Neutrino and Cosmic Ray Signals from the Moon

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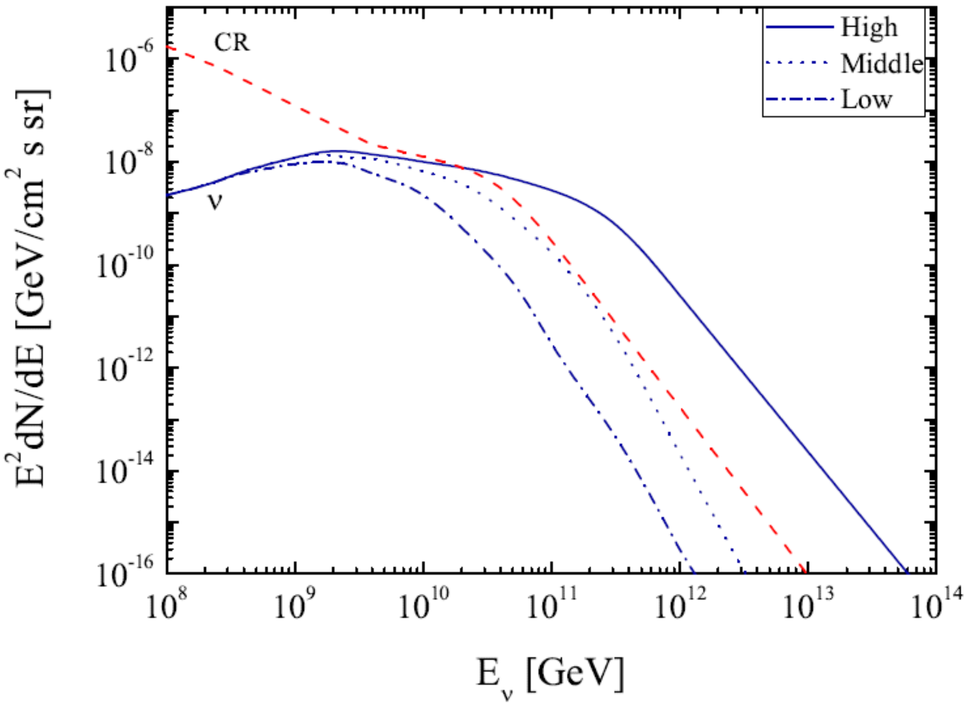
Jeong, Reno and Sarcevic, Astroparticle Physics 35 (2012) 383
[arXiv:1108.2549]

Outline

- Cosmogenic neutrinos
- Radio Cherenkov detection
- Effective aperture
- Signals of neutrinos and cosmic rays
- Signal changes with the cross sections and the flux

Ultra High Energy Cosmic Rays and Neutrinos



JRS (2012)

- Cosmogenic neutrinos

$$p + \gamma \;\rightarrow\; n + \pi^+$$

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

$$\rightarrow (e^+ + \nu_e + \overline{\nu}_\mu) + \nu_\mu$$

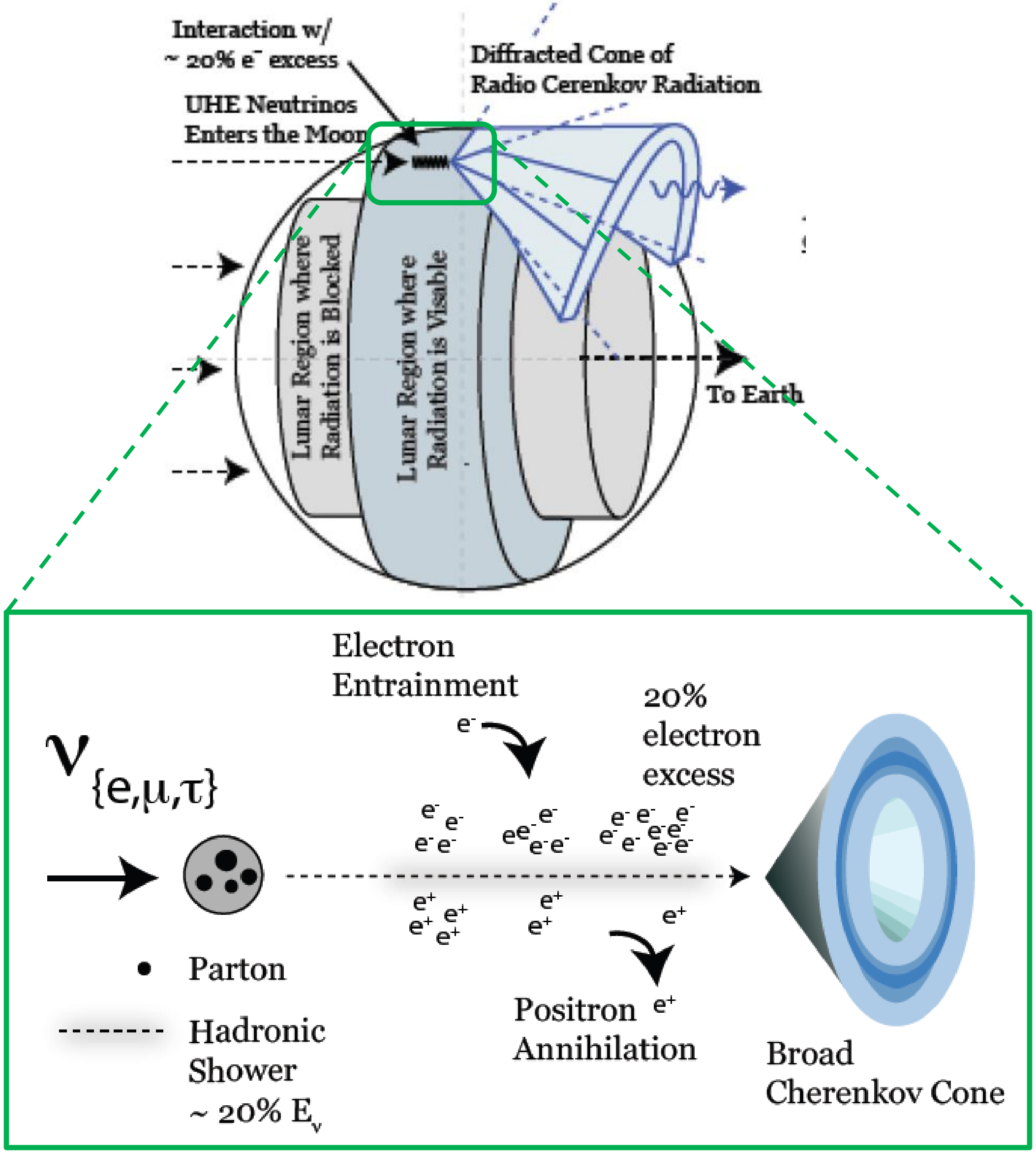
$$n \rightarrow p + e^- + \overline{\nu}_e$$

- Neutrino fluxes: from K. Kotera, D. Allard, and A. V. Olinto (JCAP, 2010)
- Cosmic ray flux: from the Pierre Auger Collaboration (PLB 685, 2010)

The Moon as a detector

- The area of the Moon ~ 10^7 km^2 -> good as a big detector
- For E>10^7 GeV, neutrinos interact inside the Moon.
- The Moon was suggested as a neutrino detector by Dagkesamanskii and Zhelenznykh (1989) based on the prediction of Askaryan effect.
- Askaryan Effect (1962) – High energy particle interactions in the materials (e.g. salt, ice, dry rock) produce about 20% net charge excess.

Detection Method – Radio Cherenkov



- High energy neutrinos produce showers in the lunar regolith.
- While the shower develop in the regolith, 20% of electron excess is created. => Askaryan Effect (G. Askaryan(1962))
- The bunch of electrons generates the Cherenkov radiation.
- This Cherenkov radiation is observed by the array of antennas.

resun.physics.uiowa.edu

Experiments (Lunar Target)

- Parkes telescope, Hankins et al (1996)
- Goldstone Lunar UHE Neutrino experiment, Gorham et al. (2001; 2004)
- Beresnyak et al. (2005) Kalyazin telescope
- Buitink et al. (2008), nuMoon with Westerbork Synthesis Radio Telescope
- Jaeger et al., RESUN with VLA

Event Rate

$$\Gamma = \int_{E_{min}} dE_\nu \Phi(E_\nu, X(\theta_\nu)) A_\nu(E_\nu)$$

- $\Phi(E_\nu, X(\theta_\nu)) \simeq e^{-2R\cos\theta_\nu/\lambda}\Phi(E_\nu, 0)$: the flux
- $A_\nu(E) = A_0 \int d\hat{V}_m \int d\hat{\Omega}_\gamma \int d\hat{\Omega}_\nu \, e^{-\tau_\nu} \mathcal{H}_R \mathcal{H}_D$

  $= A_0 P_\nu(E)$: the effective aperture

A_0 : the maximum cross sectional area of the detector

$P_\nu(E)$: Probability of Interaction within the detector

Effective Aperture

$$\boxed{A_\nu(E) = A_0 P_\nu(E)}$$

$A_0 = 4\pi(\pi R_M^2)$: the maximum geometric aperture of the Moon

$$P_\nu(E) = \frac{(n_r^2 - 1)}{8n_r}\frac{L_\gamma}{L_\nu} f_0^3 \Delta_0 (\Psi_{ds} + \Psi_{dr} + \Psi_u)$$

: the neutrino interaction probability in the Moon

$$L_\gamma = 5 \times 10^{-6} R \left(\frac{\nu}{\mathrm{GHz}}\right)^{-1}$$

$$L_\nu = \frac{1}{\sigma_{\nu N}^{tot} N_A}$$

: interaction lengths of photon and neutrinos

$n_r = 1.73$: the index of refraction

K. G. Gayley, R. L. Mutel, and T. R. Jaeger Astropart. Phys. 706, 1556 (2009)

Effective Aperture – more parameters

$$f_0 = \sqrt{\ln\left(\frac{0.6\varepsilon_0}{\varepsilon_{min}}\right)}$$

: Ratio of the full thickness of the Cherenkov cone to the thickness at the minimum detectable electric field

ε_{min} : the minimum detectable electric field

$$\varepsilon_0 = 0.0845\left[\frac{d}{\mathrm{m}}\right]^{-1}\left[\frac{E_s}{\mathrm{EeV}}\right]\left[\frac{\nu}{\mathrm{GHz}}\right]\left[1+(\frac{\nu}{2.32})^{1.23}\right]^{-1}$$

: Maximum electric field

$$E_s = \langle y\rangle\, E_\nu \;=\; 0.2E_\nu$$

: the shower energy

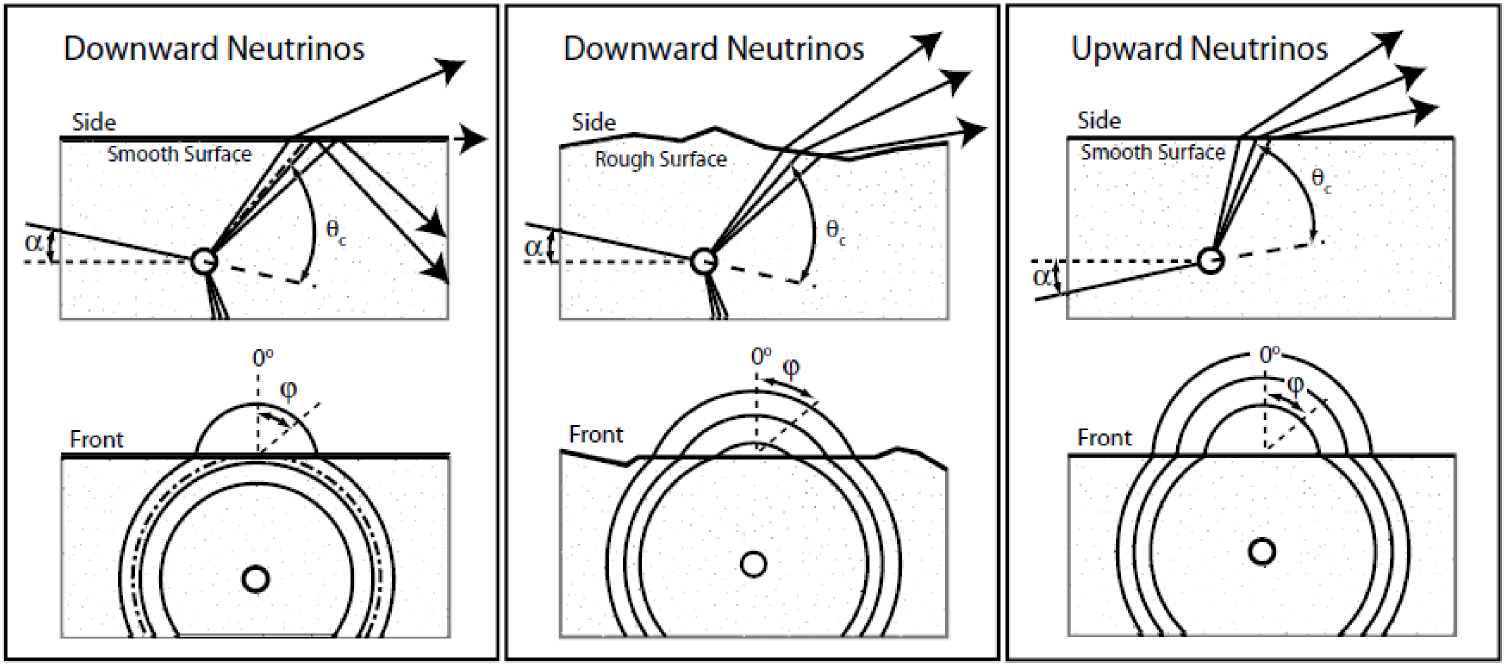
$$\Delta_0 = 0.05\left[\frac{\mathrm{GHz}}{\nu}\right]\left[1+0.075\mathrm{log}\left(\frac{E_s}{10^{19}\mathrm{eV}}\right)\right]^{-1}$$

: the half width of the Cherenkov cone

K. G. Gayley, R. L. Mutel, and T. R. Jaeger Astropart. Phys. 706, 1556 (2009)

Effective Aperture

$$\begin{aligned}\Psi_{ds} &= f_0\Delta_0\\ \Psi_{dr} &= \frac{16}{3\pi^{3/2}}\sigma_0 = 0.96\sqrt{2}\tan^{-1}(0.14\nu^{0.22})\\ \Psi_u &= \frac{16}{3}\left(\frac{\lambda}{2R}\right) = \frac{16}{3}\left(\frac{L_\nu}{2R\kappa}\right)\end{aligned}$$



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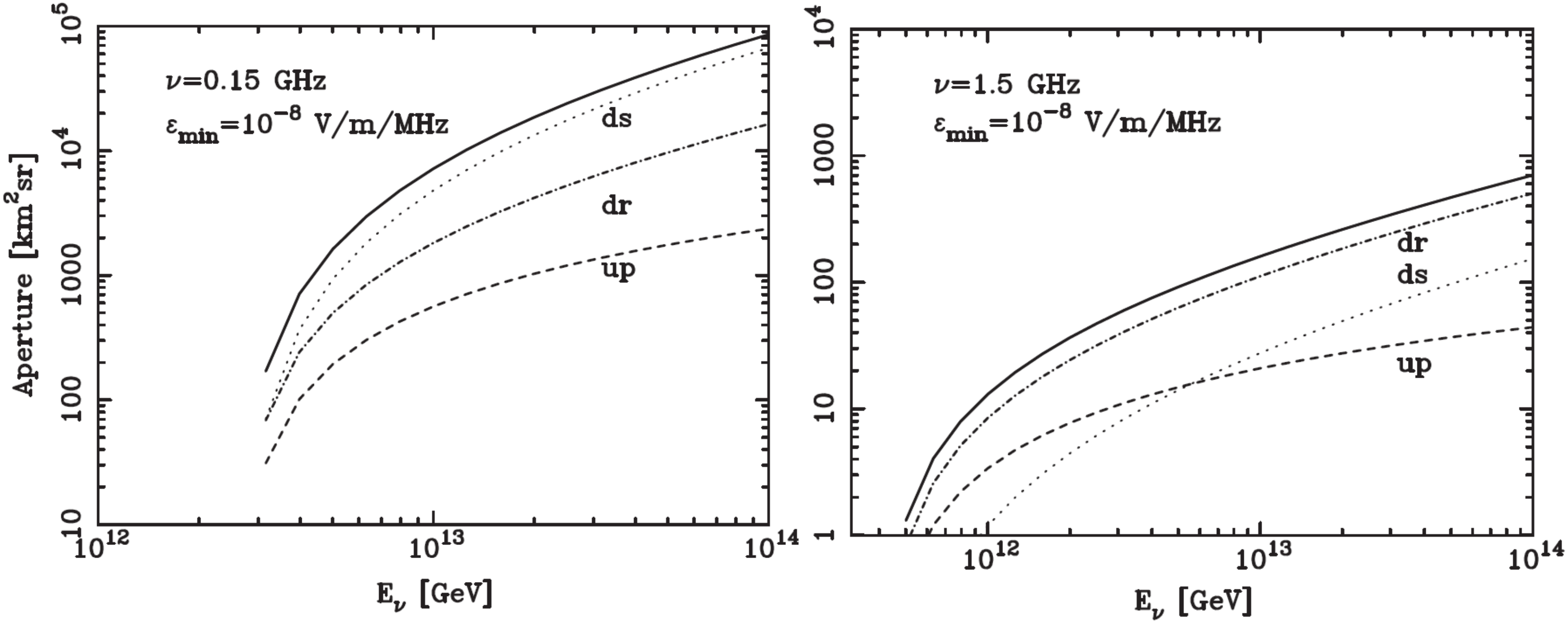
Effective aperture for neutrinos



Width of Cherenkov cone is wider for lower frequencies

→ At low frequency – more smooth contributions.

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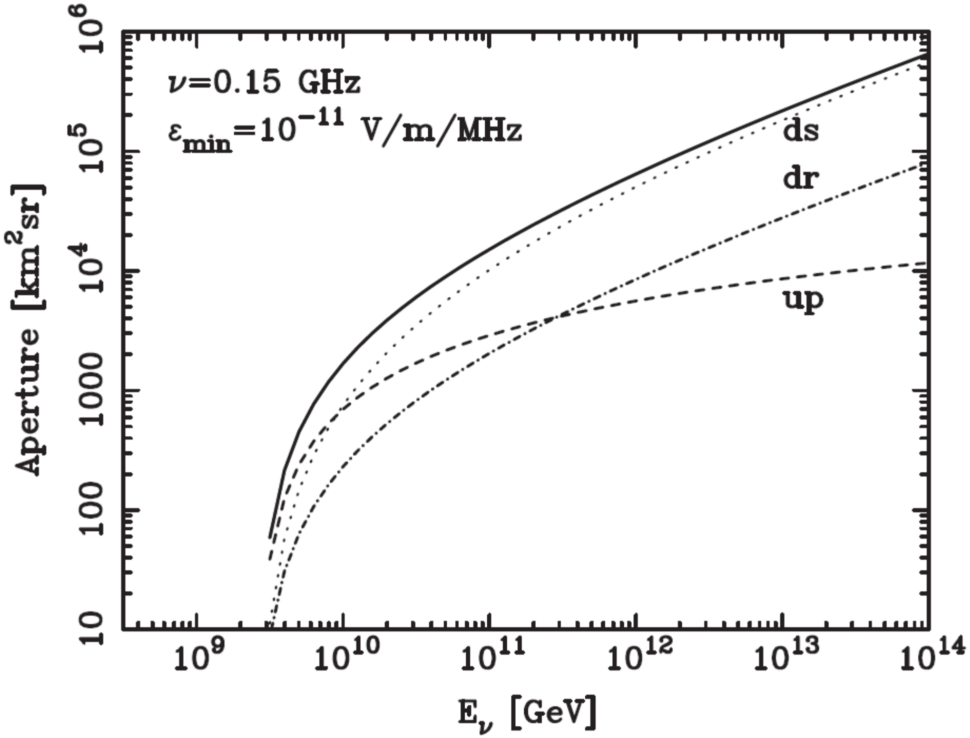
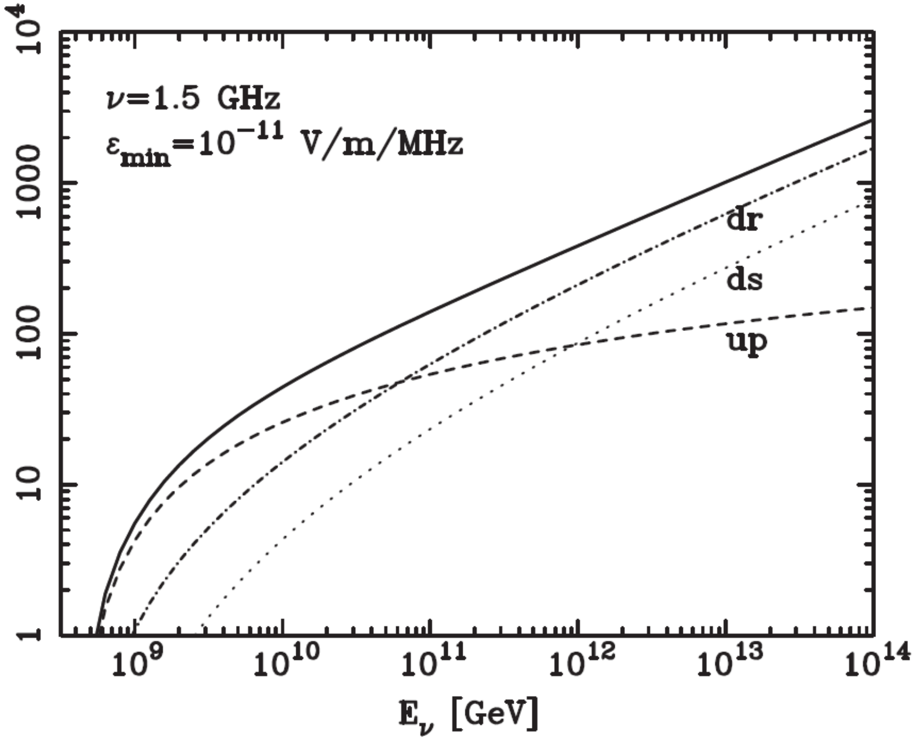
Effective aperture for neutrinos





Lower minimum detectable electric field reduces the minimum energy of neutrinos.

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Cosmic ray signals

- ➢ Interaction length of cosmic rays is short.
- ➢ There is attenuation effect for the downward particles.
- ➢ There is no contribution from the upward particles.

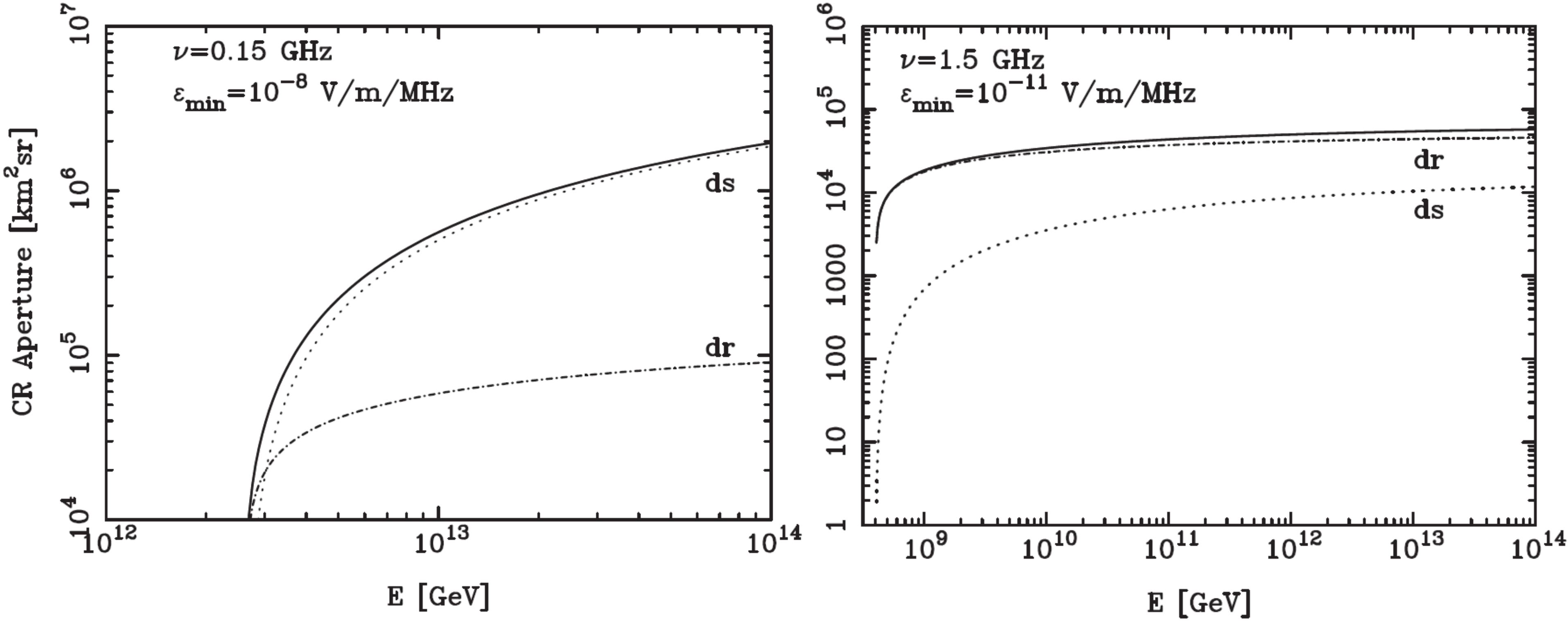
- The effective aperture for cosmic rays

$$A_{CR}(E) = A_{ds} + A_{dr} = A_0 P_{CR}(E)$$

$$P_{CR}(E) = \frac{\sqrt{n_r^2 - 1}}{8} f_0 \Delta_0 \left(\frac{2}{3} f_0^2 \Delta_0^2 + \frac{1}{2} \sigma_0 \right)$$

➢ The effective aperture and event rate for cosmic rays are independent of the cross section.

Effective aperture for cosmic rays



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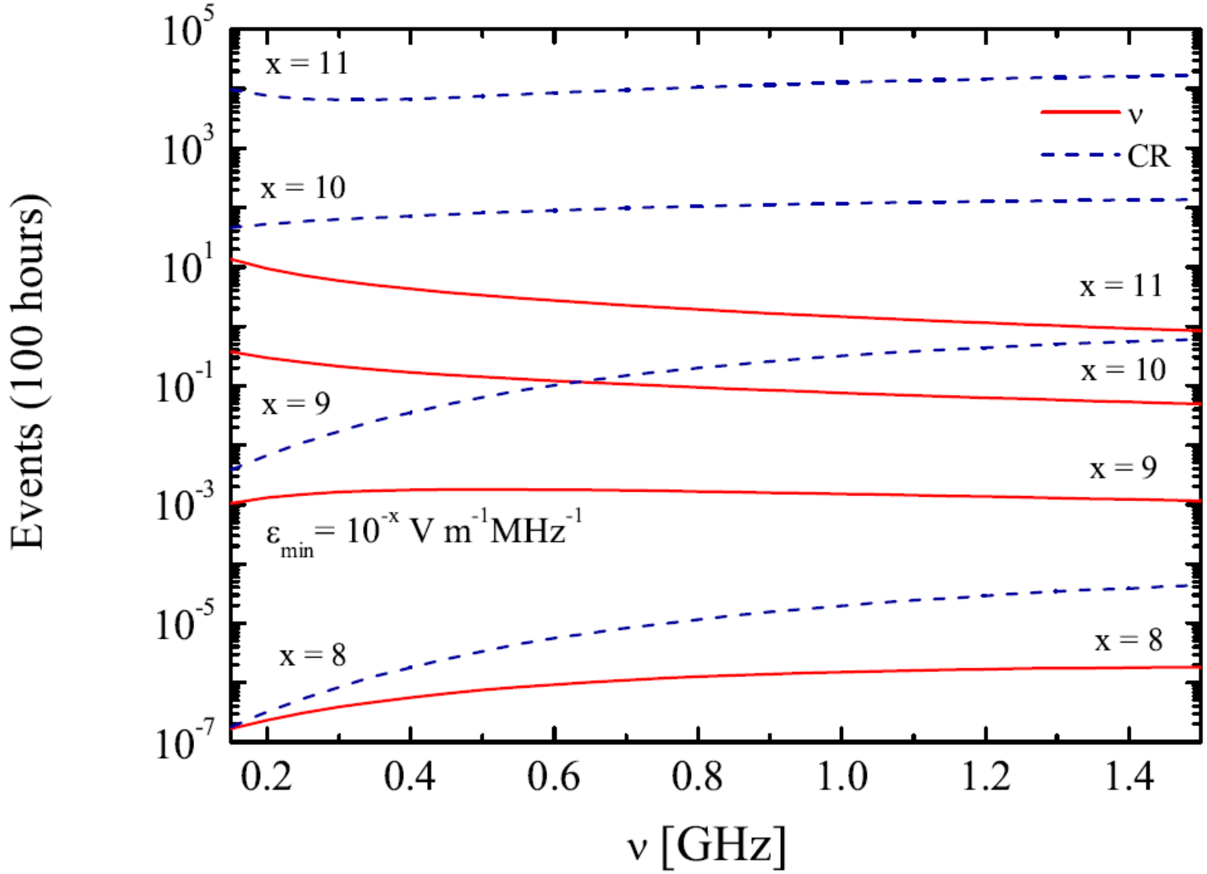
Events of Cosmic Rays and Neutrinos



The Cosmic ray events exceeds the neutrino events.
→ NOT possible to detect the neutrino signal in the SM.

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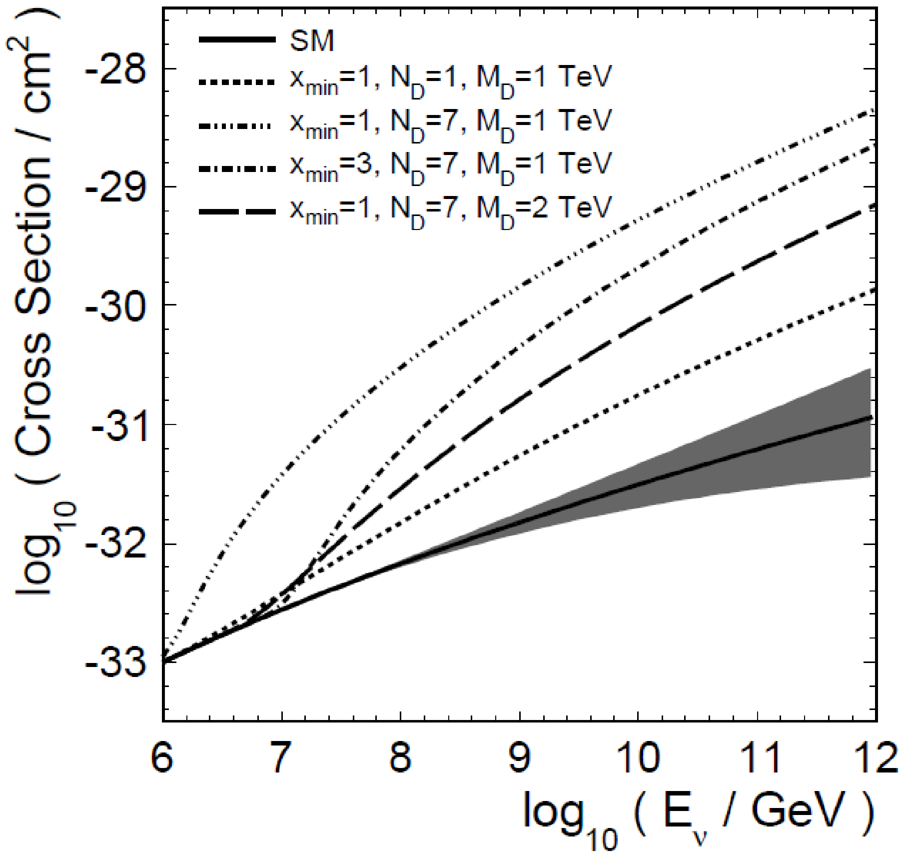
How to obtain the higher neutrino events

- To increase the neutrino cross section
- To increase the neutrino flux

Neutrino Cross Section for mini-Black Hole



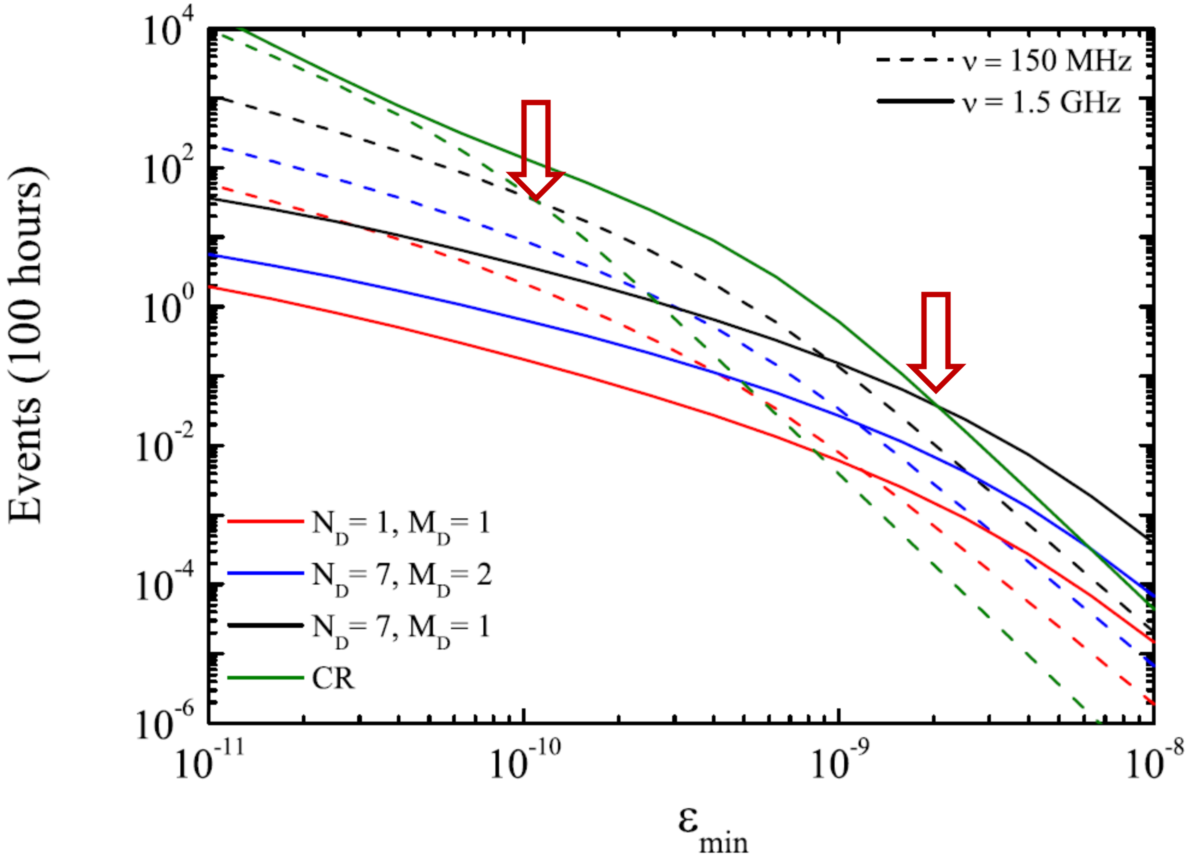
$$\hat{\sigma}^{BH}(\nu i \to \mathrm{BH}) = \pi r_s^2(\sqrt{\hat{s}})$$

$$r_s = \frac{1}{M_D}\left[\frac{M_{\mathrm{BH}}}{M_D}\left(\frac{2^n \pi^{\frac{n-3}{2}}\Gamma(\frac{3+n}{2})}{2+n}\right)\right]^{\frac{1}{1+n}}$$

$$\sigma(\nu N \to \mathrm{BH}) = \sum_i \int_{(M_{\mathrm{BH}}^{\mathrm{min}})^2/s}^{1} dx\ \hat{\sigma}_i^{\mathrm{BH}}(xs) f_i(x, Q^2) \qquad M_{\mathrm{BH}}^{\mathrm{min}} = x_{\mathrm{min}} M_D$$

A. Connolly et al. Phys. Rev. D. 83. 113009 (2011)

Events with the cross sections for mini-Black Hole production



For ν = 150 MHz,
at $\varepsilon_{min} \sim 10^{-10}$ V m^{-1} MHz^{-1},
$N_{CR} < N_{\nu}(\sigma^{\text{non-SM}})$.

For ν = 1.5 GHz,
at $\varepsilon_{min} \sim 10^{-9}$ V m^{-1} MHz^{-1},
$N_{CR} < N_{\nu}(\sigma^{\text{non-SM}})$.

Electric field threshold is too low for current capability.

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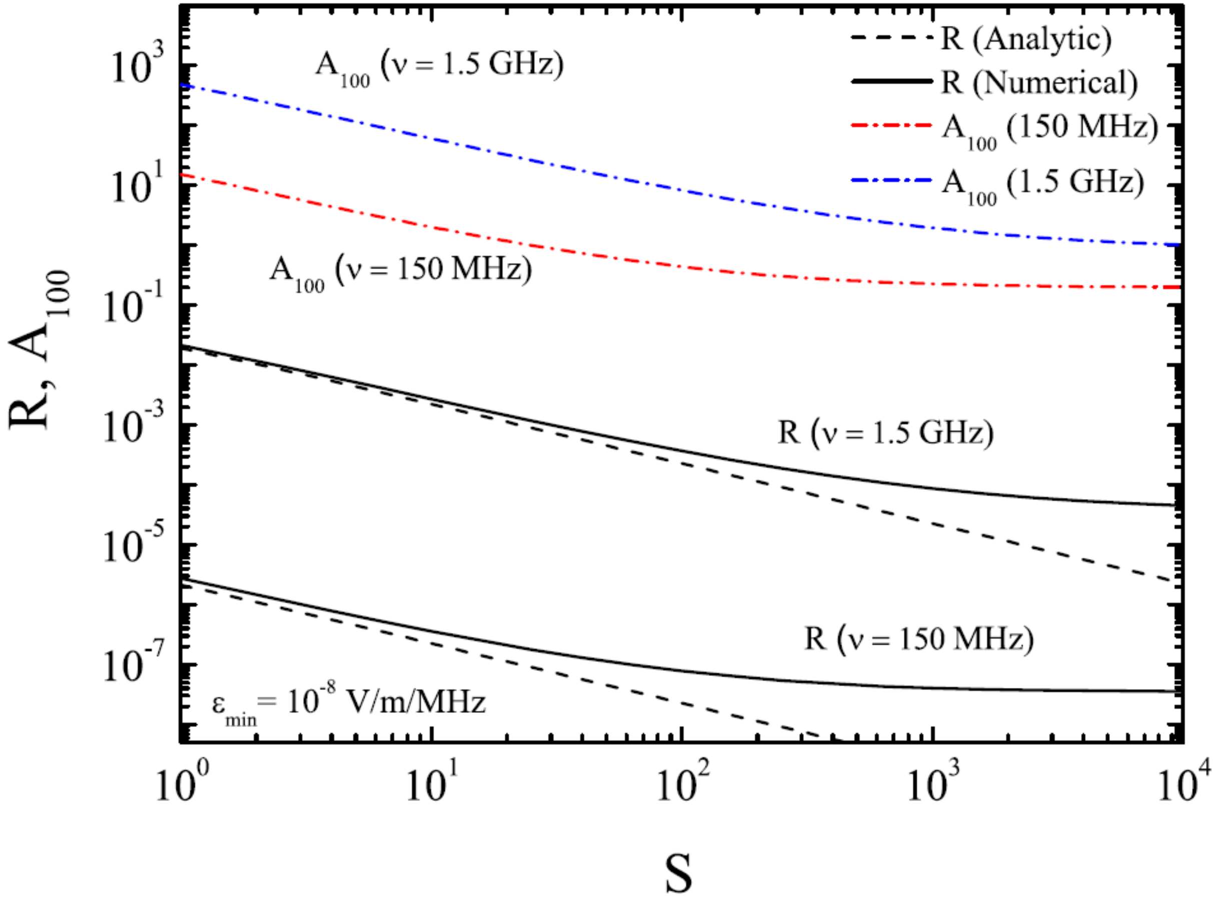
Astrophysical neutrinos



$$A_{100}$$

Minimum A to produce one neutrino event in 100 hr.

$$R = \Gamma_{CR}/\Gamma_\nu$$

$$(A = 1)$$

$$S = \sigma_{\nu N}/\sigma_{\nu N}^{SM} \qquad E^2 \Phi_\nu(E_\nu) = A \times 10^{-8}\ \mathrm{GeV/cm^2/s/sr}$$

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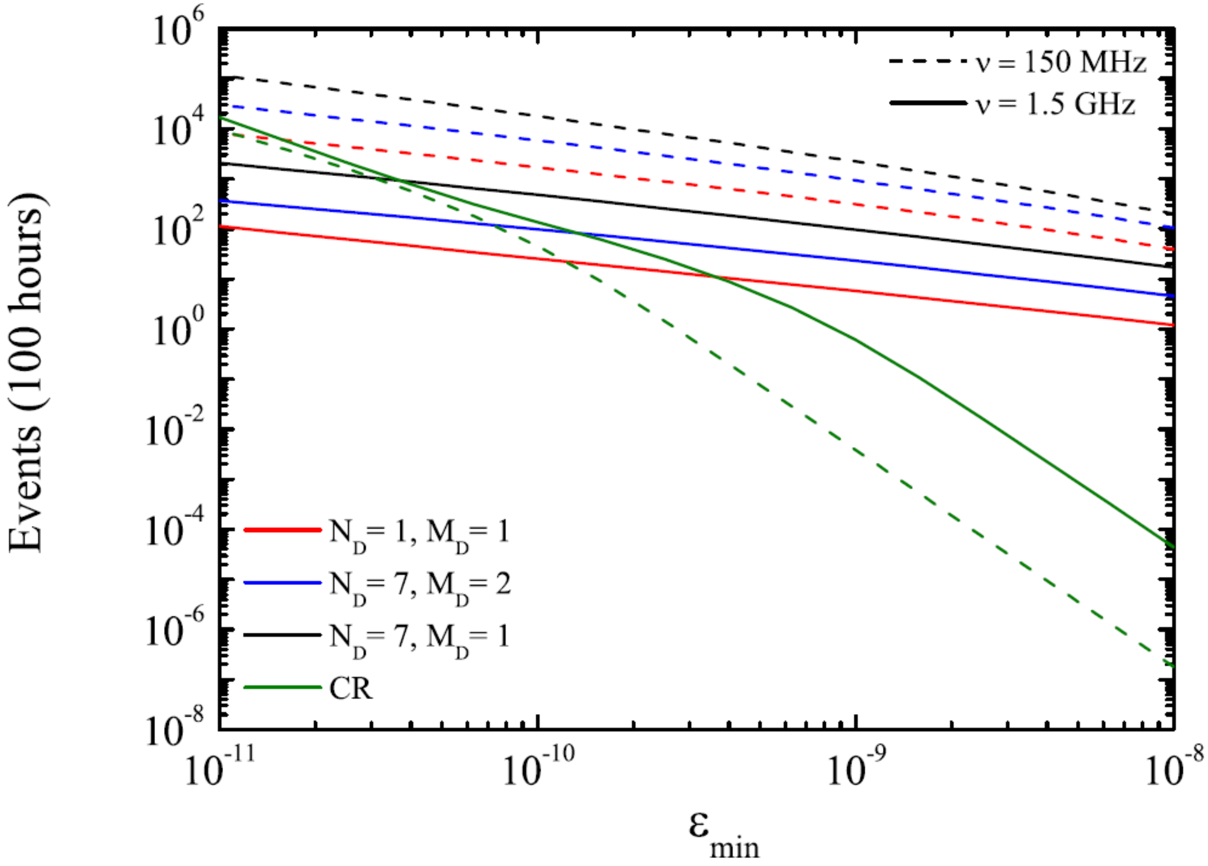
Conclusion

- Cosmic ray signals are independent of the cross section.
- In the standard model, the cosmic ray signals overwhelm the cosmogenic neutrino signals.
- With the enhanced cross sections (in the non-standard model), neutrinos can be detected. But the detection threshold is currently not attainable.
- Both enhanced neutrino fluxes and enhanced cross sections could make the neutrino signals observable.

Extra

Astrophysical neutrinos



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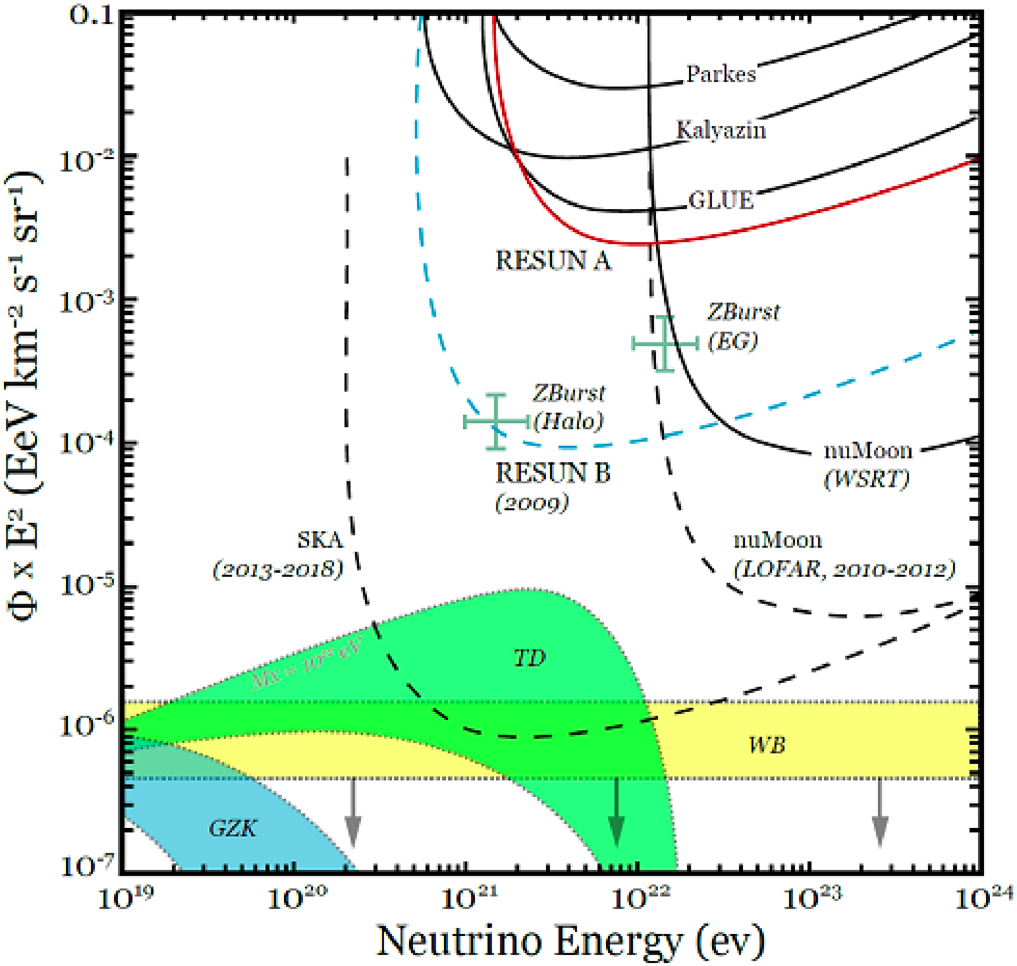
Limits



Parkes
Kalyazin
GLUE
RESUN A
ZBurst (EG)
ZBurst (Halo)
RESUN B (2009)
nuMoon (WSRT)
SKA (2013-2018)
nuMoon (LOFAR, 2010-2012)
$Mx = 10^{28}$ eV
TD
WB
GZK
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{19}
10^{20}
10^{21}
10^{22}
10^{23}
10^{24}
Neutrino Energy (ev)
$\Phi \times E^2$ (EeV km^{-2} s^{-1} sr^{-1})