The lunar technique: history and current status

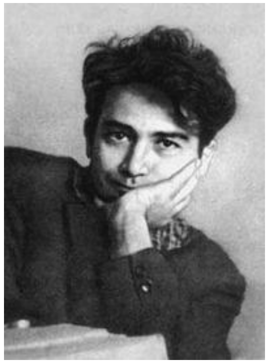
ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Clancy James
COSMIC 2015, Jodrell Bank, UK

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS
FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

The Askaryan Effect, and the Lunar Technique

Askaryan



- Sov. Phys. JETP 14 (1962) 441
- "The presence of a moving uncompensated charge in a shower may increase by many orders of magnitude a flash of Cerenkov, bremsstrahlung, or transition radiation in the radio range"

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

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

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

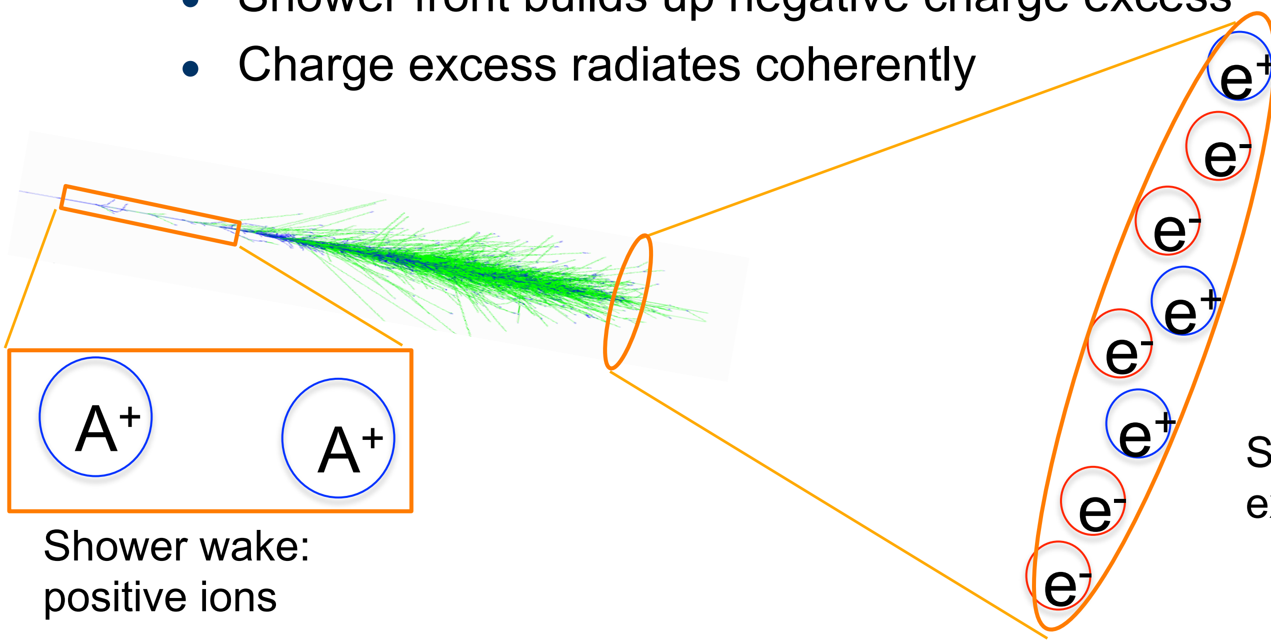
$$e^\pm \xrightarrow[bremss]{} e^\pm + \gamma$$

$$\gamma + e_m^- \xrightarrow[Compton]{} \gamma + e_c^-$$

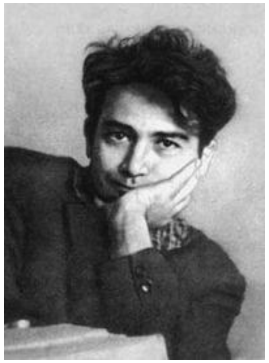
$$e_c^- + e_m^- \xrightarrow[Moeller]{} e_c^- + e_c^-$$

$$e_c^+ + e_m^- \xrightarrow[Bhabha]{} e_c^+ + e_c^-$$

$$e_c^+ + e_m^- \xrightarrow[annih.]{} \gamma + \gamma$$



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



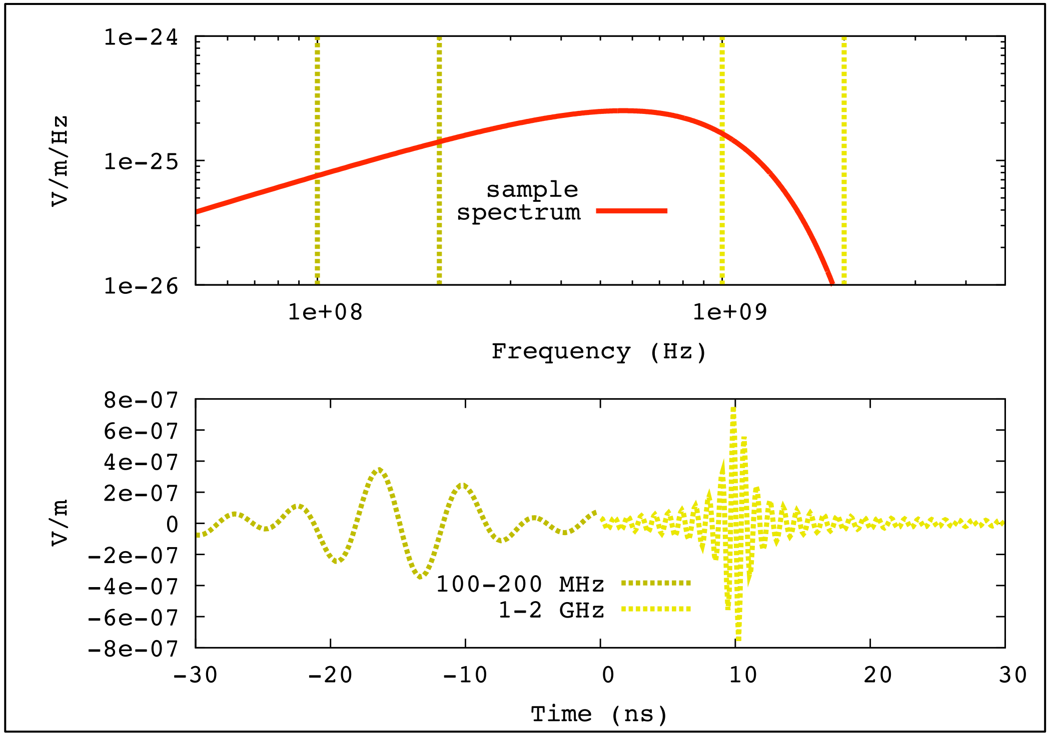
Askaryan

- Sov. Phys. JETP 14 (1962) 441
- "The presence of a moving uncompensated charge in a shower may increase by many orders of magnitude a flash of Cerenkov, bremsstrahlung, or transition radiation in the radio range"
- "…in the range of wavelengths greater than the dimensions of the cascade, the intensity of radiation is proportional to v^2"

Askaryan pulses

$$E_{thresh} \sim \left(\Delta\nu A_{eff}\right)^{-0.5}$$

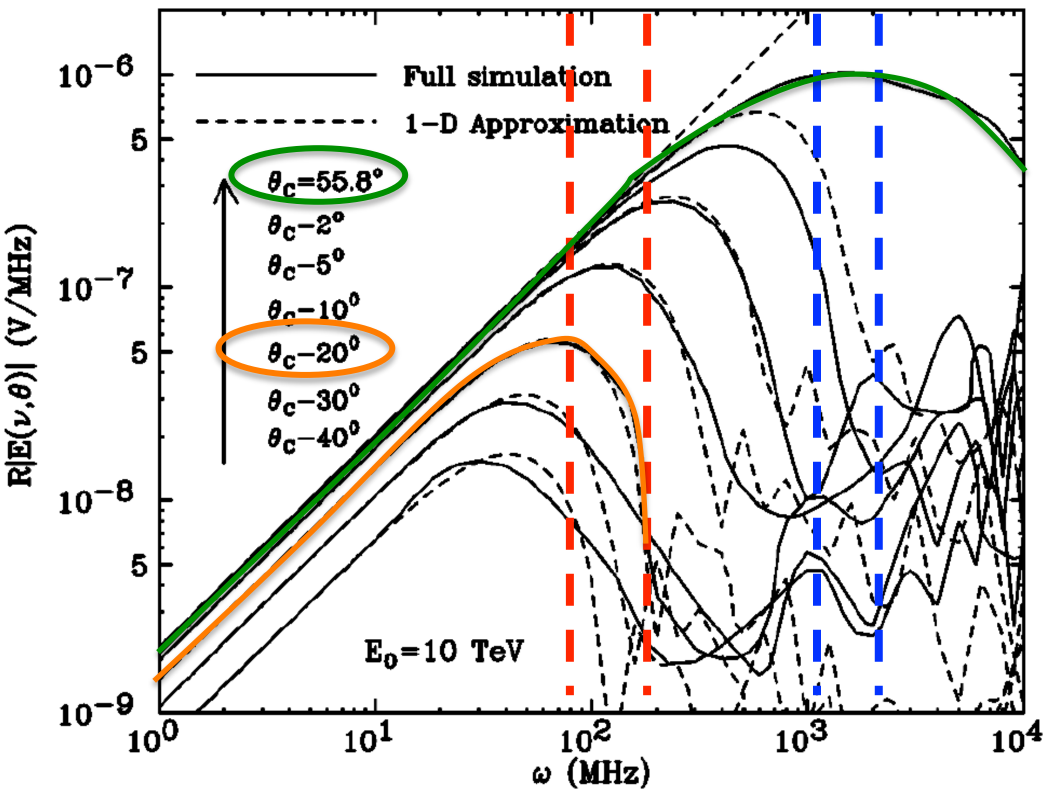
- 100% Linear polarised
- Short, impulse-like signature – need high time resolution!
- Turnover frequency depends on observation angle

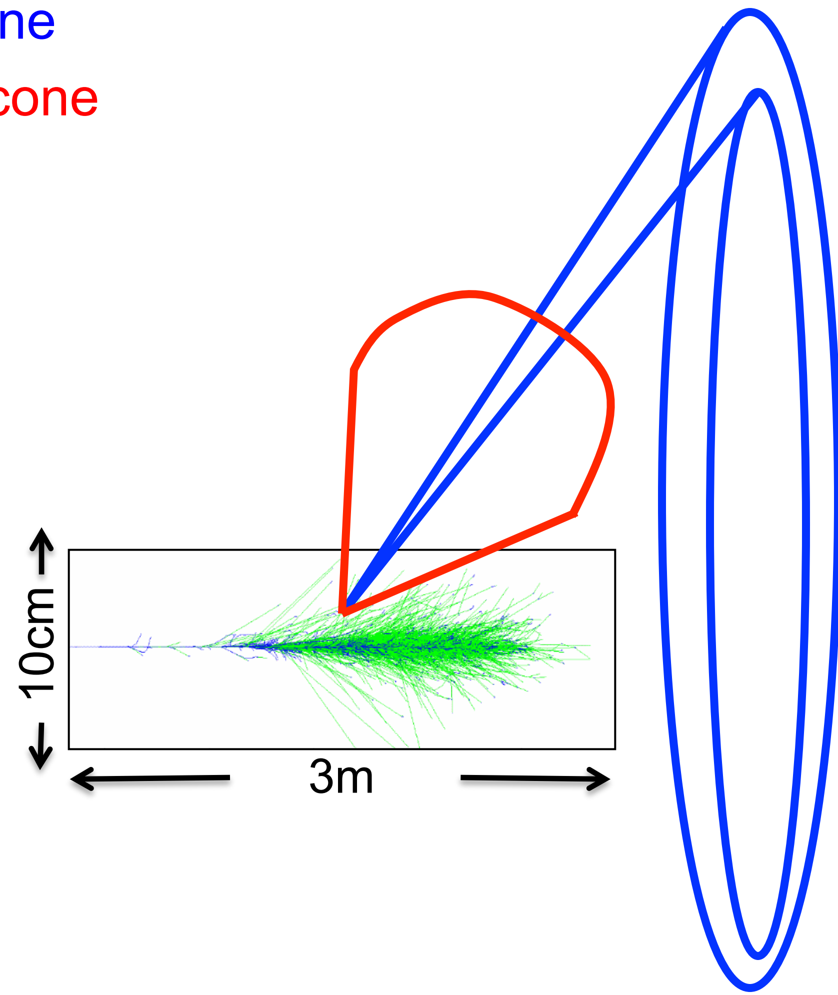


Expected Askaryan emission (early simulations in ice)

- 2 GHz – strong emission in narrow cone
- ~100 MHz – weak emission in broad cone

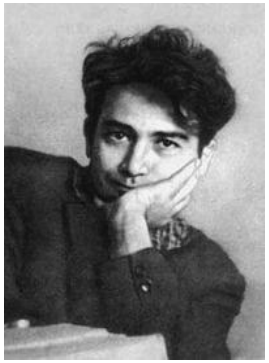
Alvarez-Muniz, Vazquez, Zas, PRD 62 (2000) 063001





ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

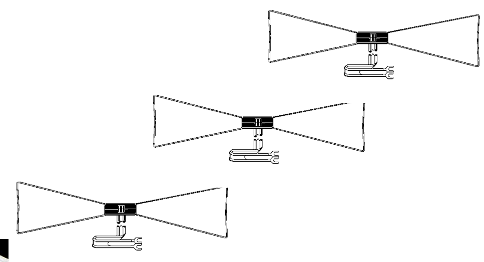
Askaryan



- Sov. Phys. JETP 14 (1962) 441
- "The presence of a moving uncompensated charge in a shower may increase by many orders of magnitude a flash of Cerenkov, bremsstrahlung, or transition radiation in the radio range"
- "…in the range of wavelengths greater than the dimensions of the cascade, the intensity of radiation is proportional to v^2"
- "The generation of radio waves by cosmic particles … facilitates the registration of flashes of radio emission of showers in the ground by means of suitable apparatus dropped on the moon"

Use the Moon!

- Lunar rock:
  - Visible area: 20,000,000 km2
  - Field absorption length: $\ell_{abs} \approx 18\text{ m}\left(\frac{\nu}{1\text{ GHz}}\right)^{-1}$
  - Effective volume at 1 GHz: 360,000 km^3
  - At 100 MHz: 3,600,000 km^3!

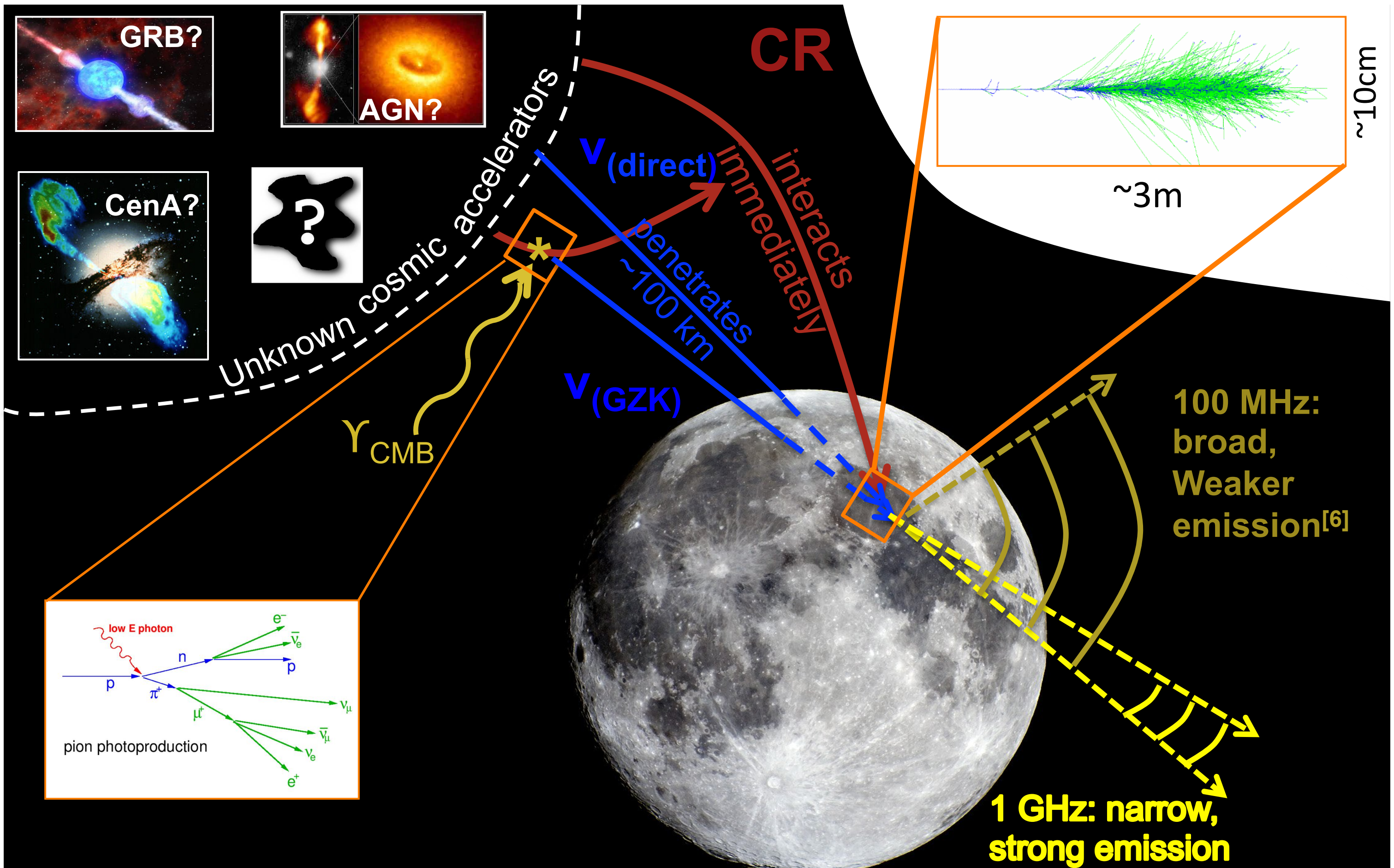


Dagkesamanskii & Zheleznykh

JETP Lett. 50 (1989) 259

- "Radio-astronomy method for detecting neutrinos and other elementary particles of superhigh energy"
  - The Moon is big – and far away!
  - Suited to highest energies / rarest particles
- "…Neutrinos with energies of 10^{20}-10^{22} are predicted in several models with superconducting strings…"
  - Several exotic models existed explaining UHE cosmic rays.
  - These predicted neutrinos at extreme energies
- "In summary, the lunar surface might prove to be an extremely good target for the radio emission of neutrinos and hadrons with energies of 10^{20} eV and up"

The Lunar Askaryan Technique

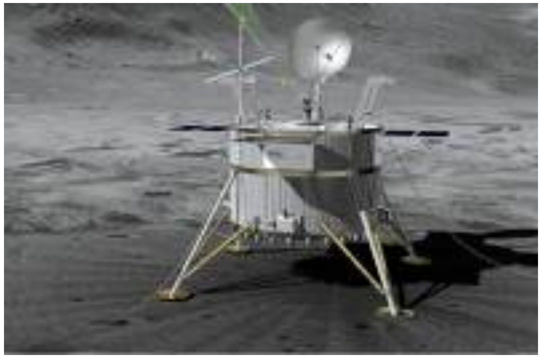


Not only ground-based telescopes

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

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

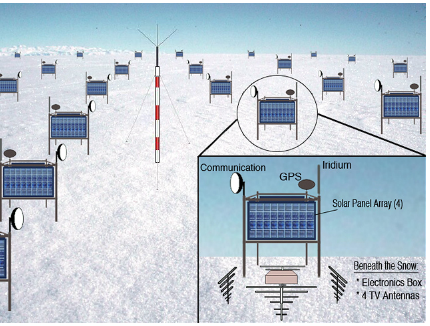
- Lunar radio astronomy explorer
  - Askaryan's original idea – put antennas on the Moon!

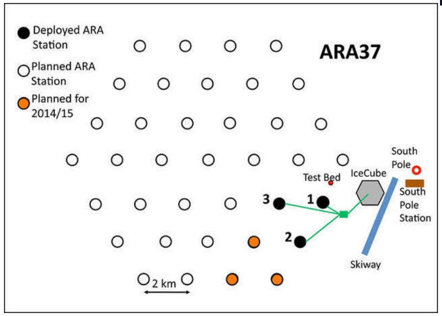


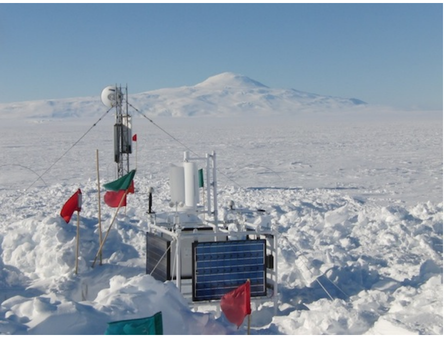
Not only the Moon…

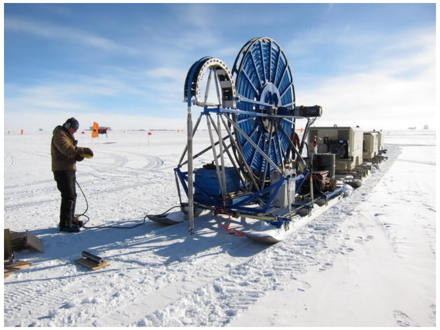
- Greenland & Antarctica

In-ice experiments:
RICE -> ARA & ARIANNA

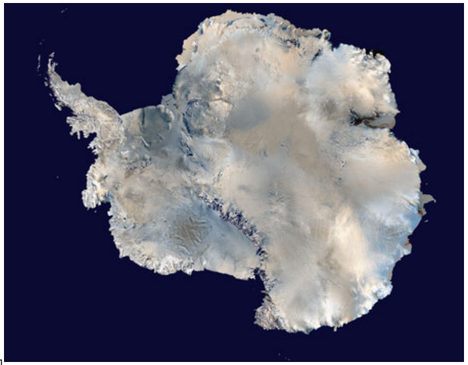


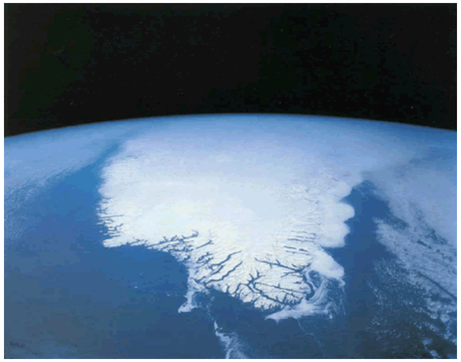




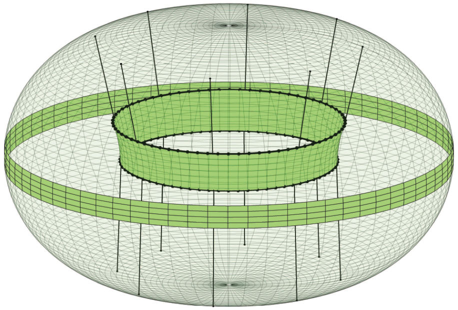


Ice (Antarctica & Greenland)





Balloons: ANITA -> Exavolt Antenna

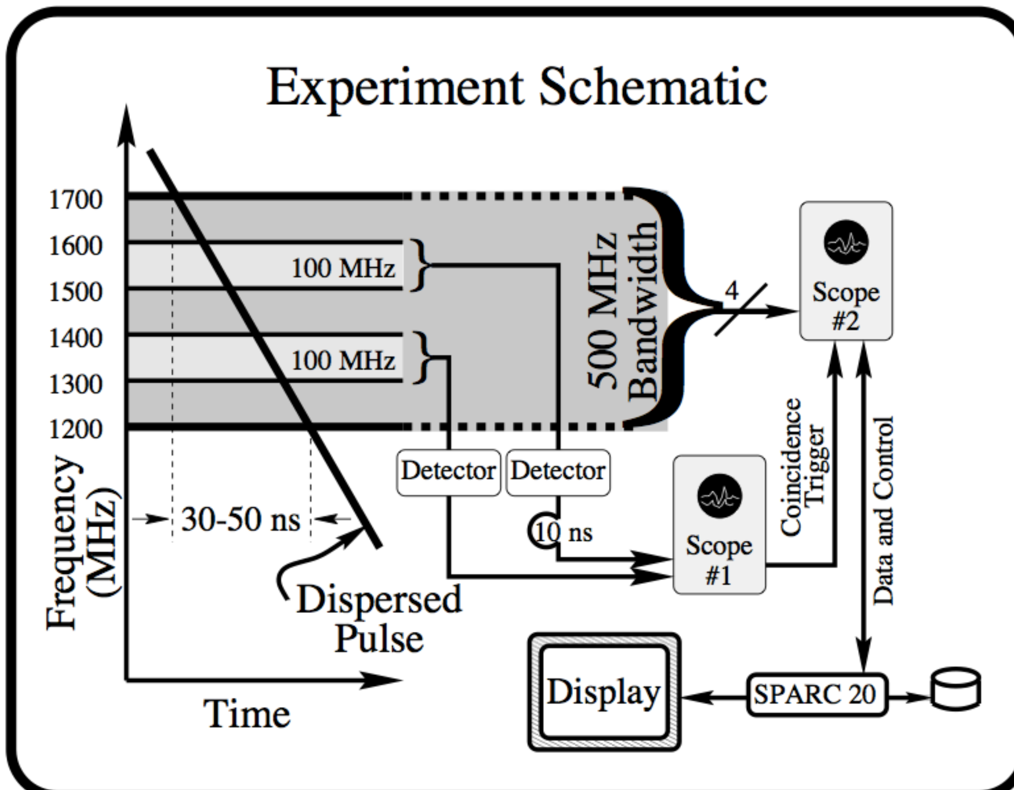


The Lunar technique -
A brief history of nanosecond timing

Parkes - 1995

Hankins, Ekers, O'Sullivan, MNRAS 283 (1996) 1027

- Observations:
  - Single beam on lunar centre
  - 1.2-1.7 GHz b/w
  - LCP & RCP channels
  - Observed for 10 hours

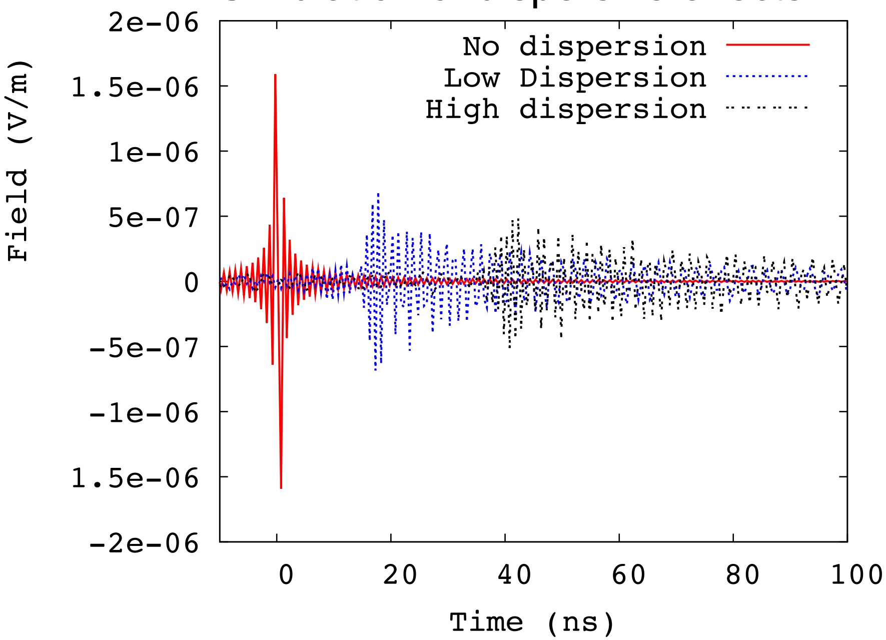


Identifying signals – ionospheric dispersion

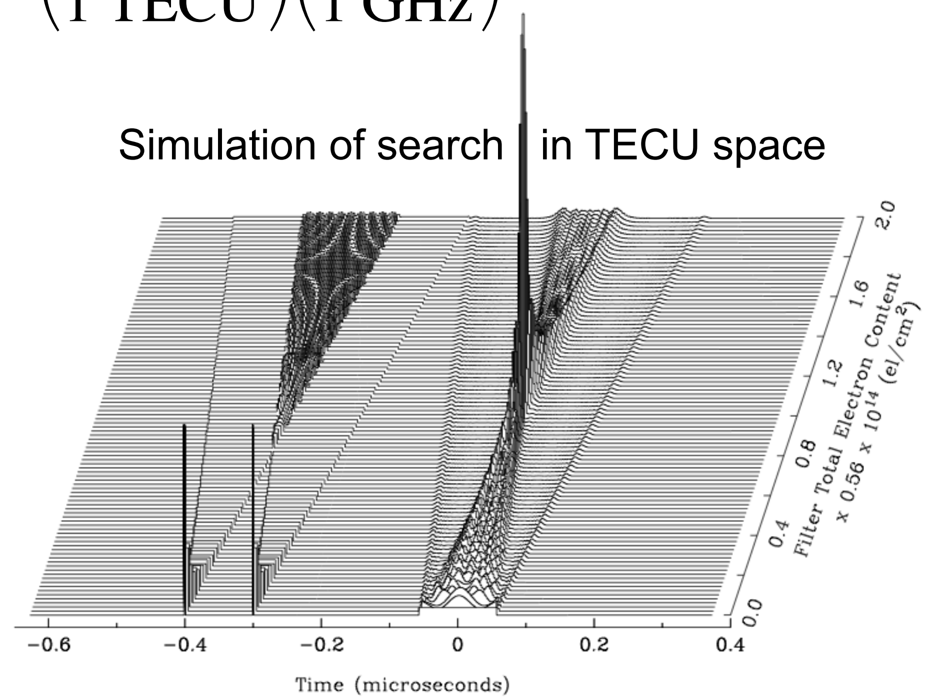
- For ns signals, the ionosphere is significant!

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

Simulation of dispersive effects



Simulation of search in TECU space



Hankins et al., Proc. RADHEP (2000)

GLUE – 1999-2003

- 34m DSS13 & 70m DSS 14 at NASA facility at Goldstone.
- Multiple antennas reject RFI
- Observations:
  - Observed 10% of the Moon for 70 hrs
  - 100% of the Moon for 50 hrs (2001-2004).
  - 70m antennas defocussed to match 34m
  - Complicated trigger scheme

- Antennas / bands used with ‘and’ coincidence: rejects RFI, but reduces sensitivity

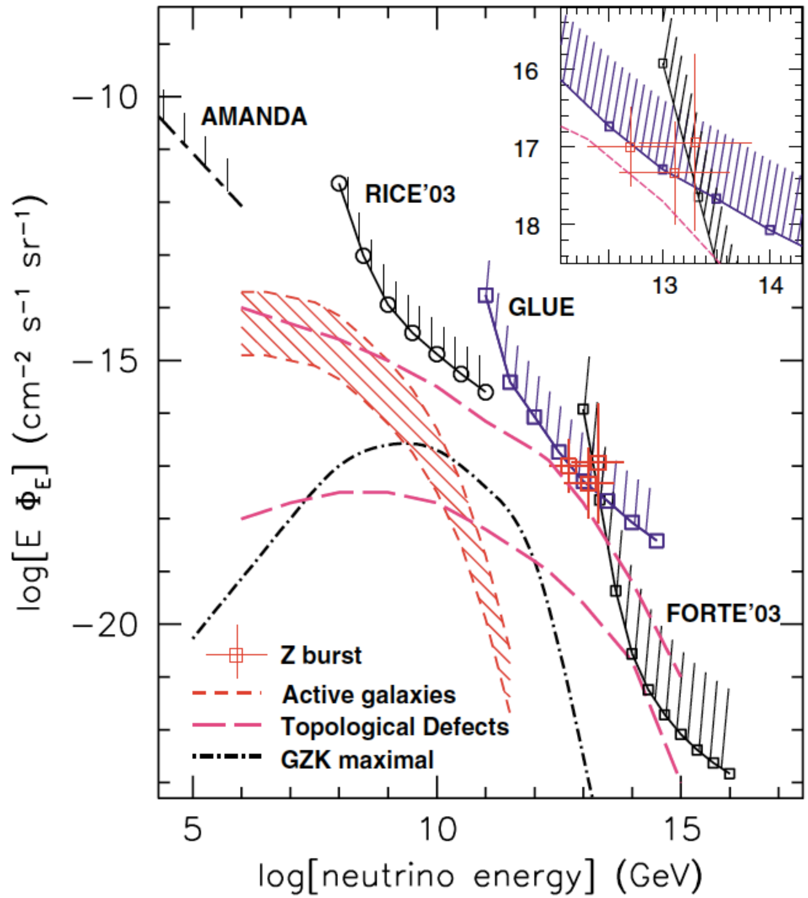
Simulations

Gorham et al, PRL 94, 4 (2004)

- Monte Carlo to simulate technique
  - Neutrino interaction in the Moon
  - Apply parameterised emission
  - Propagate out of Moon
  - Simulate detection

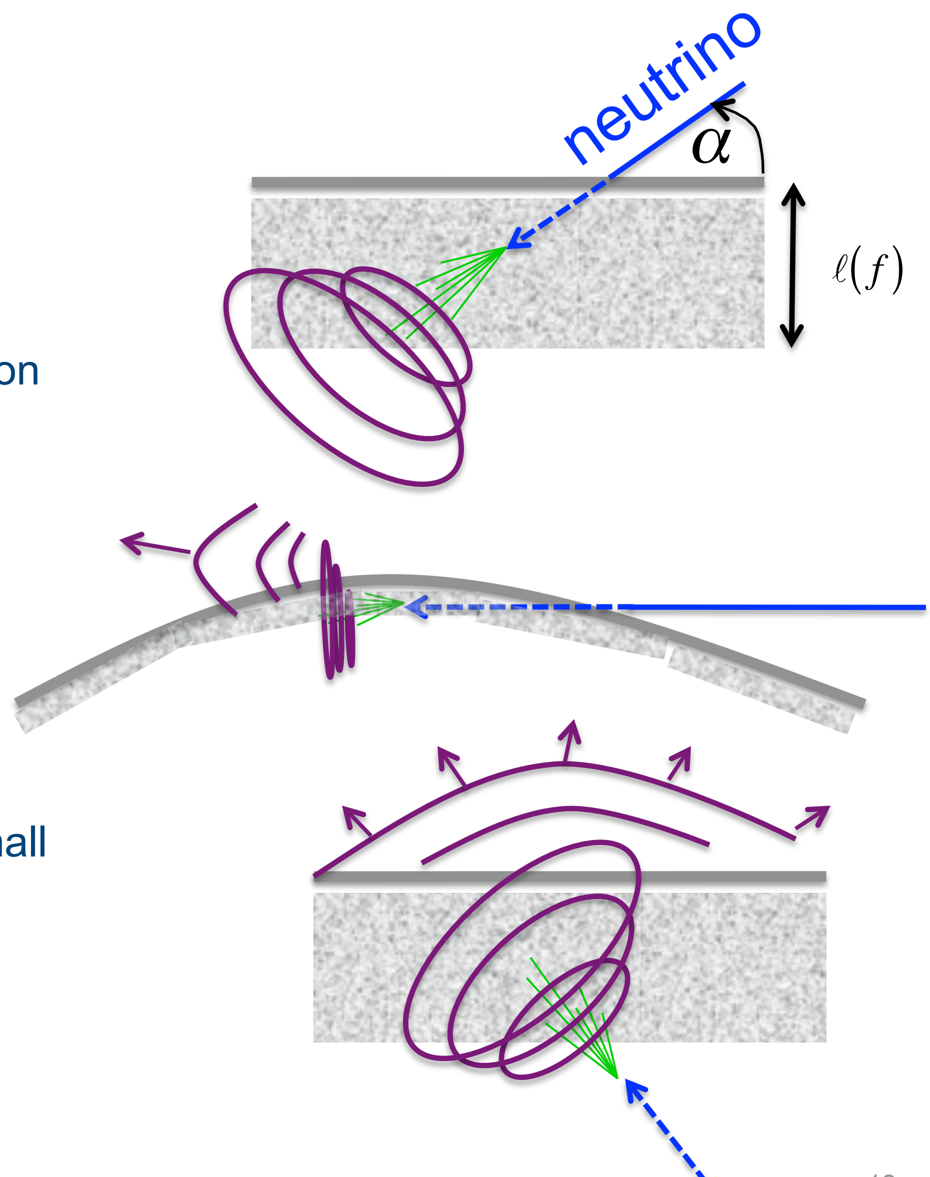
- Publish limits: near 10^{21} eV
- Constrains ‘exotic’ models

- Generates publicity in the world of astroparticle physics

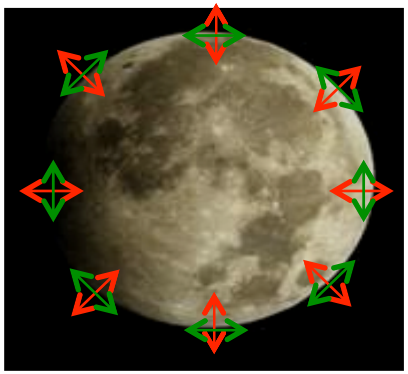


Neutrino Interactions

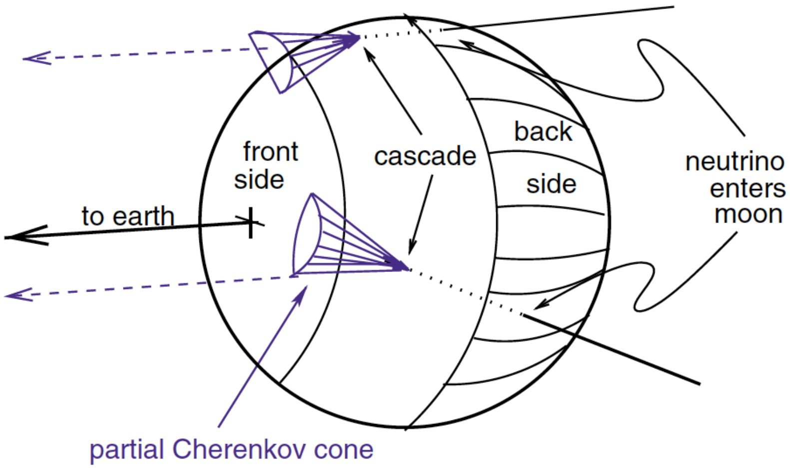
- Down-going
  - Interaction probability small
  - Radiation emitted into the Moon
  - Important near 100 MHz
- Skimming
  - Interaction probability small
  - Some radiation can escape
  - Dominant
- Up-coming
  - Interaction probability very small
  - Radiation escapes easily
  - Neutrinos absorbed in Moon



Limb brightening

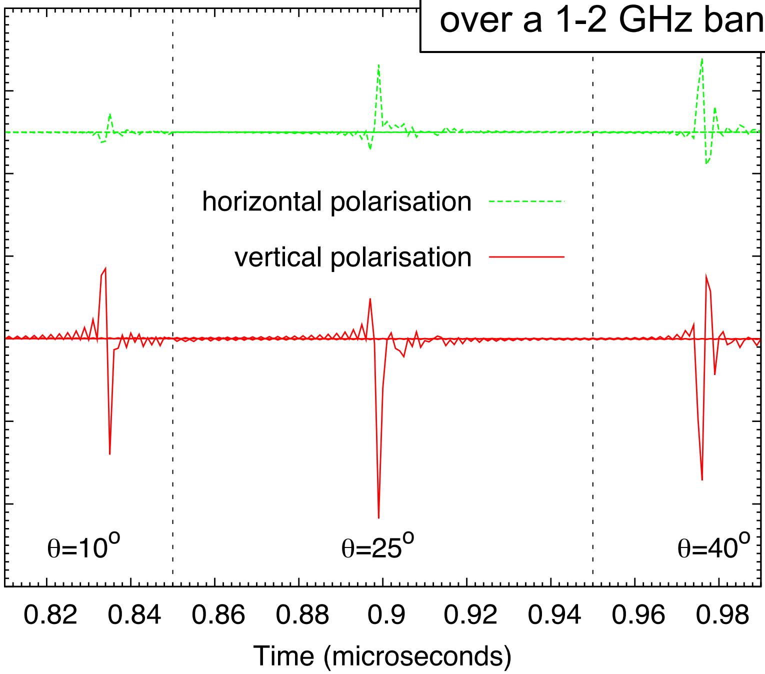


- UHE neutrinos can't penetrate the entire Moon!
  - Downgoing events radiate into the Moon
  - Expect to see skimming events
  - Excess of signals from the limb of the Moon



Gorham et al, PRL 94, 4 (2004)

Simulations of pulses over a 1-2 GHz band



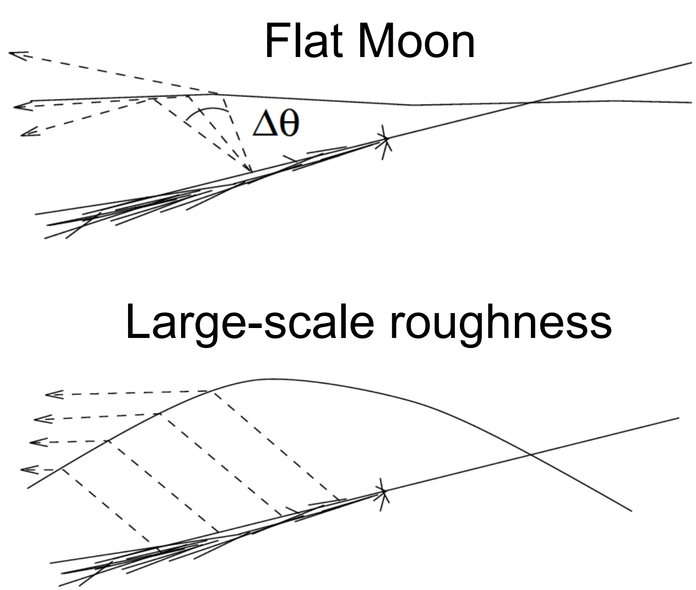
Kalyazin ('RAMHAND') ~2000-2006

Beresnyak et al. (inc. D&Z), Ast. Rep. 82 (2005) 149

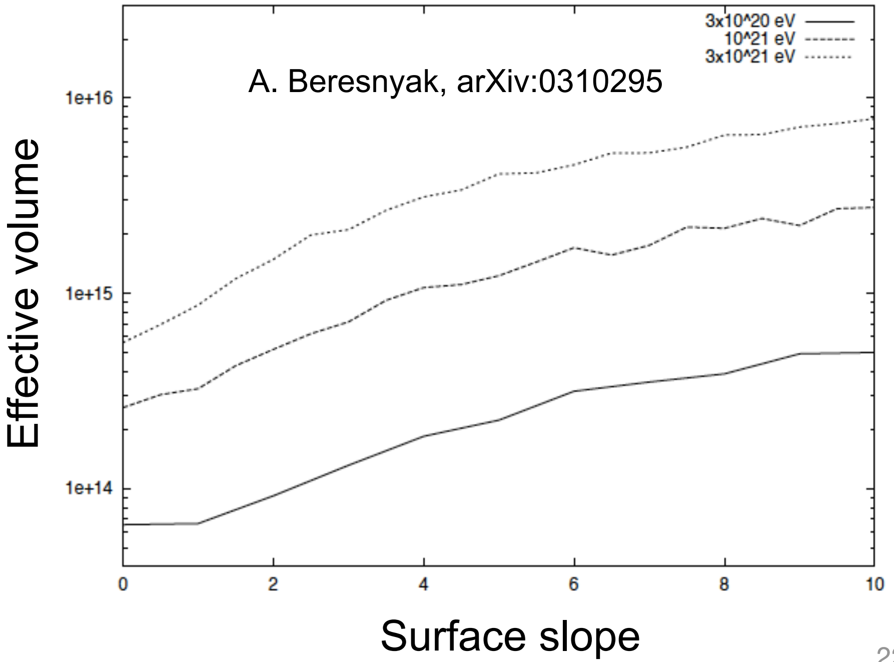
- Similar set-up to GLUE
  - Four bands from 600 MHz to 4.8 GHz
  - Main trigger at 2.3 GHz (13,500 Jy)
  - Pointed at the limb of the Moon
  - 31.3 hr
- Performed MC simulations which were almost identical to GLUE
- Results of MC a factor of 10 different… controversy!
  - Turns out GLUE were too optimistic…
- Important point: surface roughness 'helps'

Surface roughness

- Large-scale roughness
  - Cherenkov angle is complement of angle of TIR
  - For a flat moon, peak emission from skimming events never escapes!
  - Large-scale roughness helps refract peak emission out of the Moon



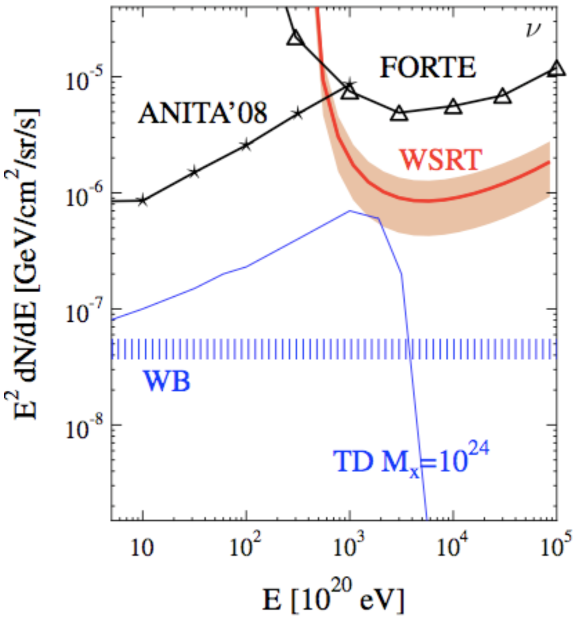
Gorham et al, arXiv 0102435 (2001)



NuMoon at WSRT (2006-2007)

Scholten et al., PRL 103 (2009) 191301

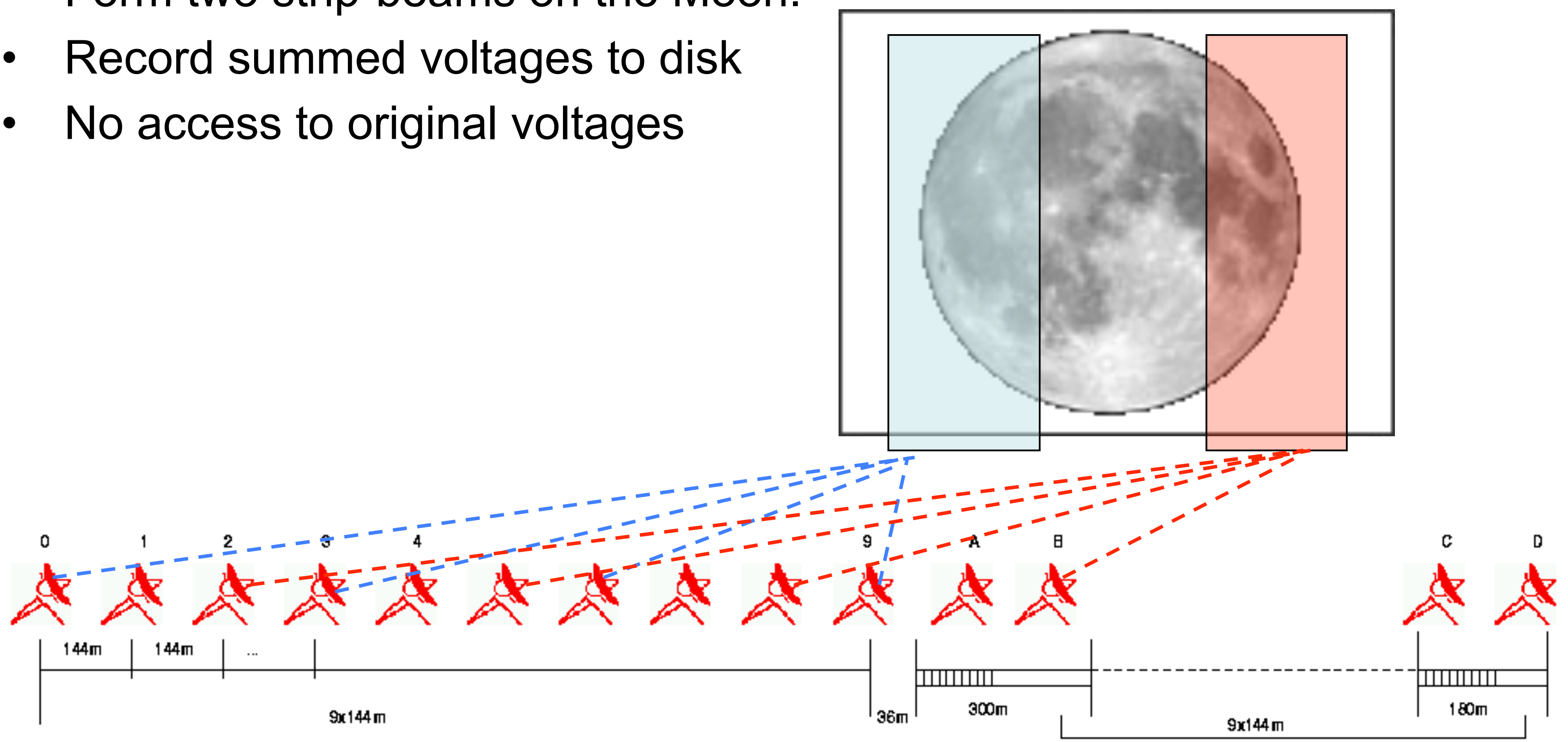
- Westerbork Synthesis Radio Telescope
  - 50hr observations
  - 115-180 MHz in 4 bands
  - Coherent beamforming of 11 dishes
  - Recorded all data for later analysis – no triggering!



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

Coherent beamforming increases sensitivity

- Form two strip-beams on the Moon.
- Record summed voltages to disk
- No access to original voltages

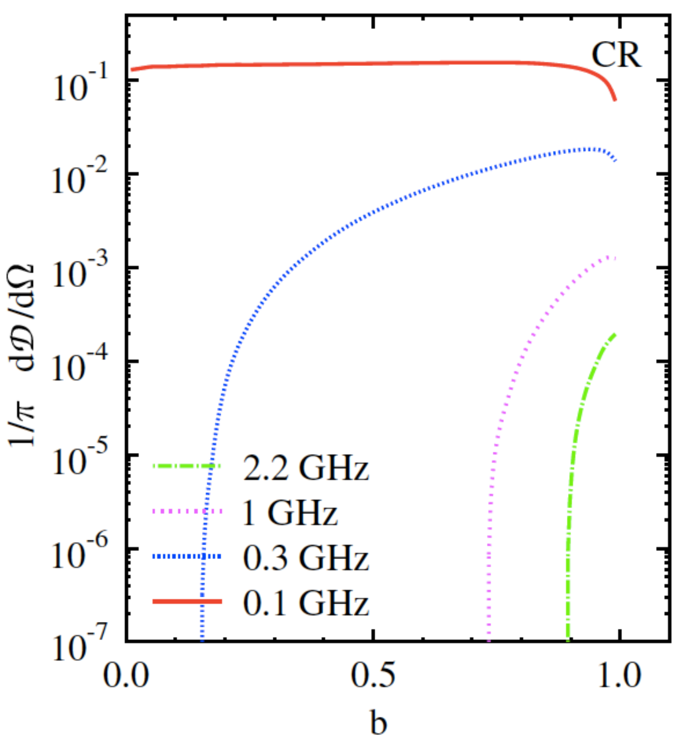


WSRT: 11 dishes of 25 m diameter, on a 2.7 km E-W baseline

What is the optimal observation frequency?

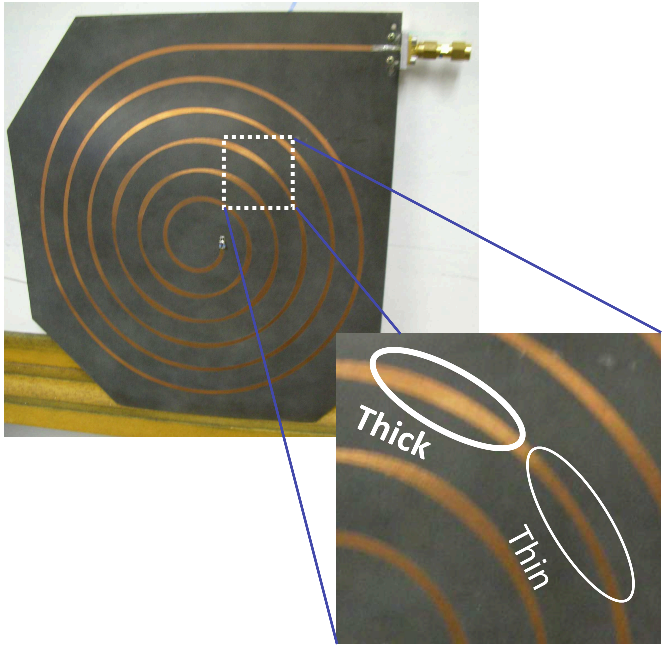
- Observe at low frequencies! (100-200 MHz)
  - Emission cone broader
  - Absorption in the Moon less
  - Telescope sees more Moon
  - Effective volume ~ λ^3
- New problems
  - Dispersion worse
  - Less available bandwidth
  - Higher threshold
- Message – go as low as you can go

O. Scholten et al, Astropart. Phys. 26 (2006) 219



LUNASKA – at ATCA (2008)

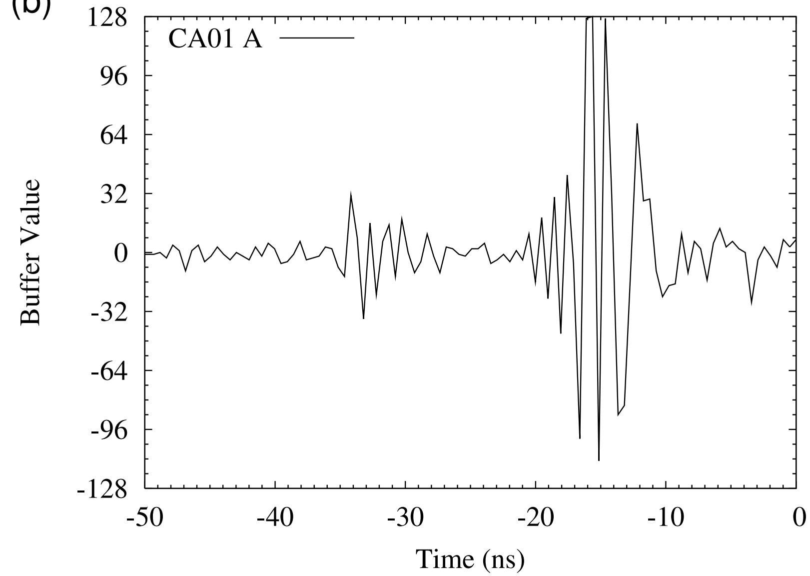
- ATCA 2008: ~26hr
  - 3 antennas x 2 polarisations
  - 1.2-1.8 GHz continuous bandwidth
  - Analogue dedispersion
- Independent triggering: sensitivity limited by what you can do in real time!
- Coherent dedispersion
  - Correct for ionosphere within an observation band
  - Hardware: set for 5 ns of dispersion over the band



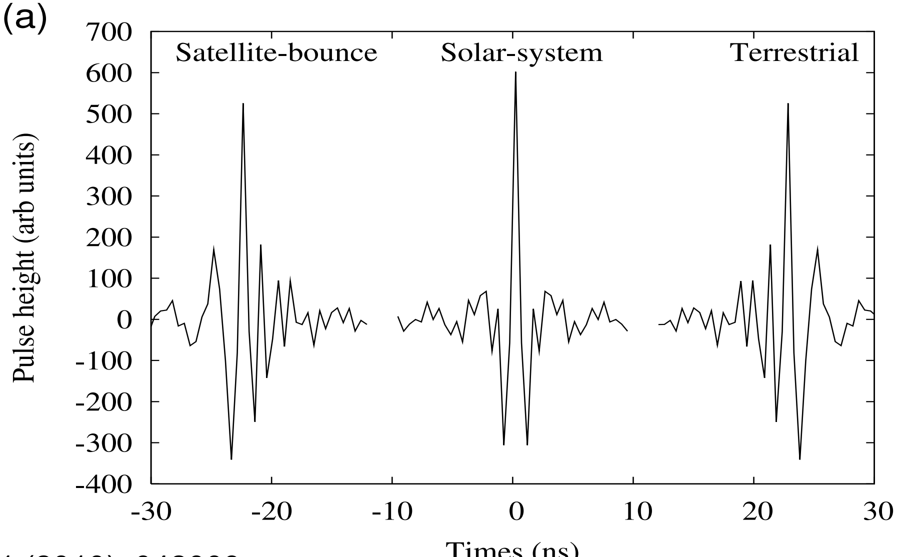
De-dispersion vs RFI

- Dedispersion must be performed coherently over the observation band prior to triggering
- Q: Where does the signal on the right come from?
- A: It must be terrestrial

(b)



(a)



C. James et al., PRD 81 (2010) 042003

Sensitivity limited by real-time trigger

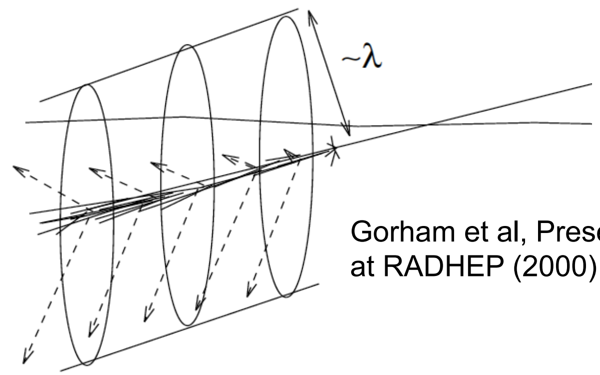
- Trigger paradigm:
  - Cannot record entire data stream.
  - Record data to real-time buffer.
  - Form trigger and record only when a candidate is seen.
- Sensitivity is limited by the real-time trigger!

All information (timing, bandwidth, collecting area) + Perfect logic, infinite computer capacity → **Theoretical sensitivity**

Less information + Fast (imperfect) logic → **Real-time trigger**

- Trigger at artificially high rate to compensate for lost information

D. Formation zone effect



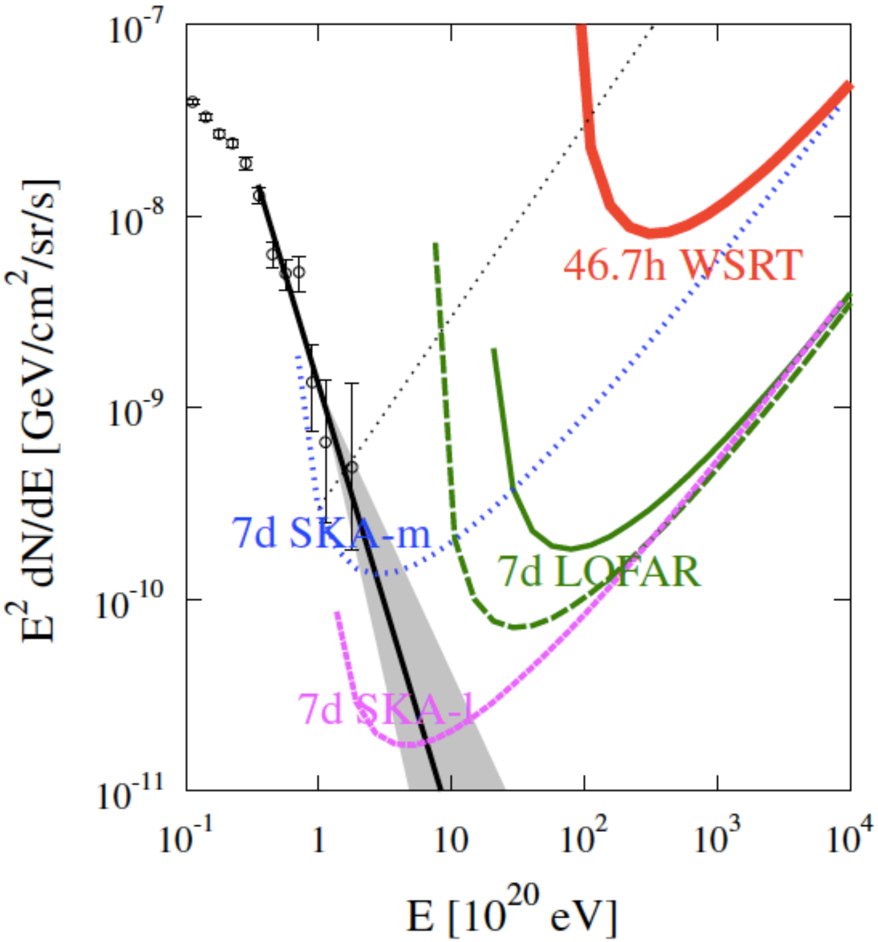
Gorham et al, Presented at RADHEP (2000)

Wait – what about cosmic rays?

- "Formation-zone effects"
  - Askaryan effect thought of as "coherent Cherenkov radiation"
  - => radiation is strongly suppressed near dielectric boundaries
  - Cosmic rays won't radiate into vacuum!
- Solution
  - Askaryan radiation is only "Cherenkov-like"
  - UHE cascade: rapid rise and fall of excess negative charge
  - Macroscopically: this is a time-variable current ter Veen et al., Phys. Rev. D 82 (2010) 103014
  - Microscopically: it is ~bremsstrahlung James et al, Phys.Rev.E 85 (2011) 056602
- Conclusion: cosmic rays are detectable via the lunar technique – and we've been modelling them correctly all along!

Sensitivity

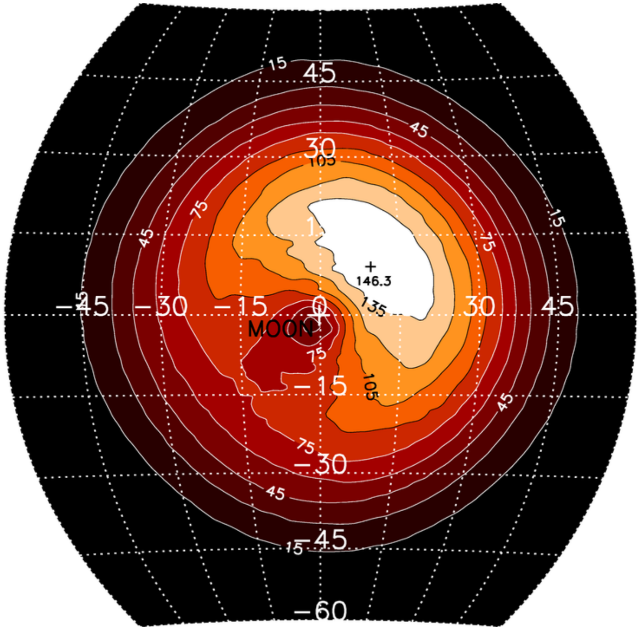
- Flux of cosmic rays known – and it turns down near 10^{20} eV
- Exotic fluxes of neutrinos (were) predicted up to 20^{25} eV!
- Experiments so far have not been sensitive enough to find cosmic rays – but could limit neutrinos
- This will change with the SKA

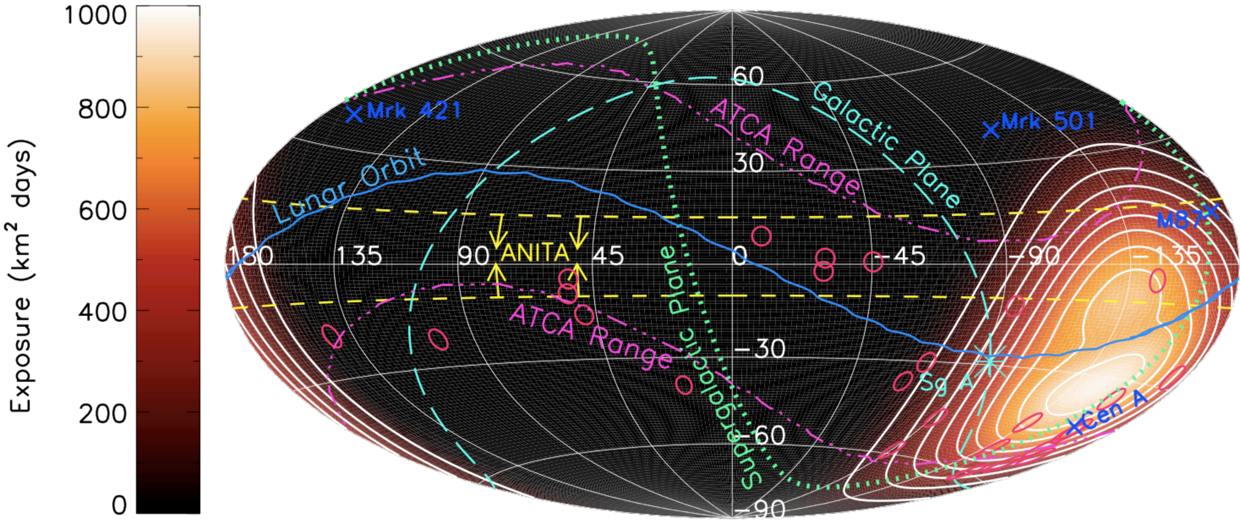


Ter Veen et al., Phys. Rev. D 82 (2010) 103014

Targeting sources

- Lunar Askaryan experiments sensitive to neutrinos from only a small patch of the sky
- To target a source – point at the limb of the Moon closest to it
- Converse: lunar Askaryan experiments do not have full-sky coverage

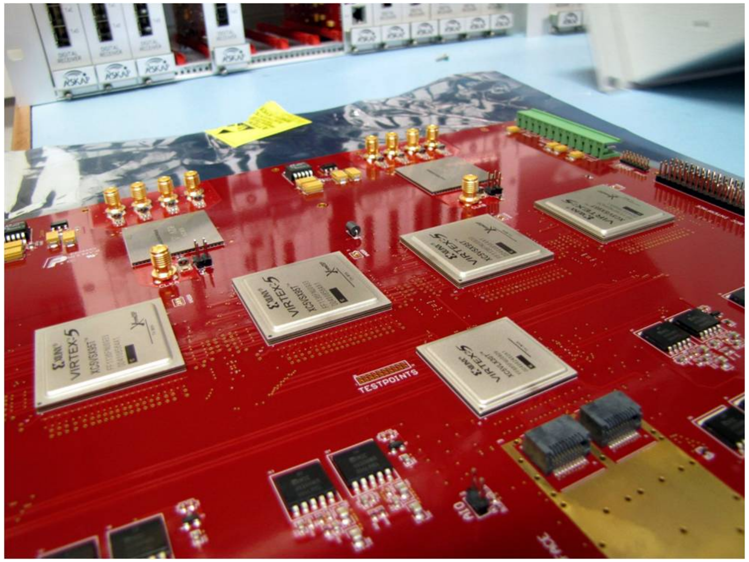




LUNASKA – Parkes 2009

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

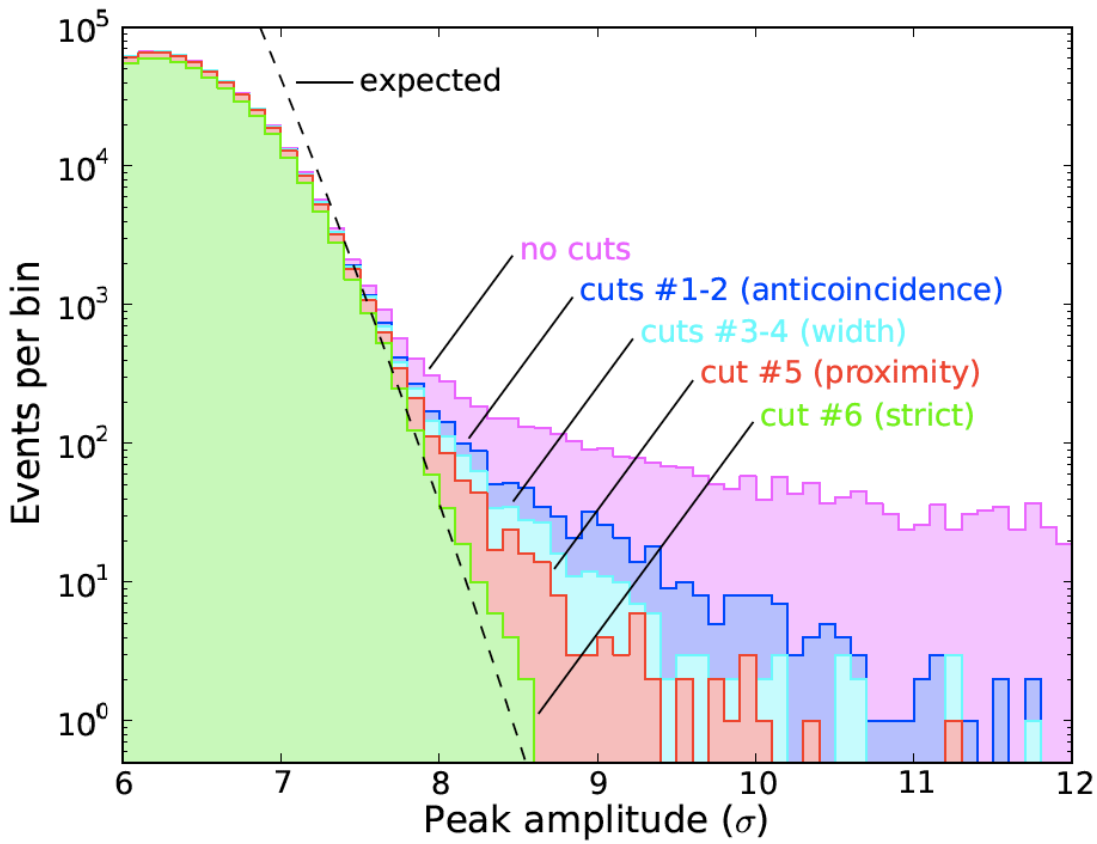
- Specialised hardware developed – the Bedlam Board
    - 8 x 512 MHz inputs (2 pols x 4 beams)
    - Digital dedispersion
    - Anti-coincidence triggering between channels
    - 127hr
    - CenA target



Noise reduction

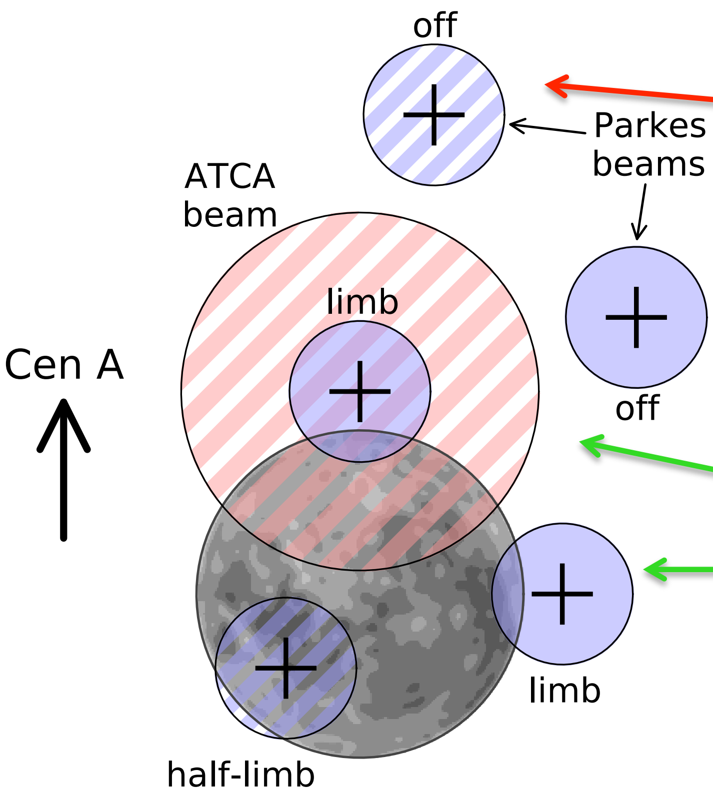
- Real-time self-veto removes most RFI (20 kHz veto)
- Offline veto
- Shape-based
- Pulse-train
- Strict anti-coincidence!

- Noise floor achieved!
- 85.5% efficiency



Single beam veto

- Multiple beams – use this to veto RFI



- 1-2 Veto Beams
  - Low Tsys – sensitive to RFI!
  - Veto Rate: 20 kHz
  - Veto time: 100ns
  - Loss from veto: 0.2%
- 2-3 Detector Beams
  - Trigger rate: ~1 Hz
  - Trig dead-time: 50 ms.
  - Loss from triggering: 5%

34

RESUN – at the EVLA (2008-2009)

Jaeger, Mutel, Gayley, Astropart. Phys. 34 (2010) 293

- 200 hr
- 50MHz b/w at 1385 & 1465 MHz
- 3 sub-arrays of 4 antennas
- Independent triggering

- Final sensitivity – less than the ATCA!
- Message – it's not how big you are, it's what you can do with it.

- Analytical aperture calculation Gayley, Mutel, Jaeger, ApJ 706 (2009) 1556
  - No Monte-Carlo: calculate apertures analytically
  - Detailed step-by-step procedure
  - Accuracy: not competitive with MCs
  - Good enough to check GLUE vs Kalyazin discrepancy (Kalyazin wins)

Lovell: 2009-2010

Spencer et al, Proc. 10th Eu VLBI symposium (2010)

- 1.418 GHz & 32 MHz bandwidth
- LCP & RCP bands
- 4.3hr obs on Moon centre, limb, & off-limb
- Slow data download: 1hr effective

- Student project – not designed for global competitive sensitivity

- (note: these experiments are great for getting to know the instrument!)

Where are we today?

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

We know what we want

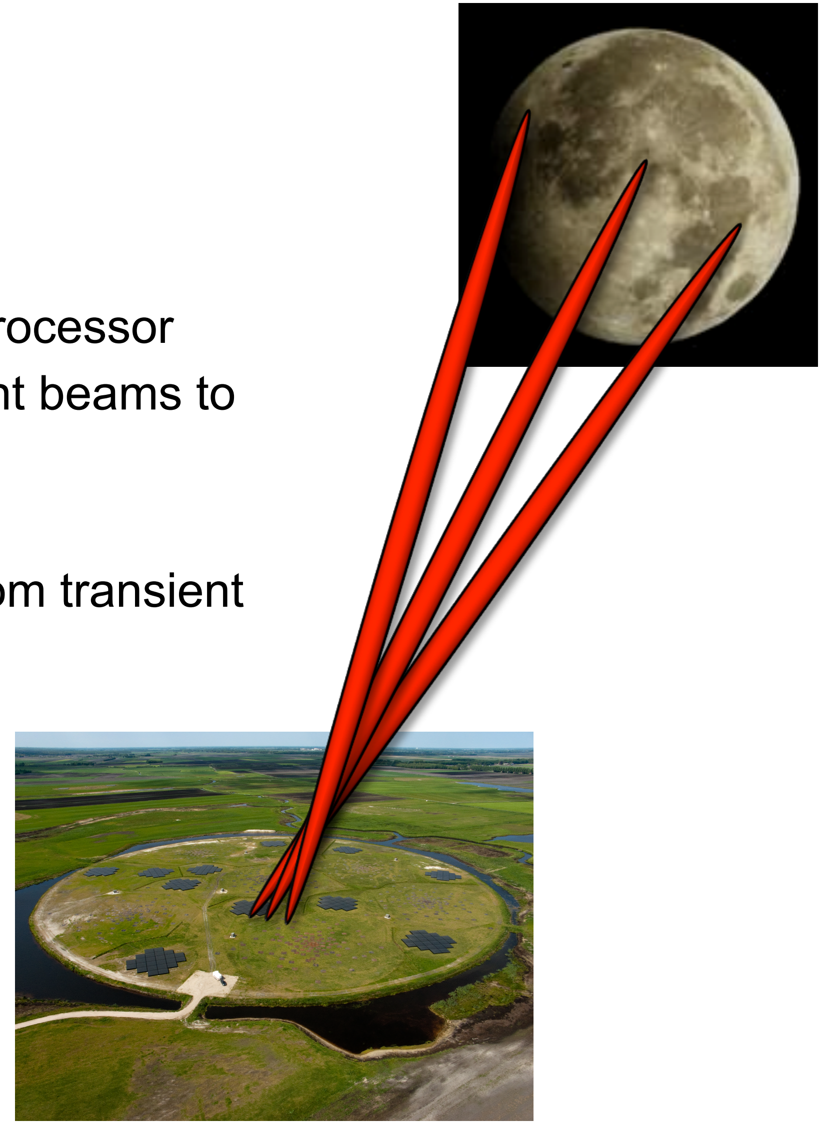
- Large effective area covering the entire Moon
  - Single large dishes (Arecibo, FAST)… with phased array feeds
  - Tied beams from an array (LOFAR, SKA)… with many beams!

- Broad bandwidths with low minimum frequency
  - Full time-domain voltages at Nyquist sampling must be retained
  - No sub-bands OR time-integration

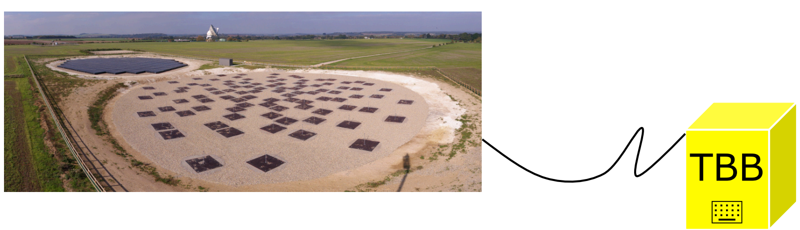
- Triggering
  - Coherent de-dispersion
  - Anti-coincidence
  - *Fast* triggering with low dead time
  - Buffers to dump raw voltages for improved analysis

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



Why is it not working yet?

- Answer #1: It's really damn complicated
  - Early years: dish + oscilloscope = experiment!
  - Now: coherent beamforming, dedispesion, detailed simulations…
  - But: is it really more complex than imaging?

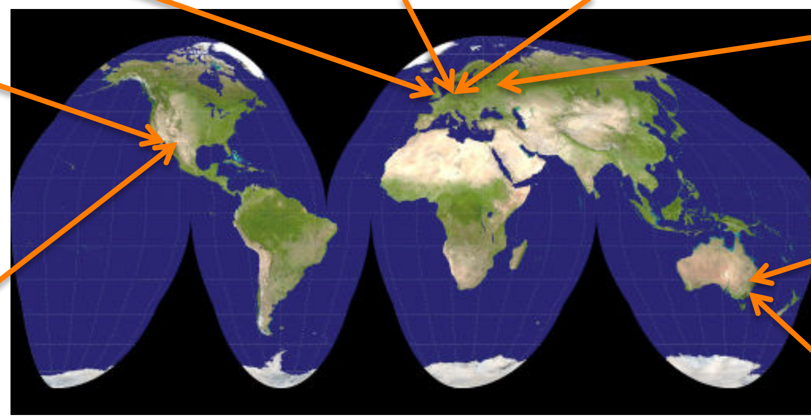
- Answer #2: This is an (astro)particle-physics motivated experiment
  - To astronomers, we're weird guys looking at cosmic rays
  - (to cosmic ray physicists, we're weird guys using radio)
  - Lunar Askaryan observations *will* get lower priority than more conventional astronomical observations
  - We have to work to make this happen!

NuMoon
WSRT 2006-2007[6]
LOFAR ???

LaLUNA
Lovell
2009-2010

RAMHAND
Kalyazin
2002- ~2006[7]

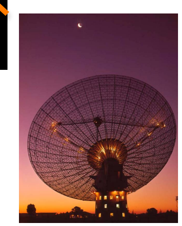
GLUE
Goldstone
1999-2004[4]



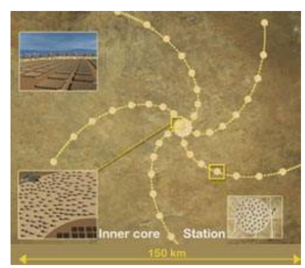
LUNASKA
ATCA
2006-2008[5]
Parkes 2009

RESUN
VLA
2008/09[8]

'Lunatics'
Parkes 1995[3]



SKA???



For most groups, the SKA has always been the goal

Conclusions

- Lunar Askaryan observations have a long history
- The required methods and technology exist
- The mystery of the highest-energy cosmic rays and neutrinos has not yet been solved
- The SKA will be the radio community's best chance to do this. This is why we're here today.

Thanks for your attention

ERLANGEN CENTRE
FOR ASTROPARTICLE
PHYSICS

Bundesministerium
für Bildung
und Forschung

FRIEDRICH-ALEXANDER
UNIVERSITÄT
ERLANGEN-NÜRNBERG