Neutrino Telescopes

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erdam
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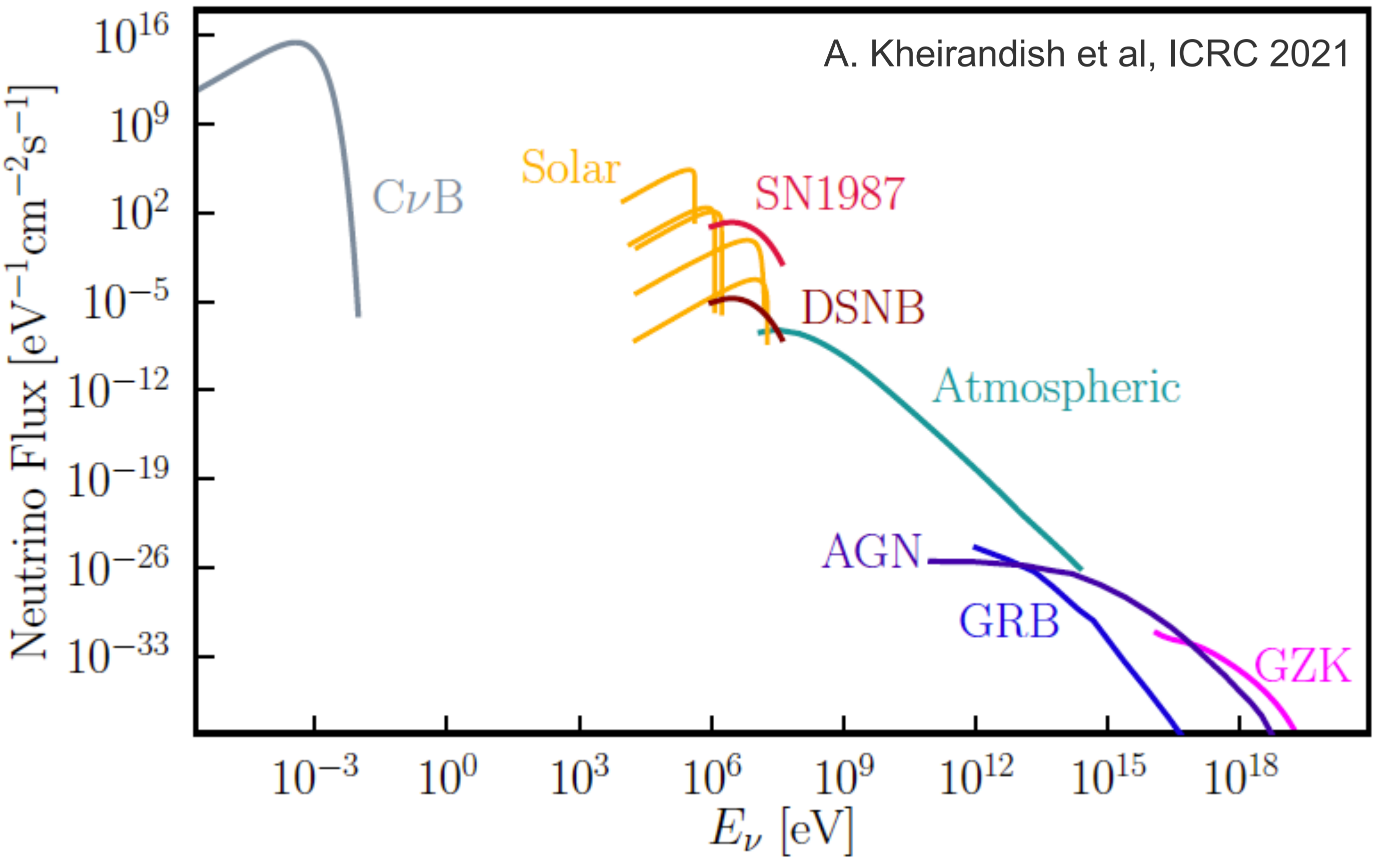
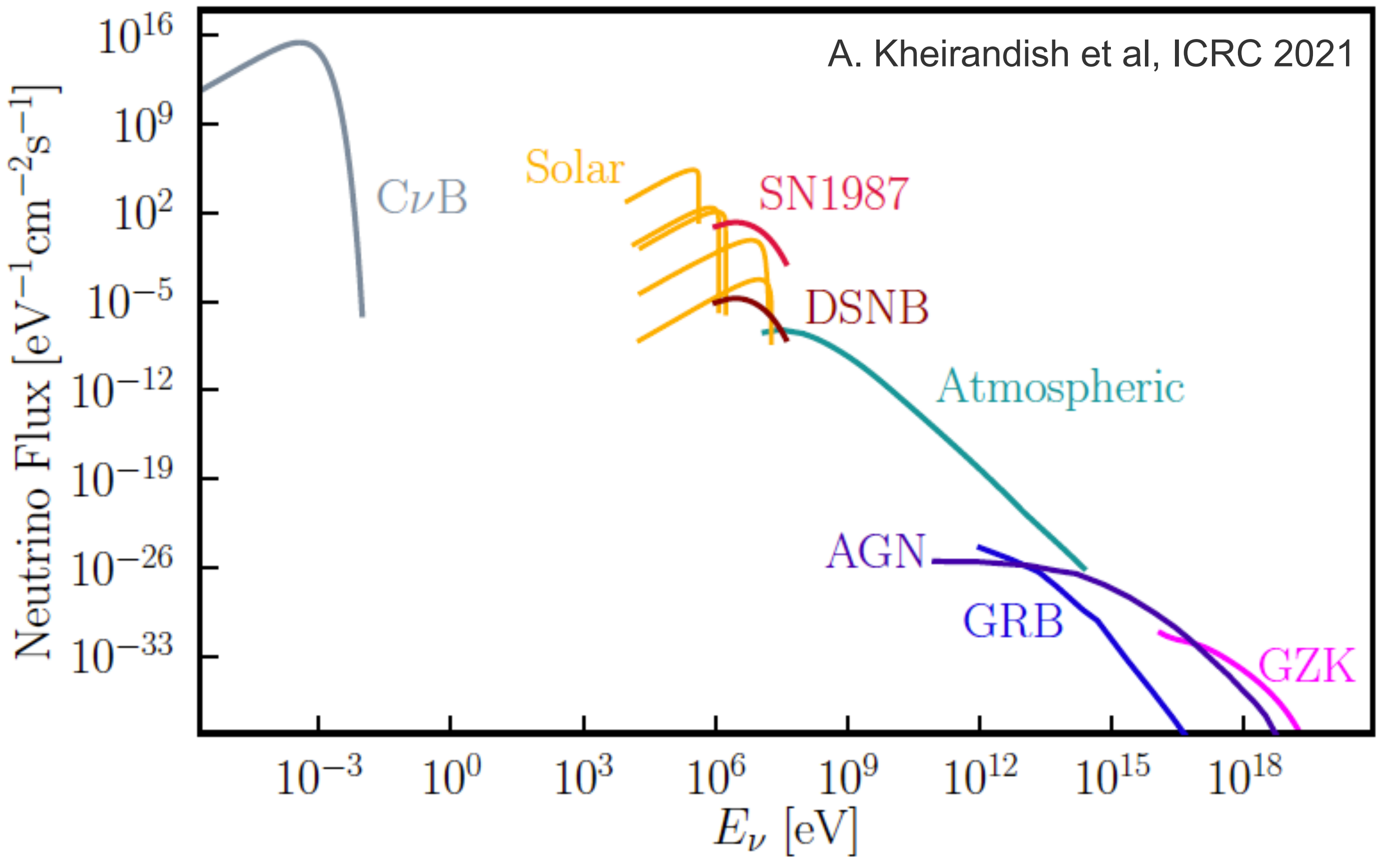
Deutschland
gien
Prag
Tschechien
München
Wien
Zürich
Österreich
Schweiz


Nachhaltig
Gemeinsam
Handeln

Learning Objectives

- How can we detect astrophysical neutrinos at various energies (focus on TeV-PeV neutrinos)?
- What is the background in the search for high-energy cosmic neutrinos and how can we disentangle it from the signal?
- Have have we detected with neutrino detectors alone (messenger searches / detections follow tomorrow)


A. Kheirandish et al, ICRC 2021
Neutrino Flux [eV^{-1}cm^{-2}s^{-1}]
10^{16}
10^{9}
10^{2}
10^{-5}
10^{-12}
10^{-19}
10^{-26}
10^{-33}
CνB
Solar
SN1987
DSNB
Atmospheric
AGN
GRB
GZK
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
10^{18}
E_ν [eV]



Ideas: neutrino capture on unstable nucleus (e.g. tritium)

Neutrino capture on stable nucleus (Chlorine, Gallium)

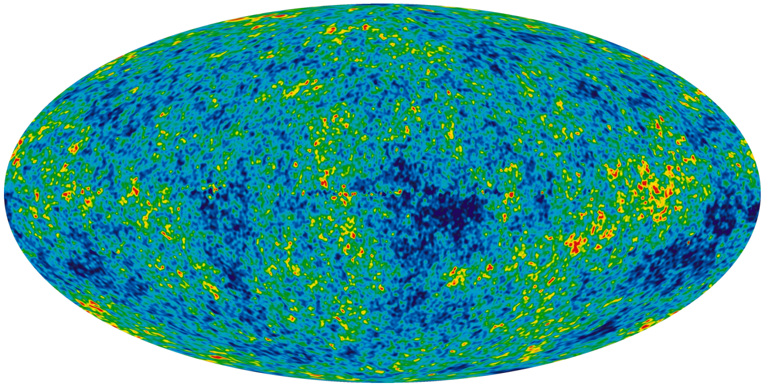
Water / ice Cherenkov detectors

Radio arrays, cosmic-ray detectors

Cosmic Neutrino Background

Cosmic micro-wave background

- Decoupled when Universe was 379,000 years old
- Density: 411 / cm^3
- Temperature: 2.725 K



Cosmic neutrino background

- Decoupled when Universe was ~1 second old
- Density: 336 / cm^3 (56 ν_e)
- Temperature: 1.95 K

Neutrino capture on beta-unstable nuclides

- For example: tritium → no energy threshold

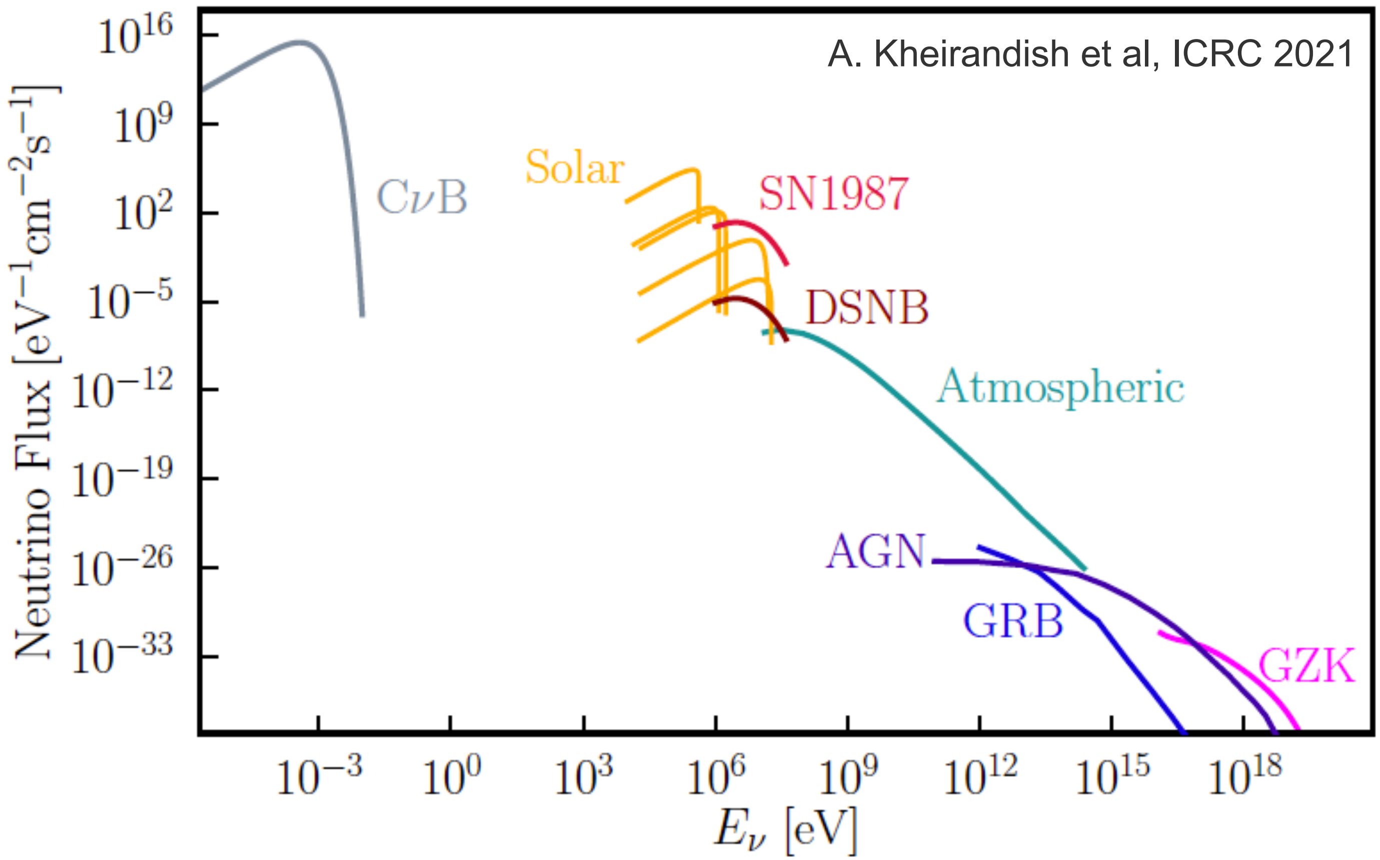
$$\nu + {}^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^-$$

- Background:

$$^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^- + \bar{\nu}$$

} Measure electrons

- Background far more numerous, but maximum energy is smaller by twice the average neutrino mass (~eV)
- detector must have excellent energy resolution to separate signal from background
- **Ptolemy:** 100g of tritium, demonstrator by 2025 in Gran Sasso with 0.2g tritium



Ideas: neutrino capture on unstable nucleus (e.g. tritium)

Neutrino capture on stable nucleus (Chlorine, Gallium)

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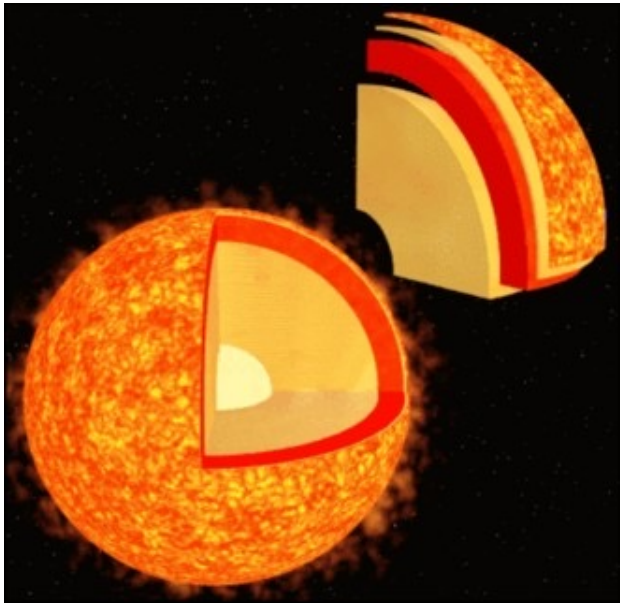
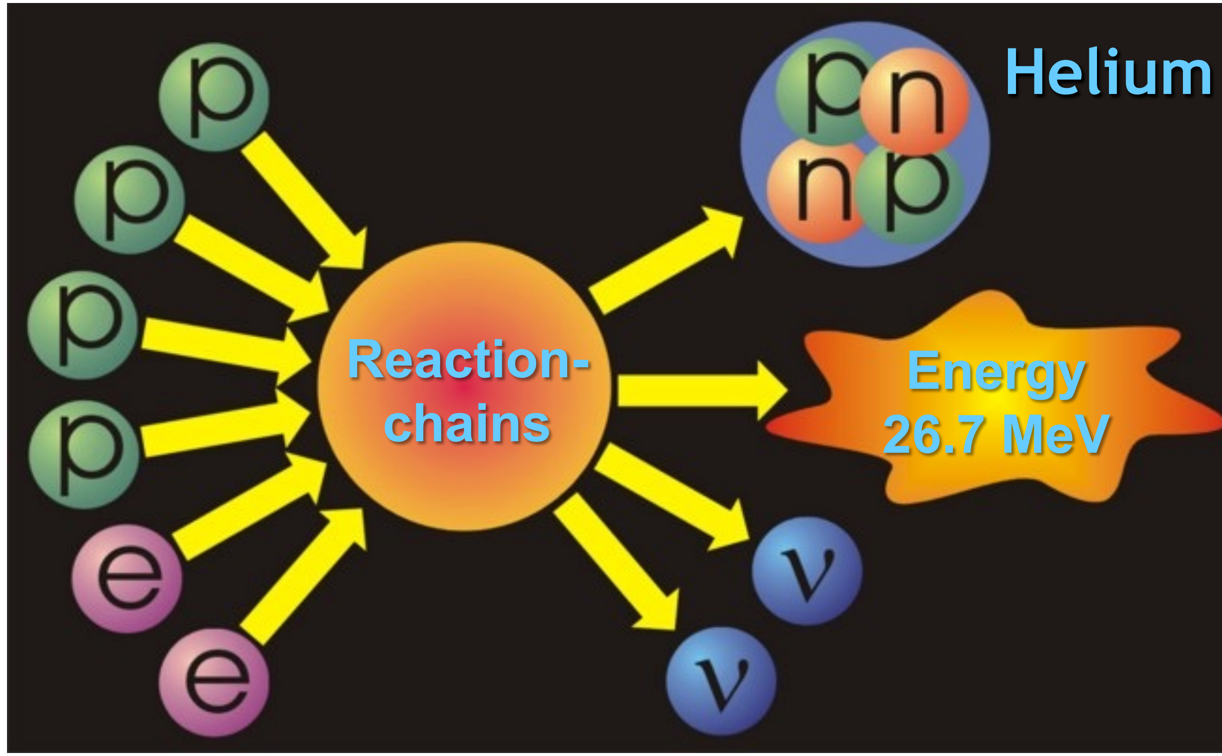
Solar Neutrinos



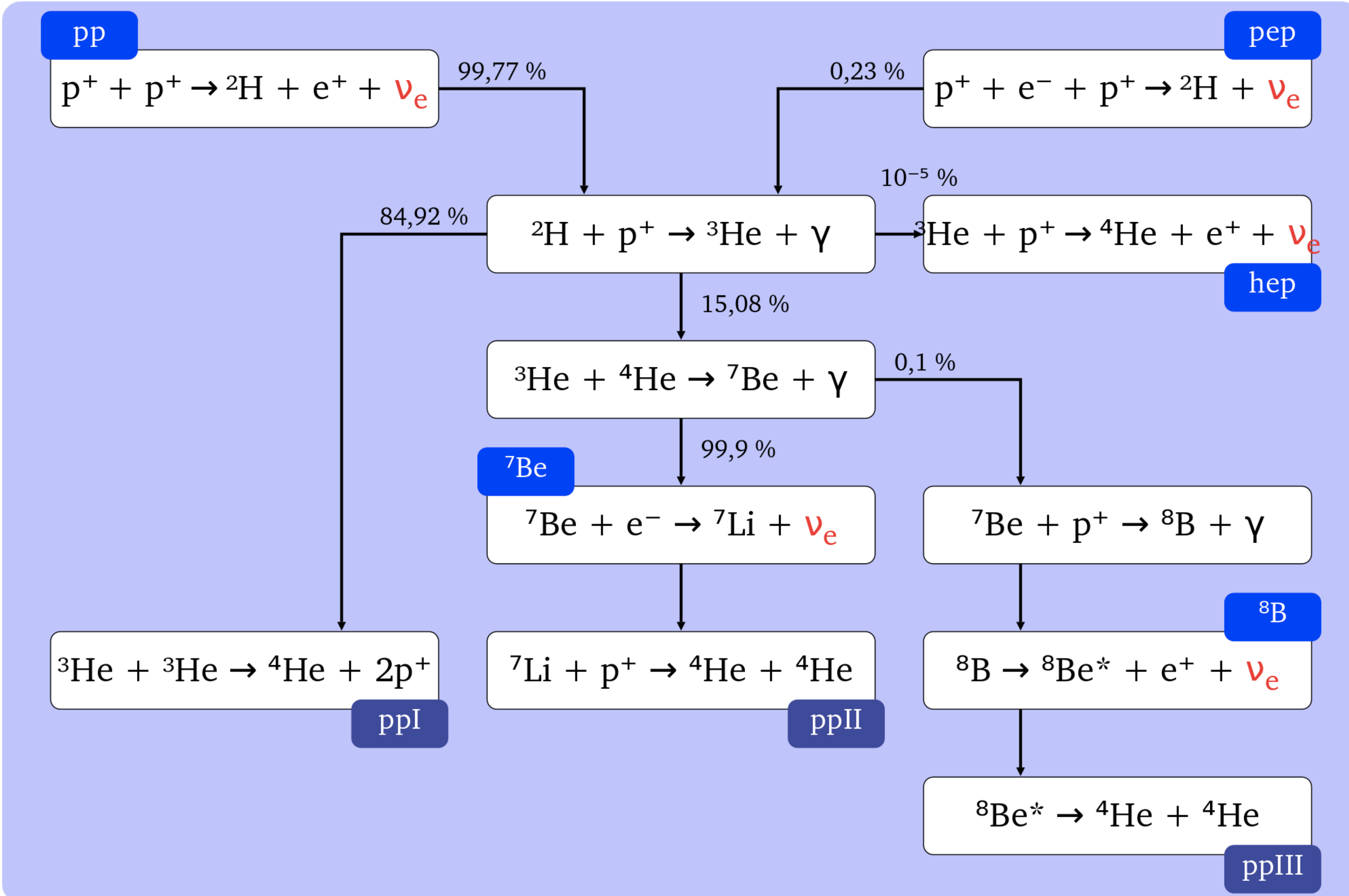


1967

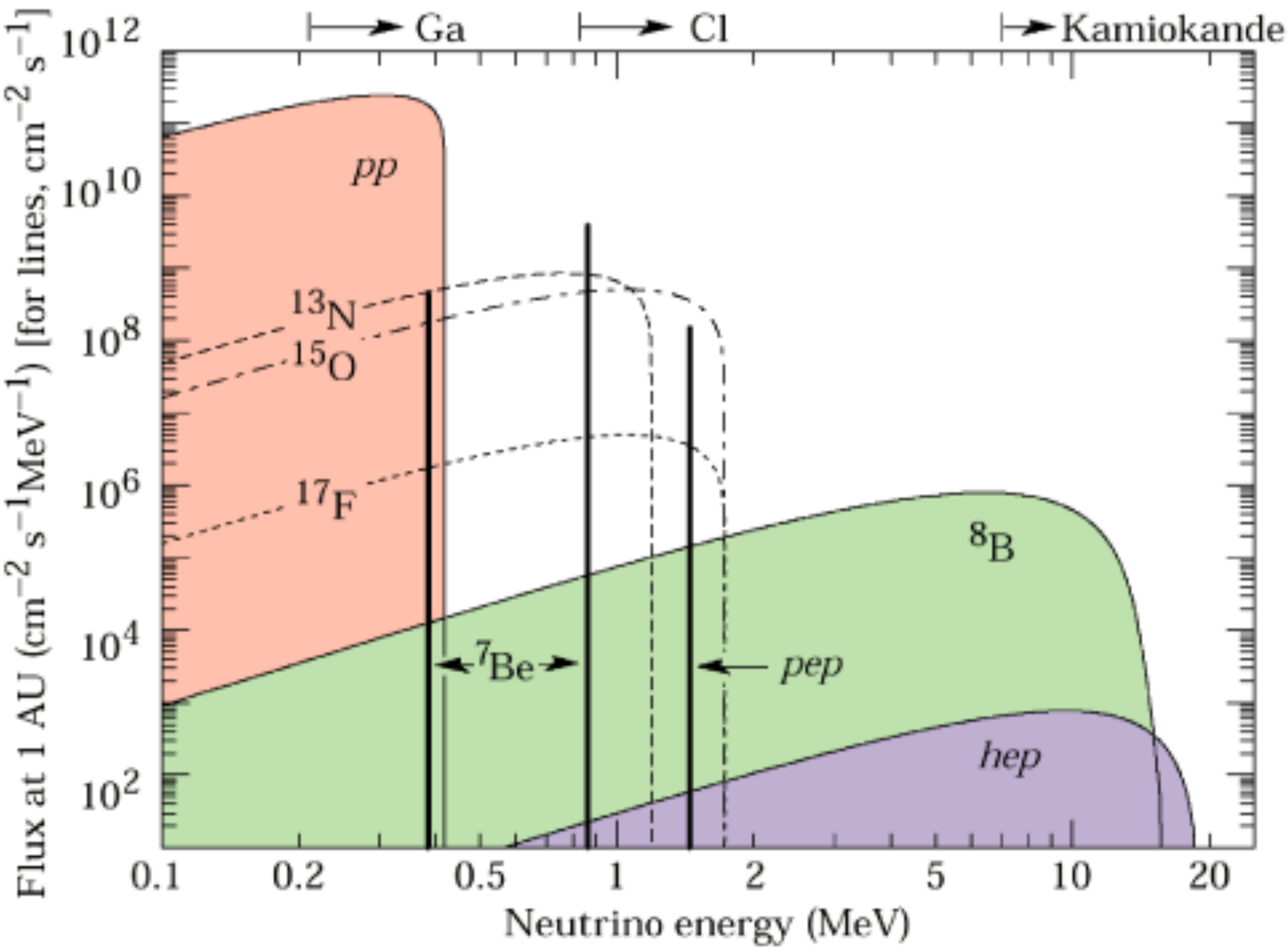
Solar radiation:

- 98% light
- 2% neutrinos → at Earth:
  66 billion neutrinos / cm^2 / s

Neutrino Production in the Sun

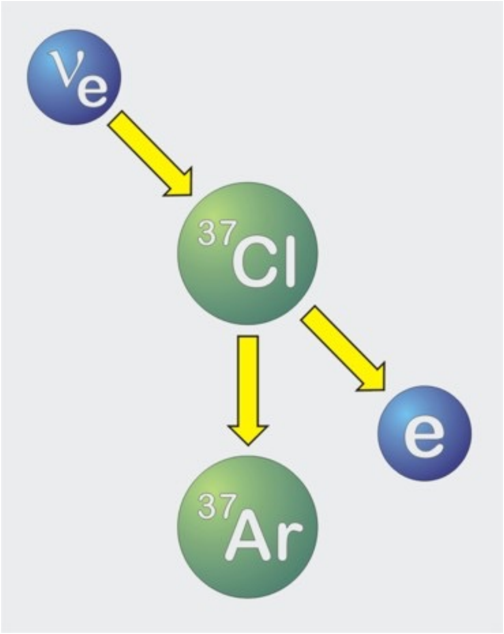


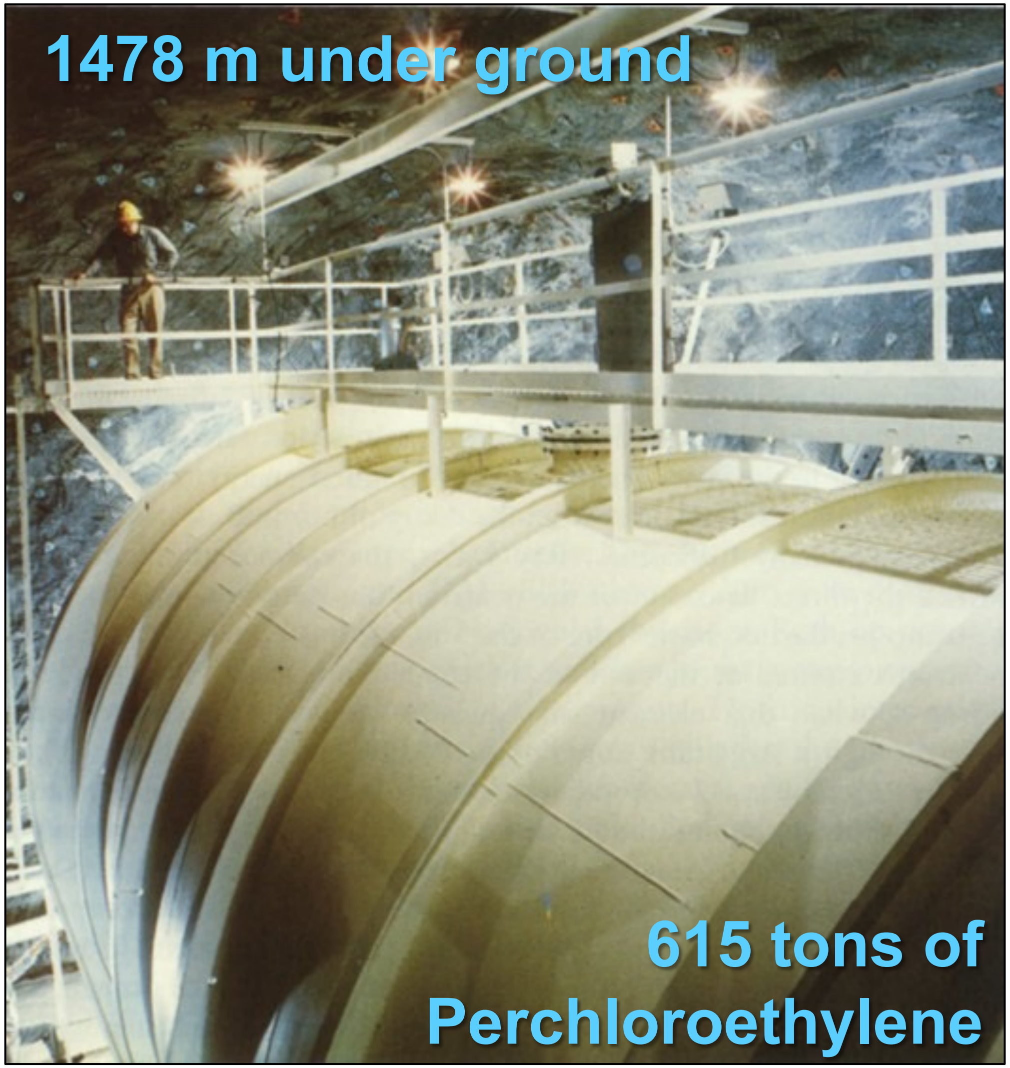
Solar Neutrino Spectrum



The Homestake Experiment

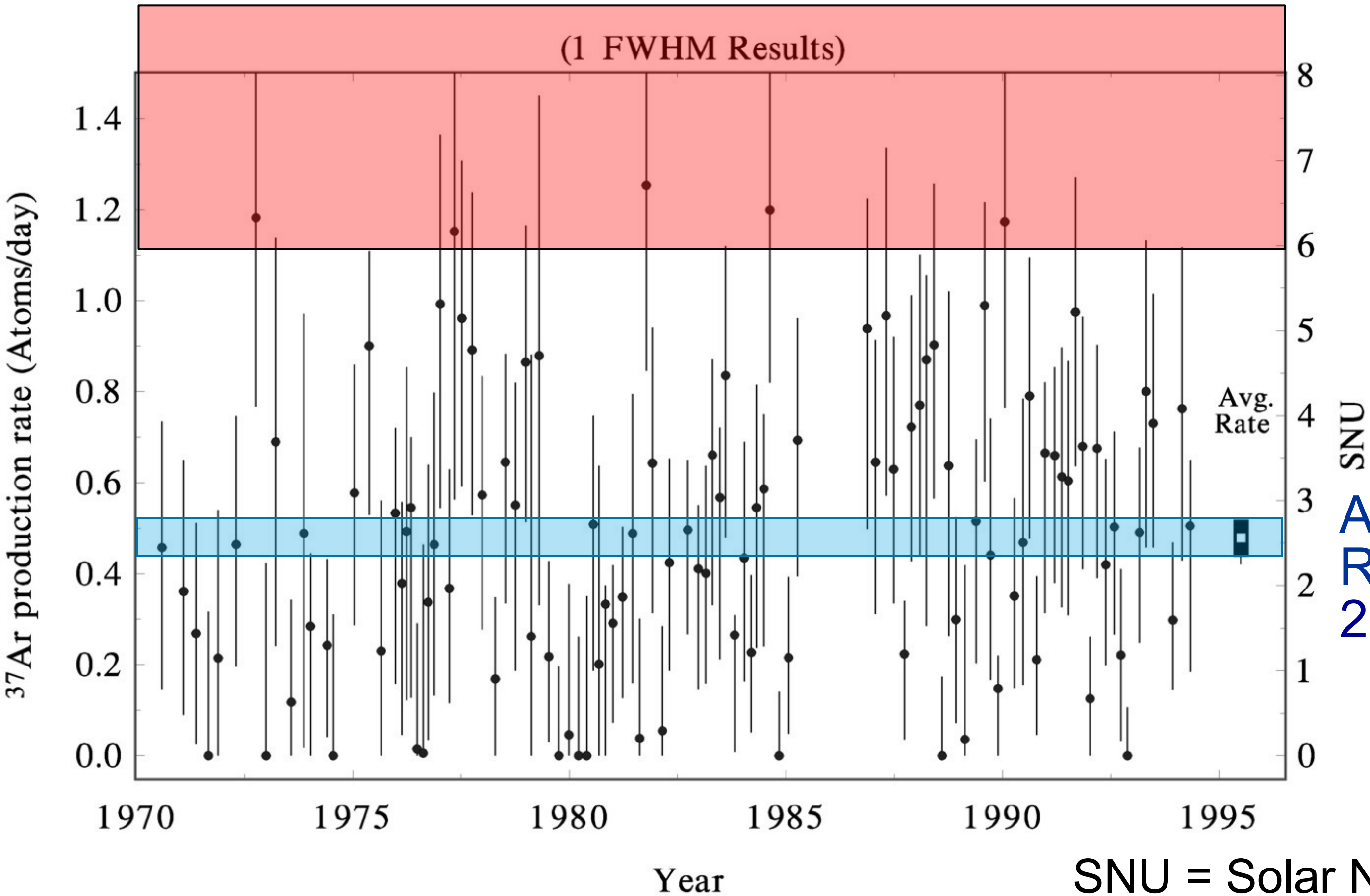
$$\nu_e + {}^{37}\mathrm{Cl} \longrightarrow {}^{37}\mathrm{Ar} + e^-$$





Homestake: Results

ApJ 496:505, 1998



Theoretical Prediction: 6-9 SNU

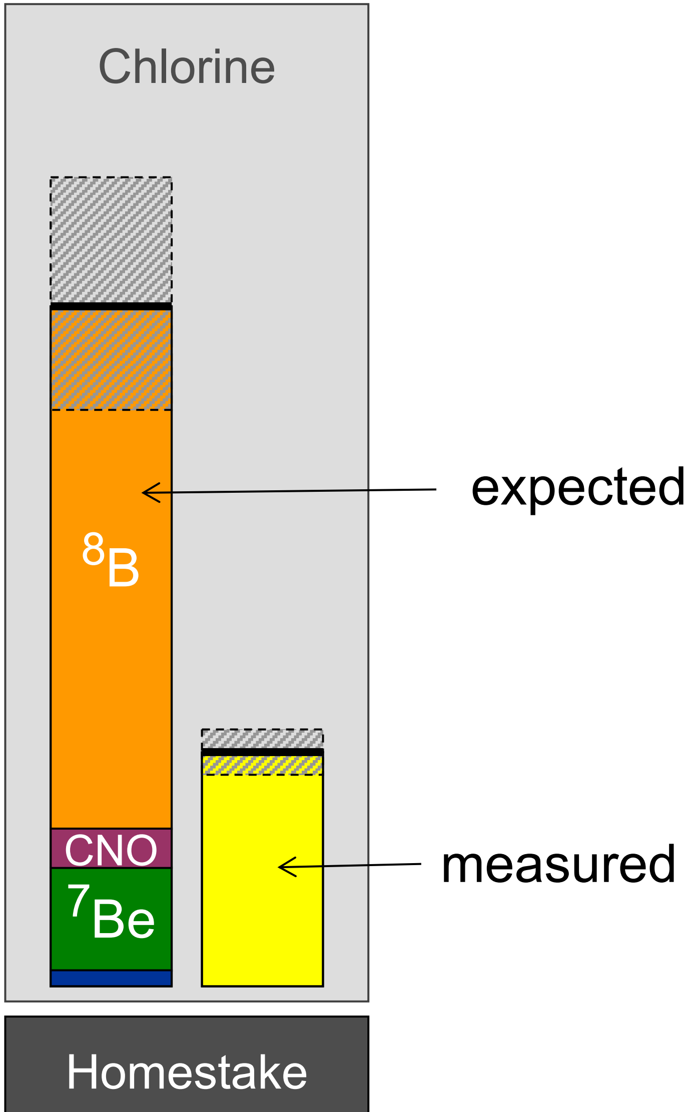
Average Rate
$2.56 \pm 0.16_{stat} \pm 0.16_{sys}$ SNU

SNU = Solar Neutrino Unit = 1 Absorption / sec / 10^{36} Atoms

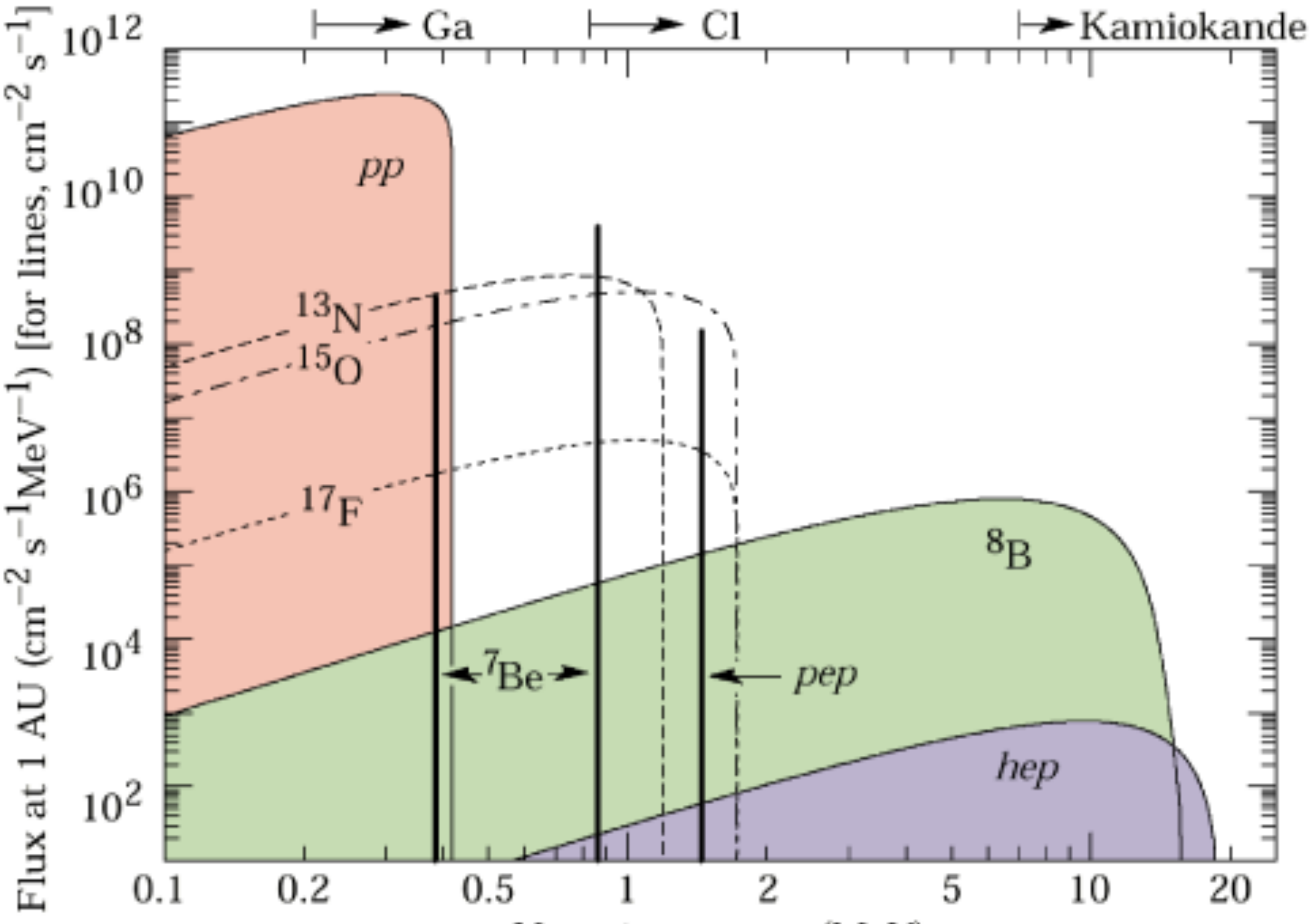
→ Solar neutrino problem

Solution to the solar neutrino problem

Electron-Neutrino Detectors

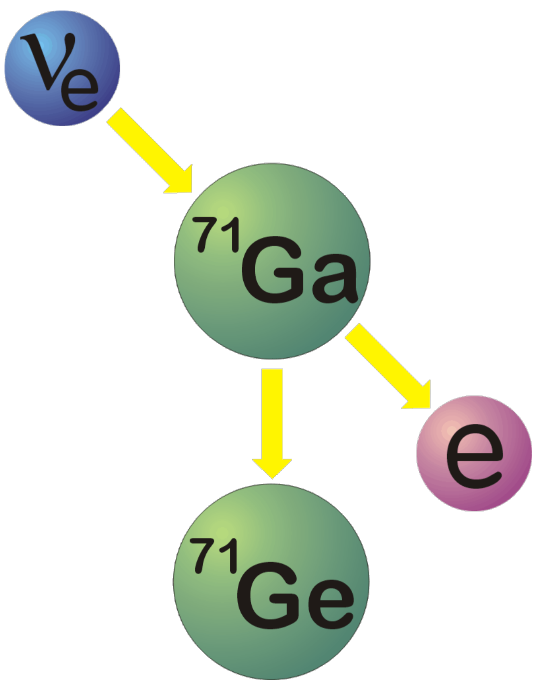


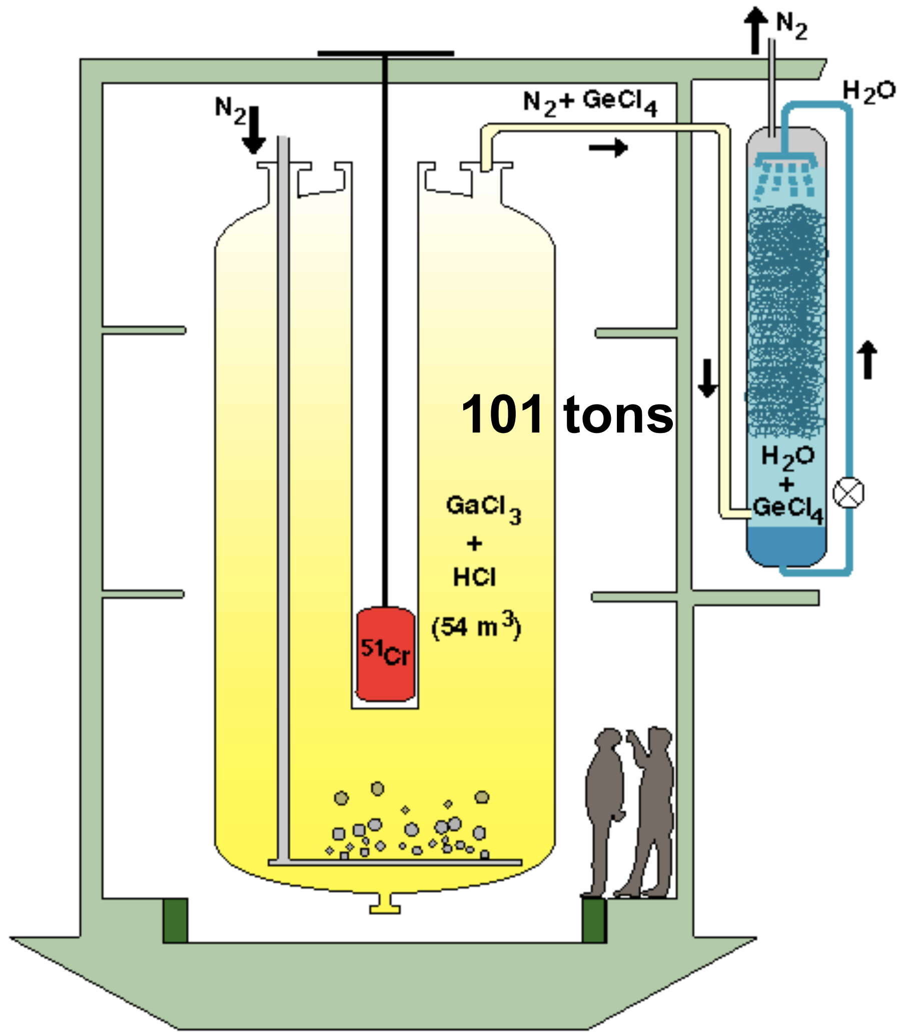
Solar Neutrino Spectrum



GALLEX / SAGE (1991-2003)

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

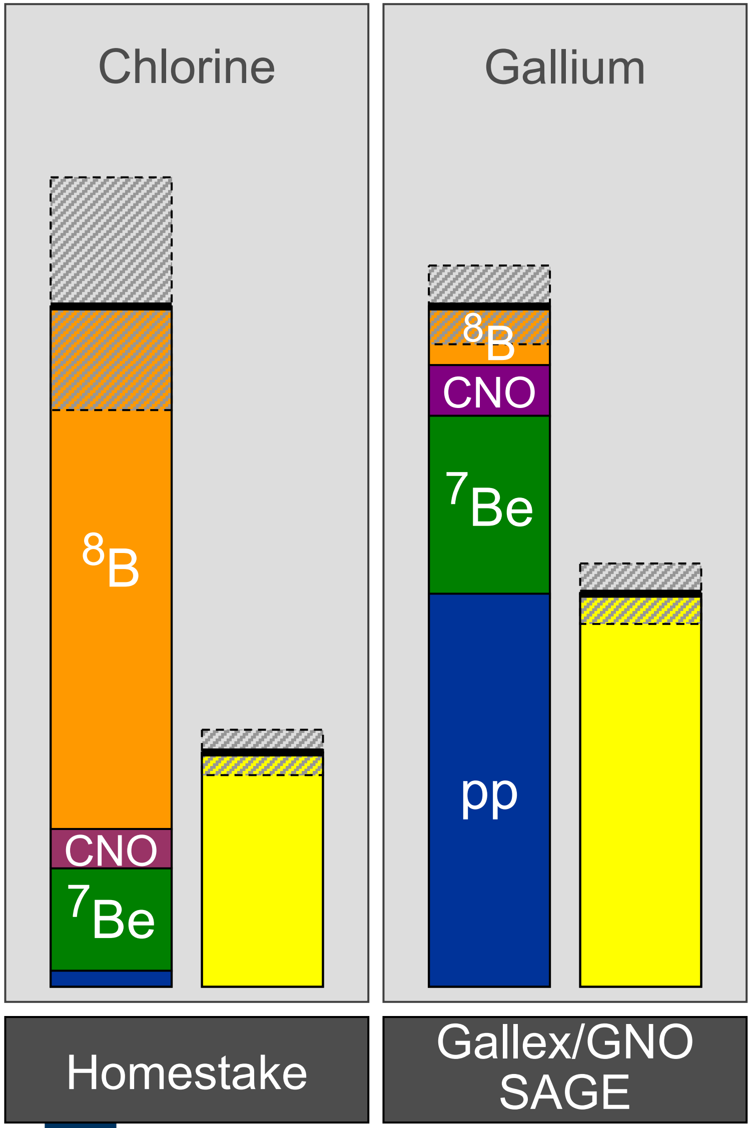




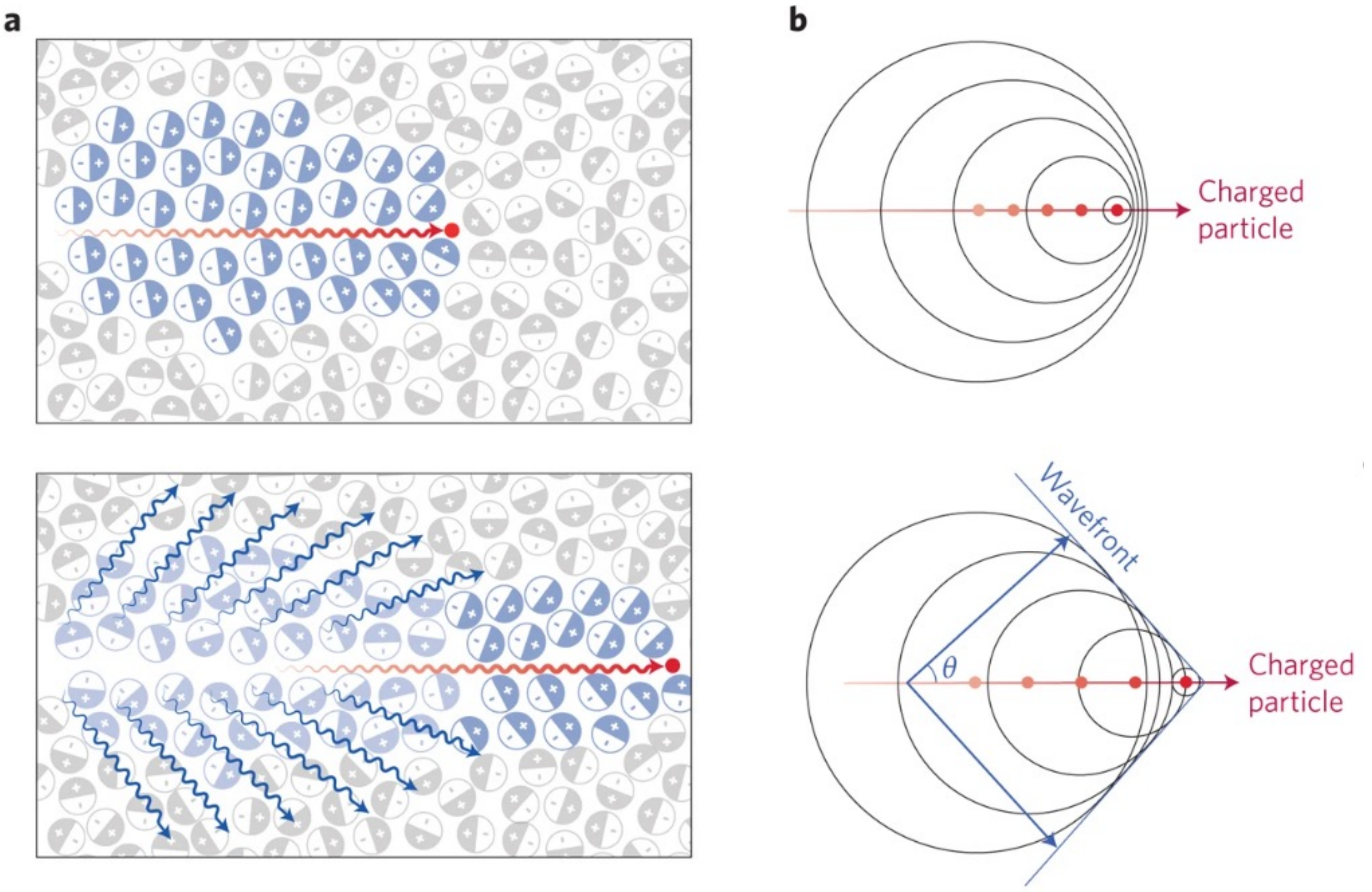
RUB

Solution to the solar neutrino problem

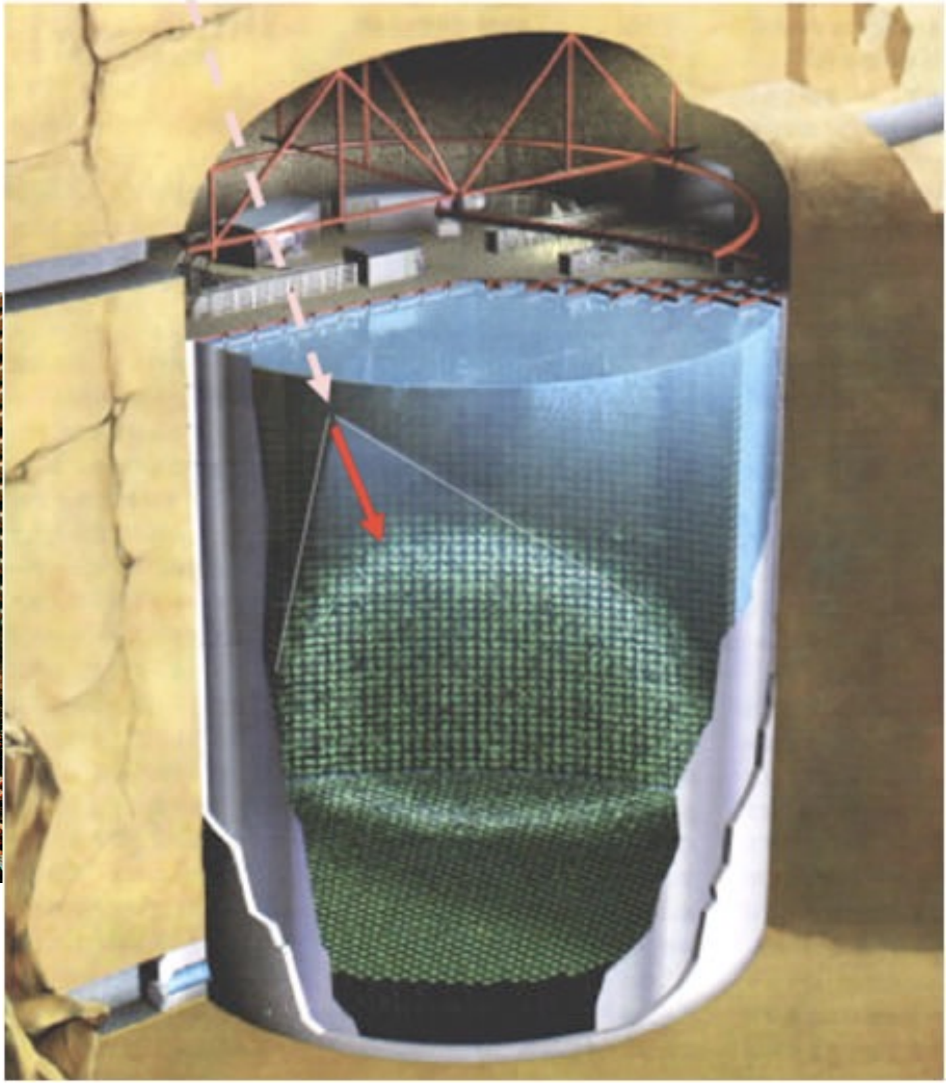
Electron-Neutrino Detectors



Different detection technique: Cherenkov Effect

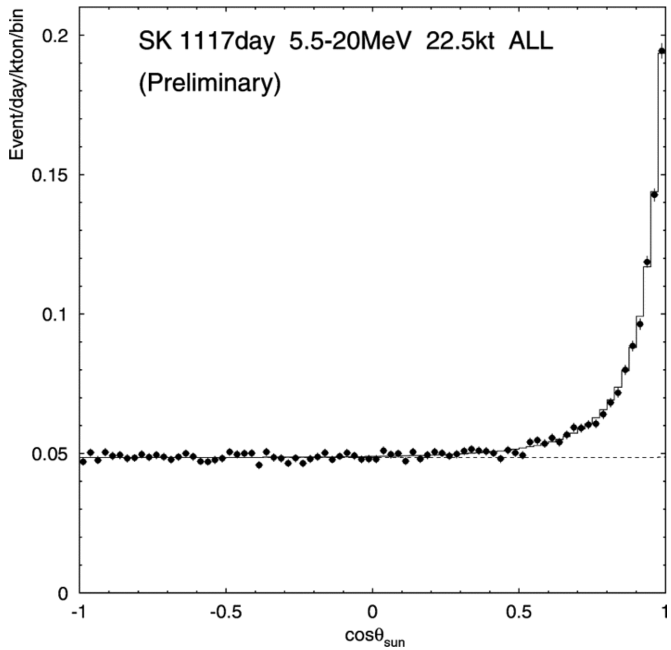


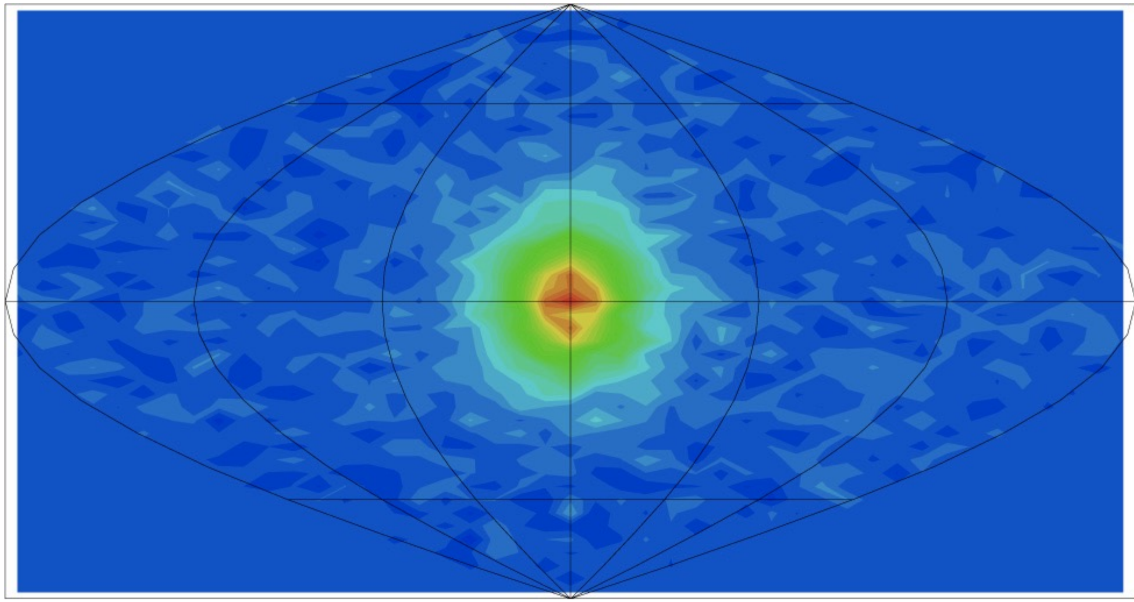
(Super) Kamiokande

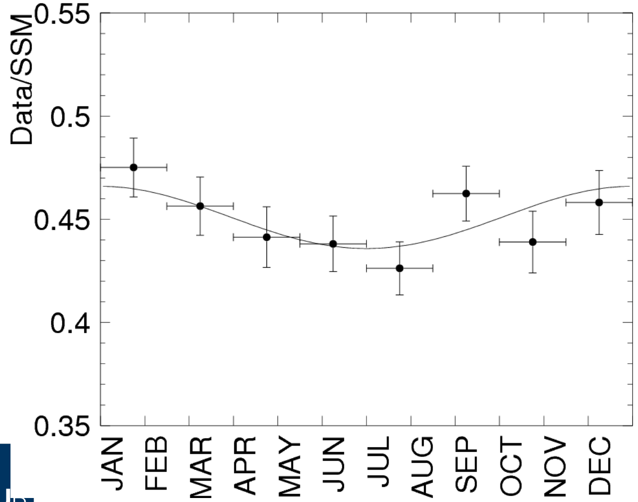


Volume: 3kT (50kT)

Super-Kamiokande – “Image” of the Sun

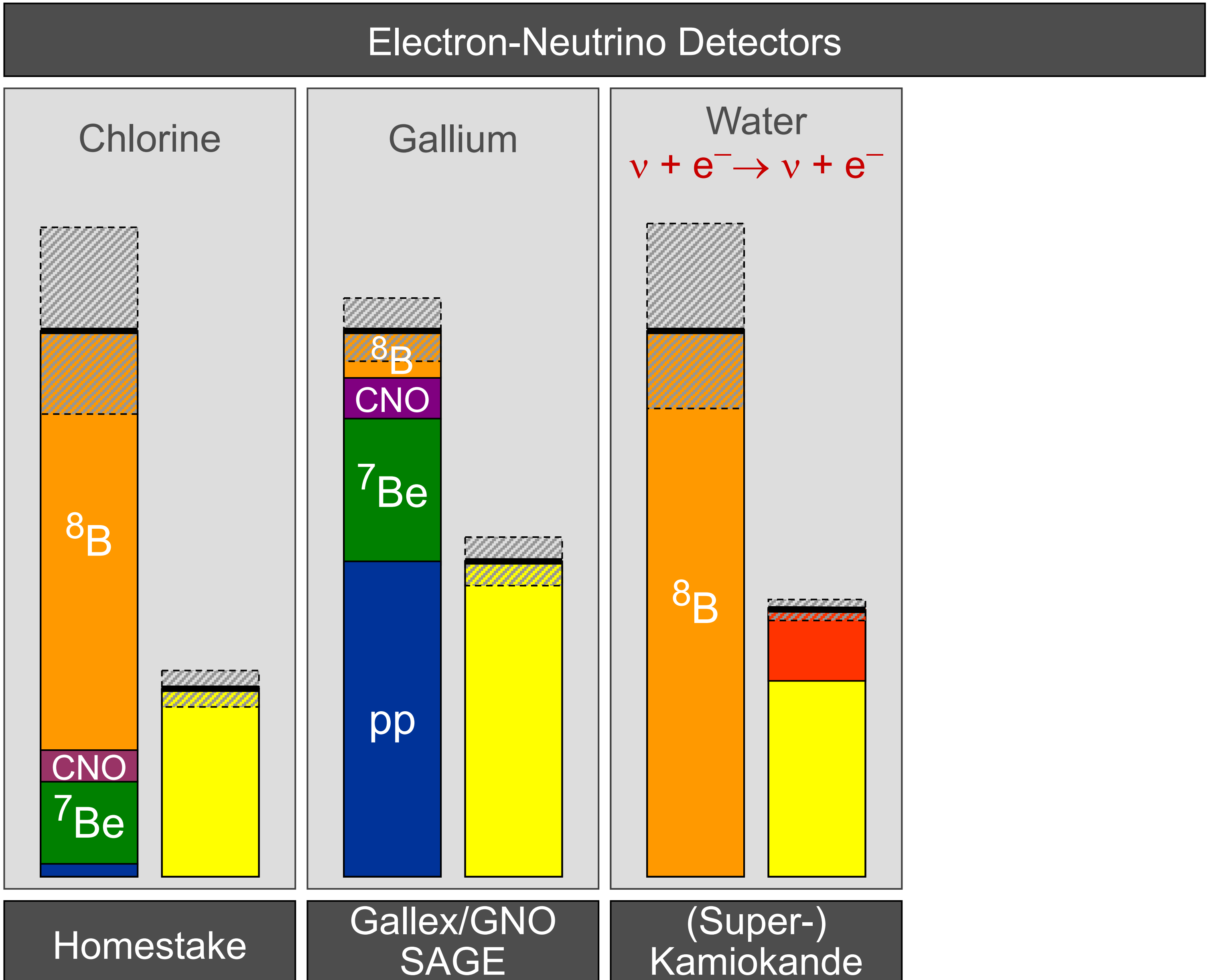




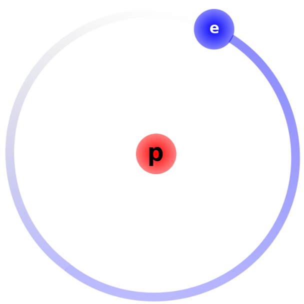


Seasonal variation due to elliptic orbit of Earth around sun

Solution to the solar neutrino problem

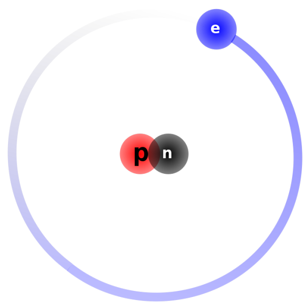


Sudbery Neutrino Observatory (SNO)



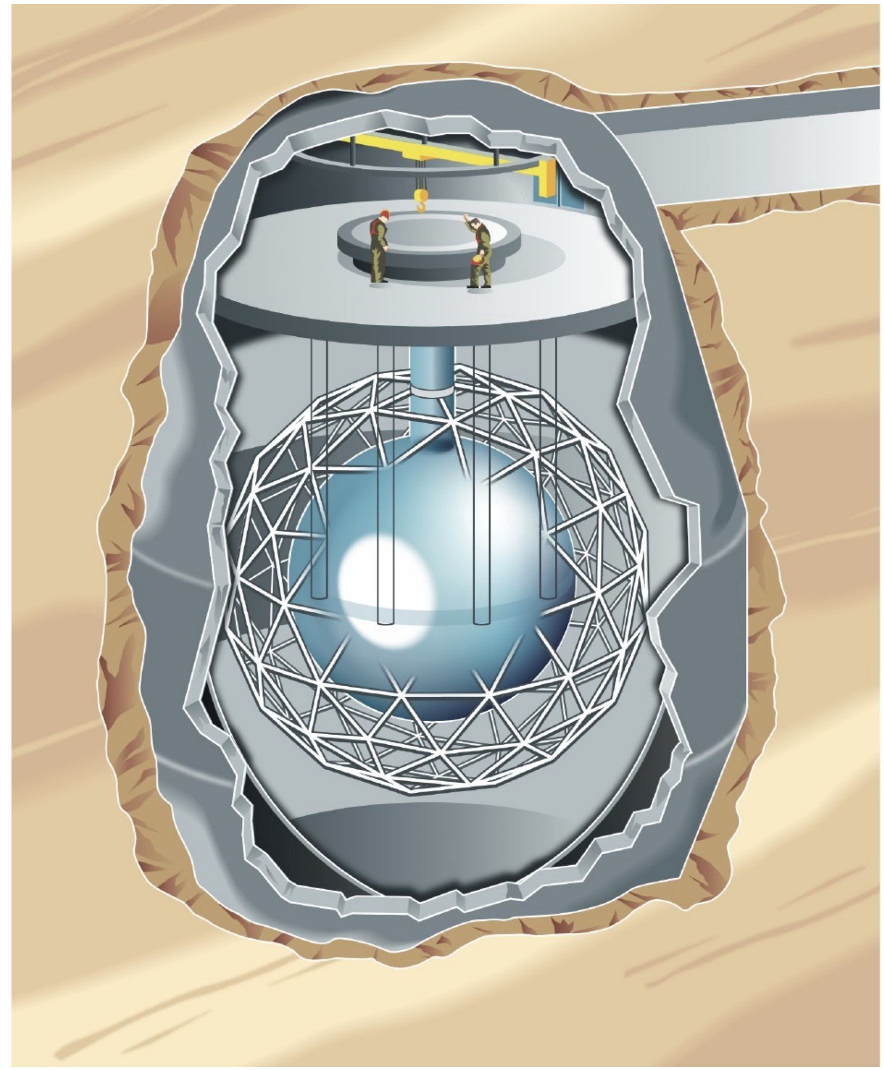
$^{1}_{1}H$

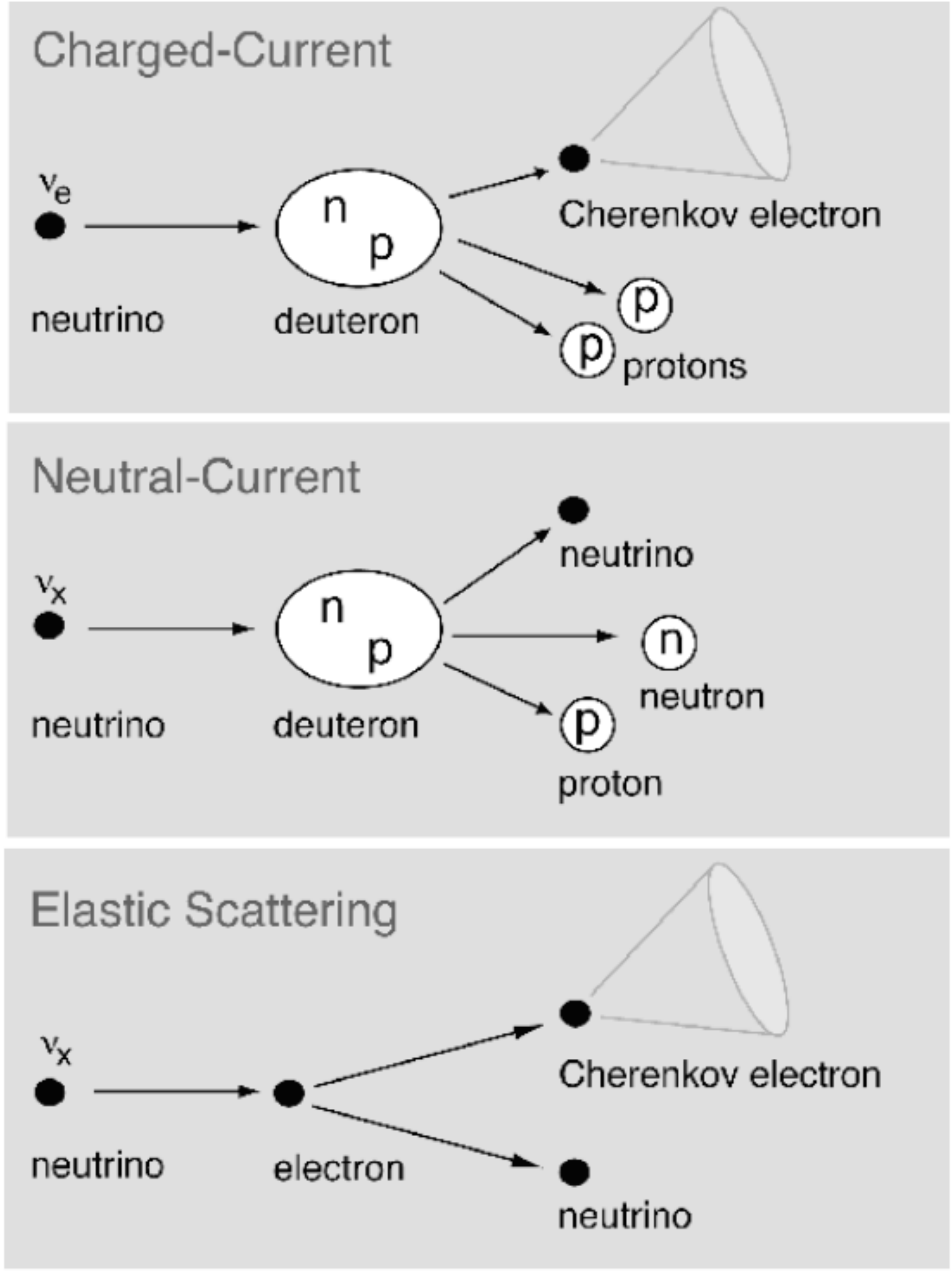
Hydrogen



$^{2}_{1}H$

Deuterium

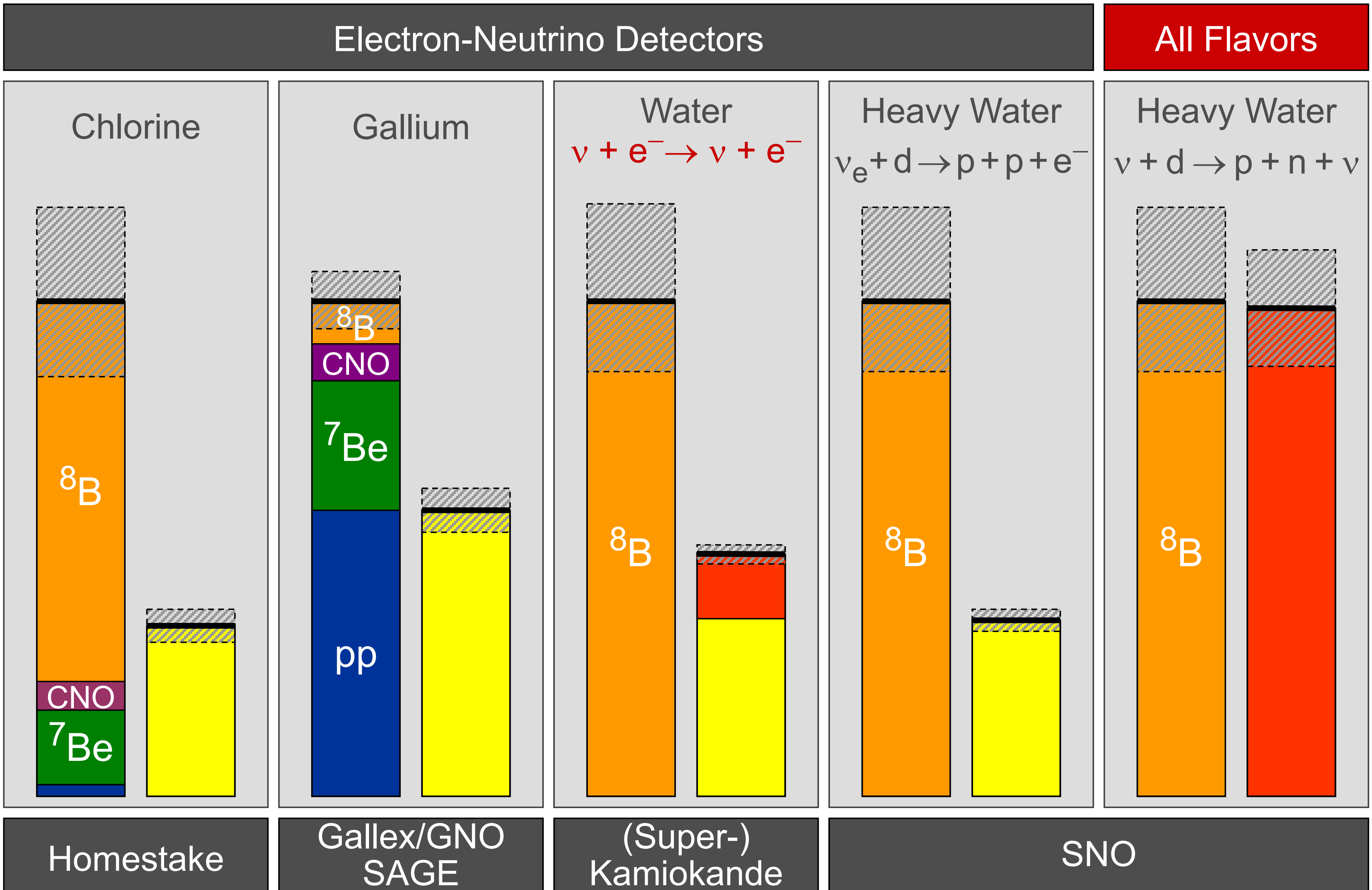


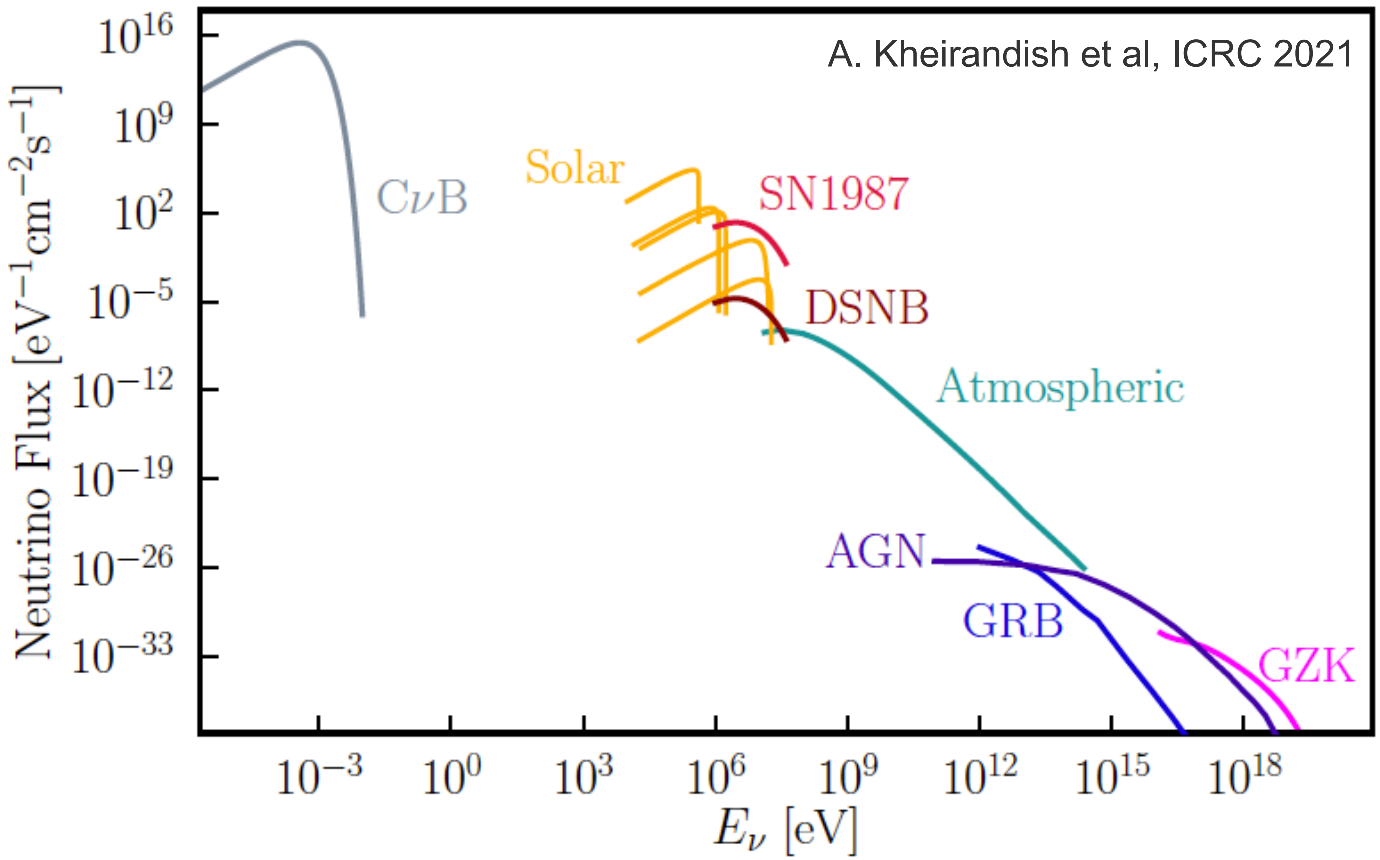


Charged-Current
νe
neutrino
n
p
deuteron
Cherenkov electron
p
p
protons
Neutral-Current
νx
neutrino
n
p
deuteron
neutrino
n
neutron
p
proton
Elastic Scattering
νx
neutrino
electron
Cherenkov electron
neutrino

RUB

Solution to the solar neutrino problem





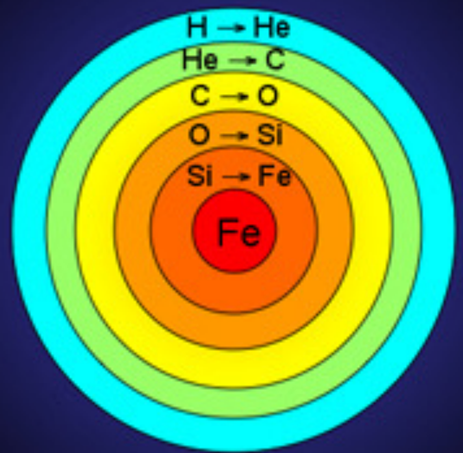
Ideas: neutrino capture on unstable nucleus (e.g. tritium)

Neutrino capture on stable nucleus (Chlorine, Gallium)

Water / ice Cherenkov detectors

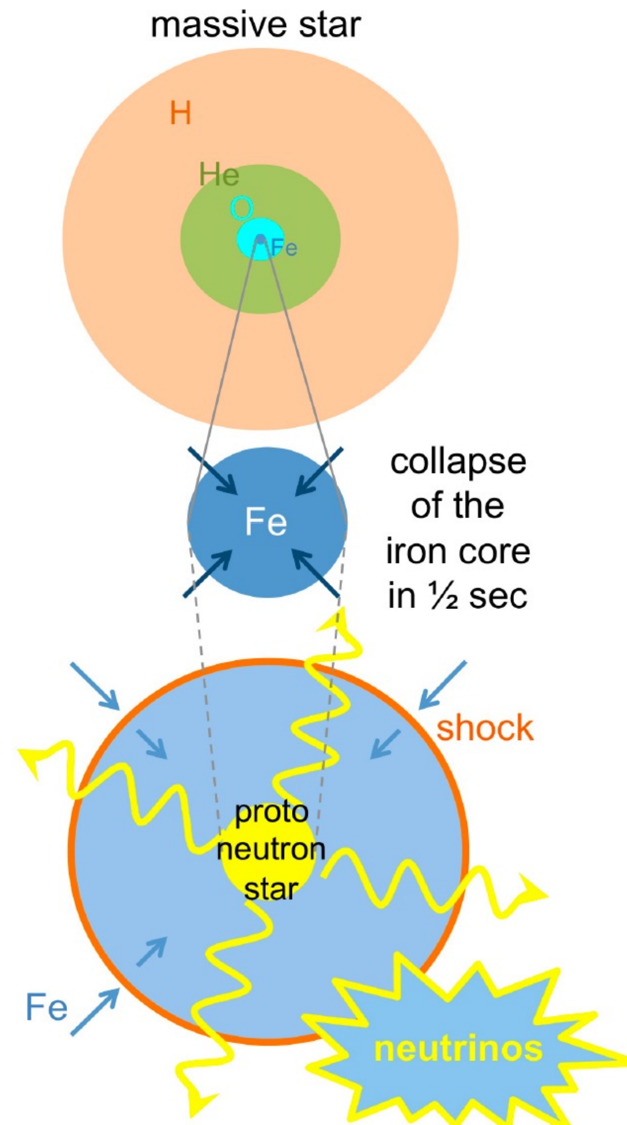
Radio arrays, cosmic-ray detectors

Supernova Neutrinos



For a 25 solar mass star:

Stage	Duration
H → He	7×10^6 years
He → C	7×10^5 years
C → O	600 years
O → Si	6 months
Si → Fe	1 day
Core Collapse	1/4 second

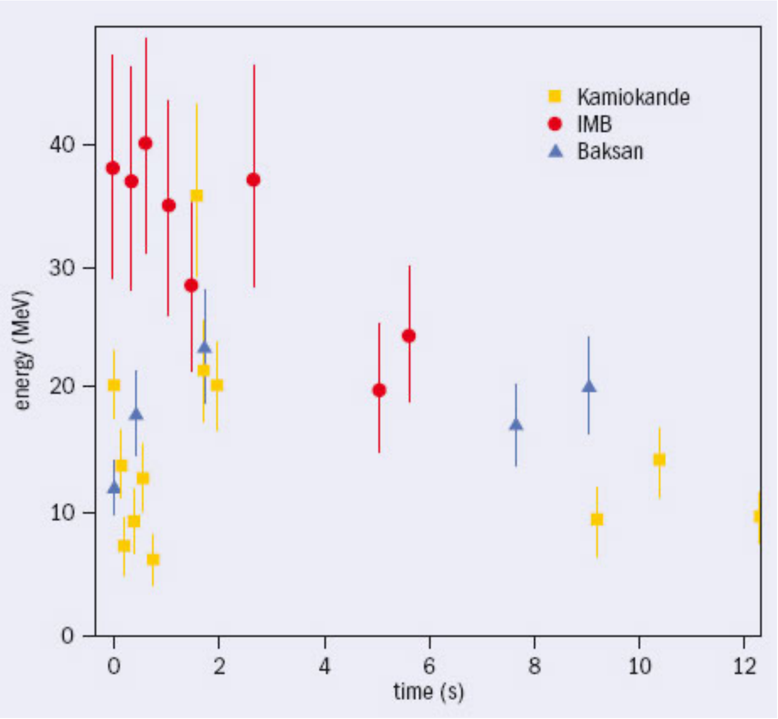


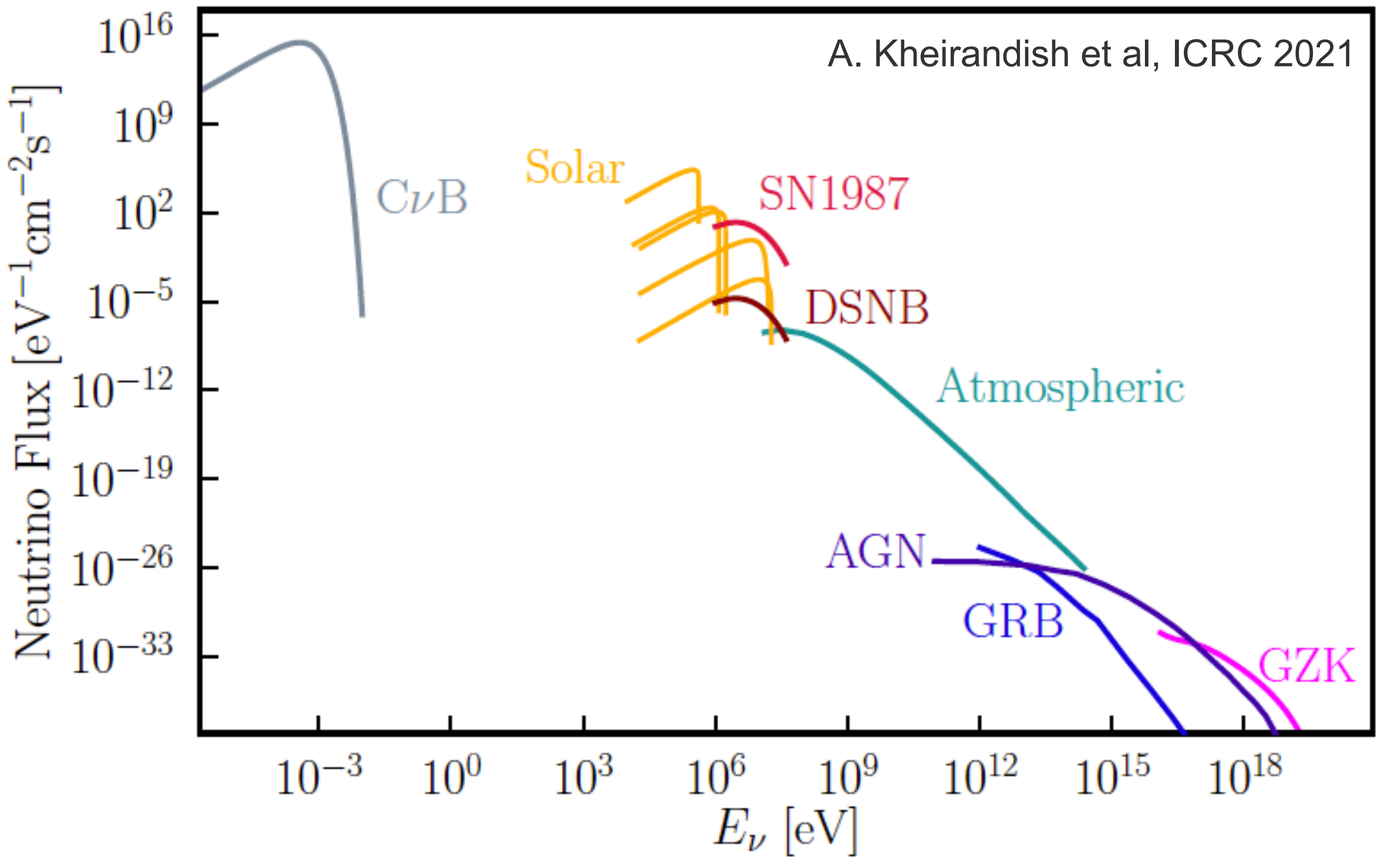
- ~10^{58} neutrinos in ~10s
- 99% of gravitational energy
- typical energy: 10-20 MeV

First and only Supernova neutrino detection

Optical detection of SN1987A in LMC

MeV neutrino burst





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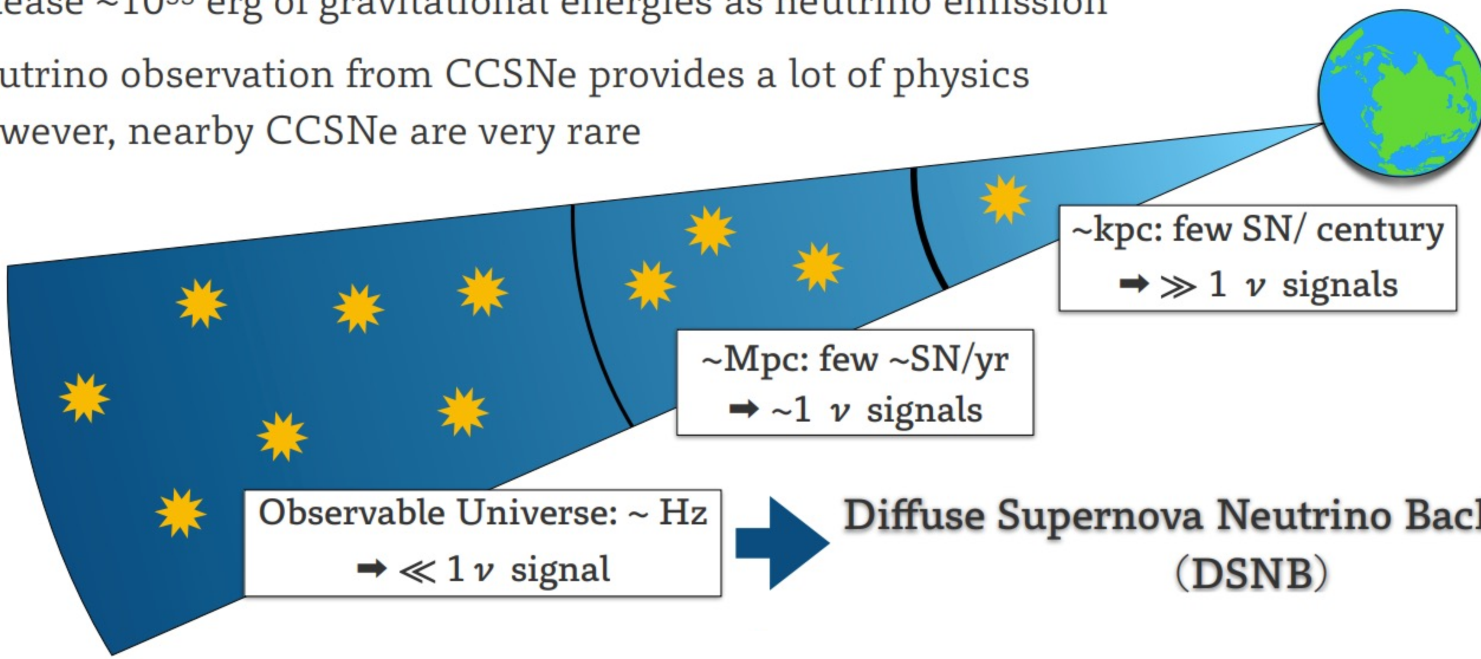
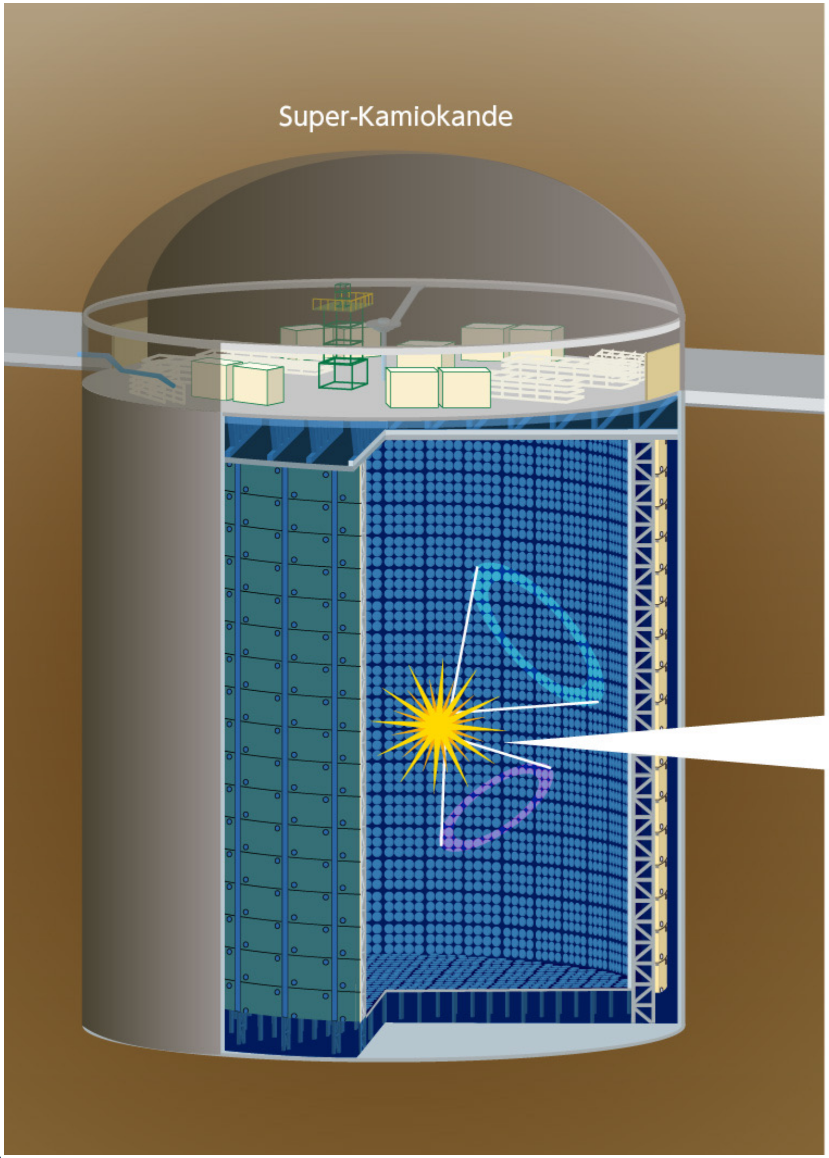
Diffuse Supernova Background (DSNB)

Core-Collapse Supernova (CCSN)

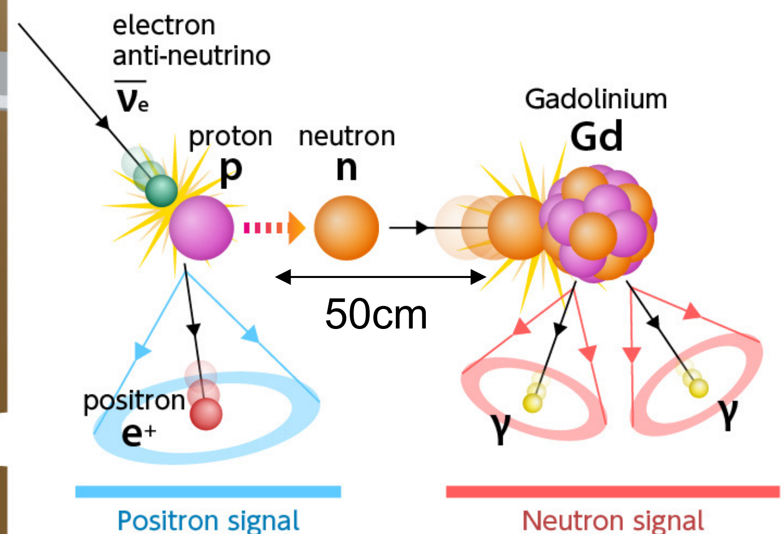
- Release ~10^{53} erg of gravitational energies as neutrino emission
- Neutrino observation from CCSNe provides a lot of physics
  However, nearby CCSNe are very rare



Super Kamiokande with Gadolinium



Gadolinium: highest affinity for capturing neutrons among all elements in nature.



0.1% concentration of Gd: 90% of neutrons will be captures
→ highly efficient background suppression

Diffuse Supernova Background (DSNB)

Core-Collapse Supernova (CCSN)

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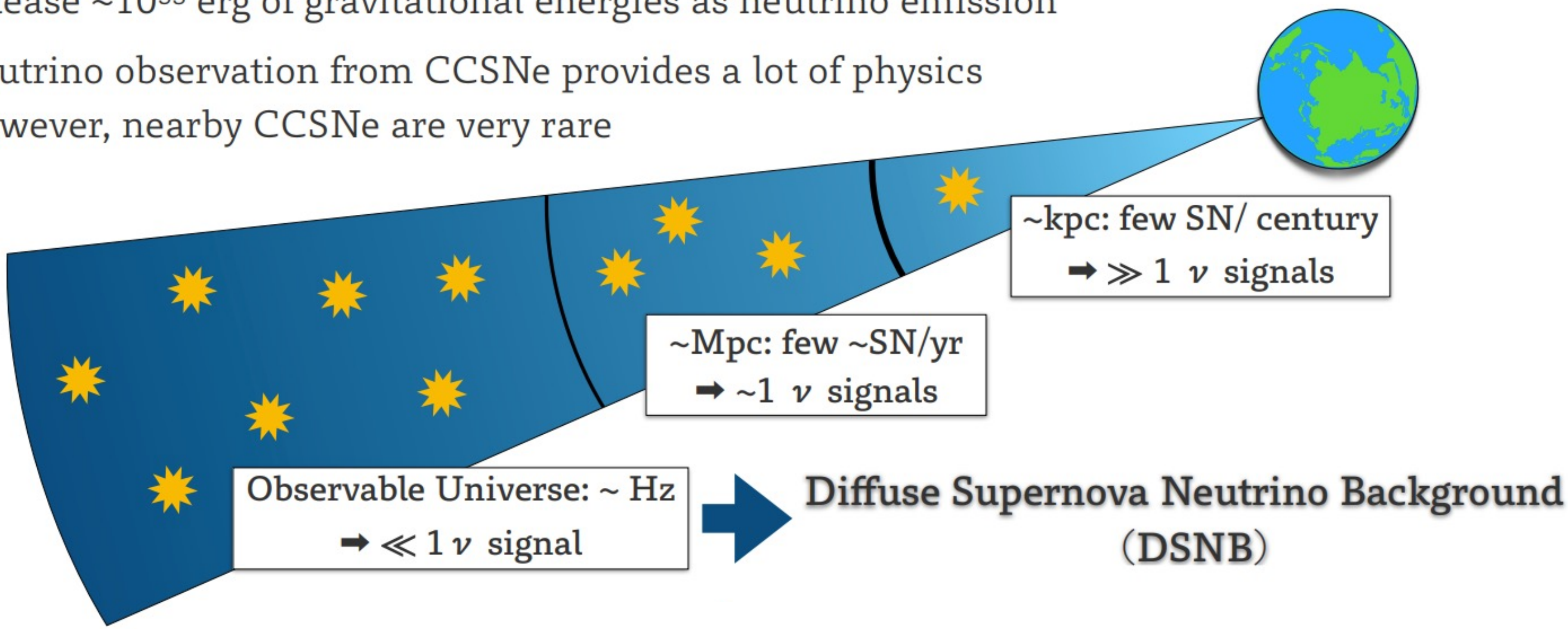
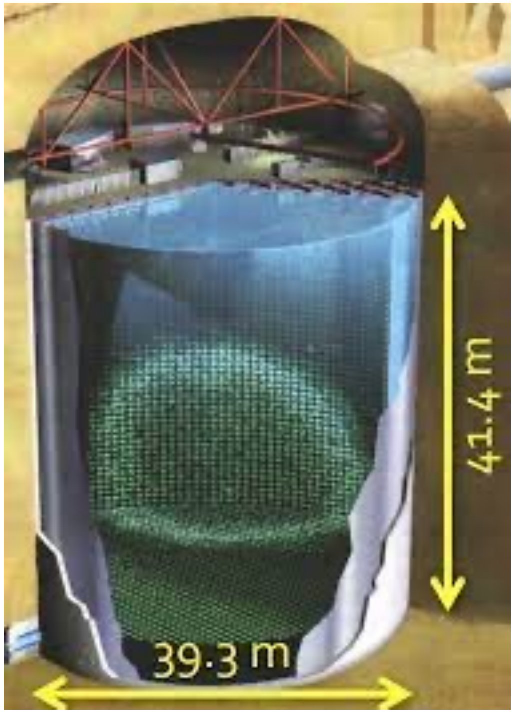


- Also, the latest update of DSNB search in SK-Gd using additional more condensed Gd-water data are exhibited
  ➡ There is no significant DSNB signal, however, some excess appears to be visible in the signal region, which is 2.3 σ tension from non-DSNB hypothesis
- Looking forward to discovery of DSNB in the next decade !!

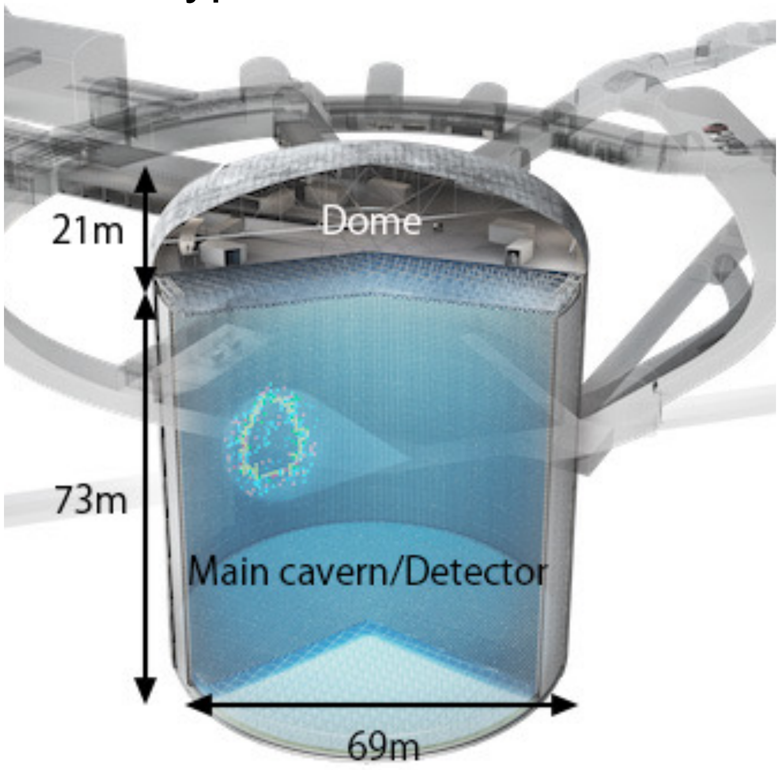
Next Generation Detector: Hyper Kamiokande

Super Kamiokande



Volume: 50kT

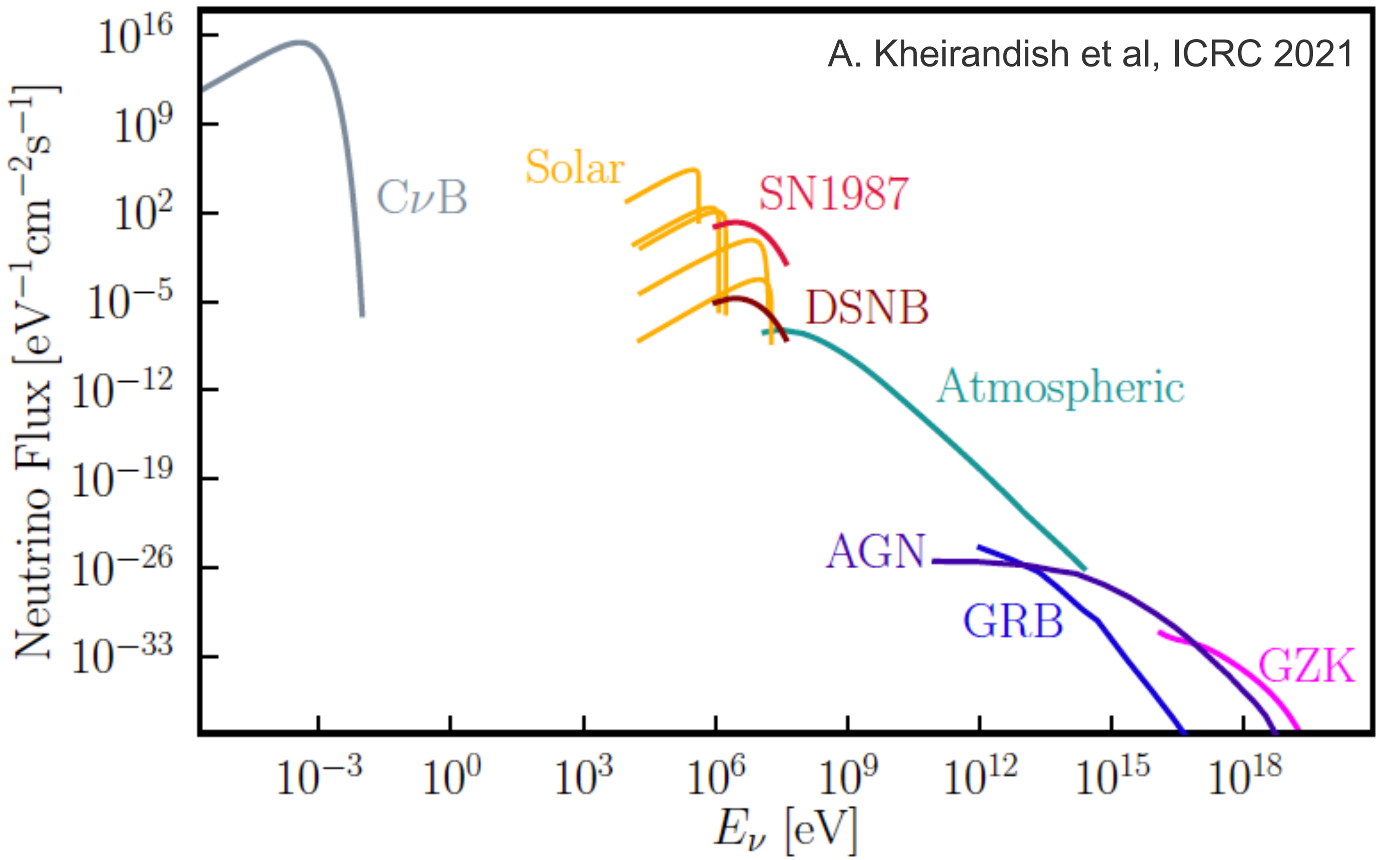
Hyper Kamiokande



Volume: 260kT

Data taking start in 2027

Questions?!



Ideas: neutrino capture on unstable nucleus (e.g. tritium)

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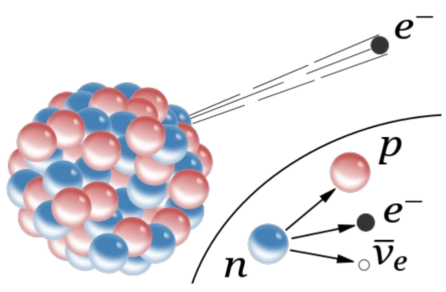
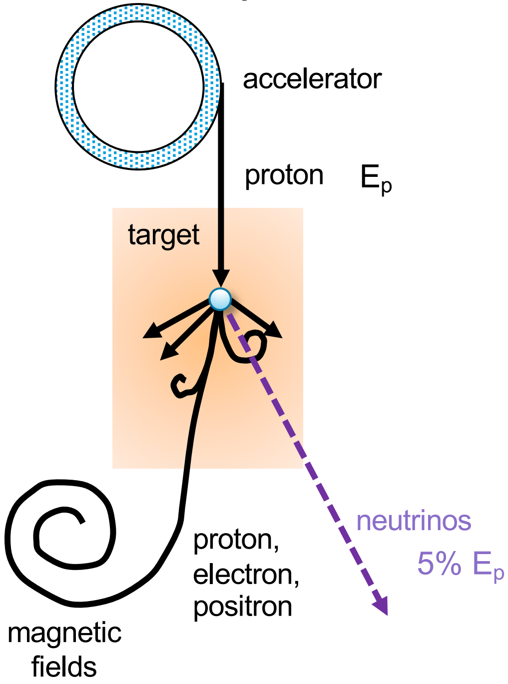
How are high-energy neutrinos produced?

MeV neutrinos from nuclear processes, (inverse) beta decay



TeV-PeV neutrinos from cosmic-ray "beam dumps"



Two ingredients:

- Proton acceleration
- Target for interaction

Neutrino Production Processes

Cosmic ray

pp

$p\gamma$ $\rightarrow$

target

$$\left\{\begin{array}{l} \ldots + \pi^{+} \rightarrow \mu^{+} + \nu_{\mu} \rightarrow e^{+} + \nu_{e} + \bar{\nu}_{\mu} + \nu_{\mu} \\ \ldots + \pi^{-} \rightarrow \mu^{-} + \bar{\nu}_{\mu} \rightarrow e^{-} + \bar{\nu}_{e} + \nu_{\mu} + \bar{\nu}_{\mu} \\ \ldots + \pi^{0} \rightarrow \gamma\gamma \end{array}\right.$$

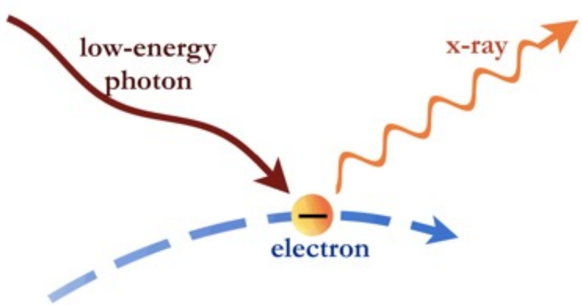
Neutrino Production Processes

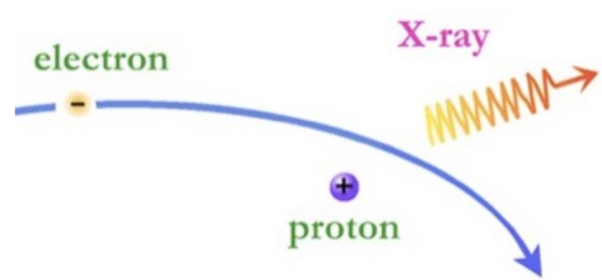
Cosmic ray

$$pp \atop p\gamma \rightarrow \begin{cases} \ldots + \pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu \\ \ldots + \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu \\ \ldots + \pi^0 \rightarrow \gamma\gamma \end{cases}$$

target

Gamma-rays are not exclusively produced in hadronic processes





Neutrino Production Processes

Cosmic ray

pp

$p\gamma$ $\rightarrow$

target

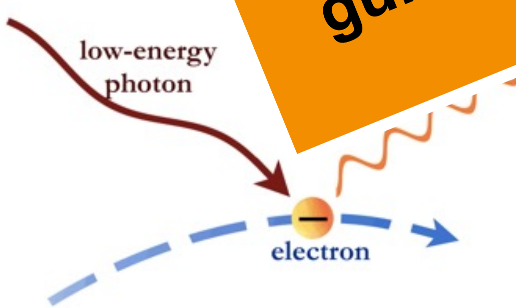
$$\ldots + \pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$

$$\ldots + \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- \ldots \nu_\mu + \bar{\nu}_\mu$$

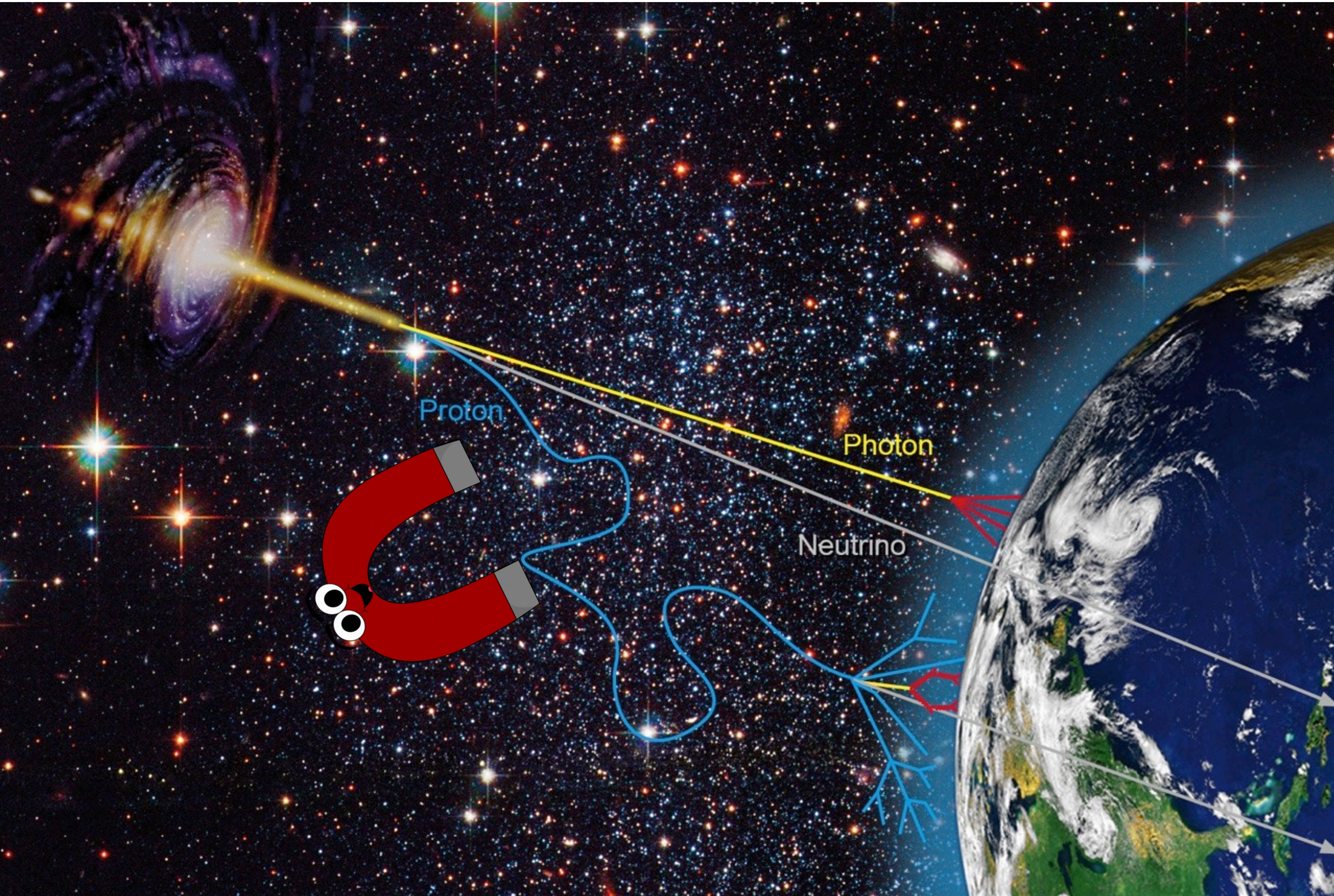
$$\ldots + \pi^0 \rightarrow \gamma\gamma$$

Neutrinos are the smoking gun signature for hadronic acceleration

Gamm… …uced in hadronic processes



What are the Cosmic-Ray Sources?

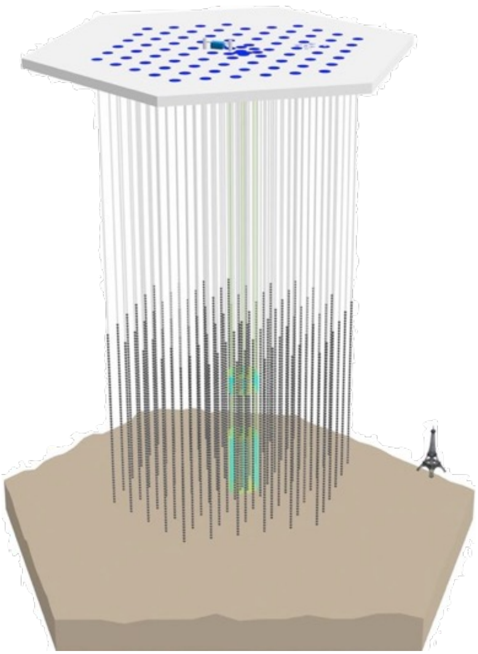


High-energy Neutrino Detectors

- Huge volumes necessary: ~1km^3 → need to use natural medium
- Transparent medium (Cherenkov emission of secondary charged particles)

High-energy Neutrino Detectors

IceCube (1 km^3)



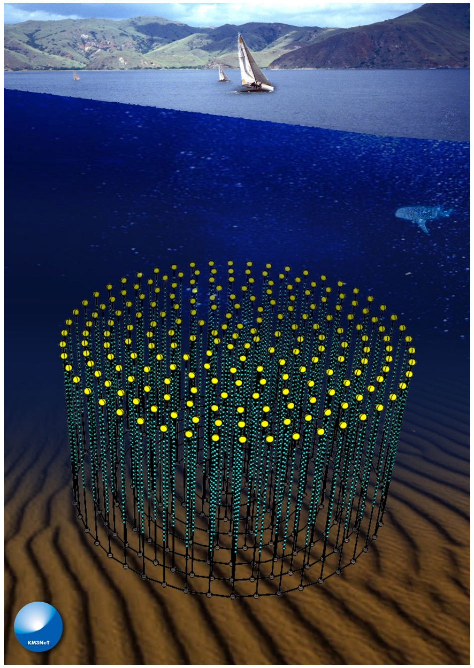
IceCube-Gen2
(8km^3) planned

M.G. Aartsen *et al* 2017 *JINST* **12** P03012
M.G. Aartsen *et al* J.Phys.G 48 (2021) 6, 060501

KM3NeT (2 x 0.5 km^3)

Under construction

Predecessor ANTARES decommissioned after 14y

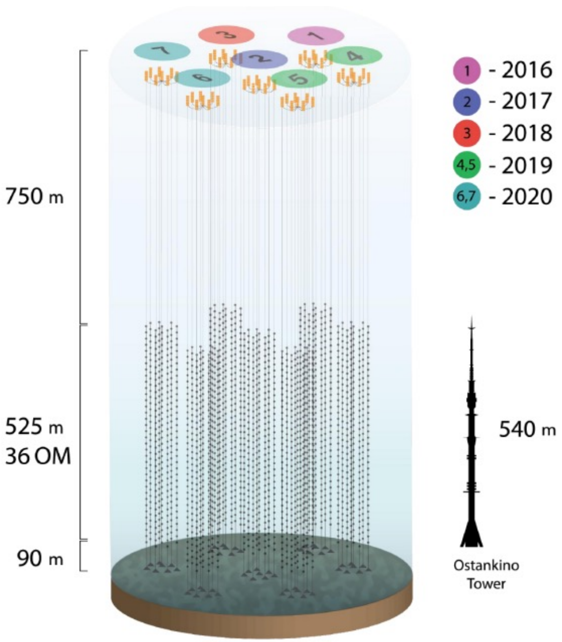


Two sites: ARCA for HE and ORCA for LE, roughly ~20% complete

S. Adrián-Martínez et al. arXiv:1601.07459

Baikal-GVD (1 km^3)

Under construction

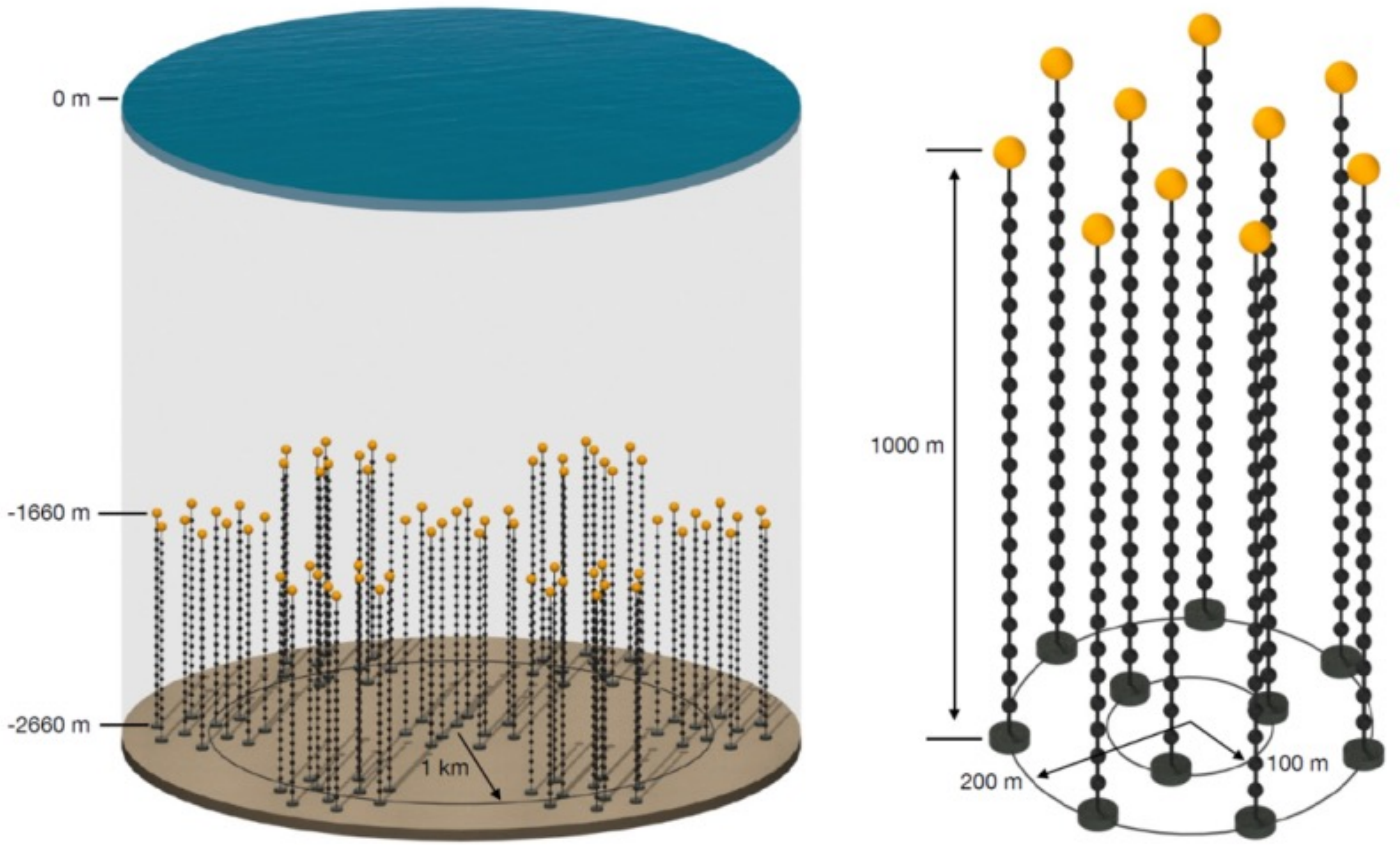


2022: 10 clusters
2026: 18 clusters

A.D. Avrorin et al. arXiv:2011.09209

High-energy Neutrino Detectors

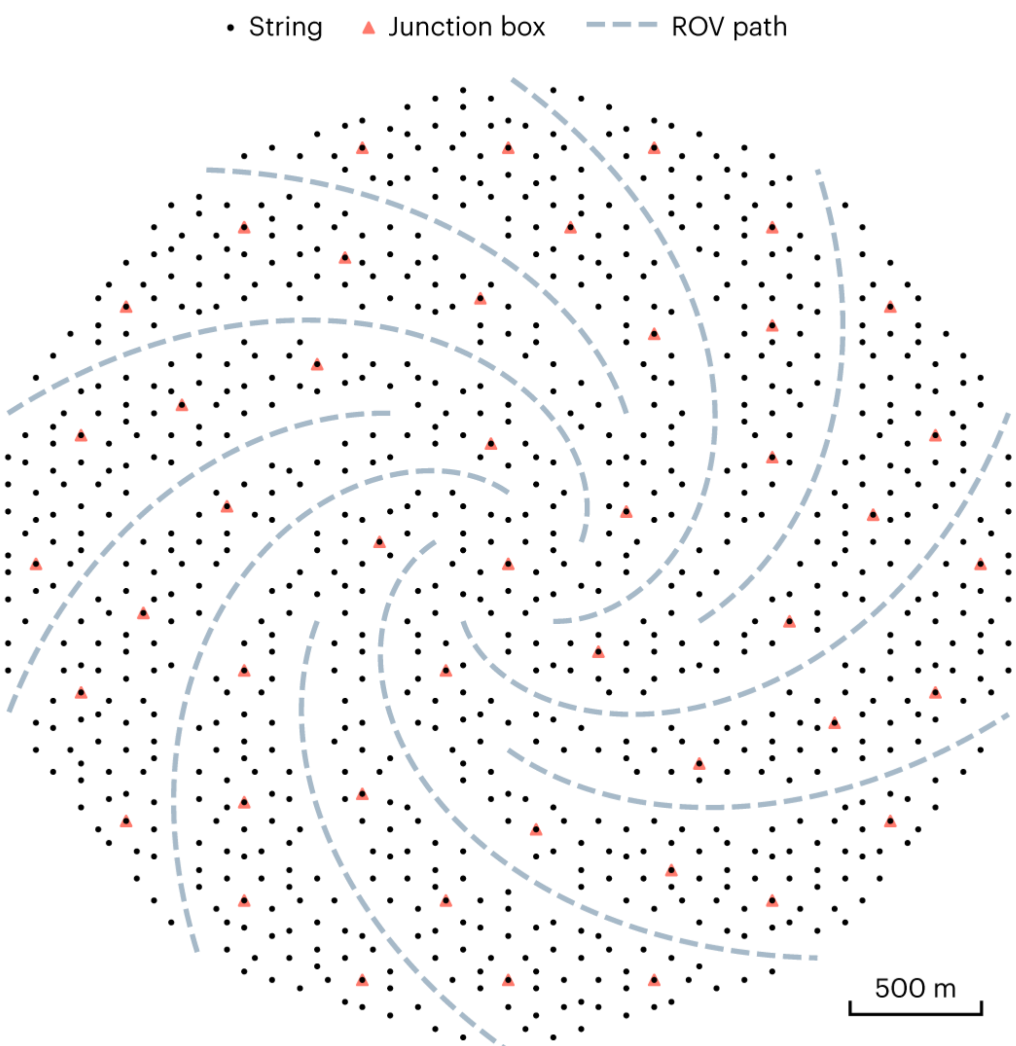
P-ONE



planned deployment of 10 strings explorer in 2023-2024
70 strings between 2028-2030

M. Agostini et al. Nature Astronomy 4 (2020)

High-energy Neutrino Detectors



Tropical Deep-sea Neutrino Telescope (TRIDENT), South Chinese Sea

depth of ~3.5 km

Volume: 7.5 km^3

2021: water quality measurements

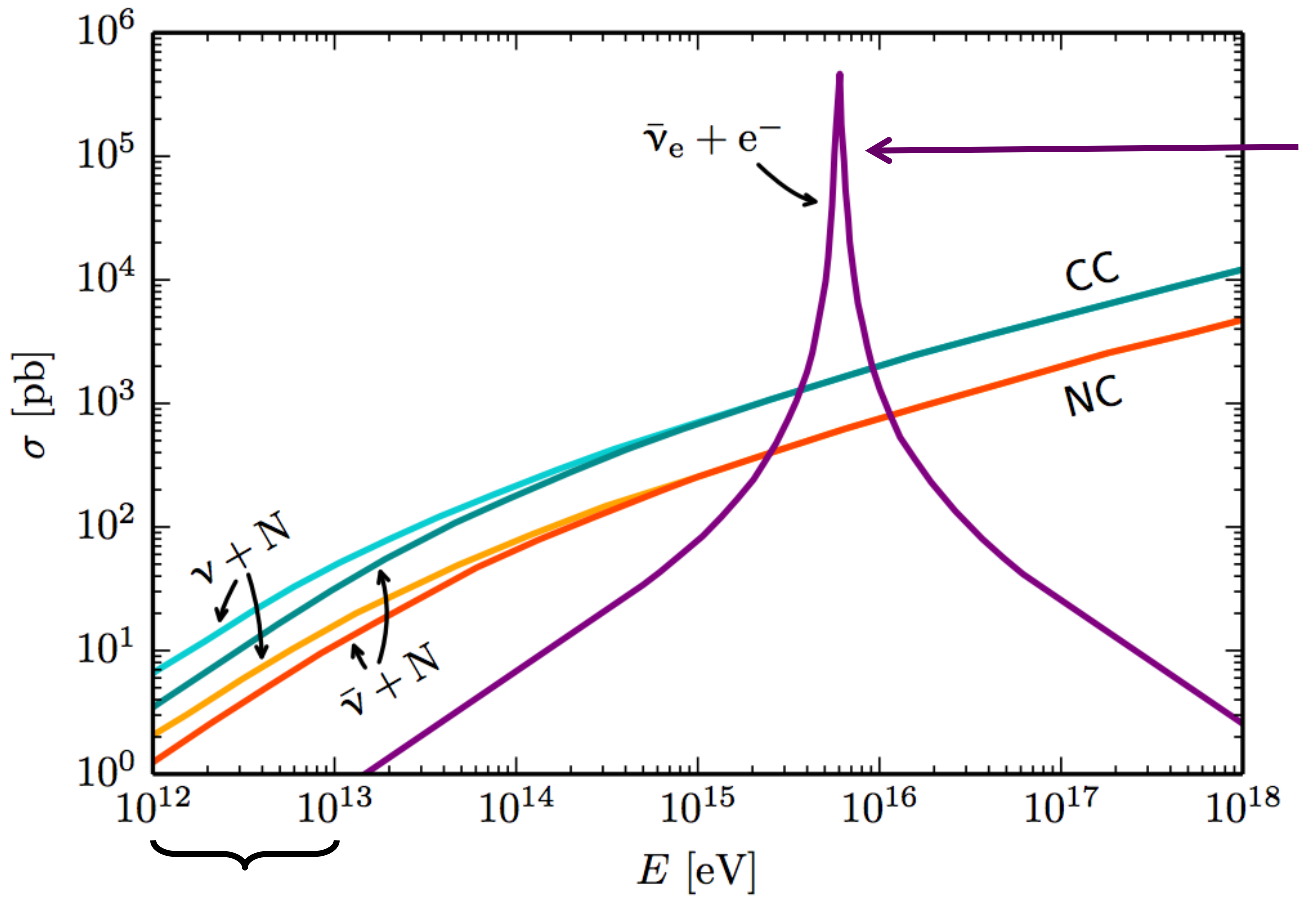
Full deployment in 2030

Differences between ice and water detectors

Property	Lake Baikal	Mediterranean (ANTARES)	Antarctic Ice
Absorption length (m)	22	60	100
Effective Scattering (m)	480	265	25
Depth	1370	2475	2450
Noise	Quiet	^{40}K, bioluminescence	Quiet
Retrieve/redeploy	Yes	Yes	No

Long scattering length in Mediterranean implies better angular resolution; long absorption length for IceCube allows sparser instrumentation. Smaller depth implies larger atmospheric muon background.

Neutrino Cross-Sections

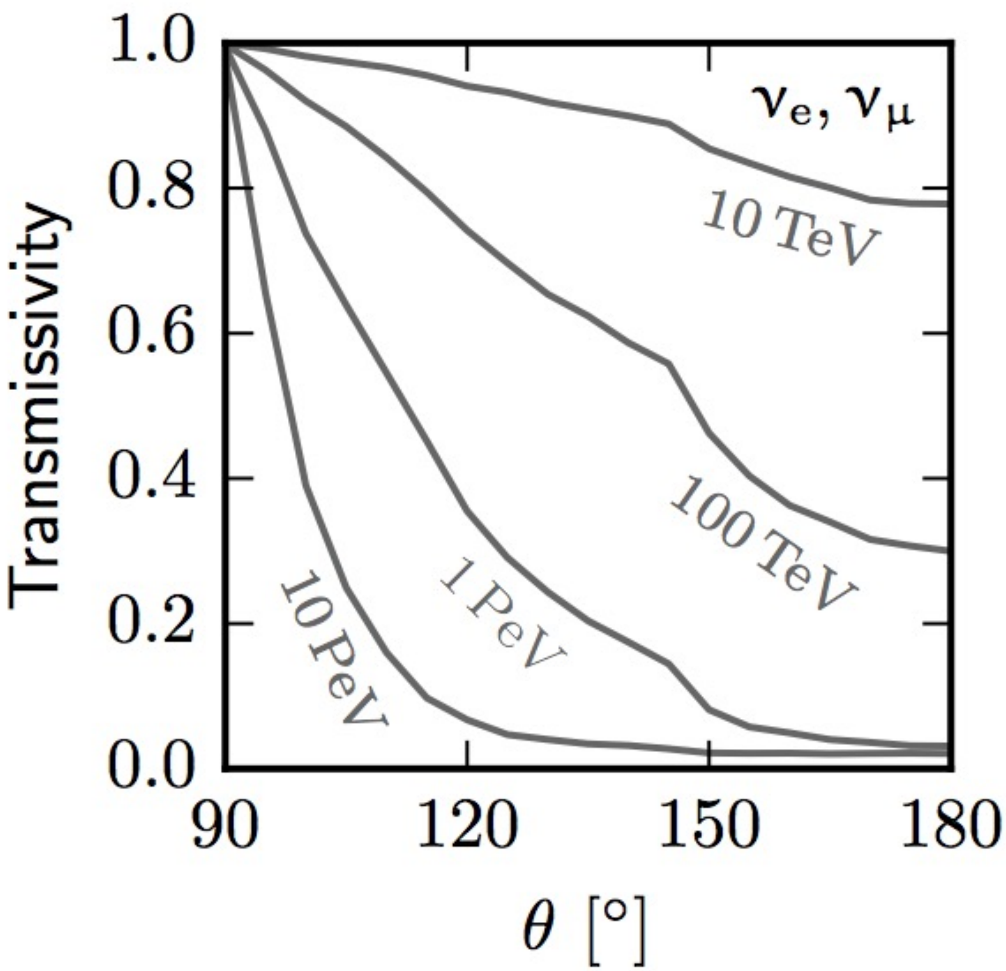


Glashow resonance: resonance when the center-of-mass energy of the system reaches the mass of the mediating boson. For electrons at rest and the mass of the $W^\pm$ boson (80 GeV), the Glashow resonance occurs at a neutrino energy of 6.3×10^{15} eV

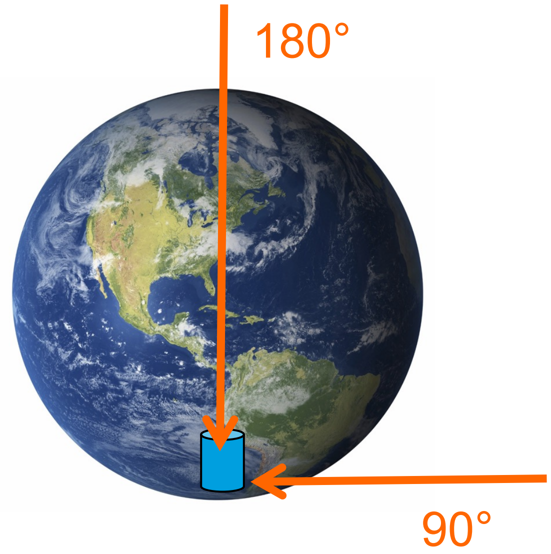
Linear with E, Smaller for anti-neutrinos due to helicity

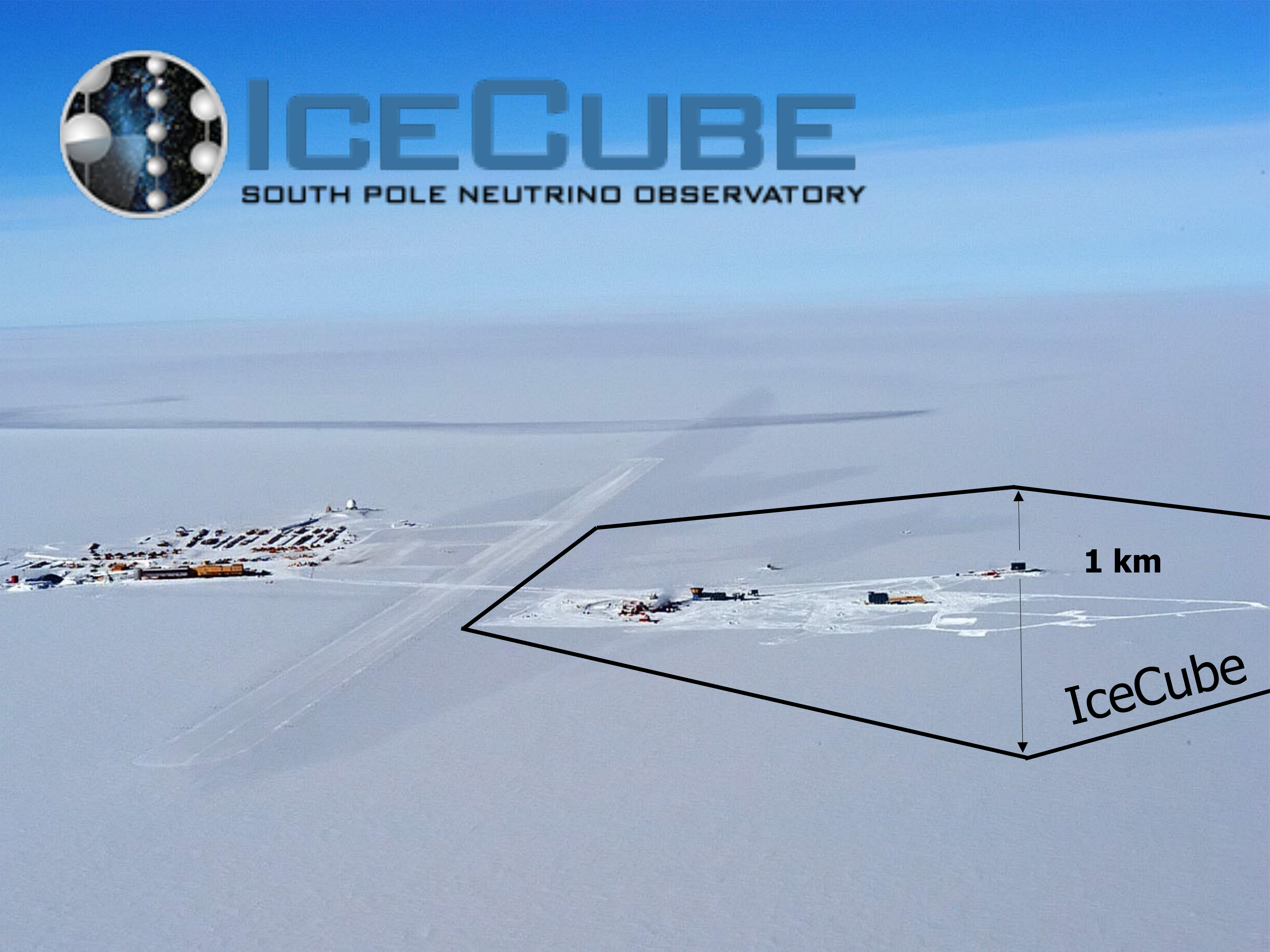
damped by the W-boson propagator

Absorption of High-Energy Neutrinos in the Earth



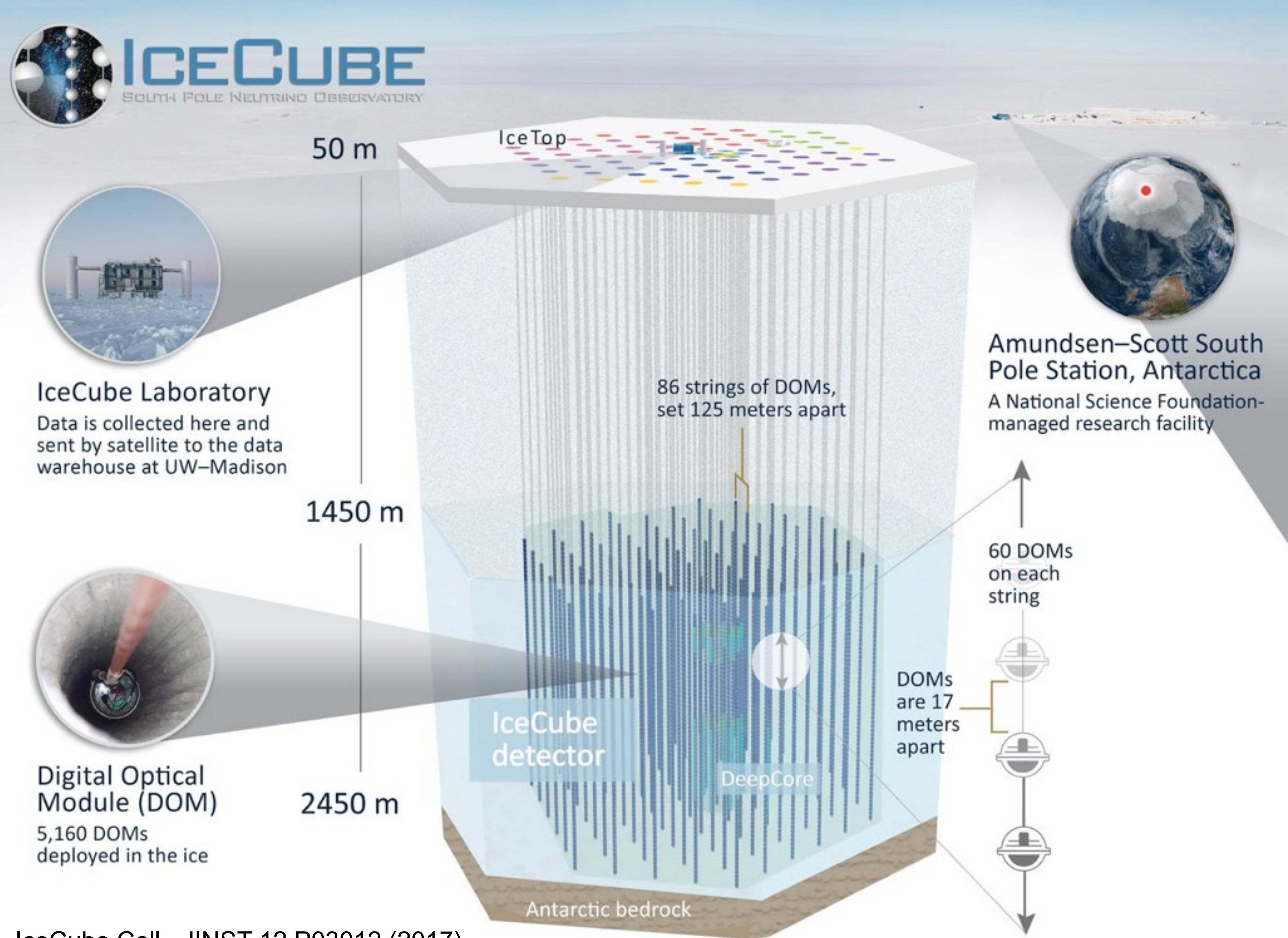
For high-energies Earth becomes opaque to neutrinos



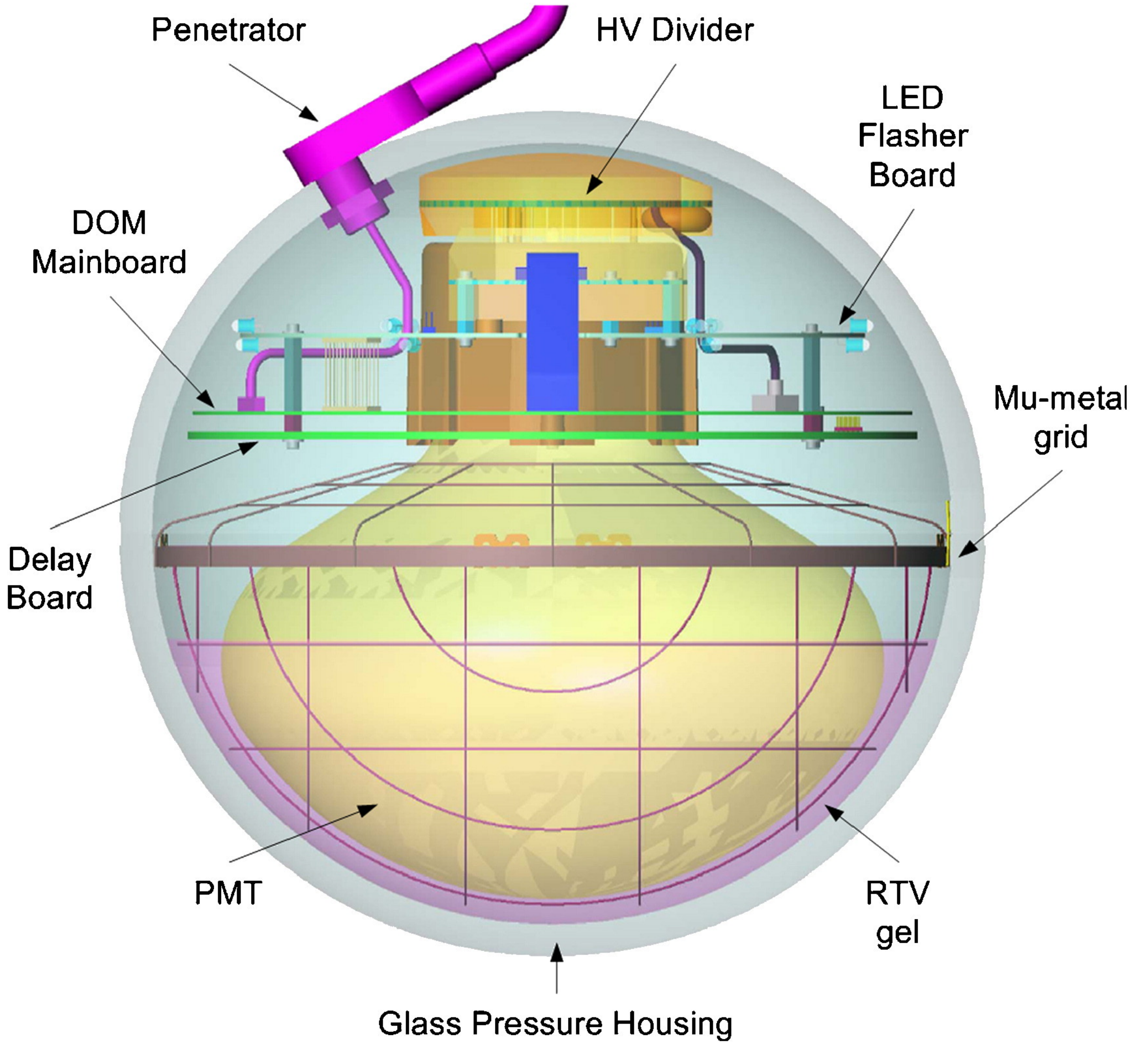

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
1 km
IceCube

The South Pole

Elevation: 2,835 m
Average temperate: -28°C (summer), -60°C (winter)



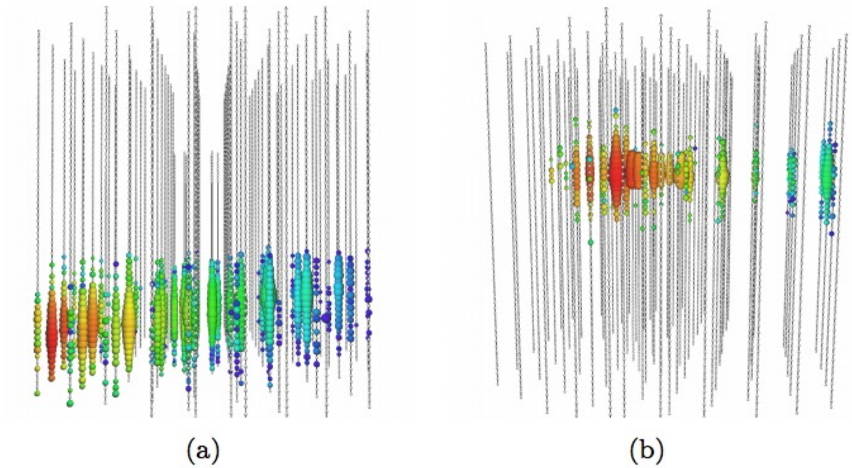
IceCube Coll., JINST 12 P03012 (2017)



5160 DOMs deployed
Failure rate: <0.3%

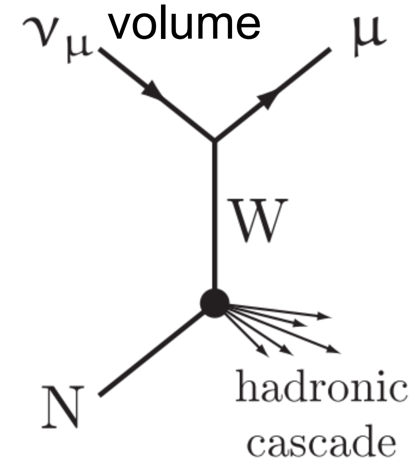
IceCube Coll., JINST 12 P03012 (2017)

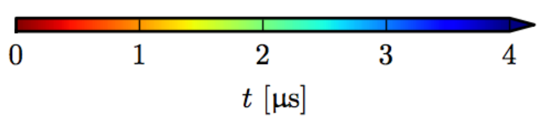
Event Signatures



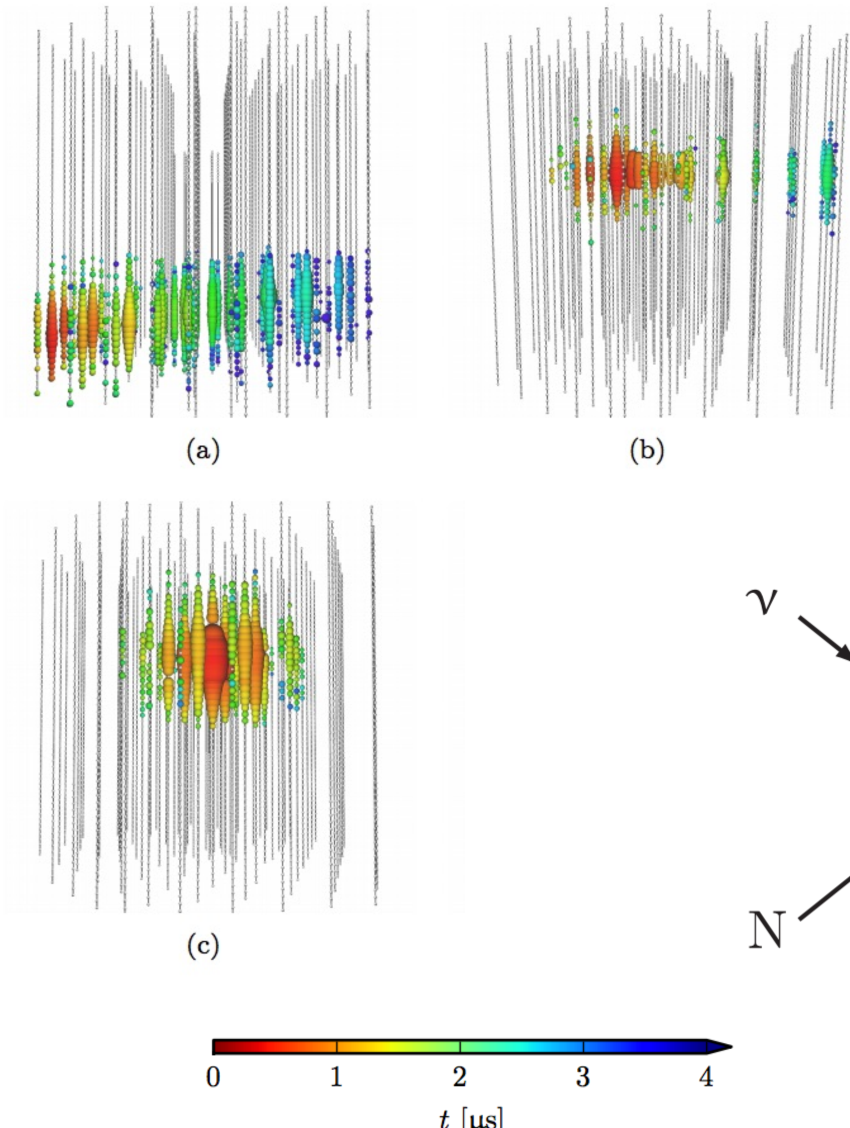
a) through-going muon track E ~ 140 TeV
b) Starting muon track E ~ 70 TeV

Charged current interaction of muon neutrino outside / inside the detector volume



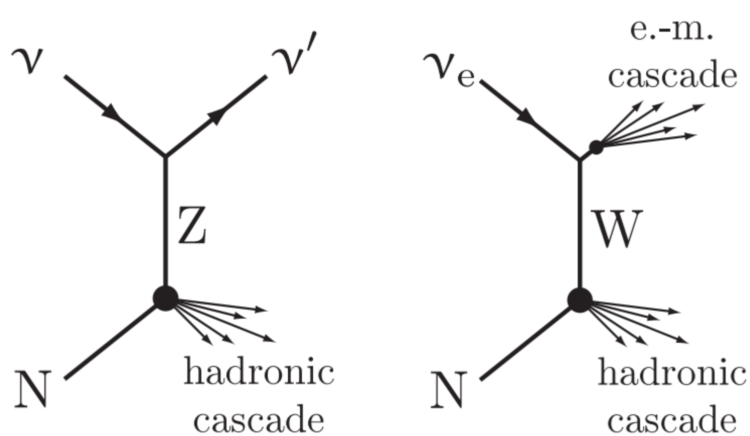


Event Signatures



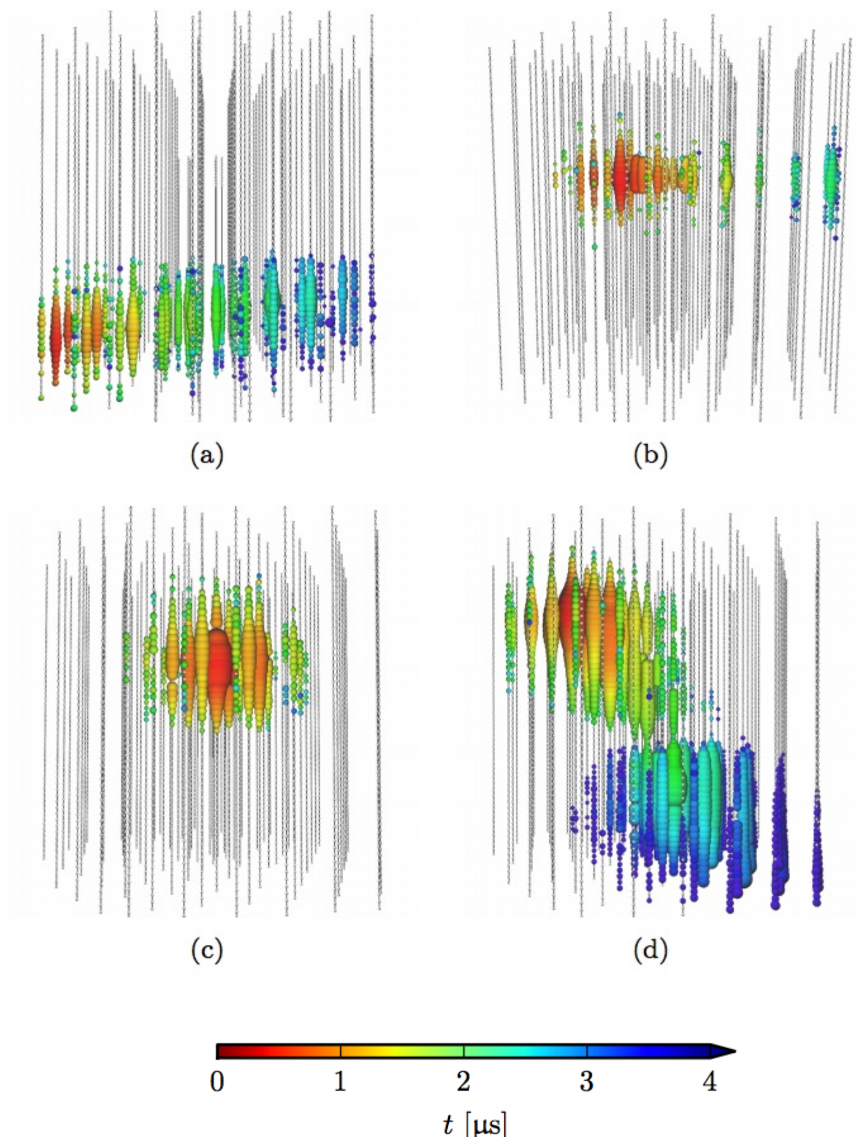
a) through-going muon track E ~ 140 TeV
b) Starting muon track E ~ 70 TeV
c) Shower event E ~ 1 PeV

Neutral current or electron neutrino charged current interaction



Cannot distinguish between showers (size few meters)

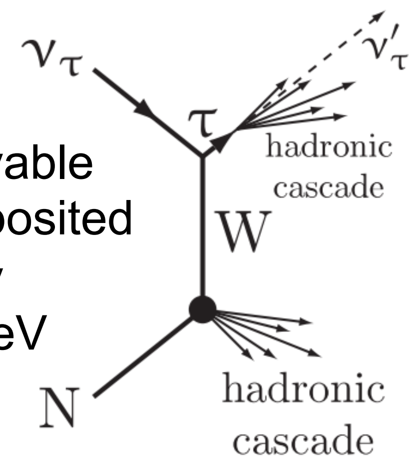
Event Signatures



a) through-going muon track E ~ 140 TeV
b) Starting muon track E ~ 70 TeV
c) Shower event E ~ 1 PeV
d) "double bang" event E ~ 200 PeV

Tau neutrino charged current interaction

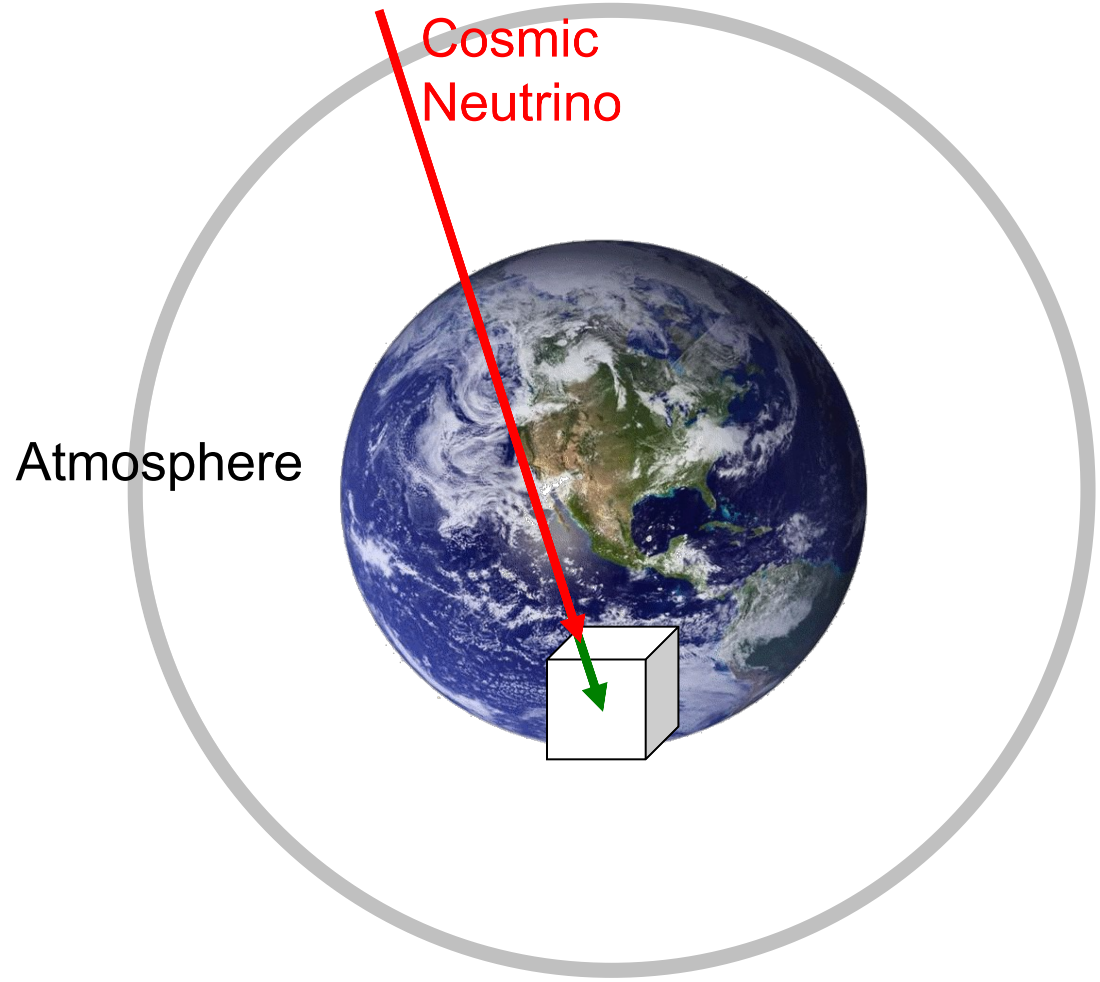
Resolvable for deposited energy >100TeV



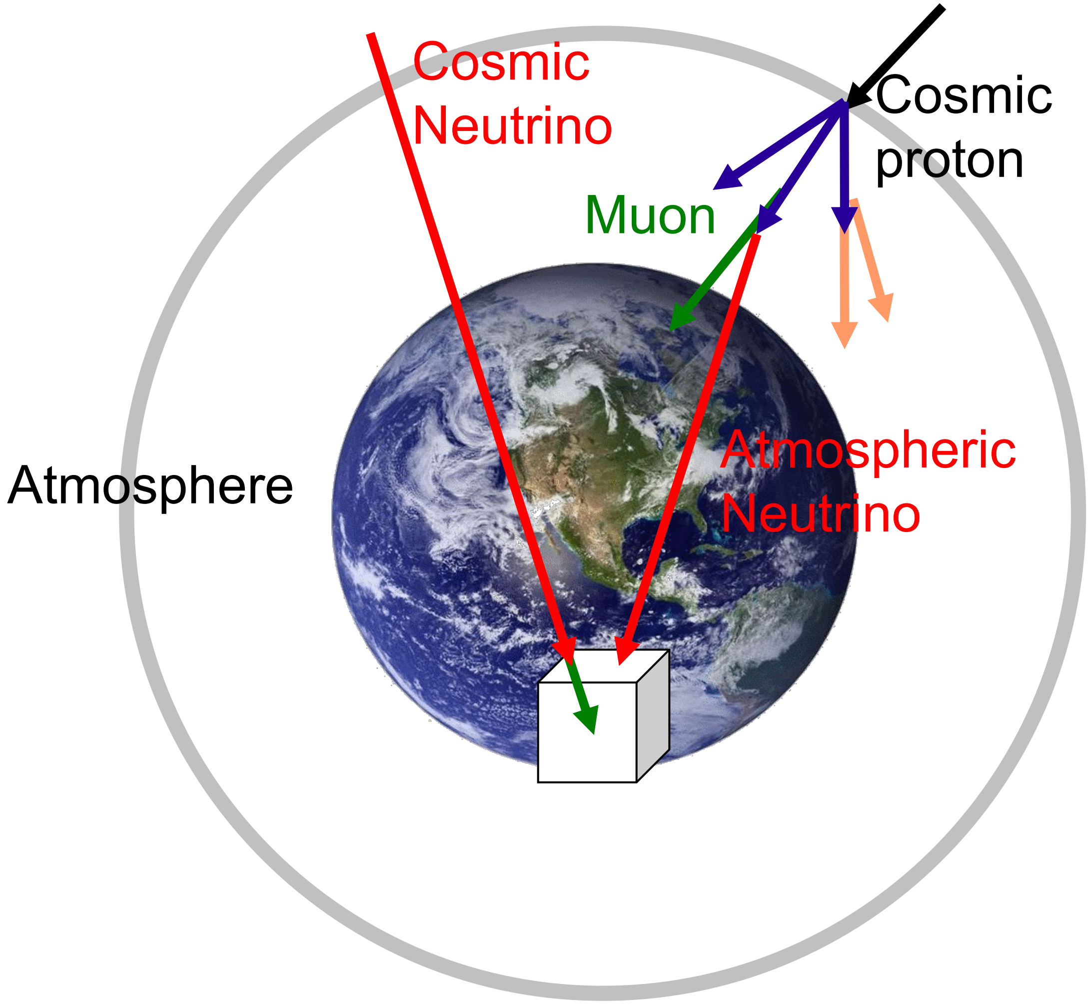
Only for very large energies the two showers can be separated (otherwise signature c)

RUB

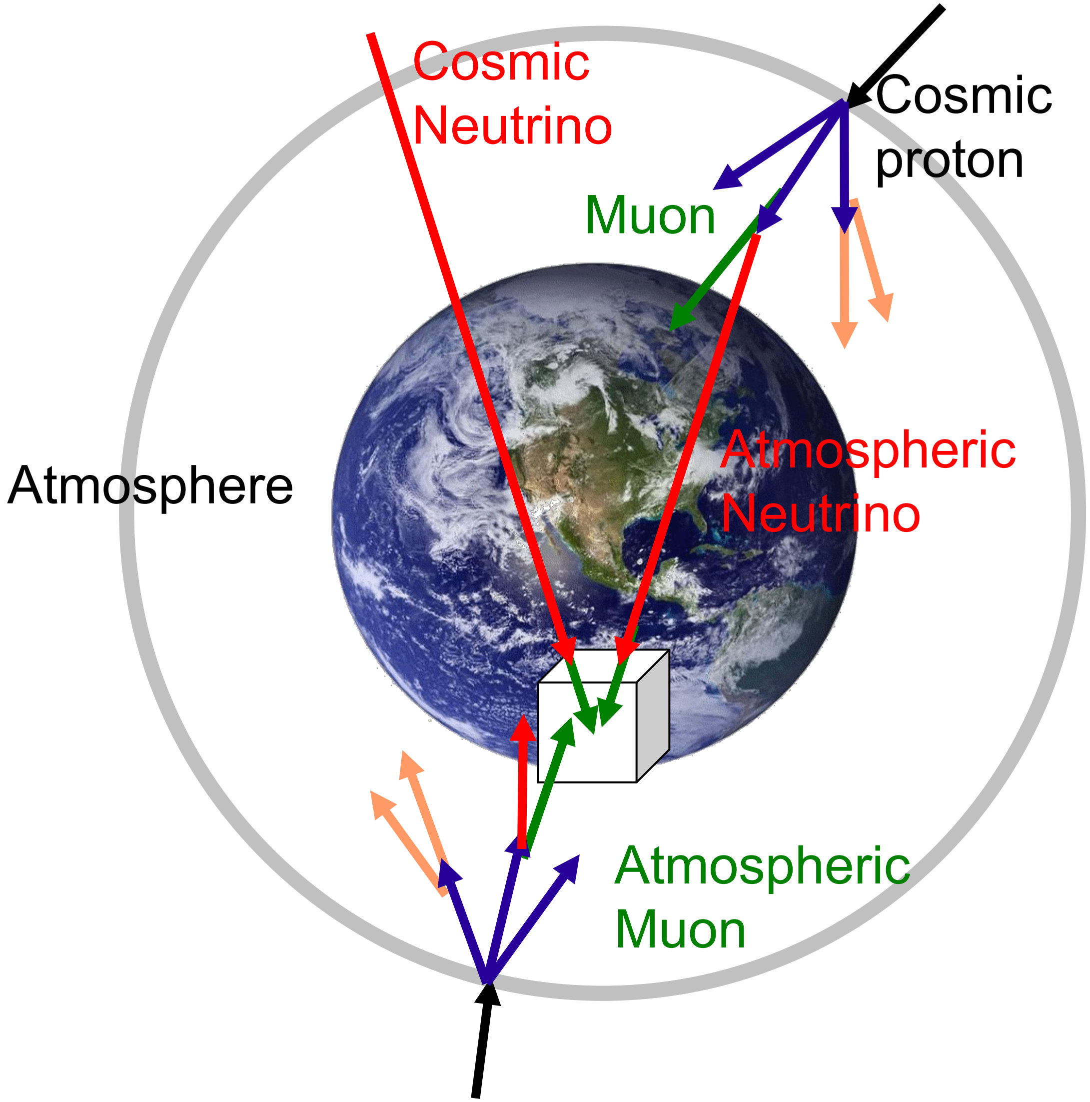
Background in Search for Cosmic Neutrinos



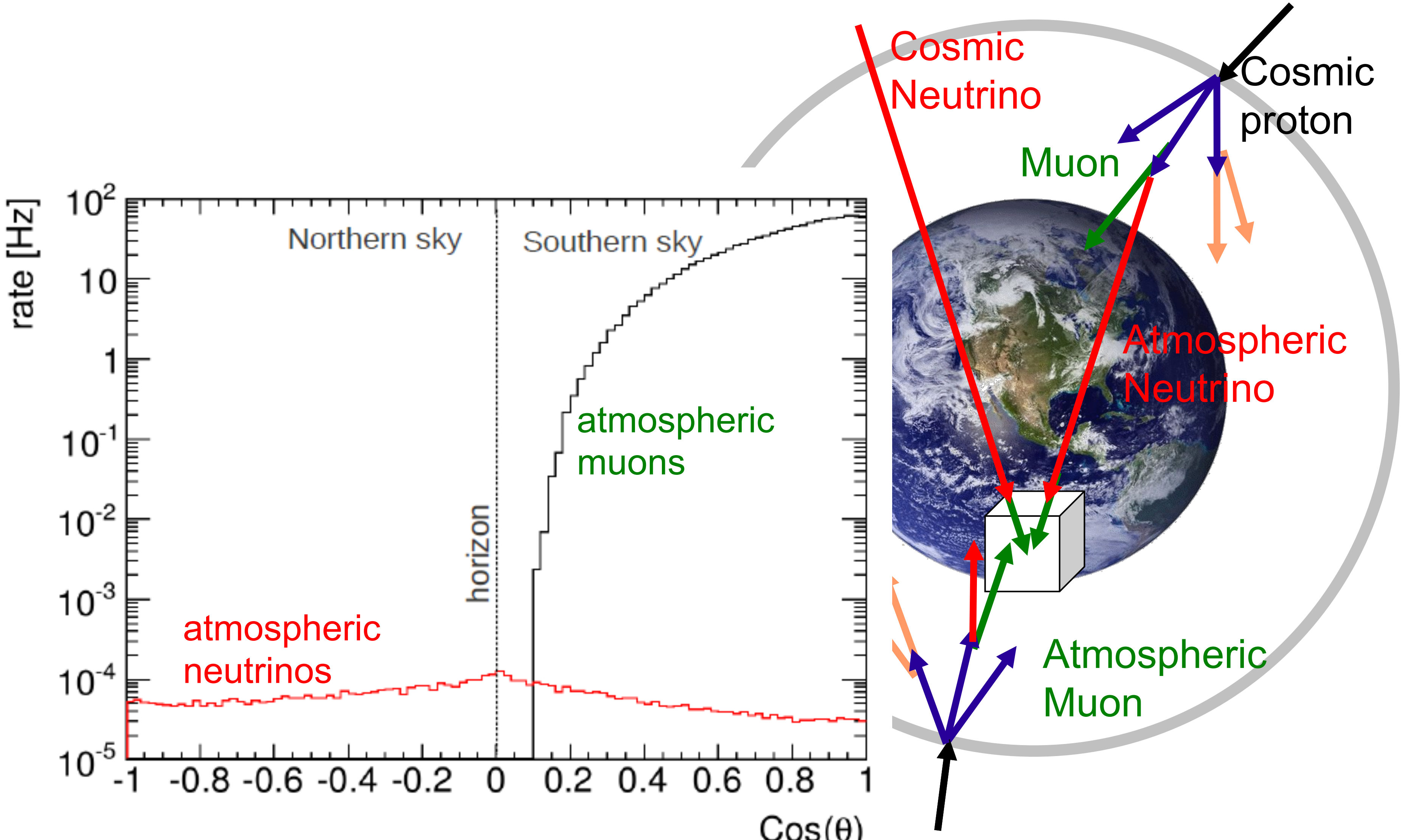
Background in Search for Cosmic Neutrinos



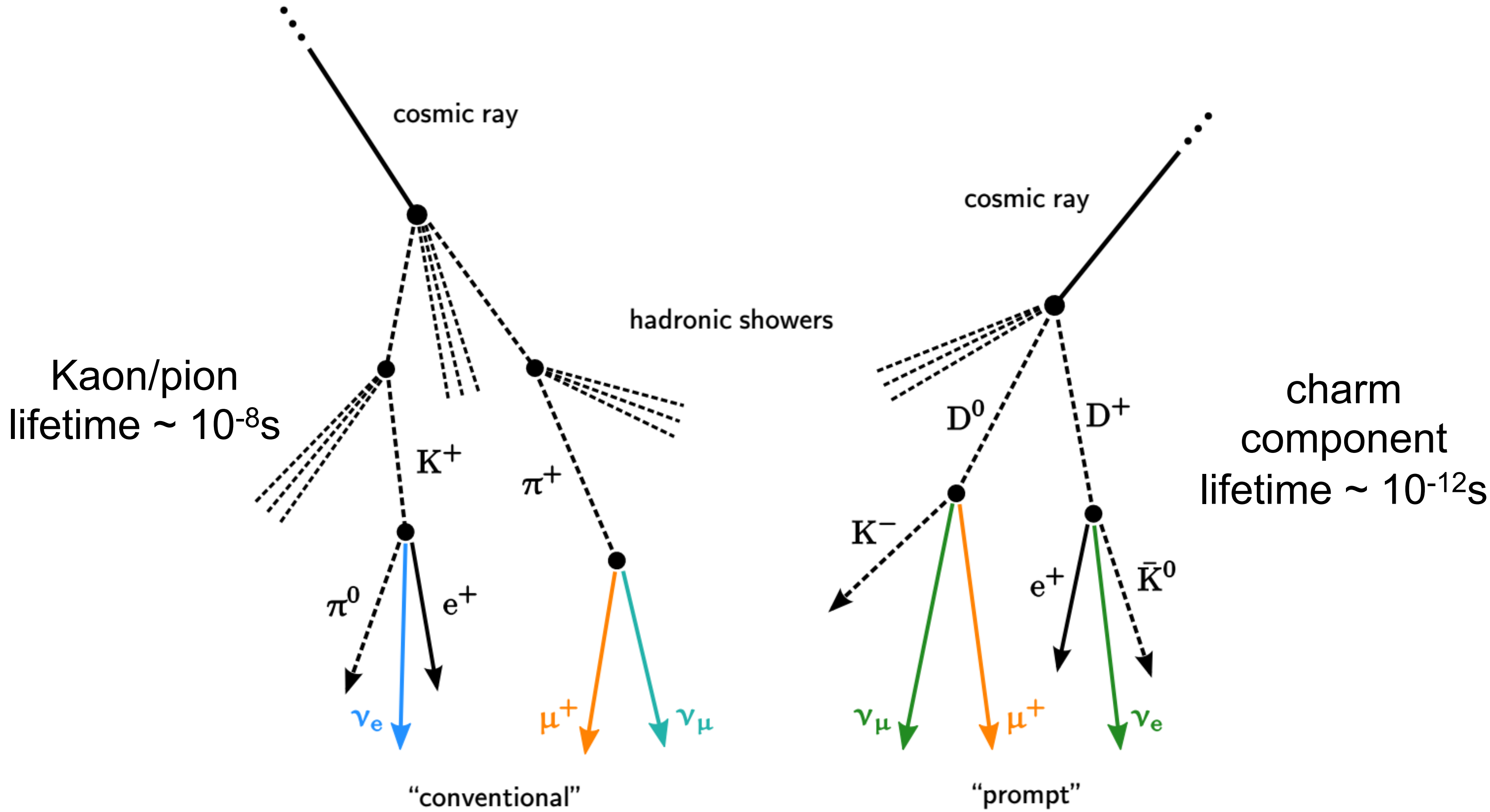
Background in Search for Cosmic Neutrinos



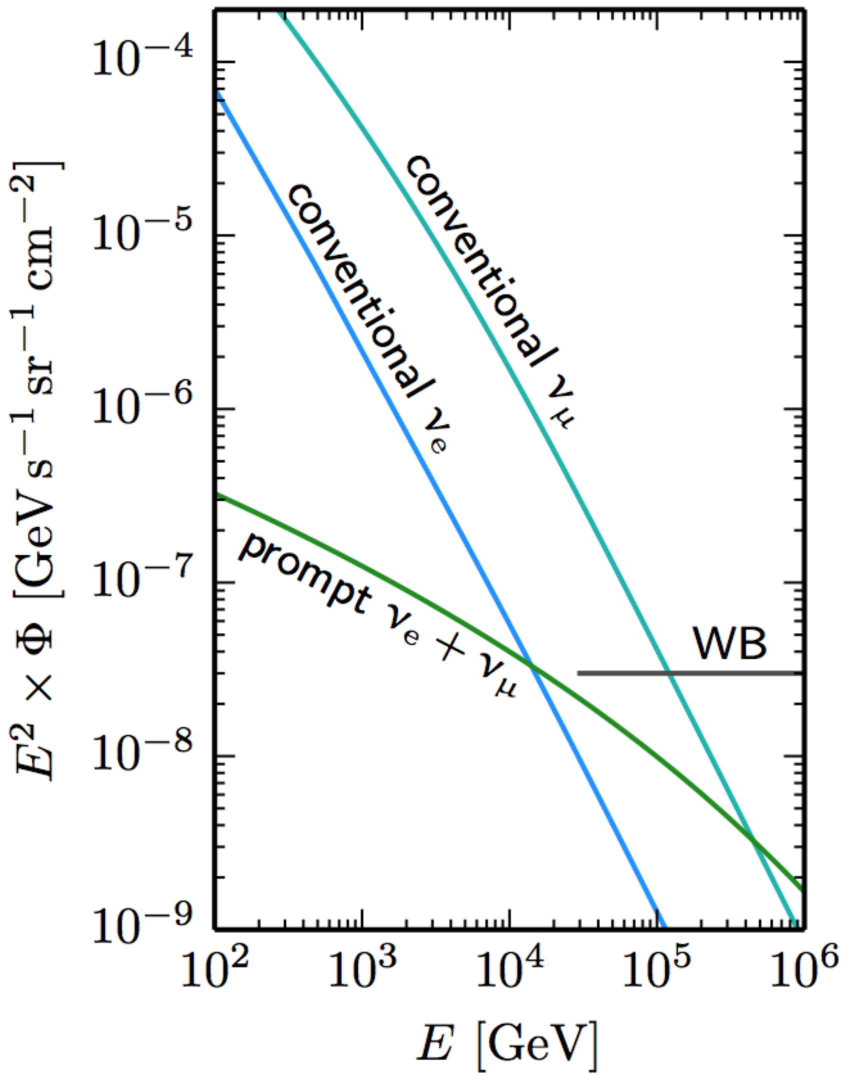
Background in Search for Cosmic Neutrinos



Atmospheric Neutrinos - Production

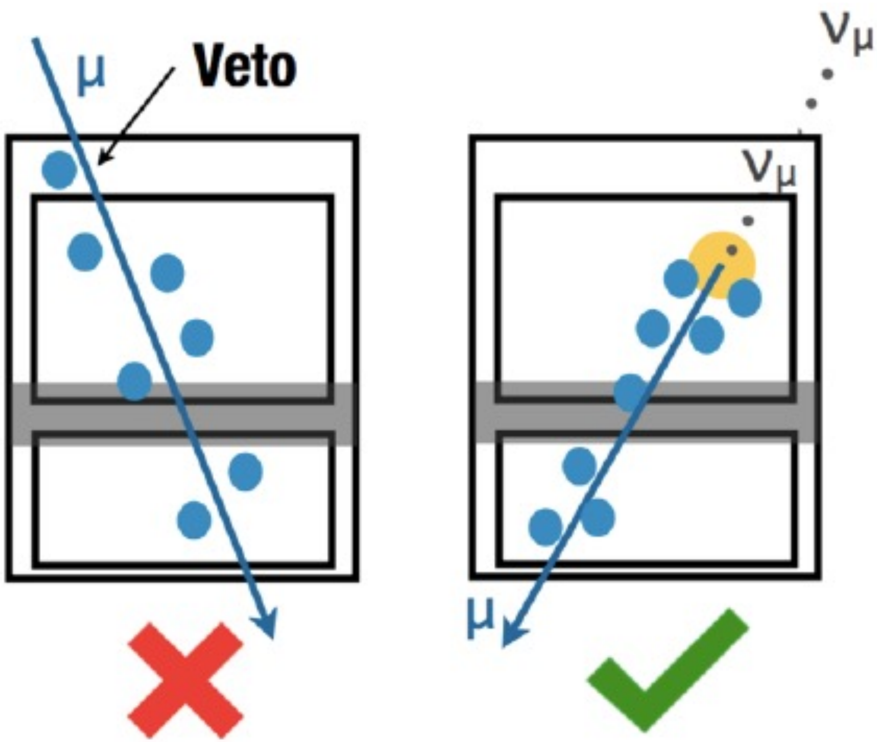


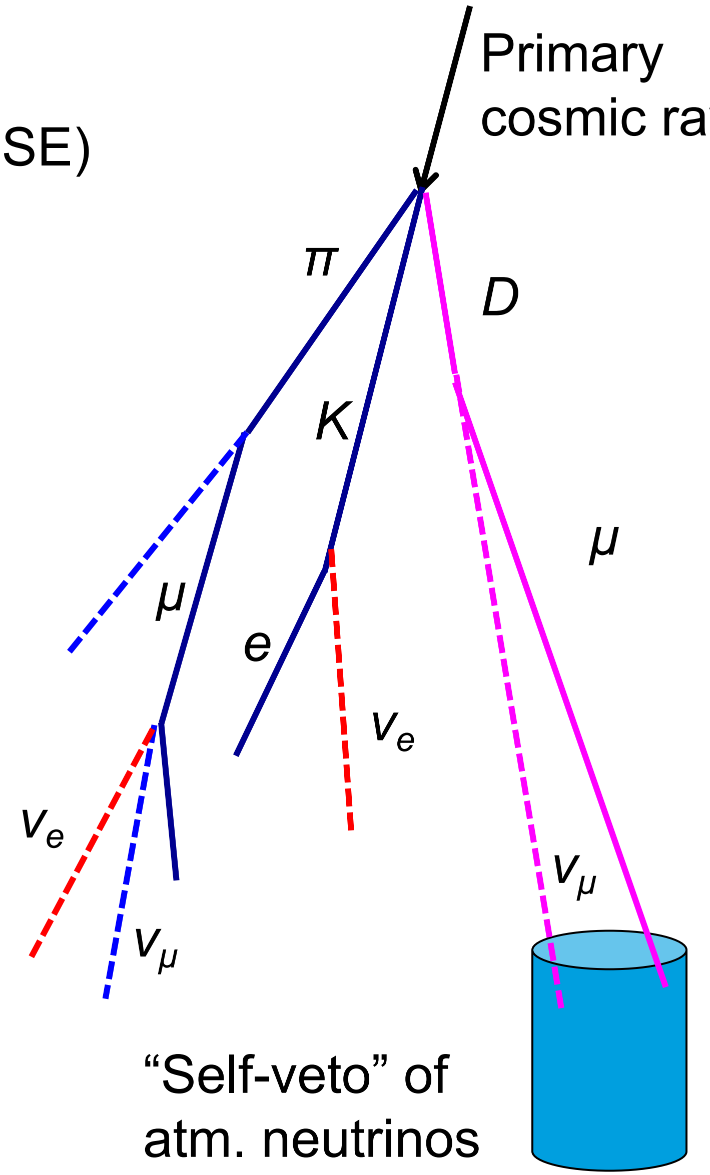
Atmospheric Neutrinos - Spectrum



Vetoing Atmospheric Muons and Neutrinos

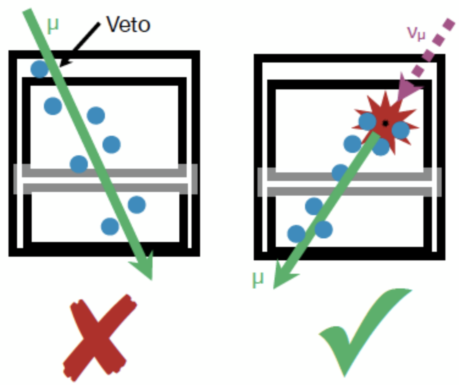
Selection of high-energy starting events (HESE)

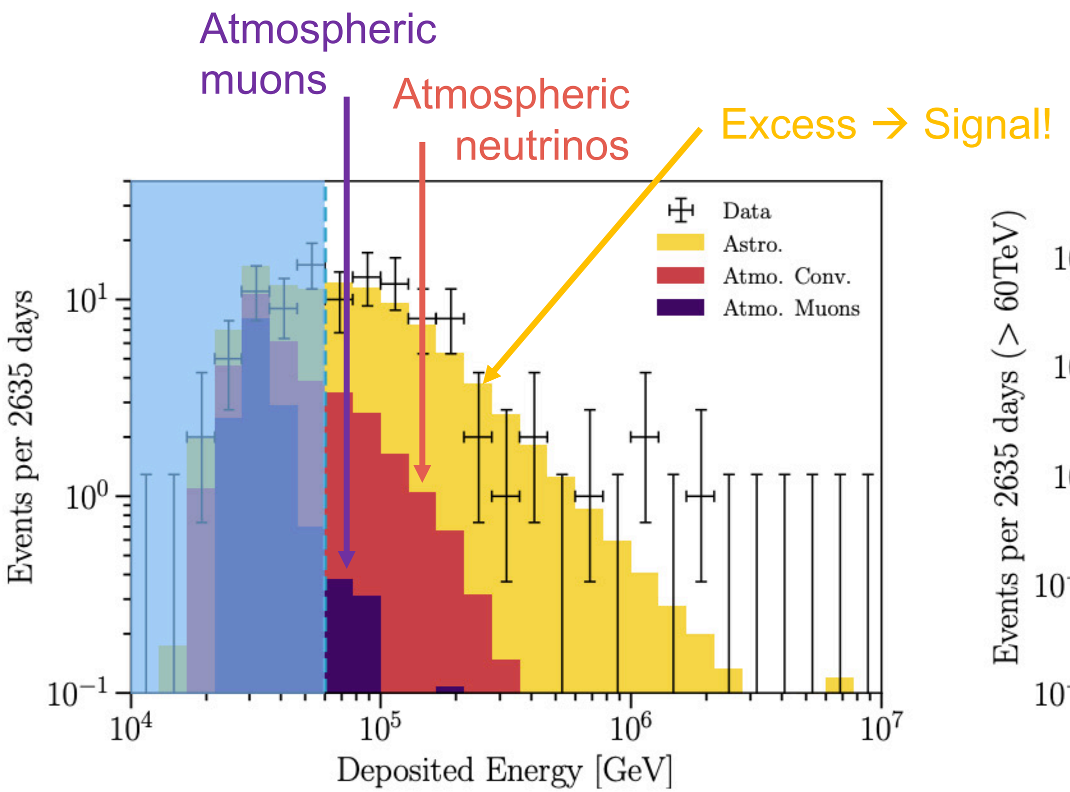


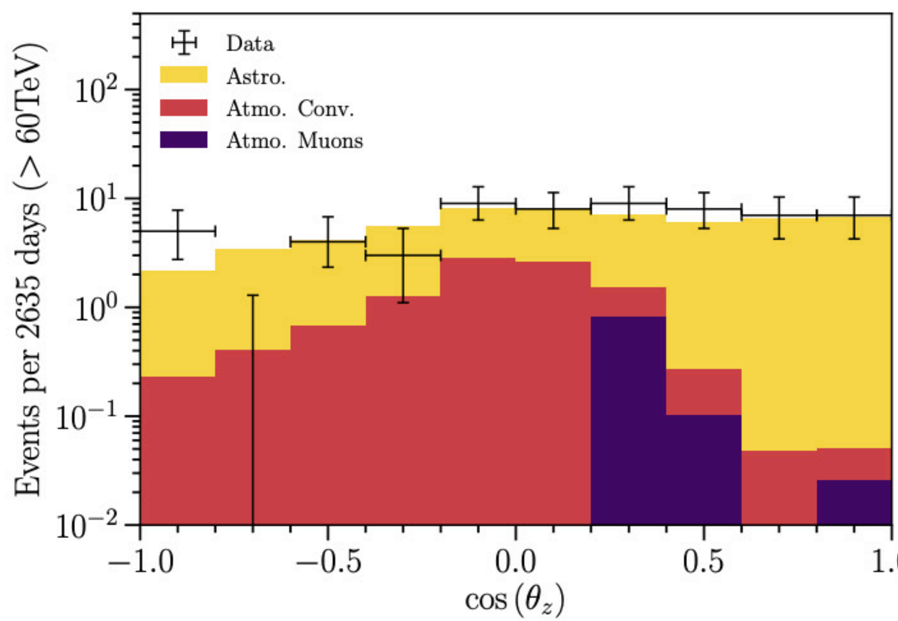


“Self-veto” of atm. neutrinos

Discovery of High-Energy Astrophysical Neutrinos





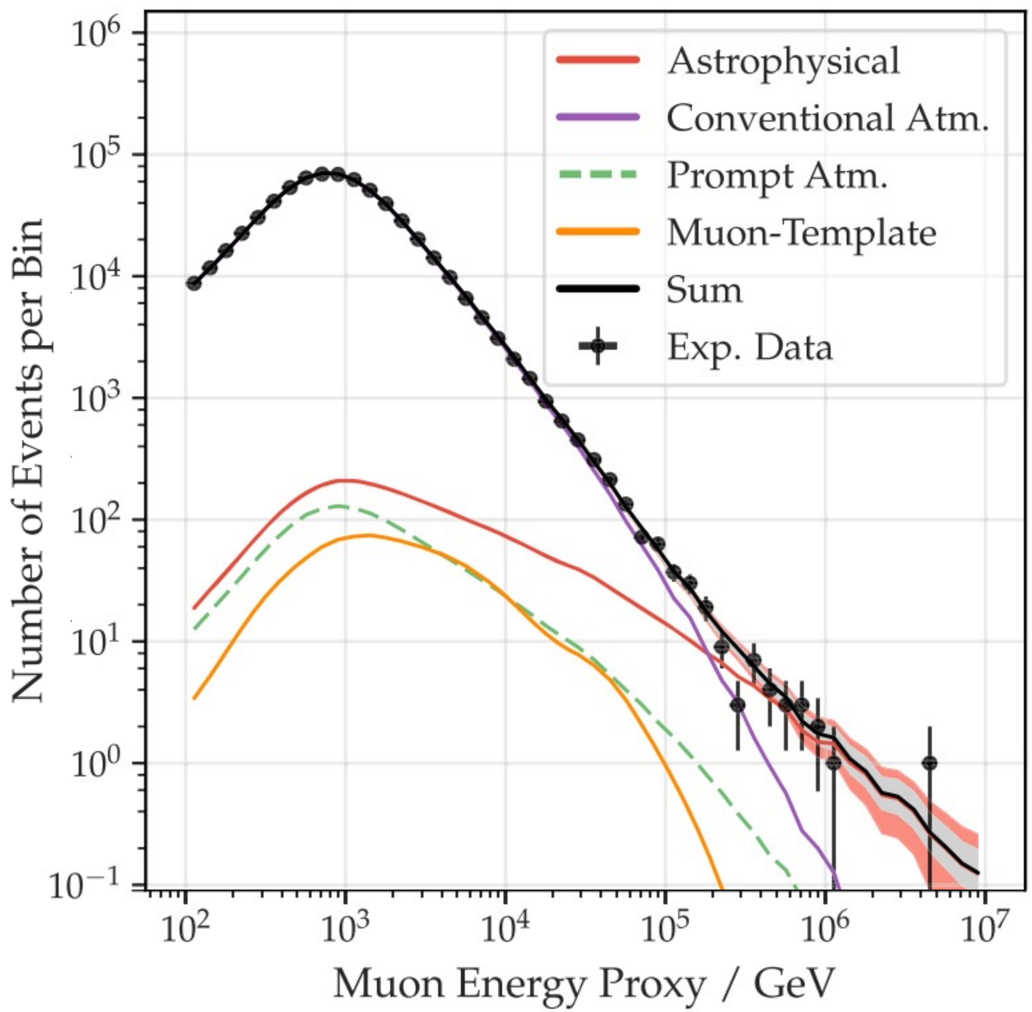


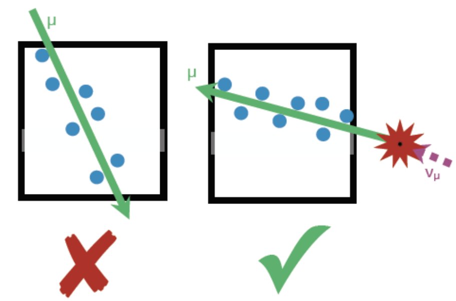
Northern sky

Southern sky

IceCube Coll., Science 342, 2013, PRL 113, 101101 (2014)

Diffuse flux now seen in different channels

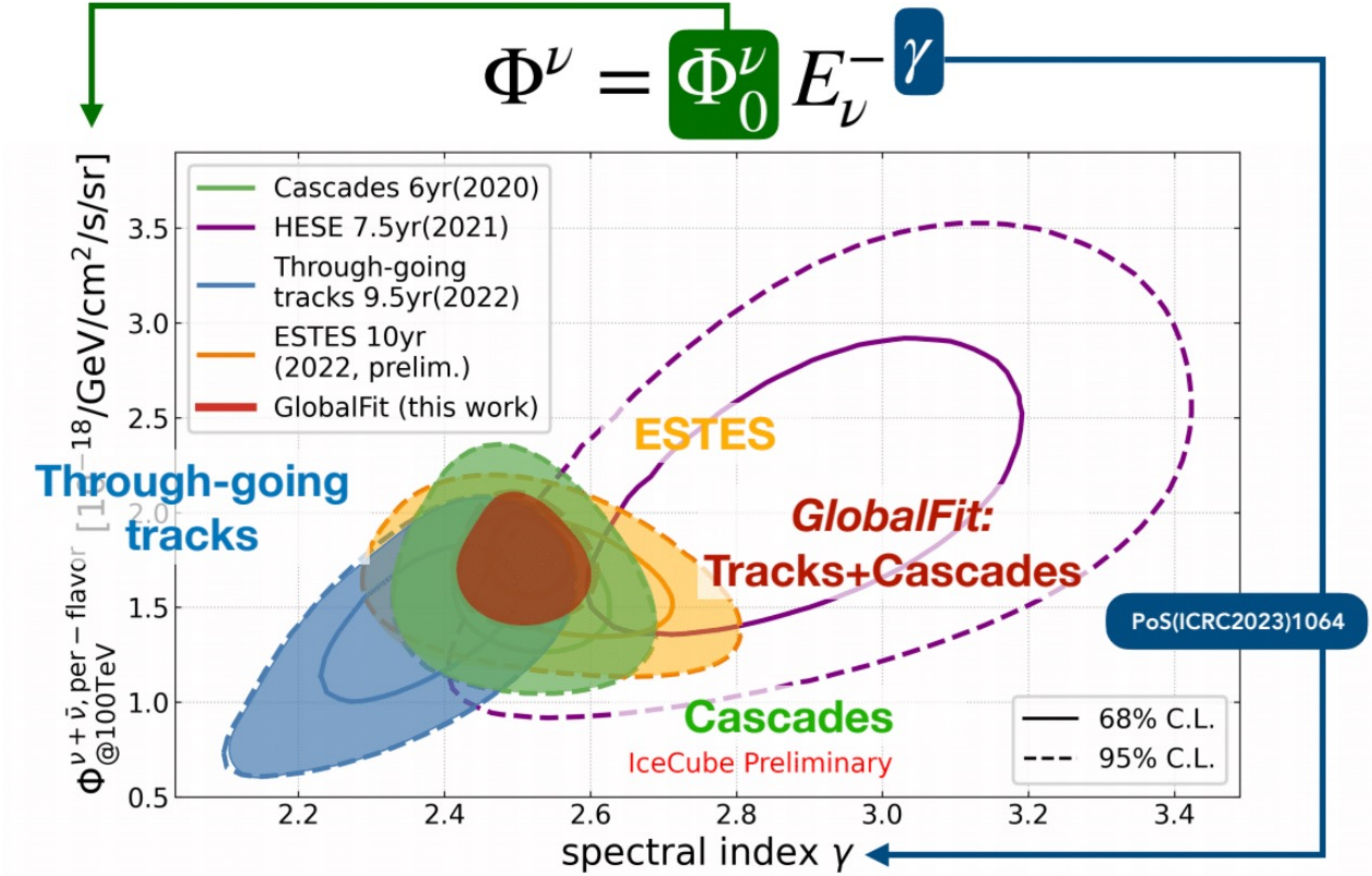




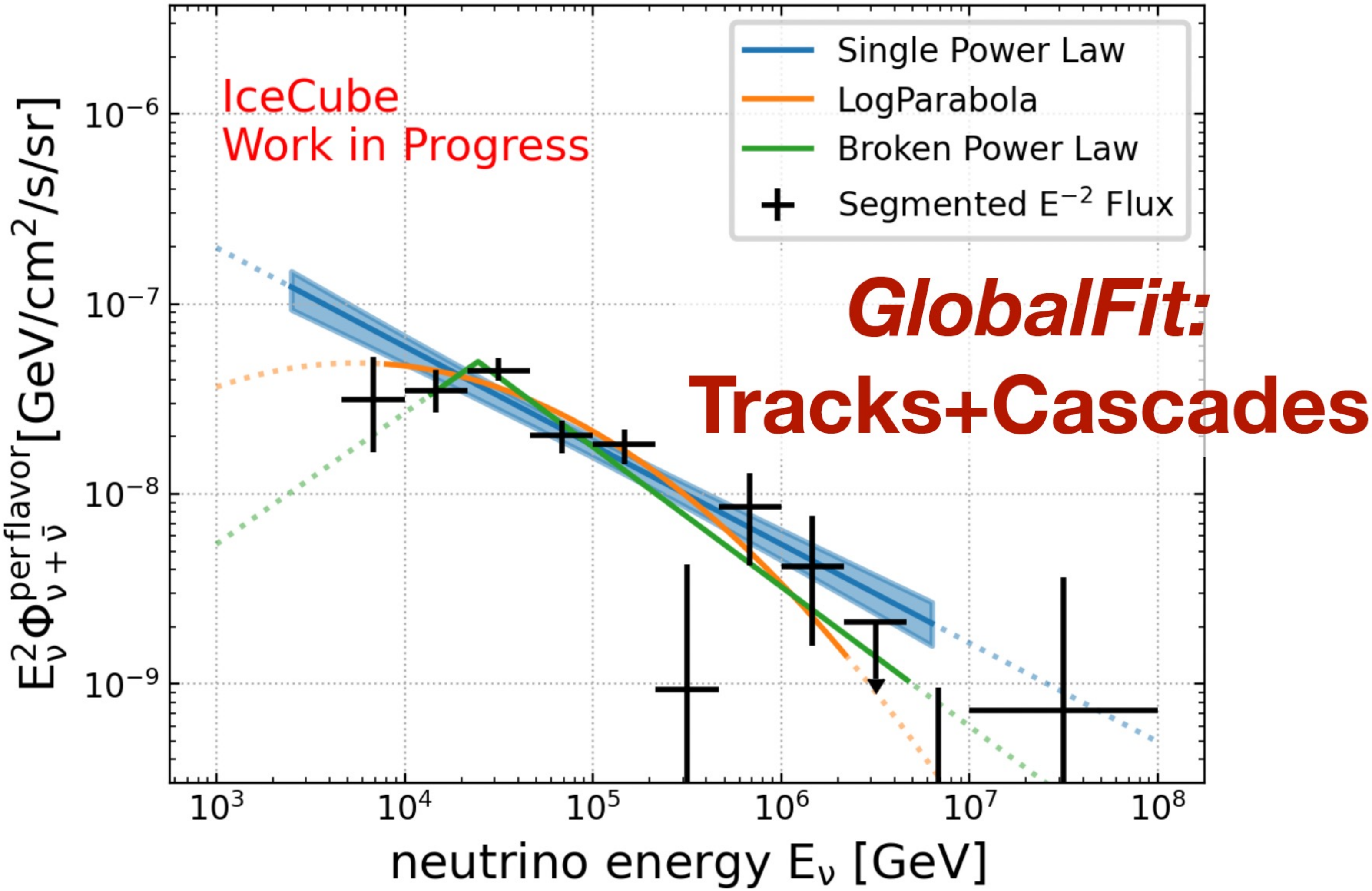
- Selected horizontal and up-going muon tracks
- Sensitive to astrophysical neutrinos above ~100 TeV

R. Abbasi *et al* 2022 *ApJ* **928** 50

Spectrum of diffuse flux



Spectrum of diffuse flux: not a power law?

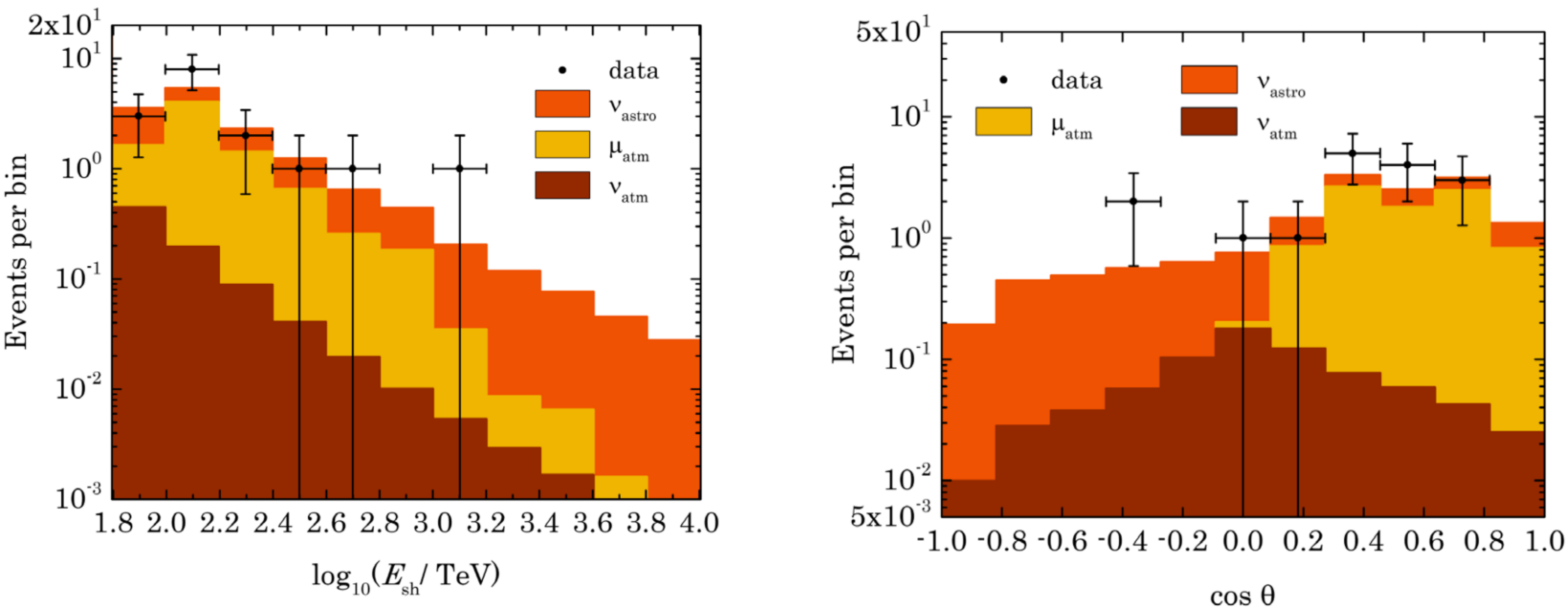


PoS(ICRC2023)1064

Can other neutrino detectors see the diffuse flux?

RUB

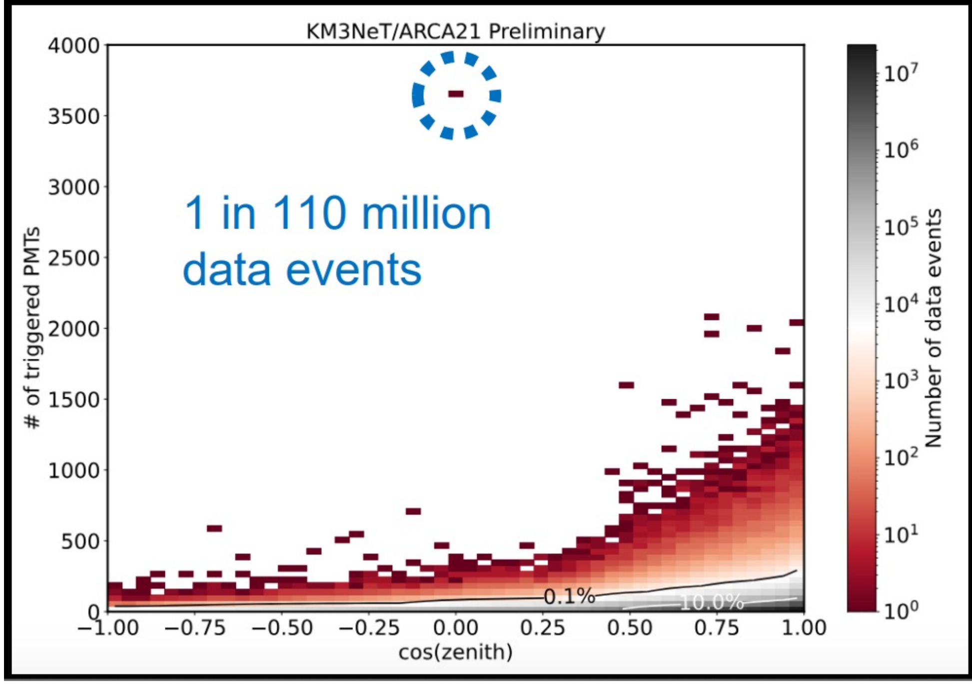
First hint for diffuse flux with Baikal-GVD

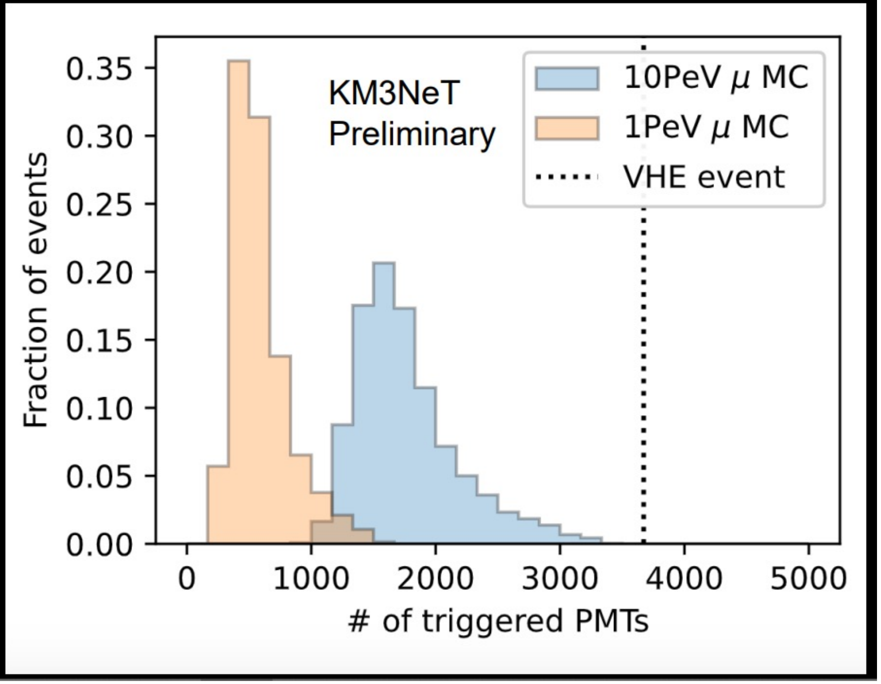


V. A. Allakhverdyan *et al.* (Baikal-GVD Collaboration) PRD **107**, 042005

Exciting First Results from KM3NeT

- Significant event observed with huge amount of light
- Horizontal event (1° above horizon) as expected since earth opaque to neutrinos at PeV scale
- 3672 PMTs (35%) were triggered in the detector
- Muons simulated at 10 PeV almost never generate this much light
  - Likely multiple 10's of PeV





Exciting First Results from KM3NeT

- Significant event observed with huge amount of light
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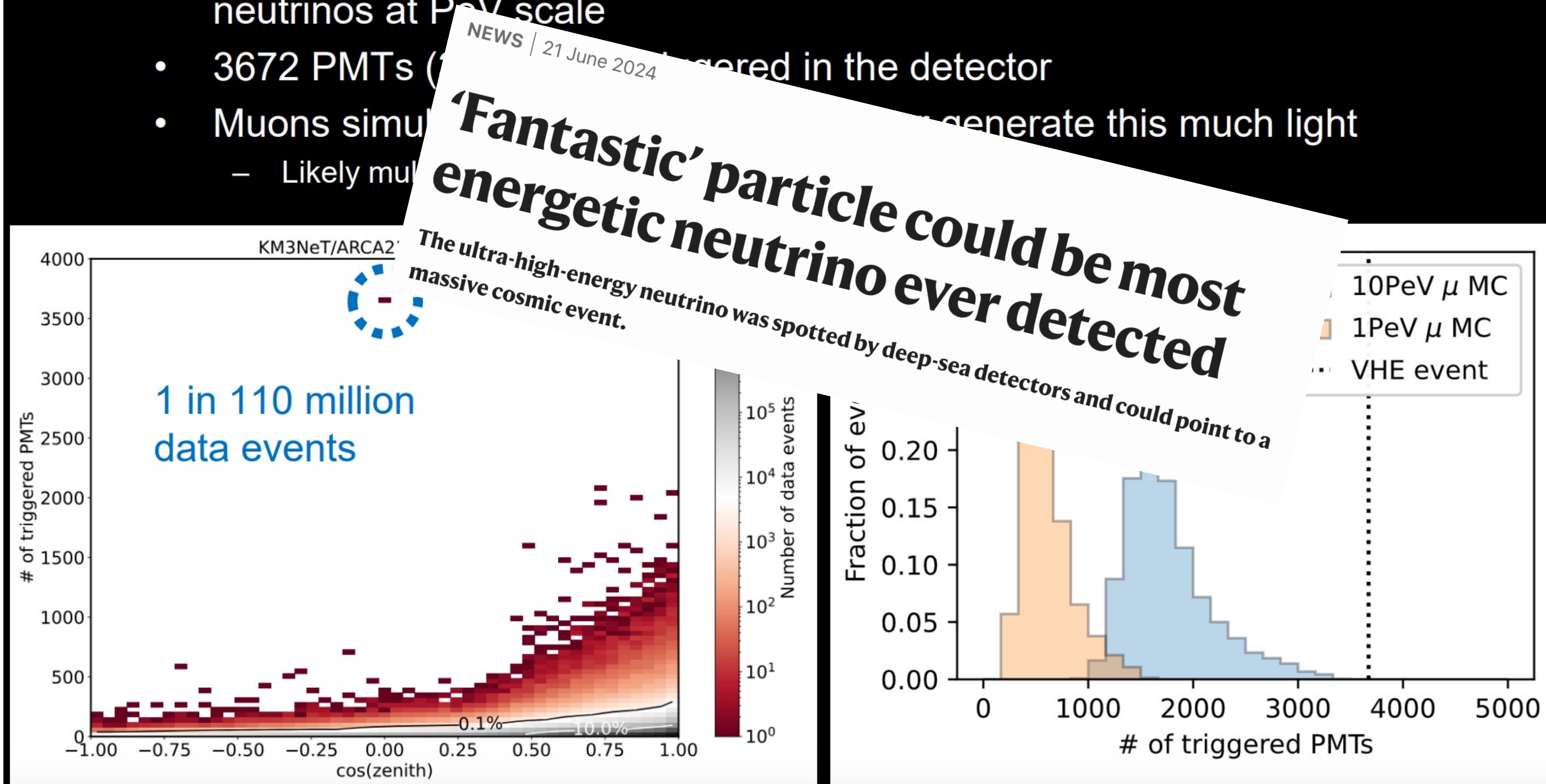
  - Likely mul…



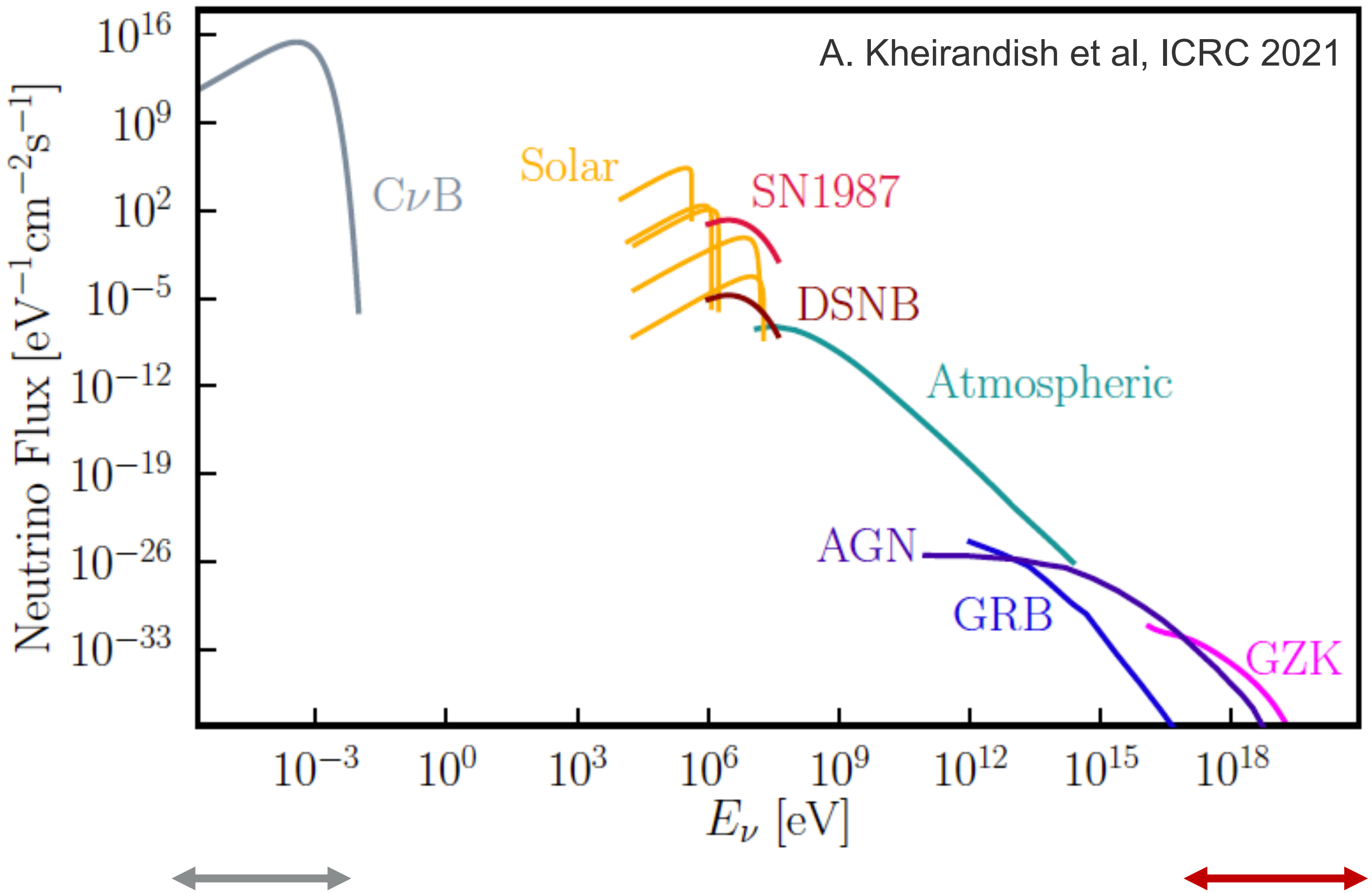
NEWS | 21 June 2024

‘Fantastic’ particle could be most energetic neutrino ever detected

The ultra-high-energy neutrino was spotted by deep-sea detectors and could point to a massive cosmic event.

What are the sources of the high-energy diffuse neutrino flux?

→ Next lecture



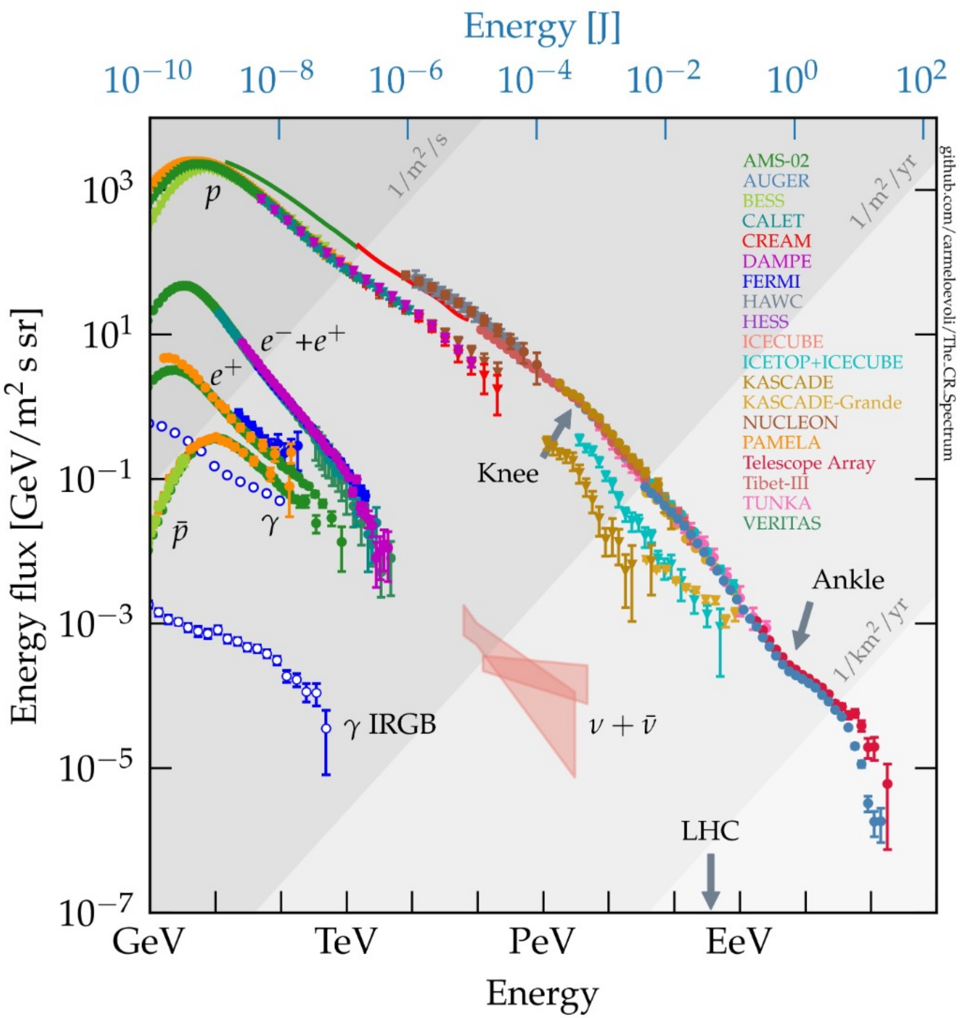
Ideas: neutrino capture on unstable nucleus (e.g. tritium)

Neutrino capture on stable nucleus (Chlorine, Gallium)

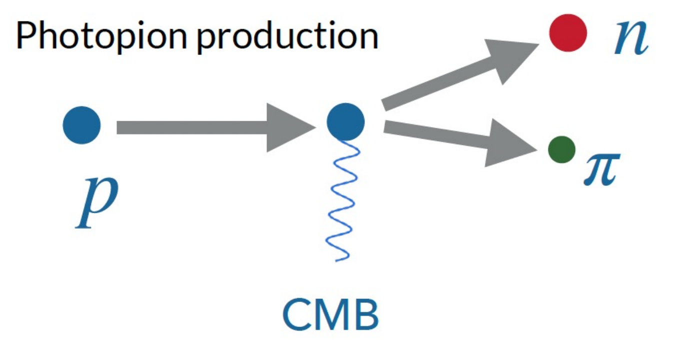
Water / ice Cherenkov detectors

Radio arrays, cosmic-ray detectors

Cosmogenic Neutrinos



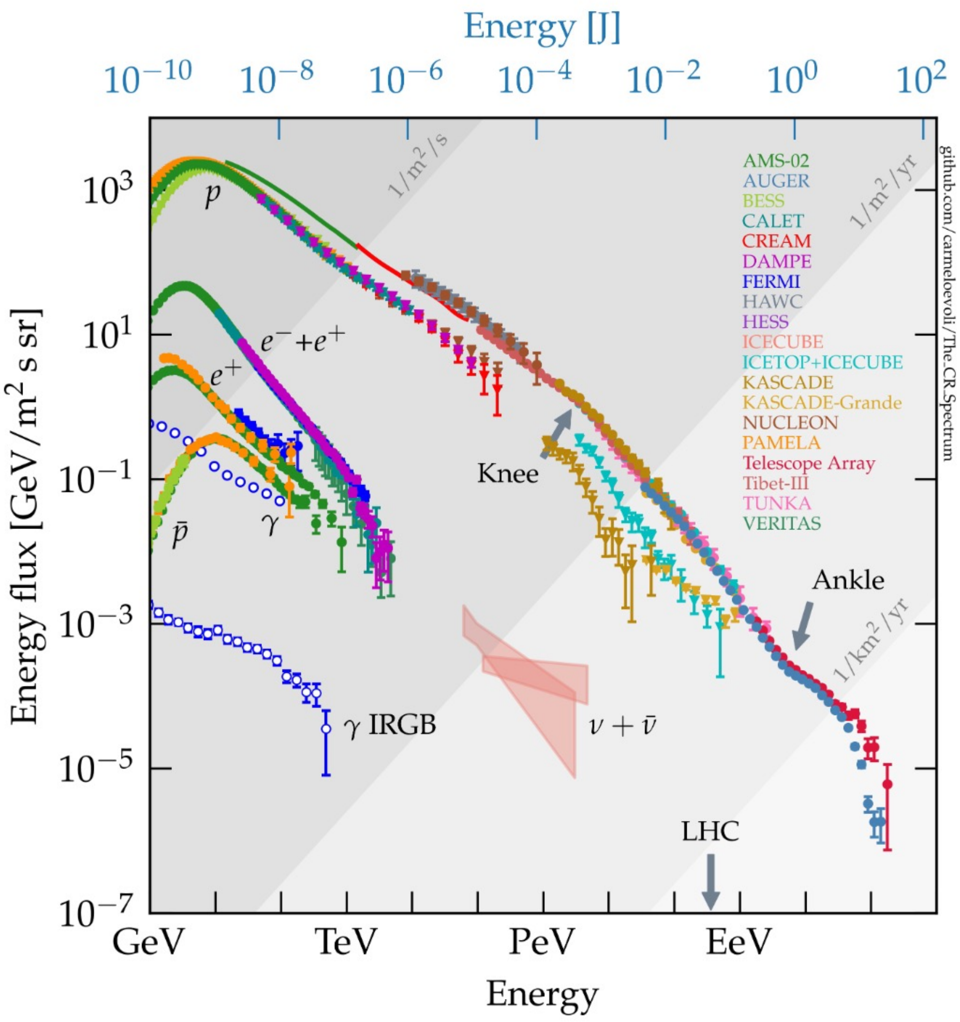
For Protons:



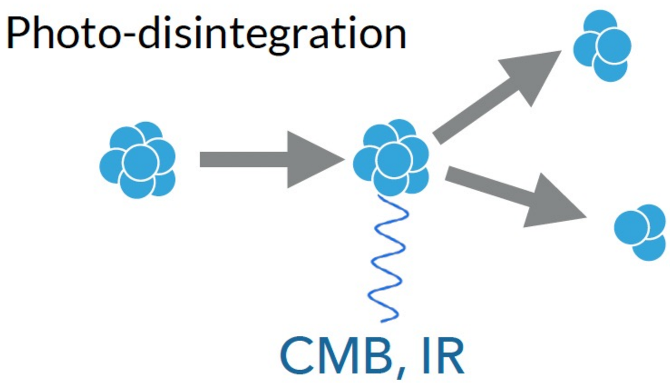
$$p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases}$$

Energy Threshold: $5 \cdot 10^{19} eV$

Cosmogenic Neutrinos



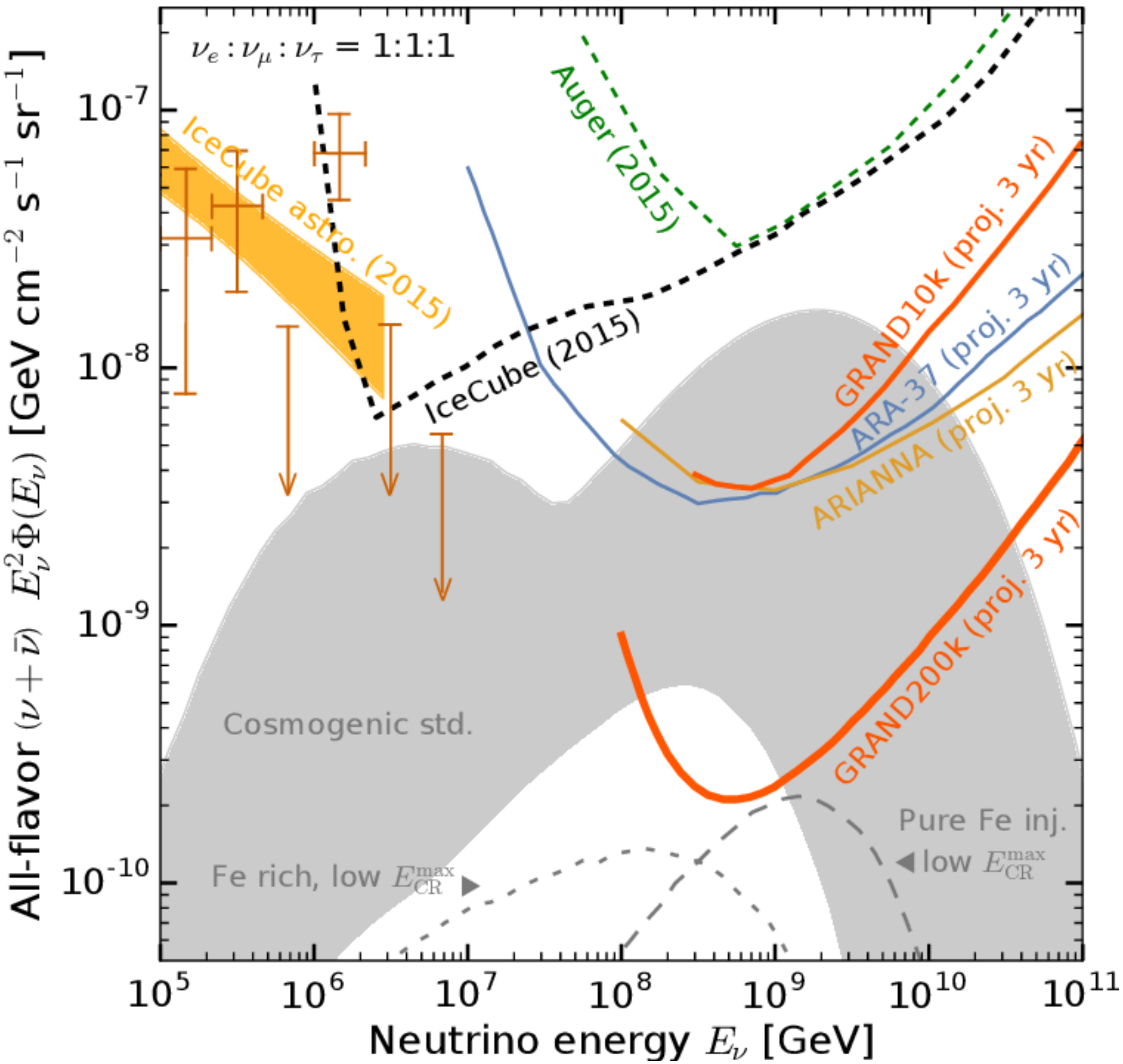
For heavier elements:



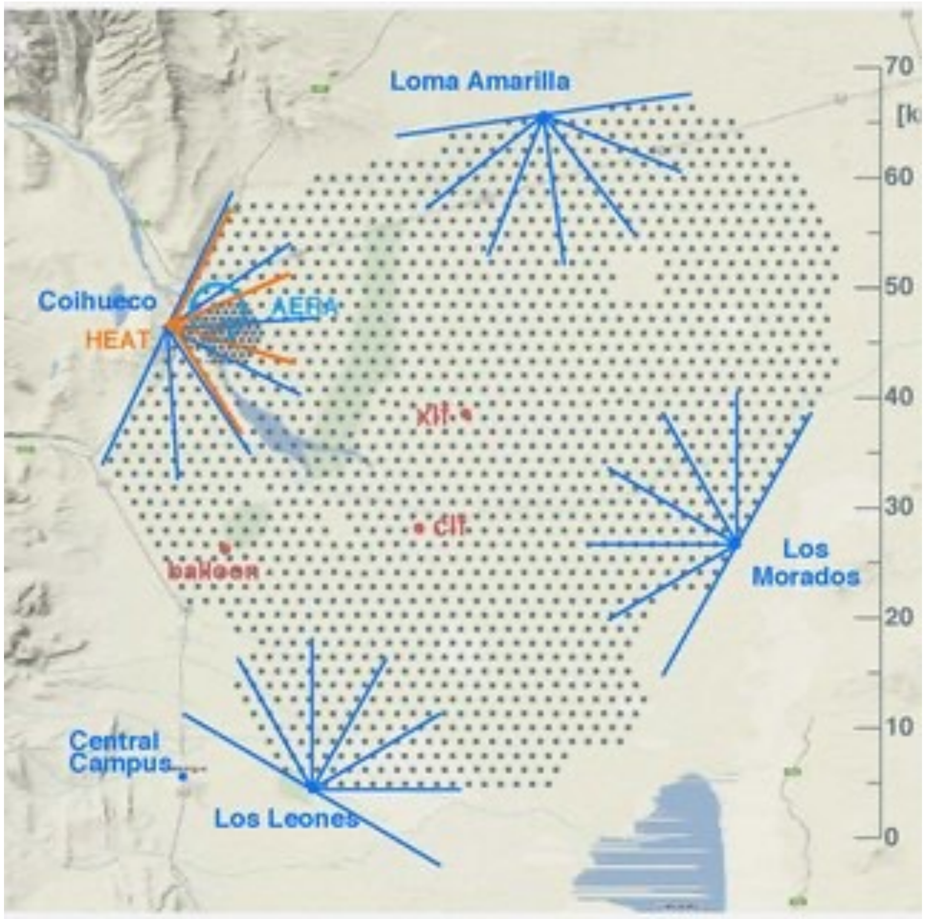
→ Neutrinos can help to infer the composition

RUB

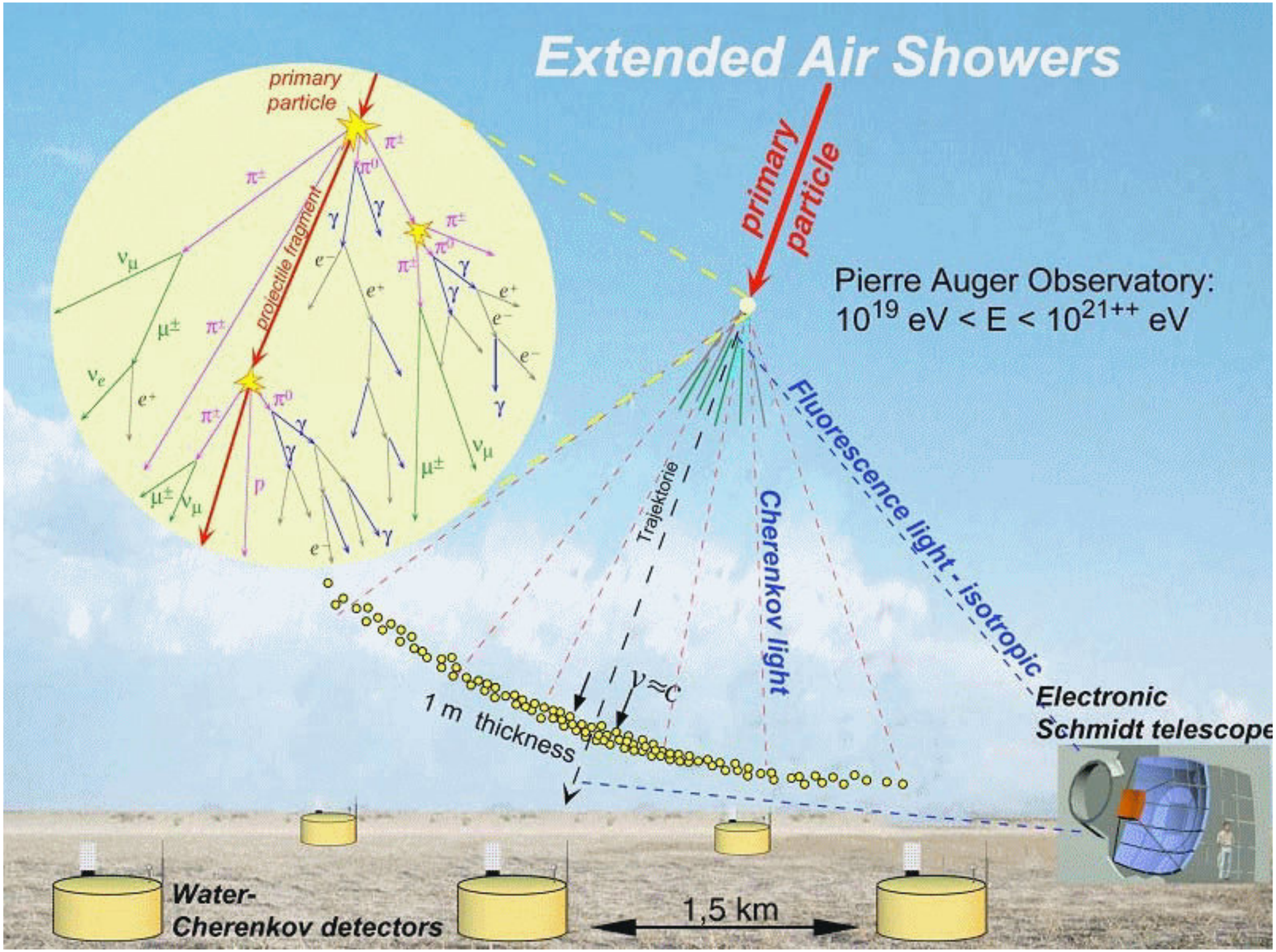
Cosmogenic Neutrinos



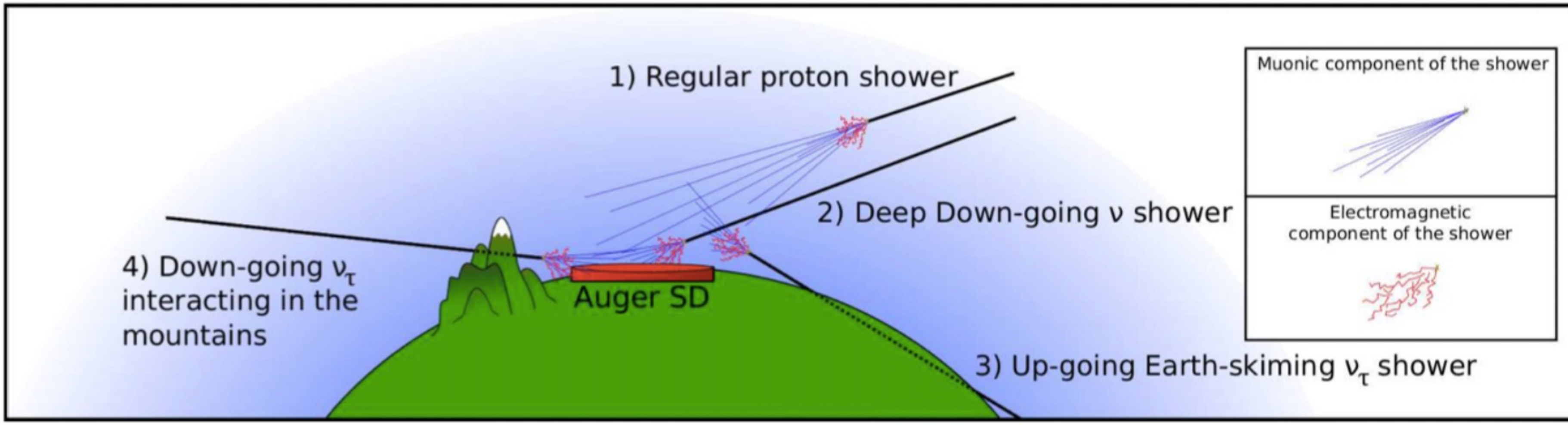
Neutrinos with the Pierre Auger Observatory



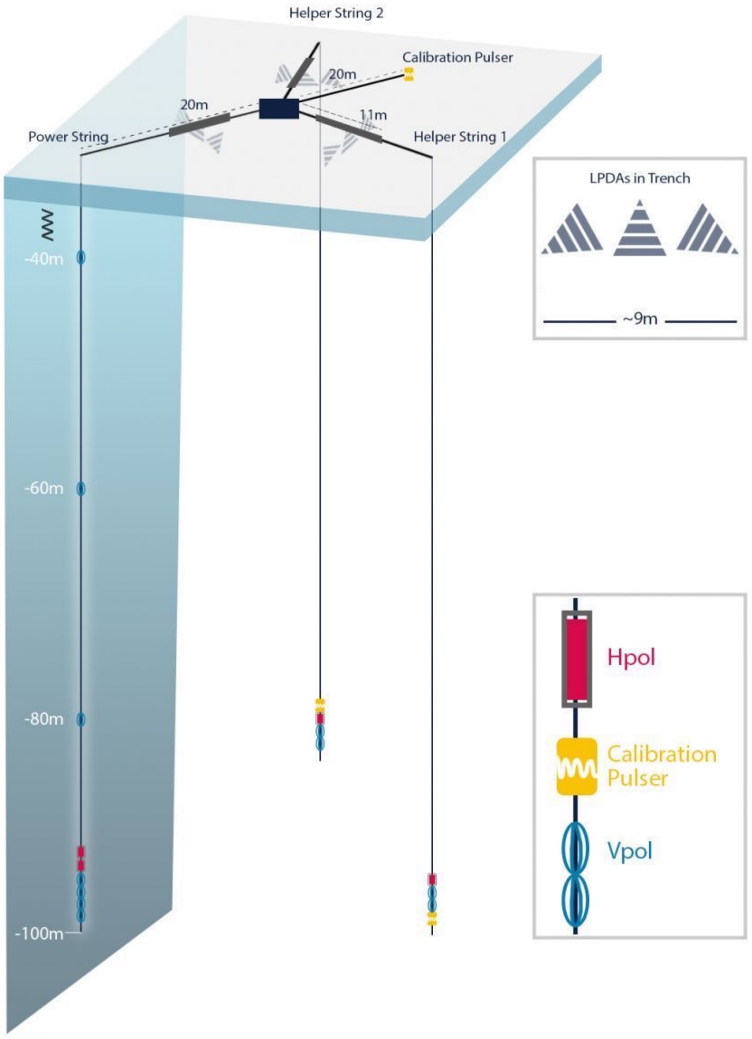
Neutrinos with the Pierre Auger Observatory



Neutrinos with the Pierre Auger Observatory



RNO-G

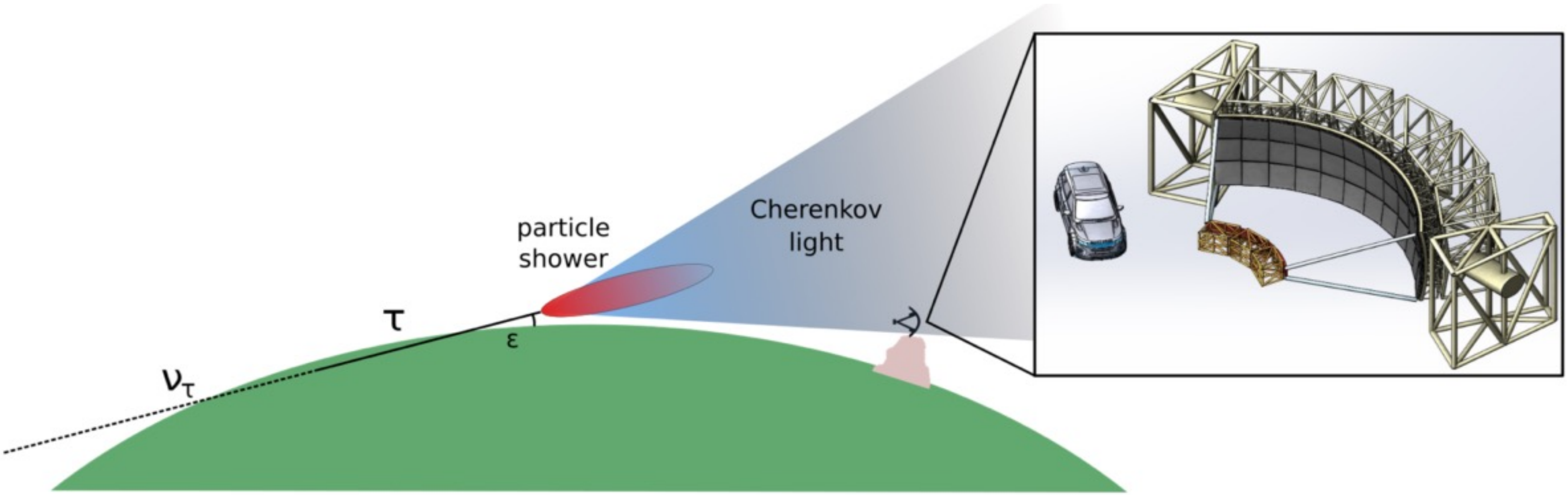


Askaryan effect:

- Charge accumulation in the shower front gives rise to a changing current, which gives rise to radio emission
- Emission is coherent at frequencies corresponding to the size of the shower

Trinity

One of 18 planned Trinity telescopes

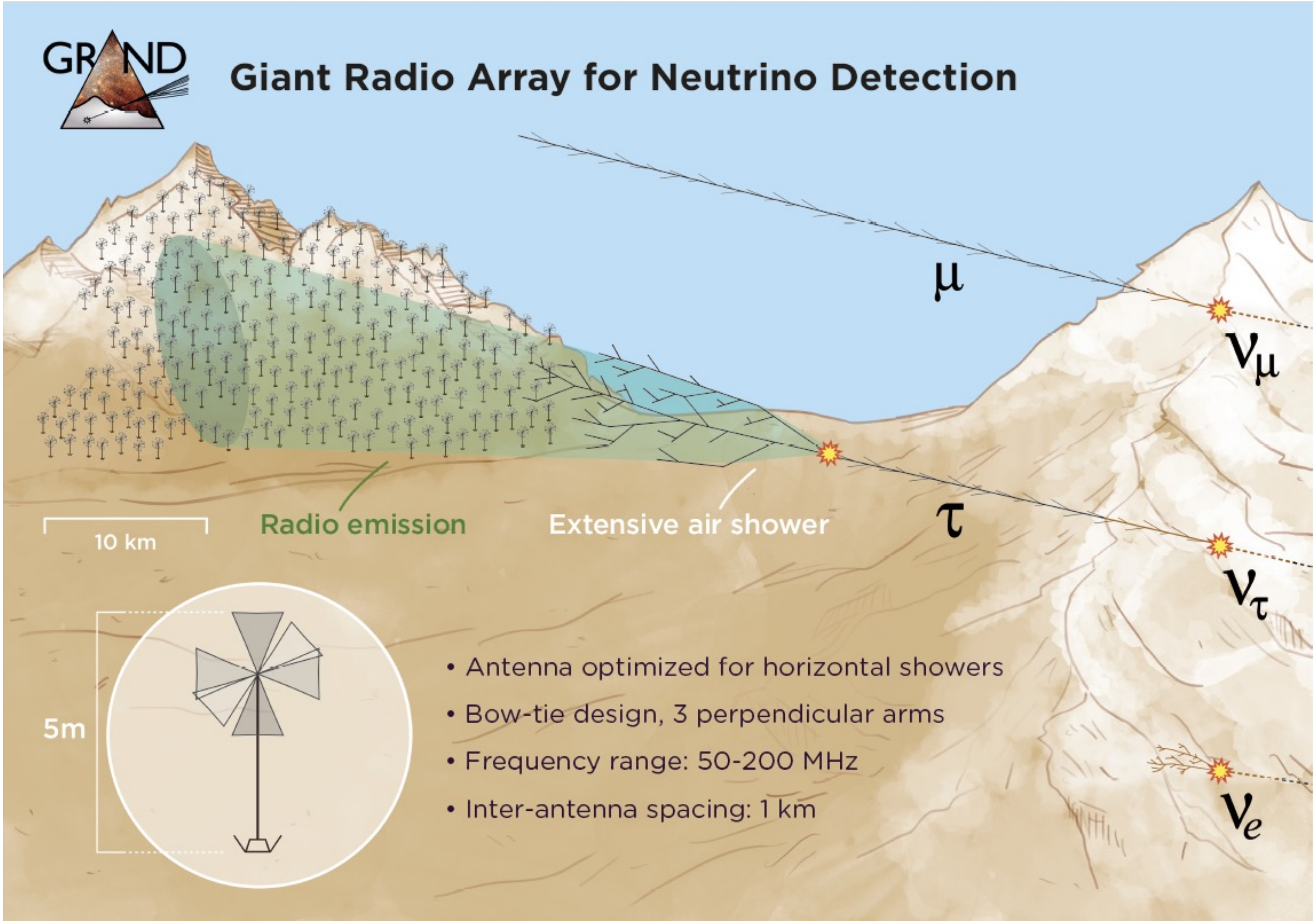


Trinity demonstrator

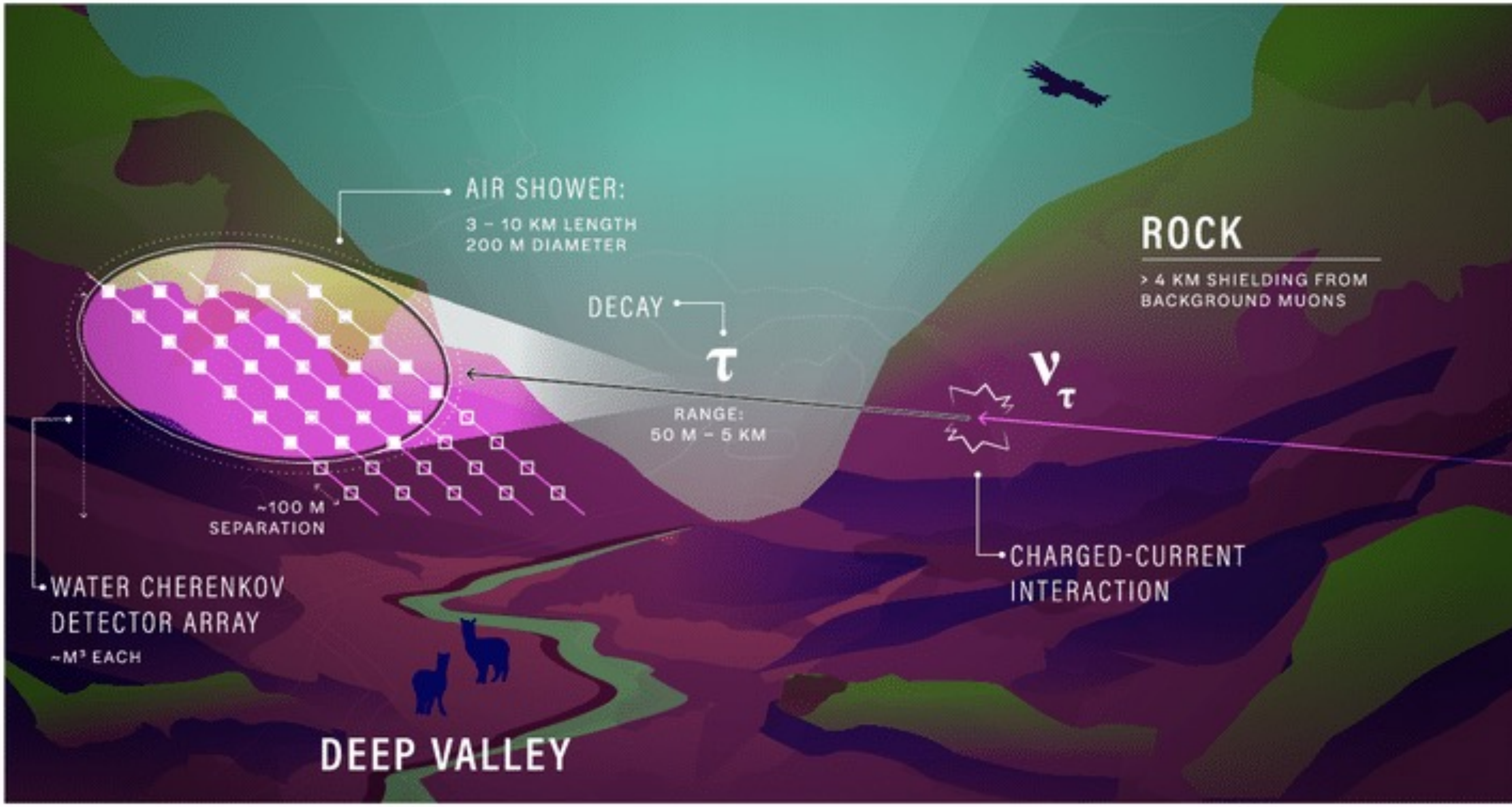
Deployed: Oct 2023

Frisco Peak, UT

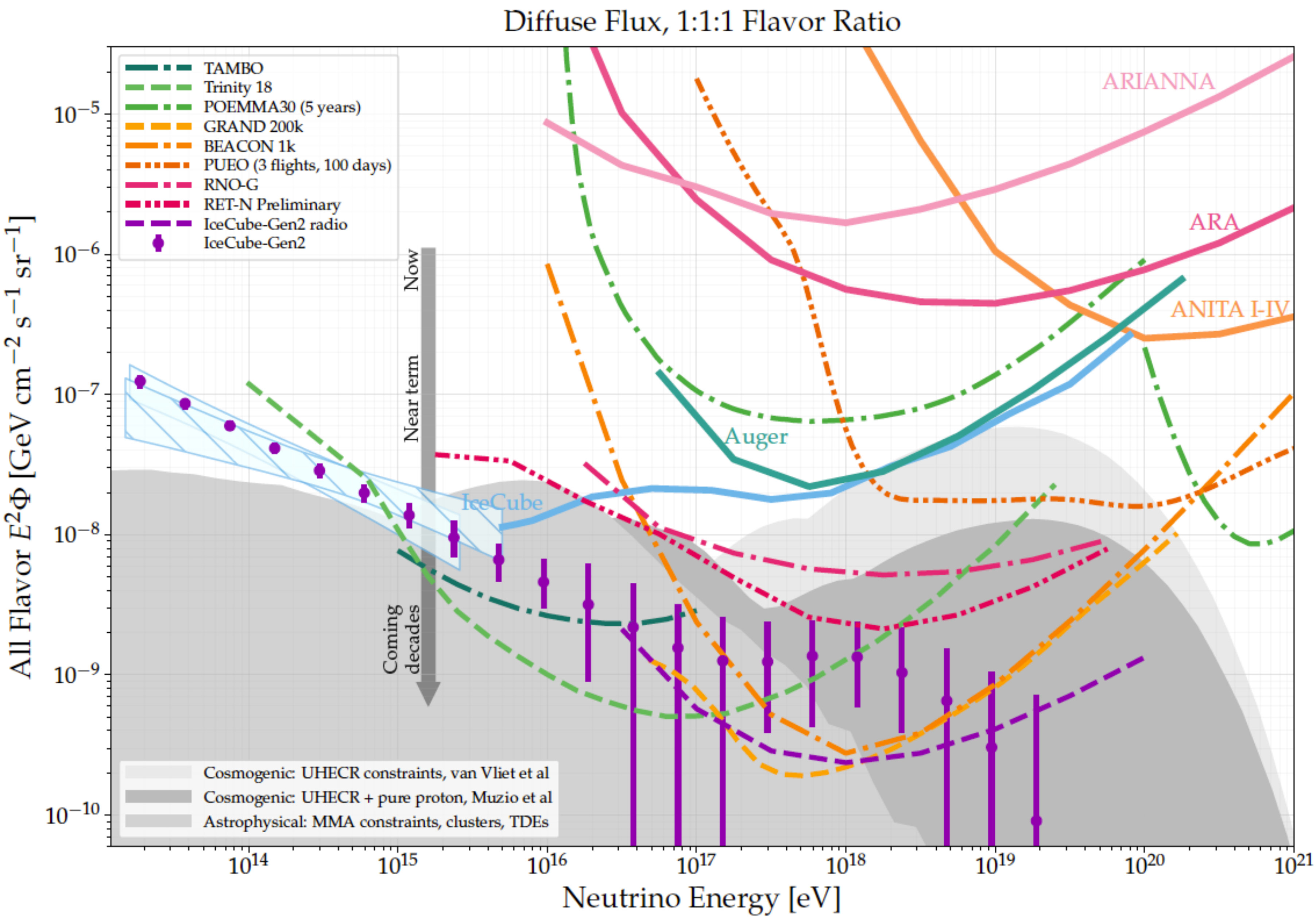
GRAND


GRAND
Giant Radio Array for Neutrino Detection
μ
ν_μ
Radio emission
Extensive air shower
τ
ν_τ
10 km
5m
ν_e
• Antenna optimized for horizontal showers
• Bow-tie design, 3 perpendicular arms
• Frequency range: 50-200 MHz
• Inter-antenna spacing: 1 km

TAMBO



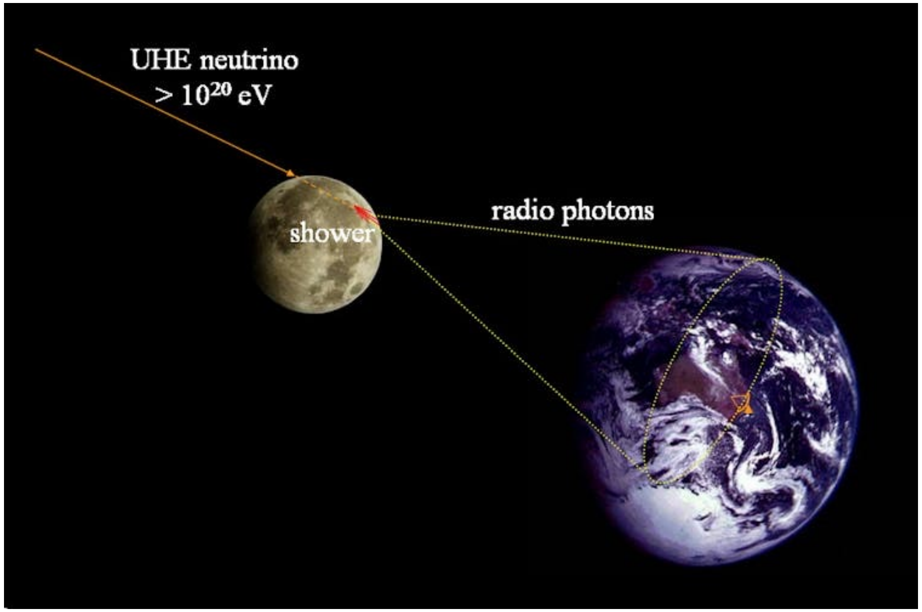
TAU AIR-SHOWER MOUNTAIN-BASED OBSERVATORY (TAMBO) · COLCA VALLEY, PERU



Ackermann et al., JHEAp 36 (2022) 55-110

RUB

Other detector Concepts



O. Scholten 2011

trees are efficient broadband antennas

S. Prohira 2024, arXiv:2401.14454

RUB

Learning Objectives

- How can we detect astrophysical neutrinos at various energies (focus on TeV-PeV neutrinos)?
  - Lowest energies (CNB): neutrino capture on unstable nucleus (e.g. tritium), extremely challenging, excellent energy resolution required
  - MeV range: Neutrino capture on stable nucleus (Chlorine, Gallium), densely instrumented water Cherenkov detectors
  - TeV-PeV range: sparsely instrumented water/ice Cherenkov detectors, challenge: atmospheric background
  - Highest energies: radio emission of neutrino induced showers in ice, Earth skimming tau events

Learning Objectives

- What is the background in the search for high-energy cosmic neutrinos and how can we disentangle it from the signal?
  - Atmospheric neutrinos and muons: restrict search to Northern sky, look for starting events, large energy threshold in Southern sky, correlation with known source positions and times (next lecture)
- Have have we detected with neutrino detectors alone (multi-wavelength searches / detections follow tomorrow)

Learning Objectives

- Have have we detected with neutrino detectors alone (multi-messenger searches / detections follow tomorrow)
  - The Sun
  - SN1987A (hint for diffuse supernova background)
  - Diffuse 10TeV-PeV flux
  - Evidence for TeV-PeV source candidates (next lecture)

Multi-messenger Astronomy with Neutrinos

Anna Franckowiak
Ruhr-University Bochum

AIRUB
Astronomisches Institut
RUHR-UNIVERSITÄT BOCHUM

RUB

Open questions

Neutrino background from stars

The DSNB dominates at higher energies (above 10 MeV), while stellar neutrinos contribute primarily at lower energies.

Thanks to Subhadip

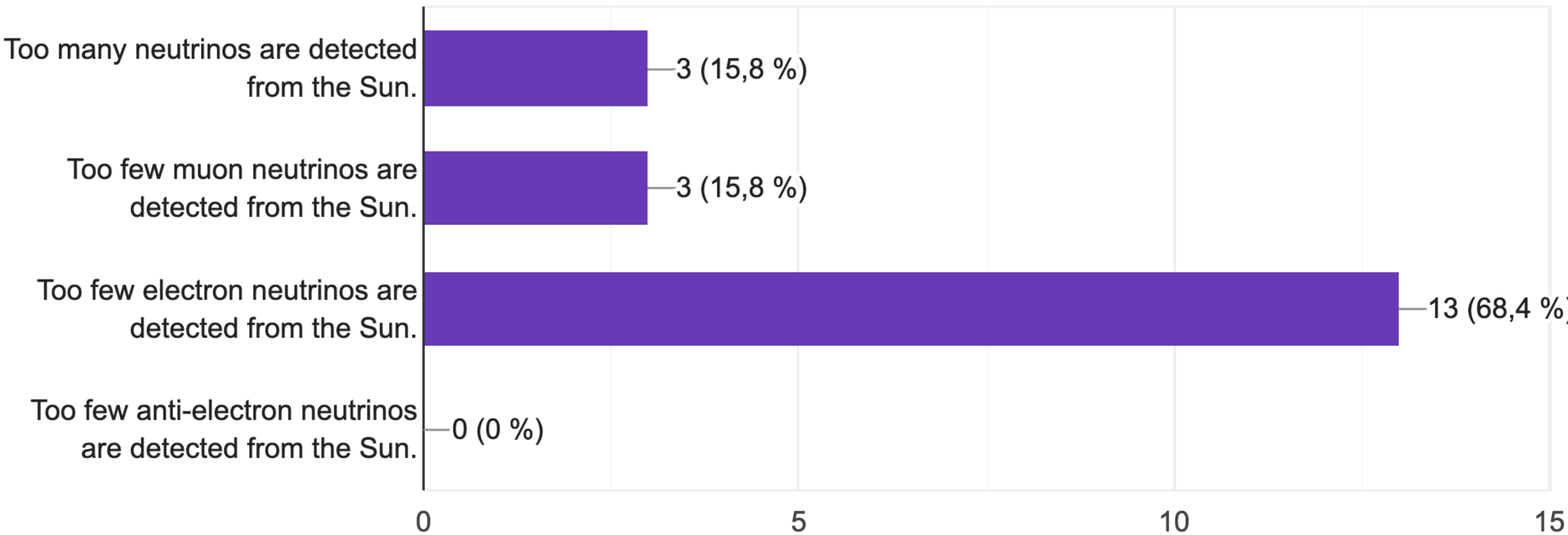
Porciani et al. Astropart.Phys.20:683-701,2004

DOM failure

- The majority of the failures (55) occurred before post-deployment commissioning; we hypothesize that these are primarily attributable to cable failures, water leaks, or freeze-in damage.
- 32 DOMs have failed after commissioning. No particular pattern in the failures is observed, other than they are typically during non-standard operation or an exceptional event: a power outage, calibration run, or flash filesystem upgrade. Diagnosis of DOM failures beyond identifying electrical shorts is challenging.
- Currently we estimate the mean failure rate to be $4.1 \pm 1.2\ yr^{-1}$, resulting in a survival fraction in 2030 of $97.4 \pm 0.3\%$. While this simplified model does not account for an increase in failure rate due to component aging, the recent observed failure rate since detector completion of $1.7\ yr^{-1}$ is significantly lower than the mean predicted rate.
- Each DOM is equipped with two ATWD chips, and each chip is provided with three different amplifier gains with nominal values of 16, 2, and 0.25 in order to completely cover the dynamic range of the PMT output (up to 150 mA, or 7.5 V, when saturated).

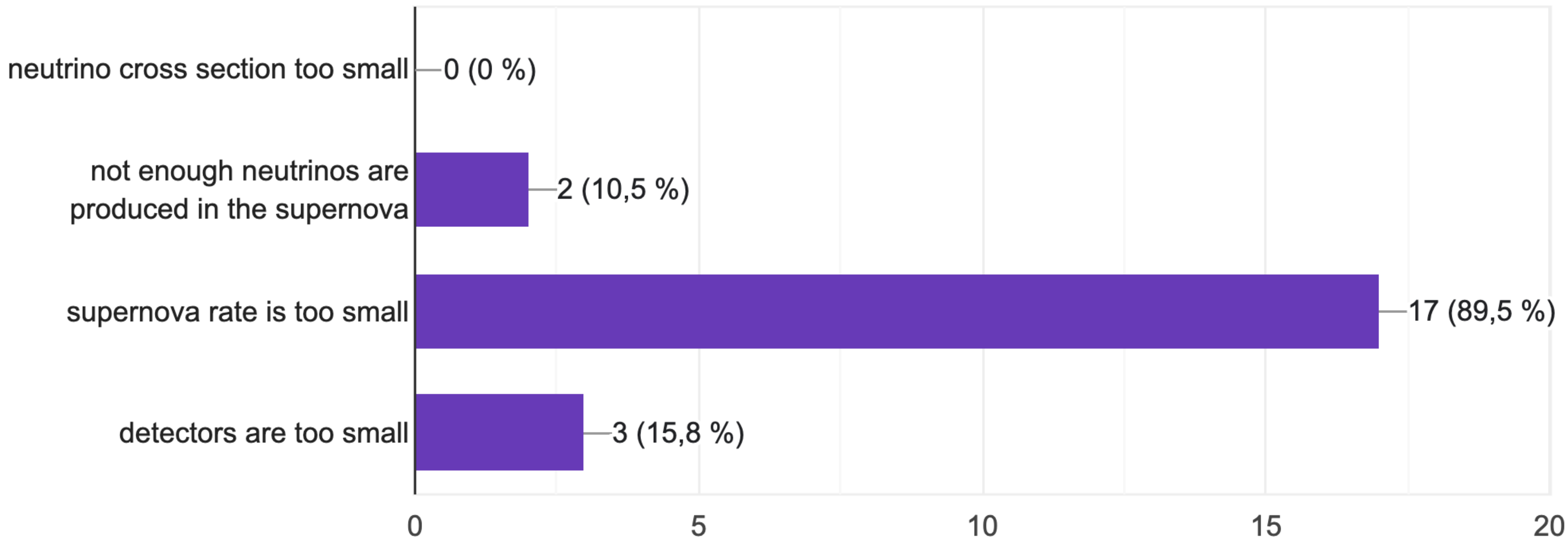
What is the solar neutrino problem?

19 Antworten



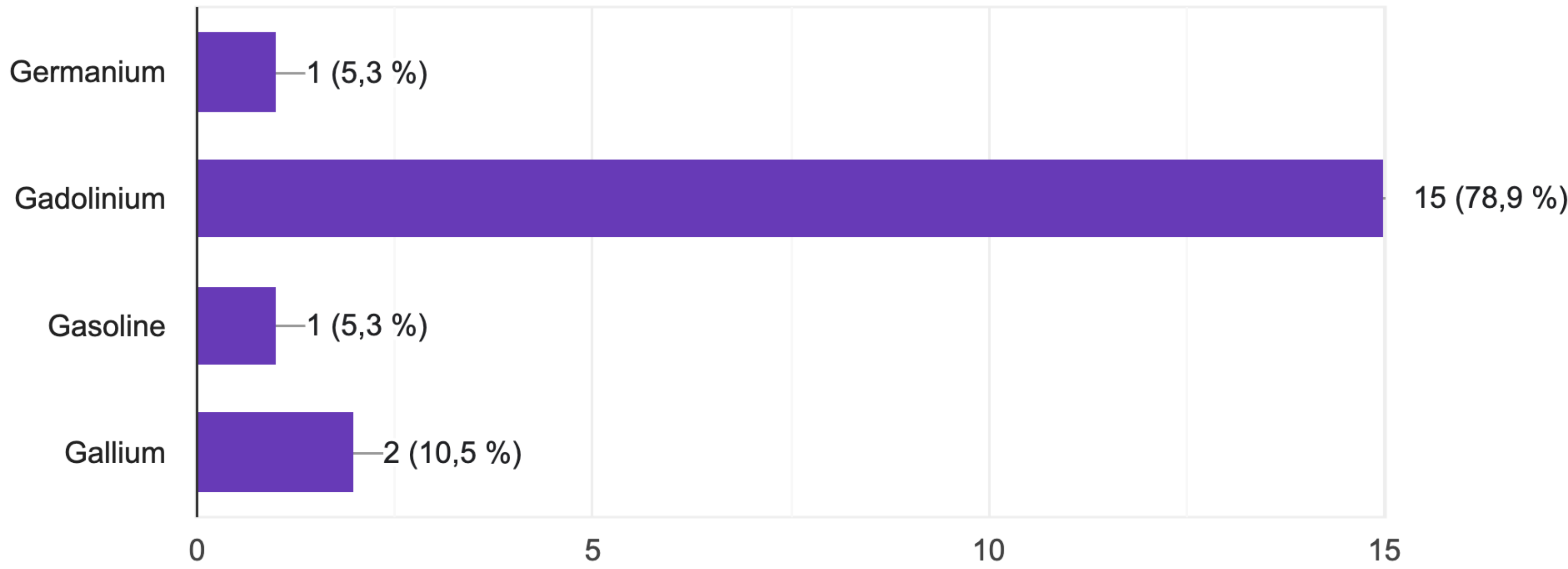
Why don't we detect neutrinos from more supernovae?

19 Antworten



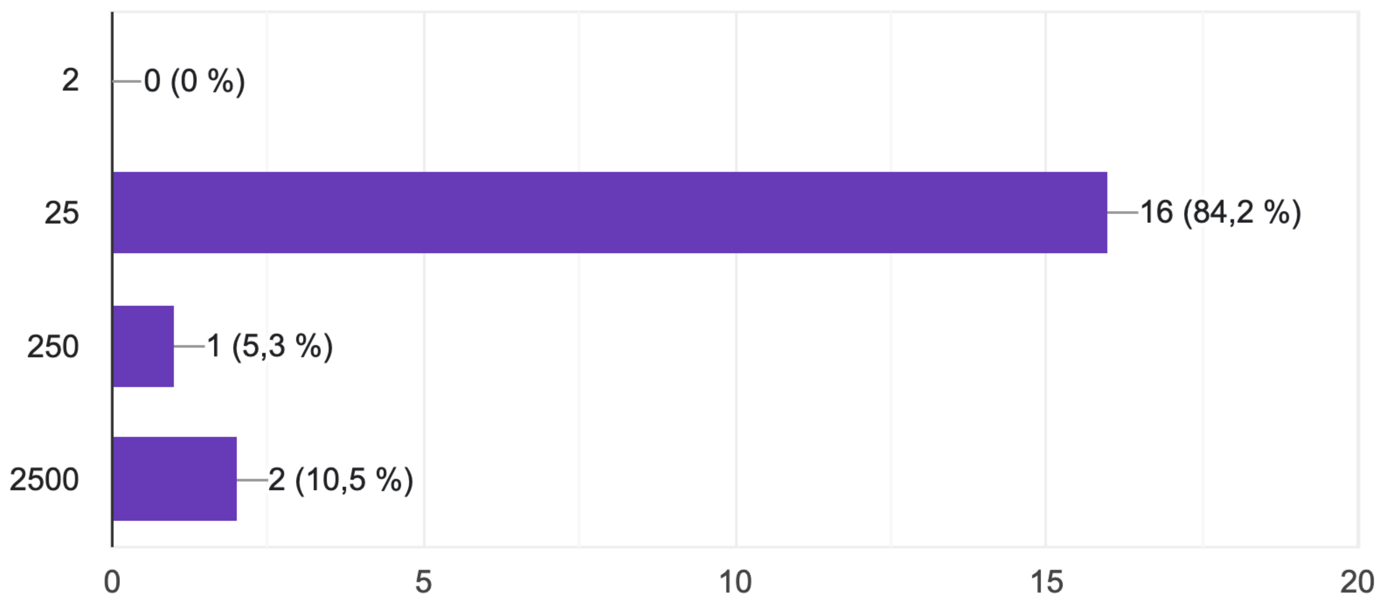
Which element was added to the water of Super-Kamiokande?

19 Antworten



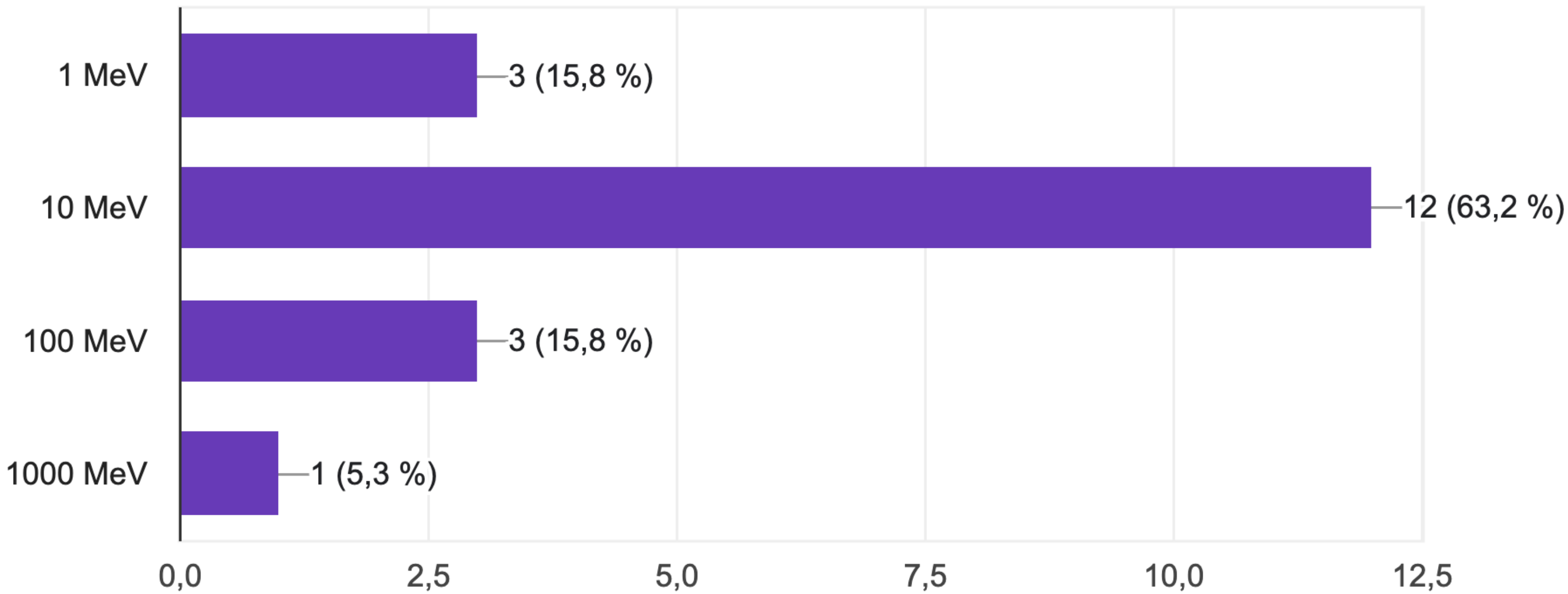
How many neutrinos were detected from supernova SN1987A?

19 Antworten



What is the average energy of supernova neutrinos?

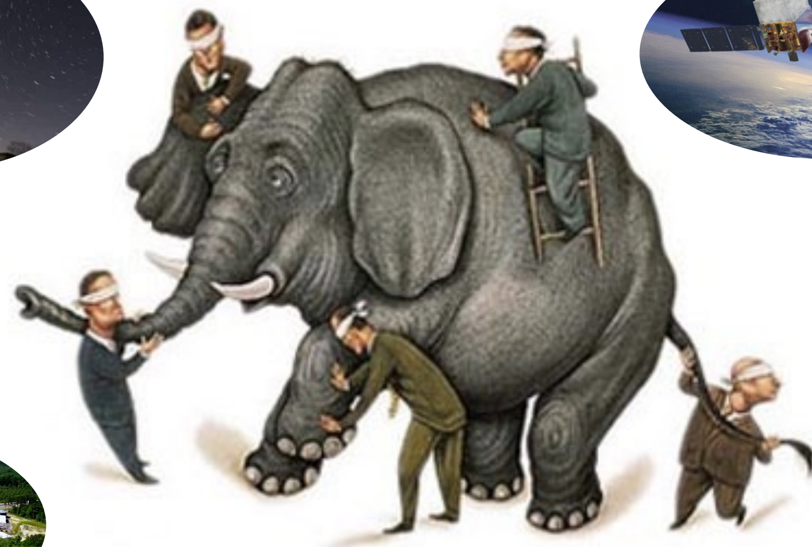
19 Antworten

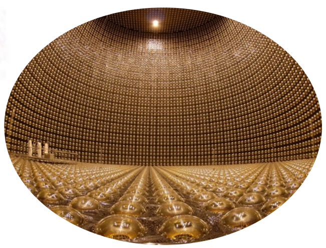


Learning Objectives

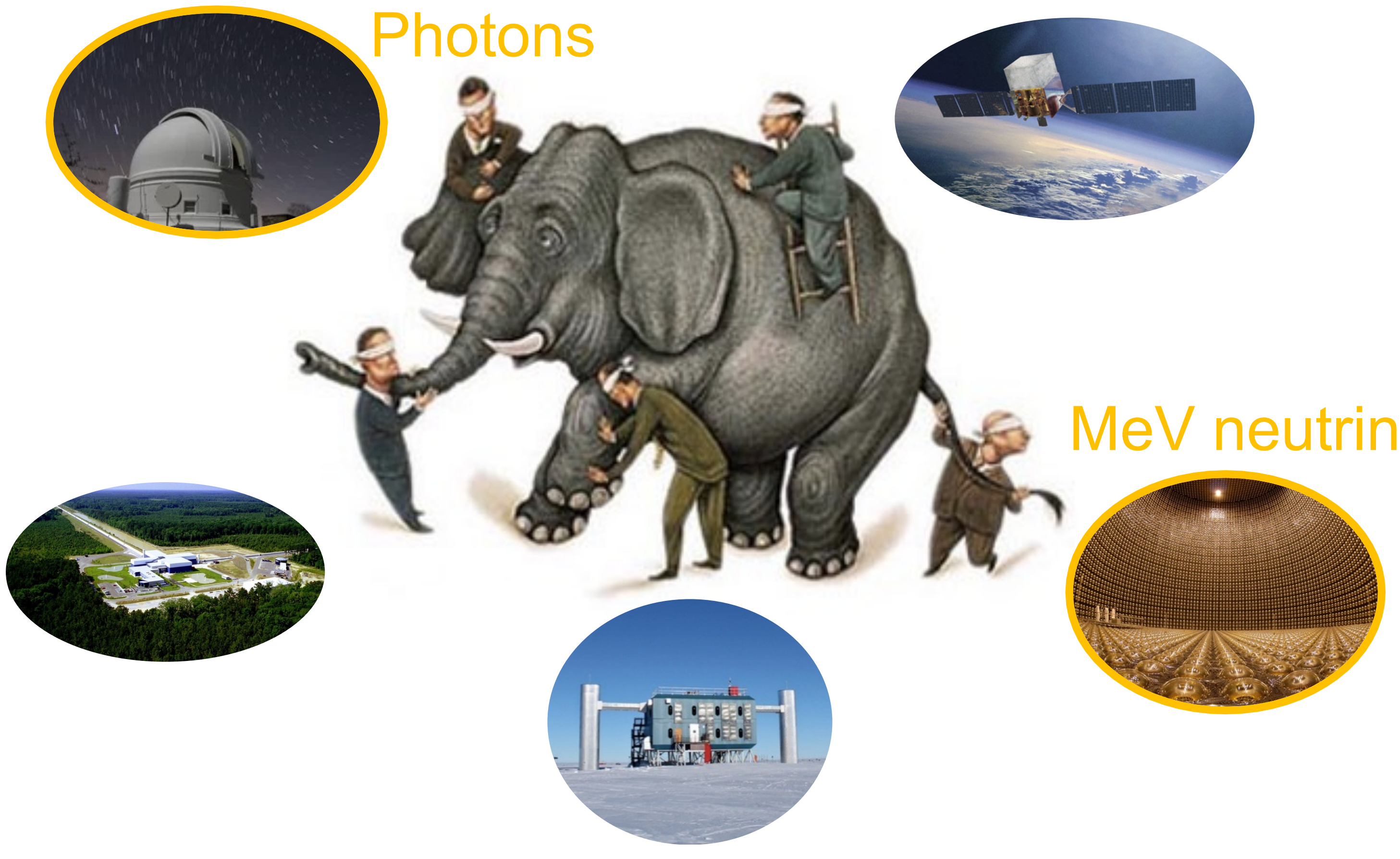
- What is multi-messenger astronomy?
- What are the multi-messenger observations involving neutrinos and what can we learn from them?

Multi-messenger Astronomy



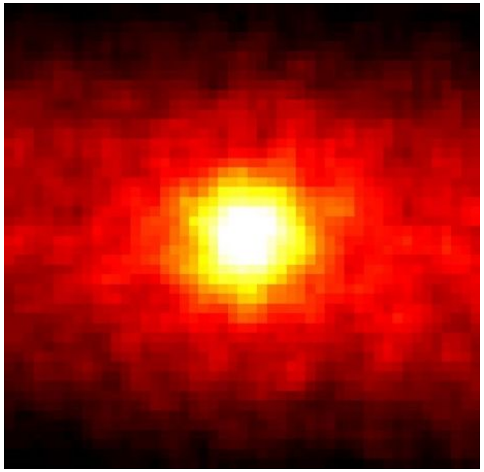


Multi-messenger Astronomy



Birth of MM Astronomy with Neutrinos

Astronomy Picture of the Day
June 5, 1998



The Sun in Neutrinos seen by Super-Kamiokande

RUB

Birth of MM Astronomy with Neutrinos

Astronomy Picture of the Day
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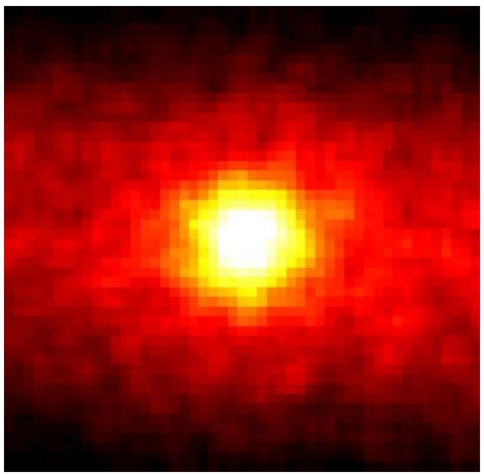


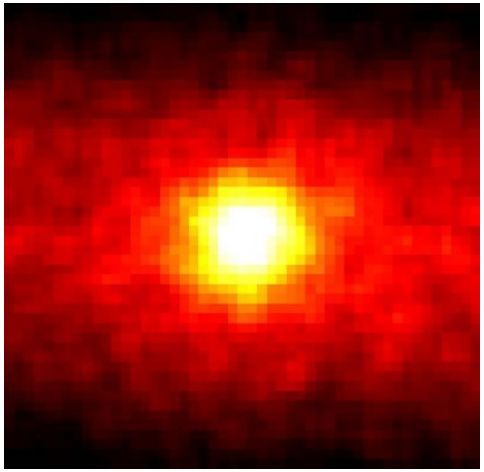
The Sun in Neutrinos seen by Super-Kamiokande

Combining neutrinos and electromagnetic information led to:

- **The solar neutrino problem**

Birth of MM Astronomy with Neutrinos

Astronomy Picture of the Day
June 5, 1998



The Sun in Neutrinos seen by Super-Kamiokande

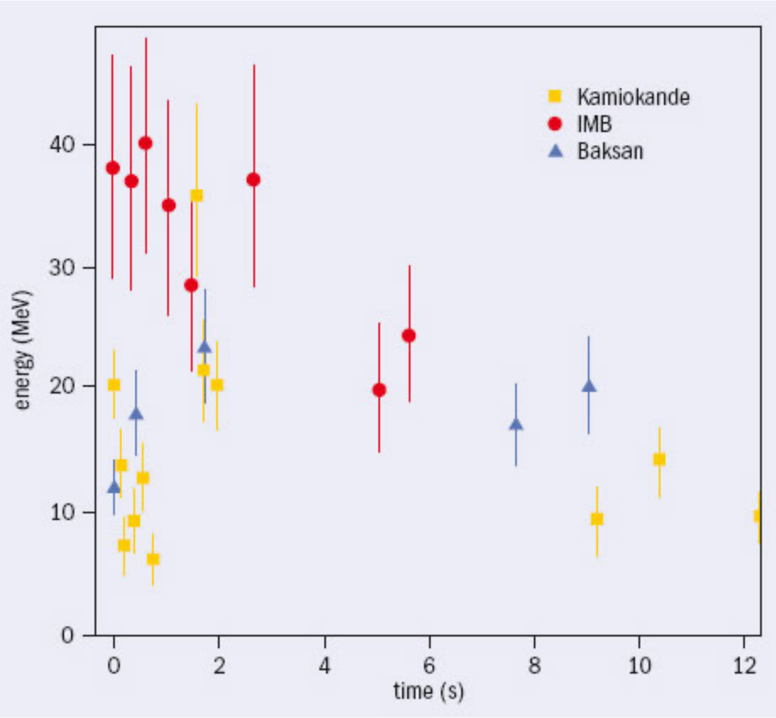
Combining neutrinos and electromagnetic information led to:

- Confirmation of model of fusion
- Breaking the standard model of particle physics

First (and only) detection of a Supernova

Optical detection of SN1987A in LMC

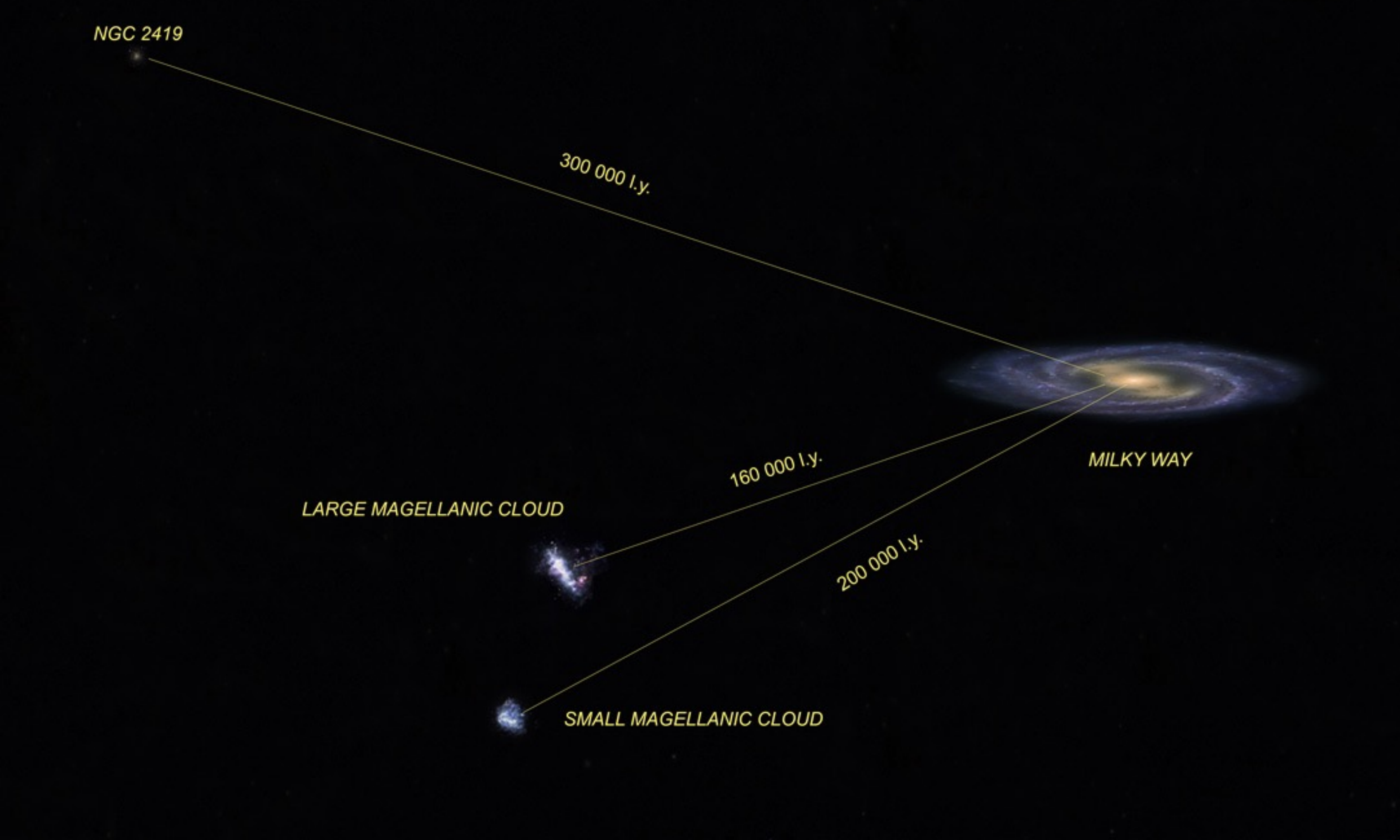
MeV neutrino burst



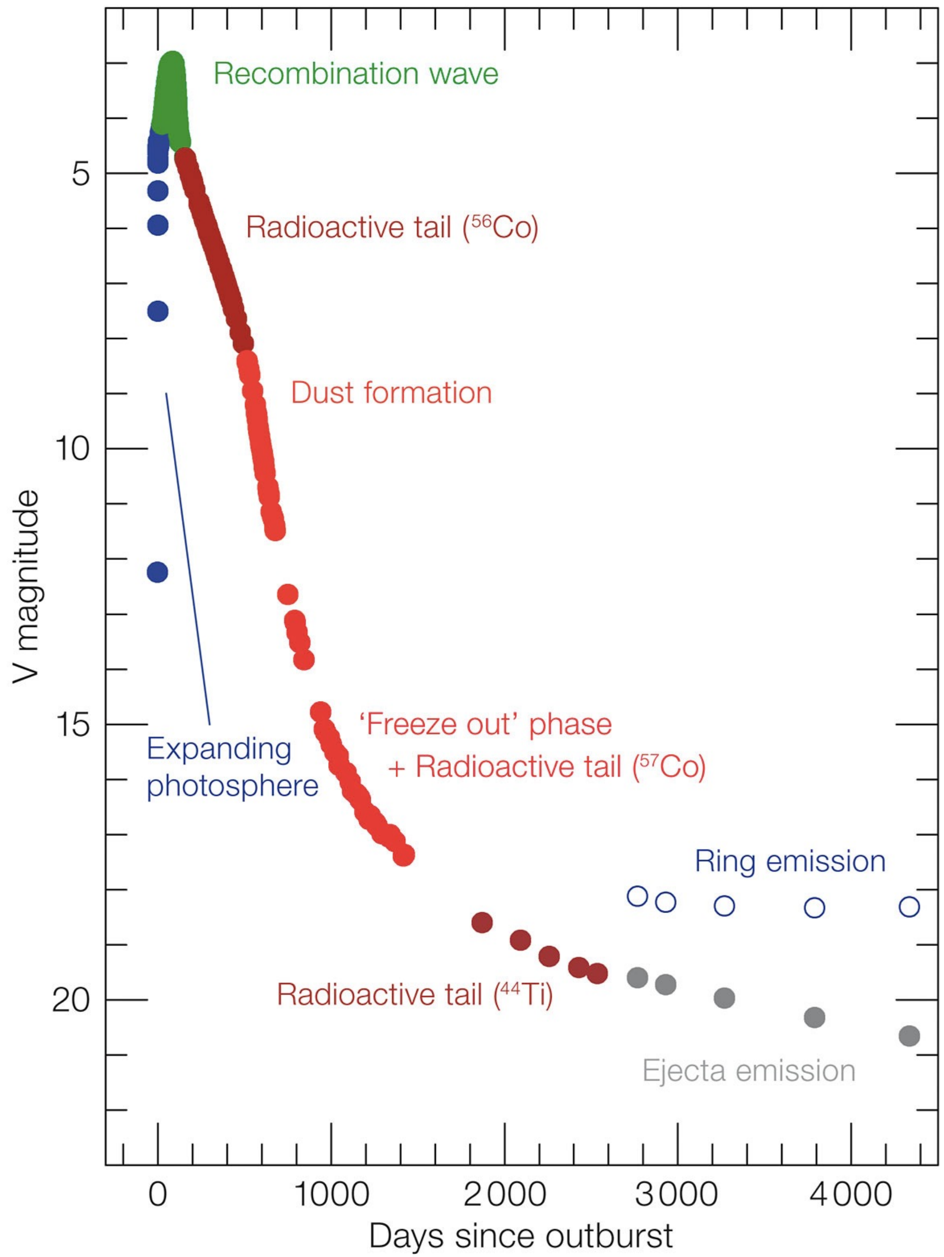
- ~10^{58} neutrinos in ~10s
- 99% of gravitational energy
- typical energy: 10-20 MeV

Location of Magellanic Clouds

Distance: 50kpc = 160000 Ly



SN1987A light curve



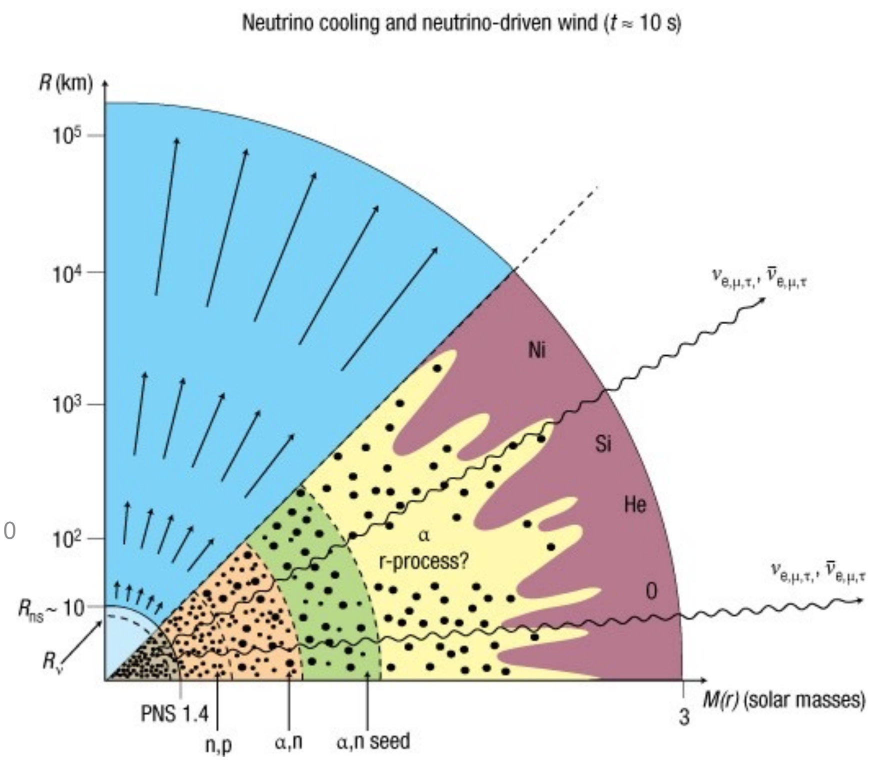
Credit: ESO

RUB

First (and only) detection of a Supernova

First direct confirmation of our
basic picture of a stellar collapse

110

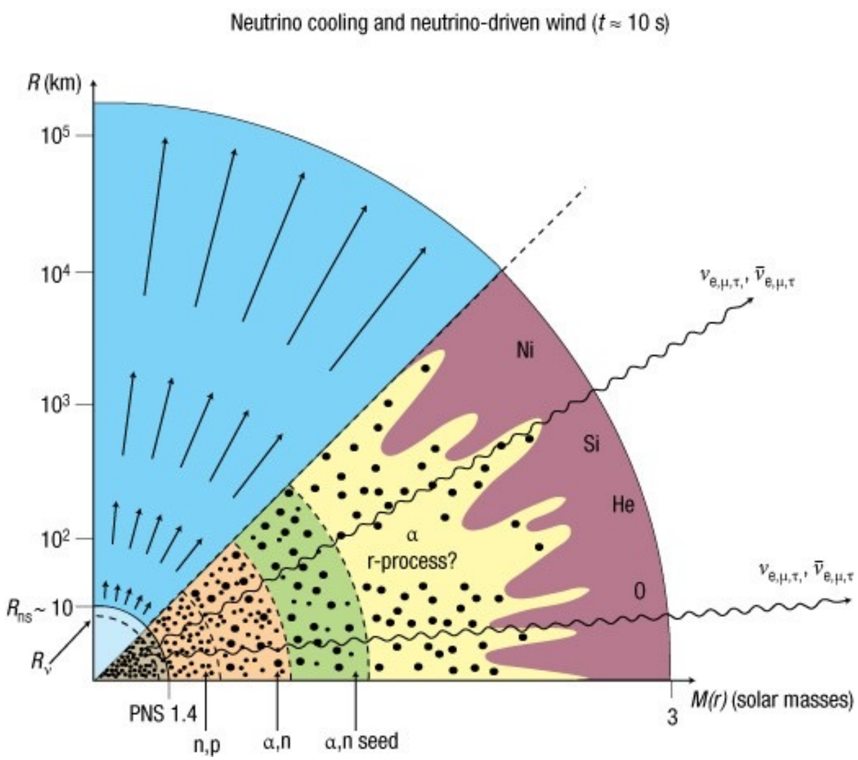


Woosely & Janka,
Nature Physics 2005

RUB

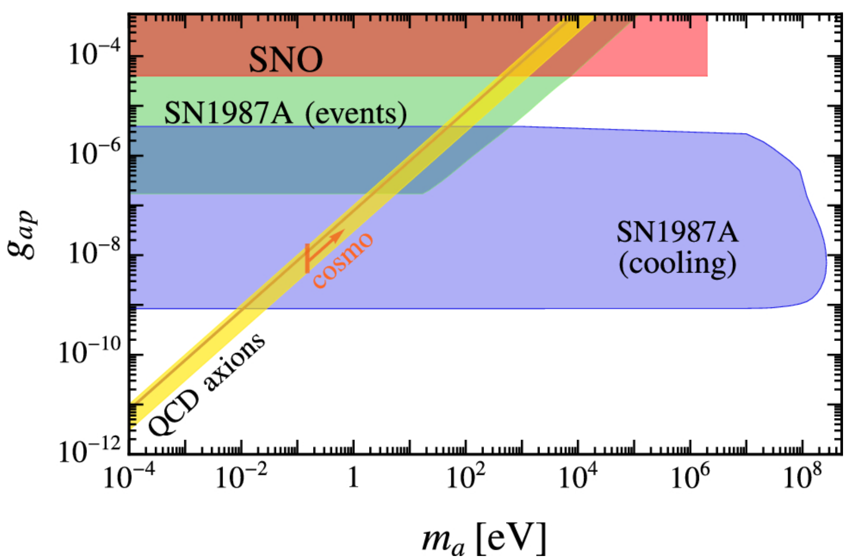
First (and only) detection of a Supernova

First direct confirmation of our basic picture of a stellar collapse



Woosely & Janka,
Nature Physics 2005

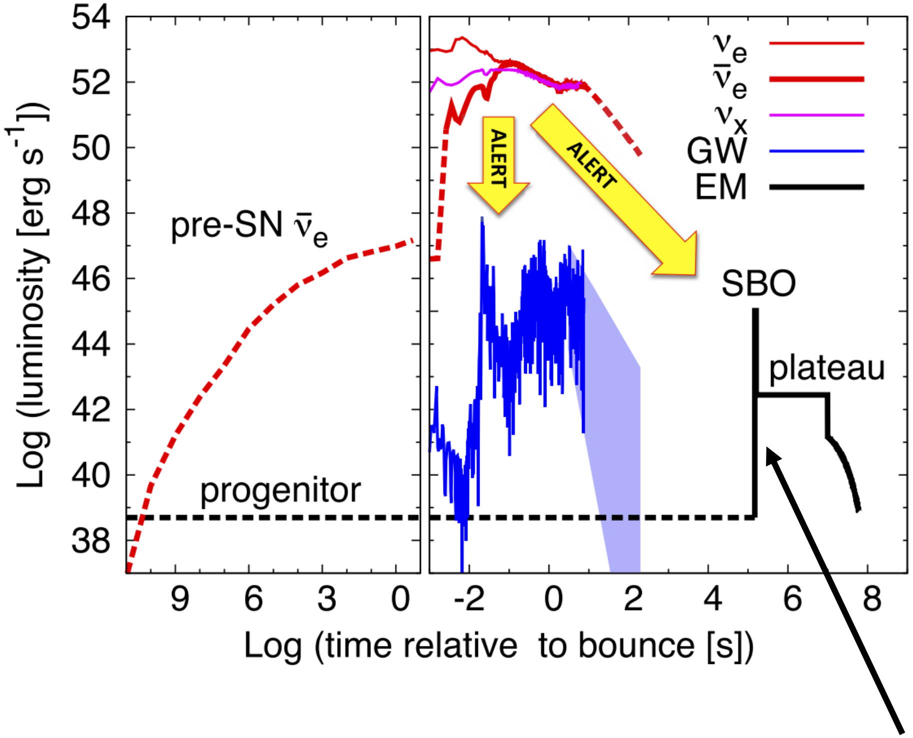
Constraints on exotic physics (e.g. axions)



Lella et al. PRD 109 (2024)

RUB

Supernova early warning system

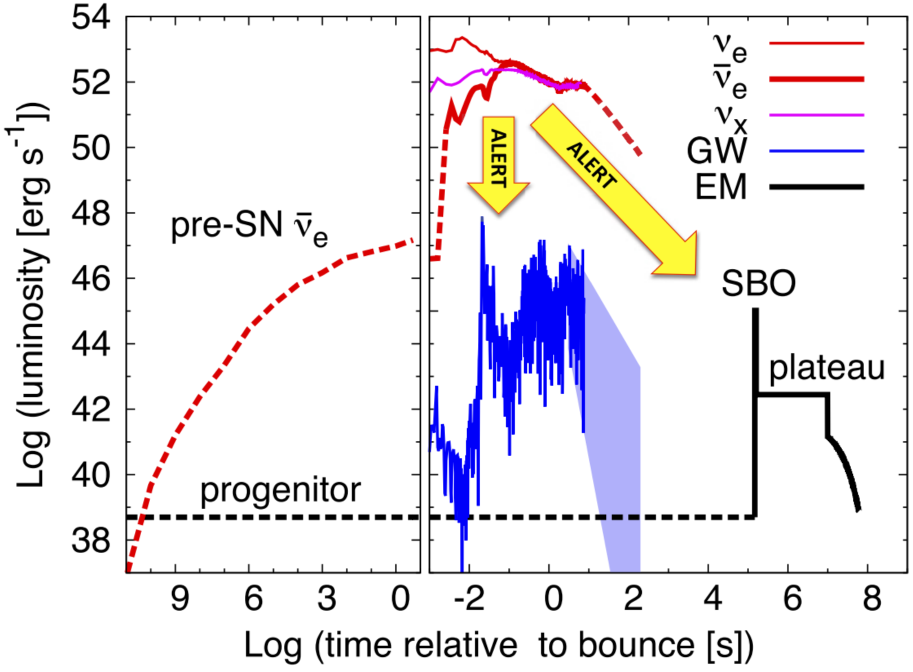


Shock breakout in X-ray and UV emission

Al Kharusi et al New J. Phys. **23** 2021

Supernova early warning system

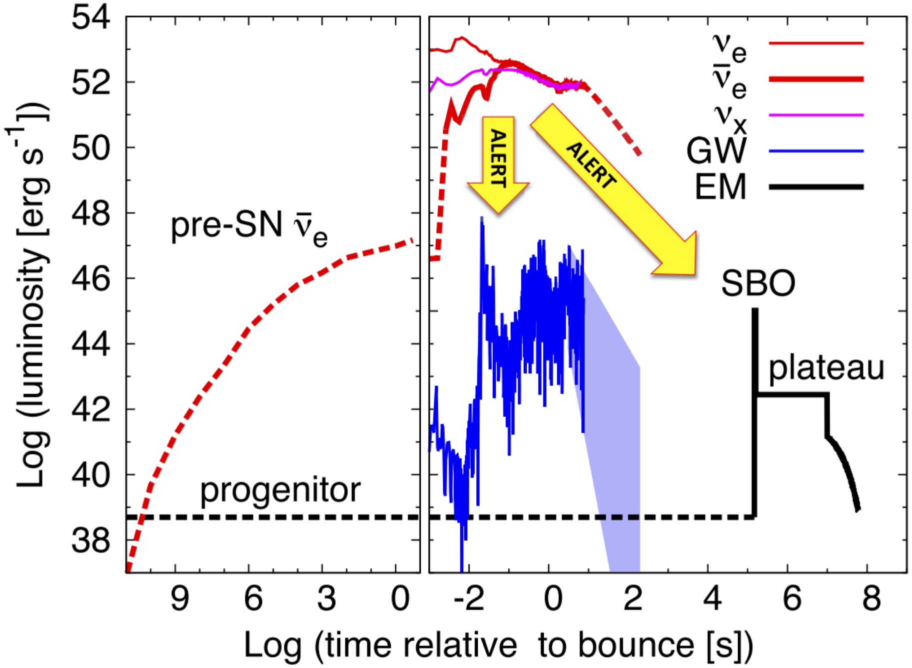
SNEWS
SUPERNOVA EARLY WARNING SYSTEM



MeV neutrino burst as trigger for electromagnetic supernovae observations

Al Kharusi et al New J. Phys. **23** 2021

Supernova early warning system



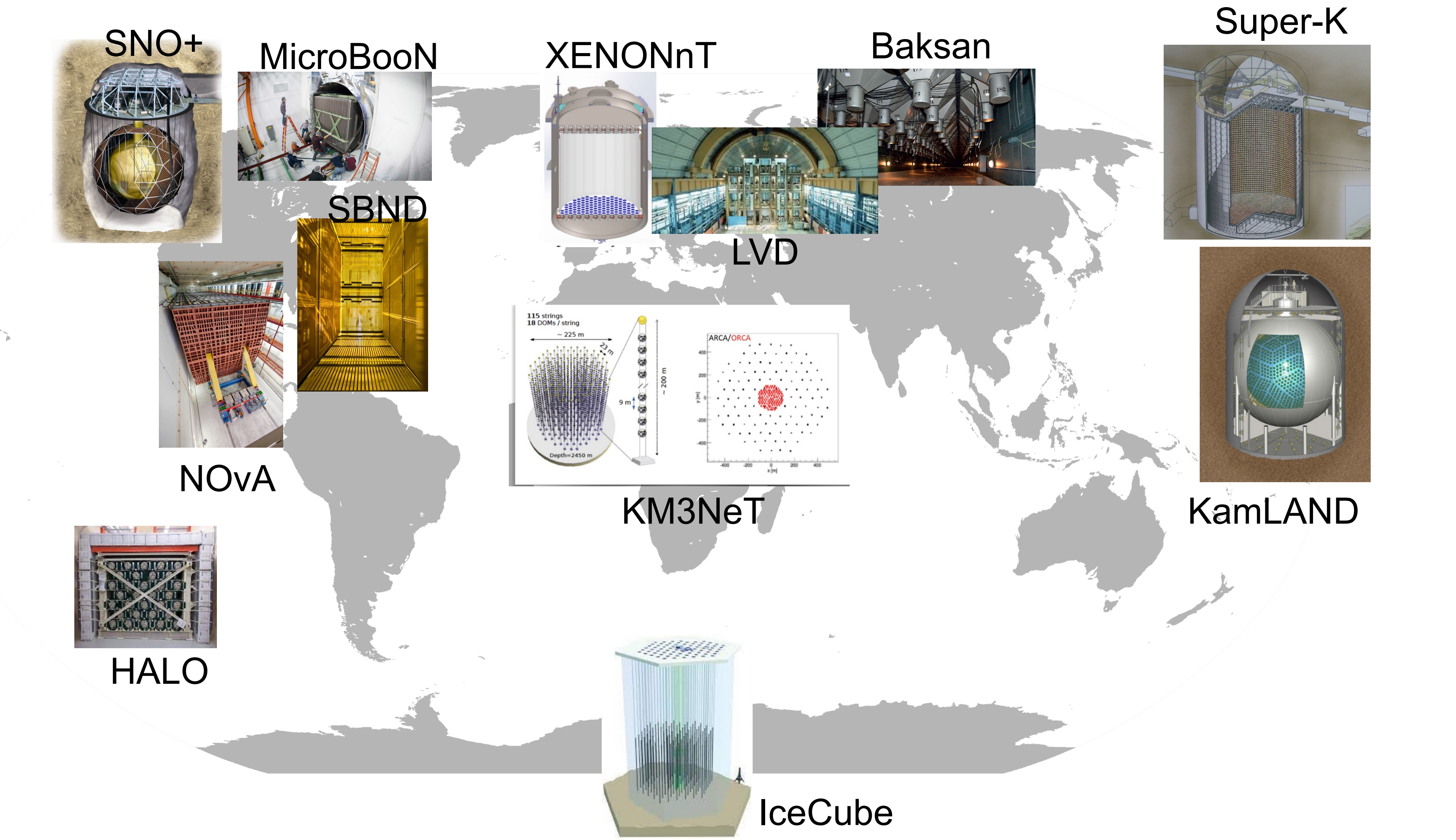
MeV neutrino burst as trigger for electromagnetic supernovae observations

SNEWS 2.0:

- new infrastructure
- public sub-threshold alerts
- pointing using inter-experiment triangulation
- searches for pre-supernova neutrinos

Al Kharusi et al New J. Phys. **23** 2021

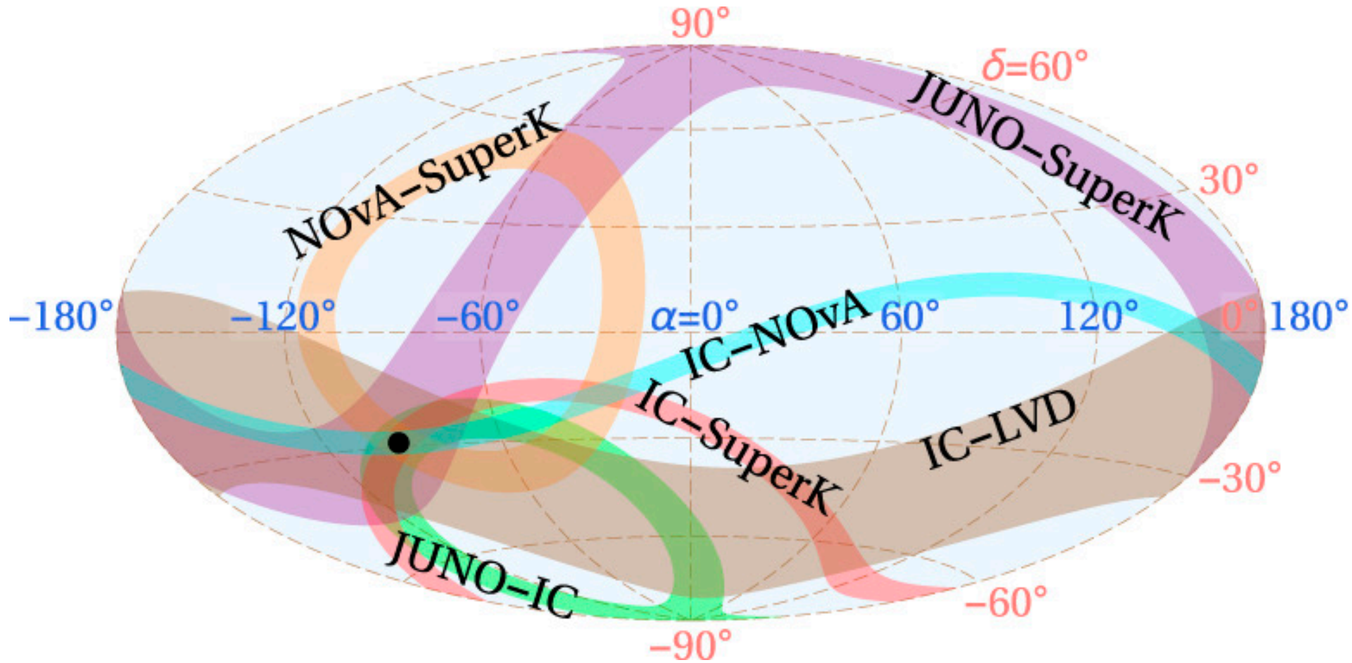
Detectors participating in SNEWS



https://snews2.org/

Supernova localization

supernova core-collapse into a neutron star



Coordinated follow-up observations with wide-field-of-view instruments are necessary

Al Kharusi et al New J. Phys. **23** 2021

Catching the next Galactic Neutrino Supernova

- Unprecedented insights into the explosion mechanism
- Information about surrounding material
- Spatially resolved imaging of early phases of explosion

Kistler et al., ApJ 778 (2013)

Catching the next Galactic Neutrino Supernova

- Unprecedented insights into the explosion mechanism
- Information about surrounding material
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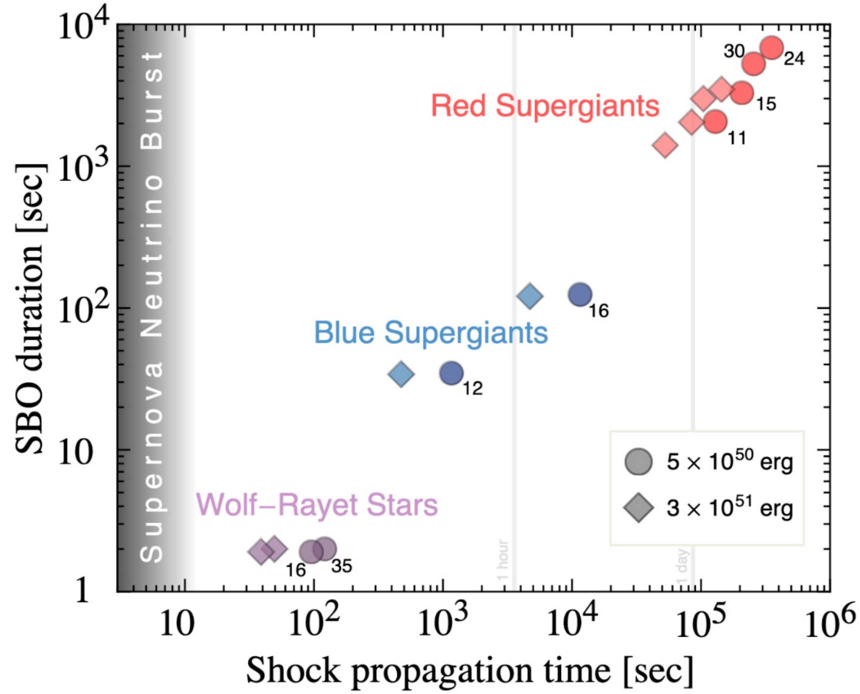
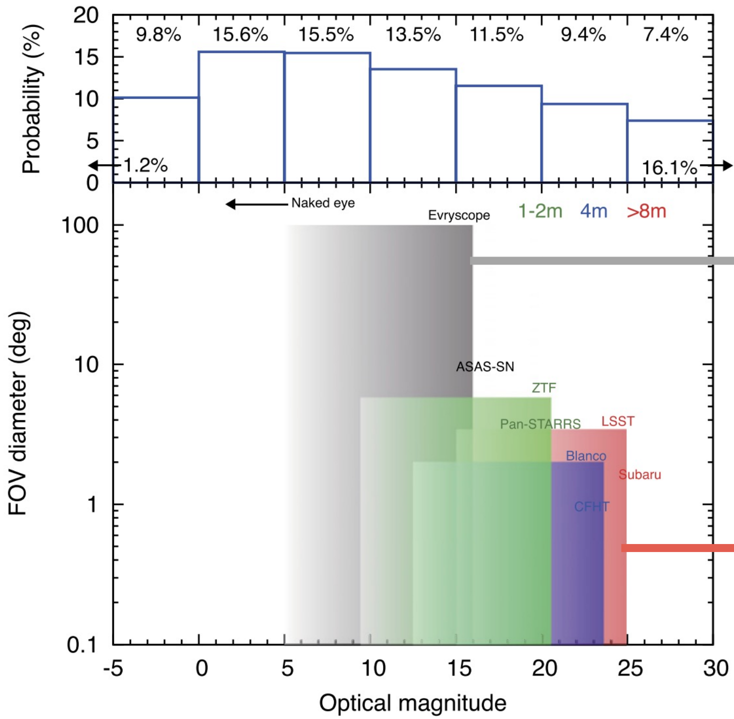
Delay between neutrino burst and optical signal: 2 min to 2 days



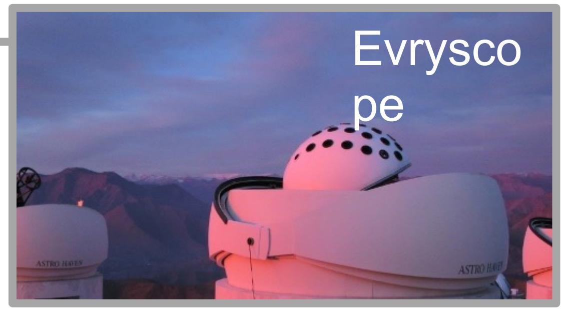
Kistler et al., ApJ 778 (2013)

Catching the next Galactic Neutrino Supernova

Detectability of shock breakout

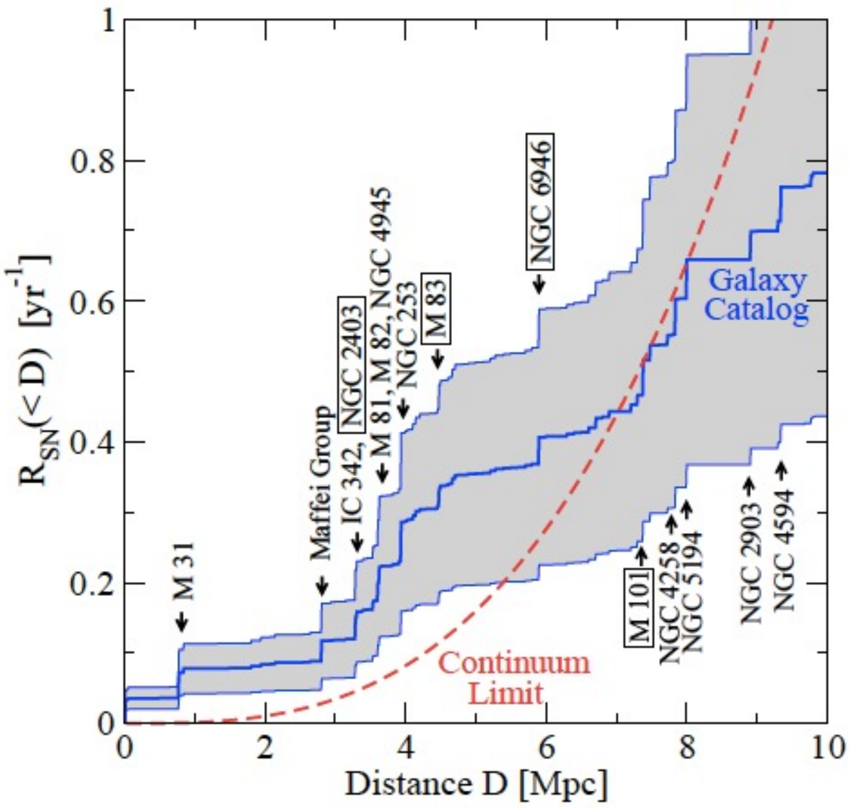


Optical counterpart can appear within minutes of neutrino alert → take full advantage of once-in-a-lifetime event

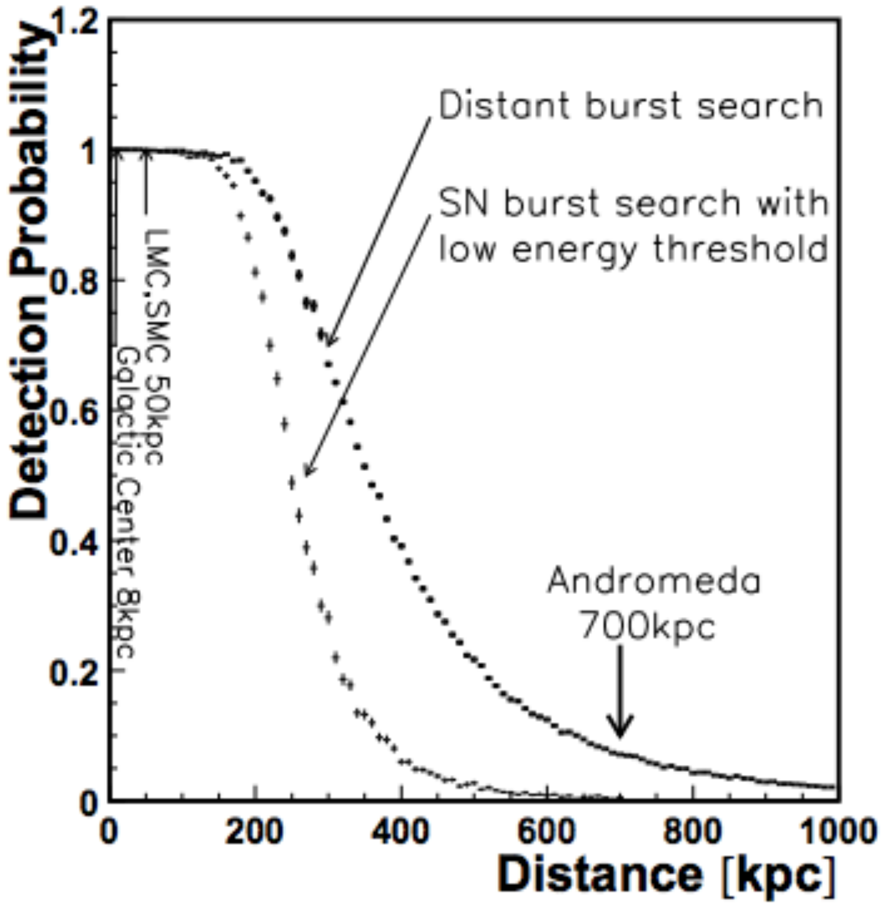


Al Kharusi et al New J. Phys. **23** 2021

Sensitivity to SN today

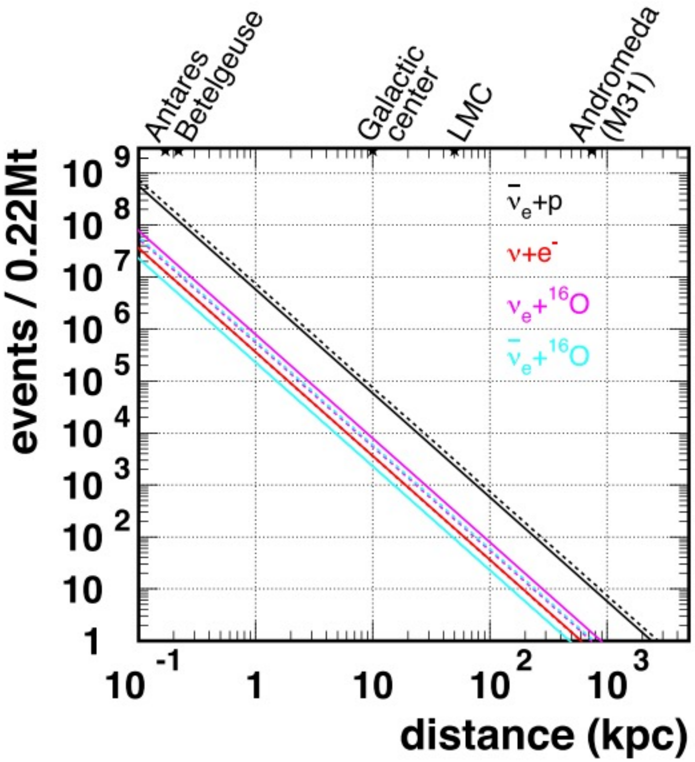


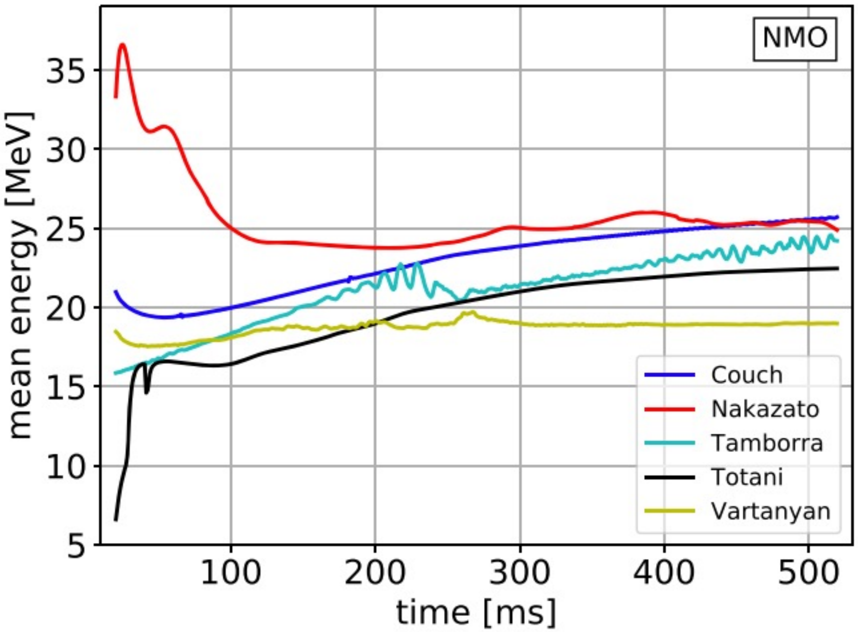
Super-Kamiokande



RUB

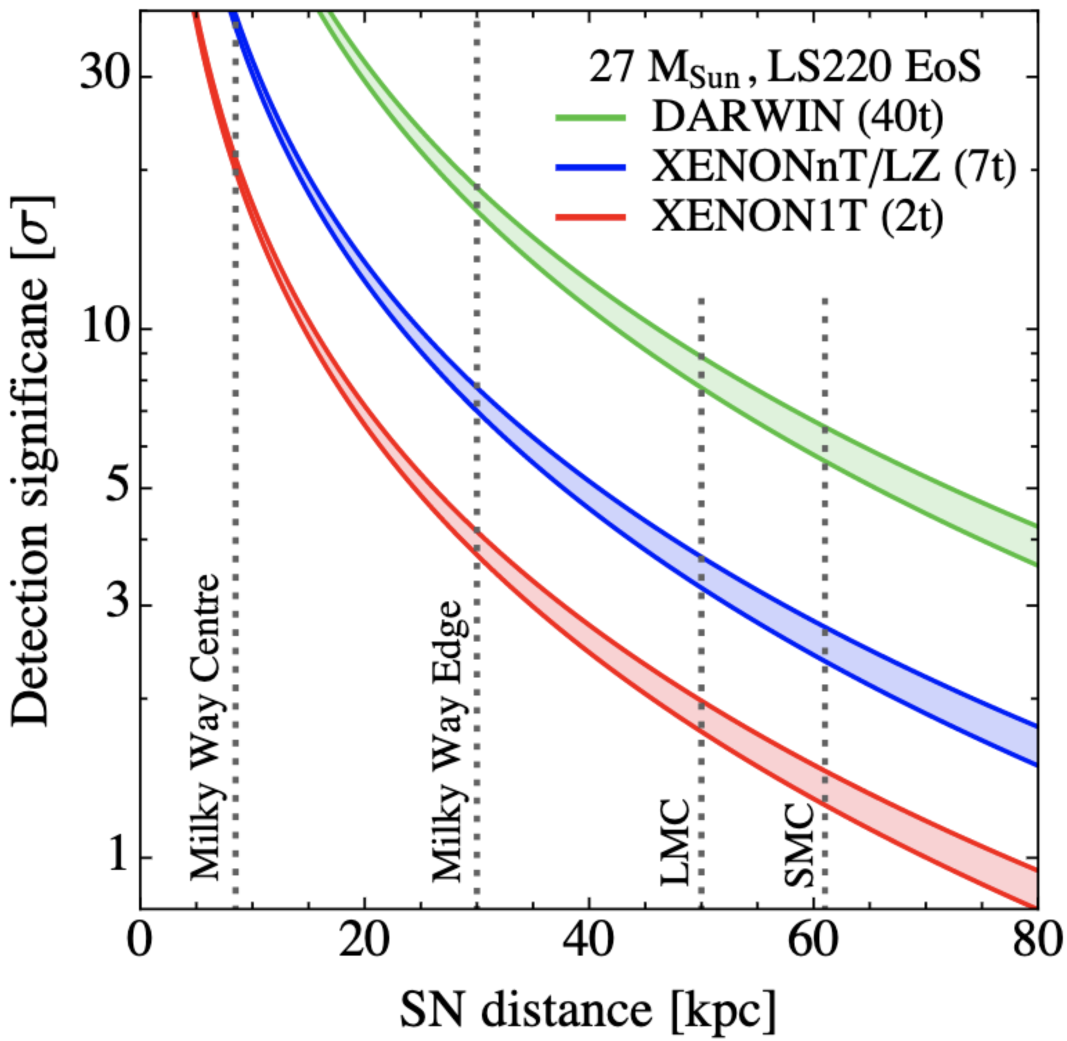
In the future: Hyper-Kamiokande (~2030)



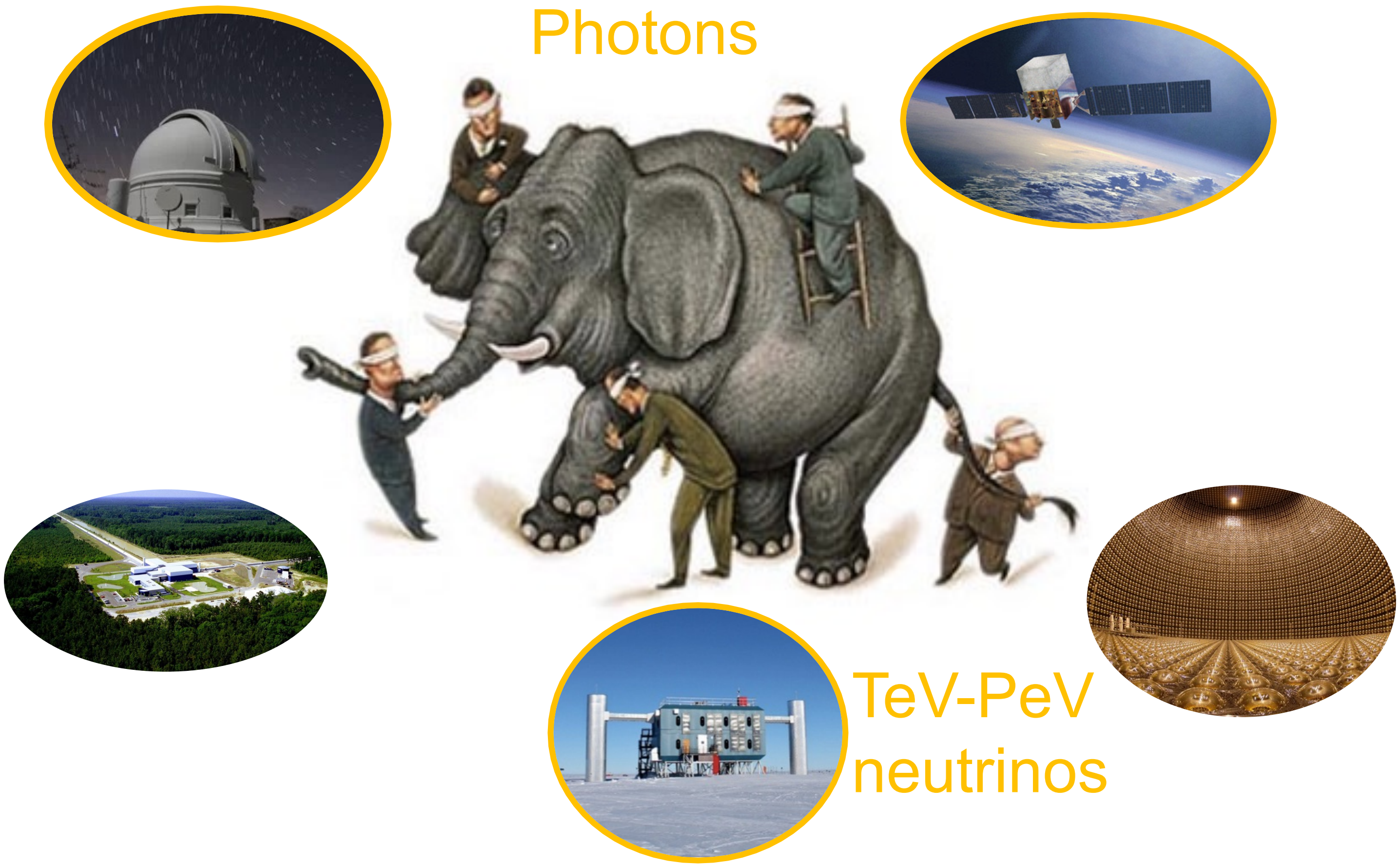


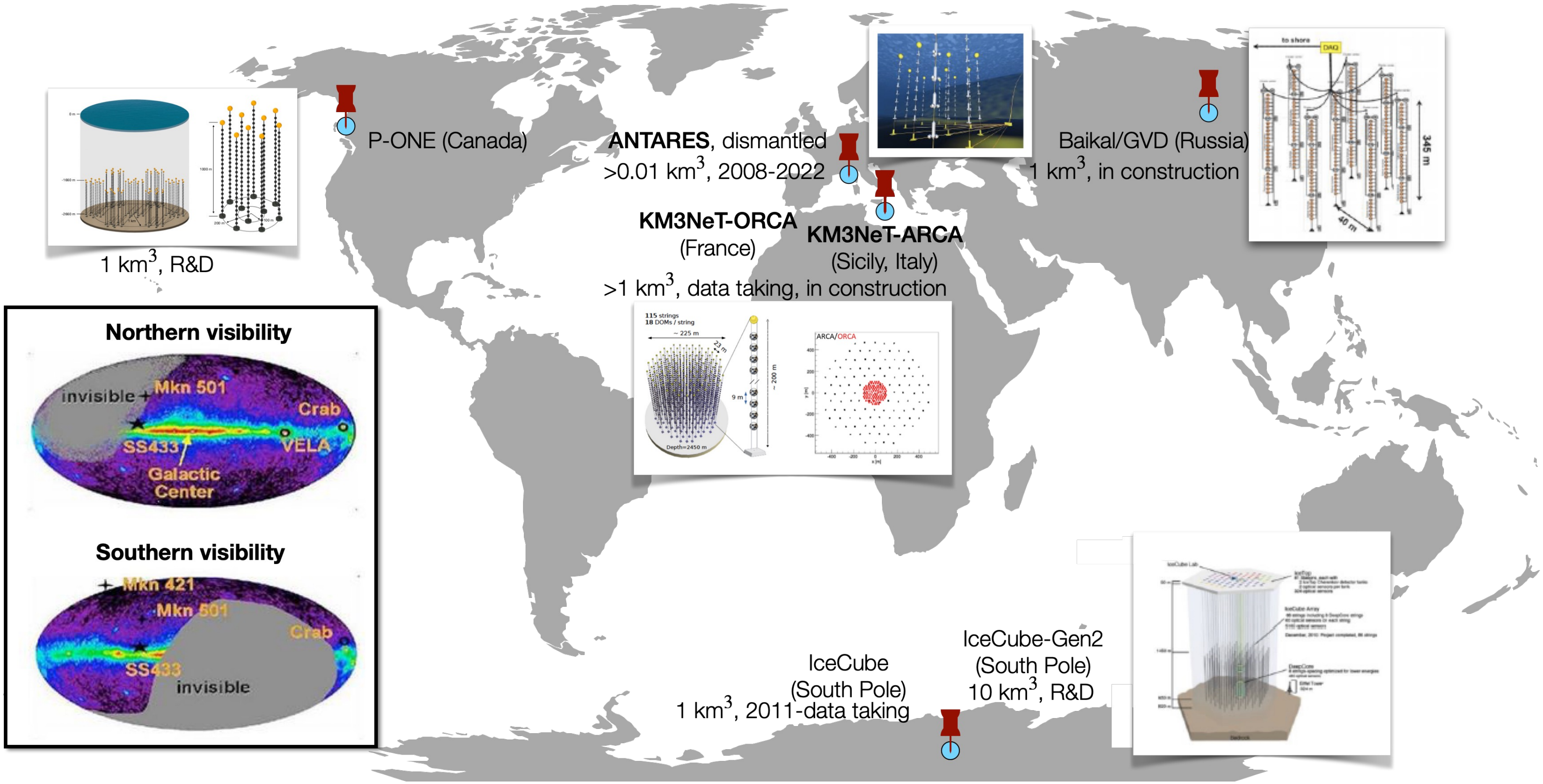
Distinguish different supernova models

Supernova detection with DM Detectors

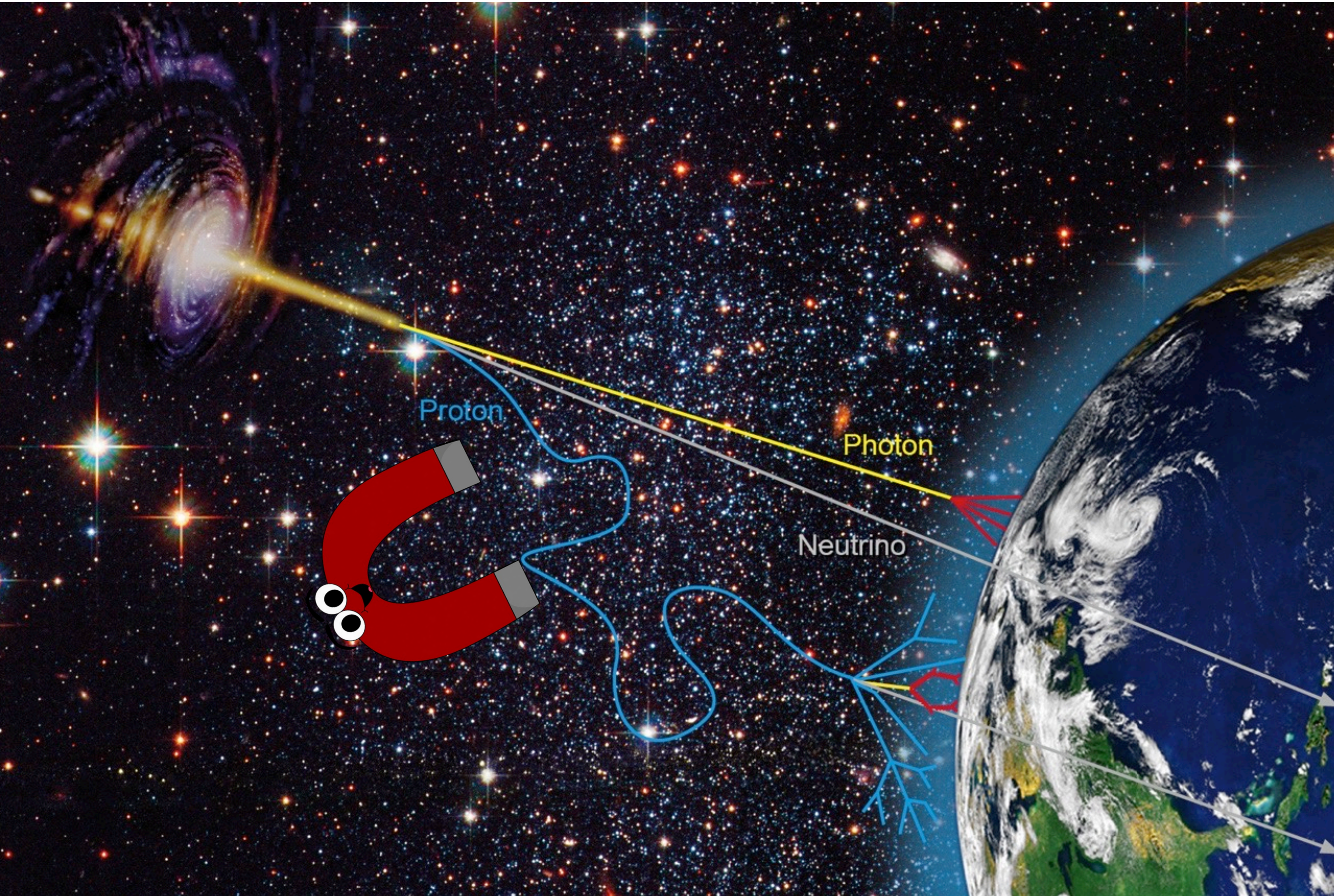


Multi-messenger Astronomy

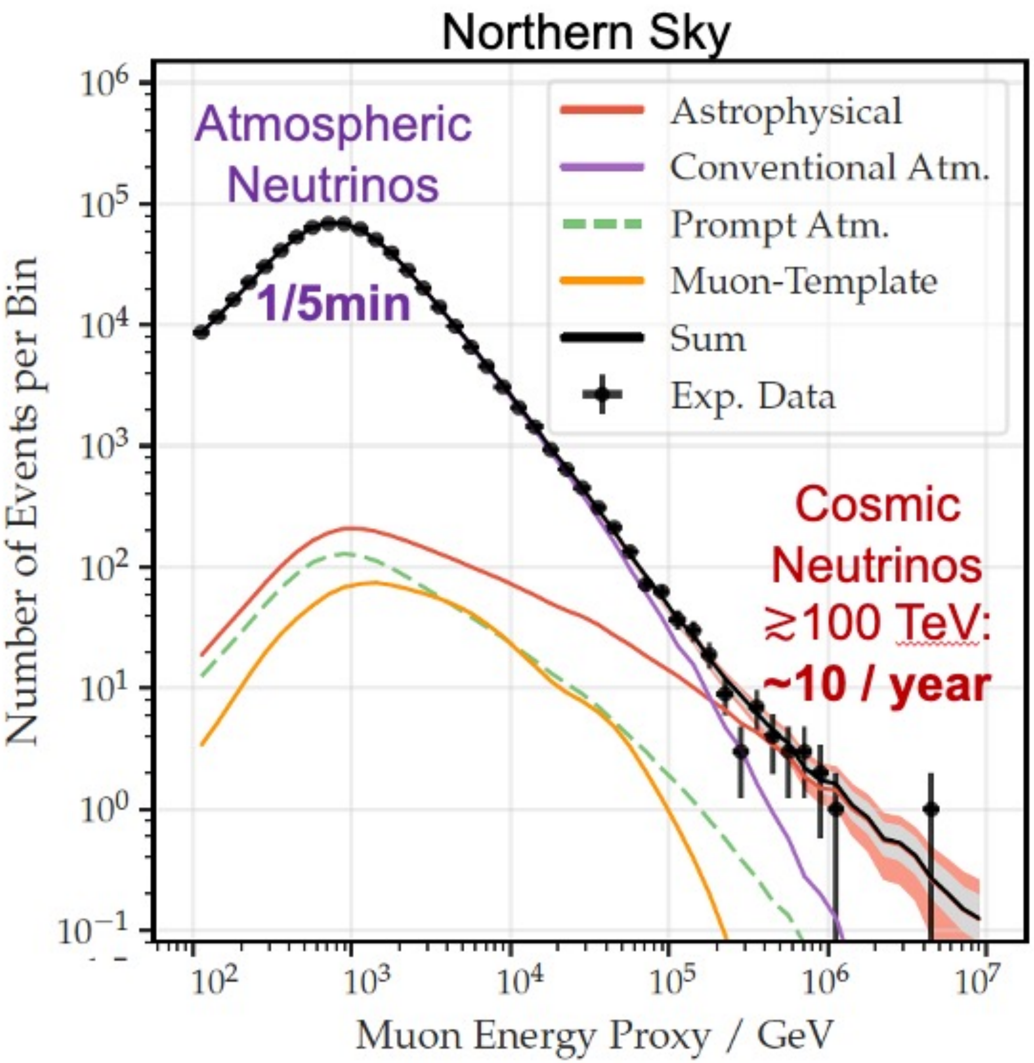



P-ONE (Canada)
1 km³, R&D
ANTARES, dismantled
>0.01 km³, 2008-2022
KM3NeT-ORCA
(France)
KM3NeT-ARCA
(Sicily, Italy)
>1 km³, data taking, in construction
115 strings
18 DOMs / string
ARCA/ORCA
Baikal/GVD (Russia)
1 km³, in construction
345 m
40 m
to shore
DAQ
Northern visibility
invisible
Mkn 501
Crab
SS433
VELA
Galactic Center
Southern visibility
Mkn 421
Mkn 501
Crab
SS433
invisible
IceCube
(South Pole)
1 km³, 2011-data taking
IceCube-Gen2
(South Pole)
10 km³, R&D

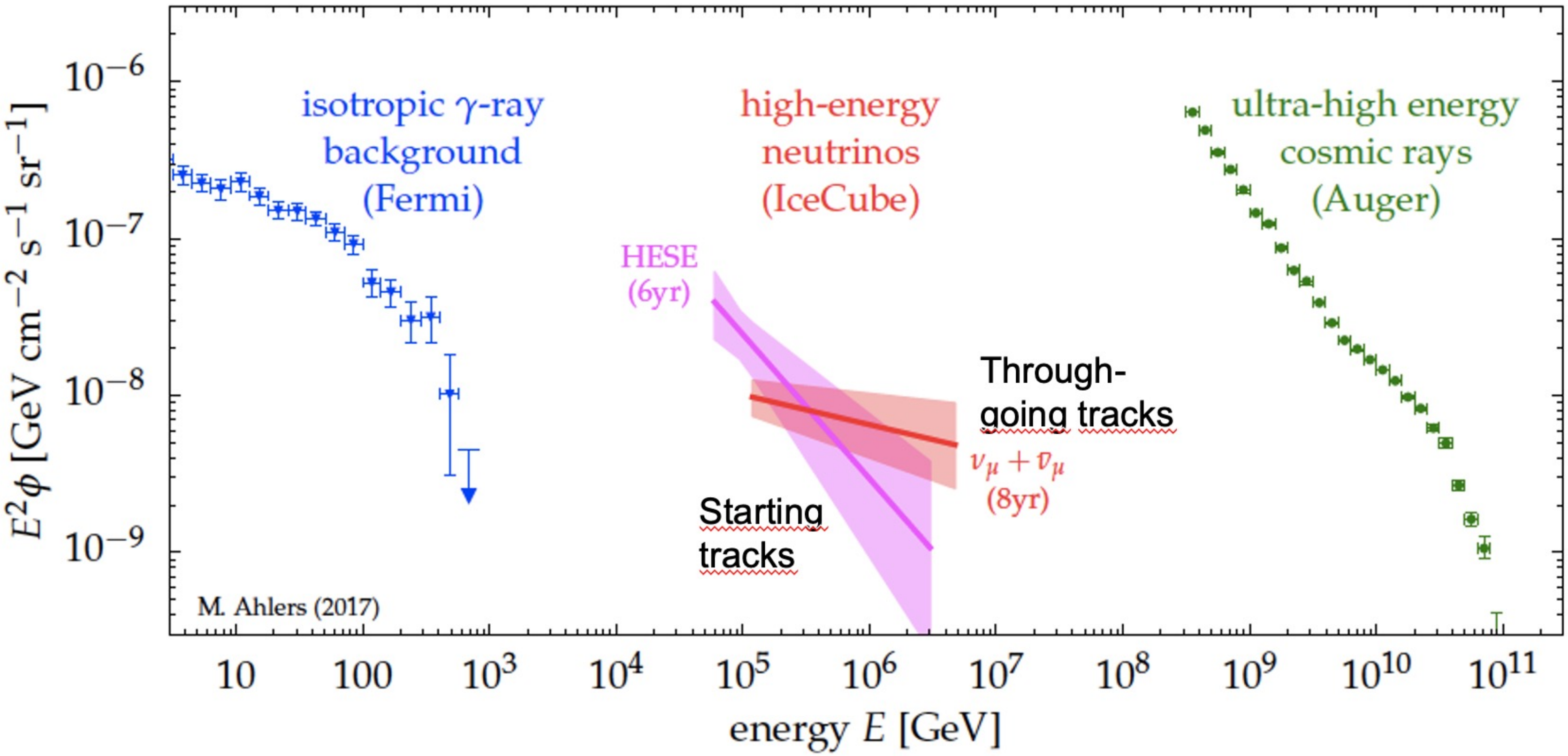
What are the Cosmic-Ray Sources?



Diffuse Neutrino Flux Detected



Multi-messenger Diffuse Flux

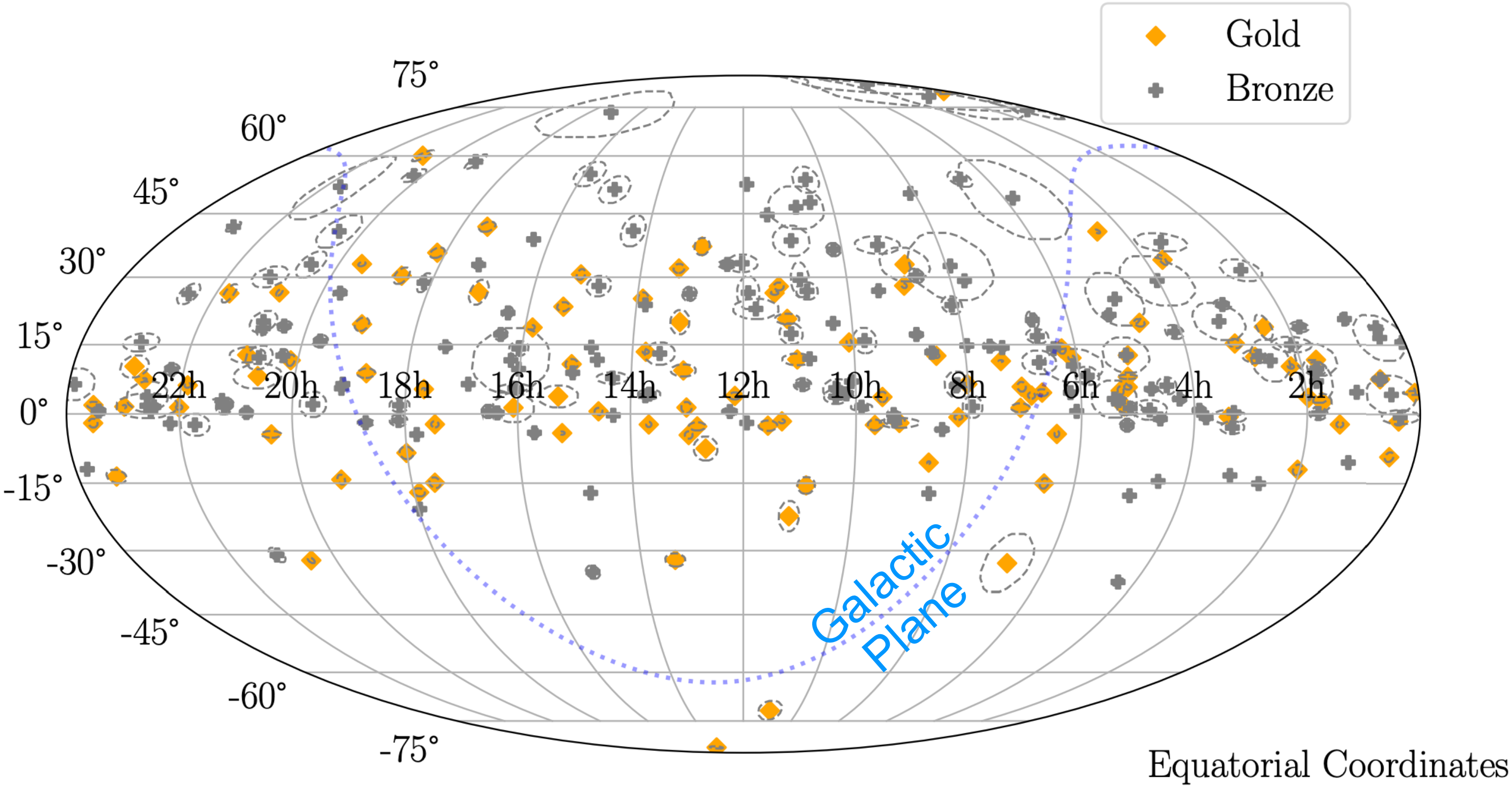


Similar energies in gamma rays, neutrinos & cosmic rays injected into our Universe

What are the sources?!

Neutrino Sky Map

IceCube neutrinos with high (>30%) probability to be of cosmic origin

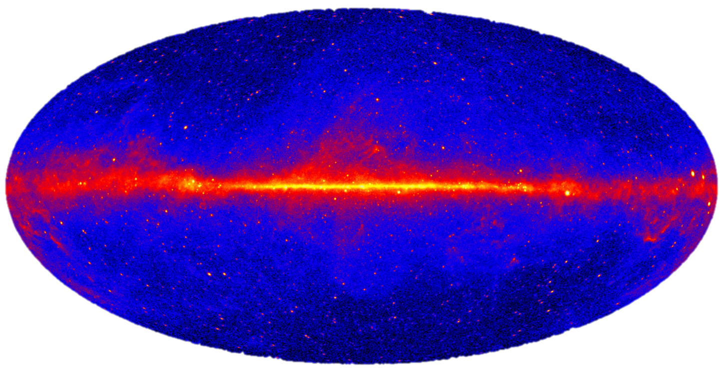


Neutrinos alone do not reveal the sources (yet)

IceCube ApJS 269 (2023)

Galactic Contribution

GeV gamma-ray sky by Fermi-LAT

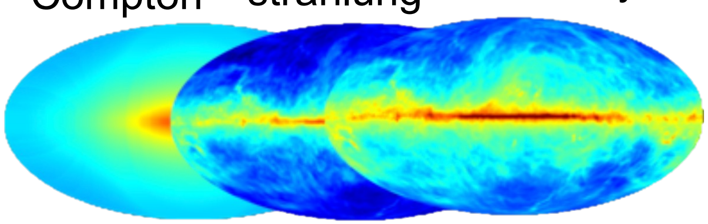


Cosmic rays propagate through the Galaxy and interact with photons and gas

Inverse Compton

Brems-strahlung

π^0 decay



IceCube Science 380 (2023)

Galactic Contribution

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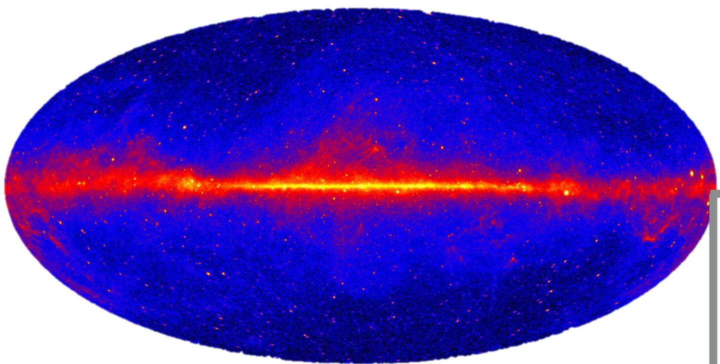

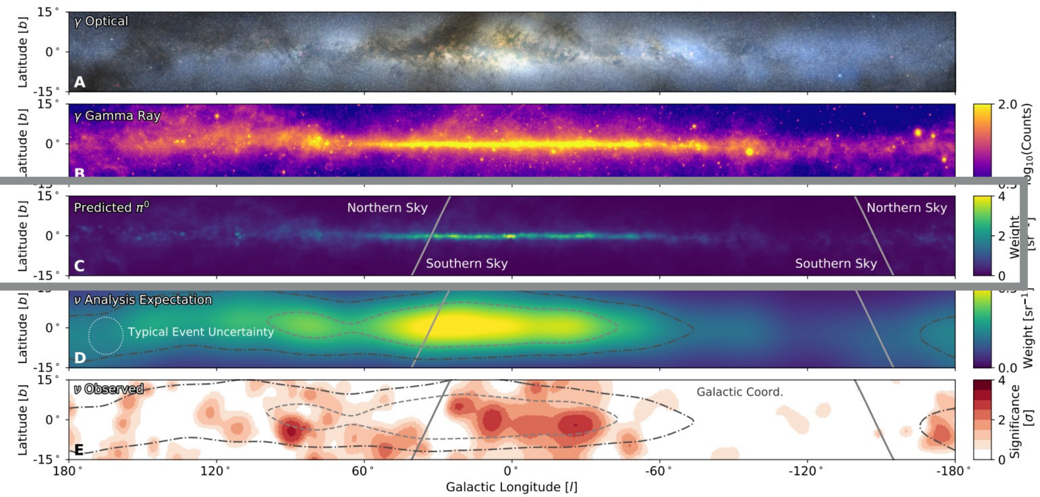

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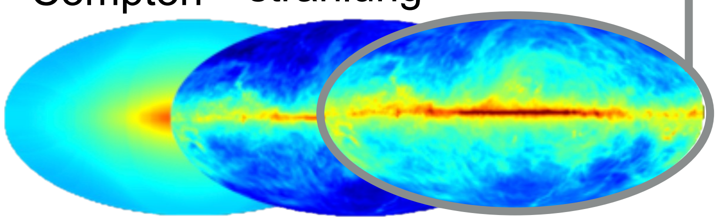
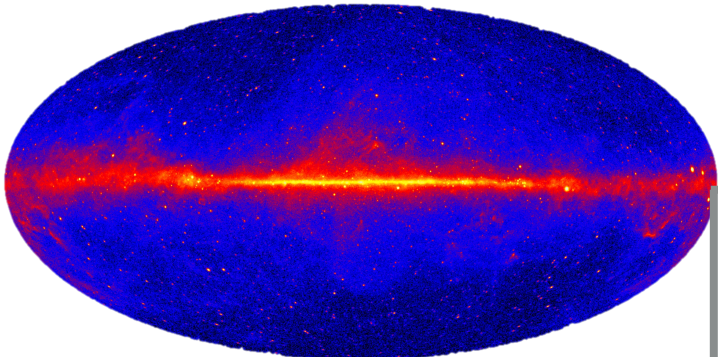


First detection of galactic plane neutrino flux thanks to gamma-ray template fit, ~10% of diffuse flux

IceCube Science 380 (2023)

Galactic Contribution

GeV gamma-ray sky by Fermi-LAT



Inverse Compton

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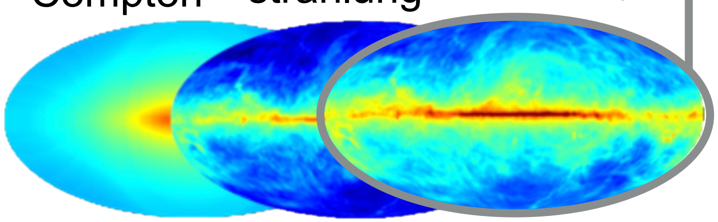
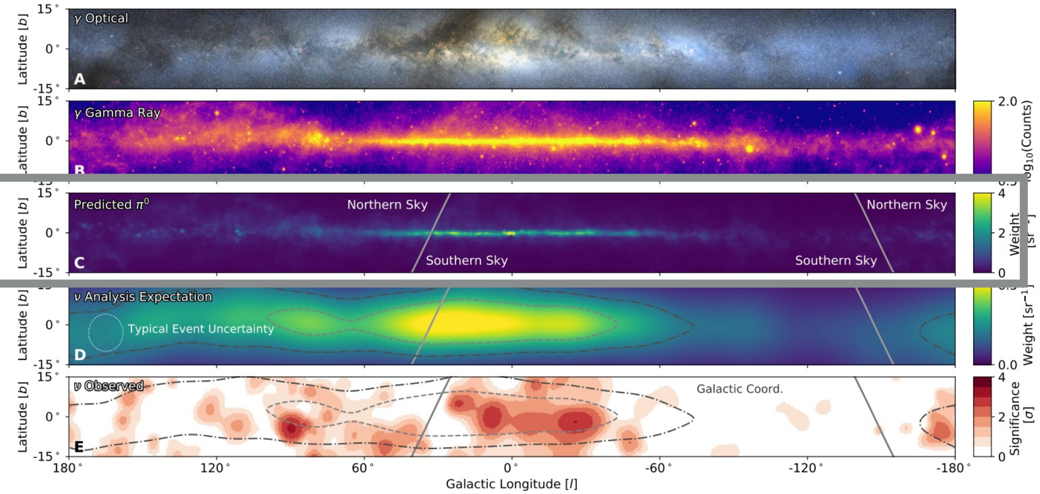
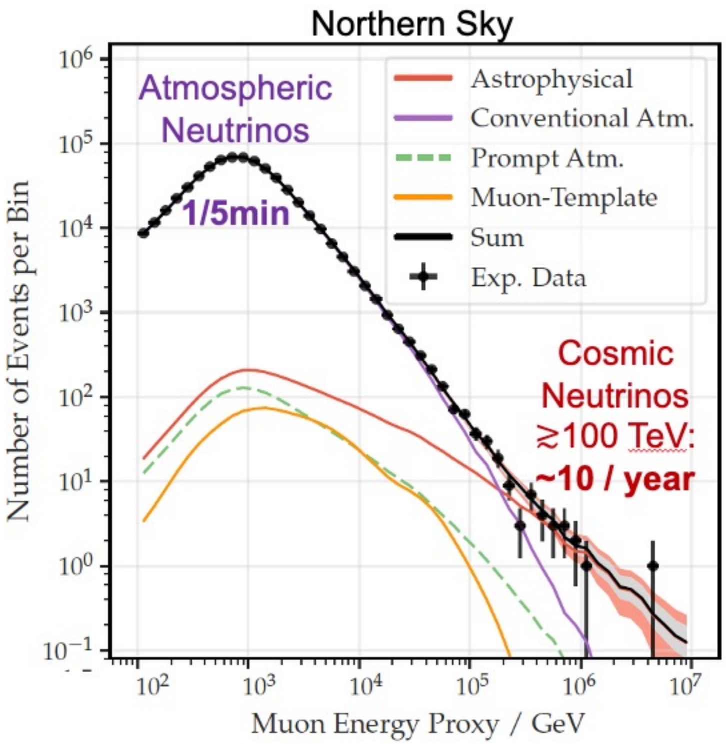




New handle to understand cosmic-ray production and propagation in our Galaxy

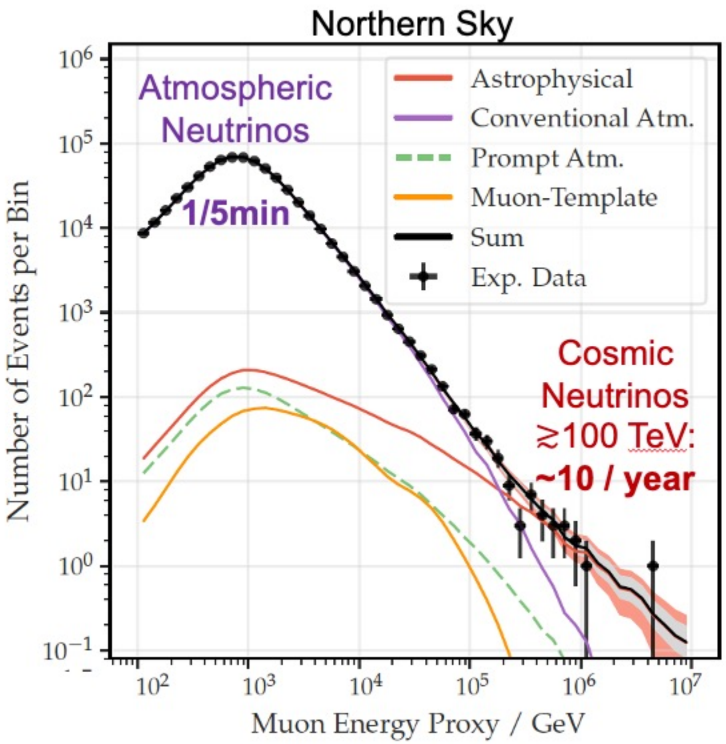
Search for Extragalactic Sources: Strategies



1. Look for hotspots in the neutrino sky → identify source candidates
2. Start from EM source catalog → look for neutrinos from source population
3. Focus on high-energy neutrinos with high signal probability → look for EM counterparts

IceCube Coll. ApJ 928 (2022) 50

Search for Extragalactic Sources: Strategies



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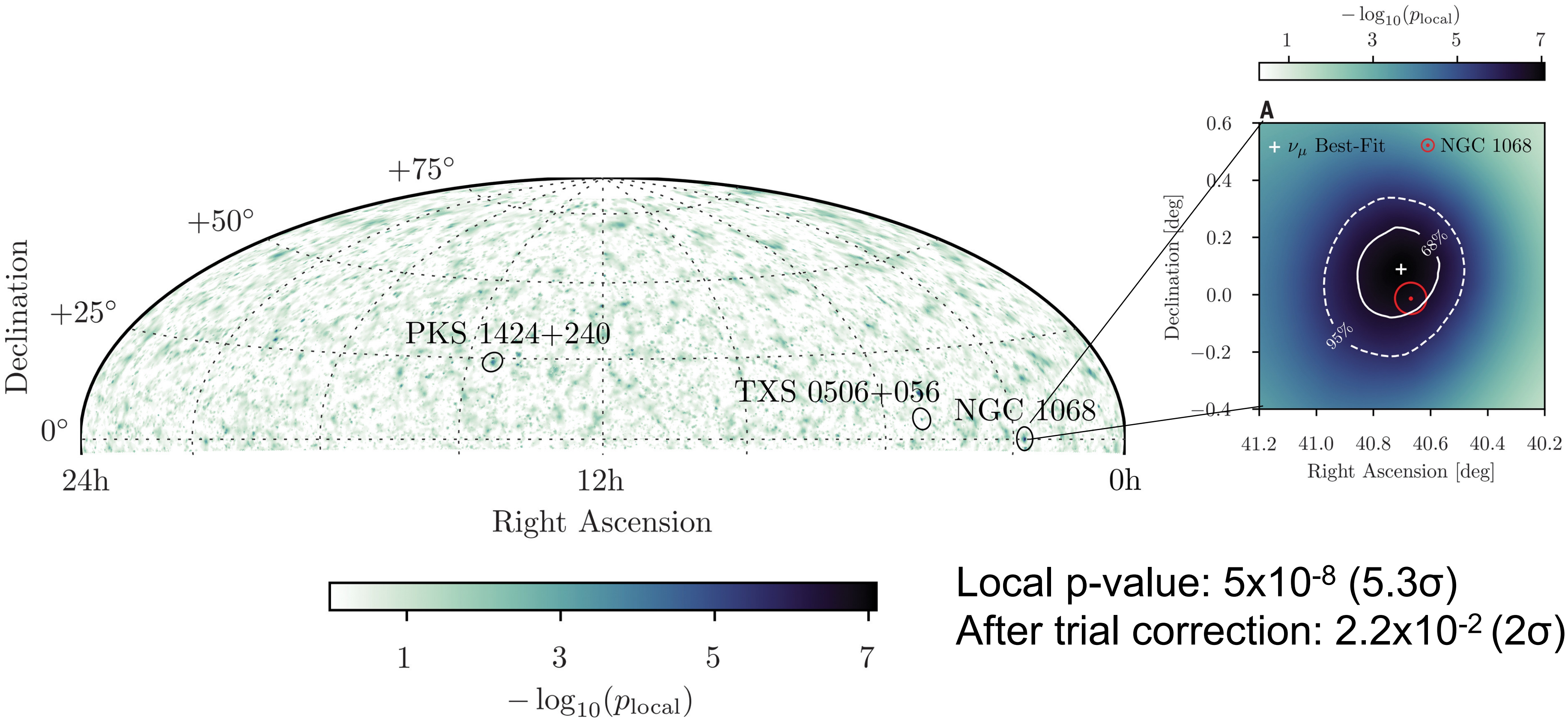
IceCube Coll. ApJ 928 (2022) 50

Extragalactic Sources: hot spot search

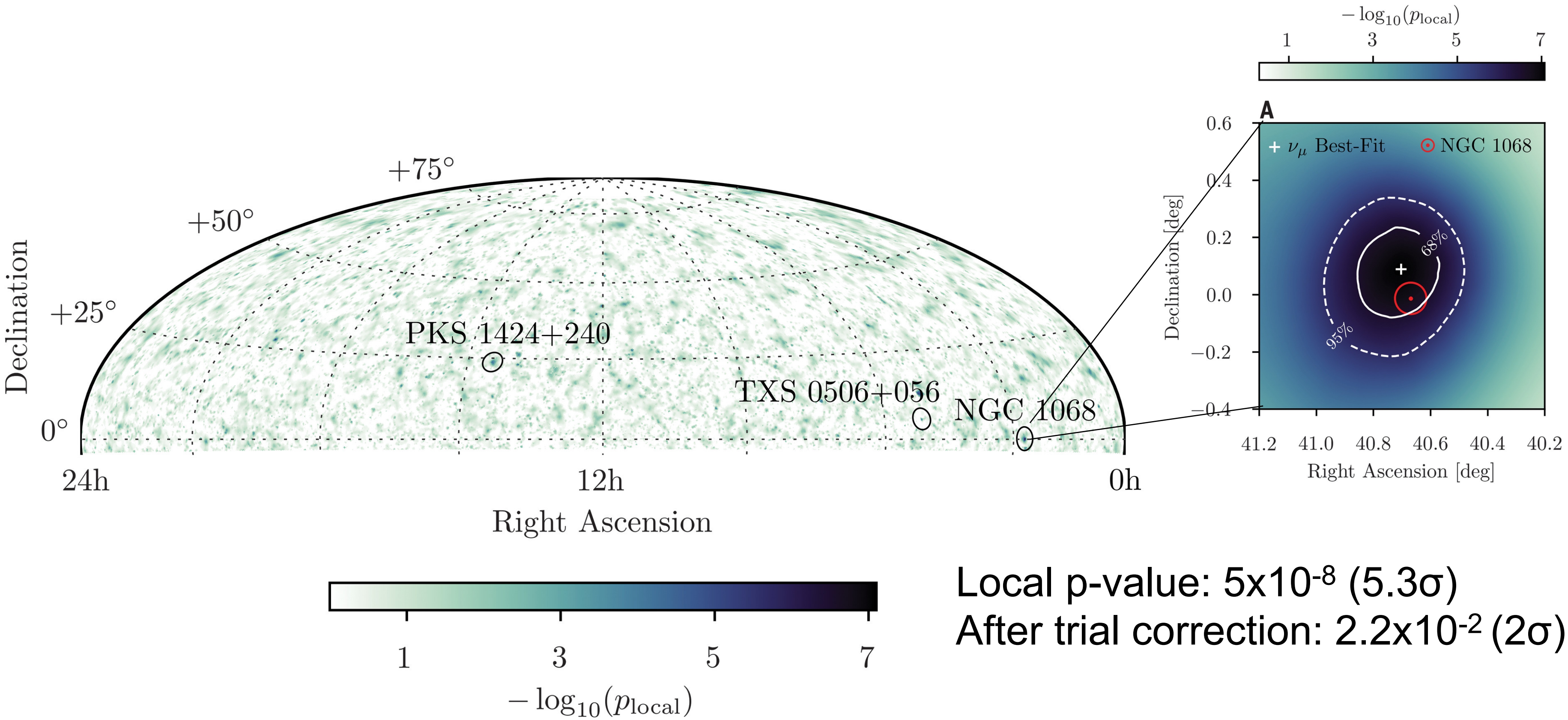


Local p-value: 5×10^{-8} (5.3σ)
After trial correction: 2.2×10^{-2} (2σ)

Challenge: Atmospheric background, large trial factor

IceCube Science 378 (2022)

Extragalactic Sources: hot spot search

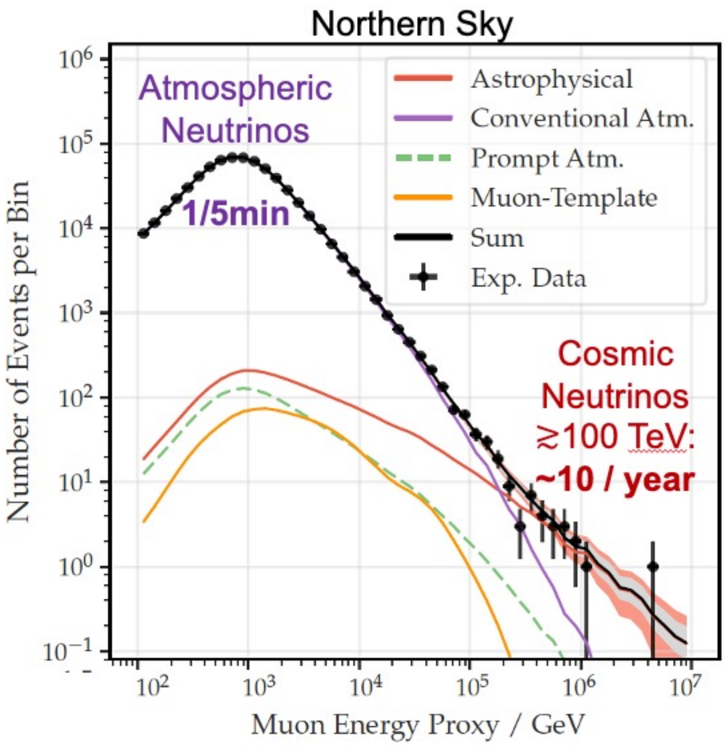


Local p-value: $5\text{x}10^{-8}$ (5.3σ)
After trial correction: $2.2\text{x}10^{-2}$ (2σ)

Solution: Use predefined source lists to reduce trials

IceCube Science 378 (2022)

Search for Extragalactic Sources: Strategies



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IceCube Coll. ApJ 928 (2022) 50

Extragalactic Sources

110 sources based on gamma-ray properties and weighted with neutrino search sensitivity

Most significant candidate:

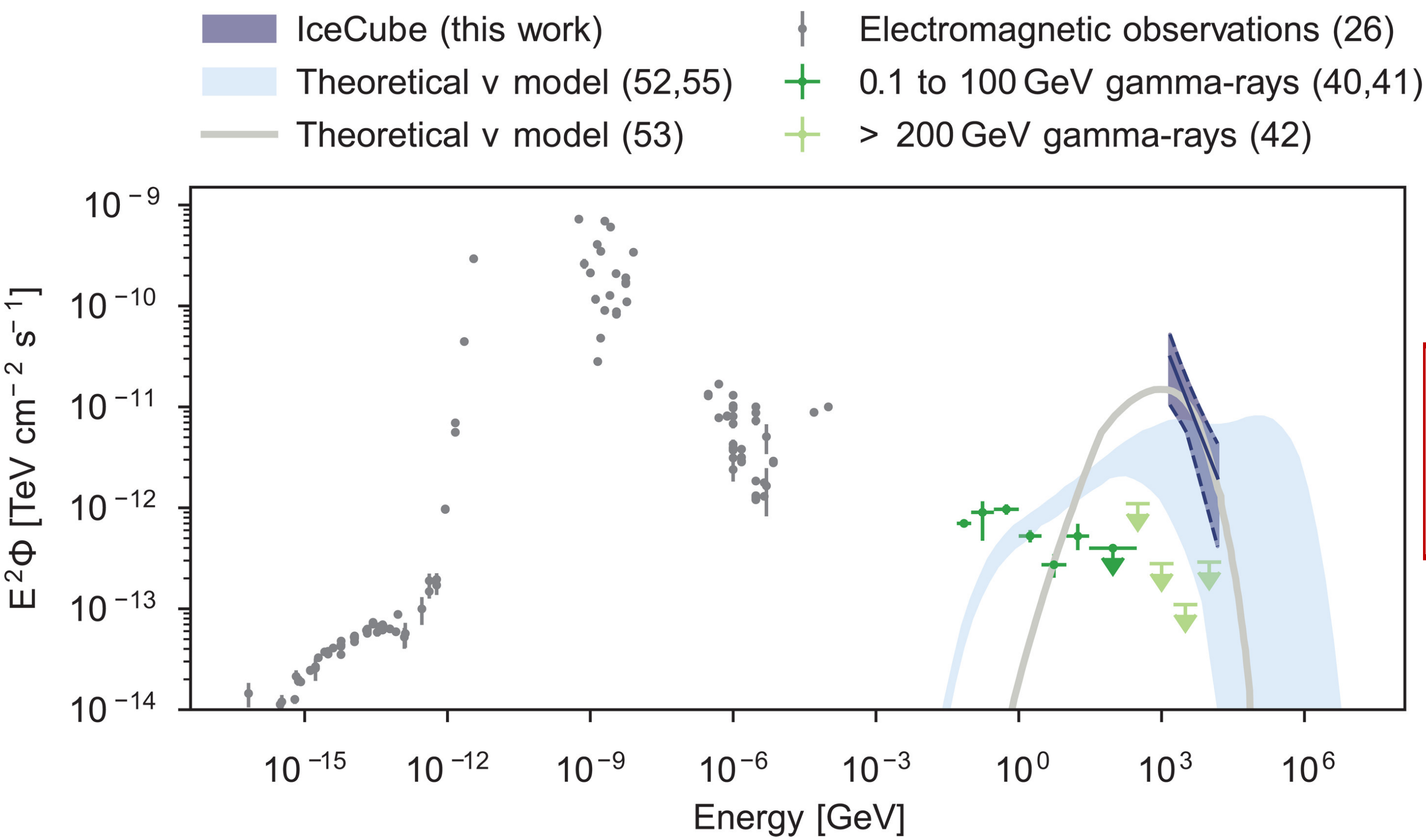
NGC 1068 (M77), 4.2σ

- Nearby (M=14Mpc) Seyfert 2 galaxy
- AGN and star-forming activity

Combining gamma-ray source list with neutrino data allowed neutrino source detection

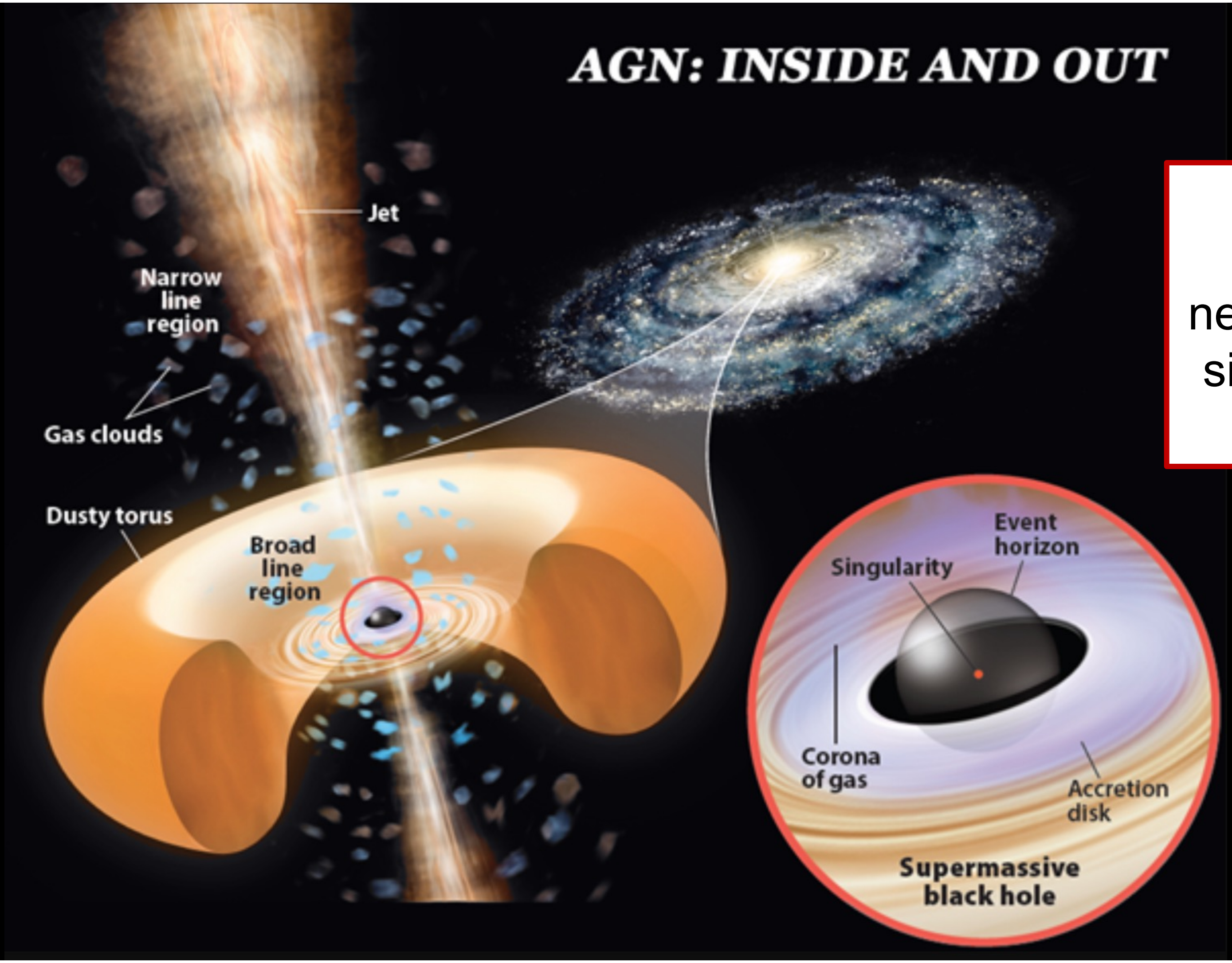
IceCube Science 378 (2022)

Complete Multi-wavelength data of NGC 1068



Gamma rays need to be absorbed

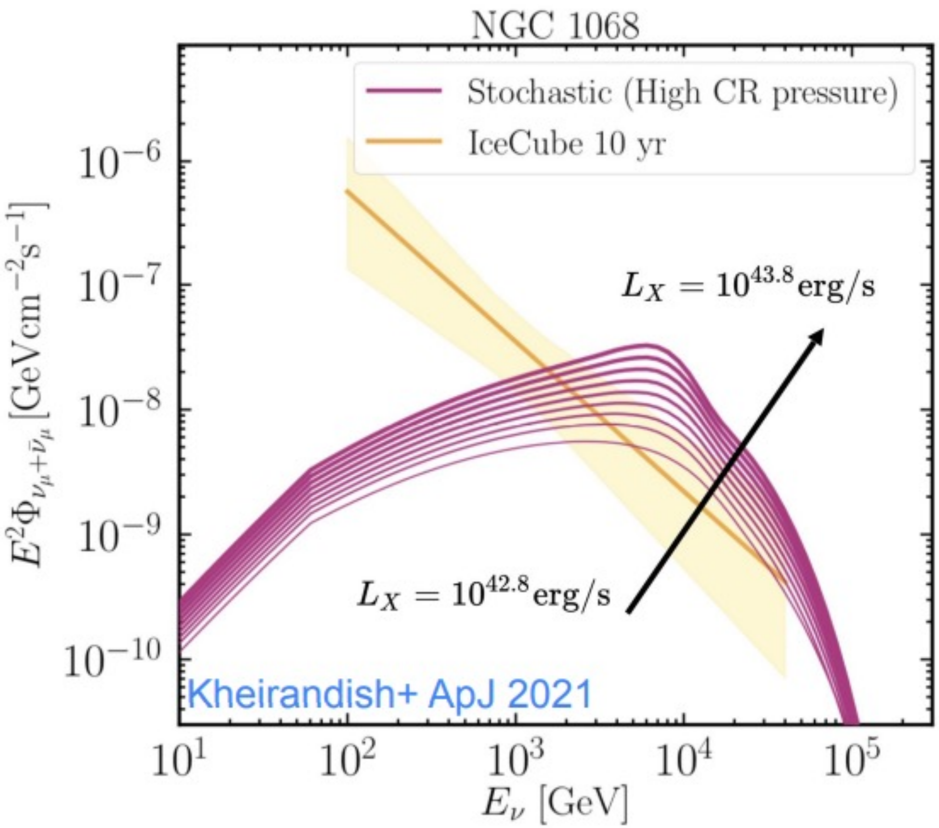
IceCube Science 378 (2022)

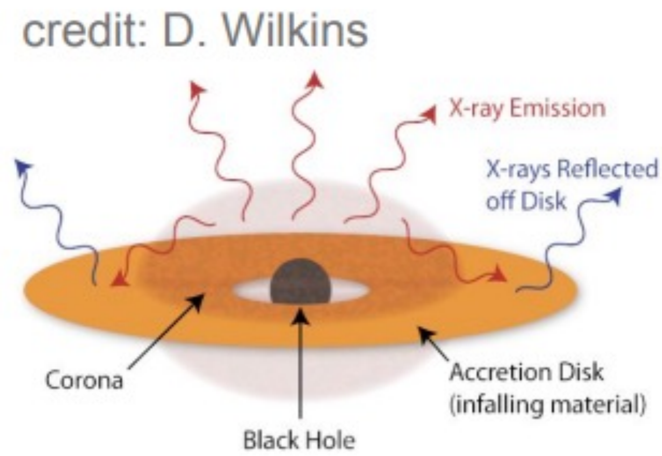


Lack of gamma rays places neutrino production site in the heart of the galaxy

More Seyferts?

Assumption: Neutrino production in disk corona, intrinsic X-ray flux (2–10 keV) as proxy for neutrino emission



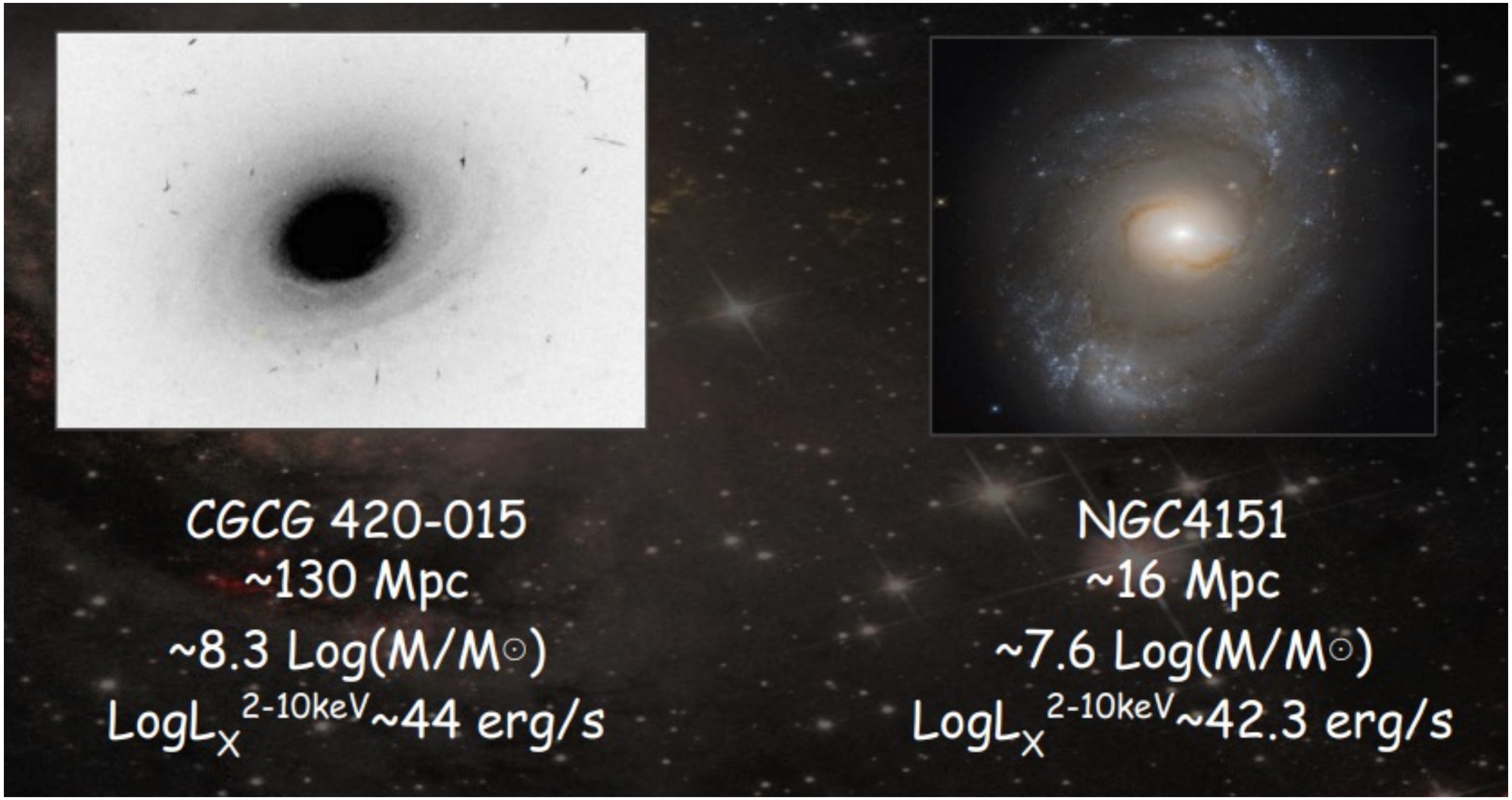


No significant emission is found in the stacking search excluding NGC 1068.

IceCube arXiv:2406.07601

More Seyferts?

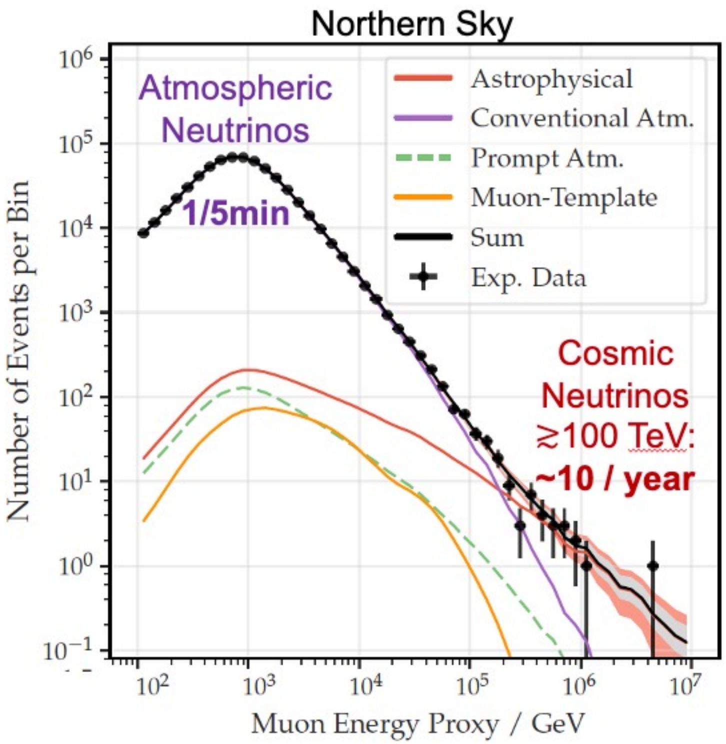
No assumption about neutrino emission model



Two more source candidates at 2.5σ and 2.1σ level

IceCube arXiv:2406.07601, see also Neronov et al. PRL 132 (2024) 10, 101002

Search for Extragalactic Sources: Strategies



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IceCube Coll. ApJ 928 (2022) 50

Neutrinos as Triggers

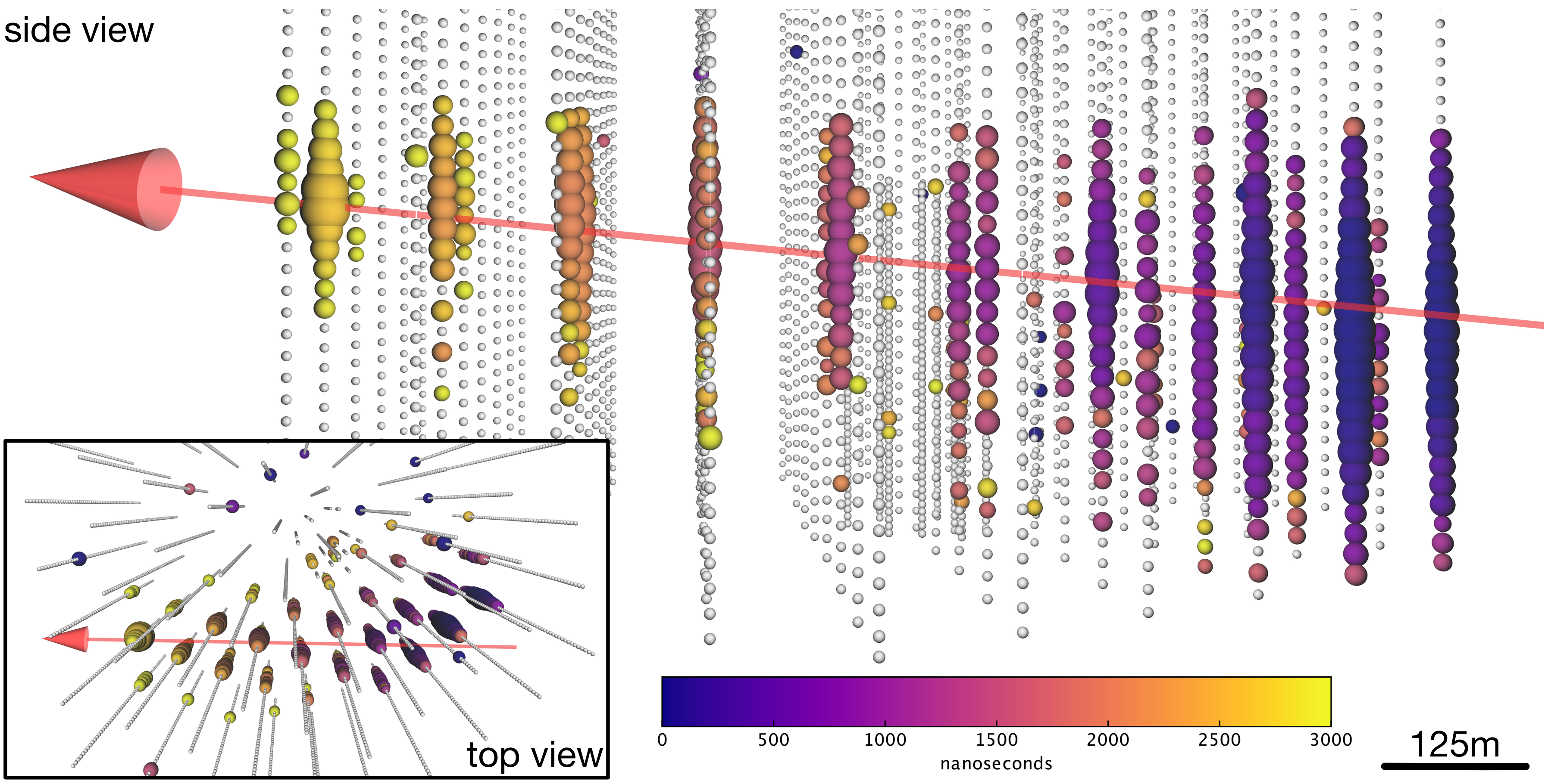
Public alerts since April 2016

- Single high-energy muon track events (> ~100TeV)
- “Gold” alert stream: 10 / yr, ~5 / yr of cosmic origin
- Median latency: 30 sec

Goal: Find electromagnetic counterpart

Astropart. Phys., 92, 30 (2017)

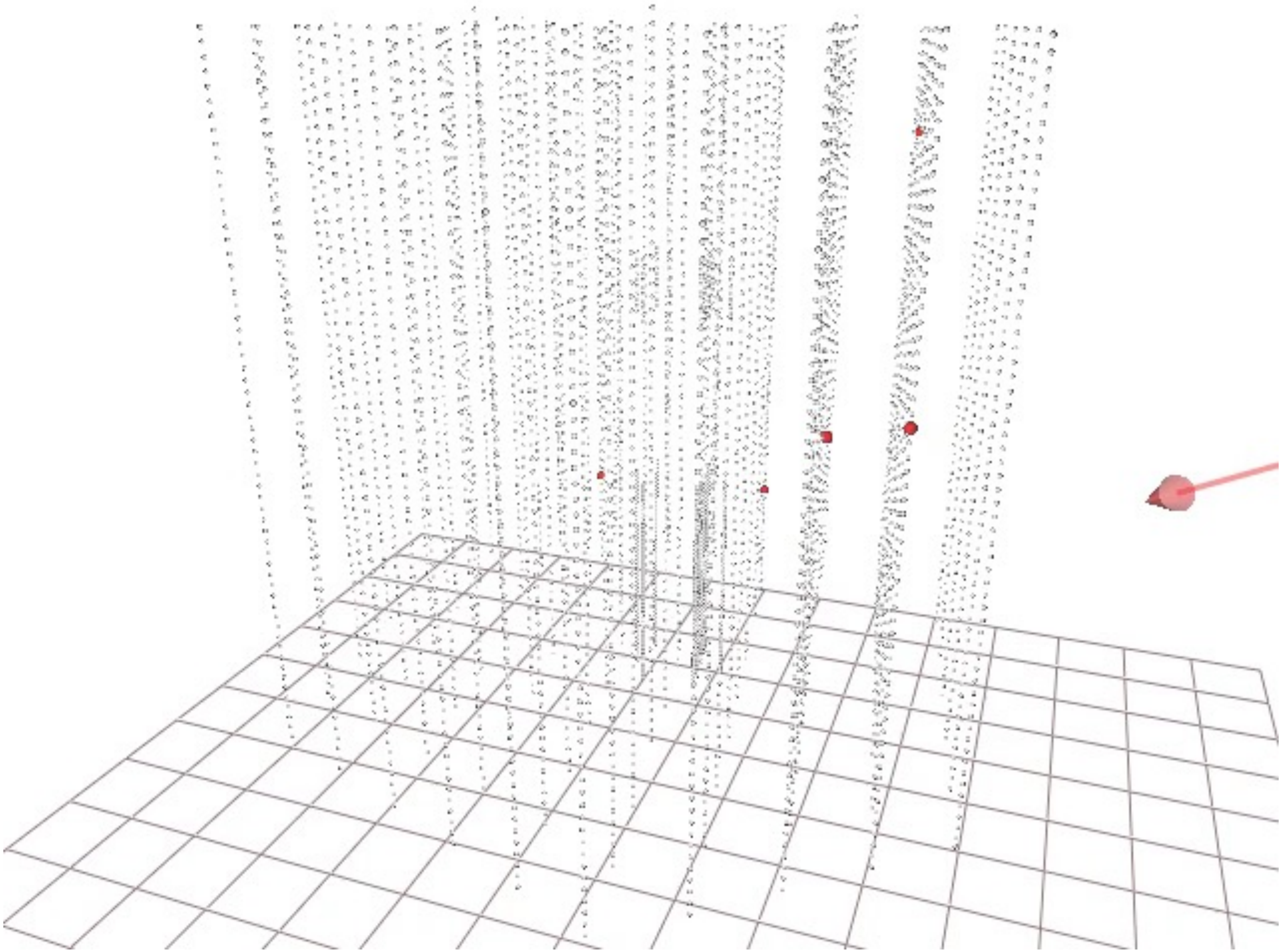
First example: IC-170922A – a 290 TeV Neutrino



Signalness: 56.5%

IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

IC-170922A – a 290 TeV Neutrino



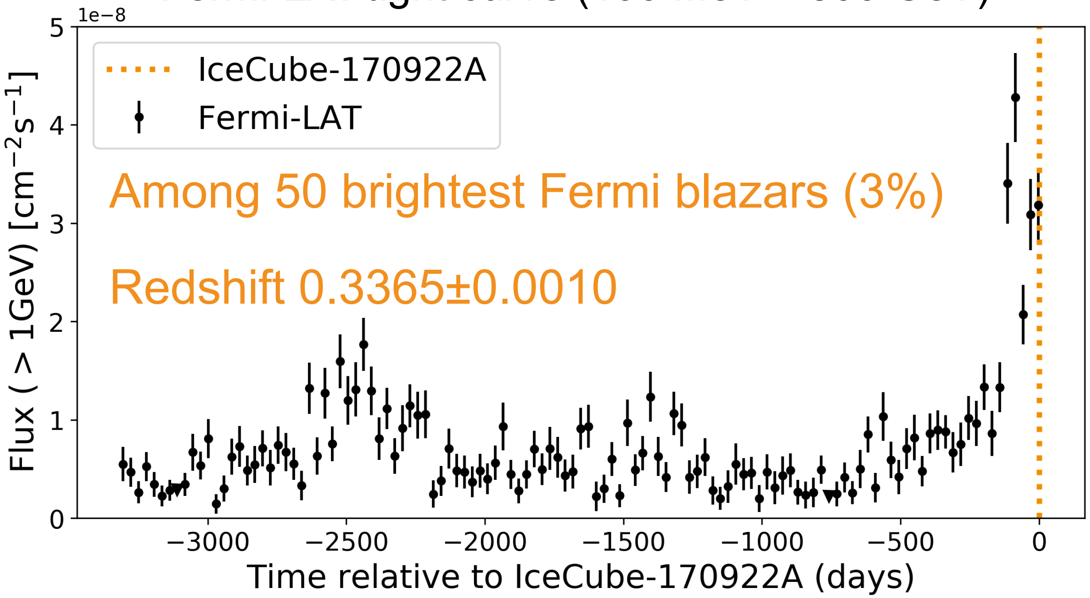
IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

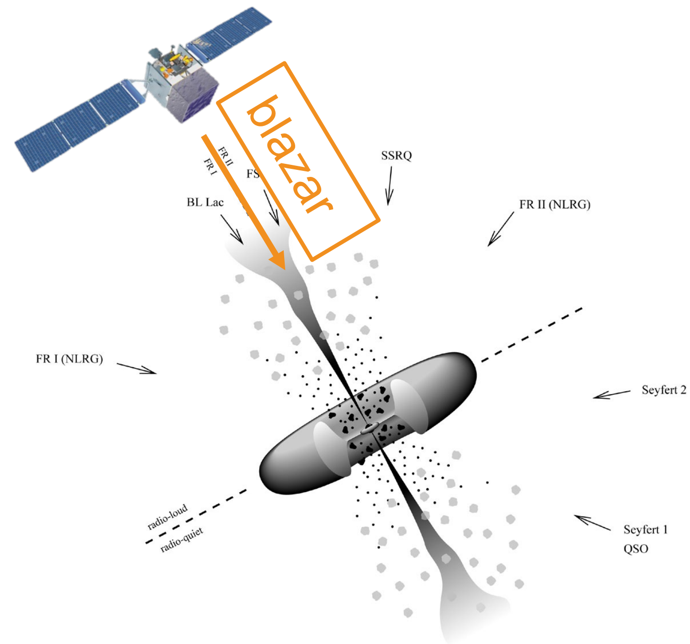
Fermi-LAT finds Flaring Source

Fermi-LAT Coll., ApJ 846, 2017, Video credits: Matteo Giomi, Fermi-LAT Collaboration

Fermi-LAT finds Flaring Blazar, TXS 0506+056

Fermi-LAT light curve (100 MeV – 300 GeV)





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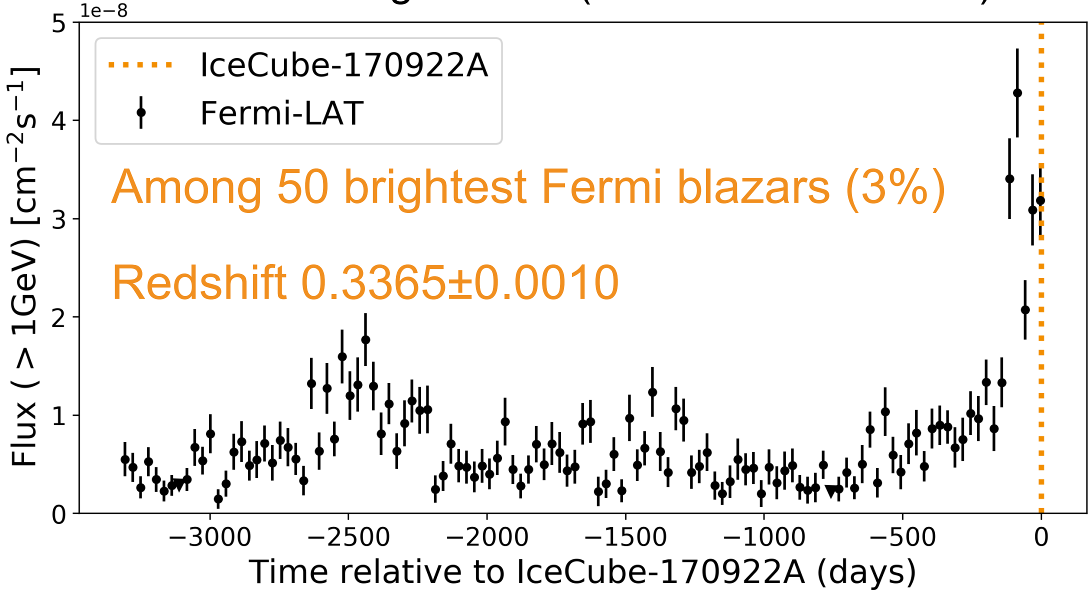
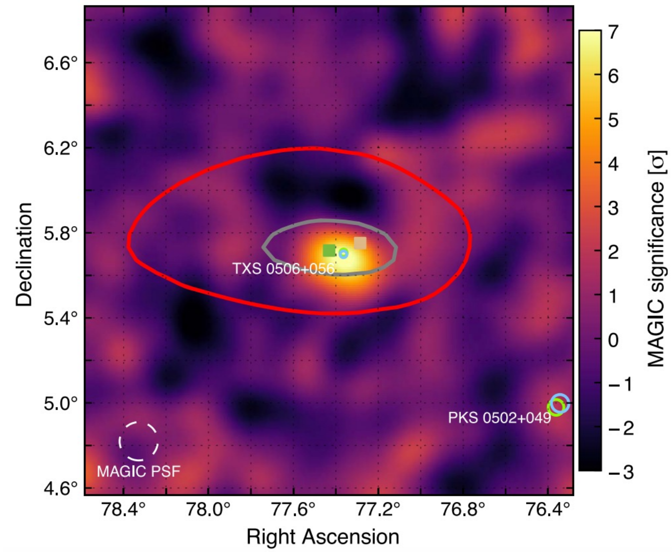
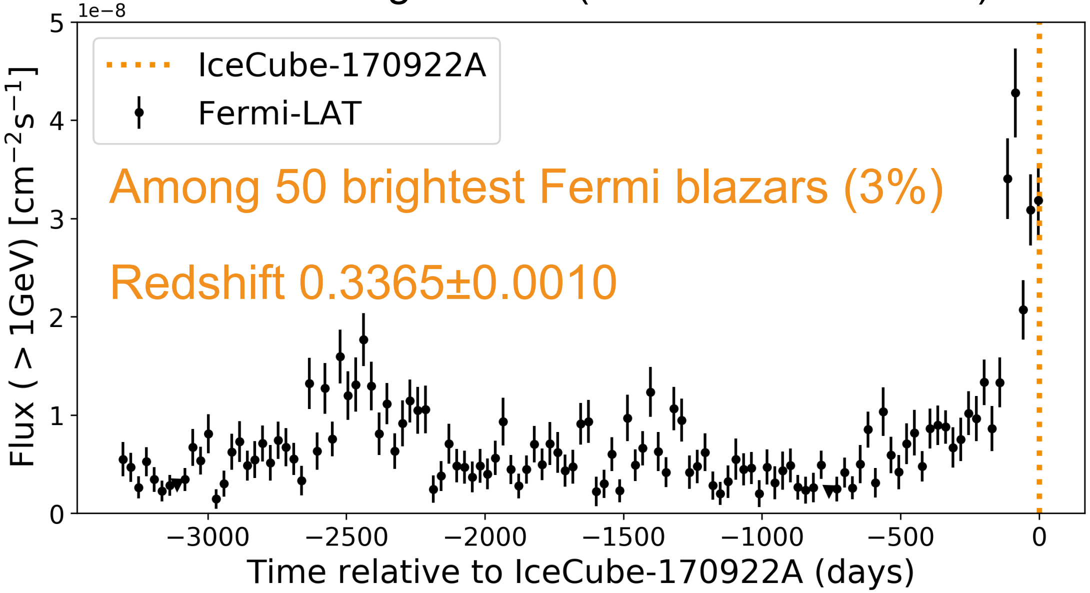


MAGIC Significance map:
TeV gamma rays

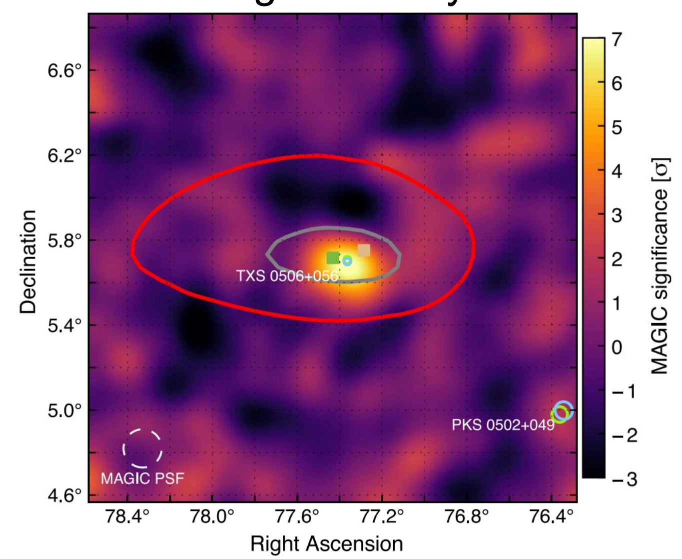


Fermi-LAT finds Flaring Blazar, TXS 0506+056

Fermi-LAT light curve (100 MeV – 300 GeV)



MAGIC Significance map:
TeV gamma rays

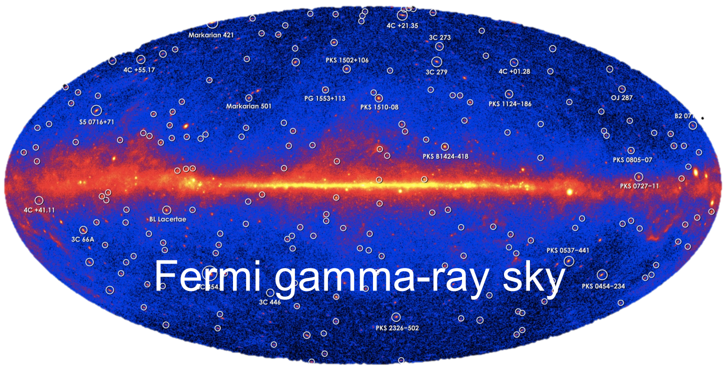


3 sigma significance including trials
> 6 PeV protons accelerated in the source

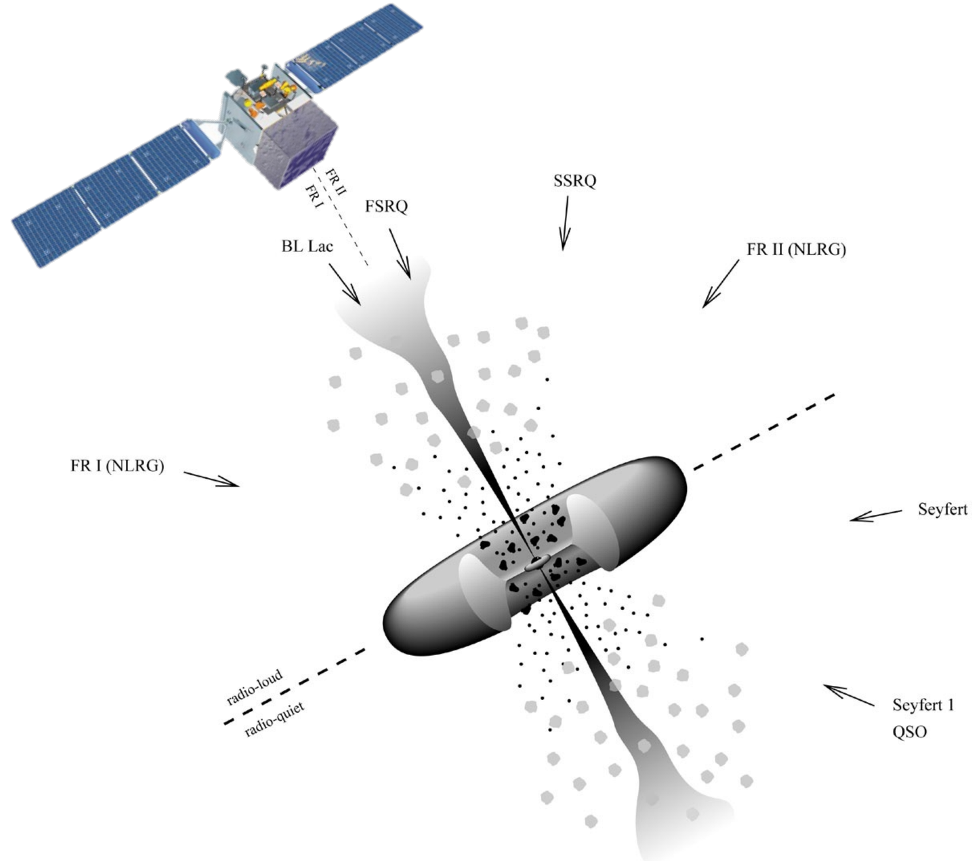
Do gamma-ray blazars produce all diffuse neutrinos?

Fermi Blazars

Gamma rays tell us **where** to look for neutrinos

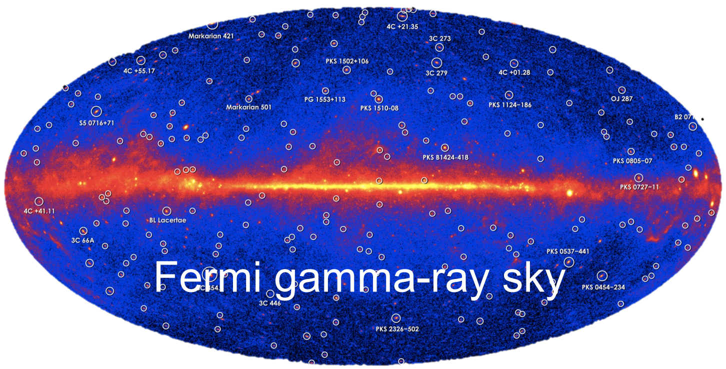


Fermi gamma-ray sky

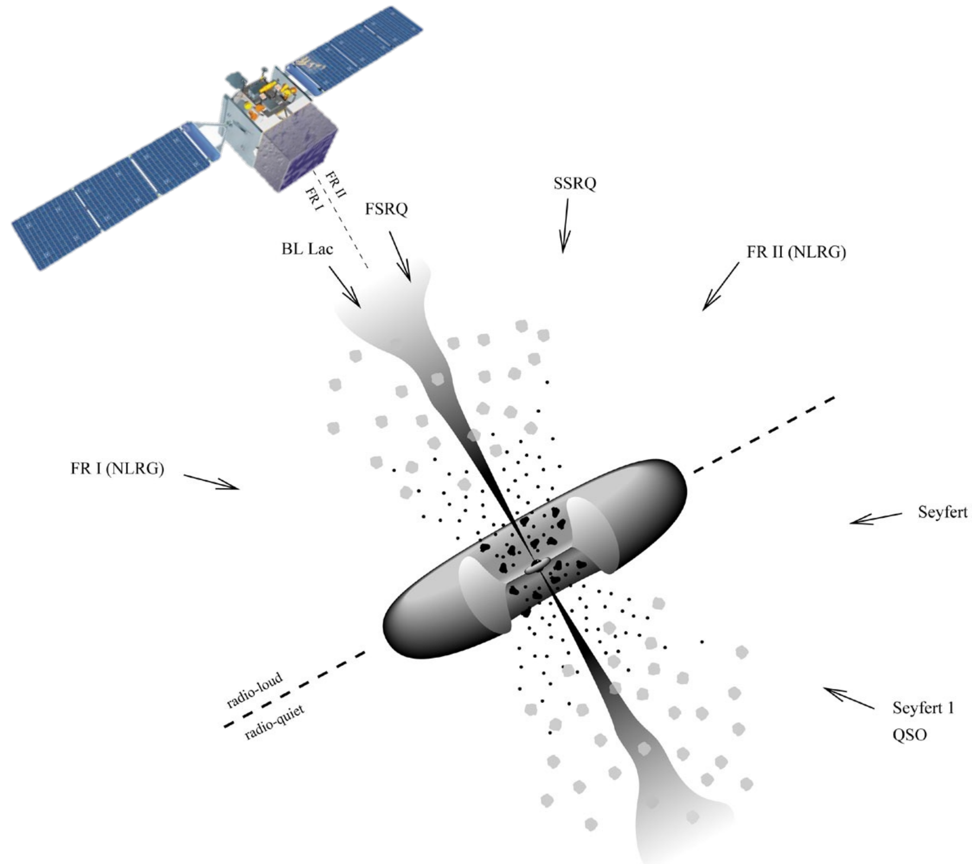


Fermi Blazars

Gamma rays tell us **where** to look for neutrinos



Correlation study of 12 years of IceCube data and 2089 ***Fermi*-LAT blazars**

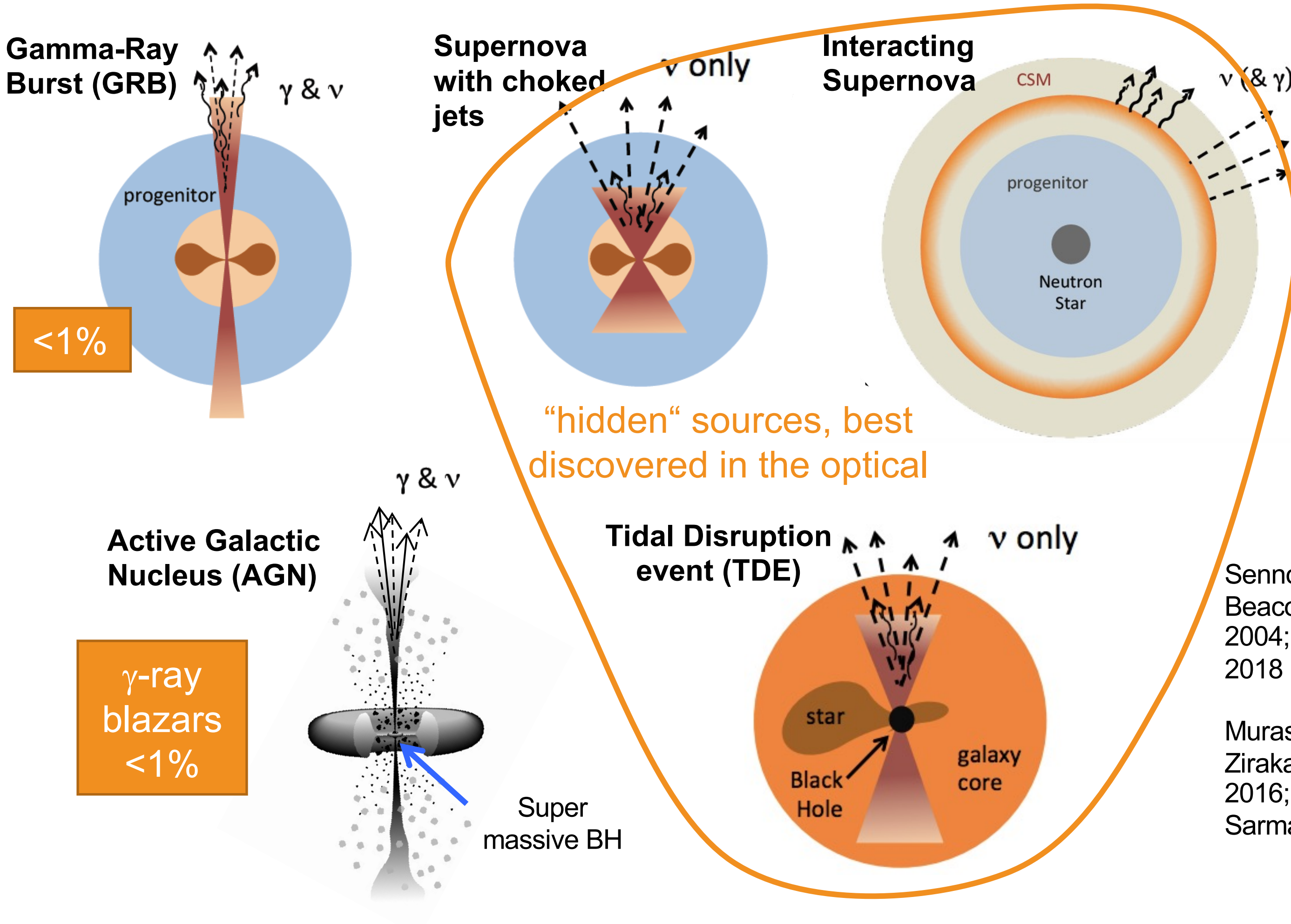


***Fermi*-LAT blazars** can only be responsible for a **small fraction** of the observed ν's.

IceCube Coll. ApJ 954 (2023) 1, 75

Other Sources?

Other neutrino source candidates



FBOTs

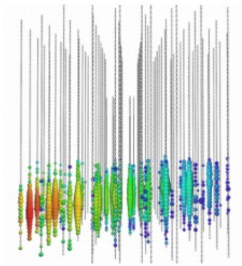
Guarini+ 2022, Fang+ 2019

Senno+ 2016; Ando & Beacom 2005; Razzaque+ 2004; Denton & Tamborra 2018

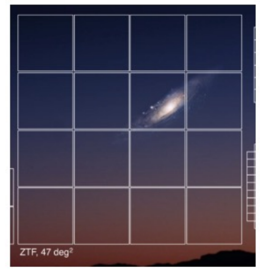
Murase+ 2011; Zirakashvili & Ptuskin 2016; Pitik+ 2022; Sarmah+ 2022

ZTF Follow-up Pipeline

Reject stars, planets, artifacts, asteroids



1. high-energy neutrino alert arrives



2. Observe with ZTF

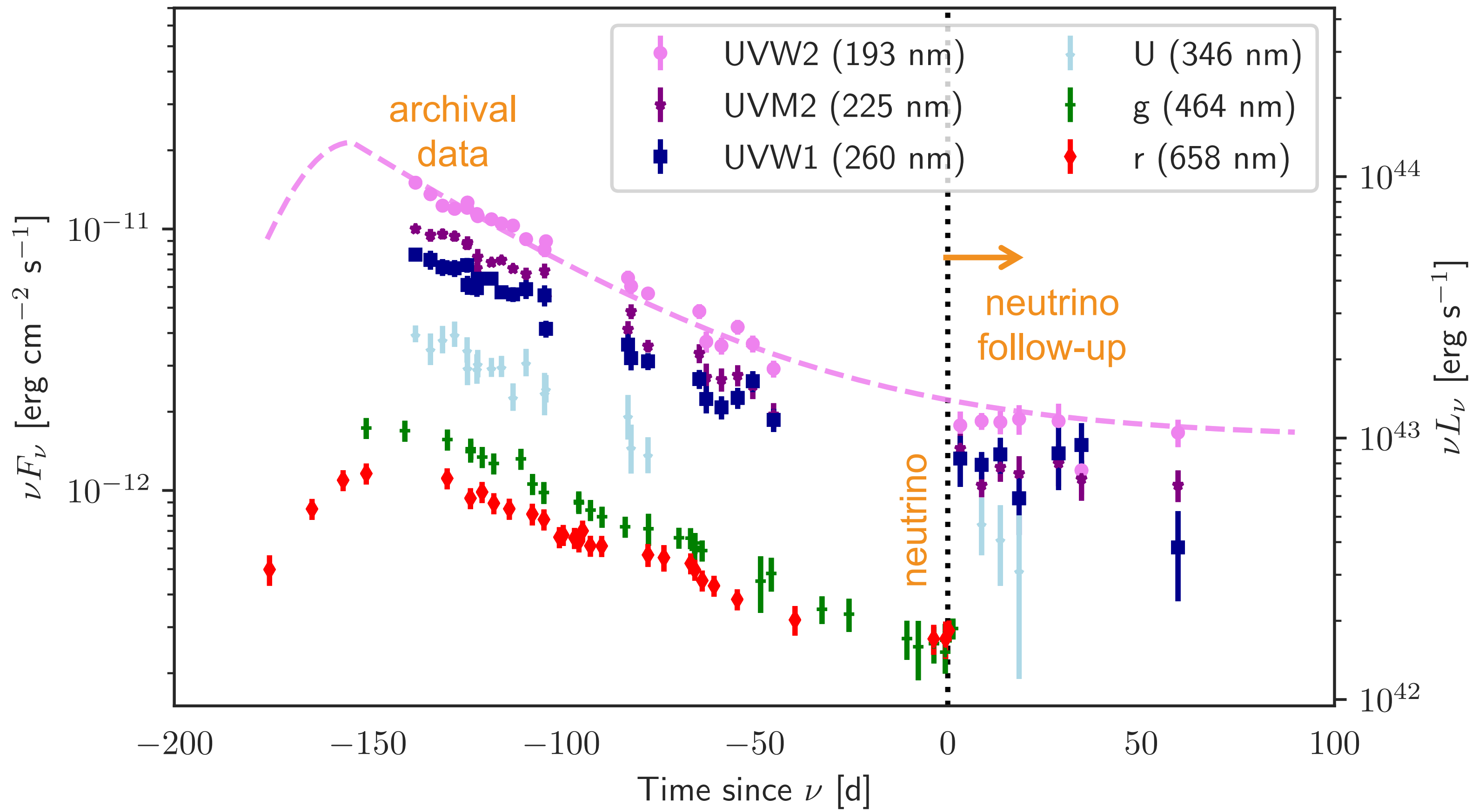
3. Follow-up with AMPEL

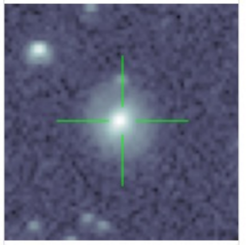
Nordin et al., A&A 631, A147 (2019)

4. Trigger further follow-up observations

Reject unrelated transients (e.g. Type Ia Supernovae)

Neutrino IC191001A (200 TeV) coincident with Tidal Disruption Event AT2019dsg



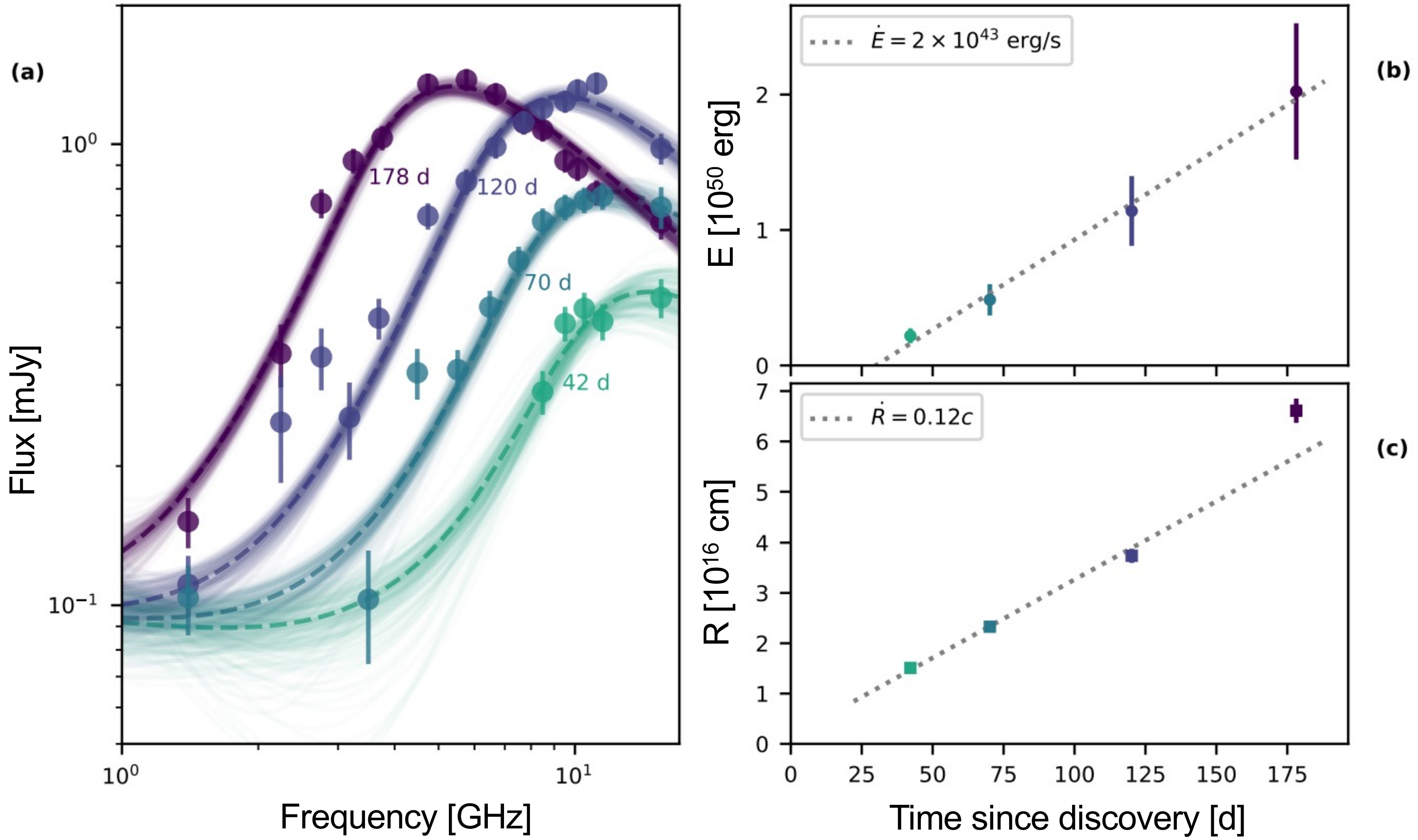


Distance: z = 0.05 (d = 230 Mpc), thermal X-rays, no gamma rays

Chance coincidence: 0.2% to find a TDE that bright (including trials)

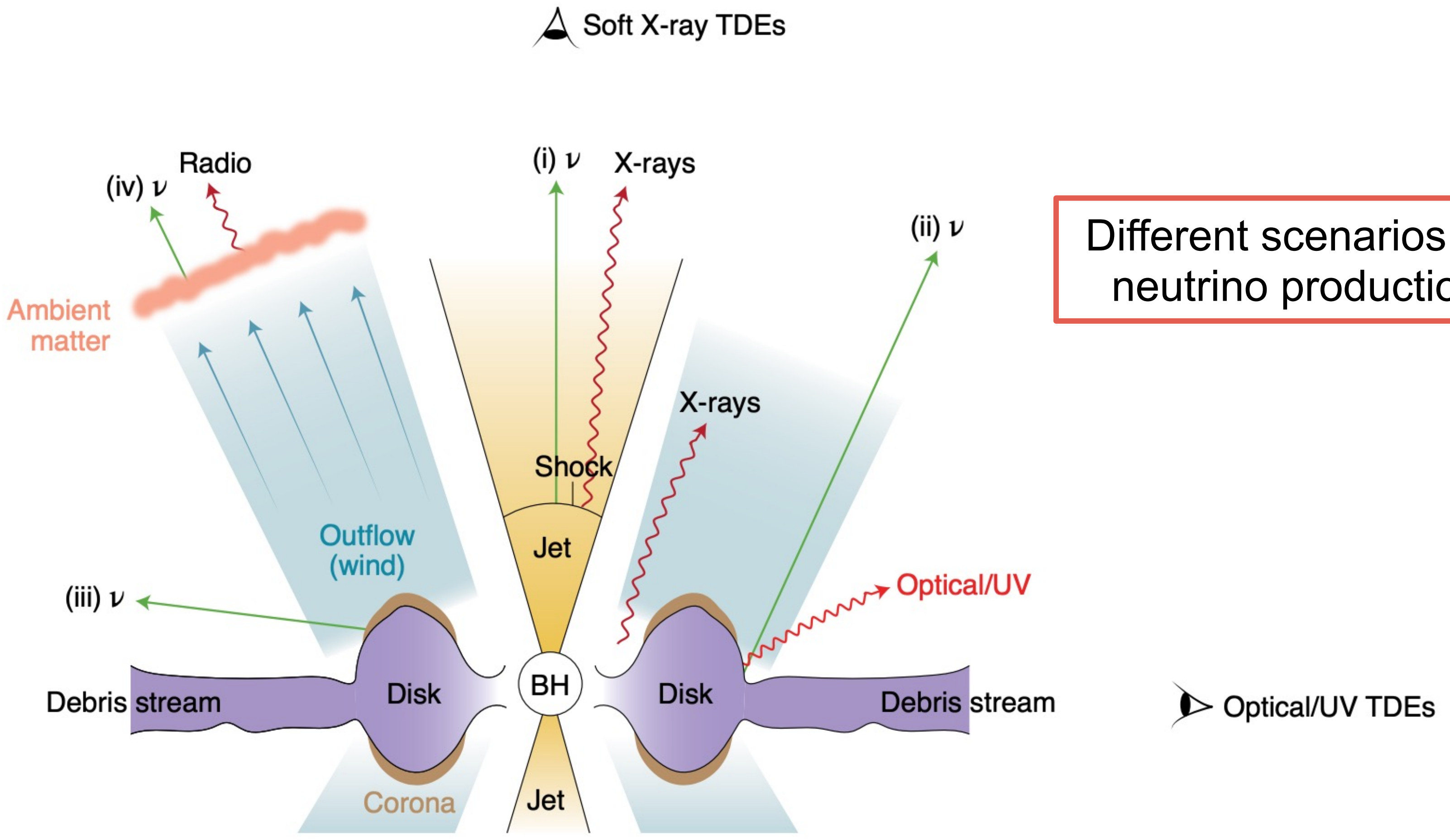
R. Stein et al., Nature Astronomy 2021

Radio Data reveal long-lasting activity of central engine



R. Stein et al., Nature Astronomy 2021, see also Y. Cendes *et al* 2021 *ApJ* **919** 127

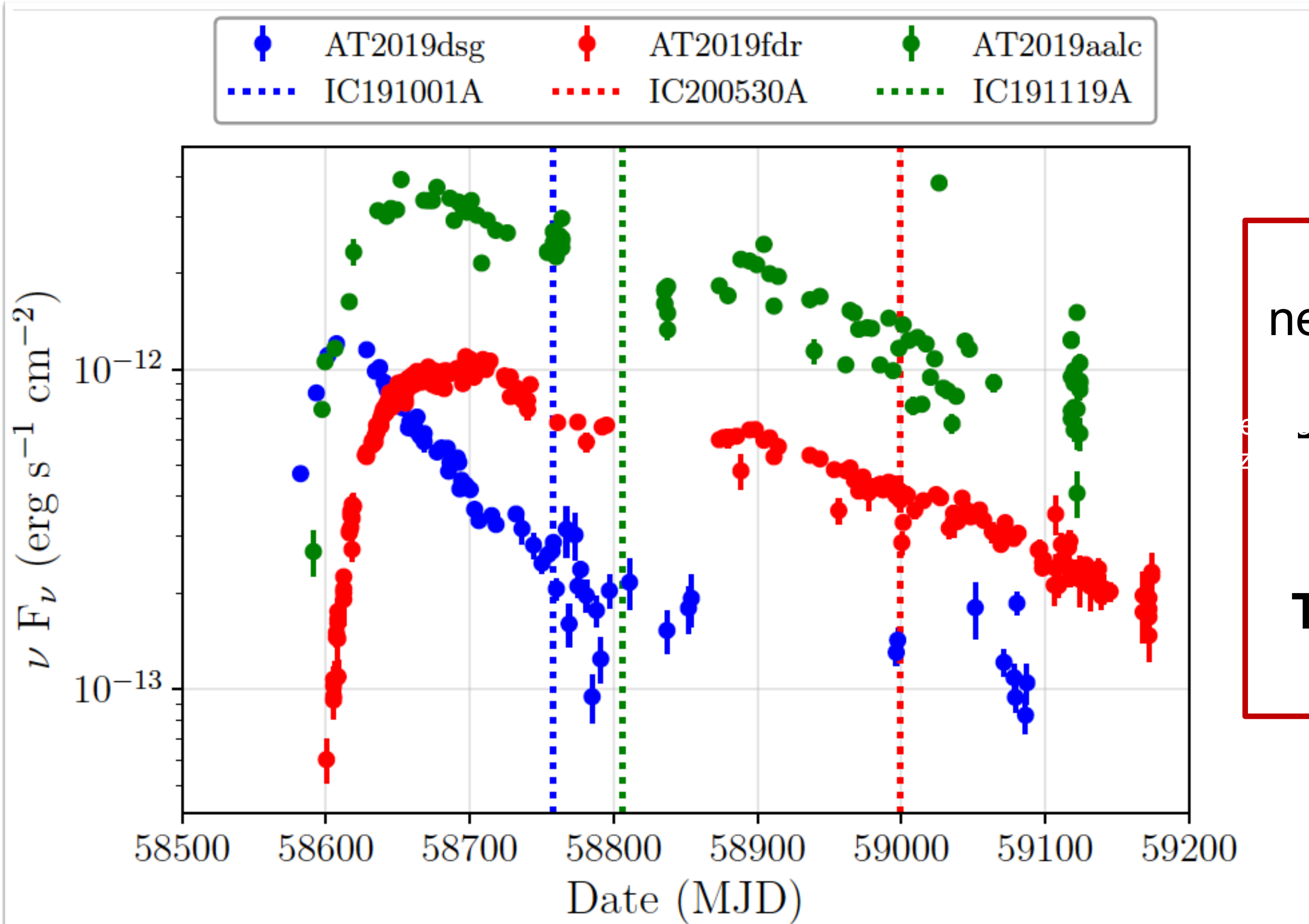
Neutrino Production in TDEs



Different scenarios for neutrino production

Hayasaki, Nature Astronomy 2021, Winter & Lunardini, Nature Astronomy 2021, Liu et al. PRD, 102 (2020) Murase et al. ApJ 902 (2020)

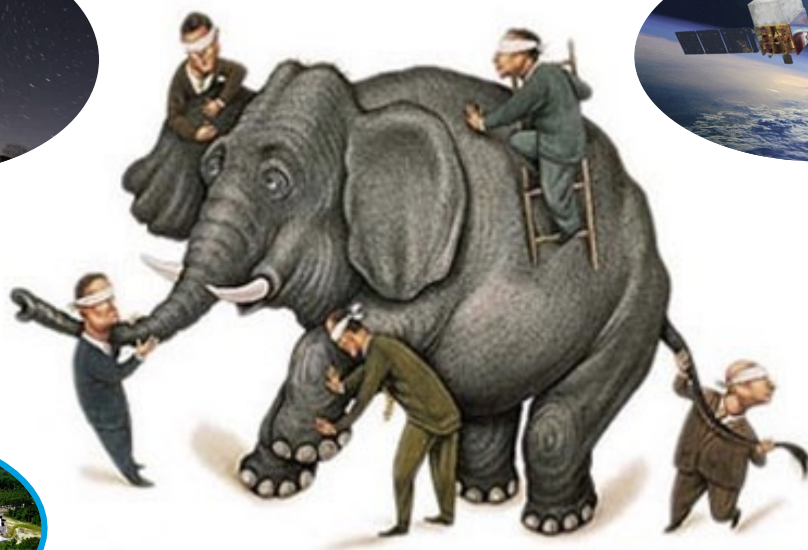
Two more TDE candidates!



First hint of neutrino production in TDEs
→ **Very efficient neutrino production in TDEs compared to AGN?**

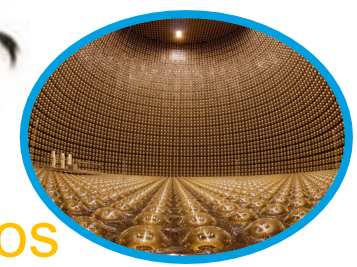
S. Reusch et al. PRL 2022, S. Van Velzen et al. MNRAS 529 (2024)

Multi-messenger Astronomy

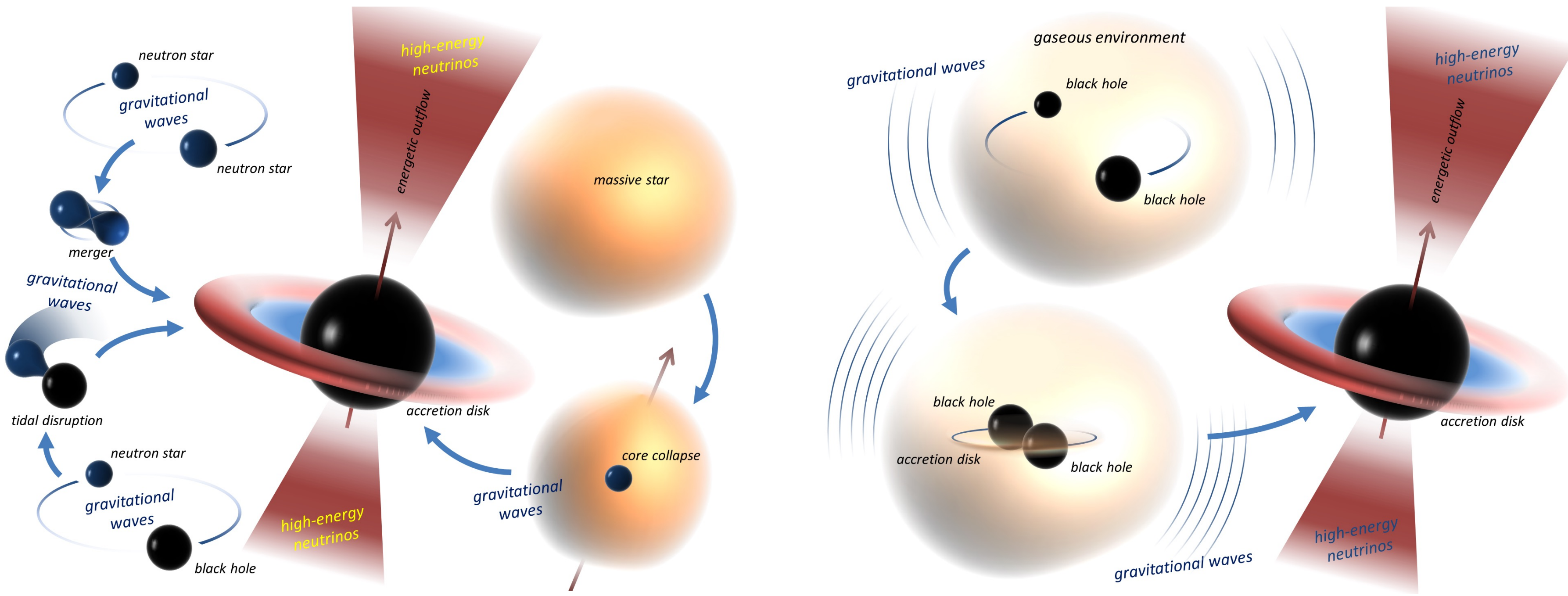


Gravitational
Waves

neutrinos

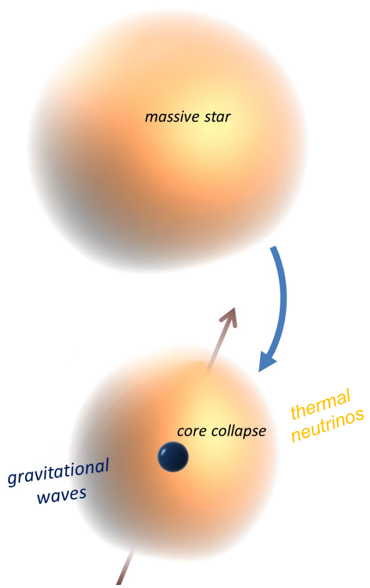


Neutrinos and Gravitational Waves



Credit: I. Bartos

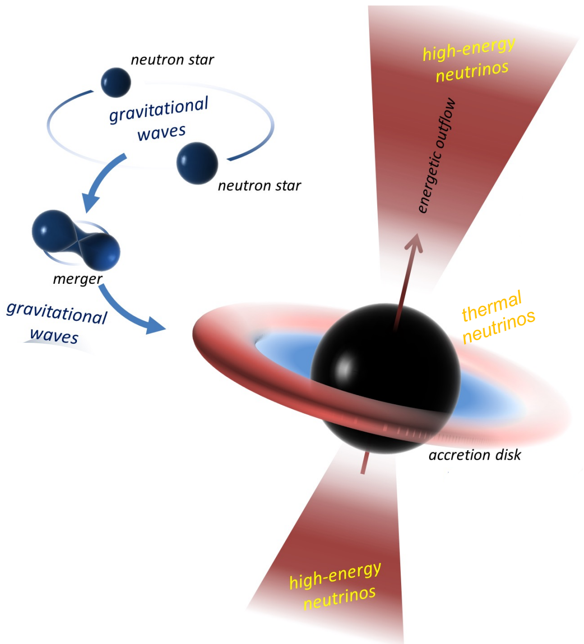
MeV Neutrinos and Gravitational Waves: CCSN



Increase detection probability of GW signal from a CCSN by combining GW and neutrino signals

O. Halim et al JCAP11(2021)021

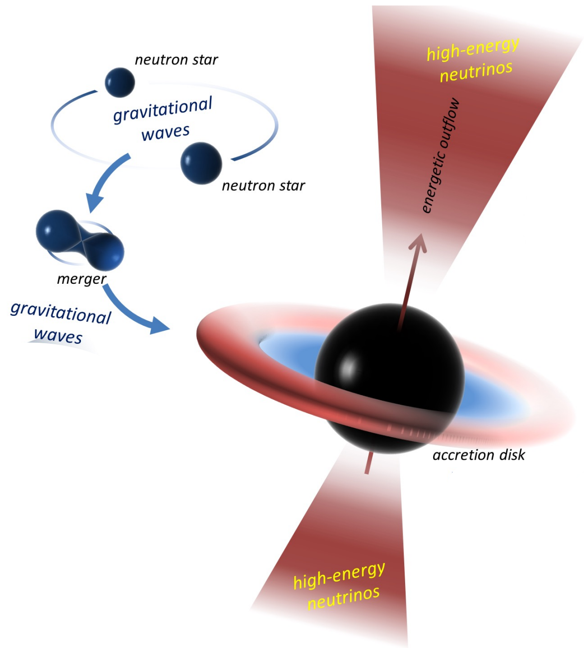
MeV Neutrinos and Gravitational Waves: BNS merger



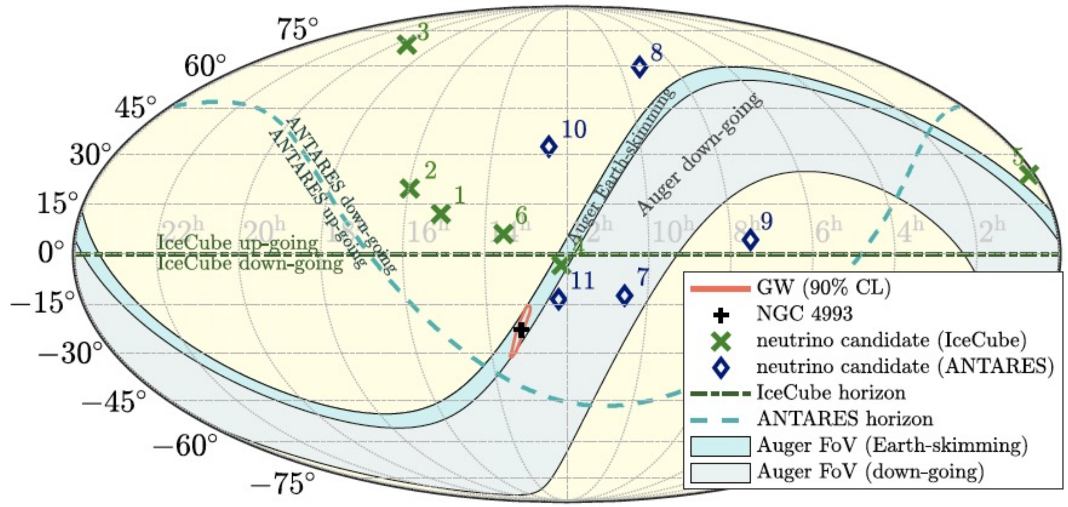
Even single MeV neutrino
→ pin down energy scale of thermal neutrino emission from BNS mergers
→ support or disfavor formation of remnant massive neutron stars

Kyutoku & Kashiyama PRD 97, 103001 (2018)

TeV Neutrinos and Gravitational Waves: BNS merger



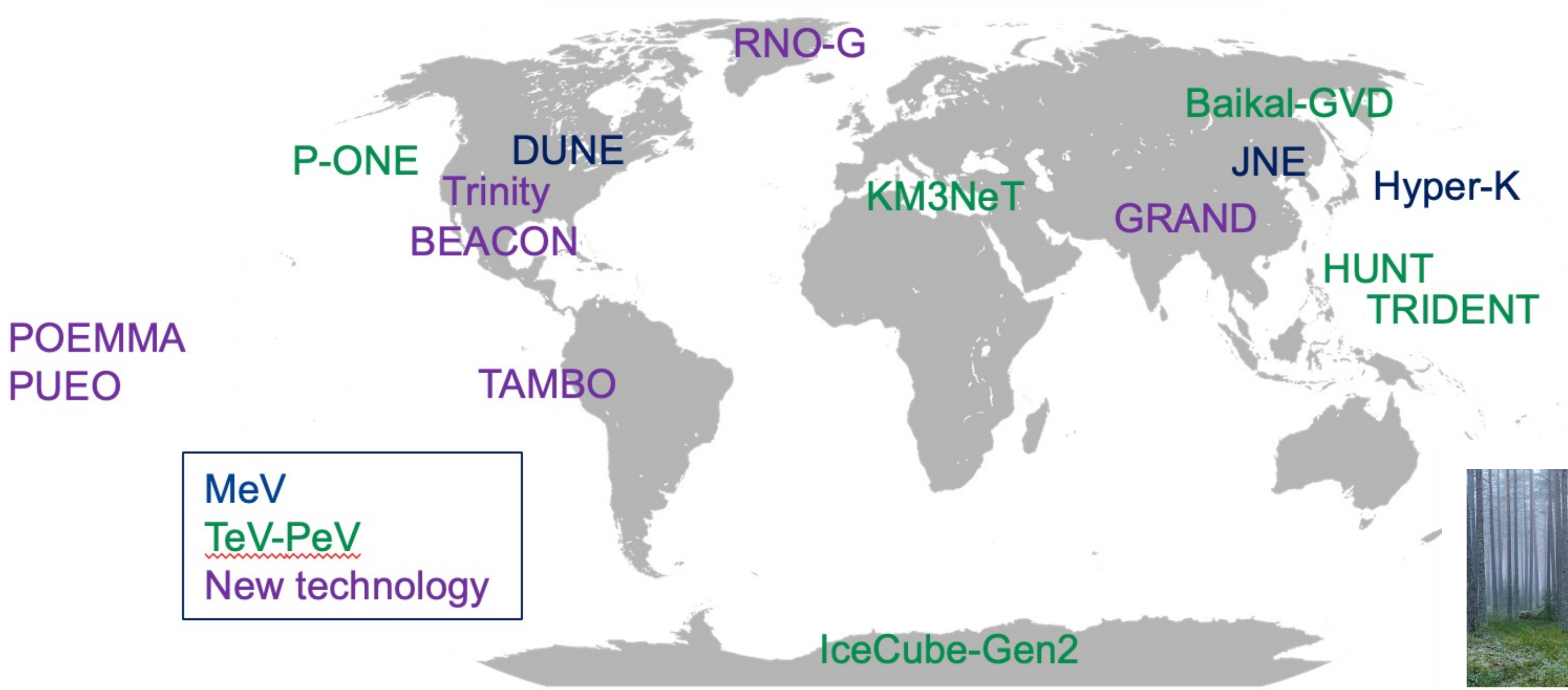
GW170817: Search for neutrinos in ANTARES, Auger and IceCube data in +/-500 s



Neutrino could help to constrain direction and teach us about the GW source environment

LIGO, Virgo, Auger, ANTARES, IceCube,ApJ 850 (2017)

New Neutrino Detectors

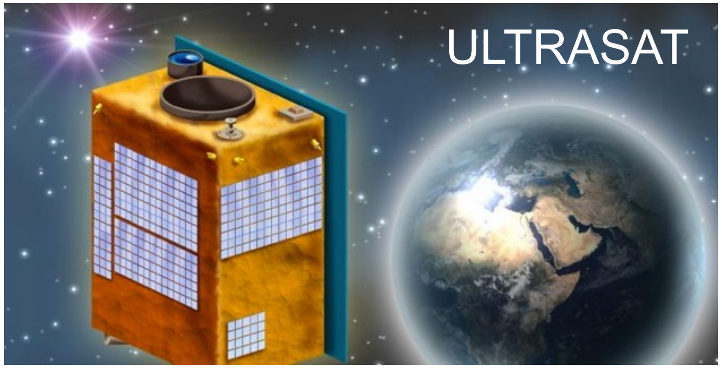


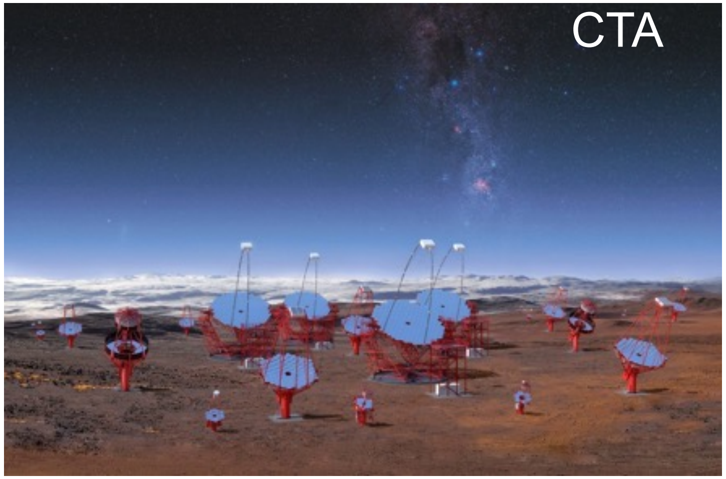
- Larger detectors
- New sites
- New technologies

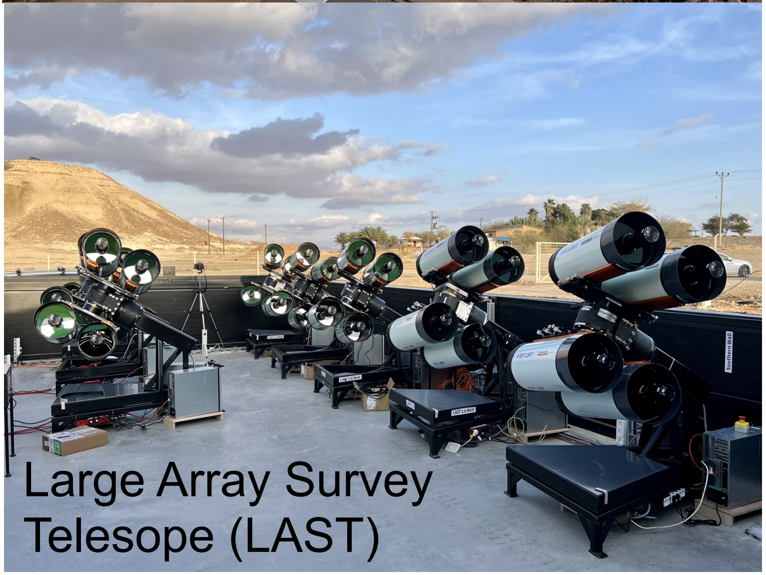
New Detectors

Multiwavelength Instruments

- Increased sensitivity
- Increased wavelength coverage
- Increased cadence



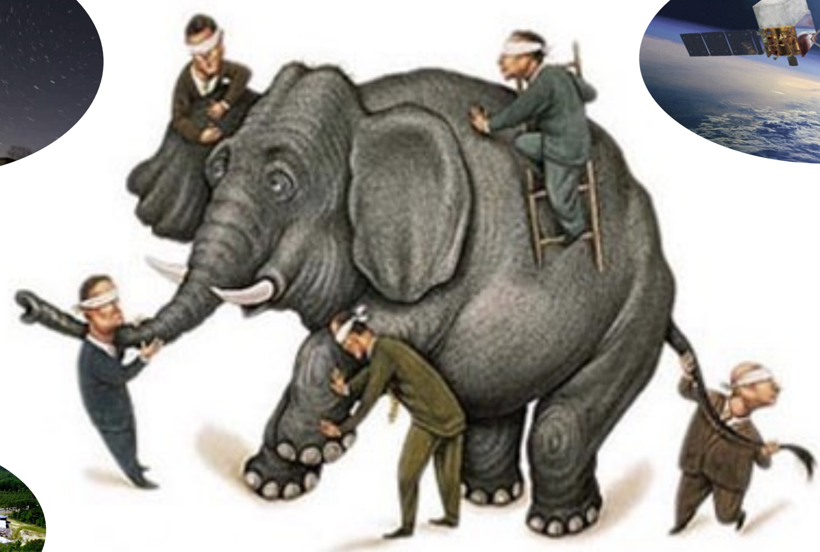


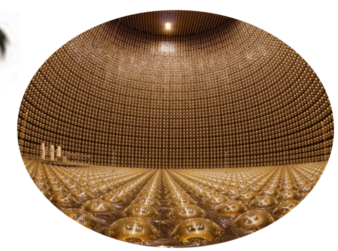


Learning Objectives

- What is multi-messenger astronomy?
  - Observing sources with neutrinos and photons or neutrinos and gravitational waves
- What are the multi-messenger observations involving neutrinos and what can we learn from them?
  - Sun: neutrino oscillation, fusion in solar core
  - SN1987A: stellar evolution, explosion mechanism
  - Diffuse flux: majority of sources are gamma-ray dark
  - Galactic Plane: cosmic-ray population and propagation
  - Seyfert galaxy NGC 1068: neutrino production in Corona
  - Blazar TXS 0506+056: origin of ~10PeV cosmic rays

Summary






Stay
Tuned!