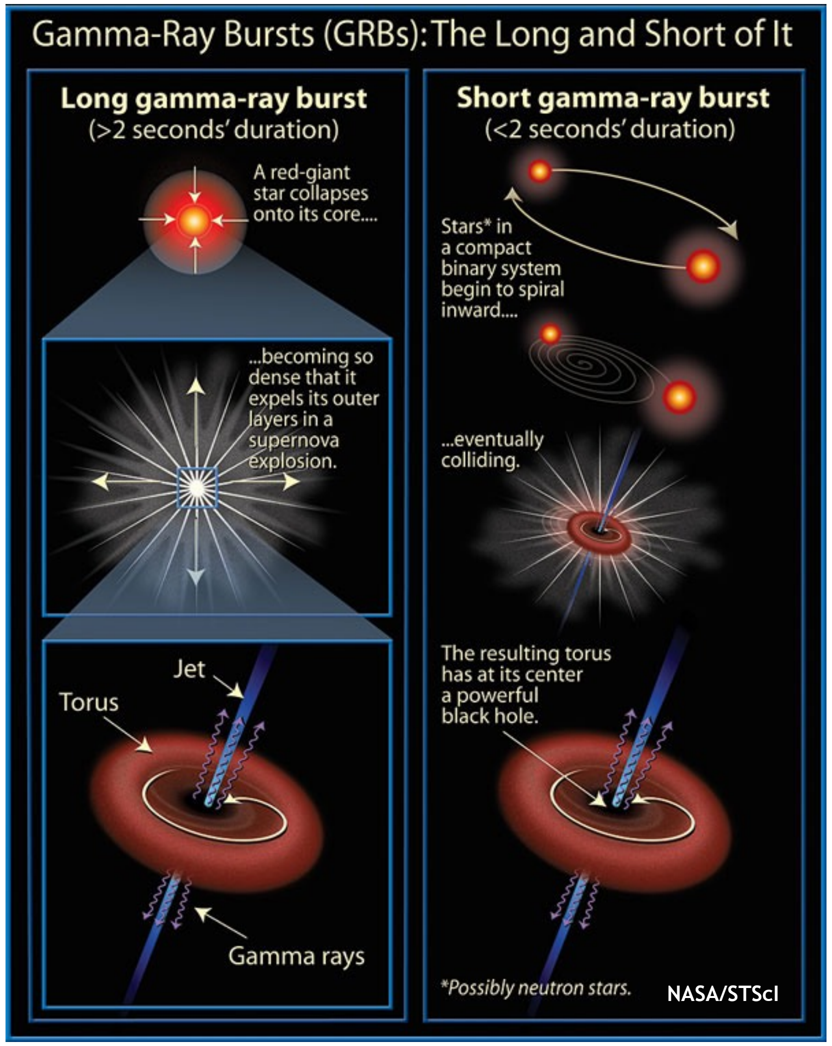
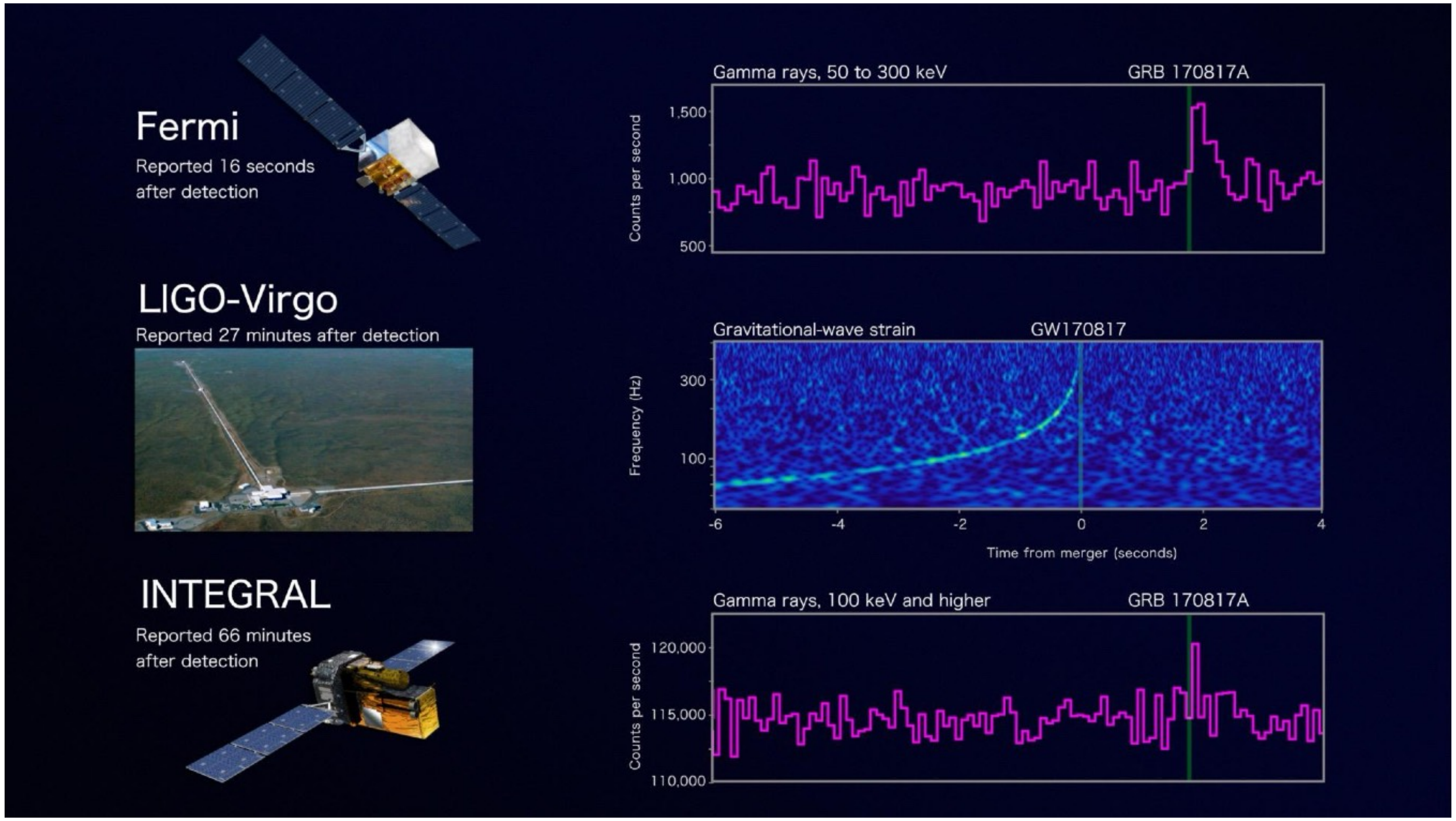
Gravitational Waves & IceCube

We have a connection between gamma rays and gravitational waves…

GW170817/GRB170817A





LIGO/Virgo; Fermi; INTEGRAL; NASA/DOE; NSF; EGO; ESA.

THE ASTROPHYSICAL JOURNAL LETTERS, 850:L35 (18pp), 2017 December 1 https://doi.org/10.3847/2041-8213/aa9aed

Search for High-energy Neutrinos from Binary Neutron Star Merger GW170817 with ANTARES, IceCube, and the Pierre Auger Observatory

ANTARES Collaboration, IceCube Collaboration, The Pierre Auger Collaboration,
and LIGO Scientific Collaboration and Virgo Collaboration
(See the end matter for the full list of authors.)

Received 2017 October 15; revised 2017 November 9; accepted 2017 November 10; published 2017 November 29

Abstract

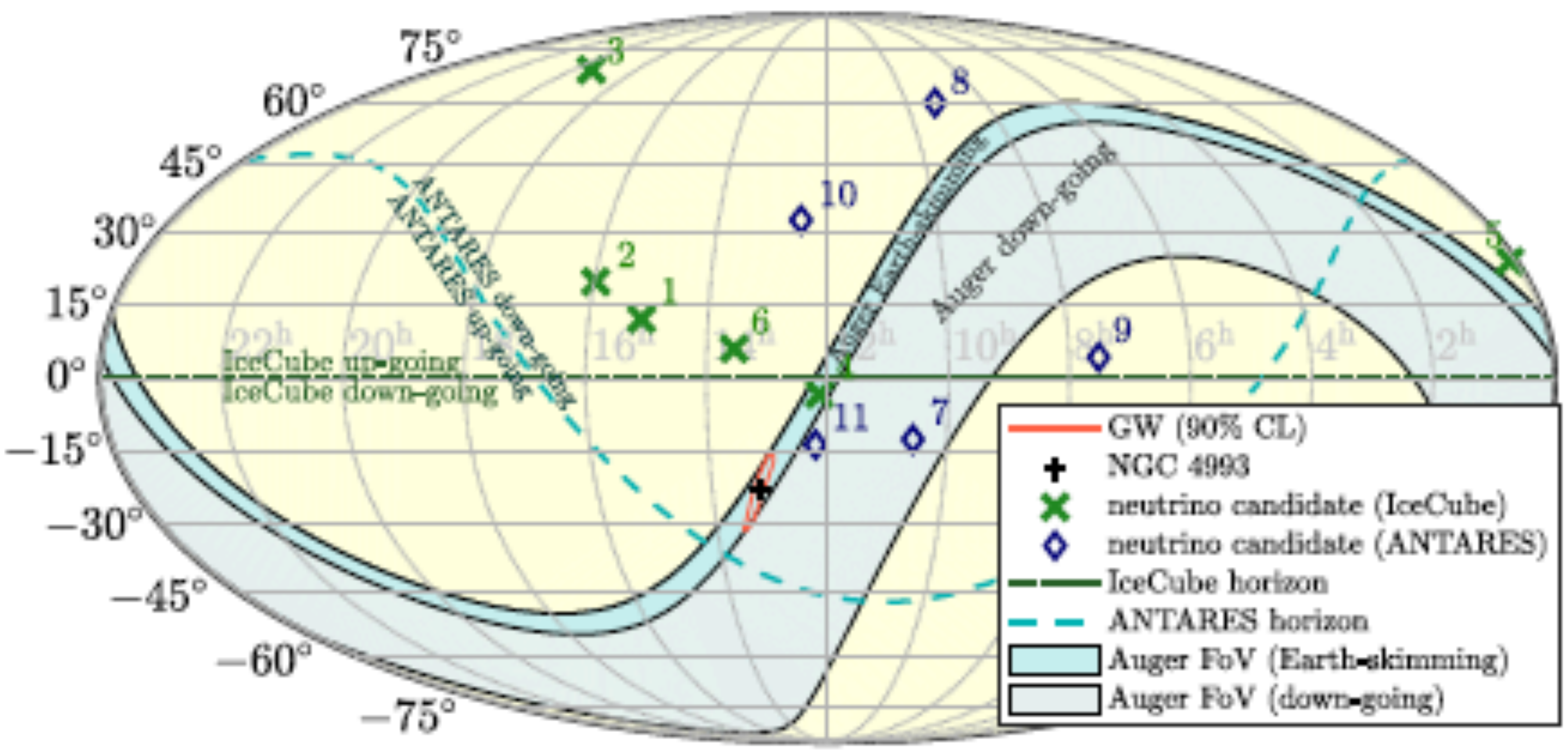
The Advanced LIGO and Advanced Virgo observatories recently discovered gravitational waves from a binary neutron star inspiral. A short gamma-ray burst (GRB) that followed the merger of this binary was also recorded by the *Fermi* Gamma-ray Burst Monitor (*Fermi*-GBM), and the Anti-Coincidence Shield for the Spectrometer for the *International Gamma-Ray Astrophysics Laboratory* (*INTEGRAL*), indicating particle acceleration by the source. The precise location of the event was determined by optical detections of emission following the merger. We searched for high-energy neutrinos from the merger in the GeV–EeV energy range using the ANTARES, IceCube, and Pierre Auger Observatories. No neutrinos directionally coincident with the source were detected within ±500 s around the merger time. Additionally, no MeV neutrino burst signal was detected coincident with the merger. We further carried out an extended search in the direction of the source for high-energy neutrinos within the 14 day period following the merger, but found no evidence of emission. We used these results to probe dissipation mechanisms in relativistic outflows driven by the binary neutron star merger. The non-detection is consistent with model predictions of short GRBs observed at a large off-axis angle.

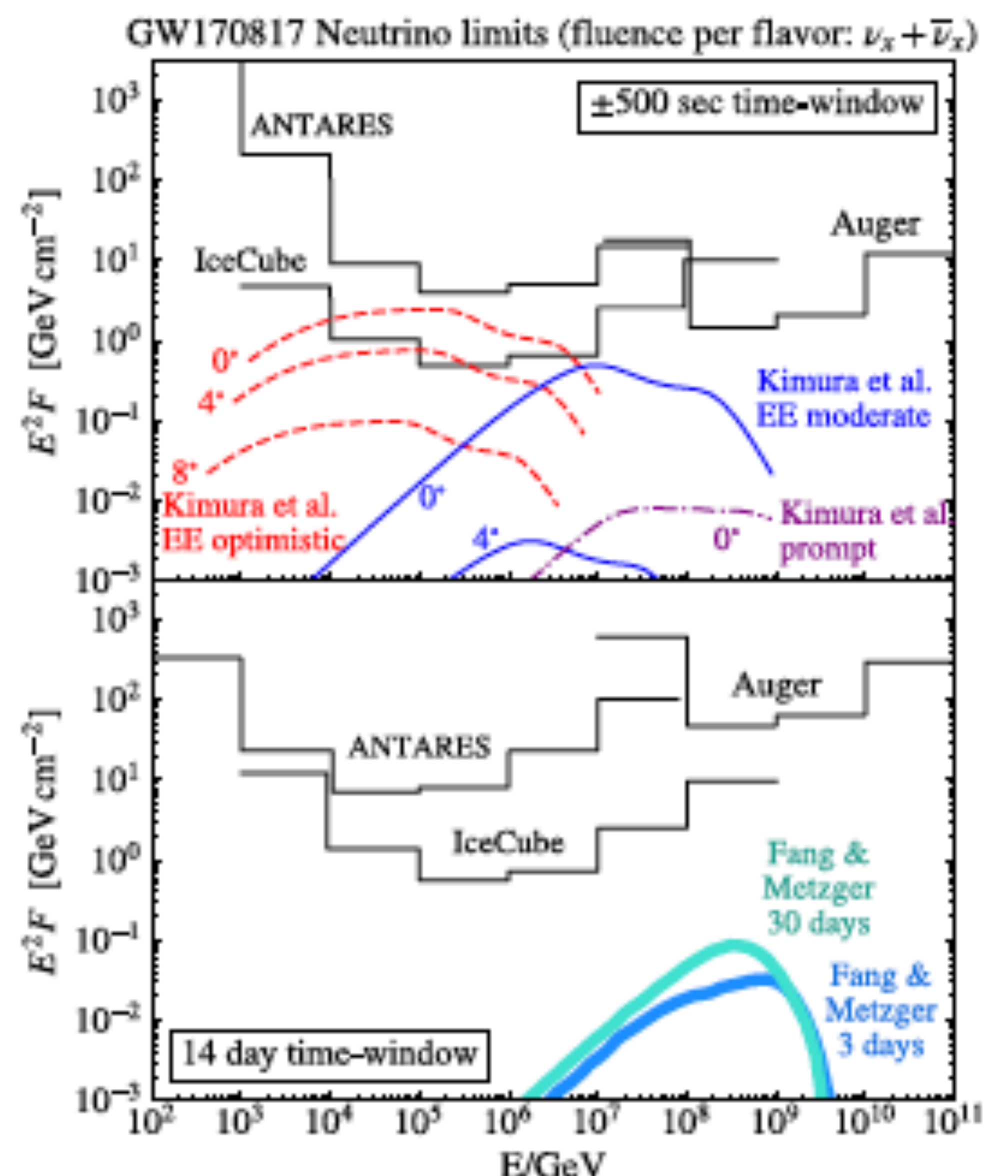
Gravitational Waves

GW170817

- binary neutron star inspiral
- followed by short GRB (observed by Fermi-GBM)

Imre Bartos Neutrino 2018



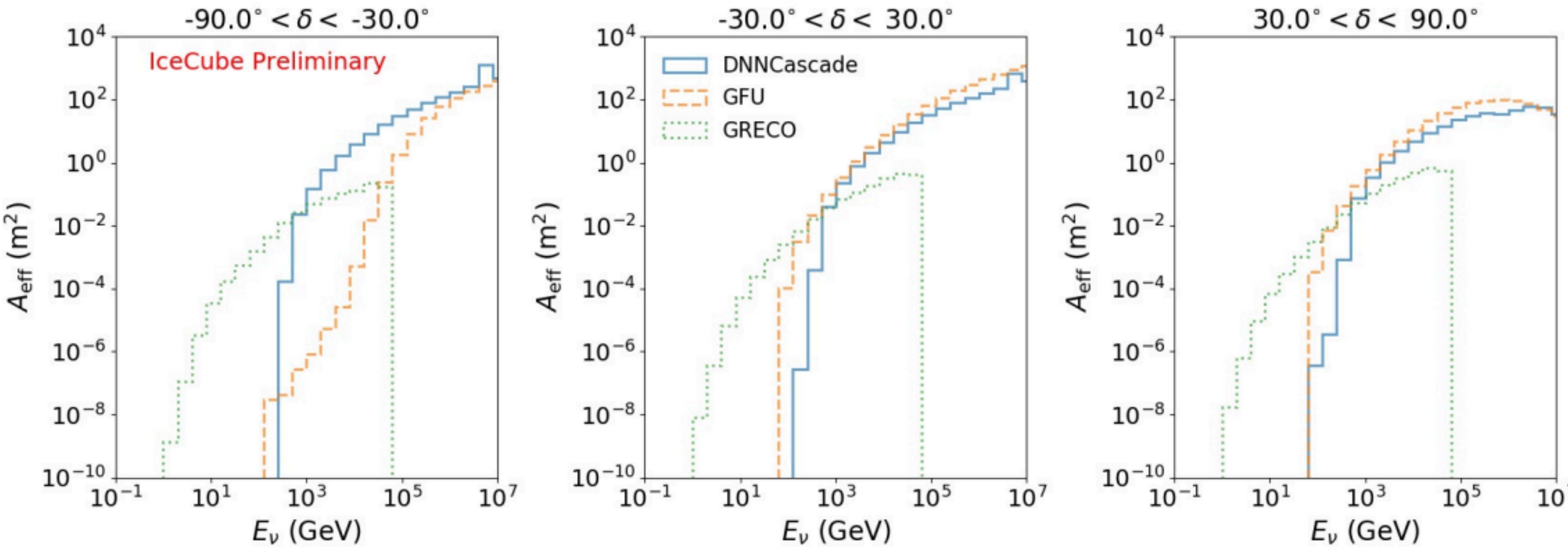


- Search within <u>1000 s</u> and <u>2-week</u> time windows (model motivated).
- Complementary sensitivity from the three detectors.
- No significant coincident detection.
- On-axis emission could have produced detectable emission in some models.

ANTARES, IceCube, Auger, LIGO, Virgo 2017

https://pos.sissa.it/444/1484/pdf

- Third observing run (O3) of the advanced LIGO and Virgo detectors,
- Low-latency follow-up of public candidate alert events in O3, an archival search on high-energy track data, and a low-energy search employing IceCube-DeepCore

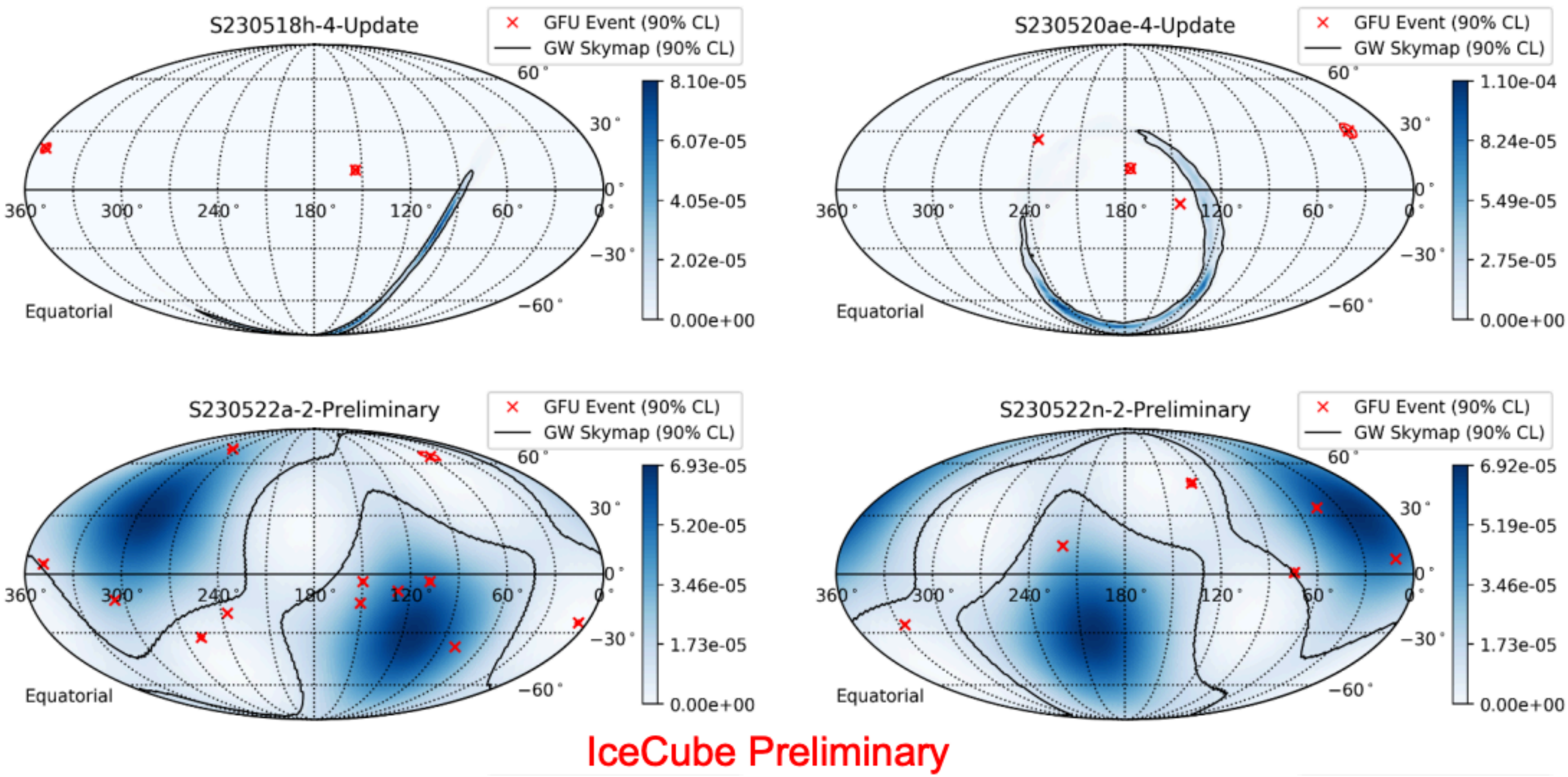


GeV Reconstructed **Events** with Containment for Oscillations (**GRECO**)

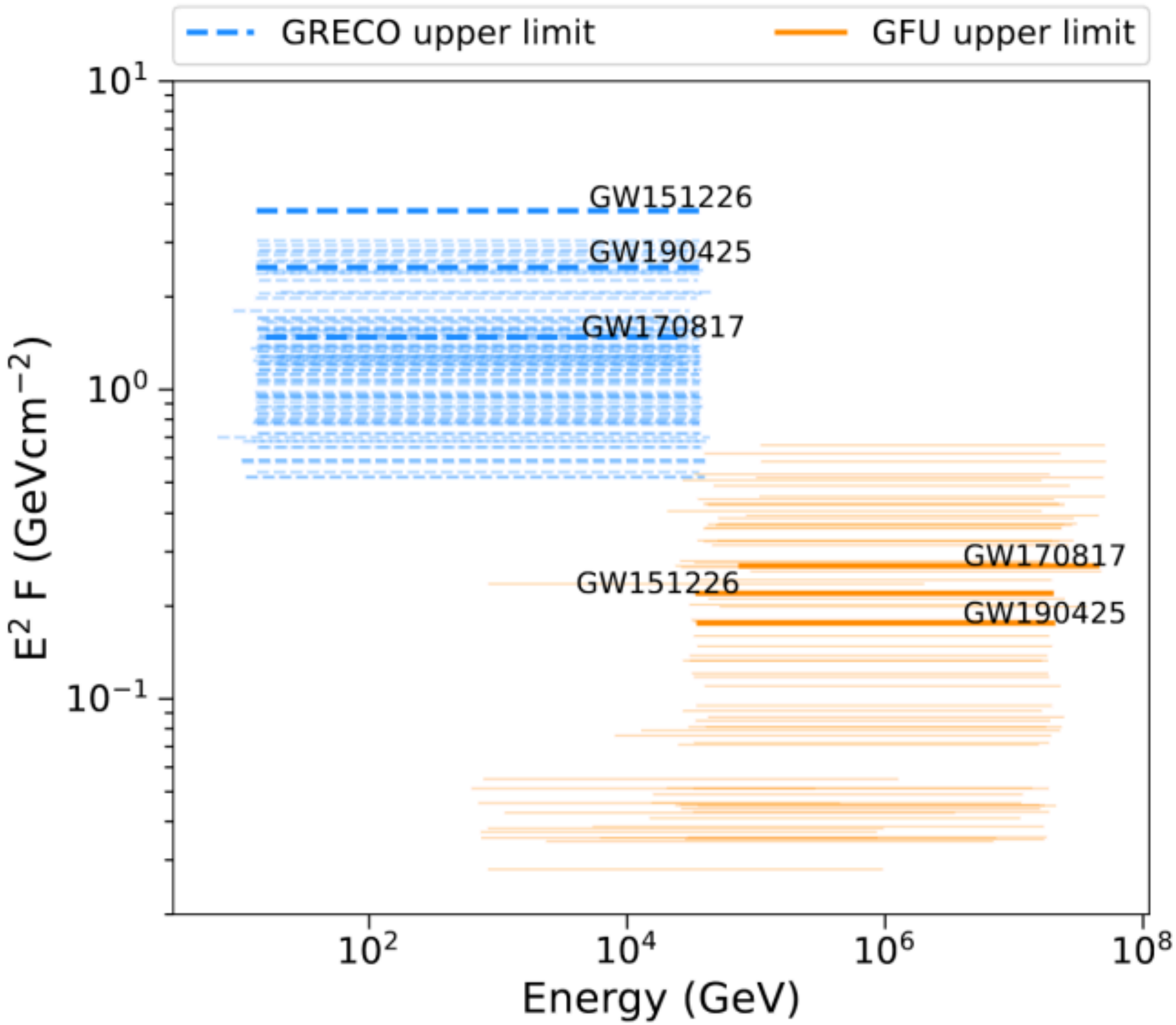
Gamma-ray Follow-Up (**GFU**)

Searches for IceCube Neutrinos Coincident with Gravitational Wave Events

https://pos.sissa.it/444/1484/pdf



https://pos.sissa.it/444/1484/pdf

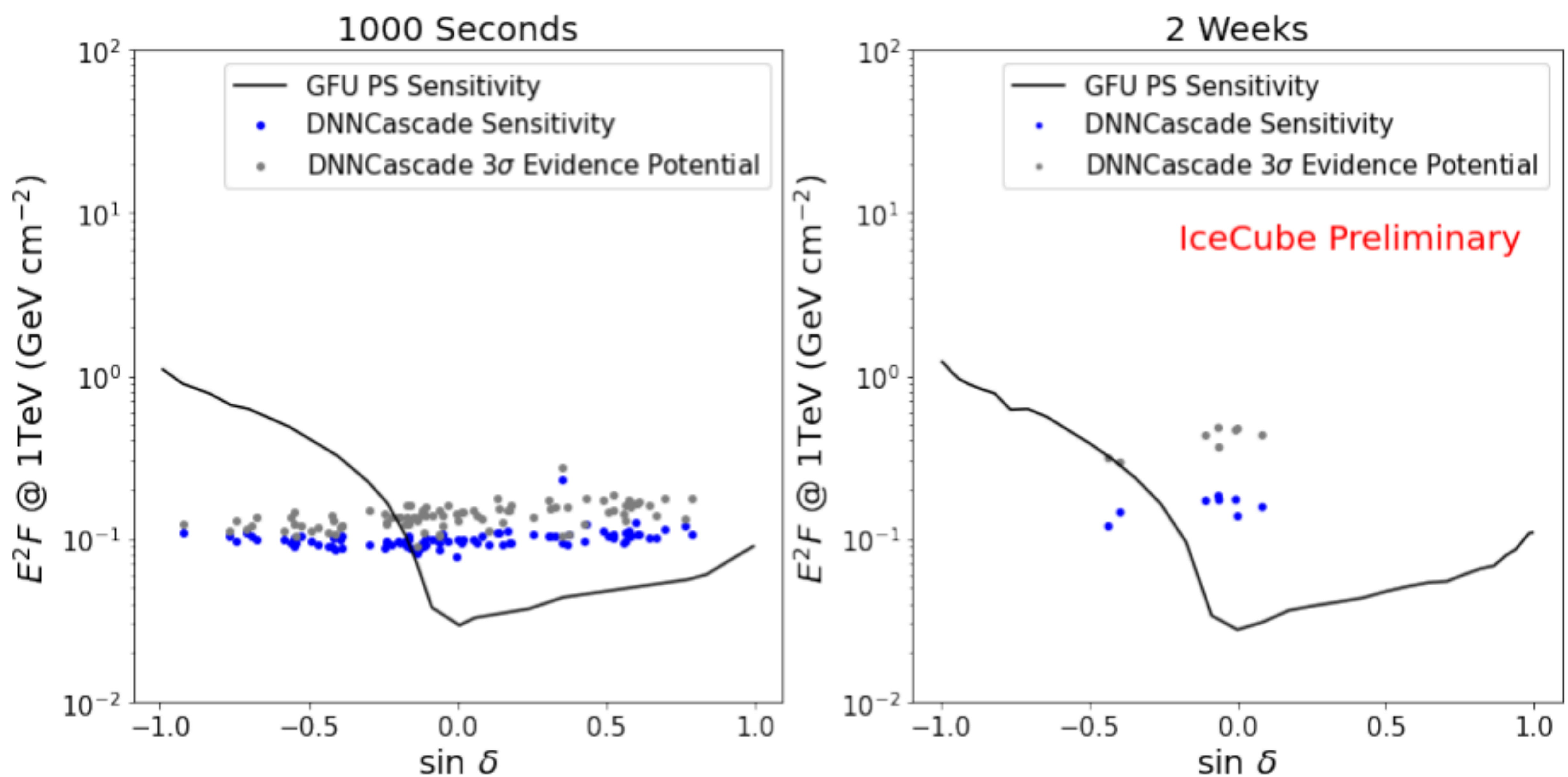


GW151226 (the event with the lowest pre-trial p-value in the GRECO analysis)

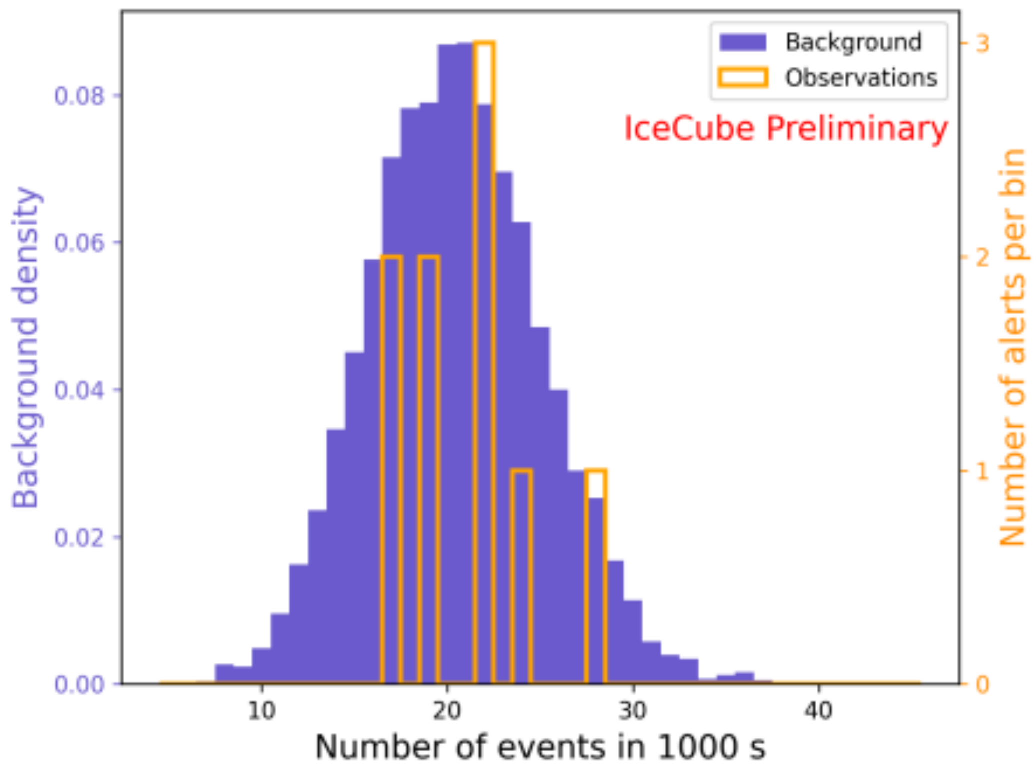
GW190425 (the only BNS event with a pre-trial p-value < 0.1)

GW170817 (first and only BNS event for which the electromagnetic counterpart has been observed)

https://pos.sissa.it/444/1484/pdf



First results of low-energy neutrino follow-ups of Run O4 compact binary mergers with the IceCube Neutrino Observatory

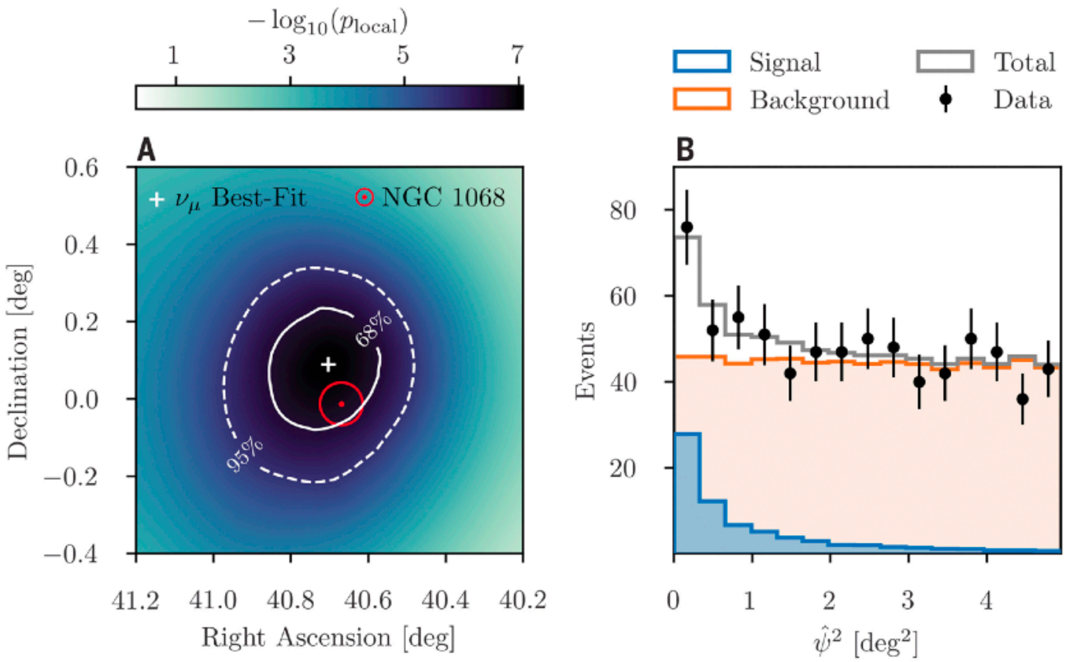


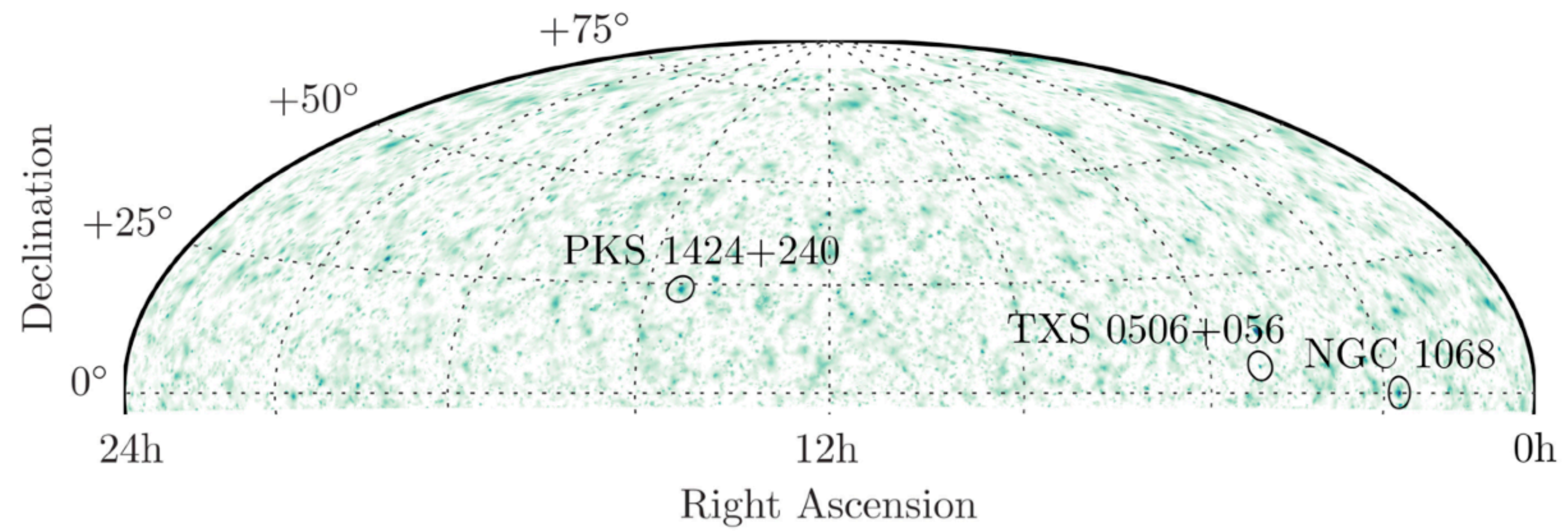
		$\langle N_{bkg} \rangle$	N_{on}	$N_{sig}^{90\%}$	Upper limits on ϕ [GeV^{-1} cm^{-2}] $\gamma = 2$	$\gamma = 2.5$	$\gamma = 3$
S230518h	[GCN]	18.81	24	12.7	1.7×10^3	5.5×10^3	1.4×10^4
S230520ae	[GCN]	19.06	22	10.6	1.4×10^3	4.6×10^3	1.2×10^4
S230522a	[GCN]	19.36	19	8.1	1.1×10^3	3.5×10^3	8.8×10^3
S230522n	[GCN]	19.82	17	6.7	8.9×10^2	2.9×10^3	7.3×10^3
S230529ay	[GCN]	20.34	19	7.6	1.0×10^3	3.3×10^3	8.3×10^3
S230601bf	[GCN]	17.67	28	17.9	2.4×10^3	7.7×10^3	2.0×10^4
S230605o	[GCN]	19.74	22	10.2	1.4×10^3	4.4×10^3	1.1×10^4
S230606d	[GCN]	19.06	17	7.0	9.3×10^2	3.0×10^3	7.6×10^3
S230609u	[GCN]	19.29	22	10.5	1.4×10^3	4.5×10^3	1.2×10^4

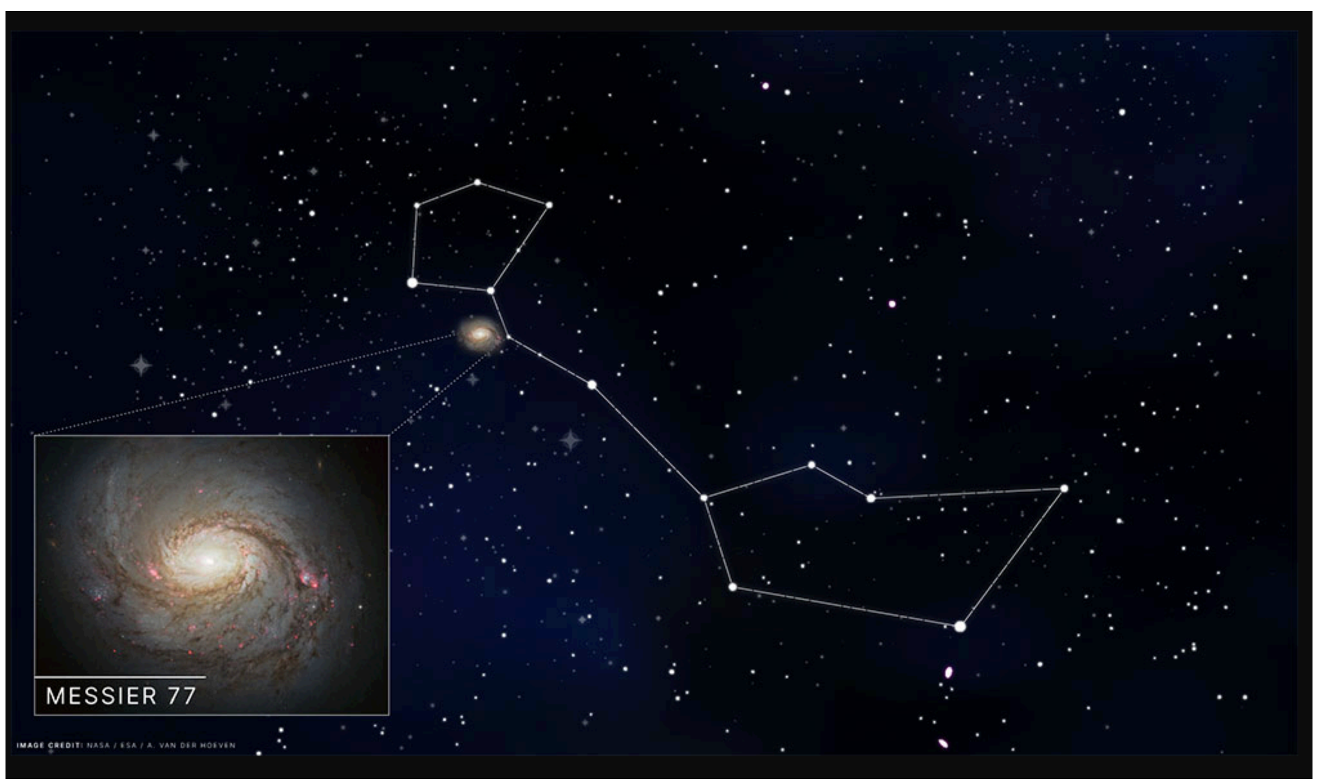
Table 1: Summary of follow-up results for the first O4 GW alerts. The first column indicates the alert name and the link to the corresponding GCN notices. The second and third columns report the numbers of events in the 1000 s time window expected from background $\langle N_{bkg} \rangle = \alpha N_{off}$ and observed N_{on}. The fourth column contains the 90% upper limit on the number of signal events, and the last three columns are the corresponding 90% upper limits on the all-flavor flux normalization ϕ for different spectral indices.

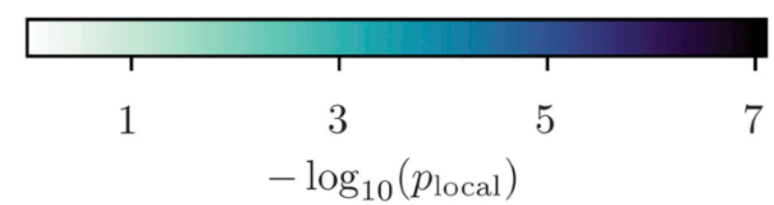
More astrophysical neutrino sources

IceCube Collaboration Science VOL. 378, NO. 6619 (2022)





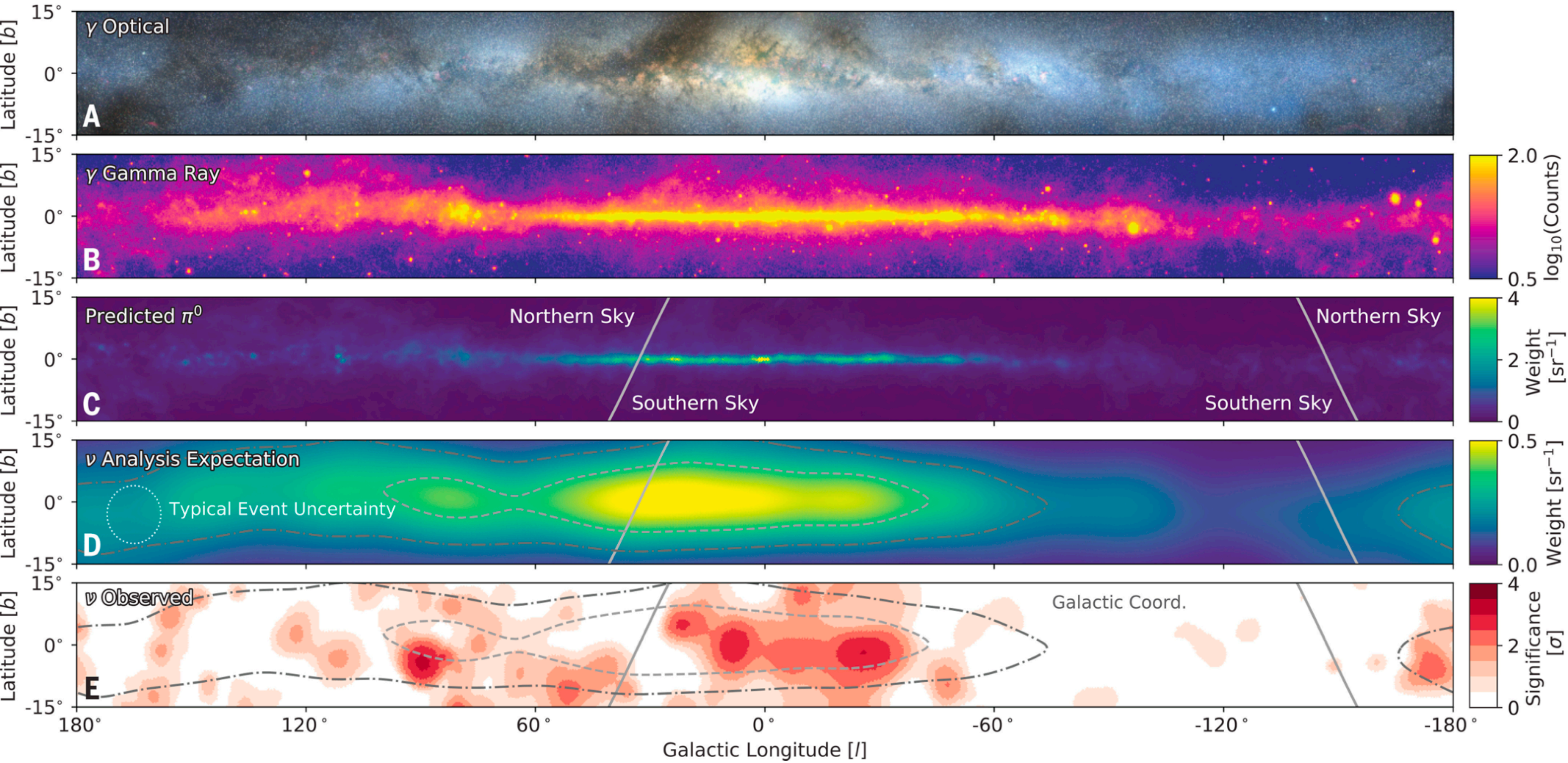




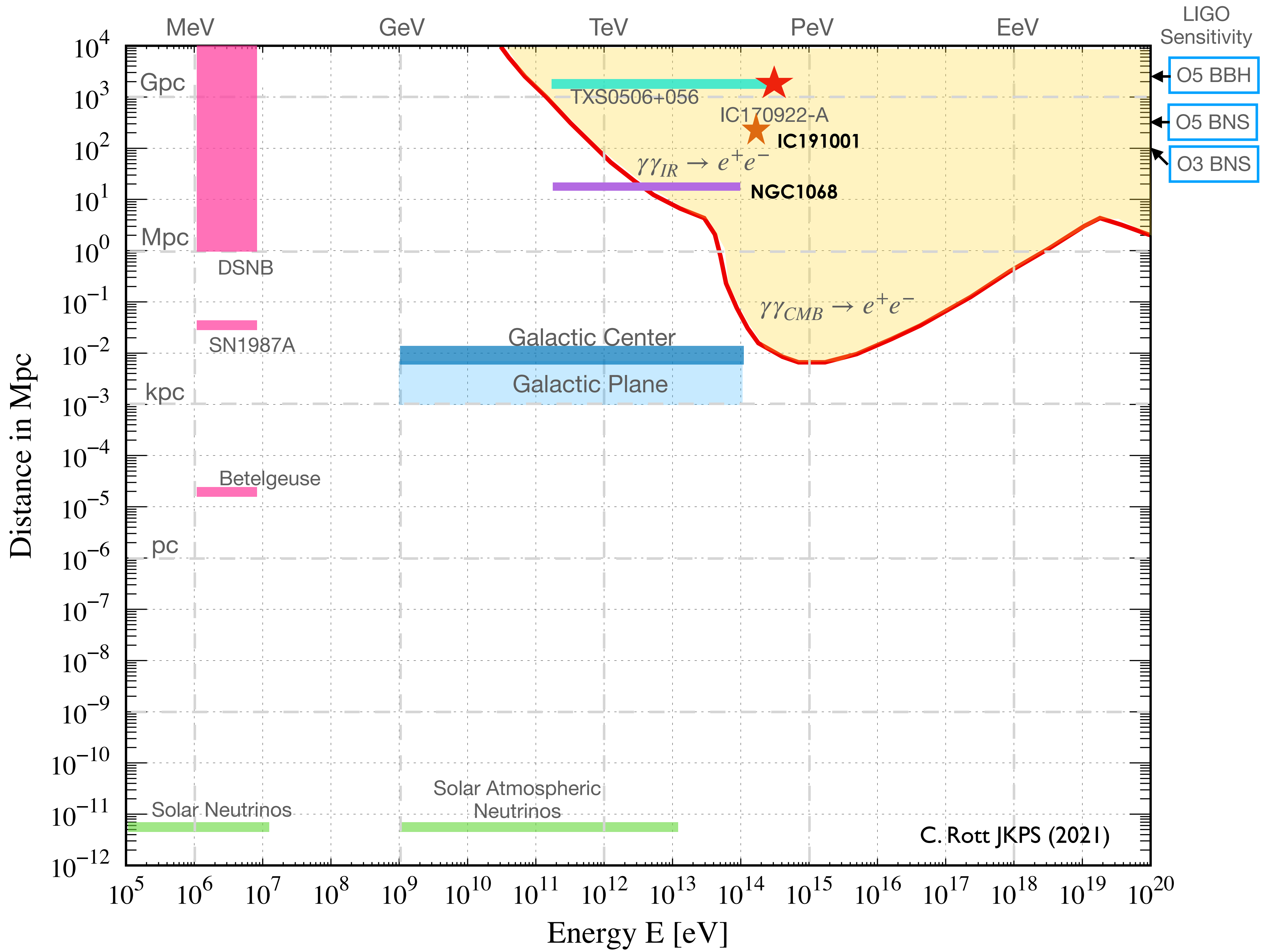
https://attheu.utah.edu/facultystaff/icecube-neutrinos-give-us-first-glimpse-into-the-inner-depths-of-an-active-galaxy/

Observation of high-energy neutrinos from the Galactic plane

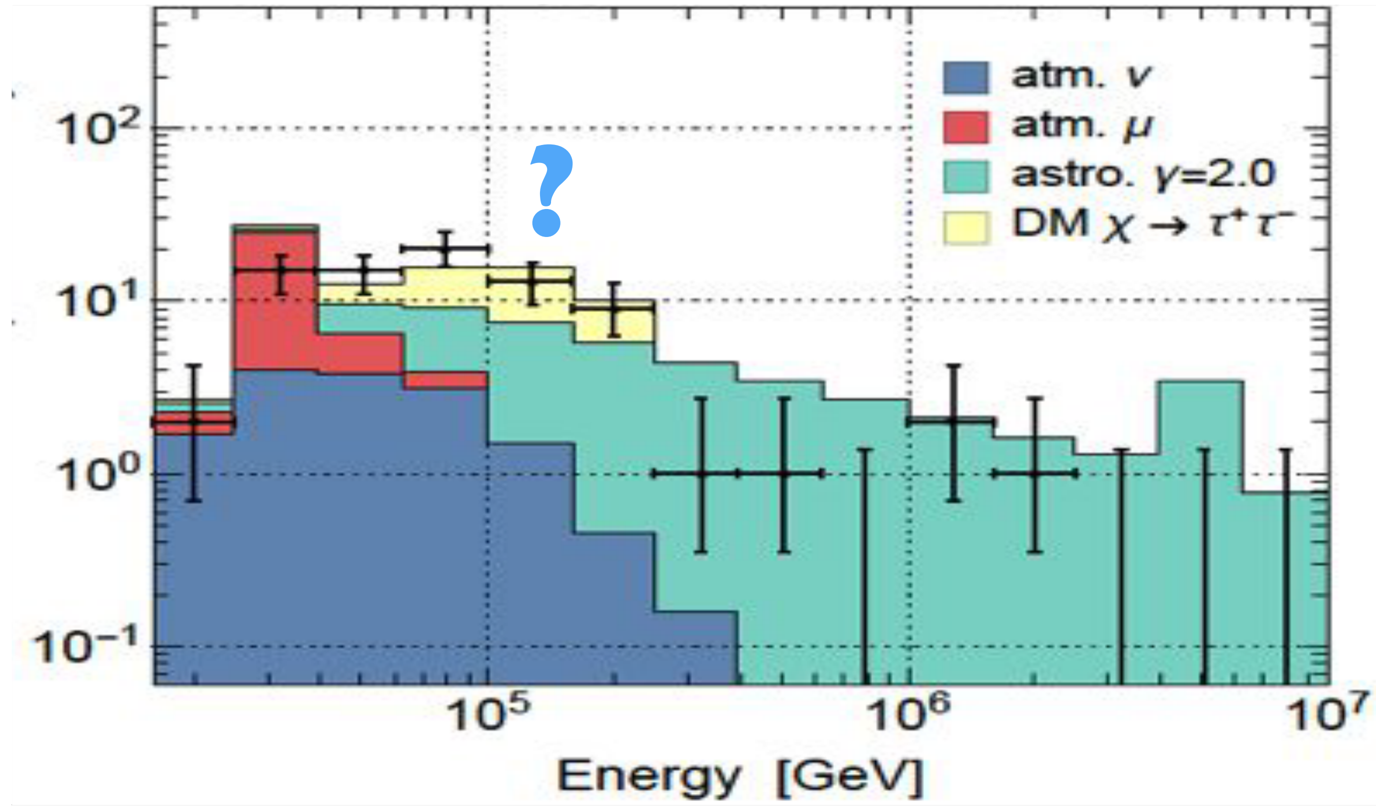
Icecube Collaboration - Science VOL. 380, NO. 6652 (2023)



Observable Universe



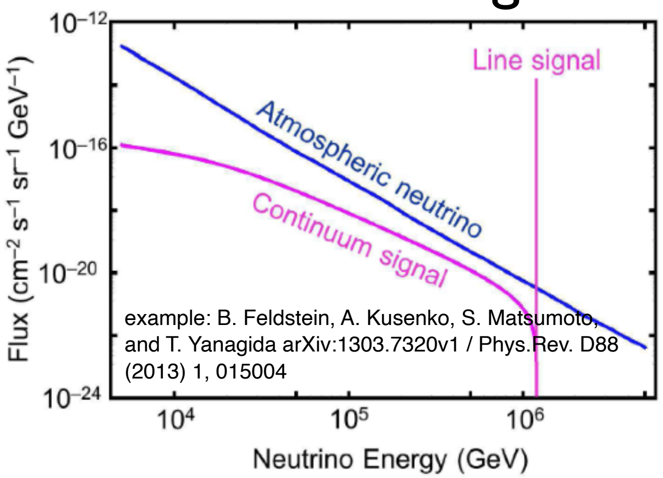
M. Chianese, M.Miele, S. Morisi Phys.Lett. B773 (2017) 591-595



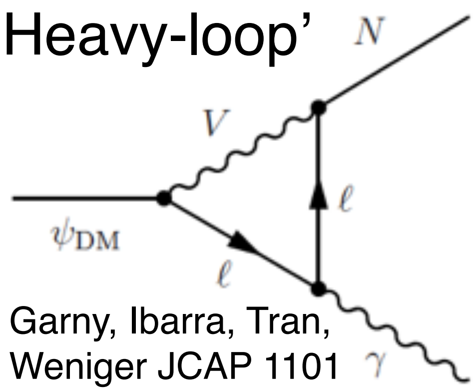
Signs of BSM in Astrophysical Neutrinos ?

Heavy Dark Matter Decay

Decay process might produce mono-energetic neutrinos

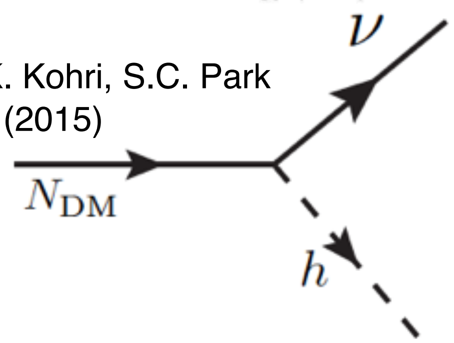


'Heavy-loop'

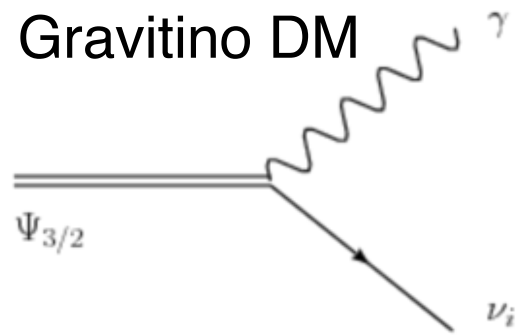


Garny, Ibarra, Tran, Weniger JCAP 1101 (2011) 032

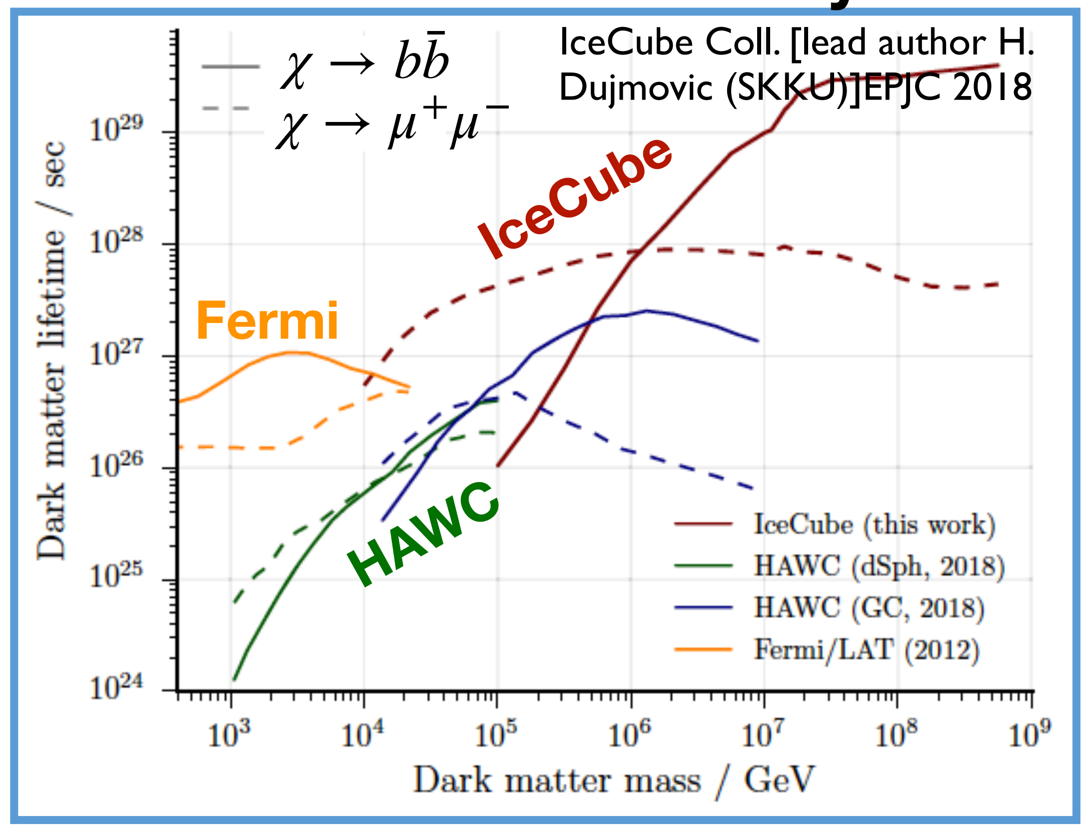
C. Rott, K. Kohri, S.C. Park PRD D92 (2015)



Gravitino DM

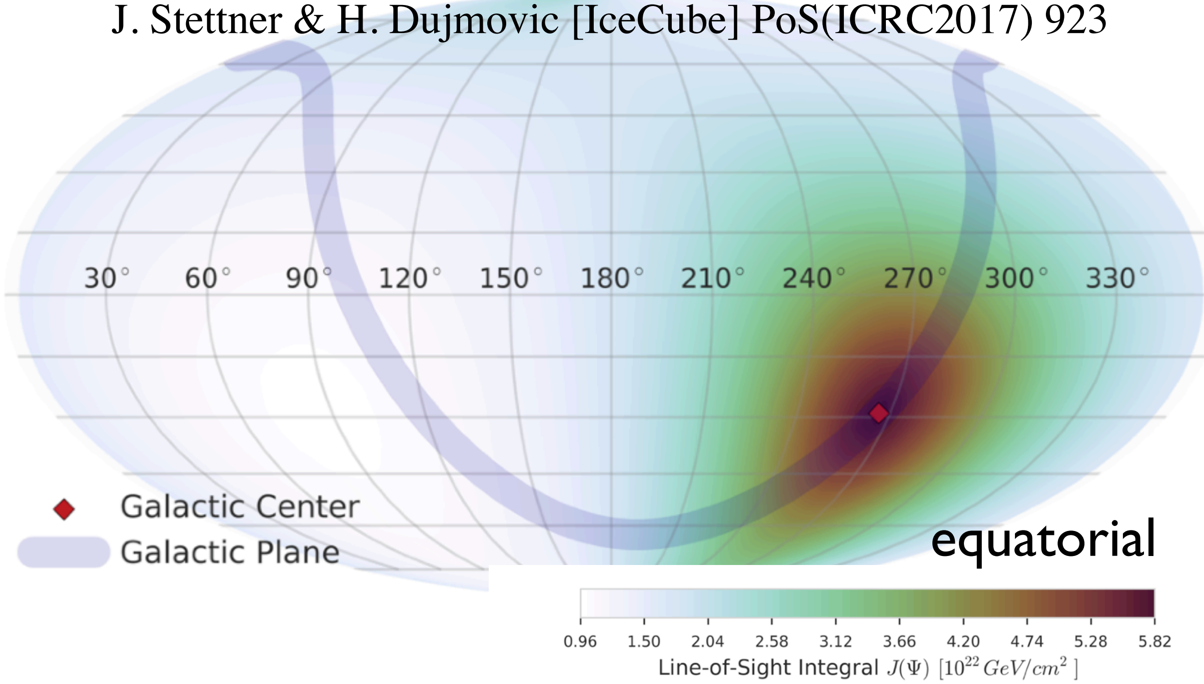


Dark Matter Decay

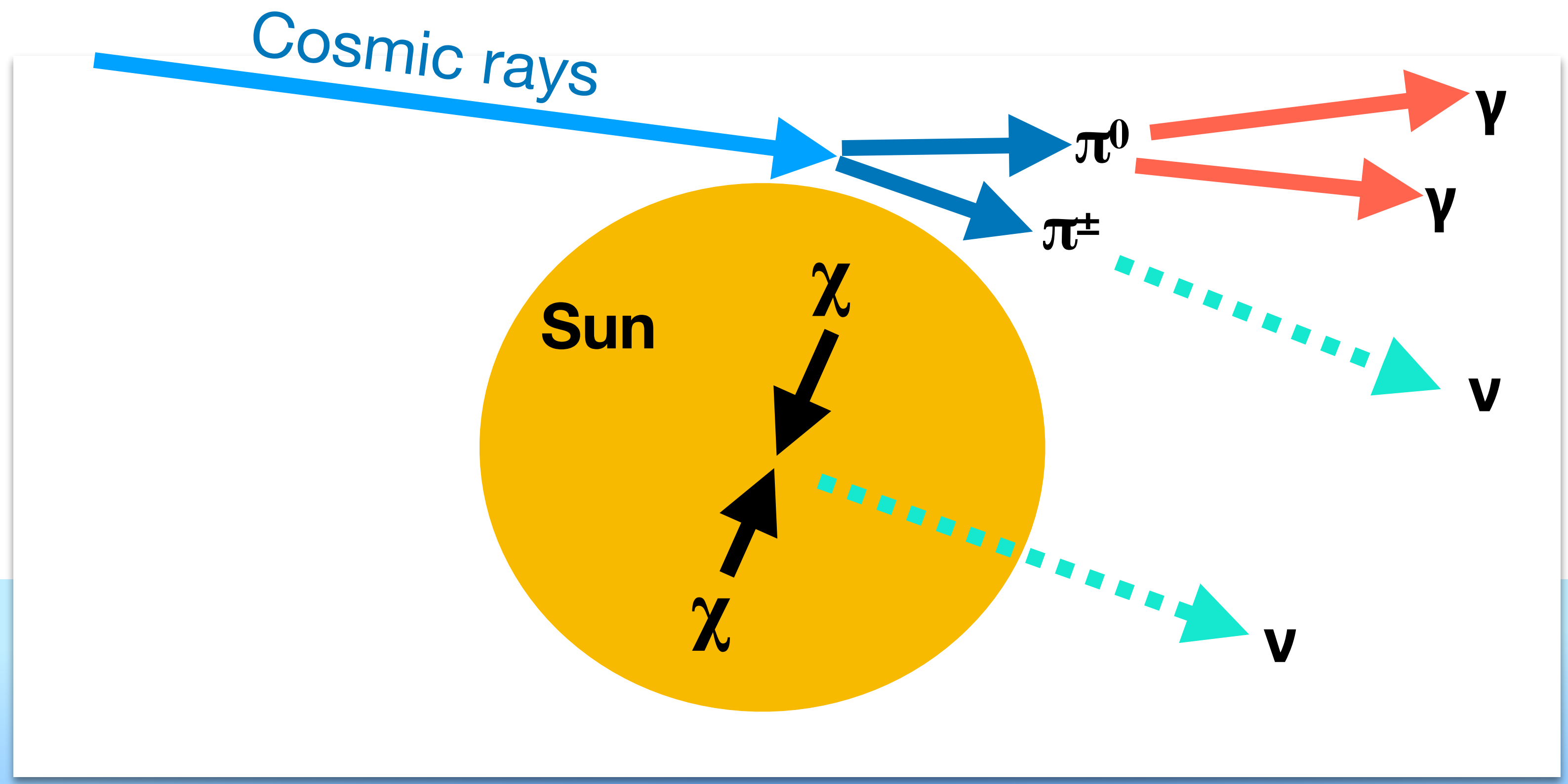


Hrvoje Dujmovic

J. Stettner & H. Dujmovic [IceCube] PoS(ICRC2017) 923



- Heavy Decaying Dark Matter hypothesis has been tested using 6 years of IceCube data and utilizing energy spectral and spacial information
- Galactic and Extra-galactic contribution needs to be considered
- World strongest bounds on dark matter lifetime for PeV masses ~10^{28}s
- IceCube Point Source Data sample will provide access to 100TeV masses, test of DM hypothesis
- Combined analyses between IceCube and HAWC could be of high interest and cover a broad range of decay and annihilation channels.



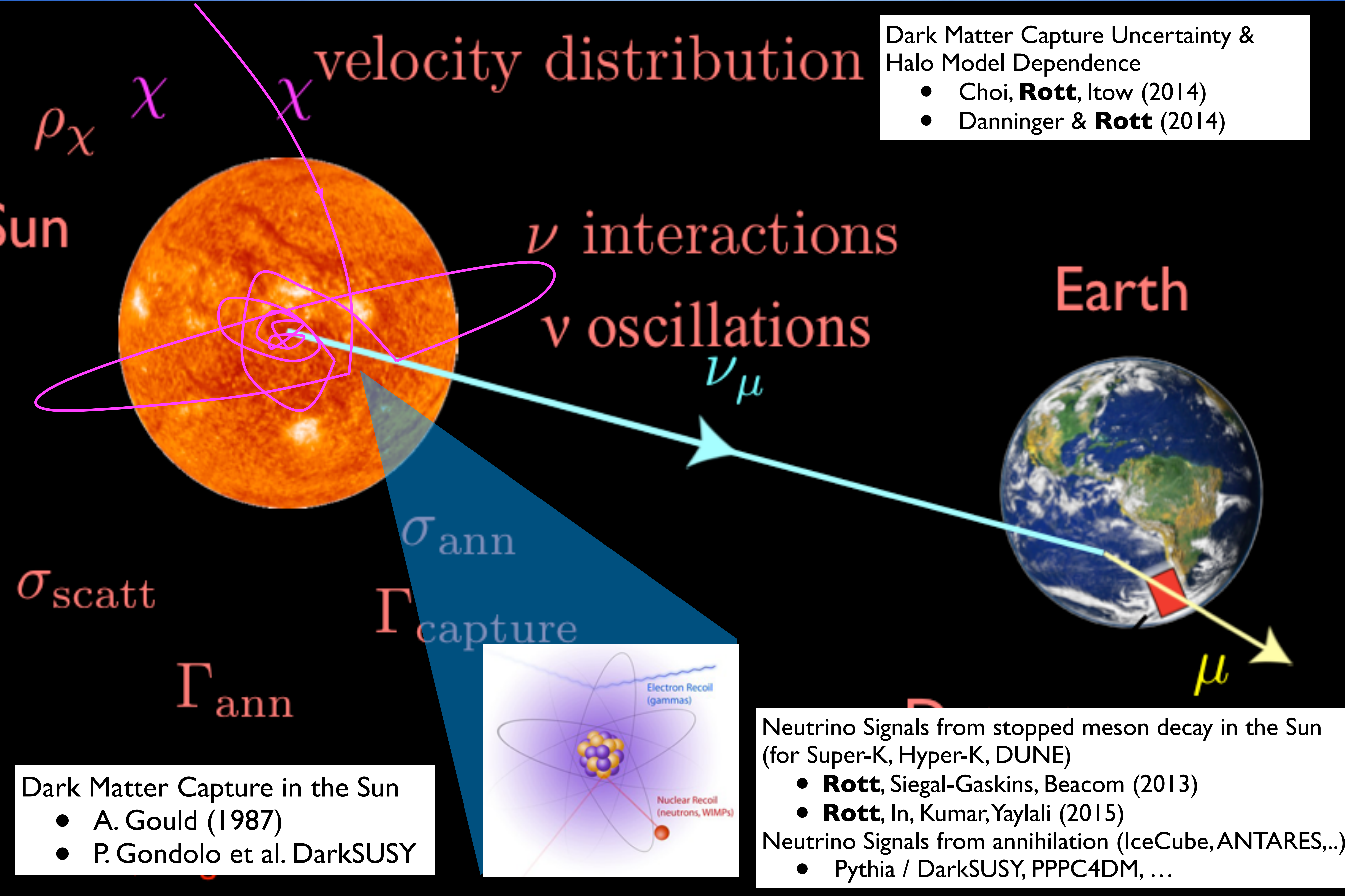
Energetic Neutrinos from the Sun

Solar Dark Matter

See also
Silk, Olive and Sredricki 85, Gaisser, Seigman, Tilav 86
Freese 86, Krauss, Sredricki, Wilczek 86

Dark Matter Capture Uncertainty & Halo Model Dependence

- Choi, **Rott**, Itow (2014)
- Danninger & **Rott** (2014)



Dark Matter Capture in the Sun

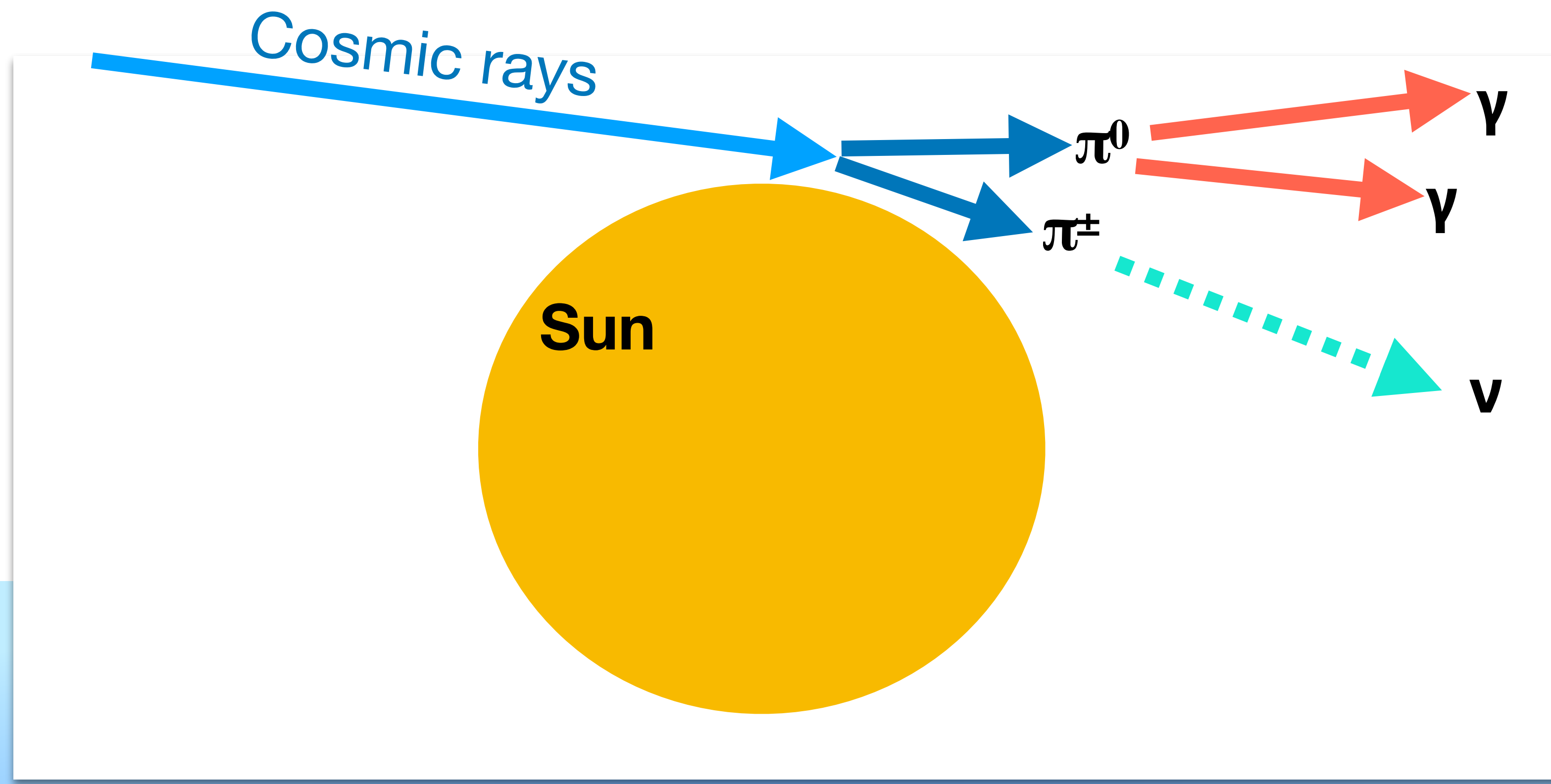
- A. Gould (1987)
- P. Gondolo et al. DarkSUSY

Neutrino Signals from stopped meson decay in the Sun (for Super-K, Hyper-K, DUNE)

- **Rott**, Siegal-Gaskins, Beacom (2013)
- **Rott**, In, Kumar, Yaylali (2015)

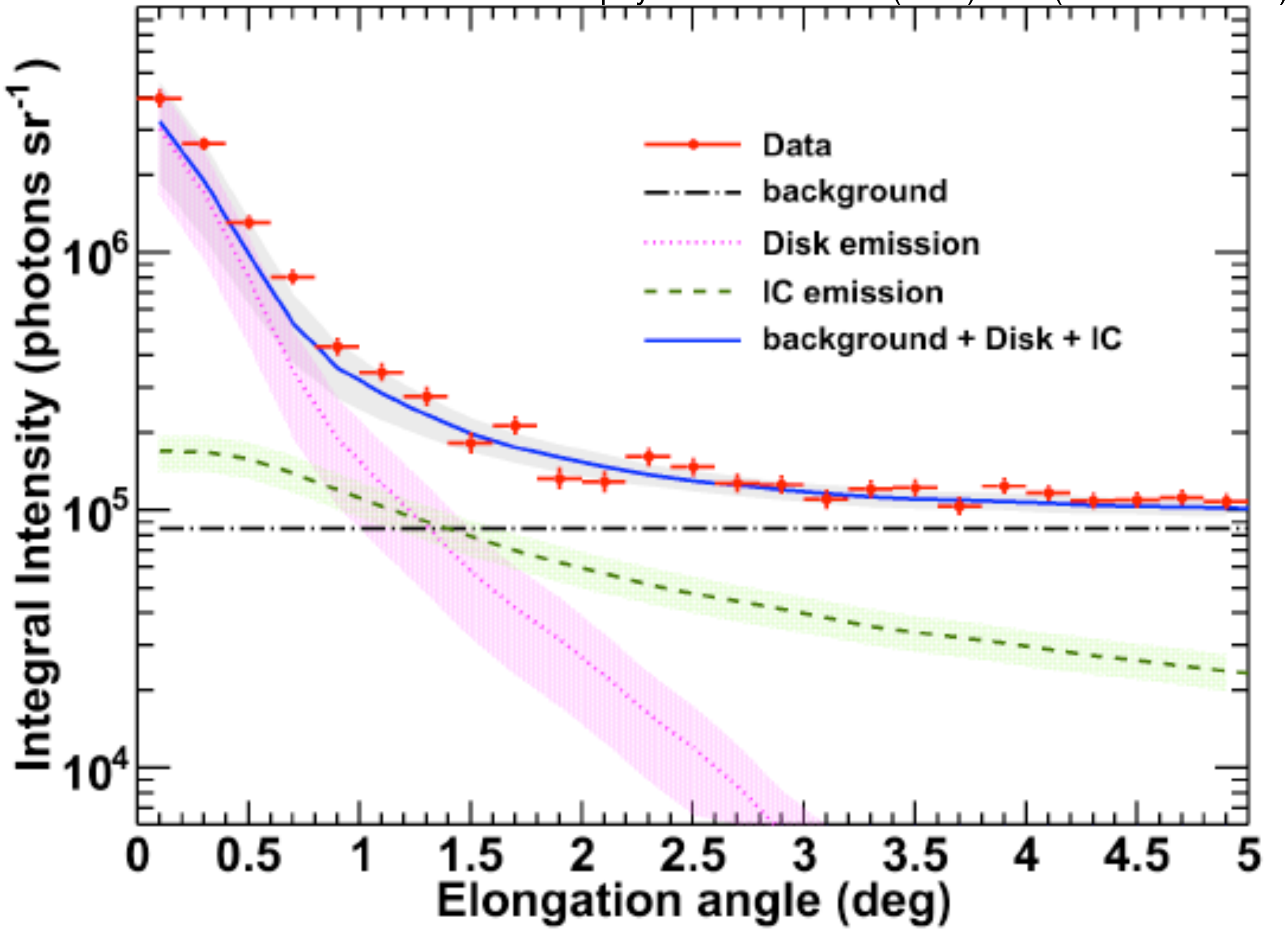
Neutrino Signals from annihilation (IceCube, ANTARES,..)

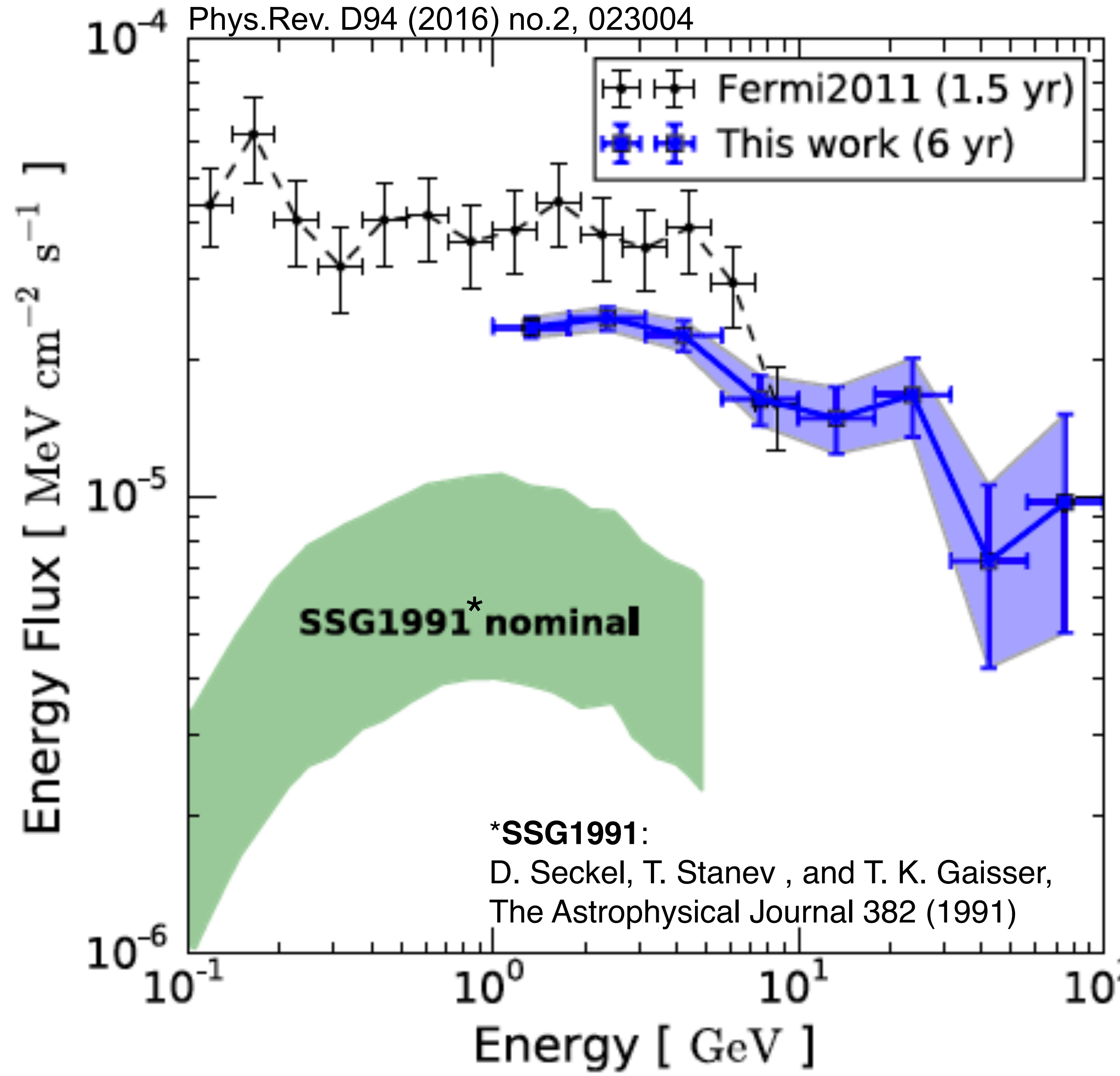
- Pythia / DarkSUSY, PPPC4DM, …



Solar Atmospheric Neutrinos

Gamma-ray emissions from the Sun



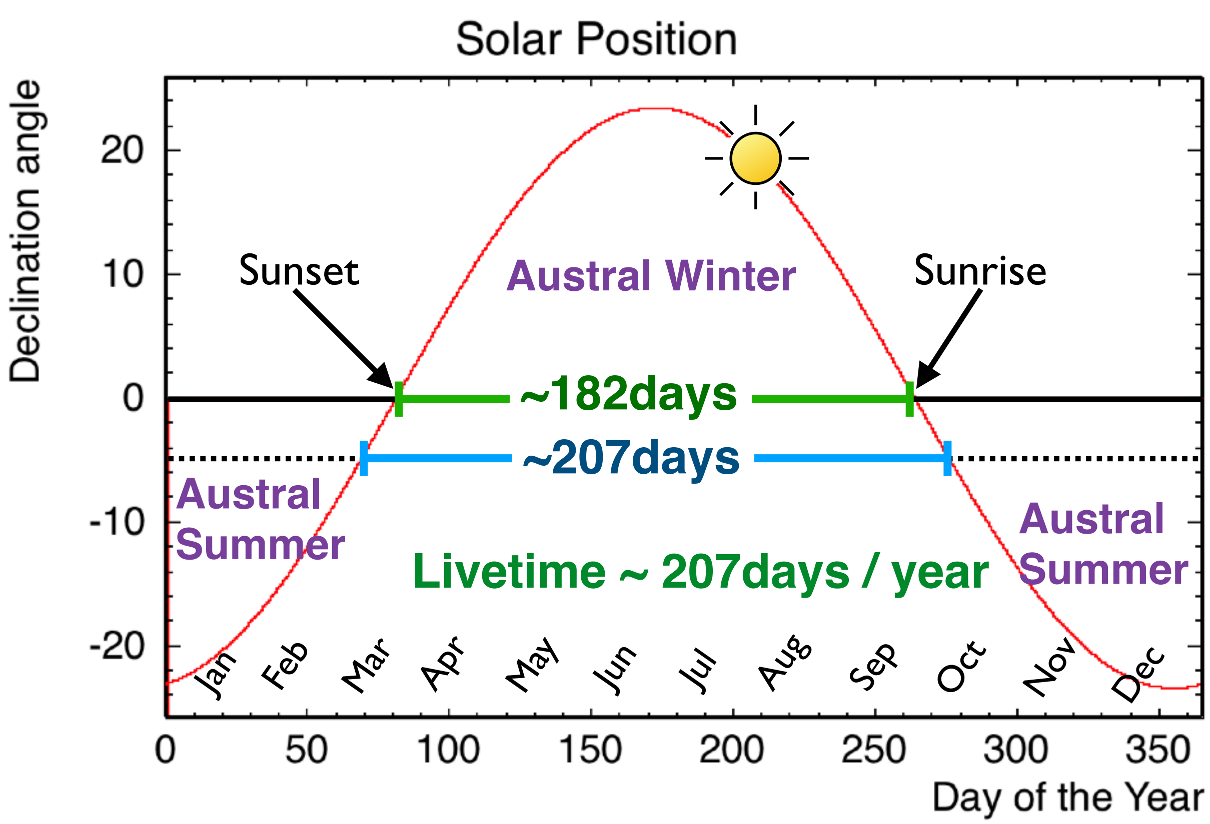


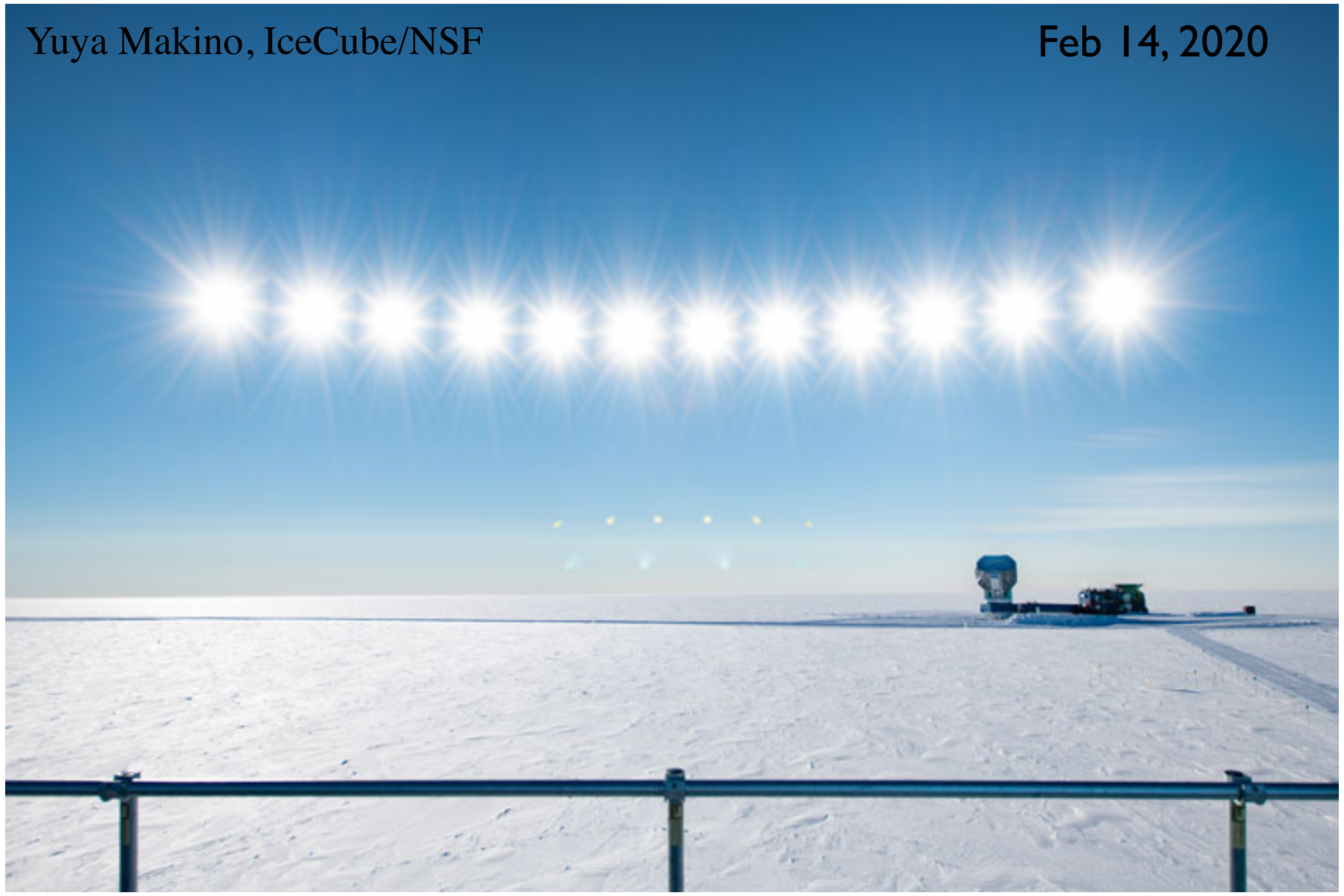
- **Cosmic ray interactions in the Solar atmosphere produce gamma-rays and neutrinos**
- **First detection** of gamma-rays up to 10GeV reported by Fermi-LAT Collaboration (2011) later shown spectrum extends beyond 100GeV in public Fermi-LAT data (K.C.Y. Ng, J. F. Beacom, A.H.G. Peter, C. Rott (2016))
- Surprisingly **little known about solar gamma-ray and neutrino production**
- Evidence that the gamma-ray flux shows a **strong dependence on the solar cycle** - significantly enhanced high-energy flux during solar minimum

Solar Atmospheric Neutrino Analysis

Seongjin In

- Conducted first search for solar atmospheric neutrinos
- The analysis utilizes data collected over a 7 year period (May 31, 2010 - May 18, 2017)
  - Up-going muon neutrino candidate events are selected using the well established IceCube point source analysis selection procedure
  - We only consider events from the winter season when the Sun is below the horizon (δ=[-5°,23°]). This results in a total analysis livetime of 1420.73 days.

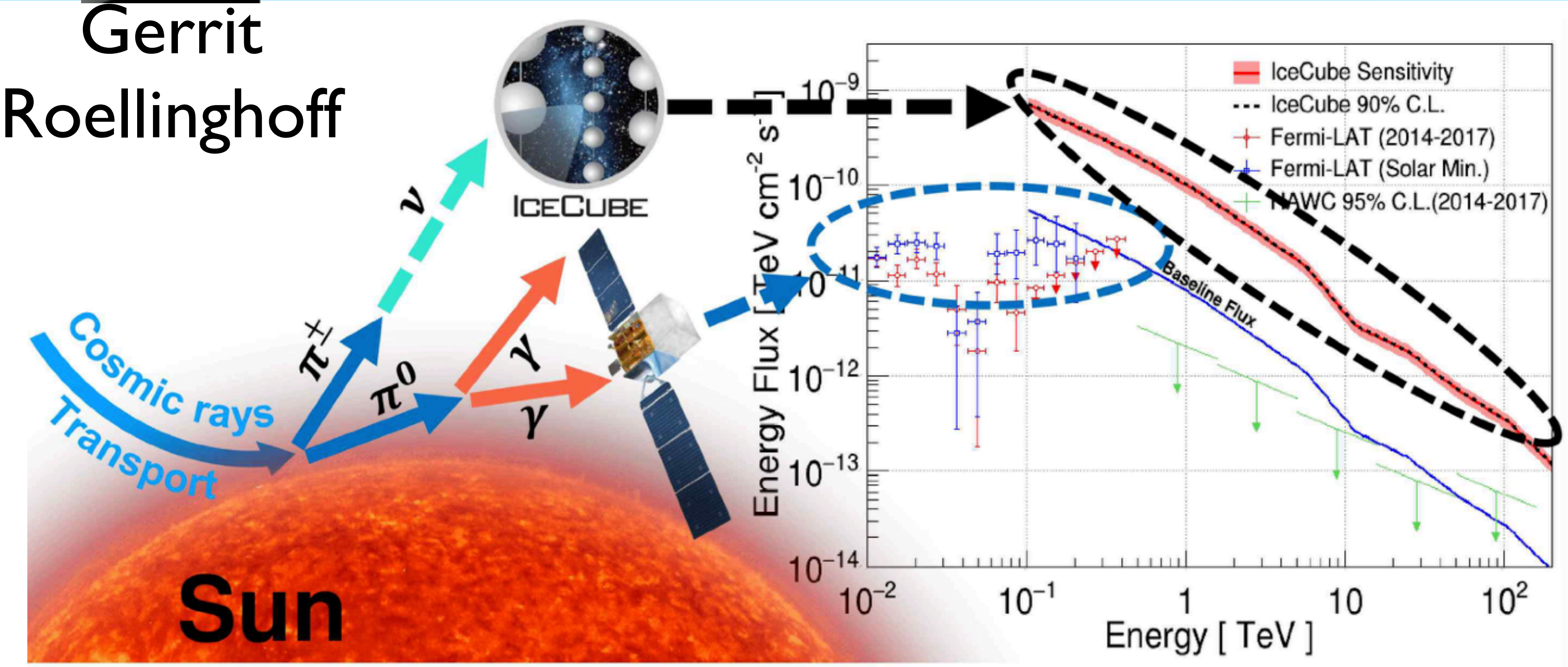


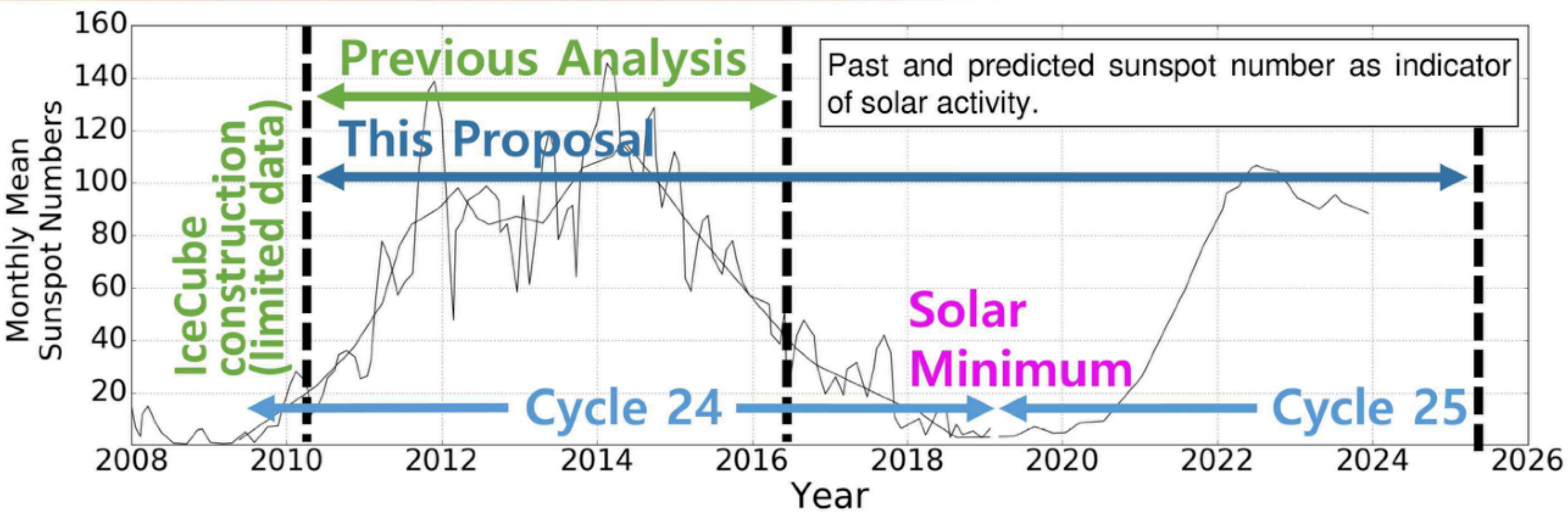


- Experimental result:
  - Flux consistent with background only
  - Details see IceCube Coll. JCAP02(2021)025

Solar Atmospheric Neutrino Prospects

Gerrit Roellinghoff





Event selection improvements (this program)

- Neutrino flavors
  - up-going muon neutrinos ⇒ all flavors
- Livetime:
  - 3.5years (winter 7yrs) ⇒ 15years
- Neutrino energies:
  - 100GeV - 100TeV ⇒ 10GeV - 100TeV
- Latest event reconstruction algorithms

Analysis improvements / techniques

- Differential flux limit (universal useful)
- Time dependent (+ time integrated) analysis

Importance of result

- **Neutrino Source Discovery** - first *steady* high-energy neutrino "point source"
- Cosmic ray transport in the inner solar system
- Understanding solar magnetic fields
- Solar atmosphere and cosmic ray interaction models

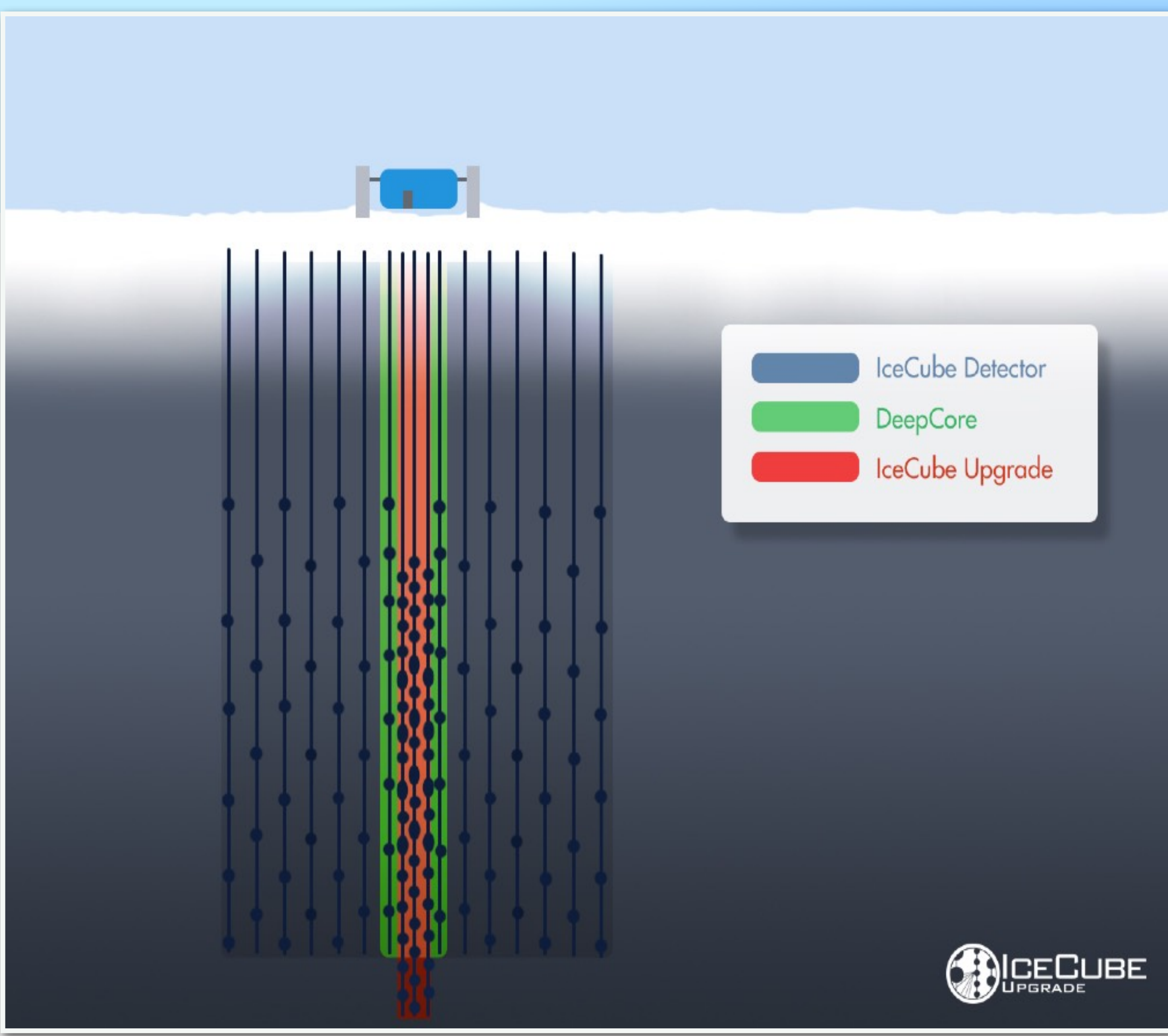
Solar Minimum (2019-2020)

- Enhanced neutrino flux expected
- Strong time dependence expected and evidence from gamma-ray observations
- First observable minimum - previous minimum (2009) during IceCube construction

Solar minimum is now ! Starting improved analysis

What's next …

IceCube Upgrade



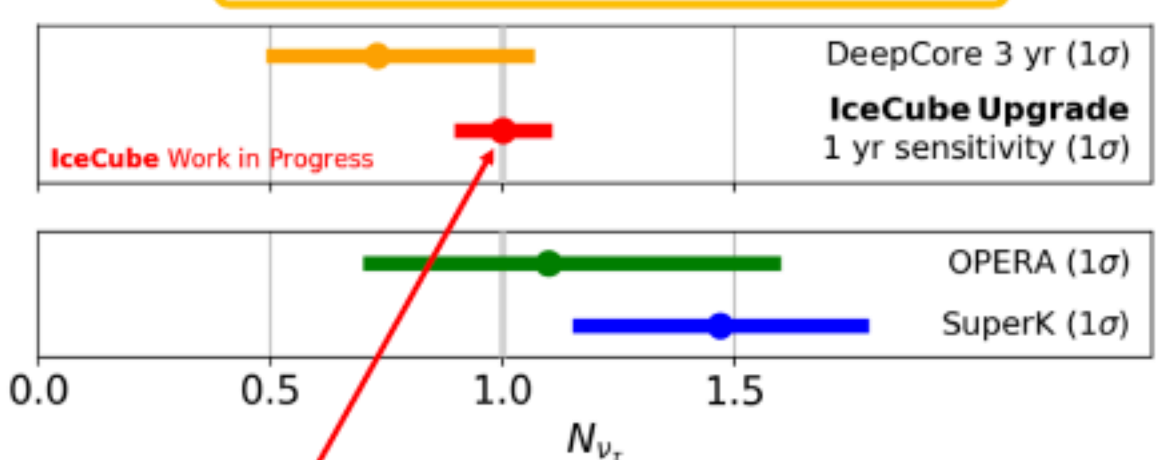
Science goals and objectives

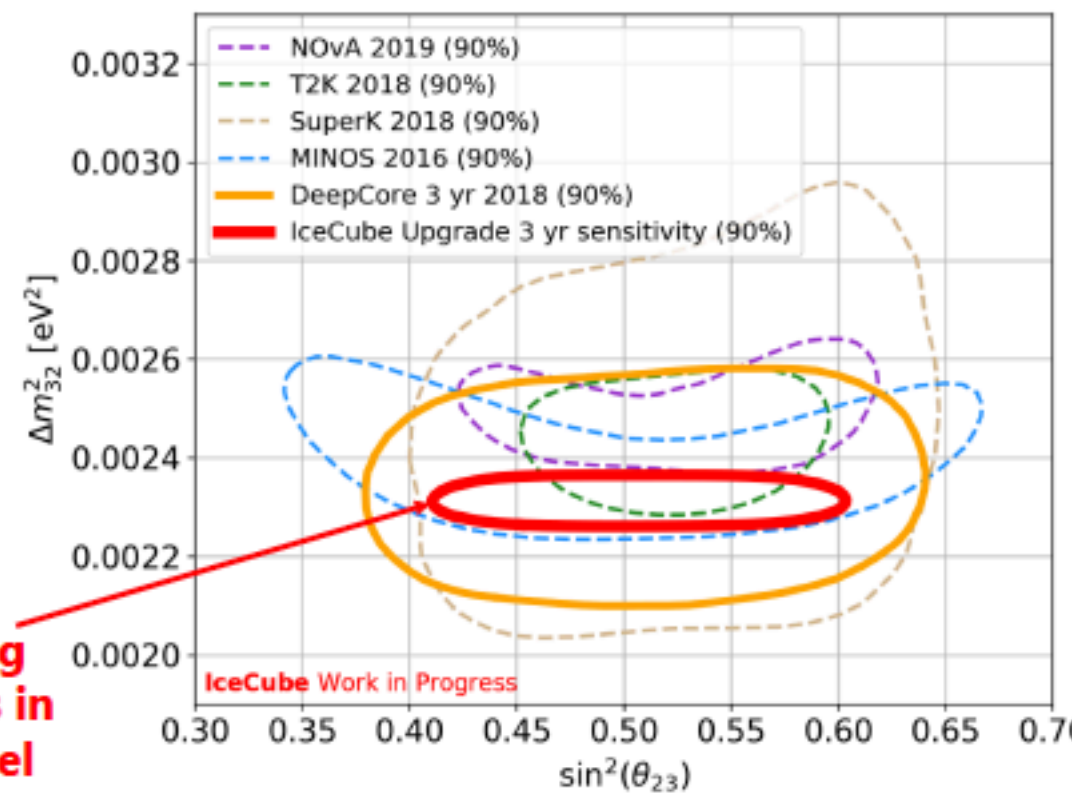
- Tau neutrino appearance - Test unitarity of the PMNS matrix
- Recalibration campaign - Retroactively apply improved ice-model to archival data (since 2010)

IceCube DOM mDOM D-Egg

ν_μ disappearance sensitivity (3 yr)

ν_τ appearance sensitivity (1 yr)



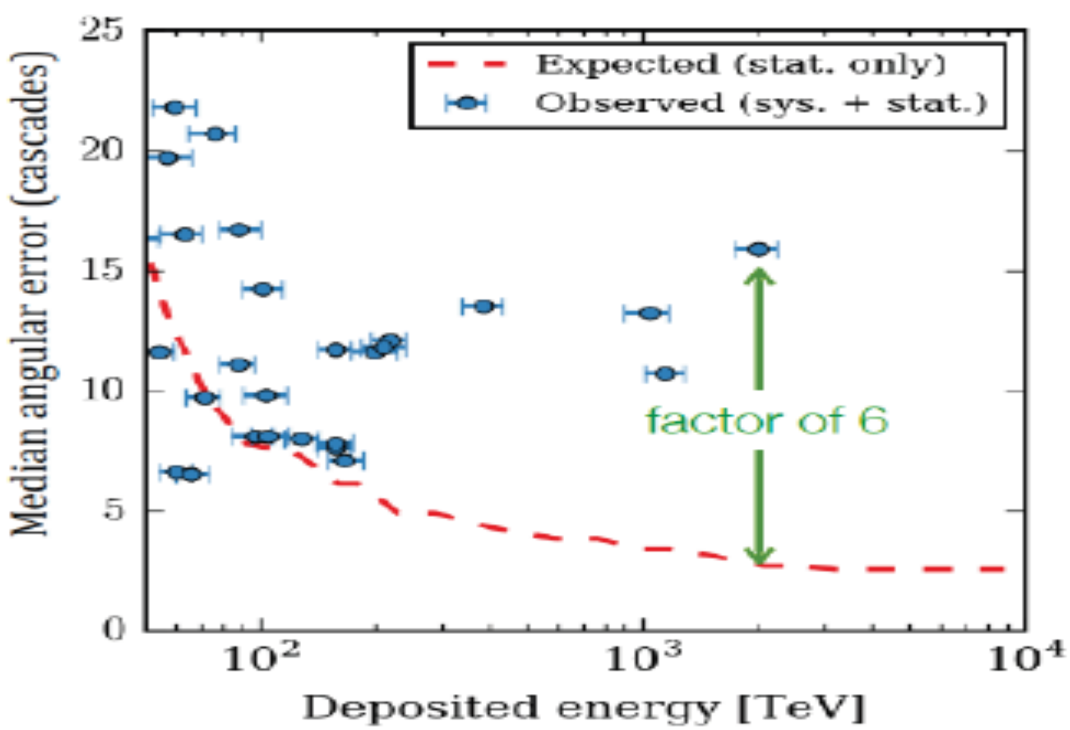


10% precision after 1 year
(6% after 3 years)

Competitive with long baseline experiments in disappearance channel

Ice Camera System

- Ice properties dominant source of sys. uncertainties for most analyses
- Solution: SKKU ice camera system
  - Monitor freeze in
  - Hole ice studies
  - Local ice environment
  - Position of the sensor in the hole
  - Geometry calibration
  - Survey capability



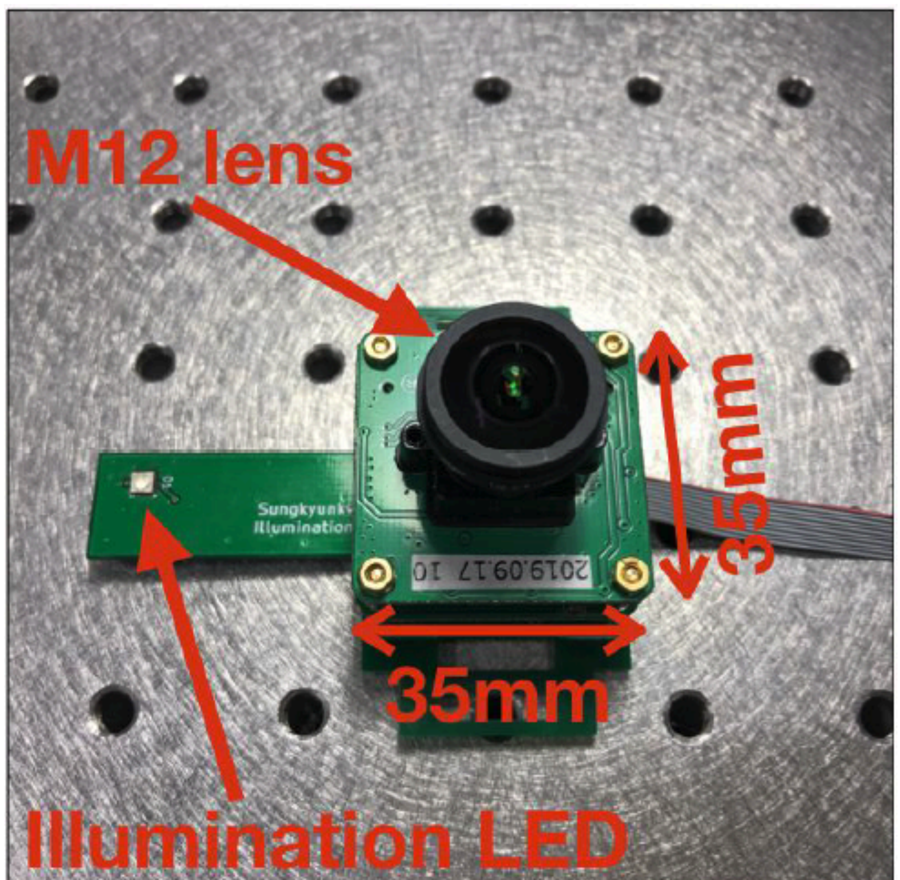
Example camera for illustration

Camera system key to comprehensive understanding of the detector medium

—> Retroactively analyze more than 10 years of IceCube data with substantially improved angular and energy resolution

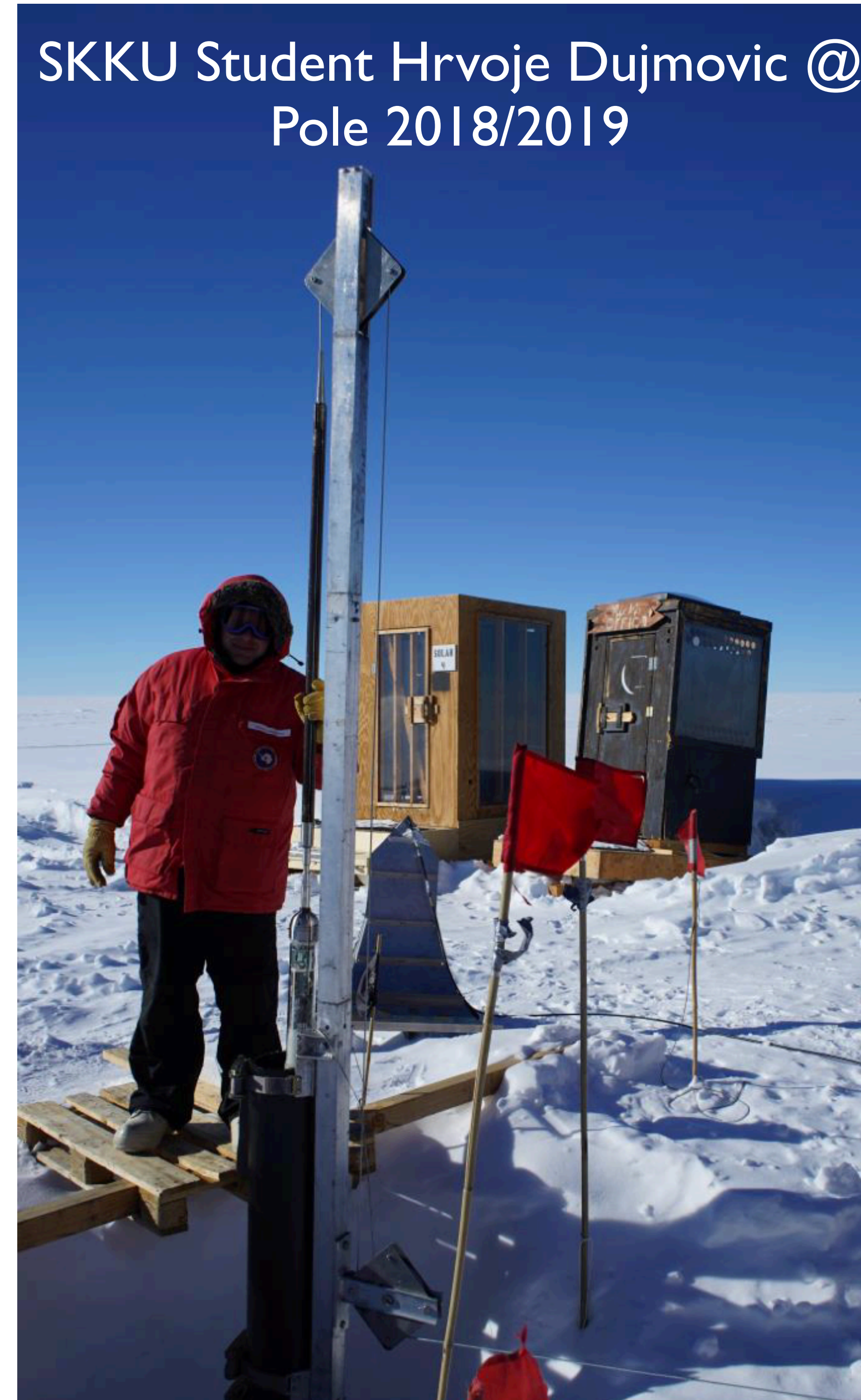
Ice Camera System

- Limited understanding of Antarctic ice properties dominant source of sys. uncertainties for most analyses
  - ⇒ better characterize detector medium
- Solution: SKKU ice camera system
  - Monitor freeze in
  - Hole ice studies
  - Local ice environment
  - Position of the sensor in the hole
  - Geometry calibration
  - Survey capability



Customized **camera module** consisting of 2 PCBs: One with the Image sensor (Sony IMX225) , M12 lens mount and lens, and second with CPLD and connectors.

Successful South Pole Deployment of Test System



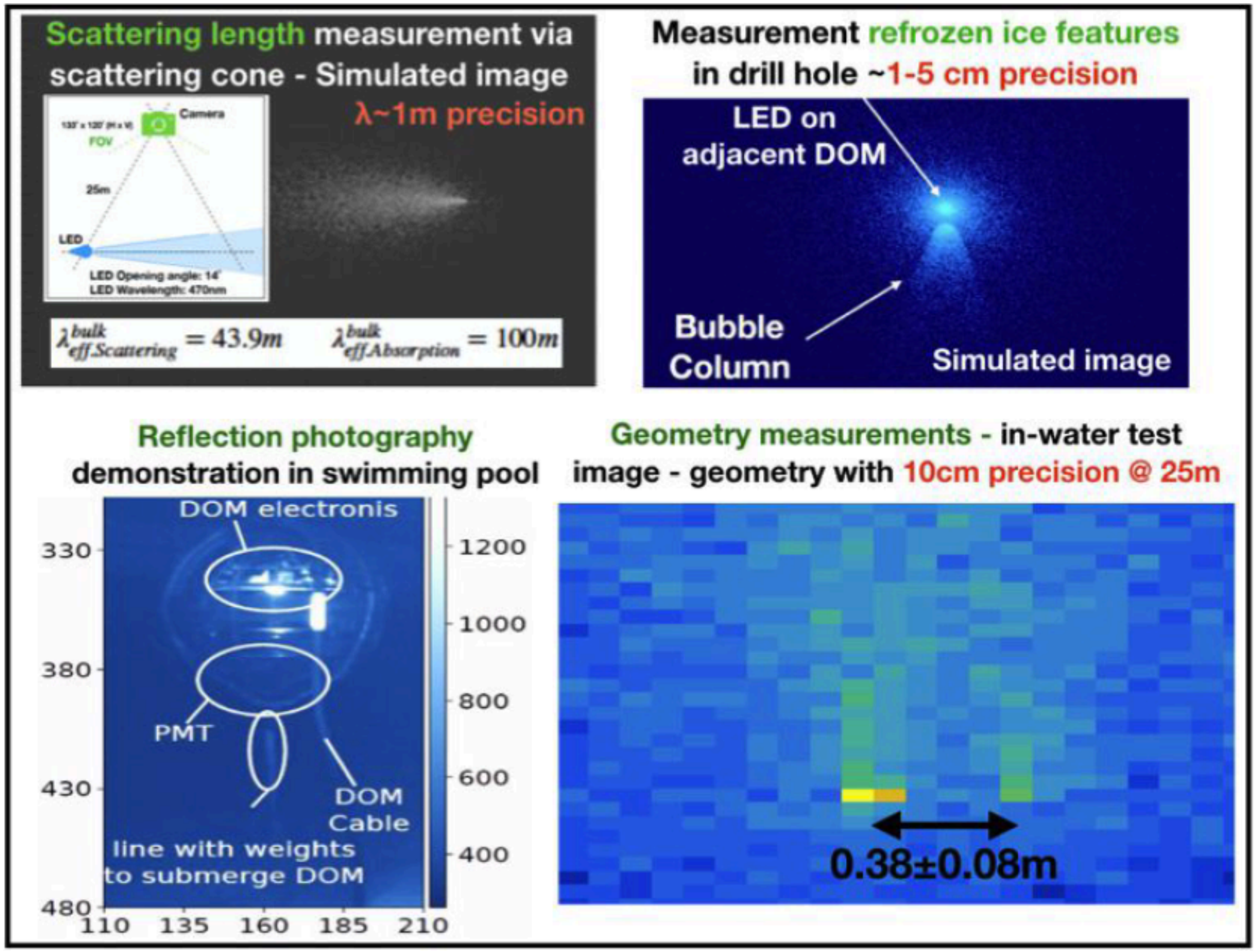
Group photo after successful passing of the camera preliminary design review (Madison May 2019)

Camera sensitivity and Field Test

Work at local high school swimming pool on IceCube camera system testing

Swimming pool at Gyeonggi Physical Education High school

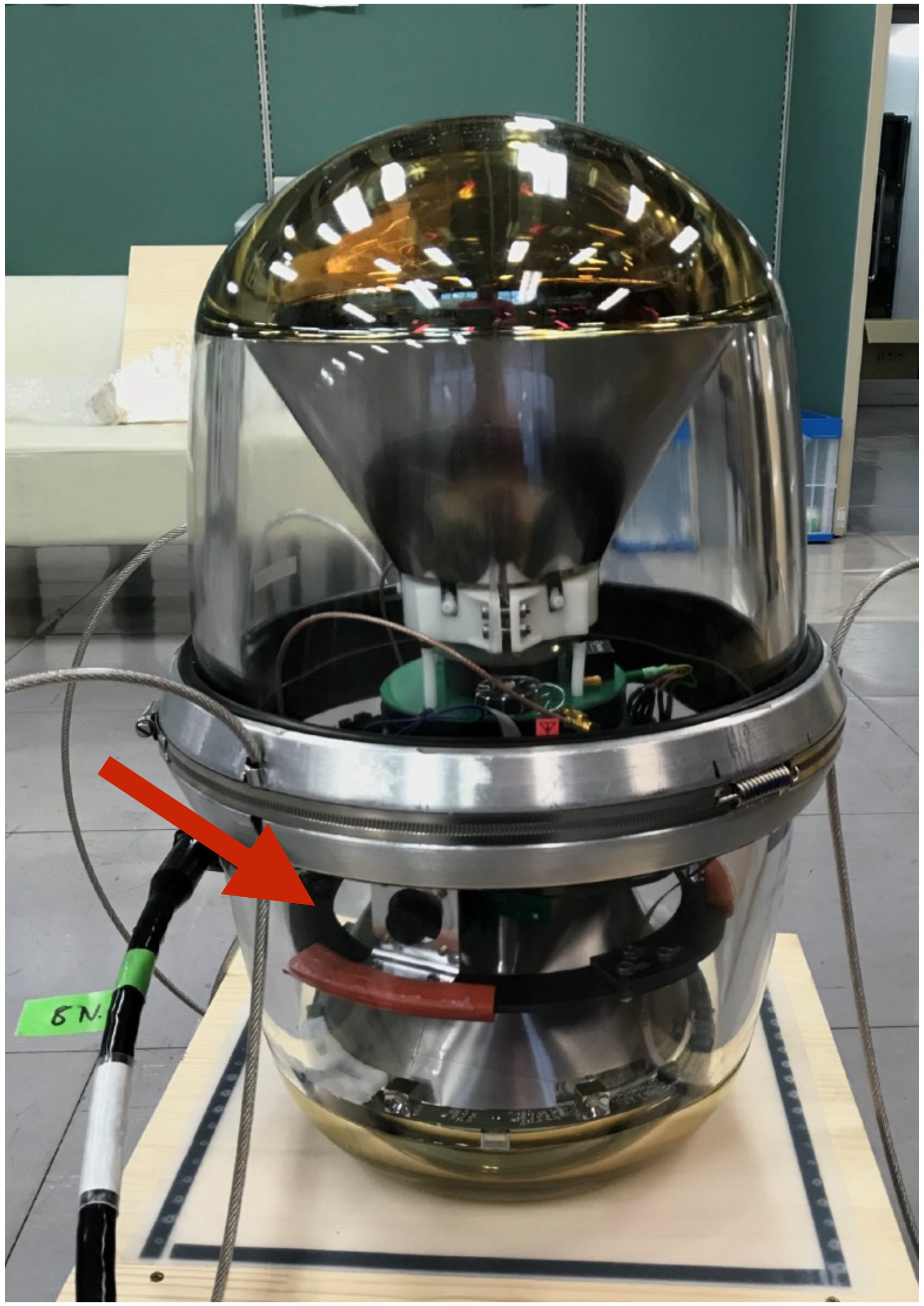
Demonstrated camera abilities in dedicated simulations and lab tests (incl. swimming pool measurements)

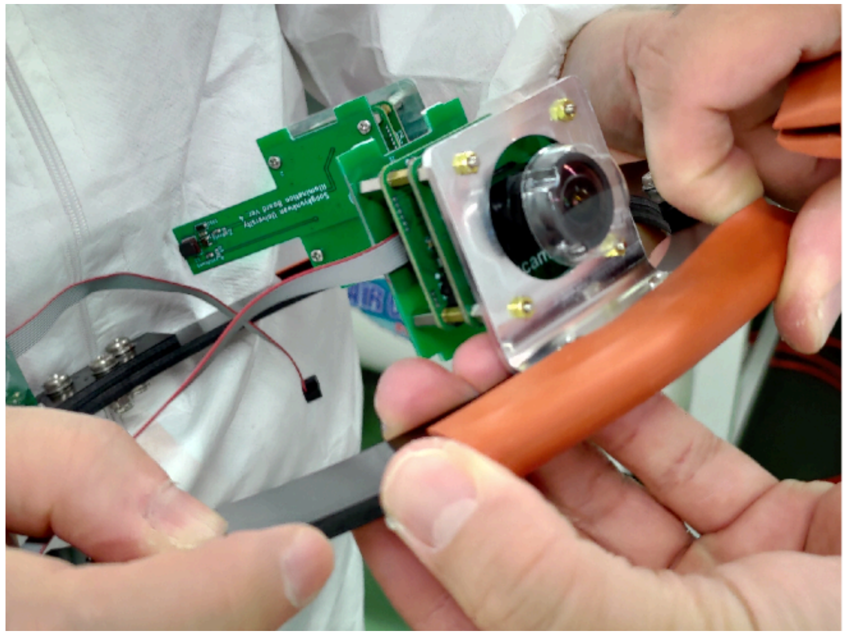


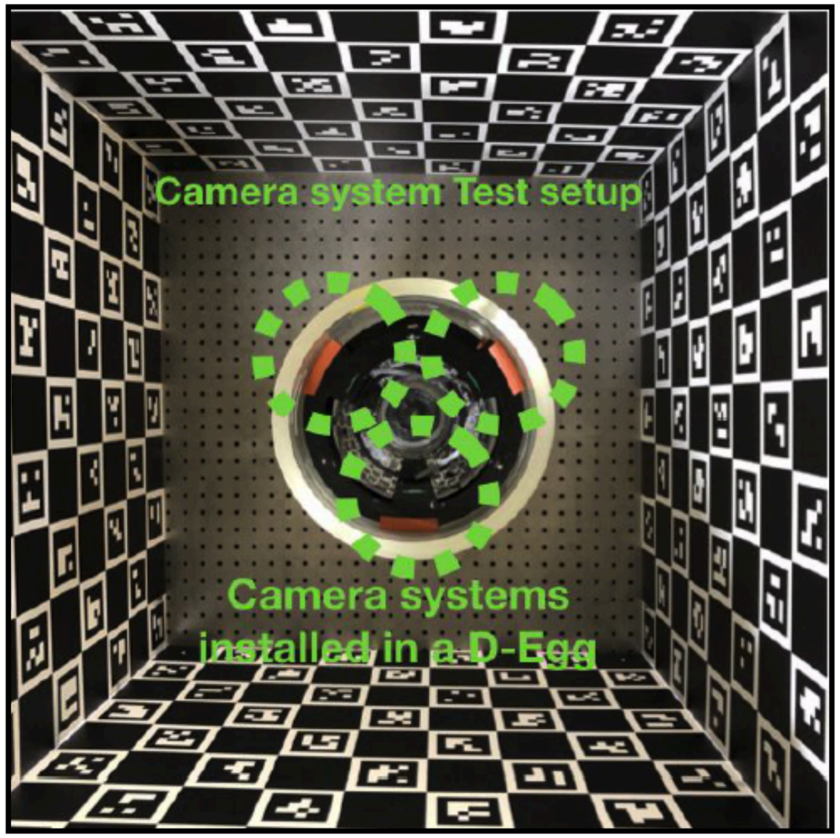
- Verified successful operations under polar conditions and demonstrated ability to measure ice properties with cameras
- **Camera system successfully passed IceCube Internal Final Design Review (FDR) in September 2019**

Camera system integration

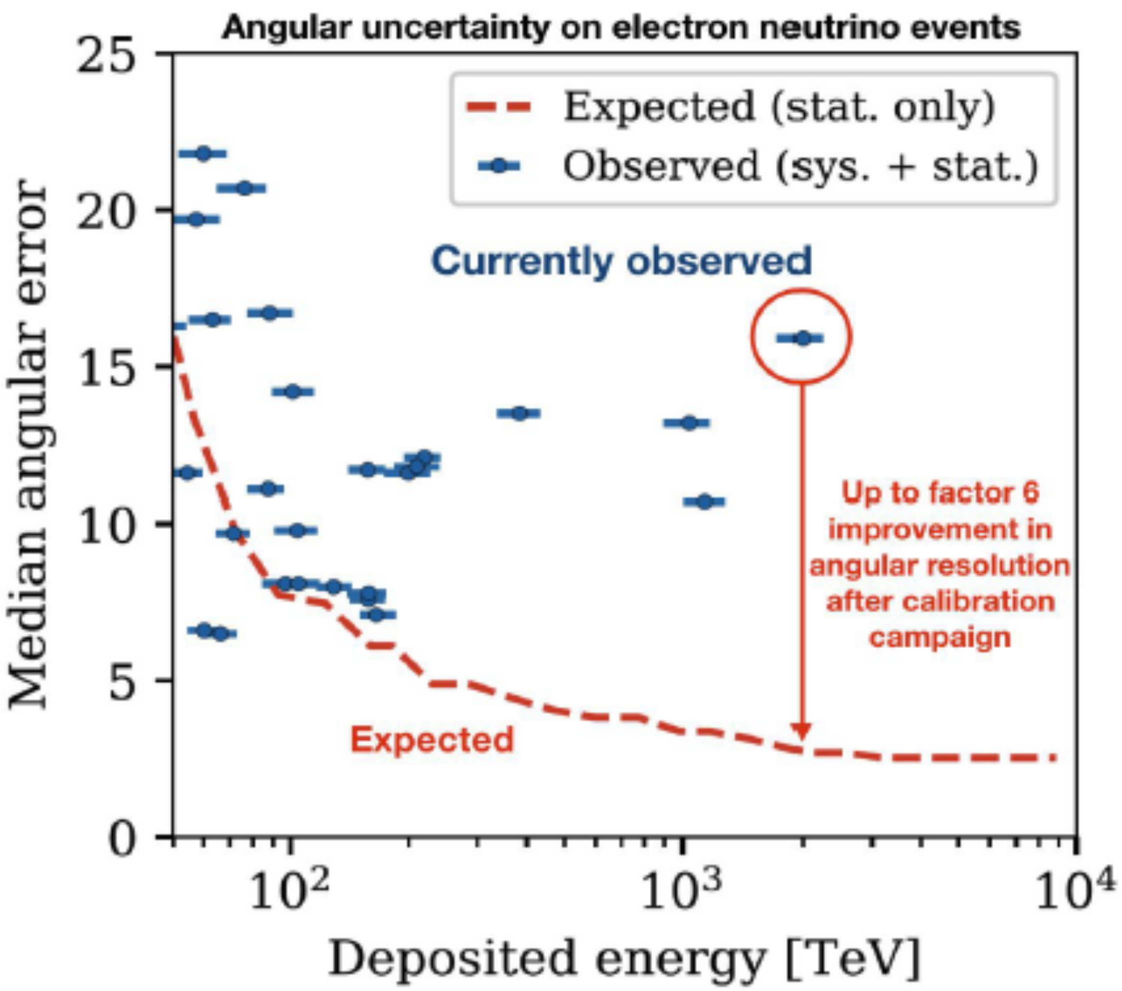
Camera system integrated in D-EGG







Camera system impact



Camera system key to comprehensive understanding of the detector medium

- ***Science multiplier*** Retroactively analyze more than 15 years of IceCube data with substantially improved angular and energy resolution
- ***Improved neutrino event pointing*** critical for multi messenger science