Neutrino Astronomy

outline

1. Introduction
2. Solar neutrinos (1960s -)
3. Supernova neutrinos (1987, 202X?)
4. Atmospheric neutrinos (1960s -)
5. Extragalactic neutrinos (2013 -)
6. Cosmogenic neutrinos (202X?)
7. Big Bang relic neutrinos (203X?)
8. Conclusion

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Teppei Katori
King's College London
December 6, 2022

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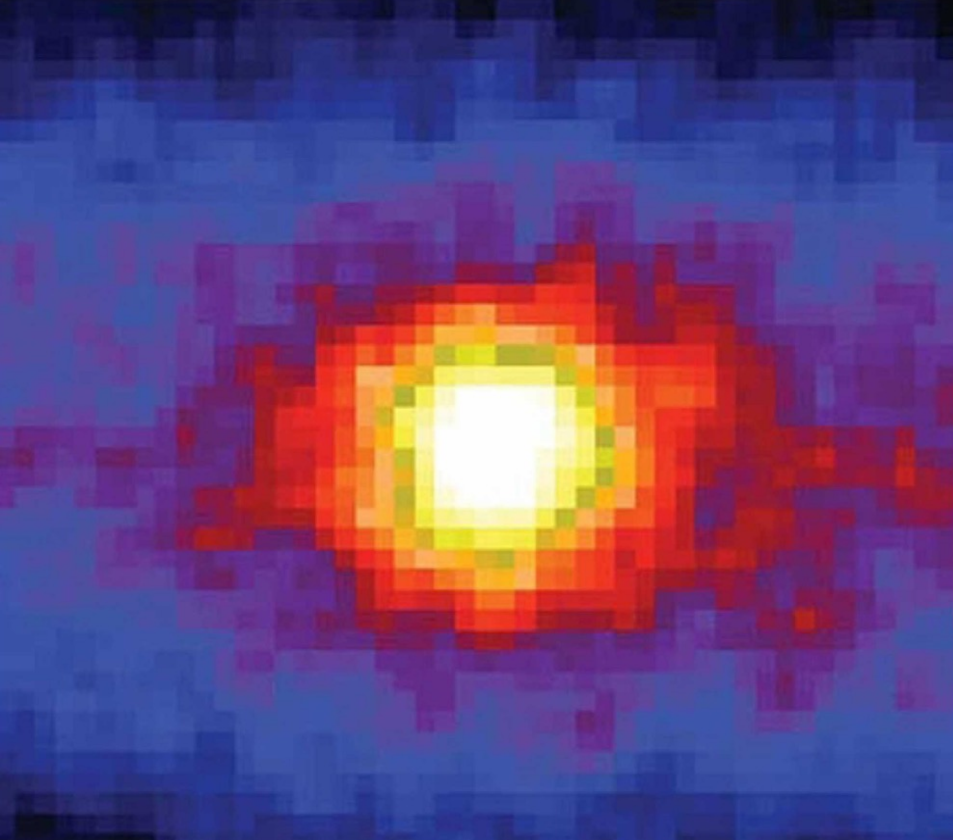
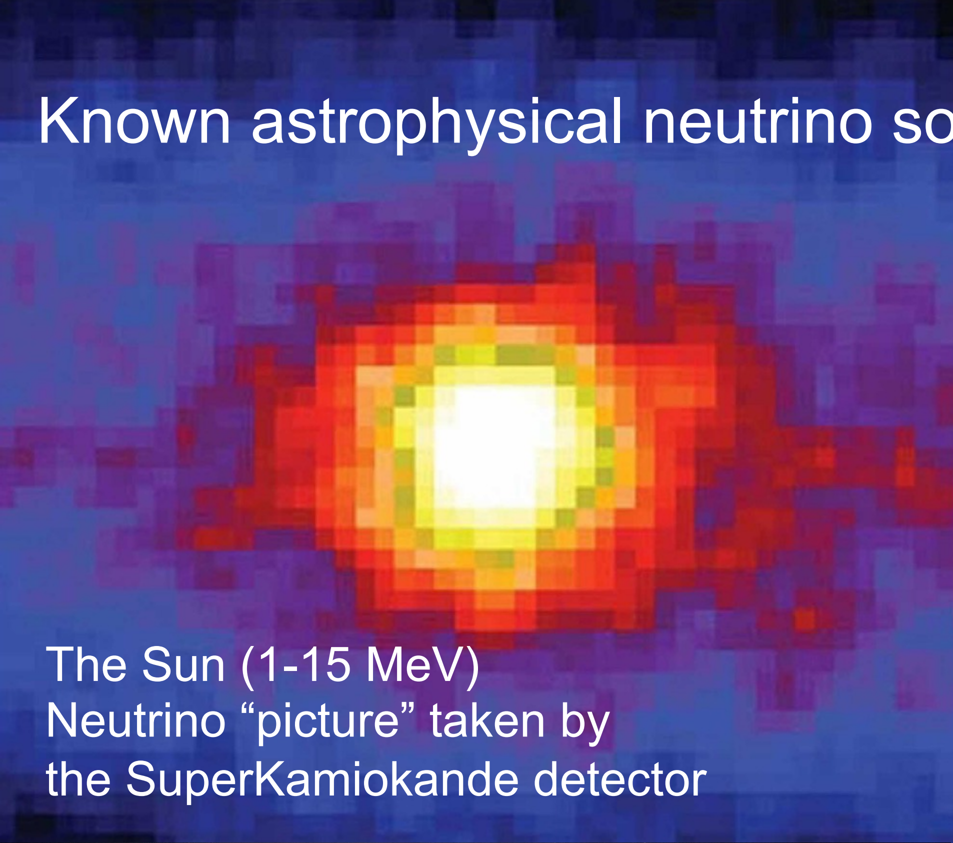
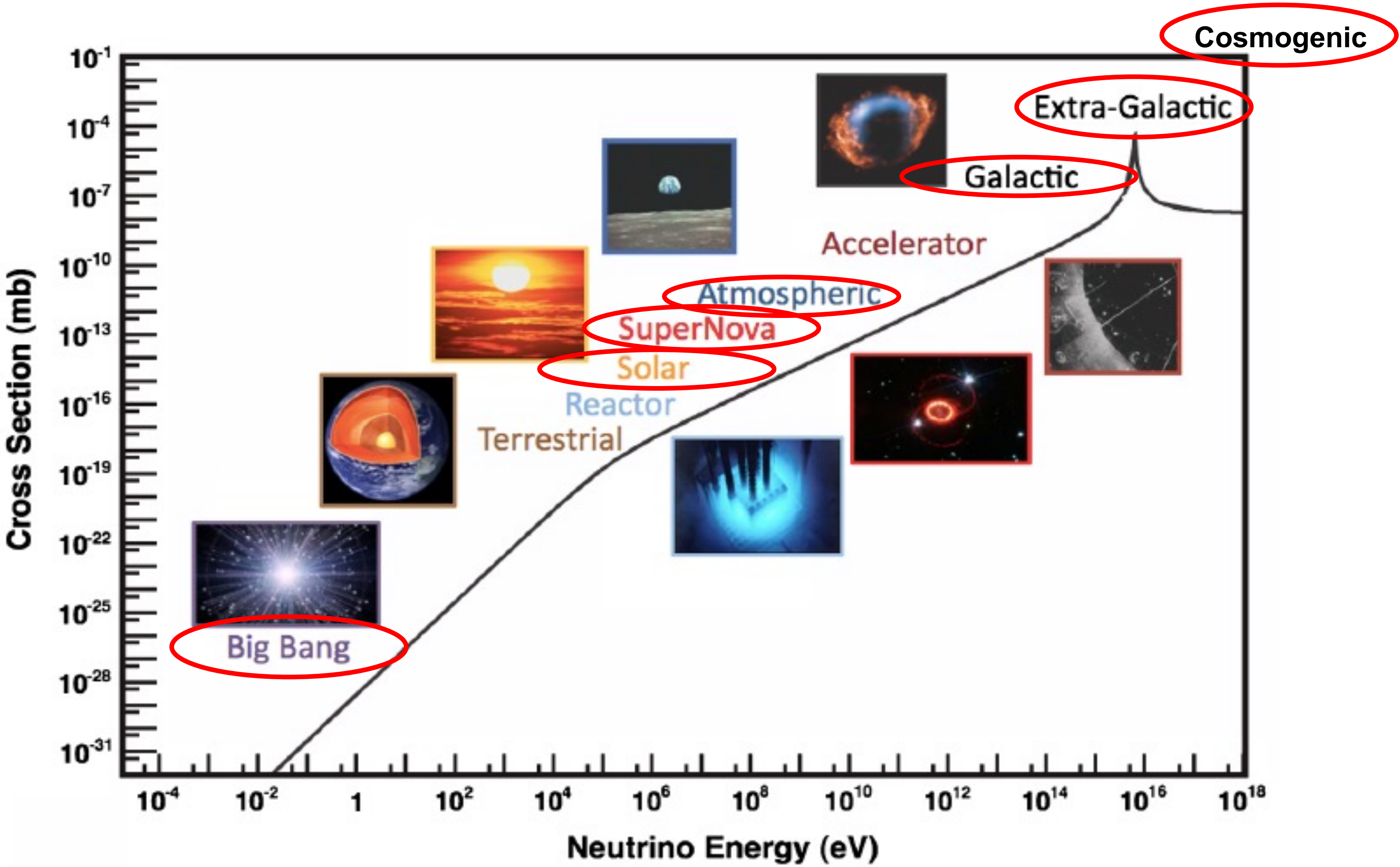



Known astrophysical neutrino sources



Formaggio and Zeller, Rev.Mod.Phys.,84 (2012) 1307

From eV to EeV: Neutrino cross sections across energy scales



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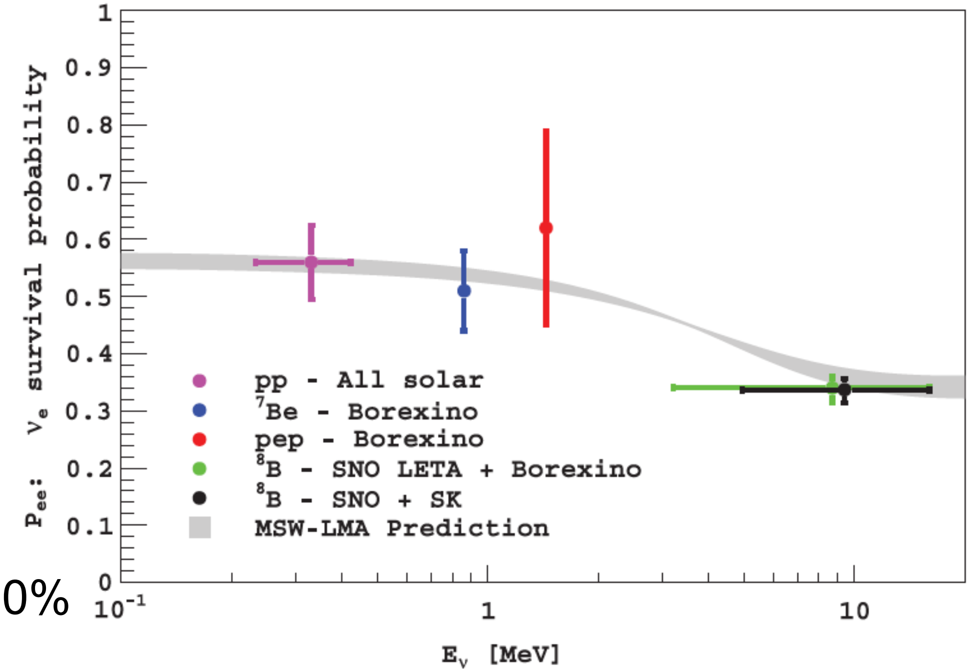
Cleveland et al.,Astrophys.J.496(1998)505, Pontecorvo,Phys.Lett.28B(1969)493
GALLEX, PLB490(2000)16;SAGE, J.Expt.Theor.Phys.95(2002)181, Borexino, PRL 108(2012)051302

2. Solar neutrino



Homestake experiment

$$\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$$

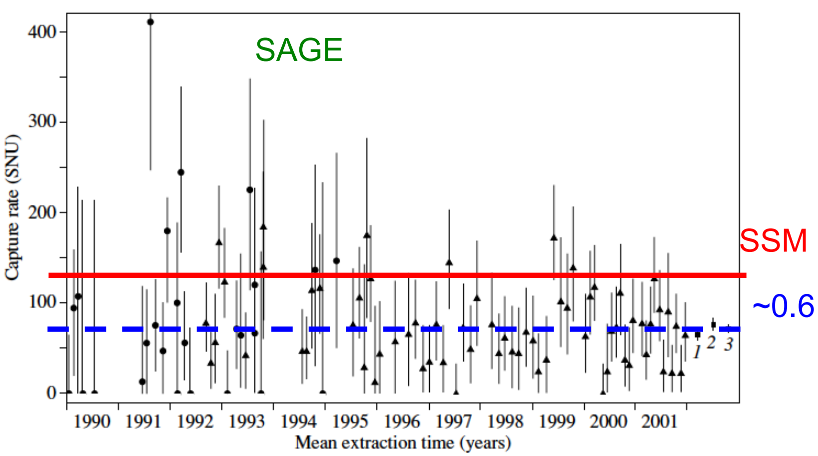
(proposed by Pontecorvo)

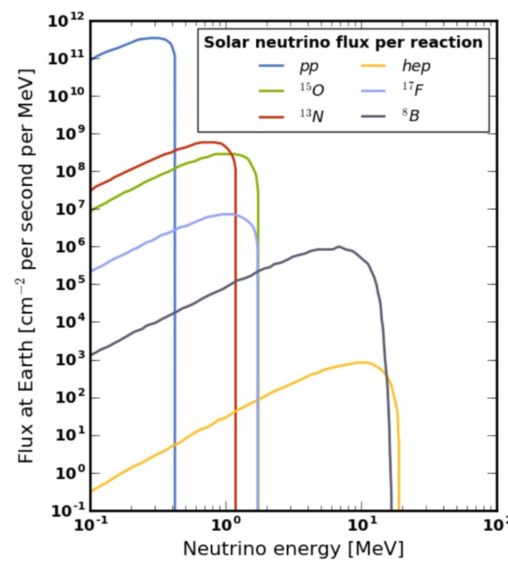
- mainly sensitive to ^{8}B neutrino (~10 MeV)

Gallium experiment

$$\nu_e + {}^{71}Ga \rightarrow e^- + {}^{71}Ge$$

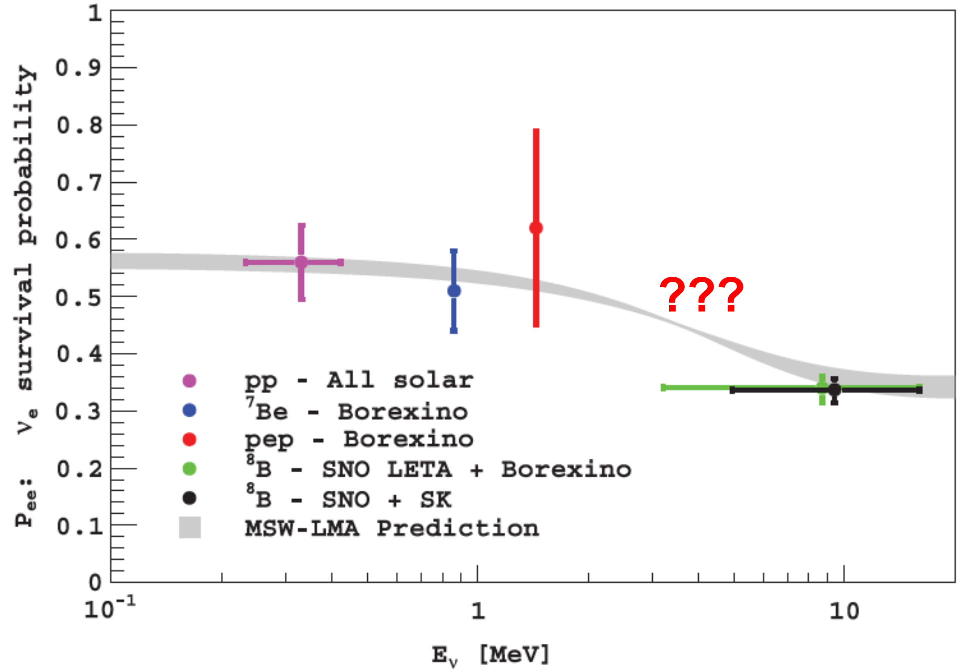
- Sensitive to pp-neutrino (0.42 MeV), 90% of total solar neutrino flux.





Snowmass21 "Report of the Topical Group on Particle Dark Matter for Snowmass 2021", arXiv:2209.07426
Borexino, PRL 108(2012)051302

2. Solar neutrino, future



Upturn

- MSW is Still many exotic scenario around 1-3 MeV

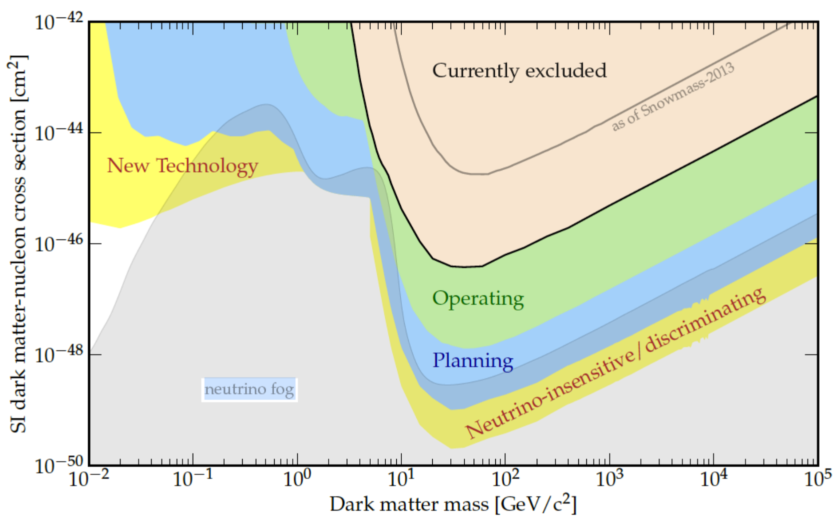
hep neutrino

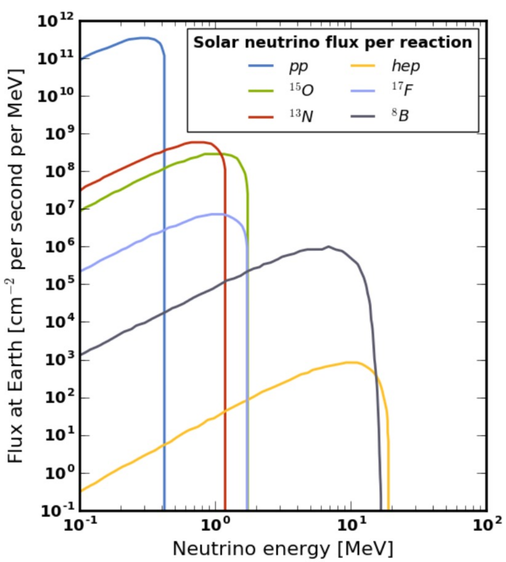
$^3He+p \rightarrow {}^4He+e^++\nu_e$ (18 MerV)

- Haven't detected yet

Neutrino floor

- Solar neutrino coherent scattering wo irreducible WIMP dark matter background





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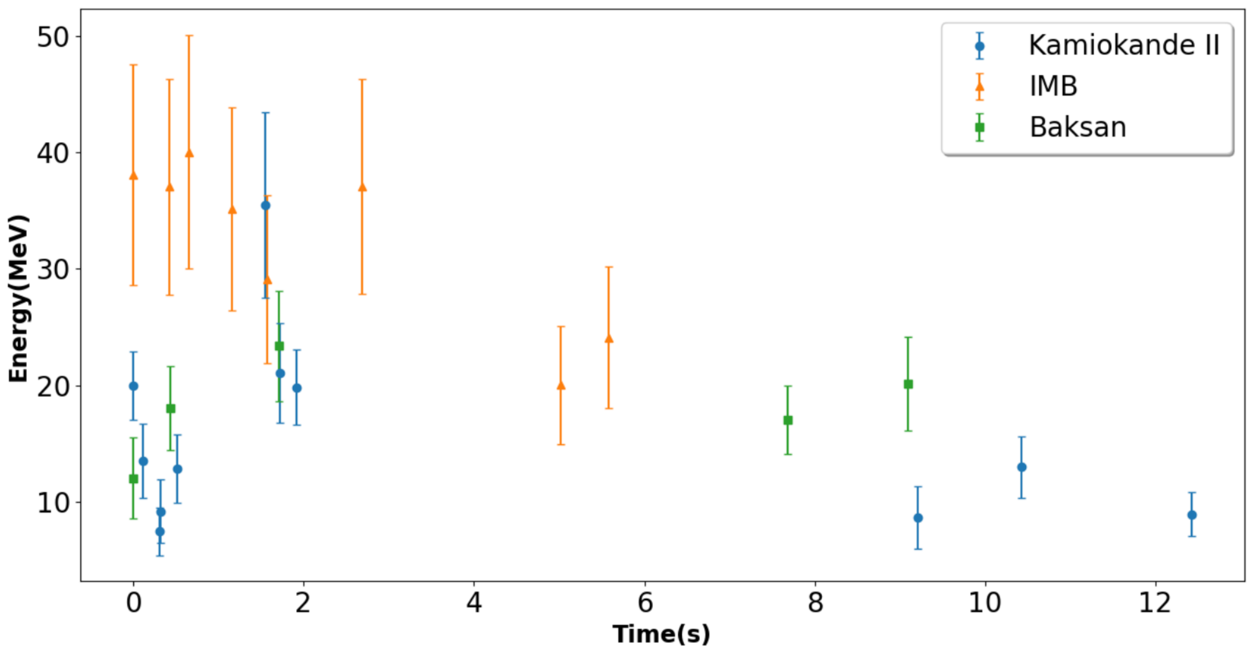
3. Supernova neutrinos

SN1987A
- Large Magellanic Cloud, 51.4 kpc
- “Most famous 25 events”, in 13 seconds

Known issues
- IMB neutrino energy > Kamiokande II energy?
- 13 seconds too long as neutrino flash (<1ms)

Neutrinos may be delay due to...
- nonzero neutrino mass
- nonzero neutrino electric charge or magnetic moment
- violation of Lorentz invariance
- etc

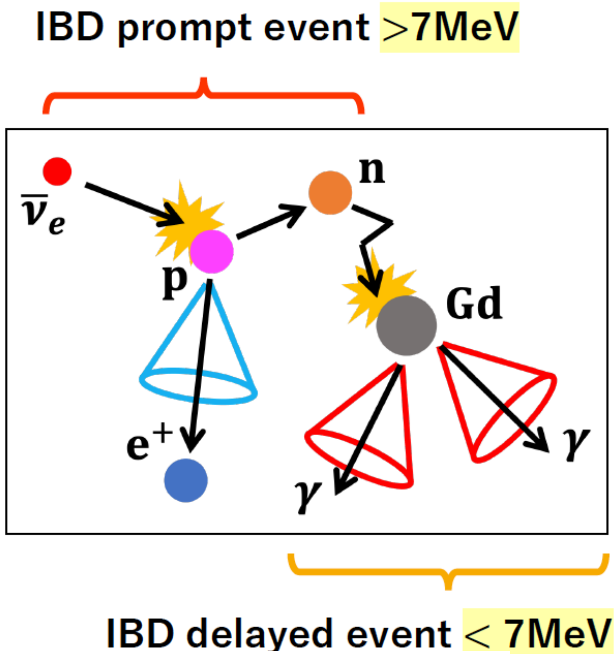


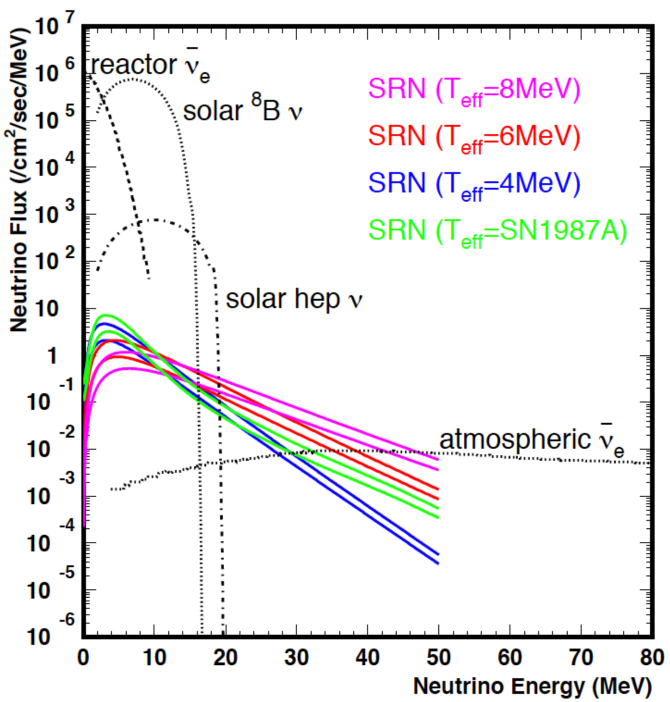
Hyper-Kamiokande, arXiv:1805.04163
Super-Kamiokande, PRD104(02021)122002

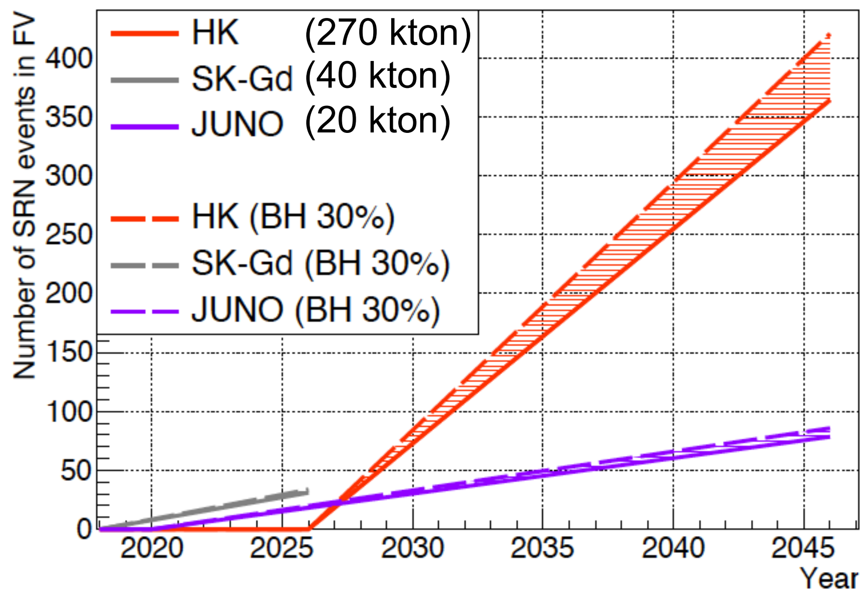
3. Supernova neutrinos, future

Diffuse Supernova Neutrino Background (DSNB)

- DSNB is always there
- Gadolinium doped Super-Kamiokande (SKGd)
- ~a few event per year
- Key is how to suppress the cosmogenic background







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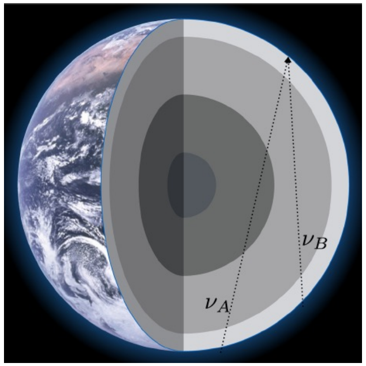
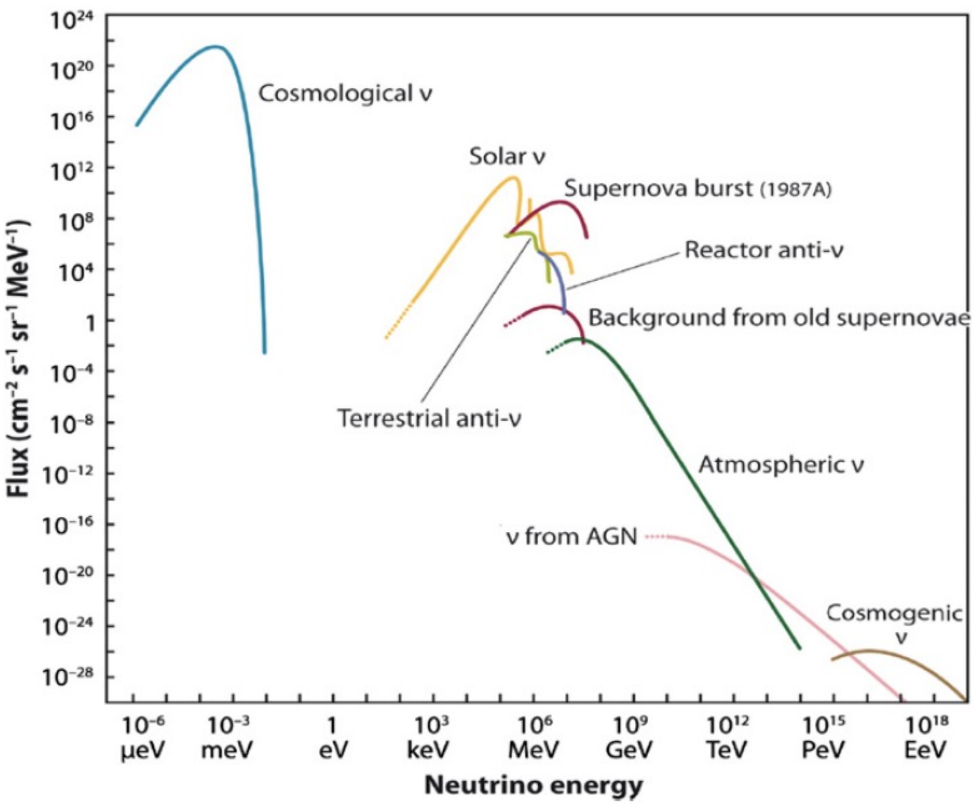
Super-Kamiokande, PRD97(2018)072001

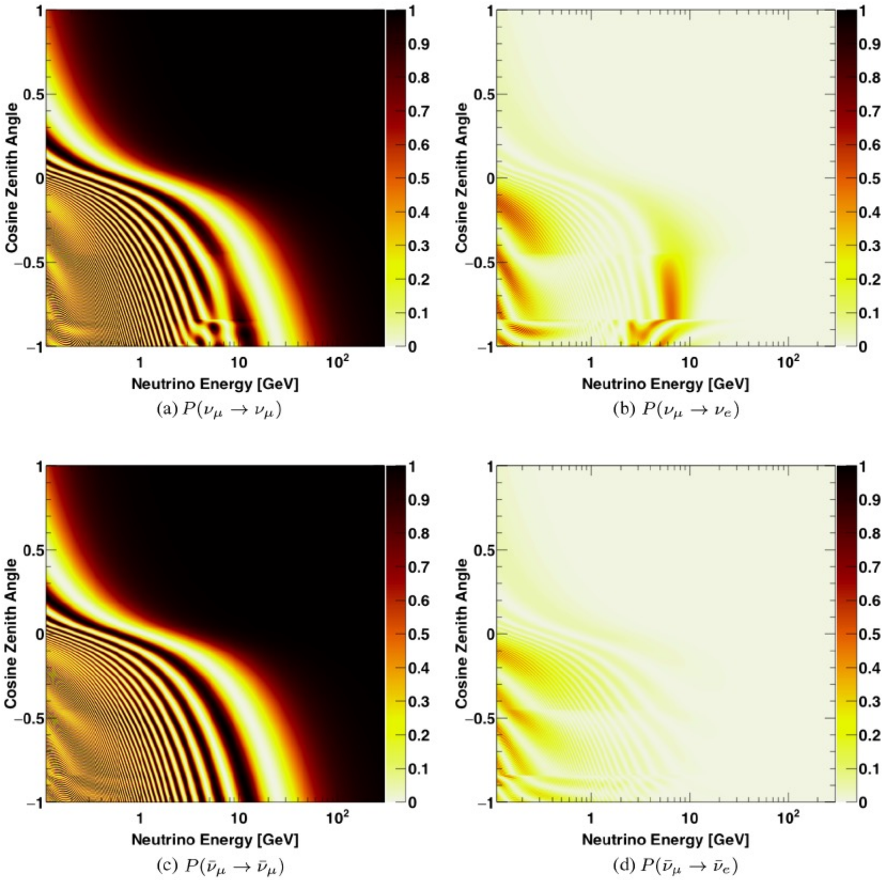
4. Atmospheric neutrinos



Conventional atmospheric neutrino

- π and K decays, up to ~10-20 TeV
- Discovery of neutrino oscillations





Super-Kamiokande oscillogram

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Super-Kamiokande, PRD97(2018)072001
IceCube, ApJ.928(2022)50

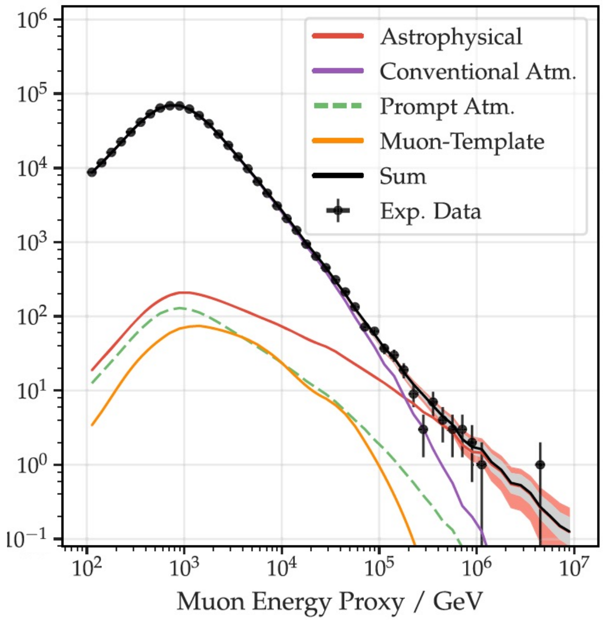
4. Atmospheric neutrinos, future

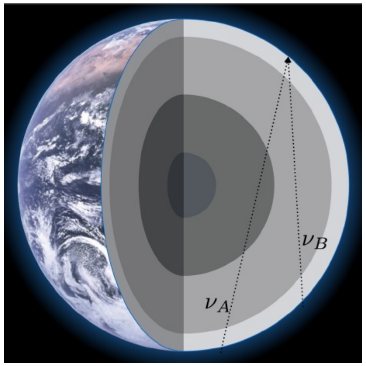
Conventional atmospheric neutrino

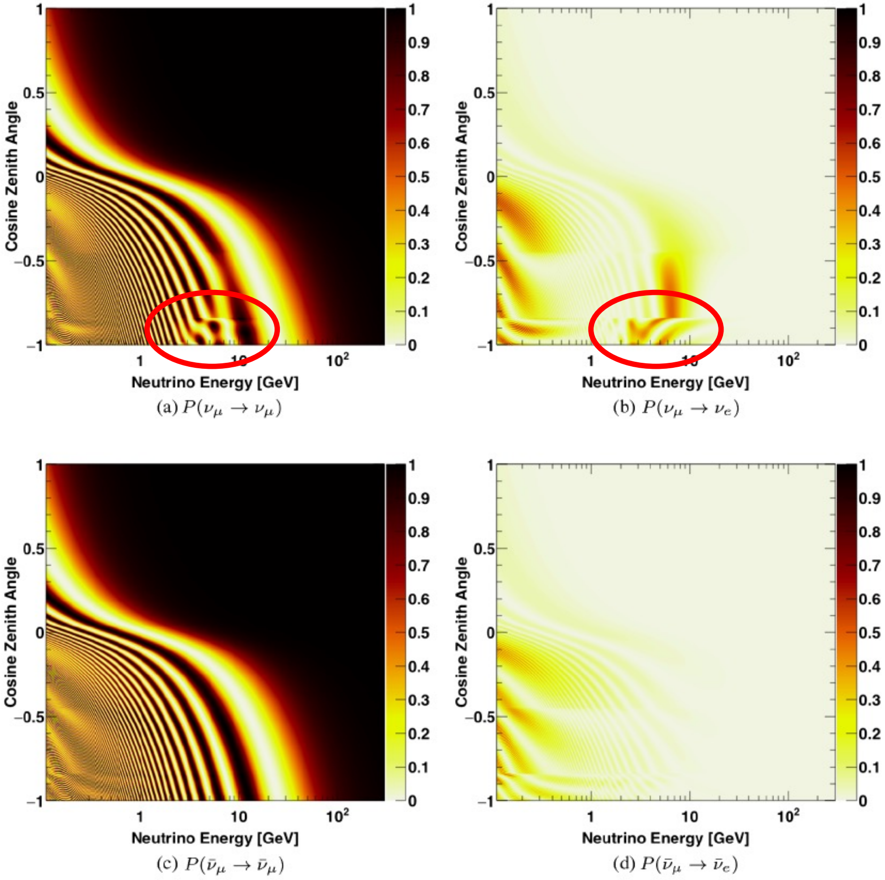
- π and K decays, up to ~10-20 TeV
- Discovery of neutrino oscillations
- Higher precision flux prediction to measure neutrino mass ordering

Prompt atmospheric neutrino

- D-meson (charm) decay neutrinos
- Significant around ~50-100 TeV?
- Not identified yet







Super-Kamiokande oscillogram

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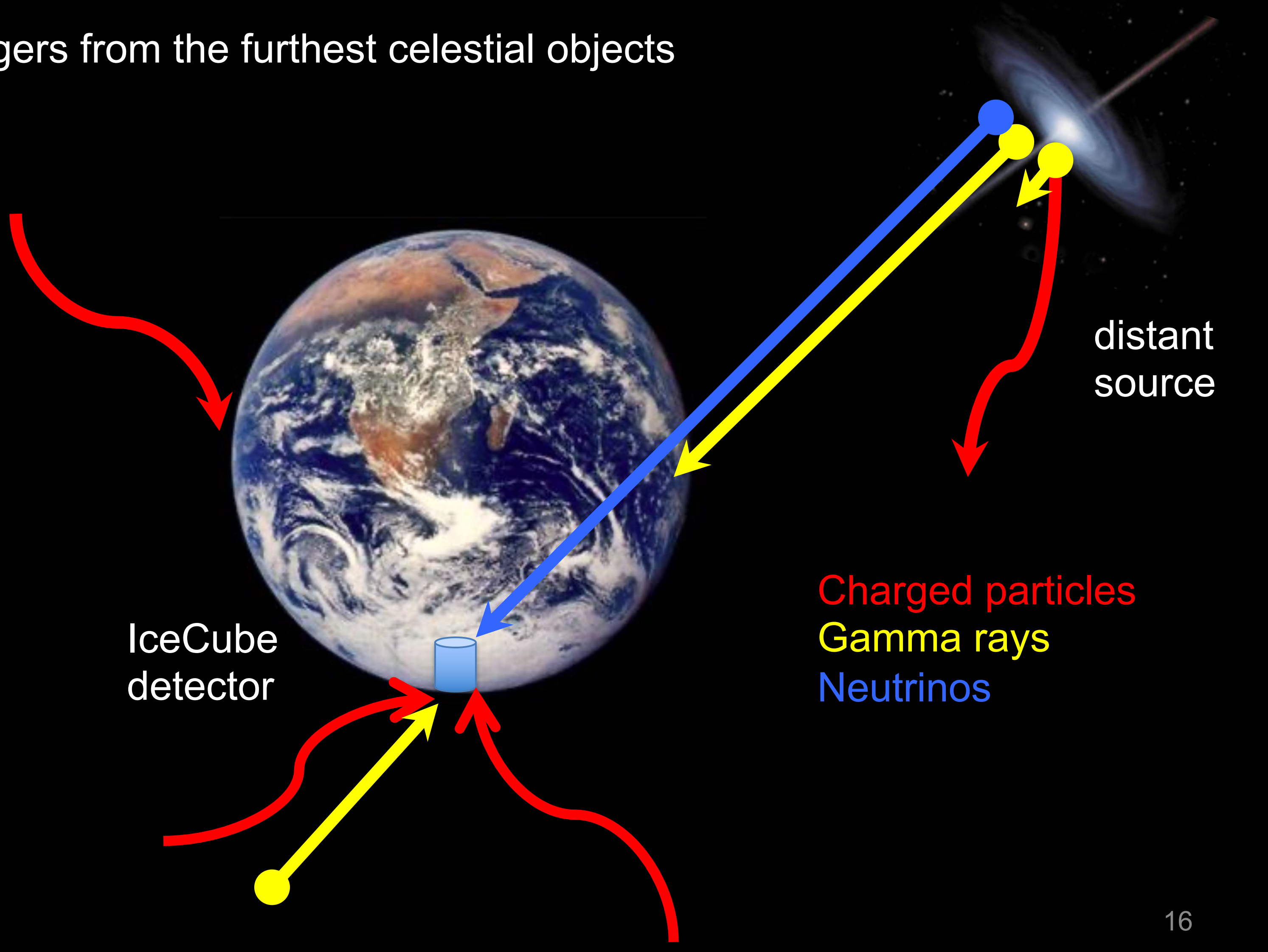
5. High-Energy Astrophysical Neutrinos

Direct messengers from the furthest celestial objects

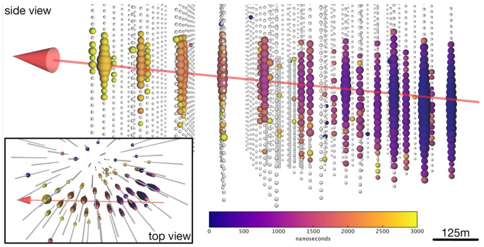


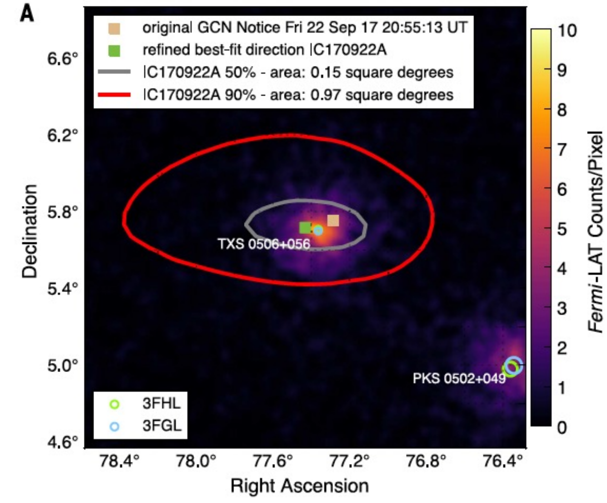
IceCube, Science361(2018)147, IceCube et al,(2018)eaat1378

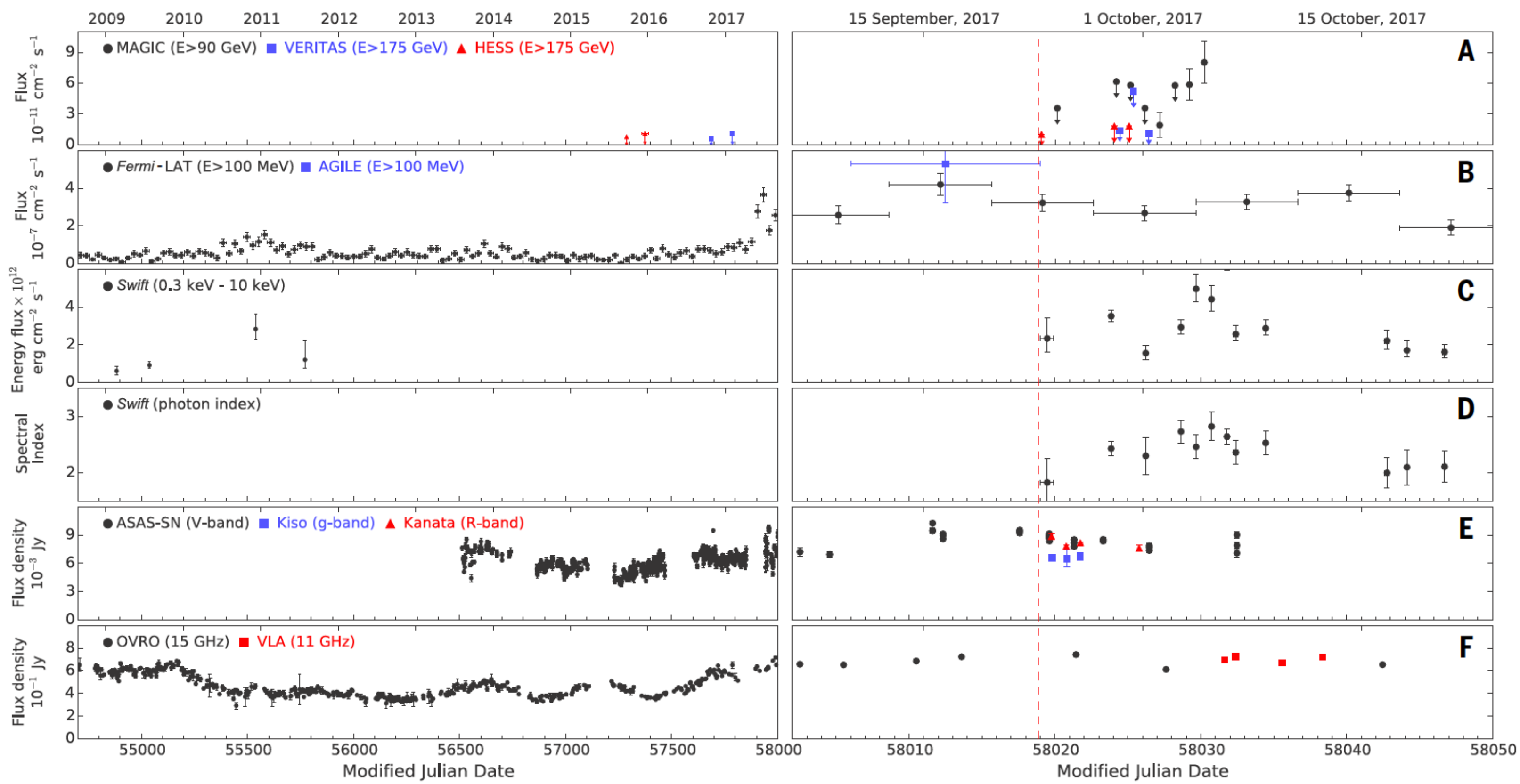
5. Multi-messenger astronomy

IC170922

- "transient" 290 TeV event
- coincide to activities







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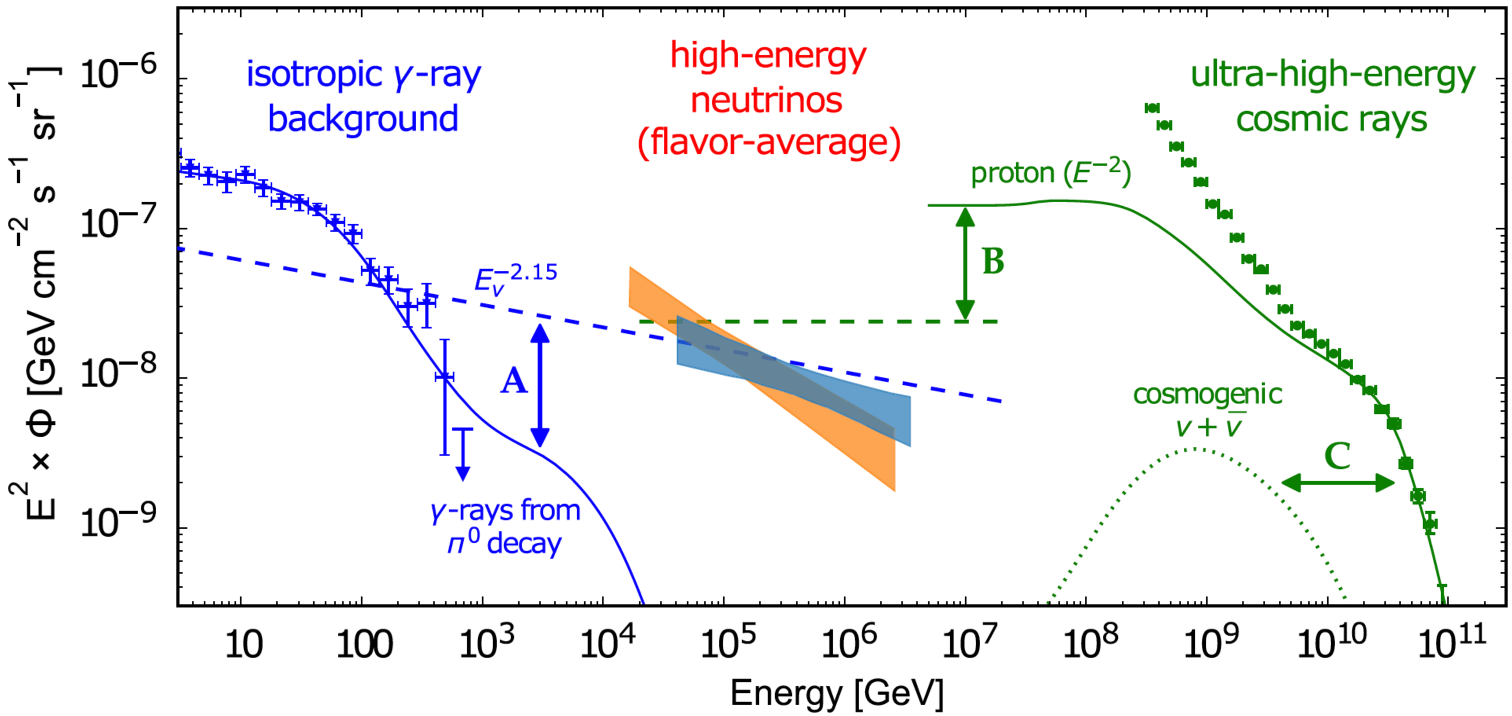
5. Multi-messenger astronomy

High-energy protons, gamma rays, and neutrinos are all related in "diffuse" spectrum

$$\begin{matrix} p+p \\ p+\gamma \end{matrix} \rightarrow X + \pi \begin{cases} \pi^0 \rightarrow \gamma\gamma \\ \pi^+ \rightarrow \mu^+ + \nu_\mu \\ \mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e \\ n \rightarrow p + e^- + \bar{\nu}_e \end{cases}$$

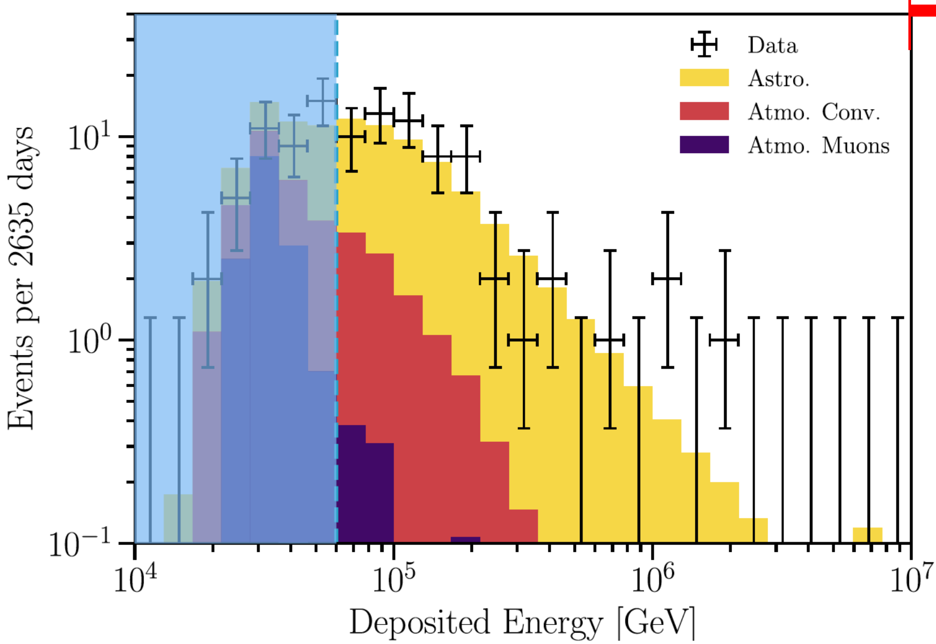


IceCube,Science.342(2013)1242856,PRD104,(2021)022002,ApJ.928(2022)50

5. High-energy astrophysical neutrinos

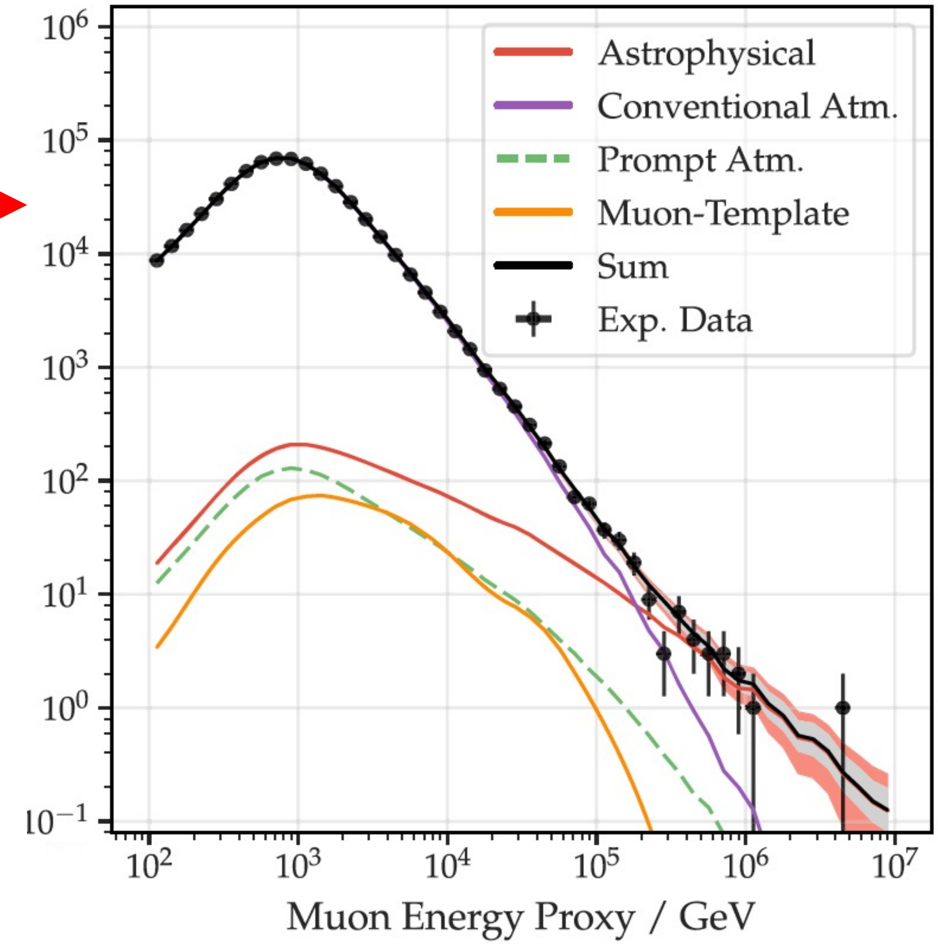
First observation (2013)
- 60-2000 TeV neutrinos
- Unlikely from atmospheric and cosmogenic neutrinos

Cosmogenic "UHE" neutrinos
$p + \gamma_{CMB} \rightarrow \Delta \rightarrow \pi \rightarrow \nu$



High-energy starting events
(shower and track)

Through going track events



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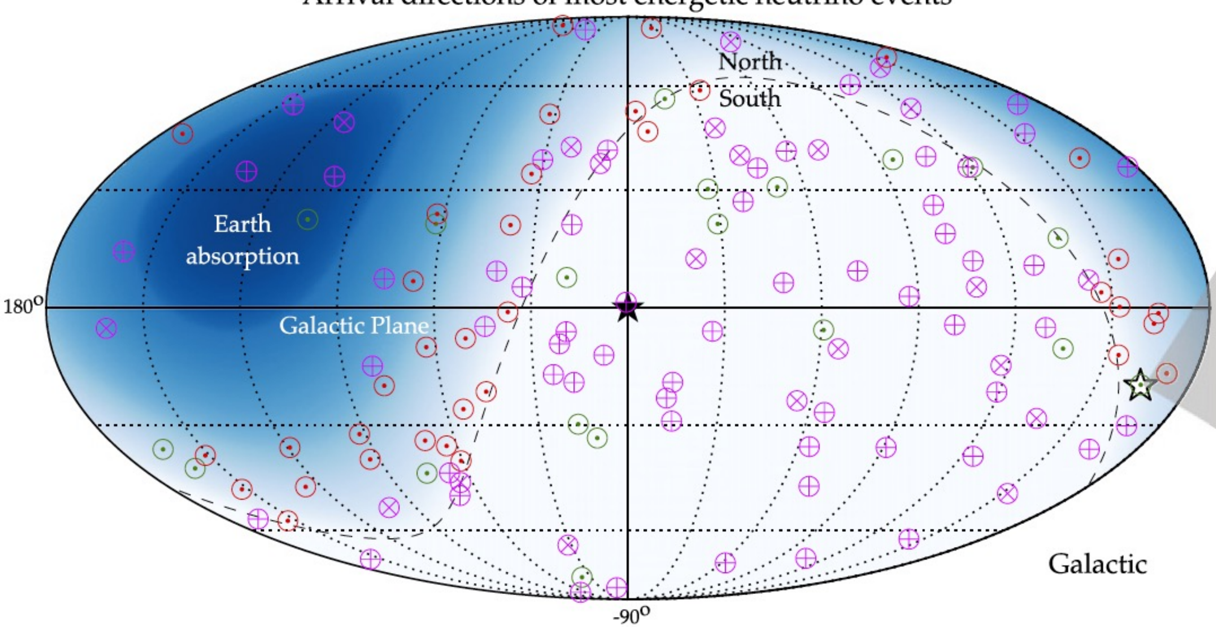
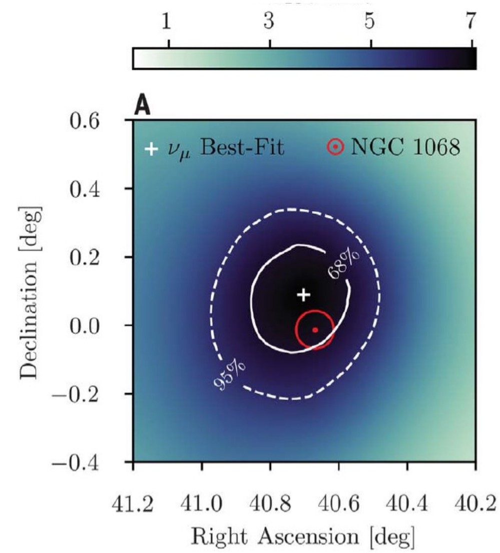
IceCube-Gen2, J.Phys.G.48(2021) 060501
IceCube, Science361(2018)147:378(2022)538

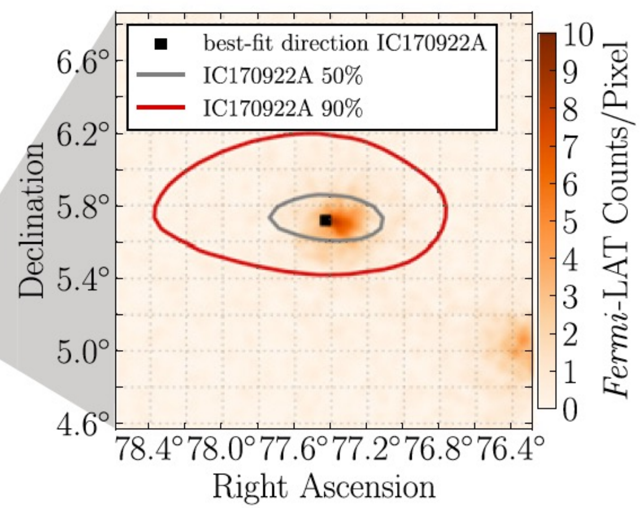
5. High-energy astrophysical neutrinos

First observation (2013)
- 60-2000 TeV neutrinos
- Unlikely from atmospheric and cosmogenic neutrinos
- Flavour not understood
- Spectrum not understood
- Sources are mostly unknown (diffuse)



NGC1068 (Radio galaxy)
- Point source





TXS 0506+056 (Blazar)
- Point source

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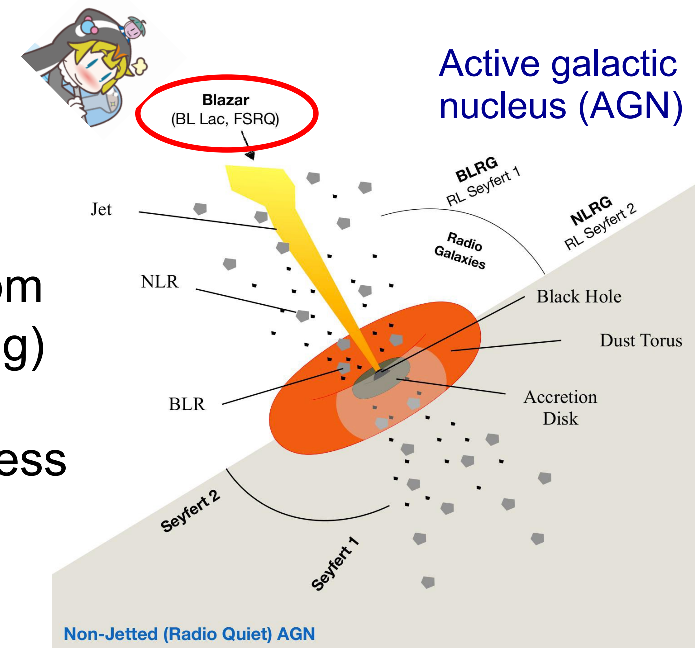
IceCube, Science361(2018)147, IceCube et al,(2018)eaat1378
Gao,Fedynitch,Winter, Pohl, Nature Astronomy 3(2019)88

5. Extragalactic neutrinos

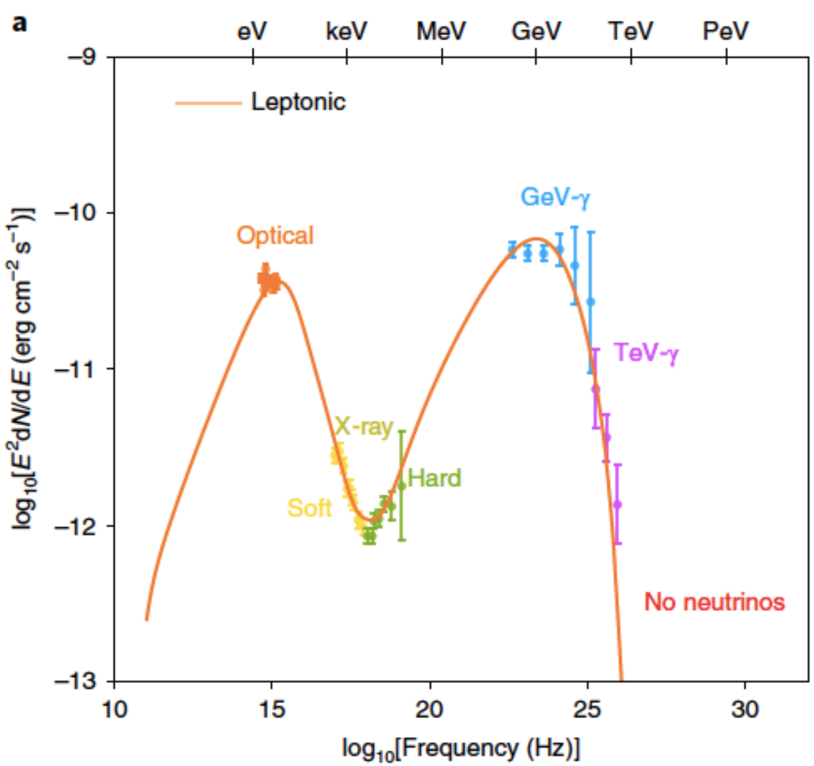


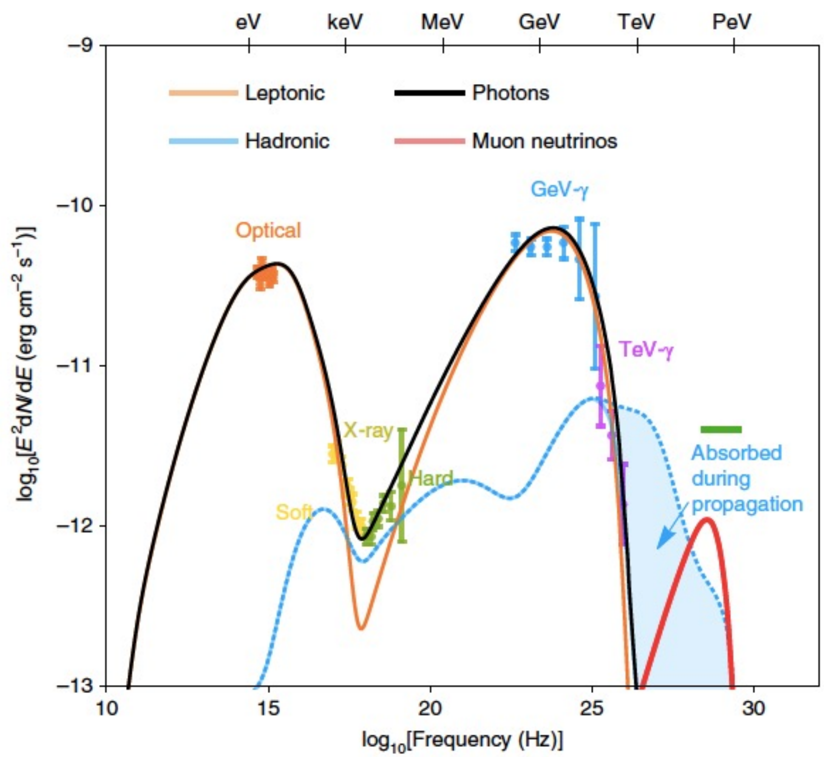
TXS056+0506 (blazar)

- leptonic process can explain all optical signals from TXS0506+056 (Synchrotron self-Compton scattering)

- Neutrino signals imply presence of hadronic process

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





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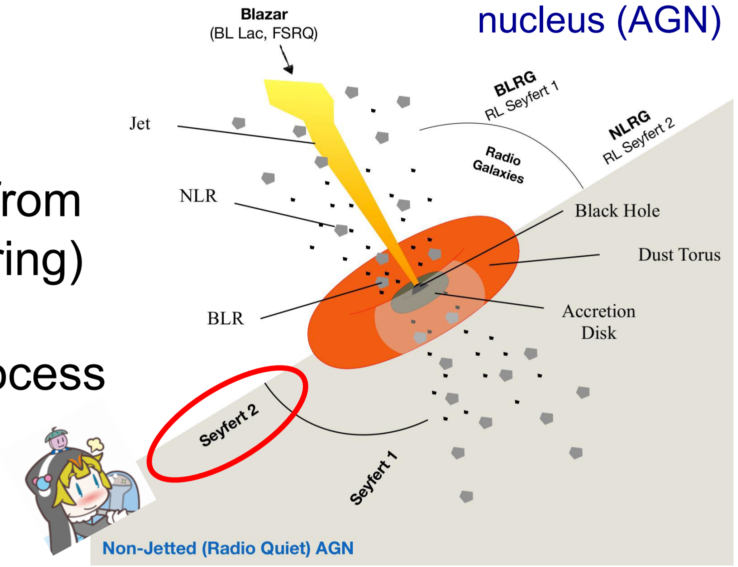
5. Extragalactic neutrinos

Active galactic nucleus (AGN)



TXS056+0506 (blazar)

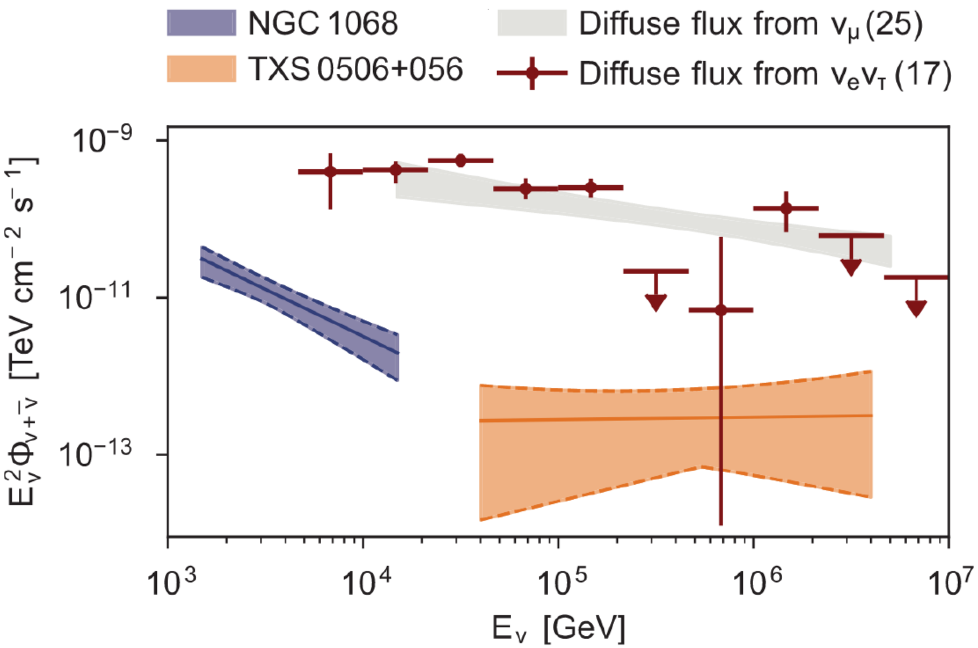
- leptonic process can explain all optical signals from TXS0506+056 (Synchrotron self-Compton scattering)

- Neutrino signals imply presence of hadronic process

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

NGC1068 (radio galaxy)

- Nearby AGN (14.4Mpc)
- 1.5 – 15 TeV with γ~3.2±0.2



Do we have more neutrino sources?

How to produce diffuse high-energy neutrino spectrum?

Any new physics information?

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Gaisser, Stanev, Tilav, Front.Phys.,2103,8(6),748

6. Cosmogenic neutrinos

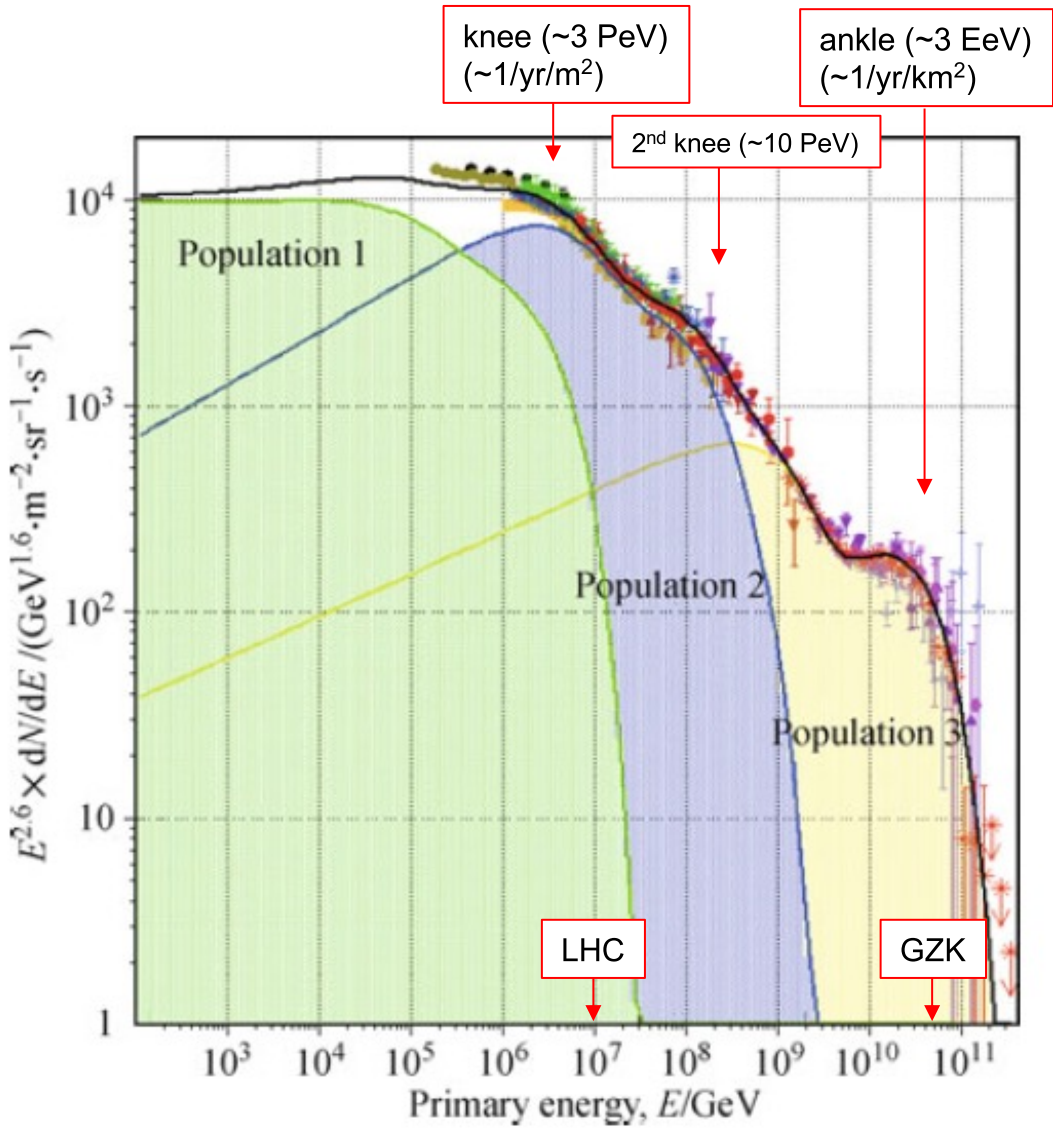
GZK cut-off

$$p + \gamma \rightarrow \Delta \rightarrow \pi + p$$

- $\pi^0 \rightarrow \gamma\gamma$: UHE γ-ray
- $\pi^+ \rightarrow \mu^+ + \nu_\mu$: UHE neutrinos

GZK cut-off of proton ~ 50 EeV
GZK cut-off of iron >> 50 EeV

Do we see the GZK cut-off????????



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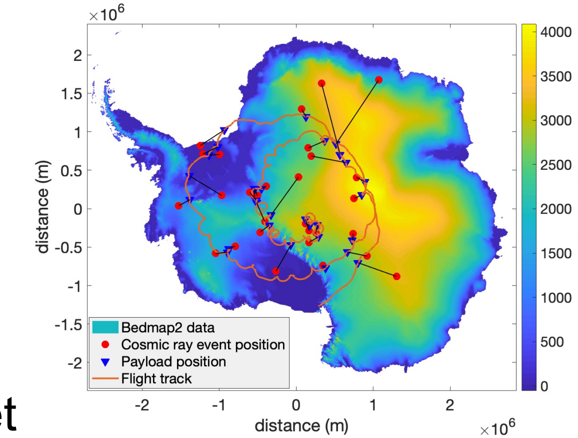
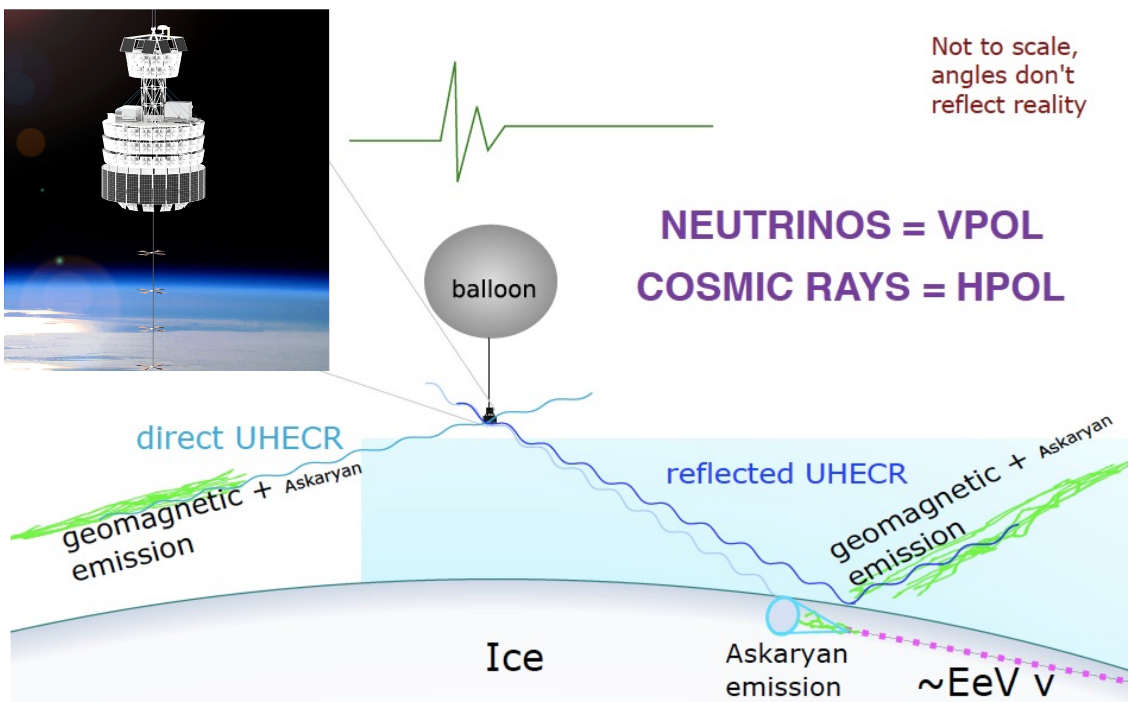
ANITA, PRL121(2018)161102,126 (2021)071103, PRD99(2019)122001
PUEO, JINST16(2021)P08035

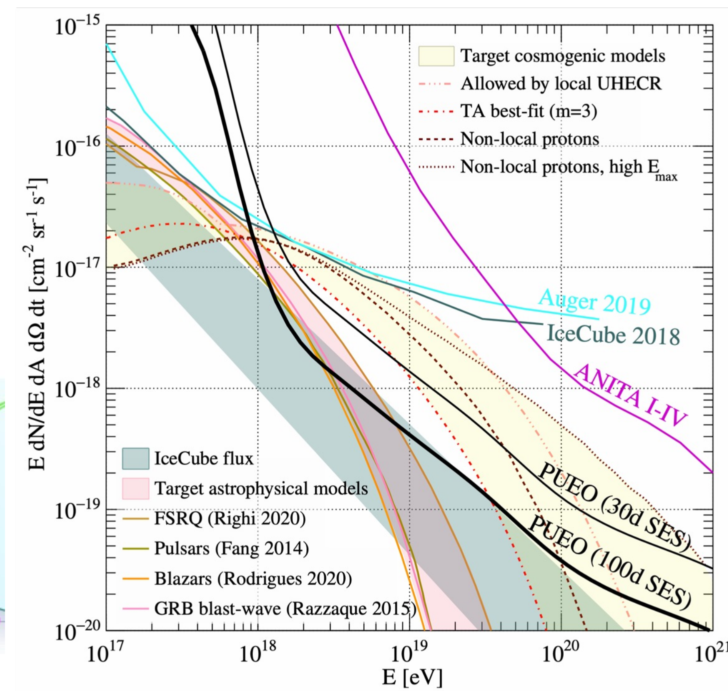
6. ANITA/PUEO



ANtarctic Impulse Transient Antenna (ANITA)

- Askaryan effect, radio emission from E&M shower in ice
- effective to measure EeV range astrophysical neutrinos
- Cosmogenic neutrinos (EeV neutrinos) not discovered yet





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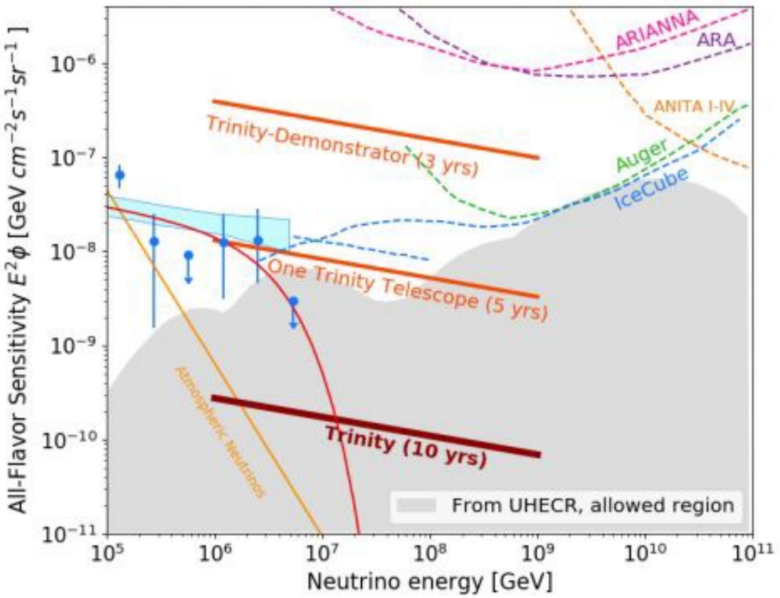
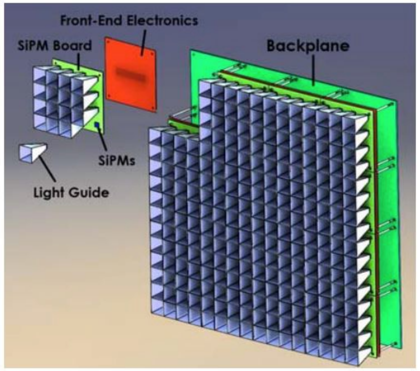
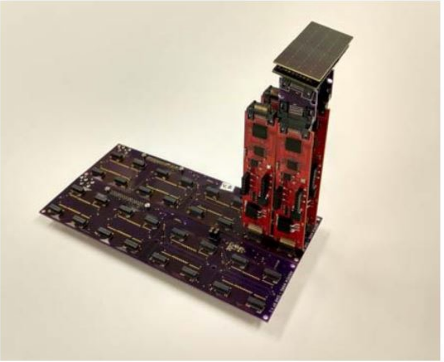
6. Trinity

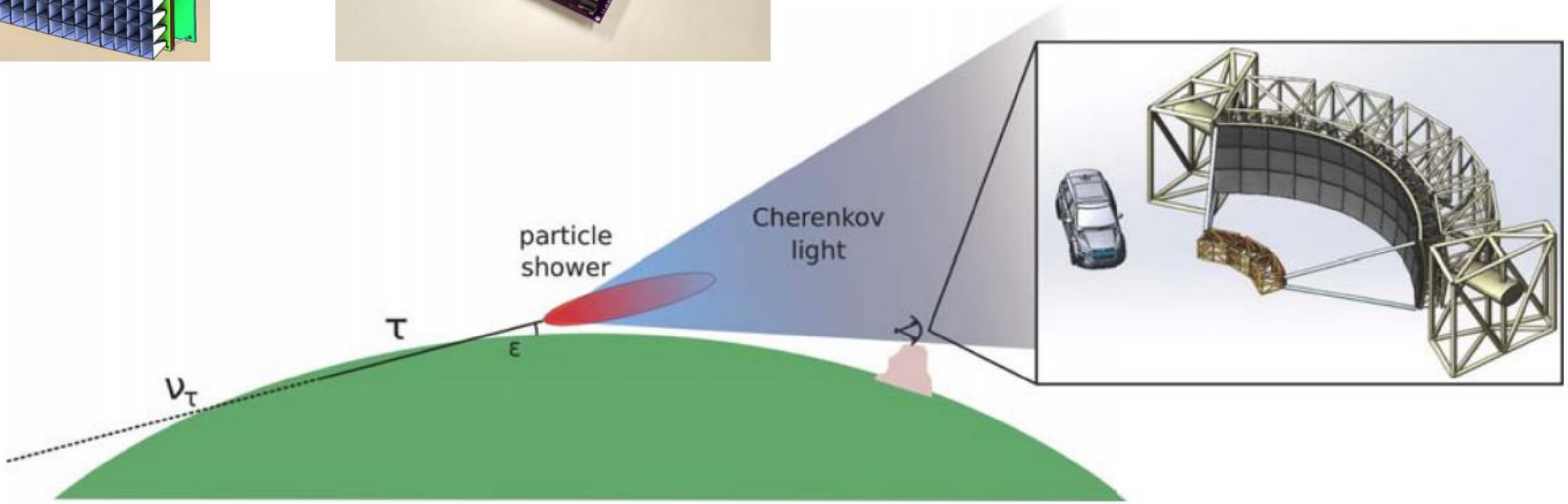
Skimming tau induced air shower

- SiPM Image Air-Cherenkov Telescope (IACT)
- 1 IACT covers 5° x 60° FoV
- 5yr operation of 1 telescope can see 1 PeV neutrino!









TAMBO, ArXiv:2002.06475

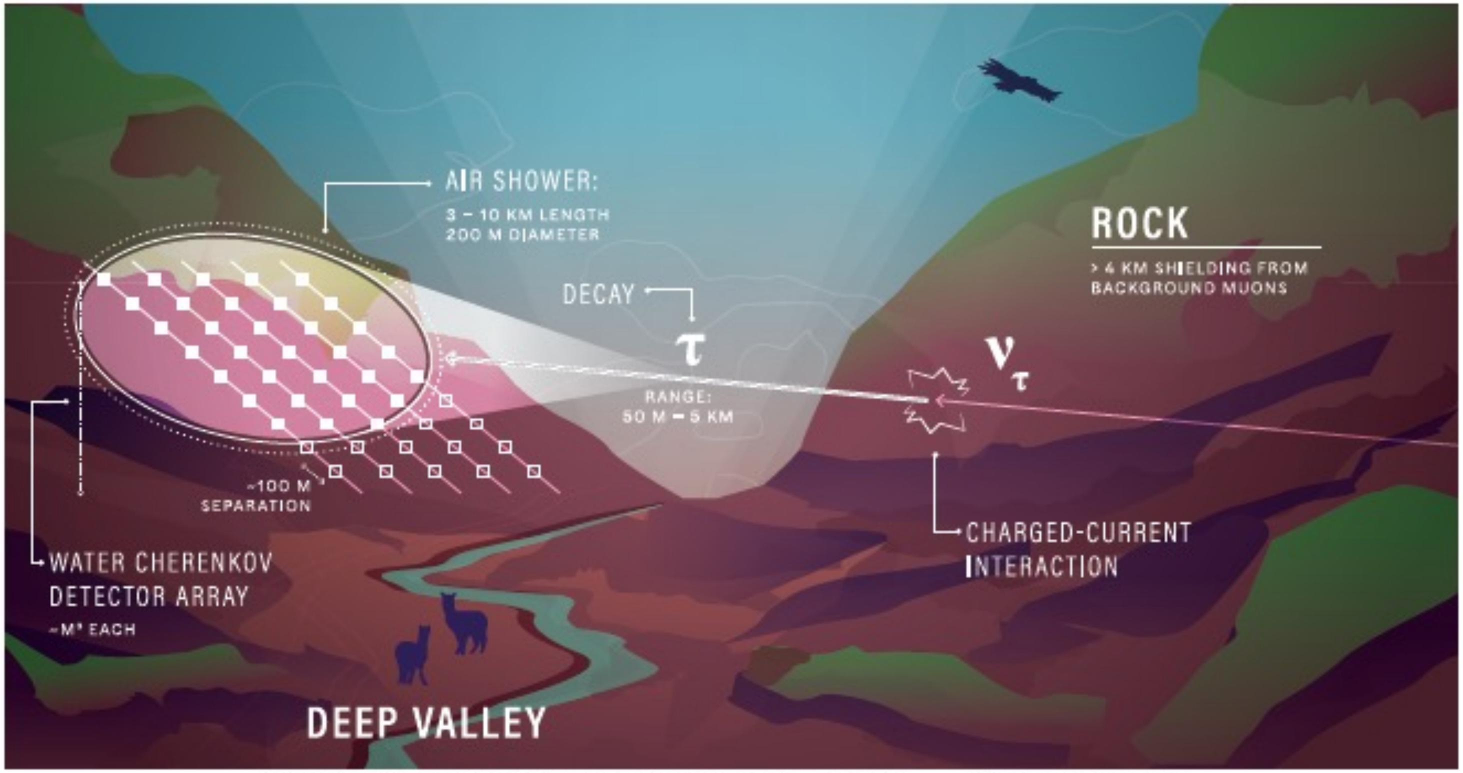
6. TAMBO

Looking for the experiment site!
(Harvard group at Tambo valley)

Carlos Argüelles (Harvard)

Tau-Air-shower Mountain-Based Observatory (Peru)

- UHE tau induced air shower
- Water Cherenkov detector array
- Relatively low energy threshold (~1PeV)



TAU AIR-SHOWER MOUNTAIN-BASED OBSERVATORY (TAMBO) • COLCA VALLEY, PERU

6. High-Energy Astrophysical Neutrinos

Many planned experiments targeting PeV-EeV neutrinos

Energy Range	Experiment	Technology	Detected Flavor	Ref.
$\lesssim 10^3$ GeV	JUNO	Liquid scintillator	All Flavors	[234]
$\lesssim 10^3$ GeV	DUNE	LArTPC	All Flavors	[671]
$\lesssim 10^3$ GeV	THEIA	WbLS	All Flavors	[486]
$\lesssim 10^3$ GeV	Super-Kamiokande	Gd-loaded Water C	All Flavors	[645]
$\lesssim 10^4$ GeV	Hyper-Kamiokande	Water Cherenkov	All Flavors	[483]
$\lesssim 10^5$ GeV	ANTARES	Sea-Water Cherenkov	ν_μ, $\bar{\nu}_\mu$ (CC)	[672]
$\lesssim 10^6$ GeV	IceCube/IceCube-Gen2	Ice Cherenkov	All Flavors	[433, 673]
$\lesssim 10^6$ GeV	KM3NeT	Sea-Water Cherenkov	All Flavors	[674]
$\lesssim 10^6$ GeV	Baikal-GVD	Lake-Water Cherenkov	All Flavors	[675]
$\lesssim 10^6$ GeV	P-ONE	Sea-Water Cherenkov	All Flavors	[676]
$1 - 100$ PeV	TAMBO	Earth-skimming WC	ν_τ, $\bar{\nu}_\tau$ (CC)	[677]
$\gtrsim 1$ PeV	Trinity	Earth-skimming Image	ν_τ, $\bar{\nu}_\tau$ (CC)	[678]
$\gtrsim 10$ PeV	RET-N	Radar echo	All Flavors	[679]
$\gtrsim 10$ PeV	IceCube-Gen2	In-ice Radio	All Flavors	[433]
$\gtrsim 10$ PeV	ARIANNA-200	On-ice Radio	All Flavors	[680]
$\gtrsim 20$ PeV	POEMMA	Space Air-shower Image	ν_τ, $\bar{\nu}_\tau$ (CC)	[681]
$\gtrsim 100$ PeV	RNO-G	In-ice Radio	All Flavors	[682]
$\gtrsim 100$ PeV	ANITA/PUEO	Balloon Radio	All Flavors	[683, 684]
$\gtrsim 100$ PeV	Auger/GCOS	Earth-skimming WC	ν_τ, $\bar{\nu}_\tau$ (CC)	[685, 686]
$\gtrsim 100$ PeV	Beacon	Earth-skimming Radio	ν_τ, $\bar{\nu}_\tau$ (CC)	[687]
$\gtrsim 100$ PeV	GRAND	Earth-skimming Radio	ν_τ, $\bar{\nu}_\tau$ (CC)	[688]

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PTOLEMY, arXiv:1808.01892
Project 8, PRD80(2009)051301

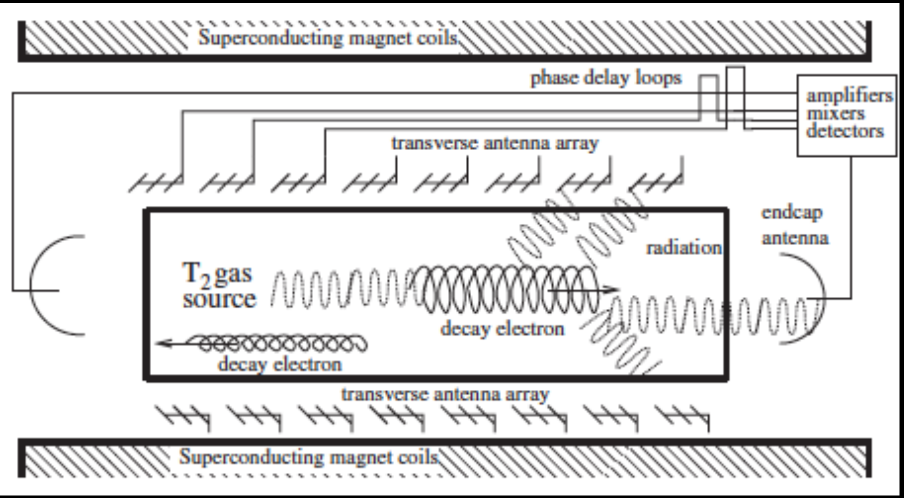
7. Cosmic Neutrino Background (CνB)

PTOLEMY and Project 8
- Motivated by KATRIN
- Nuclear ν_e capture is zero threshold

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

if M(A) – M(A') = Q>0
- Measure end point of tritium (18 keV) from cyclotron radiation of single electron RF
- Target: ~meV shift of end point due to neutrino mass.

$Q-m_\nu \rightarrow$ neutrino mass effect on β-decay
$Q+m_\nu \rightarrow$ CνB capture



Project 8 concept

Conclusion

Astrophysical neutrinos are everywhere!

Solar neutrino: up-turn, hep-neutrino, neutrino fog
Supernova neutrino: DSNB
Atmospheric neutrino: mass ordering, prompt neutrino
Extra-galactic neutrino: we don’t understand most of things

Cosmogenic neutrinos: never detected
Big bang neutrinos: never detected, really hard

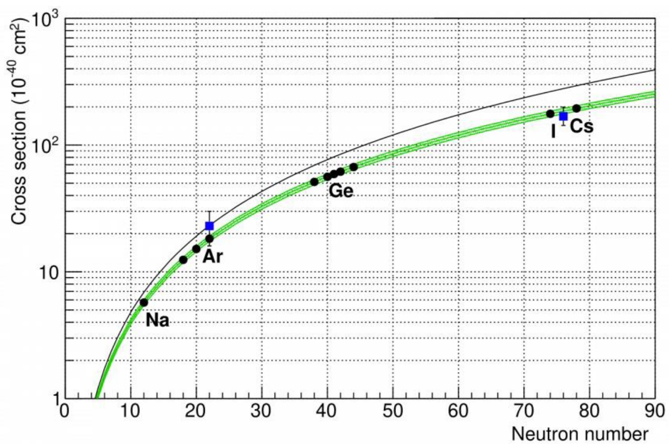
Thank you for your attention!

Backup

1. Neutrino-Nucleus coherent scattering

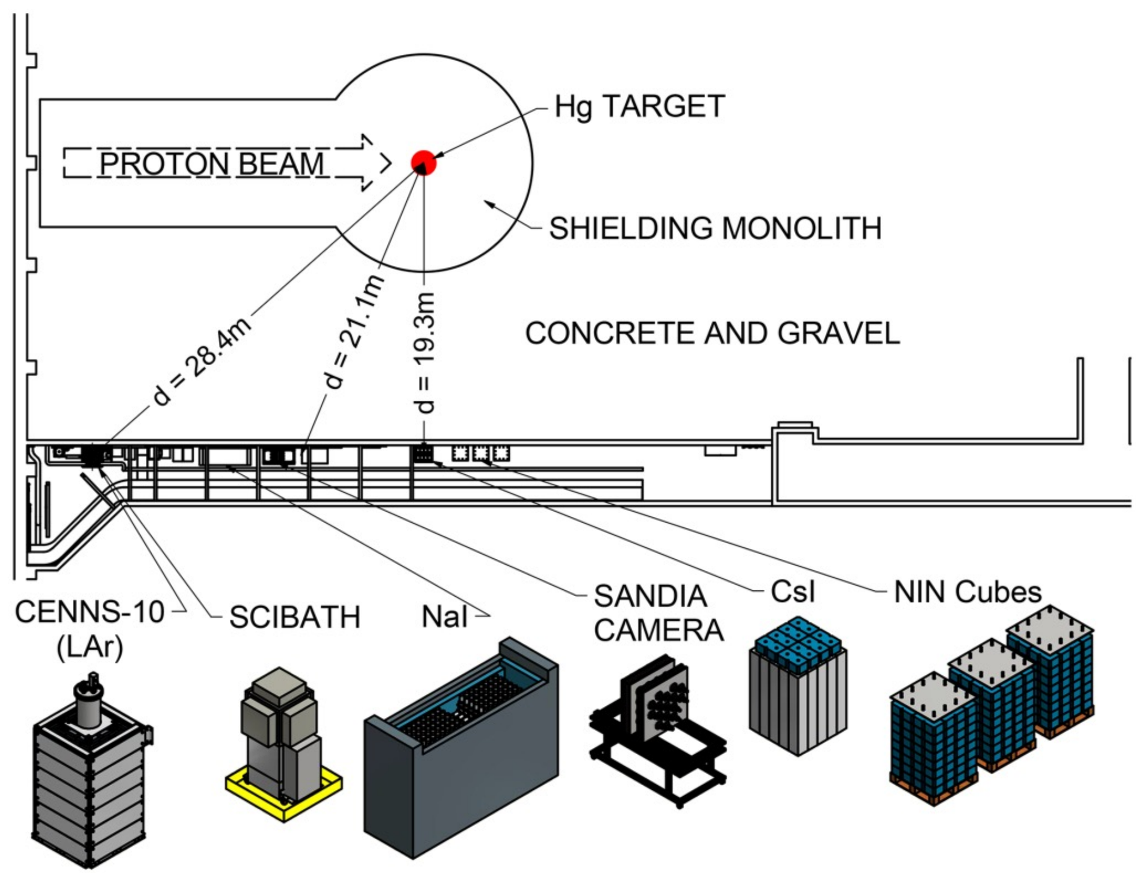
Low energy neutrinos from neutron sources at SNS (spallation neutron source), ORNL (Oak Ridge National Lab)

$$\nu + A \rightarrow \nu + A$$



Science
REPORTS
Cite as: D. Akimov *et al.*, *Science* 10.1126/science.aao0990 (2017).

Observation of coherent elastic neutrino-nucleus scattering

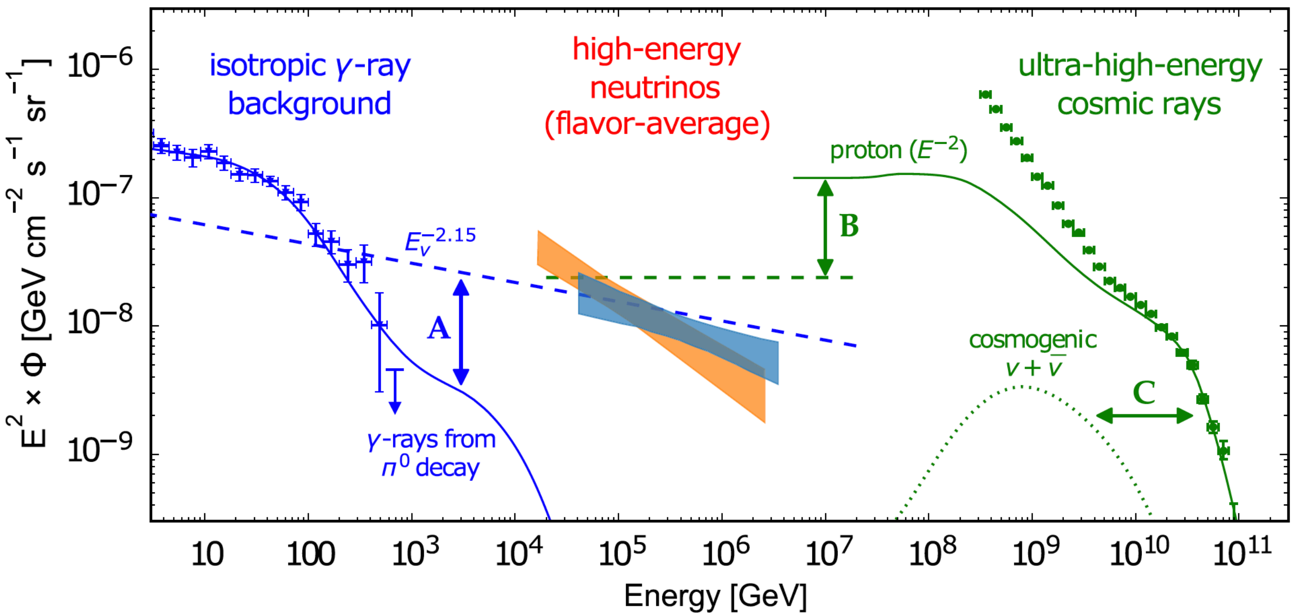


IceCube, Science361(2018)147, IceCube et al,(2018)eaat1378
IceCube-Gen2, J.Phys.G.48(2021) 060501

1. Multi-messenger astronomy

High-energy protons, gamma rays, and neutrinos are all related

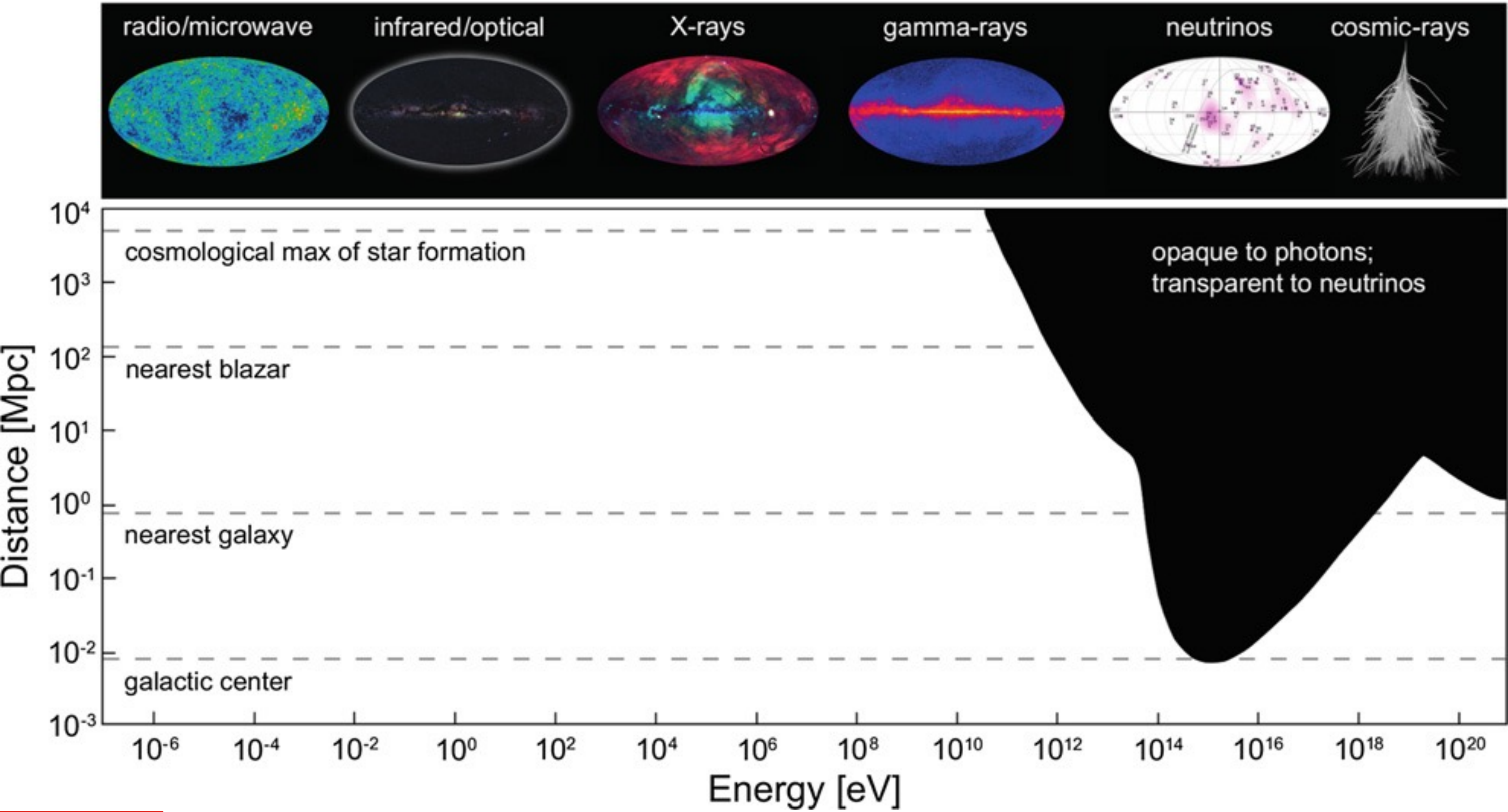
$$\begin{matrix} p+p \\ p+\gamma \end{matrix} \rightarrow X + \pi \begin{cases} \pi^0 \rightarrow \gamma\gamma \\ \pi^+ \rightarrow \mu^+ + \nu_\mu \\ \mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e \\ n \rightarrow p + e^- + \bar{\nu}_e \end{cases}$$



IceCube-Gen2, J.Phys.G.48(2021) 060501

5. High-energy astrophysics

Above ~10-100 TeV neutrinos are only direct extra-galactic messengers



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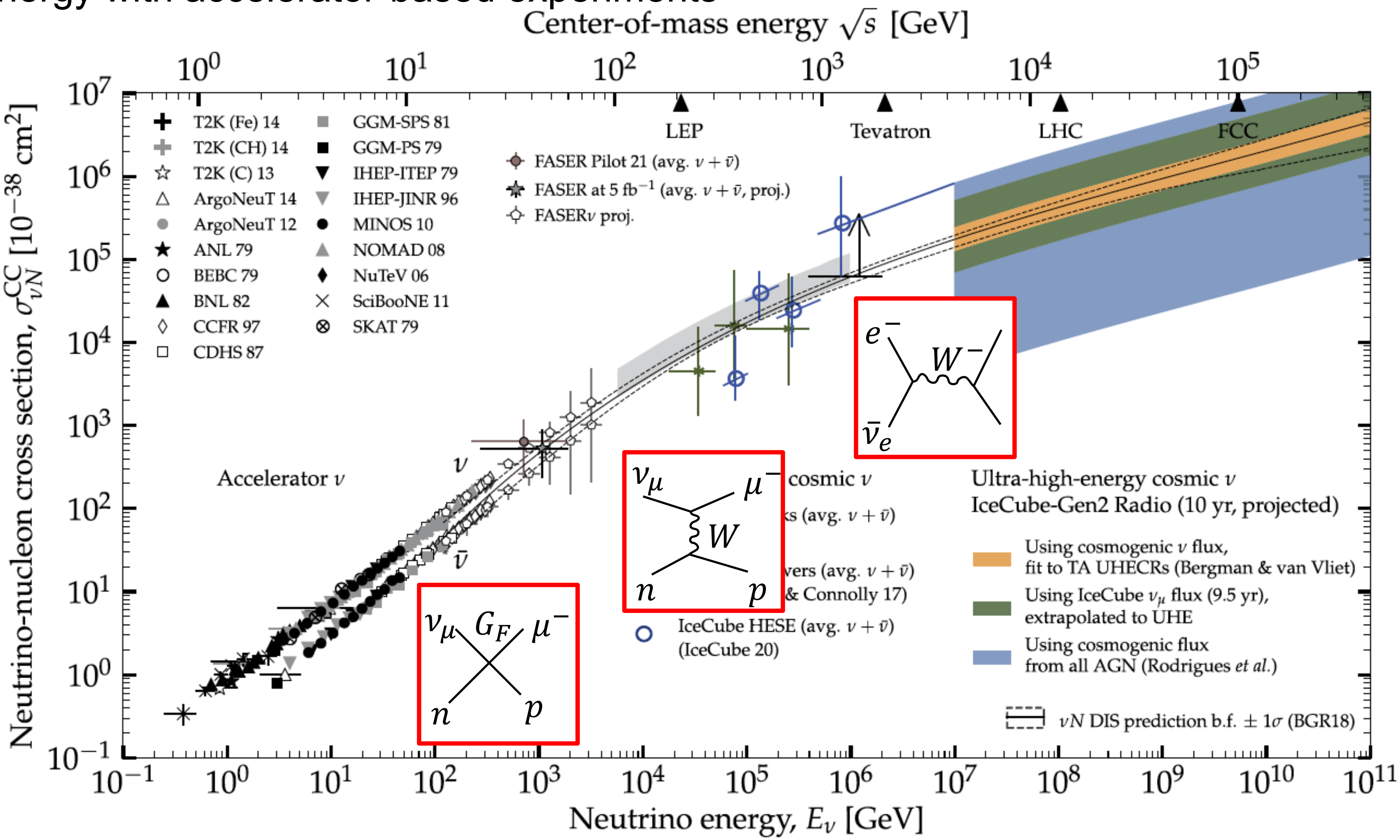
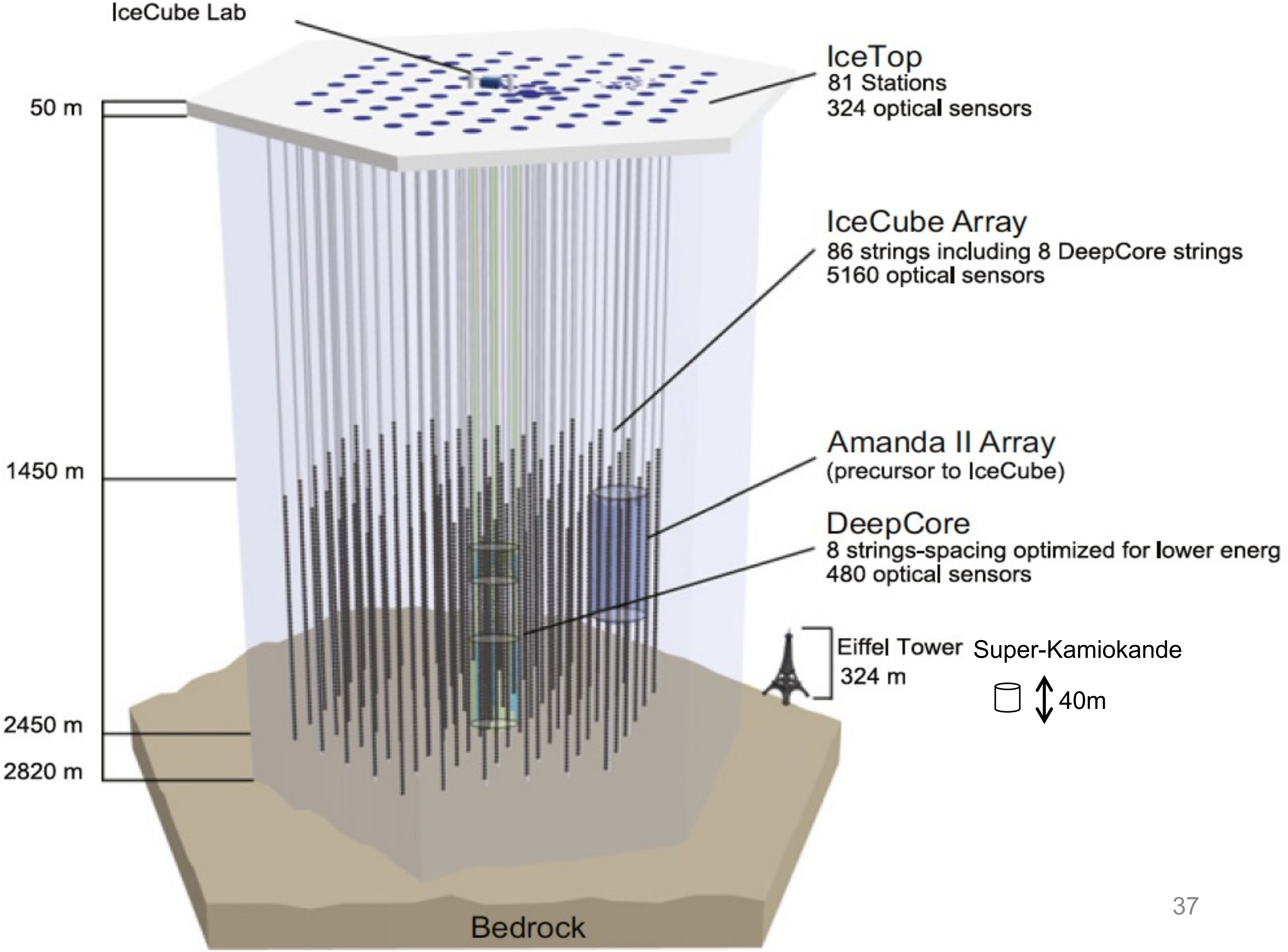
5. High-energy fixed target experiment

Synergy with accelerator-based experiments



IceCube, JINST2(2016)P03012

5. IceCube detector



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5. IceCube event morphology

Track

ν_μCC

$$\nu_\mu + N \rightarrow \mu + X$$

Cascade

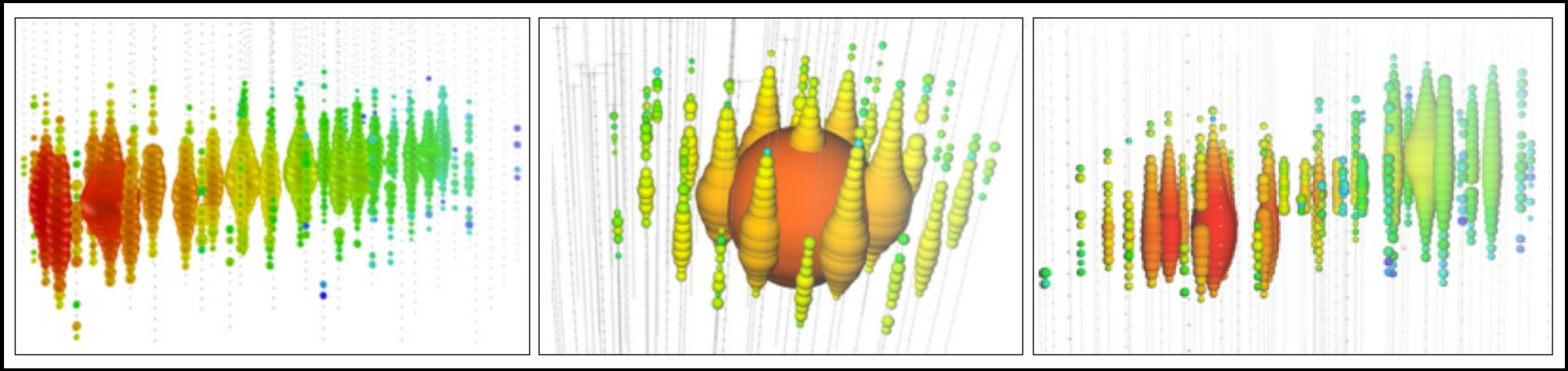
ν_eCC, ν_τCC, NC

$$\nu_e + N \rightarrow e + X$$
$$\nu_\tau + N \rightarrow \tau + X$$
$$\nu_x + N \rightarrow \nu_x + X$$

Double cascade

ν_τCC (L~50m•E/PeV)

$$\nu_\tau + N \rightarrow \tau + X$$
$$\tau \rightarrow X'$$



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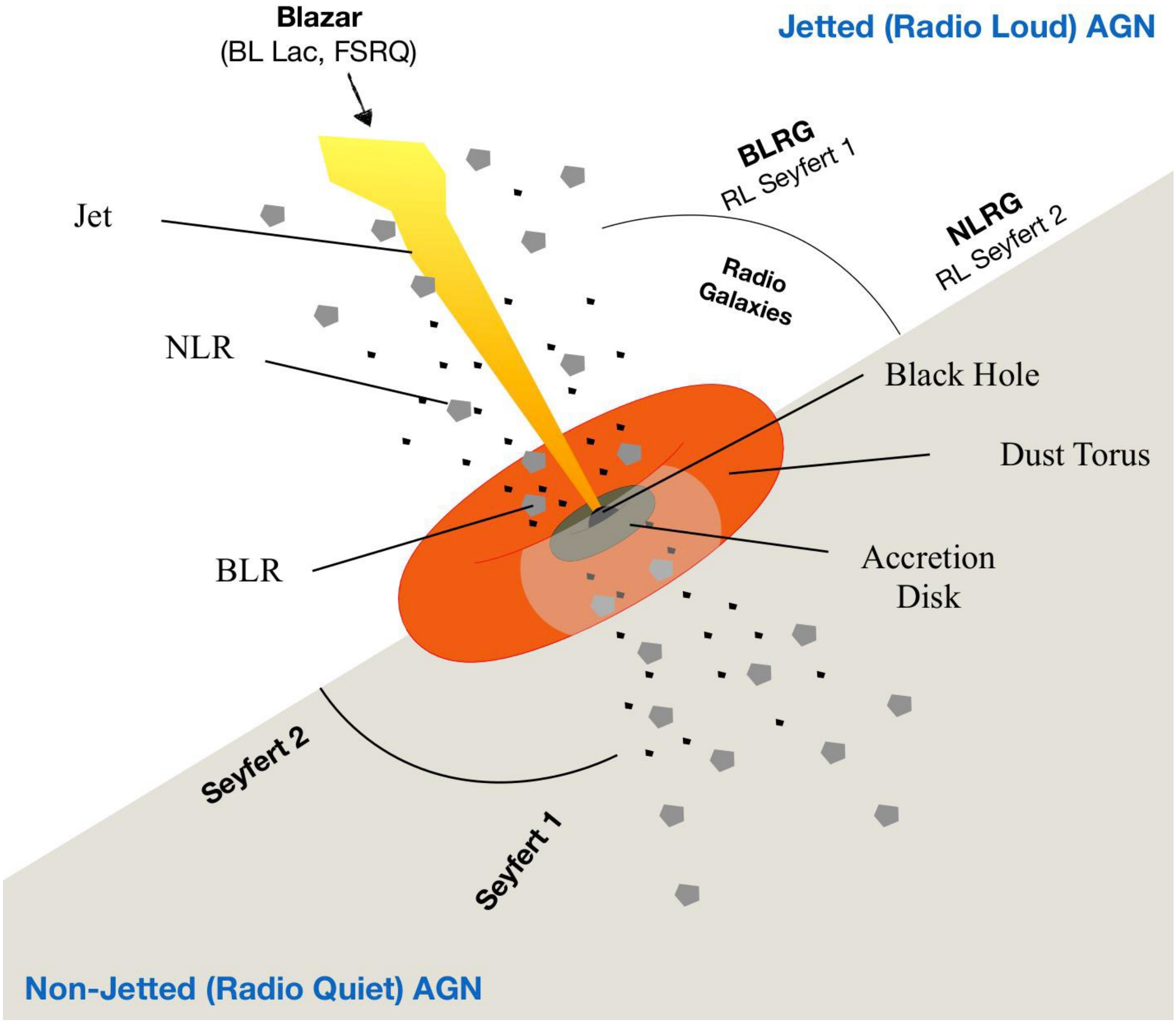
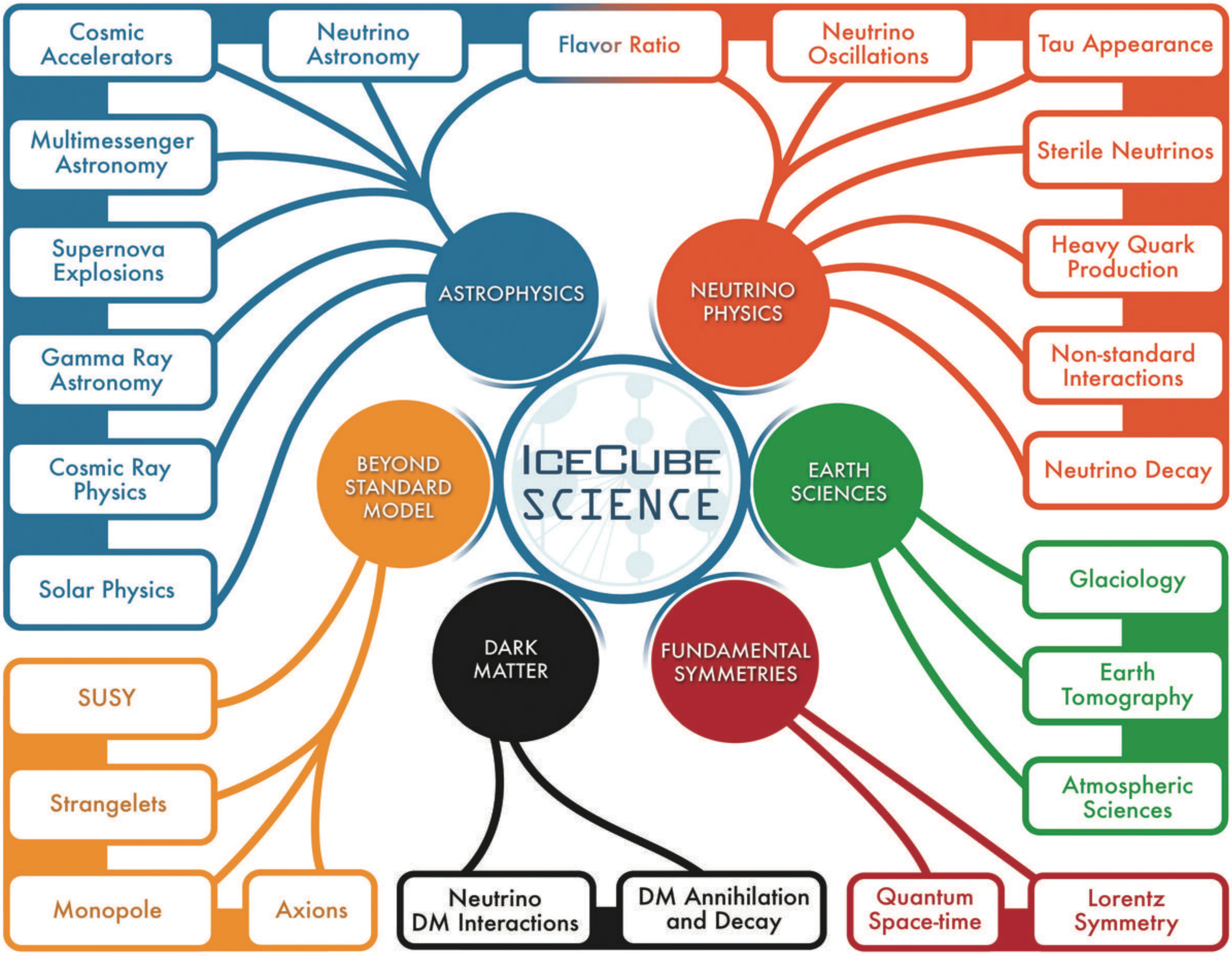
5. Active Galactic Nuclei (AGNs)

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Sterile Neutrinos
Heavy Quark Production
Non-standard Interactions
Neutrino Decay
Glaciology
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Atmospheric Sciences
SUSY
Strangelets
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