Skimming tau neutrinos and optical Cherenkov signals

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Work supported in part by the US DOE and NASA.

Multimessenger astrophysics

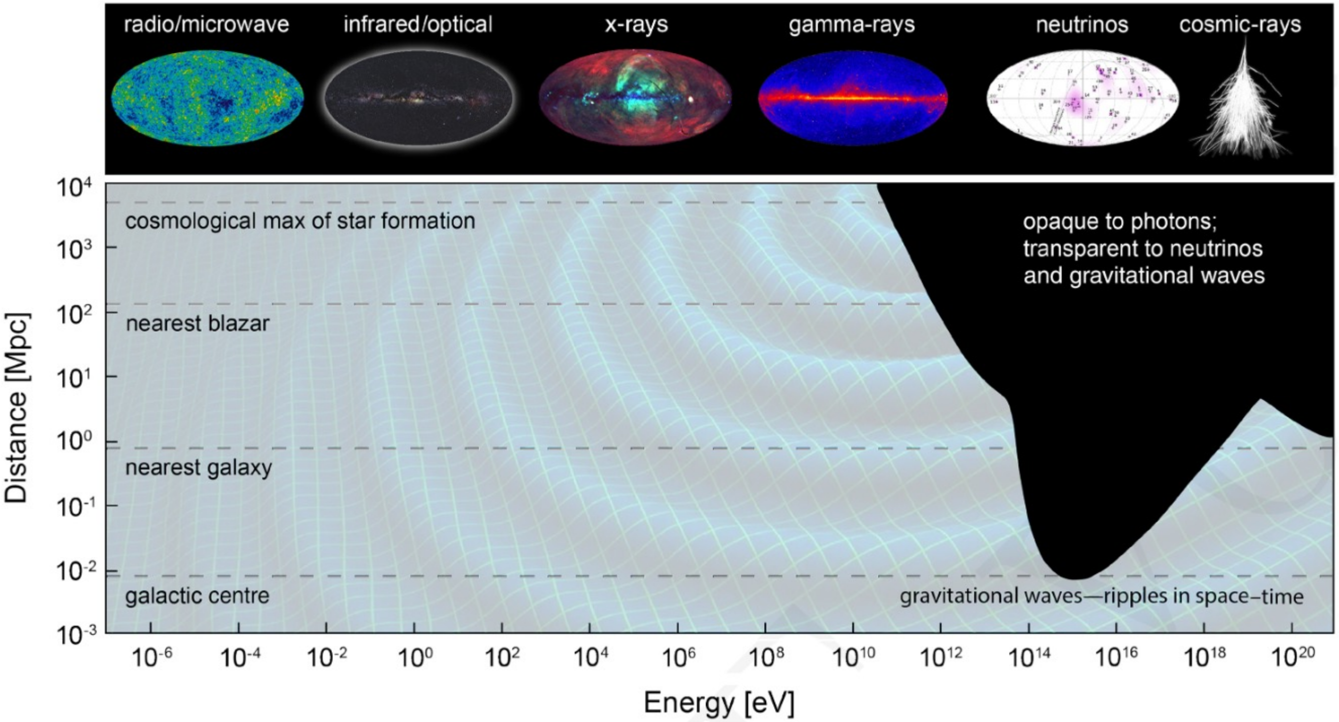
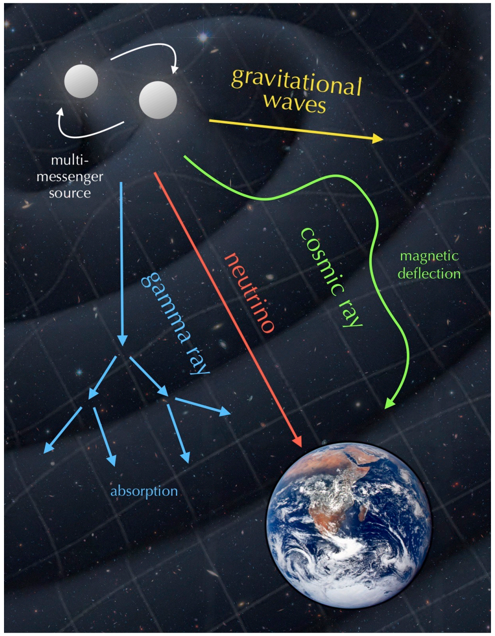
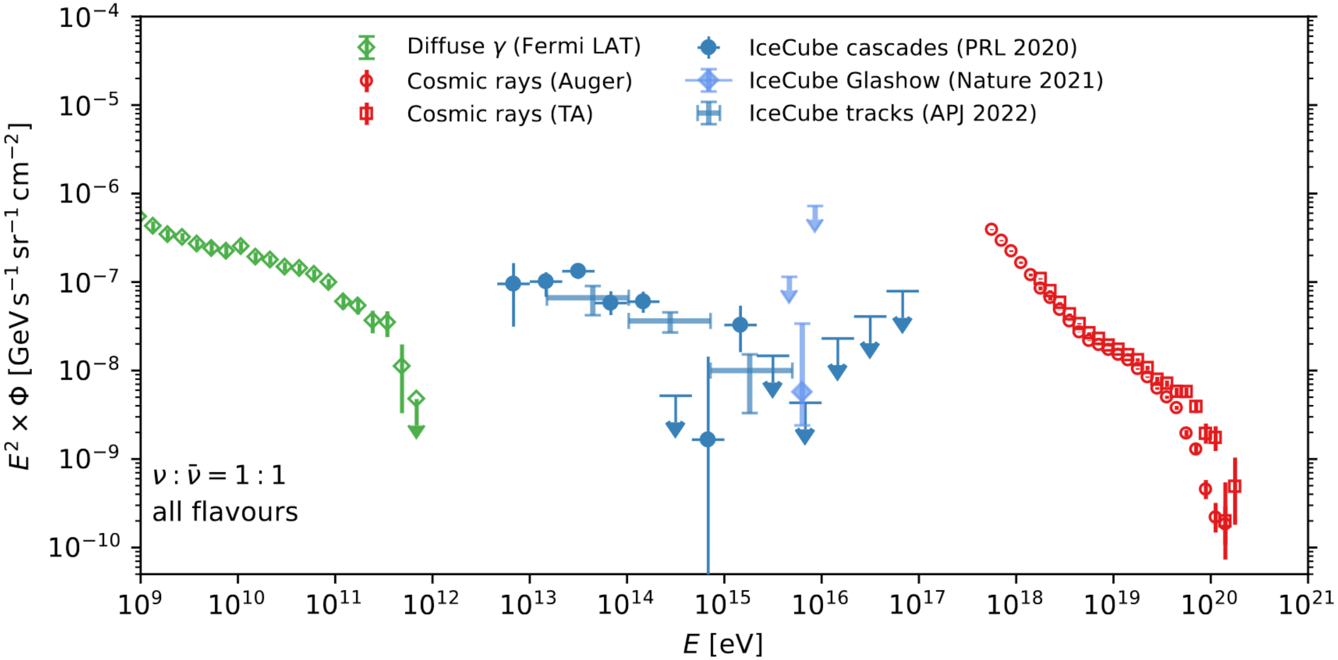


Fig. from Bartos and Kowalski, IOP 2017

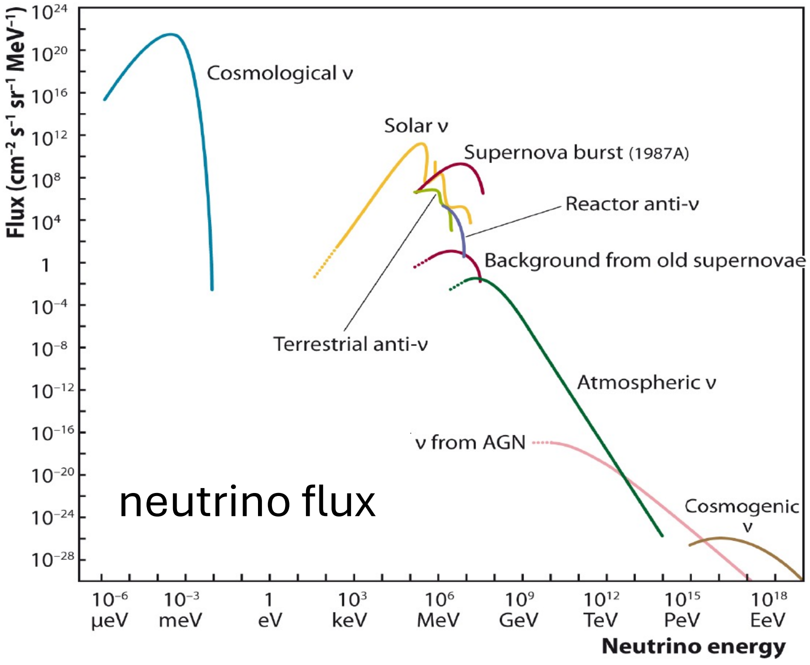
Interesting messengers of astrophysical processes



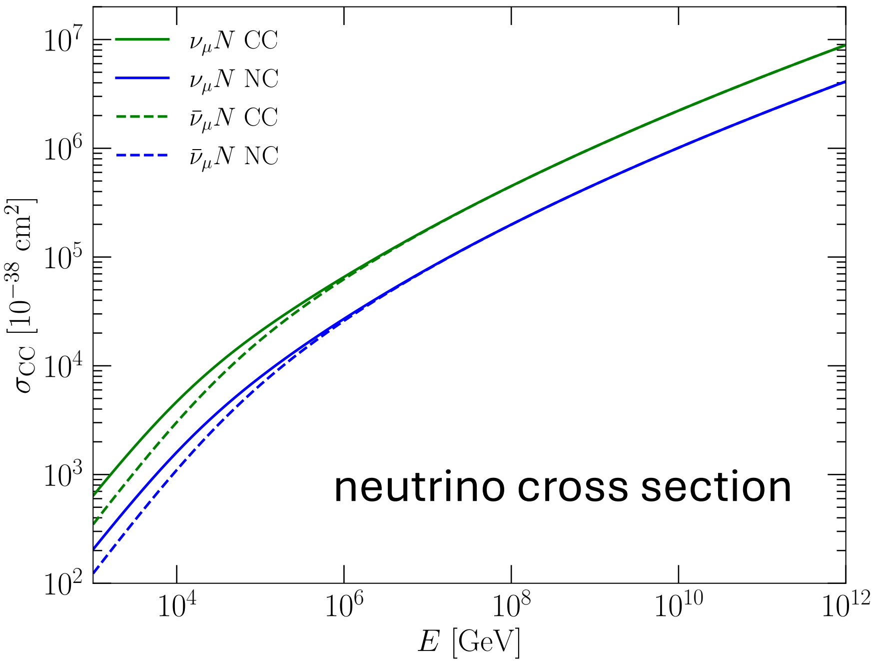


Snowmass white paper: Ackermann et al., JHEAp 36 (2022) 55-110 https://arxiv.org/pdf/2203.08096

My interest: very- (ultra-) high energy neutrinos which require large target volumes



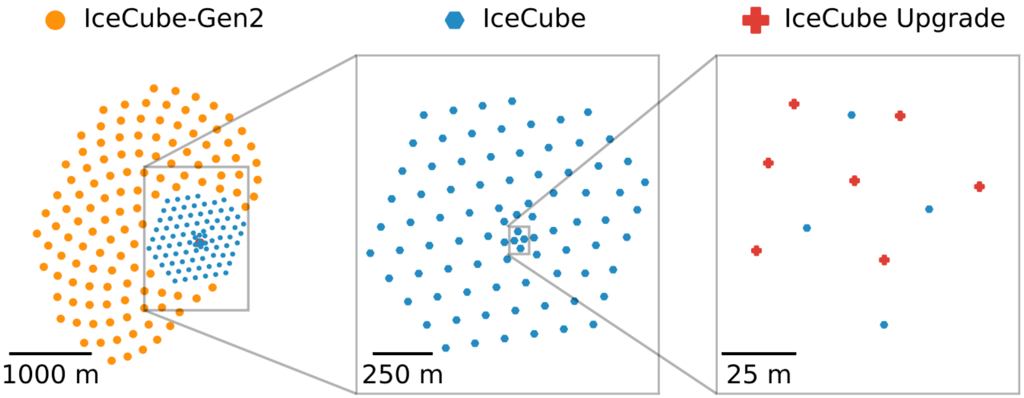
neutrino flux



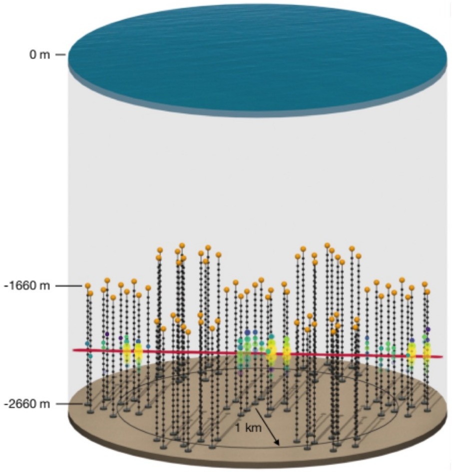
neutrino cross section

Water and ice Cherenkov detectors

IceCube optical arrays



P-one



- KM3-net: ORCA 1-100 GeV, ARCA 100-10^8 GeV, to 1 km^3
- Baikal-GVD staged instrumentation since 2016, 1 km^3 by 2025
- IceCube-Gen2 TBD

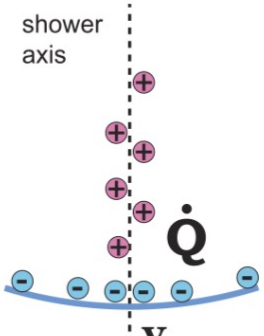
pathfinders in 2018, 2020
northern hemisphere

Figs. from Ackermann et al., JHEAp 36 (2022) 55

Terrestrial detectors

Radio Cherenkov – Askaryan effect

Fig from Paudel et al., PoS ICRC2021 (2021) 429



See review: Barwick & Glaser, arXiv:2208.04971

- Askaryan effect (JETP 14, 1962), in which interactions in material produce a 20% electron excess (time-varying).
- Showers produce electron-positron pairs and also scatter with atomic electrons to produce a radio-frequency impulse.
- The **attenuation length at radio frequencies** is of order **2 km** in South Pole ice – can increase detection volume at low cost! (Scattering & absorption of **optical light** is **~100 m**, optical sensitive to air bubbles in ice.)
- May be able to distinguish electron neutrinos and antineutrinos.

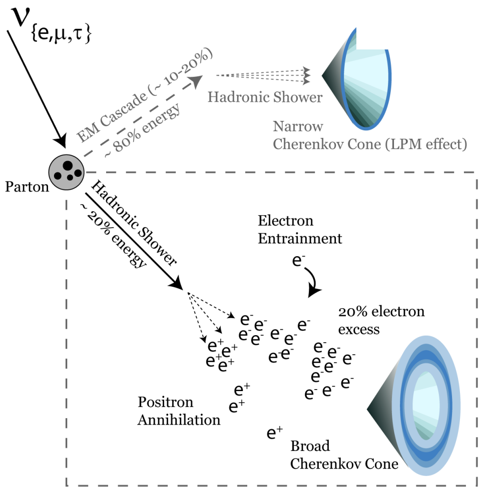


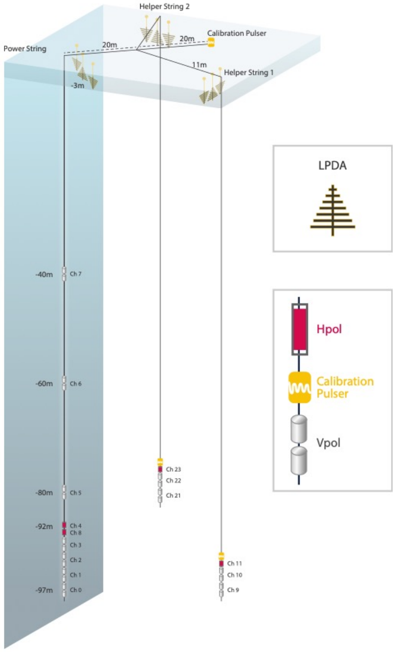
Figure from T. Jaeger, PhD thesis 2010

Terrestrial detectors

Radio Cherenkov Detectors

- RNO-G in Greenland ice, 1 km attenuation length, detector station separation1.5 km.
- Phased array of radio antennas.
- Testbed for IceCube-Gen2 Radio.

IceCube-Gen2 Radio will cover 500 km^2 of South Pole ice.
Also, Askaryan from Moon!



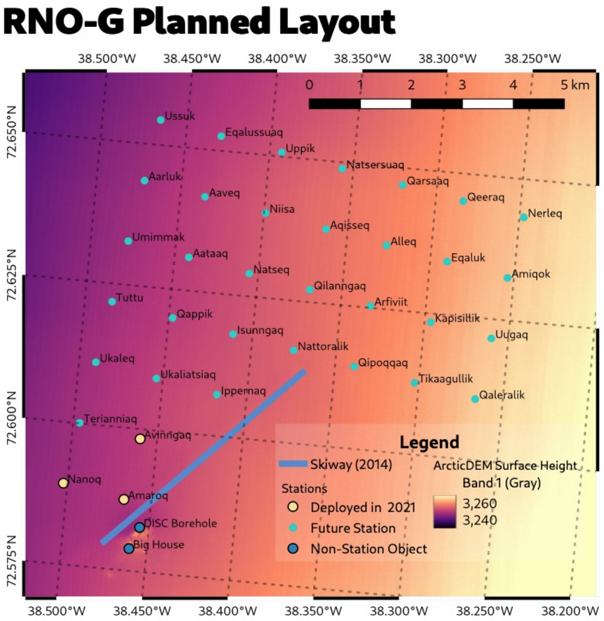


Fig. from Ackermann et al., JHEAp 36 (2022) 55

Focus here: large detection areas with atmospheric optical Cherenkov

- Overview of the process for atmospheric optical Cherenkov detection with skimming tau neutrinos.
- Detectors/telescopes. (Some actual, one hypothetical.)
- Geometry
- Neutrino & tau propagation
- Diffuse flux sensitivities
- Transient neutrino source sensitivities (most competitive here)
- Theoretical uncertainties in neutrino & tau propagation

Earth-skimming ν_τ for optical Cherenkov signals

Fig: Arguelles et al, PRD 106 (2022) 043008

- Use the Earth as a ν_τ converter. Neutrino oscillations over astronomical distances yield $\nu_e : \nu_\mu : \nu_\tau \simeq 1:1:1$.
- Tau neutrinos can produce taus that emerge from the Earth.
- Taus decay in the atmosphere – high energy hadrons produce up-going air showers.
- Air showers generate optical Cherenkov light.

e.g., $\nu_\tau N \rightarrow \tau X$

$\tau \rightarrow \nu_\tau \pi$

Optical Cherenkov in the atmosphere

Index of refraction of air $n_{air} \neq 1, \Delta n = 2.9 \times 10^{-4}$ at sea level

Energy thresholds in air:
electron: 20.75 MeV
muon: 4.4 GeV
pion: 5.6 GeV
kaon: 20.5 GeV
proton: 39 GeV

Cherenkov angle: 1.4 deg

Index of refraction of air $n_{water} = 1.33$

Energy thresholds in water:
electron: 0.75 MeV
muon: 159 MeV
pion: 204 MeV
kaon: 746 MeV
proton: 1.4 GeV

Cherenkov angle: 41.4 deg

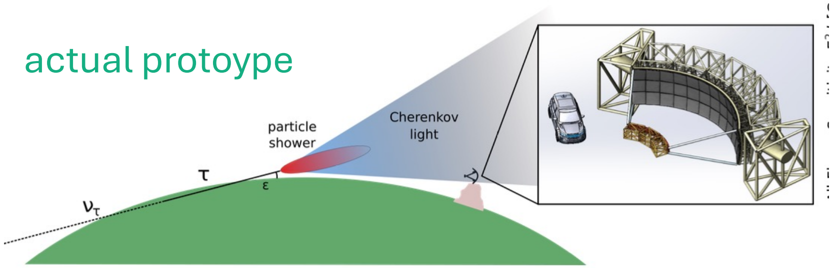
Sub-orbital/orbital detectors (and terrestrial)

Atmospheric optical Cherenkov detection

Fig. from Ackermann et al., JHEAp 36 (2022) 55

Trinity: on a mountain top

actual protoype

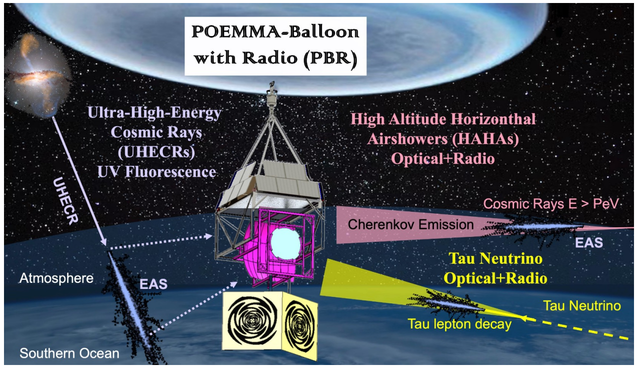


EUSO-SPB2

very short flight

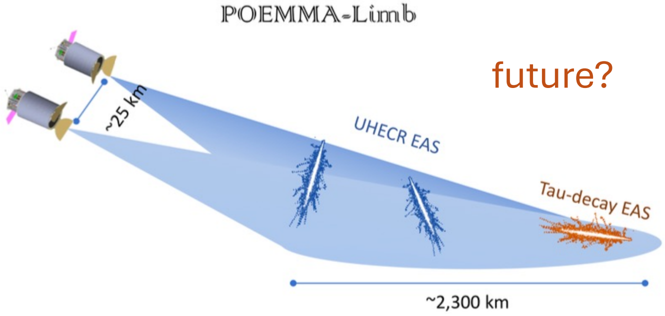
NASA APRA/Italian/France funding

PBR



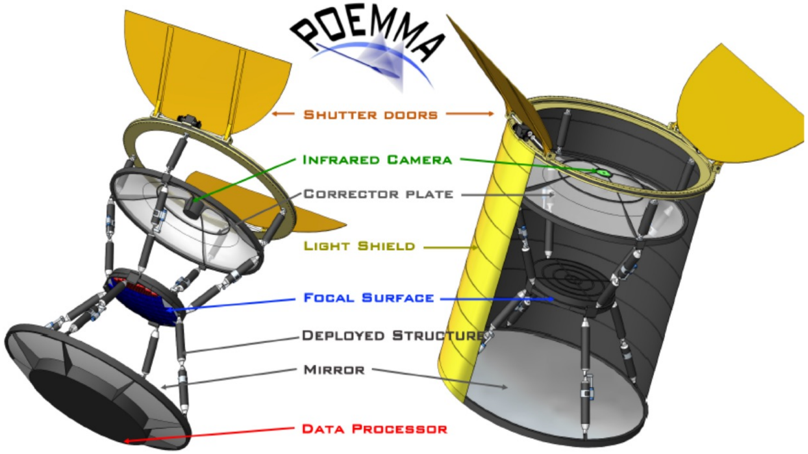
POEMMA: twin satellite

future?



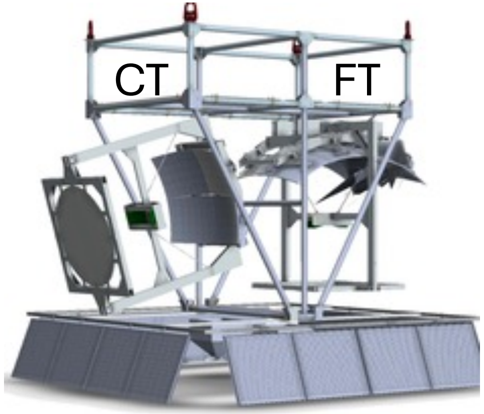
Optical Cherenkov (plus fluorescence) telescopes

POEMMA satellite, future



- Hybrid focal surface: Cherenkov and fluorescence.
- Pair of satellites.
- 525 km altitude for 5 years.
- Limb viewing mode for neutrino-induced air showers.
- A = 2.5 m^2 photon collecting area for Cherenkov.

EUSO-SPB2 balloon launched May 2023



- Launched from Wanaka, NZ.
- Potential for 100 days at 33 km altitude, actual: 2 days.
- Search for neutrino events and measure optical backgrounds.
- A = 0.35 m^2 photon collecting area.

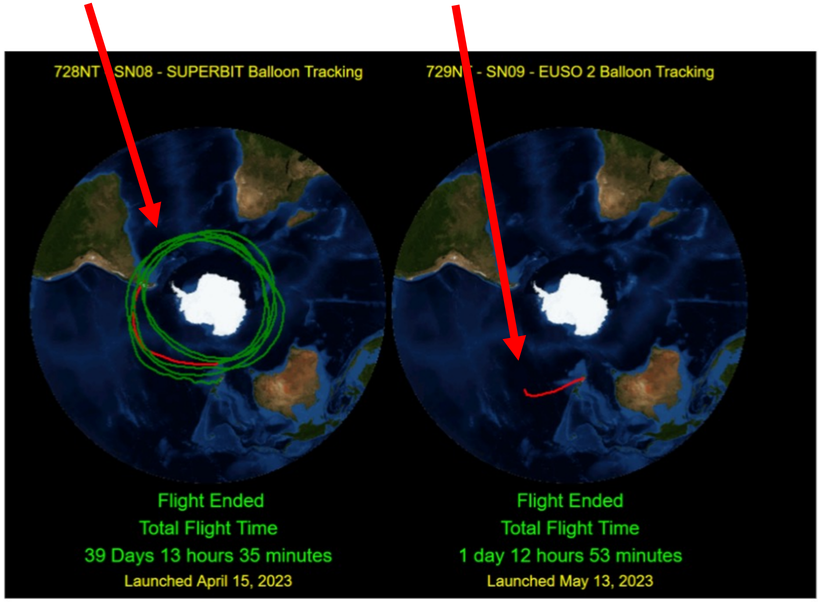
EUSO-SPB2 actual

at float, size of football field

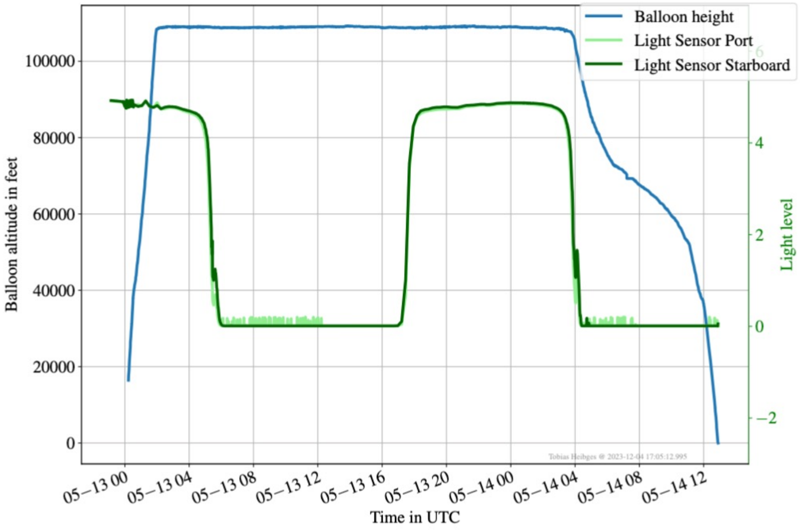
stratcat.com.ar

potential

actual



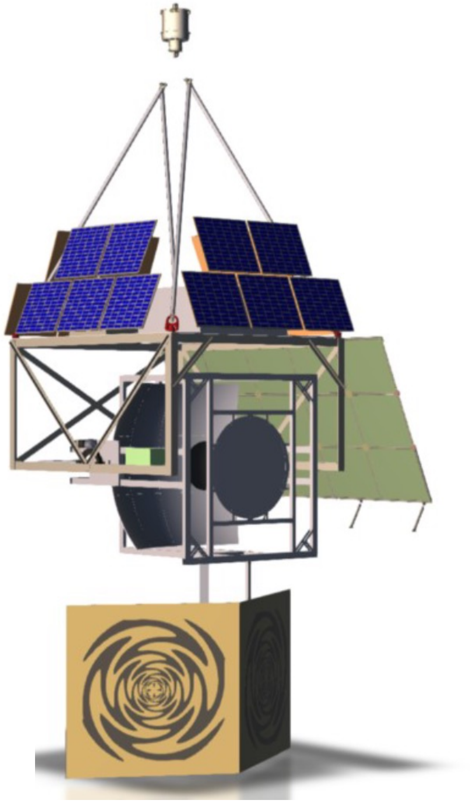
Figs: Adams, Jr. et al, in preparation



Optical Cherenkov (plus fluorescence) telescopes

POEMMA Balloon with Radio (PBR), launch in 2027

- Hybrid focal surface: Cherenkov and fluorescence, will advance technical readiness for POEMMA
- Launch from Wanaka, NZ in spring 2027.
- Potential for 100 days at 33 km altitude.
- Search for neutrino events and measure optical backgrounds.
- A ~ 0.4 m^2 photon collecting area.
- Additional radio detection 50-550 MHz,~10 PeV shower energy threshold, to detect radio and optical emission of the same shower.



Radio emission from geomagnetic effects:

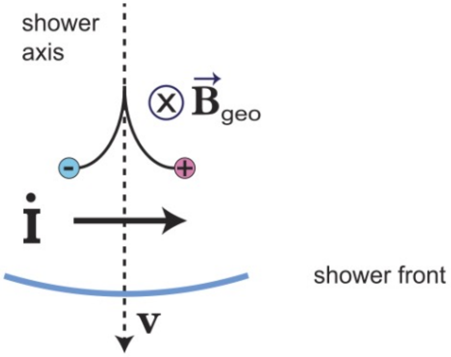


Fig: Paudel et al., PoS ICRC2021 (2021) 429
https://arxiv.org/pdf/2108.06336

Earth-skimming ν_τ for optical Cherenkov signals

Fig: Arguelles et al, PRD 106 (2022) 043008

- No signals of high energy tau neutrinos that go straight through the center of the Earth – attenuation of the flux. Hence "skimming."
- Neutrino regeneration in the Earth is important. Lower energy ν_τ comes from every τ decay:

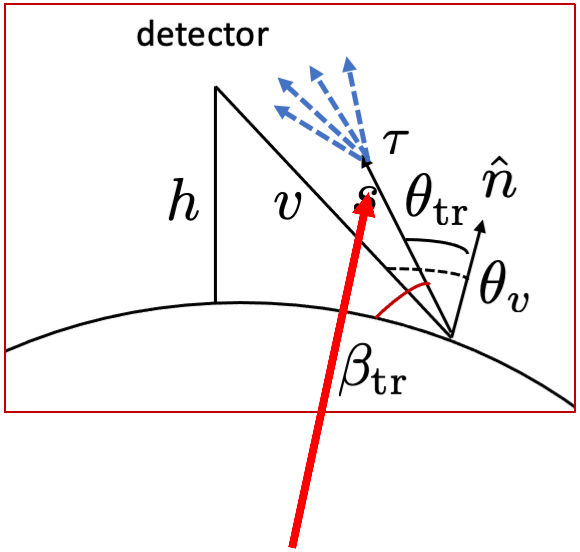
$$\nu_\tau N \to \tau X$$

$$\tau \to \nu_\tau X$$

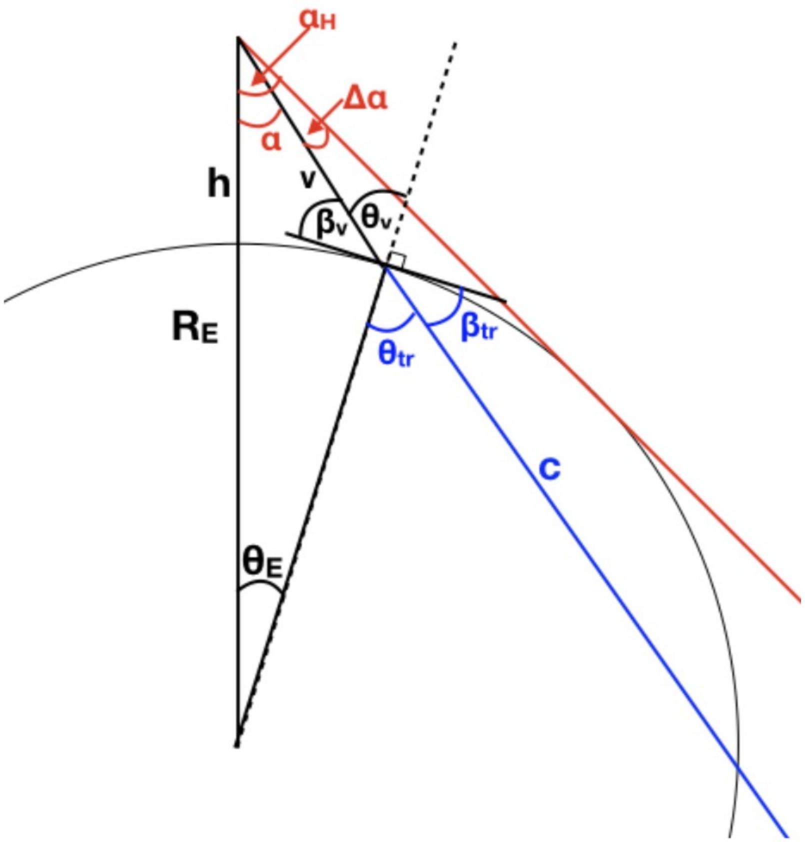
"tau neutrino regeneration" makes the Earth more transparent to tau neutrinos (but not transparent!)

Geometry

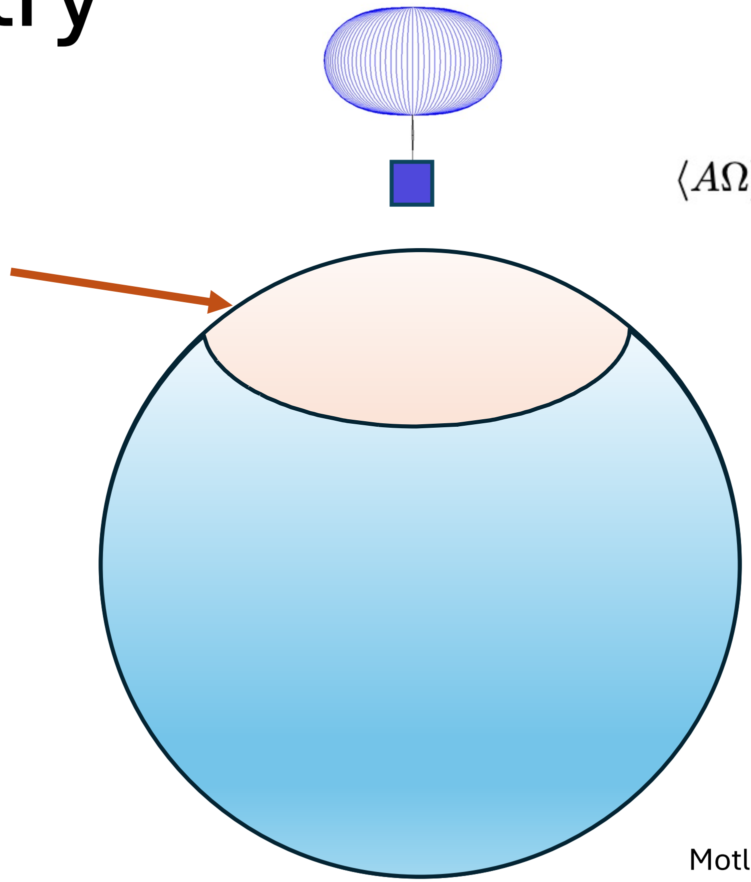
Earth emergence angle $\beta_{tr} = \beta_E$



shower axis



Geometry



“cap”

effective Ch angle θ_d

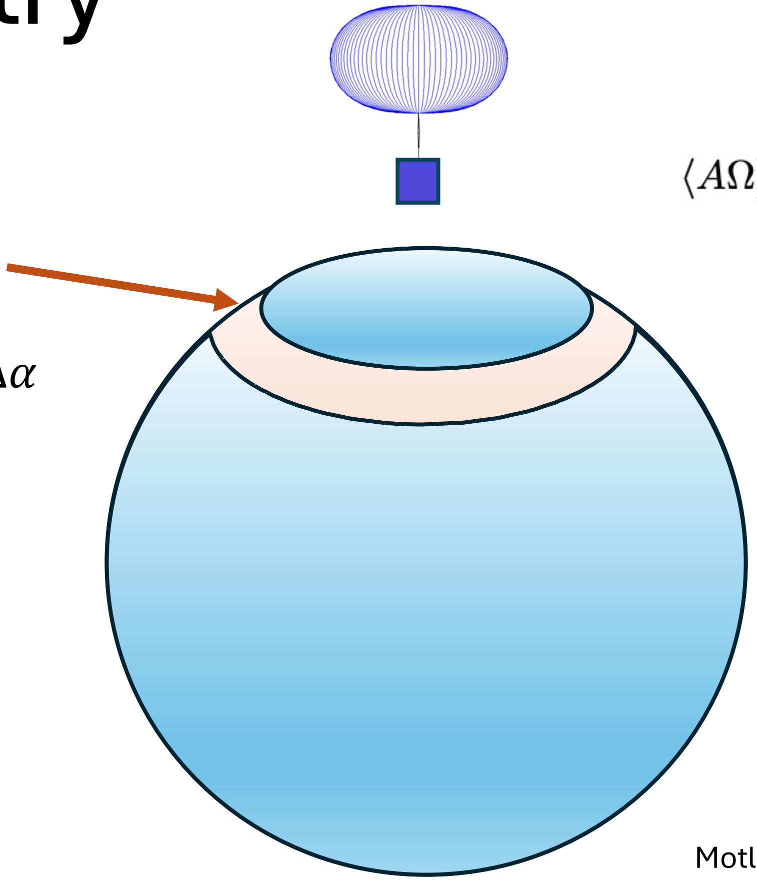
$$G = \int_S \hat{r} \cdot \hat{n}\, dS = \int_S \cos\theta_{\rm tr}\, dS$$

$$\begin{aligned} \langle A\Omega \rangle_{\rm geo} &= \int_S \int_{\Delta\Omega_d} \cos\theta_{\rm tr}\, dS\, d\Omega_{\rm tr} \\ &\simeq \pi \sin^2\theta_d G\ . \end{aligned}$$

- Integrate over surface *S*
- integrate over the shower axis directions that yield photons at the detector.

Motloch, Hollon, Privitera, Astropart. Phys. 54 (2014) 40
MHR et al., PRD 100 (2019) 063010

Geometry



Adjust for “zone”

zenith FoV angle $\Delta\alpha$

$$G = \int_S \hat{r}\cdot\hat{n}\,dS = \int_S \cos\theta_{\rm tr}\,dS$$

$$\langle A\Omega\rangle_{\rm geo} = \int_S \int_{\Delta\Omega_d} \cos\theta_{\rm tr}\,dS\,d\Omega_{\rm tr}$$

$$\simeq \pi\sin^2\theta_d G\ .$$

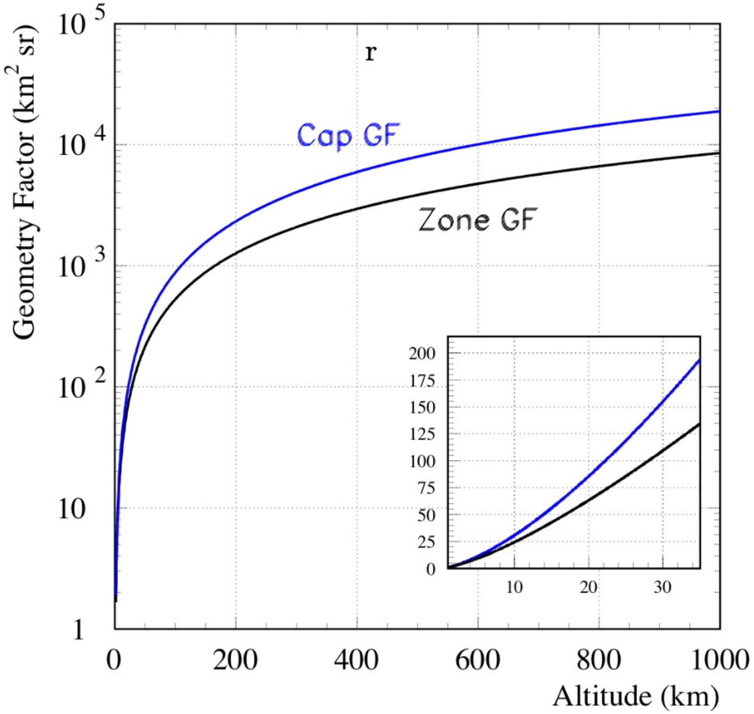
Motloch, Hollon, Privitera, Astropart. Phys. 54 (2014) 40
MHR et al., PRD 100 (2019) 063010

Geometry

Altitude h [km]	Cap [km^2 sr]	Zone [km^2 sr]	Zone/Cap
3	5.2	4.5	0.87
4	7.9	6.8	0.85
33	178	124	0.70
525	8,480	4,072	0.48
1000	18,857	8,538	0.45

$$\theta_d = 1.5^\circ \text{ and } \Delta\alpha = 7^\circ$$

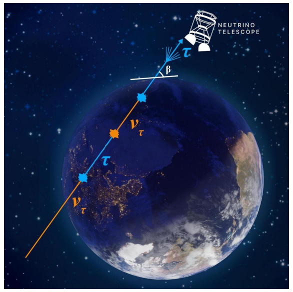
zenith FoV angle $\Delta\alpha$
effective Ch angle θ_d



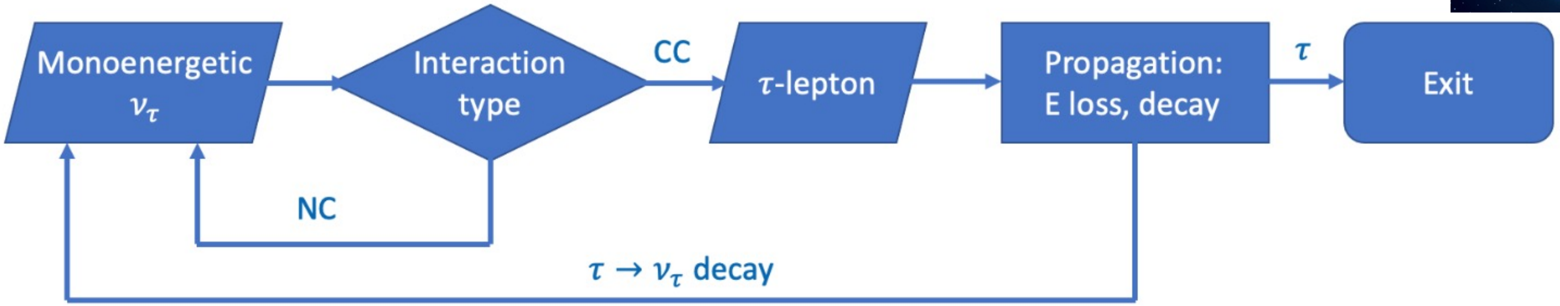
GF = geometry factor

MHR et al., PRD 100 (2019) 063010

Tau neutrino propagation



Garg et al, JCAP 01 (2023) 041



Monoenergetic ν_τ

Interaction type

CC

τ-lepton

Propagation: E loss, decay

τ

Exit

NC

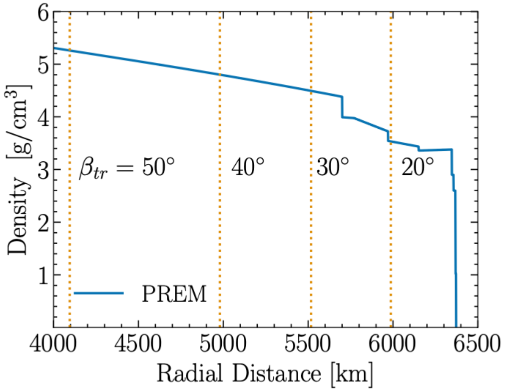
$\tau \rightarrow \nu_\tau$ decay

- Density of Earth model
- Neutrino cross section*
- Tau electromagnetic energy loss*
- Tau decay with neutrino energy distribution
- Repeat

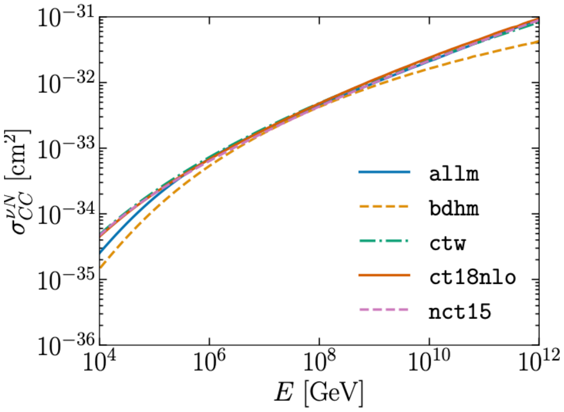
https://github.com/NuSpaceSim/nupyprop part of the NuSpaceSim end-to-end simulation package – neutrinos in, photons at the detector out.
NuPyProp generates look-up tables for NuSpaceSim.

* theory inputs that can be adjusted – high energy extrapolations are used here

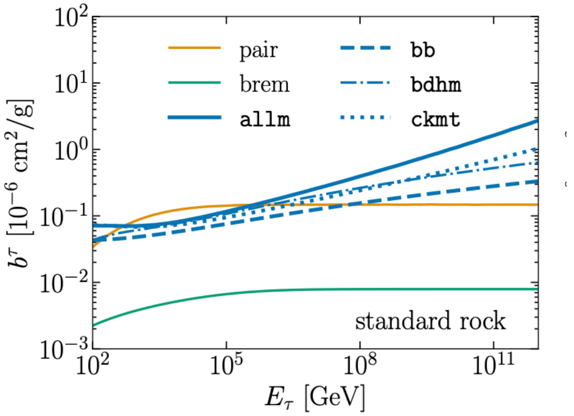
Inputs



Earth density



Cross sections

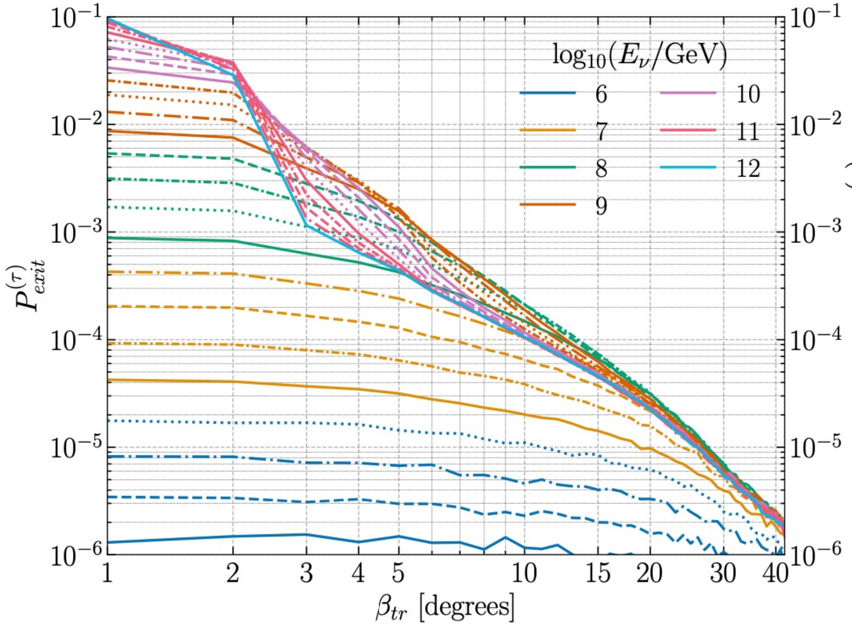

Garg et al, JCAP 01 (2023) 041

EM energy loss of tau

You can put in your own inputs – BSM cross sections?
Useful for both surface (or near surface) and sub-orbital/orbital detectors.

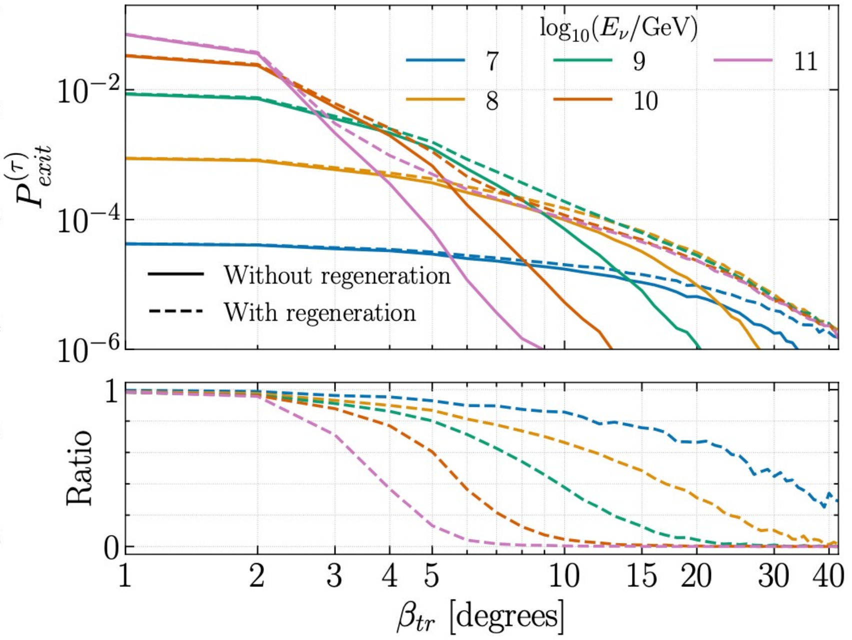
$$-\left\langle \frac{dE}{dX} \right\rangle = a^\ell + \sum_{i=\text{brem,pair,nuc}} b_i^\ell(E)E$$

NuPyProp results for $\nu_\tau \to \tau$



4 km water depth

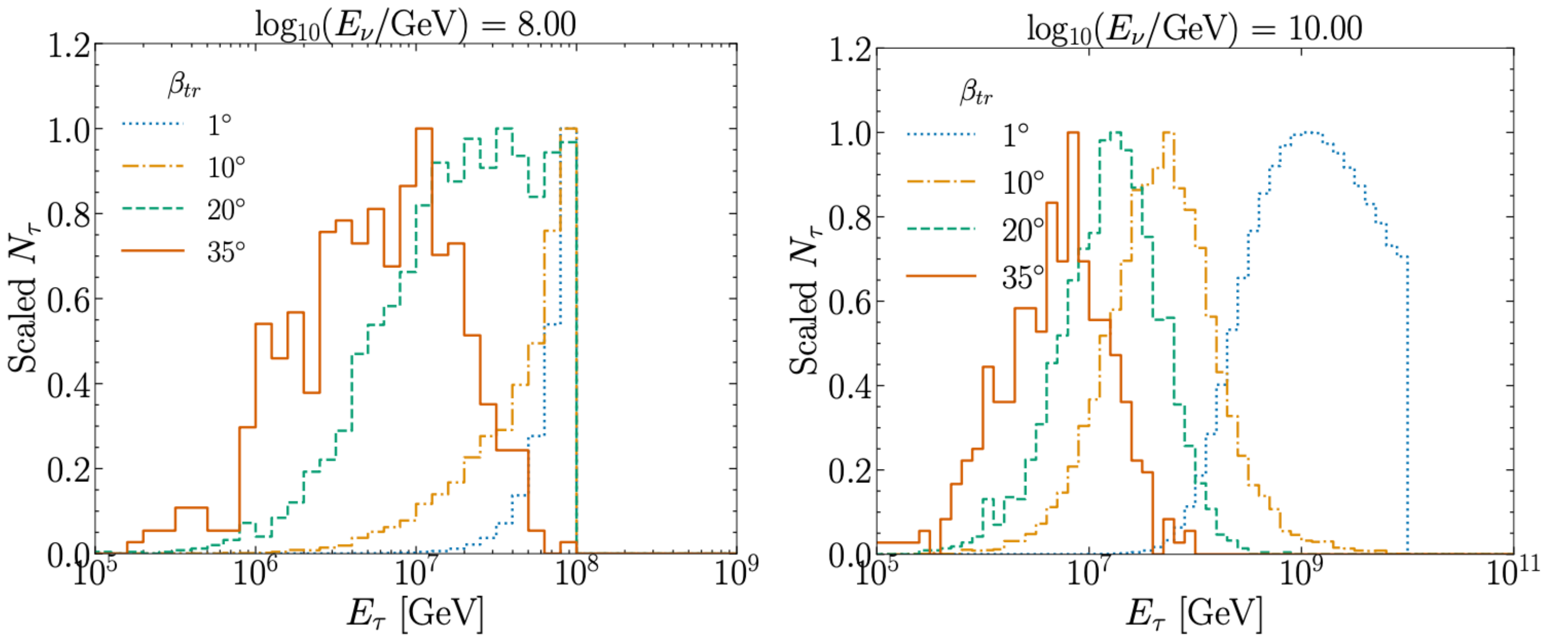
Garg et al, JCAP 01 (2023) 041



regeneration is important for high energy taus, large angles

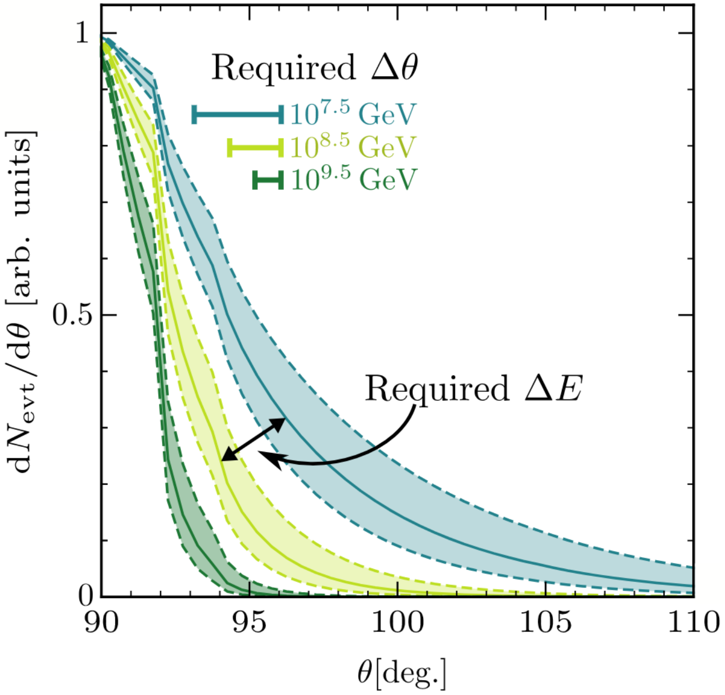
NuPyProp Results

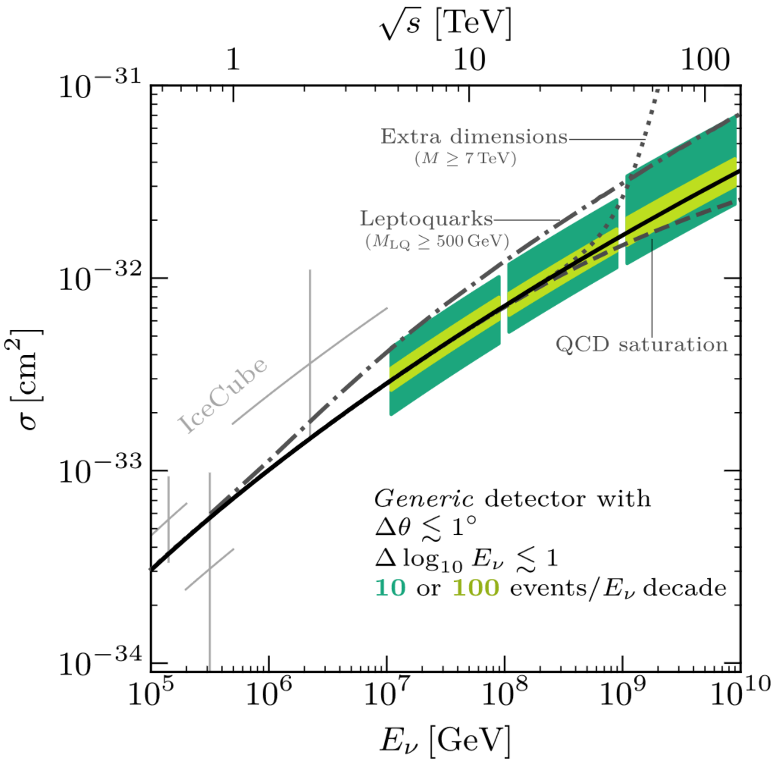
Garg et al, JCAP 01 (2023) 041



regeneration is important for high energies, large angles

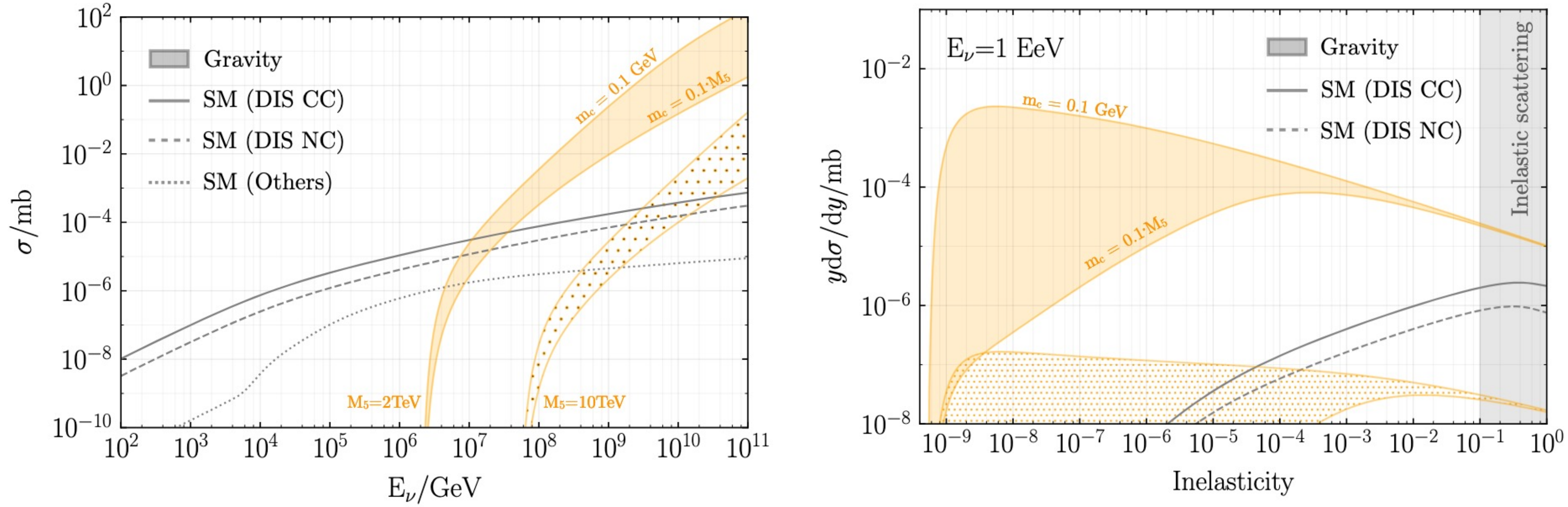
IceCube etc use Earth attenuation for cross section measurements





Esteban, Prohira & Beacom, PRD 106 (2022) 023021

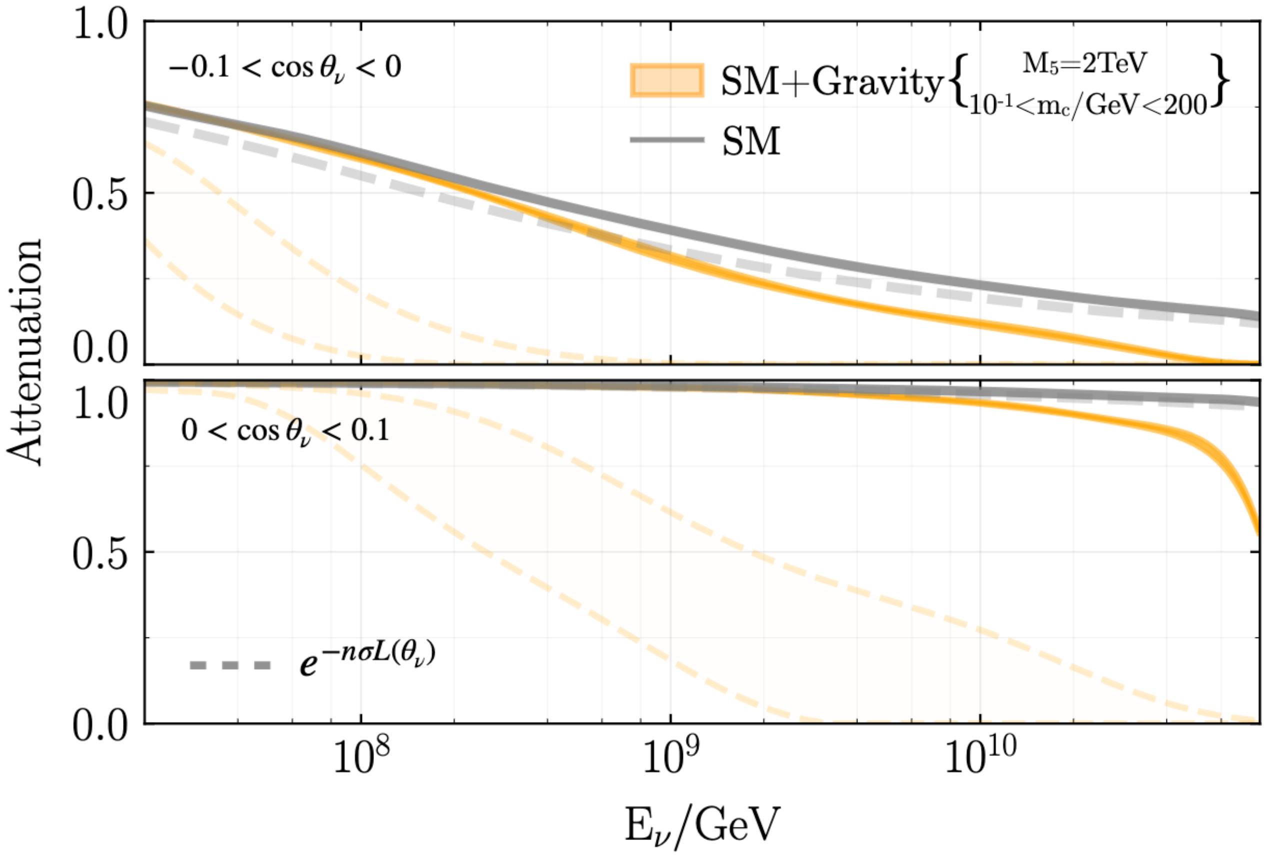
Caution!



Garcia – Soto, Garg, Reno, Arguelles, PRD 107 (2023) 033009

Example with large extra dimension (Randall-Sundrum model of TeV gravity) where the cross section rises steeply, but the neutrino energy loss is non-standard (mostly elastic). M_5 is the scale where gravity becomes strong, m_c is the mass of the first KK excitation.

Attenuation

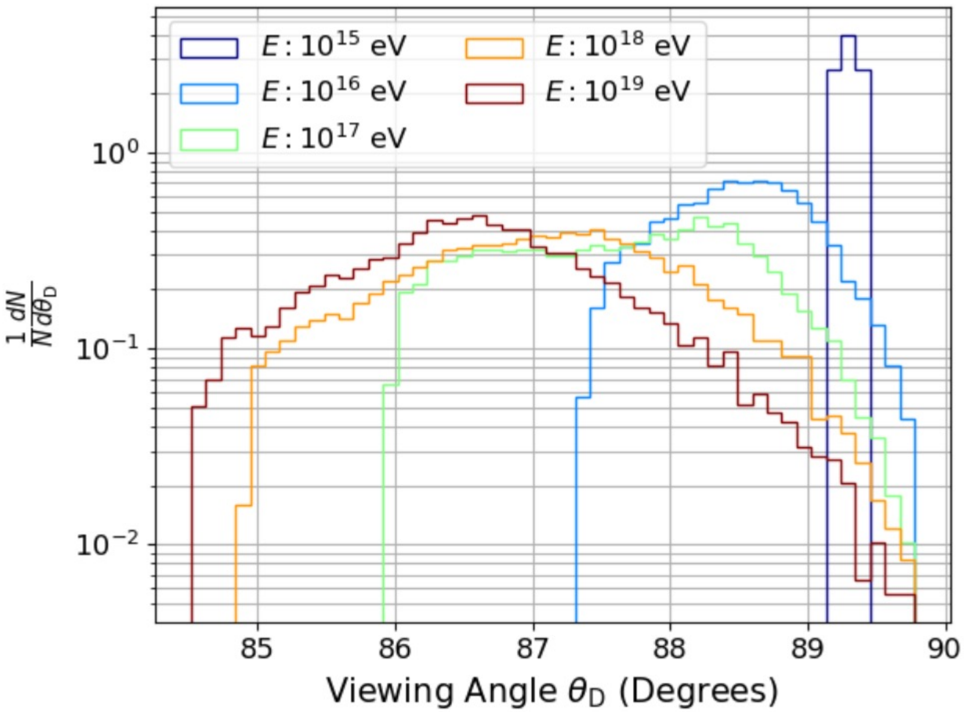


Dashed lines:
bad approximation for attenuation with SM+Gravity.

Even with small inelasticity, SM+Gravity has different signatures in IceCube Gen2, however, neutrino flux uncertainties can make unfolding BSM physics challenging.

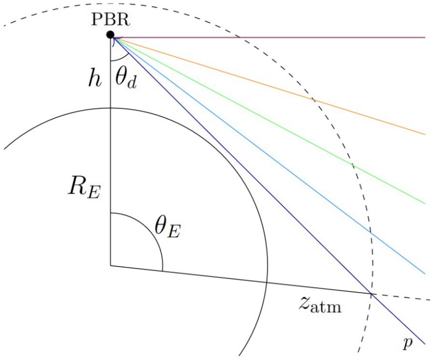
Complementary measurements help with neutrino flux uncertainties.

Aside – nearly horizontal showers from cosmic rays



HAHAs: High-Altitude Horizontal Air Showers

Cummings et al., PRD 104 (2021) 063029



- Geometric energy filter
- Shower development – composition?
- Guaranteed events! Estimated E_{shr}>0.5 PeV, 65 evts/hr

Diffuse flux sensitivity

Diffuse flux all-flavor sensitivity assuming no observed events (and no background):

$$F_{\rm sens} = \frac{2.44 \times N_\nu}{\ln(10) \times E_{\nu_\tau} \times \langle A\Omega\rangle(E_{\nu_\tau}) \times t_{\rm obs}}$$

$$N_\nu = 3$$

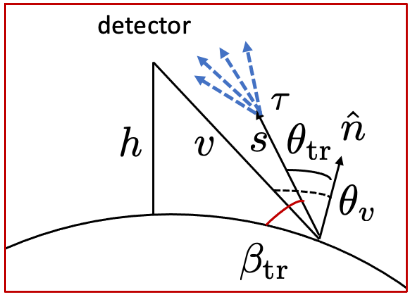
plot $E^2_{\nu_\tau} F_{\rm sens}$

Detector aperture:

$$\langle A\Omega\rangle(E_{\nu_\tau}) = \int_S \int_{\Delta\Omega_{tr}} P_{\rm obs}\, \vec{r} \cdot \hat{n}\, dS\, d\Omega_{tr}$$

(geometry factor weighted by $P_{\rm obs}$)

Observation and detection probability



$$dP_{\rm obs}(E_{\nu_\tau}, \beta_{\rm tr}, s) = ds\, P_{\rm exit}(E_{\nu_\tau}, \beta_{\rm tr}) \times \boxed{p_{\rm dec}(s)} \times P_{\rm det}(E_{\nu_\tau}, \beta_{\rm tr}, s)$$

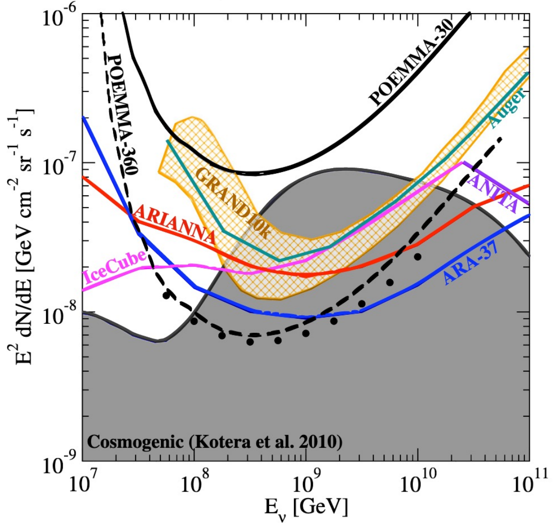
$$P_{\rm det} = H[\theta_{\rm Ch} - \theta] H[s_{\rm win} - s] H[N_{\rm PE} - N_{\rm PE}^{\rm min}]$$

also E_τ dependence (so β_{tr} dependence)

Diffuse neutrino flux sensitivity (all flavor)

POEMMA – design 30° but 360° would improve sensitivity.

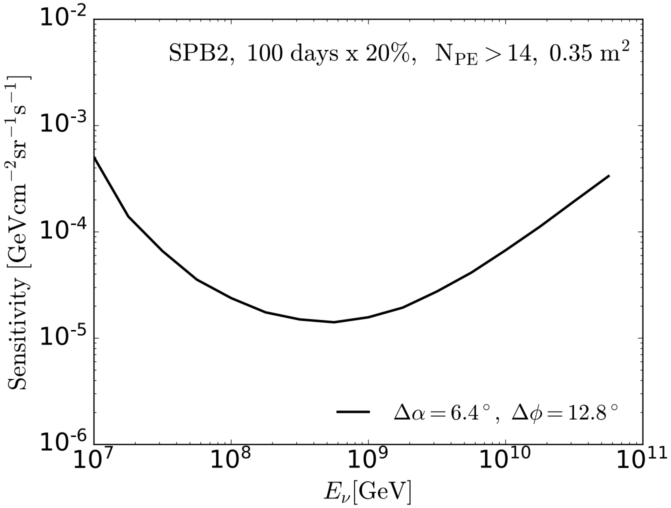
Venters et al., Phys. Rev. D 102 (2020) 123013



Tails of EAS profiles at high altitudes make some improvements (factor close to 10 for 10^{11} GeV) [Cummings et al. Phys. Rev. D 103 (2021) 043017]. See also muon detection.

Advantage, for SPB2, closer to the shower, but net, POEMMA-30 ~100x more sensitive than SPB2.

potential of SPB2: t_{obs}=1/18 of 5 years



$$\langle A\Omega\rangle = \int_{S(\Delta\phi)} \int_{\Delta\Omega_{\mathrm{tr}}} P_{\mathrm{obs}} \times \hat{r}\cdot\hat{n}\, dS\ d\Omega_{\mathrm{tr}}$$

used 20% duty cycle for POEMMA

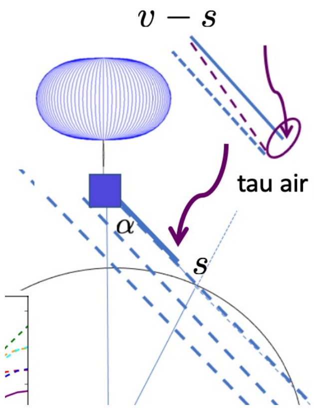
$$\mathrm{Sensitivity} = E_\nu \frac{2.44}{\ln(10)} \frac{3}{\langle A\Omega\rangle t_{\mathrm{obs}}(0.20)}$$

Transient neutrino source (ToO) sensitivity

ToO fluence all-flavor sensitivity assuming no observed events (and no background):

$$\text{Sensitivity} = \frac{2.44 \times N_\nu \times E_{\nu_\tau}}{\ln(10) \times f_t \times \langle A(E_{\nu_\tau}) \rangle_{T_0}}$$

$$A_{\text{Ch}} = \pi \theta_{\text{Ch}}^2 (v - s)^2$$



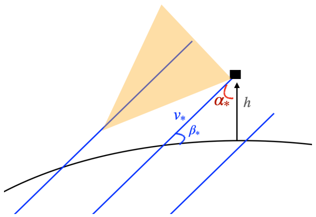
Detector effective area:

$$\langle A(E_{\nu_\tau}) \rangle_{T_0} = \frac{1}{T_0} \int_{t_0}^{t_0+T_0} dt \, dP_{\text{obs}}(E_{\nu_\tau}, \beta_{\text{tr}}, s) \, A_{\text{Ch}}(s)$$

Observation and detection probability

$$dP_{\text{obs}}(E_{\nu_\tau}, \beta_{\text{tr}}, s) = ds \, P_{\text{exit}}(E_{\nu_\tau}, \beta_{\text{tr}}) \times p_{\text{dec}}(s) \times P_{\text{det}}(E_{\nu_\tau}, \beta_{\text{tr}}, s)$$

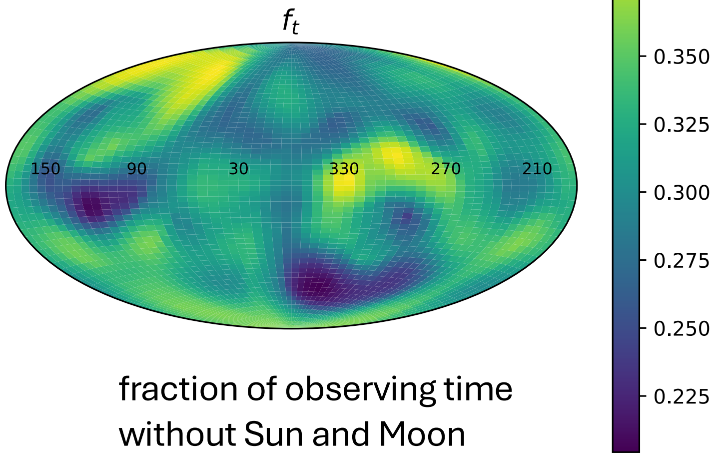
$$P_{\text{det}} = H[N_{\text{PE}} - N_{\text{PE}}^{\text{min}}]$$



Point source sky coverage

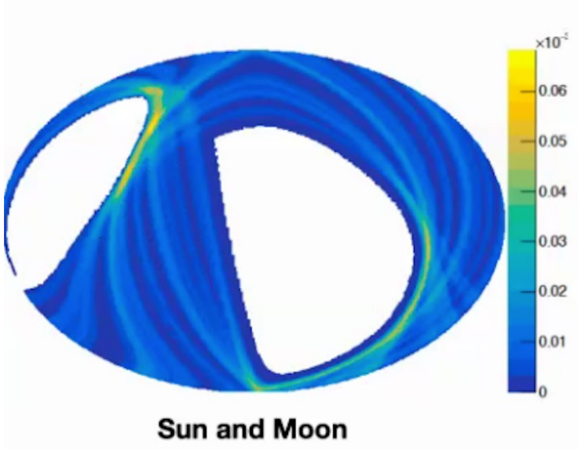
Hammer projections

POEMMA



fraction of observing time
without Sun and Moon

EUSO-SPB2



30 day effective area for 10 PeV neutrinos,
Sun and Moon over full period included.

full sky coverage (here 380 day avg)

more focused sky coverage

Nu Target Scheduler – python code for azimuthal pointing to given source – work in progress

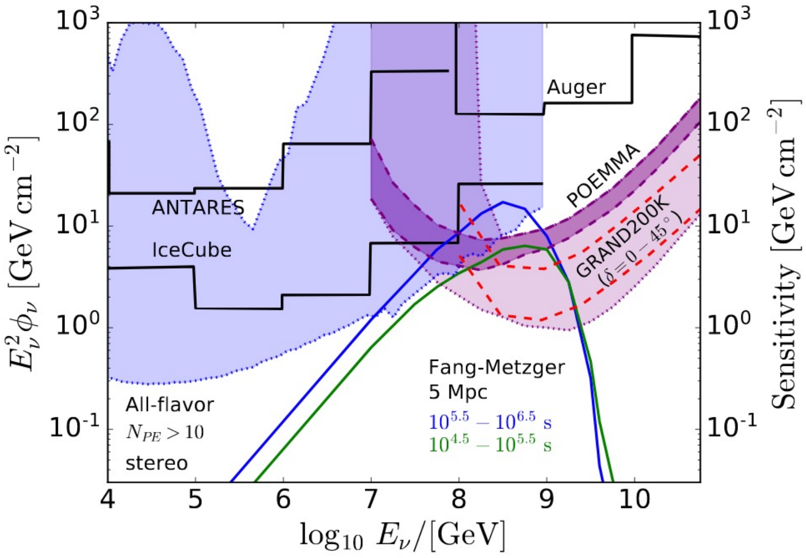
Sensitivity to long-burst transients

Per decade, all flavor, no muons.

10^6 s burst (~2 weeks), $f_t = 0.3$

POEMMA

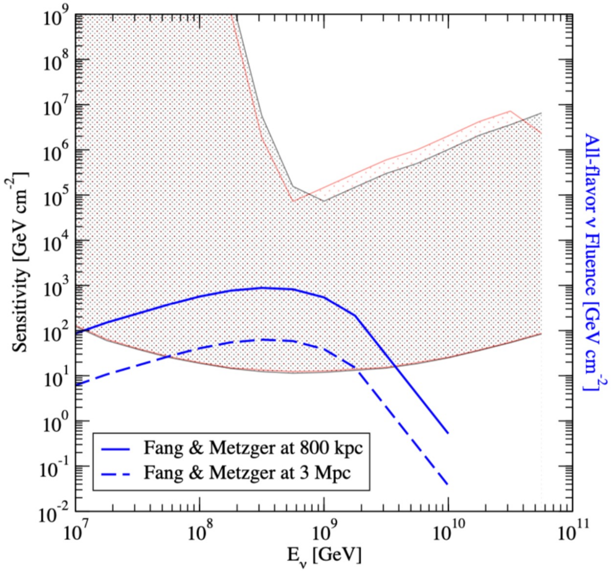
Venters et al, Phys. Rev. D 102 (2020) 123013



Theory: Fang & Metzger, Ap J 849 (2017) 153

Sensitivity to long bursts of 30 day duration assuming 20% duty cycle for Sun/Moon.

EUSO-SPB2



Red: 30 day average, black: 100 day average of effective area.

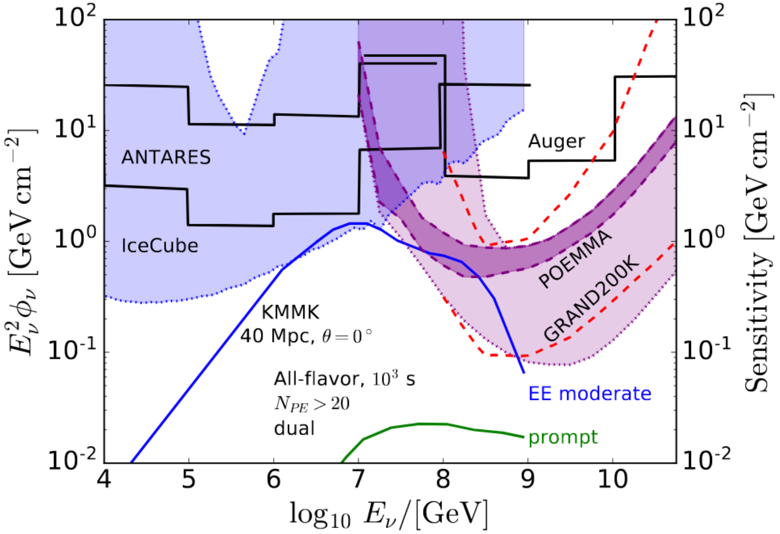
Sensitivity to short-burst transients

Best short-burst transients for 1,000 s burst, on axis viewing for short GRB.

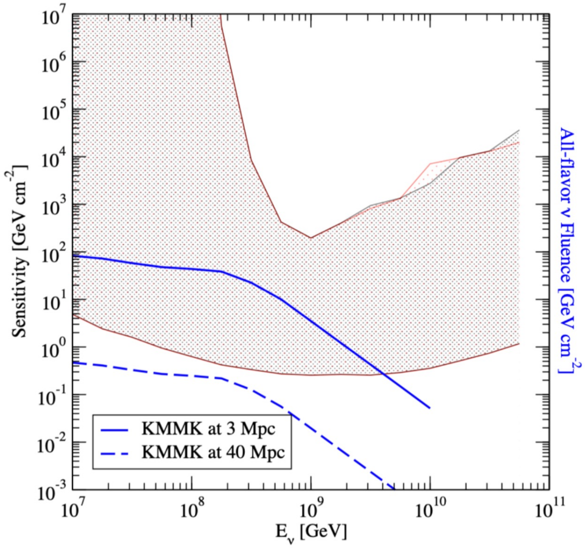
No Sun and Moon, burst occurs when viewable (part of “best”).

POEMMA

Venters et al, Phys. Rev. D 102 (2020) 123013



EUSO-SPB2



Theory: KMMK: Kimura, Murase, Meszaros, Kiuchi, Ap. J. 848 (2017) L4.

Summary for Cherenkov telescope ToO detection

POEMMA satellite, proposed for 2030+

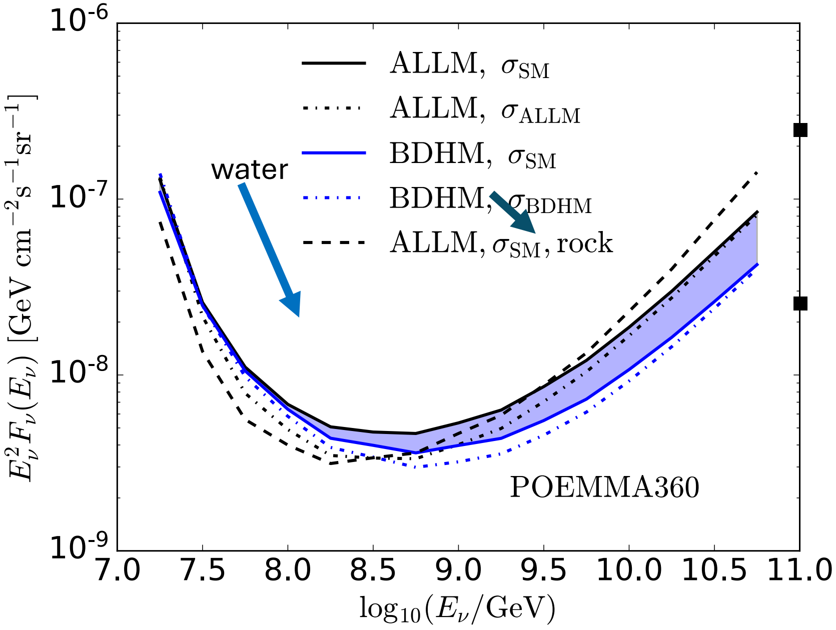
- Mono- and dual-telescope viewing.
- With external (GCN) alerts, best sensitivity to all-flavor neutrino fluences from transient sources 0.1-1 GeV/cm^2 short/long burst in EeV range.
- All sky coverage over the course of a year.
- Five years of viewing.

Balloon-based instruments

- Pathfinder instruments to POEMMA-like space-based instrument.
- With GCN alerts, sensitivity to all-flavor neutrino fluences from transient sources as good as 0.3-10 GeV/cm^2 short/long burst in EeV range based on EUSO-SPB2 projections (similar size).
- This means potential to detect events in nearby galaxies.
- Interesting cosmic ray studies.

Modeling uncertainties and backgrounds

- Neutrino cross section
- Tau energy loss
- Water or rock in final layer?



Diffuse POEMMA360
example of uncertainties

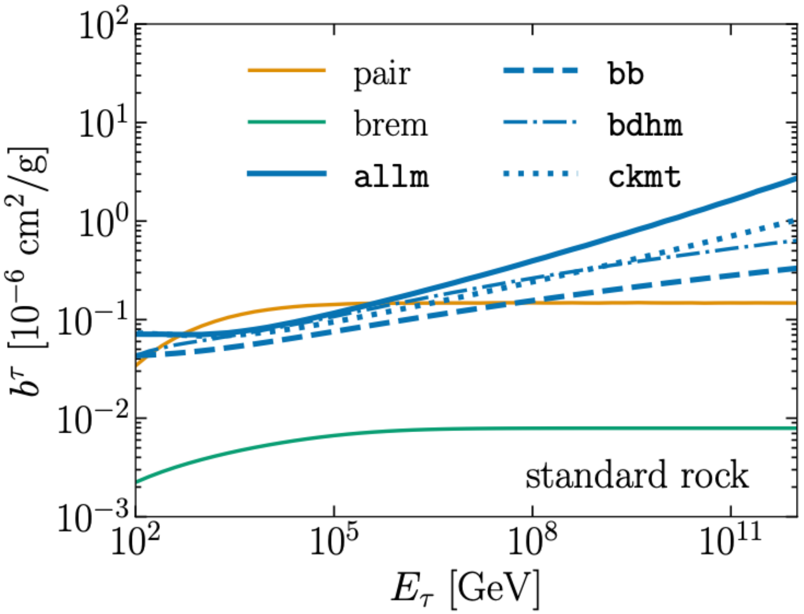
Backgrounds:

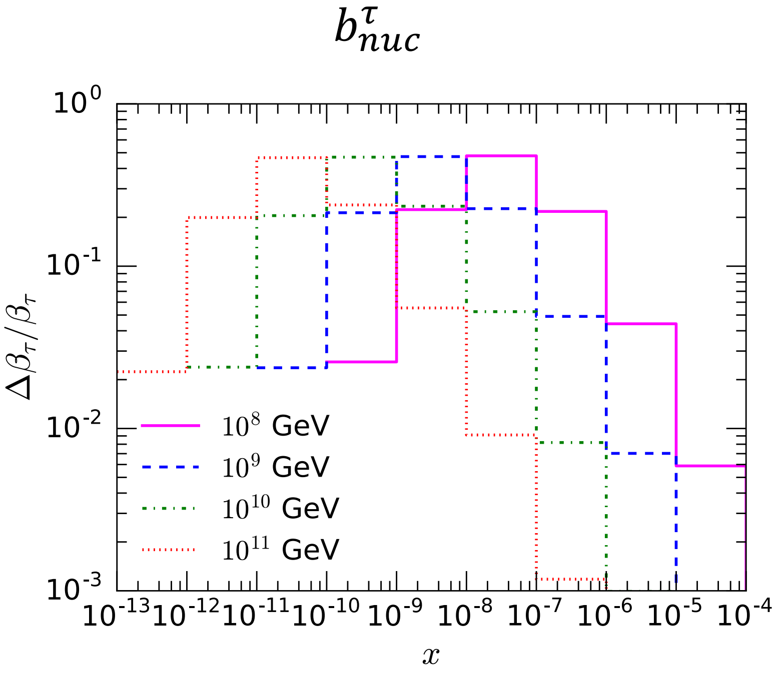
- Thresholds for night sky air glow background - fake neutrino probability is <1%.
  EUSO-SPB2 will measure air glow.
- UHECR signals reflected off the ground have the wrong timing: reflection time is large at these angles.
- Cherenkov signals from UHECR showers in the atmosphere above the limb come from a very narrow angular range.

See background discussion for ToO in Venters et al., Phys. Rev. D 102 (2020) 123013.

Tau energy loss

Electromagnetic structure function at very small *x*!



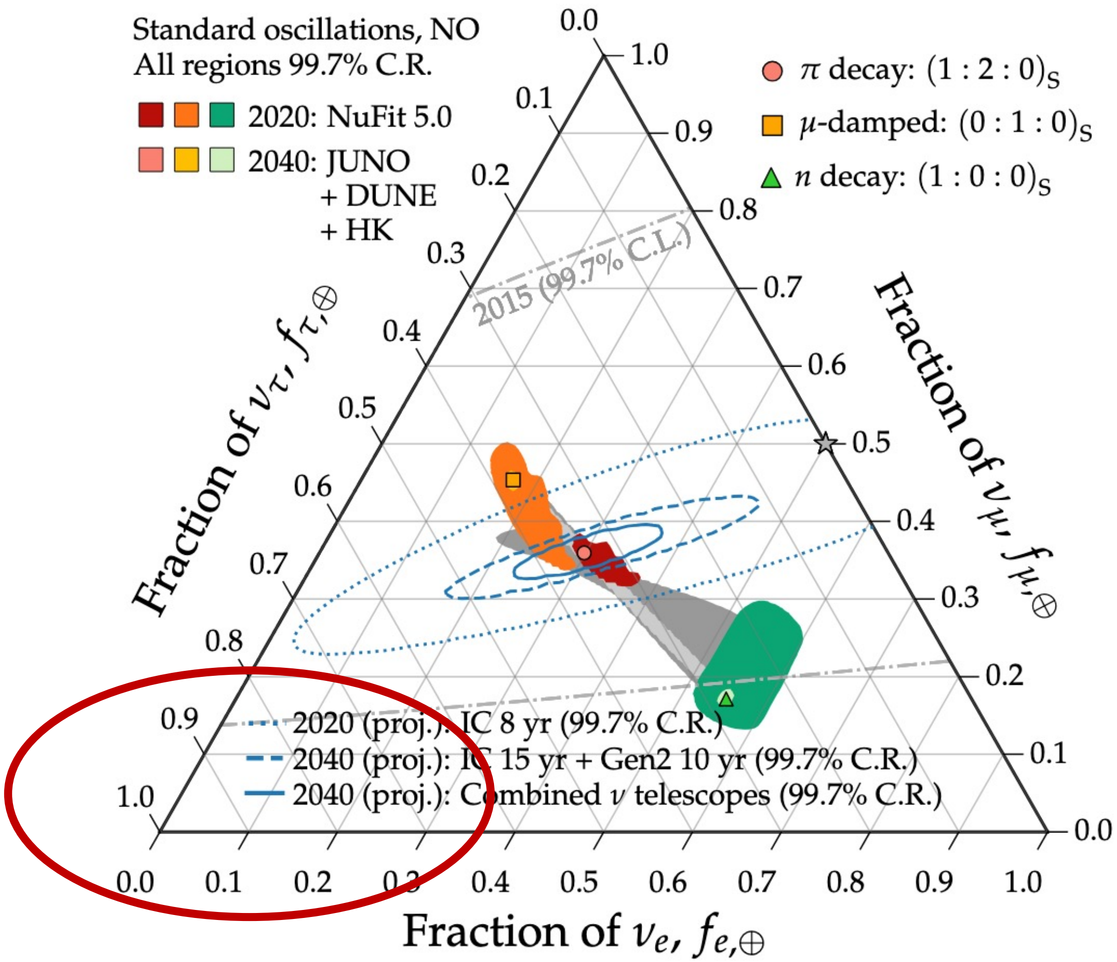


$$-\left\langle \frac{dE}{dX} \right\rangle = a^\ell + \sum_{i=\text{brem,pair,nuc}} b_i^\ell(E)E$$

$$b^\tau(E) = \frac{N}{A}\int dy\, y\, \frac{d\sigma(y,E)}{dy}$$

$$\frac{d\sigma(x,Q^2)}{dQ^2dx} = \frac{4\pi\alpha^2}{Q^4}\frac{F_2(x,Q^2)}{x}\left[1-y-\frac{Mxy}{2E} + \left(1-\frac{2m_l^2}{Q^2}\right)\frac{y^2(1+4M^2x^2/Q^2)}{2(1+R(x,Q^2))}\right]$$

BSM physics that disrupts $\nu_e : \nu_\mu : \nu_\tau \simeq \frac{1}{3} : \frac{1}{3} : \frac{1}{3}$ should be observable through combination of experiments including skimming ν_τ.



Song et al, 2012.12893

Final remarks

- There is a program in progress for sub-orbital, eventually satellite-based Cherenkov telescopes designed to detect skimming tau neutrinos via up-going air showers.
- Flavor sensitive! This will be part of a collection of instruments/neutrino telescopes to determine neutrino flavor.
- Software tools available (nuPyProp, nuSpaceSim) and in development (NuTS).
- EUSO-SPB2 data analysis in progress - only ~30 minutes pointing below the limb.
- With flight, opportunities to follow-up alerts from EM/gravitational wave events. Balloon-based telescopes have competitive sensitivities.
- Cosmic ray induced air shower observation from novel vantage point guaranteed.