Spectral Signatures of Multi-Mediator Neutrino Self-Interactions at Ultra-High Energies

Erice: INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS, 47th Course

arXiv:2609.16139

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17 Sept 2026

[7] arXiv:2609.16139 [pdf, html, other]

Multiple-Mediator-Affected Ultra-High-Energy Neutrino Attenuation: Hints for 5D $U(1)_{L_\mu - L_\tau}$ in IceCube

Atri Bhattacharya, Ayushi Kaushik, Kenji Nishiwaki

Comments: 23 pages, 5 figures and 75 citations

Subjects: **High Energy Physics - Phenomenology (hep-ph)**; High Energy Astrophysical Phenomena (astro-ph.HE)

arXiv:2609.16139

[8] arXiv:2609.16156 [pdf, html, other]

Composite dark matter at the LHC

Alan S. Cornell, Louie Corpe, Aldo Deandrea, Benjamin Fuks, Taylor Murphy, Clarisse Prat

Comments: 26 pages, 8 figures

Subjects: **High Energy Physics - Phenomenology (hep-ph)**; High Energy Physics - Experiment (hep-ex)

[9] arXiv:2609.16219 [pdf, html, other]

Enhanced Standard Model bound on charm CP violation from QCD penguins

Ali Mohamed, Maria Laura Piscopo

Comments: 38 pages, 2 figures, 5 tables

Subjects: **High Energy Physics - Phenomenology (hep-ph)**

[10] arXiv:2609.16342 [pdf, html, other]

Top-quark pair production sensitivity to heavy new physics at the FCC-ee

Jacopo De Piccoli, Gauthier Durieux, Sergio Sánchez Cruz, Michele Selvaggi

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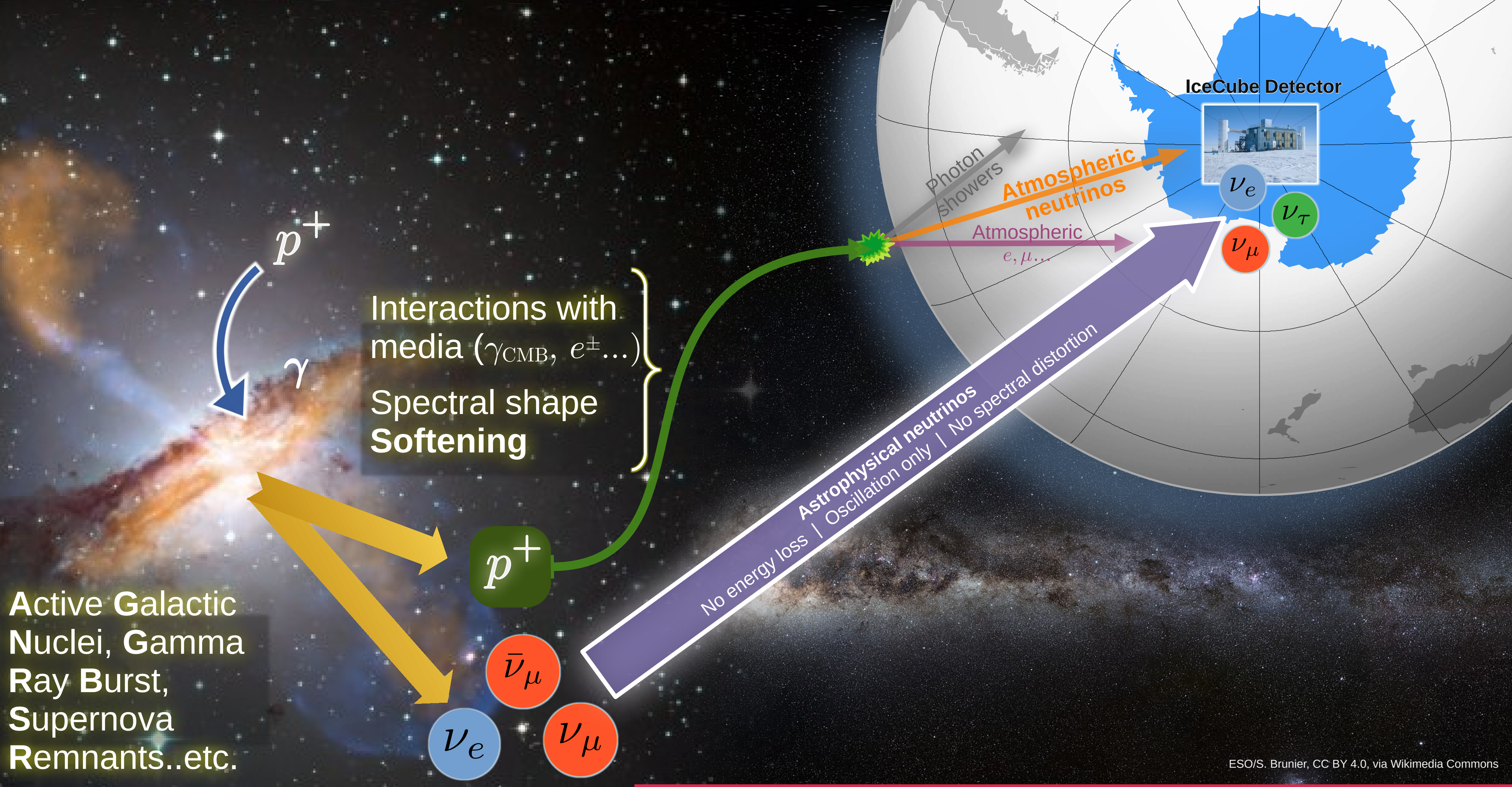
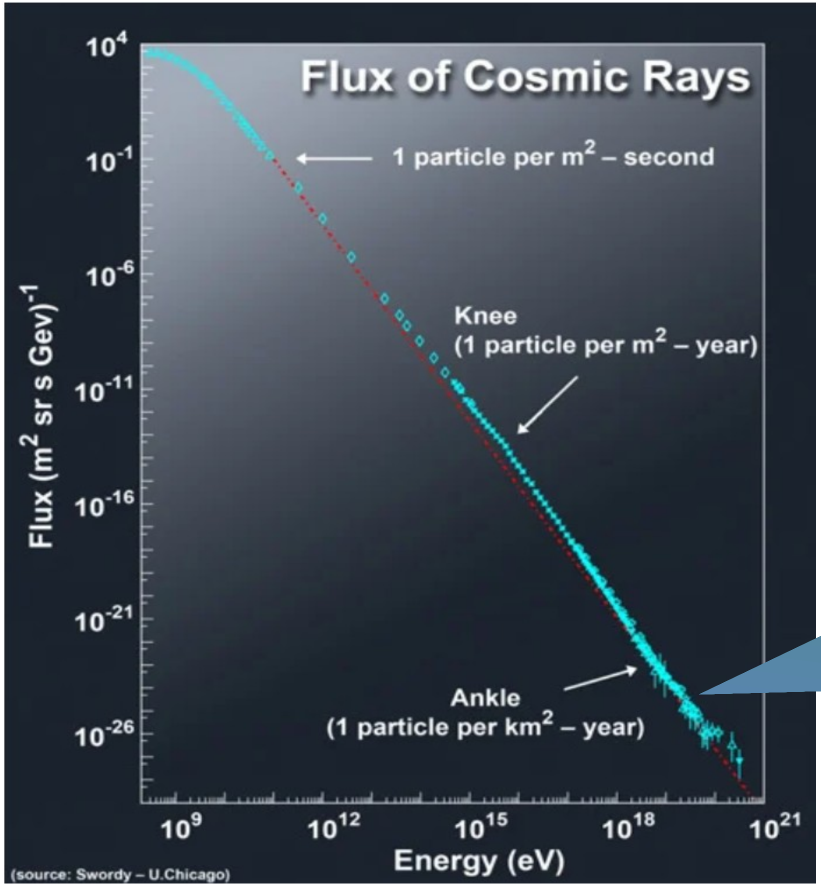


The Divergent Journeys of Cosmic Siblings

Cosmic-ray Flux

(At Earth)



- **Cosmic ray energies extend up to > 10^{20} eV**

$$\boxed{\begin{array}{c}\phi_p \propto E_p^{-\gamma_p} \\ \gamma_p = 2.7 - 3.1\end{array}}$$ @ Earth

$$p\gamma \to n\pi^+$$

$$n \to p + e^- + \bar{\nu}_e$$

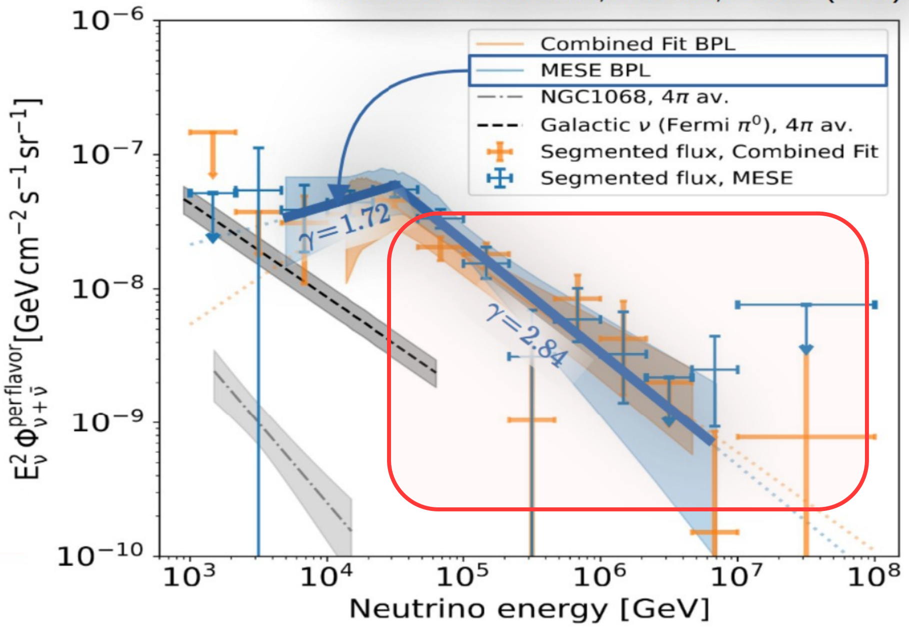
$$\pi^+ \to \mu^+ \nu_\mu$$

$$\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$$

The >60 TeV Discrepancy

- **IceCube** **High Energy Starting Events** consistently favours steeply falling spectrum
- Single power-law ($\phi_\nu \propto E^{-\gamma}$) $\Rightarrow$ *measured* best-fit index $\gamma = 2.84^{+0.11}_{-0.09}$ at IC HESE
- Beyond 60 TeV Atmospheric neutrino background is negligible
- **Conflict: Cosmic rays and Astrophysical Neutrinos connection suggests $\gamma \approx 2$@ source**

IceCube Collaboration; PRL 136, 121002 (2026)



Why Measured spectrum **much softer than expected** from cosmic-ray neutrino connection?

Astrophysical Neutrino Flux Diagnostics

PeV Energy Spectral Signatures	Expectation (Standard Model)	Reality (IceCube Measured)
Flavor Ratio	$\nu_e : \nu_\mu : \nu_\tau \approx 1 : 1 : 1$	✔
Flux Isotropy	Isotropic	✔
Spectral Index	**Single Power Law** ~~Energy loss~~ $\Longrightarrow \gamma \sim 2$ @Earth	$\Rightarrow \gamma \sim 2.8$ @Earth ✘

The Anomaly

The measured spectrum is significantly softer ($\gamma \simeq 2.8$) than expected.

Something is actively attenuating these particles during their cosmic journey.

Excessive softening of neutrino flux at high energies…

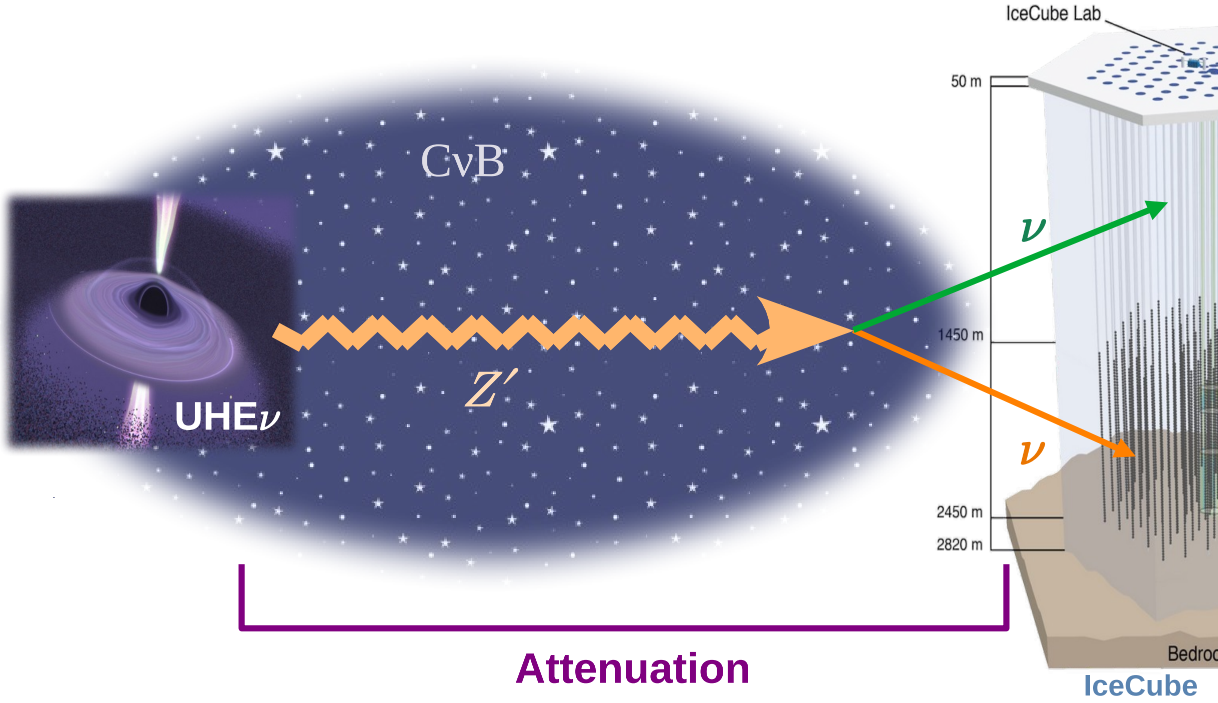
An indication of new physics?

CνB as a Translucent Medium

- **Key Idea**
  Attenuation of UHEν by scattering off cold relic neutrinos (CνB)

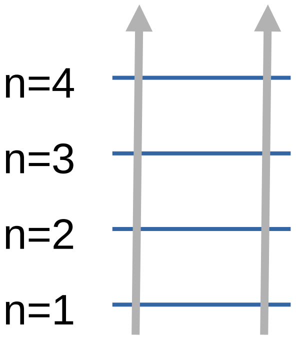
- **Not 4D SM!**
  Z boson is too heavy $(m_z = 91.2\ \text{GeV})$
  s-channel resonance well beyond 100 PeV
  νSI too weak

- **4D BSM Mechanism**
  Interactions mediated by *light gauge boson* from **broken** $U(1)_{L\mu - L\tau}$



5D Lμ-Lτ Model

- Kaluza–Klein (1920s): Introduced an extra compact spatial dimension to unify gravity and electromagnetism. Phys.Rept.283:303-380,1997
- $\mathrm{SM} \longrightarrow \mathrm{SM} \times U(1)_{L_\mu - L_\tau}{}_{\mathrm{5D}}$, while the Standard Model particles are confined to a 4d brane (D. Chakraborty, A. Chatterjee, **A. Kaushik**, K. Nishiwaki.; Phys.Rev.D 110, 095030 (2024))
- Particles propagating in the extra dimension appear in 4d as a tower of massive excitations (KK modes)



$$m_n = (2n-1)m_{\mathrm{KK}}$$

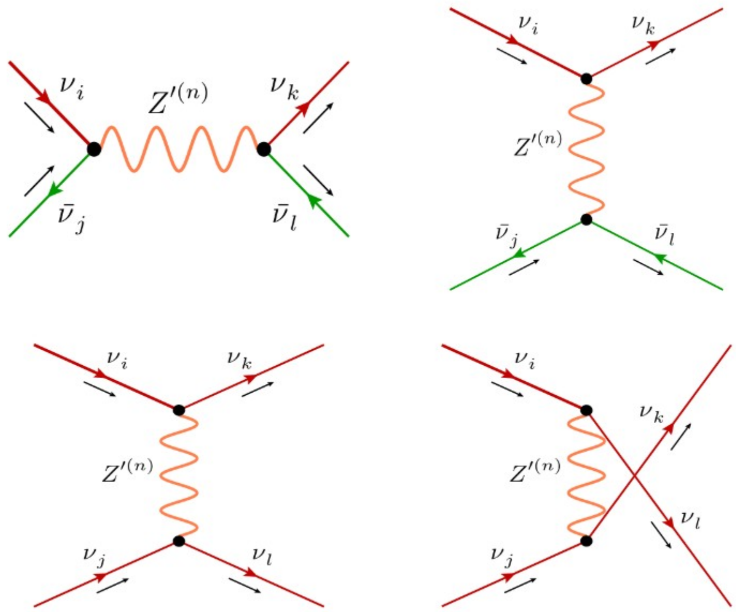
(m_{KK} is the lowest mode gauge boson's mass.)

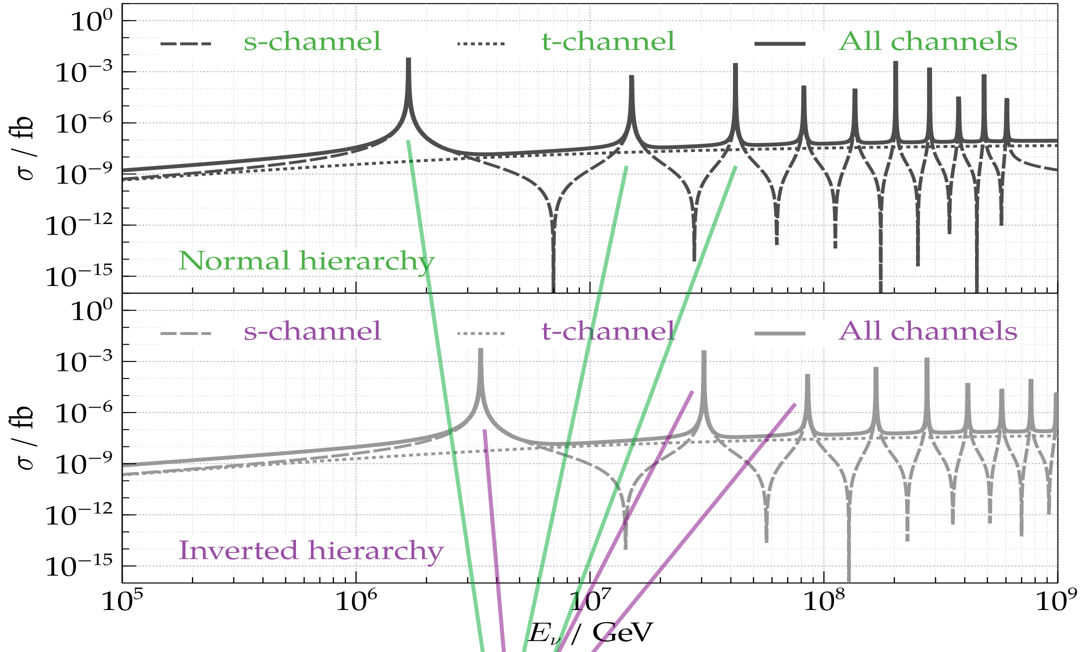
4D v/s 5D

Spatial Dimensions	4D [single Z' mediator]	**5D** **[KK tower of $Z'^{(n)}$]**
Particle Spectrum	Single Z' mediator	**Multiple Z' mediators**
Resonance Structure	Single peak per ν mass	**Multiple resonances** **[overlapping at high energies]**
Dominant Channels	s-channel dominant	**s, t & u-channels important**
Spectral features	Resonant attenuation at three specific energies	**Repeated attenuation** **@** **multiple energies**

Anatomy of 5D Scattering Cross-Section

Interaction channels





s-channel resonances at

$$\mathrm{E_{res}} = \frac{{m_n}^2}{2m_j}, m_n = (2n-1)m_{\mathrm{KK}}$$

Prior works for $4d$ scattering

Hooper et al.; arXiv:2302.03571

Francener et al.; arXiv:2403.16611

Neutrino evolution and resonances

Phys. Rev. D 108, 023007 (2023)

Evolving ν flux using Boltzmann equation

$$-(1+z)\frac{H(z)}{c}\phi_i z = \boxed{\overset{\text{Flux Injection}}{J_i(E_0,z)}} - \boxed{\phi_i(z)\sum_{j=1}^{3} n_{\nu_j}(z)\,\sigma_{ij}(E_0,z)}^{\text{Annihilation}}$$

$$\boxed{+\int_{E_0}^{\infty} E' \sum_{j,k=1}^{3}\phi_j(z)n_{\nu_k}(z)\sum_{l=1}^{3} P_{i\bar{l}}\,\sigma_{j\bar{k}\to i\bar{l}}(E',z)E_0}_{\text{Regeneration}},$$

- Multiple mediators (m_n)

  ⇒ Resonances at multiple E_{res}

$$\mathrm{E_{res}} = \frac{{m_n}^2}{2m_j}, m_n = (2n-1)m_{\mathrm{KK}}$$

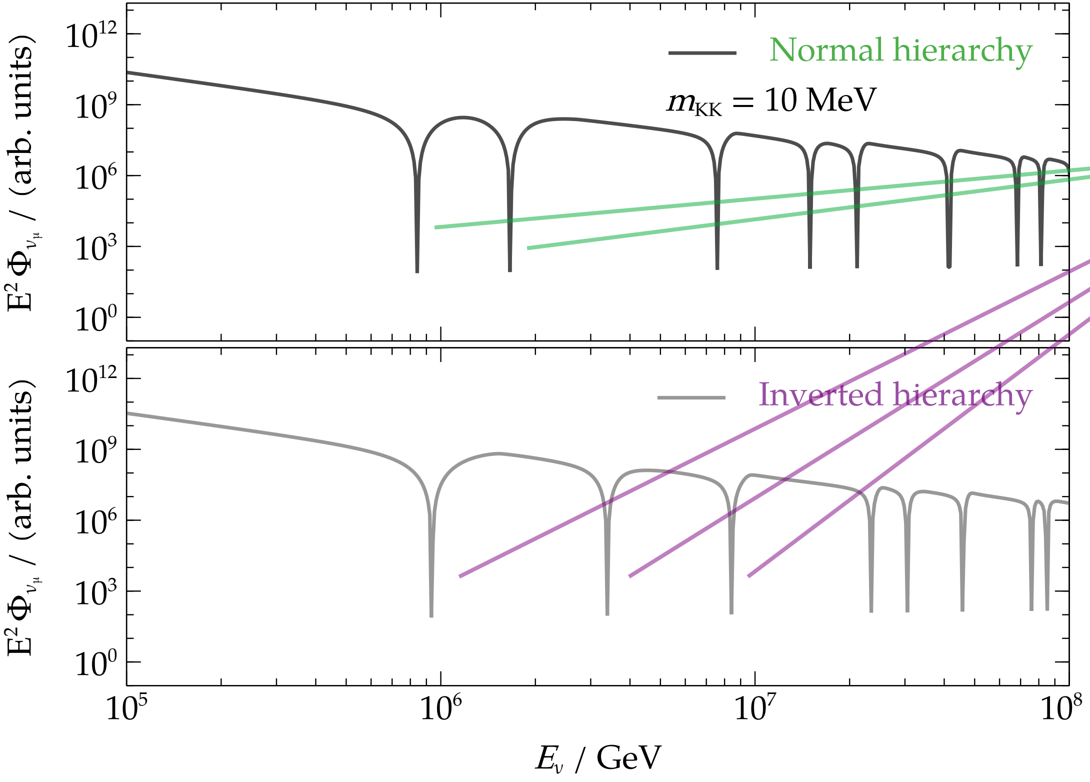
Where

- m_{KK} is the lowest mode gauge boson's mass.
- m_j is the mass of the target CνB neutrino in the j-th mass eigenstate.

$m_j = 53.0\ \mathrm{meV},\ m_{\mathrm{KK}} = 10\ \mathrm{MeV}$

Mode no. (n)	Resonance Energy (E_{res} / PeV)
1	0.943
2	8.491
3	23.585
4	46.226
5	76.415

Repeating Attenuation: Flux @ Earth



γ=2

s-channel resonances at

$$\mathrm{E}_{\mathrm{res}} = \frac{{m_n}^2}{2m_j}, m_n = (2n-1)m_{\mathrm{KK}}$$

$$g' = 10^{-4},\ y_{\mathrm{SM}} = 0,\ N_{\mathrm{KKmax}} = 10$$

Coupling Constant of $Z'^{(n)}\nu\nu$

Position of SM brane in ED

Maximum number of KK modes

Event Numbers

$$N_{\text{events}} = 4\pi T \int_{E_{\min}}^{E_{\max}} E_\nu \sum_\alpha \left[\left\{ \phi_\alpha^{\text{Earth}}(E_\nu) + \phi_{\bar{\alpha}}^{\text{Earth}}(E_\nu) \right\} A_{\text{eff}}^{\alpha+\bar{\alpha}}(E_\nu) \right]$$

Isotropic Flux

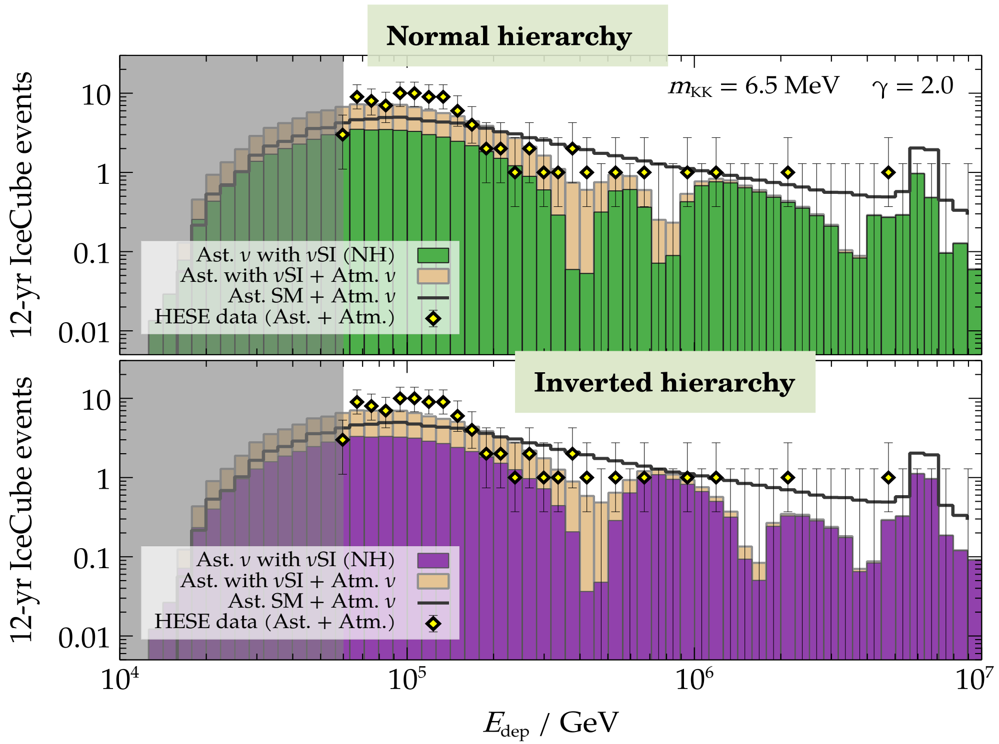
$\approx$ 12 yrs

Flux of neutrino flavour @ Earth

Flux of anti-neutrino flavour @ Earth

Flavour specific Effective area summed over particle-antiparticle

Event Rate



$g' = 10^{-4}$, $y_{\mathrm{SM}} = 0$, $N_{\mathrm{KKmax}} = 15$

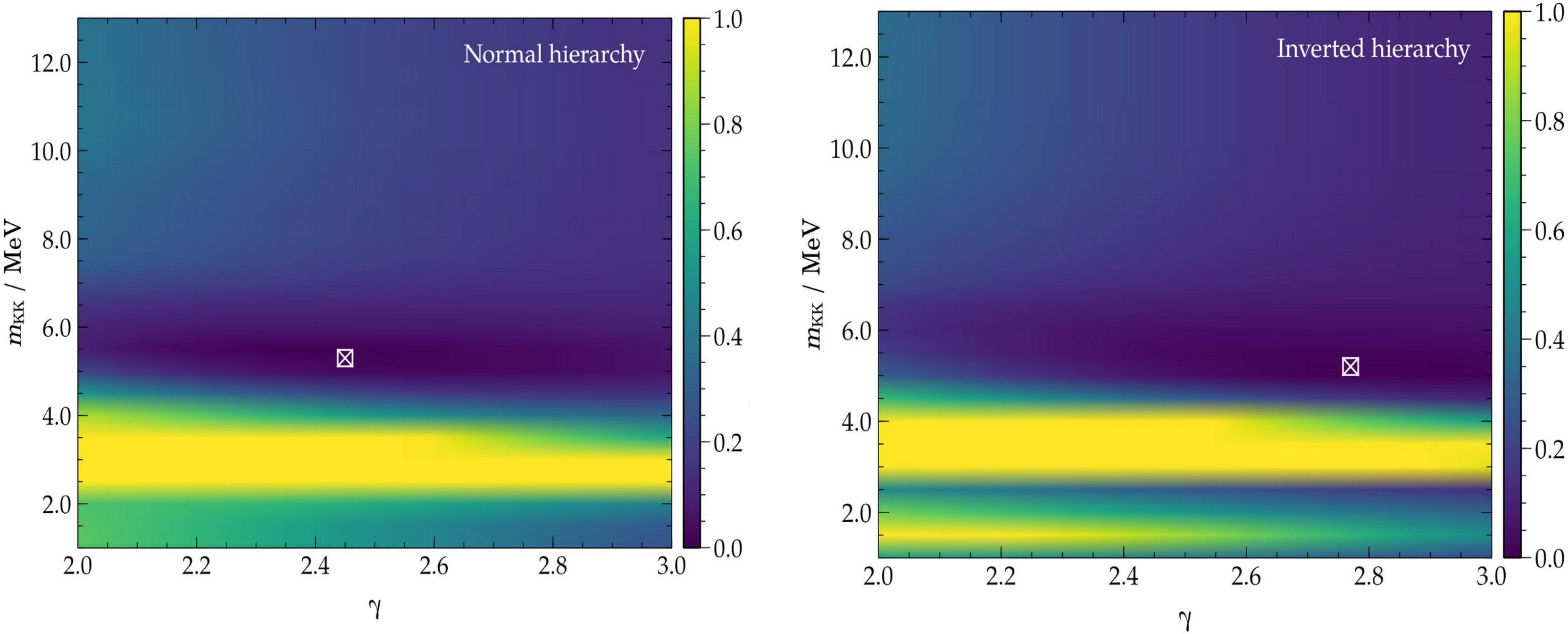
Coupling Constant of $Z'^{(n)}\nu\nu$

Position of SM brane in ED

Maximum number of KK modes

- Natural softening of spectral shape at 10 PeV+
- Consistency with HESE data even when starting with hard spectral index $\gamma \approx 2$

Mapping the parameters Space

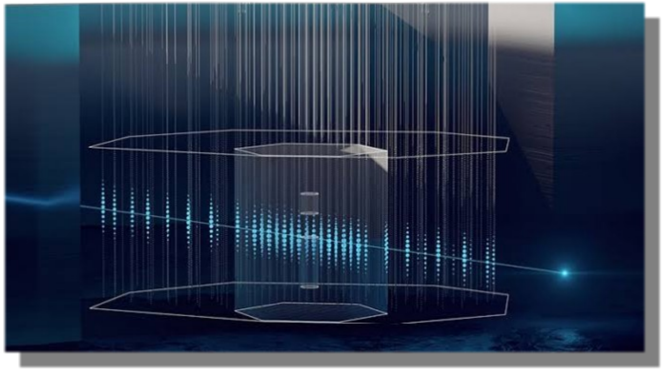


- Statistical analysis reveals a strong sensitivity to the base KK mass scale up to $\simeq$ 7MeV.
- Fits to 12-year IceCube HESE data Best fit regions: $5.0\ \mathrm{MeV} \leq m_{\mathrm{KK}} \leq 6.5\ \mathrm{MeV}$.
- Fit quality is highly degenrate for the spectral index, proving the attenuation mechanism drives the fit, not a tuned injection.

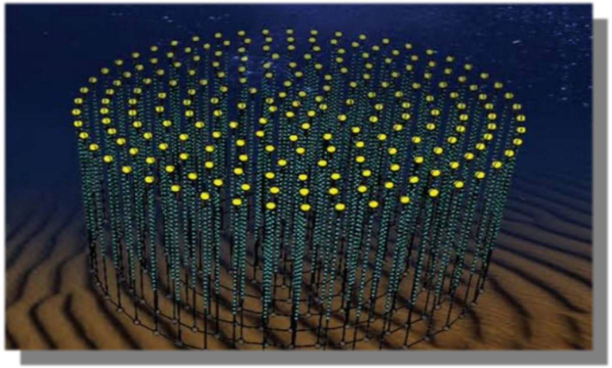
$$g' = 10^{-4},\ y_{\mathrm{SM}} = 0,\ N_{\mathrm{KKmax}} = 15$$

The Future Horizon

- Next-generation observatories like IceCube-Gen2, KM3NeT are required to statistically resolve the individual absorption dips and confirm the 5D architecture.



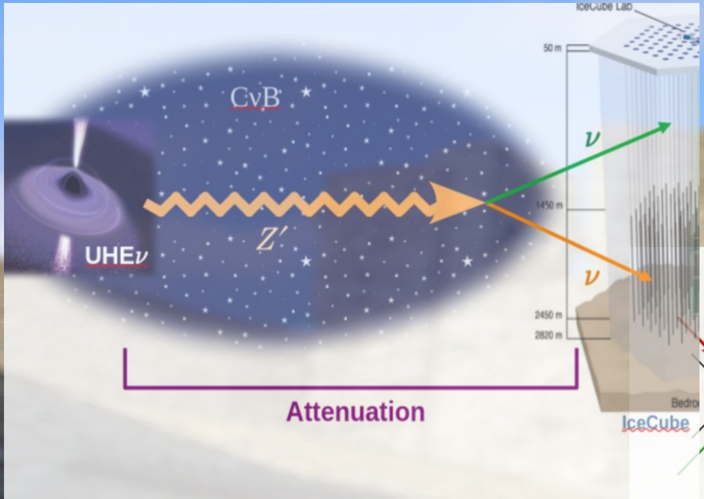
IceCube-Gen2



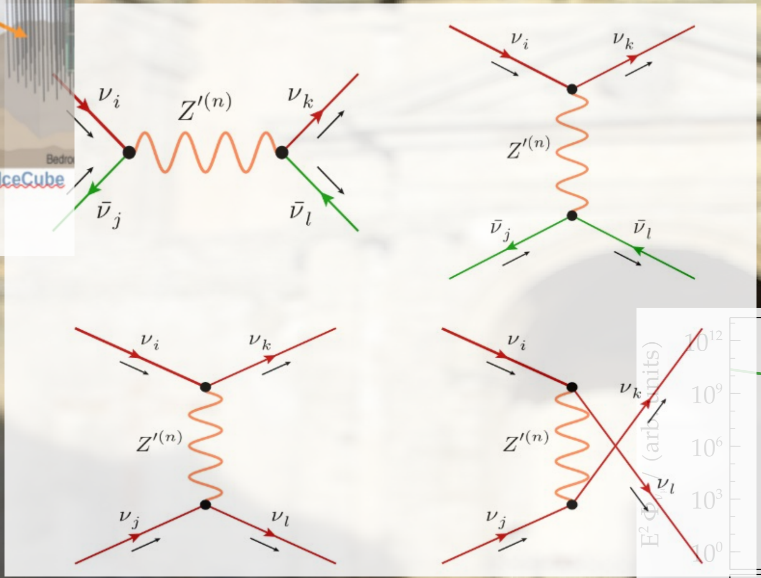
KM3NeT

Image:icecube-gen2.de, cerncourier.com

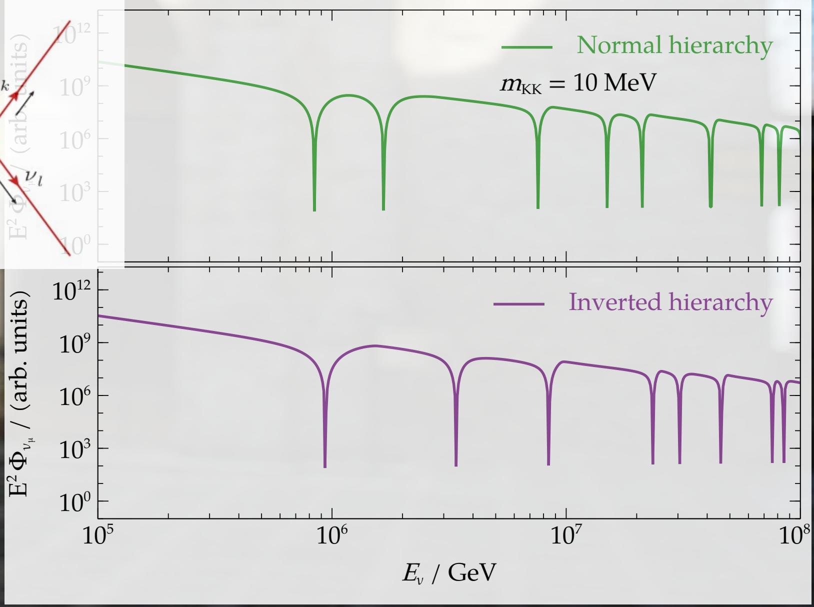
Highlights



IceCube Lab
50 m
1450 m
2450 m
2820 m
CνB
UHEν
Z′
ν
ν
Attenuation
IceCube



ν_i
$Z'^{(n)}$
ν_k
$\bar{\nu}_j$
$\bar{\nu}_l$
ν_j
ν_l



Normal hierarchy
$m_{\rm KK}$ = 10 MeV
Inverted hierarchy
$E^2\Phi_{\nu_\mu}$ / (arb. units)
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^5
10^6
10^7
10^8
E_ν / GeV

Backup slides

Multi-messenger Astronomy

Active Galactic Nuclei,
Gamma ray burst etc.

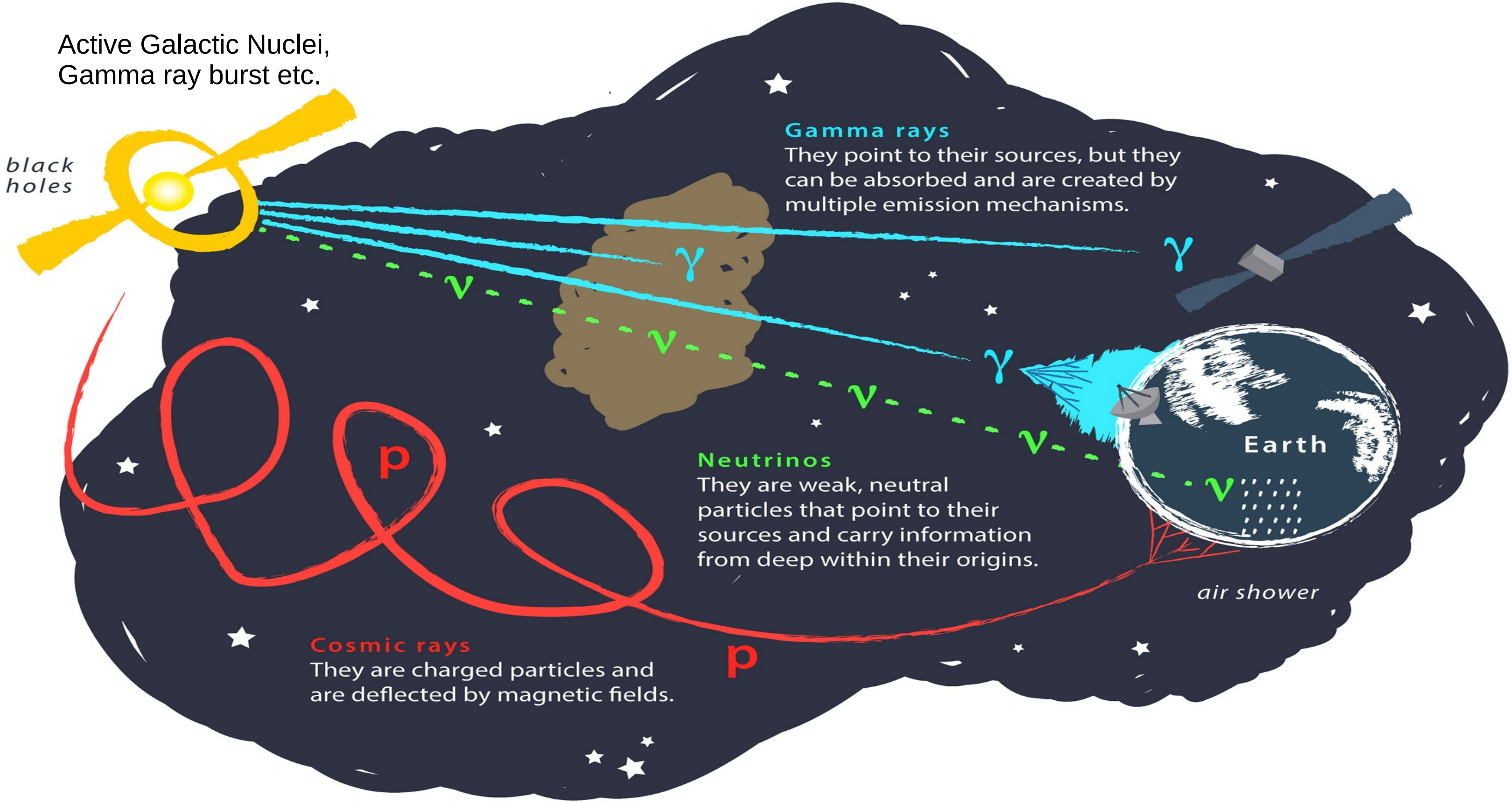


Image: Juan Antonio Aguilar and Jamie Yang. IceCube/WIPAC

Neutrino Sky and Observation

Neutrino Fluxes

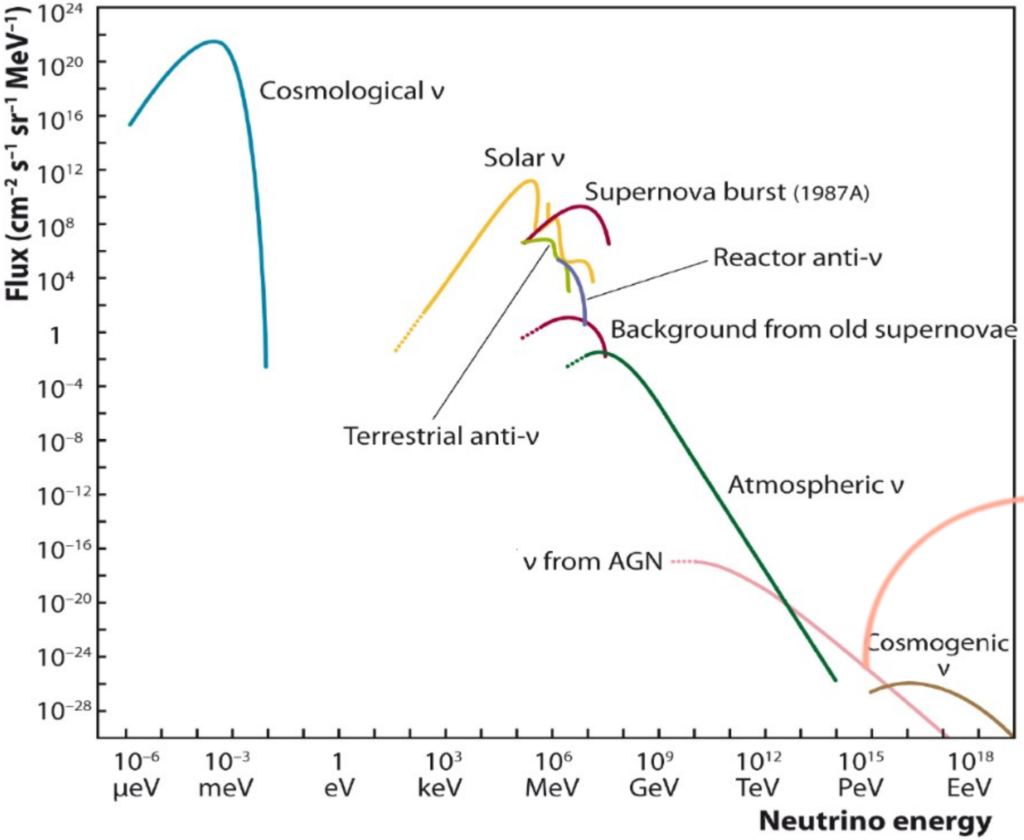
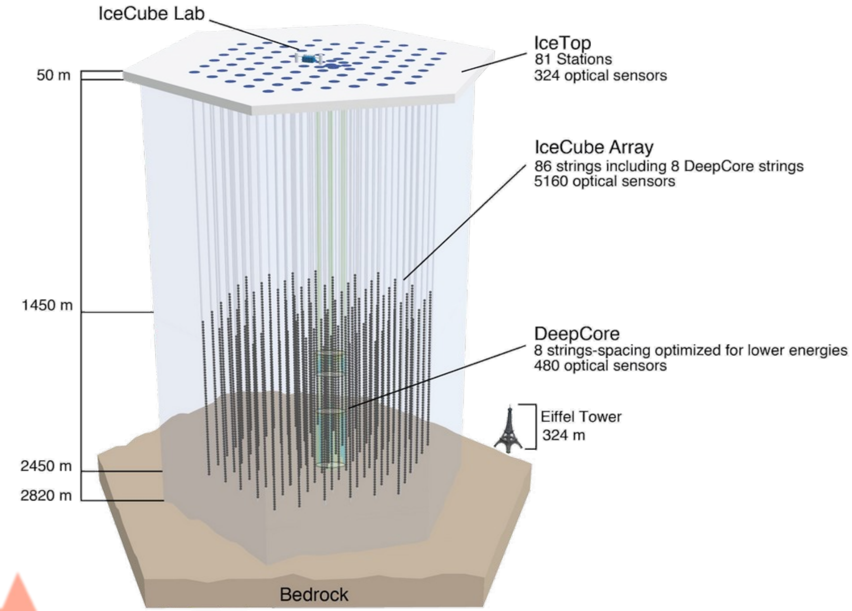
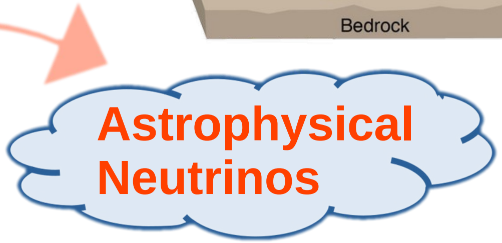


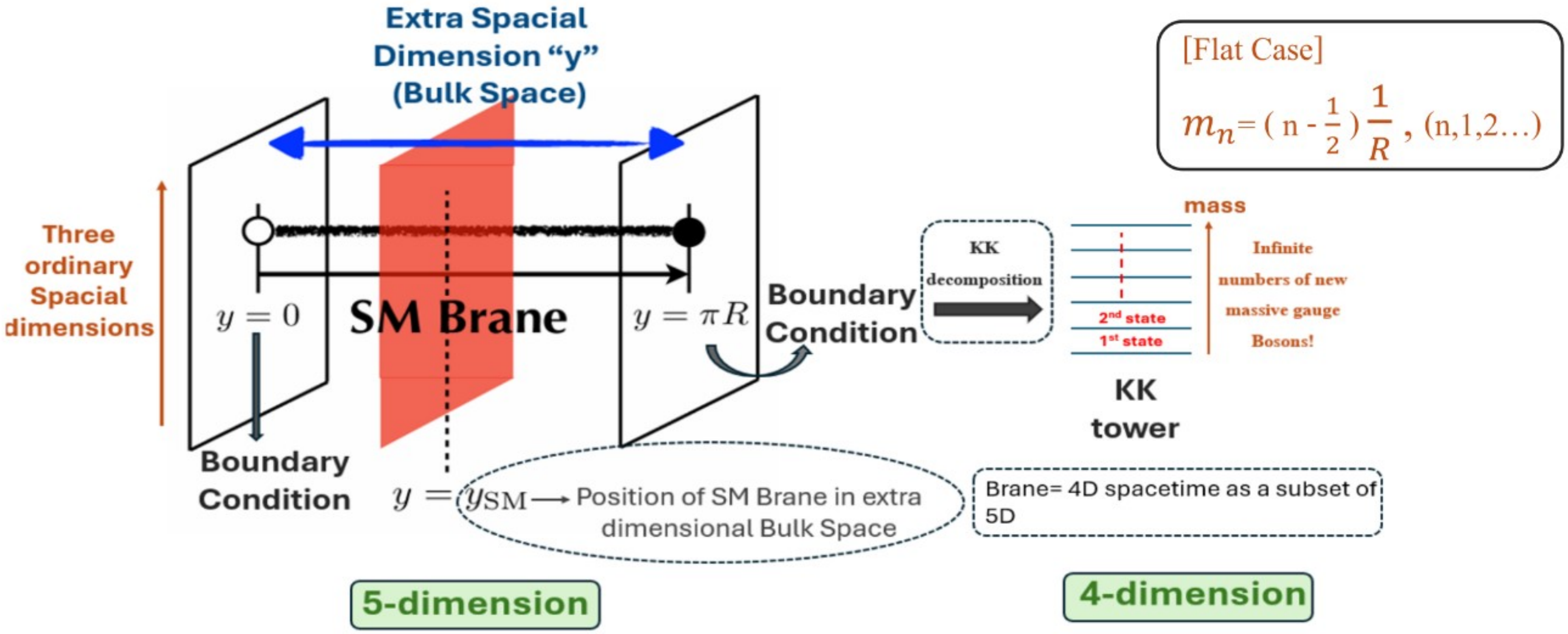
Image: Christian Spiering, arXiv: 1207.4952





Model to probe hidden dimensions

$$\mathrm{SM} \longrightarrow \mathrm{SM} \times U(1)_{L_\mu - L\tau_{\mathrm{ED}}}$$



Schematic of our Extra-dimensional Model

D. Chakraborty, A. Chatterjee, **A. Kaushik**, K. Nishiwaki.; Phys.Rev.D 110, 095030 (2024)

Lagrangian

$$\mathcal{L}_{\text{eff}}^{\text{V-free}} = \boxed{\frac{1}{4}\sum_n V_{\mu\nu}^{(n)} V^{(n)\mu\nu}} - \frac{1}{4} Z_{\mu\nu} Z^{\mu\nu} - \frac{1}{4} A_{\mu\nu} A^{\mu\nu} + \frac{1}{2} m_{Z,0}^2 Z_\mu Z^\mu + \boxed{\frac{1}{2}\sum_n M_n^2 V_\mu^{(n)} V^{(n)\mu}} + \mathcal{O}(\epsilon_n^2)$$

Kinetic term for ED Z'

mass term for ED Z'

$V_{\mu\nu}^{(n)}$	ED gauge field strength
$Z_{\mu\nu}$	SM Z boson field strength
$A_{\mu\nu}$	Photon Field strength
$m_{Z,0}$	Z boson mass
M_n	nth ED gauge boson mass

D. Chakraborty, A. Chatterjee, **A. Kaushik**, K. Nishiwaki.; Phys.Rev.D 110, 095030 (2024)

Starting Events

High Energy Starting Events (HESE)

- Interaction vertex inside the detector
- Outer detector acts as a veto against atmospheric muons
- Energy range: ~60 TeV–10 PeV.
- Cleaner astrophysical neutrino sample

Medium Energy Starting Events (MESE)

- Lower energy extension of HESE
- Energy range: ~1 TeV–10 PeV
- Increased statistics at lower energies
- Atm. ν analysis is performed using machine learning techniques.