The lunar Askaryan technique with the SKA

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

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On behalf of the SKA HECP Focus Group
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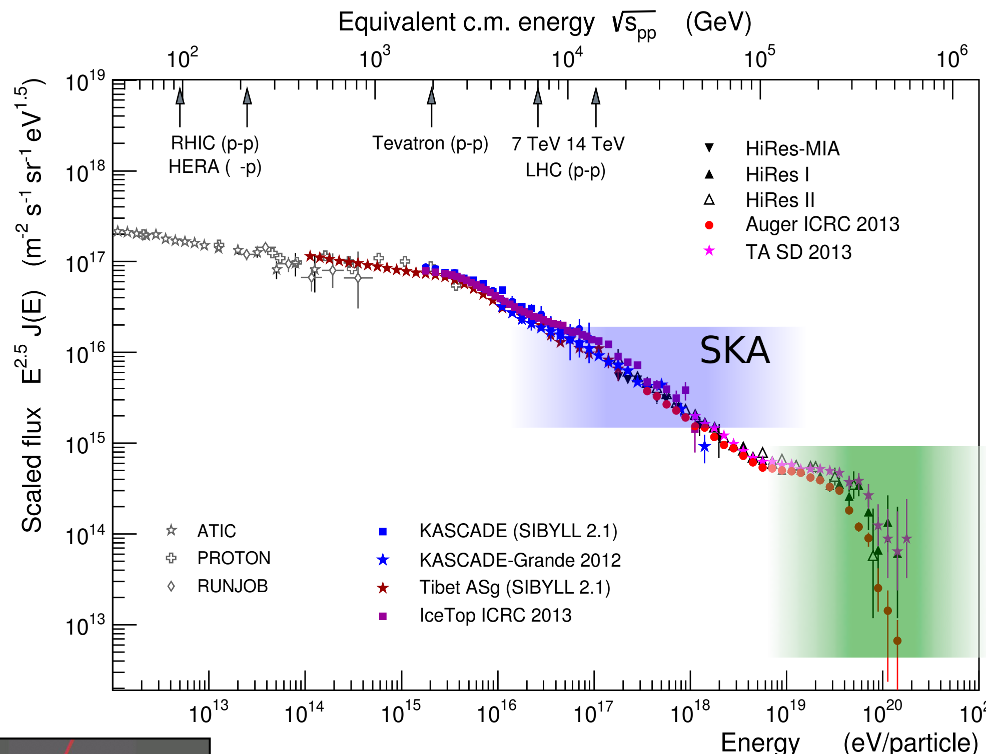
FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

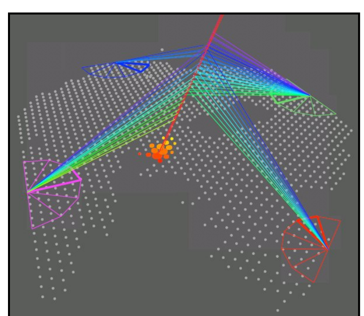
Ultra-high-energy cosmic rays

Ultra-high-energy cosmic rays

- The highest energies
  - EAS: 10^{17}-10^{19}
  - Lunar: $>10^{19}$

- Pierre Auger Observatory
  - 3000 km^2
  - Water-Cherenkov tanks
  - Fluorescence telescopes
  - Radio antennas

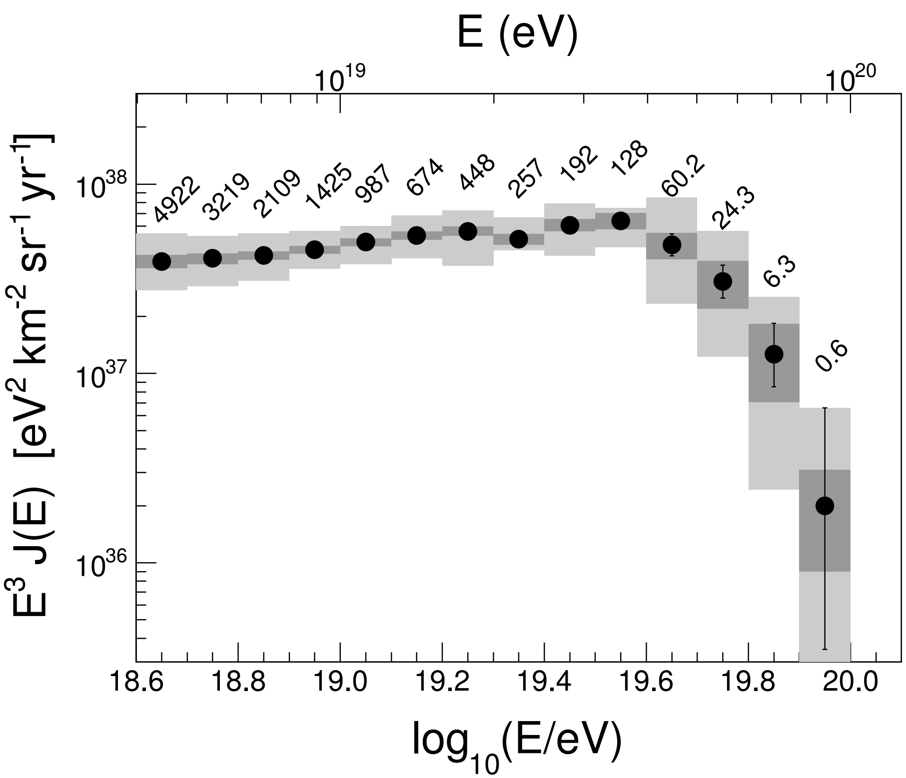




Energy spectrum and composition

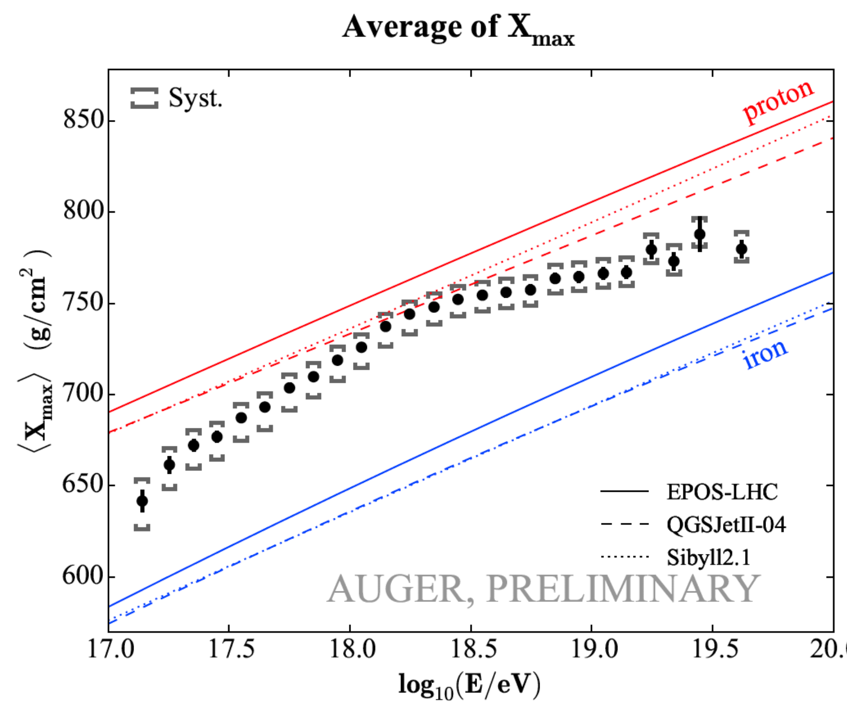
- Spectrum

  Aab et al., JCAP 08 (2015) 049



- Composition

  A. Porcelli for Pierre Auger, arXiv: 1509.03732, #3.1



Arrival directions

- Arrival direction tests:
  - Blind search, correlation with AGN catalogues, Cen A
  - Most significant excess: Cen A at 15^o scales (p-value 1.4%)
  - Best correlation with E_{CR} > 58 EeV
  - ~20 events/year

Excess map (12^o smearing)

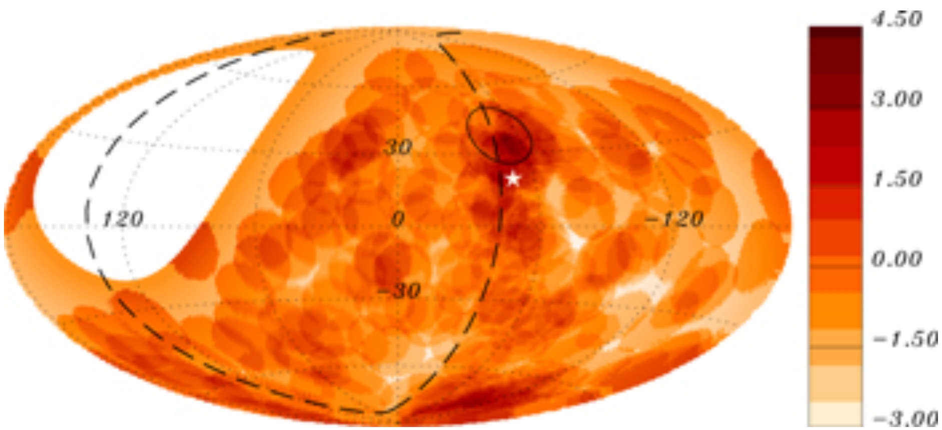


Table 1
Summary of the Parameters of the Minima Found in the Cross-correlation Analyses

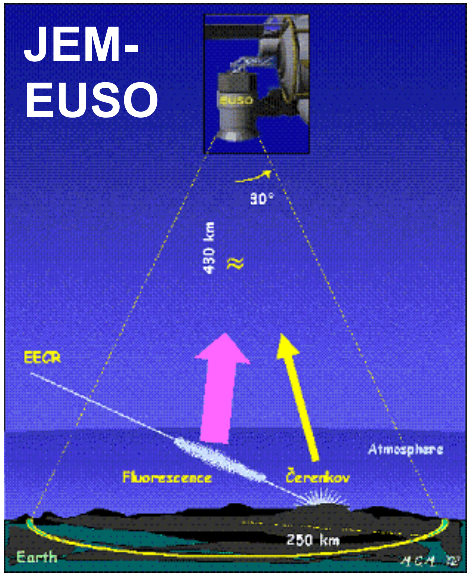
Objects	E_{th} (EeV)	Ψ (°)	D (Mpc)	$\mathcal{L}_{min}$ (erg s^{-1})	f_{min}	$\mathcal{P}$
2MRS Galaxies	52	9	90	...	1.5×10^{-3}	24%
Swift AGNs	58	1	80	...	6×10^{-5}	6%
Radio galaxies	72	4.75	90	...	2×10^{-4}	8%
Swift AGNs	58	18	130	10^{44}	2×10^{-6}	1.3%
Radio galaxies	58	12	90	$10^{39.33}$	5.6×10^{-5}	11%
Centaurus A	58	15	...	...	2×10^{-4}	1.4%

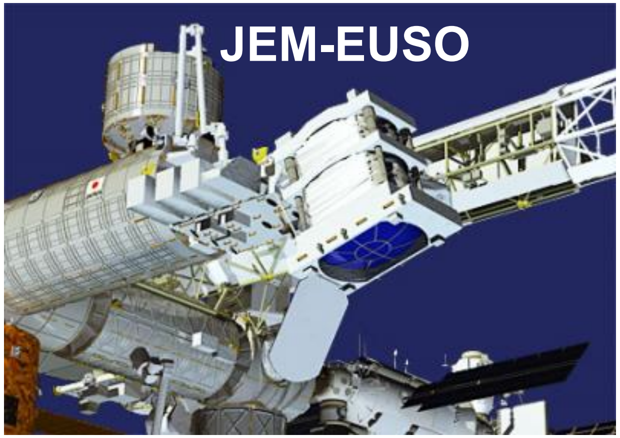
Aab et al., ApJ 804 (2015) 15

Prospects for improvement #1

- Some hints of excess at broad scales: more data can help
- Build a bigger detector!

- Options:
  - Larger ground array (Auger North)?
  - Go to space (JEM-EUSO)
  - Use the Moon!





Prospects for improvement #2

Greisen PRL 16 (1966) 748;
Zatsepin & Kuzmin, JETP Lett 4 (1966) 78;
Berezinsky & Zatsepin, PLB 28 (1969) 423

- UHE cosmic rays => UHE neutrinos
  - Photo-pion production threshold of UHE CR with CMB: ~5 10^{19} eV
  - These pions decay to produce neutrinos
- UHE neutrinos
  - Undeflected by magnetic fields
  - Not absorbed during propagation
  - Difficult to detect!

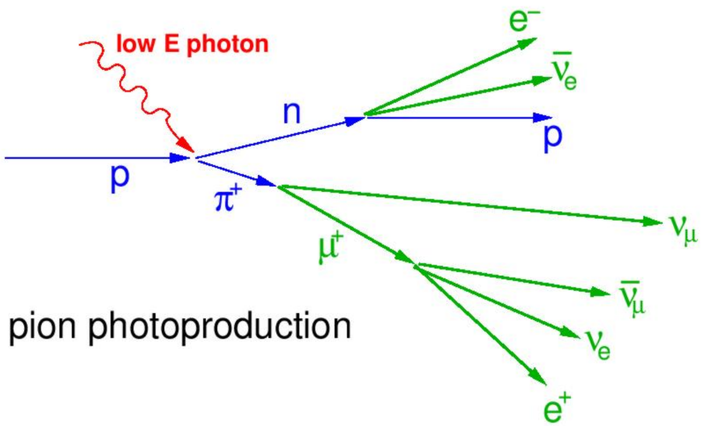


Fig courtesy K. Mannheim, R.J. Protheroe

- 'Exotic' neutrino fluxes
  - Predicted by beyond-the-standard-model physics
  - Super-heavy remnants: decay to neutrinos, and perhaps cosmic rays
  - Currently disfavoured from UHE CR spectral downturn

Lunar Askaryan technique

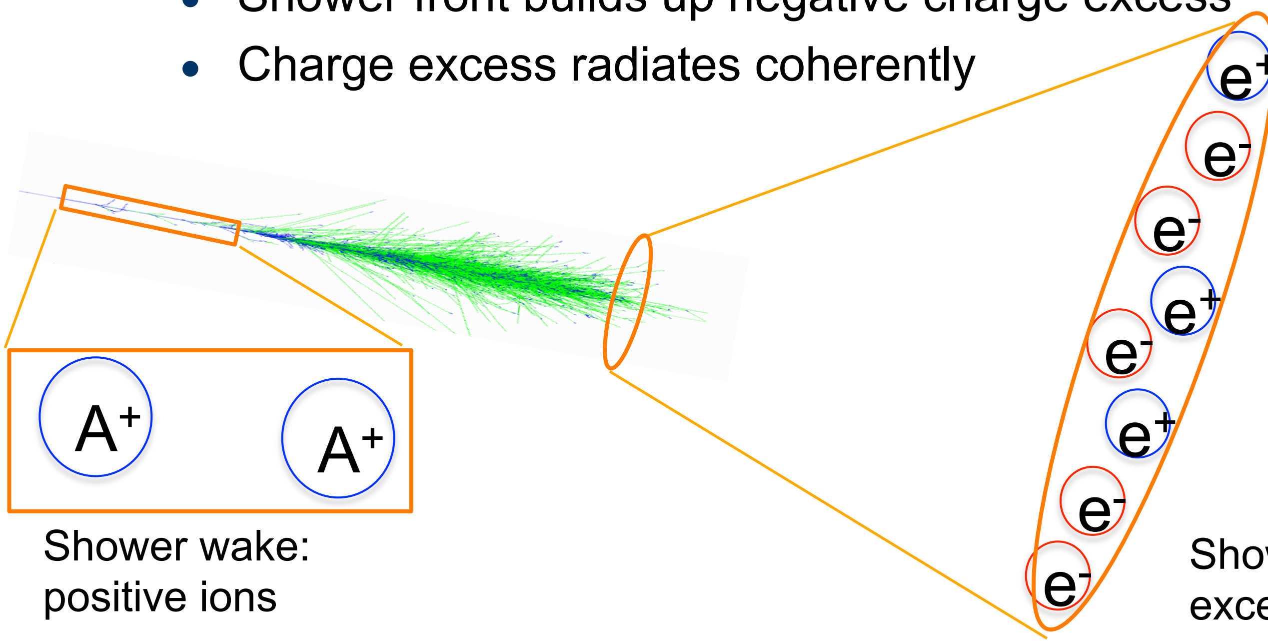
The Askaryan effect

G.A. Askaryan, Sov. Phys. JETP 14 (1962) 441

- Particle cascades in a medium
  - Cascades in medium entrain atomic electrons
  - Shower front builds up negative charge excess
  - Charge excess radiates coherently

$$\gamma \xrightarrow[pp]{} e^+ + e^-$$
$$e^\pm \xrightarrow[bremss]{} e^\pm + \gamma$$

$$\gamma + e^-_m \xrightarrow[Compton]{} \gamma + e^-_c$$
$$e^-_c + e^-_m \xrightarrow[Moeller]{} e^-_c + e^-_c$$
$$e^+_c + e^-_m \xrightarrow[Bhabha]{} e^+_c + e^-_c$$
$$e^+_c + e^-_m \xrightarrow[annih.]{} \gamma + \gamma$$



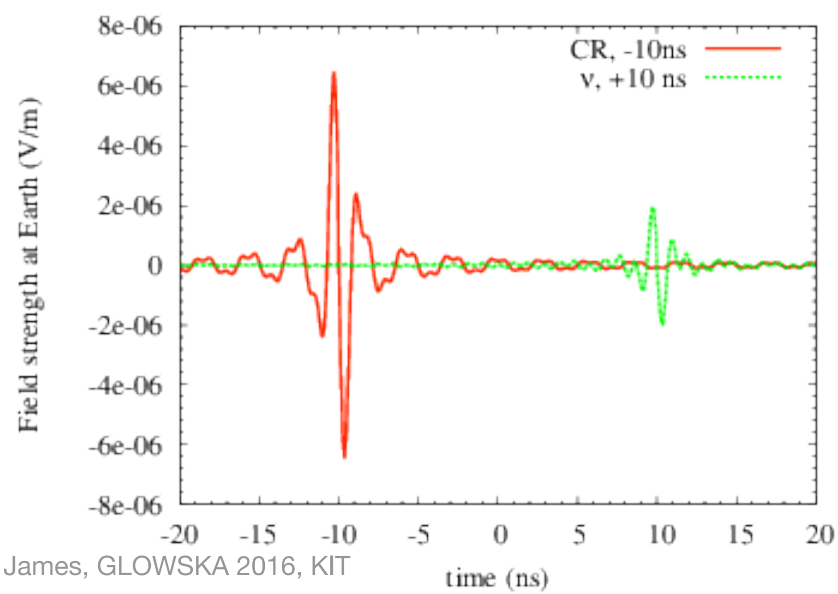
Shower wake: positive ions

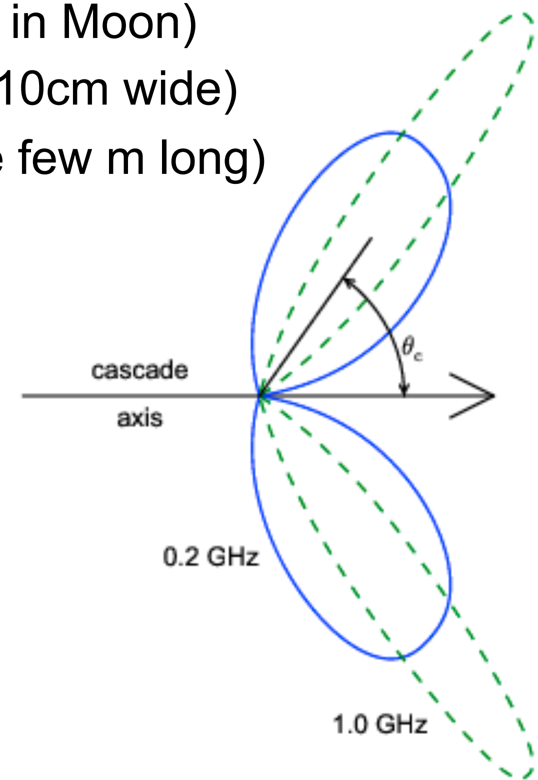
Shower front: excess electrons

CR energy	EM energy	EM particles	Excess e-
$E_0 = 10^{18}$ eV	$E_{EM} \sim 10^{18}$ eV	$N_{e^-,e^+,\gamma} \sim 10^{10}$	$n_{e^-} - n_{e^+} \sim 10^9$

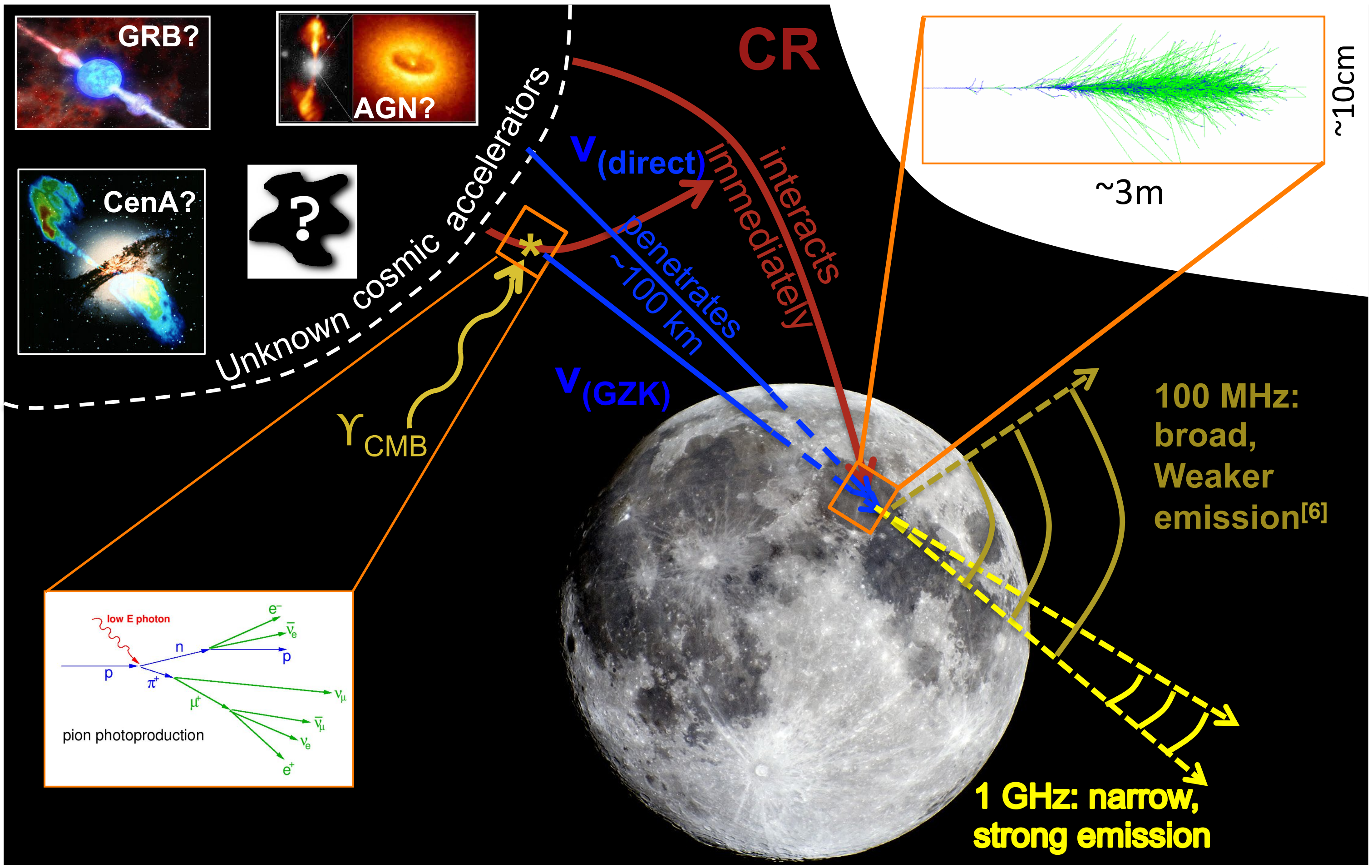
Askaryan pulses

- Phenomenology in the Moon
  - Emission peaked at Cherenkov angle (~56° in Moon)
  - 1 GHz: narrow, strong emission (cascade ~10cm wide)
  - 100 MHz: weaker, broad emission (cascade few m long)
  - Need more events: use SKA-low





The Lunar Askaryan Technique

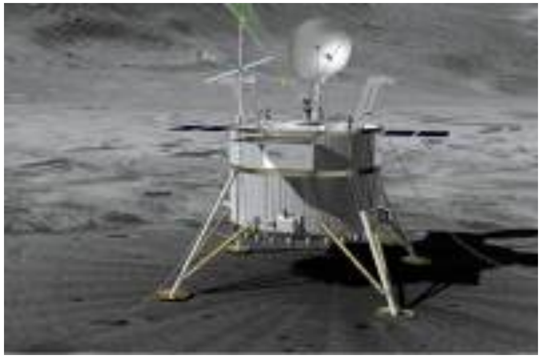


Not only ground-based telescopes

- LORD experiment
  - Experiment on-board Luna-GLOB
  - Less sensitivity – but much closer!

Ryabov, Gusev, Chechin, J.Phys.Conf. 409 (2013) 012096

- Lunar radio astronomy explorer
  - Askaryan's original idea – put antennas on the Moon!

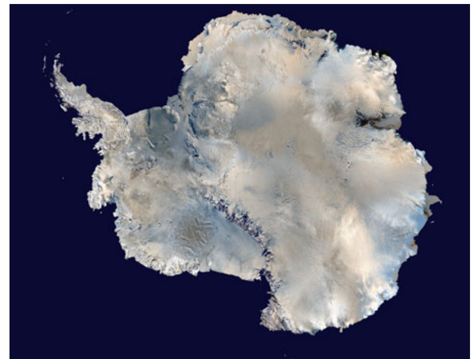


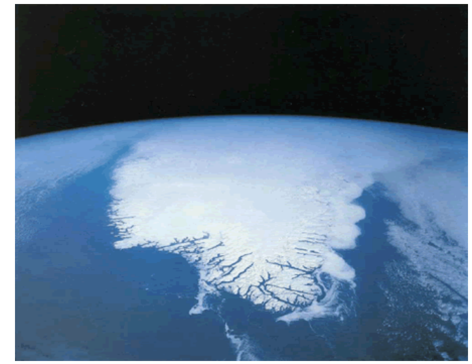
Not only the Moon…

- Greenland & Antarctica

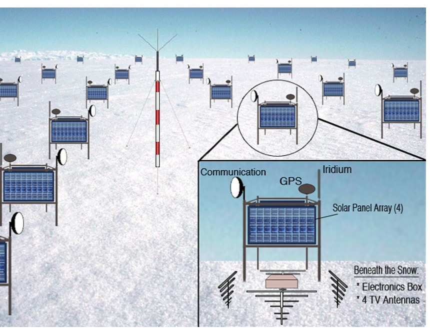
In-ice experiments:
RICE -> ARA & ARIANNA

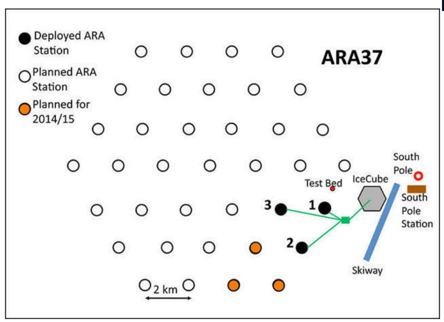
Ice (Antarctica & Greenland)

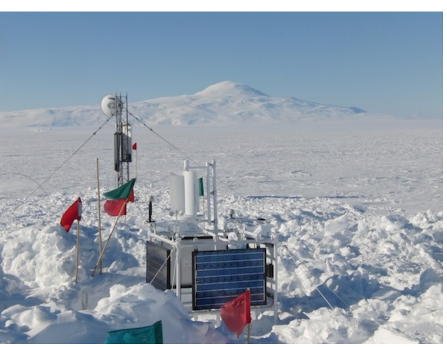


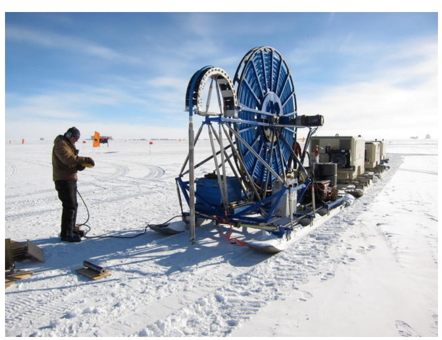


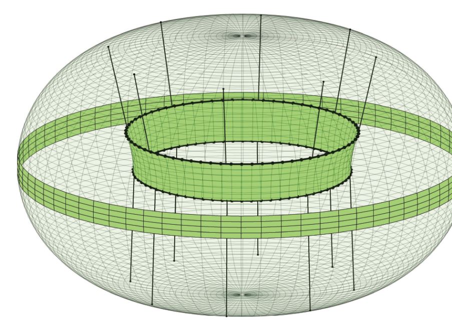
Balloons: ANITA -> Exavolt Antenna





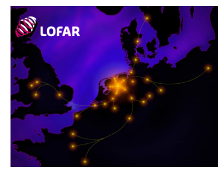






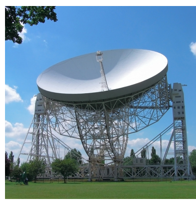
History of lunar experiments

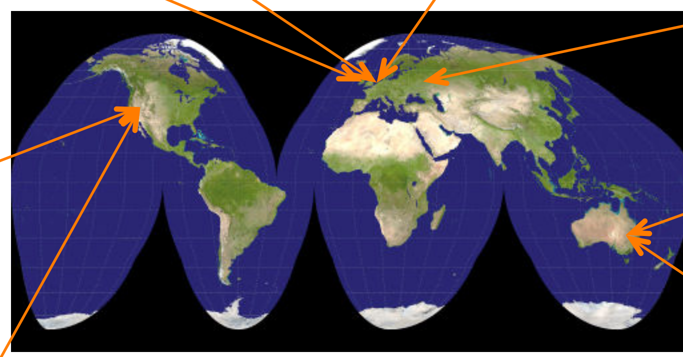
NuMoon
Westerbork 2008[6]
LOFAR UHEP



RAMHAND
Kalyazin 2002-2006[7]

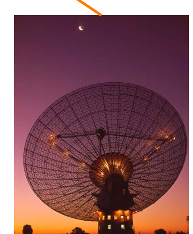
LaLUNA
Lovell 2010





GLUE
Goldstone 1999-2004[4]

LUNASKA
ATCA 2006-2012[5]
Parkes 1995[3], 2008-2012



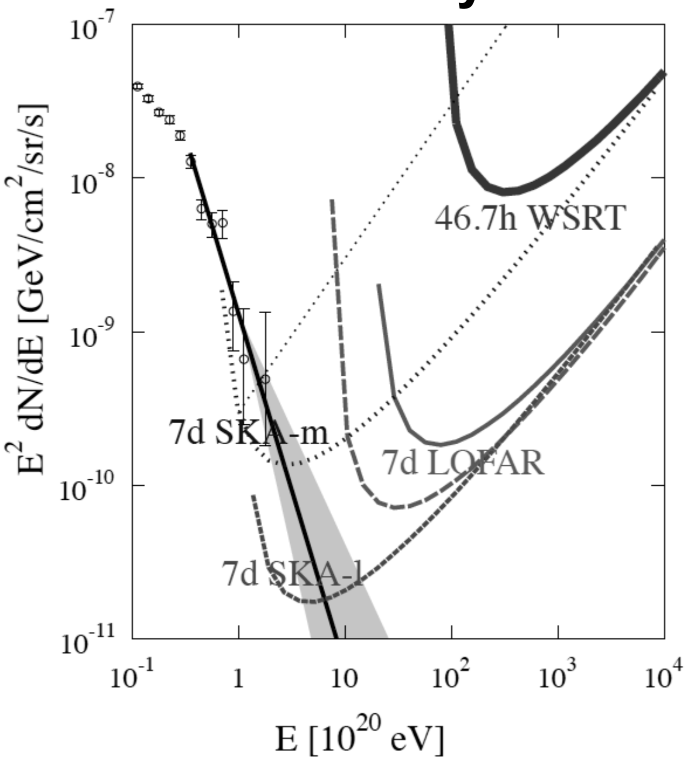
RESUN
VLA 2008-09[8]

- Technically feasible
- But just one problem…

Limits to UHE particle fluxes from past experiments

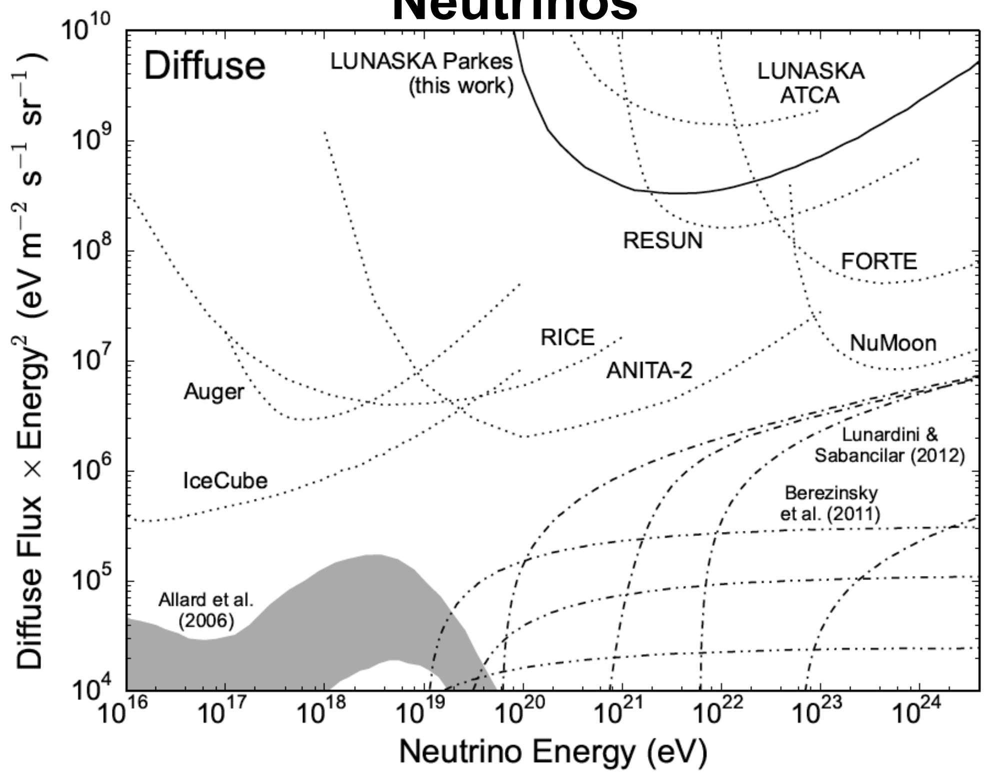
- Current limits only competitive at 10^{23} eV (NuMoon)

Cosmic Rays



S. ter Veen et al (2010)[10]

Neutrinos



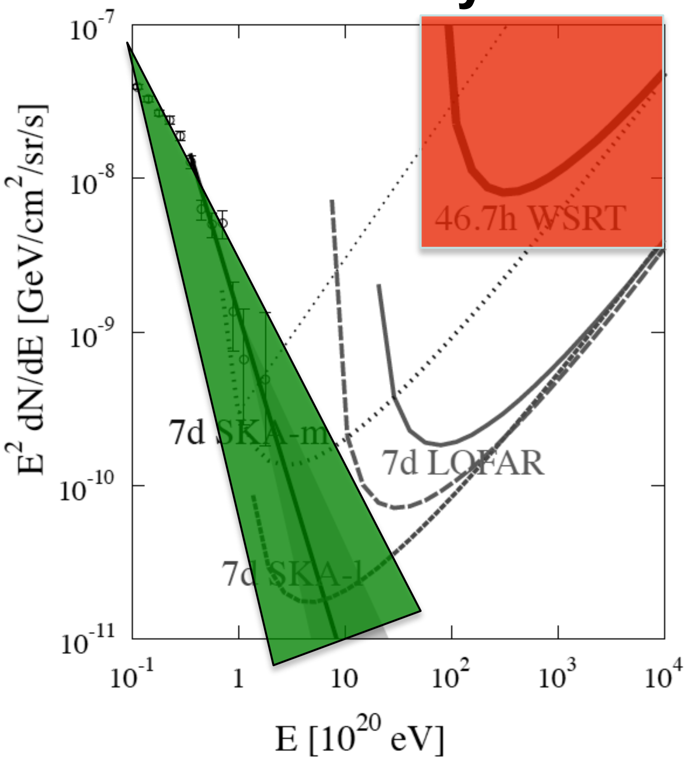
J. Bray et al. (2014)[13]

Simplified version

- Known/expected physics (CR flux)
- Potential physics (exotic)
- Lunar Askaryan

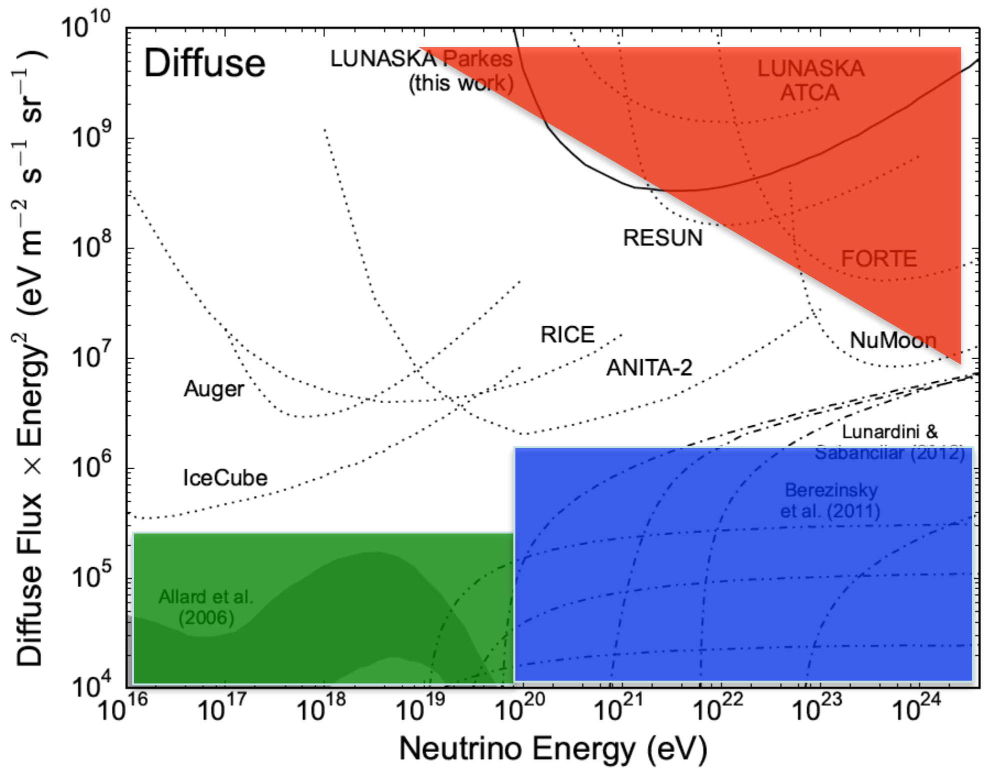
XKCD 'what if?' #13

Cosmic Rays



S. ter Veen et al (2010)[10]

Neutrinos

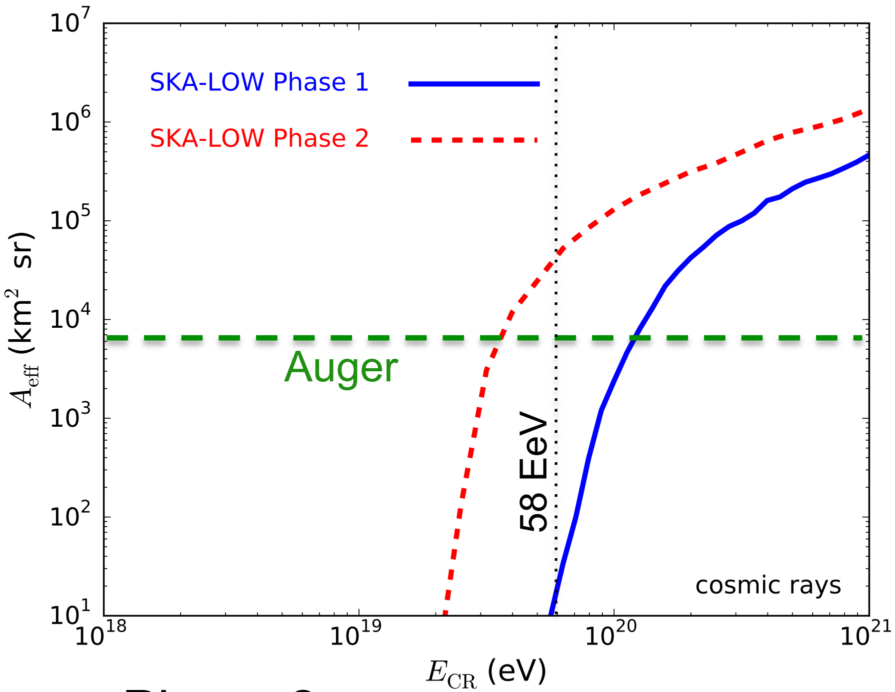


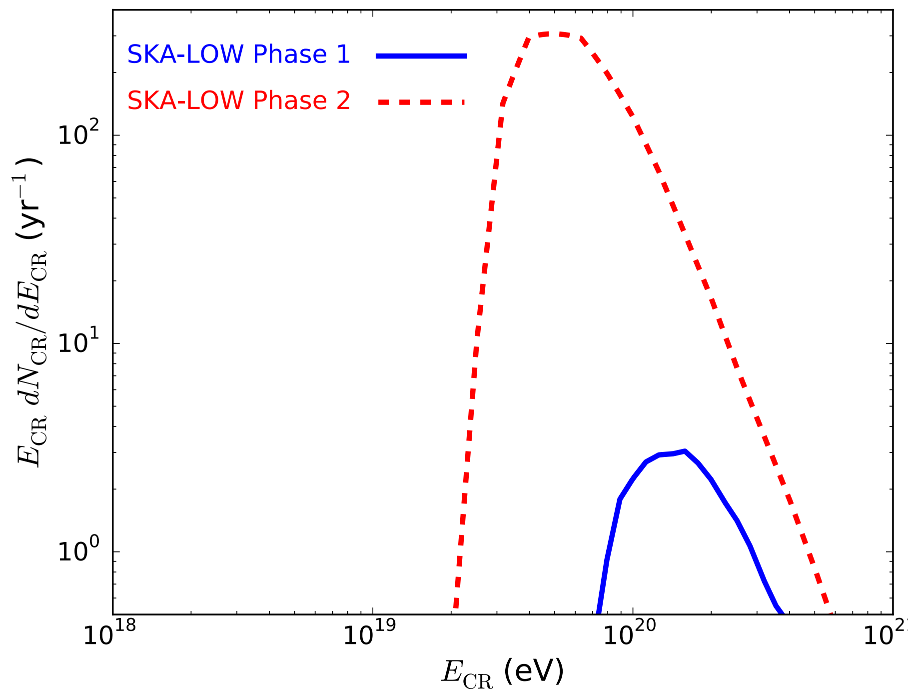
J. Bray et al. (2014)[13]

Expectations with SKA

Sensitivity to UHE CR

	A_{eff}/T_{sys} $m^2\,K^{-1}$	f_{min} MHz	f_{max} MHz	Beam coverage	σ_{thresh}
Phase 2	4,000	100	350	100%	10
Phase 1	250	100	350	$\sim$ 50%	7

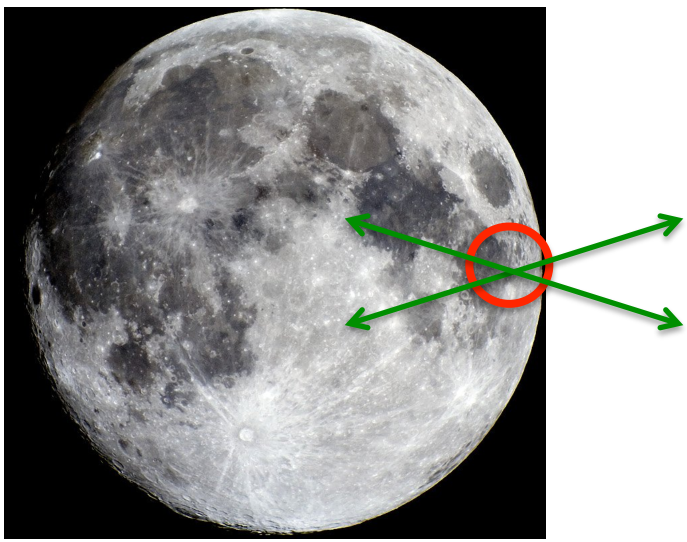


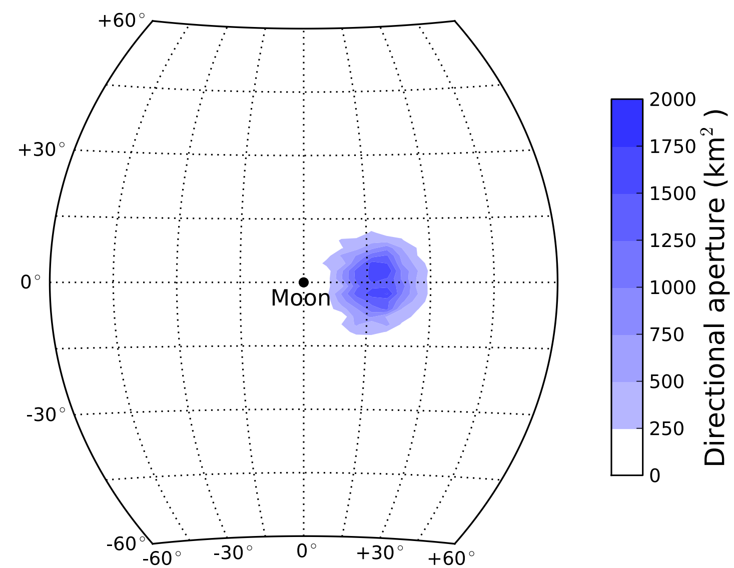


- Phase 2:
  - Aeff >100,000 km^2 sr at 10^{20} eV
  - 50 UHE CR yr^{-1} at E>56 EeV (28% lunar visibility at 30^o elev limit)
  - 2-3 x Auger, higher mean energy (more directional information)

Angular resolution

- Instantaneous sensitivity of the SKA-Moon detector





- Signal strength: 10σ (±1)
- Polarisation: 5^o (asin 1σ/10σ)
- Inner 10km : 0.5' at 100 MHz

- 'Resolution': ~5^o region
- Any explicit reconstruction should do better!

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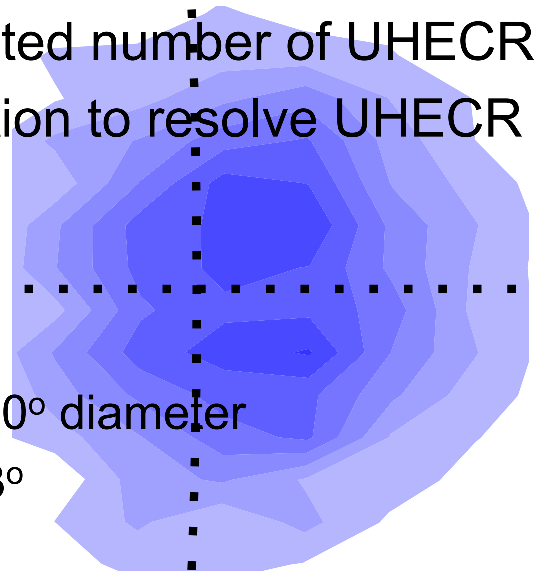
Science goal – Phase 2

- Measure an unprecedented number of UHECR
- Obtain 'sufficient' resolution to resolve UHECR sources



- 5^{o} is not great, but…
  - Cen A is ~5^{o}x5^{o}
  - Virgo cluster is O~5^{o}-10^{o} diameter
  - Bending of protons: ~3^{o}
  - Auger sig at 15^{o}

Image courtesy L. Feain & ATNF CSIRO

- Caveats:
  - No composition
  - Energy resolution?

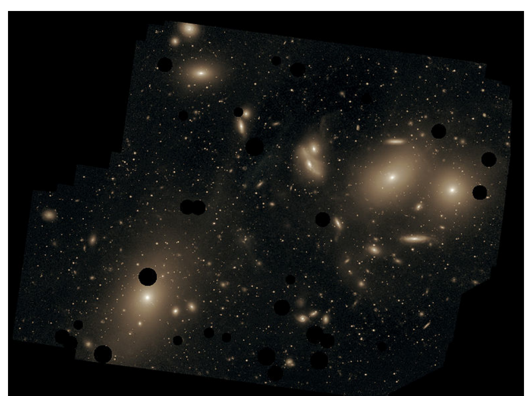
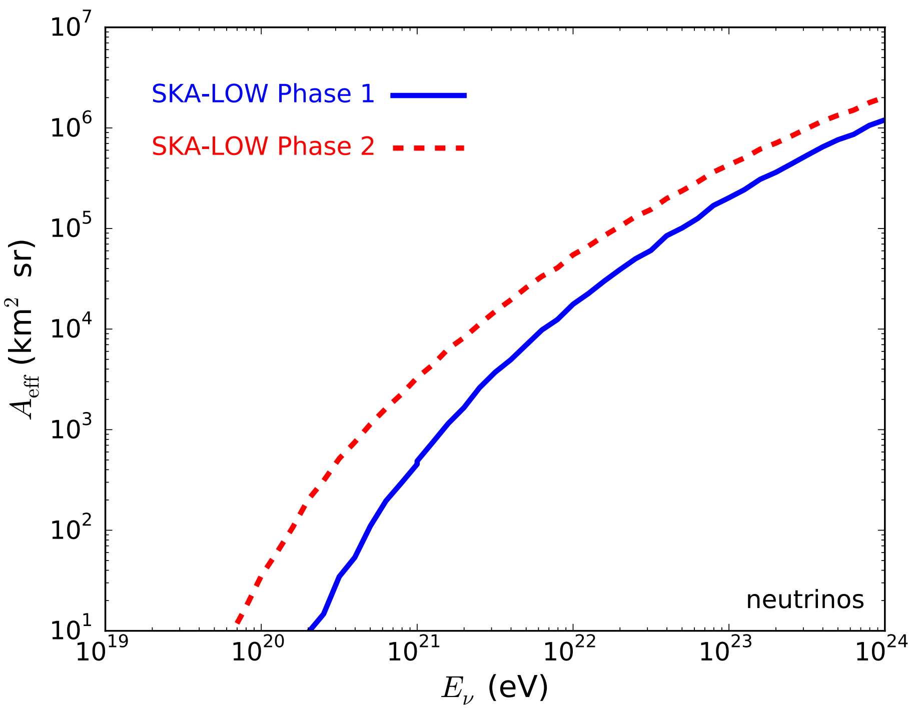
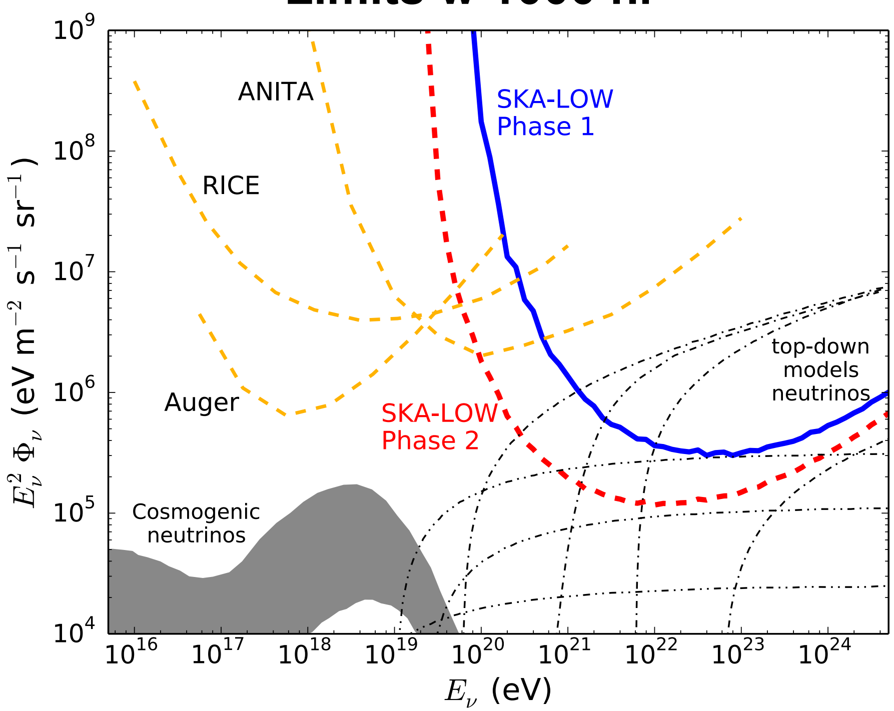


Image courtesy C. Mihgos & EUSO

Sensitivity to UHE neutrinos



Limits w 1000 hr

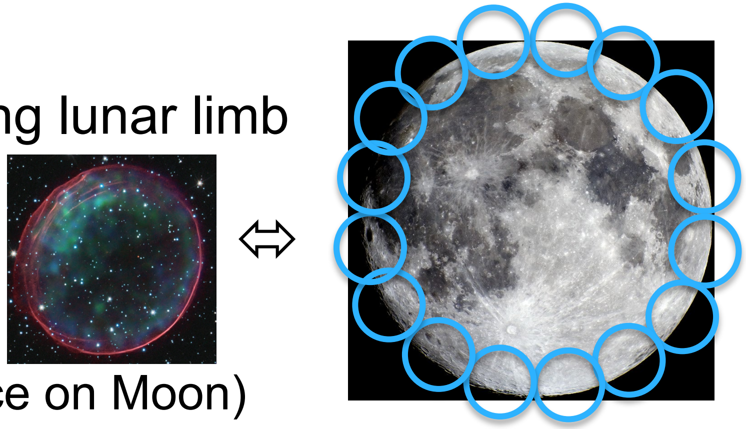


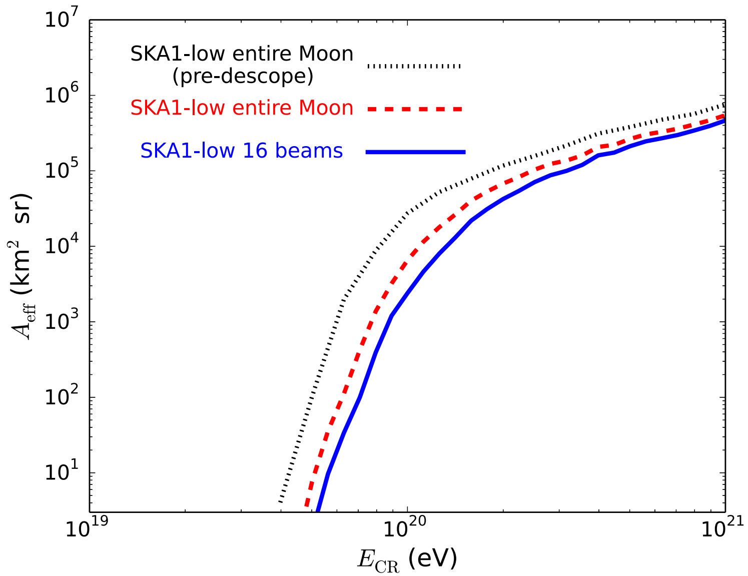
- Not sensitive to GZK – leave this to ARA & ARIANNA
- Strong constraints on remaining top-down models
- Potential science goal of Phase 1 KSP

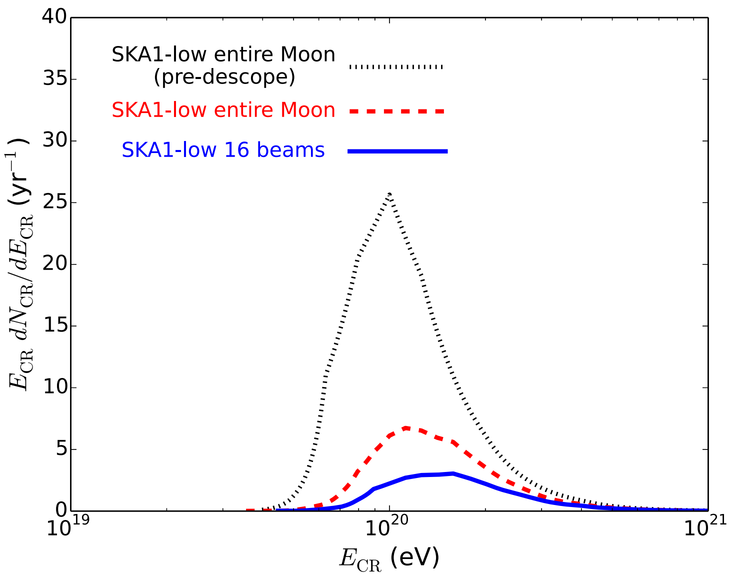
Observations with SKA-low phase 1

Sensitivity and beamforming

- Fully-coherent "array" beams covering lunar limb
  - Nbeams ~ baseline^2
  - Limit this to the core
  - Buffer remote station data
  - Phase 1: PBF gives 16 beams (place on Moon)





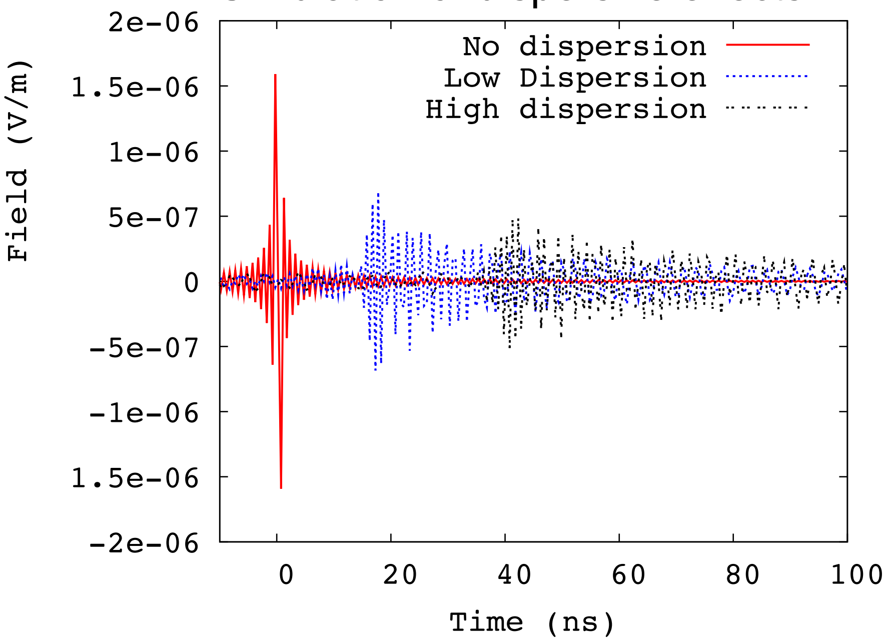


Dedispersion

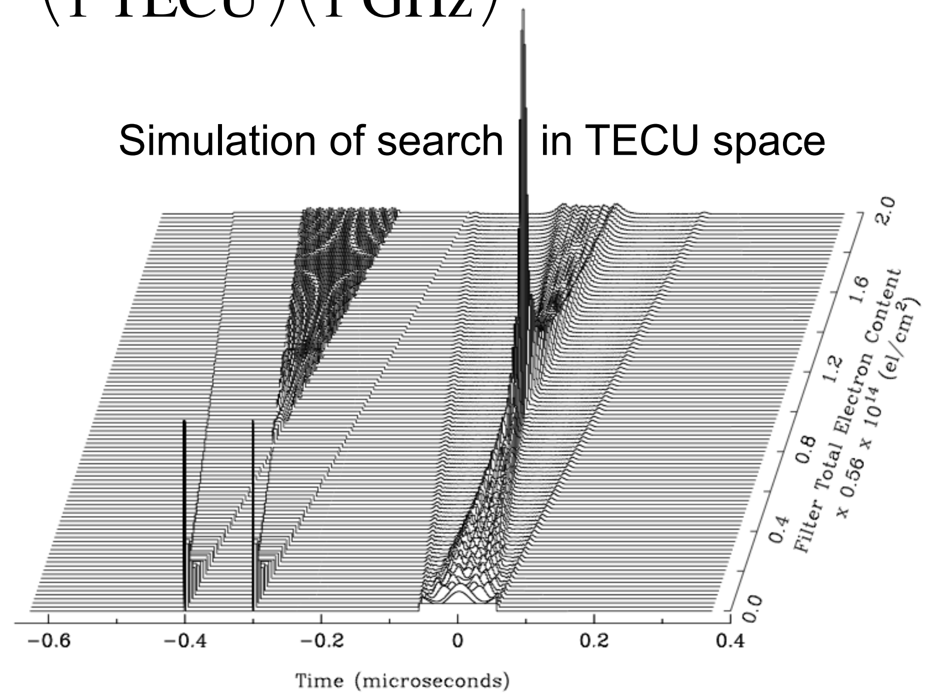
- For ns signals, the ionosphere is significant!

$$\Delta t(s) = 1.34 \cdot 10^{-9} \left(\frac{N_e}{1\ \mathrm{TECU}} \right) \left(\frac{\nu}{1\ \mathrm{GHz}} \right)^{-2}$$

Simulation of dispersive effects

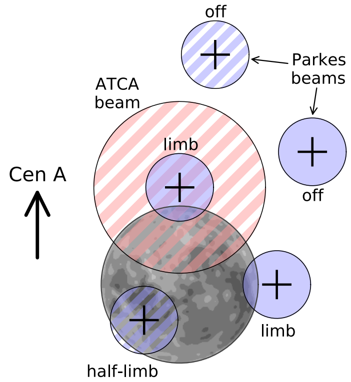


Simulation of search in TECU space



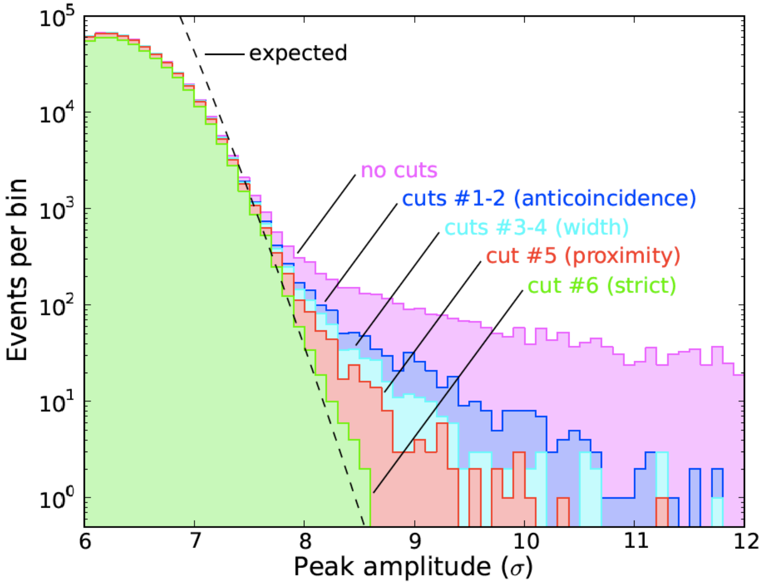
Hankins et al., Proc. RADHEP (2000)

Coincidence logic



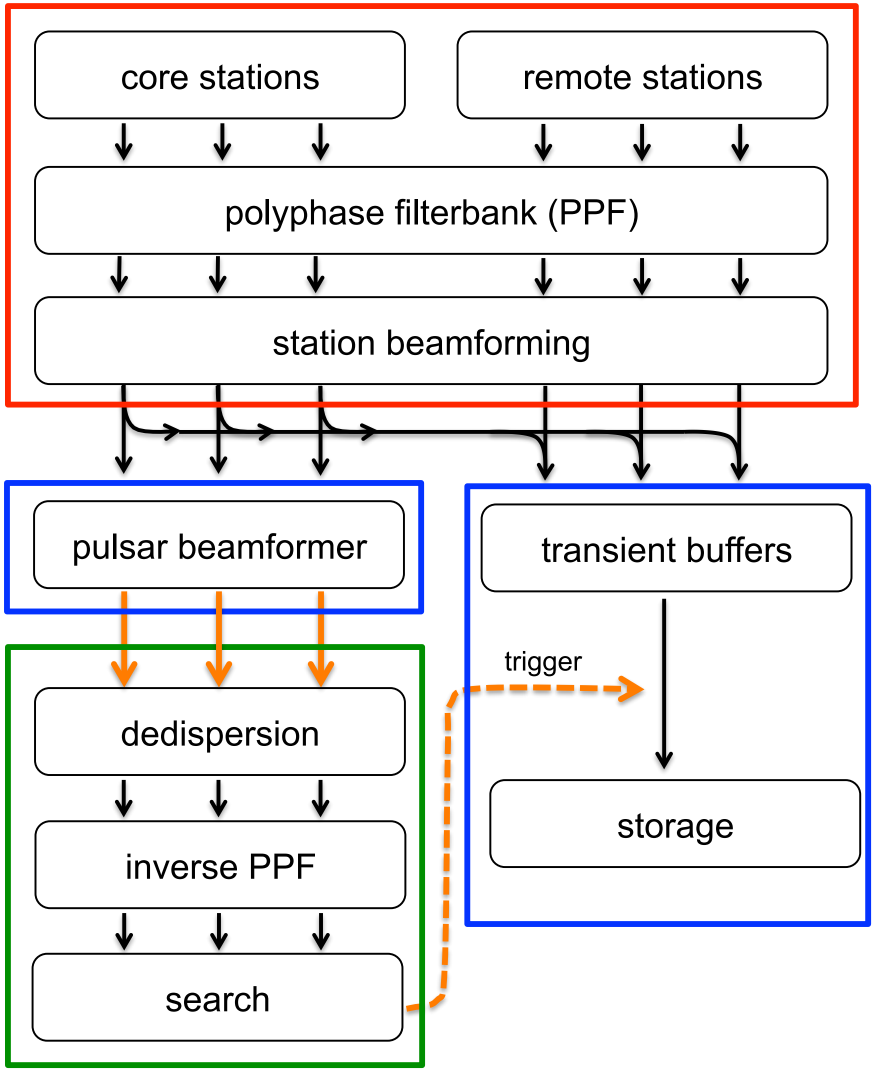
- Cuts:
  - Real-time veto
  - Offline veto
  - Shape-based
  - Pulse-train
  - Strict anti-coincidence
- Parkes:
  - Noise floor achieved!
  - 85.5% efficiency
- SKA:
  - Less noise: more efficient
  - More beams: better veto

Bray et al, Astropart.Phys. 65 (2015) 22



Data path – phase 1

- Required data flow
  - Standard imaging observations
  - Accepted ECPs
  - Dedicated lunar hardware
  - Changed interfaces
- Dedicated hardware:
  - Dedisperses signal
  - Reforms time-domain signal
  - Performs signal search
- Subject of ECP 150013 (stage 4)



Project

- SKA science chapter:

J. D. Bray, et al. Lunar detection of ultra-high-energy cosmic rays and neutrinos, aska.conf, 144 (2015).

arXiv:1408.6069B

- SKA high-energy cosmic particles focus group

- Workshop at Jodrell Bank:
  - Cosmic 2015

- Engineering change proposals:
  - ECP 150013

PoS PROCEEDINGS OF SCIENCE

Lunar detection of ultra-high-energy cosmic rays and neutrinos with the Square Kilometre Array

J.D. Bray[*1], J. Alvarez-Muñiz[2], S. Buitink[3], R.D. Dagkesamanskii[4], R.D. Ekers[5], H. Falcke[3,6], K.G. Gayley[7], T. Huege[8], C.W. James[9], M. Mevius[10], R.L. Mutel[7], R.J. Protheroe[11], O. Scholten[10], R.E. Spencer[12] and S. ter Veen[3]

[1]*Univ. of Southampton;* [2]*Univ. de Santiago de Compostela;* [3]*Radboud Univ. Nijmegen;* [4]*Lebedev Physical Institute;* [5]*CSIRO ATNF;* [6]*ASTRON;* [7]*Univ. of Iowa;* [8]*KIT;* [9]*Univ. of Erlangen-Nuremberg;* [10]*Univ. of Groningen;* [11]*Univ. of Adelaide;* [12]*Univ. of Manchester*

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The origin of the most energetic particles in nature, the ultra-high-energy (UHE) cosmic rays, is still a mystery. Only the most energetic of these have sufficiently small angular deflections to be used for directional studies, and their flux is so low that even the 3,000 km^2 Pierre Auger detector registers only about 30 cosmic rays per year of these energies. A method to provide an even larger aperture is to use the lunar Askaryan technique, in which ground-based radio telescopes search for the nanosecond radio flashes produced when a cosmic ray interacts with the Moon's surface. The technique is also sensitive to UHE neutrinos, which may be produced in the decays of topological defects from the early universe.

Observations with existing radio telescopes have shown that this technique is technically feasible, and established the required procedure: the radio signal should be searched for pulses in real time, compensating for ionospheric dispersion and filtering out local radio interference, and candidate events stored for later analysis. For the Square Kilometre Array (SKA), this requires the formation of multiple tied-array beams, with high time resolution, covering the Moon, with either SKA-LOW or SKA-MID. With its large collecting area and broad bandwidth, the SKA will be able to detect the known flux of UHE cosmic rays using the visible lunar surface — millions of square km — as the detector, providing sufficient detections of these extremely rare particles to address the mystery of their origin.

Advancing Astrophysics with the Square Kilometre Array,
June 8-13, 2014
Giardini Naxos, Sicily, Italy

*Speaker.

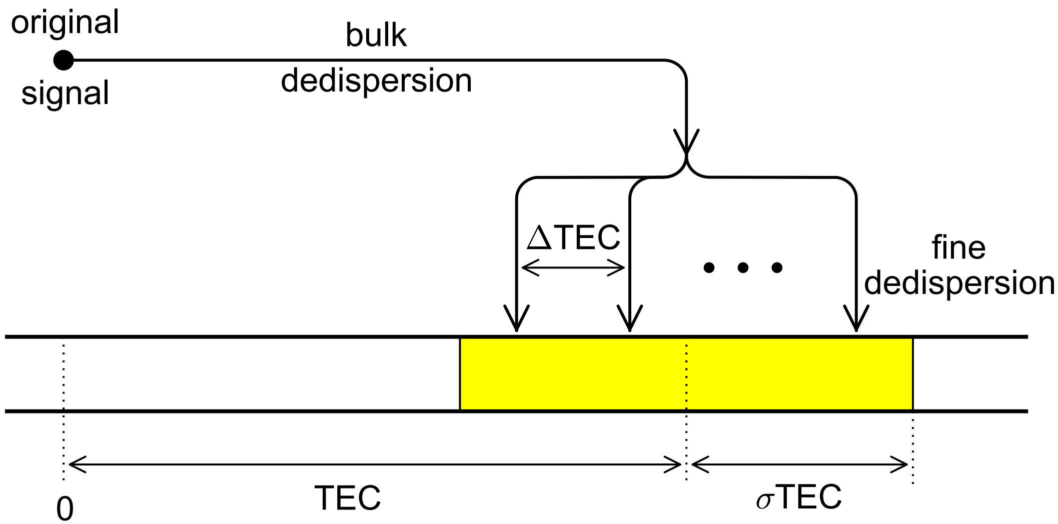
Conclusion

- Lunar Askaryan technique with the SKA can help solve the UHE cosmic ray mystery
- SKA high-energy cosmic particles focus group formed (together with EAS project)
- Proof-of-principle observations performed – we know what we have to do, and how to do it
- Fingers crossed while ECPs are evaluated
  - If “no” – wait for phase 2? Upgrades? First obs with other telescopes?
  - If “yes” – we need to get to work quickly!

backup

Dedispersion search

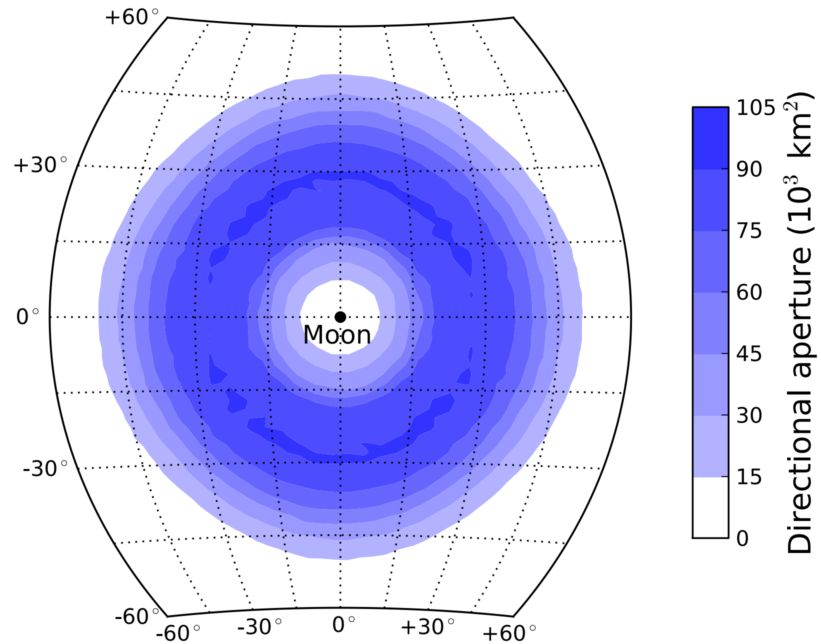
- Quasi-realtime ionospheric monitoring: aim for STEC w/in 1 TECU
- Perform bulk dedispersion on channelised (pre-beamformed) data
- Use FIR templates in beamformed data to scan remaining STEC space
- Worse TEC estimate: need longer FPGA taps (expensive), more false triggers (reduces sensitivity)



Coverage

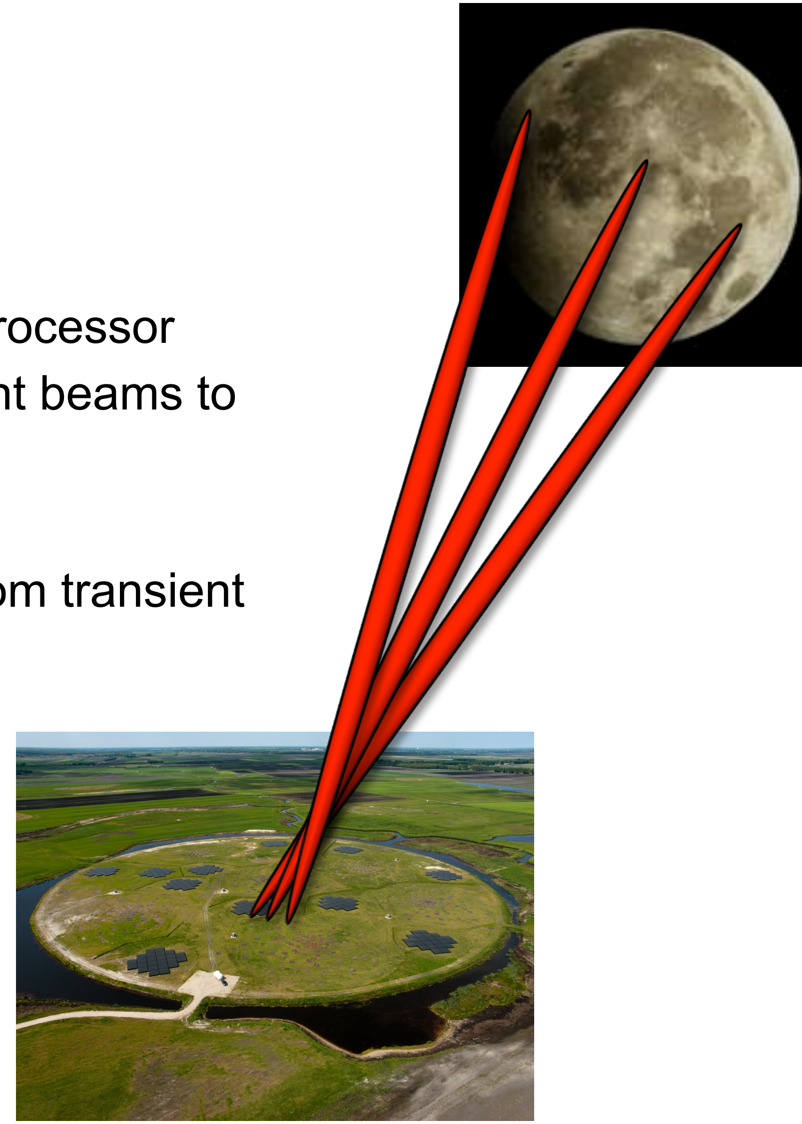
- Instantaneous sensitivity of the SKA-Moon detector

- Sources in range:
    - Cen A
    - M87
    - Sgr A*
    - …

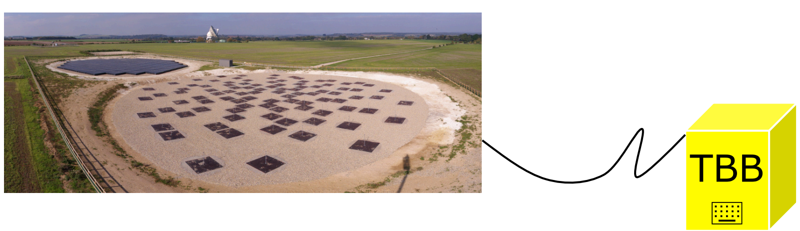


Test-bed: NuMoon at LOFAR

- LOFAR's 'UHEP' mode
  - Special mode of LOFAR's central processor
  - Central 'superterp': form 50 coherent beams to cover the Moon
  - Re-form full time-domain signal
  - Generate trigger, and dump data from transient buffer boards (TBBs)



Distant station

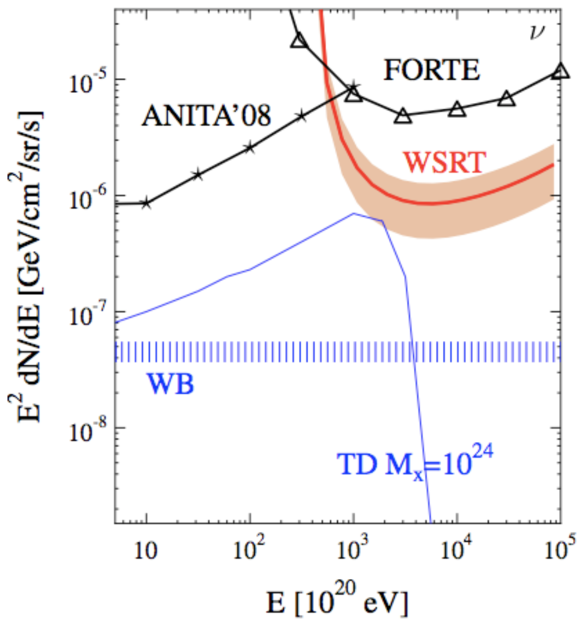


NuMoon at WSRT (2006-2007)

Scholten et al., PRL 103 (2009) 191301

- Westerbork Synthesis Radio Telescope
  - 50hr observations
  - 115-180 MHz in 4 bands
  - Coherent beamforming of 11 dishes
  - Recorded all data for later analysis – no triggering!

- Obtained best limit over all experiments at ultra-high energies



What does the signal look like?

- Simulations (inc surface roughness) of signals using 1-2 GHz b/w