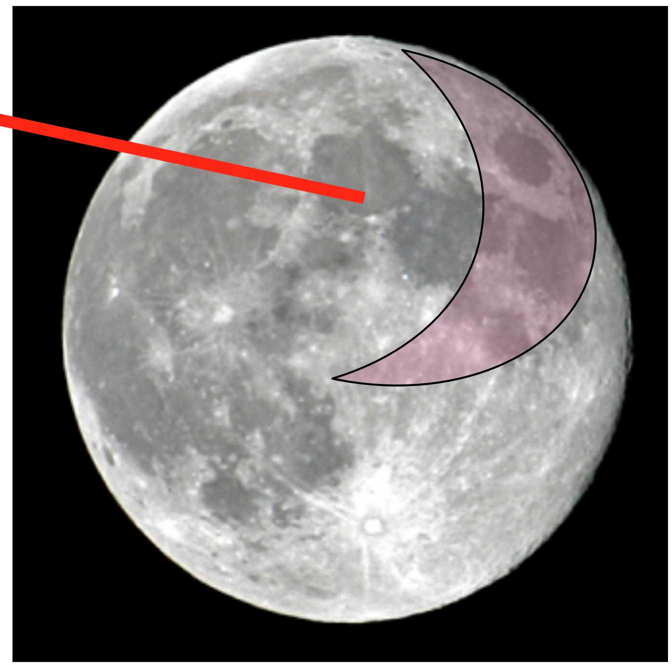
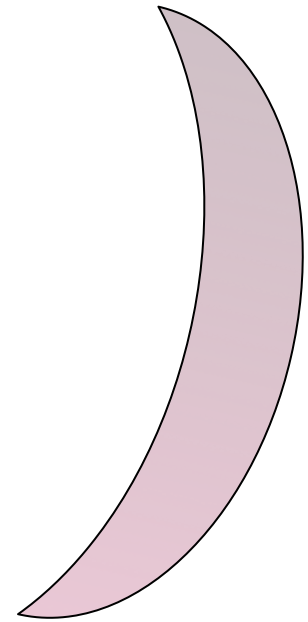
Constraints on ultra-high energy neutrino flux from radio observations of the Moon



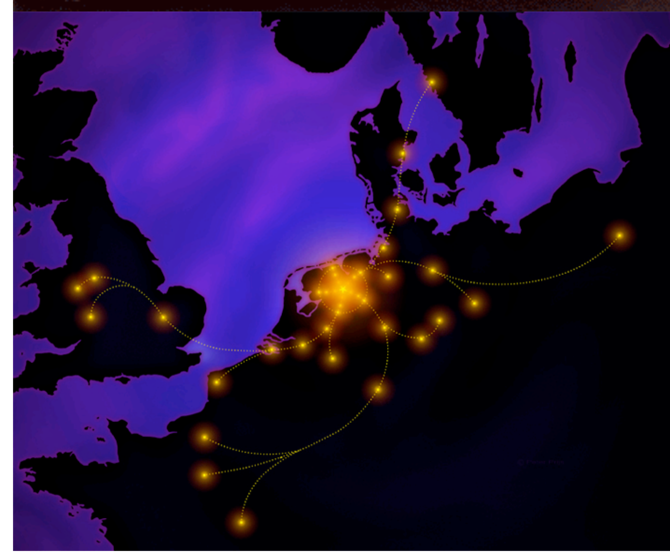


Stijn Buitink
Lawrence Berkeley National Laboratory

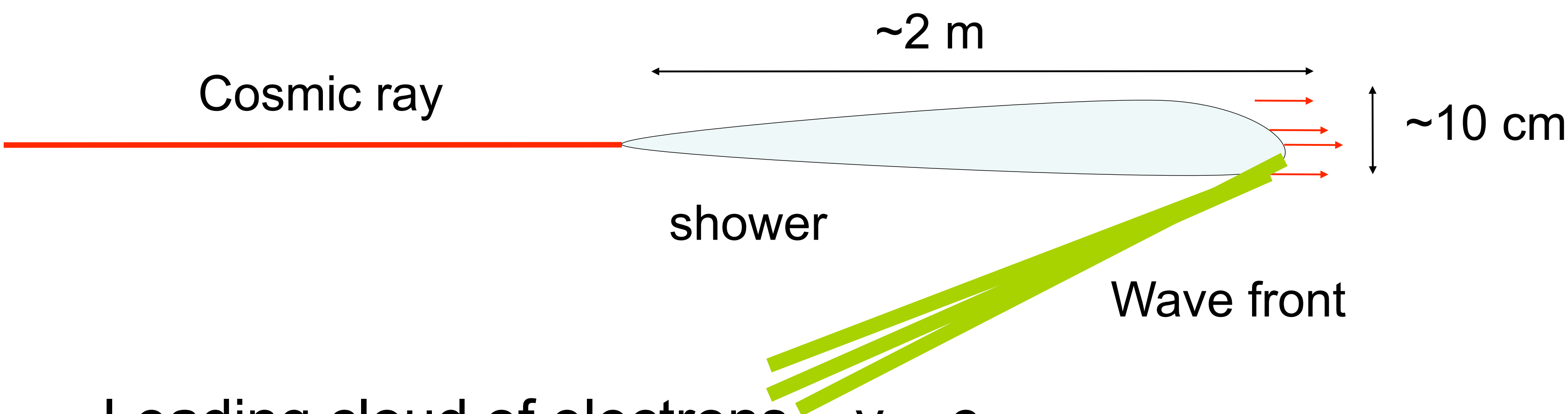
August 3 2010 - ECRS - Turku, Finland

The NuMoon Experiment

- Detecting radio signals from UHE neutrinos and CRs from the Moon
- Low frequencies <150 MHz
- Phase I: Westerbork Radio Synthesis Telescope (WSRT)
- Phase II: Low Frequency Array (LOFAR)



Askaryan effect: Coherent Cherenkov emission



- Leading cloud of electrons, $v \approx c$

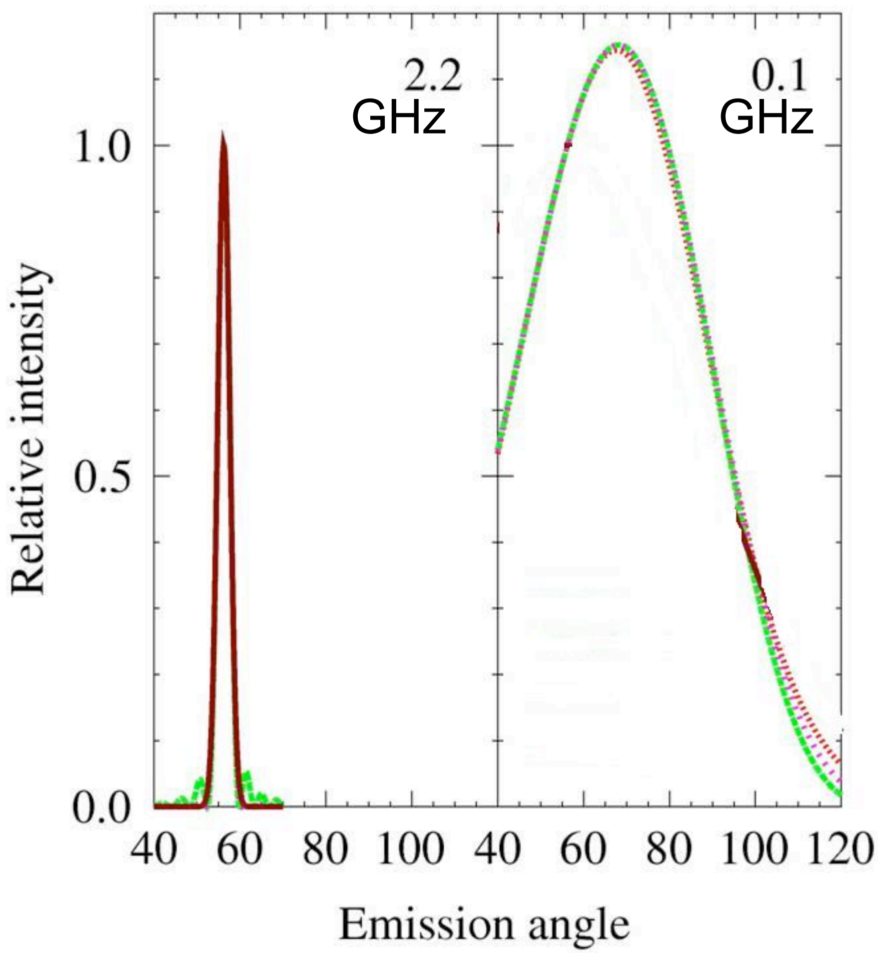
  Typical size of order 10cm

  Coherent Cherenkov for $\nu \leq$ 2-5 GHz

  $\cos \theta_c = 1/n$, $\theta_c = 56^o$ for ∞ shower length
- Length of shower, $L \approx$ few m

  Important for angular spreading

Spreading around Cherenkov-cone



Lunar regolith: n ≈ 1.8

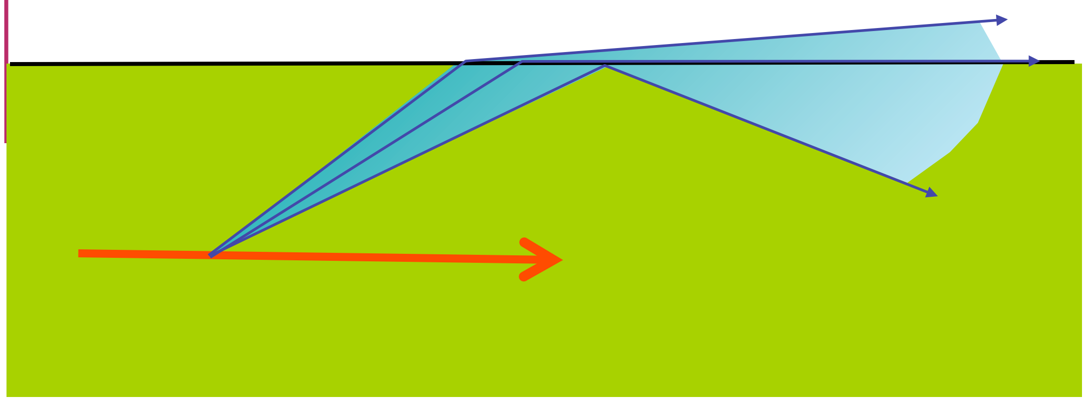
$$\chi = (n \cos\theta - 1)L/n\lambda$$

$$I_s(\theta) = \left[\frac{\sin\theta}{\sin\theta_c} \frac{\cos\pi\chi}{(1-2\chi)(1+2\chi)}\right]^2$$

Scholten et al. 2006

Reflection

Spreading is diminishing internal reflection

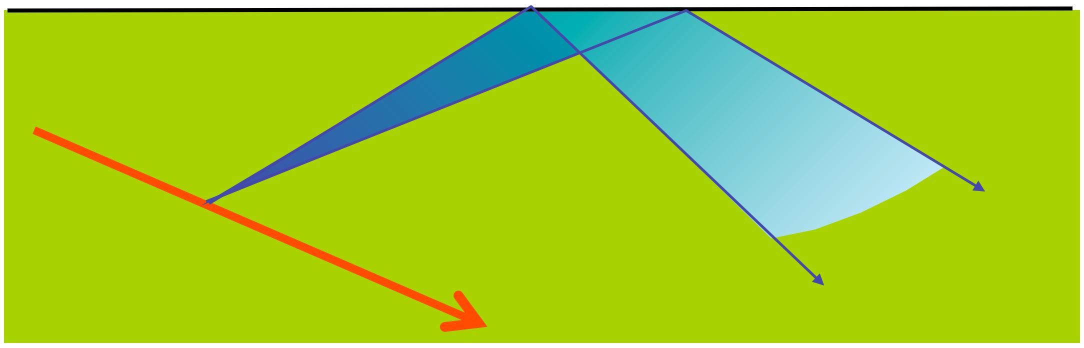


3 GHz

Reflection

Spreading is diminishing internal reflection

3 GHz



Reflection

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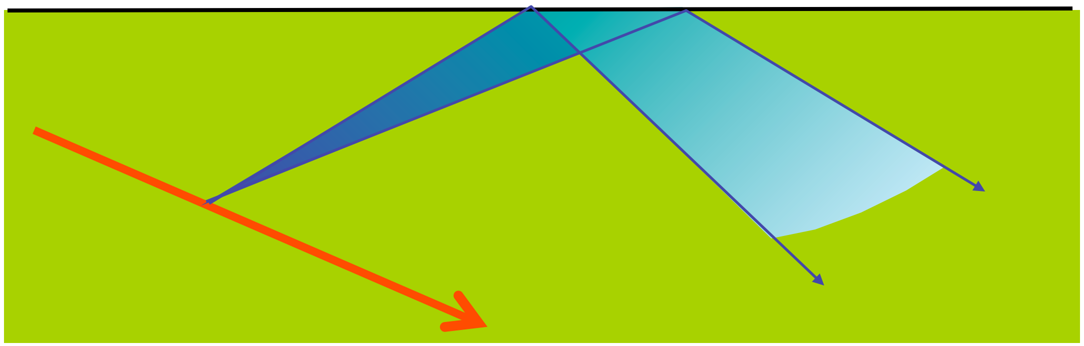
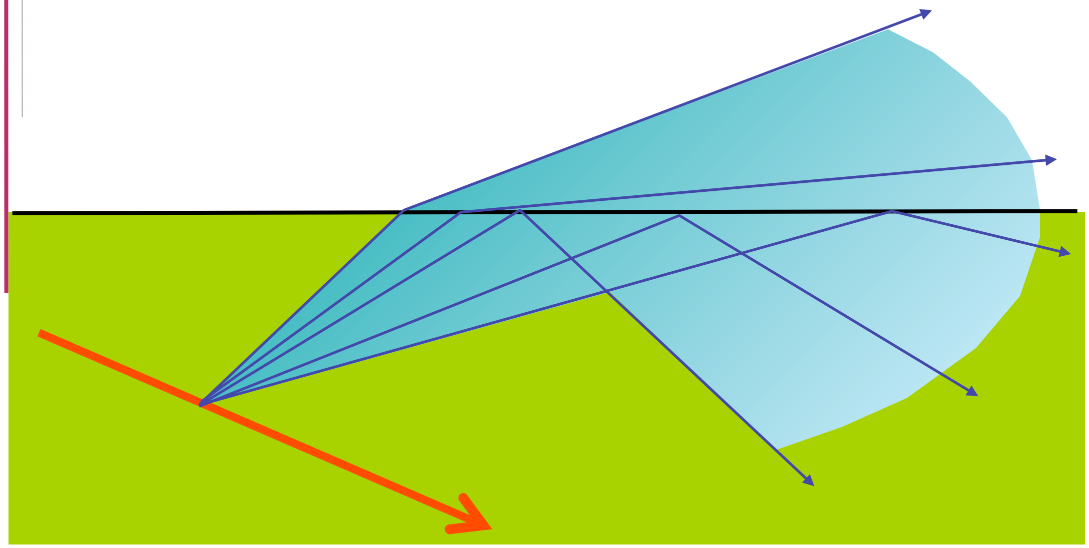


3 GHz

hi freq.: signal from rim of moon

Reflection

Spreading is diminishing internal reflection

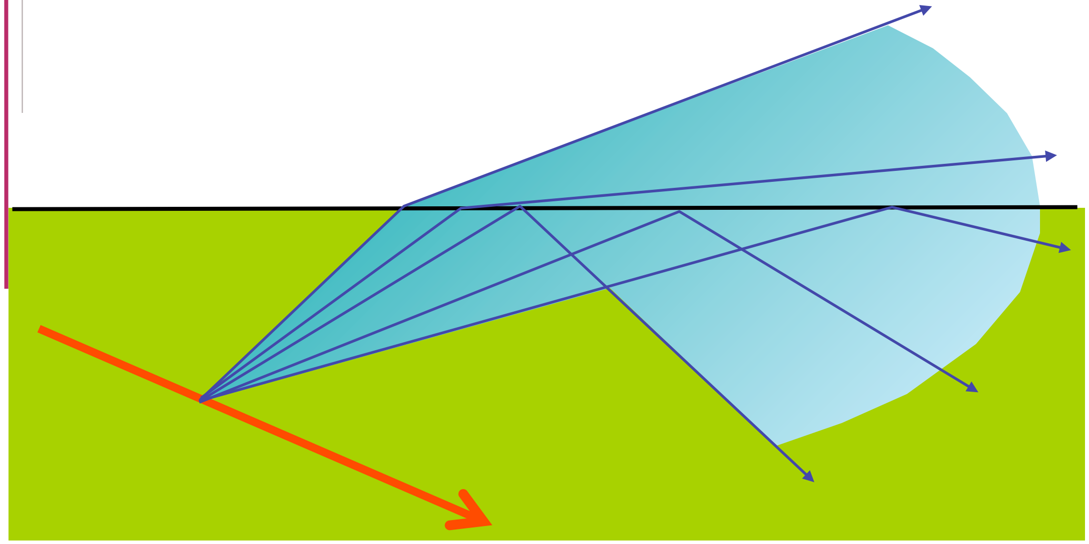


100 MHz

hi freq.: signal from rim of moon

Reflection

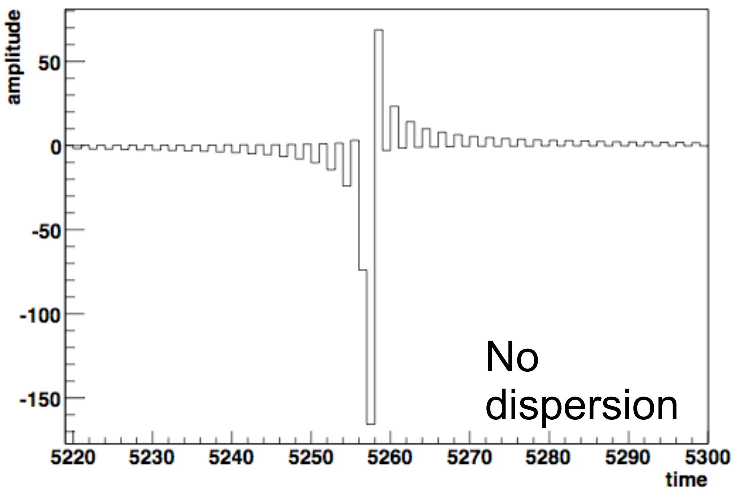
Spreading is diminishing internal reflection

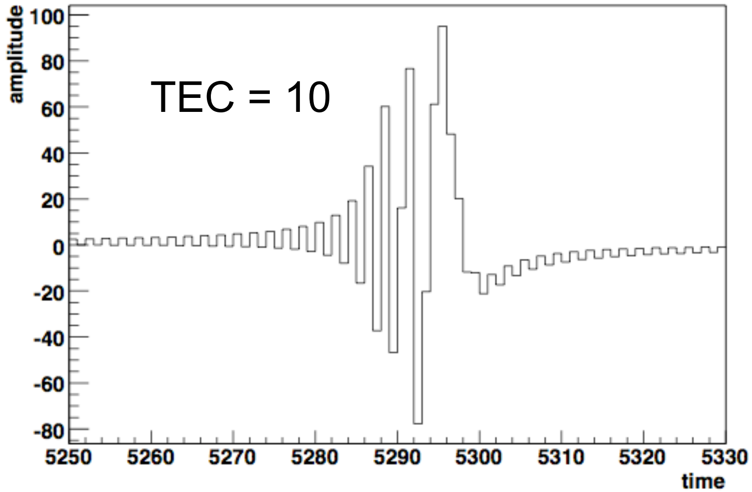


100 MHz

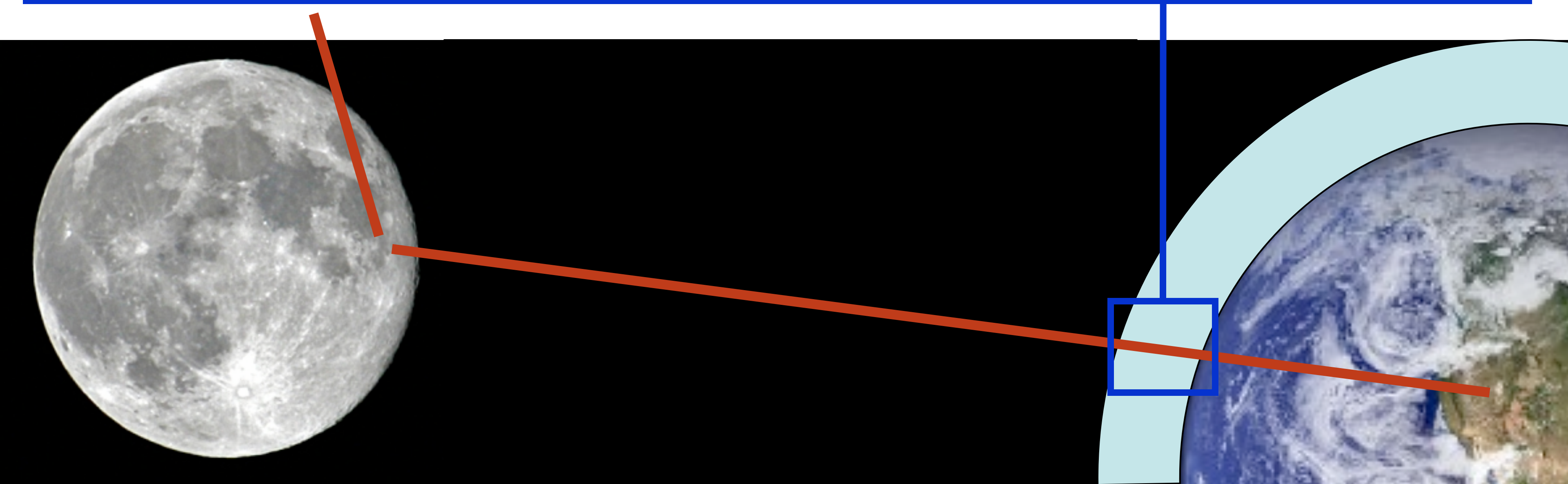
hi freq.: signal from rim of moon
lo freq.: signal from **whole Moon**

Earth ionosphere: dispersion & Faraday rotation





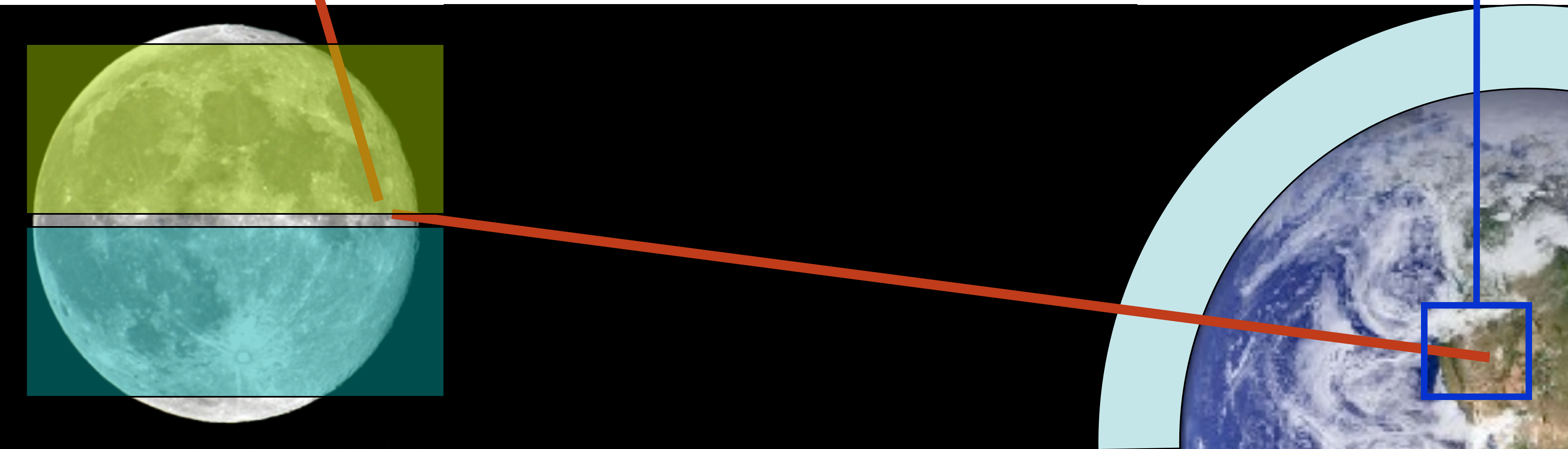
Bandwidth limited pulse, Nyquist sampled, linearly polarized



Westerbork Synthesis Radio Telescope (NuMoon phase I)

- range 113 -175 MHz
- split in four 20 MHz bands
- 11 x 25 m diameter dish
- 40 M samples/sec (PuMa2)
- full polarization information

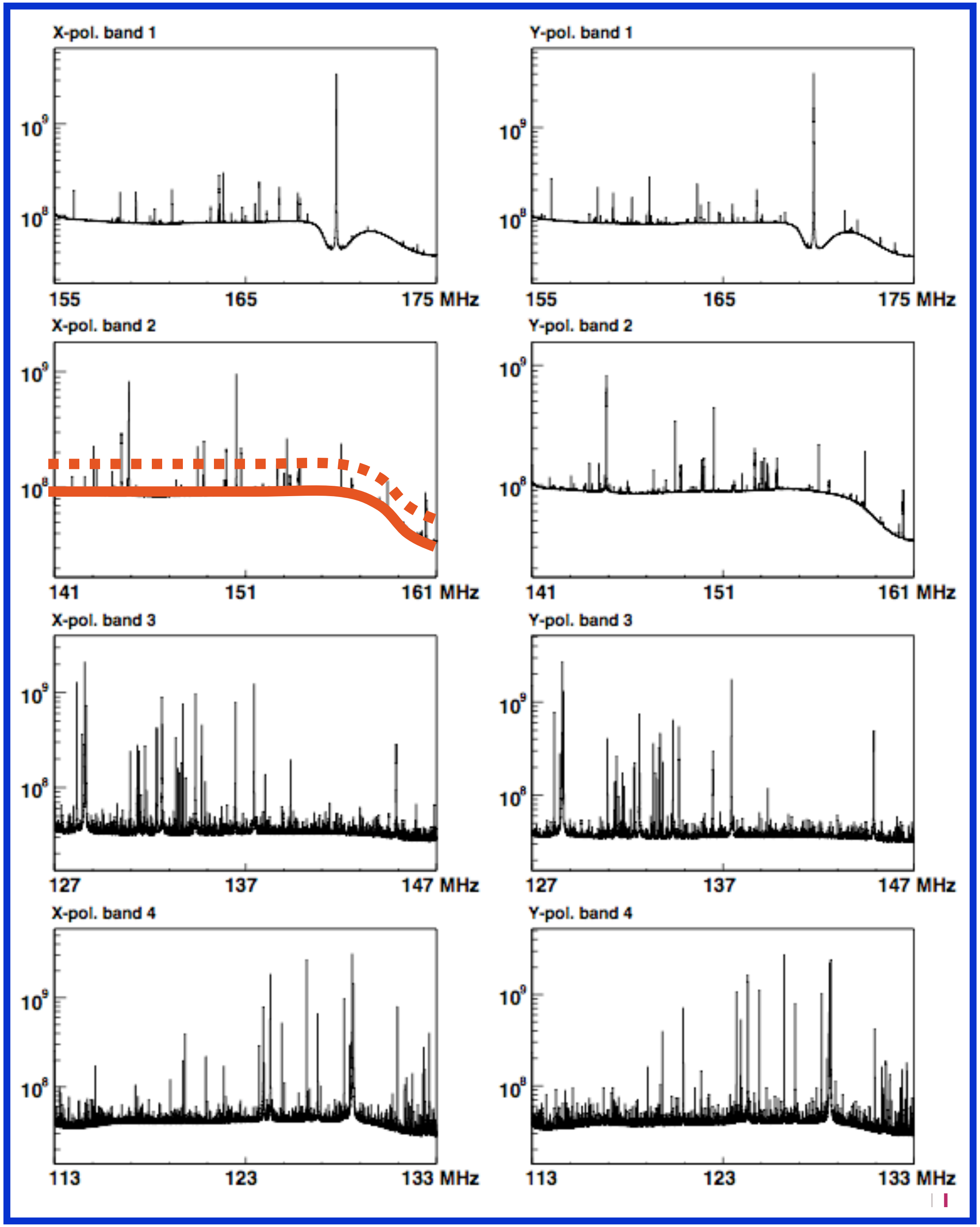
- 2 simultaneous beams

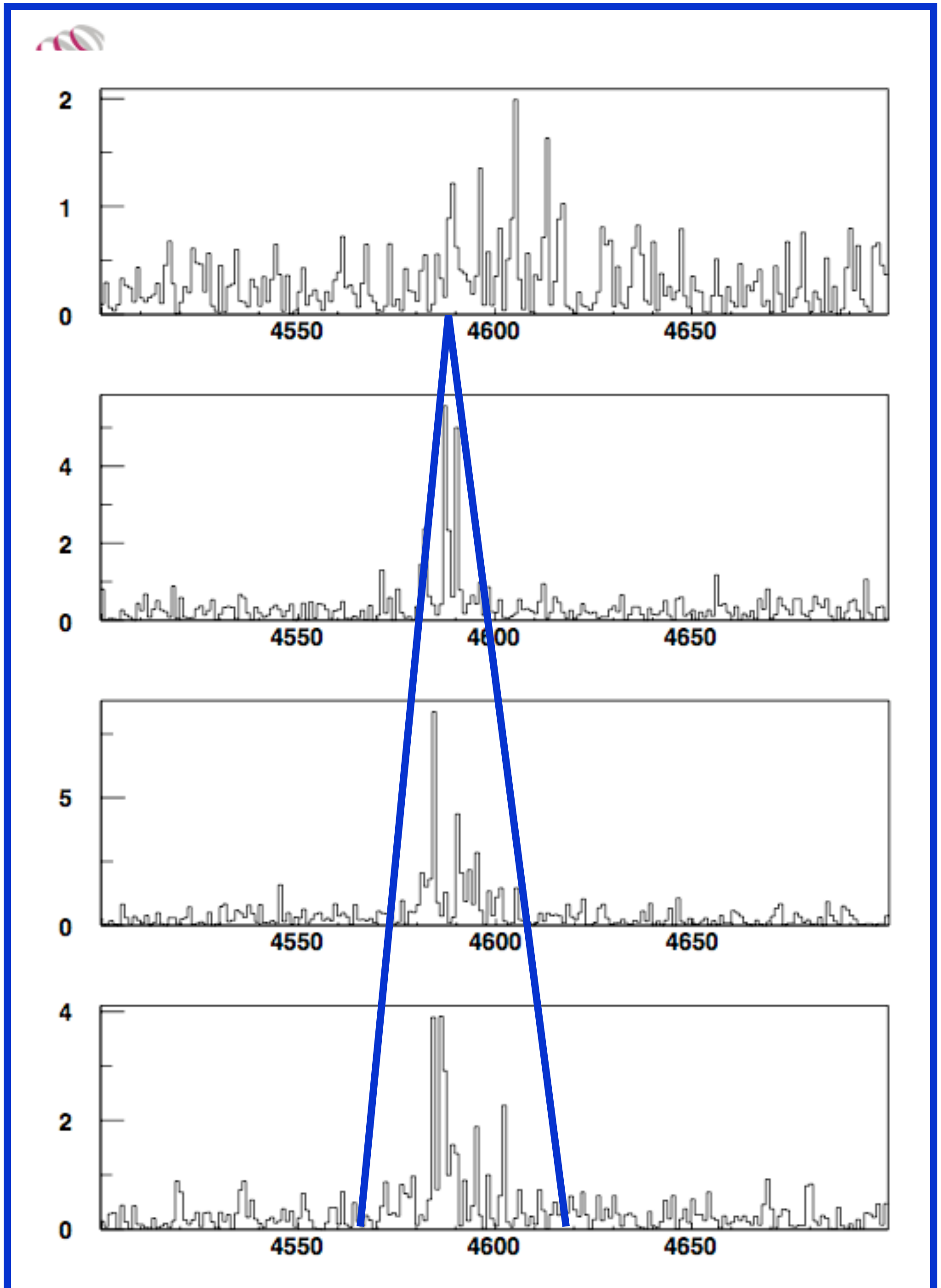


RFI cleaning

- 16 data streams:
  2 beams
  4 frequency channels
  2 polarizations

- For each stream
  - reduction of RFI
  - de-dispersion

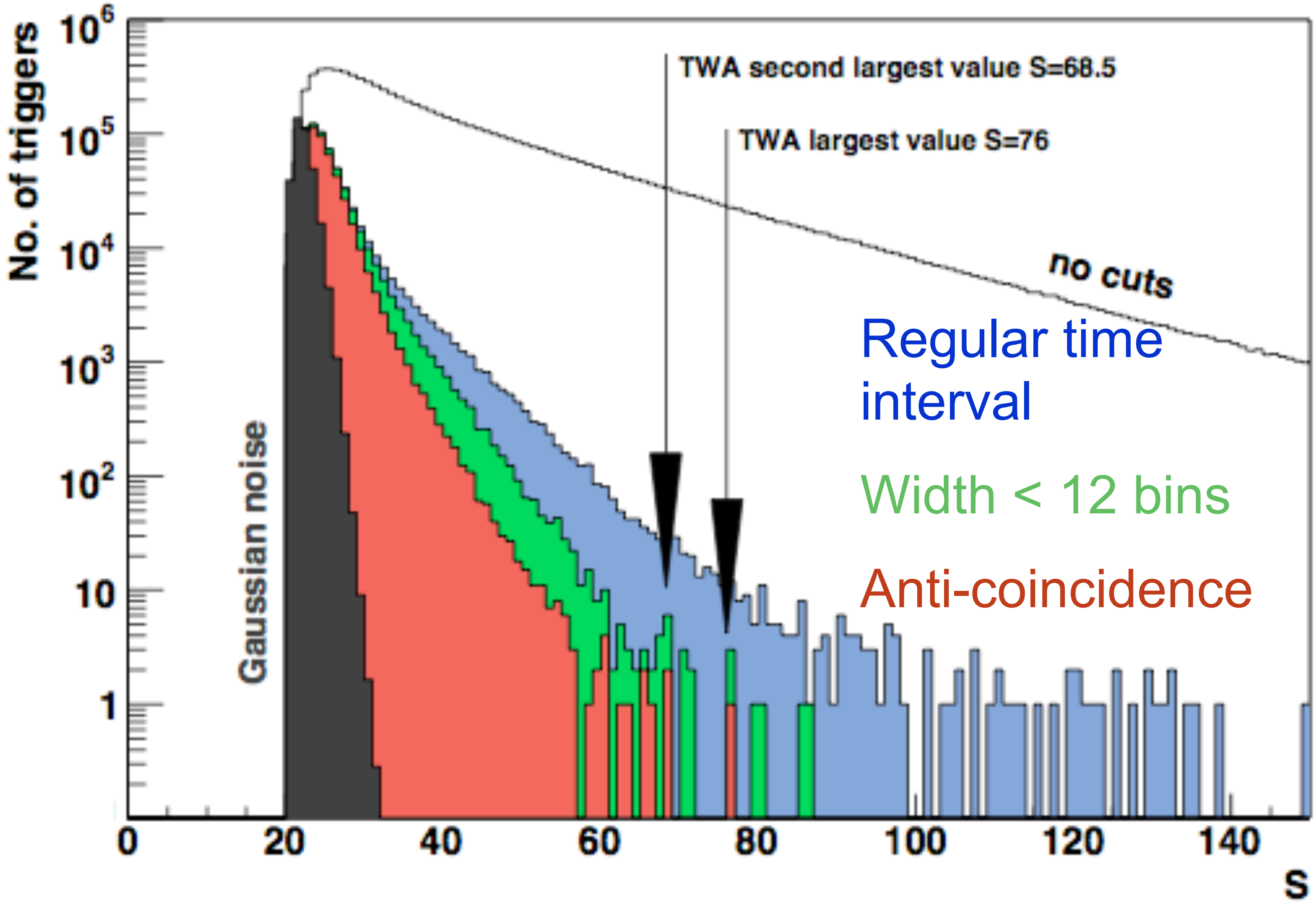




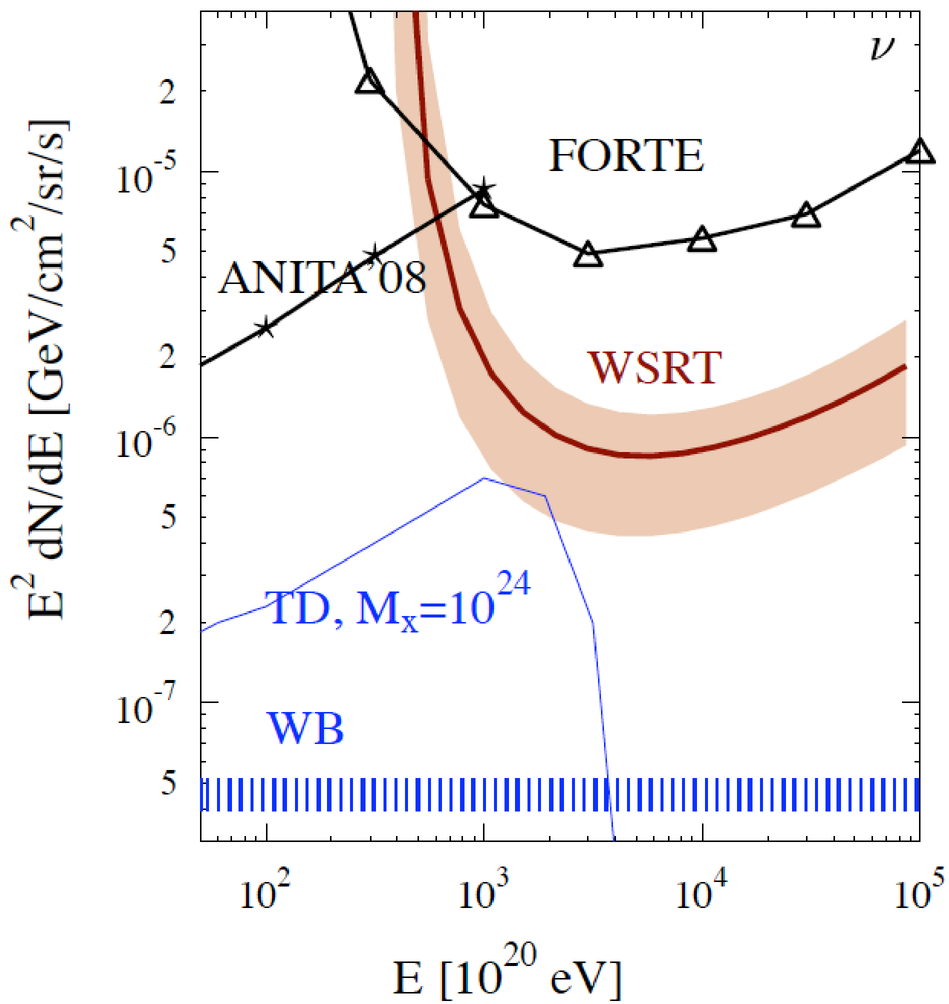
Step 3: Peak search

- $P5_i$: total power in a sliding window of 5 bins (2 polarizations) in band *i*
- Threshold $P5_i > 5\sigma$
- Allow offset for imperfect de-dispersion
- $S = \Sigma P5_i$

Distribution of *S* (46 hours)



Neutrino flux limit



No detection above 220 kJy

Detection efficiency: 87.5 %

46 hours of observation

Total syst. error 50%

90% confidence level

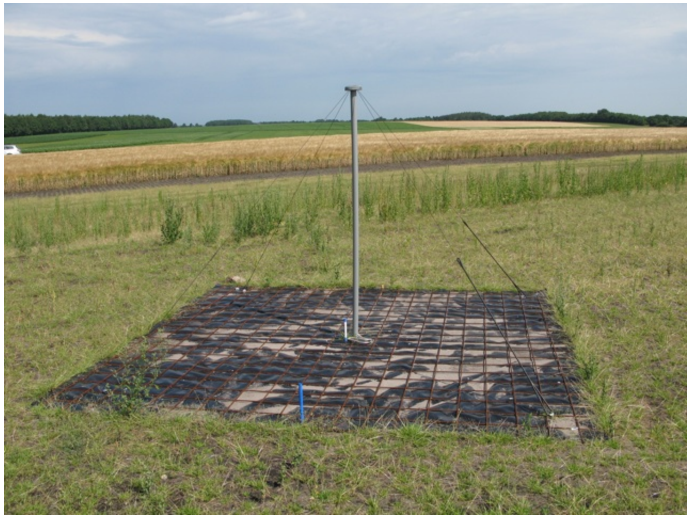
Flux limit for sum over all neutrino flavors

Results: Scholten et al. PRL 103, 1301 (2009)

Details: S.B. et al. A&A (accepted 2010)

Phase II: LOFAR

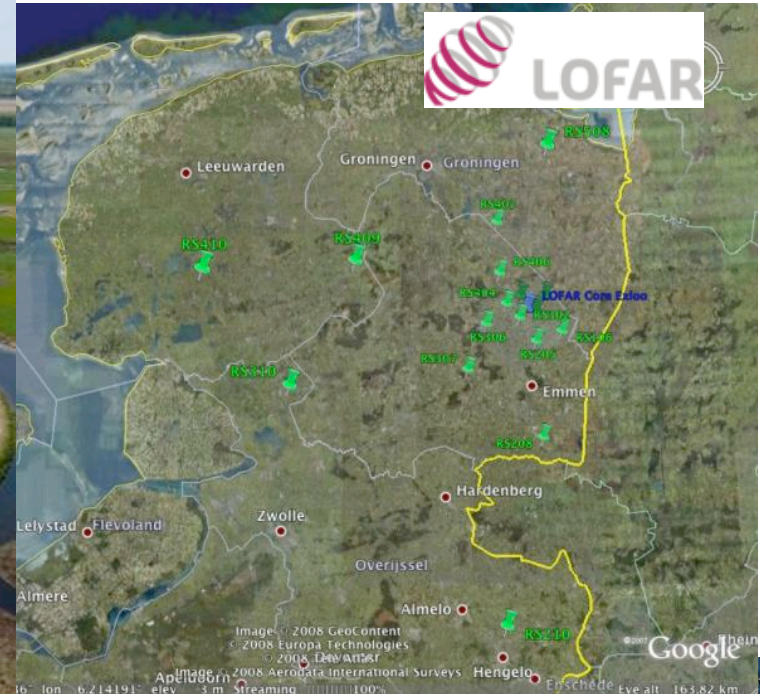
- Low Frequency Array: 36 stations of 48 HB + 96 LB antennas each



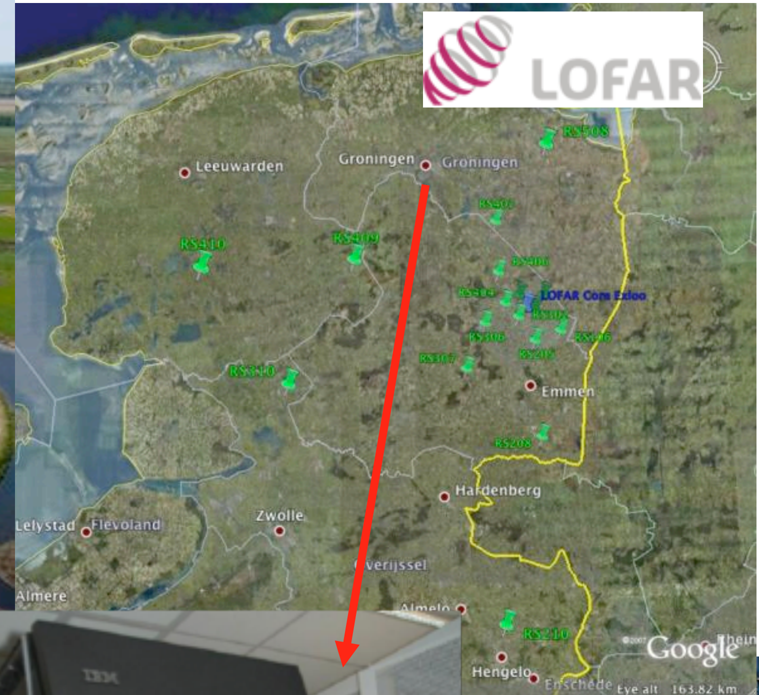
Low band: 10 - 80 MHz

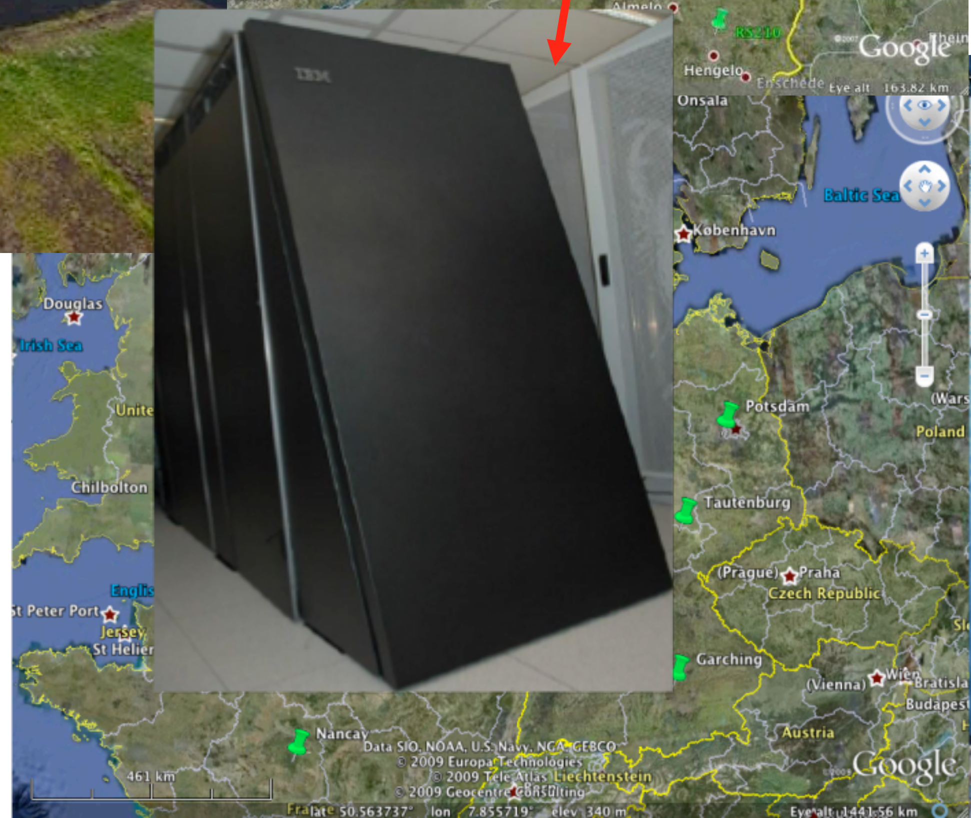
High band: 120-240 MHz

- Antennas operate as digital telescope
- LOFAR can look in multiple directions at the same



- 18 core station
- 18 remote stations
- 8 european stations



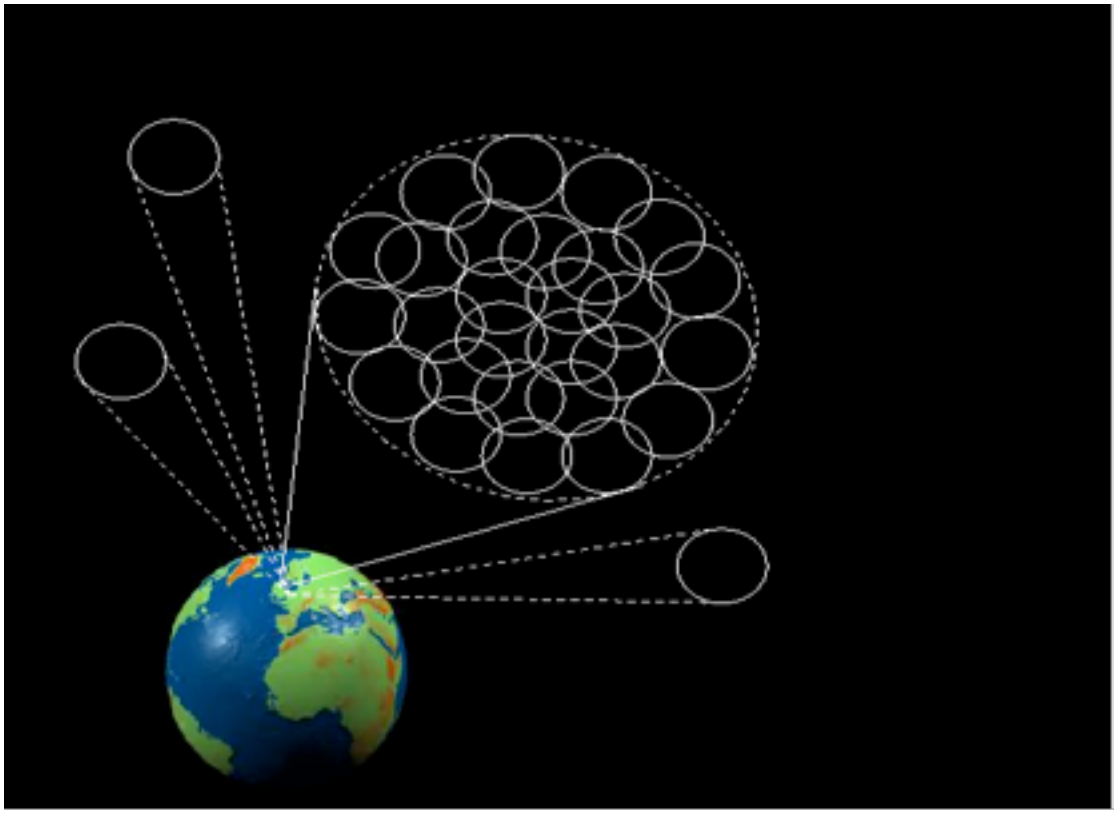


Located in Groningen:

Central Processing Facility

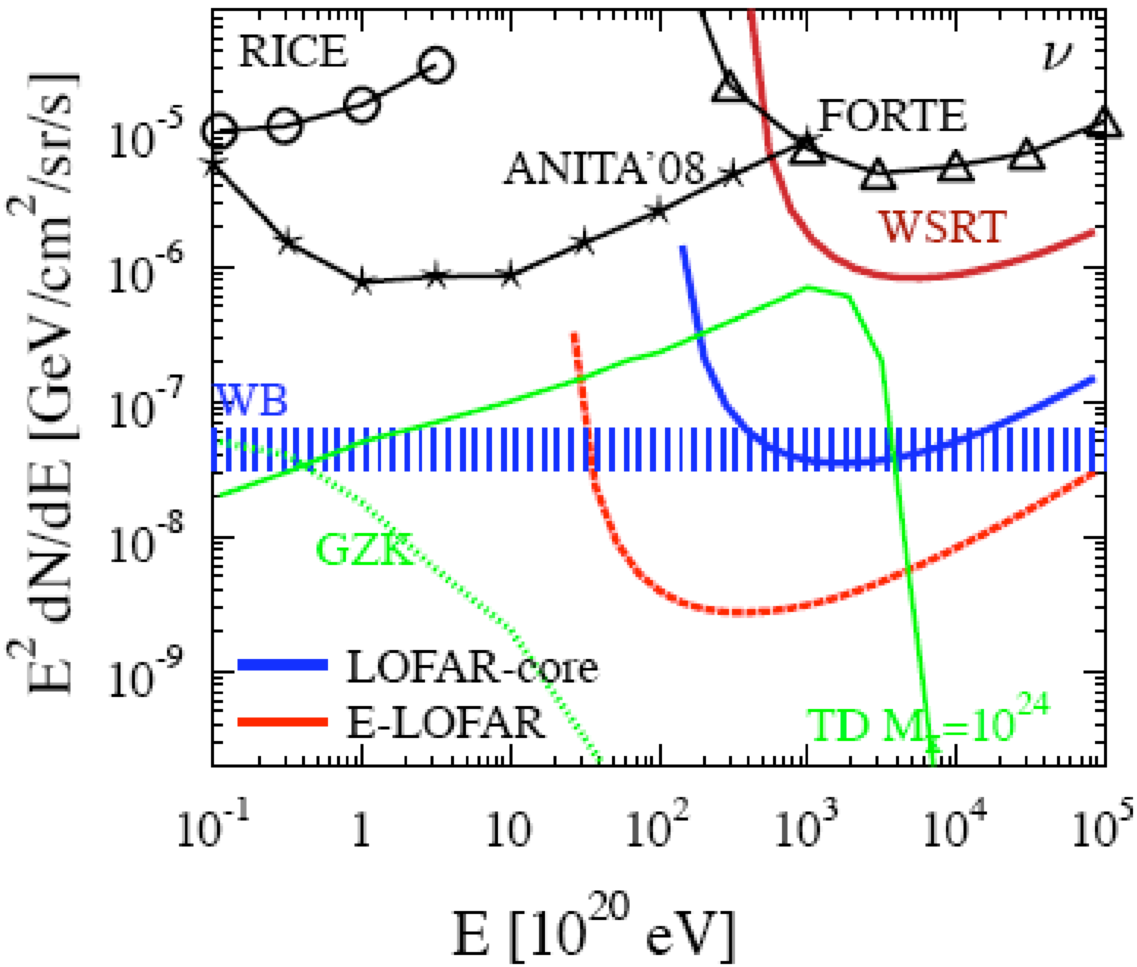
BlueGene 34 TFlops

multiple beams of ~0.05 dgr

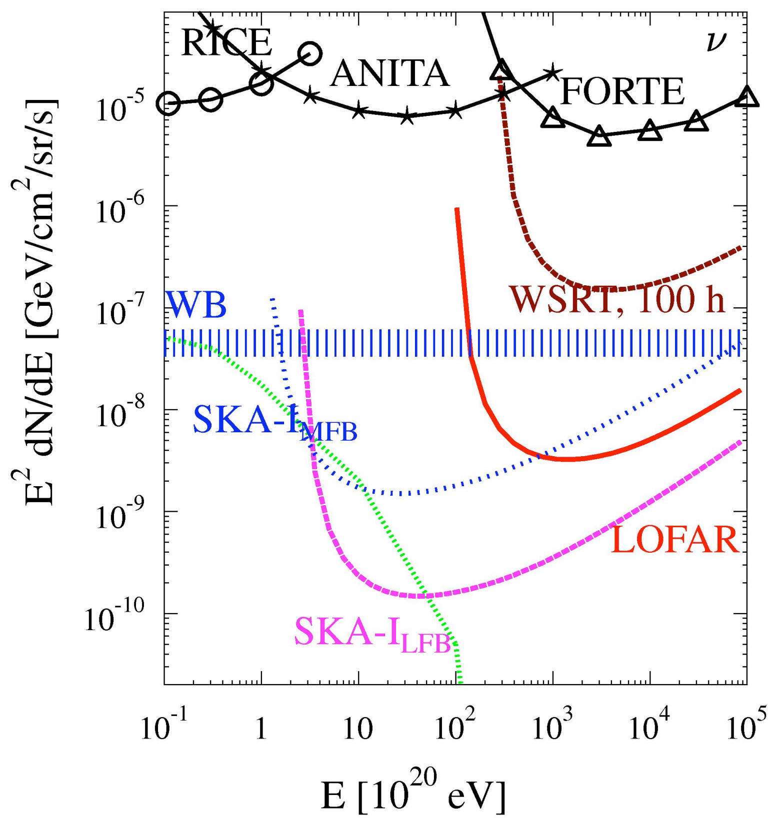


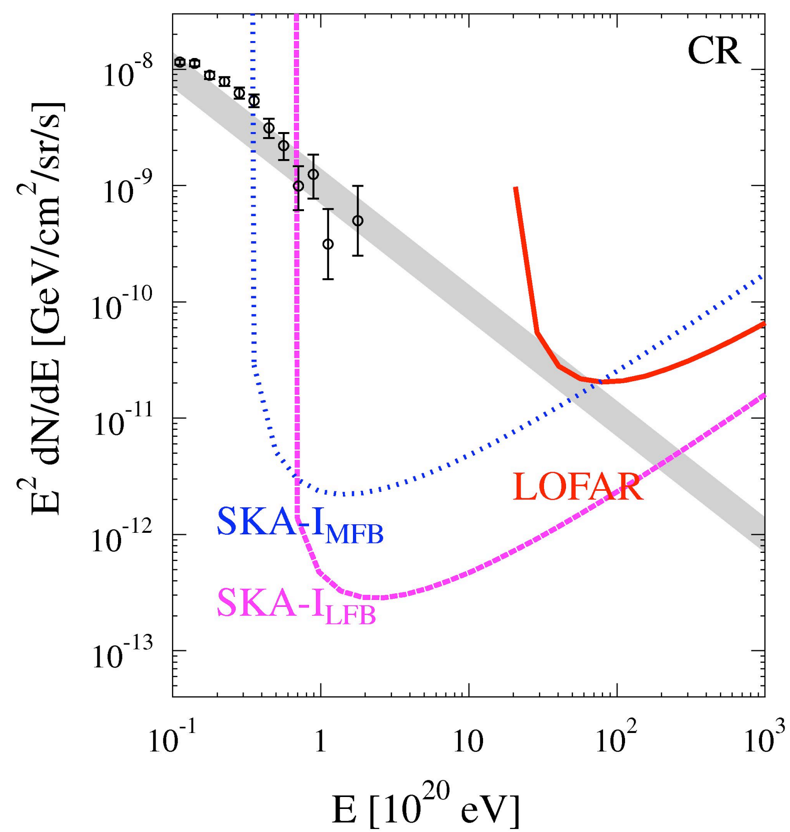
- Better signal localization
- Strong anti-coincidence veto

LOFAR Sensitivity to neutrinos



Future sensitivities





Conclusions

- Radio detection of lunar showers promising technique for detection of highest energy particles
- NuMoon @ WSRT sets competitive limits on UHE neutrino flux
- LOFAR will probe WB limit > 10^{22} eV and constrain many top-down models
- Future experiments sensitive to expected GZK neutrino flux & CR around cutoff

Thanks for your attention!

Askaryan effect: confirmation in sand

Experiment at SLAC with beams of photons
And 10^{10} e-/bunch: effective shower energies 0.06-1.10 10^{19} eV

$$F(\theta,\nu,E_s) = 3.86\times 10^4\, e^{-(n\,\cos\theta-1)^2/Z_0^2}\left(\frac{\sin\theta}{\sin\theta_c}\right)^2\left(\frac{d_{moon}}{d}\right)^2 \times\left(\frac{E_s}{10^{20}\ \mathrm{eV}}\right)^2\left(\frac{\nu}{\nu_0(1+(\nu/\nu_0)^{1.44})}\right)^2\left(\frac{\Delta\nu}{100\ \mathrm{MHz}}\right)\ \mathrm{Jy}\,,$$

1 Jy = 10^{-26} W/m^2/Hz

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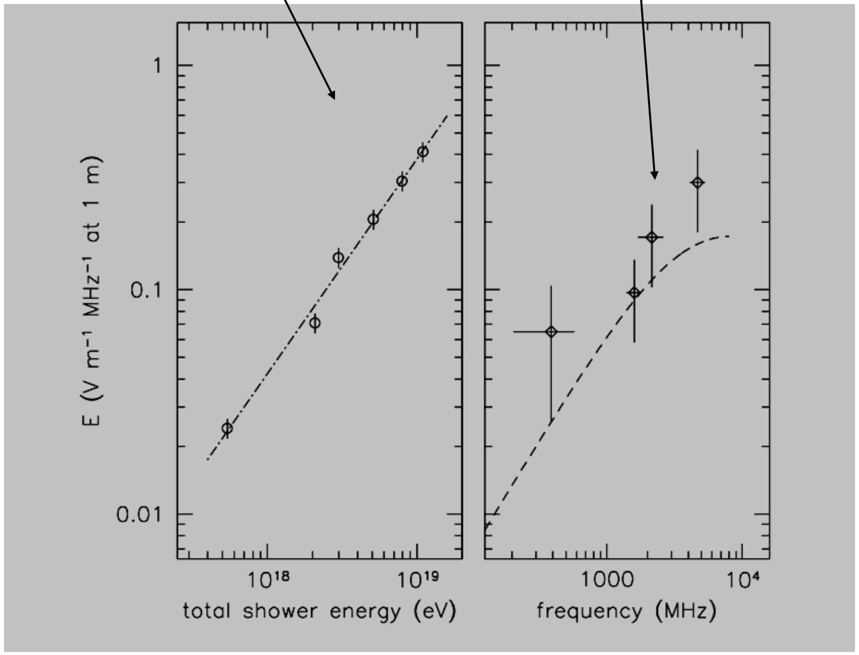

D. Saltzberg et al
PRL 86 (2001) 2802

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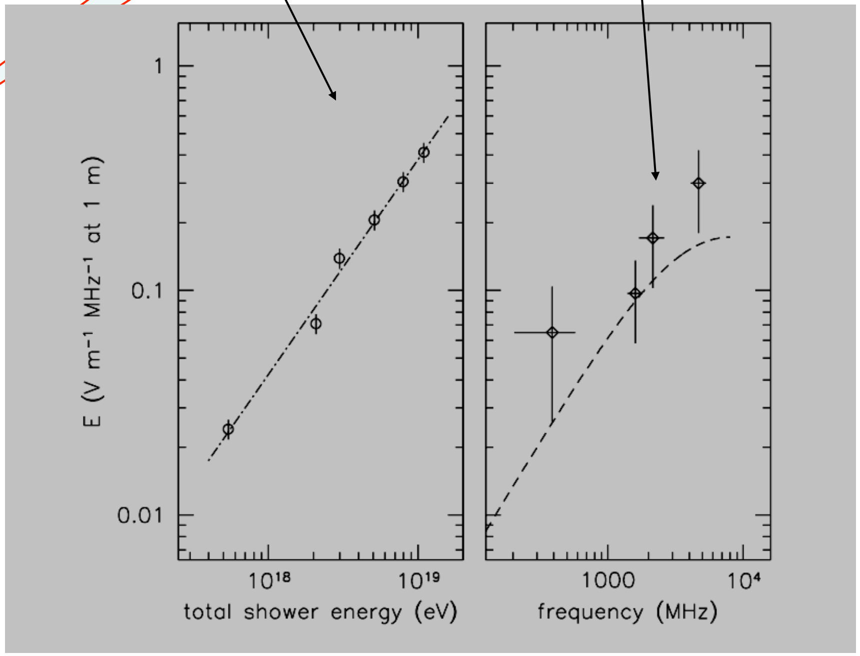
Angular spread

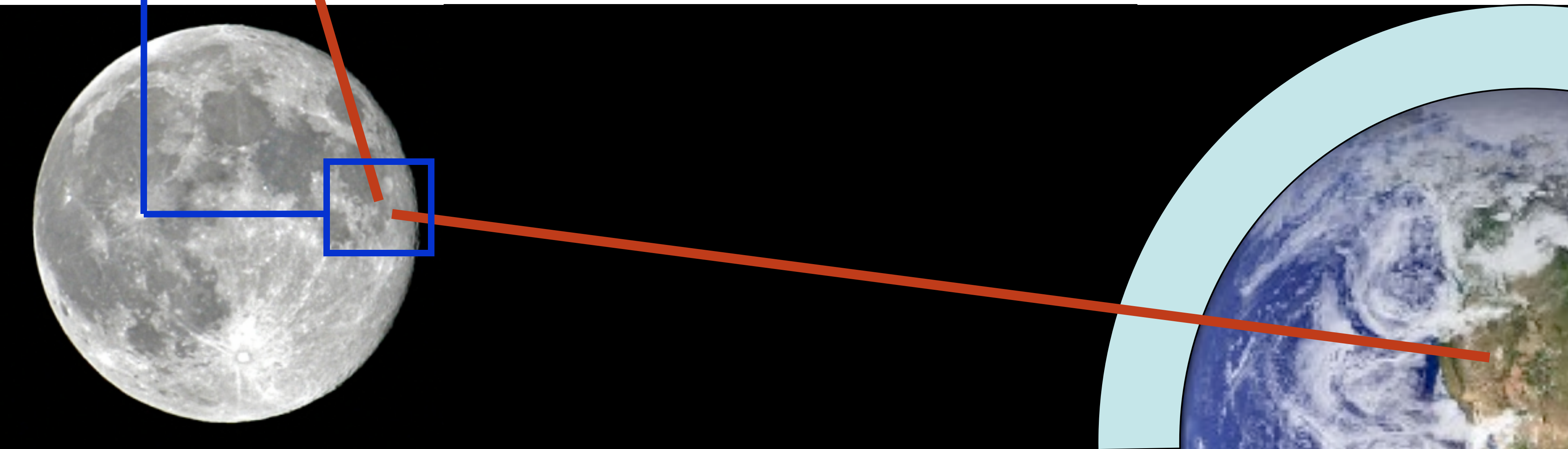
$Z_0 \sim \Delta_c \sim \lambda/L = 1/L\nu$



D. Saltzberg et al
PRL 86 (2001) 2802

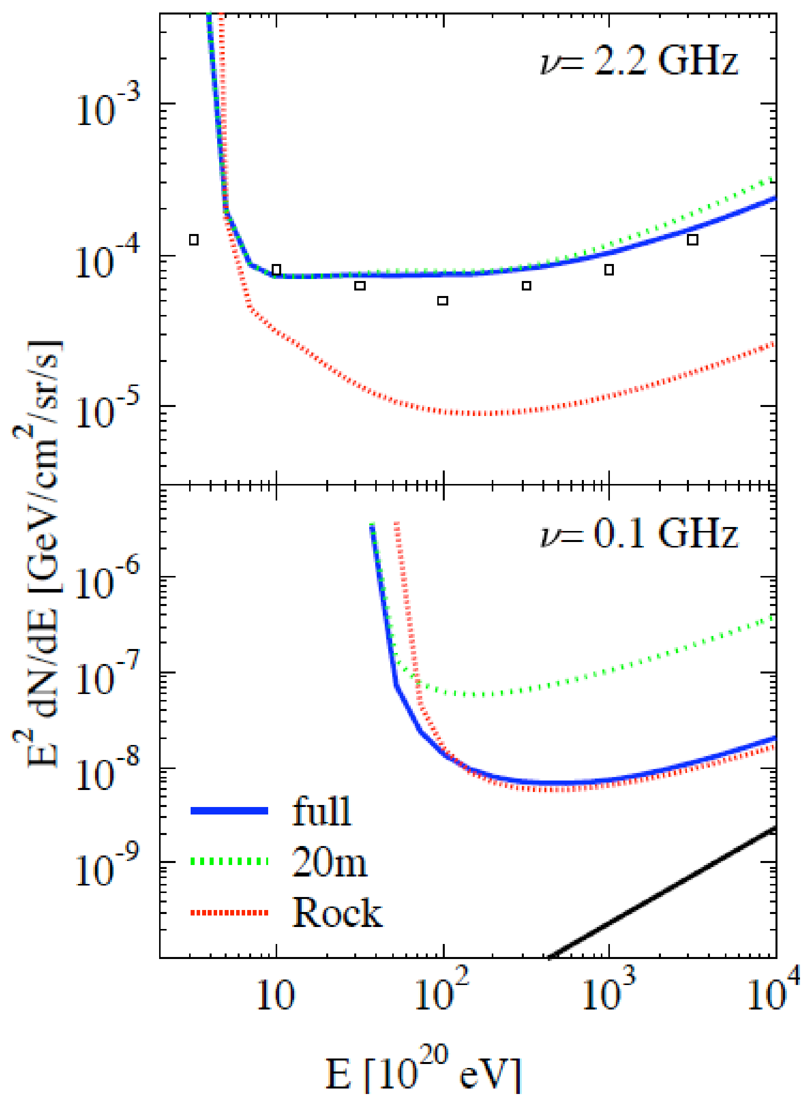
1. Neutrino or CR enter Moon
2. Extrapolated cross section -> interaction depth
3. Signal from hadronic cascade (~20% of energy)
4. Propagation through regolith
5. Inner reflection at surface / irregular surface
6. Refraction at surface

syst. error due to unknown Moon properties ~ 45%



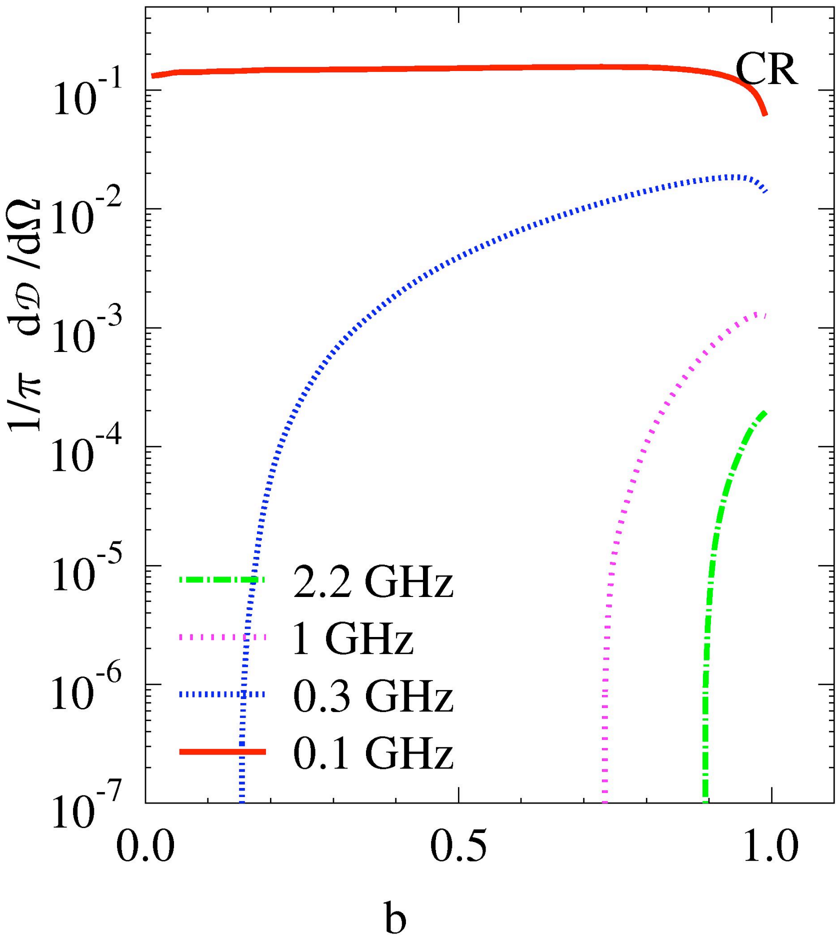
Regolith vs. Rock

- Density of rock larger
- Competing effects: more attenuation, shallower interaction, shorter cascade, larger spread around cherenkov angle
- At 100 MHz net effect is small



Position on Moon

Partial Detection probability



Normalized distance from center

Calculations for

E_{cr}=4 10^{21} eV

Detection treshold: 500 Jy for 20 MHz bandwidth

With decreasing ν :

- increasing area
- increasing probability

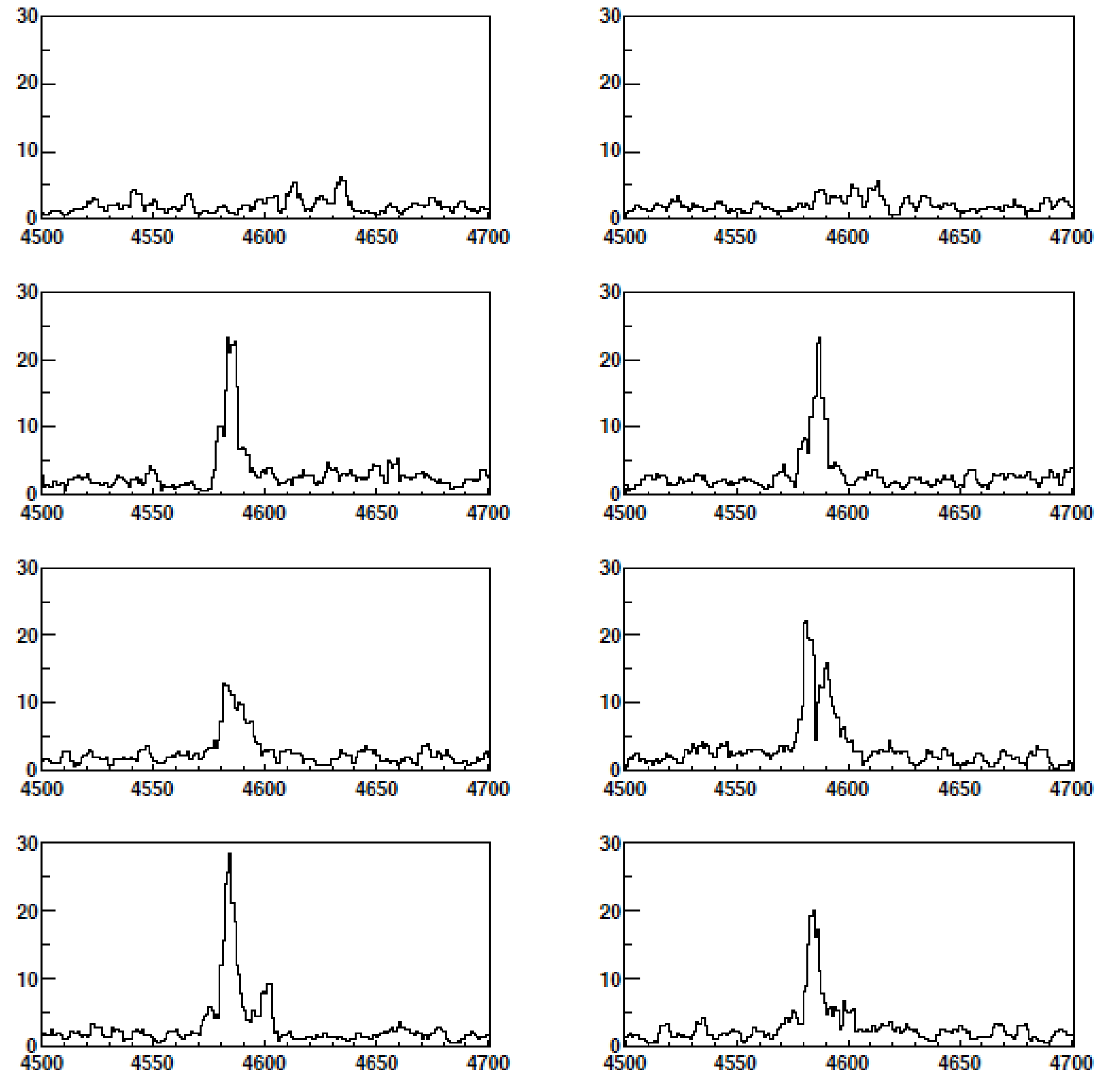
$\int$ over surface Moon

$D \propto \nu^{-3}$

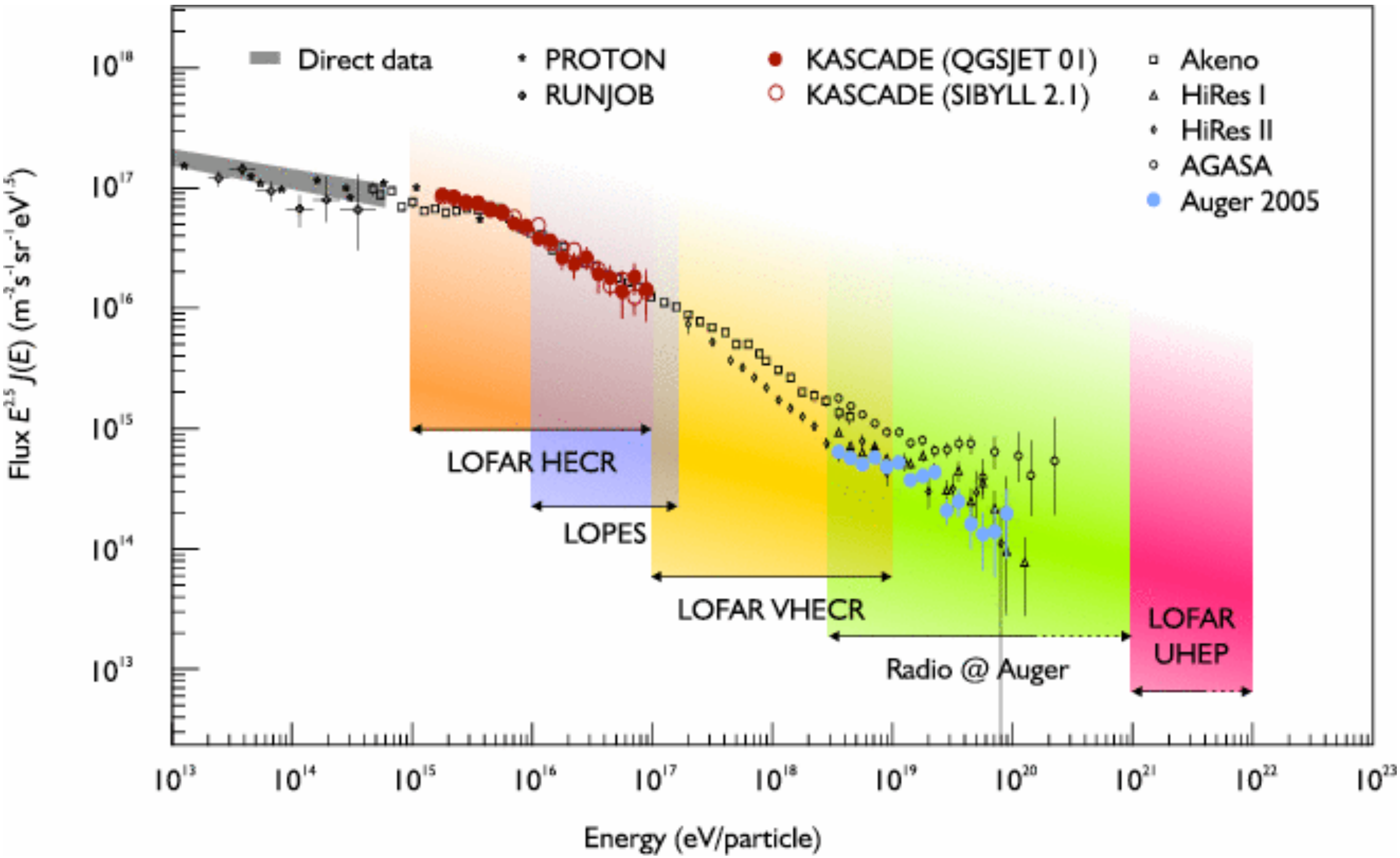
Scholten et al. Astropart. Phys. 2006

Understanding the background

- Large background pulses
- Typically coincidence veto fails when one channel is noisy
- Steady signals removed by RFI mitigation, but too much RFI gives poor dynamic range
- Pulsed noised produces spurious peaks



Ultra High Energy Cosmic Rays



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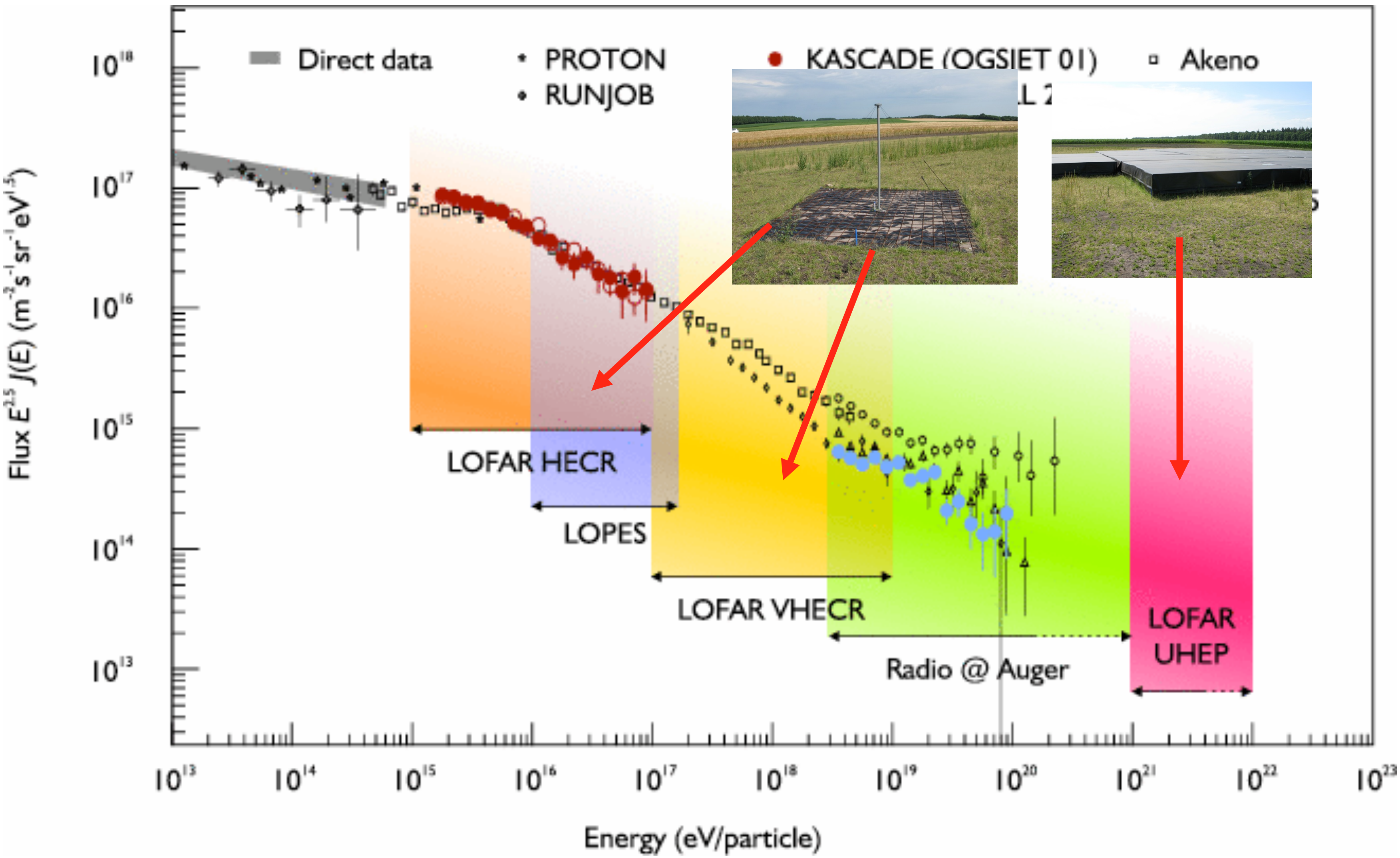

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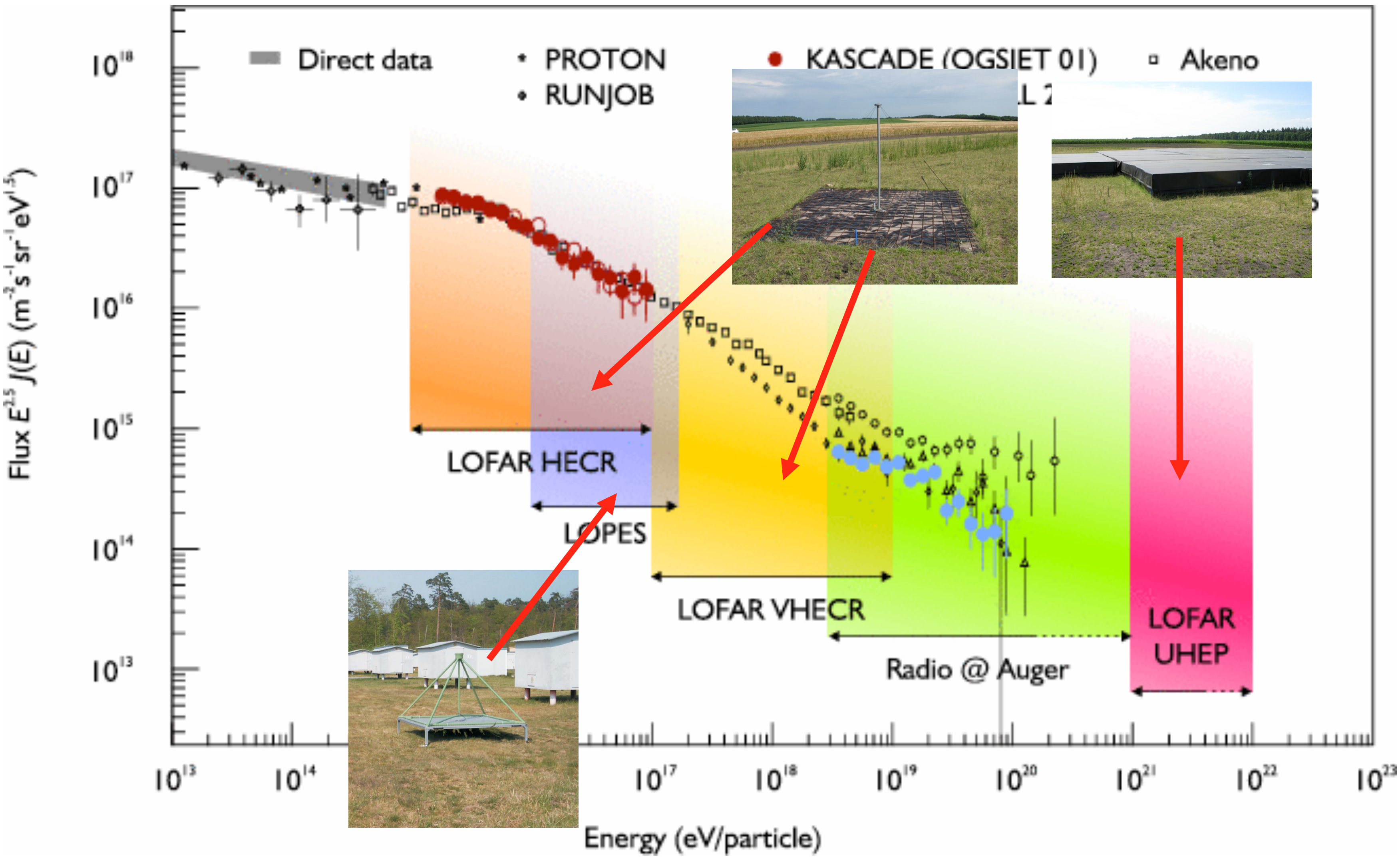

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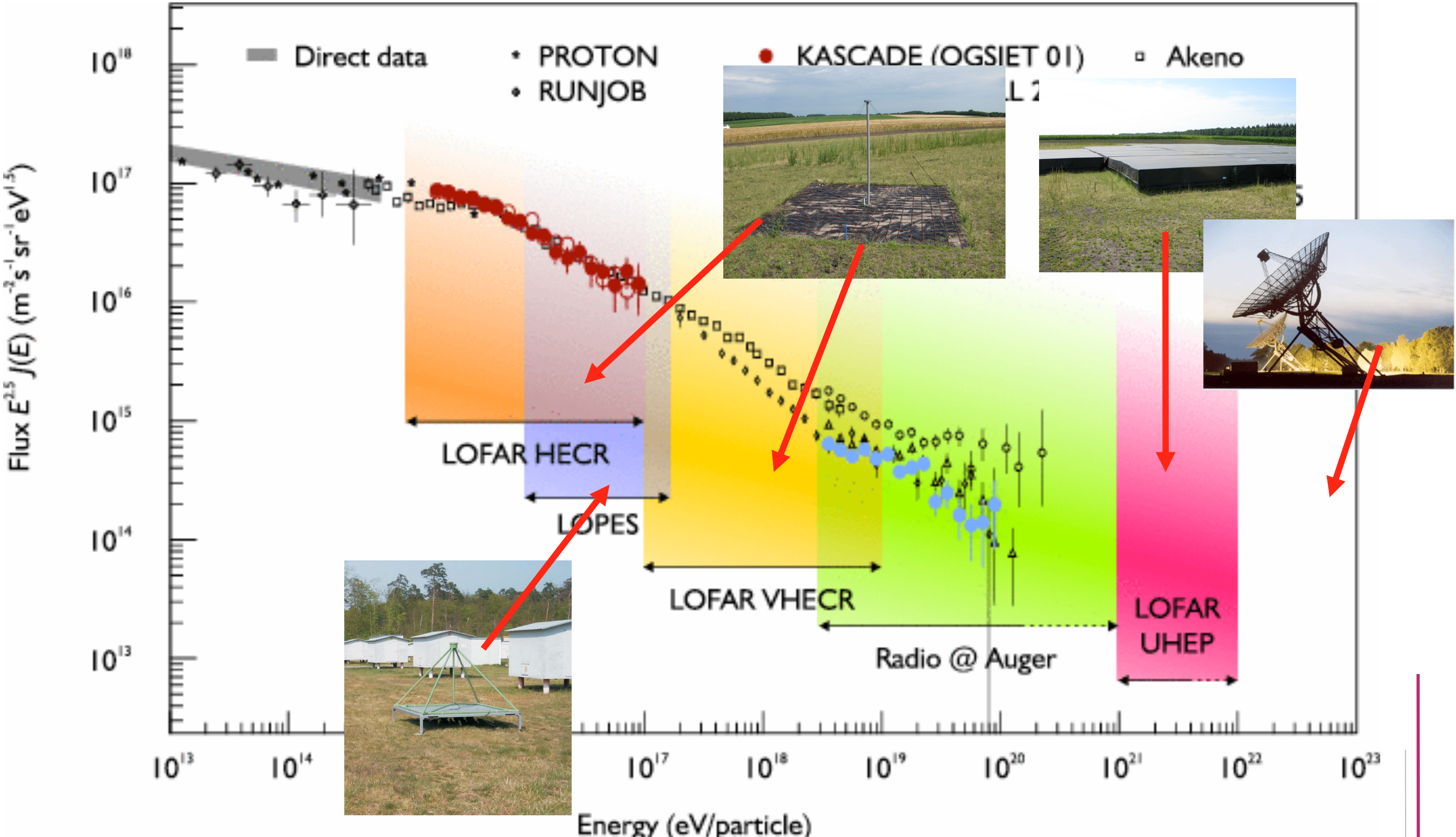
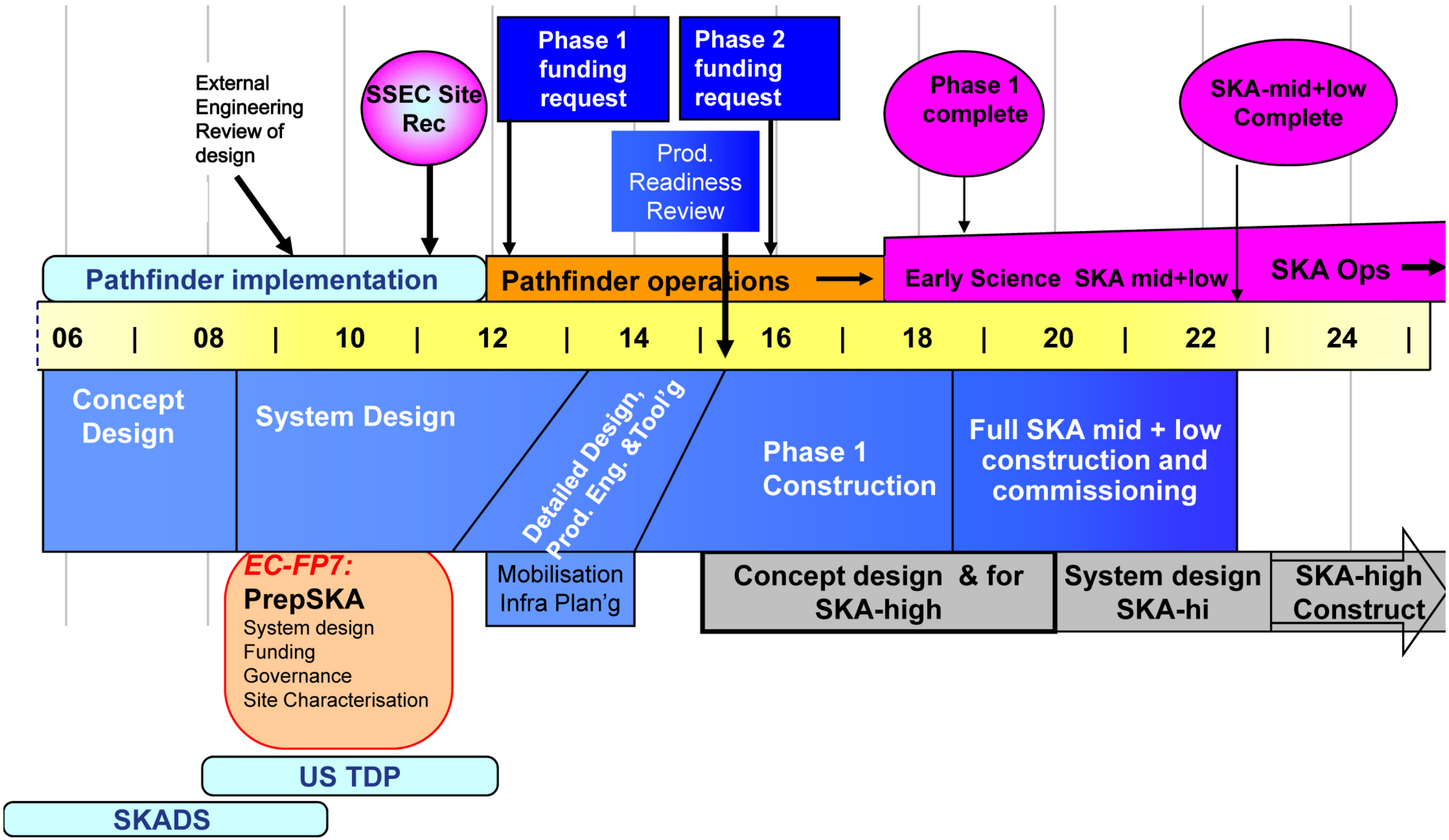
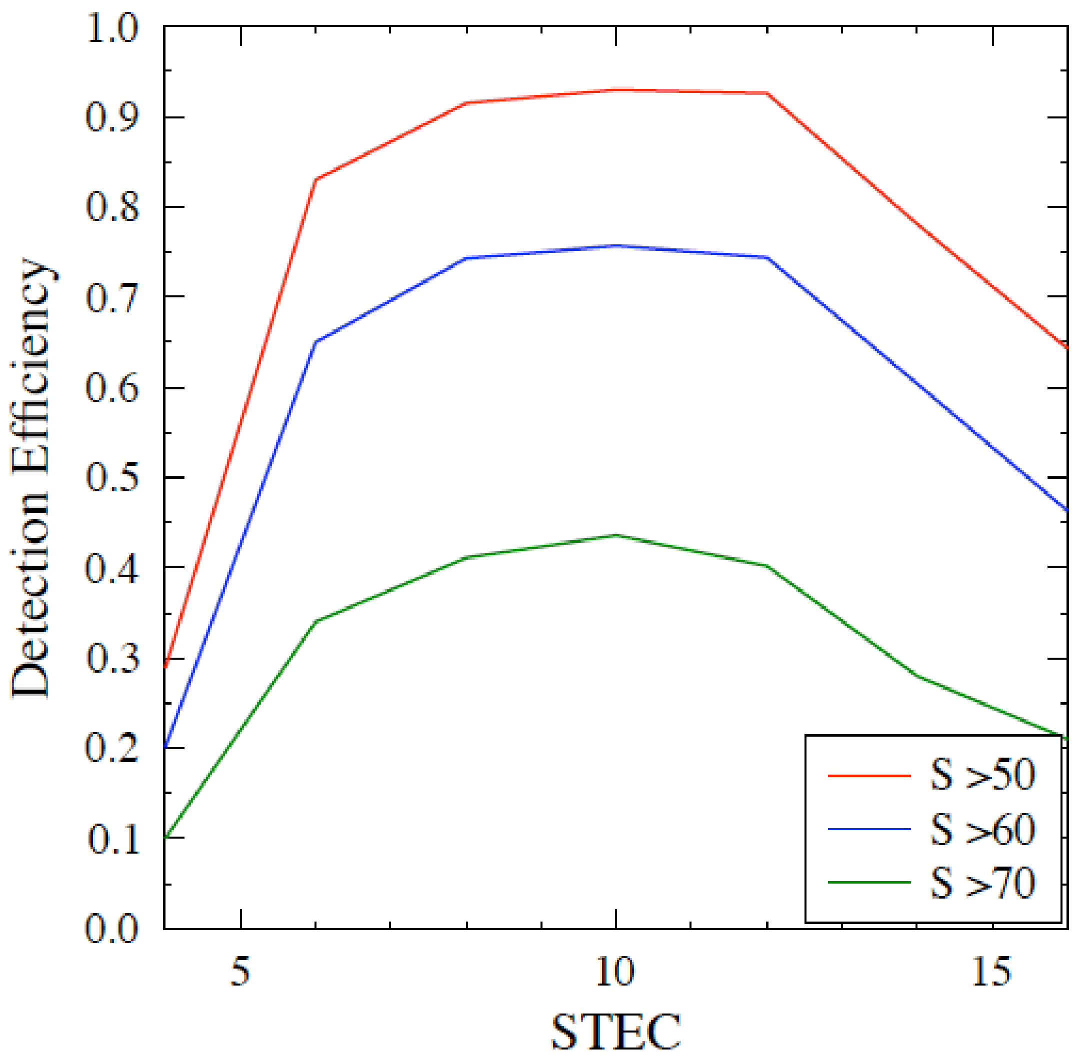


SKA timeline



26 February 2009

Detection efficiency



Input pulses simulated with STEC = 10

Reconstructed with different STEC values.

Wrong value spreads out pulse

DE fairly constant when error < 20%

UHE Cosmic rays

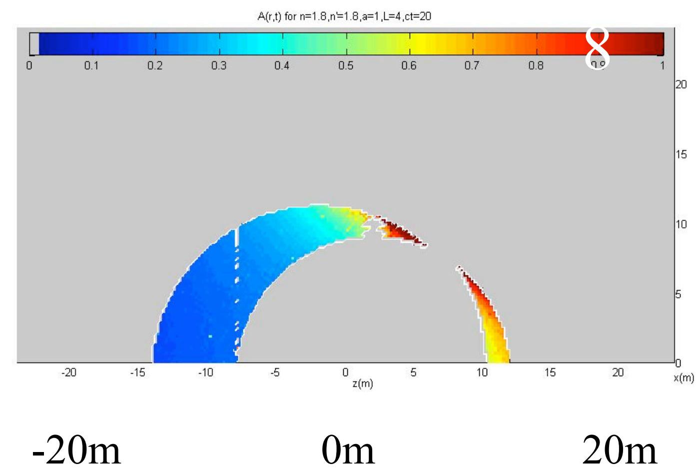
Concern: formation effects of radiation field near boundary

Simulations for boundary n=1.8 to n=1.0

For low frequencies (~100 MHz) coherent signal in all directions

Cosmic ray detection is possible and efficient!

UHE CR limits in prep



Sander ter Veen

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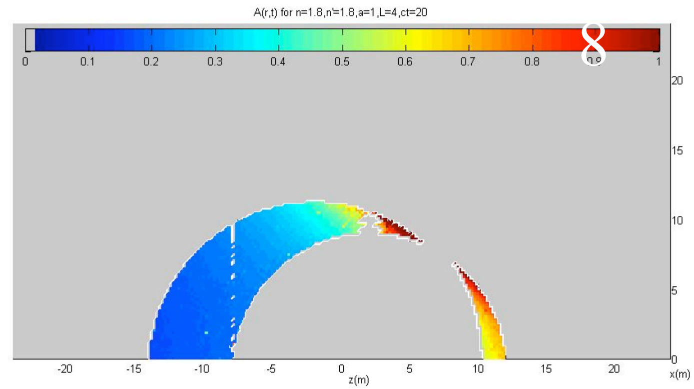

-20m 0m 20m

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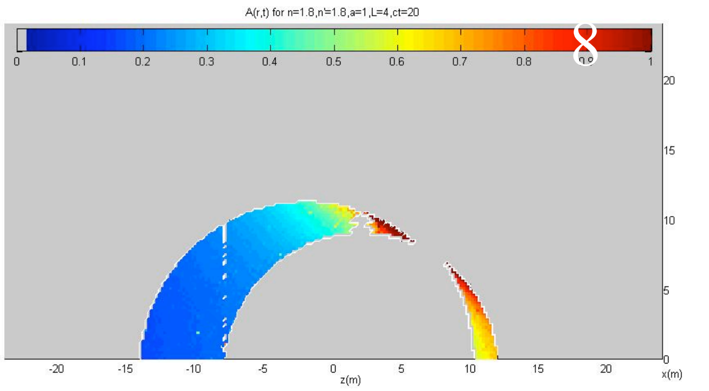

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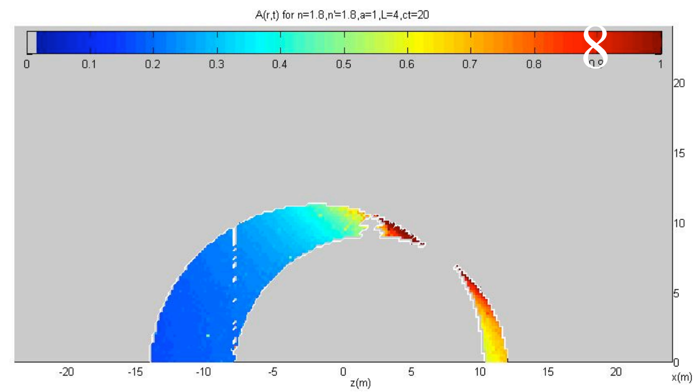

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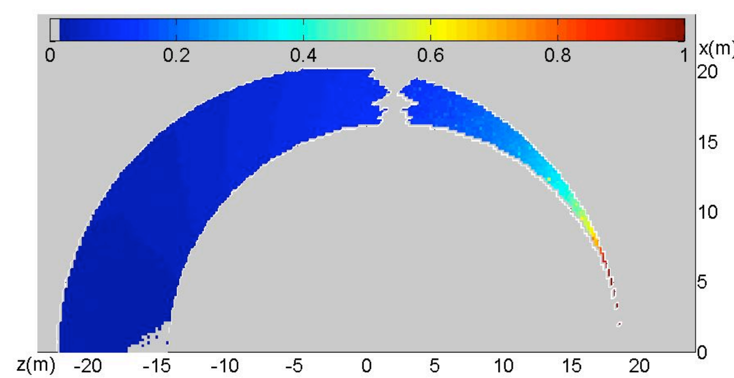

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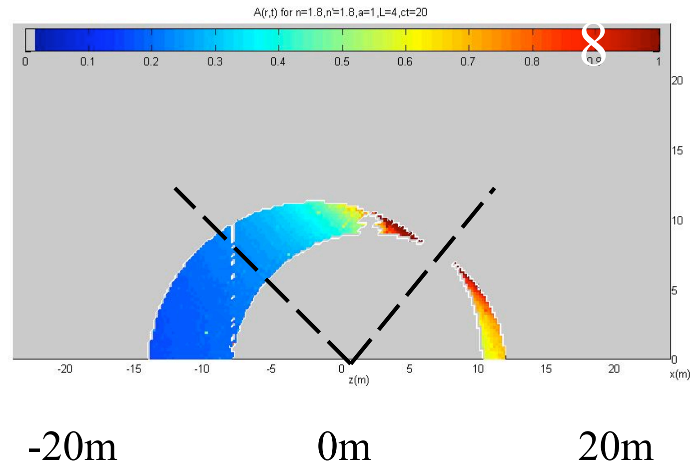

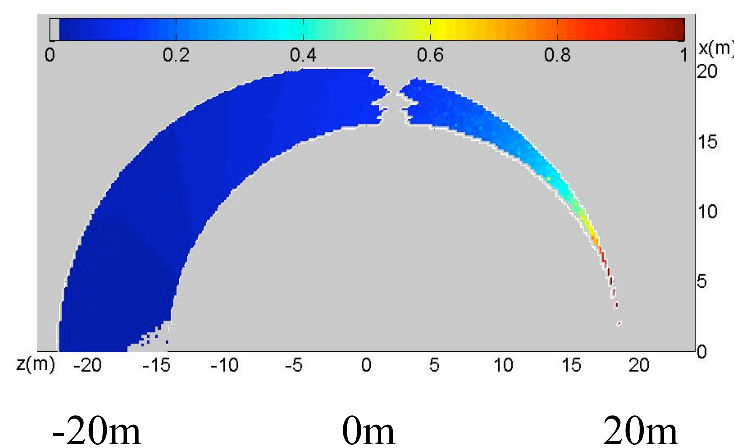

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