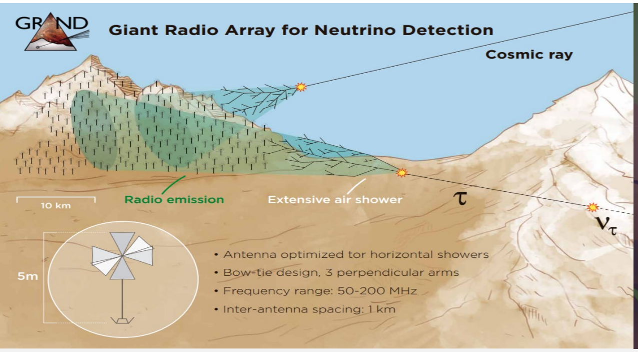
New Physics Potential of Future Tau Neutrino Telescopes

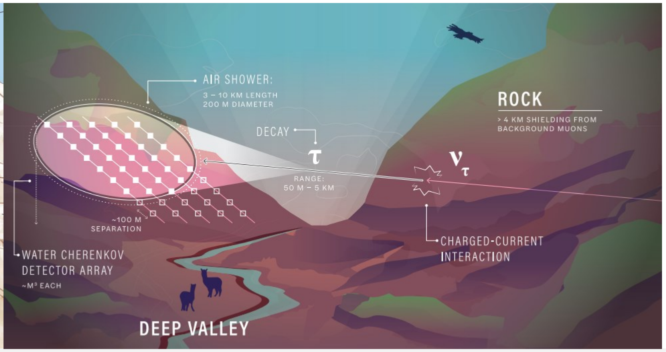
Guo-yuan Huang

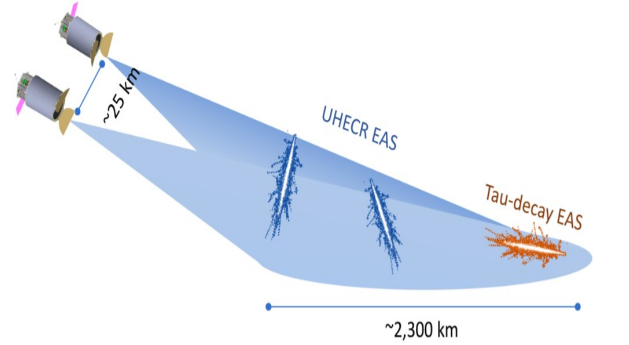
Max-Planck-Institut
für Kernphysik
Heidelberg

Unterstützt von / Supported by

Alexander von Humboldt
Stiftung / Foundation







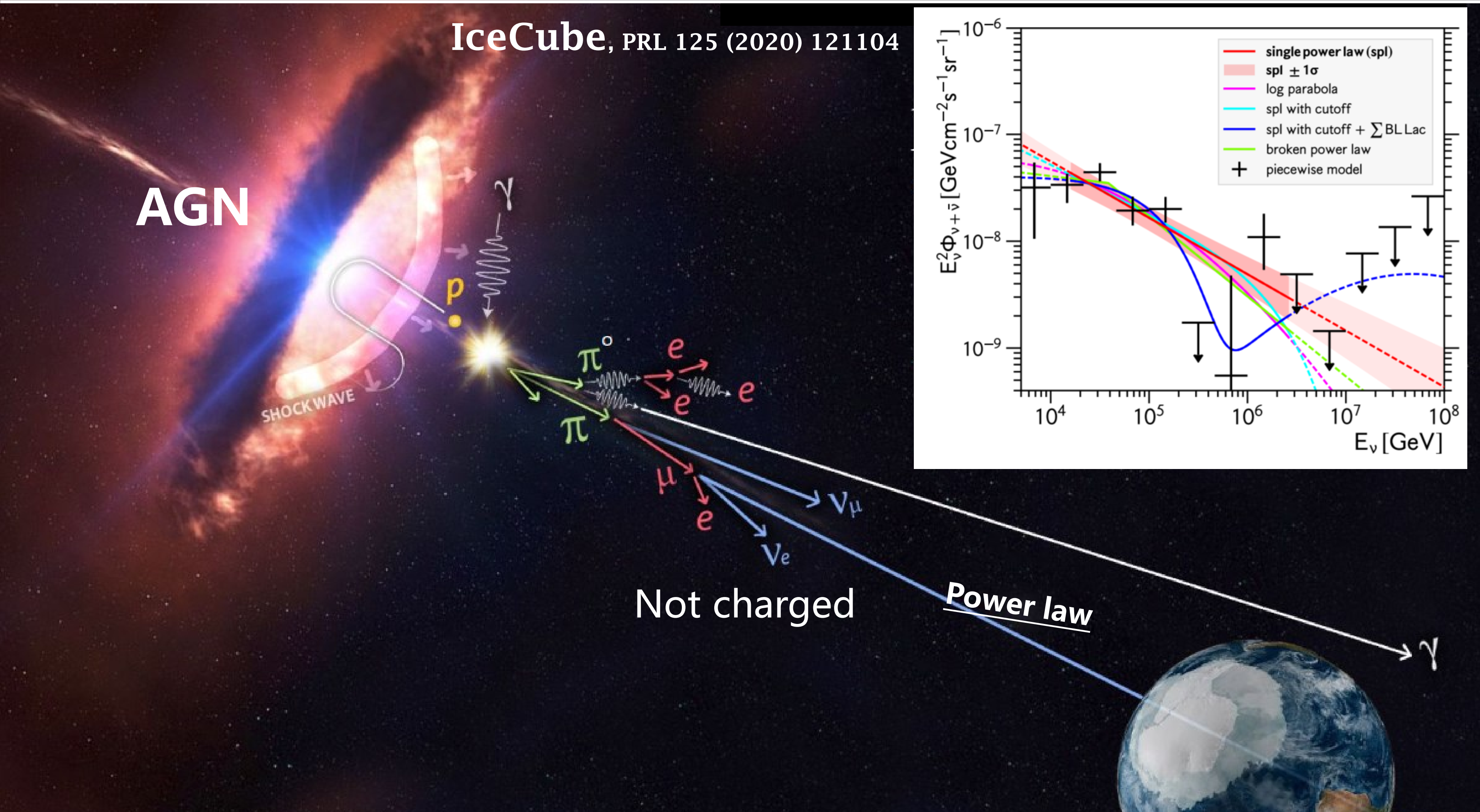
Outline

- Cosmogenic neutrinos
- Future experimental programs
- New physics prospects
- Sensitivities
- Other possibilities

Based on
JCAP02(2022)038, arXiv:2204.10347,
GYH, S. Jana, M. Lindner and W. Rodejohann
arXiv:2207.02222, GYH

UHE neutrino observations

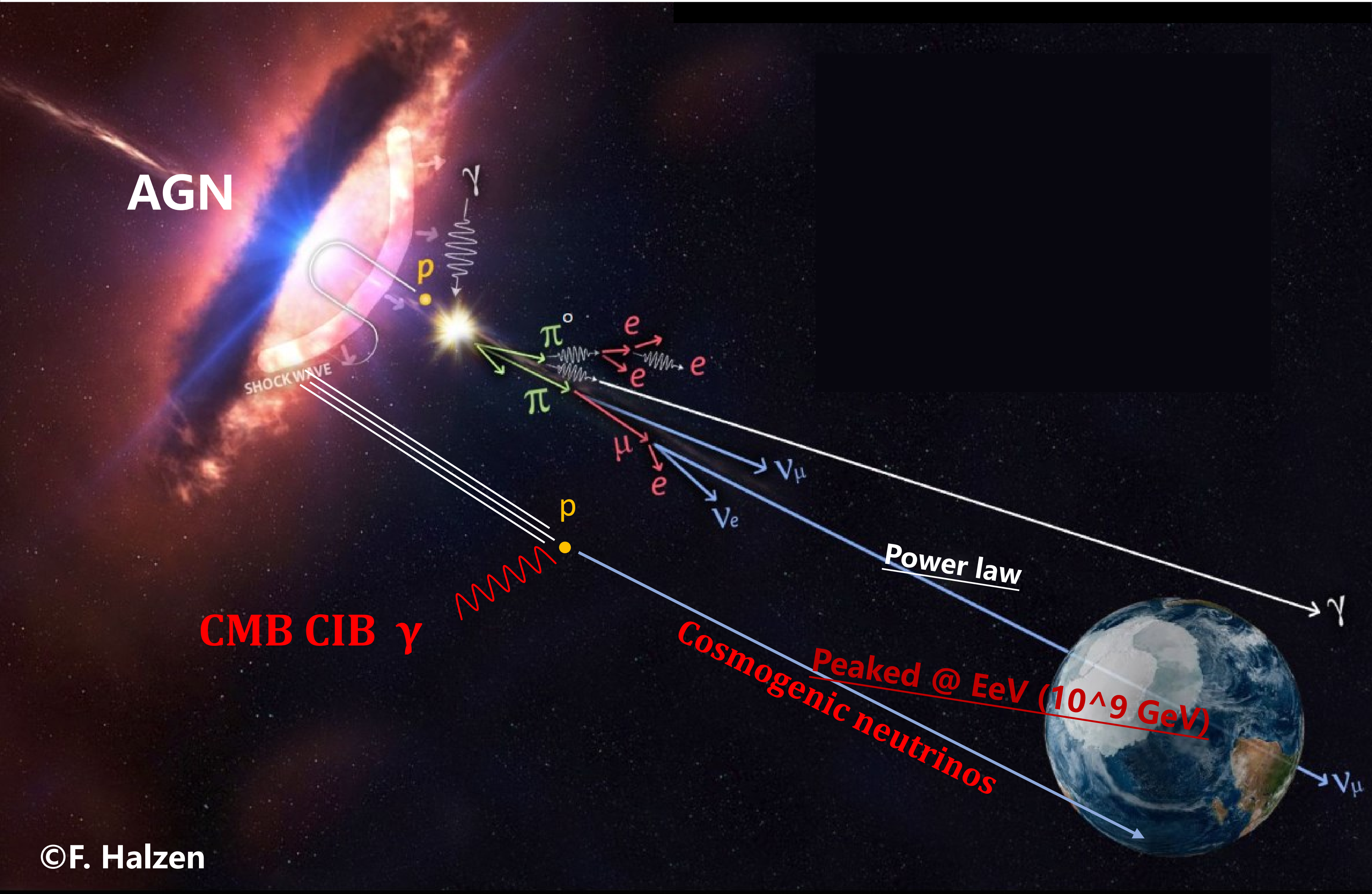
IceCube, PRL 125 (2020) 121104



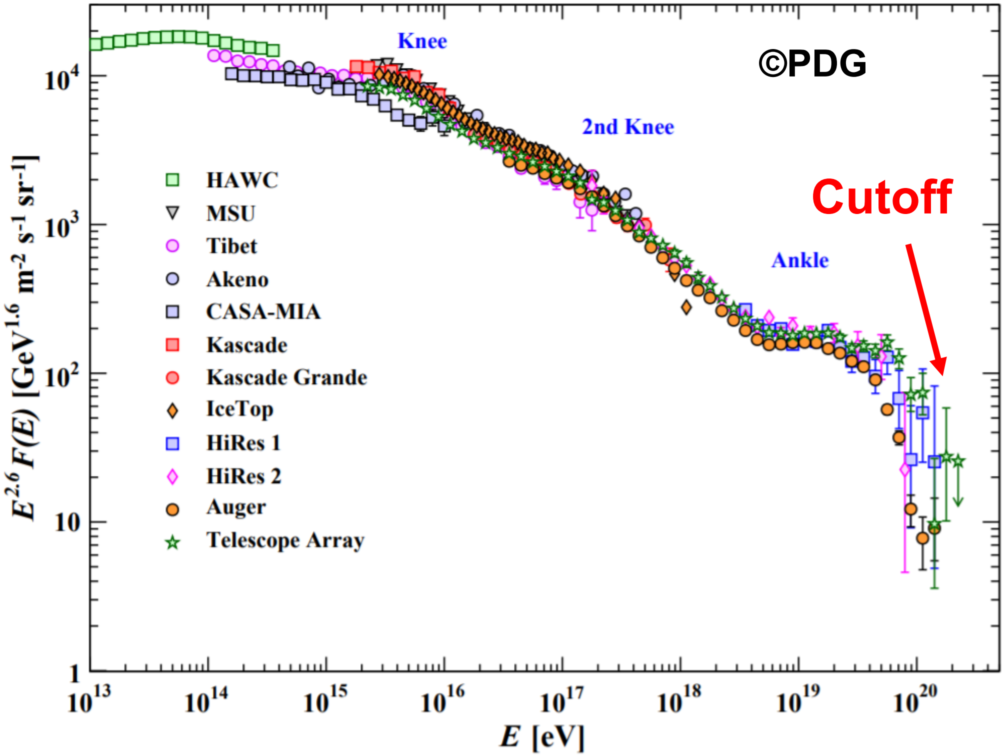
©F. Halzen

After being fully constructed in 2011, IceCube has reported more than 200 UHE nu events in (10 TeV-10 PeV), which is of clear astrophysical origin.

UHE neutrino observations



Cosmogenic neutrino fluxes



*Cosmic rays are produced from the extreme astrophysical environment possibly via the Fermi acceleration mechanism, typically following a power lower spectrum.

E. Fermi, Phys. Rev. 75 (1949) 1169

*There is a rapid cutoff in the CR spectrum predicted by Greisen, Zatsepin and Kuzmin (GZK).

K. Gerisen, PRL 16 (1966) 748,
G.T. Zatsepin and V.A. Kuzmin, JETPL 4 (1966) 78

Cosmic rays scatter off relic photons

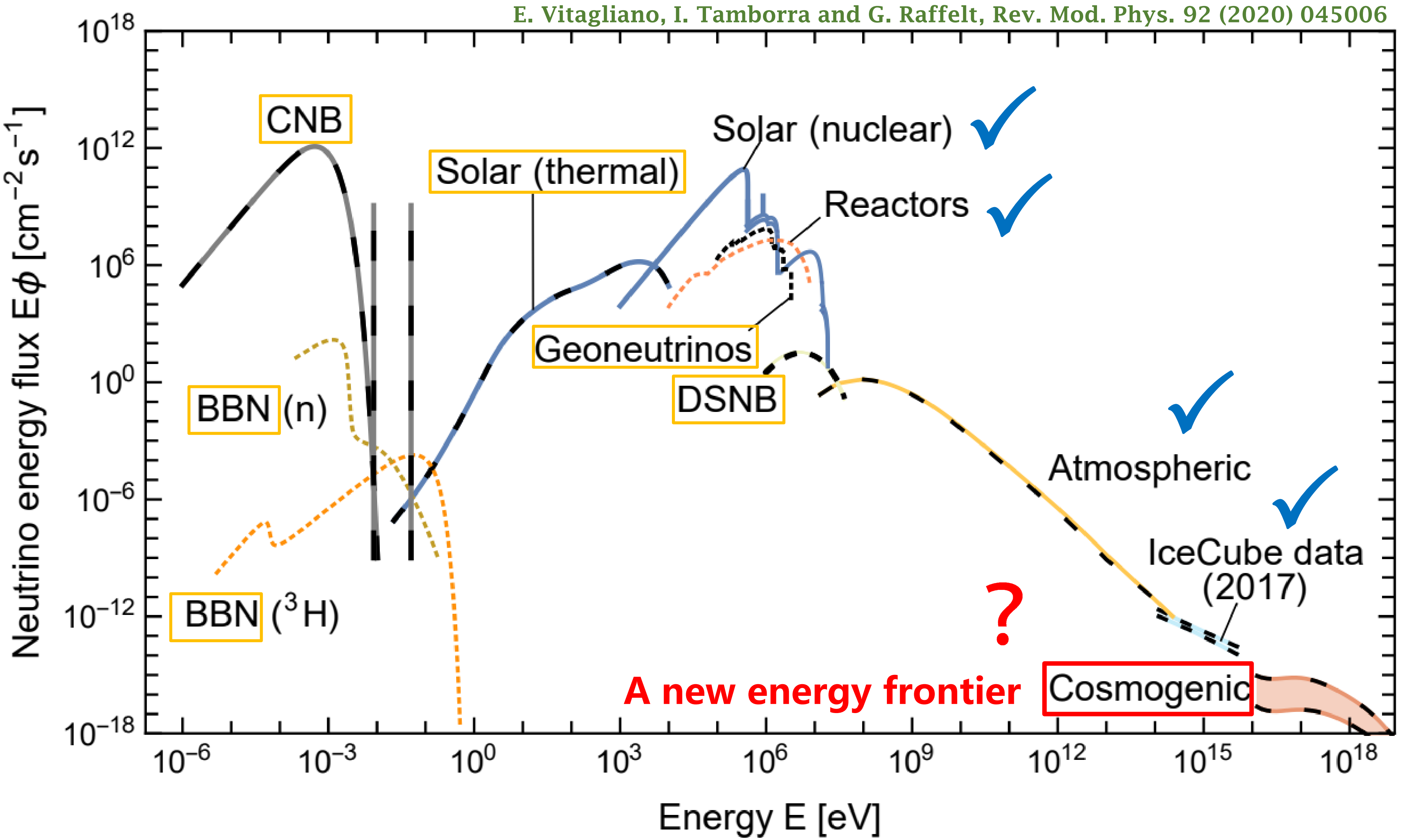
- $p+\gamma_{\rm CMB} \to p\ (\text{or } n) + \text{n}\pi$ Very efficient for $E_{\rm p} \gtrsim 50$ EeV $(p_{\rm p}+p_{\gamma})^2 > (M_{\rm n}+M_{\pi})^2$
- $p+\gamma_{\rm CMB} \to \Delta^{+}(1232) \to p+\pi^{0}(\text{or } n+\pi^{+})$
- $\pi \to \nu + \ldots$ $E_{\nu} \approx \mathcal{O}(1\ \text{EeV})$

COM energy is just around 1 GeV, everything is standard and well known here.

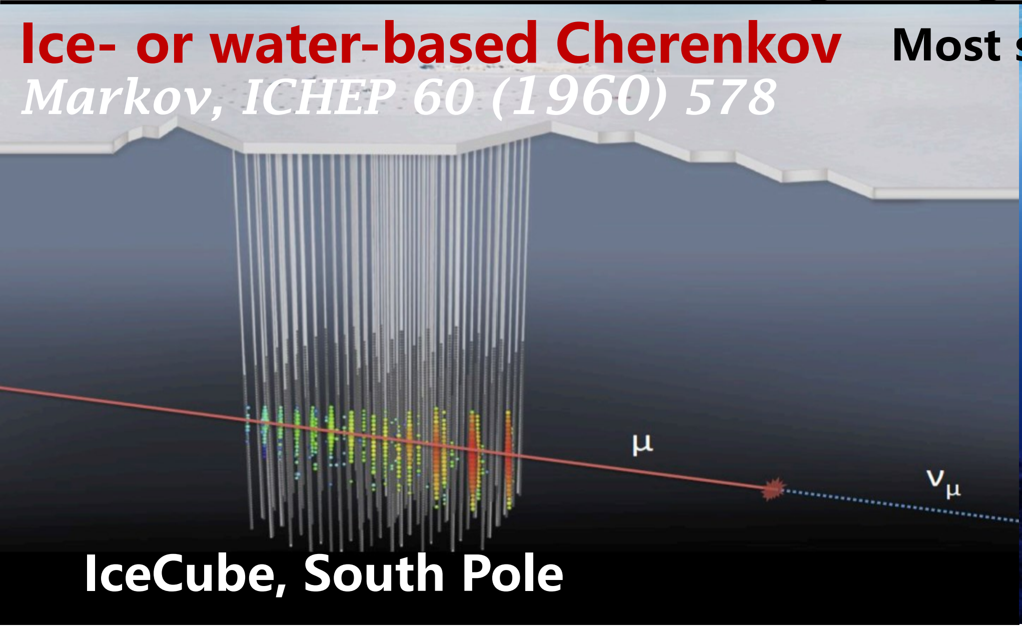
CR+CMB (CIB) = Guaranteed neutrino source at EeV!

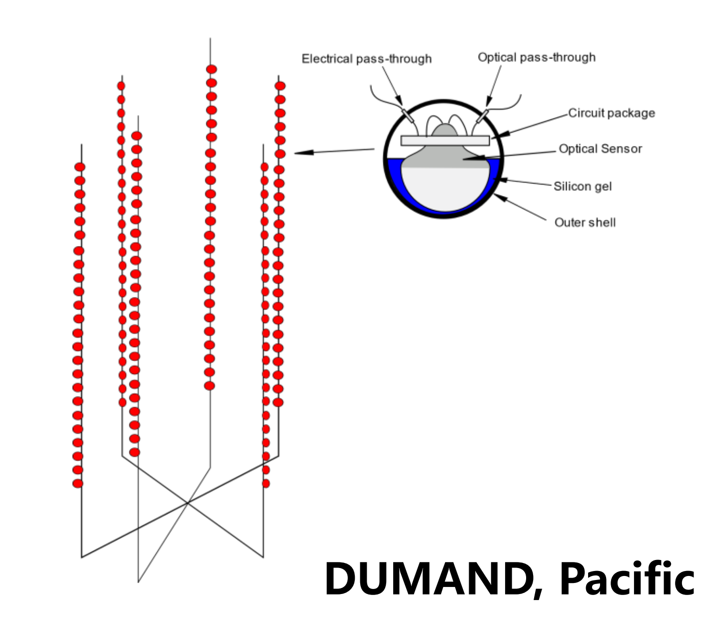
V. S. Berezinsky, G. T. Zatsepin, PLB 28 (1969) 423

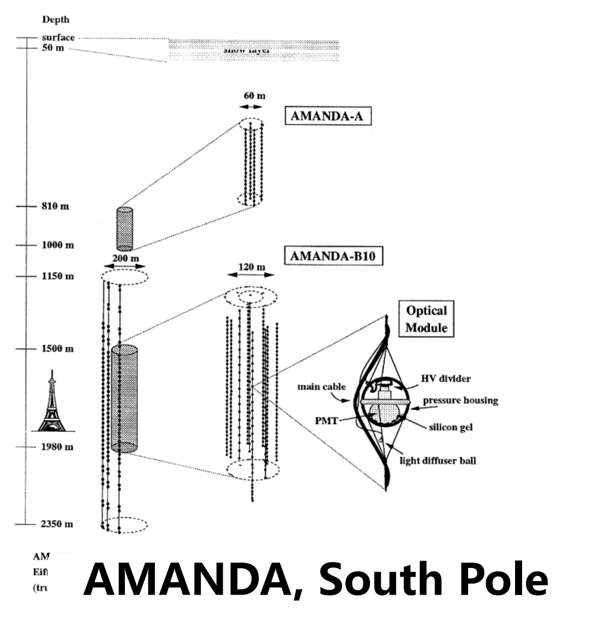
Neutrino fluxes from eV to EeV

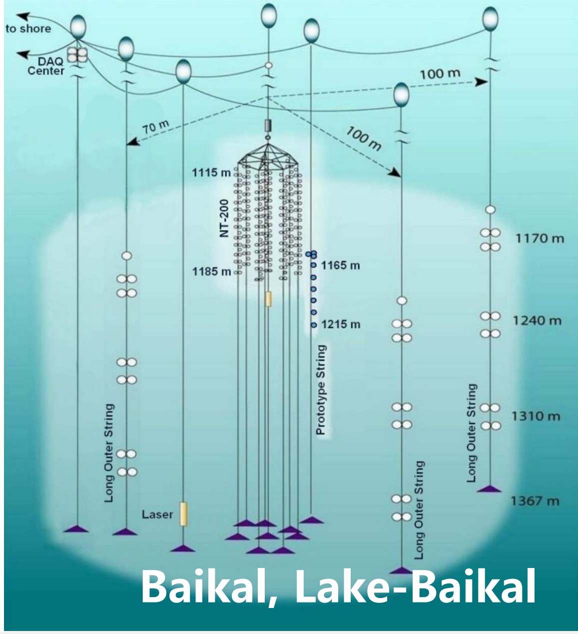


Finished and on-going experiments @PeV



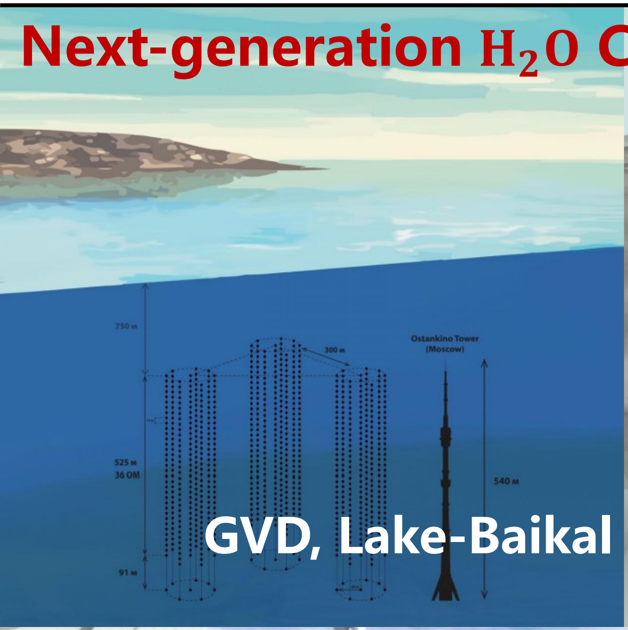


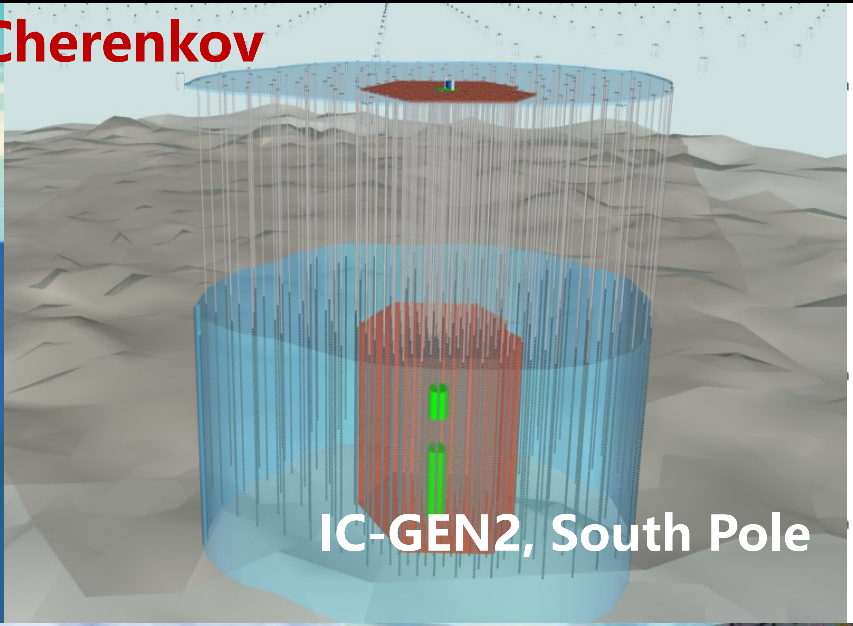


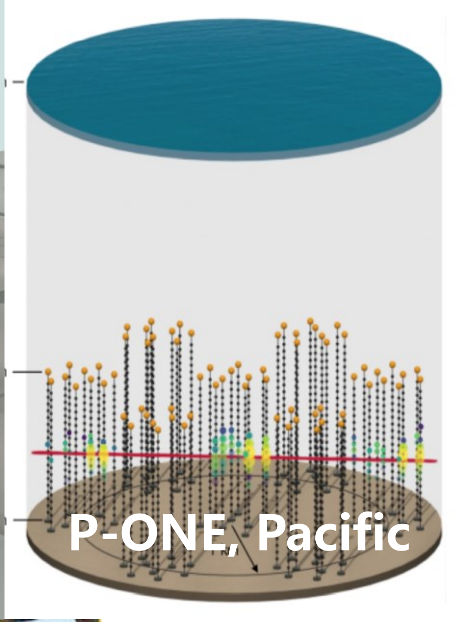


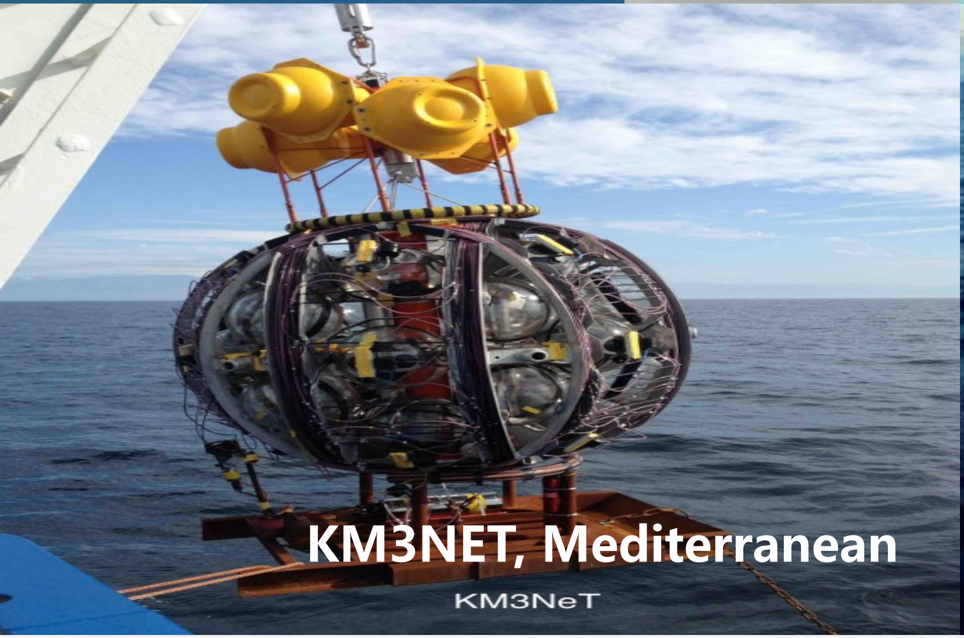
Near future projects @PeV

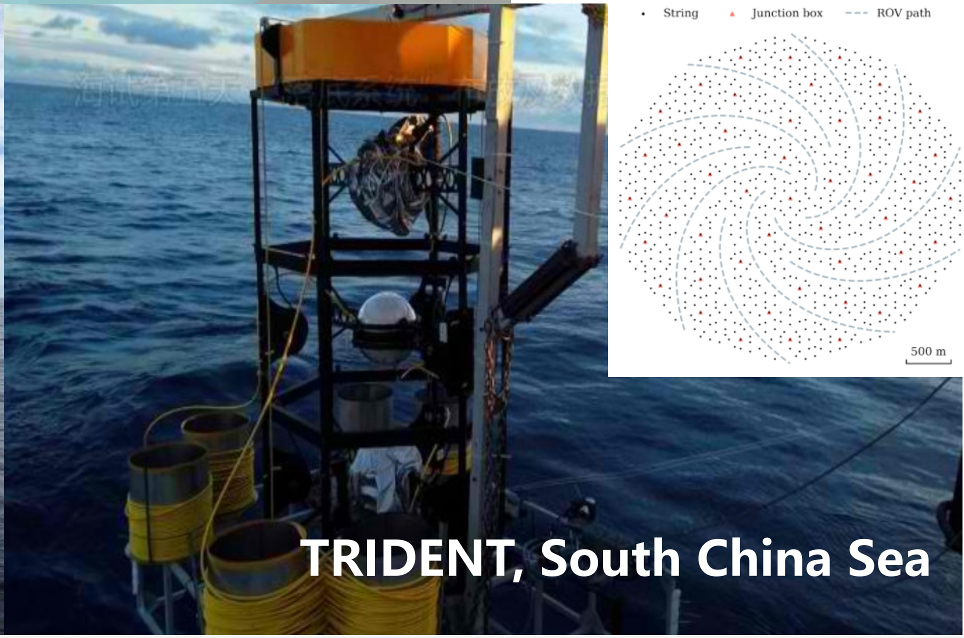
Next-generation H_2O Cherenkov





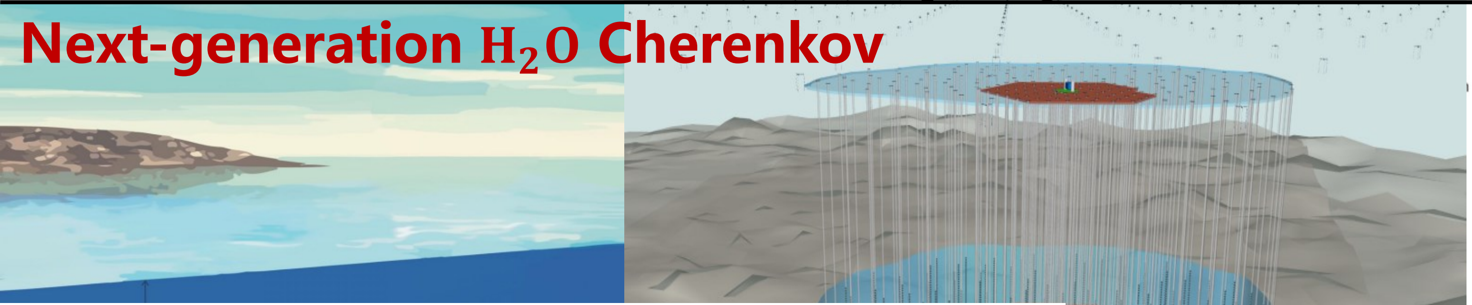


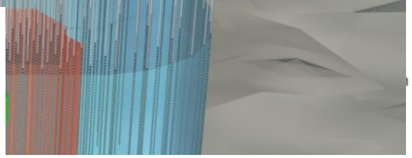


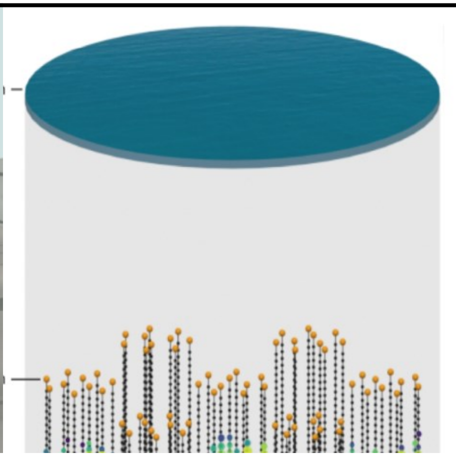


Near future projects @PeV

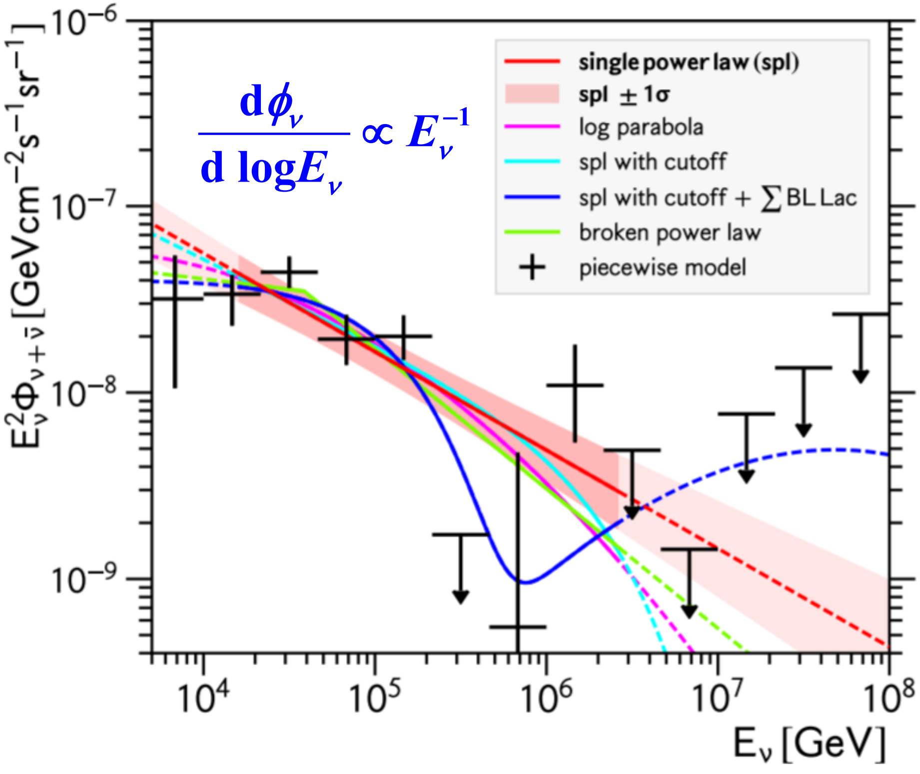
Next-generation H_2O Cherenkov

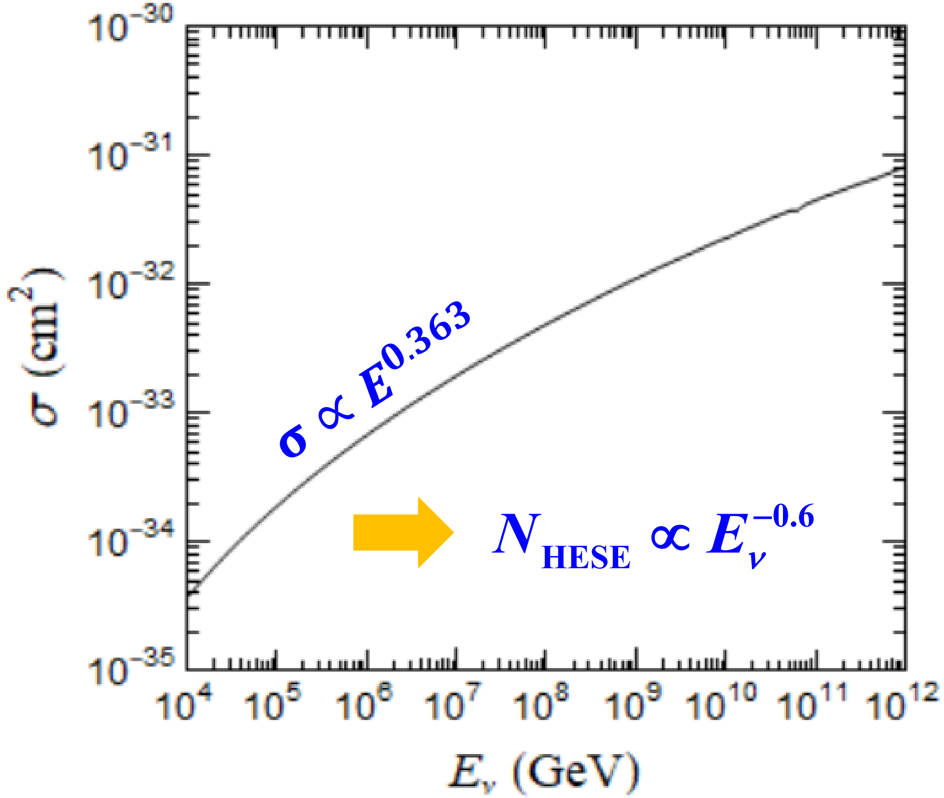






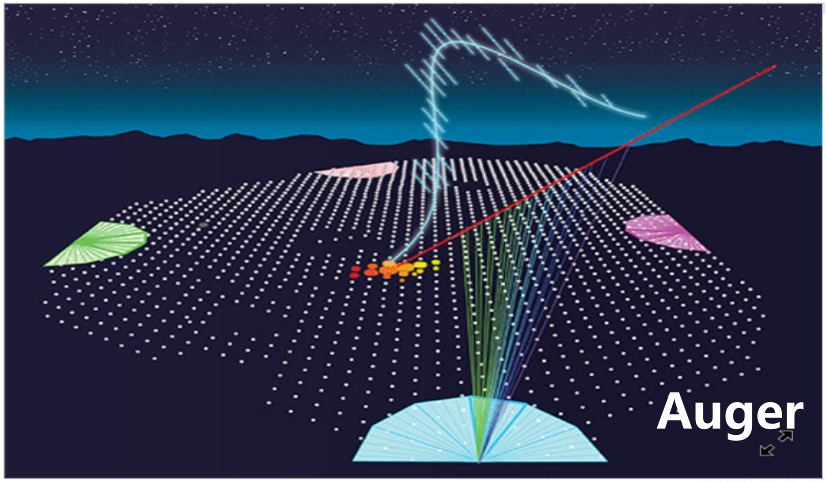
Optimized for TeV-PeV neutrinos, but not the best for EeV nu!



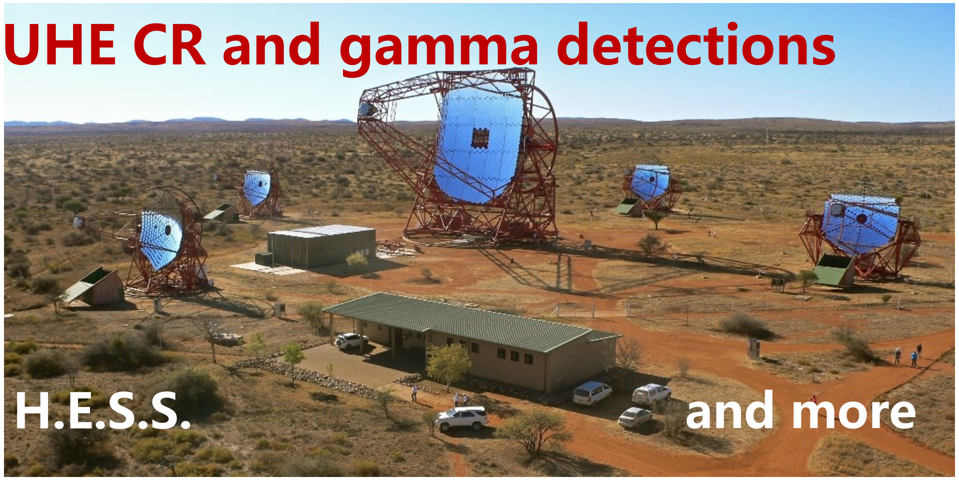


On-going campaign

Technique	Approx. time of proposal or detection
Water and Ice Cherenkov	*Markov, ICHEP 60 (**1960**) 578*
Acoustic	*Askaryan, Sov. JAE 3 (**1957**) 921*
Fluorescence	*Greisen et. al., e.g. Proc. 9thICCR (**1965**) 609*
Particle direct detection	*Linsley et. al., PRL 6 (**1961**) 485*
Atmospheric Cherenkov	*Galbraith and Jelley, Nature 171 (**1953**) 349*
Askaryan effect	*Askaryan, Sov.Phys.JETP 14 (**1962**) 441*
Air shower radio	*Jelley, Il Nuovo Cimento 8 (**1958**) 578*
Radar echo	*Blackett and Lovell, Proc. Roy. Soc., 177 (**1941**) 183*

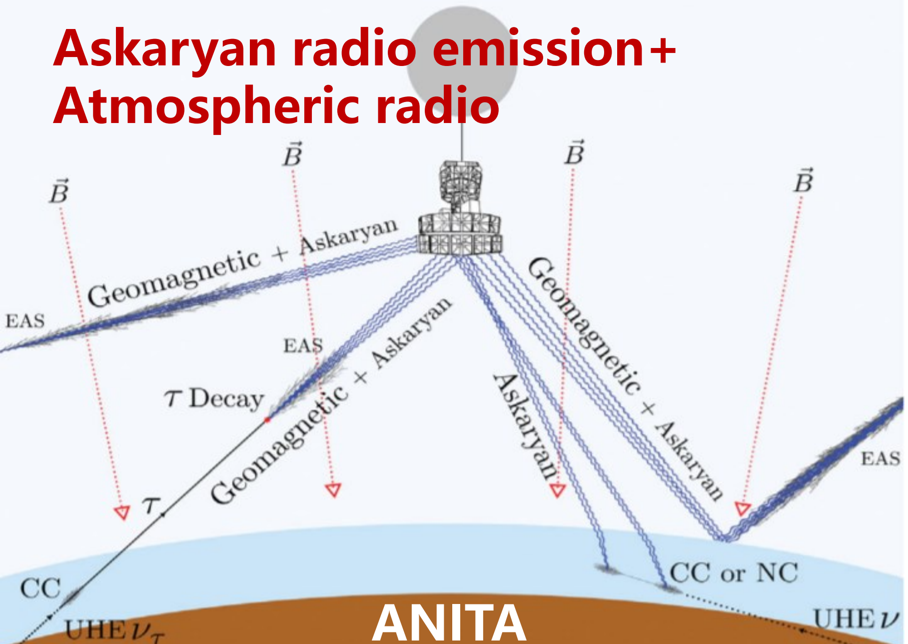


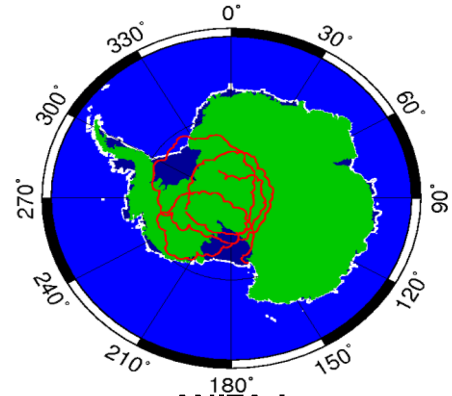
APS/Carin Cain



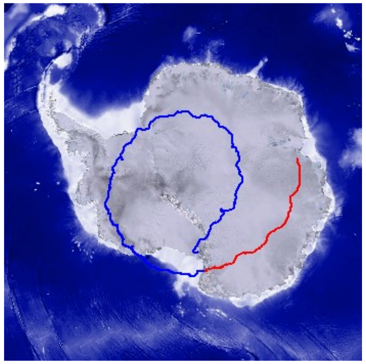
On-going campaign

Askaryan radio emission+
Atmospheric radio



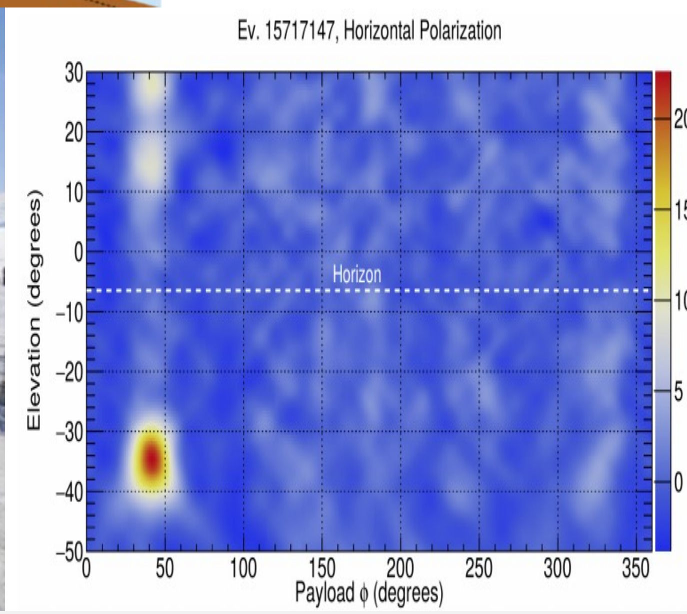


ANITA-I



ANITA-III

40+ papers about new physics explanations



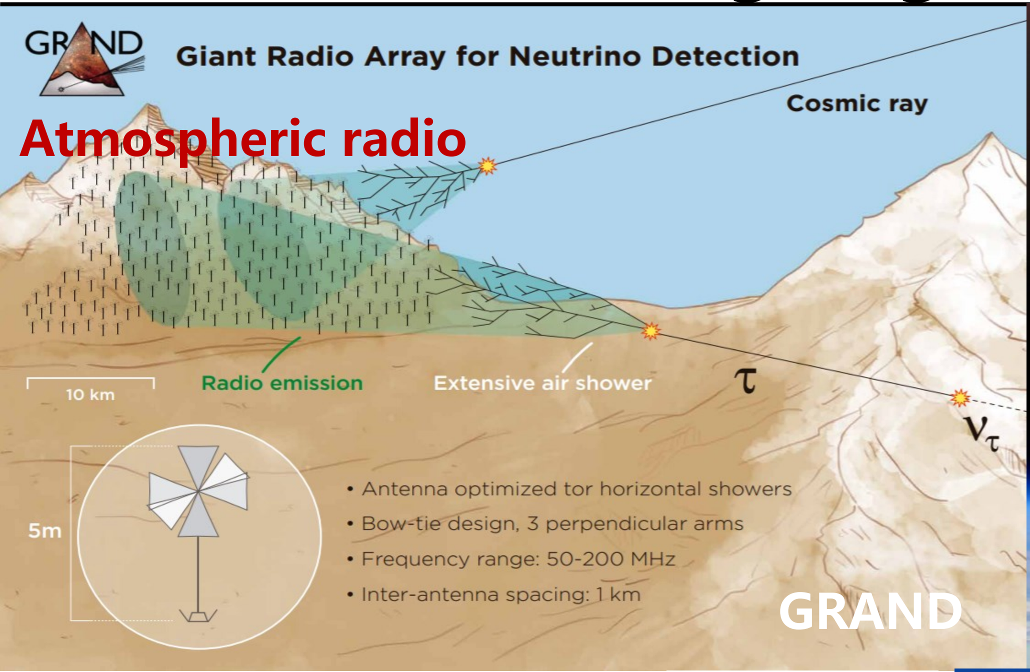
New Physics is not compatible with ANITA-IV results

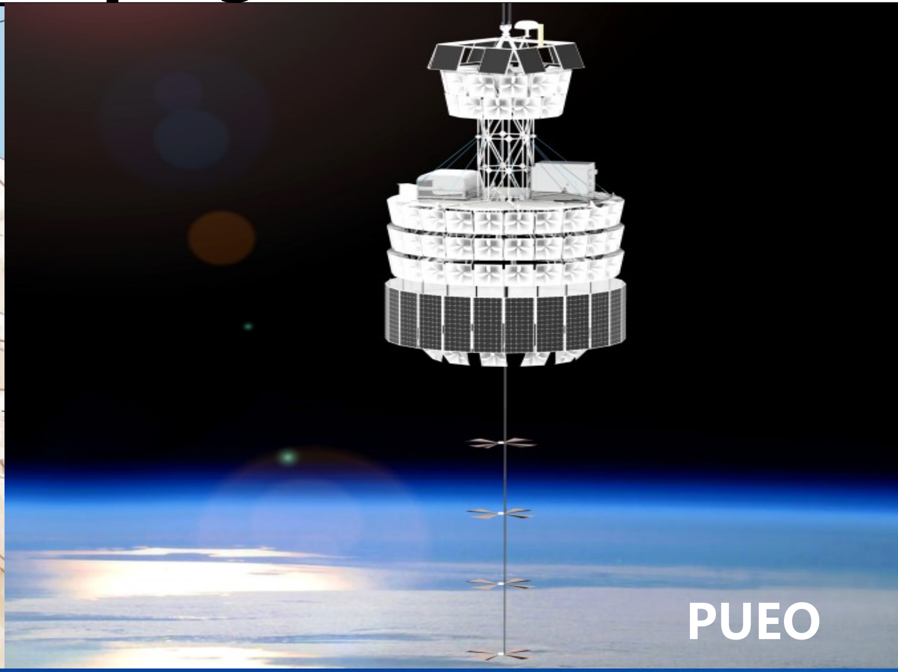
ANITA, PRL 126 (2021) 071103
ANITA, PRD 105 (2022) 042001

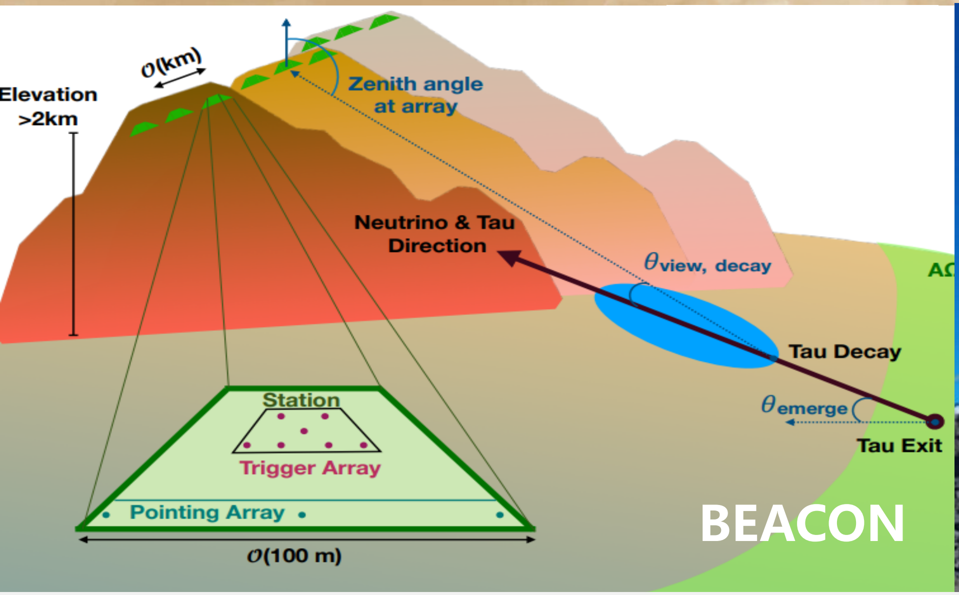
Something else not well understood like subsurface?

I. Shoemaker et al, 1905.02846
D. Smith et al., 2009.13010

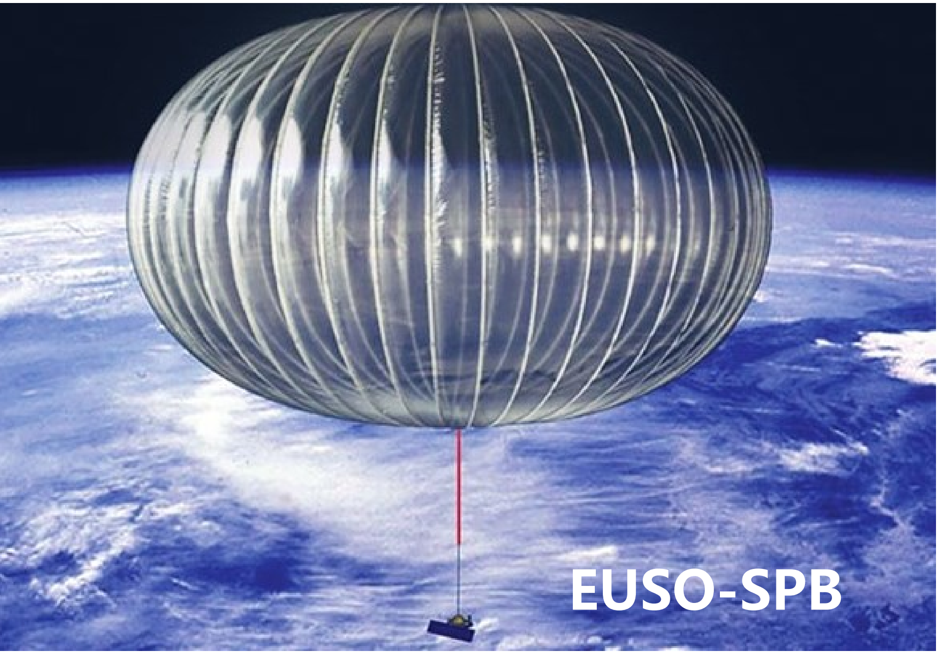
On-going campaign

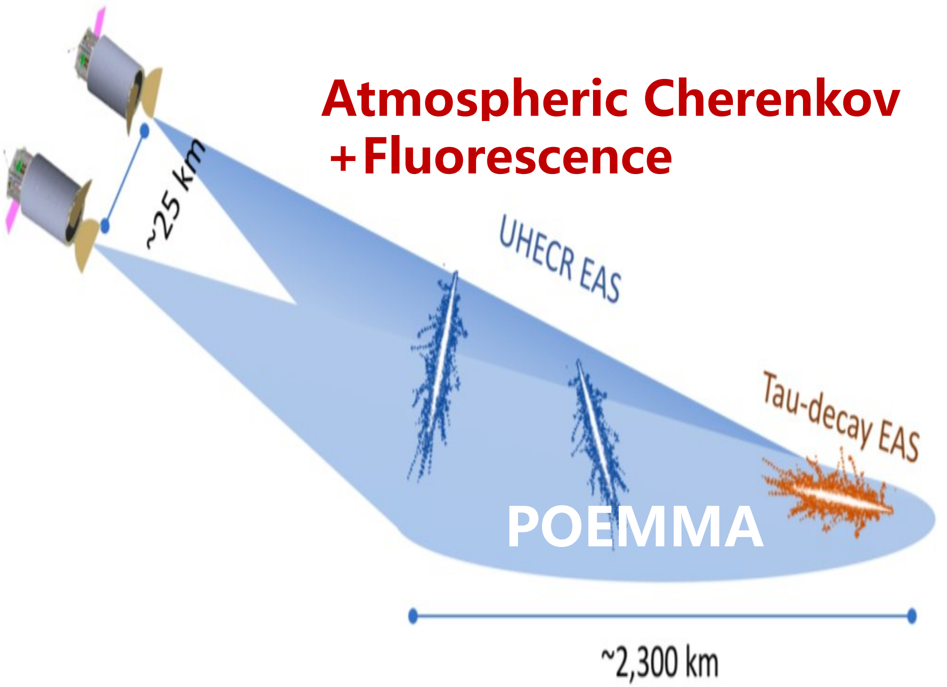


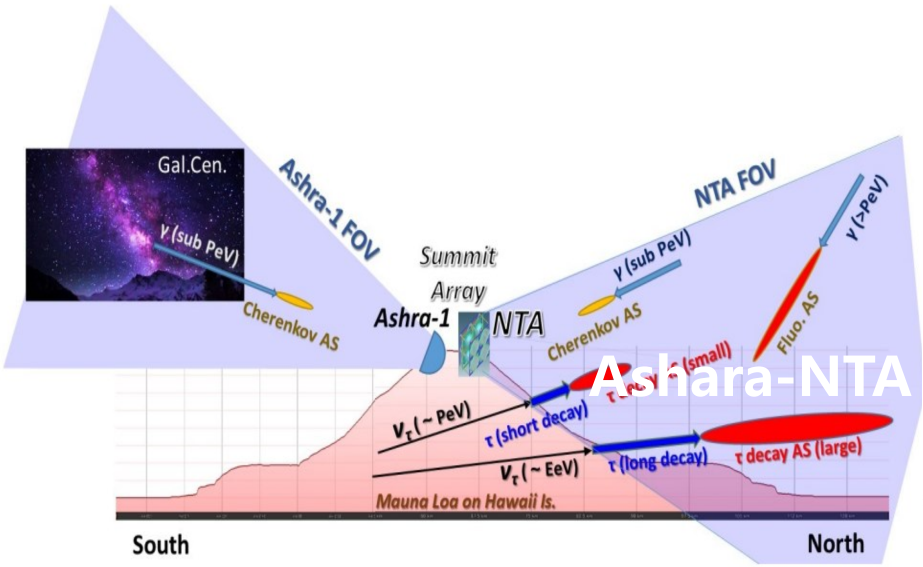


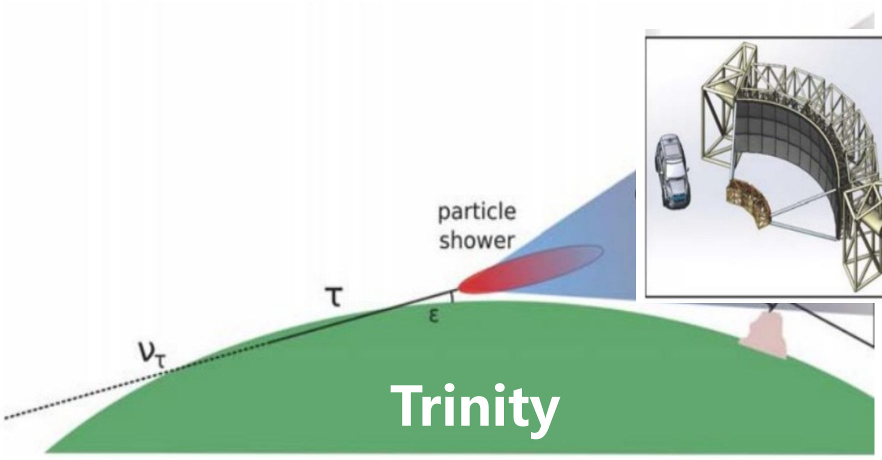


On-going campaign

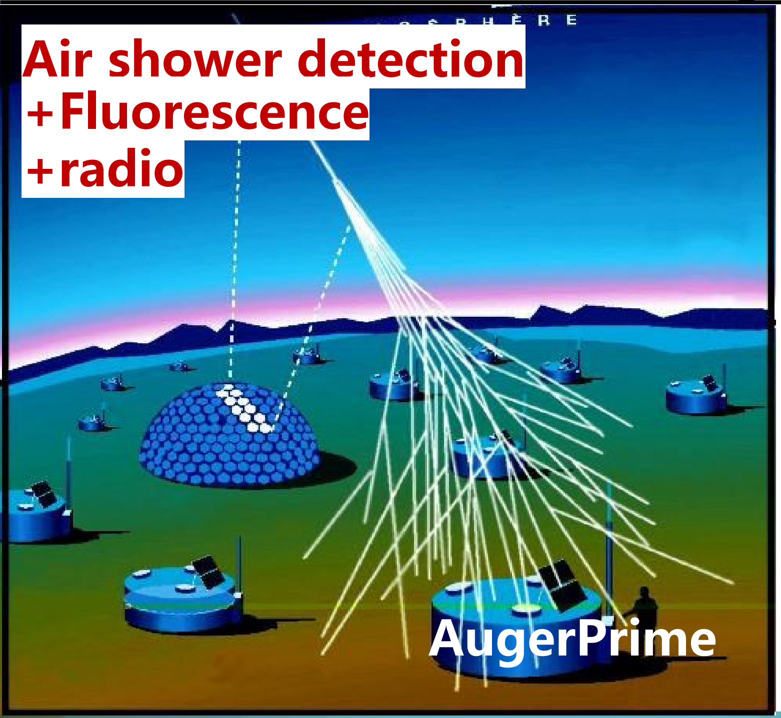




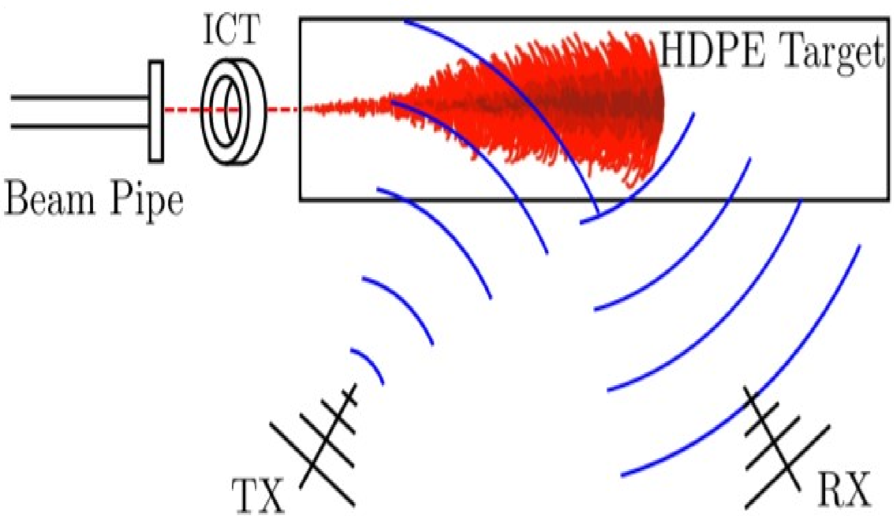




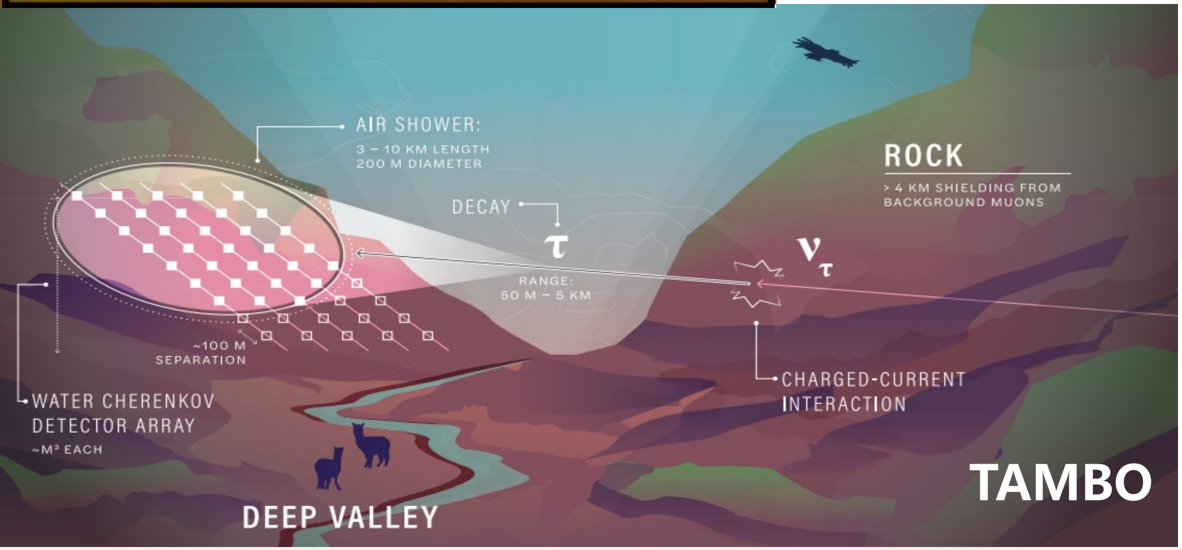
On-going campaign



Radar Echo



RET-CR



More mechanisms

- **Transition radiation**

  Ginzburg and Frank, J. Phys. 9 (1945) 353
  Motloch et al., PRD 93 (2016) 043010

- **Radio emission from sudden death of shower**

  Revenu and Marin, ICRC2013, 0398

On-going campaign

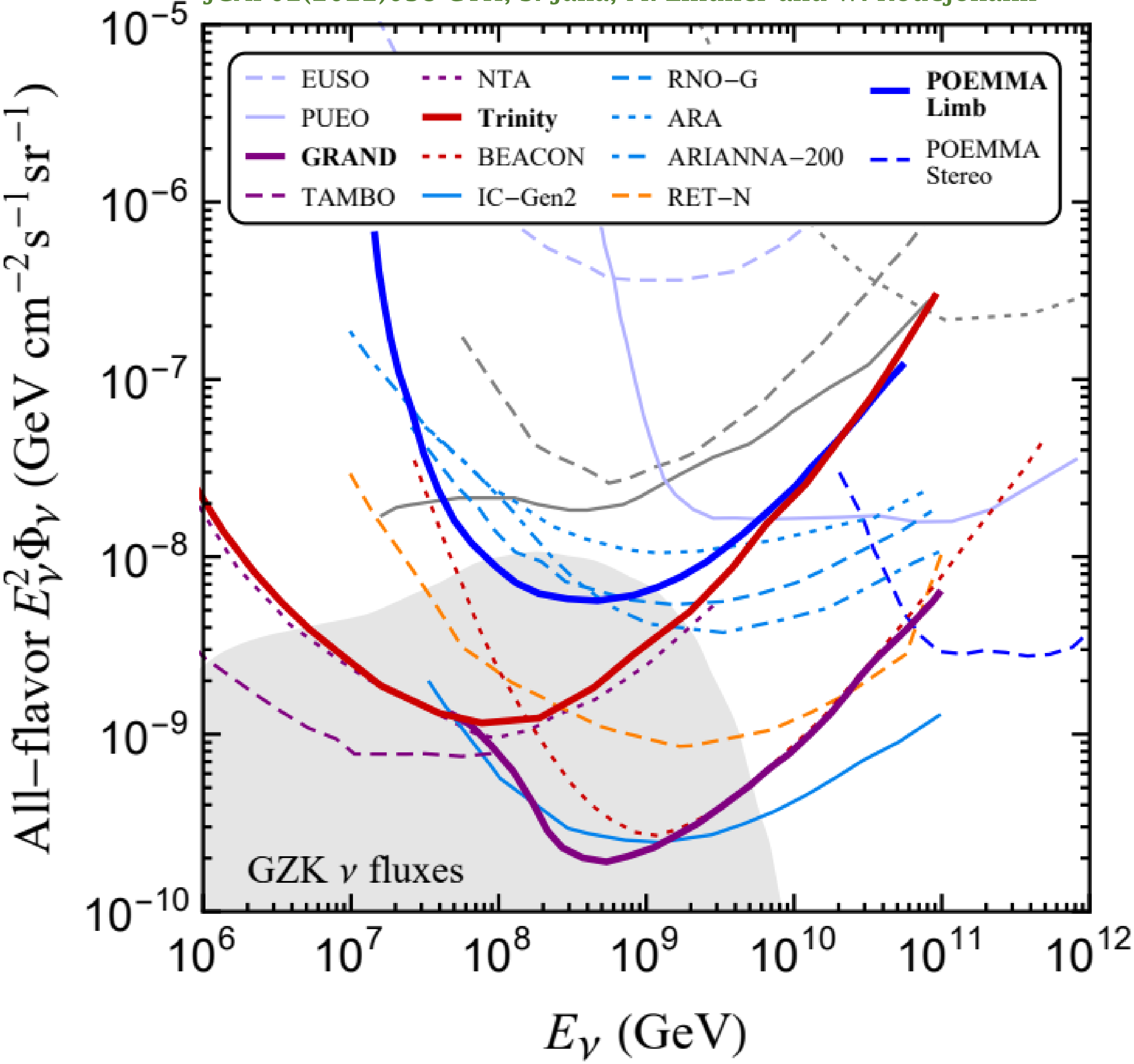
Telescope	Geography	Technique	Energy	ν flavor	$E_\nu^2\Phi_\nu$	Assumed time
EUSO-SPB2 [134–136]	Balloon	Atm-Cher, Fluo	> 10 EeV	ν_τ	2.1×10^{-7}	100 d
PUEO [137, 138]	Balloon	Atm-radio, Aska	> 0.4 EeV	ν_τ, $\nu_{e,\mu,\tau}$	6.3×10^{-9}	100 d
POEMMA-Limb [109]	Satellite	Atm-Cher	> 10 PeV	ν_τ	3.2×10^{-9}	5 yr
POEMMA-Stereo [109]	Satellite	Fluo	> 20 EeV	ν_τ	1.6×10^{-9}	5 yr
GRAND [103, 104]	Mtn-val	Atm-radio	> 50 PeV	ν_τ	1.3×10^{-10}	10 yr
TAMBO [139]	Mtn-val	Atm-Cher	> 3 PeV	ν_τ	4.6×10^{-10}	10 yr
Ashra-NTA [140]	Mtn-val	Atm-Cher, Fluo	> 1 PeV	ν_τ	5.5×10^{-10}	10 yr
Trinity [105–108]	Mtn-top	Atm-Cher	> 1 PeV	ν_τ	5.9×10^{-10}	10 yr
BEACON [141, 142]	Mtn-top	Atm-radio	> 10 PeV	ν_τ	1.9×10^{-10}	10 yr
IC-Gen2 Radio [143, 144]	In-ice	Aska	> 30 PeV	$\nu_{e,\mu,\tau}$	1.2×10^{-10}	10 yr
RNO-G [145, 146]	In-ice	Aska	> 30 PeV	$\nu_{e,\mu,\tau}$	2.4×10^{-9}	10 yr
ARA [147]	In-ice	Aska	> 30 PeV	$\nu_{e,\mu,\tau}$	4.3×10^{-9}	by 2022
ARIANNA-200 [148]	In-ice	Aska	> 10 PeV	$\nu_{e,\mu,\tau}$	1.8×10^{-9}	10 yr
RET-N [149–151]	In-ice	Radar echo	> 8 PeV	$\nu_{e,\mu,\tau}$	4.0×10^{-10}	5 yr

Experiments sensitive to EeV nu are listed

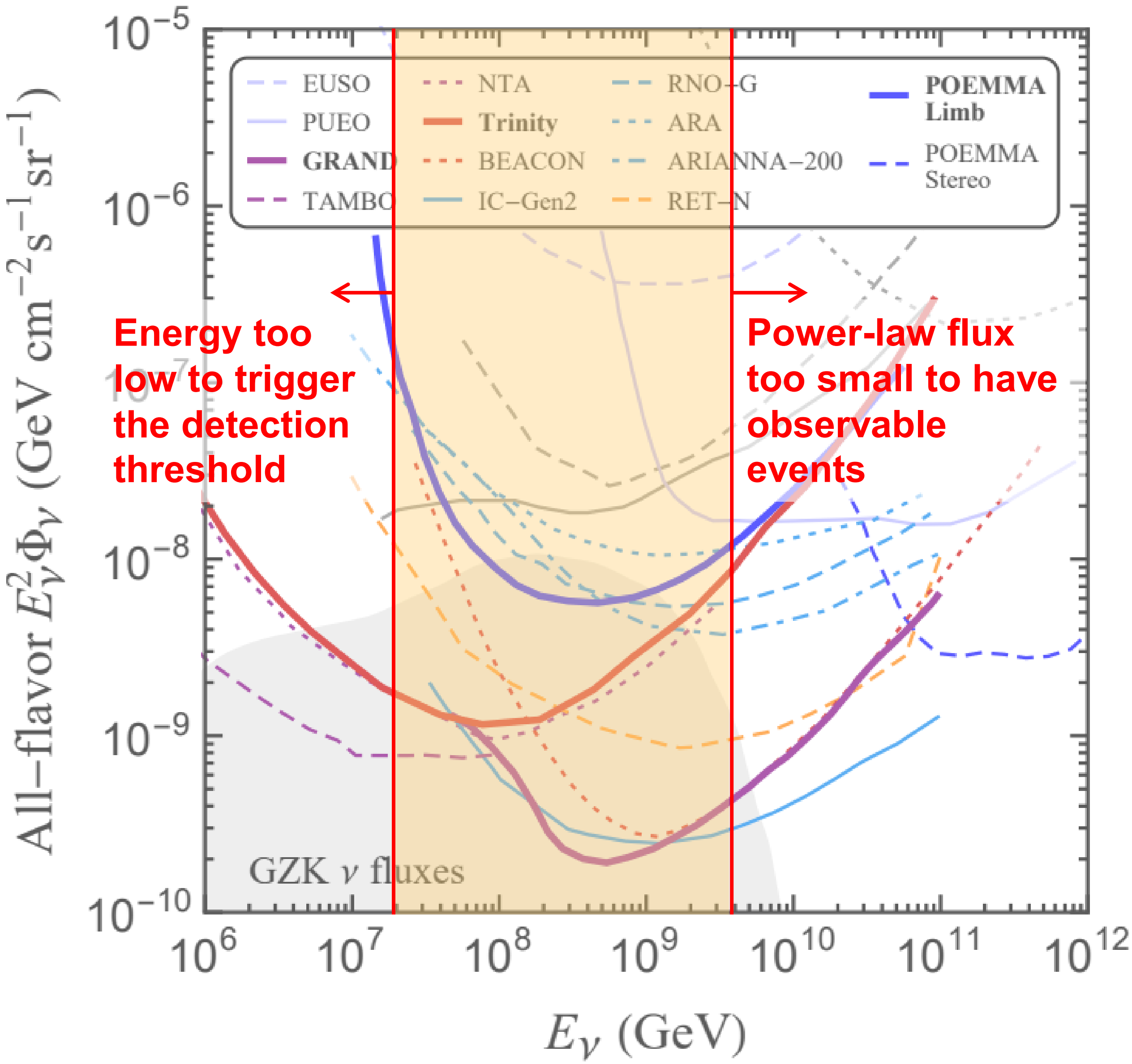
Askaryan effect and radar echo can be used to probe all three nu flavors
Other techniques are mostly sensitive to tau neutrinos, thanks to the tau decay length of 50 km at EeV energy scales.

On-going campaign

JCAP02(2022)038 GYH, S. Jana, M. Lindner and W. Rodejohann



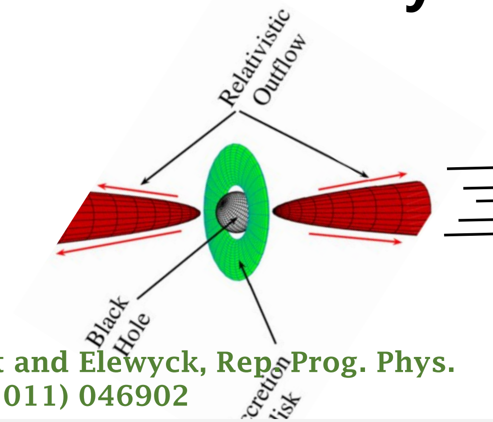
On-going campaign



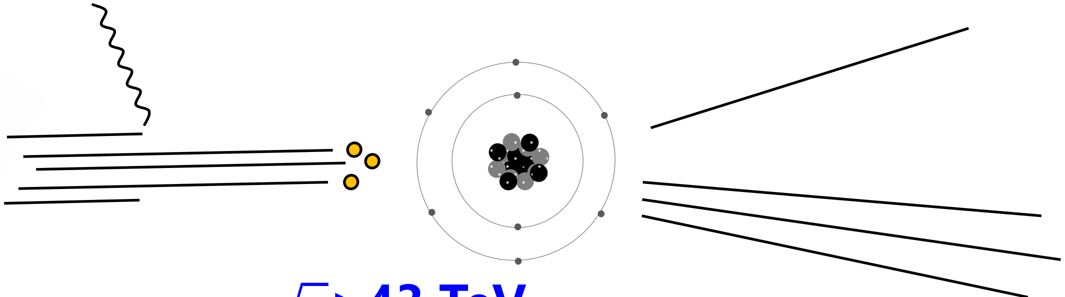
Importance for astronomy and particle physics

- **Measurement of EeV neutrinos is of great importance for multimessenger astronomy.**
  - **Improving our understanding of cosmic accelerators.**
  - **The components of cosmic ray.**
  - **The reionization history.**

- **It is also a particle collider. We have free accelerated UHE neutrino beam colliding with matter, as well as clean signal versus CR background.**
  - **COM energy can be as high as 43 TeV, for nu-N scattering.**
  - **Compare to forward facility at LHC, only 43 GeV or so.**
  - **Excellent facility to probe UV physics.**

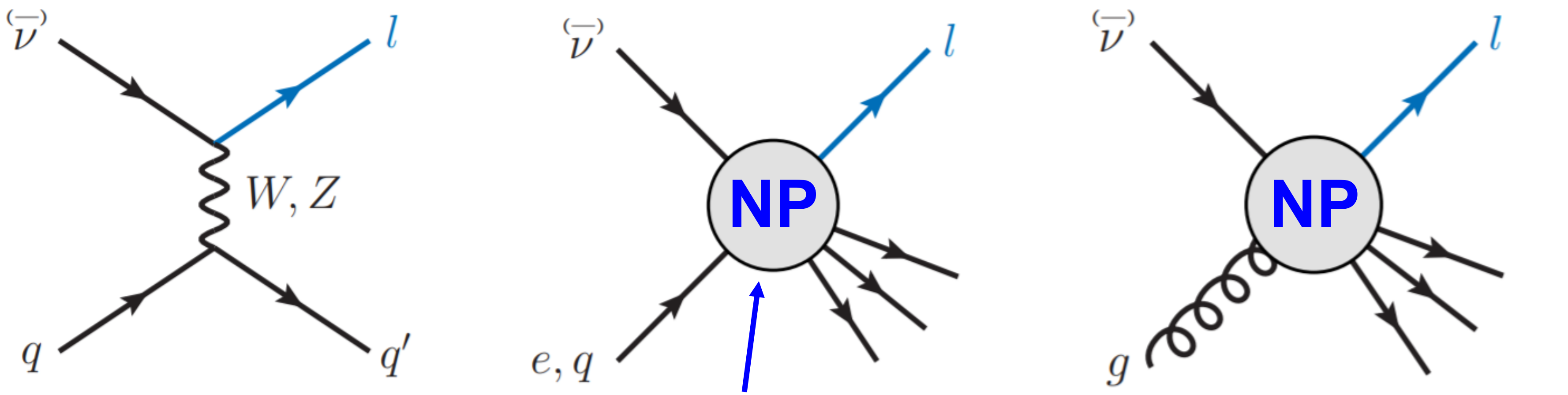


Baret and Elewyck, Rep. Prog. Phys. 74 (2011) 046902



$\sqrt{s}$>43 TeV

I. Minimal new physics



Representative diagrams

New physics is hidden here

What about photon parton?? (later)

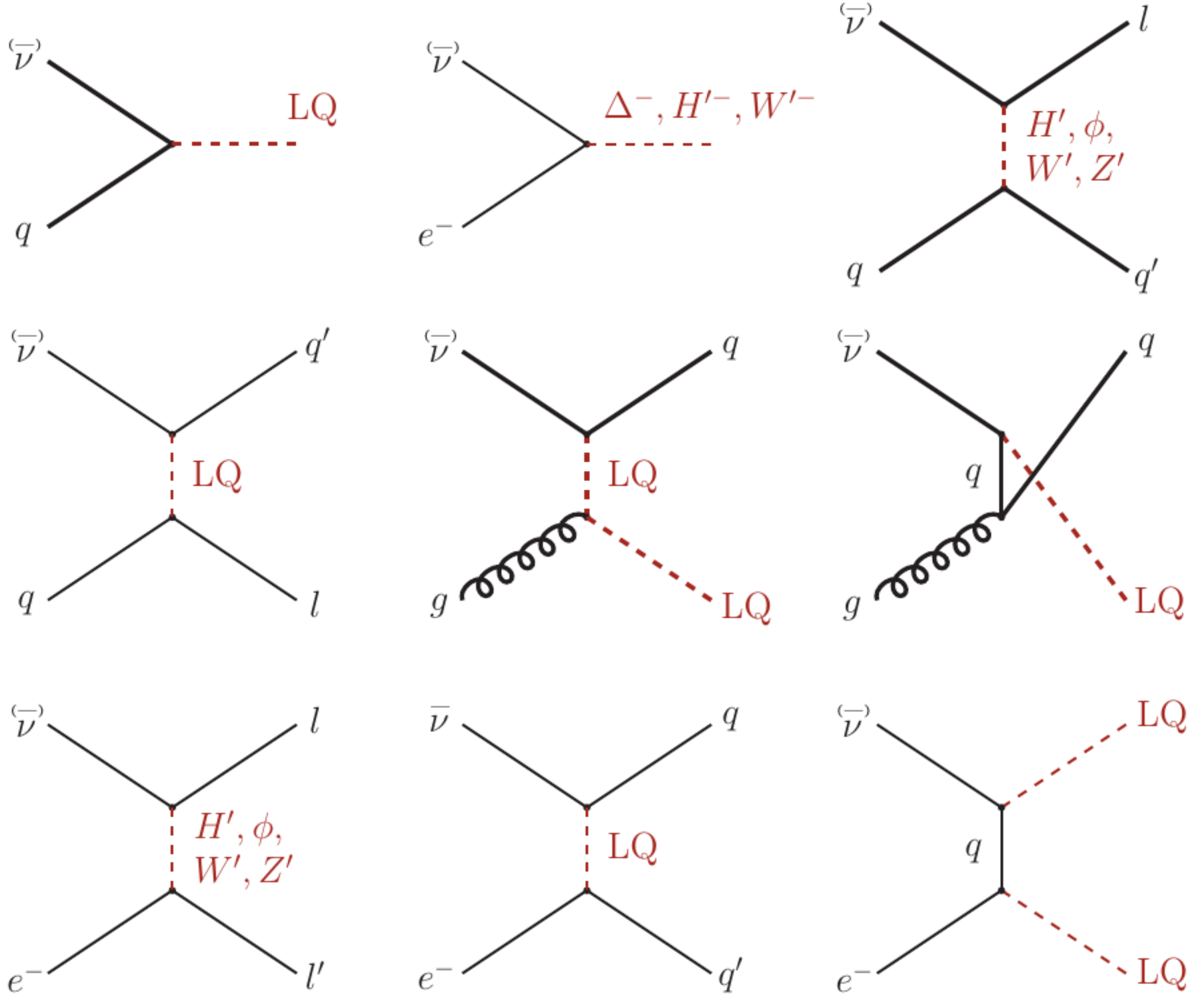
What can we do with tau neutrino telescopes?

Here, we assume no *light* fermions other than SM ones. New mediators are very short-lived and active degrees of freedom are only standard model constitutes.

There are theories with long-lived particles: sterile neutrino or dark matter particles (refer to 40+ ANITA papers for model details)

I. Minimal new physics

Our beams: neutrino + electron, quark, gluon (and photon)



Leptoquark

$$y^{\rm QL}_{i\alpha}\overline{Q^{c}}^{i}\left(\epsilon\sigma^{a}\right)L^{\alpha}S^{a}_{3}$$

Charged/neutral Higgs

$$y^{l}_{\alpha\beta}h^{-}\bar{l}_{\alpha}\nu^{c}_{\beta}+y^{q}_{\alpha\beta}h^{-}\bar{D}_{\alpha}U_{\beta}$$

W′

$$\frac{g'}{2\sqrt{2}}W'_{\mu}\bar{f}^{i}\gamma^{\mu}(1\pm\gamma_{5})f^{j}$$

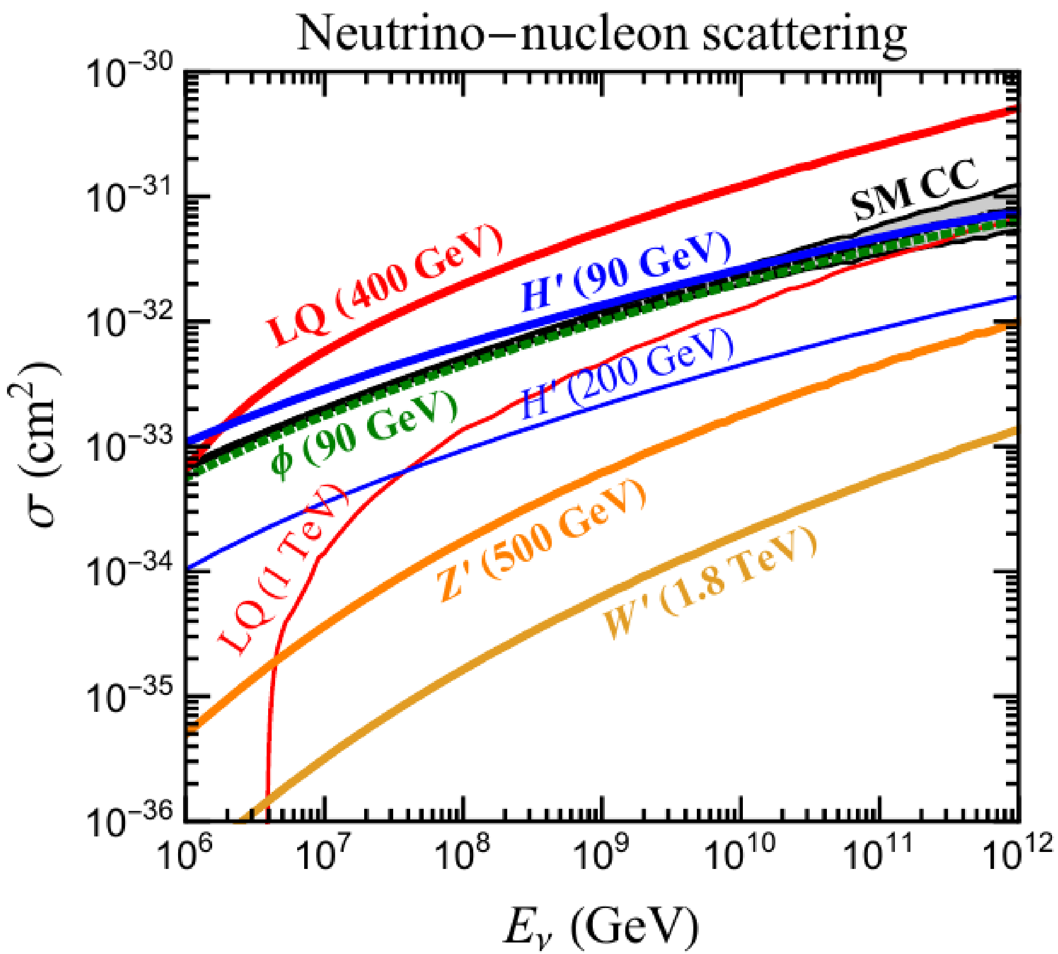
Z′

$$\frac{g'}{2\sqrt{2}}Z'_{\mu}\bar{f}^{i}\gamma^{\mu}(1\pm\gamma_{5})f^{i}$$

Leptophilic forces

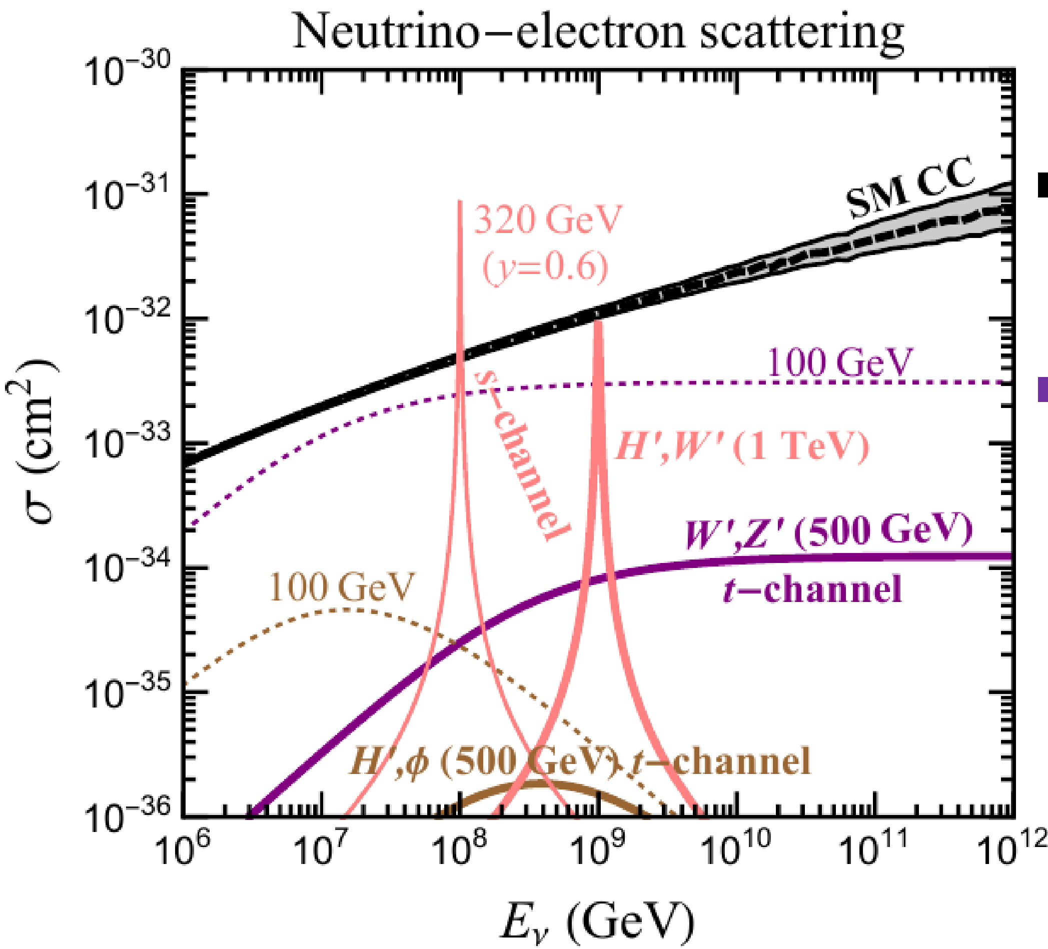
$$y^{l}\phi\bar{l}l+y^{\nu}\phi\bar{\nu}\nu$$

Modification to nu cross section



- The **hadronic interaction** benefits from the **enhancement** of **sea quark** and **gluon** PDFs, especially those of second and third families.
- However, the **SM hadronic** process is a **irreducible background**.
- Only the contributions from **leptoquark** and **charged/neutral Higgs** models can exceed the SM background.
- The cross sections are maximally allowed by laboratory limits.

Modification to nu cross section



- **Two types of contributions from the leptophilic forces.**
  - ***s*-channel resonance**
  - ***t*-channel production**

- **Unfortunately, *s*-channel resonance is suppressed at very high energies.**

$$\sigma(s) = 8\pi\Gamma^2_{H'}\frac{s/M^2_{H'}}{(s-M^2_{H'})^2+(M_{H'}\Gamma_{H'})^2}$$

- ***t*-channel processes can benefit from the small moment transfer, if the mediator is vector and has small mass.**

$$\sigma_{H'}(s) = \frac{Y^2_{\tau e}Y^2_{\beta e}\left[\frac{s(2M^2_{H'}+s)}{M^2_{H'}+s}+2M^2_{H'}\ln\frac{M^2_{H'}}{M^2_{H'}+s}\right]}{32\pi s^2}$$

$$\sigma_{W'}(s) = \frac{g^2_{\tau e}g^2_{\beta e}\left[2\left(M^2_{W'}+s\right)^2\ln\left(\frac{M^2_{W'}}{M^2_{W'}+s}\right)+s\left(2\frac{M^4_{W'}+s^2}{M^2_{W'}}+3s\right)\right]}{8\pi s^2\left(M^2_{W'}+s\right)}$$

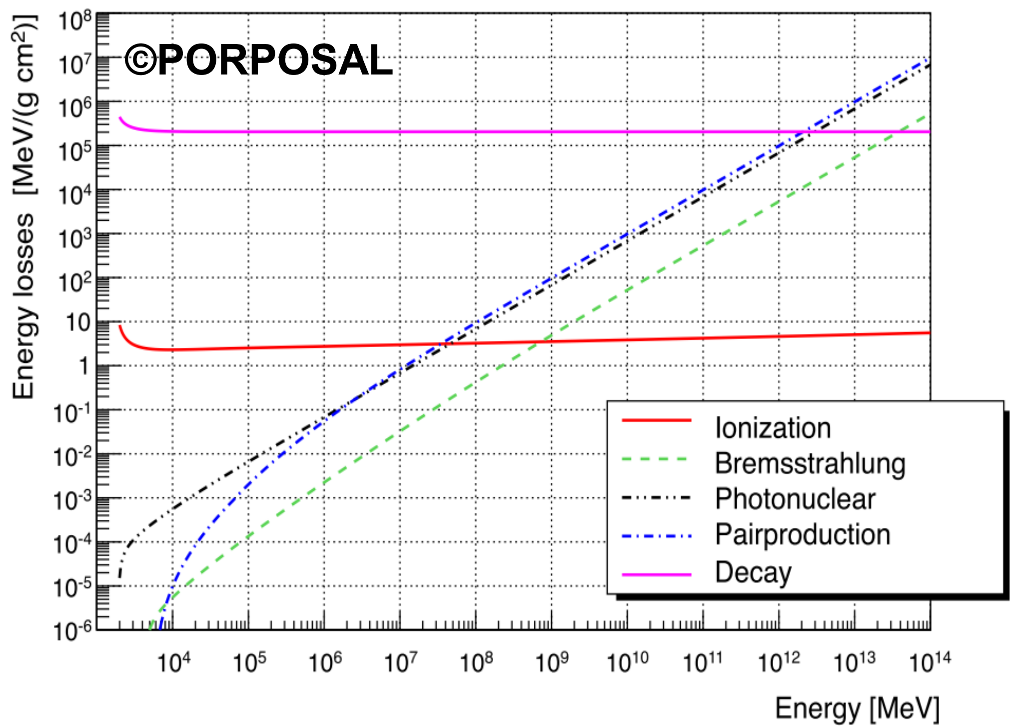
Scalar interaction flips the spin, and hence does not appreciate the long-range enhancement.

Neutrino and tau propagation

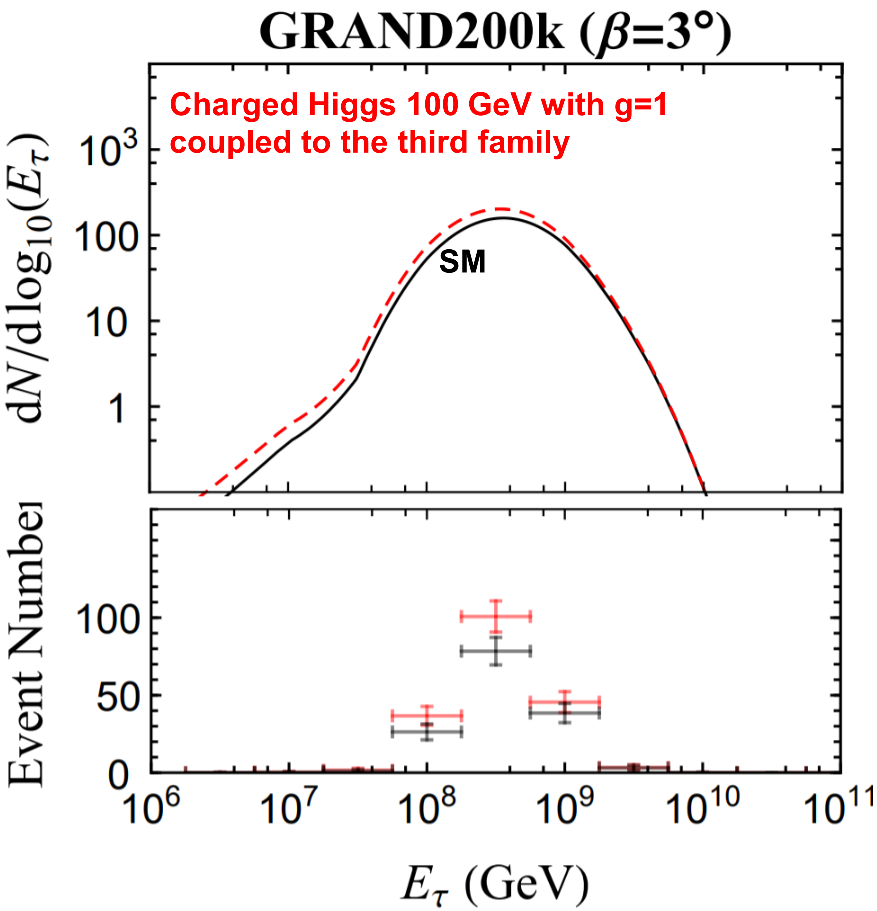
- **Solve the coupled integro-differential equations by discretizing the momentum space, including tau regeneration and energy loss.**
- **The energy loss processes include: ionization, Bremsstrahlung, Photonuclear, Pair production**

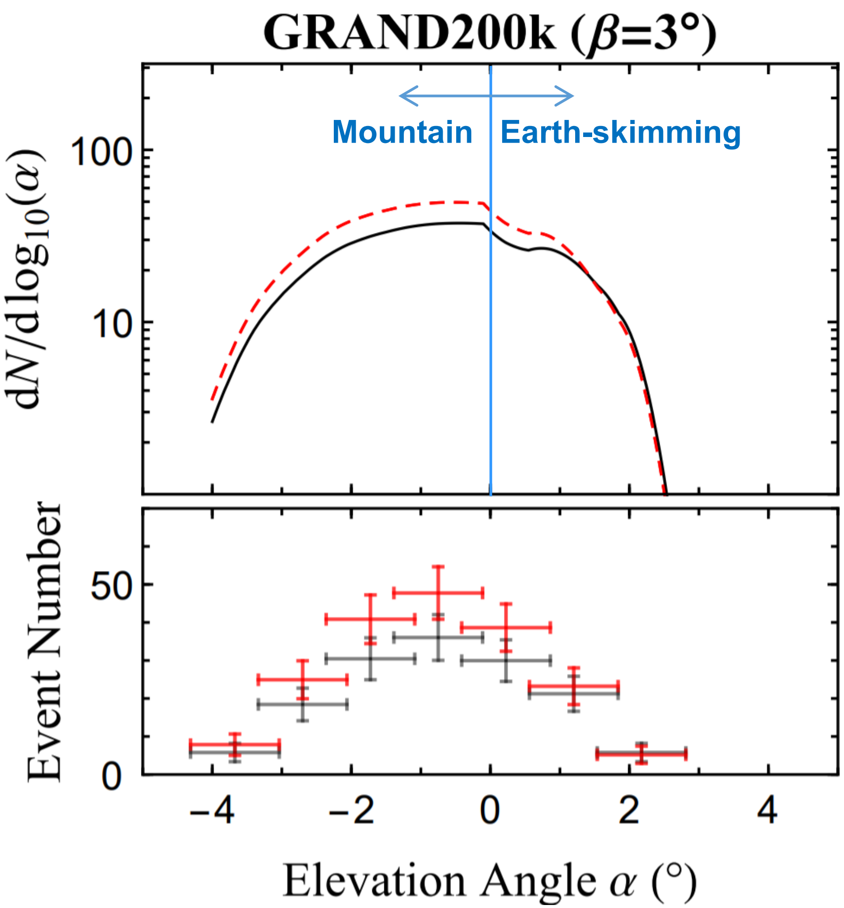
$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\mathrm{d}\Phi_\nu}{\mathrm{d}E_\nu}\right) = - N_{\mathrm{A}}\rho\left(\sigma^{\mathrm{cc}}_{\mathrm{SM}} + \sigma^{\mathrm{nc}}_{\mathrm{SM}} + \sigma_{\mathrm{NP}}\right)\frac{\mathrm{d}\Phi_\nu}{\mathrm{d}E_\nu} + N_{\mathrm{A}}\rho\int \mathrm{d}E'_\nu \frac{\mathrm{d}\Phi_\nu}{\mathrm{d}E'_\nu}\frac{1}{E'_\nu}\left(\frac{\mathrm{d}\sigma^{\mathrm{nc}}_{\mathrm{SM}}}{\mathrm{d}z} + \frac{\mathrm{d}\sigma^{\mathrm{nc}}_{\mathrm{NP}}}{\mathrm{d}z}\right)\Bigg|_{z=\frac{E_\nu}{E'_\nu}} + \int \mathrm{d}E'_\tau \frac{\mathrm{d}\Phi_\tau}{\mathrm{d}E'_\tau}\frac{1}{E'_\tau}\frac{\mathrm{d}\Gamma_\tau}{\Gamma_\tau \mathrm{d}z},$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\mathrm{d}\Phi_\tau}{\mathrm{d}E_\tau}\right) = - \Gamma_\tau\frac{\mathrm{d}\Phi_\tau}{\mathrm{d}E_\tau} - N_{\mathrm{A}}\frac{\rho}{A}\left[\sigma_{\mathrm{pp}} + \sigma_{\mathrm{pn}}\right]\frac{\mathrm{d}\Phi_\tau}{\mathrm{d}E_\tau} + N_{\mathrm{A}}\frac{\rho}{A}\int \mathrm{d}E'_\tau \frac{\mathrm{d}\Phi_\tau}{\mathrm{d}E'_\tau}\frac{1}{E'_\tau}\left(\frac{\mathrm{d}\sigma_{\mathrm{pp}}}{\mathrm{d}z} + \frac{\mathrm{d}\sigma_{\mathrm{pn}}}{\mathrm{d}z}\right)\Bigg|_{z=\frac{E_\tau}{E'_\tau}} + \rho\frac{\partial}{\partial E_\tau}\left[\left(\beta_{\mathrm{pp}} + \beta_{\mathrm{pn}} + \beta_{\mathrm{brems}}\right)E_\tau\frac{\mathrm{d}\Phi_\tau}{\mathrm{d}E_\tau}\right] + N_{\mathrm{A}}\rho\int \mathrm{d}E'_\nu \frac{\mathrm{d}\Phi_\nu}{\mathrm{d}E'_\nu}\frac{1}{E'_\nu}\left(\frac{\mathrm{d}\sigma^{\mathrm{cc}}_{\mathrm{SM}}}{\mathrm{d}z} + \frac{\mathrm{d}\sigma_{\mathrm{NP}}}{\mathrm{d}z}\right)\Bigg|_{z=\frac{E_\tau}{E'_\nu}}$$



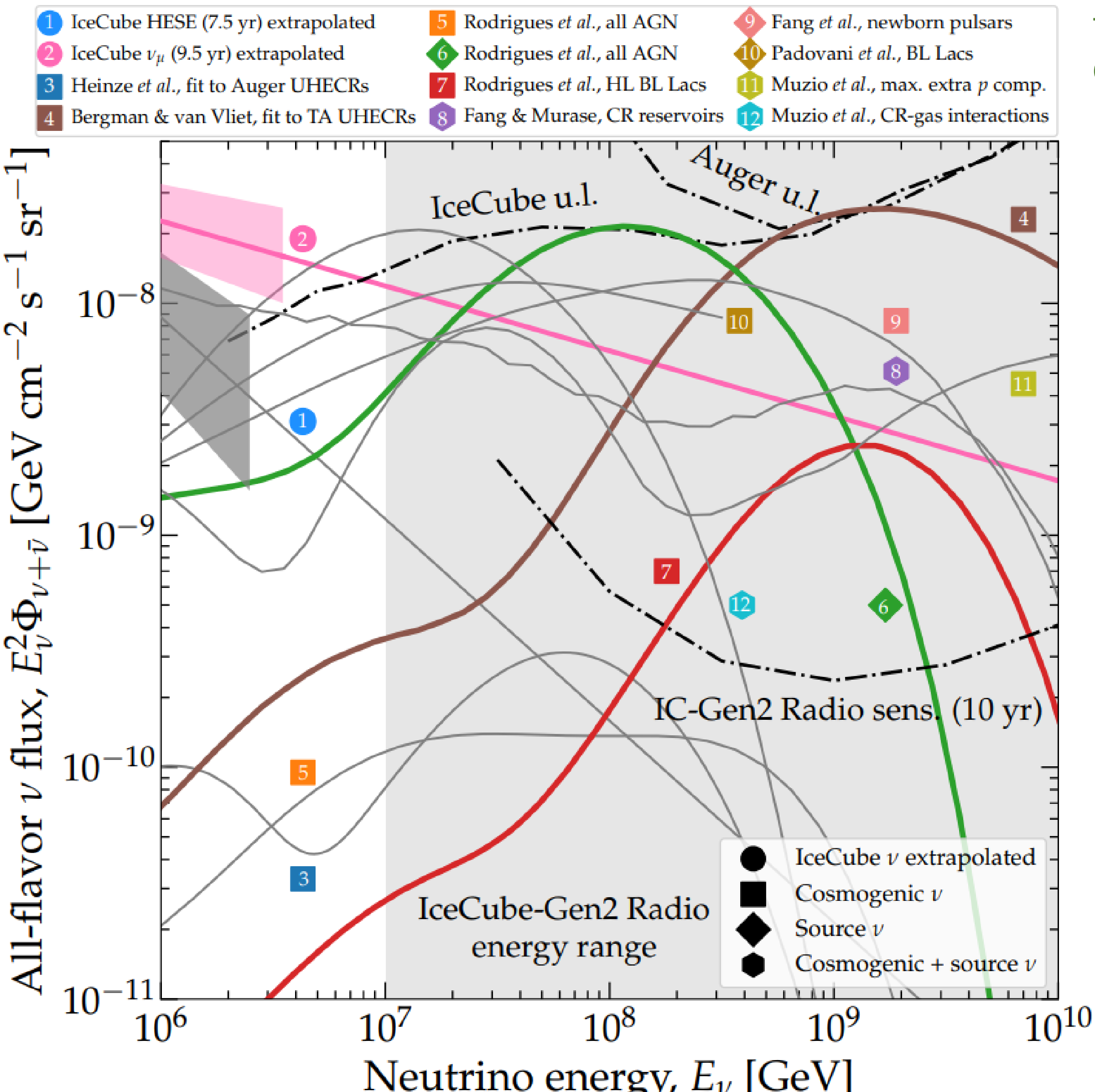
Sensitivity





- In general, the additional charged-Higgs contribution will increase the cross section, and enhance the mountain events.
- The initial neutrino flux is fixed here.

Sensitivity

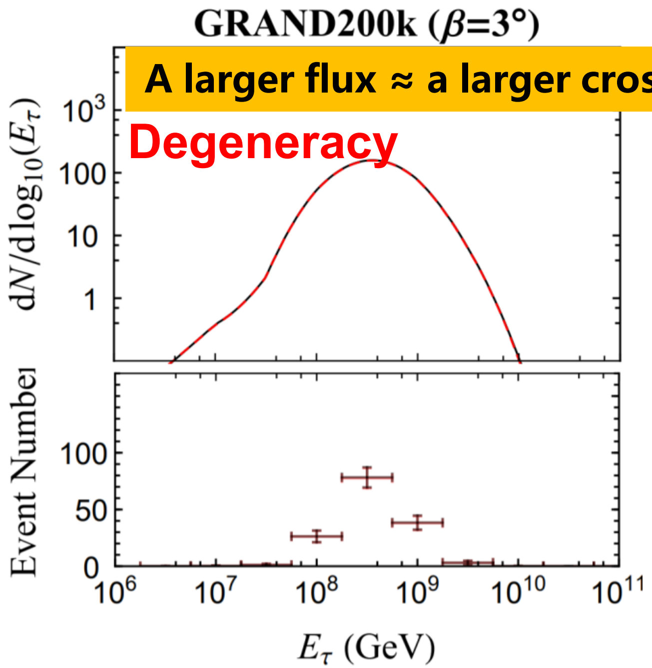


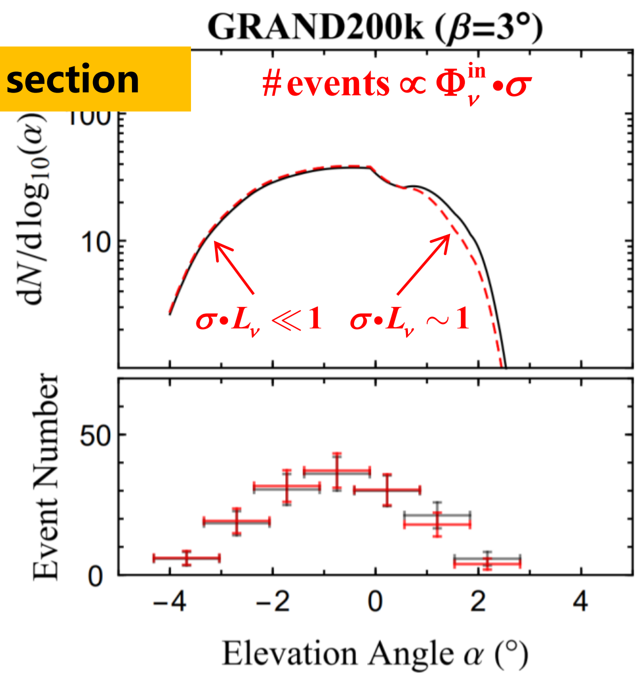
V. B. Valera, M. Bustamante, C. Glaser, JHEP 06 (2022) 105

- Cosmic ray spectrum and composition
- Reionization history
- Source modeling

Sensitivity

A larger flux ≈ a larger cross section





Fortunately, the angular distribution is sensitive to the absolute value of the xsec.

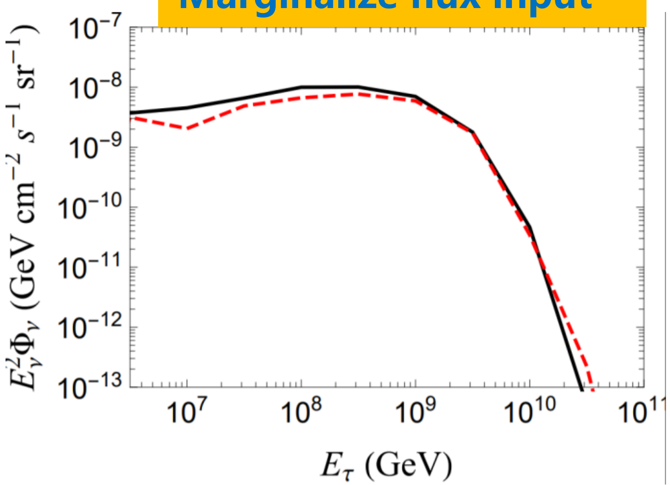
$$\#\text{events} \propto \Phi_\nu^{\text{in}} \exp(-\sigma \cdot L_\nu) \cdot \sigma$$

$$\exp(-\sigma \cdot L_\nu) \approx 1 - \sigma \cdot L_\nu + \ldots$$

$\sigma \cdot L_\nu$ should be large to resolve the flux degeneracy, e.g.,

$\sigma \cdot L_\nu \approx \mathcal{O}(1)$ **best**

Marginalize flux input

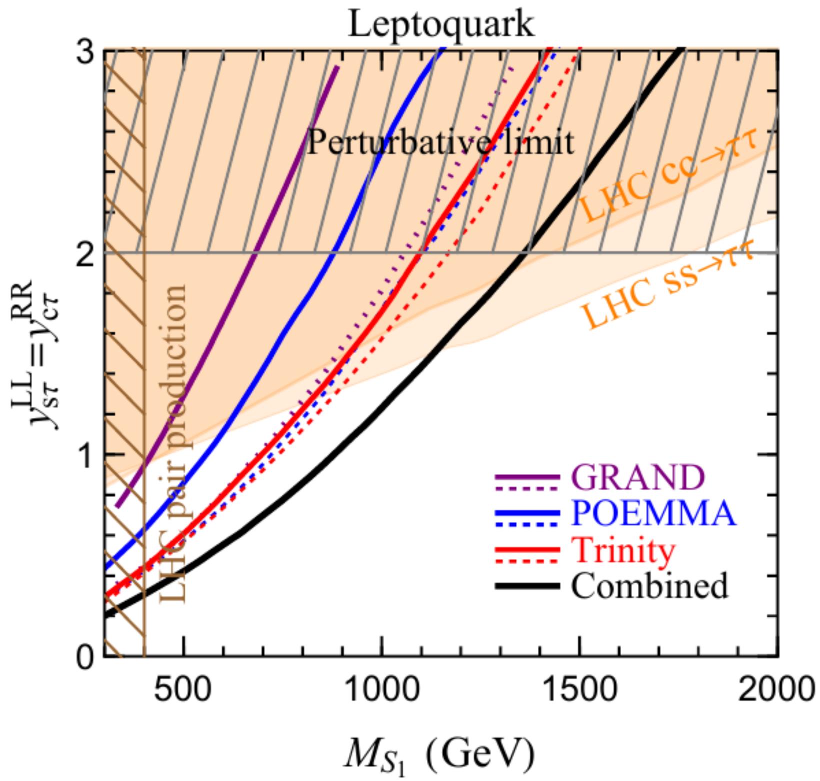


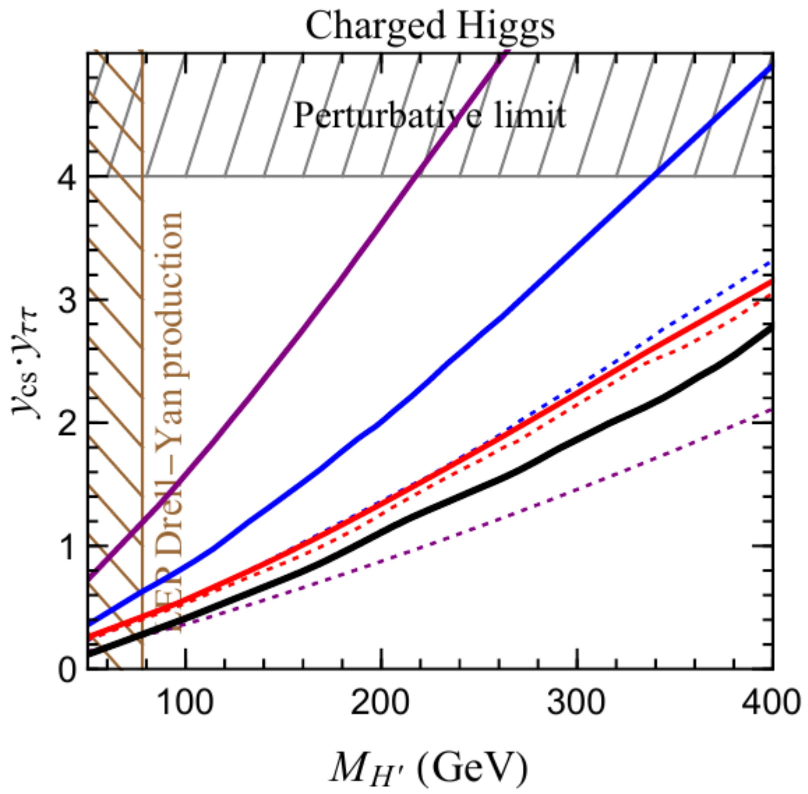
The detailed shape of initial neutrino flux is unknown, so we must marginalize over it, which reduces the uncertainty

$$\chi^2_{\min} = \underset{\Phi_\nu^{\text{in}}}{\text{Min}} \left\{ \sum_{i=1}^{N_{\text{bins}}} \frac{\left(n_i^{\text{th}} - n_i^{\text{exp}}\right)^2}{n_i^{\text{th}} + \sigma^2_{\text{PDF},i}} \right\}$$

This might be improved in conjunction with theoretical prior and other experimental observations.

Sensitivity





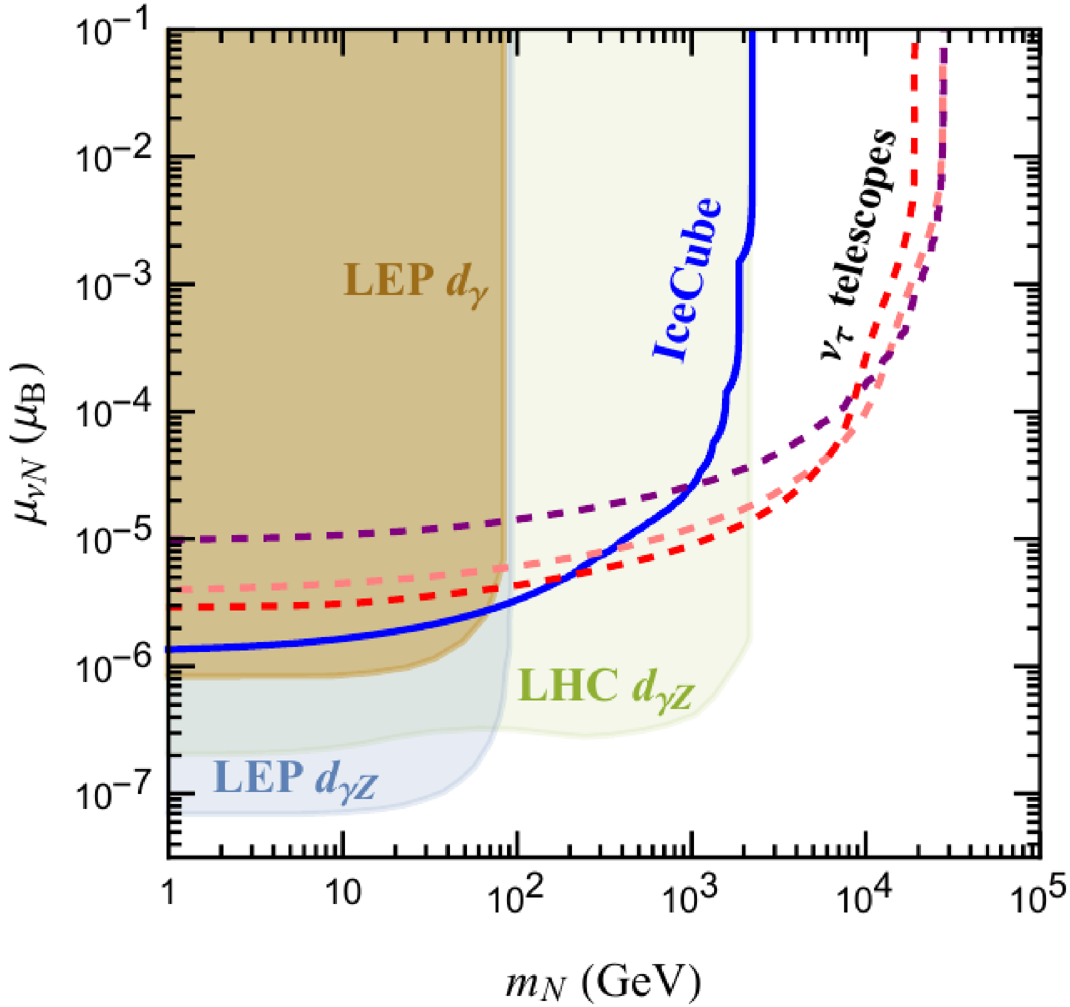
Existing bounds

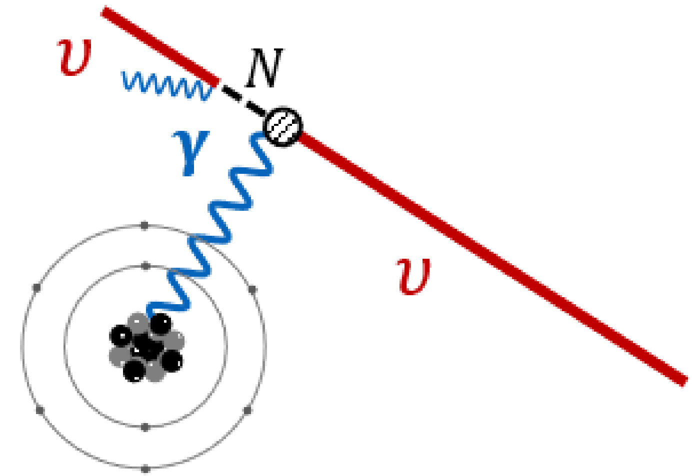
- LHC pair production process sets a lower limit
- *t*-channel leptoquark exchange at LHC
- LEP Drell-Yan production

Potential of tau nu telescopes

- For the coupling, we highlight the sensitivity to second and third families
- The combination of different telescopes is very useful

With a heavy sterile neutrino





Primakoff production of heavy sterile neutrino via nu transition magnetic moment

GYH, S. Jana, M. Linder and W. Rodejohann, arXiv:2204.10347

Strengths and weaknesses

STRENGTHS

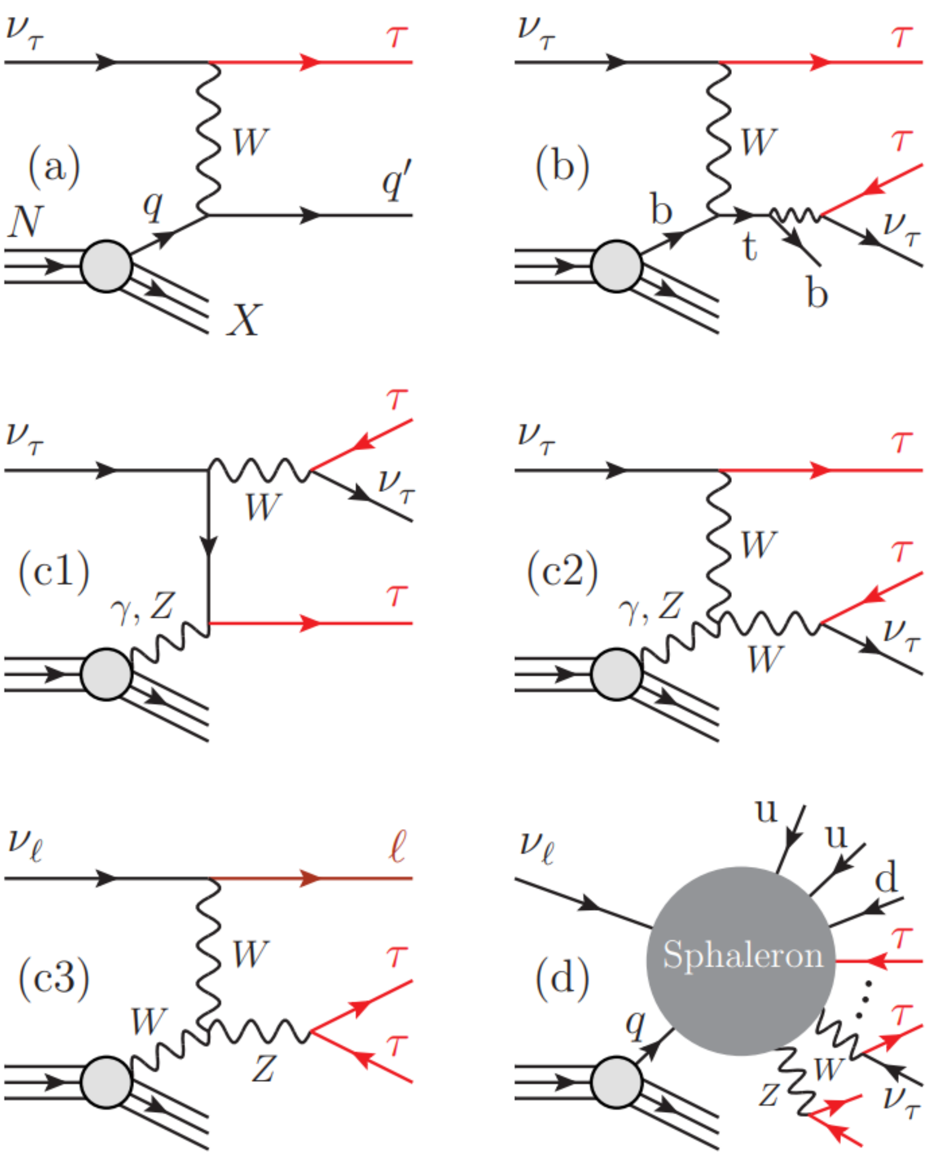
- It is a neutrino-hadron collider with COM energy as high as 43 TeV.
- PDFs of second and third generations of quarks can be comparable to the first up and down quarks.
- Such facilities are very sensitive to the new physics lying in the neutrino sector.

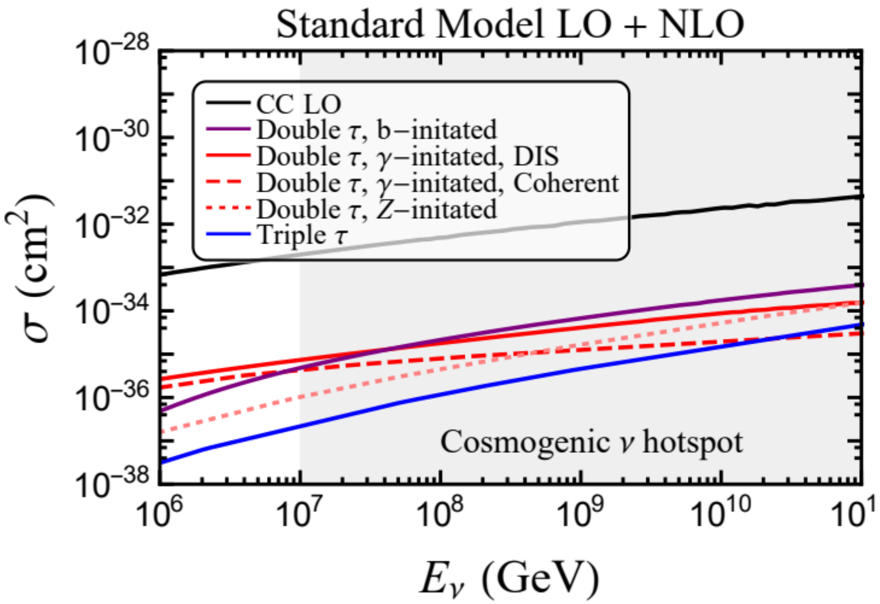
WEAKNESSES

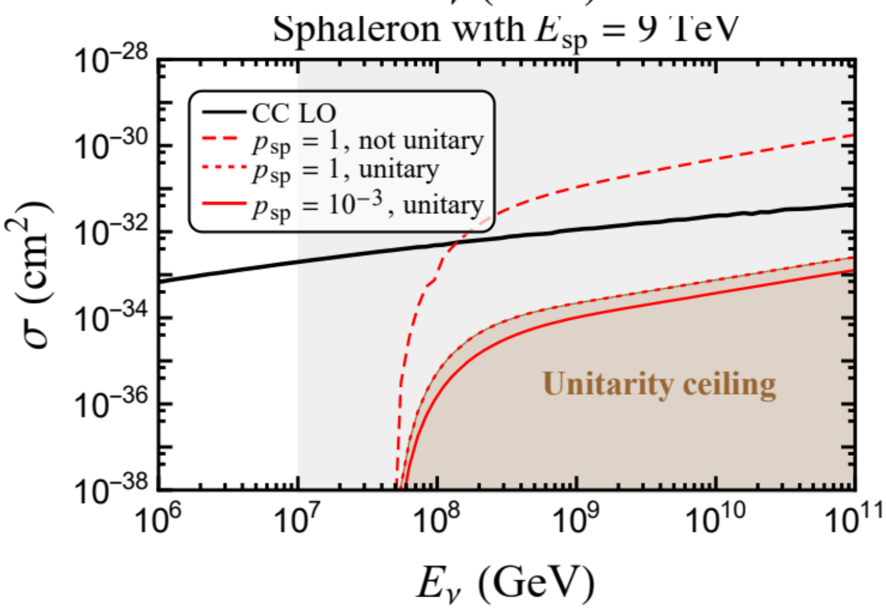
- The initial flux spreads a wide range and is not under our control.
- The SM hadronic process will be an irreducible background for the new physics processes.
- At least from its primary principle, the event topology is limited: a single tau bang.

Double and multiple bangs

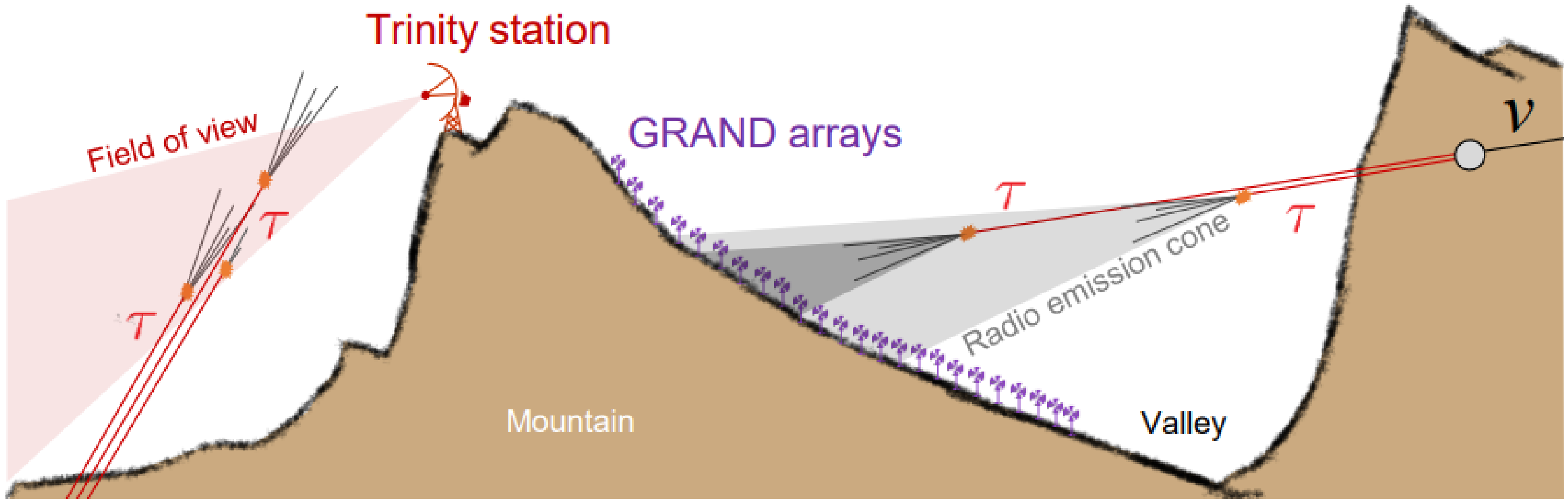
arXiv:2207.02222, GYH







Double and multiple bangs



Telescopes	Single τ	Double τ	Triple τ	Sphaleron $n\,\tau$
Ashra-NTA [33]	19	0.2	0.007	0.7 (0.5)
BEACON [30, 31]	137	1.6	0.062	7.1 (5)
GRAND [20]	178	2.1	0.082	10 (7)
Trinity [21, 22]	16	0.2	0.006	0.6 (0.4)
TAMBO [29]	> 7	> 0.1	> 0.002	> 0.11 (0.08)

Rough event estimations by convolving the cross section ratio with differential flux sensitivity

A dedicated investigation in the future should incorporate all realistic experimental effects.

Other interesting topics

- **Lorentz invariance, quantum gravity**

  S. Coleman and S. L. Glashow, PLB 405 (1997) 249; C. A. Argüelles, T. Katori and J. Salvado, PRL 115 (2015) 161303
  M.C. Gonzalez-Garcia, F. Halzen and M. Maltoni, PRD 71 (2005) 093010; J. Liao and D. Marfatia, PRD 97 (2018) 041302
  K. Murase, PRL 103 (2009) 081102; P. W. Gorham et al., PRD 86 (2012) 103006;
  IceCube, Nature Physic, 14 (2018) 961; IceCube, arXiv:2111.04654

- **Test of equivalence principle**

  A. Esmaili et al. PRD 89 (2014) 1130003;
  Z.-Y. Wang, R.-Y. Liu and X.-Y. Wang, PRL 116 (2016) 151101;
  D.F.G. Fiorillo et al., JCAP 04 (2021) 079; M. Chianese et al., Symmetry 13 (2021) 1353

- **Fifth force**

  M. Bustamante and S. K. Agarwalla, PRL 122 (2019) 061103

- **Unitarity**

  X.-J. Xu, H.-J. He and W. Rodejohann, JCAP 12 (2014) 039; M. Ahlers, M. Bustamante and S. Mu, PRD 98 (2018) 123023;
  P. B. Denton and J. Gehrlein, arXiv:2109.14575

- **Microscopic black hole**

  Y. Uehara, PTP 107 (2002) 621; J. Alvarez-Muniz et al., PRD 65 (2002) 124015;
  S. I. Dutta, M. H. Reno and I. Sarcevic, PRD 66 (2002) 033002; M. Kowalski, A. Ringwald and H. Tu, PLB 529 (2002) 1; P. Jain et al., PRD 66 (2002) 065018; D. Stojkovic, G. D. Starkman and D.-C. Dai, PRL 96 (2006) 041303; and many more....

- **Nonstandard neutrino interactions**

  K. S. Babu, P. S. B. Dev, S. Jana and Y. Sui, PRL 124 (2020) 041805

AND MORE

THANK YOU VERY MUCH!