Fundamental Physics with Ultrahigh Energy Neutrinos

Bei Zhou
Research Associate, Theory division, Fermi National Accelerator Laboratory
Associate Fellow, Kavli Institute for Cosmological Physics, University of Chicago

Neutrino physics/astrophysics: interdisciplinary

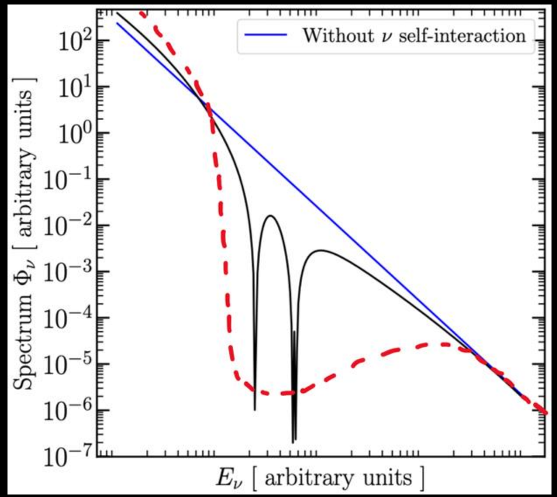
Neutrino BSM

Neutrino astrophysics

Neutrino interactions

- Only known particles with BSM (masses)
- May drive next fundamental-physics breakthroughs
- Must scrutinize all possible neutrino signals
    - Terrestrial, Astrophysical, Interactions

- Discover new astro nu (UHE, DSNB)
- Source identification helps test BSM
- BSM “directly” relevant for nu astro



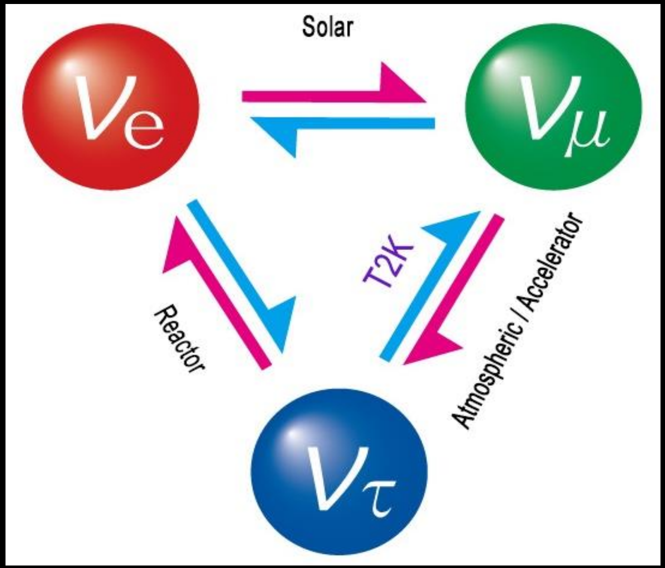
- Foundation for neutrino measurements
- Poorly understood

Neutrino physics is inherently interdisciplinary:
progress in one direction drives and benefits from advances in the others

Neutrino BSM: neutrino self interactions

Neutrinos have new physics

Neutrino oscillation indicates neutrinos have masses



$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\ \sin^2\left(1.27\,\frac{\Delta m^2\,[\mathrm{eV}^2]\cdot L\,[\mathrm{km}]}{E\,[\mathrm{GeV}]}\right)$$

Nonzero neutrino masses guarantee new physics

$$\mathcal{L}_{\mathrm{Dirac}} = -y_\nu\,\bar{L}\tilde{H}\nu_R + \mathrm{h.c.}$$

$$\Rightarrow \quad m_\nu^{\mathrm{Dirac}} = y_\nu\,\frac{v}{\sqrt{2}}$$

$$\mathcal{L}_{\mathrm{Majorana}} = \frac{c}{\Lambda}\left(\bar{L}\tilde{H}\right)\left(\tilde{H}^T L^c\right) + \mathrm{h.c.}$$

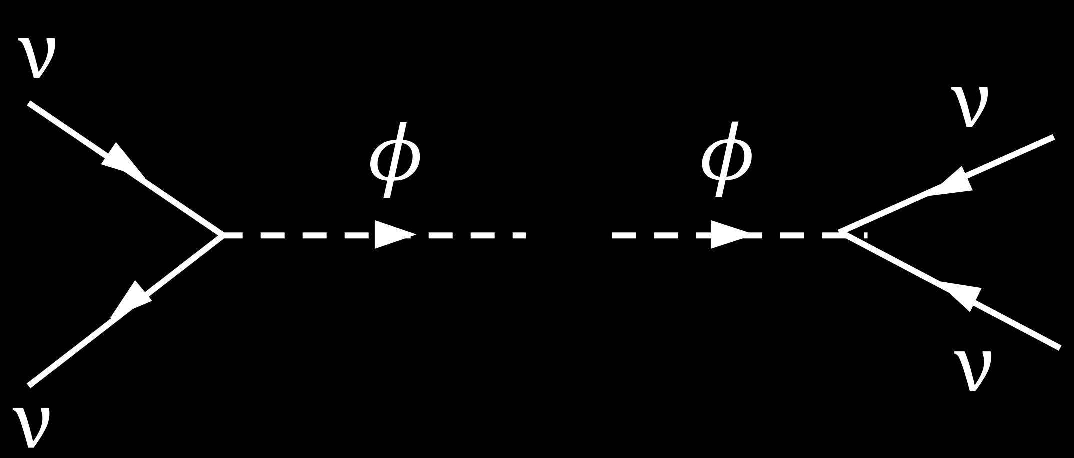
$$\Rightarrow \quad m_\nu^{\mathrm{Majorana}} \sim \frac{c\,v^2}{\Lambda}$$

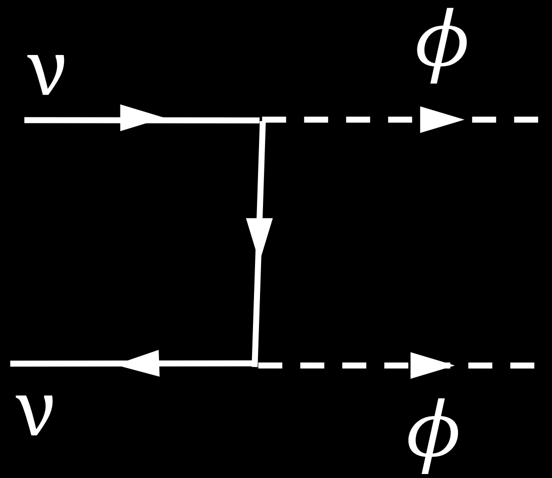
Neutrino masses motivate neutrino self-interactions (NuSI)

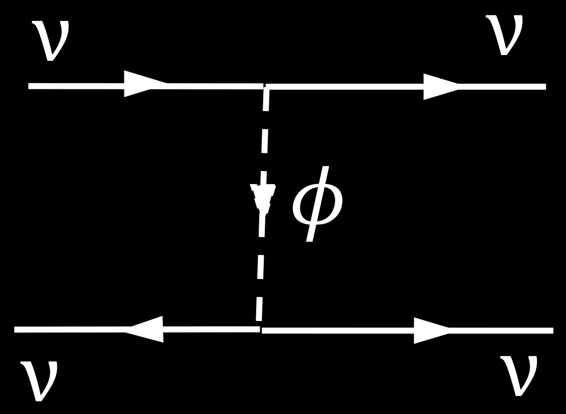
$$\mathcal{L} \supset \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m_\phi^2\phi^2 + g_\nu \phi(\nu\nu + \nu^\dagger\nu^\dagger)$$

NuSI (flavor universal)

NuSI processes → rich phenomena in particle physics, cosmology, astrophysics



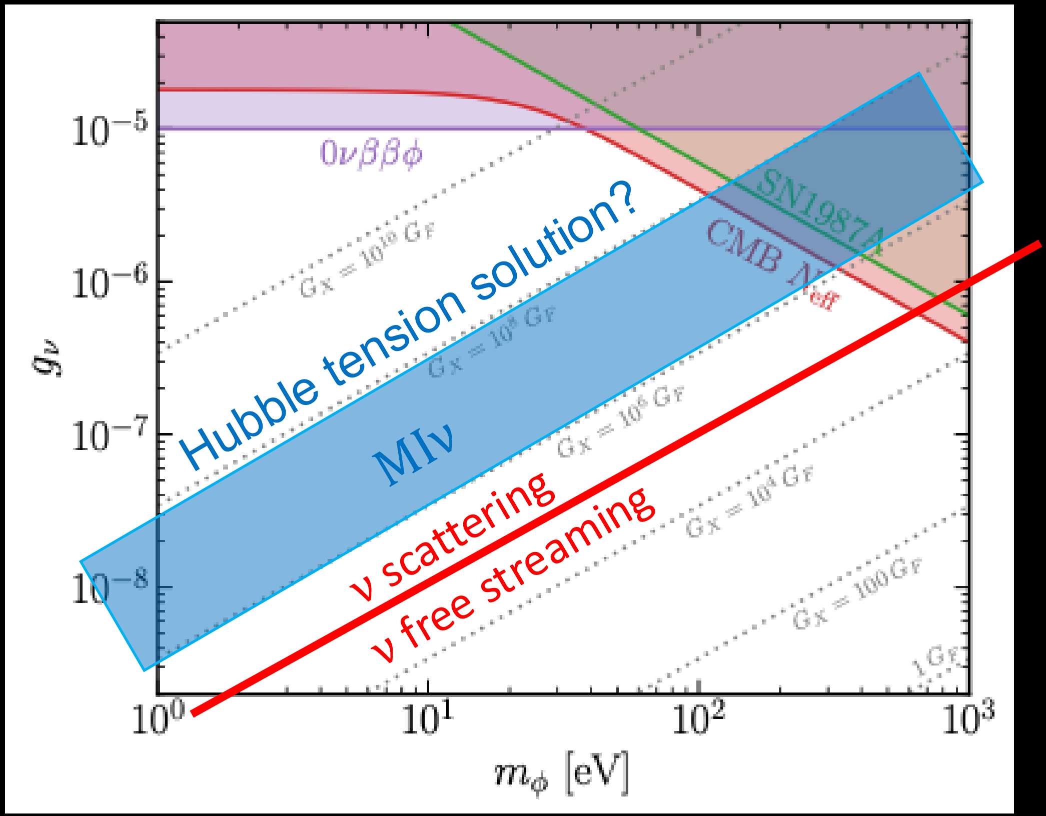




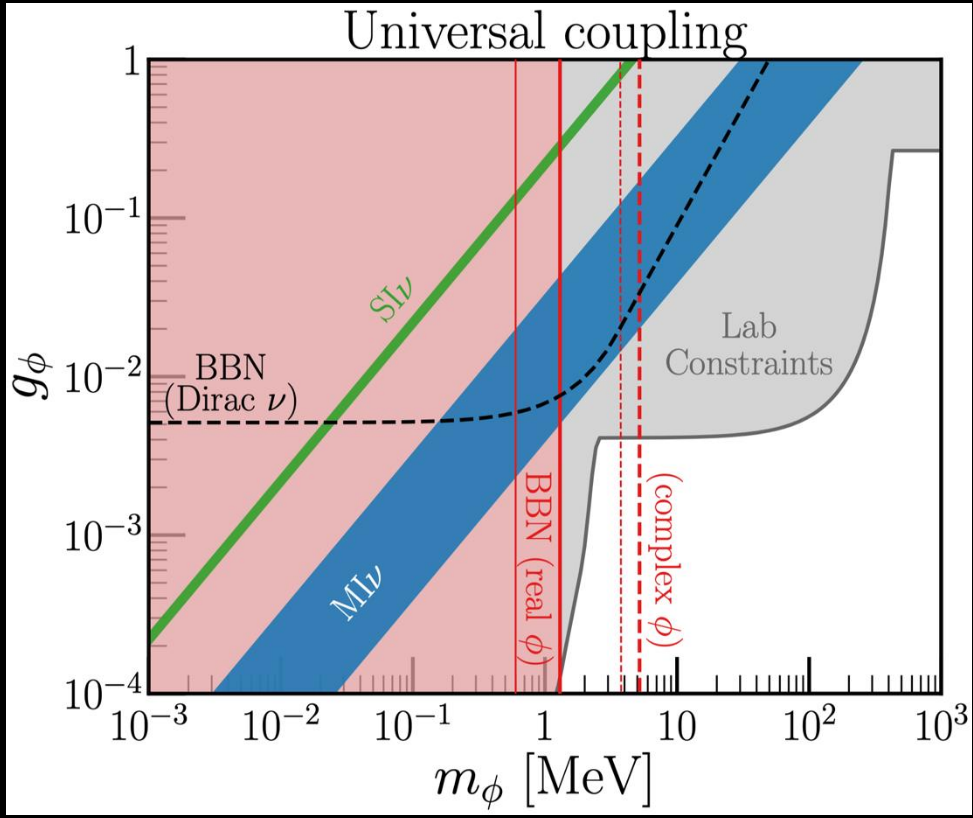
Strong constraints on NuSI from the rich phenomena

$$\mathcal{L} \supset \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m_\phi^2\phi^2 + g_\nu\phi(\nu\nu + \nu^\dagger\nu^\dagger)$$

NuSI (flavor universal)



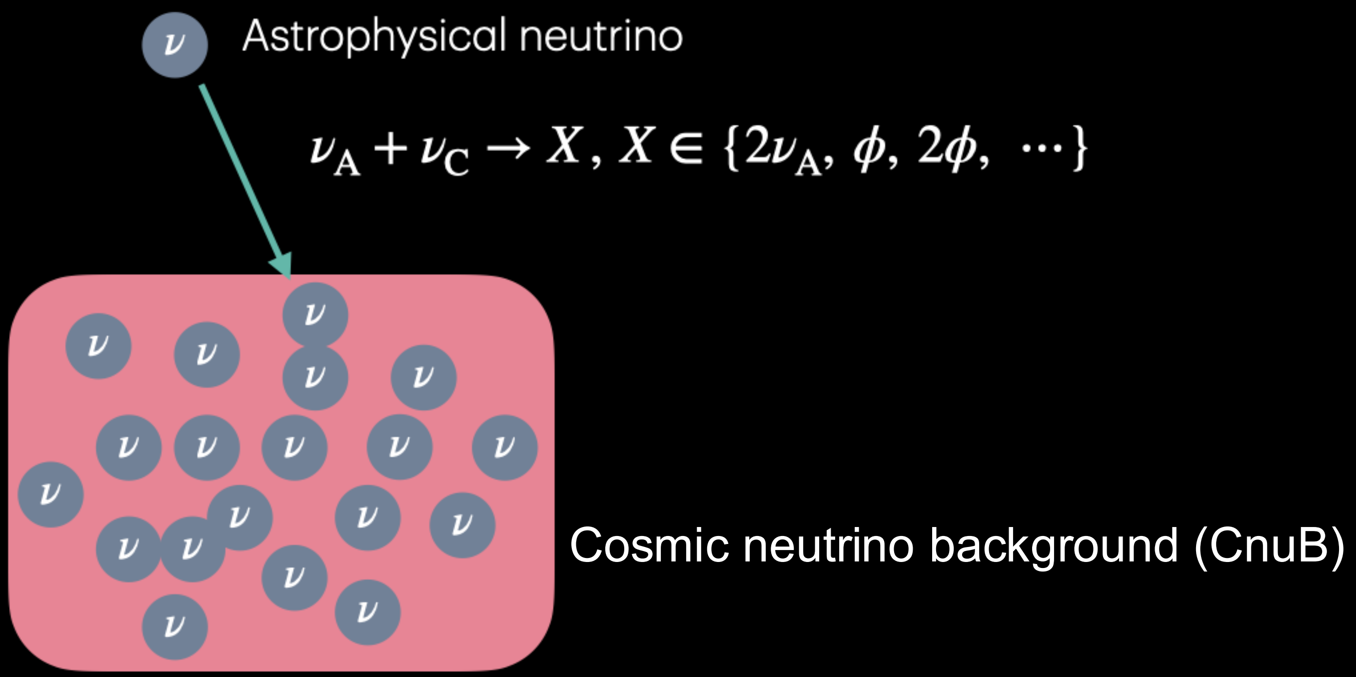
Isaac Wang, Xun-Jie Xu, BZ, 2501.07624 PRL

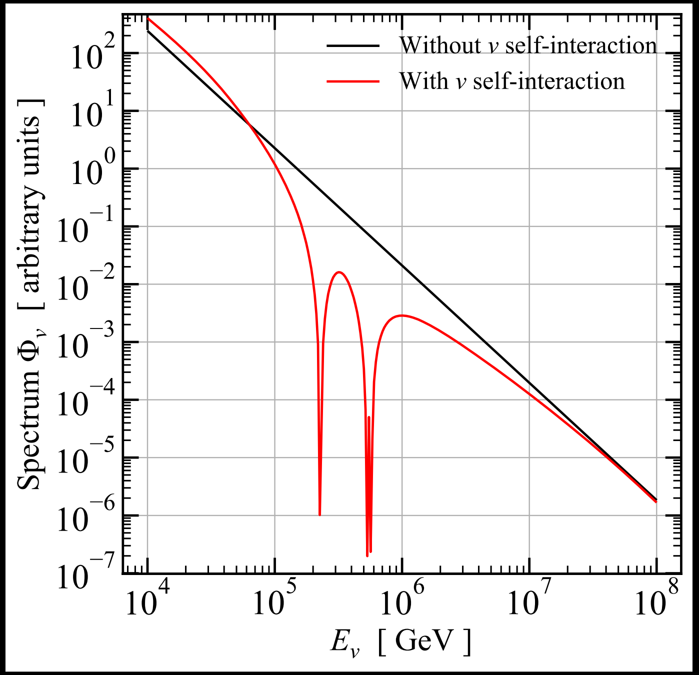


Blinov, Kelly, Krnjaic, McDermott 1905.02727

Astrophysical ν from cosmological distances probing NuSI

$$\mathscr{L} \supset \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m_\phi^2\phi^2 + g_\nu\phi(\nu\nu + \nu^\dagger\nu^\dagger)$$





Astrophysical neutrinos from cosmological distances

MeV

- Diffuse supernovae neutrino background
    - Will be detected soon

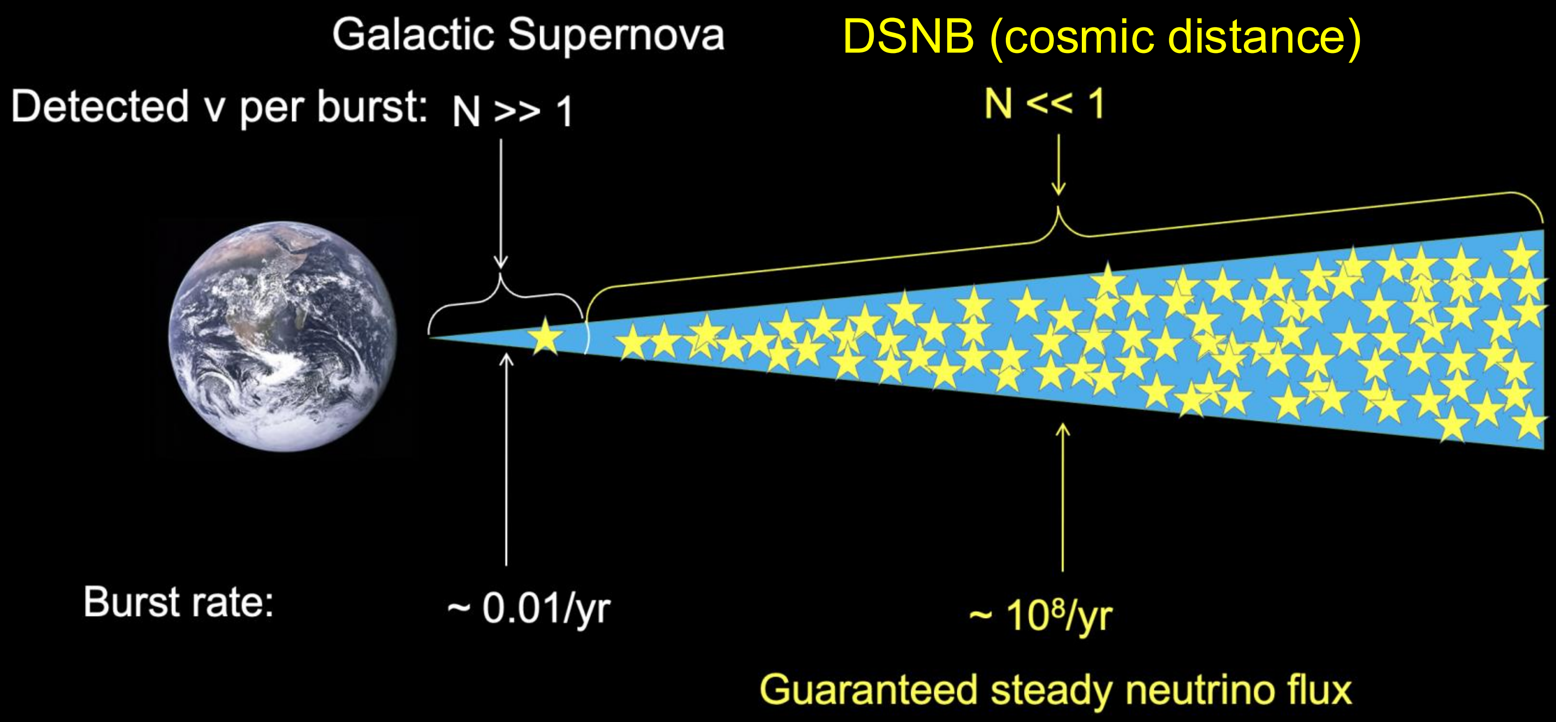
TeV—PeV (HE)

- TeV—PeV astrophysical neutrinos
    - First detected by IceCube
    - Then by other detectors

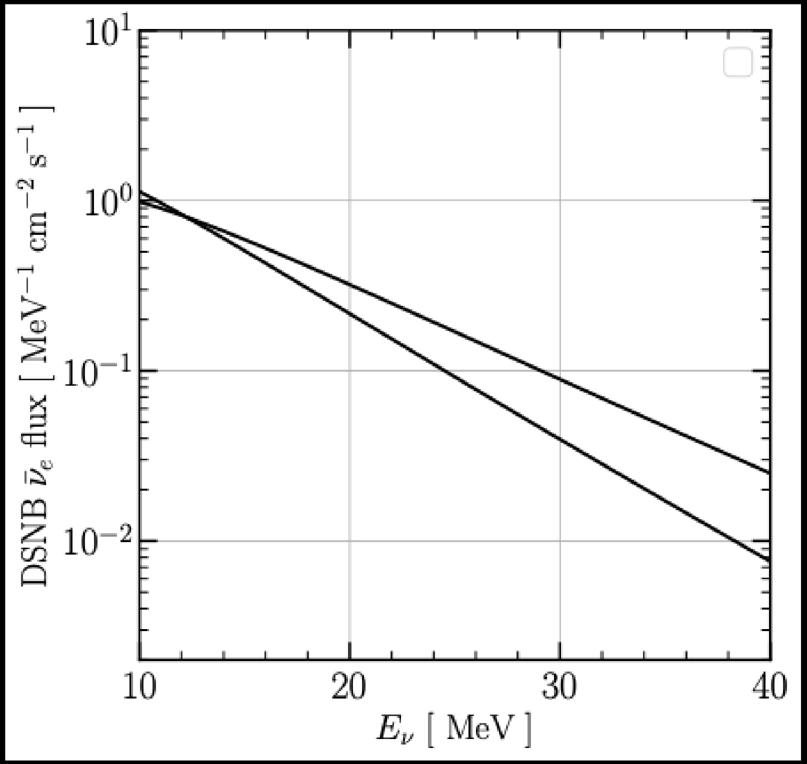
EeV (UHE)

- UHE cosmogenic neutrinos
    - Will be detected soon

Diffuse Supernova Neutrino Background (DSNB)

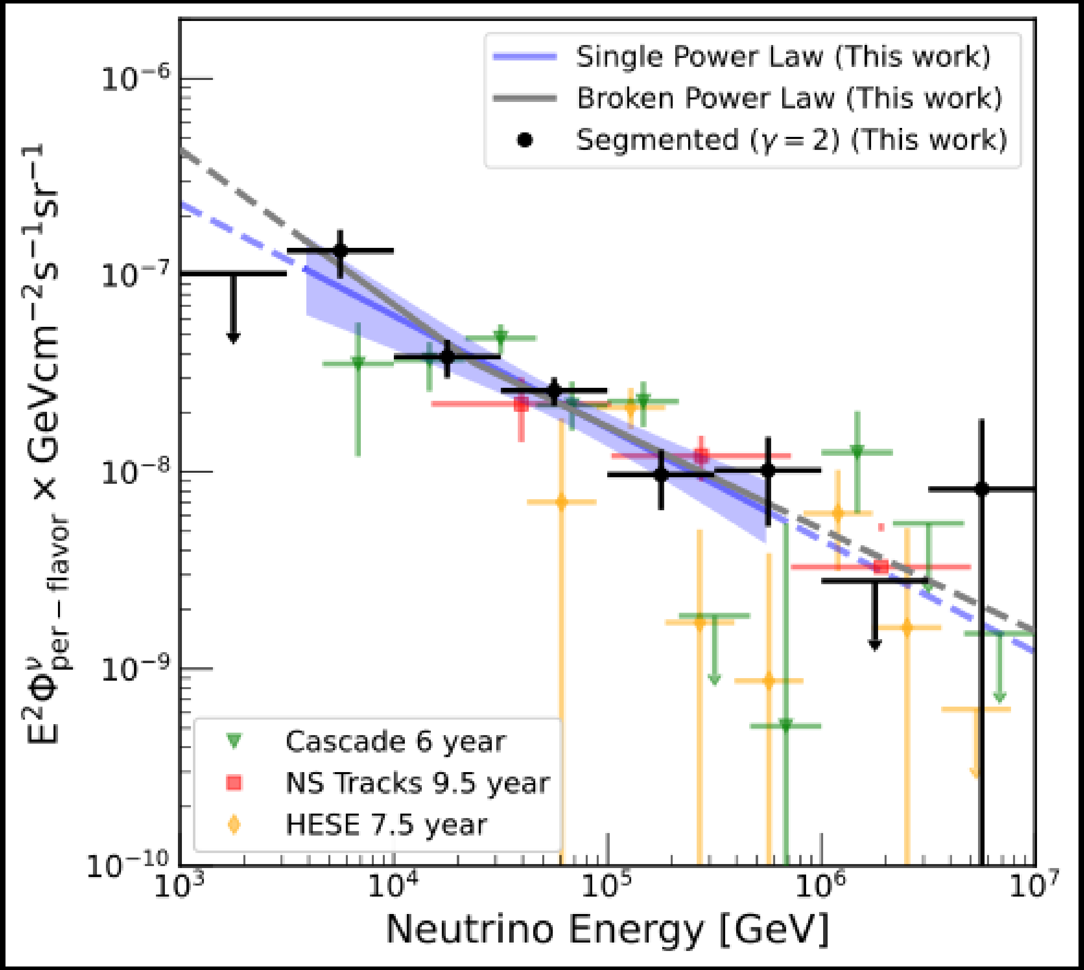


DSNB spectrum



1004.3311 John Beacom, Ann.Rev.Nucl.Part.Sci.

TeV—PeV astrophysical neutrinos



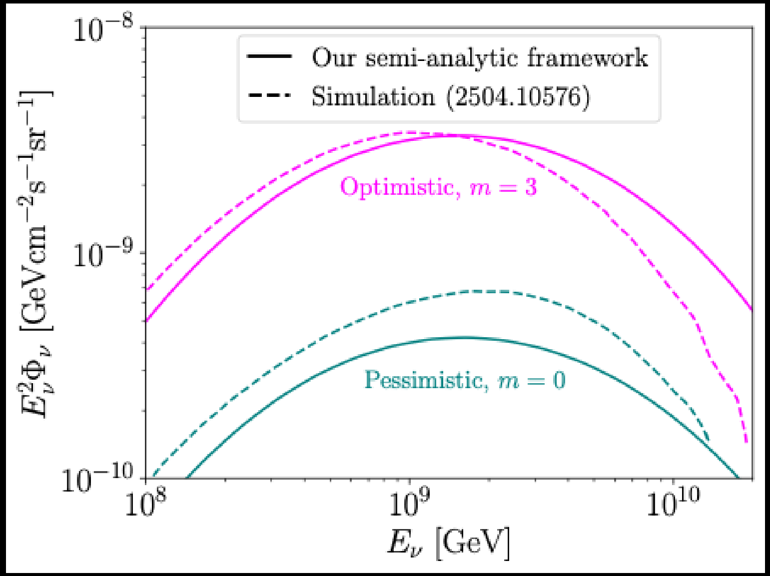
2402.18026 IceCube Collaboration

- Discovered by IceCube, confirmed by others
- Power law or broken power law
- Possible sources:
  - TXS 0506+056 blazar?
  - X-ray bright Seyfert galaxies?
    - NGC 1068
    - NGC 4151
  - Supermassive black hole binaries? (3σ)
    (2512.02099 Pugazhendhi, Bouri, BZ, Rachana, Laha)

UHE neutrinos

Cosmogenic

1. Guaranteed
2. Ultrahigh energy cosmic rays (UHECRs) scattering off cosmic microwave background
3. $p + \gamma \rightarrow \Delta \rightarrow \pi \rightarrow \nu$



2512.00165 Machado, Wang, Xu, BZ

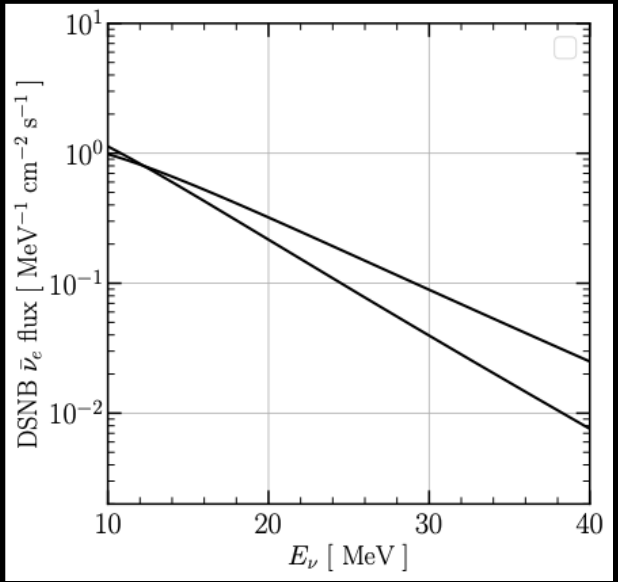
Astrophysical

1. Not guaranteed
2. Model dependent, highly uncertain

Astrophysical neutrinos from cosmological distances

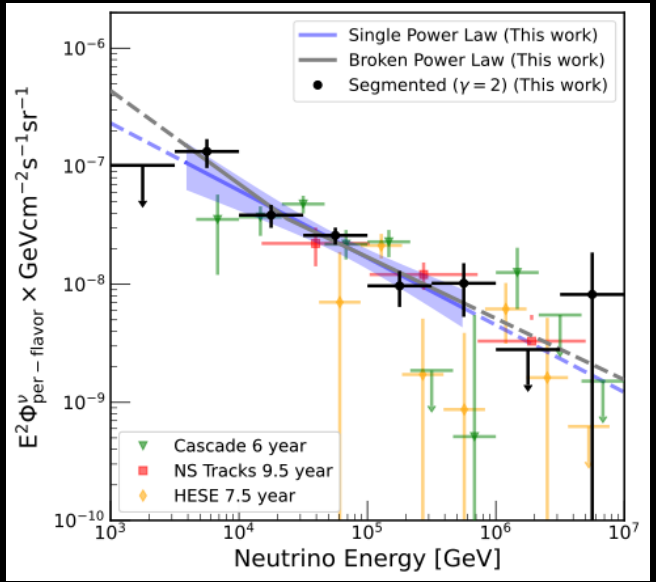
MeV

- Diffuse supernova neutrino background



TeV—PeV (HE)

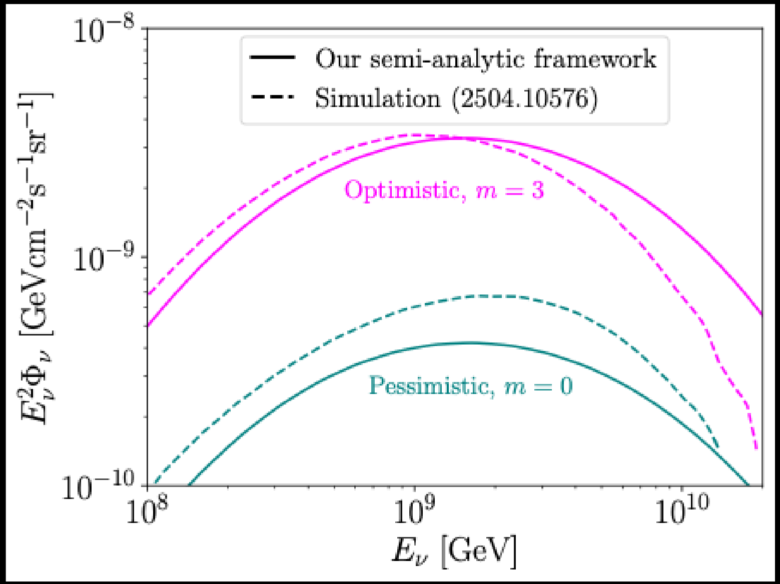
- TeV—PeV astrophysical neutrinos
  - First detected by IceCube
    Later by other detectors



2402.18026 IceCube Collaboration

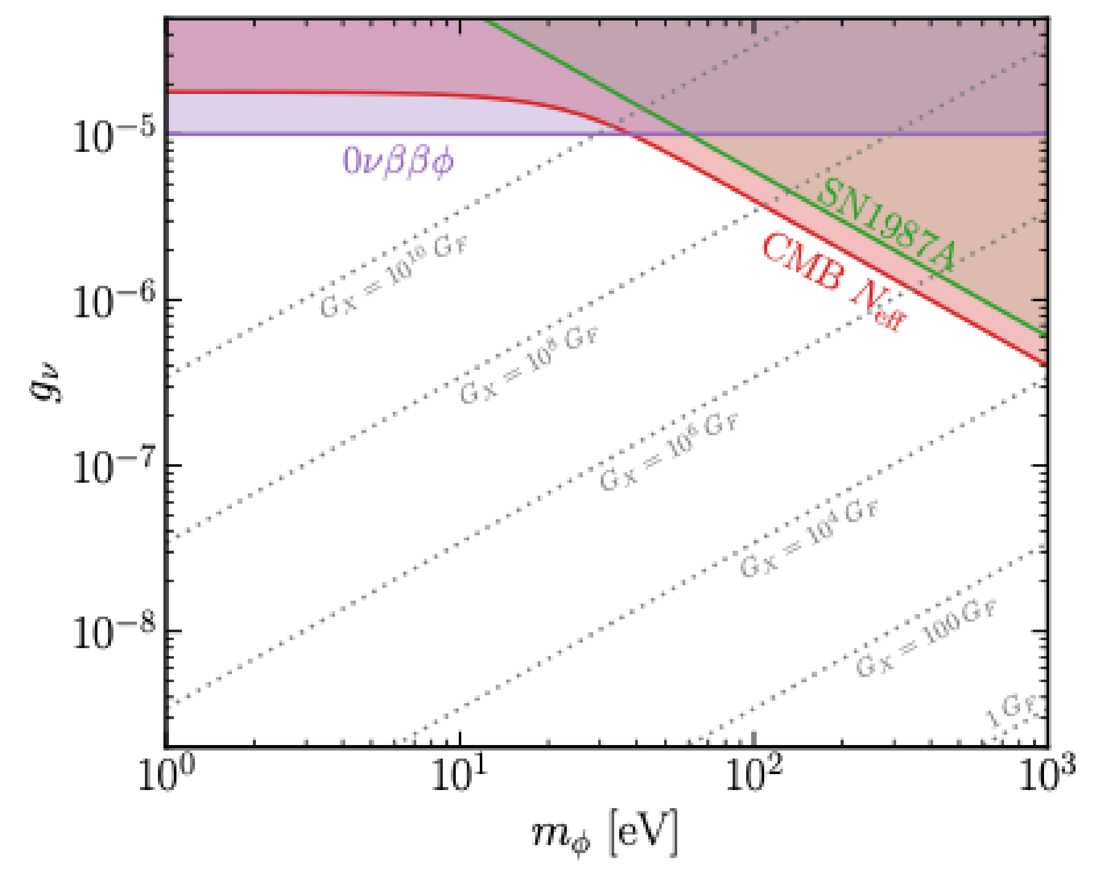
EeV (UHE)

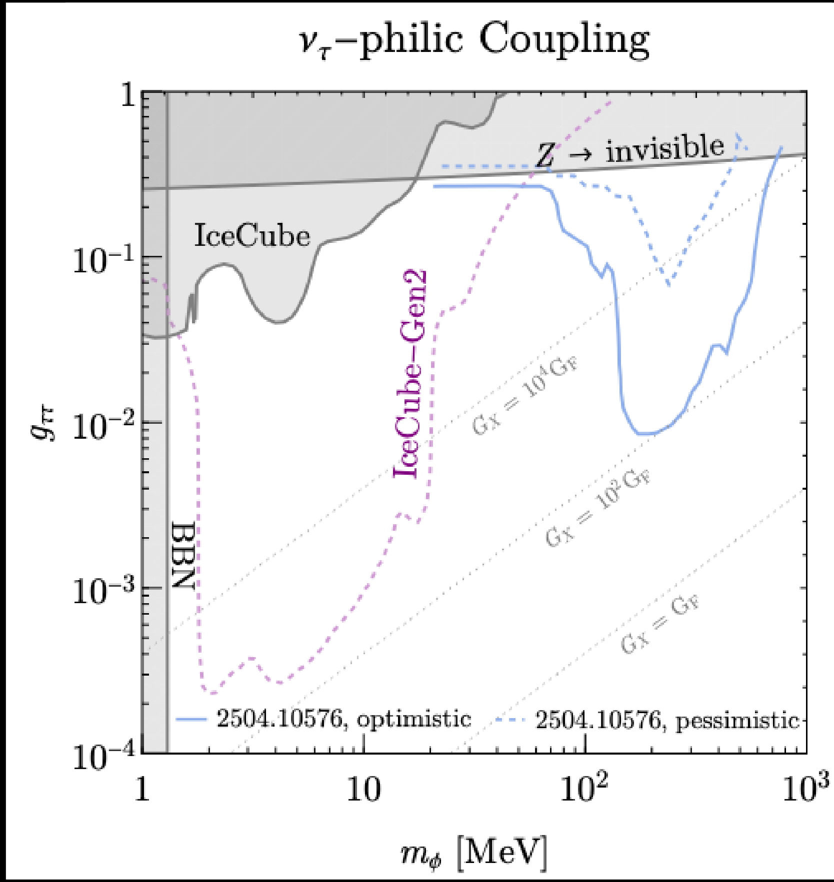
- UHE cosmogenic neutrinos



2512.00165 Machado, Wang, Xu, BZ

Astrophysical ν from cosmological distances probing NuSI





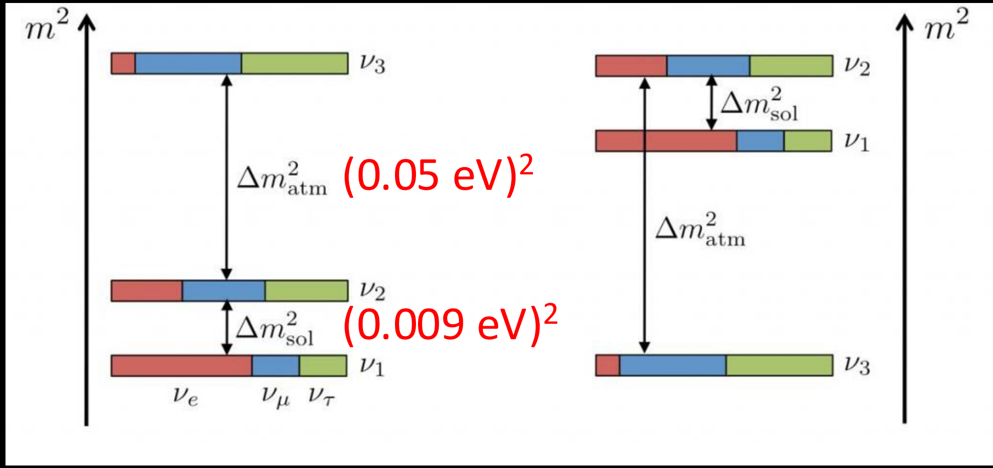
2107.13568 Esteban, Pandey, Brdar, Beacom
2504.10576 Leal, Naredo-Tuero, Funchal
2512.00165 Machado, Wang, Xu, BZ

Novel regime of NuSI

Normal ordering   Inverted ordering

Conventional:

Our idea:



What if the lowest mass state has

m_ν << T_{CnuB} ≃ 1.95 K ≃ 1.7e-4 eV ?

1. Allowed by oscillation measurements
2. Highly favored by recent DESI results

(Previous studies all assumed $\sum m\nu$ = 0.1 eV)

$$m_\phi \simeq \sqrt{2E_\nu m_\nu} \simeq \underline{1.5\ \mathrm{keV}} \left(\frac{E_\nu}{10\ \mathrm{MeV}}\right)^{\frac{1}{2}} \left(\frac{m_\nu}{0.1\ \mathrm{eV}}\right)^{\frac{1}{2}}$$

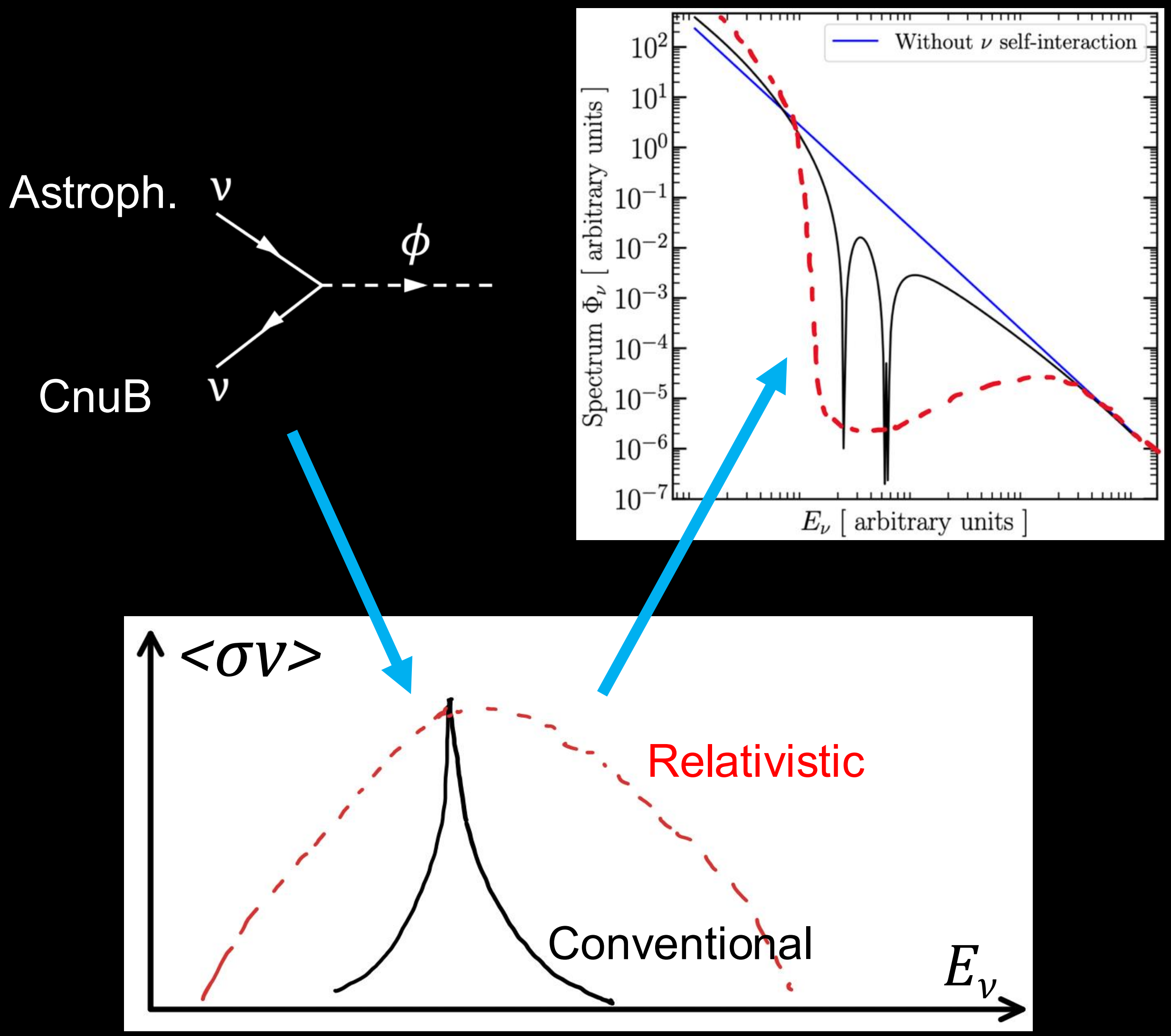
Nonrelativistic nuSI

$$m_\phi \simeq \sqrt{4E_\nu T_{C\nu B}} \simeq \underline{80\ \mathrm{eV}} \left(\frac{E_\nu}{10\ \mathrm{MeV}}\right)^{\frac{1}{2}} \left(\frac{T_{C\nu B}}{1.7\times10^{-4}\ \mathrm{eV}}\right)^{\frac{1}{2}}$$

Relativistic nuSI

Novel regime of NuSI

Widened xsec resonance → widened absorption



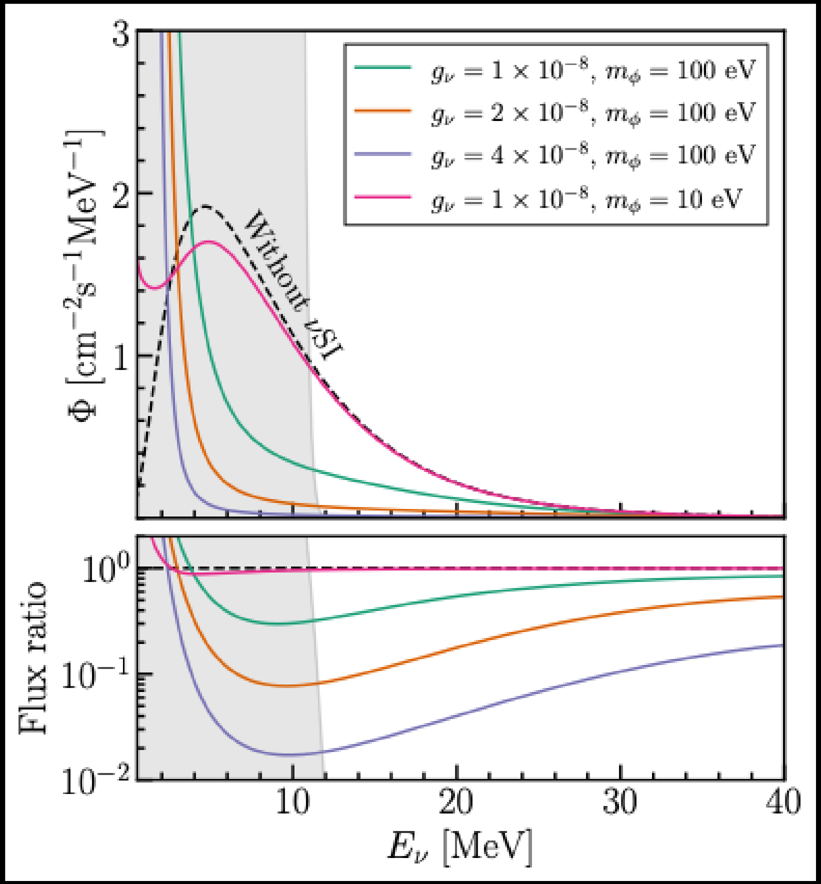
Probing very small couplings

$$\sigma \propto \frac{g^2}{m_\phi^2}$$

Relativistic and nonrelativistic NuSI

Neutrino spectra: without and with relativistic NuSI

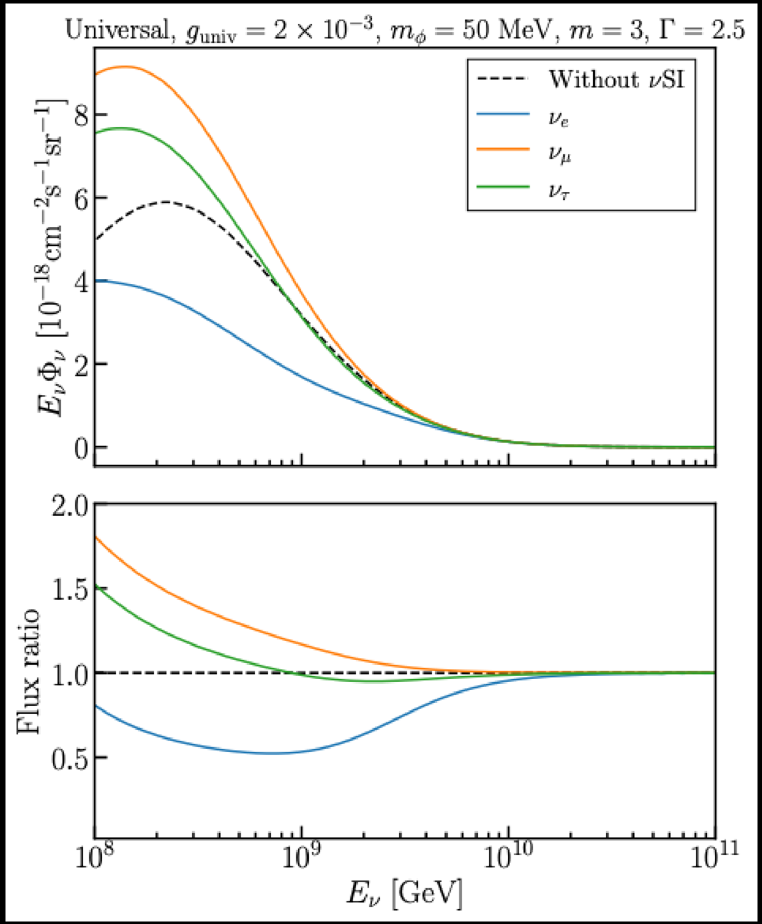
MeV DSNB



To be measured at Hyper-Kamiokande, water Cherenkov neutrino detector in Japan

Isaac Wang, Xun-Jie Xu, BZ 2501.07624 PRL

UHE cosmogenic neutrinos

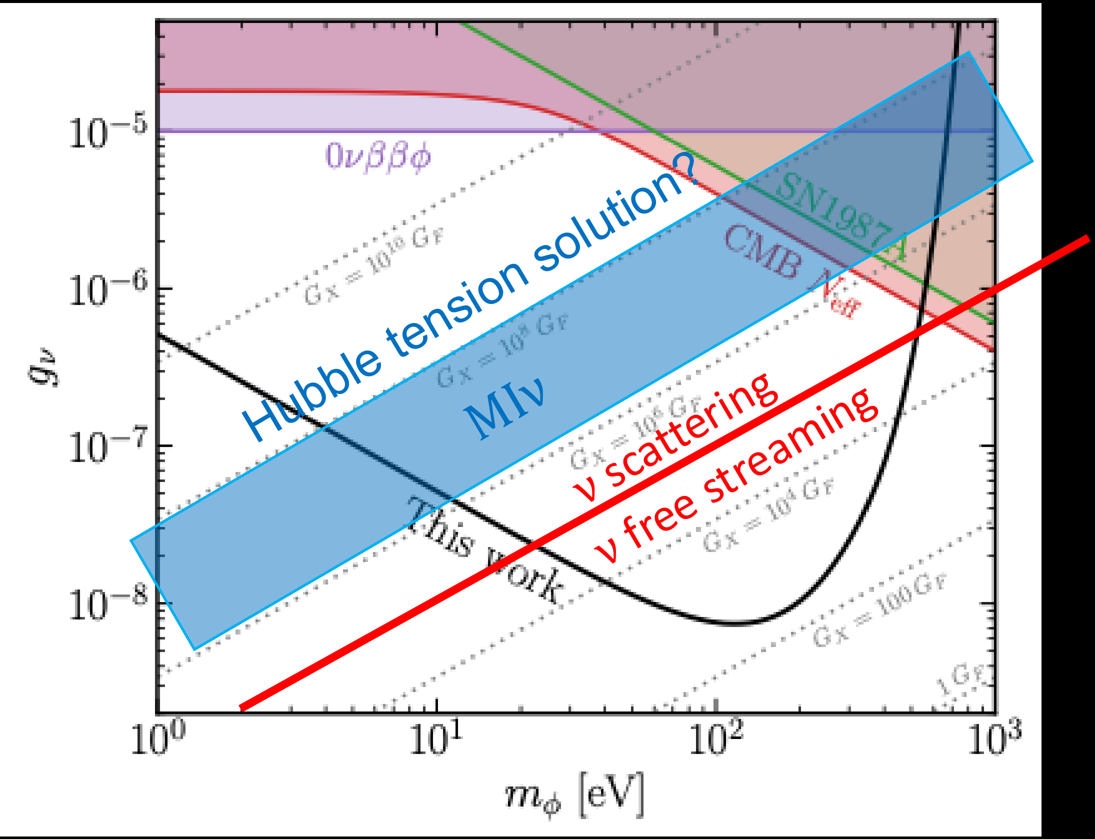


To be measured at GRAND, earth emergent tau detector

Pedro Machado, Isaac Wang, Xun-Jie Xu, BZ 2512.00165

Results: using MeV diffuse supernova neutrino background

$$\mathcal{L} \supset \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m_\phi^2\phi^2 + g_\nu\phi(\nu\nu + \nu^\dagger\nu^\dagger)$$ NuSI



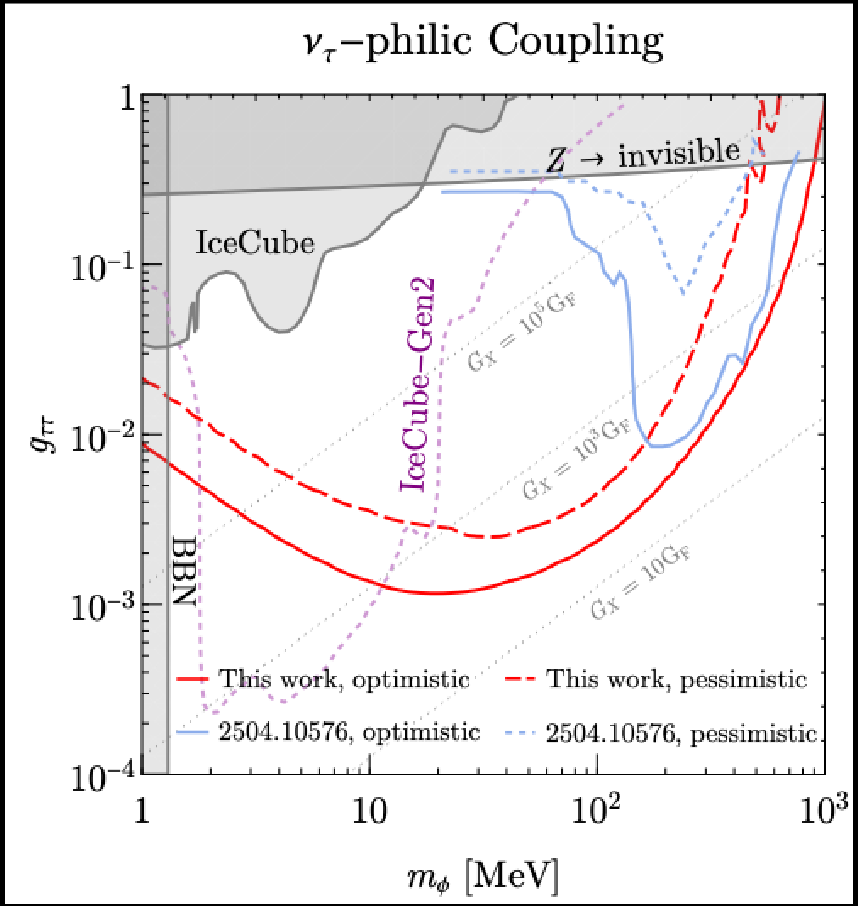
Isaac Wang, Xun-Jie Xu, BZ, 2501.07624 PRL

Relativistic NuSI + DSNB can probe NuSI with sub-keV mediator mass and couplings down to 1e-8

Results: using UHE cosmogenic neutrino background

$$\mathcal{L} \supset \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m_\phi^2\phi^2 + g_\nu\phi(\nu\nu + \nu^\dagger\nu^\dagger)$$

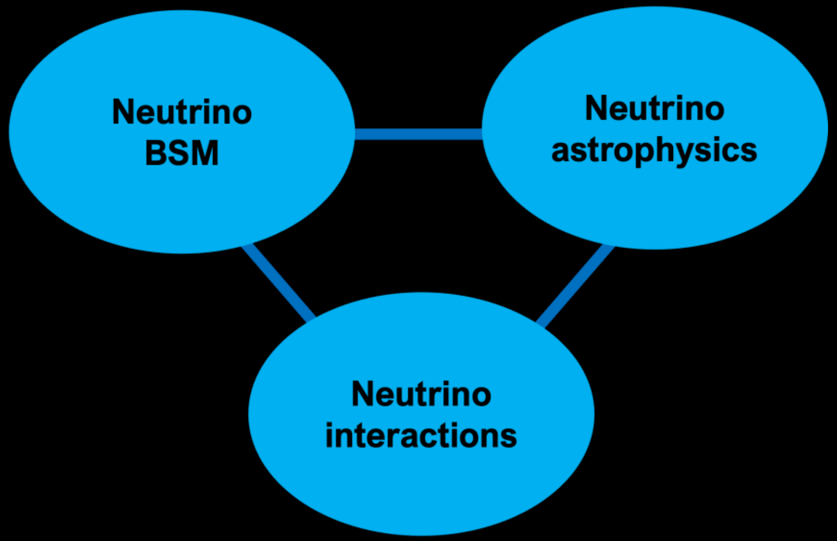
NuSI



Pedro Machado, Isaac Wang, Xun-Jie Xu, BZ 2512.00165

Neutrino interactions (UHE and HE)

Why study nu interactions



- Foundation for all neutrino-related measurements
- Poorly understood
  - Cross section underestimation → flux overestimation; vice versa
  - Similar for spectrum shape and flavor ratios
  - Absorption, arrival direction
- New event classes → new measurement opportunities
  - Flavor identification, e.g., double bang for nutau
  - BSM signatures or background, e.g., double tracks from SUSY and CCDIS *(BZ, Beacom, 2110.02974)*
- Neutrino(-nucleus) interaction theory is rich & challenging
  - Weak/electroweak
  - QED, e.g., final state ration *(Plestid, BZ, 2403.07984)*
  - Strong interactions & QCD
  - Detection physics adds further complexity

Landscape of the HE and UHE neutrino experiments

HE neutrino telescopes (~100 GeV--100 PeV)

Detector	Size	Status
IceCube	1 km^3	Running >17 yrs
KM3NET	1 km^3	Running, constructing
Baikal-GVD	2 km^3	Running, constructing
IceCube-Gen2	*7.9 km^3*	*Prototype*
TRIDENT	*7.5 km^3*	*Prototype*
HUNT	*30 km^3*	*Prototype*
P-ONE	*multi-km^3*	*Prototype*

Laboratory HE nu experiments (~10 GeV-- ~TeV)

Detector	Size	Status
FASERv	Neutrino beam from LHC	Running
SND@LHC		Running
FASERv2		*Proposed*
AdvSND@LHC		*Proposed*
FLArE		*Proposed*

UHE neutrino telescopes (>~100 PeV)

Detector	Size	Status
ANITA		Finished
ARA		Running
ARIANNA		Running
RNO-G		Constructing
PUEO		Constructing
BEACON		*Prototype*
TRINITY		*Demonstrator*
TAMBO		*Prototype*
POEMMA		*Prototype*
GRAND		*Prototype*
IceCube-Gen2 radio		*Proposed*
Etc....		

See 2203.08096, Ackermann, ..., BZ (Snowmass) for a complete list

HE/UHE nu experiments needs more precise cross sections

HE neutrino experiments

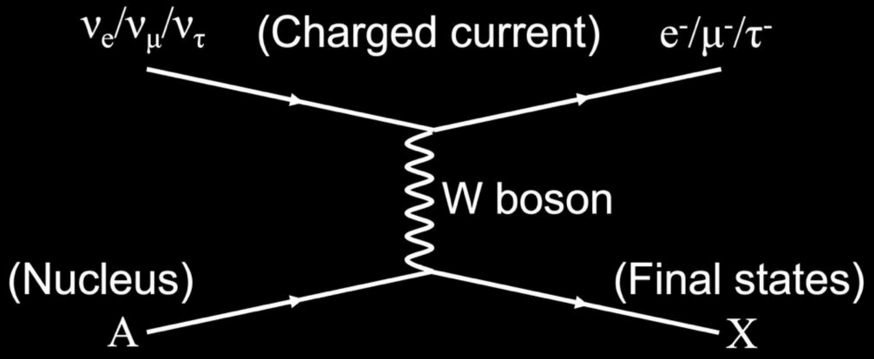
- IceCube (1 km^3) needs <10% precision after ~16 yrs observation (per Francis Halzen)
- Next generation (~10 km^3) → a few percent level
- If interactions not studied, HE neutrinos will enter a systematics dominated regime
  - ➢ Underestimated xsec → overestimated flux; vice versa
  - ➢ Similar for spectrum, flavor measurements

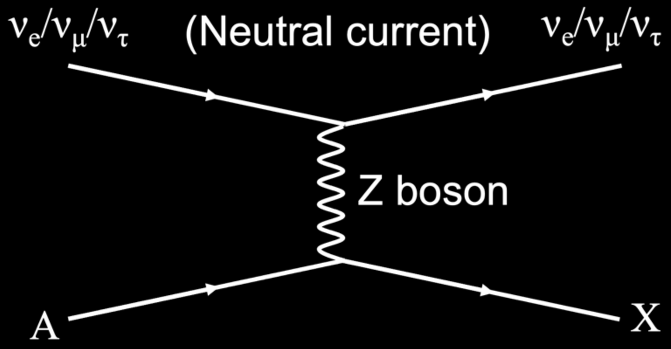
UHE neutrinos experiments

- more precision upper limits now and measurements in the future

Status of HE & UHE neutrino interactions before my contributions

Deep inelastic scattering (DIS) dominates (few% precision at TeV energies)

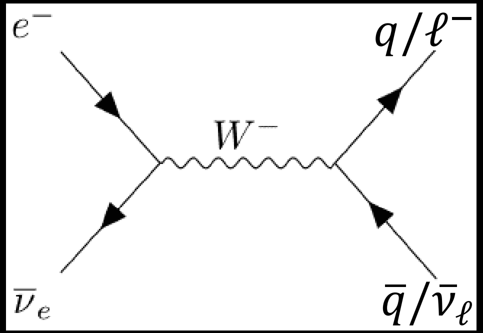




Gandhi+ 96&97, Connolly+ 11, Cooper-Sarkar+ 11, Bertone+ 16, etc.

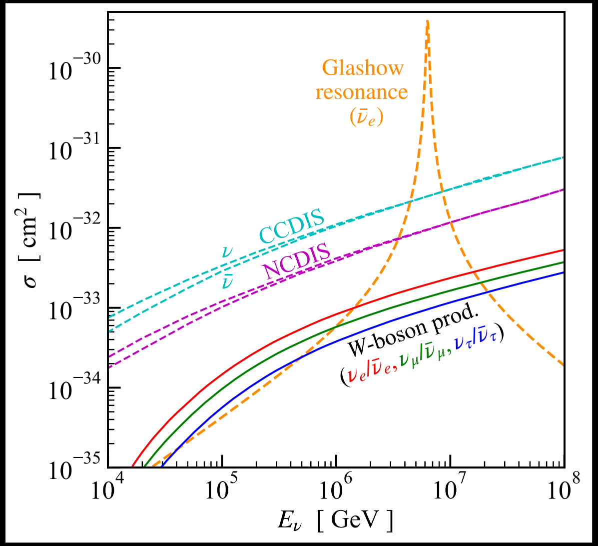
Most recent: Xie, et al. 2303.13607; Weigel, et al 2408.05866

Glashow resonance important for $\bar{\nu}_e$ (precise)



Glashow 1960
IceCube 2021

Cross sections



(BZ, Beacom, 1910.10720, PRD)

My contributions to HE & UHE neutrino interactions

- Goal: making neutrinos more and more precision probes for physics studies
- Crucial for upcoming HE & UHE neutrino detection

1. Second largest interaction: neutrino-nucleus W-boson production
   - *(1910.08090, 1910.10720, 2305.10497)*
   - (Largest interaction well understood for a while)
   - ~10% enhancement in the effective area, absorption, and other effects
   - IceCube Collaboration integrating WBP to pipeline
     - *(cited by ≃10 papers and ≃10 Ph.D. theses from IceCube Collaboration)*

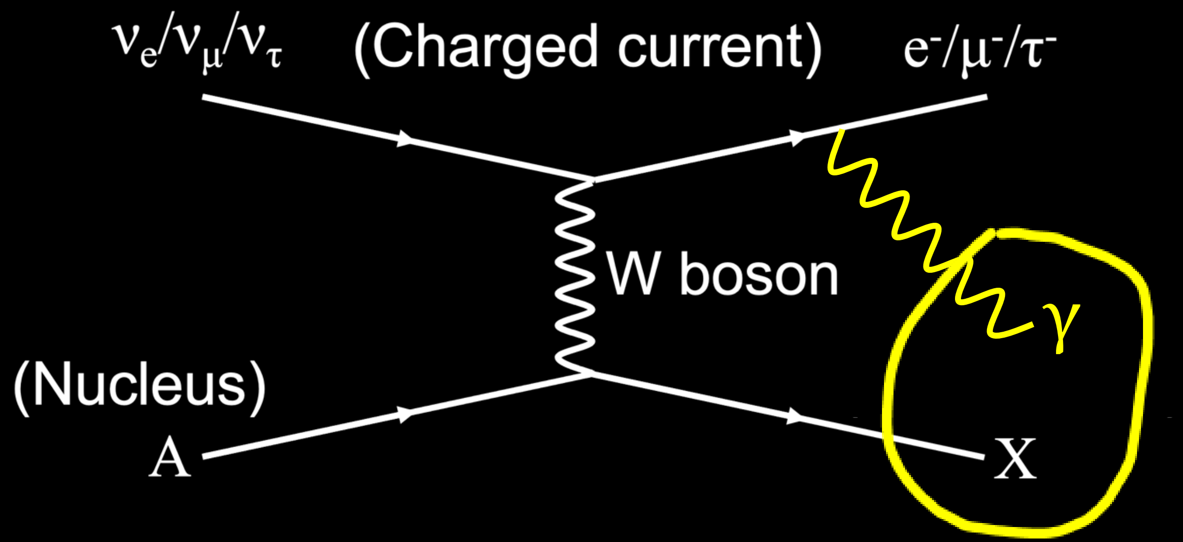
2. Largest corrections to differential cross section: final state radiation *(2403.07984)*
   - Up to 60% bias on nu flux measurements; collider neutrinos
   - IceCube and other collaborations and theorists implemented FSR *(2405.08077, 2405.08070, 2408.05866)*

3. Next event class: dimuons *(2110.02974; 2605.xxxxx)*
   - Measuring s-quark PDF; improves angular resolution, energy reconstruction, and more
   - Motivated IceCube & KM3NeT collaborations' dimuon analyses *(e.g., IceCube PhD thesis by Sourav Sarkar)*

Final state radiation

Largest corrections to differential cross sections

Our work: final state radiation (FSR) on top of neutrino CC DIS

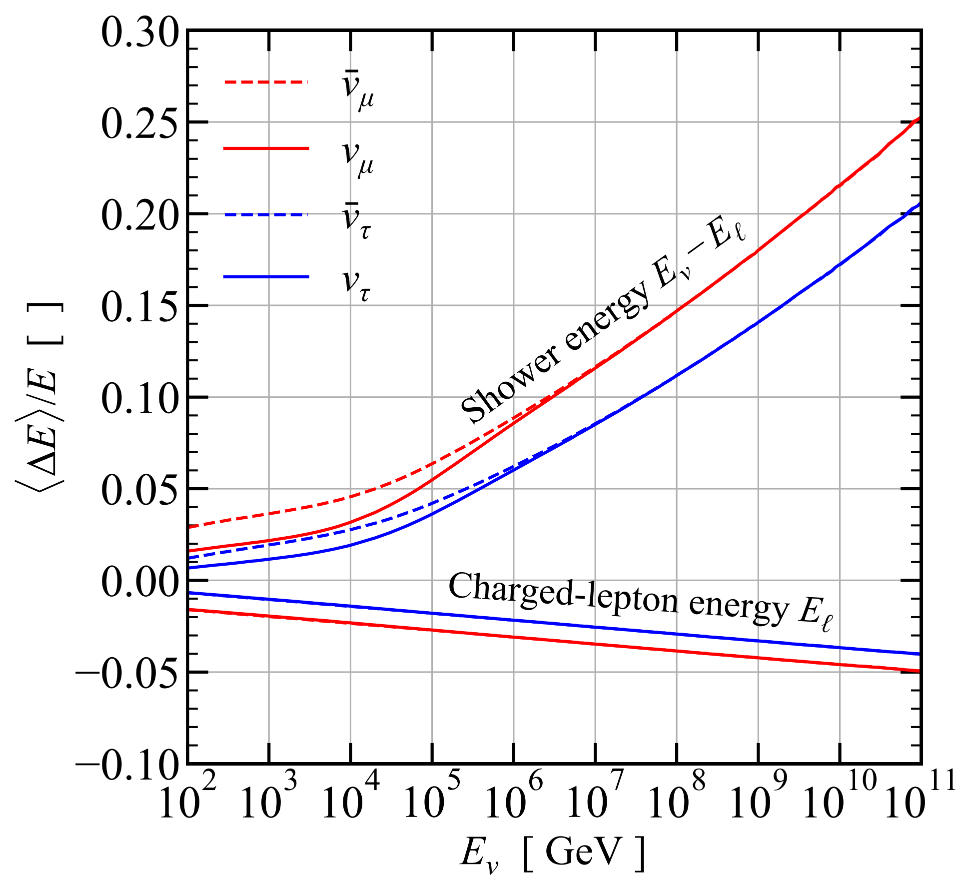


γ+X form shower
X means hadrons

Correction to total xsec: negligible

Correction to differential xsec: big, due to the kinematic logs.
→ Impacts observation as charged lepton and shower usually separable

FSR impacts the energies of the final states from HE/UHE interactions



(Plestid, BZ, 2303.08984)

Photon takes energy from the charged lepton to the shower

- Correction increases with energy, up to 25%(!)
- Correction on shower > charged lepton
- Correction on shower further enhanced by 10—20% due to light yields of EM > hadronic showers

Scaling formulae for FSR correction:

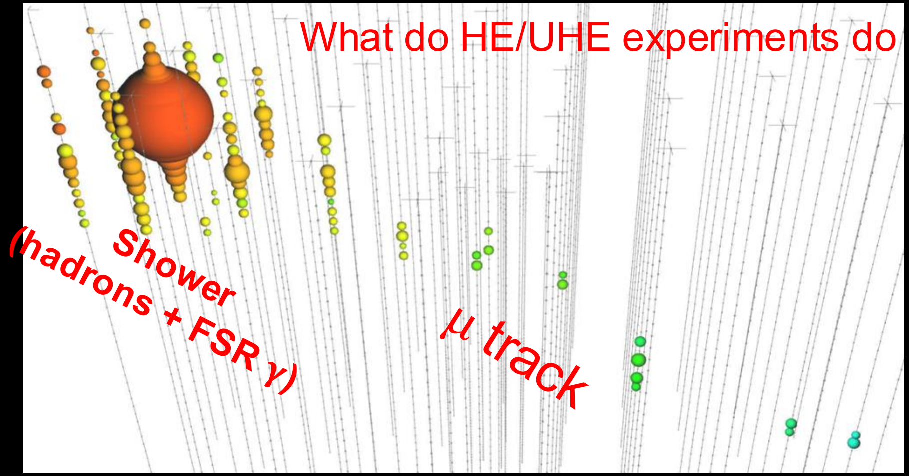
$$\frac{\langle \Delta E_\mu \rangle}{E_\mu} \simeq 4.6\% + 0.0075 \times \log_{10}\left(\frac{E_\nu}{10^{10}\,\mathrm{GeV}}\right)$$

$$\frac{\langle \Delta E_\tau \rangle}{E_\tau} \simeq 3.7\% + 0.0075 \times \log_{10}\left(\frac{E_\nu}{10^{10}\,\mathrm{GeV}}\right)$$

$$\frac{\langle \Delta E_{\mathrm{sh}} \rangle}{E_{\mathrm{sh}}} = -\frac{1-y}{y}\frac{\langle \Delta E_\ell \rangle}{E_\ell}$$

Final state radiation impacts the inelasticity (y) measurements

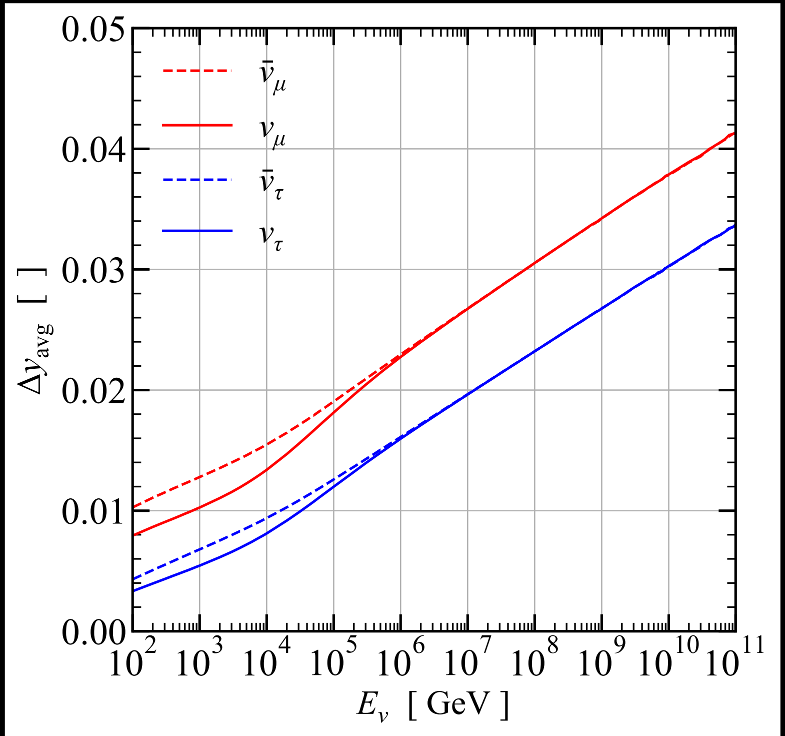
$$y_{\rm QCD} \equiv \frac{E_X}{E_\nu} = \frac{E_\nu - E_\ell}{E_\nu}$$

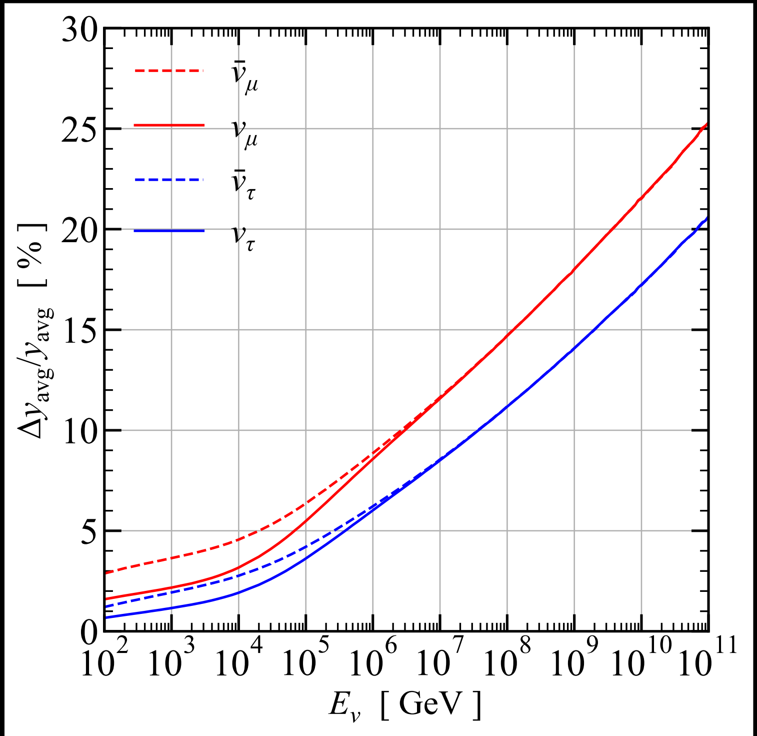


$$y_{\rm exp} \equiv \frac{E_{\rm shower}}{E_{\rm track} + E_{\rm shower}} = y_{\rm QCD} + \frac{E_\gamma}{E_\nu}$$

$$\Delta y_{\rm avg} \equiv \langle y_{\rm exp} \rangle - \langle y_{\rm QCD} \rangle = \langle E_\gamma \rangle / E_\nu$$

So, photon takes energy from the charged lepton to the shower, increasing <y>





(Plestid, BZ, 2303.08984)

Correction increases with energy, up to 25%(!)

FSR impacts high-energy neutrino observations

Measurements based on inelasticity measurement

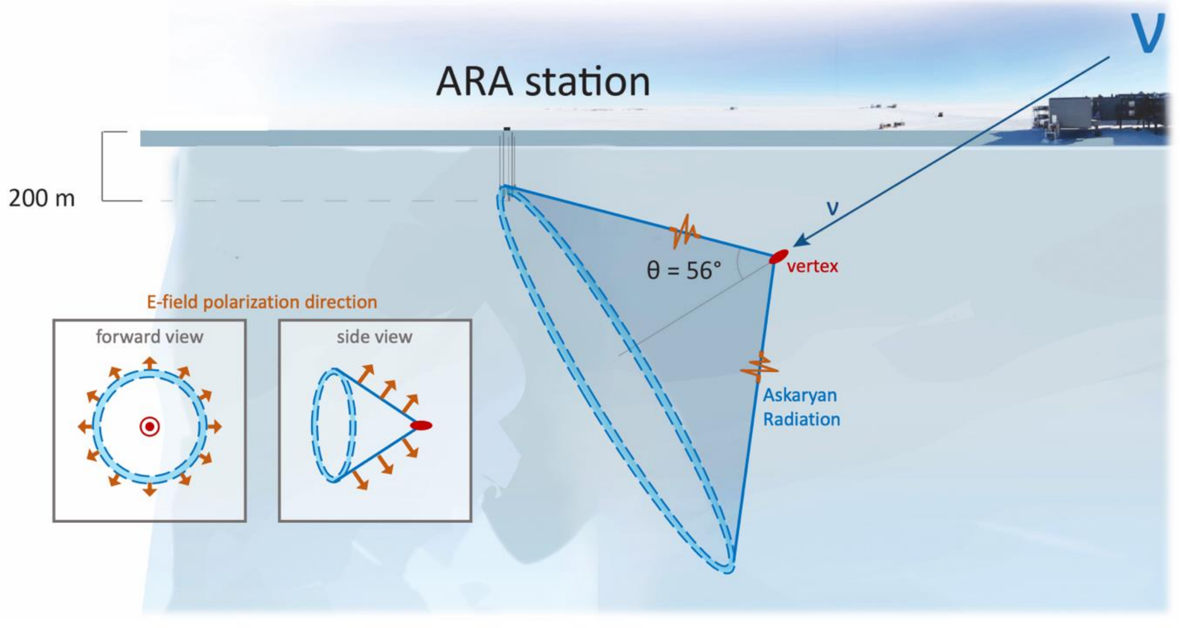
1. Neutrino-antineutrino flux ratio (~5% shift)
2. Neutrino mixing parameters
   - Inel. dist. helps to separate nu/nubar
3. Charm production from nu interactions
   - CCDIS w/ charm production has higher inelasticity

Other measurements

1. Throughgoing muons
   - Without FSR, underestimate parent $E\nu$ (up to 5%)
2. Double bang signature from tau neutrinos
   - Inference of the parent neutrino energy
   - Reduce the detectability

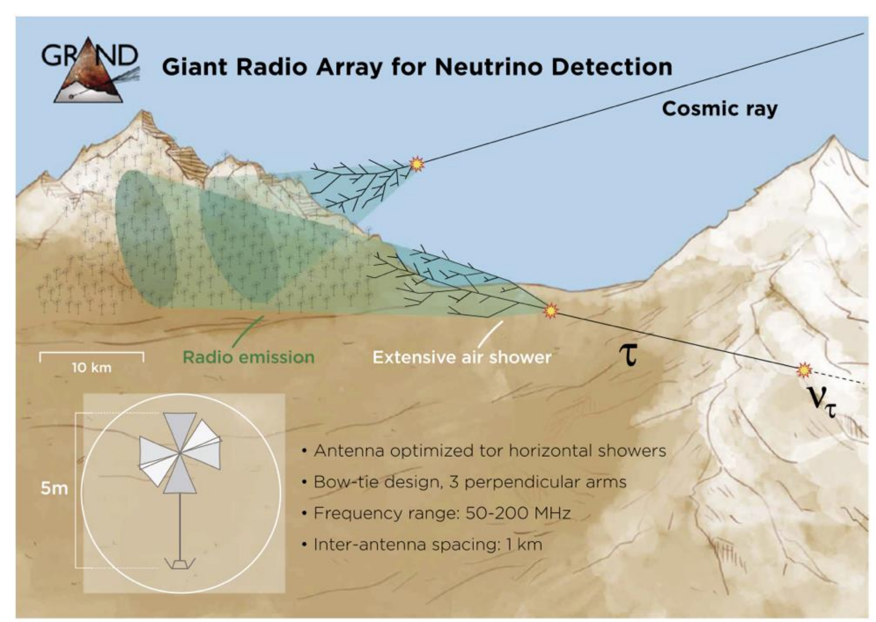
UHE nu observation: two basic kinds of detectors

In-ice radio detectors
(all flavors; hard to distinguish flavors)



1912.00987 ARA collaboration

Air shower detectors
(main for ντ)



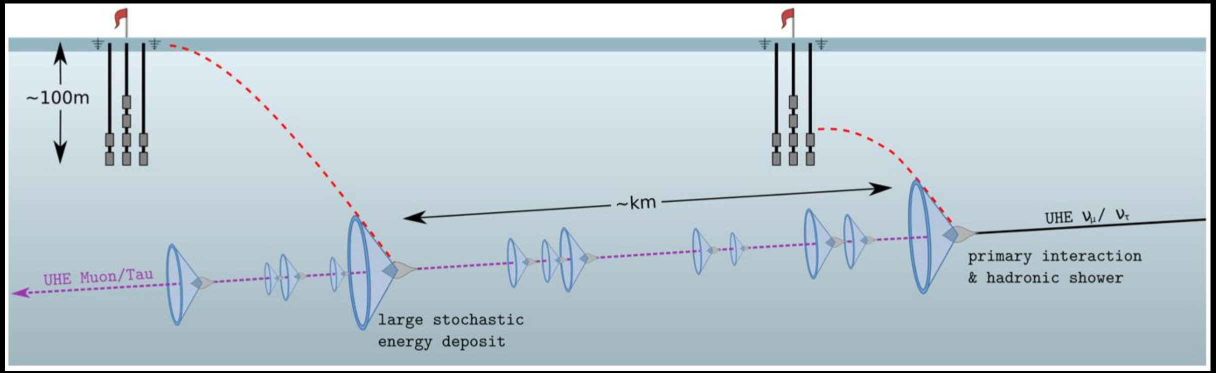
2203.08096, Ackermann, ..., BZ (Snowmass WP)

FSR impacts UHE nu observations: in-ice radio detectors

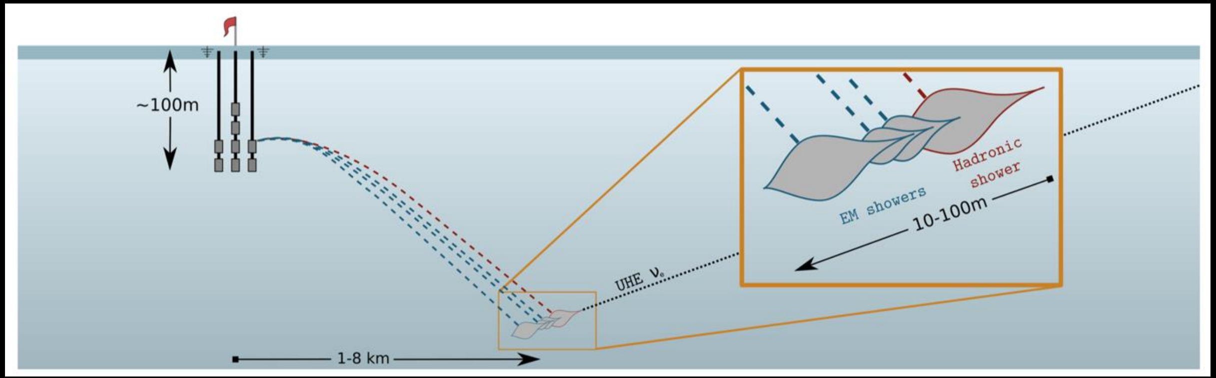
Detectors such as ANITA, PUEO, IceCube-Gen2 radio array, …

For CCDIS, FSR enhances the overall detectable (shower) energy by as much as ≃20%

- $\nu\tau$ CC, big, up to ≃20%?
- $\nu\mu$ CC, mild



- νe CC, negligible

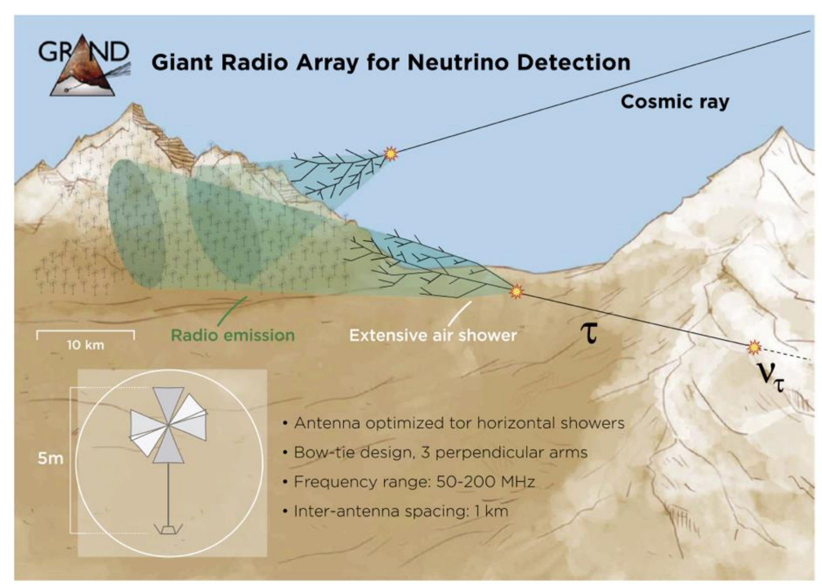


2402.02432 Coleman et al.

FSR impacts UHE nu observations: air shower detectors

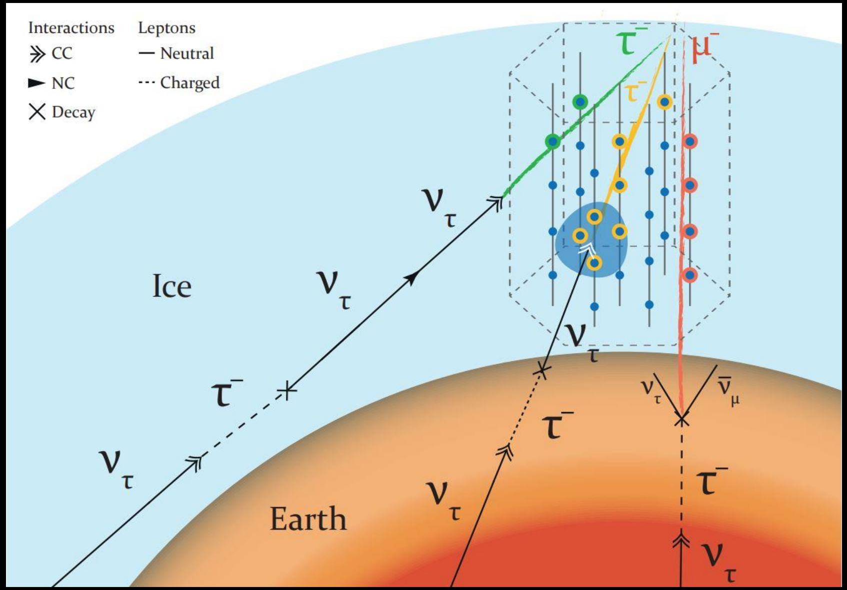
Mainly for $\nu\tau$; Detectors such as TAMBO, GRAND, POEMMA, …

Earth emergent tau lepton
≃5% energy shift



2203.08096, Ackermann, ..., BZ (Snowmass WP)

nutau regeneration
≃5%*N energy shift



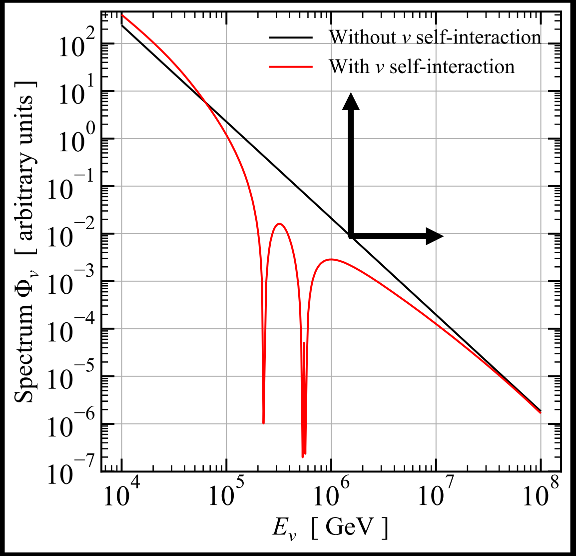
2203.08096, Ackermann, ..., BZ (Snowmass WP)

FSR impacts on the neutrino flux measurements

Flux normalization:

Bias in detectable energy (previous slides) is amplified to flux measurements by the spectral index

$$(1-\delta_E)^{-\Gamma} \simeq 1 + \Gamma * \delta_E$$



For example,

- $\Gamma=3$, $\delta_E=5\%$, the bias is 15%
  (IceCube throughgoing muons, UHE earth emergent tau @ air shower detectors)
- $\Gamma=3$, $\delta_E=20\%$, the bias is 60%
  (UHE $\nu\tau$ CCDIS in in-ice radio detectors)

Immediate impacts

A radiative correction up to tens of percent while completely overlooked by HE & UHE neutrino community

Immediate impacts on HE neutrino experiments:

IceCube has included FSR into their analyses, e.g., new physics searches, cross section measurements, etc.

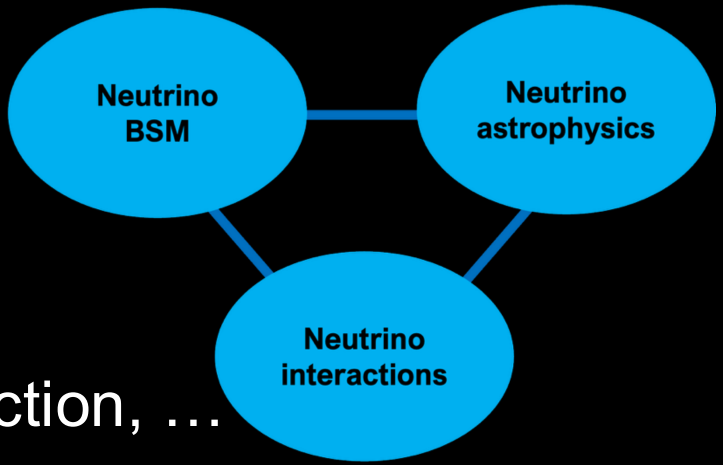
(e.g., 2405.08077, 2405.08070 by IceCube collaboration)

Immediate impacts on UHE neutrino experiments:

Immediate impacts on QCD community's calc of DIS: e.g., 2407.03894 , 2408.05866

BSM studies: e.g., 2504.10576

Summary



- Neutrinos are a interdisciplinary subject

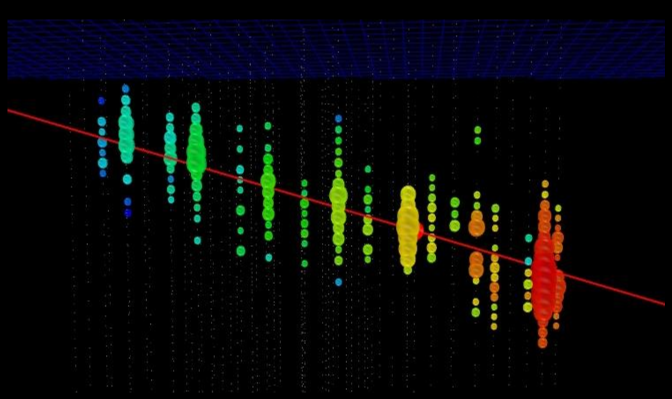
- Neutrinos are the only known particle with BSM
  - Must scrutinize all signals: terrestrial astro, interaction, …
  - Neutrino self-interactions implied by masses
  - Novel regime of nuSI

- Neutrino interactions: foundational support; poorly understood
  - Second largest interactions: neutrino-nucleus W-boson production
  - Largest corrections to differential xsec: final state radiation
  - Next event class for HE neutrinos: dimuons

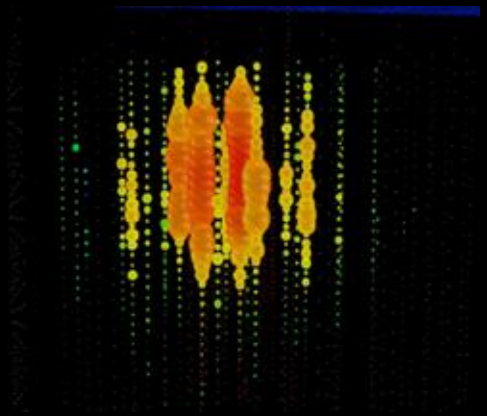
Thanks for your attention!

3. Most important new event class: dimuons

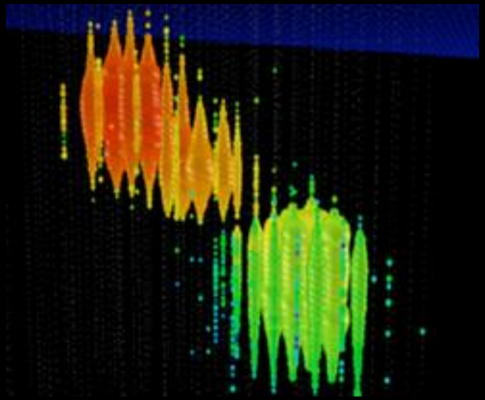
New event classes are needed to get more physics from the data



μ track

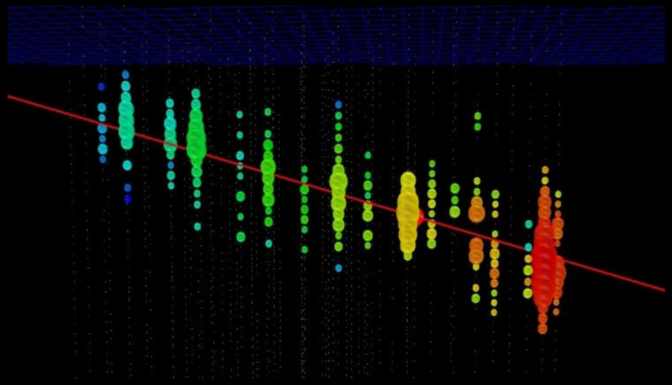


Shower (e or hadron)

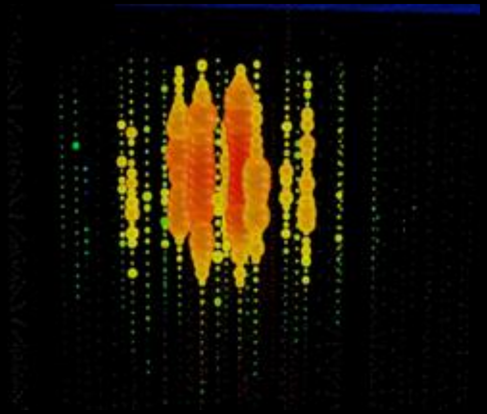


Double shower/bang ($\nu\tau$)

New event classes are needed to get more physics from the data



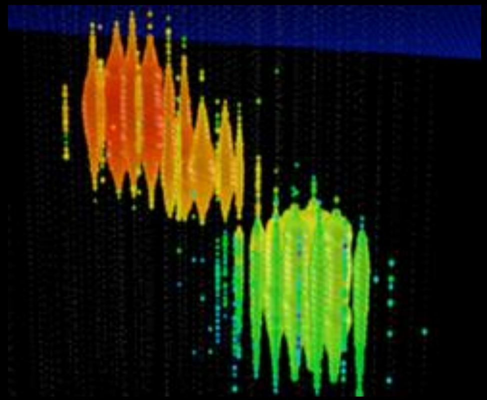
μ track



Shower (e or hadron)

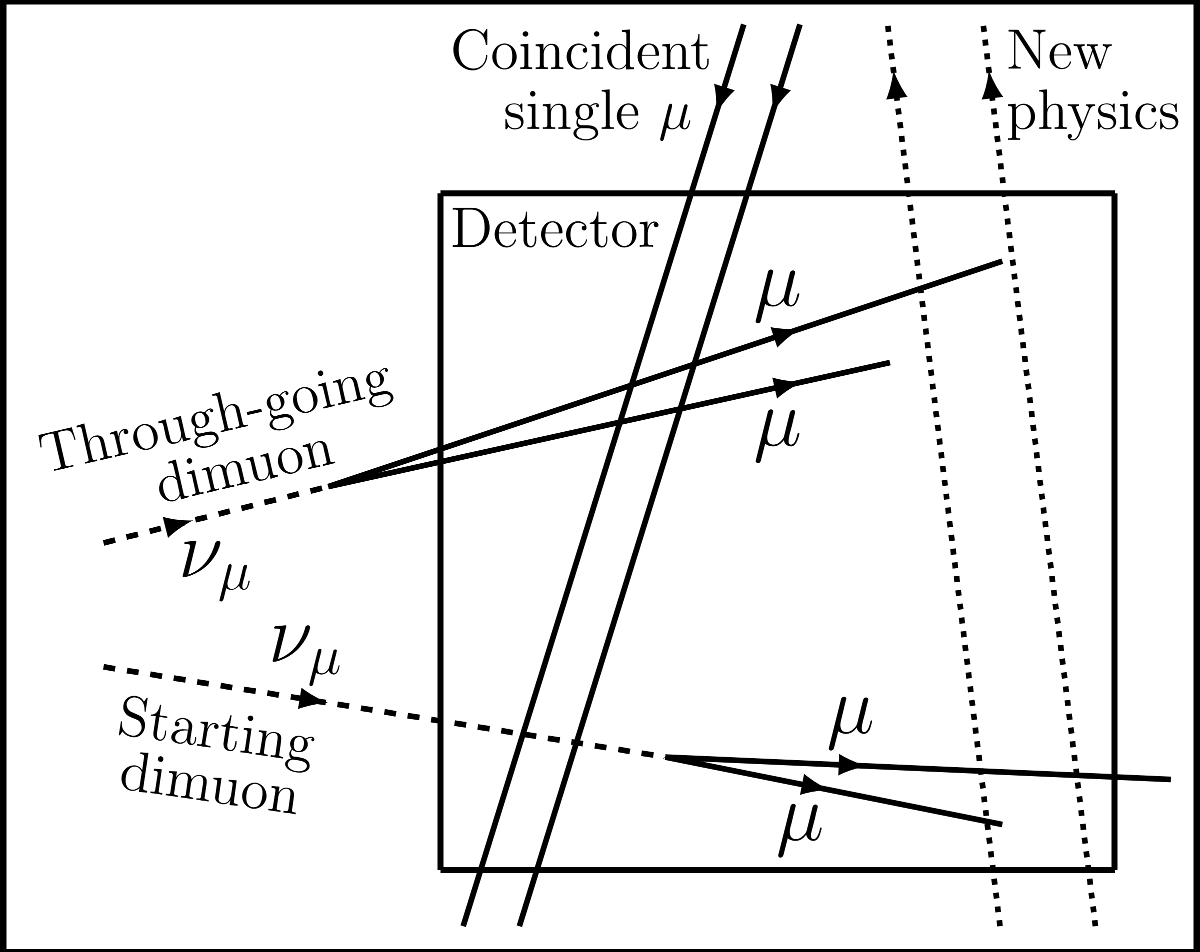
Double muons

(Dimuon)



Double shower/bang ($\nu\tau$)

What is dimuon (double muon)

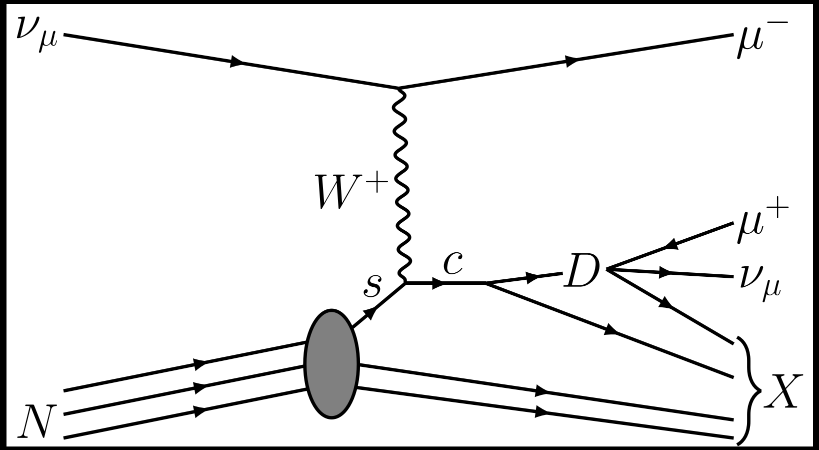


(BZ, Beacom, 2110.02974)

- Coincident single muons
  - background for dimuon,
  - negligible for most cases
- Standard model dimuon
  - Interesting, focus of our work
- BSM dimuon
  - E.g., double staus from SUSY models
  - More to be studied in this direction

How could one neutrino produce two muons

Deep inelastic scattering (DIS)

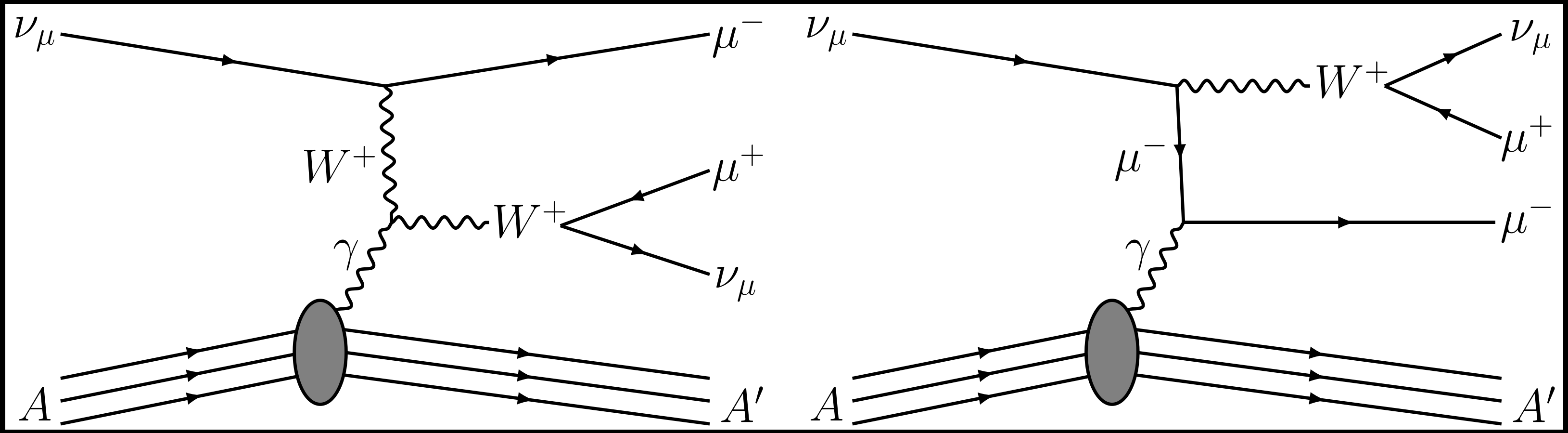


DIS is the dominate channel for detecting high-energy neutrinos.

DIS dimuons were detected at tens—hundreds GeV, never above a TeV.

Important for QCD studies.

neutrino-nucleus W-boson production (WBP)



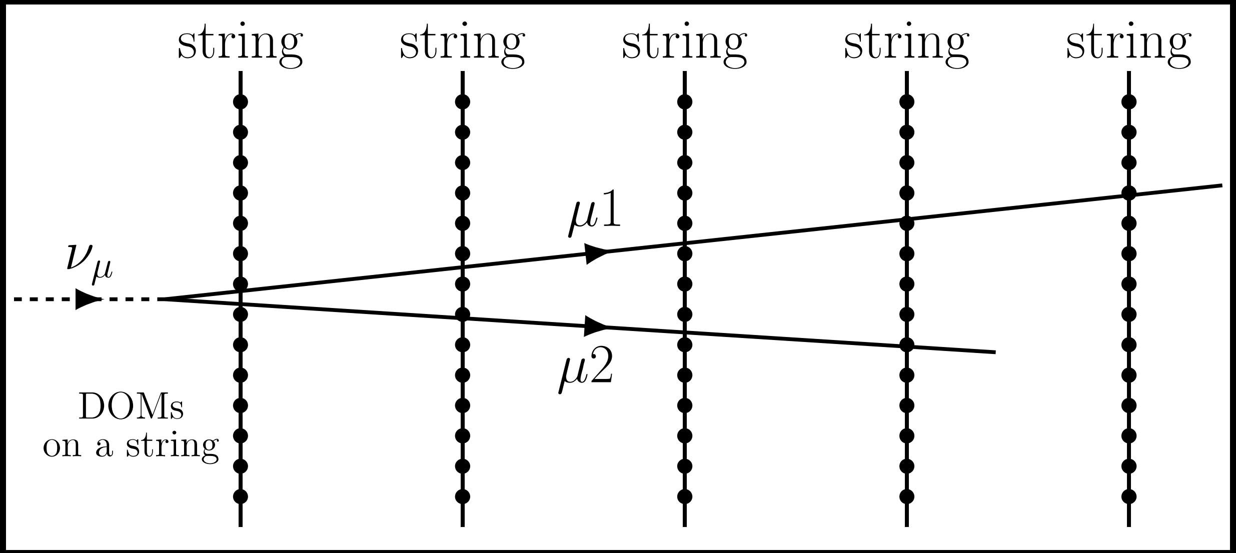
(BZ, Beacom, 1910.08090, 1910.10720)

WBP is the 2nd most important channel for detecting high-energy neutrinos, but never identified yet.

First hypothesized/calculated in 1960…

We propose a way to detect dimuons in IceCube-like detectors

Inside a HE neutrino detector



(BZ, Beacom, 2110.02974)

Angular threshold:

$$R_{\mu 2}\theta_{\mu\mu} > 2D_{\mathrm{v}}$$

μ1-μ2 separation

2*spacing between adjacent DOMs

Energy Threshold:

100 GeV for IceCube
300 GeV for IceCube-Gen2

First calculational framework for dimu in ν telescopes

(BZ, Beacom, 2110.02974)

Starting dimuons:

$$\frac{dN^{\rm st}_{\mu\mu}}{dE_{\mu1/2}} = N_t T \int_{E_{\rm th}}^{\infty} dE_\nu \frac{dF_\nu}{dE_\nu}(E_\nu) \frac{d\sigma^{\rm cuts}_{\mu\mu}}{dE'_{\mu1/2}}(E'_{\mu1/2}, E_\nu | E'_{\mu2} > E_{\rm th}) \,,$$

Throughgoing dimuons:

Flux

Interactions

Detector angular threshold

$$\frac{dN^{\rm thr}_{\mu\mu}}{dE_{\mu2}} = \frac{A_{\rm det} T N_A}{\alpha + \beta E_{\mu2}} \int_{E_{\mu2}}^{\infty} dE_\nu \frac{dF_\nu}{dE_\nu}(E_\nu) \int_{E_{\mu2}}^{E_\nu} dE'_{\mu2} \frac{d\sigma^{\rm cuts}_{\mu\mu}}{dE'_{\mu2}}(E'_{\mu2}, E_\nu) \,, \text{ and}$$

$$\frac{dN^{\rm thr}_{\mu\mu}}{dE_{\mu1}} = \frac{A_{\rm det} T N_A}{\alpha + \beta E_{\mu1}} \int_{E_{\mu1}}^{\infty} dE_\nu \frac{dF_\nu}{dE_\nu} \int_{E_{\mu1}}^{E_\nu} dE'_{\mu1} \int_{E'_{\mu2,\rm th}}^{E'_{\mu1}} dE'_{\mu2} \frac{d^2\sigma^{\rm cuts}_{\mu\mu}}{dE'_{\mu1} dE'_{\mu2}}(E'_{\mu1}, E'_{\mu2}, E_\nu) \,,$$

Energy losses

Detector energy threshold

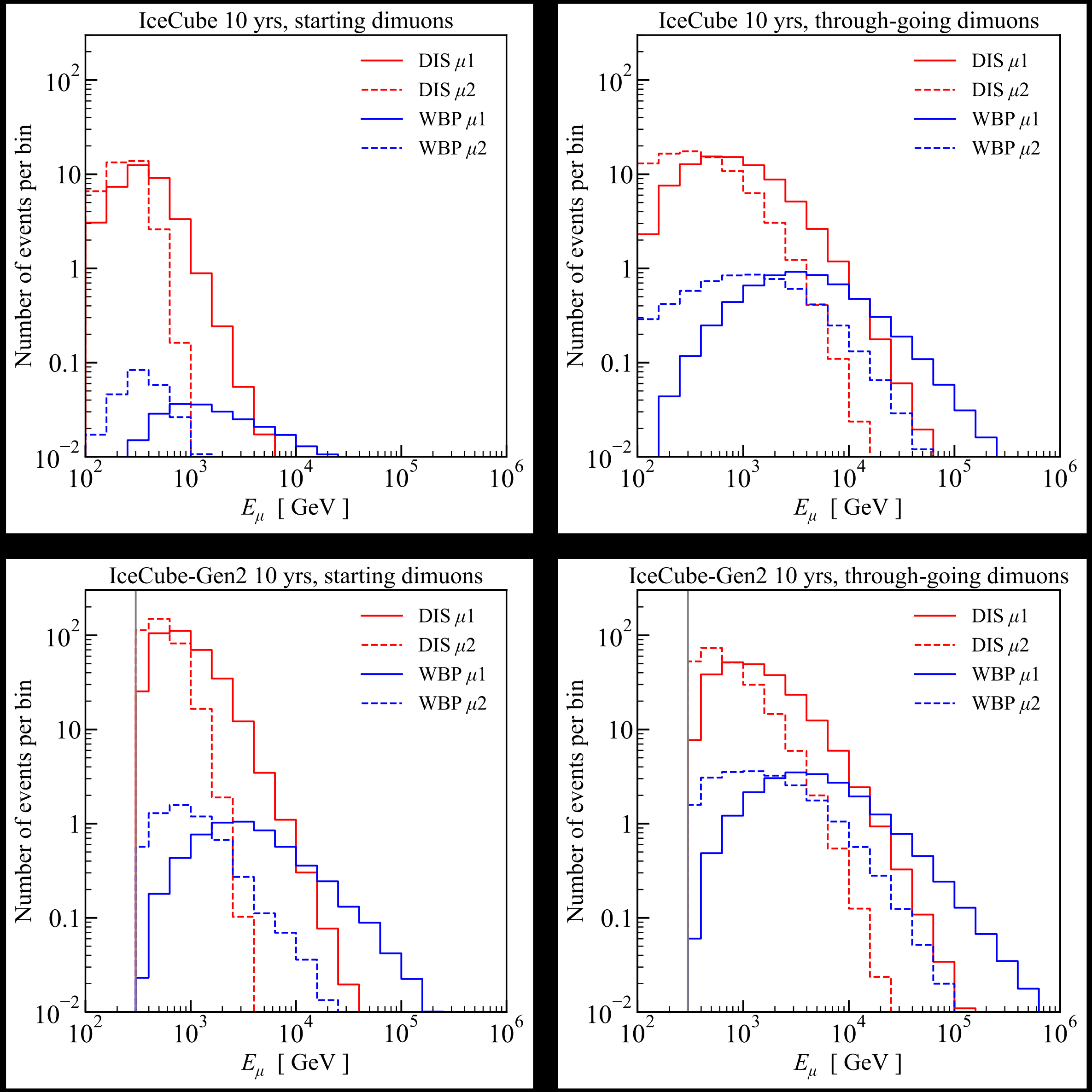
$$E'_{\mu2,\rm th} = \left(\frac{E'_{\mu1} + \epsilon}{E_{\mu1} + \epsilon}\right)(E_{\rm th} + \epsilon) - \epsilon$$

Dimuon rates in IceCube and IceCube-Gen2

Our predicted number of dimuons

	Starting		Throughgoing	
	DIS	WBP	DIS	WBP
IceCube, 10 yrs	37	0.3	85	6.0
IceCube-Gen2, 10 yrs	370	5.8	231	22

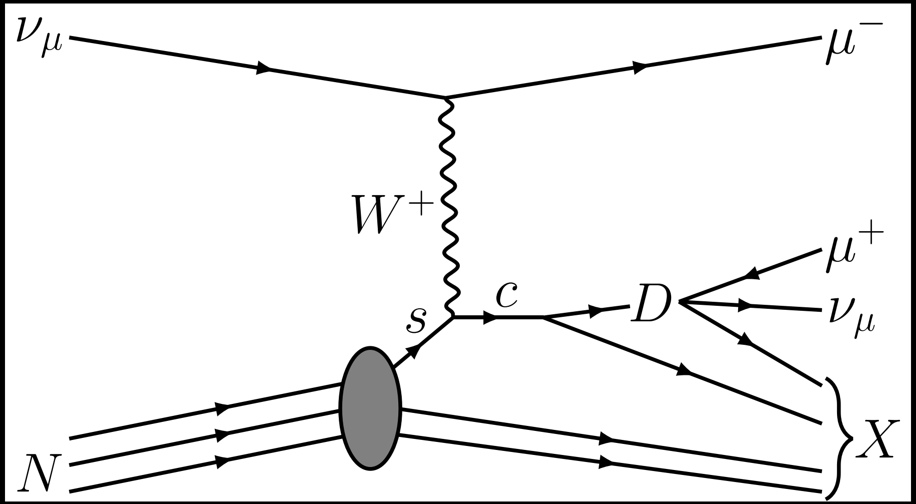
(Note IceCube has run for > 10 years)

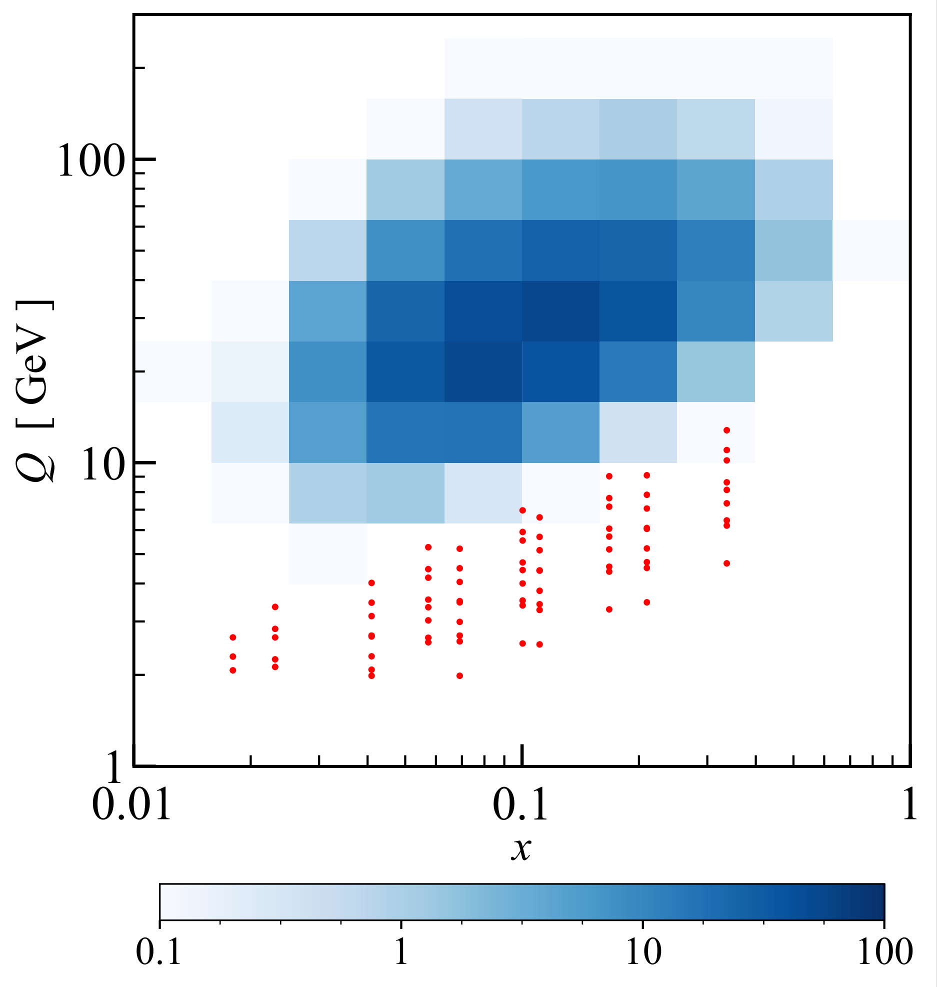


Physics potential: measuring the strange-quark PDF

(Note this measurement can be done with current IceCube data)

Deep inelastic scattering (DIS)



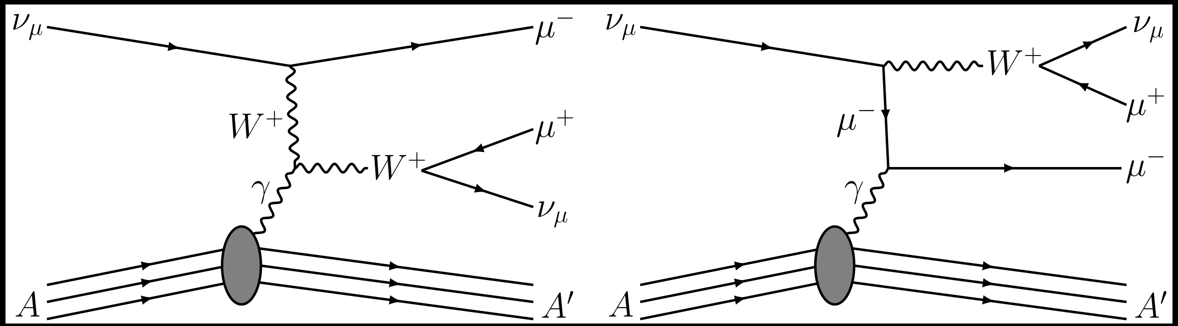


(BZ, Beacom, 2110.02974)

Physics potential: first detection of WBP

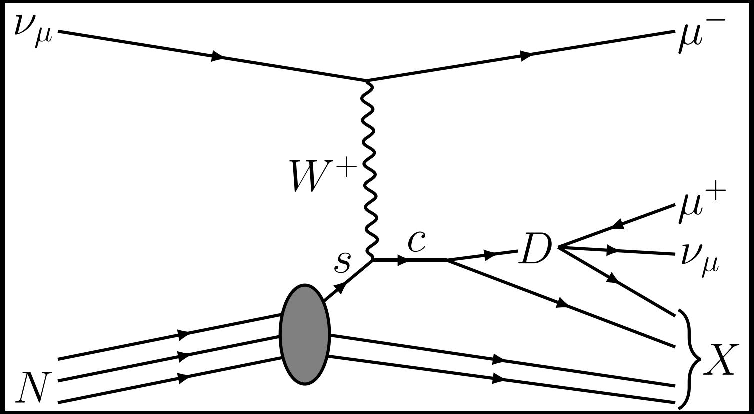
with showerless starting dimuons

Signal: W-boson production (WBP)

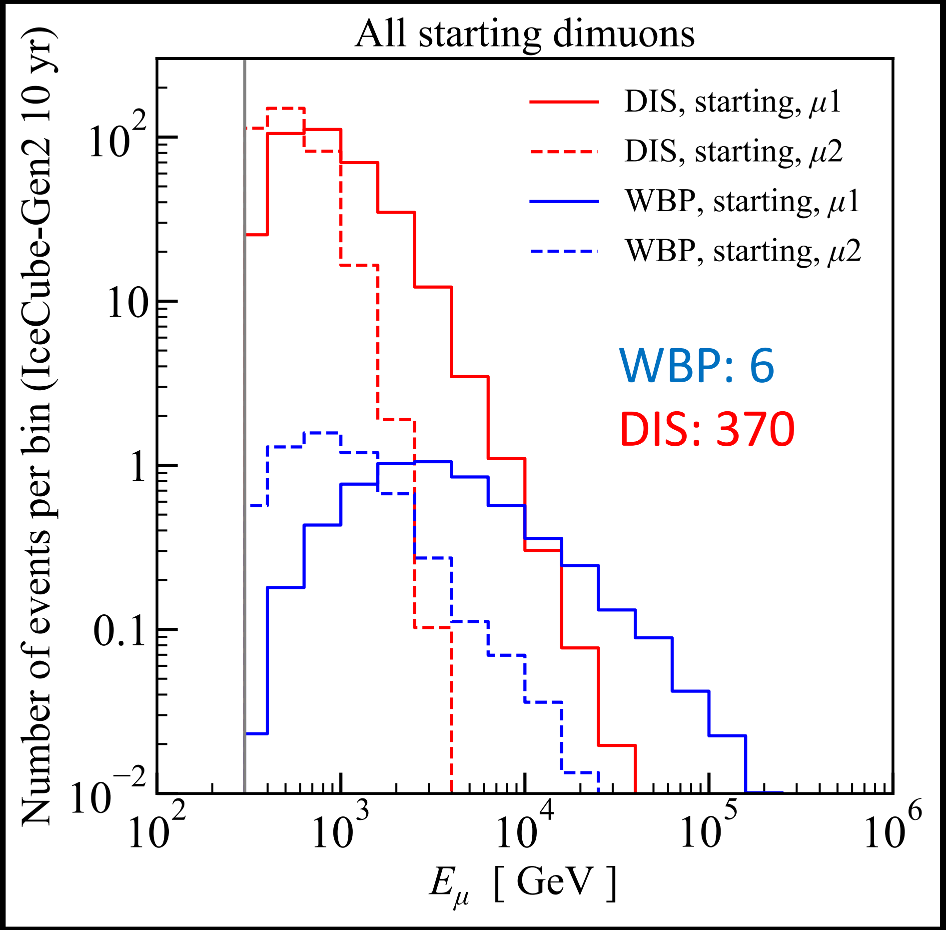


A': No shower

Background: deep inelastic scattering (DIS)



X: Mostly shower



(BZ, Beacom, 2110.02974)

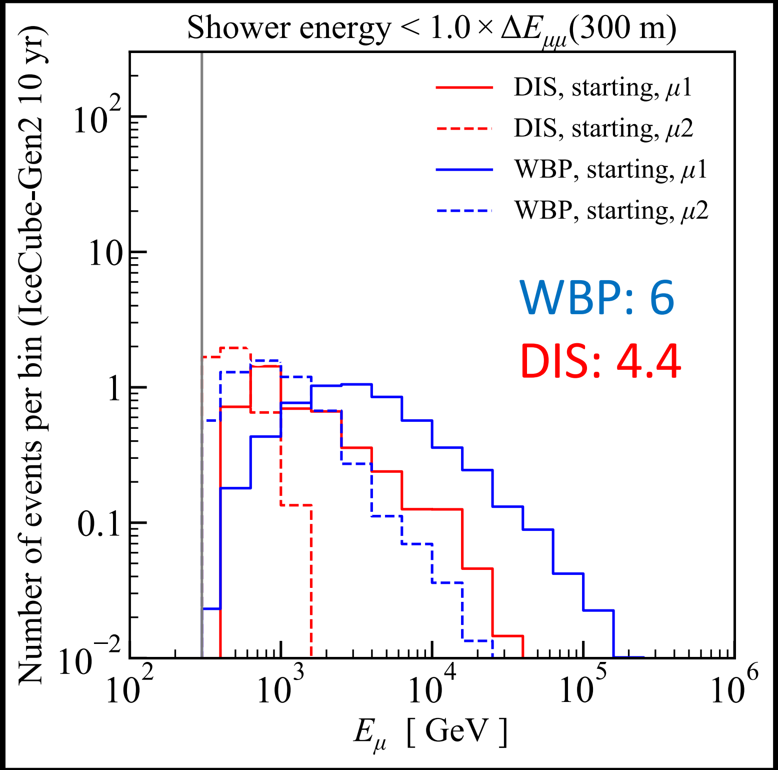
Physics potential: first detection of WBP

with showerless starting dimuons

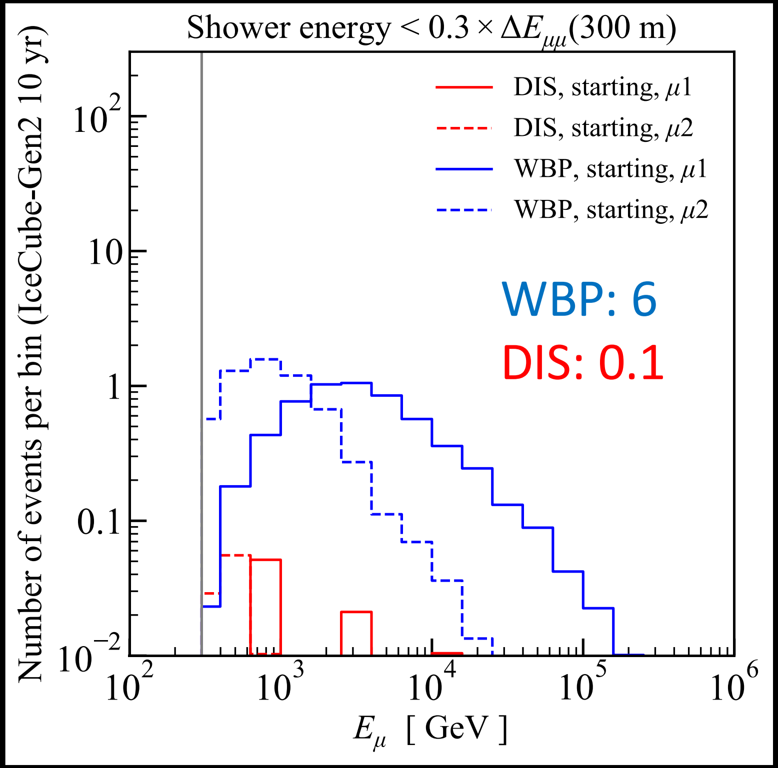
Shower energy threshold

$$E_{\text{shower}} < f \times \Delta E_{\mu\mu}(L)$$

L = 300 m >~ spatial resolution
f ~ energy resolution ~ 10%



f = 1.0



f = 0.3

(BZ, Beacom, 2110.02974)

Dataset and analysis

List of the 19 dimuon candidates we found

- Ten years of public IceCube data (1,134,450 muon events; 2008--2018)
- Data obtained after multiple strong cuts optimized for point-source search, not dimuon search.
- We analyze the data by looking for muon pairs arriving close in time and direction

MJD1 [day]	MJD2 (= MJD1)	$E_{\mu 1}$ [TeV]	$E_{\mu 2}$	RA1 [deg]	RA2	Dec1	Dec2	AngErr1	AngErr2	AngDis	DisErr
56068.26557772	56068.26557772	1.23	1.05	25.065	25.860	18.168	18.466	0.38	1.85	0.81	1.89
56115.78056499	56115.78056499	2.29	0.65	296.835	296.891	41.777	46.922	3.10	0.41	5.15	3.13
56235.14756523	56235.14756523	2.19	2.19	179.781	185.182	20.271	28.274	2.50	1.57	9.39	2.95
56582.68675378	56582.68675378	2.29	1.35	120.687	121.892	26.630	24.994	1.47	0.78	1.96	1.66
56653.19502448	56653.19502448	3.31	1.48	48.106	47.781	30.840	30.100	0.75	1.19	0.79	1.41
56784.87114671	56784.87114671	1.35	0.35	126.690	126.357	69.524	70.871	1.97	2.83	1.35	3.45
56813.78701082	56813.78701082	0.91	0.83	184.136	181.708	31.627	31.957	3.01	0.83	2.09	3.12
56895.78341718	56895.78341718	1.91	0.79	295.288	303.817	14.387	16.670	1.94	1.61	8.53	2.52
56932.15214130	56932.15214130	1.70	0.98	175.546	173.549	36.710	35.972	1.17	0.86	1.77	1.45
56940.02405671	56940.02405671	5.13	3.72	1.404	0.541	11.716	9.353	3.13	2.38	2.51	3.93
57214.99298310	57214.99298310	1.51	0.83	13.089	14.760	39.101	39.034	3.50	0.85	1.30	3.60
57376.46221142	57376.46221142	1.66	1.55	326.795	328.022	17.543	15.199	2.11	1.15	2.62	2.40
57461.19606500	57461.19606500	1.35	1.10	308.771	307.274	31.268	30.077	1.08	1.37	1.75	1.74
57499.81363094	57499.81363094	5.89	1.70	199.430	201.527	16.454	15.029	2.55	1.30	2.47	2.86
57560.74070687	57560.74070687	1.74	0.79	219.566	219.023	12.582	13.008	1.62	0.74	0.68	1.78
57650.26270928	57650.26270928	6.17	2.40	256.189	255.088	19.588	20.293	2.03	0.77	1.25	2.17
57661.79317519	57661.79317519	1.45	0.91	24.276	21.095	23.145	24.317	1.72	2.22	3.14	2.81
58003.09416087	58003.09416087	2.29	1.23	349.095	345.586	21.328	19.554	2.17	1.30	3.74	2.53
58266.46093610	58266.46093610	2.63	1.48	296.881	294.994	19.596	20.896	1.57	1.45	2.20	2.14

(BZ, Beacom, 2110.02974)

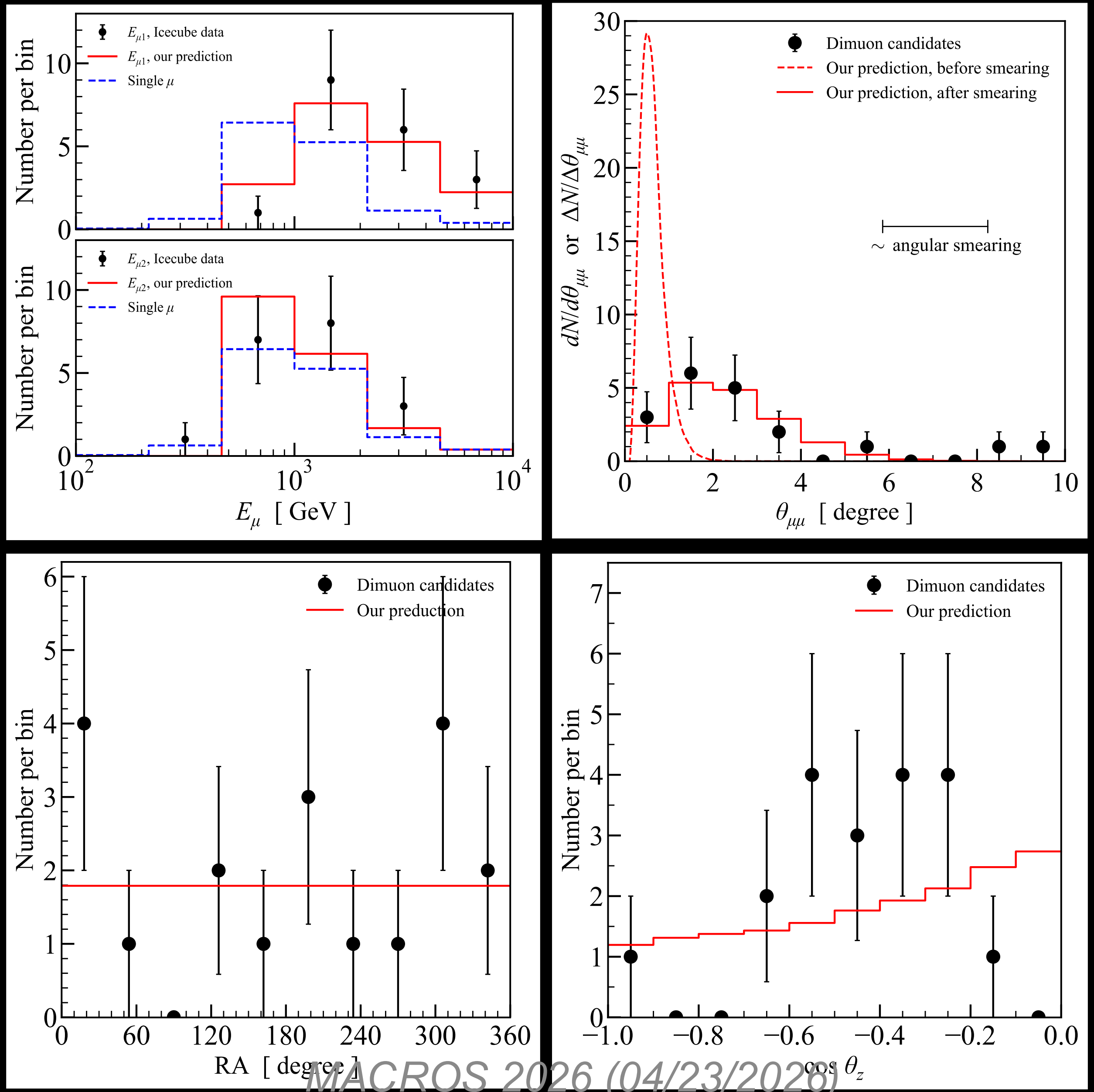
Agrees with our prediction

Energy distribution

Angular distribution

RA distribution

Zenith distribution



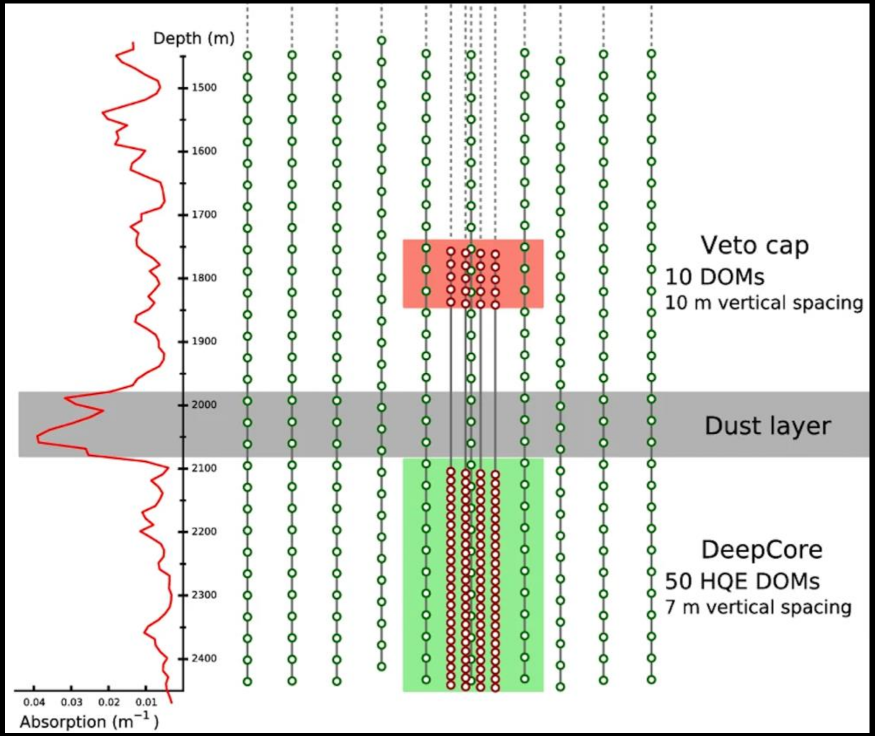
(BZ, Beacom, 2110.02974)

Outcome of these candidates

- After our paper out, IceCube collaboration did a visual inspection to these candidates, and found that they are not real dimuons.

- They are, instead, due to an internal reconstruction error that identifies some single muons crossing the dust layer as two separate muons.

Inside IceCube detector



Immediate and broader impact of this work

1. Theoretical work immediately motivates experiments

   IceCube & KM3NeT collaboration started their own dimuon searches.

   (See Ph.D. thesis by Dr. Sourav Sarkar and more to come.)

2. Particle physics work immediately affects astrophysics studies

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56235.14756523	56235.14756523	2.19	2.19	179.781	185.182	20.271	28.274	2.50	1.57	9.39	2.95
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58266.46093610	58266.46093610	2.63	1.48	296.881	294.994	19.596	20.896	1.57	1.45	2.20	2.14

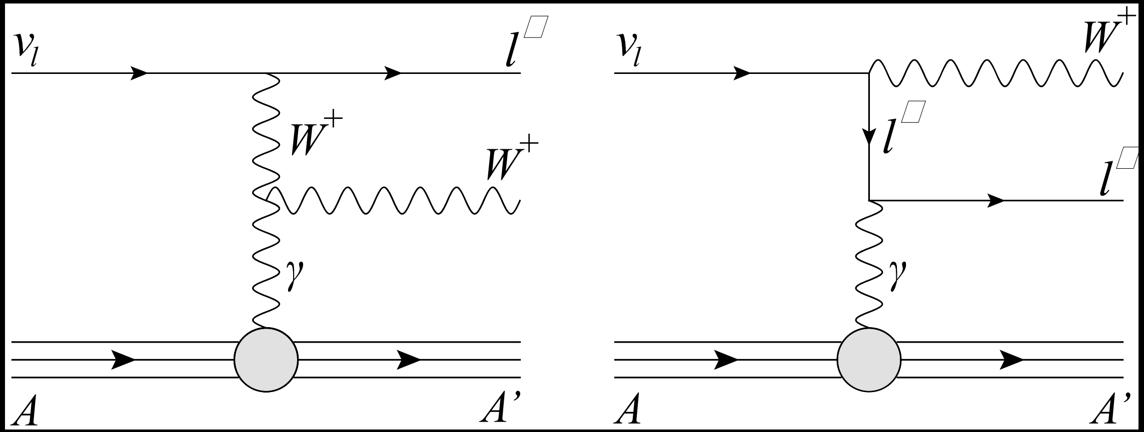
We corrected the double counted events in the IceCube public data.
https://github.com/beizhouphys/IceCube_data_2008--2018_double_counting_corrected
((Or just google "[my name] github")
and has been used by, e.g.,
2210.03088, 2306.03427, 2401.06571, 2404.06539, 2410.16394.

Neutrino interactions (HE/UHE)

Second largest interaction

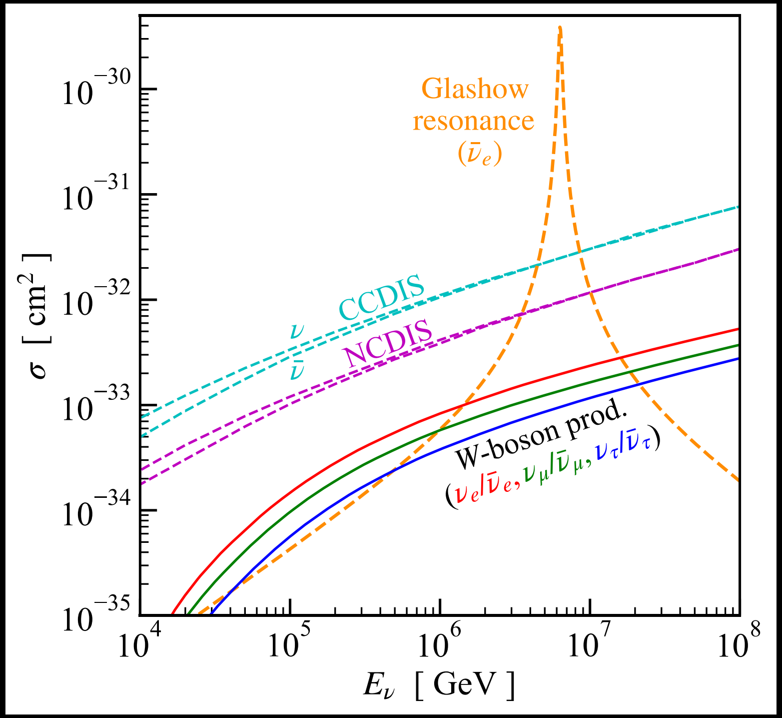
Second largest interaction

ν-nucleus W-boson production (WBP)



$$\nu_e + A \rightarrow e^- + W^+ + A'$$
$$\nu_\mu + A \rightarrow \mu^- + W^+ + A'$$
$$\nu_\tau + A \rightarrow \tau^- + W^+ + A'$$

Cross sections

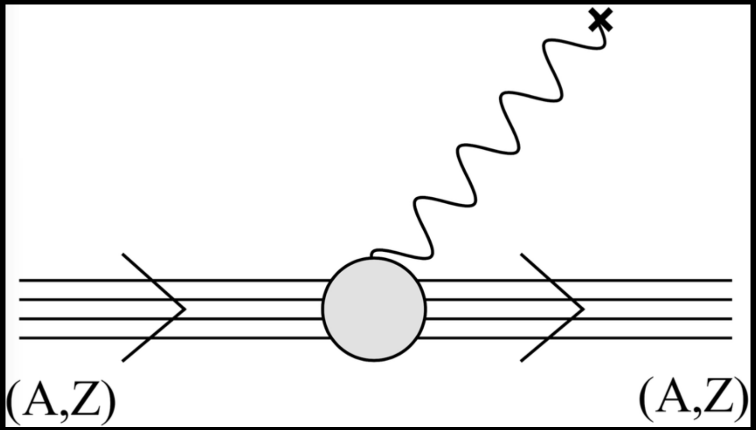


BZ, Beacom, 1910.08090, 1910.10720
Xie, BZ, Hobbs CTEQ-TEA Collaboration, 2305.10497

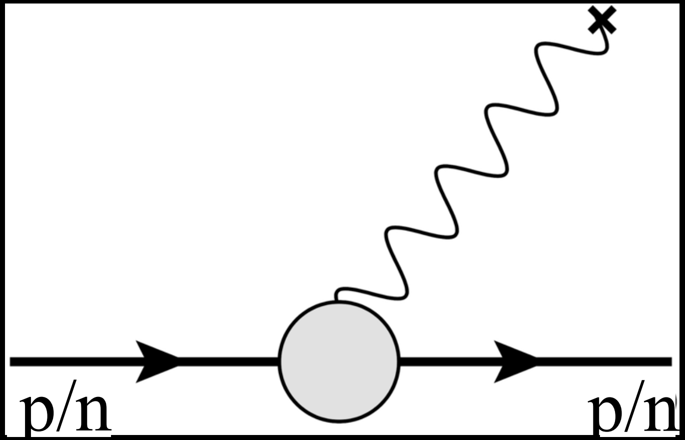
Cross section for photon coupling to the nucleus

Three kinematic regimes

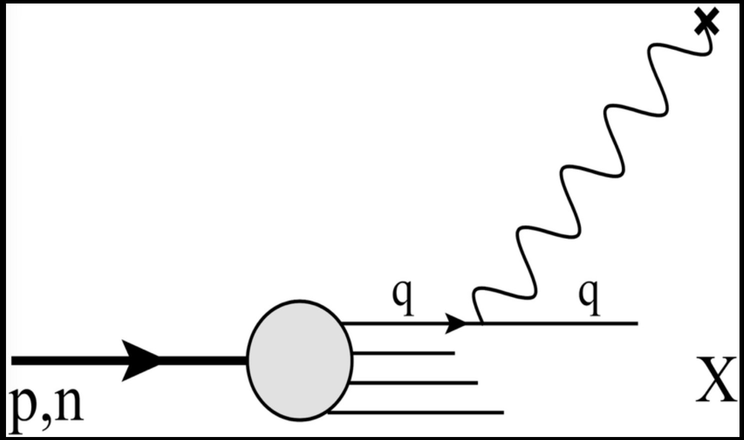
Coherent (elastic)



Diffractive (elastic)

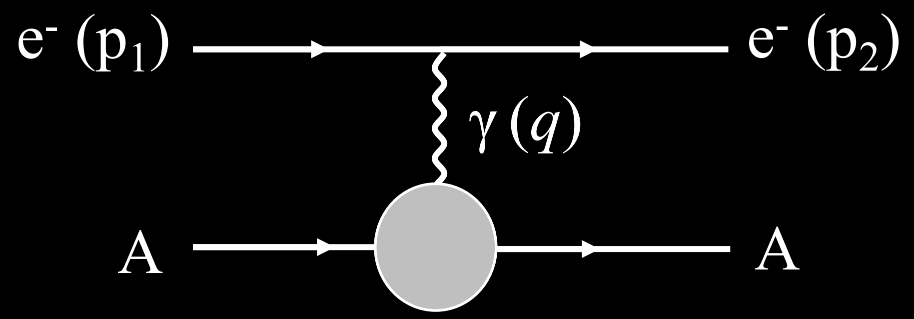


Inelastic



Invalidity of equivalent photon approximation

Previous approach: equivalent photon approximation



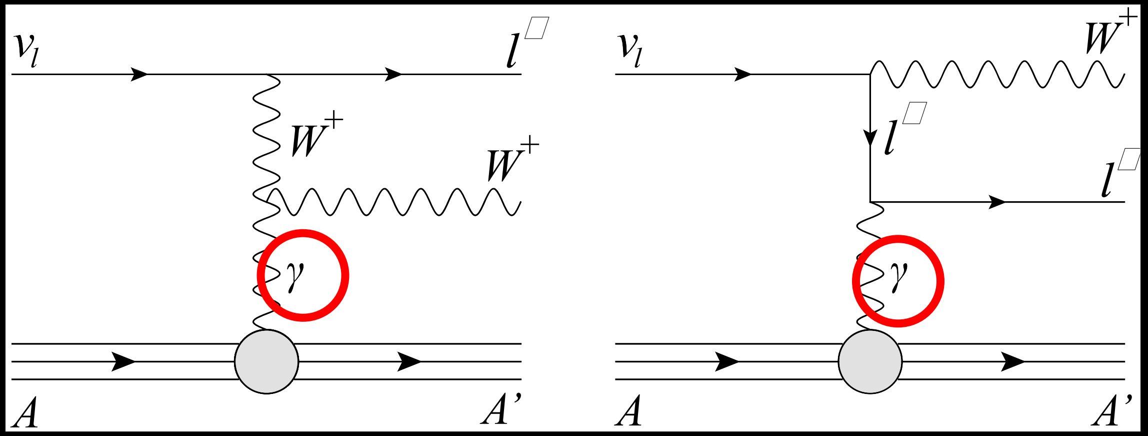
$\cos\theta \simeq 1$

$q^2 = (p_2 - p_1)^2 \propto (1 - \cos\theta) \simeq 0$, on shell photon.

$$\sigma_{eA}(s) \simeq \int \sigma_{e\gamma}(s_{e\gamma})\, H_\gamma(s_{e\gamma}, q^2)$$

D. Seckel, hep-ph/9709290, PRL
I. Alikhanov 1503.08817 PLB

ν-nucleus W-boson production (WBP)



In 1910.08090, for the first time, I observed of the breakdown of equivalent photon approximation for WBP calculations, and did the first complete calculation.

Complete approach

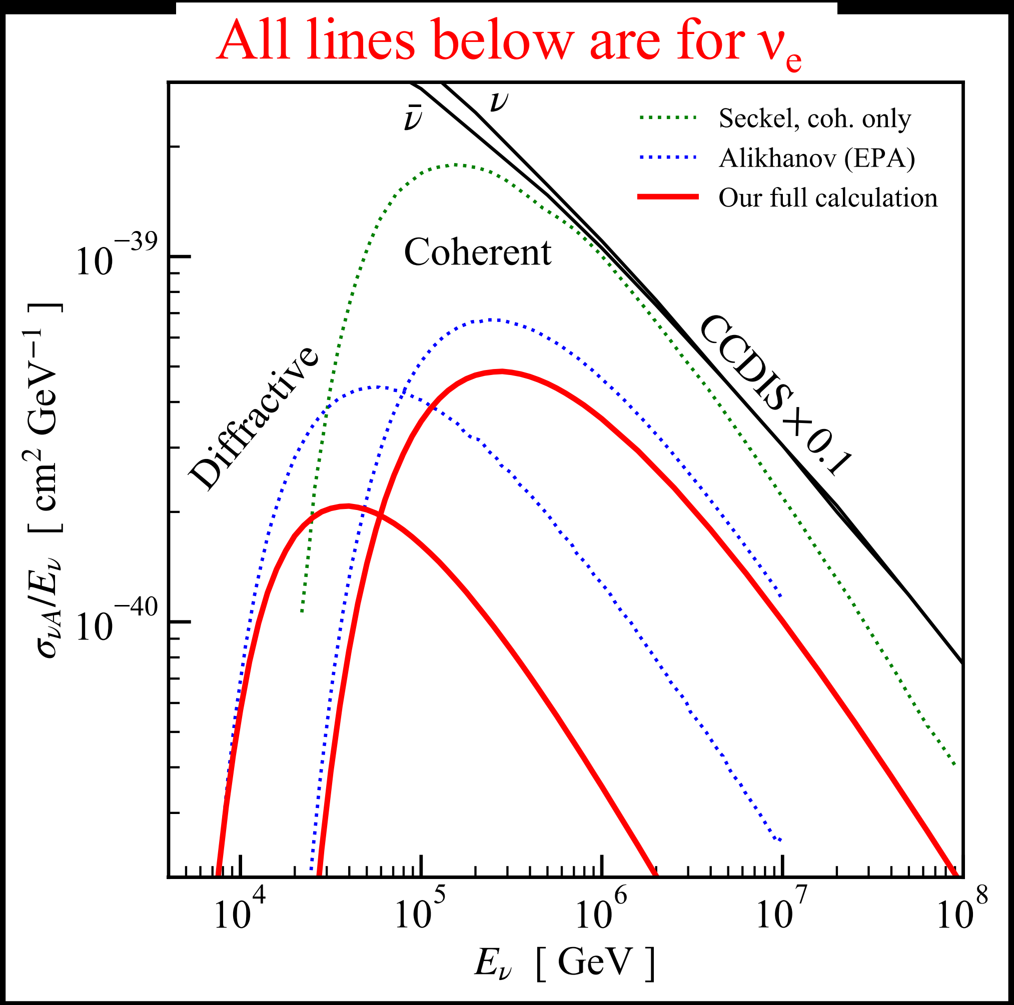
$$\frac{d^2\sigma_{\nu A}}{dq^2 d\hat{s}} = \frac{1}{32\pi^2}\frac{1}{\hat{s}q^2}\left[\sigma^T_{\nu\gamma}(q^2,\hat{s})\, h^T_X(q^2,\hat{s}) + \sigma^L_{\nu\gamma}(q^2,\hat{s})\, h^L_X(q^2,\hat{s})\right]$$

Transverse Longitudinal

$$\sigma^T_{\nu\gamma}(\hat{s},\mathrm{q}^2) = -\frac{1}{2\hat{s}}\frac{1}{2}\left(g^{\mu\nu} - \frac{4Q^2}{\hat{s}^2}p_1^\mu p_1^\nu\right)L_{\mu\nu};$$

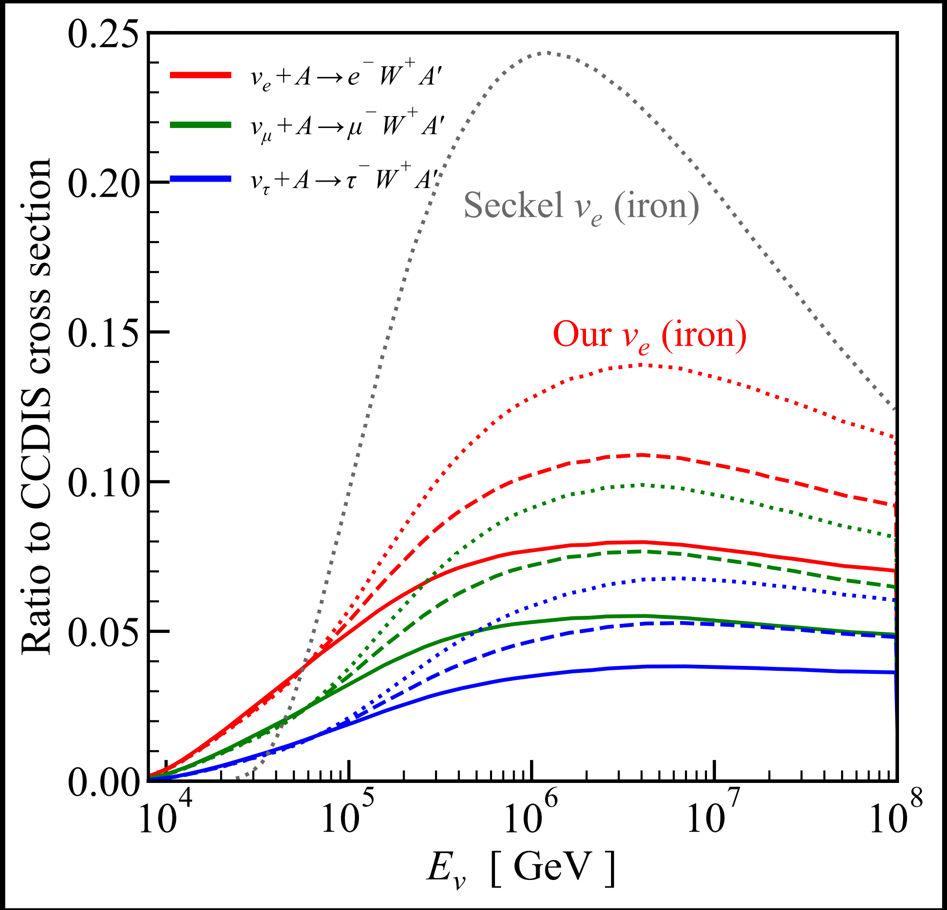
$$\sigma^L_{\nu\gamma}(\hat{s},\mathrm{q}^2) = -\frac{1}{\hat{s}}\frac{4Q^2}{\hat{s}^2}p_1^\mu p_1^\nu L_{\mu\nu};$$

Also included Pauli-blocking effects for the first time



EPA is not good. Pauli blocking should be included.

WBP/CCDIS cross sections



BZ, Beacom, 1910.08090, 1910.10720
Xie, BZ, Hobbs CTEQ-TEA Collaboration, 2305.10497

Ratios to CCDIS

- Water/ice targets (solid lines): up to 10%
- Iron targets (dotted): up to 15%

Impacts

1. WBP included in neutrino in-Earth absorptions
   Increase up to ≃15%

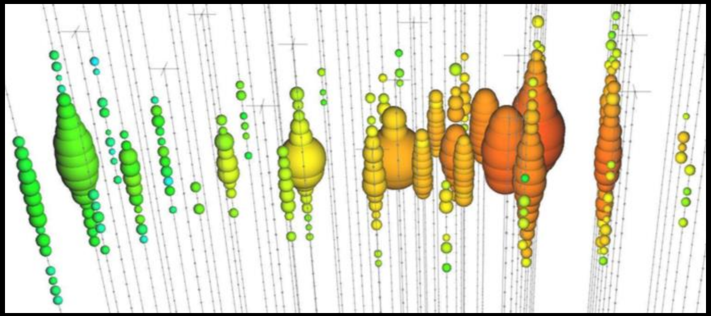
2. IceCube Collaboration integrating my calculations?

All (differential) cross section data:
https://github.com/beizhouphys/neutrino-W-boson-and-trident-production
(Or just google "bei zhou github")

Hints of WBP in IceCube's early data

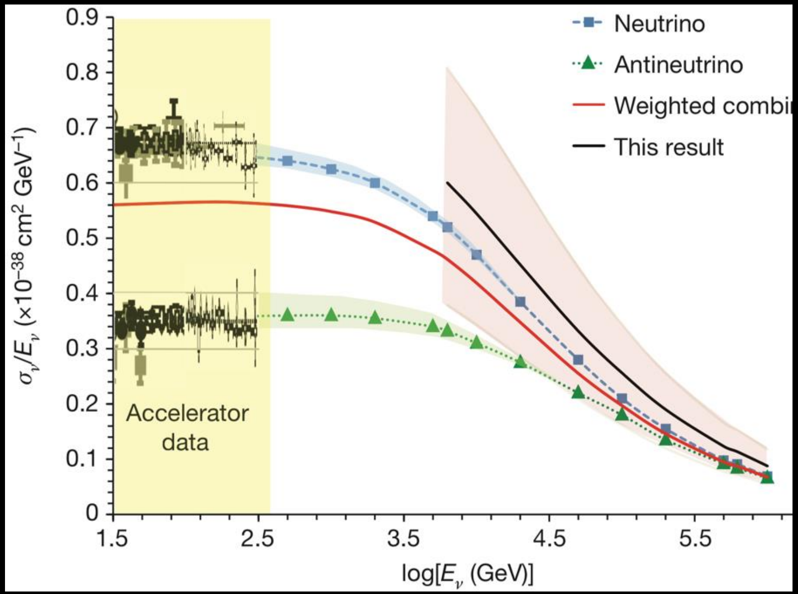
Measuring neutrino cross section

Event topology



Track without shower??

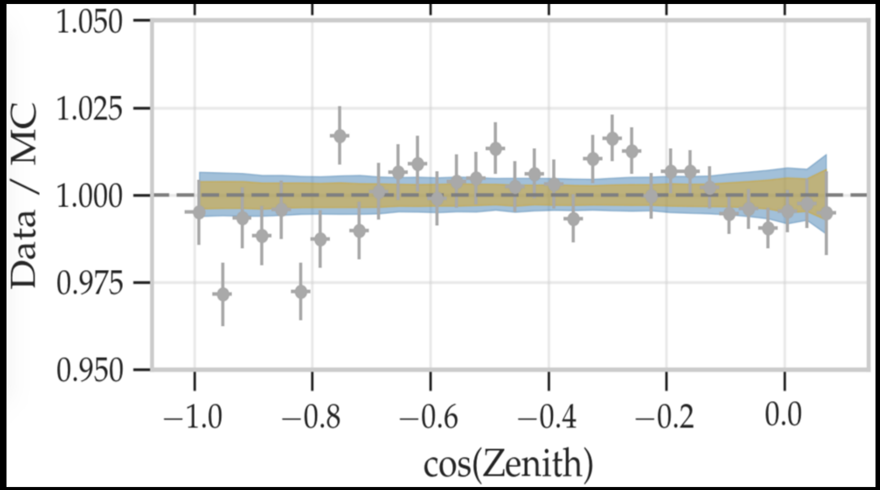
Event 5 of
IceCube, 1311.5238,
Science



1.3±0.45 of SM prediction
but only DIS is included

IceCube, 1711.08119,
Science

Diffuse Astrophysical νμ Spectrum



An unknown 2% deficit of
straight up-going events

IceCube, 1908.09551
ICRC 2019