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

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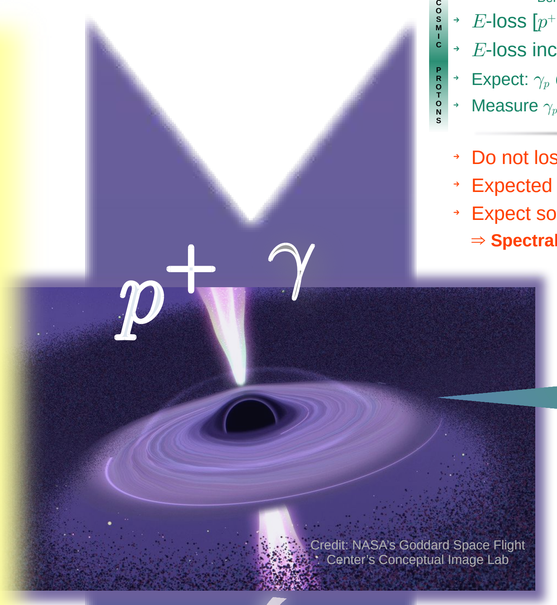
PRODUCTION

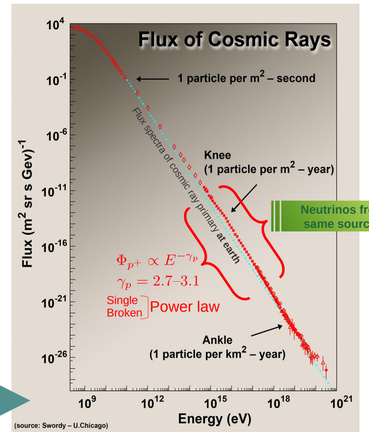


Berezinsky, et al: PRD 74, 043005 (2006)

COSMIC PROTONS
- E-loss [$p^+ + \gamma_{\rm CMB}$] during propagation
- E-loss increases with p energies
- Expect: γ_p @ Earth > γ_p @ Source
- Measure $\gamma_p \simeq 2.7$–3.1 ⇒ Source $\gamma_p \approx 2.0$–2.4

COSMIC ν
- Do not lose energy *(red-shift only)*
- Expected from same sources
- Expect souce $\gamma_\nu \approx 2.0$–2.4

⇒ **Spectral index @ Earth:** $\gamma_\nu \approx 2.0$–2.4



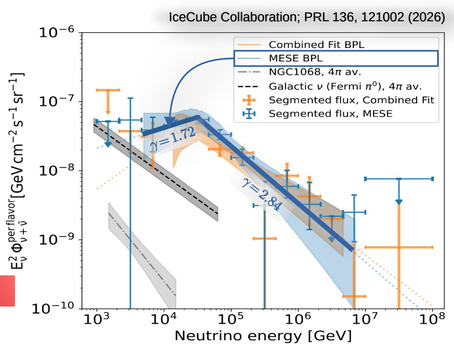
p^+

$\bar{\nu}_\mu$ ν_e ν_μ → ν_e ν_μ ν_τ

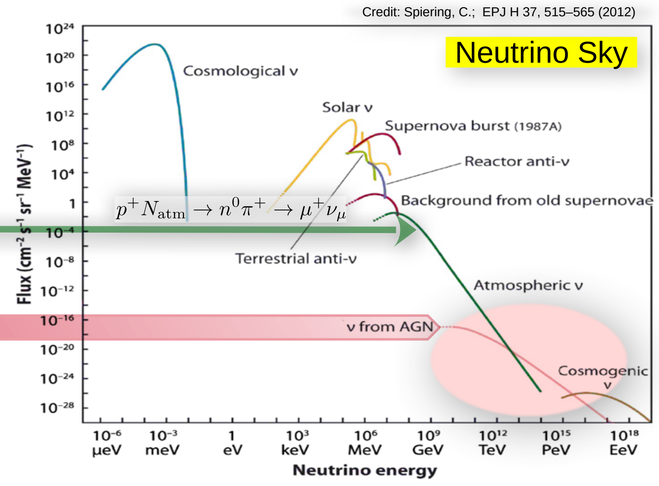
Diffuse Astrophysical ν Flux

Expectation	Reality
$\nu_e : \nu_\mu : \nu_\tau \approx 1:1:1$	✅
Isotropic flux	✅
$\Phi_\nu \propto E^{-\gamma}$ **power-law**	❌ ~~**SPL: $\gamma \sim 2.8$**~~
$\gamma \sim 2$ spectral index @source	✅ **BPL**
~~**E loss**~~ ⇒ $\gamma \sim 2$ @Earth	**S**ingle/**B**roken **P**ower **L**aw

IceCube Collaboration; PRL 136, 121002 (2026)



Credit: Spiering, C.; EPJ H 37, 515–565 (2012)



MOTIVATION

- Assume:
  Hard ν spectra **at source:** $\gamma \sim 2$
- **Attenuation during propagation**
  ⇒ Spectral softening to $\gamma \sim 2.8$
- Target: **CνB relic ν**
- Problem:
  Heavy SM med $M_Z = 91.2$ GeV
- Solution:
  BSM physics with **light** Z'

PROPAGATION

ATTENUATION AGAINST COSMIC ν BACKGROUND

Standard Model

- Propagation of UHE ν through CνB happens as if through vacuum
- Vacuum oscillation between ν flavours
- No attenuation of flux ⇒ No spectral impact

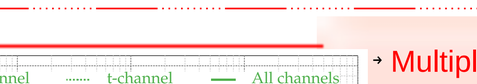
The Hunt for Low-Mass Gauge Bosons
Broken $U(1)_{L\mu - L\tau}$ gauge symmetry in $4d$

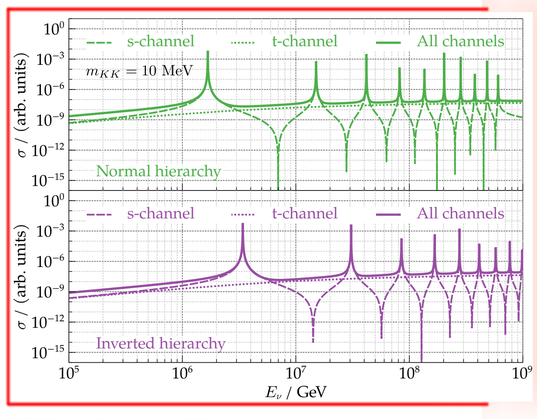
- Anomaly free $4d$ BSM with *single* goldstone boson
- Symmetry breaking ⇒ **One** new massive boson [Z'^0]
- **MeV-scale masses for Z' feasible**
  ⇒ PeV-energy ν_{ast} scattering against ν_{CvB}
  ⇒ *On-shell* Z' from s-channel resonance
  ⇒ Sensitive to ν mass **H**ierarchy: **N**ormal vs **I**nverted
- Possible to probe at UHE ν detectors like IceCube…
  ⇒ ...**not enough attenuation to soften PeV spectra**
  ⇒ Only three peaks for any given Z' mass
  ⇒ *Requires* soft ν flux spectrum at source

Multiple MeV-scale Gauge Bosons
Broken $U(1)_{L\mu - L\tau}$ gauge symmetry in KK $5d$

Single $5d$ gauge field ⇒ Tower of gauge bosons in $4d$

$$m_{Z'^{(n)}} = (2n-1) m_{KK}$$



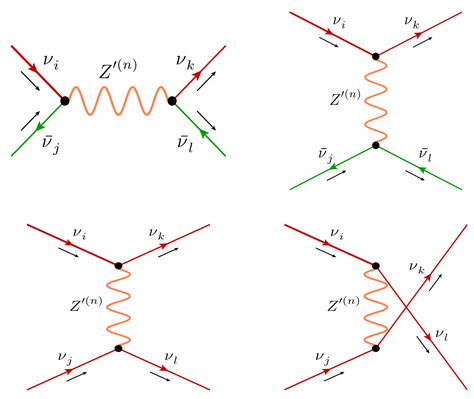


- Multiple resonances in $\sigma(\nu_{\rm ast}\, \nu_i \to \nu_j \nu_k)$
- Interference: Amp mediated by $Z'^{(n)}$ $n = 1, 2...$
- Destructive interference between s-channel resonances
- Dips in cross-section not seen in single Z' case (only *single* s-channel)
- Non-resonant t/u channels wipe out interference dips
- Must **include all possible t/u channel** diagrams

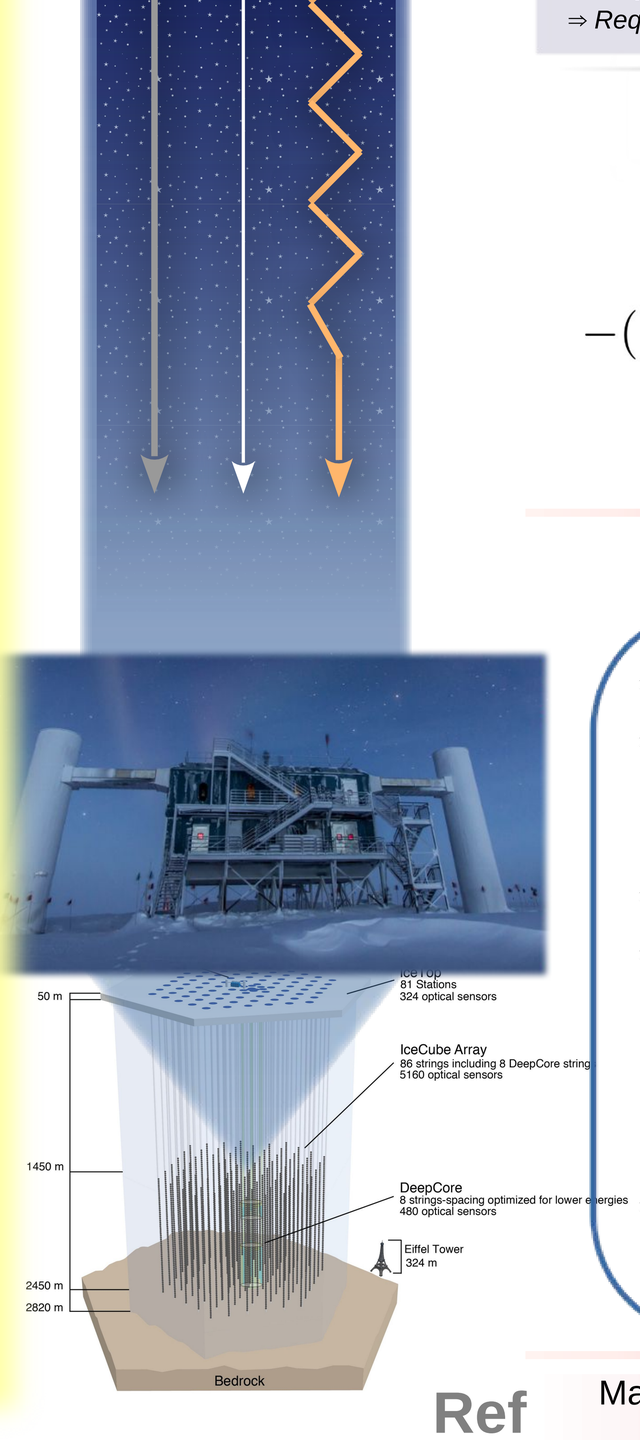
Evolving ν flux using Boltzmann equation

$$-(1+z)\frac{H(z)}{c}\frac{d\phi_i}{dz} = \begin{cases} J_i(E_0, z) - \phi_i \sum_j \langle n_{\nu_i}(z)\, \sigma_{ij}(E_0, z)\rangle \\ + \int_{E_0}^{\infty} dE' \sum_{j,k} \phi_k \left\langle n_{\nu_j}(z) \frac{d\sigma_{kj}(E', z)}{dE_0}\right\rangle \end{cases}$$

Neutrino flux (Red-shift) · Flux injection $\gamma \propto 2$ · Annihilation · Regeneration

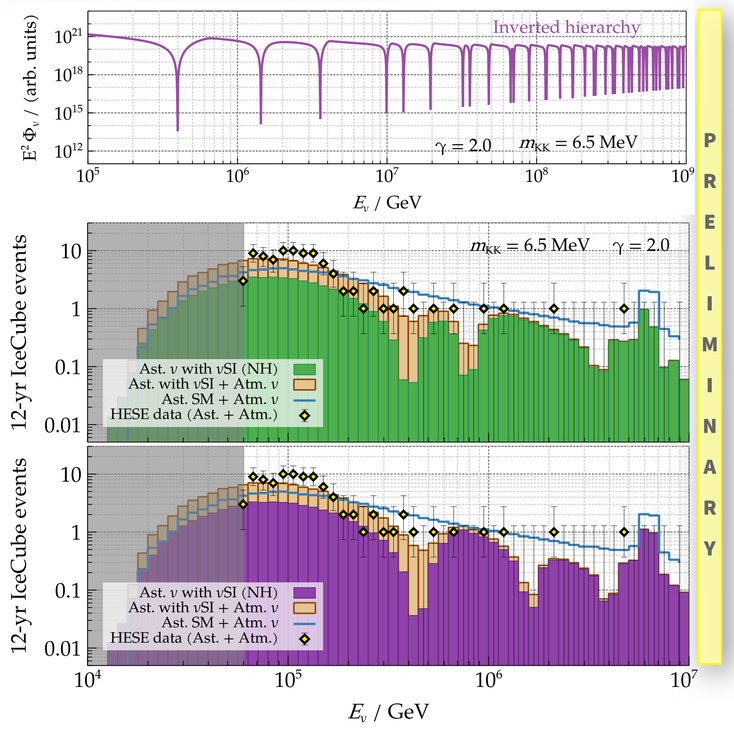


DETECTION



EFFECT ON ICECUBE HIGH ENERGY STARTING EVENTS

- Scattering via **multiple** MeV-mass mediators
- Tower of gauge bosons
  ⇒ **Multiple s-channel resonances in x-section**
  ⇒ Multiple dips in flux spectrum
- Narrower resonances with increasing Z' mass
- **Repeated resonant attenuation** with increasing astrophysical ν energy
  ⇒ **Natural softening of spectral shape at 1 PeV+**
  ⇒ **Consistency with HESE data** even when *originating with hard spectral index* $\gamma \approx 2$
- Rich phenomenology with impact on other searches: MuSIC, NA64, FμBD etc. …



PRELIMINARY

Ref

Main: A. Bhattacharya, A. Kaushik, and K. Nishiwaki; *Work-in-progress*

Related: Hooper et al, PRD 108,023007 (2023); nuSIProp PRD 104, 123014 (2021); D. Chakraborty et al PRD 110, 095030 (2024) and PRD 113, 115038 (2026)

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