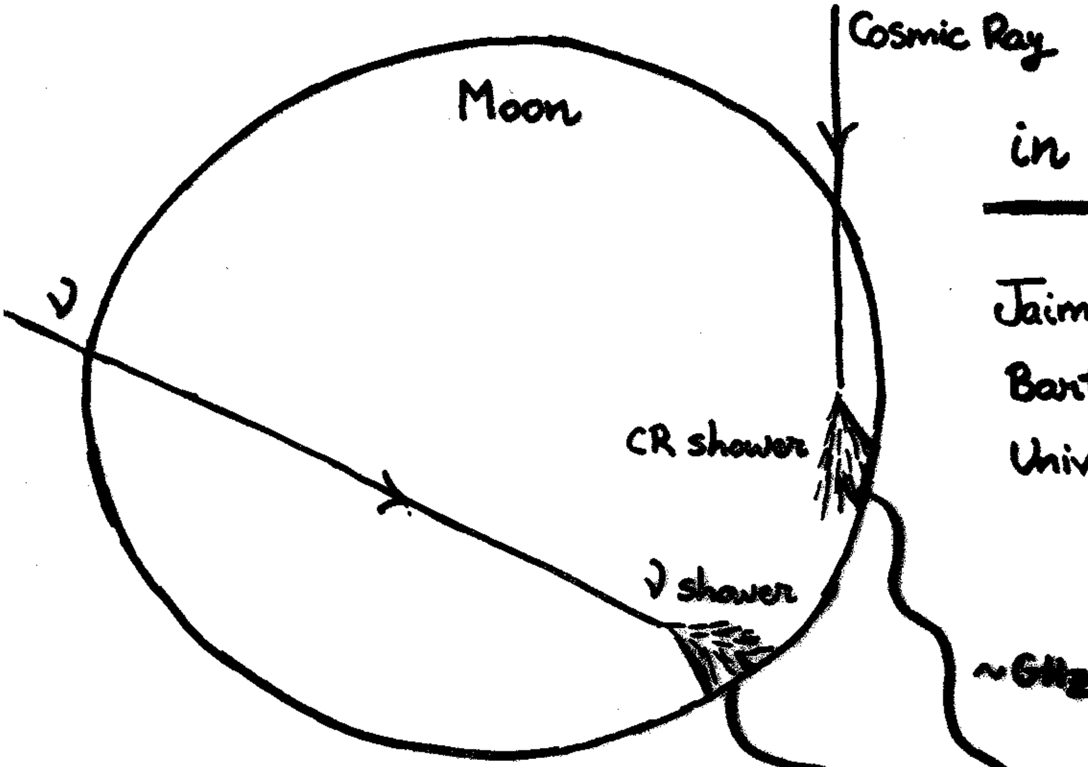
Radio Detection of EHE particles

in the Moon



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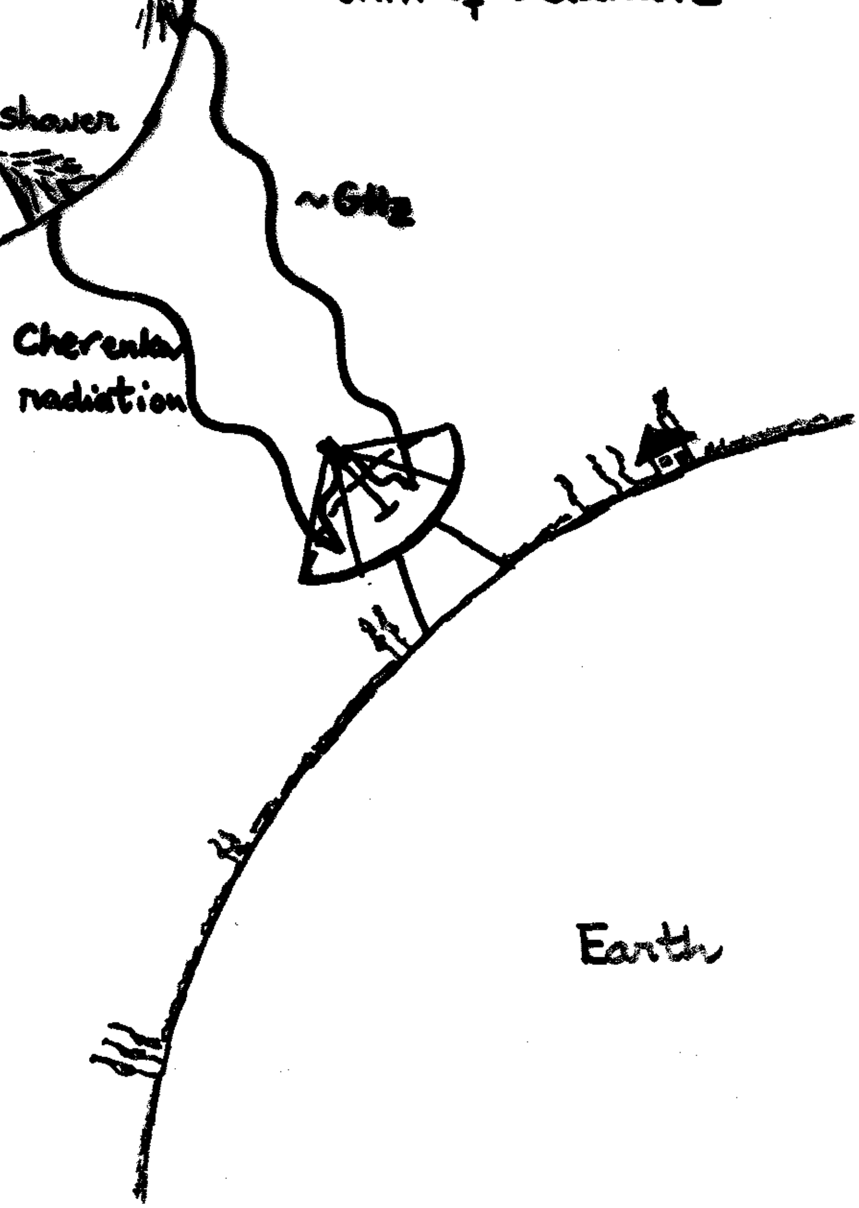


Askar'yan

Dagkesamanskiǐ
Zeleznykh

Filonenko

Hankins
Ekers
O'Sullivan

Gorham
Liewer
Naudet
Saltzberg

Zas
Vázquez
A-M ...

Outline

1.– Radiopulses from EHE ν and CR showers in the Moon: Energy threshold.

2.– Aperture of the Moon:

- CR showers
- ν showers $\begin{cases} \nu_e \text{ Charged Current DIS (CC)} \\ \begin{cases} \nu_e \text{ Neutral Current DIS (NC)} \\ \nu_\mu \text{ CC + NC} \end{cases} \end{cases}$

3. CR and ν event rates.

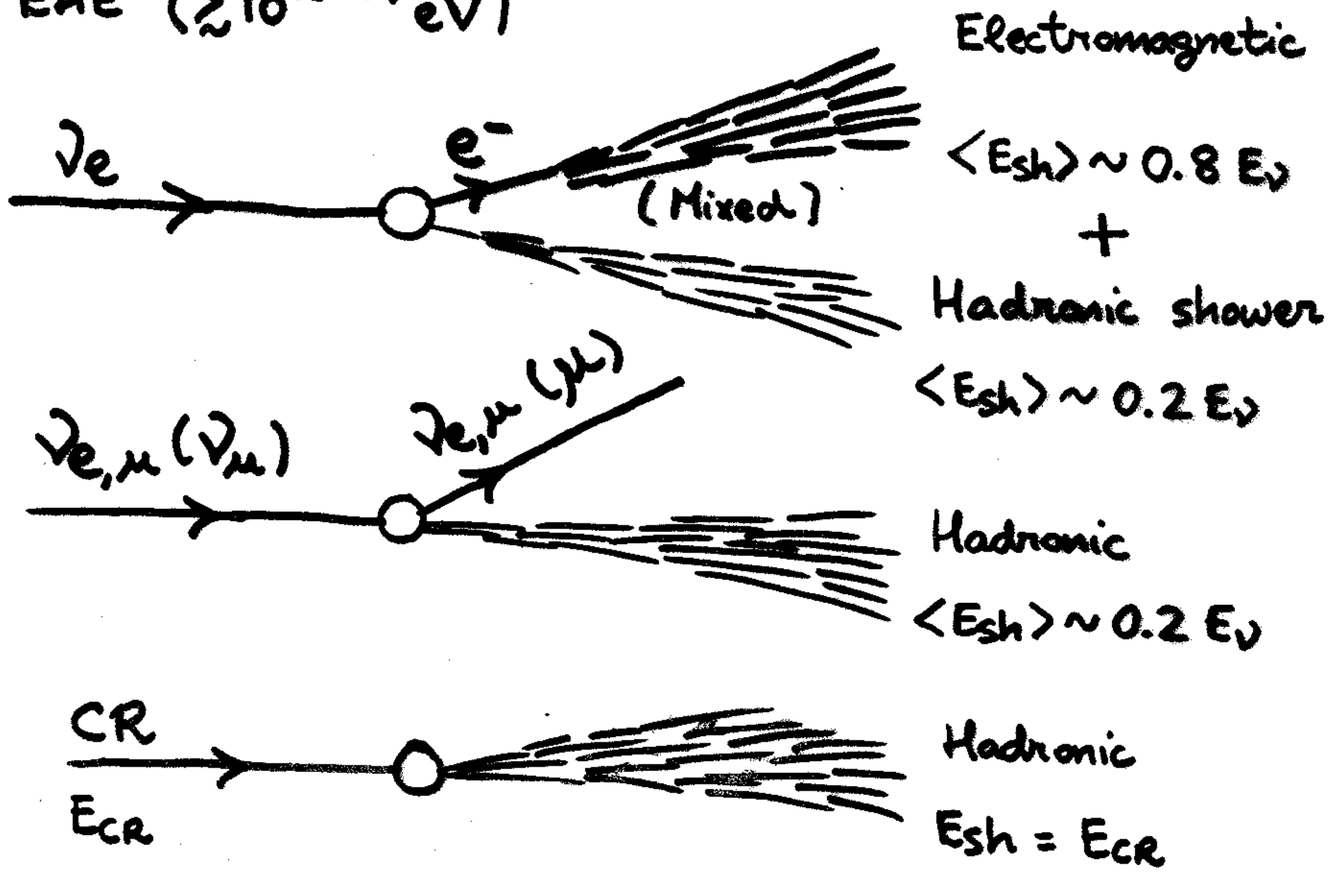
4. Improvements to the calulation.

+

Conclusions.

Radiopulses from EHE showers in the Moon

At EHE ($\gtrsim 10^{18-19}$ eV)



Coherent Cherenkov Radiation

Excess of $\ominus$ charge in the electromagnetic comp.

$\left\{ \begin{array}{l} \text{Compton, Bhabha, Möller} \\ \text{Annihilation of } e^+ \end{array} \right.$ $\rightarrow$ pull out atomic e^-

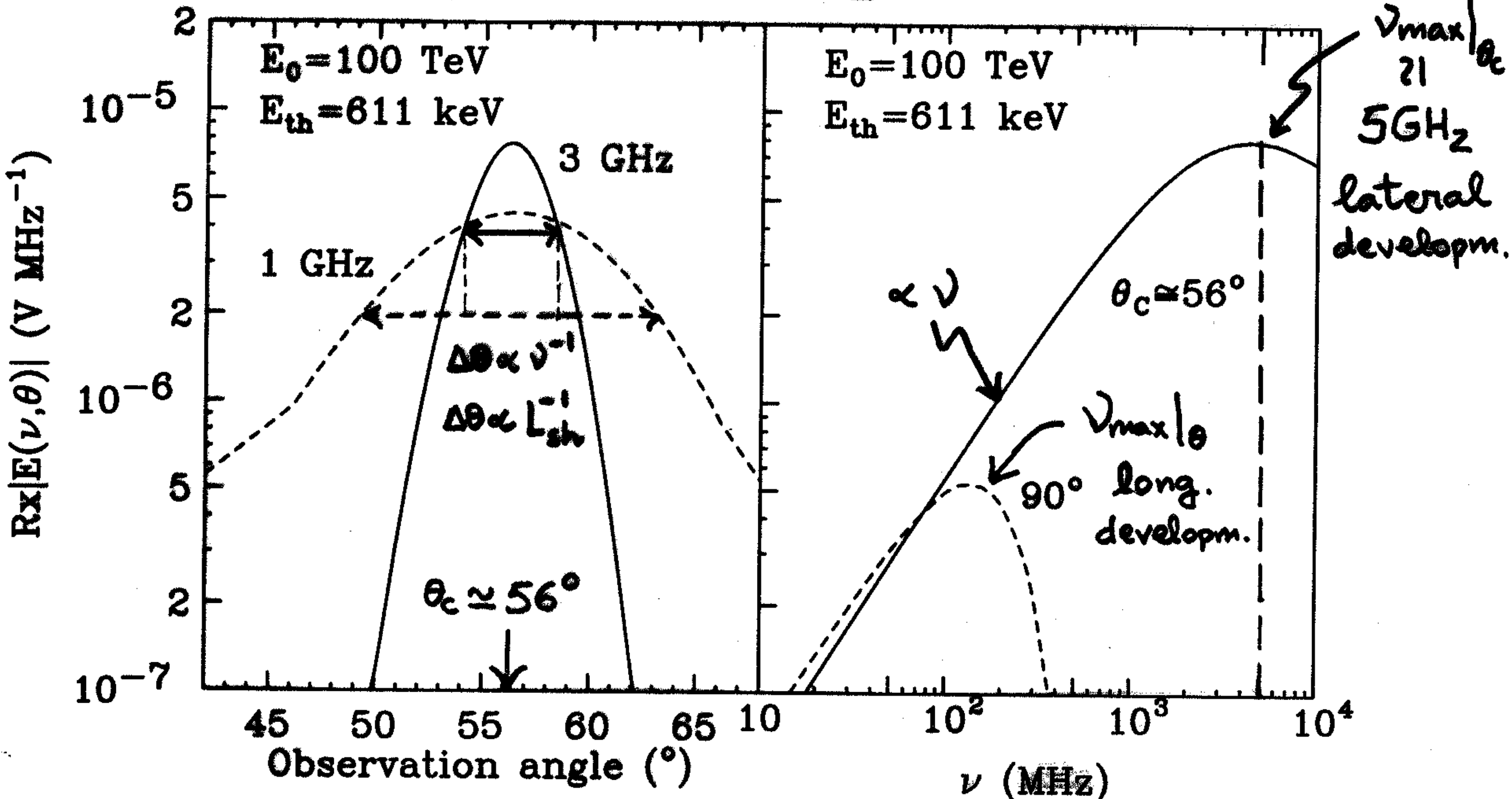
$$\Delta q^- \sim 20\text{-}25\%\ N_{e^-+e^+}$$

Hadronic showers : $\pi^0 \rightarrow \gamma\gamma$ $E_{elem} \sim 90\%\ E_{shower}$

Electromagnetic Showers

ICE → MOON

Radiopulses in the Moon MC ZHS adapted



$$R\,|\vec{E}(\nu,R,\theta_c)| = 1.57\times10^{-7}\ \frac{E_{electr.}}{1\ \mathrm{TeV}}\left[\frac{1}{1+(\nu/\nu_0)^{1.55}}\right]\frac{\nu}{\nu_0}\quad V\cdot MHz^{-1}$$

$\nu_0 = 2830\ MHz$

Electromagnetic showers

When $E_{shower} > E_{LPM} \sim 400\ TeV$

LPM effect
$$\left\{ \begin{array}{l} \lambda_{int}^{e^- \text{brems}} \propto \sqrt{E_{e^-}} \\ \lambda_{int}^{\text{pair}} \propto \sqrt{E_\gamma} \end{array} \right.$$

$(\propto 1/\log E_e)$

@ $E < E_{LPM}$

$(\propto \sim$ constant$)$ with E_γ

$\downarrow$

$$\text{Shower length} \propto E_{shower}^{1/3}$$

$\downarrow$

$$\Delta\theta \propto L_{shower}^{-1} \propto E_{shower}^{-1/3}$$

(scaling of $\Delta\theta$ ice results $\rightarrow$ Moon)

$\hookrightarrow \left\{ \begin{array}{l} X_0|_{Moon} \\ \rho_{Moon} \end{array} \right.$

$R|\vec{E}|_{Moon} \rightarrow$ normal.

Hadronic showers

Normalization $\longrightarrow R|\vec{E}|_{Moon}$ with $E_{electn.} \sim 90\%\ E_{sh}$

LPM effect is mitigated

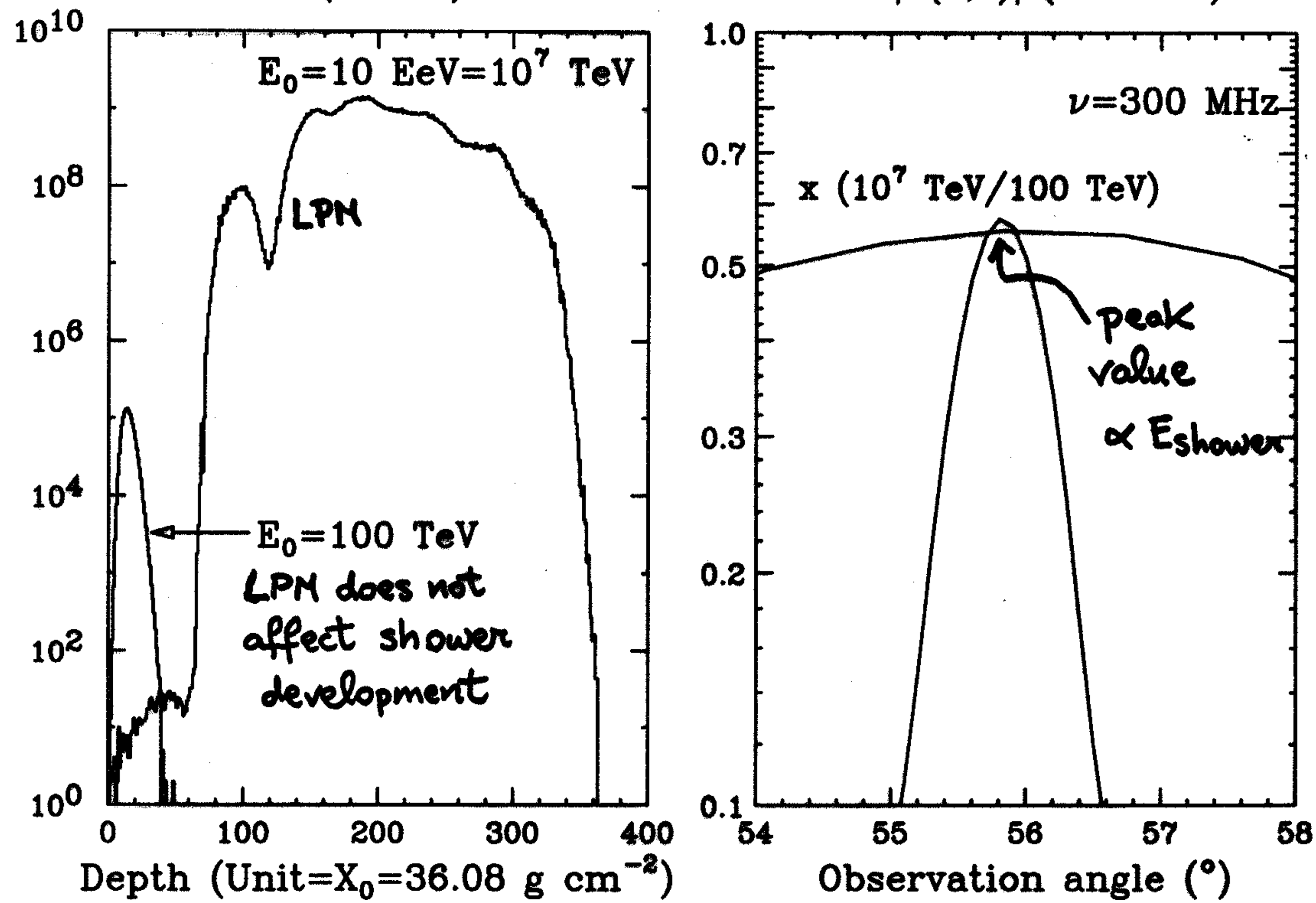
$$E_{\pi^0} \gtrsim \epsilon_{\pi^0} \simeq 2\ PeV ;\ \cancel{\pi^0 \rightarrow 2\gamma}$$

Suppression of γ's with $E > E_{LPM}$

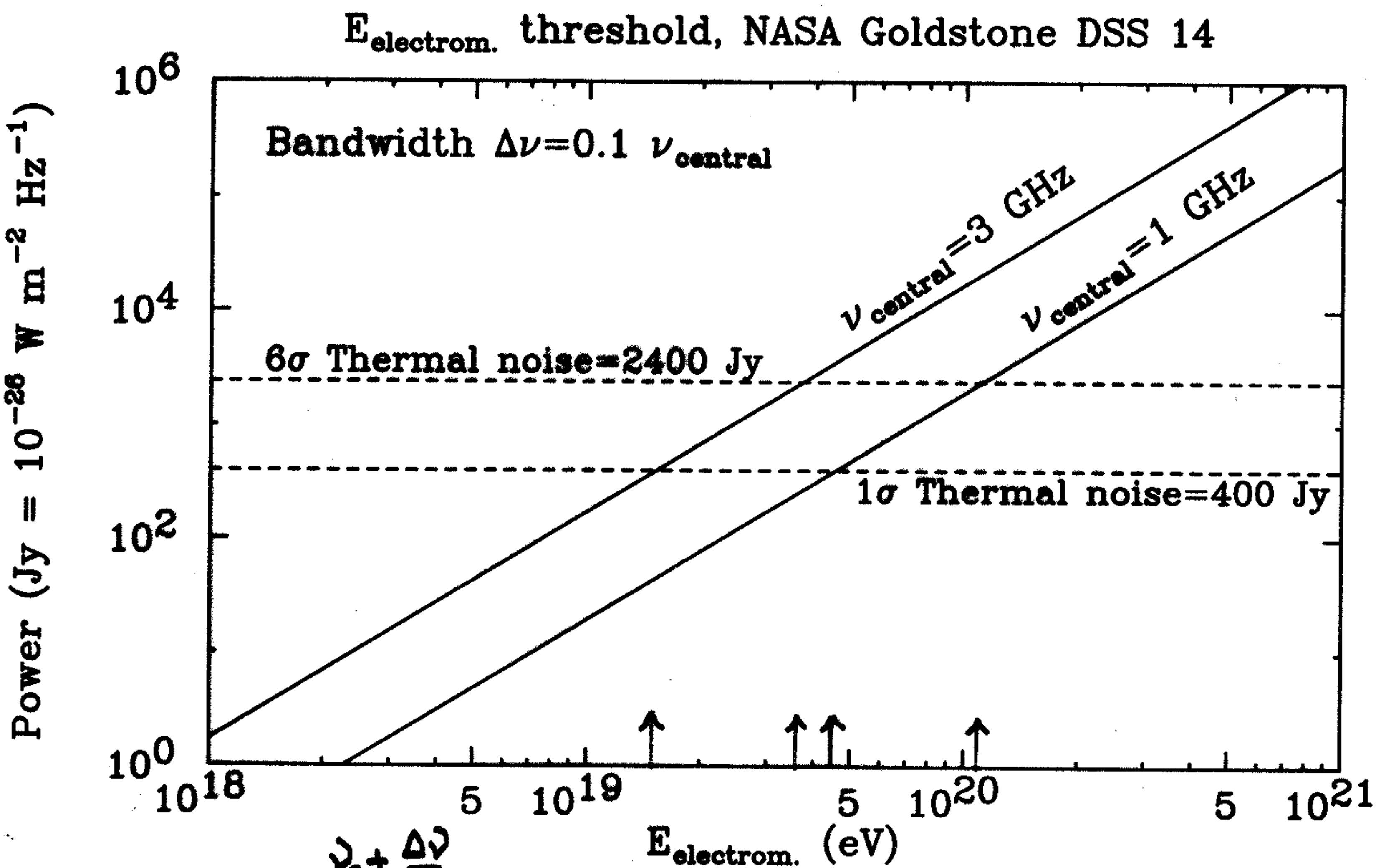
(scaling of $\Delta\theta$ ice $\rightarrow$ Moon ; $\epsilon_{\pi^0}|_{ice} \sim 7\ PeV \gtrsim \epsilon_{\pi^0}|_{Moon}$)

$E_{LPM}|_{ice} \sim 2$ PeV

ICE



$$\left(\text{Scaling} \Rightarrow \Delta\theta_{Moon} \sim \frac{X_0|_{ice}\, \rho_{Moon}}{X_0|_{Moon}\, \rho_{ice}} \sim 5.2\, \Delta\theta_{ice} \right)$$

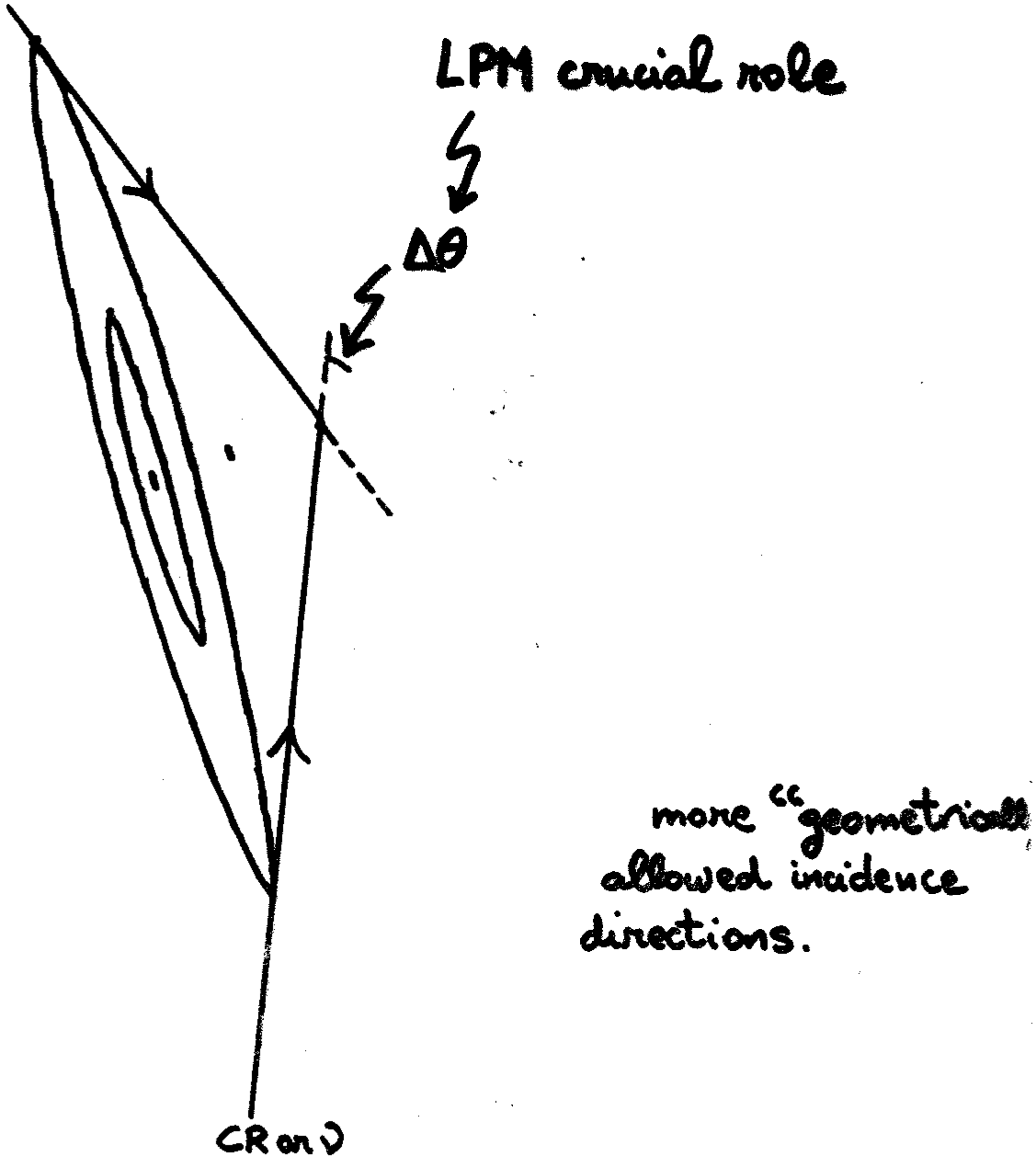


$$\text{Signal} \propto \int_{\nu_c - \frac{\Delta\nu}{2}}^{\nu_c + \frac{\Delta\nu}{2}} |R\,\vec{E}(\nu, R, \theta_c)|^2\, d\nu \Big/ R^2_{\text{Earth}\to\text{Moon}}$$

MC ZHS Moon

$$\text{Noise} = 2K_B T_{\text{antenna}} \Big/ \left(\sqrt{\Delta t \Delta\nu}\ A_{\text{telescope}}\right)$$

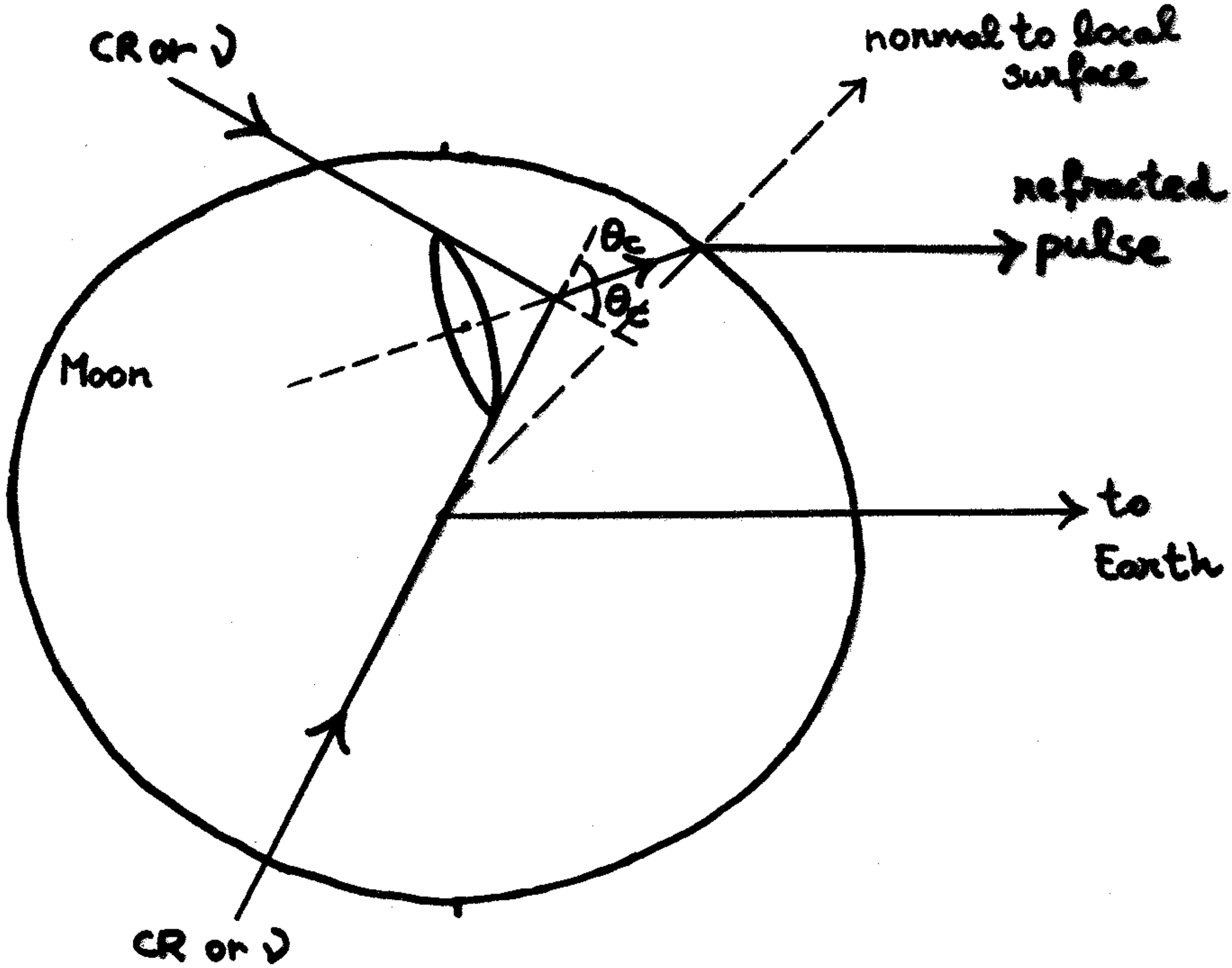
$\Delta t \equiv$ duration of the pulse

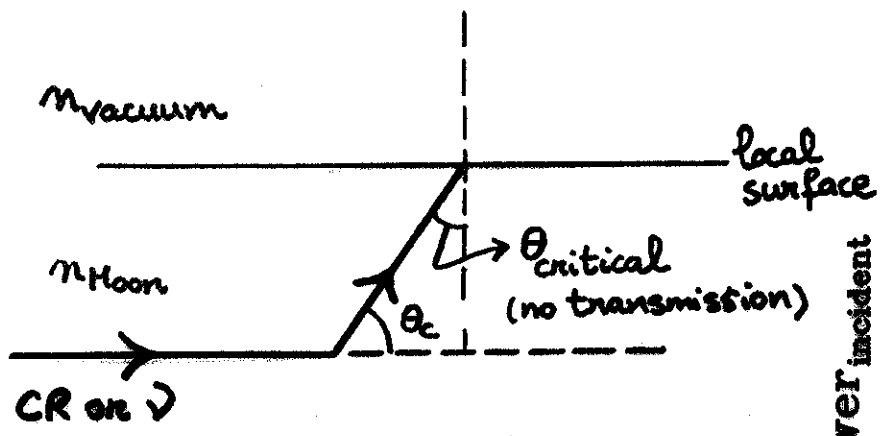


CODE:

1) Geometrically allowed incidence directions $\rightarrow \Omega^{max}$
2) Eliminate those for which CR or ν are absorbed inside the Moon
   - CR observation $\rightarrow$ narrow rim
   - ν, $E_\nu > 10$ PeV are absorbed.
3) Eliminate directions signal < noise @ Earth (For each E_ν or E_{CR} and each point on the surface).

Aperture

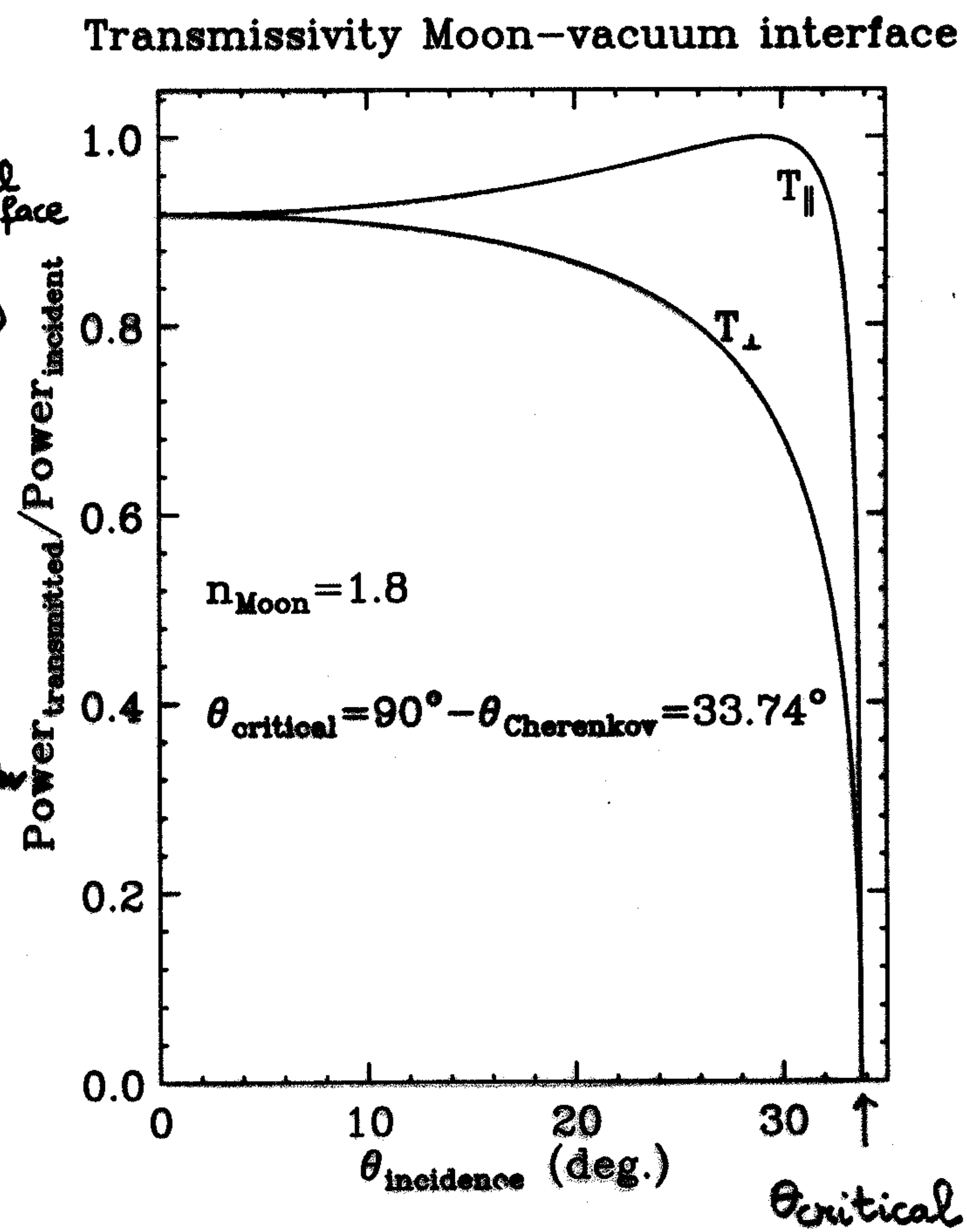

CR or ν
normal to local surface
refracted pulse
θ_c
θ_t
Moon
to Earth
CR or ν



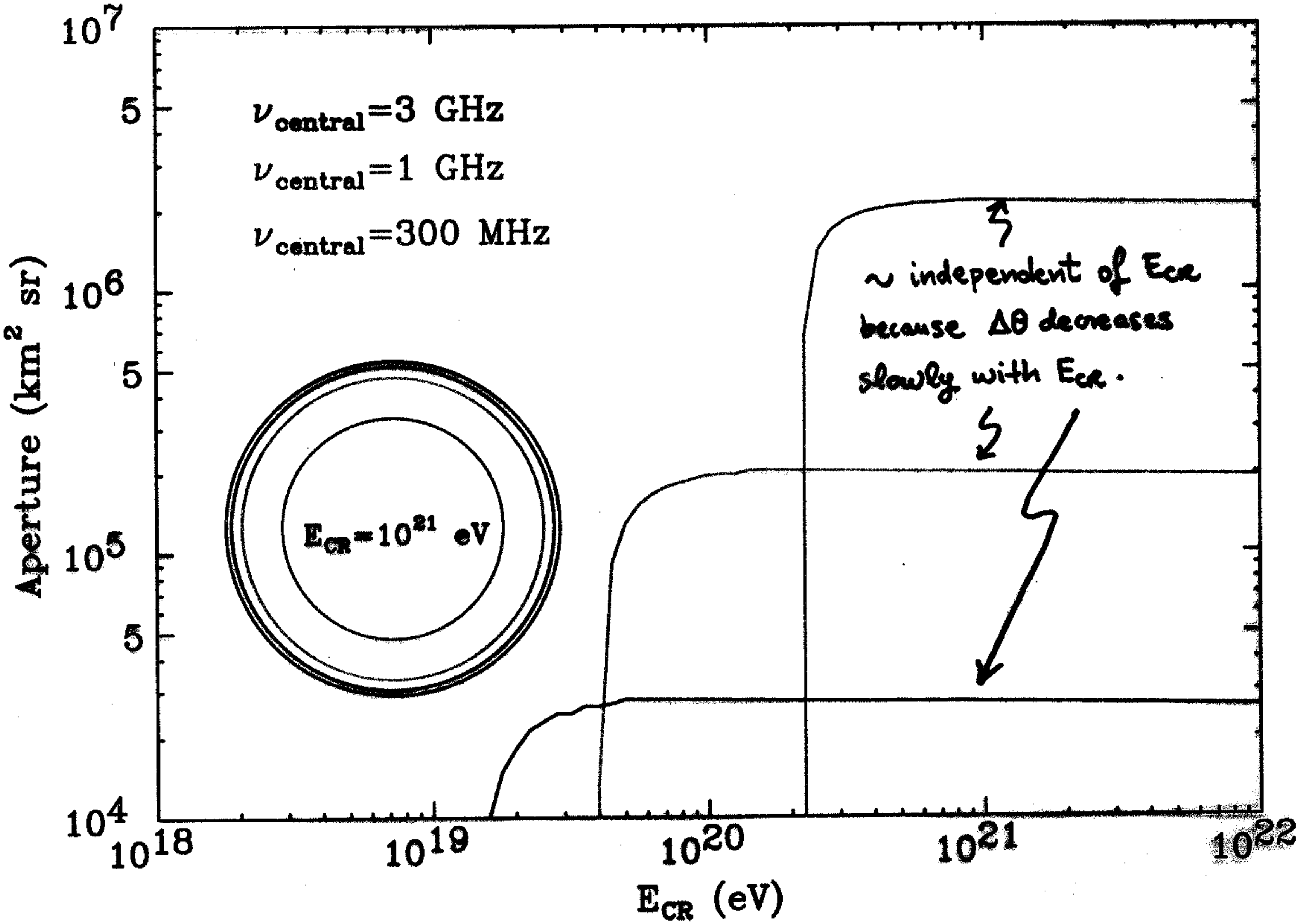
$$n_{Moon} \sin\theta_{critical} = n_{vac.} \sin\frac{\pi}{2} = 1$$

$$\sin\theta_{critical} = \frac{1}{n_{Moon}} = \cos\theta_{Cherenkov}$$

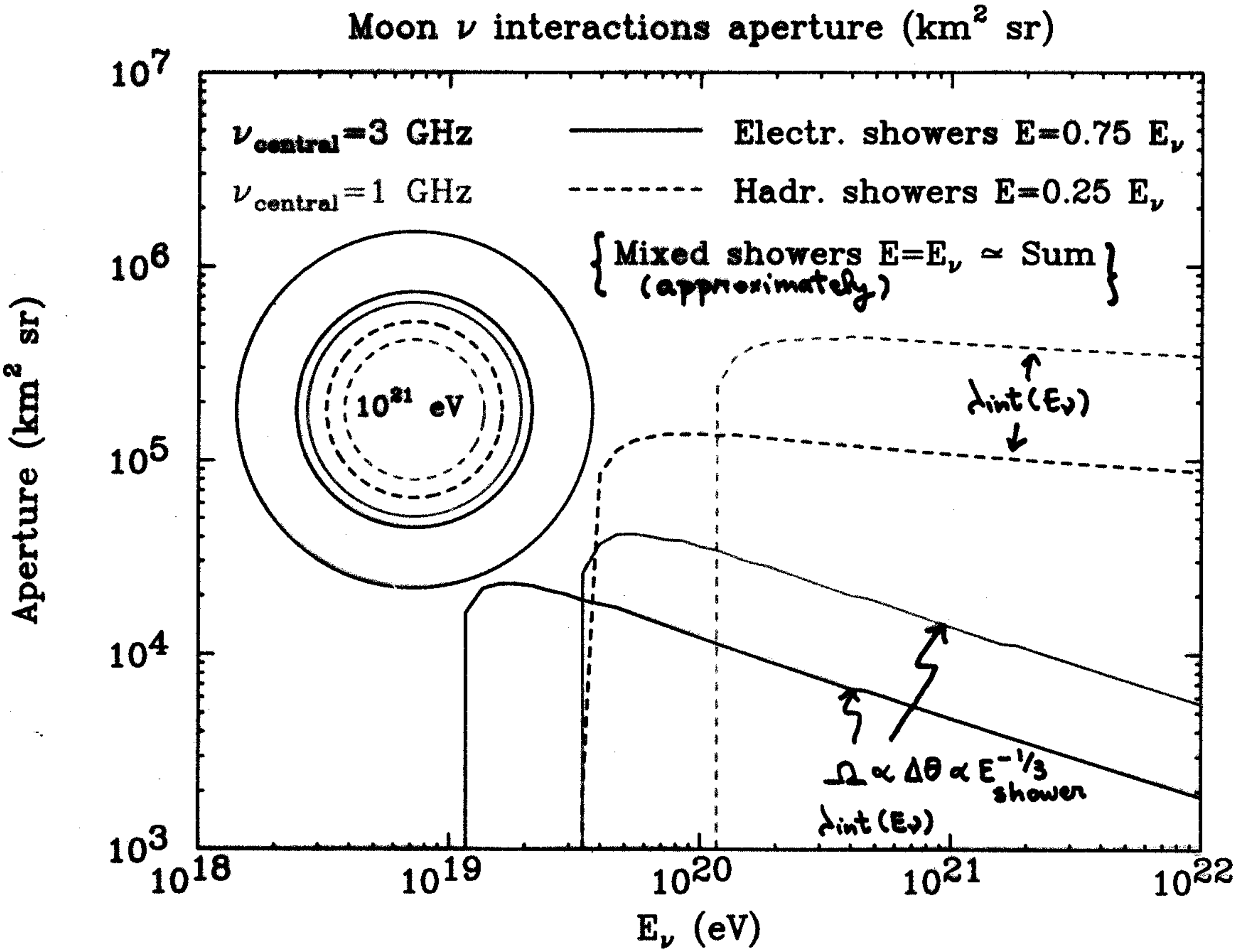
$$\theta_{critical} = \frac{\pi}{2} - \theta_{Cherenkov}$$



Moon cosmic ray aperture (km^2 sr)



$\nu\uparrow \Rightarrow E_{threshold}\downarrow$ but $\Omega\downarrow$ too due to $\Delta\theta \propto \nu^{-1}$



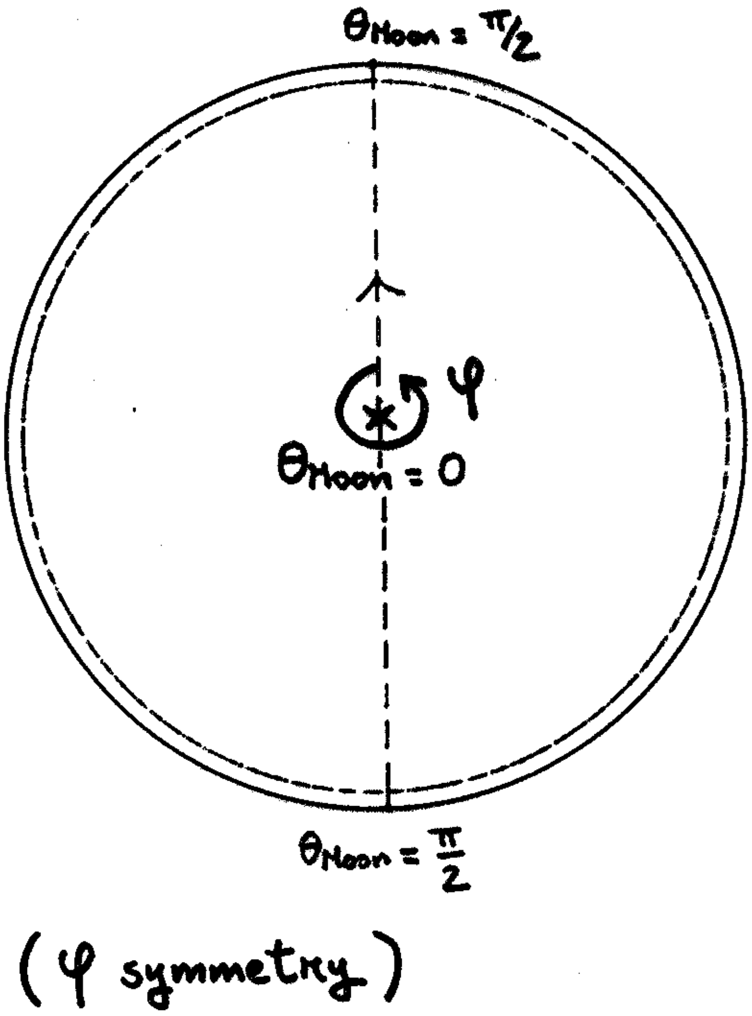
Moon ν interactions aperture (km² sr)
Aperture (km² sr)
ν_central=3 GHz
ν_central=1 GHz
Electr. showers E=0.75 E_ν
Hadr. showers E=0.25 E_ν
Mixed showers E=E_ν ≃ Sum
(approximately)
10²¹ eV
λint(Eν)
Ω ∝ Δθ ∝ E_shower^(-1/3)
λint(Eν)
E_ν (eV)

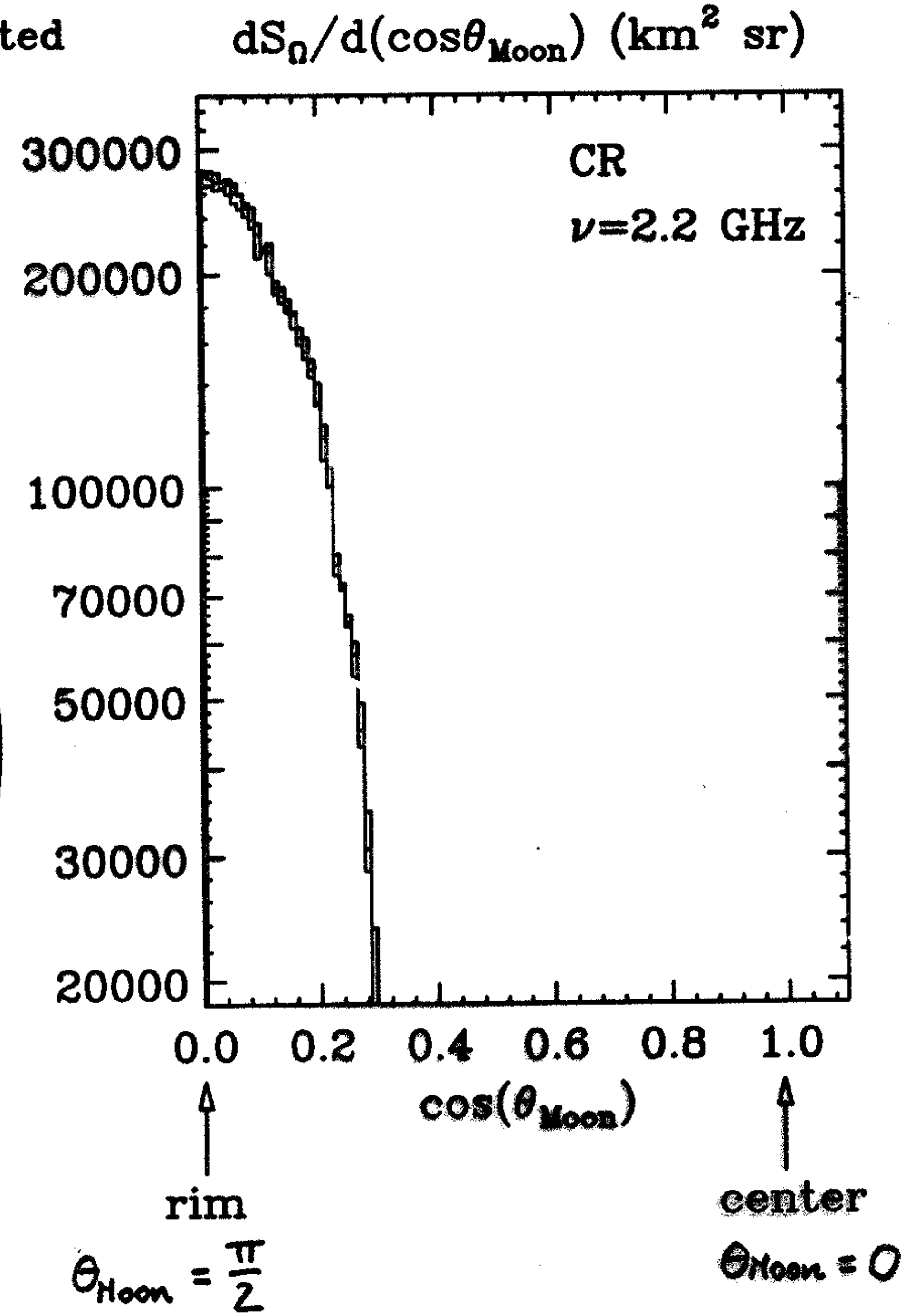
Size of rim where CR obs. is expected

$E_{CR}=10^{20}$ eV

$E_{CR}=10^{21}$ eV

$E_{CR}=10^{22}$ eV

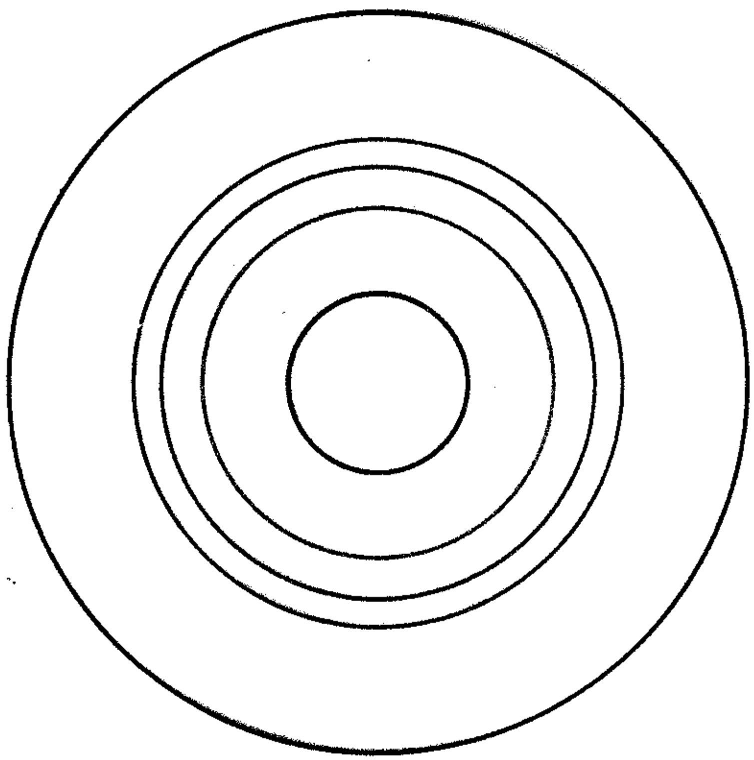




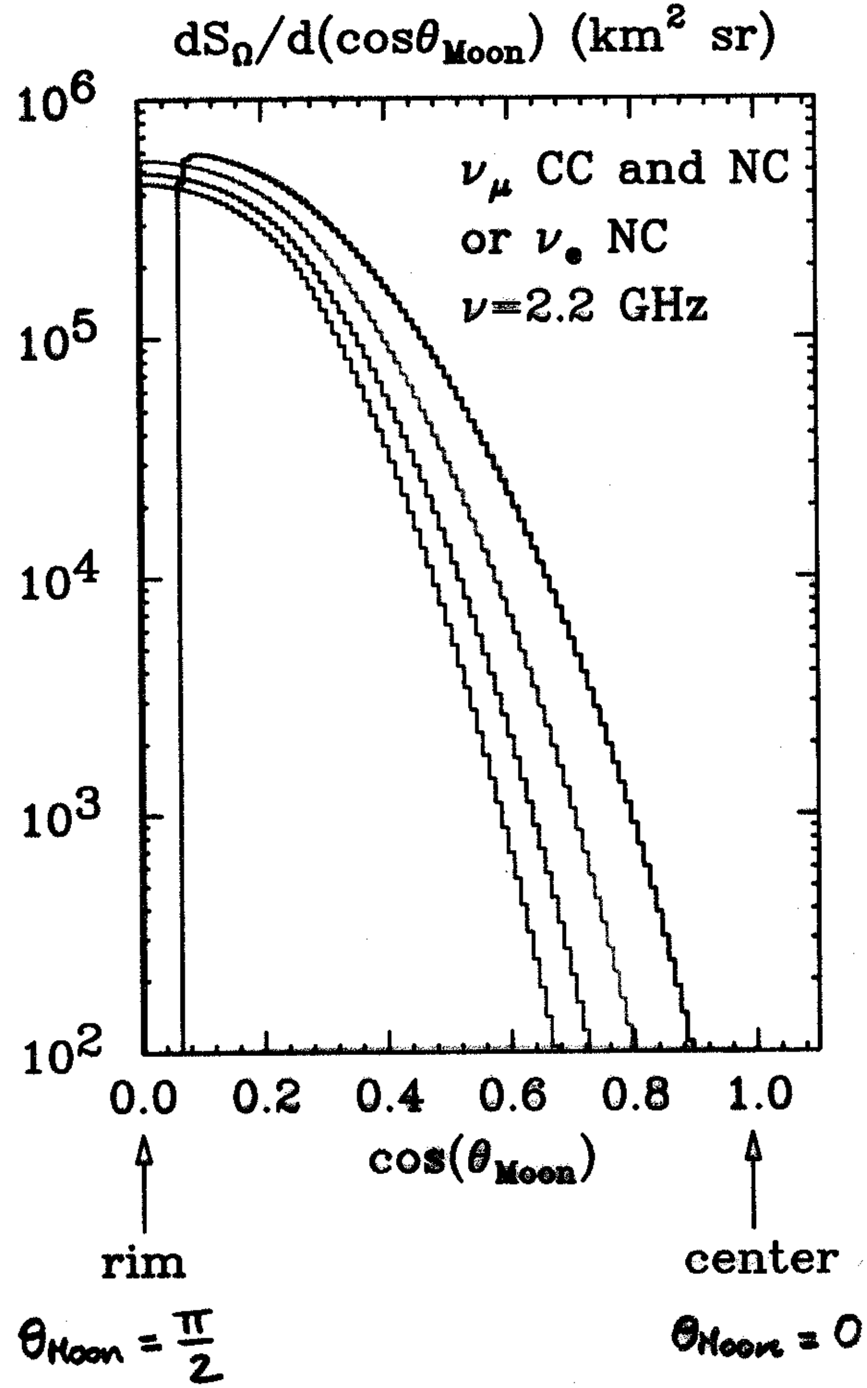
Size of rim where ν obs. is expected

$E_{CR}=10^{20}$ eV $E_{CR}=10^{21}$ eV

$E_{CR}=10^{22}$ eV $E_{CR}=10^{23}$ eV



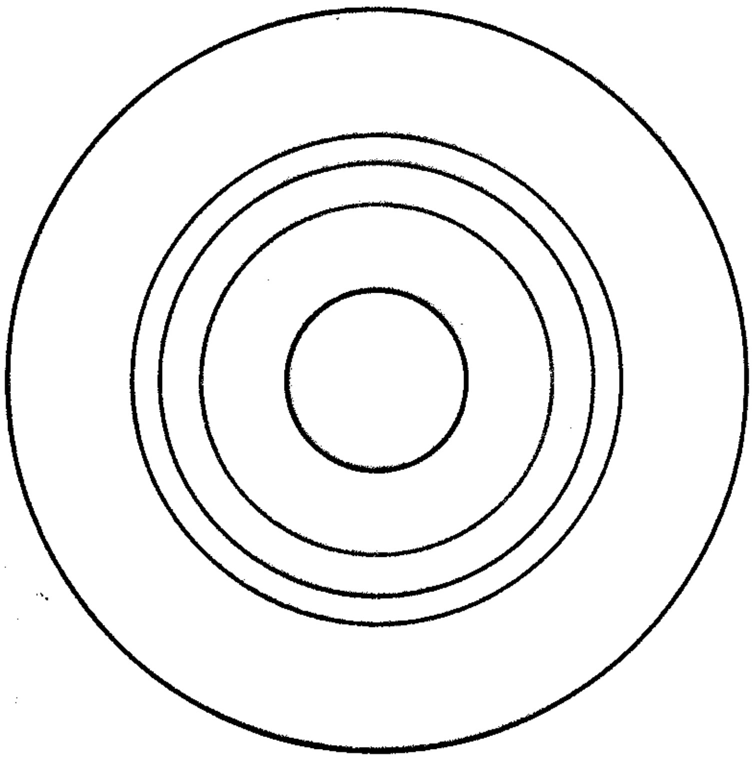
Bigger rims as compared to the CR case because ν's can penetrate deeper

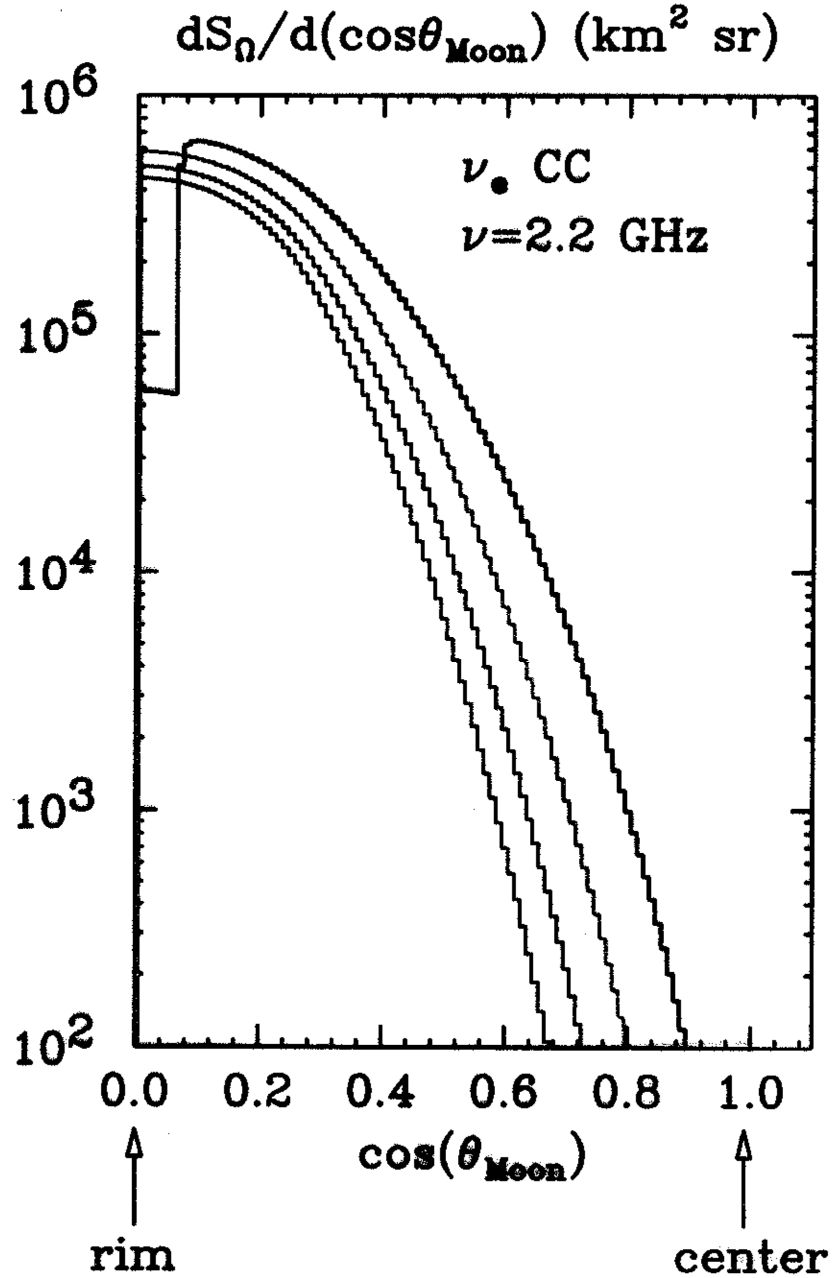


Size of rim where ν obs. is expected

$E_{CR}=10^{20}$ eV $E_{CR}=10^{21}$ eV

$E_{CR}=10^{22}$ eV $E_{CR}=10^{23}$ eV

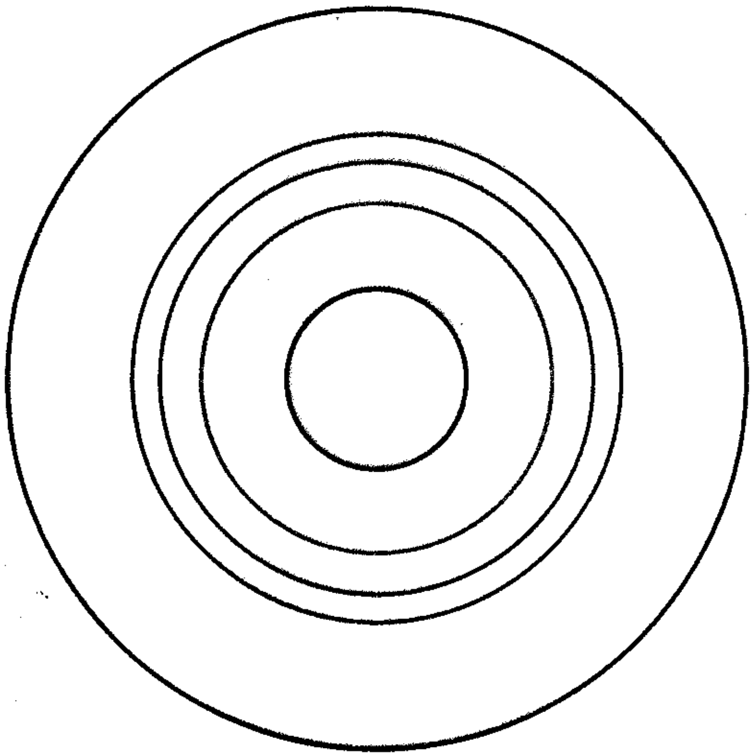


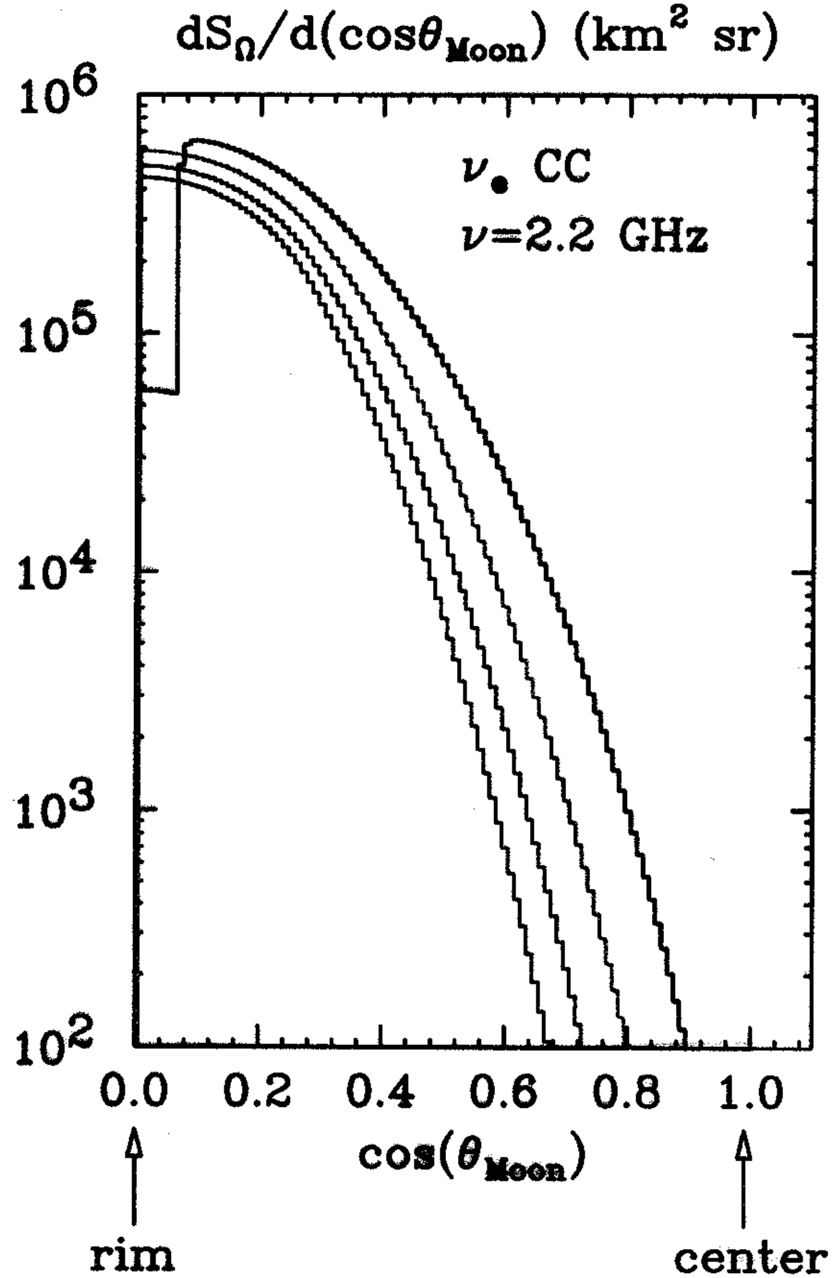


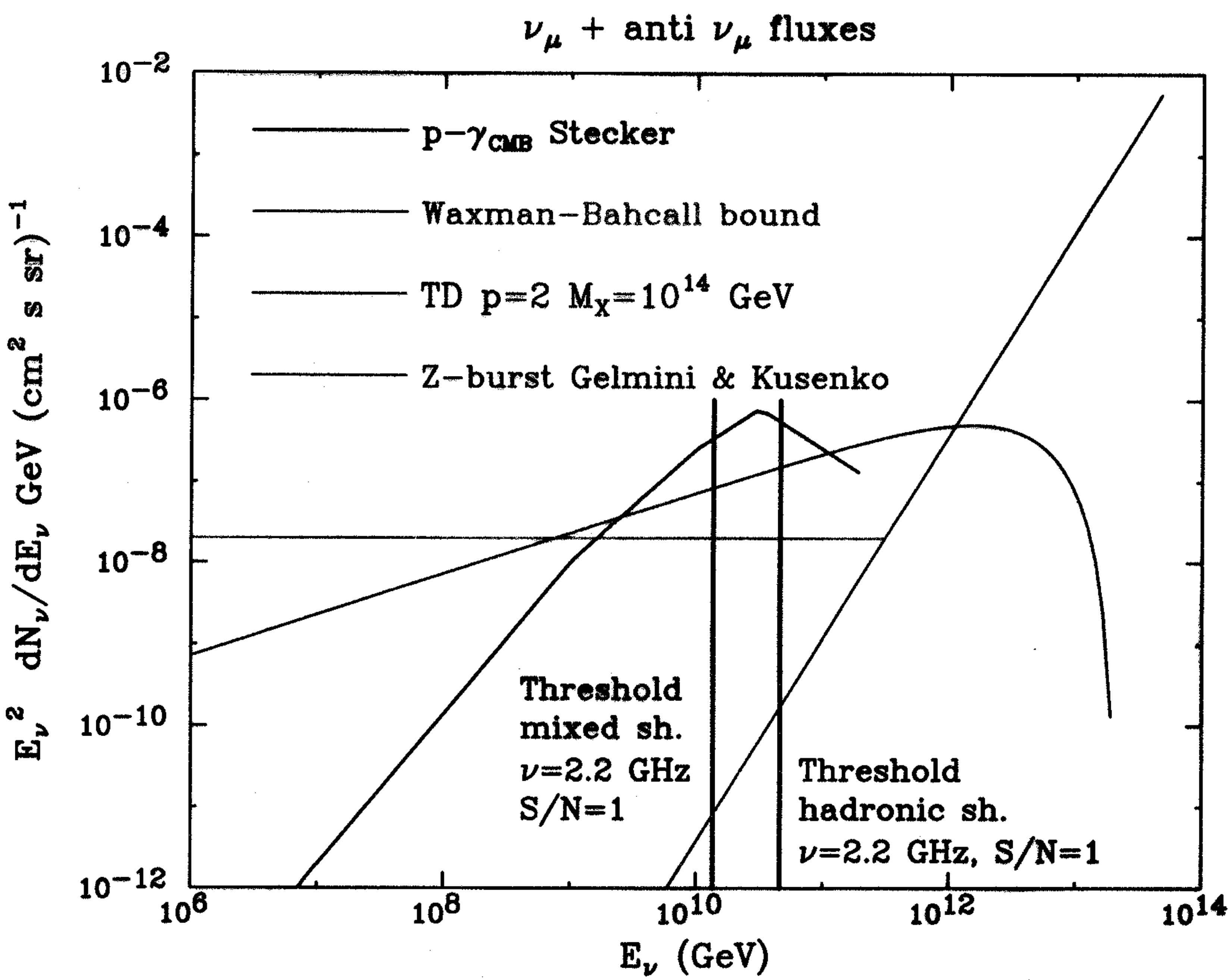
Size of rim where ν obs. is expected

$E_{CR}=10^{20}$ eV $E_{CR}=10^{21}$ eV

$E_{CR}=10^{22}$ eV $E_{CR}=10^{23}$ eV

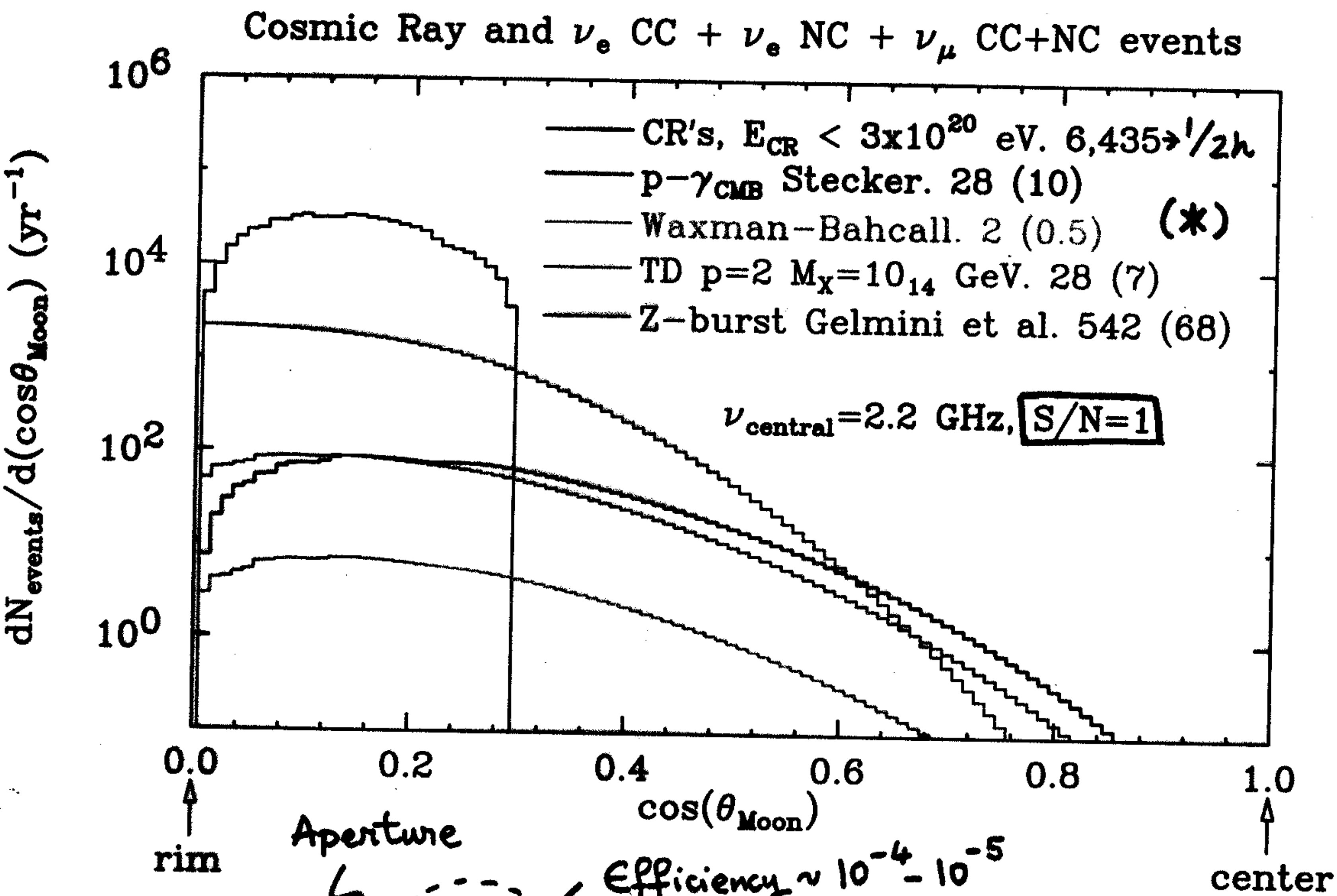






ν_μ + anti ν_μ fluxes
$E_\nu^{\,2}\ dN_\nu/dE_\nu$ GeV (cm^2 s sr)$^{-1}$
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
p$-\gamma_{CMB}$ Stecker
Waxman–Bahcall bound
TD p=2 $M_X=10^{14}$ GeV
Z–burst Gelmini & Kusenko
Threshold
mixed sh.
ν=2.2 GHz
S/N=1
Threshold
hadronic sh.
ν=2.2 GHz, S/N=1
10^6
10^8
10^{10}
10^{12}
10^{14}
E_ν (GeV)

(*)#'s in parenthesis indicate events from the region on the surface where CR's are not exptd.



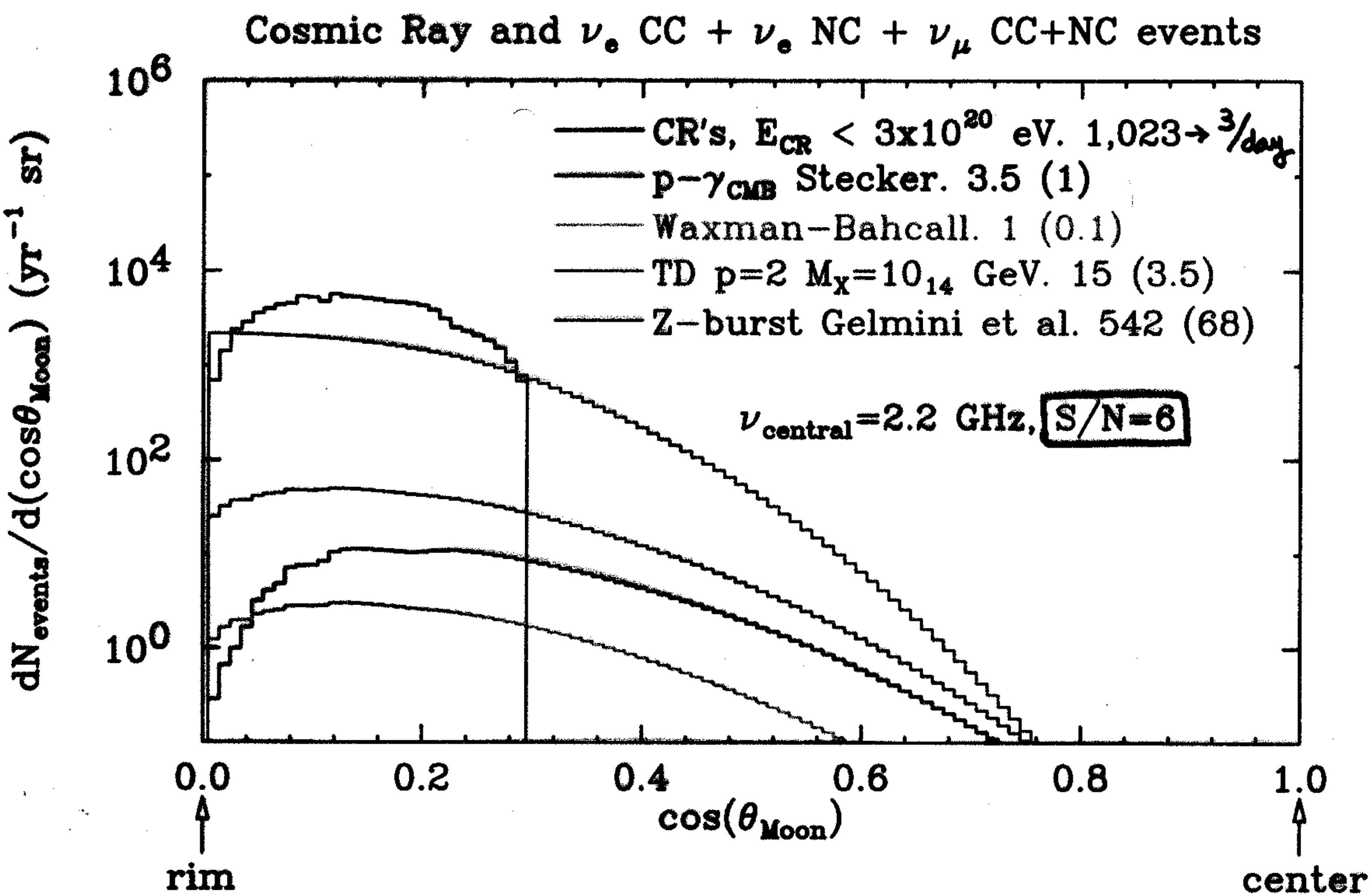
Aperture

Efficiency ~ 10^{-4} - 10^{-5}

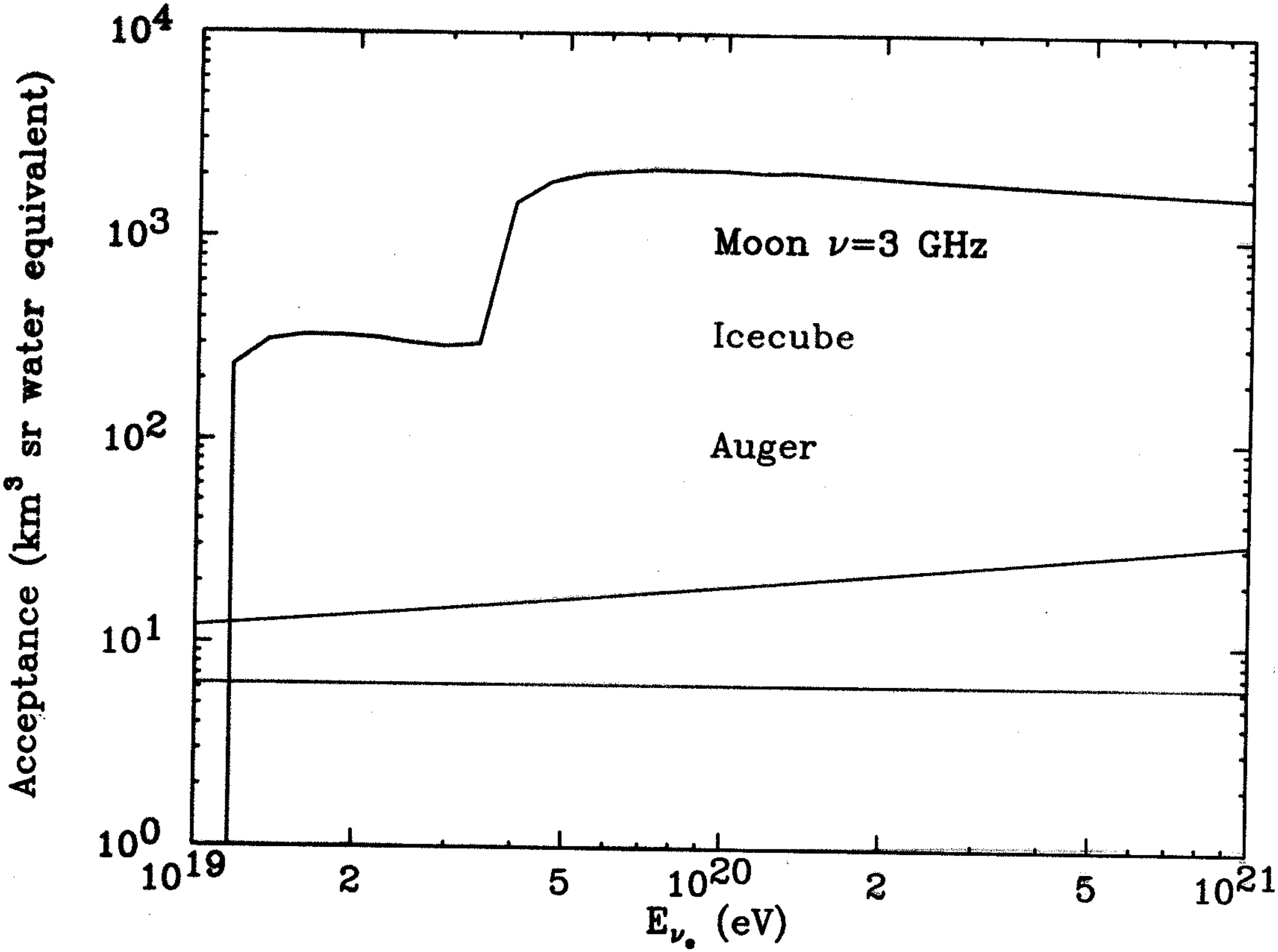
$$N_\nu \sim \int_{E_\nu} \frac{d\phi_\nu}{dE_\nu} S_\Omega^\nu \frac{\lambda^\omega_{abs}}{\lambda^\nu_{int}} dE_\nu$$

λ^ω_{abs} ≡ Absorption length of radiowaves in the Moon

$\lambda^\omega_{abs} \sim 15\,m \times (1\,GHz/\nu)$



Cosmic Ray and ν_e CC + ν_e NC + ν_μ CC+NC events
CR's, E_{CR} < $3x10^{20}$ eV. 1,023→ 3/day
$p-\gamma_{CMB}$ Stecker. 3.5 (1)
Waxman–Bahcall. 1 (0.1)
TD p=2 $M_X=10_{14}$ GeV. 15 (3.5)
Z–burst Gelmini et al. 542 (68)
$\nu_{central}$=2.2 GHz, S/N=6
$dN_{events}/d(\cos\theta_{Moon})$ (yr^{-1} sr)
10^6
10^4
10^2
10^0
0.0
0.2
0.4
0.6
0.8
1.0
$\cos(\theta_{Moon})$
rim
center



Acceptance (km³ sr water equivalent)
10⁰
10¹
10²
10³
10⁴
10¹⁹
2
5
10²⁰
2
5
10²¹
E_νe (eV)
Moon ν=3 GHz
Icecube
Auger

CR events:

3/day in the whole rim ($6\sigma \sim 2400$ Jy)

Radiotelescopes only see ~10% of the

Moon's limb $\Rightarrow$ $3/_{10\,\text{days}}$

or

$\boxed{1/80 \text{ hours}}$ $\left(^{10}/_{\text{month}}\right)$

$\left\{\begin{array}{l}\text{K. Liewer, C. Naudet,} \\ \text{P. Gorham, D. Saltzberg et al.} \rightarrow 100 \text{ hours}\end{array}\right.$

T. Hankins, R. Ekers, J. O'Sullivan → ? hours

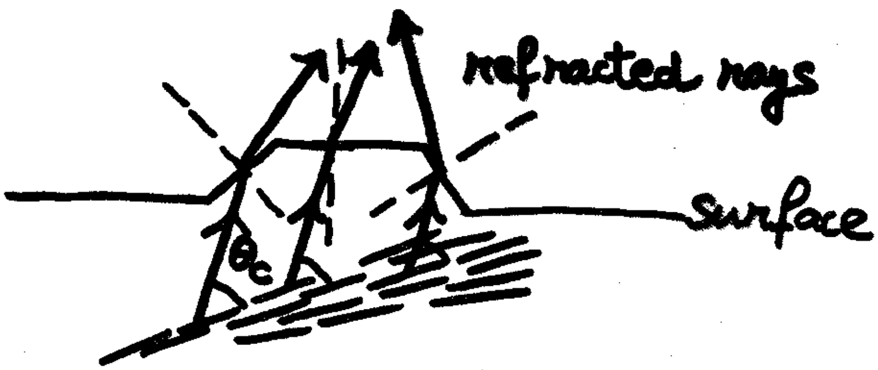
Look @ the limb !!!

Find Cosmic Rays !!!

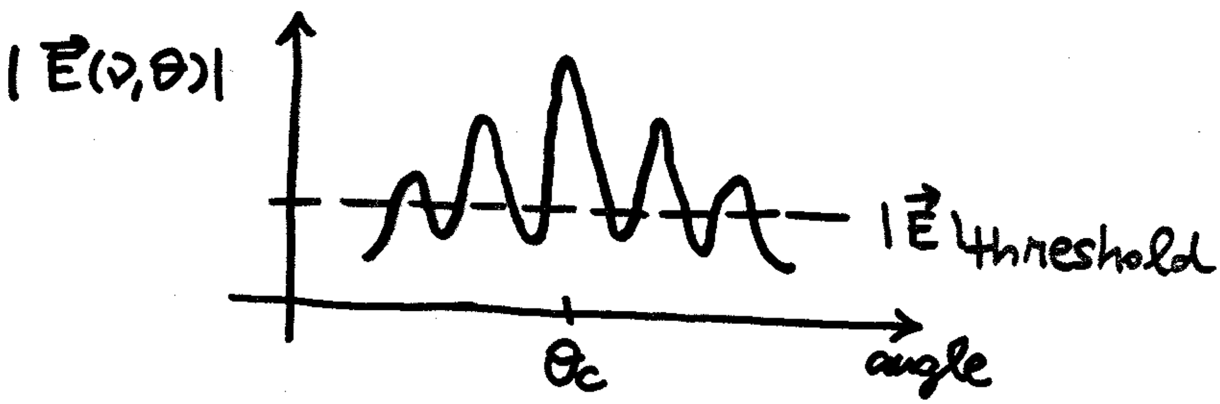
and celebrate !!  ← Spanish "Rioja" or "Ribera del Duero"

Improvements

× Roughness of the Moon's surface



× Secondary diffractive peaks @ EHE's



× Cascades produced by μ bremsstrahlung

(P. Gorham)