Max-Planck-Institut für Kernphysik Heidelberg

Max Planck Gesellschaft

# Inferring astrophysical neutrino sources from the Glashow resonance

based on 2303.13706


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# Content

- The Glashow resonance and its cross section
- Detection of the Glashow resonance
- Neutrino sources
- Likelihood analysis
- Outlook and Conclusions

# The Glashow resonance

PHYSICAL REVIEW VOLUME 118, NUMBER 1 APRIL 1, 1960

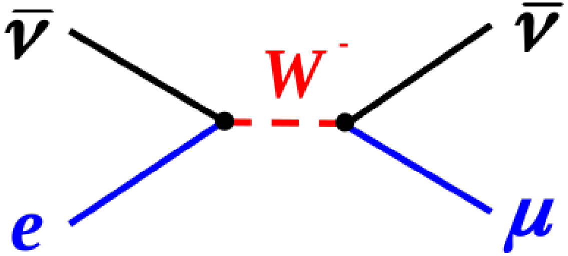
## Resonant Scattering of Antineutrinos

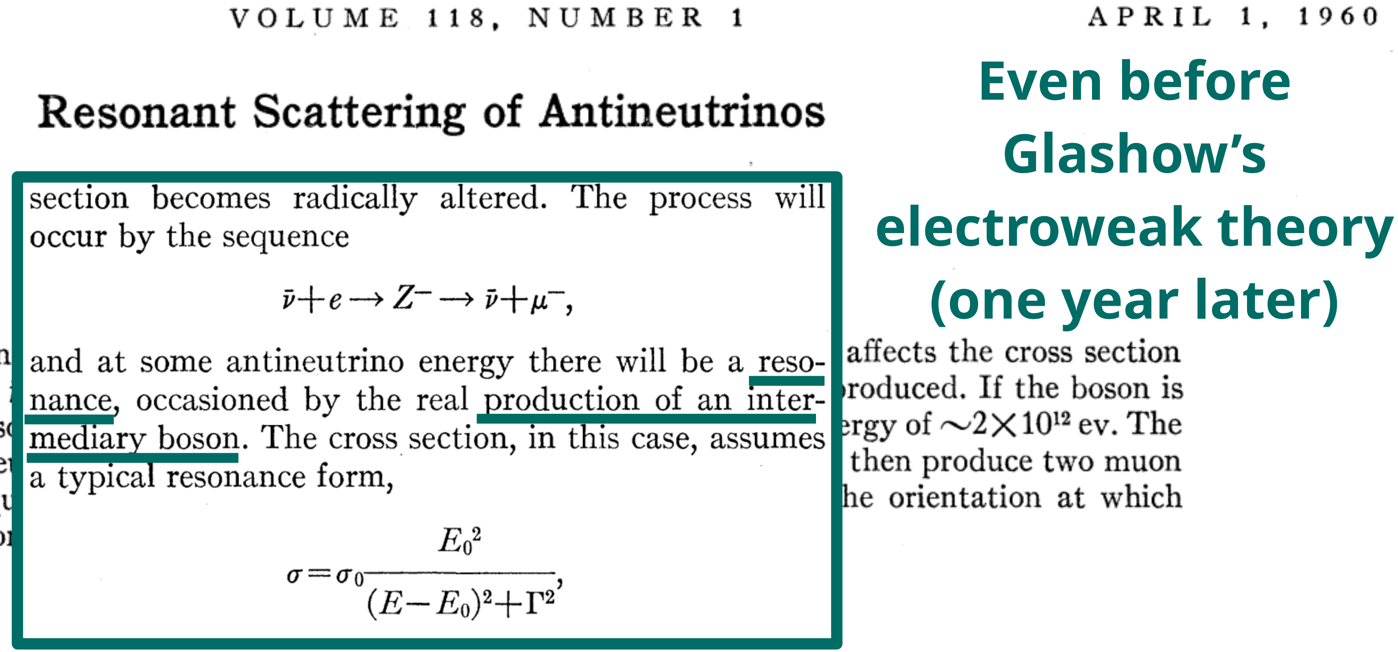
Sheldon L. Glashow*
*Institute for Theoretical Physics, Copenhagen, Denmark*
(Received October 26, 1959)

The hypothesis of an unstable charged boson to mediate muon decay radically affects the cross section for the process $\bar{\nu}+e \rightarrow \bar{\nu}+\mu^-$ near the energy at which the intermediary may be produced. If the boson is assumed to have $K$-meson mass, the resonance occurs at an incident antineutrino energy of $\sim 2\times 10^{12}$ ev. The flux of energetic antineutrinos produced in association with cosmic-ray muons will then produce two muon counts per day per square meter of detector, independently of the depth and the orientation at which the experiment is performed.

**Even before Glashow's contribution to electroweak theory (one year later)**

# The Glashow resonance



VOLUME 118, NUMBER 1 APRIL 1, 1960

**Resonant Scattering of Antineutrinos**

The hypothesis of an
for the process $\bar{\nu}+e\rightarrow$
assumed to have $K$-meso
flux of energetic antine
counts per day per squ
the experiment is perfor

section becomes radically altered. The process will occur by the sequence

$$\bar{\nu}+e\rightarrow Z^-\rightarrow\bar{\nu}+\mu^-,$$

and at some antineutrino energy there will be a resonance, occasioned by the real production of an intermediary boson. The cross section, in this case, assumes a typical resonance form,

$$\sigma=\sigma_0\frac{E_0{}^2}{(E-E_0)^2+\Gamma^2},$$

affects the cross section
roduced. If the boson is
ergy of $\sim 2\times 10^{12}$ ev. The
then produce two muon
he orientation at which

**Even before Glashow's electroweak theory (one year later)**

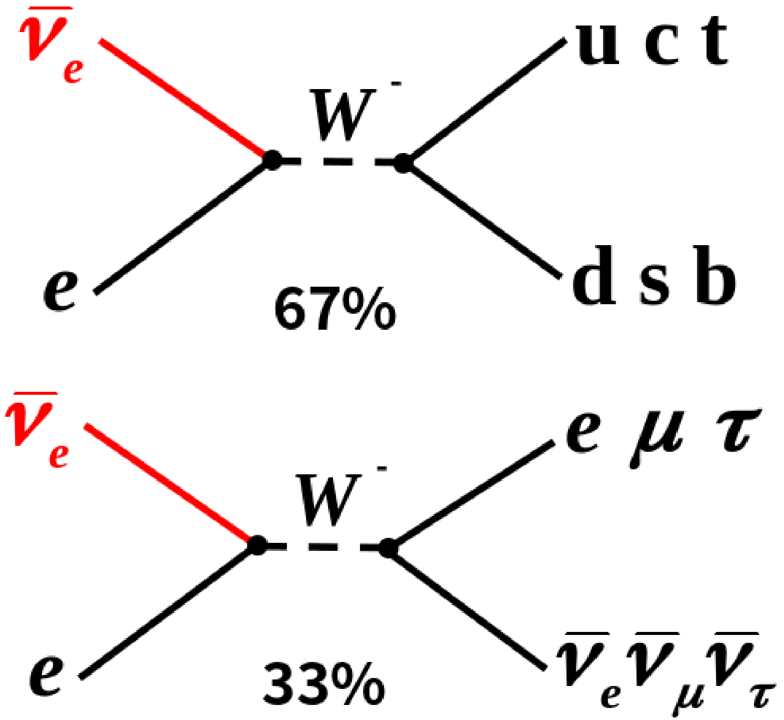
# The Glashow resonance

- **Cross section**

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

- **Resonance at**

$$E_\nu \approx \frac{M_W^2}{2m_e}$$



# Corrections to the GR cross section: Doppler broadening

## Resonant Scattering of Antineutrinos

SHELDON L. GLASHOW*
*Institute for Theoretical Physics, Copenhagen, Denmark*
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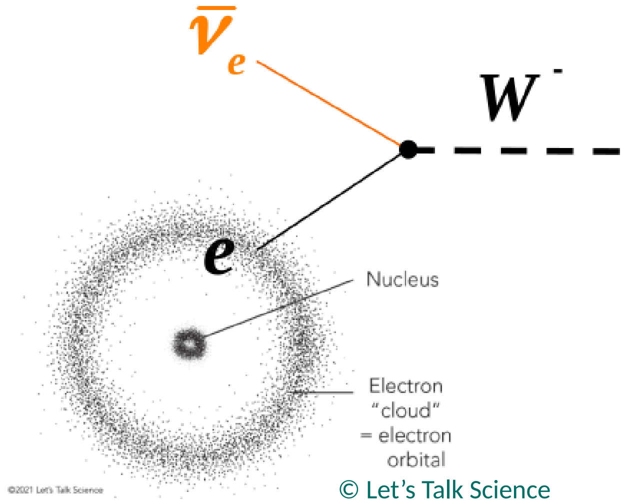
With $m_Z = m_N$, the energy of the incident antineutrino energy at the resonance is $9\times10^{11}$ ev and the width of the resonance is $2\times10^{6}$ ev, while with $m_Z = m_K$, $E_0 = 2.3\times10^{11}$ ev and $\Gamma = 1.5\times10^{5}$ ev.

Although the natural width of the resonance is quite small, a significant broadening is produced by the spread in velocity of the target electrons. In a collision with an electron of velocity $\beta c$ along the direction of incidence, the resonance occurs at the antineutrino energy

$$E_0' = (1+\beta)^{-1}E_0.$$

Thus the experimental width of the resonance will be approximately $(\mathfrak{z}/137)E_0$, where $\mathfrak{z}$ is the mean atomic number of the target material. Upon earth, antineu-

- **Discussed by A. Loewy, S. Nussinov & S. Glashow in 1407.4415**
- **Broadening due to the motion of atomic electrons**



# Corrections to the GR cross section: Doppler broadening

- **Doppler broadened cross section:**

$$\sigma(E_\nu) = \frac{1}{4\pi}\int \mathrm{d}\phi \int \mathrm{d}\beta F(\beta) \int \mathrm{d}x' \sigma^{(0)}[E_\nu(1-\beta x')]$$

- **Electron velocity distribution for ice:**

$$F_{\mathrm{ice}}(\beta) = \frac{2F_{\mathrm{H}}(\beta) + 8F_{\mathrm{O}}(\beta)}{10}$$

- **Distribution for an electron with quantum numbers n and l:**

$$f_{n\,l}(\beta) = m_e \int \mathrm{d}\Omega_k k^2 |\Psi_{n\,l}(k)|^2$$

$$f_{1s}(k) = \frac{32}{\pi}\frac{\mu_{1s}^5 k^2}{(\mu_{1s}^2 + k^2)^4},$$

$$f_{2s}(k) = \frac{32}{3\pi}\frac{\mu_{2s}^5 (3\mu_{2s}^2 k - k^3)^2}{(\mu_{2s}^2 + k^2)^6},$$

$$f_{2p}(k) = \frac{512}{3\pi}\frac{\mu_{2p}^7 k^4}{(\mu_{2p}^2 + k^2)^6},$$

$$f_{3s}(k) = \frac{1024}{5\pi}\frac{\mu_{3s}^7 (\mu_{3s}^3 k - \mu_{3s} k^3)^2}{(\mu_{3s}^2 + k^2)^8},$$

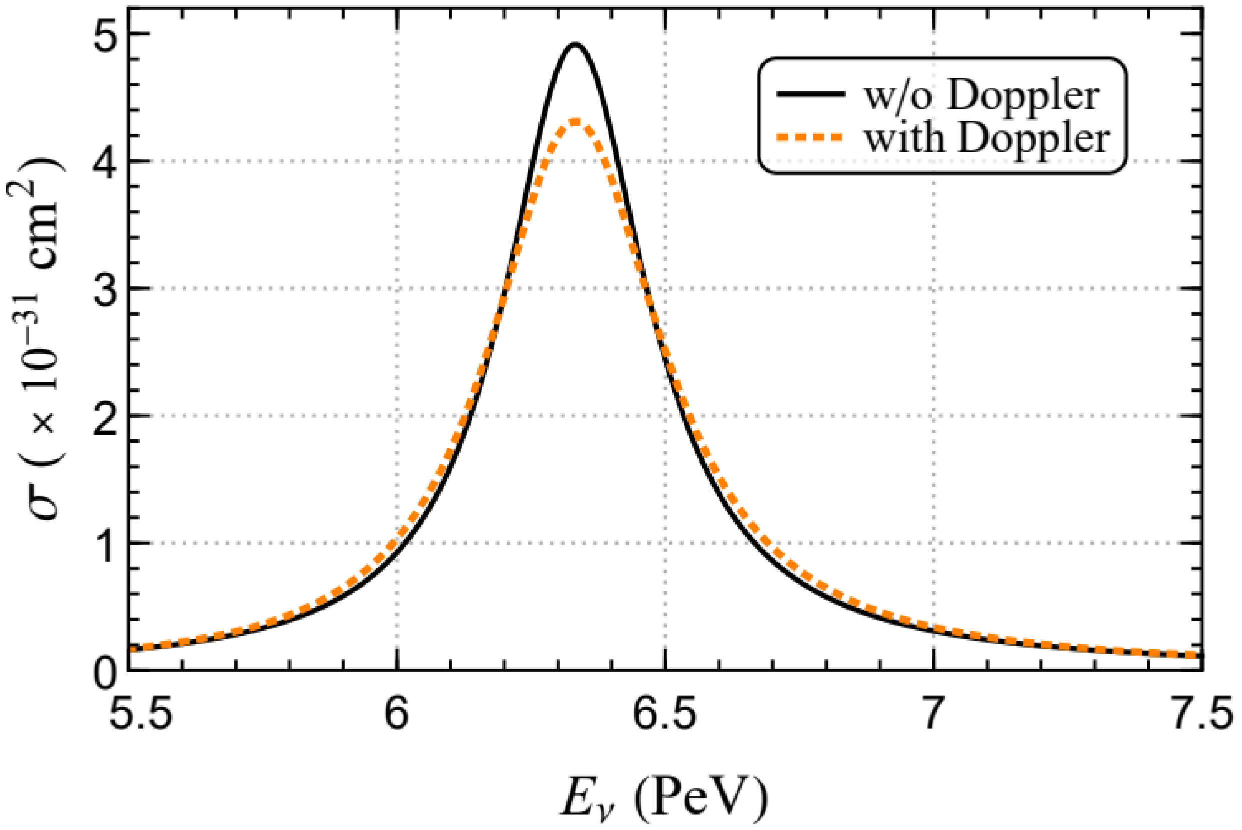
$$f_{3p}(k) = \frac{1024}{45\pi}\frac{\mu_{3p}^7 (5\mu_{3p}^2 k^2 - k^4)^2}{(\mu_{3p}^2 + k^2)^8},$$

$$f_{3d}(k) = \frac{4096}{5\pi}\frac{\mu_{3d}^9 k^6}{(\mu_{3d}^2 + k^2)^8},$$

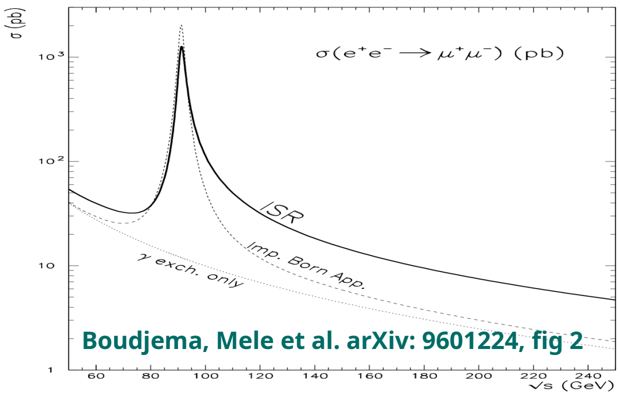
$$f_{4s}(k) = \frac{512}{35\pi}\frac{\mu_{4s}^9 (5\mu_{4s}^4 k - 10\mu_{4s}^2 k^3 + k^5)^2}{(\mu_{4s}^2 + k^2)^{10}}$$

# Corrections to the GR cross section: Doppler broadening

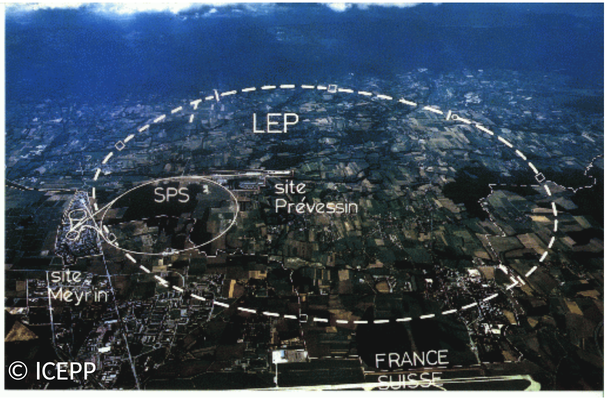
- **Doppler bro**
  **section:**
  $\sigma(E_\nu) = \frac{1}{4\pi}\int \mathrm{d}$
- **Electron ve**
  **for ice:**
  $F_{\text{ice}}(\beta) = \frac{2F}{}$
- **Distributio**
  **with quant**
  $f_{n\,l}(\beta) = m$



# Corrections to the GR cross section: initial state radiation

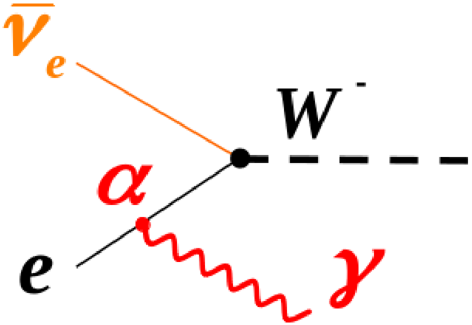



Boudjema, Mele et al. arXiv: 9601224, fig 2






- **Initial state radiation (ISR) also relevant for neutrino telescopes**
- **ISR cross section near the GR: collinear enhancement**

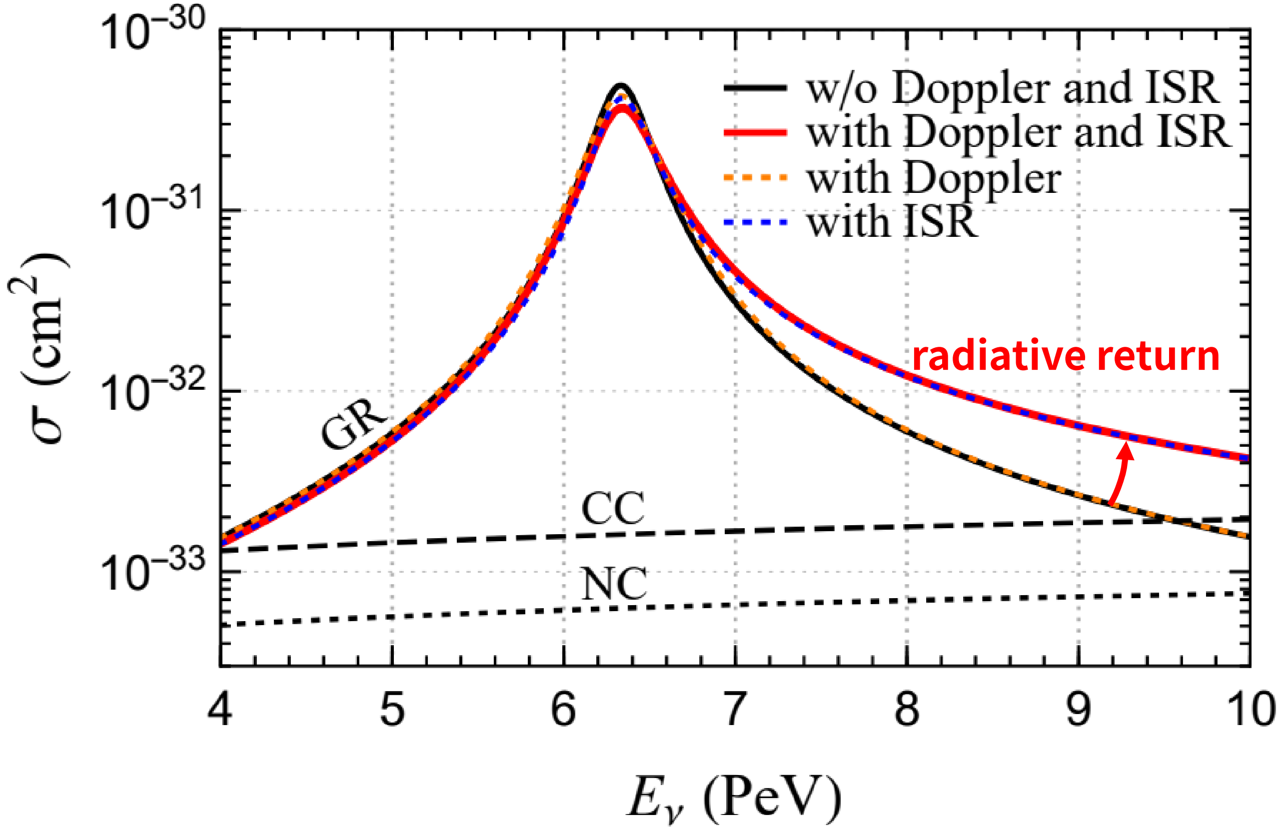



$$\sigma(E_\nu) = \int \mathrm{d}x\, \Gamma_{e/e}(x, Q^2)\sigma^{(0)}(x, Q^2, E_\nu)$$

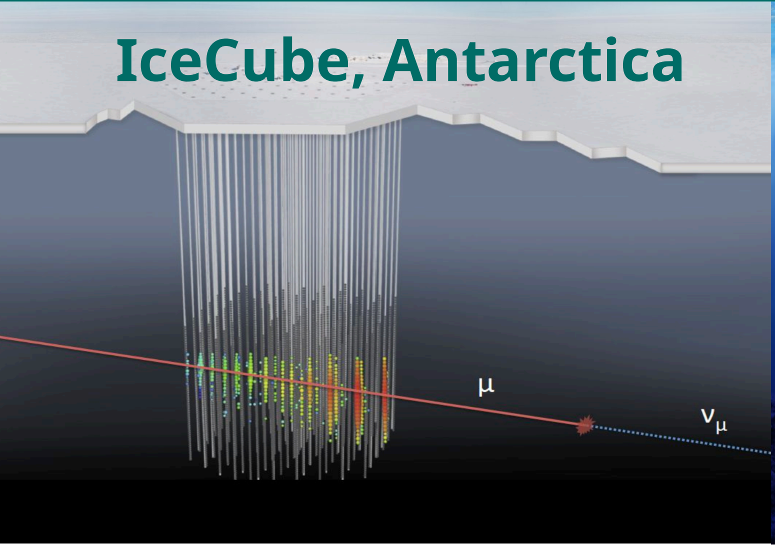
Structure function

Xsec without ISR

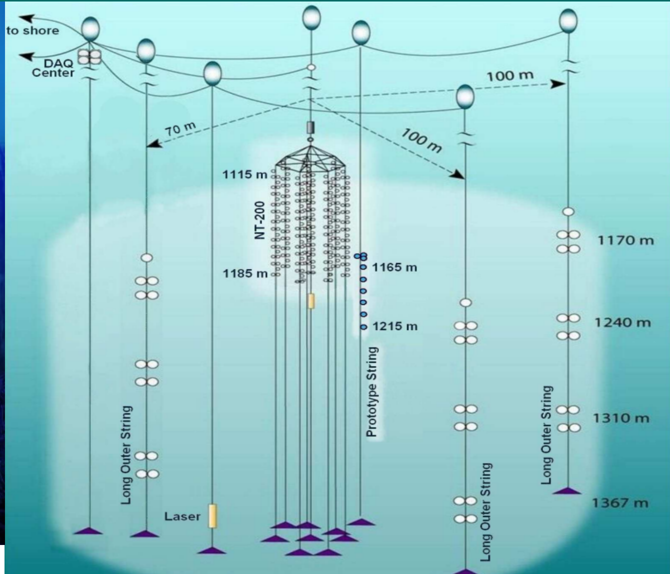
# Corrections to the GR cross section



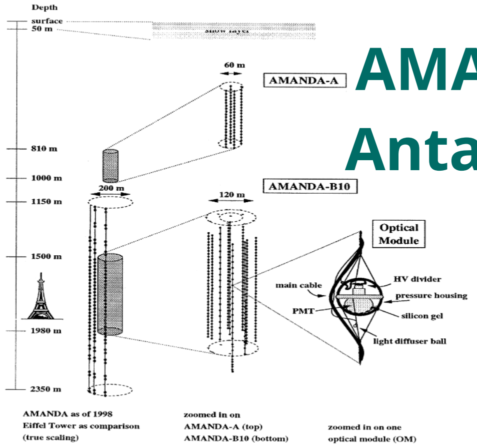
# Detection of the Glashow resonance



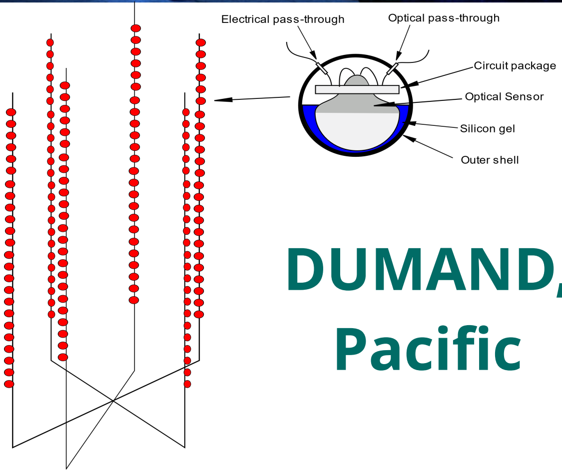





Baikal, Lake Baikal

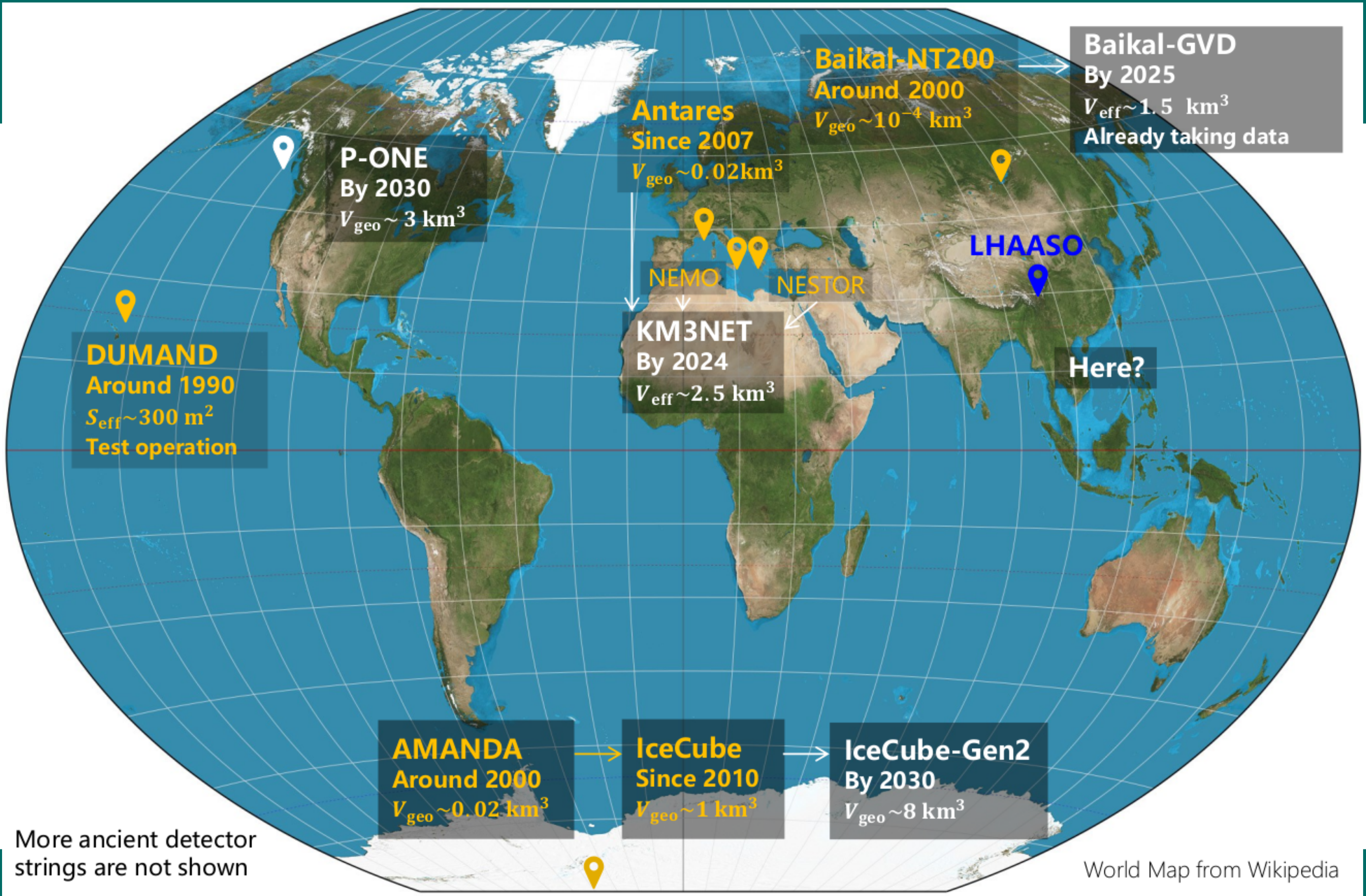



AMANDA,
Antarctica

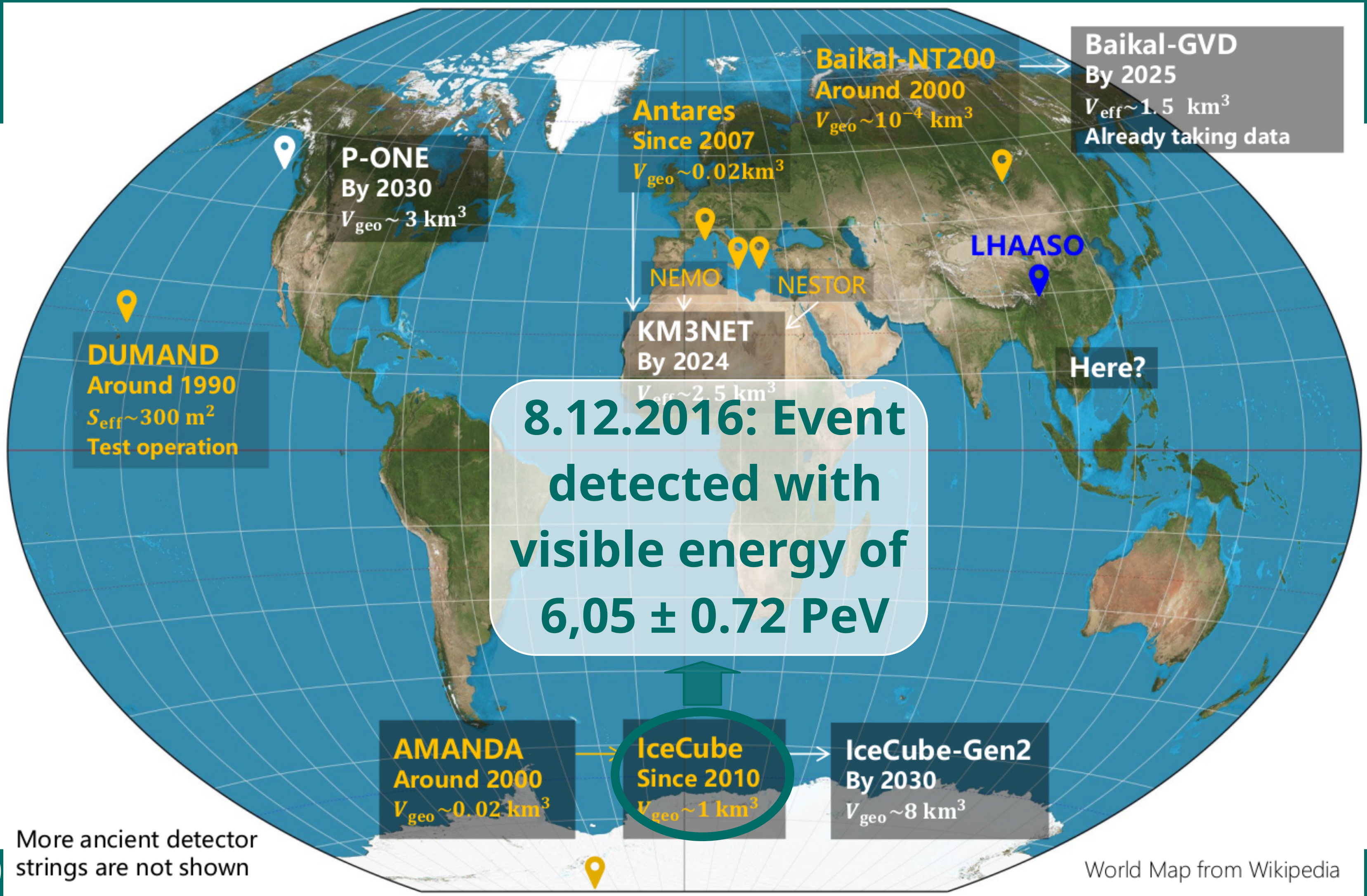



DUMAND,
Pacific

# Detection of the Glashow resonance



# Detection of the Glashow resonance



# Neutrino sources we want to distinguish

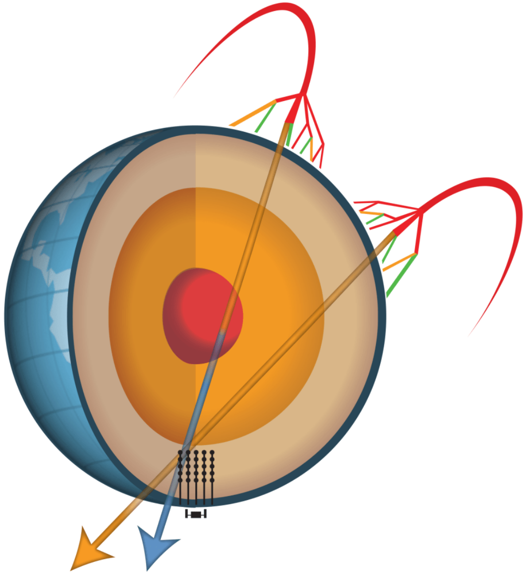
- **pγ source**
  - cosmic rays collide with photons to produce charged pions (mostly $\pi^+$)
  - followed by the decays $\pi^+ \rightarrow \mu^+ \nu_\mu$ and $\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$
  - results in more neutrino flux than antineutrino flux (ratio 2:1)
- **pp source**
  - nearly equal fractions of $\pi^+$ and $\pi^-$
  - leads to ratio 1:1
- **μ-damped pγ source**
  - muons from pion decay significantly lose energy via synchotron radiation before decaying, ratio 1:0

# Likelihood analysis: flux models

- **Two benchmark flux models**
  - unbroken single power-law model

$$\frac{\mathrm{d}\Phi_{6\nu}}{\mathrm{d}E_\nu} = \Phi_0 \left(\frac{E_\nu}{100\ \mathrm{TeV}}\right)^{-\gamma} 10^{-18}\ \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

  - single power-law model with an exponential energy cutoff (add $\exp\left(-E_\nu/E_{\mathrm{cutoff}}\right)$)
    - reachable energy of astrophysical accelerators always features a cutoff due to the Hillas criterion



# Likelihood analysis

## Likelihood analysis of unbinned data

$$L_{\overline{\nu}_e} = \prod_{i=1}^{n} \left[\mu_{\rm DIS} P_{\rm DIS}(\#i|\Theta) + \mu_{\rm GR} P_{\rm GR}(\#i|\Theta)\right] \times \frac{1}{n!} e^{-(\mu_{\rm DIS}+\mu_{\rm GR})}$$

**expected event numbers with a deposited energy between 4 and 10 PeV**

**normalized probability to have an event at #i's energy**

$$\mu_{\rm DIS} = \int_{\rm cut} dE_{\rm dep} \cdot \left( \frac{dN^{\rm CC}_{\nu_e+\overline{\nu}_e}}{dE_{\rm dep}} + \sum_{\alpha} \frac{dN^{\rm NC}_{\nu_\alpha+\overline{\nu}_\alpha}}{dE_{\rm dep}} \right)$$

$$\mu_{\rm GR} = \int_{\rm cut} dE_{\rm dep} \cdot \left( \frac{dN^{{\rm GR},jj}_{\overline{\nu}_e}}{dE_{\rm dep}} + \frac{dN^{{\rm GR},e\nu}_{\overline{\nu}_e}}{dE_{\rm dep}} \right)$$

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

# Likelihood analysis

## Likelihood analysis of unbinned data

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

**normalized probability to have an event at #i's energy**

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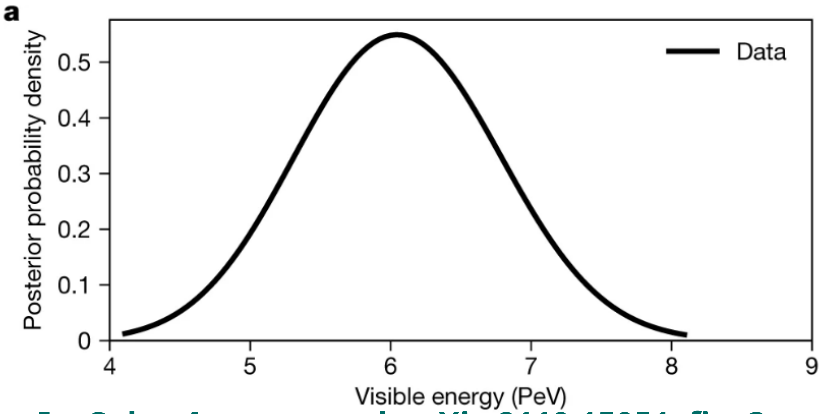
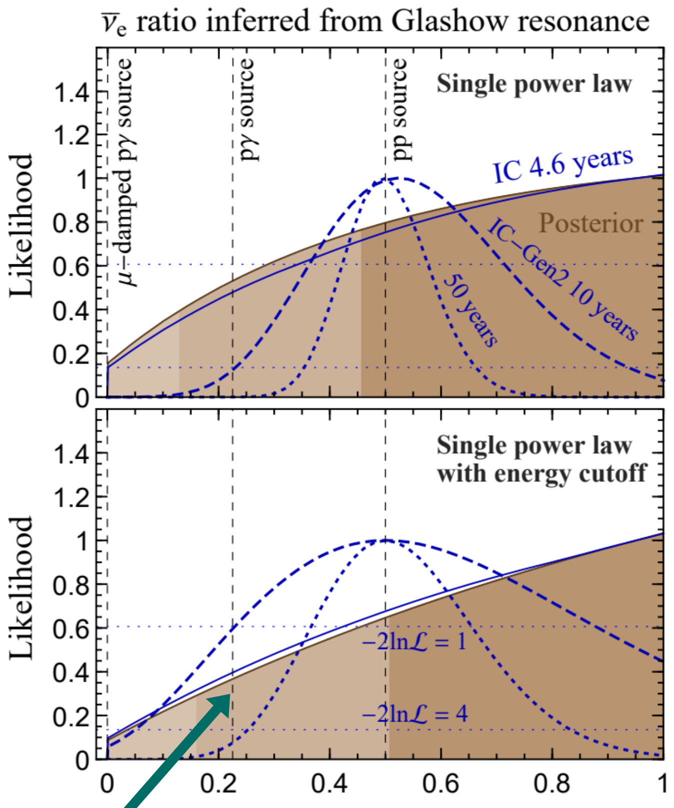
$$P_{\mathrm{DIS/GR}}(\#i|\Theta) = \int \mathrm{d}E_{\mathrm{dep}} P(\#i|E_{\mathrm{dep}}) f_{\mathrm{DIS/GR}}(E_{\mathrm{dep}}|\Theta)$$




**IceCube, Aartsen et al. arXiv:2110.15051, fig. 3a**

# Likelihood analysis




At earth: f ≈ 0.23 $f_{\bar{\nu}_e}^{\oplus} \equiv \phi_{\bar{\nu}_e}^{\oplus}/(\phi_{\bar{\nu}_e}^{\oplus}+\phi_{\nu_e}^{\oplus})$

- Both frequentist and Bayesian interpretation
- μ-damped pγ source is excluded at around 2σ level
- Current IceCube 4.6-year data weakly favor the pp source

# Remark: follow-up paper

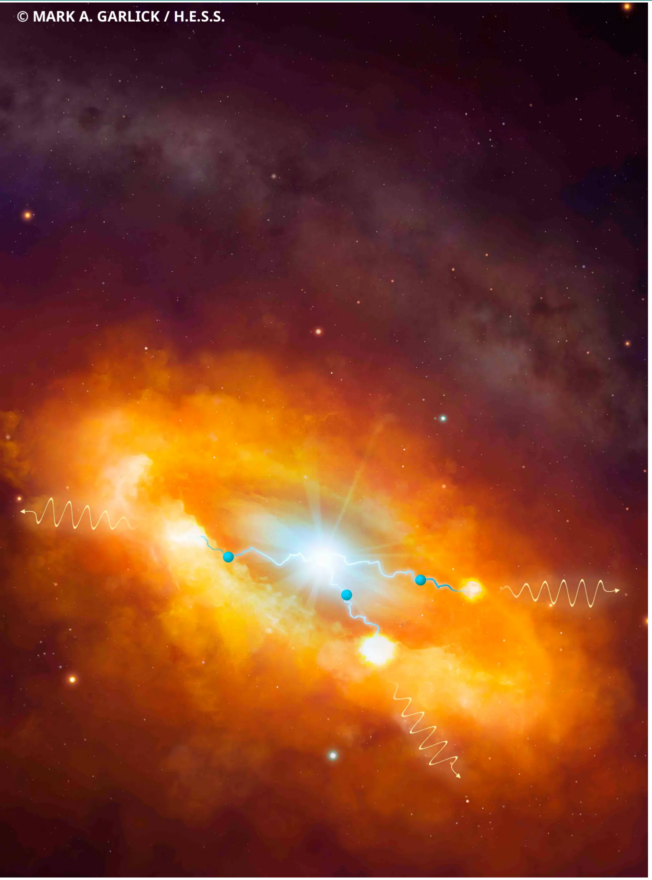
Probing neutrino production in high-energy astrophysical neutrino sources with the Glashow Resonance

Qinrui Liu,[1, 2, 3, *] Ningqiang Song,[4, 5, †] and Aaron C. Vincent[1, 2, 3, ‡]

arXiv: 2304.06068

- Very similar to our analysis
- Does not include Doppler broadening and ISR
- Projected sensitivities based on the combined exposure of planned Cherenkov neutrino telescopes
- Claims that pp and pγ can be distinguished at a 2σ significance level in the next decades
- Consider mixed production mechanisms

# Outlook




- Many projects such as IceCube-Gen2, Baikal-GVD, KM3NeT, P-ONE, TAMBO, TRIDENT
- By measuring the spectrum precisely in the future, one may go beyond the assumptions of the single power-law flux model
- In case of the increased statistics: Produce a map of the sky, identify associated PeVatrons

# Conclusions

- The observation of the Glashow resonance provides information about neutrino sources
- We introduced secondary modifications of the leading cross section which become more important once more Glashow resonance events are detected
- The candidate event observed by IceCube can already rule out the μ-damped pγ source at 2σ level; currently pp source weakly favoured

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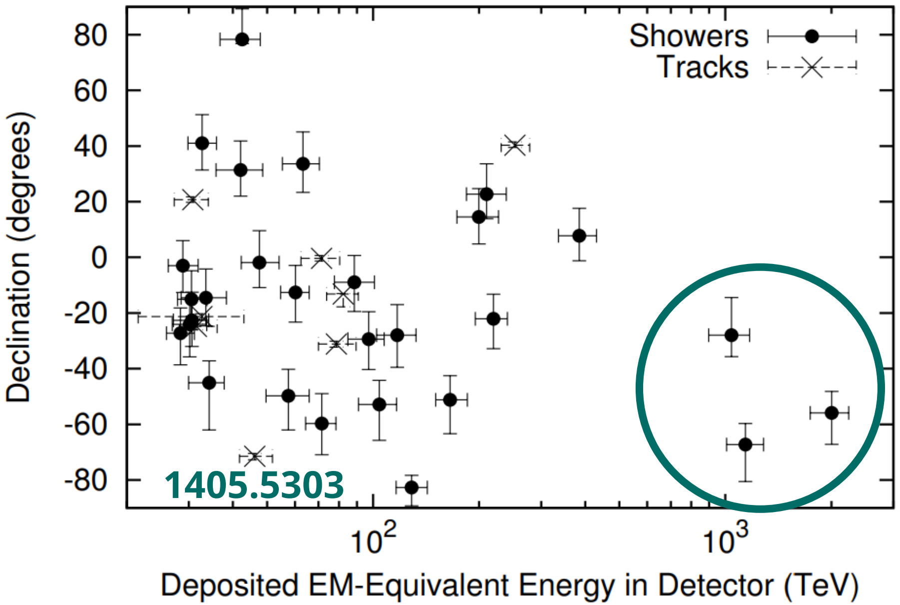
# Thank you for your attention!

# Backup: energy cuts

- One PEPE event with an energy deposition of 6.05 ±0.72 PeV
- Three HESE events below 3 PeV
- When calculating the expected event numbers, the event cut is Edep ∈ [4, 10] PeV



# Backup: flux parameters - likelihood

- To confine the flux parameters we use the likelihood

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

  and results from IceCube, R. Abbasi et al., Phys. Rev. D 104 (2021) 022002, arXiv: 2011.03545

- Best-fit values

$$\Phi_0^{\mathrm{bf}} = 6.37 \text{ and } \gamma^{\mathrm{bf}} = 2.87$$

- 1σ errors

$$\sigma(\Phi_0) = 1.54 \text{ and } \sigma(\gamma) = 0.2$$

# Backup: flux parameters - Ecutoff

- **For the cutoff model we further derive the likelihood for $E_{cutoff}$ from the plot on the left**

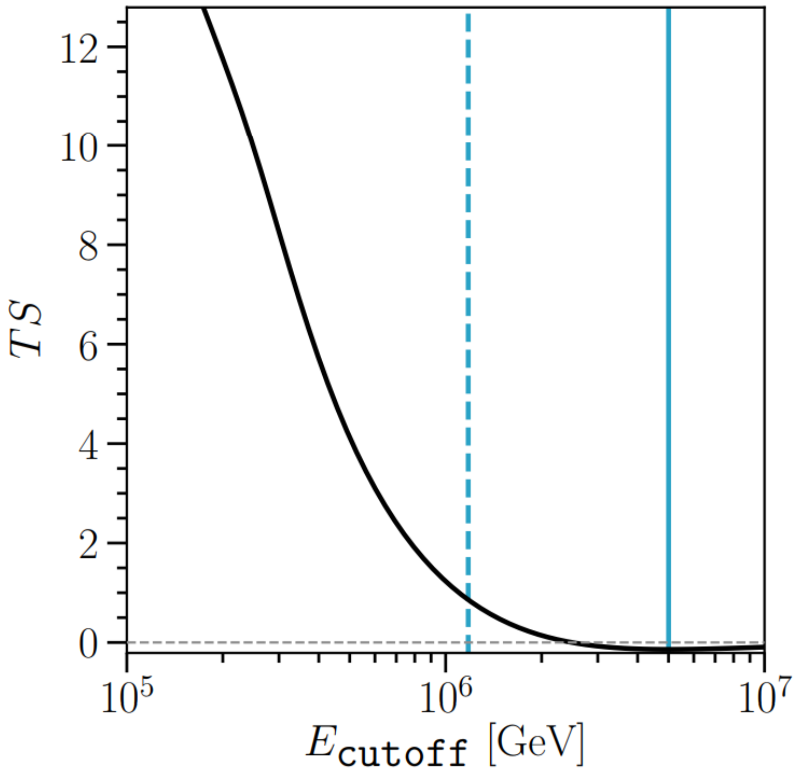



FIG. VI.9. ***Cutoff model comparison using frequentist test-statistic.*** The test-statistic comparing the cutoff hypothesis and the single power-law hypothesis is plotted as the black curve. The gray dashed line indicates where the cutoff model's test-statistic and the single power-law model are equal; there is a slight preference for the cutoff scenario in the several PeV region, although this is not statistically significant. We also report the results of parameter estimation for the cutoff model in this plot. The best-fit value for the cutoff energy, $E_{\texttt{cutoff}}$, is shown as the solid blue line and the dashed blue line indicates the boundary of the 68.3 % confidence interval.

IceCube, arXiv: 2011.03545