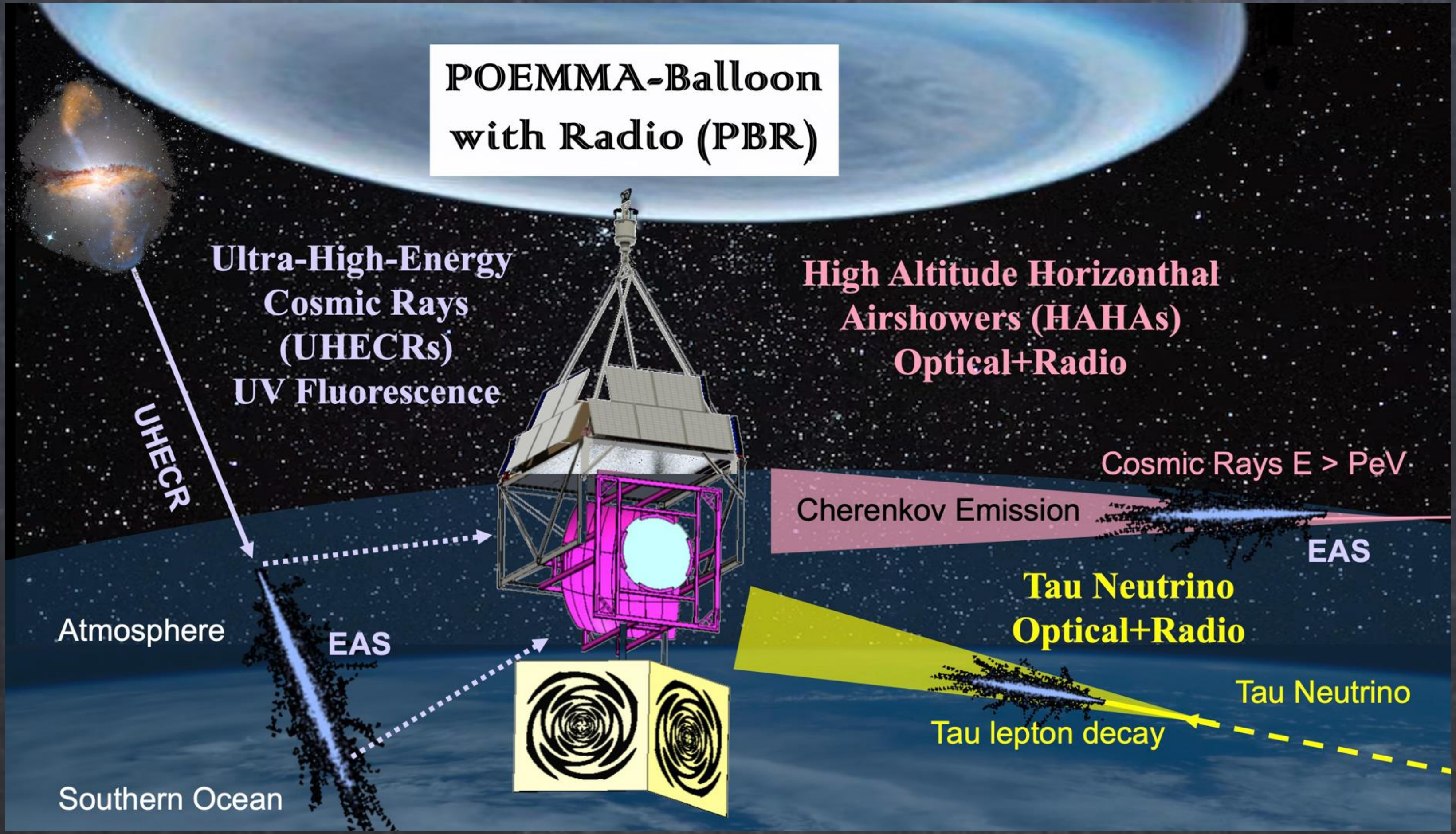
In Situ measurements with PBR and GSFC modeling status

John Krizmanic NASA/GSFC

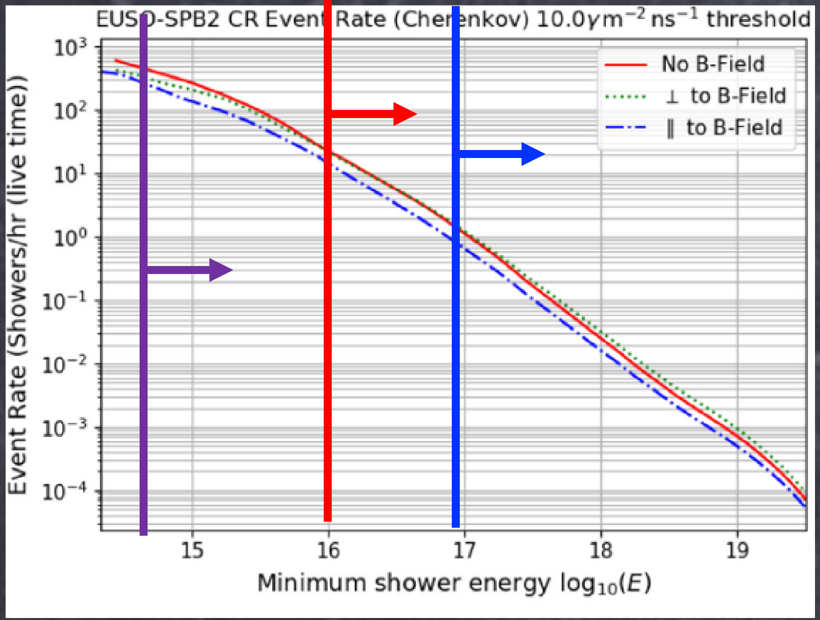


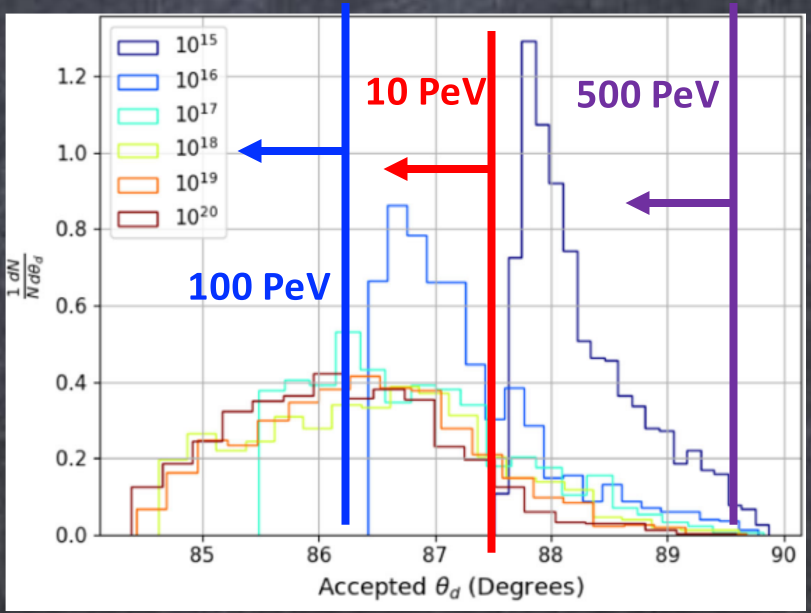
For PBR, there is significant geometry factor for the PBR instruments to be within the EAS cascade development:

- Provides a unique environment for in Situ EAS measurements
- EAS development is in rarified atmosphere that provides a different ‘medium’ (e.g. vs downward moving) that influences the cascade development.
- What EAS measurements can be performed -> guide the instrument suite/response for PBR.

What we know ……

1. There is GF for events where PBR will be in the midst of the EAS development.
2. The energy threshold for these events will be < PeV.
3. CR event rate should be significant.





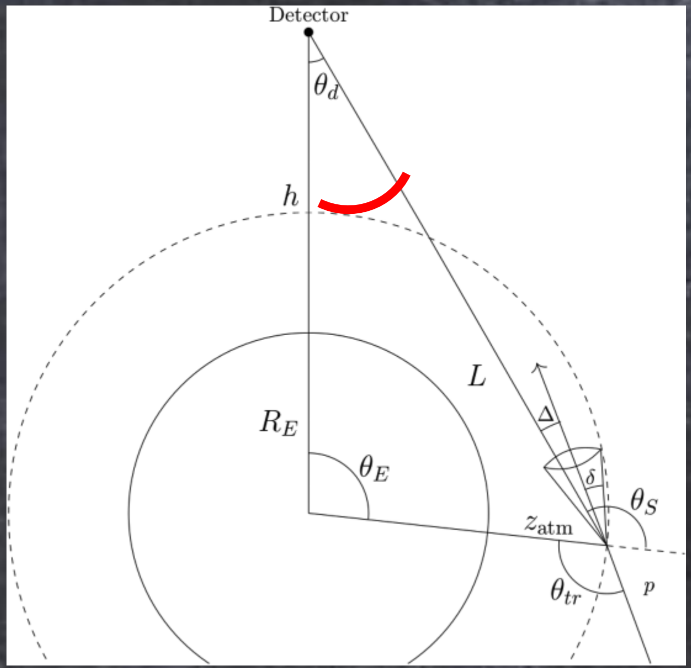
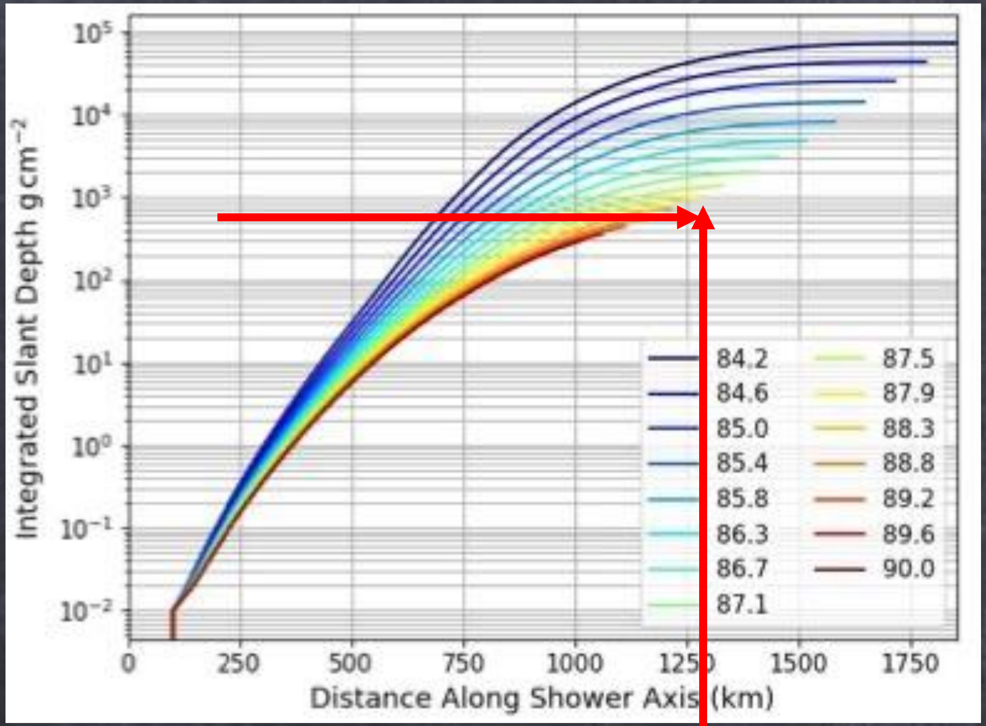


FIG. 1. Geometry of measuring the Cherenkov signal from cosmic rays arriving from above the Earth horizon in the case of a space based instrument.

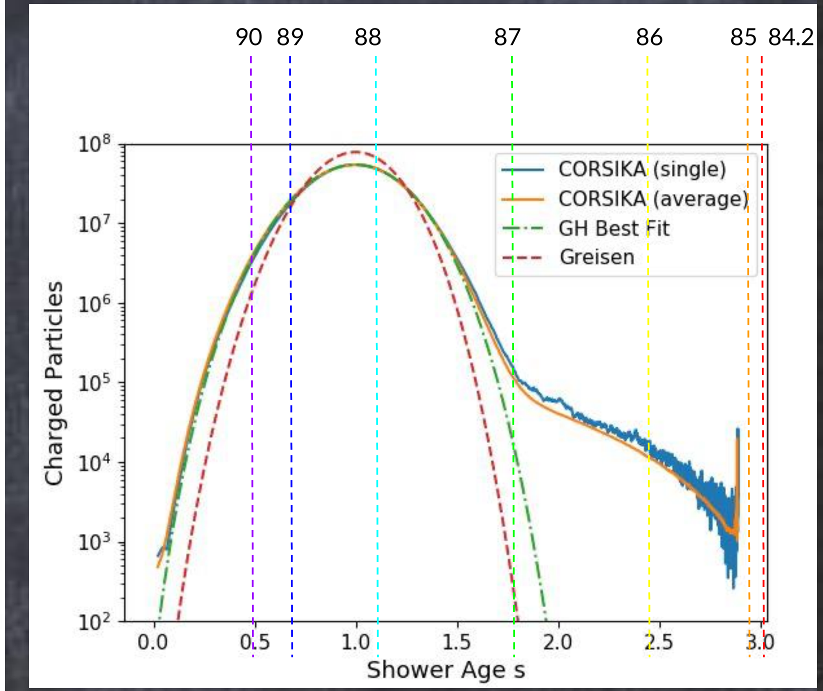
> 500 TeV ~65 CRs/livehour	> 10 PeV ~3 CRs/livehour	> 100 PeV ~0.11 CRs/livehour

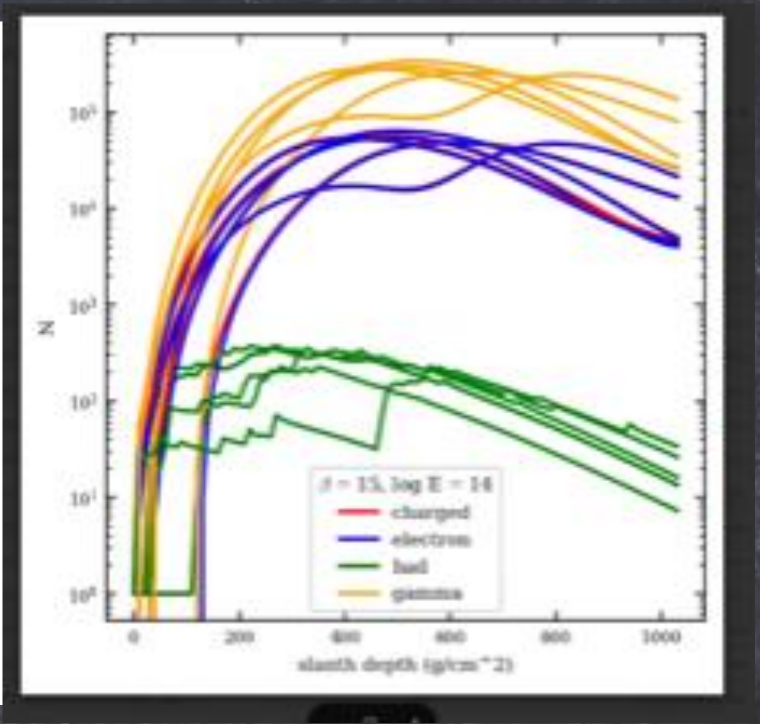
SPB2 CT: A_{EFF} = 0.68 m², 6.4° x 12.8° angular span (Δnadir vs Δazimuth angles), 0.4° pixel size

500 g/cm² can be a long > 1000 km length ….



~1300 km

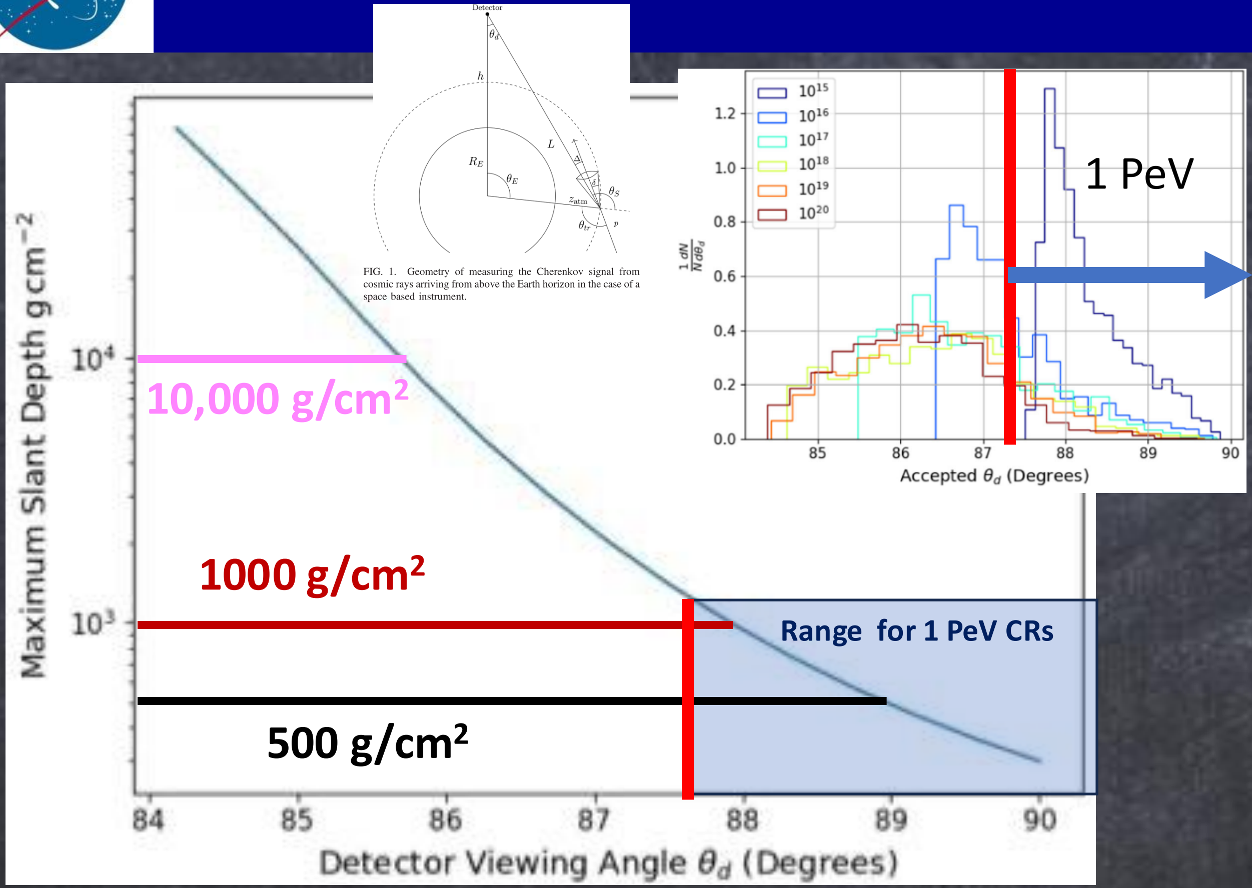


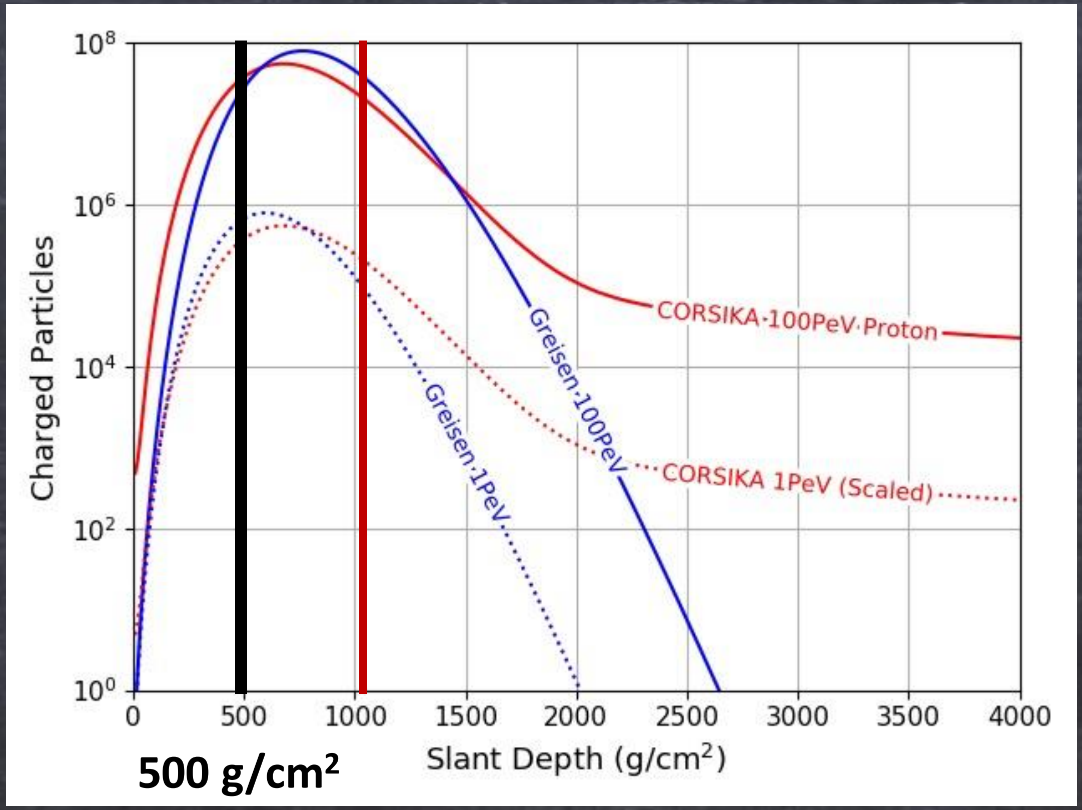


100 TeV upward, β_E = 5 deg, proton starting at 10 km altitude

- PeV-scale EAS can have development to Xmax on > 1000 km length which is much larger than that for that for downward EAS development.
- If $\lambda_I \sim 60$ g/cm² , this would correspond to ~100 km length, initial hadronic interactions can be widely spaced away from each other …

HaHa’s have very large range of slant depths thru the atmosphere

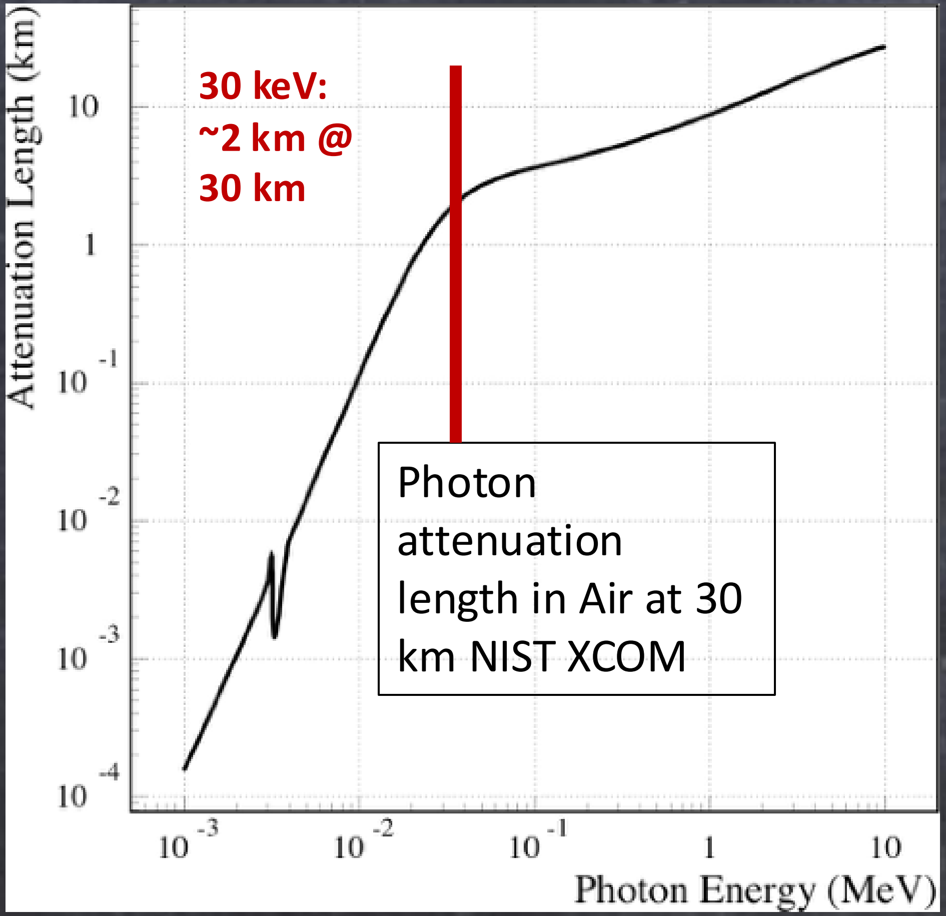




Balloon-borne instrument can be within the early stage of development for EAS with small slant depths before and around shower max!

EASVAEL : EAS Viewed Above the Earth’s Limb in Cherenkov

Potential for X-ray measurements from $e^{+/-}$ synchrotron radiation



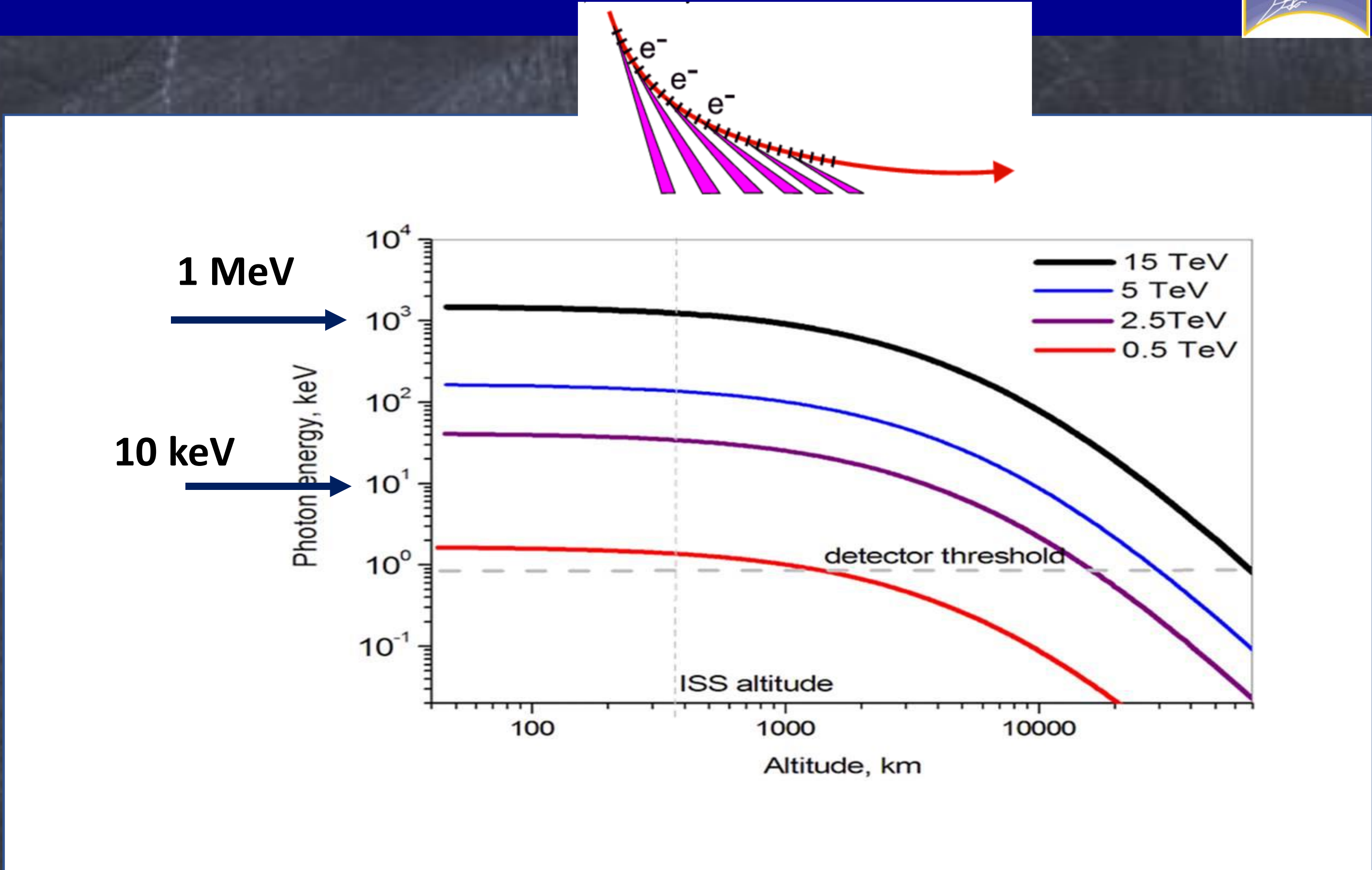


Figure 2. Average energy of synchrotron photons emitted by electrons with different energ

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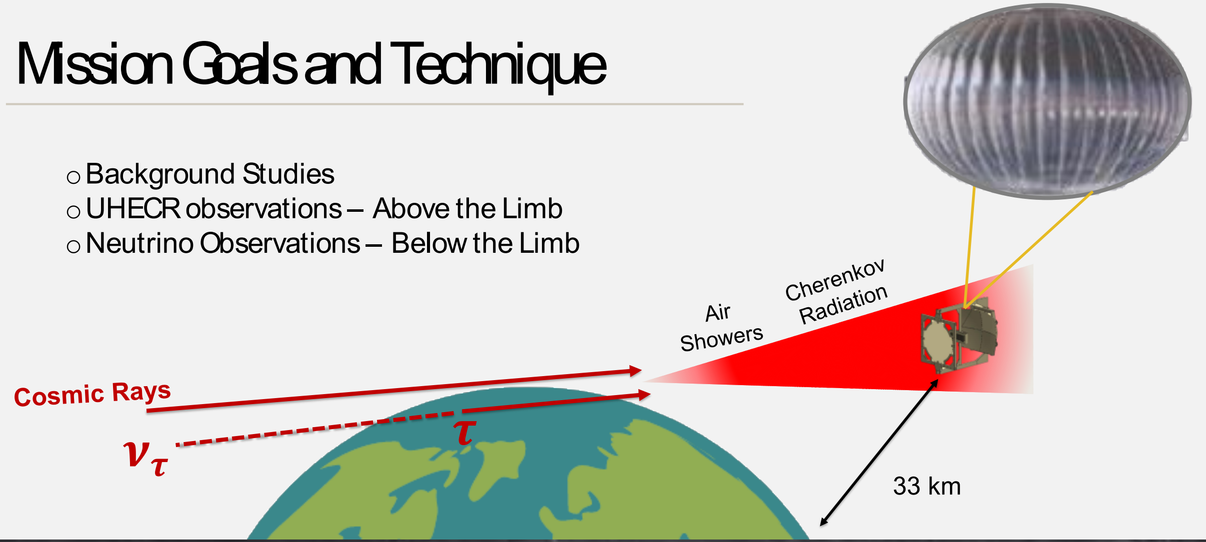
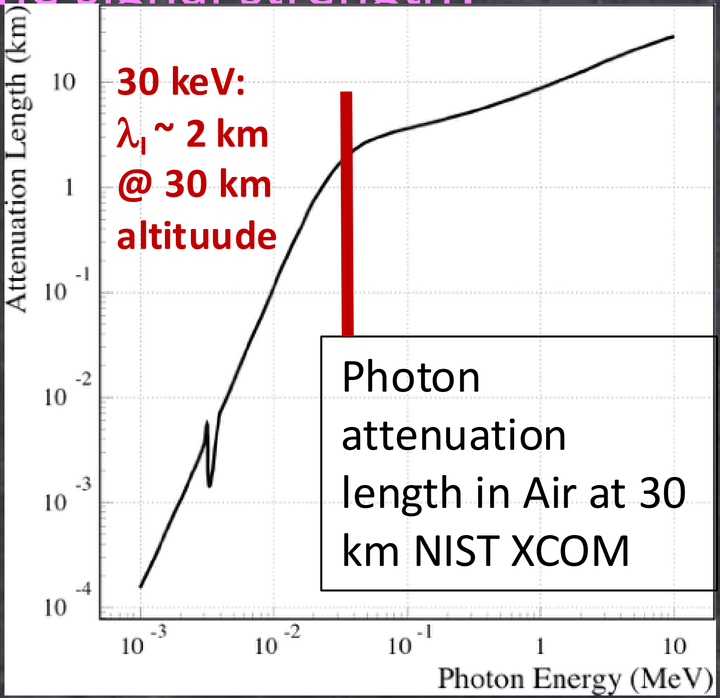
High energy positron detection via synchrotron emission in magnetosphere

To cite this article: A M Galper *et al* 2017 *J. Phys.: Conf. Ser.* 798 012176

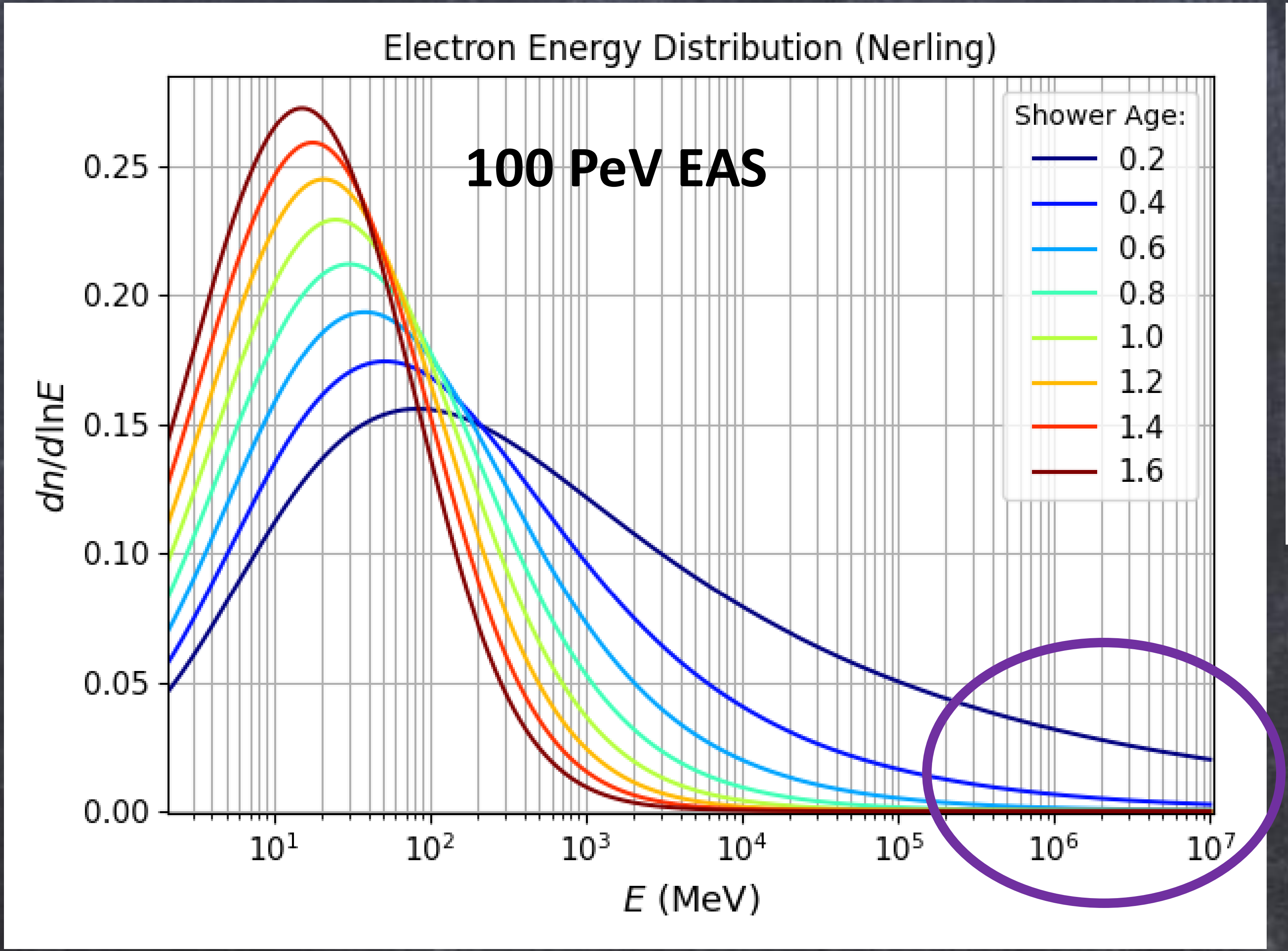
What in situ measurements of EAS do we want to make with PBR …

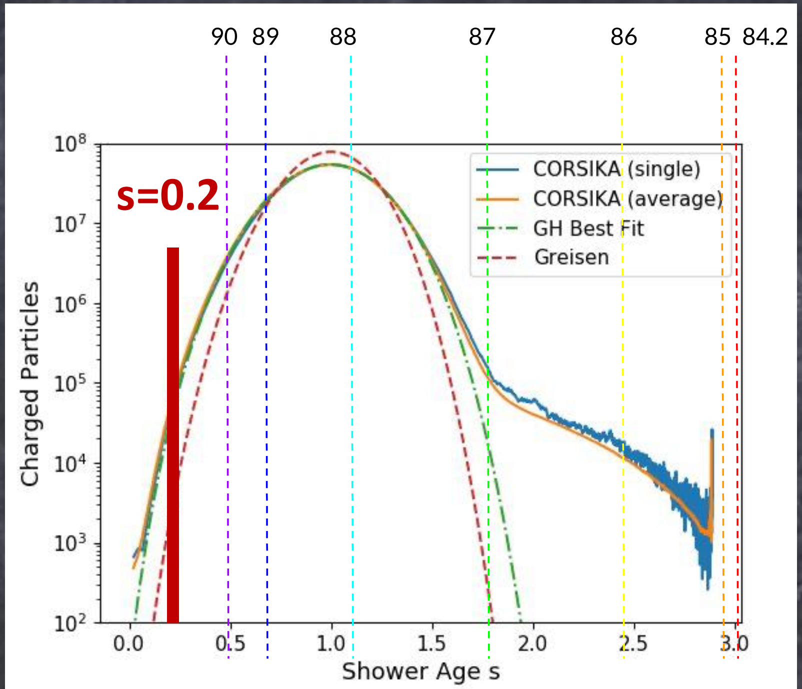
1. Will have Cherenkov from the EAS …
2. Will have geomagnetic radio from the EAS …
3. Measurements of charged particles depends on shower age … early age will have a core component : **quantification needs to be performed.**
4. The early age, trans-TeV electron/positron component will lead to an X-ray/g-ray signal due to synchrotron and bremsstrahlung : what is the signal strength?





EAS $e^{+/-}$ population vs shower age





There exists a significant population (> 1e3) of $e^{+/-}$ at early EAS age with energies larger than 1 TeV

EAS trans-TeV $e^{+/-}$ generated: Initial results from CREST experiment studies

S. Coutu et al. / Nuclear Physics B (Proc. Suppl.) 215 (2011) 250–254

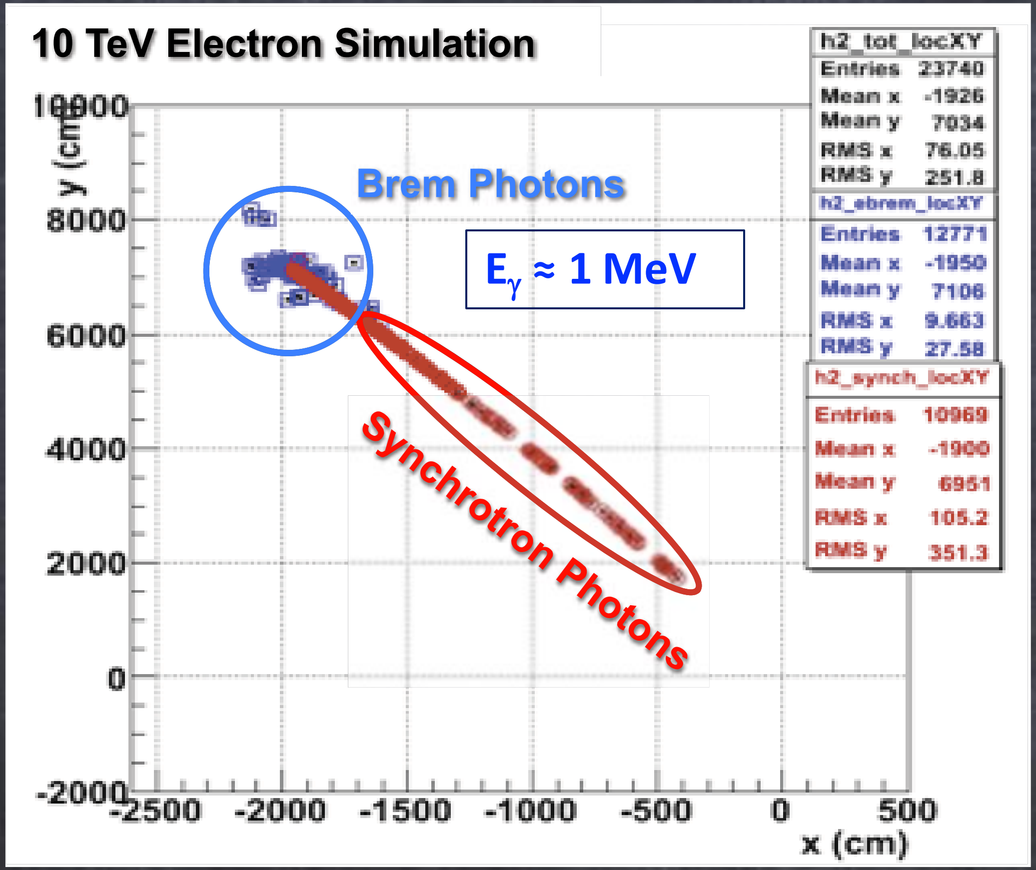
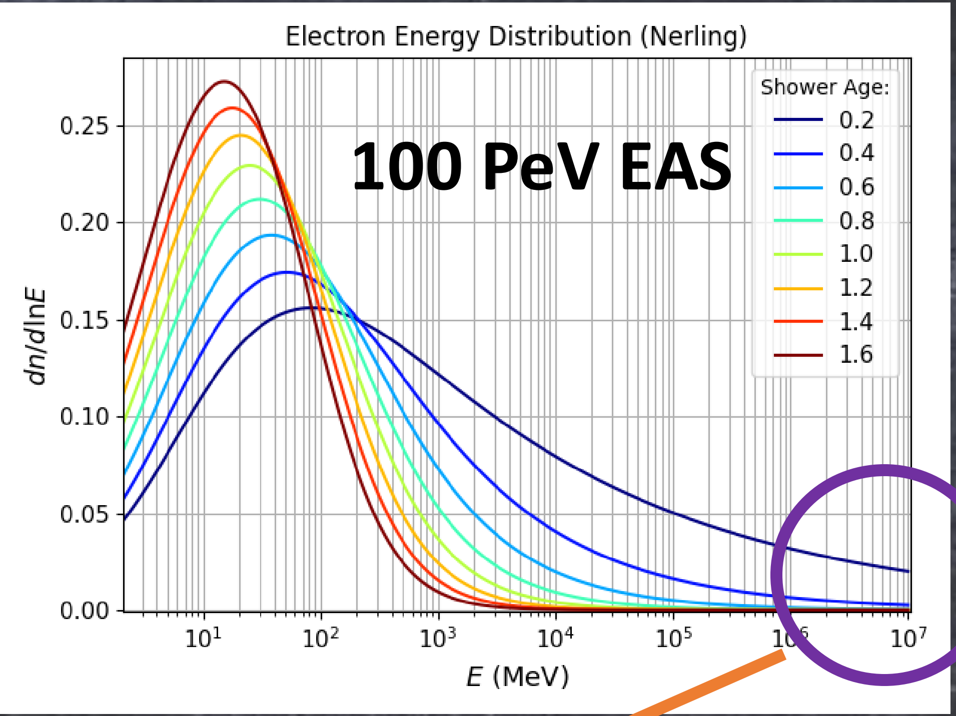


Figure 3. Example of a simulated x-ray photon geometric distribution at balloon altitudes for a 10 TeV incident electron.

Total: 23,740

Brem: 12,771

Synch: 10,969



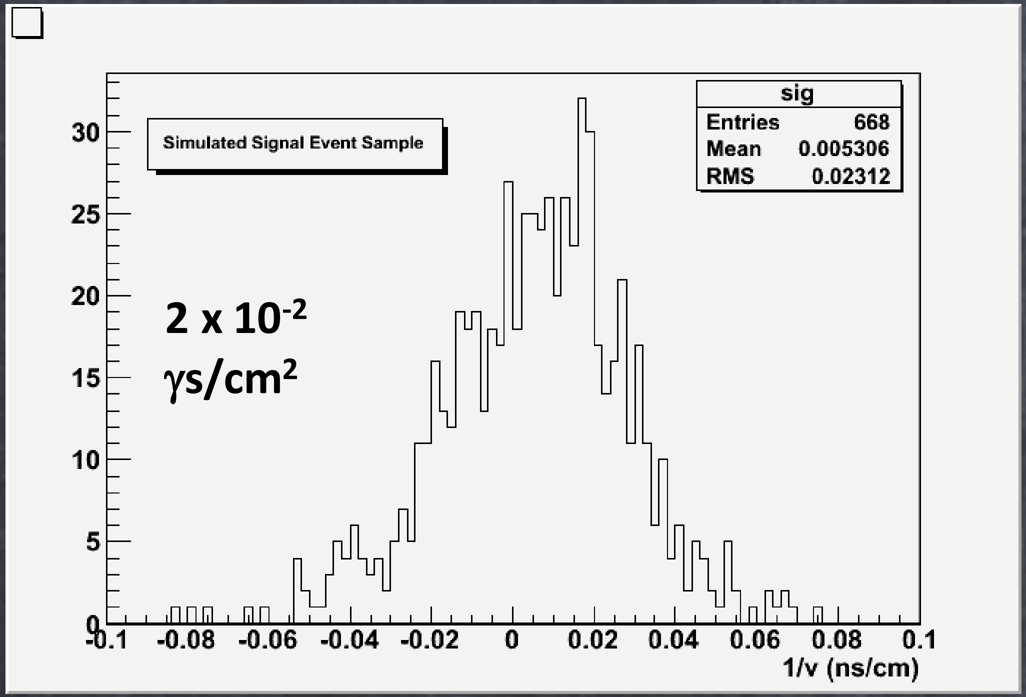
0.02×10^4 [electrons] $\times 10^4$ [Photons/electron] $= 2 \times 10^6$ [Brem Photons]

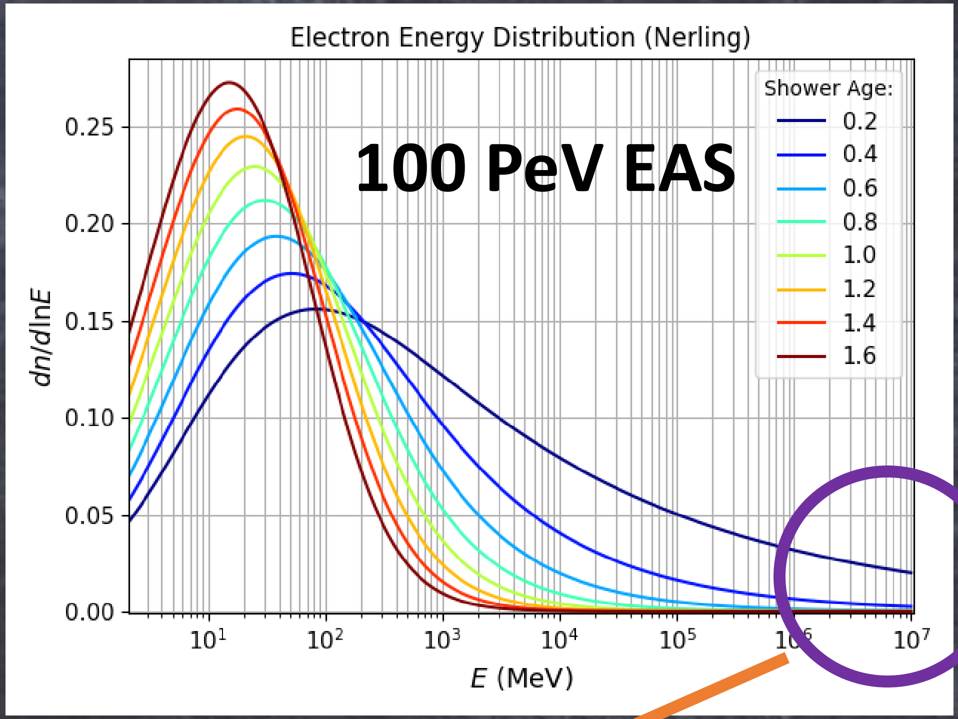
$2 \times 10^6 / 2.5 \times 10^5$ [cm^2] ≈ 10 Brem (1 MeV) photons/cm^2

≈ 10 Synch photons/cm^2 (?)

EAS trans-TeV $e^{+/-}$ generated: Initial results from CREST experiment studies

S. Coutu/CREST TeVPA2013





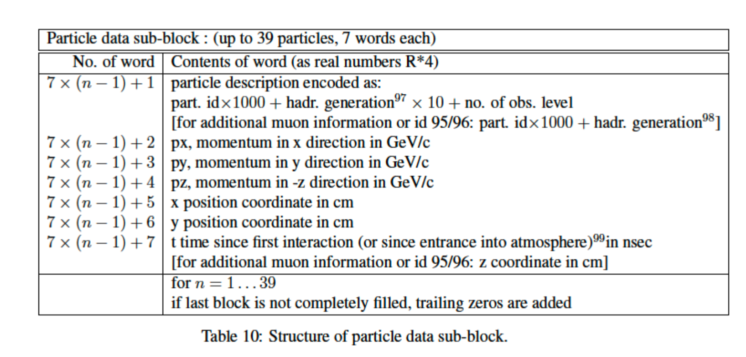
0.02×10^4 [electrons] @ 10 TeV

1 MeV photo signal from one 10 TeV Electron:
MC has minimal time spread for signal photons.

0.02×10^4 [electrons] $\times\ 10^{-2}$ [Photons/cm^2] = 2 [Photons/ cm^2]

Issues and Path Forward …

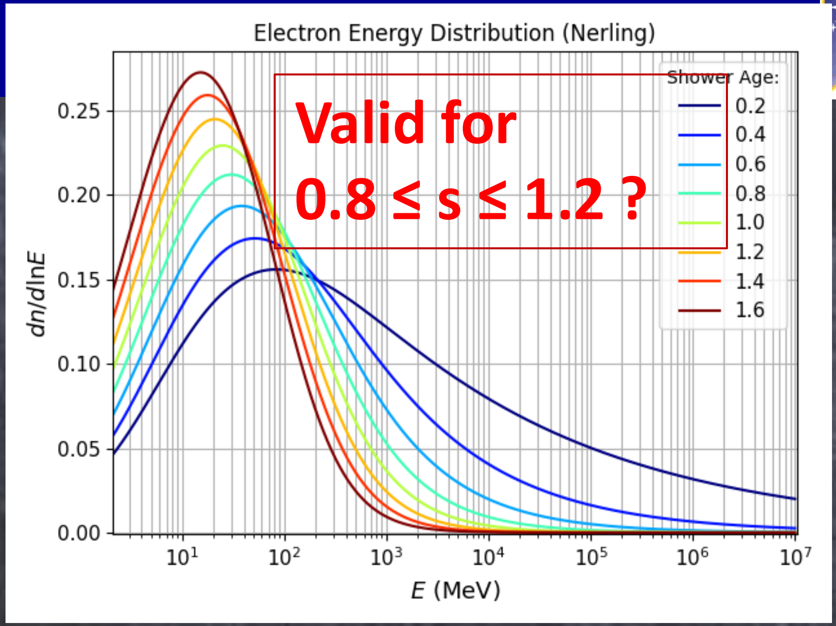
1. While not stated in Nerling (doi:10.1016/j.astropartphys.2005.09.002) in Appendix A: the paper states the work is based on shower age around s = 1.
   - Need to use CORSIKA or Cosmos to determine $e^{\pm}$ at early shower ages.

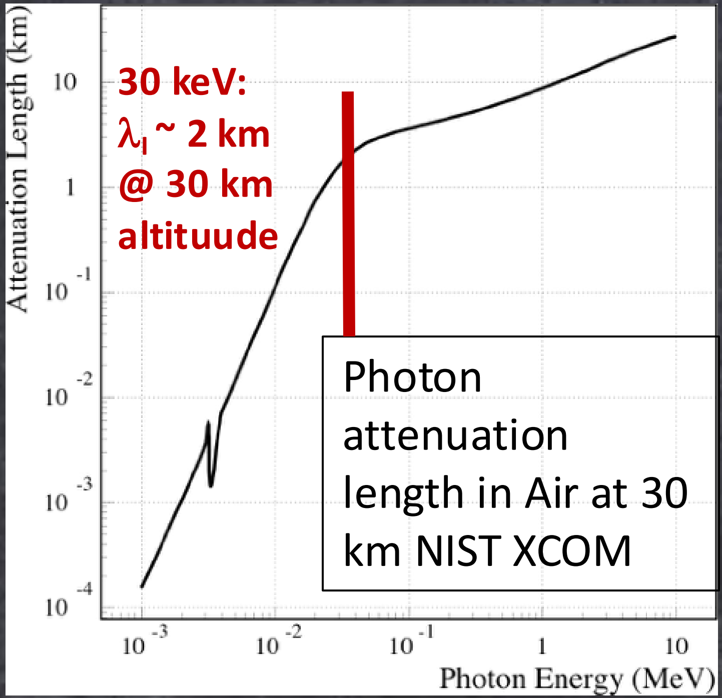


Particle data sub-block : (up to 39 particles, 7 words each)	
No. of word	Contents of word (as real numbers R*4)
$7 \times (n-1) + 1$	particle description encoded as: part. id×1000 + hadr. generation[97] × 10 + no. of obs. level [for additional muon information or id 95/96: part. id×1000 + hadr. generation[98]]
$7 \times (n-1) + 2$	px, momentum in x direction in GeV/c
$7 \times (n-1) + 3$	py, momentum in y direction in GeV/c
$7 \times (n-1) + 4$	pz, momentum in -z direction in GeV/c
$7 \times (n-1) + 5$	x position coordinate in cm
$7 \times (n-1) + 6$	y position coordinate in cm
$7 \times (n-1) + 7$	t time since first interaction (or since entrance into atmosphere)[99] in nsec [for additional muon information or id 95/96: z coordinate in cm]
	for $n = 1 \ldots 39$ if last block is not completely filled, trailing zeros are added

Table 10: Structure of particle data sub-block.

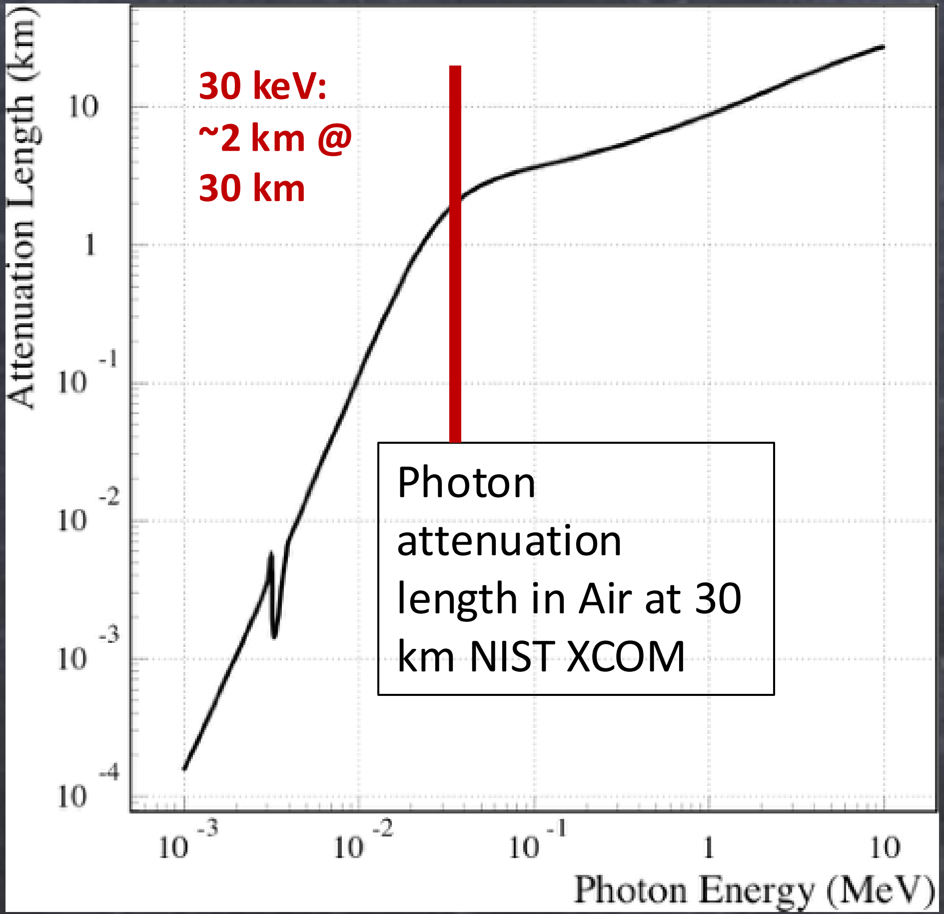
1. CREST used GEANT4 model to calculate X-ray/γ-ray Synch/Brehm from trans-TeV electrons: model robust.
2. Guidance for PBR GX instrument:
   - As of now, most important input is that X-ray energy threshold needs to be below 30 keV.
   - Fast timing should help with reducing background.
3. Near area of research … still have work to do …





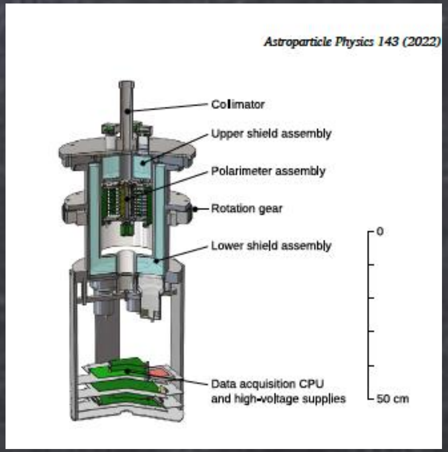
Backup Slides

Requirements for X-ray measurements in situ of EAS: signal 10+ γ/cm^2



1. Energy Range: 10 keV - 1 MeV
2. Minimal Area : TDB – but ~ cm^2 looks ok
3. Directionality: TDB: but Bkgnd at 1 MeV:

3×10^{-4} [counts/s/cm^2/keV] x 100 [keV] ~ 0.03 [counts/s/cm^2]



X-Calibur LDB Background Measurement

Astroparticle Physics 143 (2022) 102749

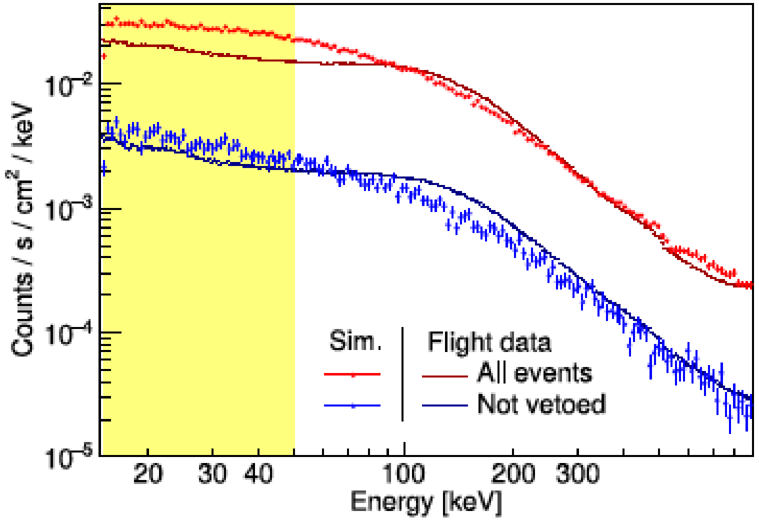
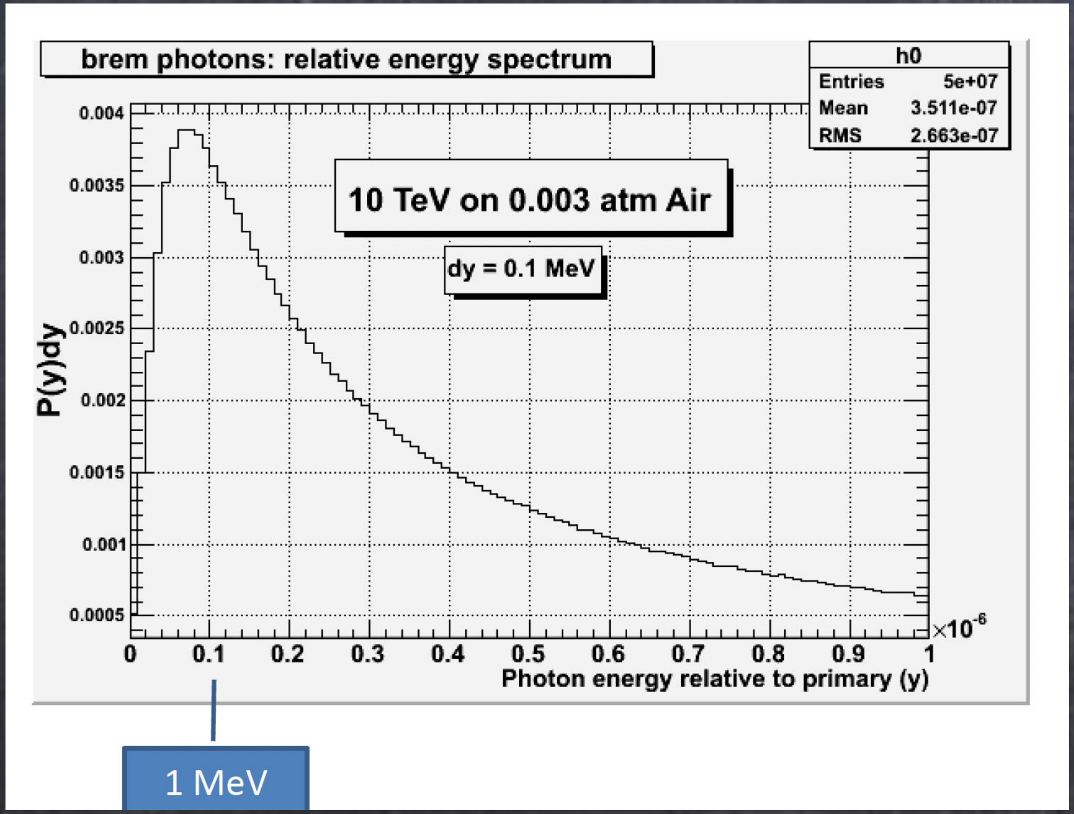
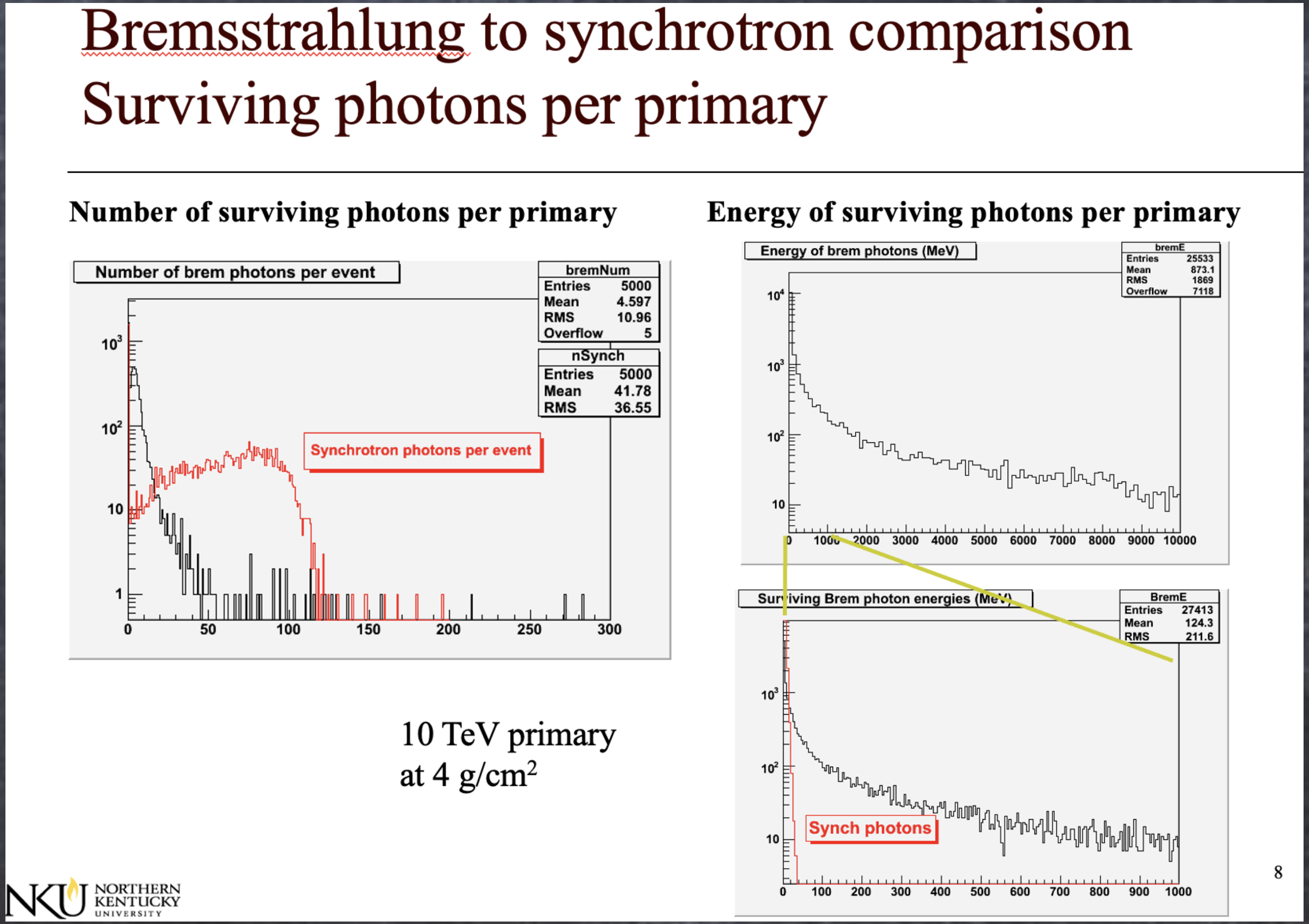


Fig. 17. Background spectrum measured during flight, excluding the ASIC of the rear-end detector that only worked intermittently, and the result of the Geant4 simulation. Counts are normalized to geometric area of the CZT detectors. The shaded region indicates the core energy range for polarization measurements.

Synch vs Brehm : Update based on input from Scott Nutter





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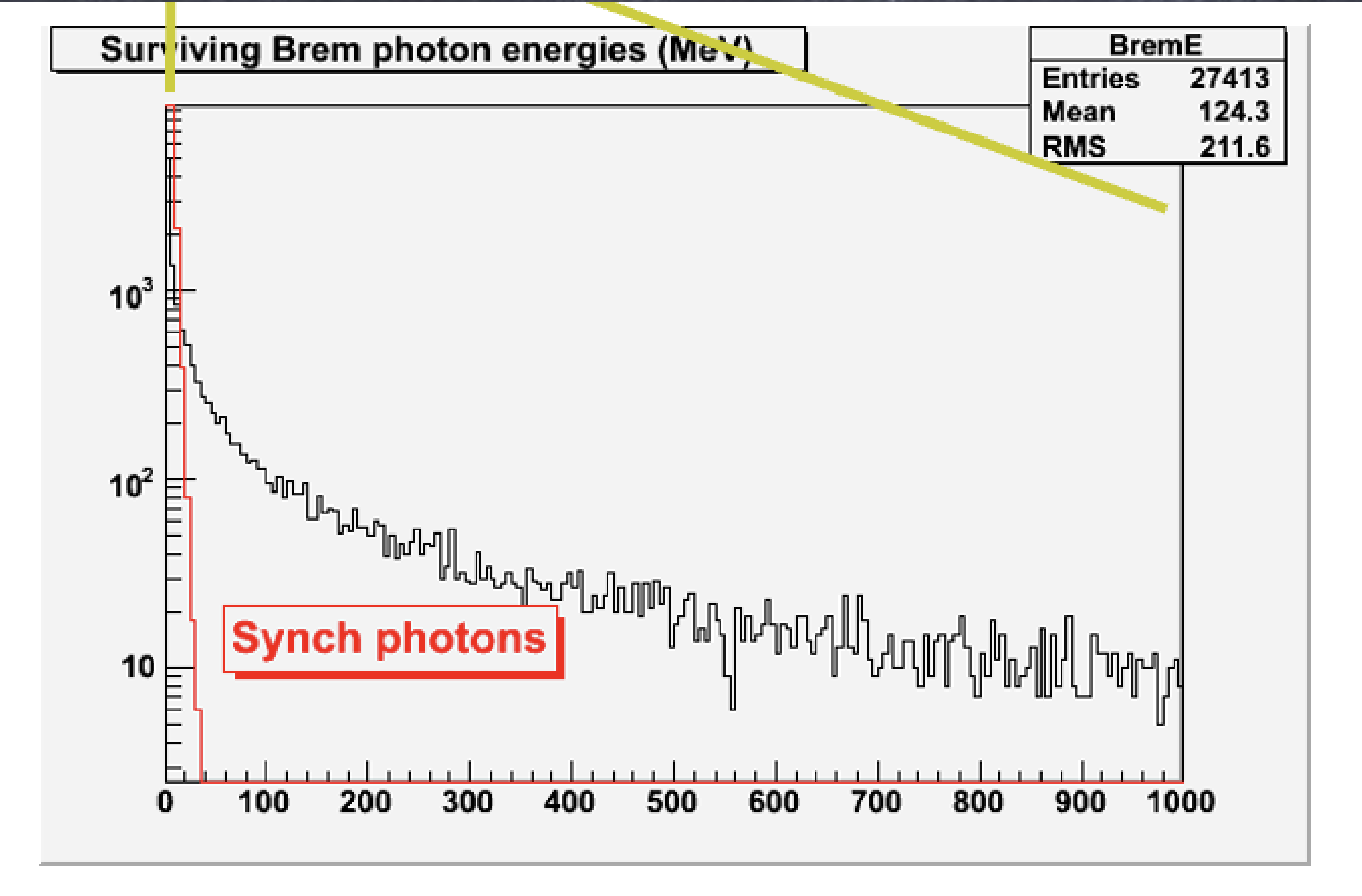
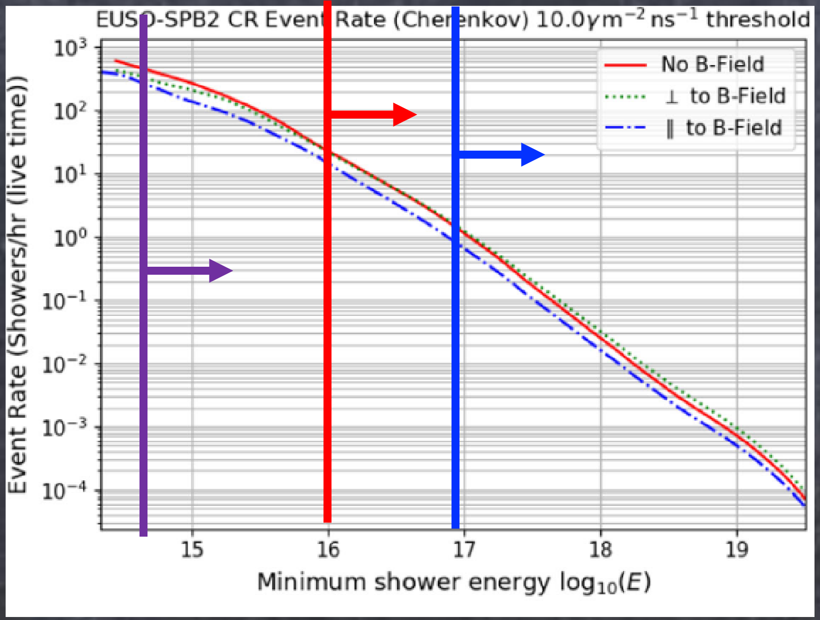
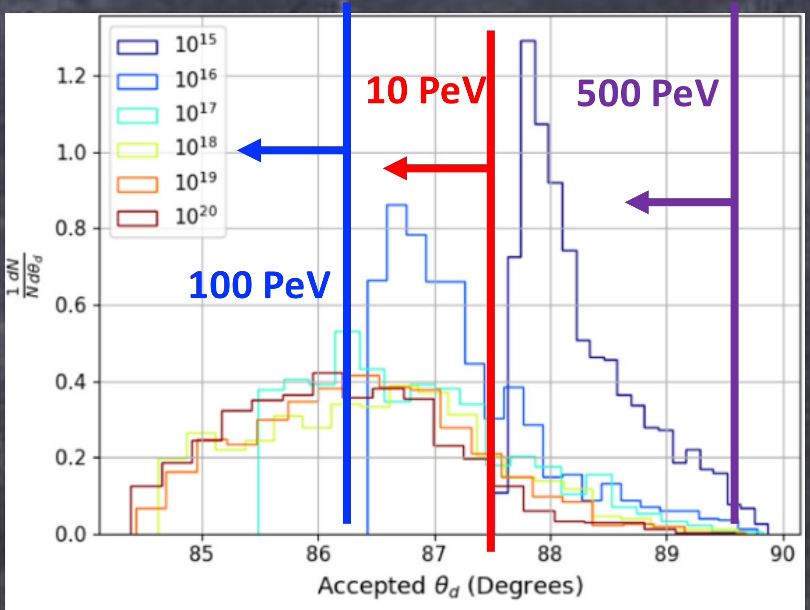


Need to assess low energy spectra of brehm photons, in particular at X-ray energies

The rate of HaHa CR events w/PBR will be significant





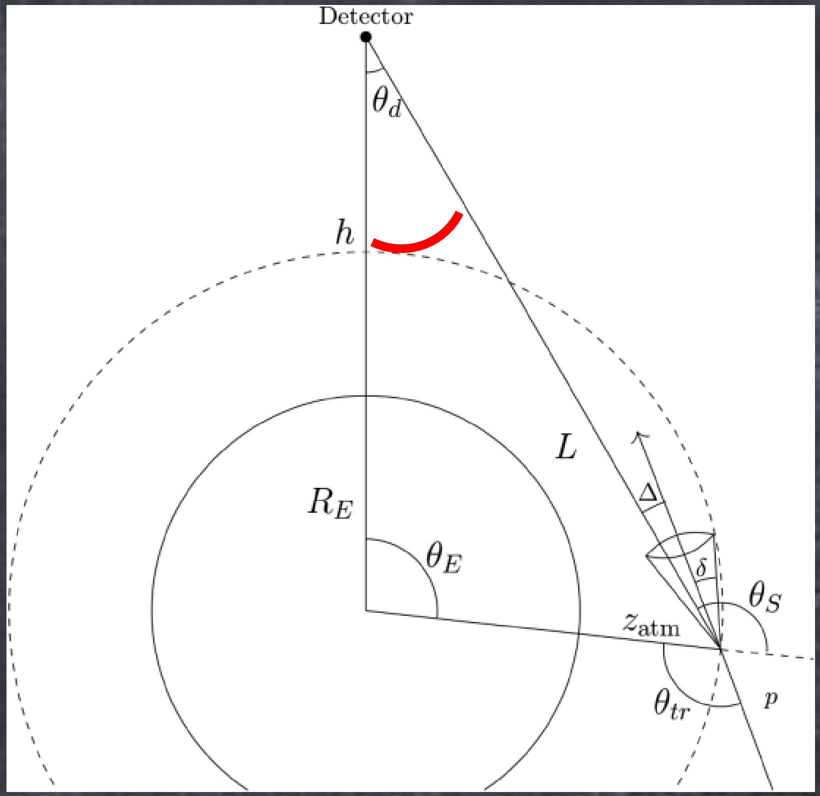


FIG. 1. Geometry of measuring the Cherenkov signal from cosmic rays arriving from above the Earth horizon in the case of a space-based instrument.

> 500 TeV	> 10 PeV	> 100 PeV
~65 CRs/livehour	~3 CRs/livehour	~0.11 CRs/livehour

SPB2 CT: A_{EFF} = 0.68 m^2, 6.4° x 12.8° angular span (Δnadir vs Δazimuth angles), 0.4° pixel size

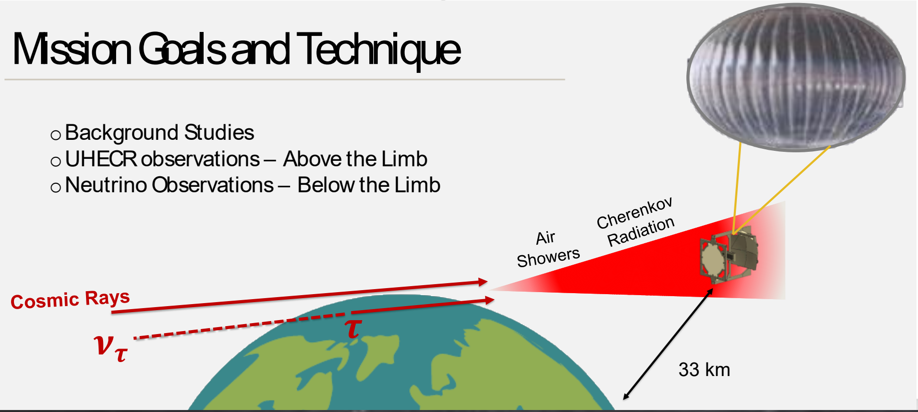
Earth's Atmosphere acts as an energy filter due to increased Cherenkov light attenuation as the viewing angle from nadir θ_d gets close to that for the limb (θ_{LIMB} = 84.2°)

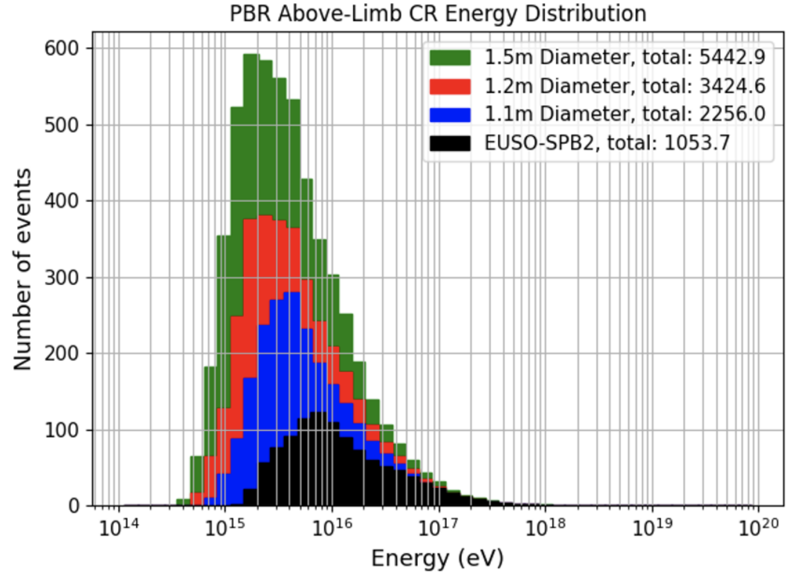
Austin’s EASCherSim studies: PBR should have lower E_{Thr} and ↑ CRrate

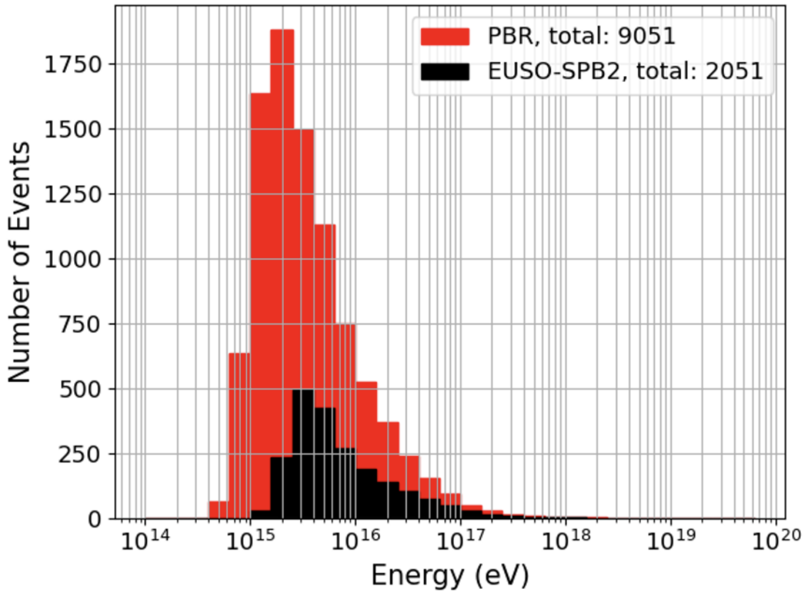
Note:
iFoV = 0.2 deg : PBR
iFoV = 0.4 deg : EUSO-SPB2

Result

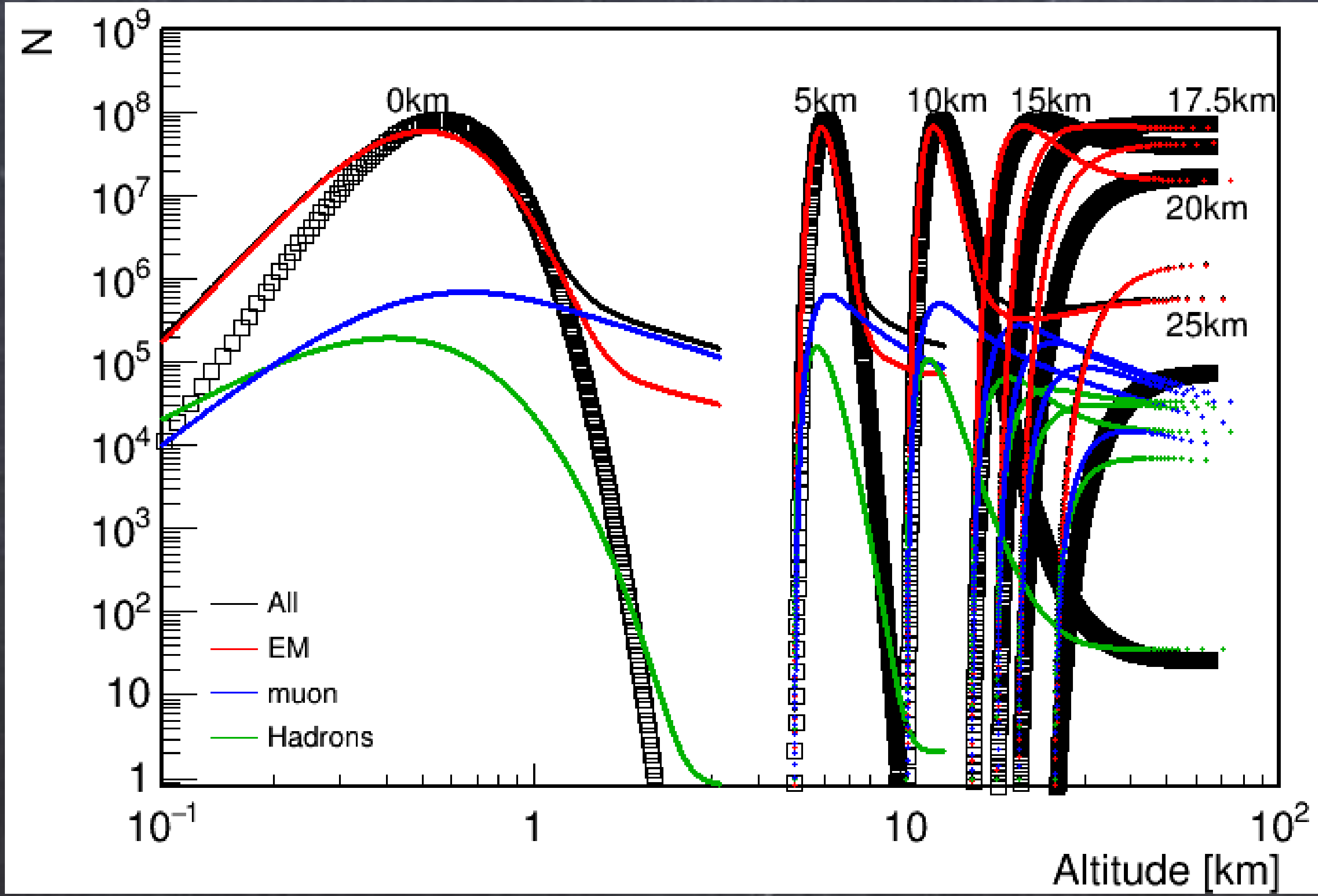
- Total event rate increase x2
  - ~9000 over 30d flight, ~62.5/h
- Important energies:
  - Threshold: 700TeV → 400TeV
  - Max sensitivity: 4PeV → 2PeV
- Curves are generated only for protons
  - Heavier primaries would result in more events (~2 drop in threshold)





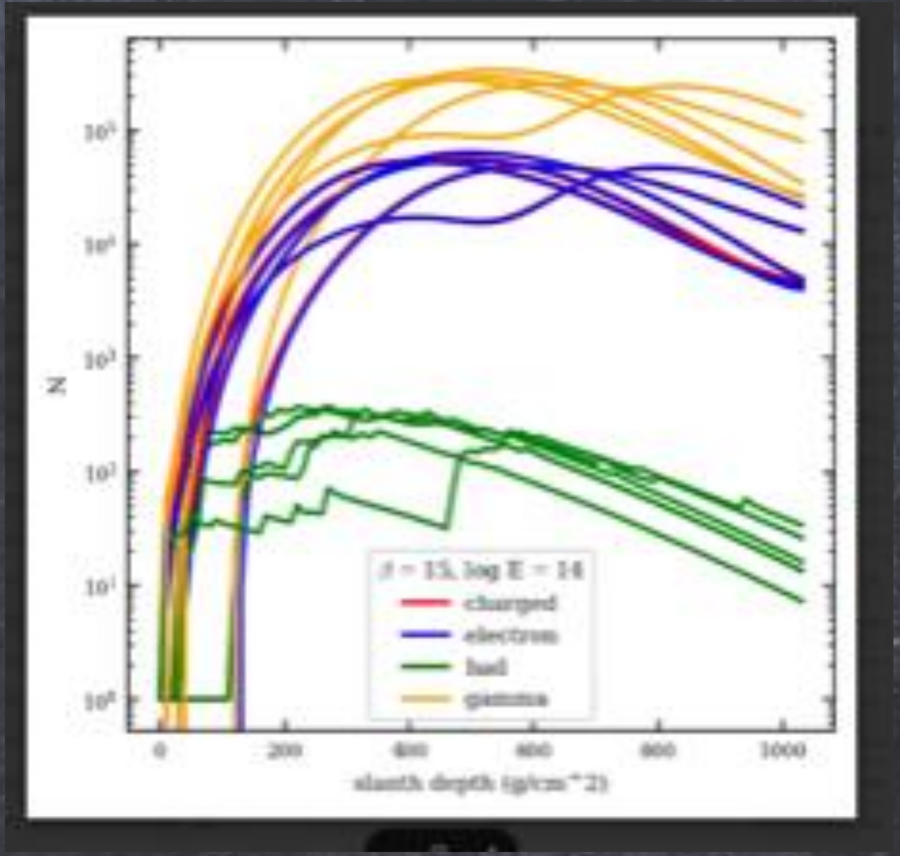


EAS development can be' frozen' in the rarified atmosphere and can have modified longitudinal profiles …



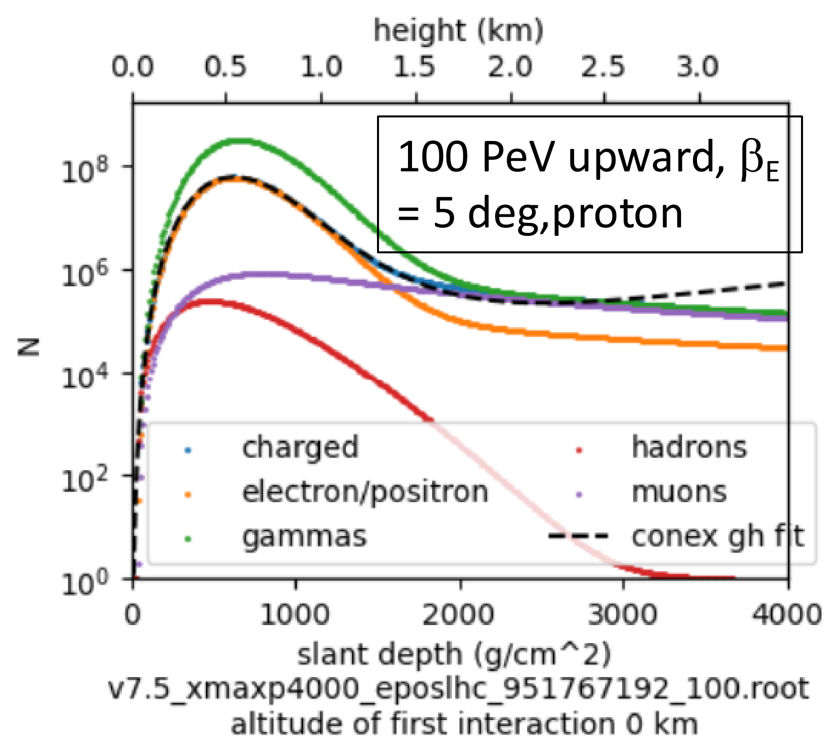
100 PeV upward, β_E = 5 deg,proton

CONEX Simulation Results

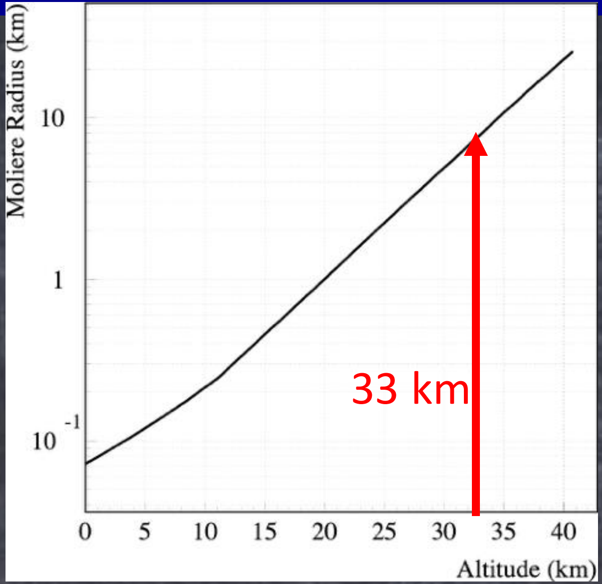


100 TeV upward, β_E = 5 deg, proton starting at 10 km altitude

EAS components densities in the rarified atmosphere …

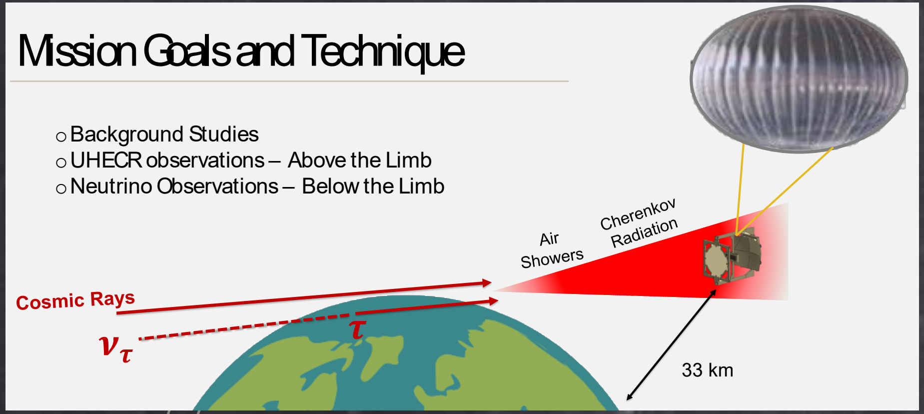


- At 33 km altitude, pressure is < 0.1 atm -> EAS width at Xmax (Moliere radius) ~ 8 km
- If N=10^8 particles, then get < 1e-4 particles/cm^2 from bulk (EM component) of EAS



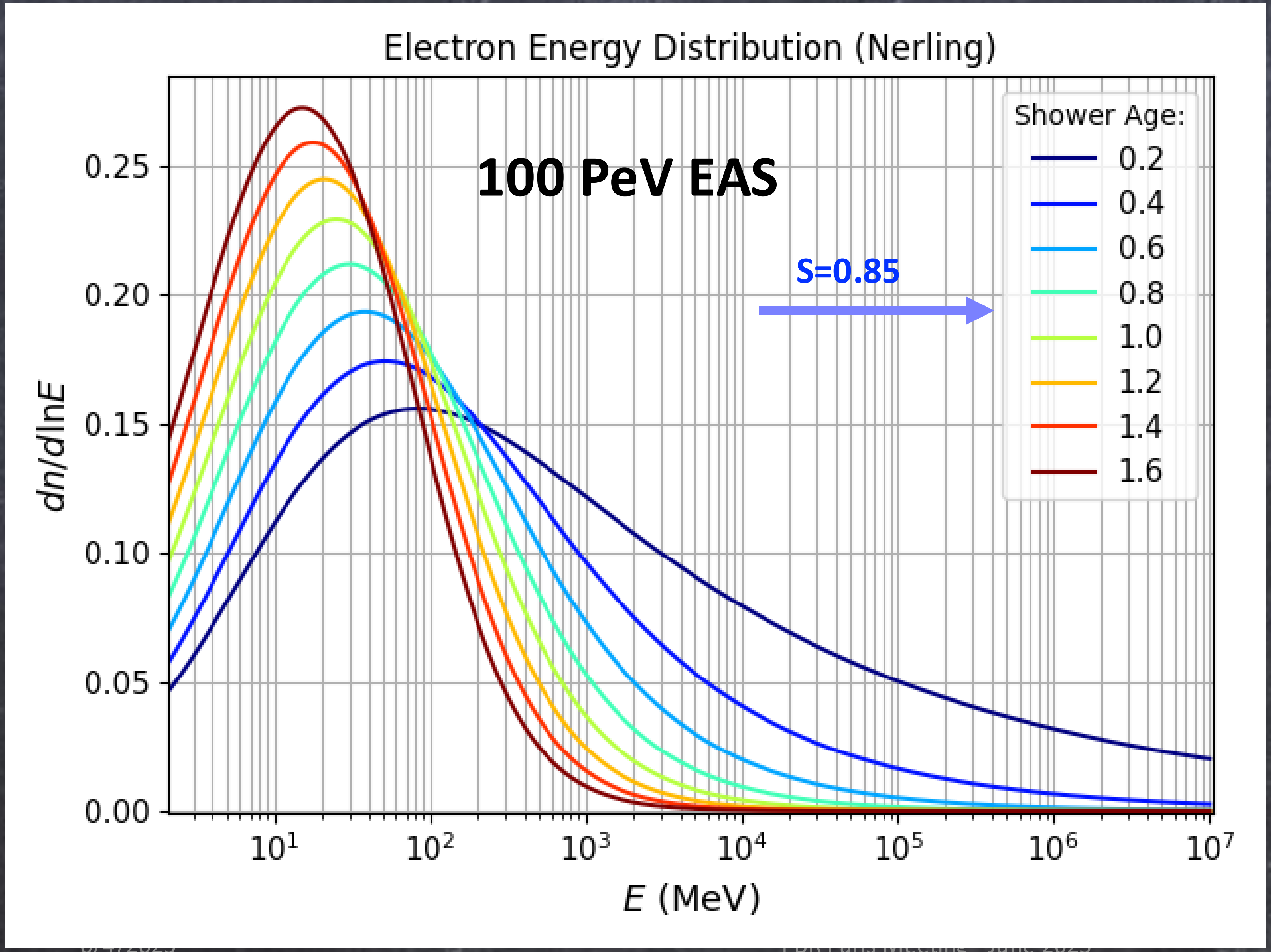
$$\rho(R) = \frac{N_e}{2\pi R_M^2}\, C(s)\, \left(\frac{R}{R_M}\right)^{(s-2)} \left(\frac{R}{R_M} + 1\right)^{(s-4.5)}$$

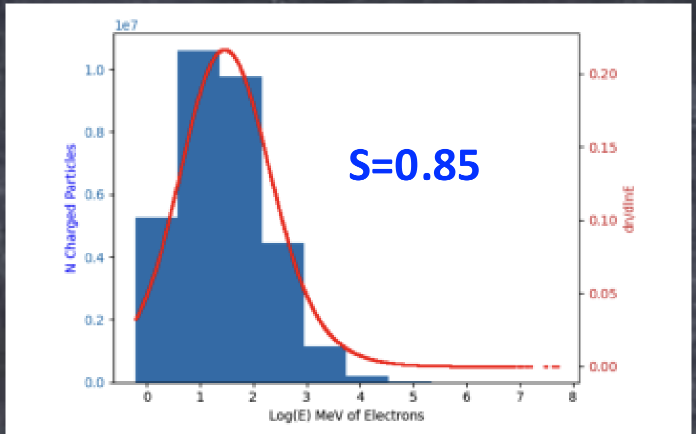
NKG formula: $0.8 < s < 1.6$



- **If measurements occur earlier in shower age, EAS still has a strong core which would increase charged particle density.**

EAS $e^{+/-}$ population vs shower age: Initial results from CORSIKA





(b) Electron energy distribution that I generated for a 100 PeV cosmic ray event with a downward going EAS observed at the shower age of, s = 0.85. Zenith angle was set to $\theta = 5°$.

Results from initial CORSIKA runs accessing $e^{\pm}$ 4-momentum

EAS trans-TeV $e^{+/-}$ generated: Initial results from CREST experiment studies

S. Coutu et al. / Nuclear Physics B (Proc. Suppl.) 215 (2011) 250–254

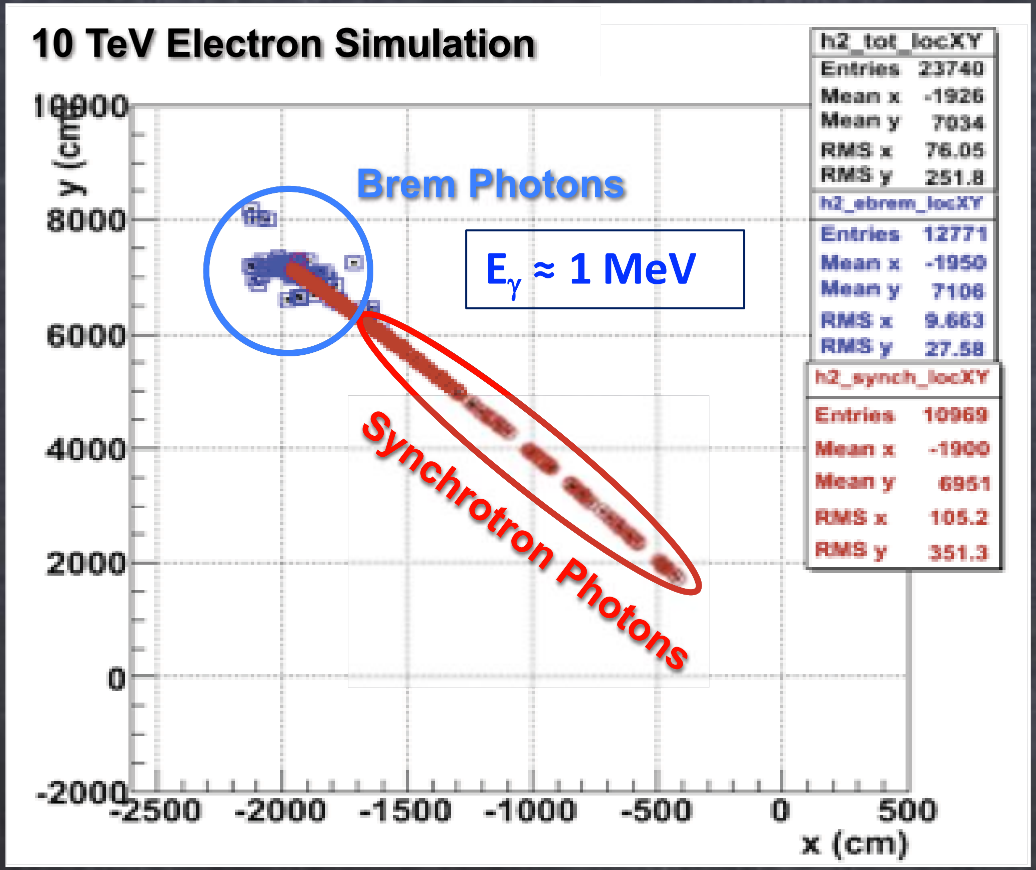


Figure 3. Example of a simulated x-ray photon geometric distribution at balloon altitudes for a 10 TeV incident electron.

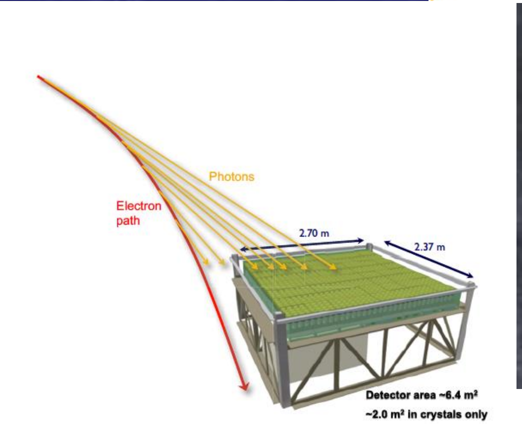
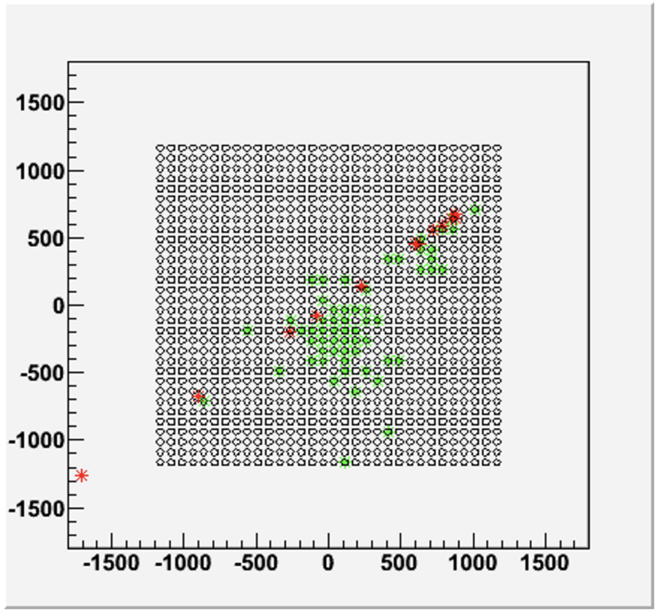


Figure 2. Schematic representation of the CREST payload layout and the electron detection technique via the geosynchrotron x-ray photons.

Example brem event

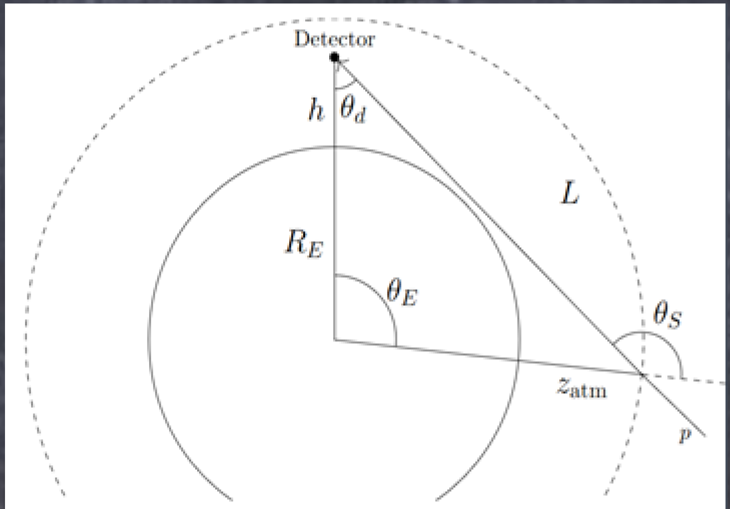


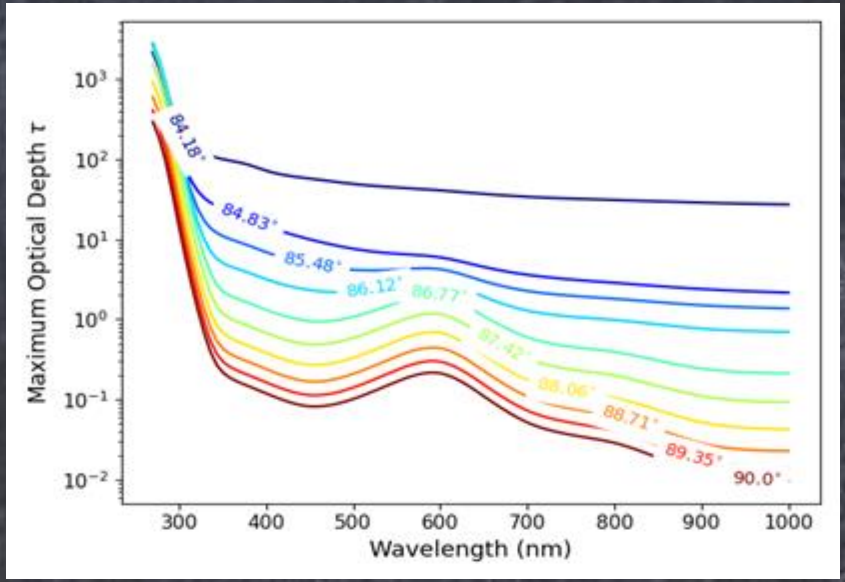
Red=photons from Crestmag thrown at CREST

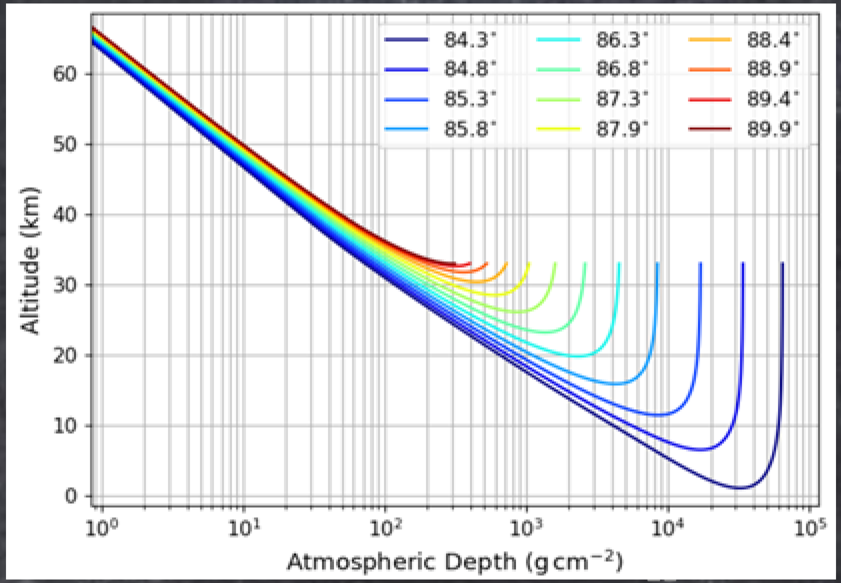
Green=crystals with E_{dep}>40keV

4 brem photons in this event

EASVAEL have very large range of optical attenuation correlated to slant depths







- Non-insignificant amount of grammage for shower development
  - Typical EAS develop over ~1000g/cm^2
  - >100g/cm^2 even above θ_D = 90° for balloon altitudes

- Atmospheric extinction is minimal
  - Dominated by ozone absorption

EAS Cascade Development Primer

Significant EAS energy put into EM component at very early EAS stage ….

Can we use this to study the EAS itself including probing hadronic interactions?

Pion Counting

1st Interaction

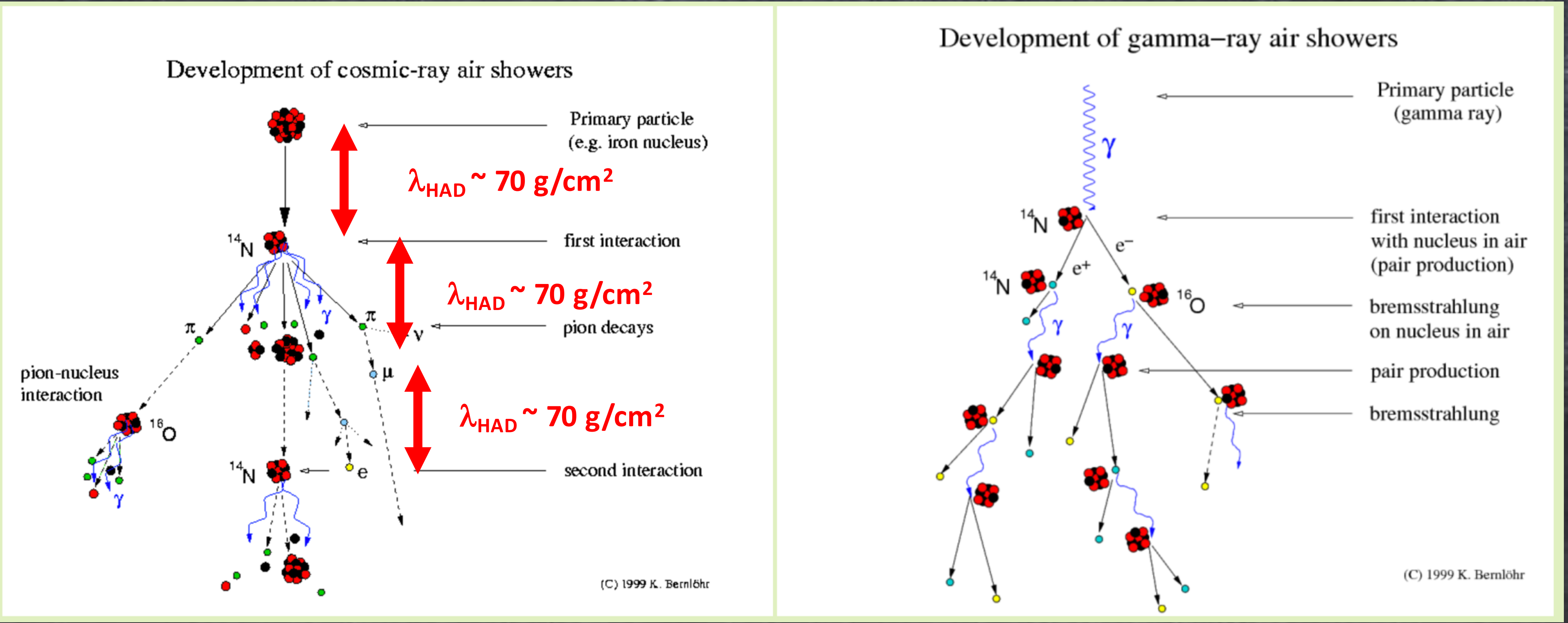
π^+ , π^- , π^0
(2/3 hadronic, 1/3 EM)

2nd Interaction

π^+ , π^- , π^0
(4/9 hadronic, 5/9 EM)

3rd Interaction

….



https://www.mpi-hd.mpg.de/hfm/CosmicRay/Showers.html

Radio work from νSpaceSim Development: Saturation of geomagnetic radiation for high-altitude EAS

Simulations of Upgoing EAS Observed from Low-Earth Orbit Andrés Romero-Wolf

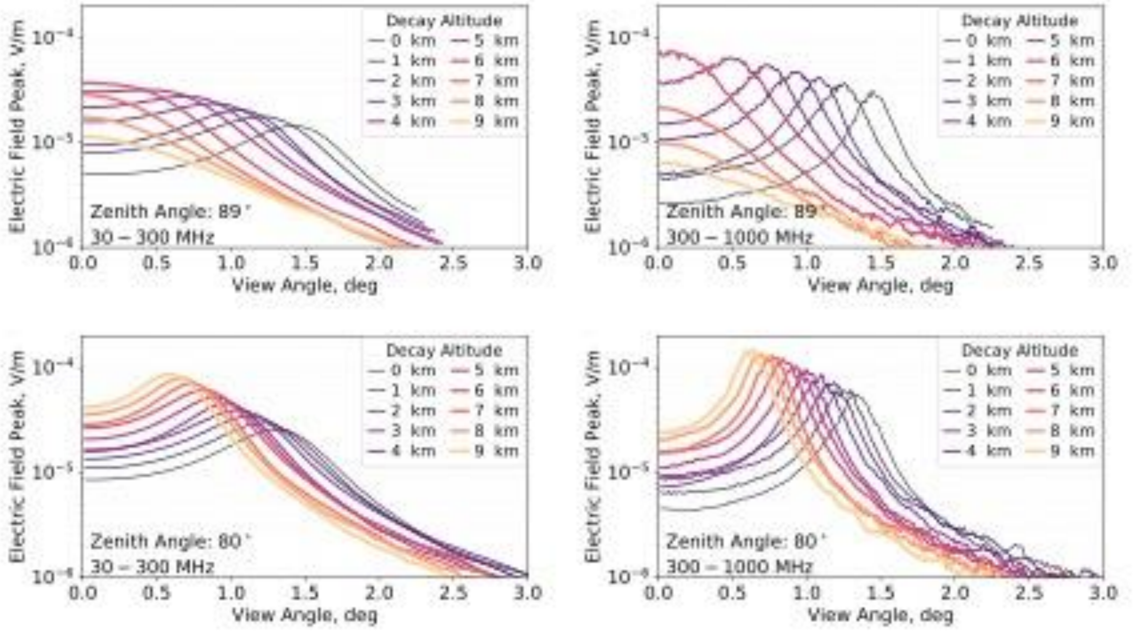


Figure 4: Radio emission profiles upgoing extensive air shower from a tau decay at ground altitude observed at 525 km. Top left is for a shower zenith angle of 89° in the 30-300 MHz band while top right is for the same zenith angle in the 300-1000 MHz band. The bottom left and right at for a shower zenith angle of 80° in the 30-300 MHz band (bottom left) and 300-1000 MHz band (bottom right).

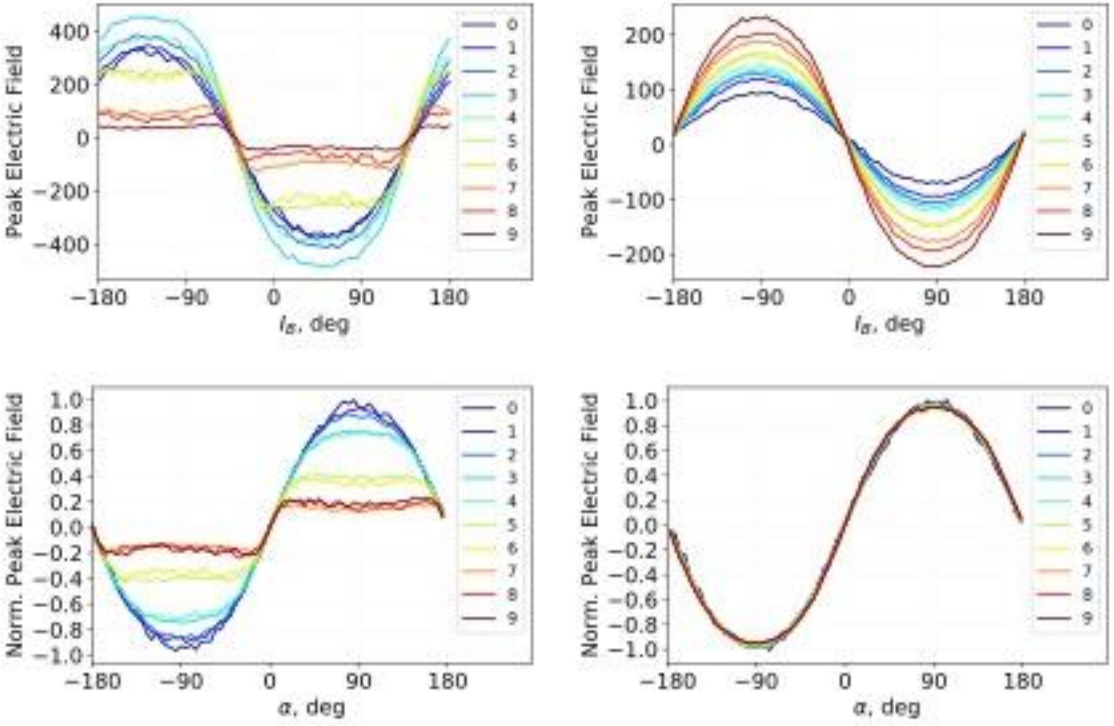


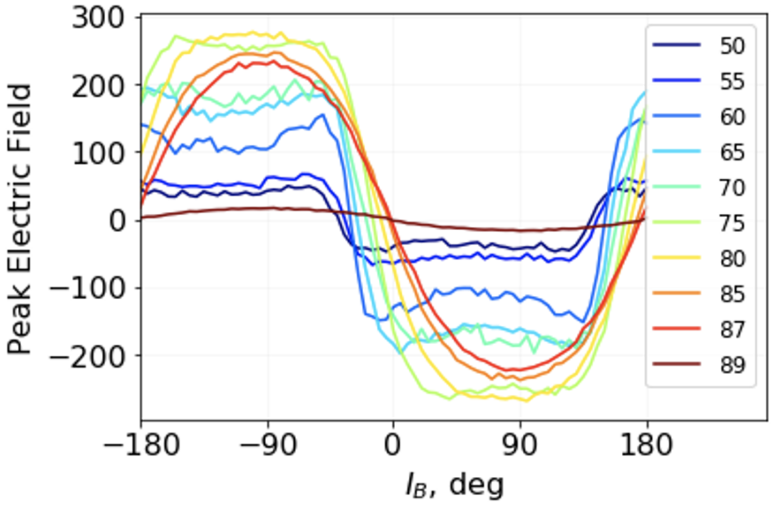
Figure 5: Geomagnetic field angle dependence on radio emission. Top left: the peak electric field value as a function of geomagnetic field inclination angle I_B for a 50° zenith angle shower. The colors indicate the decay altitude of each shower. Bottom left: the trends in the plot above have been fitted to a clipped sine wave and normalized by the peak amplitude of the fitted sinusoid and plotted in terms of the angle between the geomagnetic field vector and the shower axis (α) to illustrate the effect of the geomagnetic emission clipping fraction. Right top and bottom are the same as the left top and bottom, respectively, but for a shower zenith angle of 87°.

[PoS(ICRC2021)1031]

Radio work from Austin Cummings

Radio

- Results from past simulations:
  - Saturation effect of electric field w.r.t the geomagnetic angle I_B at high altitudes
  - Large decrease in Electric field from $\theta_{EE} = 87° \rightarrow \theta_{EE} = 89°$
- Active simulation efforts to improve the modeling in ZHAireS



Fixed 9km decay altitude with different Earth emergence angles (red is steep)

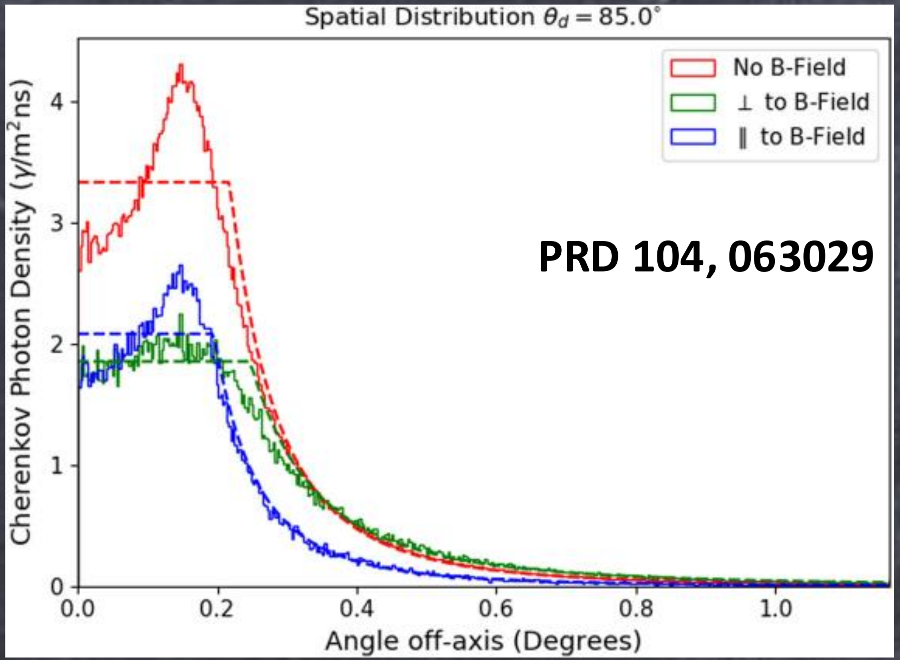
PennState

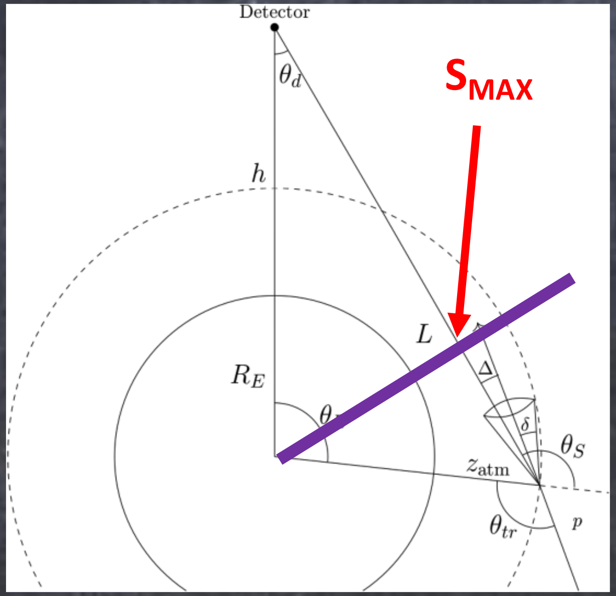
'Elevator-Level' Science Summary CR & EAS Science

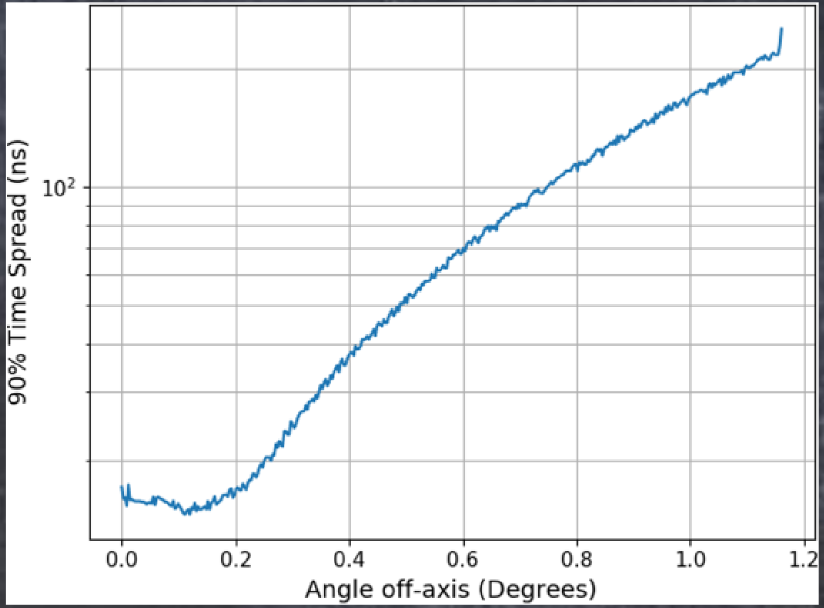
1. How does the cosmic ray nuclear composition evolve in the energy range 500 TeV to 1 EeV, which spans the energy range between direct and indirect cosmic ray measurements.
   - PBR will use a new technique using Optical Cherenkov and geomagnetic radio from EAS to perform these measurements (different measurement with different systematics than measuring particle content on the ground, e.g. IceTop, KASCADE, etc.
   - Method has history with non-imaging Cherenkov techniques on the ground, e.g. NICHE.
2. Using the unique environment of the rarified atmosphere to measure the EAS electromagnetic development and evolution early in the EAS (and near the first interaction) to distinguish between primary CR (hadronic) interaction models.
   - Need to define what $e^{+/-}$ measurements early in the EAS can accomplish to distinguish between hadronic interaction models.

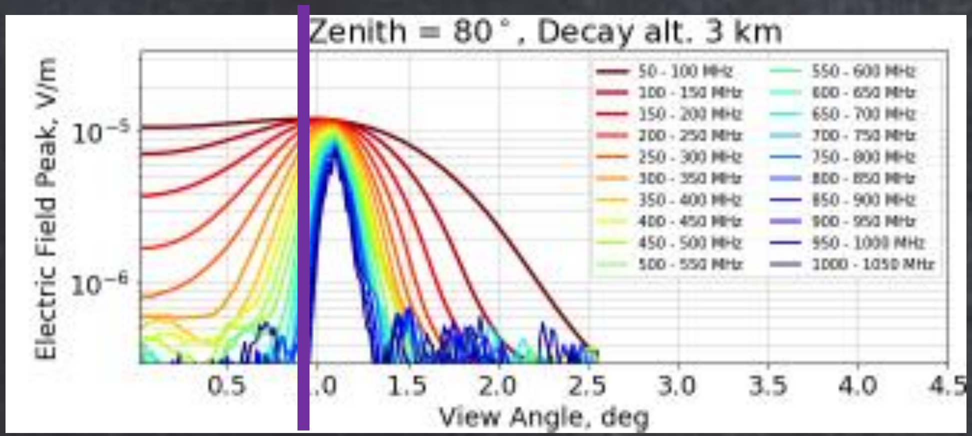
Cherenkov and radio signal dominated by S_{MAX} contribution

PHYS. REV. D 104, 063029 (2021)









Combination of optical and radio signal strengths (vs frequency) and temporal width of pulse provides location information that can be used to determine distance to S_{MAX}

Air Fluorescence

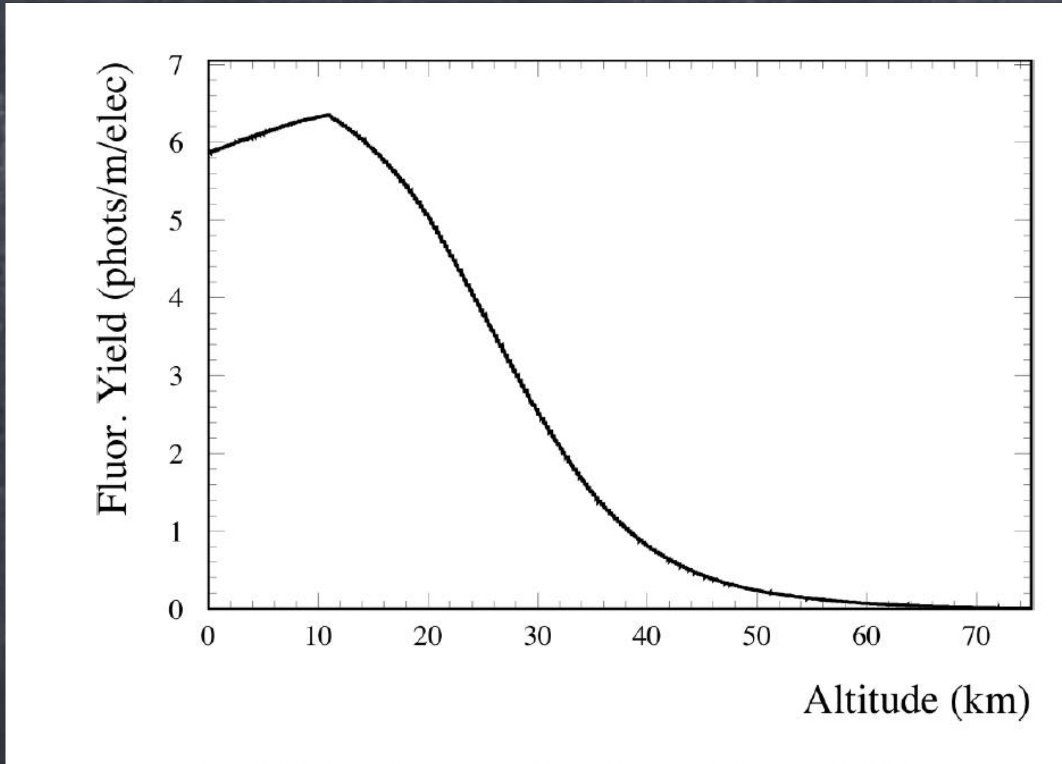
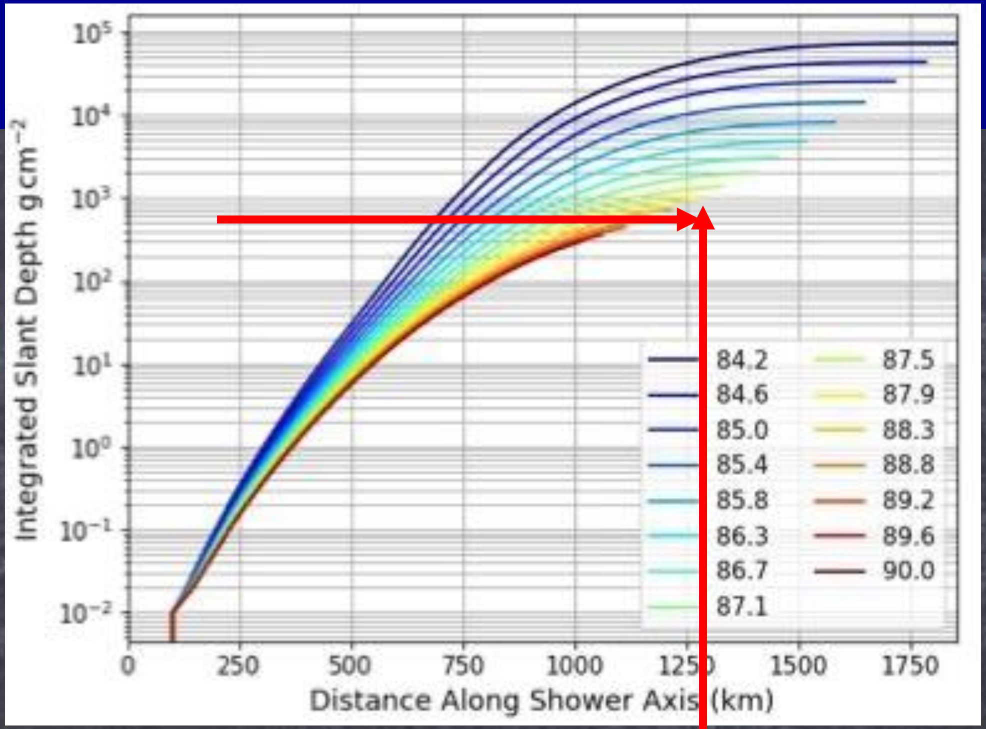
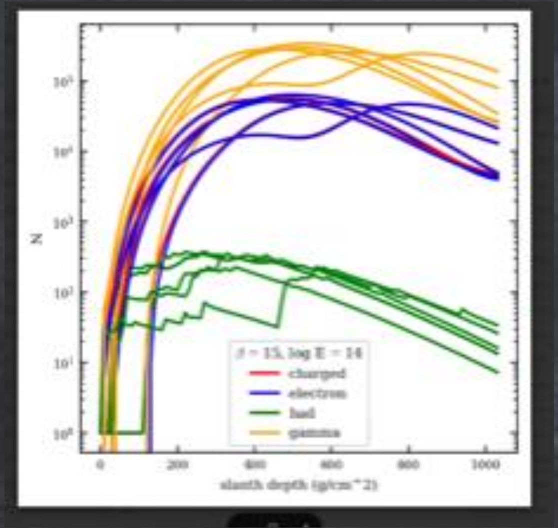


Figure 9: The air fluorescence yield as a function of altitude.



~1300 km

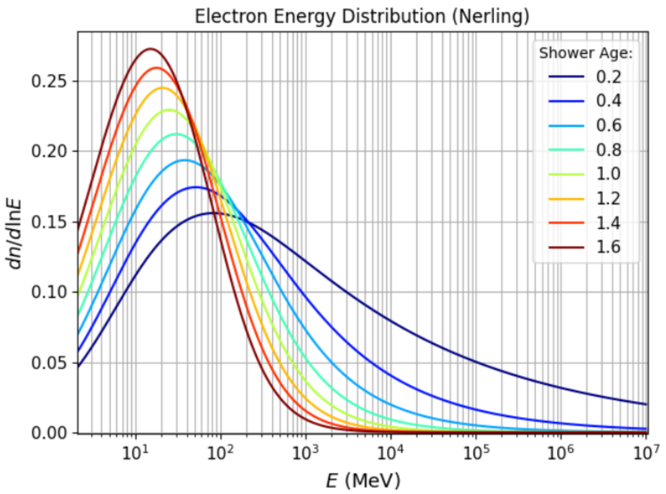


100 TeV upward, β_E = 5 deg, proton starting at 10 km altitude

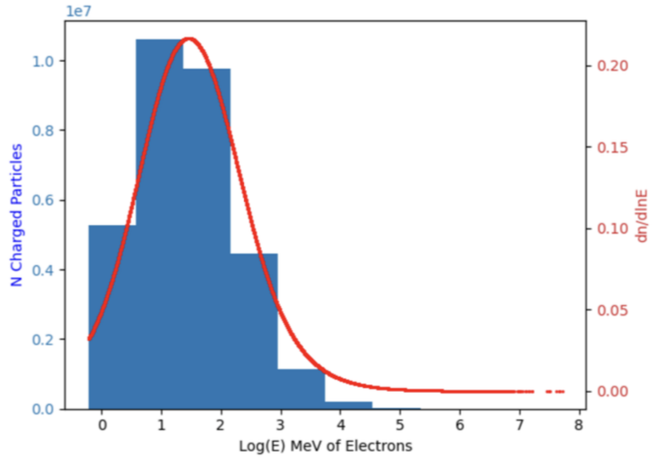
Initial CORSIKA Results by Mehreen Sultana

ISSUES:

1. If choose detector plane (measurement) at early shower age, do not have rest of EAS development, i.e. may not have EAS X_{MAX} for these events.
   - Need to reuse event random numbers to study full profile.
2. **Individual particle info is available in CORSIKA Particle data subblock.**



(a) The electron energy distribution[4] of a ...smic ray induced EAS as a func- ...er age determined by the Nerling ...Ref. [24].



(b) Electron energy distribution that I generated for a 100 PeV cosmic ray event with a downward going EAS observed at the shower age of, s = 0.85. Zenith angle was set to $\theta = 5°$.

...re 6: Characterization of a CORSIKA simulated 100 PeV induced EAS.[4]

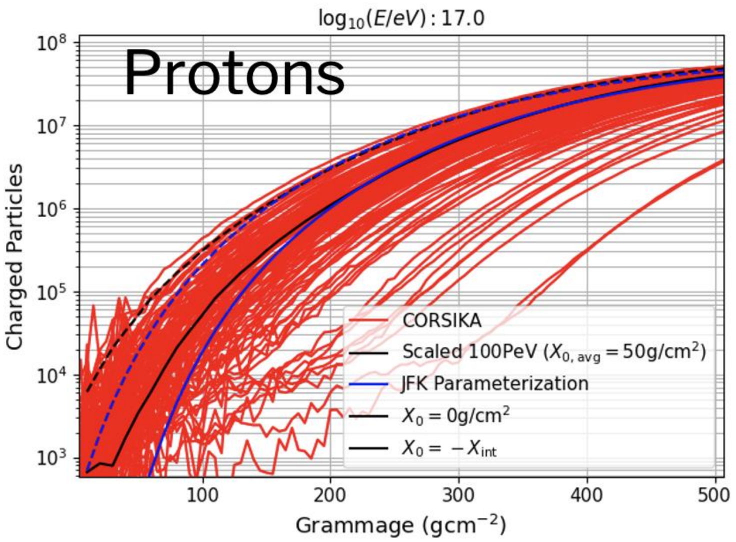
Particle data sub-block : (up to 39 particles, 7 words each)	
No. of word	Contents of word (as real numbers R*4)
$7 \times (n-1) + 1$	particle description encoded as: part. id×1000 + hadr. generation[101] × 10 + no. of obs. level [for additional muon information or id 95/96: part. id×1000 + hadr. generation[102]]
$7 \times (n-1) + 2$	px, momentum in x direction in GeV/c
$7 \times (n-1) + 3$	py, momentum in y direction in GeV/c
$7 \times (n-1) + 4$	pz, momentum in -z direction in GeV/c
$7 \times (n-1) + 5$	x position coordinate in cm
$7 \times (n-1) + 6$	y position coordinate in cm
$7 \times (n-1) + 7$	t time since first interaction (or since entrance into atmosphere)[103]in nsec [for additional muon information or id 95/96: z coordinate in cm]
	for $n = 1 \ldots 39$ if last block is not completely filled, trailing zeros are added

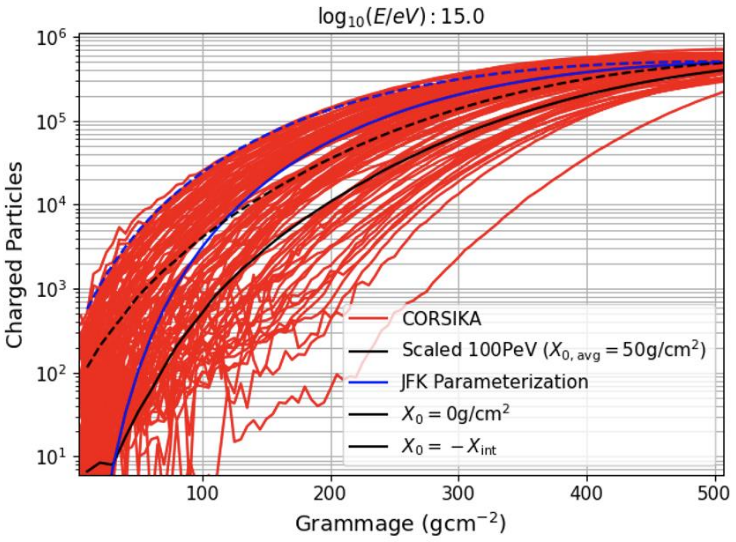
Table 10: Structure of particle data sub-block.

Longitudinal Profiles

- X0 has a huge effect on the number of electrons emitting near the detector
  - 2 orders of magnitude for Xtot < 300g/cm2

- Mistake in my Cherenkov calculations…
  - Using a scaled 100PeV profile to represent 1PeV underestimates particle content by a factor of ~3-10
  - Being in active shower development requires careful handling!





Early EAS Variability modeling from Austin Cummings

Longitudinal Profiles

- X0 has a huge effect on the number of electrons emitting near the detector
  - 2 orders of magnitude for Xtot < 300g/cm2
- Mistake in my Cherenkov calculations…
  - Using a scaled 100PeV profile to represent 1PeV underestimates particle content by a factor of ~3-10
  - Being in active shower development requires careful handling!
- Heavier nuclei add another factor of 2!