Connections between neutrino interaction physics and astrophysics/astroparticle physics

Hallsie Reno (University of Iowa)

NuSTEC Summer School
CERN
June 10-13, 2024

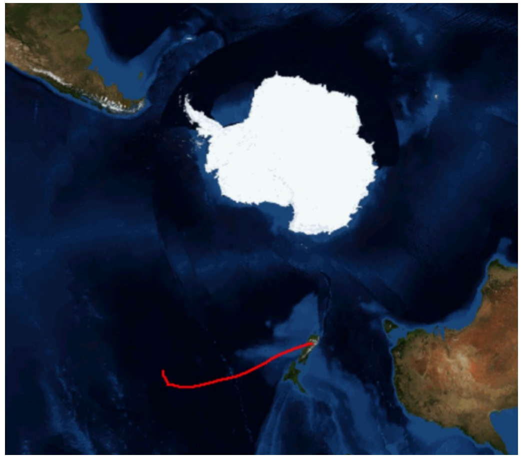
Work supported in part by the US DOE.

Who am I?

I’m a neutrino phenomenologist interested in neutrino astroparticle physics, neutrino interactions and BSM physics with neutrino (and neutrino-like) signals.

Professor at the University of Iowa (and now department chair), advisor of Luke Kupari who is here!

Also a member of the EUSO-SPB2 balloon mission collaboration and the nuSpaceSim Collaboration.



SpaceSim

Introduction

Neutrinos are special!

Multimessenger astrophysics

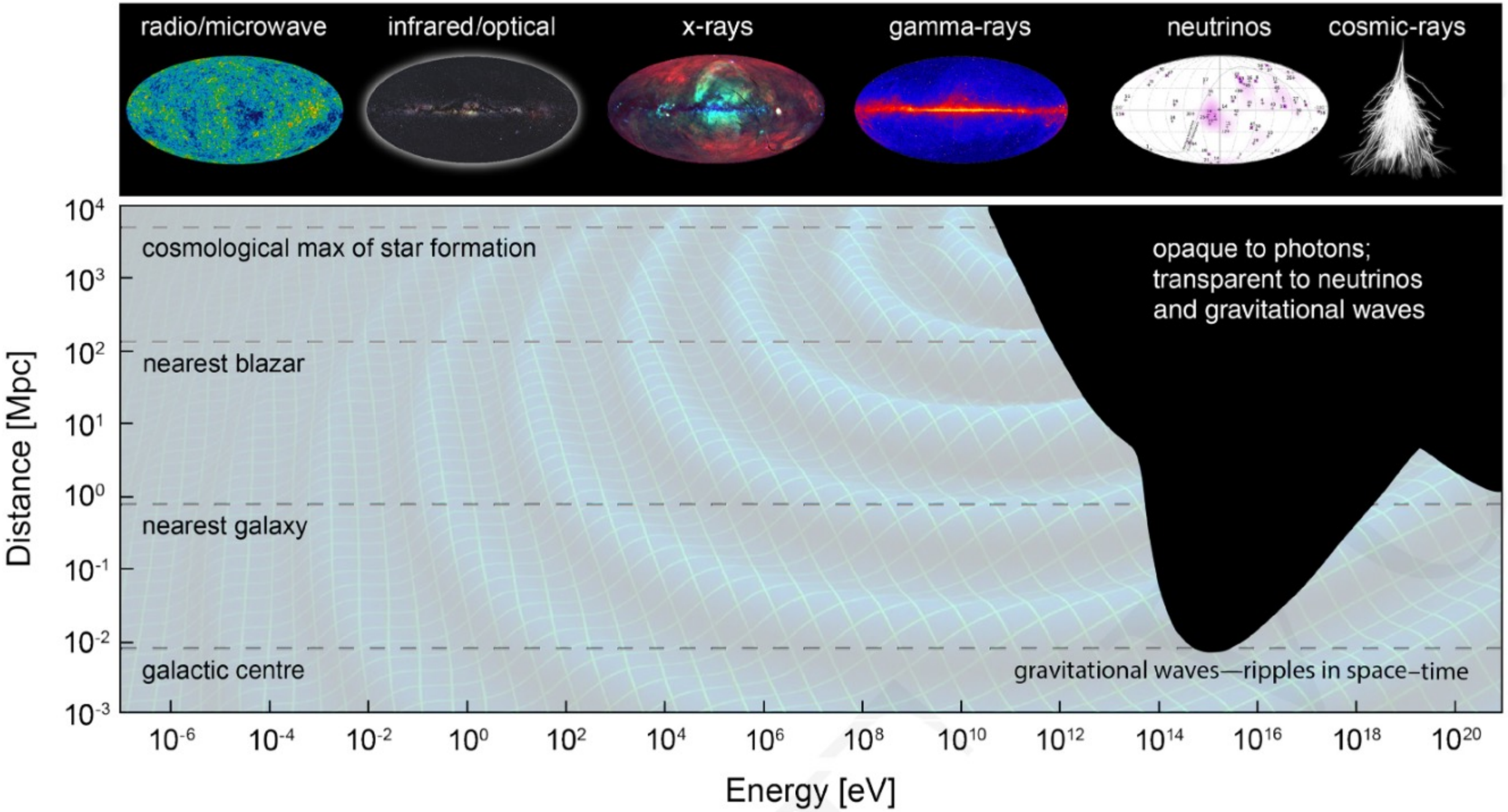


Fig. from Bartos and Kowalski, IOP 2017

Neutrinos are special!

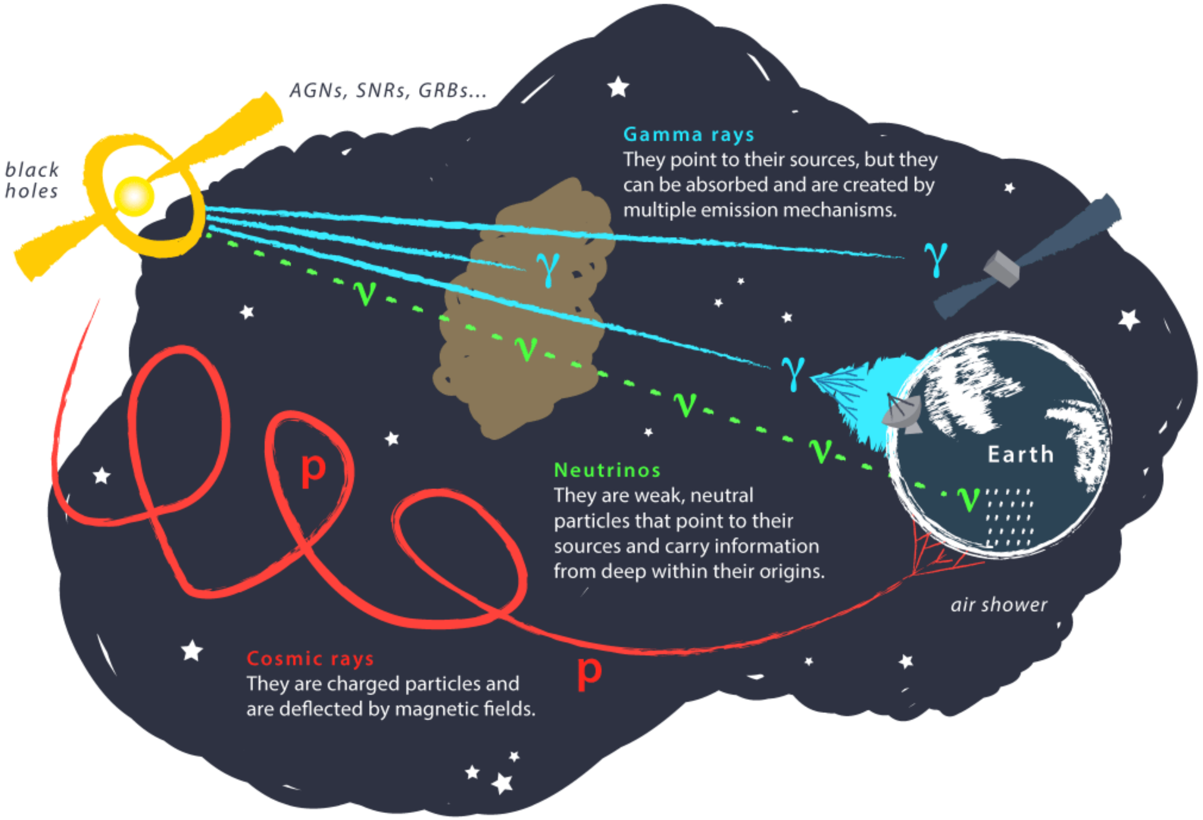
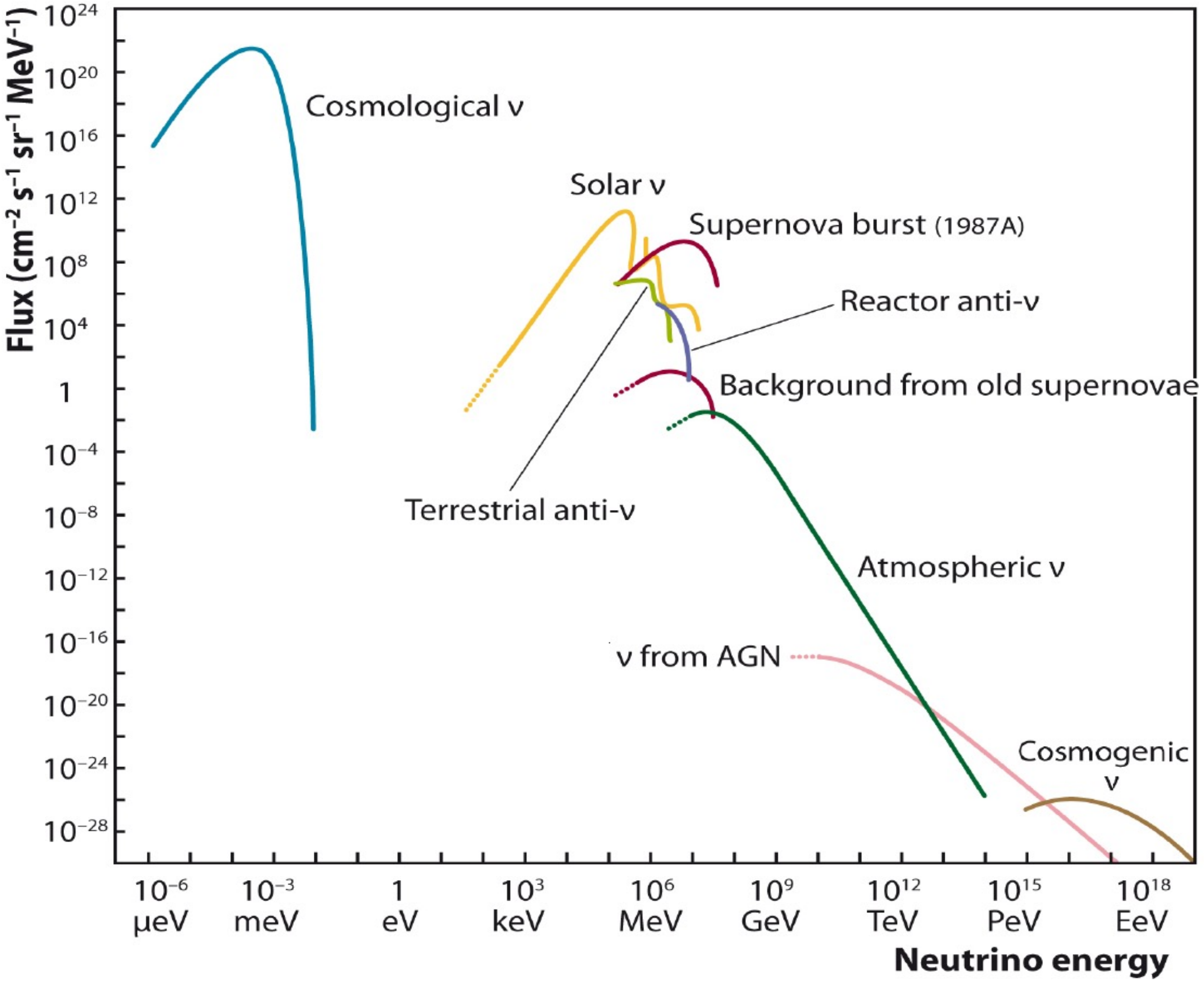


Fig. from IceCube/WIPAC

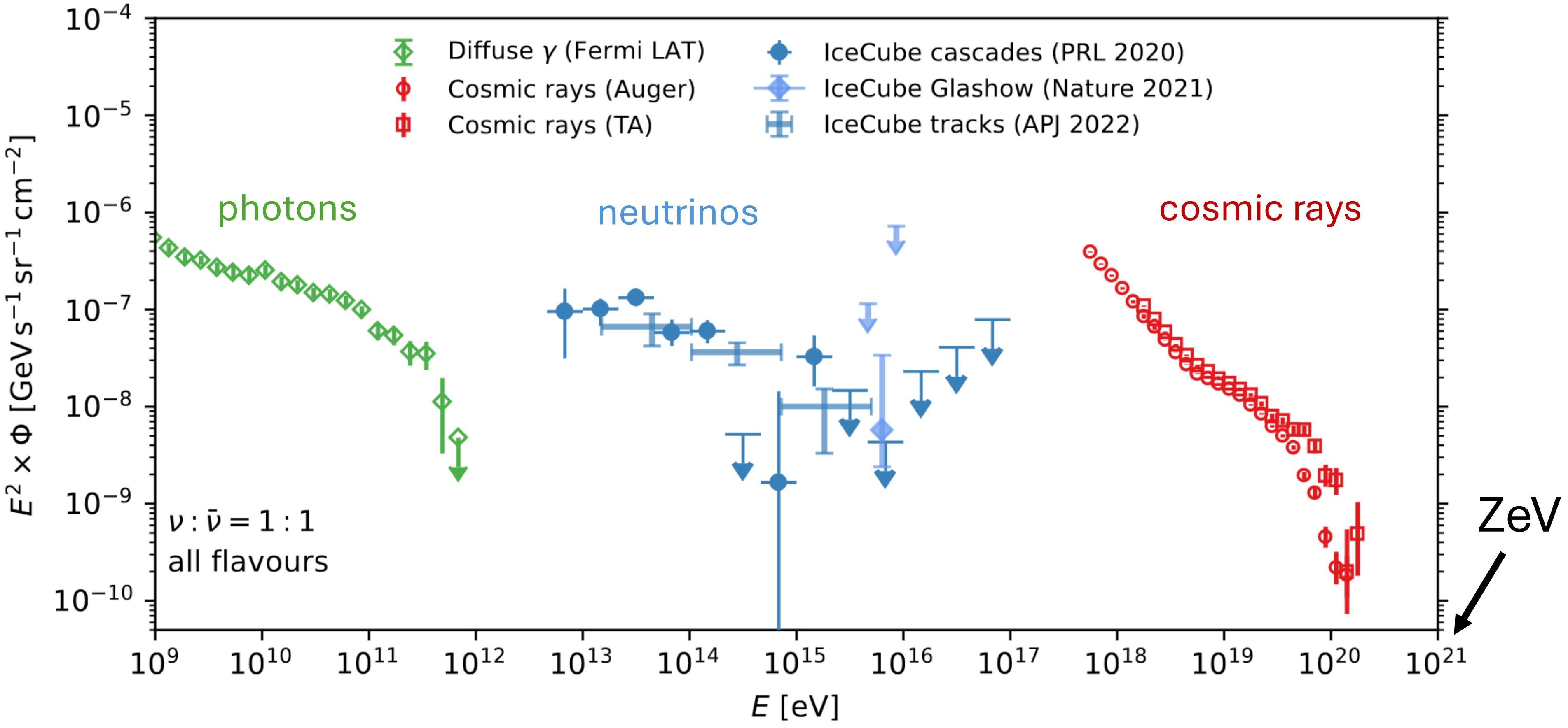
Sources of astrophysical neutrinos



1 TeV = 10^3 GeV
1 PeV = 10^6 GeV
1 EeV = 10^9 GeV
1 ZeV = 10^{12} GeV

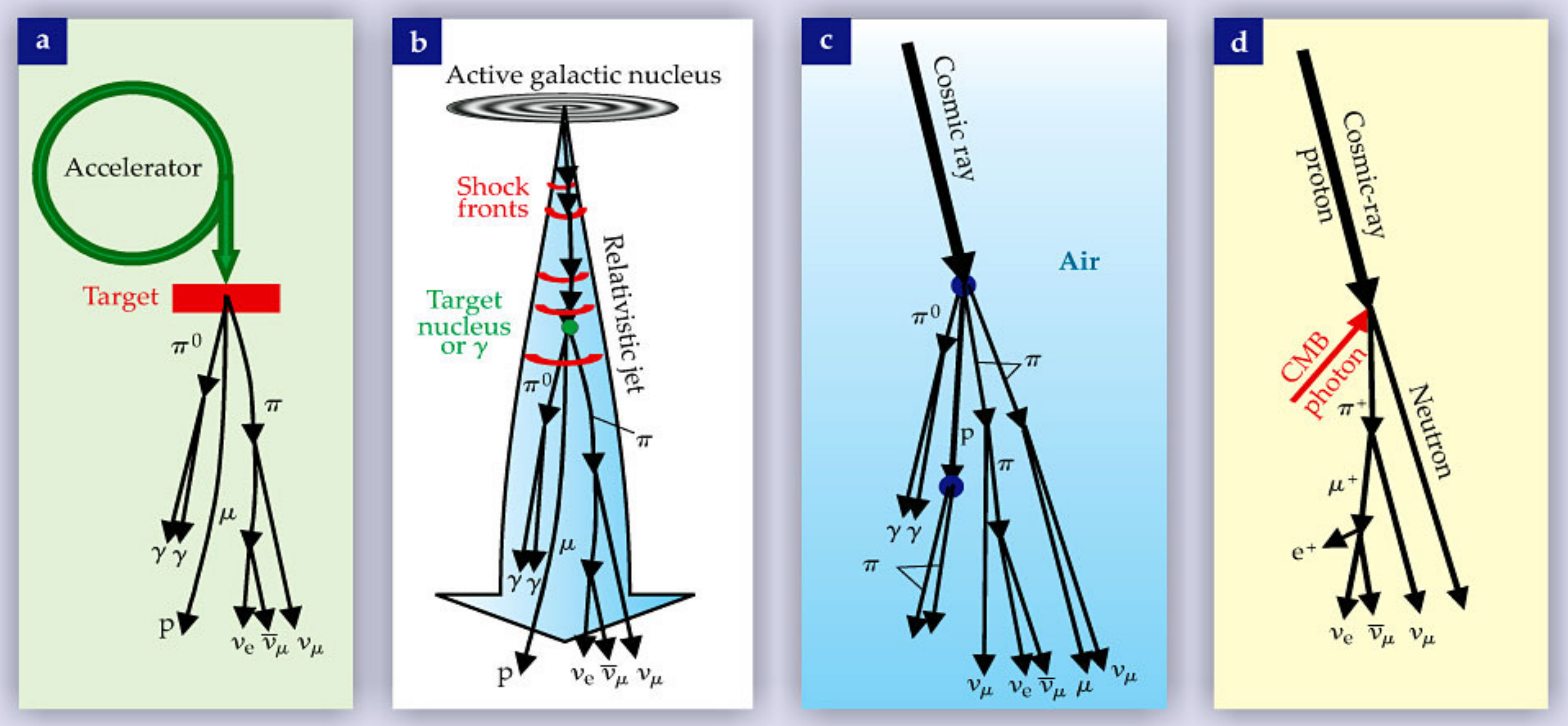
Neutrinos arrive at higher energies than from any terrestrial/accelerator source.

Multimessenger connection



Snowmass white paper: Ackermann et al., JHEAp 36 (2022) 55-110 https://arxiv.org/pdf/2203.08096

Neutrino production



F. Halzen and S. Klein, Physics Today, May 2008

Same production mechanism for accelerator beams, inside astrophysical objects, in the atmosphere, and for the cosmogenic neutrino flux.

Plan for lectures

- Neutrino cross sections: DIS and extrapolation to ultrahigh energies (UHE)
- Glashow resonance, sub-leading contributions
- Neutrino detection: across the energies

- Atmospheric neutrinos
- Astrophysical neutrinos: diffuse neutrino flux and transient sources
- Cosmogenic neutrinos: diffuse neutrino flux from cosmic rays in transit through Universe
- Some BSM physics examples with astrophysical neutrinos

Neutrino cross sections at VHE, UHE

Access to these cross sections are only possible with astroparticle sources of neutrinos.

References

For example, and references therein:

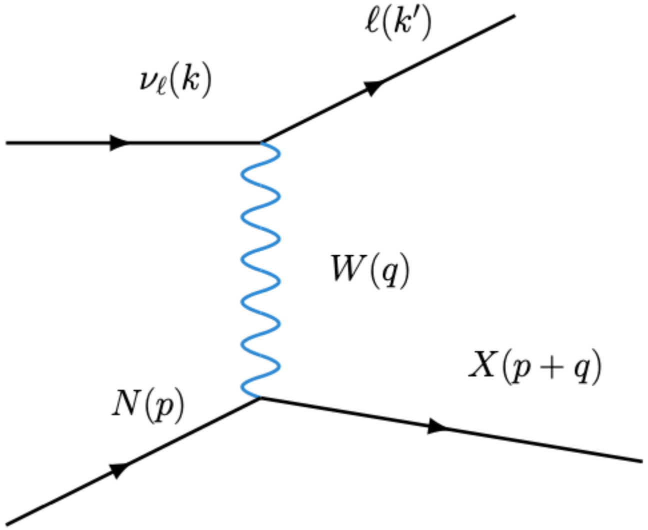
- Bertone, Gauld & Rojo, JHEP 01 (2019) 217
- Cooper-Sarkar, Mertsch & Sarkar, JHEP 08:042 (2011)
- Connolly, Thorne & Waters, JHEP 08 (2011) 042
- Garcia et al, JCAP 09 (2020) 025
- Gandhi … MHR… et al, Phys. Rev. D 58 (1998) 093009
  MHR, Ann Rev Nucl Part Sci 73 (2023) 1

Charged-current cross section at VHE, UHE

$$\frac{d^2\sigma}{dx\,dy} = \frac{2G_F^2 M E_\nu}{\pi}\left(\frac{M_W^2}{Q^2+M_W^2}\right)^2\left[xq(x,Q) + x\bar{q}(x,Q)(1-y)^2\right]$$

To the extent that we can ignore Q^2,

$$\sigma \simeq \frac{2G_F^2 M E_\nu}{\pi}\int dx\,dy\,xq(x,Q) + x\bar{q}(x,Q)(1-y)^2$$



This means $\sigma \sim G_F^2 s$

$s=2ME$

Charged-current cross section at VHE, UHE

νN

$$\frac{d^2\sigma}{dx\,dy} = \frac{2G_F^2 M E_\nu}{\pi}\left(\frac{M_W^2}{Q^2+M_W^2}\right)^2\left[xq(x,Q)+x\bar{q}(x,Q)(1-y)^2\right]$$

Q^2 dependence in propagator and in PDFs, eventually $Q^2 \sim M_W^2$

(Remember the Q^2 dependence of PDFs is logarithmic.)

$x \sim \frac{M_W^2}{M E_\nu}$ gives a rough scaling: $x \sim 10^{-2}\left(\frac{10^6\ \text{GeV}}{E_\nu}\right)$

Charged-current cross section at VHE, UHE

$$x \sim \frac{M_W^2}{ME_\nu}$$

gives a rough scaling:

$$x \sim 10^{-2}\left(\frac{10^6\ \mathrm{GeV}}{E_\nu}\right)$$

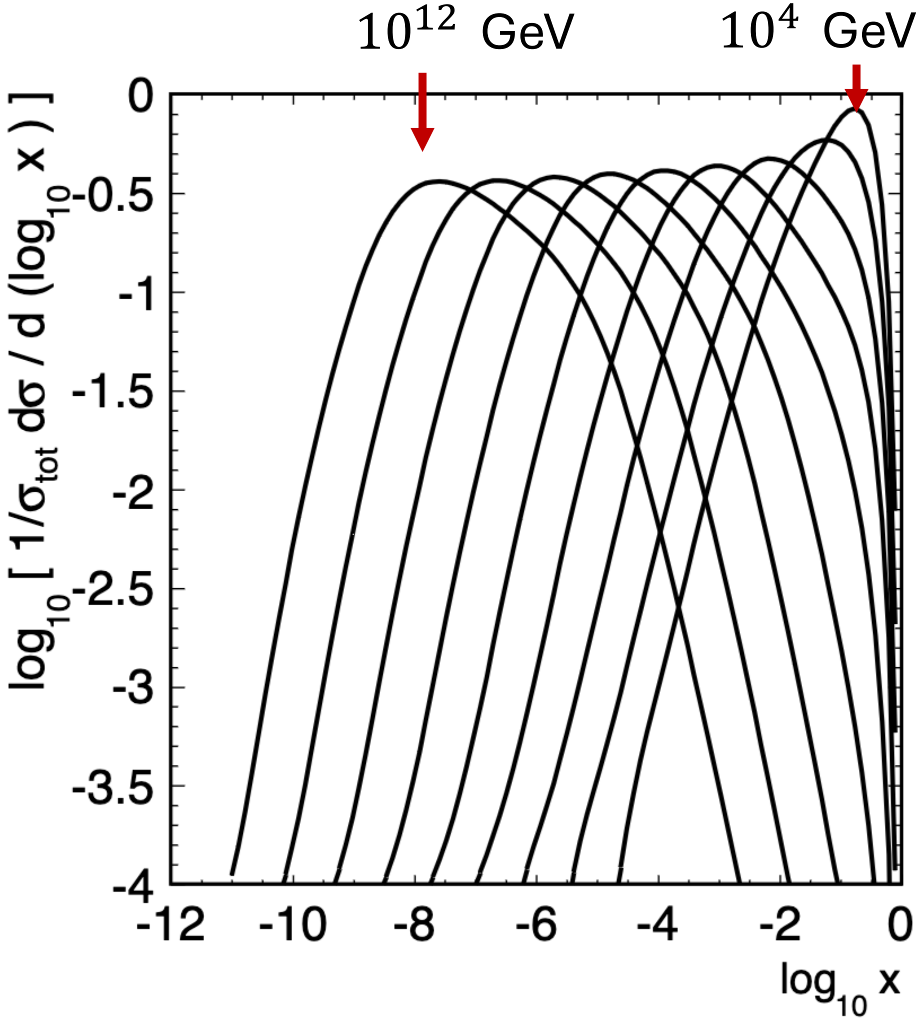
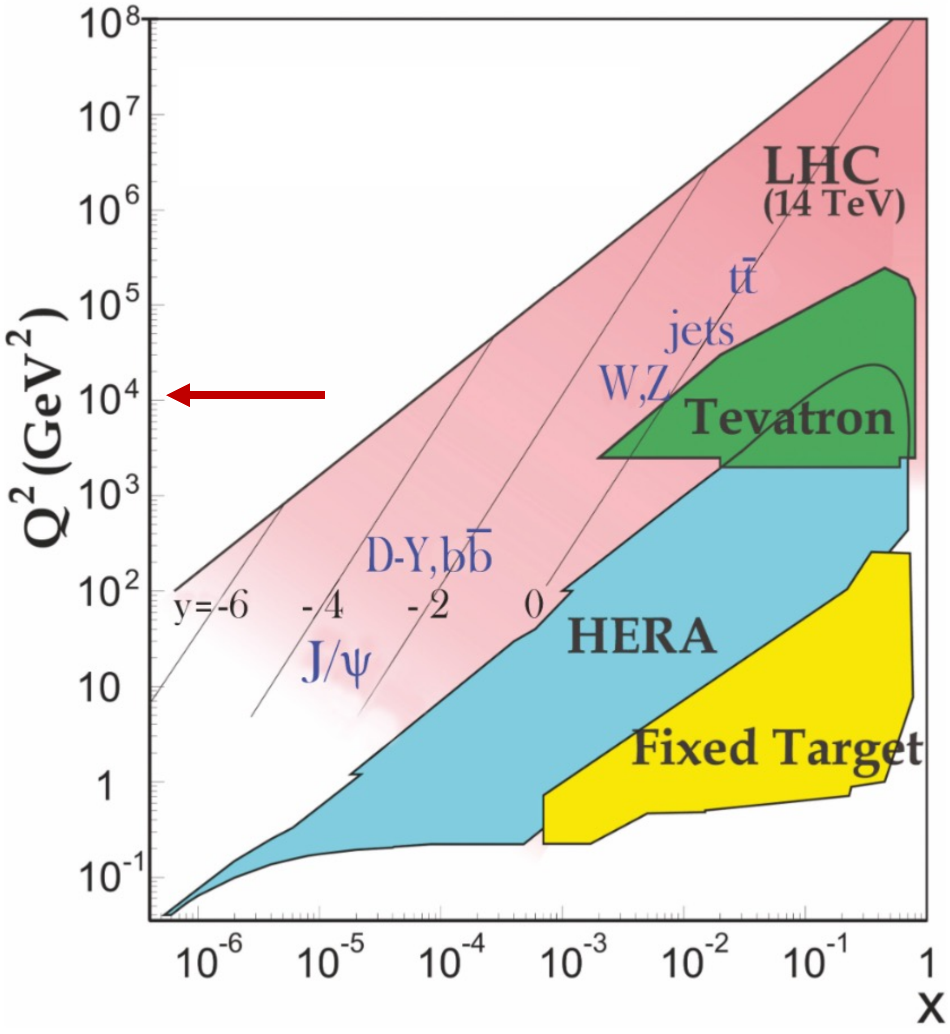
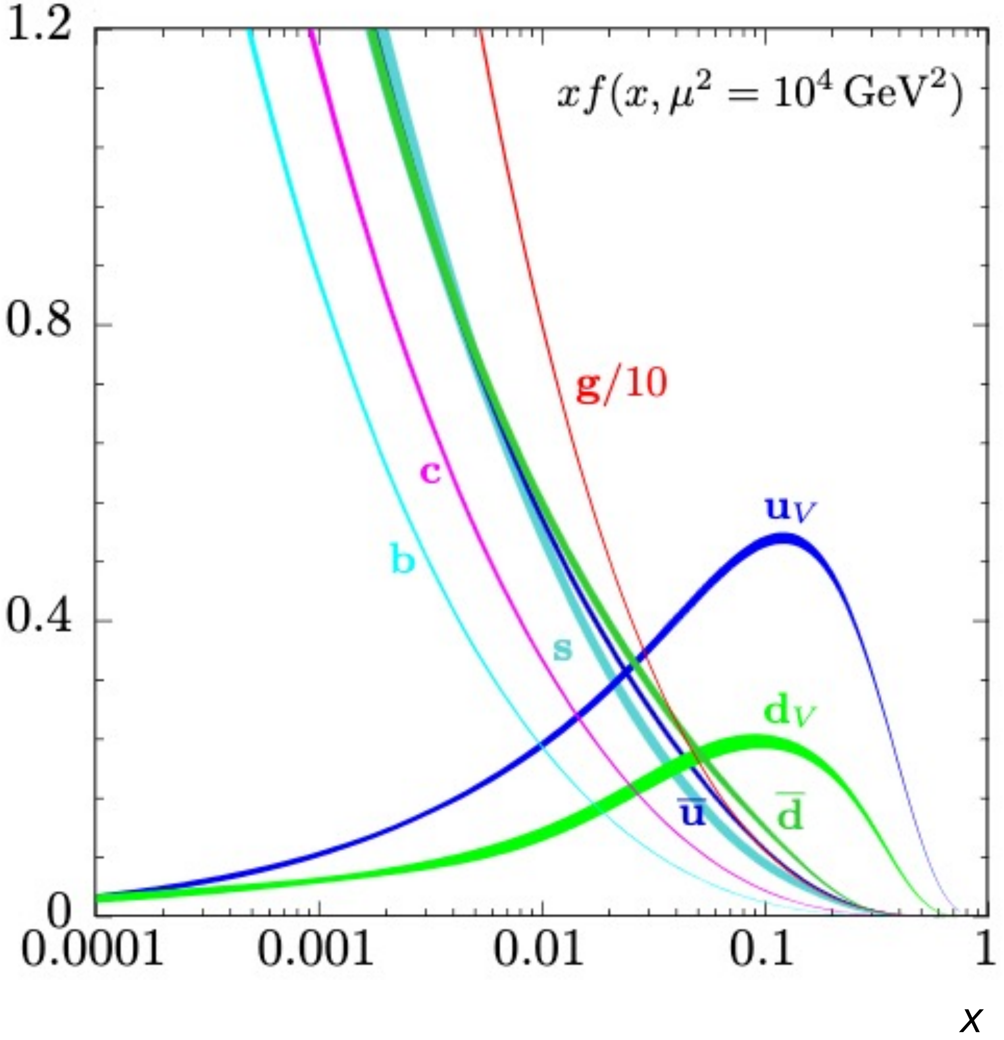


Fig. from Connolly, Thorne & Waters, JHEP 08 (2011) 042

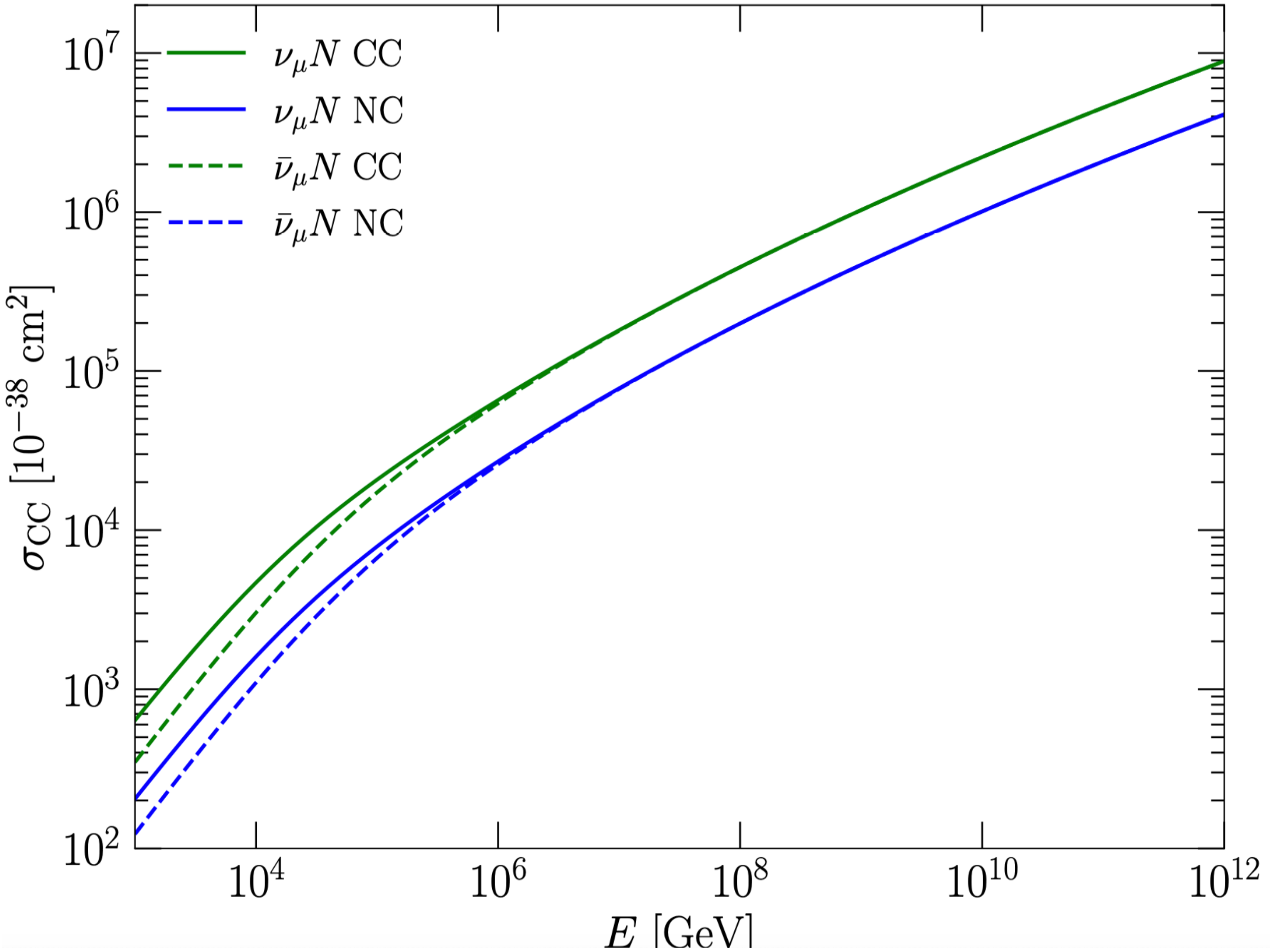
Parton Distribution Functions (PDFs)





pdg.lbl.gov

Cross sections

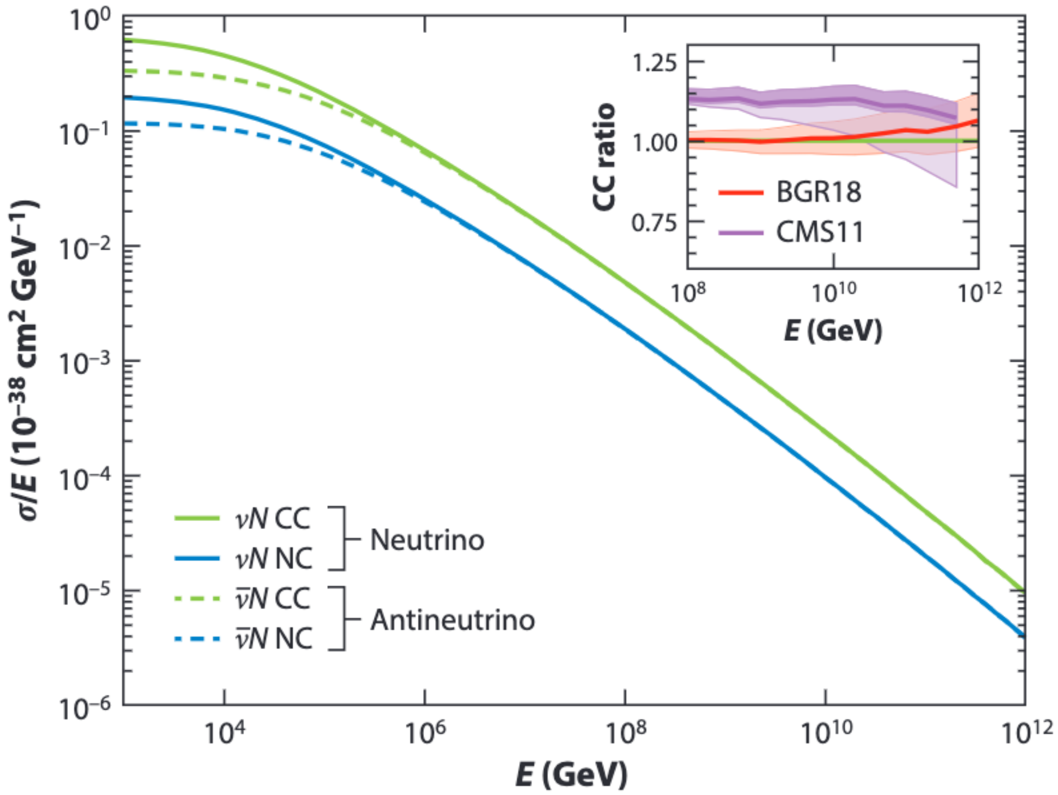


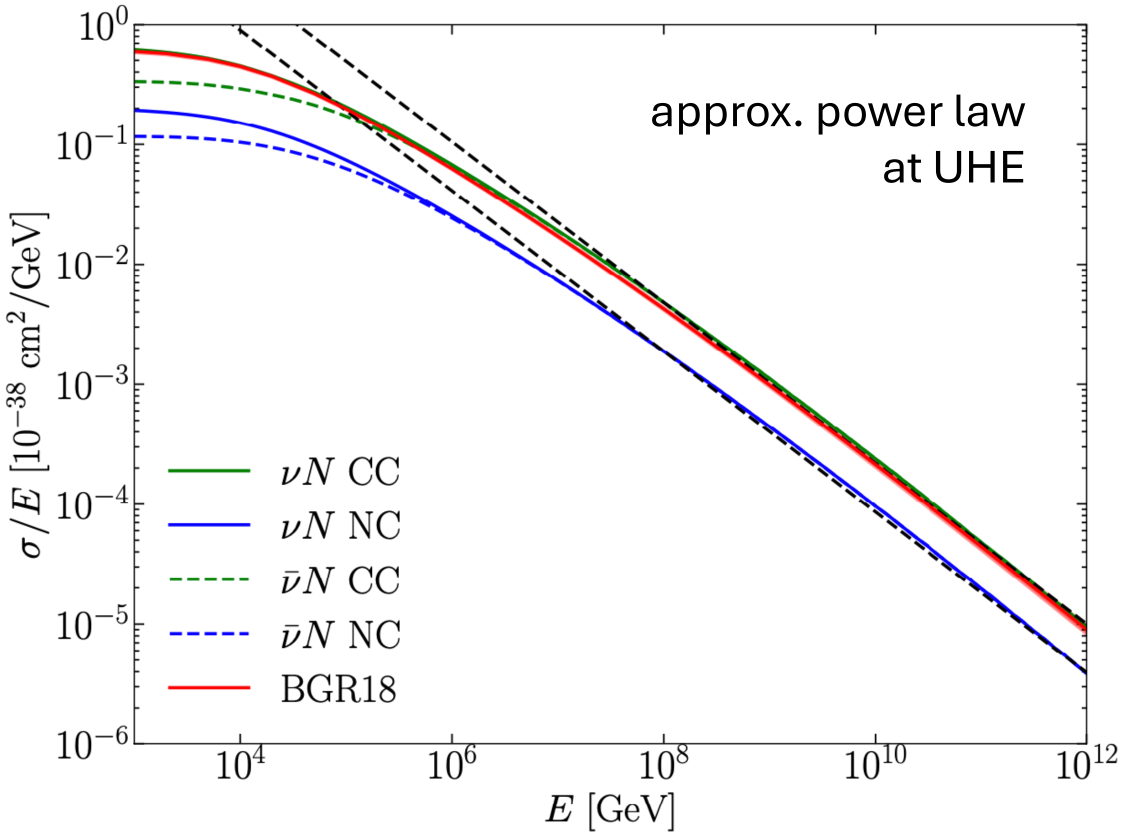
Notice:

- change in energy behavior

PDFs: ct18nlo

CC cross section divided by energy





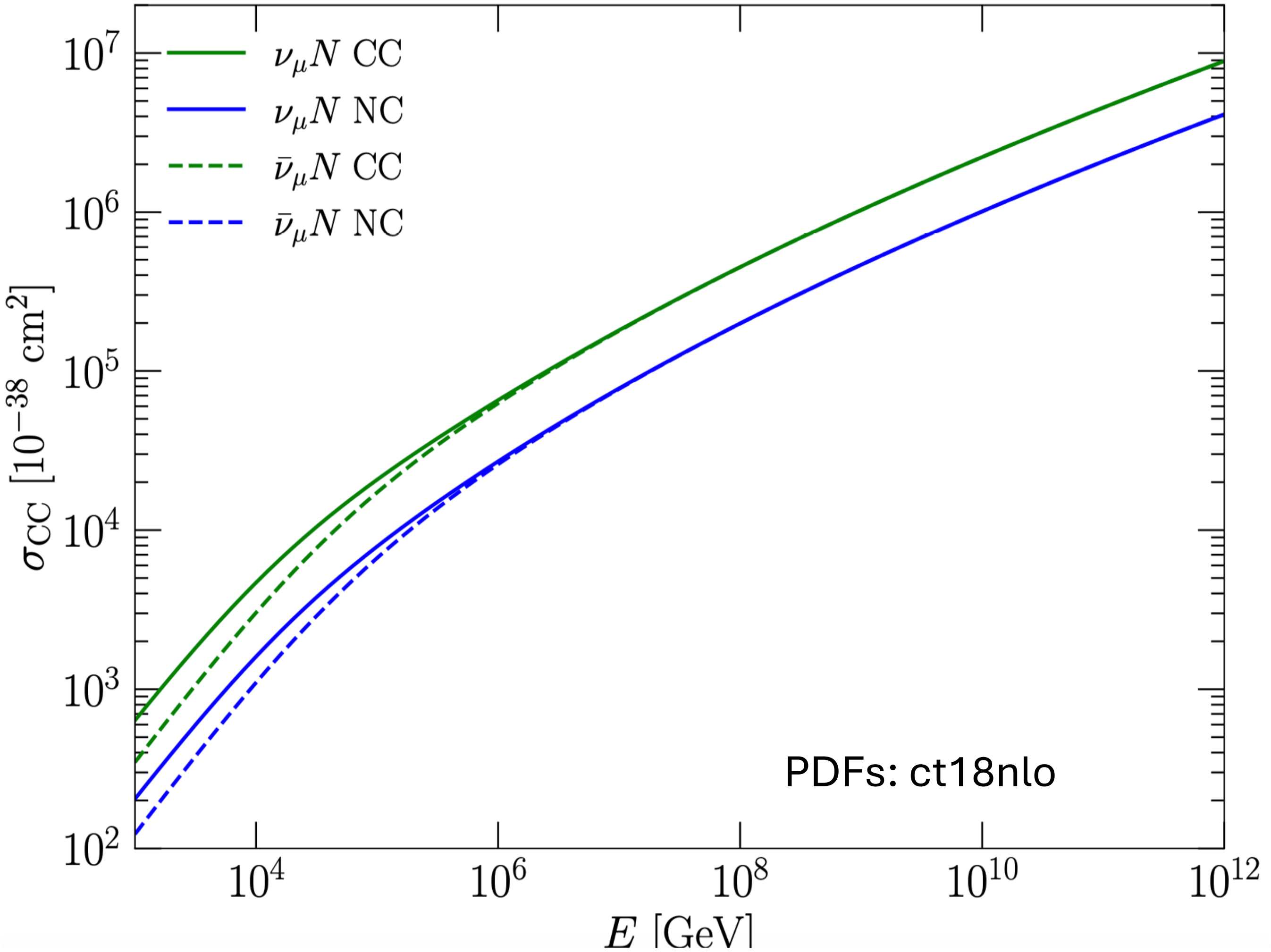
approx. power law
at UHE

BGR18 = Bertone, Gauld & Rojo, JHEP 01 (2019) 217 (NNLO+NNLx), CMS11 = Cooper-Sarkar, Mertsch & Sarkar, JHEP 08:042 (2011) (NLO)

Figs. from MHR, Ann Rev Nucl Part Sci 2023, blue and green with ct18nlo (NLO)

Cross sections

$$\nu N \qquad \frac{d^2\sigma}{dx\,dy} = \frac{2G_F^2 M E_\nu}{\pi}\left(\frac{M_W^2}{Q^2+M_W^2}\right)^2\left[xq(x,Q) + x\bar{q}(x,Q)(1-y)^2\right]$$



<u>Notice</u>:

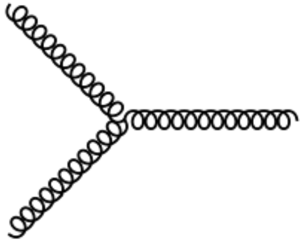
- change in energy behavior
- neutrino and antineutrino cross sections become equal – sea quark dominated
- (for $\bar{\nu}$ scattering, the *(1-y)²* goes to the quark, not antiquark)

$$\nu_\mu d \to \mu u \qquad \bar{\nu}_\mu \bar{d} \to \bar{\mu}\bar{u}$$

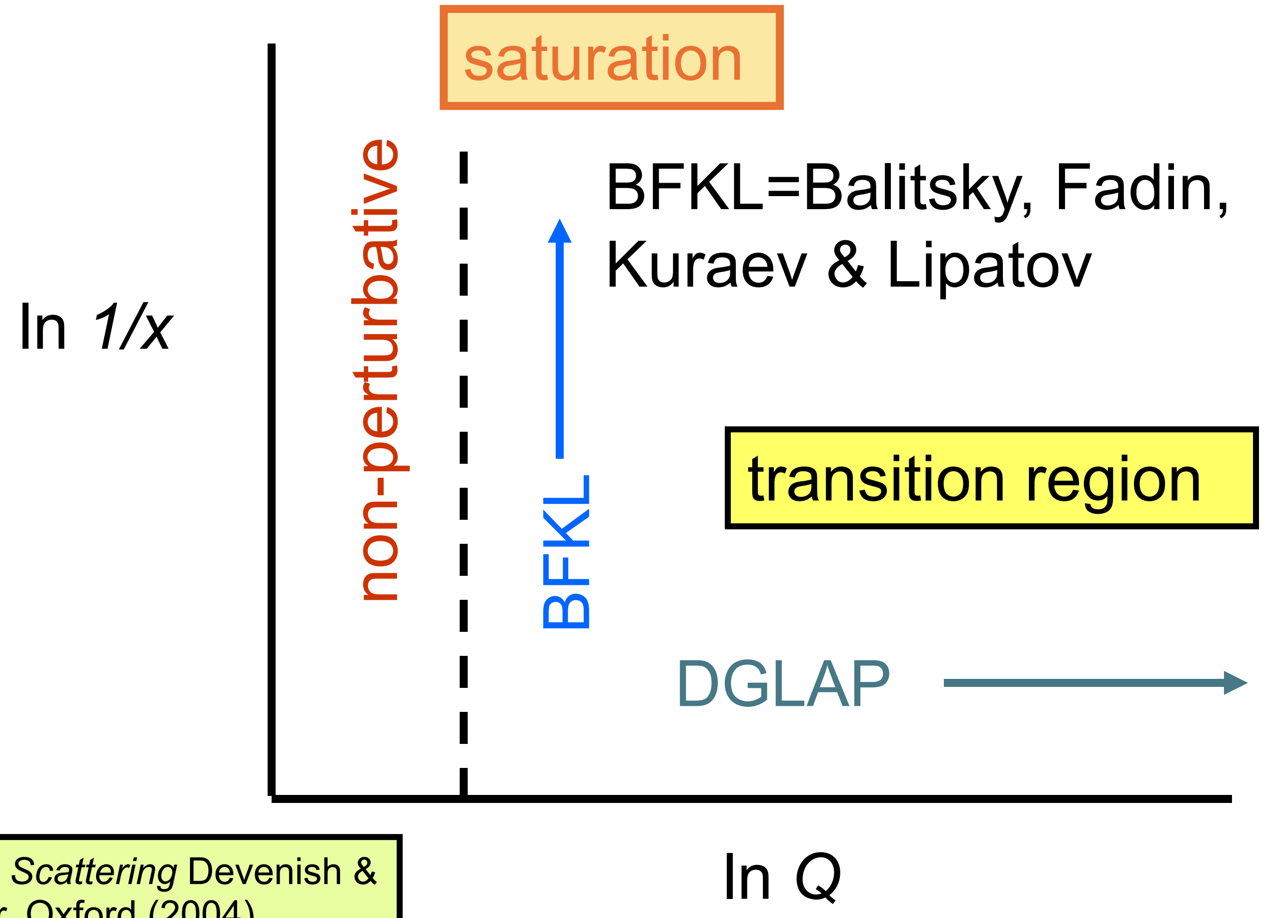
$$\nu_\mu \bar{u} \to \mu \bar{d} \qquad \bar{\nu}_\mu u \to \bar{\mu} d$$

- NC/CC ratio is ~ 0.4

Uncertainties in small *x*



gluon recombination



saturation

non-perturbative

BFKL

transition region

DGLAP

ln *1/x*

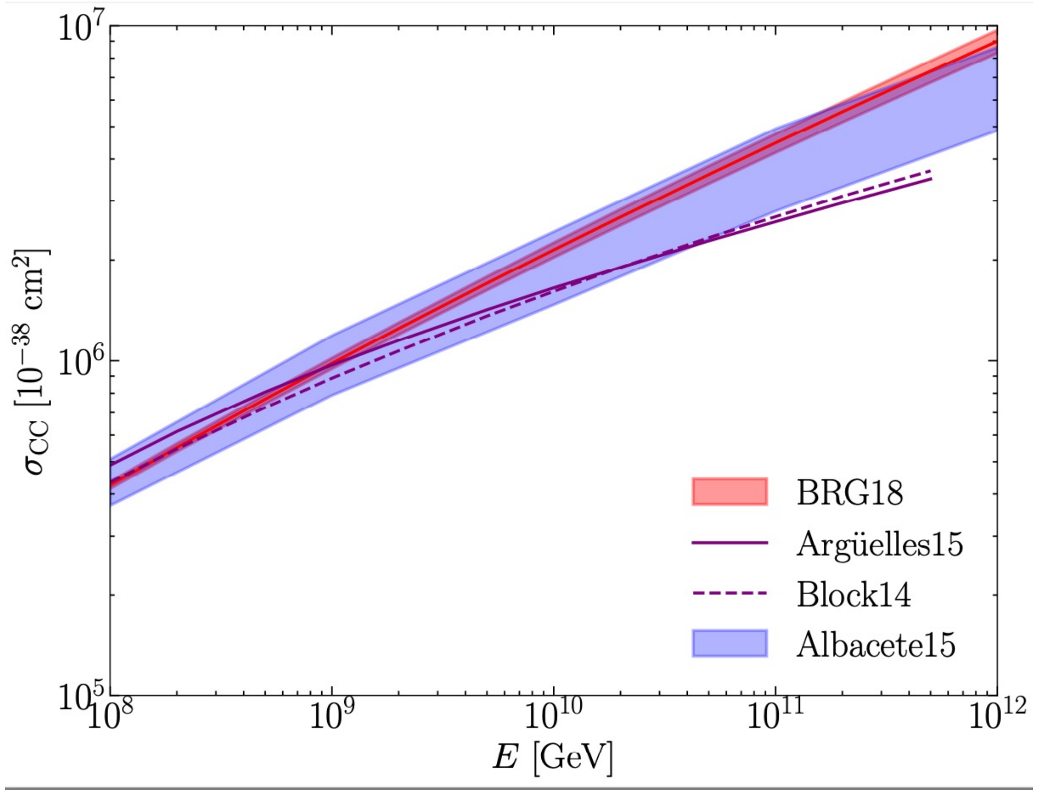
ln *Q*

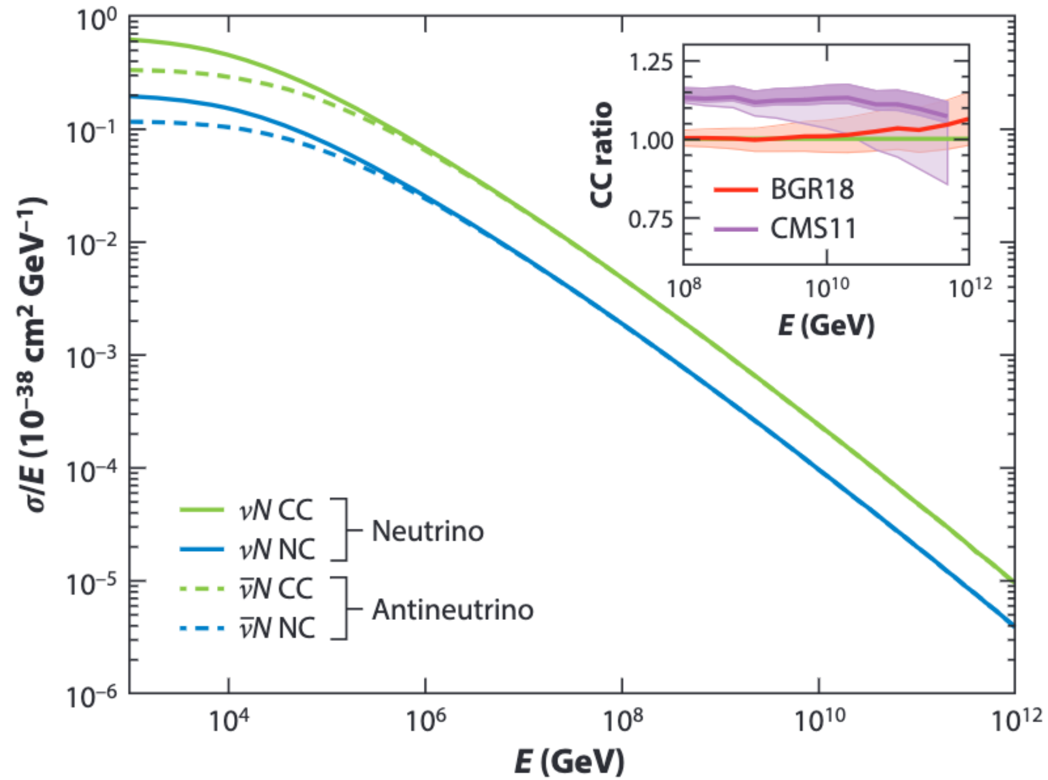
BFKL=Balitsky, Fadin,
Kuraev & Lipatov

DGLAP=Dokshitzer,
Gribov, Lipatov, Altarelli
& Parisi

Deep Inelastic Scattering Devenish &
Cooper-Sarkar, Oxford (2004)

High energy uncertainty





BGR18 = Bertone, Gauld & Rojo, JHEP 01 (2019) 217 (NNLO+NNLx), CMS11 = Cooper-Sarkar, Mertsch & Sarkar, JHEP 08:042 (2011) (NLO); Figs. from MHR, Ann Rev Nucl Part Sci 2023, blue and green with ct18nlo (NLO); Arguelles15 = PRD 92 (2015) 074040 (dipole motivated); Block14 = PRD 89 (2014) 094027 (ln$^2 s$ form); Albacete15 = PRD 92 (2015) 014027 (dipole model)

More about the high energy cross section

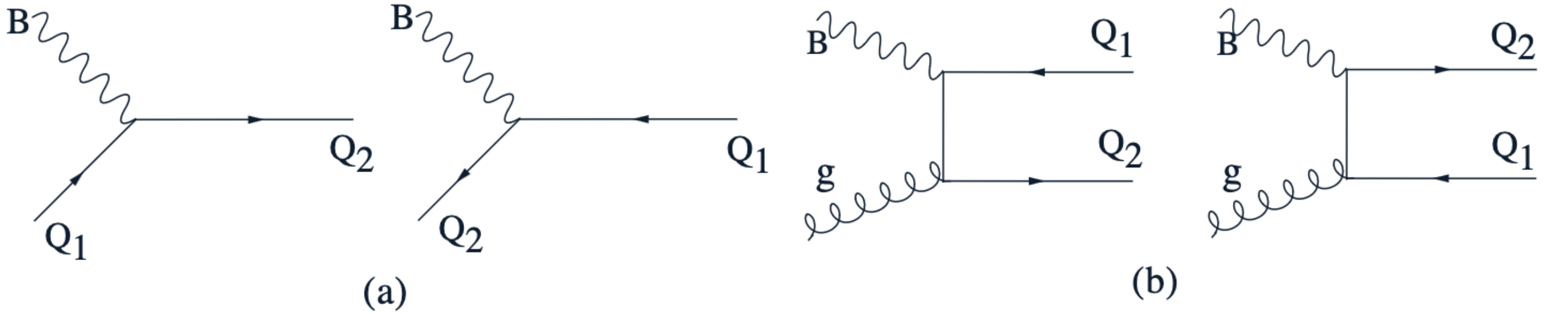


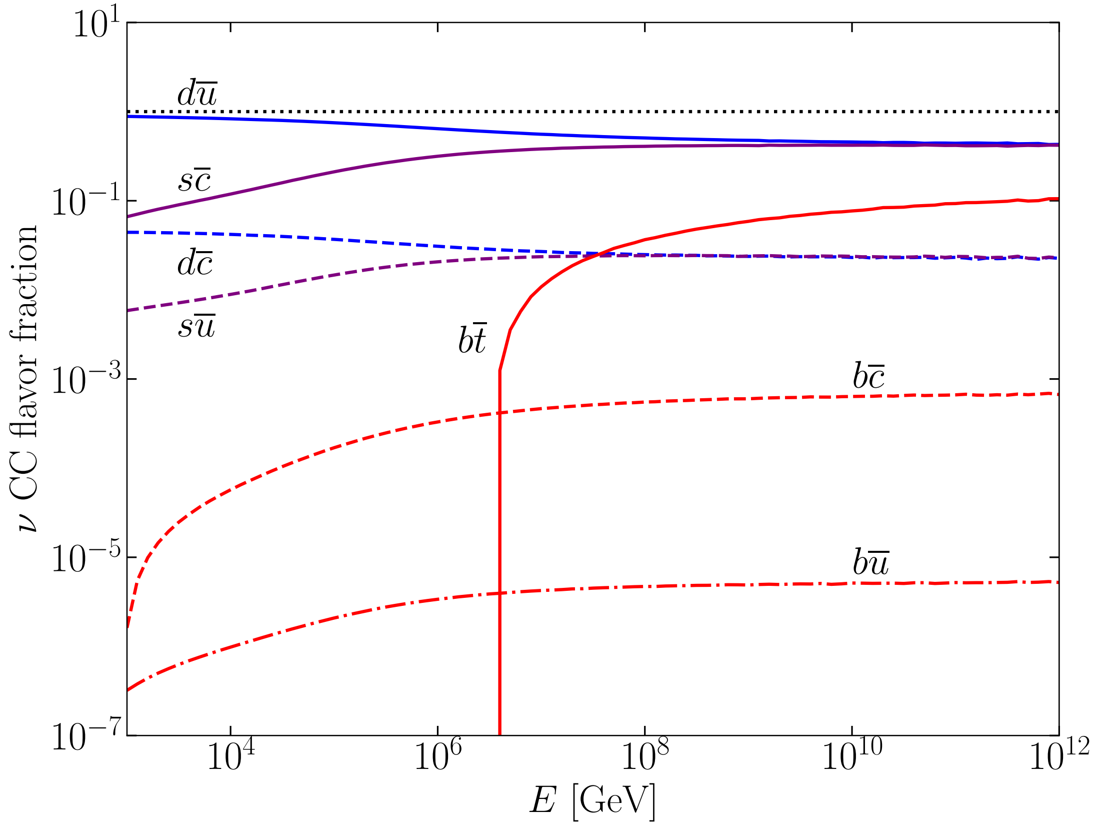
Fig. from Aivazis et al PRD 50 (1994) 3102 (ACOT)

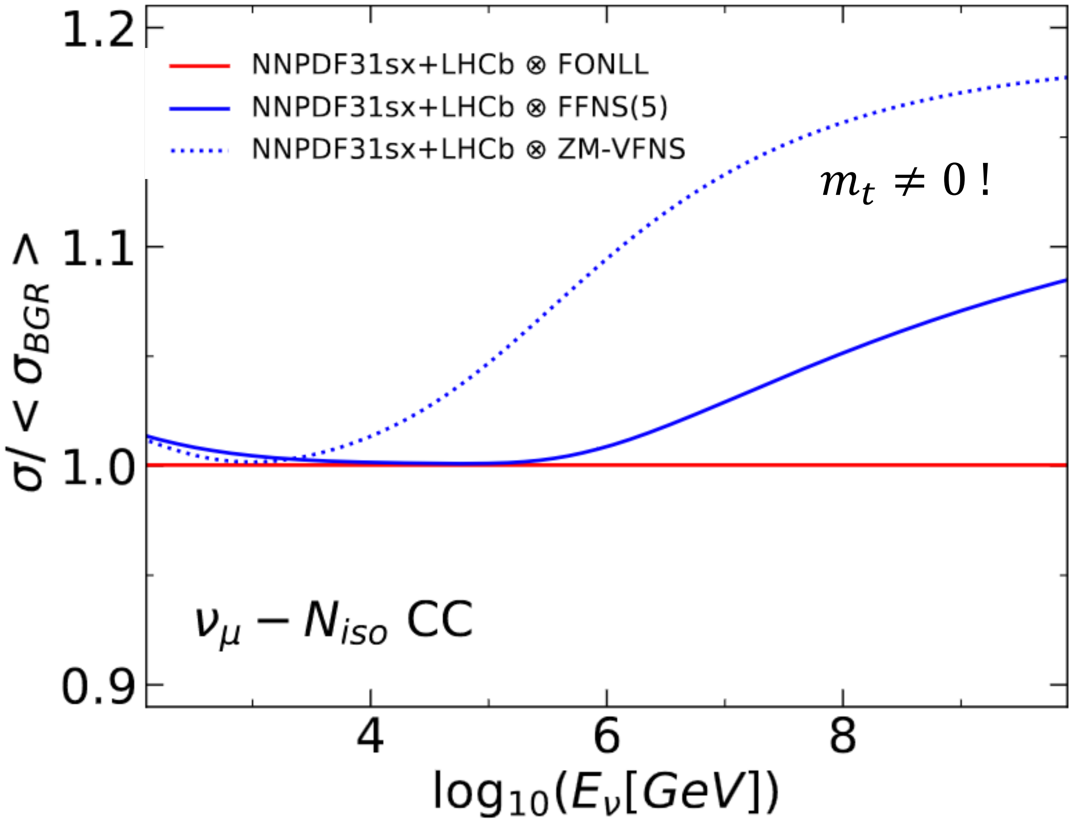
νN : example

$$Q_1 = d,\ Q_2 = u$$
$$\bar{Q}_2 = \bar{u},\ \bar{Q}_1 = \bar{d}$$

Leading order, can separate $d, \bar{u}$ but not so at NLO.

Quark flavor contributions to CC cross section

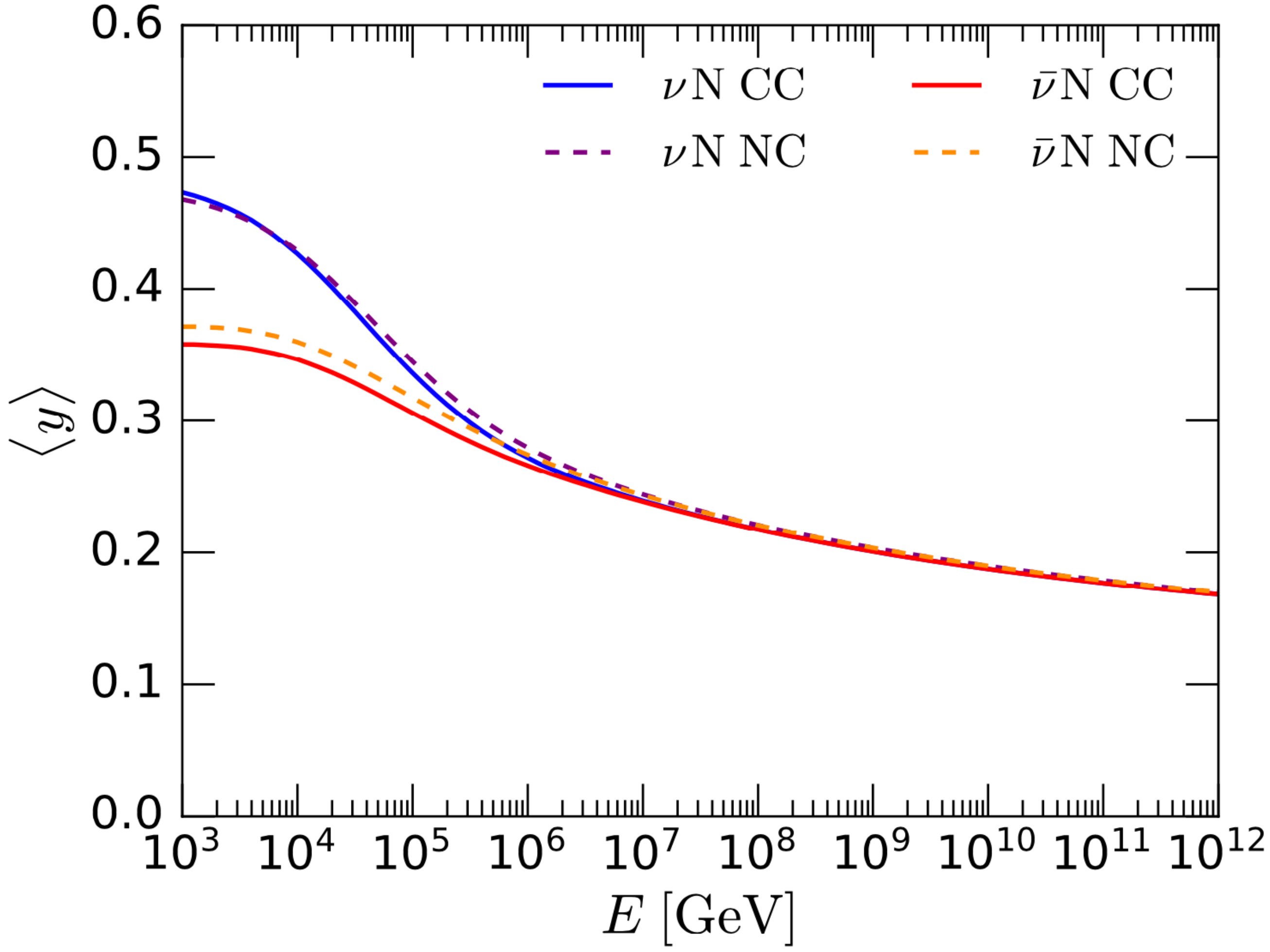




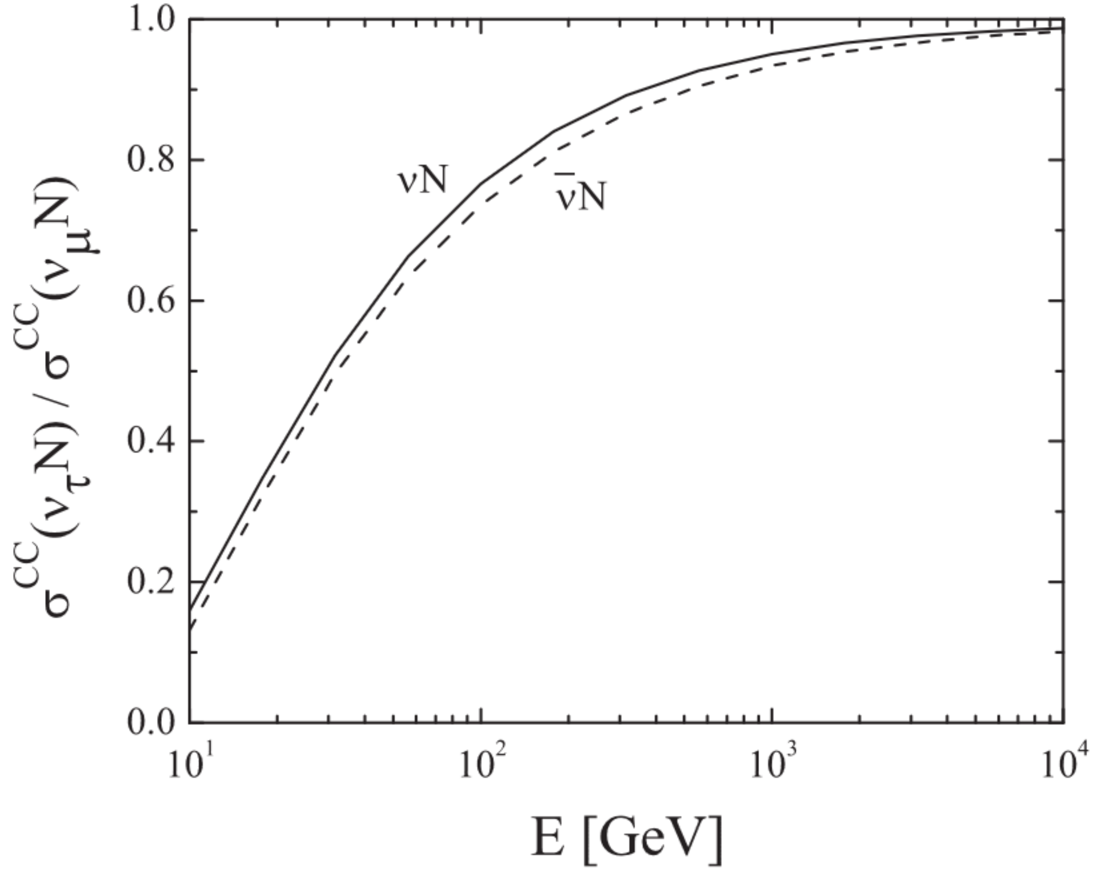
Following Jeong & MHR, Phys.Rev.D 81 (2010) 114012
See also Aivazis et al PRD 50 (1994) 3102 (ACOT)

Garcia et al., JCAP 09 (2020) 025
Bertone et al., Eur. Phys. J. C 77 (2017) 837

Average inelasticity in neutrino DIS



CC interactions: ν_τ, ν_μ - lepton mass effects



Kinematics plus 2 more structure functions.

$$\frac{m_\tau^2}{2M(E_\nu - m_\tau)} \le x \le 1 \,,$$
$$a - b \le y \le a + b \,,$$

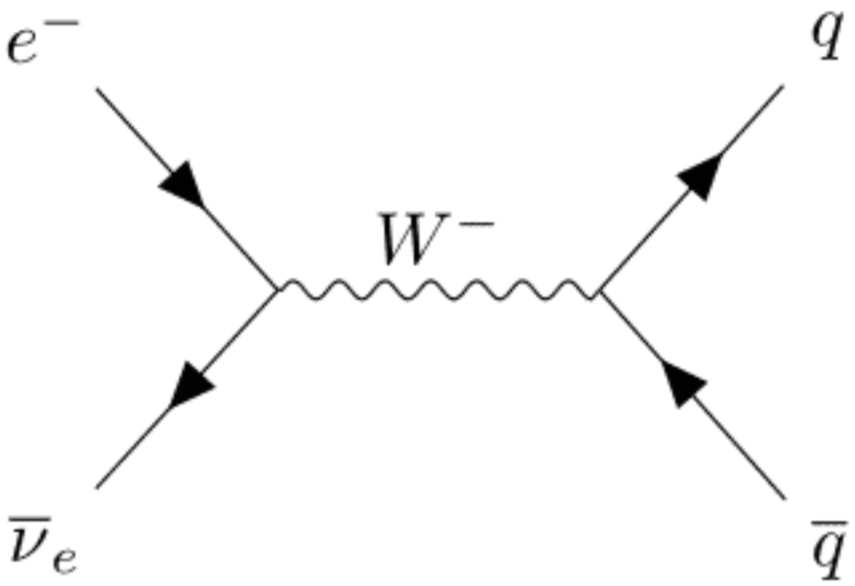
where the quantities a and b are

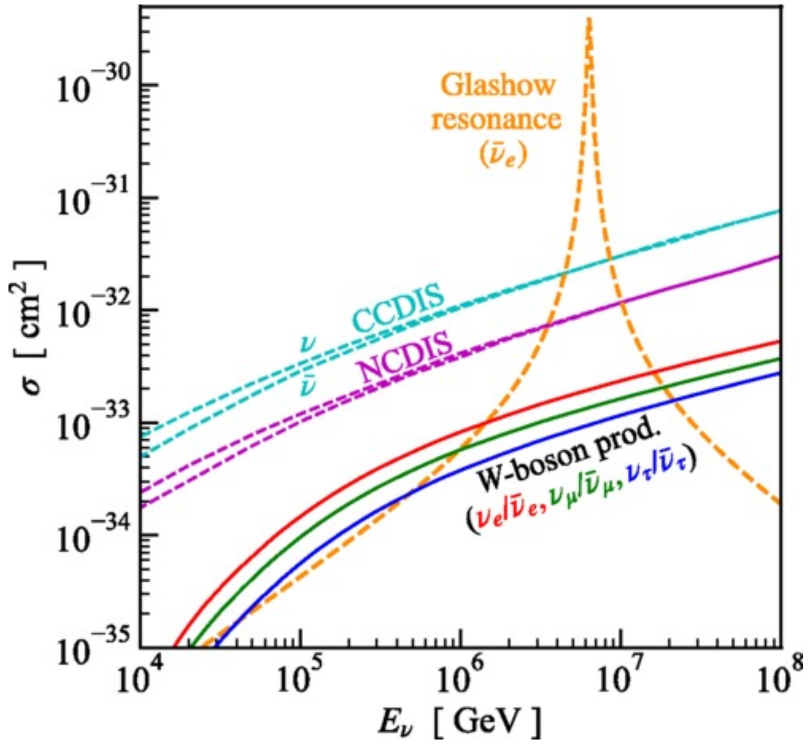
$$a = \left[1 - m_\tau^2\left(\frac{1}{2ME_\nu x} + \frac{1}{2E_\nu^2}\right)\right] / (2 + Mx/E_\nu)$$
$$b = \left[\left(1 - \frac{m_\tau^2}{2ME_\nu x}\right)^2 - \frac{m_\tau^2}{E_\nu^2}\right]^{1/2} / (2 + Mx/E_\nu) \,.$$

Jeong & MHR, PRD 82 (2010) 033010

Glashow resonance

special status of the electron antineutrino



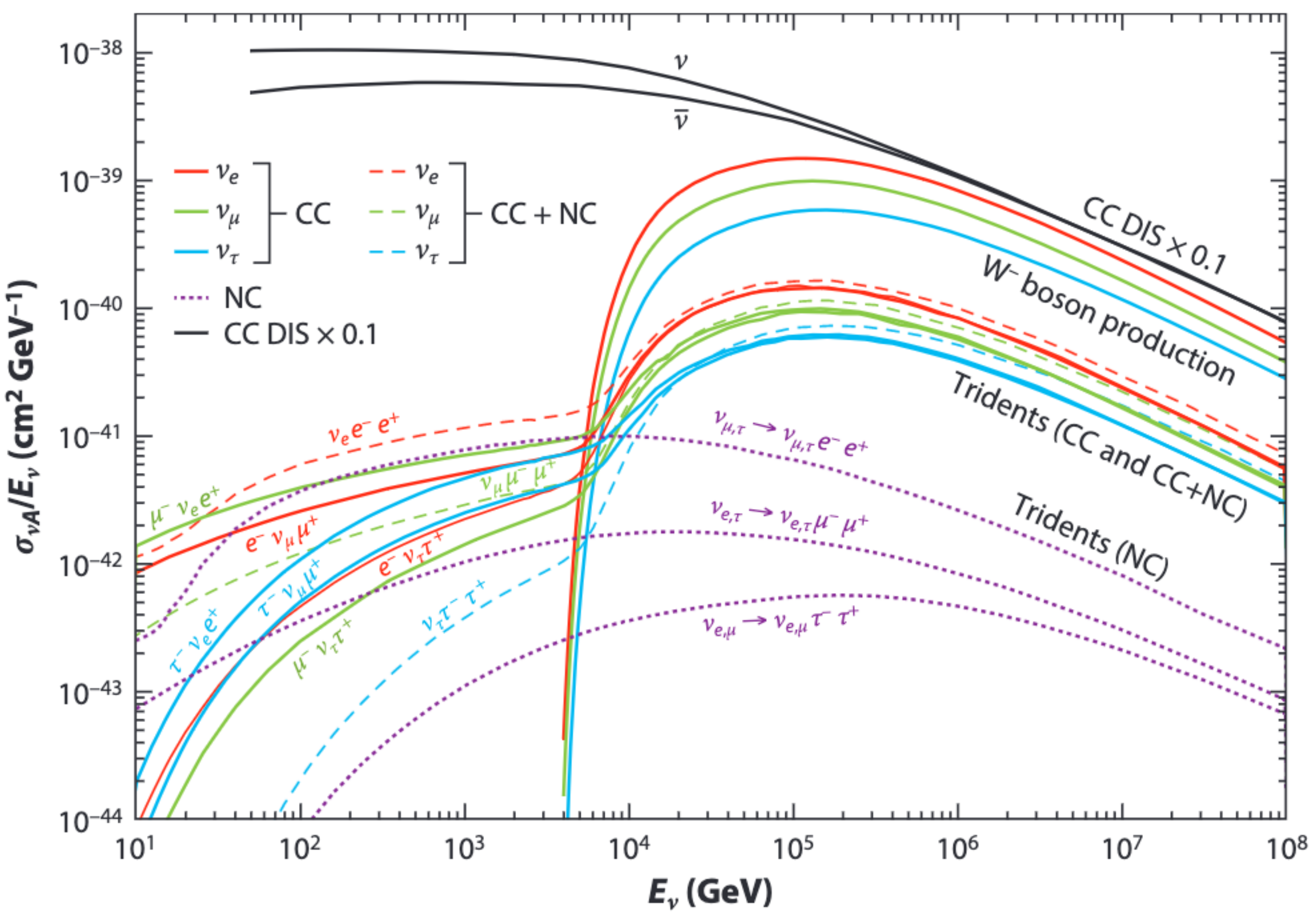


Zhou & Beacom, PRD 101 (2020) 3

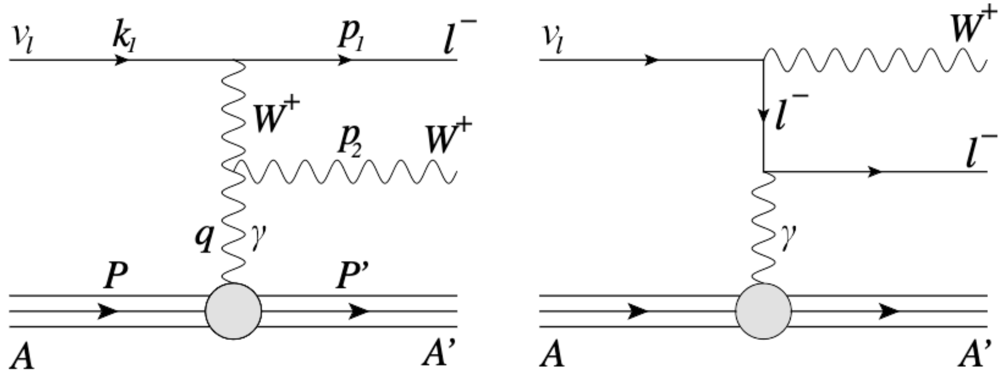
$$2m_e E_{\bar{\nu}_e} = M_W^2 \rightarrow E_{\bar{\nu}_e} = 6.3\ \text{PeV}$$

$$\sigma(s) = 24\pi\Gamma_W^2 \cdot B_{W^-\rightarrow\bar{\nu}_e+e^-} \frac{s/M_W^2}{(s-M_W^2)^2+\Gamma_W^2 M_W^2}$$

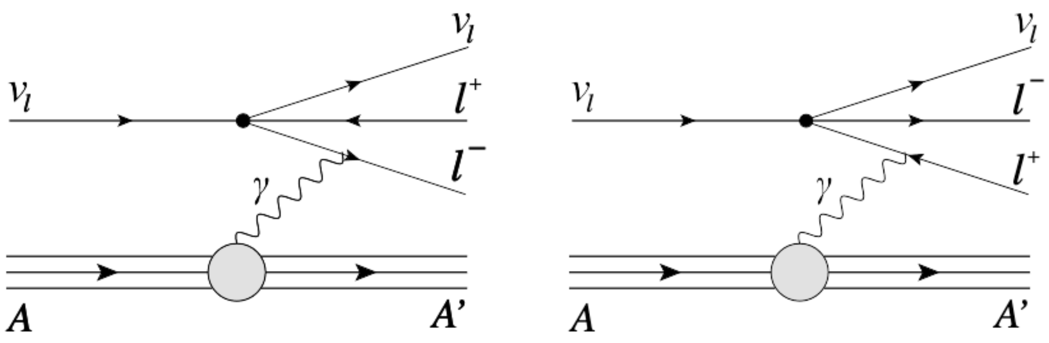
Sub-leading cross sections & “hidden Glashow”



MHR, Ann Rev Nucl Part Sci 2023 adapted from Zhou & Beacom, PRD 101 (2020) 036011

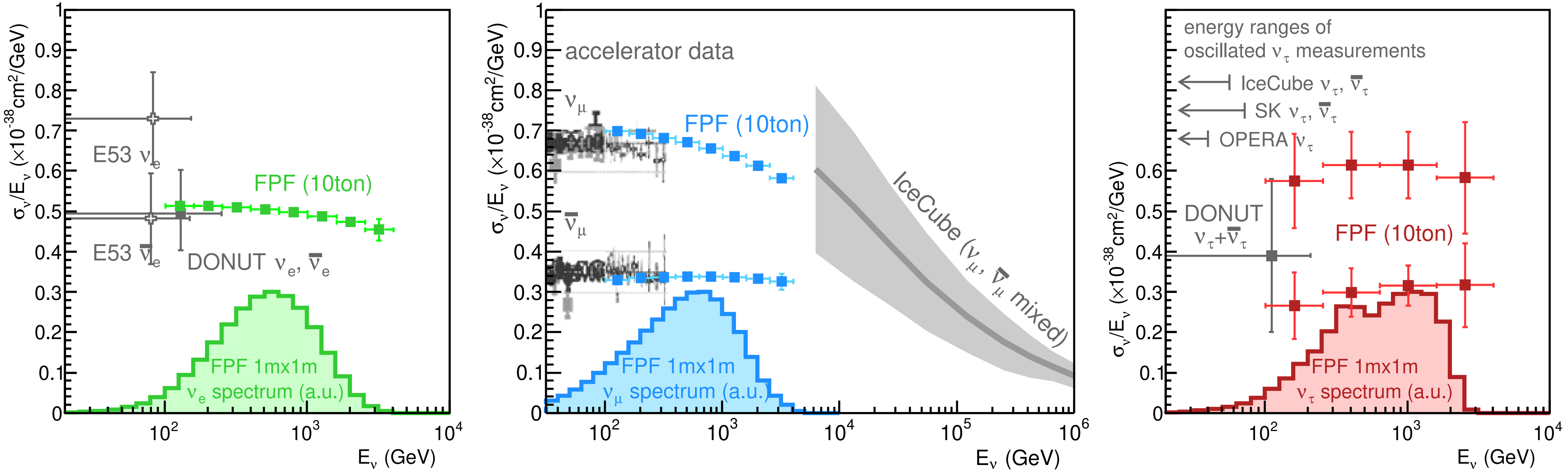


See also, Alikhanov, PLB 741 (2016) 247.



See also, Ballett et al. JHEP 01 (2019) 119

Where is the neutrino cross section measured?



Snowmass white paper: Feng et al., Phys.*G* 50 (2023) 030501

More on the IceCube measurement later.

ASIDE

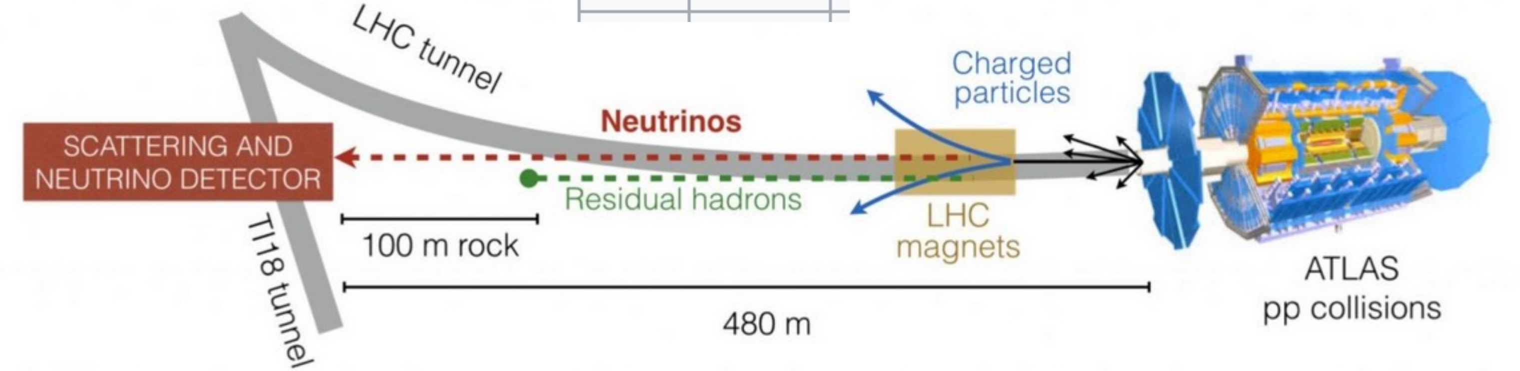
LHC Run 3

Both experiments installed, in T12 and T18 existing injector tunnels on either side of the ATLAS IP.

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

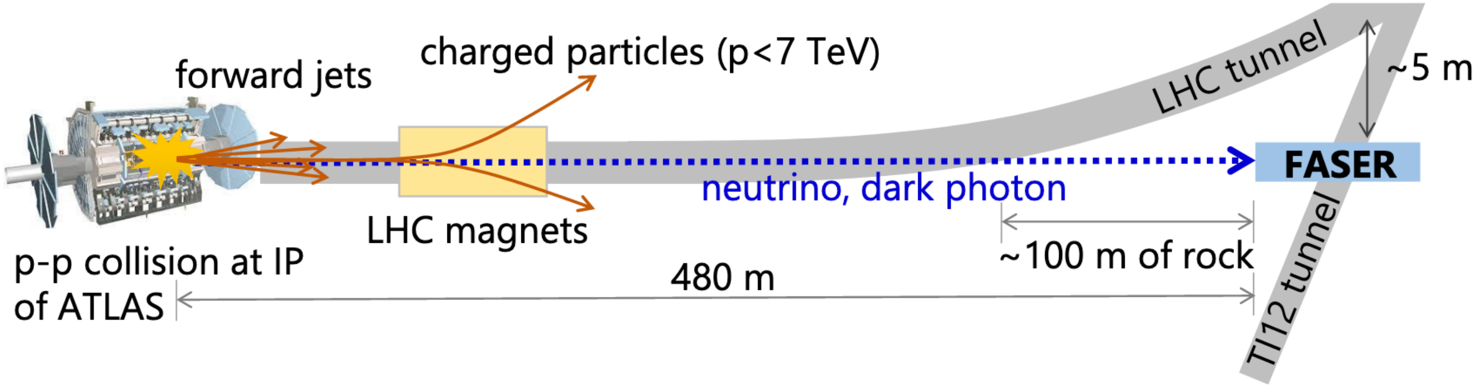
θ	η
0°	∞
0.1°	7.04
0.5°	5.43
1°	4.74

SND@LHC



https://www.epfl.ch/labs/lphe/en/4266-2/

FASERν



Figures "not to scale."

FASERν 1.2 ton, 25 cm x 25cm

on axis, $\eta > 8.5$

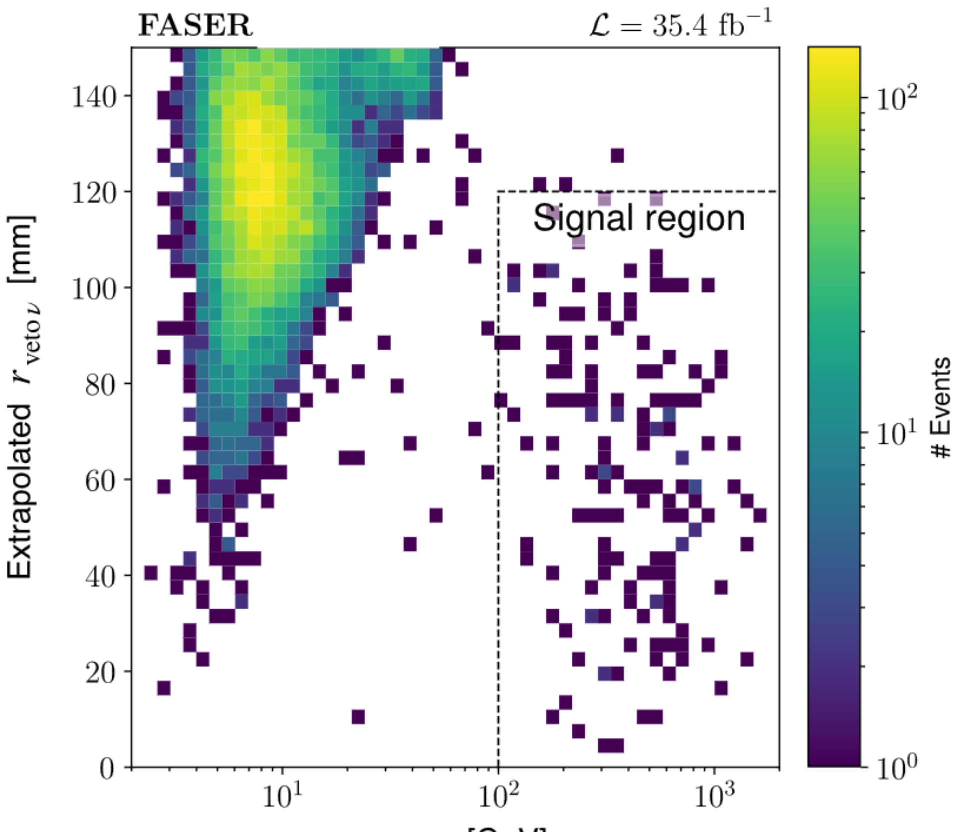
SND@LHC 800 kg, 39 cm x 39 cm

off axis, $8.5 > \eta > 7$

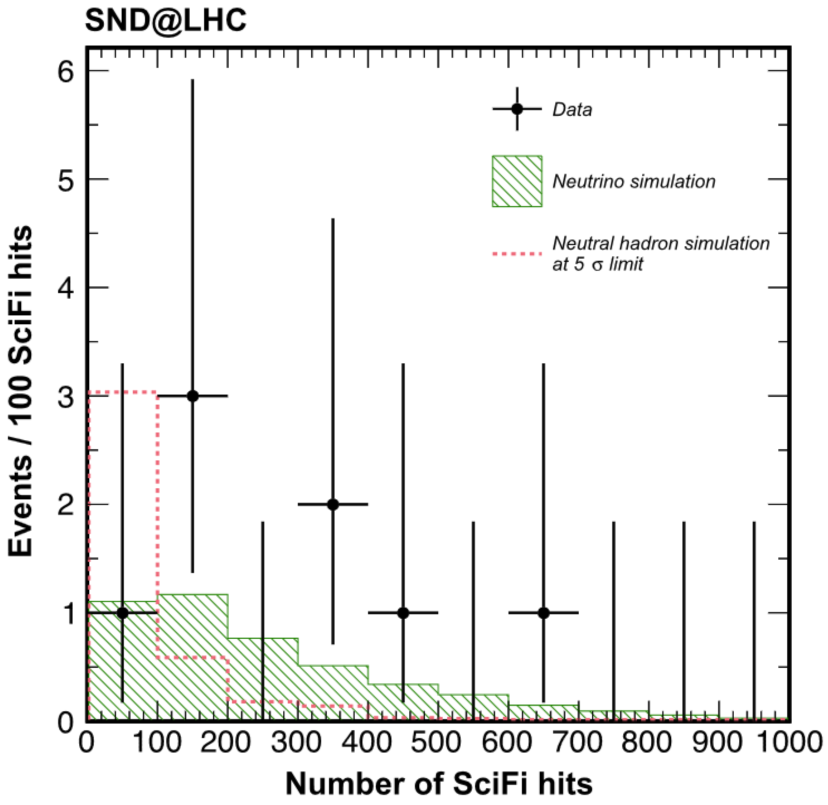
150 fb^{-1}

ASIDE

First neutrino events at LHC Run 3: $\nu_\mu CC$ (muons)



$$n_\nu = 153^{+12}_{-13}(\text{stat})\ ^{+2}_{-2}(\text{bkg}) = 153^{+12}_{-13}(\text{tot})$$



FASER Collab, PRL 131 (2023) 031801

SND@LHC Collab, PRL 131 (2023) 031802

ASIDE

Envisioned Forward Physics Facility at the high intensity LHC :

- Neutrinos produced in the forward region related to neutrino production in cosmic ray interaction processes.
- Neutrino measurements in new energy regimes, nuclear targets.

Snowmass white papers

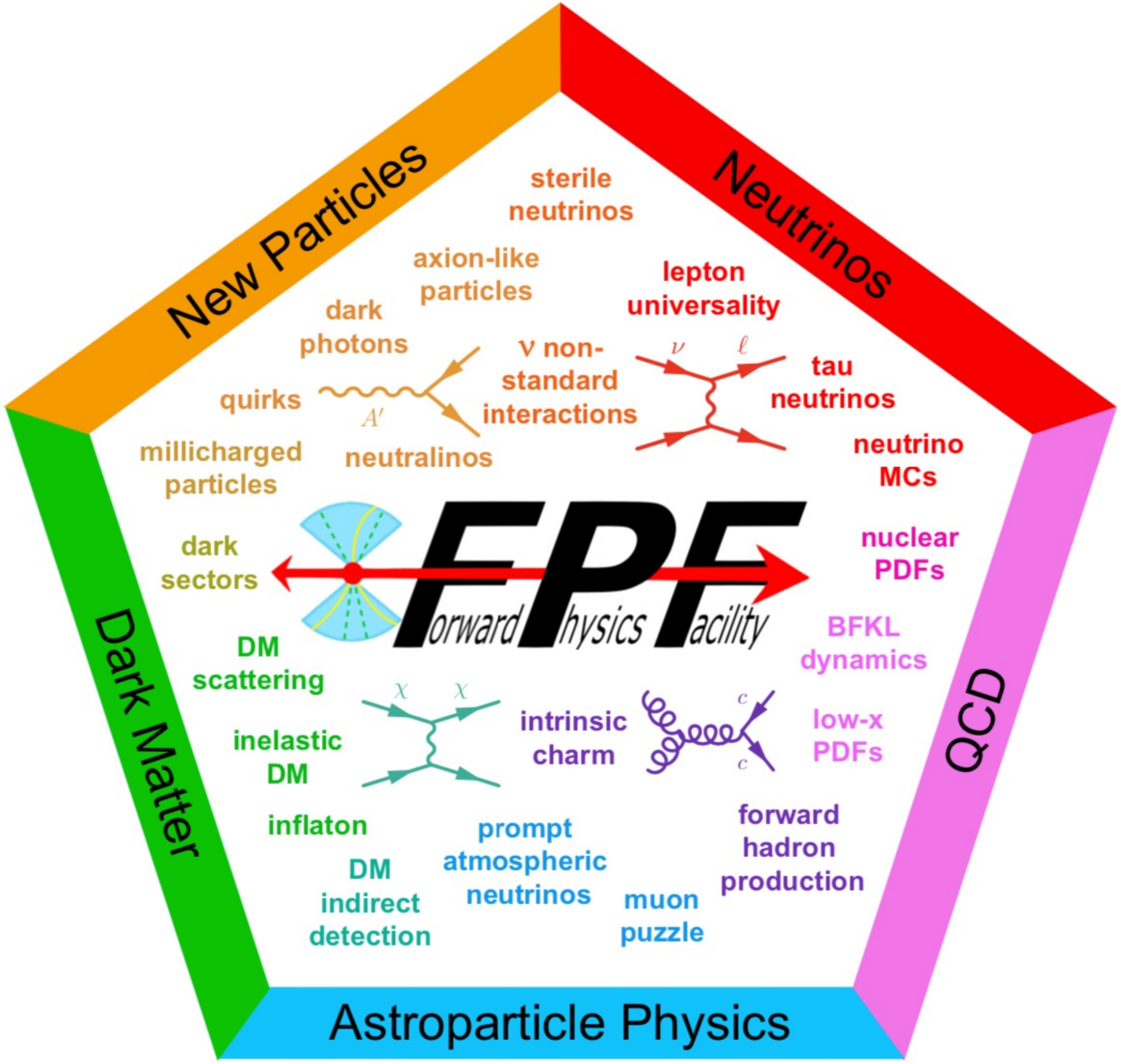
short: Anchordoqui et al, 2109.10905

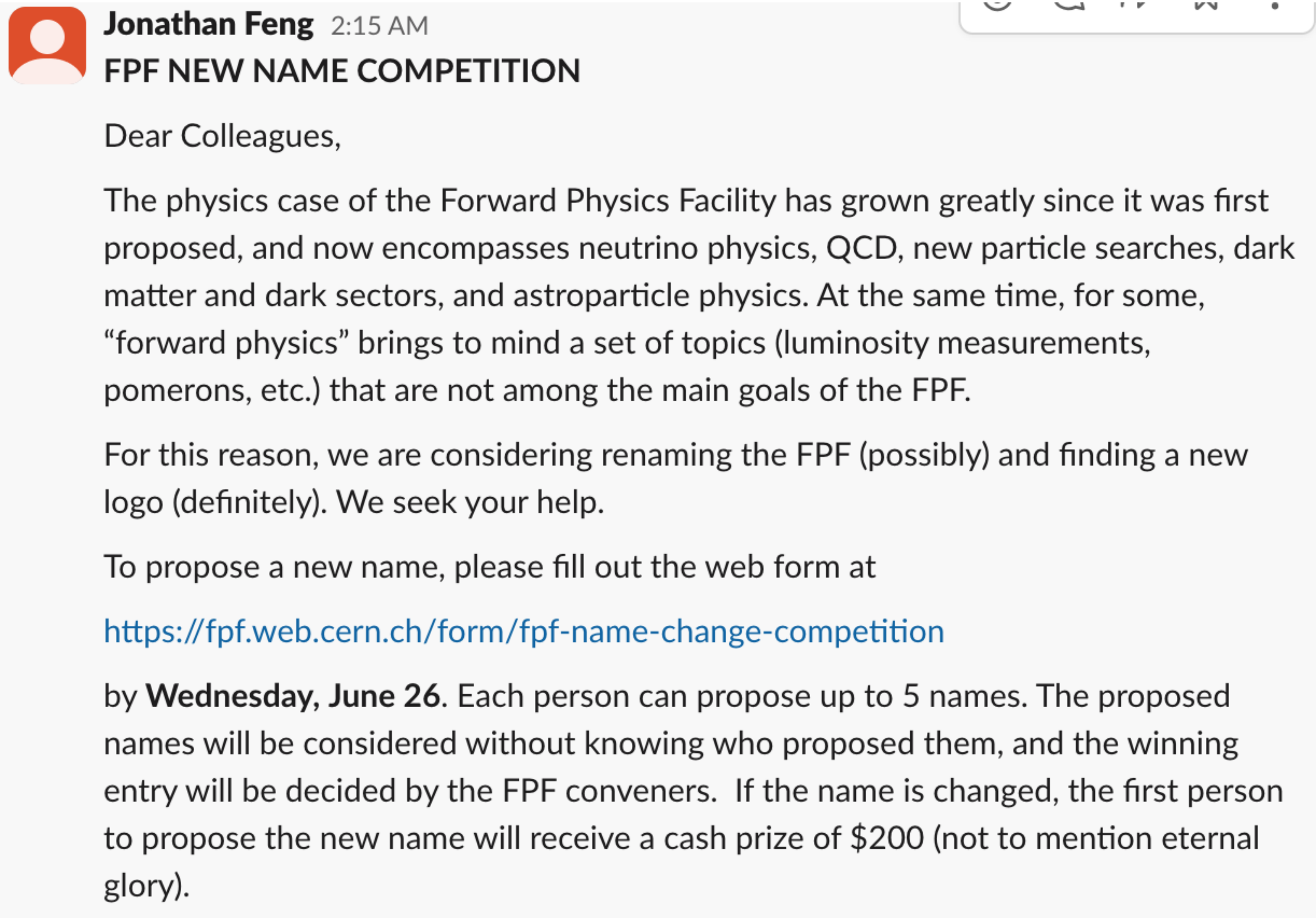
Phys. Rept. 968 (2022) 1 (50 pages)

long: Feng et al, 2203.05090

J. Phys. G 50 (2023) 030501 (411 pages)

and see references therein!





Jonathan Feng 2:15 AM

FPF NEW NAME COMPETITION

Dear Colleagues,

The physics case of the Forward Physics Facility has grown greatly since it was first proposed, and now encompasses neutrino physics, QCD, new particle searches, dark matter and dark sectors, and astroparticle physics. At the same time, for some, “forward physics” brings to mind a set of topics (luminosity measurements, pomerons, etc.) that are not among the main goals of the FPF.

For this reason, we are considering renaming the FPF (possibly) and finding a new logo (definitely). We seek your help.

To propose a new name, please fill out the web form at

https://fpf.web.cern.ch/form/fpf-name-change-competition

by **Wednesday, June 26**. Each person can propose up to 5 names. The proposed names will be considered without knowing who proposed them, and the winning entry will be decided by the FPF conveners. If the name is changed, the first person to propose the new name will receive a cash prize of $200 (not to mention eternal glory).

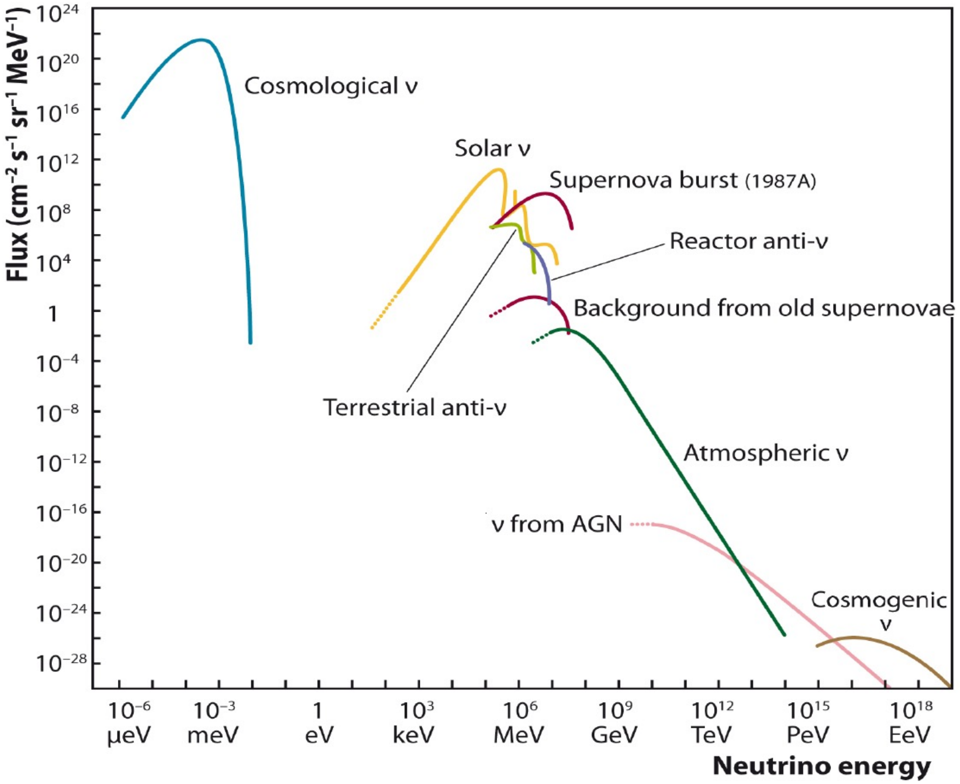
Neutrino detection through the energies

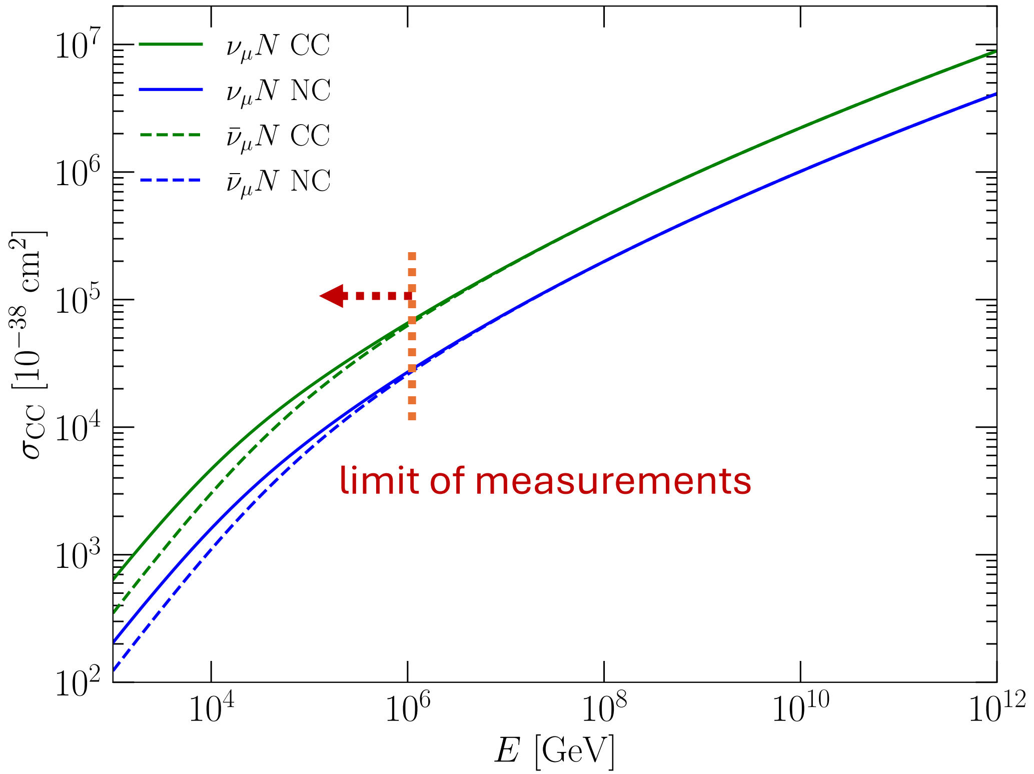
References

Snowmass white papers and reviews (and references therein):

- Ackermann et al., High-energy and ultra-high-energy neutrinos: A Snowmass white paper, JHEAp 36 (2022) 55-110 https://arxiv.org/pdf/2203.08096
- Mammen Abraham et al., Tau neutrinos in the next decade: from GeV to EeV, J.Phys.G 49 (2022) 110501
- Spiering, Neutrino Detectors Under Water and Ice, https://link.springer.com/chapter/10.1007/978-3-030-35318-6_17
- Barwick & Glaser, Chapter 6: Radio Detection of High Energy Neutrinos in Ice, 2208.04971

Neutrino events





limit of measurements

Notice how steeply the flux falls relative to the rising neutrino cross section.

Detector sizes – km^3 scale detectors

$$N_{\rm evt} = n_{\rm nuc} \cdot V_{\rm det} \cdot 2\pi \cdot \Delta t \int_{10^5\ {\rm GeV}} dE_\nu \sigma_{\rm CC}(E_\nu)\Phi_{\nu+\bar\nu}(E_\nu)$$

number of neutrinos

$$n_{\rm nuc} = N_A \rho = 6\times 10^{23}/{\rm cm}^3$$

how much sky

$$E_\nu^2 \Phi_{\nu+\bar\nu} \simeq 2\times 10^{-8}\ \frac{\rm GeV}{\rm cm^2\, s\, sr}$$

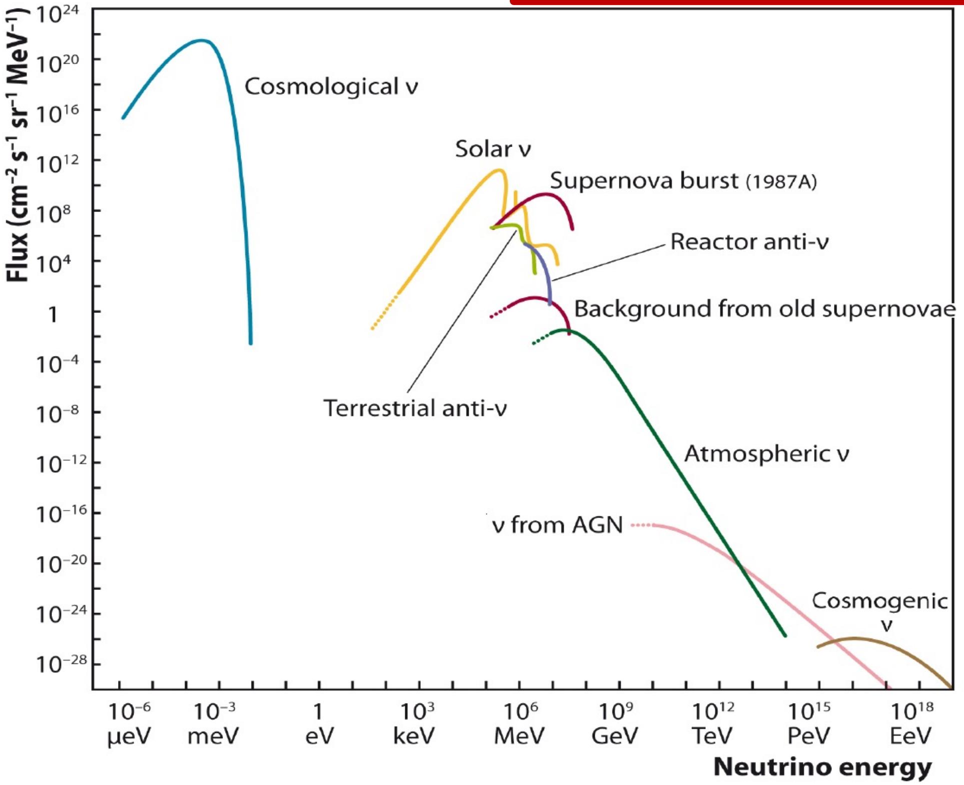
obs time

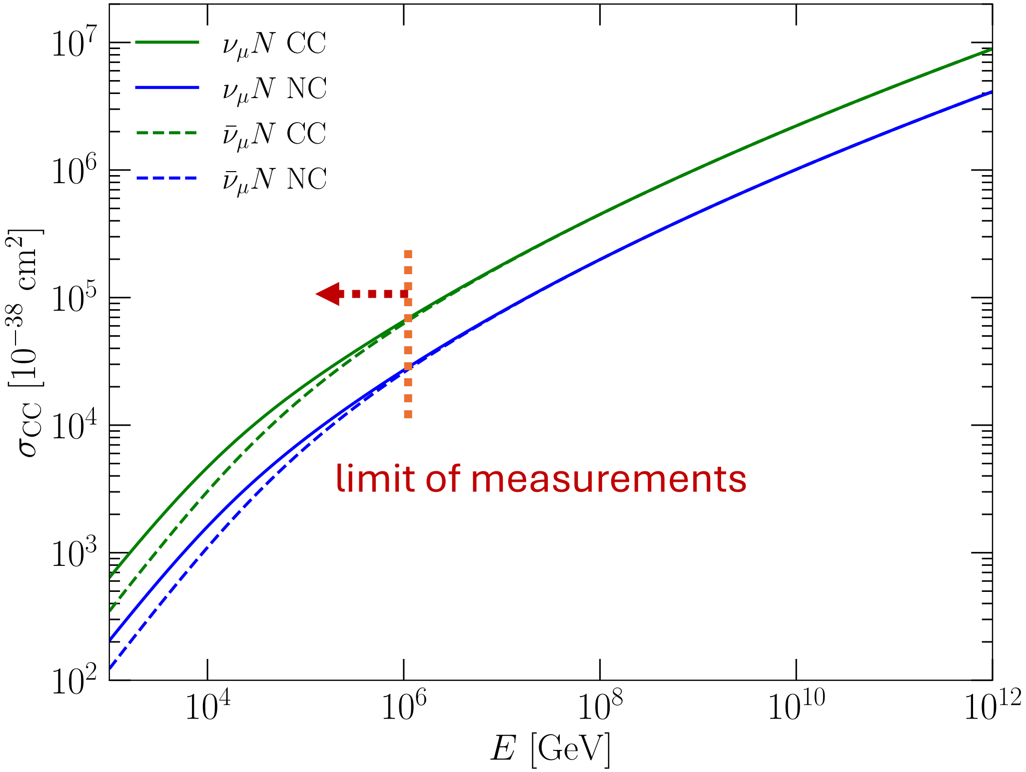
$$\boxed{\frac{N_{\rm evt}}{\rm yr} \simeq 18\, \frac{V_{\rm det}}{\rm km^3}}$$

$$\sigma_{\rm CC}(E_\nu) \simeq 5\times 10^{-33}\ {\rm cm}^2\, (E_\nu/10^8\ {\rm GeV})^{0.33}$$

Neutrino events

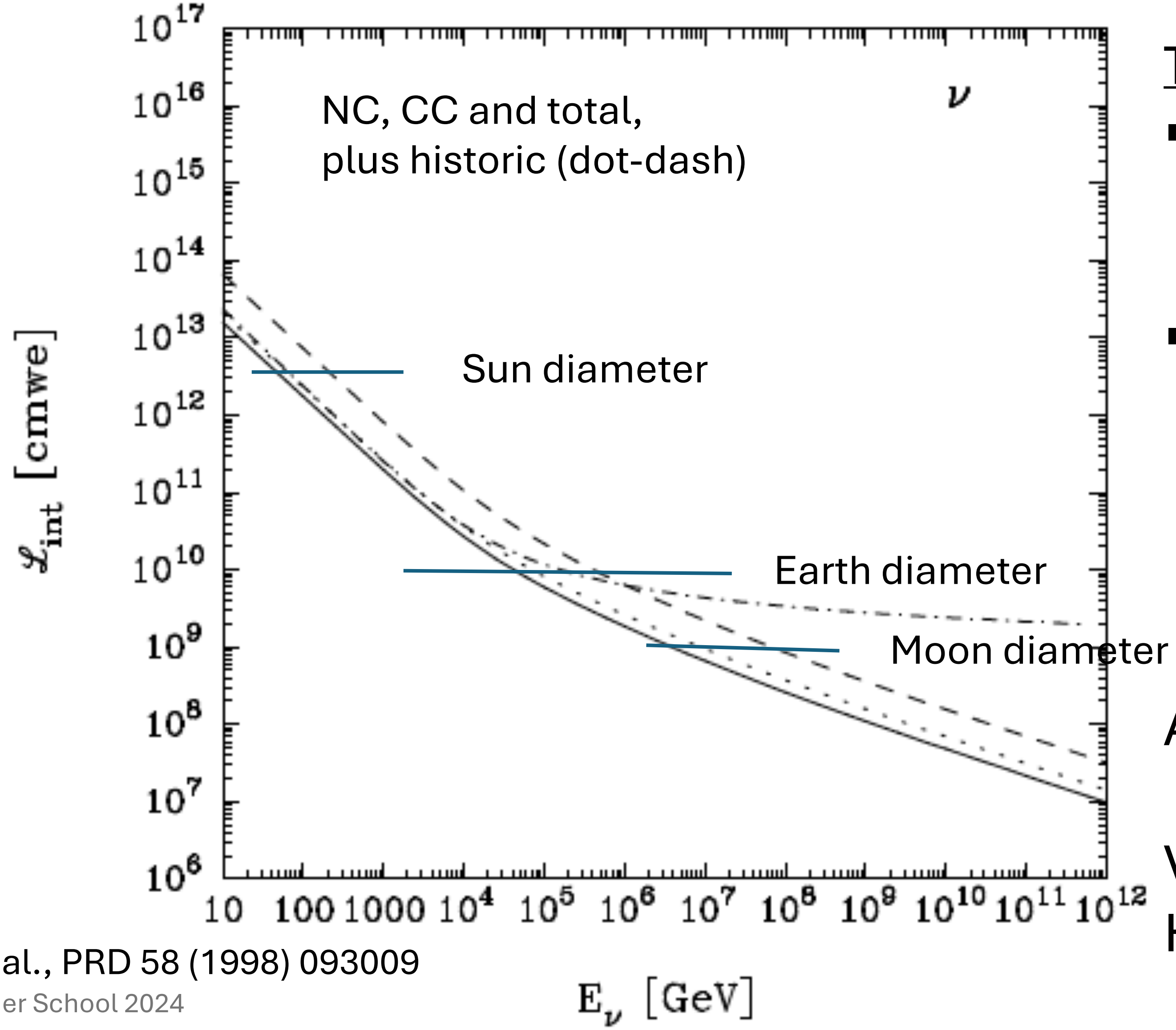
Higher energies mean larger volumes.





Notice how steeply the flux falls relative to the rising neutrino cross section.

Neutrino interaction length



Gandhi … MHR…et al., PRD 58 (1998) 093009

Take home lessons:

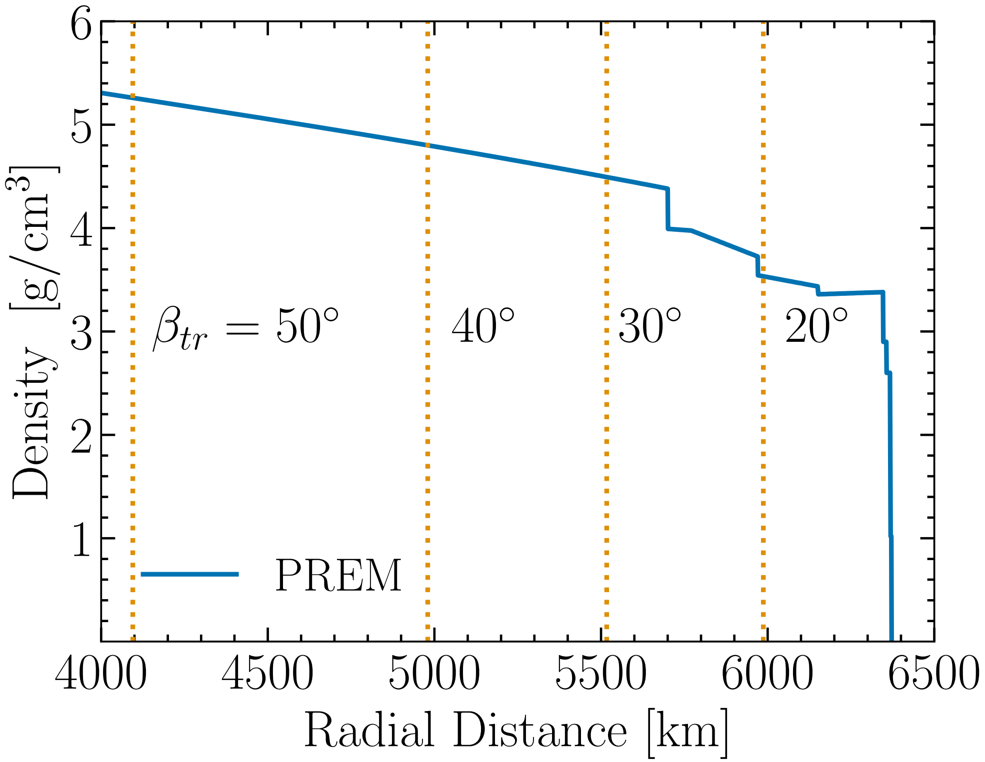
- Neutrinos don't go directly through the center of the Earth for E>40 TeV.
- Hardly any interactions in the atmosphere, more likely horizontal than vertical.

Atmospheric column depth:

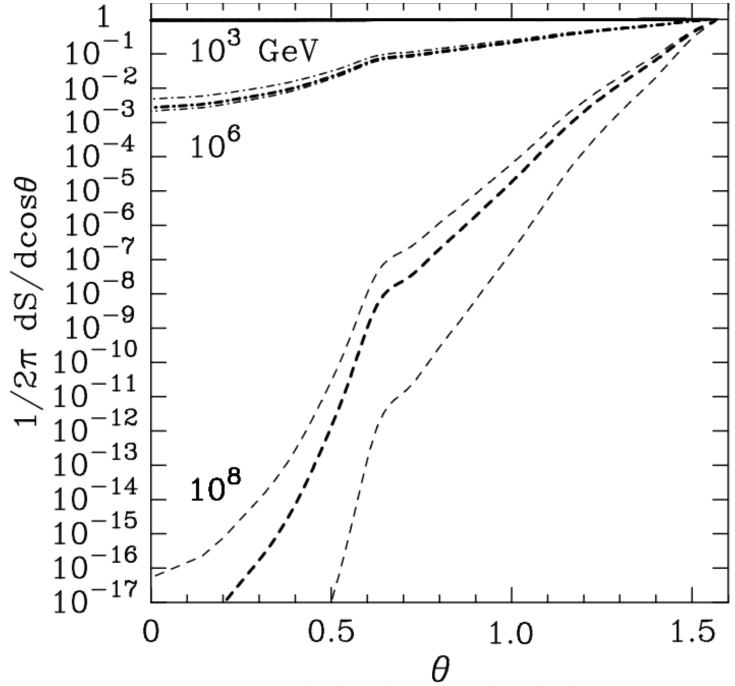
Vertical: 1,033 cmwe
Horizontal: 36,000 cmwe

Neutrino attenuation in Earth

$$S(E_\nu) = \frac{1}{2\pi}\int_{-1}^{0} d\cos\theta \int d\phi \exp\left[-z(\theta)/\mathcal{L}_{\rm int}(E_\nu)\right] .$$

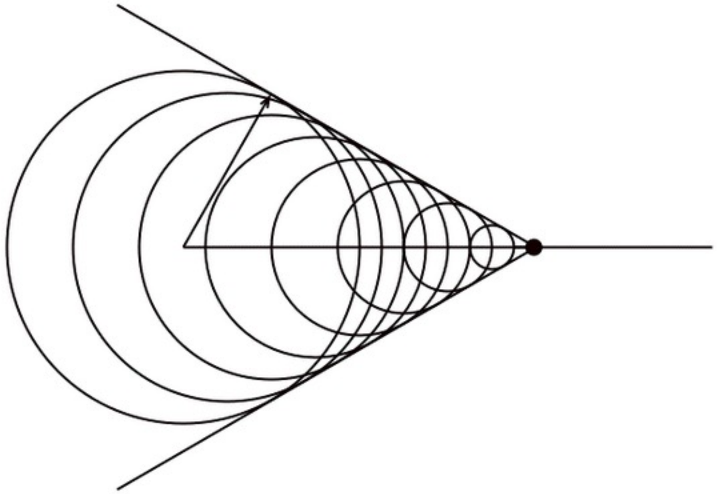


Angles relative to the local horizontal.



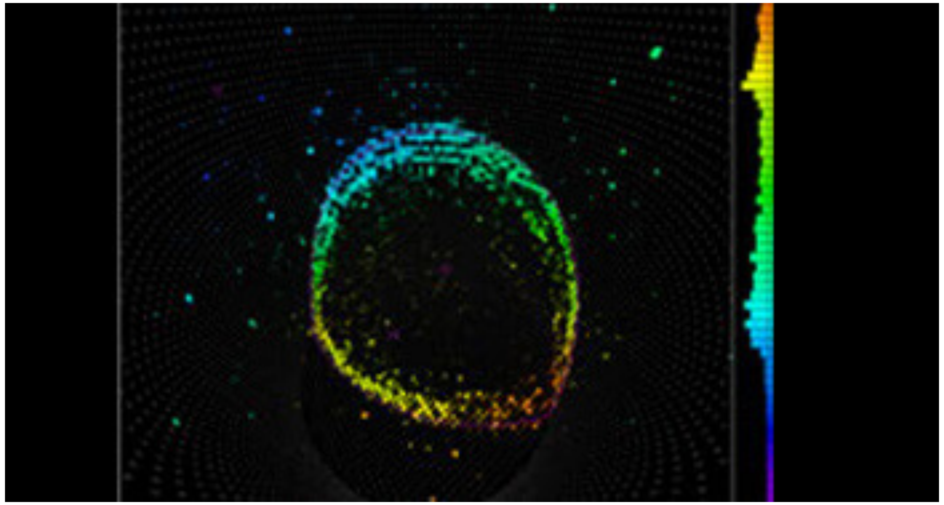
Historic figure: Gandhi et al., PRD 58 (1998) 093009

Water and ice Cherenkov detectors



Speed of the charged particle faster than the speed of light in the medium

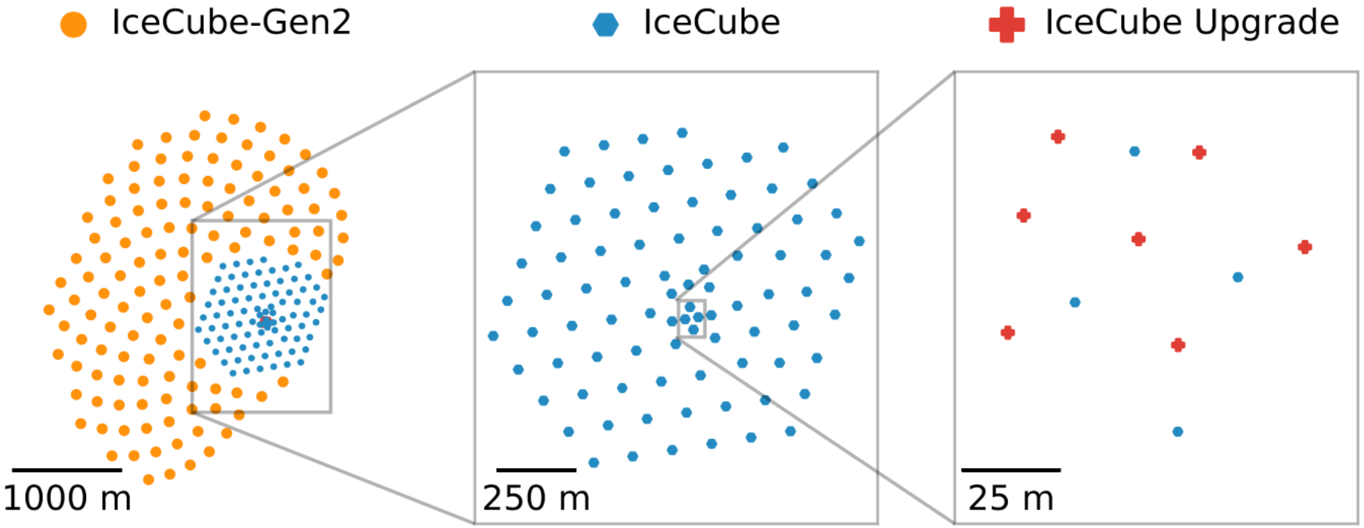
$$u > v = \frac{c}{n}$$



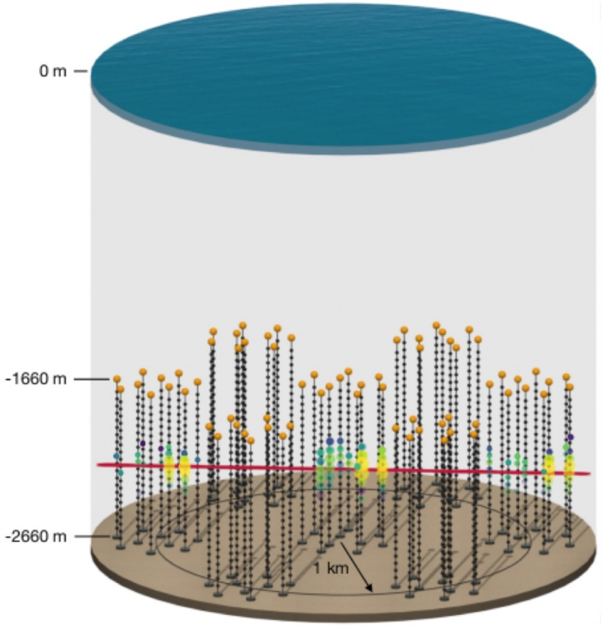
https://www-sk.icrr.u-tokyo.ac.jp/en/sk/about/detector/

Water and ice Cherenkov detectors

IceCube



P-one

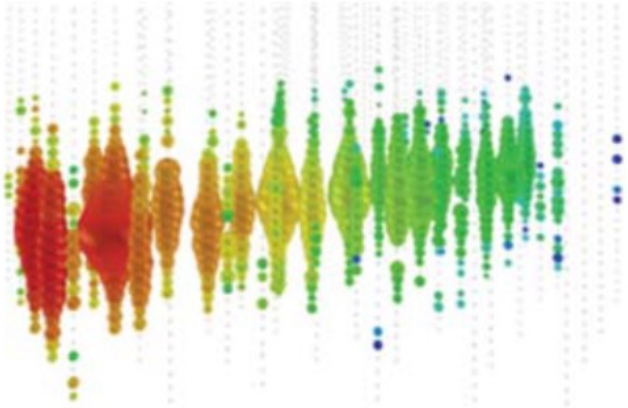


- KM3-net: ORCA 1-100 GeV, ARCA 100-10^8 GeV, to 1 km^3
- Baikal-GVD staged instrumentation since 2016, 1 km^3 by 2025
- IceCube-Gen2 TBD

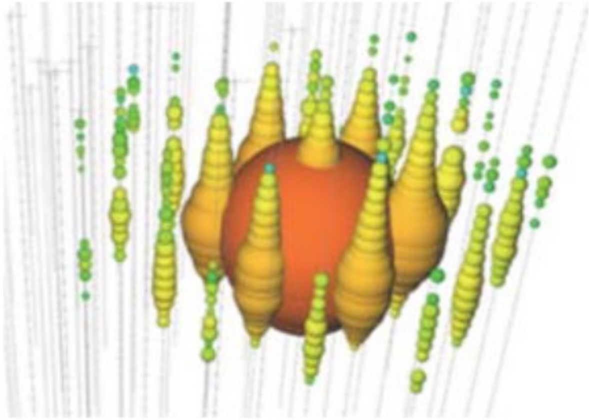
pathfinders in 2018, 2020
northern hemisphere

Fig. from Ackermann et al., JHEAp 36 (2022) 55

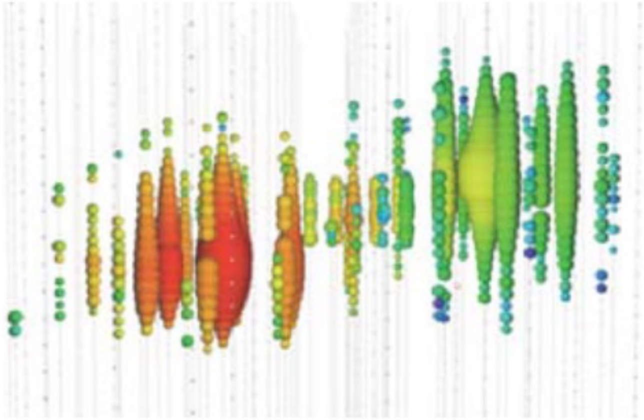
IceCube event signatures



track-like
(muons)



cascade
(NC, CC)

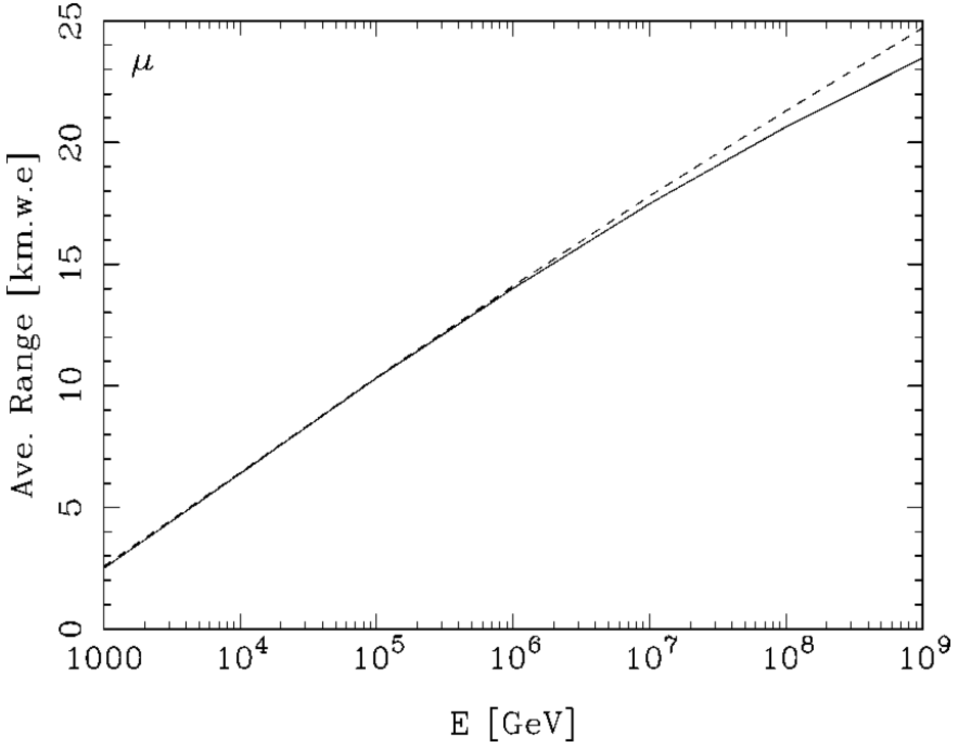


double bang
(taus)

Size of spheres: energy, colors: timing – early red, late blue

Kowalski for IceCube, J Phys: Conf. Series 888 (2017) 012007

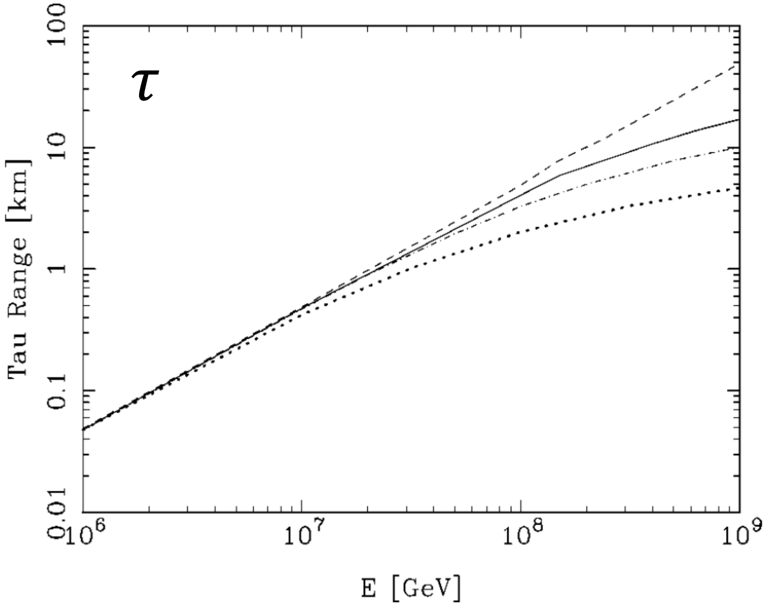
Muon range helps detector effective volume



Dutta, MHR,...et al, PRD 63 (2001) 094020

Average range of muons in rock. Energy > 1 GeV, accounting for electromagnetic energy loss.

decay length, water, rock, iron



Water vs ice for optical Cherenkov detection

Spiering, https://bib-pubdb1.desy.de/record/452265/files/Spiering2020_Chapter_NeutrinoDetectorsUnderWaterAnd.pdf

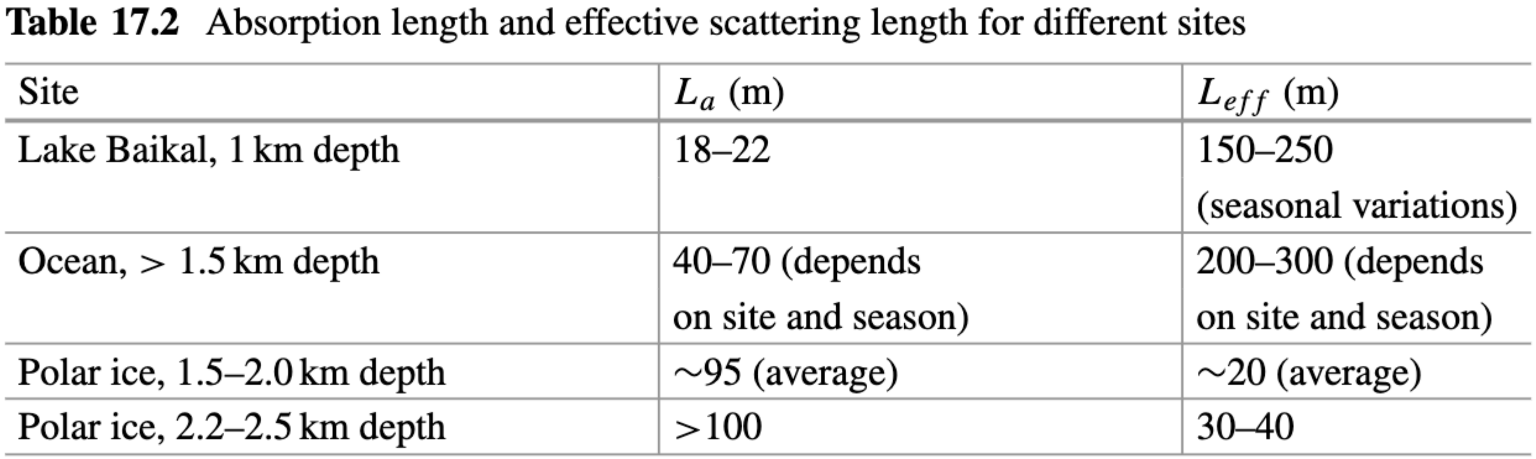


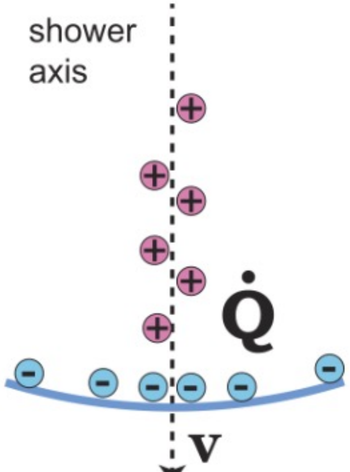
Table 17.2 Absorption length and effective scattering length for different sites

Site	L_a (m)	L_{eff} (m)
Lake Baikal, 1 km depth	18–22	150–250 (seasonal variations)
Ocean, > 1.5 km depth	40–70 (depends on site and season)	200–300 (depends on site and season)
Polar ice, 1.5–2.0 km depth	~95 (average)	~20 (average)
Polar ice, 2.2–2.5 km depth	>100	30–40

Angular resolution, better for water than ice because of less scattering, but shorter attenuation length means more detectors per unit volume.
Ice is better for VHE, UHE neutrinos because of the volume benefit.

Water: wet, bioluminesce.
Ice: cold, infrastructure.cold vs wet, bioluminesce vs ice bubbles

Fig from Paudel et al., PoS ICRC2021 (2021) 429



Radio Cherenkov – Askaryan effect

See review: Barwick & Glaser, arXiv:2208.04971

- Askaryan effect (JETP 14, 1962), in which interactions in material produce a 20% electron excess (time-varying).
- Showers produce electron-positron pairs and also scatter with atomic electrons to produce a radio-frequency impulse.
- The attenuation length at radio frequencies is of order 2 km in South Pole ice – can increase detection volume at low cost! (Scattering & absorption of optical light is ~100 m, optical sensitive to air bubbles in ice.)
- May be able to distinguish electron neutrinos and antineutrinos.

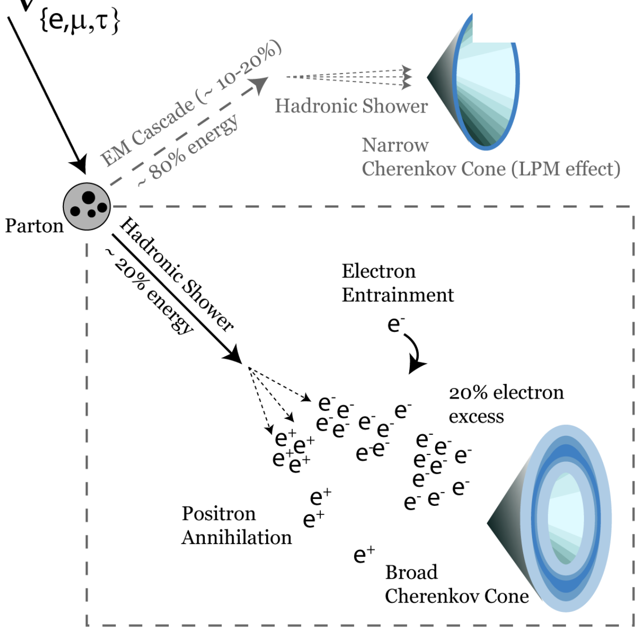


Figure from T. Jaeger, PhD thesis 2010

Radio signals – sample trajectories

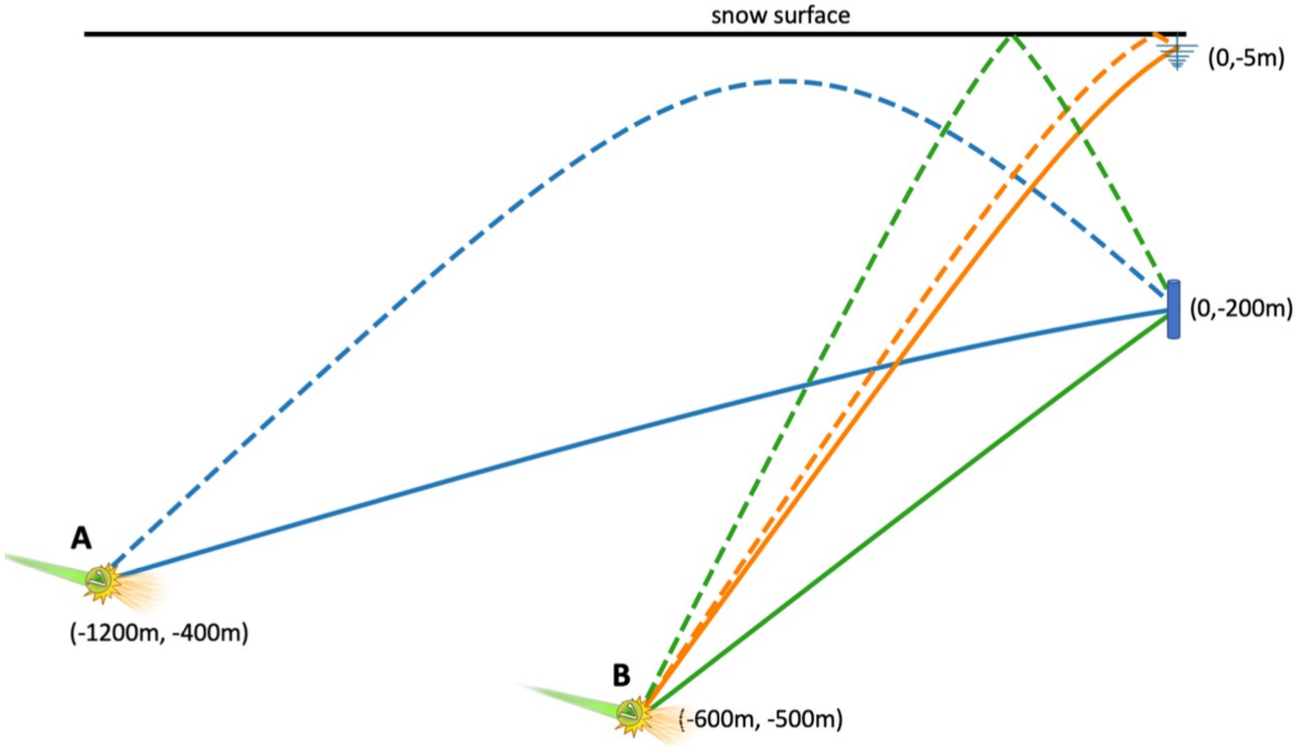
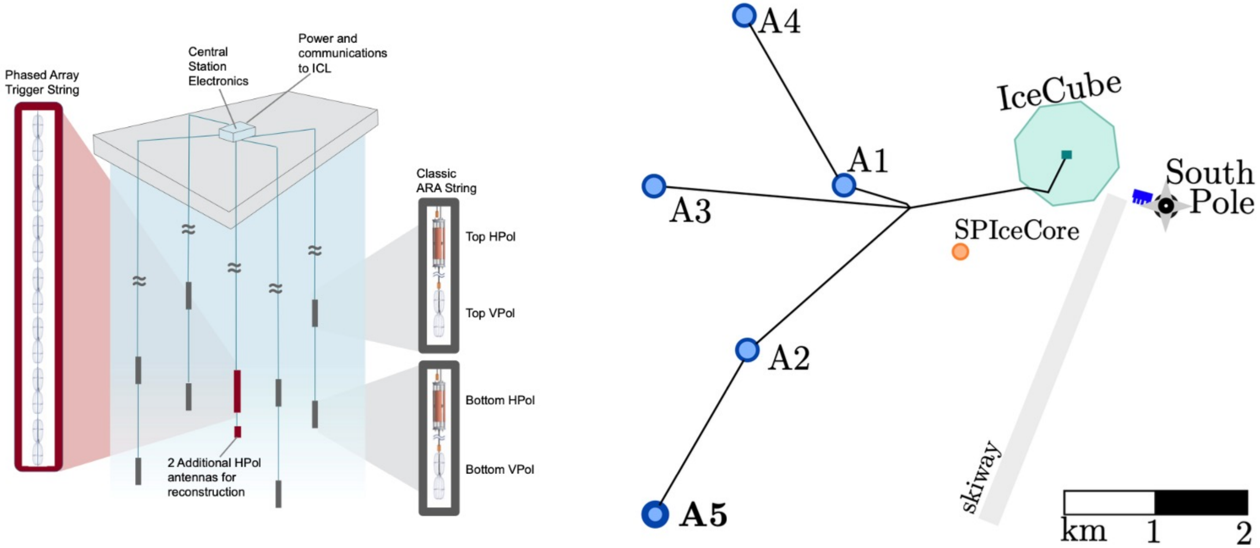


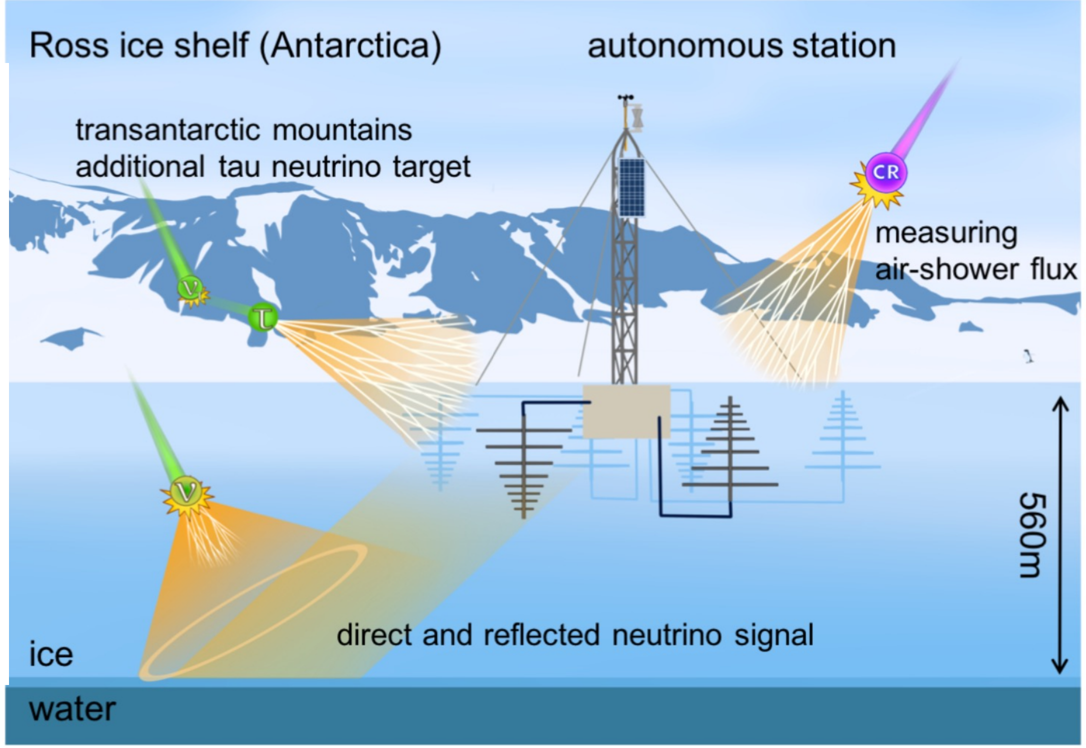
Figure from Barwick & Glaser, arXiv:2208.04971

- Cherenkov angle 56 deg in deep ice.
- Shower length is about 10 m.
- Transverse size about 10 cm.
- Sensitivity to 10^8 GeV to a few times 10^{10} GeV neutrinos, about a degree resolution.
- Amplitude of electric field is proportional to the shower energy.

Radio Cherenkov Detectors

ARA at South Pole





Developing understanding of in-ice radio detection techniques.

Fig. from Ackermann et al., JHEAp 36 (2022) 55

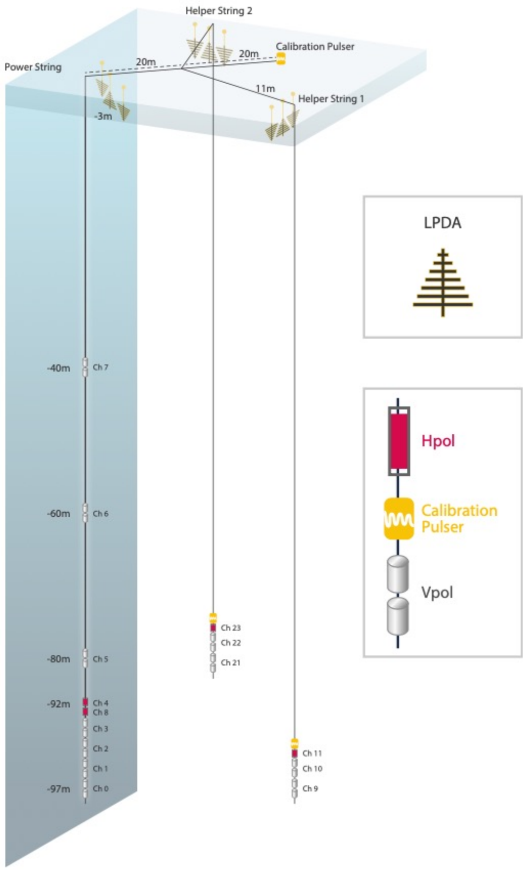
ARIANNA@ the Ross Ice Shelf in Antarctica

Radio Cherenkov Detectors

- RNO-G in Greenland ice, 1 km attenuation length, detector station separation1.5 km.
- Phased array of radio antennas.
- Testbed for IceCube-Gen2 Radio.

IceCube-Gen2 Radio will cover 500 km2 of South Pole ice.

Also, Askaryan from Moon!



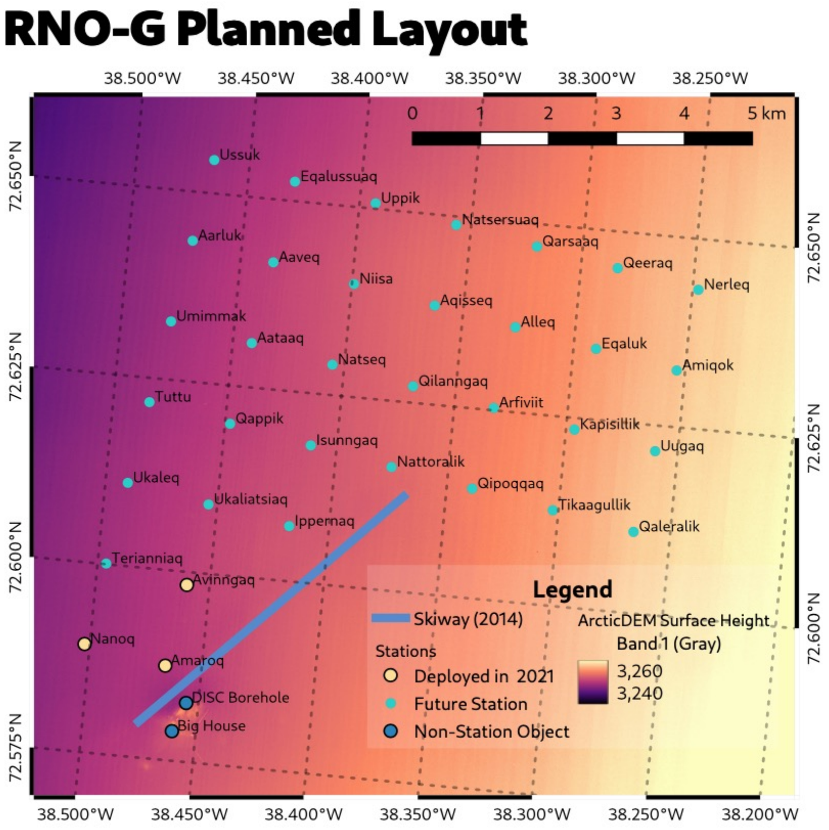


Fig. from Ackermann et al., JHEAp 36 (2022) 55

Optical Cherenkov in the atmosphere

Index of refraction of air $n_{air} \neq 1, \Delta n = 2.9\times 10^{-4}$ at sea level

Energy thresholds in air:
electron: 20.75 MeV
pion: 5.6 GeV
proton: 39 GeV
muon: 4.4 GeV
kaon: 20.5 GeV

Cherenkov angle: 1.4 deg

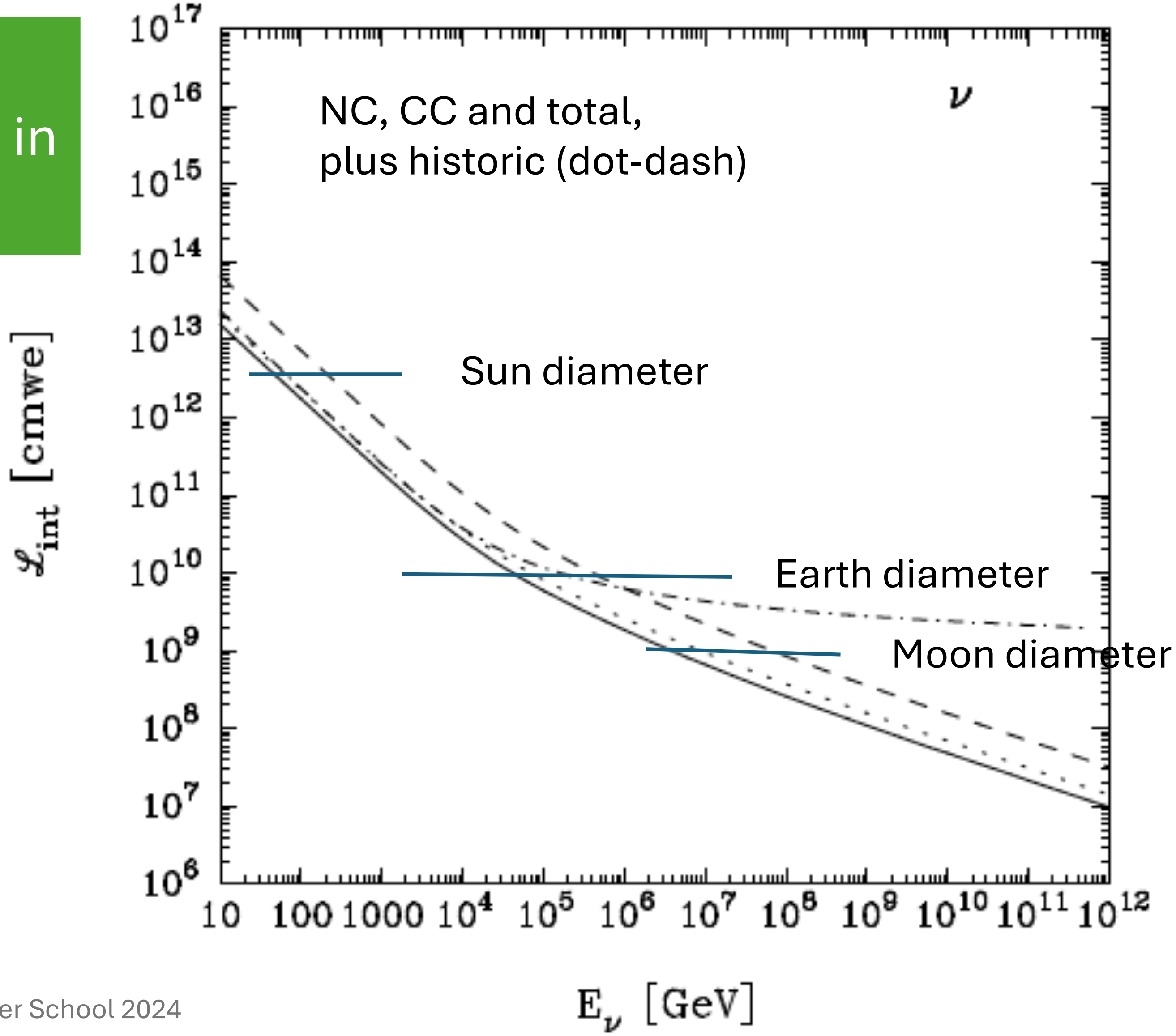
Index of refraction of air $n_{water} = 1.33$

Energy thresholds in water:
electron: 0.75 MeV
pion: 204 MeV
proton: 1.4 GeV
muon: 159 MeV
kaon: 746 MeV

Cherenkov angle: 41.4 deg

Neutrino interaction in atmosphere? interaction length

Neutrino interactions in air?

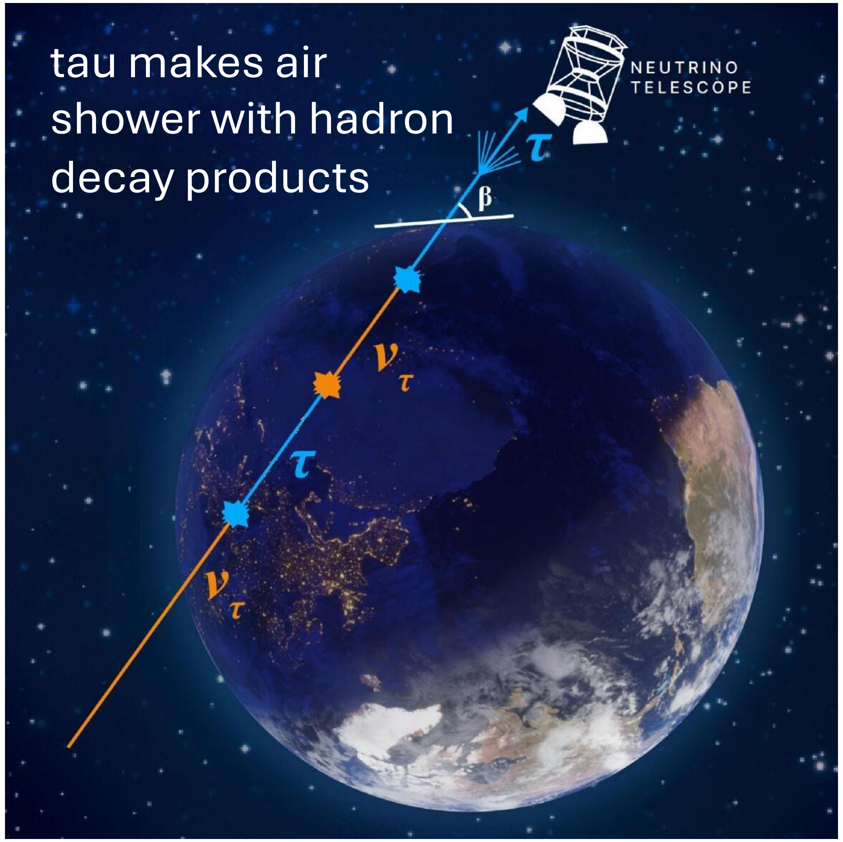

NC, CC and total,
plus historic (dot-dash)

Atmospheric column depth:

Vertical: 1,033 cmwe
Horizontal: 36,000 cmwe

Low probability of neutrino interactions in the atmosphere – optical Cherenkov techniques target Earth-skimming tau neutrinos.

Earth-skimming tau neutrinos for optical Cherenkov signals



Arguelles et al, PRD 106 (2022) 043008

- No signals of high energy tau neutrinos that go straight through the center of the Earth – attenuation of the flux.
- Earth-skimming neutrinos can yield signals from the tau decays (hadrons!).
- Earth-skimming tau neutrinos can yield signals in the atmosphere:

$$\nu_\tau N \rightarrow \tau X$$

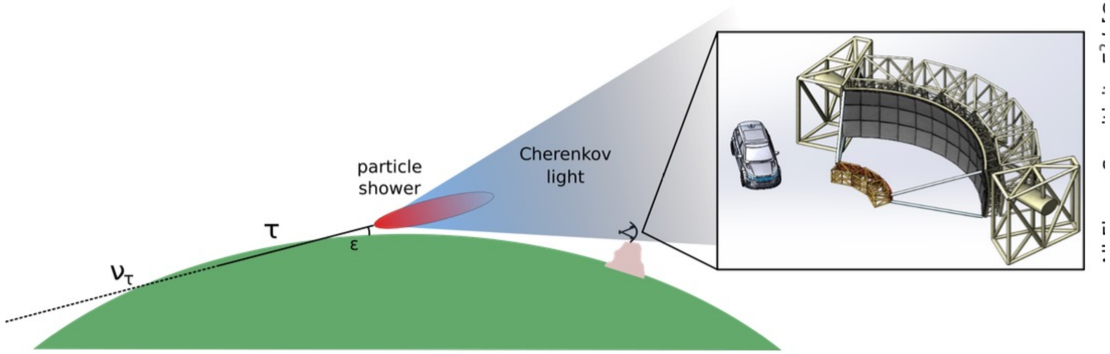
$$\tau \rightarrow \nu_\tau X$$

"tau neutrino regeneration" makes the Earth more transparent to tau neutrinos (but not transparent!)

Atmospheric optical Cherenkov detection

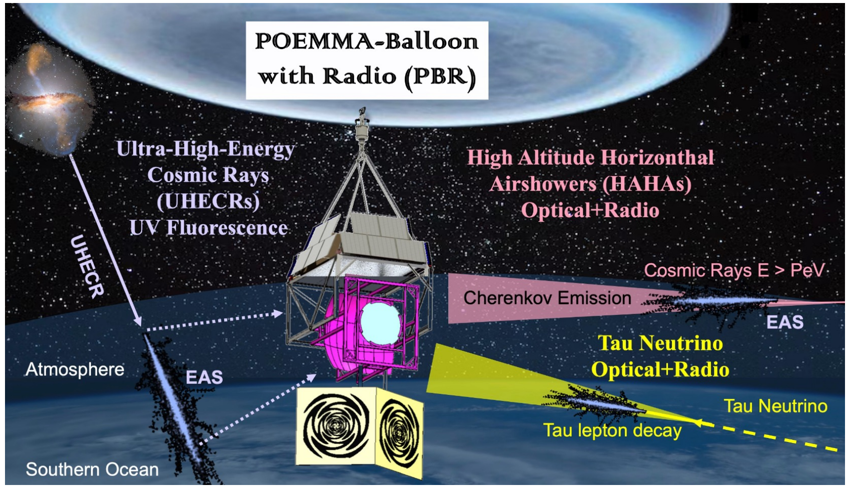
Fig. from Ackermann et al., JHEAp 36 (2022) 55

Trinity: on a mountain top

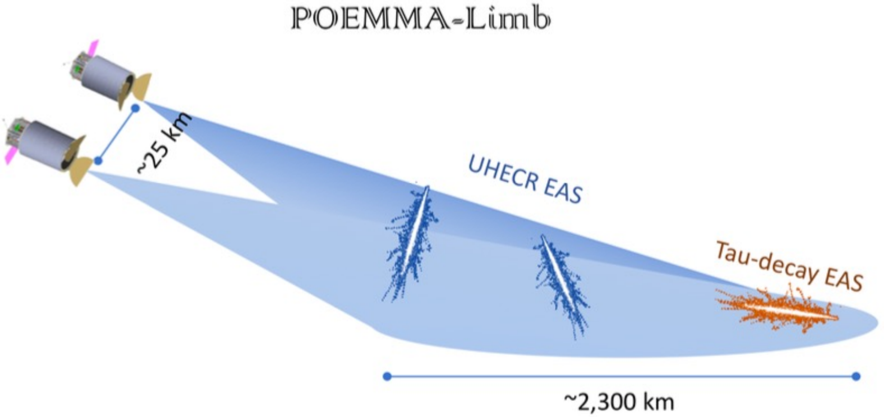


EUSO-SPB2

PBR

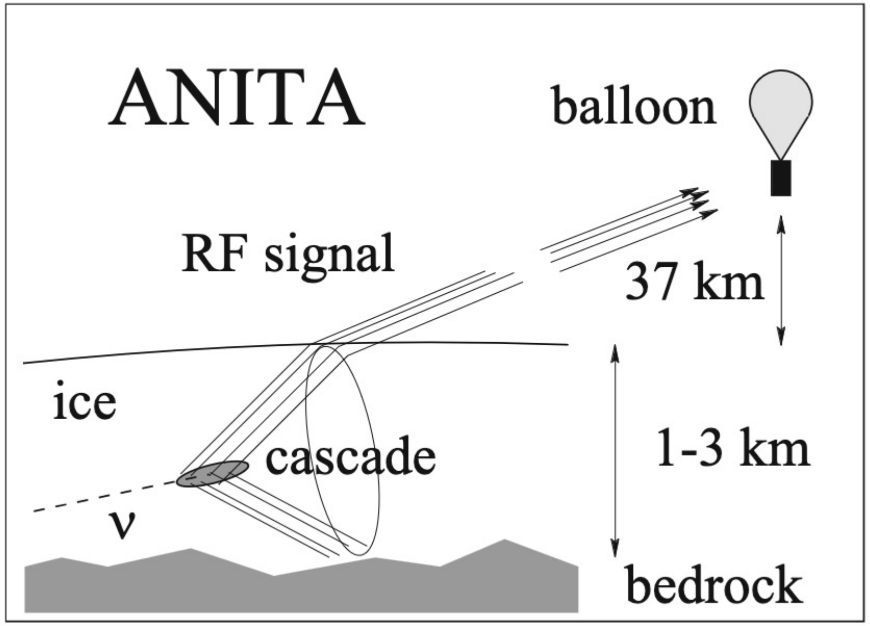


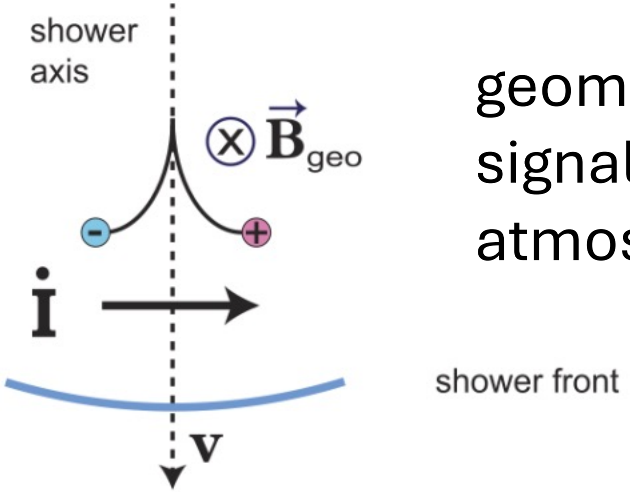
POEMMA: twin satellite (future?)



Atmospheric radio Cherenkov

refracted Askaryan, signal generated in ice





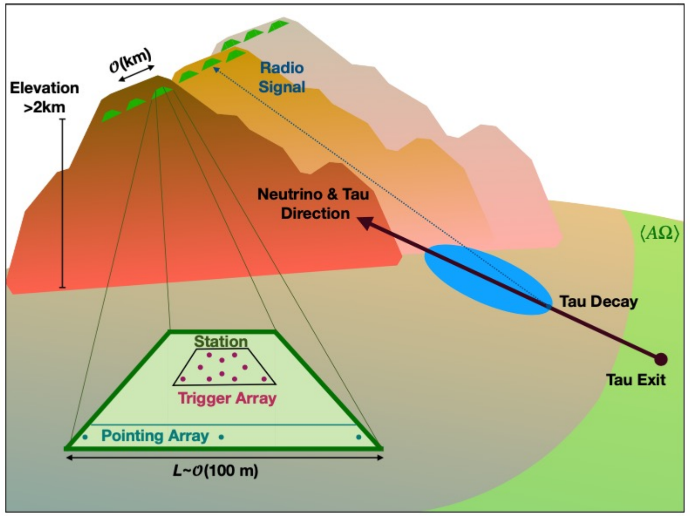
geomagnetic, signal generated in atmosphere

Paudel et al., PoS ICRC2021 (2021) 429
https://arxiv.org/pdf/2108.06336

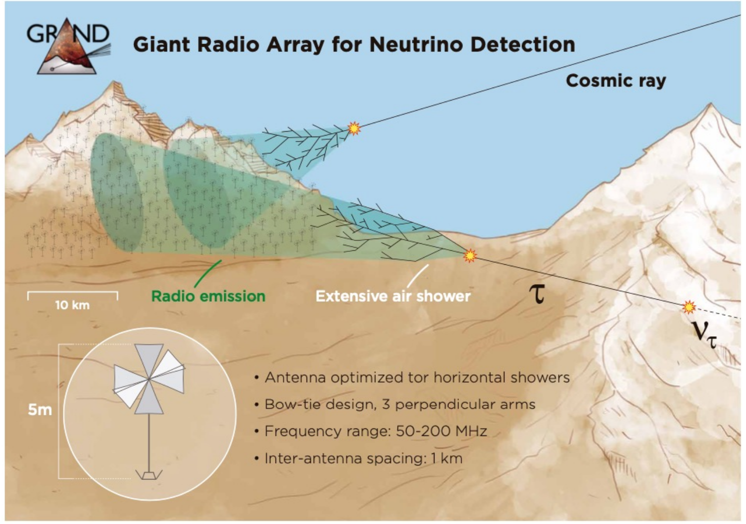
Spiering, https://bib-pubdb1.desy.de/record/452265/files/Spiering2020_Chapter_NeutrinoDetectorsUnderWaterAnd.pdf

Atmospheric radio Cherenkov detection

Beacon



GRAND



PUEO

Surface detectors

TAROGE, TAROGE-M

PUEO is successor to ANITA, balloon detectors

Fig. from Ackermann et al., JHEAp 36 (2022) 55

Particle detectors

Pierre Auger Observatory uses showers, fluorescence. AugerPrime adds radio.

TAMBO (future?)

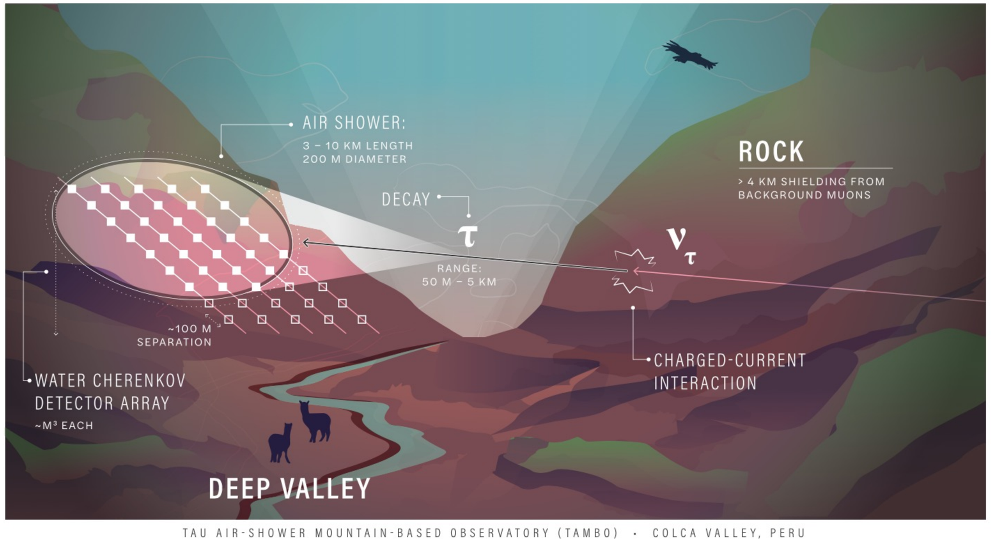


Fig. from Ackermann et al., JHEAp 36 (2022) 55

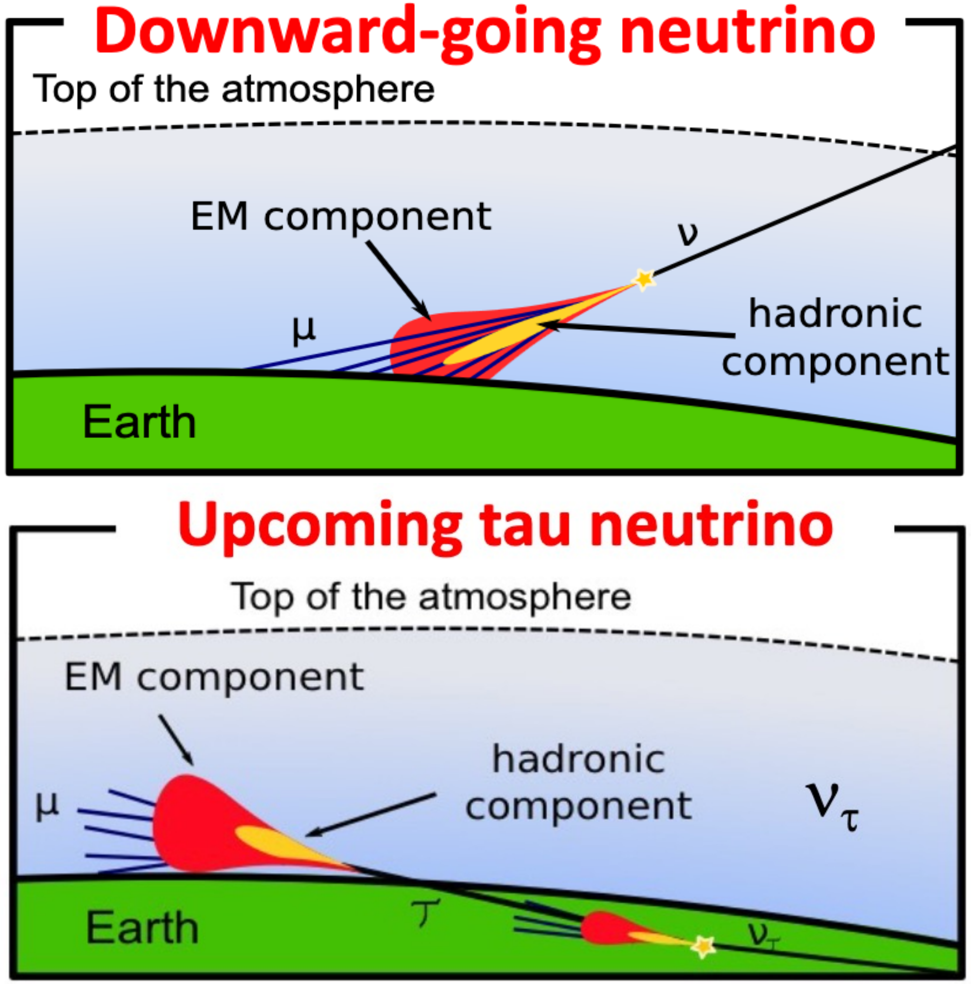
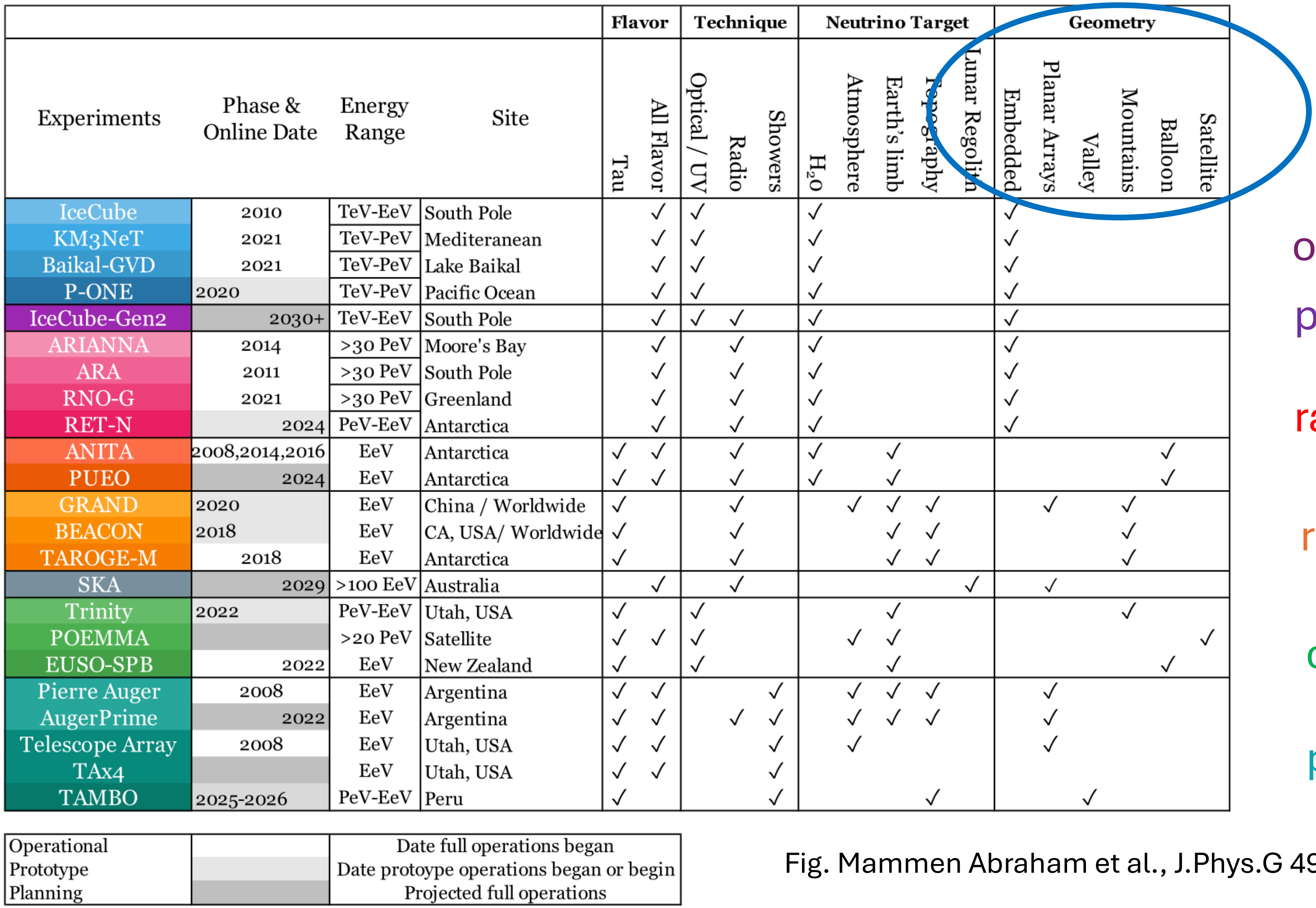


Fig from Jaime Alvarez-Muñiz

Summary



				Flavor		Technique			Neutrino Target					Geometry					
Experiments	Phase & Online Date	Energy Range	Site	Tau	All Flavor	Optical / UV	Radio	Showers	H_2O	Atmosphere	Earth's limb	Topography	Lunar Regolith	Embedded	Planar Arrays	Valley	Mountains	Balloon	Satellite
IceCube	2010	TeV-EeV	South Pole		✓	✓			✓					✓					
KM3NeT	2021	TeV-PeV	Mediteranean		✓	✓			✓					✓					
Baikal-GVD	2021	TeV-PeV	Lake Baikal		✓	✓			✓					✓					
P-ONE	2020	TeV-PeV	Pacific Ocean		✓	✓			✓					✓					
IceCube-Gen2	2030+	TeV-EeV	South Pole		✓	✓	✓		✓					✓					
ARIANNA	2014	>30 PeV	Moore's Bay		✓		✓		✓					✓					
ARA	2011	>30 PeV	South Pole		✓		✓		✓					✓					
RNO-G	2021	>30 PeV	Greenland		✓		✓		✓					✓					
RET-N	2024	PeV-EeV	Antarctica		✓		✓		✓					✓					
ANITA	2008,2014,2016	EeV	Antarctica	✓	✓		✓		✓		✓							✓	
PUEO	2024	EeV	Antarctica	✓	✓		✓		✓		✓							✓	
GRAND	2020	EeV	China / Worldwide	✓			✓			✓	✓	✓			✓		✓		
BEACON	2018	EeV	CA, USA/ Worldwide	✓			✓				✓	✓					✓		
TAROGE-M	2018	EeV	Antarctica	✓			✓				✓	✓					✓		
SKA	2029	>100 EeV	Australia		✓		✓						✓		✓				
Trinity	2022	PeV-EeV	Utah, USA	✓		✓					✓						✓		
POEMMA		>20 PeV	Satellite	✓	✓	✓				✓	✓								✓
EUSO-SPB	2022	EeV	New Zealand	✓		✓					✓							✓	
Pierre Auger	2008	EeV	Argentina	✓	✓			✓		✓	✓	✓			✓				
AugerPrime	2022	EeV	Argentina	✓	✓		✓	✓		✓	✓	✓			✓				
Telescope Array	2008	EeV	Utah, USA	✓	✓			✓		✓					✓				
TAx4		EeV	Utah, USA	✓	✓			✓											
TAMBO	2025-2026	PeV-EeV	Peru	✓				✓				✓				✓			

Operational		Date full operations began
Prototype		Date protoype operations began or begin
Planning		Projected full operations

optical Cherenkov

plus radio

radio Cherenkov

radio Cherenkov

optical Cherenkov

particles/showers

Fig. Mammen Abraham et al., J.Phys.G 49 (2022) 110501

The Earth as a neutrino converter

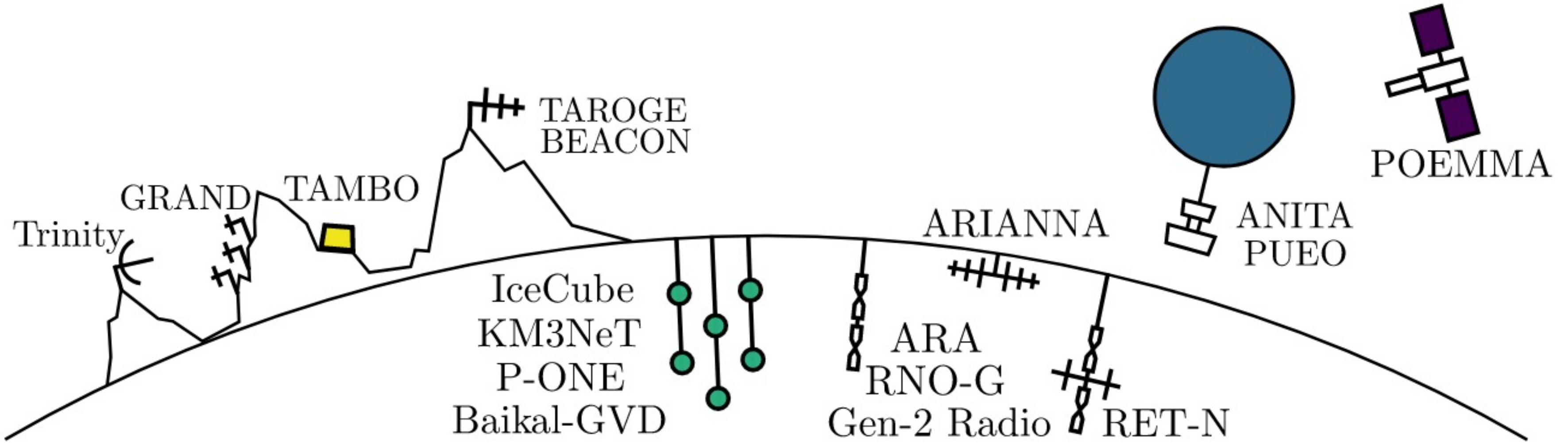


FIG. 2. Proposed strategies to detect UHE neutrinos. *The variety guarantees complementary physics opportunities.*

Fig. from Esteban et al., PRD 106 (2022) 023021

Homework

To the first approximation, at small x, the gluon PDF scales as $xg(x, Q^2) \sim x^{-\lambda(Q^2)}$ and the sea quark PDFs are proportional to the gluon PDF.
Make a back of the envelope argument that the neutrino-nucleon cross section scales with energy to a power: $\sigma_{\nu N} \sim E^{\alpha}$ and relate α to λ.

From slide 15, can you estimate λ and find an approximate α?