Probing the Glashow resonance and beyond with ultrahigh energy neutrino telescopes

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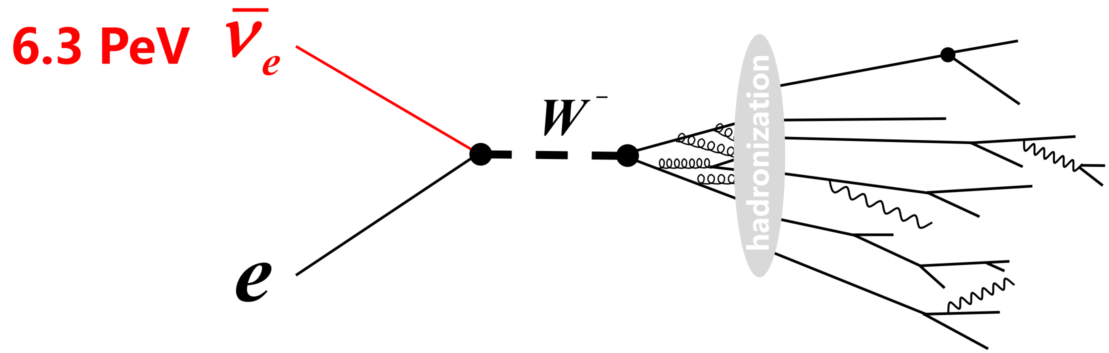
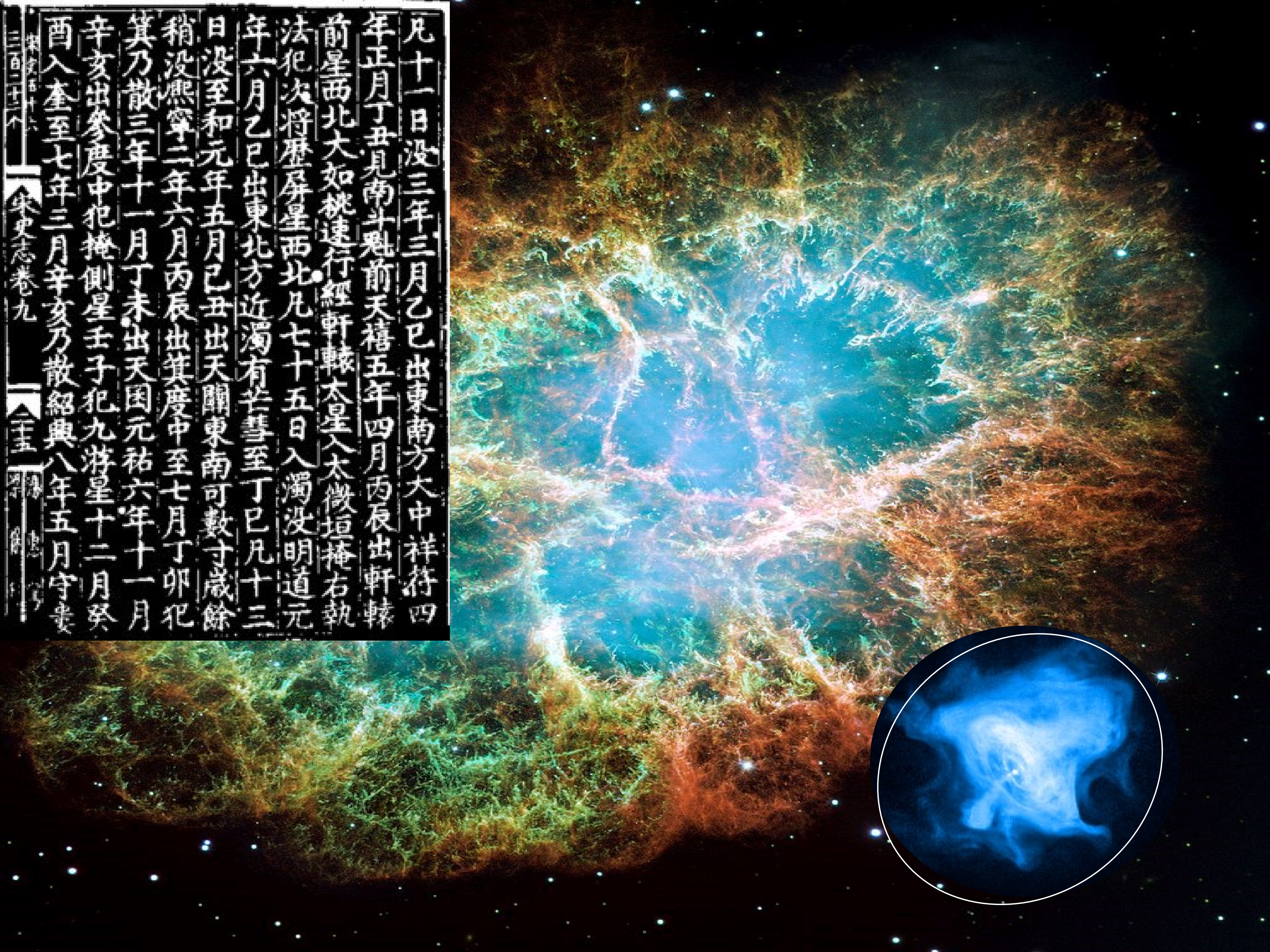
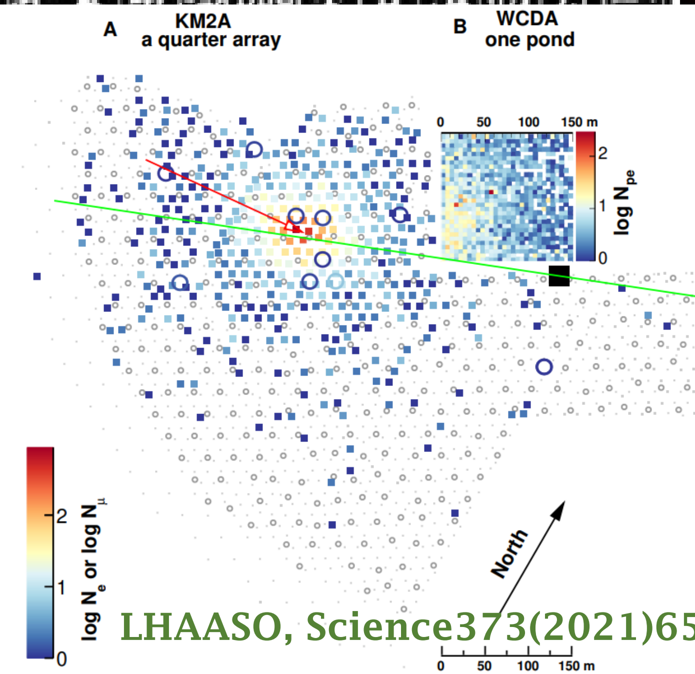
Based on arXiv:2303.13706 in collaboration with M. Lindner and N. Volmer



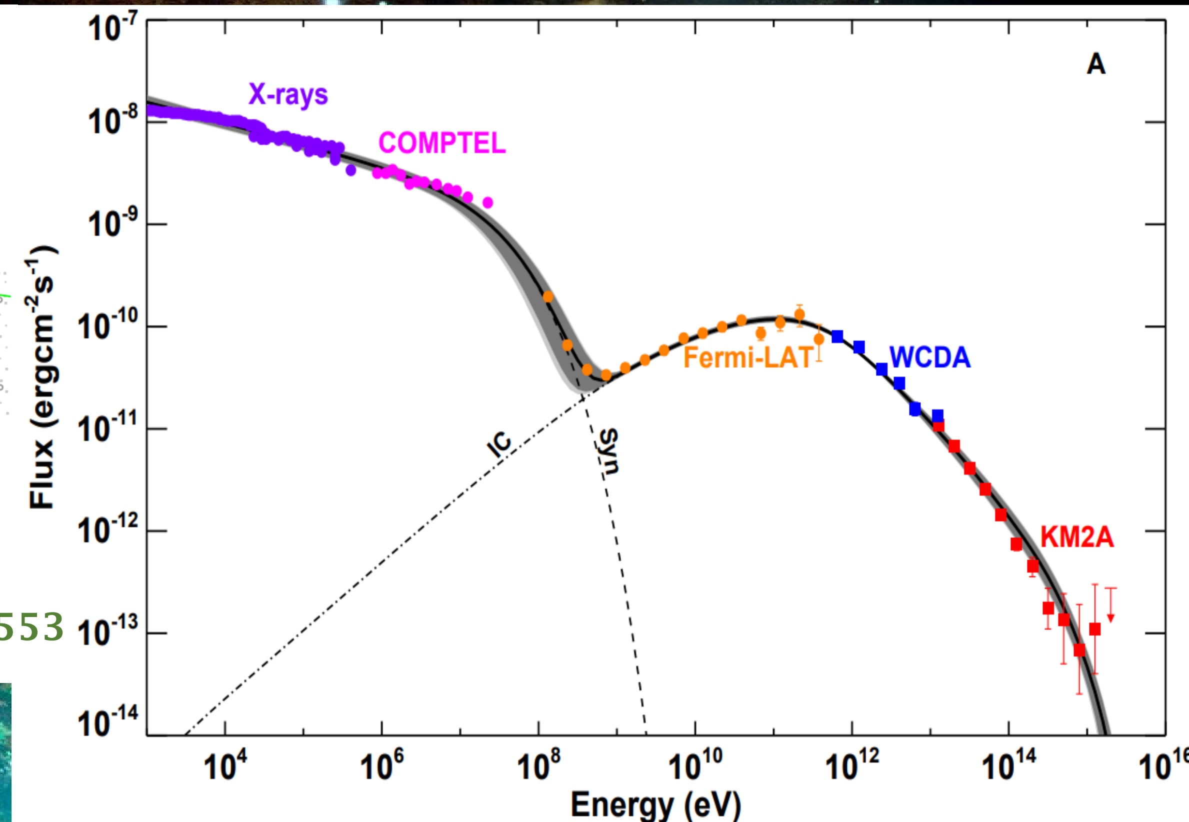
- Introduction
- The Glashow resonance
- The candidate event in IceCube
- Potential of air shower neutrino telescopes
- Conclusion

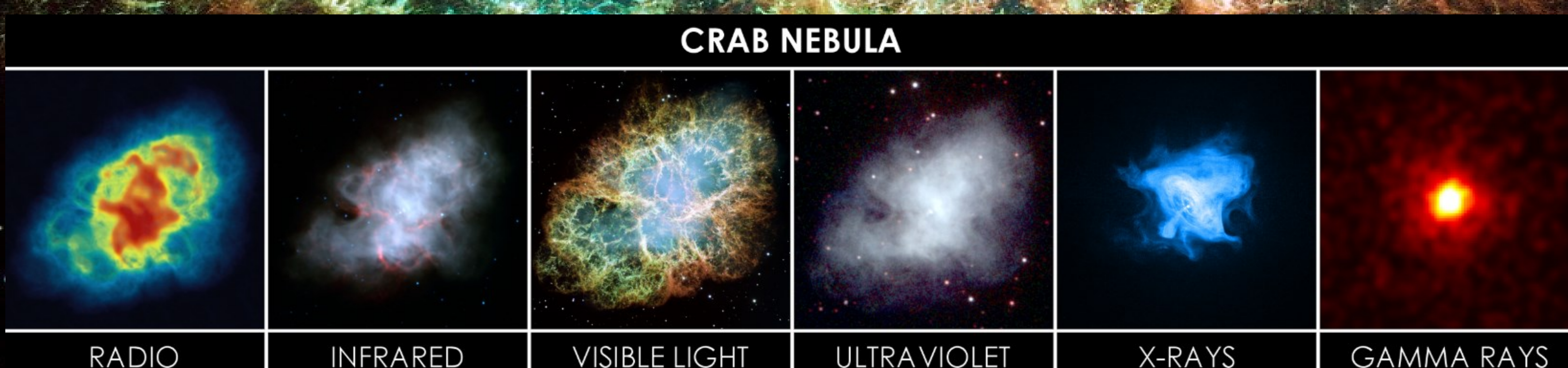


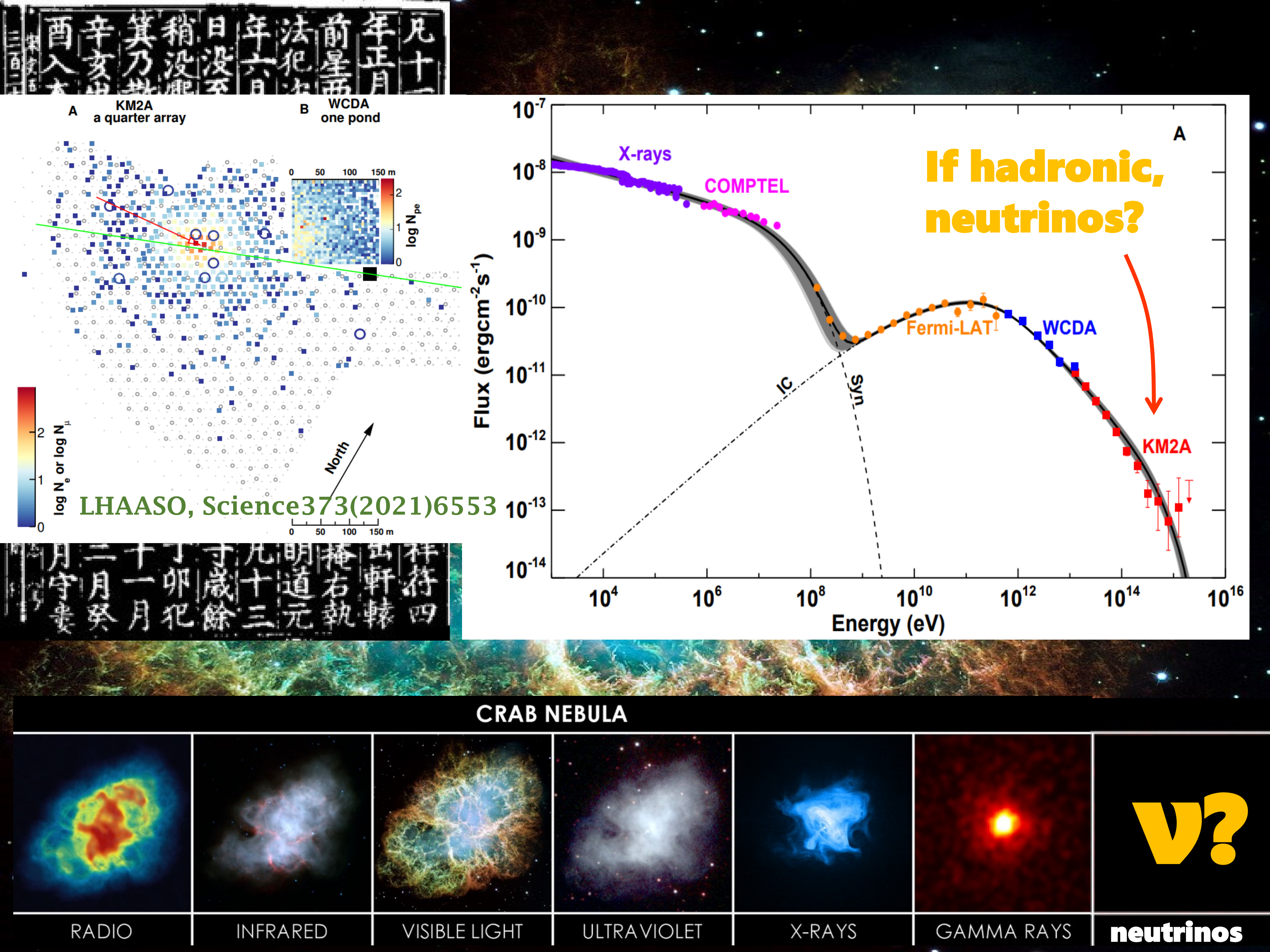
凡十一日沒三年三月乙巳出東南方大中祥符四
年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅
前星西北大如桃速行經軒轅太星入太微垣掩右執
法犯次將歷屛星西北凡七十五日入濁沒明道元
年六月乙巳出東北方近濁有芒彗至丁巳凡十三
日沒至和元年五月己丑出天關東南可數寸歲餘
稍沒熙寧二年六月丙辰出箕度中至七月丁卯犯
箕乃散三年十一月丁未出天囷元祐六年十一月
辛亥出參度中犯掩側星壬子犯九游星十二月癸
酉入奎至七年三月辛亥乃散紹興八年五月守婁



LHAASO, Science373(2021)6553





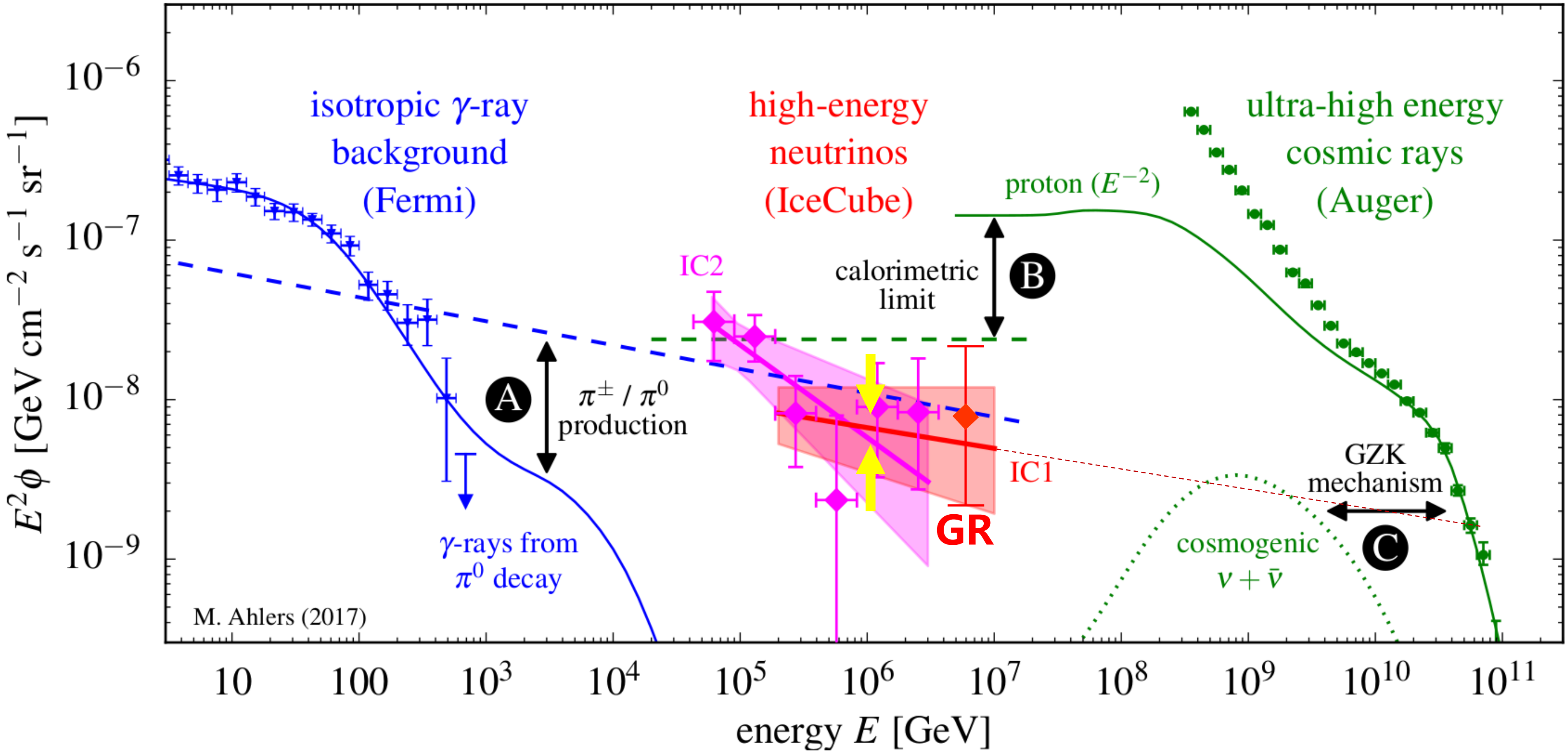


A KM2A a quarter array
B WCDA one pond
0 50 100 150 m
log N_pe
log N_e or log N_μ
North
LHAASO, Science373(2021)6553
Flux (ergcm^-2s^-1)
Energy (eV)
X-rays
COMPTEL
Fermi-LAT
WCDA
KM2A
IC
Syn
If hadronic, neutrinos?
CRAB NEBULA
RADIO
INFRARED
VISIBLE LIGHT
ULTRAVIOLET
X-RAYS
GAMMA RAYS
ν?
neutrinos


ν ν ν
γ γ
γ
p
©DESY

Cosmic rays, gamma rays and neutrinos

Ahlers and Halzen, RPNP102(2018)73



Consistent with our understanding of particle physics

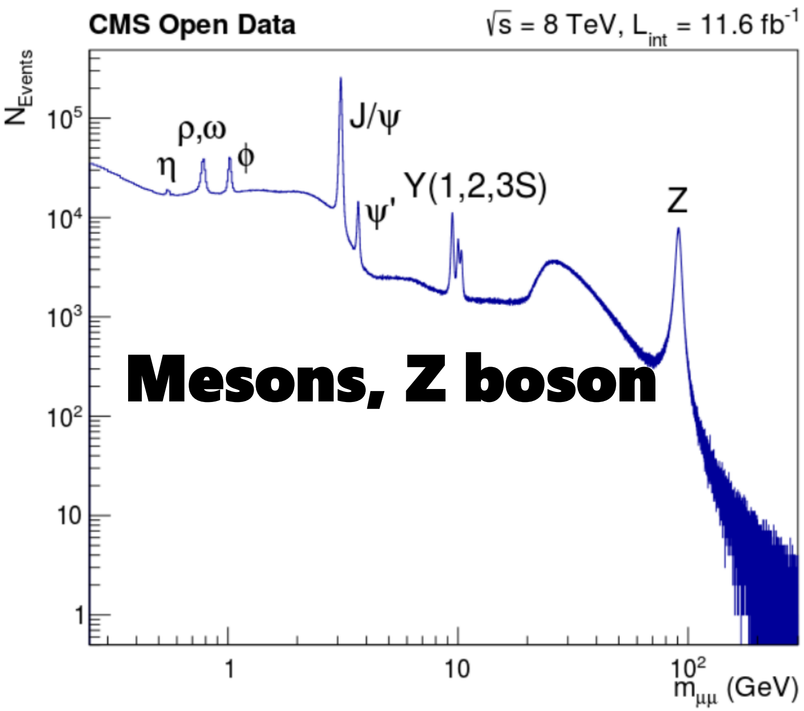
Why astrophysics is important for particle physics

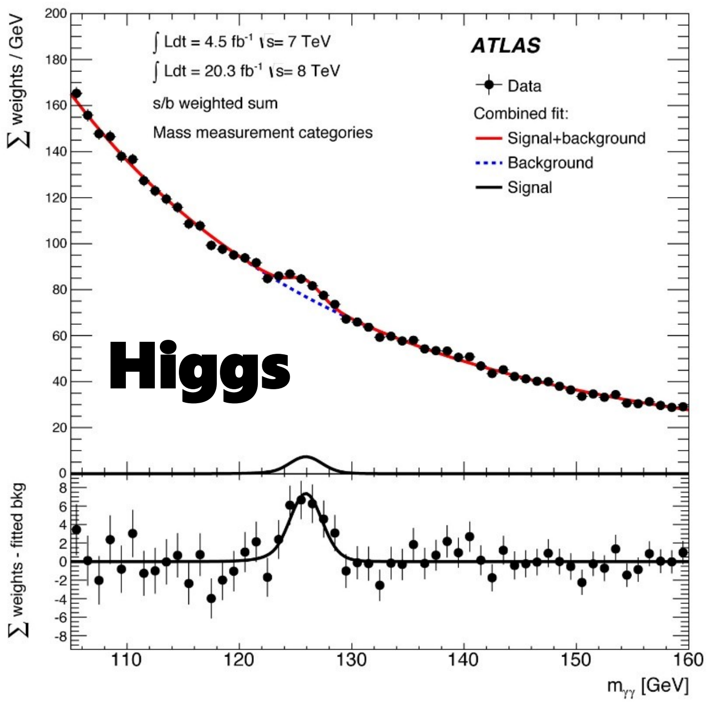
- Historic discoveries of positron, muon, pion, kaon
- Solar neutrinos and atmospheric neutrinos
- Dark matter and dark energy
- Extreme density and extreme energy for testing particle physics

Why particle physics is important for astrophysics

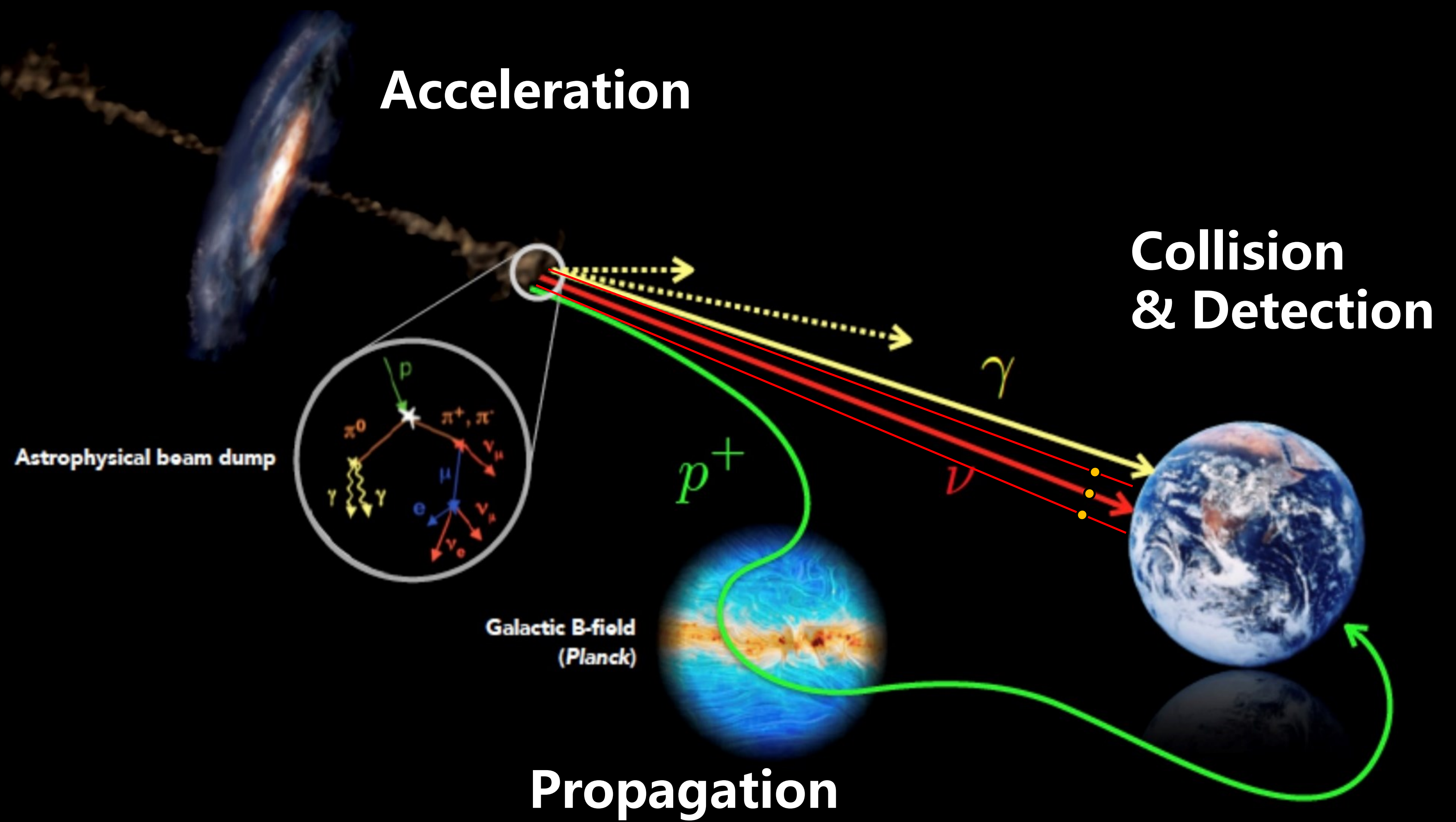
- Essential for understanding and modelling the astrophysical phenomena
- Essential for propagation and detection
- New physics leads to testable predictions

Resonance in colliders

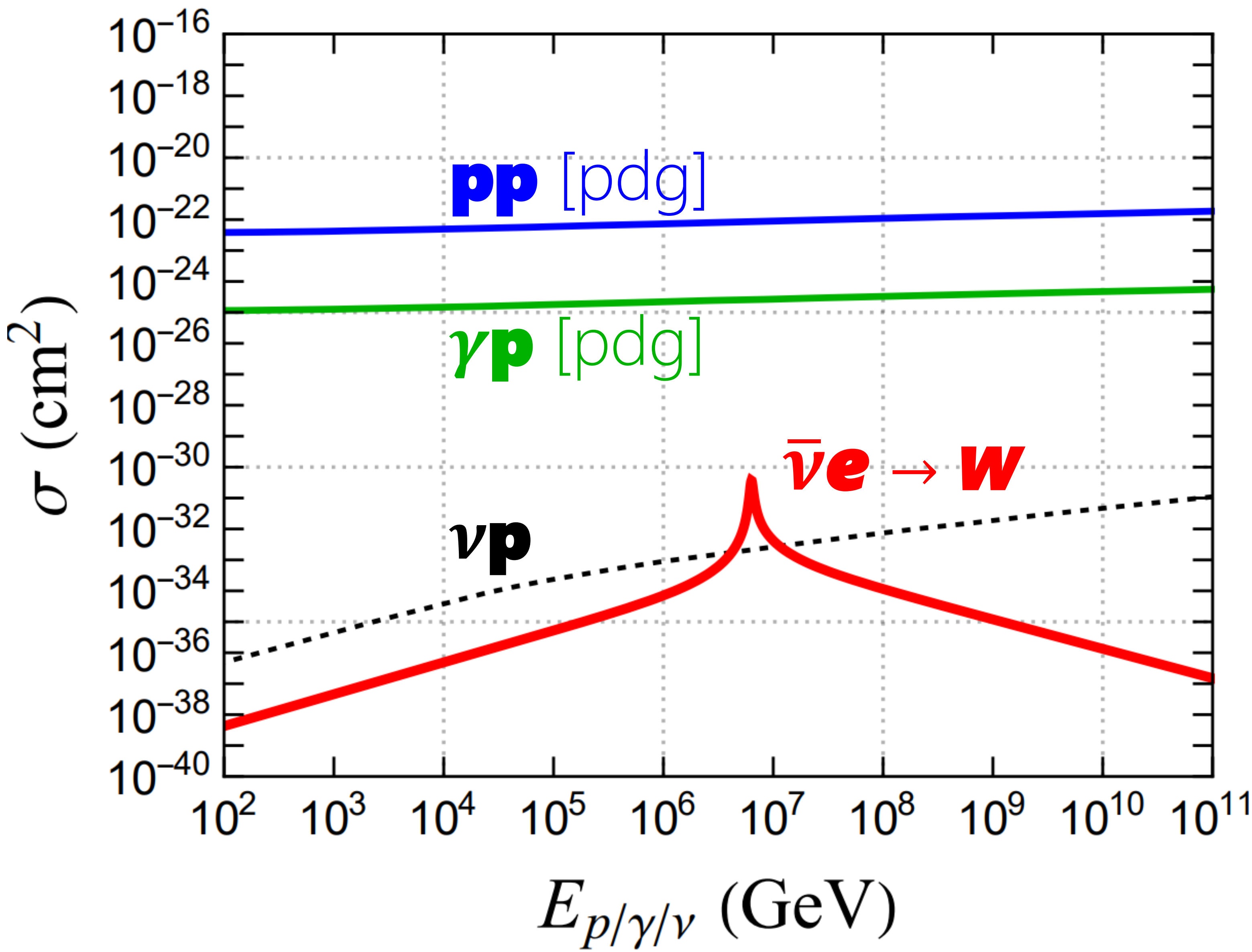




Cosmic ``accelerator and collider”



Cross sections



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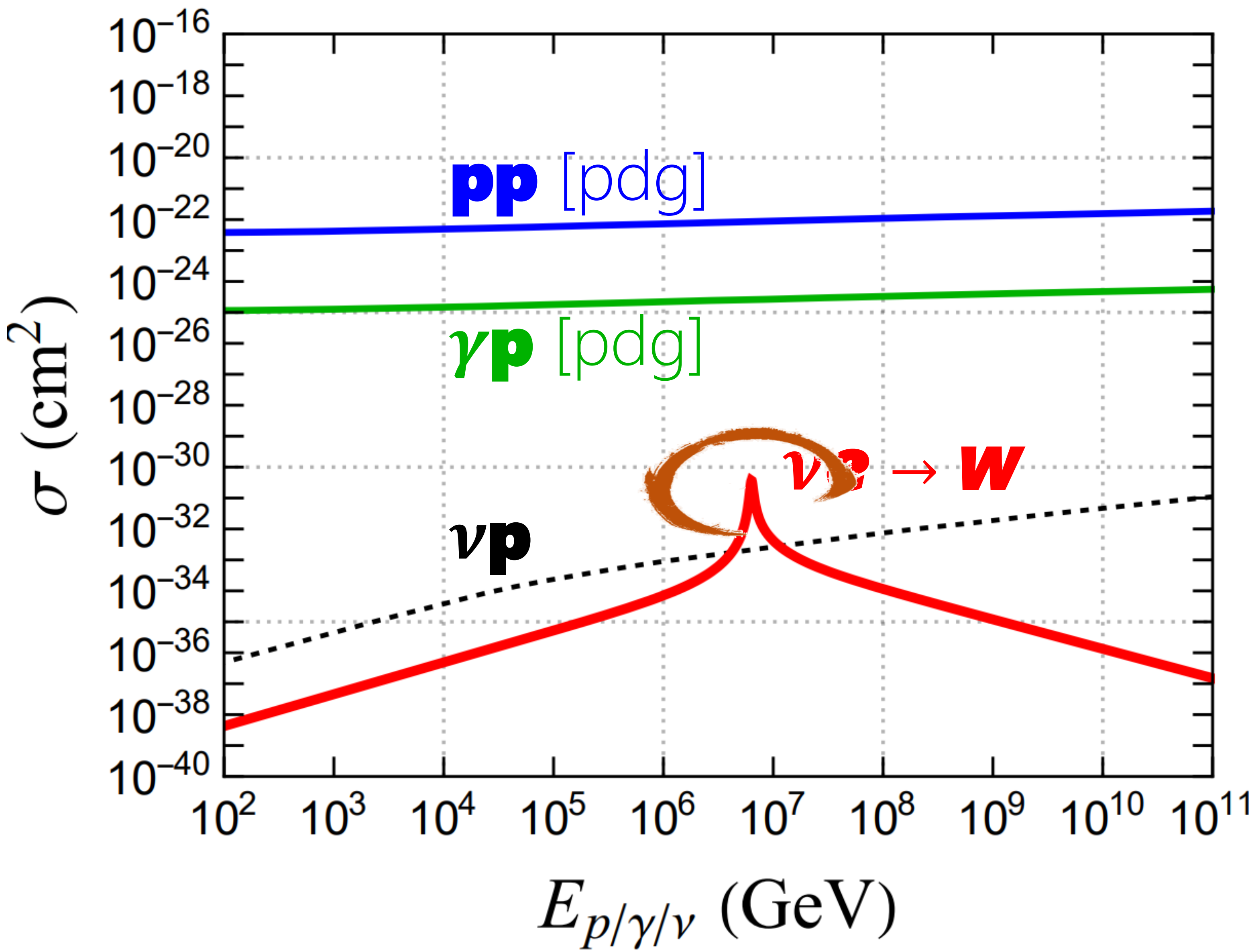


The Glashow resonance

PHYSICAL REVIEW VOLUME 118, NUMBER 1 APRIL 1, 1960

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

Resonant Scattering of Antineutrinos

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

Atmospheric

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.

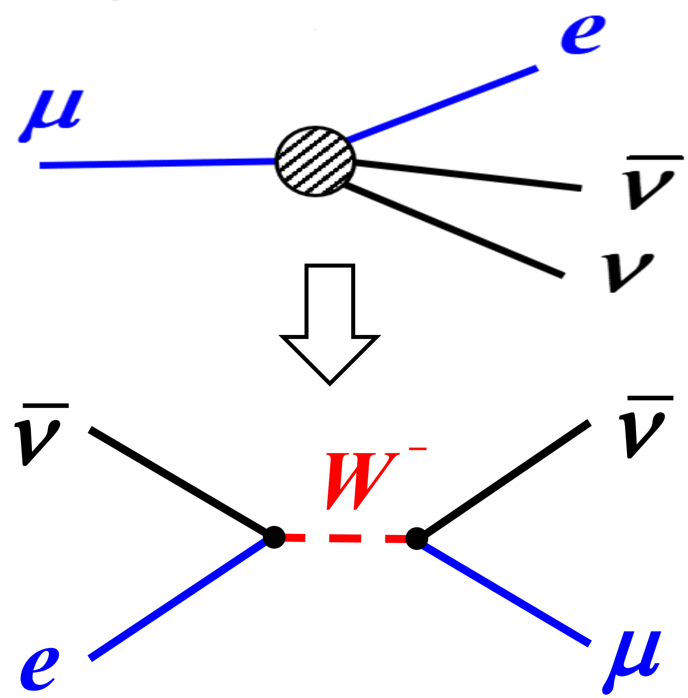
~TeV

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,

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



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$\sim$**TeV**

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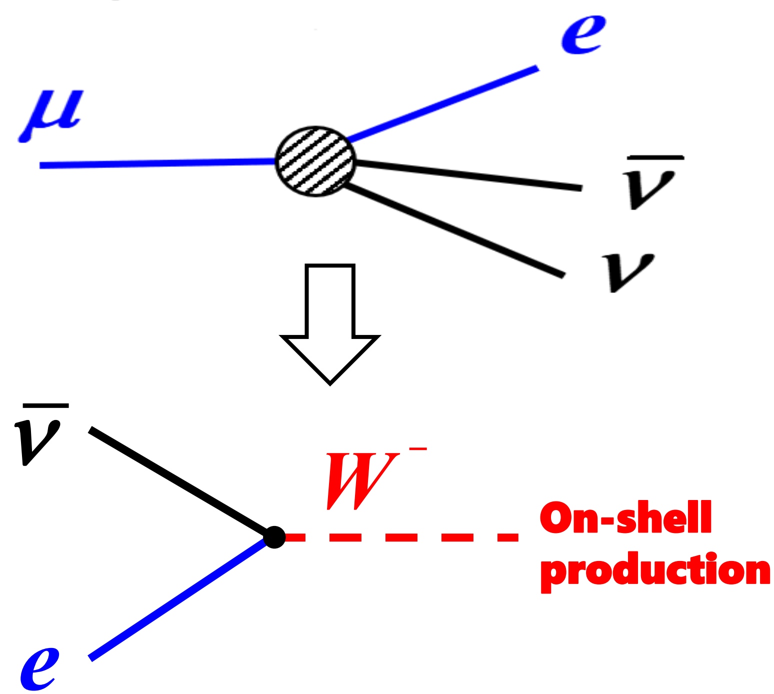
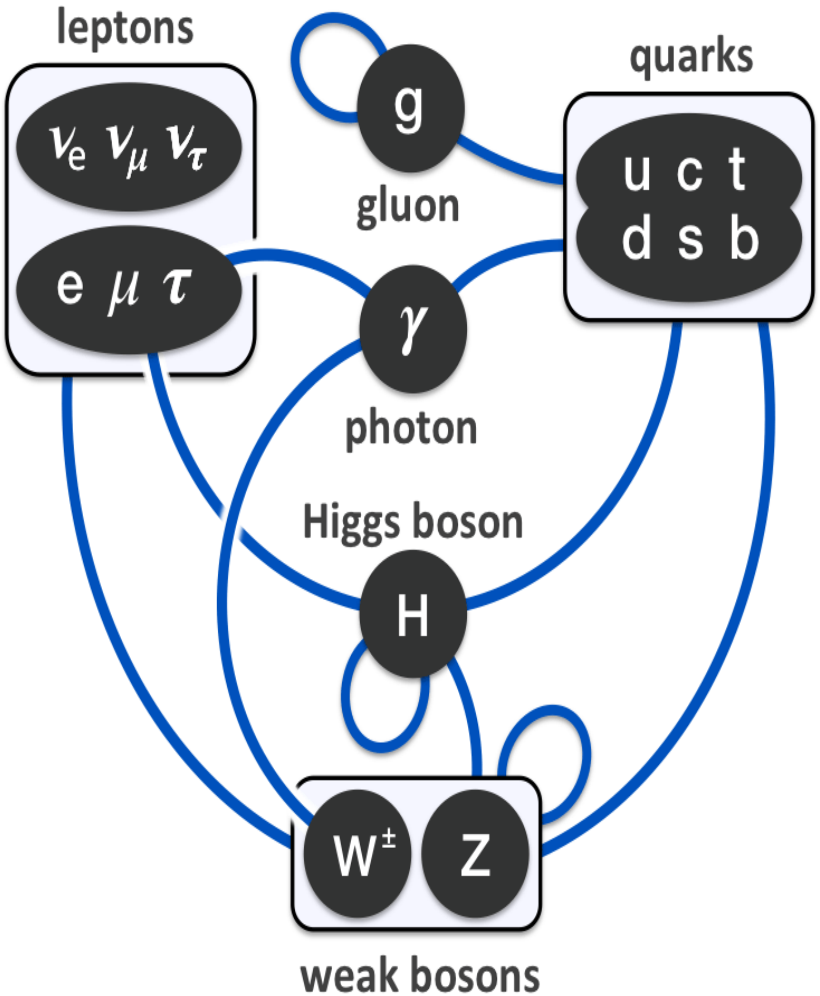
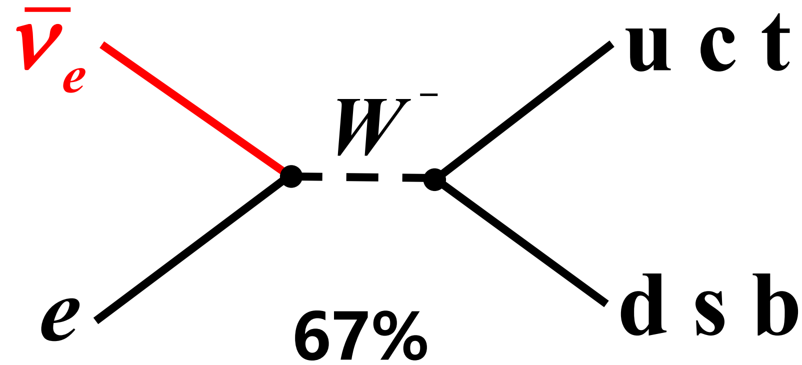
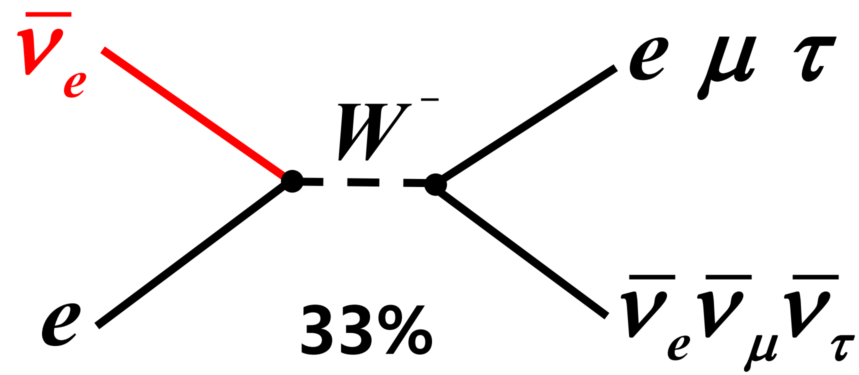


The Glashow resonance

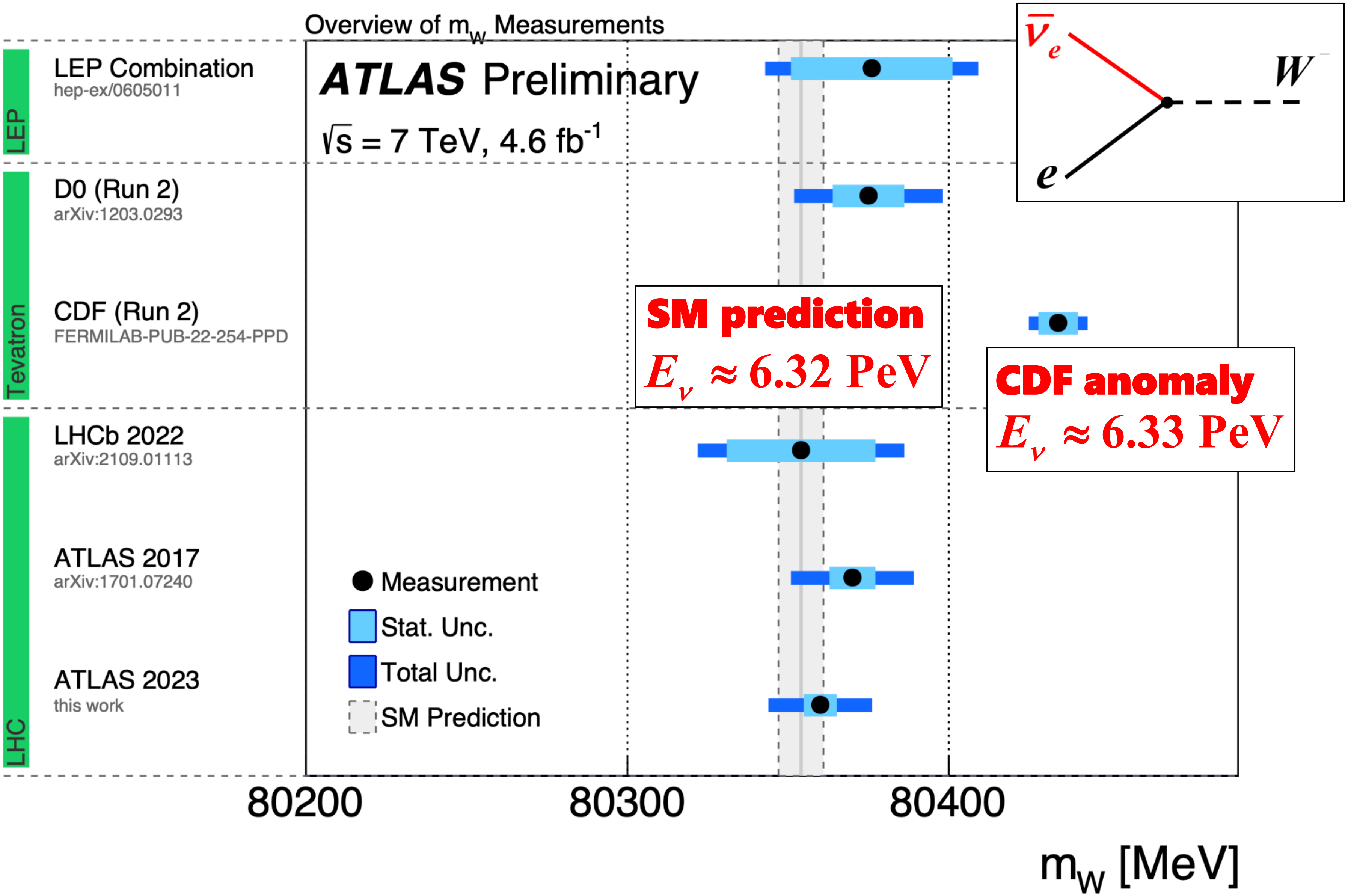




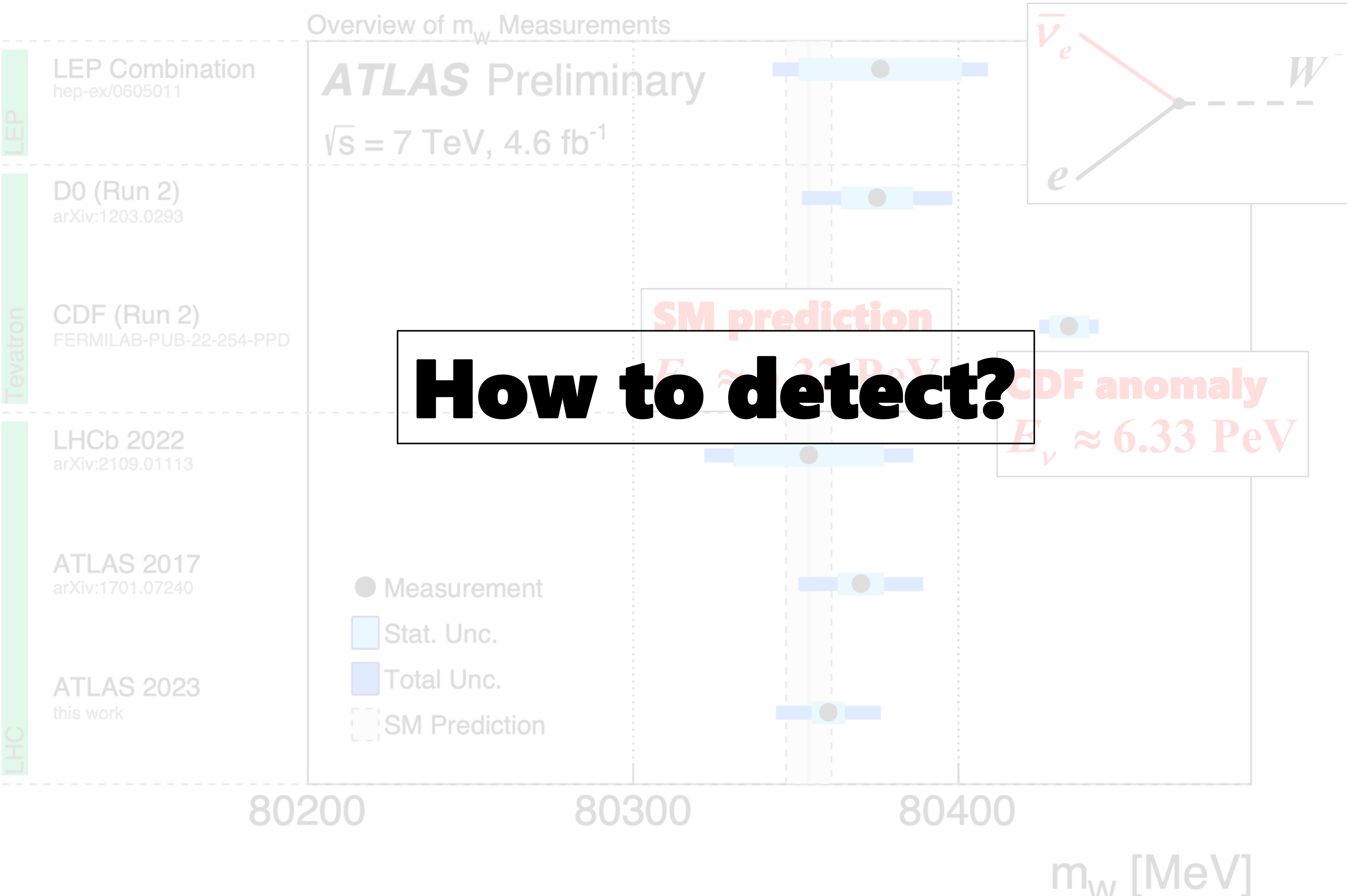


Resonance happens at $E_\nu \approx \dfrac{m_W^2}{2m_e}$

The Glashow resonance

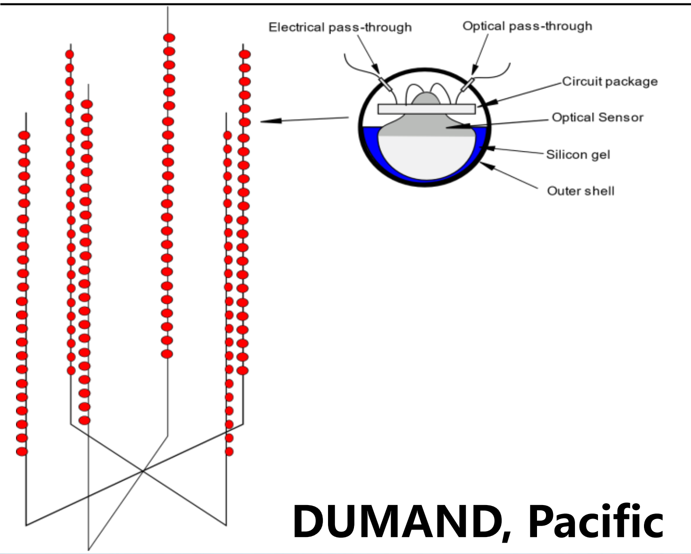


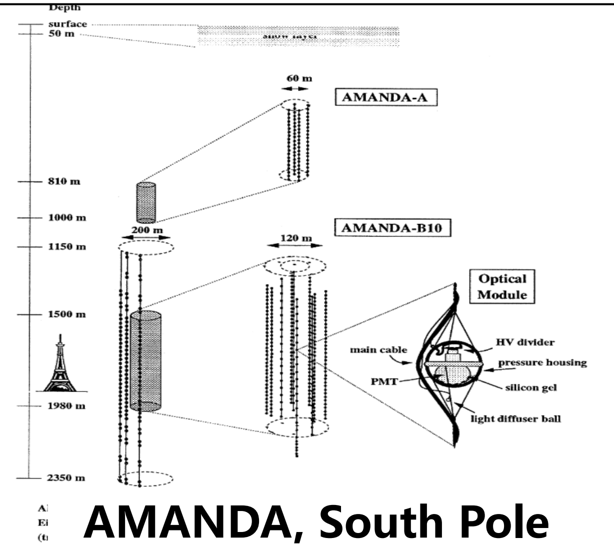
The Glashow resonance

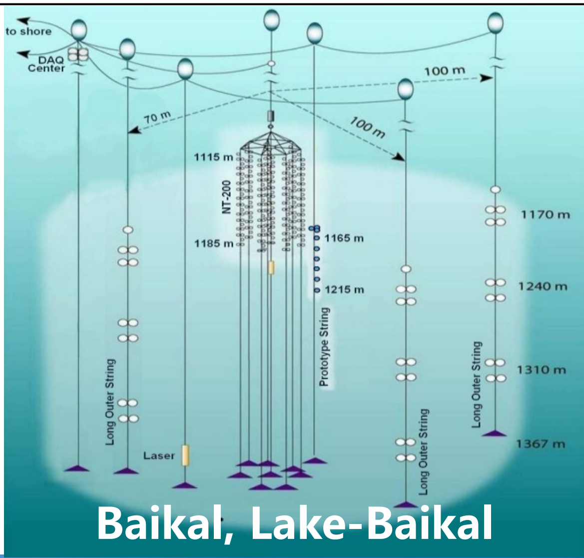


How to detect?

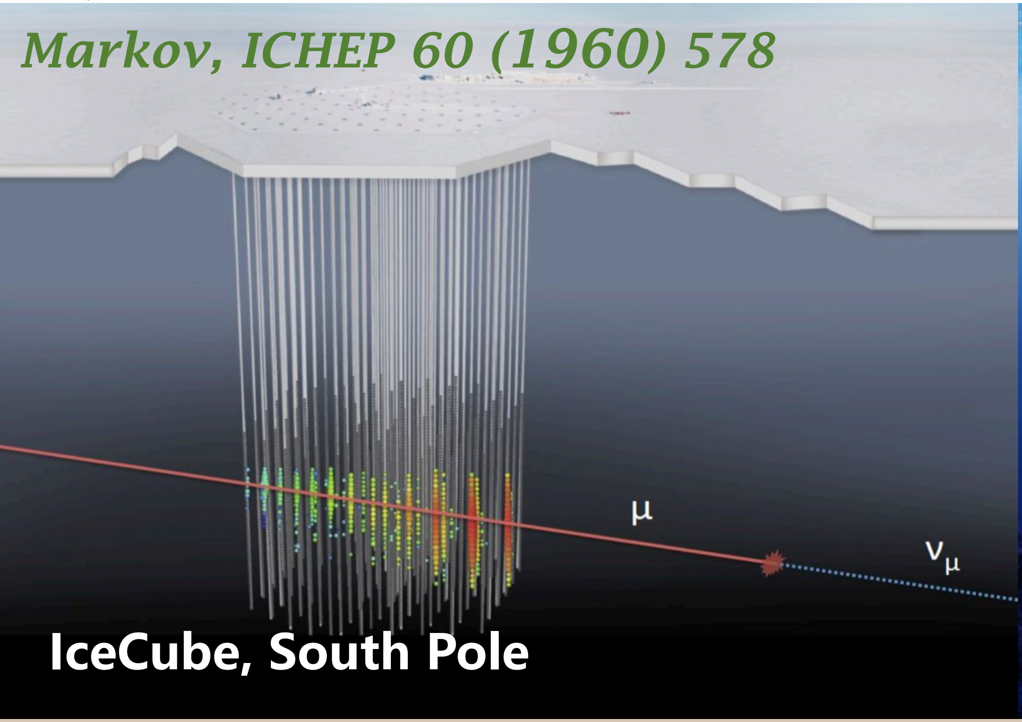
Water/Ice Cherenkov telescopes



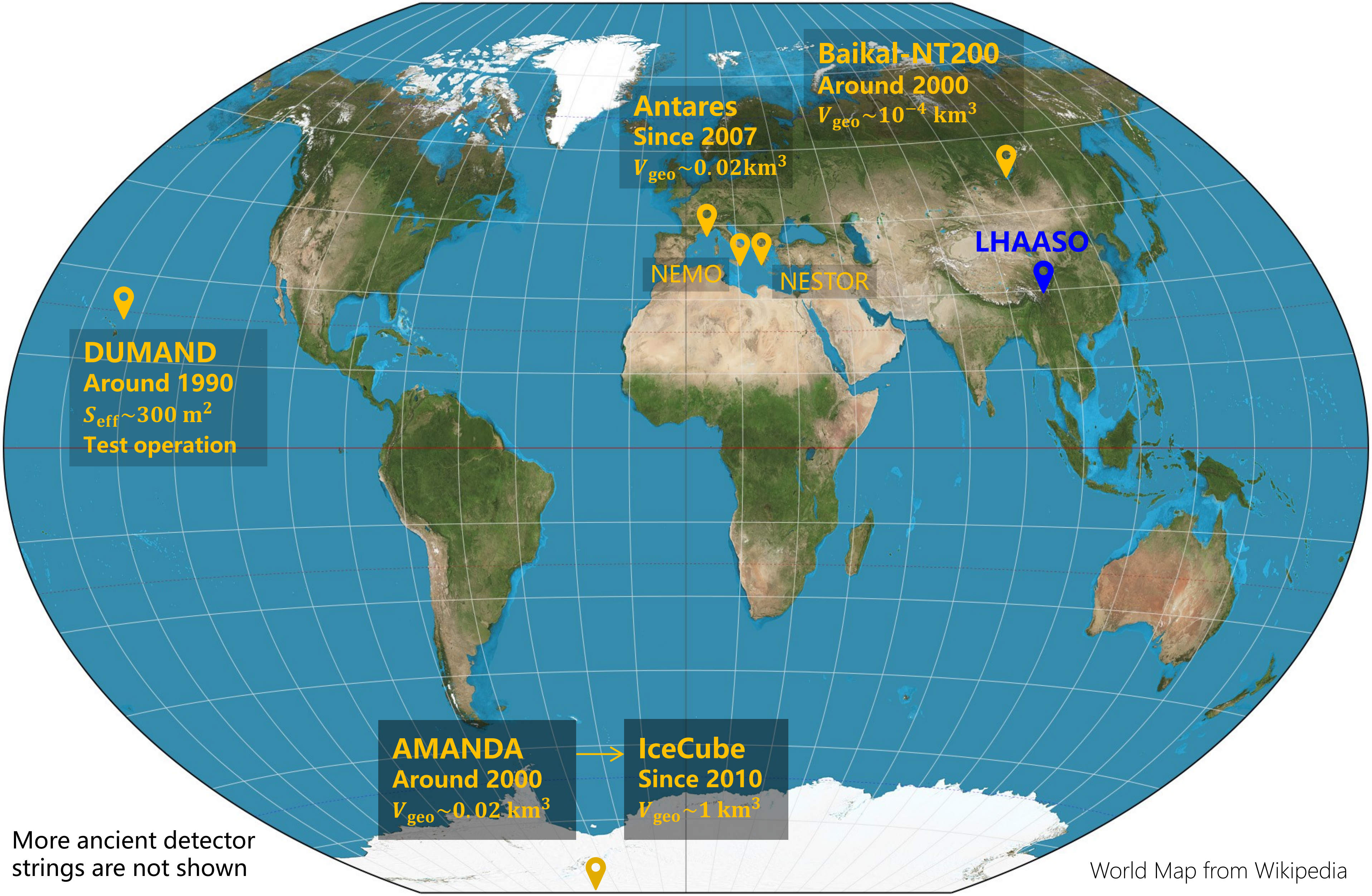




Markov, ICHEP 60 (1960) 578



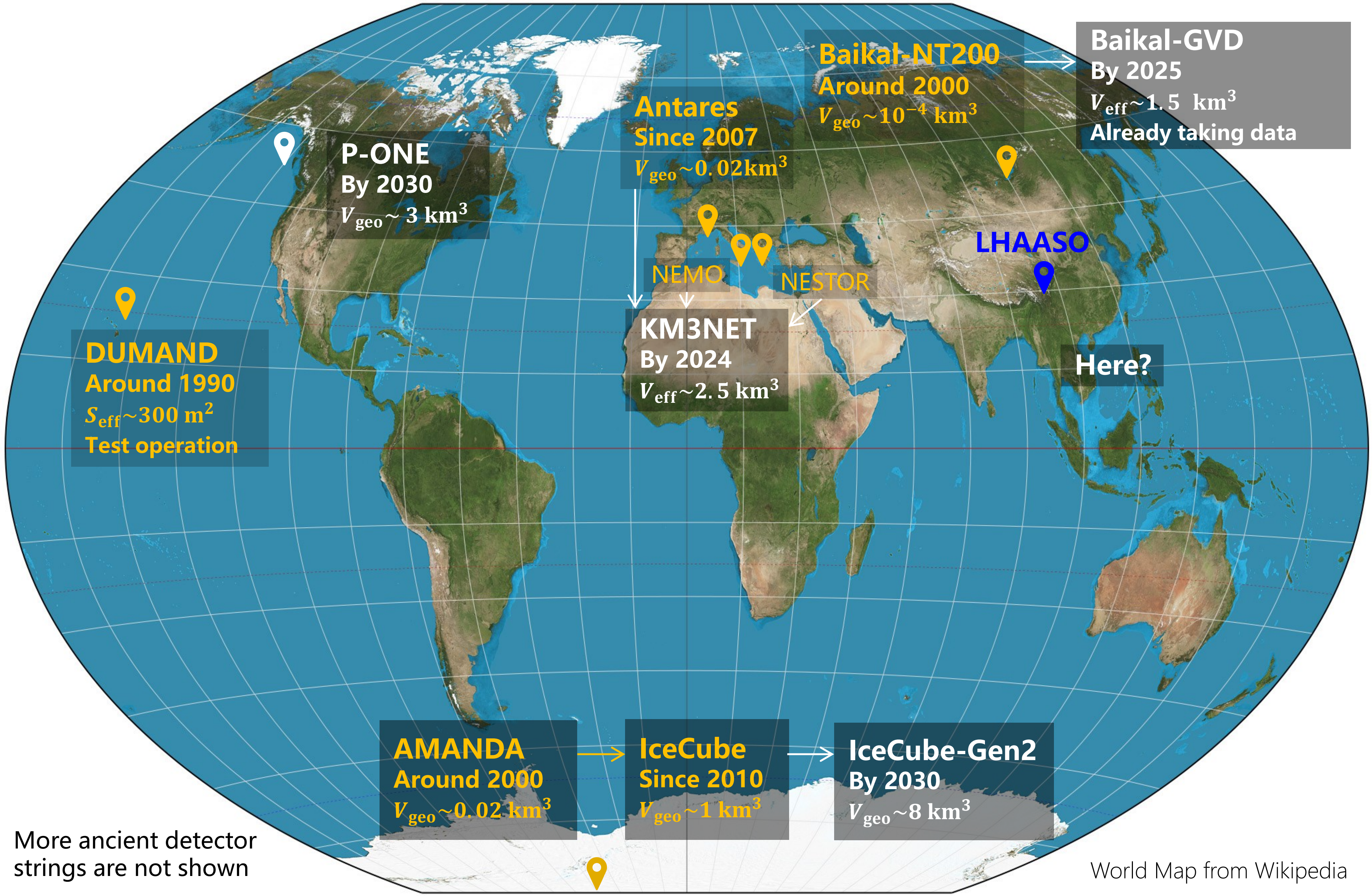
A map of water/Ice Cherenkov telescopes



More ancient detector strings are not shown

World Map from Wikipedia

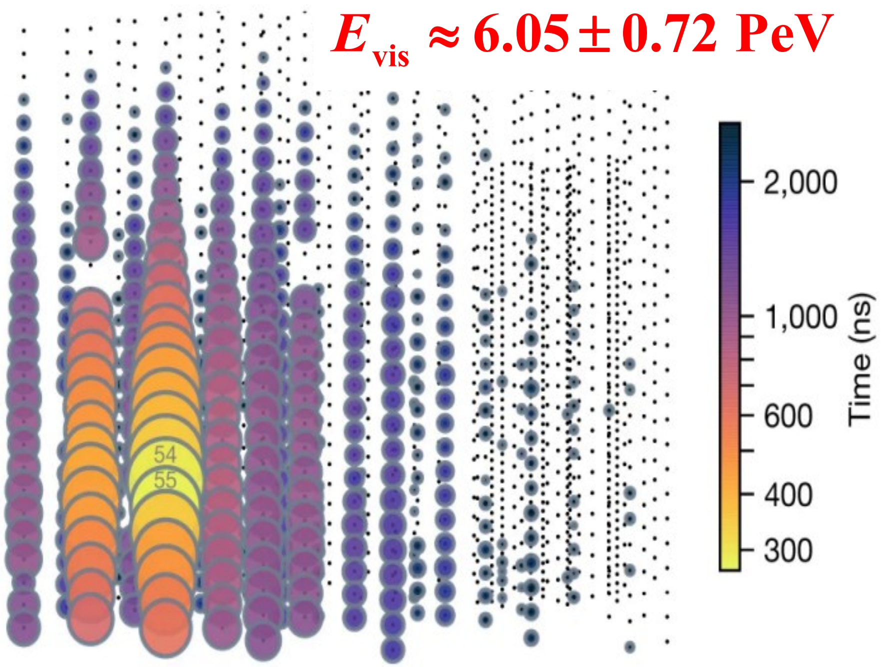
A map of water/Ice Cherenkov telescopes



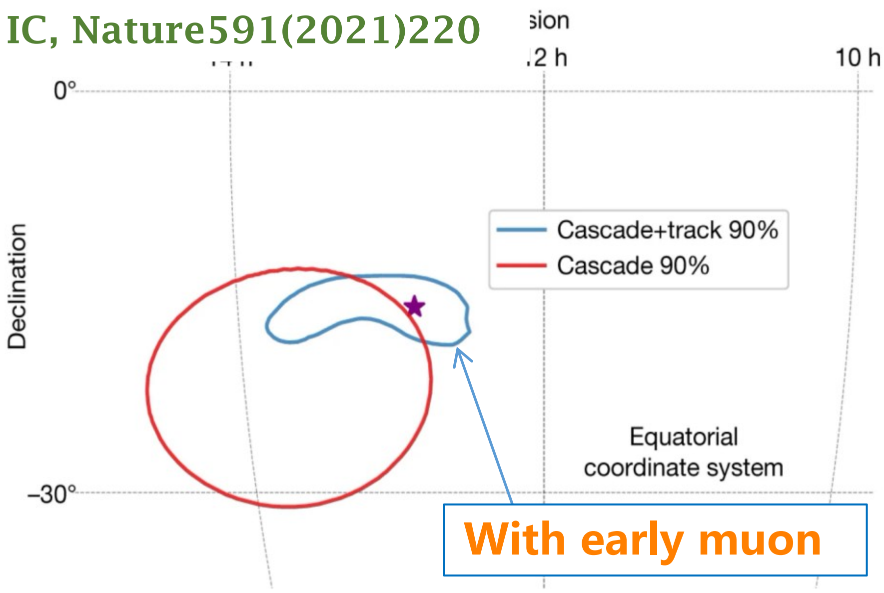
More ancient detector strings are not shown

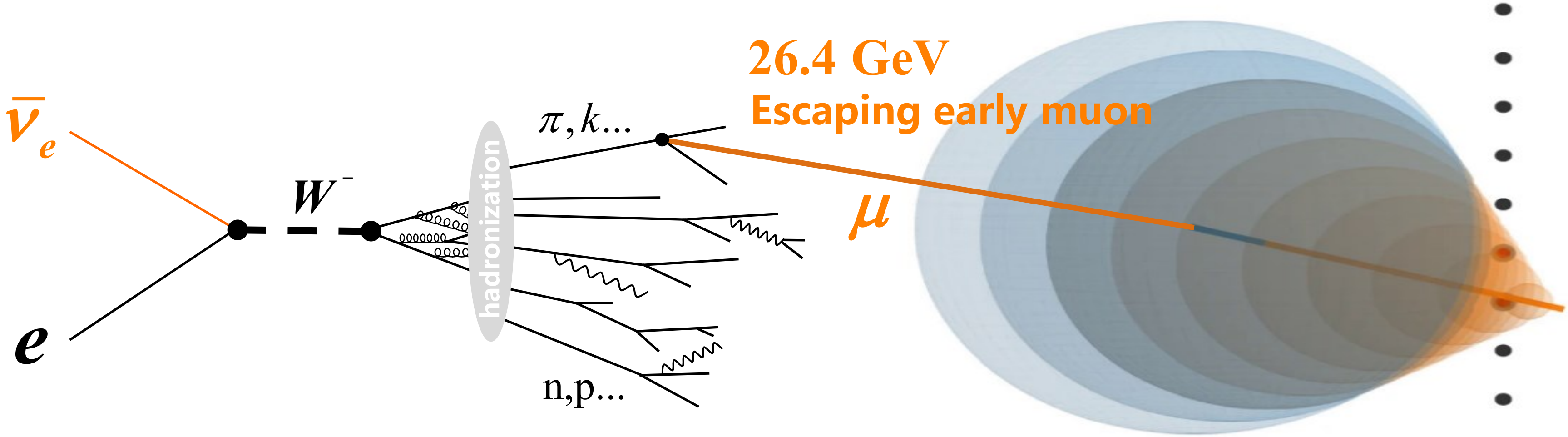
Water/Ice Cherenkov telescopes

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

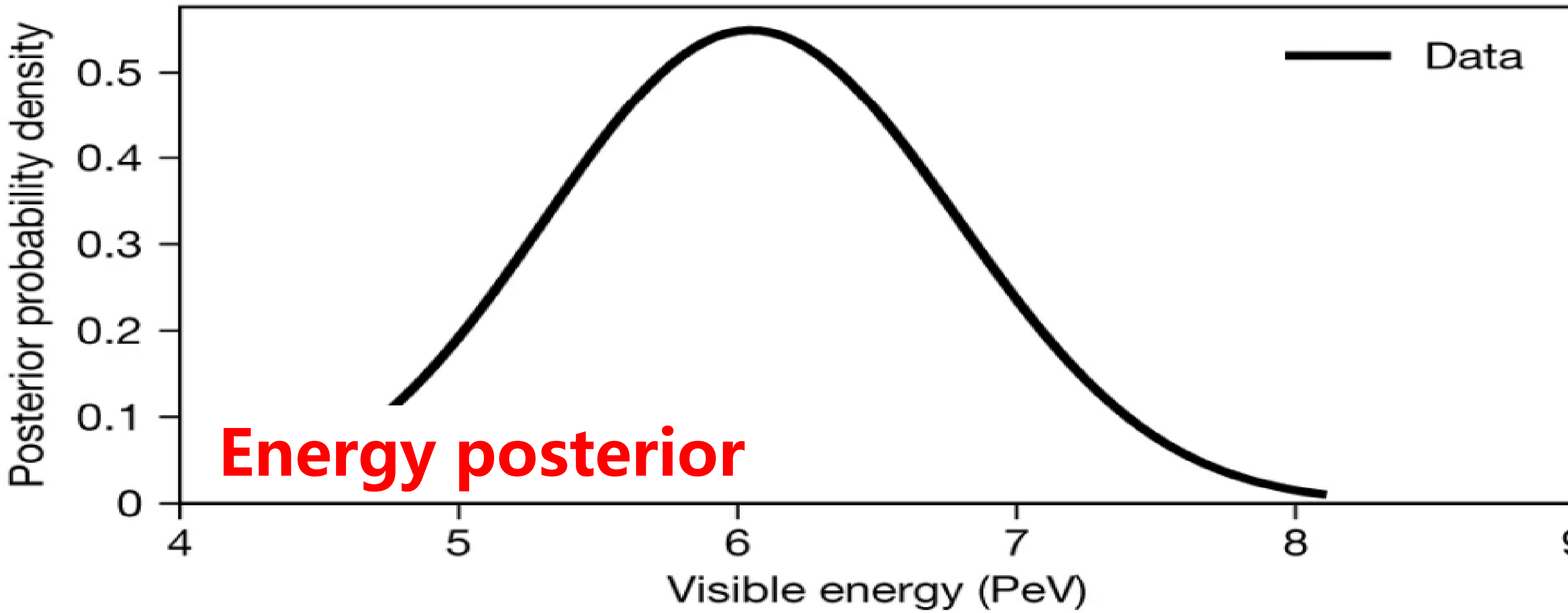


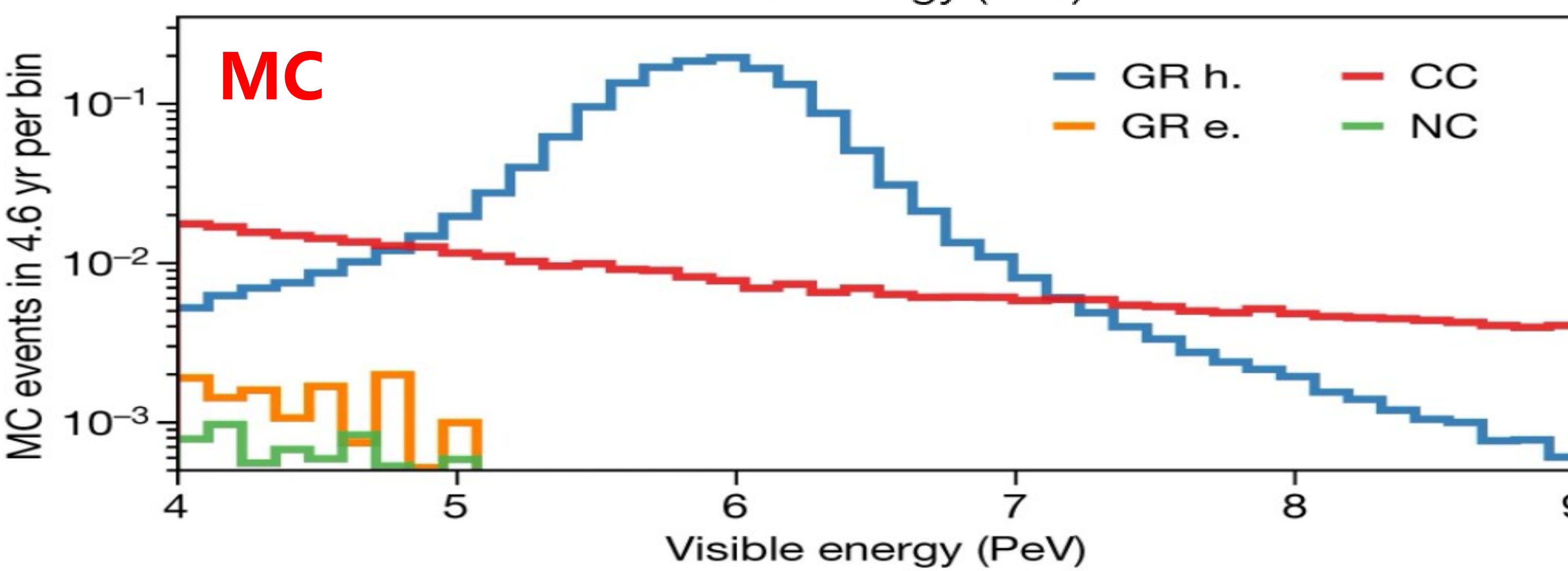
IC, Nature591(2021)220



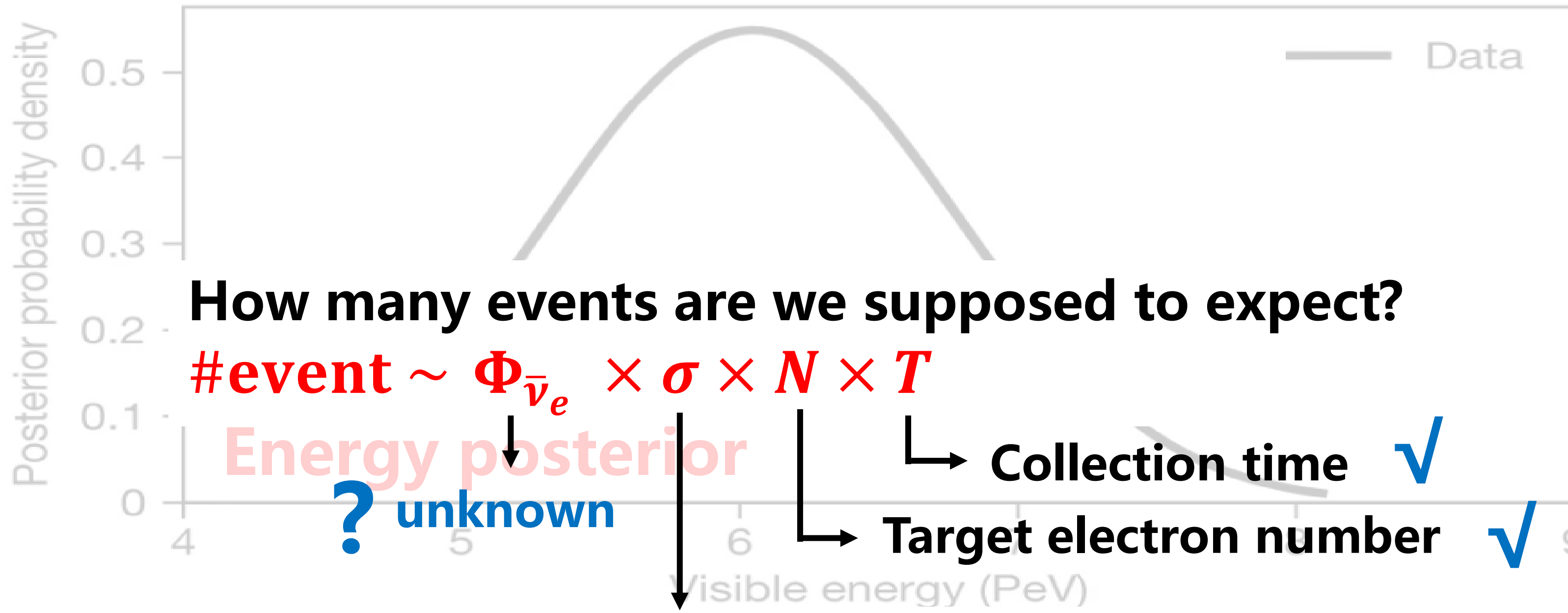


Water/Ice Cherenkov telescopes





Water/Ice Cherenkov telescopes



How many events are we supposed to expect?

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

Energy posterior

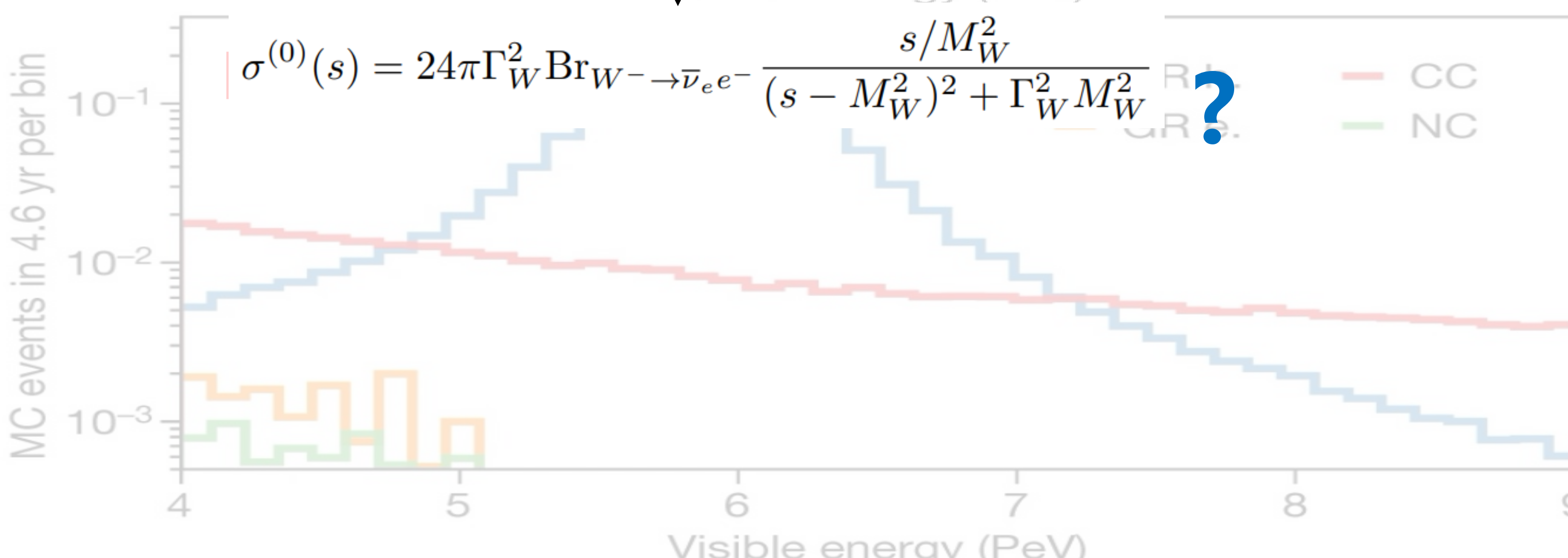
$\Phi_{\bar{\nu}_e}$ → ? unknown

T → Collection time √

N → Target electron number √

σ →

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



Effect 1: Doppler broadening

Resonant Scattering of Antineutrinos

Sheldon L. Glashow*
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mediary boson. The cross section, in this case, assumes a typical resonance form,

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

in which the incident antineutrino energy at the reso-

With $m_Z = m_N$, the energy of the incident antineutrino energy at the resonance is 9×10^{11} ev and the width of the resonance is 2×10^6 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 βc 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-

High Energy Physics - Phenomenology

[Submitted on 16 Jul 2014]

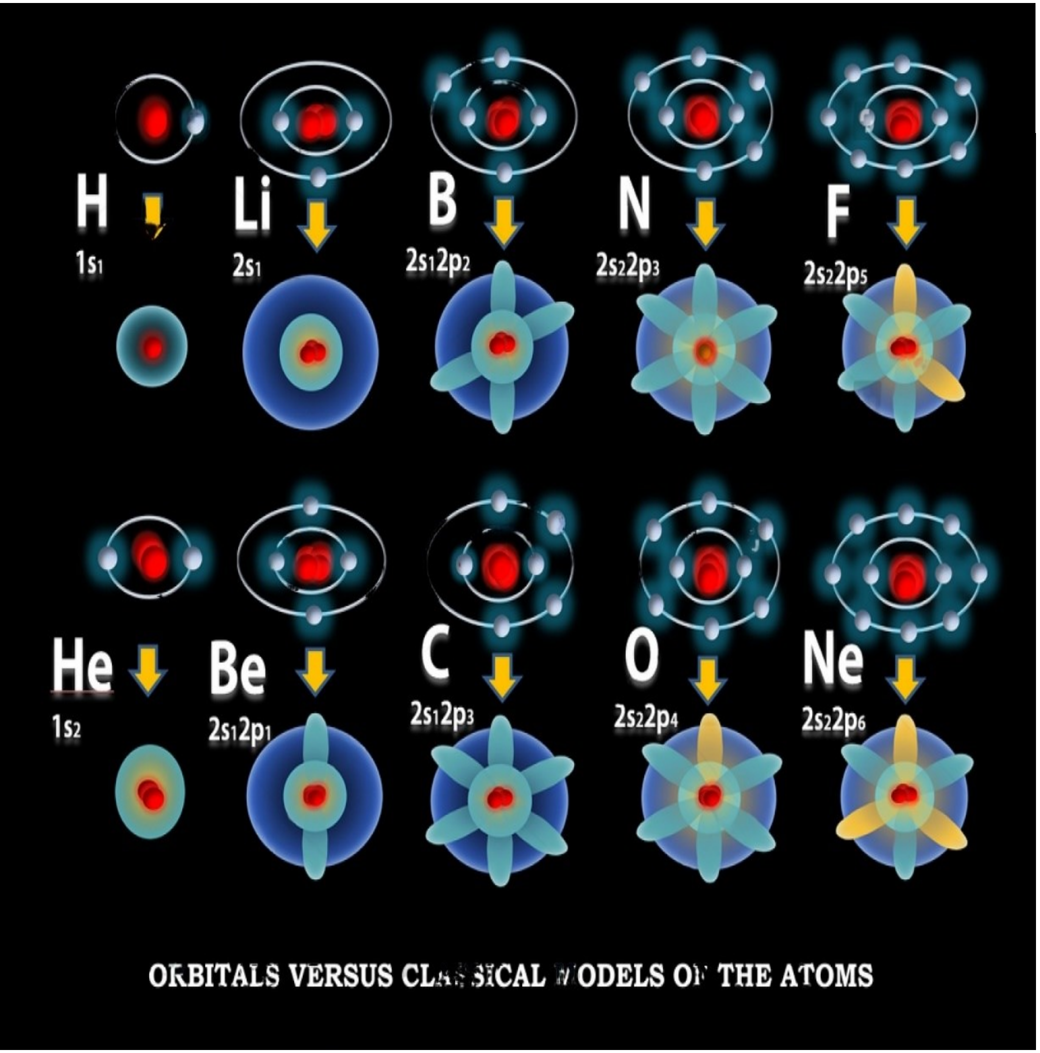
The Effect of Doppler Broadening on the $6.3\ PeV\ W^-$ Resonance in $\bar{\nu}_e e^-$ Collisions

Amit Loewy, Shmuel Nussinov, Sheldon L. Glashow

We calculate the Doppler broadening of the W^- resonance produced in $\bar{\nu}_e e^-$ collisions of cosmic anti-neutrinos with $E_\nu \approx 6.3\ PeV$ with electrons in atoms up to Iron. Revisiting this issue is prompted by recent observations of PeV neutrinos by Ice-Cube. Despite its poor energy resolution, the 20% Doppler broadening of the resonance due to electronic motions can produce observable effects via non-linear neutrino absorption near the resonance. The attendant suppression of the peak cross section allows $\bar{\nu}_e$ to travel correspondingly longer distances. While this effect is unlikely to be directly detected in the near future, it may facilitate terrestrial tomography at depths of $\sim 10\ km$, complementing deeper explorations using the more frequent nuclear interactions at lower energies.

Subjects: **High Energy Physics - Phenomenology (hep-ph)**; High Energy Astrophysical Phenomena (astro-ph.HE)
Cite as: arXiv:1407.4415 **[hep-ph]**
(or arXiv:1407.4415v1 **[hep-ph]** for this version)
https://doi.org/10.48550/arXiv.1407.4415

Effect 1: Doppler broadening



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

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

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

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

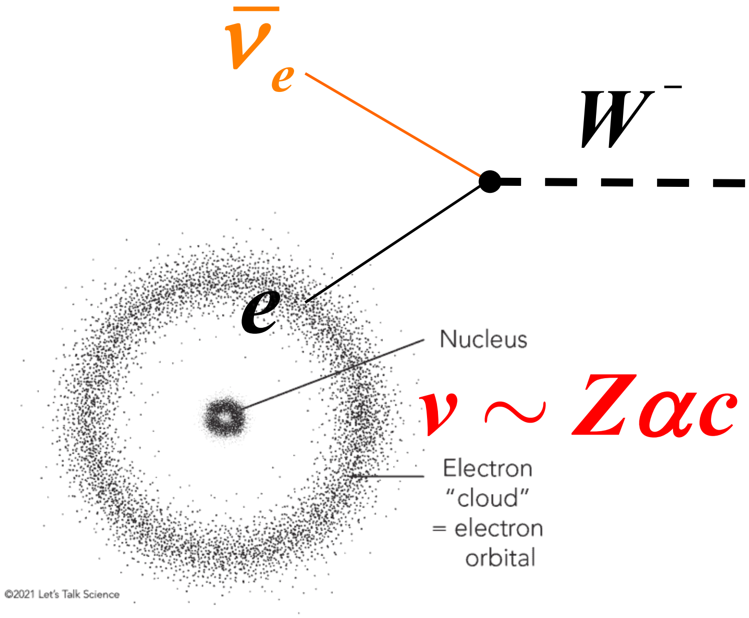
$$f_{3s}(k) = \frac{1024}{5\pi} \frac{\mu_{3s}^7 (\mu_{3s}^3 k - \mu_{3s} k^3)^2}{(\mu_{3s}^2 + k^2)^8} \,,$$

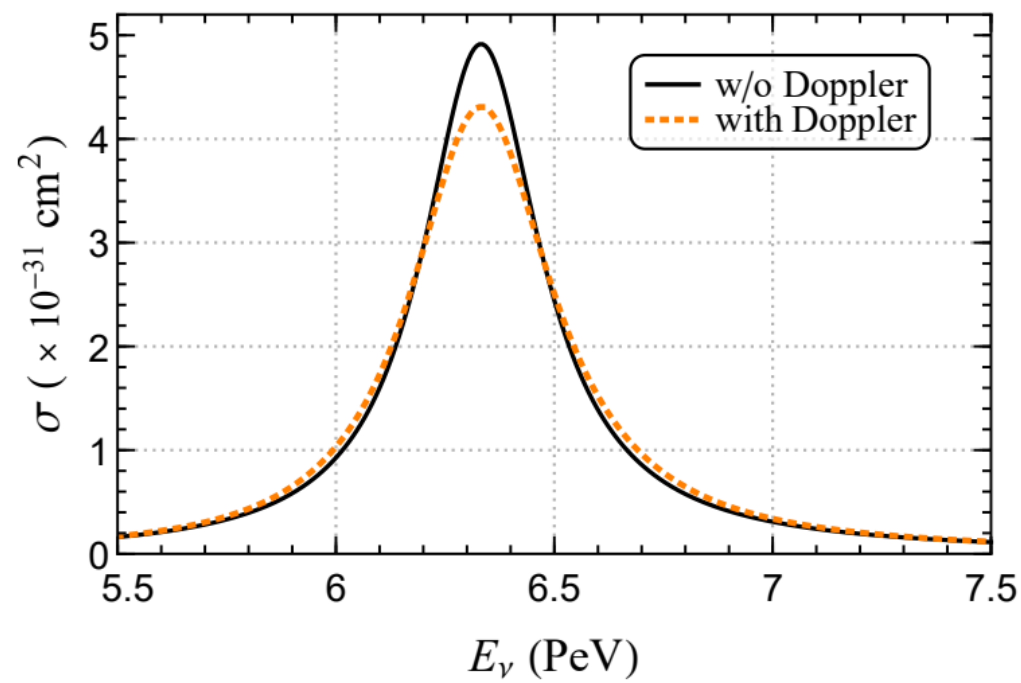
$$f_{3p}(k) = \frac{1024}{45\pi} \frac{\mu_{3p}^7 (5\mu_{3p}^2 k^2 - k^4)^2}{(\mu_{3p}^2 + k^2)^8} \,,$$

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

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

Effect 1: Doppler broadening



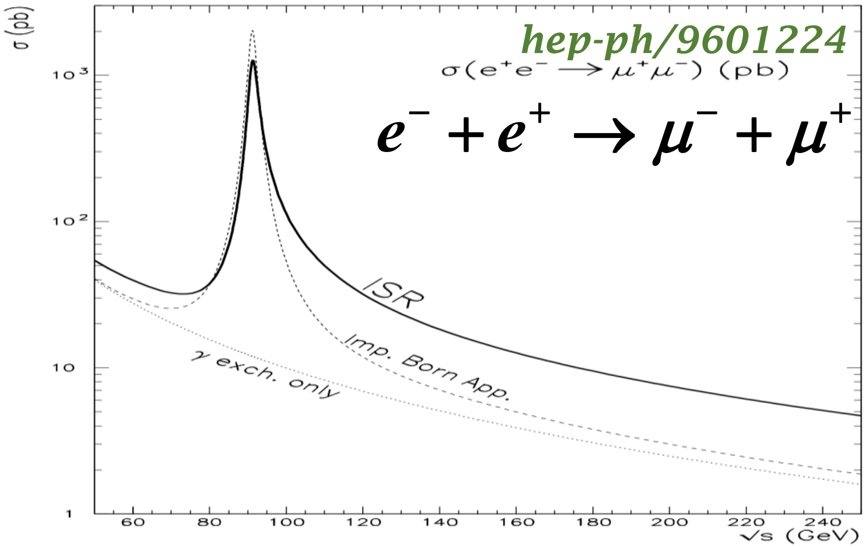


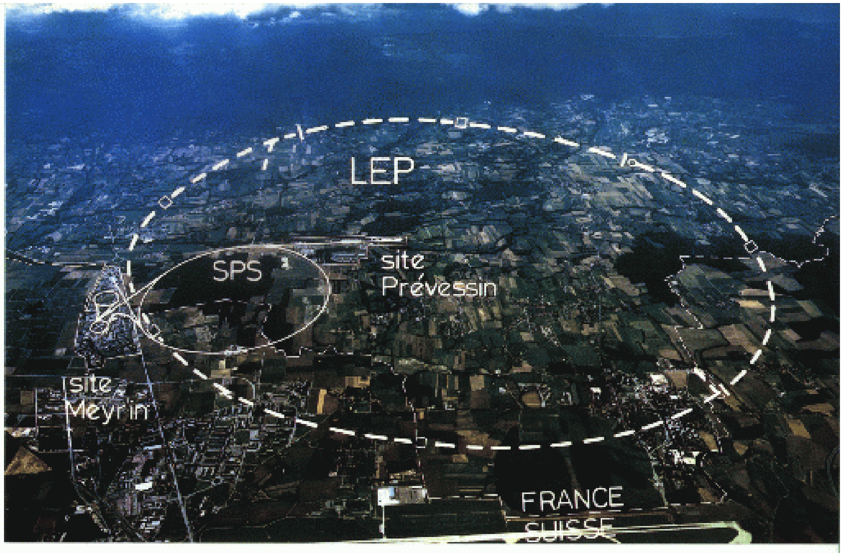
$$\sigma(E_\nu) = \frac{1}{4\pi}\int \mathrm{d}\phi \int \mathrm{d}\beta F(\beta) \int \mathrm{d}x' \sigma^{(0)}[E_\nu(1-\beta x')]$$

$$\sigma(E_\nu) = \frac{6\pi\Gamma_W^2 \mathrm{Br}_{W^-\to\bar{\nu}_e e^-}}{M_W m_e E_\nu} \int d\beta \frac{F(\beta)}{\beta} \left\{ \frac{1}{2M_W}\left[\ln(y_h^2+1) - \ln(y_l^2+1)\right] + \frac{1}{\Gamma_W}\left[\arctan(y_h) - \arctan(y_l)\right] \right\}$$

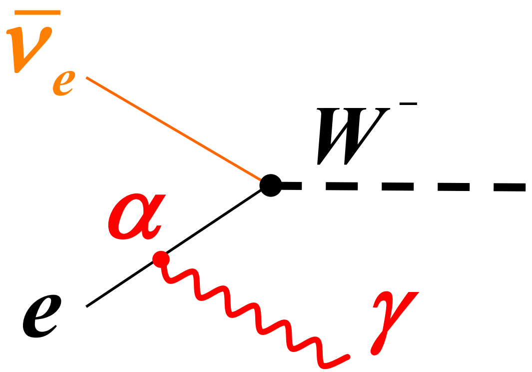
$$y_h = \frac{2m_e E_\nu(1+\beta) + m_e^2 - M_W^2}{\Gamma_W M_W} \quad \text{and} \quad y_l = \frac{2m_e E_\nu(1-\beta) + m_e^2 - M_W^2}{\Gamma_W M_W}$$

Effect 2: Initial state radiation



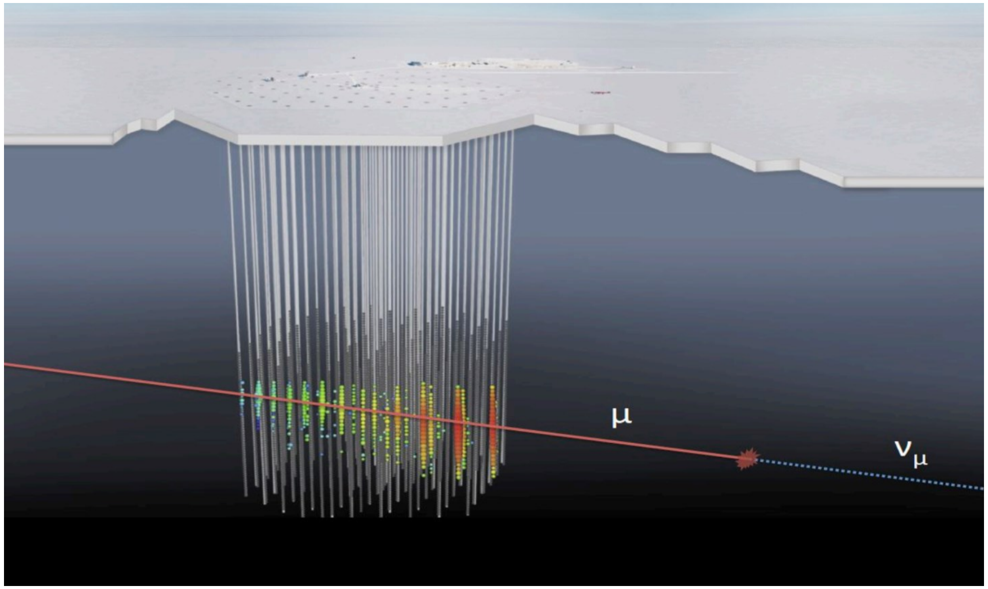


Why initial state radiation could also be important for neutrino telescopes?



Collinear enhancement

$\propto \log(M_W / m_e) \approx 12$



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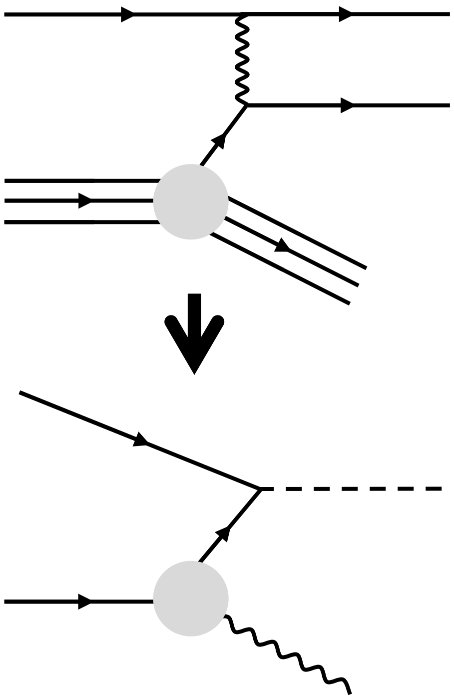
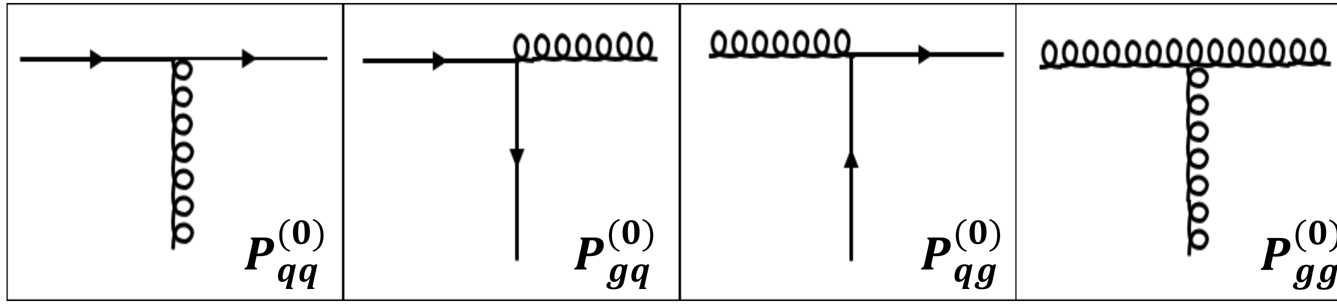
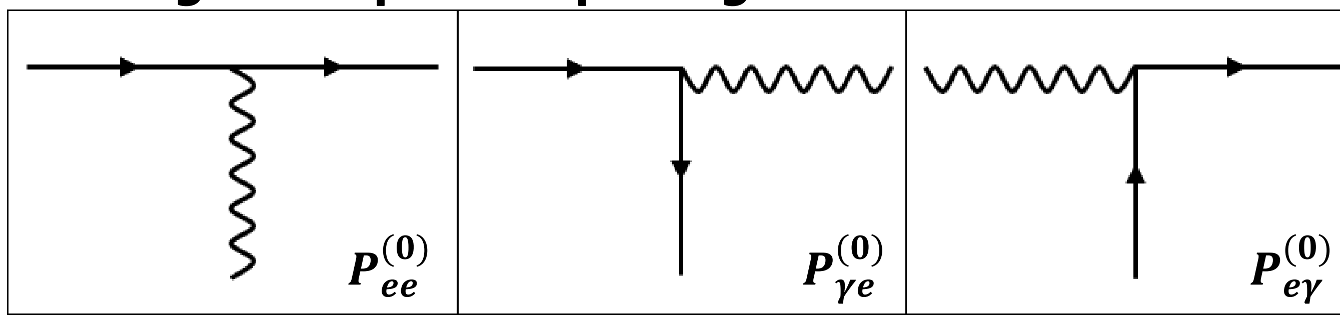
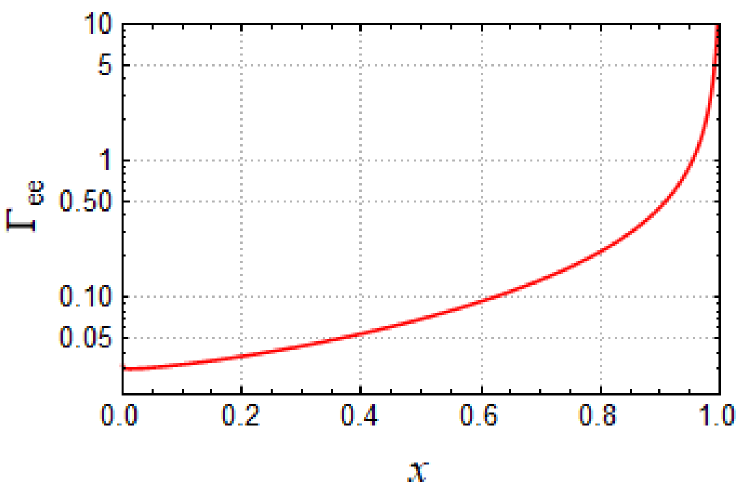




Leading-order parton splitting functions

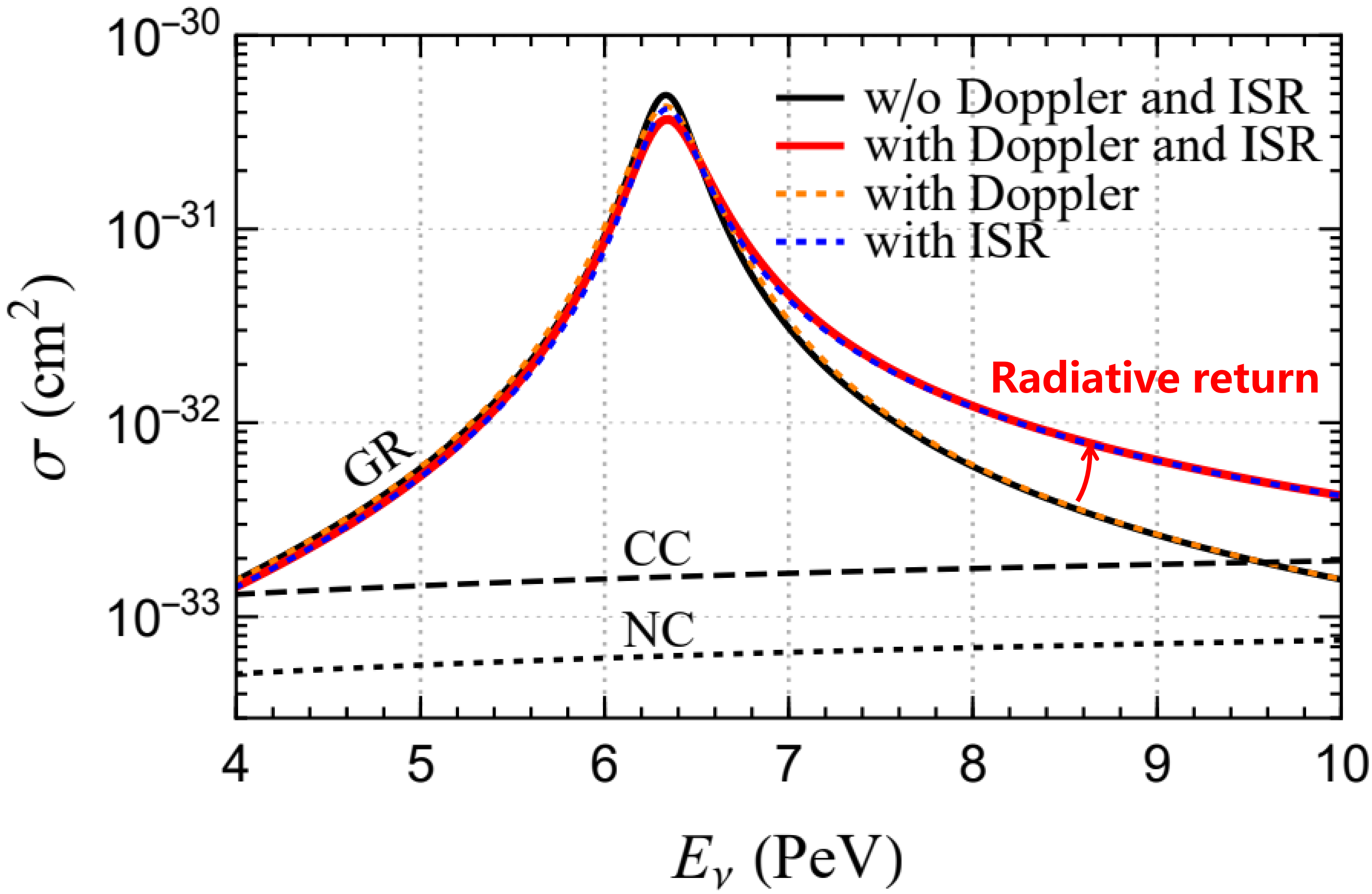




$$\sigma(E_\nu) = \int \mathrm{d}x\, \Gamma_{e/e}(x, Q^2)\sigma^{(0)}(x, Q^2, E_\nu)$$

Structure function **Xsec without ISR**

Cross section



Cross section

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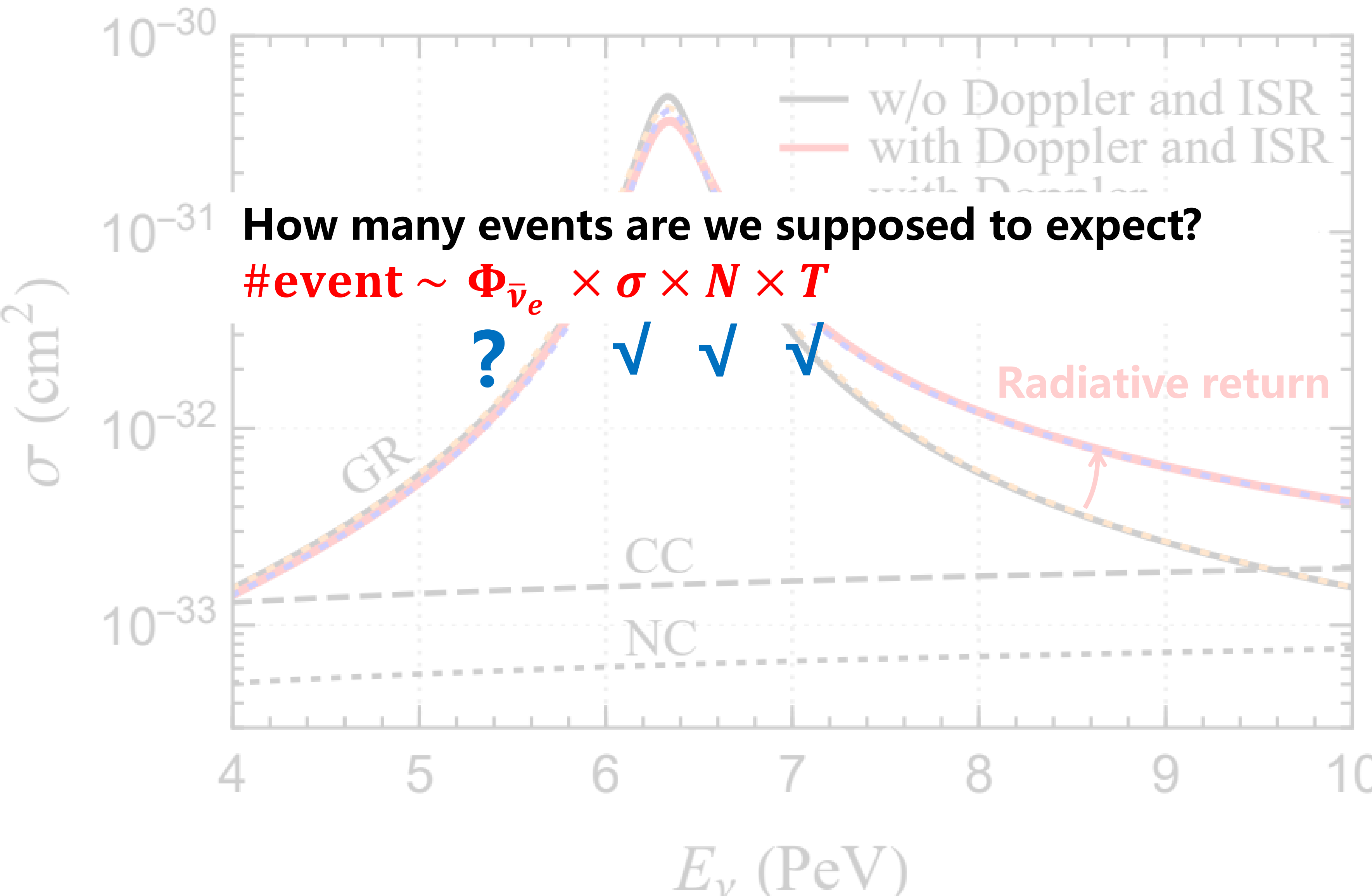
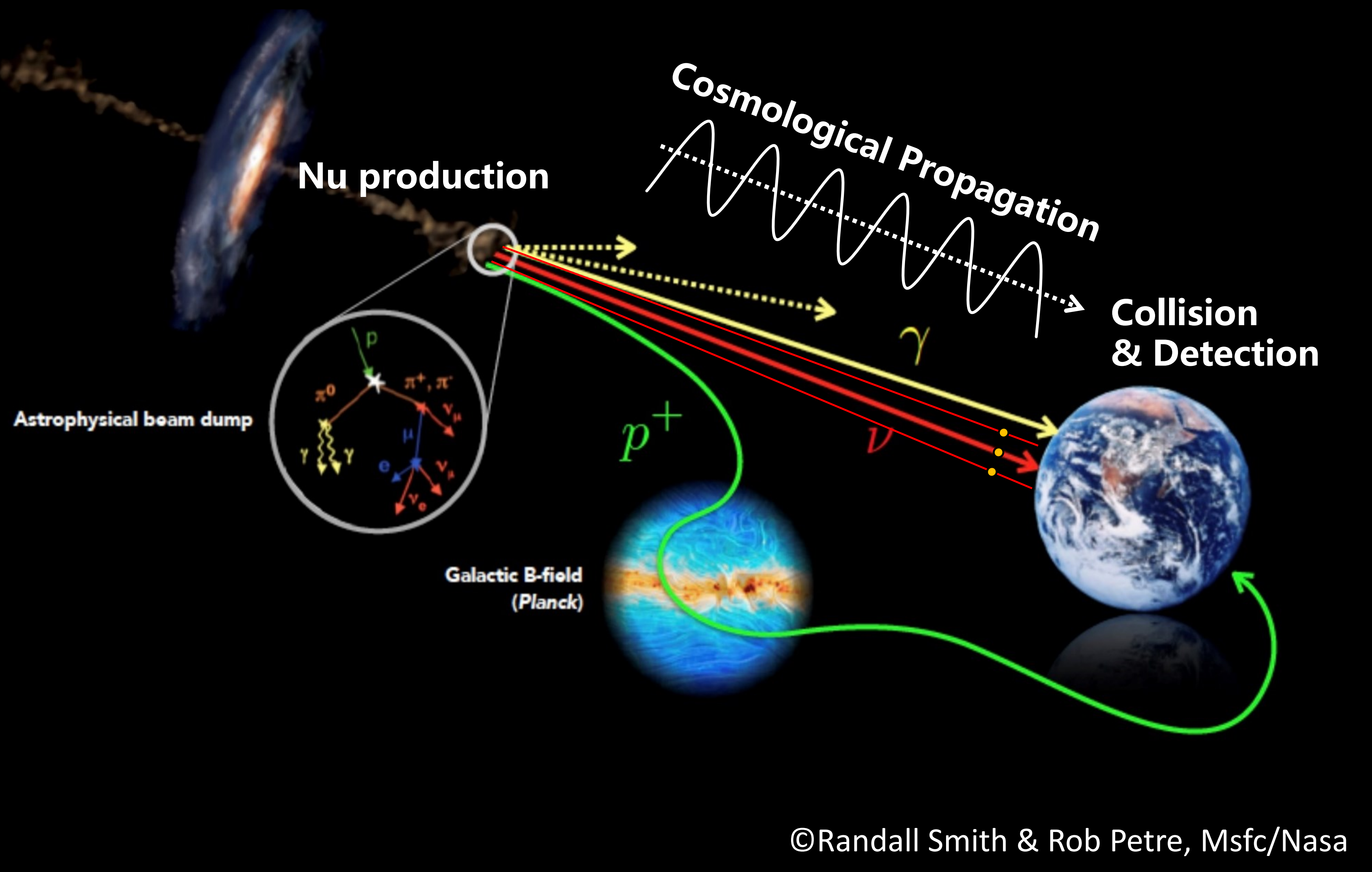
$\#\text{event} \sim \Phi_{\bar{\nu}_e} \times \sigma \times N \times T$

? √ √ √

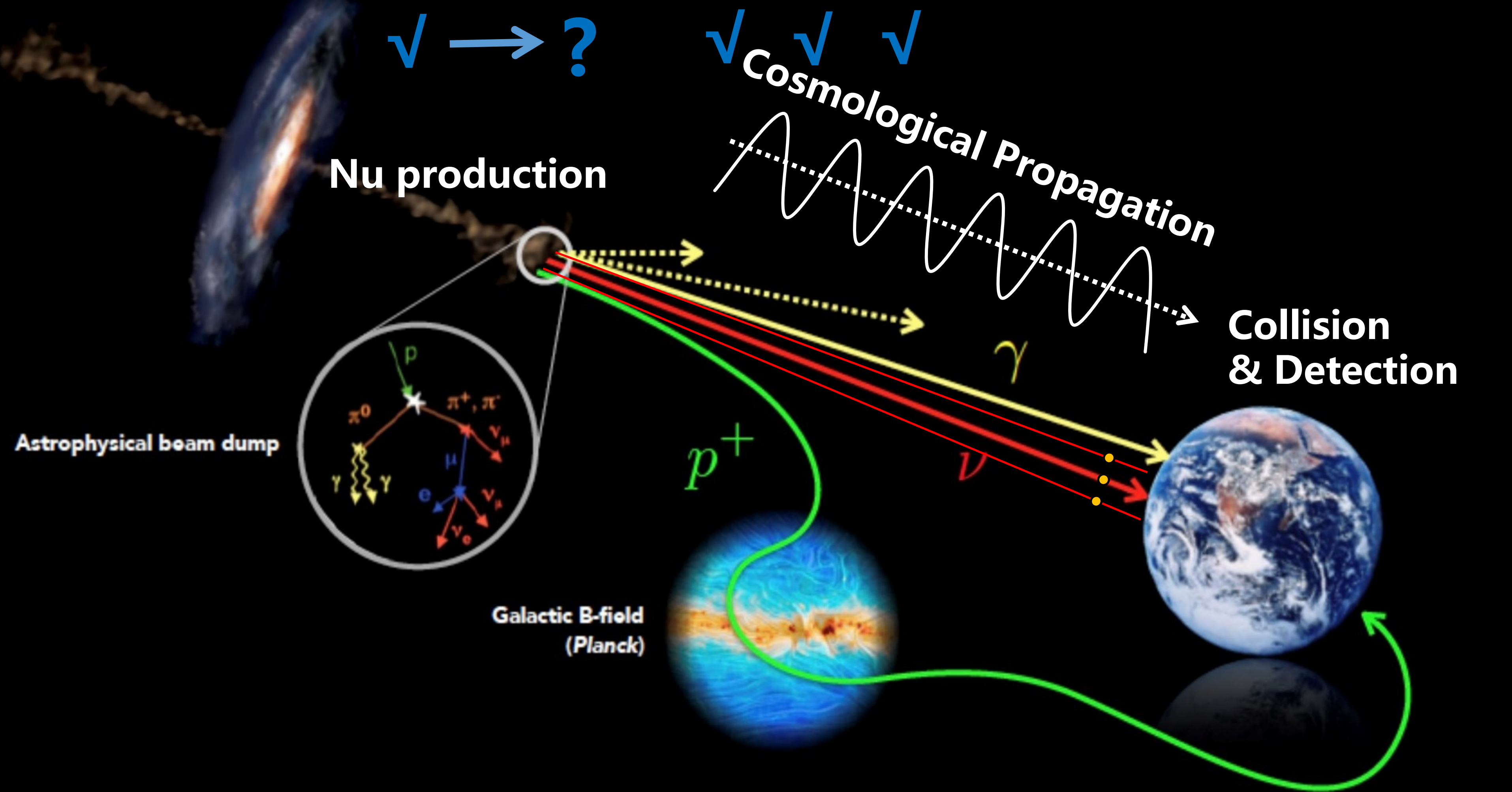




Nu production
Cosmological Propagation
Collision & Detection
Astrophysical beam dump
p
π^0
π^+, π^-
γ
γ
ν_μ
μ
e
ν_μ
ν_e
γ
ν
p^+
Galactic B-field
(Planck)
©Randall Smith & Rob Petre, Msfc/Nasa

How many events are we supposed to expect?

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



Continuous efforts in this direction

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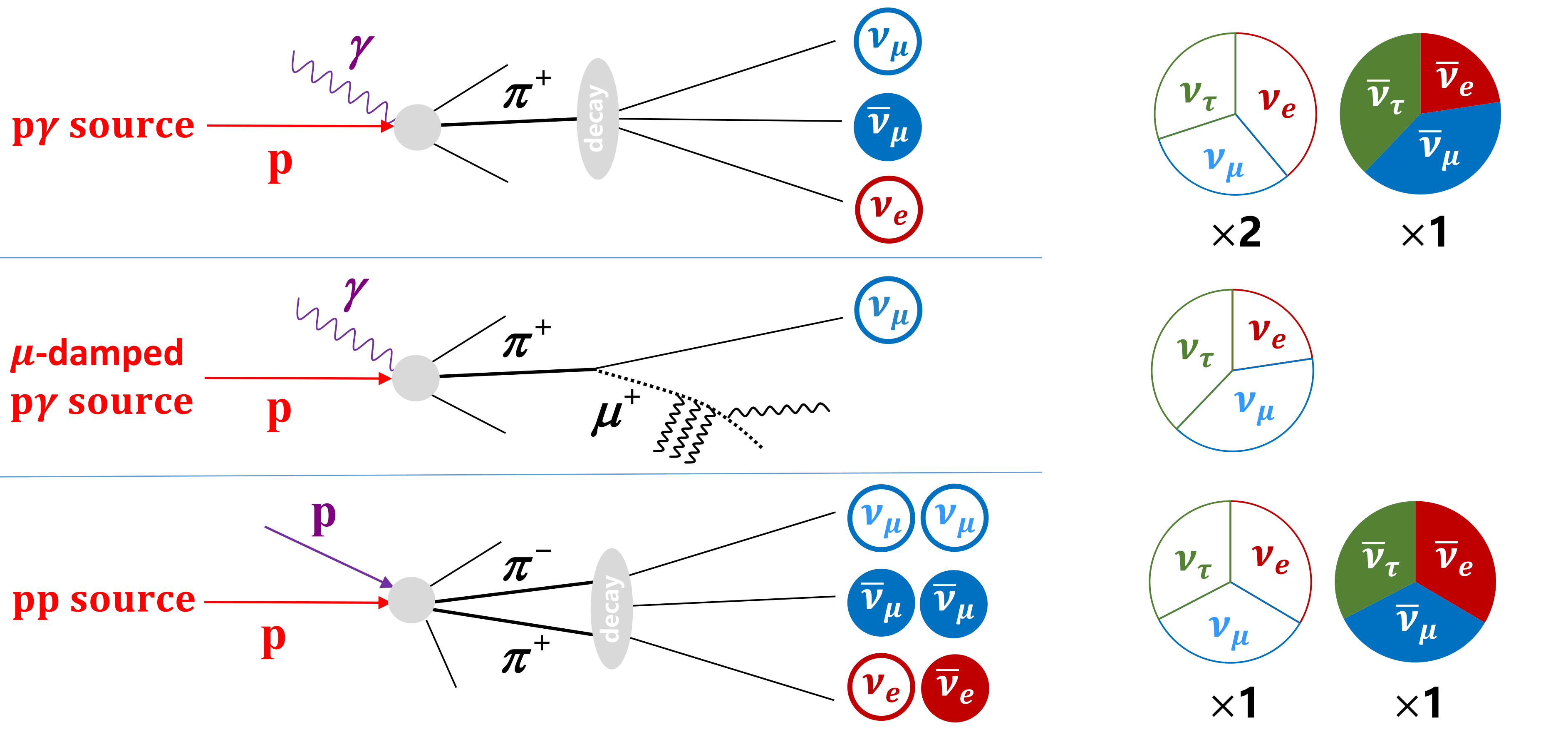
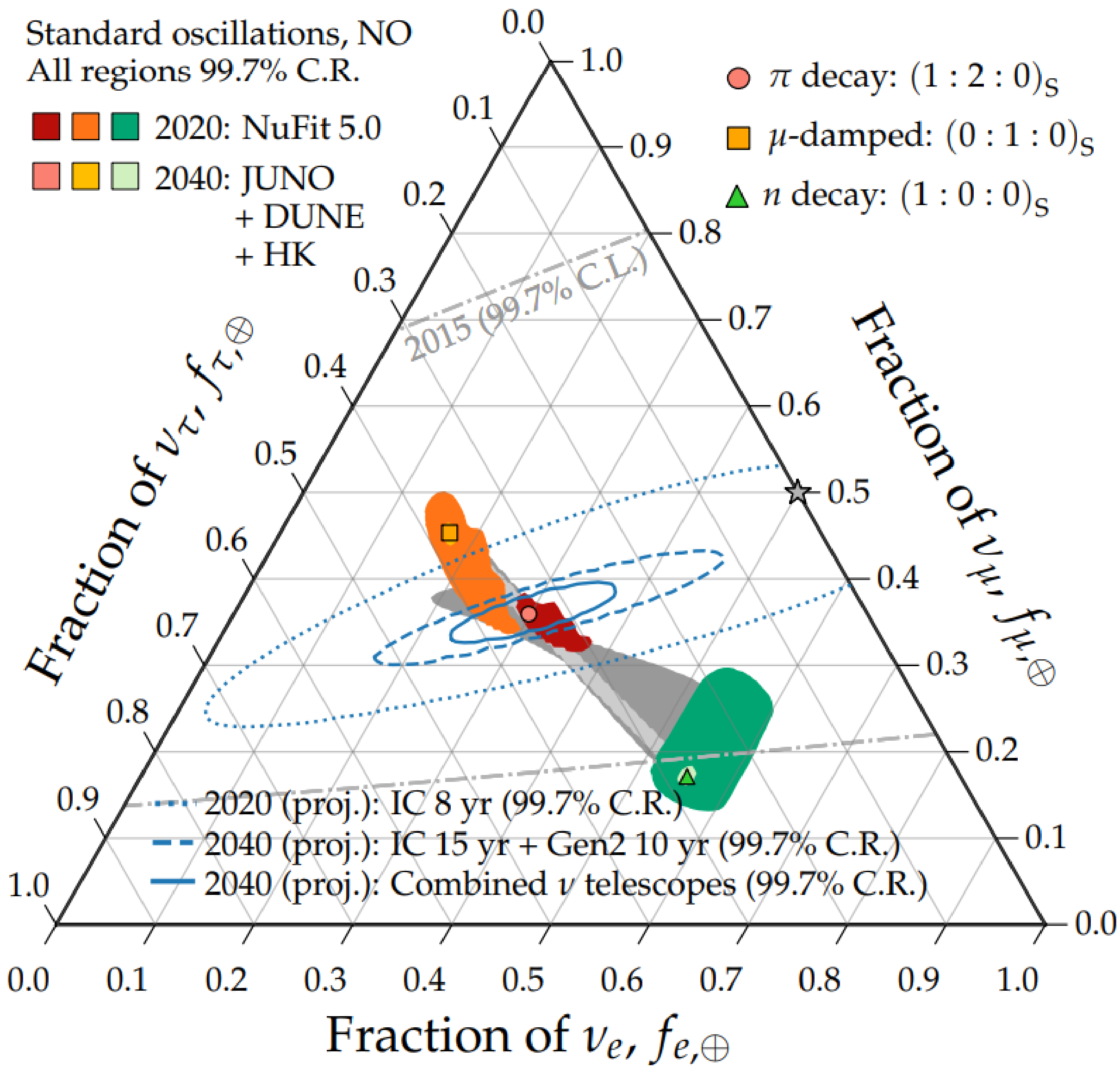
Flavor composition of UHE Neutrinos

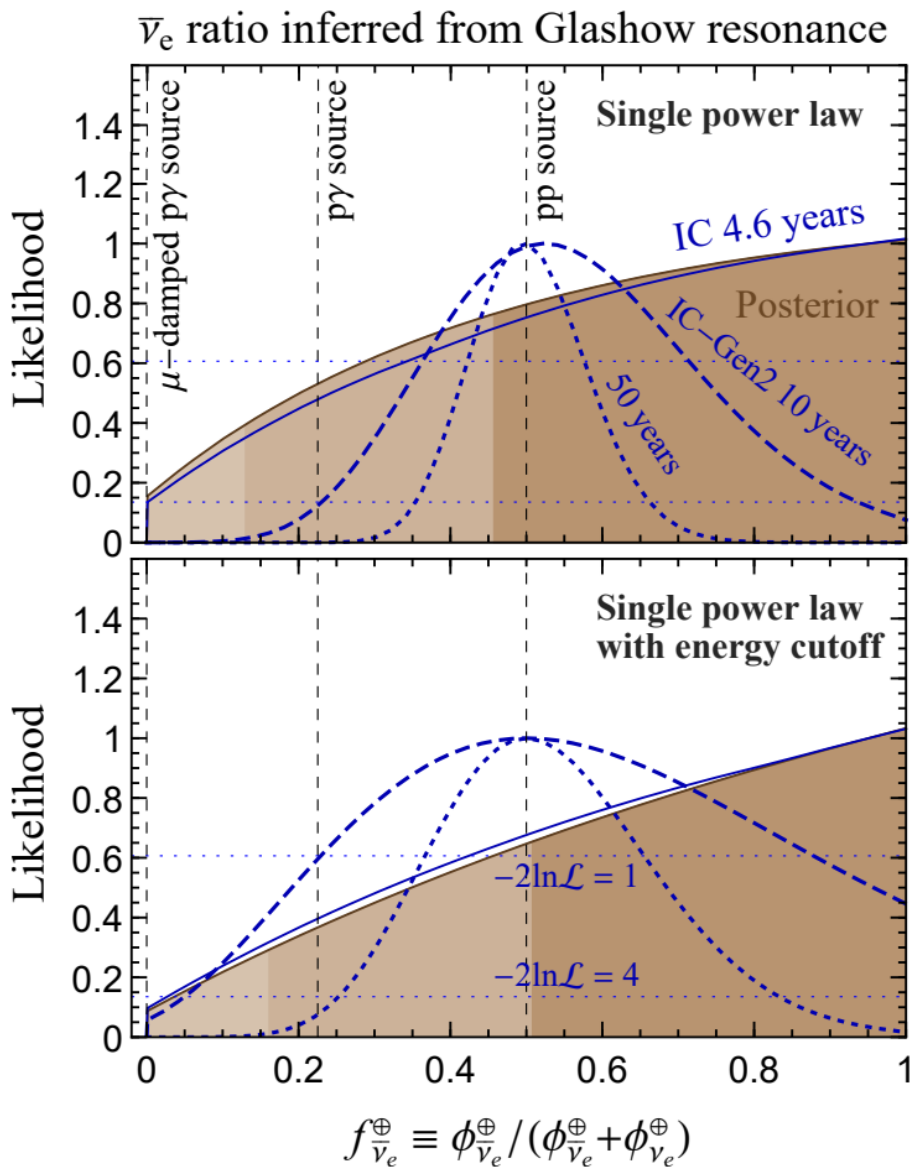
Production	Source flavor ratio	Earth flavor ratio $\nu + \bar{\nu}$	Earth flavor ratio
pp	$\{1,1\} : \{2,2\} : \{0,0\}$	$0.33 : 0.34 : 0.33$	$\{0.17, 0.17\} : \{0.17, 0.17\} : \{0.16, 0.16\}$
$pp\ \mu$ damped	$\{0,0\} : \{1,1\} : \{0,0\}$	$0.23 : 0.39 : 0.38$	$\{0.11, 0.11\} : \{0.20, 0.20\} : \{0.19,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

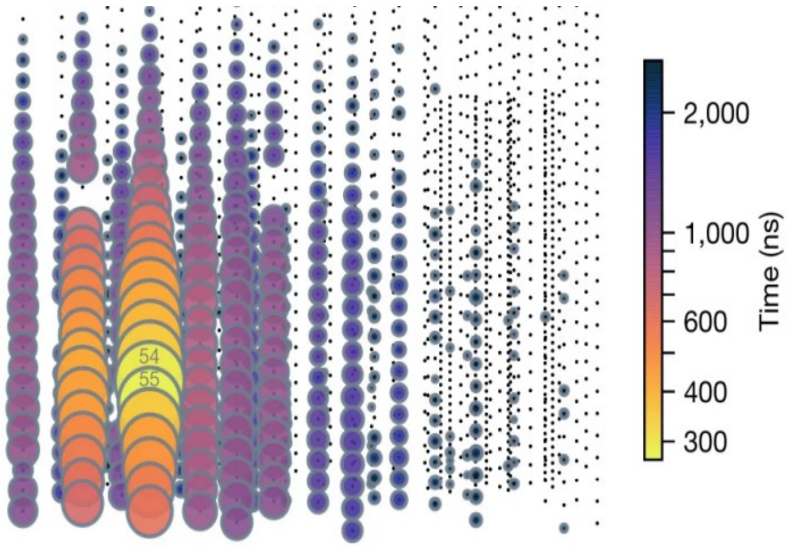


Flavor composition of UHE Neutrinos



Inference of the fraction





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

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

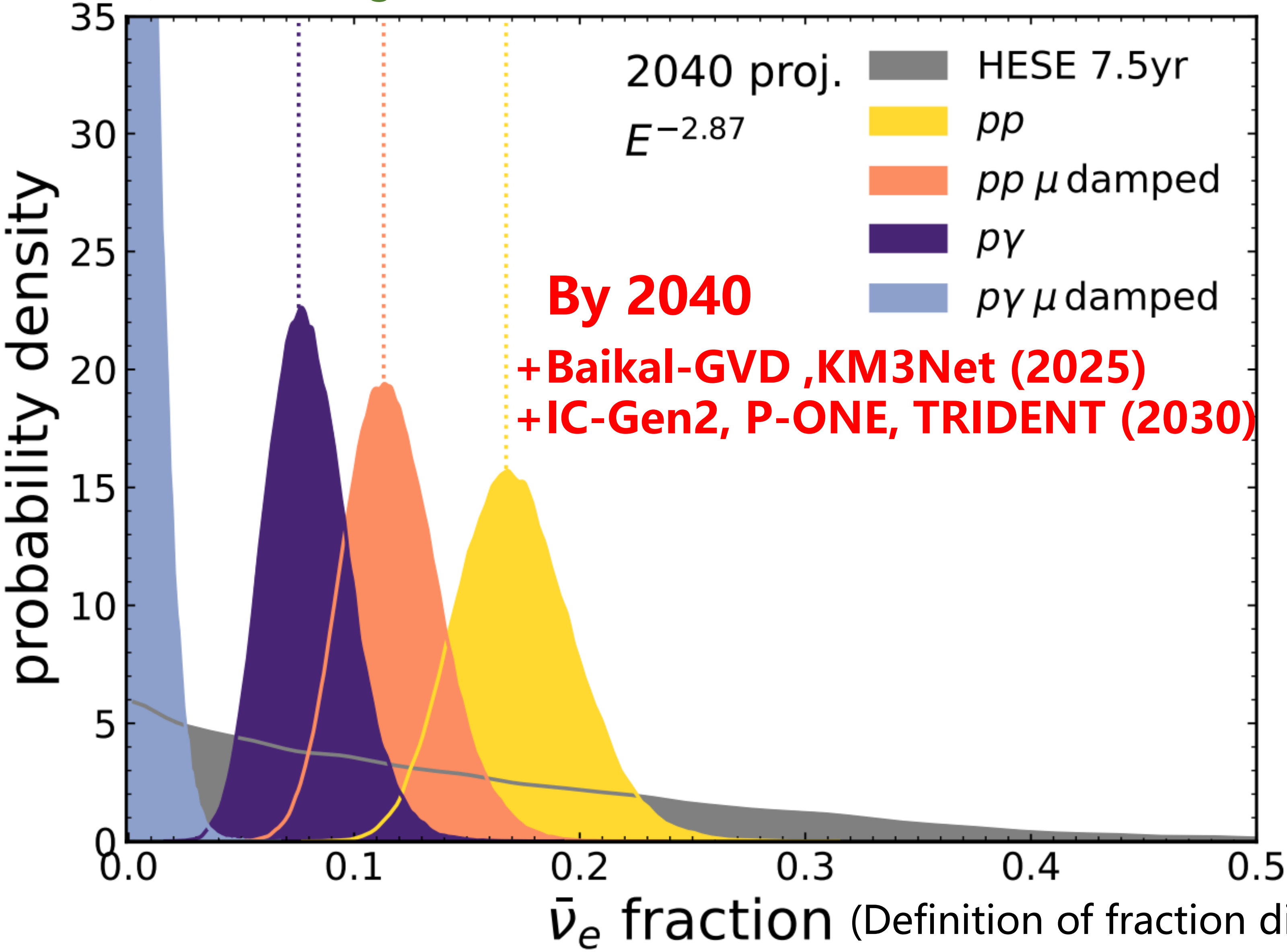
$$\mu_{\rm DIS} = \int_{\rm cut} {\rm d}E_{\rm dep}\cdot\left(\frac{{\rm d}N^{\rm CC}_{\nu_e+\overline{\nu}_e}}{{\rm d}E_{\rm dep}} + \sum_{\alpha}\frac{{\rm d}N^{\rm NC}_{\nu_\alpha+\overline{\nu}_\alpha}}{{\rm d}E_{\rm dep}}\right)$$

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

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

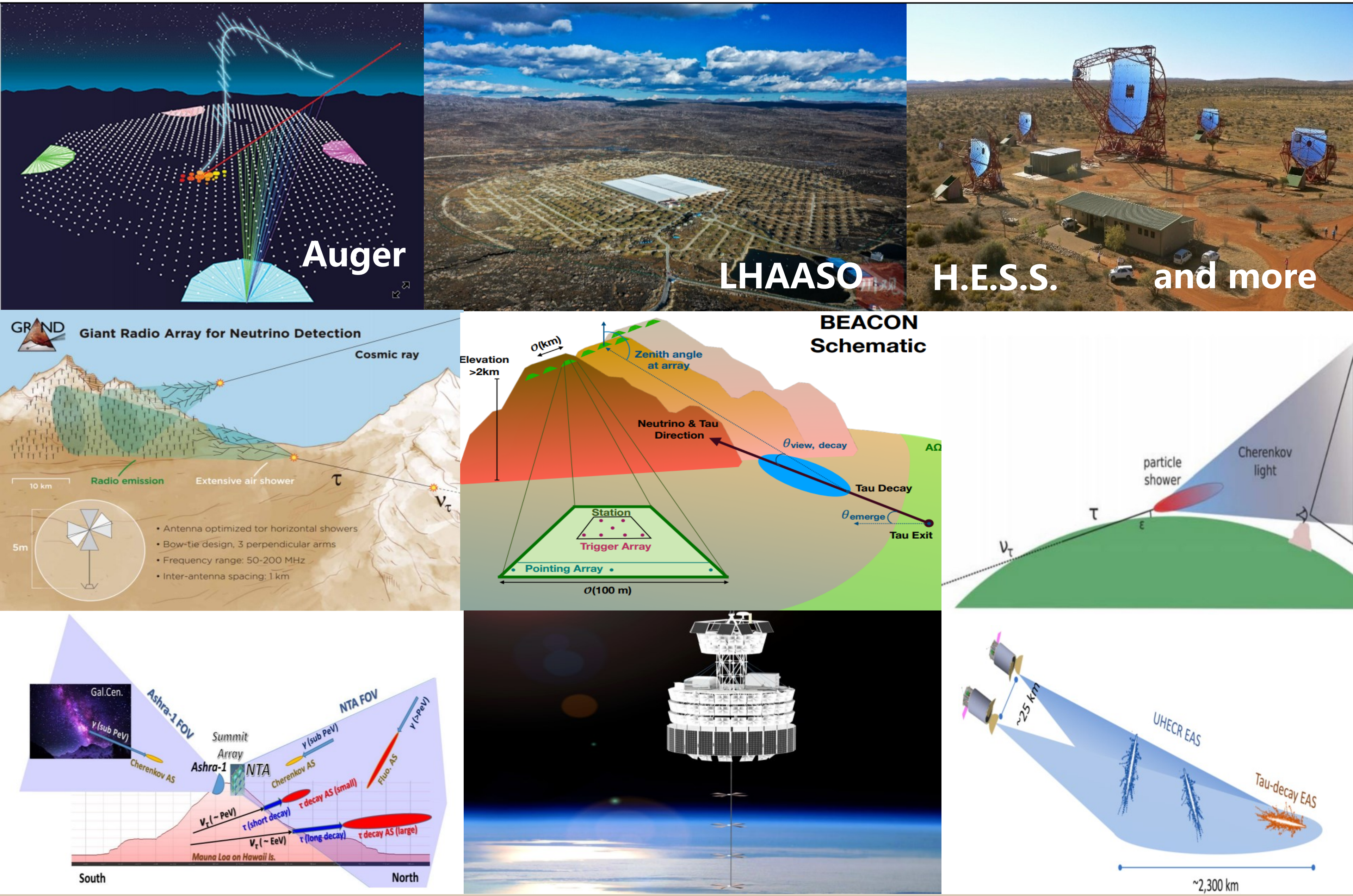
Projection of future Cherenkov telescopes

Q. Liu, N. Song, A. Vincent, arXiv:2304.06068



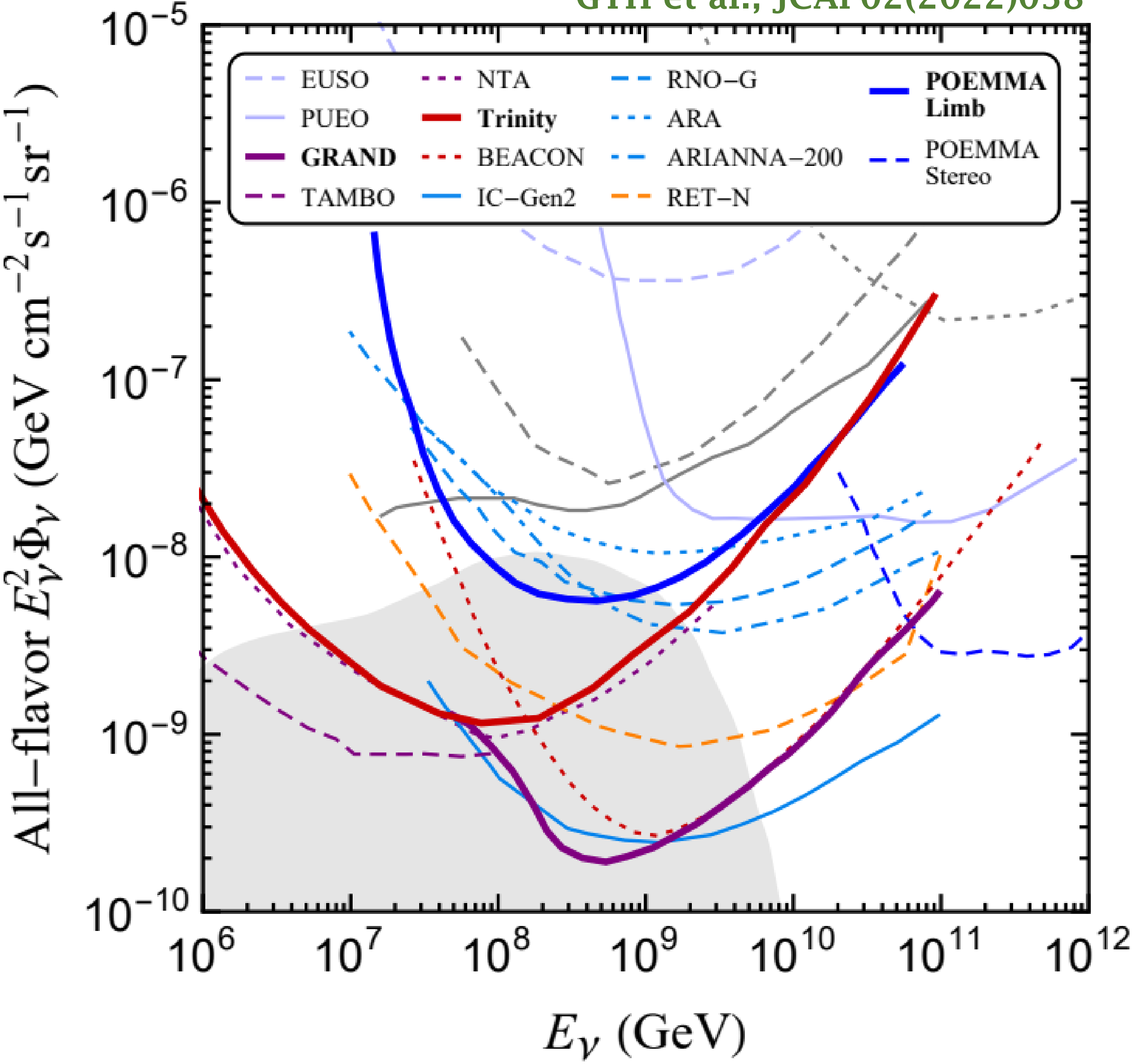
(Definition of fraction differs)

Air shower neutrino telescopes

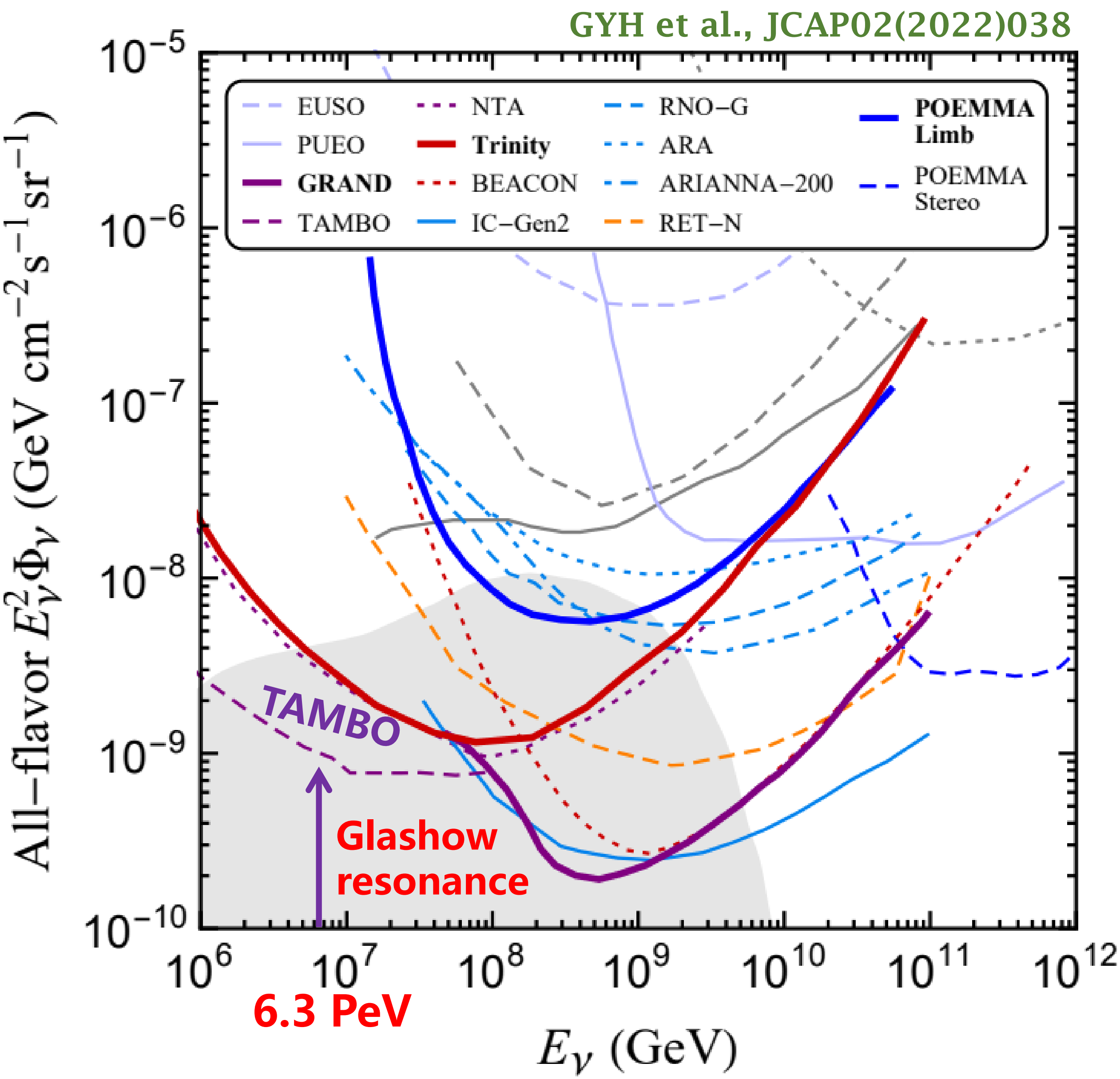


Glashow resonance potential

GYH et al., JCAP02(2022)038

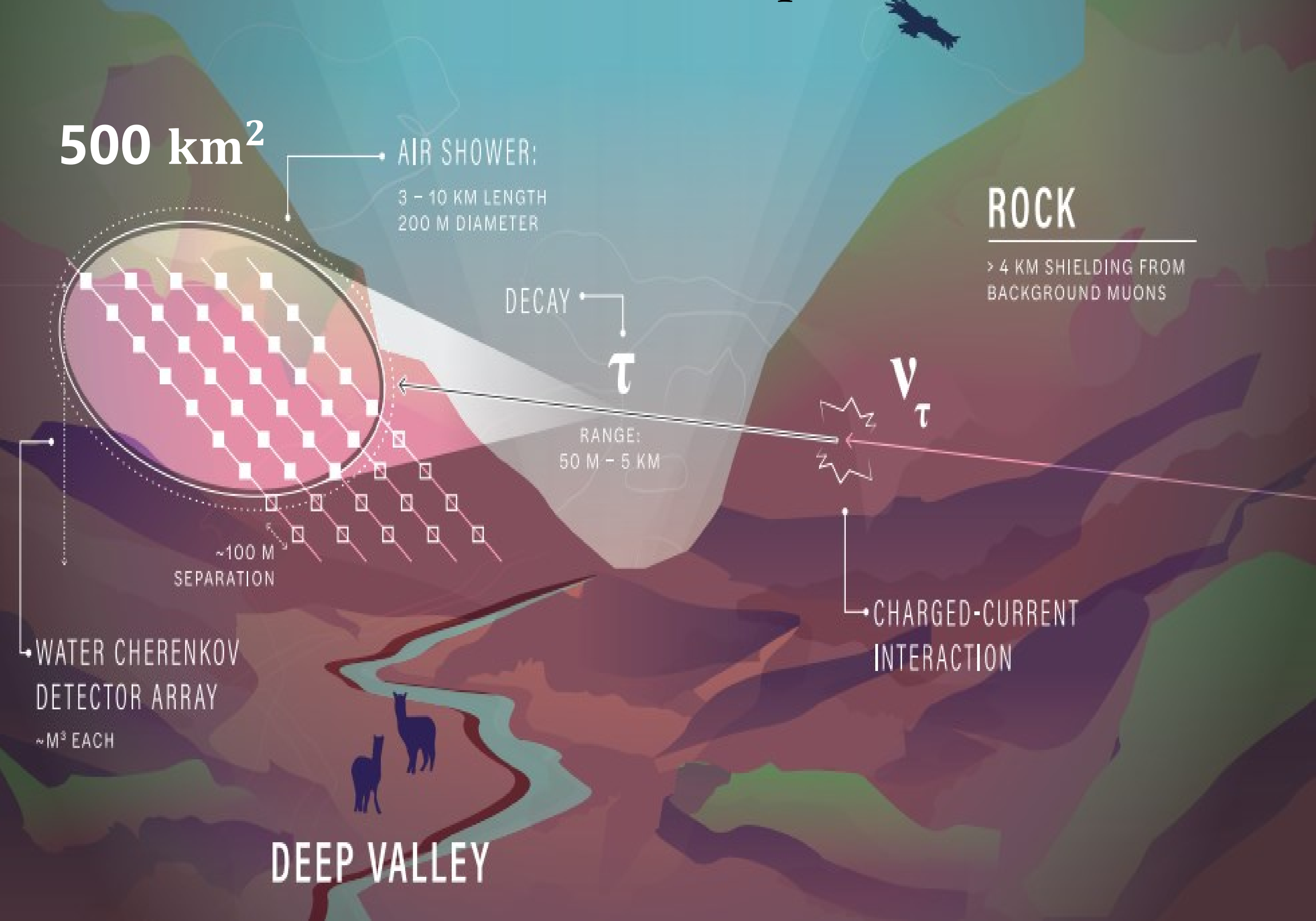


Glashow resonance potential

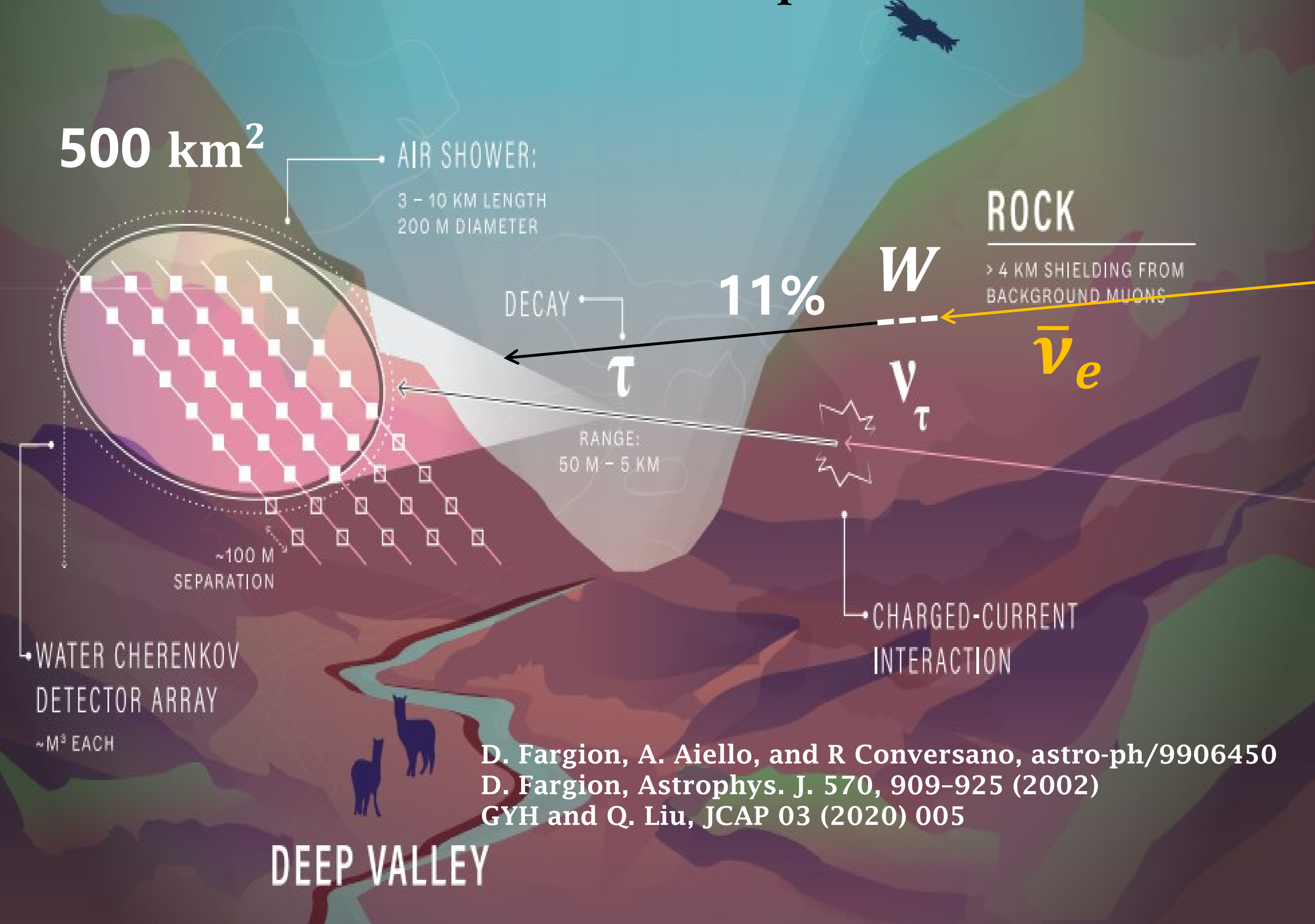


Glashow resonance potential

TAMBO



Glashow resonance potential



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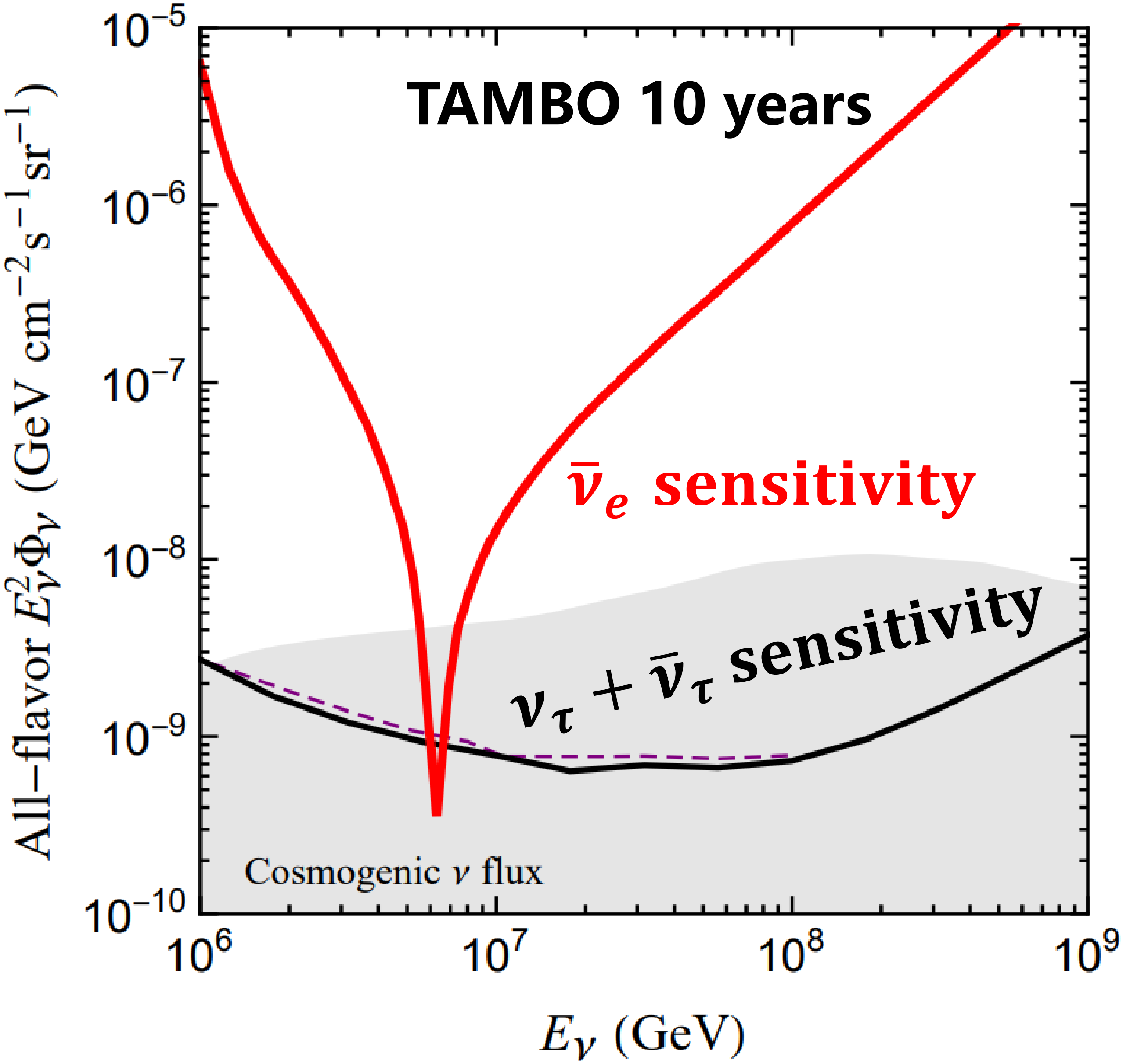
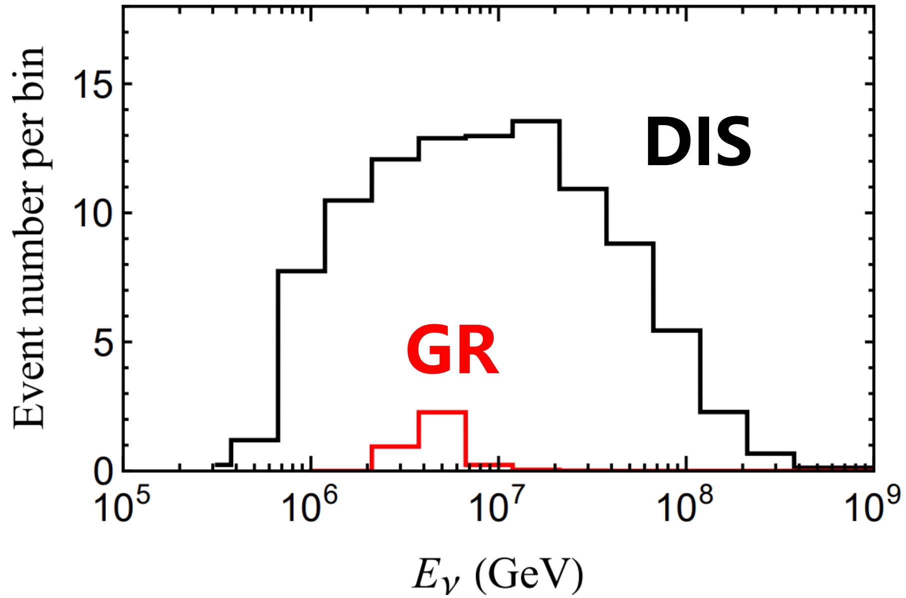
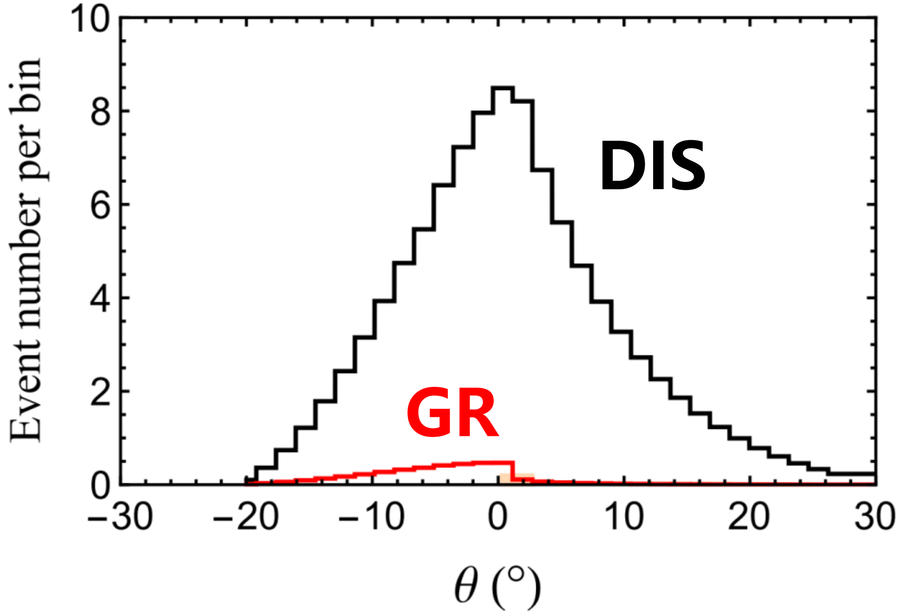
Glashow resonance potential



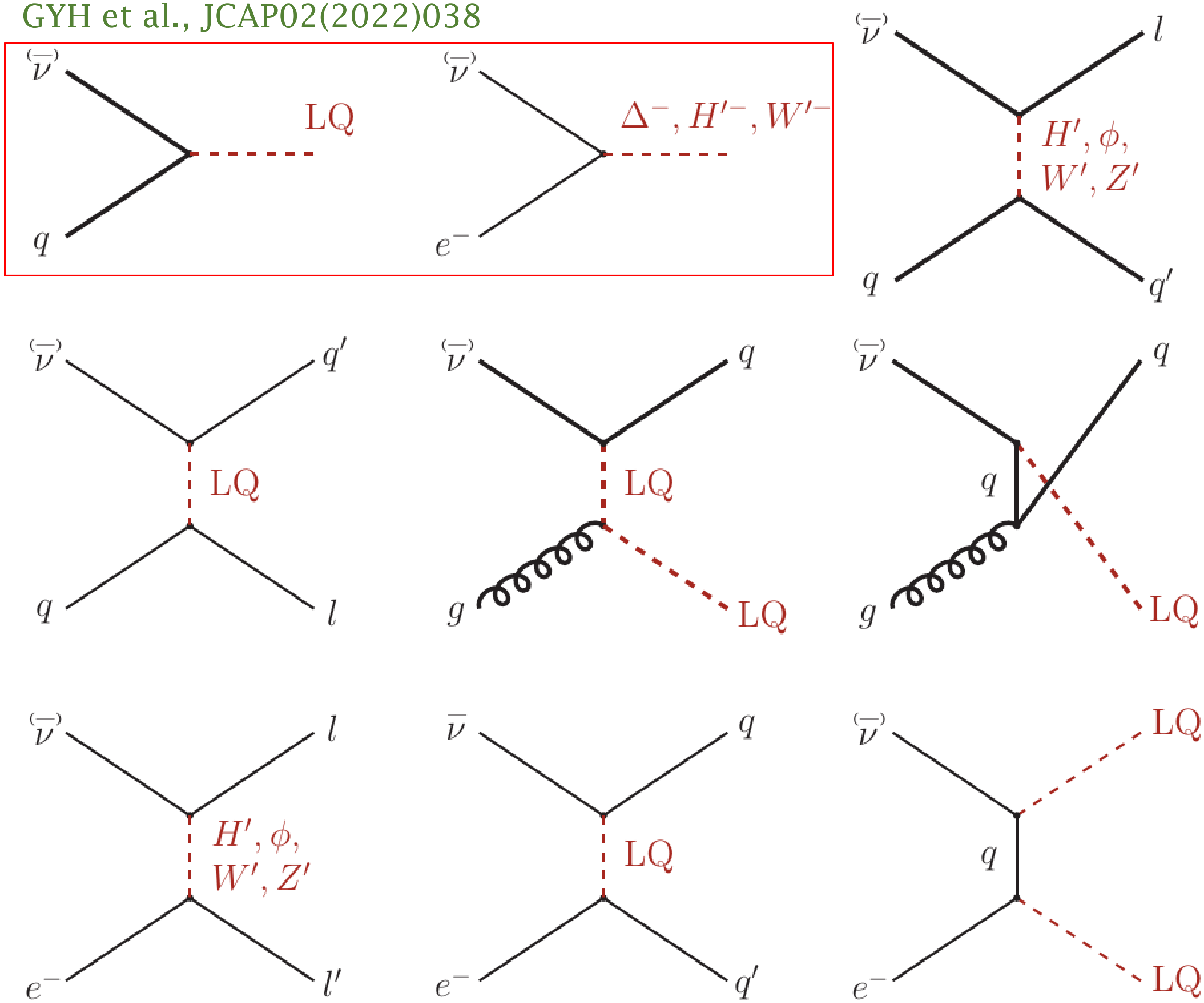
Glashow resonance potential



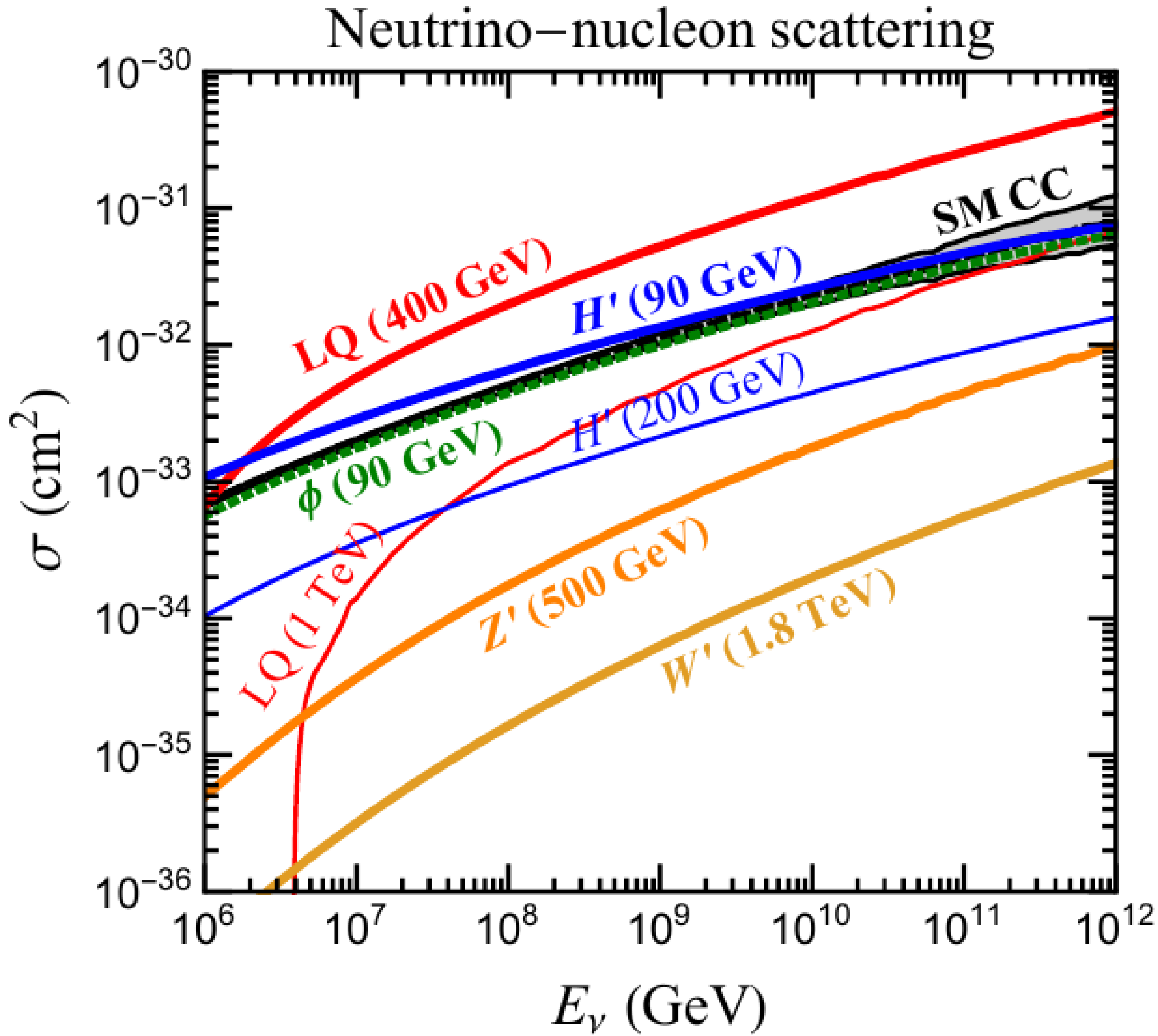


Resonances from new physics?

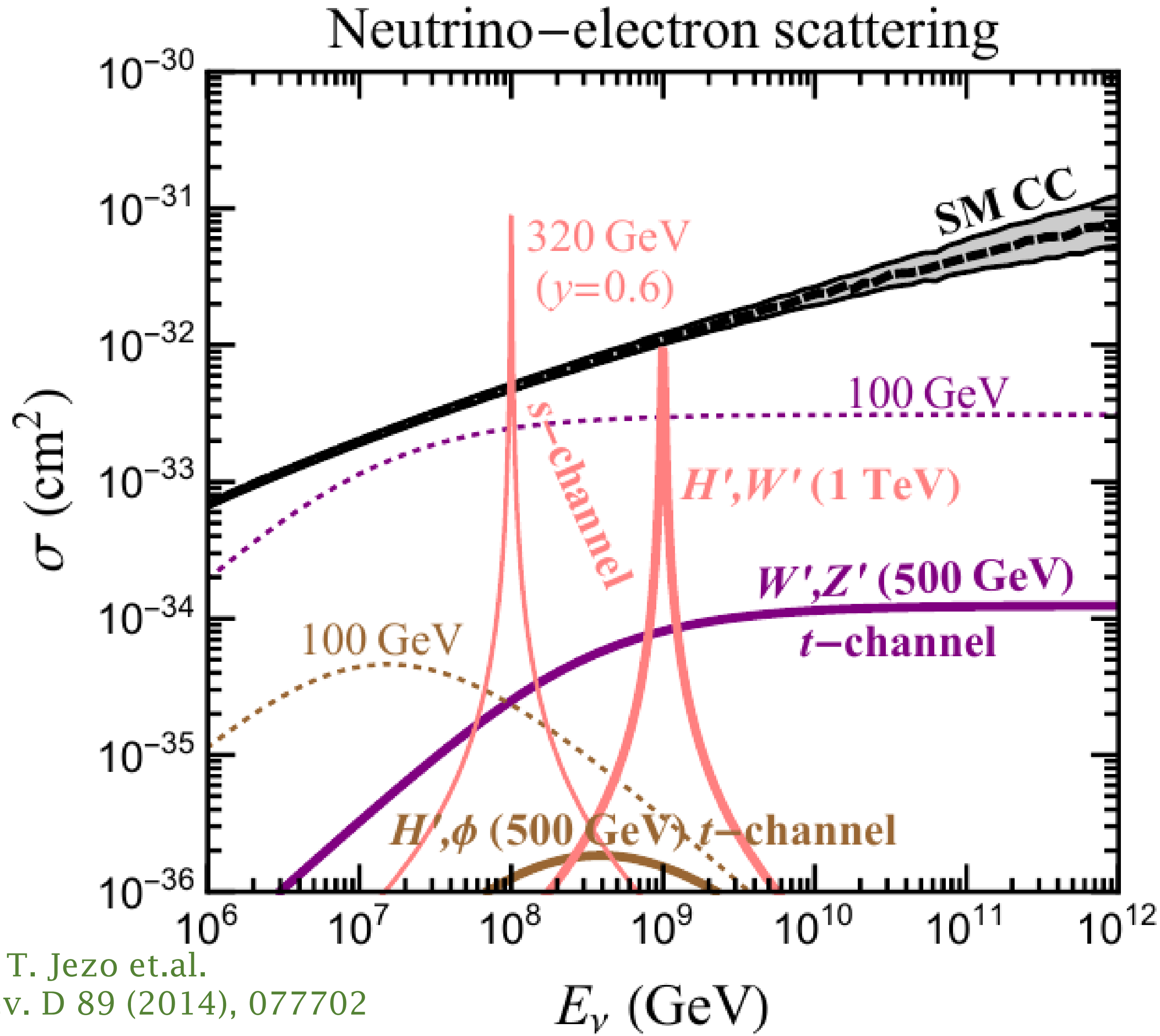
GYH et al., JCAP02(2022)038



Resonances from new physics?



Resonances from new physics?



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

Conclusion

- The observation of the Glashow resonance is not only another test of the yet robust Standard Model, but also provides us information about sources.

- The candidate event observed by IceCube can already rule out the μ-damped $\mathrm{p}\gamma$ source at the 2σ level.

- Besides the water/ice Cherenkov telescopes, air shower neutrino telescopes in principle can also be sensitive to the Glashow resonance. However, we find the sensitivity is poor for a rather aggressive setup TAMBO.

- Resonances induced by new physics can arise in those telescopes. The sensitivity is good around PeV neutrino energies. However, when going to EeV energies, we will lose the sensitivity.

Many thanks!