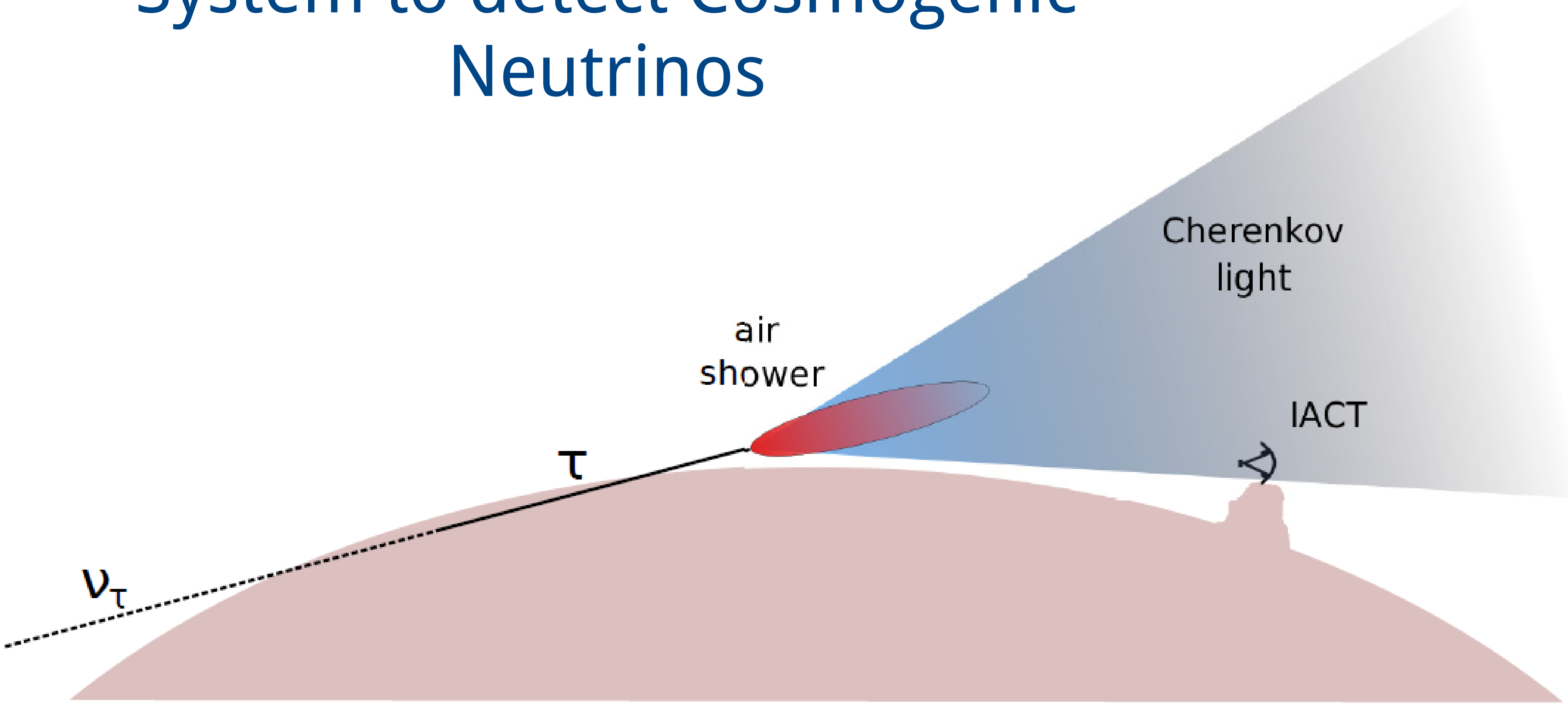
Trinity

A Cherenkov/Fluorescence Telescope System to detect Cosmogenic Neutrinos



Nepomuk Otte

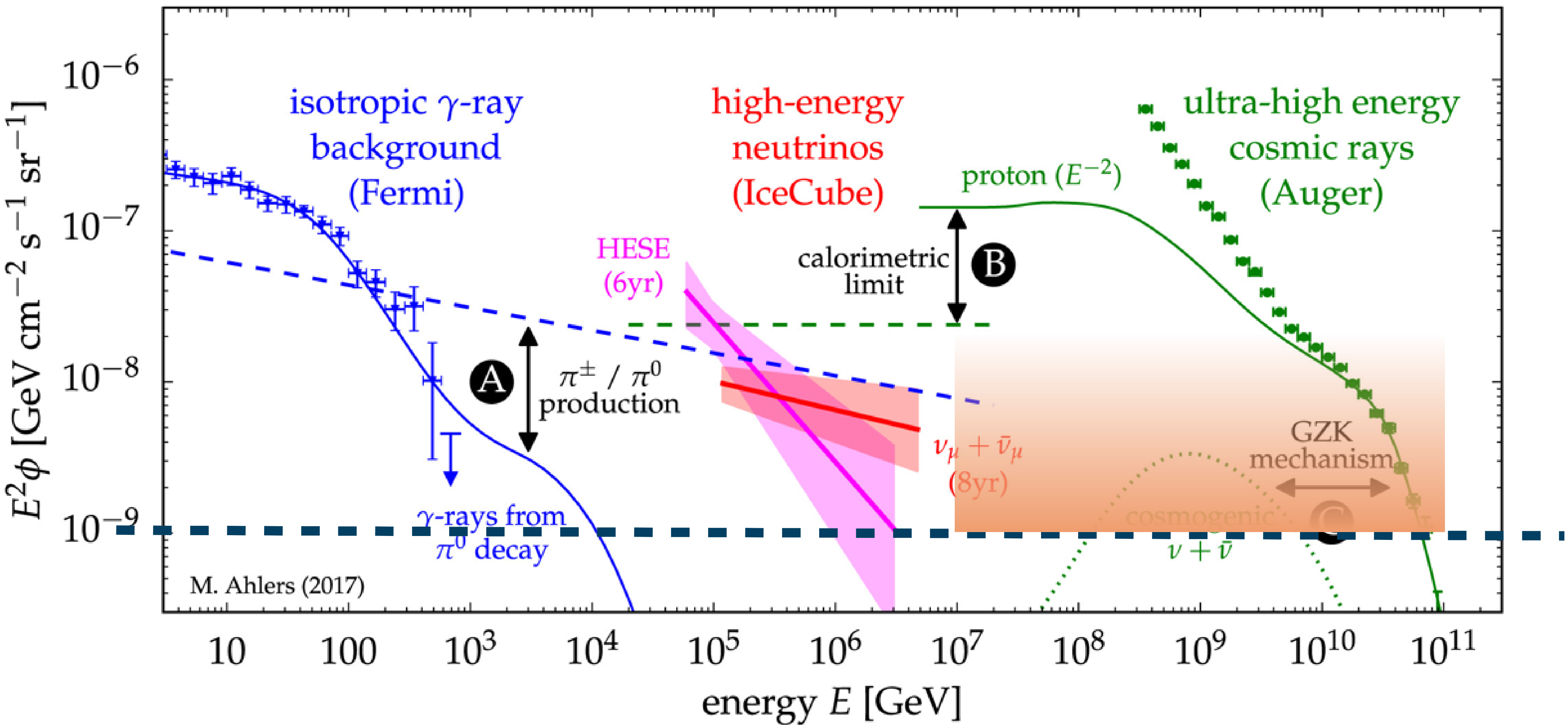
School of Physics
&
Center for Relativistic Astrophysics

Georgia Tech Physics College of Sciences

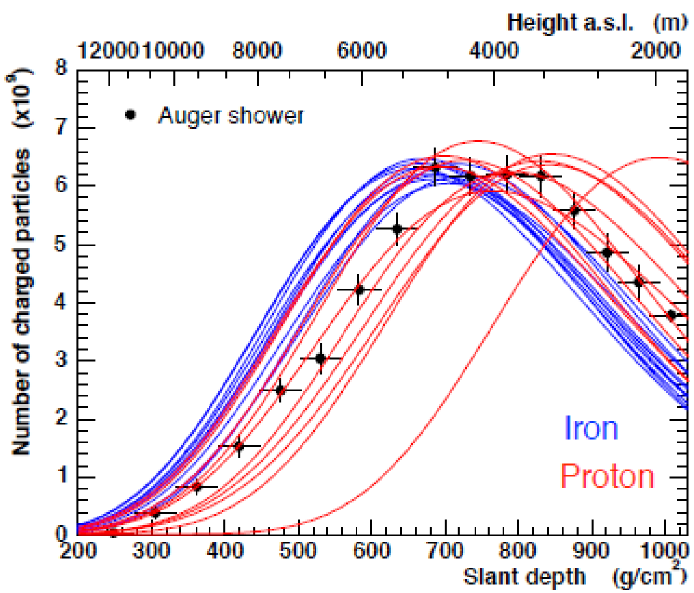
Content

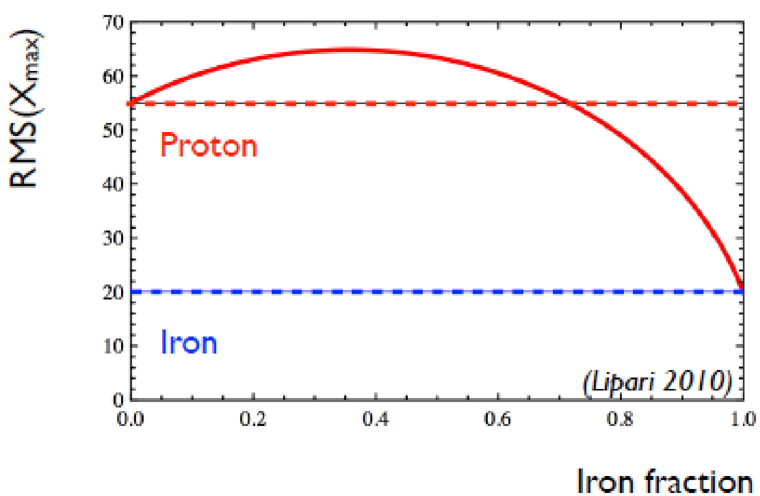
- Science with ultra-high energy neutrinos
- UHE neutrino detection techniques
- Tau neutrino interaction in Earth and tau shower physics
- Trinity detector layout
- Acceptance and sensitivity dependence on detector parameters

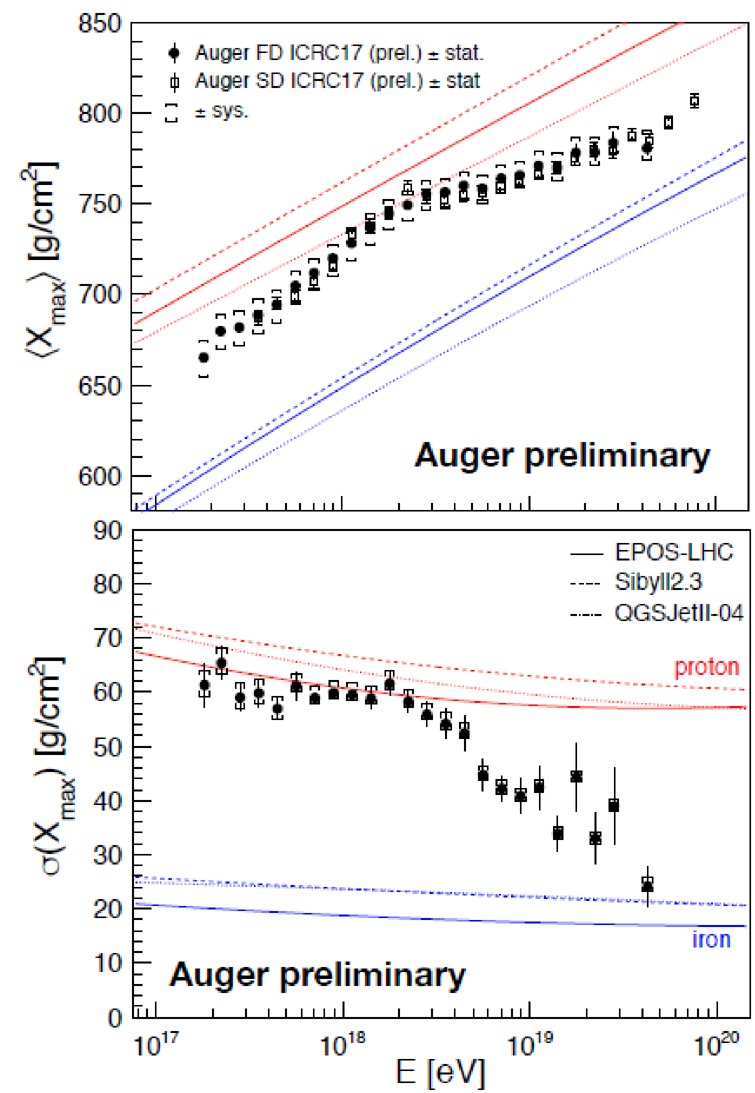
The Era of Multi-Messenger Astrophysics



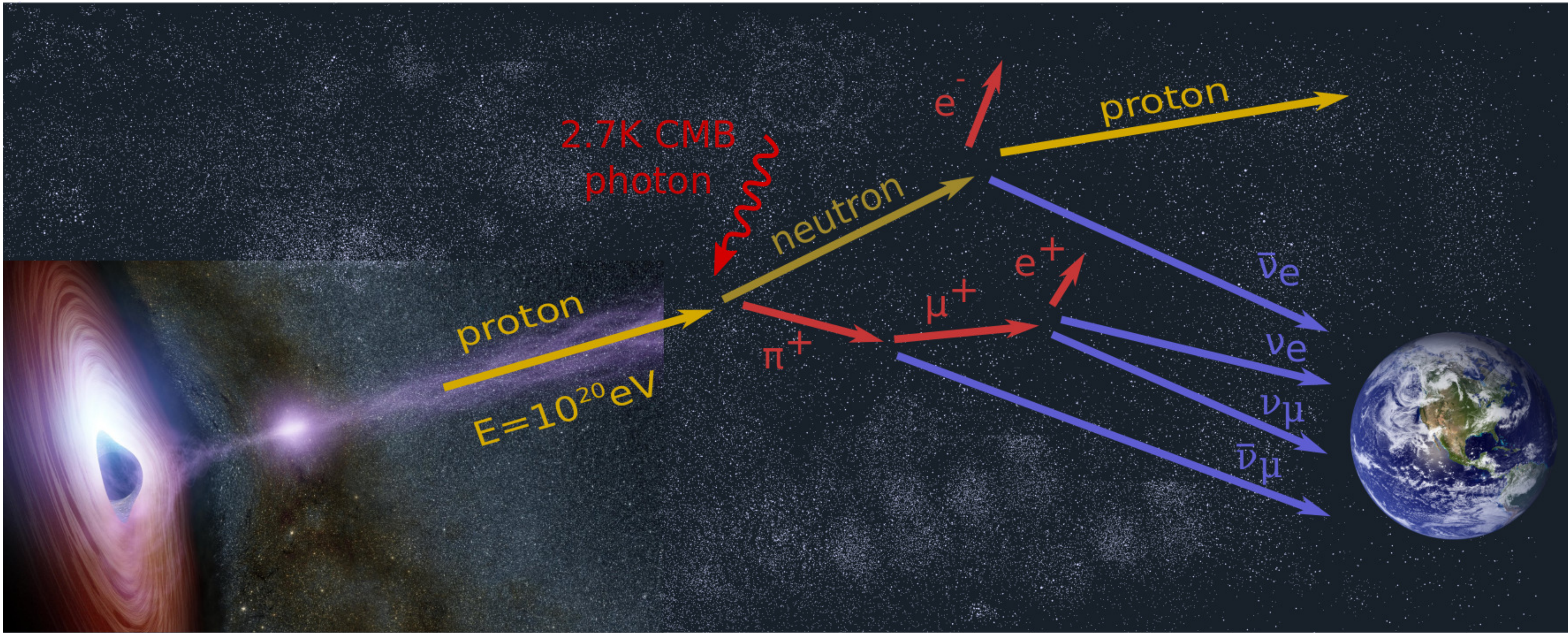
Composition & Sources of UHECR



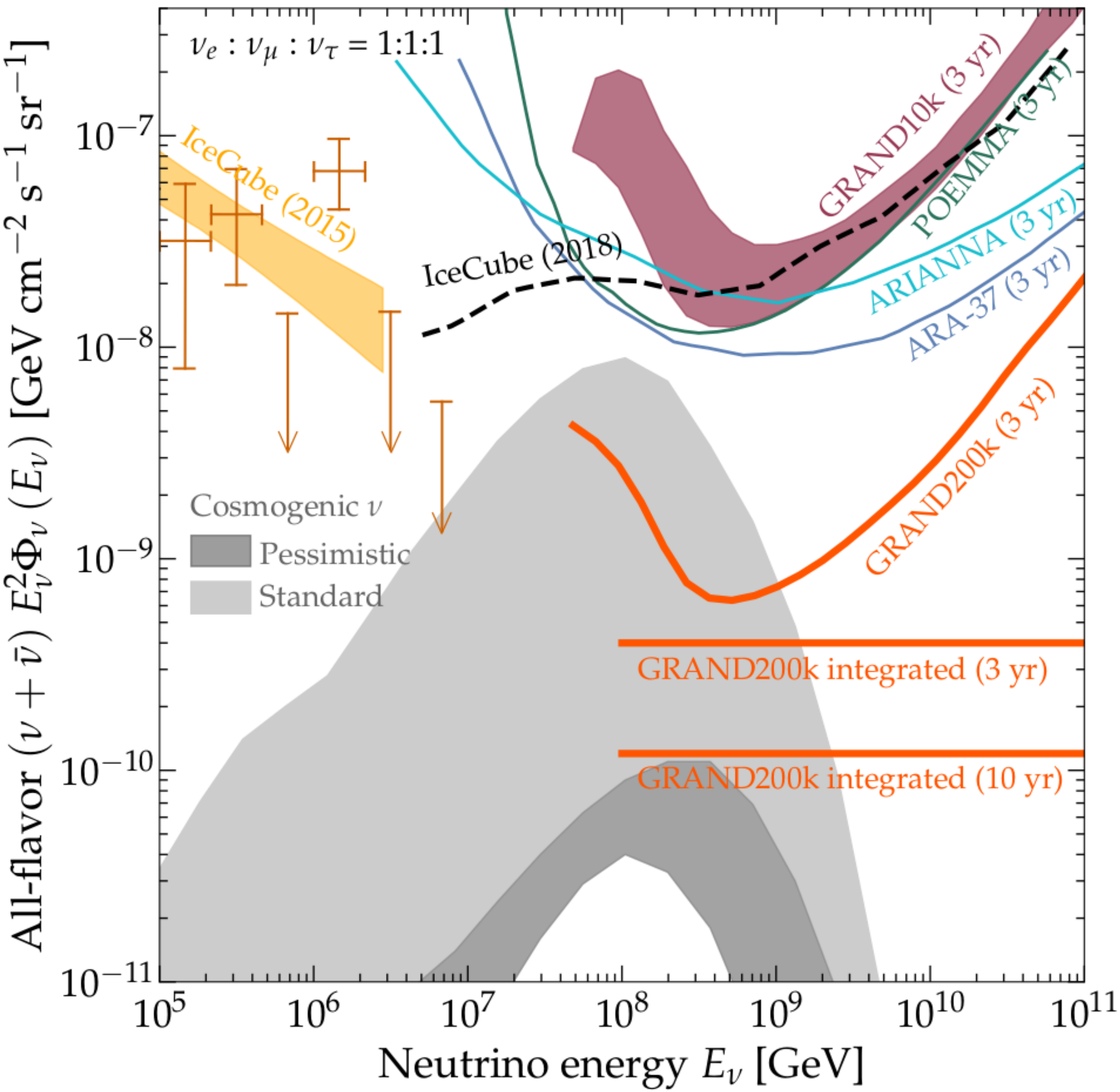




From R. Engel @ TeVPA2017



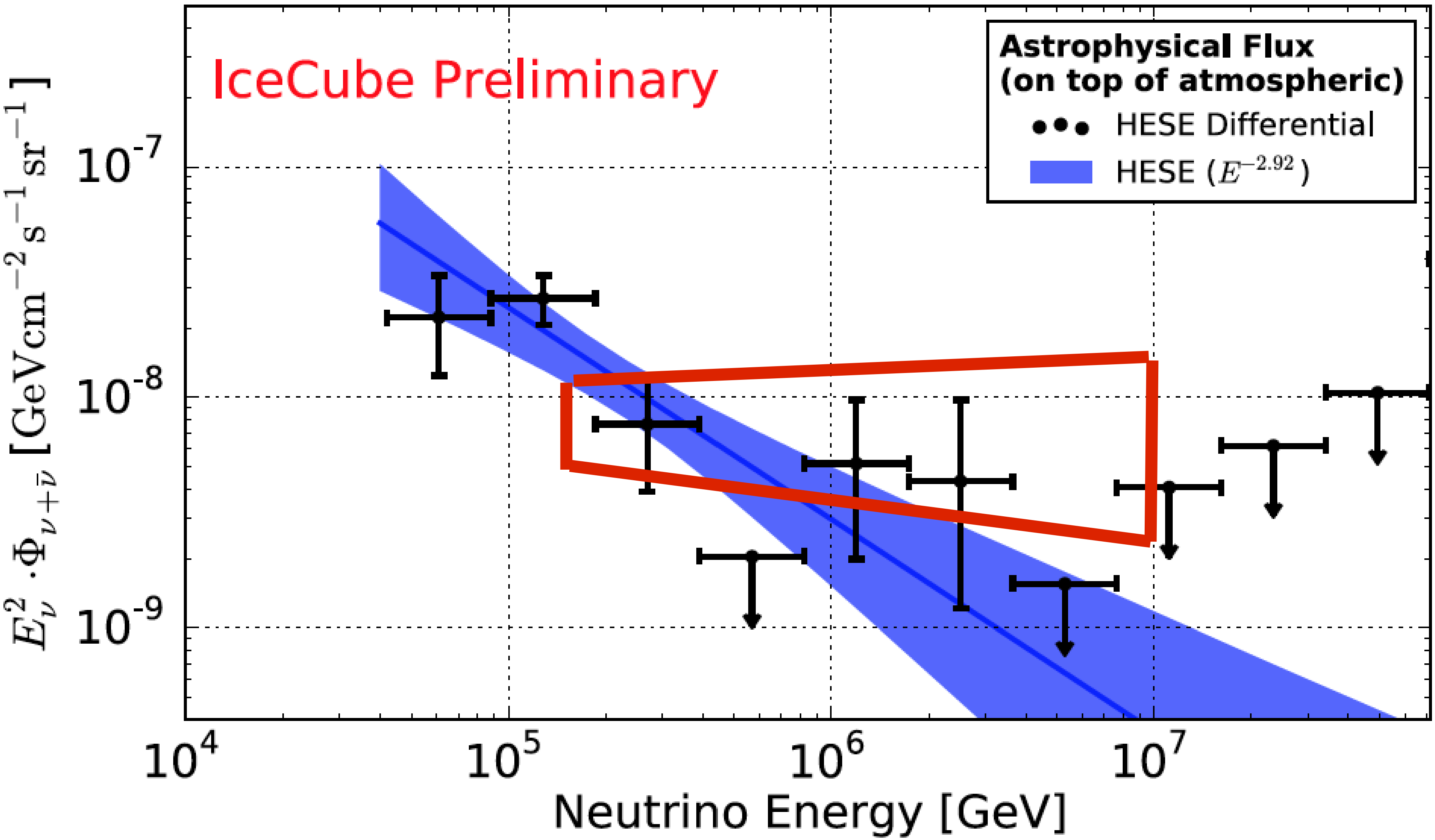
2.7K CMB photon
proton
$E=10^{20}$eV
neutron
π^+
μ^+
e^-
e^+
proton
$\bar{\nu}_e$
ν_e
ν_μ
$\bar{\nu}_\mu$



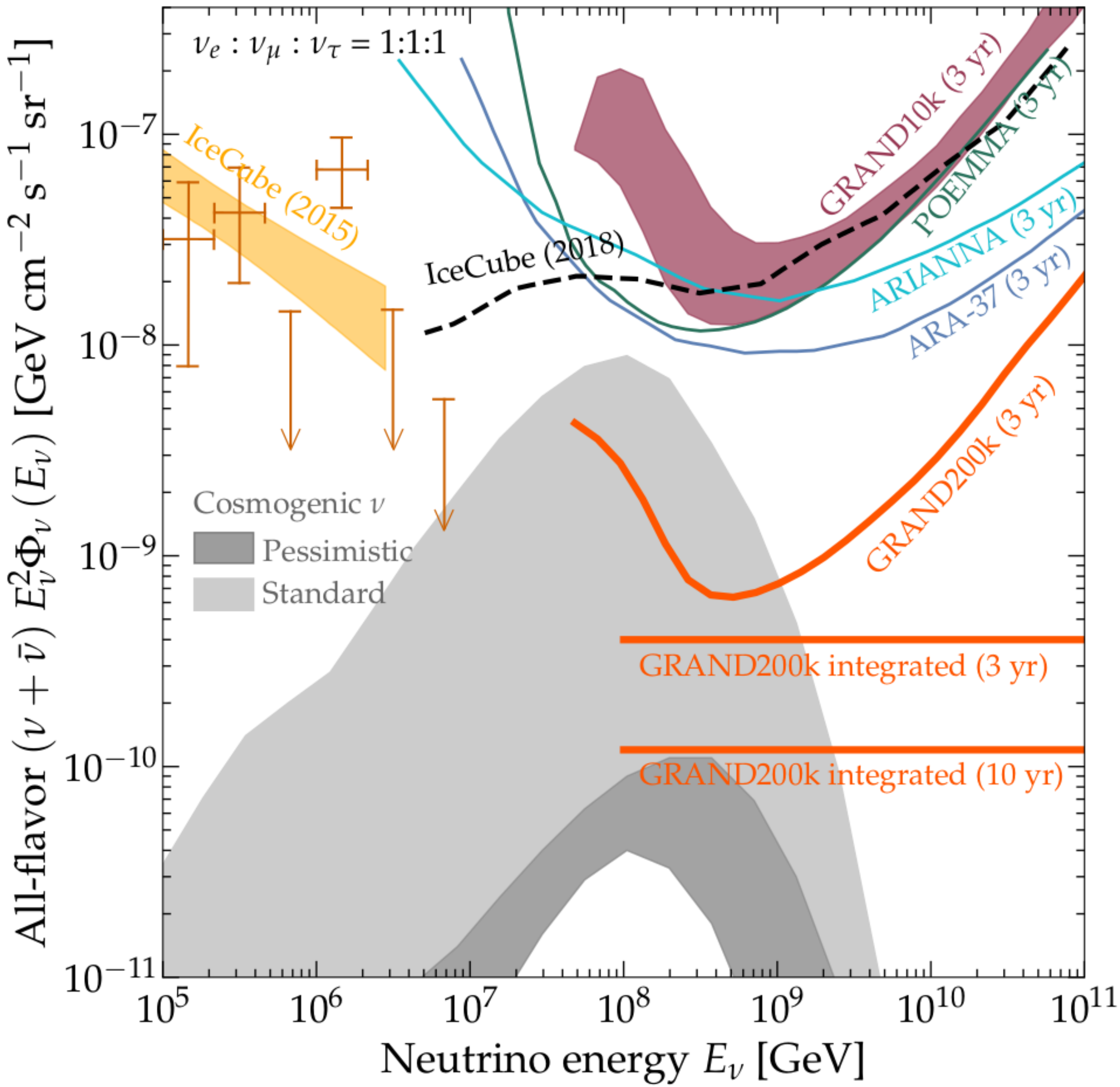
Science Motivation:

- **What is the composition of UHECR?**
- **What are the sources of UHECR?**

Astrophysical Neutrinos



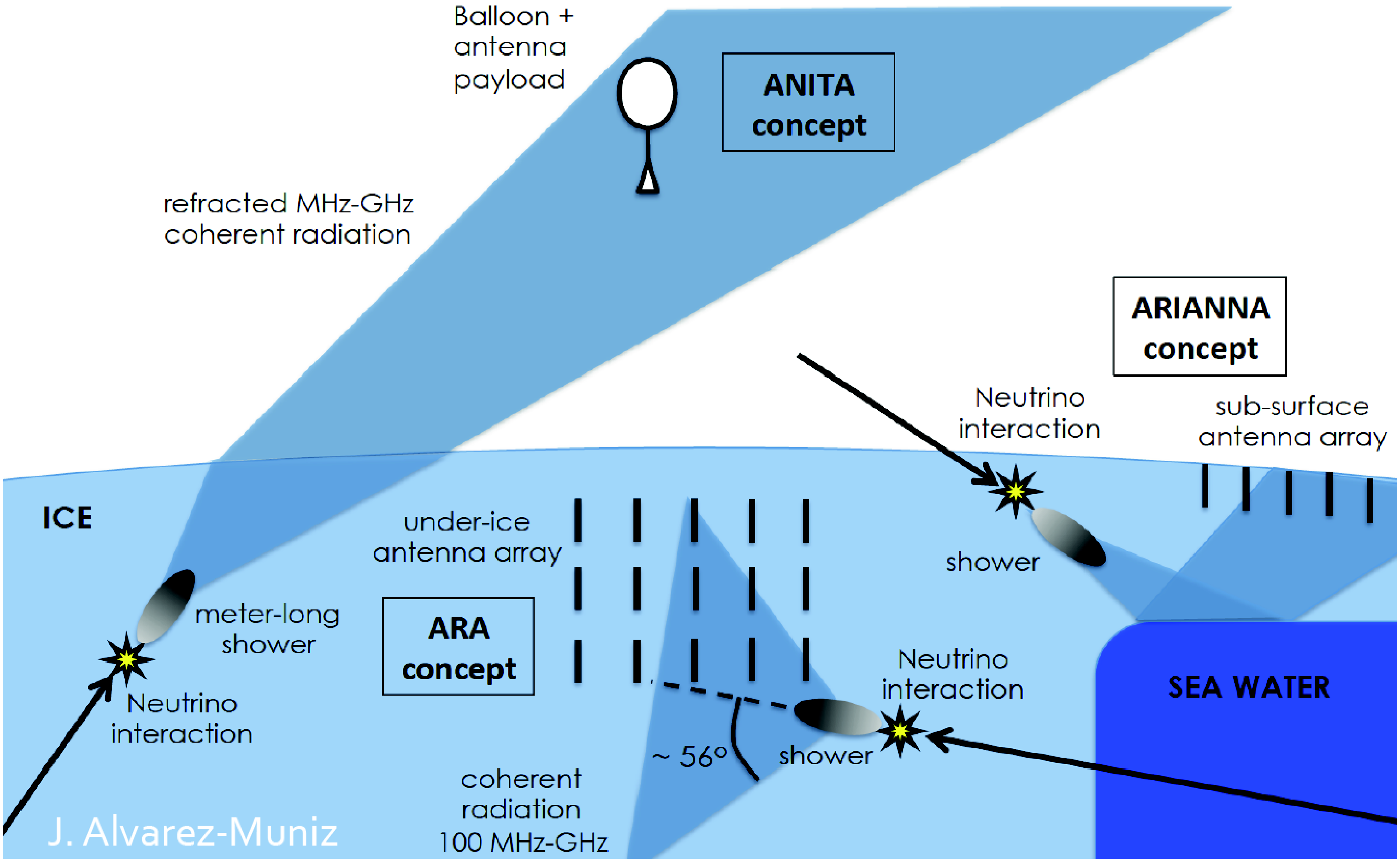
F. Halzen @ TeVPA2017



Science Motivation:

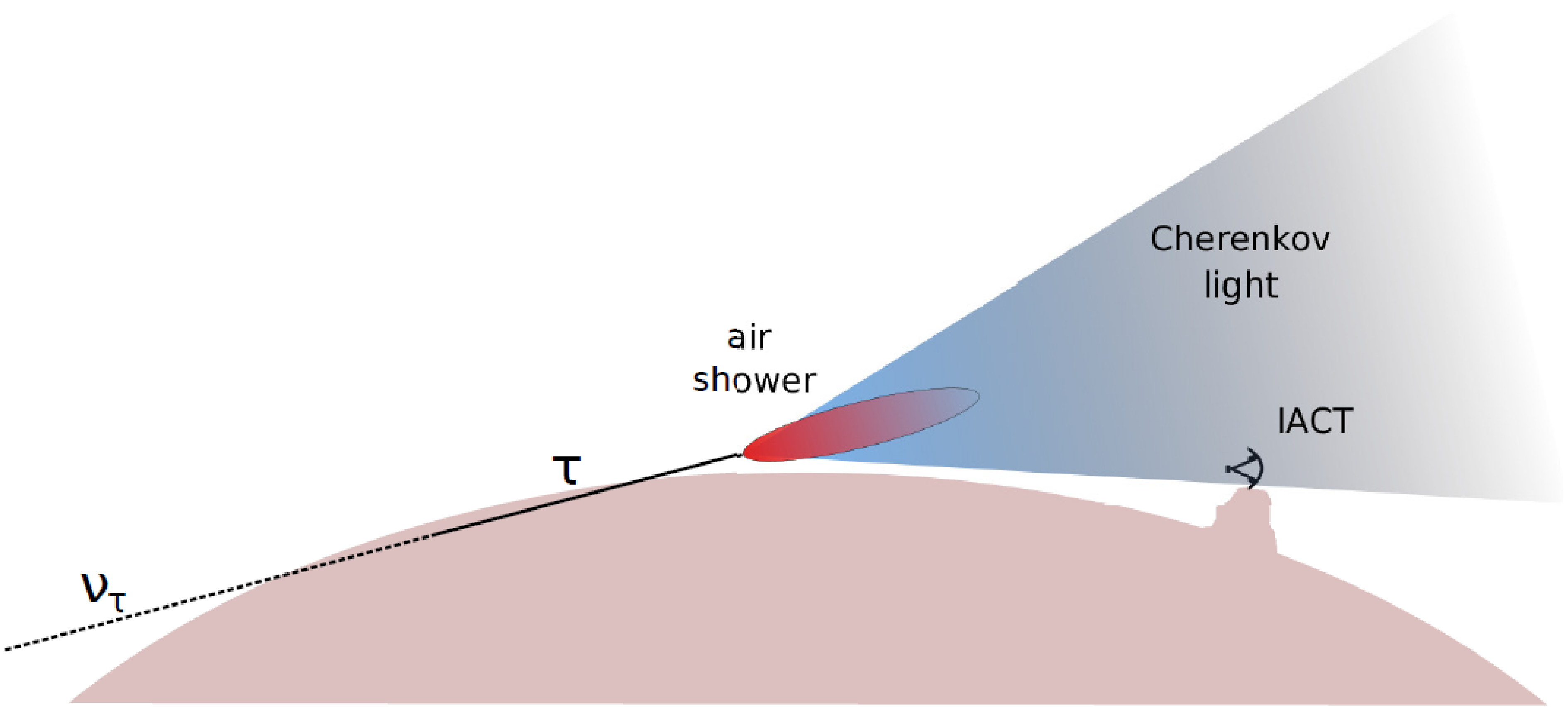
- What is the composition of UHECR?
- What are the sources of UHECR?
- Extension of IceCube detected ν flux to 10^9 GeV?
- Test of fundamental physics

Radio Techniques

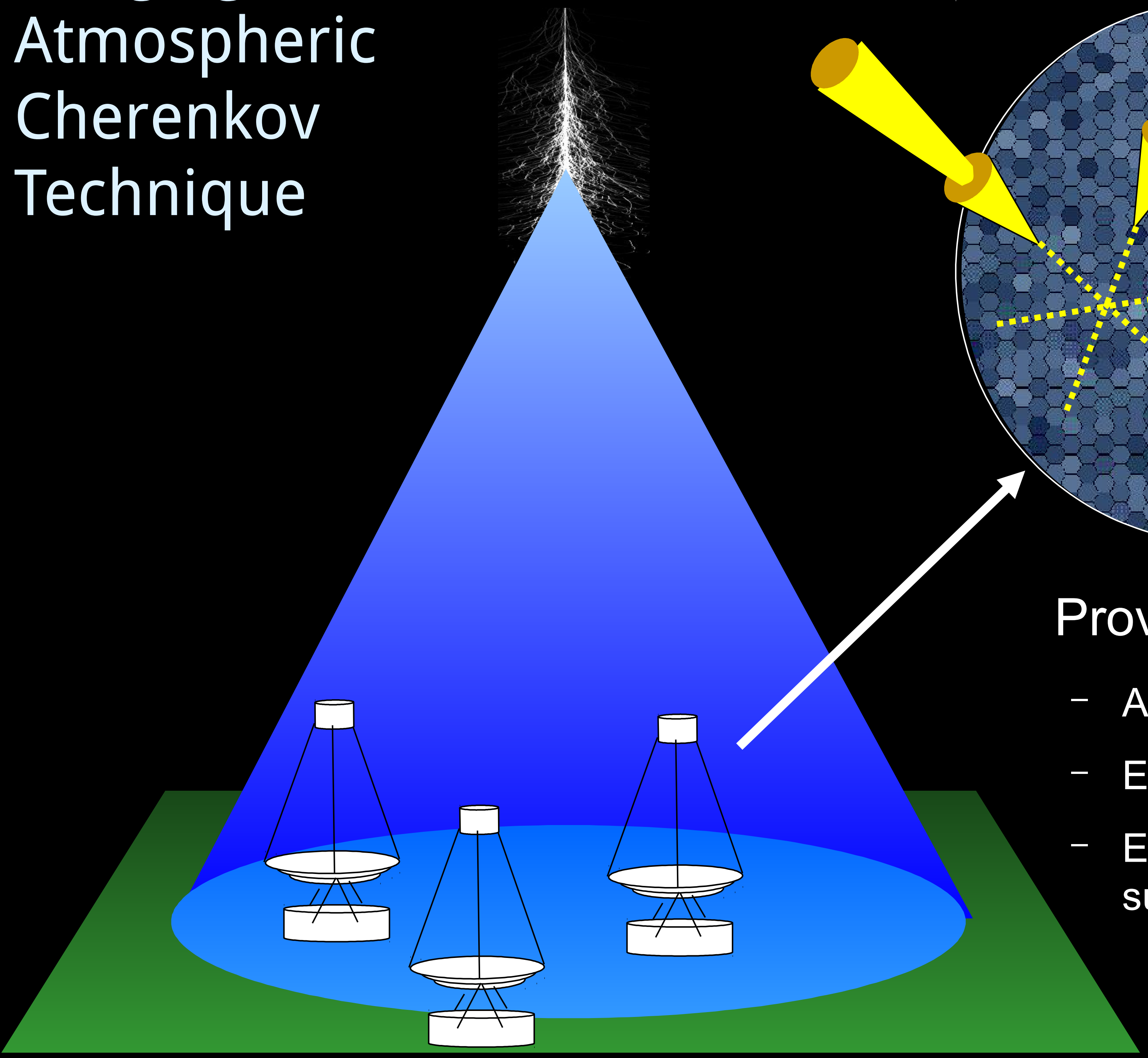


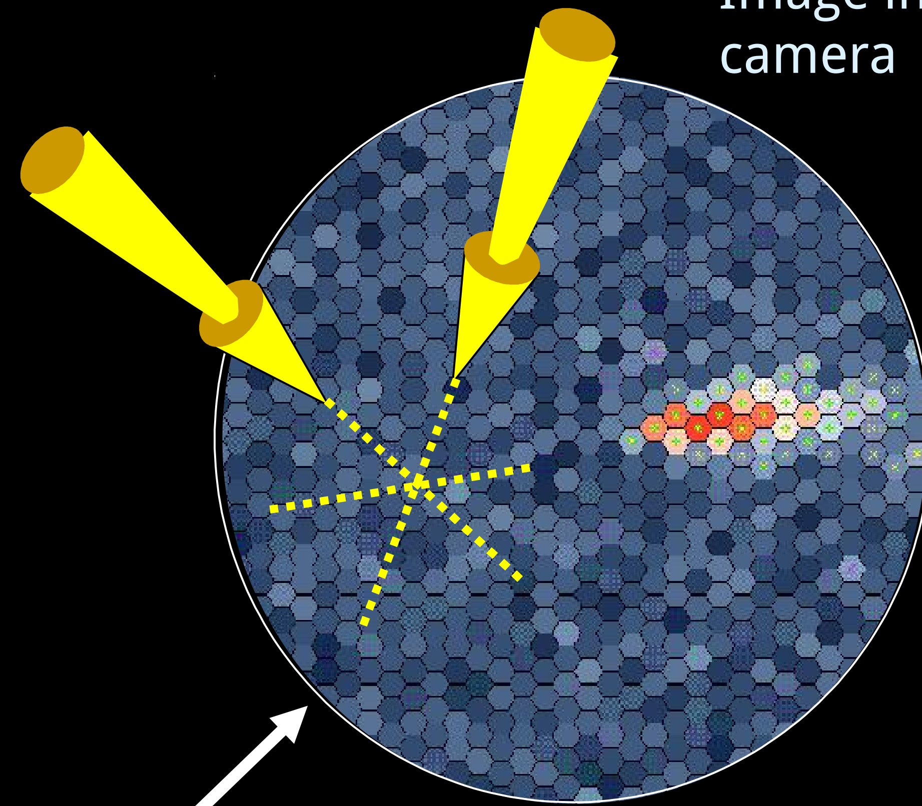

GRAND
The GRAND Project
- the Giant Array for Neutrino Detection
200,000 radio antennas over 200,000km²
Mountainous area near Ulastai, West China

Let there be Light!



Imaging Atmospheric Cherenkov Technique



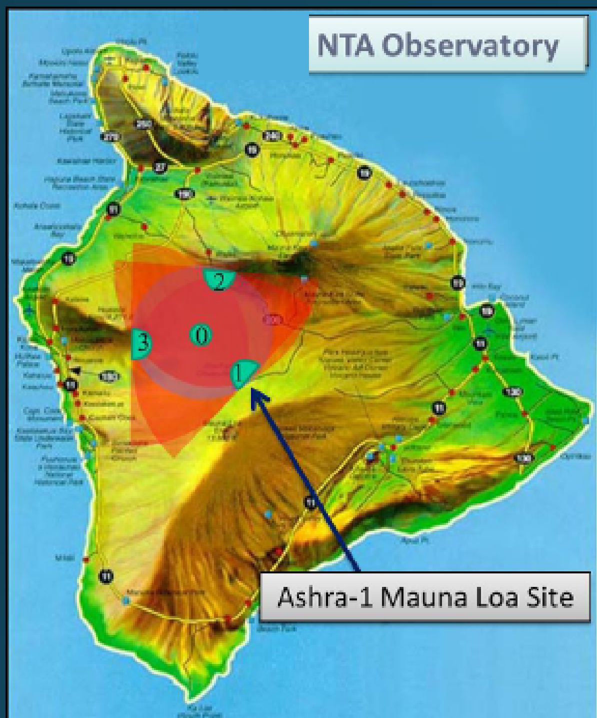


Proven Technique

- Angular resolution <0.1°
- Energy resolution 10%
- Excellent background suppression

NTA Baseline Design

Ashra-1 Light Collector



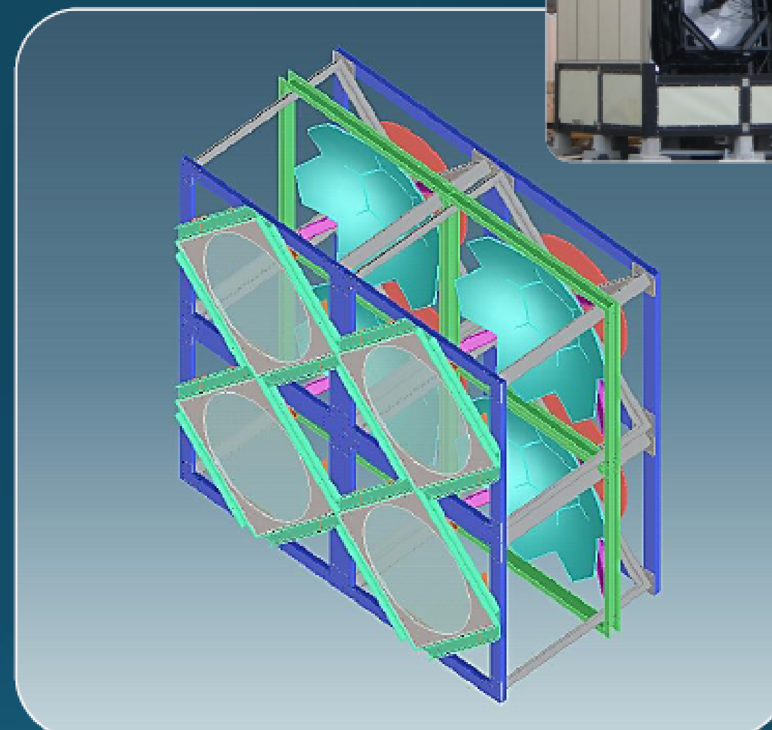


Table 1. Coordinates and FOV coverage of the Ashra NTA sites.

Site ID	Location	X [km]	Y [km]	Z [km]	FOV [sr]
Site0	Center	0.000	0.00	2.03	π
Site1	Mauna Loa	9.91	-10.47	3.29	$\pi/2$
Site2	Mauna Kea	4.12	13.82	1.70	$\pi/2$
Site3	Hualalai	-14.02	-3.35	1.54	$\pi/2$

⇒ Concept:
Ashra-1 x 1.5 scaled-up
+ same trigger & readout

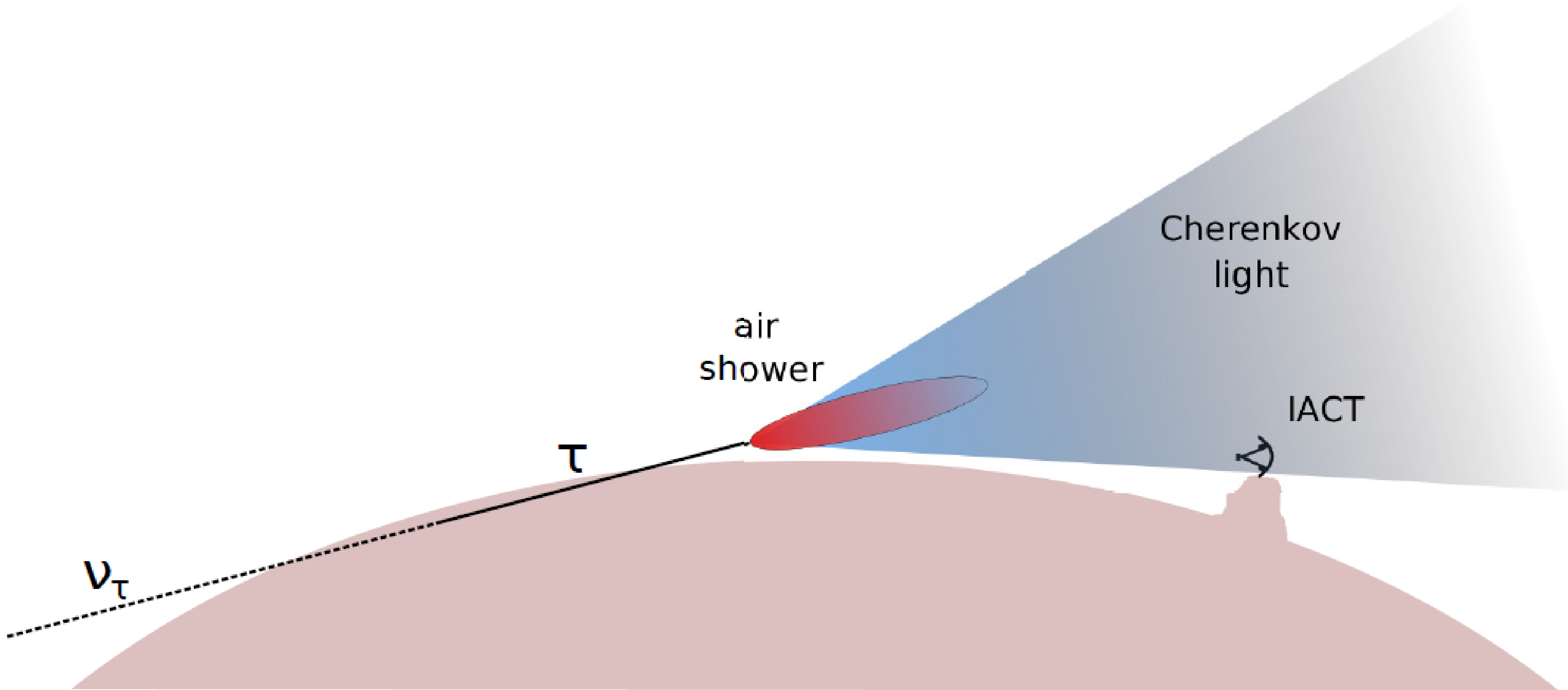
Light Collector (LC)
Optics with φ1.5m pupil
FOV 28° = focal sphere φ50cm

Detector Unit (DU)
4 LCs watching same FOV
Superimposed 4 images
⇒ **Effective pupil = φ3m**

12 DU's per π coverage

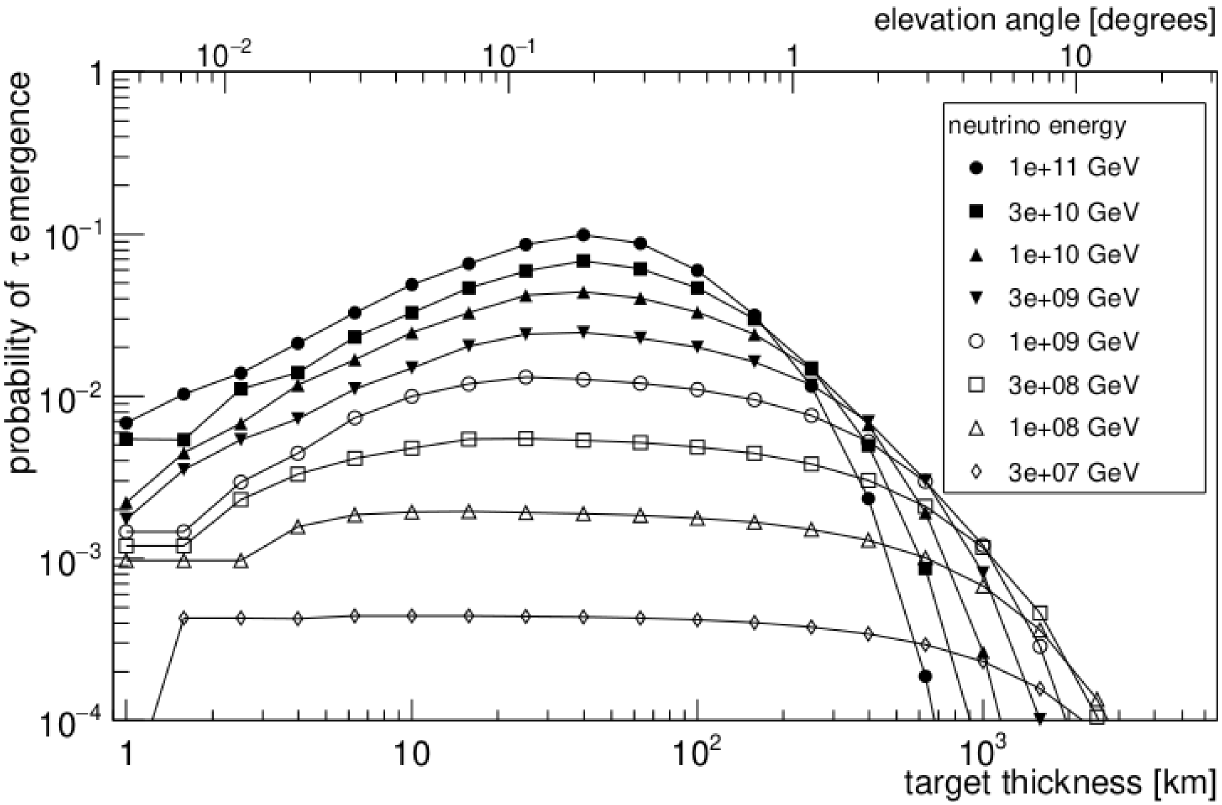
~1000km^2 stereo

Need at least 30 DU's for Coverage



- Detector on top of mountain and look into the distance
- Earth is approximated as a smooth sphere made of rock

Probability of τ Emergence



Probability if ν conversion and emergence of τ from ground

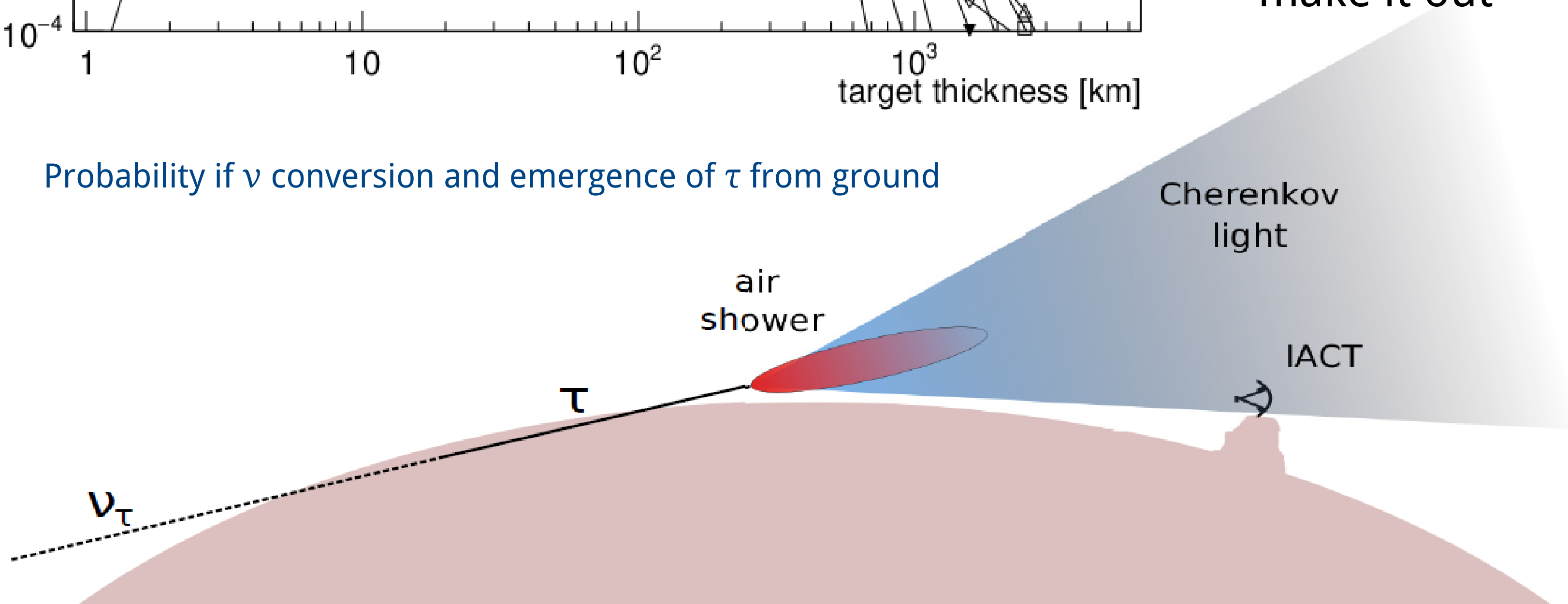
Target material:
Rock with ρ = 2.65 g/cm³

Works best for:

- **>10⁸ GeV**
- ~50 km target

Limiting factors:

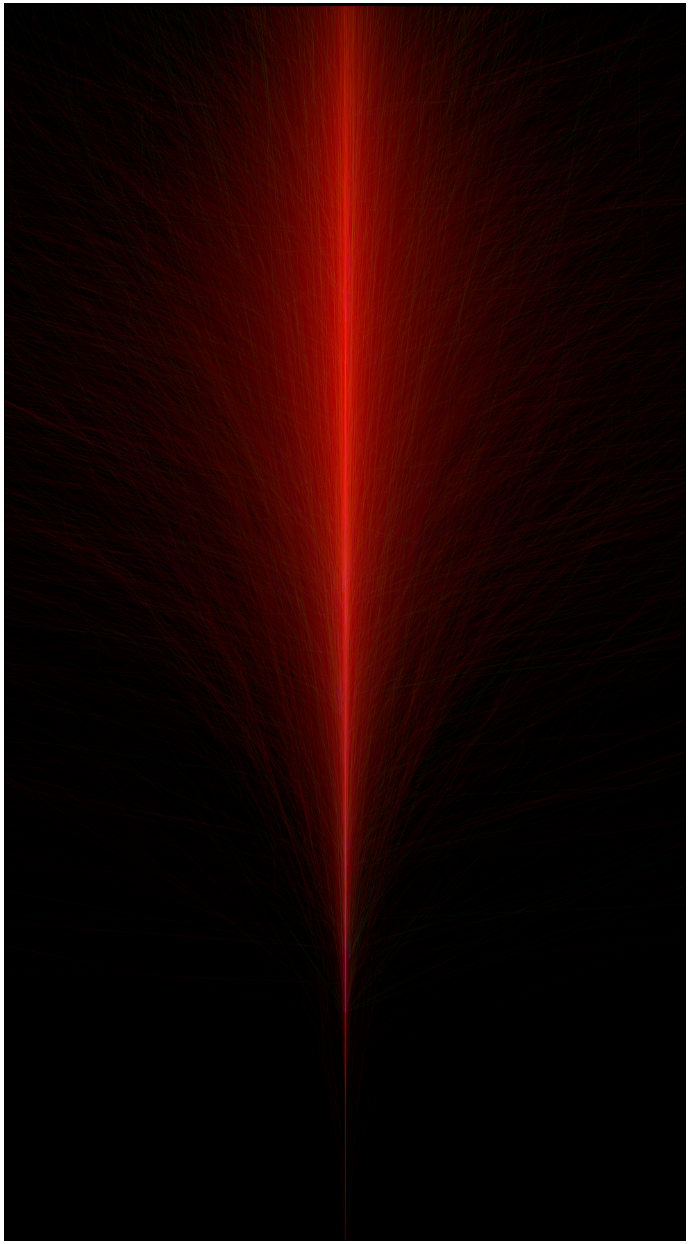
- Target to thin: ν does not convert
- Target to thick: τ does not make it out



Tau Shower Fun Facts

- Tau emergence angle is ~1°
- Tau decay length 49 km x $E_{tau}/10^9$ GeV
- Tau decay modes
  - 18% electron + neutrinos
  - 65% hadronic (pions + neutrinos)
  - 17% muon + neutrinos → no shower

  → **A shower develops in 80% of decays**
- Assume 50% of tau energy go into shower
- 10^7-10^{10} GeV shower develops in ~30 radiation length → ~10km



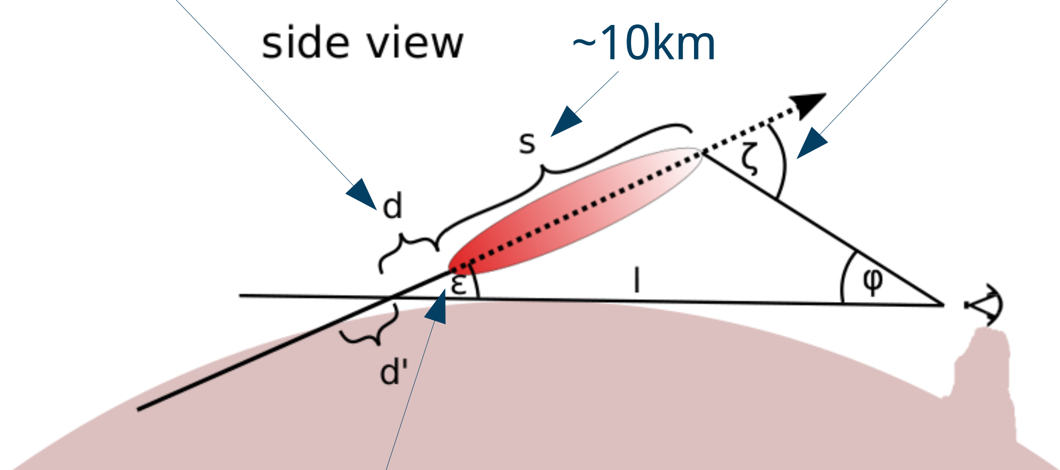
100 TeV tau shower

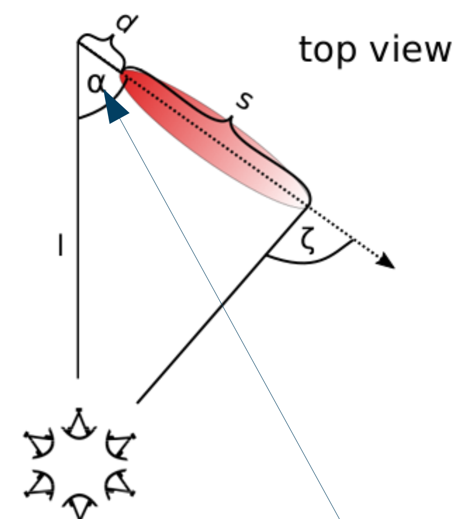
It is all about Geometry!

Maximum decay length set by requirement of image containment in camera

Enough light needs to reach the telescope

~10km





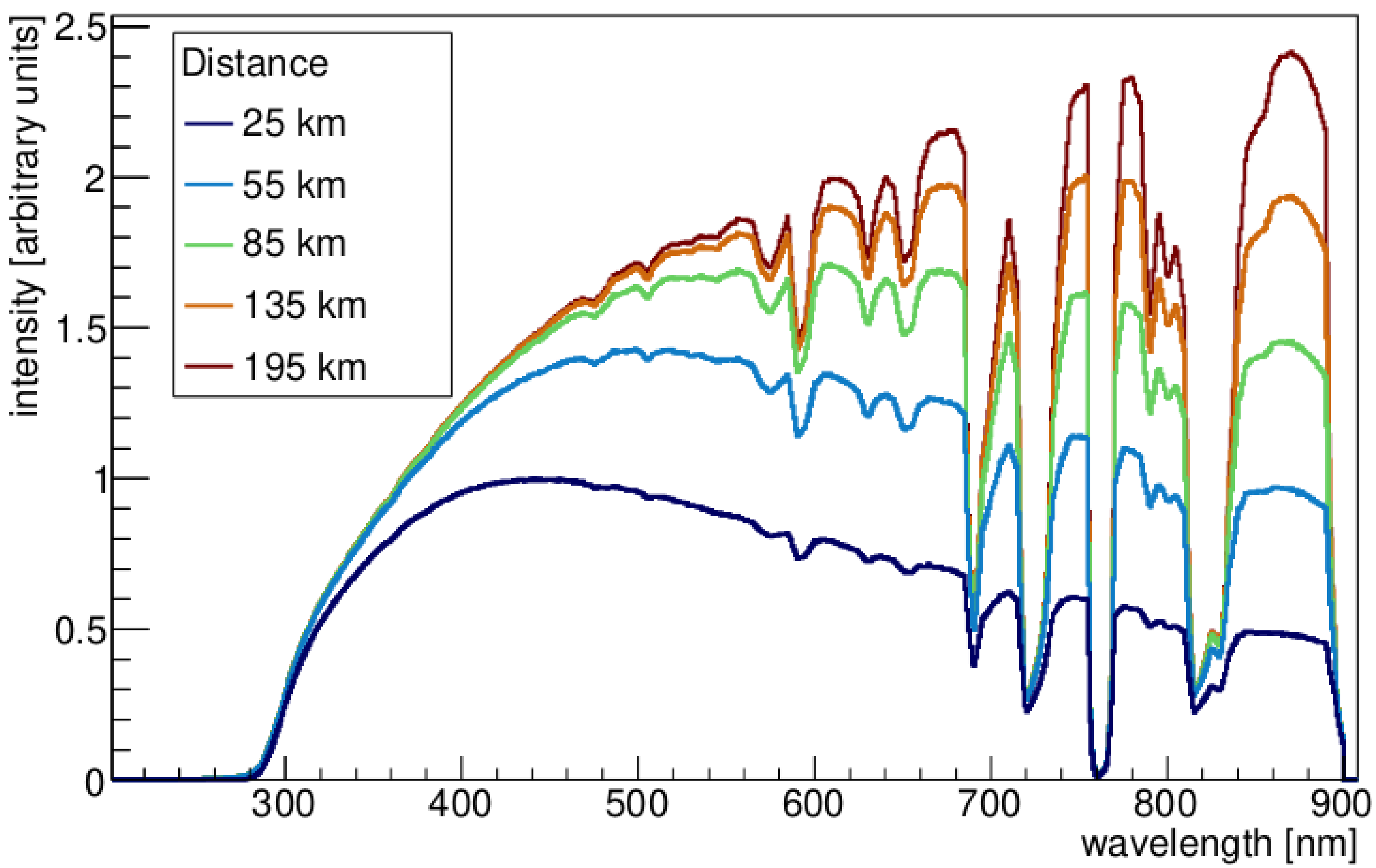
Elevation fixed by neutrino interaction cross section; ~1°

Azimuth angle ~viewing angle

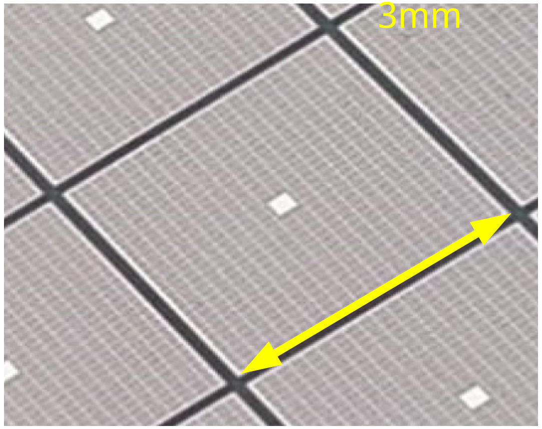
Atmospheric Absorption

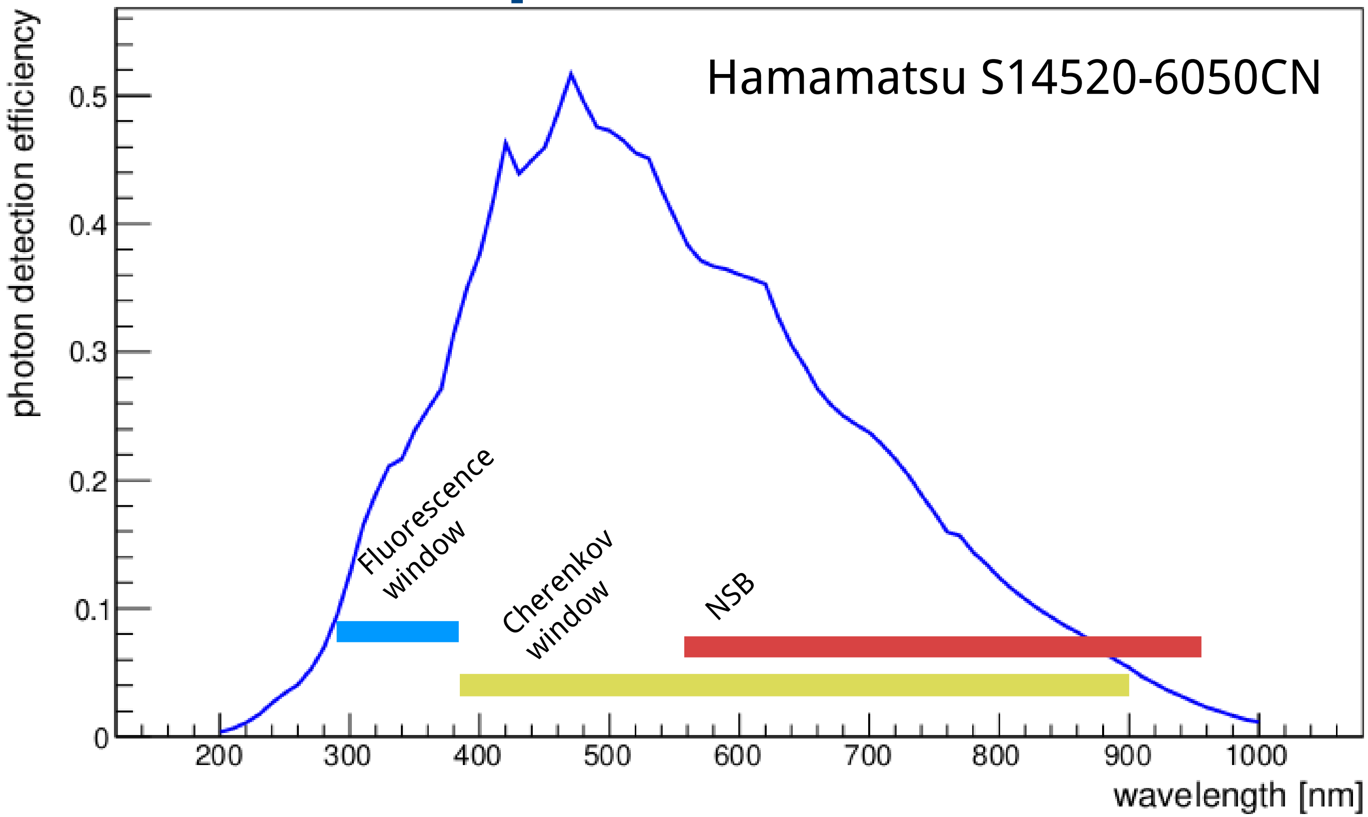
Cherenkov Spectrum after Absorption

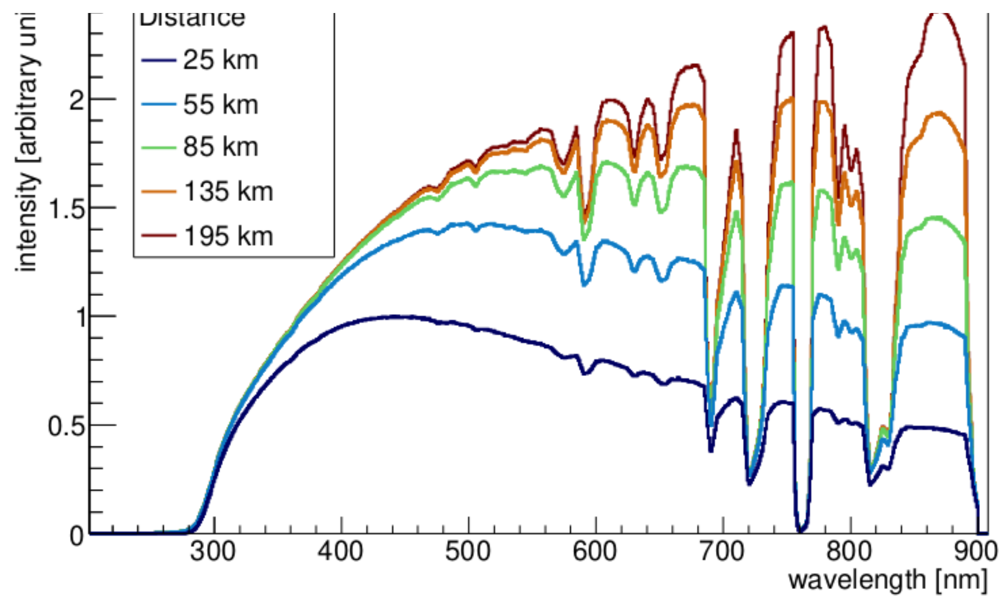
Shift of spectral peak
for larger distances



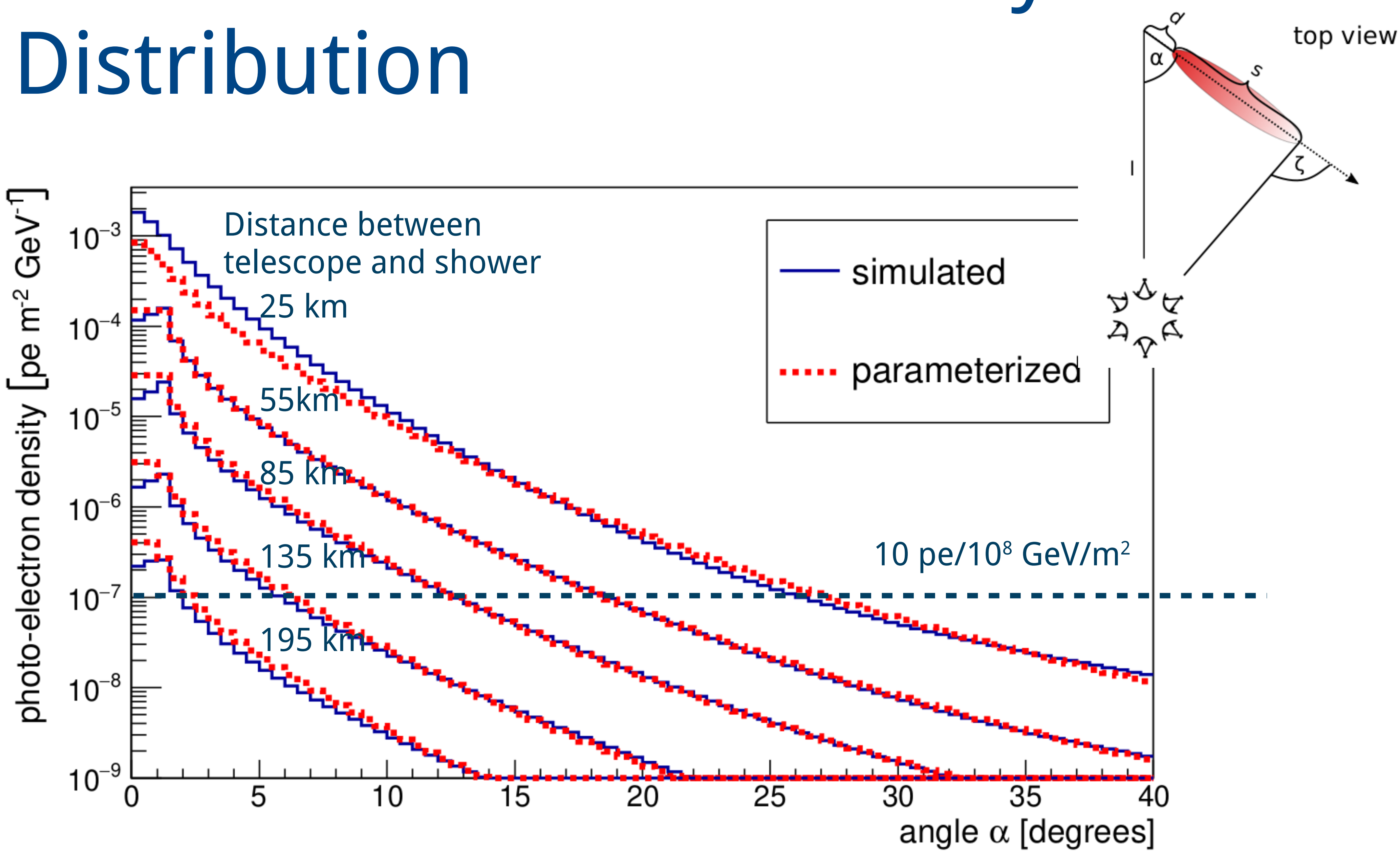
Silicon Photomultipliers





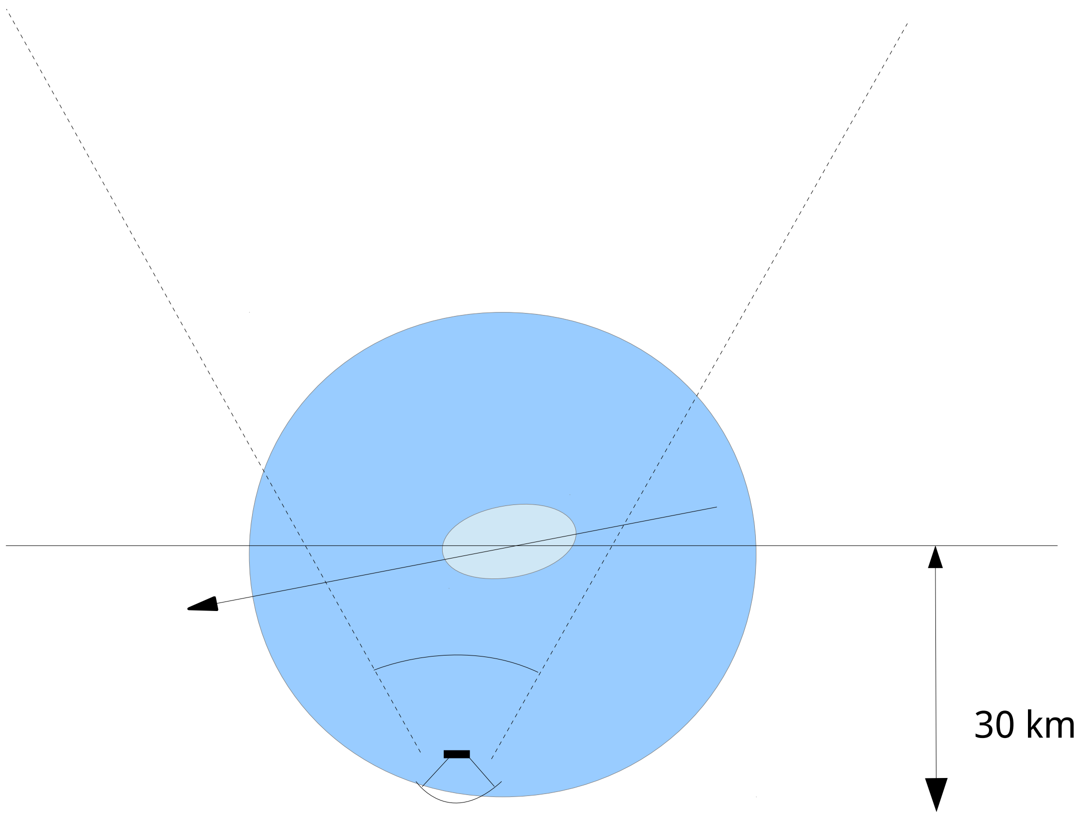


Radial Cherenkov Intensity Distribution



Telescope 1 km above ground, shower elevation 1°

The Top View: Fluorescence



Isotropic emission

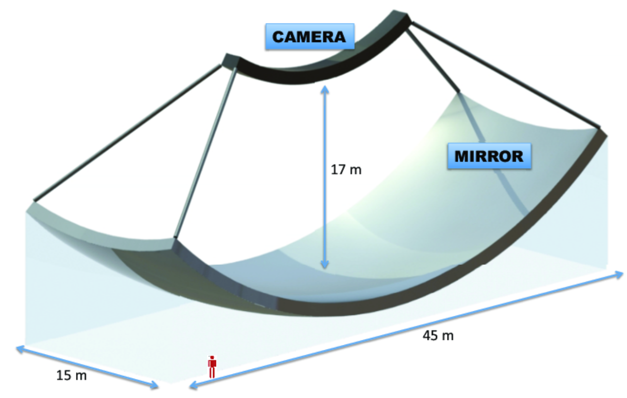
Emission band: 300 nm – 400 nm

Yield: 6000 photo electrons / GeV

Attenuation length: 9.5 km

For 10^8 GeV τ:
~3 photoelectrons per m^2
in 30 km distance

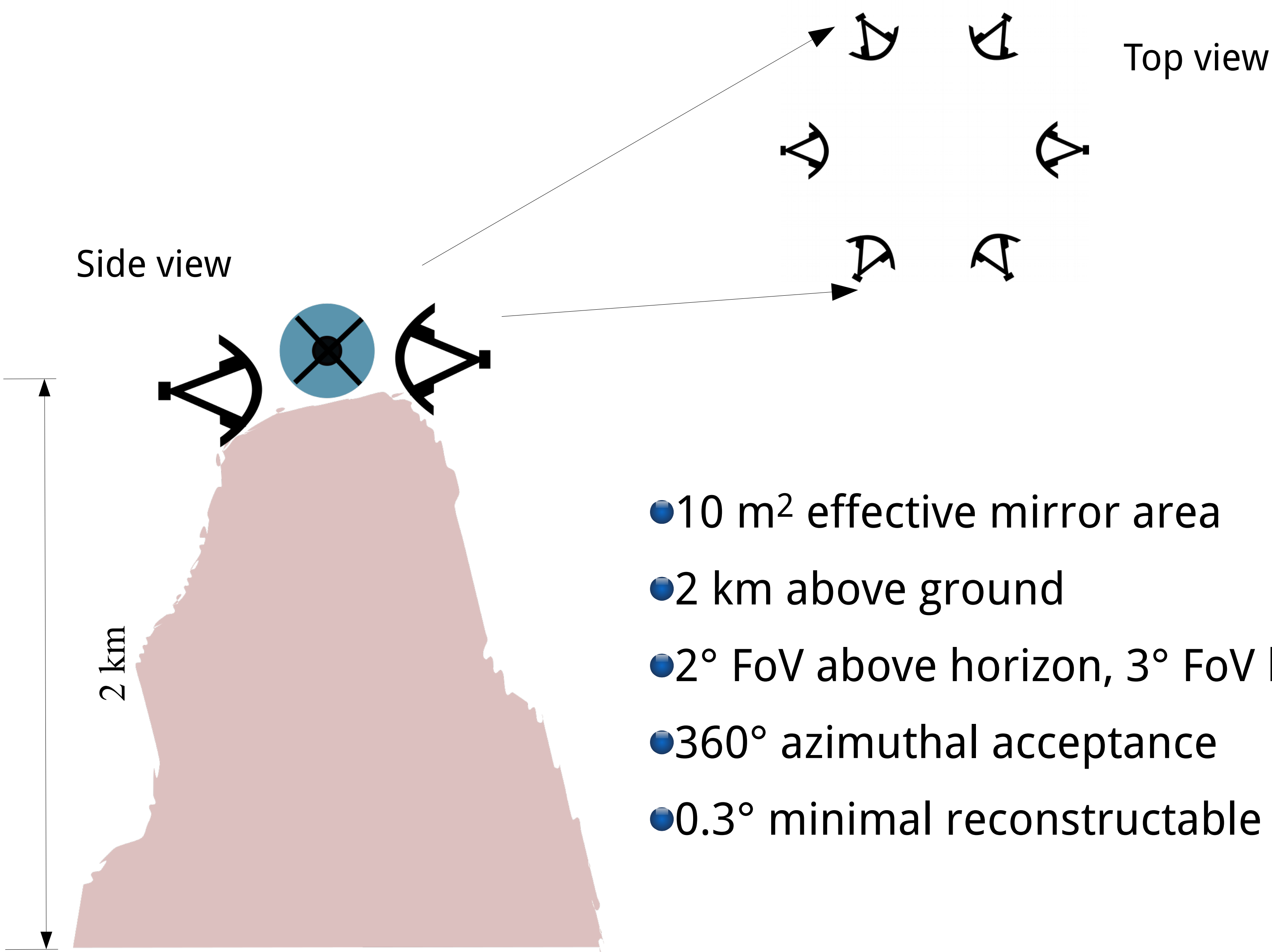
Trigger Threshold



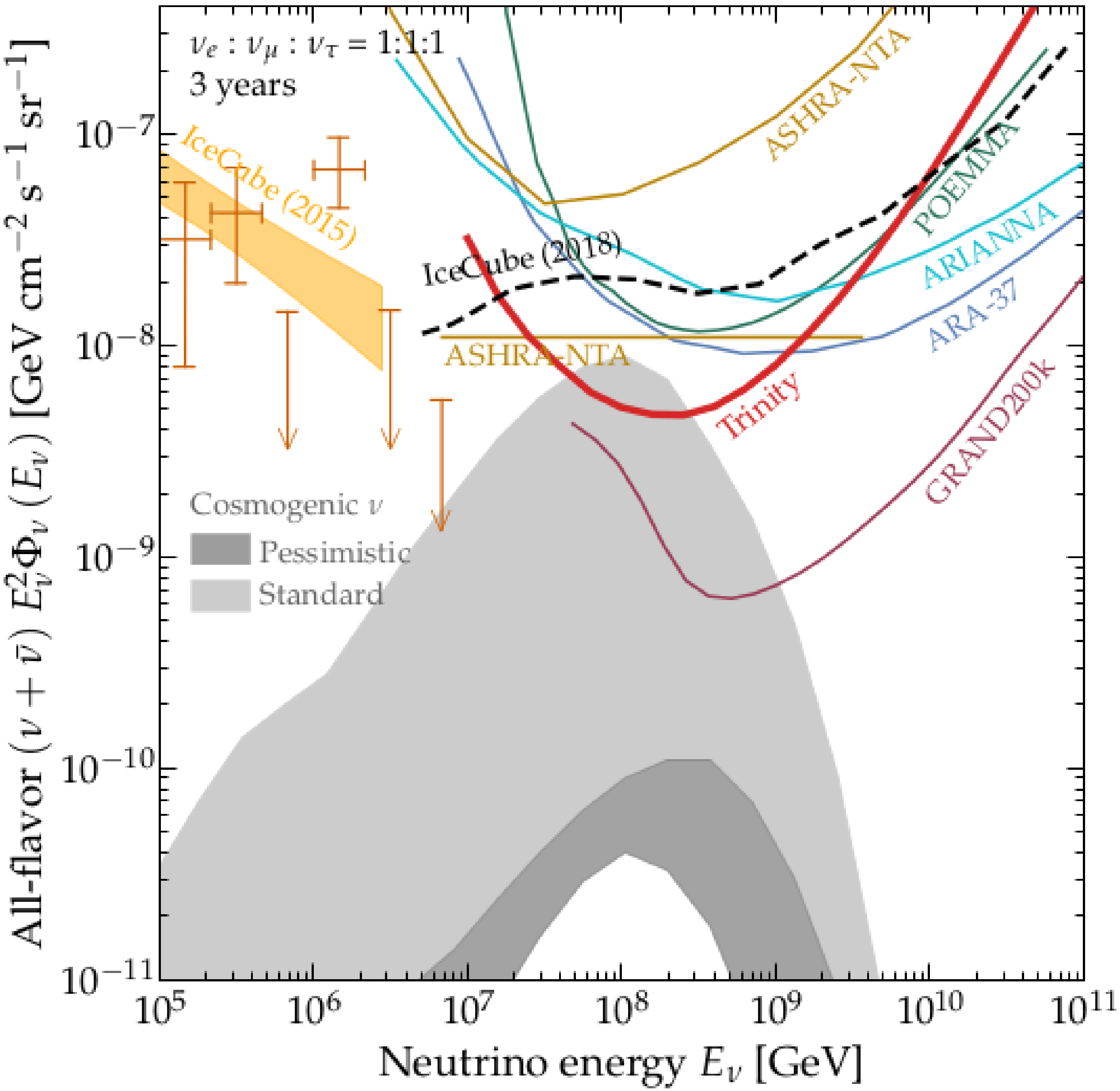
- Detected Night Sky Background:
  $3.7 \cdot 10^6$ counts/s/mm^2/sr
- Assume MACHETE Optics
  - 5° x 60° field of view
  - 0.3° pixel size
- 10 ns coincidence window
- Two neighbor coincidence for telescope trigger
- 1Hz accidental trigger rate

Thresholds of 10 pe, 22 pe, 24 pe, and 155 pe,
for 1m^2, 5m^2, 10m^2, and 100 m^2 effective mirror area

Trinity: Baseline Configuration

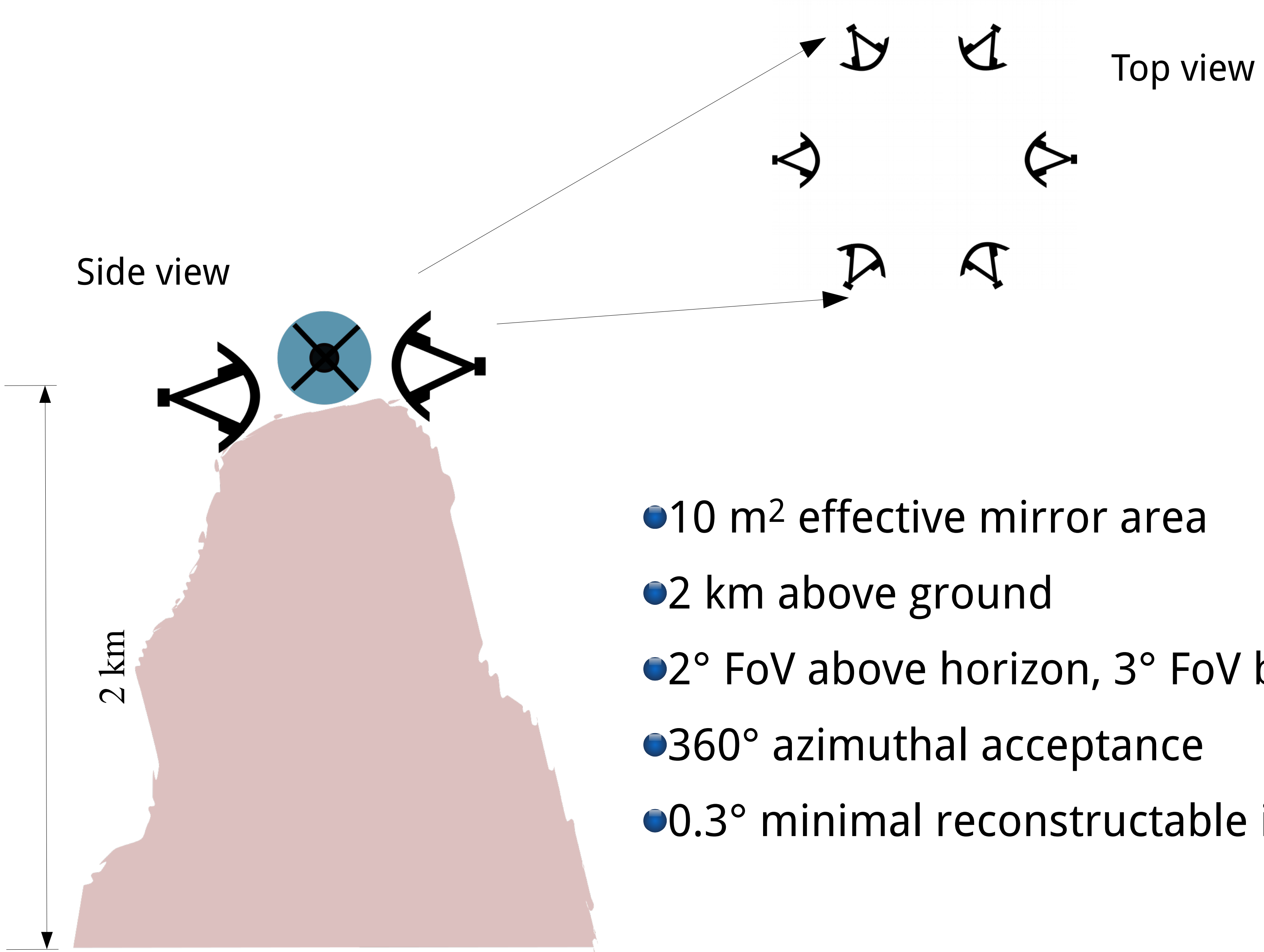


- 10 m² effective mirror area
- 2 km above ground
- 2° FoV above horizon, 3° FoV below horizon
- 360° azimuthal acceptance
- 0.3° minimal reconstructable image length



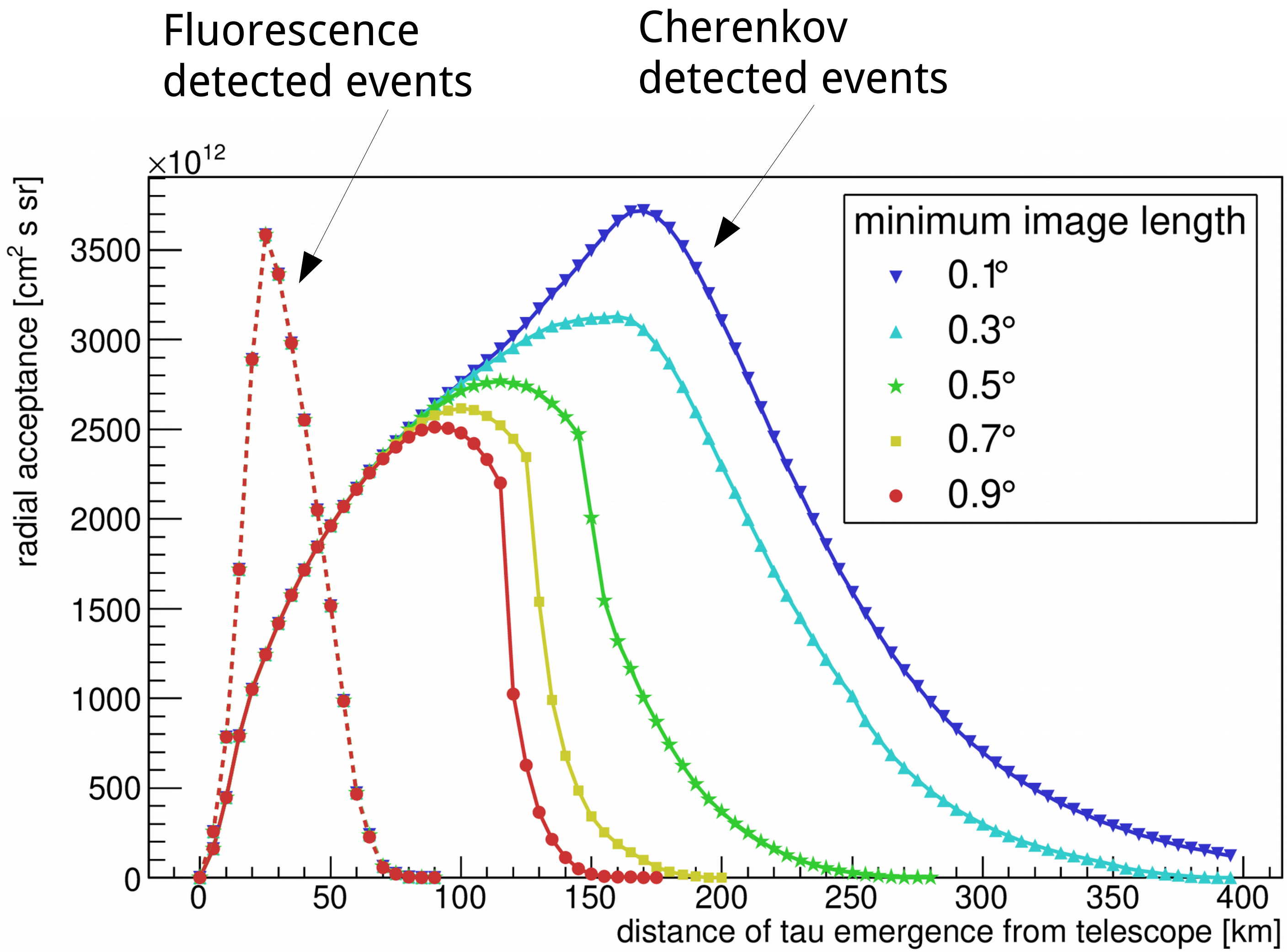
- Sensitivity given per decade of energy
- All neutrino flavor flux sensitivity
- 3 years of observation with 20% duty cycle
- 1 detected tau neutrino
- Background free assumption

Trinity: Baseline Configuration

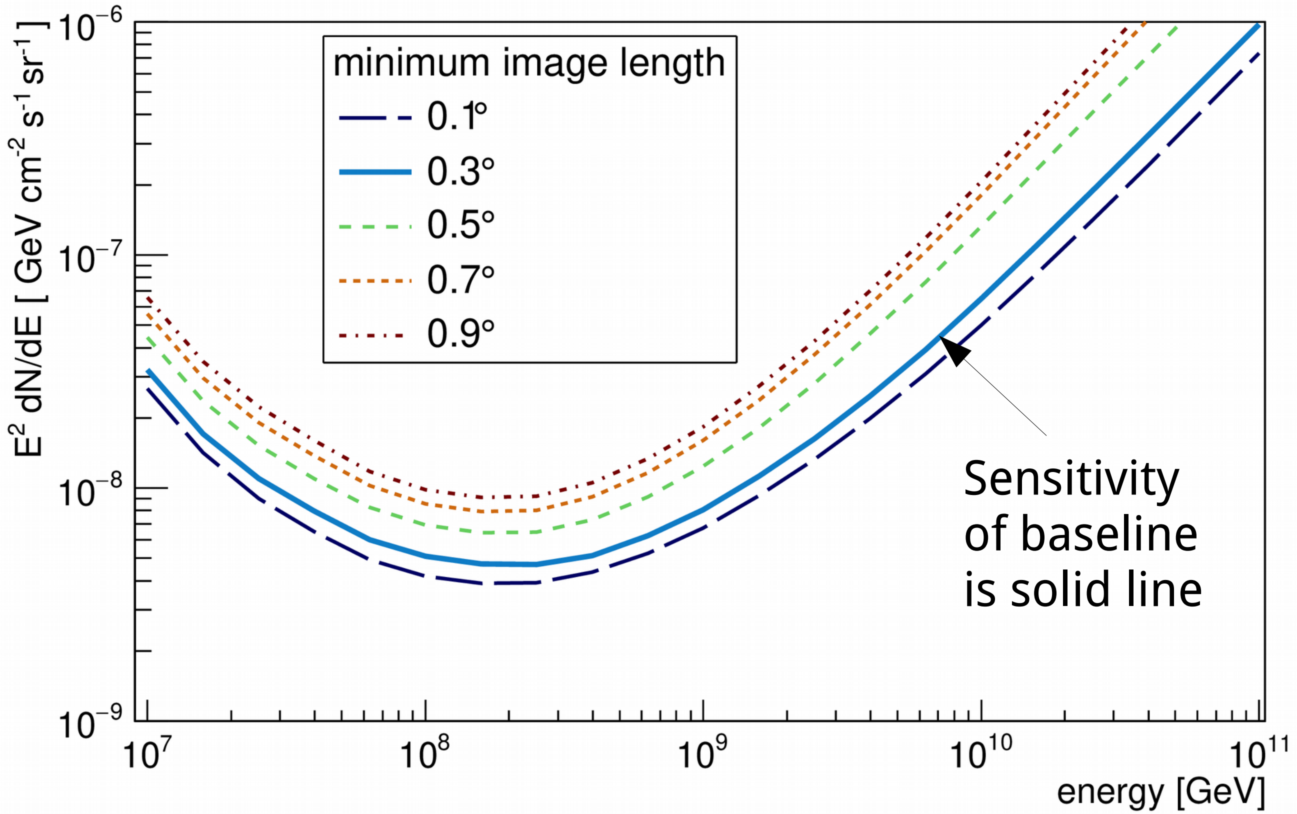


- 10 m^2 effective mirror area
- 2 km above ground
- 2° FoV above horizon, 3° FoV below horizon
- 360° azimuthal acceptance
- 0.3° minimal reconstructable image length

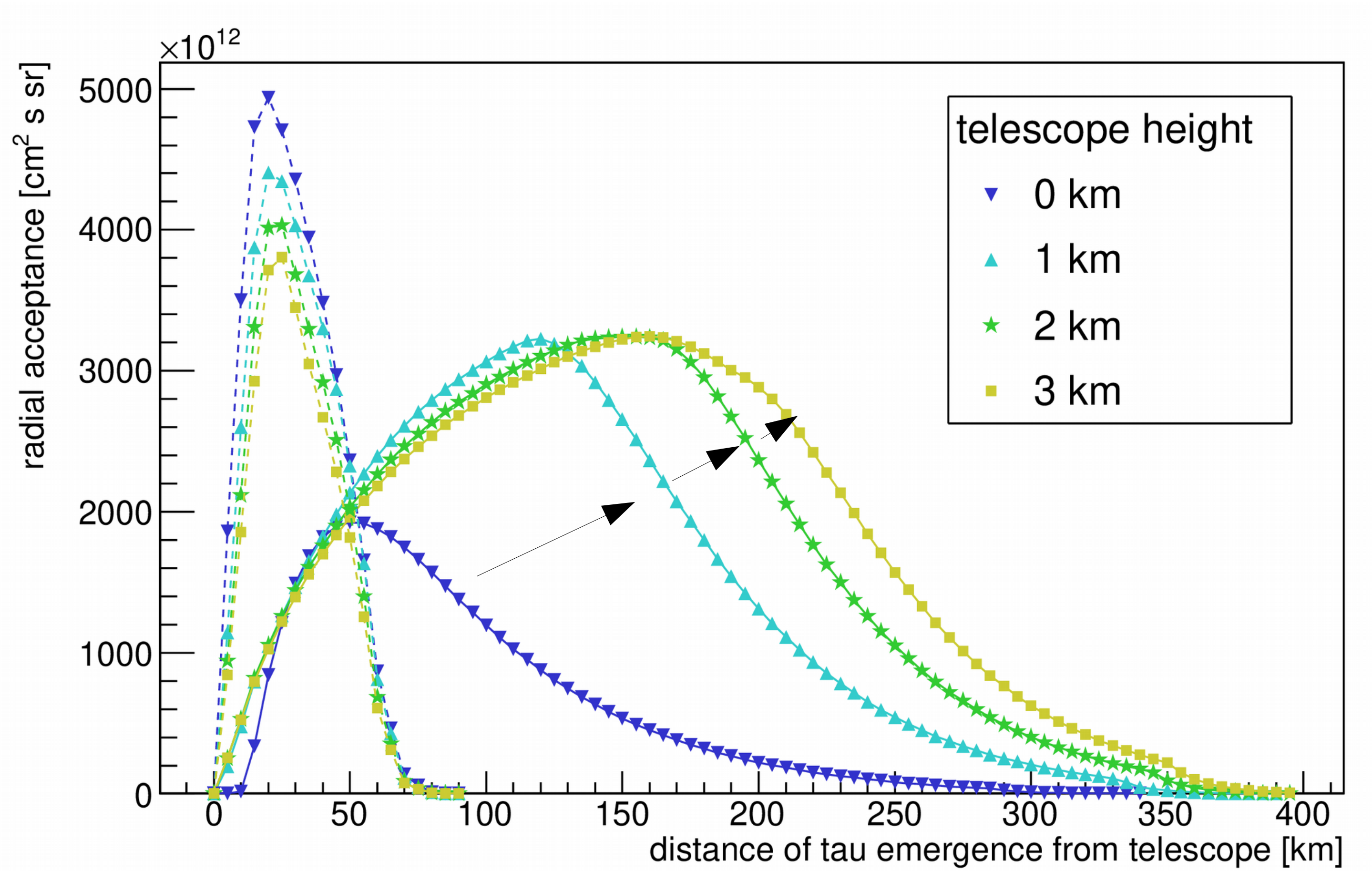
Minimum Reconstructable Image Length



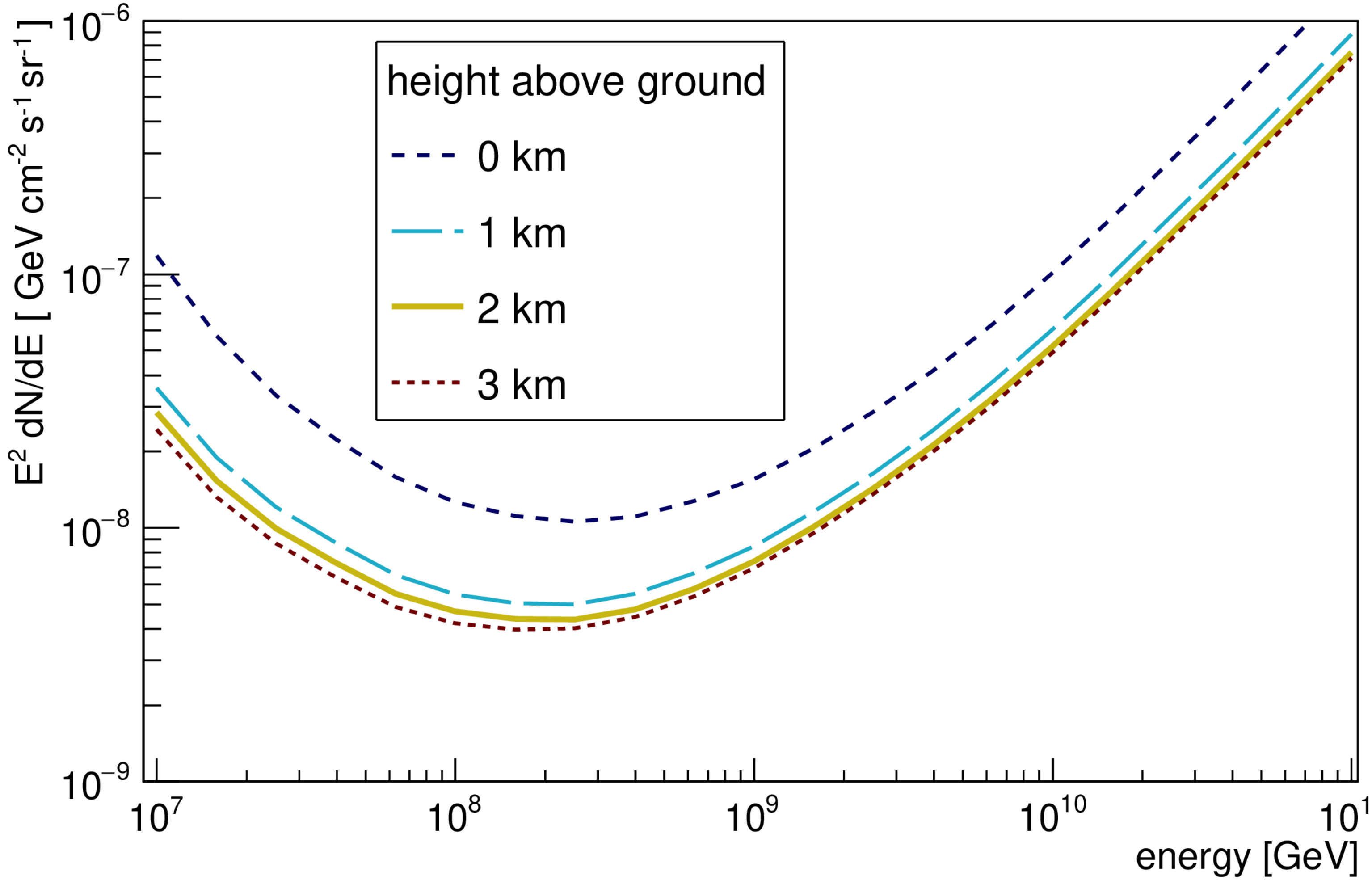
10^9 GeV neutrinos


minimum image length
0.1°
0.3°
0.5°
0.7°
0.9°
E^2 dN/dE [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}
energy [GeV]
Sensitivity
of baseline
is solid line

Telescope Location above Ground



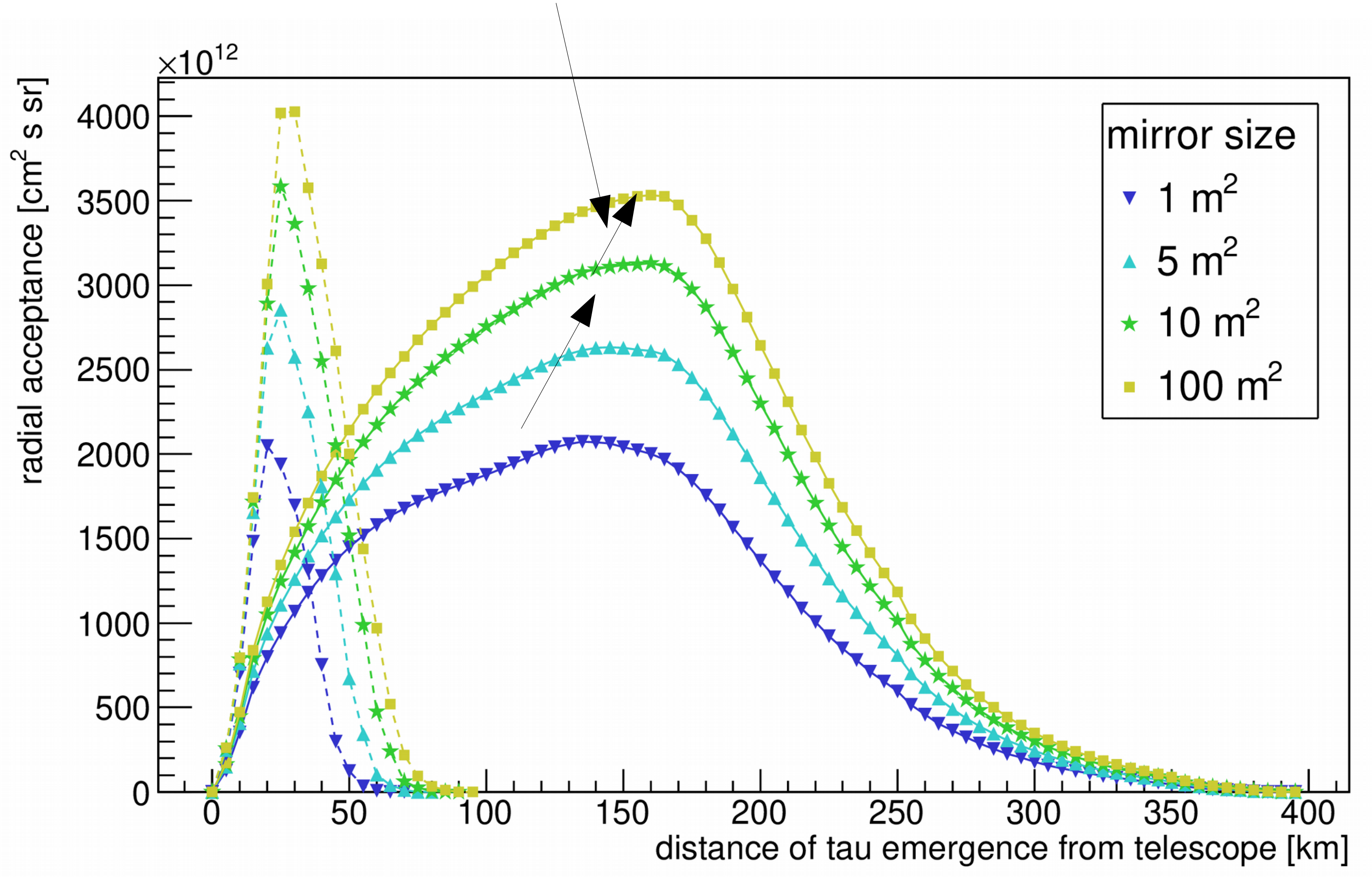
Can see more distant showers if higher above ground

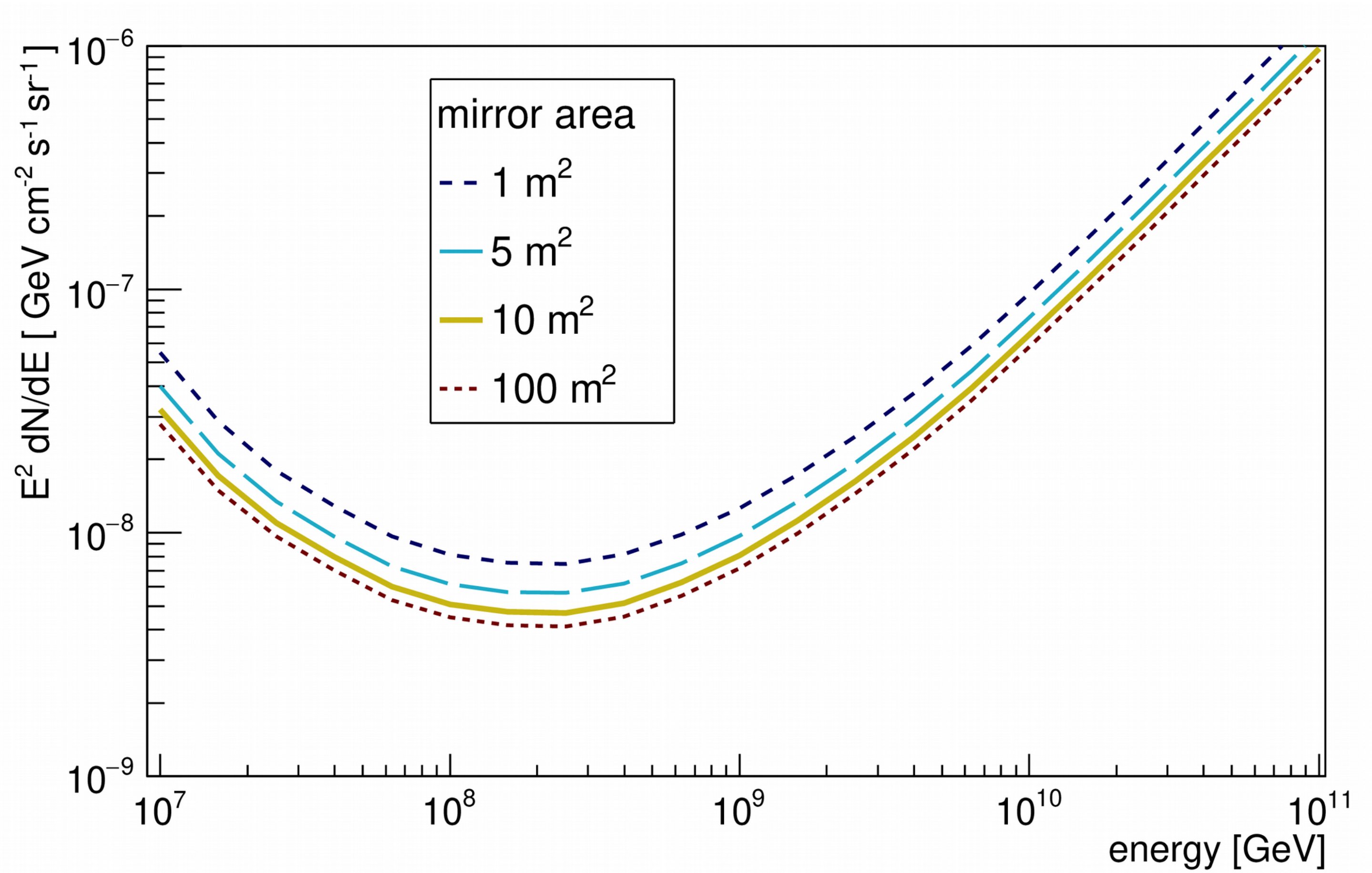


Not much sensitivity gain if higher than 1 km above ground

Mirror Size

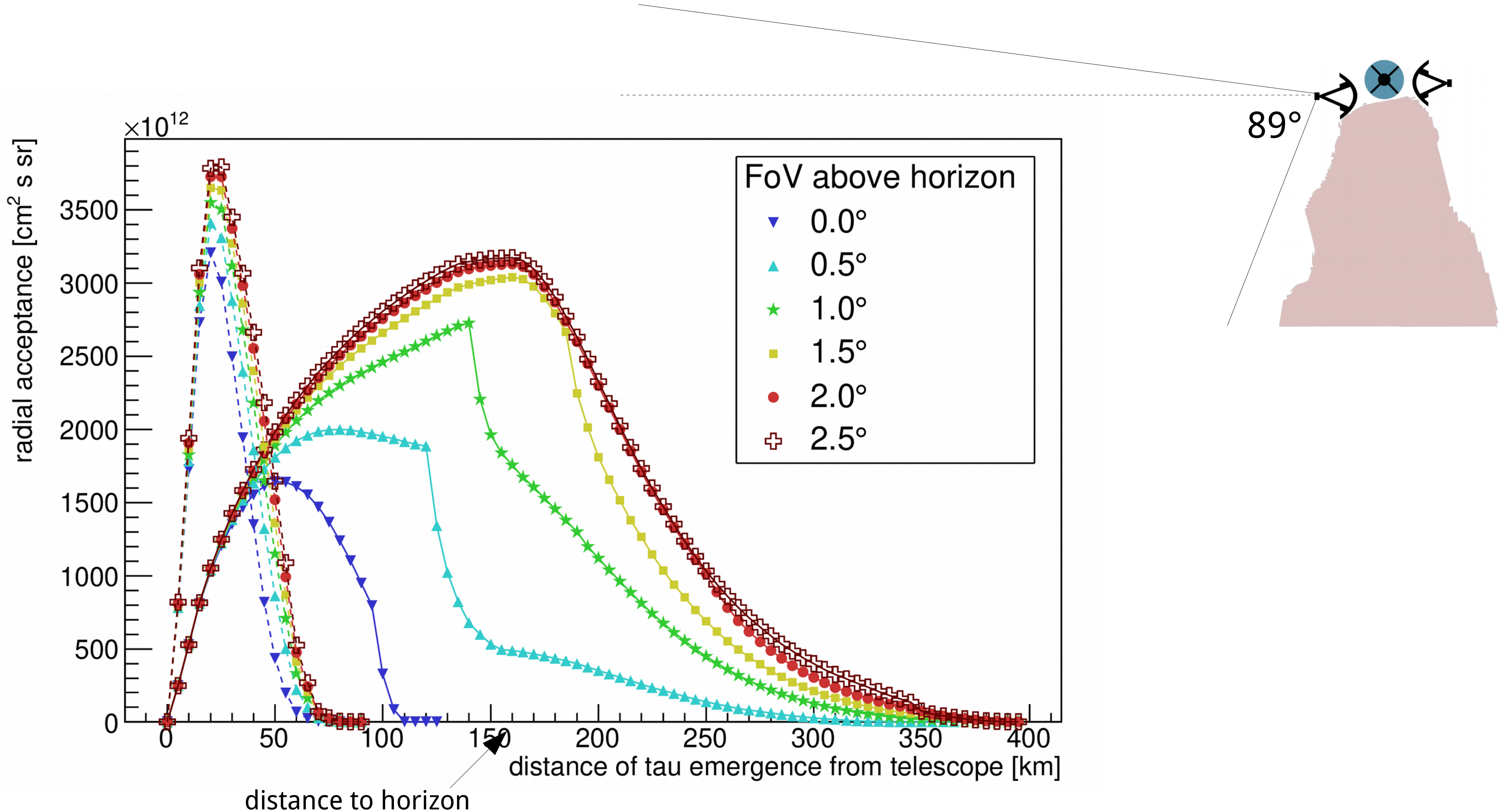
$10m^2$ to $100m^2$ mirror area, only 13% more acceptance



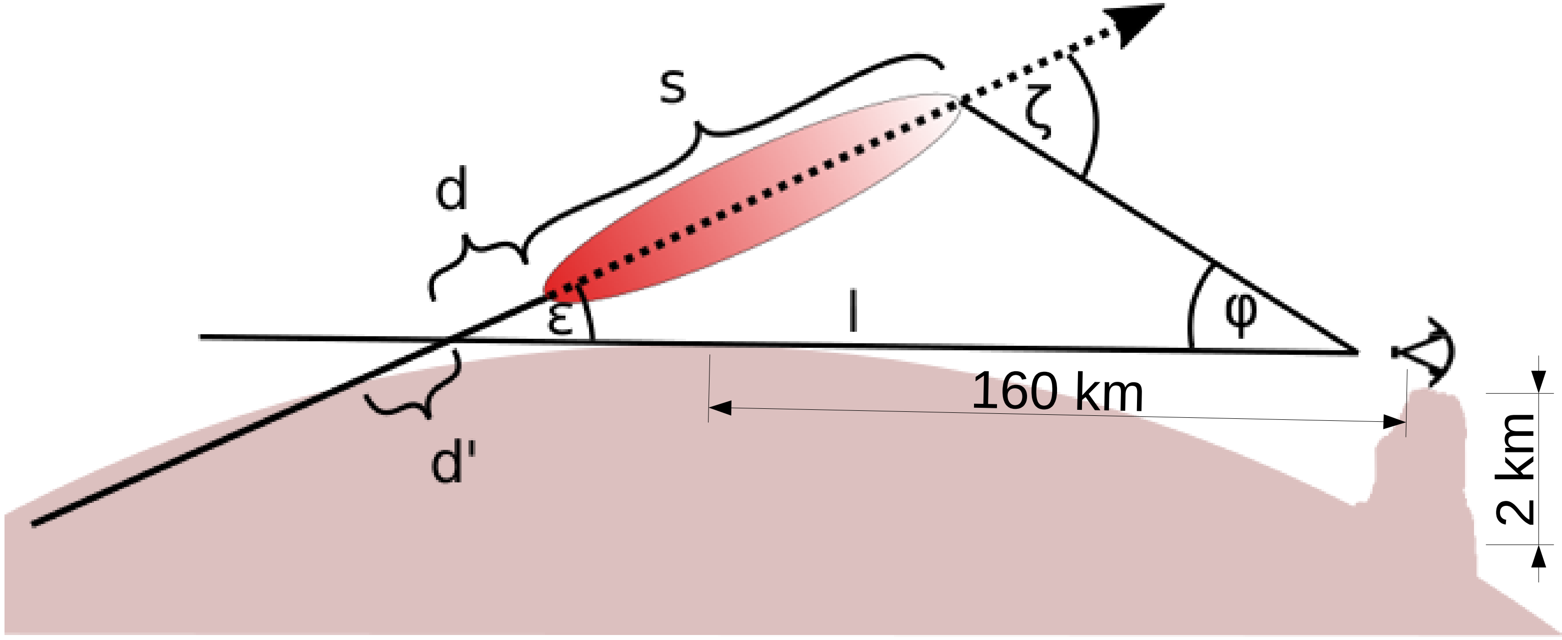


mirror area
1 m2
5 m2
10 m2
100 m2
E2 dN/dE [GeV cm-2 s-1 sr-1]
10−6
10−7
10−8
10−9
107
108
109
1010
1011
energy [GeV]

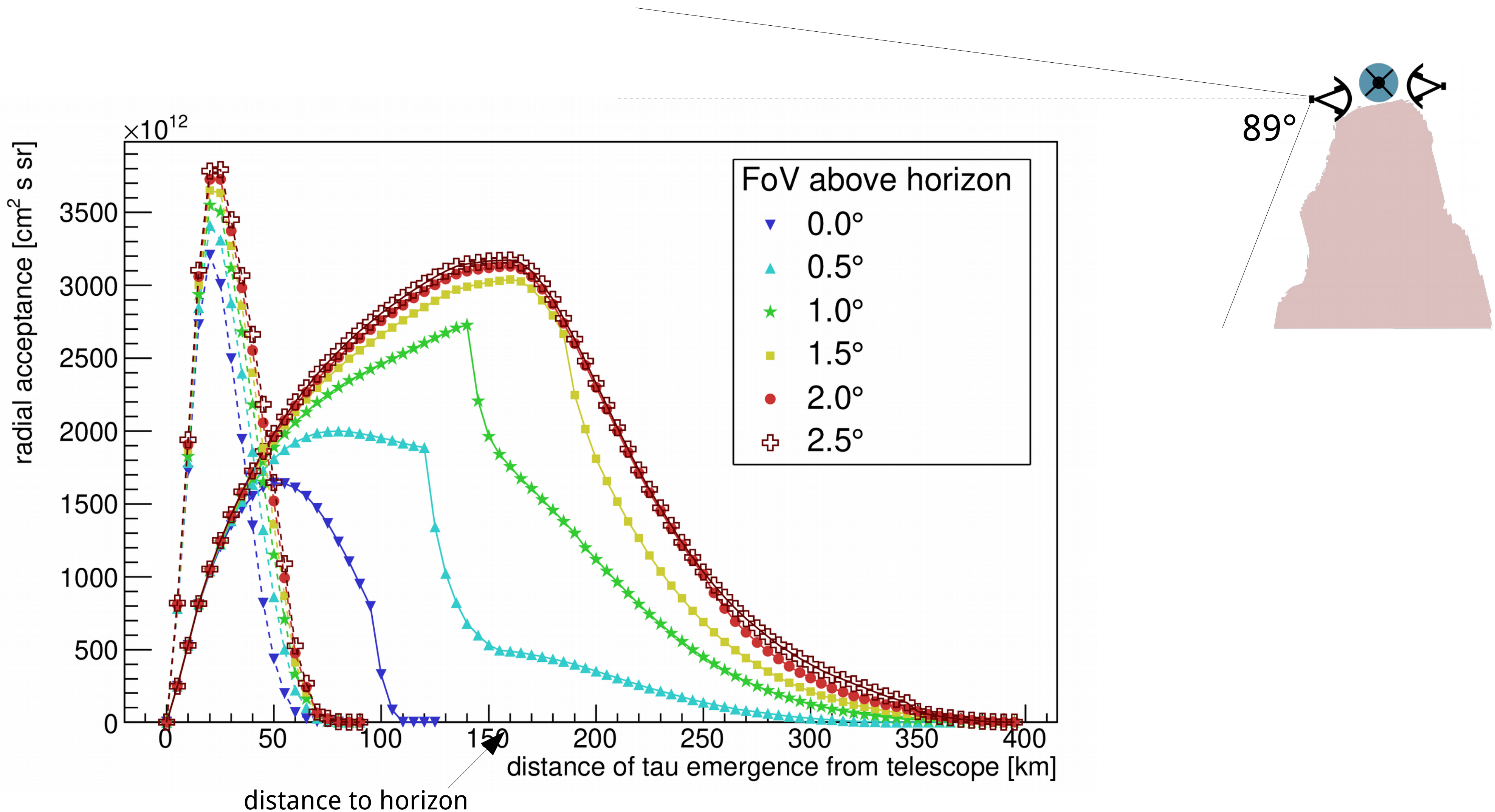
Field of View Above Horizon



Acceptance maximal for 2° field of view above horizon.
Biggest impact on detection of distant showers.

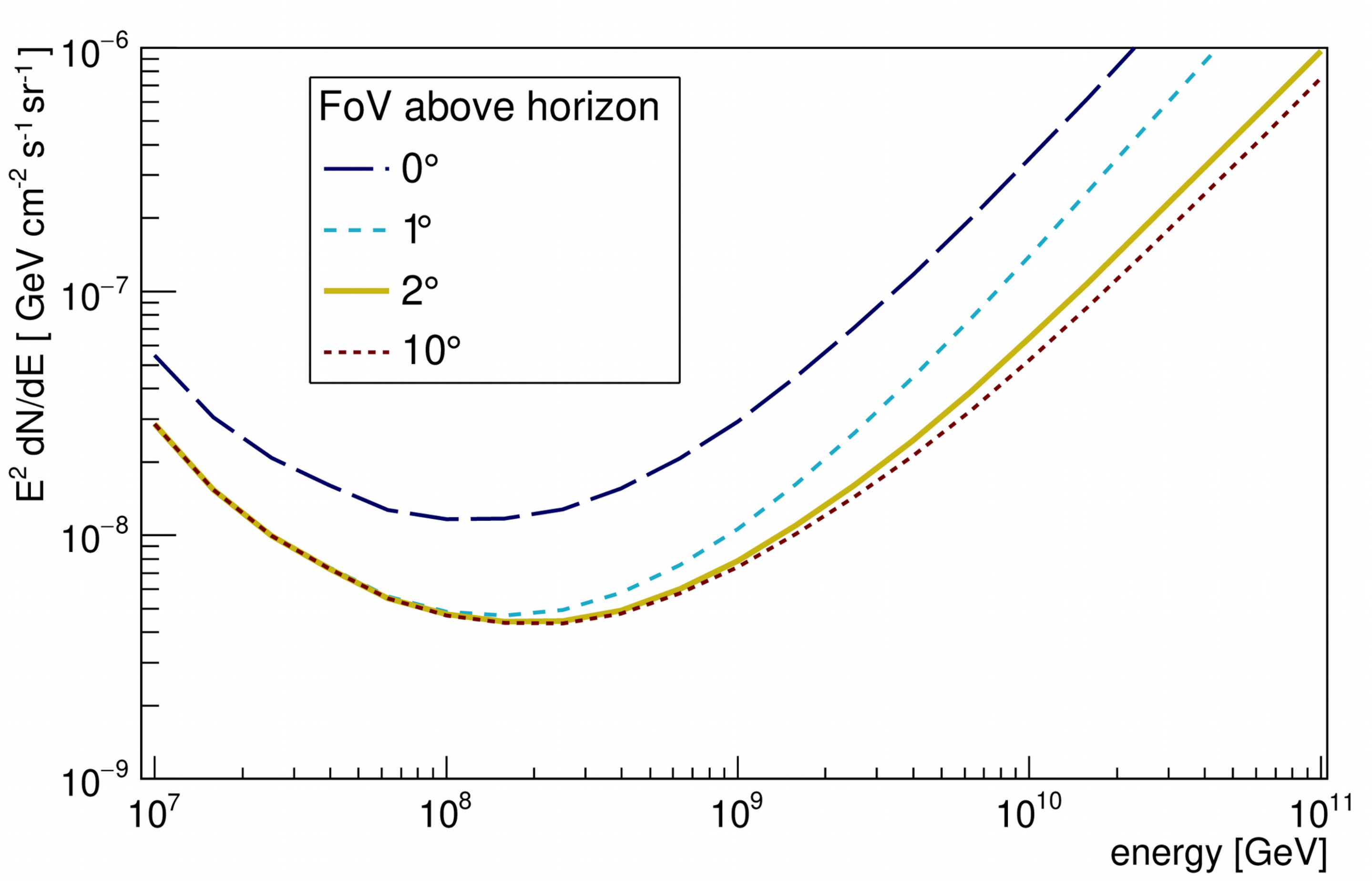

s
d
ζ
ε
l
φ
160 km
d'
2 km

Field of View Above Horizon



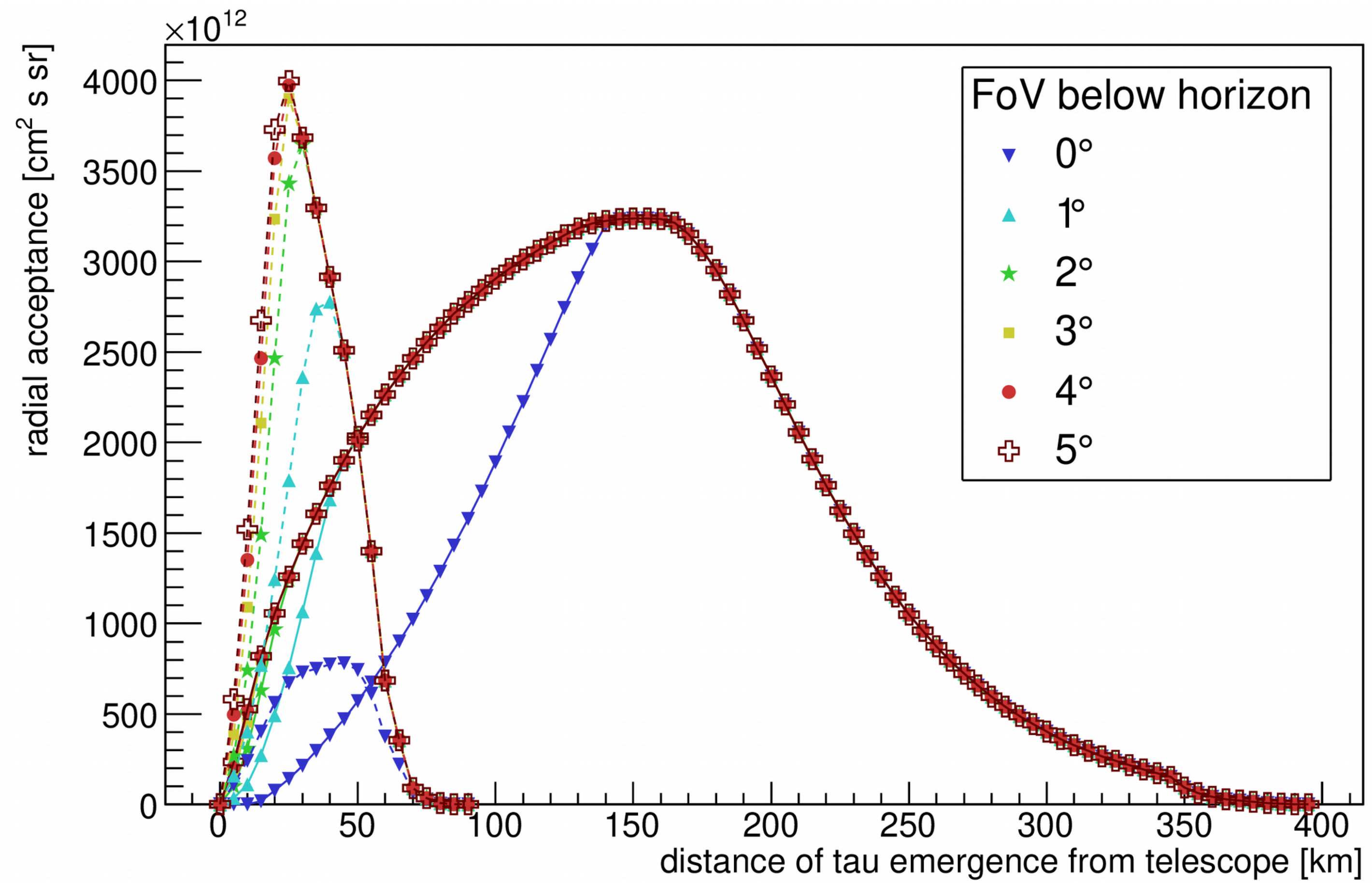
Acceptance maximal for 2° field of view above horizon.
Biggest impact on detection of distant showers.

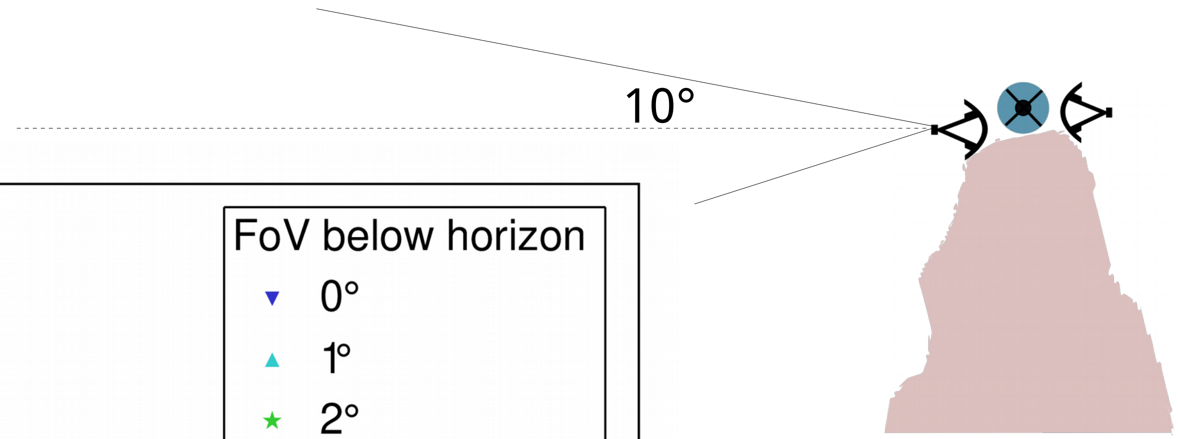
Sensitivity vs. FoV above Horizon



Nepomuk Otte

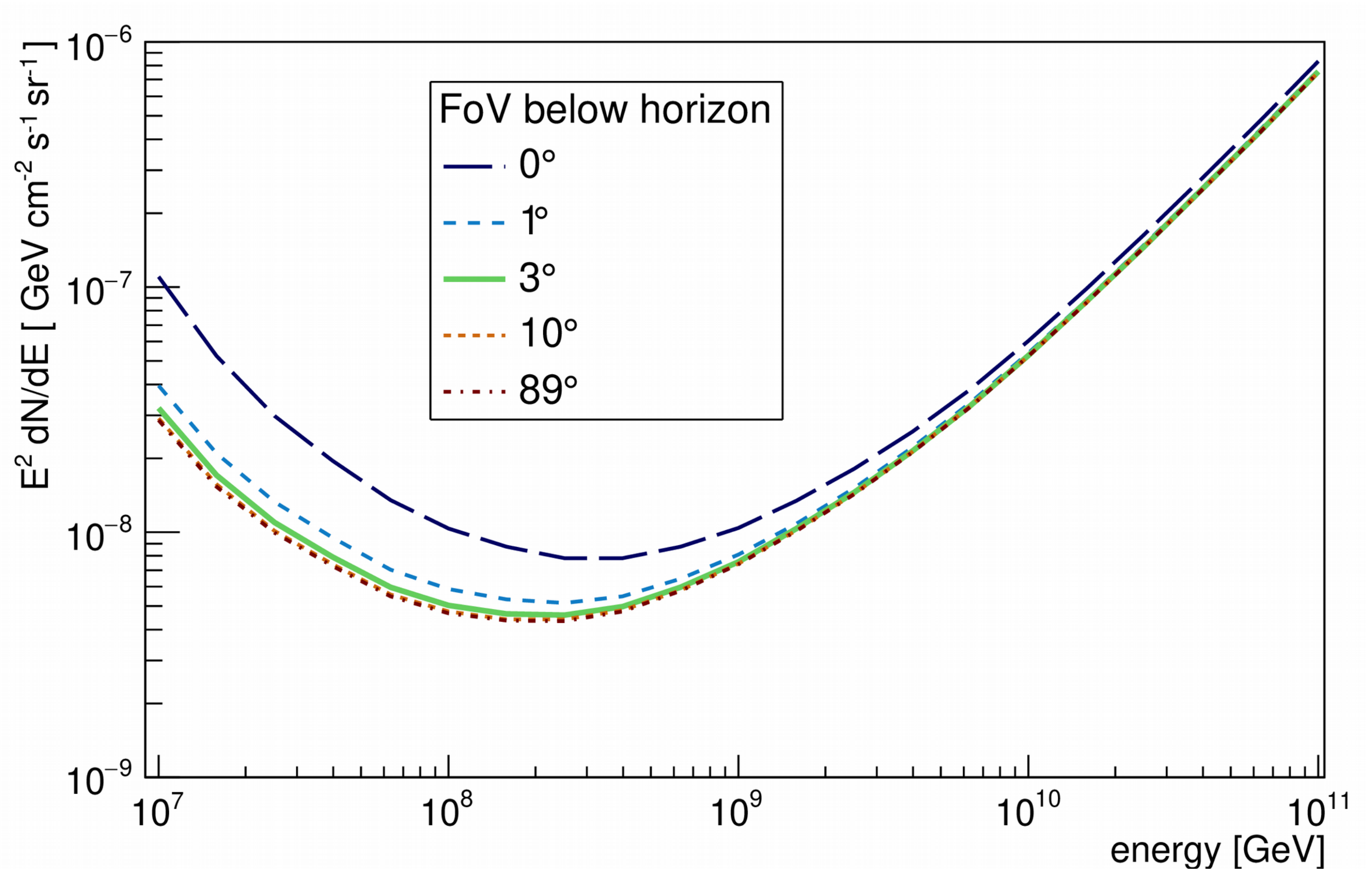
Field of View Below Horizon





Biggest impact for the detection of close showers.
Acceptance maximal for ~3° field of view below horizon.

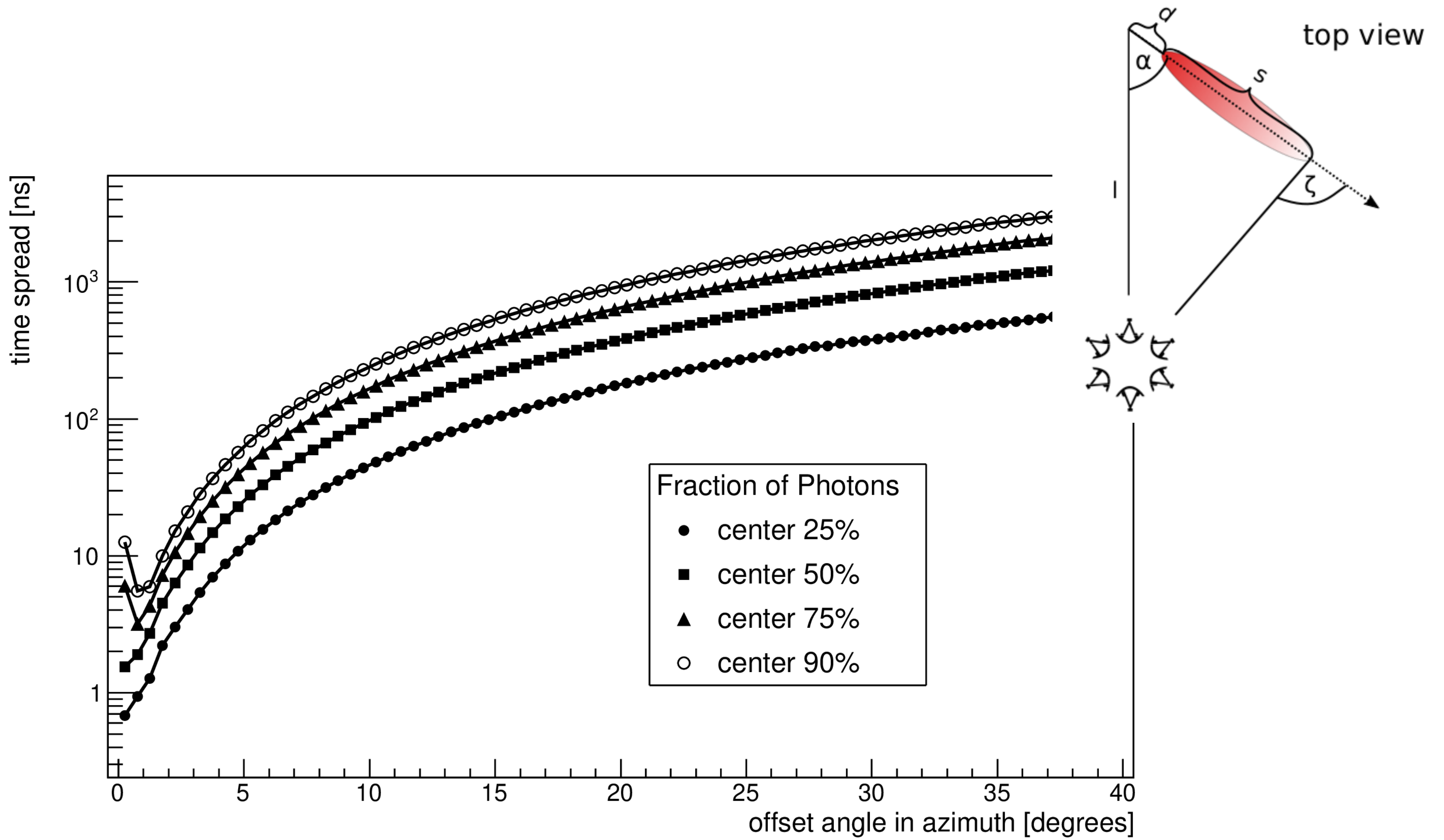
Sensitivity: FoV below Horizon



Background?!

- Cosmic Rays, meteorites, lightning
  - FoV where tau events are expected is narrow → Veto
  - Photon arrival time distribution
  - Stereo imaging
- Muons
  - Energy independent low intensity
  - Negligible spread in arrival time
  - Stereo imaging
- Accidentals
  - Higher trigger threshold
  - Stereo imaging

Photon Arrival Time Distribution

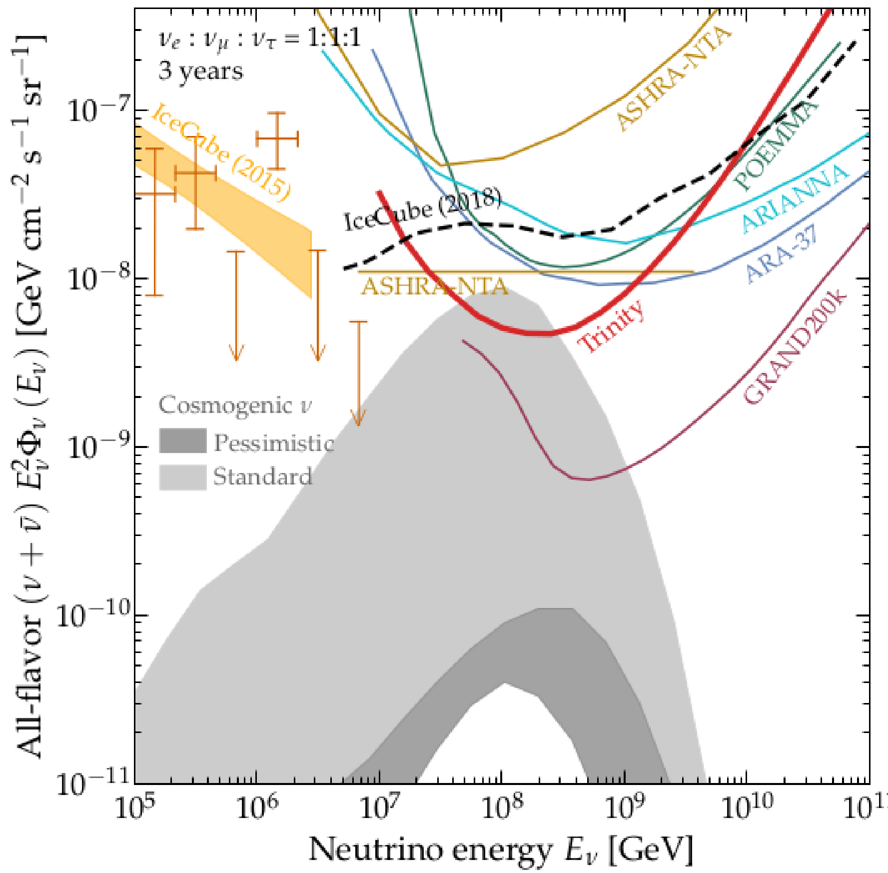


Background?!

- Cosmic Rays, meteorites, lightning
  - FoV where tau events are expected is narrow $\rightarrow$ Veto
  - Photon arrival time distribution
  - Stereo imaging
- Isolated Muons
  - Intensity does not depend on energy
  - Intensity is low (10 m^2 mirror)
  - Negligible spread in arrival time
  - Stereo imaging
- Accidentals
  - Higher trigger threshold
  - Stereo imaging

Conclusions

- A dedicated air shower imaging system delivers competitive sensitivity
- Several stations around the world increase sensitivity
- Not expensive
- Motivation to start developing a 1 m^2 prototype



Detector Design Requirements

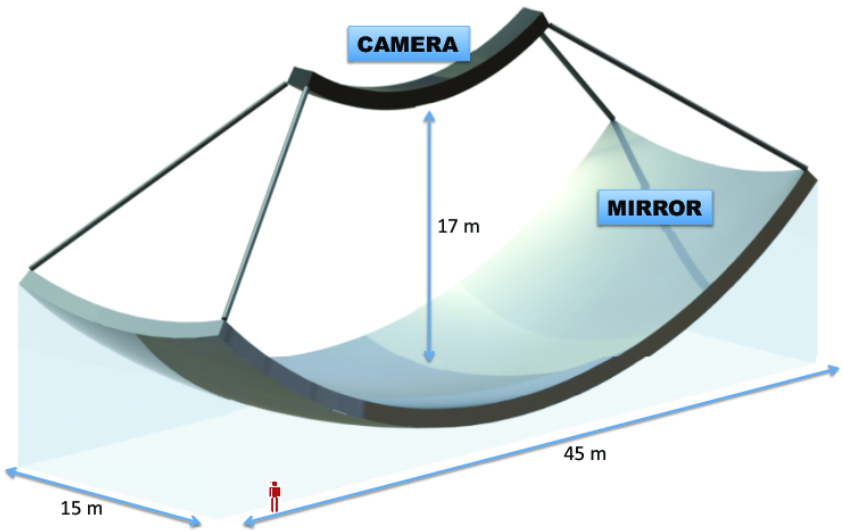
- 360° azimuthal FoV and 5° vertical FoV
- 10m^2 effective mirror area
- Minimum 0.3° angular resolution
  → >10 pixel per image
- Signal sampling speed 100 MS/s
- Single photoelectron resolution

MACHETE

A transit imaging atmospheric Cherenkov telescope to survey half of the very high energy γ-ray sky

J. Cortina, R. López-Coto, A. Moralejo

Astropart.Phys. 72 (2016) 46-54



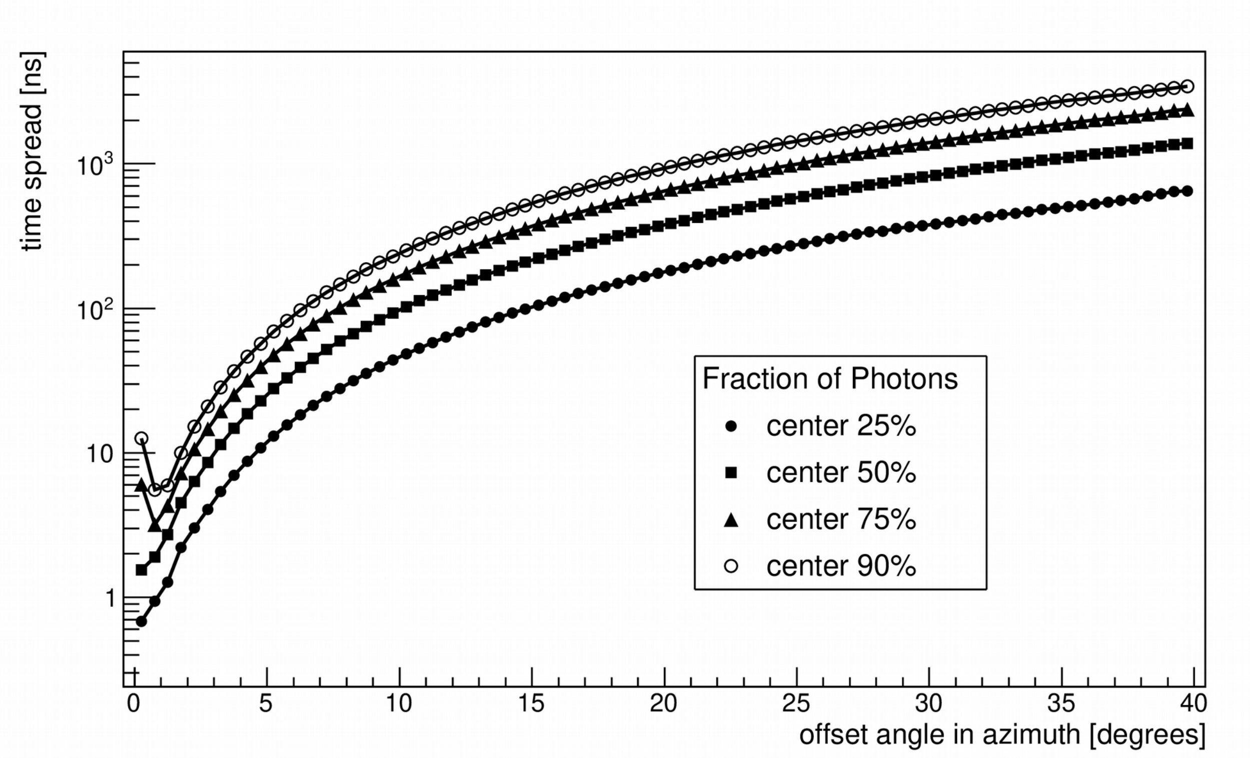
FOV of 5 × 60 sq deg

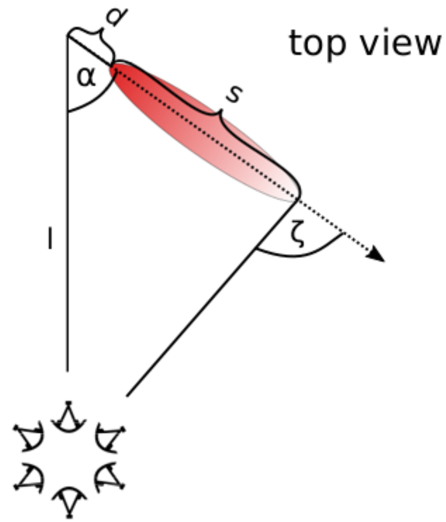
Scaled down to 1m² mirror:

- D=1.2 m, f=1.2 m, f/D=1
- **Mirror surface**: 4.1 m x 7.9 m
- **90% containment**: 0.42°
- **Pixel size**: 20 x 20 mm², 0.3° diameter → 4200 pixel
- **Light concentrator**: factor 4
  → sensor size 9x9mm² (SiPMs)

Costs per station (optics only): ~$500,000

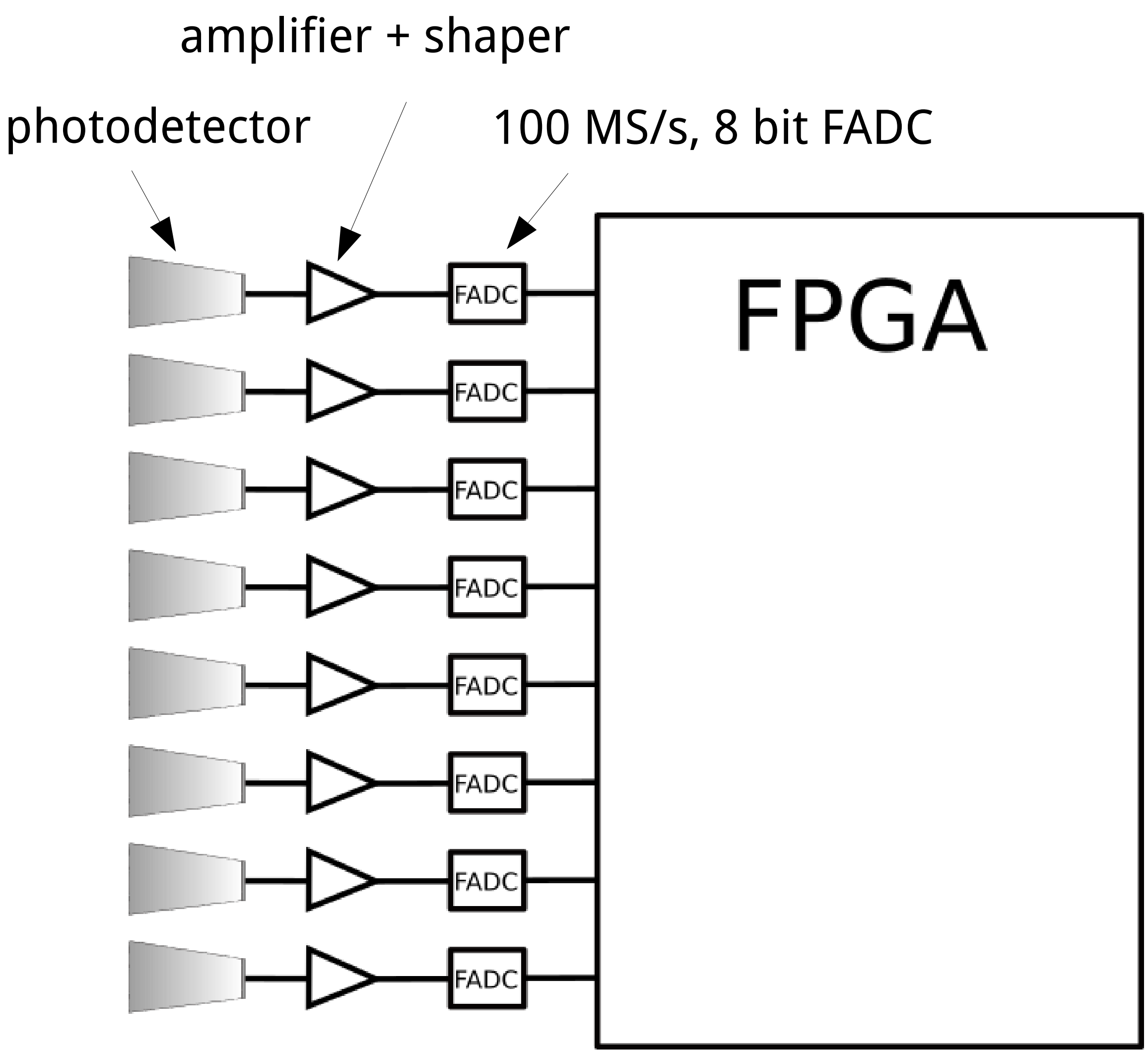
Data Acquisition Requirements





- Photon arrival times spread out to ~10 μs
  → “slow” 100MS/s DAQ sufficient
- NSB: 36mm^2 pixel record about
  → 4 photon / 1 μs
- Single pe signal stretched to 100 ns

Signal Chain



- Continuous sampling with 100 MS/s
- Signal processing and trigger in FPGA
  - Allows flexible trigger schemes using time and amplitude information

Cost per channel ~$100

Back on the Envelope Cost Estimate

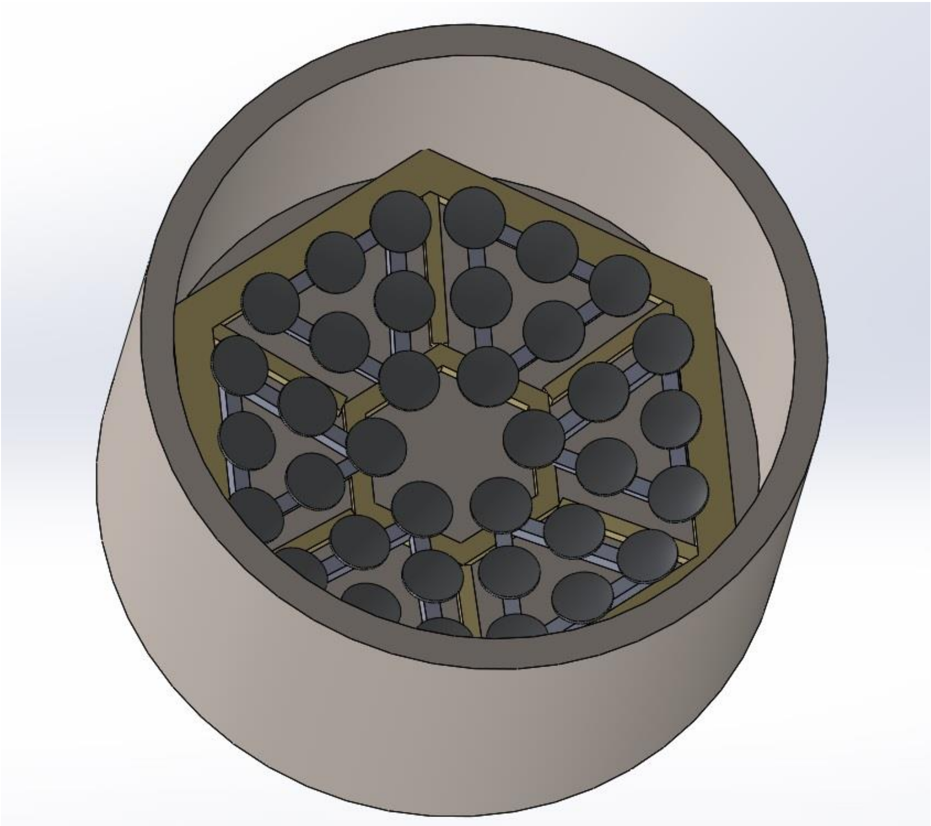
6 Detector stations for 360° FoV:

- 25,000 pixel * $100/channel (sensor + readout) = $2.5M
- Optics ~$4M
- Infrastructure ~$500k

$7M total + R&D costs ~$500k

Next Steps

PREF
+031.69168° / -110.88498° 8436ft 13:15:52
MAIL
POSITION - ALTITUDE - TIME
MAP
LOG
HORIZON
+00.8°
ANGLE
ELEVATION
-01.9°
ANGLE
-05
00
+05
AZIMUTH - BEARING
301° N59W 5351mils TRUE
ZERO
A-B
CAL
W
300
330
LENS
1.0X
S



Conclusions

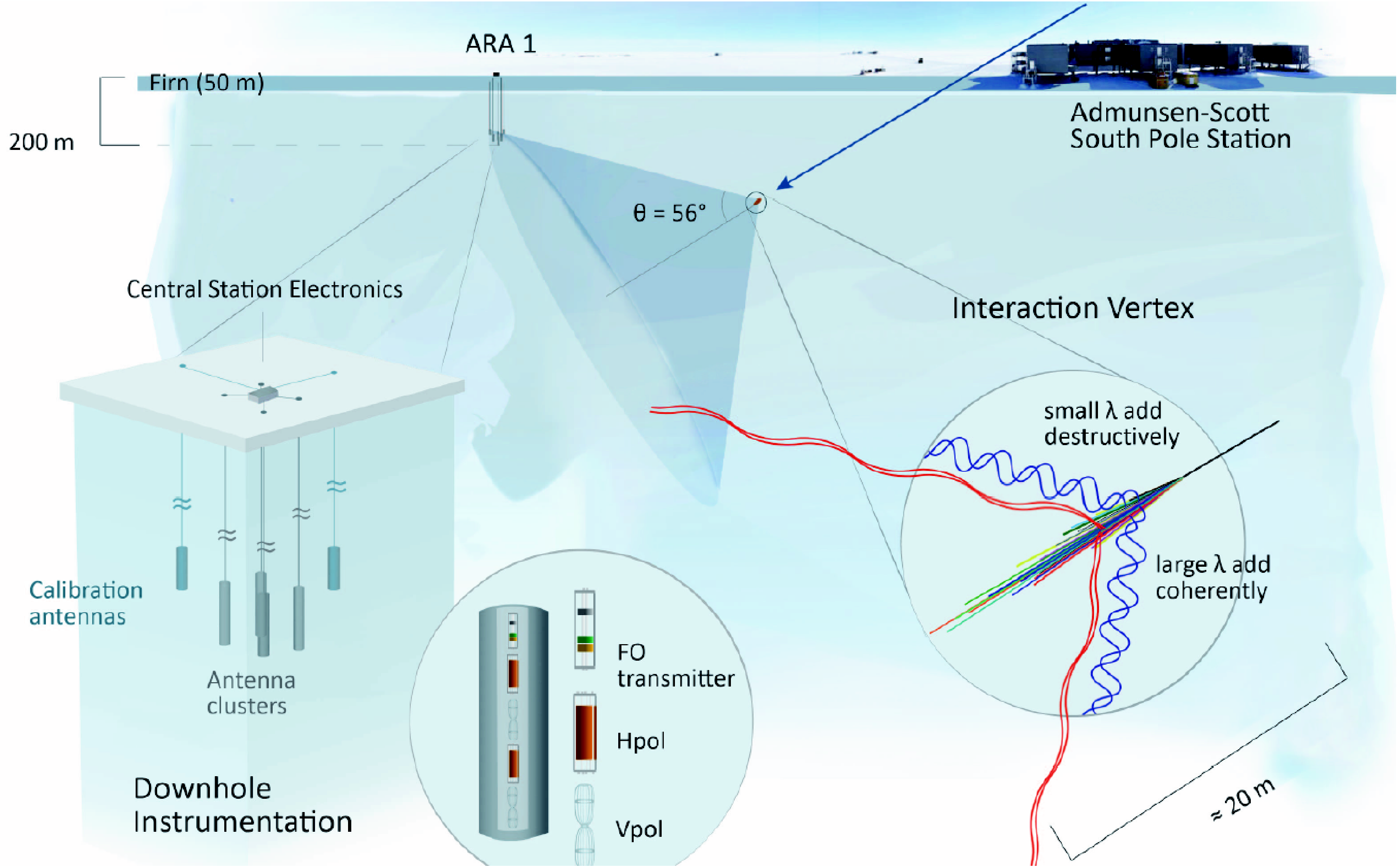
- A dedicated Cherenkov/fluorescence instrument can deliver a sensitivity comparable to ARA/ARIANNA
  - Both techniques are complementary:
    - Sensitive to different neutrino flavors → combining results tests physics BSM
    - View different portions of the sky
    -
- Technique is proven and well established in the VHE gamma ray and UHECR communities
  - Very good angular resolution and energy reconstruction
- Open issues need to be addressed with a small prototype
  - Background photon rates
  - Cosmic Ray background
  - Signal extraction and triggering
    - Advanced methods can significantly improve sensitivity and lower energy threshold
  - Data analysis: How well can up-going showers separated from down-going ones
  - Finding optimal site (geometrical acceptance, infrastructure, ...)

Backup

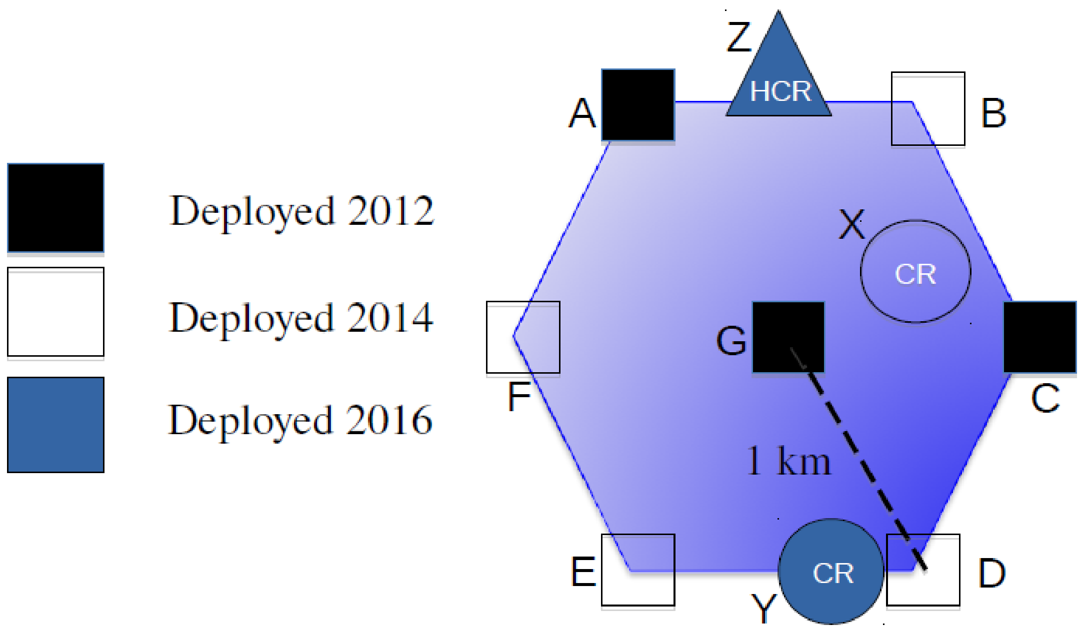
Prototype Site

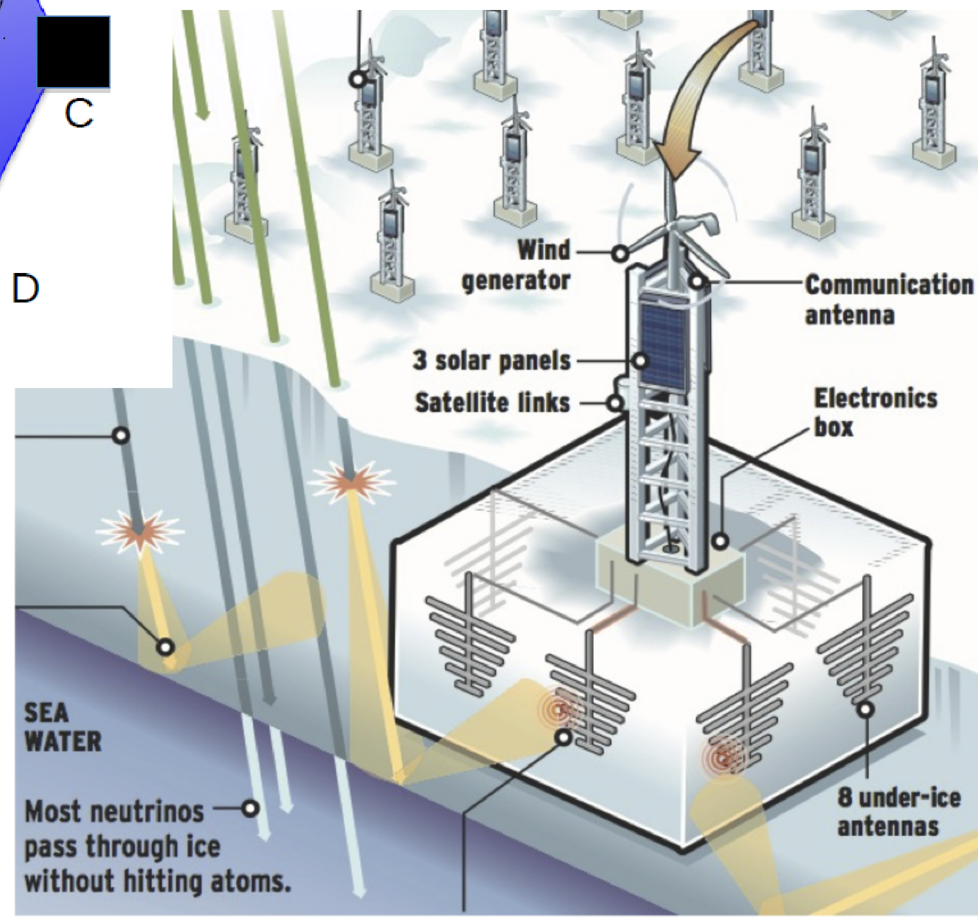
IOTA site on Kitt Peak, AZ

Askaryan Radio Array (ARA)



ARIANNA


Deployed 2012
Deployed 2014
Deployed 2016
Z
HCR
A
B
X
CR
G
C
F
1 km
E
CR
D
Y


Wind generator
Communication antenna
3 solar panels
Satellite links
Electronics box
SEA WATER
Most neutrinos pass through ice without hitting atoms.
8 under-ice antennas

Radio Technique

Pros:
- Allows instrumentation of large volume
- Cheap?

Cons:
- Prone to radio interference
- Large angular resolution of several degrees for in ice radio
- Energy resolution of >50% for in ice radio
- Relatively new experimental technique

What about other detection techniques?

Figure of Merit: cost*sensitivity