

# A new calculation of Earth-skimming very- and ultra-high energy tau neutrinos

Mary Hall Reno (University of Iowa)

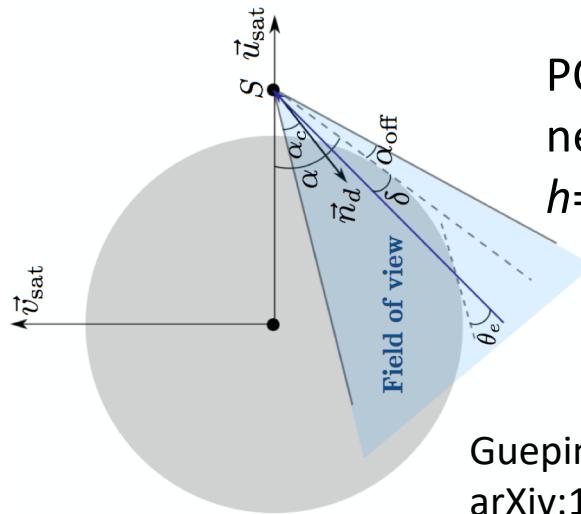
and T. M. Venters, J. F. Krizmanic, L. A. Anchordoqui, C. Guepin and A. V. Olinto for the POEMMA collaboration

ICRC 2019

# Some related talks & posters

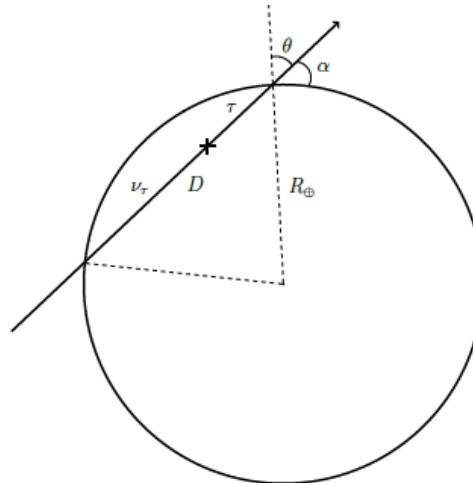
- A. V. Olinto et al., POEMMA: Probe of Extreme Multi-Messenger Astrophysics, PoS(ICRC2019)378
- N. Otte et al., Development of a Cherenkov Telescope for the Detection of Ultrahigh Energy Neutrinos with EUSO-SPB2 and POEMMA, PoS(ICRC2019)977
- J. F. Krizmanic et al., nuSpaceSim: A Comprehensive Neutrino Simulation Package for Space-based & Suborbital Experiments, PoS(ICRC2019)936

# Upward-going air showers from tau decays (for POEMMA)



POEMMA in  
neutrino mode  
 $h=525$  km

Guepin et al,  
arXiv:1812.07596



Use the Earth as a neutrino converter. Convert tau neutrinos to tau leptons.

Tau decays make  
(upward-going) air  
showers.

Domokos & Kovesi-Domokos, AIP Conf. 433(1998); Halzen & Saltzberg, PRL 81 (1998) 4305; Bertou et al., Astropart. Phys. 17 (2002) 183; Lachaud et al, TAUP 2001, Fargion, Ap.J. 570 (2002) 909; Fargion et al, Ap. J. 613 (2004) 1285; Athar et al, PRD 62 (2000) 093010; Feng et al, PRL 88 (2002) 161102; Kusenko & Weiler, PRL 88 (2002) 161101; Hou & Huang astro-ph/0204145. Later work includes: Tseng et al, PRD 68 (2003) 063003; Aramo et al, Astropart Phys 23 (2005) 083003; Dutta et al, PRD 72 (2005) 013005; Armesto et al, PRD 77 (2008) 013001; Neronov et al, PRD 95 (2017) 023004 Recently, e.g.: Jeong et al, PRD 96 (2017) 043003; Alvarez-Muniz et al, PRD 97 (2018) 023021; MHR, Krizmanic & Venter, arXiv:1902.11287, Venter et al., arXiv:1906.07209

# Hot topic – ANITA unusual events (are they upward-going tau's?)

TABLE I. ANITA-I,-III anomalous upward air showers.

| event, flight                    | 3985267, ANITA-I                               | 15717147, ANITA-III                           |
|----------------------------------|--|---|
| date, time                       | 2006-12-28,00:33:20UTC                         | 2014-12-20,08:33:22.5UTC                      |
| Lat., Lon. <sup>a</sup>          | -82.6559, 17.2842                              | -81.39856, 129.01626                          |
| Altitude                         | 2.56 km  | 2.75 km                                       |
| Ice depth                        | 3.53 km  | 3.22 km                                       |
| El., Az.                         | $-27.4 \pm 0.3^\circ$ , $159.62 \pm 0.7^\circ$ | $-35.0 \pm 0.3^\circ$ , $61.41 \pm 0.7^\circ$ |
| RA, Dec <sup>b</sup>             | 282.14064, +20.33043                           | 50.78203, +38.65498                           |
| $E_{\text{shower}}$ <sup>c</sup> | $0.6 \pm 0.4$ EeV                              | $0.56^{+0.3}_{-0.2}$ EeV                      |

<sup>a</sup>Latitude, Longitude of the estimated ground position of the event.

<sup>b</sup>Sky coordinates projected from event arrival angles at ANITA.

<sup>c</sup>For upward shower initiation at or near ice surface.

P. W. Gorham et al. (ANITA Collaboration), PRL 121 (2018) 161102  
(No!, see, e.g., Romero-Wolf et al, PRD 99 (2019) 063011; Chipman et al., arXiv:1906.11736  
and many others.)

# High energy neutrinos: transient sources and diffuse flux

Target of opportunity sources: neutrino flares of finite duration.

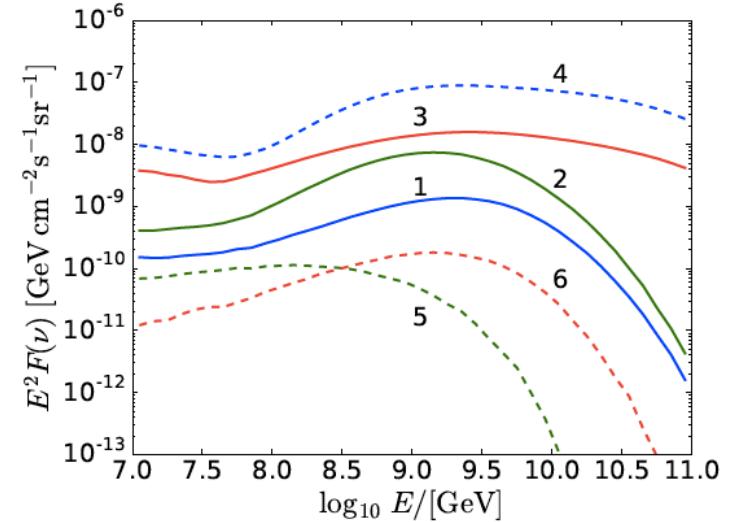
Diffuse flux, e.g., GZK neutrinos from cosmic ray interactions with the cosmic background radiation.

Ratios at production:

$$\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$$

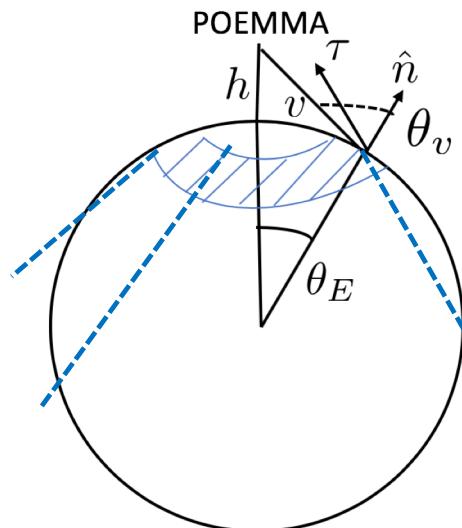
Ratios at Earth thanks to neutrino oscillations:

$$\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$$



*Cosmogenic neutrino fluxes (diffuse, isotropic)* from Kotera et al., JCAP 10 (2010) 013 based on inputs that reproduce the UHECR spectrum. Depends on cosmic ray composition, evolution of CR sources, maximum accelerator energy.

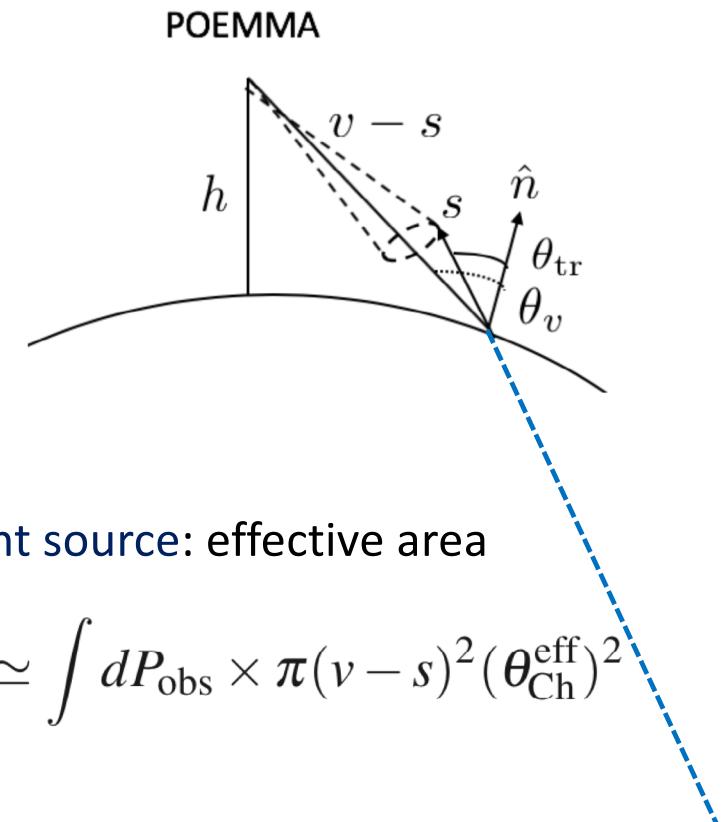
# Neutrino and tau propagation



Diffuse flux:  
effective aperture

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

$$dP_{\text{obs}} = ds' P_{\text{exit}}(E_{\nu_\tau}, \theta_{\text{tr}}) p_{\text{decay}}(s') P_{\text{det}}(E_{\nu_\tau}, \theta_v, \theta_{\text{tr}}, s')$$

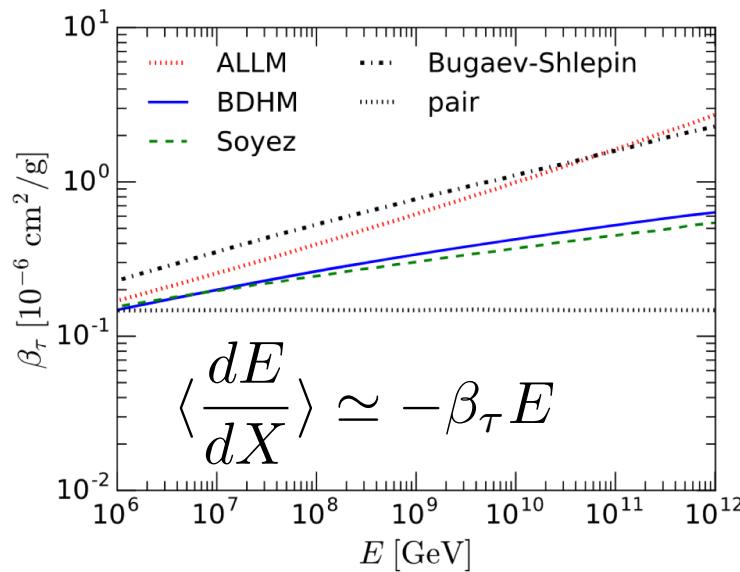
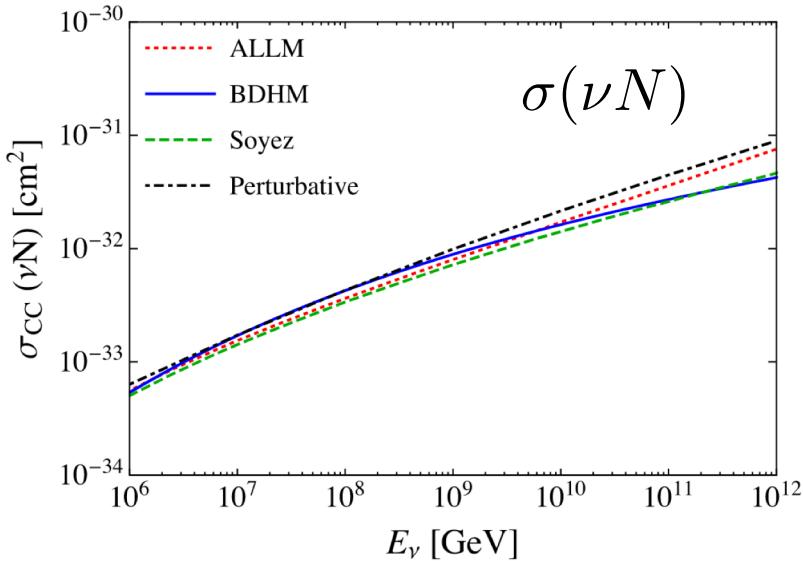


Transient source: effective area

$$A(\theta_{\text{tr}}, E_{\nu_\tau}) \simeq \int dP_{\text{obs}} \times \pi(v - s)^2 (\theta_{\text{Ch}}^{\text{eff}})^2$$

# $P_{exit}$ : weak, electromagnetic interactions

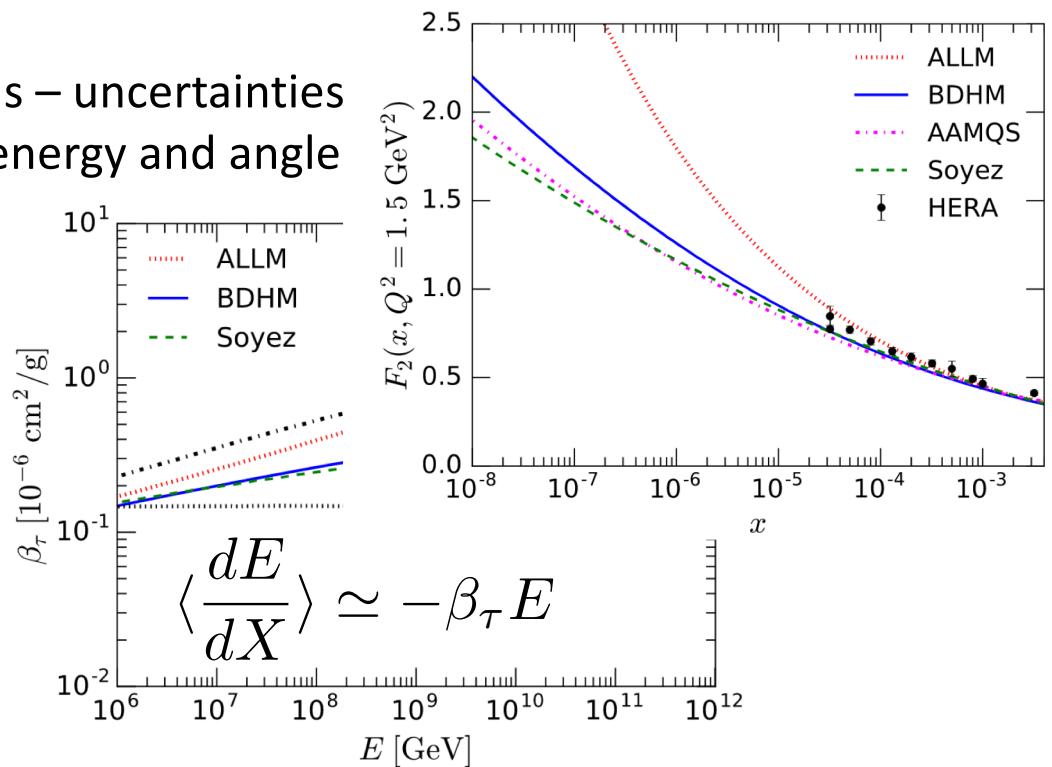
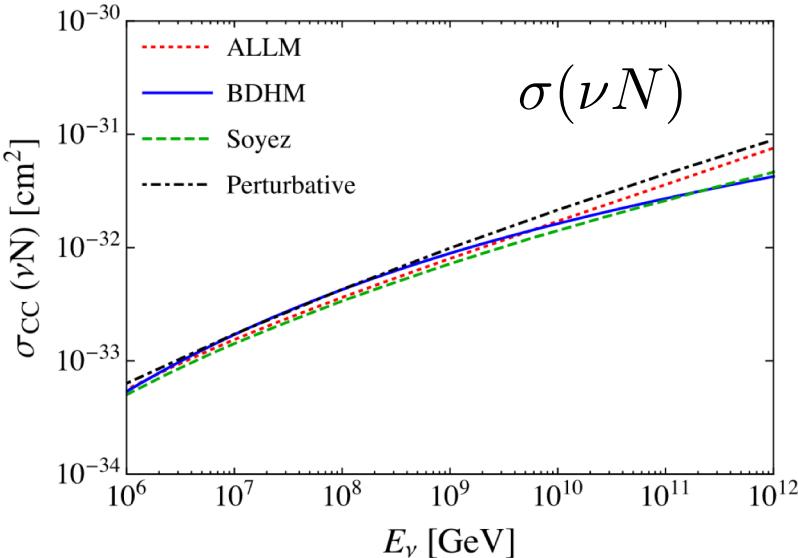
Both require high energy extrapolations – uncertainties in the exit probability as a function of energy and angle



See, e.g., Jeong, Luu, MHR, Sarcevic, PRD 96 (2017) 043003, Dutta, MHR, Sarcevic, Seckel, PRD 63 (2001) 094020

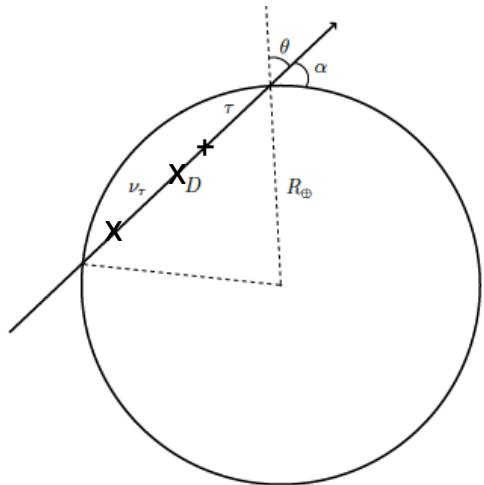
# $P_{exit}$ : weak, electromagnetic interactions

Both require high energy extrapolations – uncertainties in the exit probability as a function of energy and angle



See, e.g., Jeong, Luu, MHR, Sarcevic, PRD 96 (2017) 043003, Dutta, MHR, Sarcevic, Seckel, PRD 63 (2001) 094020

# Neutrino and tau propagation

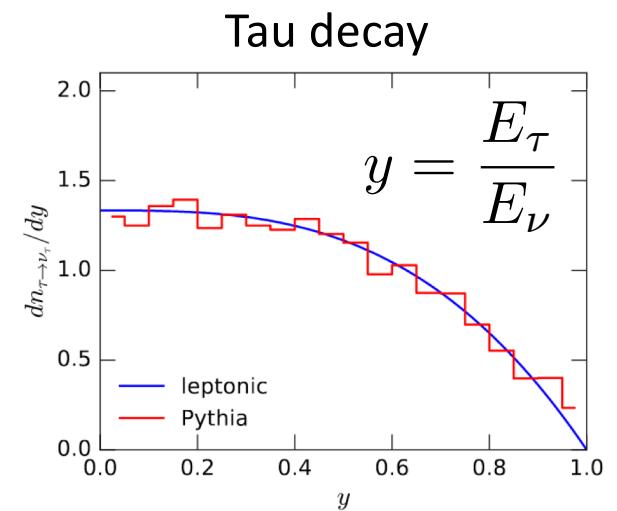


Monte Carlo evaluation:

- neutrino interaction (CC and NC)  
outgoing lepton energy
- tau decay or energy loss?
- stochastic energy loss

Tau decay?

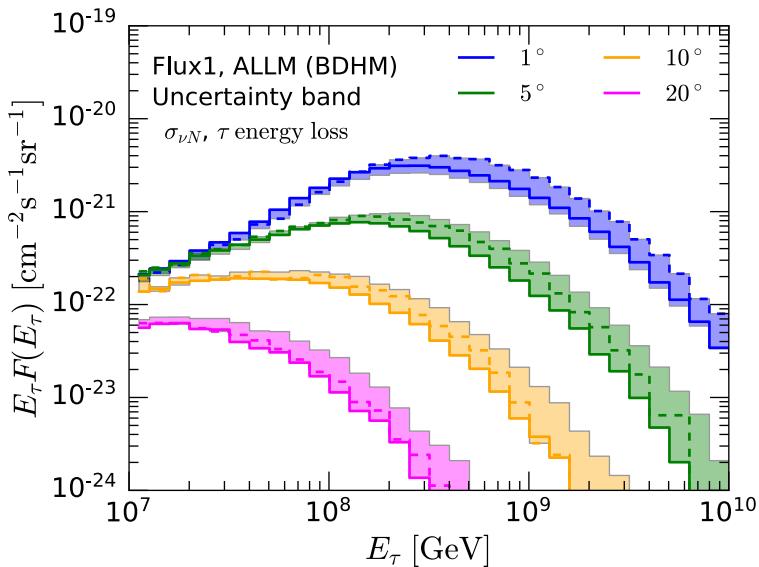
- decay neutrino from decay distribution
- regeneration, leads to lower energy tau neutrino spectrum – see I. Safa et al,  
PoS(ICRC2019)995



# Tau transmission, effective aperture

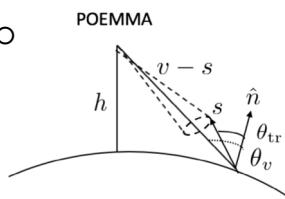
input  $\nu$  flux, find ratio of outgoing tau's to incoming  $\nu$ 's at common energy

$$\beta_{\text{tr}} = 90^\circ - \theta_{\text{tr}} = 1^\circ, 5^\circ, 10^\circ, 20^\circ$$

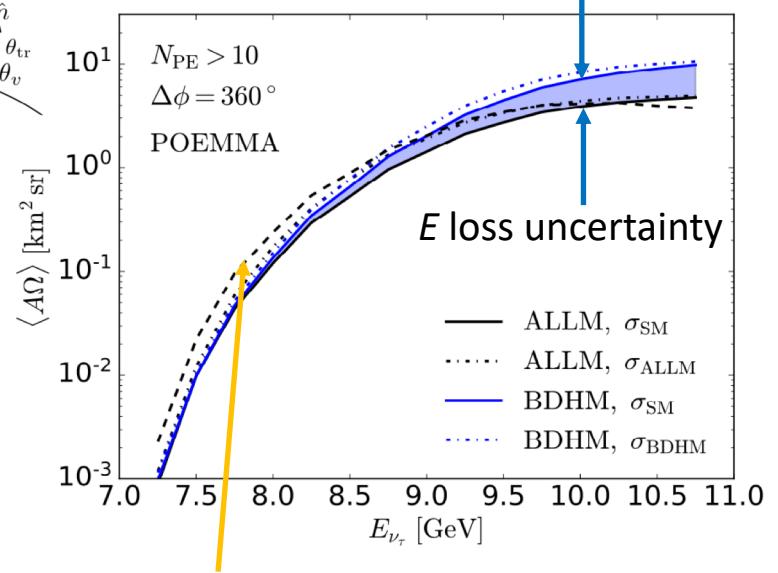


larger uncertainties for larger elevation angles  
(more propagation in the Earth)

7/30/19



flux independent,  
POEMMA's effective aperture



all rock in outer layer, need higher  $E$  for water advantage, see, e.g.,

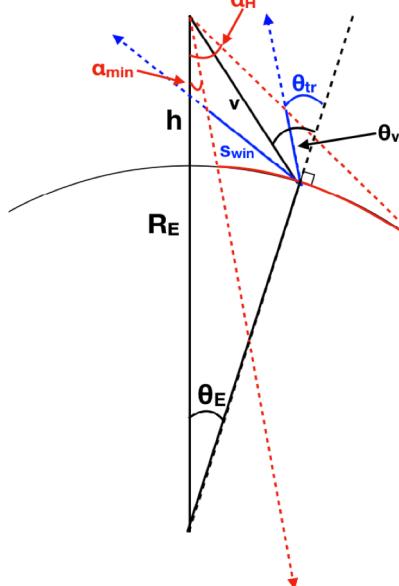
Palomares-Ruiz, Irimia, Weiler, PRD 73 (2006) 083003

$$p_{\text{det}}(E_\tau, \theta_E, \beta_{\text{tr}}, s_d)$$

$$\begin{aligned} p_{\text{det}} &= H[\theta_{\text{Ch}} - \theta_\delta] \\ &\cdot H[s_{\text{win}} - s_d] \\ &\cdot H[N_{\text{PE}} - N_{\text{PE}}^{\min}] \end{aligned}$$

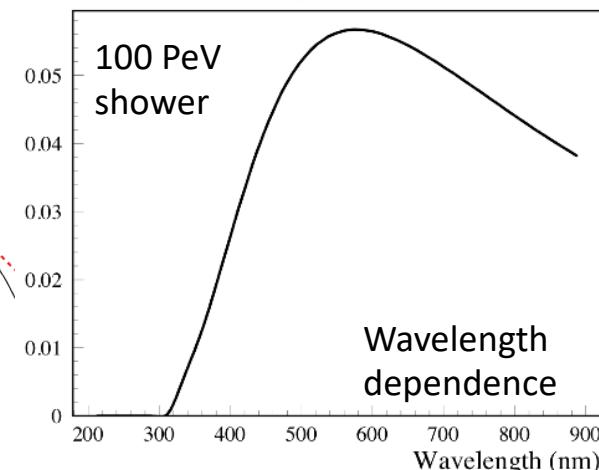
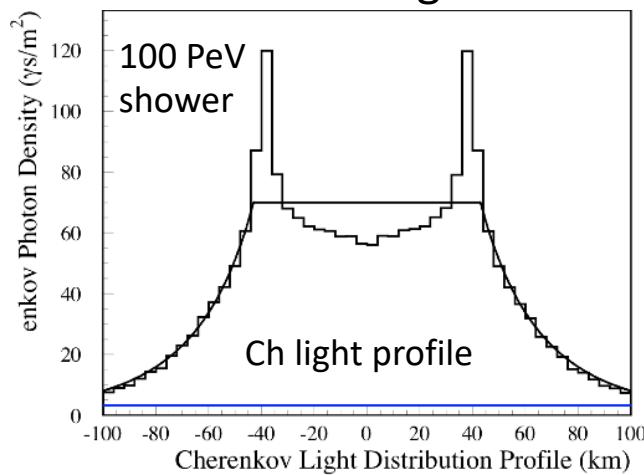
$$N_{\text{PE}}^{\min} = 10$$

for diffuse  
limits

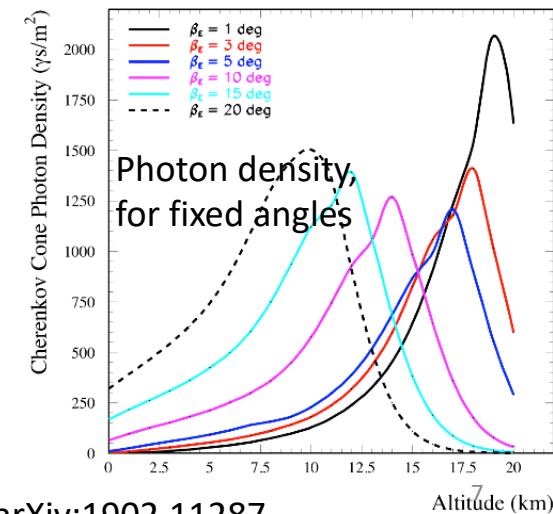
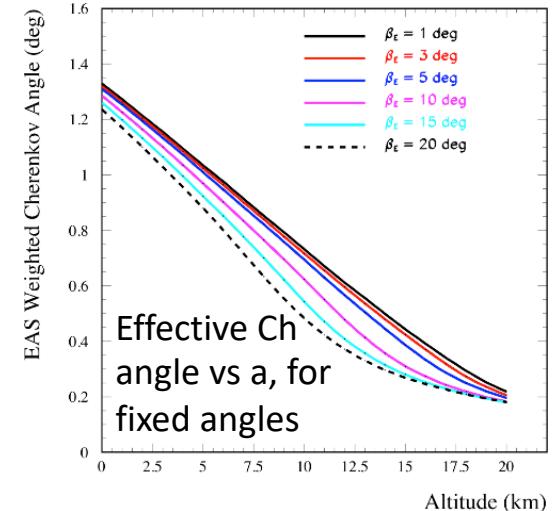


7/30/19

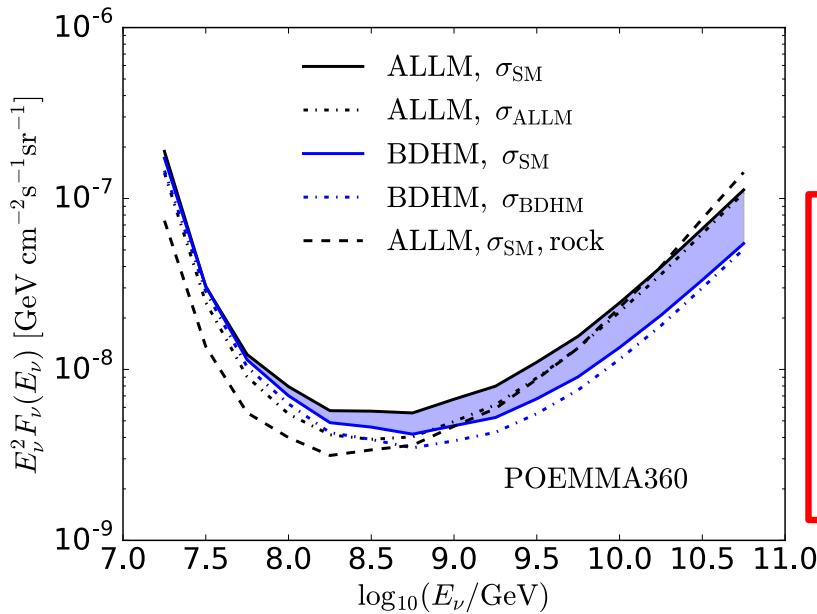
## POEMMA sensitivity inputs based on modeling showers:



Reno, Krizmanic & Venter, arXiv:1902.11287

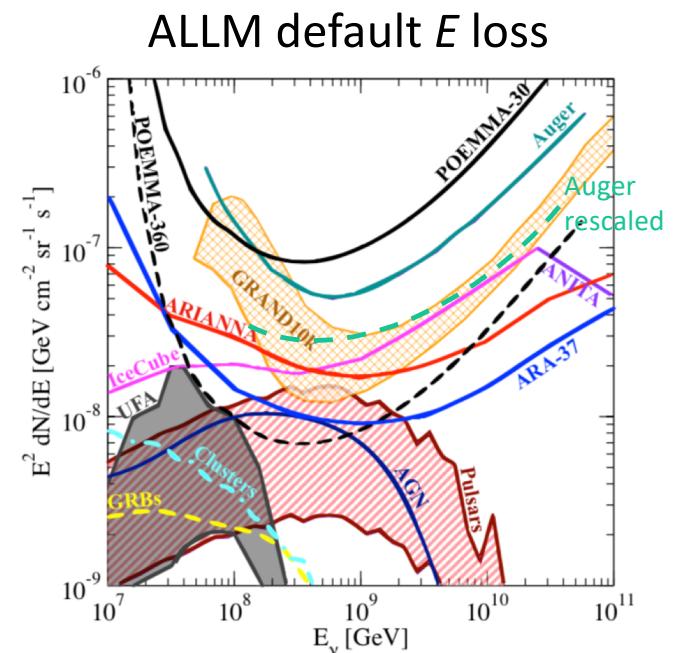


# POEMMA – all flavor diffuse neutrino flux sensitivity, 90% CL per energy decade



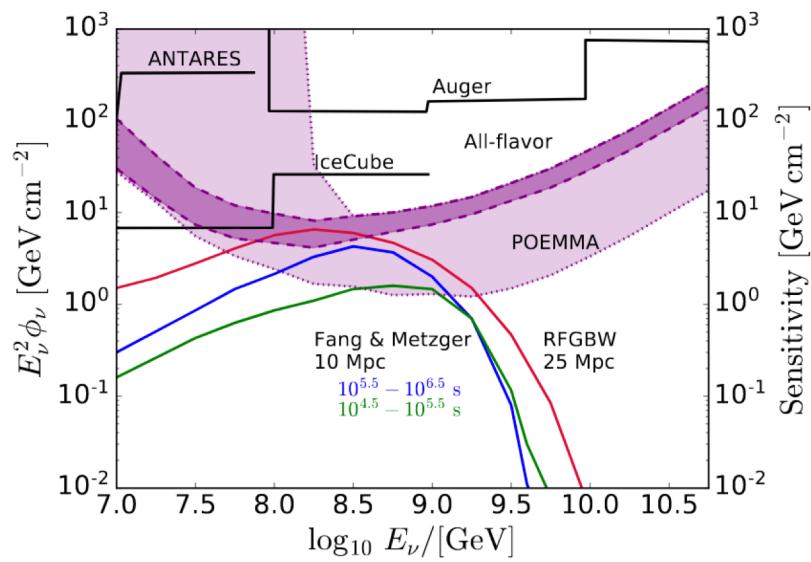
Conclusion:  
need 360<sup>0</sup>  
coverage for  
competitive  
diffuse limits

5 years, 20% duty cycle, 10 PE threshold,  
0.2 quantum efficiency



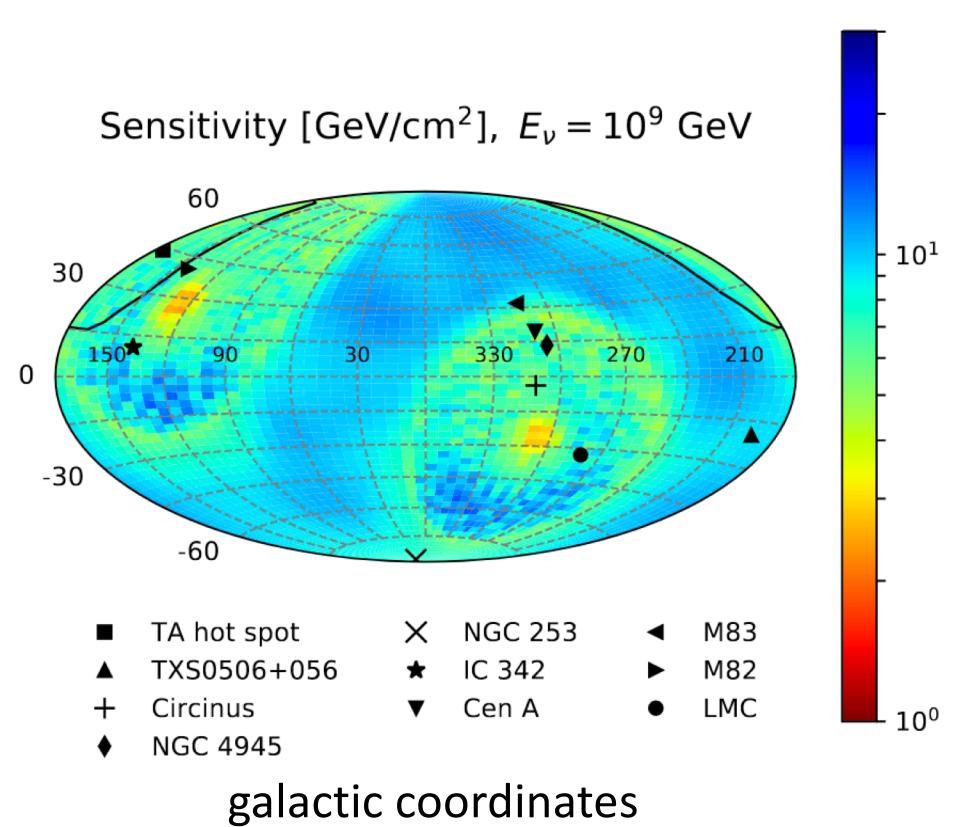
MHR, Krizmanic, Venters,  
arXiv:1902.11287

# POEMMA – transient source sensitivities (targets of opportunity) – long bursts, 90% CL per energy decade



Venters et al, arXiv:1906.07209; Fang & Metzger, millisecond magnetars from binary NS merger, ApJ 849 (2017) 153;  
Rodrigues et al, blazar flare, ApJ 854 (2018) 54.

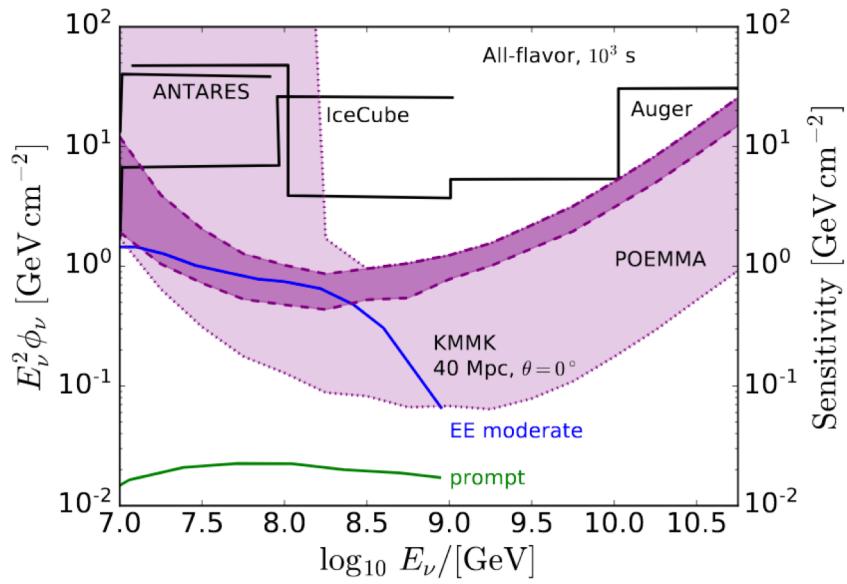
7/30/19



Mary Hall Reno, University of Iowa

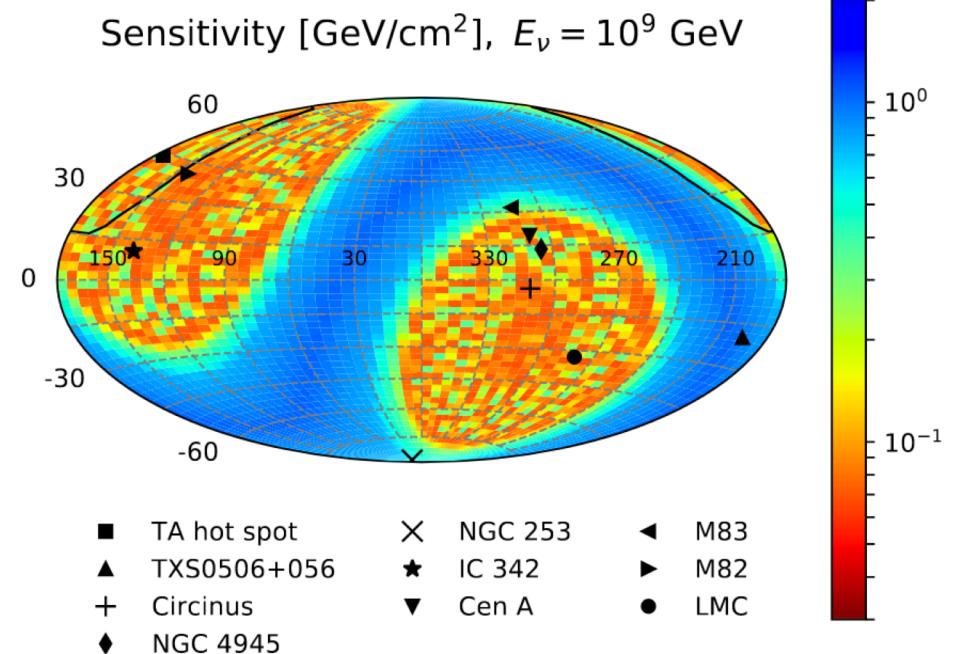
13

# POEMMA – transient source sensitivities (targets of opportunity) – short bursts with optimal viewing conditions, 90% CL per energy decade



Venters et al, arXiv:1906.07209; Kimura et al., short GRB, ApJ 848 (2017) L4.

7/30/19



different color scale than previous plot

Mary Hall Reno, University of Iowa

14

# Sources in view – ToO and luminosity distances

- Models of tidal disruption events, blazar flares, black hole-black hole mergers, neutron star-neutron star mergers give most optimistic number of events for POEMMA.

| Source Class  | No. of $\nu$ 's at GC | No. of $\nu$ 's at 3 Mpc | Largest Distance for 1.0 $\nu$ per event | Model Reference  |
|---------------|-----------------------|--------------------------|--|--|
| TDEs          | $2.23 \times 10^8$    | $1.44 \times 10^3$       | <b>115.20 Mpc</b>                        | <b>Lunardini and Winter [18]</b><br>$M_{\text{SMBH}} = 5 \times 10^6 M_{\odot}$<br>Lumi Scaling Case |
| TDEs          | NA*                   | $1.07 \times 10^3$       | <b>100.03 Mpc</b>                        | <b>Lunardini and Winter [18]</b><br>$M_{\text{SMBH}} = 1 \times 10^5 M_{\odot}$ Strong Scaling Case  |
| Blazar Flares | NA*                   | $1.91 \times 10^2$       | <b>42.96 Mpc</b>                         | <b>RFGBW [19] – FSRQ proton-dominated advective escape model</b>                                     |

# Conclusions

- POEMMA is best suited to target of opportunity measurements, with a 90 degree slew in 8 minutes.
- To be competitive for the diffuse flux, a 360 degree azimuthal coverage is needed for POEMMA.
- Tau energy loss uncertainties are at the level of 40% for  $E_\nu = 10^9$  GeV.
- Plans: include the effect of tau decays to muons (see Cummings et al, PoS(ICRC2019)862) and clouds.
- Part of a larger program to provide a software tool for tau neutrino induced upward-going air showers (see Krizmanic et al, PoS(ICRC2019)936).