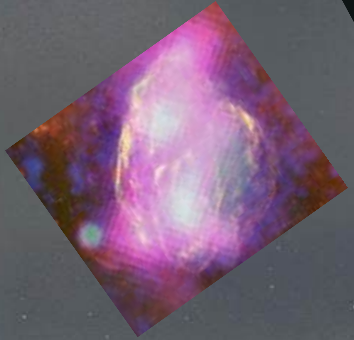
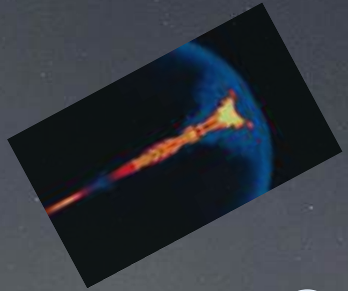
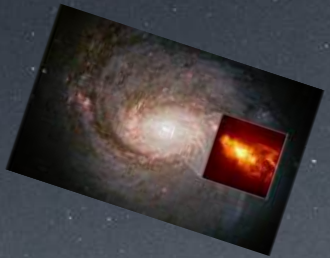
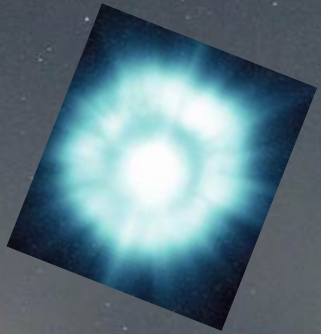
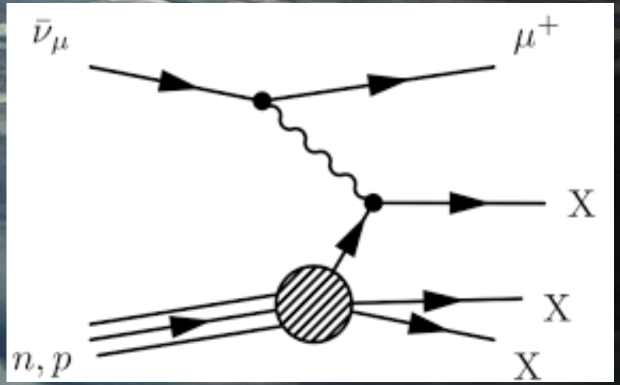



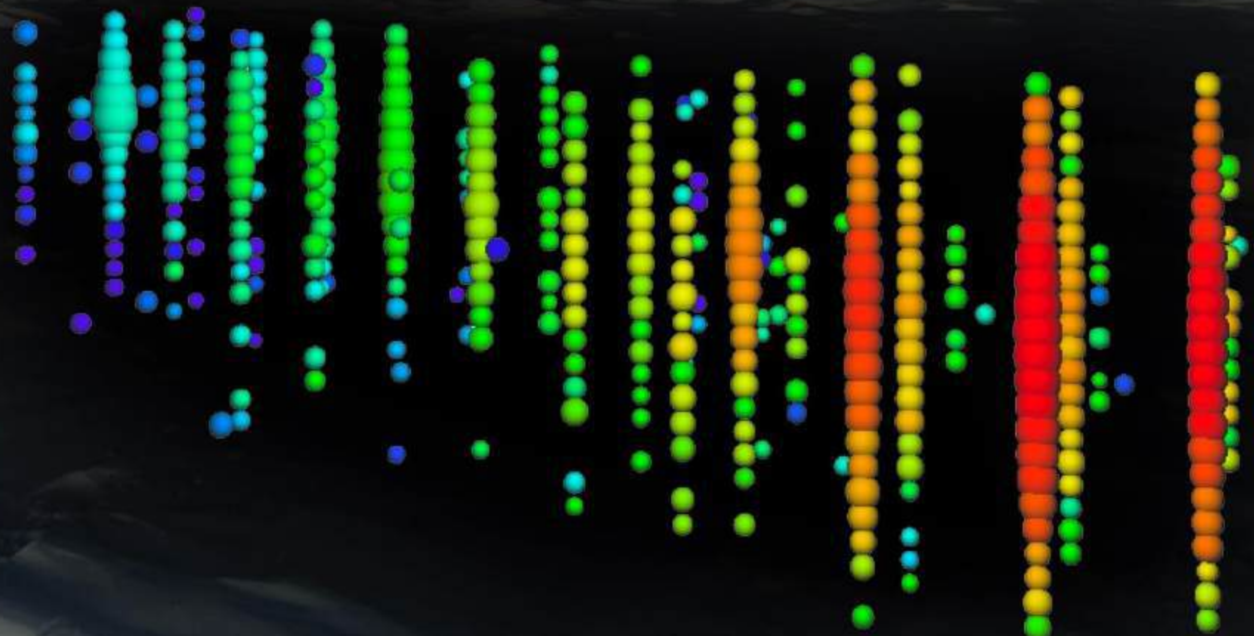



Seeing the high energy universe with νs II

Subir Sarkar





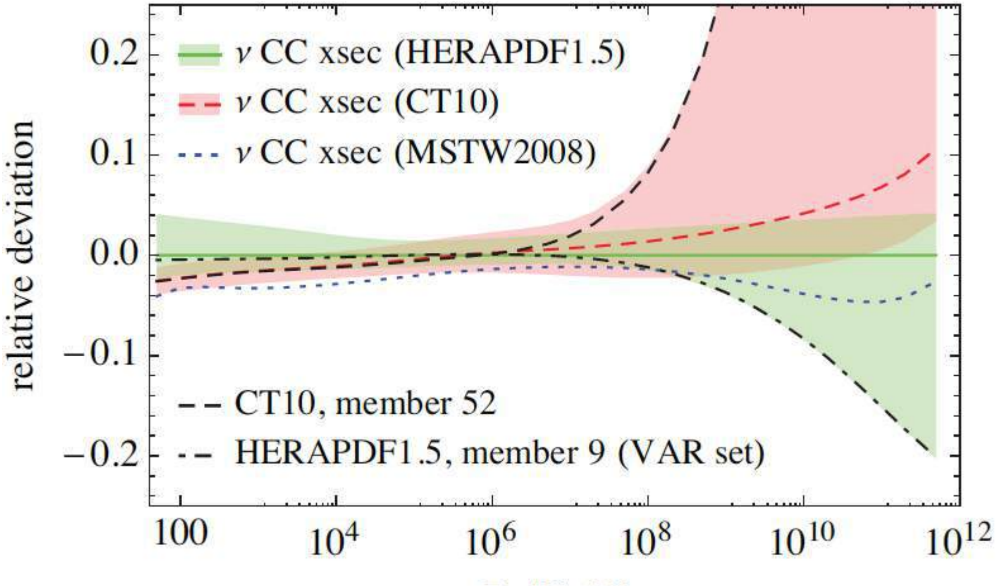
$$\frac{\partial^2\sigma^{CC,NC}_{\nu,\bar\nu}}{\partial x\,\partial y} = \frac{G_F^2 ME}{\pi}\left(\frac{M_i^2}{Q^2+M_i^2}\right)$$

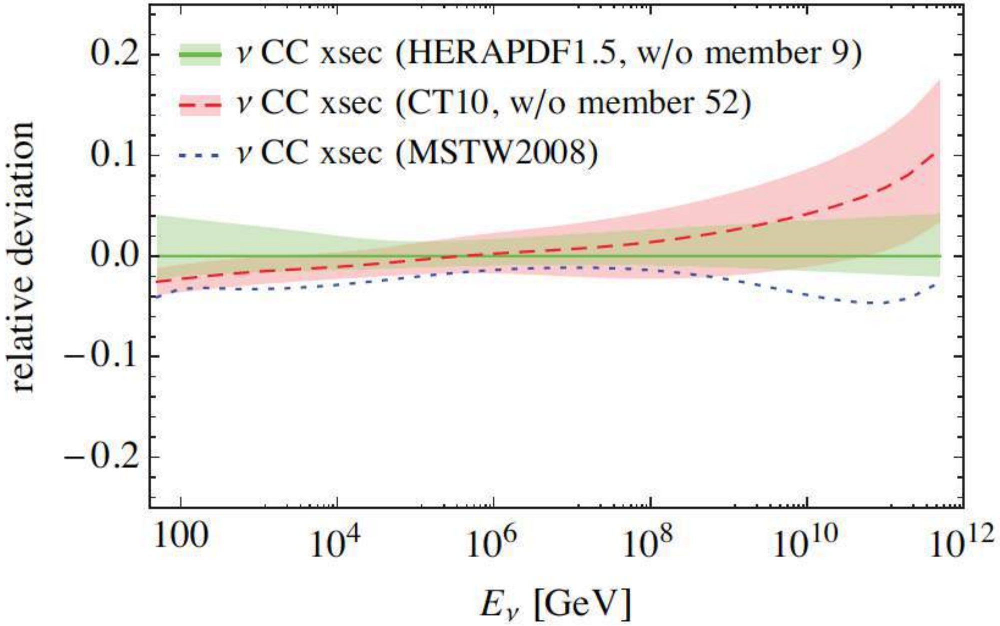
$$\left[\frac{1+(1-y)^2}{2}F_2^{CC,NC}(x,Q^2) - \frac{y^2}{2}F_L^{CC,NC}(x,Q^2)\right.$$

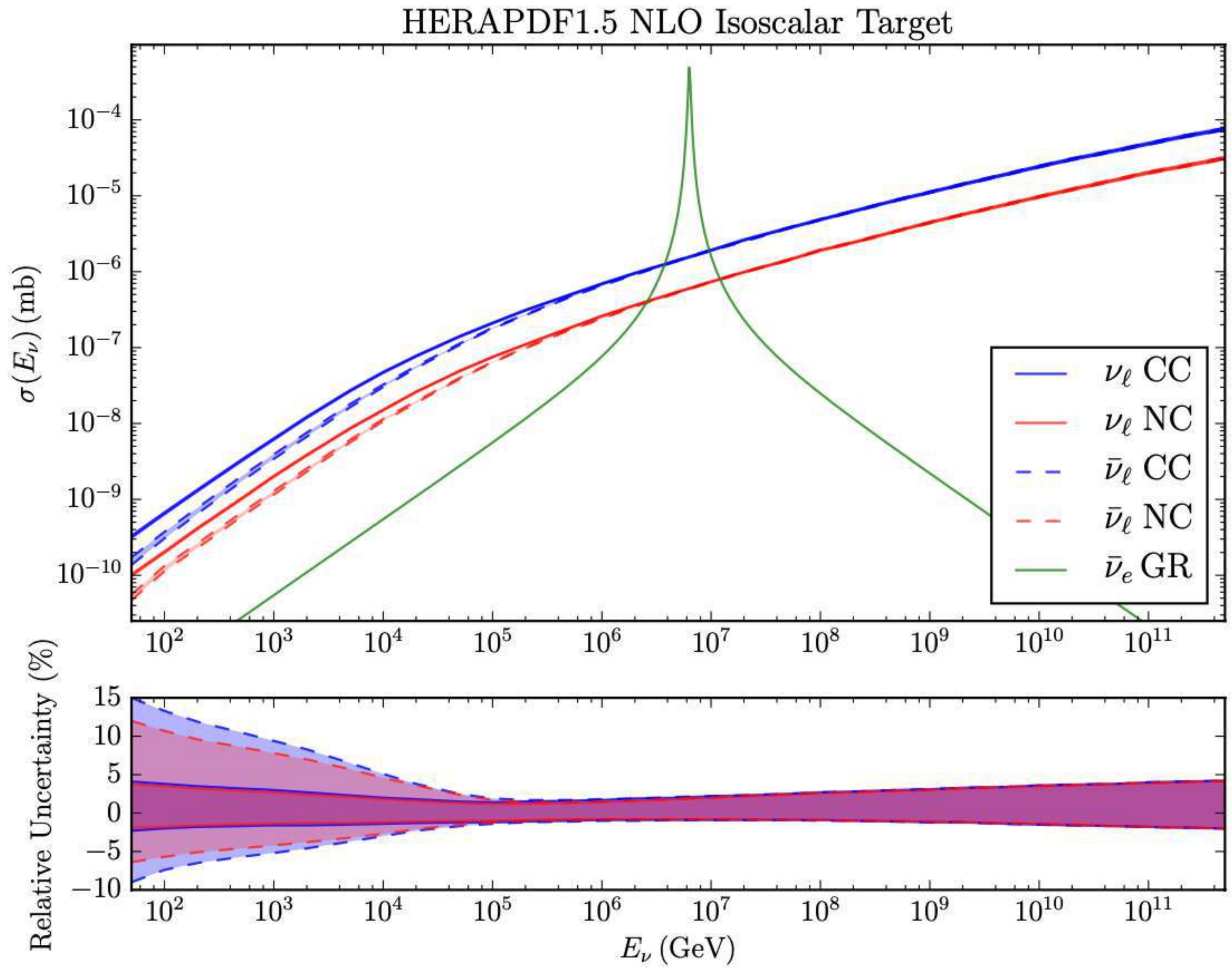
$$\left.\pm y\left(1-\frac{y}{2}\right)xF_3^{CC,NC}(x,Q^2)\right]$$

IITB-CFNS-CTEQ School, Mumbai, 9-15 February 2026

After the full HERA data release, we updated the *ν-N* cross-section @ NLO using HERAPDF1.5, including the effect of heavy quarks on the DGLAP evolution … Code available on: https://dispred.hepforge.org/





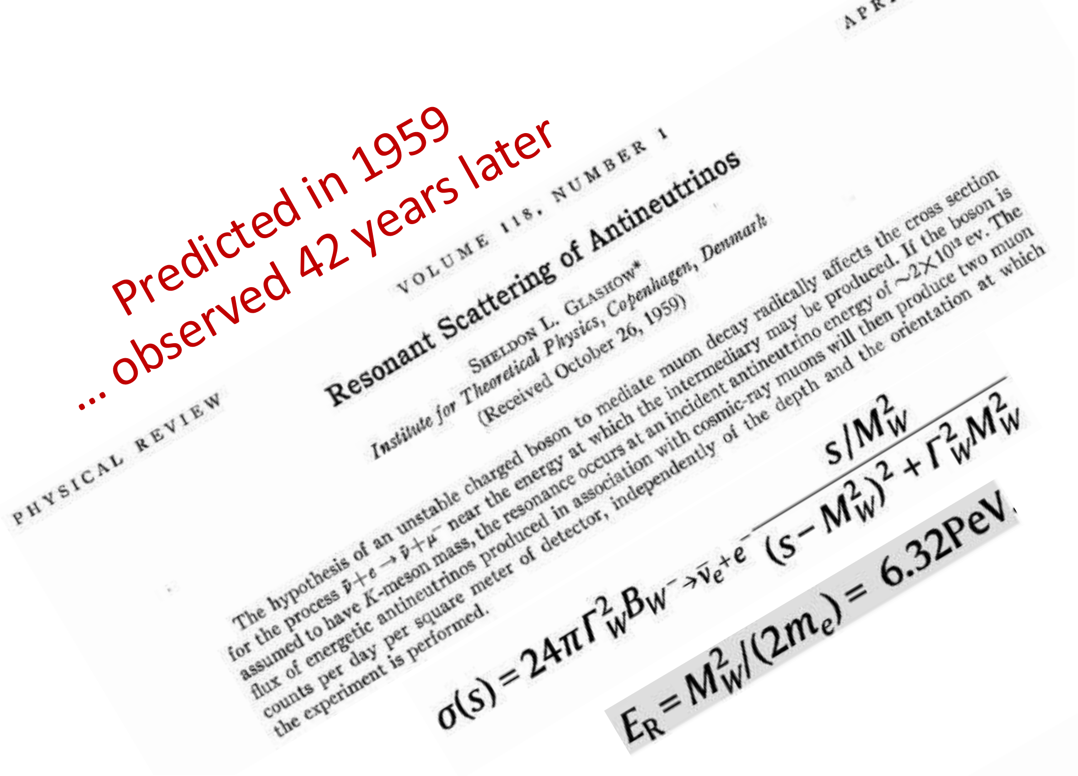


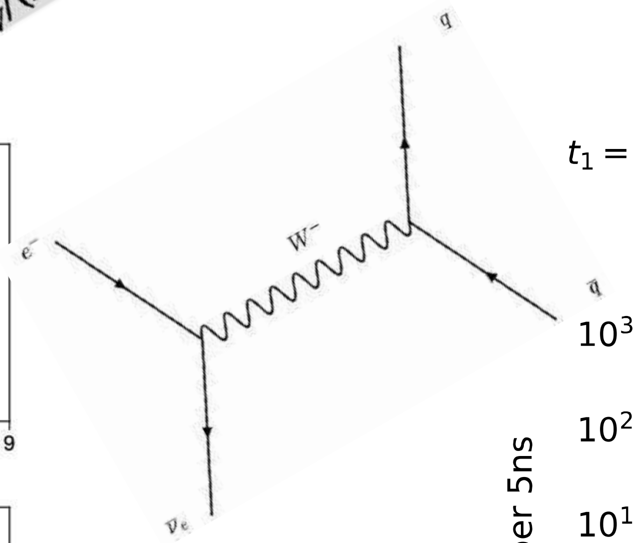
We find *good* agreement between different PDF sets after rejecting unphysical members which would have yielded *negative* values for the structure function F_L (or violated the Froissart bound)

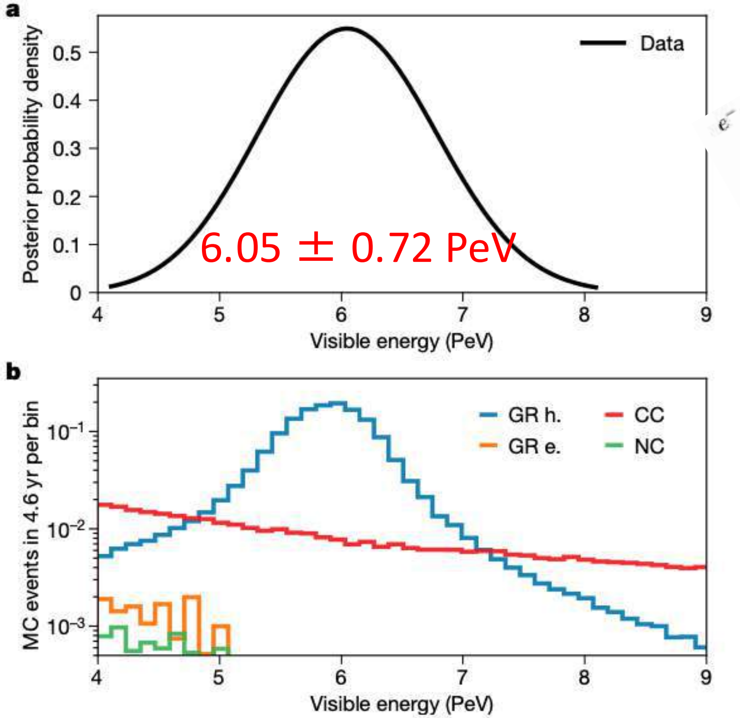
Mertsch, Cooper-Sarkar, Sarkar, JHEP **08**:042,2011 ⇒ **CSMS** 2011

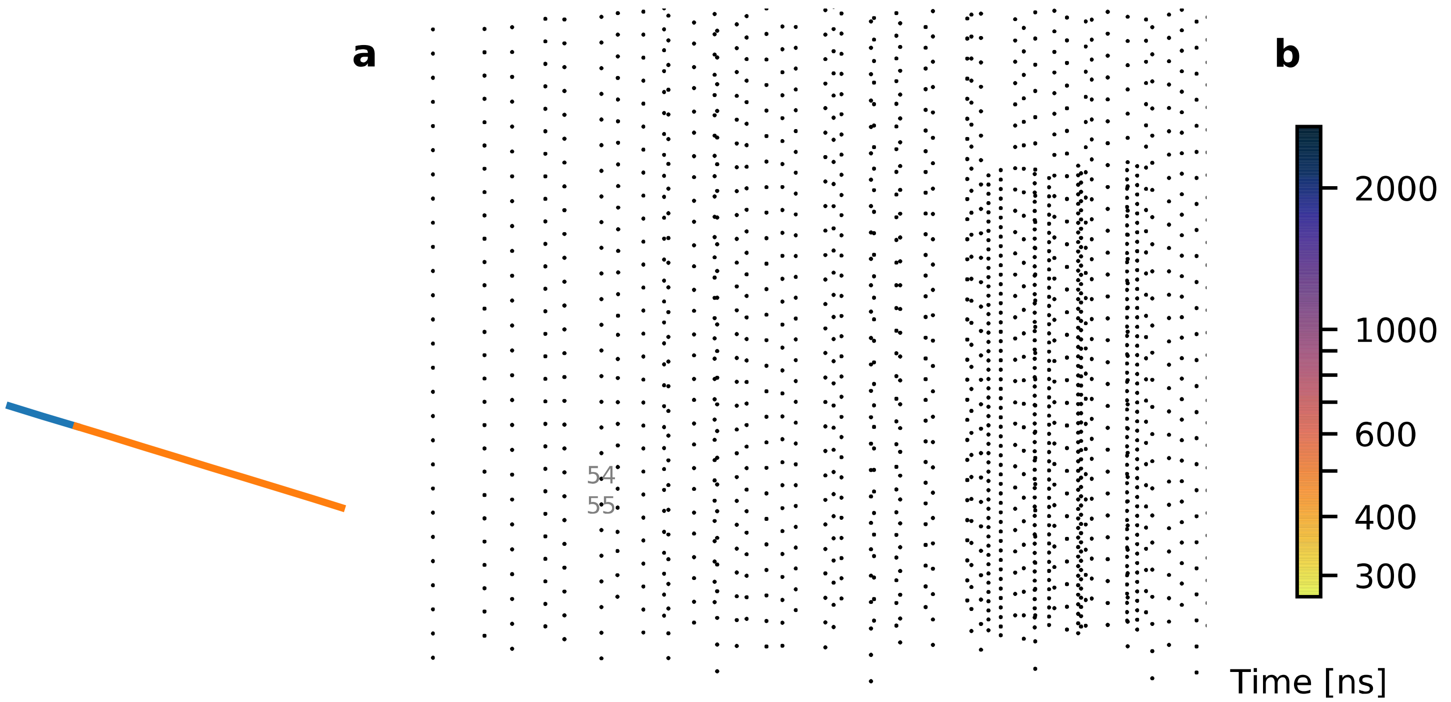
Nature | Vol 591 | 11 March 2021

Detection of a particle shower at the Glashow resonance with IceCube



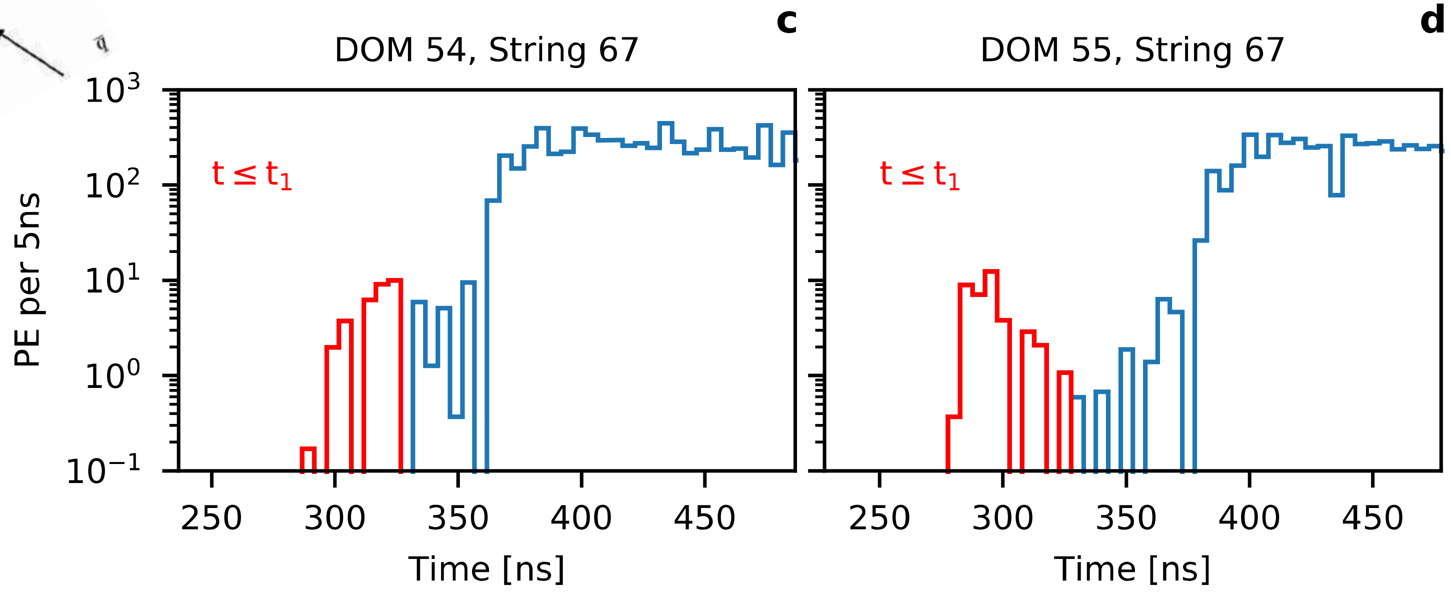




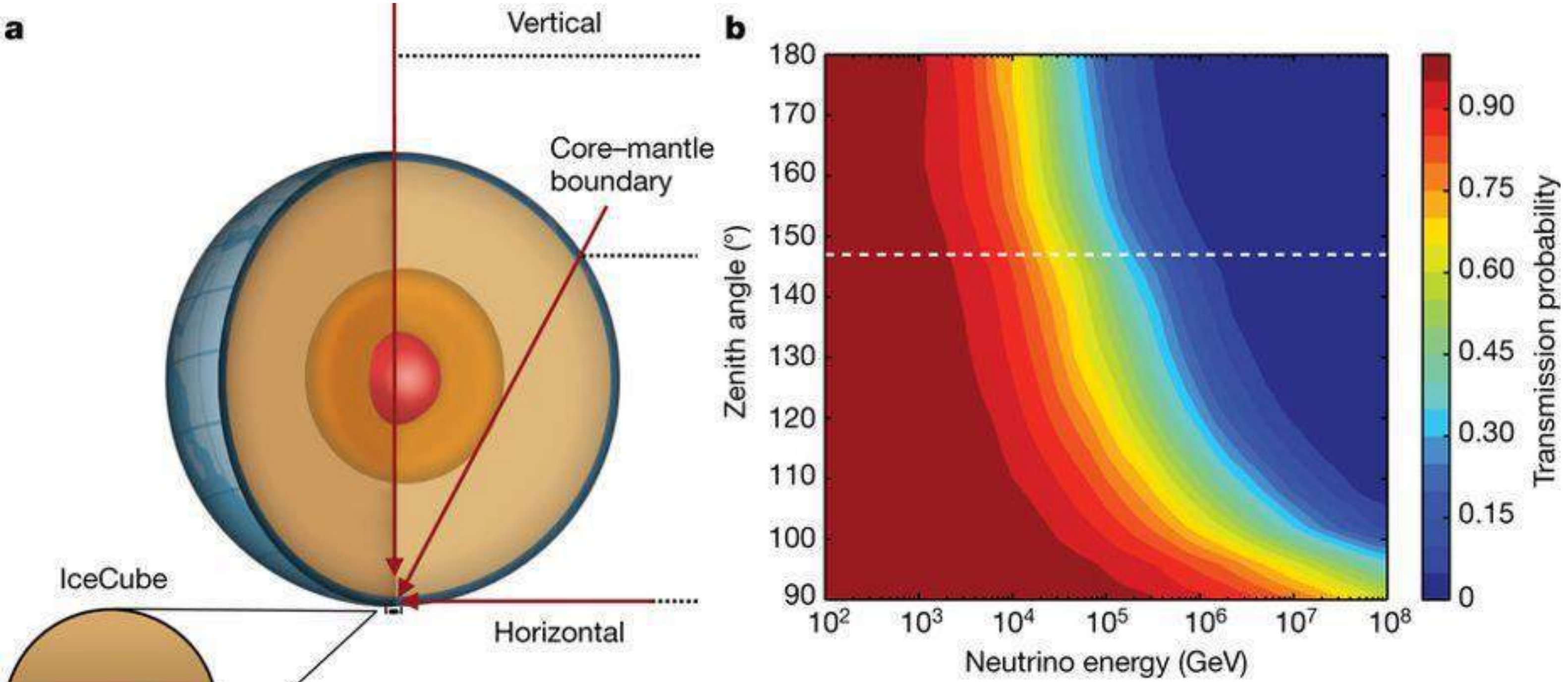


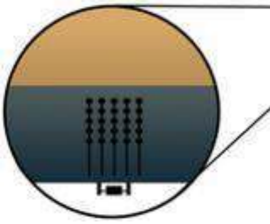
$t_1 = 328\,\mathrm{ns}$

3ms after t_1



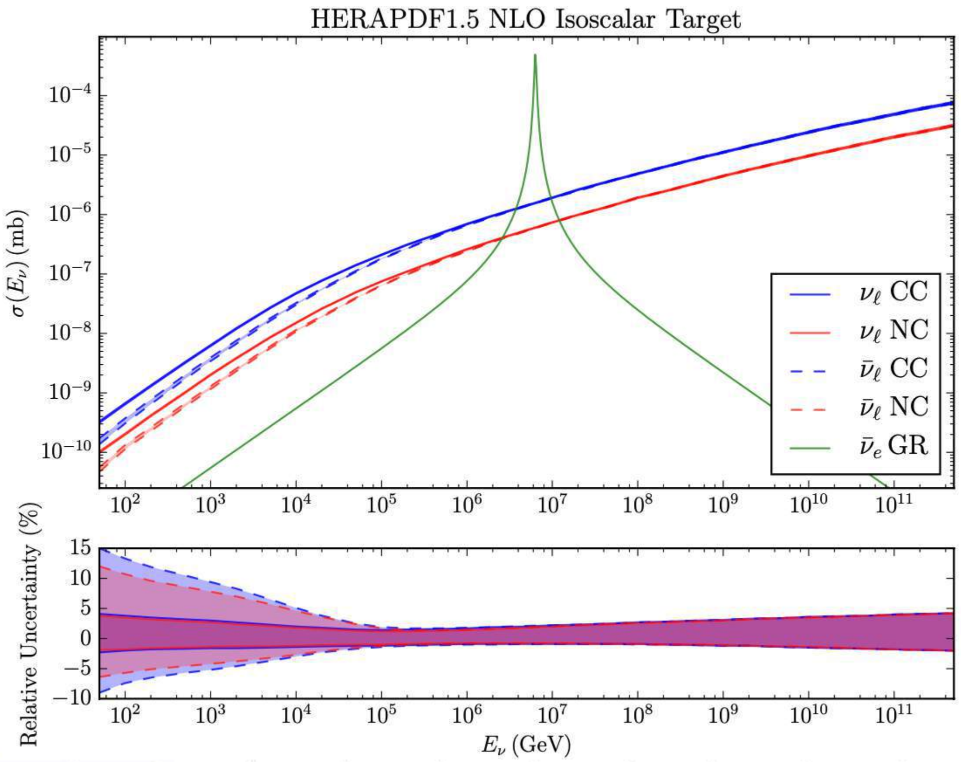
the predicted UHE ν-*N* cross-section can be checked by studying ν absorption in the Earth

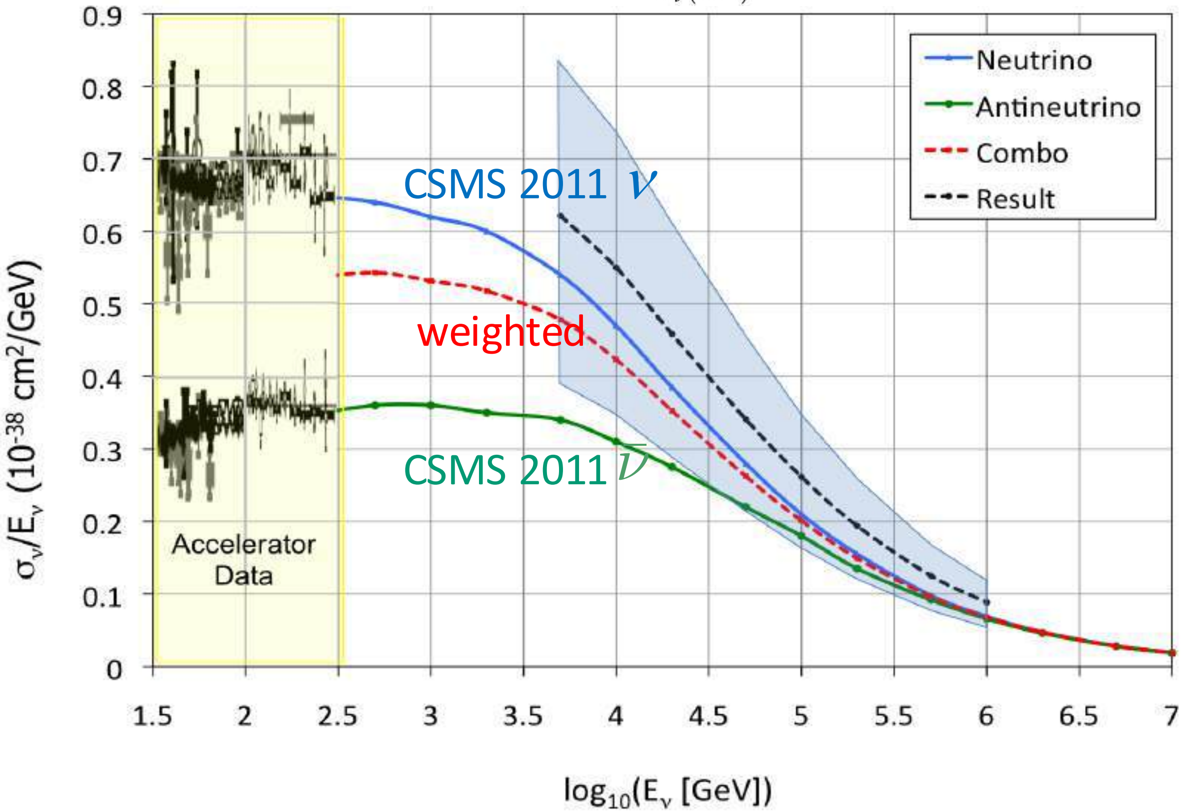




Preliminary Reference Earth Model (PREM)

Earth diameter = interaction length at $E_\nu \sim$ 40 TeV





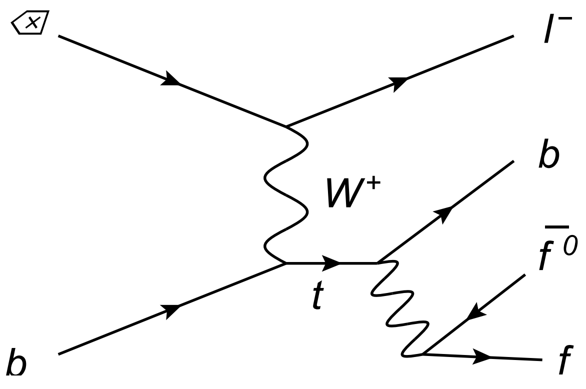
Can *invert* the argument to perform tomography of the Earth (Donnini *et al, Nature Phys.* **15**:37,2019)!

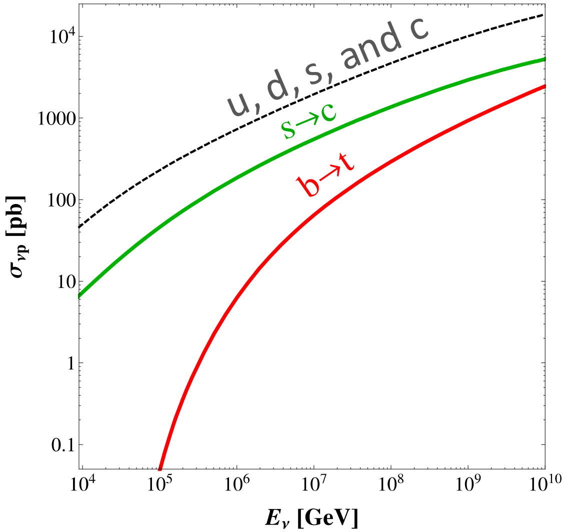
Cooper-Sarkar, Mertsch, SS (CSMS), JHEP **08**:042,2011

IceCube Collaboration, Nature **551**:596,2017

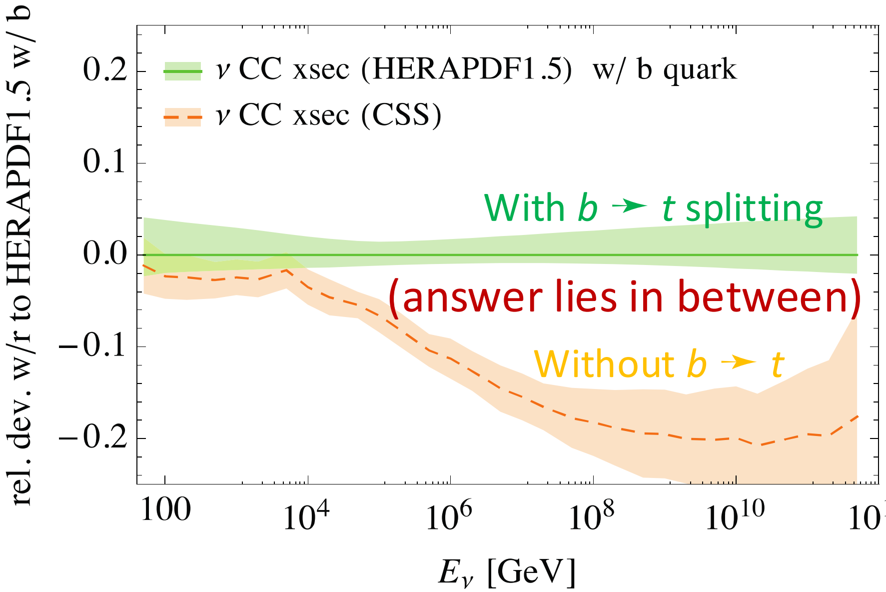
As experimental precision improves, further effects need to be considered

* Heavy quark effects on DGLAP evolution:





Barger *et al*, *PRD* **95**:093002,2017

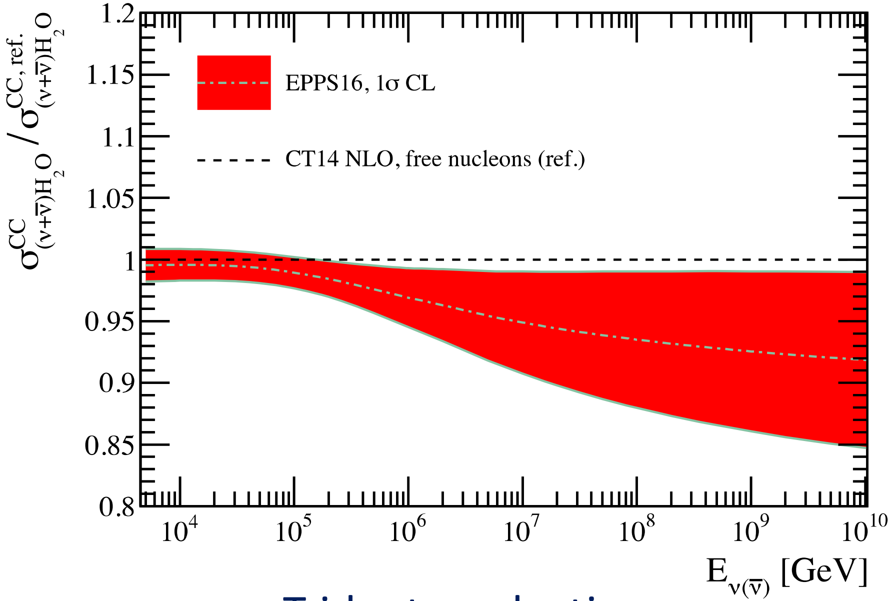


CSMS, *JHEP* **08**:042,2011

The exact way the *b* ➛ *t* contribution turns on ⇒ ~10% syst. uncertainty

* Nuclear binding effects:

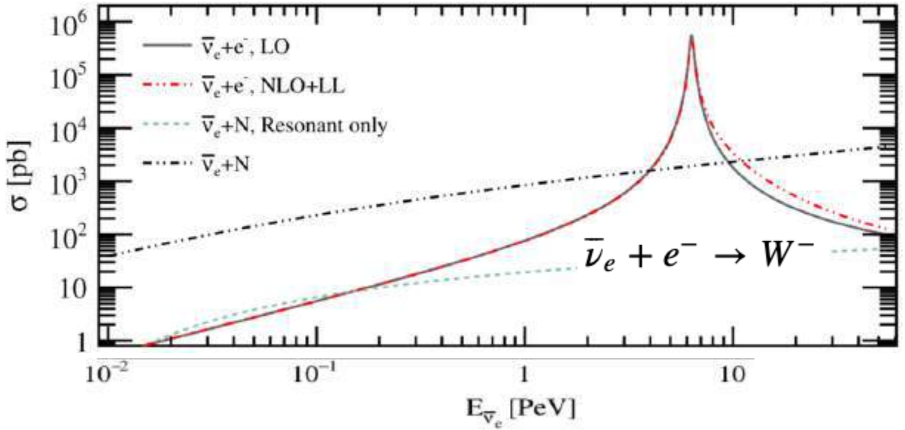
There is *no* experimental evidence for ‘shadowing’ but theoretical arguments suggest it may depress the cross-section by 5-10% at UHE



Bertone *et al*, *JHEP* **01**:217,2019

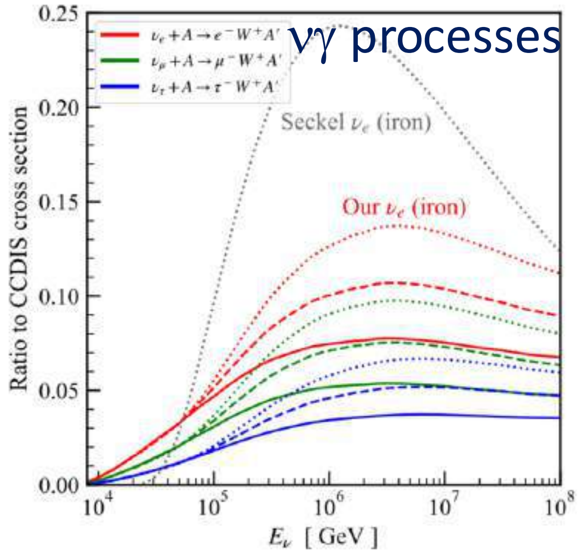
* Other contributions:

Glashow resonance @ 6.3 PeV



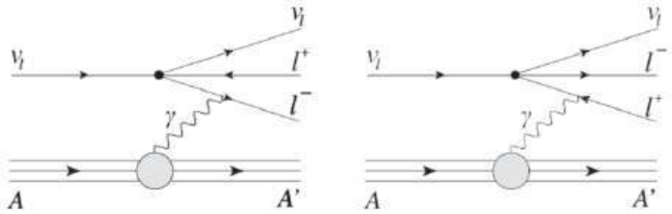
Gauld, *PRD* **100**:091301,2019

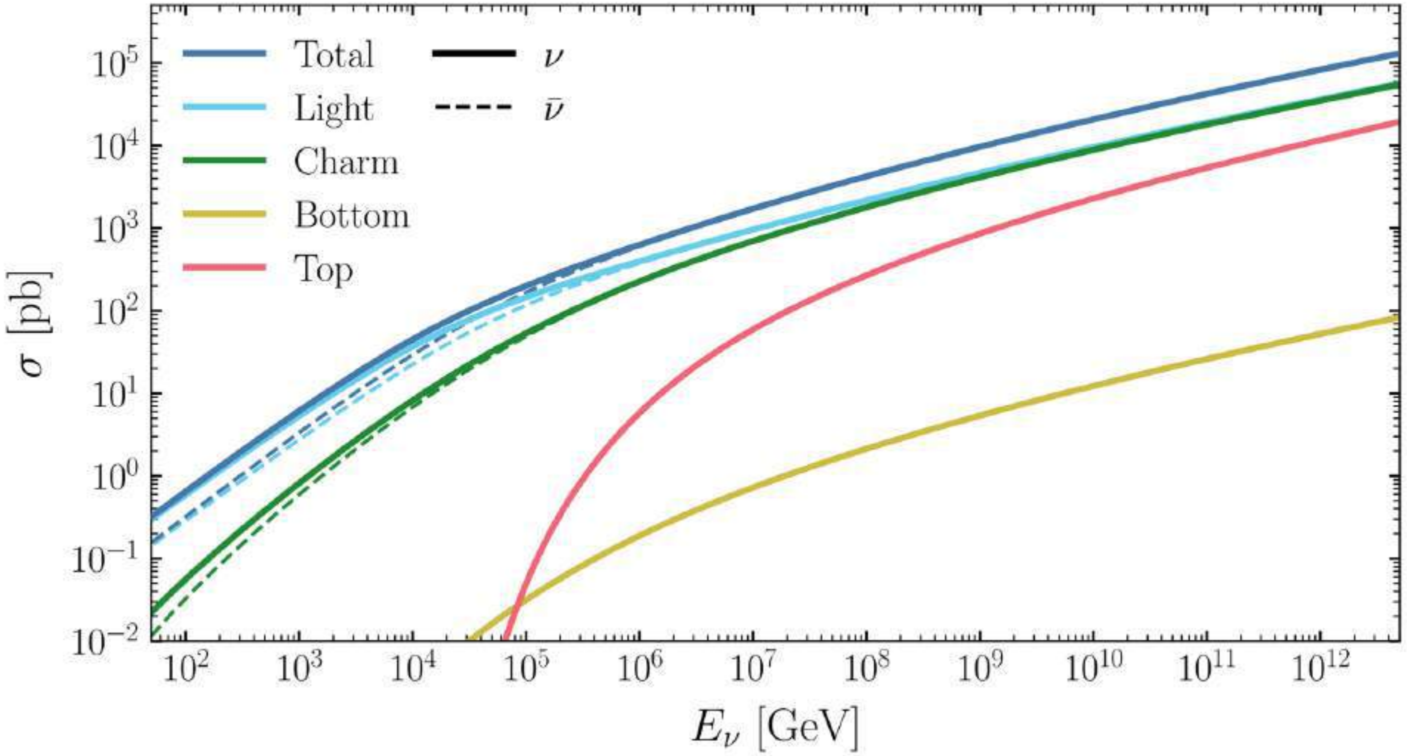
νγ processes



Zhou & Beacom, *PRD* **101**:036001,2019

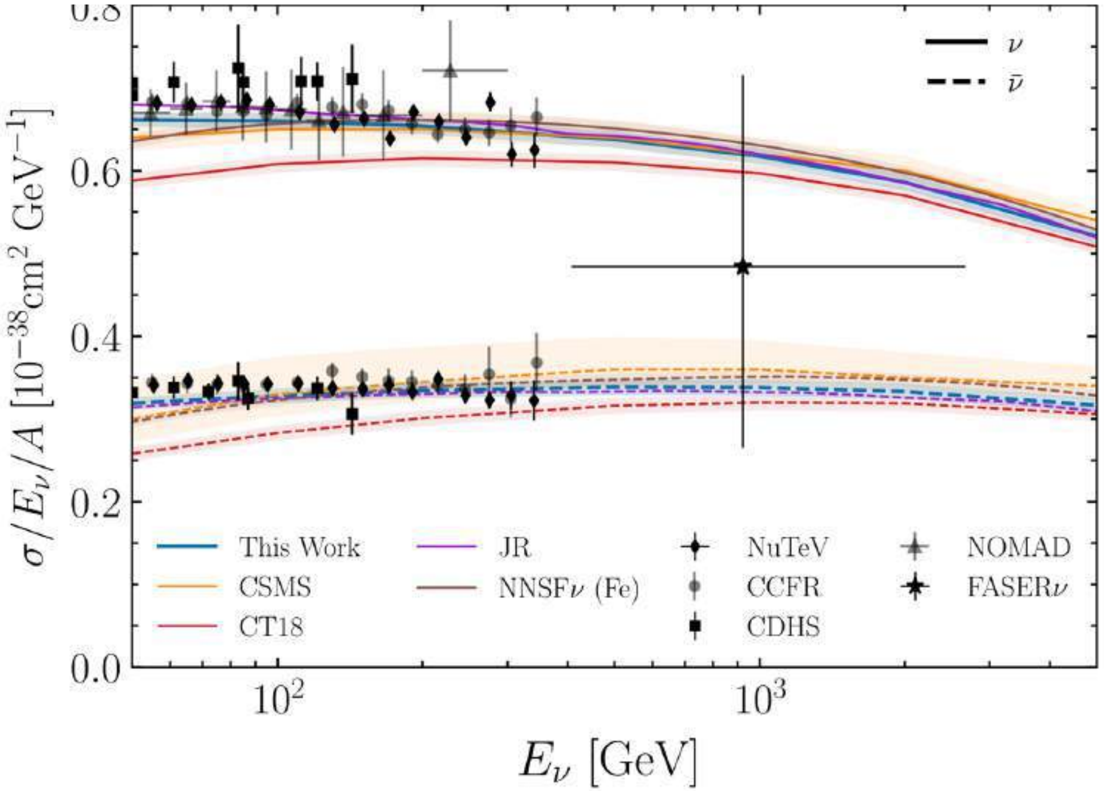
Trident production

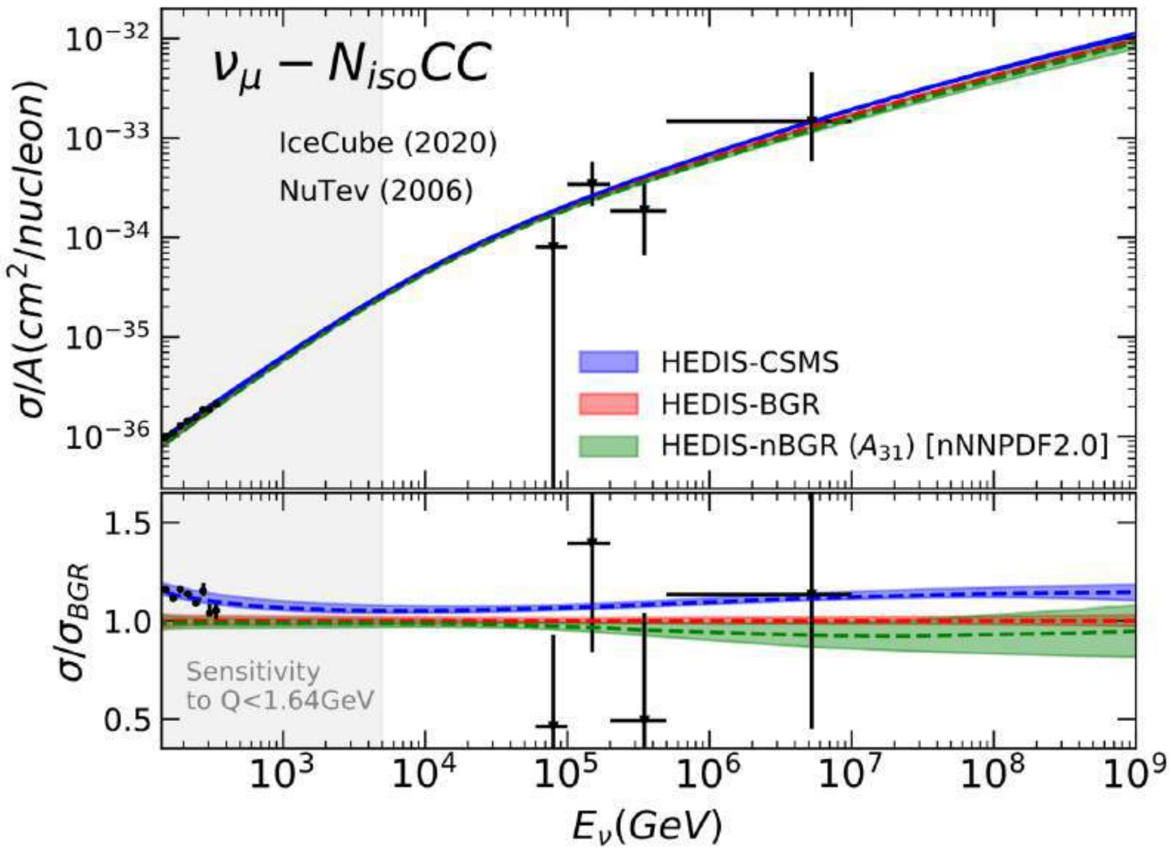




CC DIS isoscalar nucleon cross-sections separated by the flavour components of the structure functions, using CT18ANNLO PDFs evolved with small-*x* resummation (Weigel *et al*, *Phys.Rev.D***111:** 043044,2025)

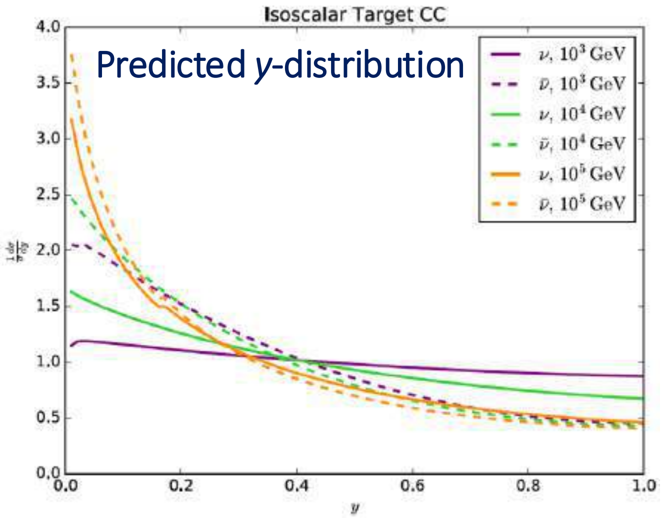
… compared with low energy experimental data from NuTeV, CCFR, CDHS, NOMAD, and FASERν





NB: `GENIEv3` has a `HEDIS` module offering a choice of UHE #-section calculations (*Eur.Phys.J.ST* 230:4449,2021)

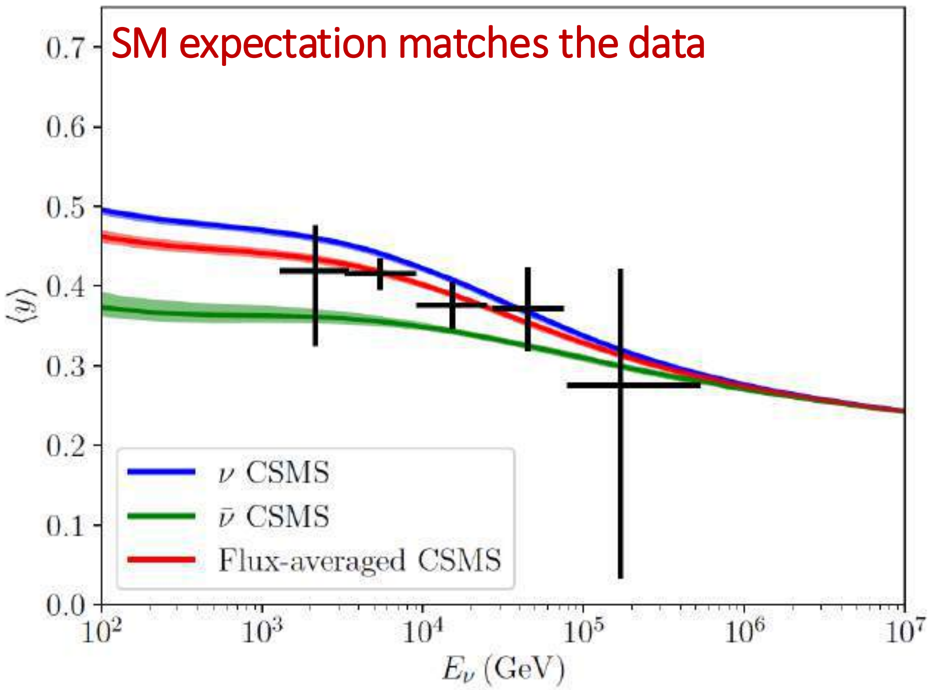
An even more sensitive test is the inelasticity distribution

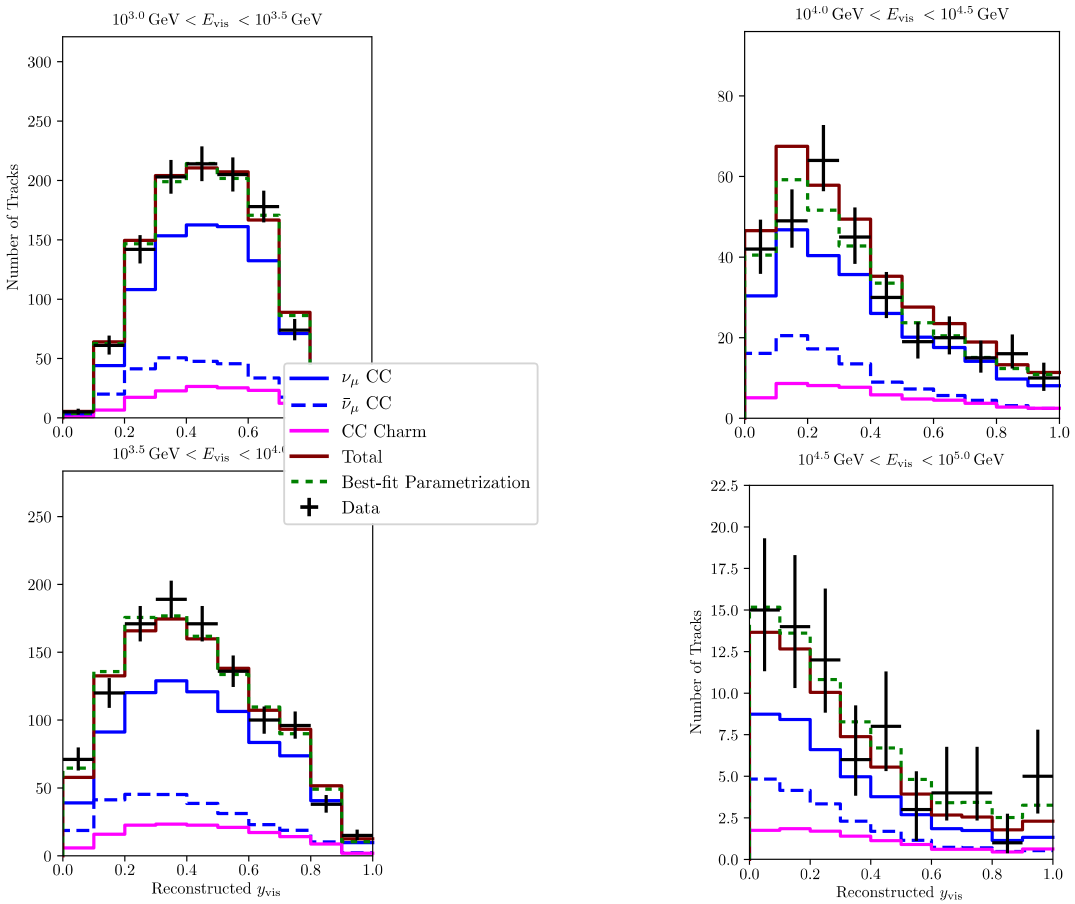


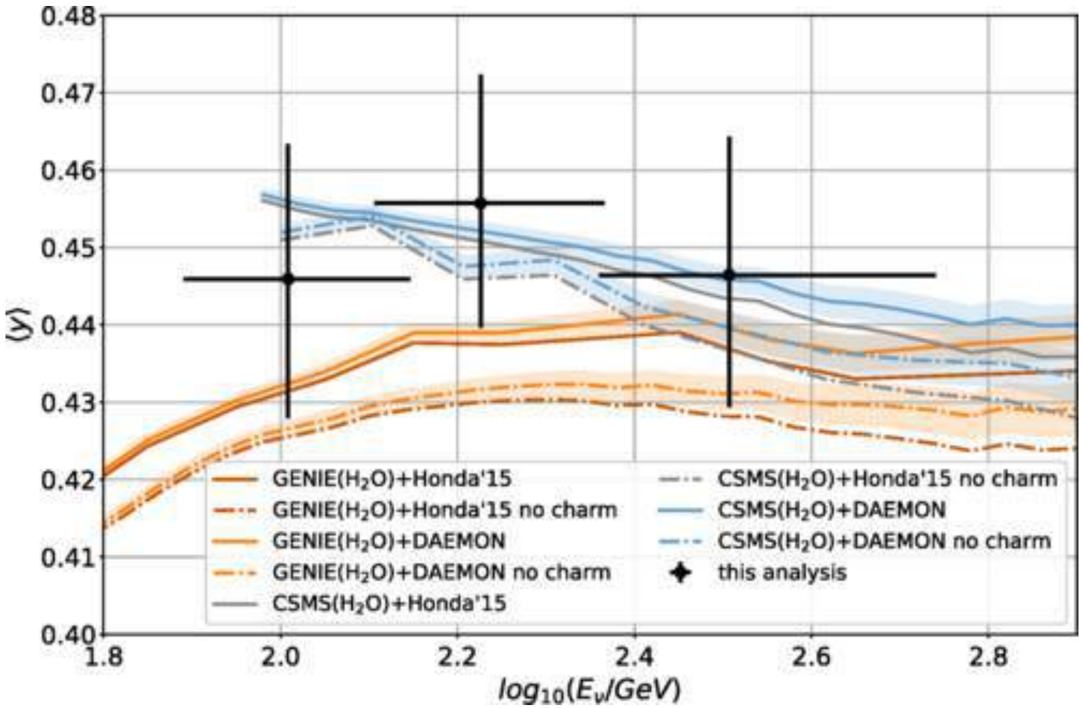
$y = 1 - E_{\text{lepton}}/E_\nu$

$$\frac{dp}{dy} = N(1+\epsilon(1-y)^2)y^{\lambda-1},$$

$$N = \frac{\lambda(\lambda+1)(\lambda+2)}{2\epsilon+(\lambda+1)(\lambda+2)}$$



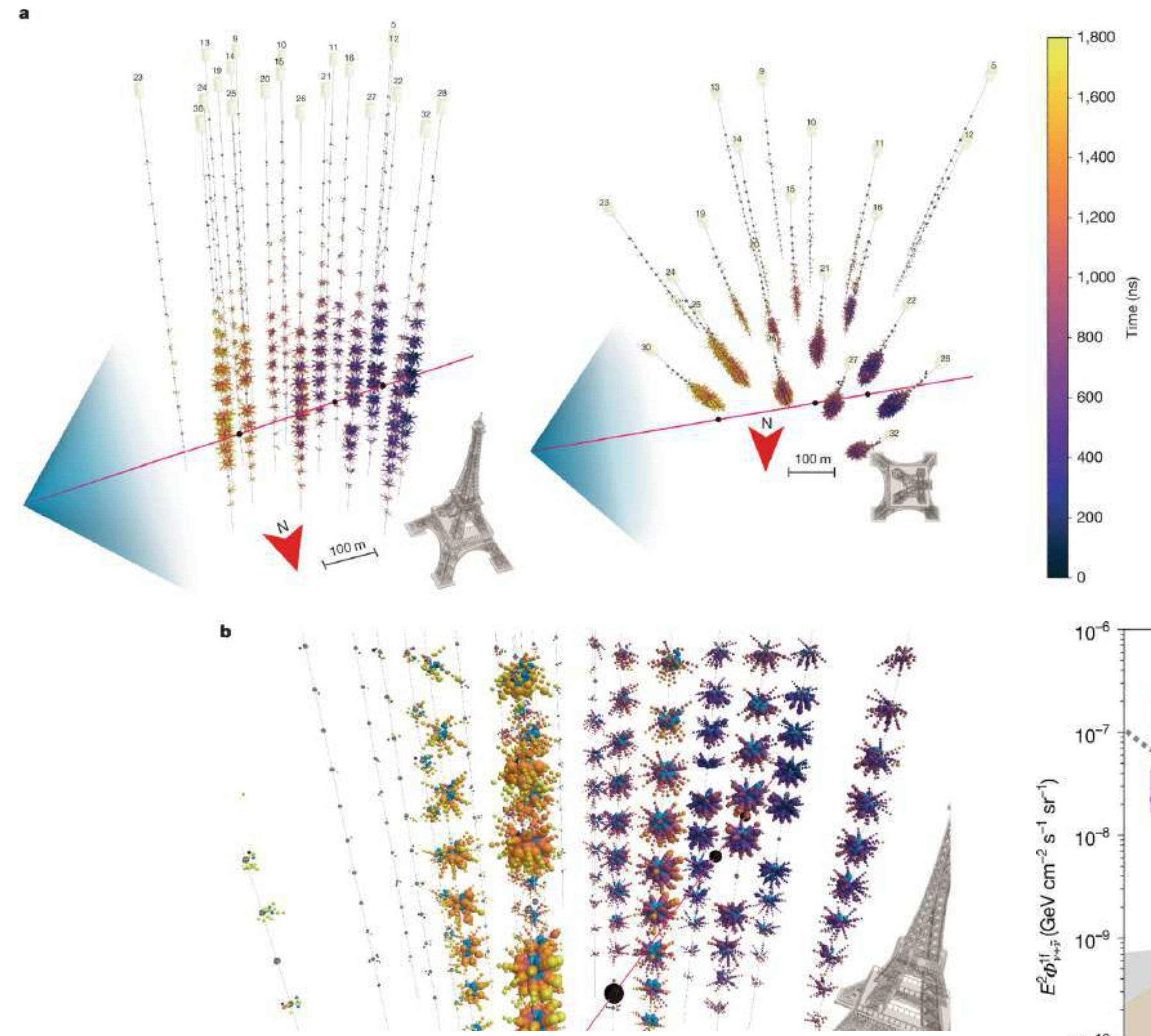


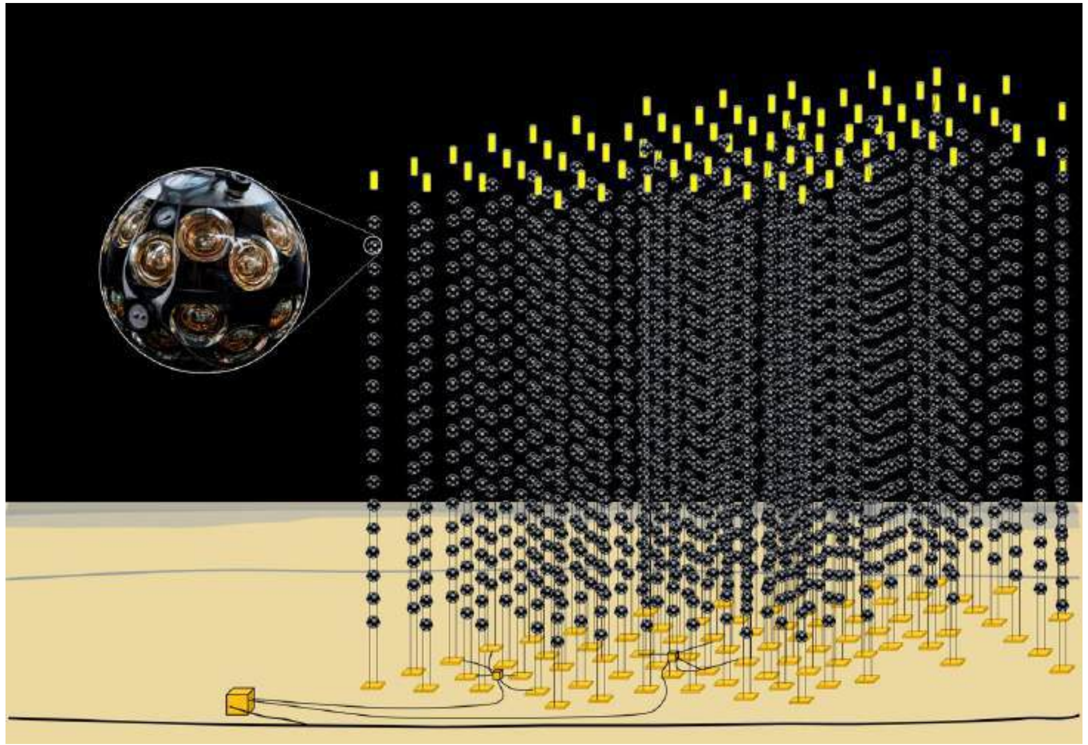


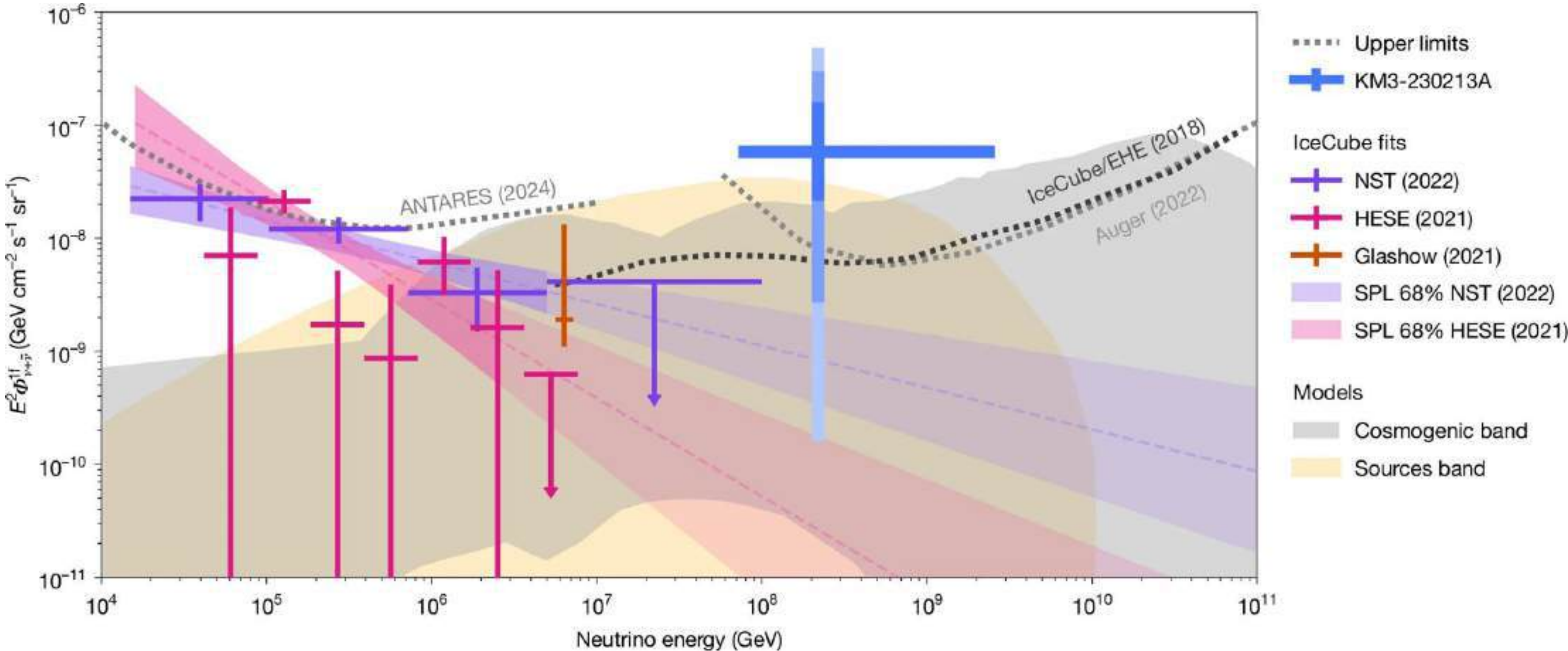
IceCube collaboration., Phys.Rev.D99:032004,2019

IceCube collaboration., Phys.Rev.D111:112001,2025

KM3NeT detects the highest energy neutrino ever observed

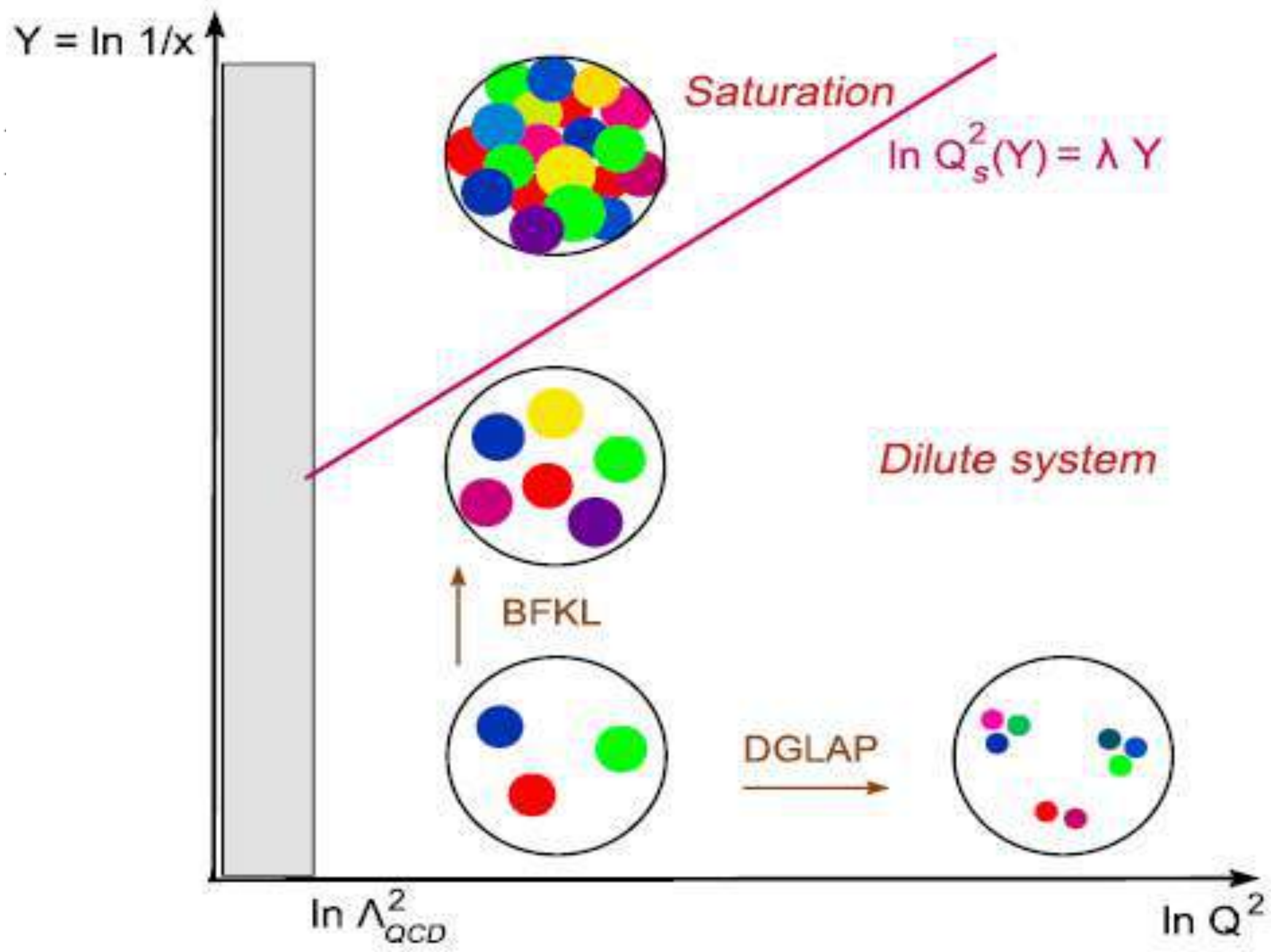






Nature **638**:8050,2025

As the gluon density rises at low *x*, non-perturbative effects must become important …
a Colour Glass Condensate may form (and this has support from RHIC & ALICE data)



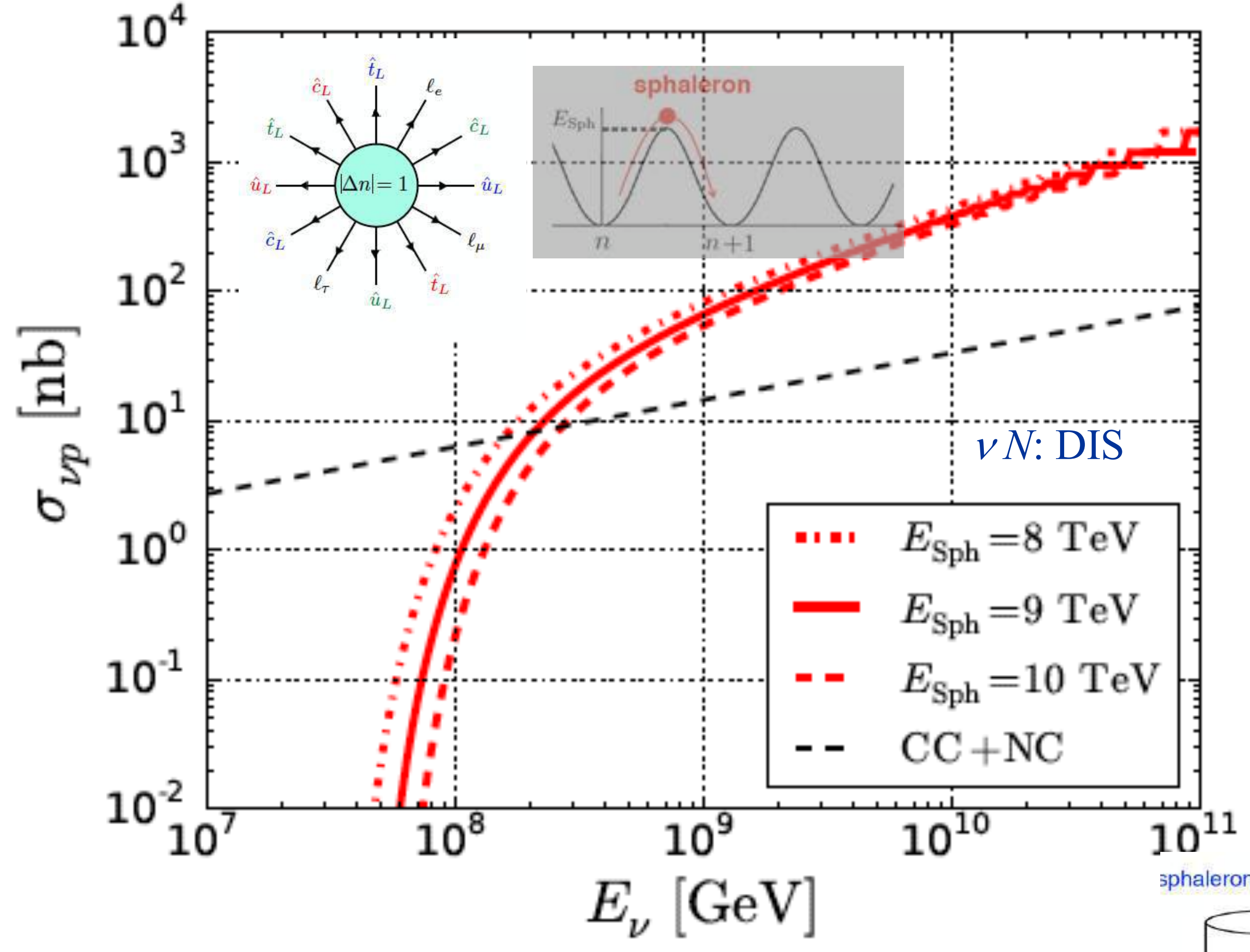
This would strongly suppress the ν-N #-secn below its (unscreened) SM value
… can we test this experimentally with UHE cosmic neutrinos?

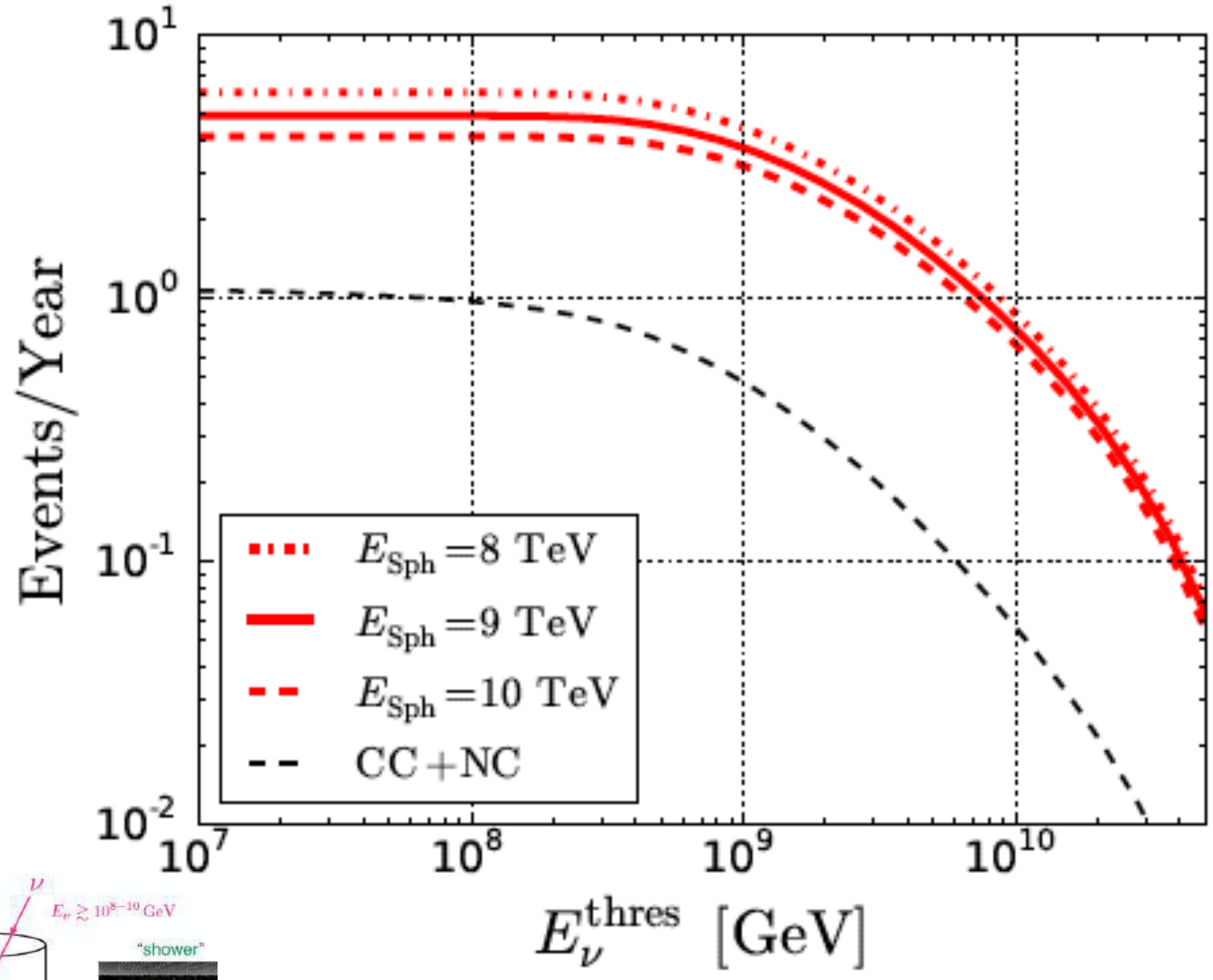
Electroweak instanton-induced interactions in the SM

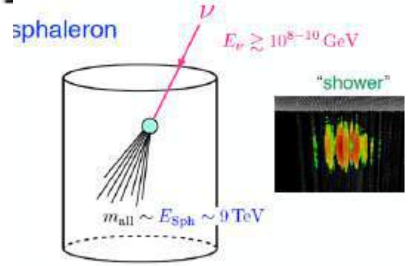
Non-perturbative transitions between degenerate *SU*(2) vacuua (with different *B+L* #) are *exponentially* suppressed below the "sphaleron" mass: ~ $M_W/\alpha_W \simeq 9$ TeV … *can boost* the cross-section for *ν-N* scattering at higher cms energies:

$$E_\nu \geq E_{\rm sph}^2/2xm_N \simeq 4 \times 10^7/x \sim 10^{9-11}\ \text{GeV}$$

Han & Hooper, PLB **582**:21,2004

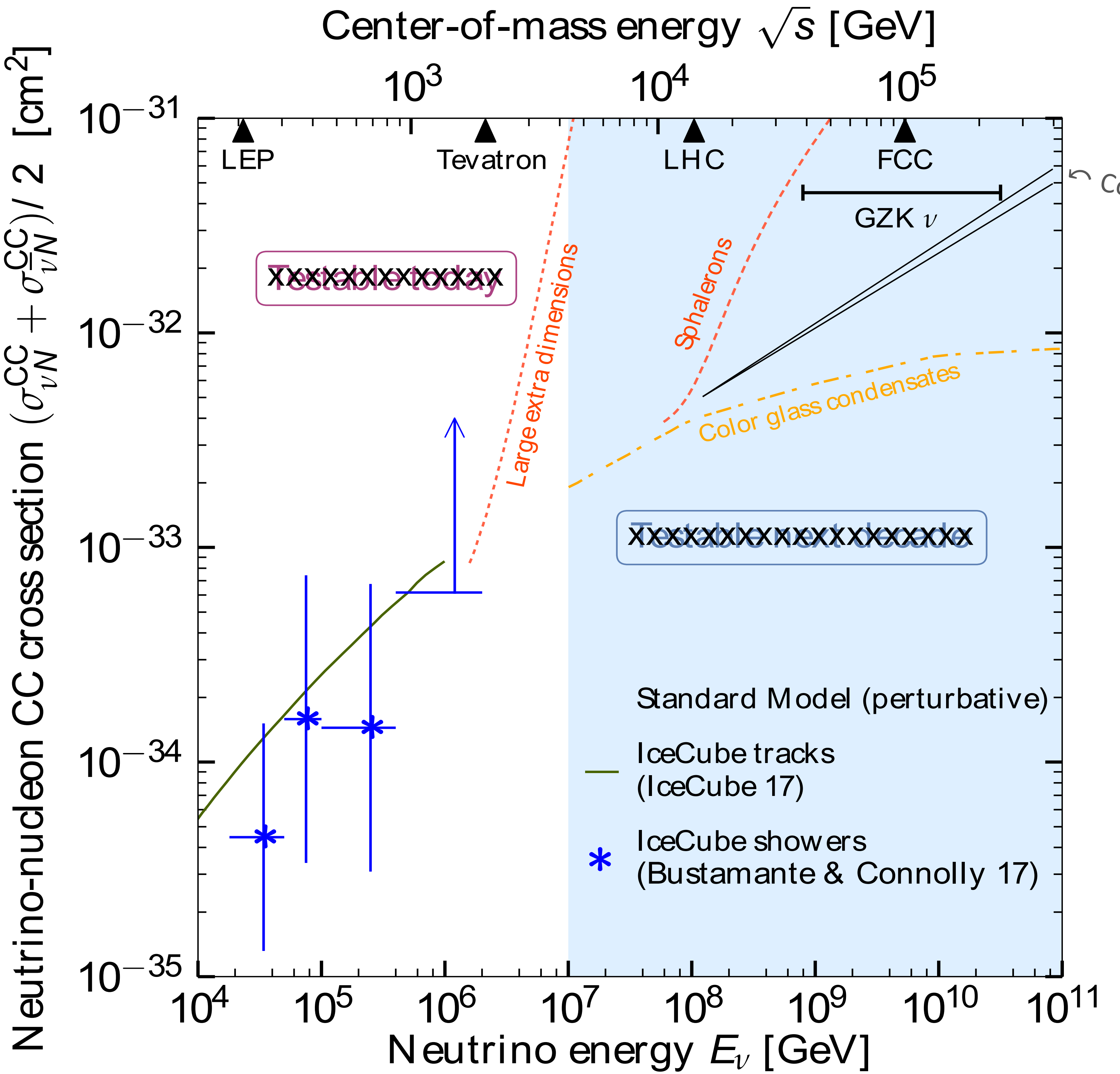






IceCube has sensitivity to sphalerons comparable to that of the LHC!

Ellis, Sakurai & Spannowsky, JHEP **05** (2016) 085

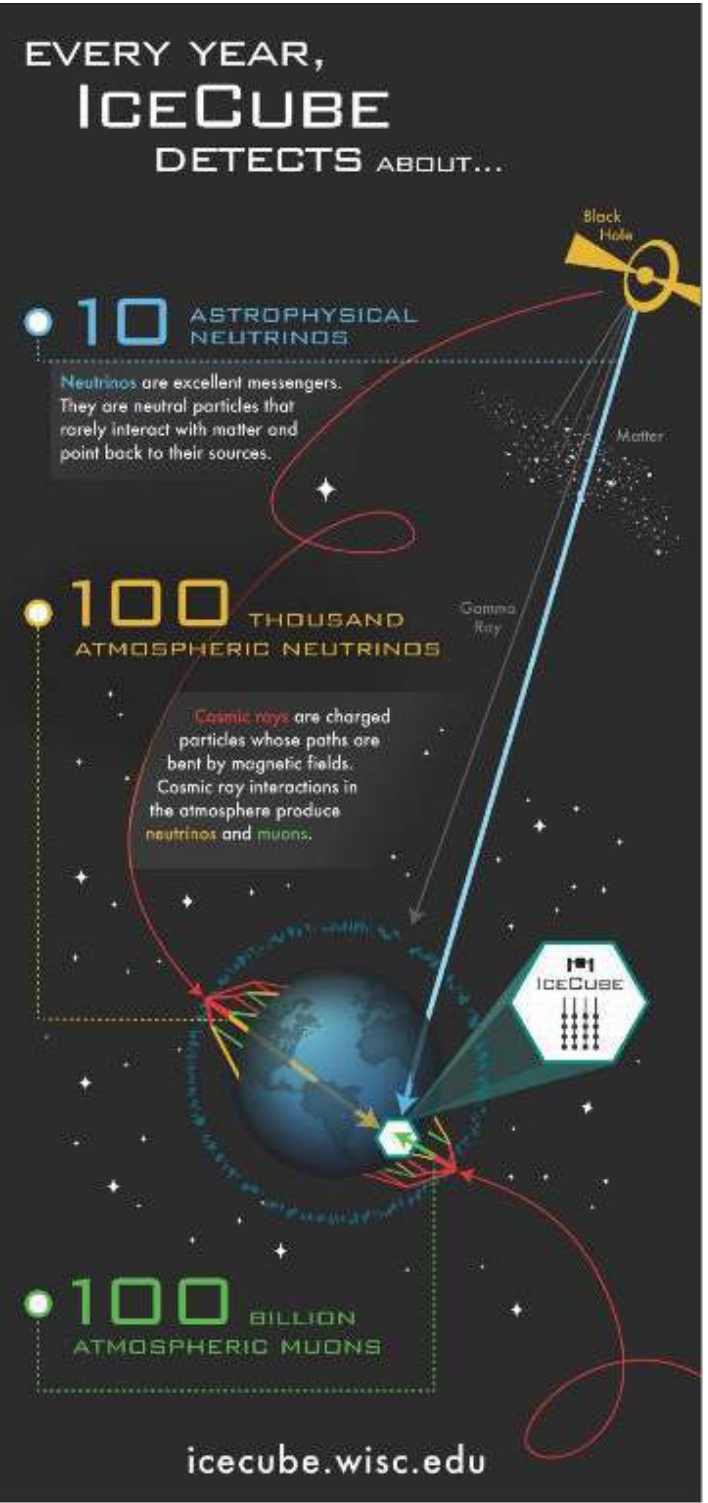


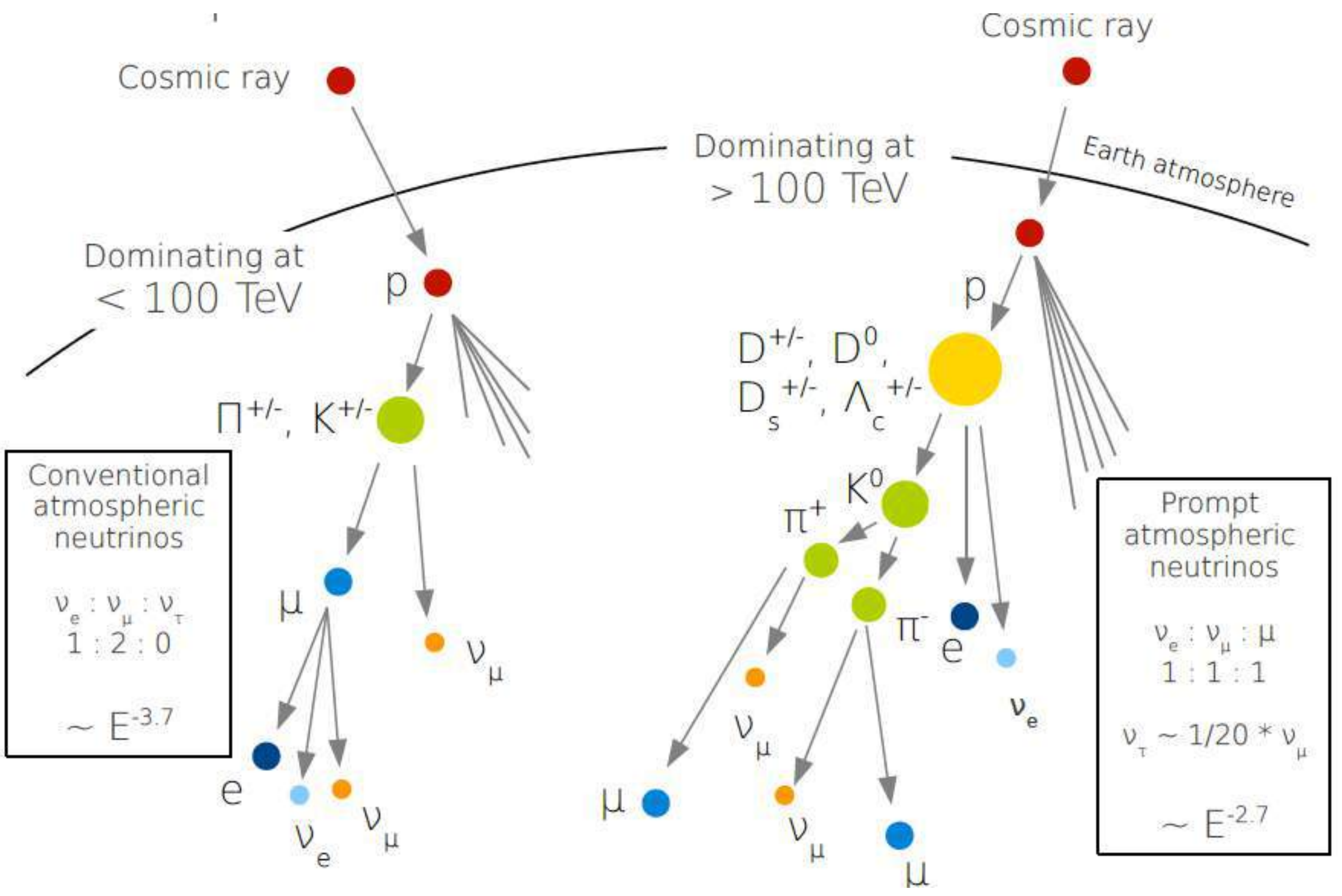
↶ Cooper-Sarkar *et al*, JHEP **08**:042,2011

Powerful test of new physics beyond the SM (e.g. leptoquarks, new dimensions, sphalerons, colour glass condensate *etc*)

... should be able to probe up to ~10^{10-11} GeV using flux of cosmogenic ν
- with **IceCube-Gen2**

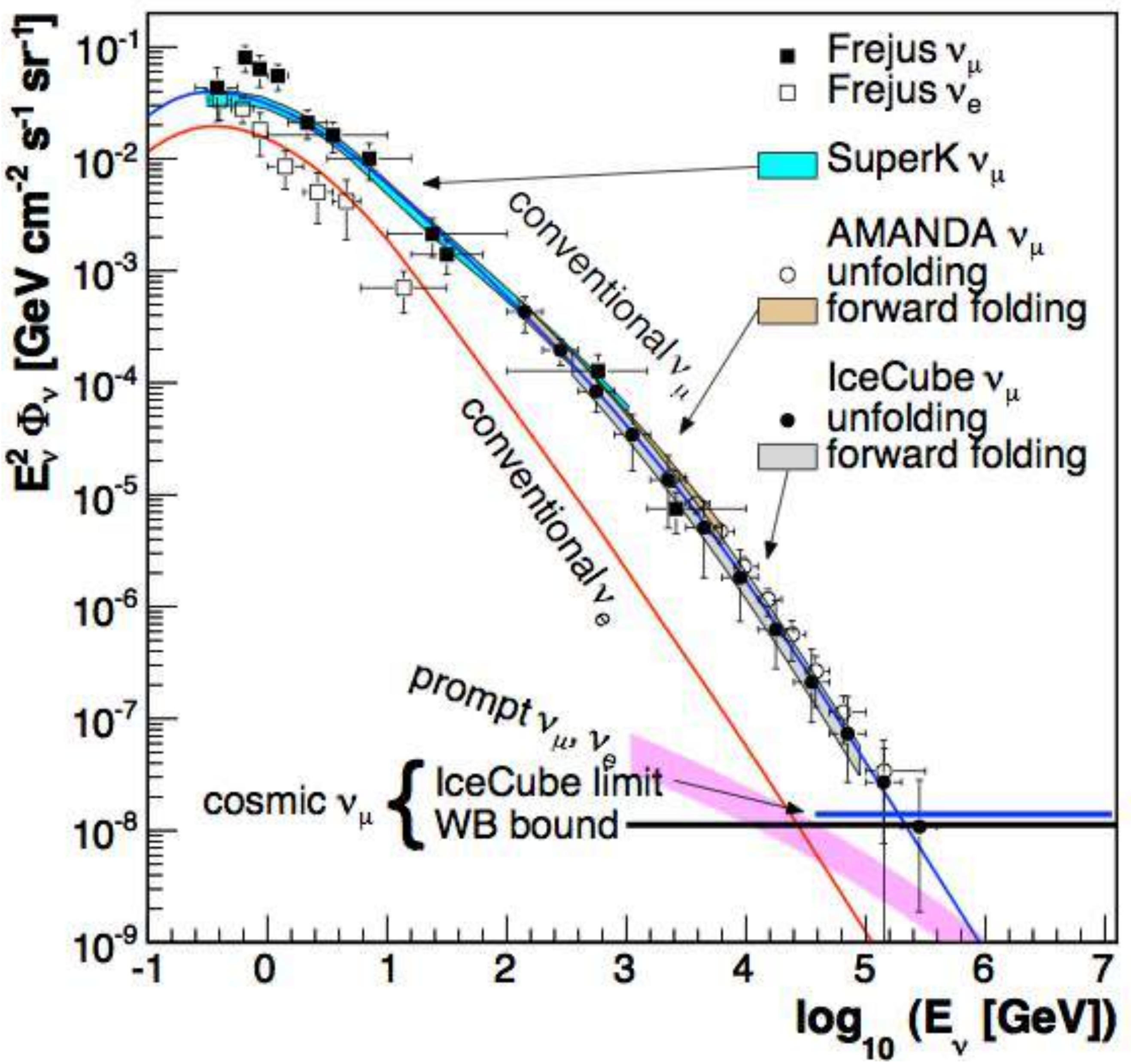
Neutrino telescopes look for a cosmic signal buried in a huge background of atmospheric neutrinos

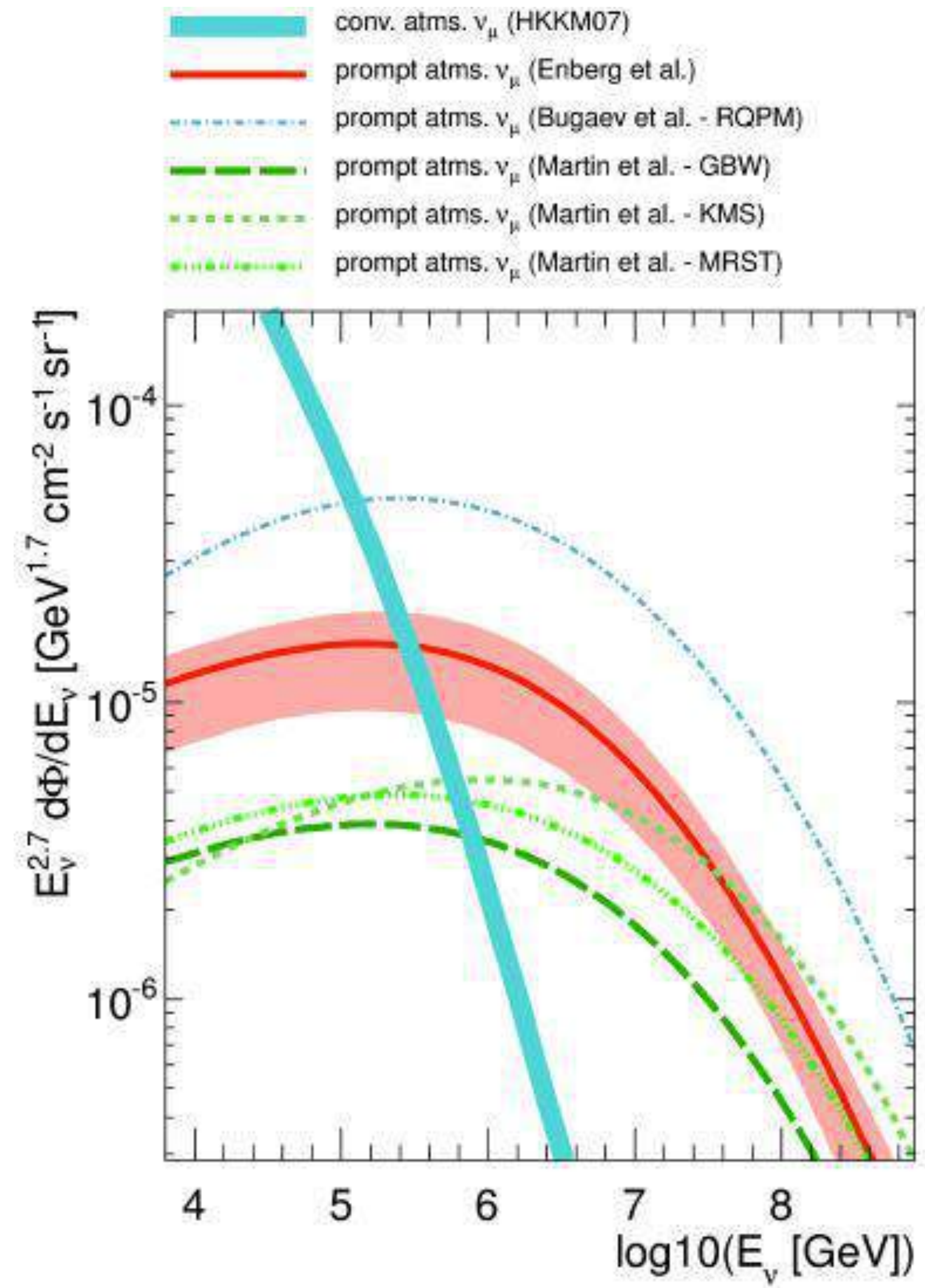




Courtesy: Anne Schukraft

The ‘conventional flux’ is well understood as it is calibrated against many observations but uncertainties in charm production make the prompt flux less so although it is the most important background for the astrophysical flux!



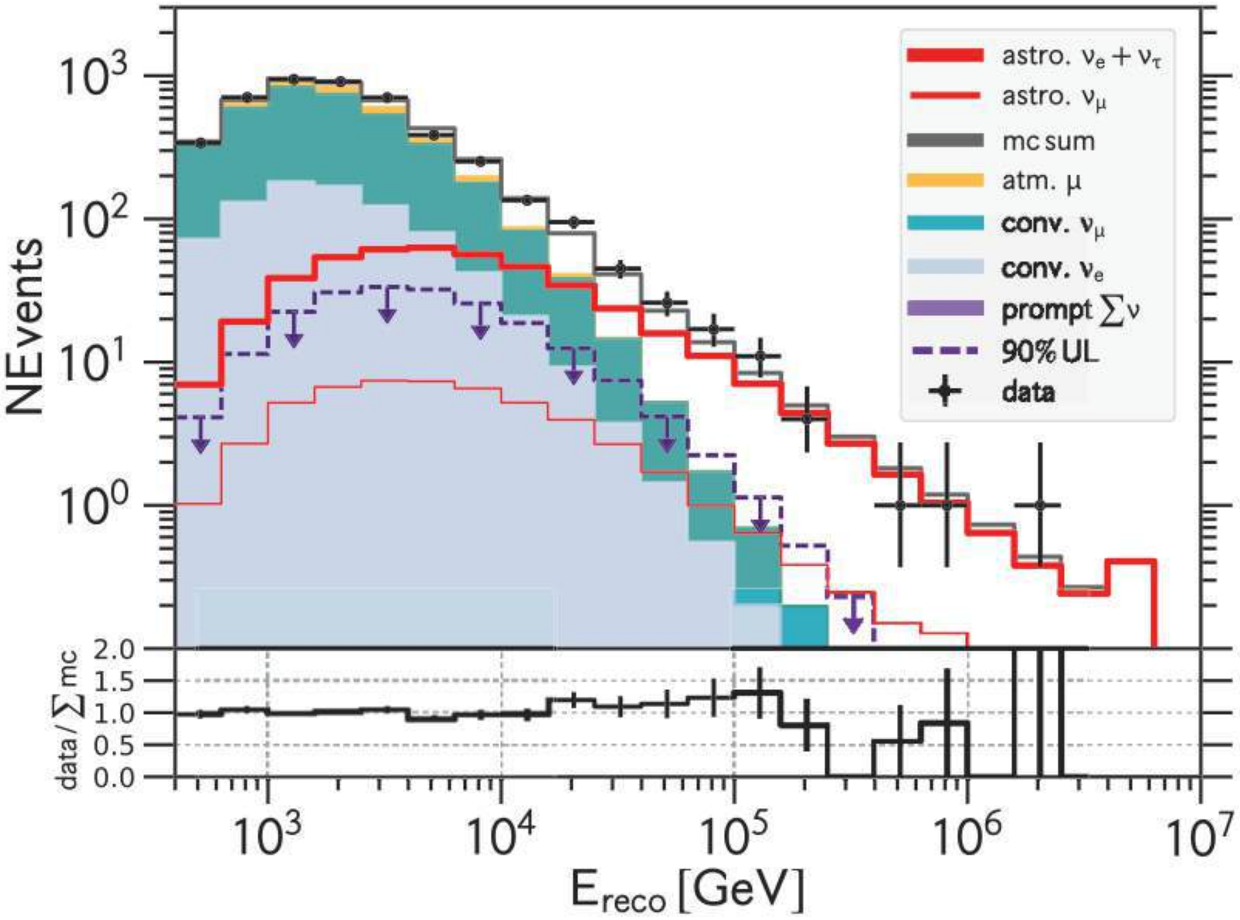


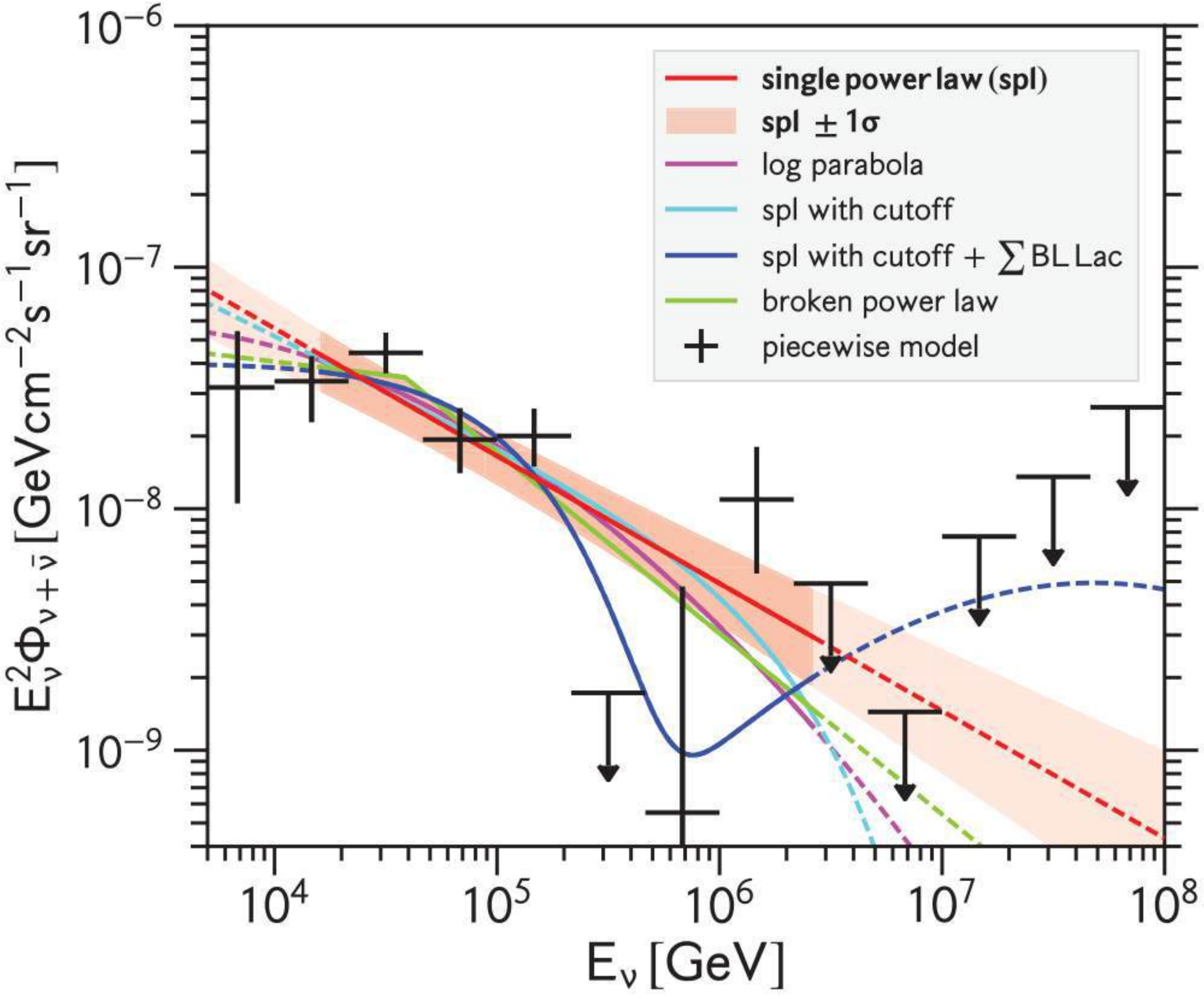
The prompt flux is *harder* than the conventional flux, and was predicted to *dominate* the total flux at $E > 10^{5-6}$ GeV

Why is the atmospheric prompt flux important for neutrino telescopes?

The astrophysical ν flux can be fitted by a power-law, broken power-law, spline with a cut-off, log-parabola …

Need to discriminate between these in order to identify the source(s) – but this requires better estimate of atmospheric background





Aartsen *et al*, *PRL* **125**:121104,2020

To measure this at an accelerator requires:
$\sqrt{s} = \sqrt{2E_\nu m_p} \simeq 10$ TeV, for $E_\nu \sim 10^7$ GeV: **LHC**
$x_{1,2} \sim (m_c/\sqrt{s})\, e^{\pm\eta} \Rightarrow \eta \sim 7\text{-}9$: **Forward detector**

The quantity needed to determine charm production in cosmic ray air showers is:

$$Z_{ph} = \int_E^\infty dE' \frac{\phi_p(E')}{\phi_p(E)} \frac{A}{\sigma_{pA}(E)} \frac{d\sigma(pp \to c\bar{c}Y; E', E)}{dE}$$

- The **differential cross-section** can be calculated in a variety of formalisms, e.g. using the 'colour dipole model' of Enberg, Reno & Sarcevic (*PRD* **78**:043005,2008) which is empirical … so hard to estimate uncertainties

However, **perturbative QCD (with DGLAP evolution)** *can* describe charm production data for the entire kinematical region of interest, hence can calculate with **NLO+PS Monte Carlo event generators** (*modulo* theoretical uncertainties re. validity of factorisation theorem, choice of starting scale *etc*)

- Can use LHCb hadroproduction data … conversion from CM to rest frame of the (atmospheric) fixed target:

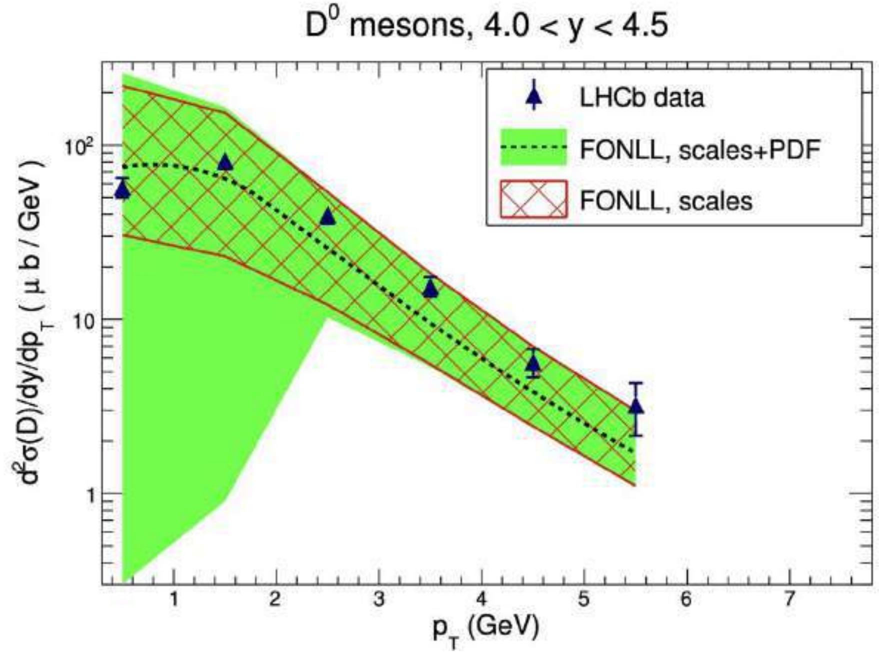
$$\sqrt{s} = 7\ [TeV] \longleftrightarrow E_b = 2.6 \times 10^7\ [GeV]$$

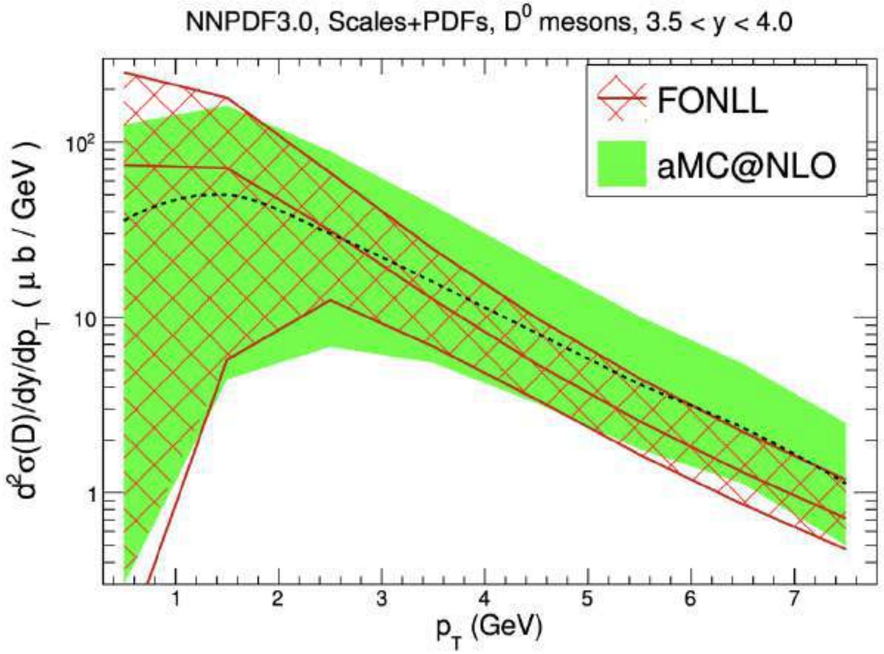
We can therefore predict the prompt neutrino flux at energies **up to 10^7 GeV** … at these energies, charm production is dominated by **gluon fusion**, hence sensitive to the behaviour of the **gluon PDF at small-*x***

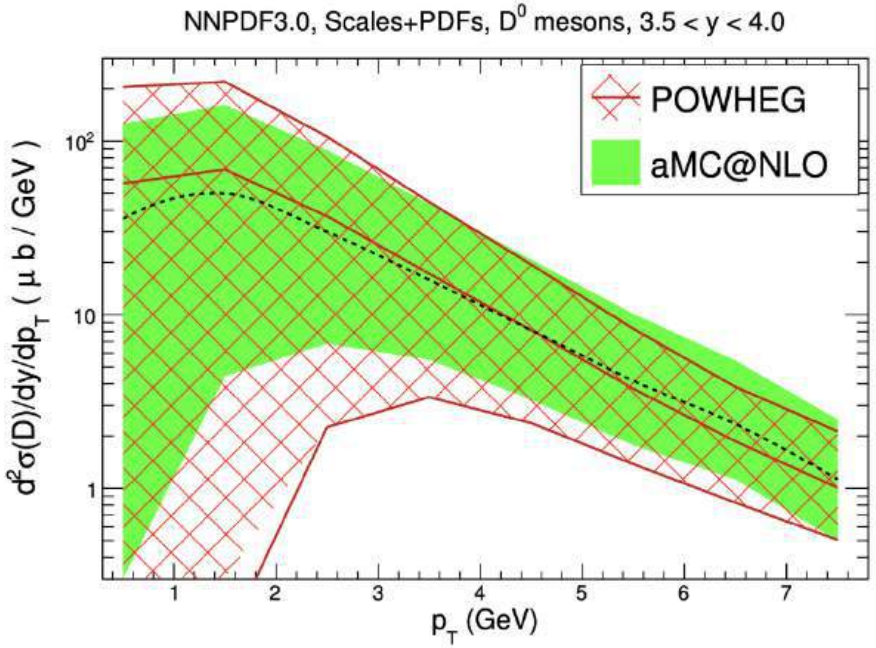
Gauld *et al*, *JHEP* **02**:130,2016

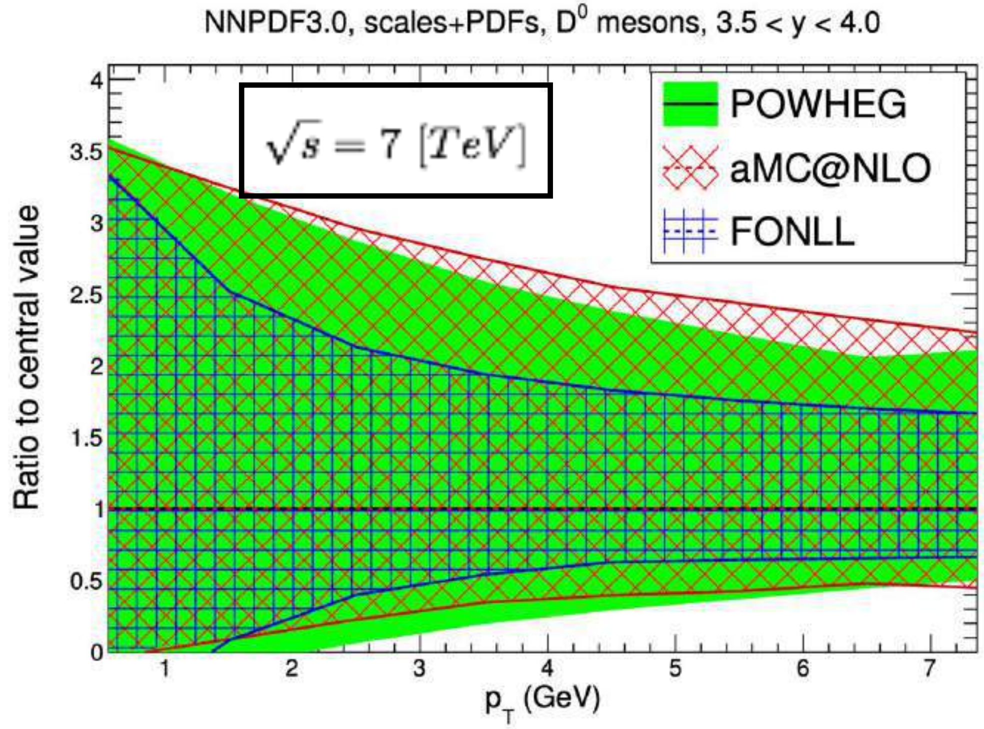
Forward Charm Production & LHCb

LHCb collab. *NPB* **871**:1,2013

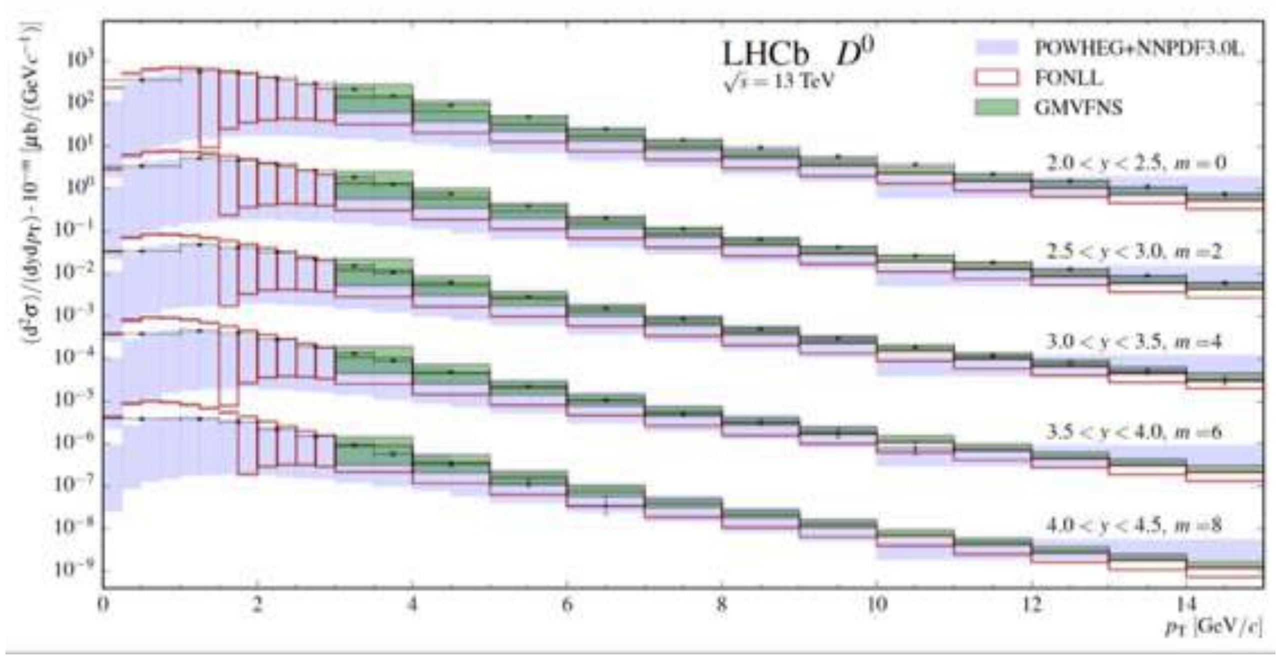








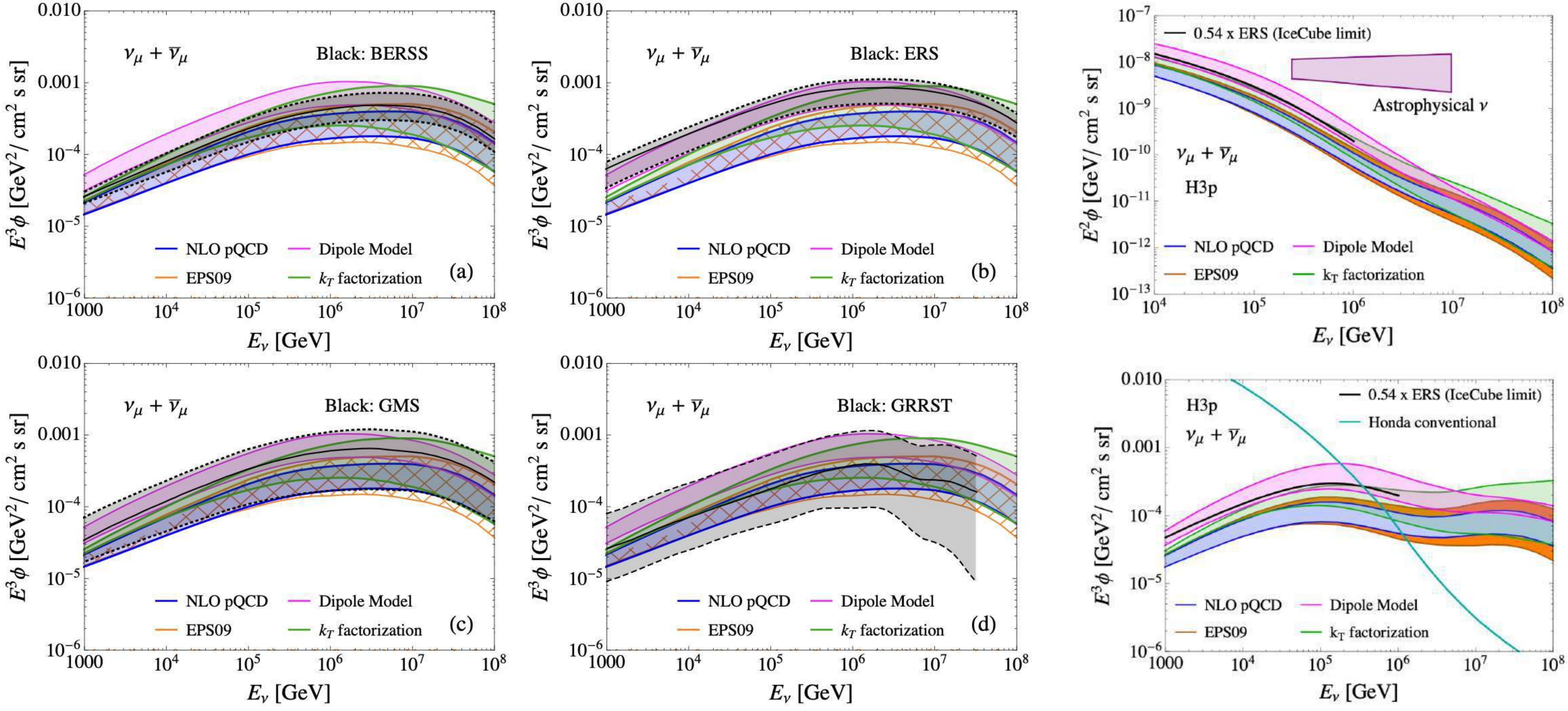
Prediction for 13 TeV matched the data!



Gauld *et al*, *JHEP* **11**:009,2015

NLO predictions for forward charm production validated with LHCb data

Range of predictions narrowed further with input from LHCb



Bhattacharya *et al*, *JHEP* 11:167,2016

FASERν & SND@LHC will measure the prompt neutrinos in a *more* forward region ($|y| > 7.2$) than LHCb can access

LHC provides a collimated beam of TeV energy neutrinos in the far forward direction

NEUTRINO AND MUON PHYSICS IN THE COLLIDER MODE OF FUTURE ACCELERATORS*)

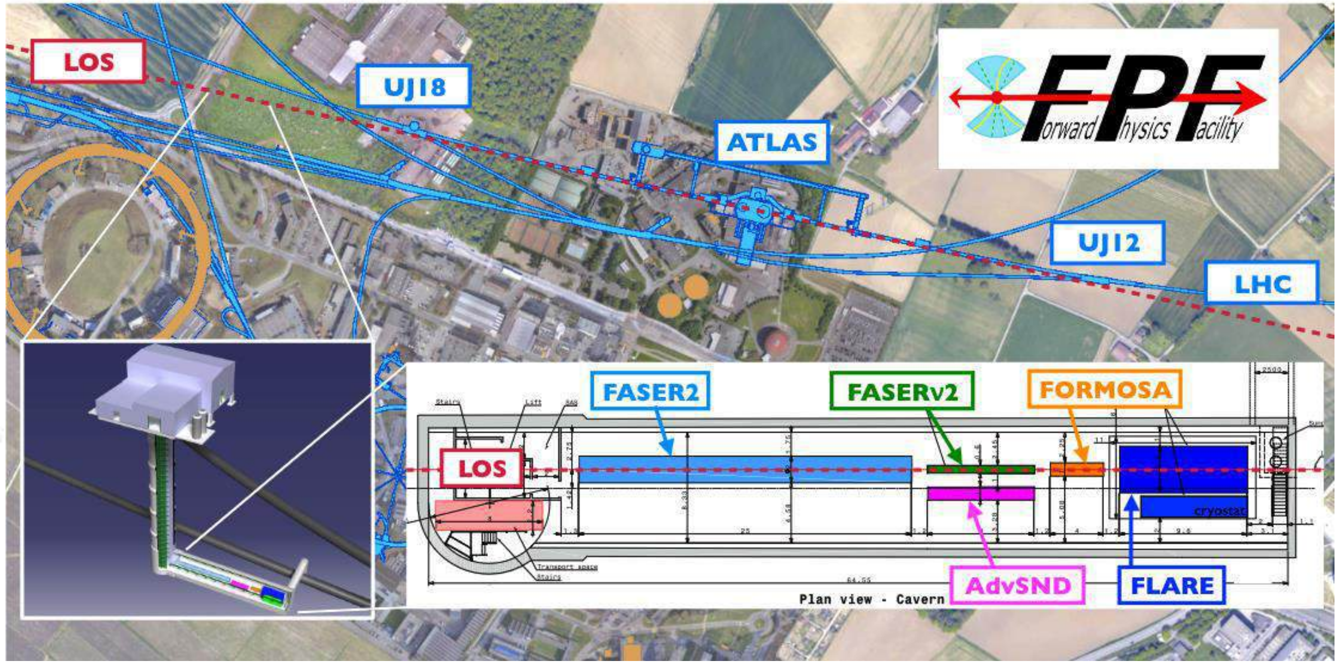
A. De Rújula and R. Rückl

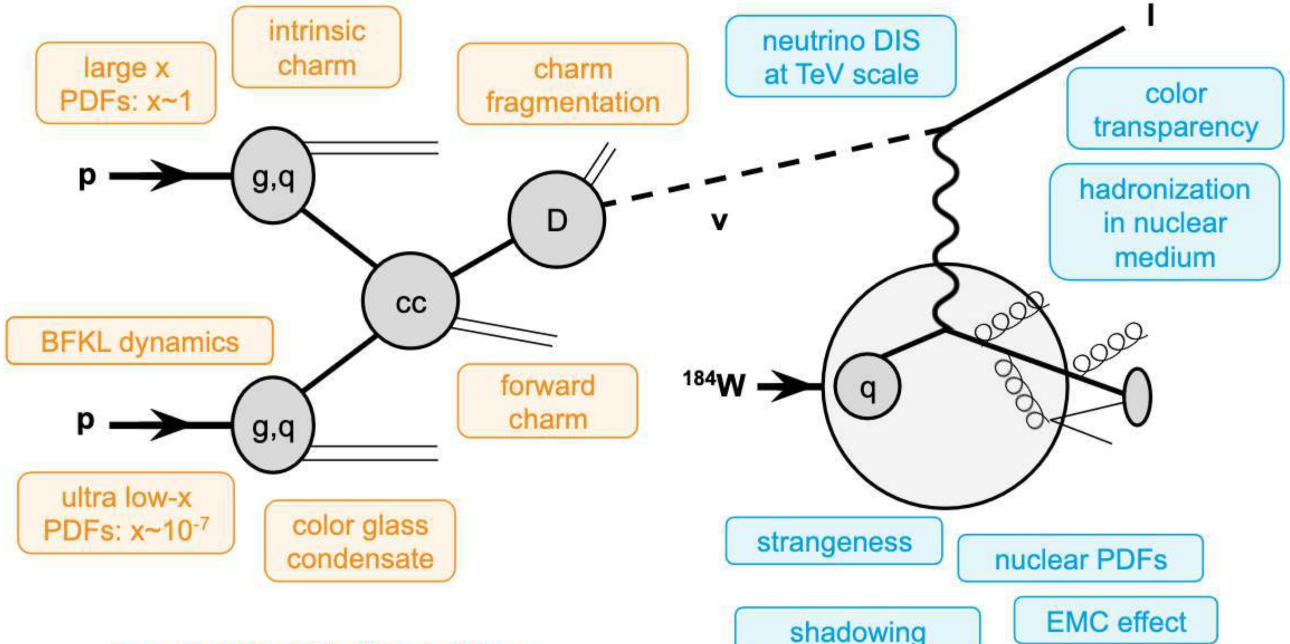
CERN, Geneva, Switzerland

Proc. ECFA-CERN Workshop on large hadron collider in the LEP tunnel: 21-27 Mar 1984

ABSTRACT

Extracted beams and fixed target facilities at future colliders (the SSC and the LHC) may be (respectively) impaired by economic and "ecological" considerations. Neutrino and muon physics in the multi-TeV range would appear not to be an option for these machines. We partially reverse this conclusion by estimating the characteristics of the "prompt" ν_μ, ν_e, ν_τ and μ beams necessarily produced (for free) at the pp or $\bar{p}p$ intersections. The neutrino beams from a high luminosity (pp) collider are not much less intense than the neutrino beam from the collider's dump, but require no muon shielding. The muon beams from the same intersections are intense and energetic enough to study μp and μN interactions with considerable statistics and a Q^2-coverage well beyond the presently available one. The physics program allowed by these lepton beams is a strong advocate of machines with the highest possible luminosity: pp (not $\bar{p}p$) colliders.



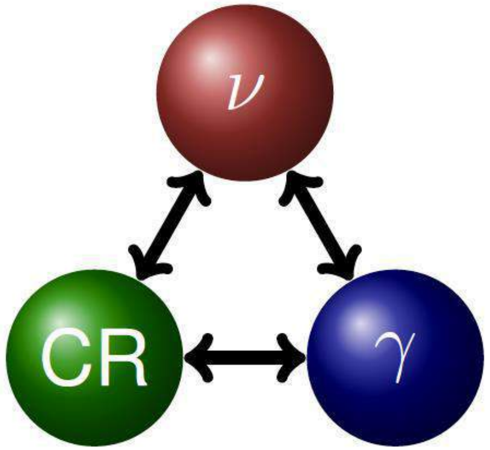


Forward Particle Production

This provides the means to study interesting open issues in QCD – of relevance to **neutrino telescopes***;* to study forward production of light hadrons – of relevance to **cosmic ray air shower arrays;** and enables searches for long-lived particles arising in BSM physics (axions, dark photons, heavy neutral leptons, milli-charged particles, scalar dark matter *etc*) – of relevance to various **dark matter experiments** (both direct and indirect searches) (FPF collab., *Phys.Rep.***968**:1,2022, *J.Phys.G***50**:030501,2023)

Multi-messenger paradigm

… now back to astrophysics with Uhe neutrinos

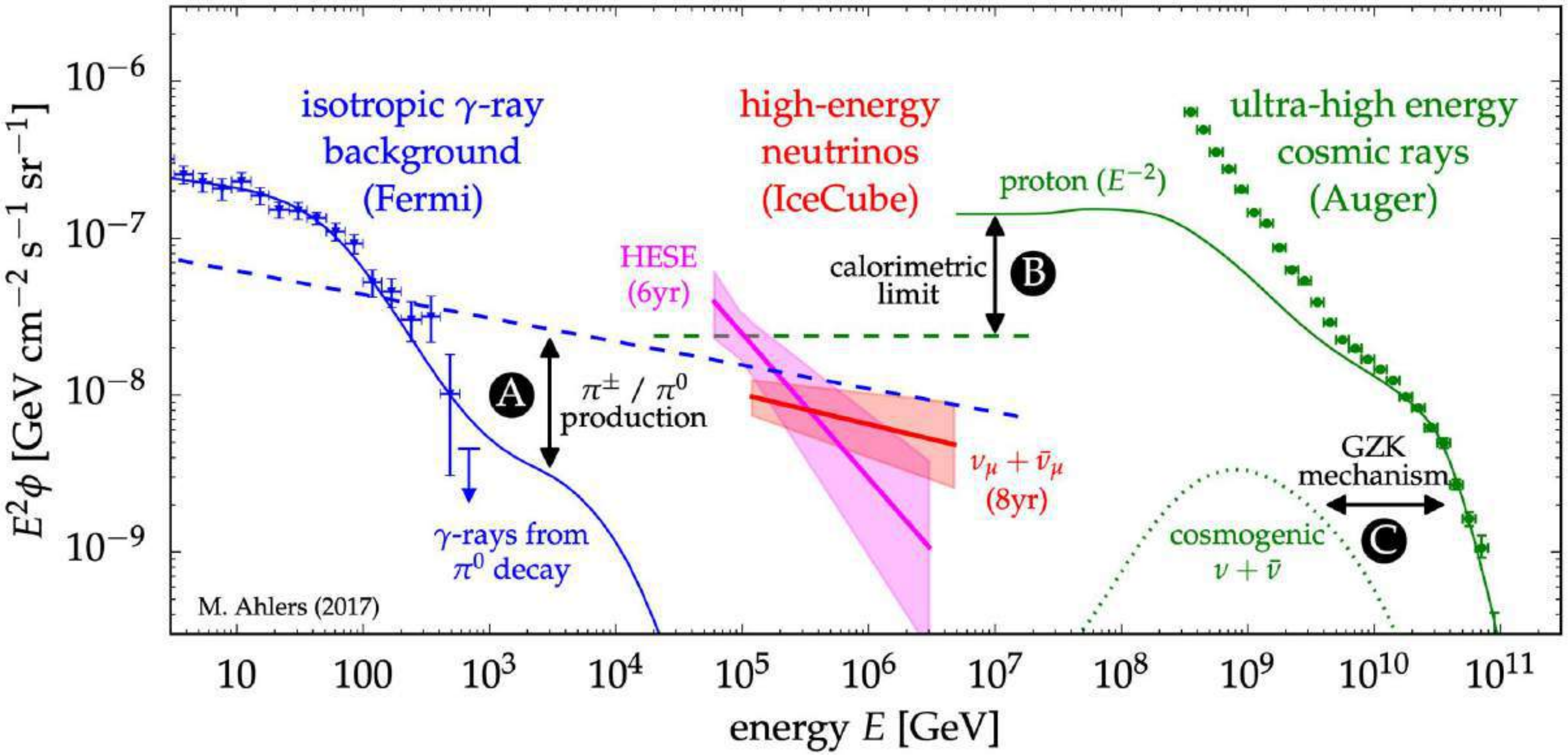


- Neutrino production is closely related to the production of cosmic rays (CRs) and γ-rays.

- 1 PeV neutrinos correspond to 20 PeV CR nucleons and 2 PeV γ-rays

→ **very interesting** energy range:

  - Glashow resonance?
  - galactic or extragalactic?
  - isotropic or point-sources?
  - chemical composition?
  - *pp* or $p\gamma$ origin?



Multi-messenger Astronomy

Photons

>1 cm ~1 mm ~10 µm ~1 nm <0.1 nm

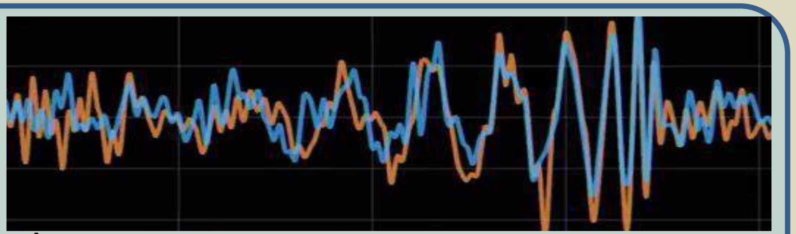
10^{-6} eV 10^{-4} eV 10^{-1} eV ~1 KeV > 100 KeV

Pulsars, Quasars, Radio galaxies The Big Bang (CMB) Stars Non thermal processes (GRBs …)

Cosmic Rays

Protons, heavy nuclei, electrons, … : 10^{8} - 10^{20} eV – detected (1912) Origin(s) unknown

Gravitational Waves

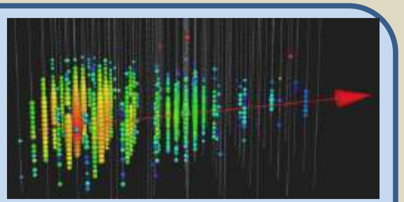


Predicted by General relativity – detected (2015)

BH-BH merger ~410 Mpc away

More events incl. NS-NS mergers + stochastic background (2023)

Neutrinos

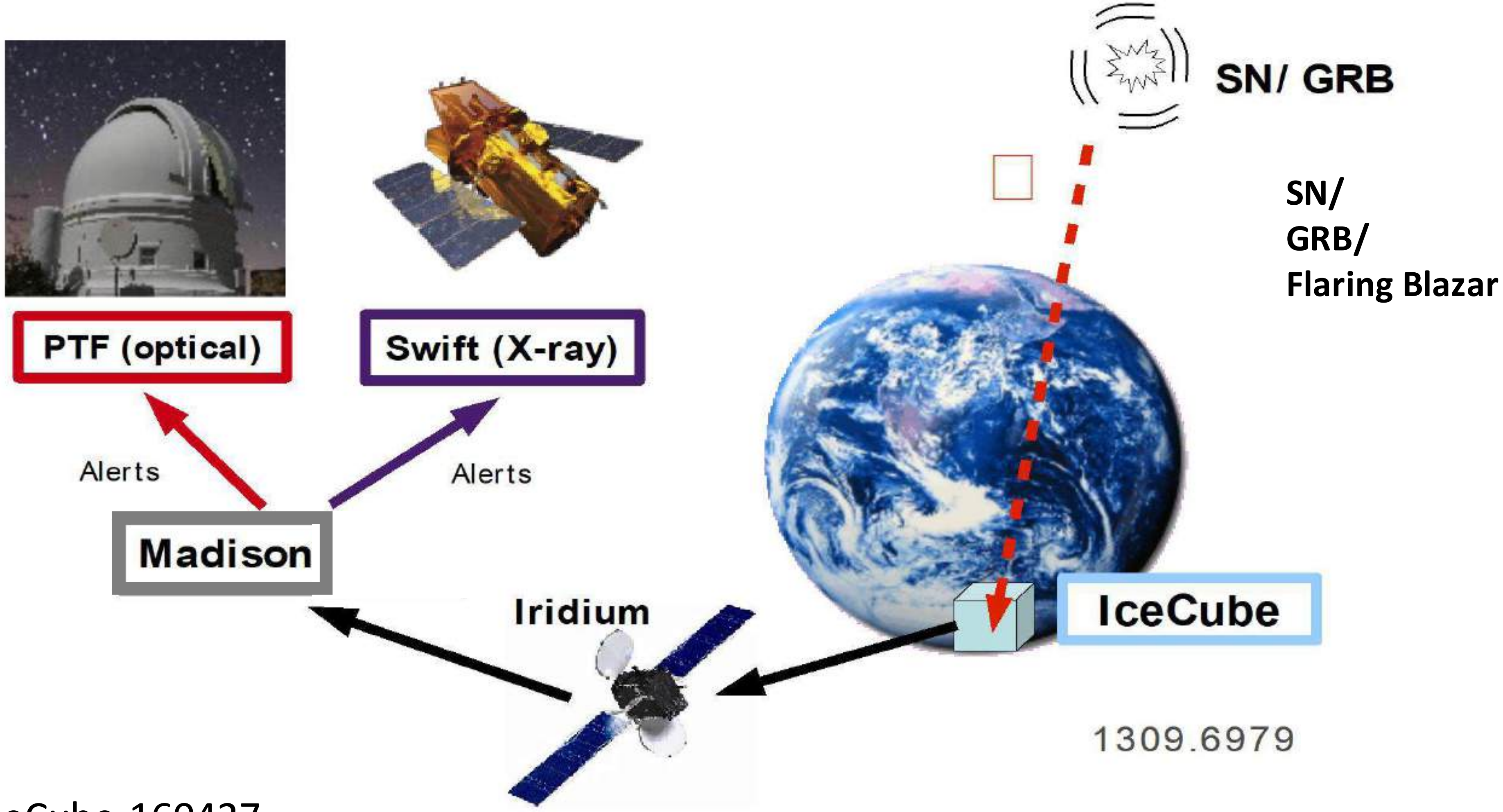


Proposed (1931), detected (1959) neutral, weakly interacting … mass < 1 eV, 1 mass > 0.1 eV

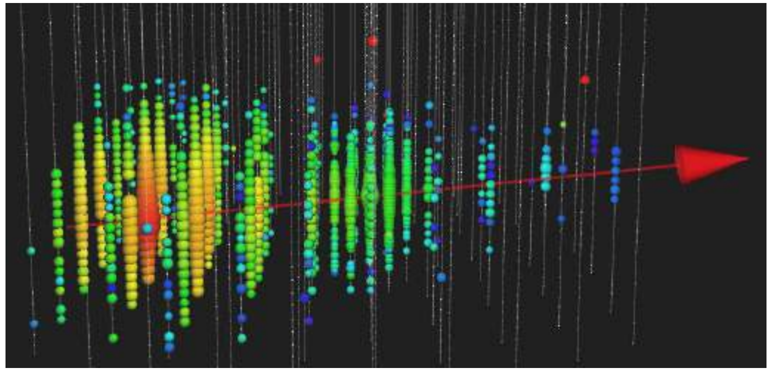
Detected from the Sun (1966-) and Supernova 1987a @ 10 MeV

Diffuse astrophysical flux @ > 50 TeV (2013), First extragalactic source (2017): flaring blazar 1.7 Gpc away, Milky Way (2023)

IceCube public realtime ν alerts



First public ν Alert: IceCube-160427



Gold: ~10/yr with average astrophysical `signalness' of 50% (index 2.19)

Bronze ~20/yr with average astrophysical `signalness' of 30% (index 2.19)

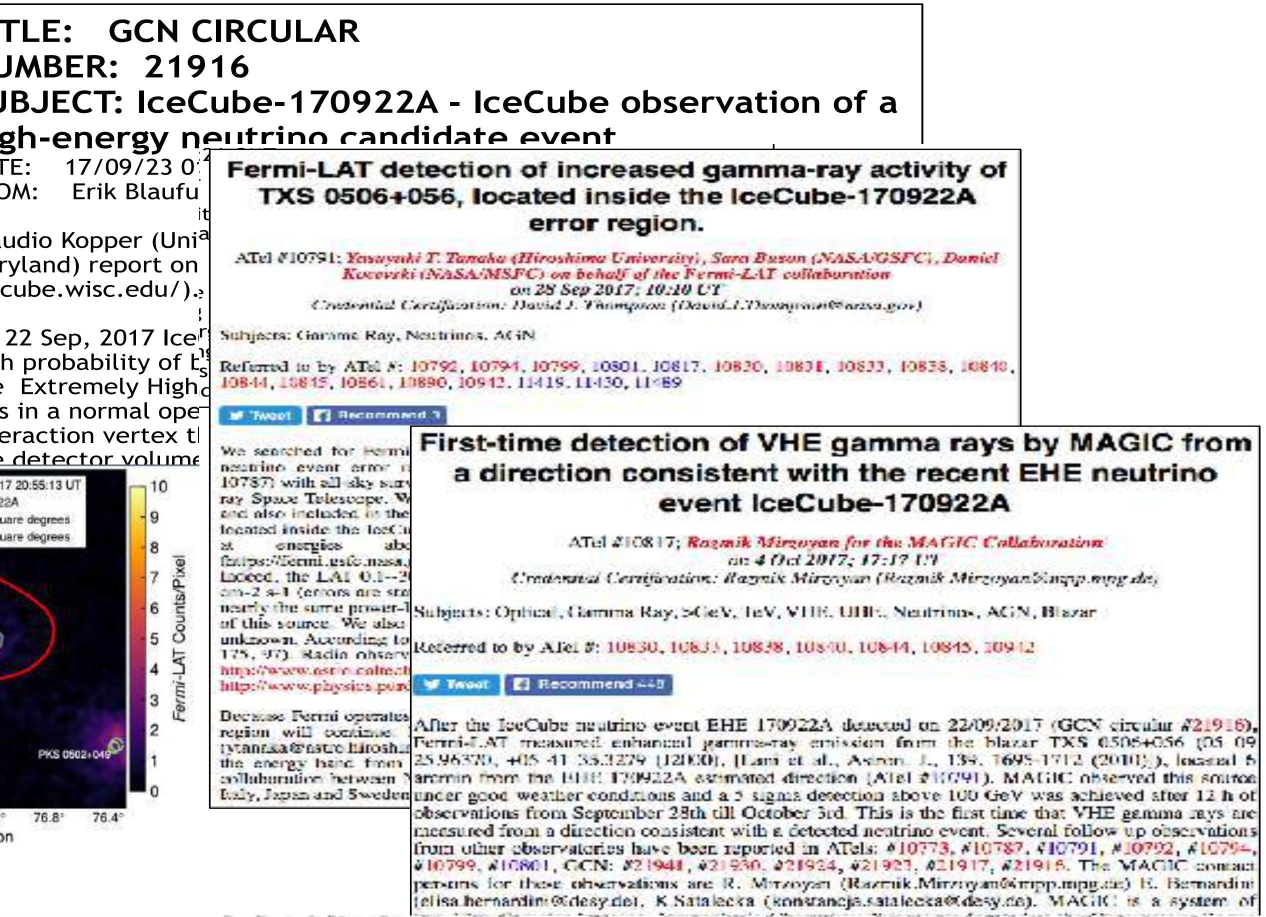
Active since Apr 2016 (IceCube, Astropart. Phys. **92**:30,2017)

Redesign (v2) active since Jun 2019 (Blaufuss *et al*. PoS-ICRC2019)

Multi-messenger alerts: TXS 0506+056

On September 22, 2017, IceCube issued a neutrino alert:

- A muon track event created by a ~290 TeV neutrino (IceCube-170922A)
- Spatially coincident with a blazar (TXS 0506+056) in a flaring state (Fermi-LAT)
- Blazar also detected in γ-rays up to 400 GeV by MAGIC after the alert
- Multi-messenger follow-up campaign of observations from radio to γ-rays.


TITLE: GCN CIRCULAR
NUMBER: 21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino candidate event
DATE: 17/09/23 0
FROM: Erik Blaufu

Claudio Kopper (Uni
Maryland) report on
icecube.wisc.edu/).

On 22 Sep, 2017 Ice
high probability of b
the Extremely High
was in a normal ope
interaction vertex t
the detector volume

Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration
on 28 Sep 2017; 10:10 UT

Subjects: Gamma Ray, Neutrinos, AGN

Referred to by ATel #: 10792, 10794, 10799, 10801, 10817, 10830, 10831, 10833, 10838, 10840, 10844, 10845, 10861, 10890, 10942, 11419, 11430, 11489

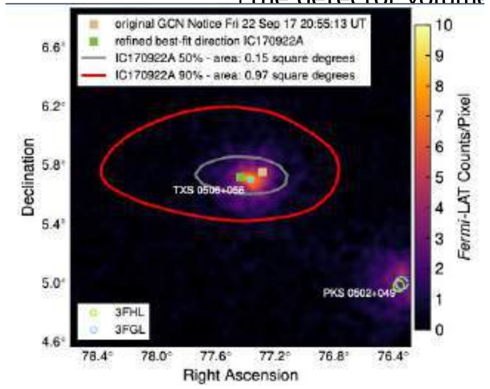
First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

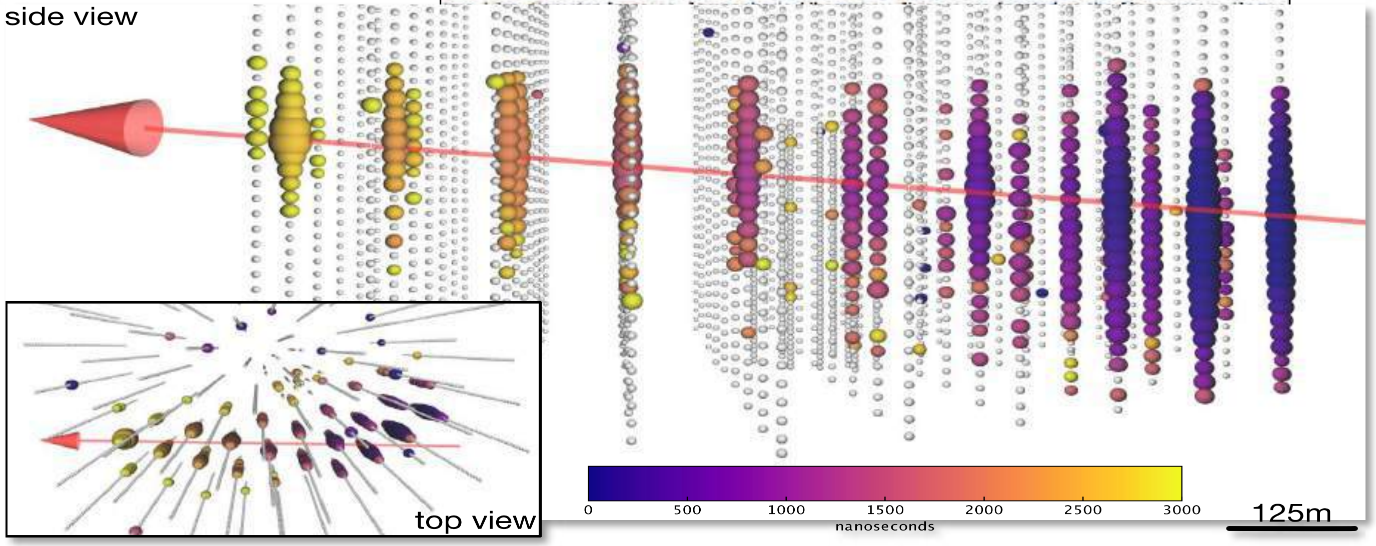
ATel #10817; Razmik Mirzoyan for the MAGIC Collaboration
on 4 Oct 2017; 17:17 UT

Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845, 10942

After the IceCube neutrino event EHE 170922A detected on 22/09/2017 (GCN circular #21916), Fermi-LAT measured enhanced gamma-ray emission from the blazar TXS 0506+056 ... MAGIC observed this source under good weather conditions and a 5 sigma detection above 100 GeV was achieved after 12 h of observations from September 28th till October 3rd. This is the first time that VHE gamma rays are measured from a direction consistent with a detected neutrino event. Several follow up observations from other observatories have been reported in ATels: #10773, #10787, #10791, #10792, #10794, #10799, #10801, GCN: #21941, #21930, #21924, #21923, #21917, #21916. The MAGIC contact persons for these observations are R. Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de), E. Bernardini (elisa.bernardini@desy.de), K Satalecka (konstancja.satalecka@desy.de). MAGIC is a system of

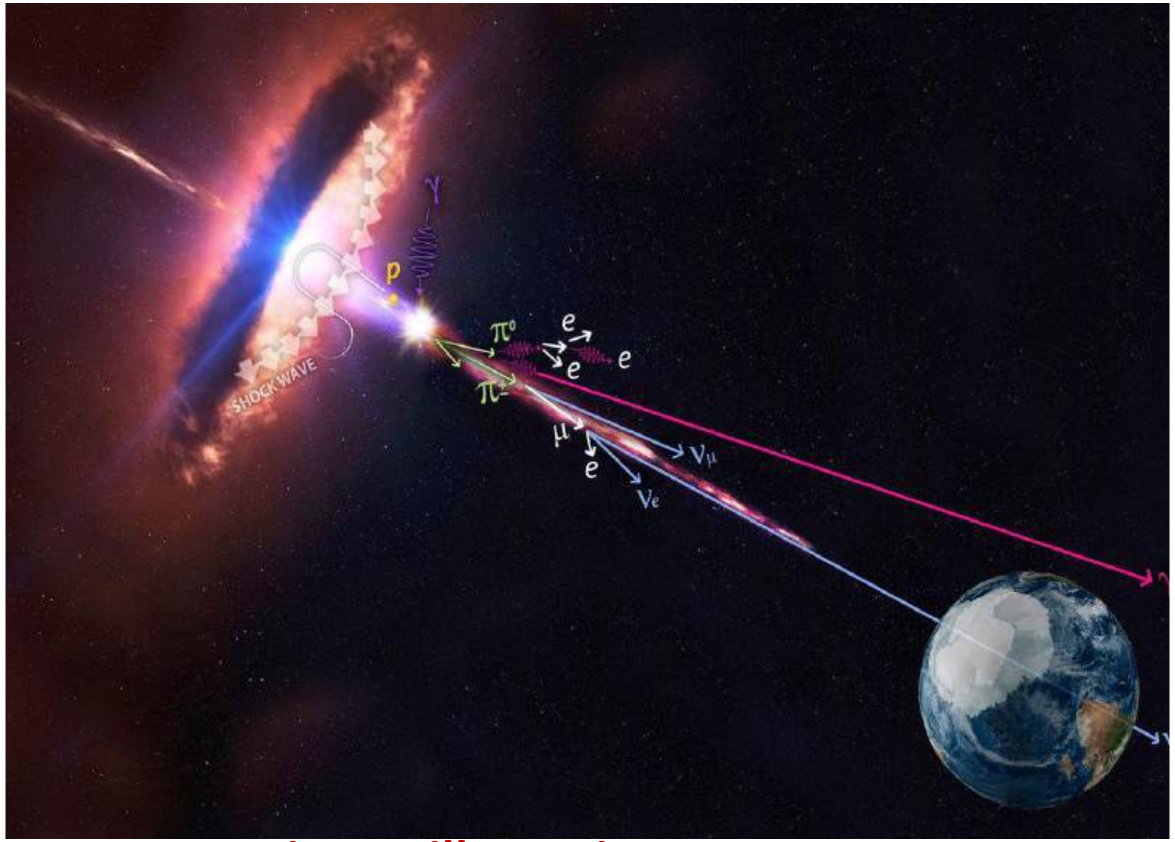


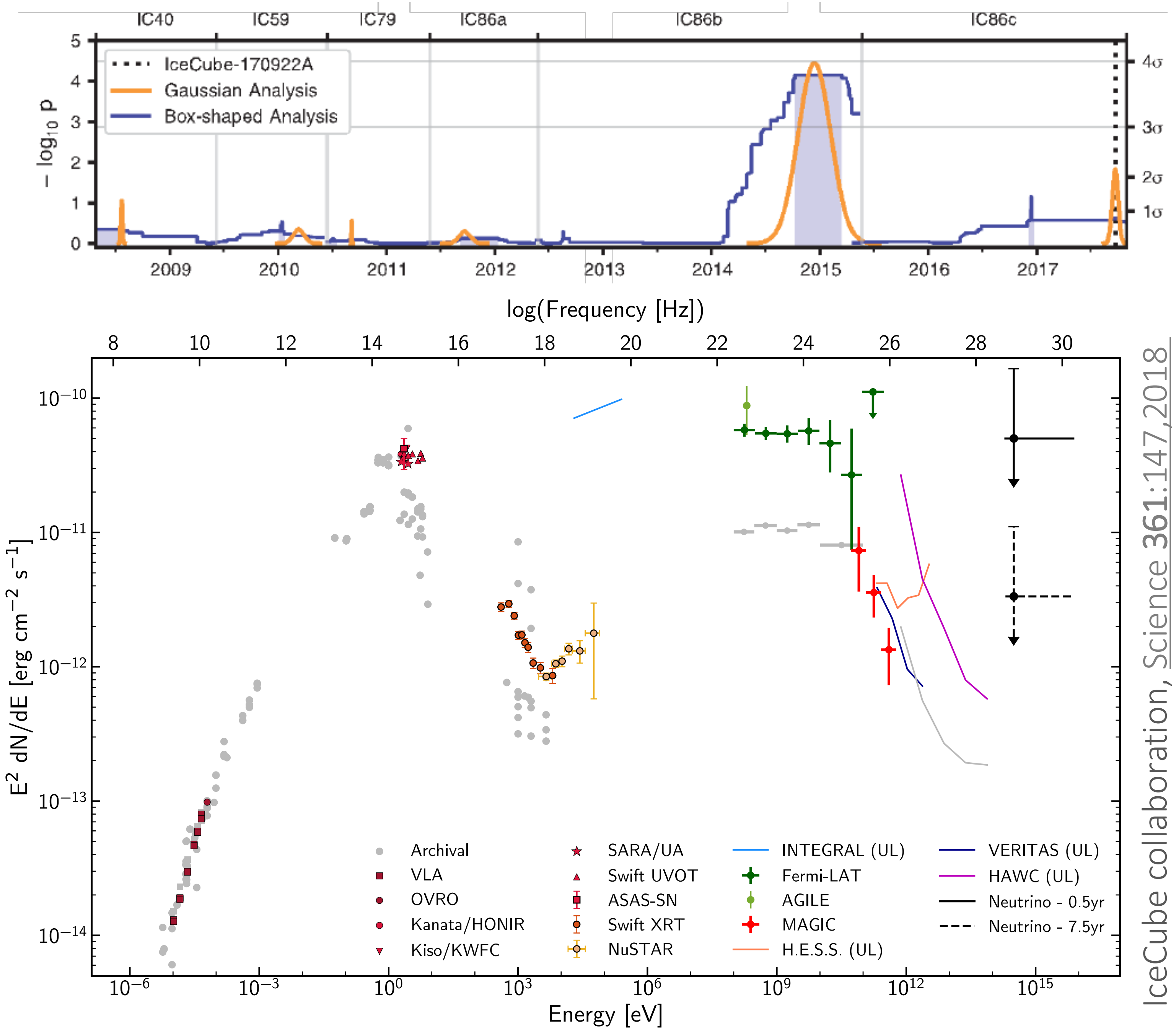


Redshift measured:
$z = 0.3365 \pm 0.0010$

IceCube collaboration, Science **361**:146,2018

Archival records show that TXS 0506+056 is indeed a source of high energy astrophysical νs





IceCube collaboration, Science 361:147,2018

Many questions still remain

- Why TXS 0506+056?
  - A distant (~4 Bly) and very luminous blazar … why not closer blazars?
- What other objects are out there like TXS 0506+056?
  - Ongoing investigations with MM partners to resolve this …
  - Continued issuing of alerts

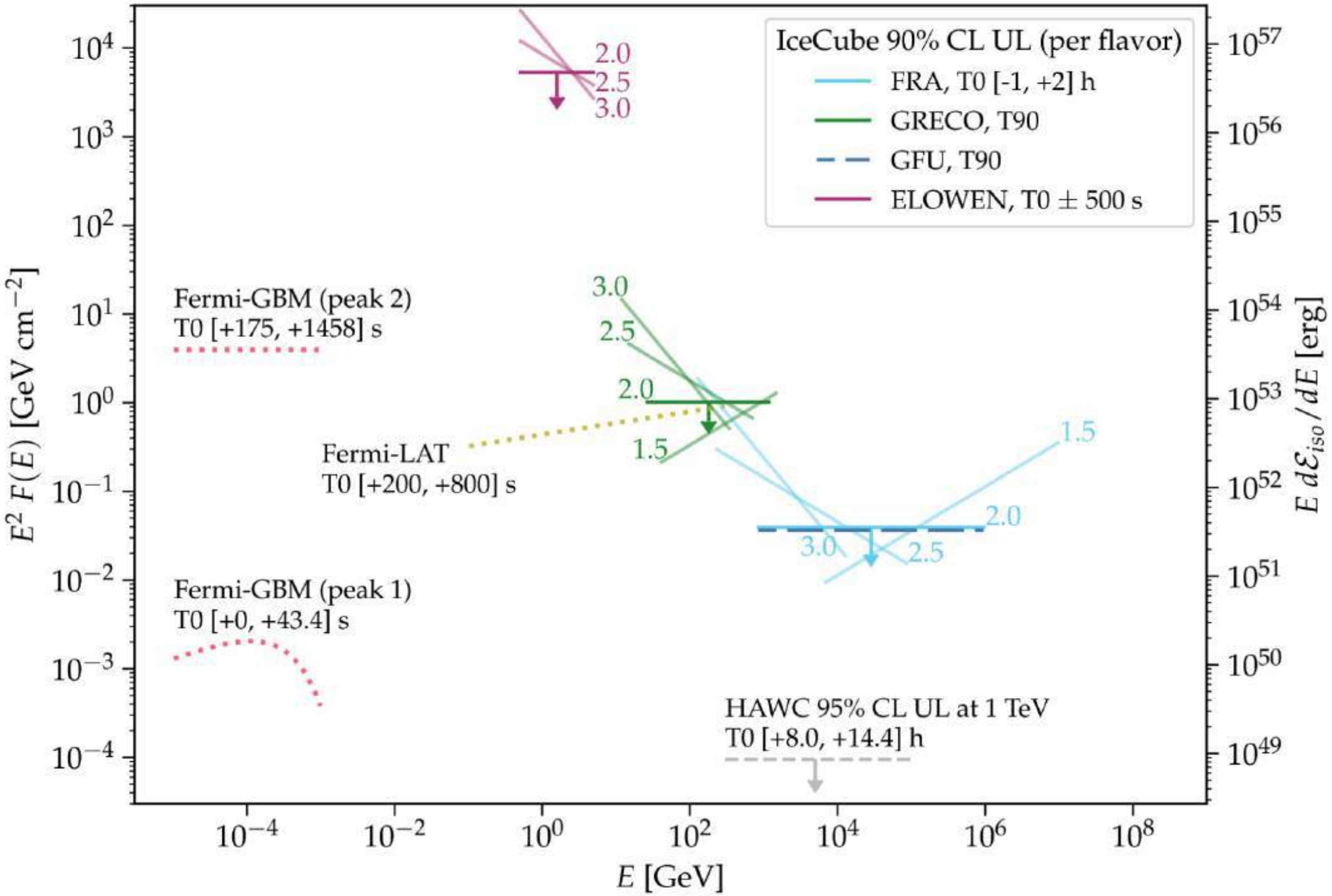
However *no* neutrinos have yet been observed from γ-ray Bursts

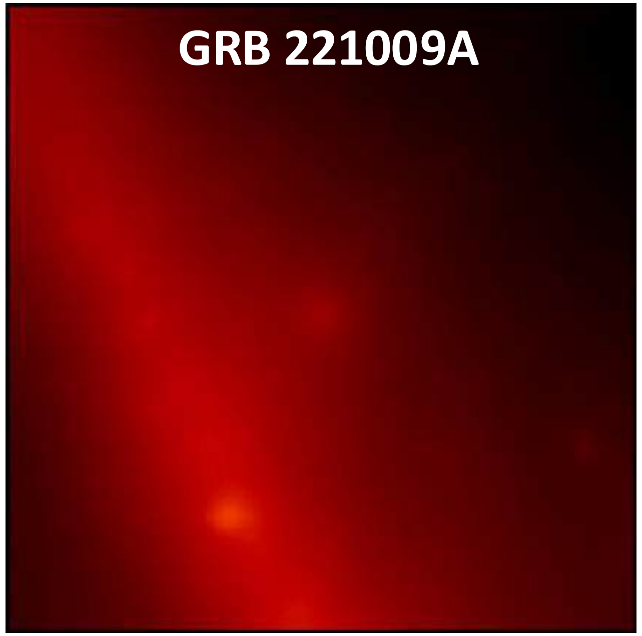
IceCube collaboration, Astrophys.J.**939**:116,2022 … Nature **484**:351,2012)

Brightest of all time (@ z = 0.151) – observed by a plethora of instruments

Highest energy photon (~18 TeV) ever observed – by LHASSO (Huang *et al.* GCN 32677)

IceCube collaboration, ApJL **946**:L26,2023

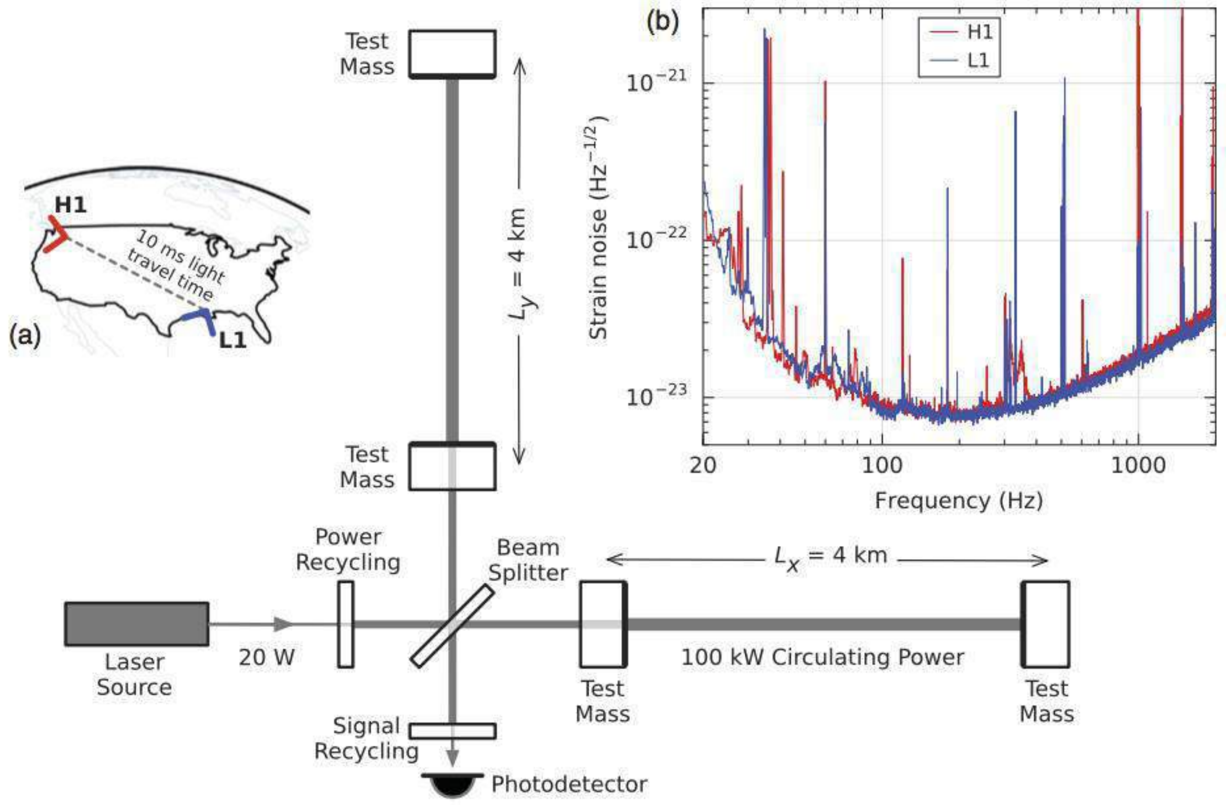


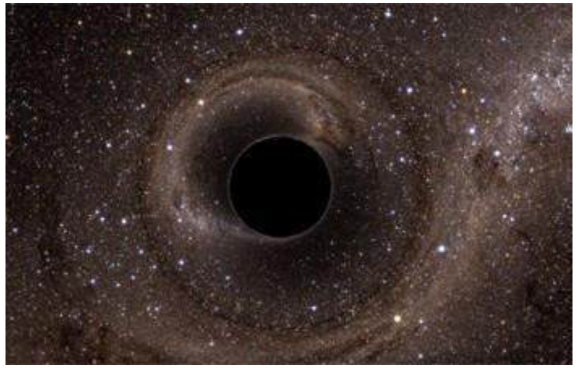


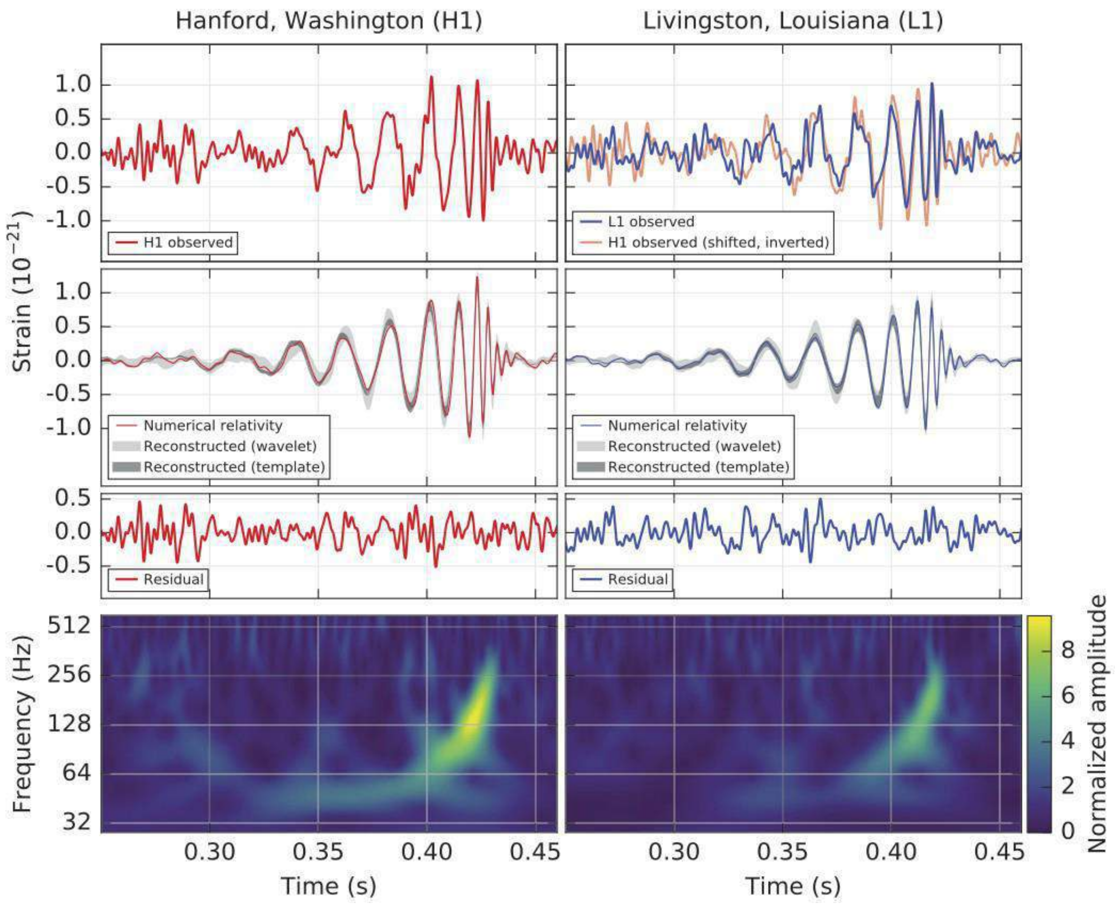
- Initial response via Fast Response Analysis
- *No* neutrino emission found in -1 day +2 days (Thwaites *et al*. GCN Circular 32665)
- Severe constraints on theoretical models

IceCube collaboration, Science **361**:147,2018; **939**:116,2022

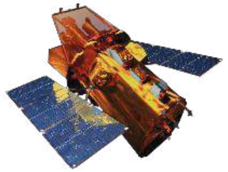
Meanwhile another new window has opened on the sky … in gravitational waves

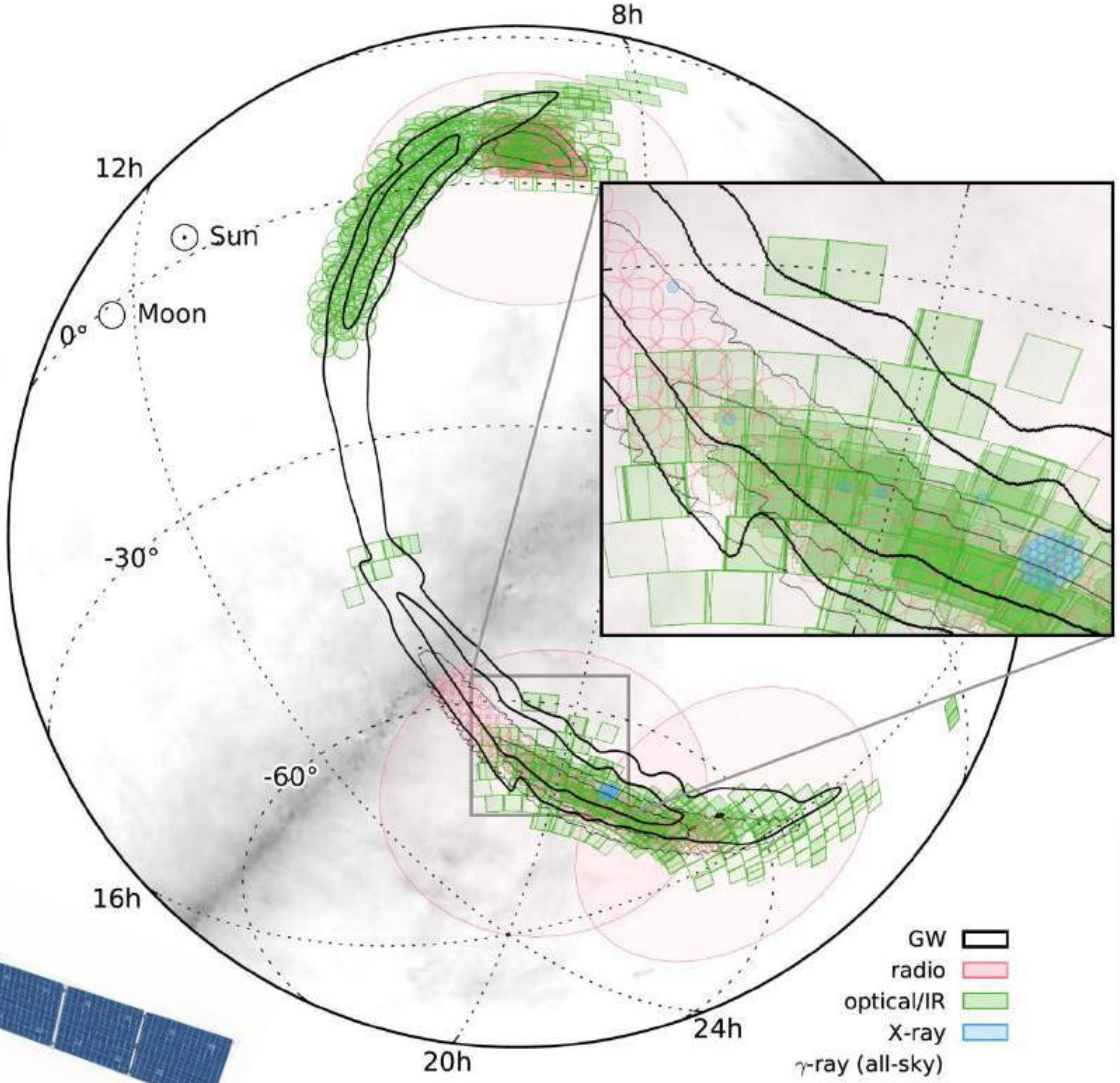


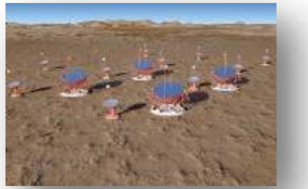




Multi-messenger astronomy



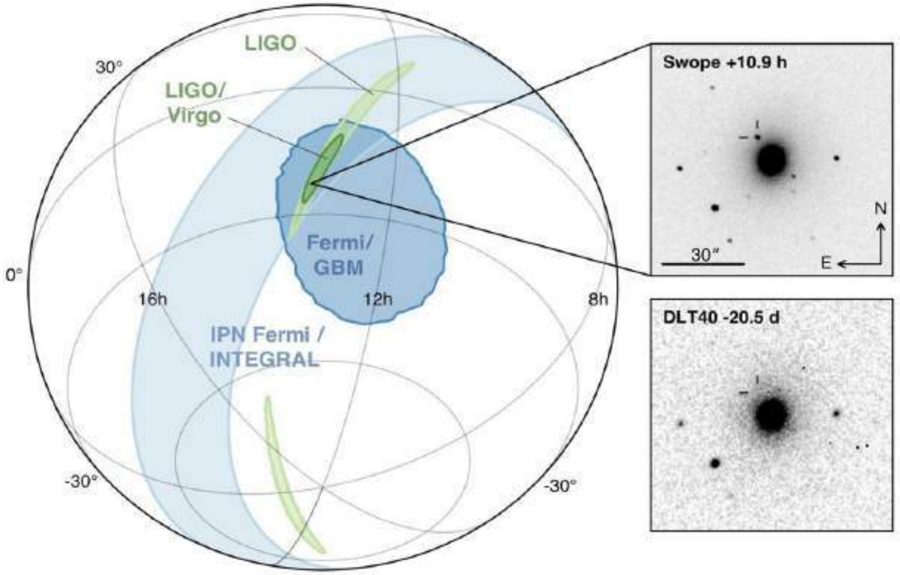


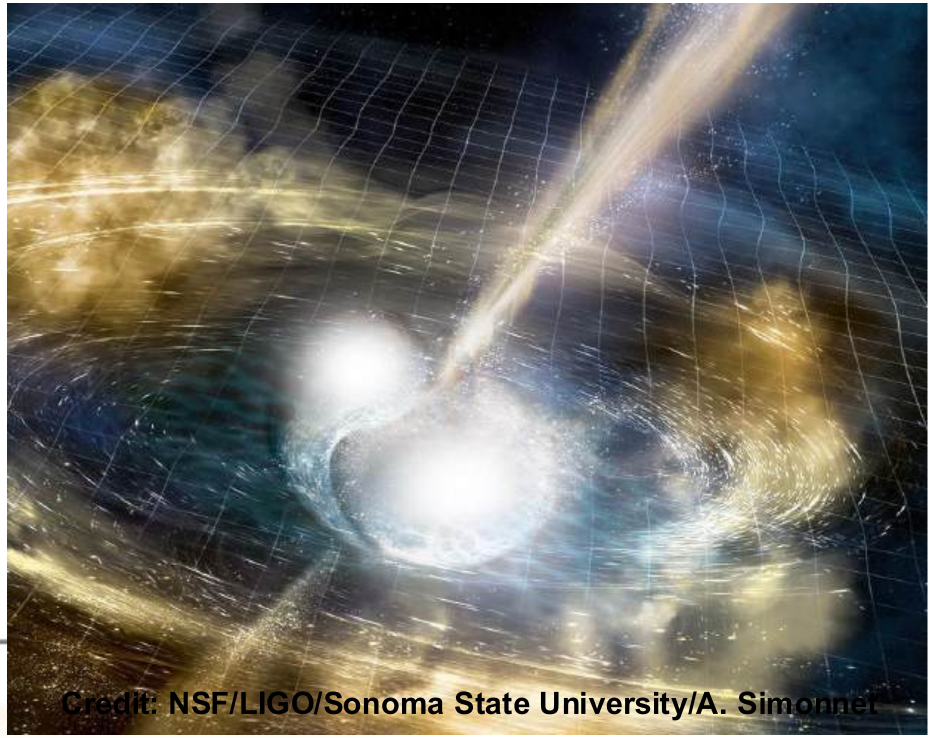


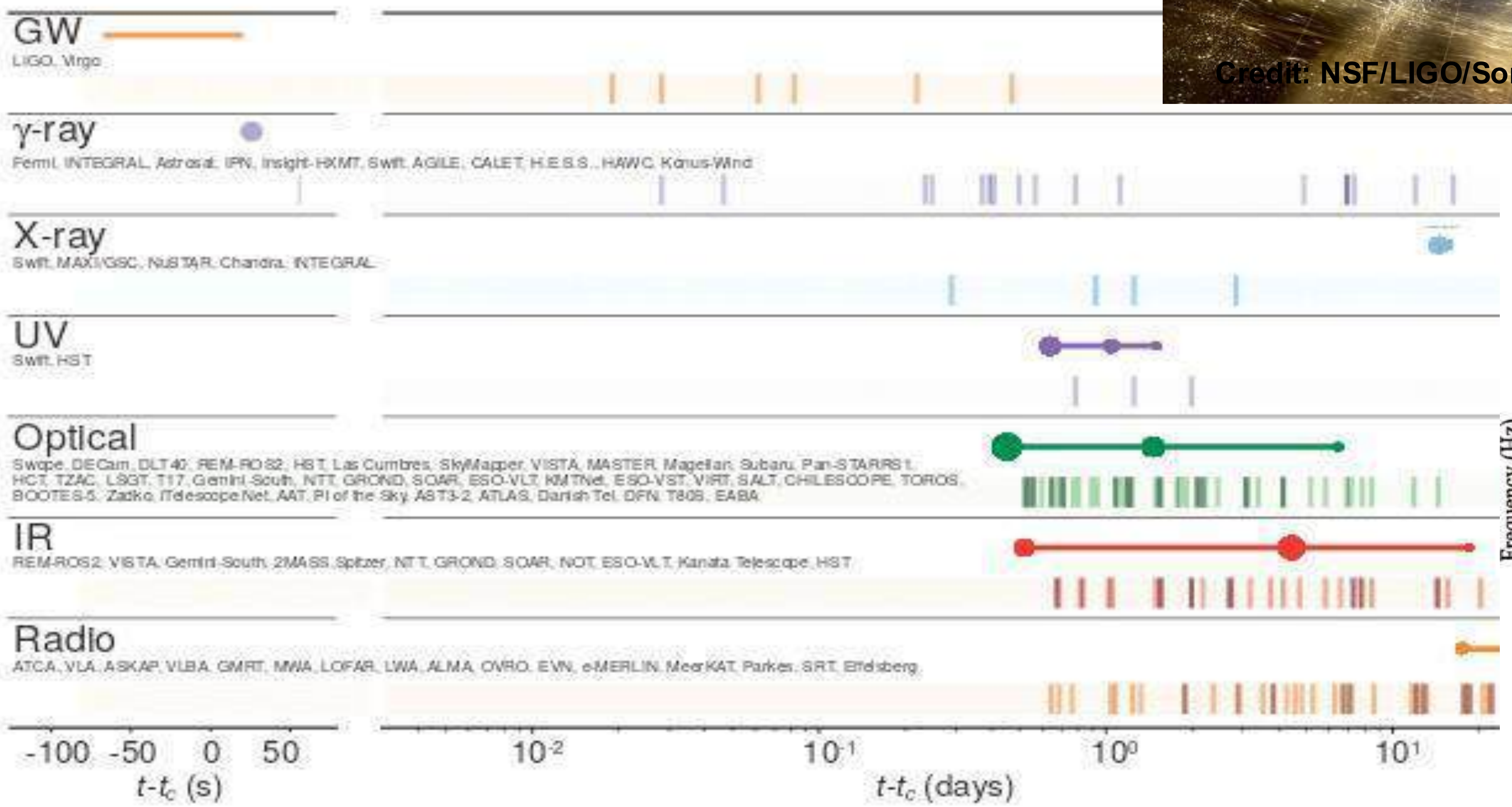
Astrophys. J..826, L13 (2016)

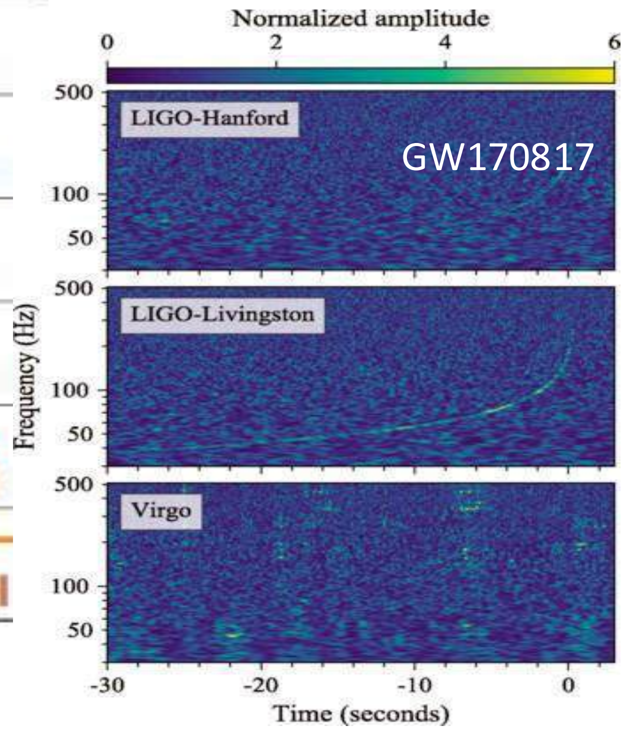
For BH mergers no coincident signals have been seen in photons (*not* unexpected however)

However photons *were* detected from a neutron star – neutron star merger



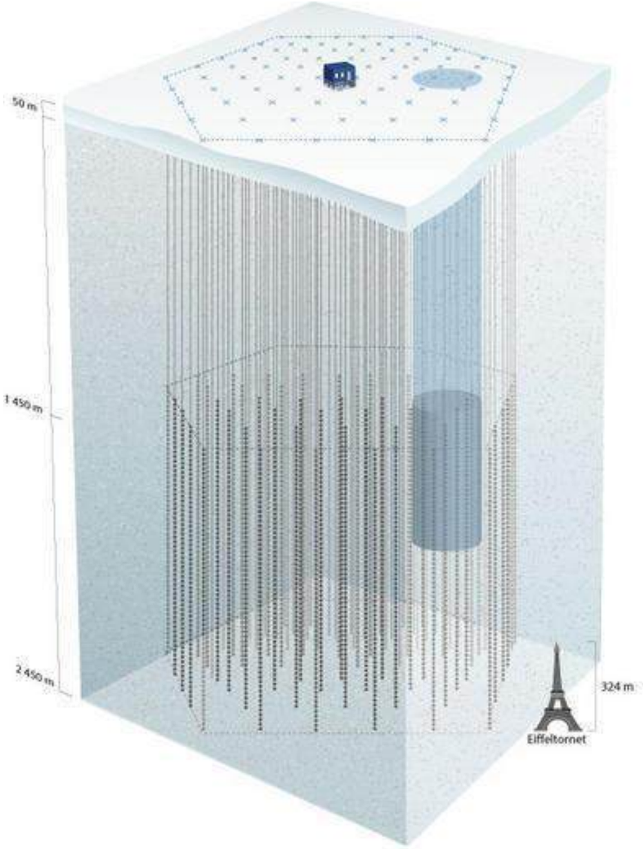




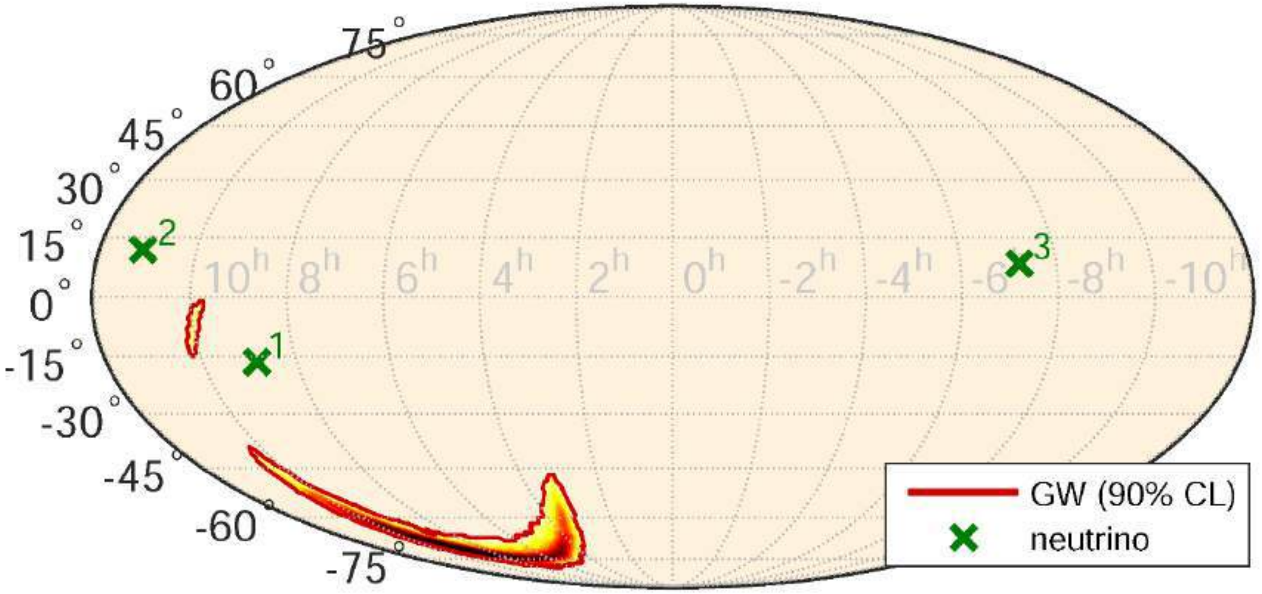


Astrophys. J. Lett. 848:L12,2017

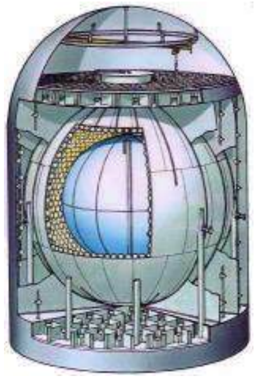
So far *no* coincident neutrinos seen from any GW event



IceCube

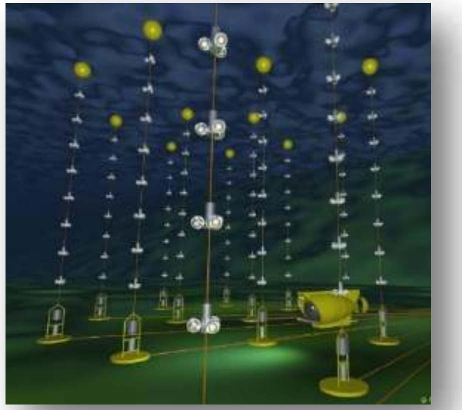


KamLAND



1606.07155

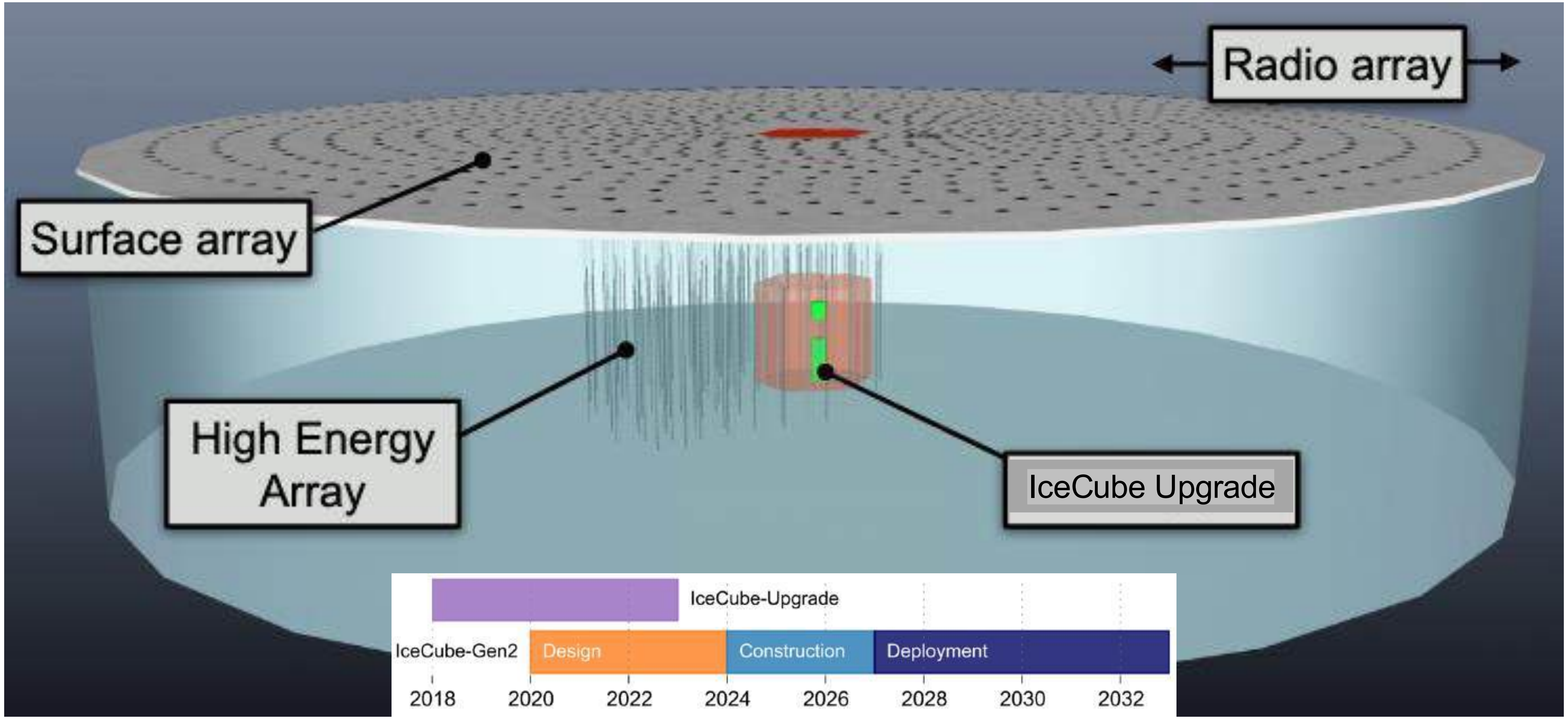
ANTARES



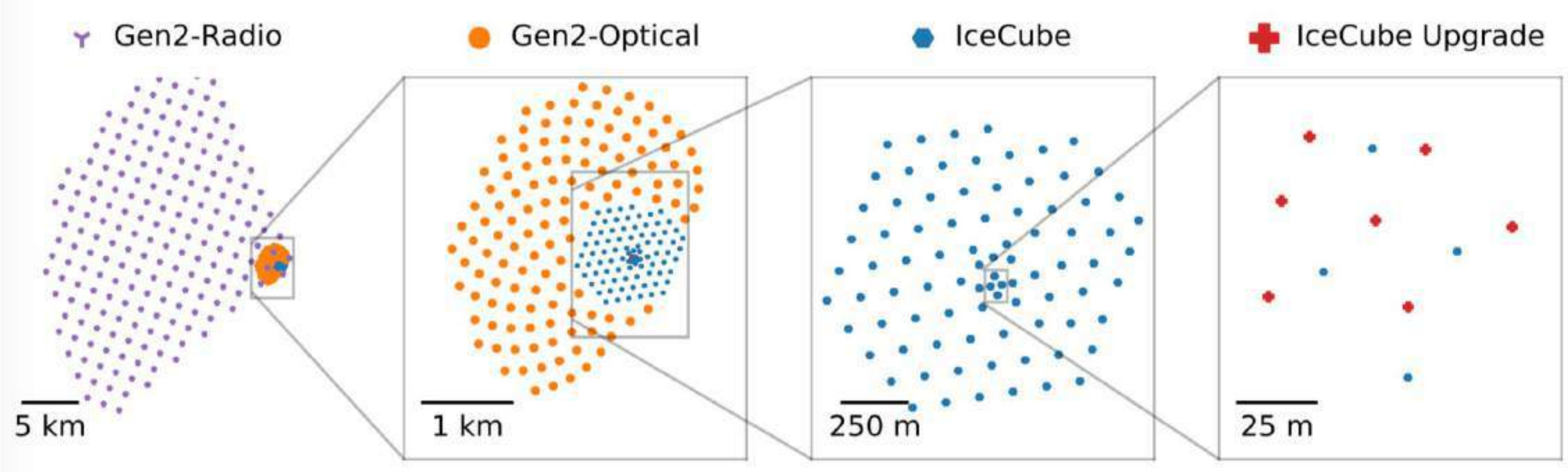
#	ΔT [s]	RA [h]	Dec [°]	σ_μ^{rec} [°]	E_μ^{rec} [TeV]	fraction
1	+37.2	8.84	−16.6	0.35	175	12.5%
2	+163.2	11.13	12.0	1.95	1.22	26.5%
3	+311.4	−7.23	8.4	0.47	0.33	98.4%

ANTARES+IceCube+LIGO+Virgo, Phys. Rev. D93, 122010 (2016)

To do astronomy & particle physics with cosmic neutrinos think BIG!



IceCube-Gen2 collaboration, arXiv:2008.04323



THE ICECUBE-GEN2 COLLABORATION

AUSTRALIA
University of Adelaide

BELGIUM
UCLouvain
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

CANADA
Queen's University
University of Alberta–Edmonton

DENMARK
University of Copenhagen

GERMANY
Deutsches Elektronen-Synchrotron
ECAP, Universität Erlangen-Nürnberg
Humboldt–Universität zu Berlin
Karlsruhe Institute of Technology
Ruhr-Universität Bochum
RWTH Aachen University
Technische Universität Dortmund
Technische Universität München
Universität Mainz
Universität Wuppertal
Westfälische Wilhelms-Universität Münster

INDIA
Tata Institute of Fundamental Research

ITALY
University of Padova

JAPAN
Chiba University
Osaka Metropolitan University

NEW ZEALAND
University of Canterbury

REPUBLIC OF KOREA
Sungkyunkwan University

SWEDEN
Stockholms universitet
Uppsala universitet

SWITZERLAND
Université de Genève

TAIWAN
Academia Sinica

UNITED KINGDOM
University of Oxford

UNITED STATES
Clark Atlanta University
Columbia University
Drexel University
Georgia Institute of Technology
Harvard University
Lawrence Berkeley National Lab
Loyola University Chicago
Marquette University
Massachusetts Institute of Technology
Mercer University
Michigan State University
Ohio State University
Pennsylvania State University
South Dakota School of Mines and Technology
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California, Berkeley
University of California, Irvine
University of Chicago
University of Delaware
University of Kansas
University of Maryland
University of Nevada, Las Vegas
University of Notre Dame
University of Rochester
University of Texas at Arlington
University of Utah
University of Wisconsin–Madison
University of Wisconsin–River Falls
Whittier College
Yale University

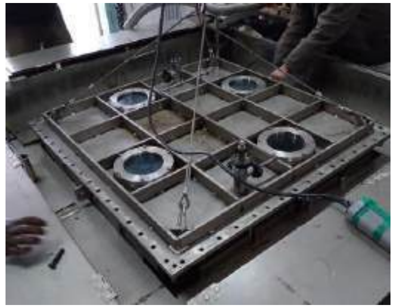
ICECUBE GEN2

ICECUBE-GEN2.WISC.EDU

opportunities opening up with TIFR National Centre for Cosmic Rays, Ooty

Strong interest in participation of India in IceCube-Gen2

M Rameez (DHEP, TIFR) is Associate Member of IceCube and Full Member of IceCube Gen2 from Apr 2021



Proposed contributions to Cabling, Computing, Scintillators, Radio, …
+ astroparticle theory input

Summary

- Neutrino telescopes have already measured the ν DIS cross-section up to cms energies ~10 times higher than are attainable at the LHC … finding *no* deviation from the SM

  - **This sets constraints on BSM physics that can increase the cross-section e.g. new TeV-scale dimensions, leptoquarks, …**

(ruled out already in Run II of LHC – but with cosmic ν can go much further in energy)

- There may be *non*-perturbative SM processes which can affect the ν DIS cross-section at higher energies, e.g. electroweak sphalerons and QCD colour glass condensate - to probe this will require studying the highest energy (GZK) cosmic neutrinos at $\sim 10^{10}$ GeV

- The measured ν flavour ratio is sensitive to any process that can affect the coherence of neutrino oscillations over astronomical baselines, e.g. ν decay or non-standard interactions, or even LI-violation and 'space-time foam' at the Planck scale

To probe the cosmic energy frontier we *must* think **big** (IceCube-Gen2, KM3NeT, …)

The real voyage of discovery consists not in seeking new lands but in seeing with new eyes - Marcel Proust