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

(i.e. that chapter from the Sicily meeting)

Justin Bray

May 5, 2015

PROCEEDINGS OF SCIENCE

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

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[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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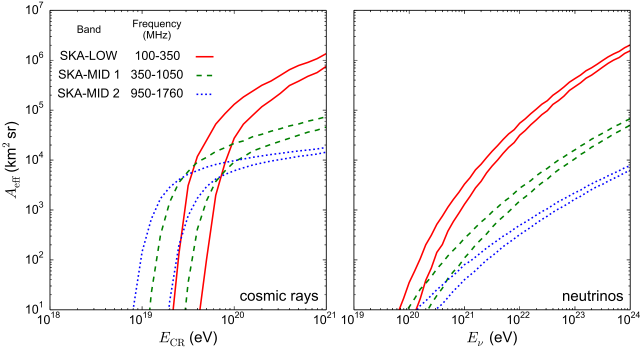
GLUE, LUNASKA, NuMoon, RESUN, LaLuna, etc. . . . leading to this.

Contents

- Science prospects.
  - neutrinos
  - cosmic rays
- Engineering.

Feel free to chime in.

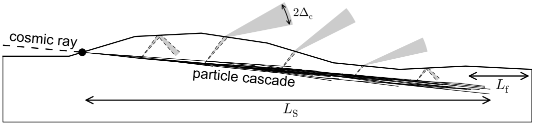
Aperture calculation

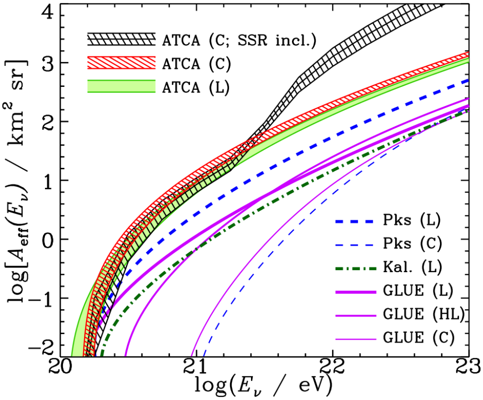


Clancy's Monte Carlo code.

Results compatible* with Olaf's simulations, Ken Gayley's analytic model.

Small-scale surface roughness





James et al., Phys. Rev. D 81, 042003 (2010)

At high frequencies.

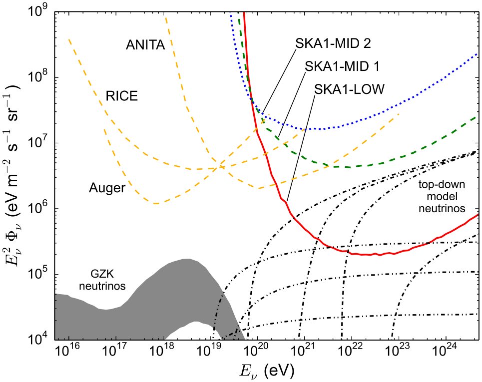
Increases threshold; increases aperture.

Omitted from current models.

Potentially huge effect.

Major cause of uncertainty.

Projected neutrino limits (1000 hrs)



GZK neutrinos: certain* to exist, but way below threshold.

Top-down model neutrinos: detectable, but models constrained by:

- neutrino limits
- photon fraction limits
- composition results

Unlikely to exist.

GLUE

LUNASKA

NuMoon

RESUN

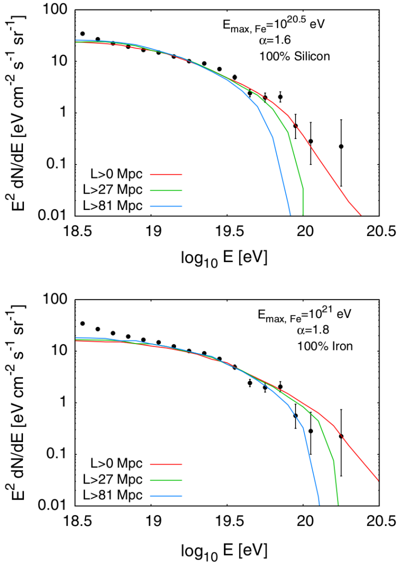
LaLuna

Emphasis on neutrinos.

Original idea from Dagkesamanskii & Zheleznykh (1989):

“. . . neutrinos and other elementary particles . . .”

Cosmic rays



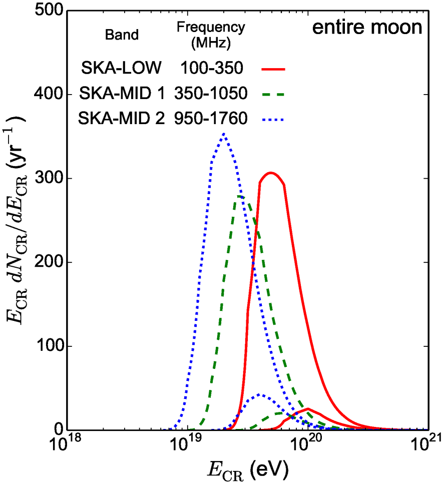
Spectrum at high energies not well-constrained.

Models:

- source distribution
- composition
- injection spectrum

Underlying systematic energy uncertainty $\sim 20\%$.

Taylor et al., Phys. Rev. D 84, 105007 (2011)



Detections expected (/1000 hrs):

SKA1-LOW: 2.8–9.4

SKA1-MID1: 2.6–4.9

SKA1-MID2: 5.4-7.8

Large model uncertainty, but detection highly likely.

Model discrimination eventually possible.

Resolution

New simulations by Clancy.

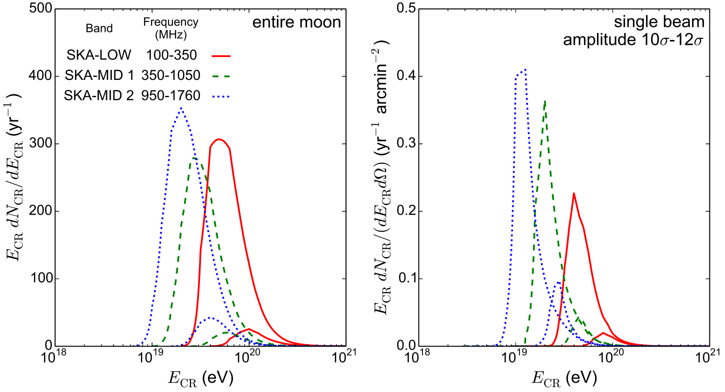
Constrain:

- event position: within 0.1–0.5′ (10 km baseline)
- pulse amplitude: $11 \pm 1\sigma$
- pulse polarisation: $\pm 5^\circ$

Do not constrain:

- pulse spectrum
- other pulse structure
- variation over Earth

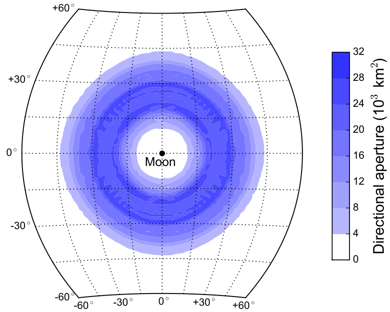
Energy resolution



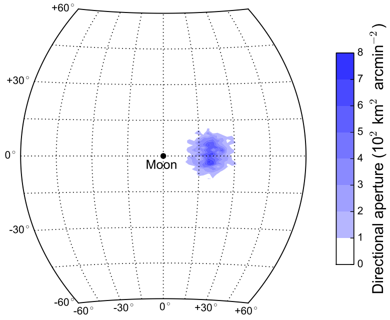
Energy “resolution”.

Uncertainty factor: 1.3–1.5

Directional resolution



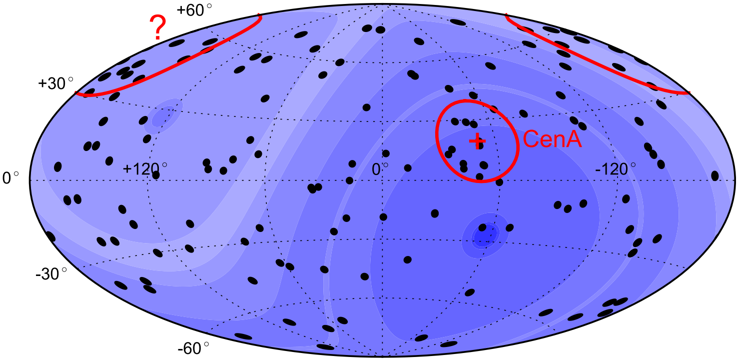
whole moon



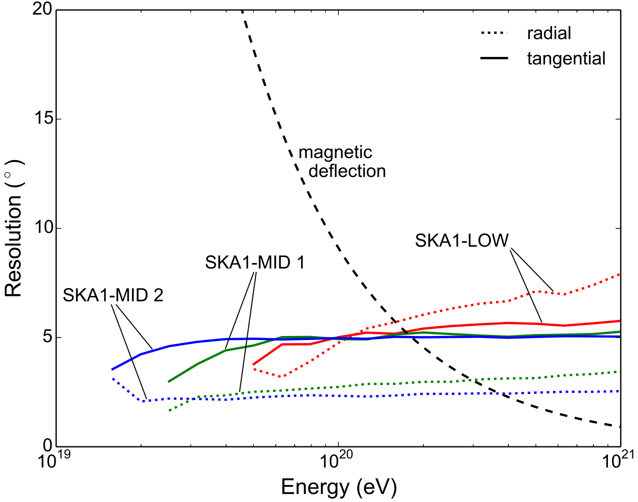
constrained

resolution $\sim 5^\circ$

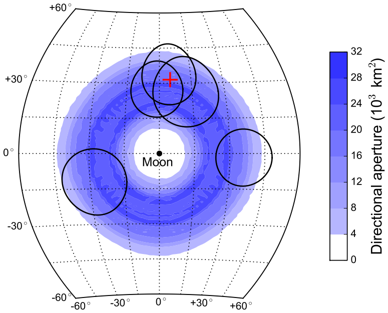
UHE cosmic ray arrival directions



Pierre Auger Collaboration 2010, Astropart. Phys., 34, 314;
Telescope Array Collaboration 2014, ApJ, 790, 21



Magnetic deflection is fairly model-agnostic.



Test for source.

Figure of merit:

$$M = \sum \theta^{-2}\,\Omega(E)^{-1}$$

$\theta =$ observed deflection

$\Omega(E) =$ expected resolution

Simulations for 1000 hrs, targeted.

For TA (northern hemisphere) hotspot.

$M = 5000$ rad^{-2} is $>$ 95%-confidence threshold.

Exceeded in 76% of trials for best-fit spectrum from Taylor et al.

Less for other spectra tested.

Needs more work. Assumptions:

- local source has typical spectrum (pessimistic)
- composition is energy-independent (optimistic)
- no information from pulse spectrum (pessimistic)
- cosmic ray spectrum known (optimistic)

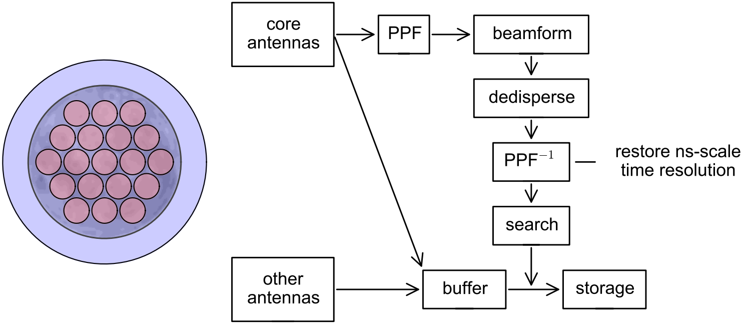
Various other approximations:

- resolution for fixed location, amplitude, polarisation
- hotspot at fixed distance from moon
- etc.

But: first numerical test of prospects for cosmic ray directional studies with lunar technique.

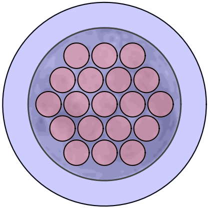
On the technical side . . .

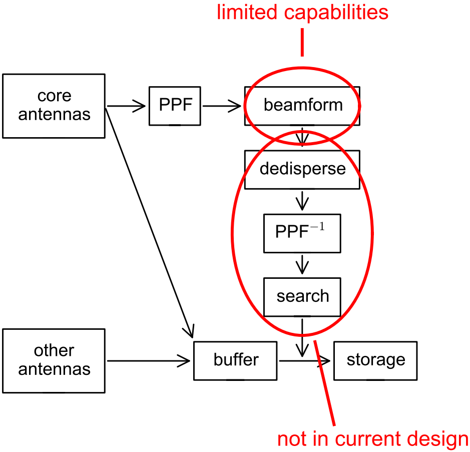
Real-time: partial sensitivity, 7σ threshold, 1 Hz

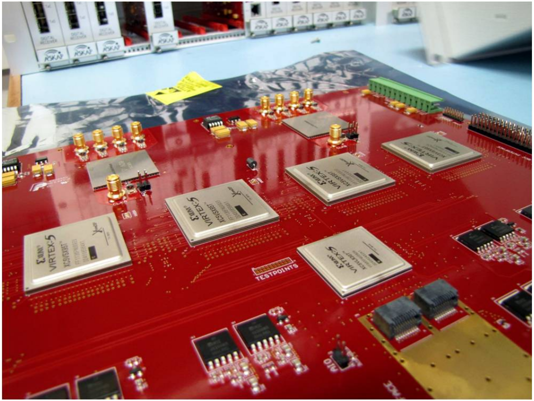


Retrospective: full sensitivity, 10σ threshold, 10^{-12} Hz

On the technical side . . .







LUNASKA Parkes: 4 beams, 300 MHz, in 2010

SKA-MID: 500 beams, 800 MHz, in 20??

SKA-LOW: 60 beams, 300 MHz, in 20?? . . . parallel dedispersion

Costs

Dedicated hardware: O($millions)

1000+ SKA hrs: O($millions)

Within an order of magnitude of dedicated facilities.

Need comparable justification.

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Within beamformer capability by that measure.

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Engineering Change Proposal

Proposal: modify beamformer to allow this capability.

Avoid "designing out" this experiment.

Conclusions

- Science case is slightly promising.
  - Cosmic ray detection is highly likely.
  - Directional result is moderately likely.
  - Needs more detailed analysis.
- Engineering side is difficult.
  - Impossible with current beamformer design.
  - Requires additional hardware, and interface with beamformer.