Large zenith angle observations with IACTs: MAGIC detection of Crab Nebula up to 100 TeV and prospects for CTA

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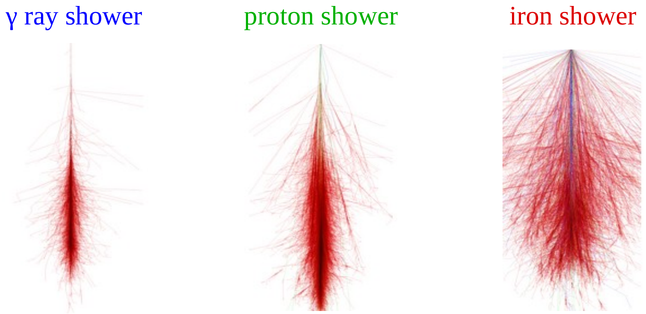
ICRR, The University of Tokyo

The extreme Universe viewed in very-high-energy gamma rays 2021
21.02.2022, online

IACTs and VHE shower detection technique

Atmosphere as a detector medium



E=1 TeV. Credit: CORSIKA website

Imaging Atmospheric Cherenkov Telescopes (IACTs)

- detect: Cherenkov light from secondaries
- location: below the shower
- observations: pointing
- collection area: light pool size

Lower energy threshold
Better angular resolution

Can IACTs get this?

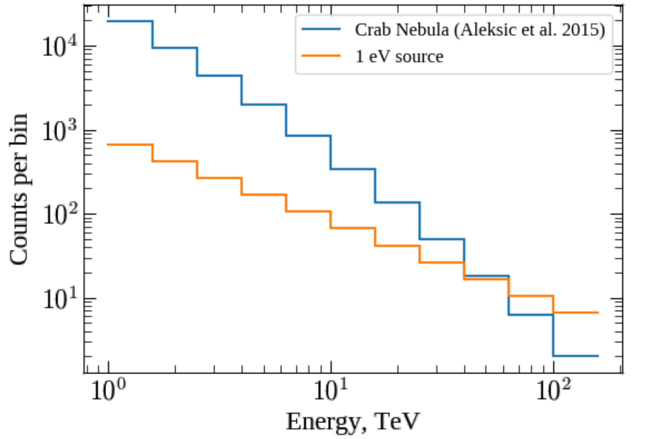
Surface arrays

- detect: secondaries
- location: submerged into the shower
- observations: all-sky
- collection area: array area

Larger collection area / exposure

Challenge of IACT
>100 TeV observations

Expected counts for A_{eff} = 1 km^2 and T_{obs}=50 hr



Main obstacle – low expected count rates.

To keep observation time short,
A_{eff} > 1 km^2 is required.

Multi-telescope setups

- boost A_{eff} with more telescopes (e.g. CTA SSTs)

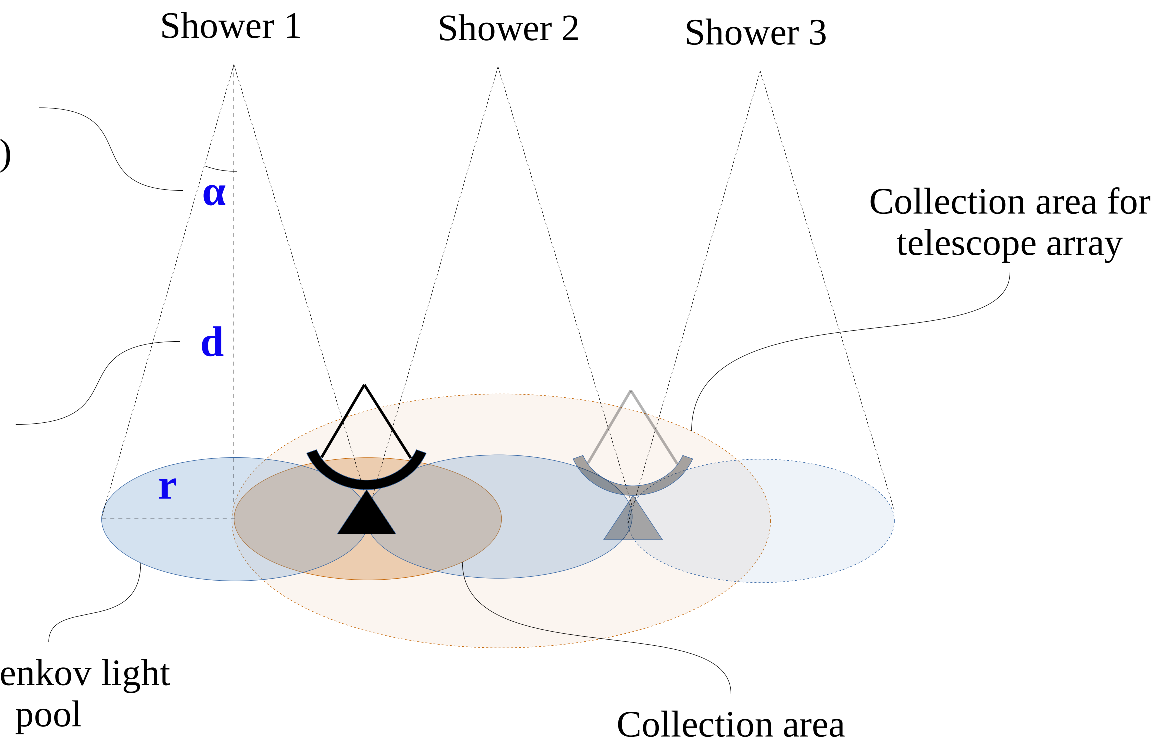
Large zenith angle observations

- boost A_{eff} with extending the light pool
- expand the energy range

This talk

IACT collection area

Collection area of the IACTs is determined by the cherenkov light pool size



Cherenkov angle
Set by the air density
(doesn’t change much)

Shower distance
Depends on air density
and shower energy

Collection area for
telescope array

Cherenkov light
pool

Collection area
(single telescope)

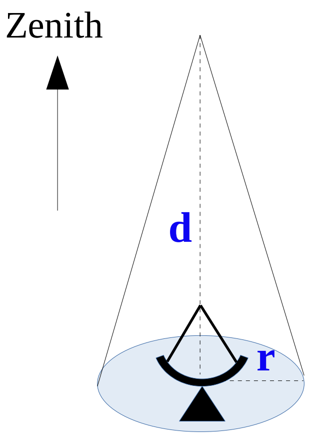
Increasing the collection area:

- more telescopes (expensive)
- increasing distance to shower

Larger zenith angle observations

Vertical observations

(typical observational mode of IACTs)



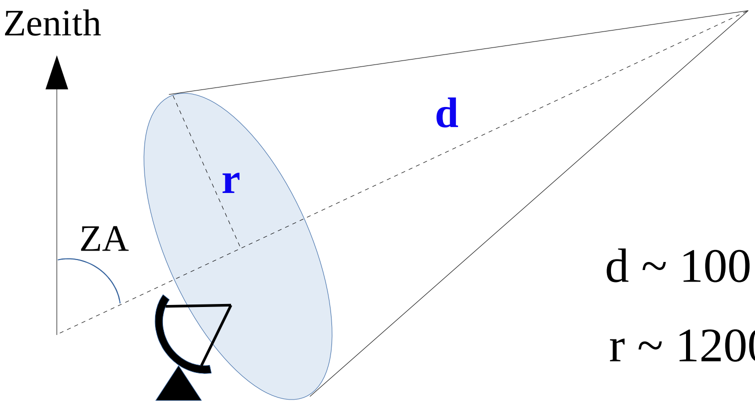
d ~ 10 km

r ~ 120 m

Usually ZA ~ [0^0; 60^0] and shower distance d ~ 10-20 km

Large zenith angle observations

(proposed setup)



d ~ 100 km

r ~ 1200 m

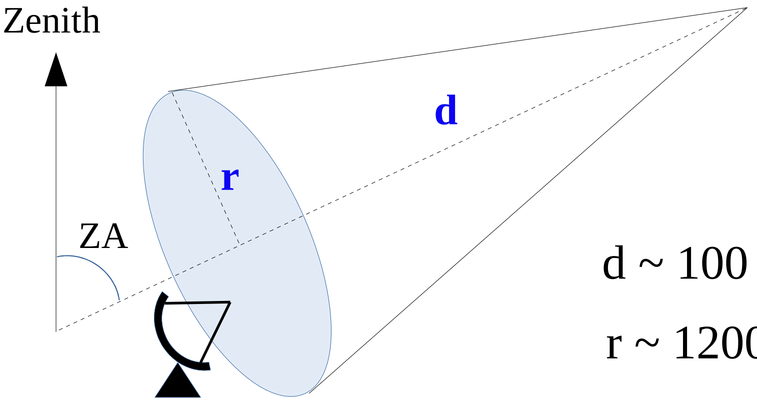
d ~ 10 km /cos(ZA)

ZA > 70^0
shower distance d > 50 km

Larger zenith angle observations

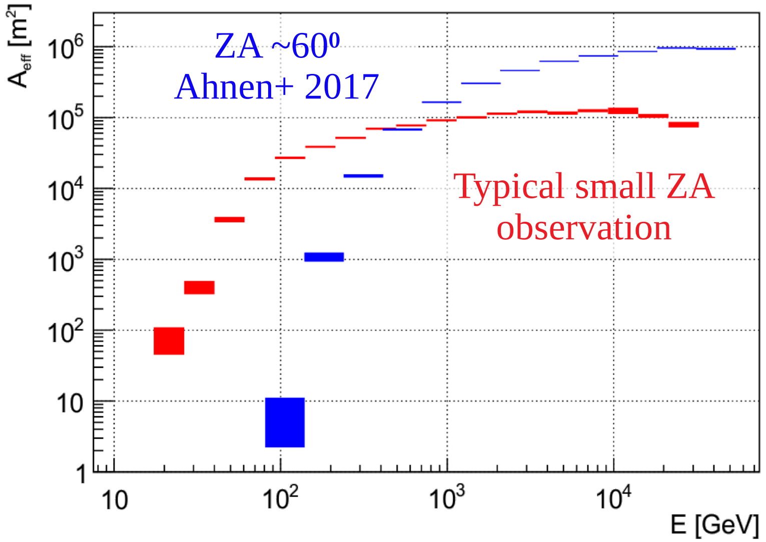
Originally proposed by Konopelko+ ‘99

Observations up to ZA~60^0 already employed for specific sources (e.g. Ahnen+ 2017).
Yield a boost in A_{eff} at high energy end.

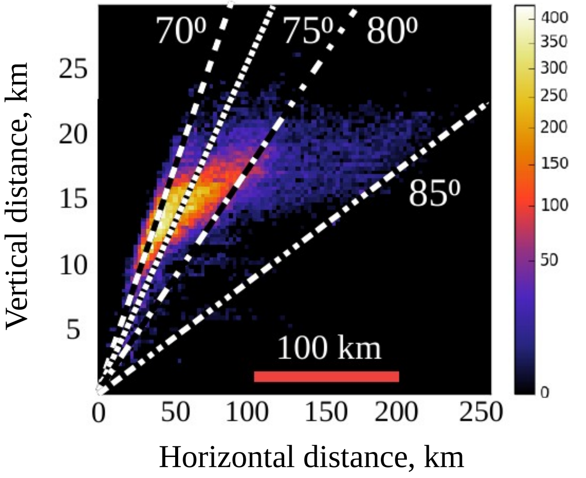


d ~ 100 km

r ~ 1200 m



Cherenkov emission location (MC)

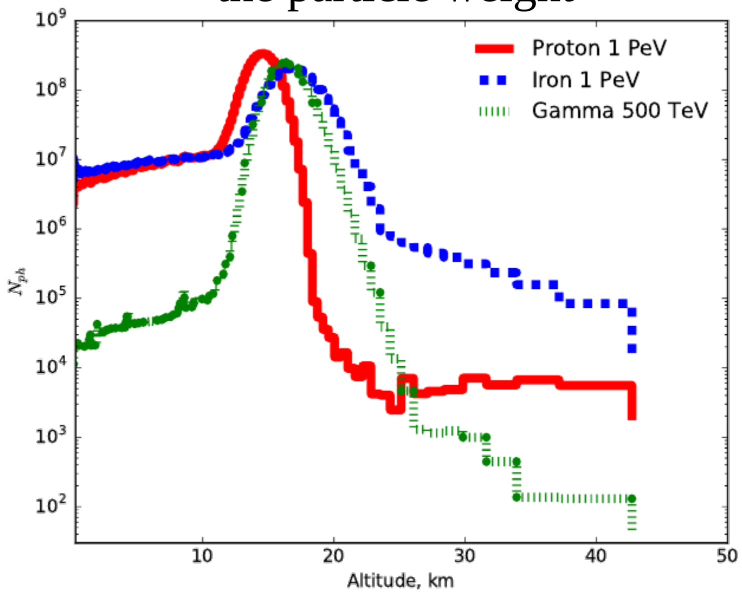


Cosmic ray EAS development at large zenith angles

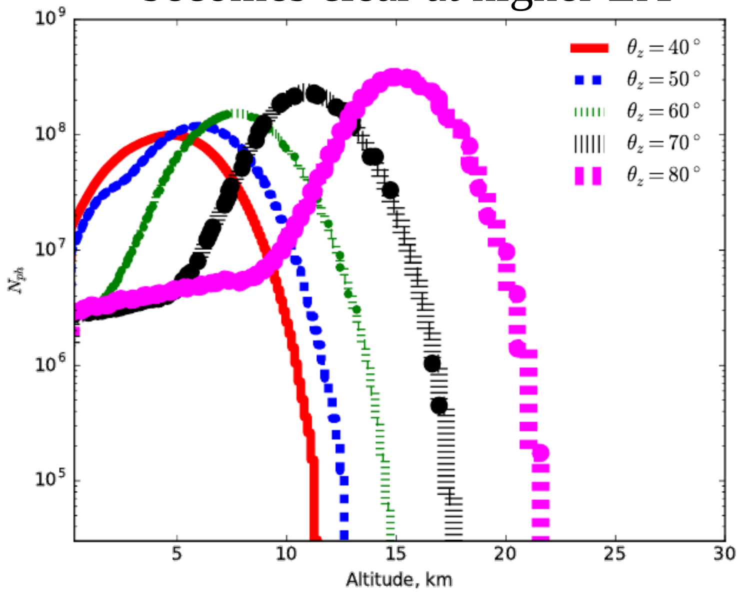
Neronov+ ‘16

Electrons in EAS cool over ~0.1-1 km path.
Muons require ~20-500 km to loose their energy.

Muon richness increases with the particle weight



Muon contribution develops gradually, becomes clear at higher ZA



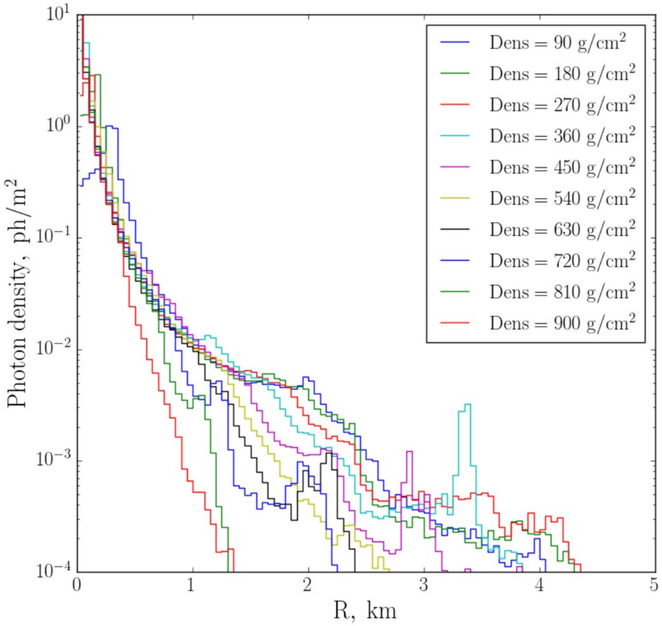
→ High zenith angle observation may enable measurements of muon “tail” also with IACTs.

Formation of the muon “tail”

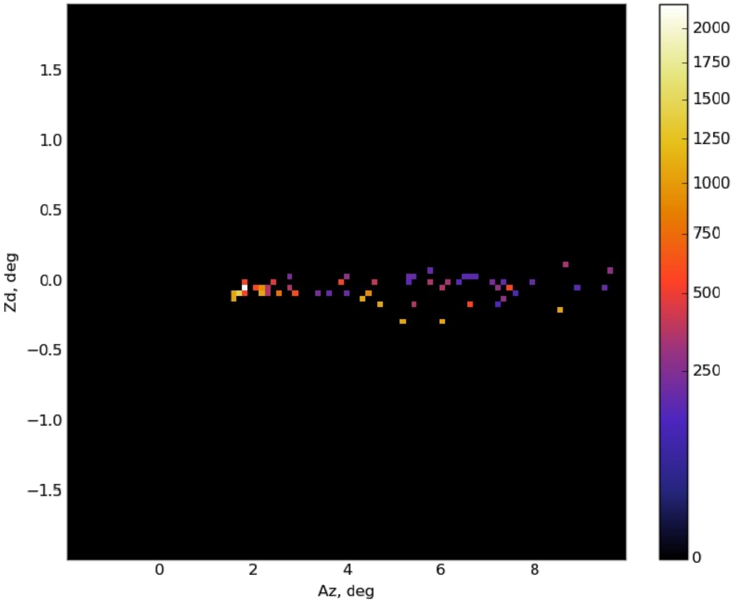
Neronov+ ‘16

At high ZA muon light density is small. Why can we see them?

Muon light from ZA=87°



Simulated EAS image from individual muons



→ Though single muons (rings) are too dim, large number of muons form the tail.

Imaging and timing of CR EAS

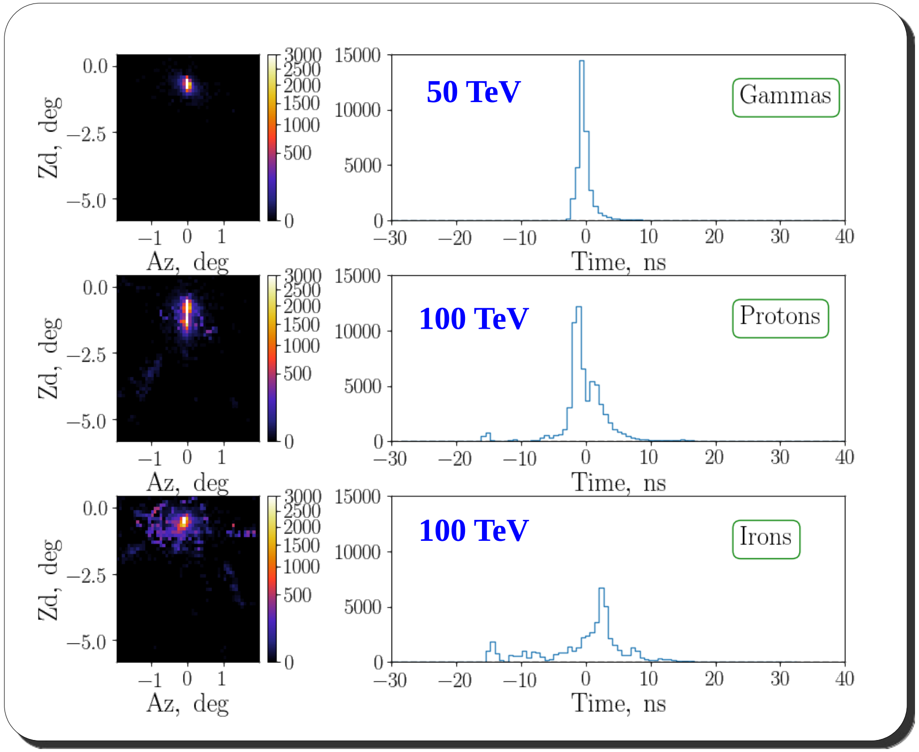
Neronov+ ‘16

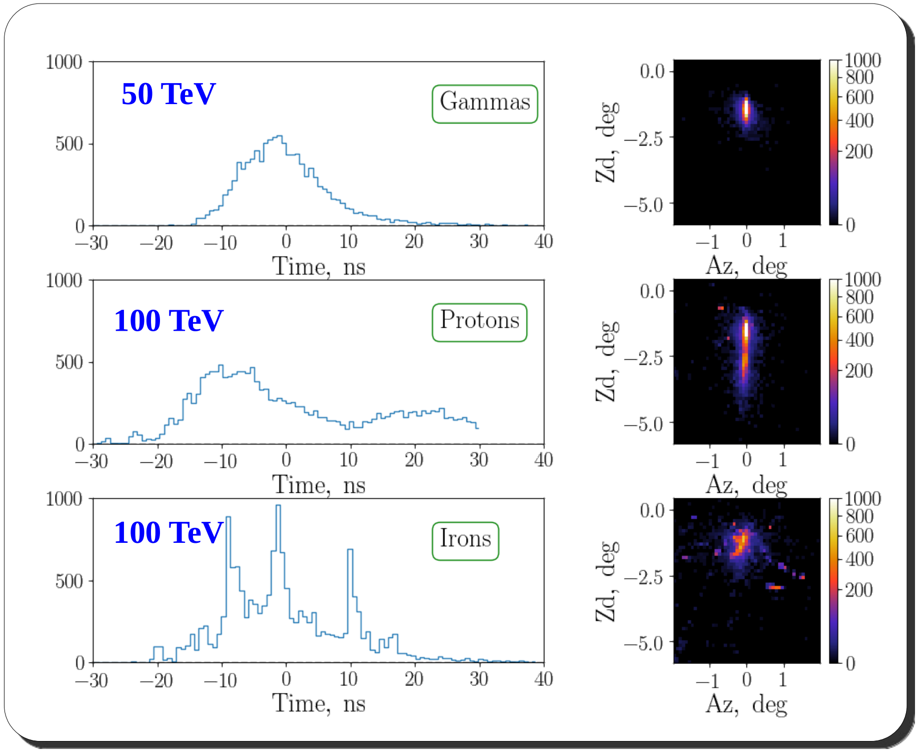
Another profound difference of the high-ZA showers is their longitudinal (temporal) evolution (Neronov+ ‘16)

Impact parameter (@ ZA=70°)

0.5 km

1.0 km





Towards the composition measurement with LZA data

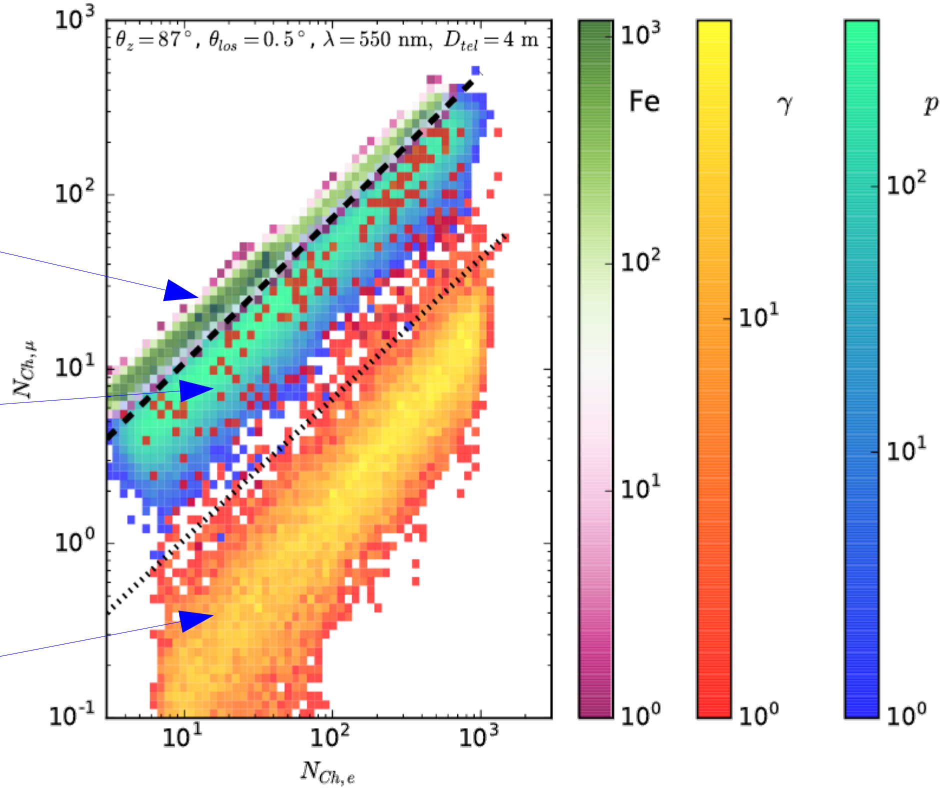
Neronov+ ‘16

Muons richness → primary’s identity

Iron

Protons

Gamma rays



N_μ and N_e can be estimated from data using the extended (leading) and core (delayed) emission

Added complexity of LZA observations

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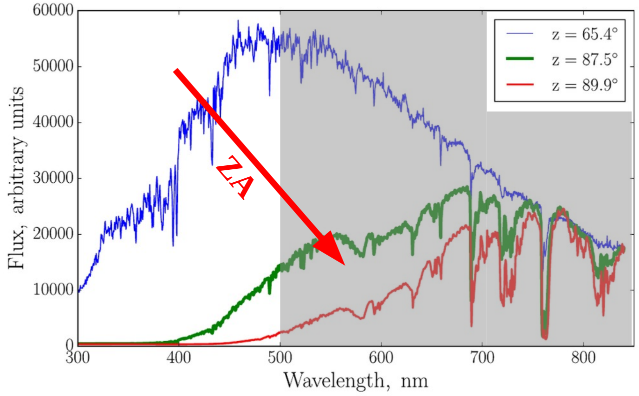
University of Tokyo

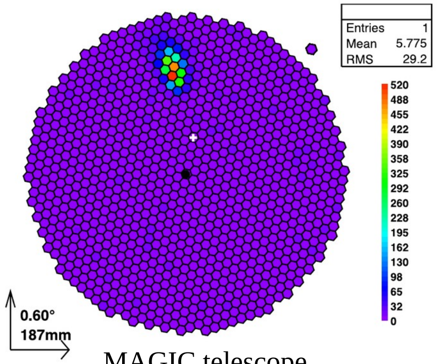
Mirzoyan+ ‘20

Light absorption



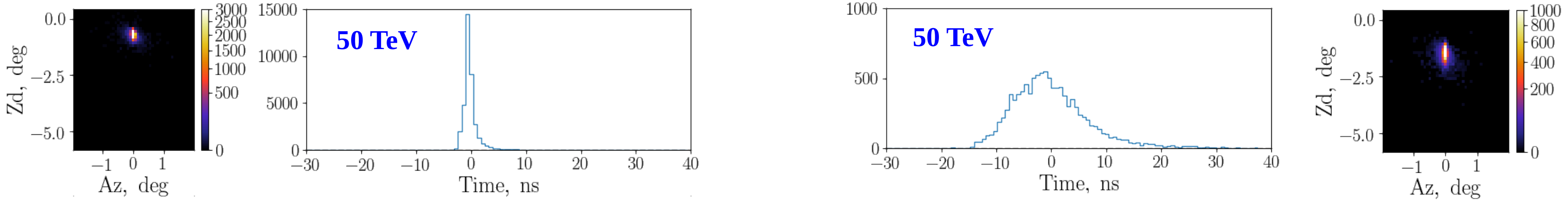
- Larger light absorption:
  higher energy threshold.
- Smaller shower images:
  degradation of parameter reconstruction.
- Longer lasting showers:
  possible issues when recording data.

Smaller image size



MAGIC telescope
E=144 TeV @ZA=78 deg

Longer lasting showers from larger impact distances



0.5 km

1.0 km

Impact distance

Neronov+ ‘16

IACTs capable of LZA observations

Northern Hemisphere Array Rendering
by Cherenkov Telescope Array Observatory

Cherenkov Telescope Array project

ICRR
Institute for Cosmic Ray Research
University of Tokyo

The largest Cherenkov observatory every built

~1500 scientists and engineers
~200 institutes
31 countries

→ Large international effort

Southern site (Chile)

Northern site (Canary Islands)

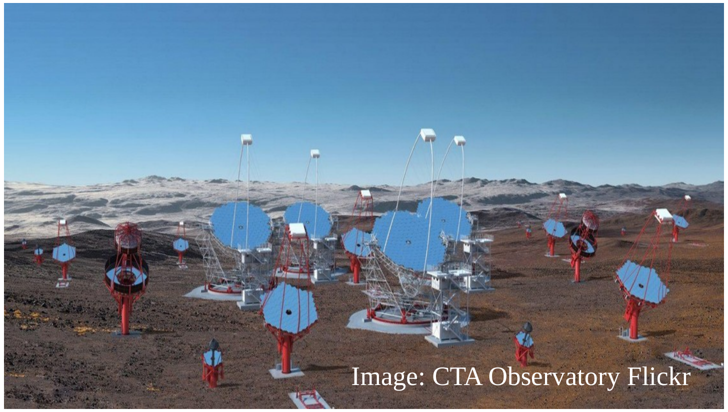


Image: CTA Observatory Flickr


Image: CTA Observatory Flickr

Layout: 4 large-sized telescopes
25 medium-sized telescopes
70 small-sized telescopes

Layout: 4 large-sized telescopes
15 medium-sized telescopes

Extremely rich scientific outcome is expected

MAGIC telescope system

Aleksic+ ‘16
MAGIC Collaboration ‘20

Image: Max Planck Institute for Physics/R. Wagner

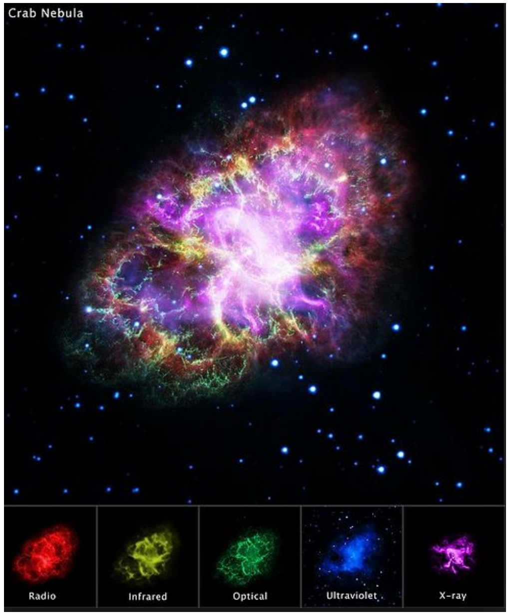
Stereoscopic system of 2 IACTs,
located at La Palma, Spain

Telescopes:	two D=17m
Site:	La Palma (Canary Islands)
Energy range:	15 GeV – above 50 TeV
Resolution:	0.07°-0.14° (0.1-1 TeV)
Sensitivity:	0.6% Crab units (integral)
Field of view:	3.5 deg

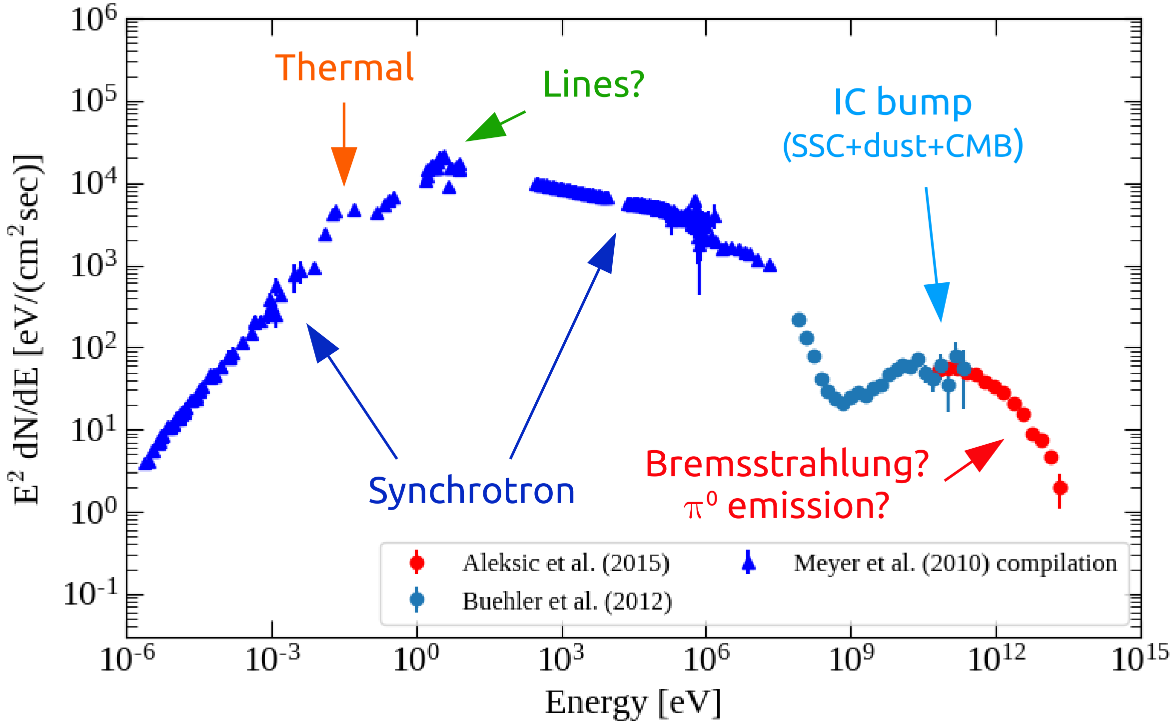
Performed LZA observations of Crab Nebula up to 100 TeV
(MAGIC Collaboration ‘20)

Crab Nebula: a (the?) pulsar wind nebula

Nearby (d ~ 2 kpc), young (age ~ 1ky), powerful (L_{sd}~5x10^{38} ergs/s), magnetized (B~100 μG)



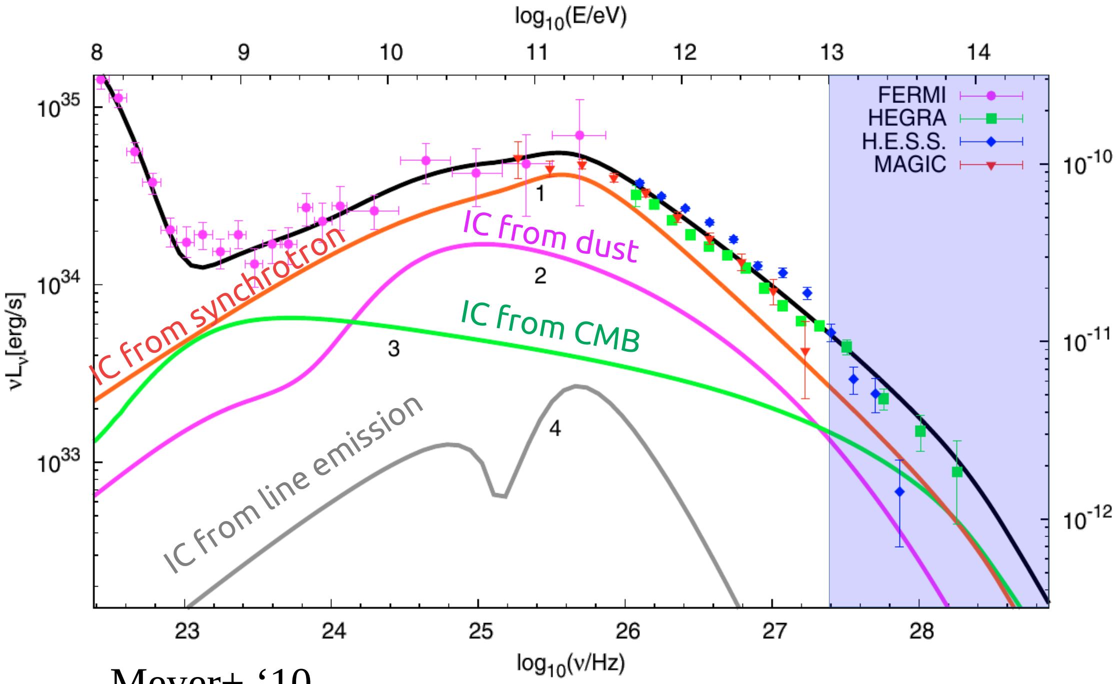
Credit: NASA, STScI



Multiple electron populations argued (Atoyan & Aharonian ‘96).
Contribution of hadronic emission in HE band is unclear.
VHE emission is extended (H.E.S.S. Collaboration ‘20)
PeV photons detected (LHASSO Collaboration ‘21)

VHE emission – solution to (some of) the puzzle(s)

GeV-TeV emission is produced by several competing mechanisms.
Multiple electron populations (“radio”, “wind”, possibly “flare”).



Meyer+ ‘10

>10 TeV energies some of the mechanisms are sub-dominant

In particular, above 30 TeV IC on CMB may be dominant.

→ B-field constraints
→ Links to GeV flares
→ SSC contribution constraints

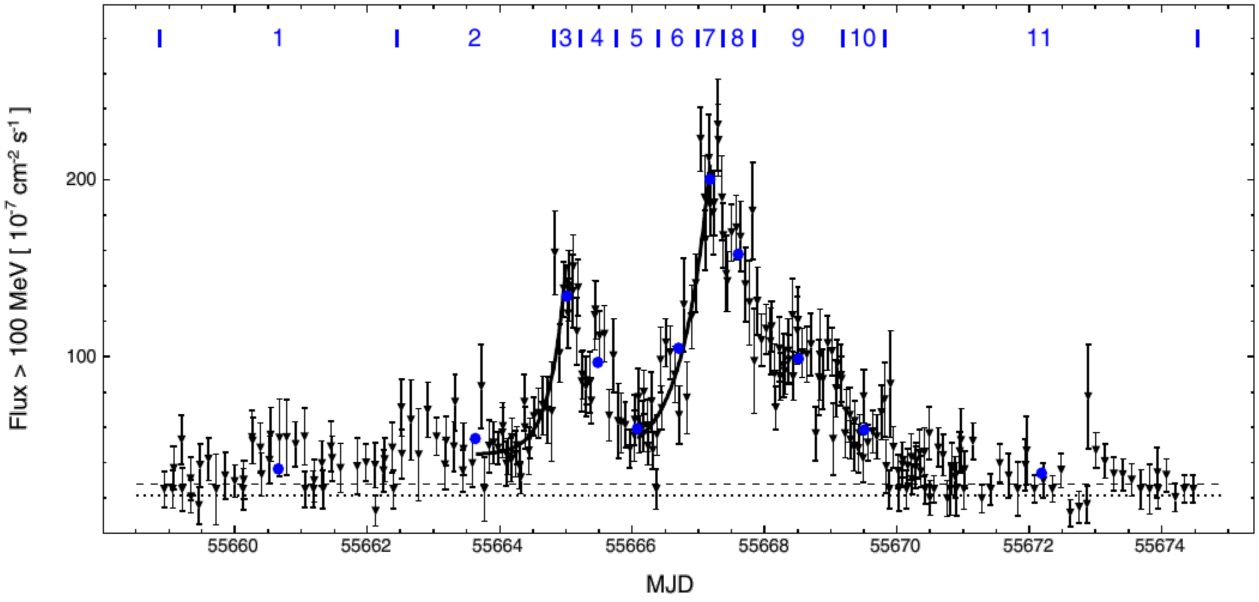
SSC depends on (1) electron spectrum, (2) B-field and (3) emission region size.

Hadronic contribution in >10 TeV range?

(Atoyan & Aharonian ‘96, Bednarek & Protheroe ‘97, Amato+ ‘03)

Crab Nebula variability

>10x flux variability @ E < 1 GeV!



Buehler+ ‘12

100 MeV synchrotron emission corresponds to ~100 TeV IC.

Counterparts for Fermi flares are expected in the 100 TeV band, though the strong corresponding B-field (> 1 mG, Buehler & Blandford ‘14) would suppress the IC emission.

Detection of the ~100 TeV emission
with current generation of ground based IACTs
is demanding

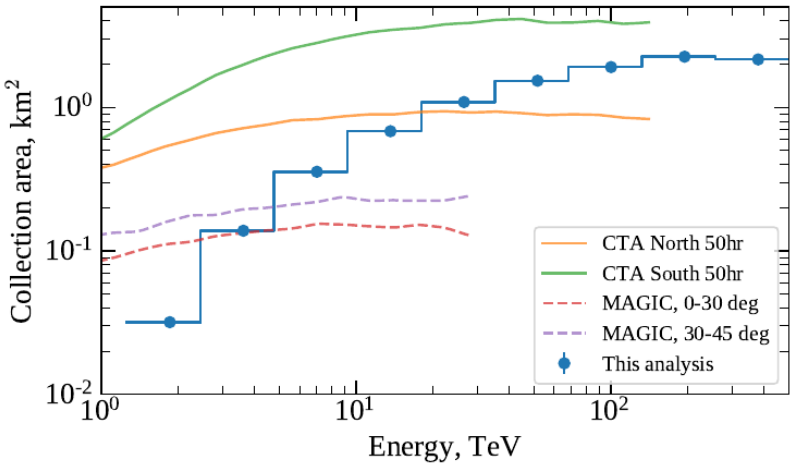
MAGIC LZA detection of Crab Nebula at highest energies

MAGIC Collaboration ‘20

First LZA observations in the range ZA=70-80⁰

Addressing the associated systematics:
atmosphere transmission, defocused imaging, small image size

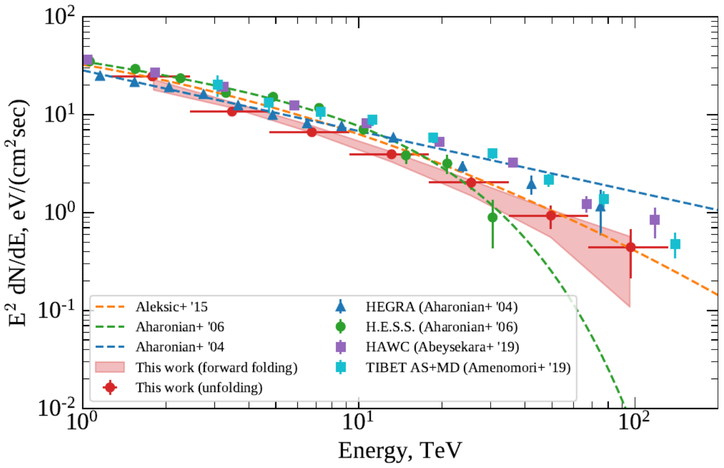
Reconstructed collection area



A$_{\mathrm{eff}}$ @100 TeV is comparable to CTA predictions (at 20° zenith angle).

http://www.cta-observatory.org/science/cta-performance/ (version prod3b-v1)

Reconstructed SED

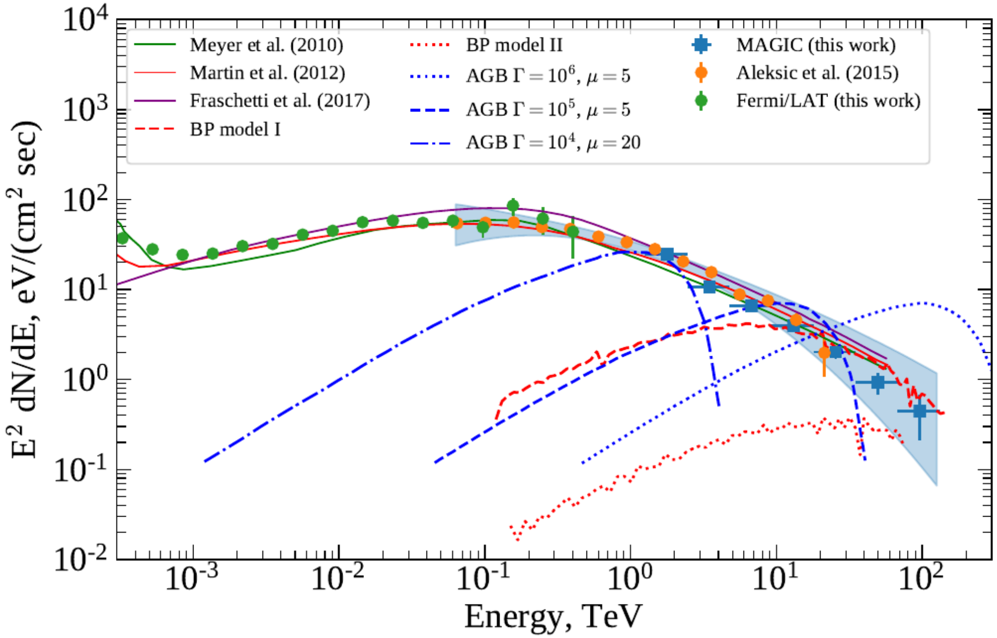


- larger E$_{\max}$: 30 TeV → 100 TeV (compared to Aleksic+ ‘15)
- 8x shorter observation time compared to earlier HEGRA measurements (Aharonian+ ‘04)

“Pathfinder” for future CTA observations

Constraining the hadronic contribution

MAGIC Collaboration '20



Accelerated electrons ≡ accelerated protons (likely)

Nuclei can be (1) ripped from the pulsar surface, (2) accelerated on shock wave(s) resulting from the wind or (3) accelerated during the magnetic re-connection events.

Interactions may be ~10 fold intensified in the nebula filaments.

Tested models from Bednarek & Protheroe (1997) and Amato+ (2003)

→ No obvious contribution from hadronic component.

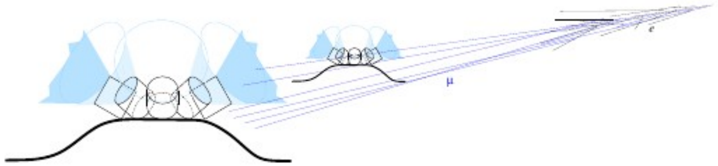
LHASSO measurements should be even more constraining.

Demonstration of the LZA observations potential in extending the IACT energy range.

LZA observations with CTA

Neronov+ ‘16

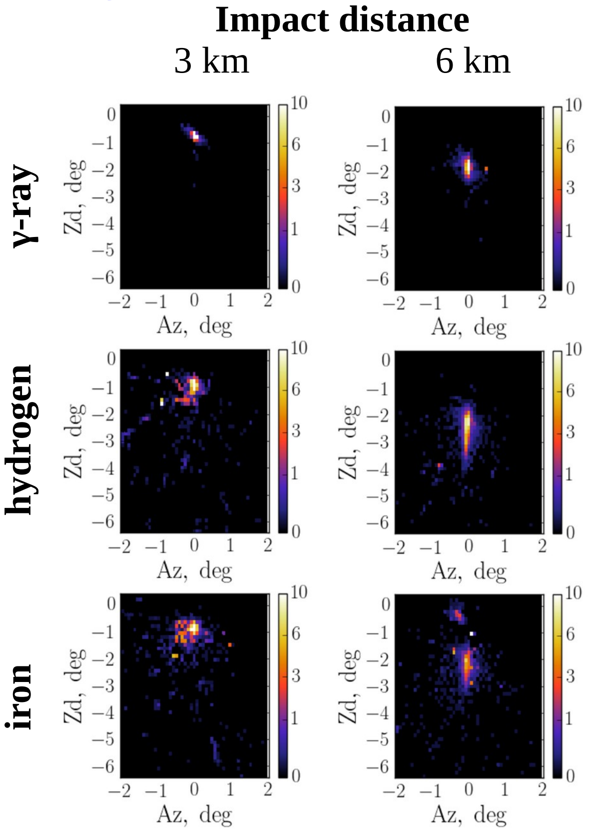
CTA LZA observations:
large FoV and sensitivity in multi-PeV range



- A_{eff} gain at ZA > 80 deg
- Large FoV cameras can grasp both muon “halo” and electron “core” Cherenkov light
- Many individual telescopes (CTA SSTs)

↓

- A_{eff} ~ 10^4 km^2 (@ 87 deg)
- Large “grasp” $g=A_{eff}\,\Omega$

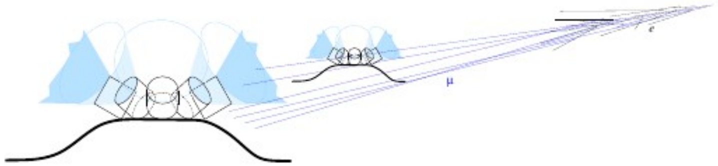


Shower images as may be seen by CTA SSTs
(0.5 PeV photon and 1 PeV hydrogen / iron)

LZA observations with CTA

Neronov+ ‘16

CTA LZA observations:
large FoV and sensitivity in multi-PeV range

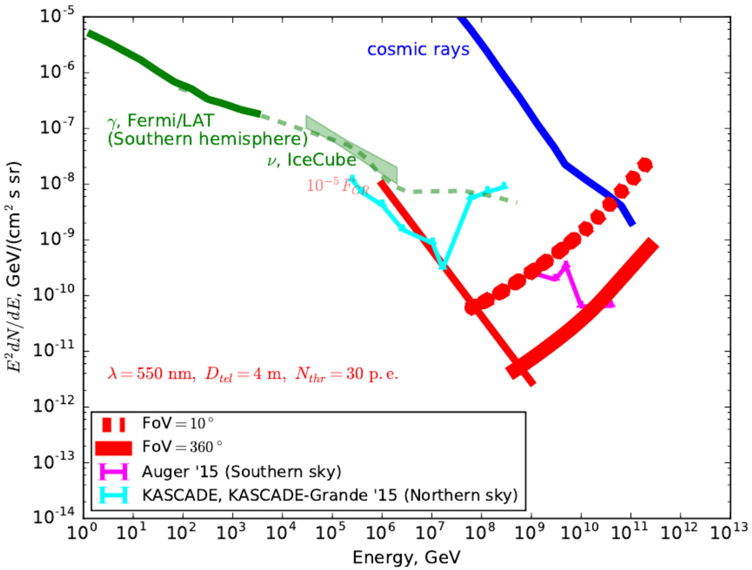


- A_{eff} gain at ZA > 80 deg
- Large FoV cameras can grasp both muon “halo” and electron “core” Cherenkov light
- Many individual telescopes (CTA SSTs)

↓

- CR composition measurements
- Background-free observations for E > 0.1-1 PeV
- Unprecedented sensitivity to the diffuse (extra)galactic gamma-ray emission

CTA sensitivity to diffuse gamma-rays
(1 year with duty cycle of 0.1)



→ Potentially unique opportunity for multi-PeV gamma-ray and CR studies

Summary

Large zenith angle observations – a promising, novel way to perform >100 TeV observations with IACTs.

Such observations may require specific hardware features (small pixels, longer read-out, auxiliary atmosphere monitoring), achievable with current and future IACT systems.

First LZA Crab Nebula observations with MAGIC present demonstrate a potential of LZA approach in boosting the collection area at highest energies.

Future CTA LZA observations may open a new window of multi-PeV gamma-ray and CR measurements.