

The lunar Askaryan technique with the Square Kilometre Array

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PHYSICS

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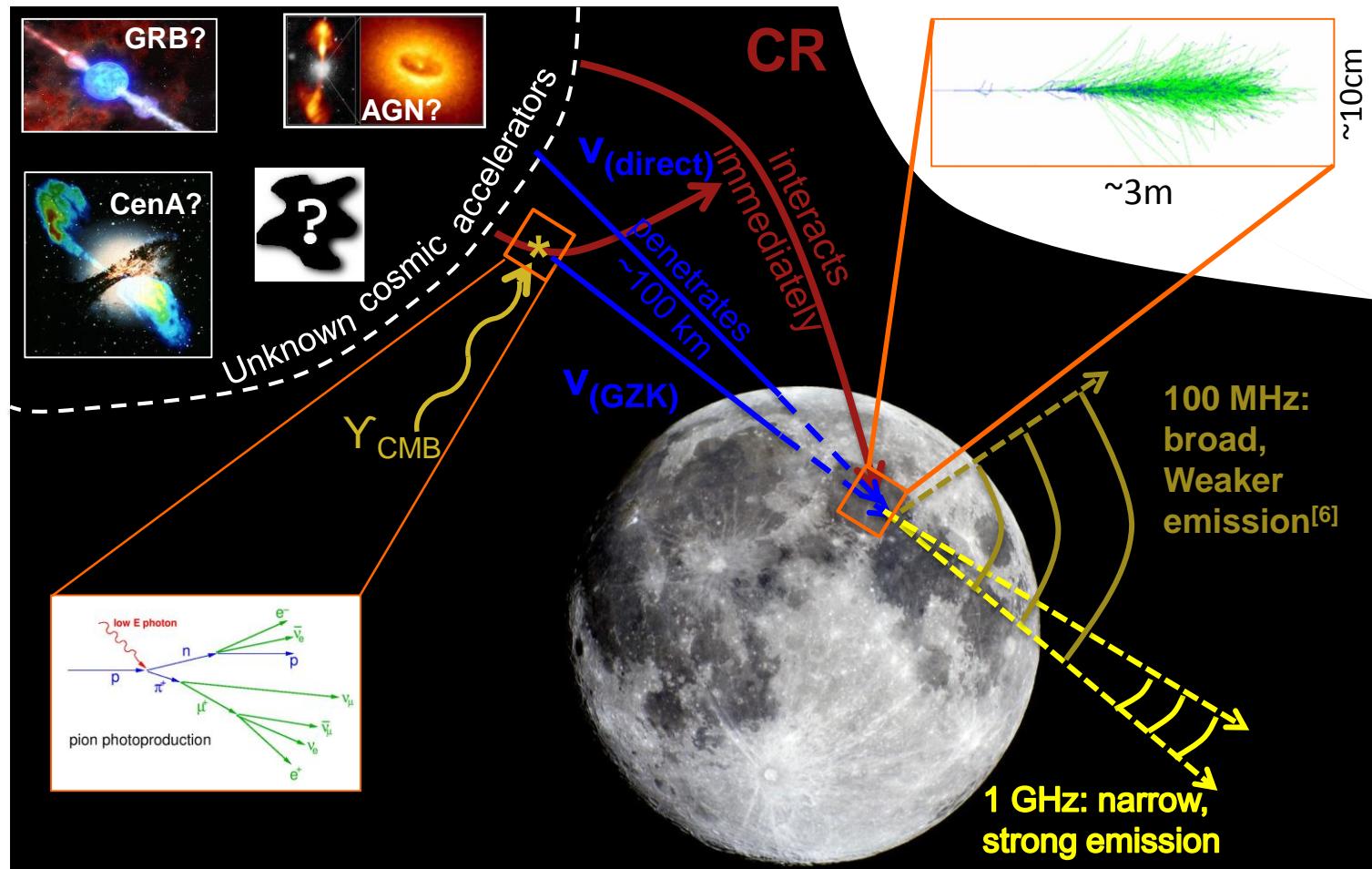


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The Lunar Askaryan Technique



History of lunar experiments

LaLUNA
Lovell 2010



NuMoon
Westerbork 2008^[6]
LOFAR UHEP

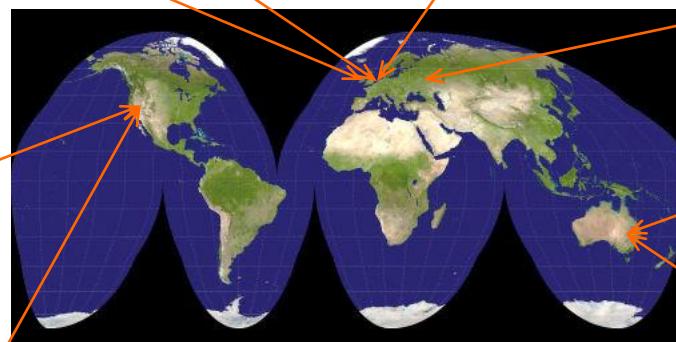


RAMHAND
Kalyazin 2002-2006^[7]



GLUE

Goldstone 1999-2004^[4]



RESUN
VLA 2008-09^[8]



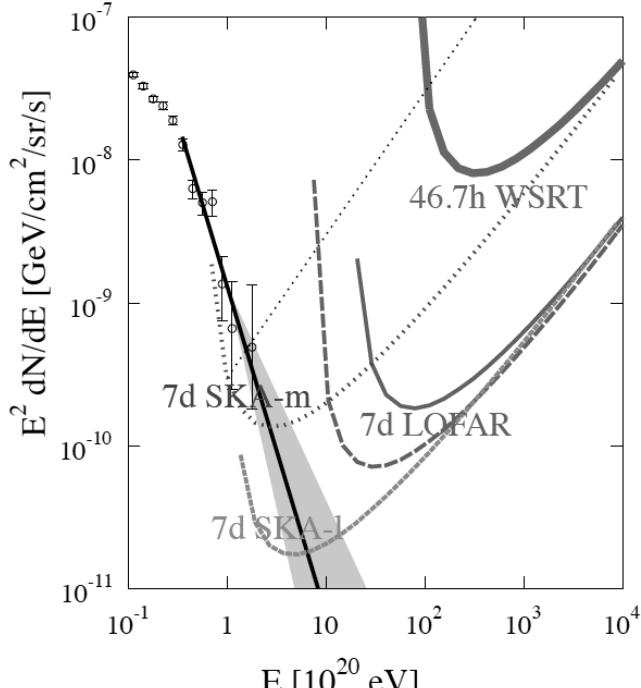
- Technically feasible
- But just one problem...



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

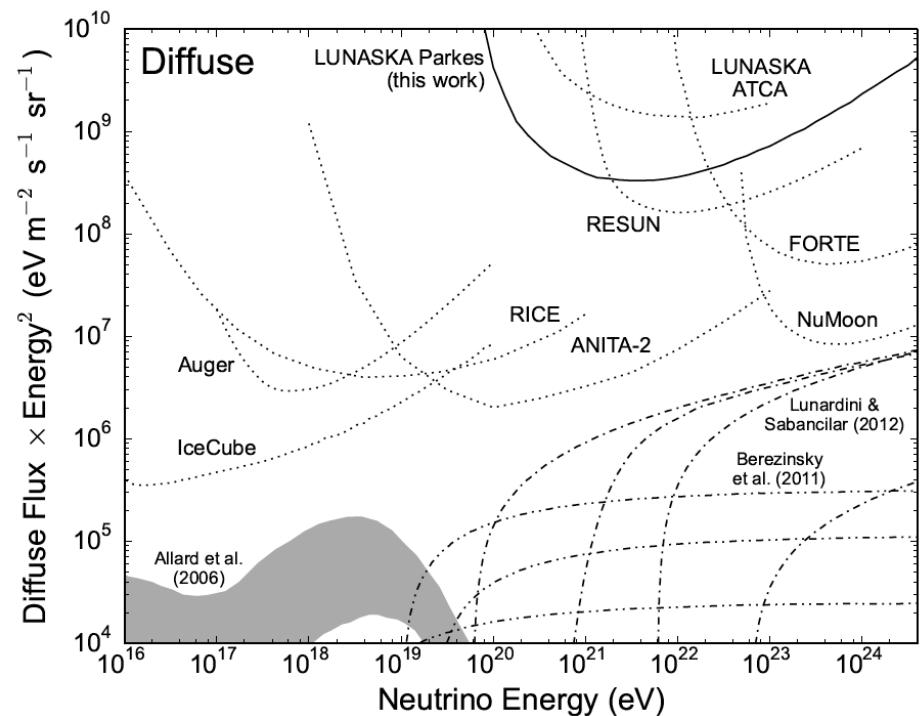
Limits to UHE particles fluxes from past experiments

- Current limits on neutrinos only competitive at 10^{23} eV (NuMoon)
- Sensitivity not enough to detect UHE CR flux



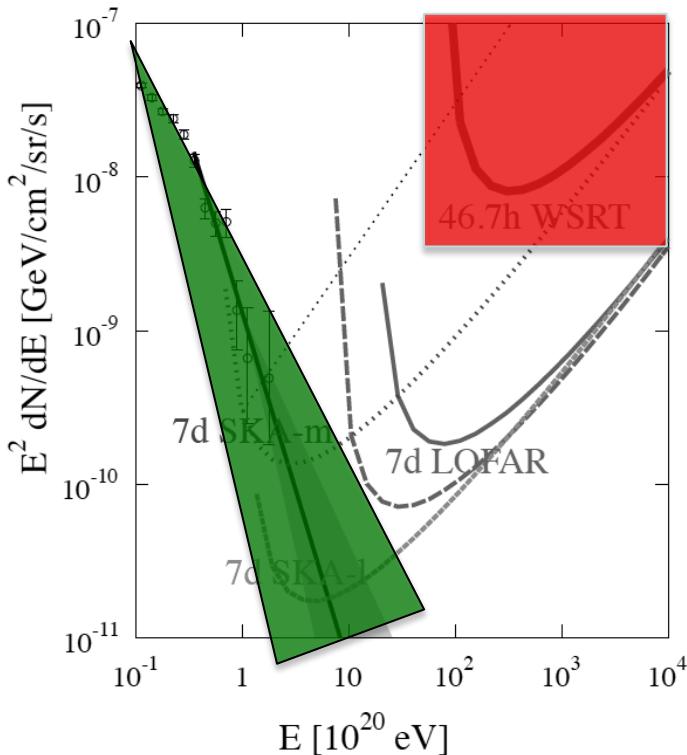
S. ter Veen et al (2010)^[10]

C.W. James, 34th ICRC, The Hague, NL



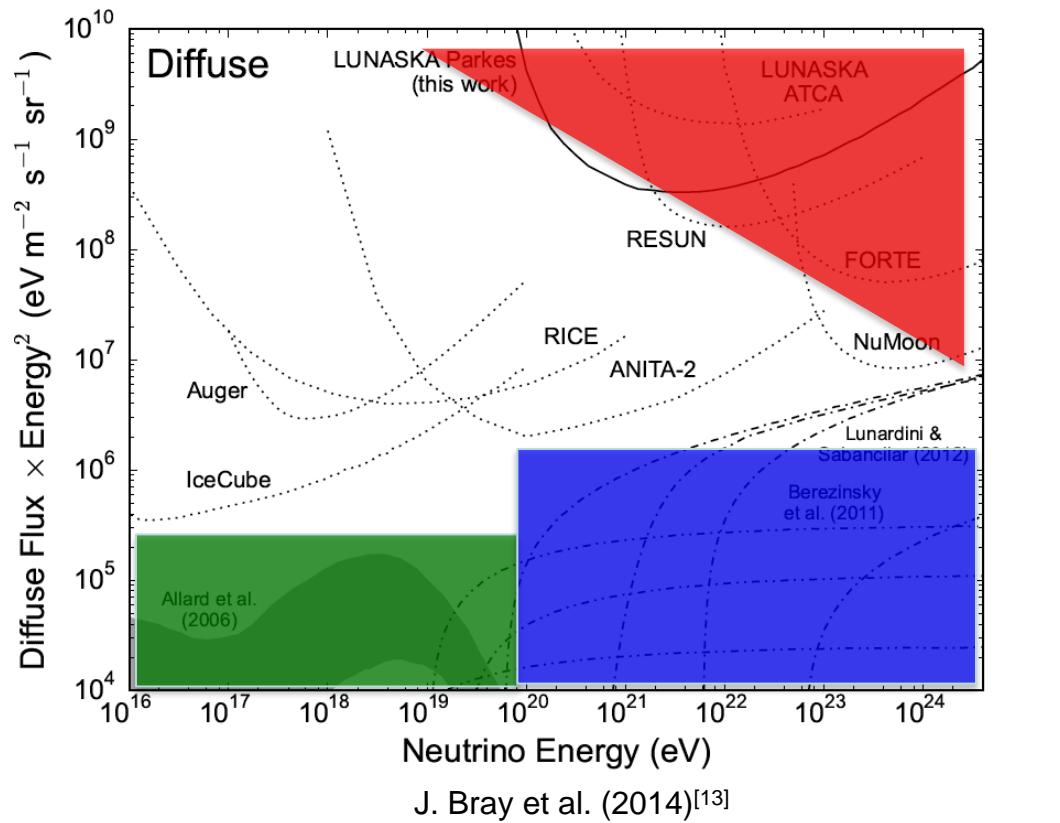
J. Bray et al. (2014)^[13]

Simplified version



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

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



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

WHAT IF WE TRIED
MORE POWER?



SKA - concept

- A giant radio-telescope array with 1 km² collecting area
- Frequency range: 50 MHz-20 GHz:



Low-frequency
aperture array
(50 – 350 MHz)



Mid-frequency
aperture array
(400-1000 MHz)



Dishes (>700 MHz)

SKA – Timelines

- Phase 1 (2018-2023)
 - SKA1 LOW: 130,000 dipole antennas (Australia)
 - SKA1 MID: 200 15m dishes (South Africa)
- Phase 2 (completion ~2030)
 - SKA1 LOW: x4-10 (approx)
 - SKA1 MID: x4-10 (approx)
 - +Mid-frequency aperture array

South Africa (Meerkat pathfinder)



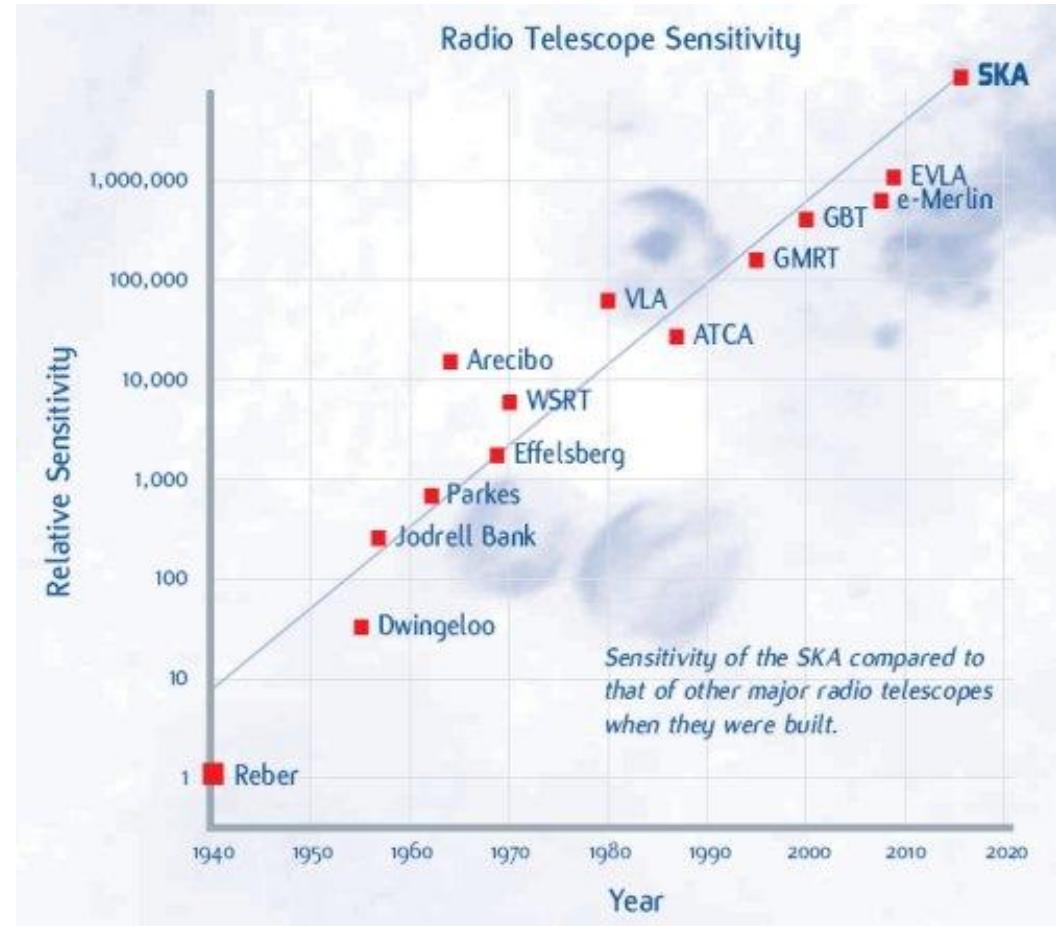
Australia (ASKAP pathfinder)



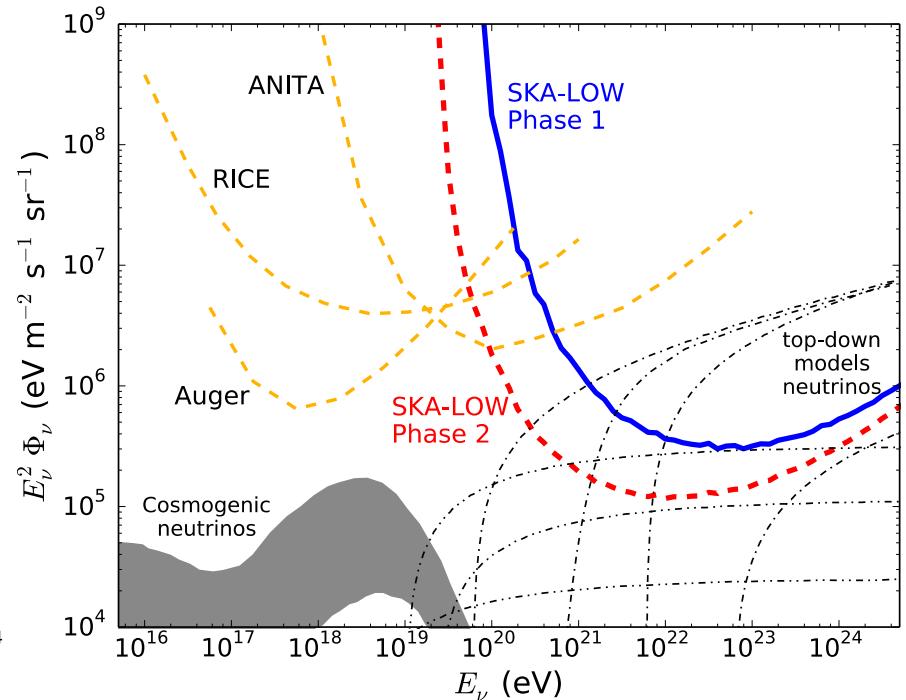
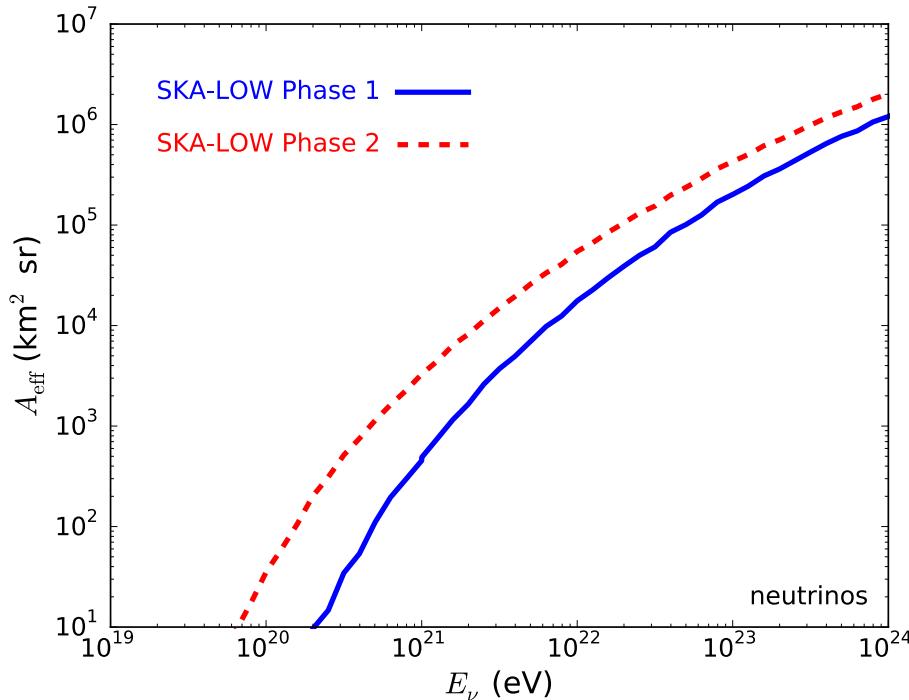
Some superlatives

- Final SKA performance:
 - Huge effective area
 - Broad bandwidths
 - Low-RFI environment
- Science potential
 - Cosmic magnetism
 - Galaxy evolution
 - Pulsars & Grav Waves
 - Epoch of Reionisation
 - ...
- How good will this be with the lunar Askaryan technique?

www.skatelescope.org

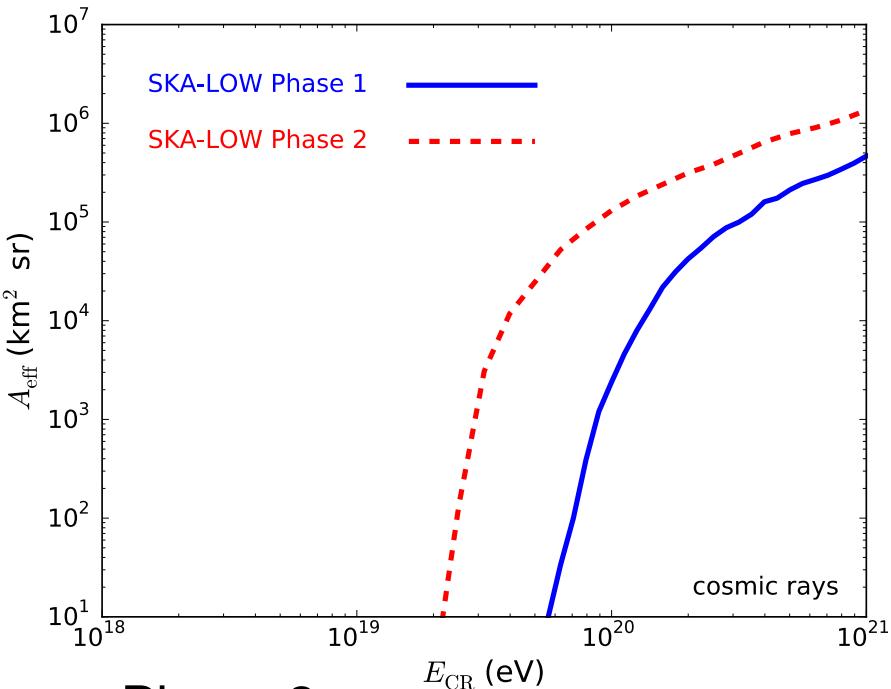


Limits on UHE neutrinos with 1000 hr



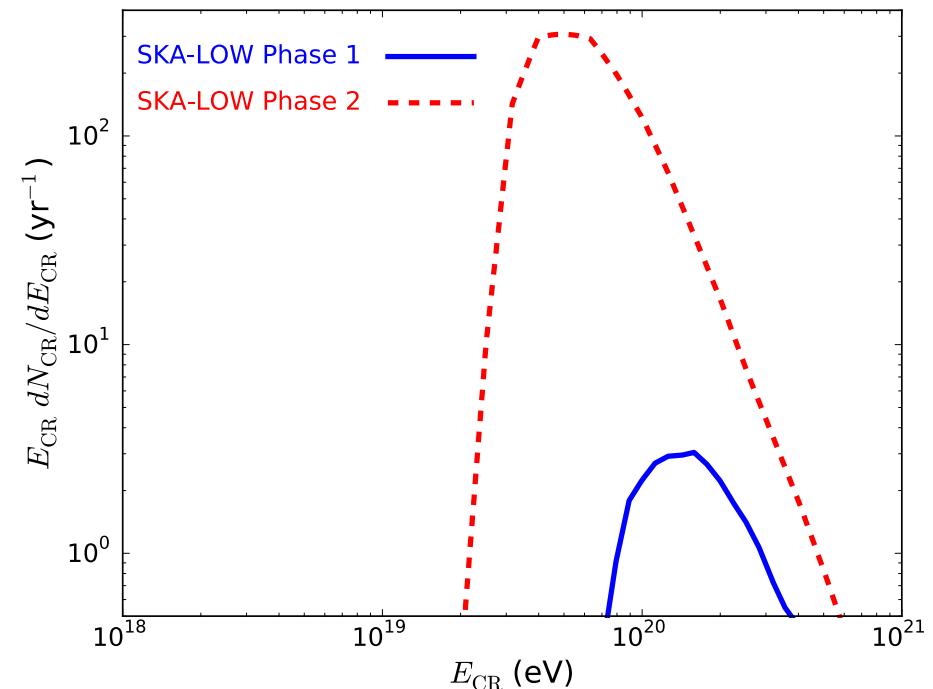
- Strong constraints on remaining top-down models
- Not sensitive to GZK – leave this to ARA & ARIANNA

Sensitivity to UHECR



- Phase 2:
 - $A_{\text{eff}} > 100,000 \text{ km}^2 \text{ sr}$ at 10^{20} eV
 - 50 UHE CR yr^{-1} at $E > 56 \text{ EeV}$

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

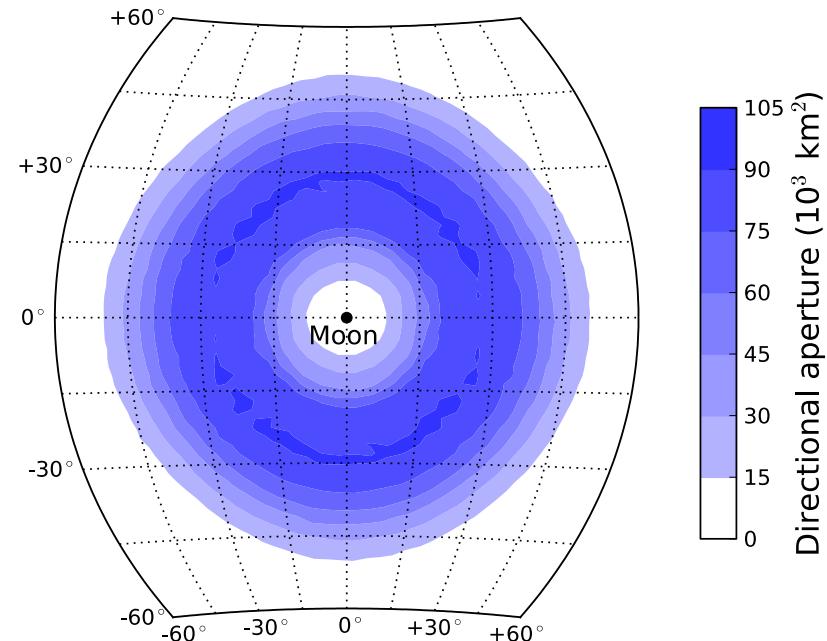


Coverage

- Instantaneous sensitivity of the SKA-Moon detector

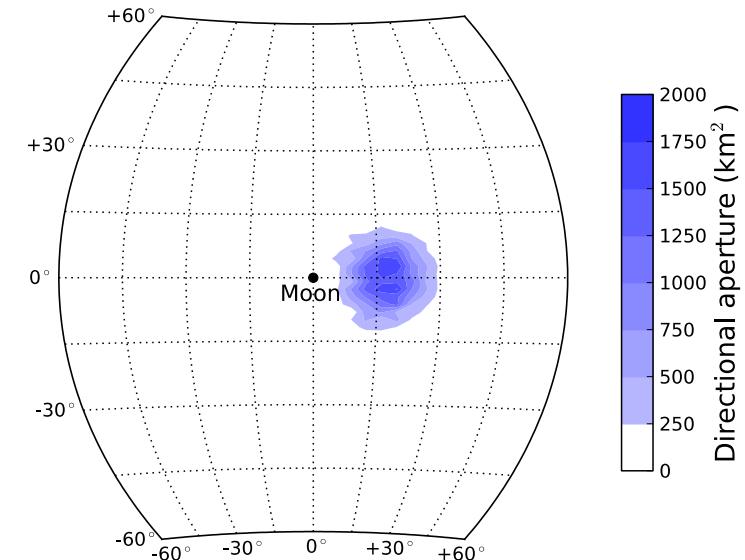
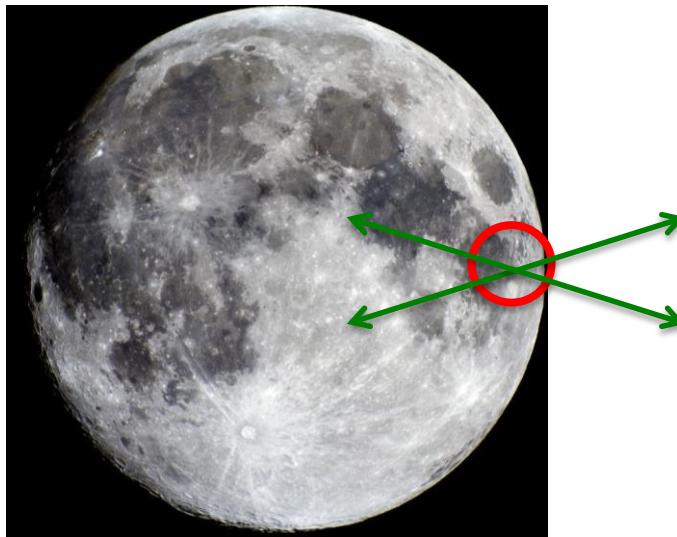
- Sources in range:
 - Cen A
 - M87
 - Sgr A*
 - ...

- Direction reconstruction?
 - None yet— but we will measure polarisation, amplitude, and position on the Moon. How is this related to the cosmic ray origin?



Angular resolution

- Instantaneous sensitivity of the SKA-Moon detector



- Signal strength: 10σ (± 1)
- Polarisation: 5° ($\text{asin } 1\sigma/10\sigma$)
- Inner 10km : $0.5'$ at 100 MHz
- 'Resolution': $\sim 5^\circ$ region
- Any explicit reconstruction should do better!

Clear science goal

- Measure an unprecedented number of UHECR
- Obtain ‘sufficient’ resolution to resolve UHECR sources
- 5° is not great, but...
 - Cen A is $\sim 5^\circ \times 5^\circ$
 - Virgo cluster is $0\sim 5^\circ\text{--}10^\circ$ diameter
 - Bending of protons: $\sim 3^\circ$
- Caveats:
 - No composition
 - Energy resolution?

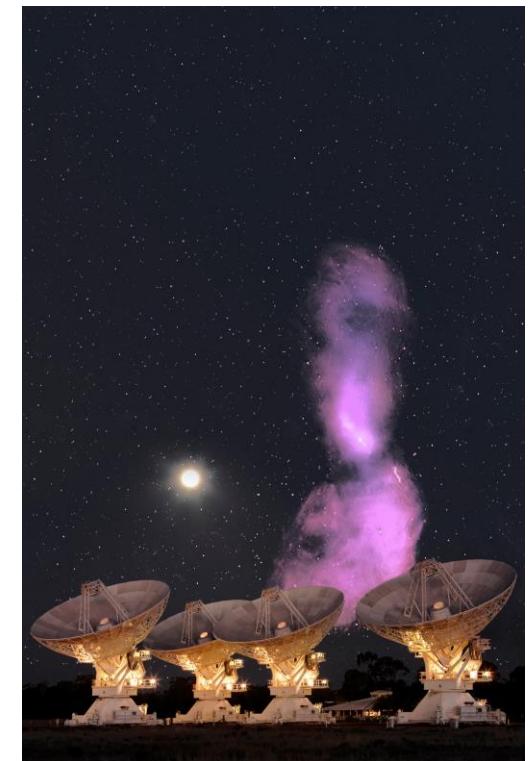
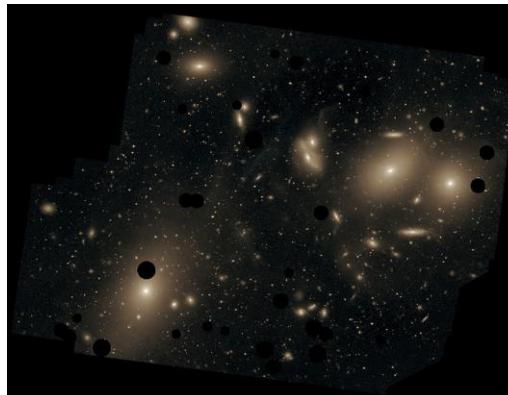
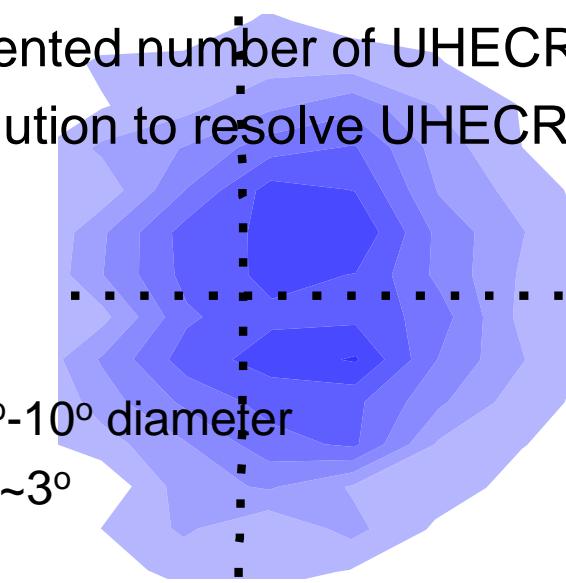
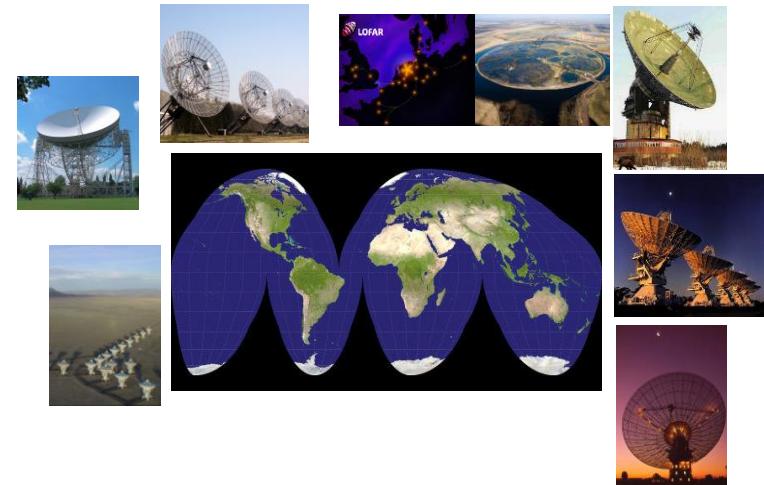


Image courtesy L.
Feain & ATNF CSIRO

Getting it done:

- The SKA High Energy Cosmic Particles Focus Group (lunar + EAS)
- SKA science chapter:
 - J. Bray et al, *Lunar detection of ultra-high-energy cosmic rays and neutrinos with the Square Kilometre Array*, arXiv 1408.6069 (2014)
- Cosmic 2015: May 5th-7th 2015
 - Meeting with SKA engineers at Jodrell Bank, UK
- **Engineering requirements: J. Bray (ID 533)**
 - Engineering change proposal submitted to SKAO for Phase 1
 - Good news: buffer capability and beamforming already accepted!

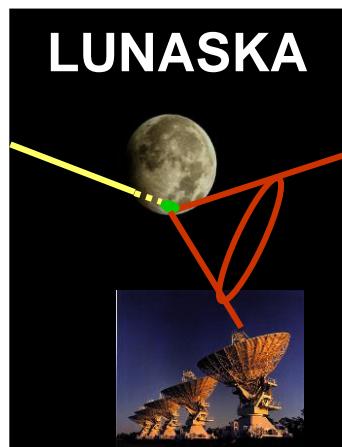


Conclusions

- Lunar Askaryan Technique with the SKA:
 - Limit top-down neutrino models
 - Detect large numbers of UHECR
 - Enable directional studies
- Status:
 - SKA Focus Group formed
 - Technical feasibility studied
 - Science promising!
 - Still needs to be accepted by the SKA organisation

In Memoriam

- Raymond J. Protheroe:
 - Passed away Wednesday July 1st 2015
 - Renowned theoretical astrophysicist
 - LUNASKA co-founder
 - PhD supervisor
 - Friend



The Eaton logo is a dark blue watermark located in the top right corner. It features the word "eaton" in a lowercase, sans-serif font. Above the letters "e", "t", and "a", there is a stylized graphic element consisting of a circle with several thin, radiating lines.

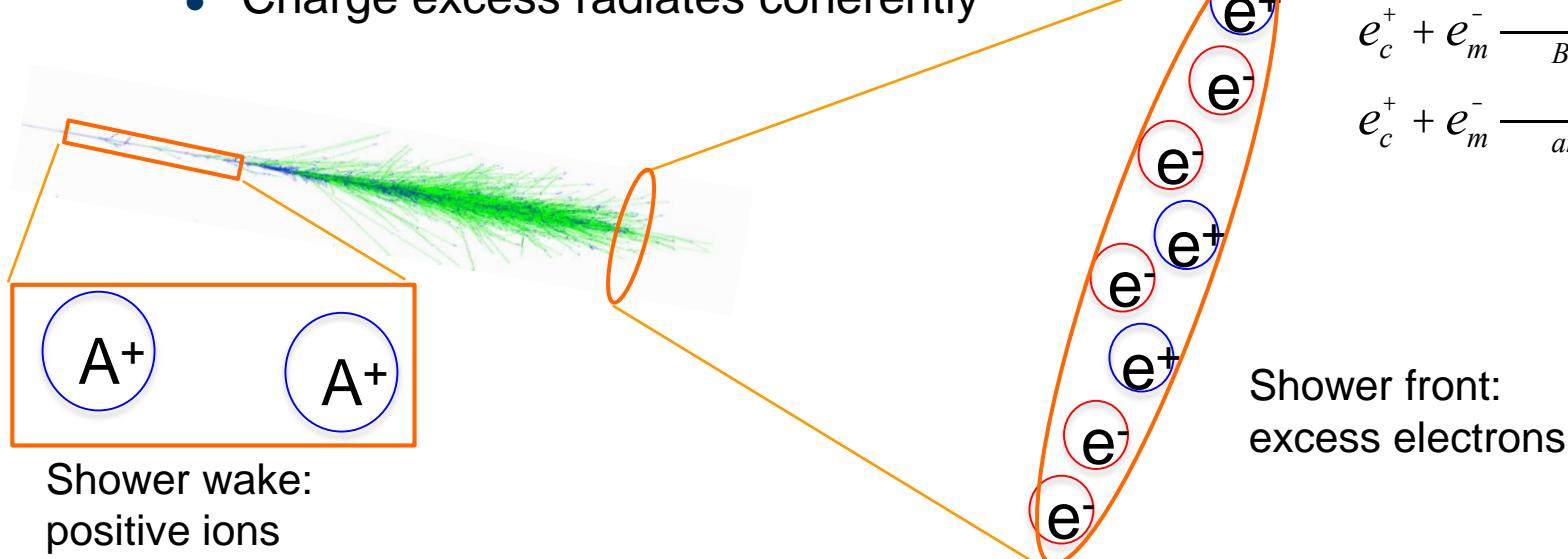
eaton

BACKUP

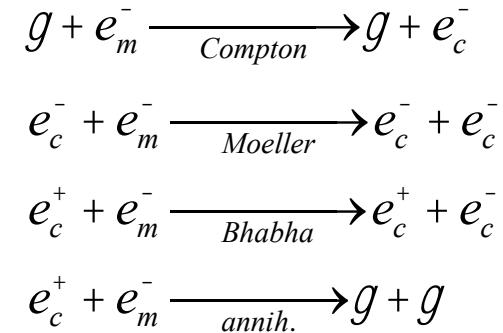
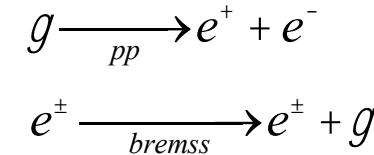
G.A. Askaryan, Sov. Phys. JETP 14 (1962) 441; 48 (1965) 988.

The Askaryan effect

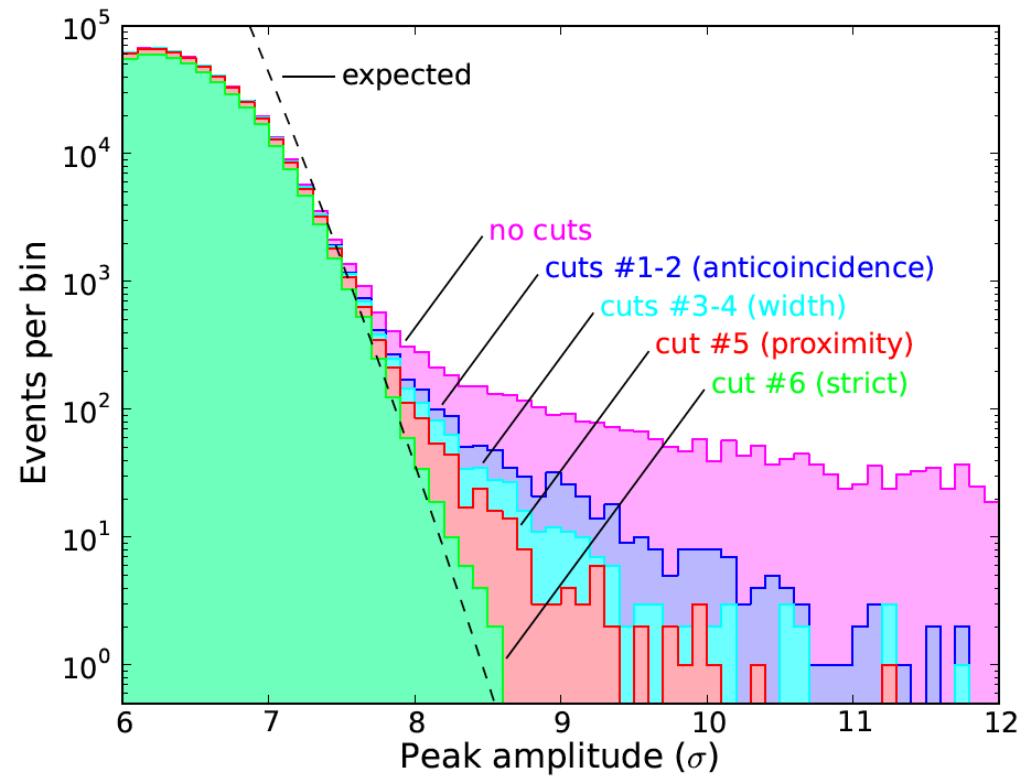
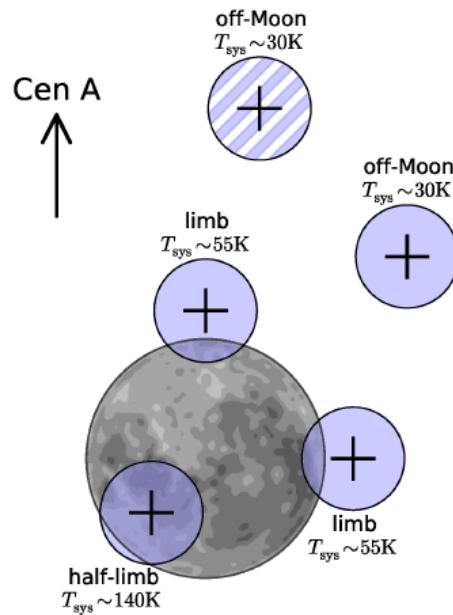
- Particle cascades in a medium
 - Cascades in medium entrain atomic electrons
 - Shower front builds up negative charge excess
 - Charge excess radiates coherently



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

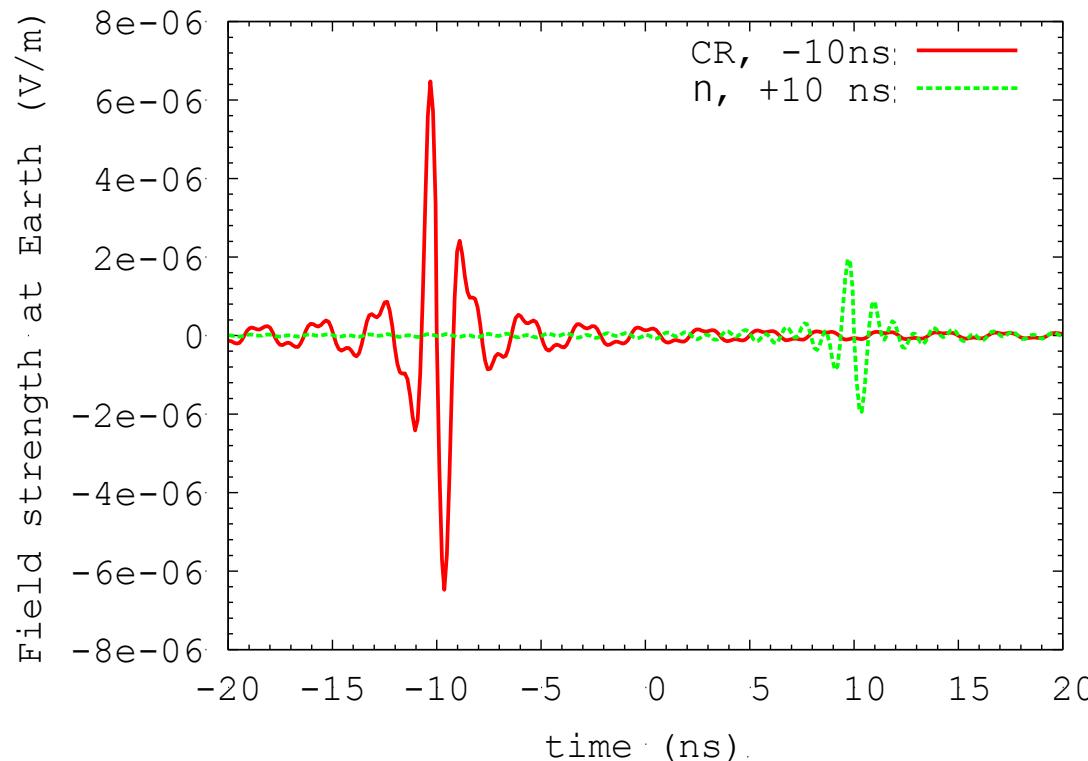


RFI discrimination – results from Parkes



- With SKA: this will be much easier!

Example signals (no noise or surface roughness added)



- Neutrinos: absorption in lunar rock (attenuation length $\sim 20\text{m}$)
- Cosmic rays: interact pointing into the Moon

SKA – assumed sensitivities (inc. lunar emission)

Band			Phase 1		Phase 2	
	f_{\min} (MHz)	f_{\max} (MHz)	$A_{\text{eff}}/T_{\text{beam}}$ m^2/K	E_{thresh} $\text{V}/\text{m}/\text{MHz}$	$A_{\text{eff}}/T_{\text{beam}}$ m^2/K	E_{thresh} $\text{V}/\text{m}/\text{MHz}$
LOW	100	350	1000	1.4×10^{-9}	4000	7.2×10^{-10}
MID 1	350	1050	143	2.3×10^{-9}	844	9.4×10^{-10}
MID 2	950	1760	143	2.1×10^{-9}	844	8.7×10^{-10}

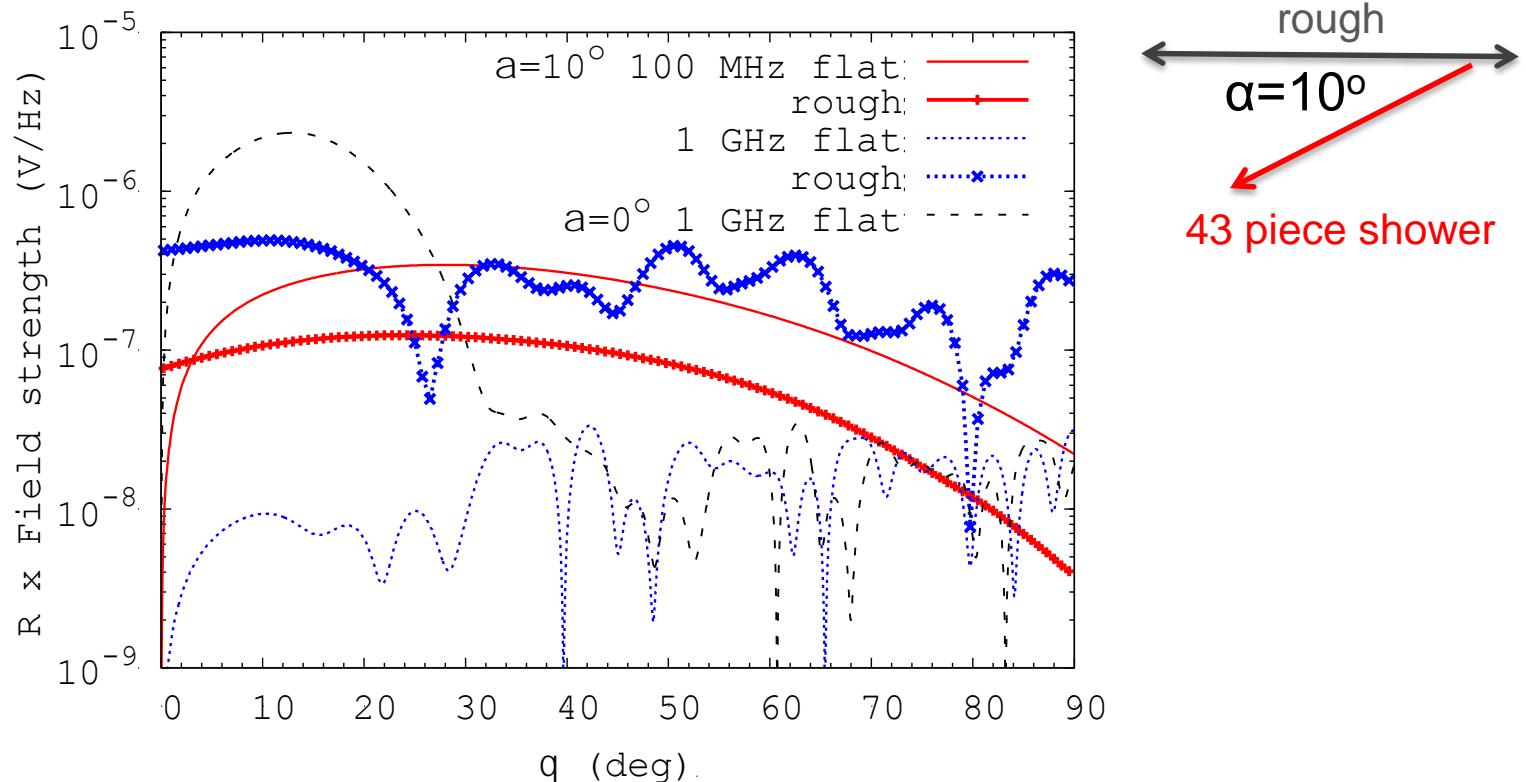
Table 1: Estimated sensitivities ($A_{\text{eff}}/T_{\text{beam}}$, including lunar thermal emission) and signal detection threshold thresholds (V/m/MHz) for SKA observation bands. SKA-MID Phase 1 treats both 64 MeerKAT and 190 SKA antennas identically, while SKA-MID Phase 2 uses 1,500 SKA antennas.

- Note: beamforming on the Moon implies we see the full ~220 K lunar emission

Tentative results: cosmic rays

PRELIMINARY
(numerical dials still need turning)

- 10^{20} eV hadronic cascade, 10° angle of incidence, shower max 4.6m after initial point



References

SKA-EAS: T. Huege et al, *Precision measurements of cosmic ray air showers with the SKA*, arXiv1408.5288 (2014)

SKA-Lunar: J. Bray et al, *Lunar detection of ultra-high-energy cosmic rays and neutrinos with the Square Kilometre Array*, arXiv 1408.6069 (2014)

- [1] G.A. Askaryan, Sov. Phys. JETP 14, 441 (1962)
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- [8] T.R. Jaeger et al, Astroparticle Physics 34, 293 (2009)
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- [10] S. ter Veen et al, PRD 82, 103014 (2010)
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- [12] J. Bray et al., arXiv 1502.03313 (2015)