High-energy neutrinos: a new window for particle physics and astrophysics

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Collaborators: John Beacom, Po-Wen Chang, Tim Hobbs, Marc Kamionkowski, Kohta Murase, Yun-feng Liang, Keping Xie, etc.

TeV—PeV neutrinos (detected by IceCube)

Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector #1

IceCube Collaboration • M.G. Aartsen (Adelaide U.) et al. (Nov 20, 2013)

Published in: *Science* 342 (2013) 1242856 • e-Print: 1311.5238 [astro-ph.HE]

pdf links DOI cite claim reference search 1,501 citations

First observation of PeV-energy neutrinos with IceCube #1

IceCube Collaboration • M.G. Aartsen (Adelaide U.) et al. (Apr 19, 2013)

Published in: *Phys.Rev.Lett.* 111 (2013) 021103 • e-Print: 1304.5356 [astro-ph.HE]

pdf links DOI cite claim reference search 874 citations

Why do we study high-energy neutrinos

- Astrophysics: Origin of HE astrophysical neutrinos
  - Sources of HE cosmic rays (> 60-year problem)
  - Cosmic particle acceleration, propagation
  - Cosmic gamma ray sources, hadronic vs leptonic mechanism
  - Dense astrophysical environments
  - Essential for multi-messenger astrophysics (highlighted by astro2020)

- Particle physics:
  - Neutrino interactions in the SM (Deep-inelastic scattering, W-boson production, Glashow resonance)
  - Neutrino mixing parameters
  - BSM (ν portal to DM, new ν interactions, sterile ν, magnetic moment, etc.)

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High-energy neutrino interactions

Why study neutrino interactions

- Neutrino interactions is the cornerstone of all kinds of neutrino-related measurements
  - Astrophysics: energy spectrum, flavor composition, arrival direction, etc.
  - Particle physics: mixing parameters; all BSM studies contingent on well-understood SM interactions

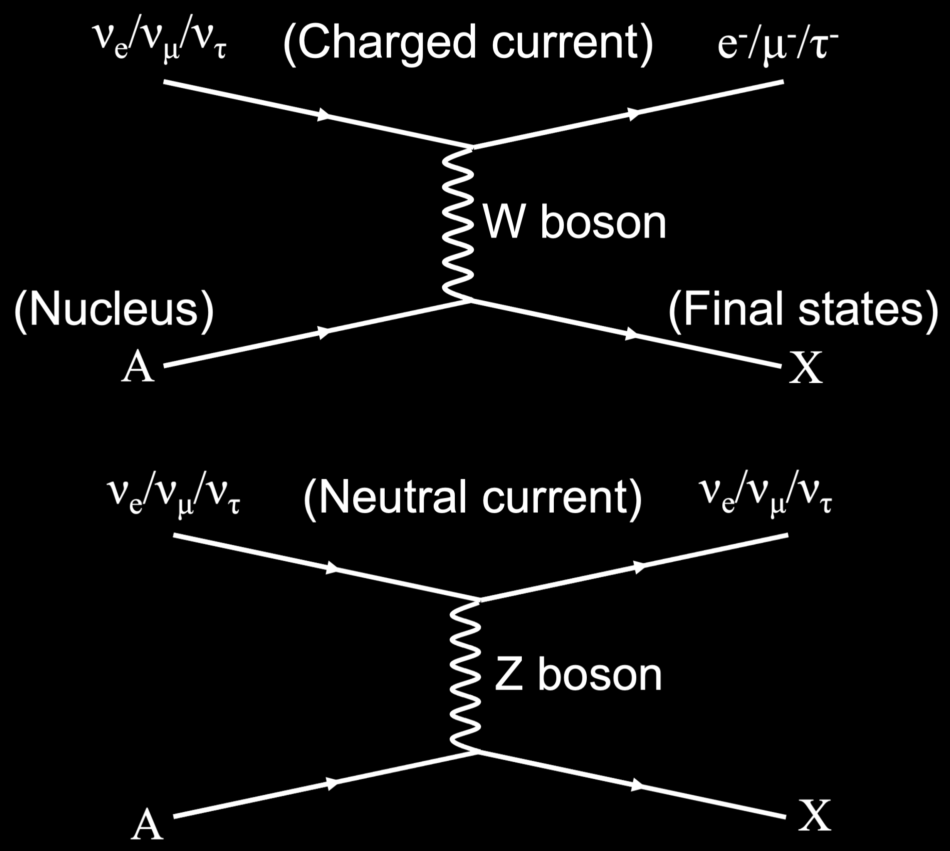
- Neutrino(-nucleus) interaction theory is interesting and difficult:
  - Entanglement of particle physics, nuclear physics, QCD, etc.

- Help us to find new event classes: useful for both astrophysics and particle physics studies
  - E.g., dimuons for high-energy neutrino detection (*2110.02974 BZ, Beacom*).

Detecting neutrinos through neutrino interactions

Deep inelastic scattering (DIS) dominates

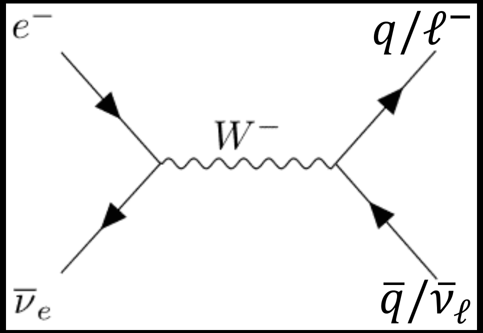
(≃2% precision)



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

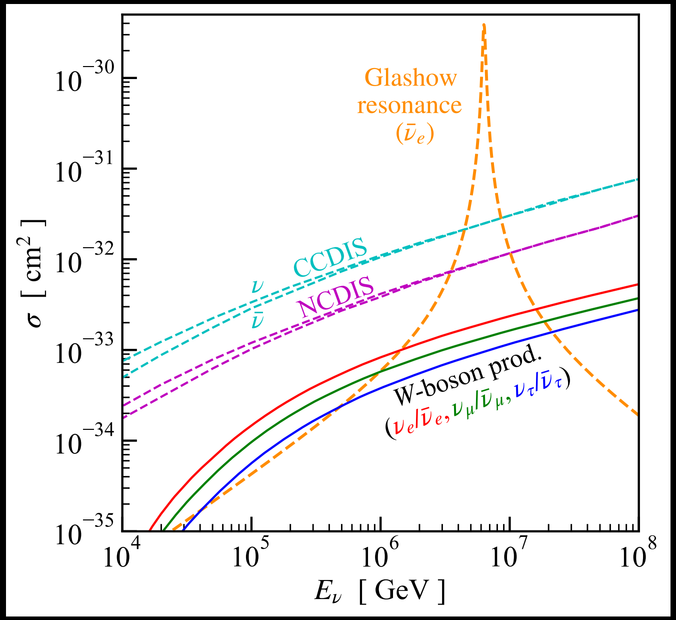
Most recent, Keping Xie, et al. 2303.13607

Glashow resonance important for $\bar{\nu}_e$



Glashow 1960
IceCube 2021

Cross sections



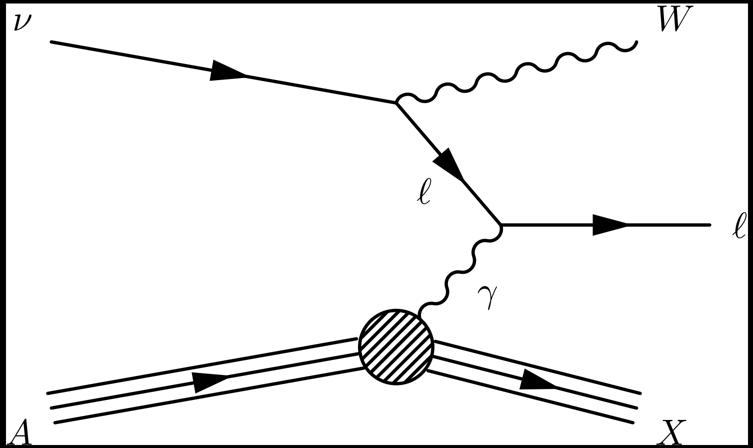
(BZ, Beacom, 1910.10720, PRD)

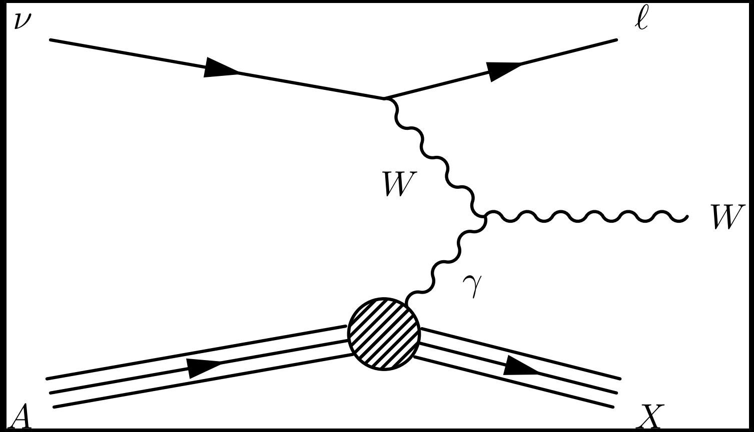
Increasing data needs study subdominant interactions

Increasing data demands studying subdominant interactions

Detector	Size	Status	Detector	Size	Status
IceCube	1 km^3	Running for ~14 yrs	TRIDENT	7.5 km^3	Proposed
KM3NET	1 km^3	Running, constructing			
Baikal-GVD	1 km^3	Running, constructing	FASERν	Neutrino beam	Running
P-ONE	multi-km^3	Proposed	FASERν2	Neutrino beam	Proposed
IceCube-Gen2	7.9 km^3	Proposed			

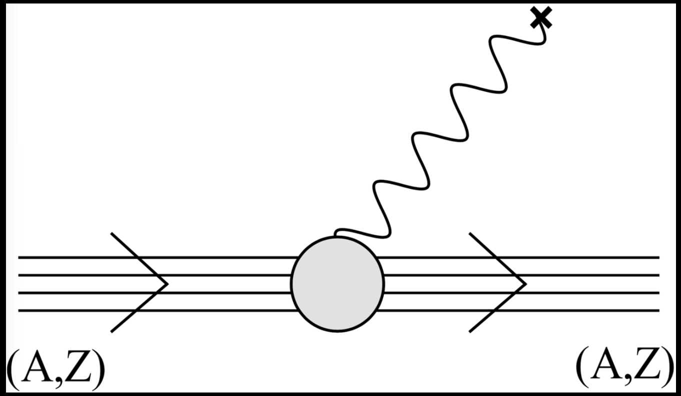
Subdominant interactions: W-boson production



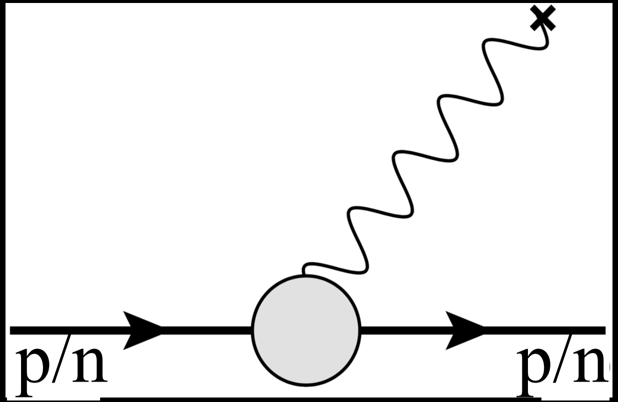


Three kinematic regimes

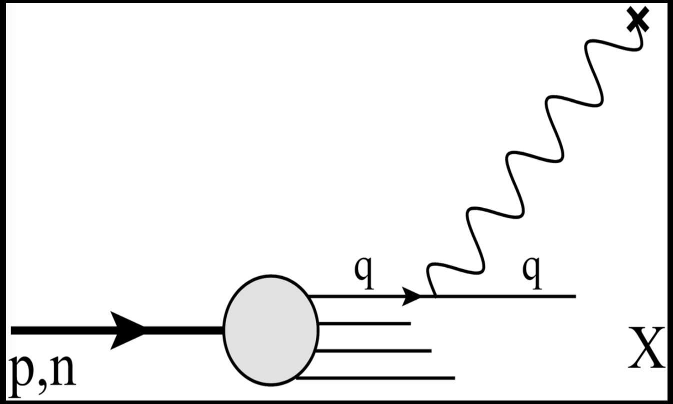
Coherent (elastic)



Diffractive (elastic)



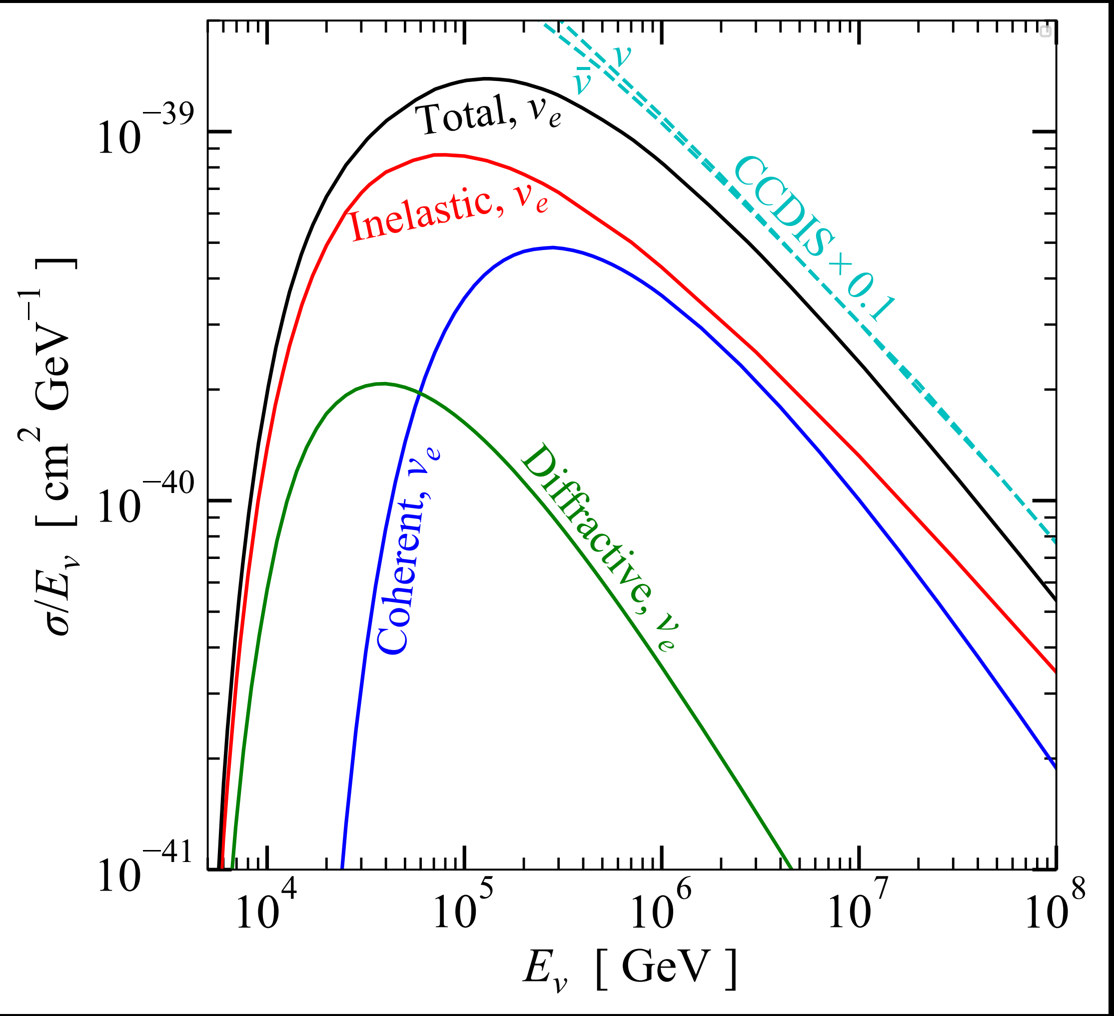
Inelastic



WBP xsec (on oxygen) at different regimes

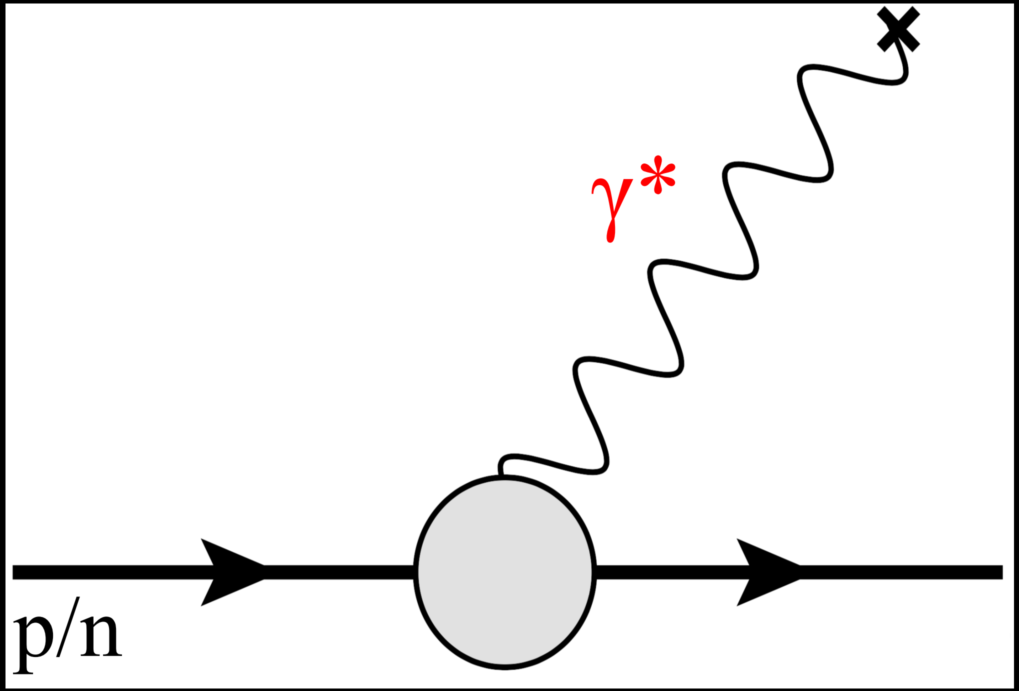
Inelastic component:

- Largest cross section
- Sets the threshold (FASERν, FASERν2)
- Largest uncertainty, especially near threshold



(BZ, Beacom, 1910.08090, PRD)

Inelastic component relies on the photon PDF



Increasing precision in collider physics and others requires:

- NNLO in QCD
- NLO in electroweak → photon PDF (and QED correction to the DGLAP equation)

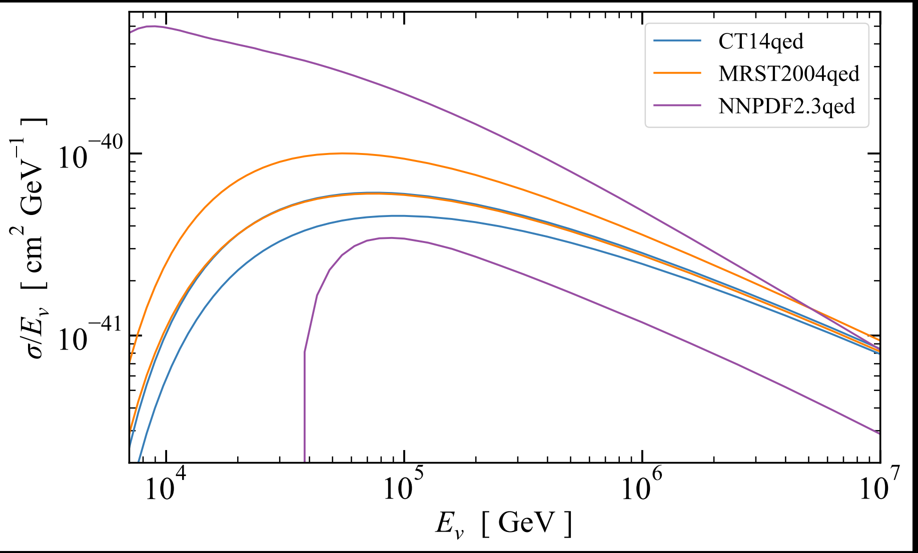
How different photon PDFs affects WBP precision

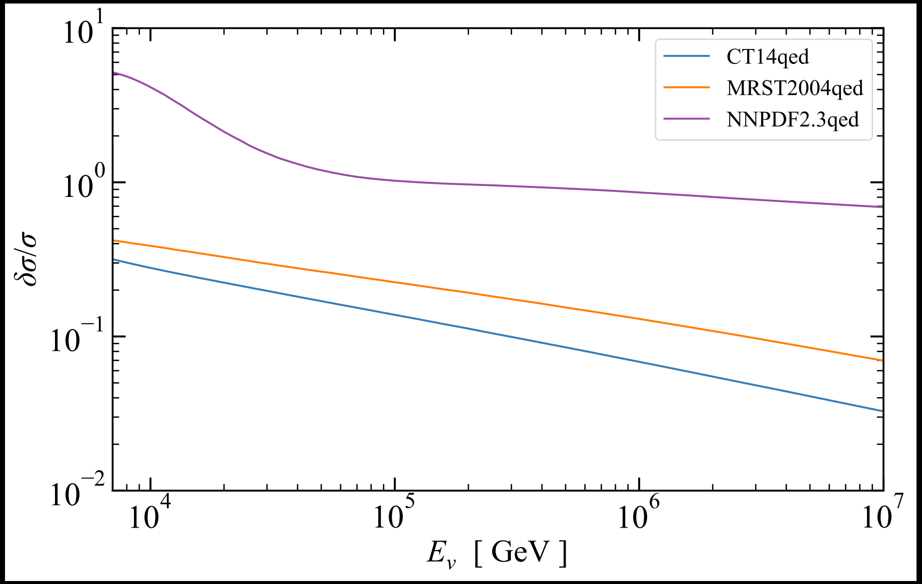
First generation photon PDFs

NNPDF2.3_qed:
Model-indep parameterization of photon pdf +
LHC Drell-Yan data

MRST2004qed:
Collinear photon emission from valence quark at low scale + DGLAP evolution to high scale

CT14qed:
Similar to MRST, but further constrained by ZEUS ep → eγ + X, which is important





(Xie, BZ, Hobbs CTEQ-TEA Coll., 2305.10497)

How different photon PDFs affects WBP precision

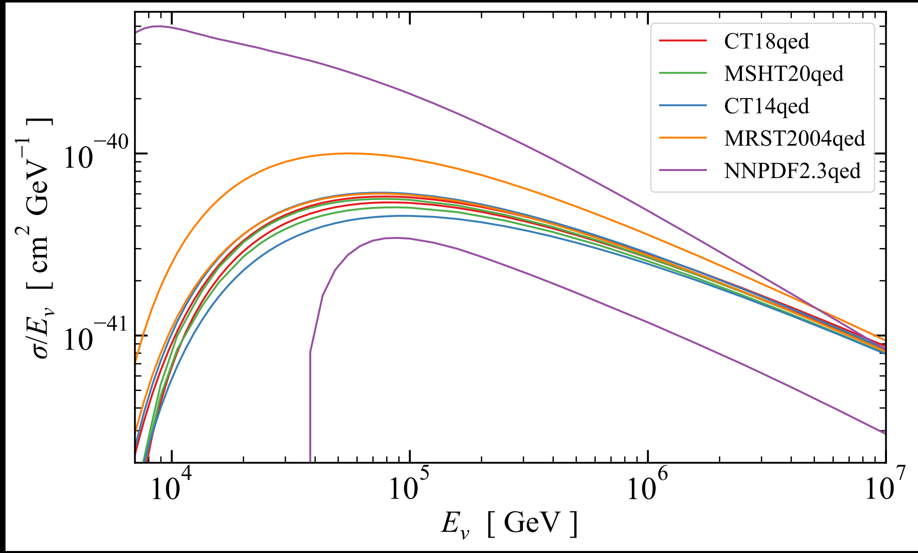
Second generation photon PDFs

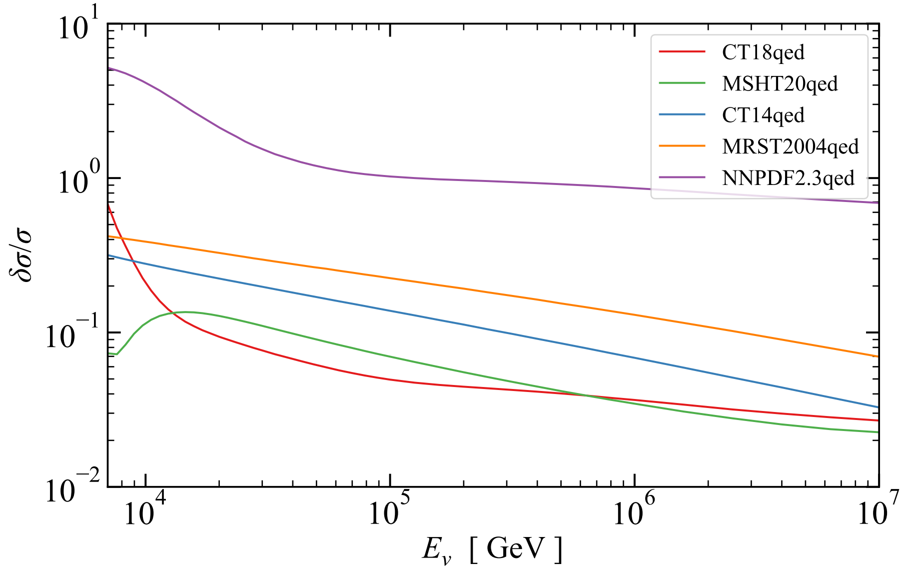
LUXqed formalism (game changer):
(1607.04266 Manohar et al. PRL)
Proton photon PDFs written into proton structure functions → percent level precision

MSHT20qed, first neutron photon PDF using the LUXqed formalism

CT18qed, better calculation, especially the error estimation at large x (smaller Eν).

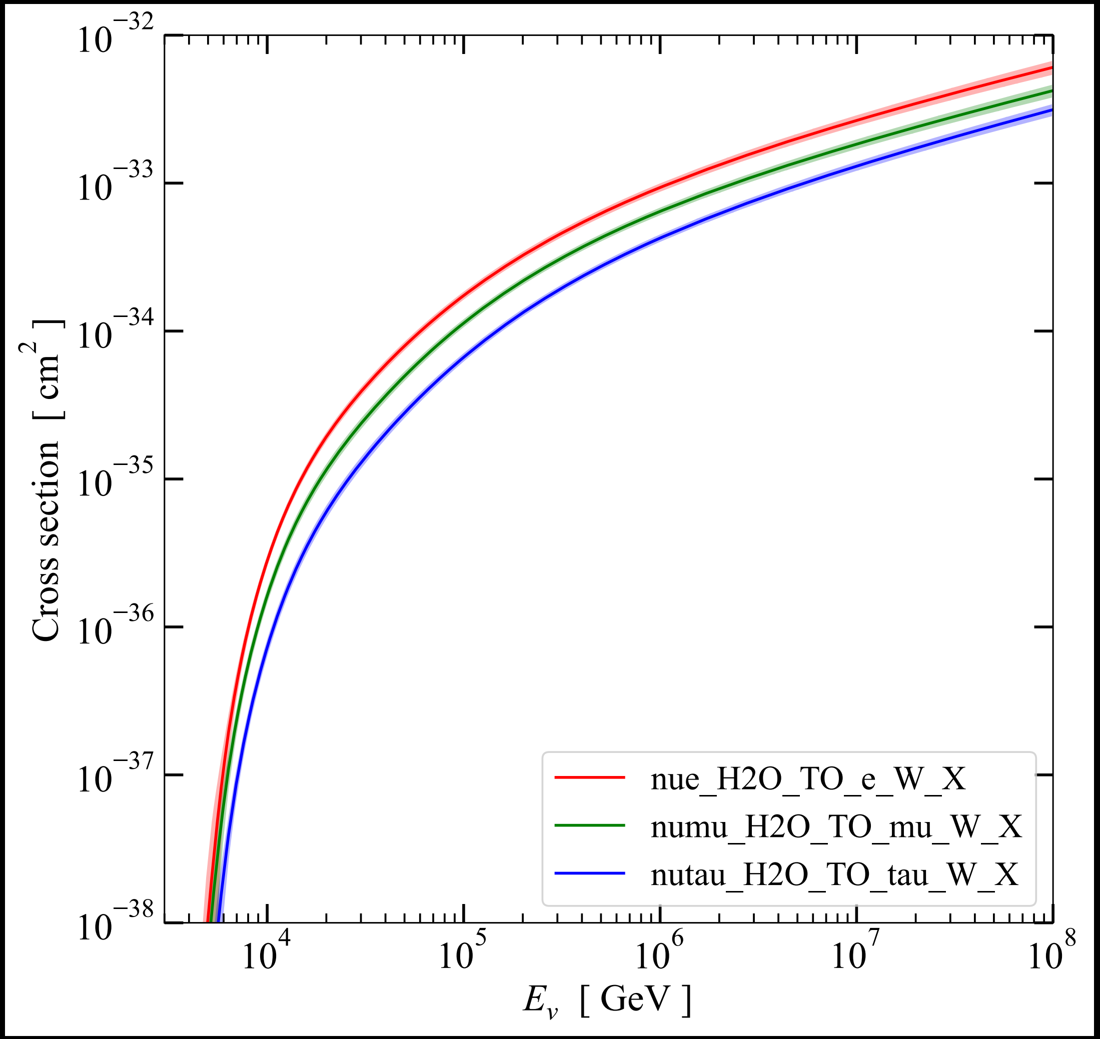
The 2nd generation photon PDF increase WBP precision to percent level





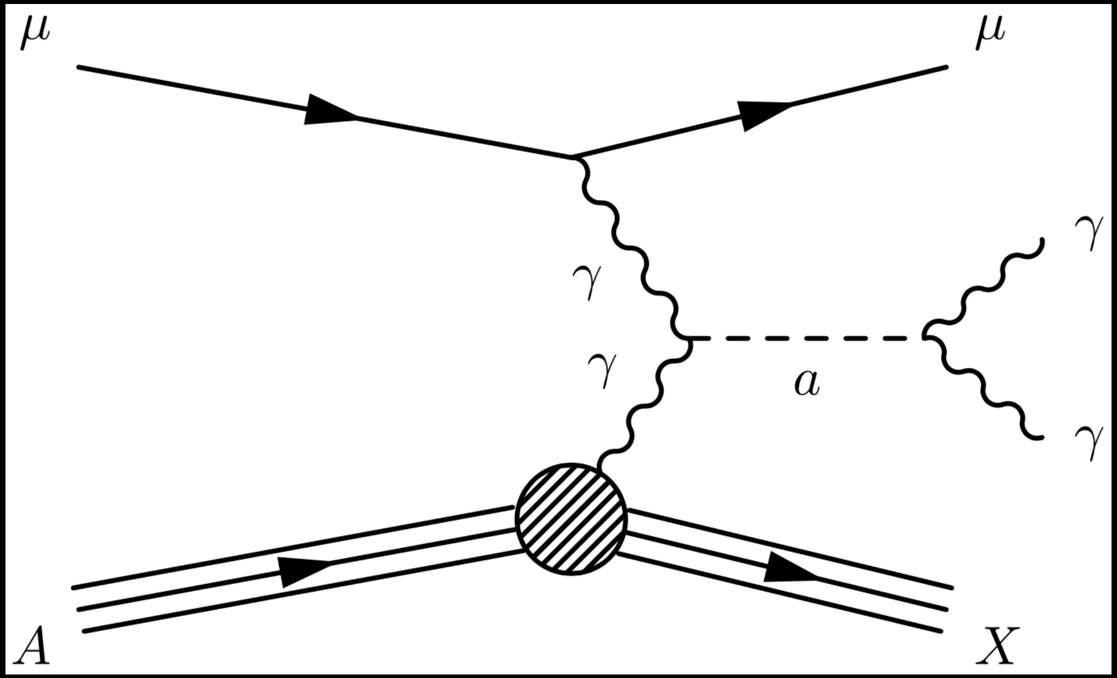
(Xie, BZ, Hobbs CTEQ-TEA Coll., 2305.10497)

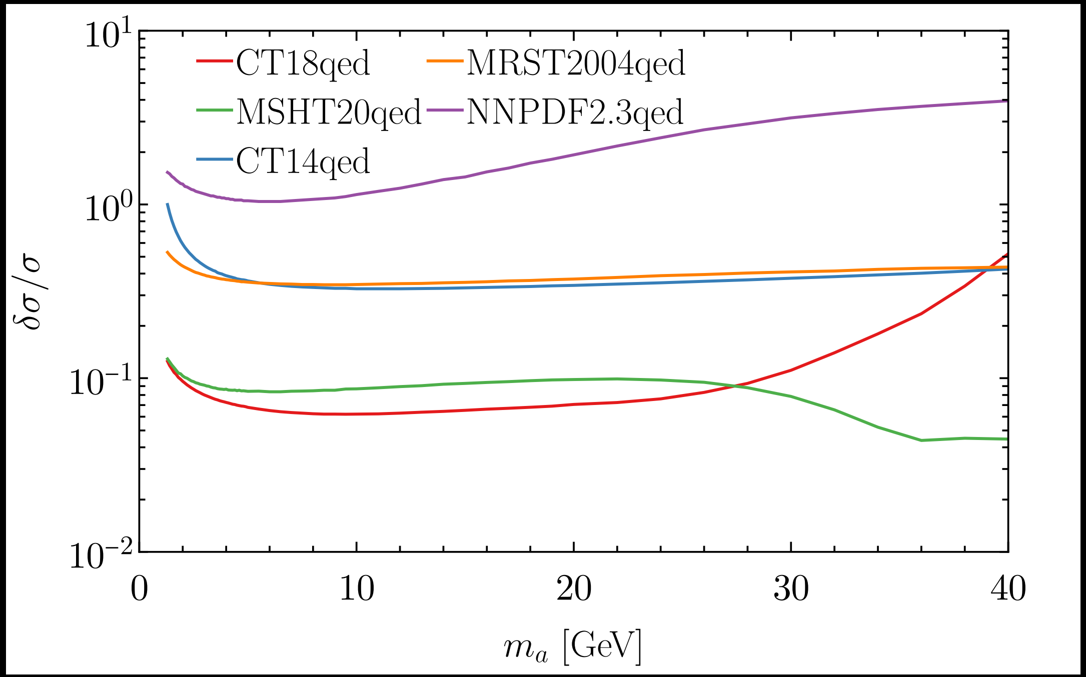
The most precise calculation of WBP so far



The cross section data with uncertainties can be found on the GitHub webpage (just google “[my name] github”).

Example: Axion-like particle in a muon beam dump experiment





E_μ = 1.5 TeV, f_a = 1 TeV^-1

(Xie, BZ, Hobbs CTEQ-TEA Coll., 2305.10497)

CT18qed for photon PDFs

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CT18qed PDFs
https://cteq-tea.gitlab.io/project/00pdfs/

Will be available on
https://lhapdf.hepforge.org/pdfsets soon.

High-energy neutrino sources

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  - Cosmic gamma ray sources, hadronic vs leptonic mechanism
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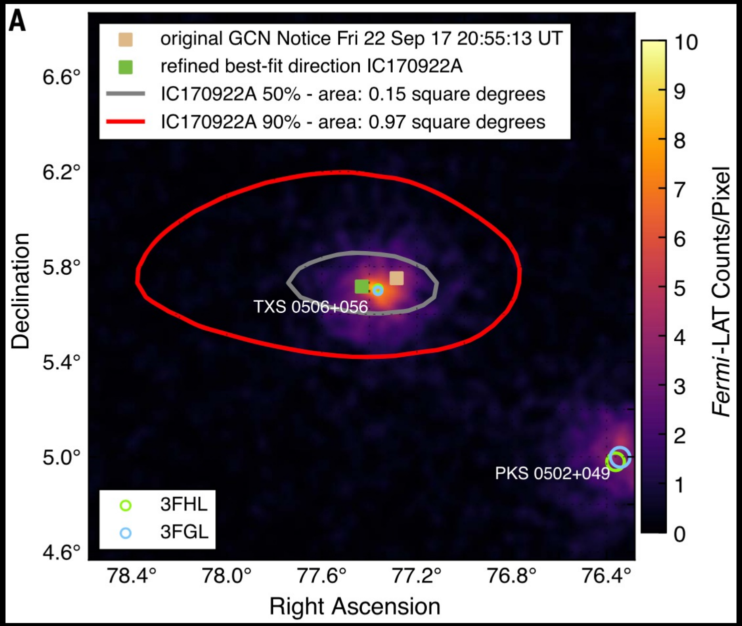
  - Essential for multi-messenger astrophysics (highlighted by astro2020)

Searches for the sources of high-energy neutrinos

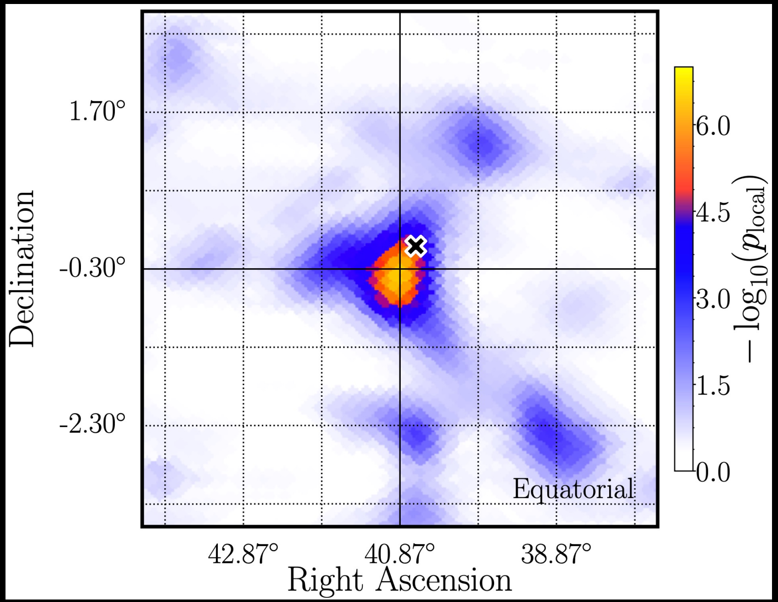
TXS 0506+056 (Blazar)



Association with ~300 TeV neutrino
3.0σ (global)
1807.08816 Science, IceCube

Neutrino flare ~2015
3.5σ (global);
1807.08794 Science, IceCube

NGC 1068 (Seyfert II galaxy)



2.9σ (global)
1910.08488 PRL, IceCube

4.2σ (global)
2211.09972 Science, IceCube

Tidal disrupt events

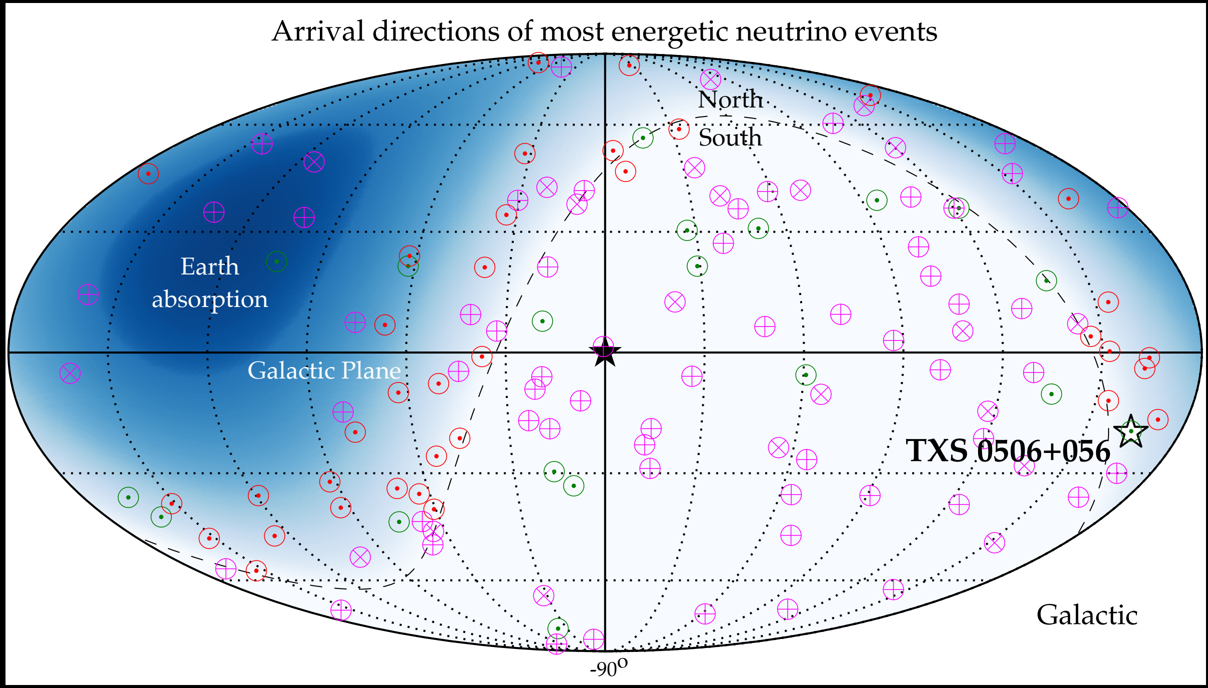
AT2019dsg (2005.05340),

AT2019fdr (2111.09390),

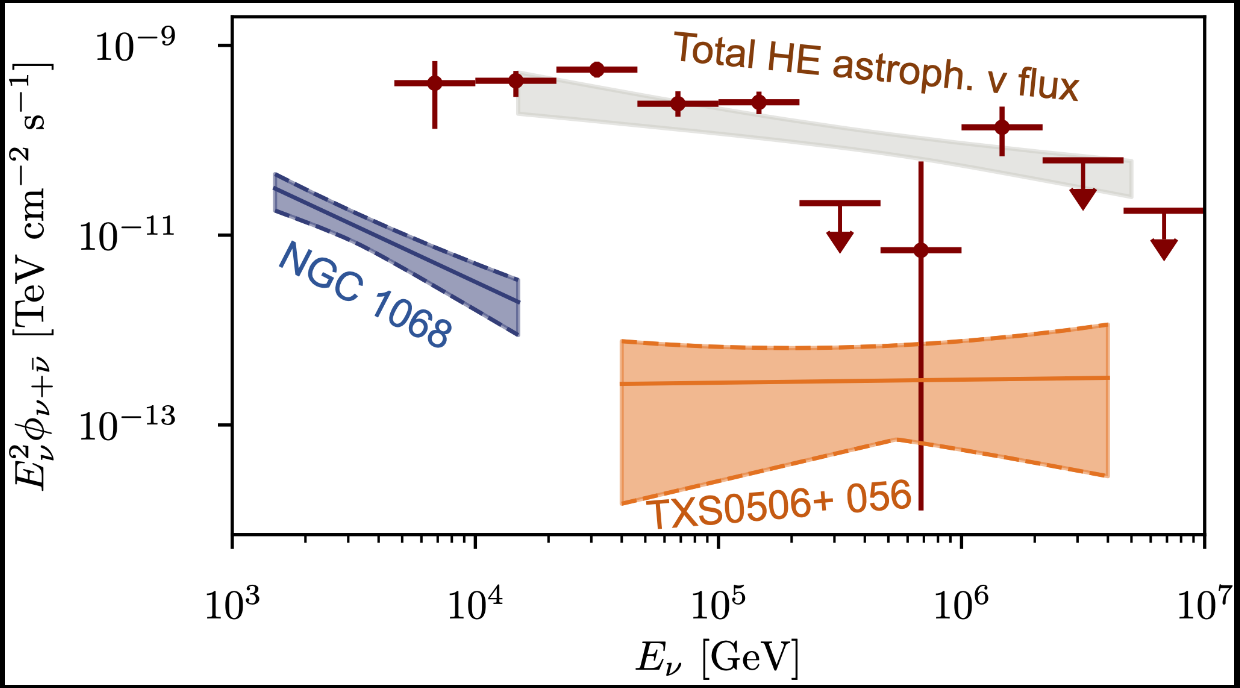
AT2019aalc (2111.09391)

possibly associated with HE neutrinos found in multi-messenger follow-ups

Vast majority of HE astrophysical neutrinos remain unexplained



1903.04334 Ackermann et al



2211.09972 IceCube

We must find the dominant sources of the all-sky diffuse HE astrophysical neutrinos

Blazars (<~ 30% contribution)

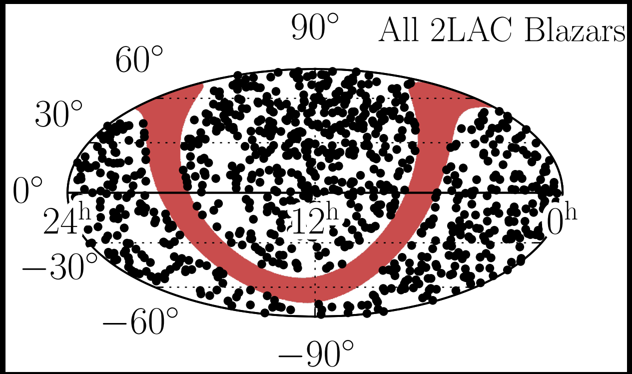
γ rays produced along with ν

$p+p \text{ or } p+\gamma \rightarrow \pi^0\, \pi^+\, \pi^-$

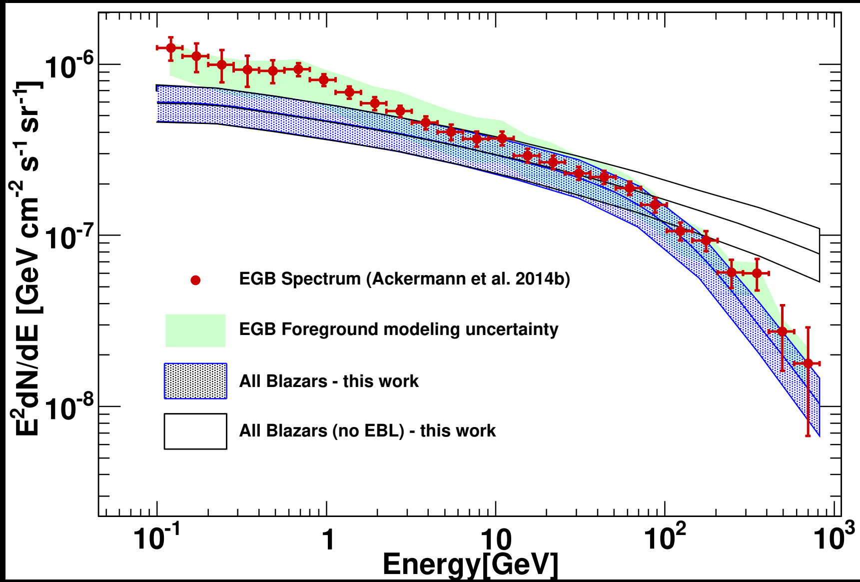
$\pi^0 \rightarrow \gamma\, \gamma$

$\pi^+\, \pi^- \rightarrow e\, \nu_\mu\, \nu_e$

Fermi-LAT observed ~10^3 Blazars, stacking analyses w/ HE nu

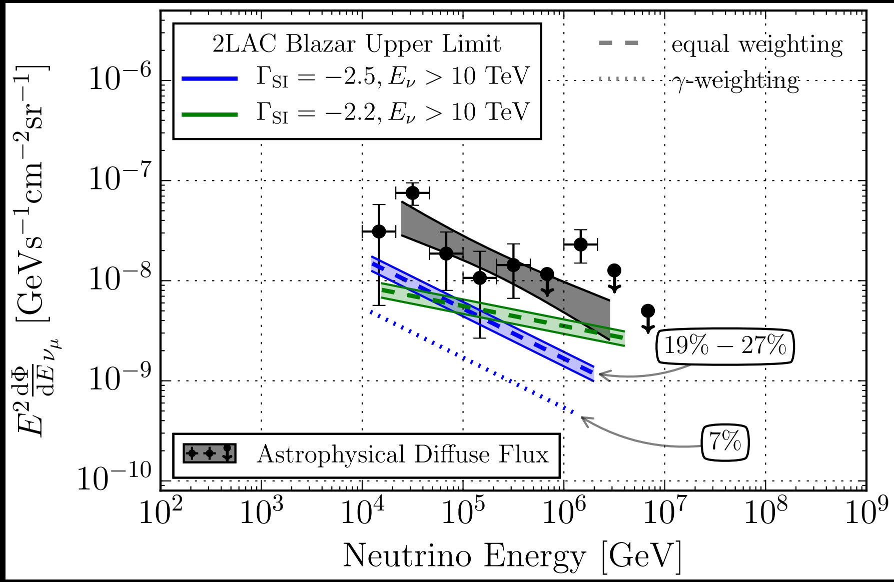


Extragalactic gamma ray background (EGB) dominated by blazars



1903.04334 Ajello et al.

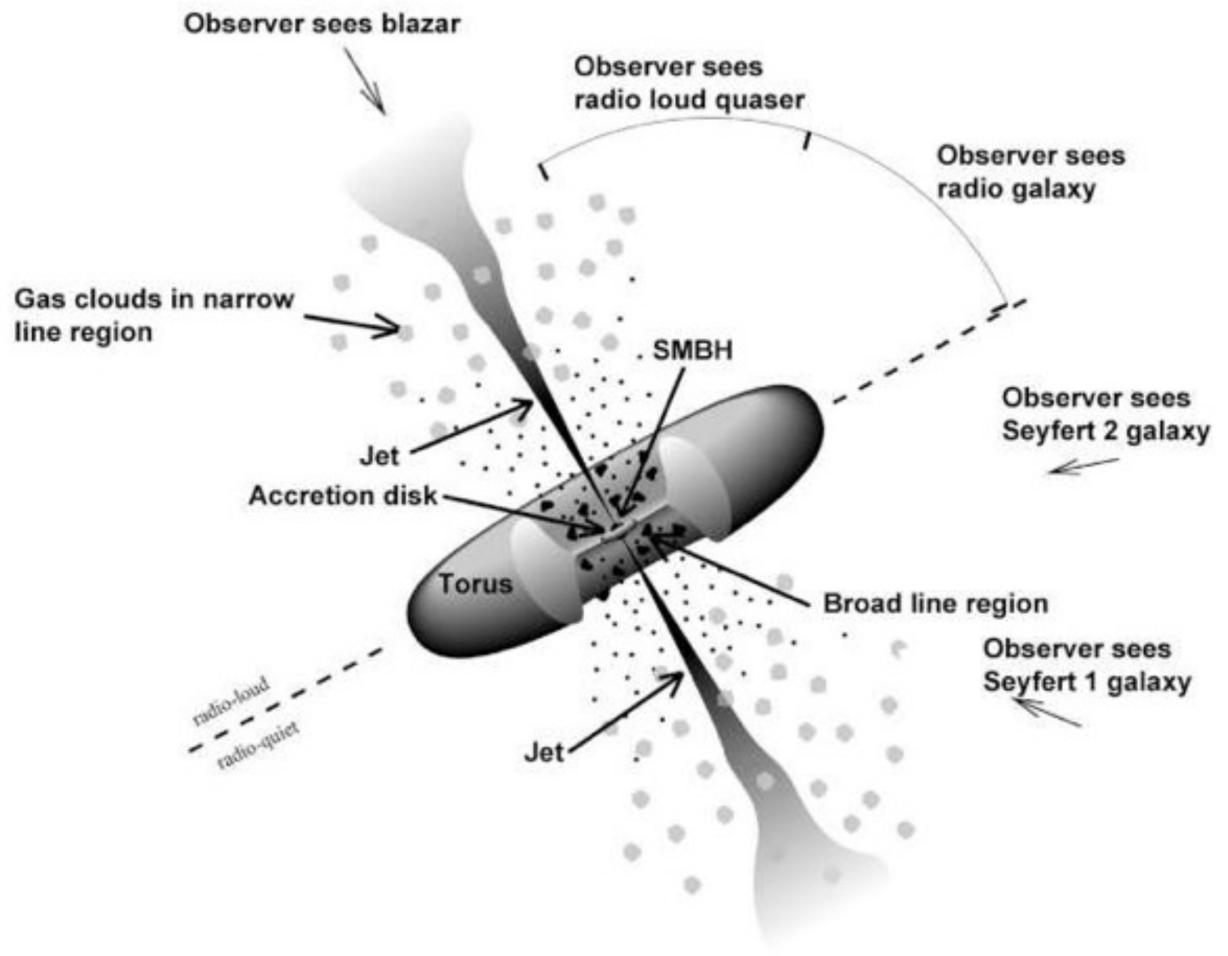
No HE nu emission found; constraints set



1611.03874 IceCube (See also Smith+ 20 JACP, Yuan+ 20 ApJ)

Radio-bright active galactic nuclei (AGN)

Radio bright AGN: radio blazars, radio galaxies, etc.
Another major contribution to extragalactic gamma rays



Radio-bright AGN, discovery?

2001.00930 Plavin et al.

- ≃3400 radio-bright AGNs with 8 GHz flux density > 0.15 Jy
- 56 high-energy muon-neutrino events
- Found 3.1σ significance

2009.08914 Plavin et al.

- ≃3400 radio-bright AGNs with 8 GHz flux density > 0.15 Jy
- Pre-trial p-value map from IceCube
- Found 3.0σ significance

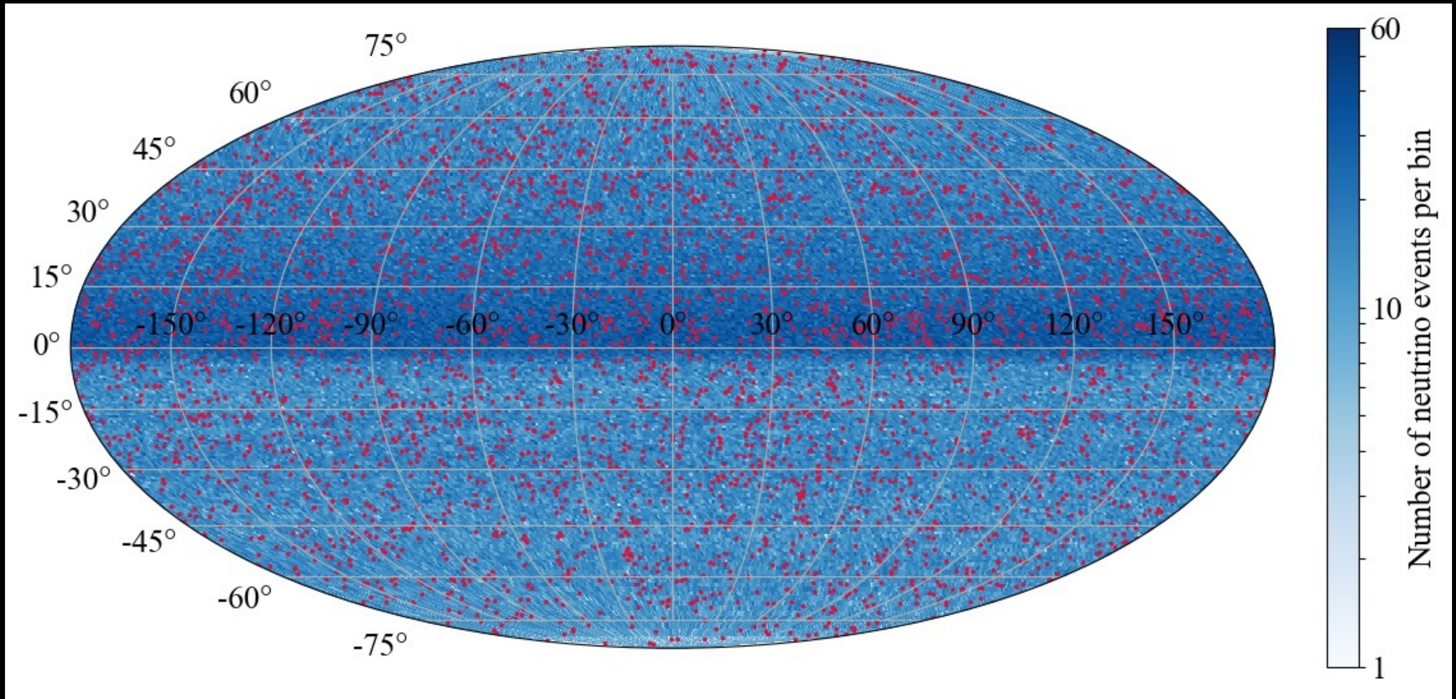
- 4.1σ combining the two analysis (2009.08941)
- These sources could explain all the HE astroph. nu of IceCube (2009.08941)
- 8-GHz flux of AGN may be an indicator of HE nu emission (Both papers)
- But…

Radio-bright AGN: our work

- Unbinned maximum-likelihood-ratio method
    - Routinely used by IceCube and others (Fermi-LAT, Super-K, etc.)
    - Extensively used by theorists.
    - Info of every single event

- Same sources (≃3400 radio bright AGN)

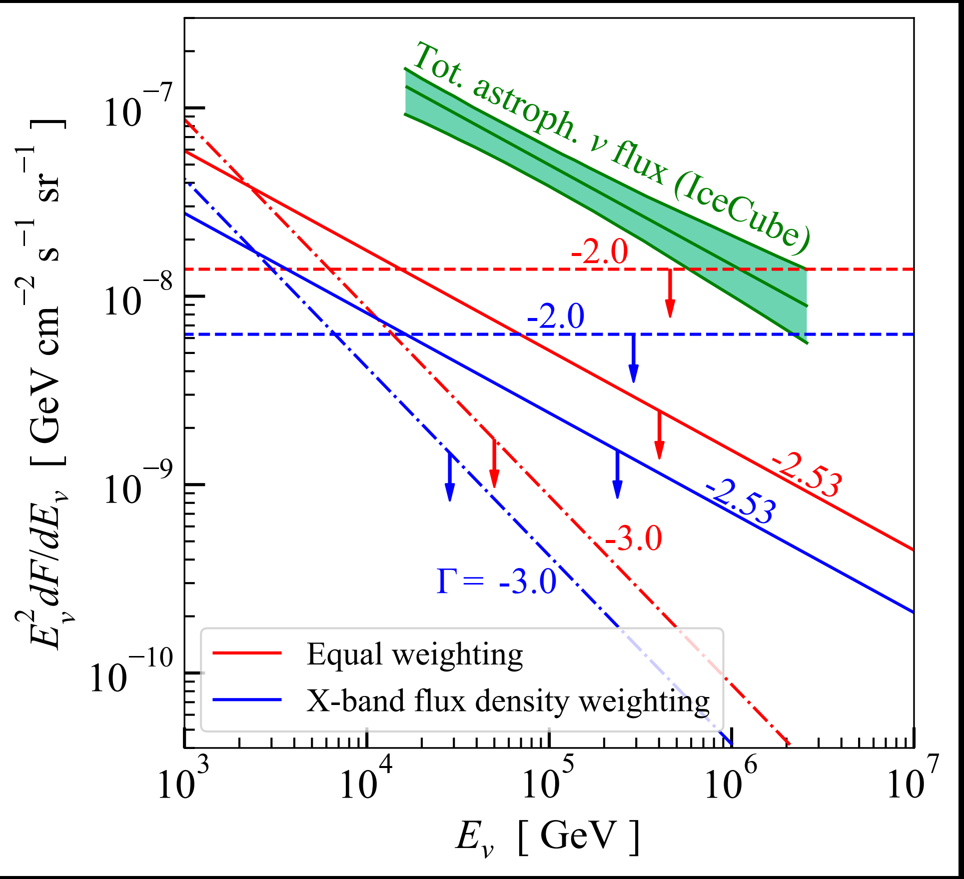
- Ten years of IceCube ν_μ data (1,134,450 events)



2103.12813 BZ, Kamionkowski, Liang

Radio-bright AGN: our results

Upper limits

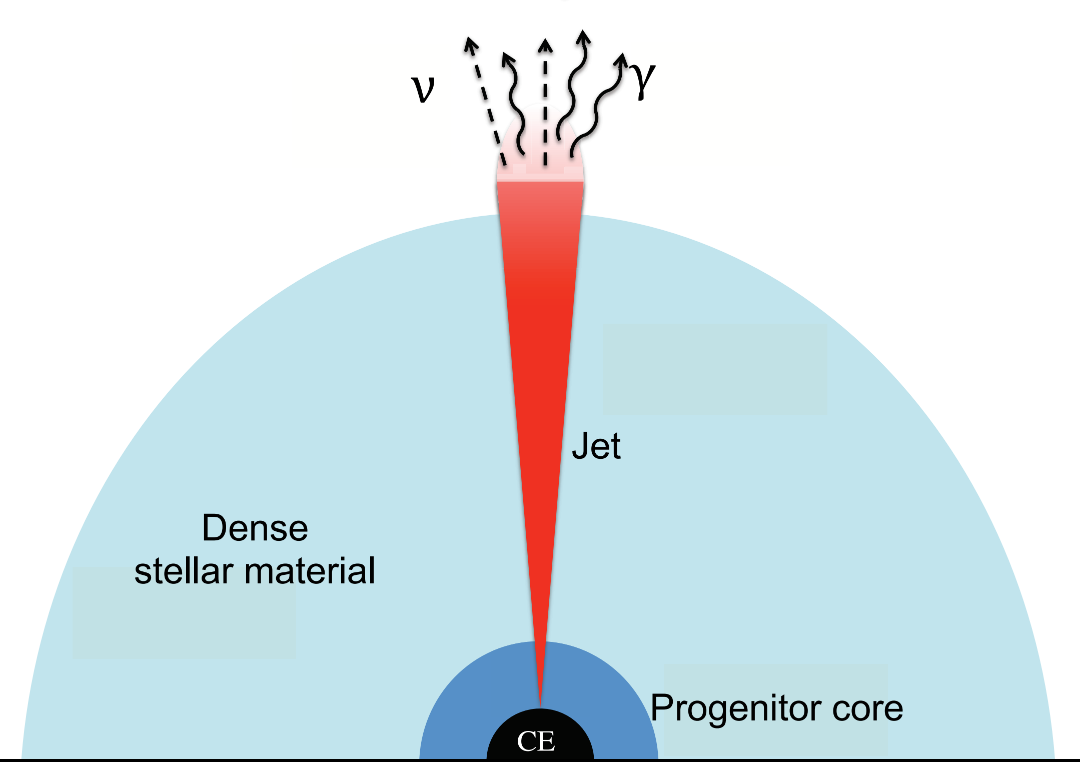


2103.12813 BZ, Kamionkowski, Liang

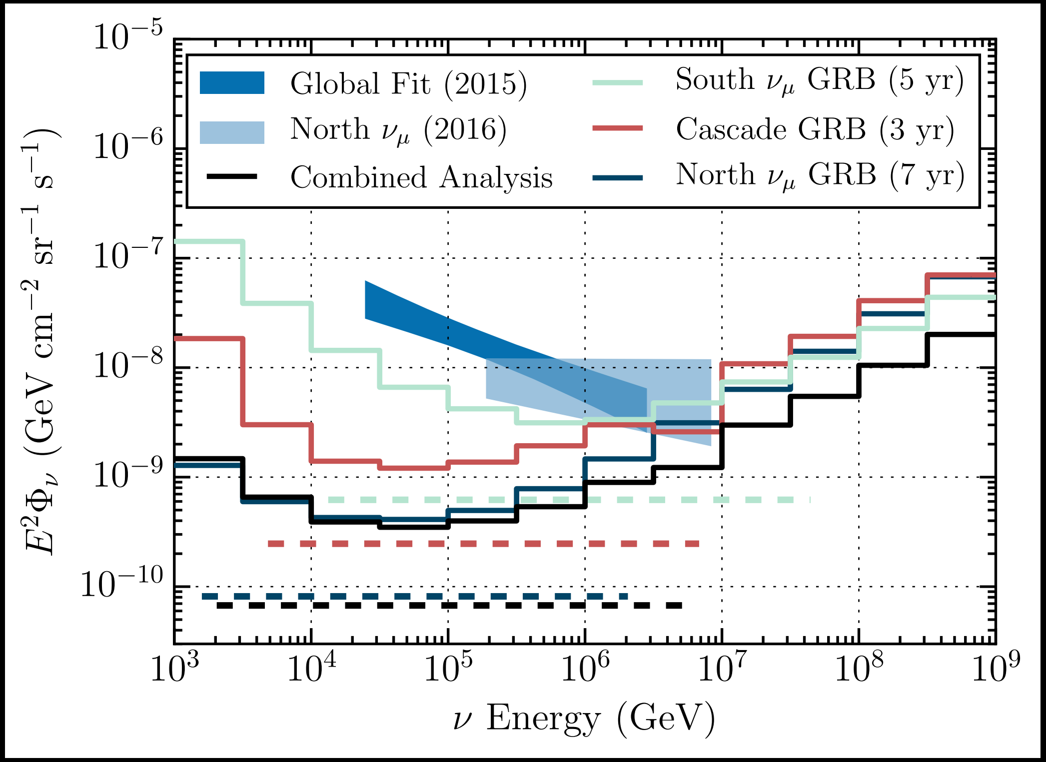
1. No significance.
2. Contribute < 30% of HE astro nu flux.
3. 8-GHz radio emission might not be an indicator of HE nu emission.

Confirmed by 2304.12675 IceCube Collaboration

Gamma-ray bursts (GRBs) (<1%)



Long gamma-ray burst



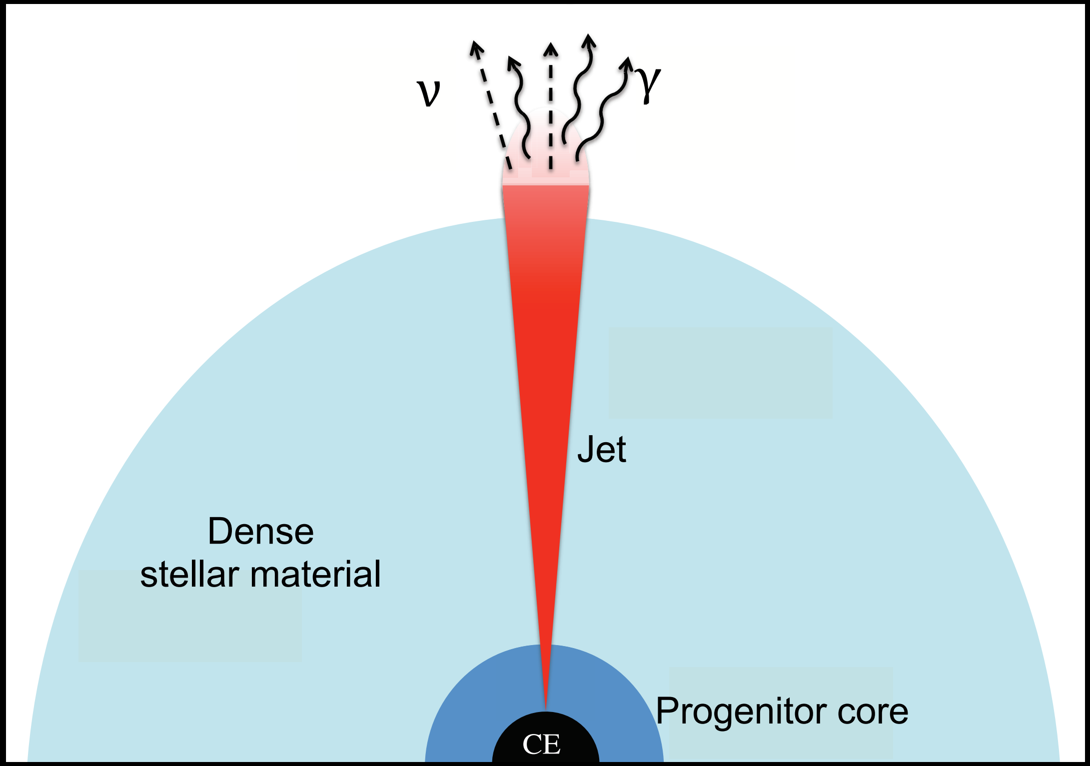
1702.06868 IceCube

5-year IceCube data and 1172 GRBs

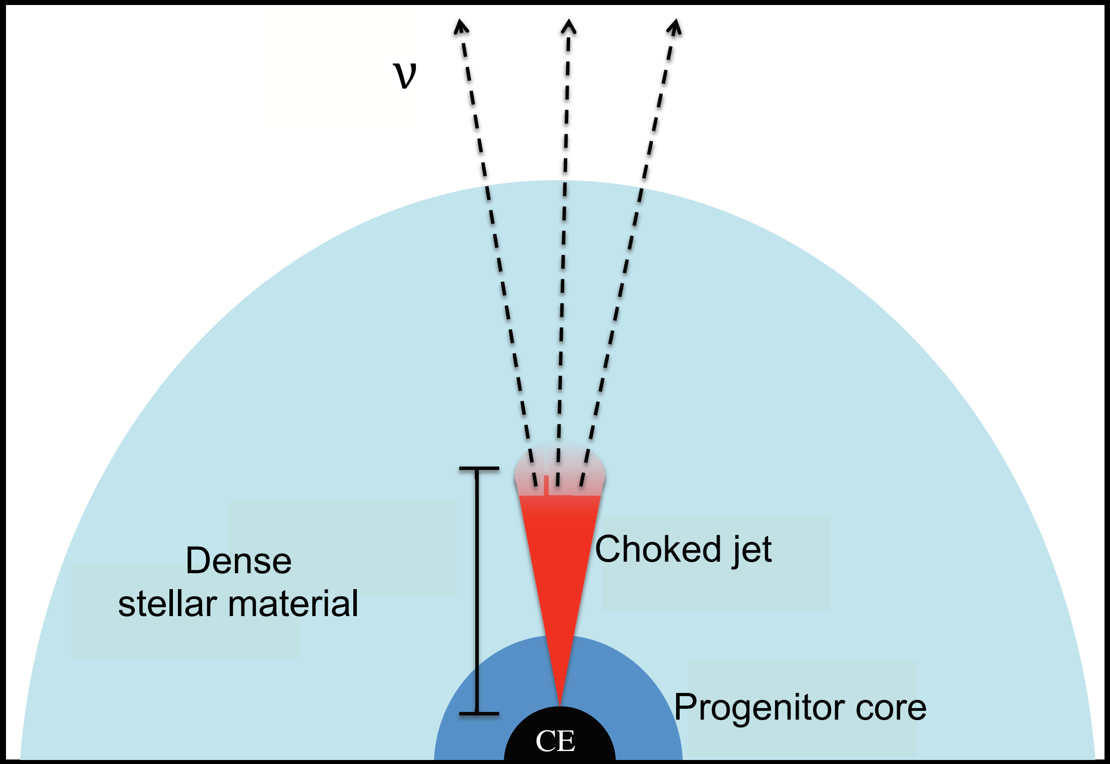
GRBs contribute < 1% of HE nu

Short GRBs could also produce HE neutrinos

Choked-jet supernova as sources of HE neutrinos



Long gamma-ray burst



Choked-jet scenario

1512.08513 Senno, Murase, Meszaros

Choked-jet SN: new analysis considerations

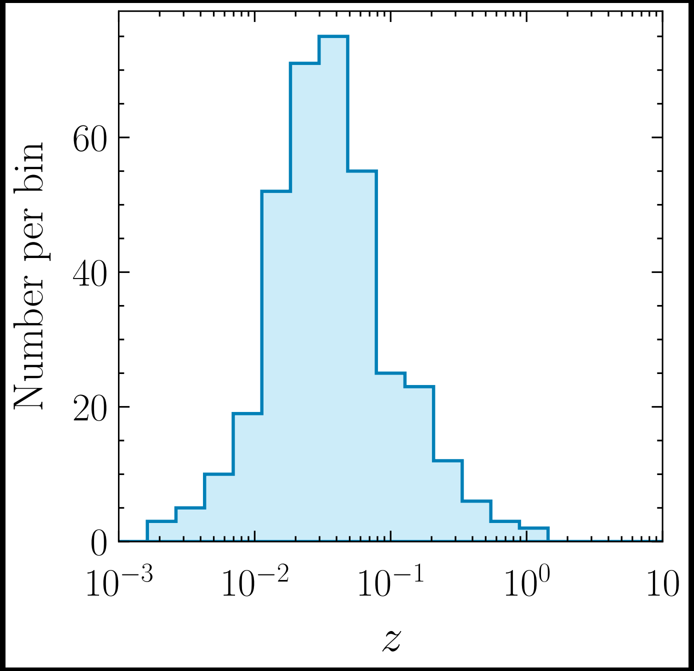
Data

Same ten-yrs of IceCube data

Remove the 19 double-counted events due to a misreconstruction error
(*found by 2110.02974 BZ, Beacom*).

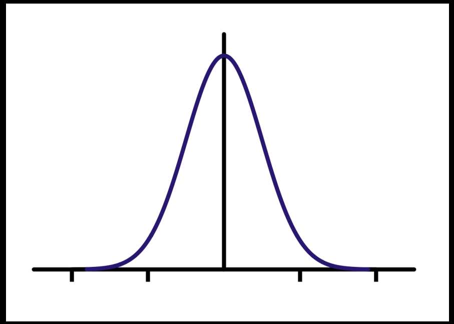
SN sample

Collected 386 type Ib/c SN between 2008—2018, from several public SN catalogs



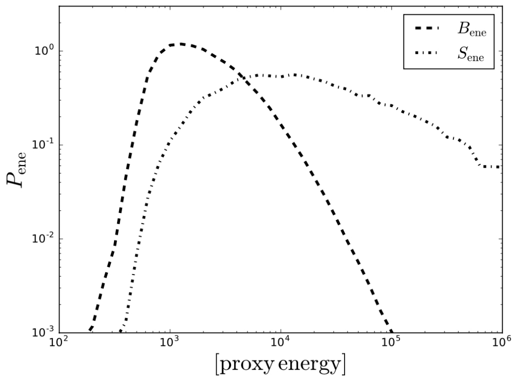
Analysis formalism

Temporal PDF



σ_T = 4 days
Center: 13 days before SN max

Energy pdf



Choked-jet SN models

Two classes of models

1. Power-law

   1706.02175 Senno, Murase, Mészáros

2. More realistic model

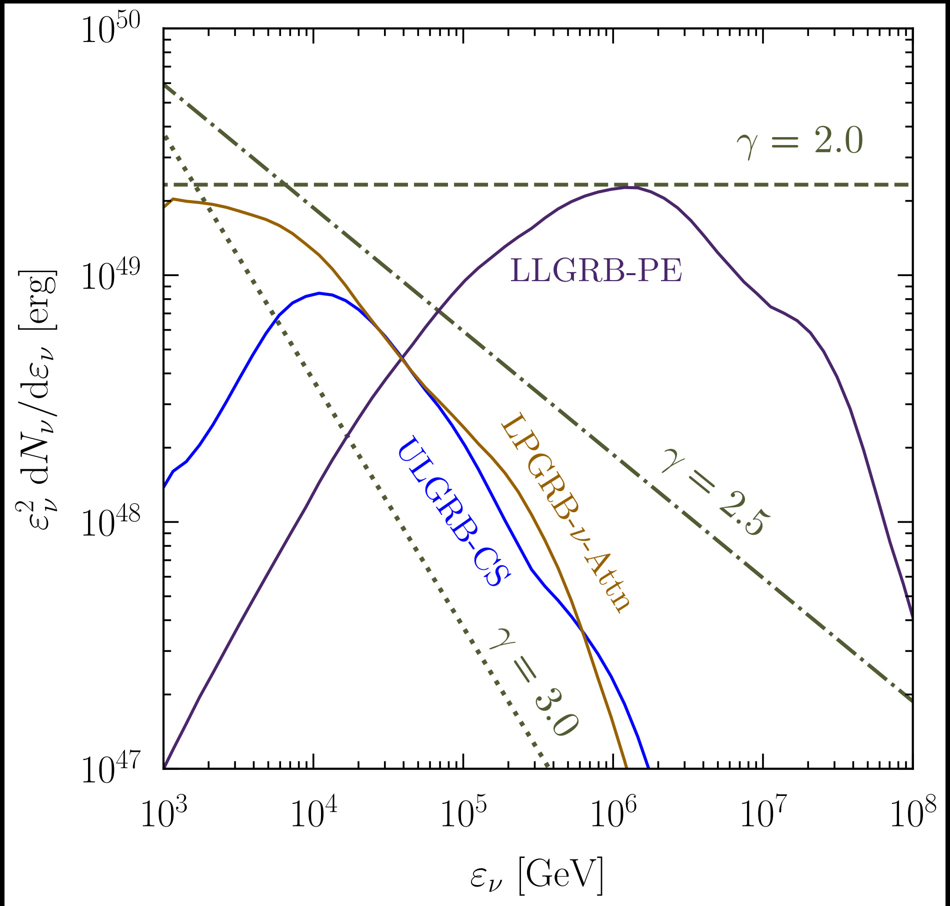
   astro-ph/0607104 Murase et al.

   1306.2274 Murase & Ioka

Universal parameters

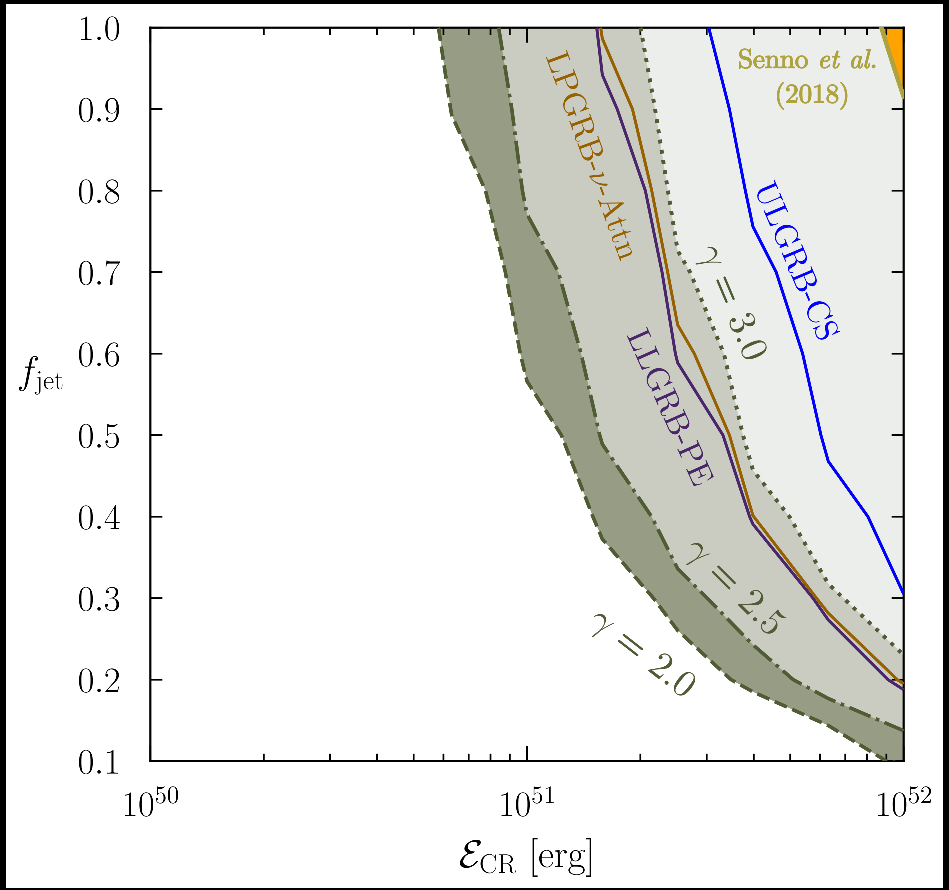
E_p: isotropic equivalent cosmic ray energy injection

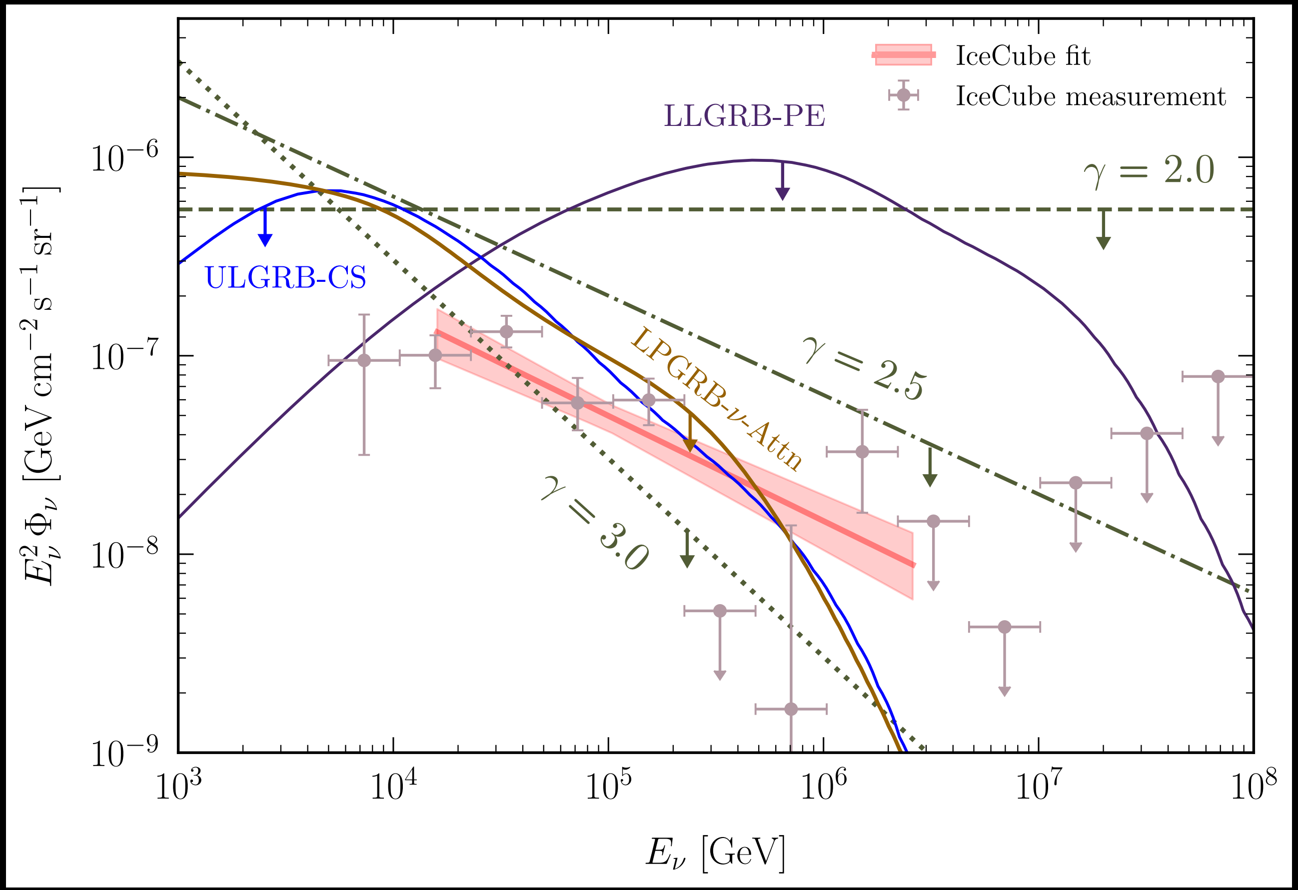
f_{jet}: fraction of type Ib/c SNe that have jet



2210.03088 Chang, BZ, Murase, Kamionkowski

Choked-jet SNe: could still explain most/all of IceCube observation





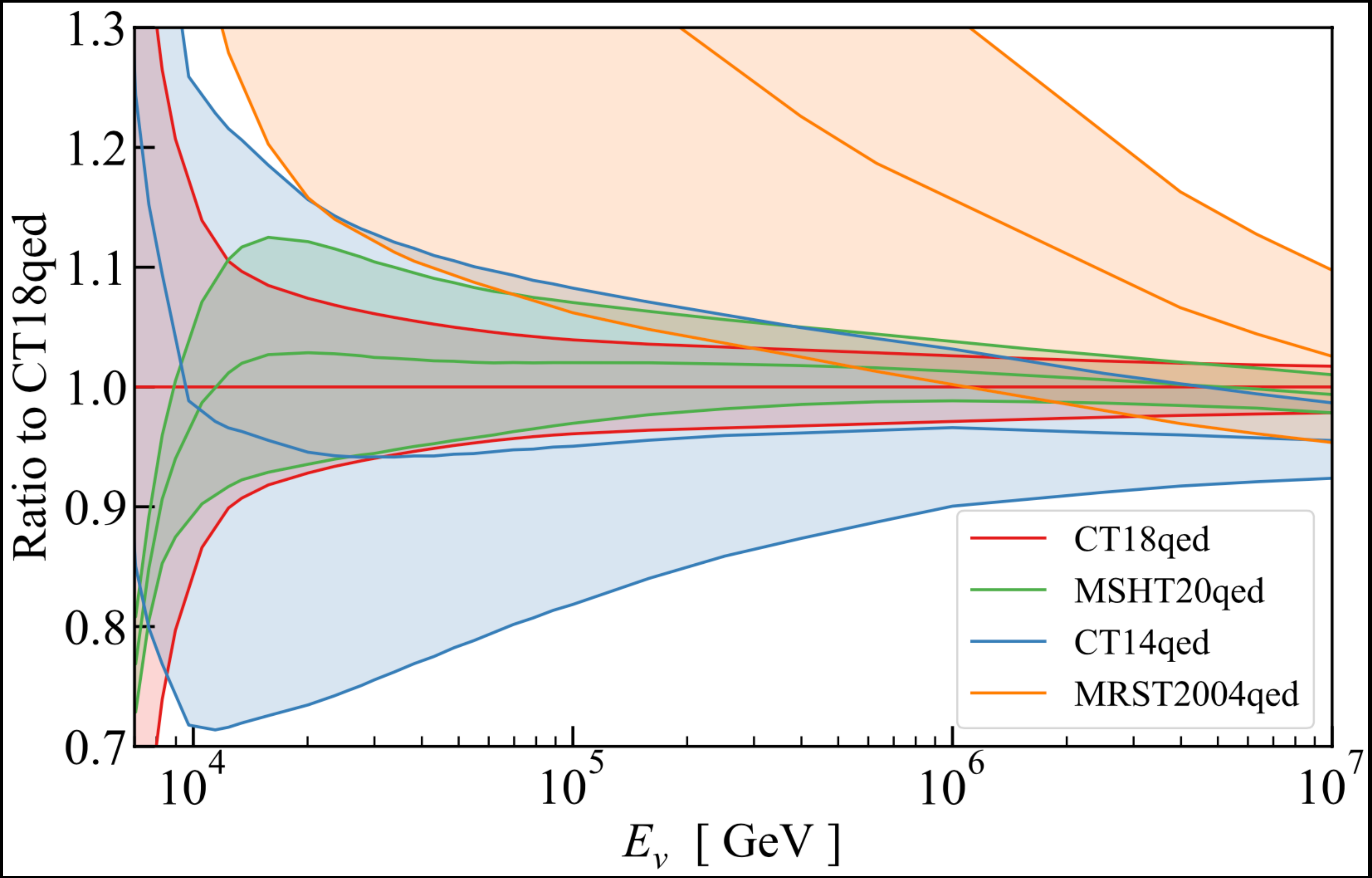
> 10 times stronger than previous work
1706.02175 Senno, Murase, Mészáros
1809.09610 Esmaili, Murase

2210.03088 Chang, BZ, Murase, Kamionkowski
(See also 2303.03316 by IceCube collaboration)

Summary of looking for HE nu sources

- Critical for all the astrophysical studies
- Still looking for the dominant sources of HE neutrinos
- Some excluded:
  γ-ray blazars, γ-ray bursts, galaxy clusters, etc.
- Some need more data (neutrino/EM) :
  Radio bright AGN, radio-quiet AGN, choked-jet SN, interaction SN, ultra-long GRB, etc.

Thanks for your attention!

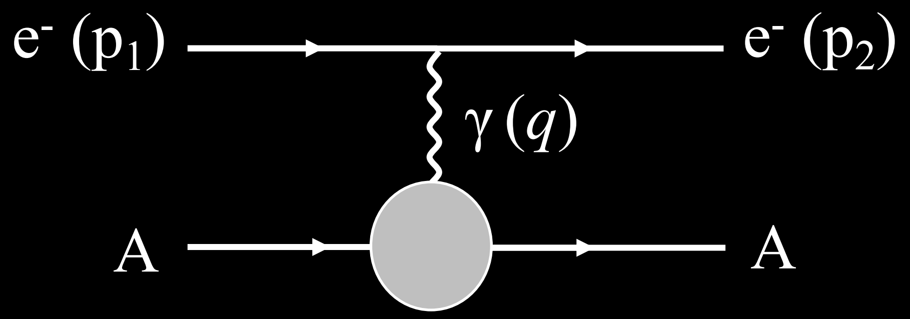


1.3
1.2
1.1
1.0
0.9
0.8
0.7
Ratio to CT18qed
10^4
10^5
10^6
10^7
E_ν [GeV]
CT18qed
MSHT20qed
CT14qed
MRST2004qed

Coherent and diffractive: Invalidity of equivalent photon approximation

(or Weizsäcker-Williams approximation)

Equivalent photon approx.



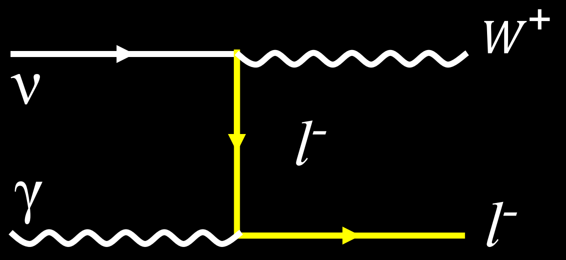
$\cos\theta \simeq 1$

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

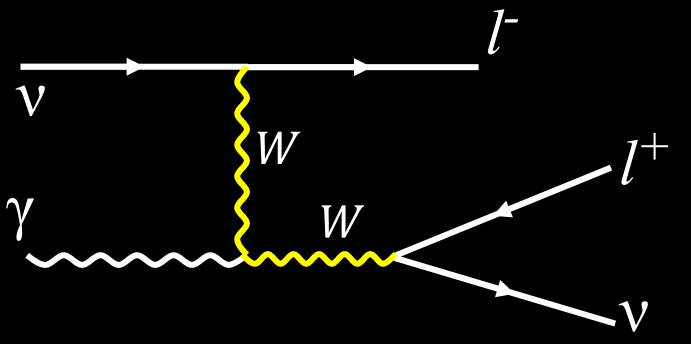
$$\sigma_{eA}(s) \simeq \int \sigma_{e\gamma}(s_{e\gamma})\, H_\gamma(s_{e\gamma}, q^2)$$

But not valid for WBP & Tridents

W-boson production



Tridents



Ballett et al., 1807.10973 showed the invalidity of EPA for tridents.

We show the invalidity for W boson production, for the first time

Coherent and diffractive: complete approach

$$i\,M = L^{\mu}\frac{-ig_{\mu\nu}}{q^2}H^{\nu};\quad \frac{d^2\sigma_{\nu X}}{dq^2 d\hat{s}} = \frac{1}{32\pi^2(s-M_X^2)^2}\frac{H^{\mu\nu}L^{\mu\nu}}{q^4};$$

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

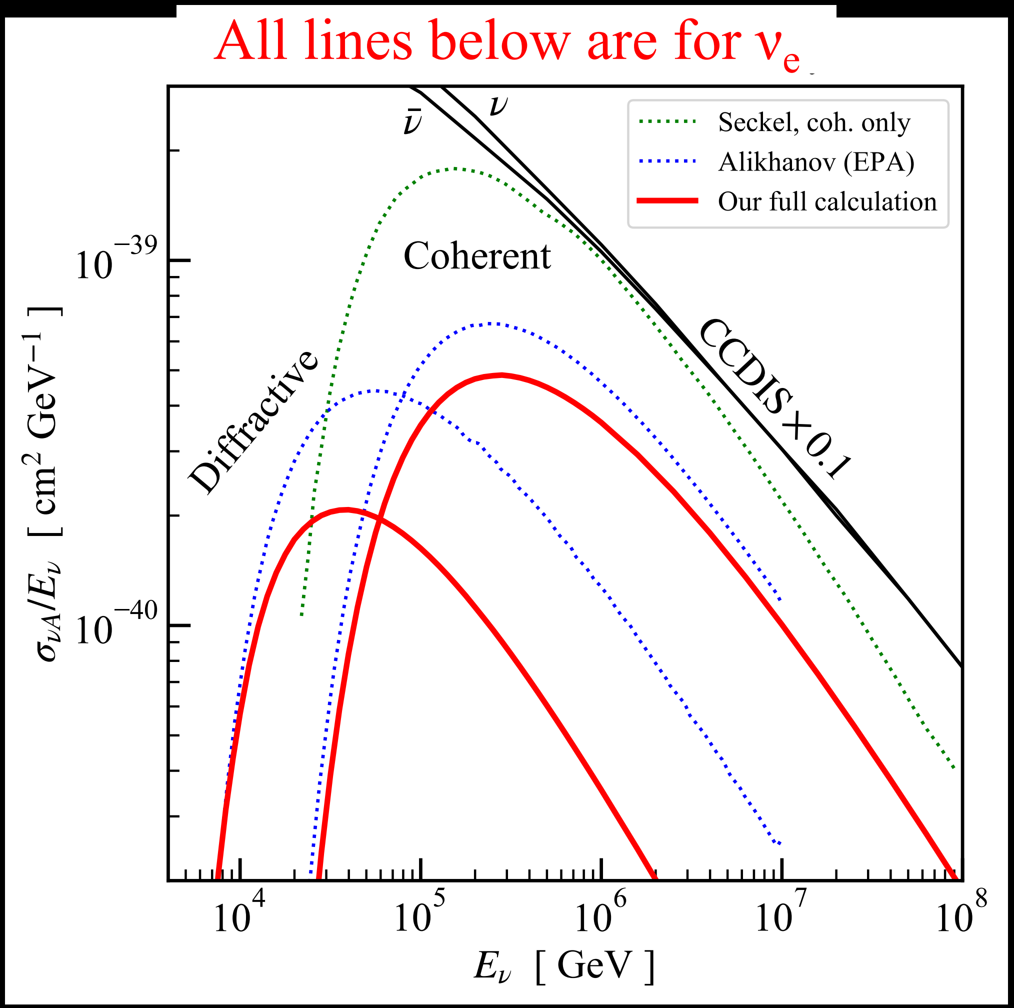
Transverse Longitudinal

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

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

$h_X^{T/\mathrm{L}}$ inludes the form factors.

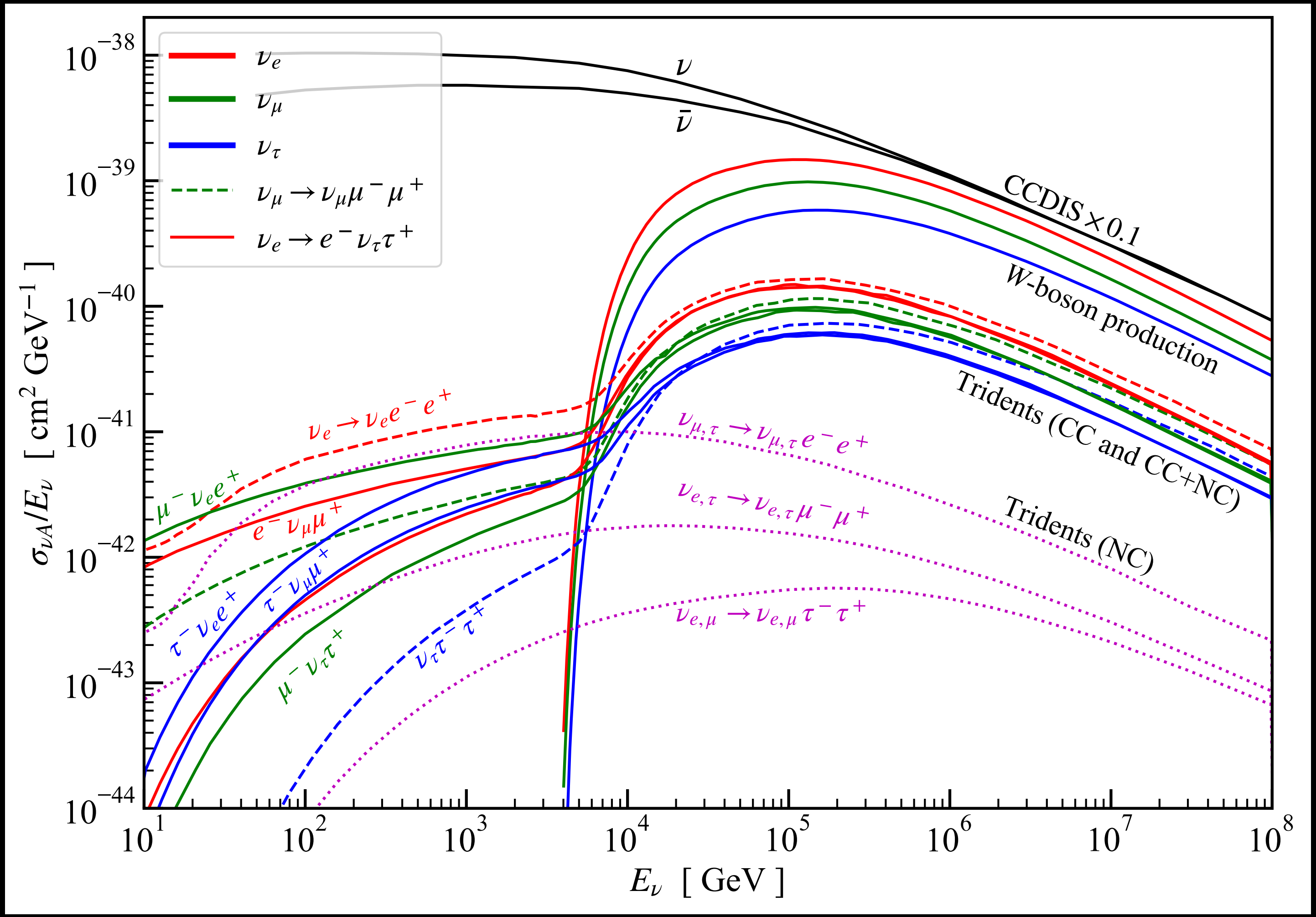
(WBP as an example, similar for tridents)



Diffractive regime: included Pauli-blocking effects for the first time assuming ideal Fermi gas of nucleons with equal density

EPA is not good. Pauli blocking should be included.

Total neutrino-nucleus (Oxygen) cross section



W-boson production:
First comprehensive calculation

Tridents:
First calculation at TeV—PeV

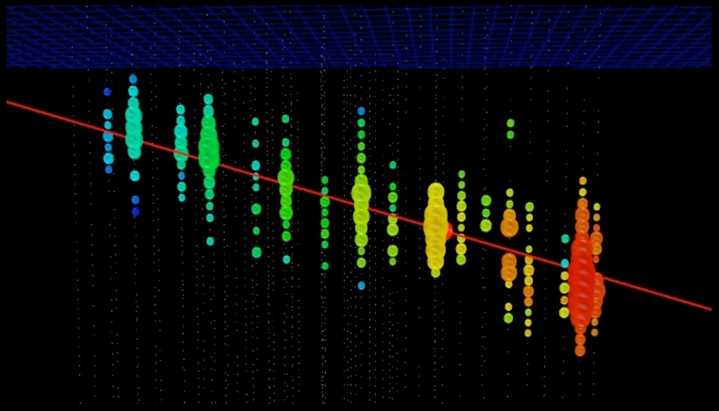
(BZ, Beacom, 1910.08090, PRD)

Implications from large WBP xsec

1. Neutrino absorption in Earth (increase as large as $\simeq$15%)

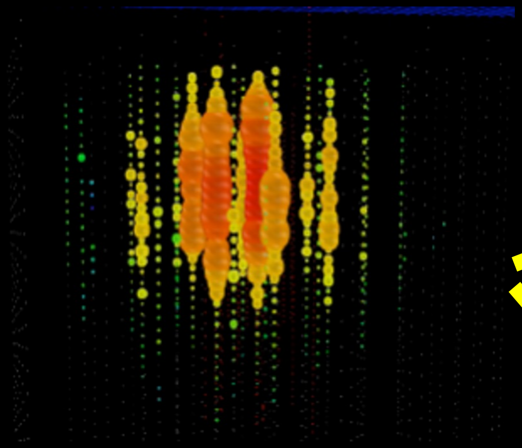
2. Detections in IceCube, IceCube-Gen2, etc. (Next few slides.)

Brief review of IceCube detection



μ track

mainly $\nu\mu$ CCDIS

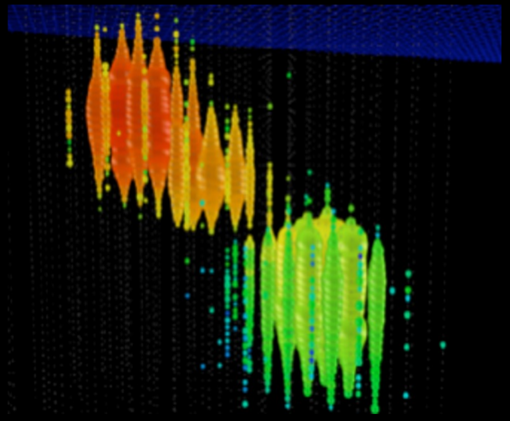


Shower

(e or hadron)

e: mainly from νe CCDIS

hadrons: All CC/NC DIS



Double bang/pulse (τ)

($\nu\tau$ CCDIS >~1e5 GeV)

EM shower (e)

vs

Hadronic shower

WBP mainly showers

$\nu_e + A \rightarrow e + W + A'$

$\nu_\mu + A \rightarrow \mu + W + A'$

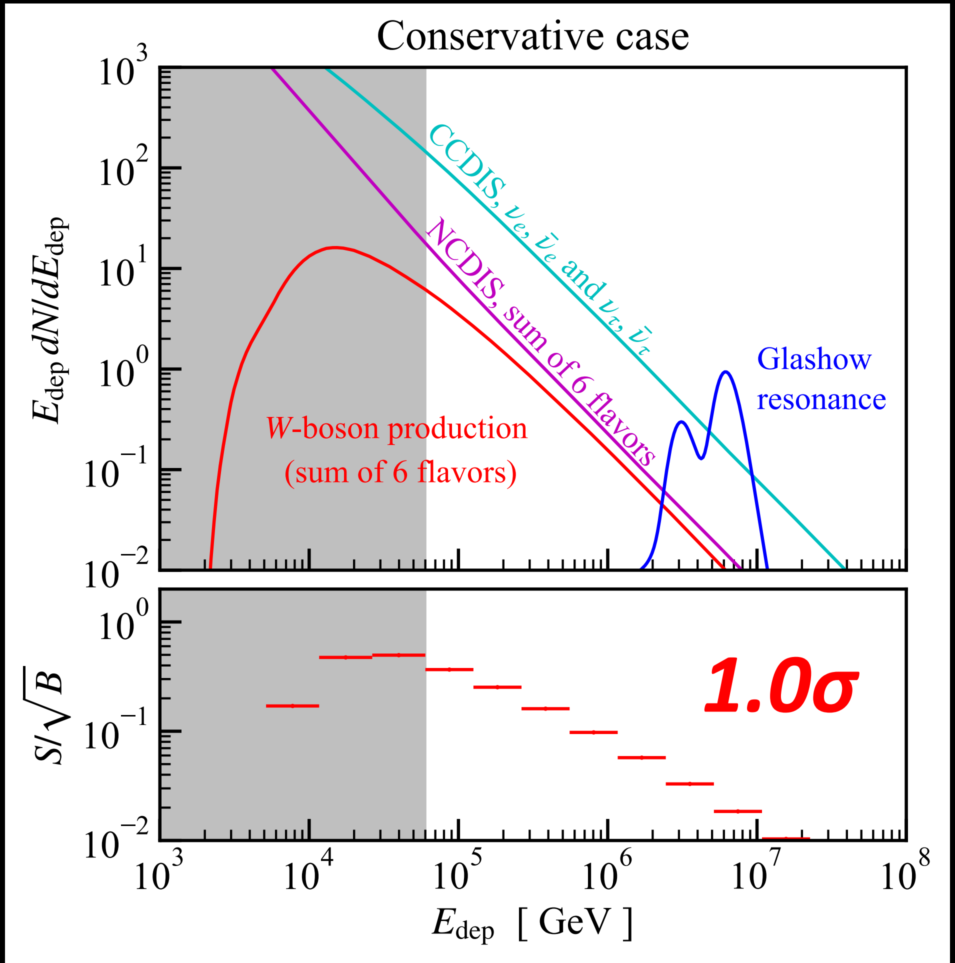
$\nu_\tau + A \rightarrow \tau + W + A'$

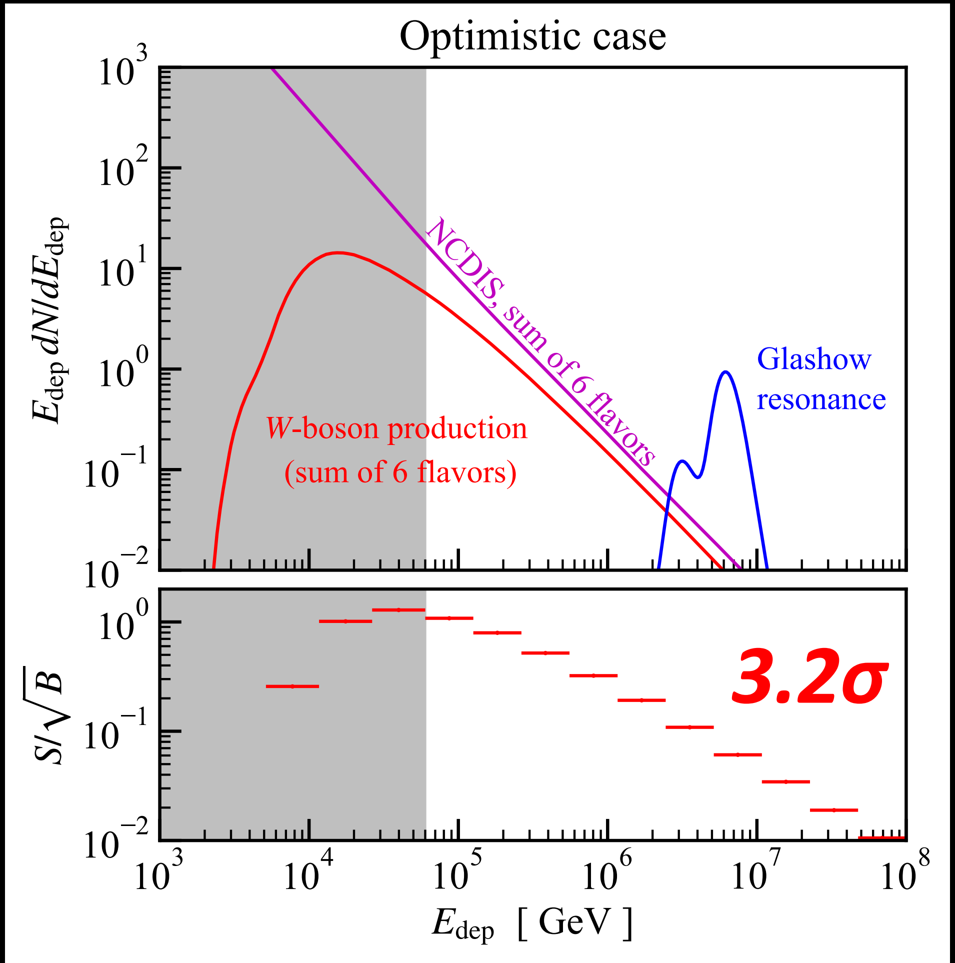
W decay

$\rightarrow e$	(11%)
$\rightarrow \mu$	(11%)
$\rightarrow \tau$	(11%)
$\rightarrow$ hadrons	(67%)

Shower spectrum: WBP contributes and detectable

For 10 years observation by IceCube (=1 year IceCube-Gen2)





$\simeq$ 6 WBP shower events (> 60 TeV)

(BZ, Beacom, 1910.10720, PRD)

New event classes

1. Double track/Dimuon (showerless) 0.34 events (> 60 TeV, 10yrs IceCube or 1yr Gen)
   Mainly from: $\nu_\mu + A \to \mu + W + A'$ with $W \to \mu$

2. Track without shower 0.96 events ……
   Mainly from: $\nu_\mu + A \to \mu + W + A'$ with $W \to \mu$, and two tracks are inseparable
   $\nu_e + A \to e + W + A'$ with $W \to \mu$, and e undetectable

3. Pure EM shower 0.82 events ……
   Mainly from: $\nu_e + A \to e + W + A'$ with $W \to e$

(BZ, Beacom, 1910.10720, PRD)

High-energy neutrino interactions

1. *WBP and tridents:*
    1. *Cross section calculations*
    2. *Detections in IceCube/IceCube-Gen2*
2. New event class: dimuons

Dataset and analysis

- 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

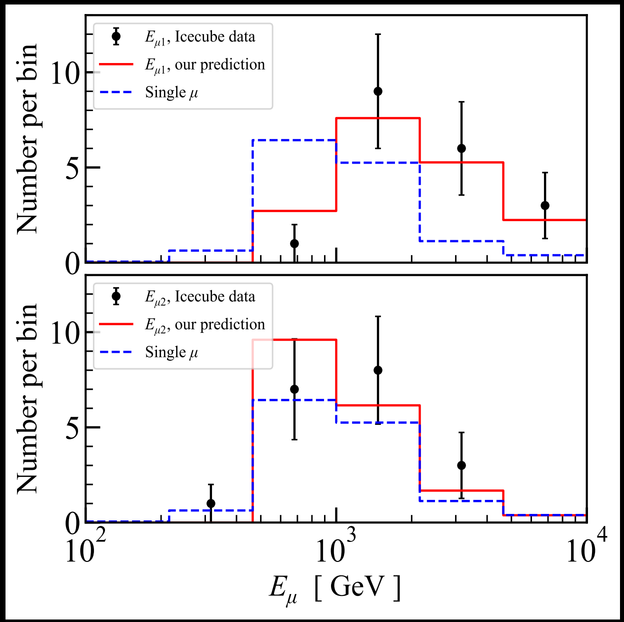
List of the 19 dimuon candidates we found

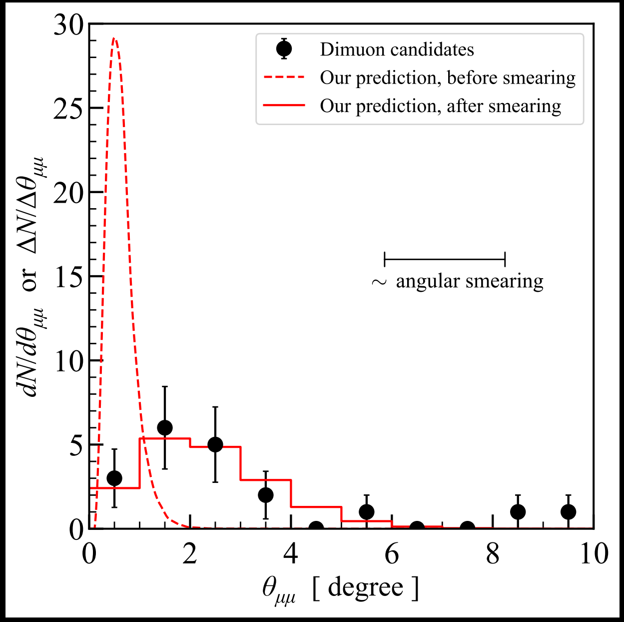
MJD1 [day]	MJD2 (= MJD1)	$E_{\mu 1}$ [TeV]	$E_{\mu 2}$	RA1 [deg]	RA2	Dec1	Dec2	AngErr1	AngErr2	AngDis	DisErr
56068.26557772	56068.26557772	1.23	1.05	25.065	25.860	18.168	18.466	0.38	1.85	0.81	1.89
56115.78056499	56115.78056499	2.29	0.65	296.835	296.891	41.777	46.922	3.10	0.41	5.15	3.13
56235.14756523	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

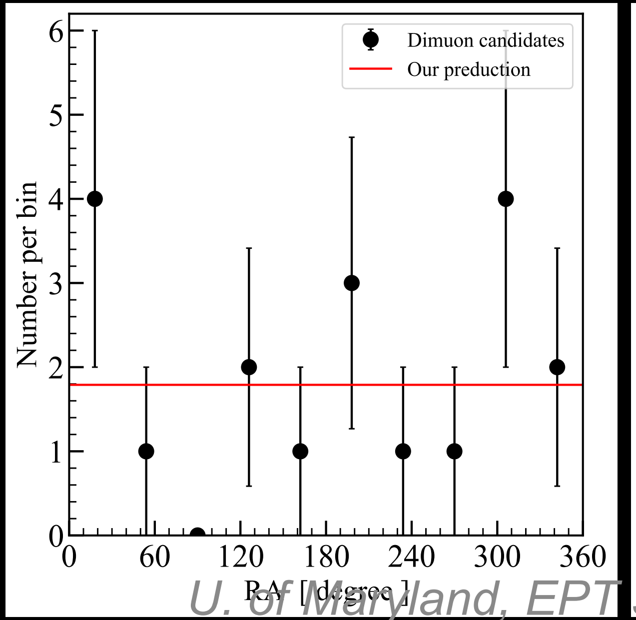
energy distribution

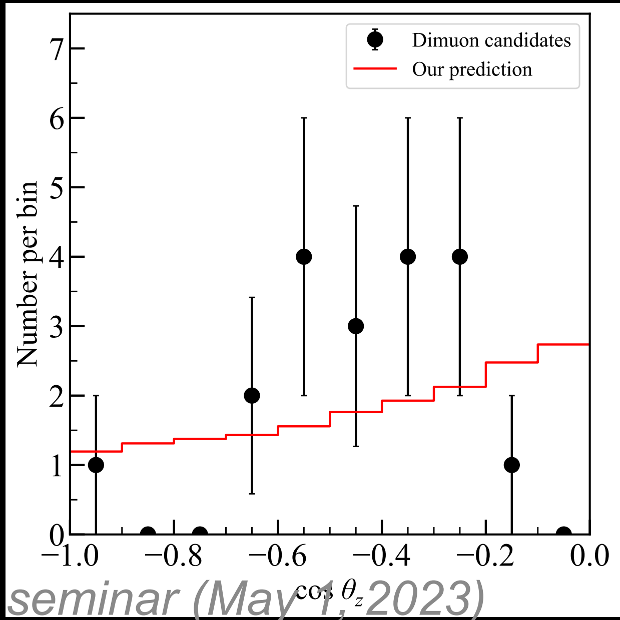




angular distribution

RA distribution





zenith distribution

(BZ, Beacom, 2110.02974)

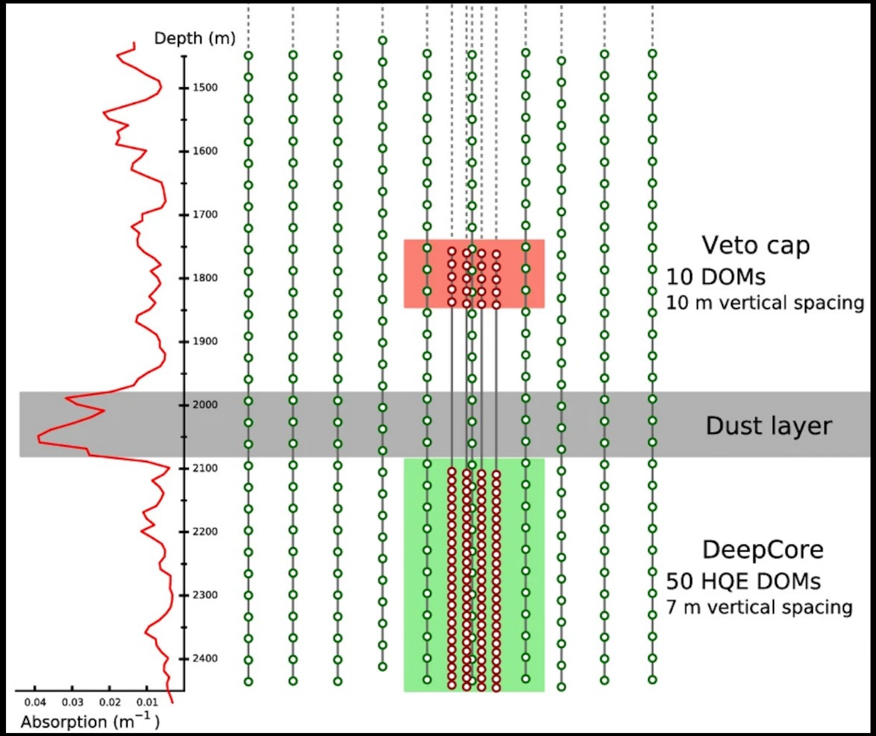
Outcome of these candidates

- 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.

- IceCube has started an analysis searching for dimuons events.

Inside IceCube detector



Unbinned maximum-likelihood-ratio method

2103.12813 BZ, Kamionkowski, Liang

Data samples

\# of signal events, to be fit

Each ν event

Background PDF

$$\mathcal{L}(n_s) = \prod_k \prod_{i\in k} \left[\frac{n_s^k}{N_k} S_i^k + \left(1 - \frac{n_s^k}{N_k}\right) B_i^k \right]$$

Tot # of neutrinos in the sample

Signal PDF

$$S_{ij}^k \equiv S_k(\vec{x}_i, \sigma_i, \vec{x}_j) = \frac{1}{2\pi\sigma_i^2} \exp\left(-\frac{D(\vec{x}_i, \vec{x}_j)^2}{2\sigma_i^2}\right)$$

$$\mathrm{TS}(n_s) = 2\ln \frac{\mathcal{L}(n_s)}{\mathcal{L}(n_s = 0)}$$

Events from sources & background

Events from background only

Sqrt(TS_max) ≃ significance

Search for neutrino emission from each source

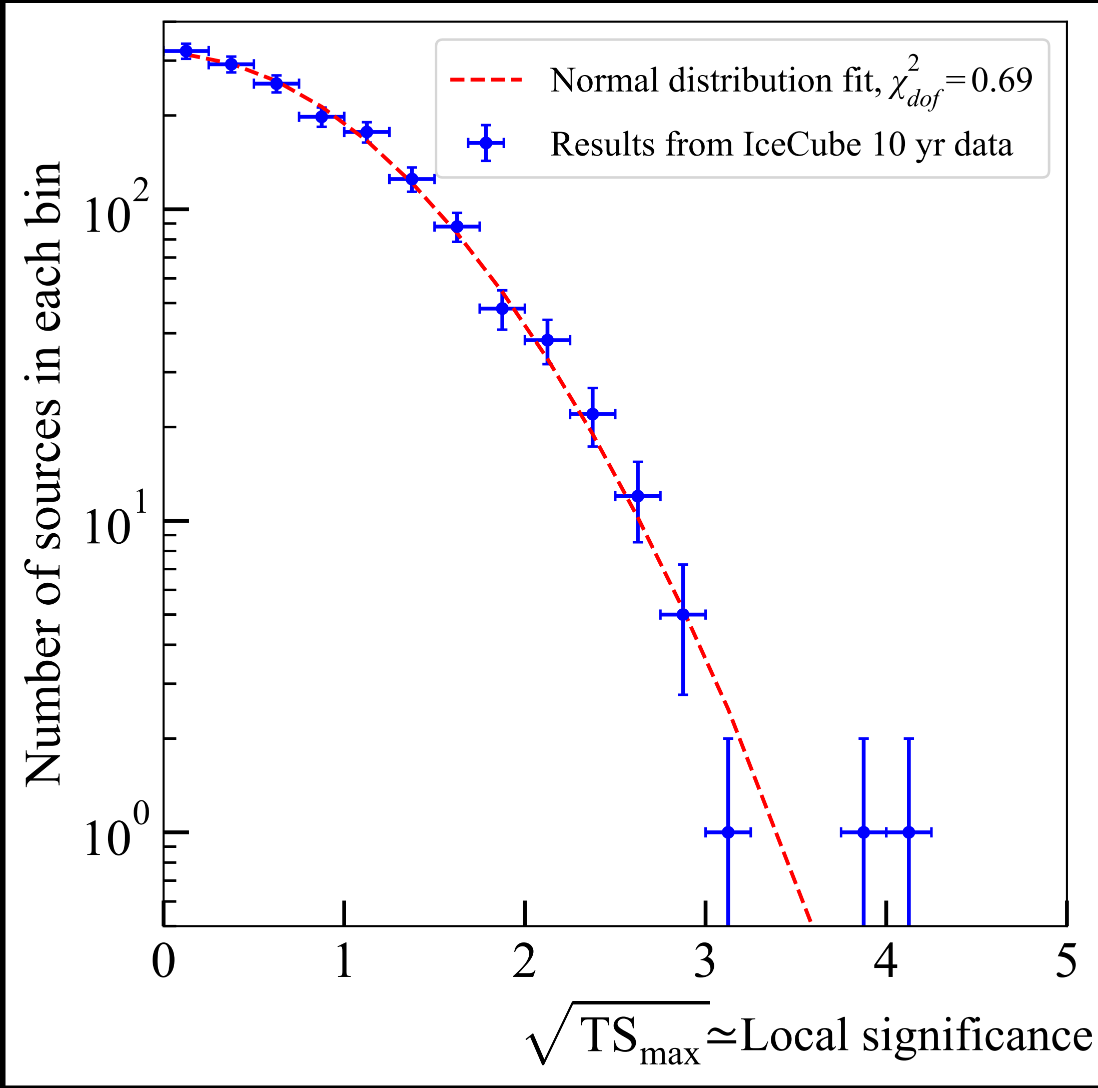
TABLE I. List of the five sources with highest significance.

IVS name	J2000 name	X-band flux density (Jy)	$\hat{n}_s$	TS_{max}	Pretrial p value, significance	Post-trial p value, significance
1303-170	J1306-1718	0.208	21.6	16.6	2.28×10^{-5}, 4.1σ	0.074, 1.5σ
2245+029	J2247+0310	0.434	50.8	14.5	7.14×10^{-5}, 3.8σ	0.21, 0.8σ
0228-163	J0231-1606	0.162	15.9	9.8	8.90×10^{-4}, 3.1σ	0.95, 0
1424+240	J1427+2348	0.187	38.1	8.9	1.42×10^{-3}, 3.0σ	0.99, 0
0958+559	J1001+5540	0.180	27.2	8.3	2.02×10^{-3}, 2.9σ	1.0, 0

We don't find any sources that have significant neutrino emission

Search for neutrino emission from each source

2103.12813 BZ, Kamionkowski, Liang



1. None of the sources show a large global significance

   The two highest-significant sources

   I. 1.5σ (global), 4.1σ (local)

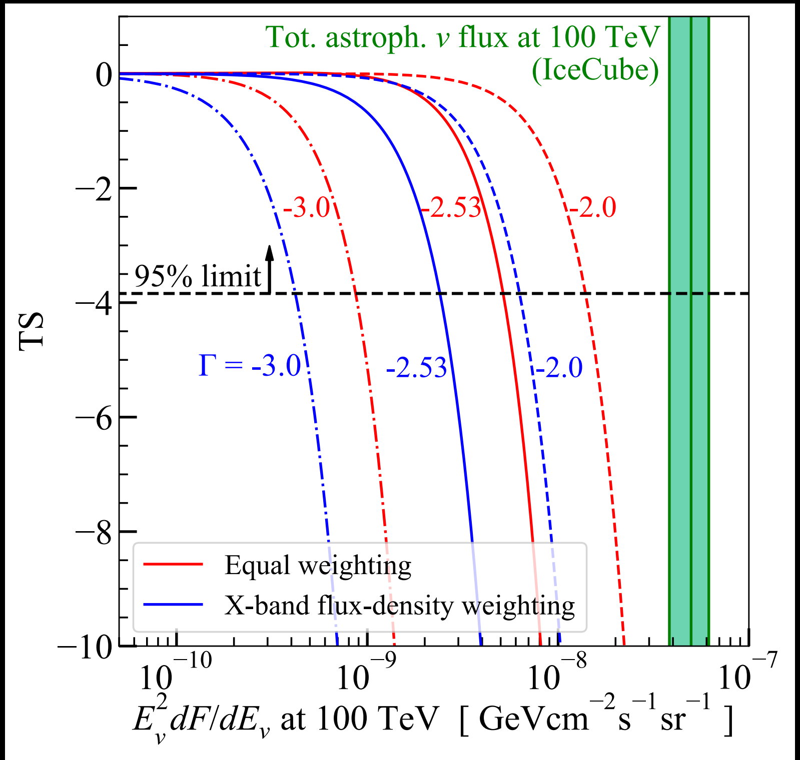
   II. 0.8σ (global), 3.8σ (local)

2. So, the ≃3400 radio-bright AGN might not have a strong correlation with HE nu

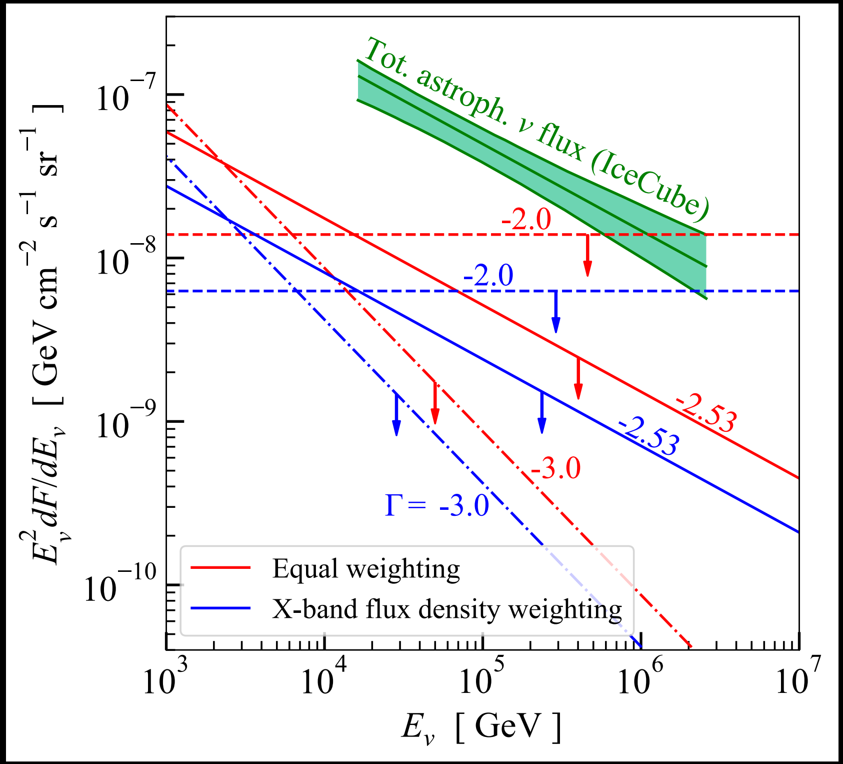
3. 8-GHz flux density might not be an indicator of HE nu emission.

Correlation between all srcs & events (Stacking analysis)

Significance



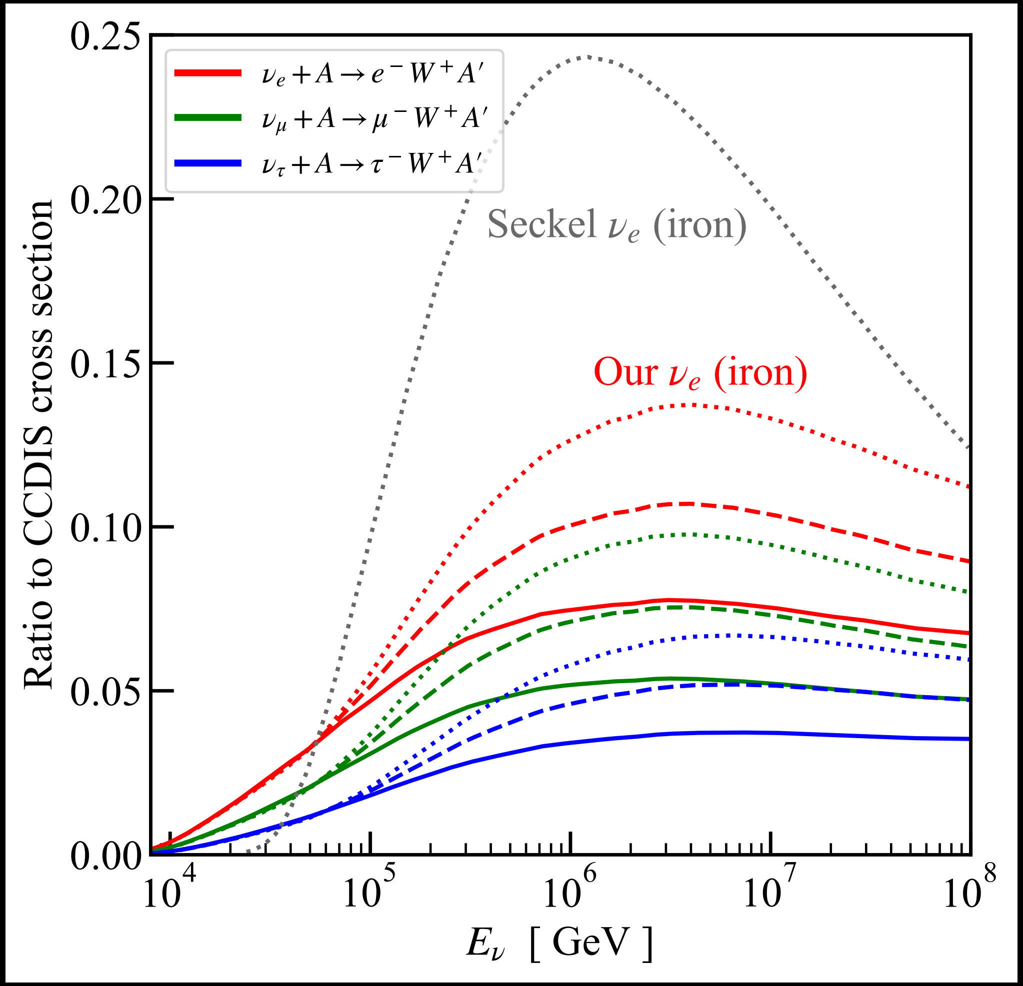
Upper limits



1. No significance.
2. Contribute < 30% of HE astro nu flux.
3. 8-GHz radio emission might not be an indicator of HE nu emission.

2103.12813 BZ, Kamionkowski, Liang

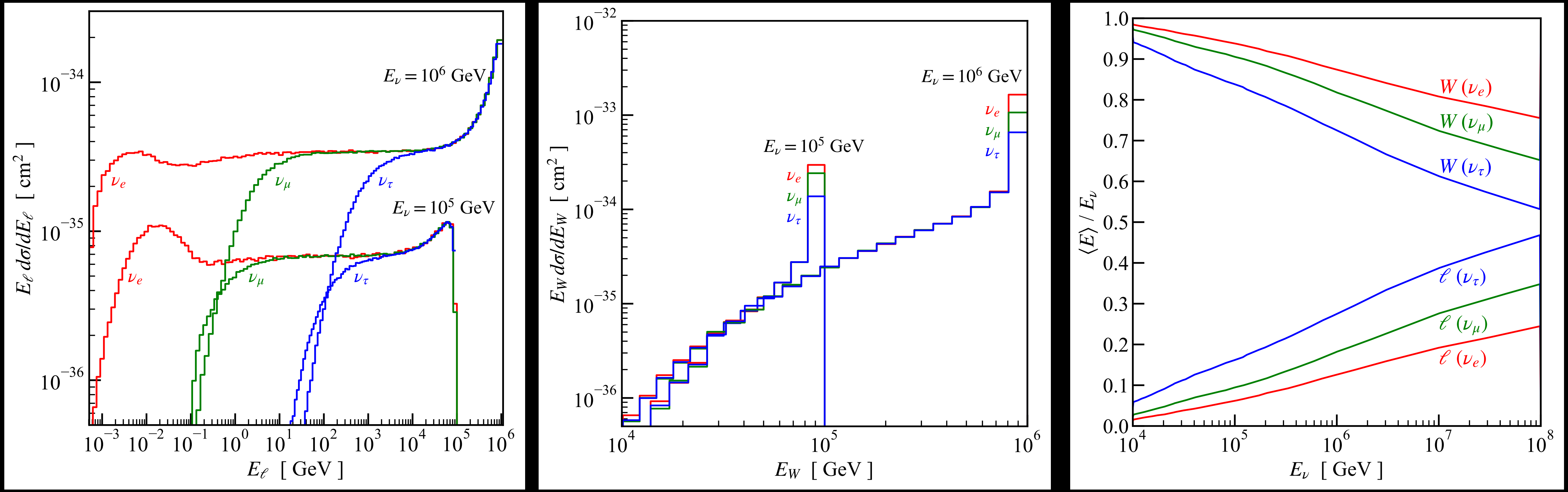
Ratios of WBP to CCDIS cross section



(Zhou, Beacom, 1910.08090, PRD)

Implications:

1. Neutrino absorption in Earth (Increase as large as ≃15%)
2. Detections in IceCube, etc.

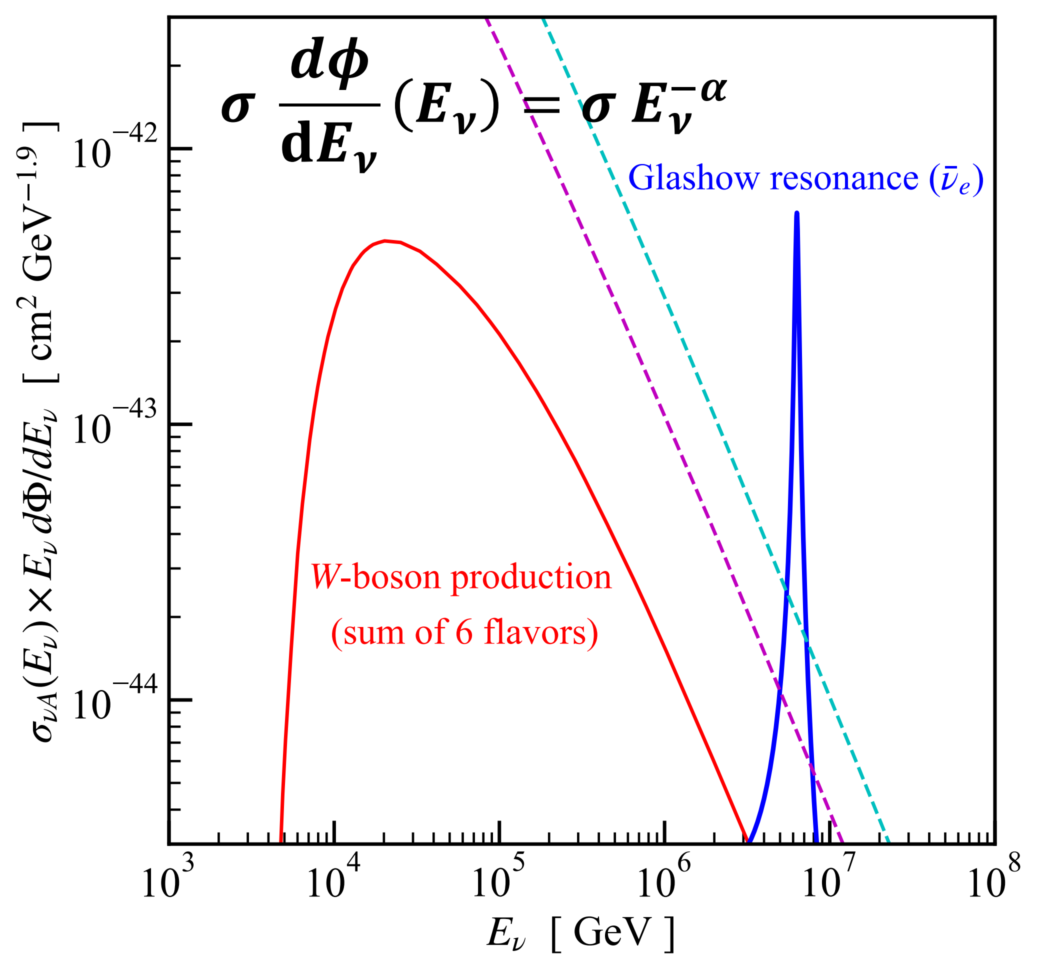


Features:

And W takes most of the energy

Energy transferred to nucleus is negligible

WBP produces more W's than Glashow resonance



(BZ, Beacom, 1910.10720, PRD)

$\alpha = 2.9$ A factor of 20 (right figure →)
(2.9 is from fitting IceCube data)

$\alpha = 2.5$ A factor of 3.5
$\alpha = 2.0$ A factor of 0.5

So, WBP is the dominant source of on-shell W bosons unless the spectrum is extremely hard.

Increase neutrino attenuation in Earth

Neutrino flux ϕ, after attenuation is $\phi\times A$

Attenuation factor:

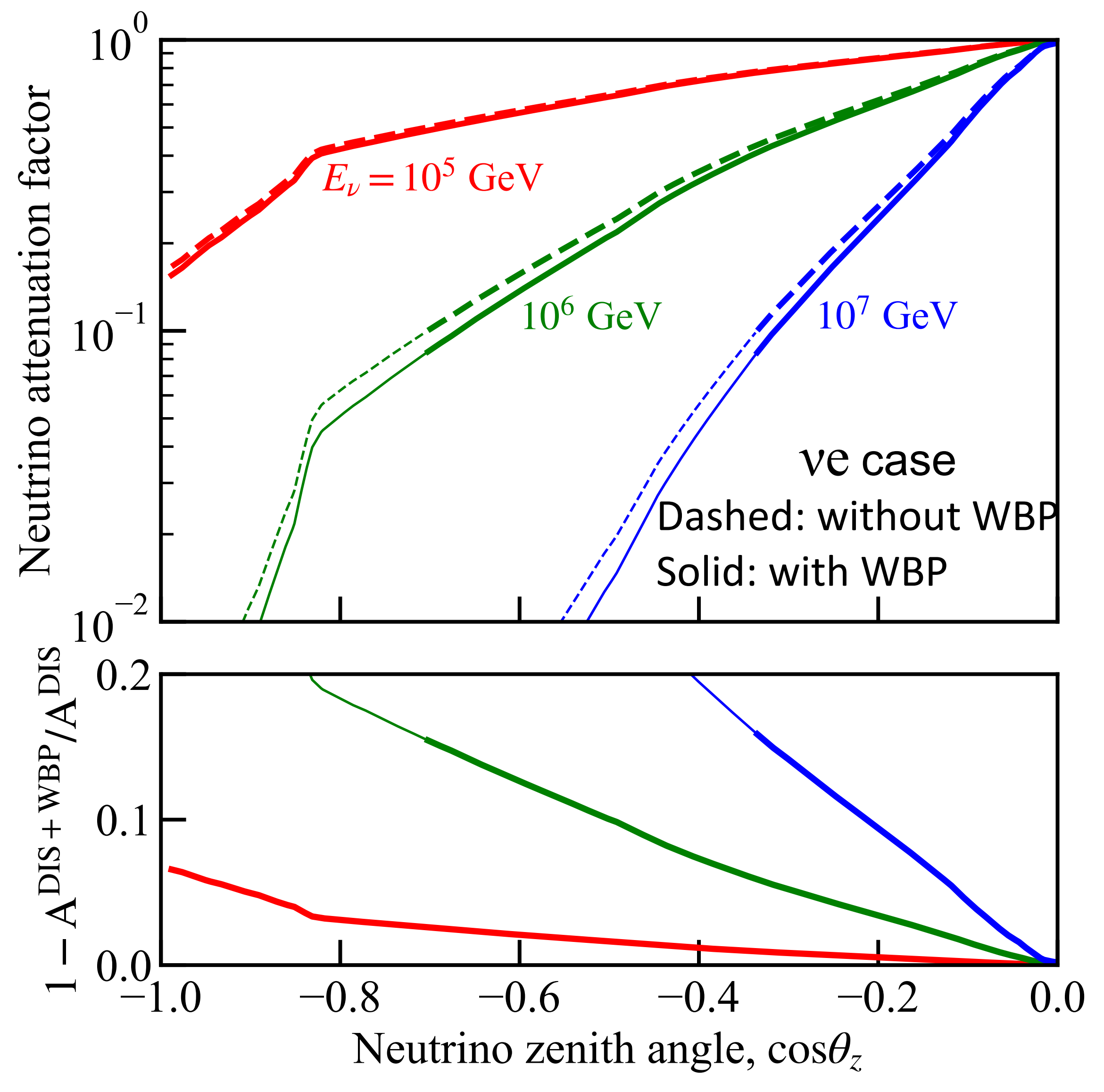
$$A = e^{-C(\cos\theta_z)\,\sigma(E_\nu)}$$

$C(\cos\theta_z)$: column density, well known

$\sigma(E_\nu)$: total xsec. WBP was not included.

Inseparable part of measuring xsec by IceCube.

1.3±0.45 of SM, but WBP not included



Channel	W decay	Final state	τ decay	Signature	Fraction	Counts
$\nu_e \to eW$ (7.5% rel. to CCDIS)	$e\nu_e$, 11%	e e		**Pure EM shower**	11%	0.34
	$\mu\nu_\mu$, 11%	e μ		**Track without**/with **shower**	11%	0.34
	$\tau\nu_\tau$, 11%	e τ	e, 18%	**Pure EM shower**	2.0%	0.06
			μ, 17%	**Track without**/with **(displaced) shower**	1.9%	0.06
			h, 65%	Shower	7.2%	0.22
	$q\bar{q}$, 67%	e h		Shower	67%	2.08
$\nu_\mu \to \mu W$ (5.0% rel. to CCDIS)	$e\nu_e$, 11%	μ e		**Pure EM shower**/Track with shower	11%	0.56
	$\mu\nu_\mu$, 11%	μ μ		**Single/Double tracks without shower**	11%	0.56
	$\tau\nu_\tau$, 11%	μ τ	e, 18%	**Pure EM shower/Track with (displaced) shower**	2.0%	0.10
			μ, 17%	**Single/Double tracks without shower**	1.9%	0.10
			h, 65%	Shower/**Shower with (displaced) track**	7.2%	0.36
	$q\bar{q}$, 67%	μ h		Shower/Shower with track	67%	3.41
$\nu_\tau \to \tau W$ (3.5% rel. to CCDIS)	$e\nu_e$, 11%	τ e	e, 18%	**Pure EM shower**	2.0%	0.02
			μ, 17%	**Pure EM shower/Track with (displaced) shower**	1.9%	0.02
			h, 65%	**Pure EM shower**/Shower	7.2%	0.09
	$\mu\nu_\mu$, 11%	τ μ	μ, 17%	**Single/Double tracks without shower**	1.9%	0.02
			e or h, 83%	**Track without shower/with (displaced) shower**	9.1%	0.11
	$\tau\nu_\tau$, 11%	τ τ	e e, 3%	**Pure EM shower**	0.4%	0.004
			μ μ, 3%	**Single/Double tracks without shower**	0.3%	0.004
			μ e/h, 29%	**Track without shower/with (displaced) shower**	3.1%	0.04
			h h/e, 65%	Shower/Double bang	7.2%	0.09
	$q\bar{q}$, 67%	τ h	e or h, 83%	Shower	56%	0.69
			μ, 17%	Shower/Shower with track	11%	0.14
Total counts						9.44

Glashow resonance vs. W-boson production

	Glashow resonance	W-boson production
Process	$\bar{\nu}_e + e^- \to W^-$	$\nu_x + A \to x^- + W^+ + A'$ $\bar{\nu}_x + A \to x^+ + W^- + A'$
Neutrino energy	$E\nu \simeq$ 6.3 PeV	$E\nu$ > ~10 TeV
First predicted by	Sheldon L. Glashow	T. D. Lee & C. N. Yang
First predicted in	1960 (Phys. Rev.)	1960 (PRL)
First "Detected" in	March 2021, IceCube (2.3σ; *Nature*)	

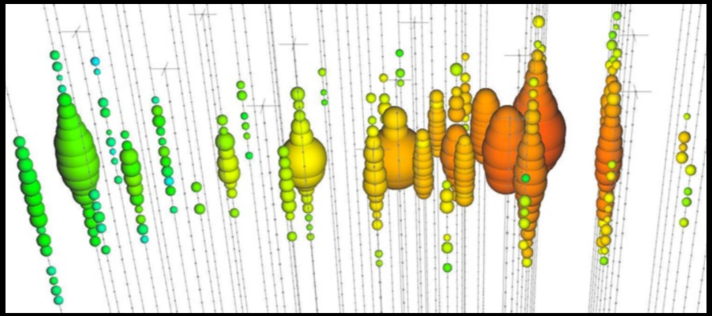
WBP could produce ~10 times more W bosons in neutrino telescopes

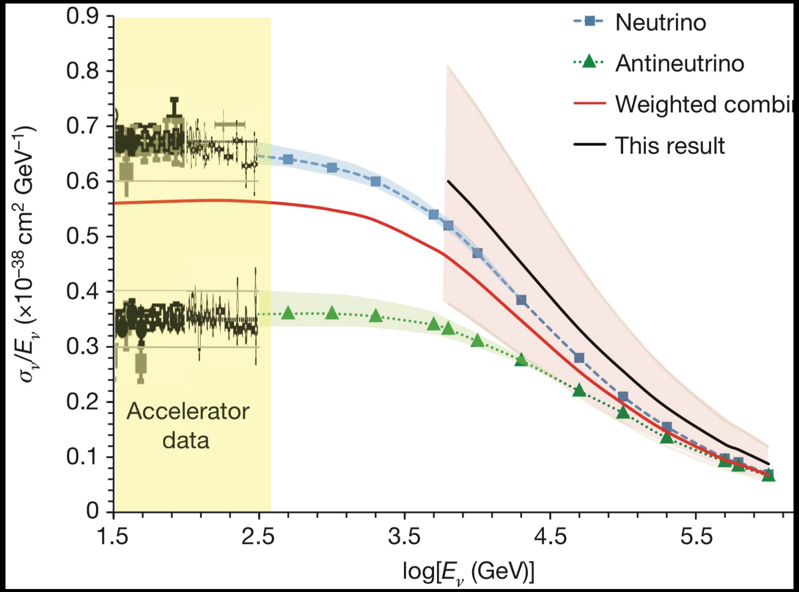
Encouraging hints from current IceCube data

(BZ, Beacom, 1910.10720, PRD)

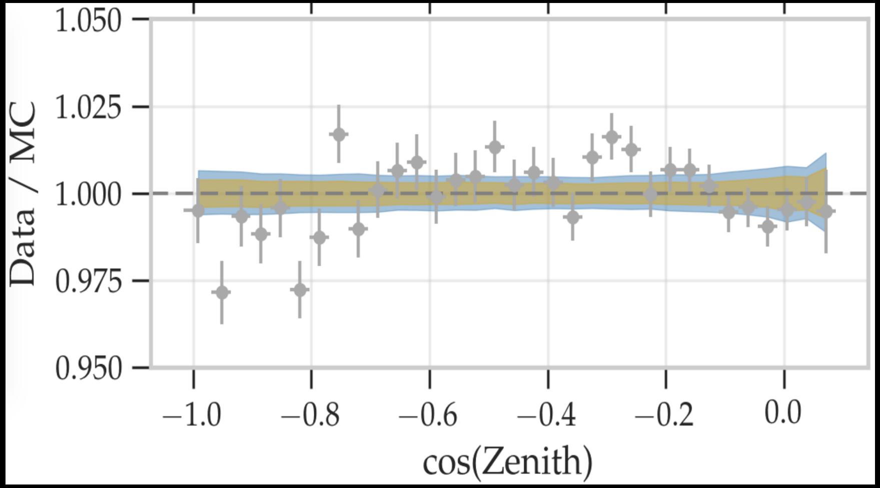
Measuring neutrino cross section

Event topology





Diffuse Astrophysical νμ Spectrum



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

An unknown 2% deficit of straight up-going events

IceCube, 1908.09551 ICRC 2019