@西昌，5月8日，2024

Particle physics opportunities with ultrahigh-energy neutrino telescopes

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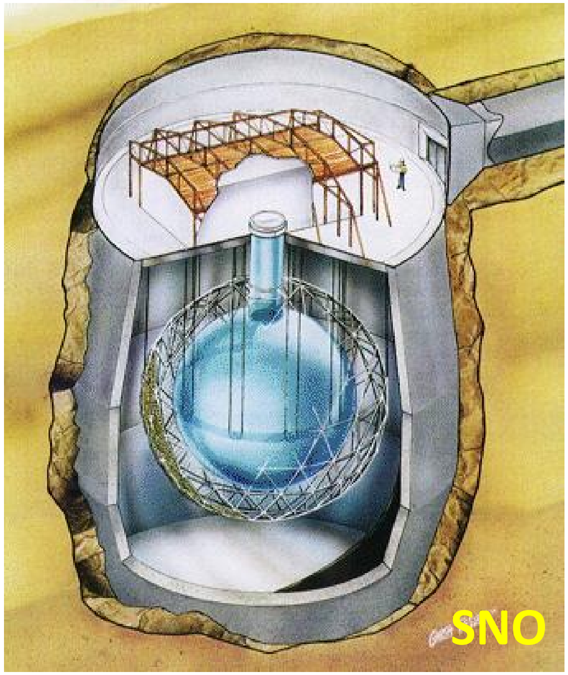
Based on JHEP11(2023)164, GYH, M. Lindner and N. Volmer

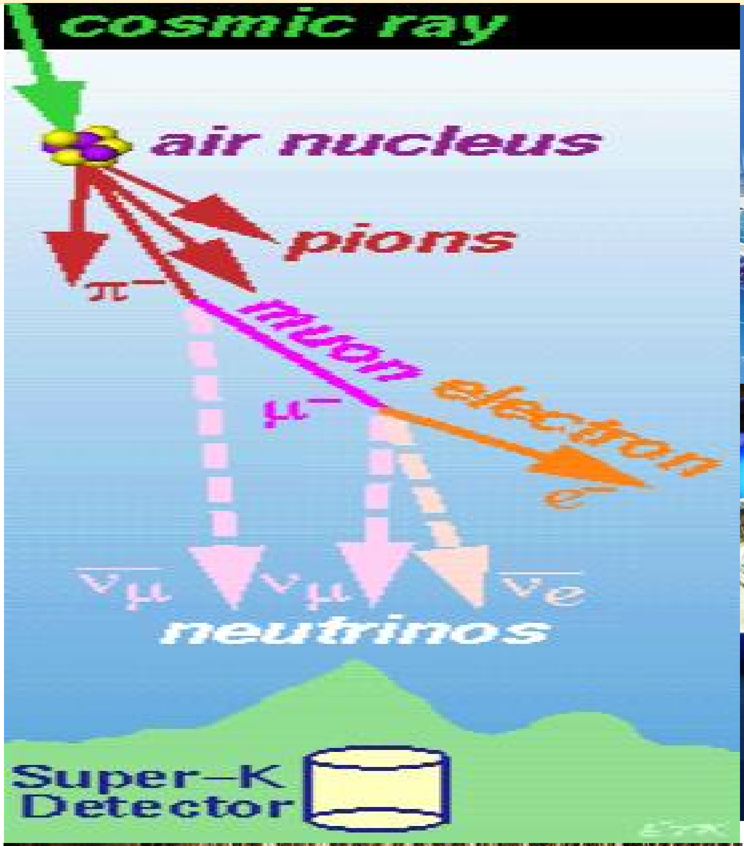
JCAP02(2022)038, GYH, S. Jana, M. Lindner and W. Rodejohann

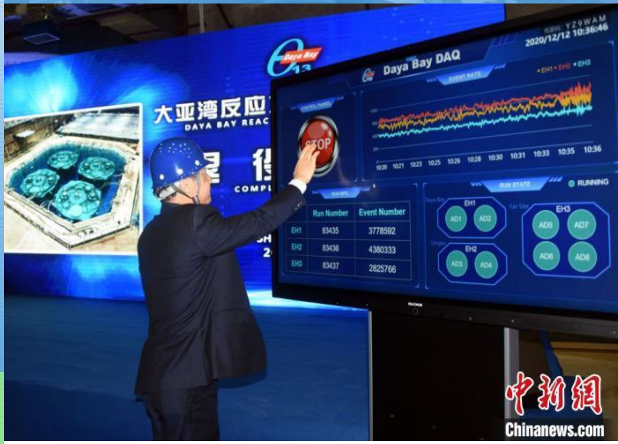
PRD98(2018)043019, GYH

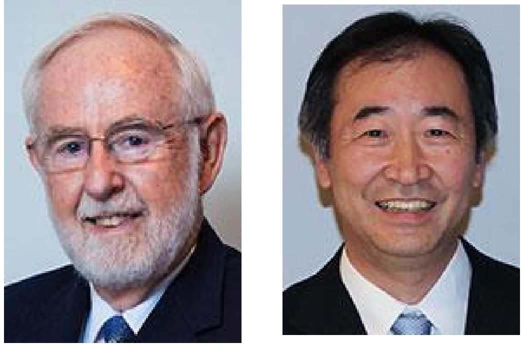
arXiv:2307.12153, GYH

Neutrinos beyond Standard Model

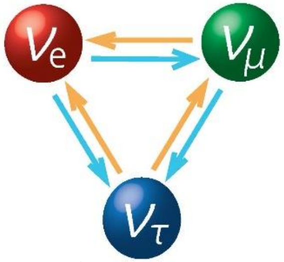








Nobel Prize in 2015



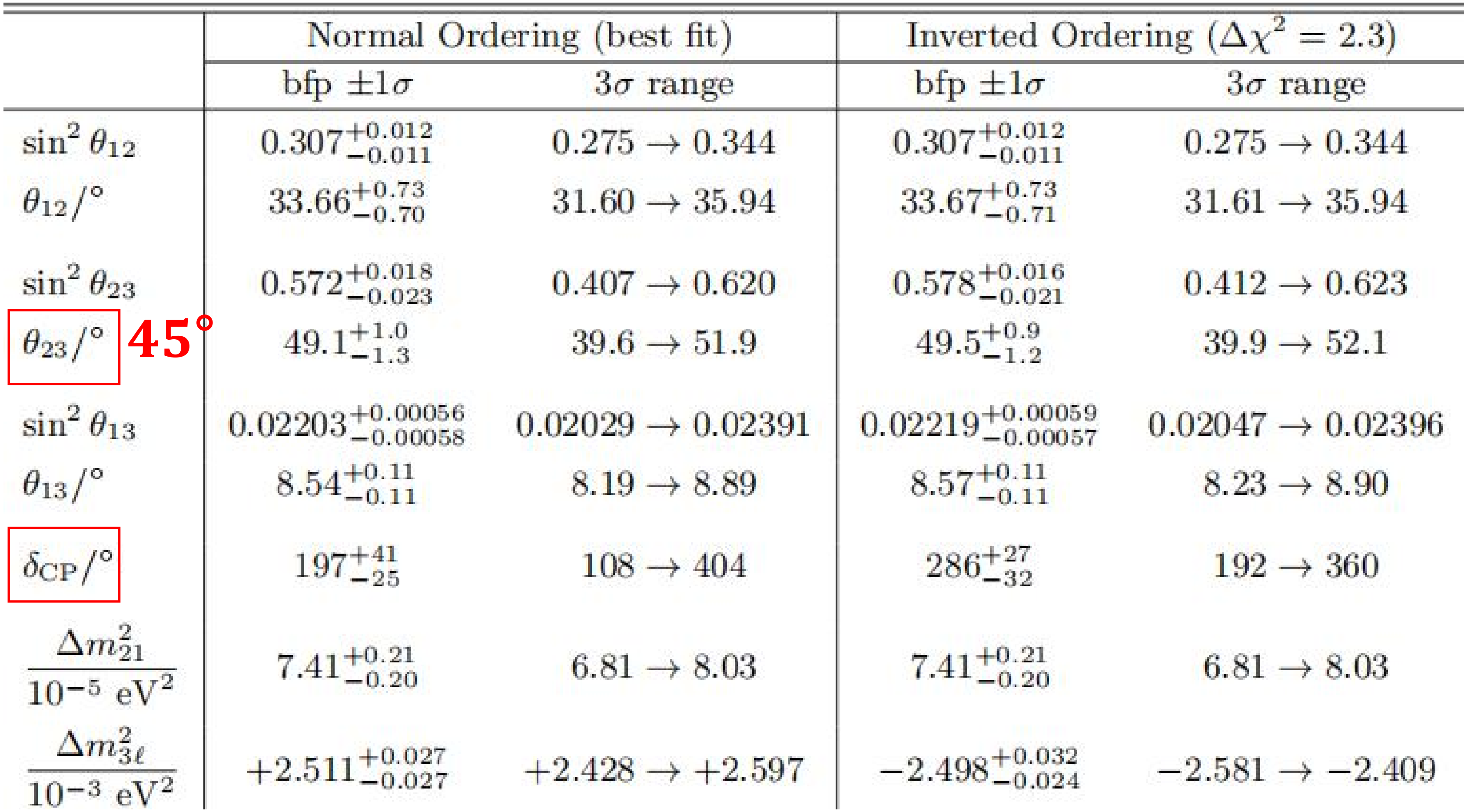
- Neutrinos are massive !!!
- New physics beyond the SM

Neutrinos beyond Standard Model

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

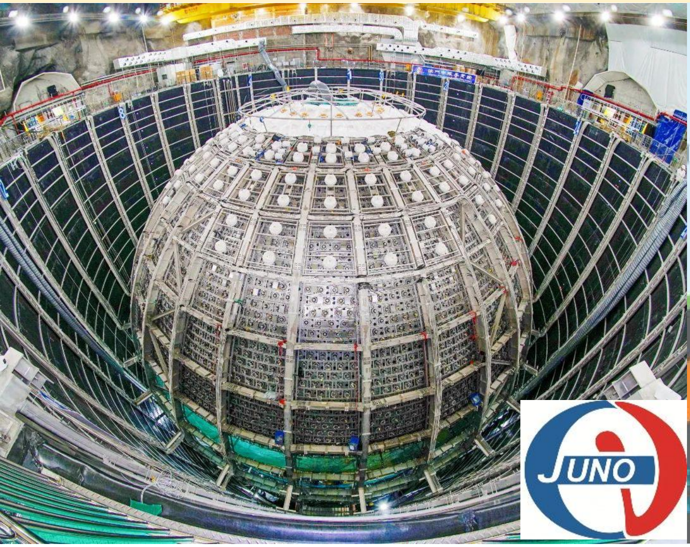
- **Octant of θ_{23}, the CP-violating phase δ (@DUNE/Hyper-K),**
- **The neutrino mass ordering (@JUNO)**

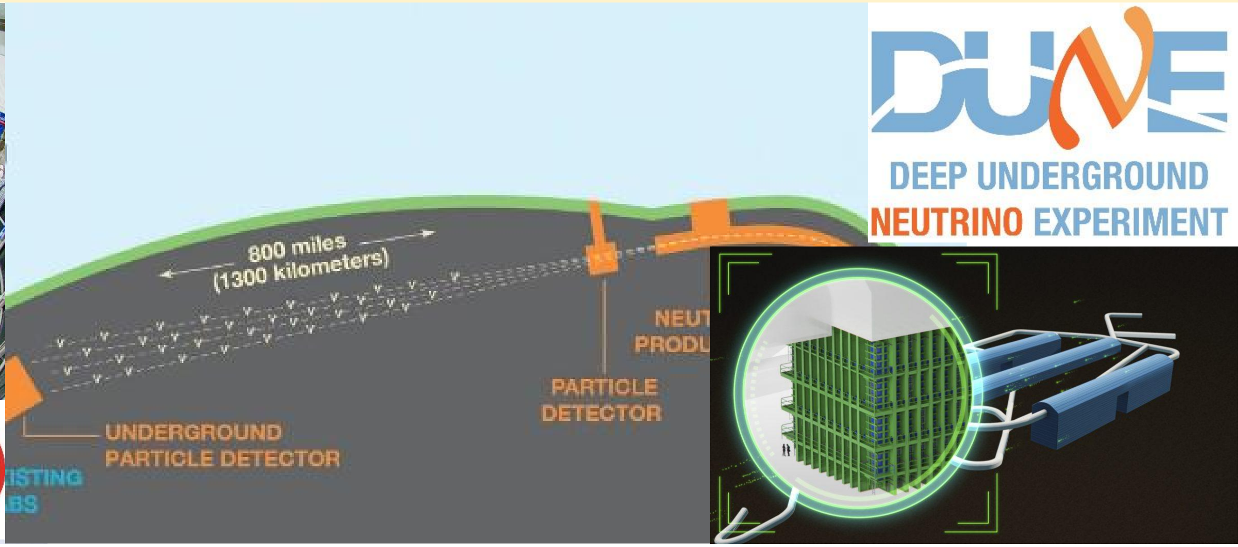
I. Esteban, M. C. Gonzalez-Garcia, A. Hernandez-Cabezudo, et al., NuFIT 5.3 (2024)



Accuracy (1σ/bf)		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.3$)	
		bfp $\pm1\sigma$	3σ range	bfp $\pm1\sigma$	3σ range
2% √	$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$
	$\theta_{12}/^\circ$	$33.66^{+0.73}_{-0.70}$	$31.60 \to 35.94$	$33.67^{+0.73}_{-0.71}$	$31.61 \to 35.94$
	$\sin^2\theta_{23}$	$0.572^{+0.018}_{-0.023}$	$0.407 \to 0.620$	$0.578^{+0.016}_{-0.021}$	$0.412 \to 0.623$
2% ?	$\boxed{\theta_{23}/^\circ}$ 45°	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$	$49.5^{+0.9}_{-1.2}$	$39.9 \to 52.1$
1% √	$\sin^2\theta_{13}$	$0.02203^{+0.00056}_{-0.00058}$	$0.02029 \to 0.02391$	$0.02219^{+0.00059}_{-0.00057}$	$0.02047 \to 0.02396$
	$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.11}$	$8.19 \to 8.89$	$8.57^{+0.11}_{-0.11}$	$8.23 \to 8.90$
17% ?	$\boxed{\delta_{\rm CP}/^\circ}$	197^{+41}_{-25}	$108 \to 404$	286^{+27}_{-32}	$192 \to 360$
3% √	$\frac{\Delta m^2_{21}}{10^{-5}\ \rm eV^2}$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$
1% ?	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \rm eV^2}$	$+2.511^{+0.027}_{-0.027}$	$+2.428 \to +2.597$	$-2.498^{+0.032}_{-0.024}$	$-2.581 \to -2.409$

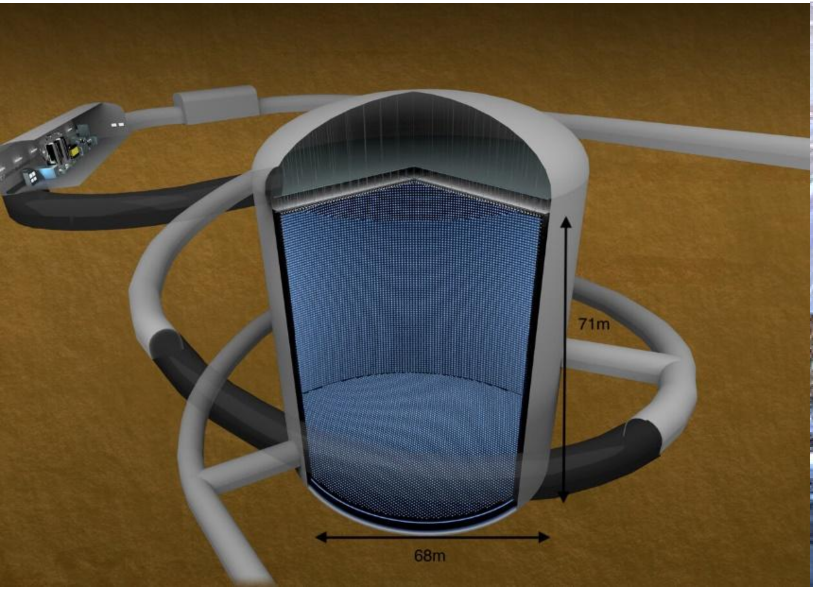
Future detectors





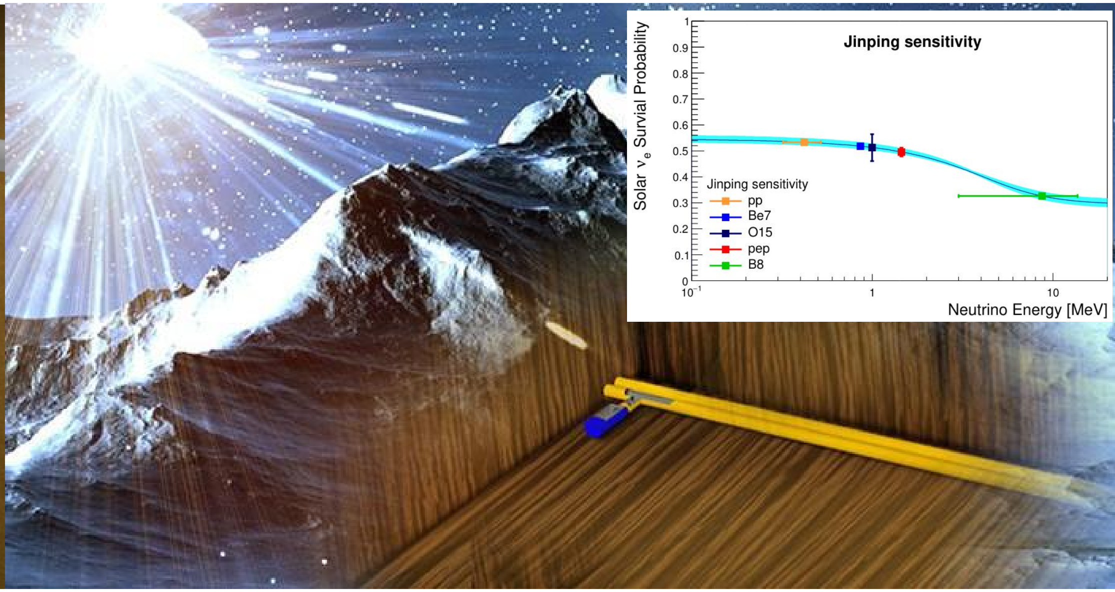
JUNO: 2024, 20 kt liquid-scintillator

DUNE: late 2020s, 34 kt liquid-Argon



Hyper-Kamiokande: 2027

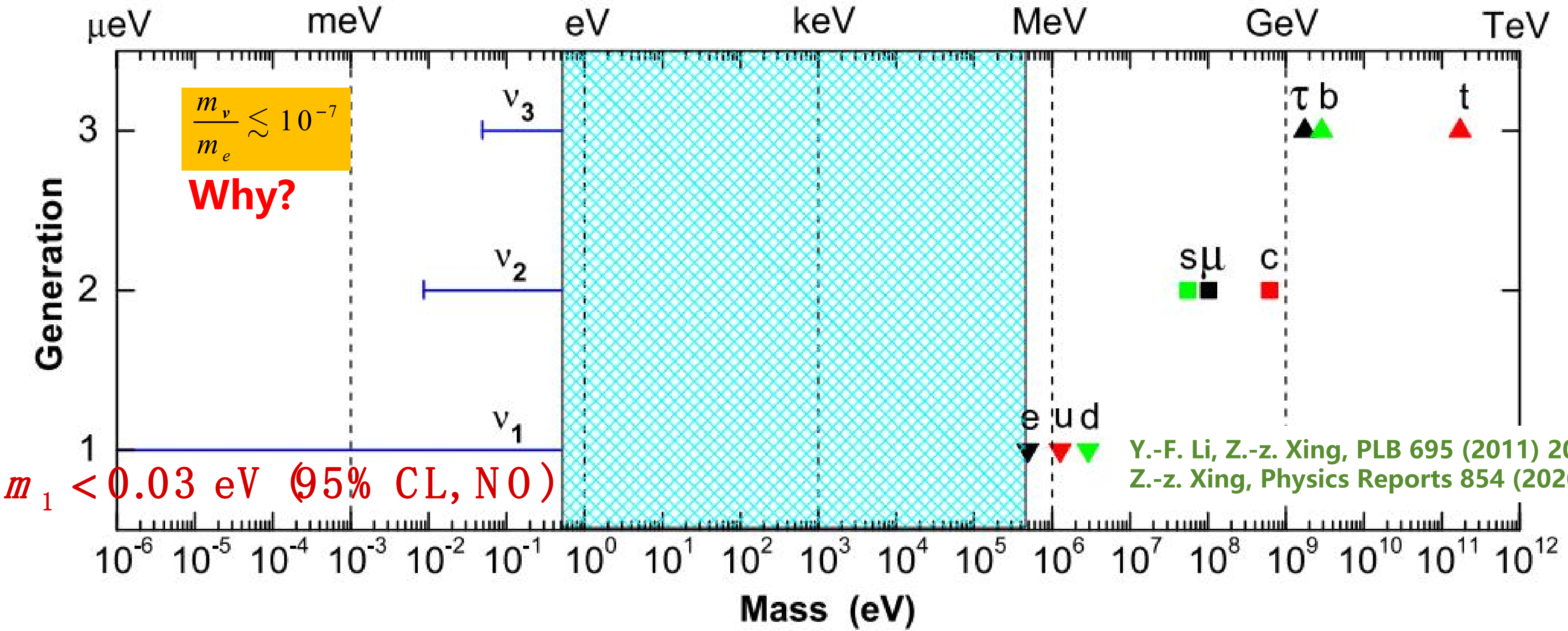
188 kiloton water = 8 x Super-K



Jinping Neutrino Experiment

and more...

Neutrino masses and new physics



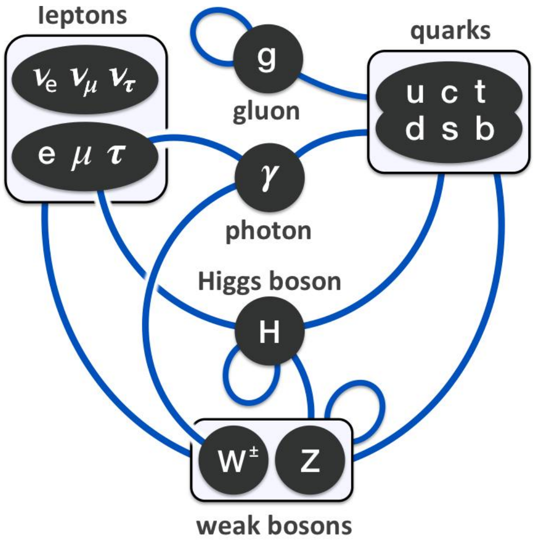
$\frac{m_\nu}{m_e} \lesssim 10^{-7}$

Why?

$m_1 < 0.03$ eV (95% CL, NO)

Y.-F. Li, Z.-z. Xing, PLB 695 (2011) 205
Z.-z. Xing, Physics Reports 854 (2020) 1

$\ell =$



$D \leq 4$ **No right-handed neutrinos in SM**

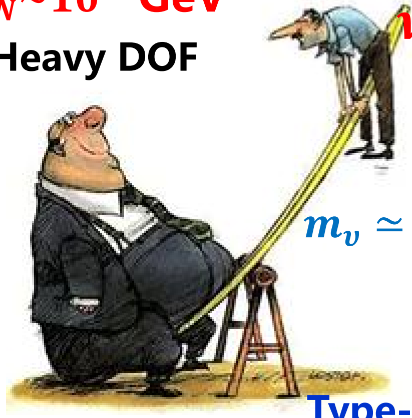
$\ell\ell H = 2\times 2\times 2 = 2+2+4 \quad \mathrm{SU(2)_L}$

$Y_{\rm D}\ell H N_{\rm R} \qquad Y_{\rm D} \lesssim 10^{-12}$

$\overline{N^{\rm c}_{\rm R}} N_{\rm R}$ **Lepton number conservation is accidental**

Standard Model is not perfect

Neutrino masses and new physics



$m_N \sim 10^{14}$GeV

Heavy DOF

N

$m_\nu \lesssim 0.1$ eV

Neutrinos

ν_1, ν_2, ν_3

$m_\nu \simeq \frac{m_D^2}{m_N}$

Type-I

$$D=5 \quad \ell\ell H H = 1 + 1 + 3 + 3 + 3 + 5$$

$$D = 6,7,8\ldots$$

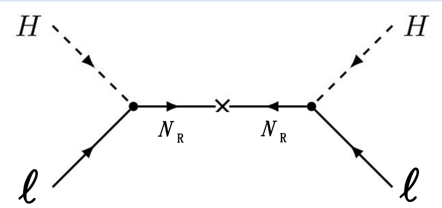
Weinberg Operator

S. Weinberg, PRL 43 (1979) 1566

$$-\mathcal{L} \supset \frac{1}{\Lambda}\overline{\ell_L}\tilde{H}\tilde{H}^T Y_M (\ell_L)^c + \text{h.c.}$$

Three different ways of realizing seesaw

Type-I

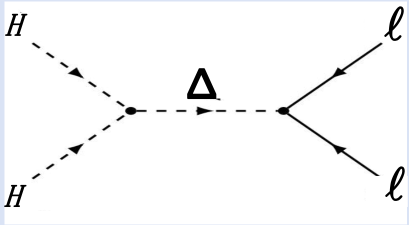


P. Minkowski, PLB 67 (1977) 421

⋮

$$-\mathcal{L}_I = \overline{\ell_L} Y_D \tilde{H} N_R + \frac{1}{2}\overline{N_R^c} M_R N_R + \text{h.c.}$$

Type-II

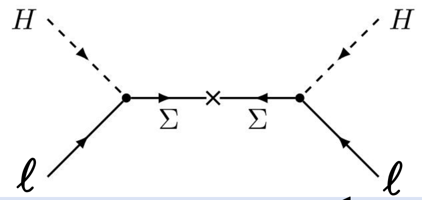


R.N. Mohapatra, G. Senjanovic, PRD 23 (1981) 165

⋮

$$-\mathcal{L}_{II} = \frac{1}{2}\overline{\ell_L^c} Y_\Delta i\sigma_2 \Delta \ell_L + \frac{1}{4} M_\Delta^2 \text{Tr}(\Delta^+\Delta) + \text{h.c.}$$

Type-III



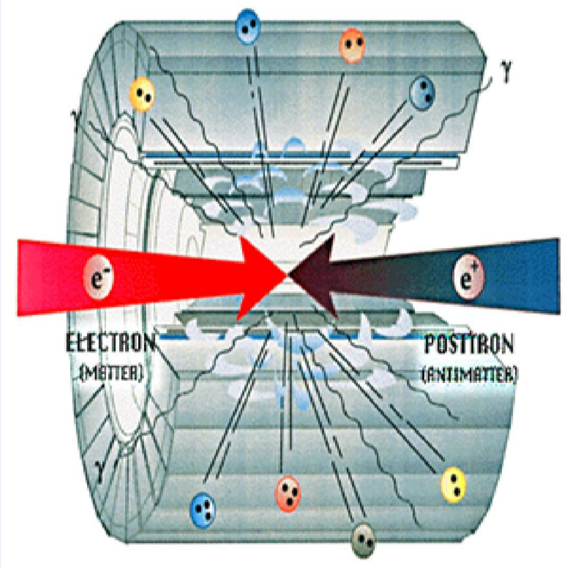
R. Foot, H. Lew, X.-G. He, et al., Z. Phys. C, 44 (1989) 441

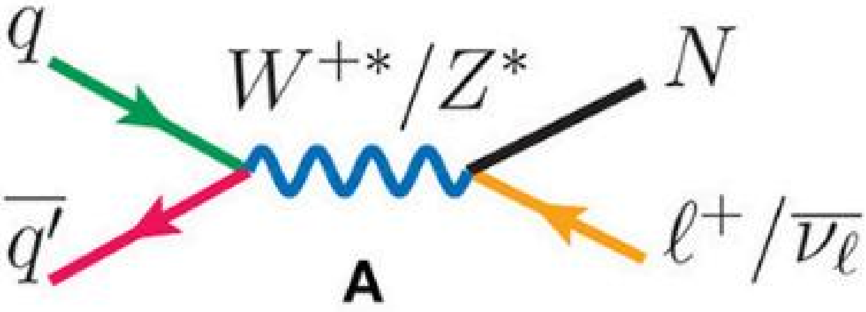
$$-\mathcal{L}_{III} = \overline{\ell_L^c} Y_\Sigma i\sigma_2 \Sigma_L H + \frac{1}{4}\text{Tr}(\overline{\Sigma_L^c} M_\Sigma \Sigma_L) + \text{h.c.}$$

Higher-order seesaw, radiative seesaw…

High energy frontiers

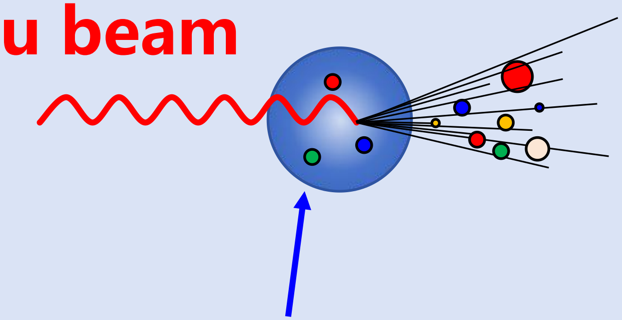
Option 1





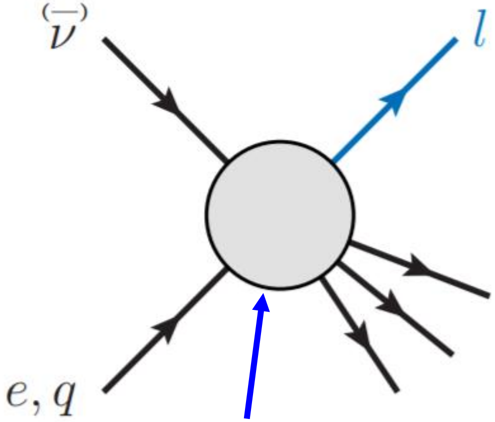
Test of nu mass models in colliders with final states

Option 2

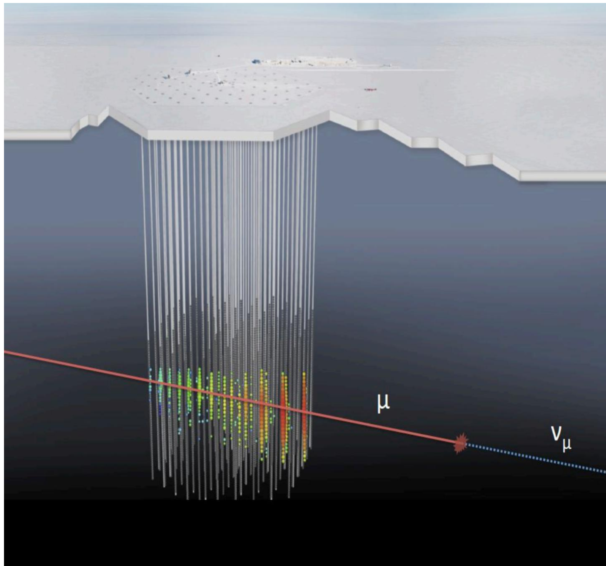


nu beam

Target

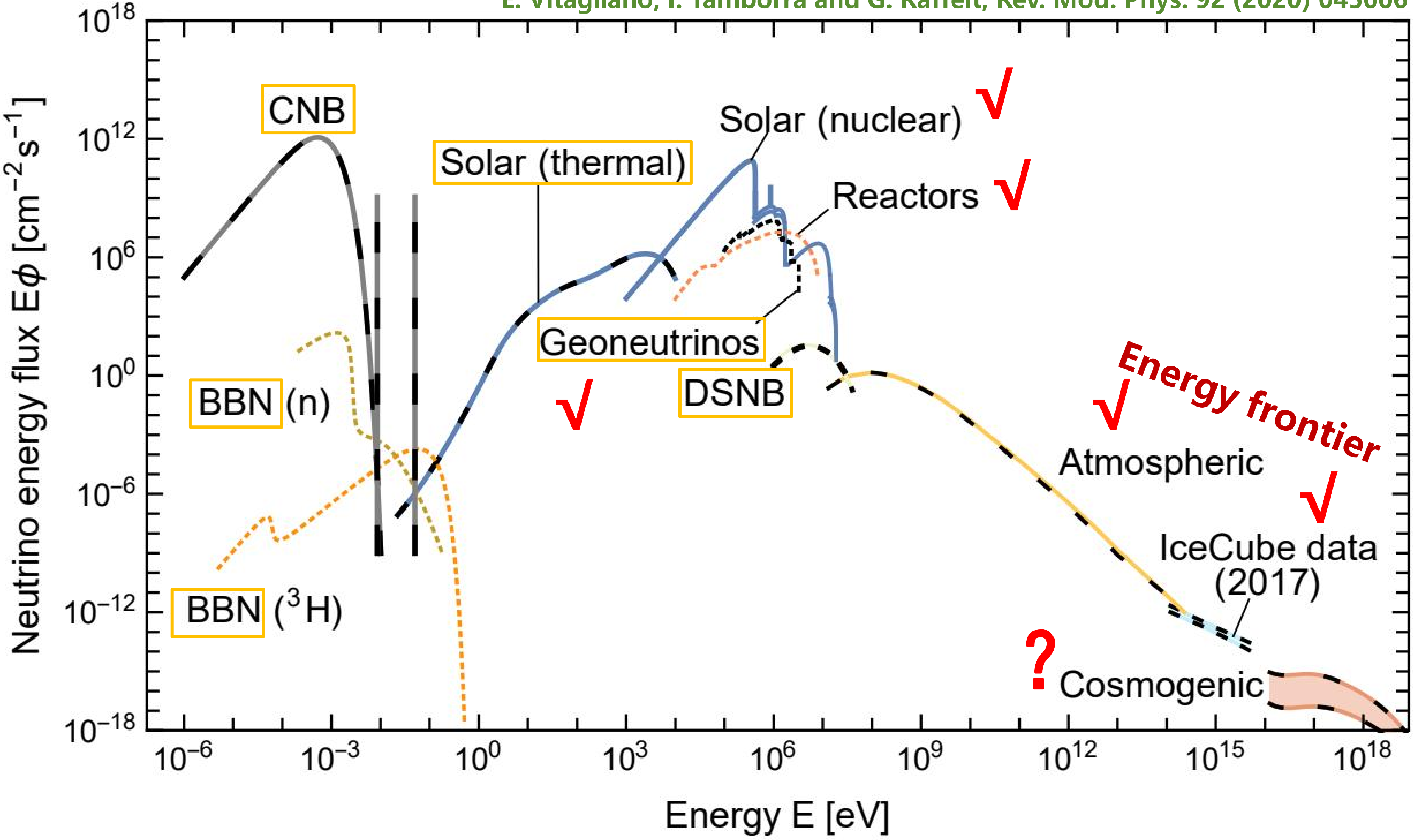


SM+NP



High energy frontiers

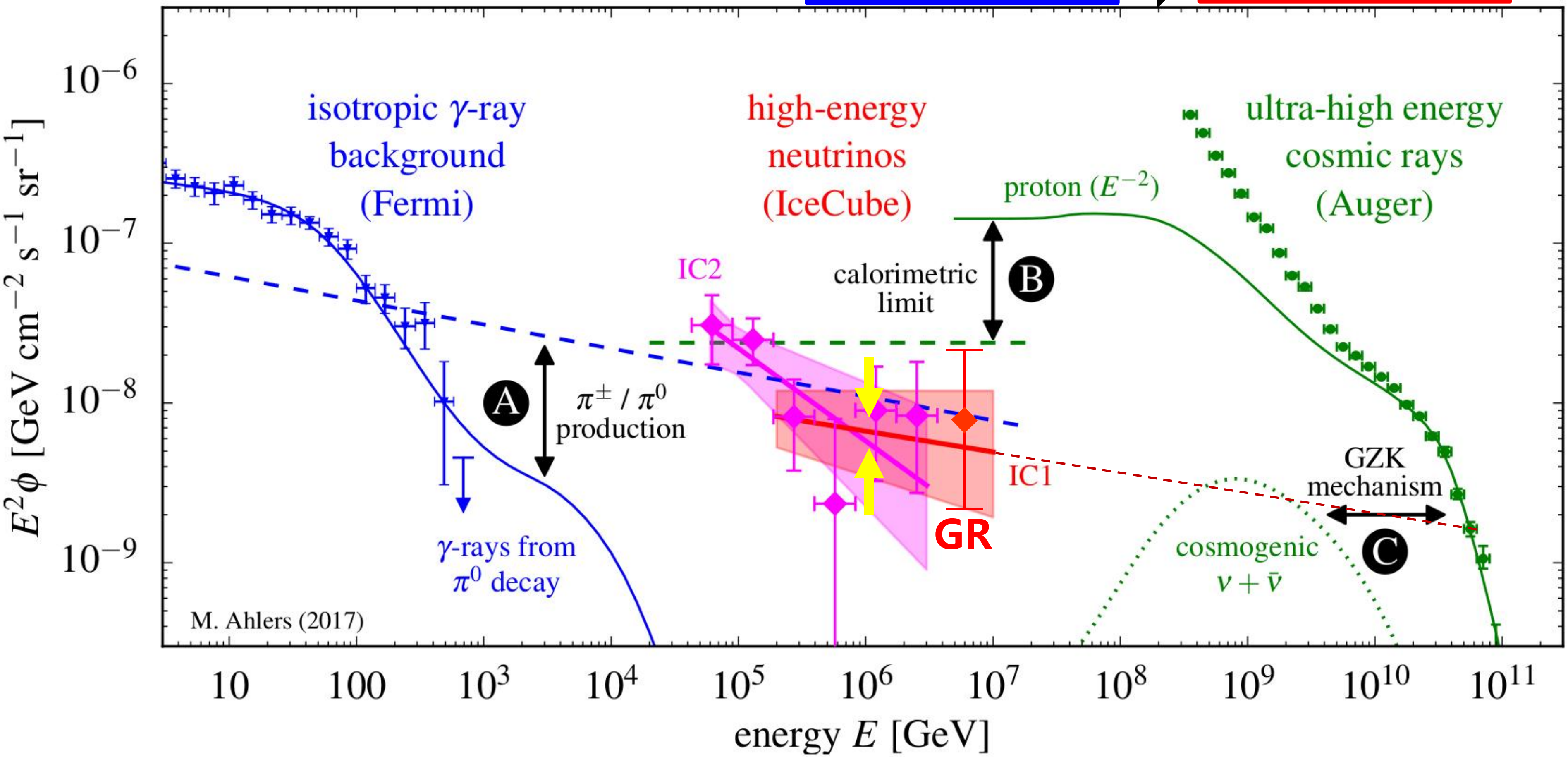
E. Vitagliano, I. Tamborra and G. Raffelt, Rev. Mod. Phys. 92 (2020) 045006



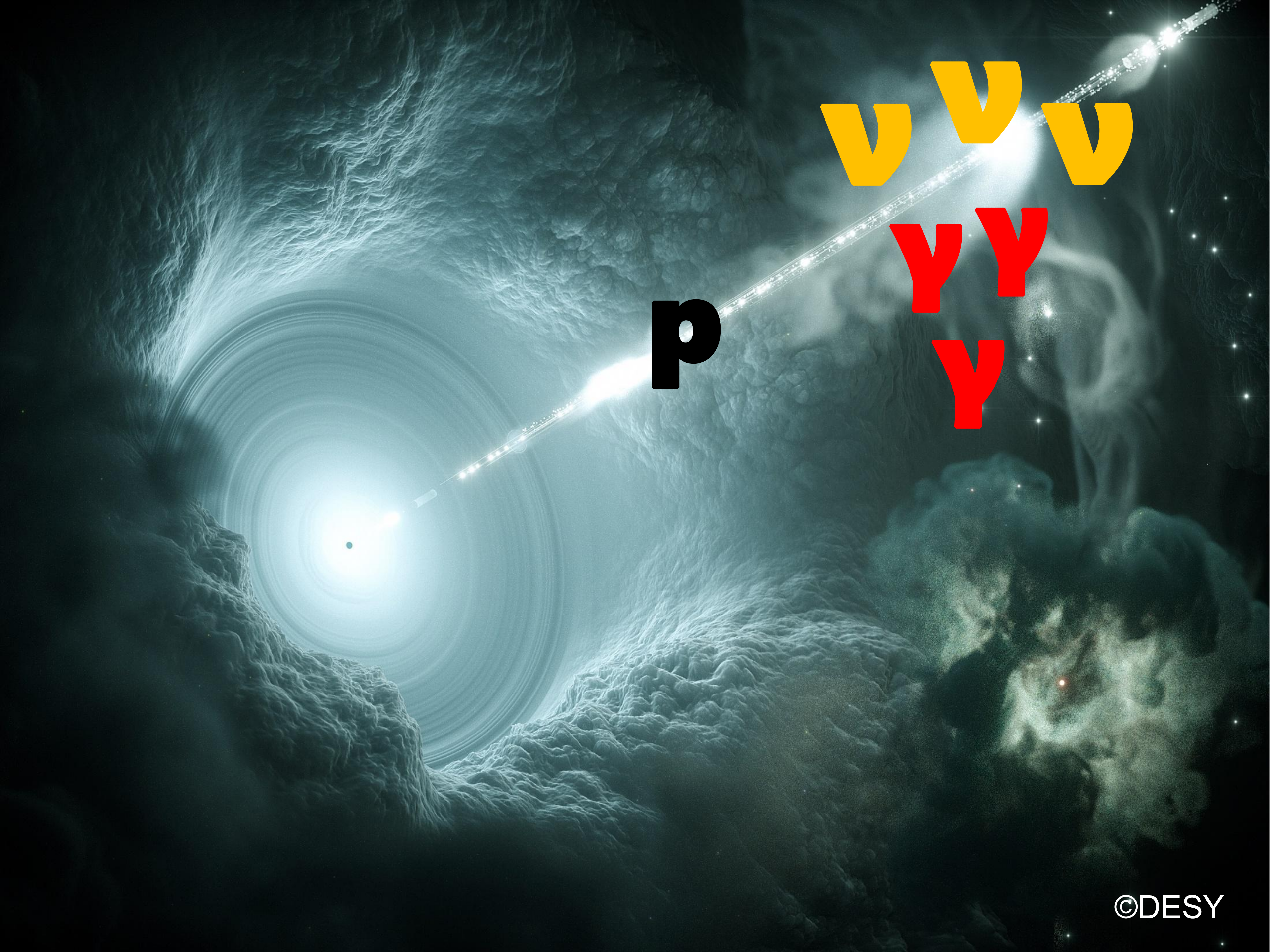
Cosmic neutrinos

Ahlers and Halzen, PPNP102(2018)73

$E_\nu > 1$ PeV ⇒ **$\sqrt{s} > 1$ TeV**

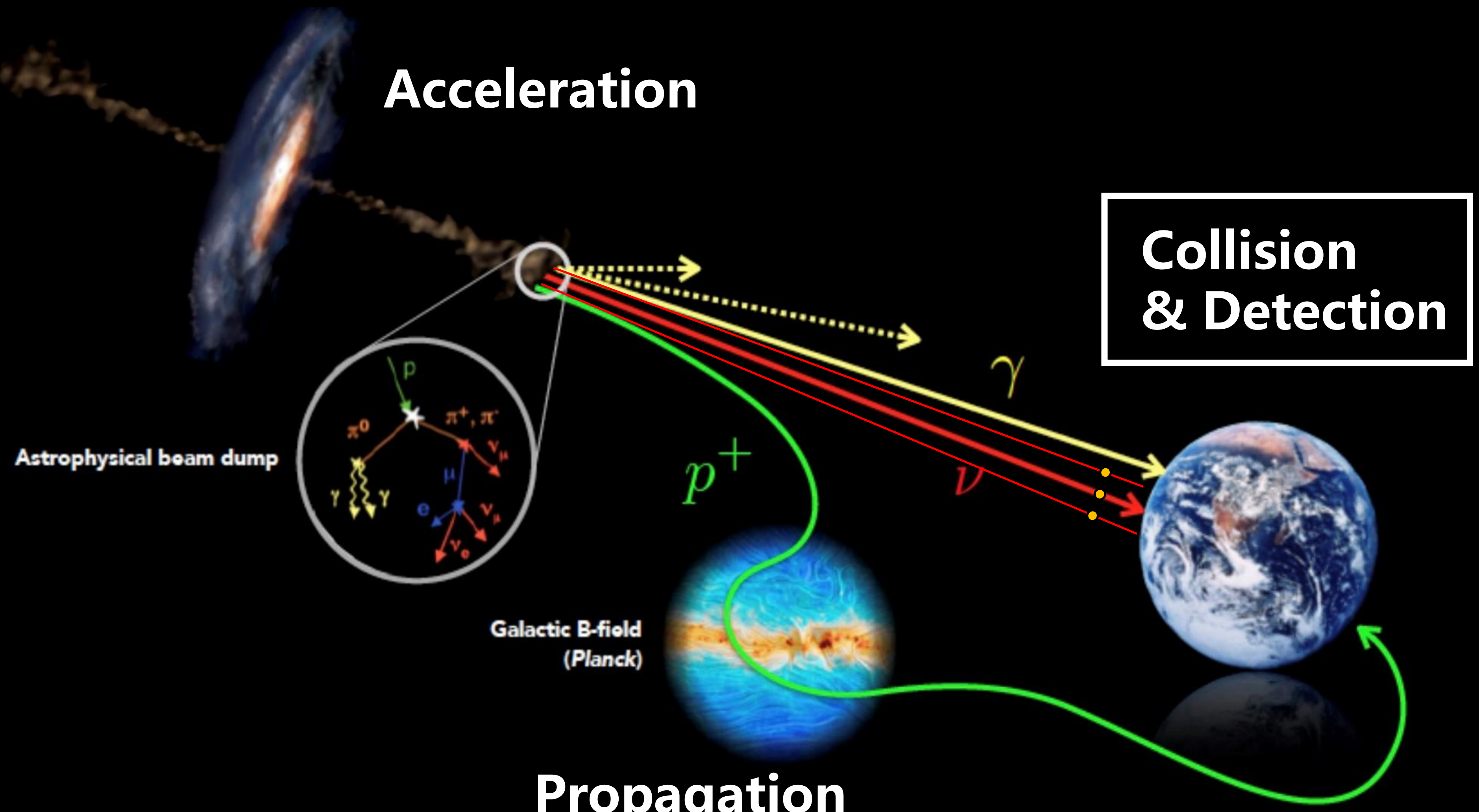


Currently consistent with our understanding of particle physics



©DESY

Cosmic neutrinos



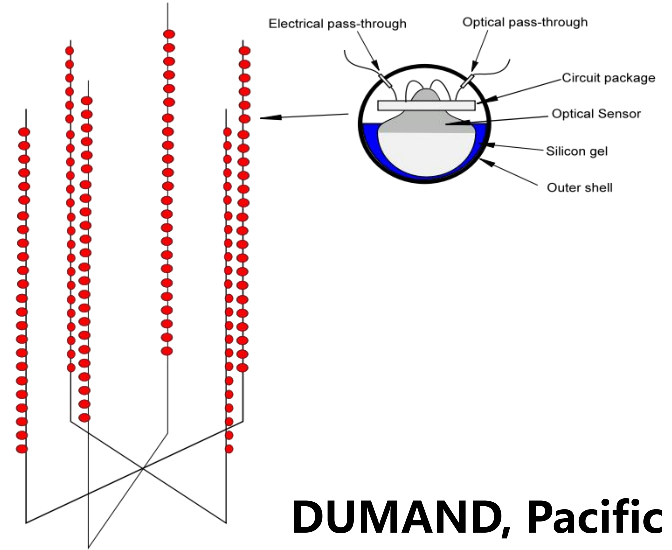
Acceleration

Collision & Detection

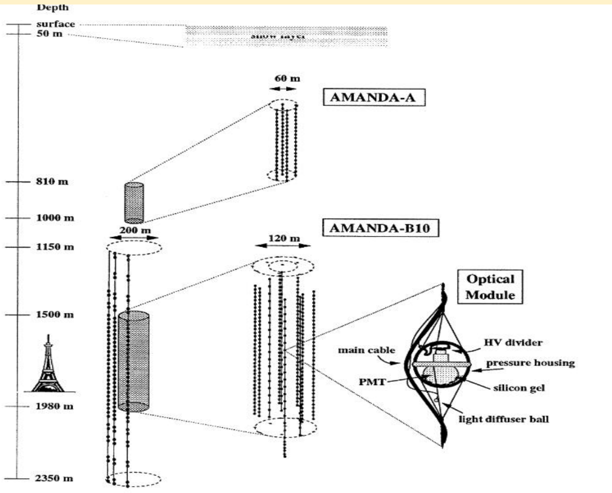
Propagation

©Randall Smith & Rob Petre,

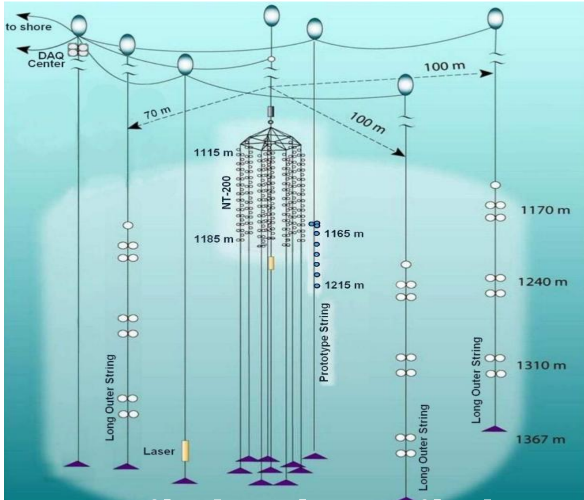
Cosmic neutrinos



DUMAND, Pacific

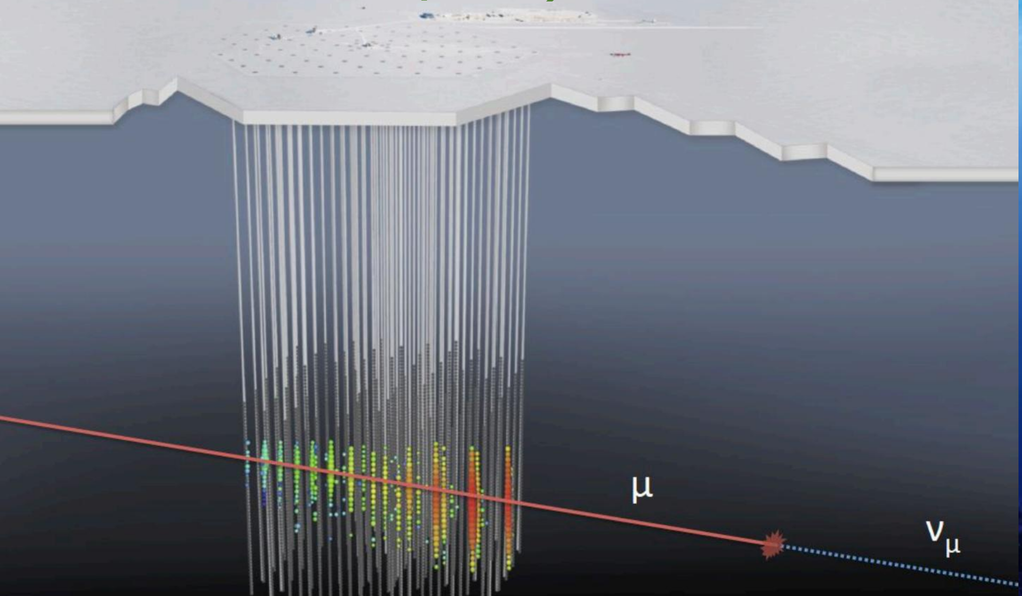


AMANDA, South Pole



Baikal, Lake-Baikal

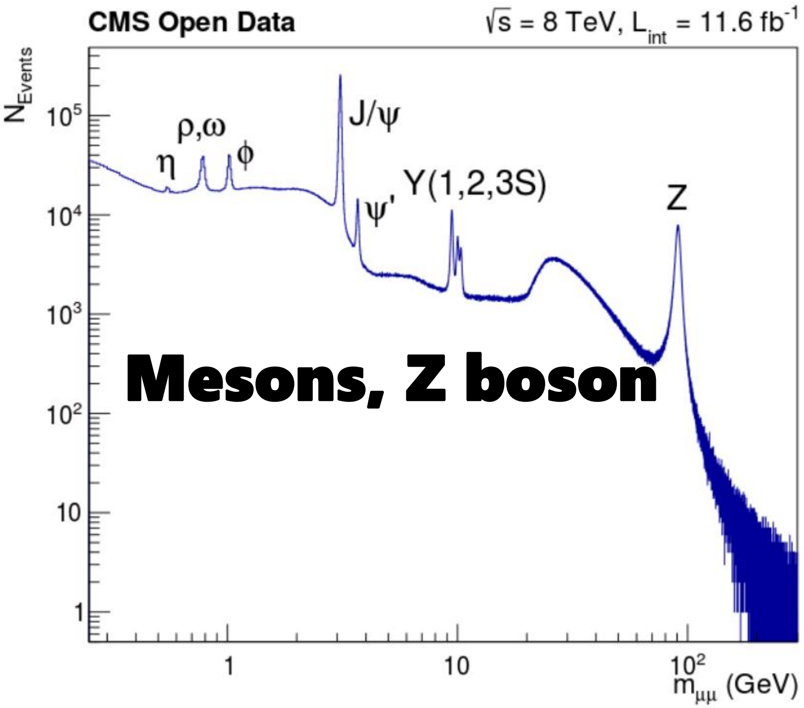
Markov, ICHEP 60 (1960) 578



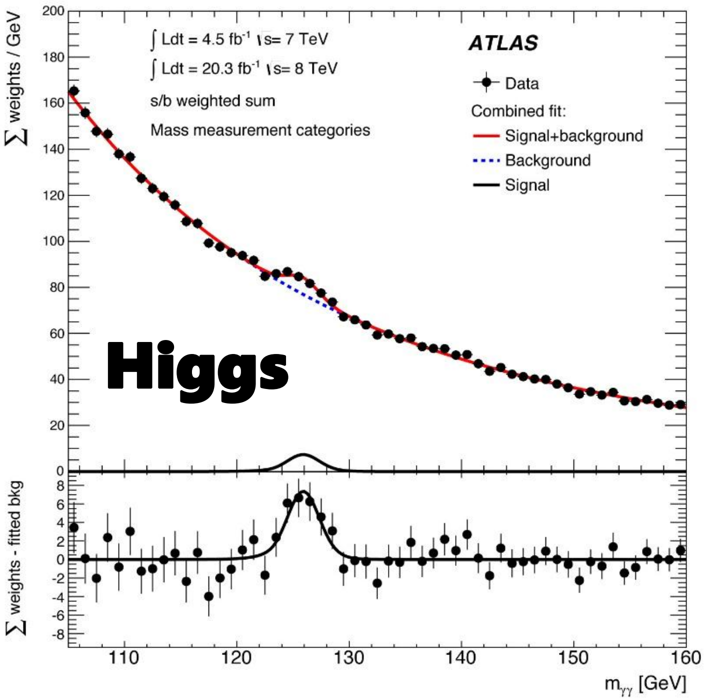
IceCube, South Pole

ANTARES, Mediterranean

Particle resonance

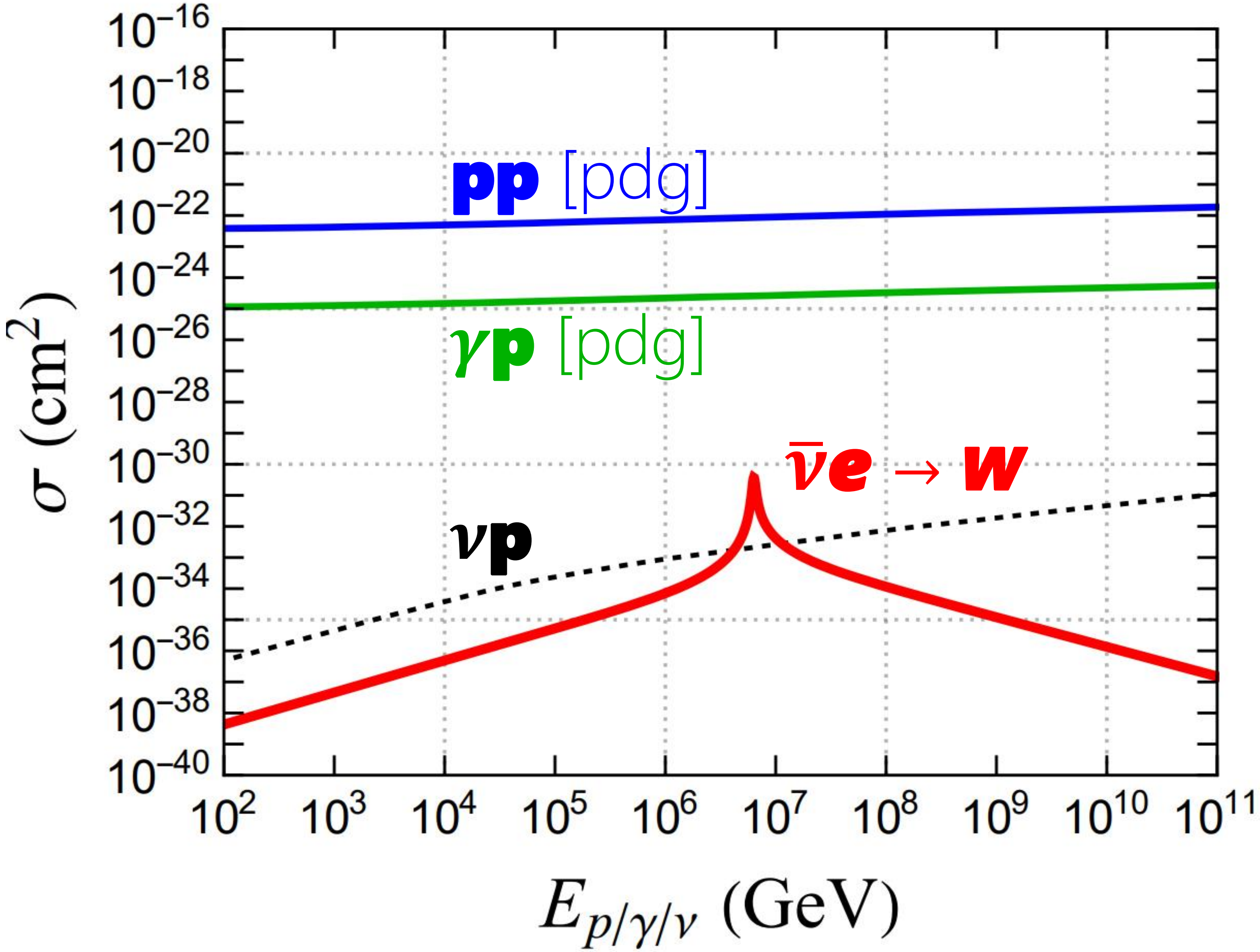


Mesons, Z boson

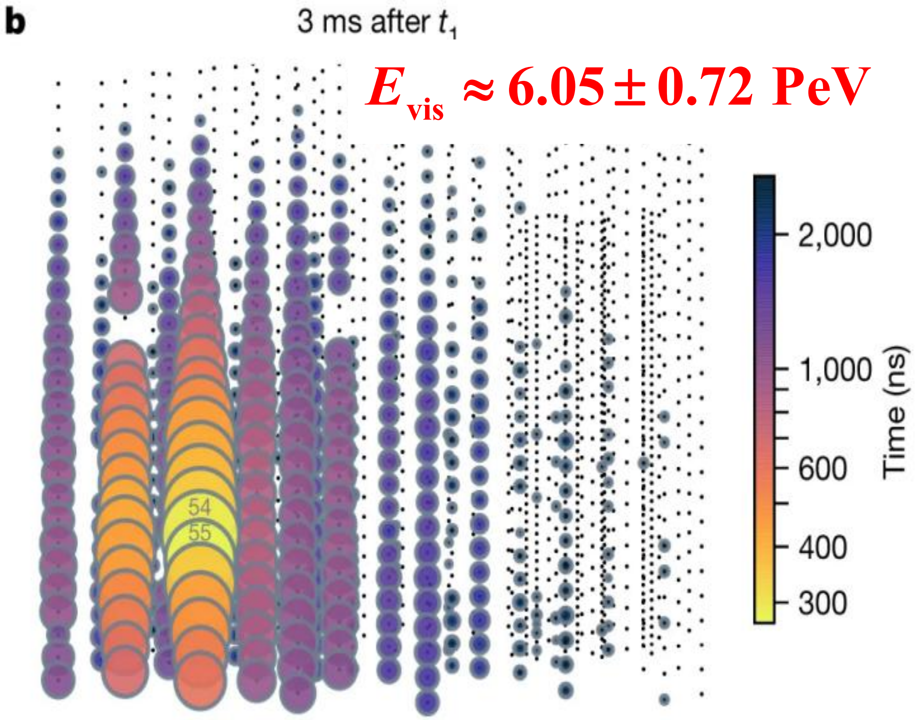


Higgs

Glashow resonance event

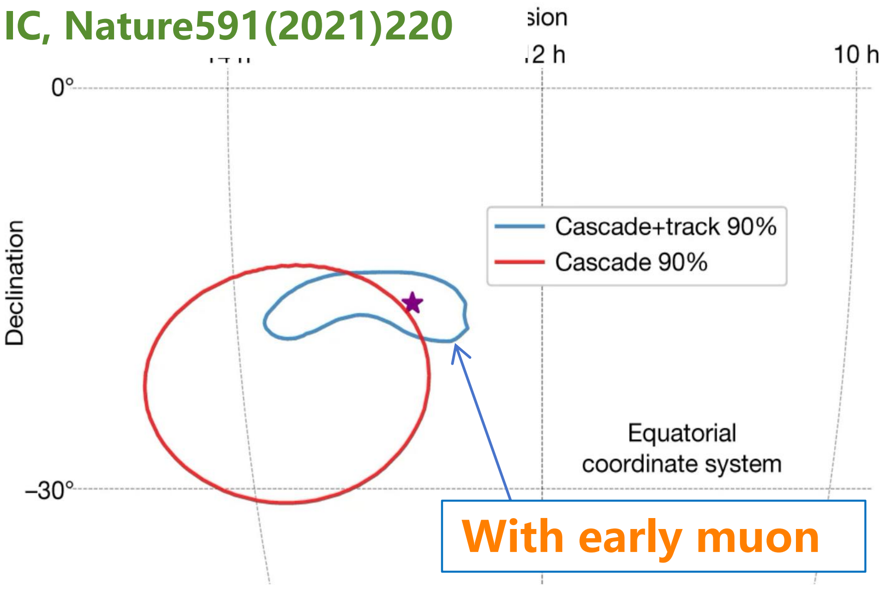


Glashow resonance event

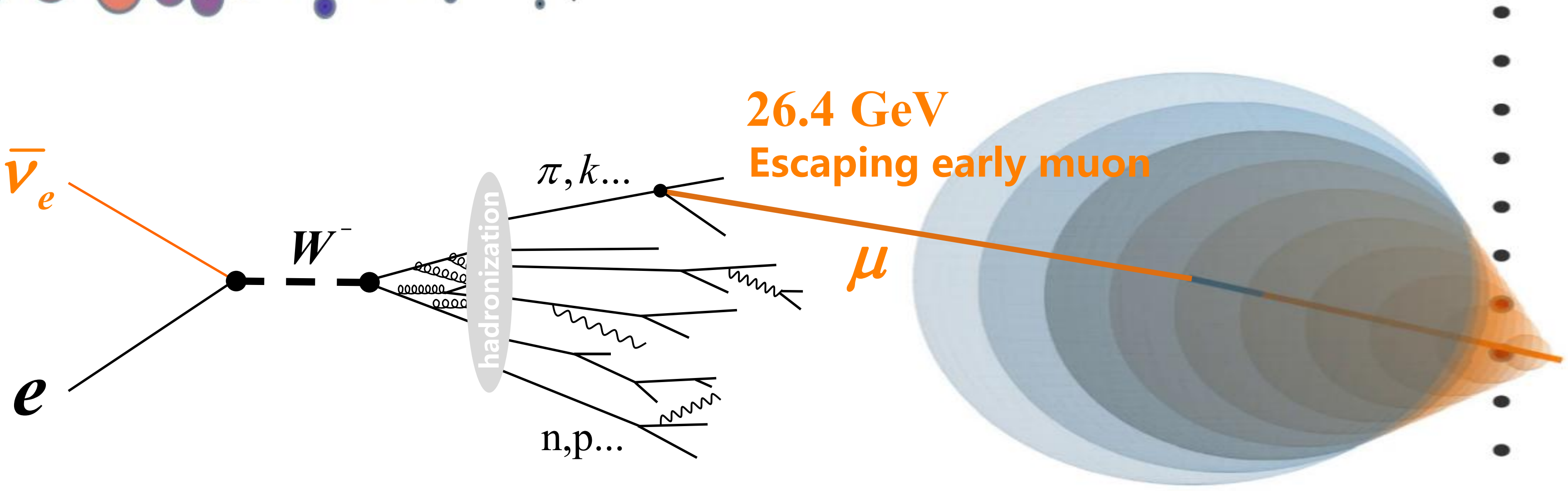


$E_{\text{vis}} \approx 6.05 \pm 0.72$ PeV

IC, Nature591(2021)220



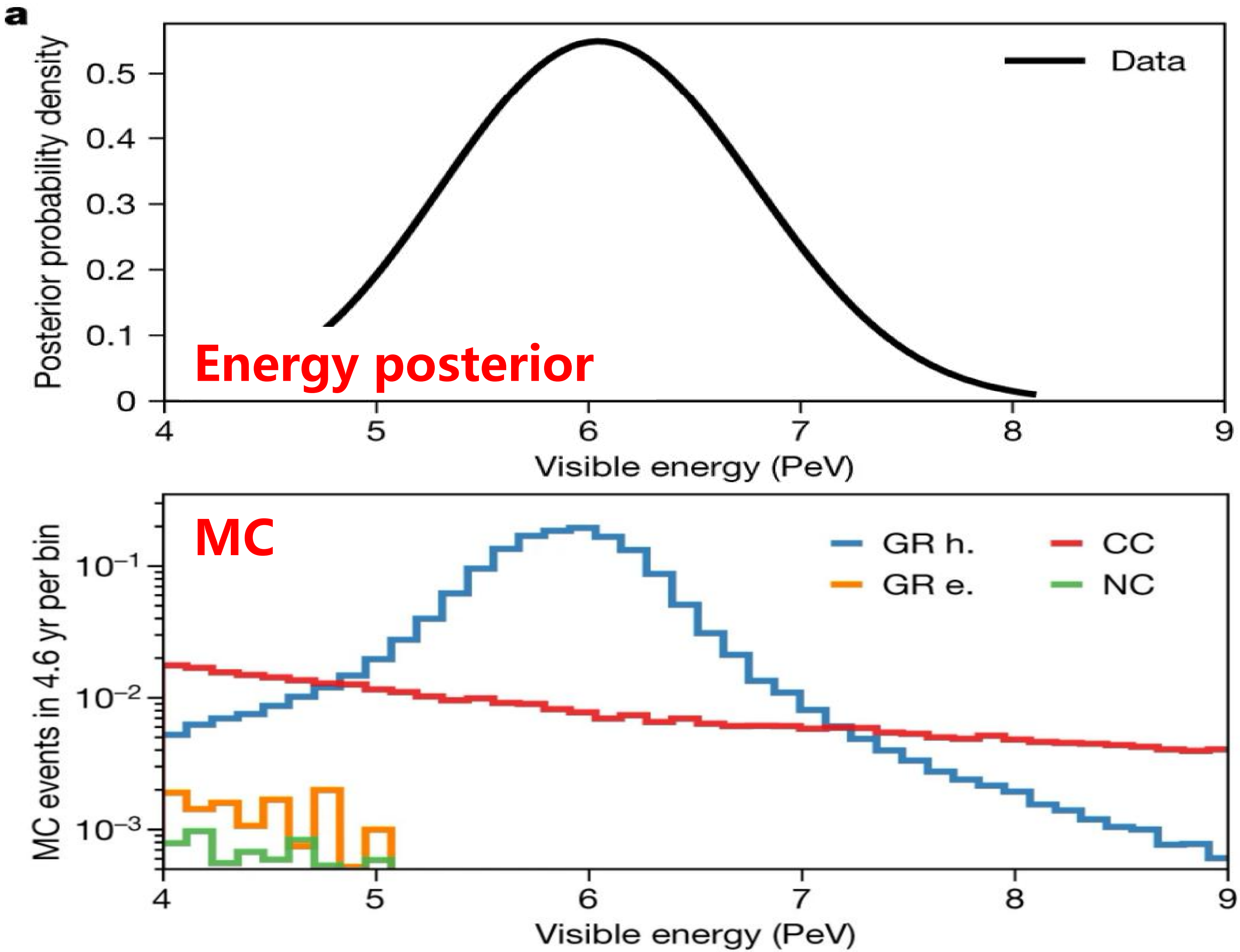
With early muon



26.4 GeV

Escaping early muon

Glashow resonance event



Energy posterior

MC

Glashow resonance event

- **On the one hand, this is a robust test of Standard Model by using neutrino flux**
- **On the other hand, providing good understanding of the physical process, this can be used to probe neutrino sources !**

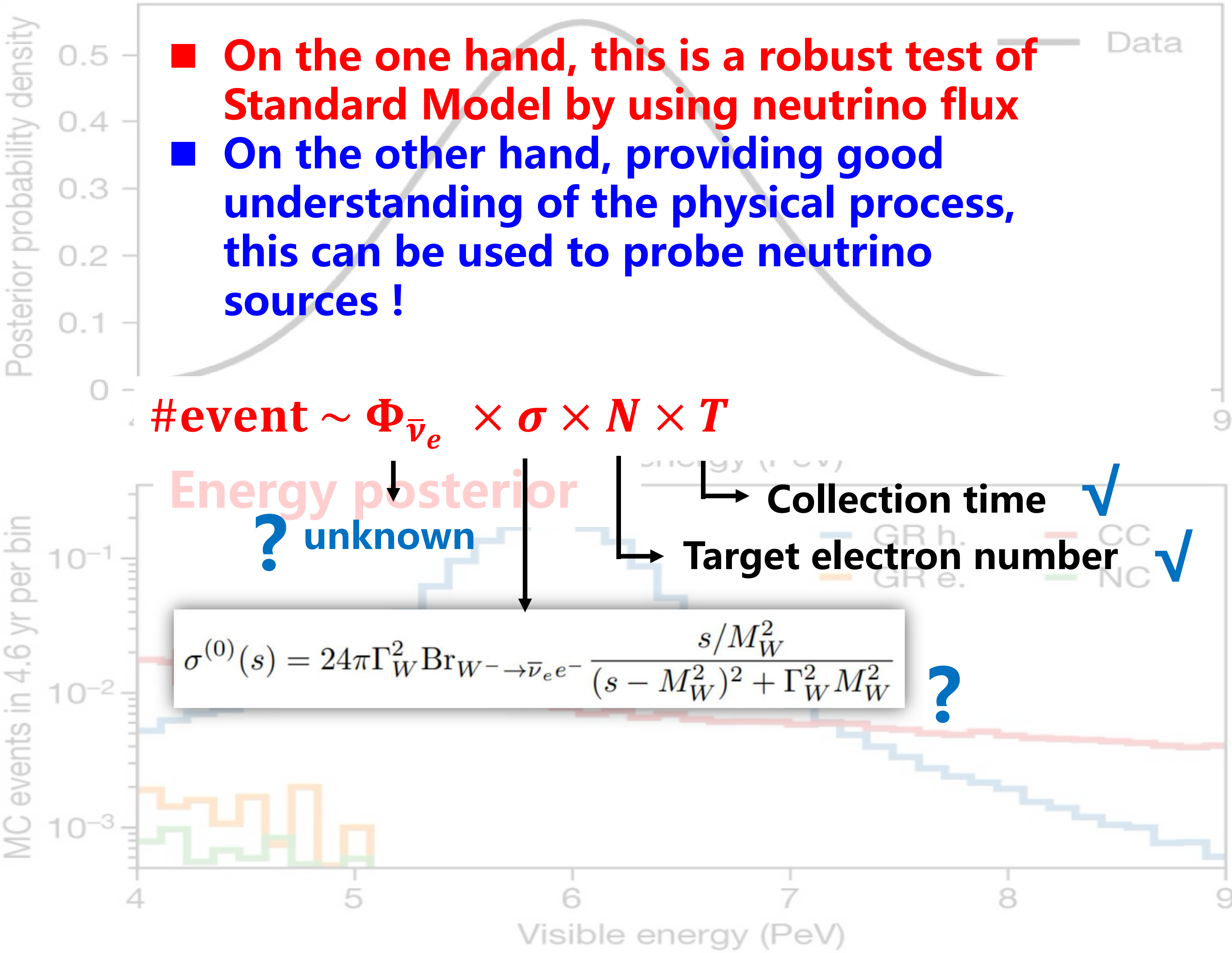
$$\#\text{event} \sim \Phi_{\bar{\nu}_e} \times \sigma \times N \times T$$

? **unknown**

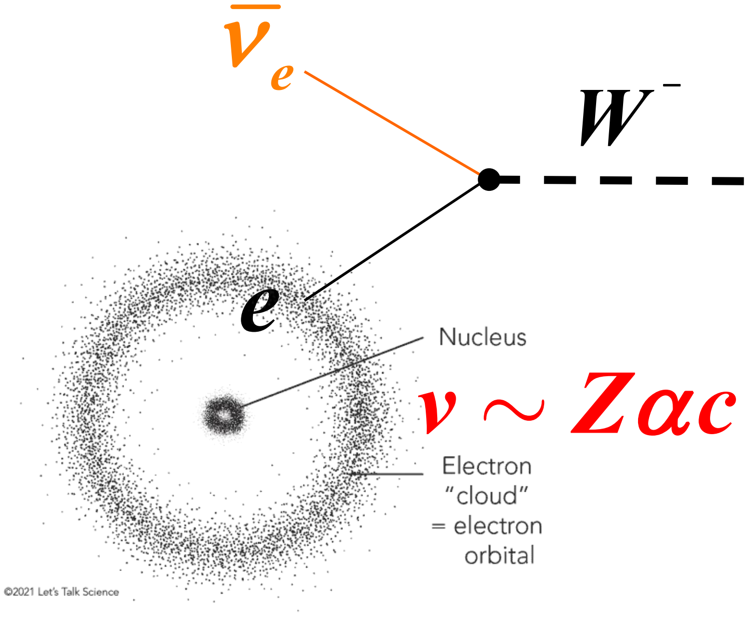
$$\sigma^{(0)}(s) = 24\pi\Gamma_W^2 \mathrm{Br}_{W^- \to \bar{\nu}_e e^-} \frac{s/M_W^2}{(s-M_W^2)^2 + \Gamma_W^2 M_W^2}$$ **?**

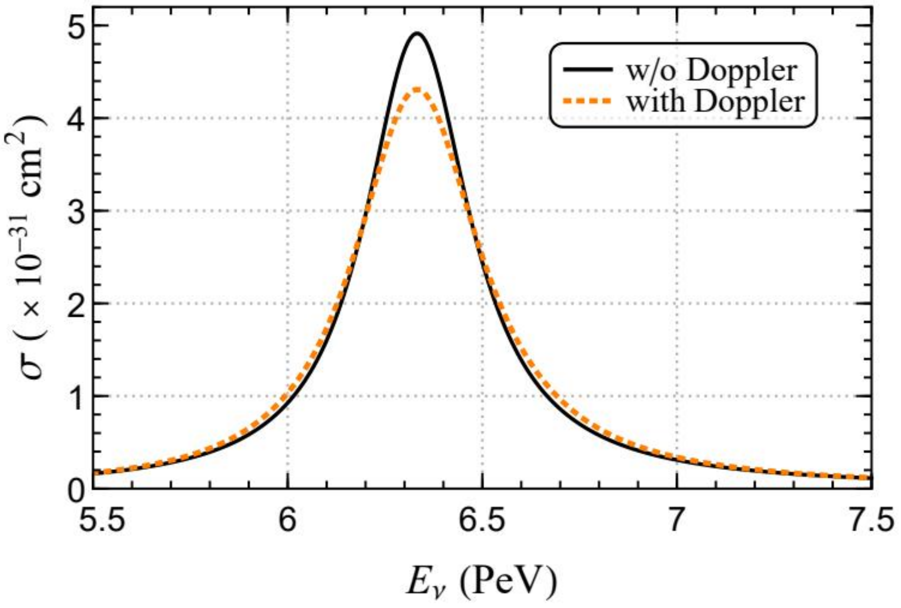
Target electron number √

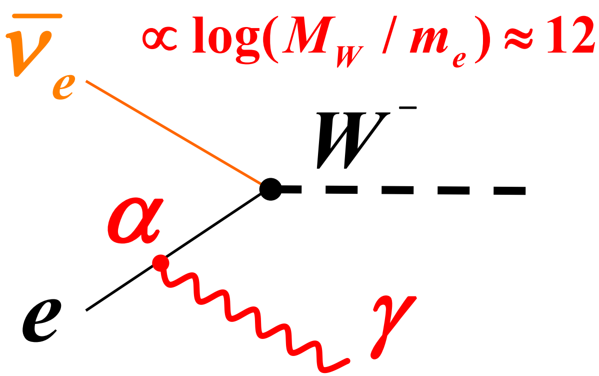
Collection time √



Glashow resonance event

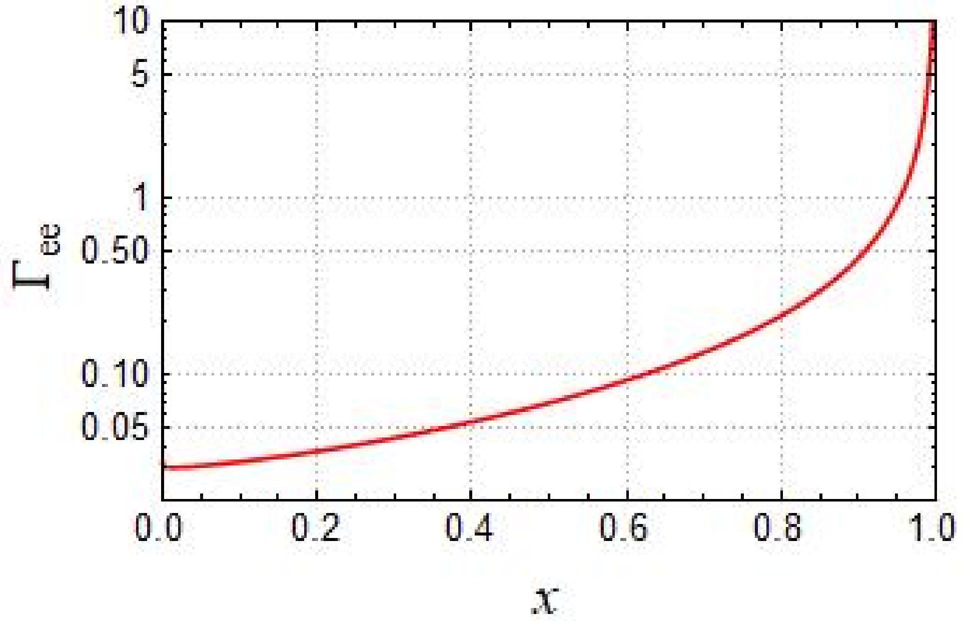




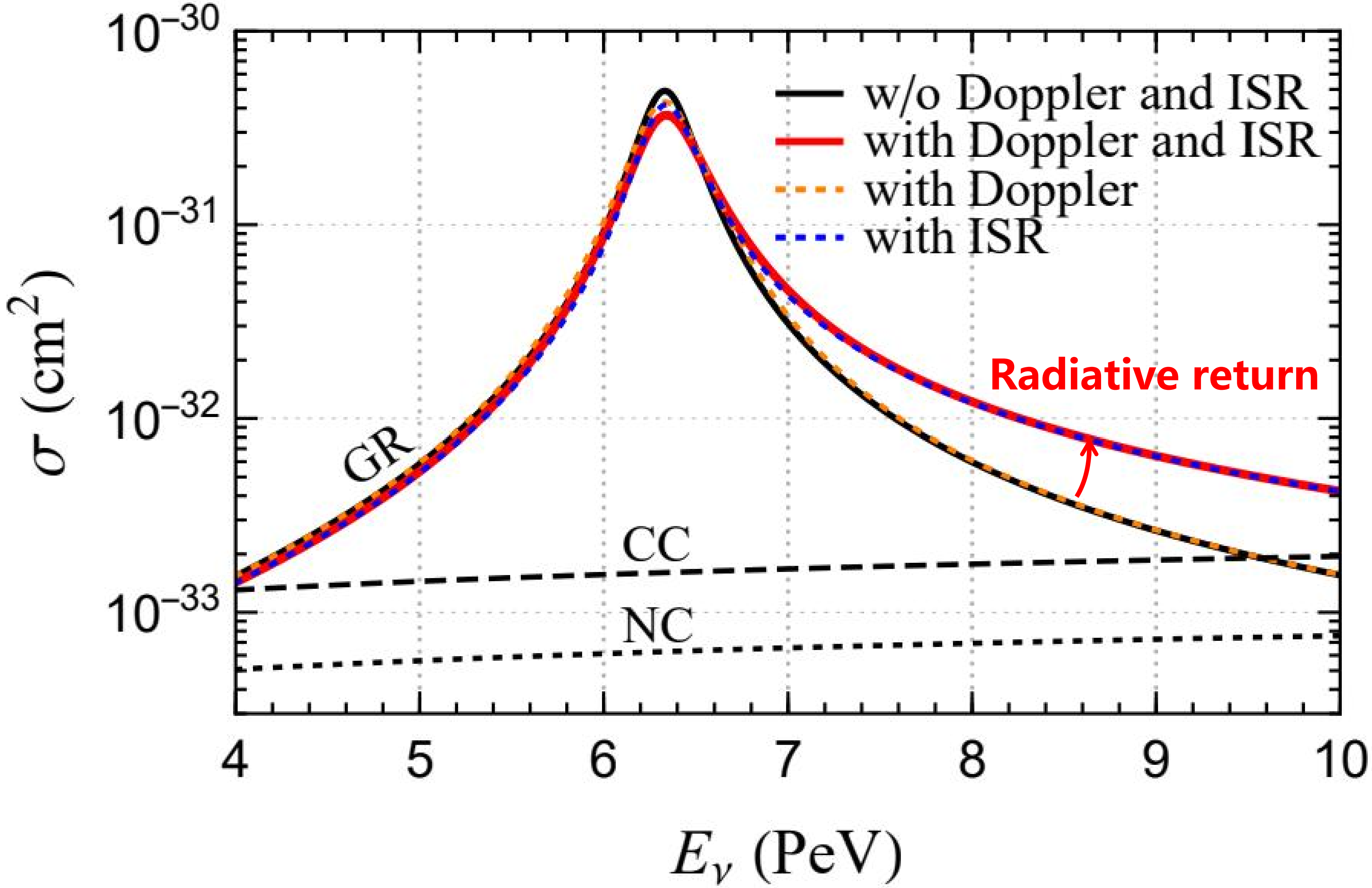


Collinear enhancement

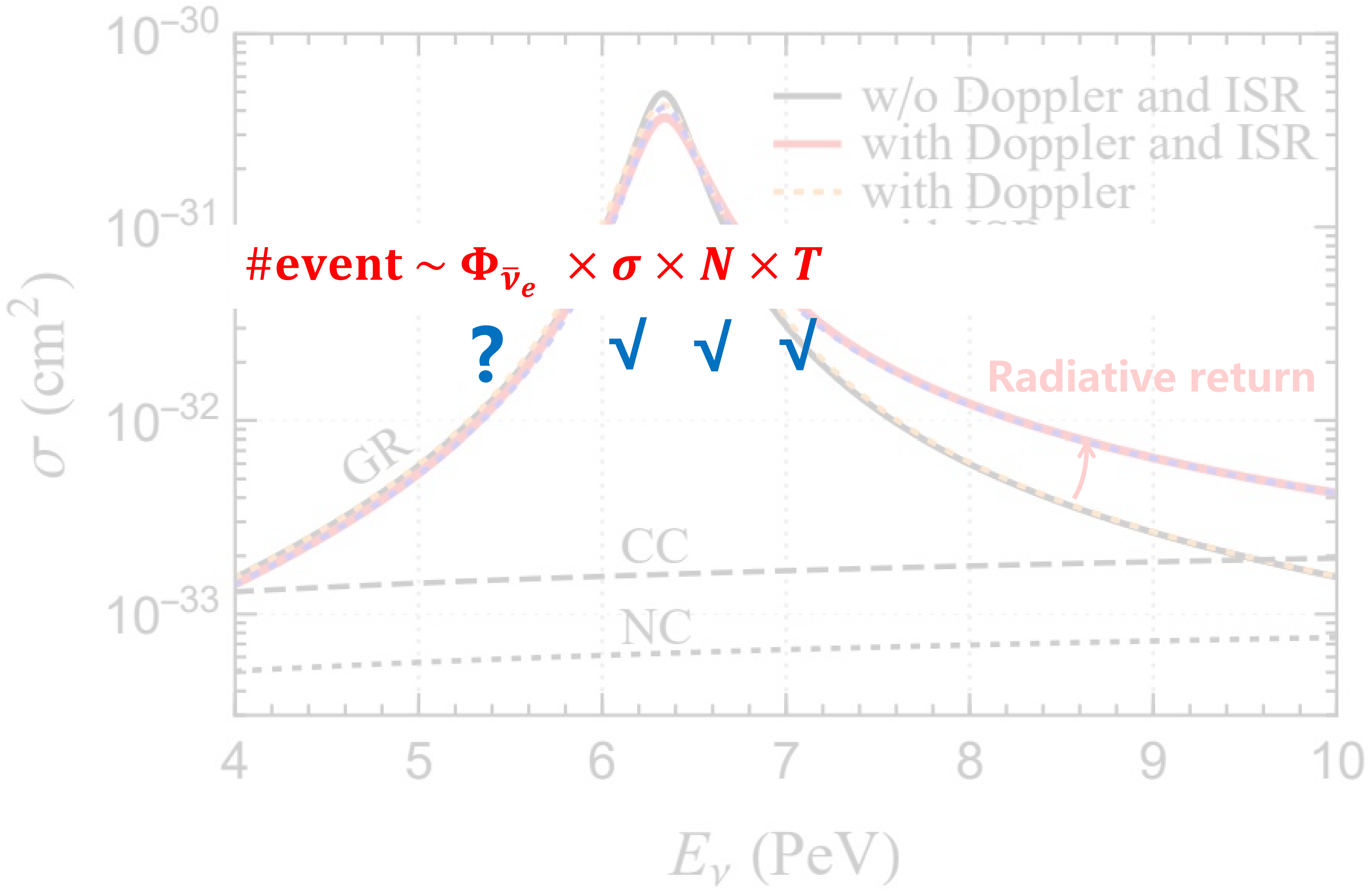
$$\sigma(E_\nu) = \int \mathrm{d}x\, \Gamma_{e/e}(x, Q^2)\sigma^{(0)}(x, Q^2, E_\nu)$$



Cross section



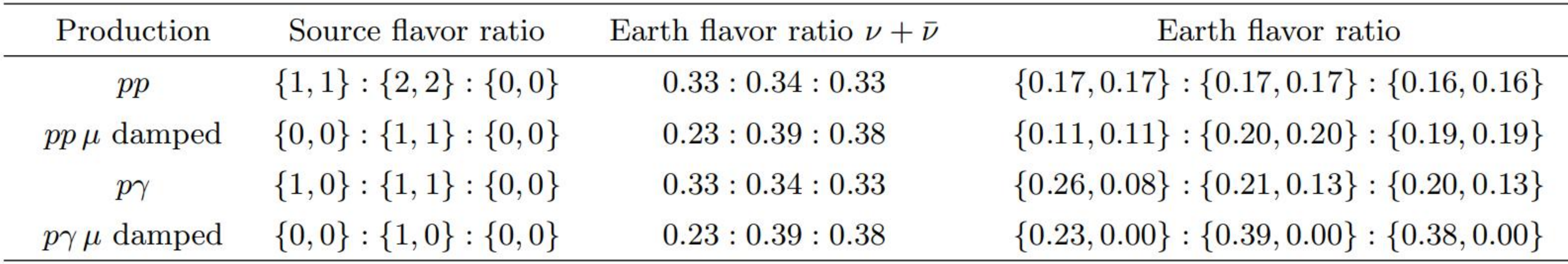
Cross section



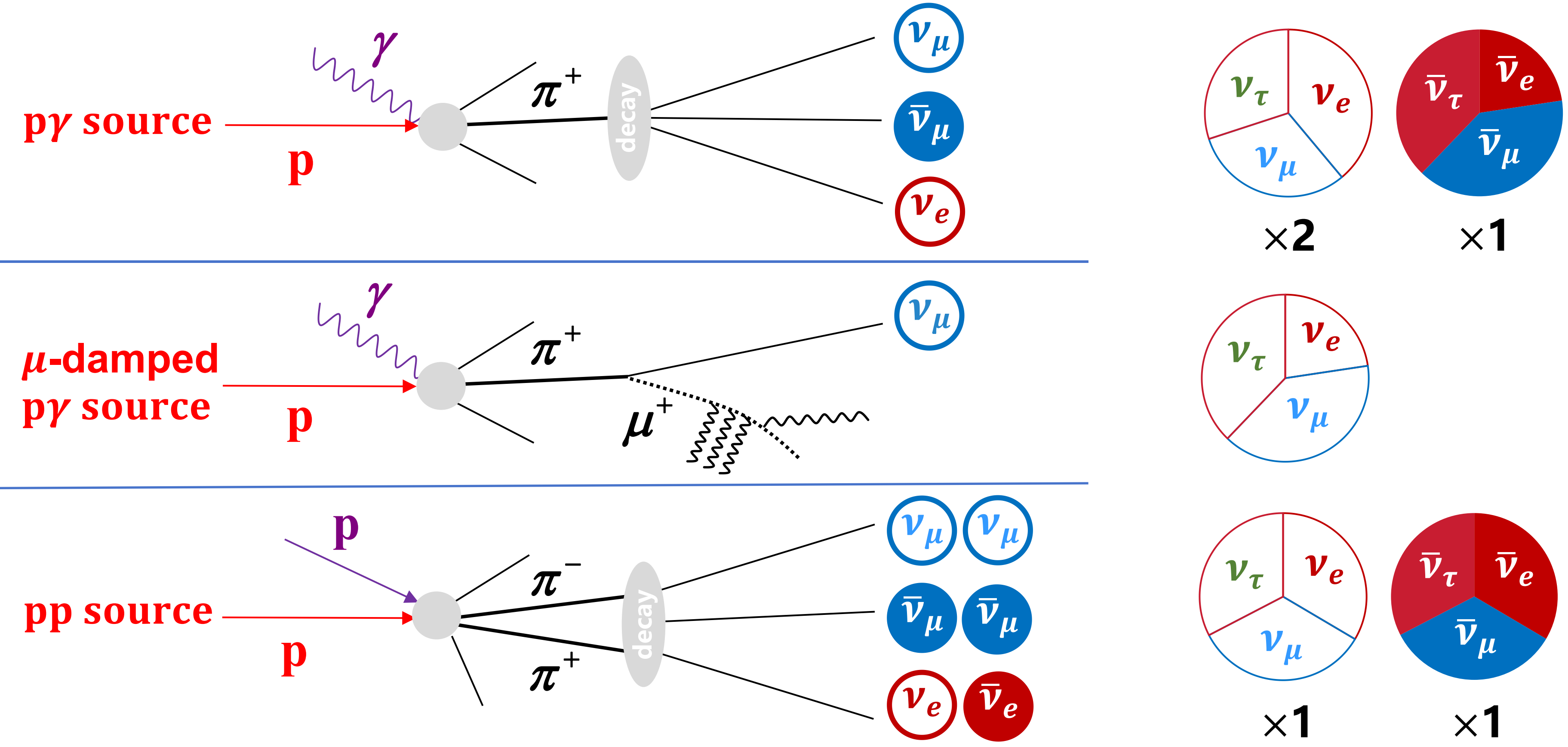
$\#\text{event} \sim \Phi_{\bar{\nu}_e} \times \sigma \times N \times T$

? √ √ √

Flavor composition



Production	Source flavor ratio	Earth flavor ratio $\nu+\bar{\nu}$	Earth flavor ratio
pp	$\{1,1\}:\{2,2\}:\{0,0\}$	$0.33:0.34:0.33$	$\{0.17,0.17\}:\{0.17,0.17\}:\{0.16,0.16\}$
pp μ damped	$\{0,0\}:\{1,1\}:\{0,0\}$	$0.23:0.39:0.38$	$\{0.11,0.11\}:\{0.20,0.20\}:\{0.19,0.19\}$
$p\gamma$	$\{1,0\}:\{1,1\}:\{0,0\}$	$0.33:0.34:0.33$	$\{0.26,0.08\}:\{0.21,0.13\}:\{0.20,0.13\}$
$p\gamma$ μ damped	$\{0,0\}:\{1,0\}:\{0,0\}$	$0.23:0.39:0.38$	$\{0.23,0.00\}:\{0.39,0.00\}:\{0.38,0.00\}$



Continuous efforts in this direction

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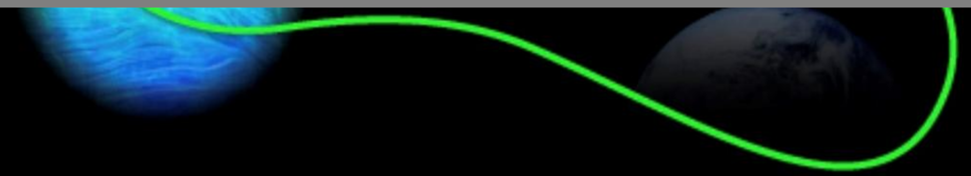
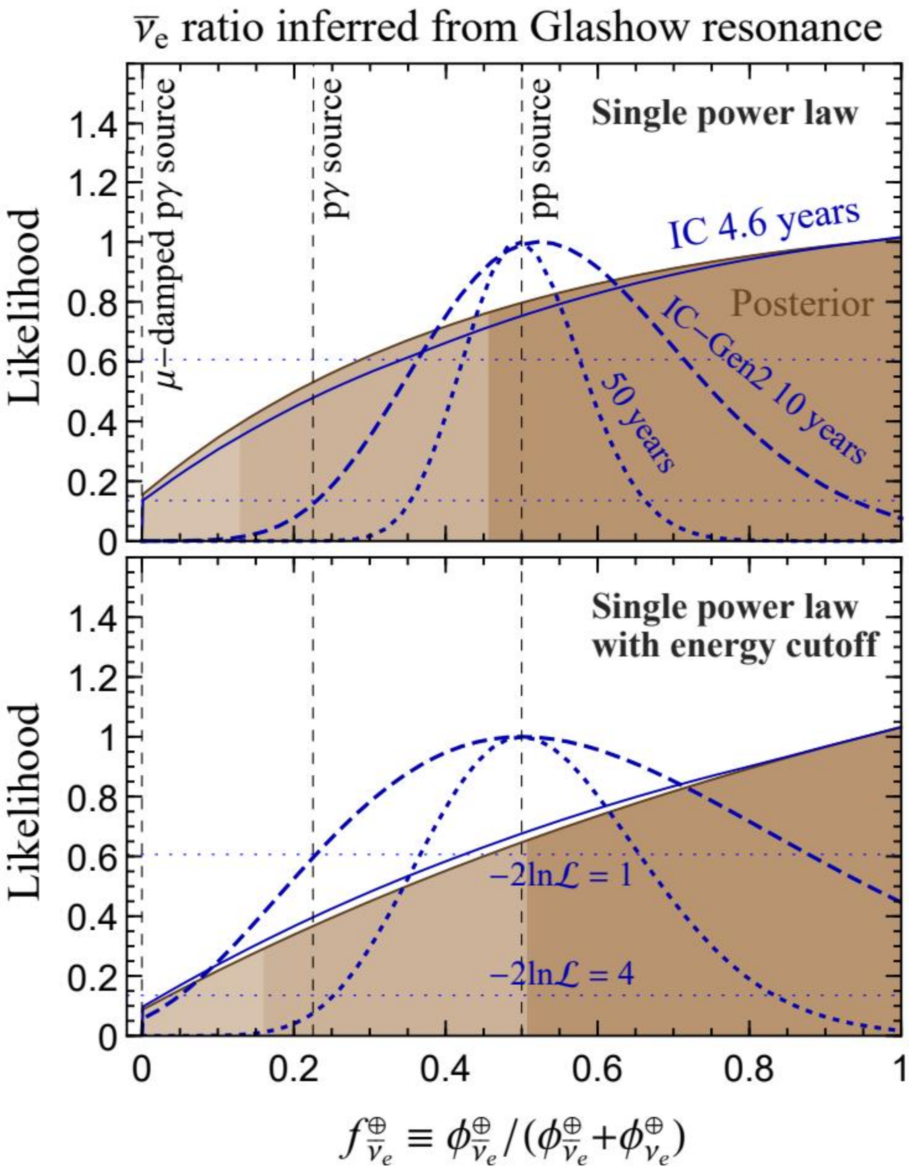
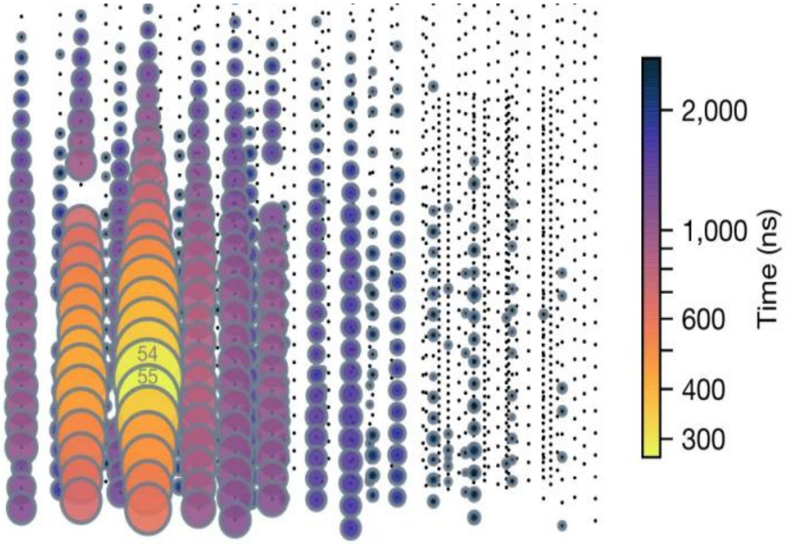
G.-y. Huang and Q. Liu, JCAP 03 (2020) 005
S. Zhou, arXiv:2006.06181



©Randall Smith & Rob Petre,

Ratio inference





$$-2\ln\mathcal{L}_{6\nu} = \frac{(\Phi_0 - \Phi_0^{\mathrm{bf}})^2}{\sigma(\Phi_0)^2} + \frac{(\gamma - \gamma^{\mathrm{bf}})^2}{\sigma(\gamma)^2}$$

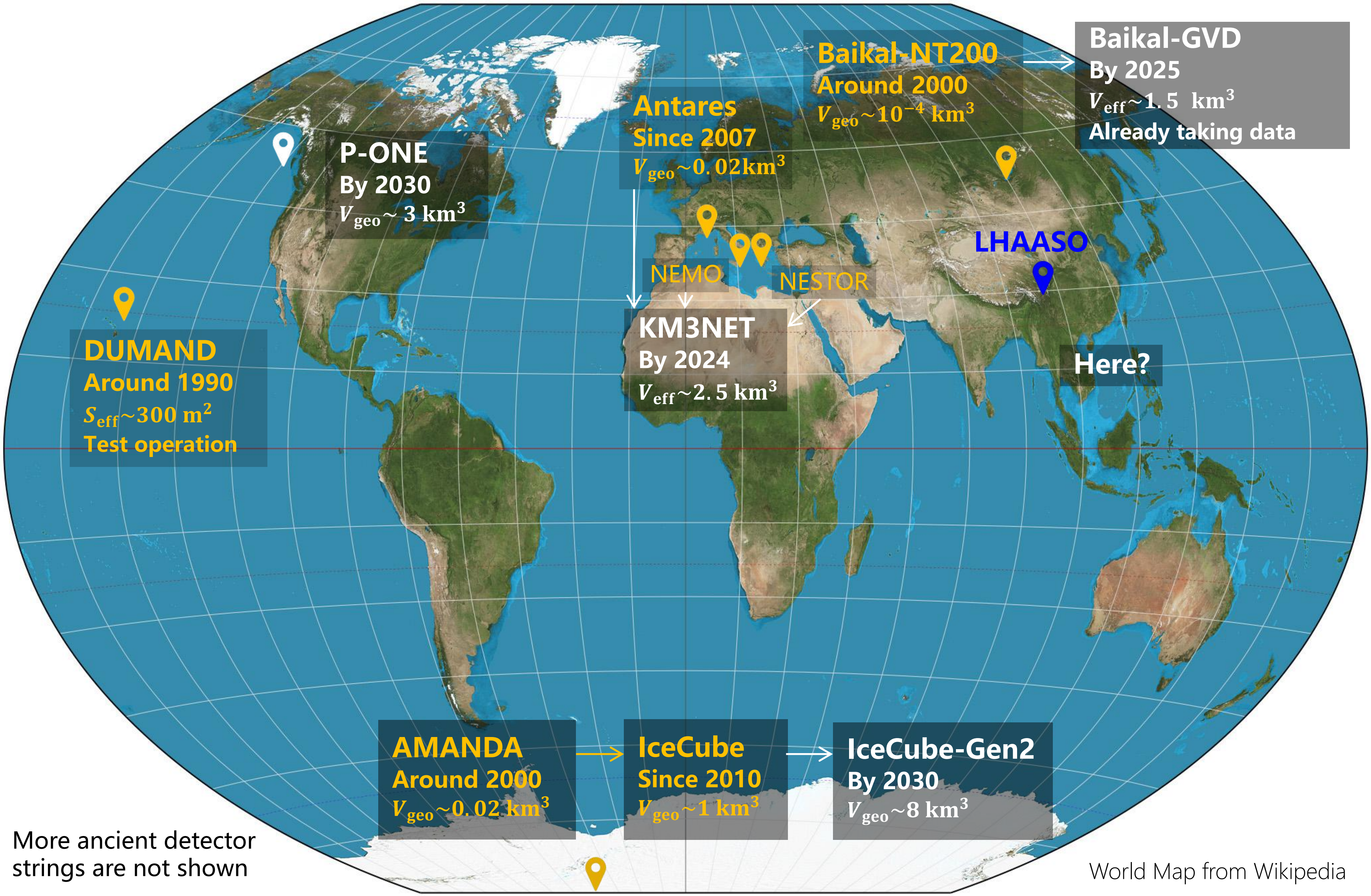
$$\mathcal{L}_{\bar{\nu}_e} = \prod_{i=1}^{n} \left[\mu_{\mathrm{DIS}} P_{\mathrm{DIS}}(\#i|\Theta) + \mu_{\mathrm{GR}} P_{\mathrm{GR}}(\#i|\Theta)\right] \times \frac{1}{n!} \mathrm{e}^{-(\mu_{\mathrm{DIS}}+\mu_{\mathrm{GR}})} ,$$

$$\mu_{\mathrm{DIS}} = \int_{\mathrm{cut}} \mathrm{d}E_{\mathrm{dep}} \cdot \left(\frac{\mathrm{d}N^{\mathrm{CC}}_{\nu_e+\bar{\nu}_e}}{\mathrm{d}E_{\mathrm{dep}}} + \sum_{\alpha} \frac{\mathrm{d}N^{\mathrm{NC}}_{\nu_\alpha+\bar{\nu}_\alpha}}{\mathrm{d}E_{\mathrm{dep}}} \right)$$

$$\mu_{\mathrm{GR}} = \int_{\mathrm{cut}} \mathrm{d}E_{\mathrm{dep}} \cdot \left(\frac{\mathrm{d}N^{\mathrm{GR},jj}_{\bar{\nu}_e}}{\mathrm{d}E_{\mathrm{dep}}} + \frac{\mathrm{d}N^{\mathrm{GR},e\nu}_{\bar{\nu}_e}}{\mathrm{d}E_{\mathrm{dep}}} \right) .$$

$$P_{\mathrm{DIS/GR}}(\#i|\Theta) = \int \mathrm{d}E_{\mathrm{dep}} P(\#i|E_{\mathrm{dep}}) f_{\mathrm{DIS/GR}}(E_{\mathrm{dep}}|\Theta)$$

Future projection



DUMAND
Around 1990
$S_{\text{eff}}\sim 300\ \text{m}^2$
Test operation

P-ONE
By 2030
$V_{\text{geo}}\sim 3\ \text{km}^3$

Antares
Since 2007
$V_{\text{geo}}\sim 0.02\text{km}^3$

Baikal-NT200
Around 2000
$V_{\text{geo}}\sim 10^{-4}\ \text{km}^3$

Baikal-GVD
By 2025
$V_{\text{eff}}\sim 1.5\ \text{km}^3$
Already taking data

NEMO

NESTOR

KM3NET
By 2024
$V_{\text{eff}}\sim 2.5\ \text{km}^3$

LHAASO

Here?

AMANDA
Around 2000
$V_{\text{geo}}\sim 0.02\ \text{km}^3$

IceCube
Since 2010
$V_{\text{geo}}\sim 1\ \text{km}^3$

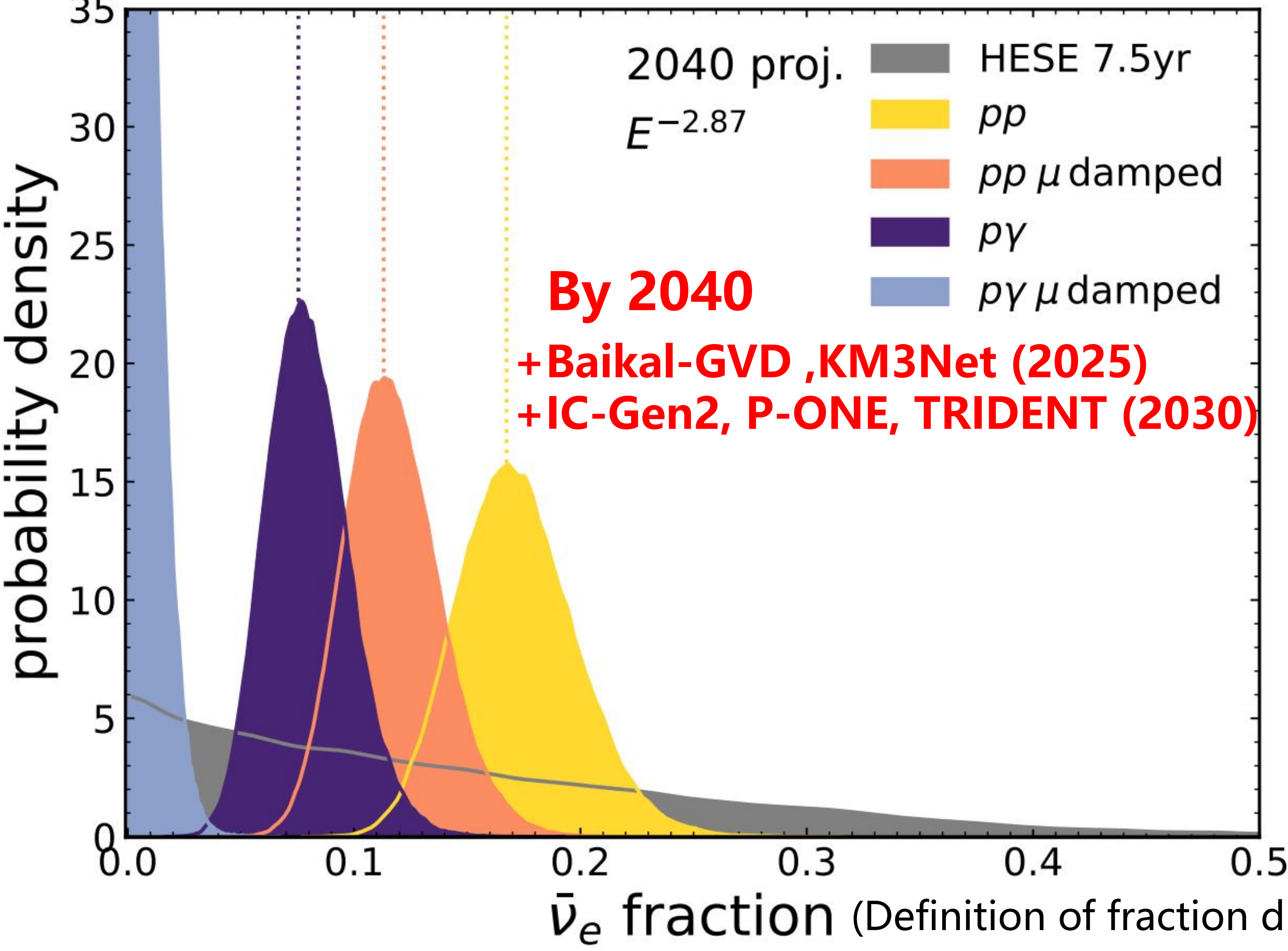
IceCube-Gen2
By 2030
$V_{\text{geo}}\sim 8\ \text{km}^3$

More ancient detector strings are not shown

World Map from Wikipedia

Future projection

Q. Liu, N. Song, A. Vincent, PRD 108(2023)043022



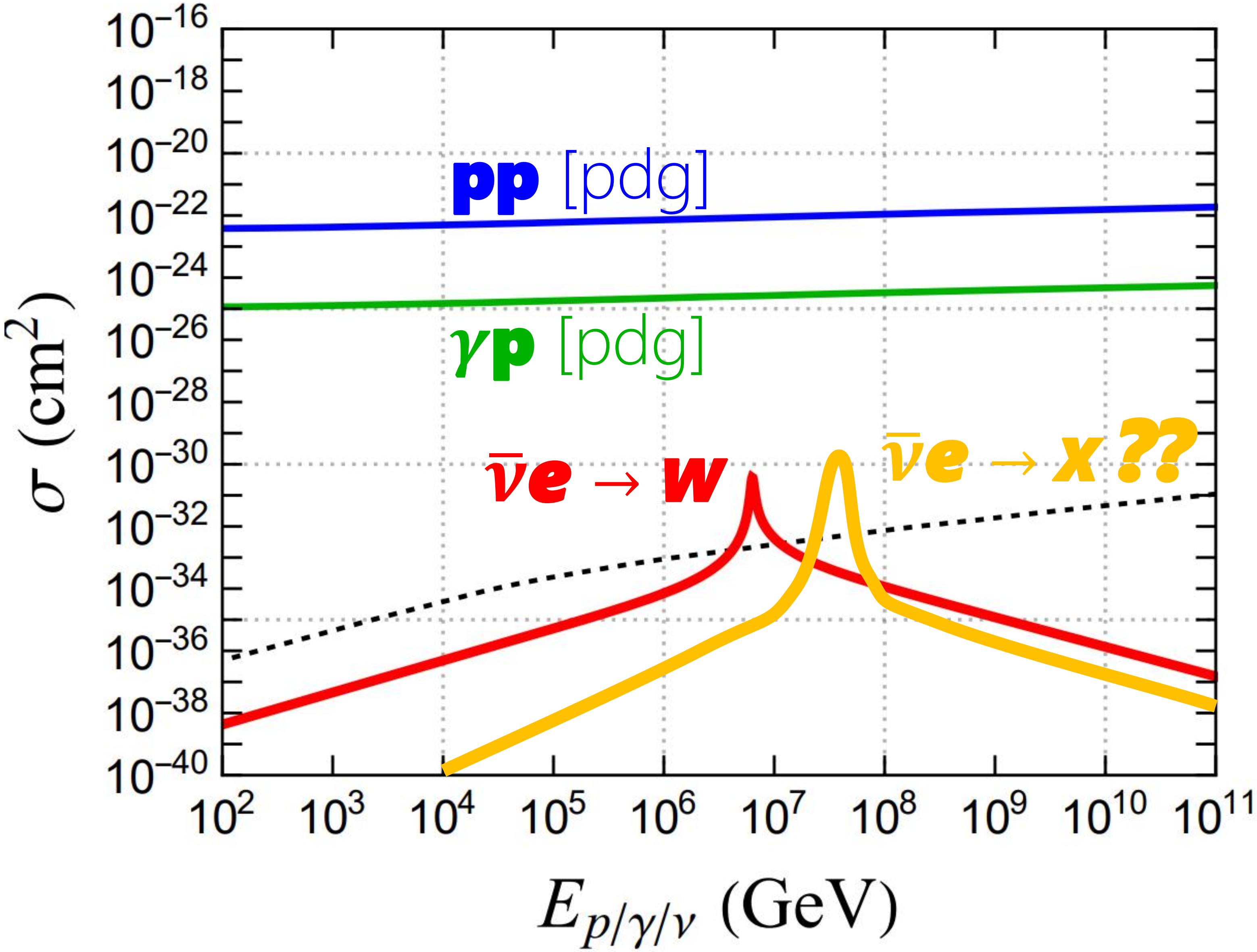
By 2040

+Baikal-GVD ,KM3Net (2025)

+IC-Gen2, P-ONE, TRIDENT (2030)

(Definition of fraction differs)

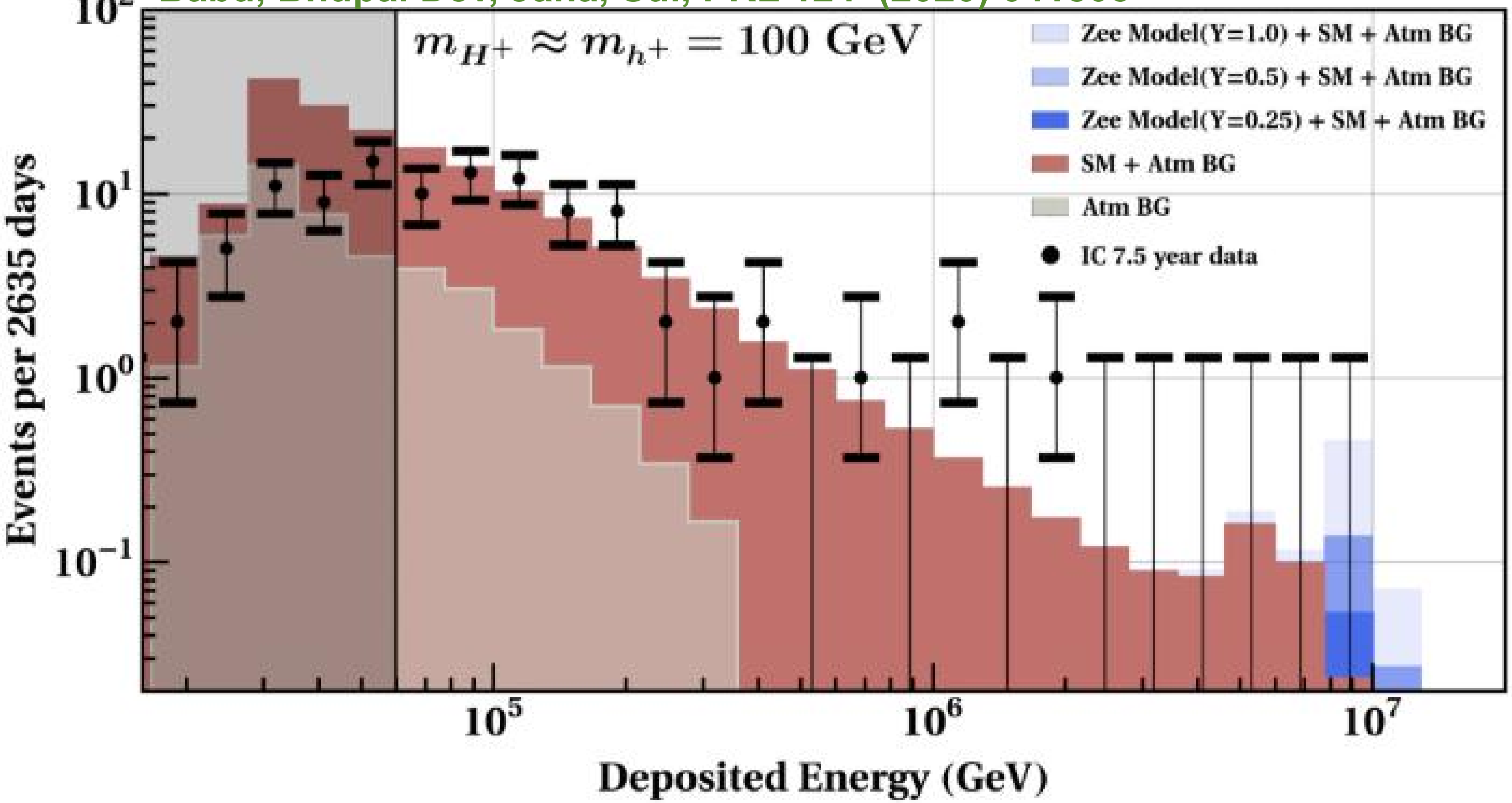
Any new resonances?



Any new resonances?

$\bar{\nu}e \rightarrow X \rightarrow anything$

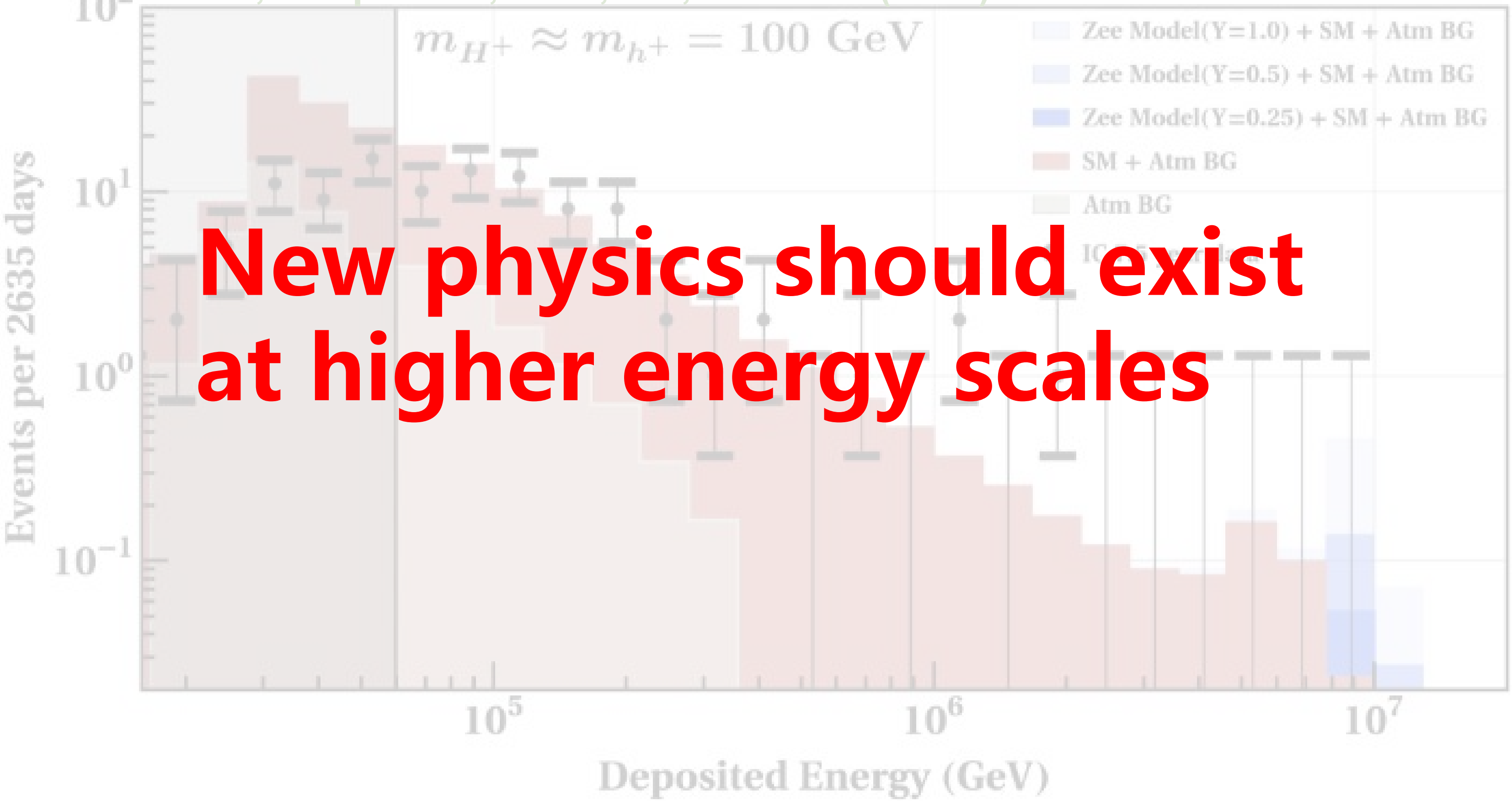
Babu, Bhupal Dev, Jana, Sui, PRL 124 (2020) 041805



Zee-Burst? No such signal in IC data

Any new resonances?

$\bar{\nu}e \to X \to anything$



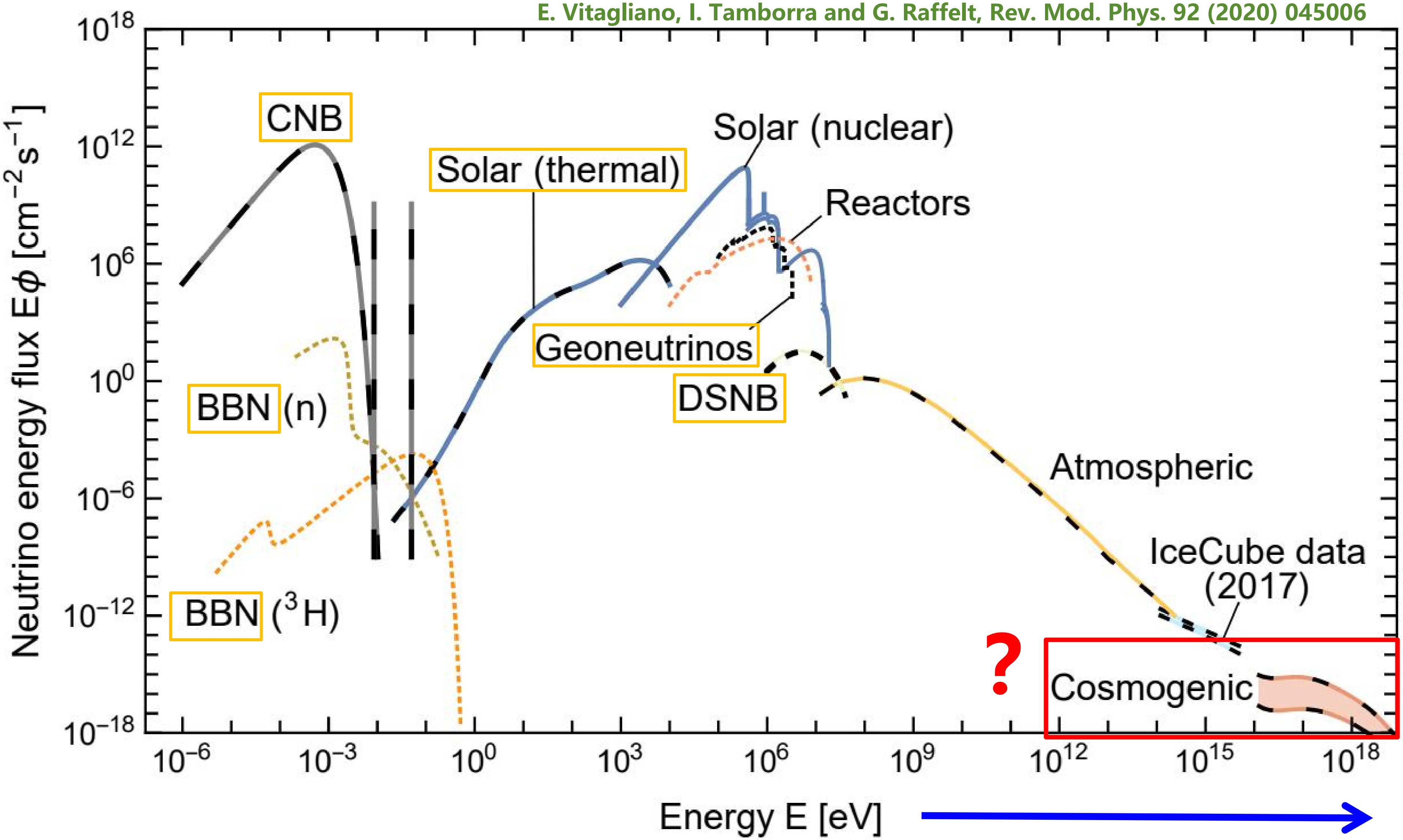
Babu, Bhupal Dev, Jana, Sui, PRL 124 (2020) 041805

New physics should exist at higher energy scales

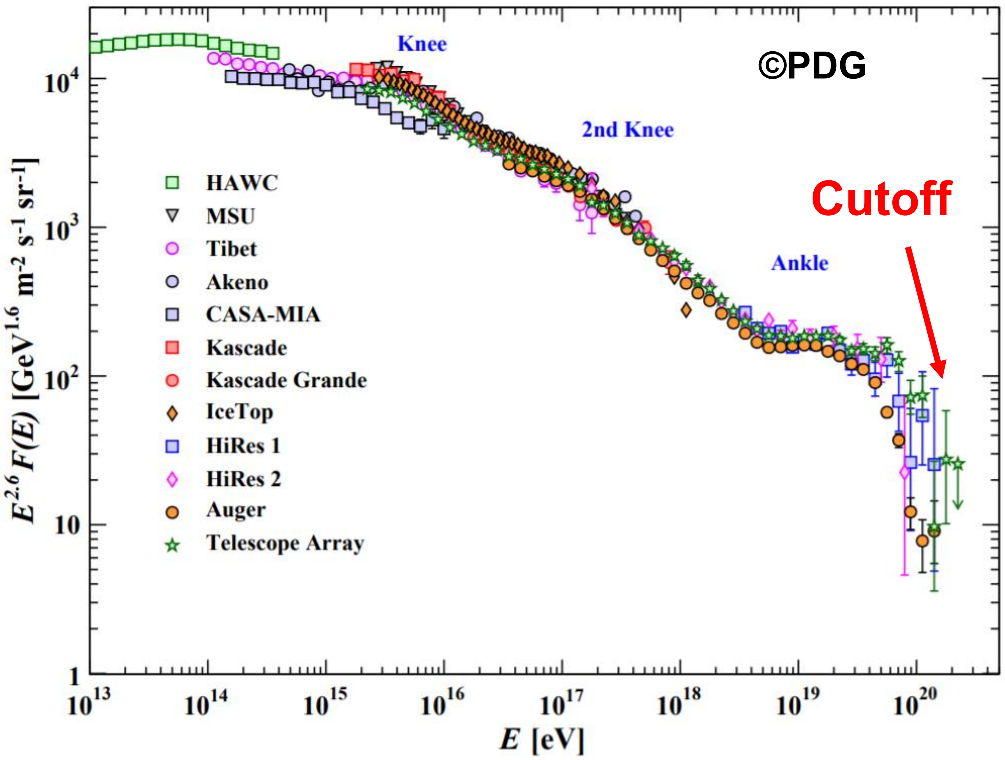
Zee-Burst? No such signal in IC data

Cosmogenic neutrino flux

E. Vitagliano, I. Tamborra and G. Raffelt, Rev. Mod. Phys. 92 (2020) 045006



Cosmogenic neutrino flux



Cutoff

*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

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

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

EeV neutrino telescopes

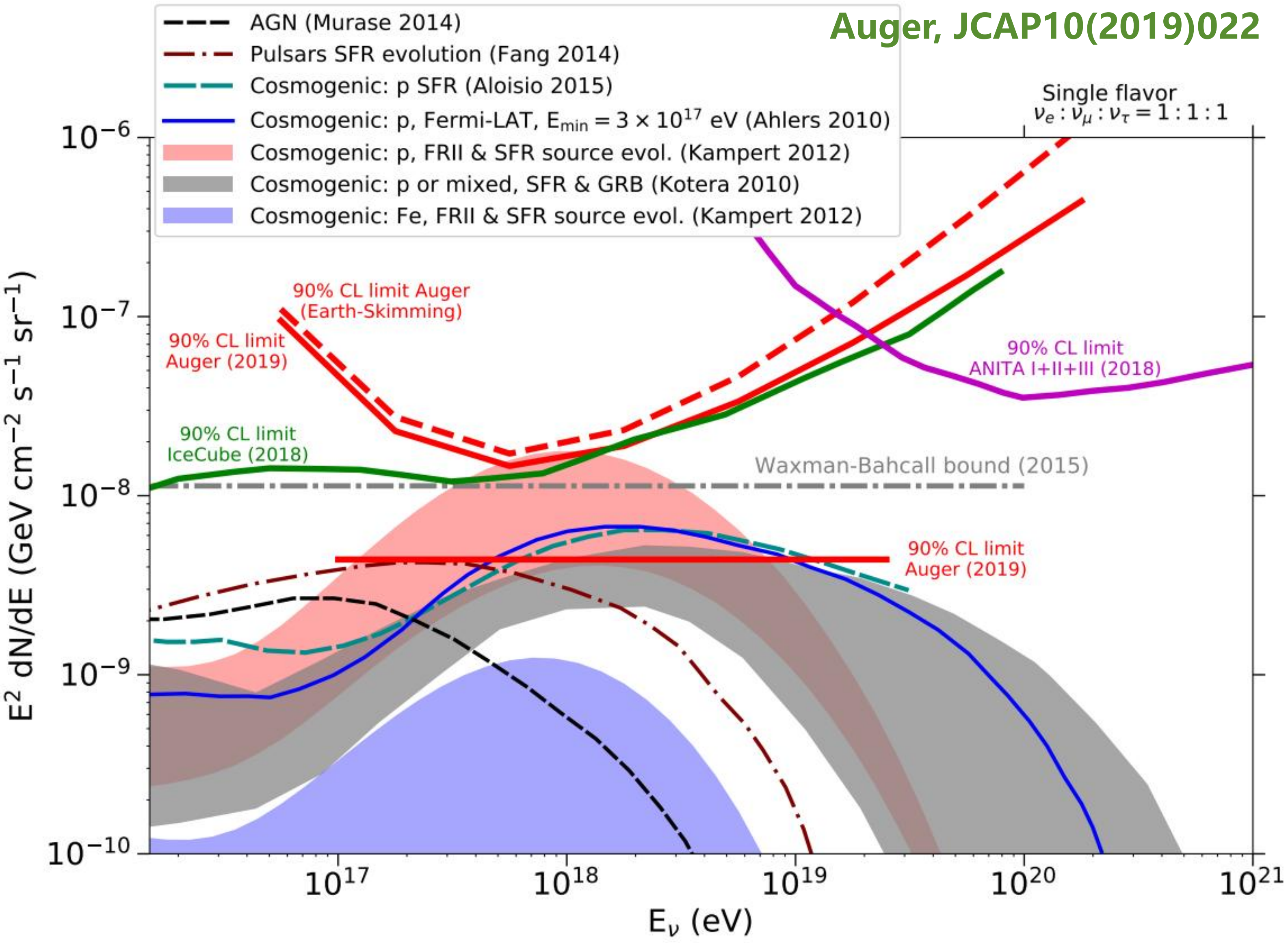
Berezinsky and Smirnov, Astro. Space. Sci.32(1975)461
Feng et al. PRL88(2002)161102
Cao et al., JPG31(2005)571

Technique	Approx. time of the proposal
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 (detected)*
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*


UHE CR and gamma detections

APS/Carin Cain

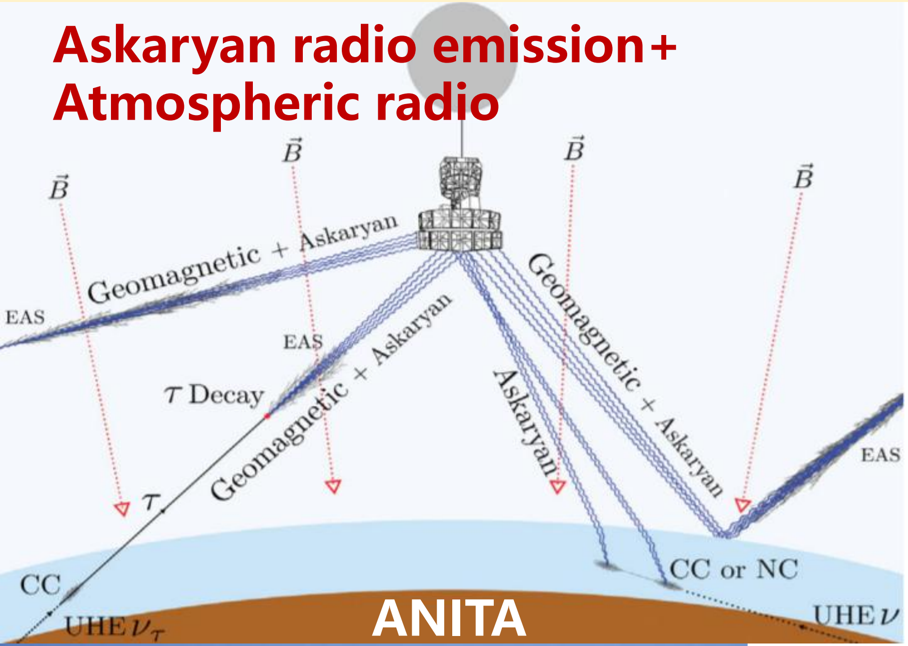
EeV neutrino telescopes

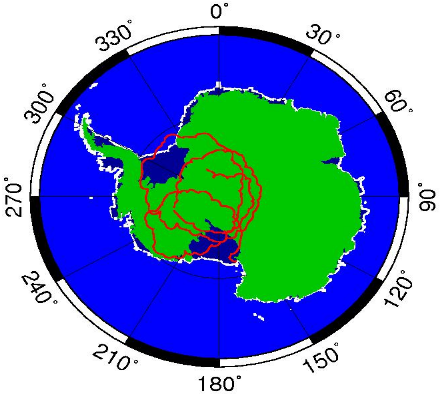


Auger, JCAP10(2019)022

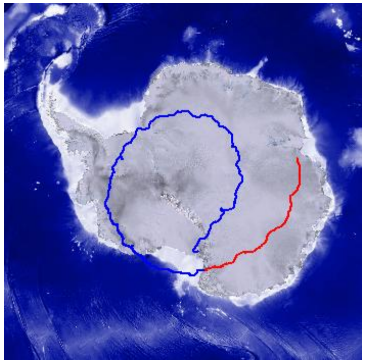
EeV neutrino telescopes

Askaryan radio emission+
Atmospheric radio

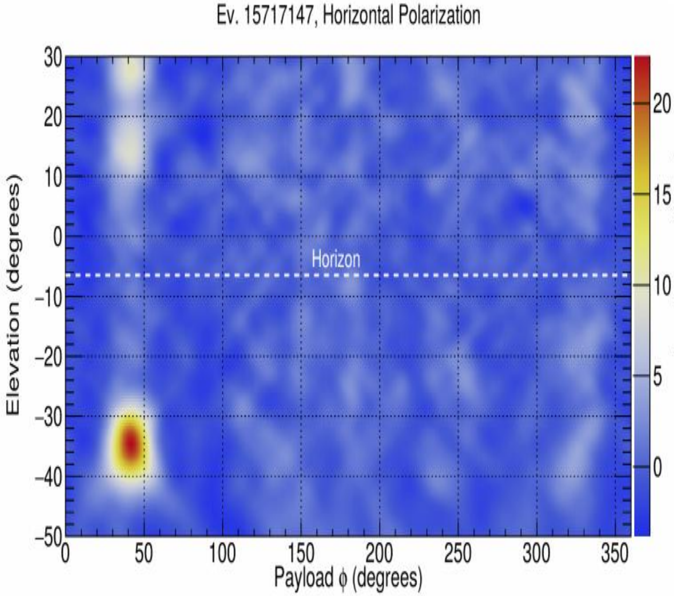




ANITA-I



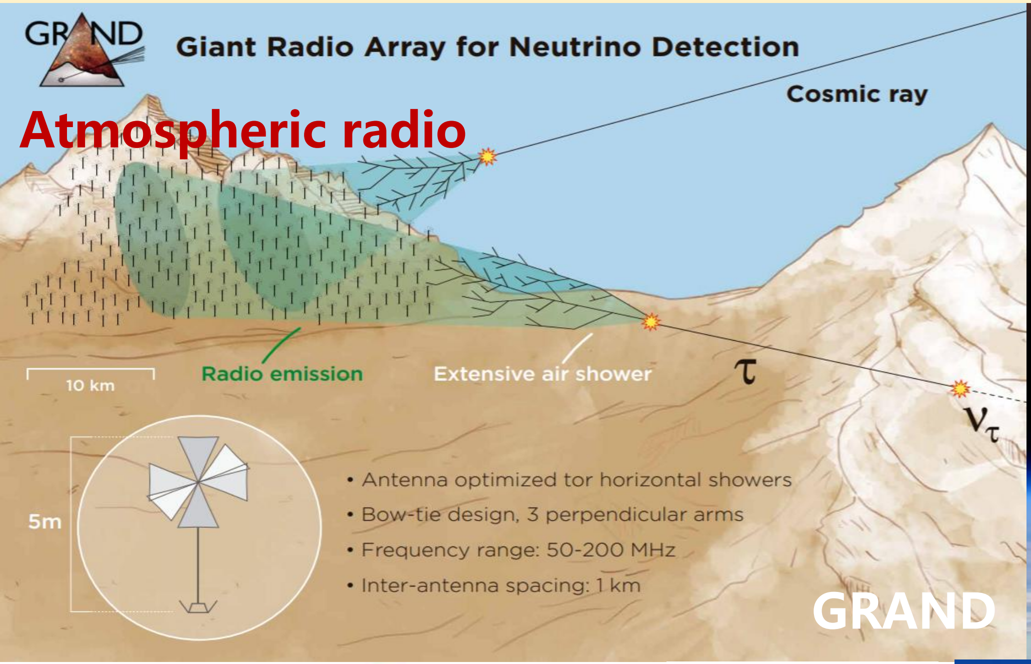
ANITA-III



40+ of papers about new physics explanations

New Physics is not compatible with ANITA-IV results

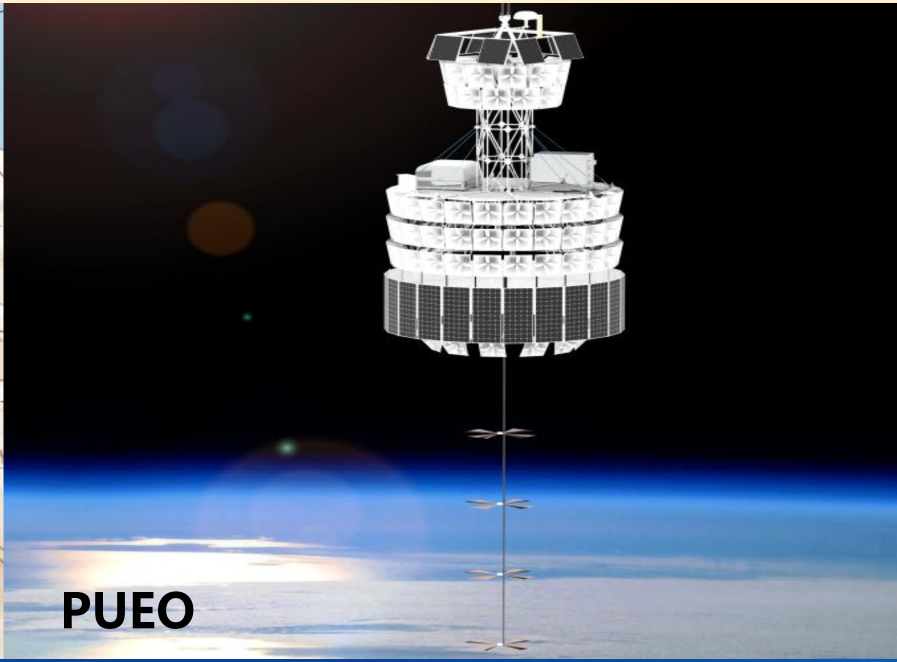
EeV neutrino telescopes



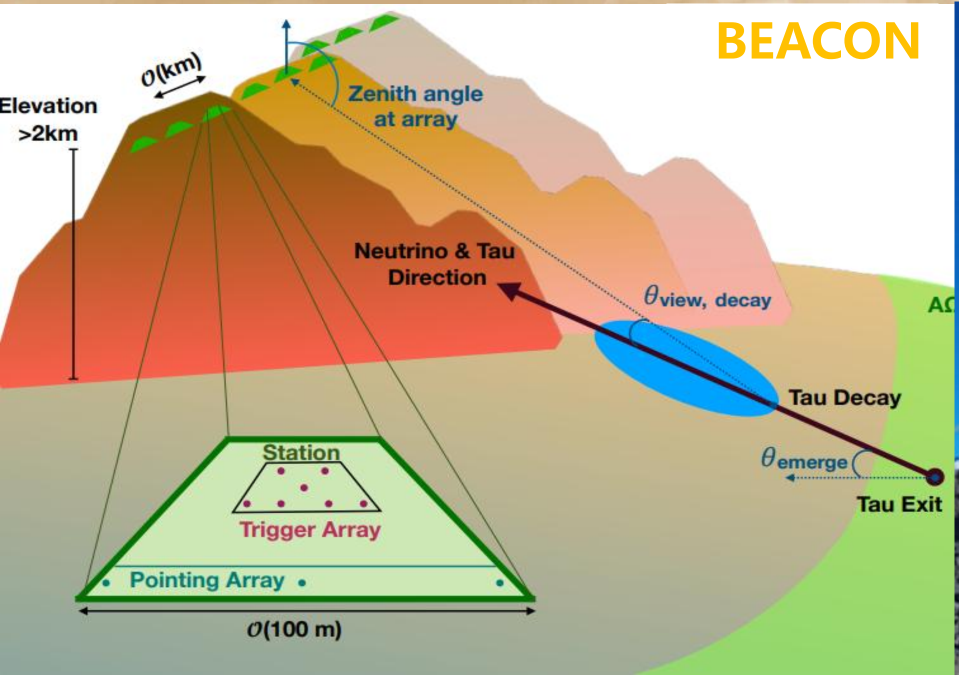
Atmospheric radio

- Antenna optimized for horizontal showers
- Bow-tie design, 3 perpendicular arms
- Frequency range: 50-200 MHz
- Inter-antenna spacing: 1 km

GRAND



PUEO



BEACON

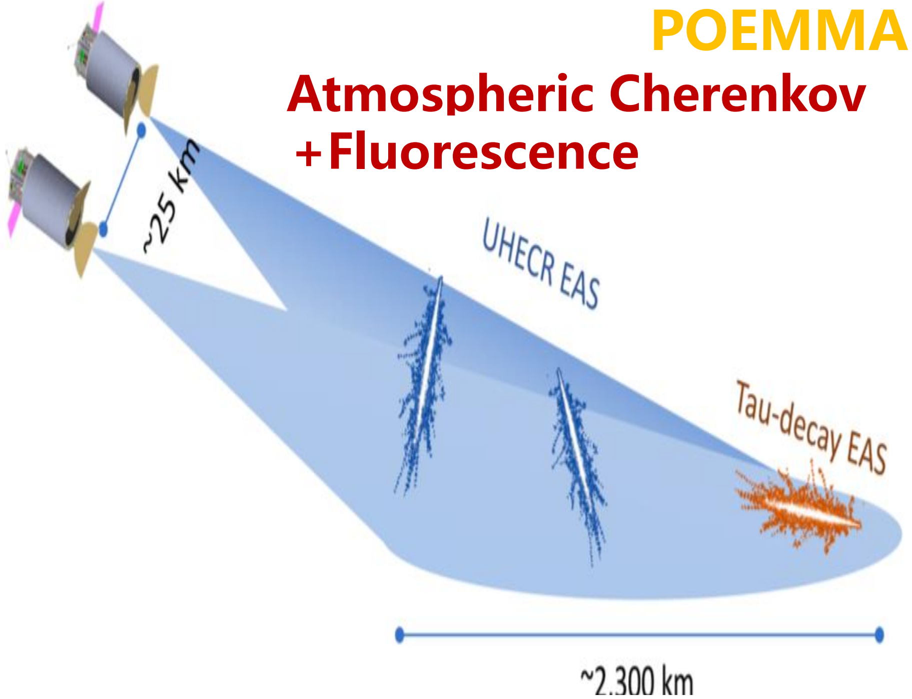
TAROGE-M

EeV neutrino telescopes

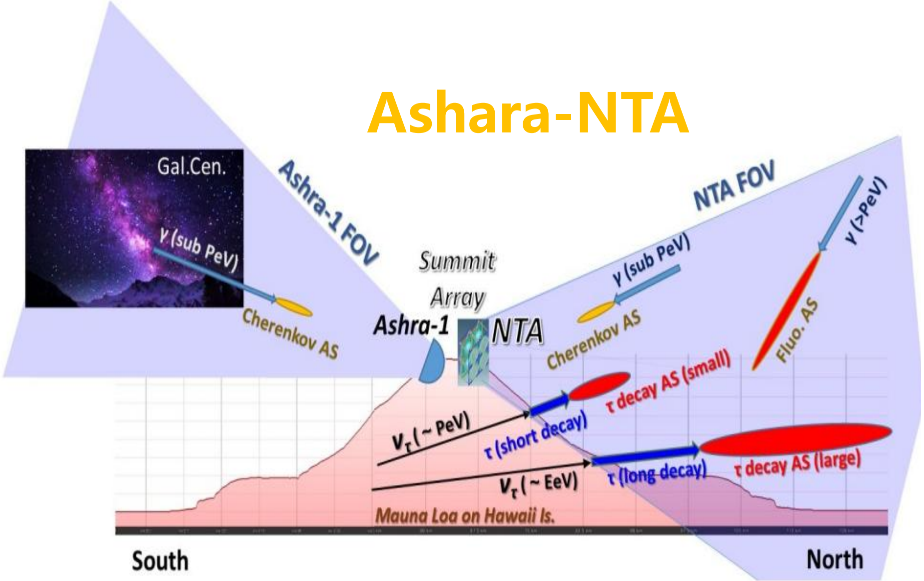
EUSO-SPB

POEMMA

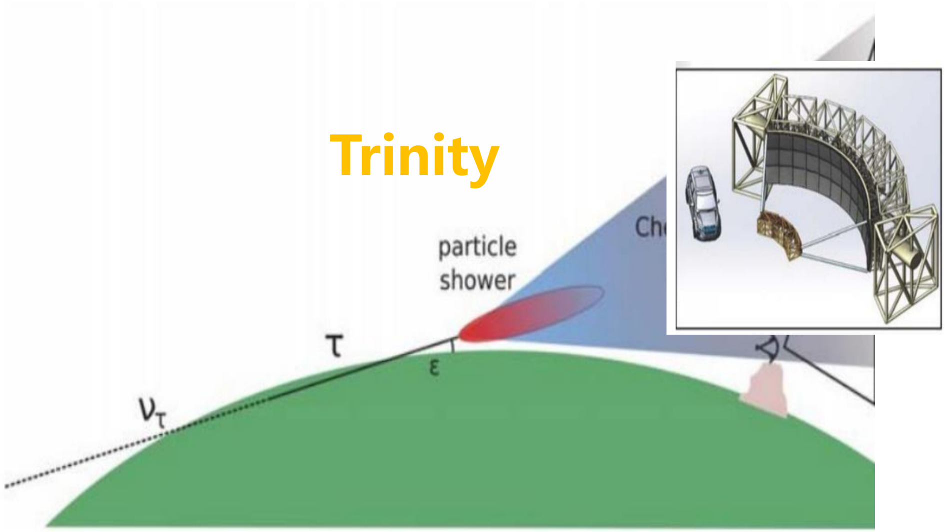
Atmospheric Cherenkov +Fluorescence



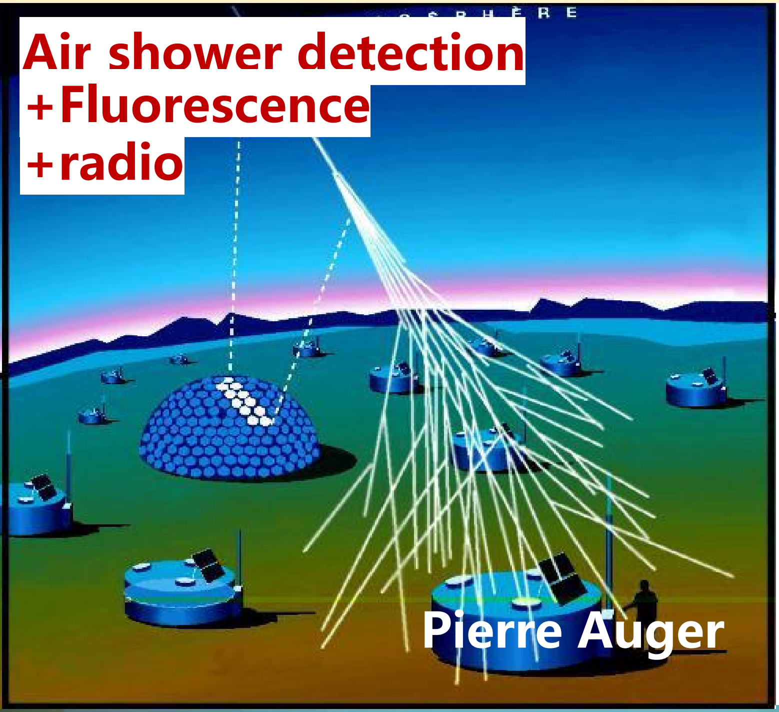
Ashara-NTA



Trinity

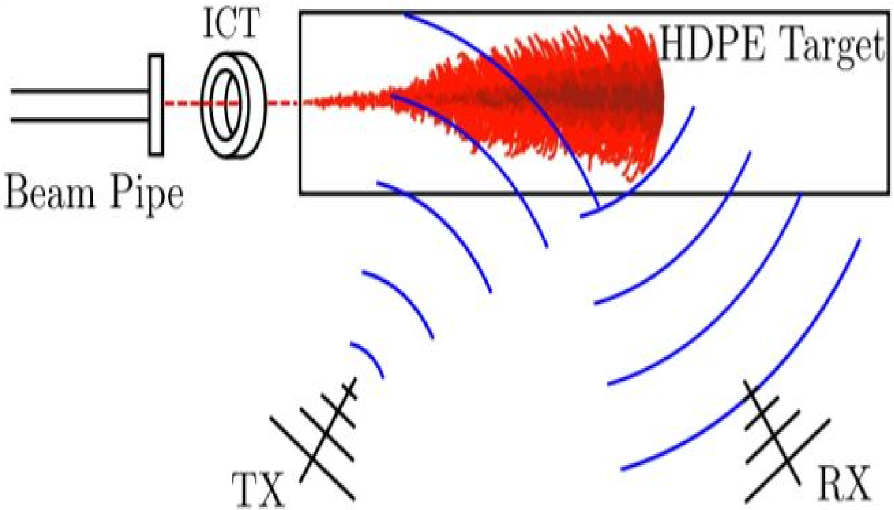


EeV neutrino telescopes

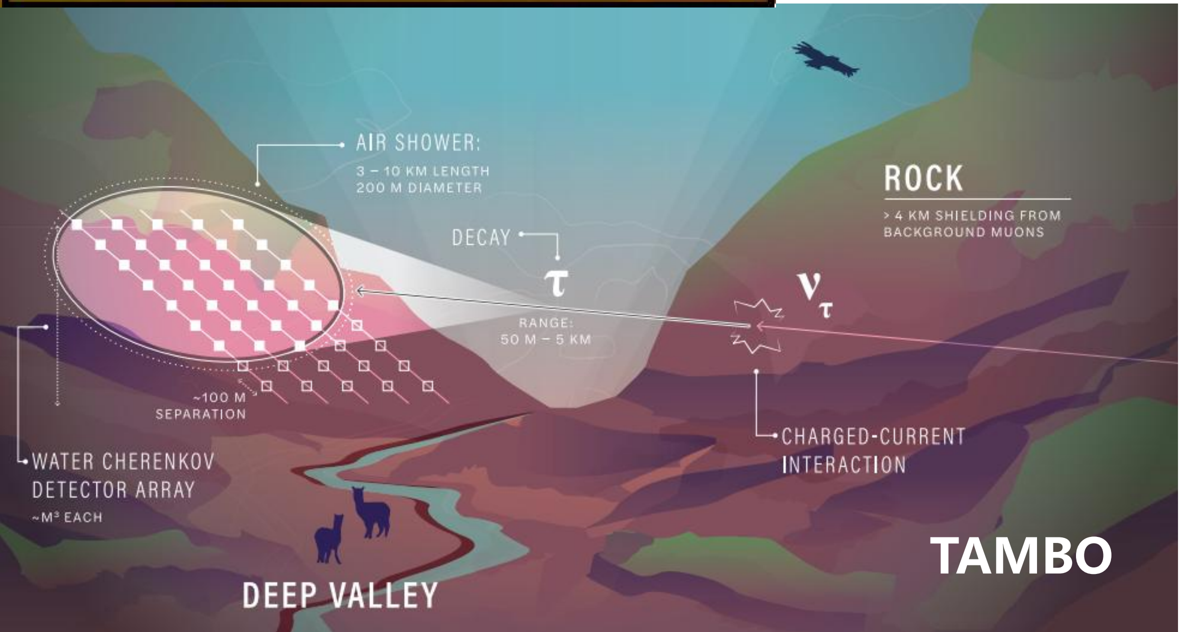

Air shower detection
+Fluorescence
+radio

Pierre Auger

Radar Echo



RET-CR



TAMBO

There are more techniques

- **Transition radiation**

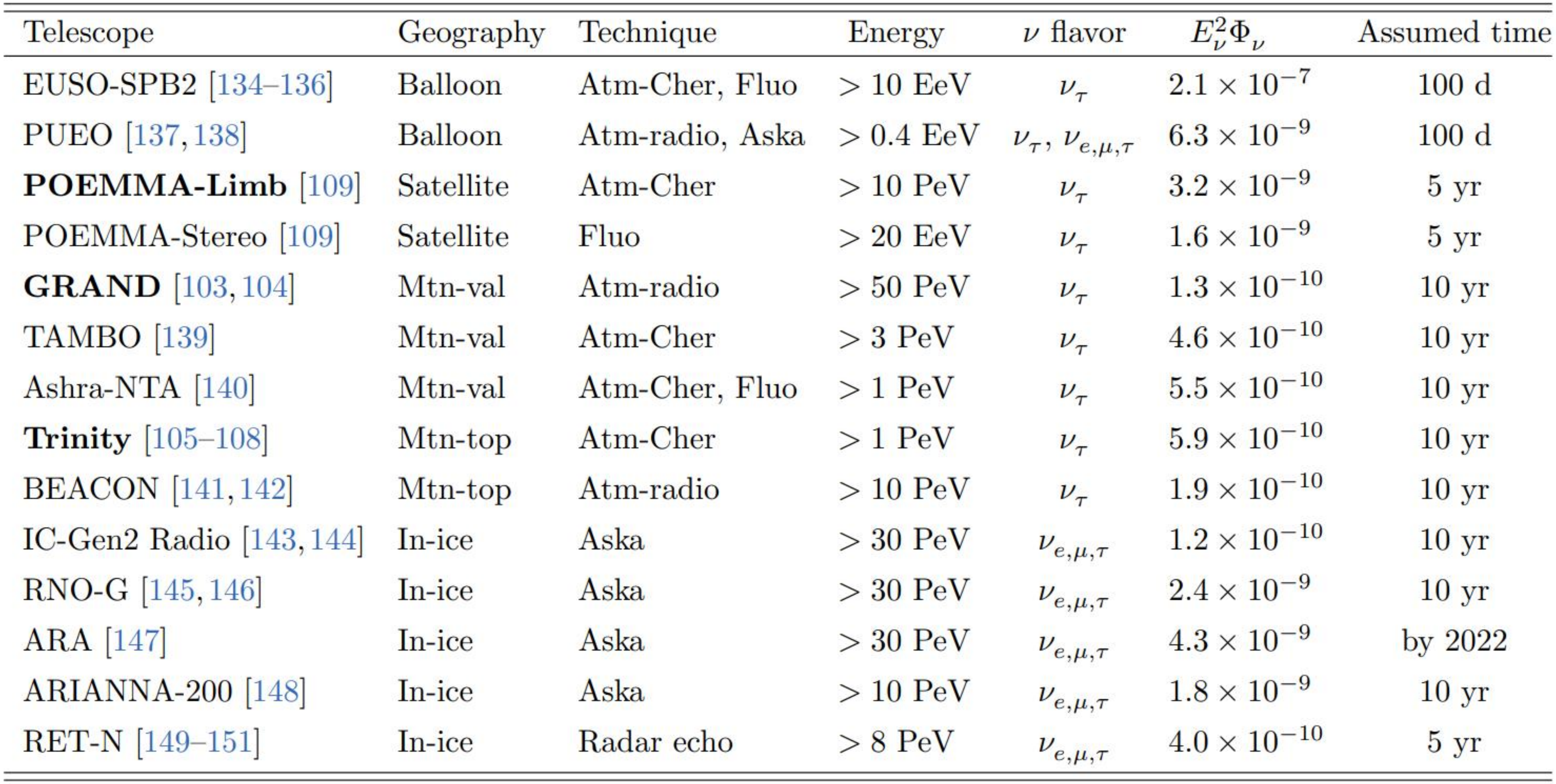
  Ginzburg and Frank, J. Phys. 9 (1945) 353
  Motloch et al., PRD 93 (2016) 043010

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

  Revenu and Marin, ICRC2013, 0398

…

EeV neutrino telescopes



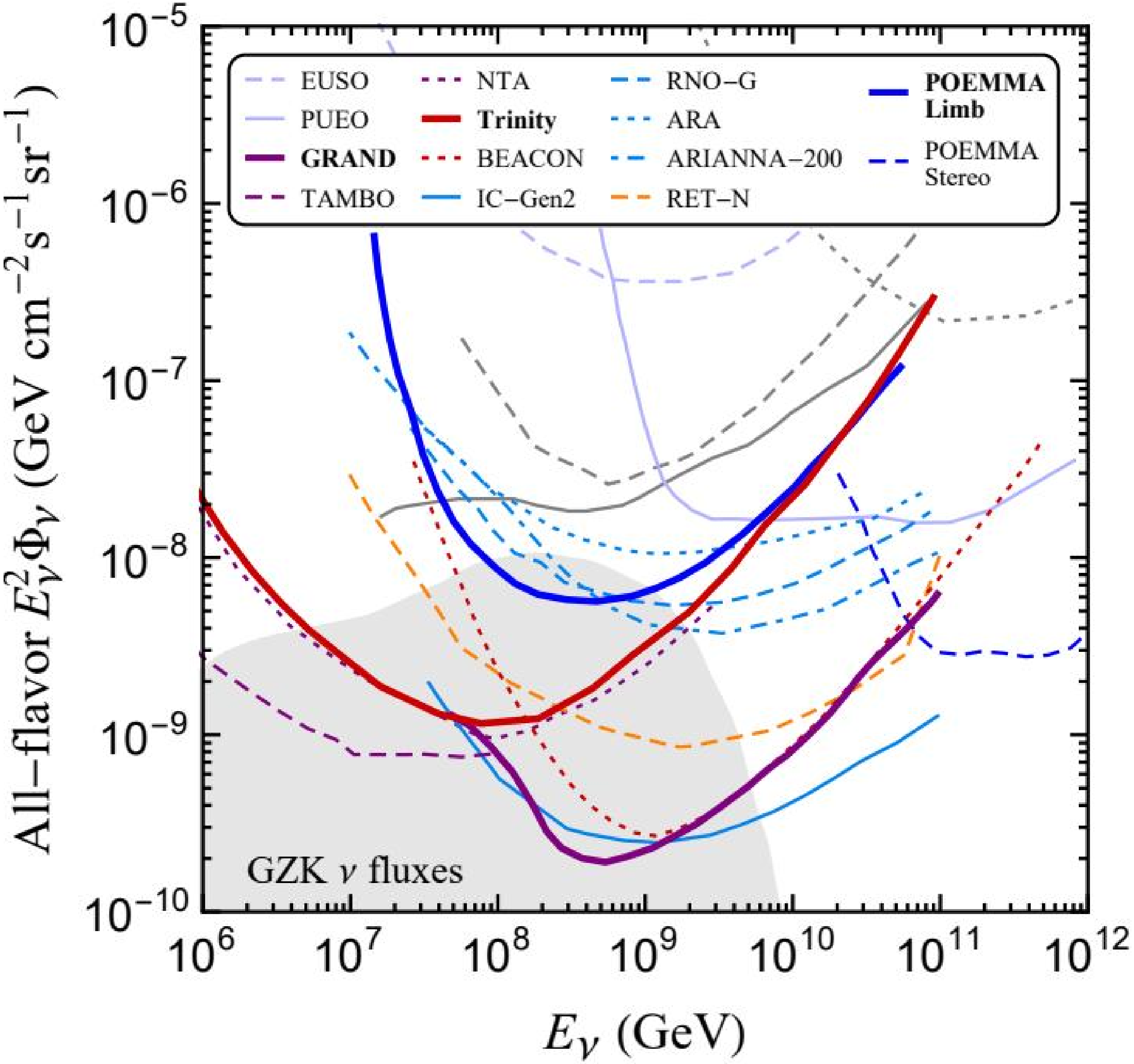
Telescope	Geography	Technique	Energy	ν flavor	$E_\nu^2\Phi_\nu$	Assumed time
EUSO-SPB2 [134–136]	Balloon	Atm-Cher, Fluo	> 10 EeV	ν_τ	2.1×10^{-7}	100 d
PUEO [137, 138]	Balloon	Atm-radio, Aska	> 0.4 EeV	ν_τ, $\nu_{e,\mu,\tau}$	6.3×10^{-9}	100 d
POEMMA-Limb [109]	Satellite	Atm-Cher	> 10 PeV	ν_τ	3.2×10^{-9}	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

EeV neutrino telescopes



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

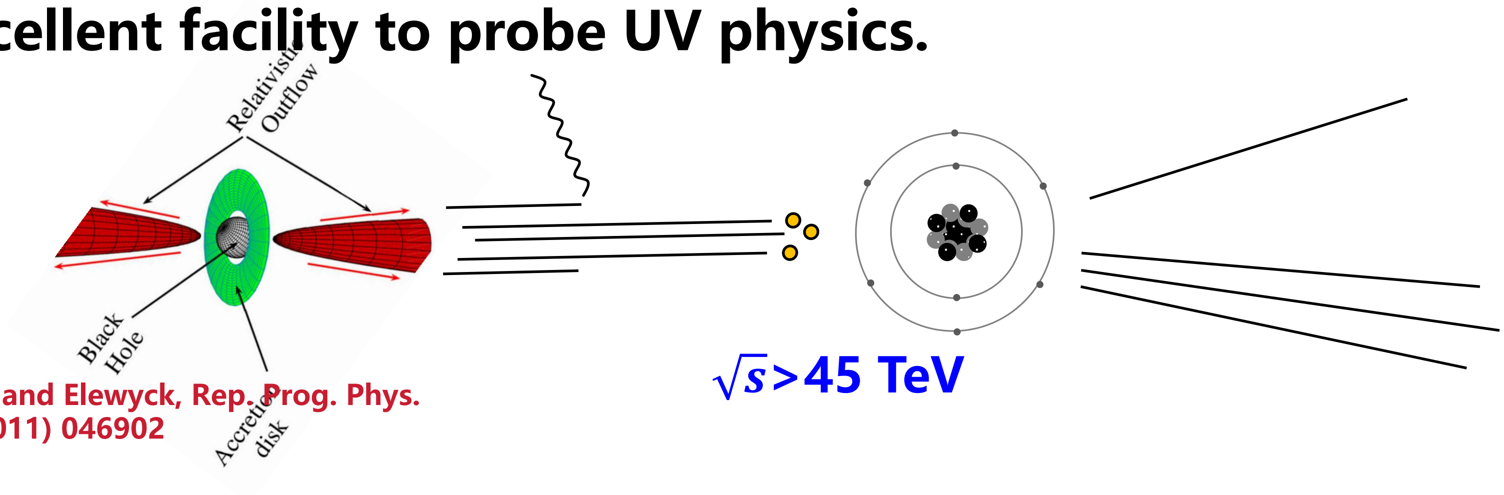
Importance for astroparticle physics

- 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.

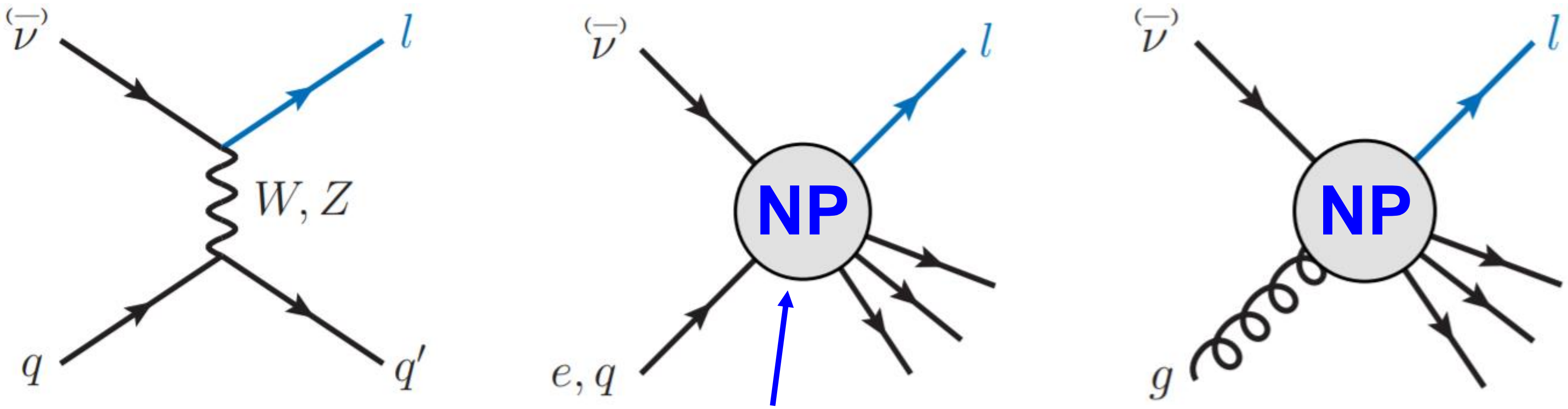
 * COM energy can be as high as 45 TeV.
 * Compare to forward facility at LHC, only 45 GeV or so.
 * Excellent facility to probe UV physics.



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

$\sqrt{s}$>45 TeV

Minimal new physics



Representative diagrams

New physics is hidden here

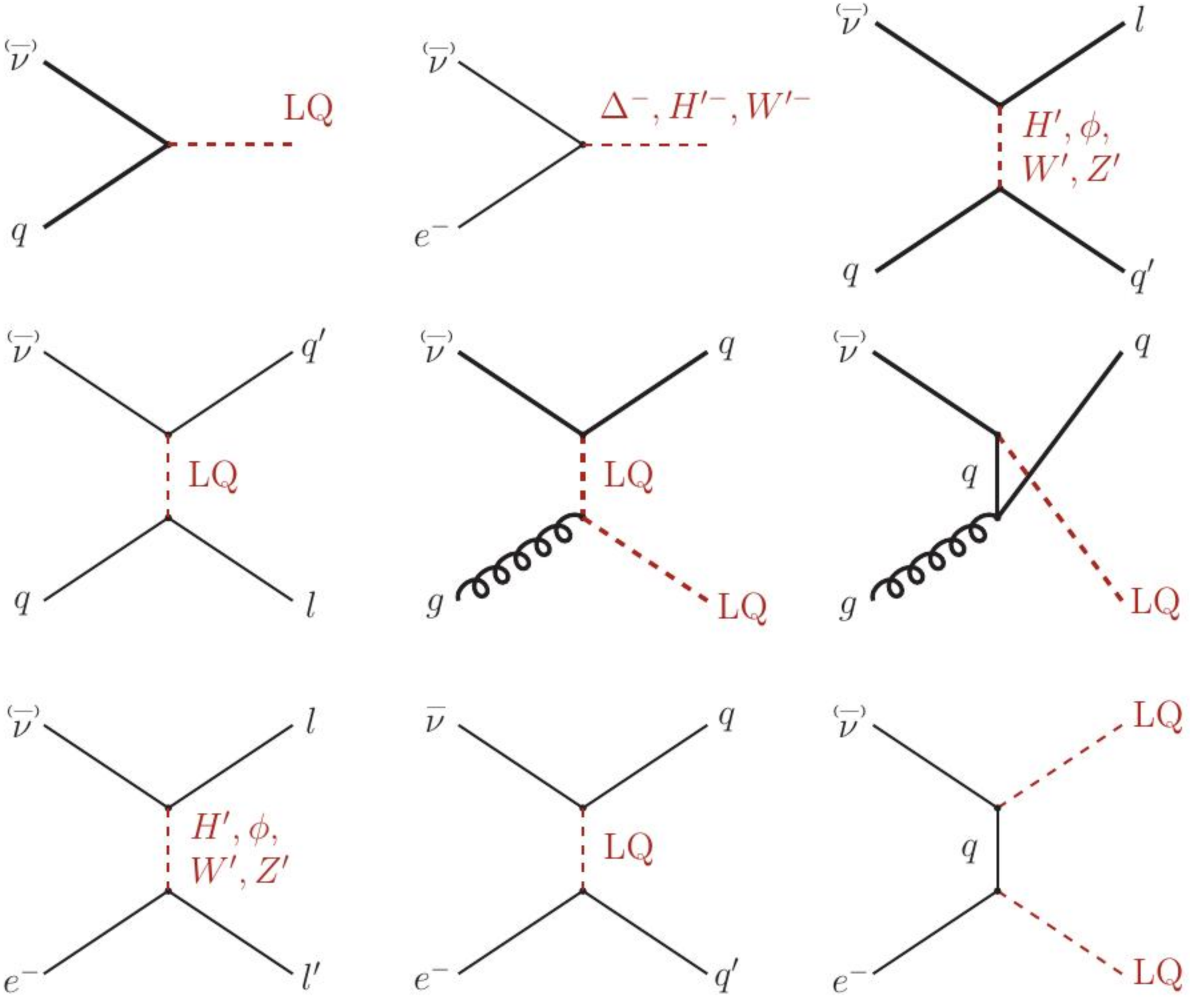
What can we do with tau neutrino telescopes?

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)

Minimal new physics

Our beams: neutrino + electron, quark, gluon



Leptoquark

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

Charged/neutral Higgs

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

W′

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

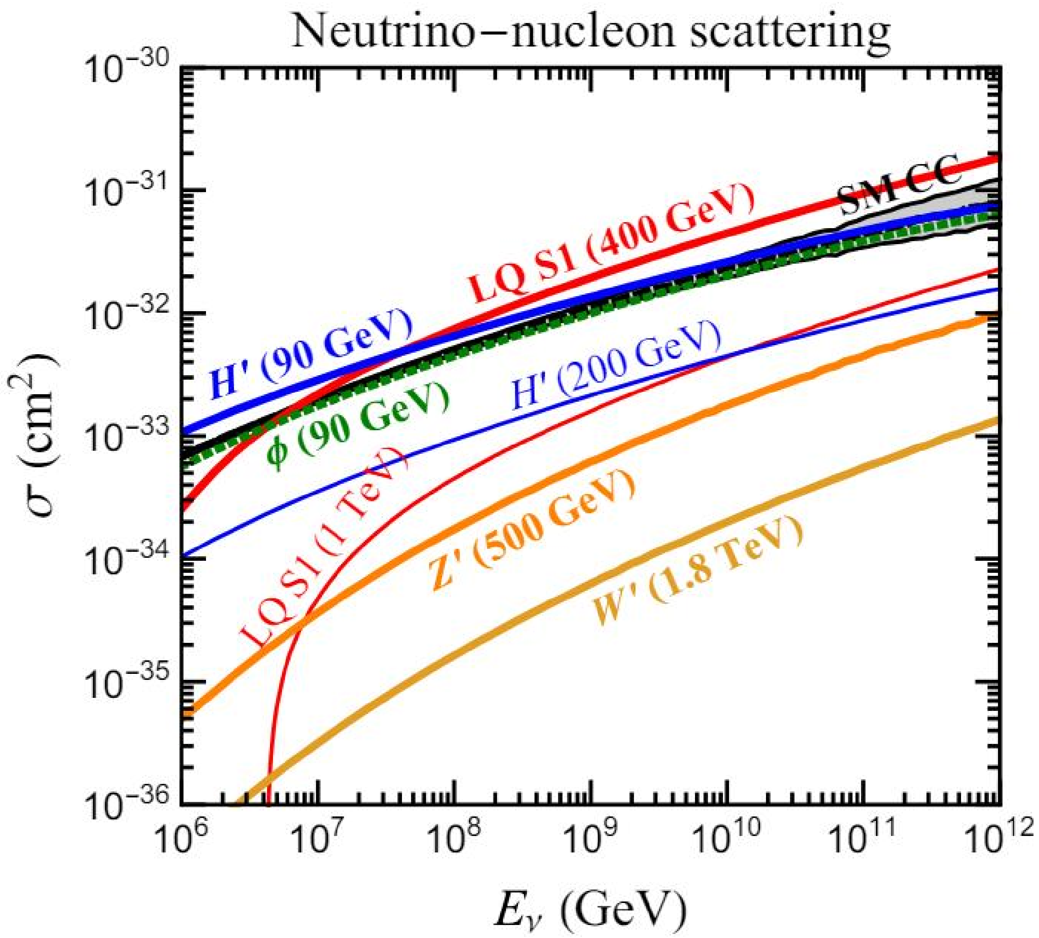
Z′

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

Leptophilic forces

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

Modification to nu cross section



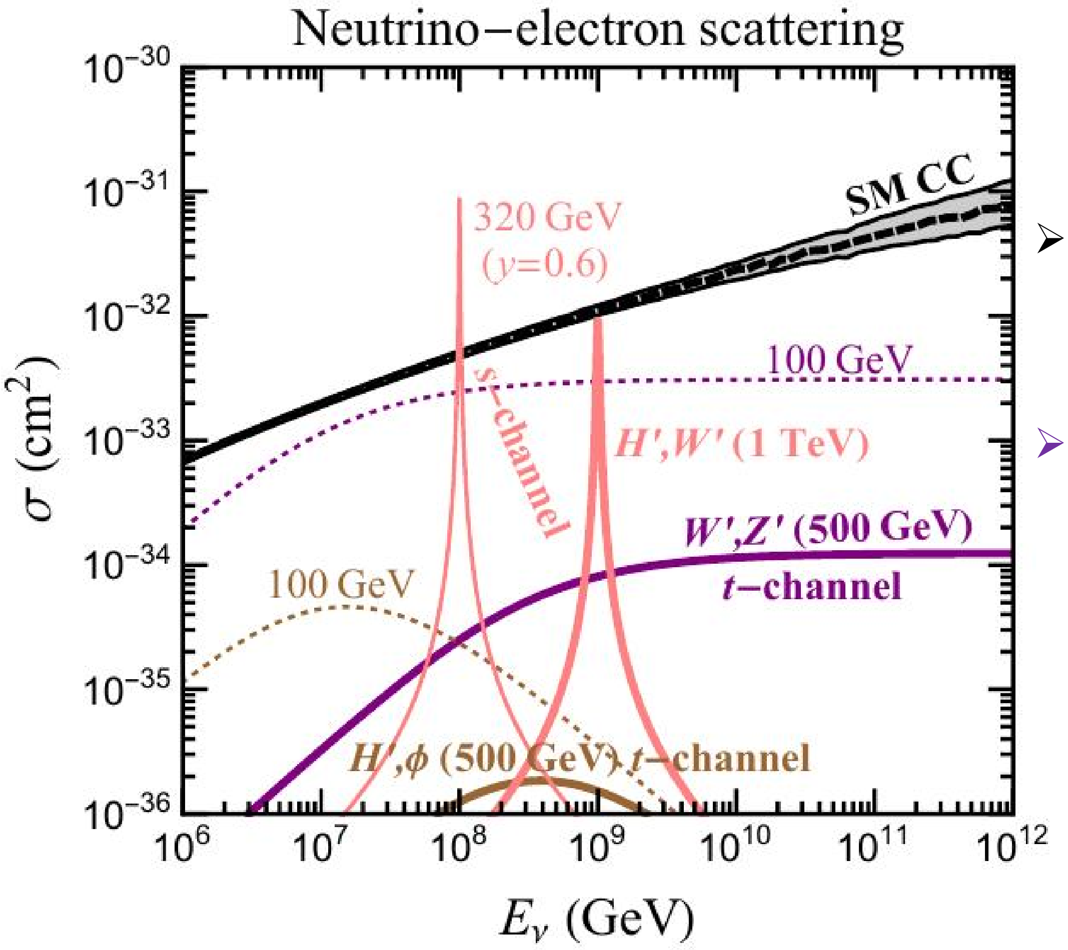
- **The hadronic interaction benefits from the enhancement of sea quark and gluon PDFs, especially those of second and third families.**

- **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



See also T. Jezo et.al.
Phys. Rev. D 89 (2014), 077702

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

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

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

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

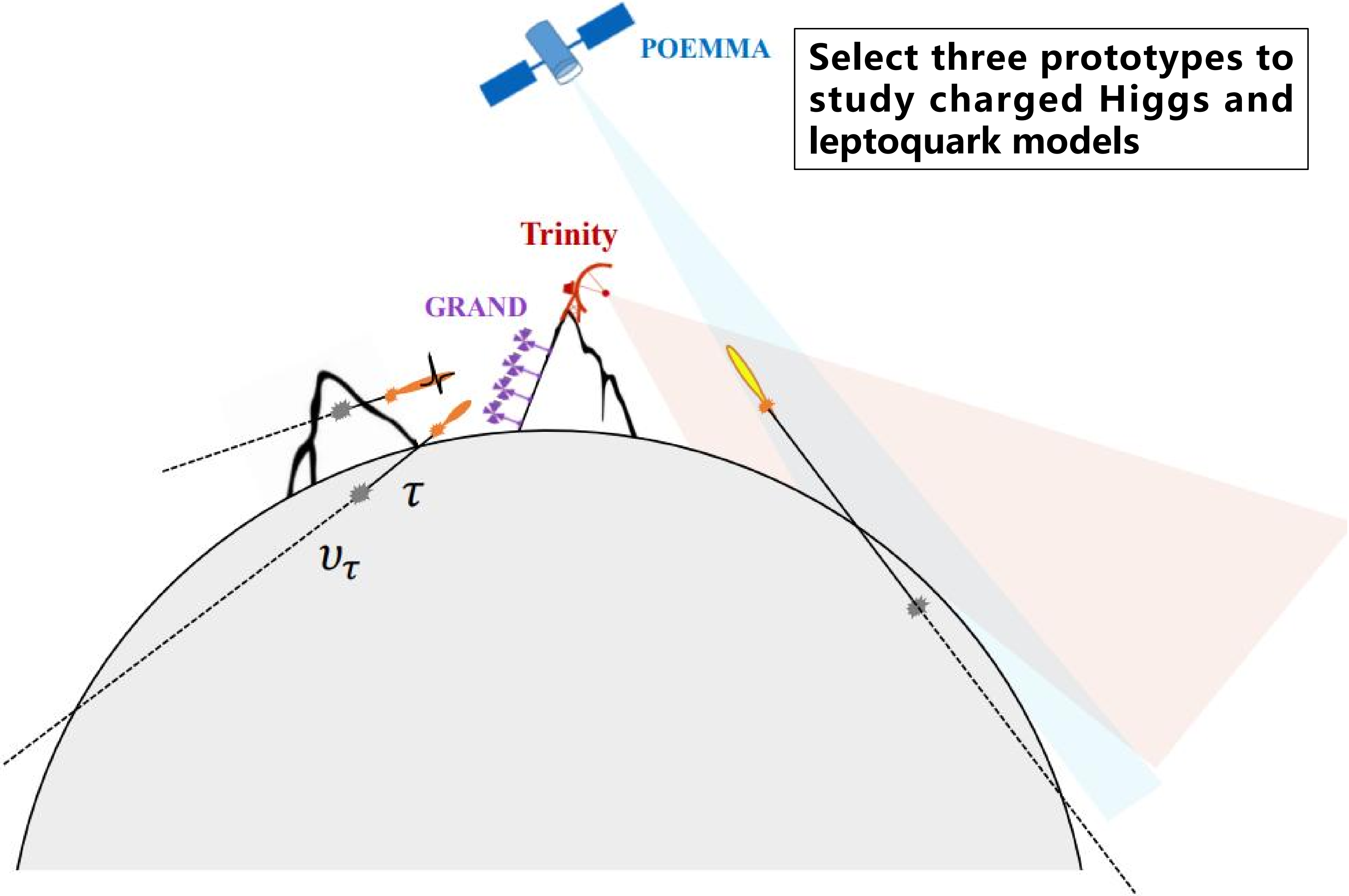
$$\sigma_{H'}(s) = \frac{Y_{\tau e}^2 Y_{\beta e}^2 \left[\frac{s(2M_{H'}^2+s)}{M_{H'}^2+s} + 2M_{H'}^2 \ln\frac{M_{H'}^2}{M_{H'}^2+s}\right]}{32\pi s^2}$$

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

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

Propagation equations

Select three prototypes to study charged Higgs and leptoquark models



Propagation equations

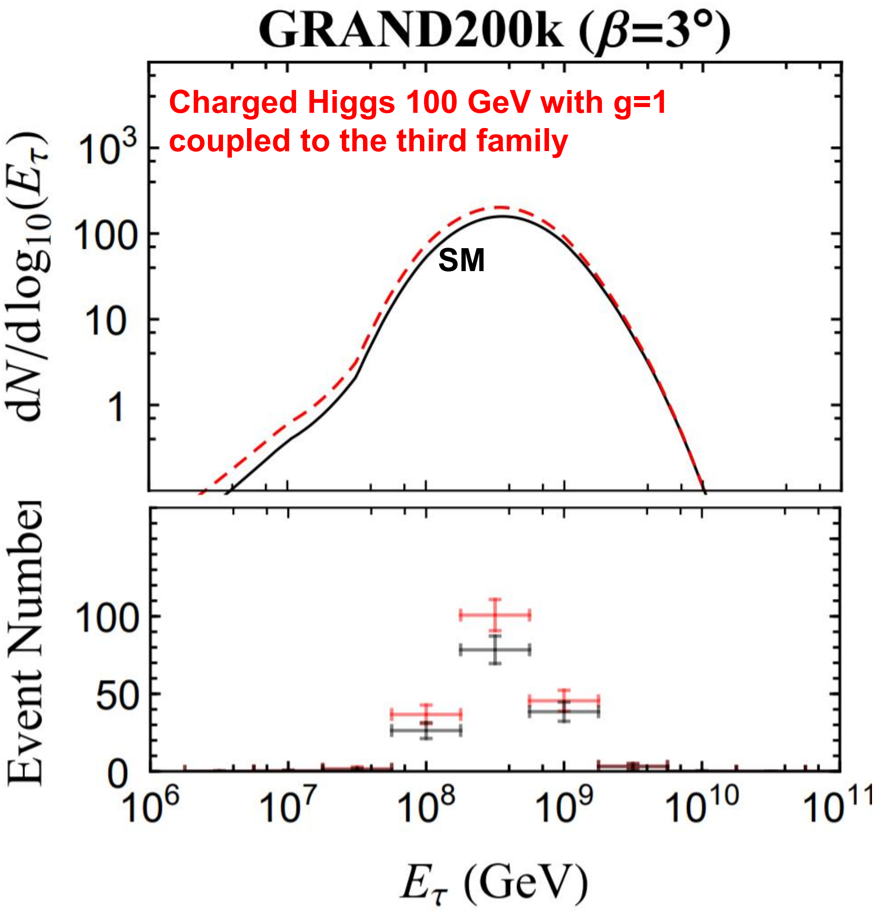
$$
\begin{aligned}
\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\mathrm{d}\Phi_\nu}{\mathrm{d}E_\nu}\right) = &- N_\mathrm{A}\rho\left(\sigma_\mathrm{SM}^\mathrm{cc}+\sigma_\mathrm{SM}^\mathrm{nc}+\sigma_\mathrm{NP}\right)\frac{\mathrm{d}\Phi_\nu}{\mathrm{d}E_\nu} && \text{— attenuation}\\
&+ N_\mathrm{A}\rho\int \mathrm{d}E'_\nu \frac{\mathrm{d}\Phi_\nu}{\mathrm{d}E'_\nu}\frac{1}{E'_\nu}\left(\frac{\mathrm{d}\sigma_\mathrm{SM}^\mathrm{nc}}{\mathrm{d}z}+\frac{\mathrm{d}\sigma_\mathrm{NP}^\mathrm{nc}}{\mathrm{d}z}\right)\Bigg|_{z=\frac{E_\nu}{E'_\nu}} && \text{— neutral-current regeneration}\\
&+ \int \mathrm{d}E'_\tau \frac{\mathrm{d}\Phi_\tau}{\mathrm{d}E'_\tau}\frac{1}{E'_\tau}\frac{\mathrm{d}\Gamma_\tau}{\Gamma_\tau \mathrm{d}z}\,, && \text{— tau regeneration}\\
\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\mathrm{d}\Phi_\tau}{\mathrm{d}E_\tau}\right) = &- \Gamma_\tau\frac{\mathrm{d}\Phi_\tau}{\mathrm{d}E_\tau} - N_\mathrm{A}\frac{\rho}{A}\left[\sigma_\mathrm{pp}+\sigma_\mathrm{pn}\right]\frac{\mathrm{d}\Phi_\tau}{\mathrm{d}E_\tau} && \text{— tau decay and hard energy loss}\\
&+ N_\mathrm{A}\frac{\rho}{A}\int \mathrm{d}E'_\tau \frac{\mathrm{d}\Phi_\tau}{\mathrm{d}E'_\tau}\frac{1}{E'_\tau}\left(\frac{\mathrm{d}\sigma_\mathrm{pp}}{\mathrm{d}z}+\frac{\mathrm{d}\sigma_\mathrm{pn}}{\mathrm{d}z}\right)\Bigg|_{z=\frac{E_\tau}{E'_\tau}} && \text{— regeneration from hard scattering}\\
&+ \rho\frac{\partial}{\partial E_\tau}\left[\left(\beta_\mathrm{pp}+\beta_\mathrm{pn}+\beta_\mathrm{brems}\right)E_\tau\frac{\mathrm{d}\Phi_\tau}{\mathrm{d}E_\tau}\right] && \text{— continuous energy loss}\\
&+ N_\mathrm{A}\rho\int \mathrm{d}E'_\nu \frac{\mathrm{d}\Phi_\nu}{\mathrm{d}E'_\nu}\frac{1}{E'_\nu}\left(\frac{\mathrm{d}\sigma_\mathrm{SM}^\mathrm{cc}}{\mathrm{d}z}+\frac{\mathrm{d}\sigma_\mathrm{NP}}{\mathrm{d}z}\right)\Bigg|_{z=\frac{E_\tau}{E'_\nu}}\,, && \text{— tau conversion from neutrinos}
\end{aligned}
$$

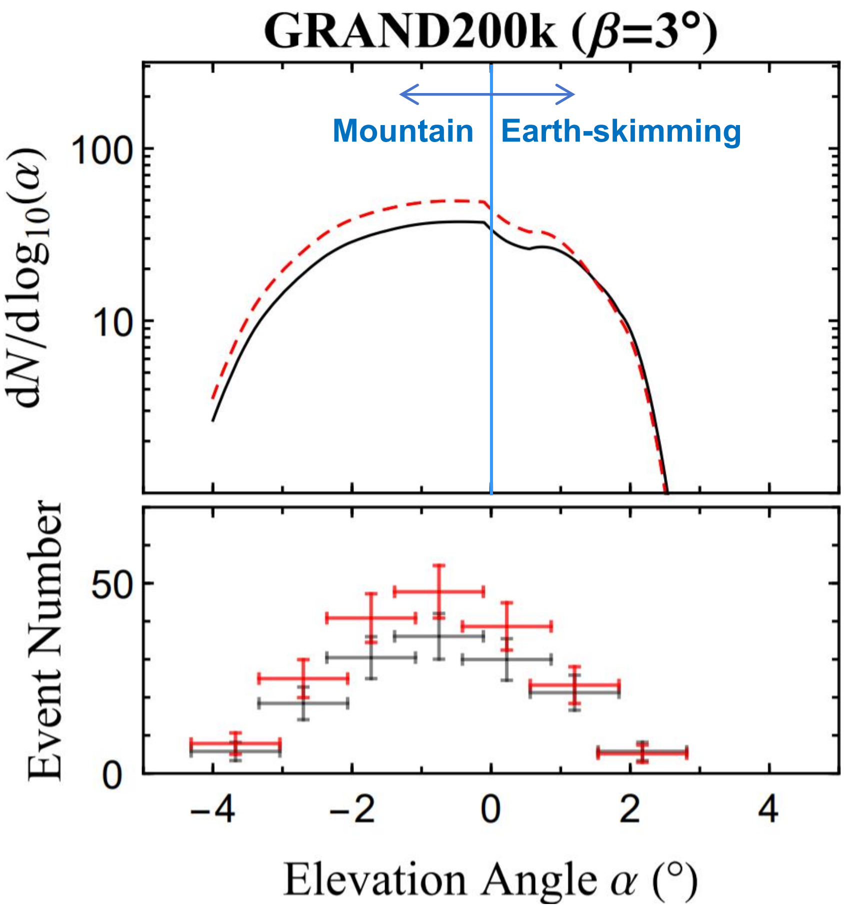
Obtain the emitting tau flux

$$
N_\mathrm{P} = \int \mathrm{d}E_\tau \int \mathrm{d}\cos\theta_\oplus \int \mathrm{d}\cos\theta_\mathrm{tr} \int \mathrm{d}\phi_\mathrm{tr}\, \frac{\mathrm{d}\Phi_\tau}{\mathrm{d}E_\tau \mathrm{d}\Omega_\mathrm{tr}} \cos\theta_\mathrm{tr}\; 2\pi R_\oplus^2\; P_\mathrm{det}\; T
$$

$$
P_\mathrm{det} = \int \mathrm{d}s\; p_\mathrm{decay}(E_\tau, s)\; p_\mathrm{det}(E_\tau, \theta_\oplus, \theta_\mathrm{tr}, \phi_\mathrm{tr}, s)
$$

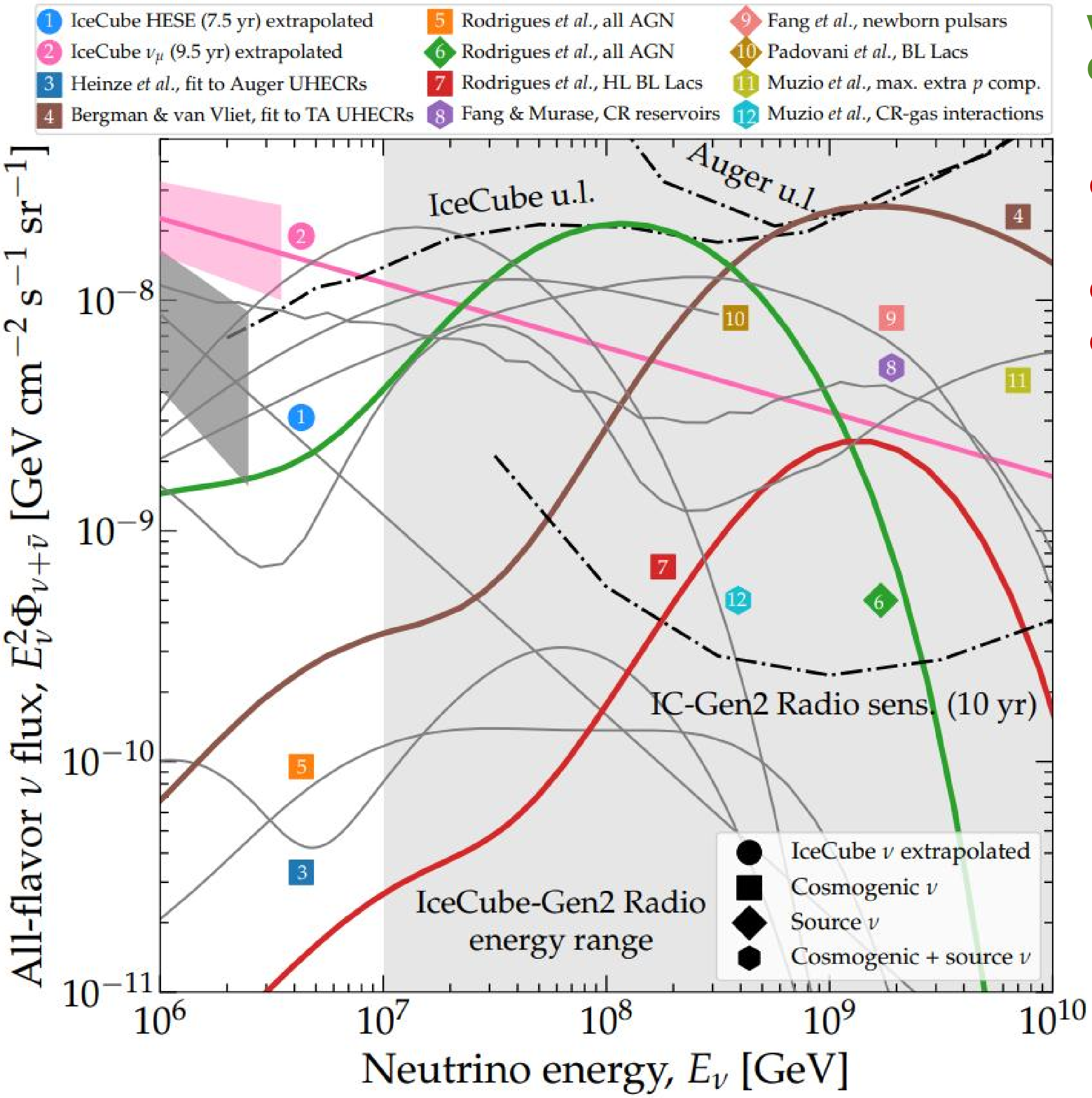
Uncertainties of the initial neutrino flux





- In general, the additional charged-Higgs contribution will increase the cross section, and enhance the mountain events.
- For Earth-skimming events, a larger cross section does not necessarily mean a greater event number.

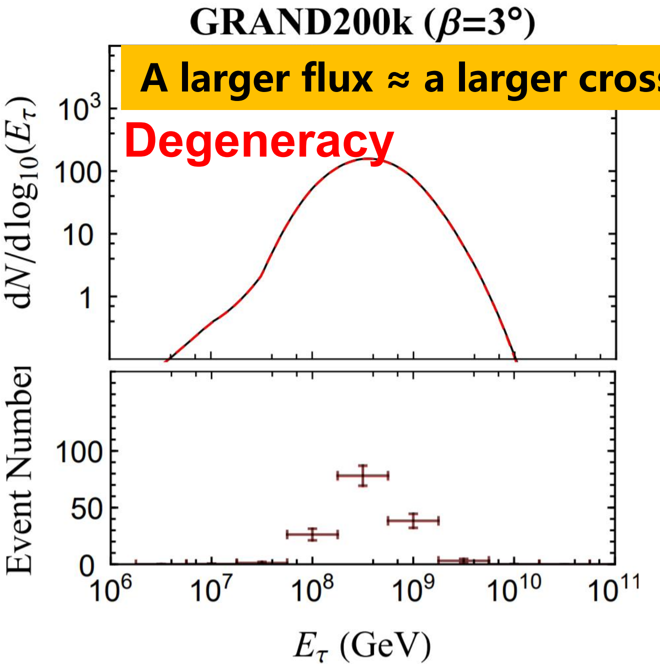
Uncertainties of the initial neutrino flux



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

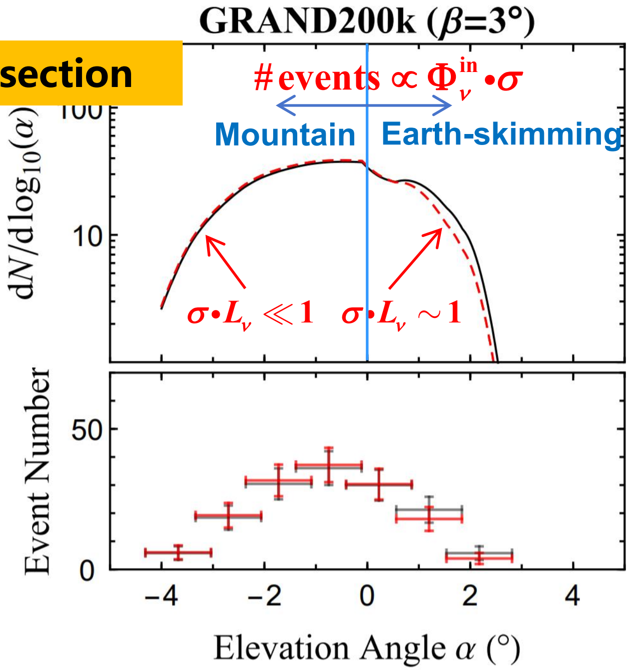
- **Cosmic ray spectrum and composition**
- **Reionization history**
- **Source modeling**

Observable effects



A larger flux ≈ a larger cross section

Degeneracy



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

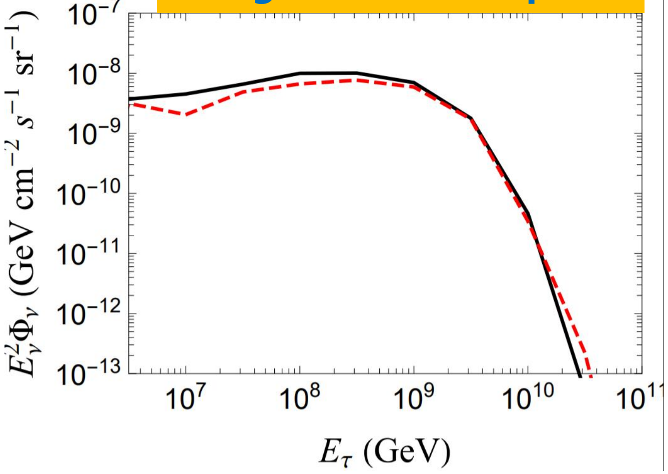
$$\#\text{events} \propto \Phi_\nu^{\text{in}} \exp(-\sigma \bullet L_\nu) \bullet \sigma$$

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

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

$\sigma \bullet L_\nu \approx \mathcal{O}(1)$ **Best!**

Marginalize flux input



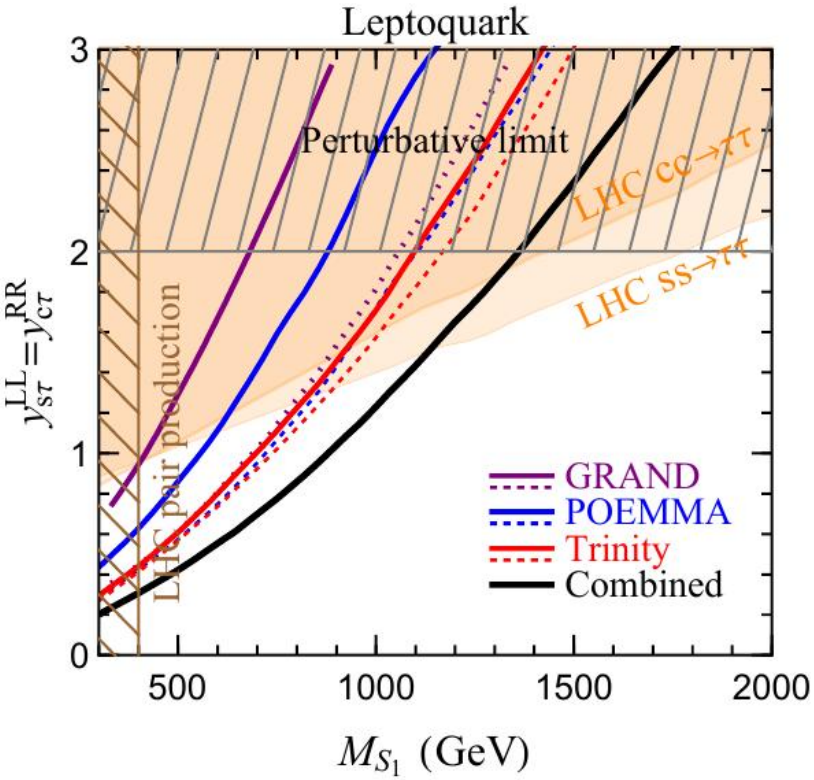
See also Valera, Bustamante, and Glaser, JHEP 06 (2022) 105
Denton and Kini, PRD 102 (2020) 123019
Esteban, Prohira, Beacom, PRD 106 (2022) 023021

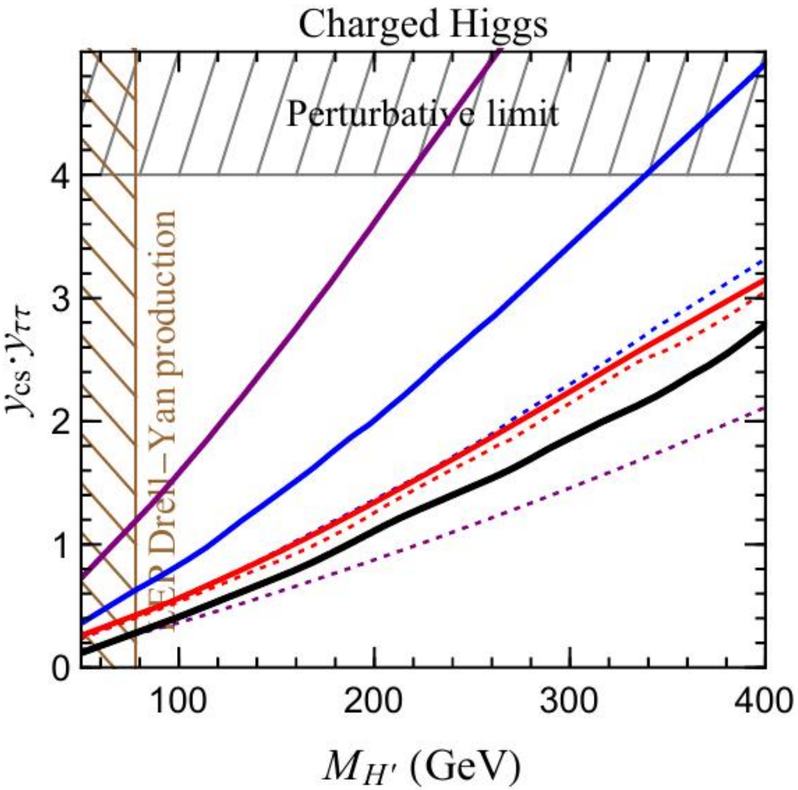
The detailed shape of initial neutrino flux is unknown, so we must marginalize over it, which increases the uncertainty

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

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

Sensitivity





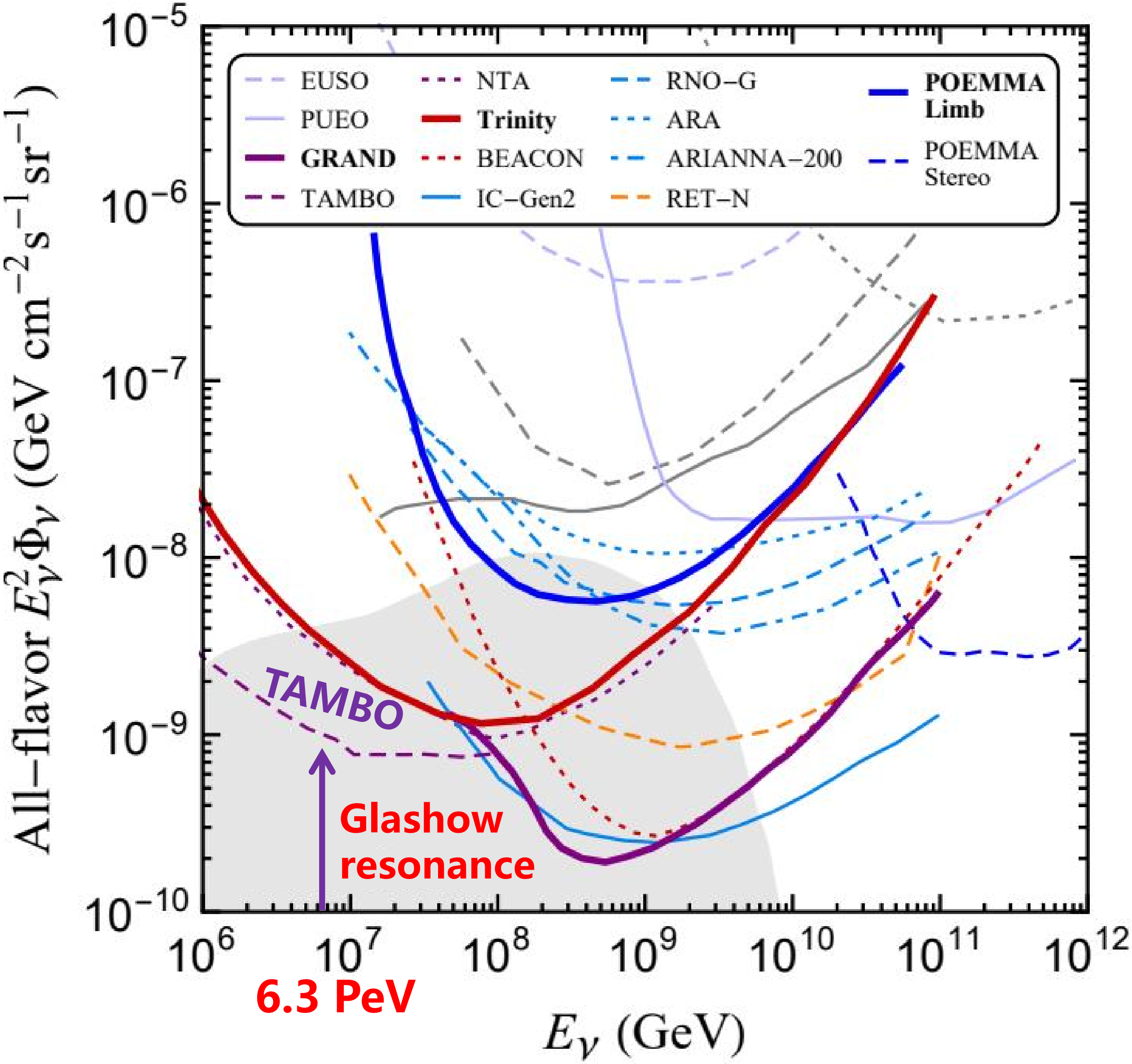
Existing bounds

- **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**

Glashow resonance potential



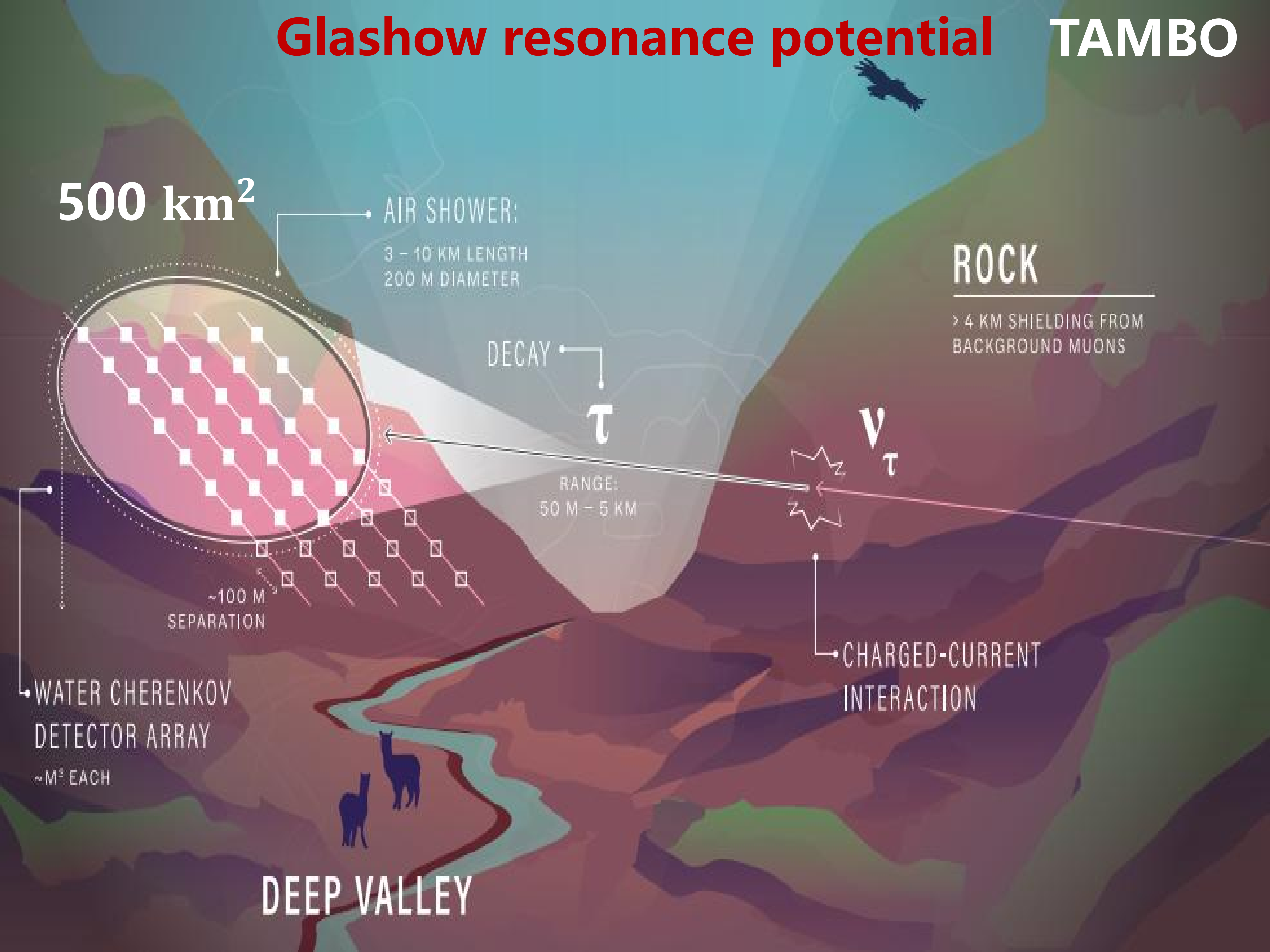
TAMBO

Glashow resonance

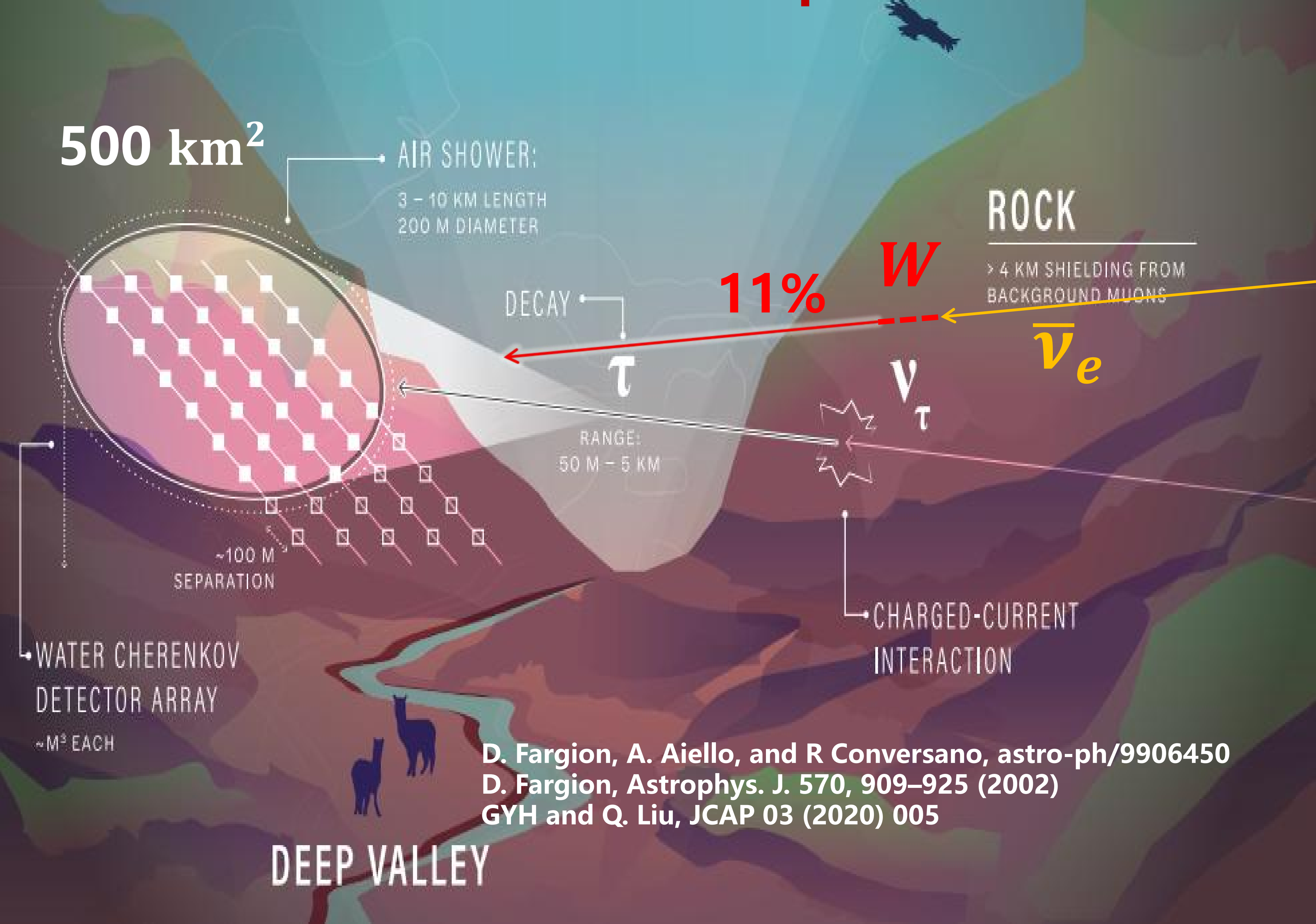
6.3 PeV

Glashow resonance potential

TAMBO

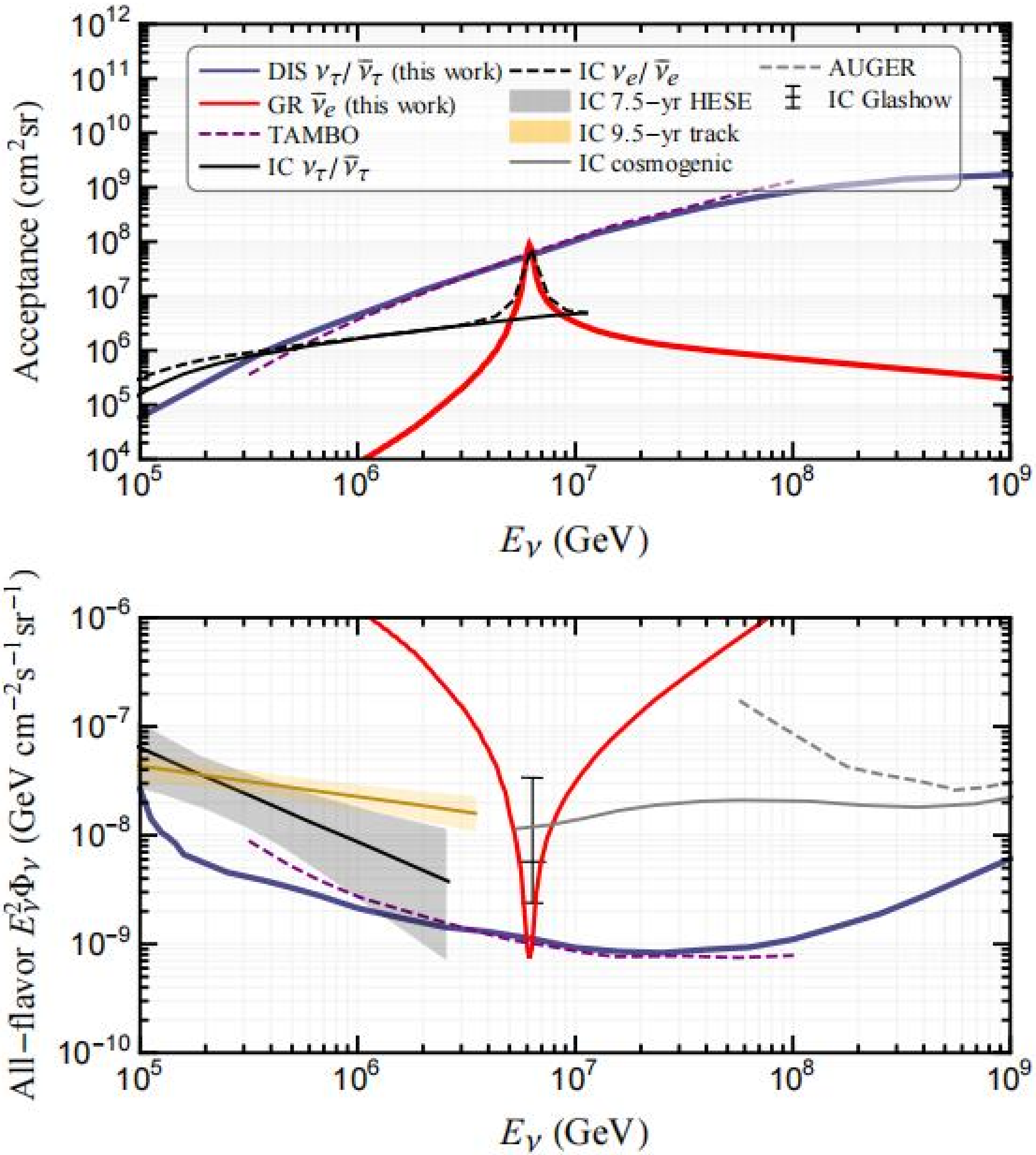


Glashow resonance potential TAMBO



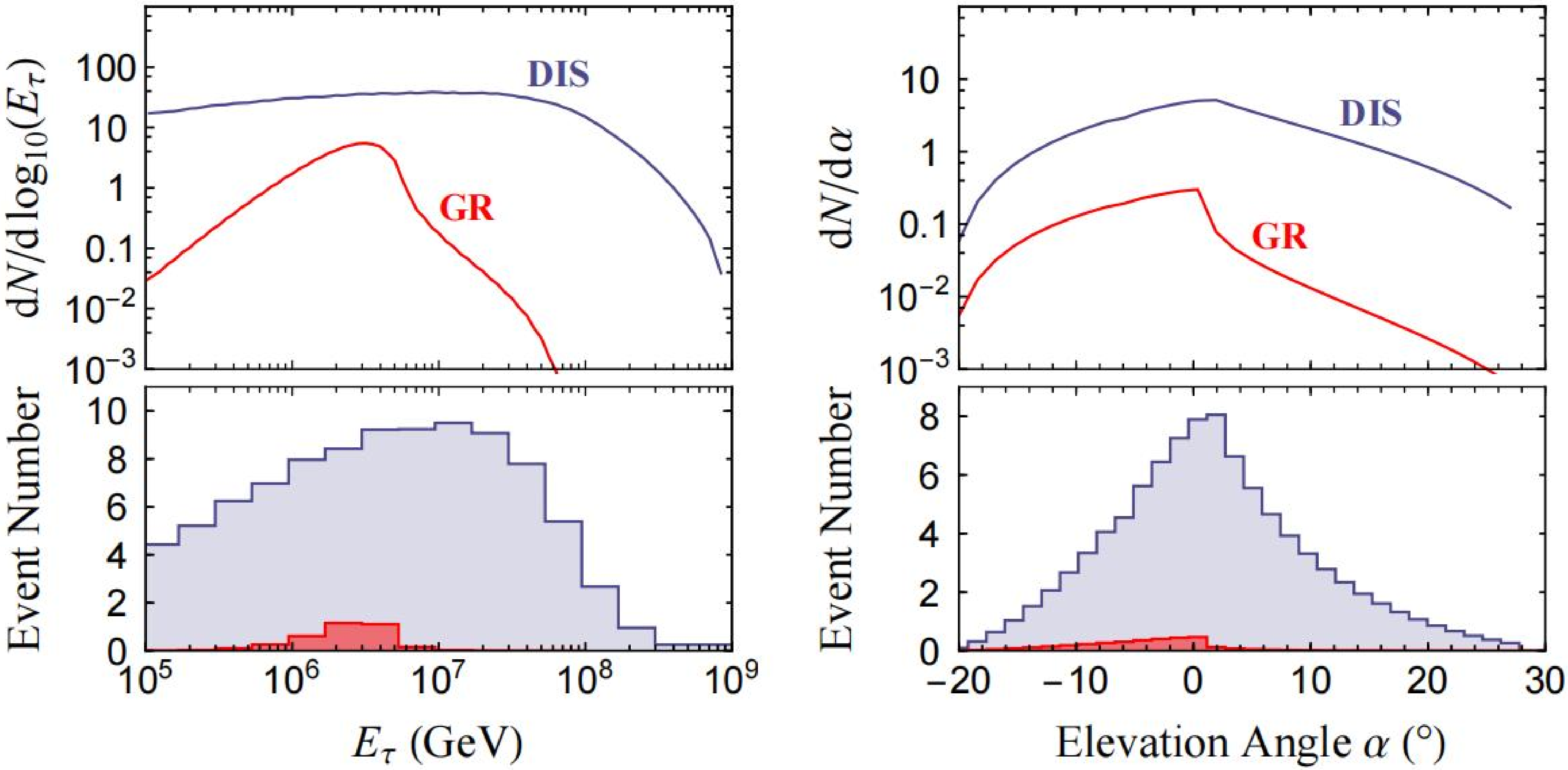
D. Fargion, A. Aiello, and R Conversano, astro-ph/9906450
D. Fargion, Astrophys. J. 570, 909–925 (2002)
GYH and Q. Liu, JCAP 03 (2020) 005

Glashow resonance potential

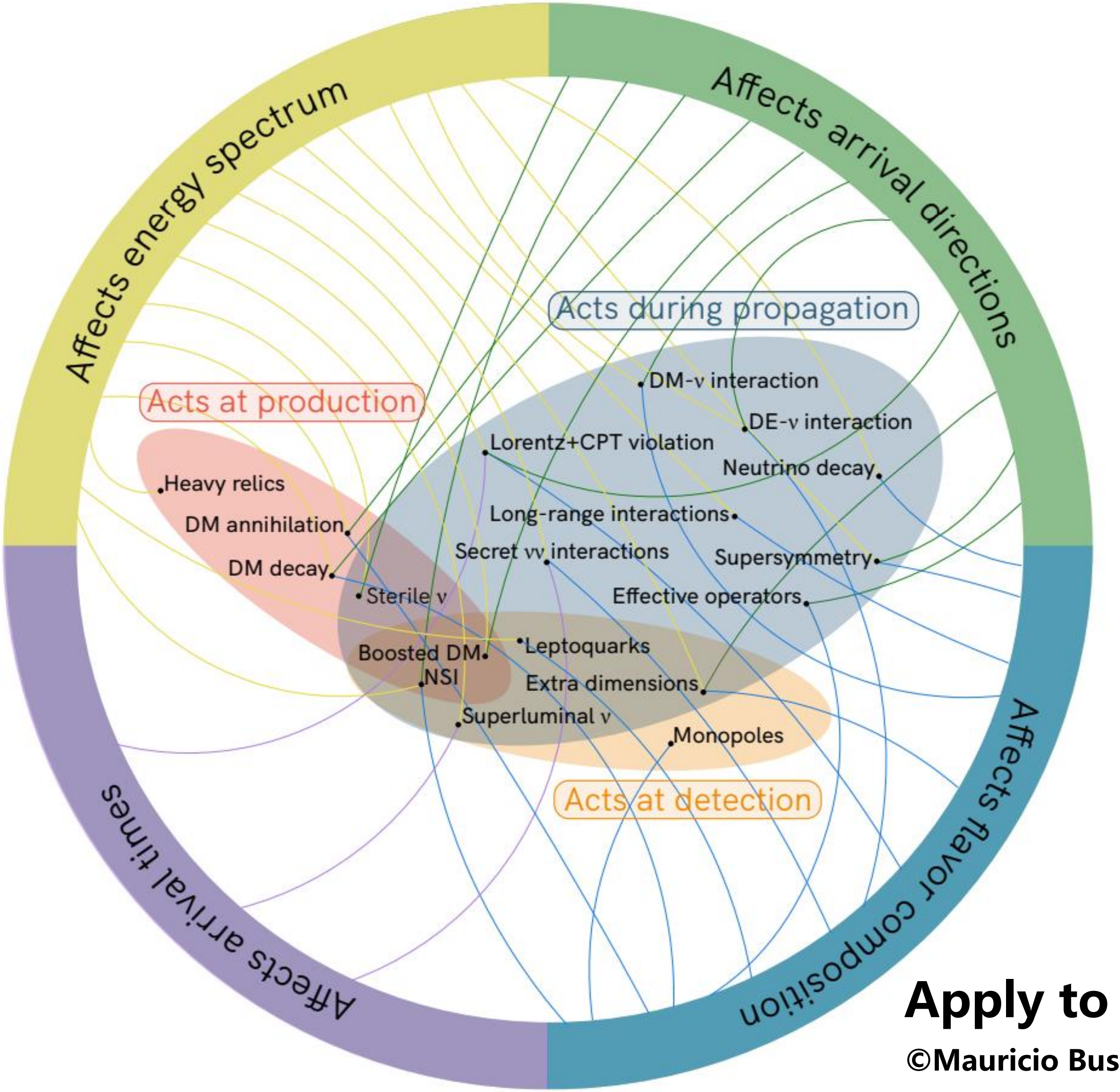


arXiv:2307.12153, GYH

Glashow resonance potential



Other interesting topics



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Conclusion

- **On the one hand, particle physics is essential for us to understand the astrophysical phenomena; on the other hand, astrophysics provides extreme energy and length scales for testing particle physics.**

- **The observation of the Glashow resonance is not only another test of the Standard Model by using neutrino flux, but also provides us information about sources.**

- **Besides the water/ice Cherenkov telescopes, air shower neutrino telescopes can also be sensitive to particle physics models. We attempt to inclusively explore the new physics cases which modify the neutrino-matter interaction at the energy range relevant for tau neutrino telescopes. Among them, we find that the charged/neutral Higgs and leptoquark models can potentially have significant impacts.**

- **Resonances induced by new physics can arise in those tau neutrino telescopes. However, future experiments do not have sufficient sensitivity to resonance, including the Glashow resonance.**

- **Many other opportunities considering production and propagation.**