Search for new physics with high energy neutrinos

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Yonsei University Lecture Series

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Outline

- Motivation
  - New Opportunities with High-energy Neutrinos
  - Why search for BSM physics with Neutrinos
  - Introduction Neutrino Telescopes
- State of the Field
  - Selected Searches & Results
- Future Prospects
  - Experimental landscape
  - How to improve searches
  - Priorities for the next decade
- Outlook & Conclusions

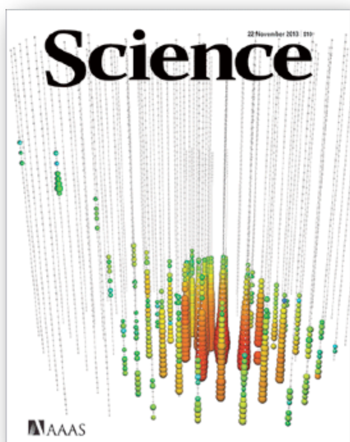
Motivation

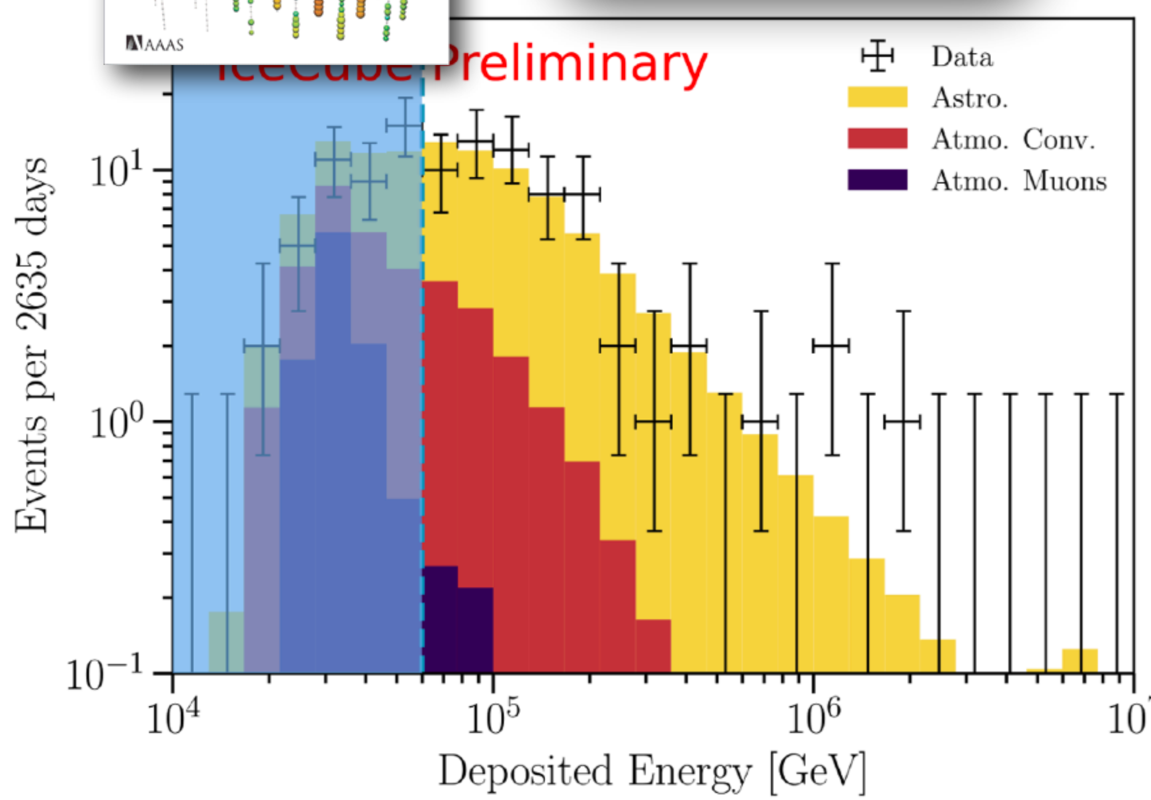
New Window to the Universe !

2002

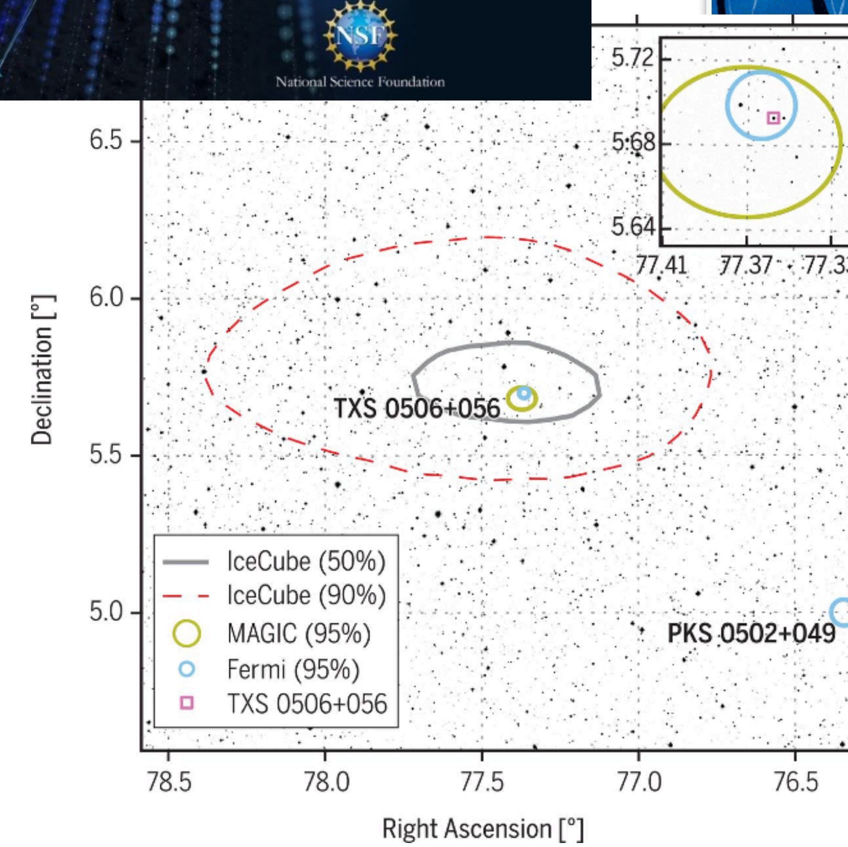
Following the observation of supernova burst neutrinos in 1987, *neutrino astronomy is becoming a reality quickly now …*

2013 Discovery of diffuse astrophysical neutrino flux





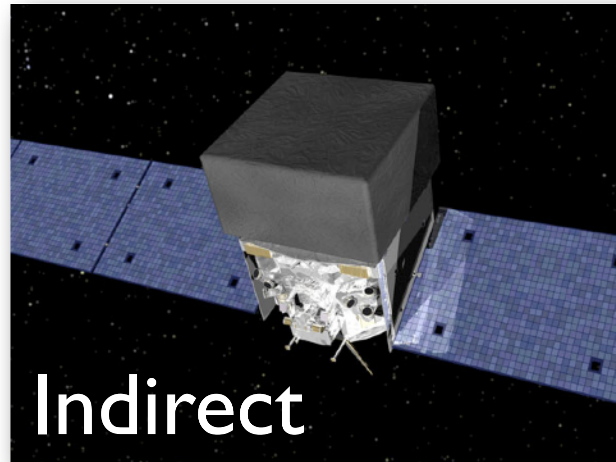
2018 Neutrino multi-messenger astroparticle physics



Indirect Searches with Neutrinos

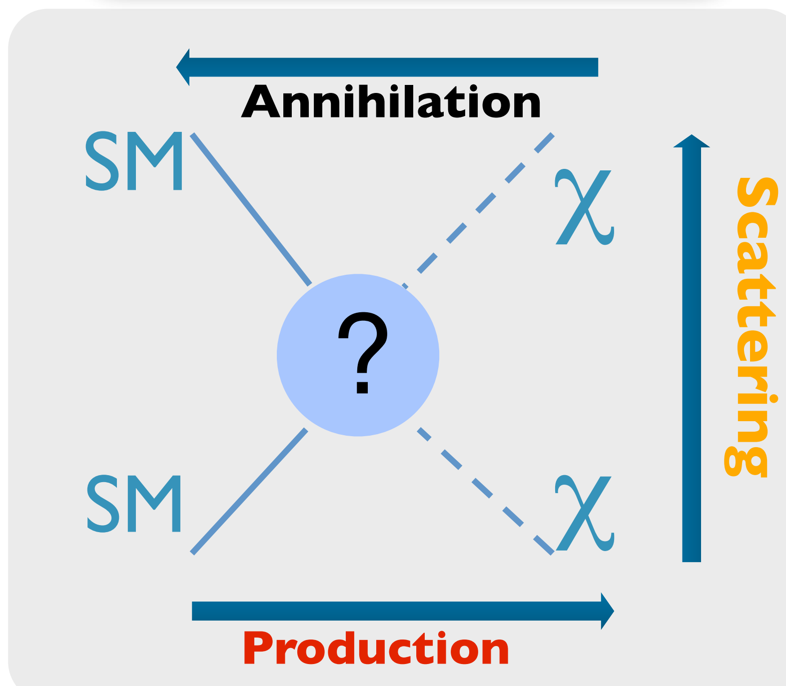
- Why neutrinos:
  - Explore energy scales beyond the reach of colliders and those accessible by other indirect search channels
  - Large variety of dark matter model hypotheses can be probed
  - Searches are largely model independent

Role of Neutrinos in Dark Matter Searches

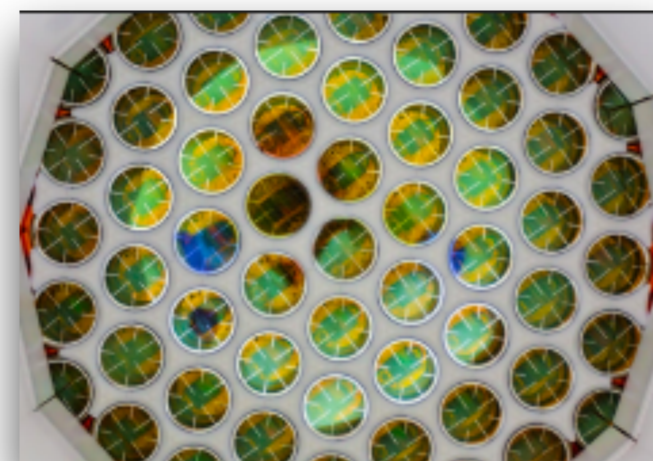


Neutrinos from

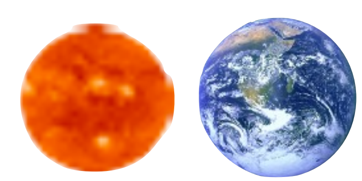
…

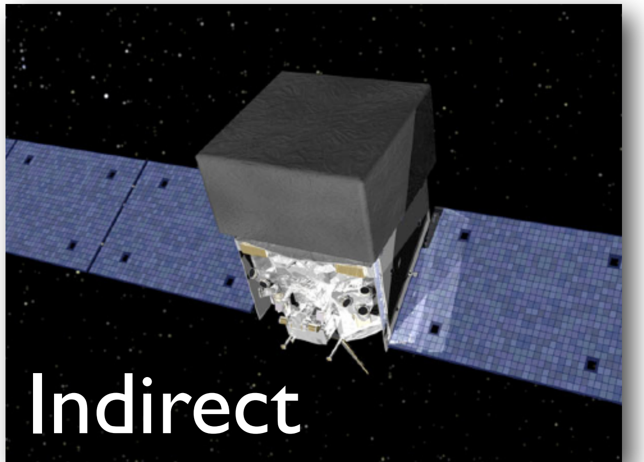


Direct



Neutrinos from





Neutrinos from

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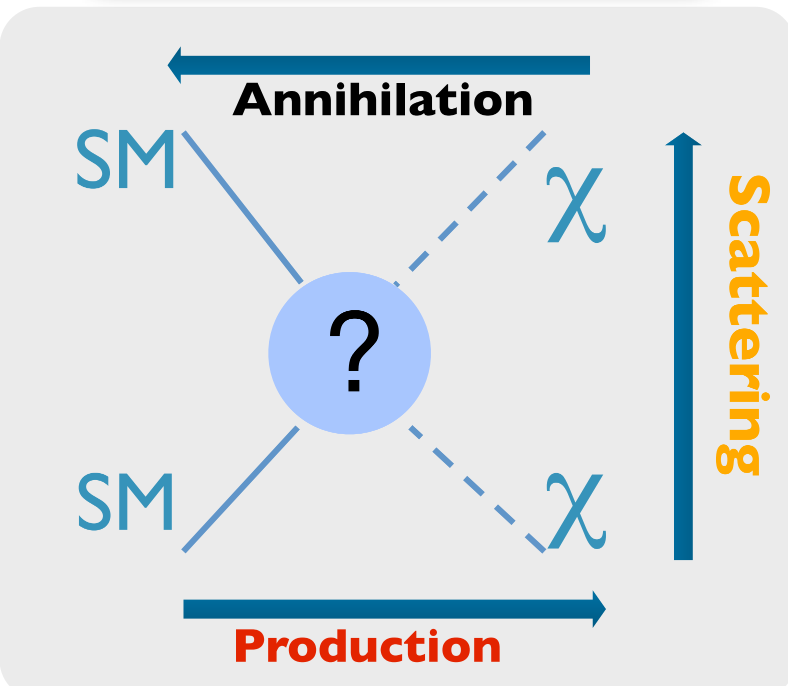
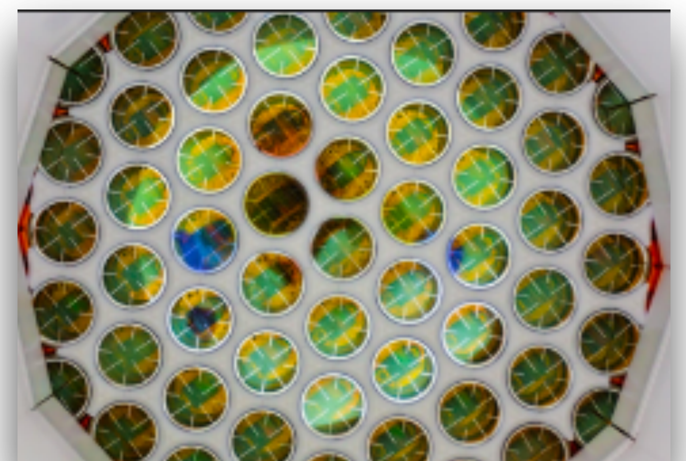
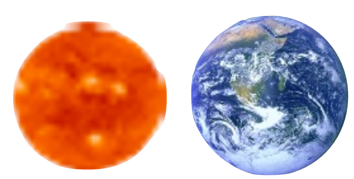


Direct



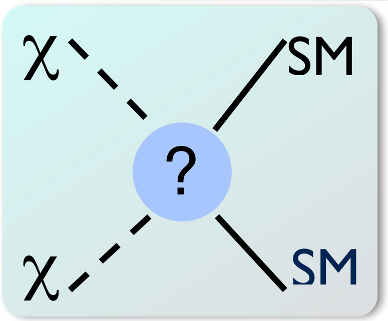
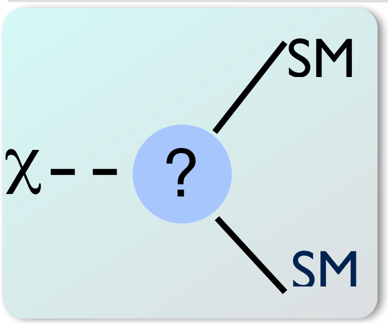
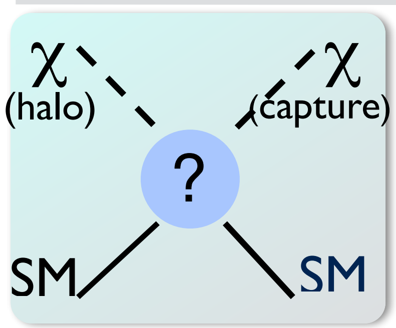
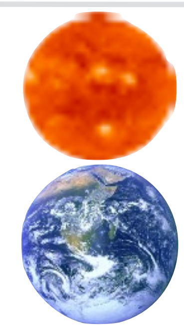
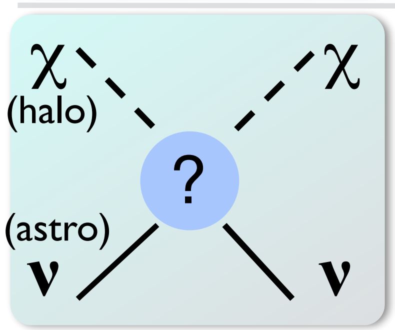
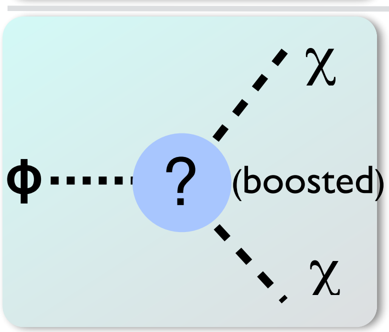
Neutrinos from



The case for Neutrinos

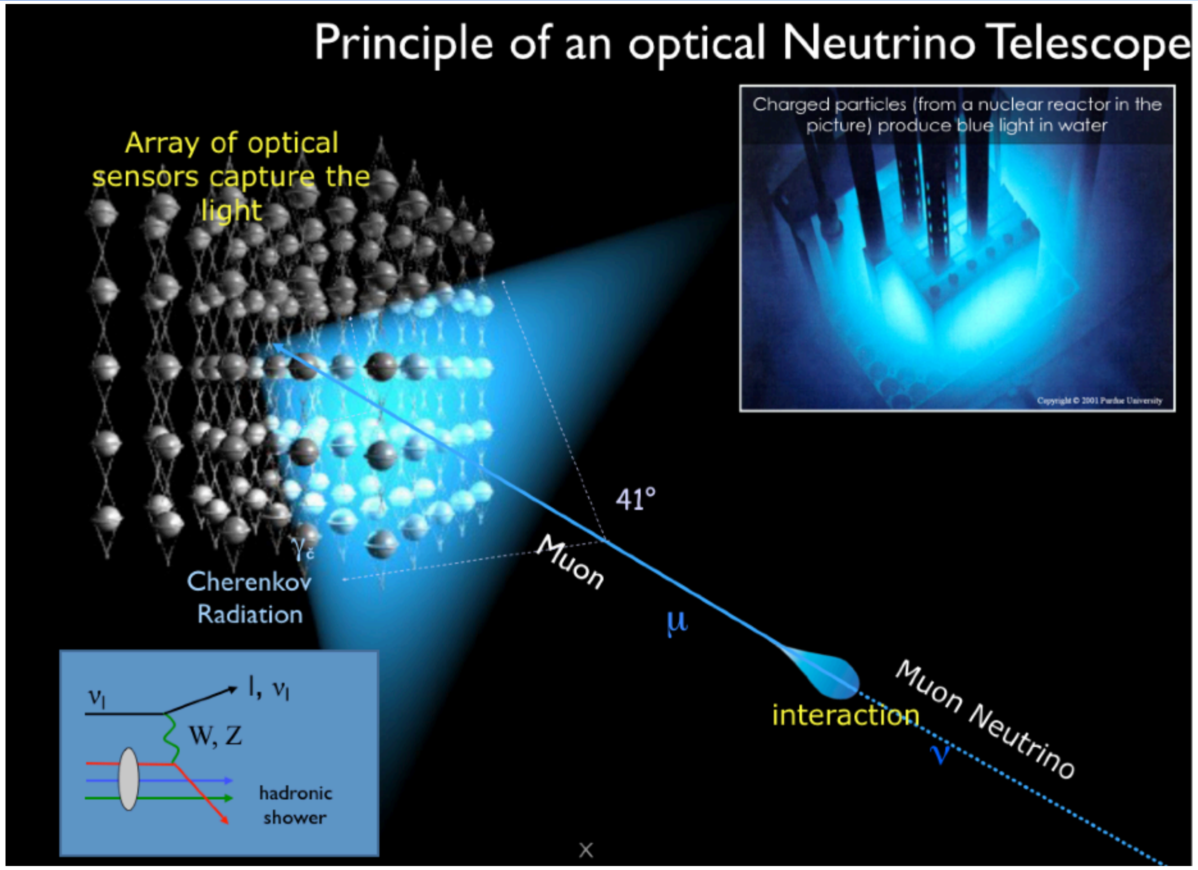
- Search for signals from the Galaxy, etc.
  - Probe DM self-annihilation cross section or lifetime (for decaying DM)
- Search for signals of dark matter captured in the Sun (and Earth)
  - Probe DM-Nucleon scattering
- Neutrino detectors naturally observe the entire sky (all-sky coverage)
- Neutrino detection efficiency rises with energy, and angular resolution improves

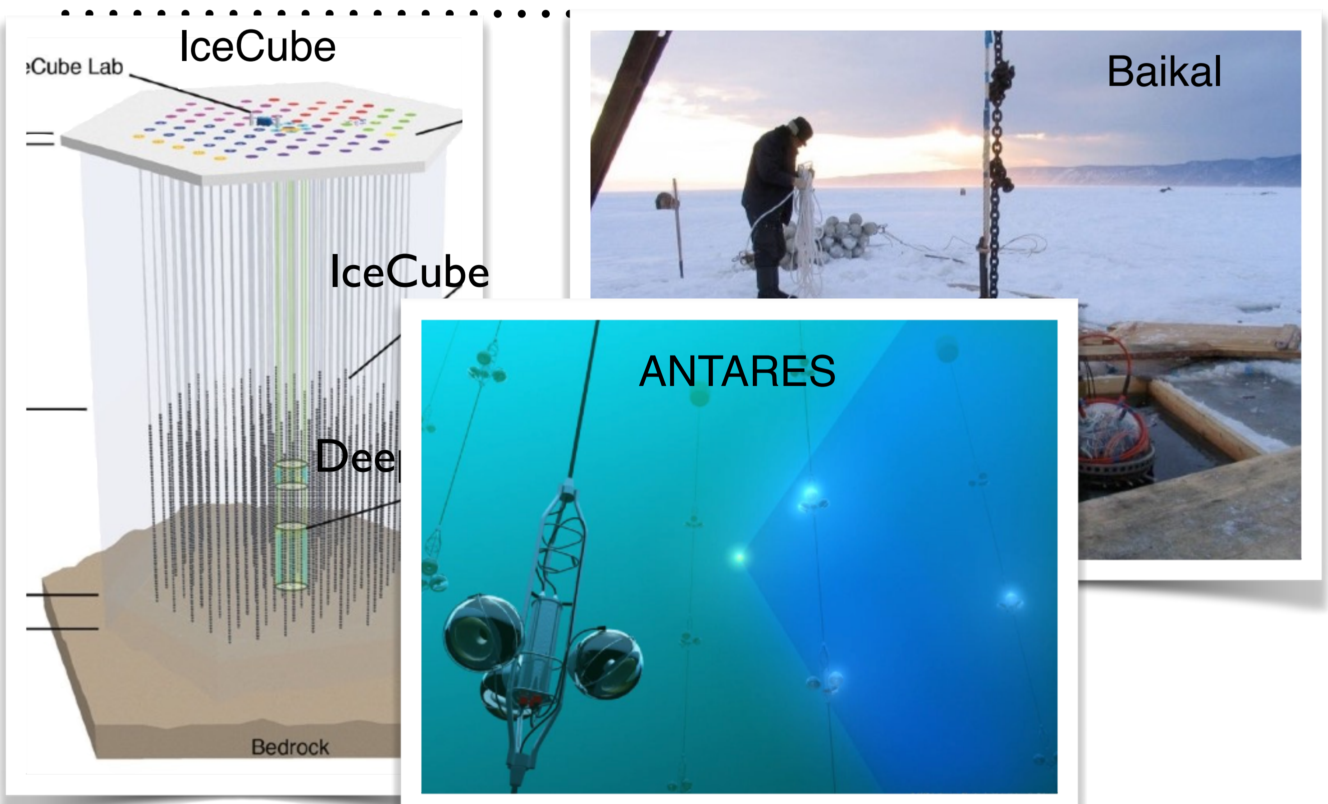
Signatures of Dark Matter (χ) in Neutrino Detectors

Channel	Type of Search	Typical Sources	Measures
	**DM Annihilation searches** ν from SM particle decay, direct neutrinos production - helicity suppressed for Majorana DM	• Galactic Center • Galactic Halo • Dwarf Spheroidals • Galaxy clusters • … 	Self-annihilation cross section **<σv>** DM Mass $\mathbf{m}_\chi$ (Branching fractions)
	**DM Decay searches** ν from SM particle decay or directly produced	• Extragalactic • Galactic Halo • Galaxy clusters • … 	DM Lifetime τ_χ DM Mass $\mathbf{m}_\chi$ (Branching fractions)
	**DM Nucleon scattering** Following χ capture, annihilation. Once annihilation and capture in balance (equilibrium) - no dependence on **<σv>** Test SD/SI scattering	• Sun • Earth 	DM-Nucleon scattering cross section σ^{SD} / σ^{SI} DM Mass $\mathbf{m}_\chi$ (Branching fractions)
	**Neutrino DM scattering** Astrophysical ν from distant sources probe rare interactions / Astrophysical ν interact with χ from Galactic halo →Anisotropy, spectral distortions, and time delays	• Galactic Halo • Distant point sources 	Combination of coupling strength **g** and masses $\mathbf{m}_\phi$ $\mathbf{m}_\chi$
	**Boosted DM** Highly boosted χ from the decay or annihilation of a heavy DM particle $\mathbf{m}_\phi$ interacts directly in the detector	• Galactic Center • Galactic Halo • Sun • … 	DM Lifetime τ_χ … or self-annihilation cross section **<σv>** DM mass $\mathbf{m}_\phi$

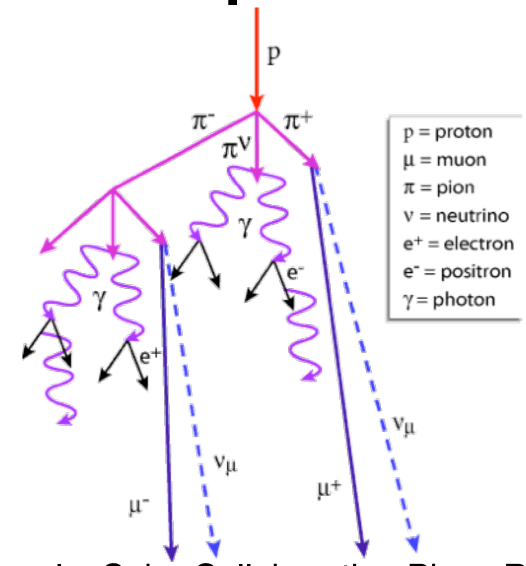
Detection/Backgrounds

Neutrino detection via water/ice **Cherenkov light**





Atmospheric Neutrinos / Muons

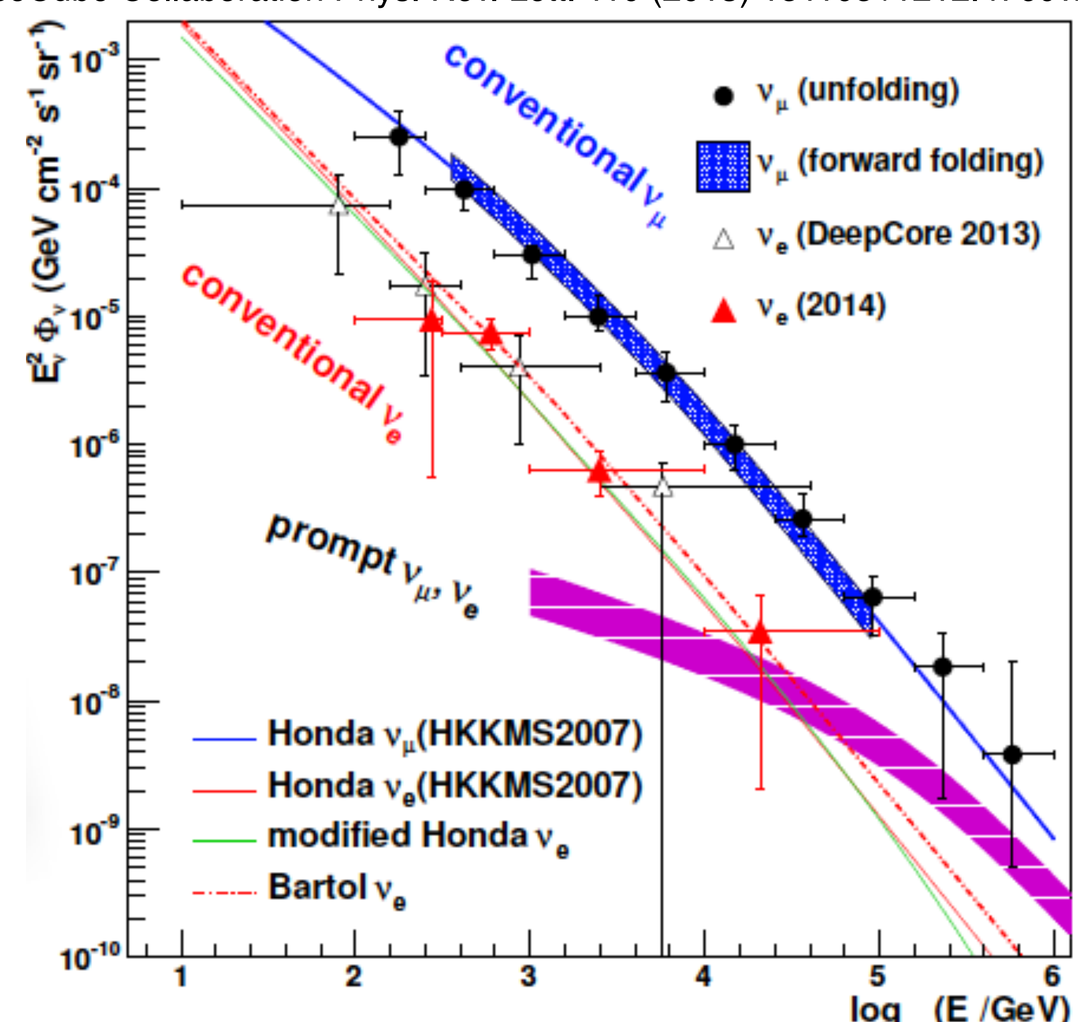


Cosmic rays interact in the upper atmosphere:

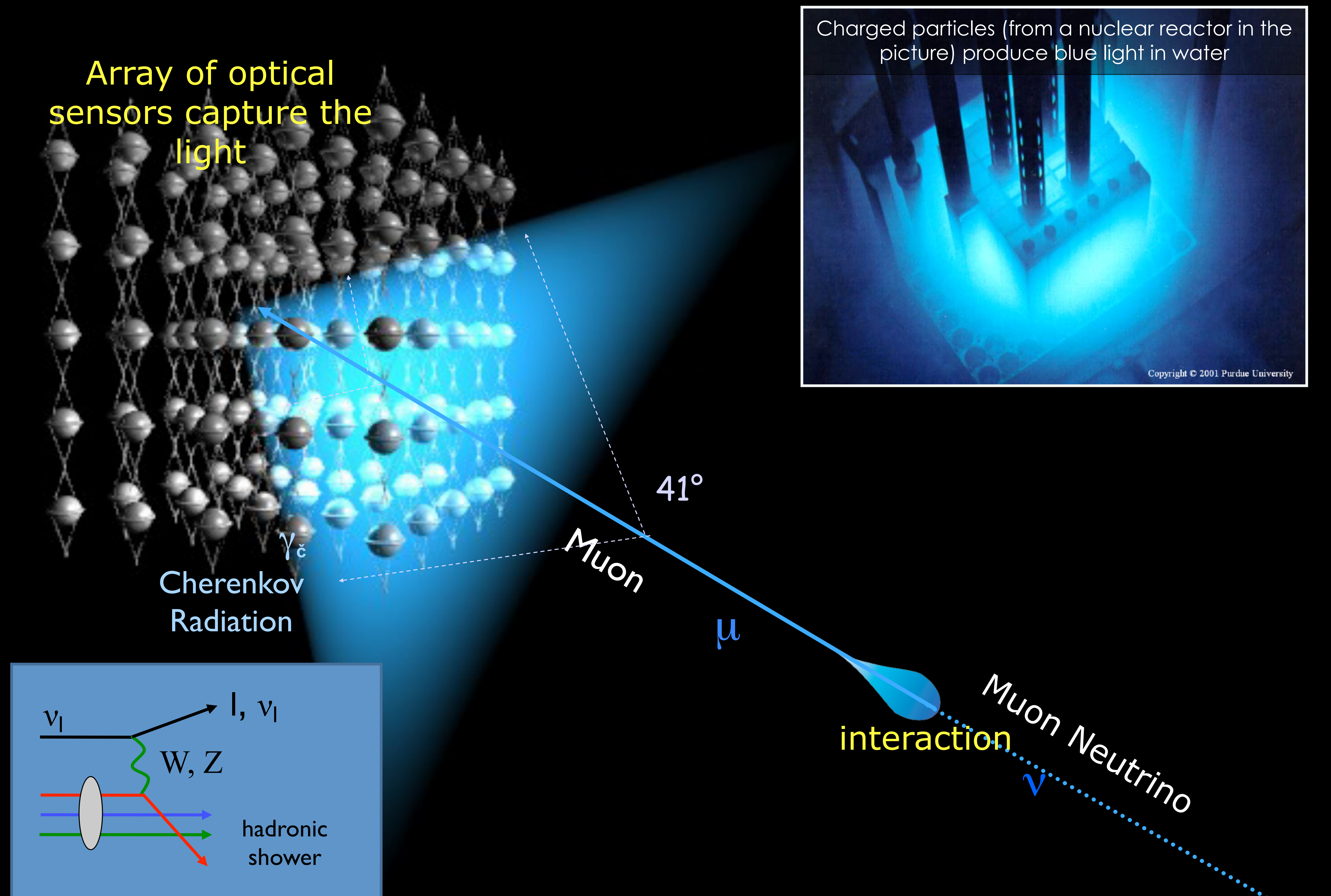
$p + A \rightarrow \pi^{\pm}$ $(K^{\pm})$ + other hadrons ...

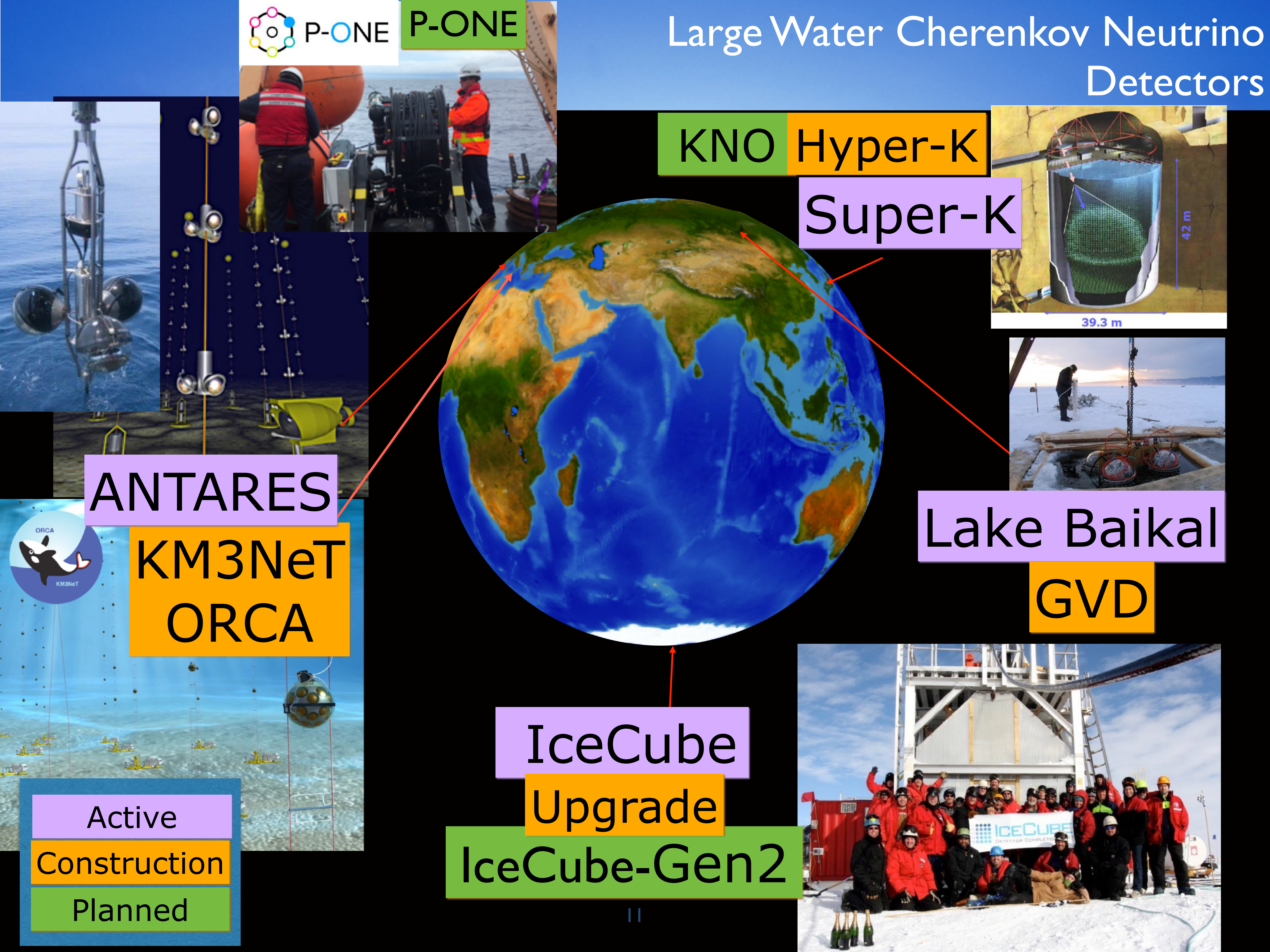
$\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \nu_\mu \nu_\mu$

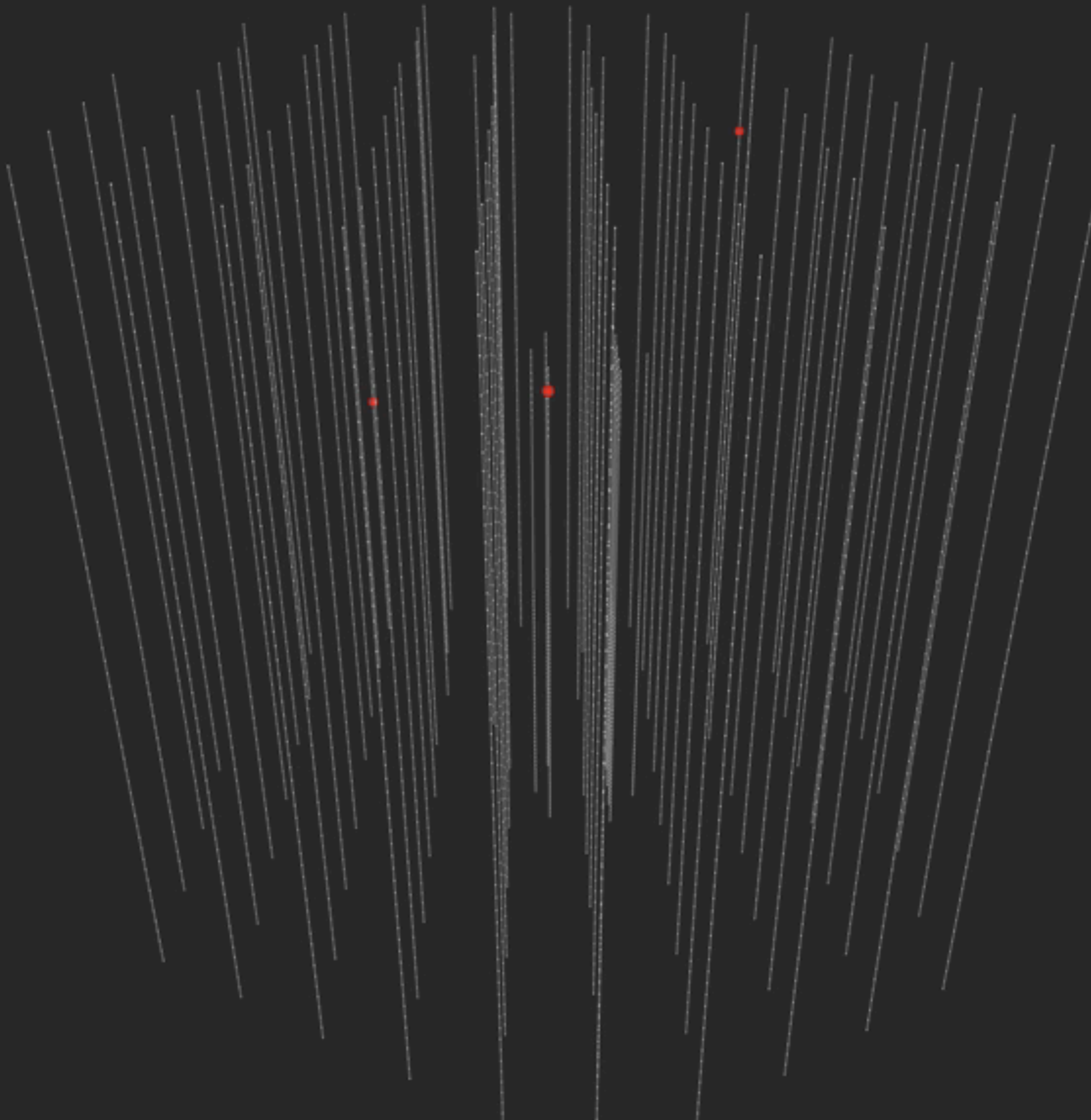
IceCube Collaboration Phys. Rev. Lett. 110 (2013) 151105 /1212.4760v2



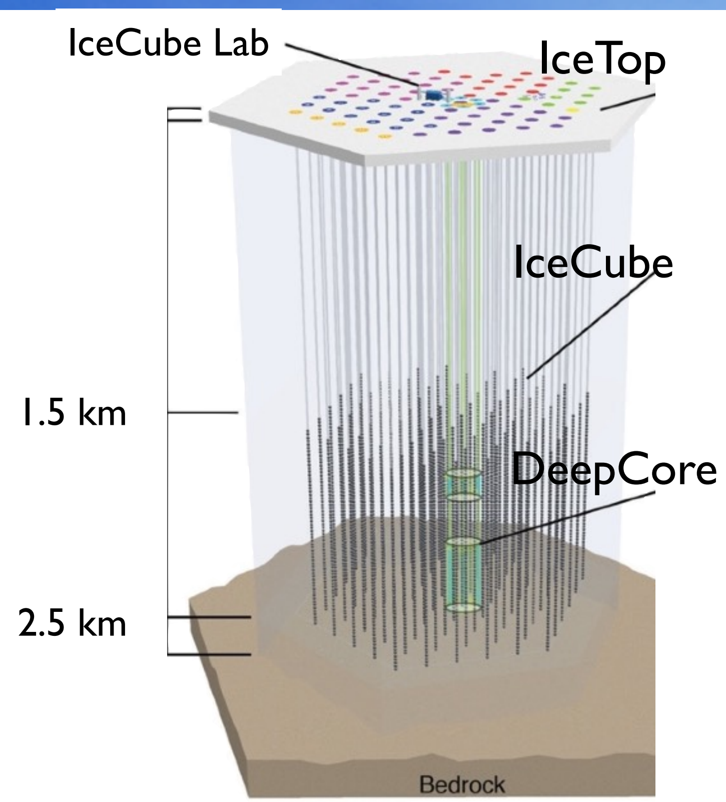
Principle of an optical Neutrino Telescope



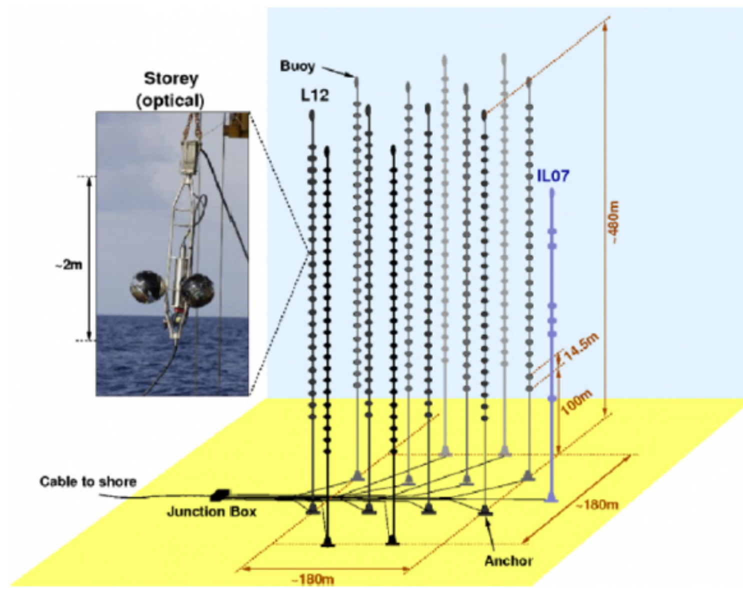

Large Water Cherenkov Neutrino Detectors
P-ONE
P-ONE
KNO
Hyper-K
Super-K
42 m
39.3 m
Lake Baikal
GVD
ANTARES
KM3NeT
ORCA
ORCA
KM3NeT
IceCube
Upgrade
IceCube-Gen2
ICECUBE
Active
Construction
Planned



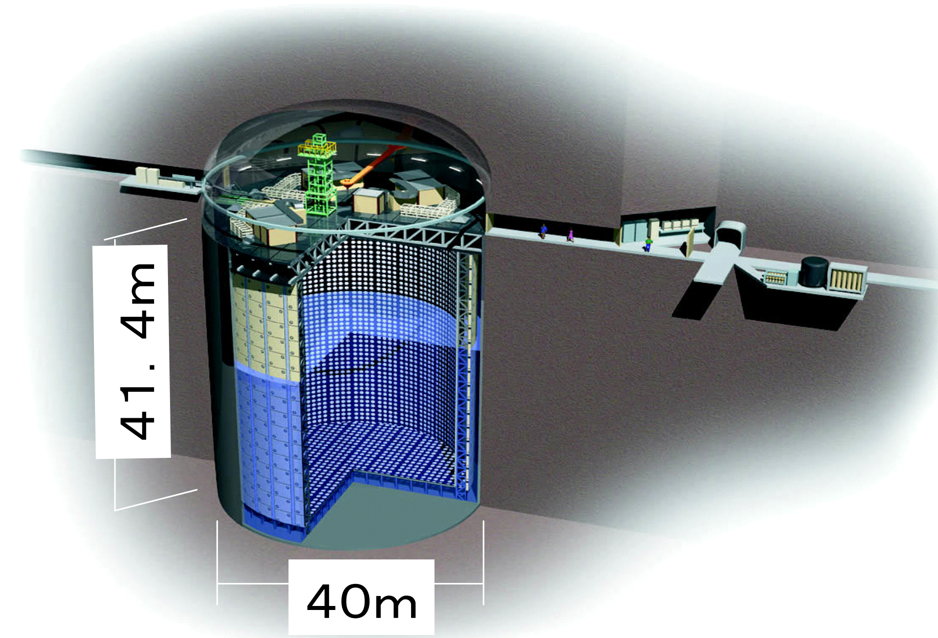
Neutrino Telescopes / Detectors Searching for Dark Matter …



- **IceCube** at the Geographic South Pole
- 5160 10"PMTs in Digital optical modules distributed over 86 strings instrumenting ~1km³
- Physics data taking since 2007 ; Completed in December 2010, including **DeepCore** low-energy extension



- **ANTARES** is located at a depth of 2475 m in the Mediterranean Sea, 40 km offshore from Toulon
- Consists 885 10"PMTs on 12 lines with 25 storeys each.
- Detector was competed in May 2008 ; Phyiscs data taking since 2007



- **Super-Kamiokande** at Kamioka uses 11K 20" PMTs
- 50kt pure water (22.5kt fiducial) water-cherenkov detector
- Operating since 1996

Detect Cherenkov light from neutrino interaction products

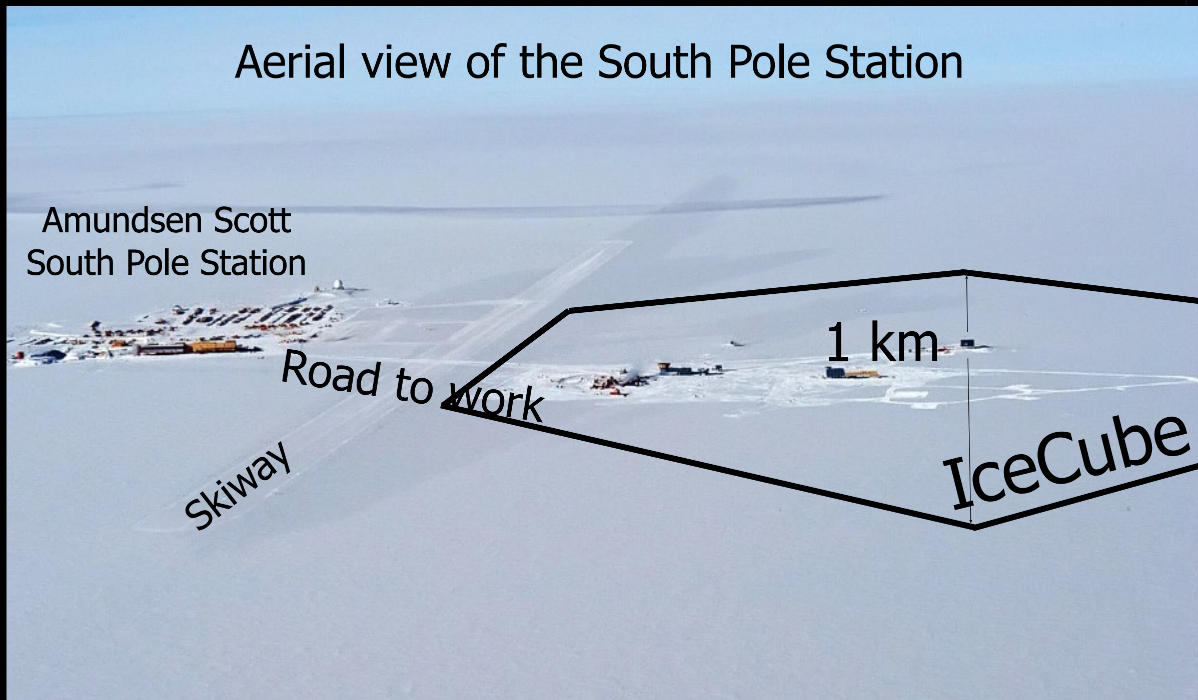
Main backgrounds: Atmospheric neutrino, atmospheric muons (down-going)

The IceCube Neutrino Telescope

300 scientists from
52+1 member
institutions
from 12 countries

Sungkyunkwan University
since 2013

University of Utah
since 2020

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2008


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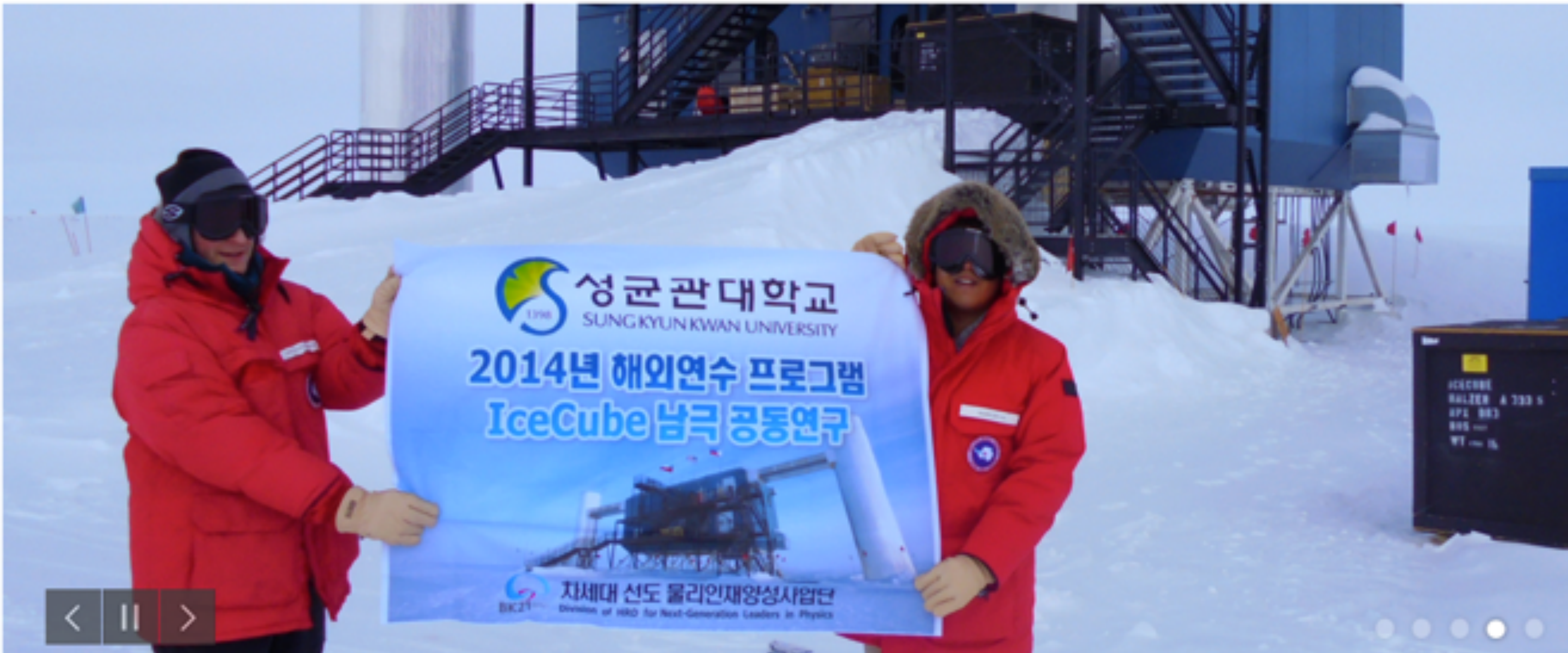
SUNG KYUN KWAN UNIVERSITY (SKKU)

SEARCH GO

About SKKU | Admissions | Academics | Research | Univ-Industry Collabo. | International | Campus Life



Brain Korea(BK) Project, Ice Cube Antartica Joint Reserch

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- Leading 'humanism Renaissance' by 617 years of ...
- The World cup star, Seol Kihyeon is retired, beco...
- Lee Wangeun, Chairman of Shinsung Solar Energ...

Notice
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- Course lists of Dept. of Energy Science 2015 Sprin..
- Announcement to New International Students
- [Dormitory] 2015 Spring Myeongnyunhaksa Admi..

SKKU Reputation

SKKU News

Academics

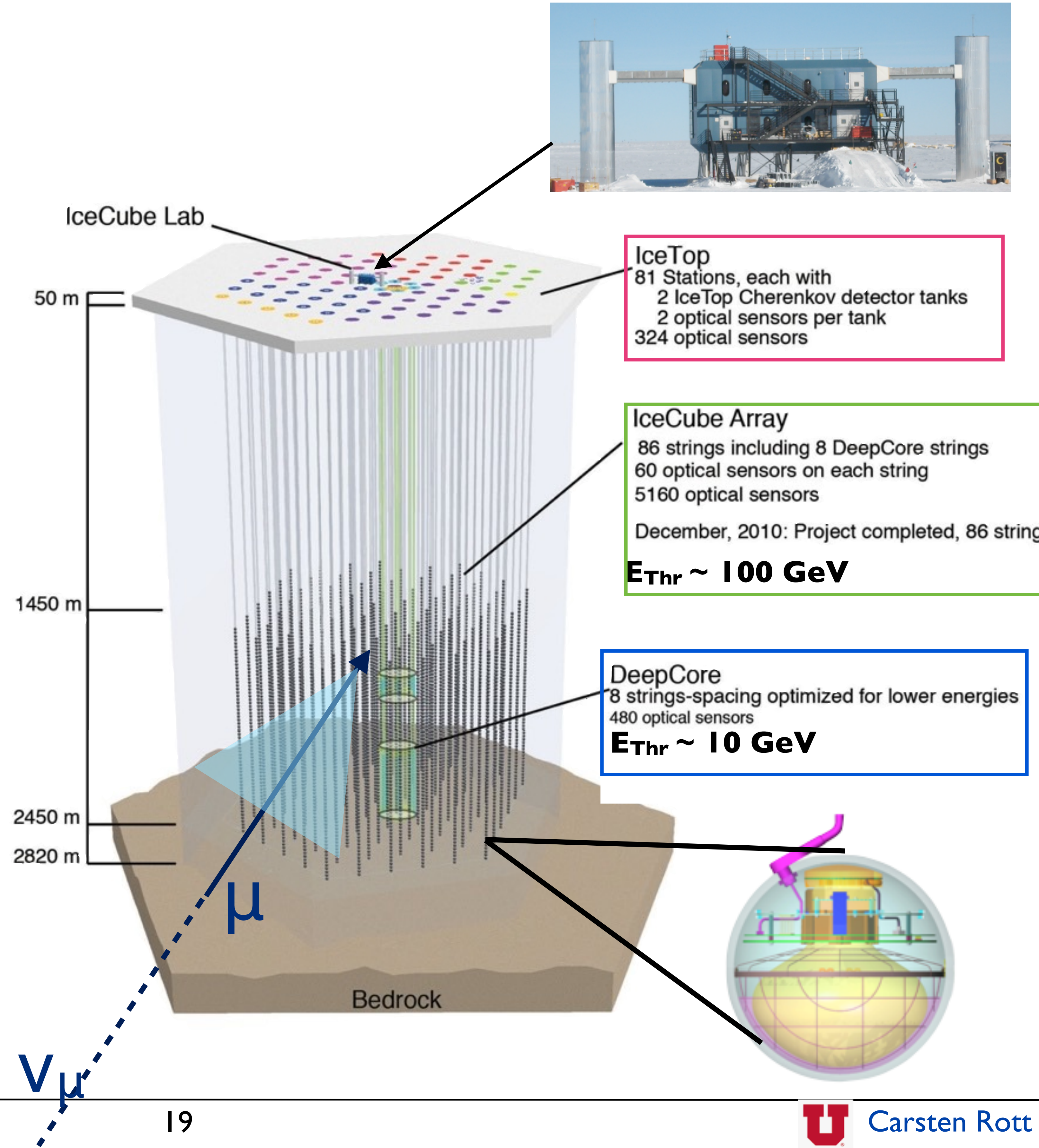
The IceCube Neutrino Telescope

- Gigaton Neutrino Detector at the Geographic South Pole
- 5160 Digital optical modules distributed over 86 strings
- Completed in December 2010
- Extremely stable: >99% uptime and 98% of sensor modules in perfect condition !
- Neutrinos are identified through Cherenkov light emission from secondary particles produced in the neutrino interaction with the ice


〈이 기사는 2014년 01월 06일자 신문 23면에 게재되었습니다.〉

"한국 '세계적 리더' 될 좋은 기회"

기초과학 투자 의지 활발, 한국에 새 연구 터전 둥지.. 연구자-학생 영입해 연구

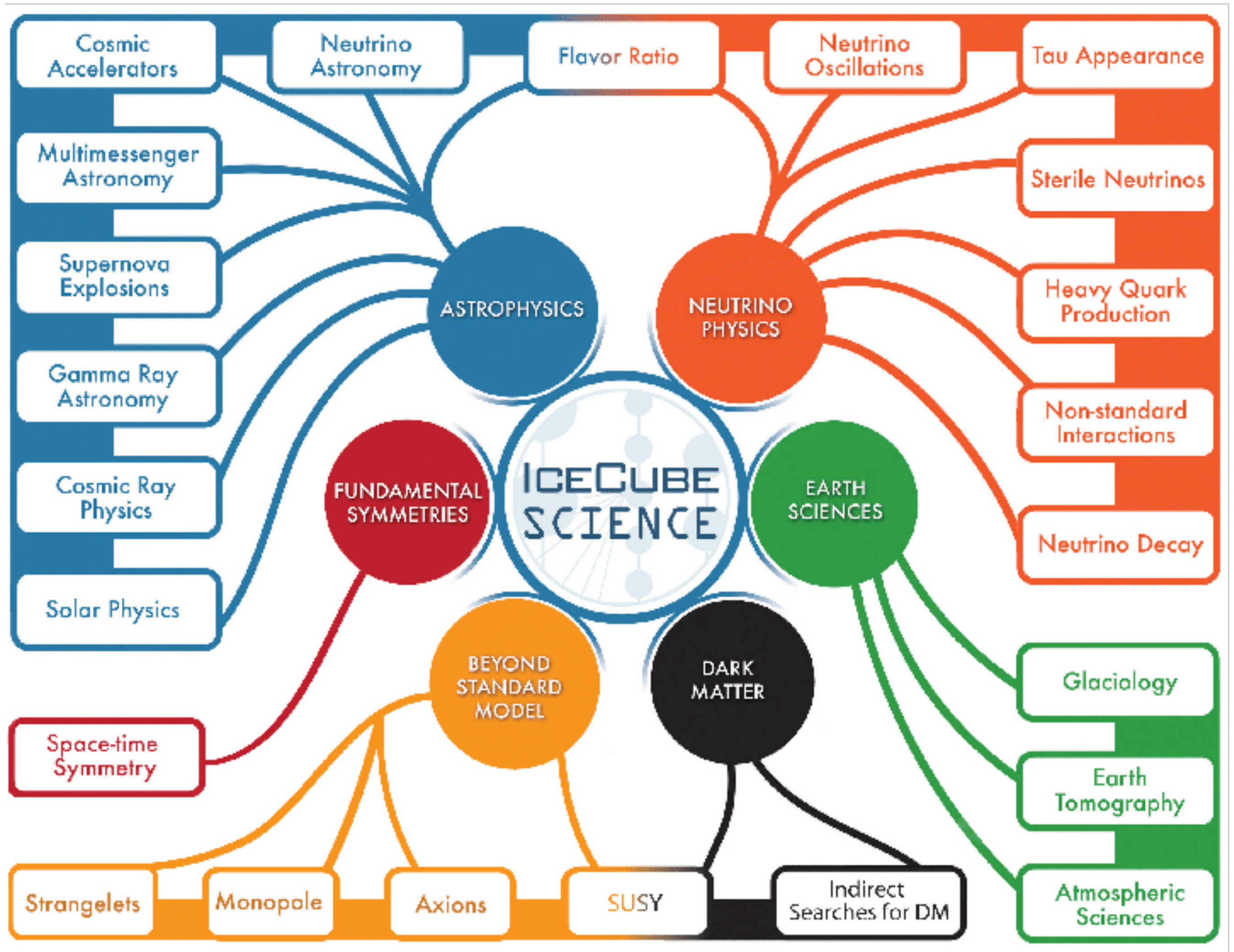


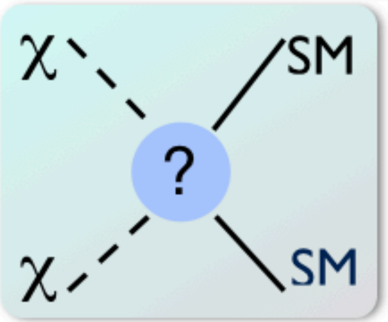
Neutrino Telescope Science

Scientific Scope

- ASTROPHYSICS & NEUTRINO SOURCES
  - Point sources of ν's (SNR, AGN …), extended sources
  - Transients (GRBs, AGN flares …)
  - Solar Atmospheric Neutrinos
  - Diffuse fluxes of ν's (all sky, cosmogenic, galactic plane …)
- BSM PHYSICS & DARK MATTER
  - Indirect DM searches (Earth, Sun, Galactic center/ halo)
  - Magnetic monopoles
  - Violation of Lorentz invariance
- PARTICLE PHYSICS
  - ν oscillations, sterile ν's
  - Charm in CR interactions
  - Neutrino Cross Sections
- COSMIC RAY PHYSICS
  - Energy spectrum around "knee", composition, anisotropy
- SUPERNOVAE (galactic/LMC)
- GLACIOLOGY & EARTH SCIENCE

Very diverse science program, with neutrinos from 10GeV to EeV, and MeV burst neutrinos





DM Annihilation searches

ν from SM particle decay, direct neutrinos helicity suppressed

- Galactic Center
- Galactic Halo
- Dwarf Spheroidals
- Galaxy clusters
- …

Self-annihilation cross section **<σv>**

DM Mass $\mathbf{m}_\chi$
(Branching fractions)

Dark Matter Self-annihilations

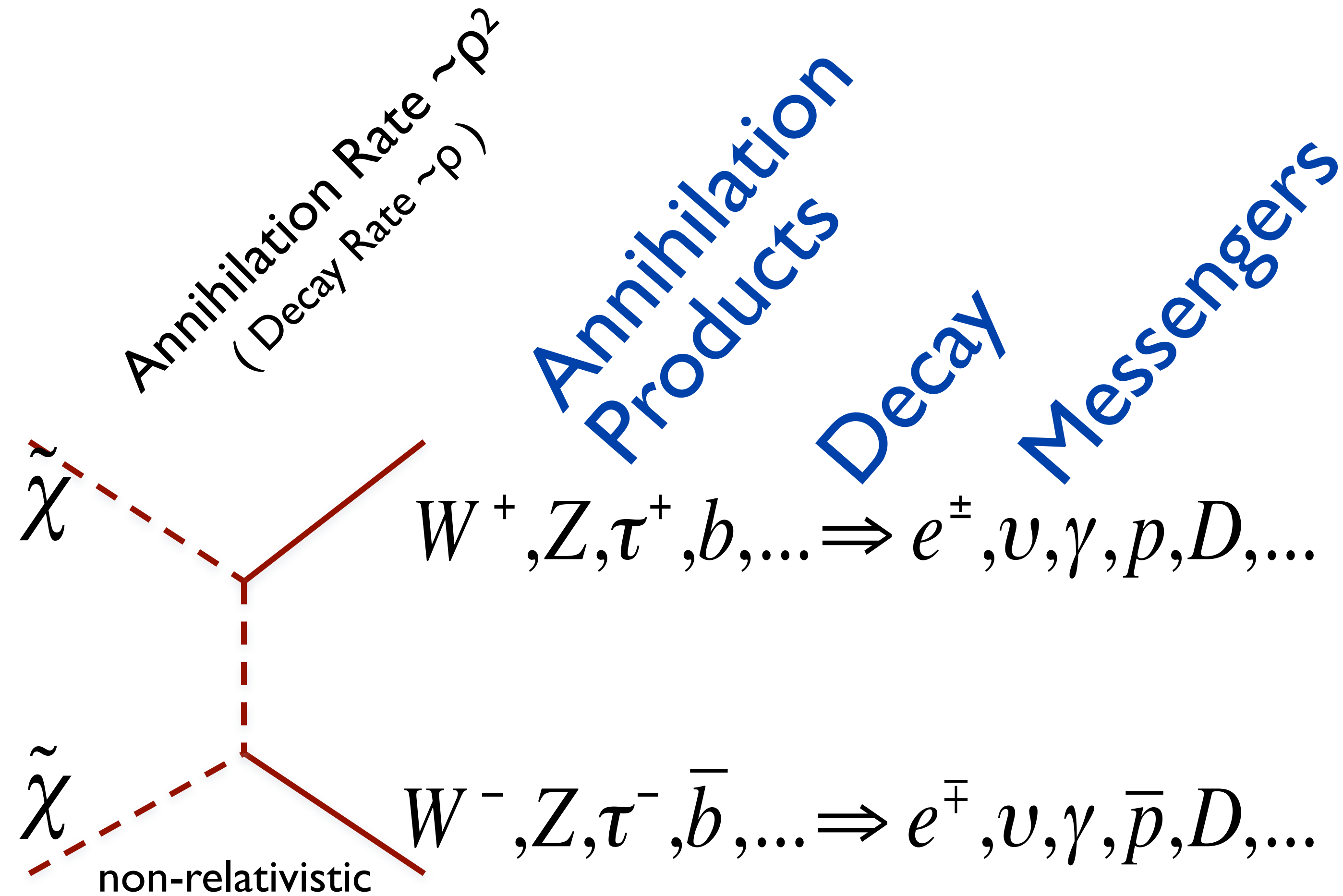
$<\sigma_A v>$

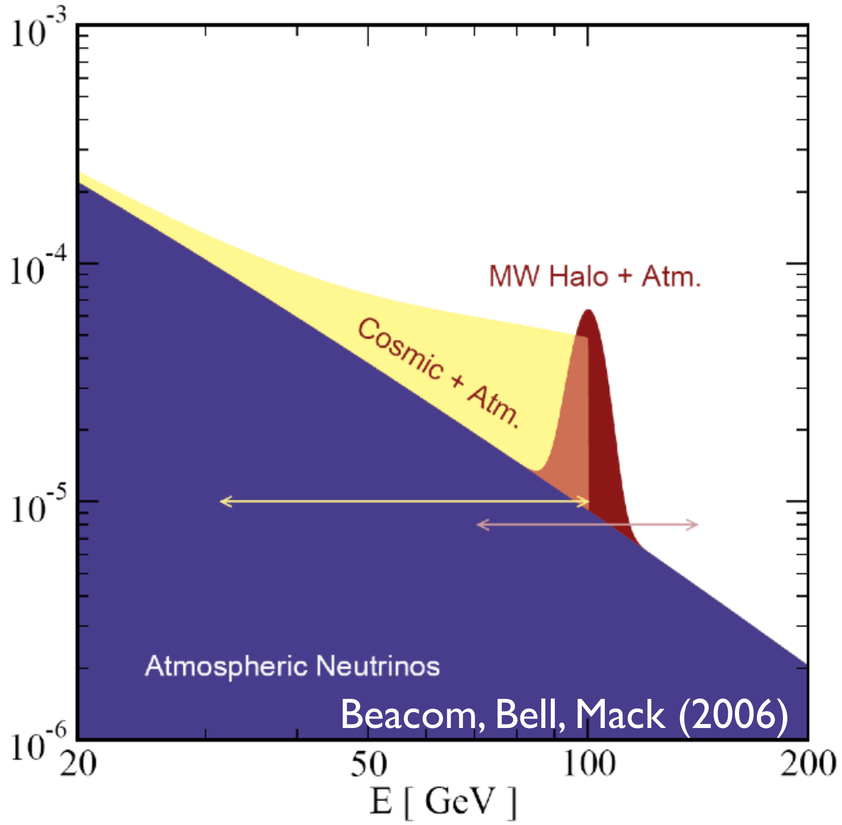
Dark Matter Signals

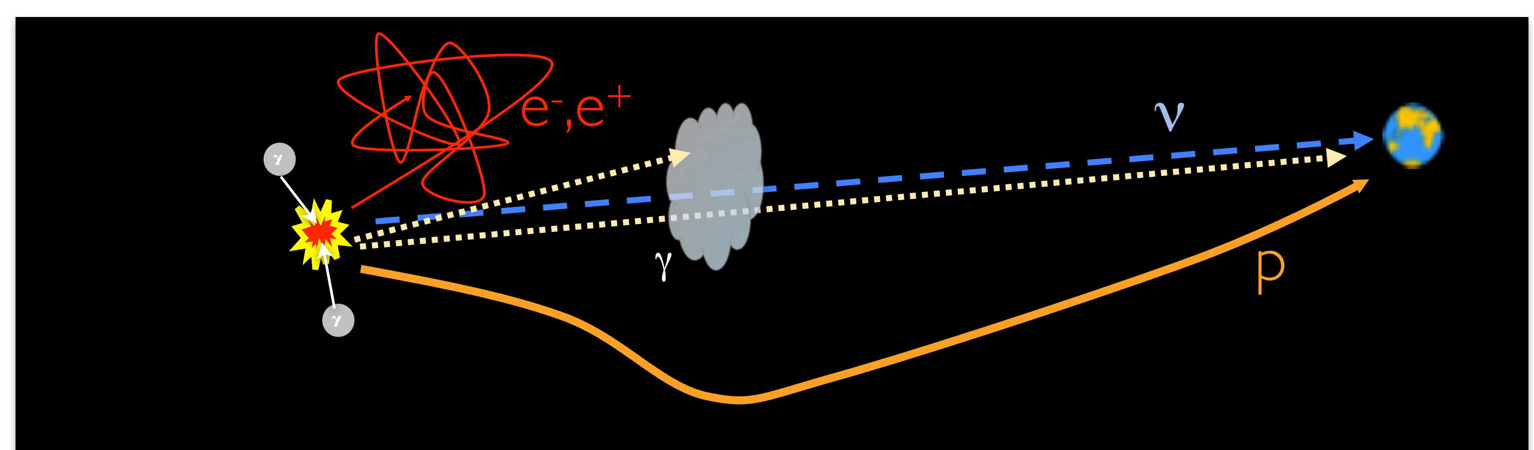
- Identify dense regions of dark matter

  ⇒self-annihilation can occur at significant rates
- Pick prominent Dark Matter target
- Understand / predict backgrounds
- Exploit features in the signal to better distinguish against backgrounds

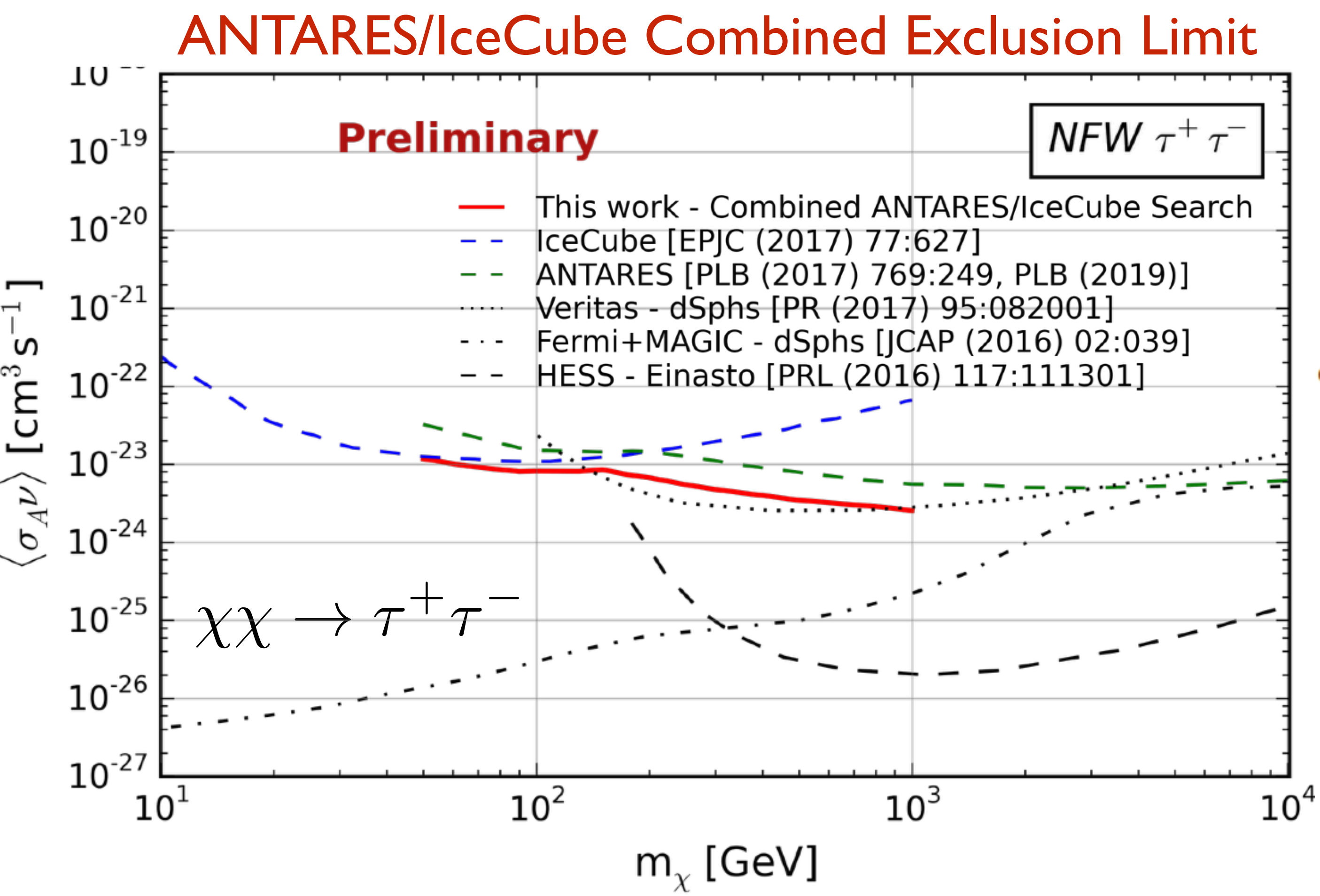
$$\frac{d\phi_\nu}{dE} = \frac{\langle \sigma_A v \rangle}{2} J(\psi) \frac{R_{\rm sc}\rho_{\rm sc}^2}{4\pi m_\chi^2} \frac{dN_\nu}{dE}$$



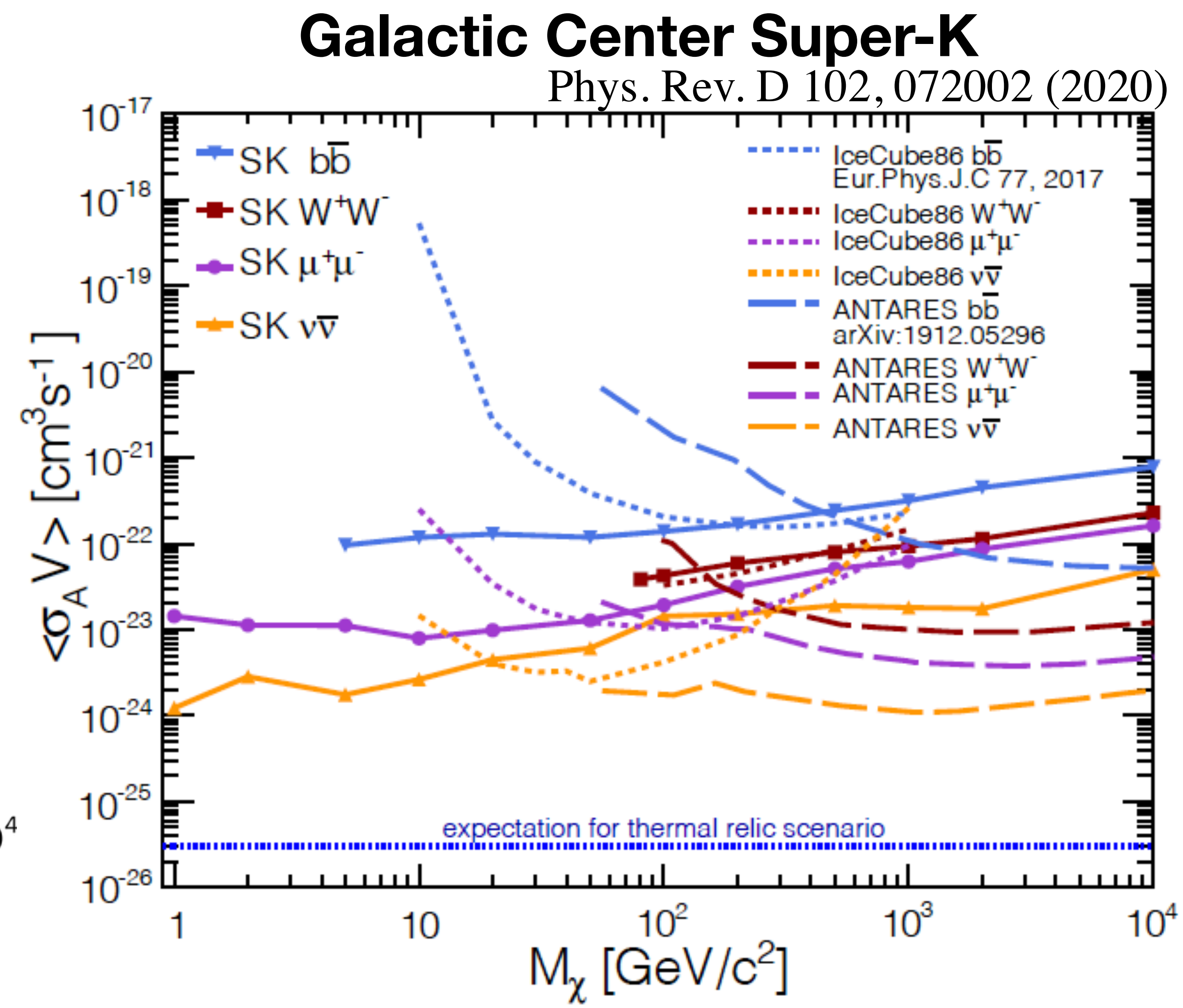




IceCube+ANTARES - Phys.Rev.D 102 (2020) 8, 082002

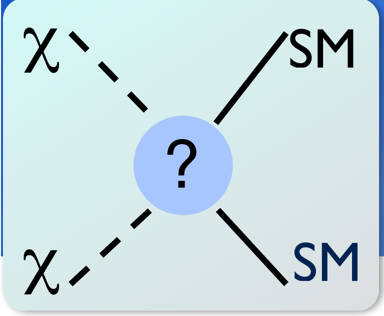


Combined Search for Neutrinos from Dark Matter Annihilation in the Galactic Center using IceCube and ANTARES

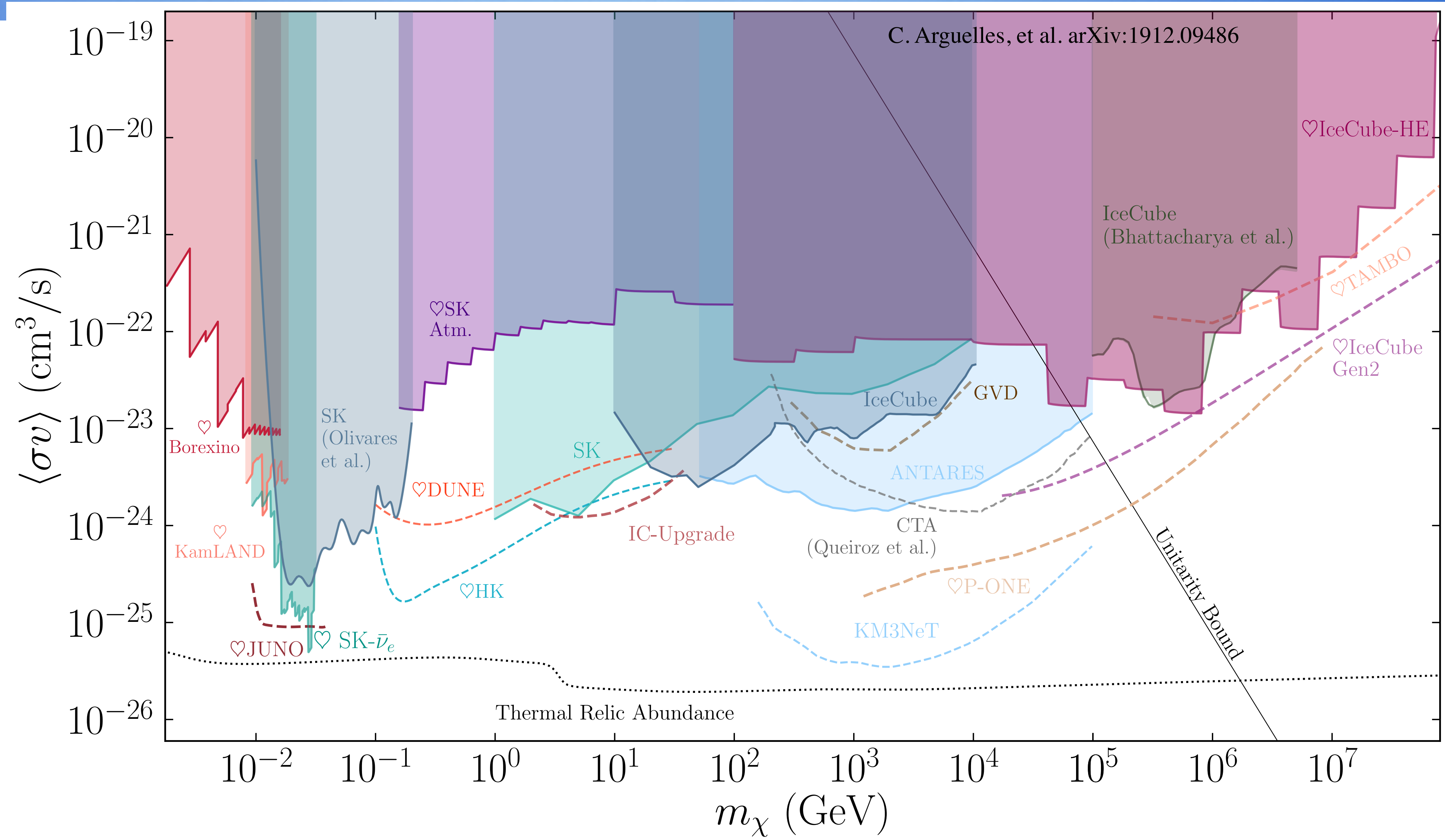


- Combined analysis enhances sensitivity in overlap region and helps to make analyses more comparable
- Very competitive result from Super-K for dark matter masses below a 100GeV

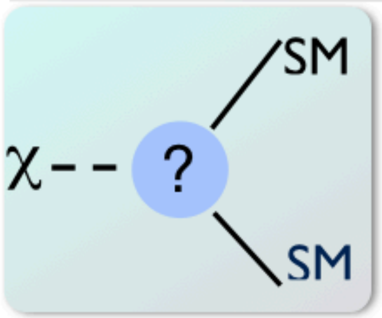
Neutrino searches have been important test to probe models motivated by observations with other messengers (example the cosmic-ray positron excess (PAMELA, AMS-02, …))



Search Dark Matter Annihilation



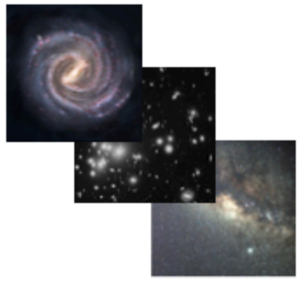
- **Current status**
  - Most competitive with other messengers for heavy dark matter and channels with high neutrino yields
  - Neutrino searches have been important test to probe models motivated by observations with other messengers (example the cosmic-ray positron excess (PAMELA, AMS-02, …))
- **Future prospects**
  - Reaching the thermal relic cross section remains challenging even with next generation detectors
  - Searches are very generic, do not rely on WIMP hypothesis.
    - Go beyond WIMP scenarios (high-mass, enhanced annihilation cross section, evade unitarity bound)



DM Decay searches

ν from SM particle decay or directly produced

- Extragalactic
- Galactic Halo
- Galaxy clusters
- …



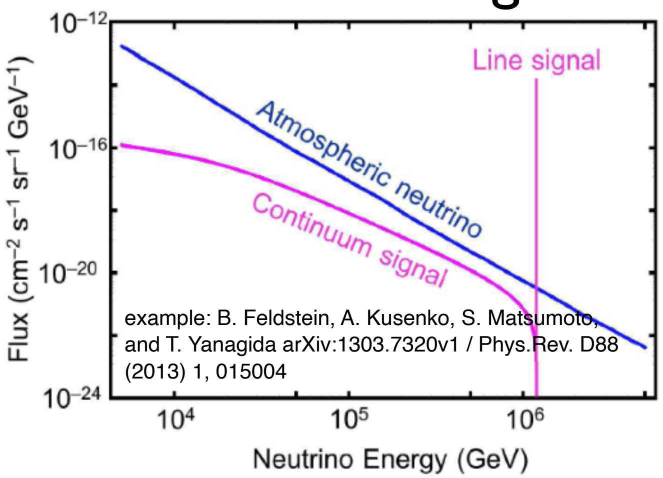
DM Lifetime τ_χ

DM Mass m_χ
(Branching fractions)

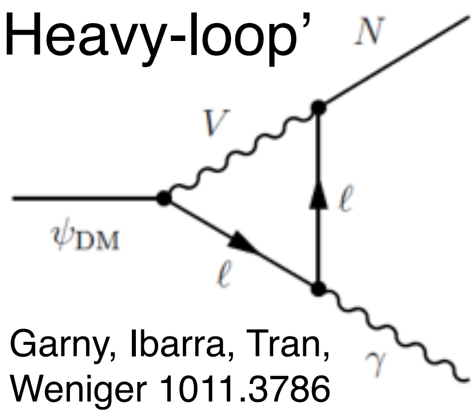
Dark Matter Decay

Heavy Dark Matter Decay

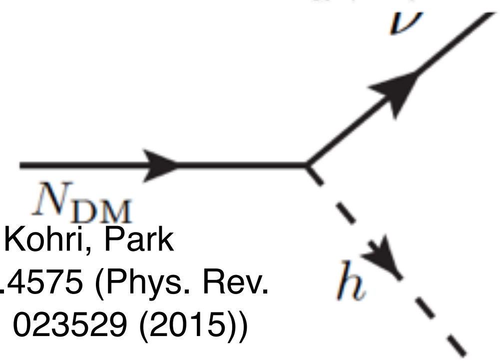
Decay process might produce mono-energetic neutrinos



'Heavy-loop'

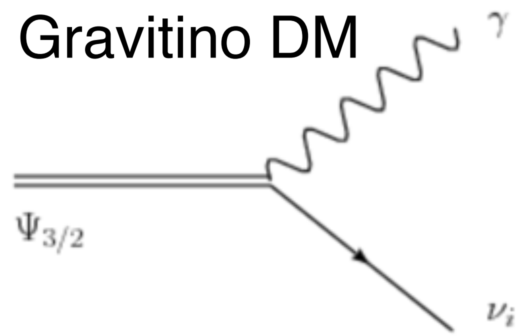


Garny, Ibarra, Tran, Weniger 1011.3786

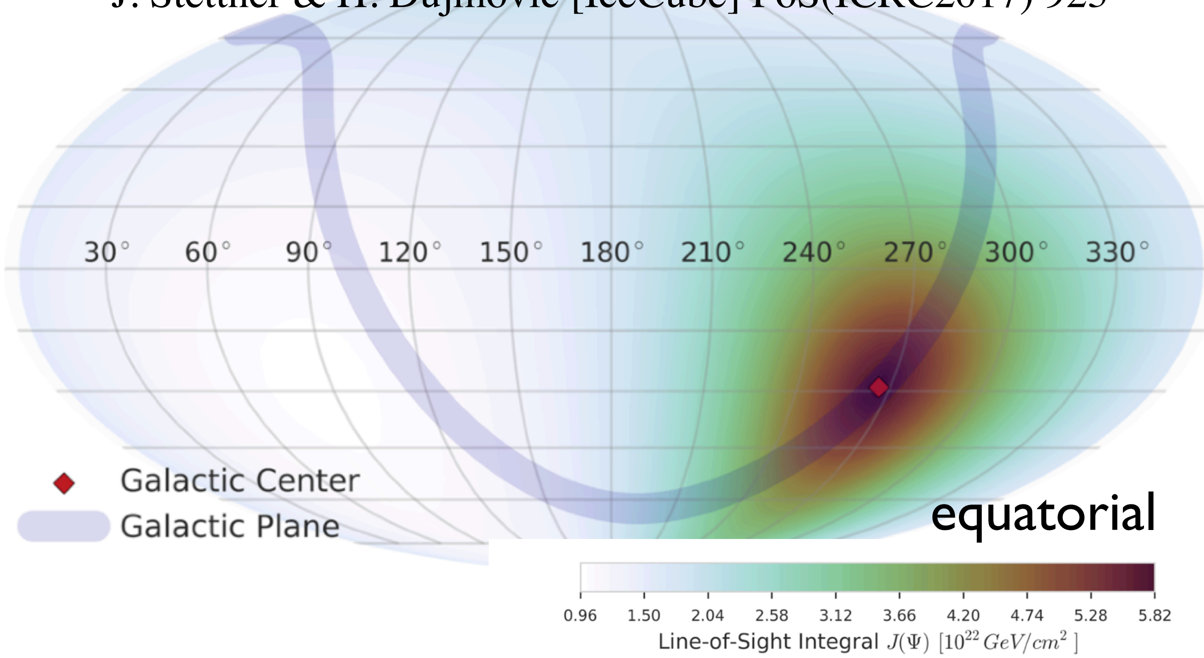


Rott, Kohri, Park 1408.4575 (Phys. Rev. D 92, 023529 (2015))

Gravitino DM



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



Two flux contributions:
Galactic and Extra galactic

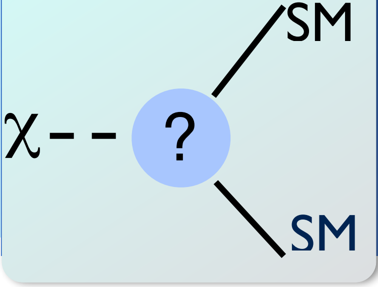
$$\frac{d\Phi_{\mathrm{DM},\nu_\alpha}}{dE_\nu} = \frac{d\Phi_{\mathrm{G},\nu_\alpha}}{dE_\nu} + \frac{d\Phi_{\mathrm{EG},\nu_\alpha}}{dE_\nu}$$

- Characteristics of the signal components:
  - (1) Dark Matter decay in the Galactic Halo (Anisotropic flux + decay spectrum)

$$\frac{\mathrm{d}\Phi^{\mathrm{G}}}{\mathrm{d}E_\nu} = \frac{1}{4\pi\, m_{\mathrm{DM}}\, \tau_{\mathrm{DM}}} \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} \int_0^\infty \rho(r(s,l,b))\, \mathrm{d}s$$

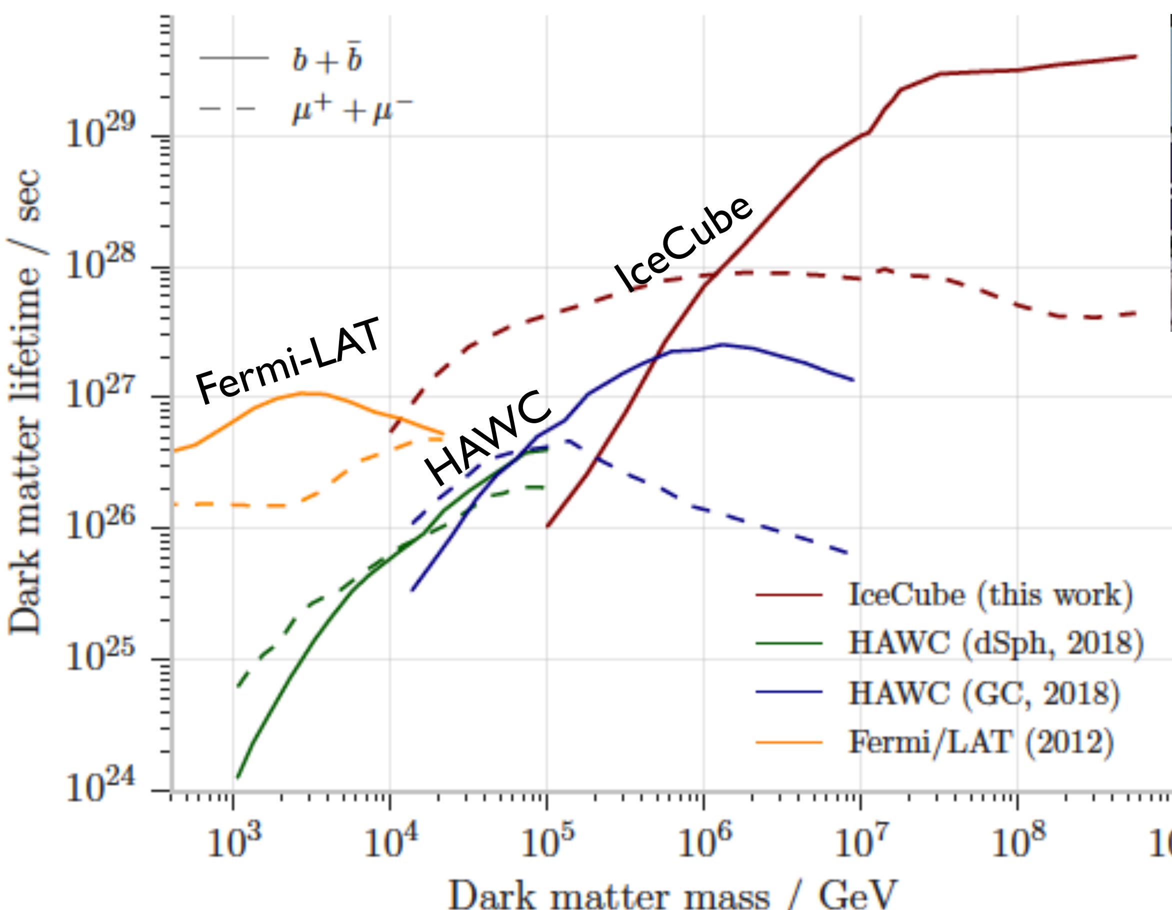
  - Dark Matter decay at cosmological distances (Isotropic flux + red-shifted spectrum)

$$\frac{\mathrm{d}\Phi^{\mathrm{EG}}}{\mathrm{d}E} = \frac{\Omega_{\mathrm{DM}}\, \rho_c}{4\pi\, m_{\mathrm{DM}}\, \tau_{\mathrm{DM}}} \int_0^\infty \frac{1}{H(z)} \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} [(1+z)E_\nu]\, \mathrm{d}z$$

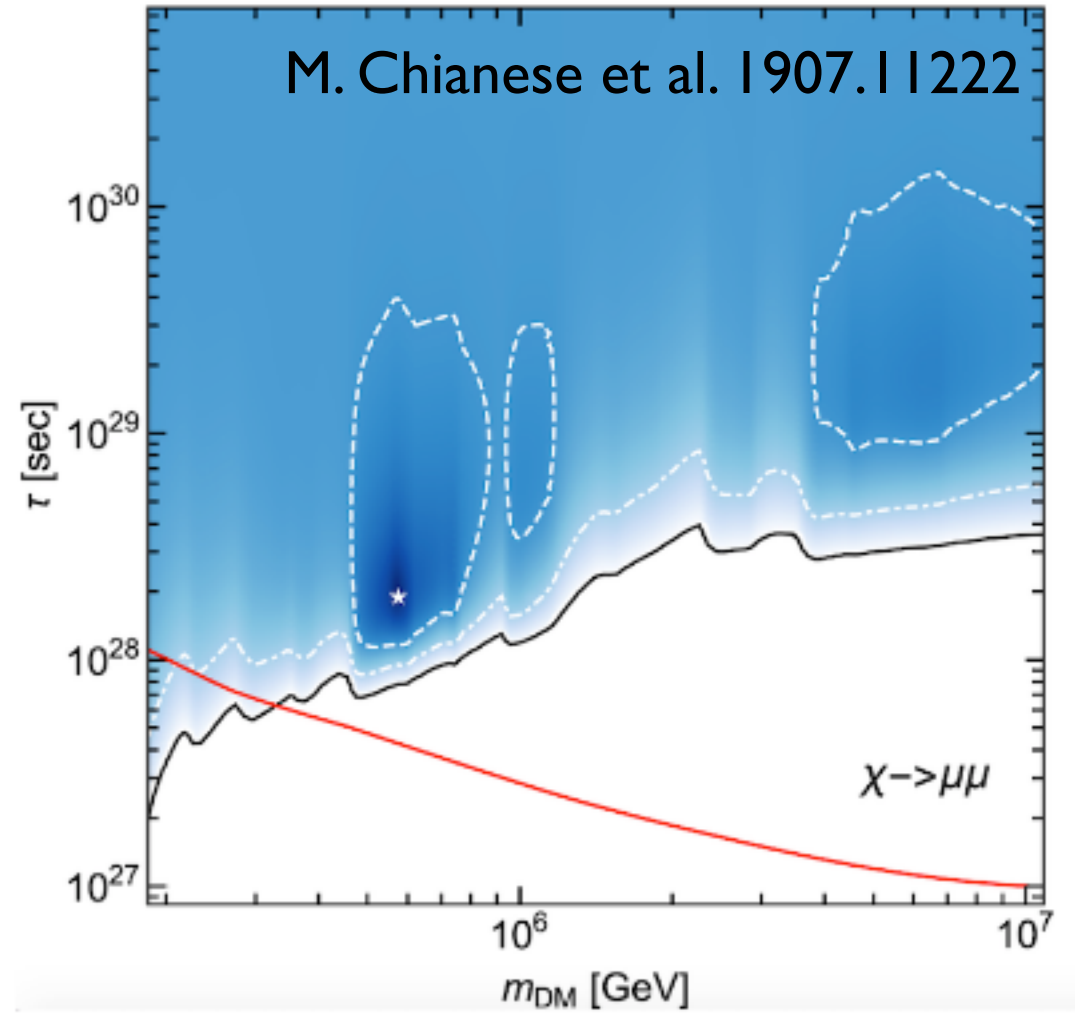


Heavy Dark Matter Decay

IceCube Collaboration arXiv:1804.03848v1 (published EPJC)



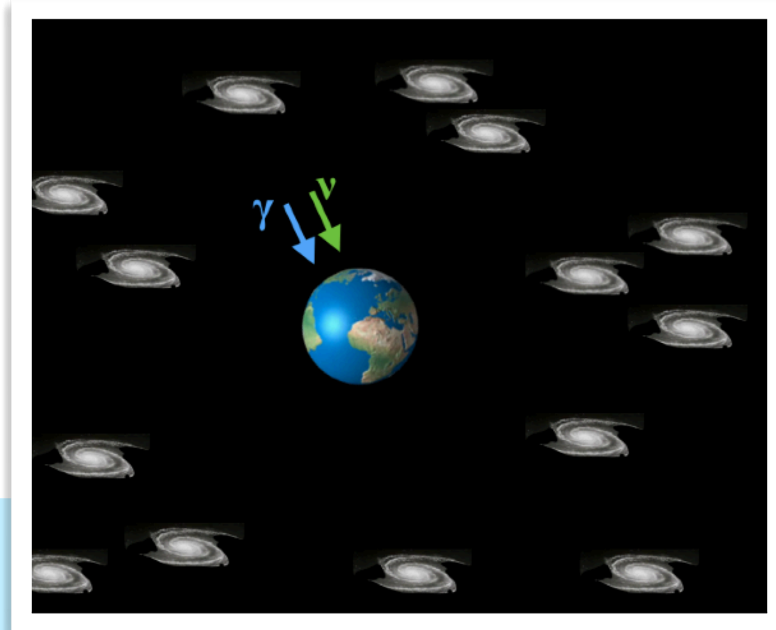
Hrvoje Dujmovic

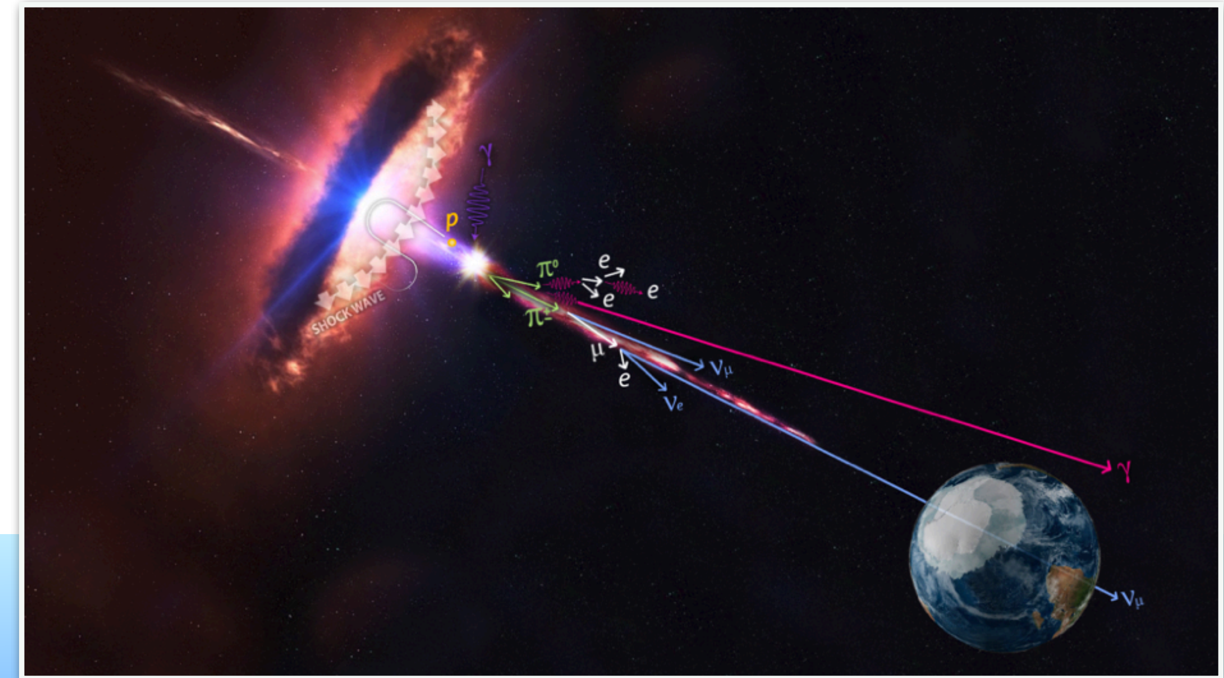


- **Current status:**
  - IceCube provides leading bounds (~10^{28}s) on heavy decaying dark matter / Neutrinos extremely competitive above ~10TeV
  - Dark matter alone cannot explain the observed astrophysical neutrino flux
- **Future prospects and priorities**
  - Opportunities for combined searches in TeV range (broader coverage of models), extremely competitive at high energies
  - Highest priority - understand astrophysical neutrino spectrum
    - Is IceCube's data already showing any hints of dark matter (TeV excess ?)

Evidence for dark matter in in the diffuse high-energy astrophysical neutrino flux ?

- B. Feldstein, A. Kusenko, S. Matsumoto, and T. T. Yanagida, PRD 88 no. 1, (2013) 015004, arXiv:1303.7320
- A. Esmaili and P. D. Serpico, JCAP11(2013) 054, arXiv:1308.1105
- Y. Ema, R. Jinno, and T. Moroi, PLB 733 (2014) 120–125, arXiv:1312.3501
- A. Bhattacharya, M. H. Reno, and I. Sarcevic, JHEP06 (2014) 110, arXiv:1403.1862
- C. Rott, K. Kohri, and S. C. Park, PRD 92 no. 2, (2015) 023529, arXiv:1408.4575
- K. Murase, R. Laha, S. Ando, and M. Ahlers, PRL 115 no. 7, (2015) 071301, arXiv:1503.04663
- L. A. Anchordoqui, V. Barger, H. Goldberg, X. Huang, D. Marfatia, L. H. M. da Silva, and T. J. Weiler, PRD 92 no. 6, (2015) 061301, arXiv:1506.08788. [Erratum: PRD 94, 069901 (2016)].
- M. Chianese, G. Miele, and S. Morisi, PLB 773 (2017) 591-595, arXiv:1707.05241
- M. Ahlers, Y. Bai, V. Barger, and R. Lu, PRD 93no. 1, (2016) 013009, arXiv:1505.03156
- ….

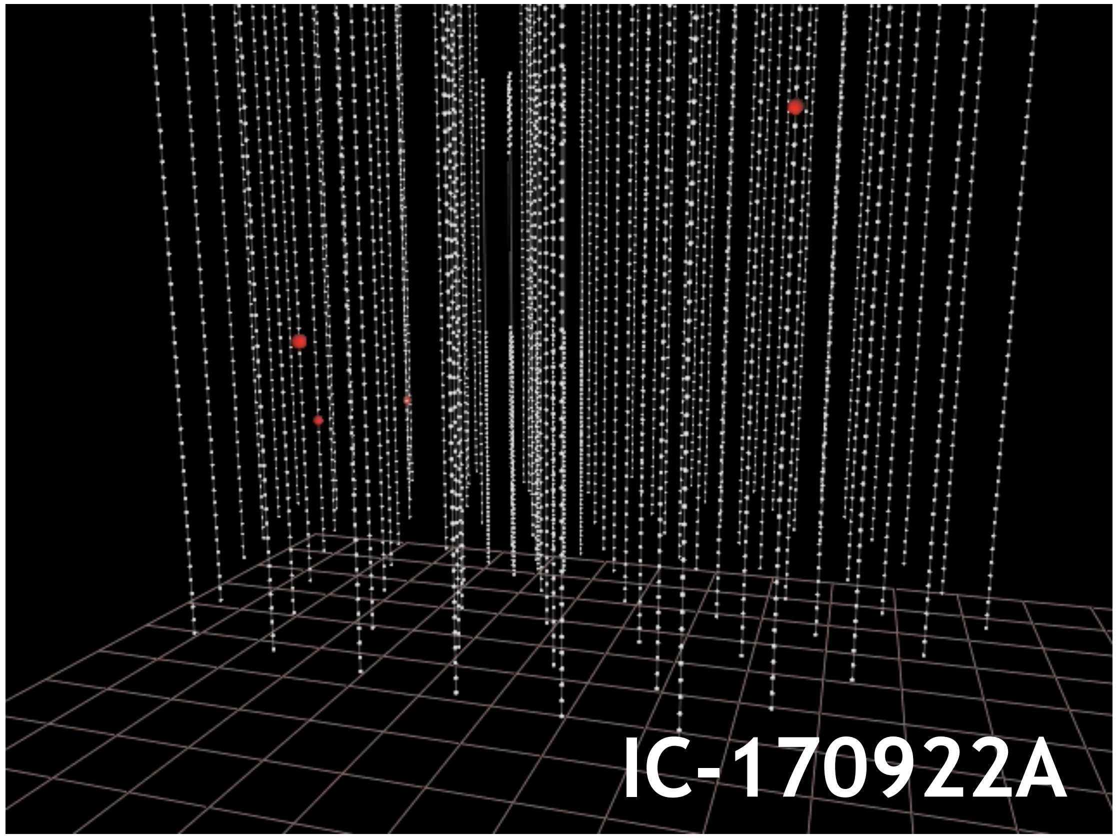


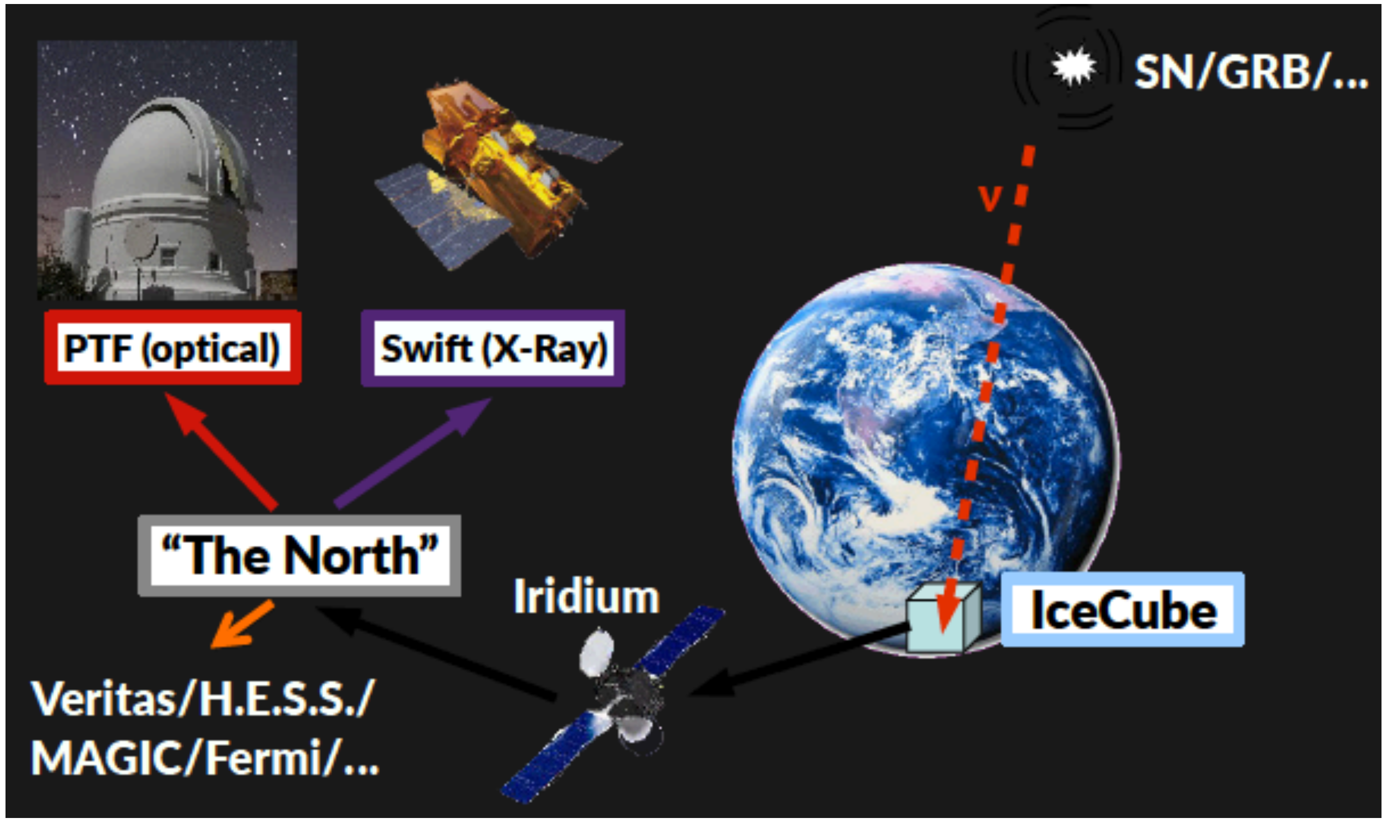


Multi-messenger Neutrino Astronomy and IceCube-170922A

Astropart. Phys. 92 (2017) 30
A&A 607 (2017) A115

IceCube-170922A

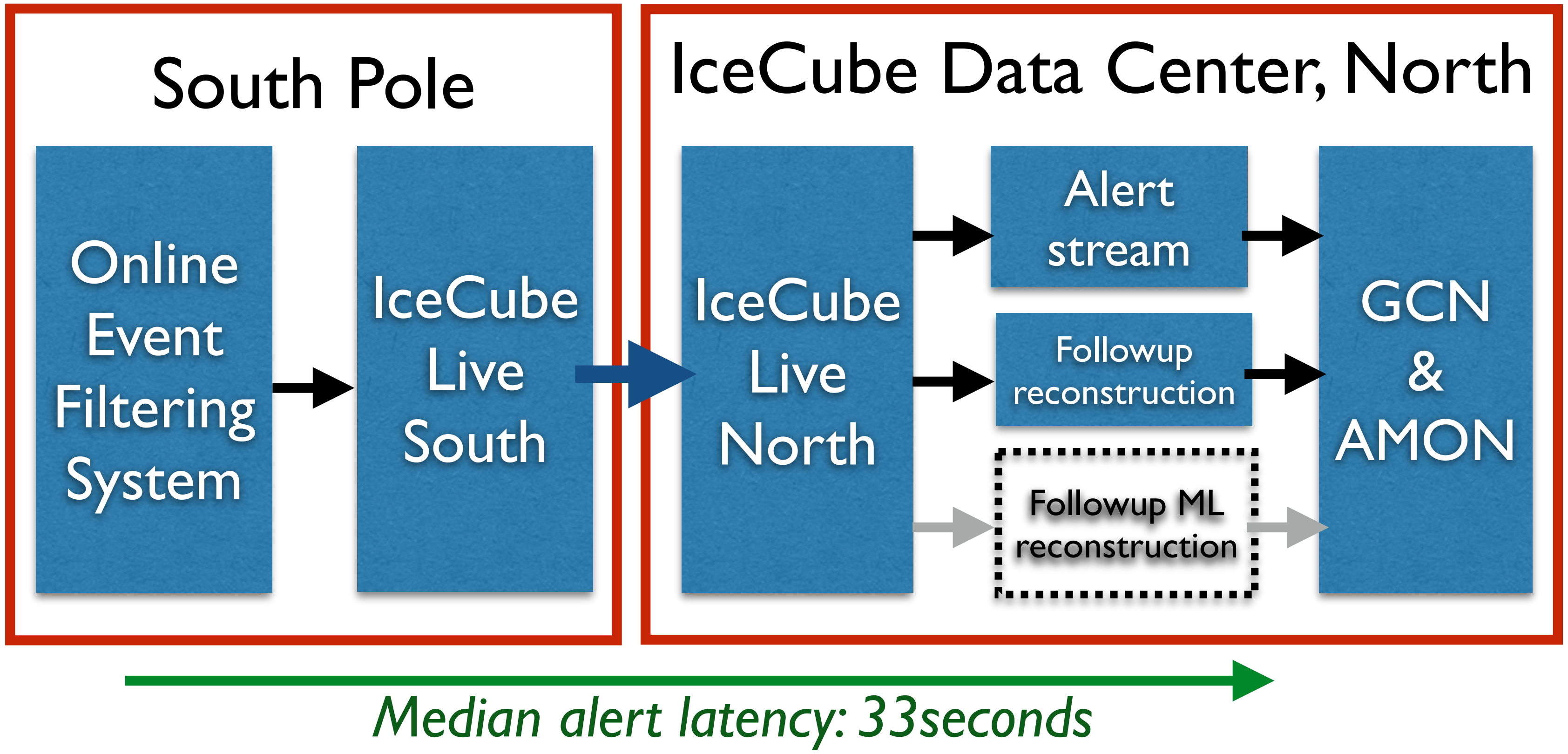




Real-time alerts

- Good angular resolution (0.5° - 2° 90% of events)

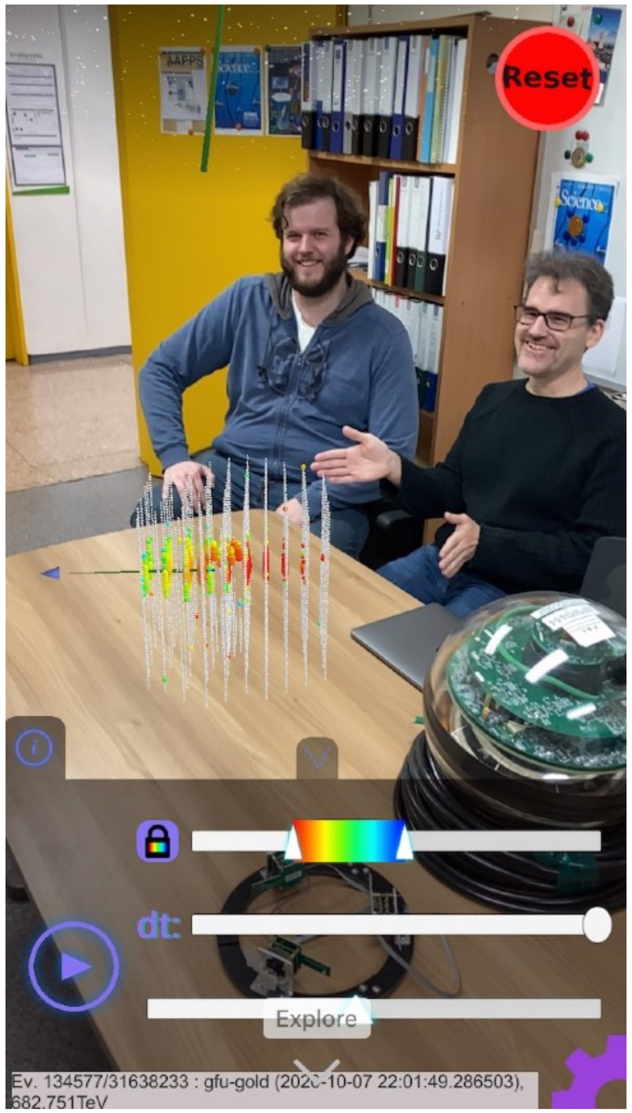
Updated alerts	Gold	Bronze
Signalness	> 50%	>30%
Expected signal/yr	6.6	2.8
Expected bkgd/yr	6.1	14.7



Astropart. Phys. 92 (2017) 30
A&A 607 (2017) A115

IceCube-170922A

IceCuBeAR - https://icecube.wisc.edu/news/view/776



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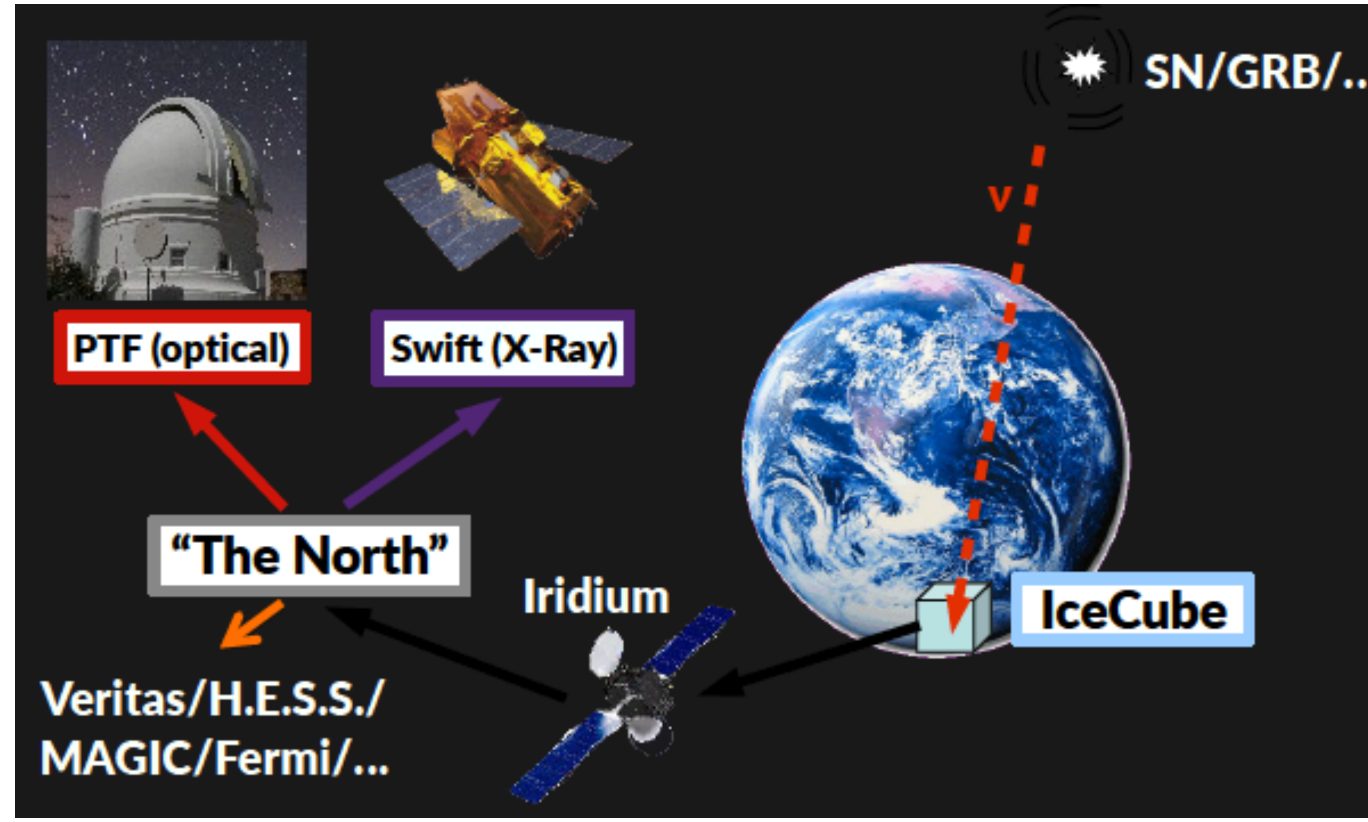
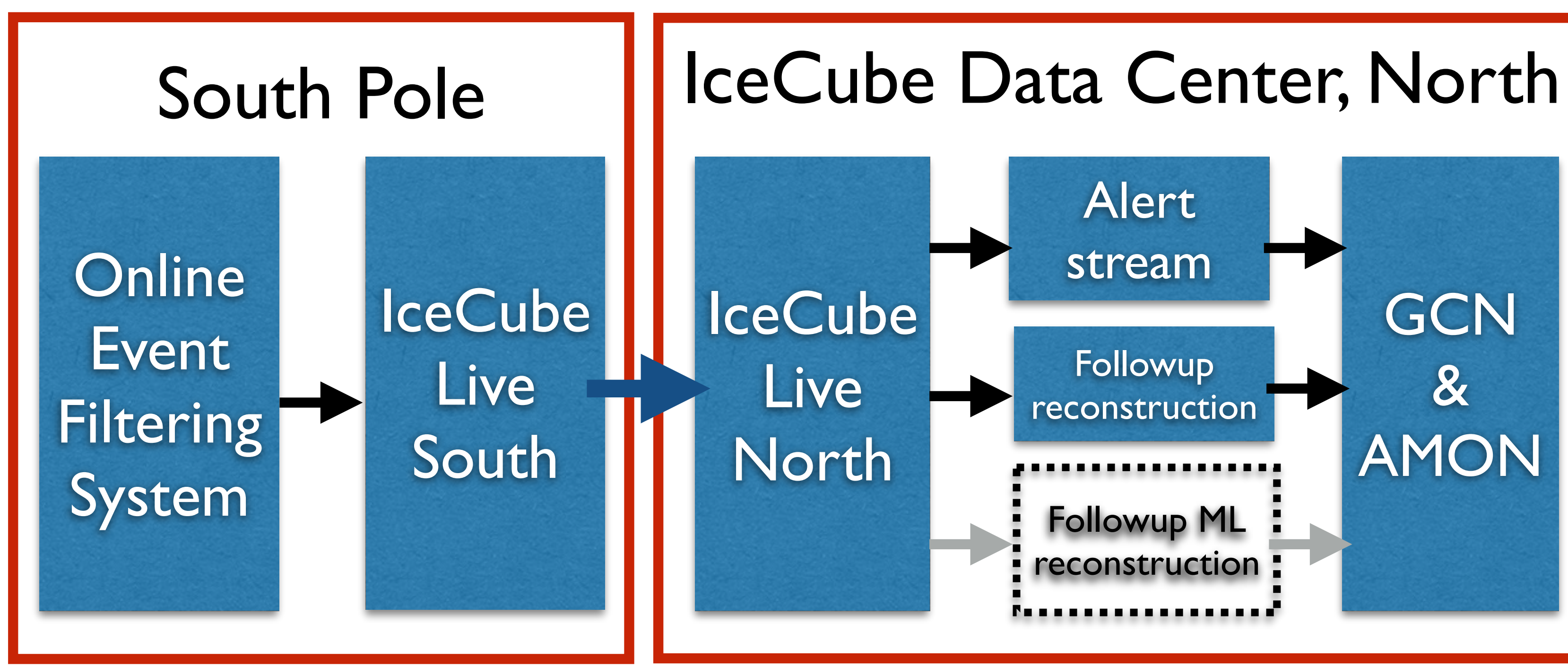




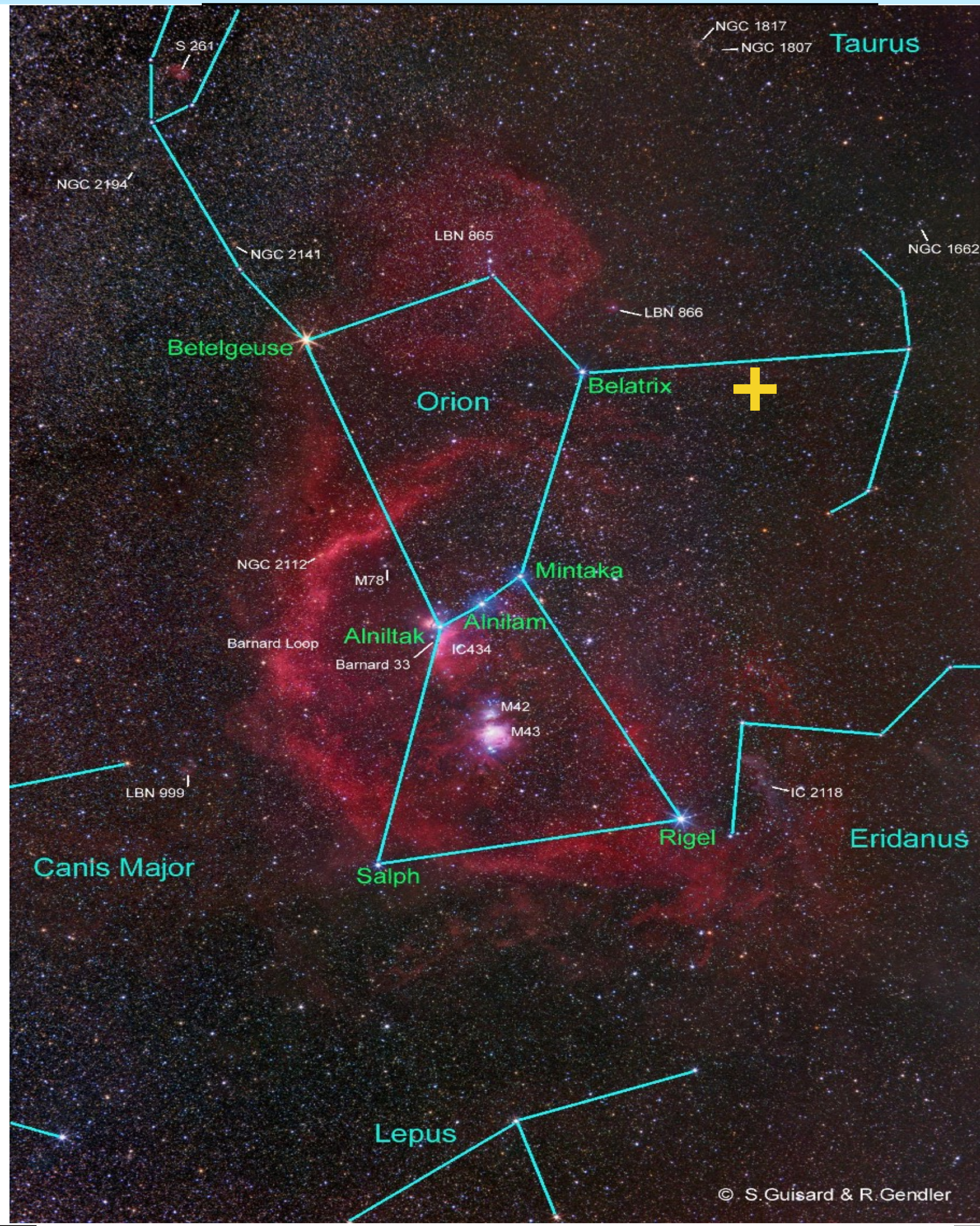
Median alert latency: 33seconds

IceCube-170922A

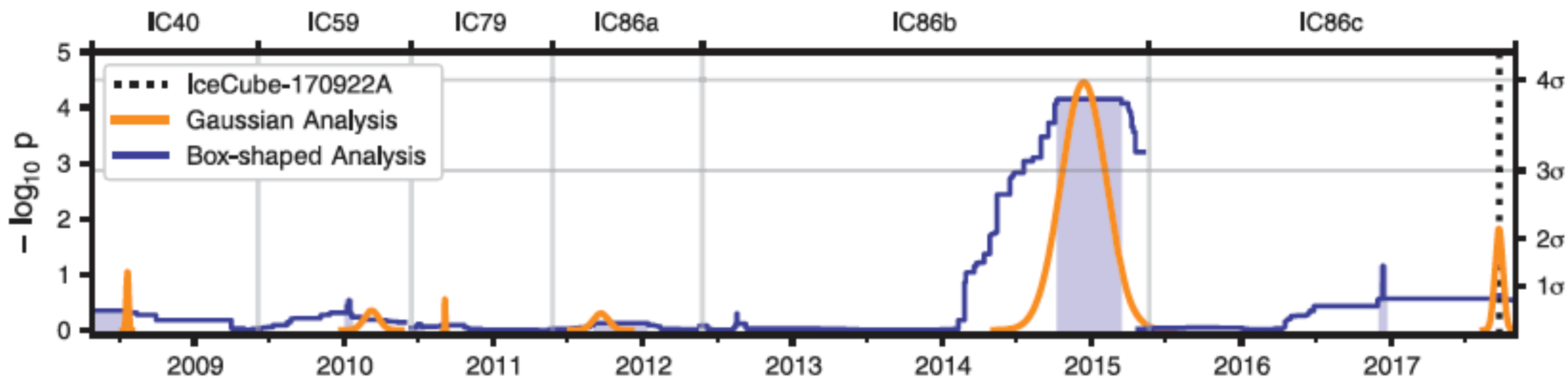
Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift*/*NuSTAR*, VERITAS, and VLA/17B-403 teams*†

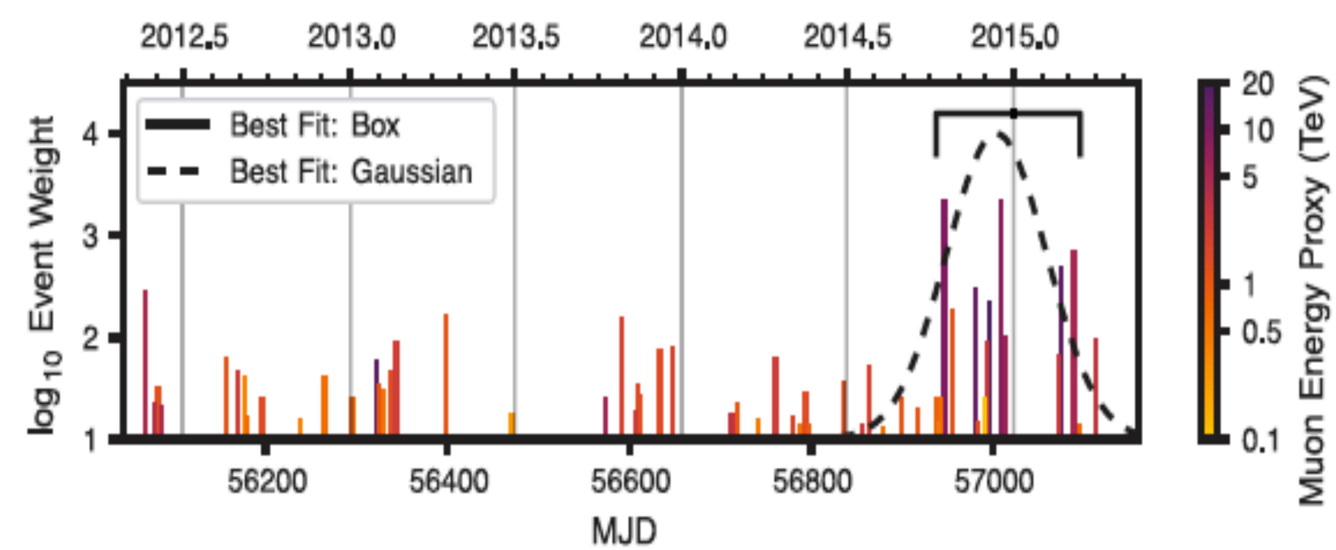
- Chance probability of a Fermi-IceCube coincident observation: **~3σ** (determined based on the historical IceCube sample and known Fermi-LAT blazars)
- Time-integrated neutrino spectrum is approximately $E^{-2.1}$
- **TXS 0506+056 redshift determined to be z=0.3365** (S. Paiano et al. ApJL 854.L32(2018))
- Time-average luminosity about an order of magnitude higher than Mkn 421, Mkn 501, or 1ES 1959+605



IceCube-170922A



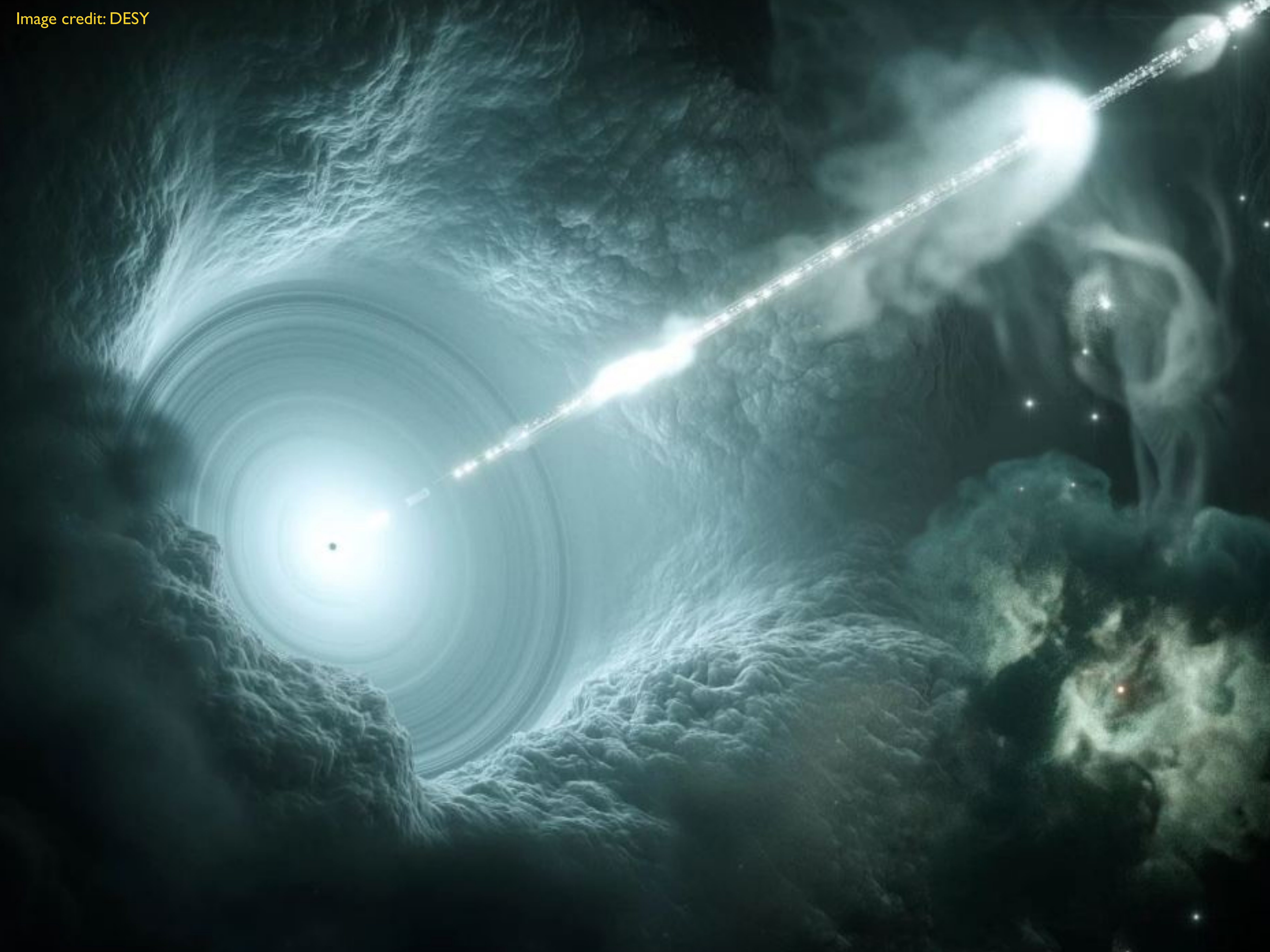
- 9.5 years of archival data was evaluated in direction of TXS 0506+056
- An excess of 13±5 events above background was observed during Sep 2014 - March 2016
- Inconsistent with background only hypothesis at **3.5σ** level (independently of the **3σ** associated with IceCube-170922A alert)



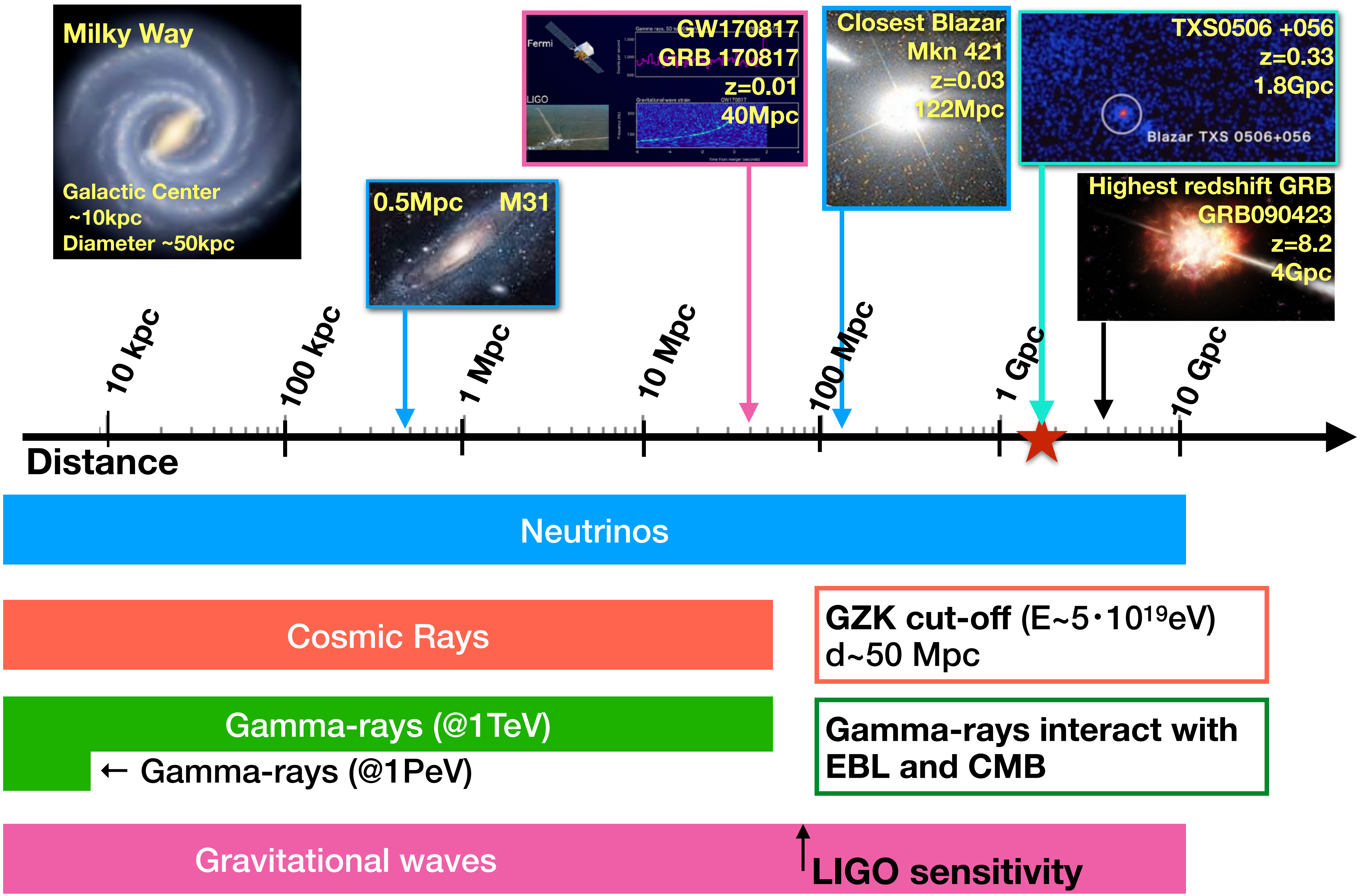
Time-independent weight of individual events during the IC86b period.

However: Maximum contribution of the 2LAC blazars to the observed astrophysical neutrino flux to be 27% or less between around 10 TeV and 2 PeV [IceCube Astrophys.J. 835 (2017) no.1, 45]

Image credit: DESY



Distance scales …

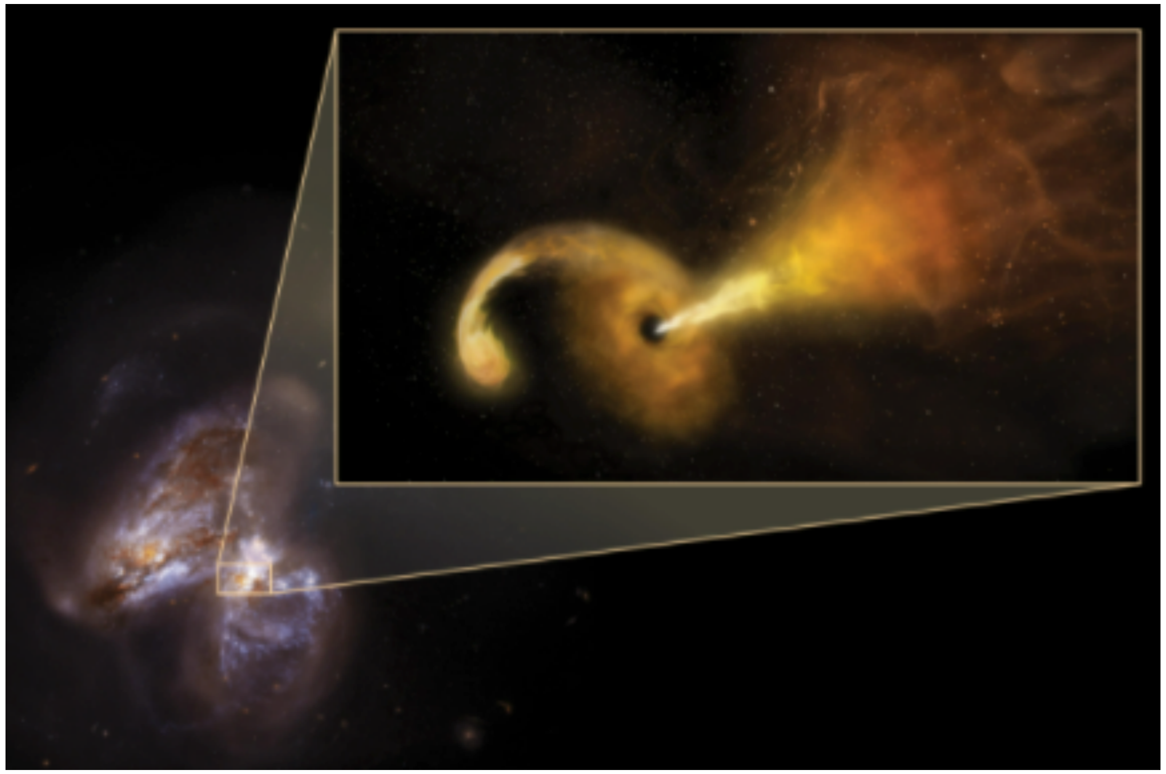


Note: Distant sources also allow to test rare interactions K.Choi, J.Kim, **C.Rott** PRD 2019

1 pc = 3.26 ly

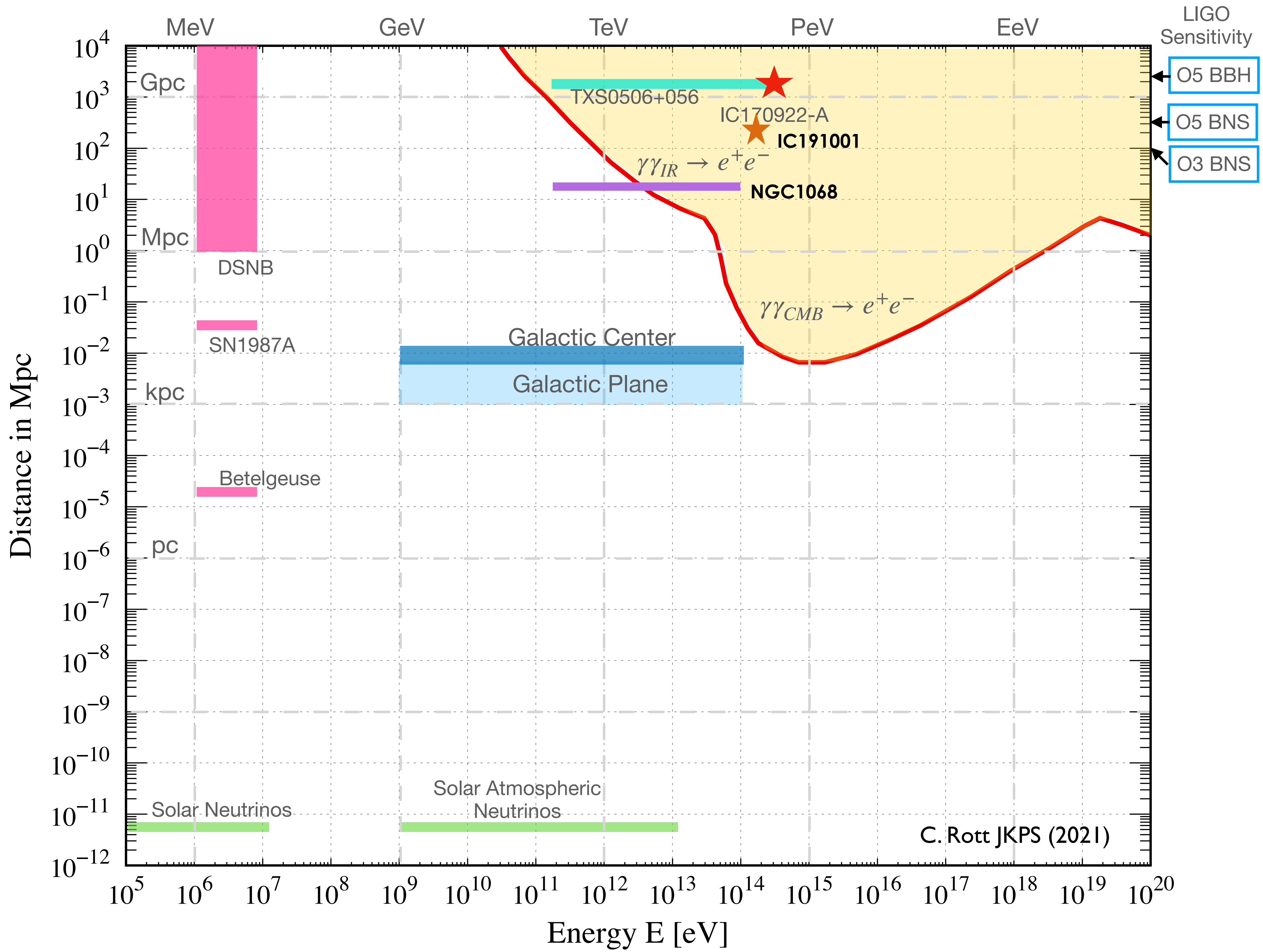
Other candidate sources

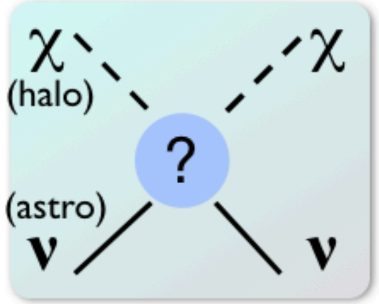
- **NGC 1068 (AGN) M77**
  - 2.9sigma excess in 10years IceCube point source search
  - distance ~14Mpc
- **Tidal Disruption Event (AT2019dsg)**
  - Radio-emitting tidal disruption event, AT2019dsg, with a high energy neutrino
  - Identified as part of ZTF (Zwicky Transient Facility) follow up of IceCube-191001A (19/10/01)
  - The probability of finding any coincident radio-emitting tidal disruption event by chance is 0.5% (Stein, R. et al. **Nat Astron (2021)**.)
  - see also W.Winter https://arxiv.org/pdf/2005.06097.pdf
    - AT2019dsg (z=0.05 / 230Mpc) / E=200TeV IC-191001



Artist illustration of the TDE example for image of the galaxy Arp299B …. Credit: NRAO/AUI/NSF/NASA/STScI

Observable Universe





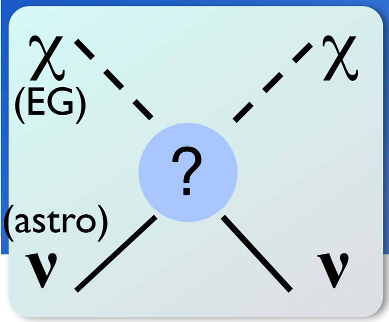
Neutrino DM scattering

Astrophysical ν scatter off χ from Galactic halo - resulting in anisotropy

- Milky Way Halo

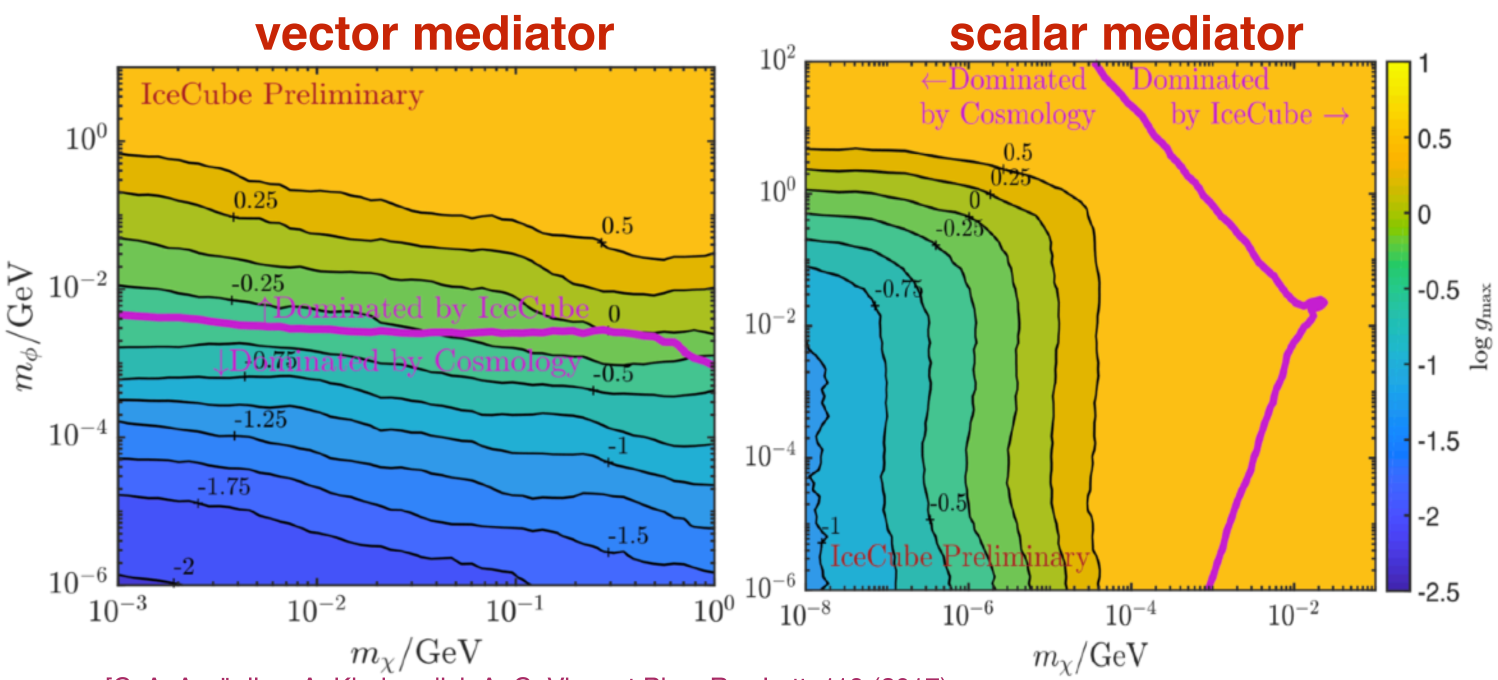
Combination of coupling strength **g** and masses $\mathbf{m}_\phi$ $\mathbf{m}_\chi$

Neutrino-Dark Matter Scattering

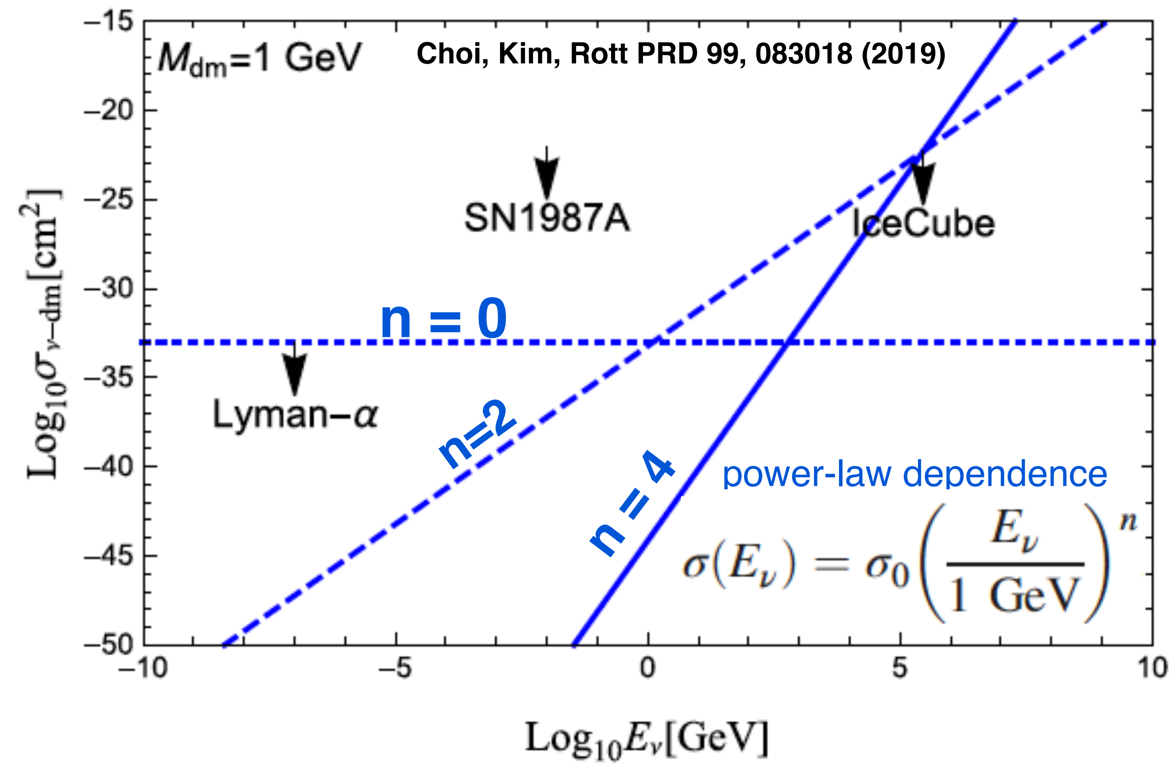


Neutrino Dark Matter Interactions - Rare Interactions

- Scattering of high energy astrophysical neutrinos on DM
  - "Isotropic" astrophysical neutrino flux on Galactic dark matter halo
  - Opportunities to probe very rare processes by observing neutrinos from distant sources
    - Example IceCube-170922A : Scattering of high energy astrophysical neutrinos from Blazar TXS0506+056 (z=0.33 / 5.7 billion light-years)



[C. A. Argüelles, A. Kheirandish A. C. Vincent Phys.Rev.Lett. 119 (2017) no.20, 201801 (arXiv:1703.00451)]

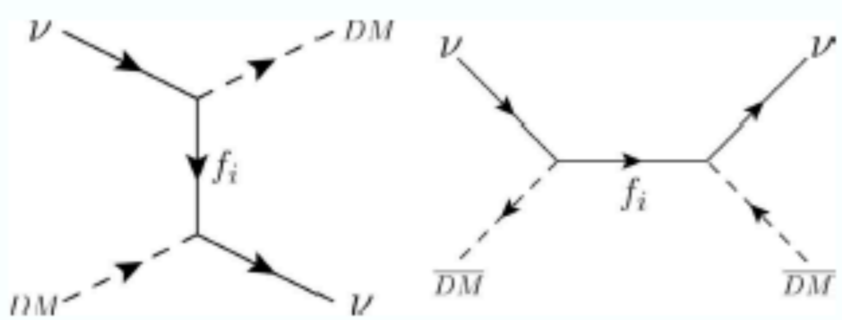


- **Current status**
  - First experimental searches have started - competitive with cosmological bounds
- **Future prospects and priorities**
  - Identification of new astrophysical neutrino sources in the future could increase sensitivities (Multi-messenger observations for timing delays ~ ex. secret interactions)
  - High statistics sample of astrophysical neutrinos essential

see also DM-neutrino coupling by looking for neutrino survival from a point source (https://arxiv.org/abs/1808.02889), deviations on the shape of the spectrum (https://arxiv.org/abs/1401.7019, but at higher energies, like https://arxiv.org/abs/2001.04994), or delays in arrival times (https://arxiv.org/abs/1903.08607).

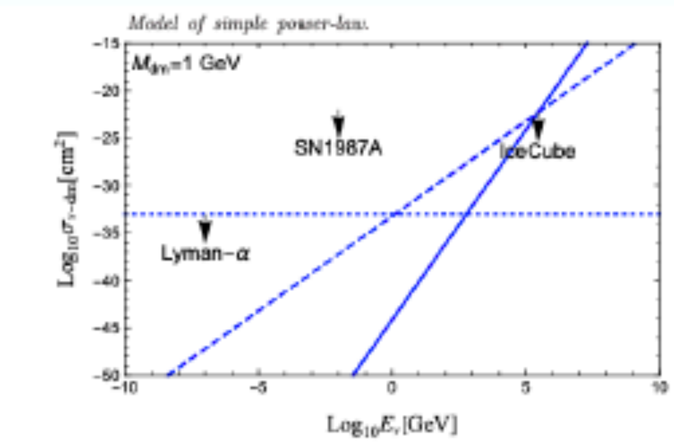
- A new approach to study the propagation of the high-energy astrophysical neutrino through the cosmological DM as well as the DM in the Milky Way from the observation of IC170922A and the identification of its origin with a known path and distance.

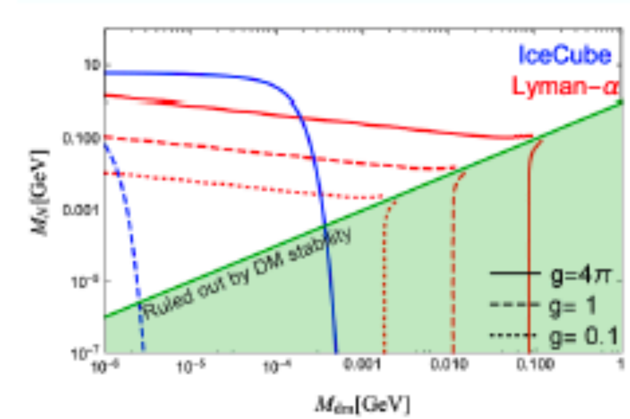
- Assuming light scalar DM; $m_{DM} < GeV$ even down to sub-eV(ultra-light DMs)

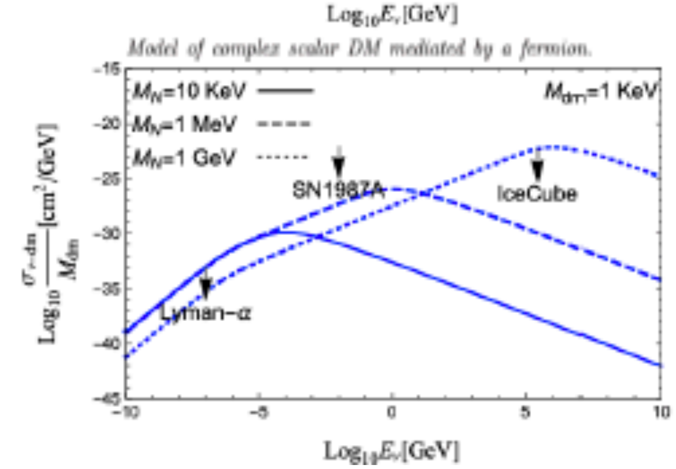


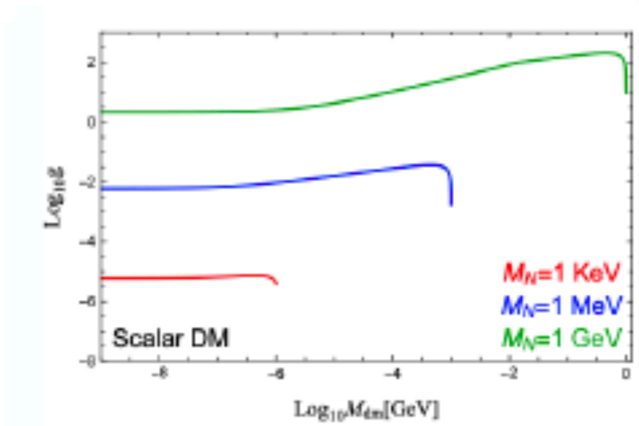
Neutrino energy	$\sigma/M_{\rm dm}[{\rm cm}^2/{\rm GeV}]$	Exp. [Ref.]
~100 eV	6×10^{-31}	CMB [13–15]
~100 eV	10^{-33}	Lyman-α [11]
10 MeV	10^{-22}	SN1987A [9]
290 TeV	5.1×10^{-23}	IceCube-170922A [1]

K.-Y Choi, J. Kim and C. Rott, Phys. Rev. D 99 (2019) 083018

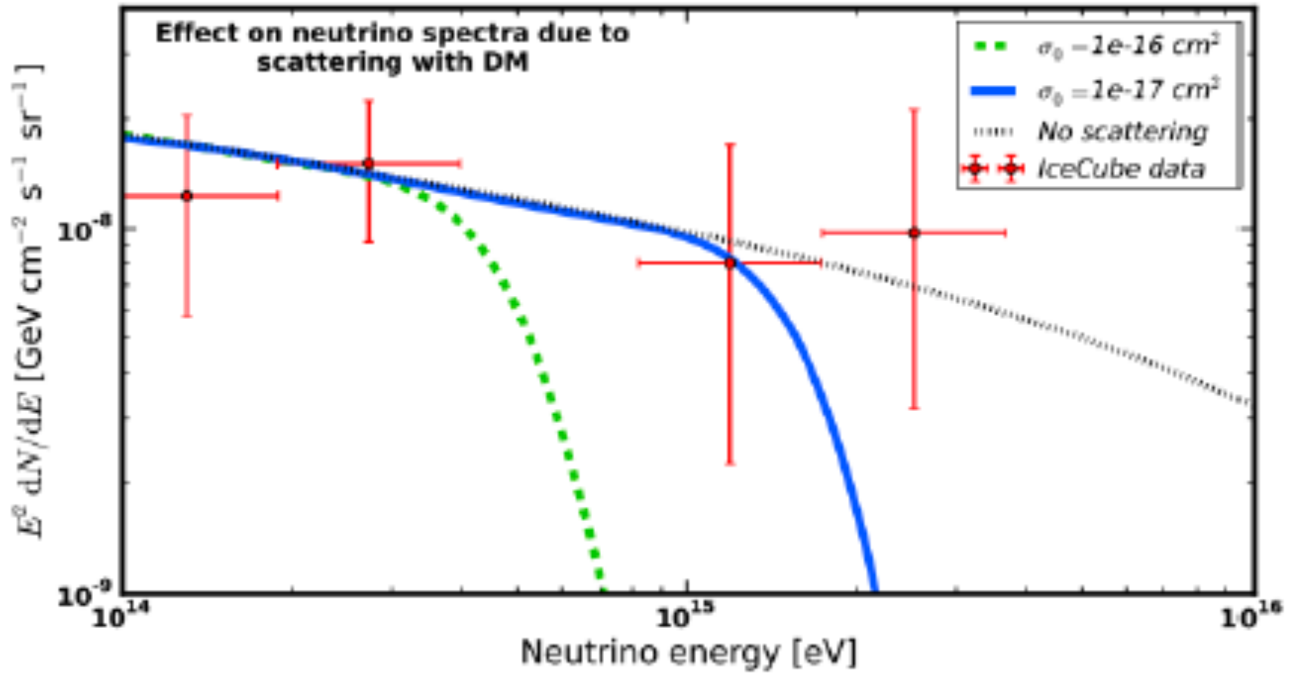




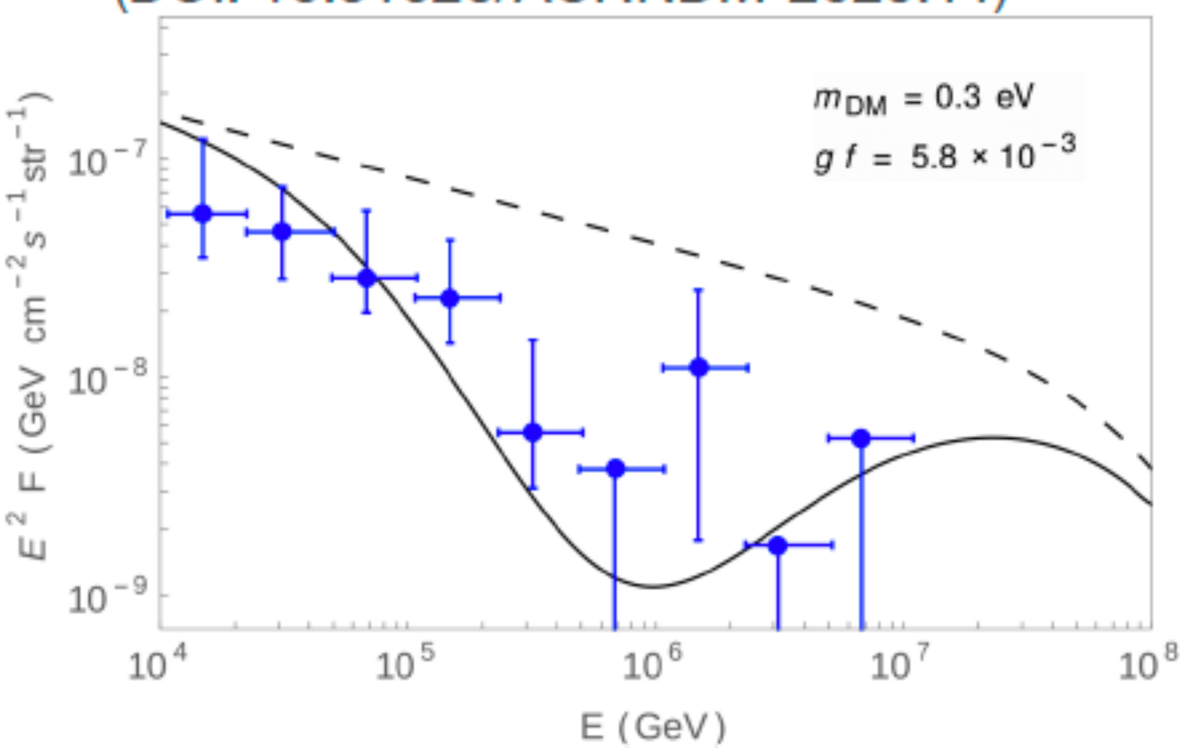


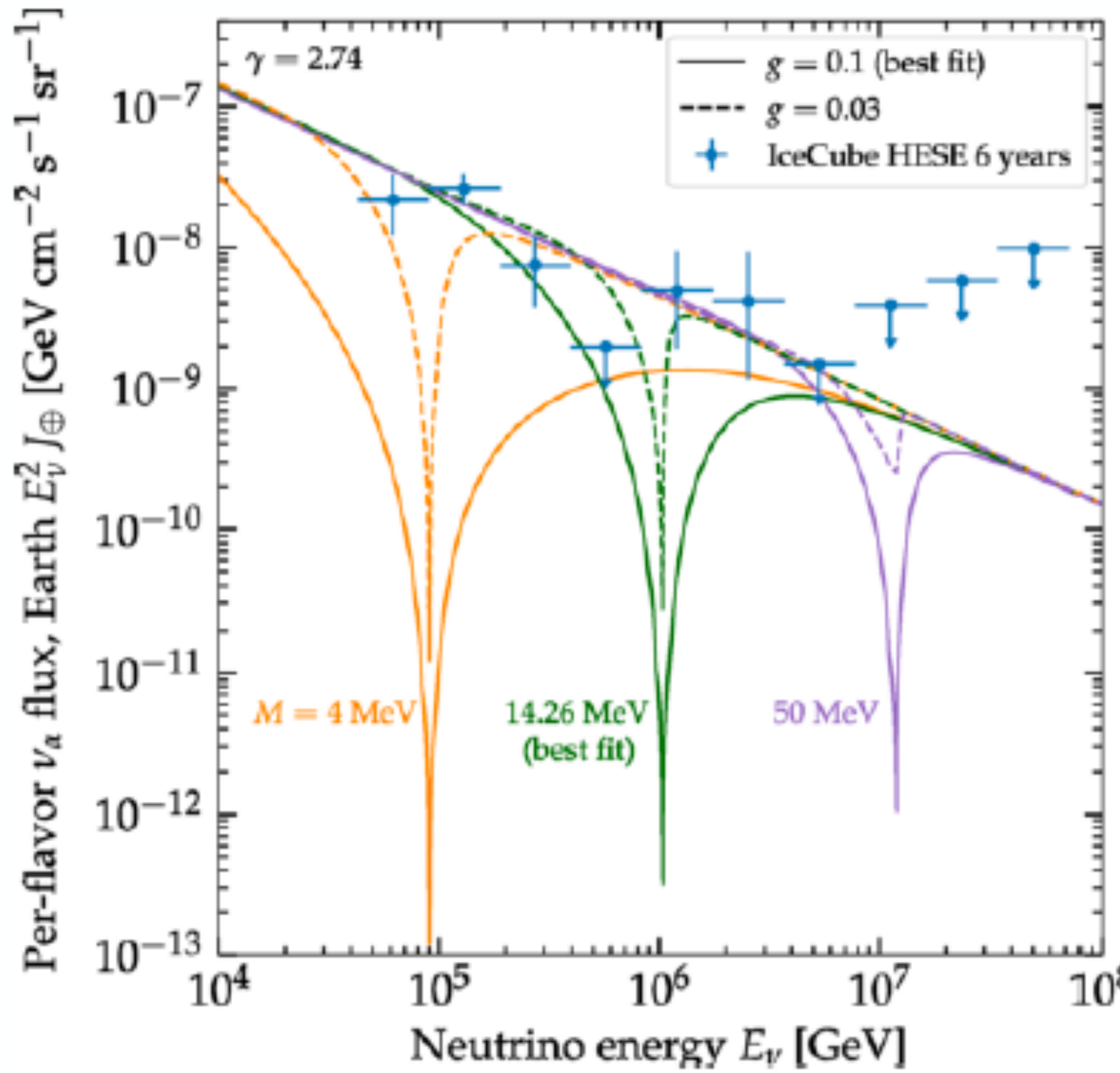


J. H. Davis and J, Silk, arXiv:1505.01843

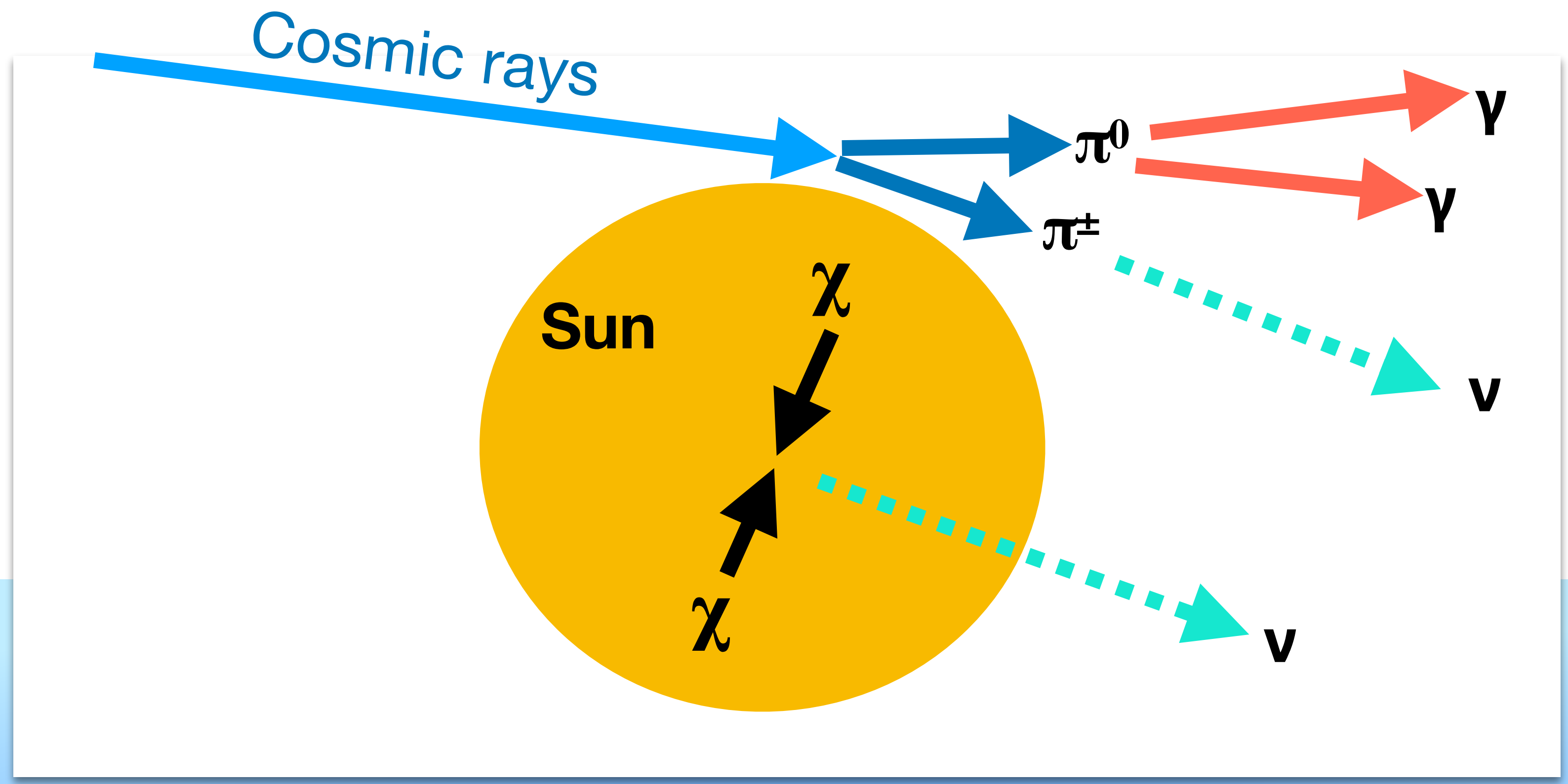


S. Pandey *et al*, NDM2020 proceeding (DOI: 10.31526/ACP.NDM-2020.11)





M. Bustamante *et al*, *Phys. Rev. D* **101**, 123024 (2020); for ‘secret’ neutrino interaction

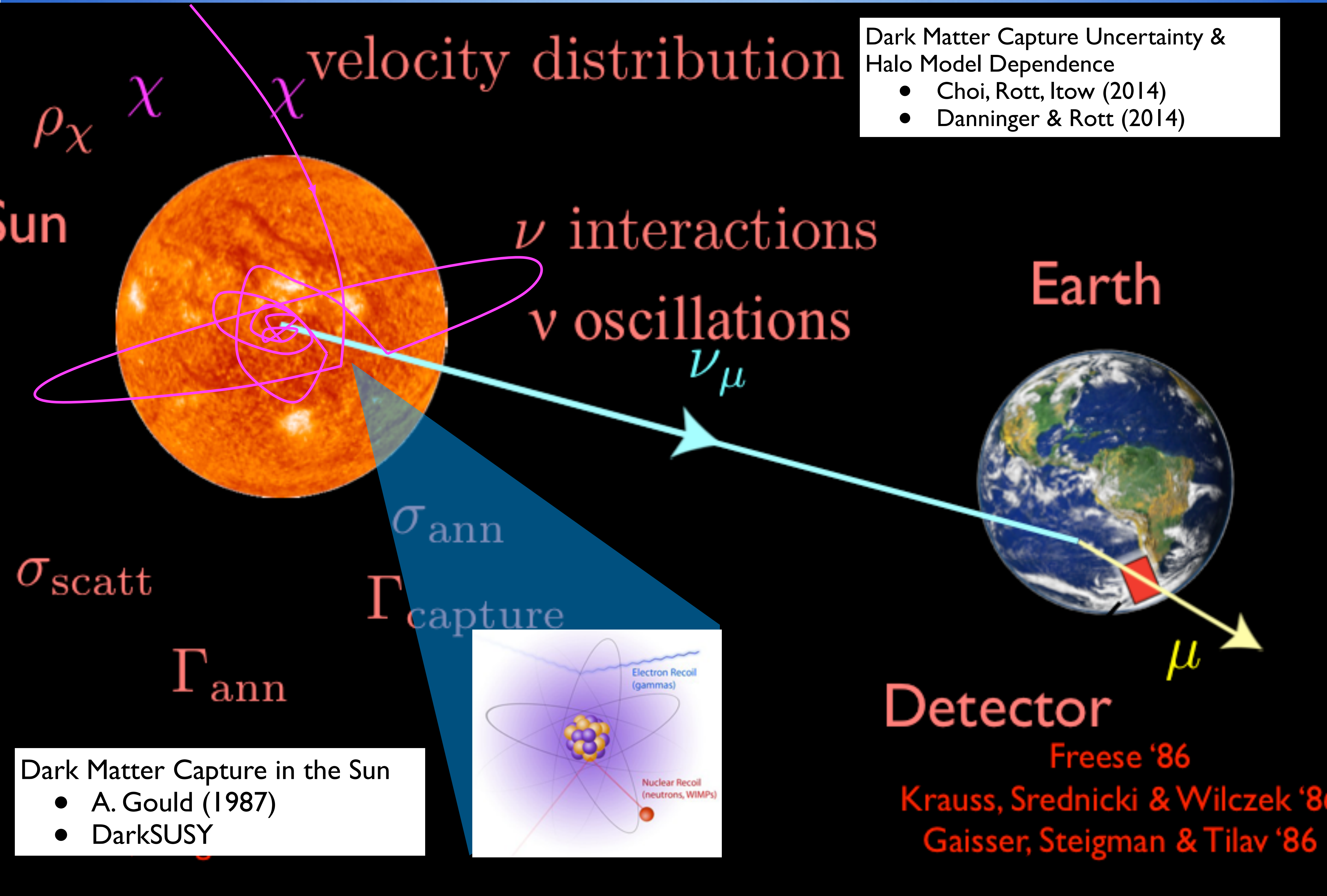


Energetic Neutrinos from the Sun

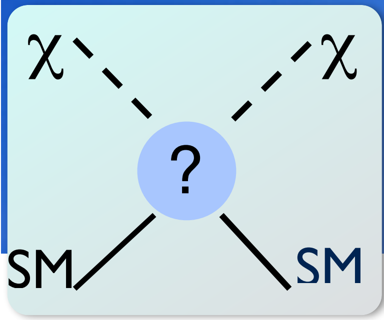
Solar Dark Matter

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)

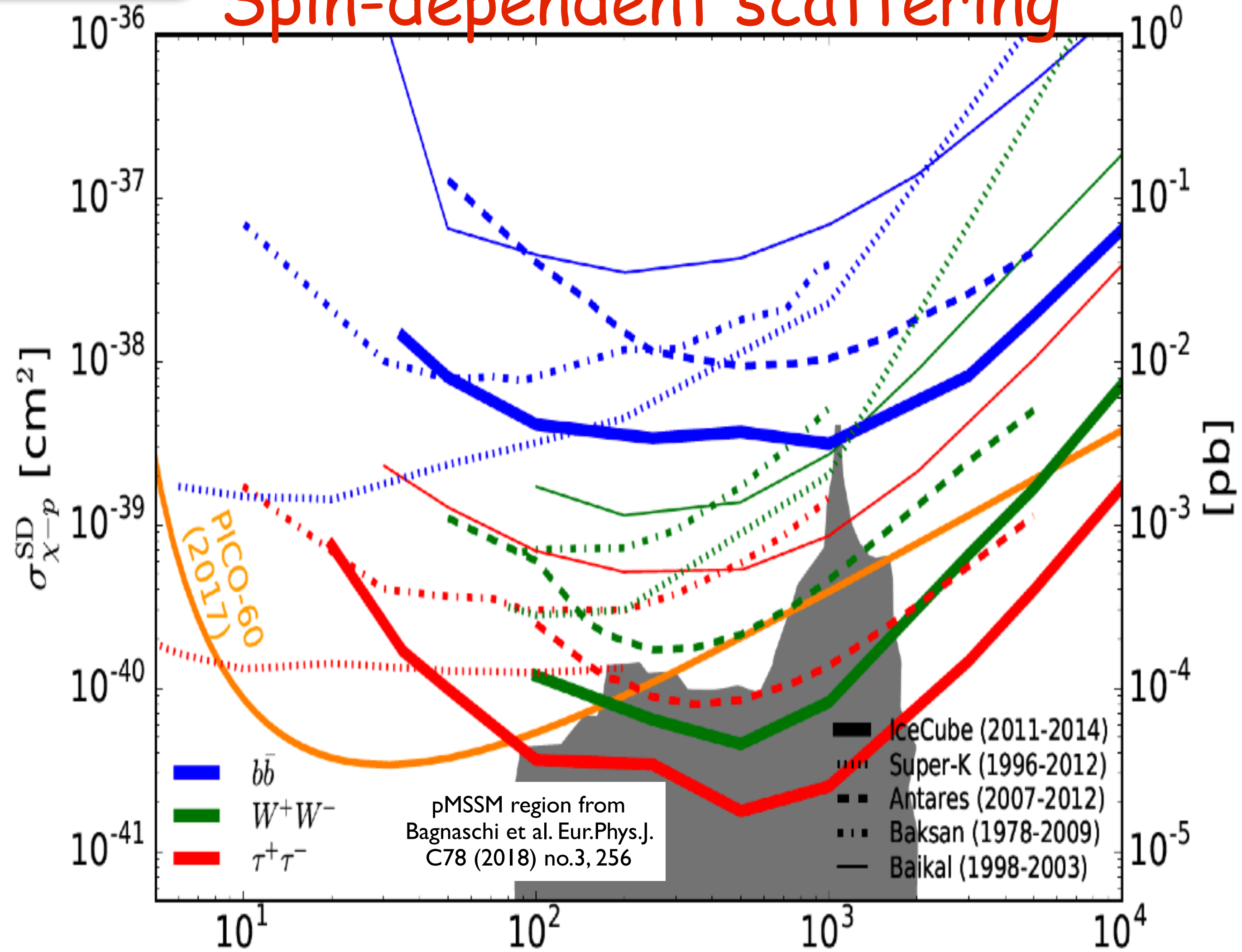


Dark Matter Capture in the Sun
- A. Gould (1987)
- DarkSUSY



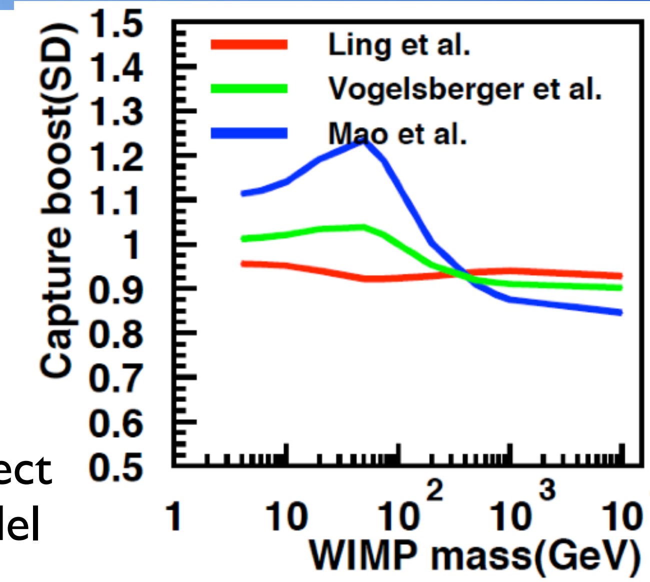
Solar Dark Matter

Spin-dependent scattering



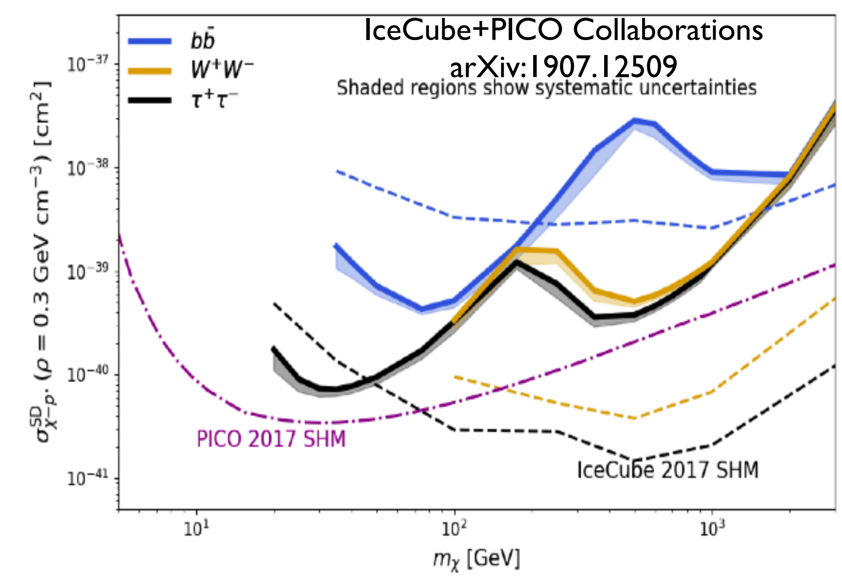
Largely halo model independent

see for example: Choi, Rott, Itow (2014), Danninger & Rott (2014), Nuñez-Castiñeyra, Nezri, Bertin (2019)

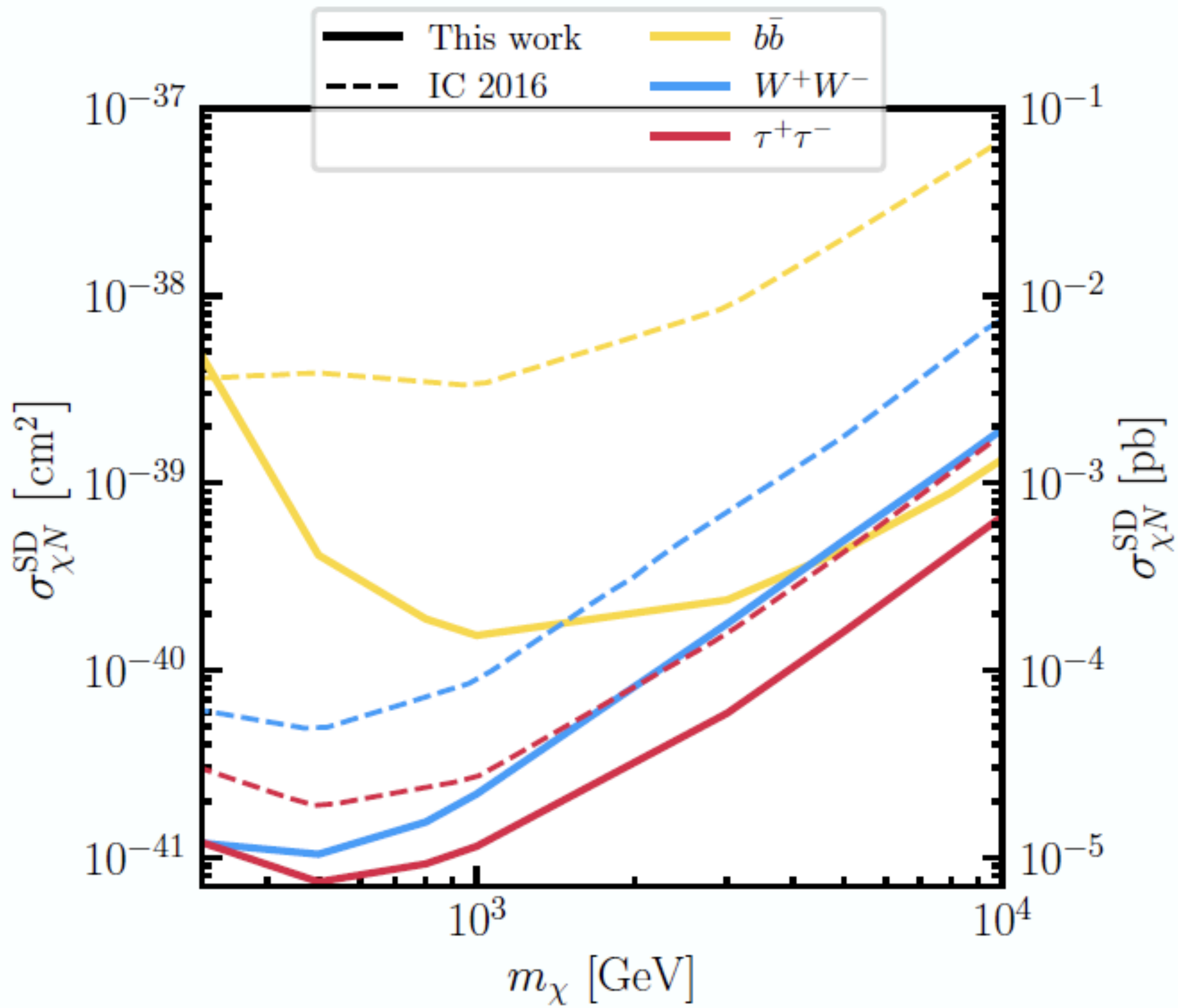


Combination with direct detection formal model independent results

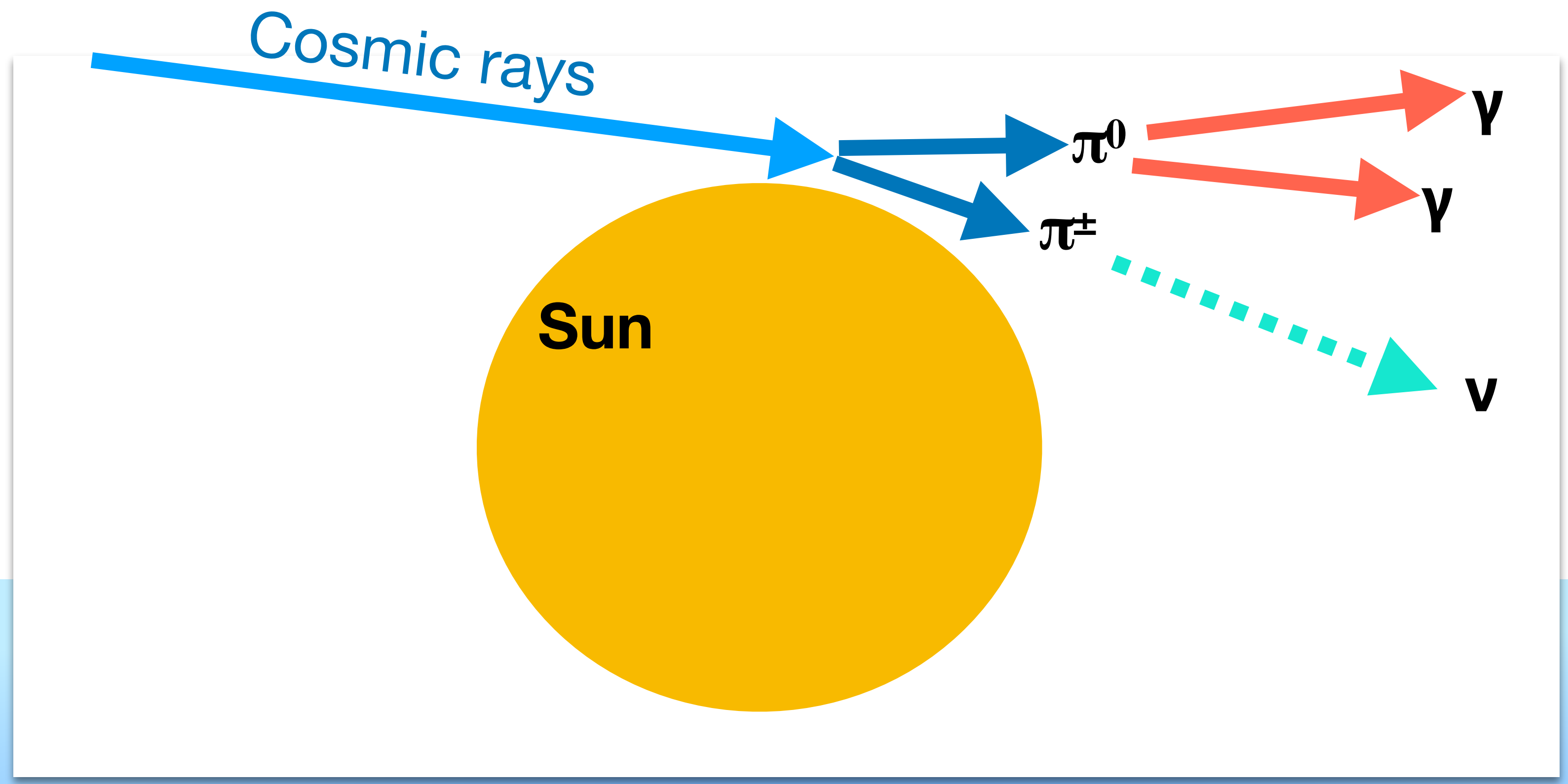
following: Ferrer Ibarra & Wild (2015)



- **Current status**
  - Very strong bounds on spin-dependent DM nucleon scattering. Leading bounds from IceCube and Super-K
  - Velocity independent framework in combination with direct detection
- **Future prospects**
  - Extremely competitive to explore DM model space from GeV - TeV range
  - Complementarity to direct detection & minimal halo model dependence
  - Marching towards the solar atmospheric neutrino floor (~x10 below current bounds) … new physics !



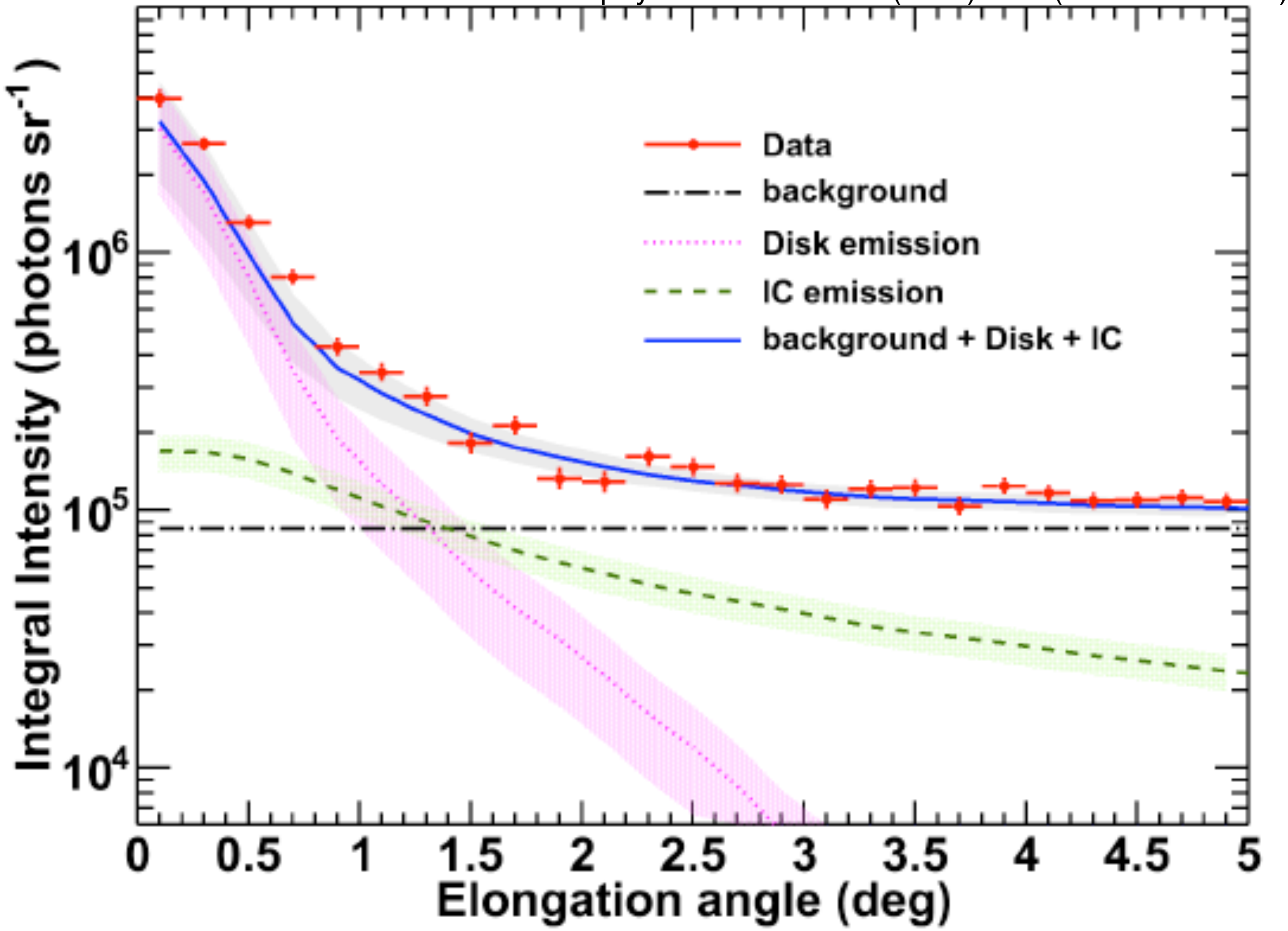
- New IceCube search using 10 years of IceCube data
- Uses PYTHIA8 with updated calculation of EW correction (using Bauer, Rodd, Weber (2020))
- Up to factor 40 increase in sensitivity
- Significant improve limits, publication in preparation



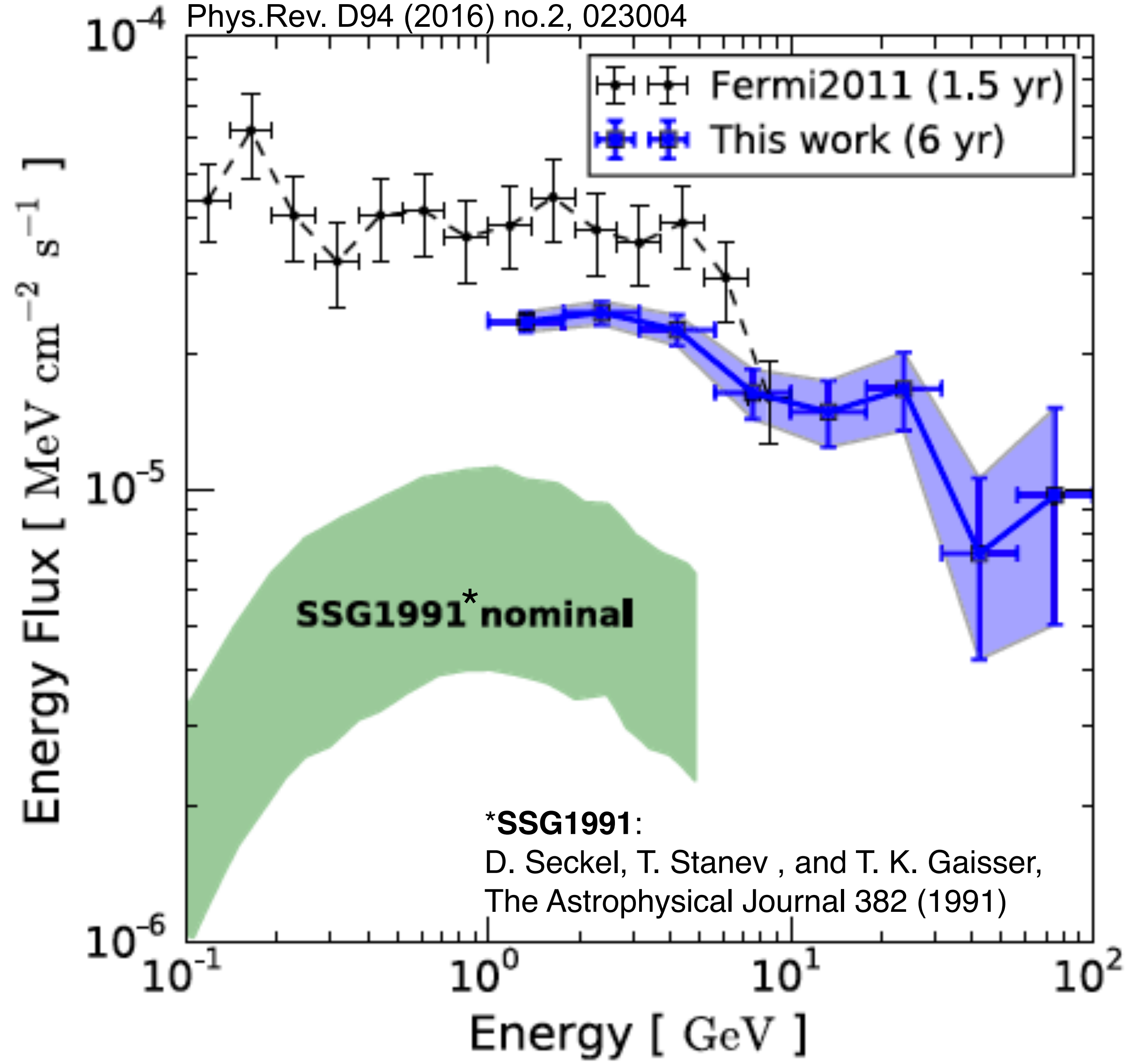
Solar Atmospheric Neutrinos

Gamma-ray emissions from the Sun

Fermi-LAT Collaboration: The Astrophysical Journal 734 (2011) 116 (arxiv:1104.2093)



Kenny C.Y. Ng, John F. Beacom, Annika H.G. Peter, **Carsten Rott**
Phys.Rev. D94 (2016) no.2, 023004

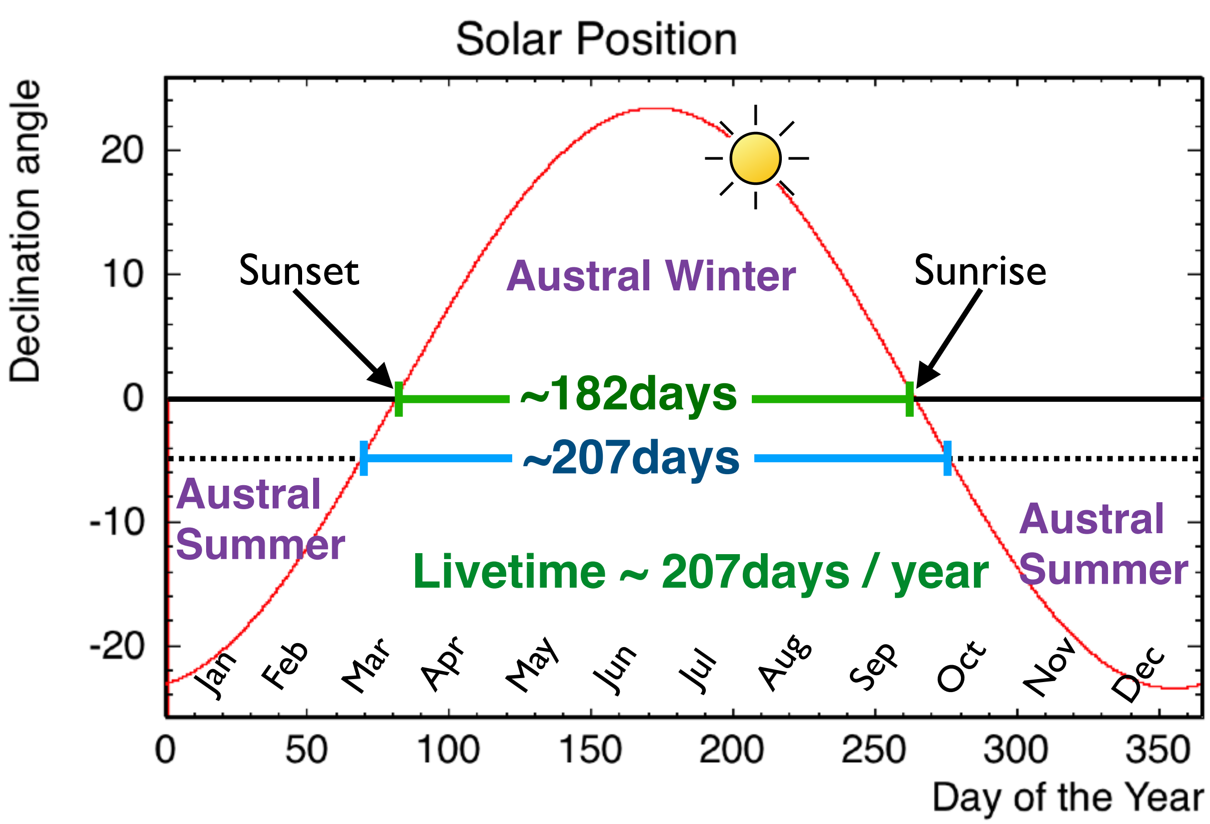


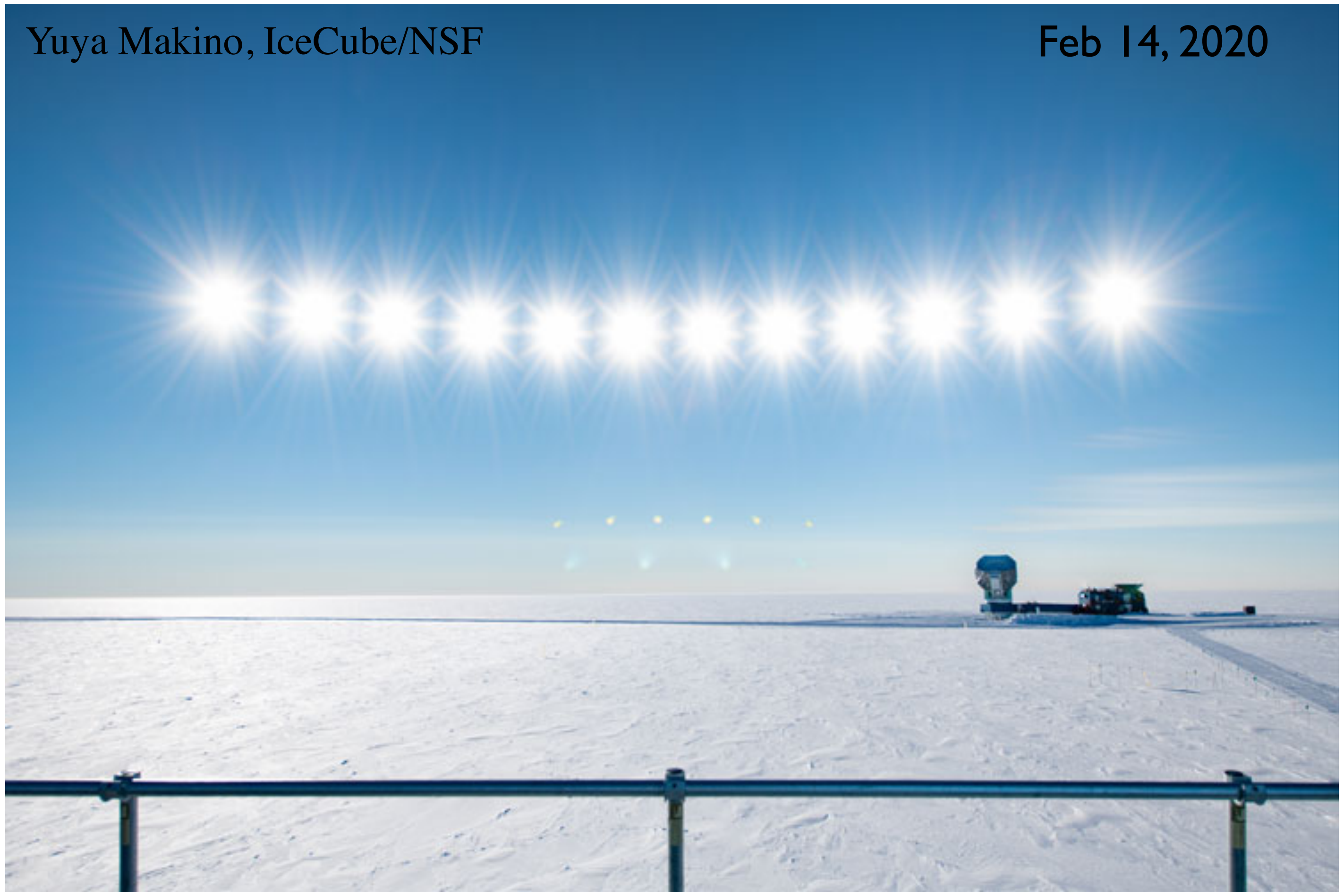
- **Cosmic ray interactions in the Solar atmosphere produce gamma-rays and neutrinos**
- **First detection** of gamma-rays up to 10GeV reported by Fermi-LAT Collaboration (2011) later shown spectrum extends beyond 100GeV in public Fermi-LAT data (K.C.Y. Ng, J. F. Beacom, A.H.G. Peter, C. Rott (2016))
- 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 (SKKU)

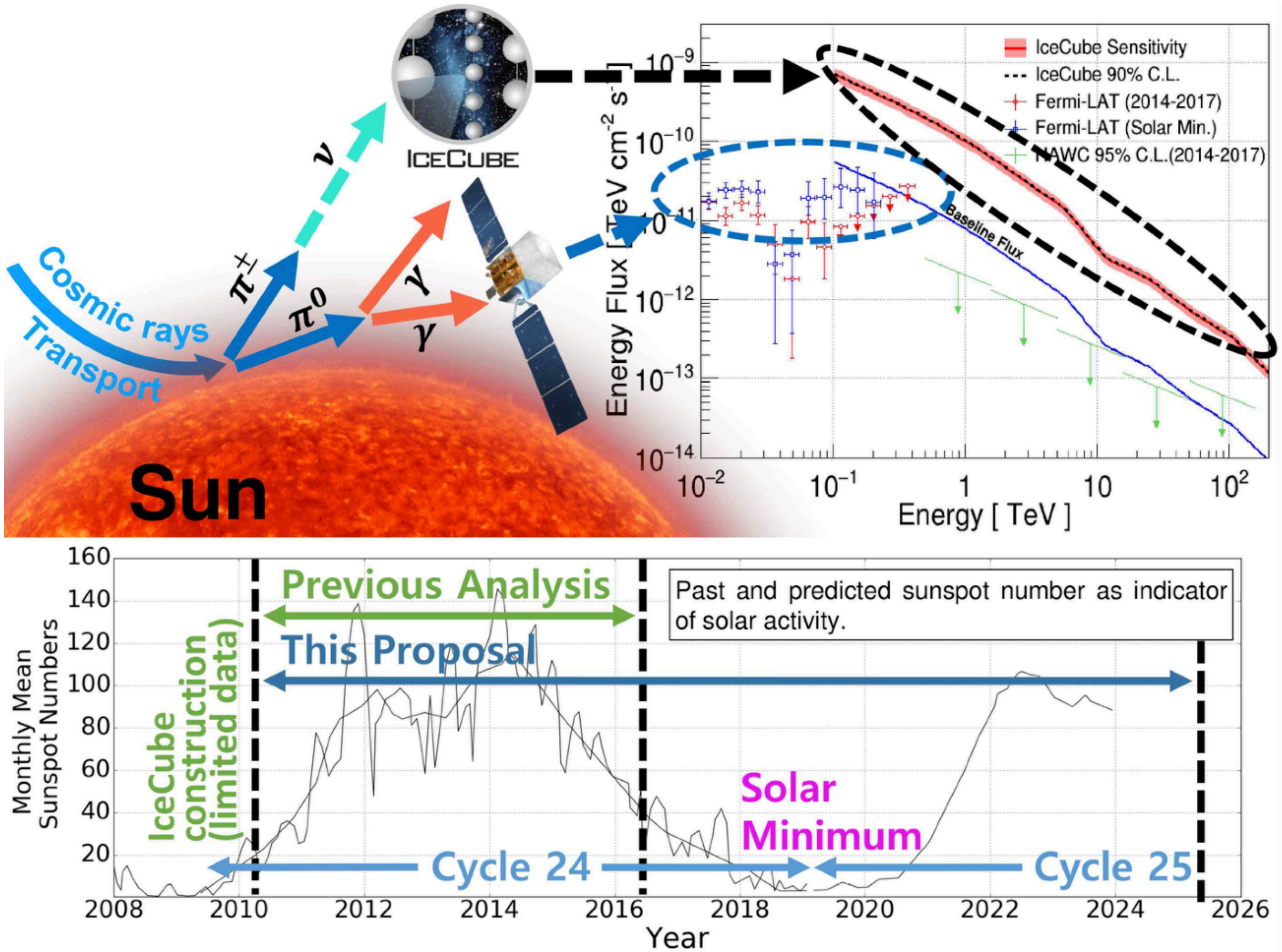
- Conducted first search for solar atmospheric neutrinos
- The analysis utilizes data collected over a 7 year period (May 31, 2010 - May 18, 2017)
  - Up-going muon neutrino candidate events are selected using the well established IceCube point source analysis selection procedure
  - We only consider 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



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

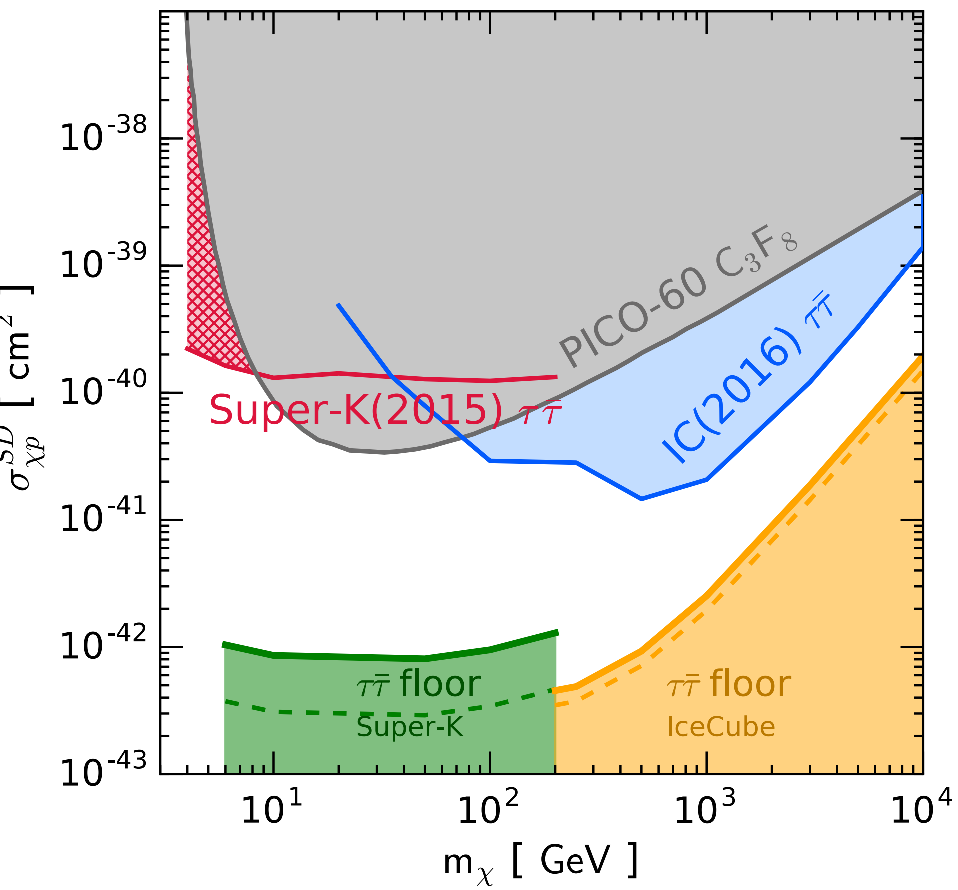
Solar Minimum (2019-2020)

- 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

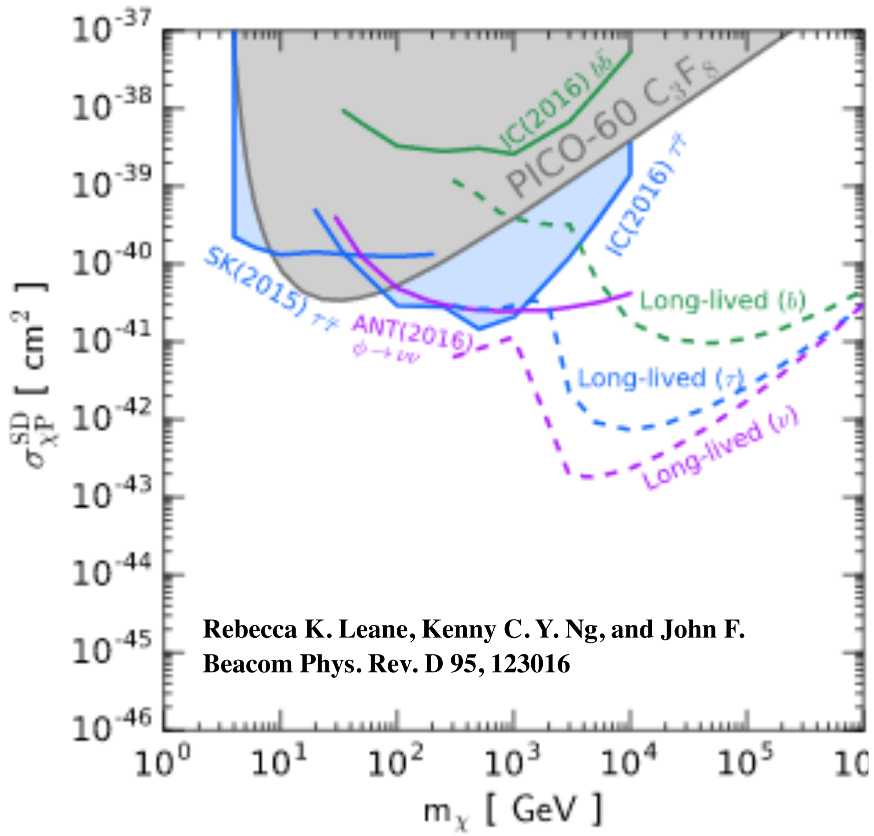
Neutrino Floor / Boosted / Secluded Dark Matter

Ng, Beacom, Peter, Rott Phys.Rev. D96 (2017) no.10, 103006



Solar Atmospheric Neutrinos / Atmospheric Neutrino Floor:

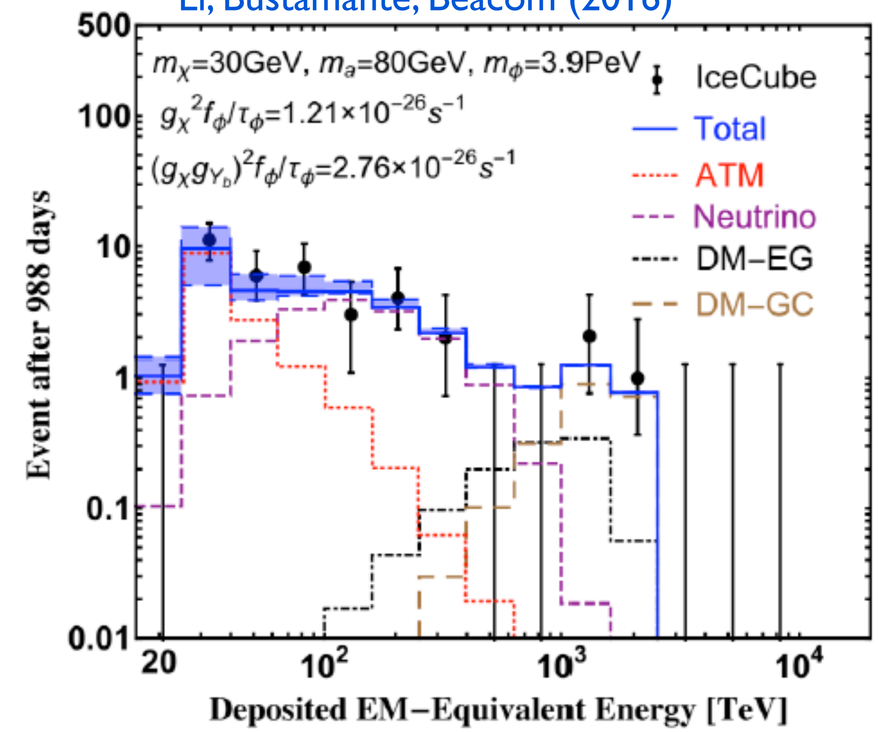
- C. Argüelles, G. de Wasseige, A. Fedynitch, B. Jones **JCAP 1707 (2017) no.07, 024** [arXiv:1703.07798]
- K. Ng, J. Beacom, A. Peter, C. Rott **Phys.Rev. D96 (2017) no.10, 103006** [arXiv:1703.10280]
- J. Edsjö, J. Elevant, R. Enberg, and C. Niblaeus, **JCAP 2017 .06 (2017), p. 033**, arXiv: 1704.02892 [astro-ph.HE]
- M. Masip **Astropart.Phys. 97 (2018) 63-68** [arXiv: 1706.01290]



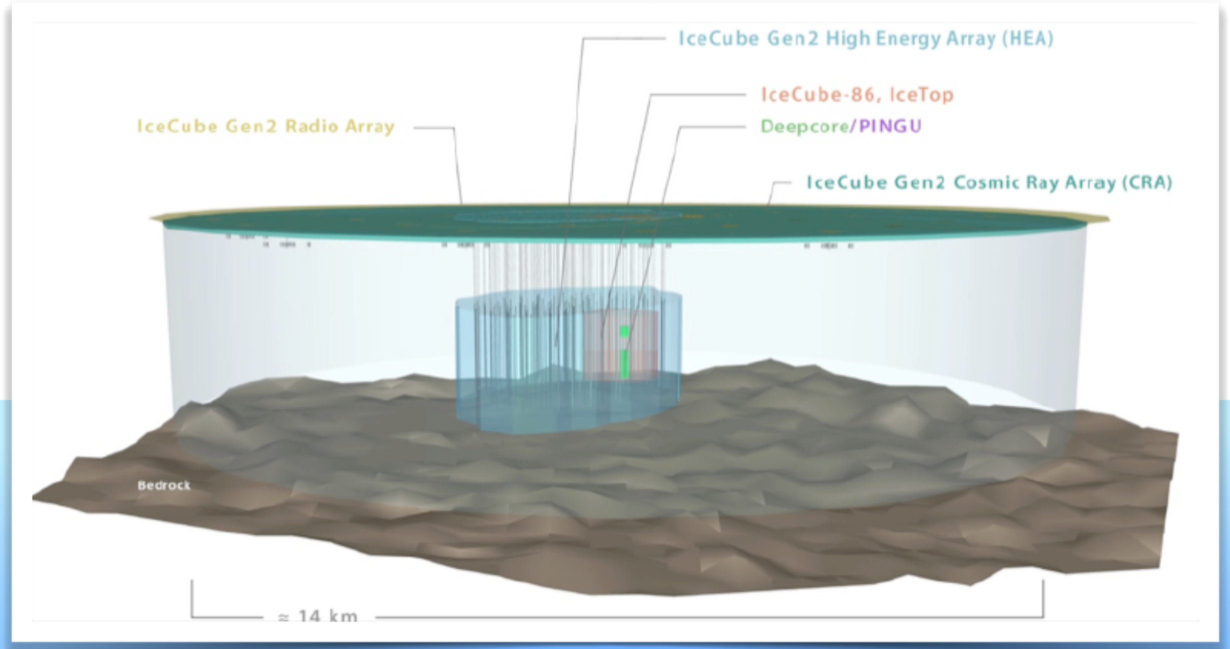
First proposed
Atri Bhattacharya, Raj Gandhi, Aritra Gupta
JCAP03(2015)027 / arXiv:1407.3280
see also
Atri Bhattacharya, Raj Gandhi, Aritra Gupta, Satyanarayan Mukhopadhyay JCAP05(2017)002 / arXiv:1612.02834

Kopp, Liu, Wan (2015)

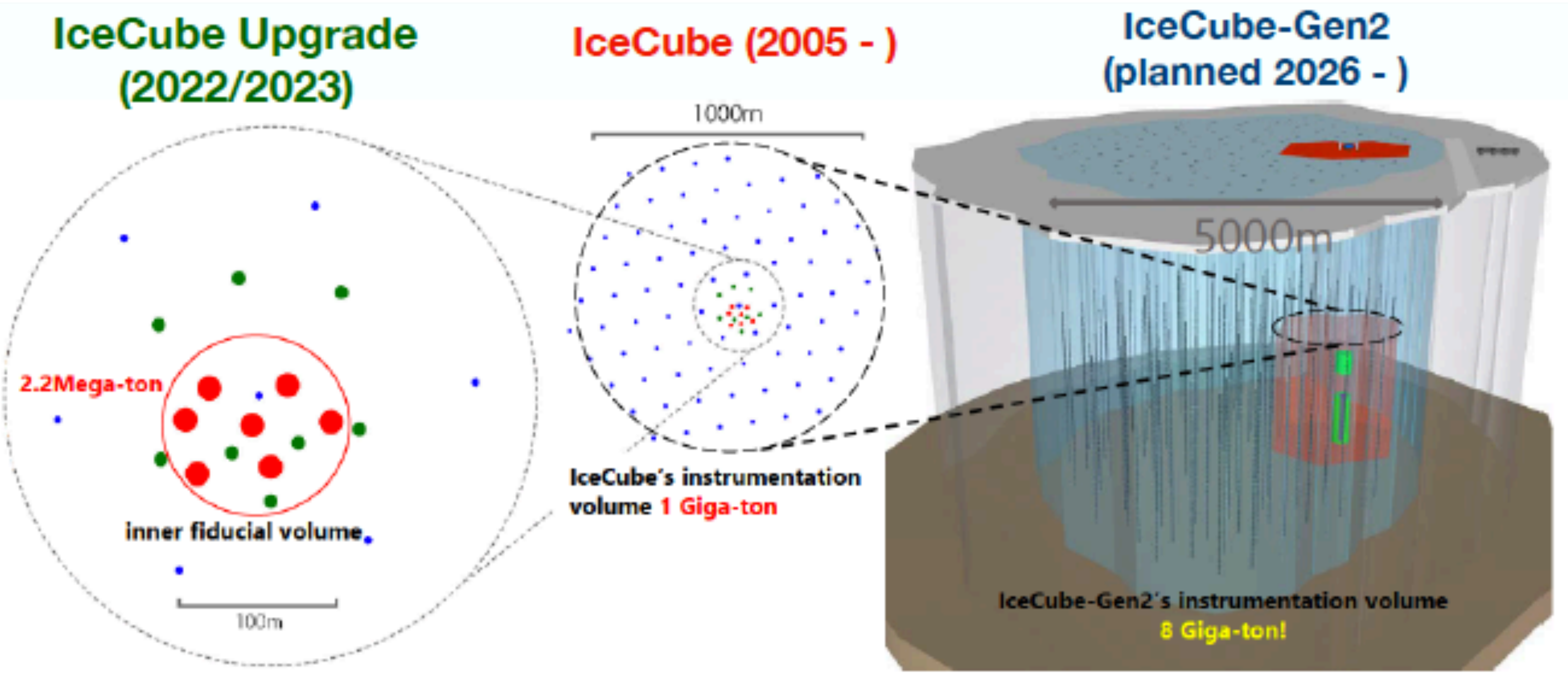
Li, Bustamante, Beacom (2016)



- Current status:
  - Growing interest in scenarios that go beyond the WIMP hypothesis
- Future Prospects:
  - Excellent prospects to explore scenarios with energetic neutrinos from the Sun
  - As a side product of solar dark matter neutrino search can lead to a guaranteed signal of solar atmospheric neutrinos

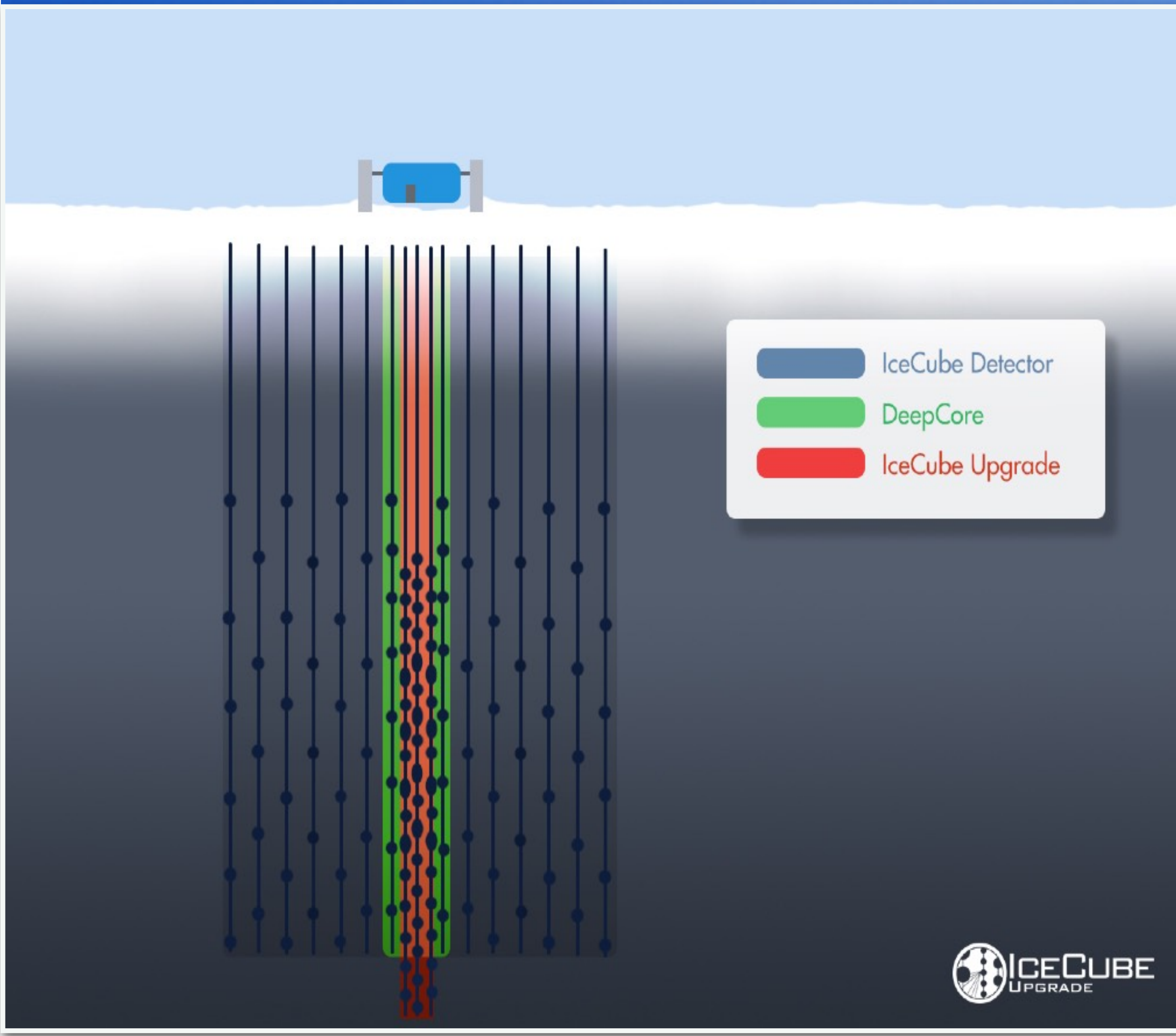

IceCube Gen2 High Energy Array (HEA)
IceCube-86, IceTop
IceCube Gen2 Radio Array
Deepcore/PINGU
IceCube Gen2 Cosmic Ray Array (CRA)
Bedrock
≈ 14 km

What's next ?



IceCube (2005 - ...)	1 Giga-ton	• Diffuse astrophysical neutrinos • Optimized for TeV Neutrinos
IceCube Upgrade (2022/2023)	2.2 Mega-ton	• GeV neutrinos, PMNS unitarity • Calibration of the IceCube detector
IceCube-Gen2 (planned 2026 -)	~ 8 Giga-ton	• Astrophysical neutrino sources • GZK neutrinos, PeV Neutrinos

IceCube Upgrade

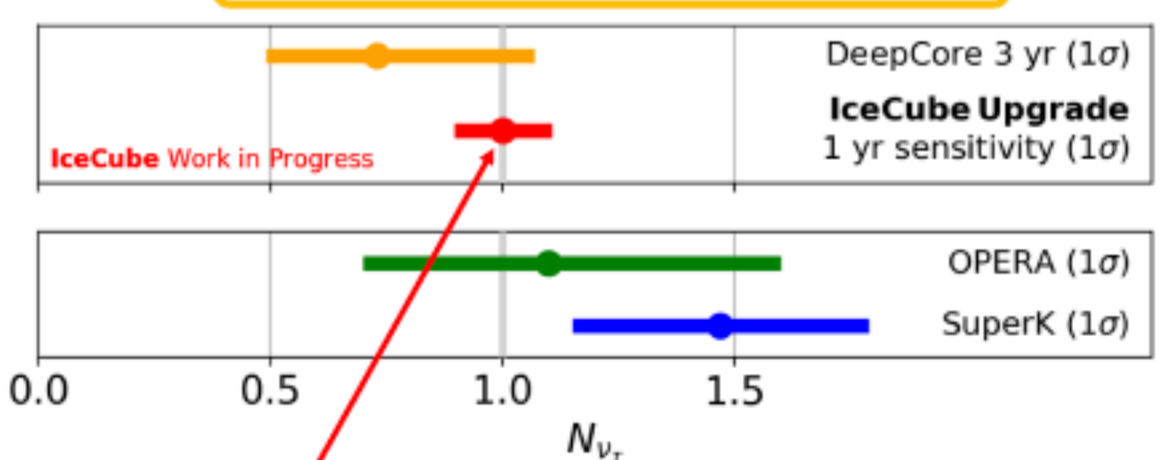


Science goals and objectives

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

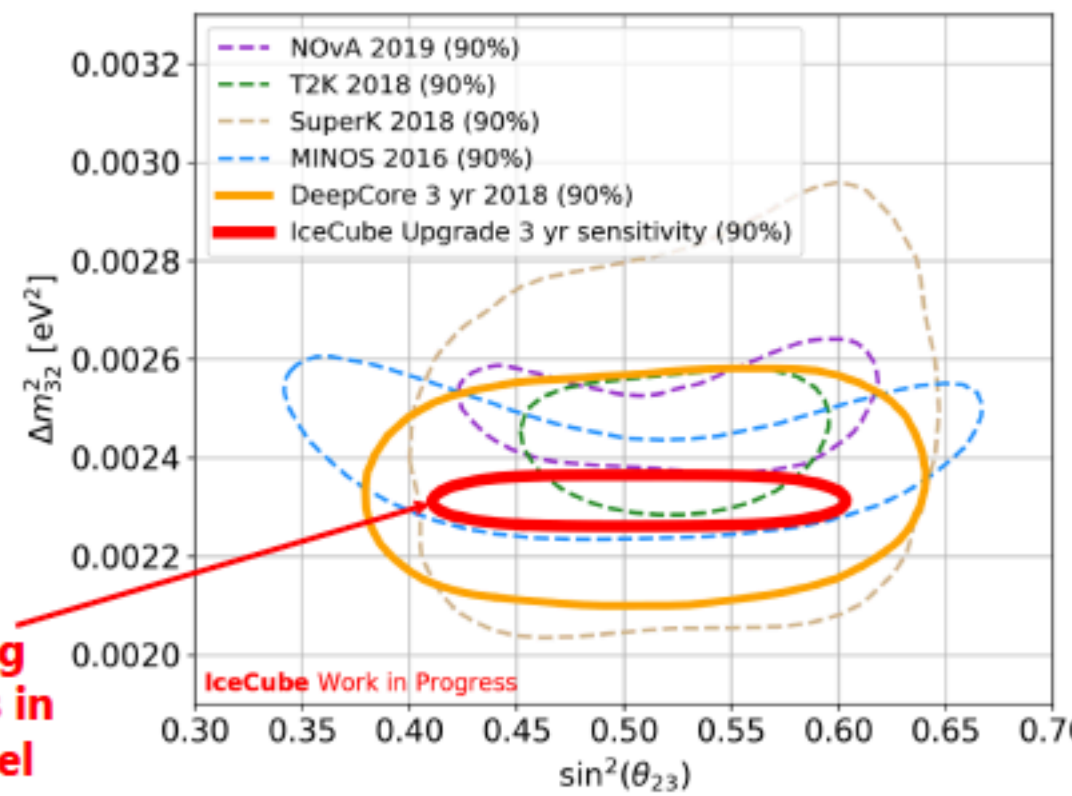
IceCube DOM | mDOM | D-Egg

ν_τ appearance sensitivity (1 yr)



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

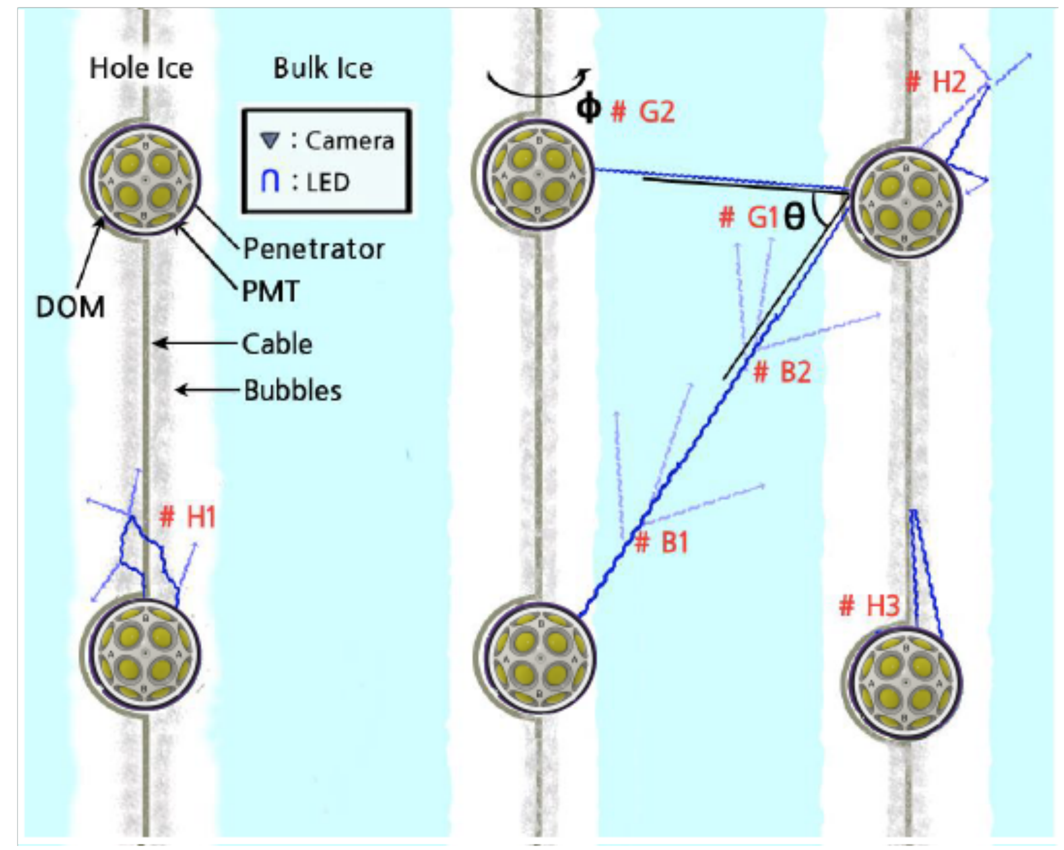
ν_μ disappearance sensitivity (3 yr)

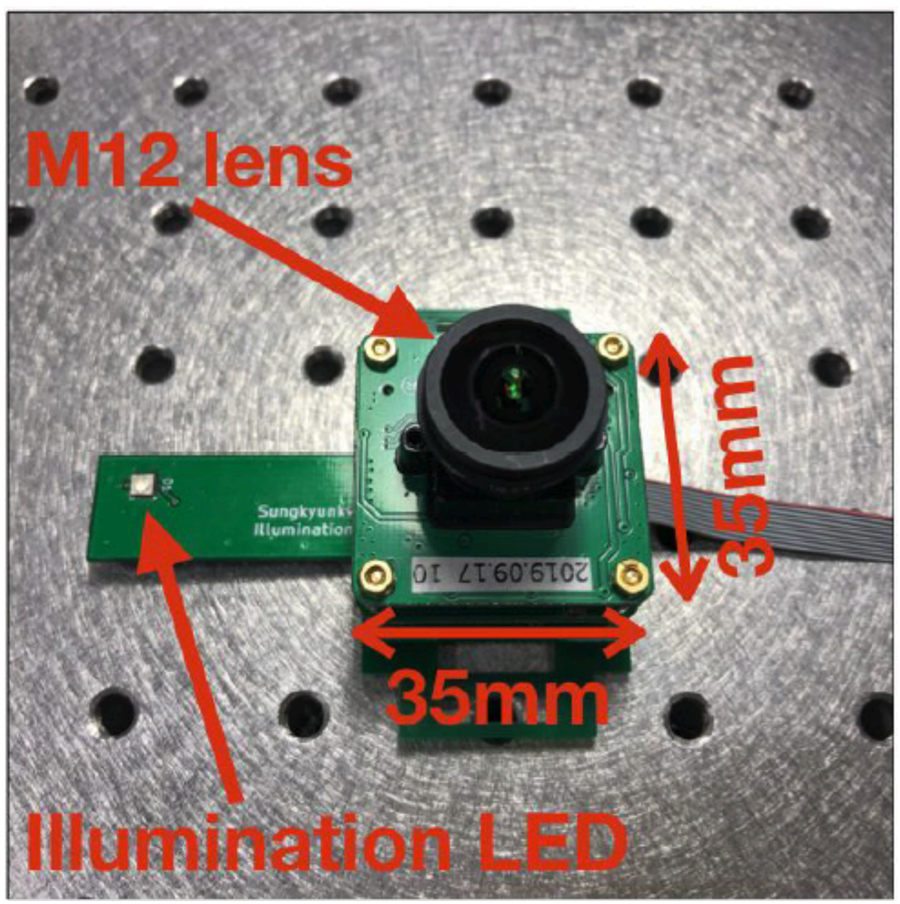


Competitive with long baseline experiments in disappearance channel

Ice Camera System

- Limited understanding of Antarctic ice properties dominant source of sys. uncertainties for most analyses
  - ⇒ better characterize detector medium
- Solution: Camera-based calibration 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.

Hole ice	Geometry (Positioning)	Geometry (DOM Orientation)
Mapping local hole profile (hole ice / bulk ice)	DOM position relative to adjacent DOMs	Orientation of camera DOM
Location of bubble column	Cable position	Orientation of neighbouring DOM on adjacent string
Impurities / cracks / …		Orientation of neighbouring DOM on same string
transmission / reflection at interface hole/bulk ice		

Freeze in process	Bulk ice properties	Others
Dust / contaminants deposition on the surface	Measurement of scattering length	Survey capability
Formation / crushing of bubbles /degasing worked ?	Measurement of absorption length	
Formation of cracks	Hole/Bulk ice interfaces	
Triboluminescence	Anisotropy of light propagation	

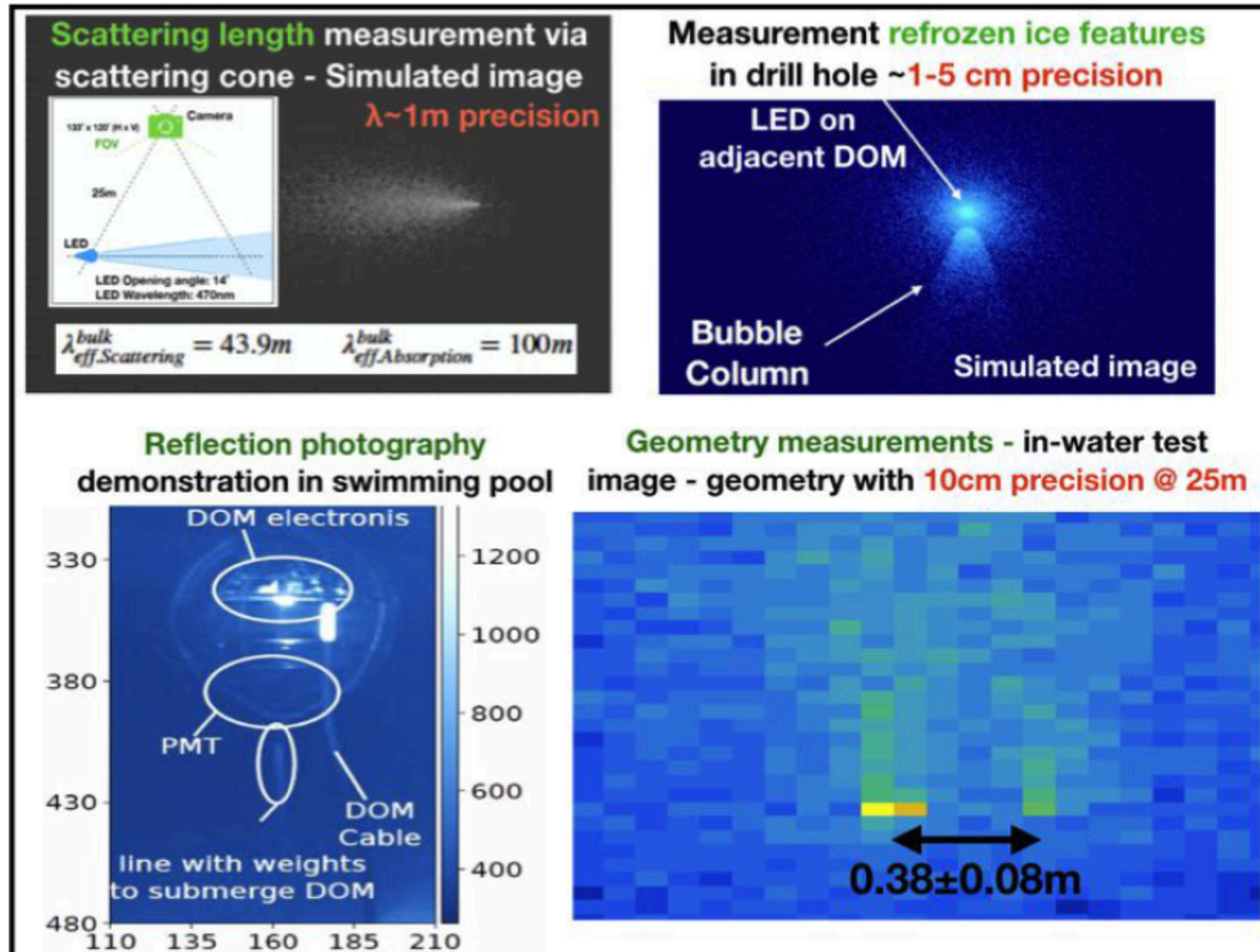
Complementary
Important
Highest Priority

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)



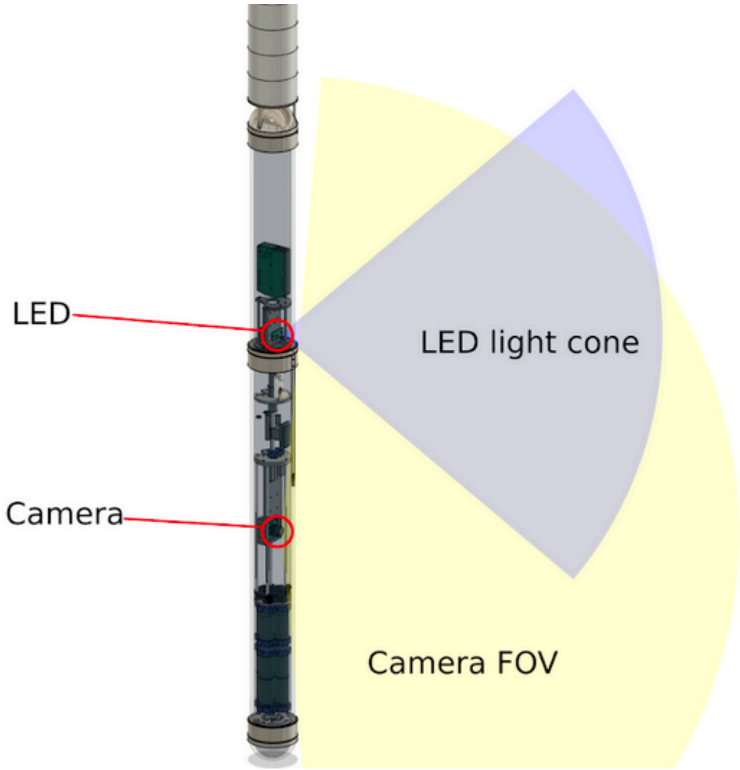
- Verified successful operations under polar conditions and demonstrated ability to measure ice properties with cameras
- **Camera system successfully passed IceCube Internal Final Design Review (FDR) in September 2019**

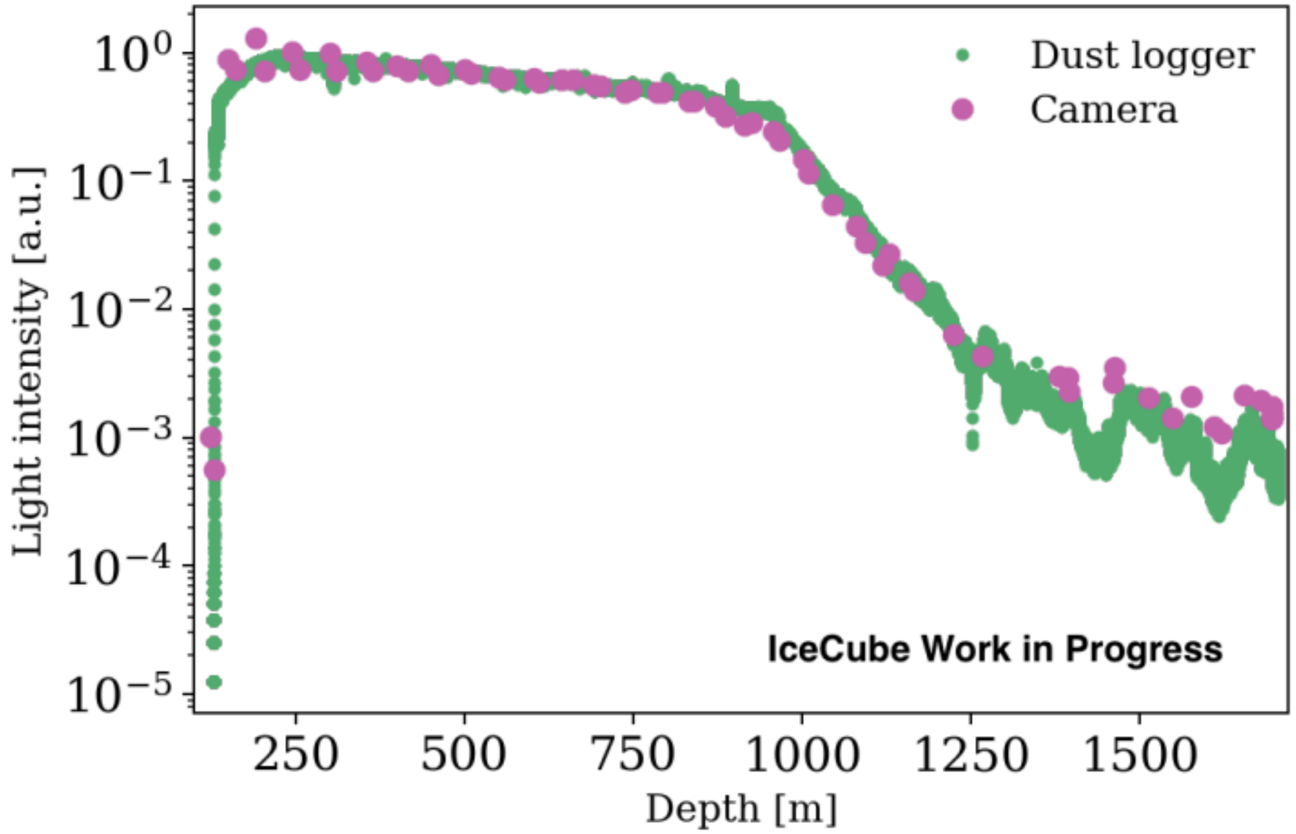
Camera sensitivity and Field Test

Successful South Pole Deployment of Test System

PoS(ICRC2019)926

- After the main deployment of the Luminescence logger a ICU camera and an LED used for the ICU camera system were installed in the logger
- The camera was installed on a special holding structure where the mirror of the logger would otherwise be
- The LED is installed below the RED pitaya pointing in the same direction as the camera
- The distance between LED and camera is 38.5cm
- The camera measures the backscattered light from the LED
- From the distribution and amount of light, we expect to estimate the scattering length in ice

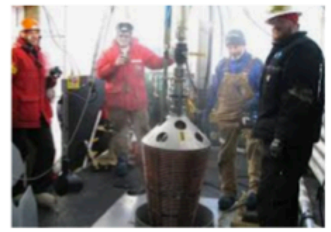




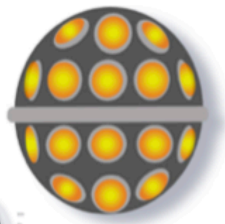
Group photo after successful passing of the camera preliminary design review (Madison May 2019)

Novel calibration system production lead by SKKU group

South Pole Operations



mDOM



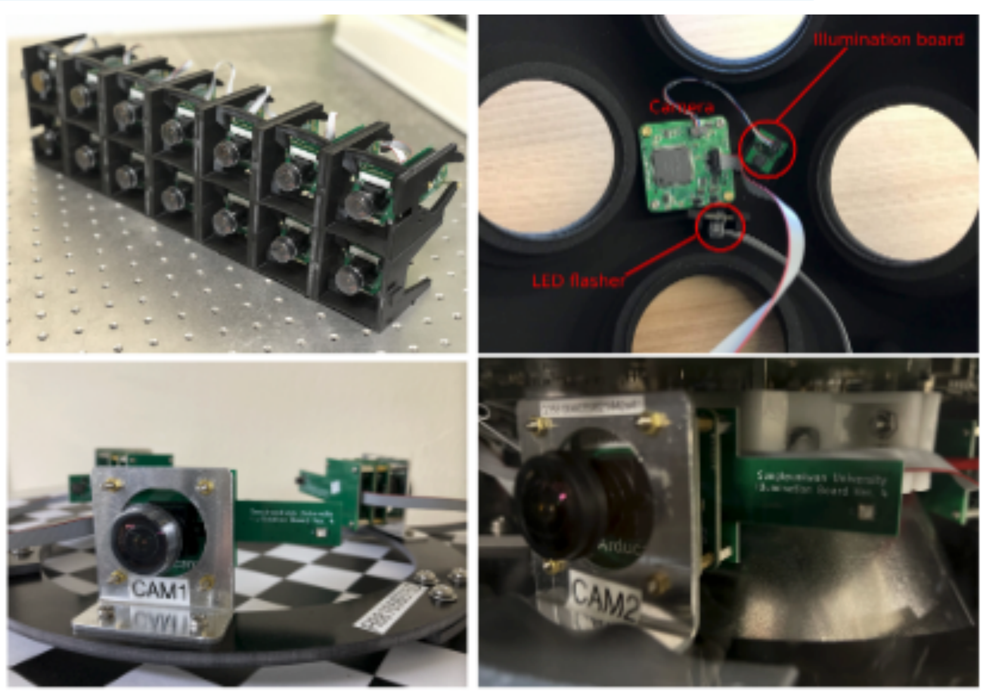
~650 sensor modules

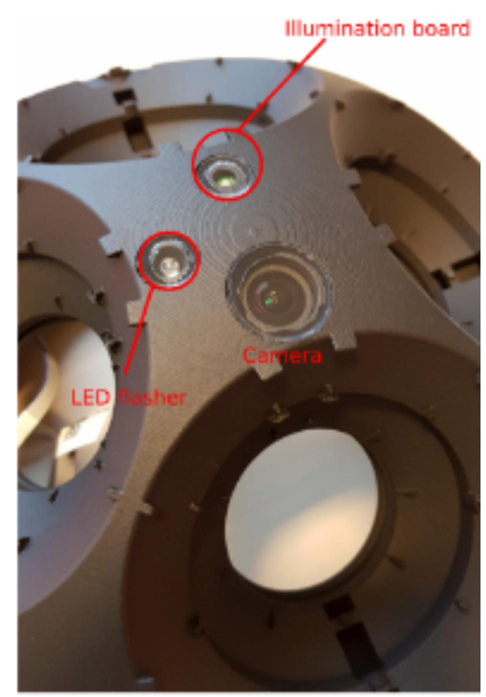
D-EGG

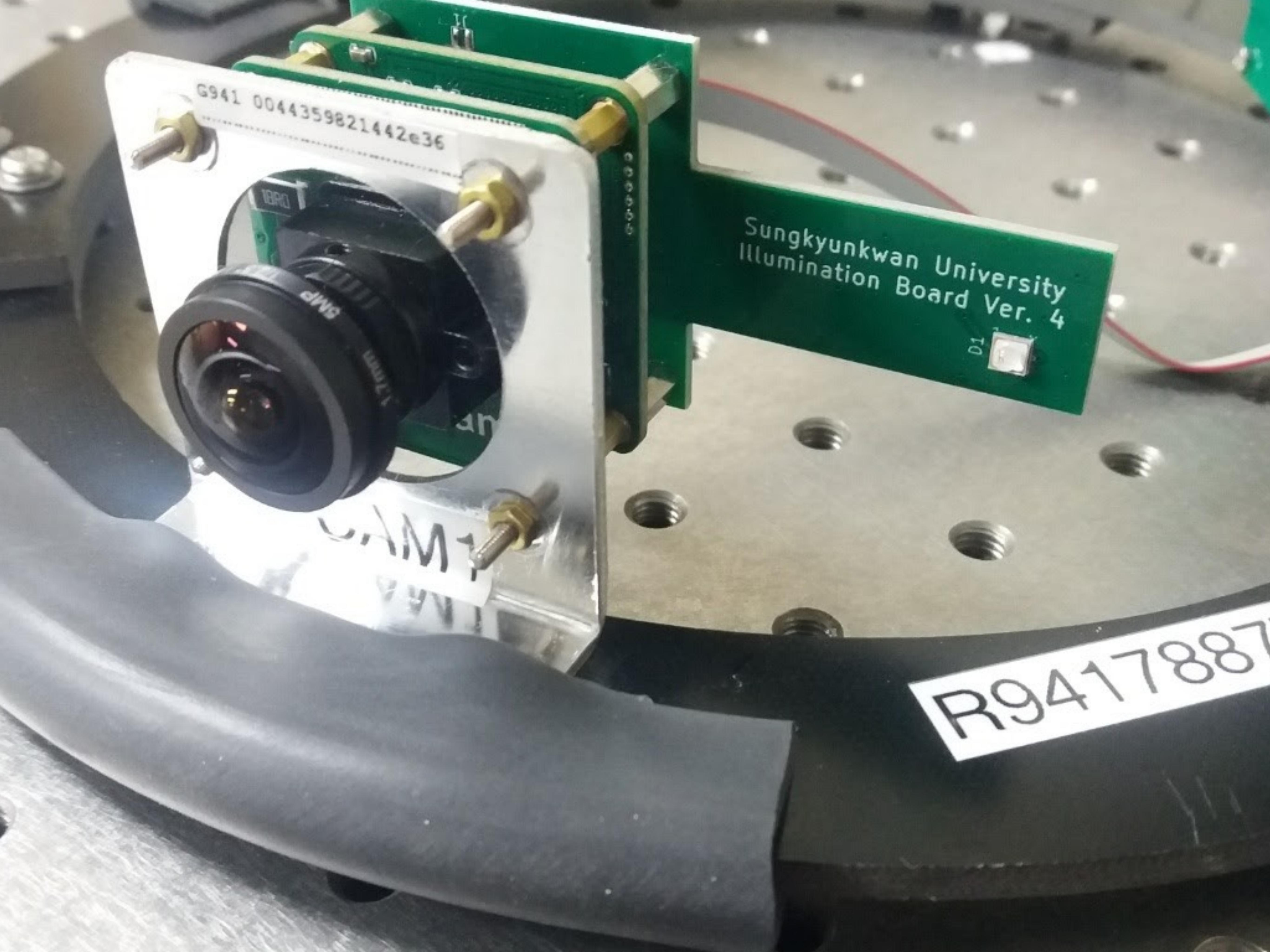
Novel calibration

~3 camera systems / module

Graduate student Jiwoong Lee (left) assembling mDOM cameras with trainee undergraduate assistants Youbin Oh (right, front) and Minji Shin (right, back). Inset shows a box being packed with camera-LED systems protected in ESD bags.



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Current status of camera production

- IceCube Upgrade deployment has been moved to 2024/2025 due to COVID-19 accessibility to pole
- Camera production well within the schedule to meet all the production and testing targets
  - D-EGG cameras integrated ~900 cameras
  - mDOM cameras tested and or shipped to production centers ~ 650 cameras
  - mDOM cameras remain to be tested at SKKU ~ 500 cameras

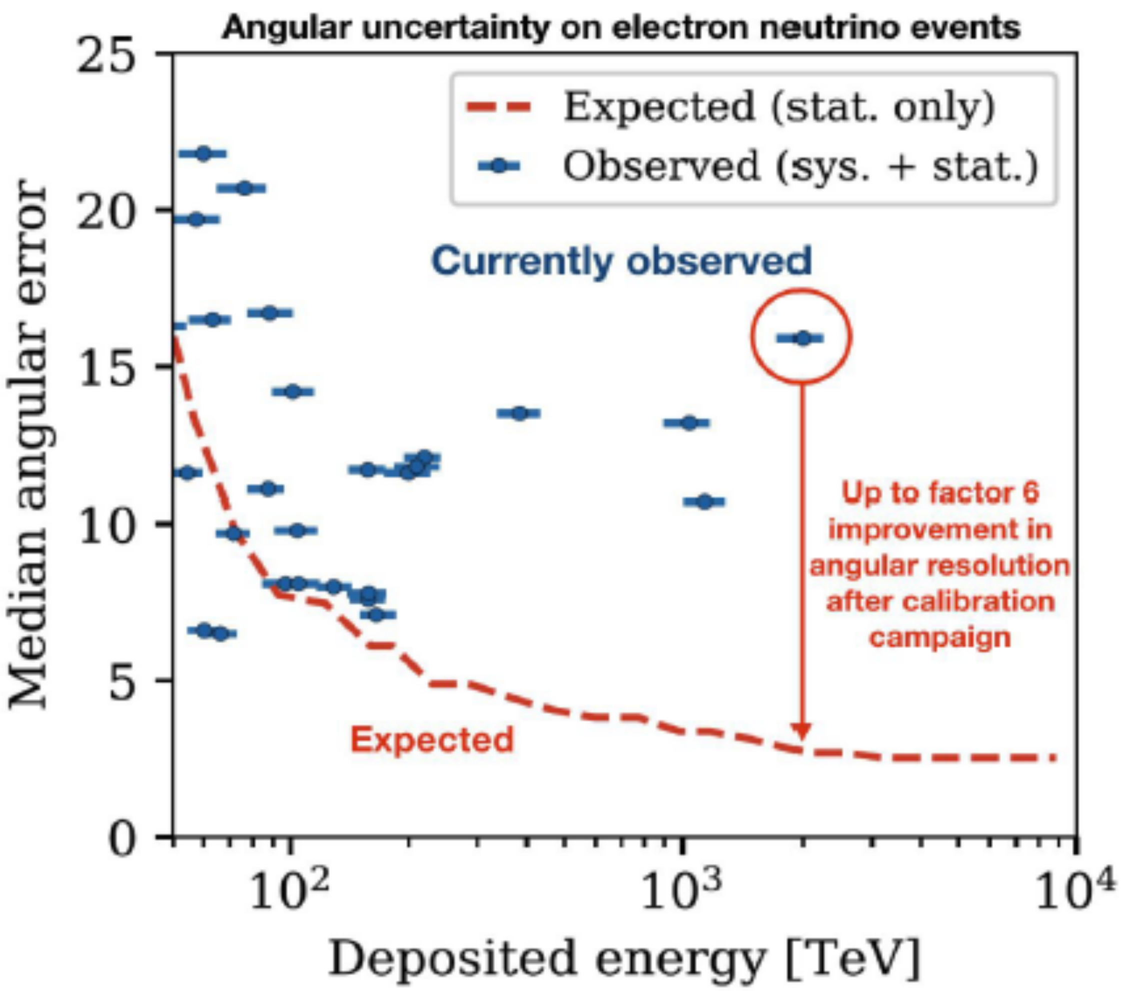
Camera status July 2022

Cameras that are at SKKU and are undergoing testing and calibration measurements

Cameras completed testing and shipped to integration centers or awaiting shipping

Cameras integrated in IceCube Upgrade optical modules

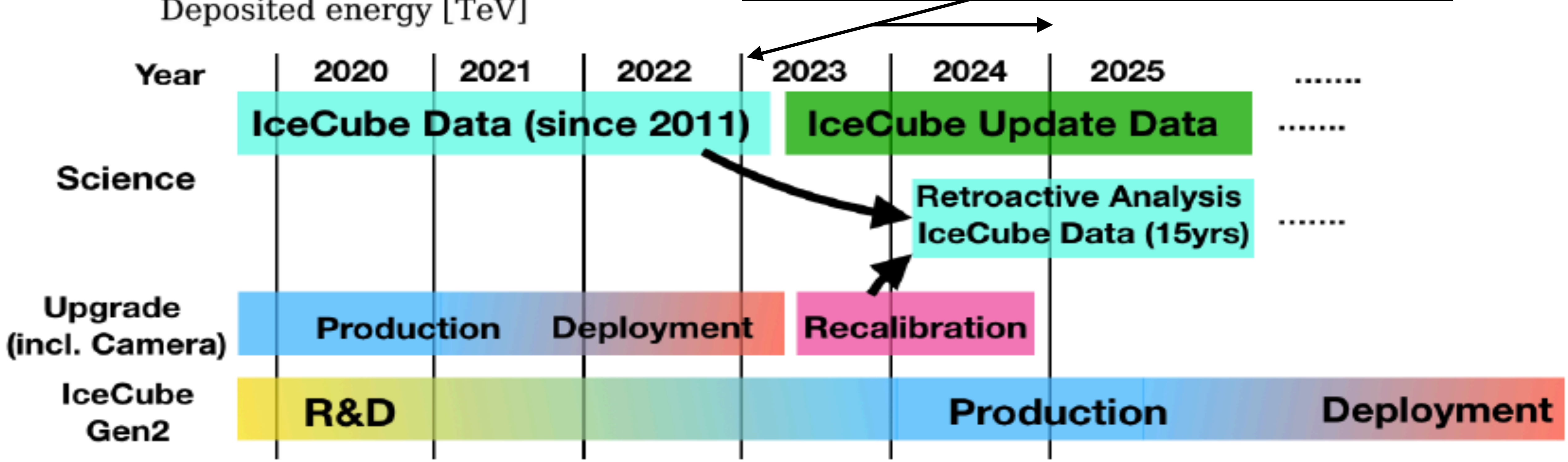
Camera system impact



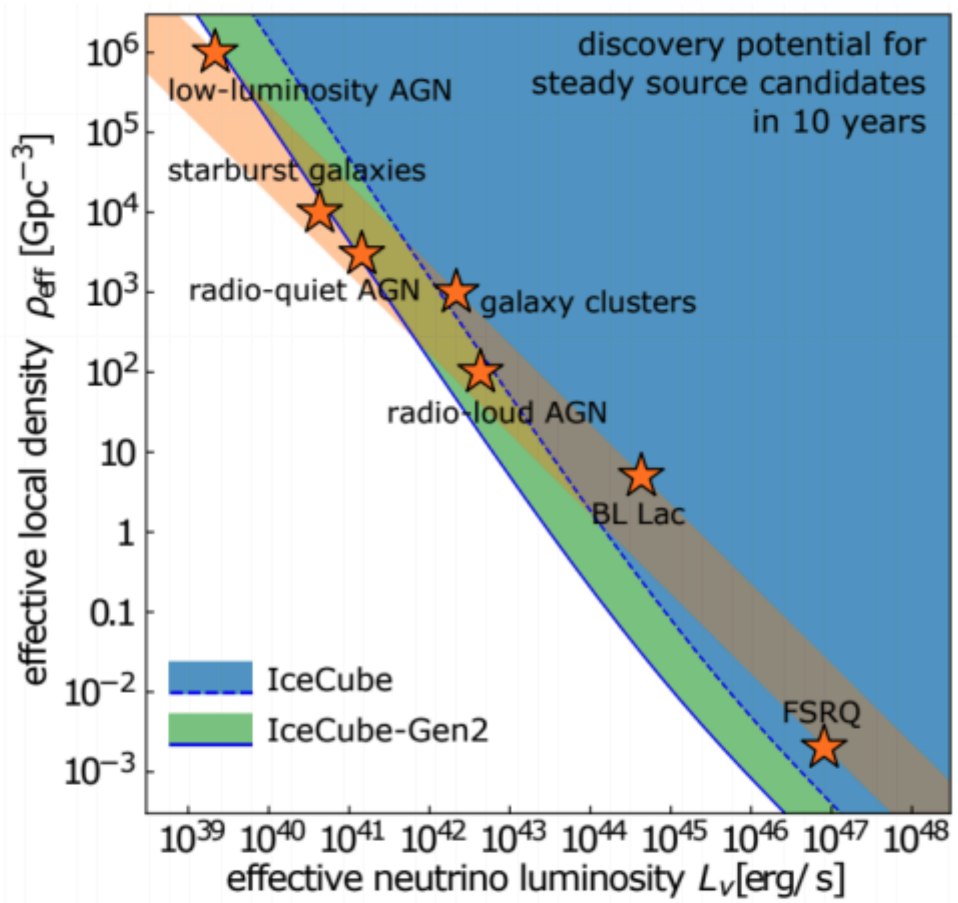
Camera system key to comprehensive understanding of the detector medium

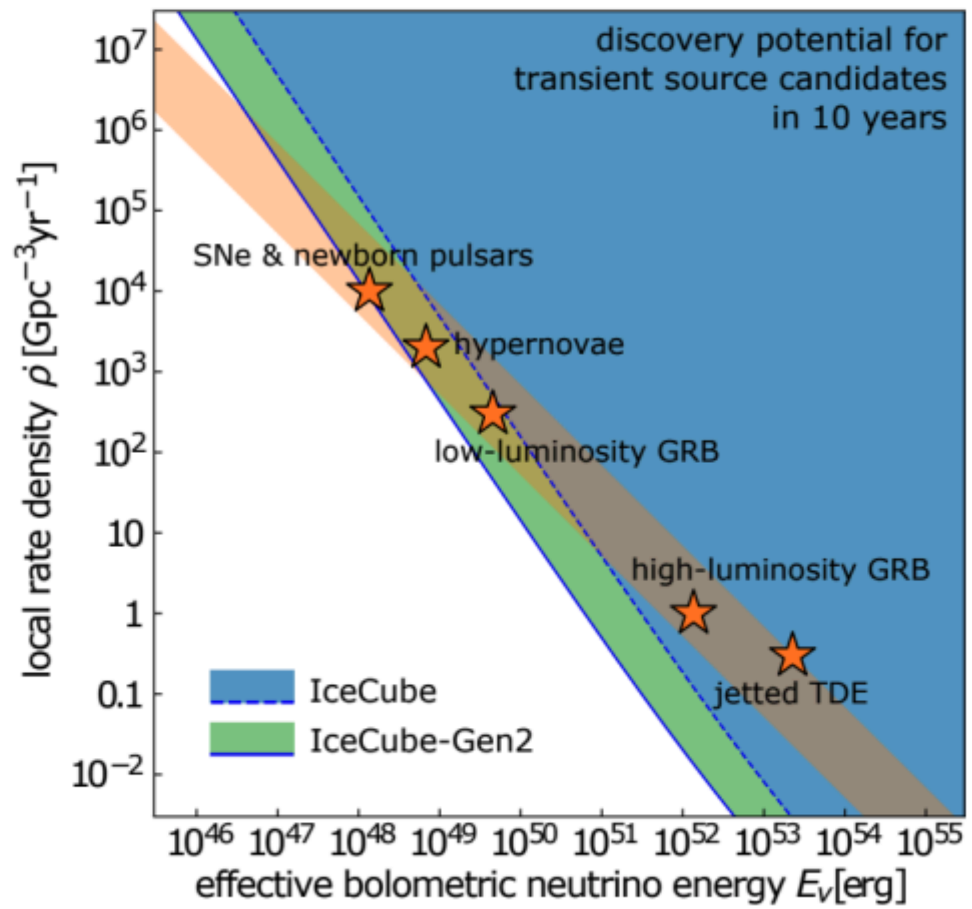
- ***Science multiplier*** Retroactively analyze more than 15 years of IceCube data with substantially improved angular and energy resolution
- ***Improved neutrino event pointing*** critical for multi messenger science

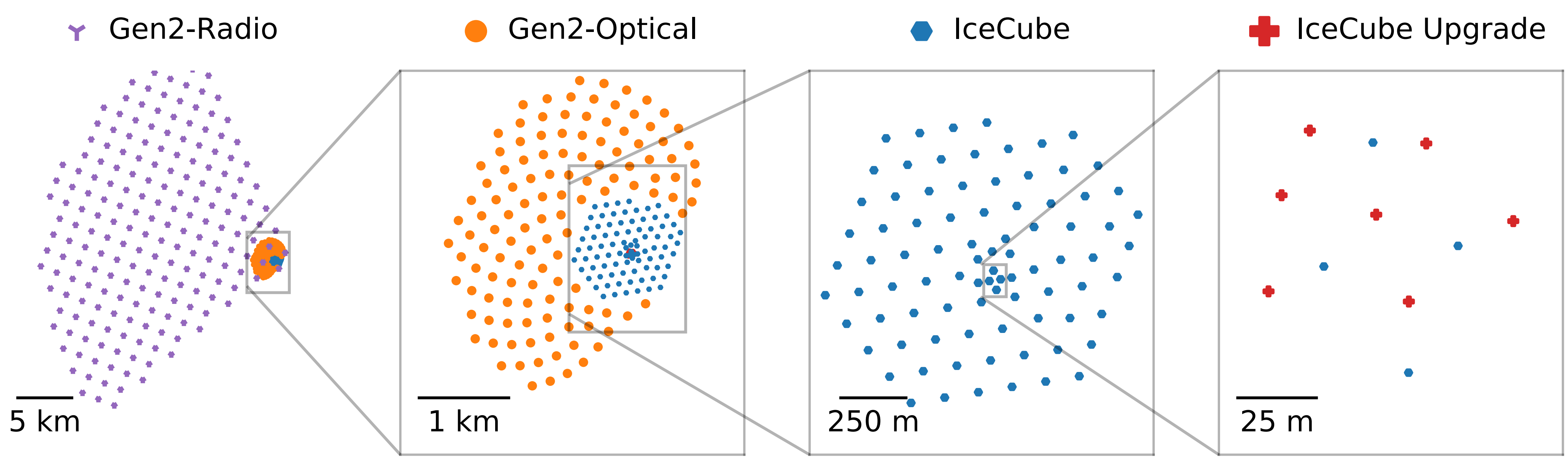
Upgrade deployment delayed by two years due to COVID-19



IceCube-Gen2

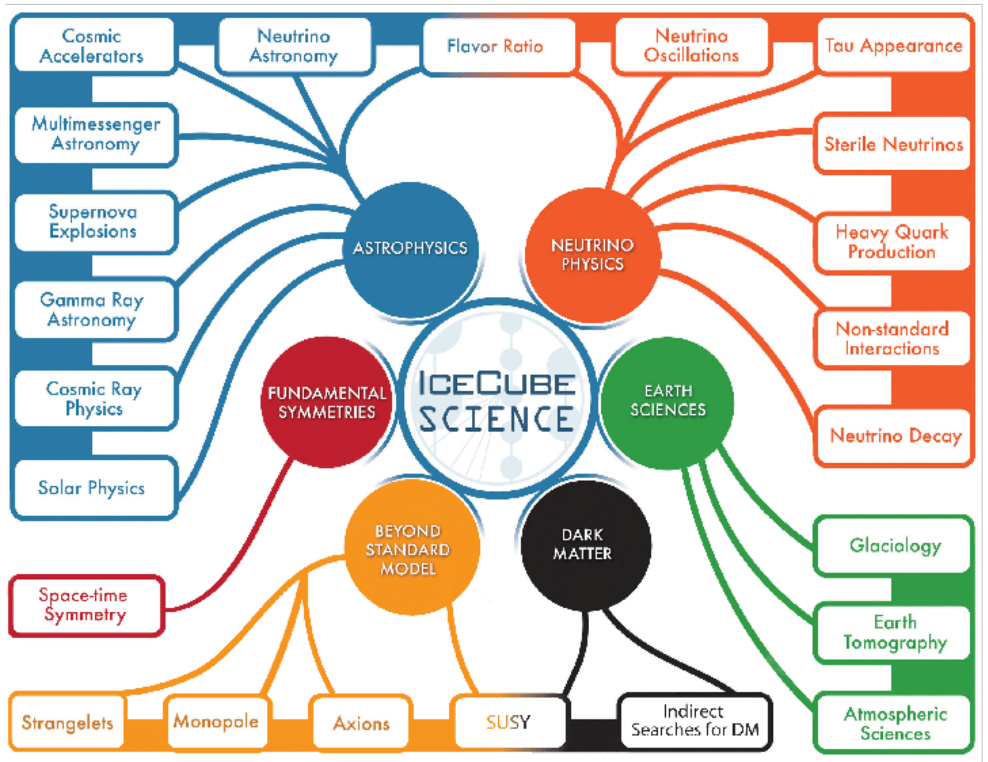


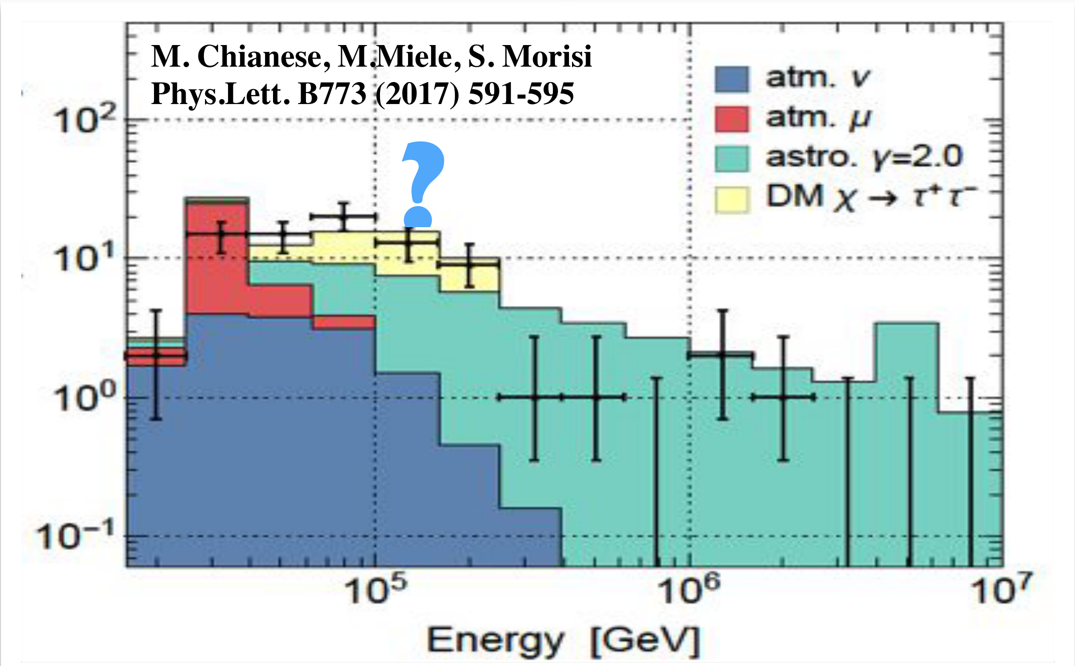




Complementarity & Outlook

- Neutrino Telescopes are discovery experiments, exploring the unknown, with a tremendous potential for BSM physics searches
  - Guaranteed science for dark matter searches & discovery potential
  - Observed astrophysical neutrino spectrum remains to be understood
    - Guaranteed discoveries, including potential to observe dark matter
  - BSM physics searches at neutrino telescopes come at essentially no additional costs (highly leveraged)
  - Independent from direct detection or other indirect searches
  - Rapidly evolving field that can provides unexpected new opportunities (example observation of new astrophysical sources or transient events)





High-energy astrophysical neutrino flux can only be understood with significantly higher event statistics (x10)

Conclusions

- Striking signatures provide high discovery potential for indirect searches for dark matter with neutrinos
- Stringent limits on dark matter self-annihilation cross section set using neutrino telescopes
- Lifetimes of heavy decaying dark matter has be constrained to 10^{28}s using neutrino signals
- Neutrino Telescopes/Detectors provide world best limits on the Spin-Dependent Dark Matter-Proton scattering cross section
- A new neutrino floor for solar dark matter searches has been calculated and might be observable in the near future
- Efforts underway to expand searches beyond WIMP hypothesis