development** (larger X_{max})
- **Lack of muons** due to a smaller photo-nuclear cross-section



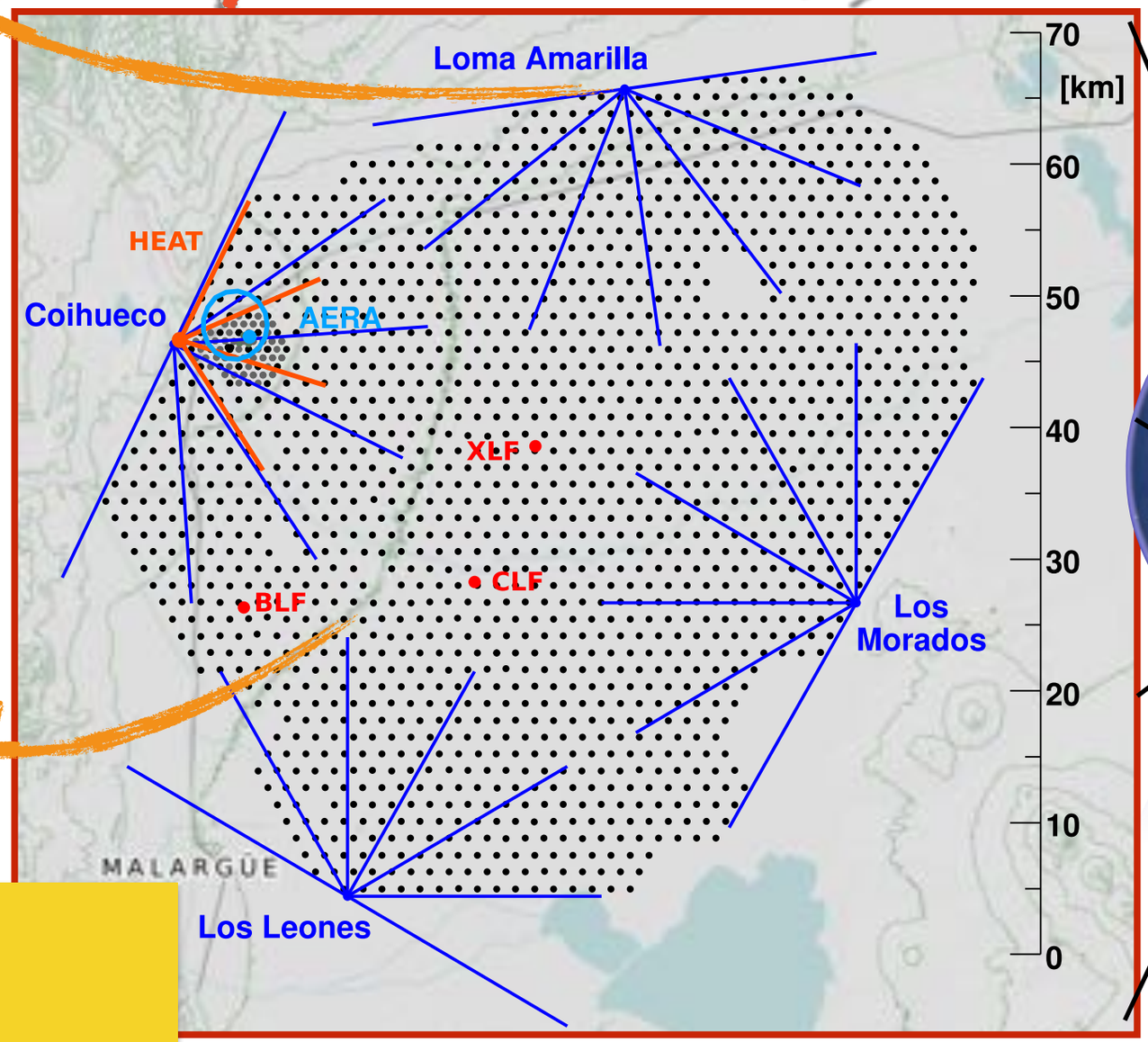
Lateral distribution:

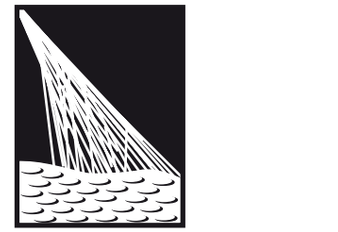
Pierre Auger Observatory





- **Measure cosmic rays with energies > 10^{17} eV**
- **18 countries**
- **~ 500 members**





- **3000 km² area**
- **1.5 km SD spacing**
- **data taking since 2004**
- **fully operational since 06 / 2008**
- **Angular resolution <1°**

Diffuse photon search

Concentrate on latest results using hybrid events

Appeared last Tuesday on arXiv (arXiv.1612.01517) and is submitted to JCAP

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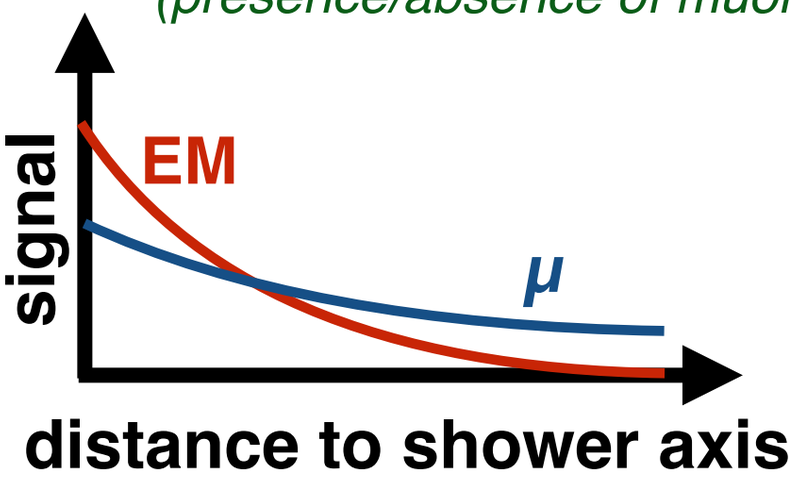
Experimental observables

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

- **Parameter S_b defined as** (SD related)

  G. Ros Astopart. Phys. 35 (2011) 140

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



$$S_b = \sum_i^N S_i \left(\frac{R_i}{R_0}\right)^b$$

distance station - shower axis

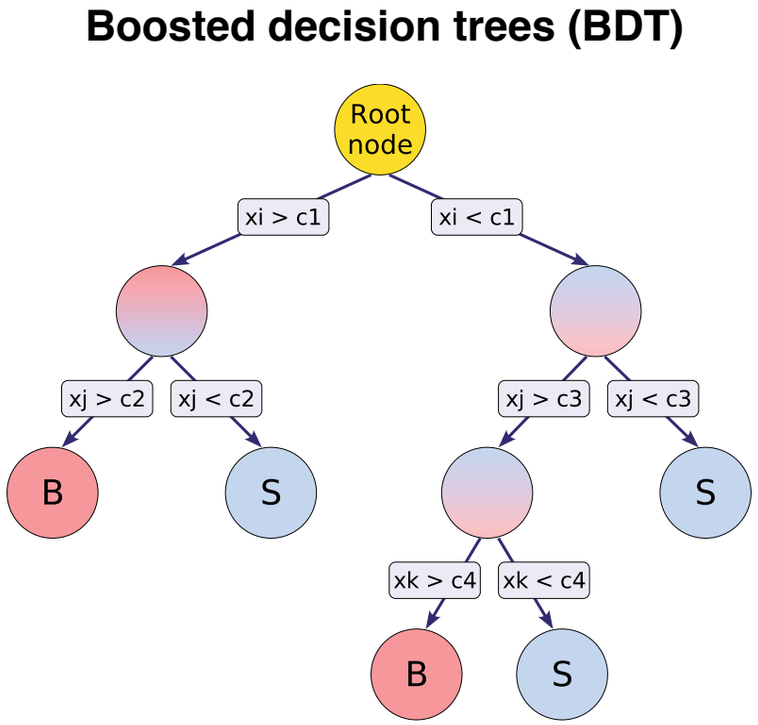
b=4 best separation

Signal in station i

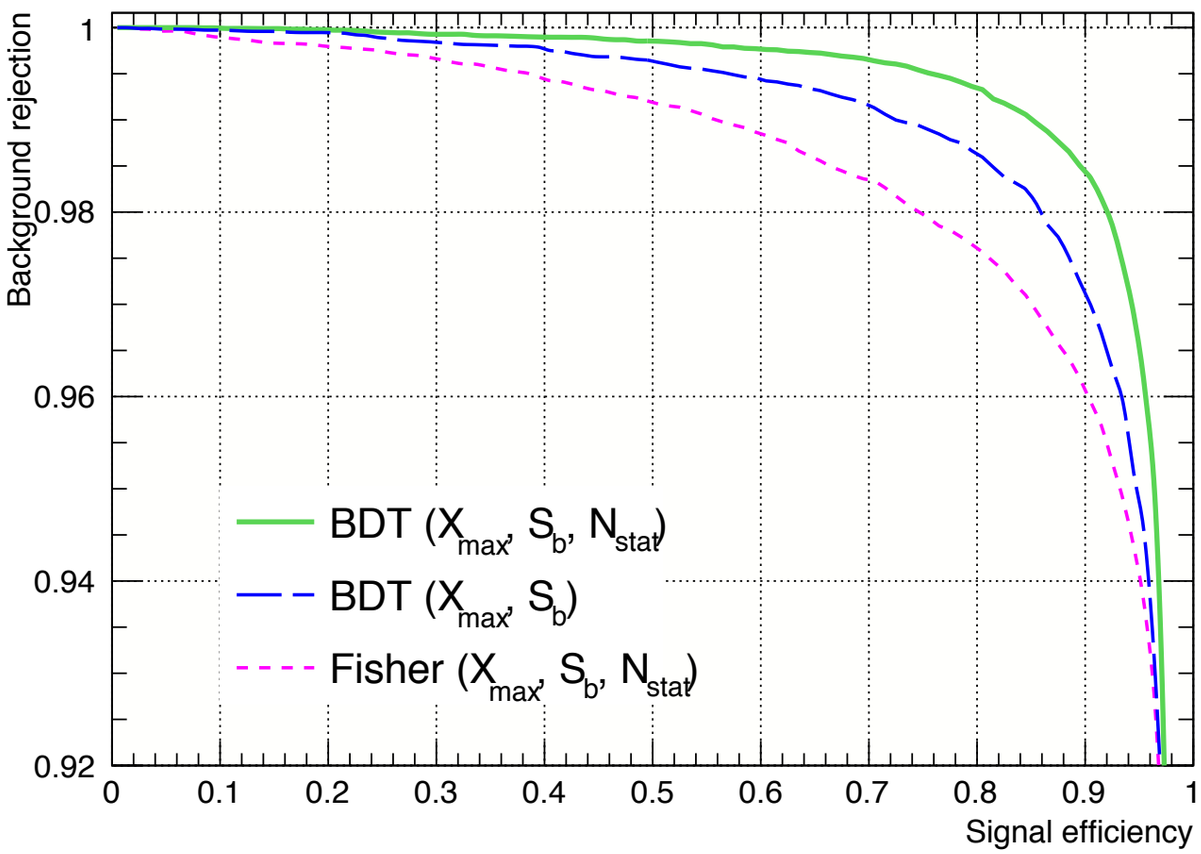
R_0=1km reference distance

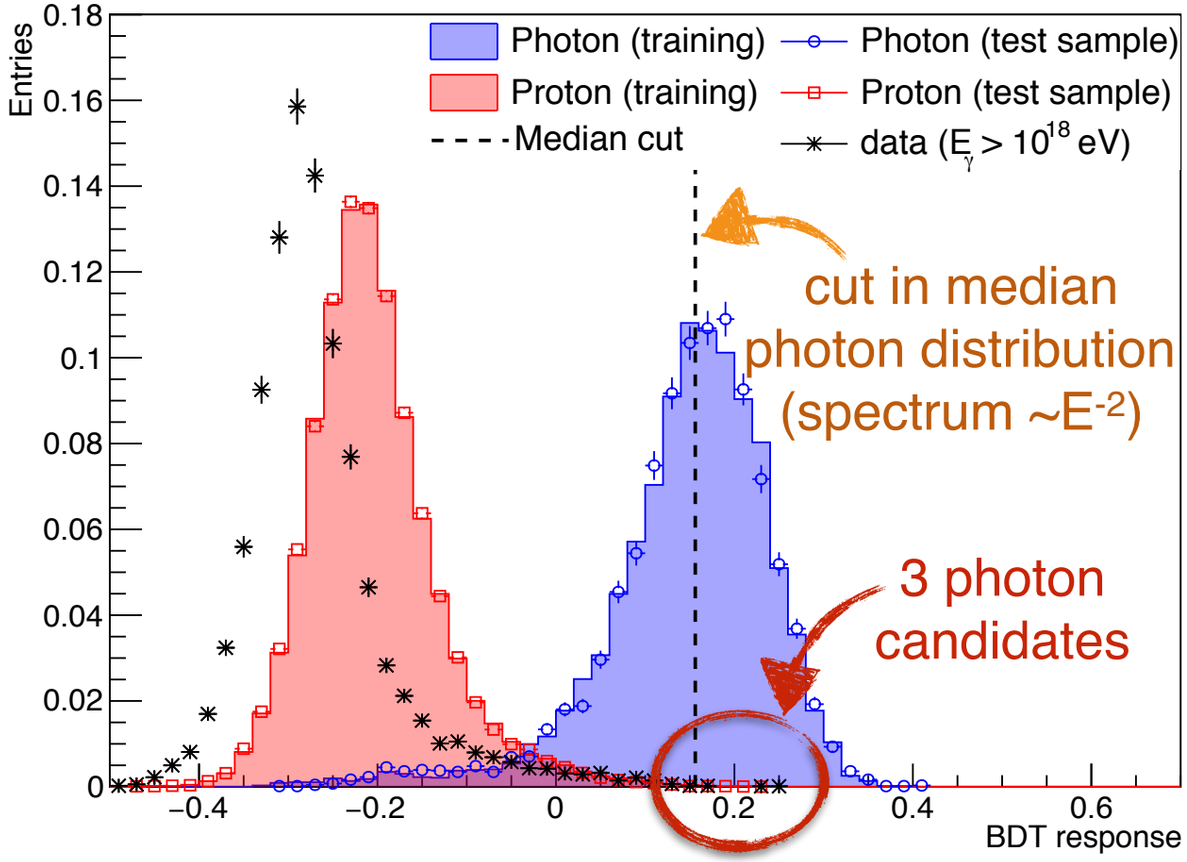
- **Number of triggered surface detector stations N_{stat}** (SD related)

Multivariate Analysis



- Train Boosted Decision Trees with photon and proton simulations (CORSIKA v. 6.990)
- Apply to data collected between Jan. 2005 and Dec. 2013 (ensure good geometry and profile reconstruction)
- Background rejection about 99% (50% photon efficiency)





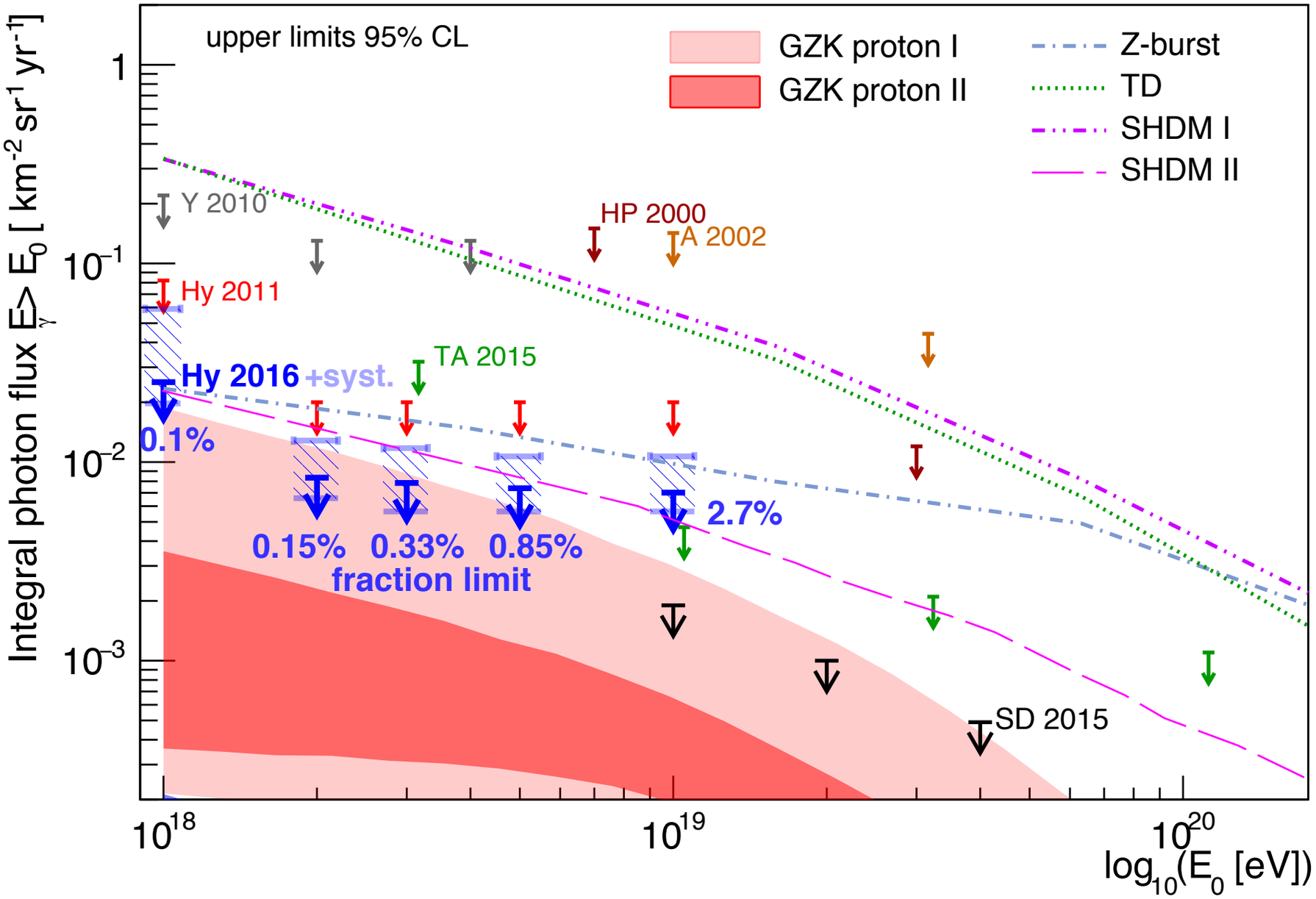
Results

- **Three candidate events compatible with background expectation**
- **Calculate upper limits**

Feldman-Cousins upper limit at 95% CL

$$\Phi_{UL}^{0.95}(E_\gamma > E_0) = \frac{N_\gamma^{0.95}(E_\gamma > E_0)}{\mathcal{E}_\gamma(E_\gamma > E_0 | E_\gamma^{-\Gamma})}$$

Integrated exposure



- **About a factor 4 improved limit**
- **Some top-down models severely constrained**
- **Optimistic GZK scenarios in reach**
- **No photon identification yet**

Idea directional searches

Directional searches for photon point sources
(A. Aab et al. ApJ 789 (2014) 160)

The signature is an

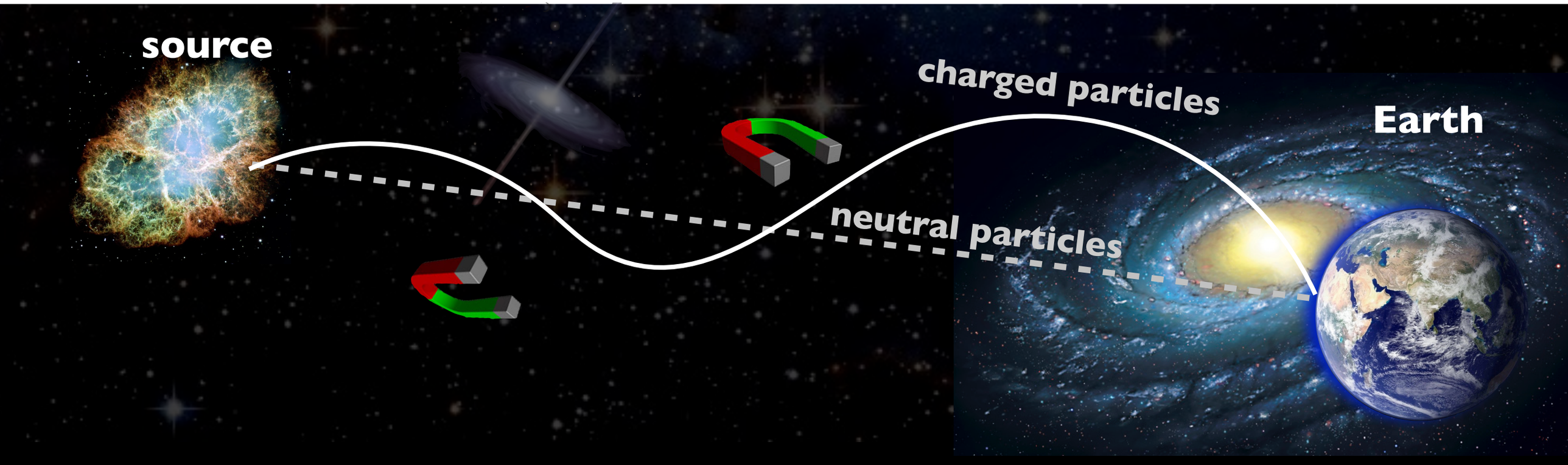
accumulation of events

from a specific direction in the sky

(neutral particles are not deflected in magnetic fields)

Idea:

Select photon-like air showers and search for an accumulation of events

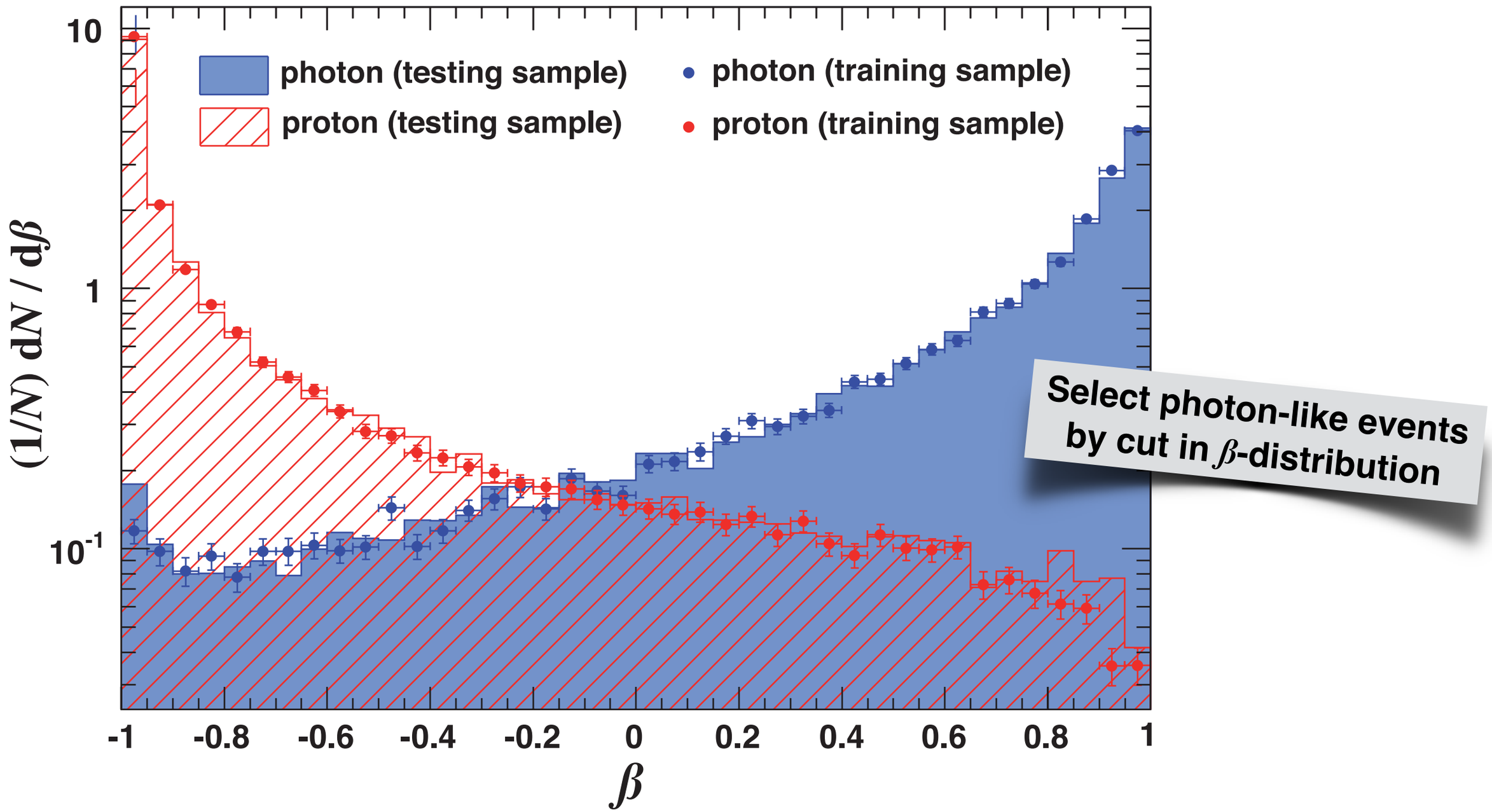


Background rejection

5 input observables
(fluorescence and surface detector)

$X^2_{Greisen}$, $E_{Greisen} / E_{FD}$, X_{max},
S_b, *shape parameter*

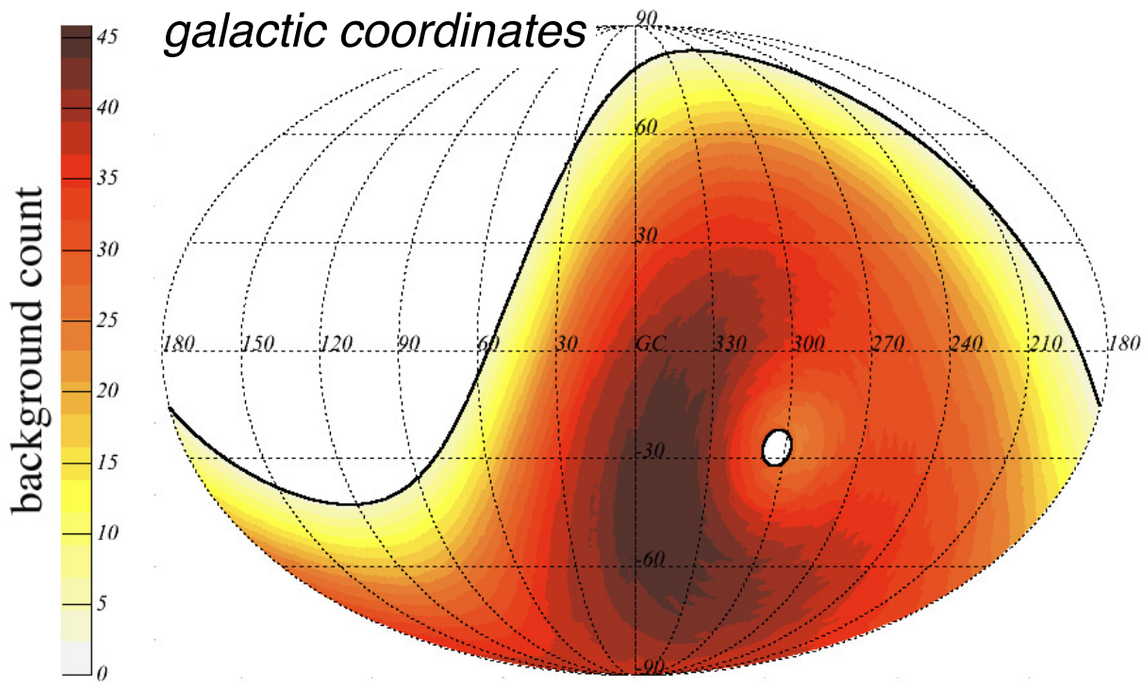
→ **Boosted decision trees** → β



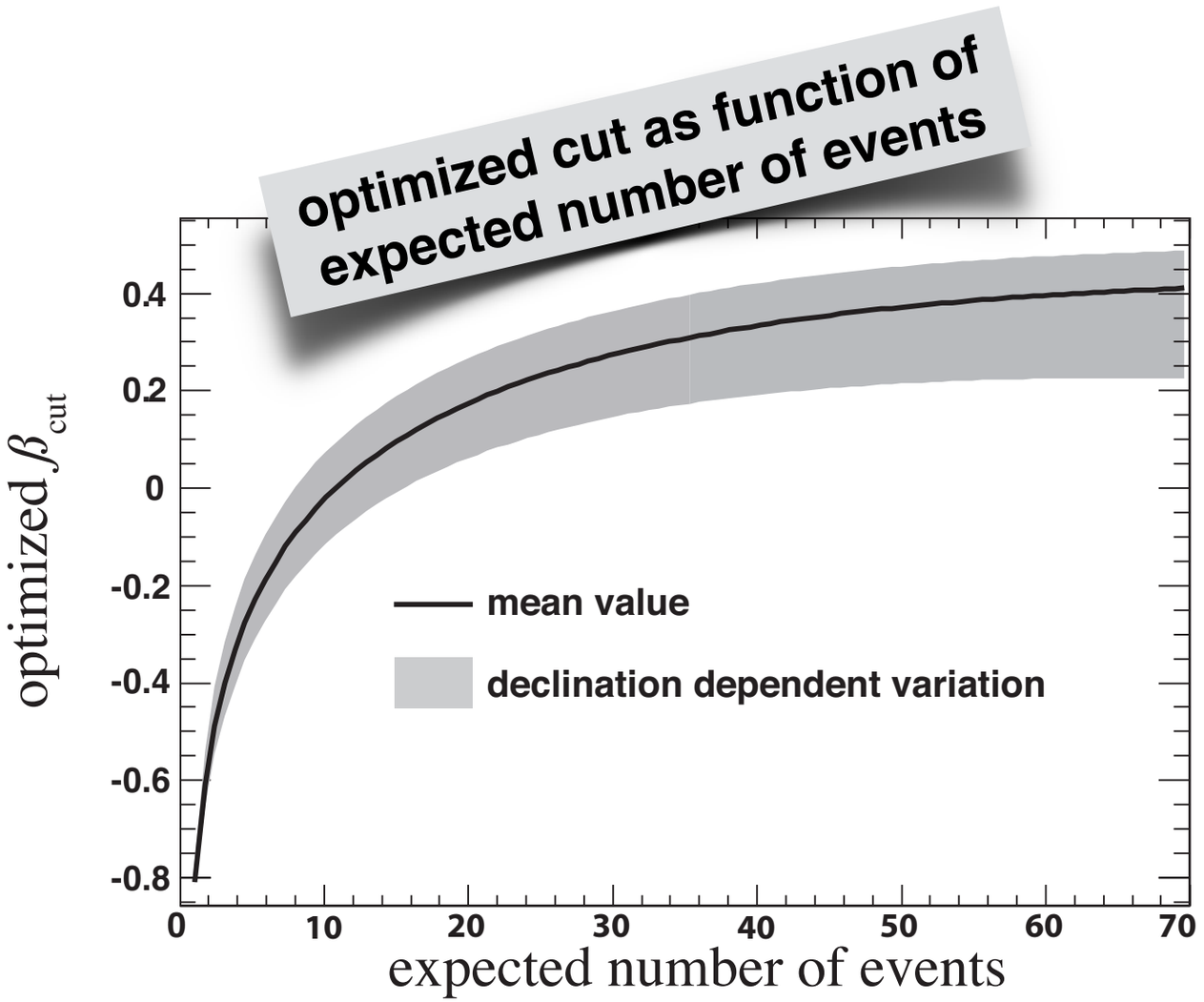
Select photon-like events by cut in β-distribution

Analysis details

- **Blind search:** 526200 target directions between declination -85° and +20°.
- Optimized β_{cut} is determined by minimizing upper limit using Zech's method
  G. Zech, NIM A277, 608-610 (1989)
- **Data:**
  - Energy range $10^{17.3} < E/\text{eV} < 10^{18.5}$
  - Zenith angle range: 0° - 60°
  - Angular resolution: 0.7°
  - Top-hat counting with radius 1°



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



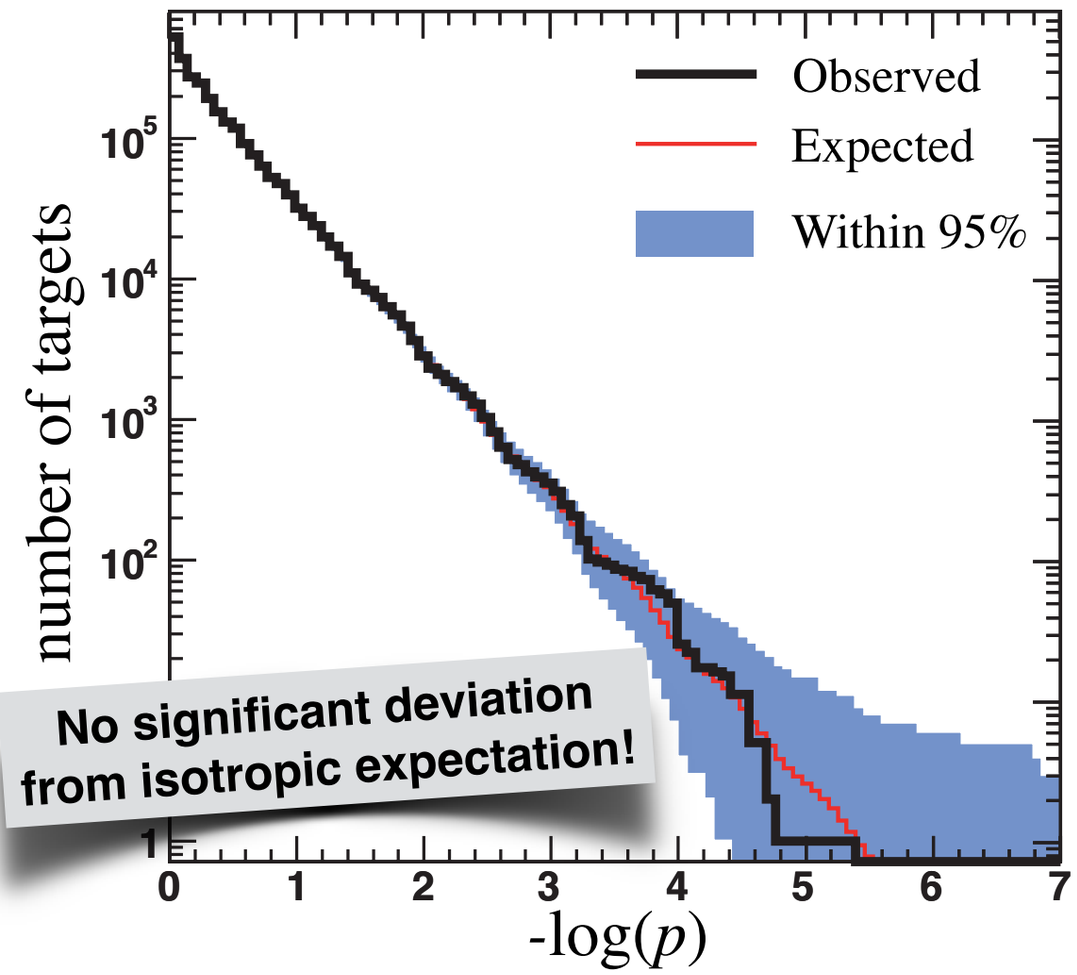
Results

Calculate p-value of observation

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

expected number

observed number



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

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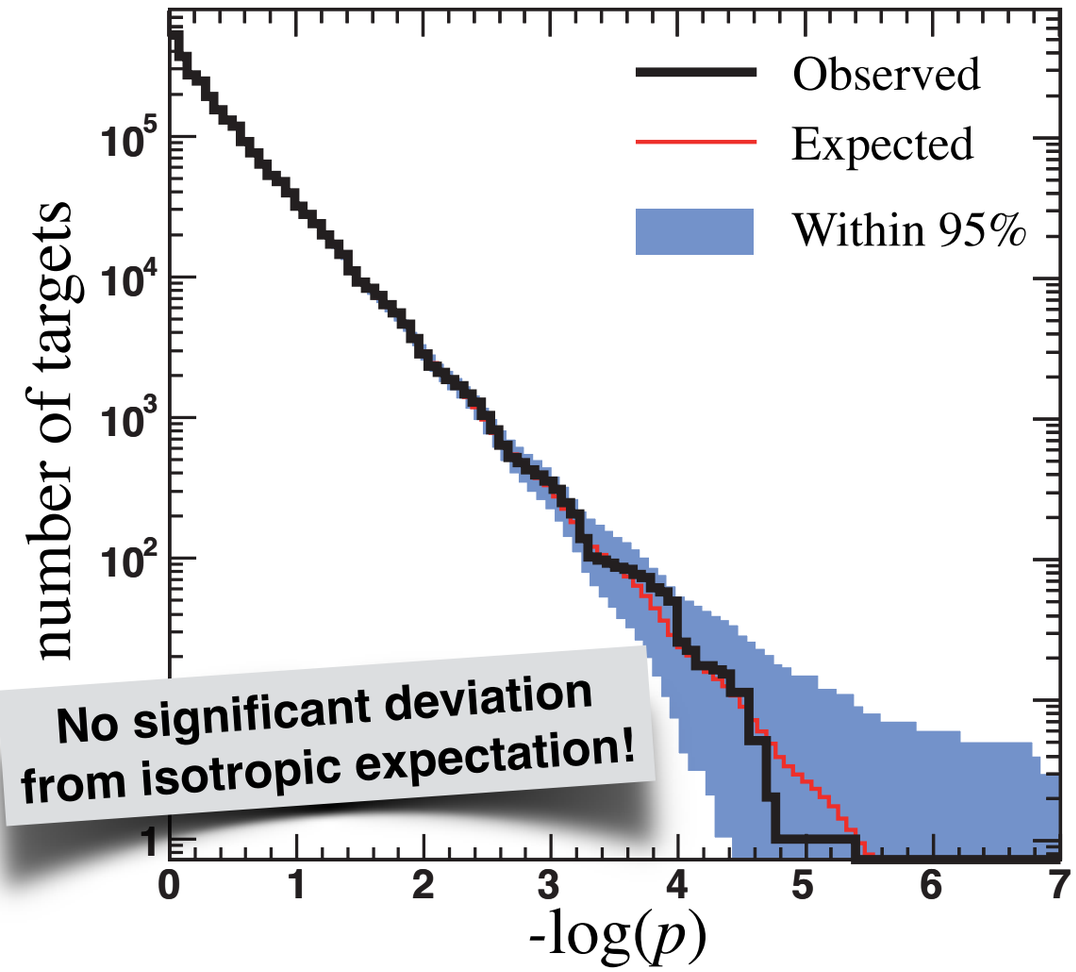


No significant deviation from isotropic expectation!

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

Derive flux upper limits

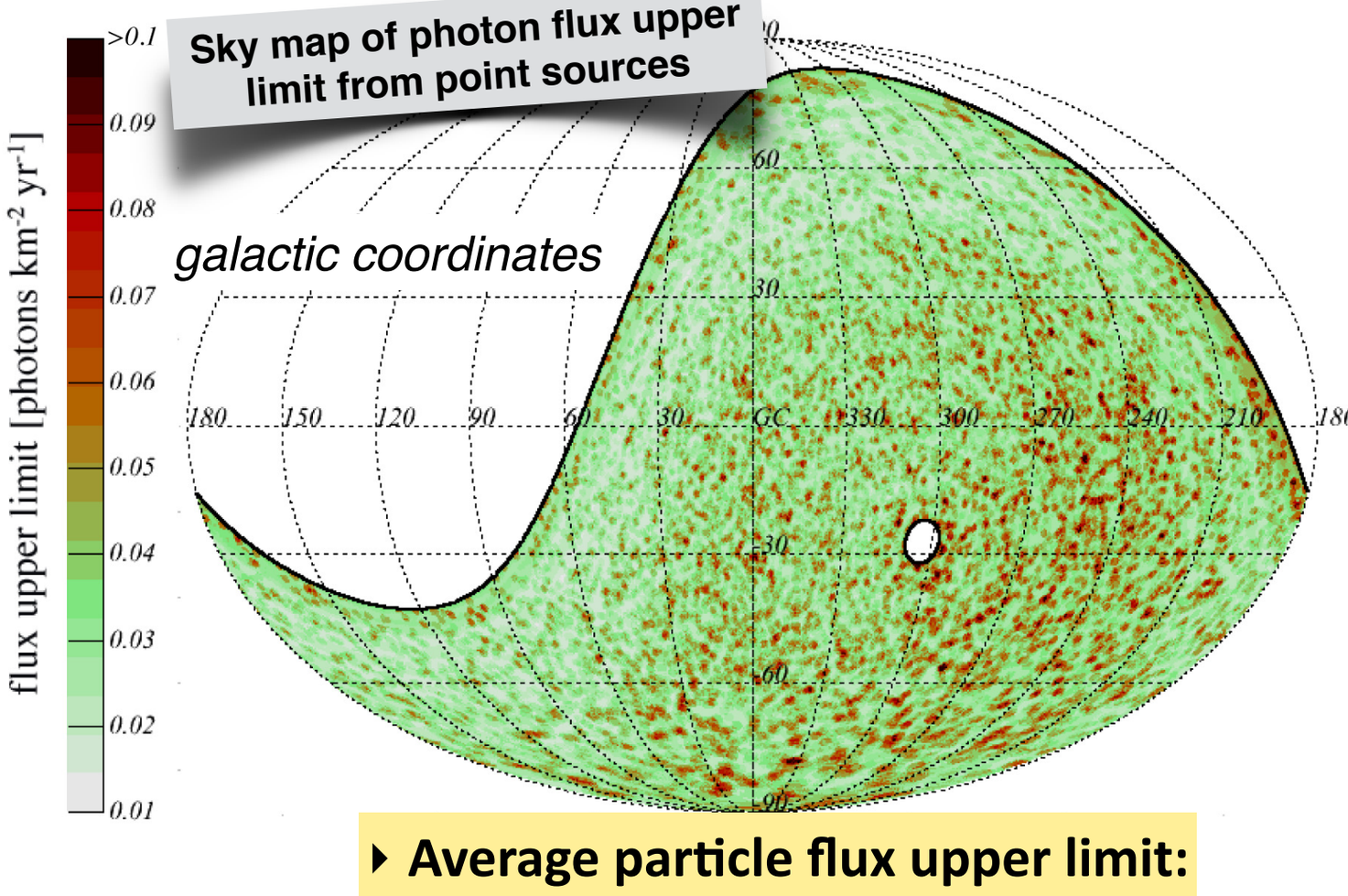
$$f^{\mathrm{UL}} = \frac{n_s^{\mathrm{Zech}}}{n_{\mathrm{inc}} \cdot \mathcal{E}_{\beta}}$$

particle upper limit

photon exposure (from time-dependent detector simulations)

correction factor for top-hat choice (=0.9)

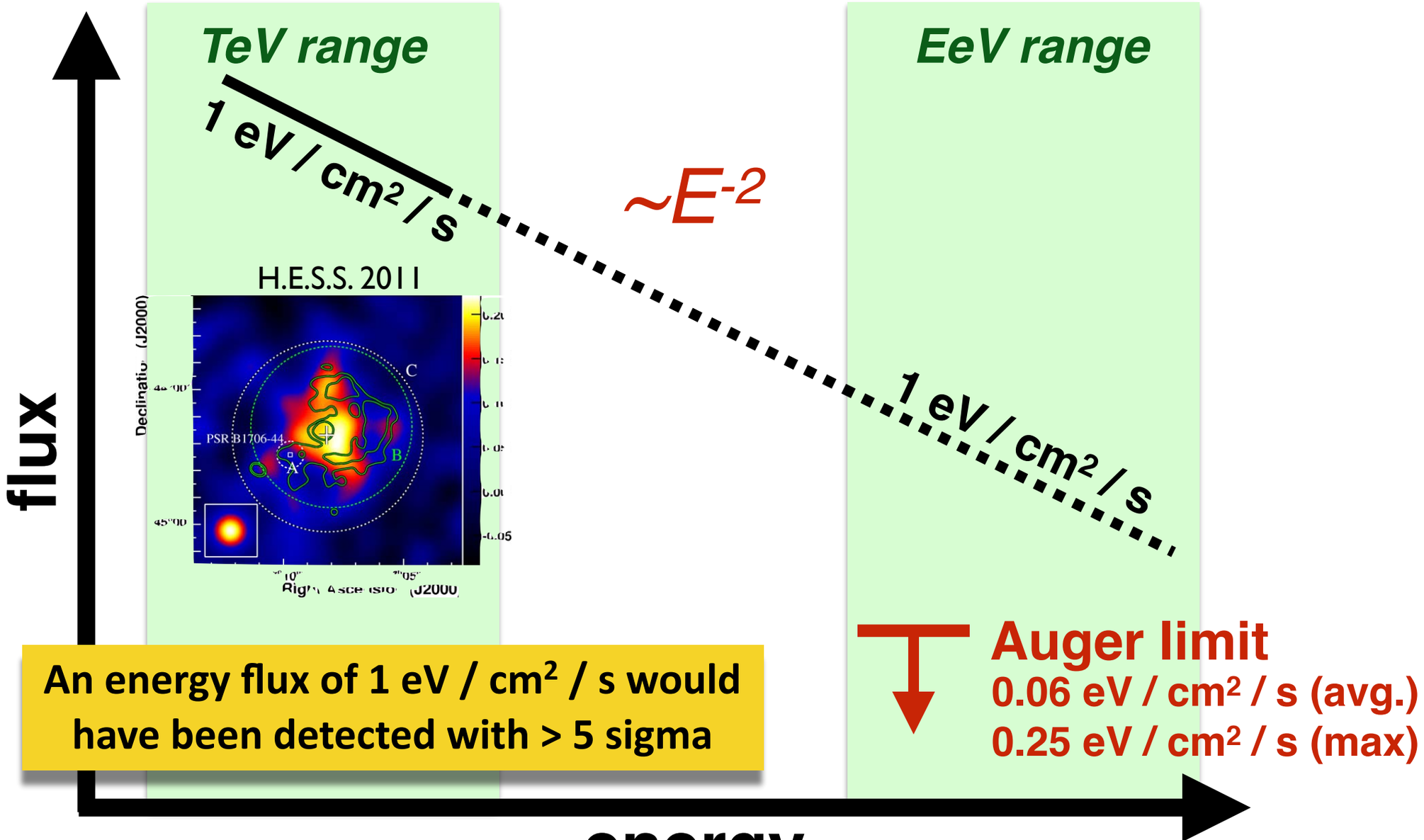
Sky map of photon flux upper limit from point sources



- **Average particle flux upper limit: 0.035 photons km^{-2} yr^{-1}**
- **Average energy flux upper limit: 0.06 eV cm^{-2} s^{-1} (energy spectral index -2)**

Interpretation

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)*

Next steps

Restrict analysis to predefined target sets (reduce trial factor)

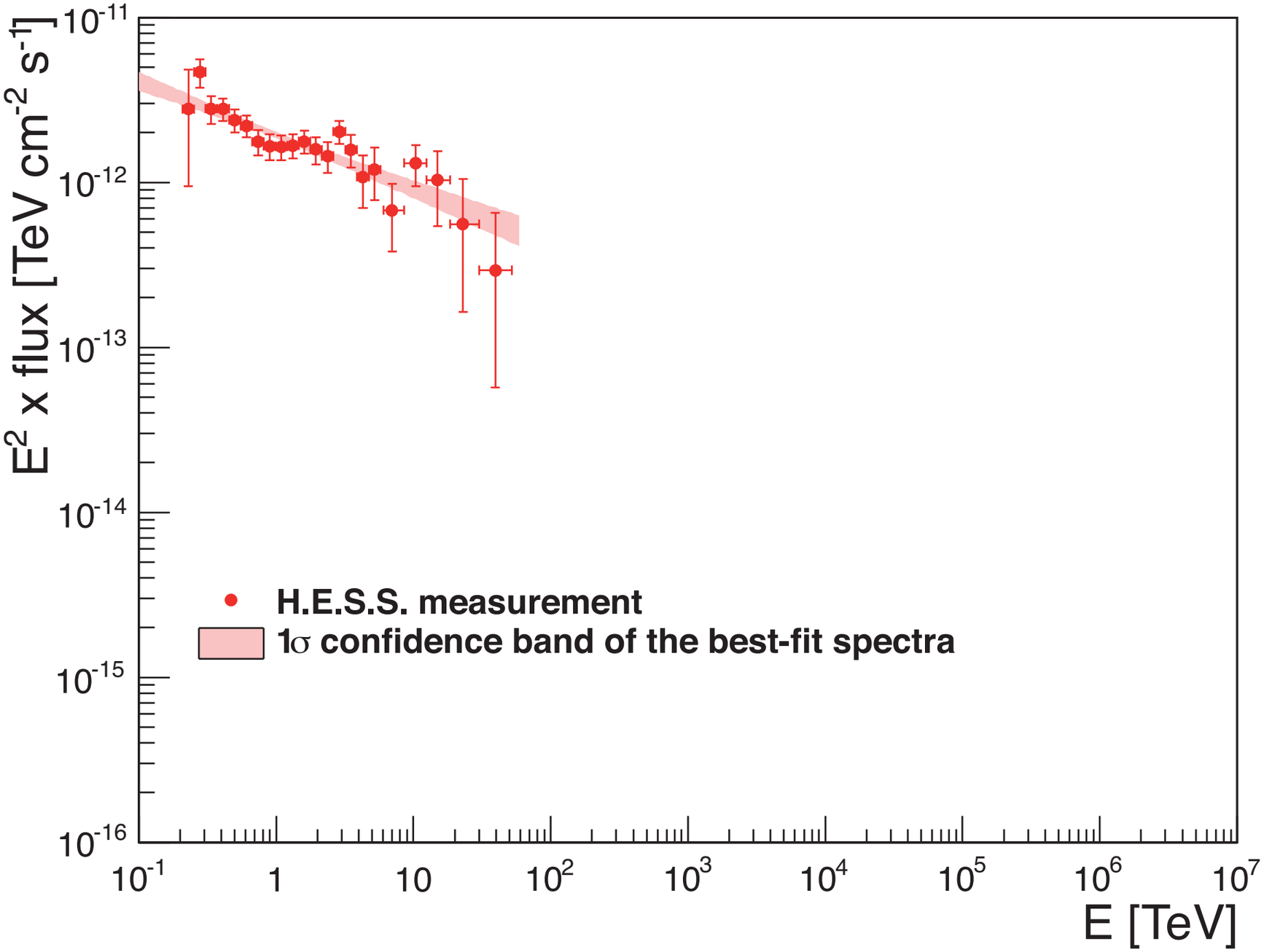
paper close to publication

Class	*No. photon search*	*galactic/extragalactic*
msec PSRs	67	galactic
γ-ray PSRs	75	galactic
LMXB	87	galactic
HMXB	48	galactic
H.E.S.S. PWN	17	galactic
H.E.S.S. other	16	galactic
H.E.S.S. UNID	20	galactic
Microquasars	13	galactic
Magnetars	16	galactic
Gal. Center	1	galactic
LMC	3	extragalactic
Cen A	1	extragalactic

- **Galactic set**: **Similar to previous neutron search paper** (ApJL 789 (2014) L34)
- **Extragalactic set**: **Include nearby extragalactic sources**
  - Cen A (d = 3.8 Mpc): Include core region
  - Large Magellanic Cloud (d = 50 kpc): (H.E.S.S. Science 347 (2015) 6220, 406)
    - N 157B J0537-691: Pulsar wind nebula
    - 30 Dor C J0535-691: Superbubble
    - N 132D J0525-696: Core-collaps SNR

Galactic center region

- **Interpretation of H.E.S.S. PeVatron results** (H.E.S.S., Nature, 531, 406 (2016))



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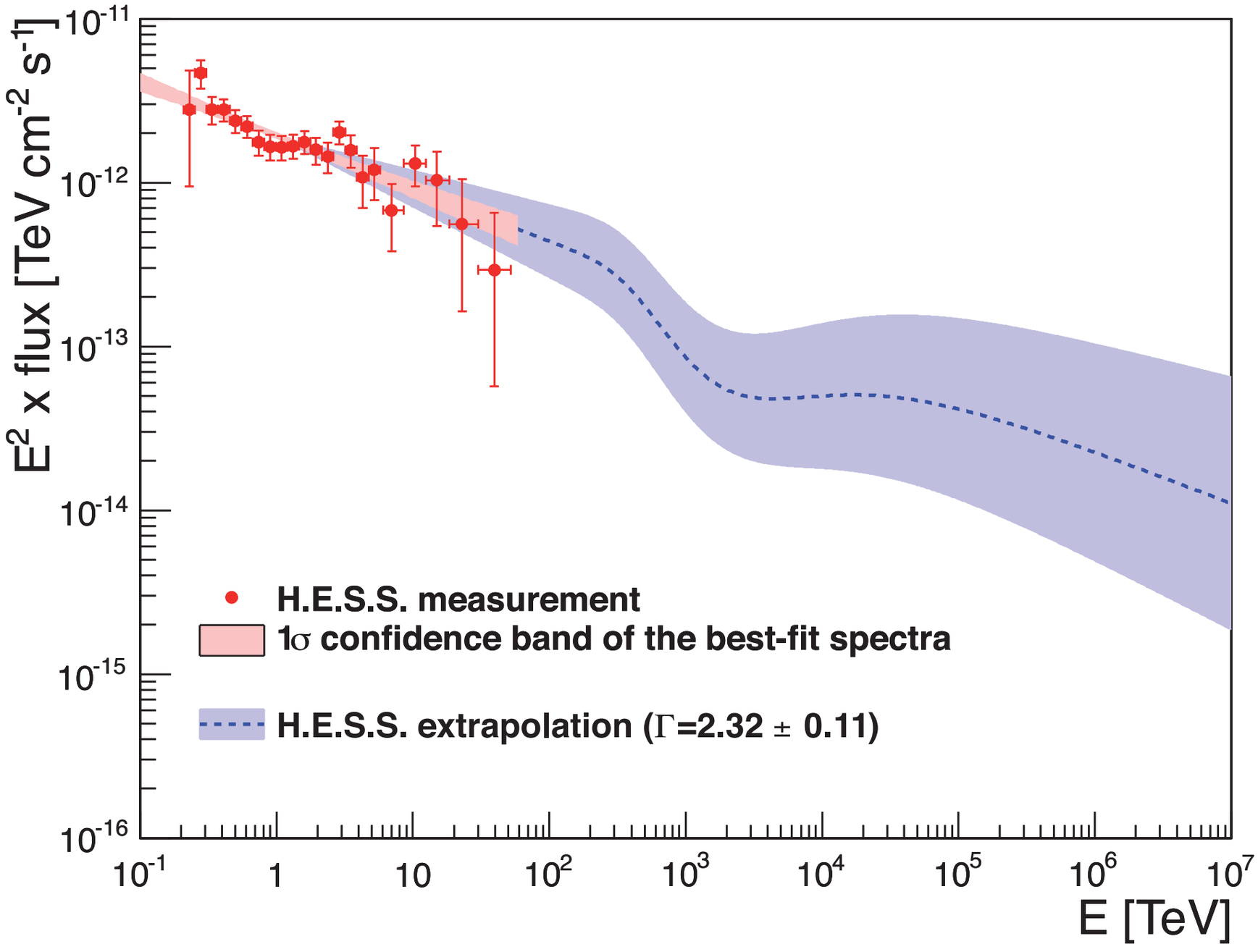

Galactic center region

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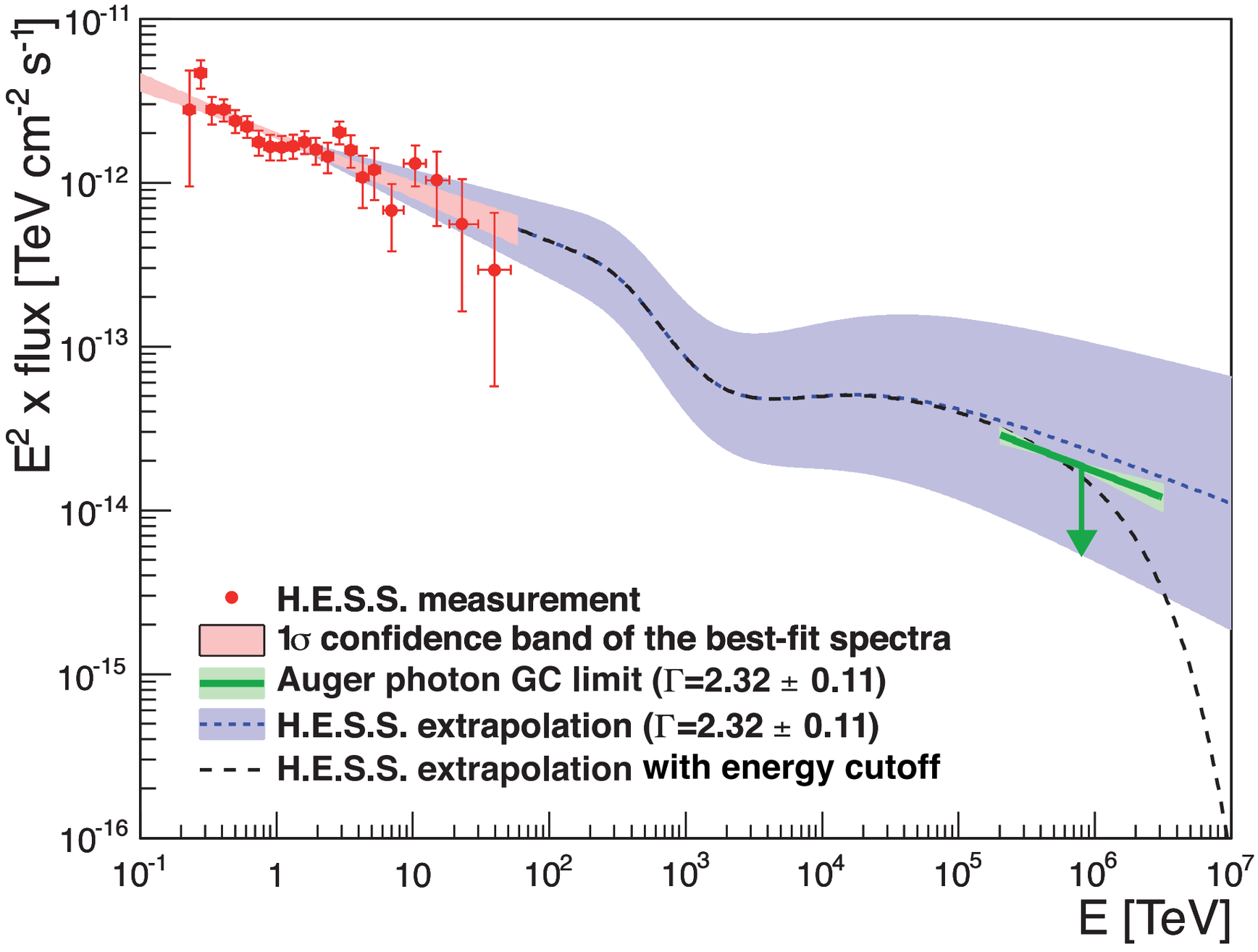


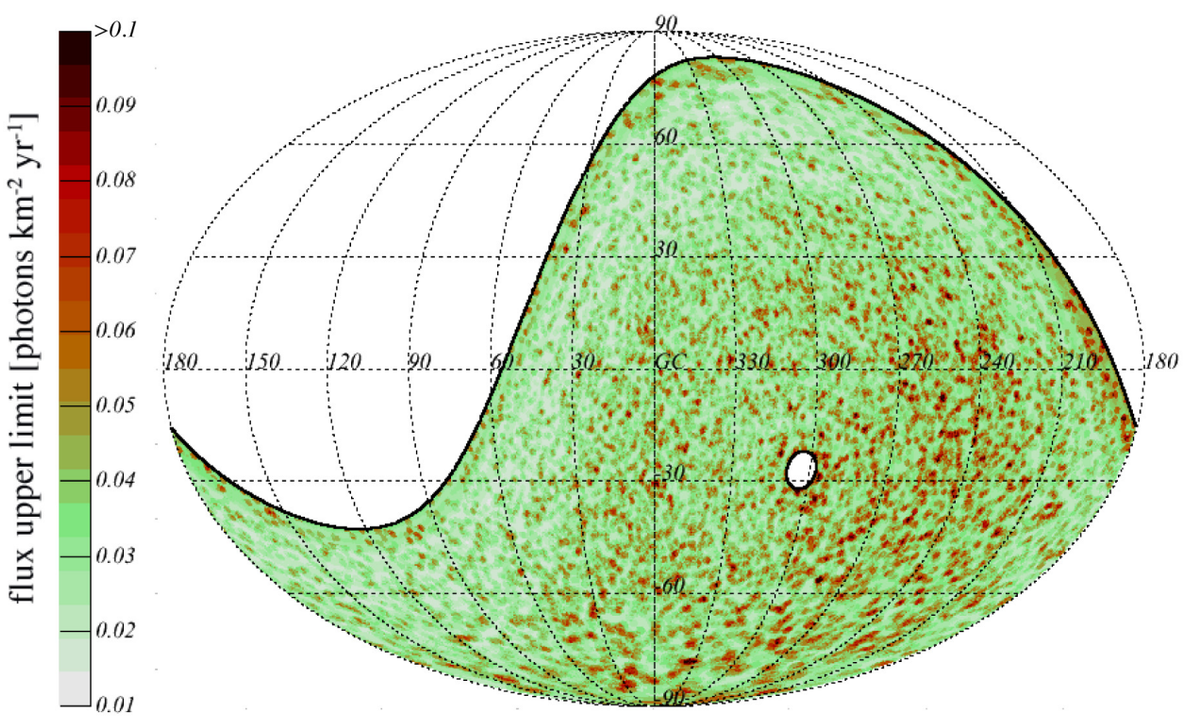
- **Constrain naive extrapolation to EeV energies**
- **Set upper limit on cutoff energy**

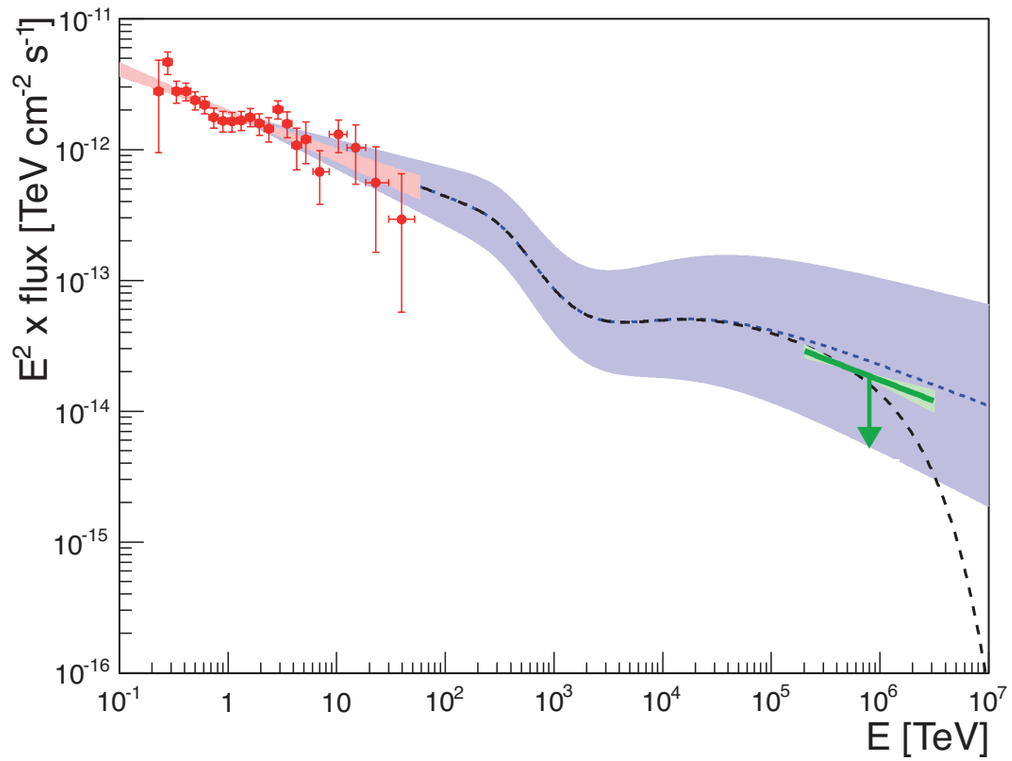
Summary

Search for UHE photons with the Pierre Auger Observatory

- **Search for ultra-high energy photons is an interesting field with high discovery potential**
- **No photons in EeV range observed so far**

- **Diffuse searches:**
  - Top-down models are strongly disfavoured
  - Upper limits start to constrain optimistic GZK-scenarios
- **Directional searches:**
  - First particle and energy flux upper limits of photon point sources in the EeV range
  - Severe constraints on the continuation of measured TeV fluxes





Backup slides

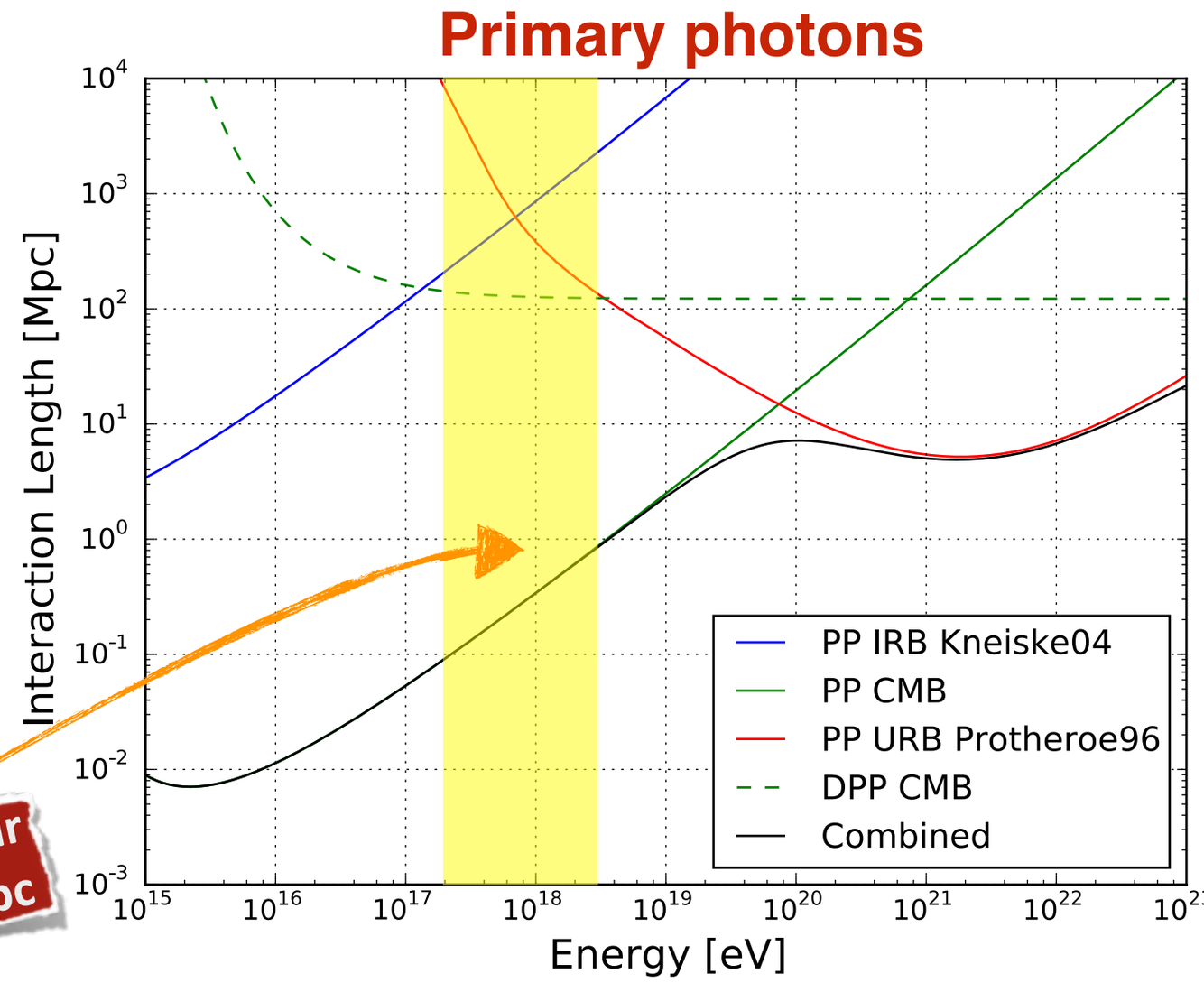
What sources can we target?

Assumption:

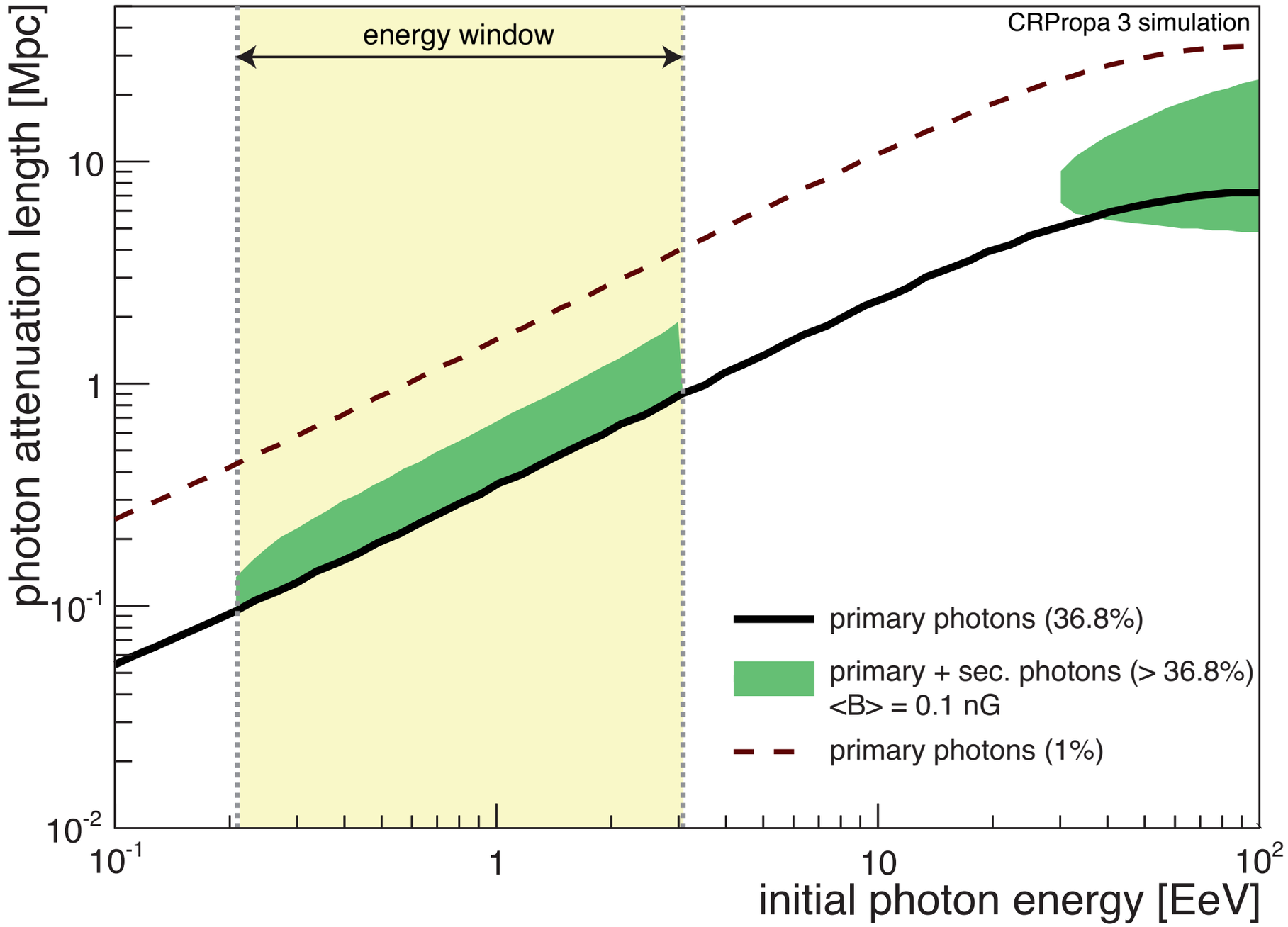
Photons are produced in the vicinity of the source, e.g. via proton-gamma or proton-proton interactions

Differentiate between:

1. **Primary photons:** Photons created in the vicinity of the source
2. **Secondary photons:** Photons created during propagation to Earth (e.g. via inverse Compton scattering)
   - *Constraints for second. photons:*
     1. 17.3 < log(E/eV) < 18.5
     2. Deflection < 1°



Photon horizon



- Primary photons can extend the photon horizon. However, strongly dependent on (unknown) extragalactic magnetic field
- Considering only primary photons galactic and nearby extragalactic sources can be targeted

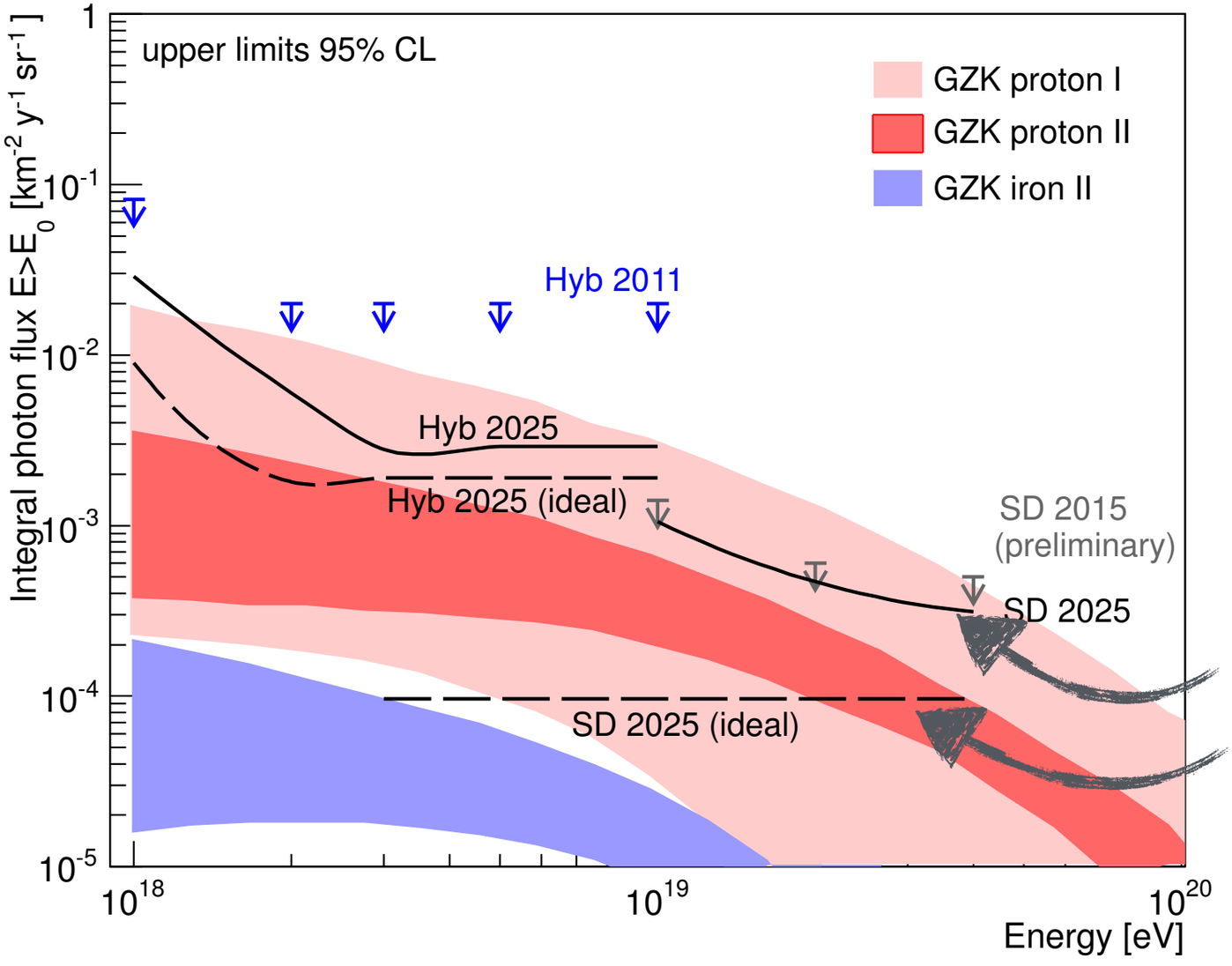
Auger upgrade

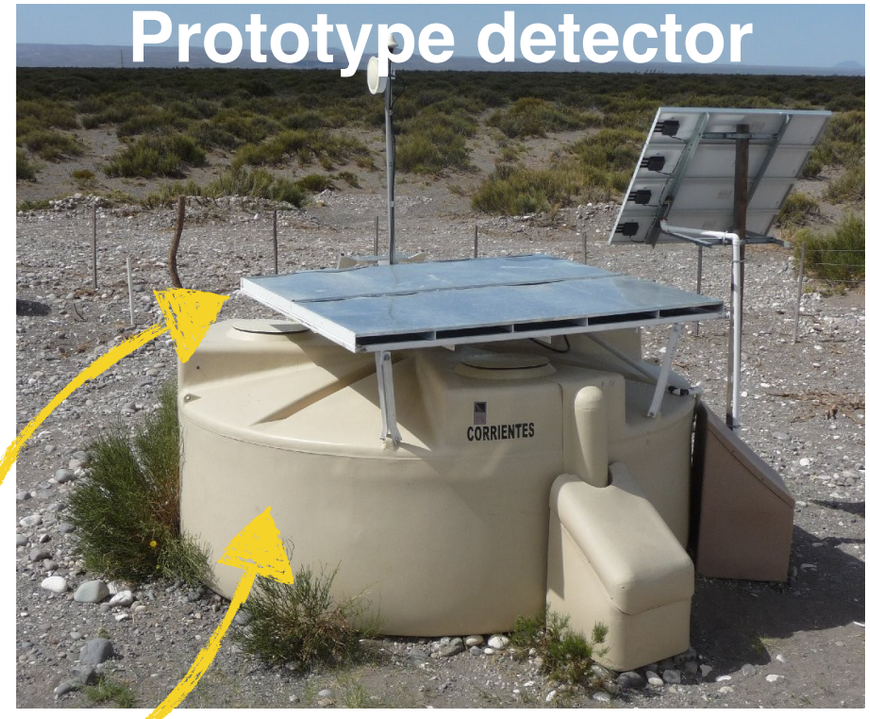
AugerPrime

Main goals:

- Origin of the flux suppression
- Proton contribution in the flux suppression region
- Fundamental particle physics

→ increase sensitivity to mass composition





10 m² water cherenkov counter
(mainly μ component)

3.8 m² scintillator
(mainly EM component)

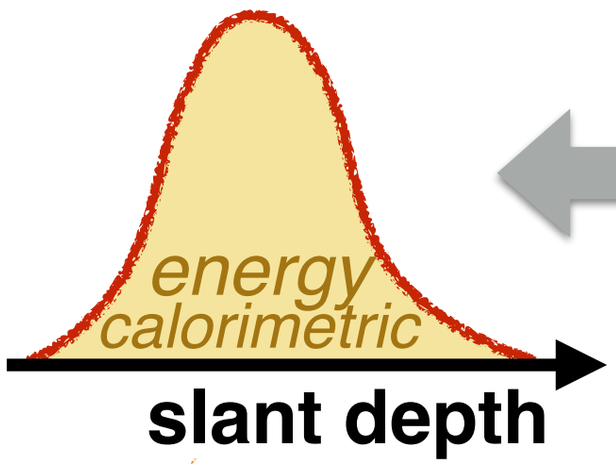
conservative estimate

ideal estimate (no background)

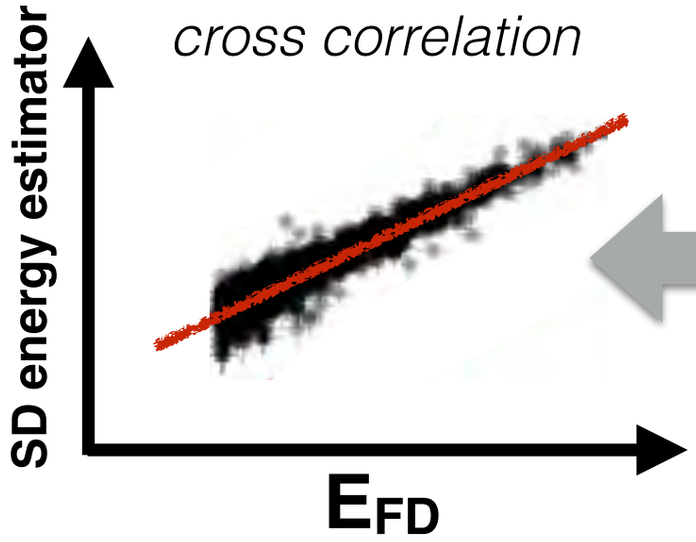
expect improvement for diffuse and directional searches

Hybrid detector

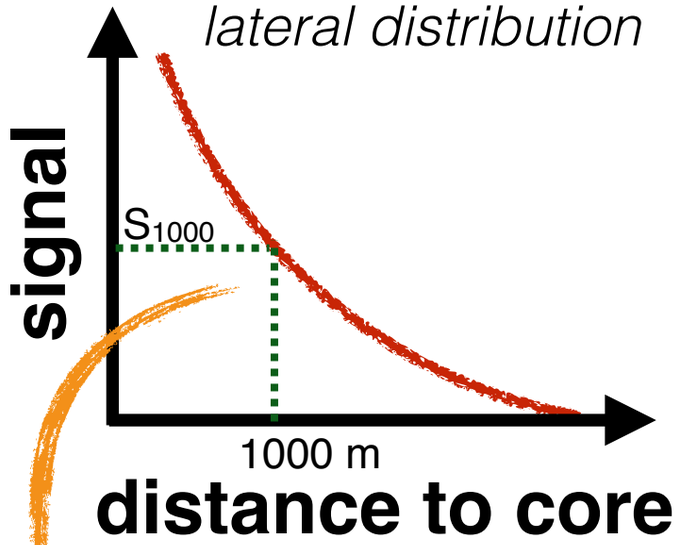
longitudinal profile

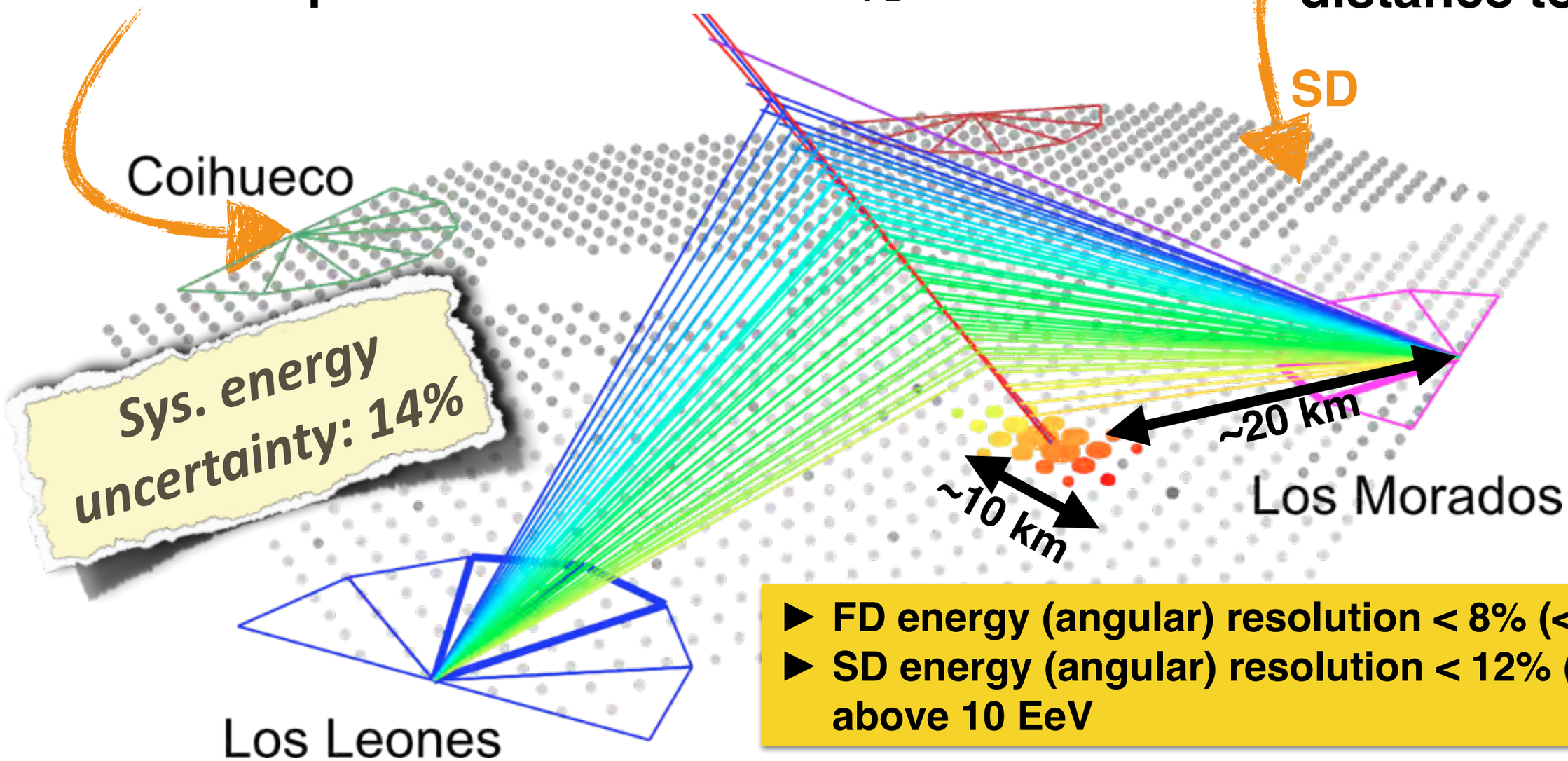


cross correlation



lateral distribution





- **FD energy (angular) resolution < 8% (<1°)**
- **SD energy (angular) resolution < 12% (<1°) above 10 EeV**