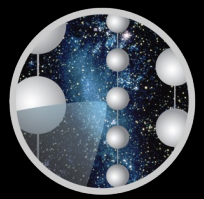
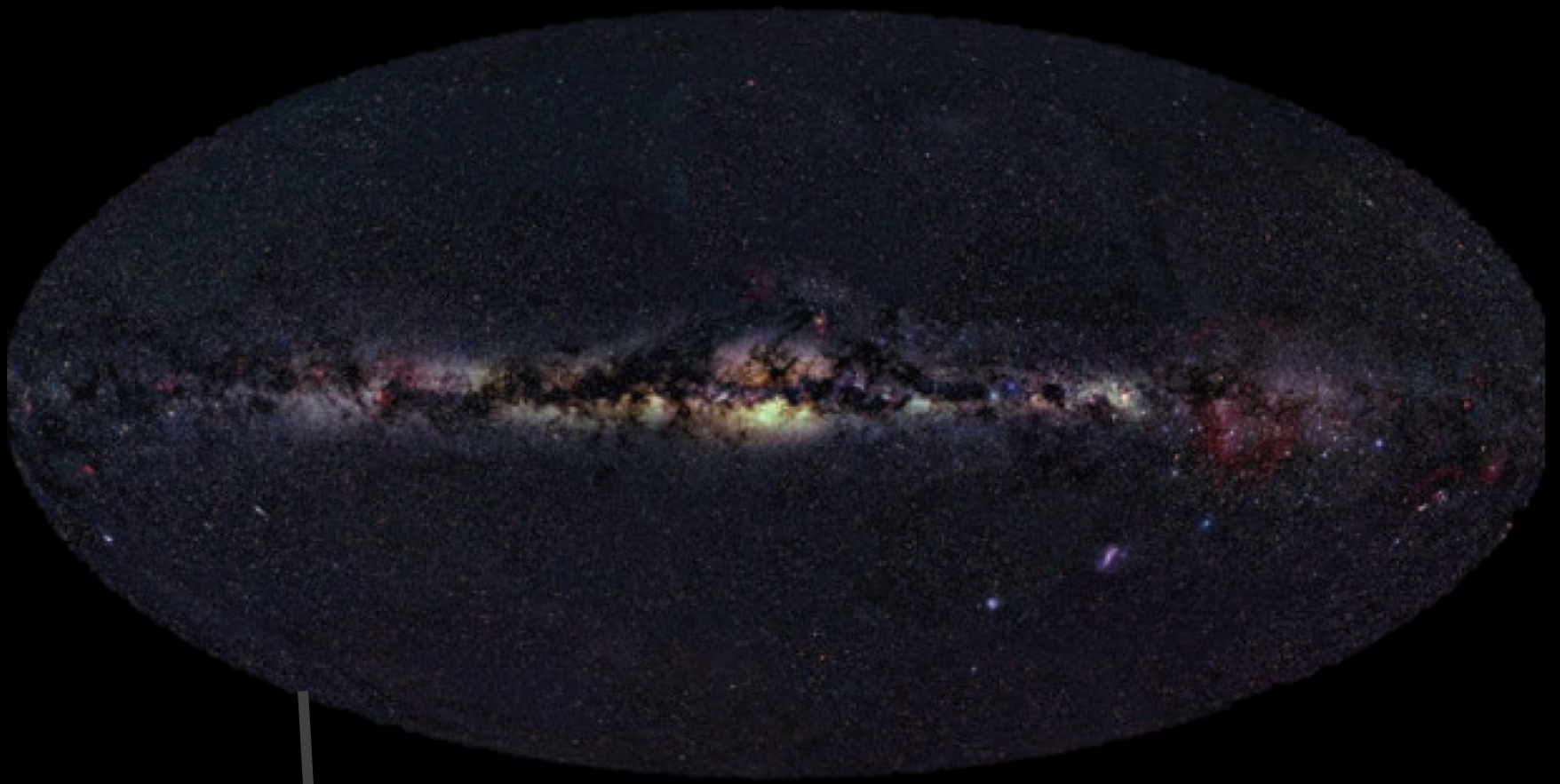
UCLouvain

Neutrino astronomy



Gwenhaël Dewasseige

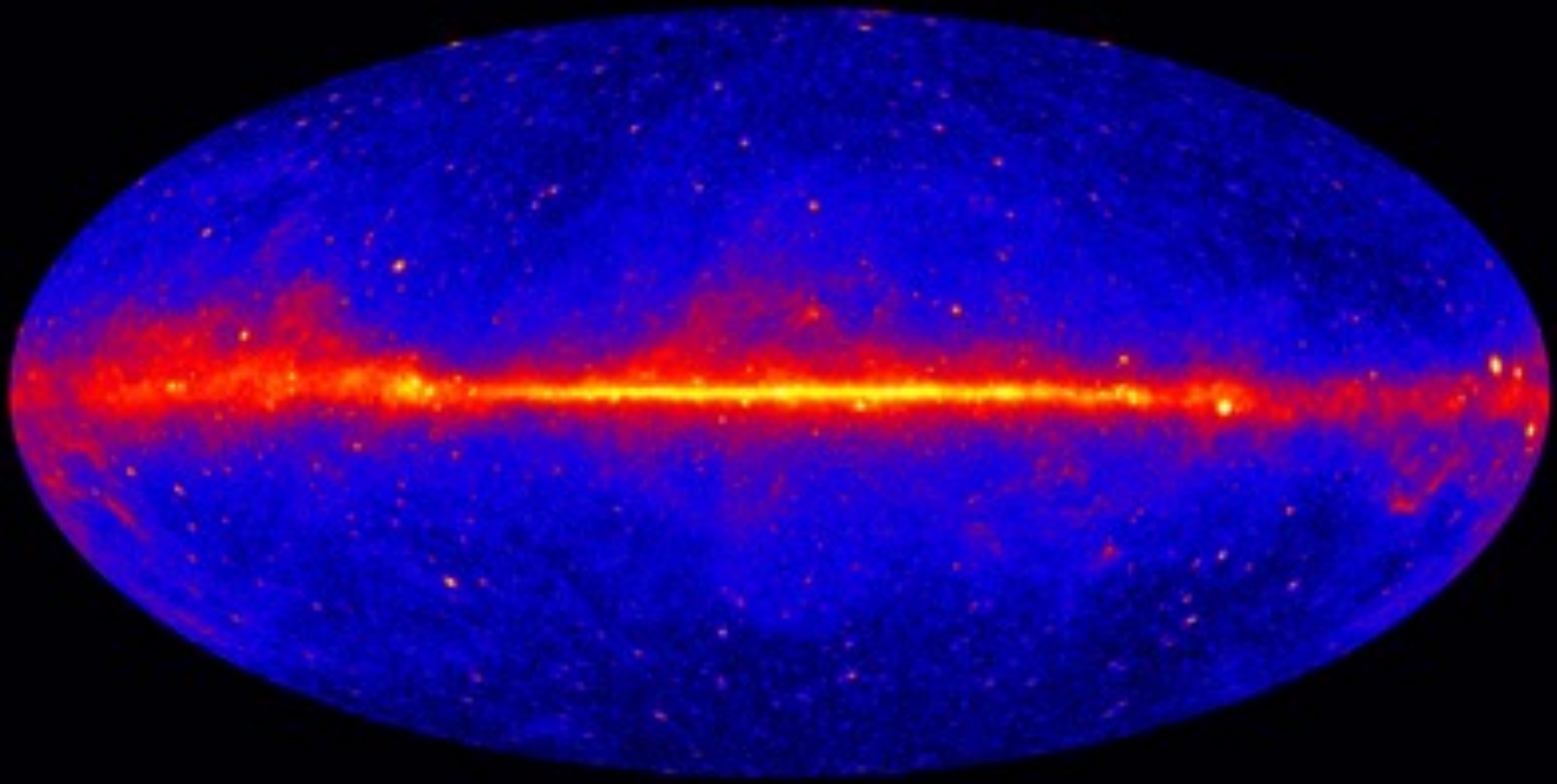


meV eV keV MeV GeV TeV PeV EeV

10^{-3} 10^{0} 10^{3} 10^{6} 10^{9} 10^{12} 10^{15} 10^{18}

Micro and radio waves | Infra red | Visible | UV | X-ray | Gamma ray

1 eV = 1,602 × 10^{-19} J



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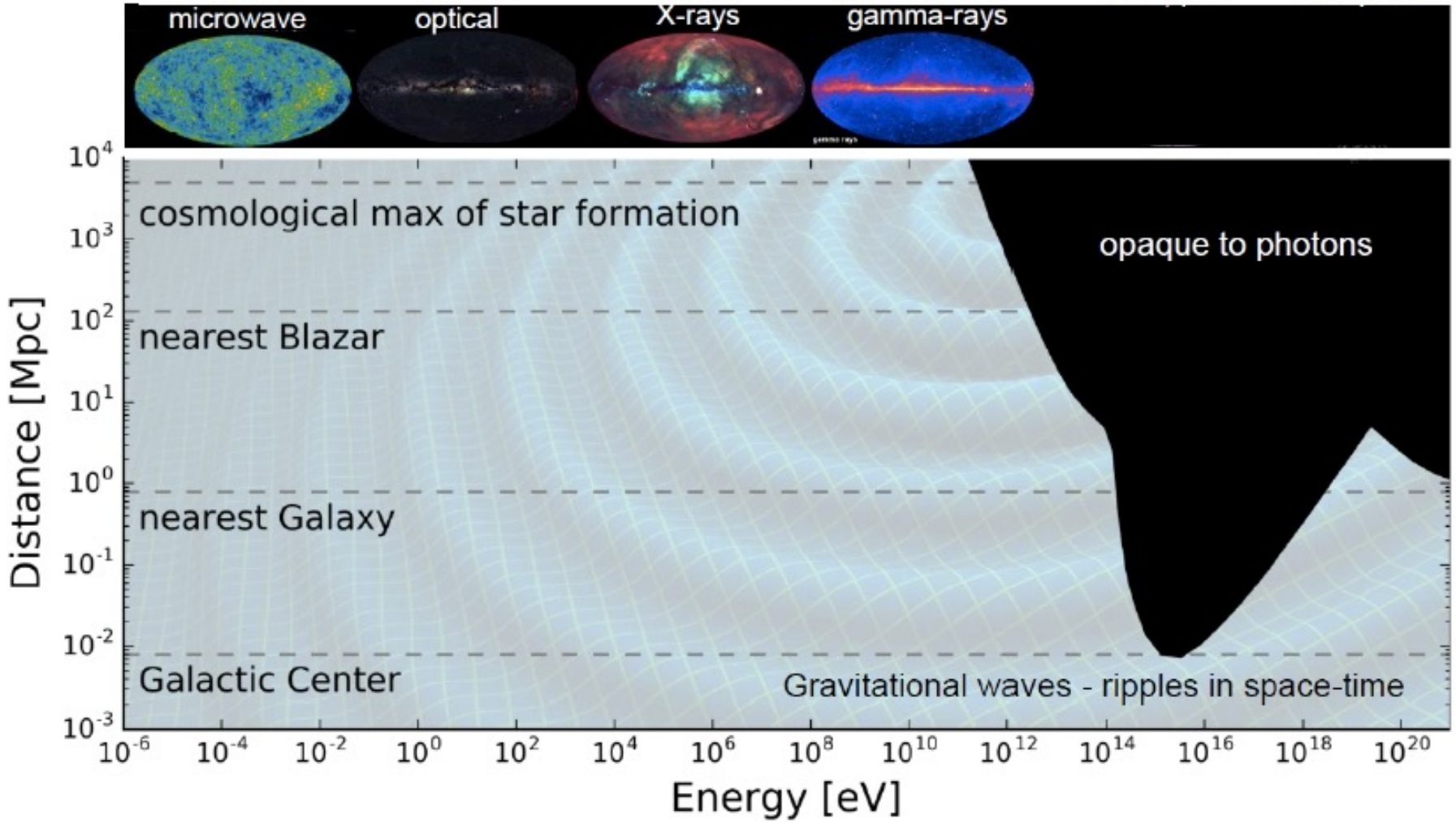
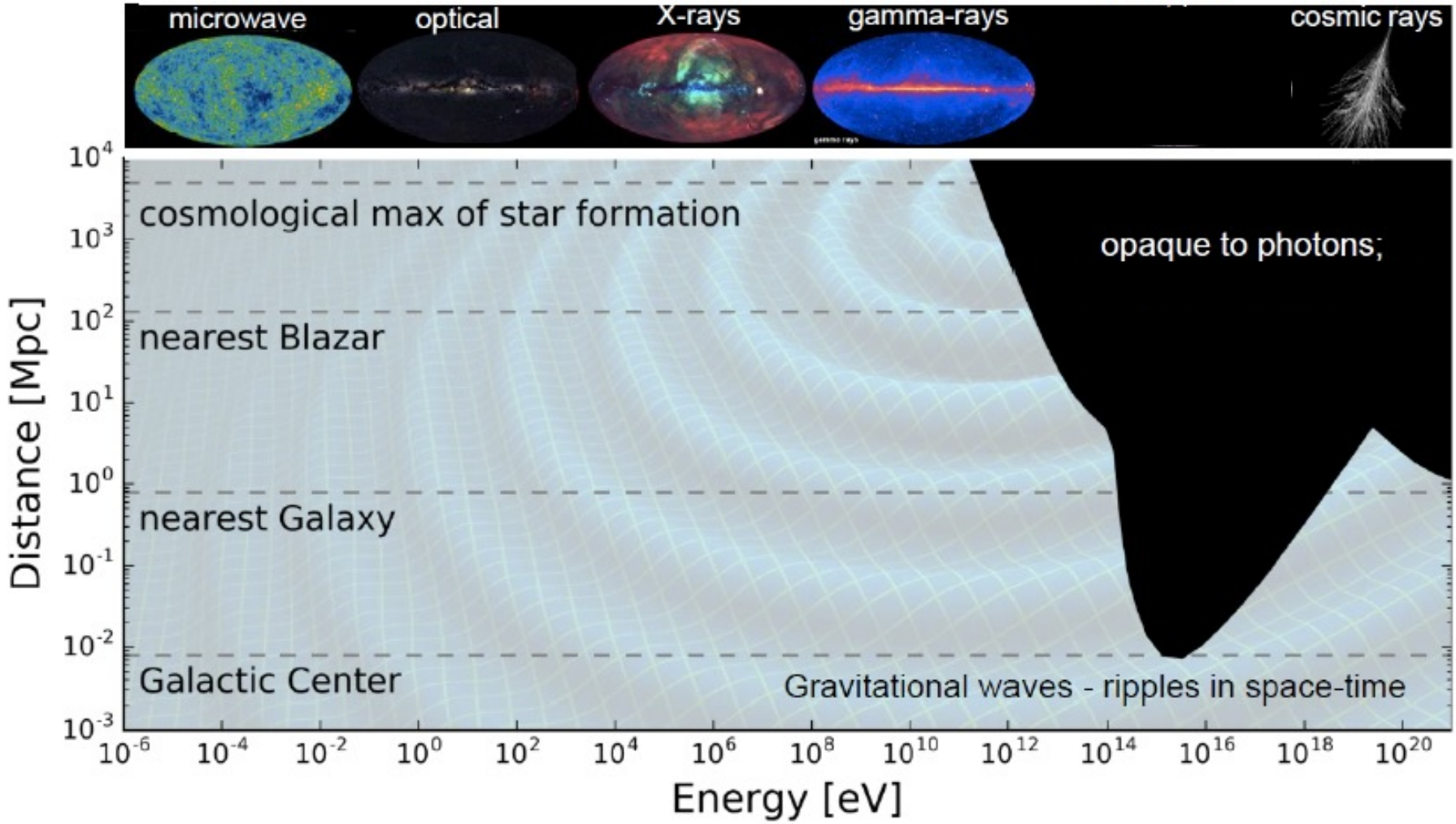


1 pc = 3,085 677 581 × 10^{16} m

= 3,2616 années-lumière



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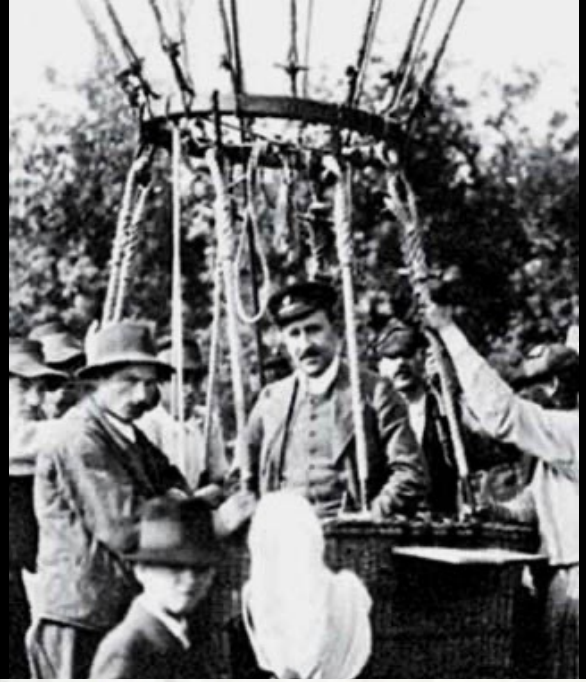
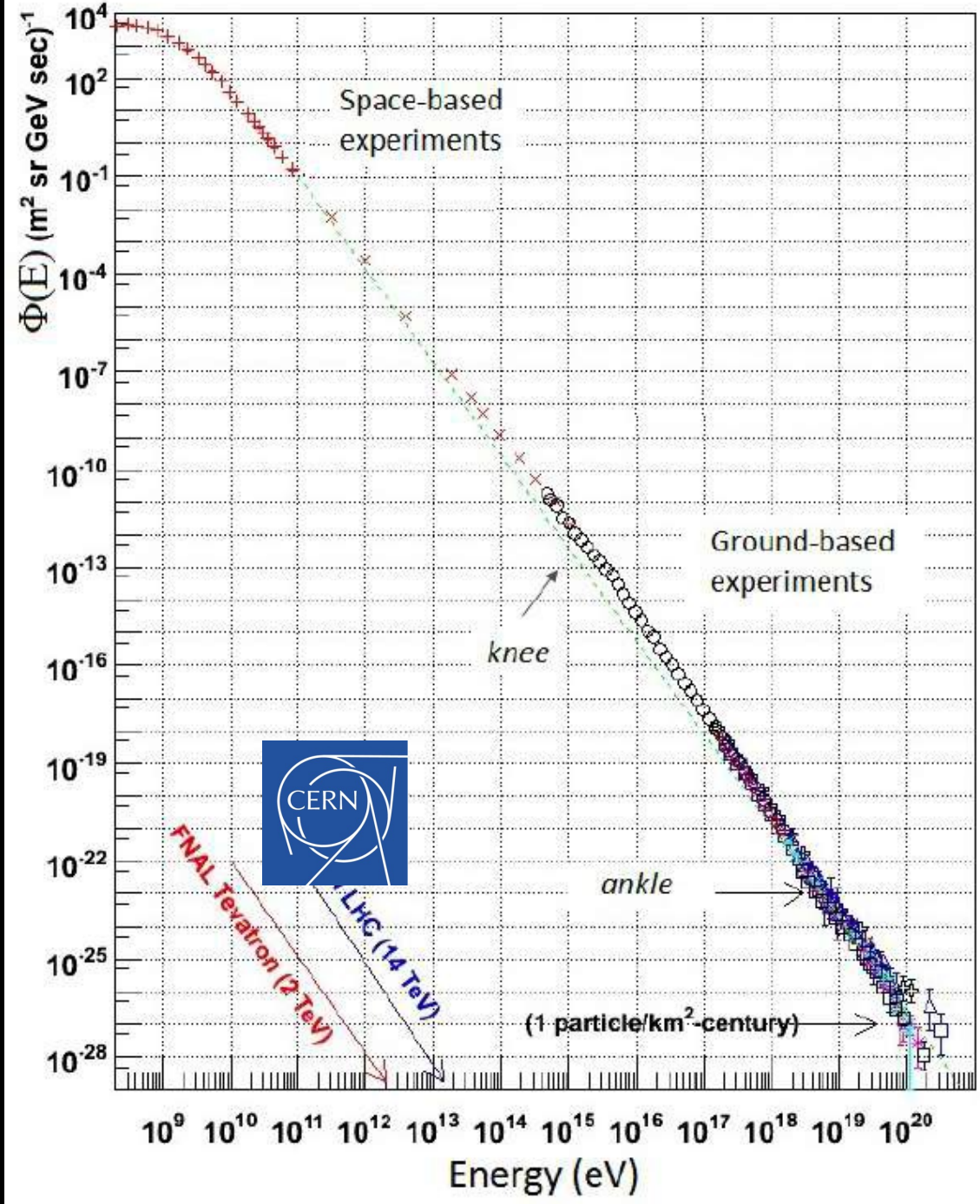
= 3,2616 années-lumière

1912



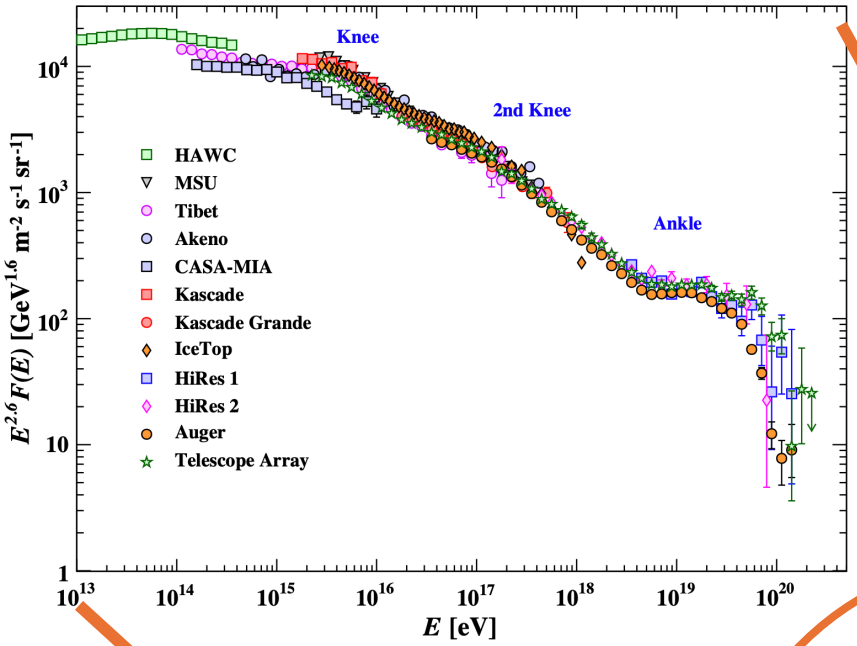
https://www.youtube.com/watch?v=SnKvtazt5So

Today



- Dominated by protons and heavier nuclei
- $\phi = A\,E^{-\alpha}$

Today



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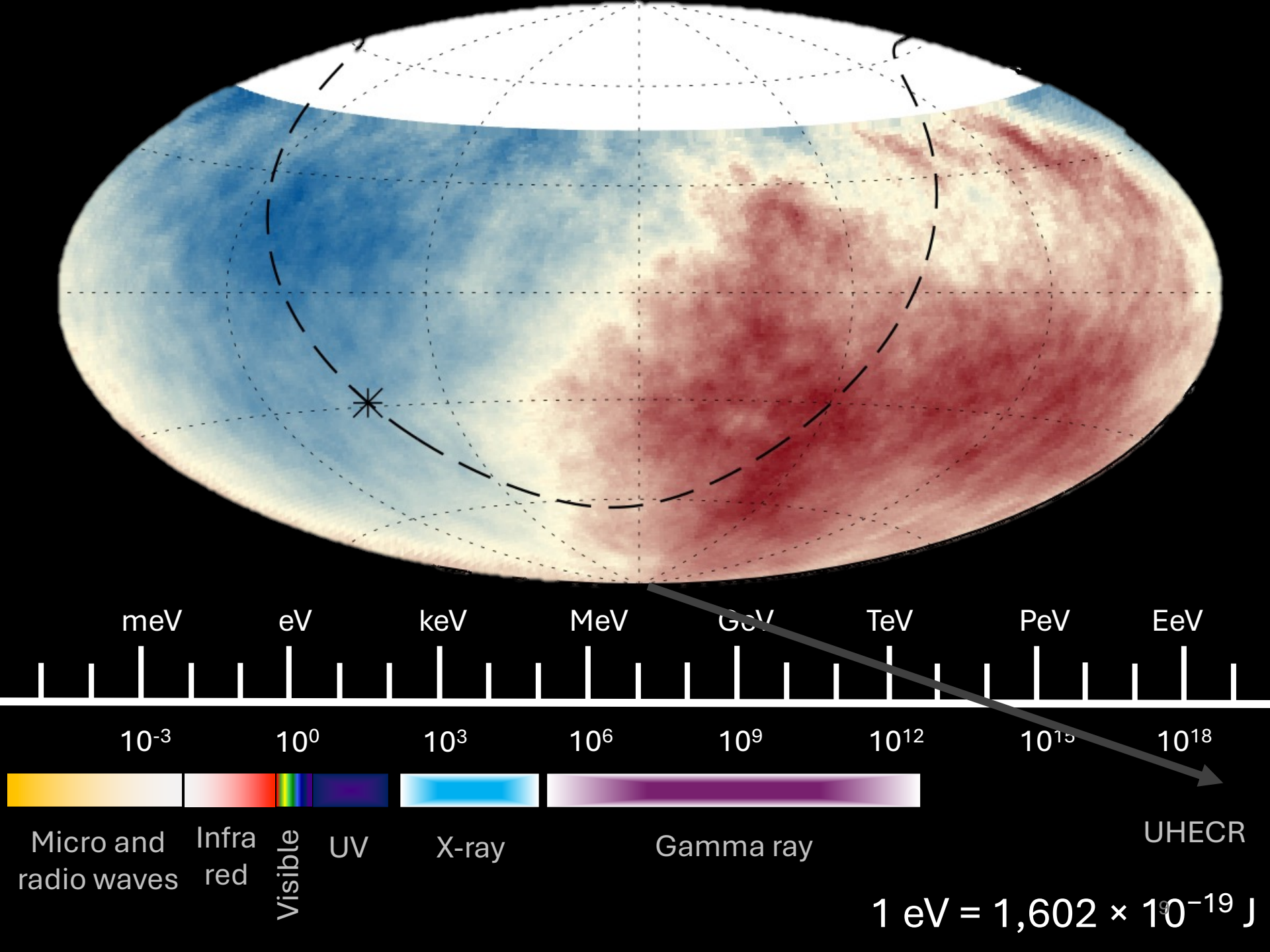
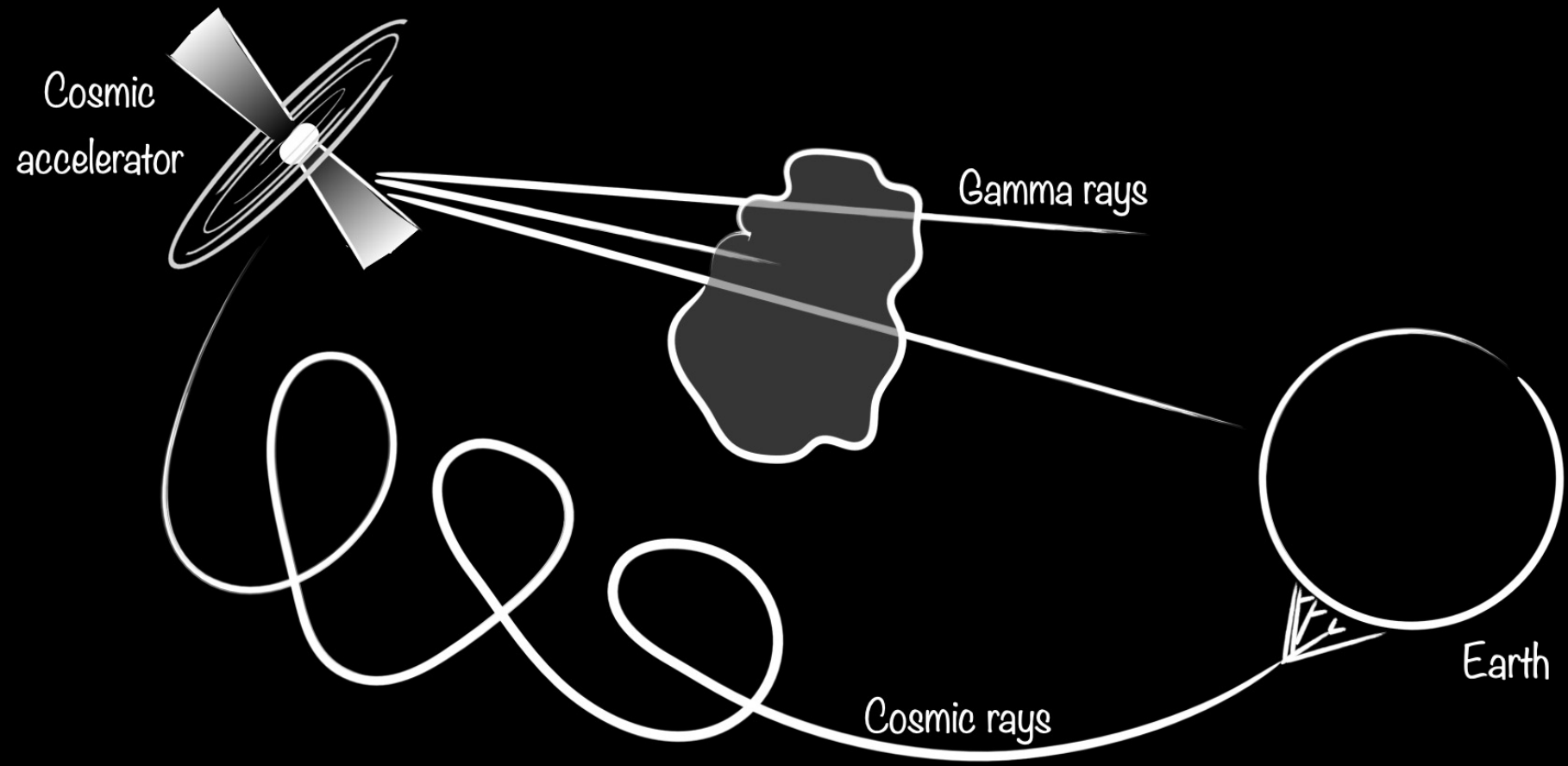
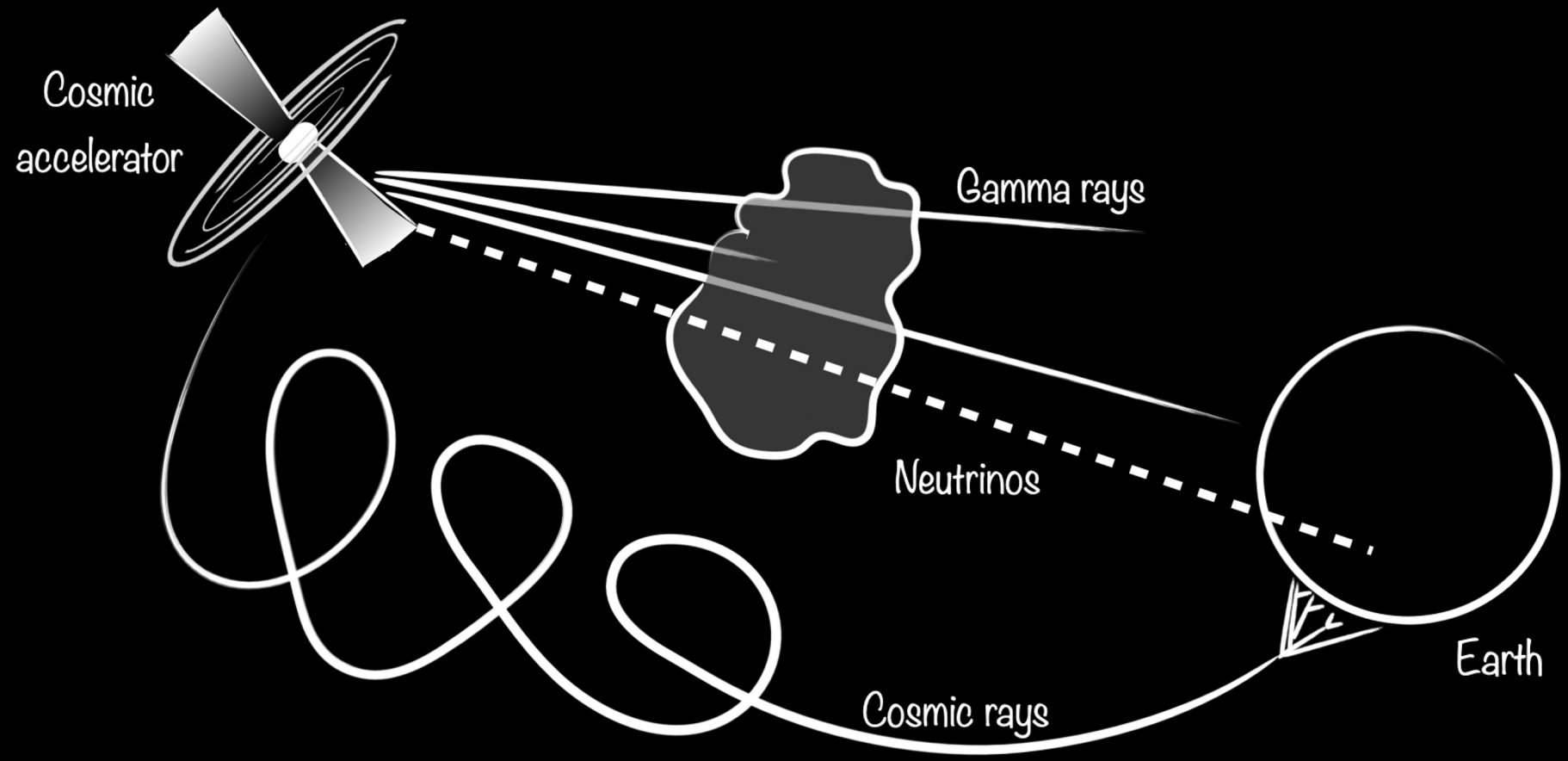
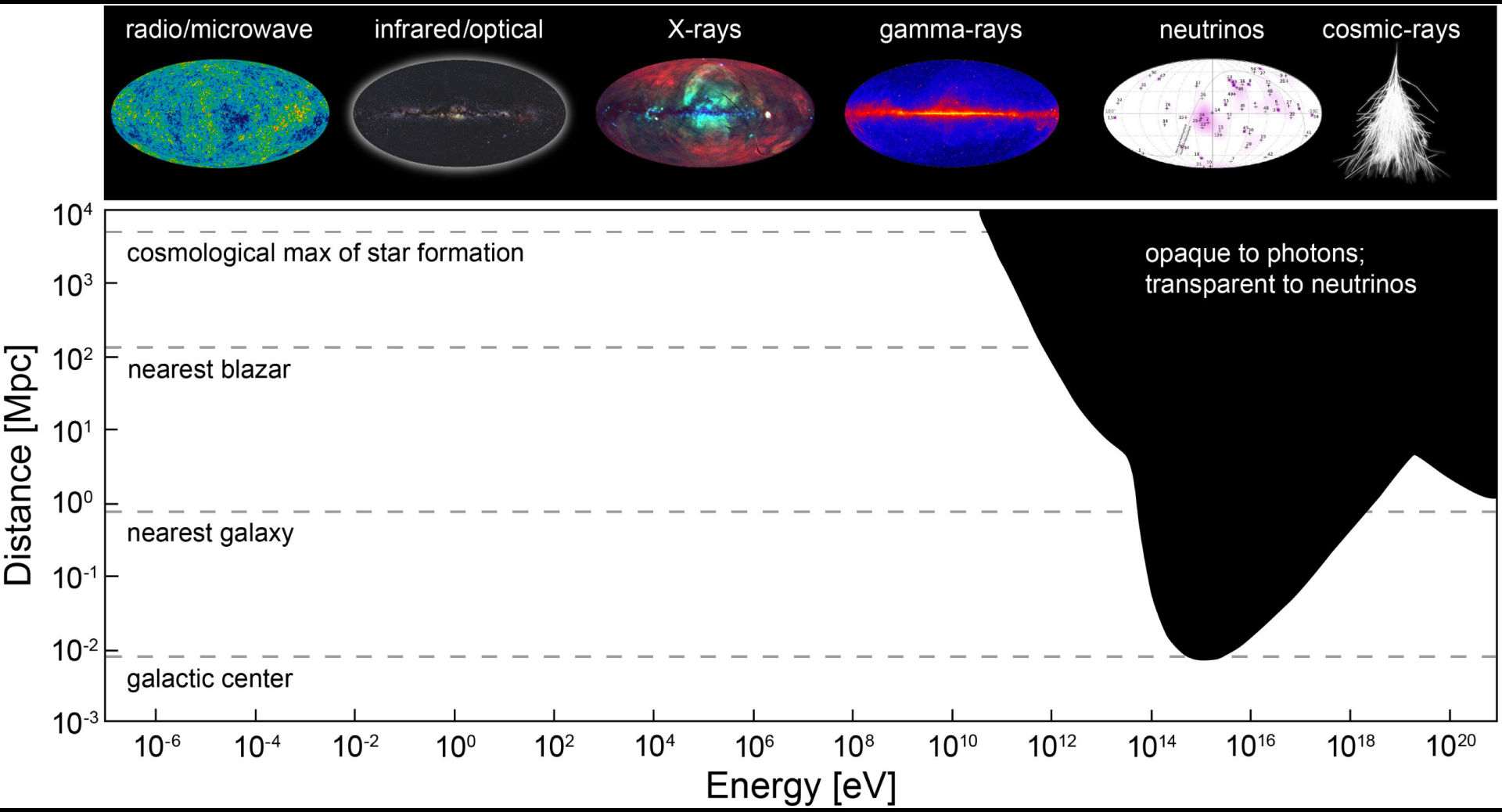
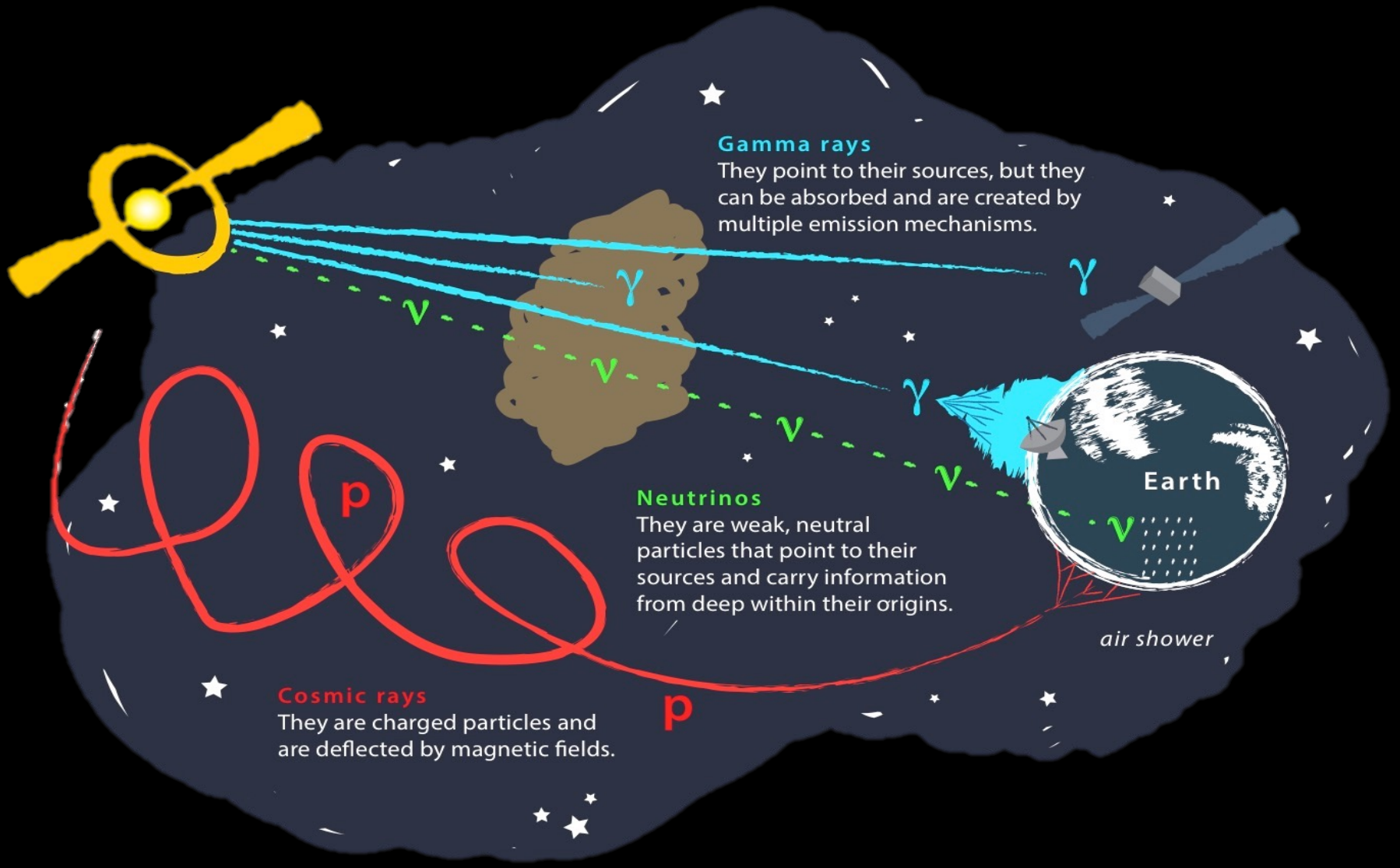

meV
eV
keV
MeV
GeV
TeV
PeV
EeV
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
10^{18}
Micro and radio waves
Infra red
Visible
UV
X-ray
Gamma ray
UHECR
1 eV = 1,602 × 10^{-19} J


Cosmic
accelerator
Gamma rays
Earth
Cosmic rays


Cosmic
accelerator
Gamma rays
Neutrinos
Earth
Cosmic rays



https://doi.org/10.1016/j.nima.2020.163678


Gamma rays
They point to their sources, but they can be absorbed and are created by multiple emission mechanisms.
γ
γ
γ
ν
ν
ν
ν
Earth
ν
p
Neutrinos
They are weak, neutral particles that point to their sources and carry information from deep within their origins.
air shower
Cosmic rays
They are charged particles and are deflected by magnetic fields.
p

Neutrinos in a few words

Elementary particles

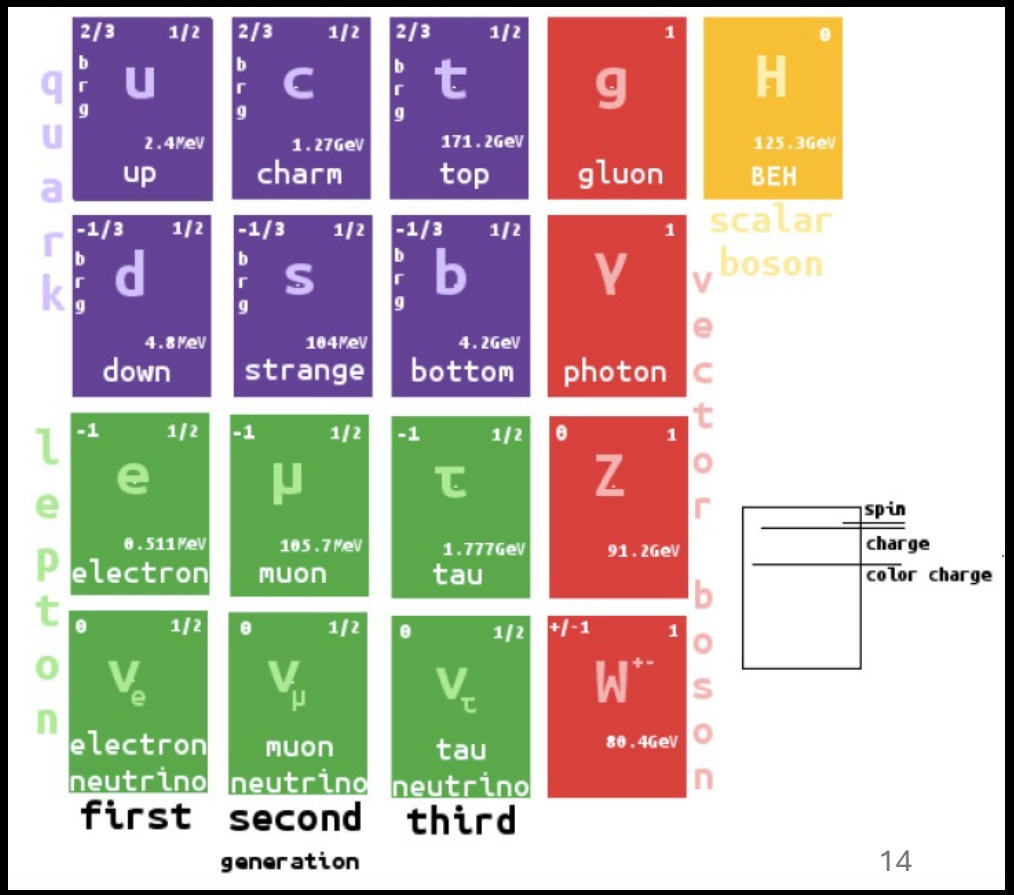
No electric charge

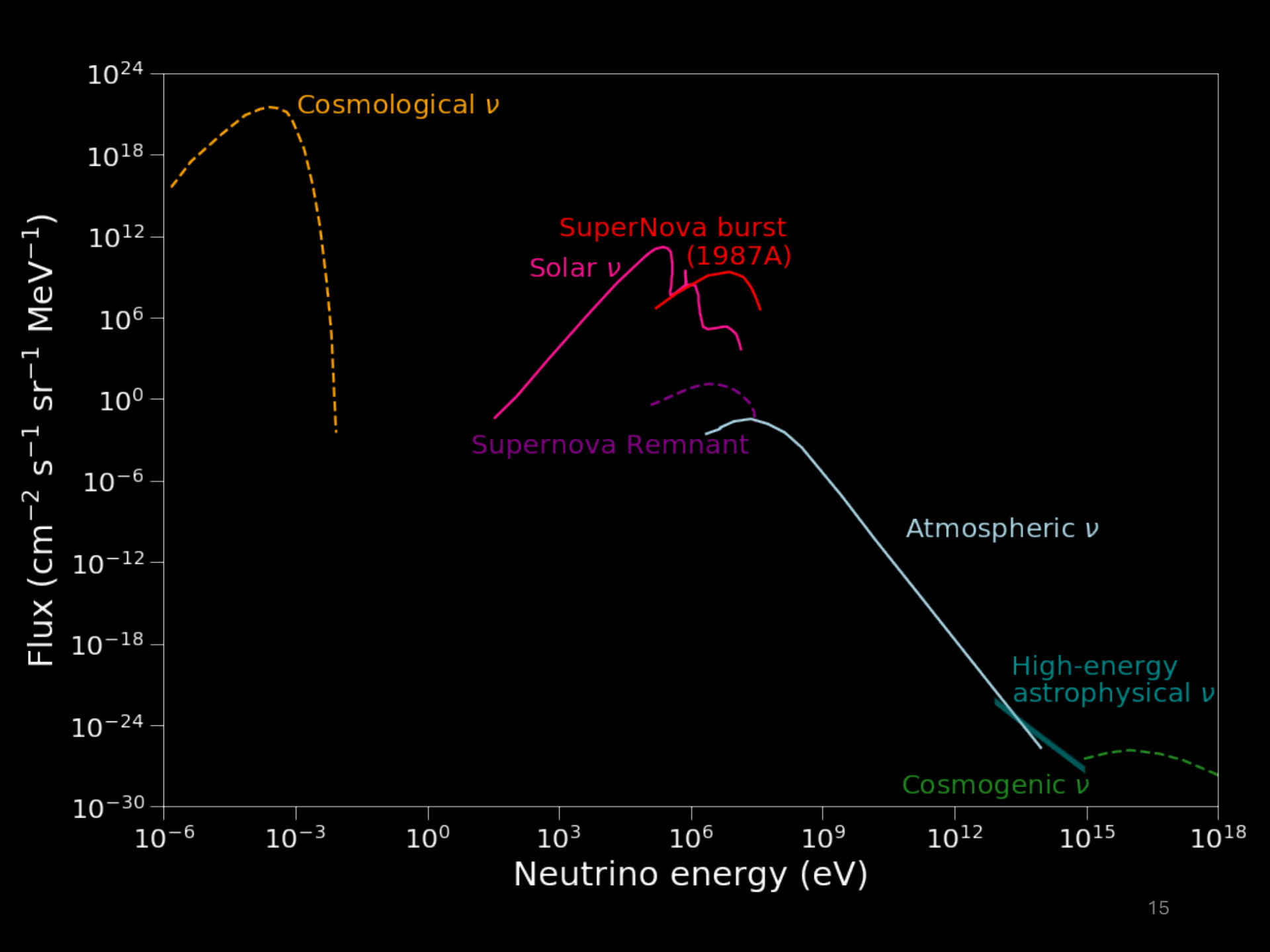
Very small cross section

Very small but nonzero masses

Oscillation from one flavor state to another

+ antiparticles




Cosmological ν
SuperNova burst
(1987A)
Solar ν
Supernova Remnant
Atmospheric ν
High-energy
astrophysical ν
Cosmogenic ν
Flux (cm^{-2} s^{-1} sr^{-1} MeV^{-1})
Neutrino energy (eV)
10^{24}
10^{18}
10^{12}
10^{6}
10^{0}
10^{-6}
10^{-12}
10^{-18}
10^{-24}
10^{-30}
10^{-6}
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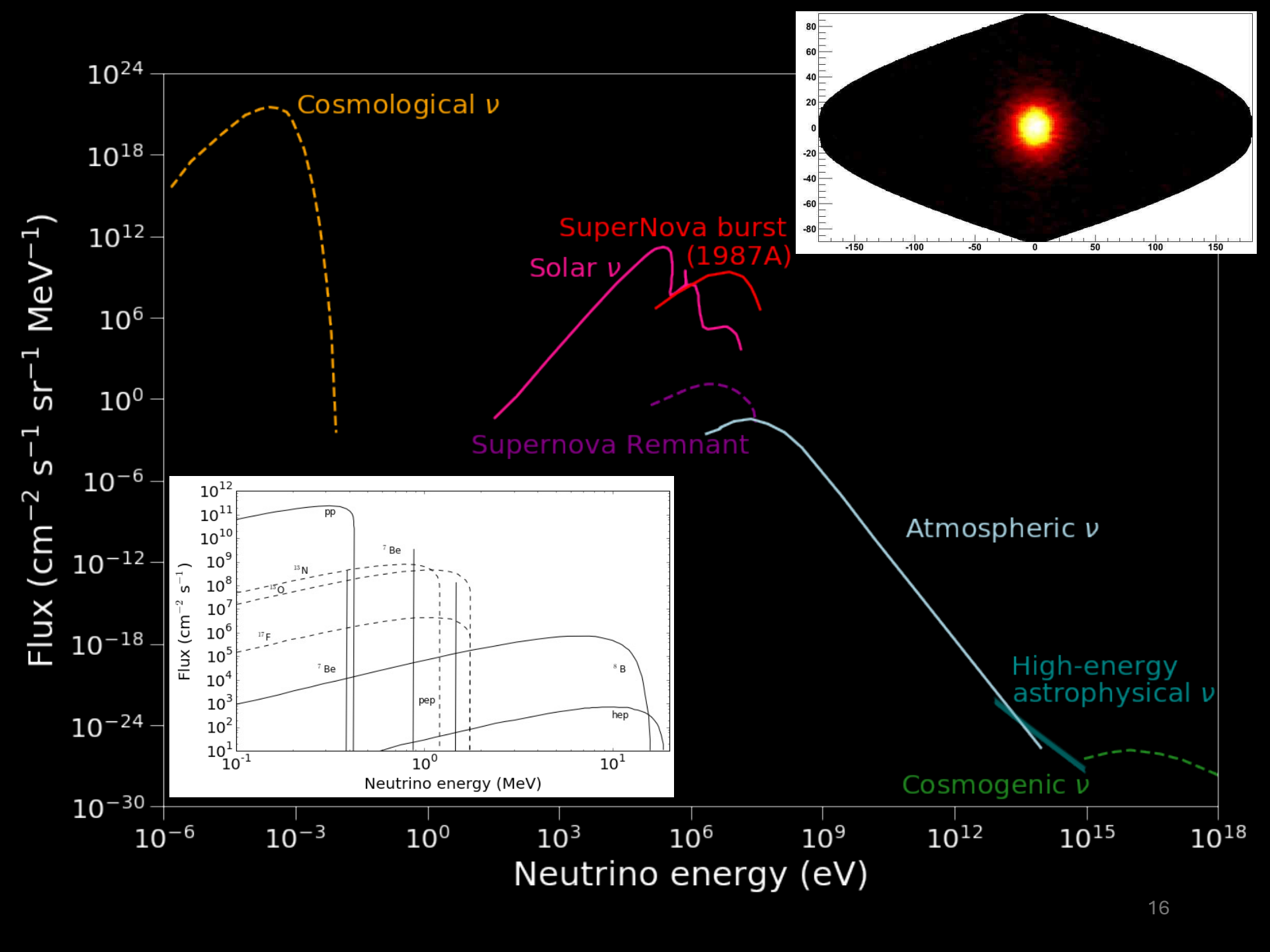
10^{6}
10^{9}
10^{12}
10^{15}
10^{18}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Neutrino energy (eV)
Flux (cm⁻² s⁻¹)
Neutrino energy (MeV)
pp
⁷Be
¹³N
¹⁵O
¹⁷F
⁷Be
⁸B
pep
hep

Homestake Solar Experiment

Scientific American, July 1969

Homestake Solar Experiment

BULLETIN BOARD

Volume 21, Number 36 — Published by the BNL Public Relations Office — September 14, 1967

9-1307-66

Solar Neutrinos Are Counted At Brookhaven

Dr. Ray Davis of Chemistry is shown placing a low level counter in a cut-down navy gun barrel which acts as a shield from stray cosmic radiation. This equipment is used in the Brookhaven Solar Neutrino Experiment.

A BNL team of scientists, headed by R. Davis, Jr., of Chemistry has gone 4850 feet into the earth to learn more about what is

and his group calculate that ten billion-billion neutrinos pass through their 20-ft. diameter by 48-ft long tank every day, yet

in low level counting experiments. Originally the gun barrels were procured from surplus, and brought to BNL for conversion to more peaceful uses. The long guns were cut into 8-foot sections, weighing about 16,000 pounds each. These guns are made from "old" iron (before the use of atom and hydrogen bombs) and contain a very small amount of residual radioactivity.

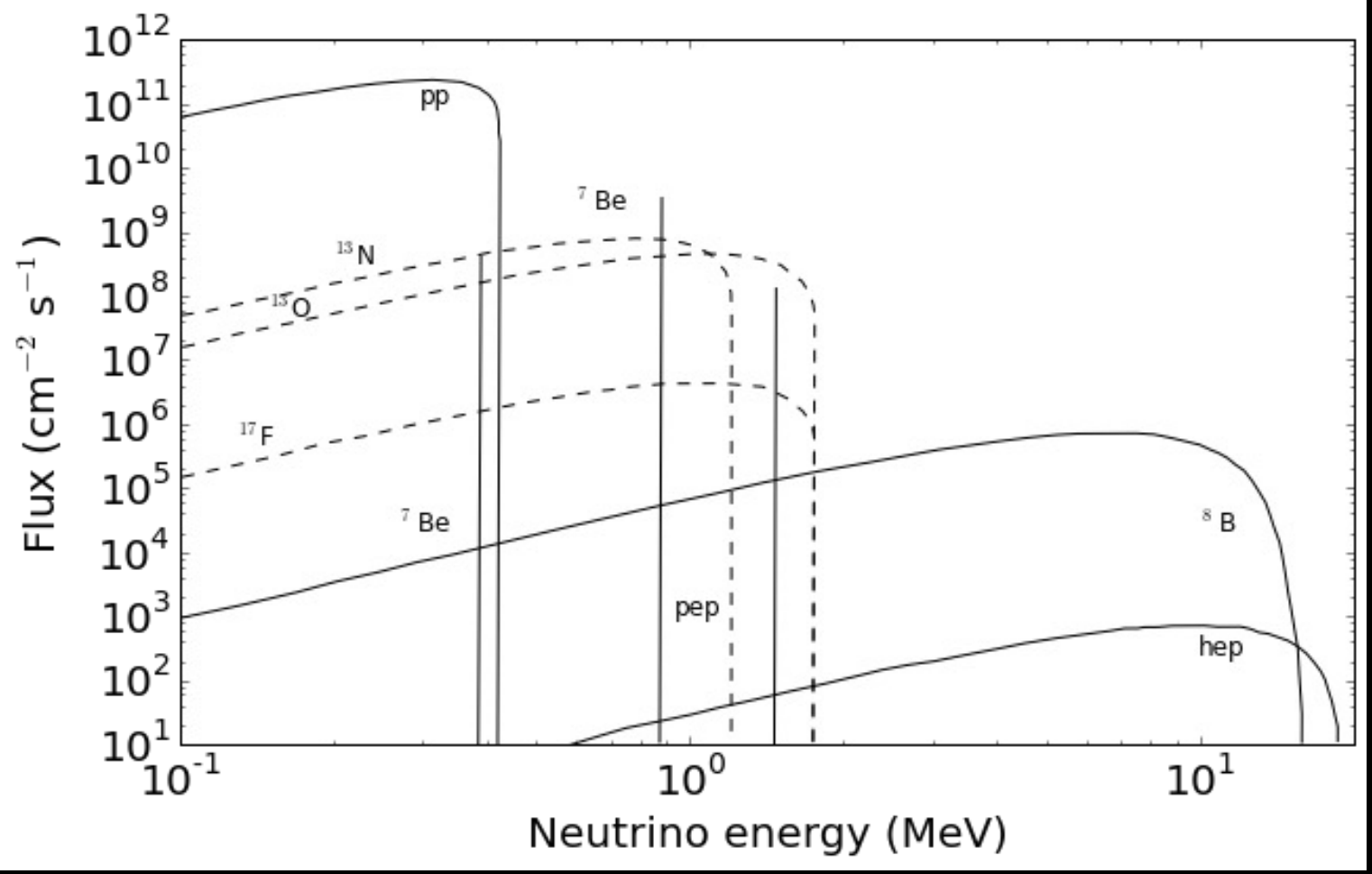
For accurate results, it is necessary to reduce the background radiation to as low a level as possible. Hence, the tank was placed deep underground to shield it from cosmic radiation and the counter was mounted in the thick gun barrel, which acts as a shield. Additional precautions, however, are taken to eliminate interferences from unrelated nuclear processes that could also produce Argon-37 in the tank and possibly result in a false neutrino reading.

Various elements, when they decay, are capable of producing neutrinos, but there is a definite energy level for each neutrino, and chemists use this method of identifying the neutrino source. In the Brookhaven experiment, the only neutrinos having enough energy to produce Argon-37 plus an electron from chlorine-37 are those produced in the decay of Boron-8, which is part of the thermonuclear process taking place in the sun.

The theoretical forecast had led scientists to believe that the neutrino emission from the sun would allow from 1.5 to 5 neutrino captures per day. In the single experiment performed to date, Dr. Davis reports that the capture rate in the underground tank was less than 2 neutrinos per day. Knowing this plus the efficiency of neutrino capture allowed Dr. Davis and his group to calculate the flux from the Boron-8 de-

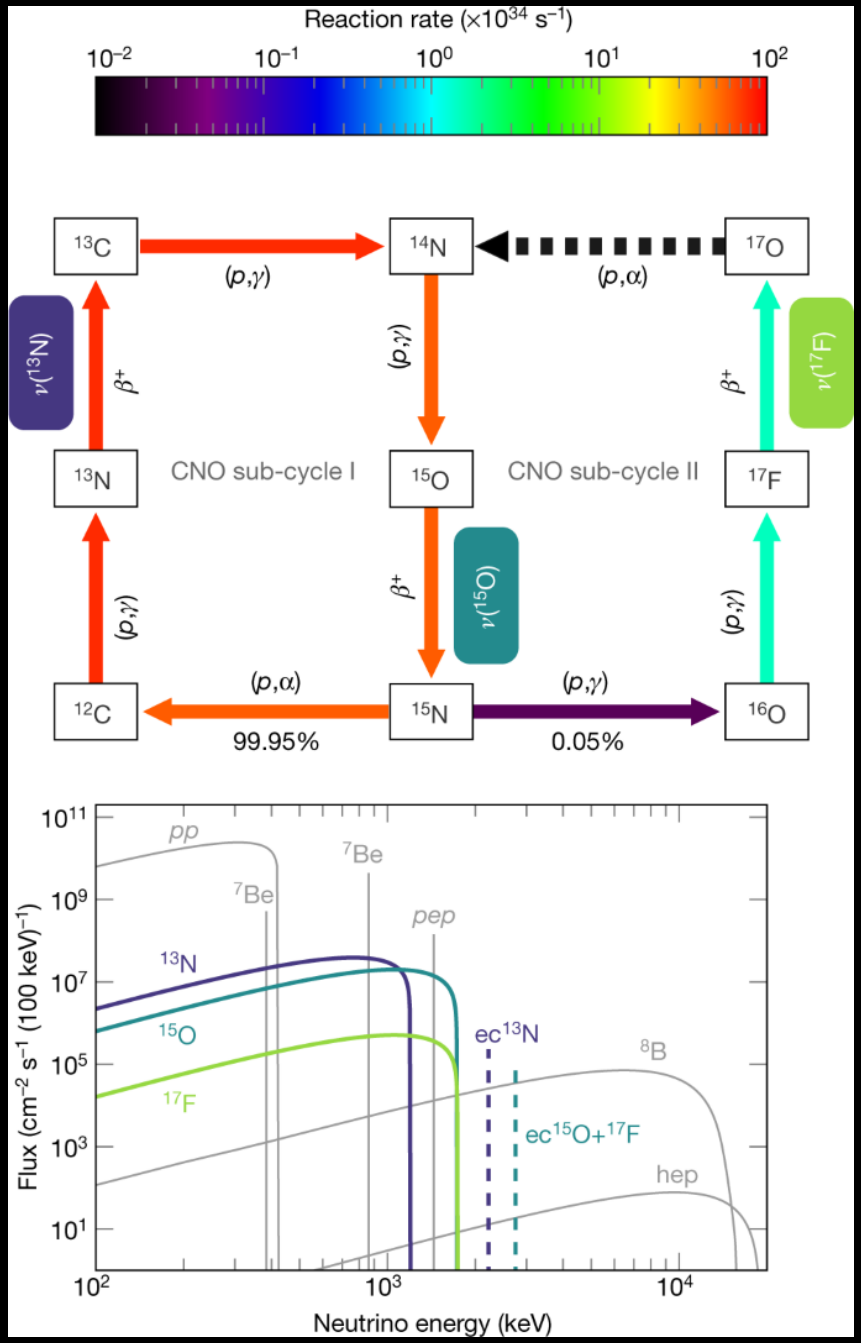
"A giant trap has been set deep underground to catch a few of the neutrinos that theory predicts should be pouring out of the sun.
Their capture would prove that the sun runs on thermonuclear power." John N. Bahcall

BNL Public Relation Office

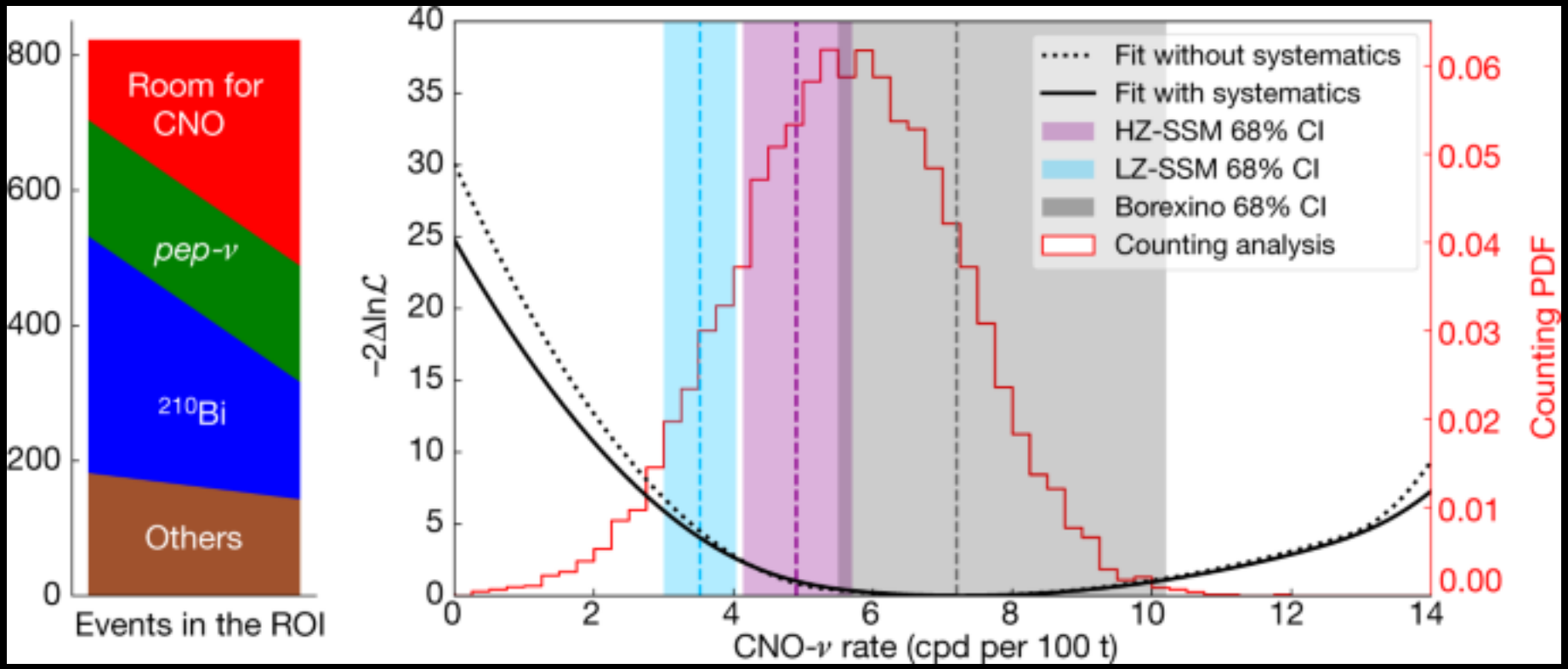


Experiment		Reaction	Threshold (MeV)	Observed/ Expected Rate
SAGE + GNO	CC	^{71}Ga $(\nu_e, e)^{71}$Ge	0.2	0.58 ± 0.04
HOMESTAKE	CC	^{37}Cl $(\nu_e, e)^{37}$Ar	0.8	0.34 ± 0.03
SNO	CC	$\nu_e + {}^2\mathrm{H} \rightarrow p + p + e$	~ 5	0.30 ± 0.05
SUPER-K	ES	$\nu + e \rightarrow \nu + e$	~ 5	0.46 ± 0.01
SNO	ES	$\nu + e \rightarrow \nu + e$	~ 5	0.47 ± 0.05
SNO	NC	$\nu + {}^2\mathrm{H} \rightarrow p + n + \nu$	~ 5	0.98 ± 0.09

CC = charged current (W-exchange); NC = neutral current (Z exchange); ES = electron scattering (via NC for ν_μ, ν_τ, and via NC and CC for ν_e)



https://www.nature.com/articles/s41586-020-2934-0



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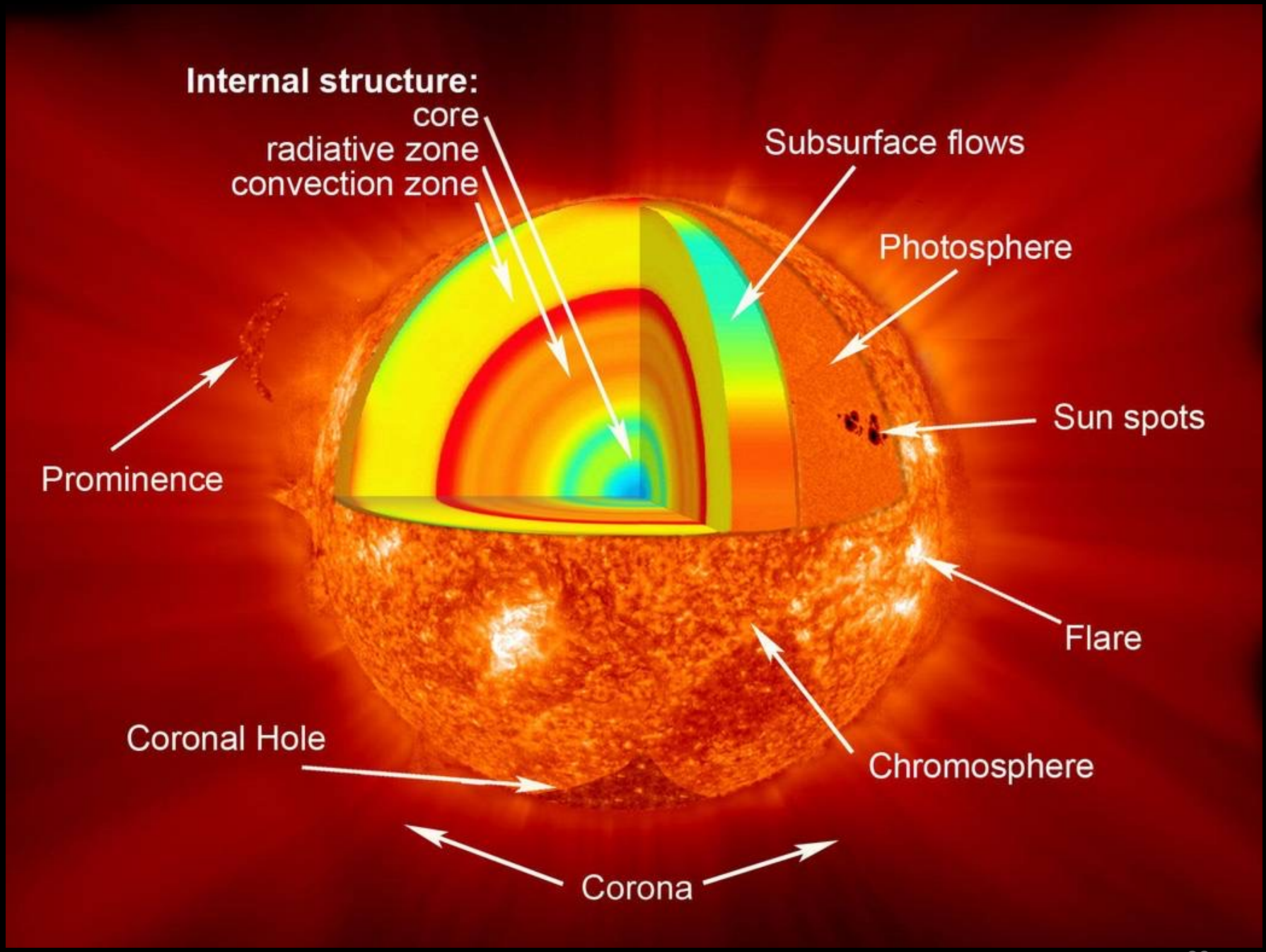
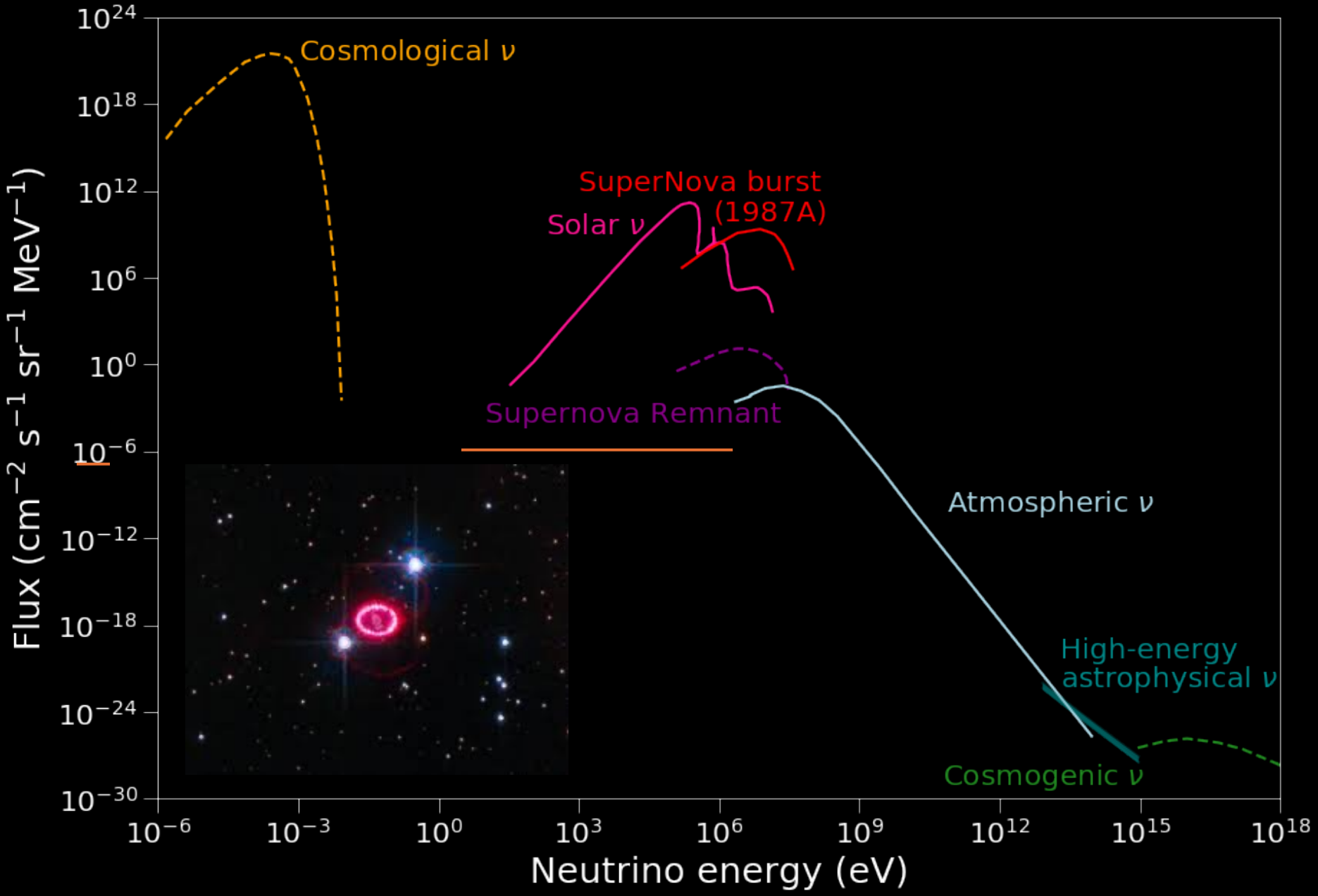


https://www.nasa.gov/mission_pages/sunearth/science/Sunlayers.html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Neutrino energy (eV)
10²⁴
10¹⁸
10¹²
10⁶
10⁰
10⁻⁶
10⁻¹²
10⁻¹⁸
10⁻²⁴
10⁻³⁰
10⁻⁶
10⁻³
10⁰
10³
10⁶
10⁹
10¹²
10¹⁵
10¹⁸

VOLUME 58, NUMBER 14 PHYSICAL REVIEW LETTERS 6 APRIL 1987

Observation of a Neutrino Burst from the Supernova SN1987A

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University of Tokyo, Tokyo 113, Japan

T. Kifune and T. Suda
Institute for Cosmic Ray Research, University of Tokyo, Tokyo 118, Japan

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National Laboratory for High Energy Physics (KEK), Ibaraki 305, Japan

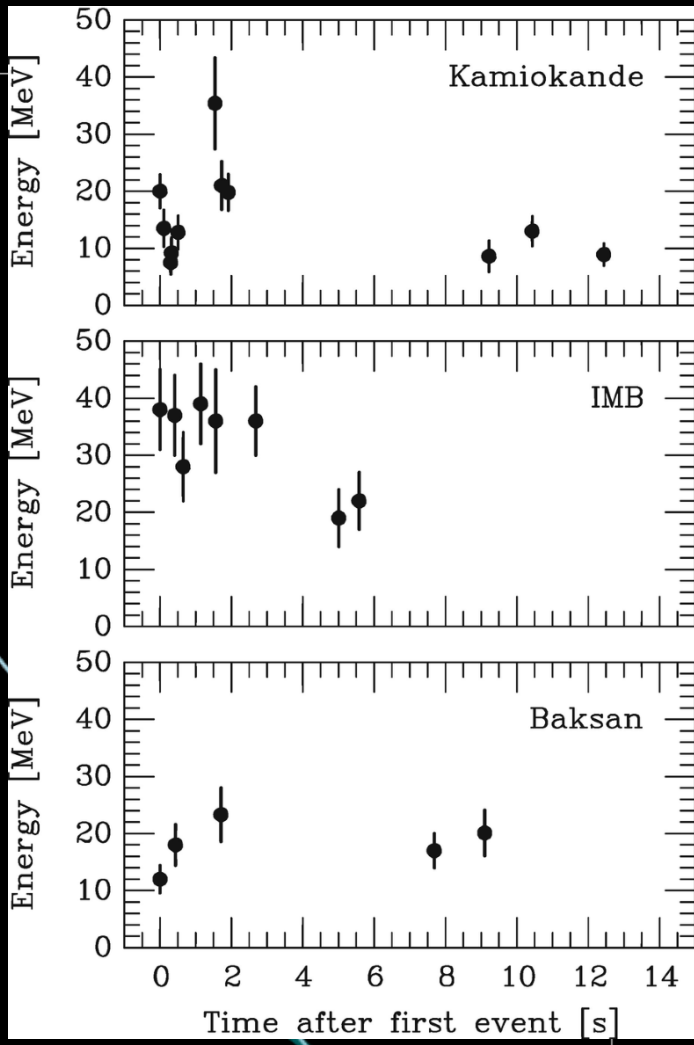
K. Miyano and M. Yamada
Department of Physics, University of Niigata, Niigata 950-21, Japan

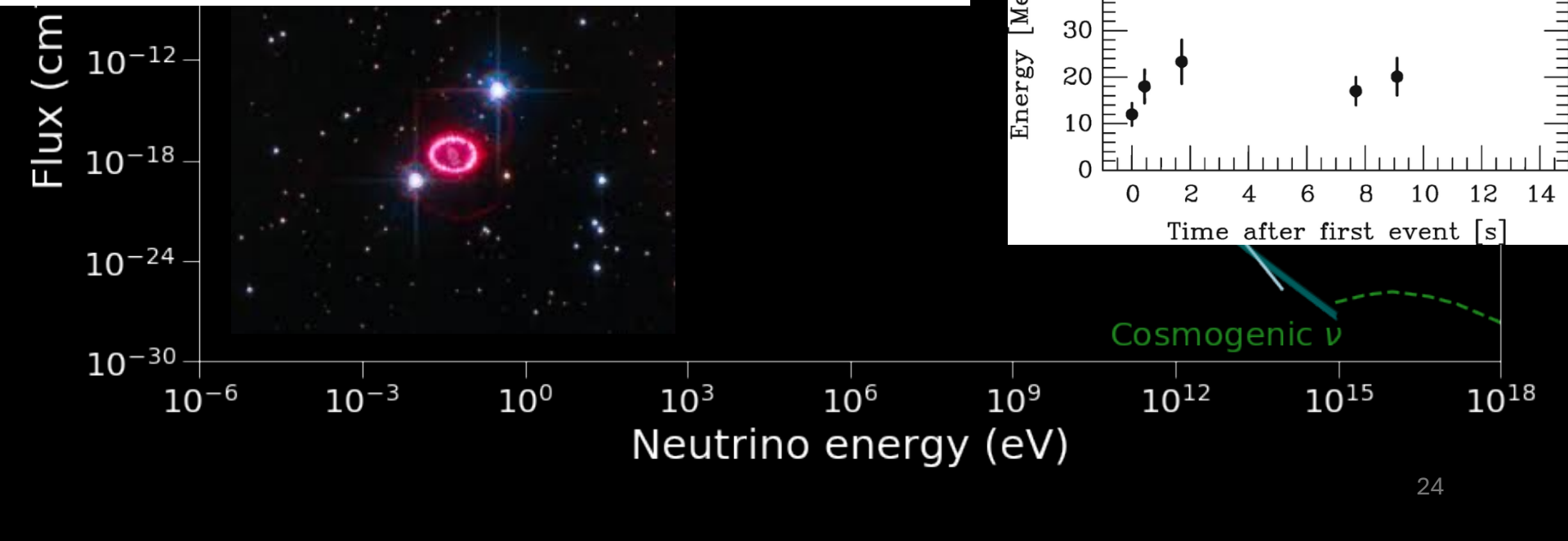
E. W. Beier, L. R. Feldscher, S. B. Kim, A. K. Mann, F. M. Newcomer, R. Van Berg, and W. Zhang
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19104

and

B. G. Cortez[(d)]
California Institute of Technology, Pasadena, California 91125
(Received 10 March 1987)

A neutrino burst was observed in the Kamiokande II detector on 23 February 1987, 7:35:35 UT (±1 min) during a time interval of 13 sec. The signal consisted of eleven electron events of energy 7.5 to 36 MeV, of which the first two point back to the Large Magellanic Cloud with angles 18° ± 18° and 15° ± 27°.





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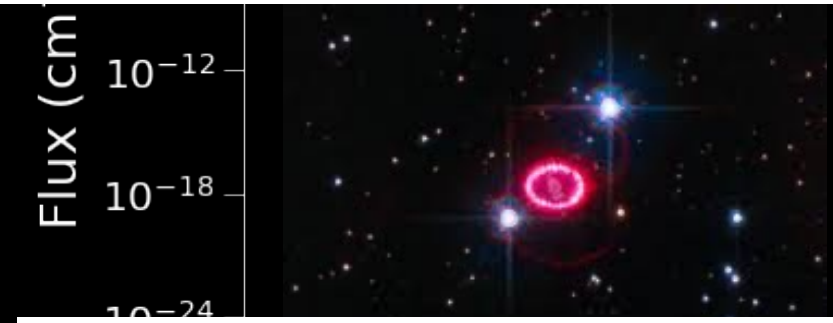
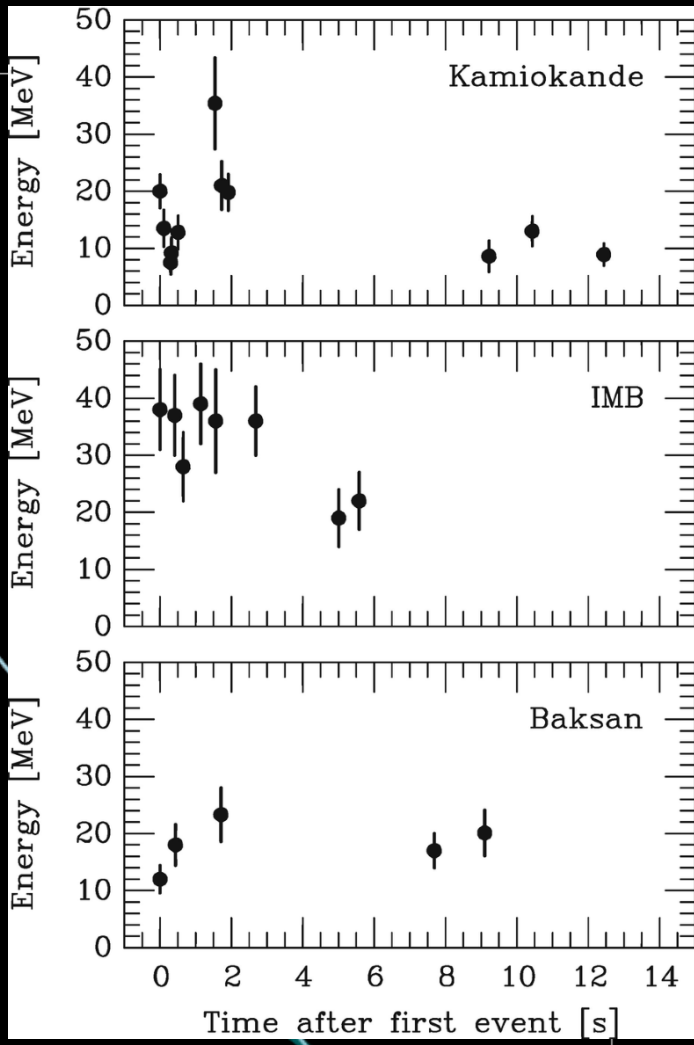
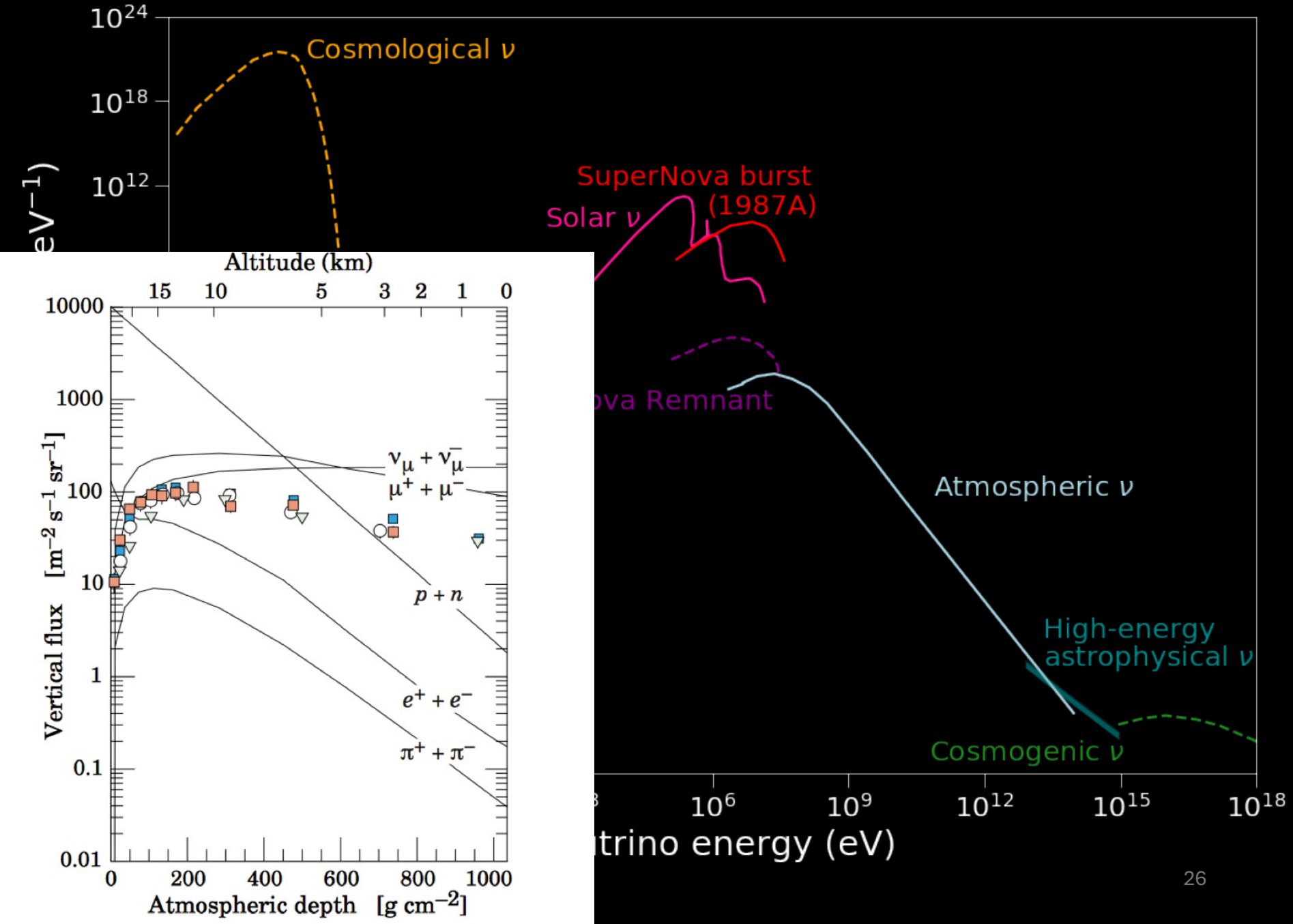




If you are interested in being notified about the occurrence of a neutrino burst from SNEWS, please sign up for our alert list.

https://snews2.org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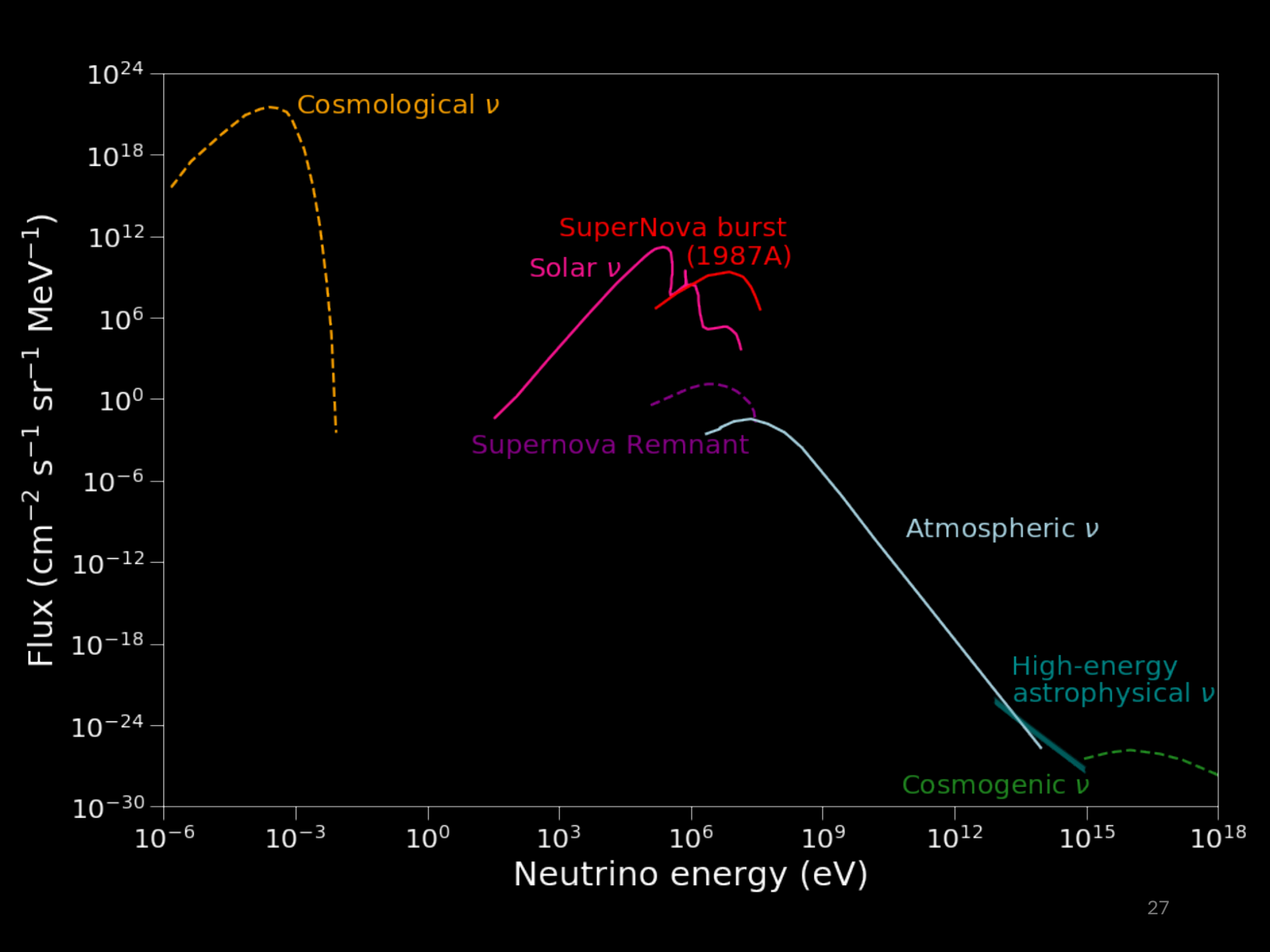
Cosmogenic ν
10^{6}
10^{9}
10^{12}
10^{15}
10^{18}
trino energy (eV)
Altitude (km)
15 10 5 3 2 1 0
10000
1000
100
10
1
0.1
0.01
Vertical flux [m^{-2} s^{-1} sr^{-1}]
$\nu_\mu + \bar{\nu}_\mu$
$\mu^+ + \mu^-$
$p + n$
$e^+ + e^-$
$\pi^+ + \pi^-$
0 200 400 600 800 1000
Atmospheric depth [g cm^{-2}]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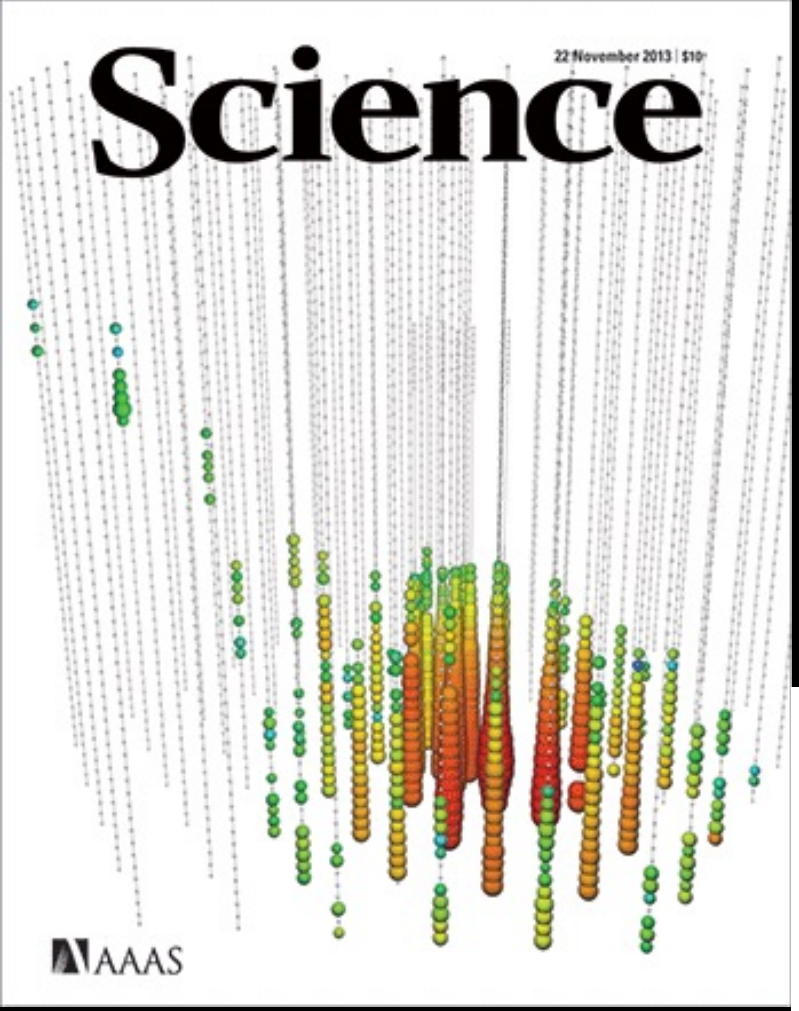
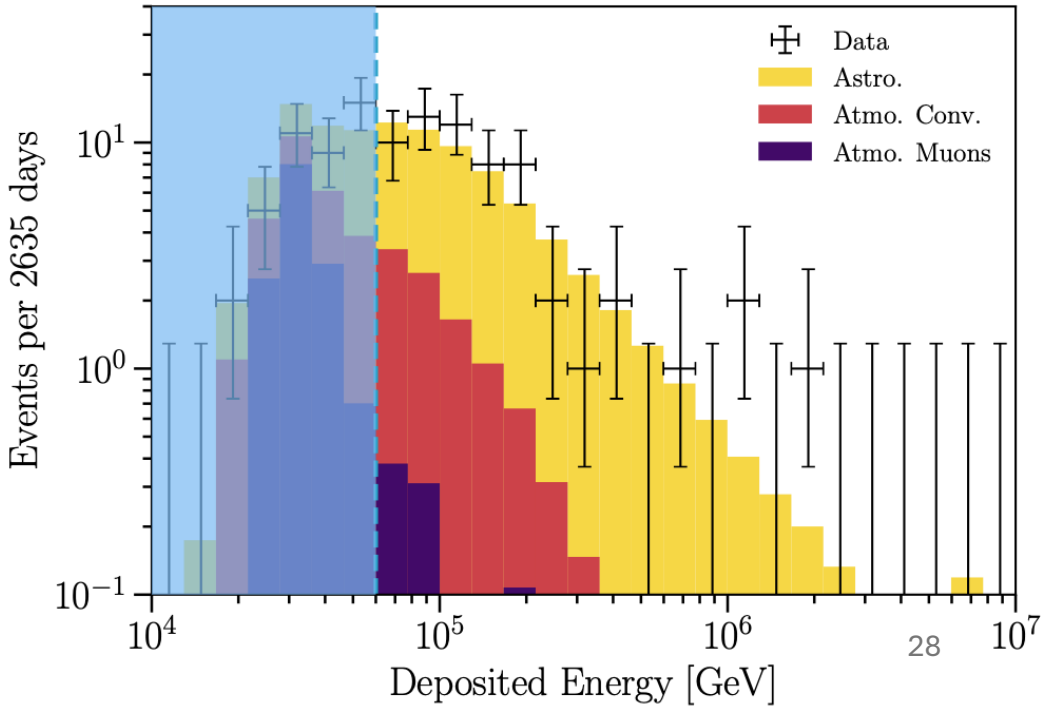
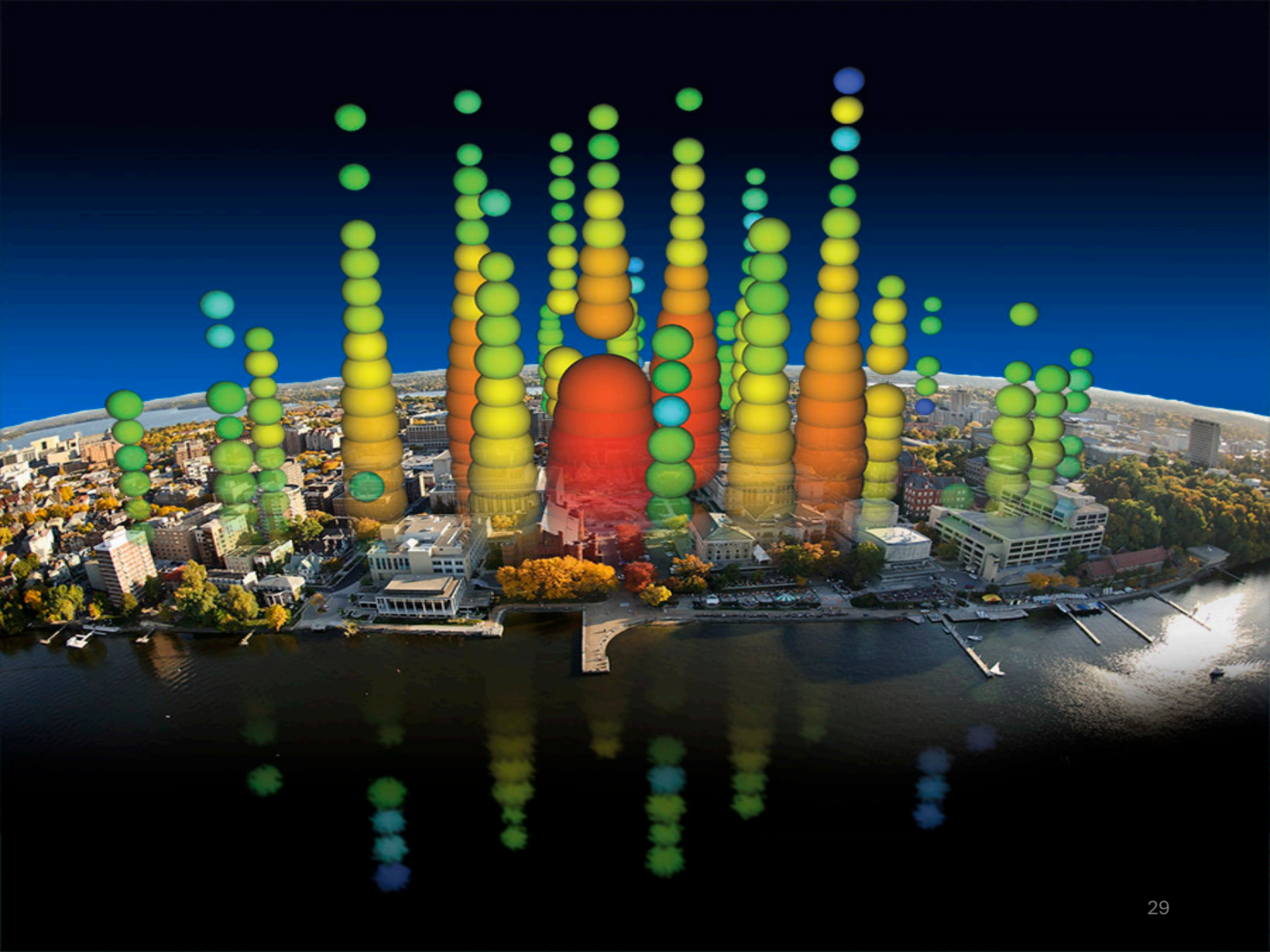


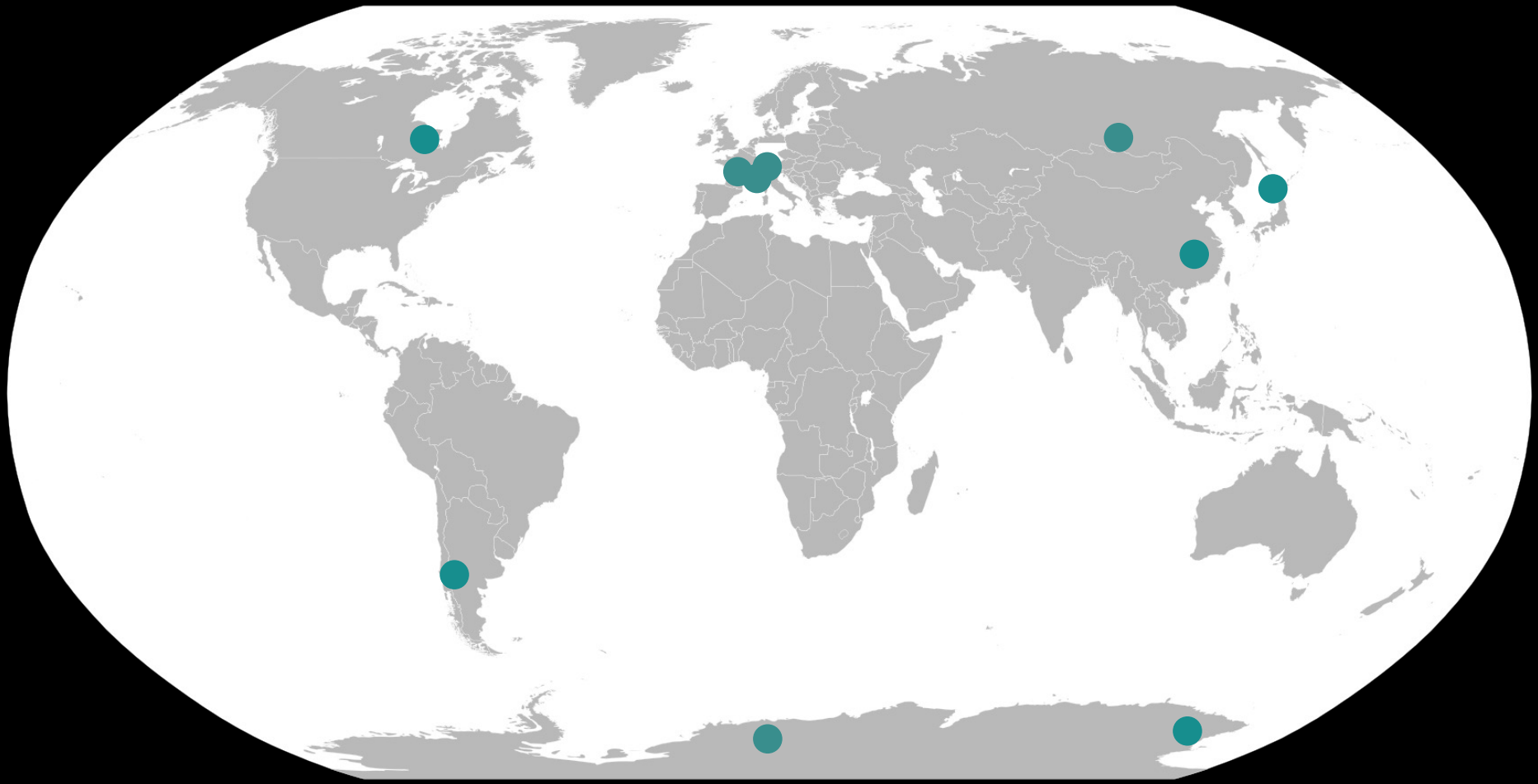
Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

22 Nov. 2013



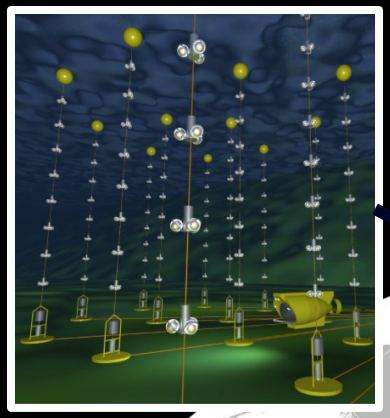


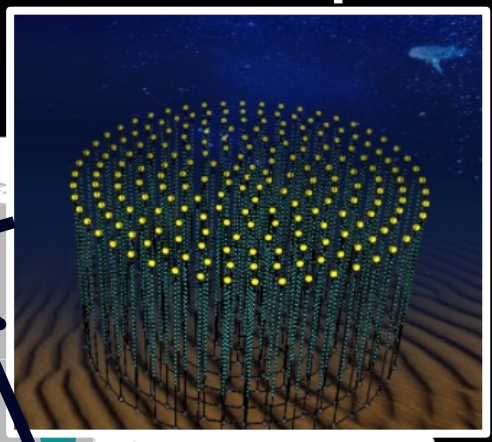
Neutrino telescopes

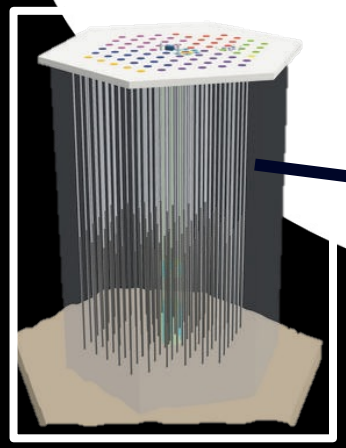


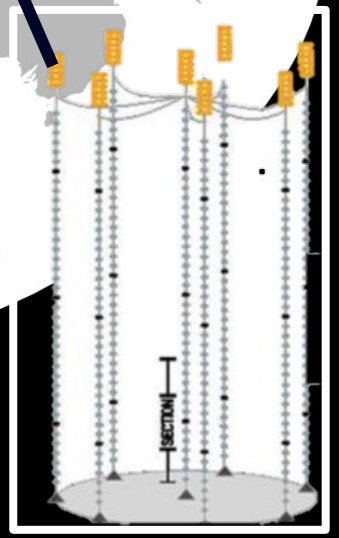
Non-exhaustive list

Neutrino telescopes



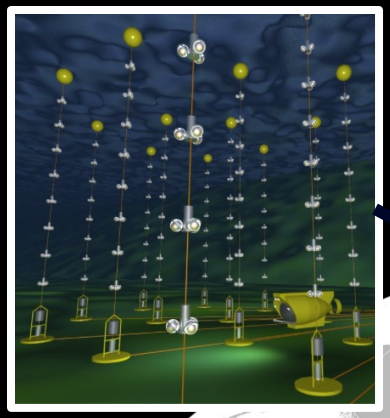


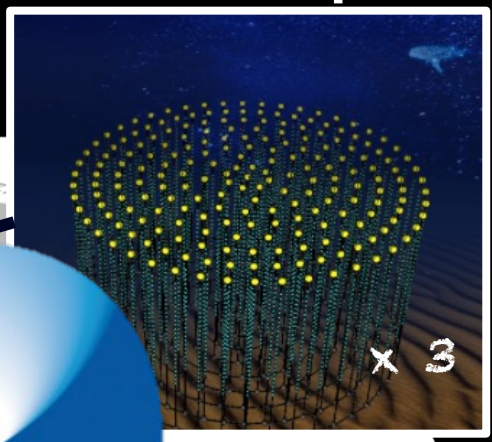




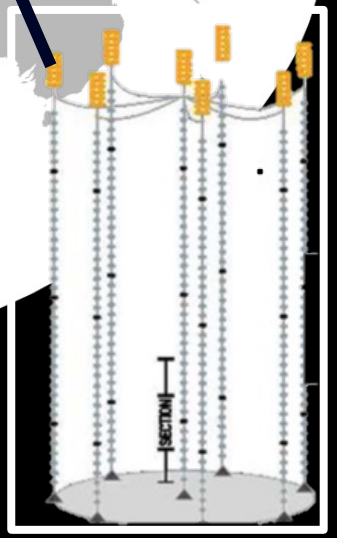
GNN
The Global Neutrino Network

Neutrino telescopes





KM3NeT

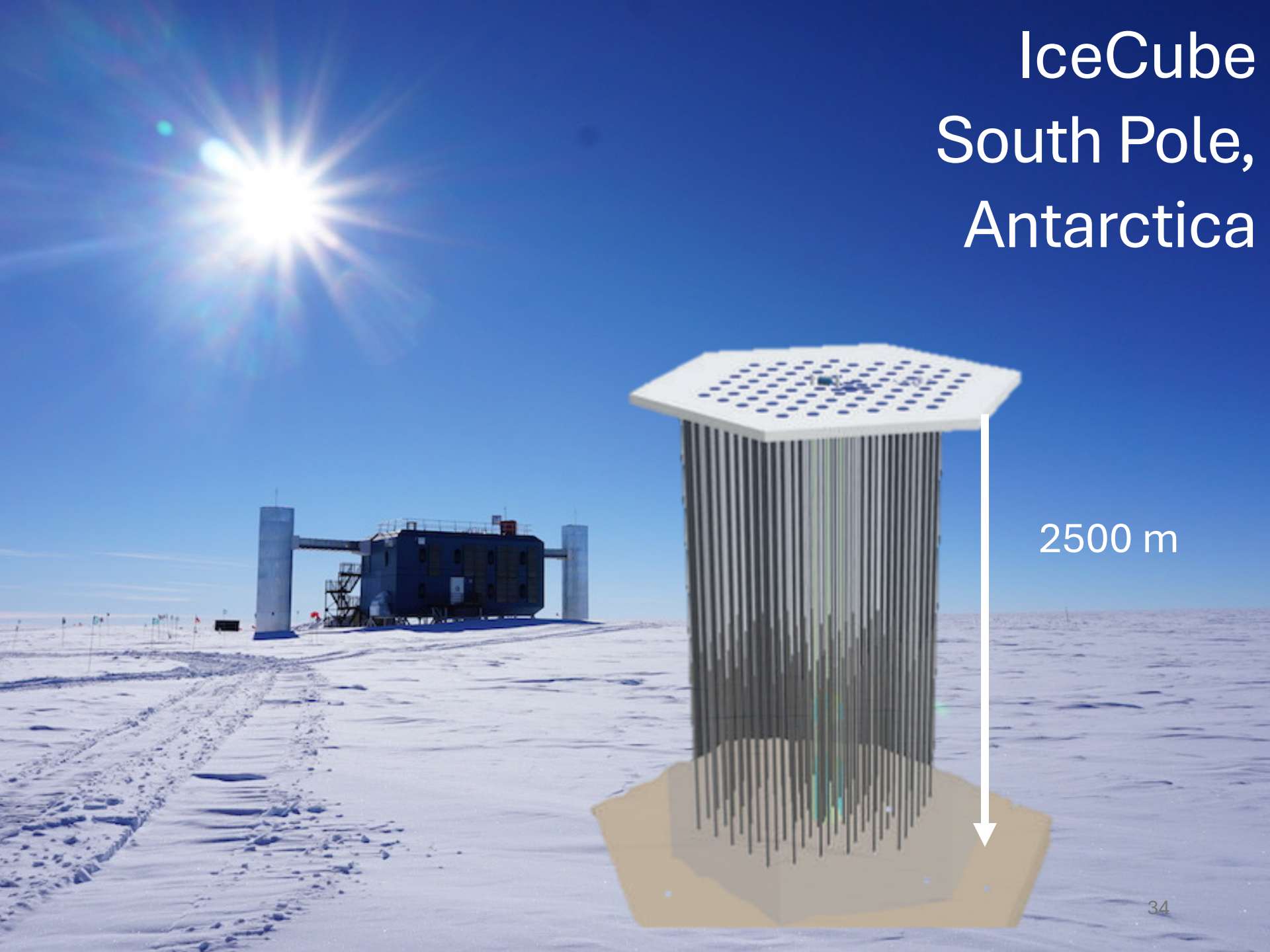


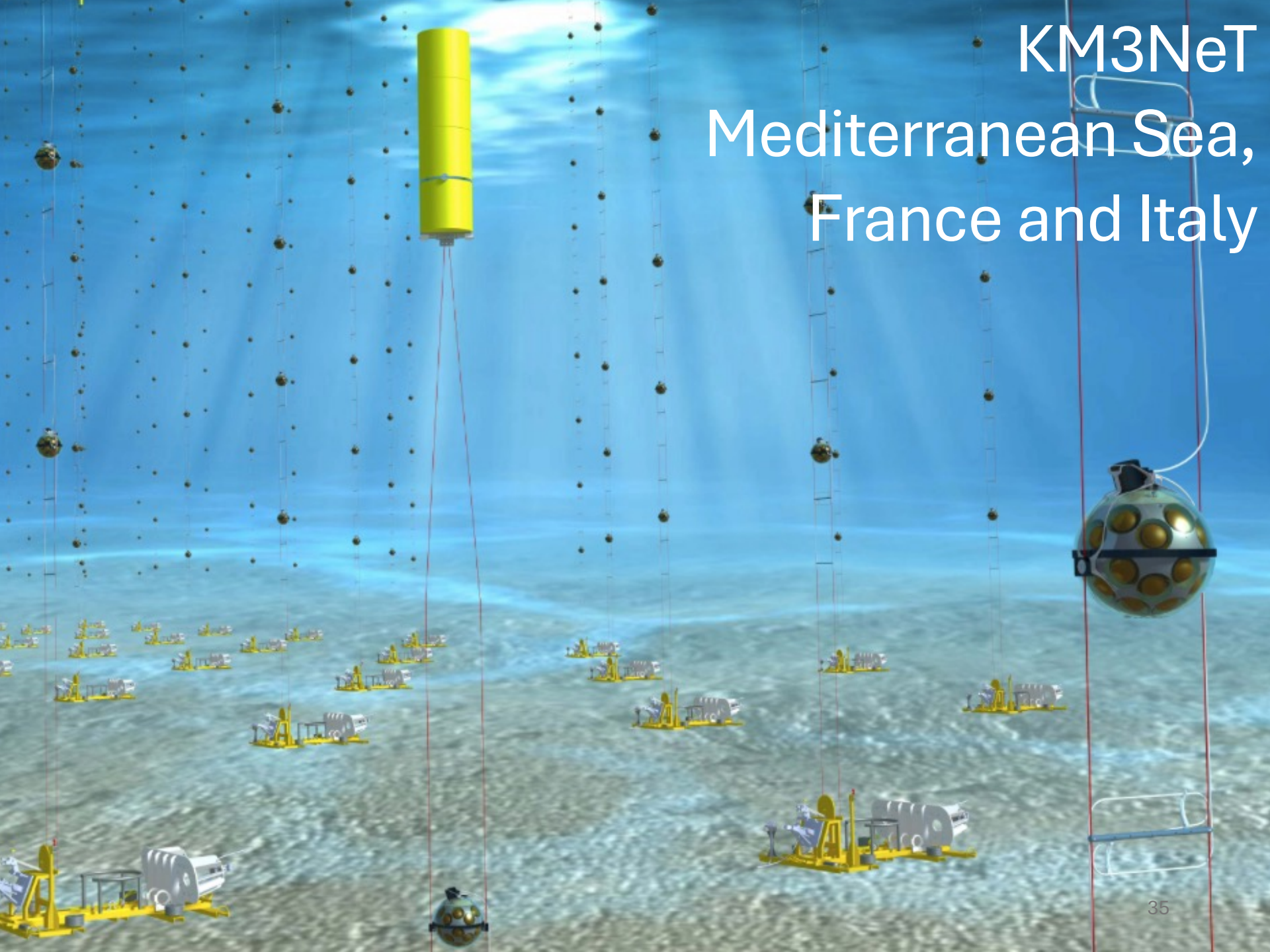
GNN
The Global Neutrino Network

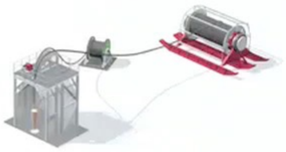
x 8

IceCube South Pole, Antarctica

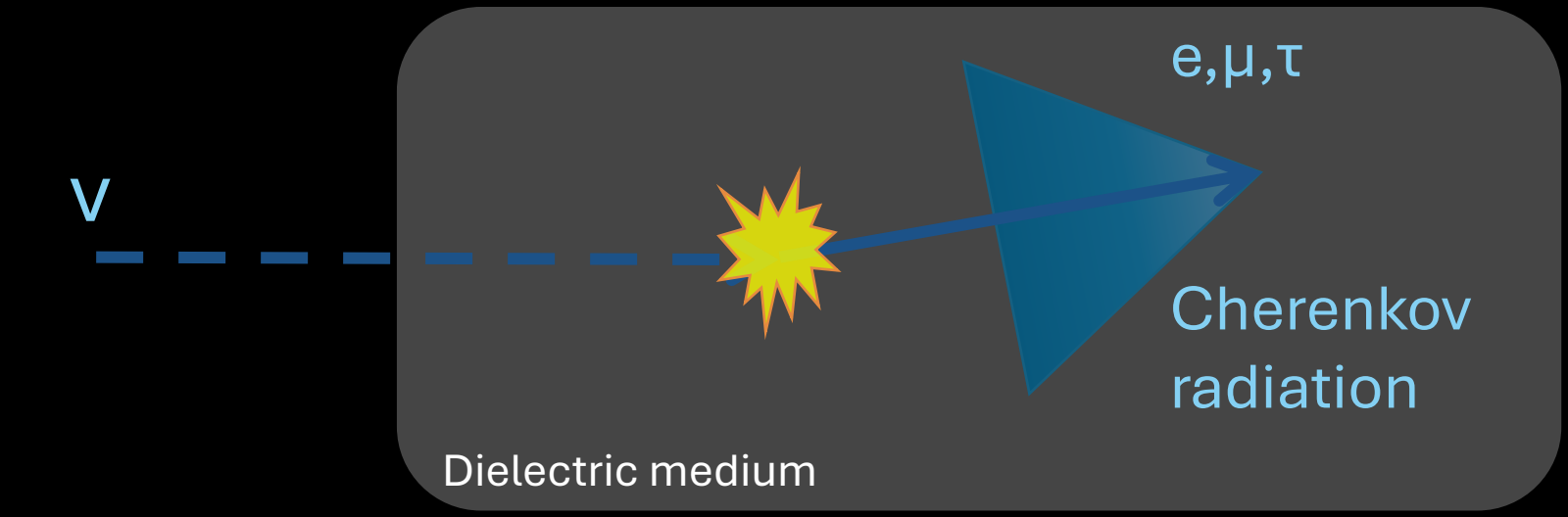
IceCube South Pole, Antarctica

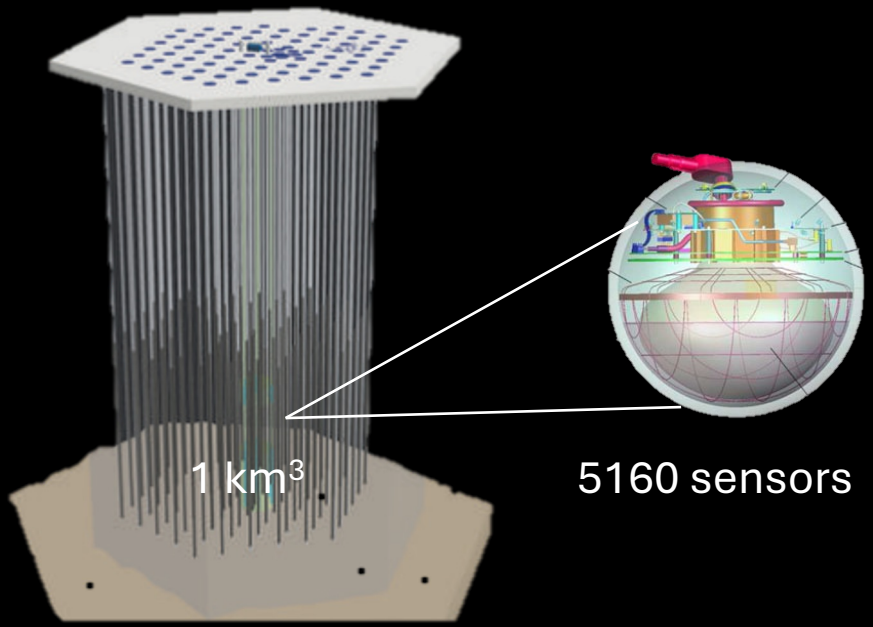



KM3NeT
Mediterranean Sea,
France and Italy

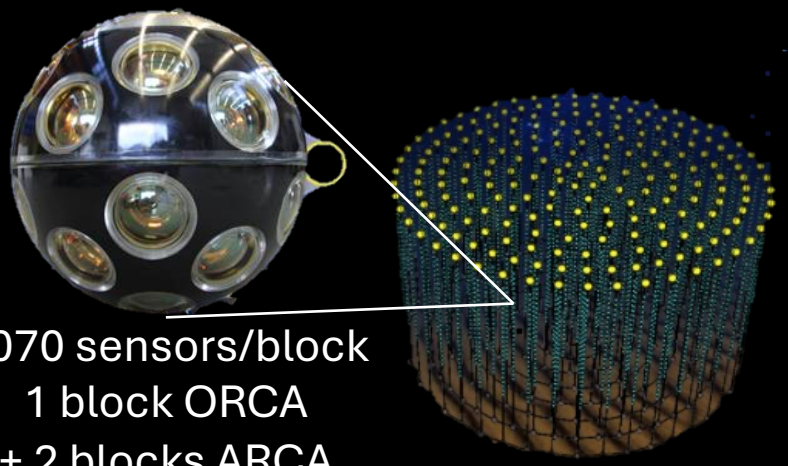


Detection strategy



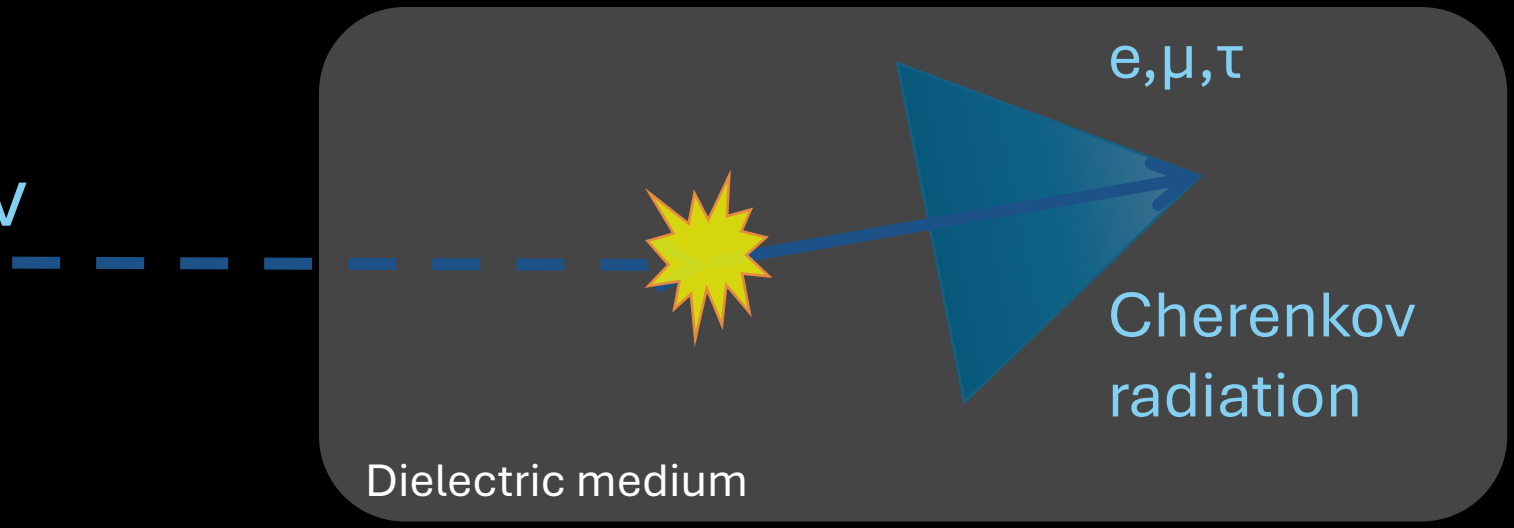


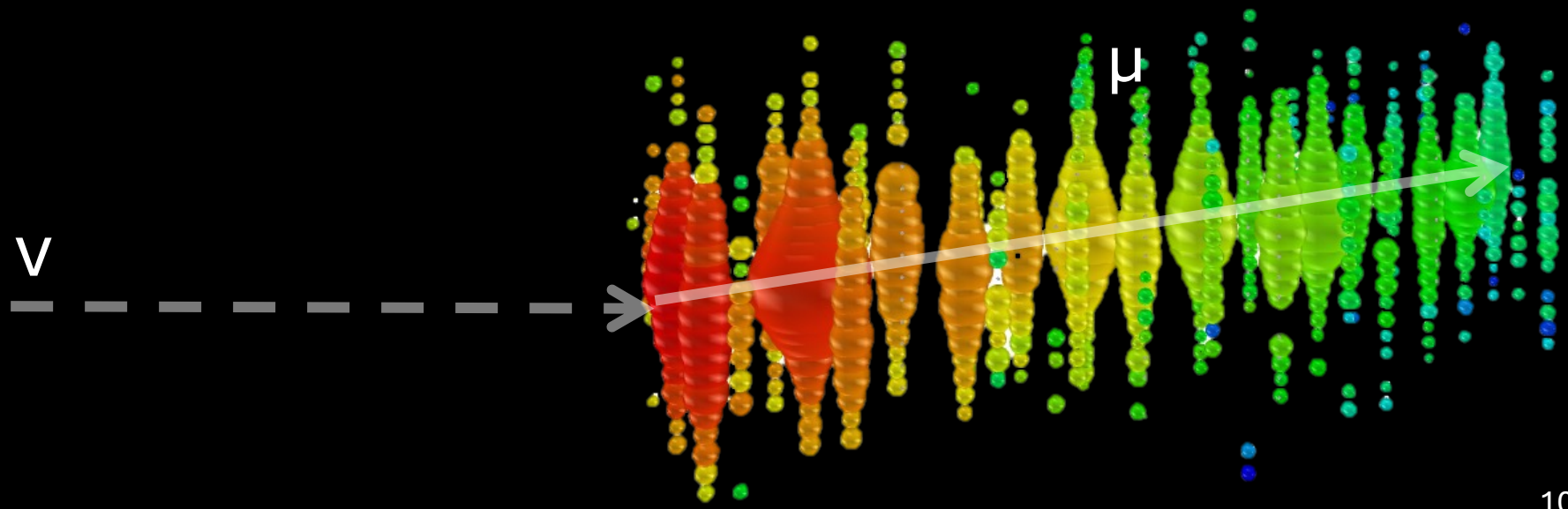
5160 sensors

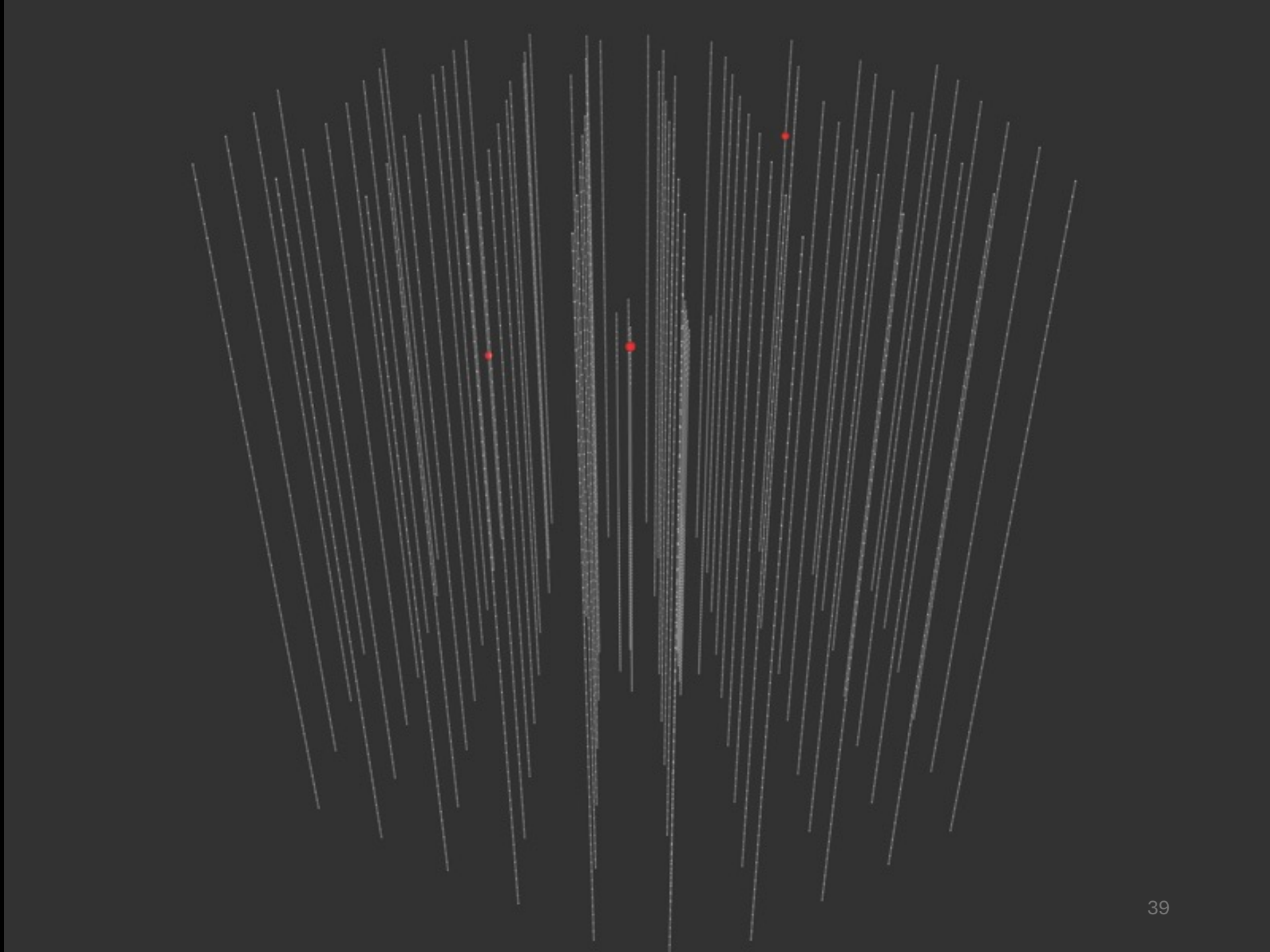


2070 sensors/block
1 block ORCA
+ 2 blocks ARCA

Detection strategy

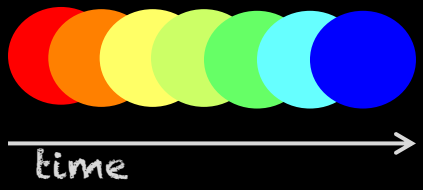


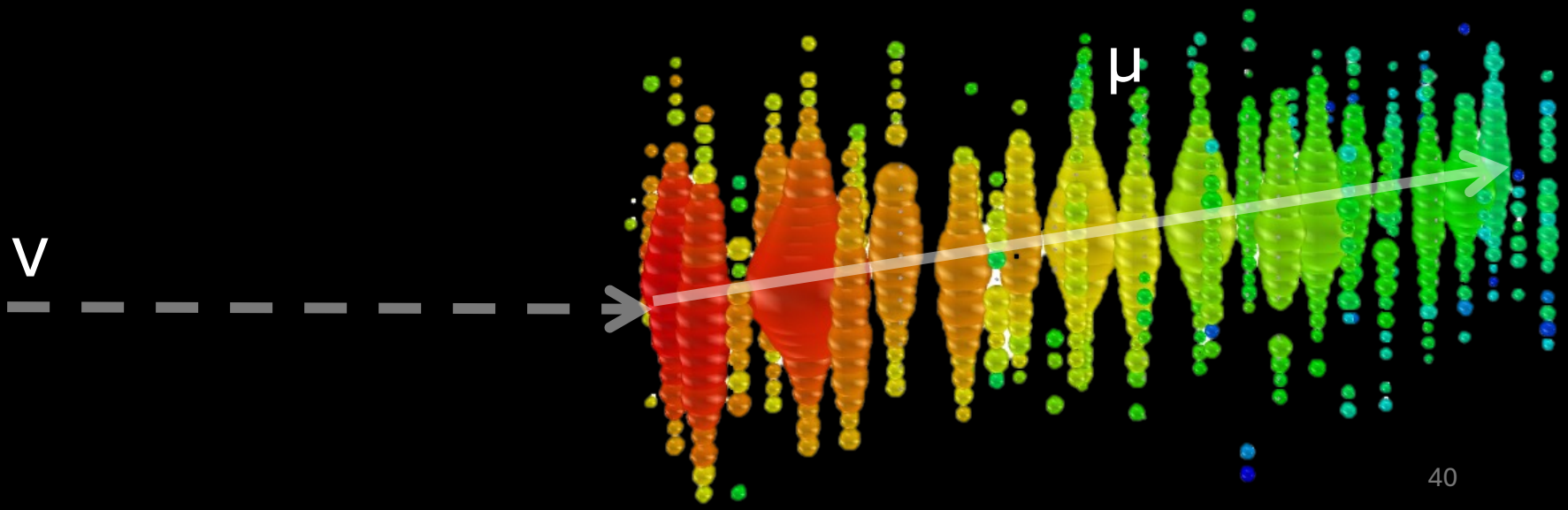




Detection strategy

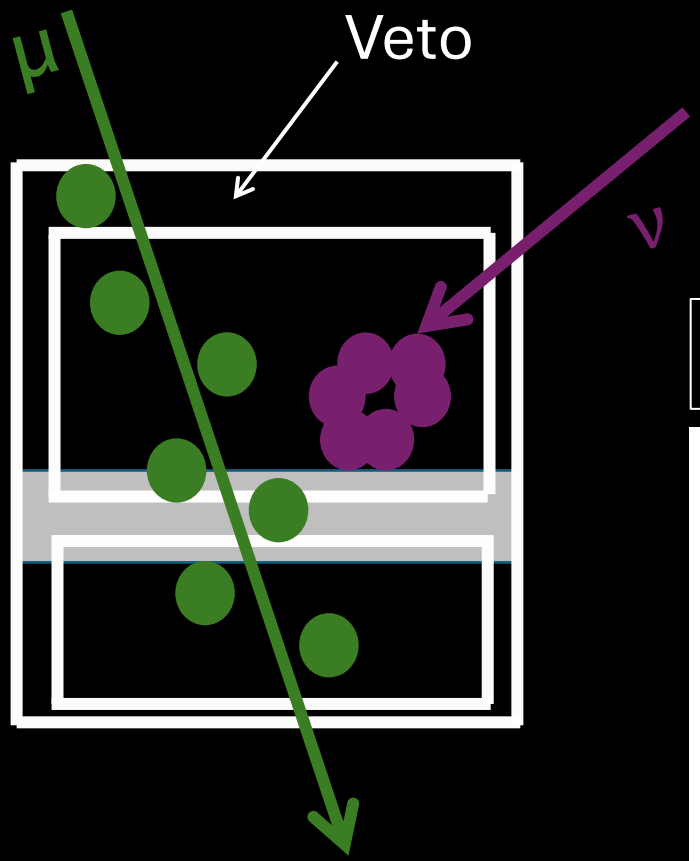
- Amount of light-> Energy
- Timing -> Direction
- Topology -> Flavor



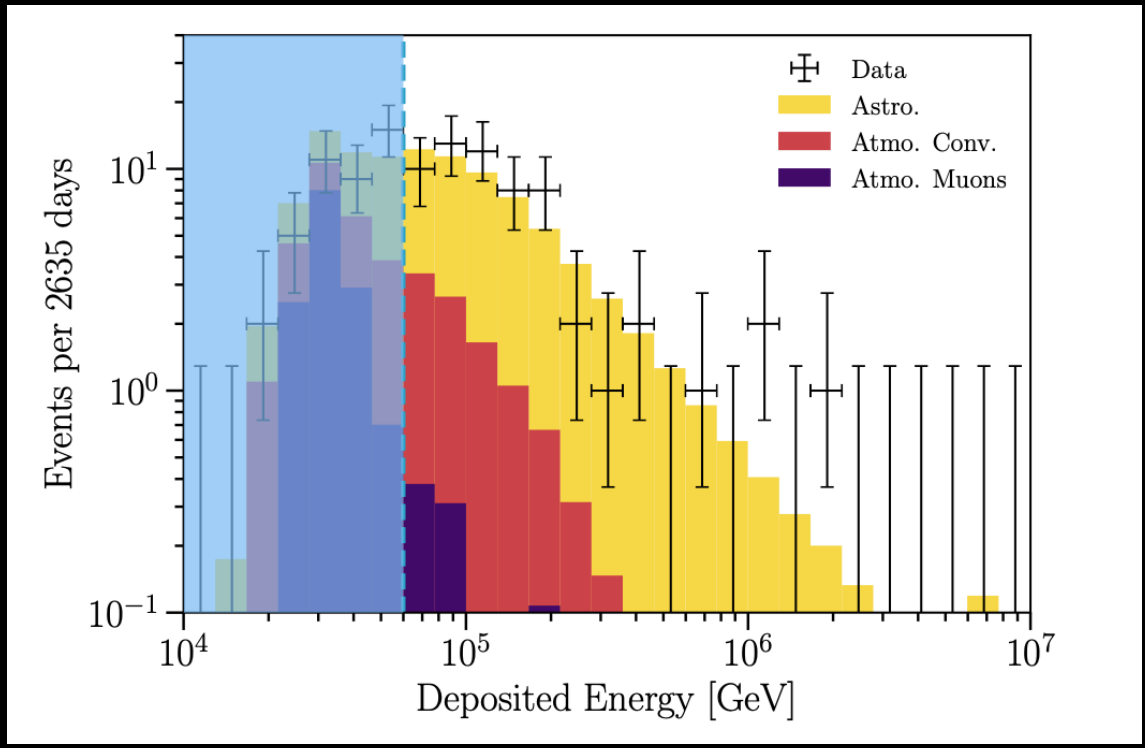


https://arxiv.org/abs/2011.03545

Diffuse neutrino flux 7.5 year

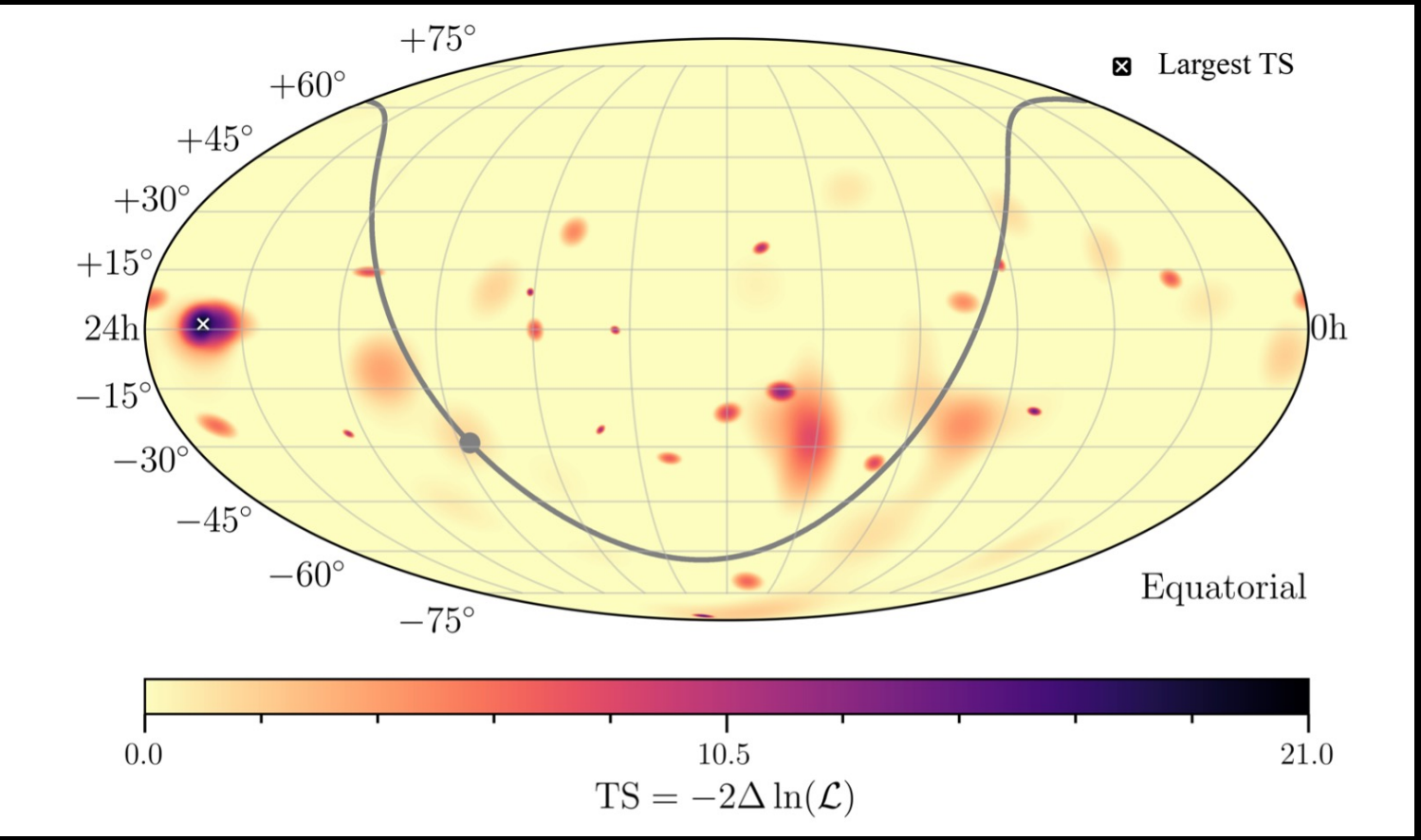


102 events, with 60 events > 60 TeV

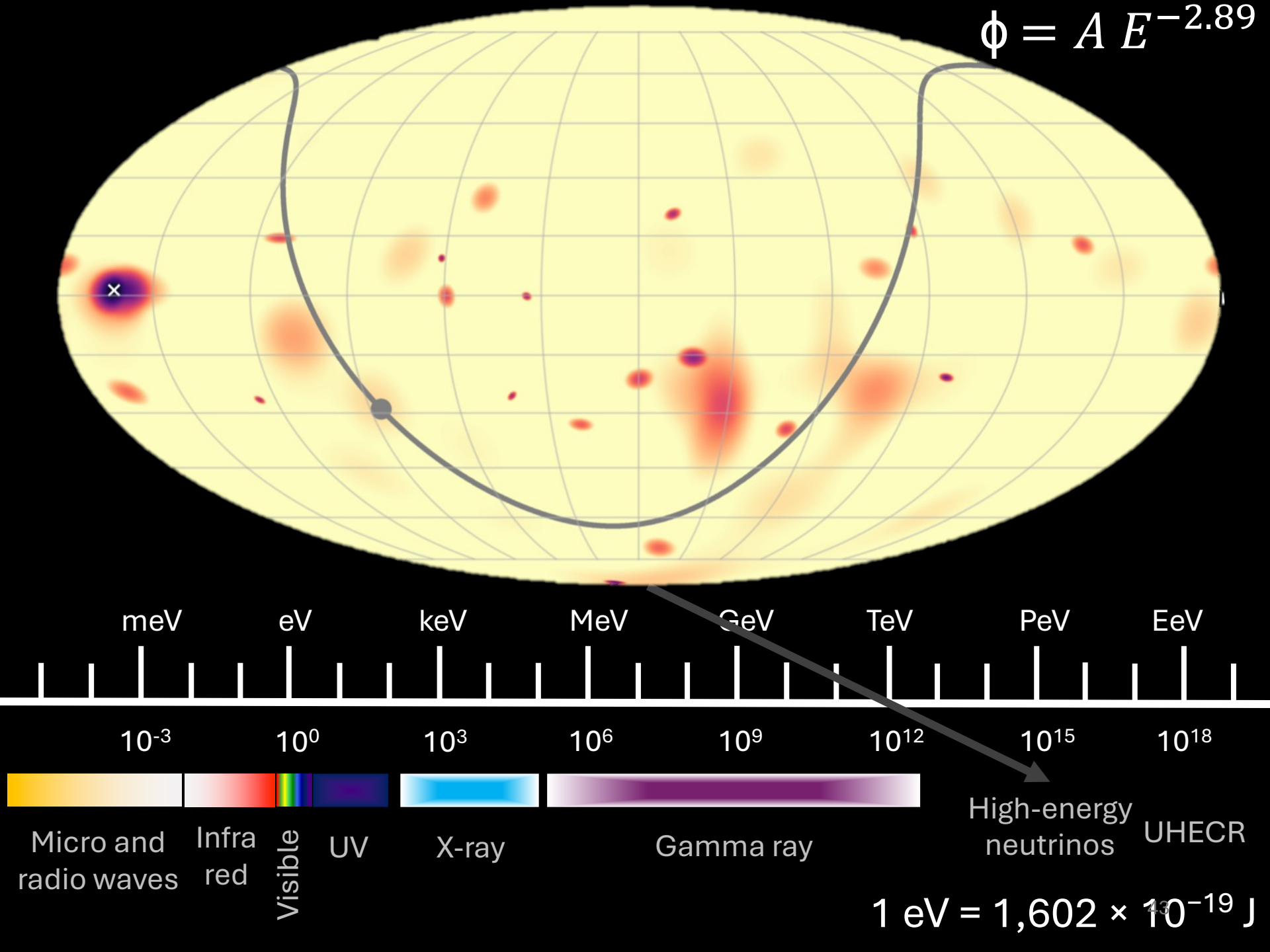


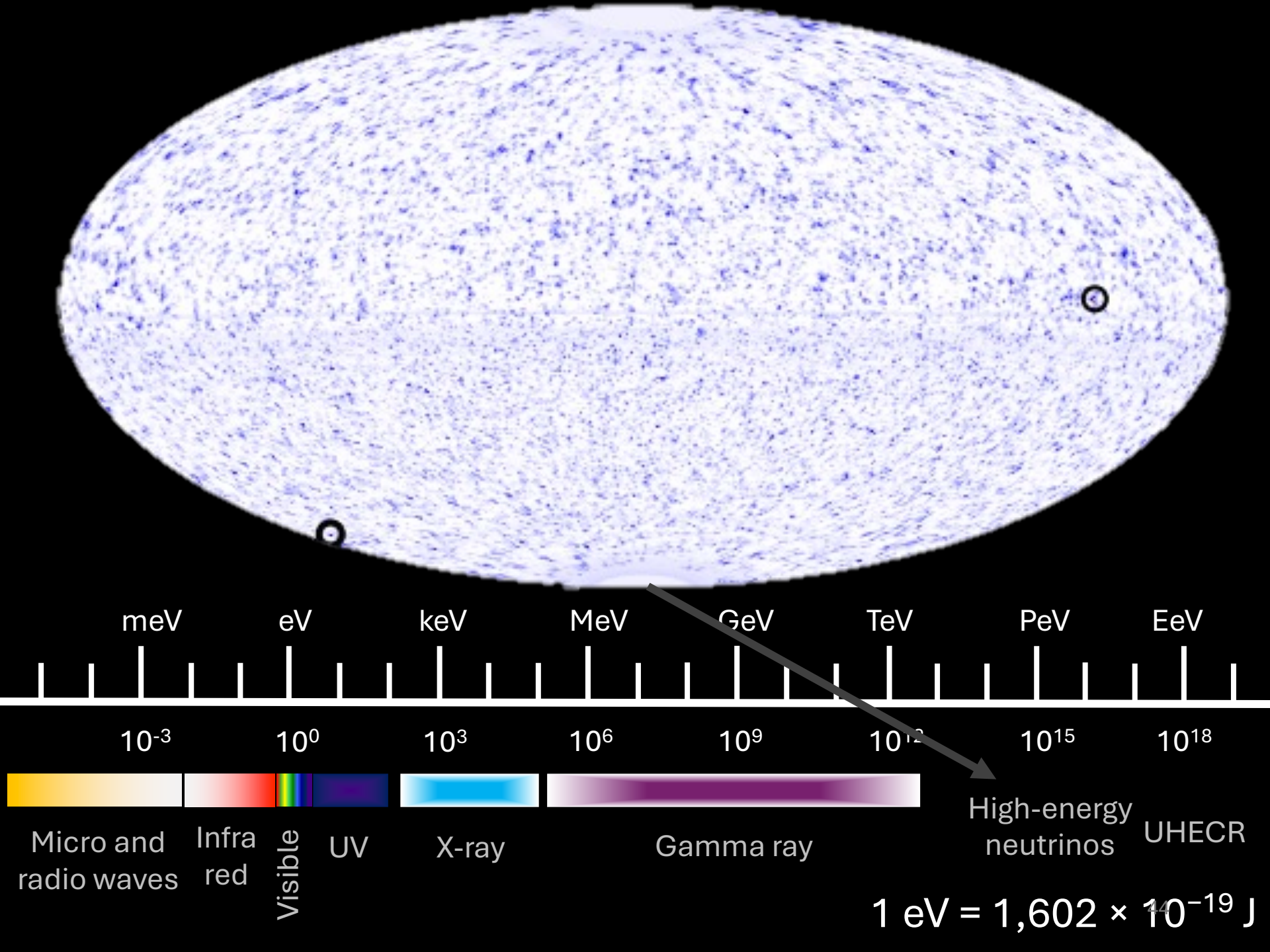
Diffuse neutrino flux

7.5 year



- No evidence for point sources
- No correlation with the galactic plane
- Best fit: Single power law with spectral index $\gamma = 2.89^{+0.20}_{-0.19}$
  all-flavor flux normalization $\Phi = 6.45^{+1.46}_{-0.46}$
- Data does not prefer a broken power law model


$\phi = A\,E^{-2.89}$
meV
eV
keV
MeV
GeV
TeV
PeV
EeV
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
10^{18}
Micro and radio waves
Infra red
Visible
UV
X-ray
Gamma ray
High-energy neutrinos
UHECR
1 eV = 1,602 × 10^{-19} J


meV
eV
keV
MeV
GeV
TeV
PeV
EeV
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{15}
10^{18}
Micro and radio waves
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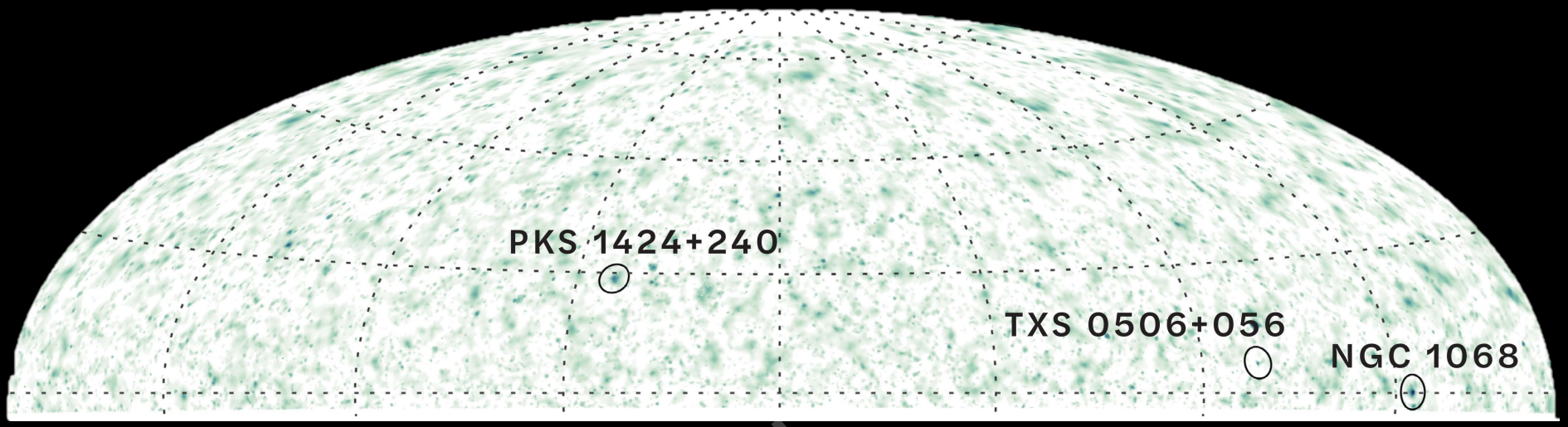


meV eV keV MeV GeV TeV PeV EeV

10^{-3} 10^{0} 10^{3} 10^{6} 10^{9} 10^{12} 10^{15} 10^{18}

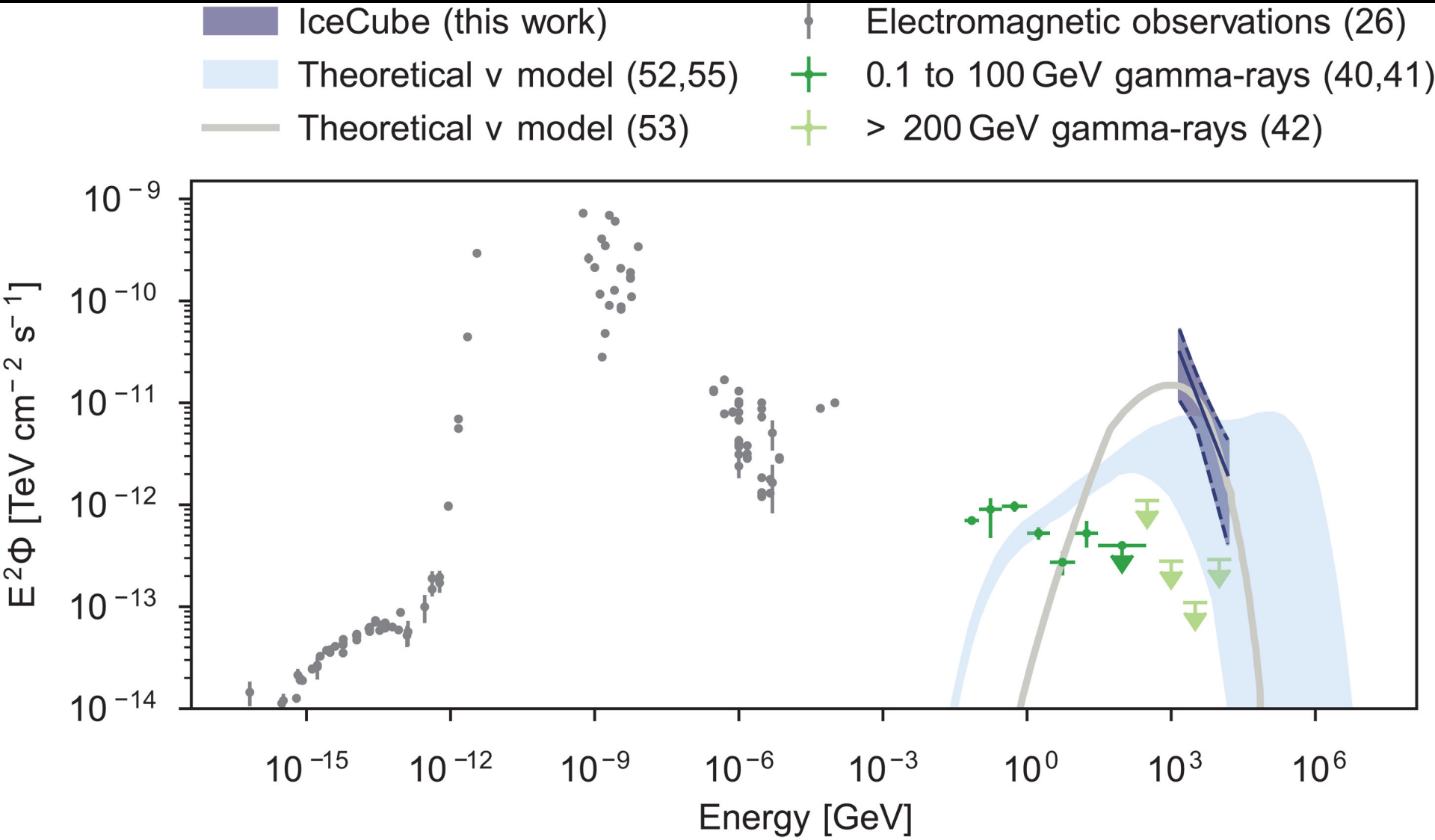
Micro and radio waves | Infra red | Visible | UV | X-ray | Gamma ray | High-energy neutrinos | UHECR

$1\ \text{eV} = 1{,}602 \times 10^{-19}\ \text{J}$

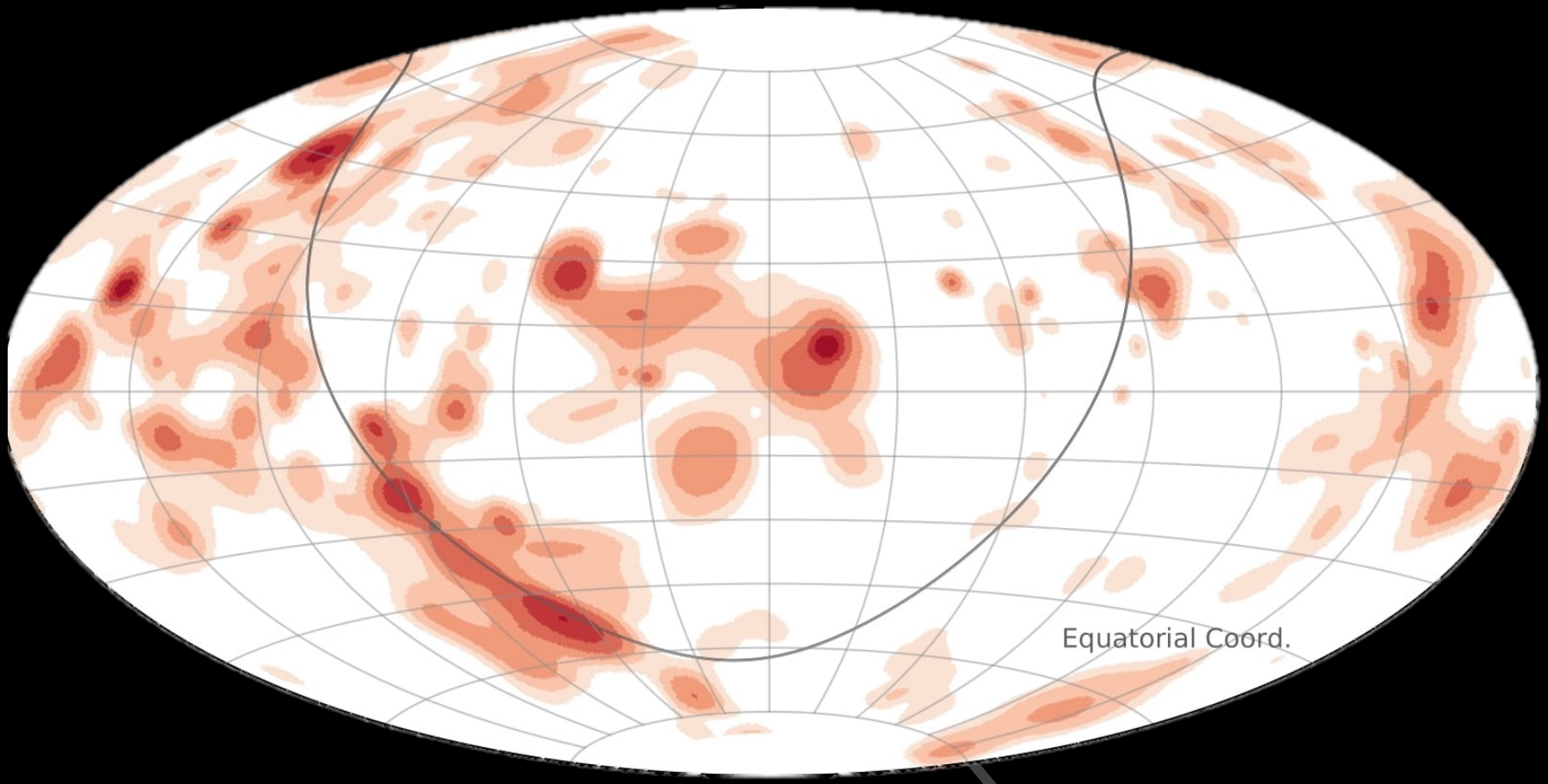

NASA, ESA & A. van der Hoeven

NASA, ESA, CSA, T. Carpentier

NGC 1068



Située à 47 millions d'années lumière



meV eV keV MeV GeV TeV PeV EeV

10^{-3} 10^{0} 10^{3} 10^{6} 10^{9} 10^{12} 10^{15} 10^{18}

Micro and radio waves

Infra red

Visible

UV

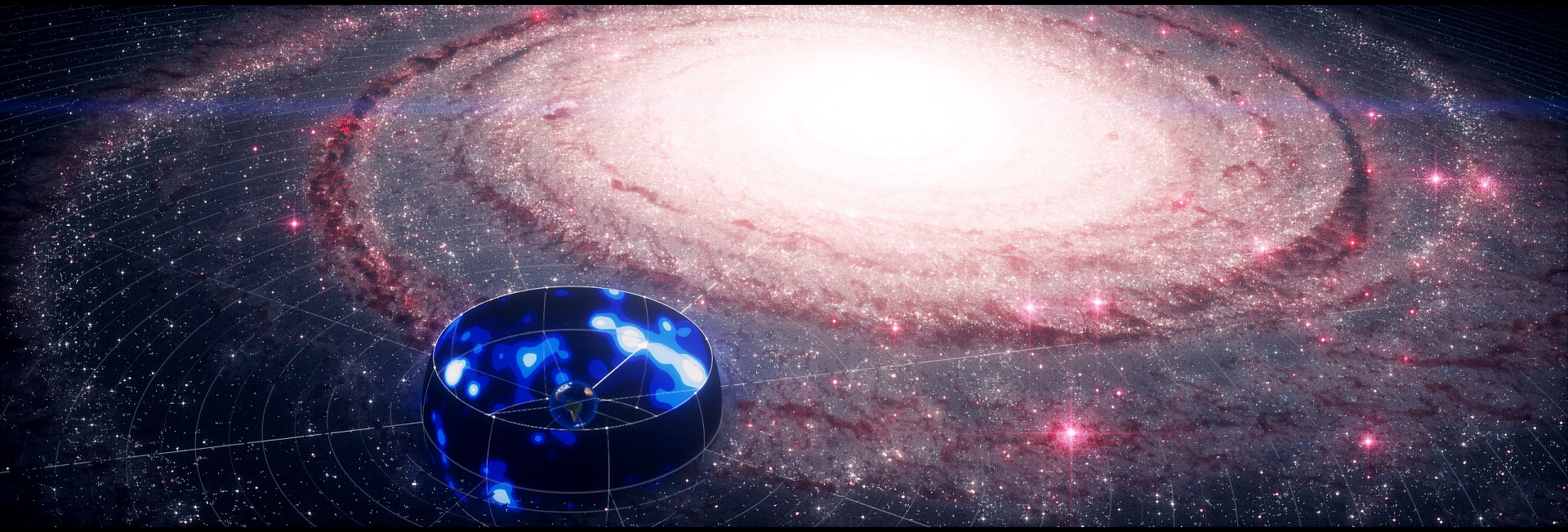
X-ray

Gamma ray

High-energy neutrinos

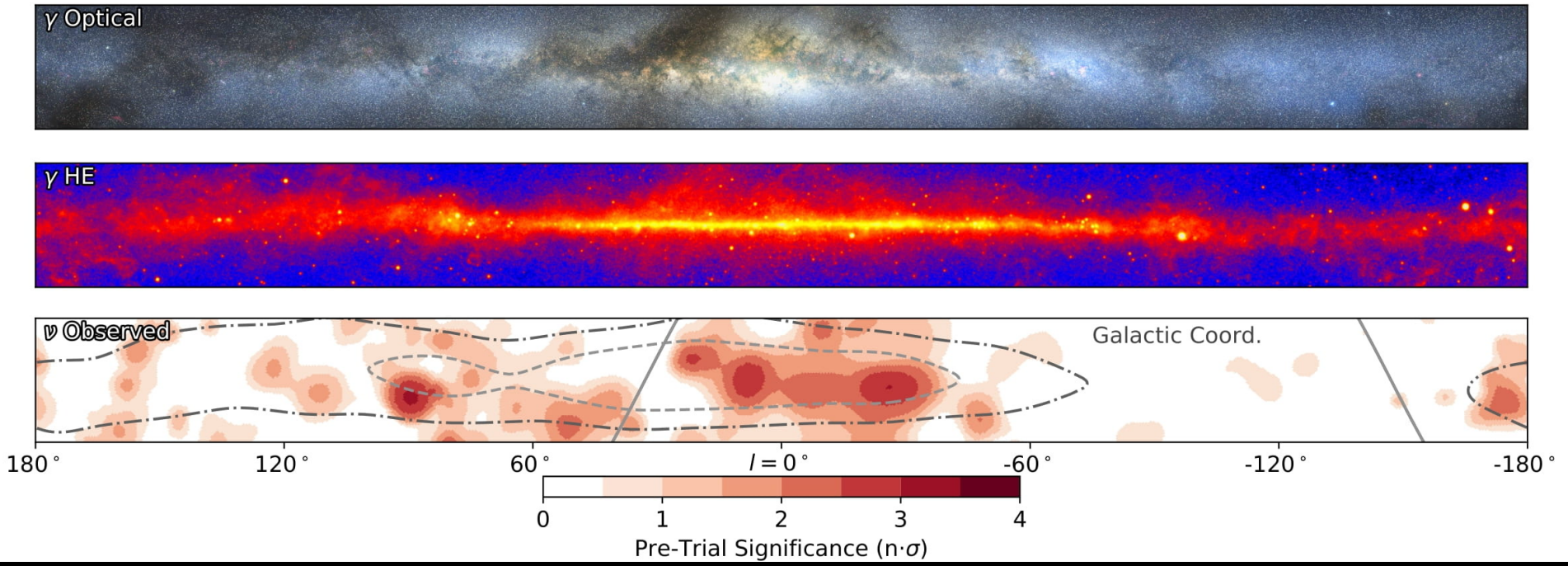
UHECR

$1\ \text{eV} = 1{,}602 \times 10^{-19}\ \text{J}$

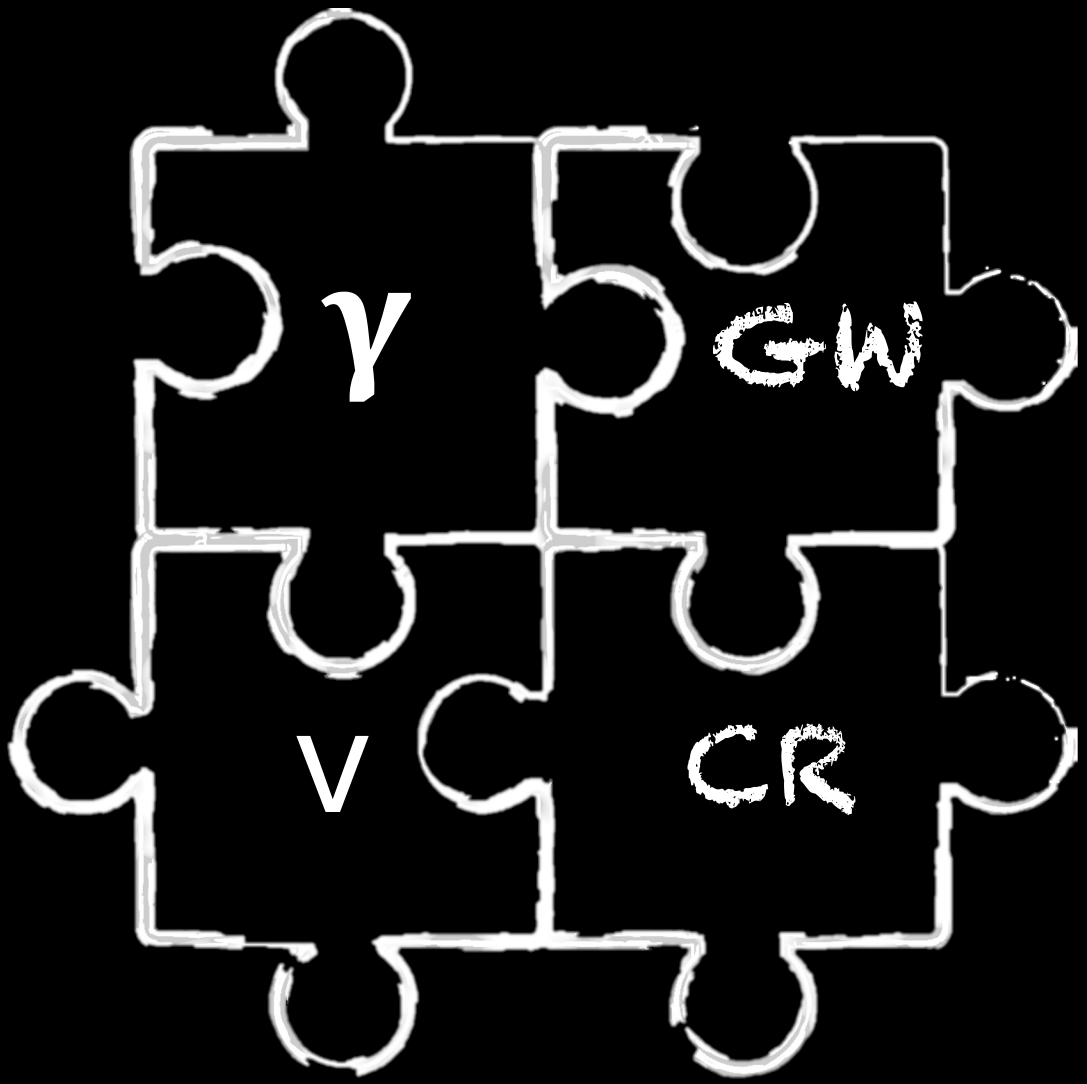


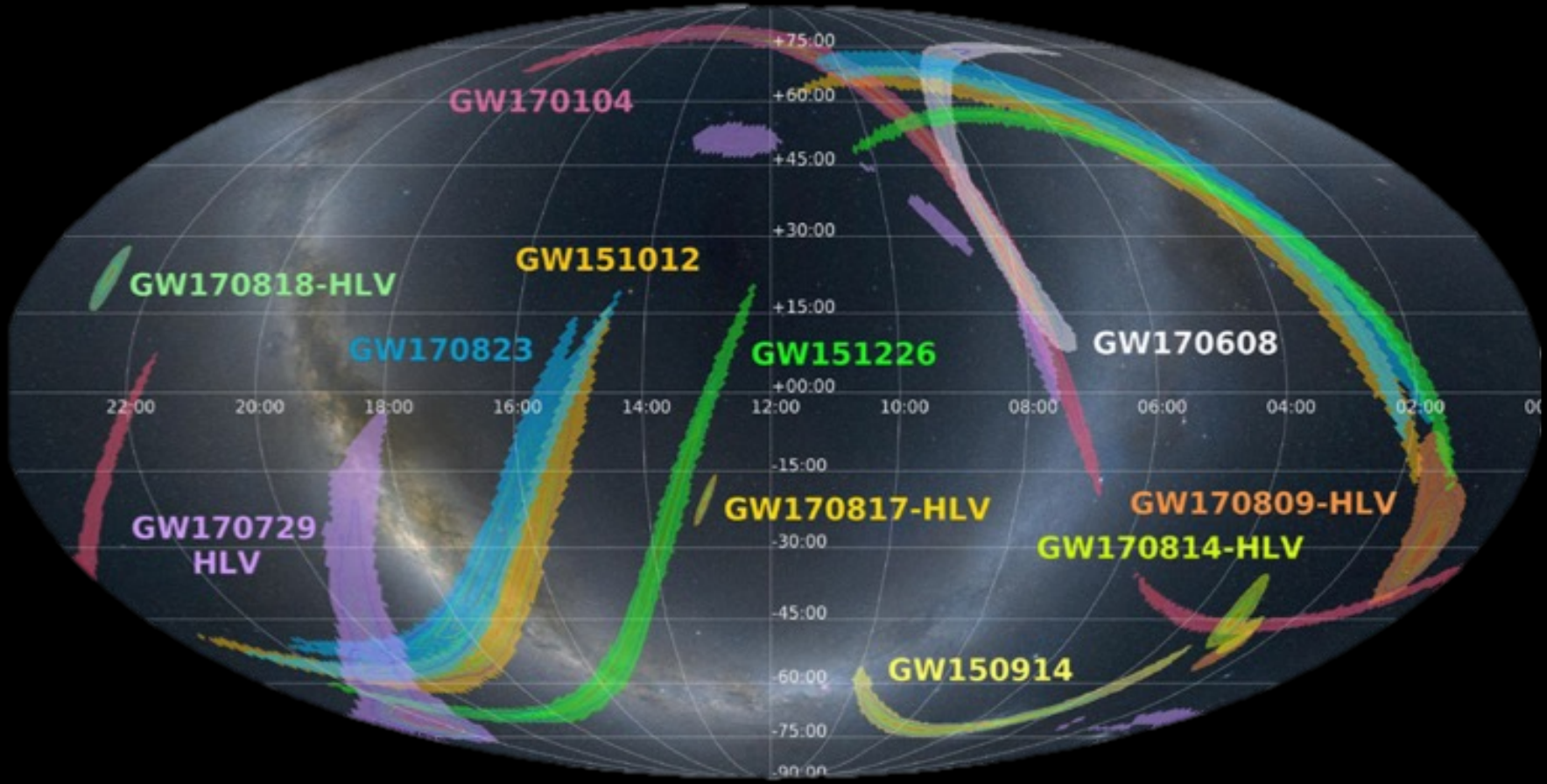
IceCube Collaboration/U.S. National Science Foundation)/ESO

IceCube Collaboration/U.S. National Science Foundation)/ESO


γ Optical
γ HE
ν Observed
Galactic Coord.
180°
120°
60°
l = 0°
-60°
-120°
-180°
0
1
2
3
4
Pre-Trial Significance (n·σ)

Multi-messenger astronomy





meV eV keV MeV GeV TeV PeV EeV

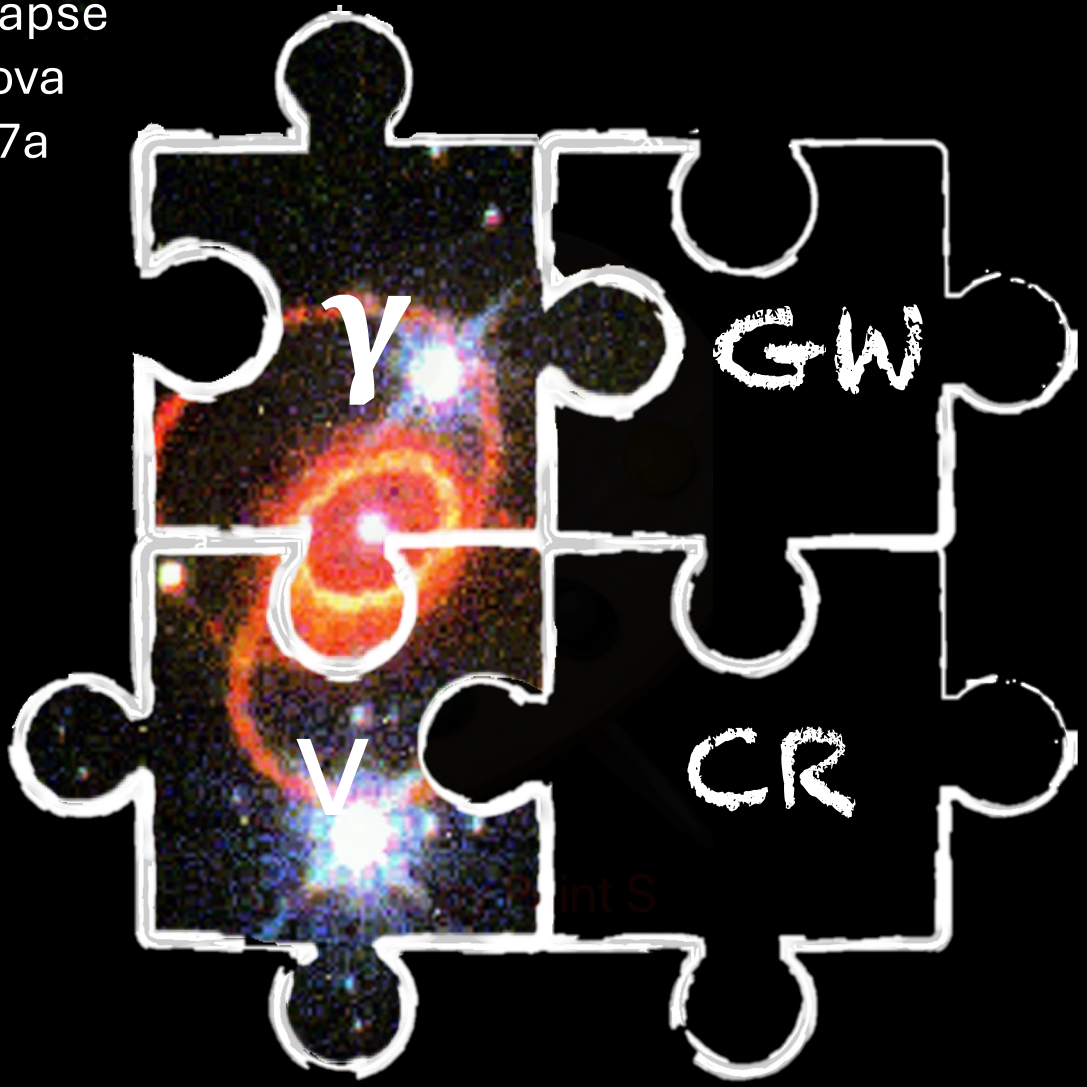
10^{-3} 10^{0} 10^{3} 10^{6} 10^{9} 10^{12} 10^{15} 10^{18}

Micro and radio waves | Infra red | Visible | UV | X-ray | Gamma ray | High-energy neutrinos | UHECR

$1\ \text{eV} = 1{,}602 \times 10^{-19}\ \text{J}$

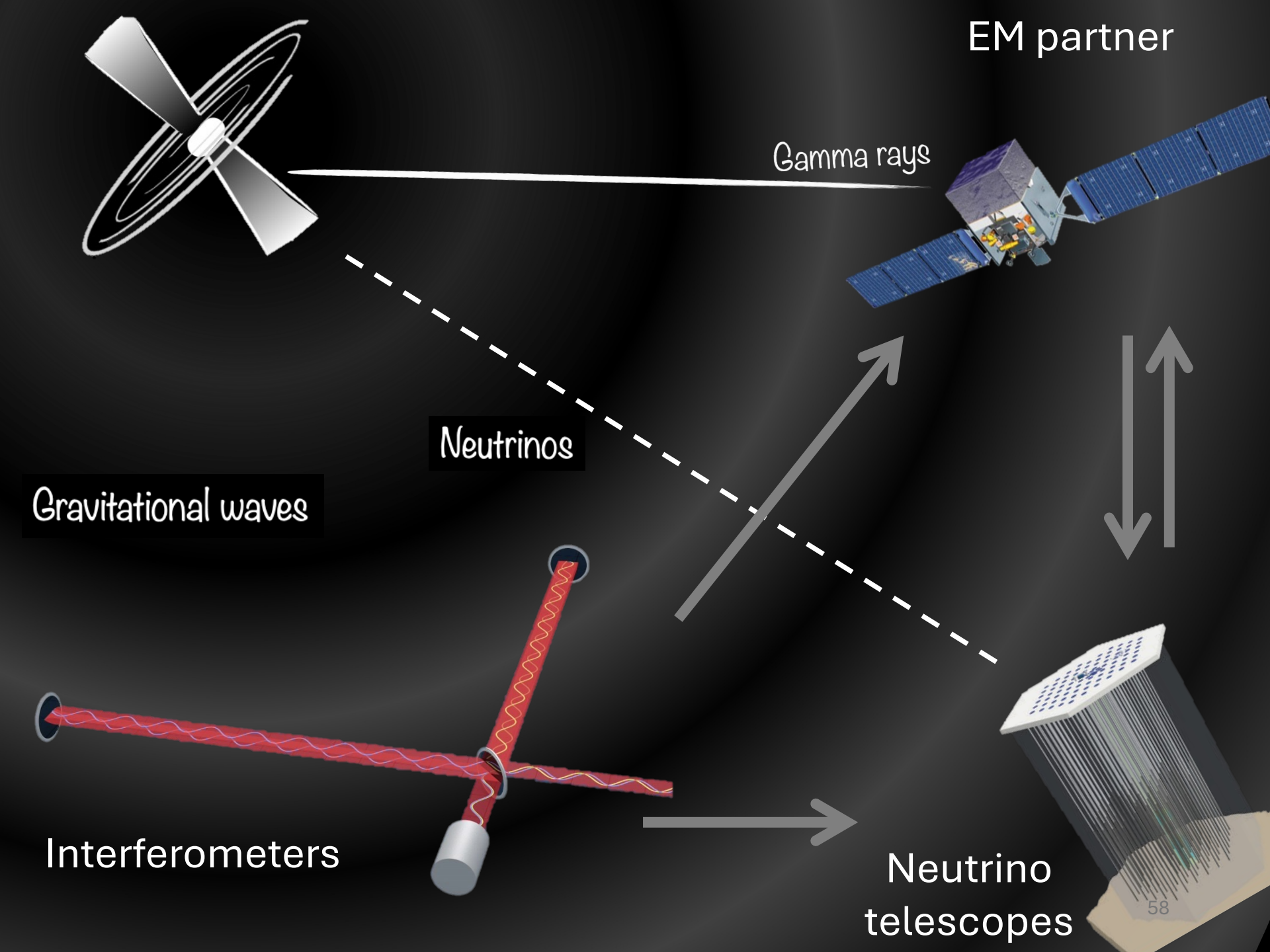
Multi-messenger astronomy

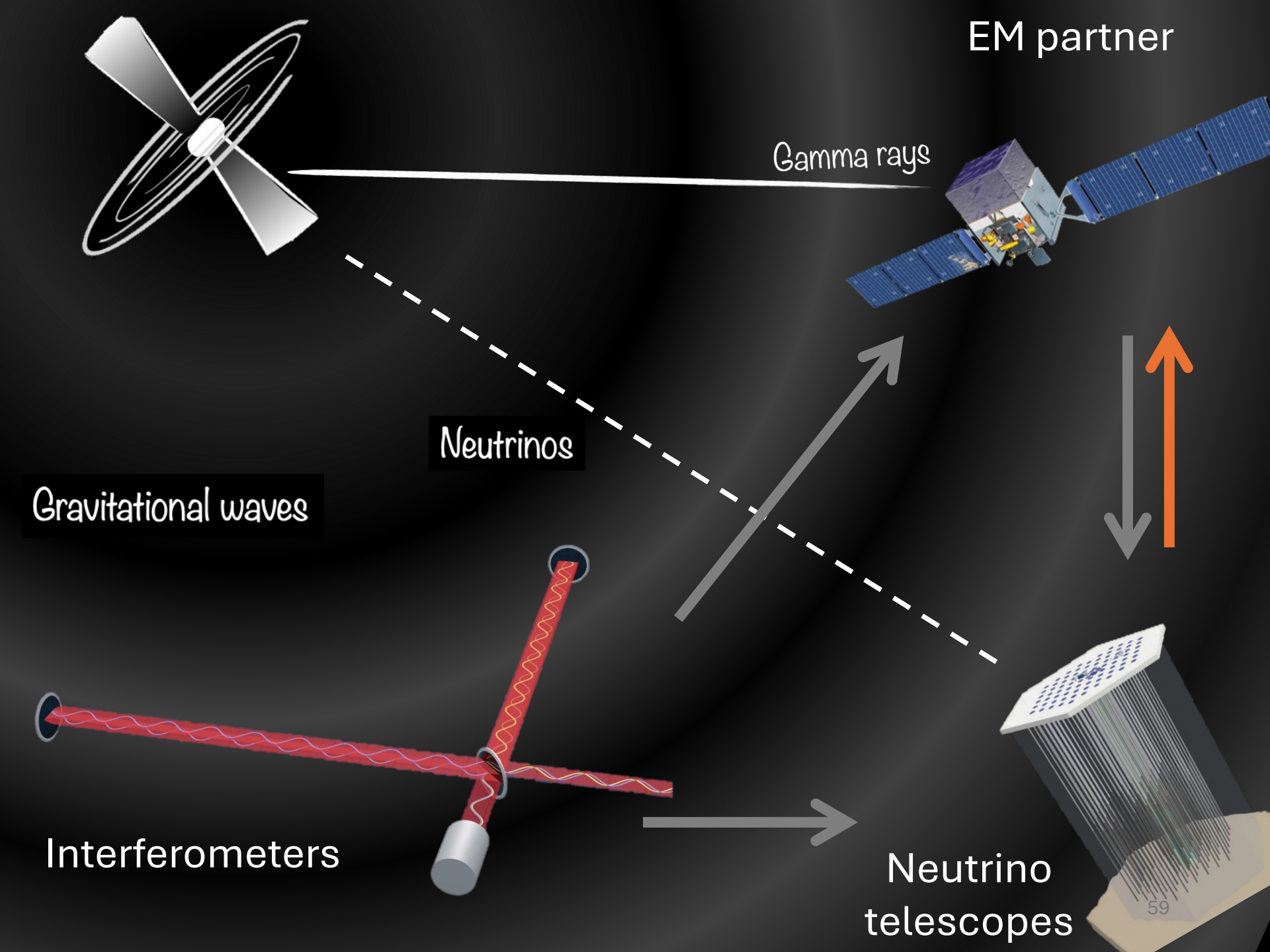
Core-collapse supernova SN1987a



Multi-messenger astronomy

Binary neutron star merger
GW170817 – GRB170817A


EM partner
Gamma rays
Neutrinos
Gravitational waves
Interferometers
Neutrino
telescopes

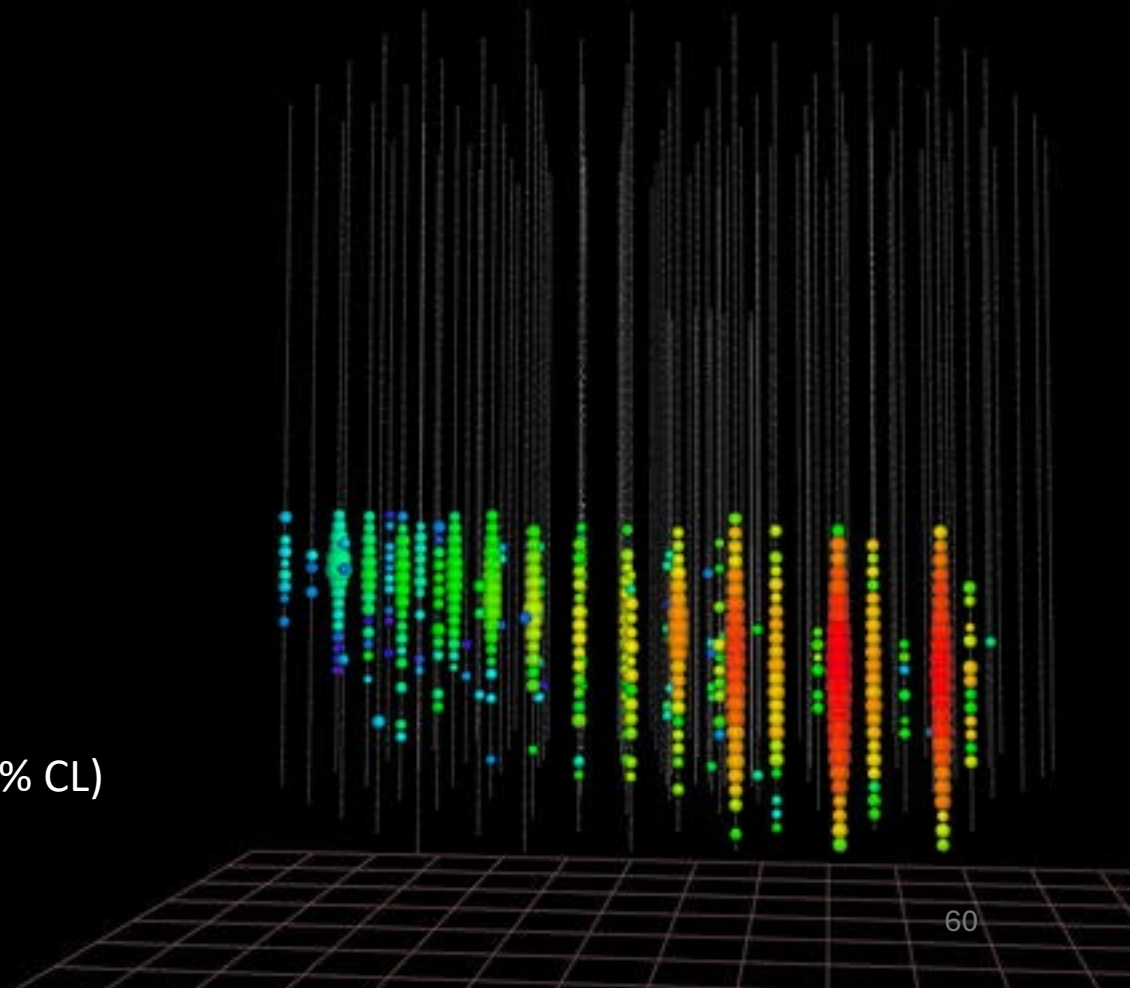

EM partner
Gamma rays
Neutrinos
Gravitational waves
Interferometers
Neutrino telescopes

https://arxiv.org/pdf/1807.08816

https://arxiv.org/abs/1807.08794

22 September 2017

IceCube-170922A

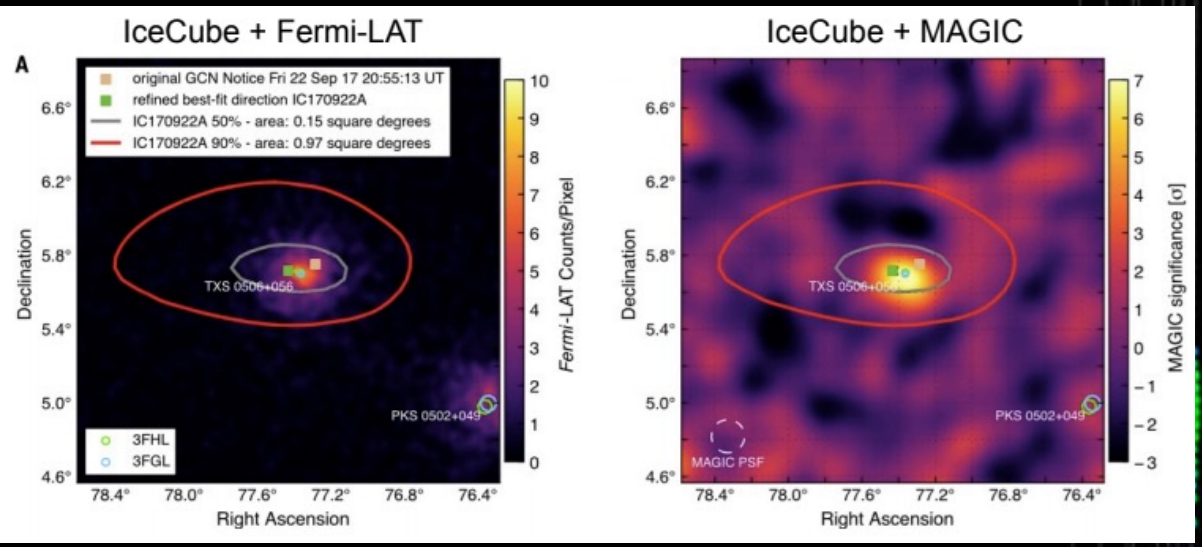


Neutrino Energy: 290 TeV (>180 TeV, 90% CL)
RA: 77.43° (-0.65°/+0.95° 90% CL)
Dec: 5.72° (-0.30°/+0.50° 90% CL)

22 Septembre 2017
IceCube-170922A

- Observation by Fermi of a known blazar TXS 0506+056, in a flaring state

- Detection by MAGIC of gamma rays > 400 GeV

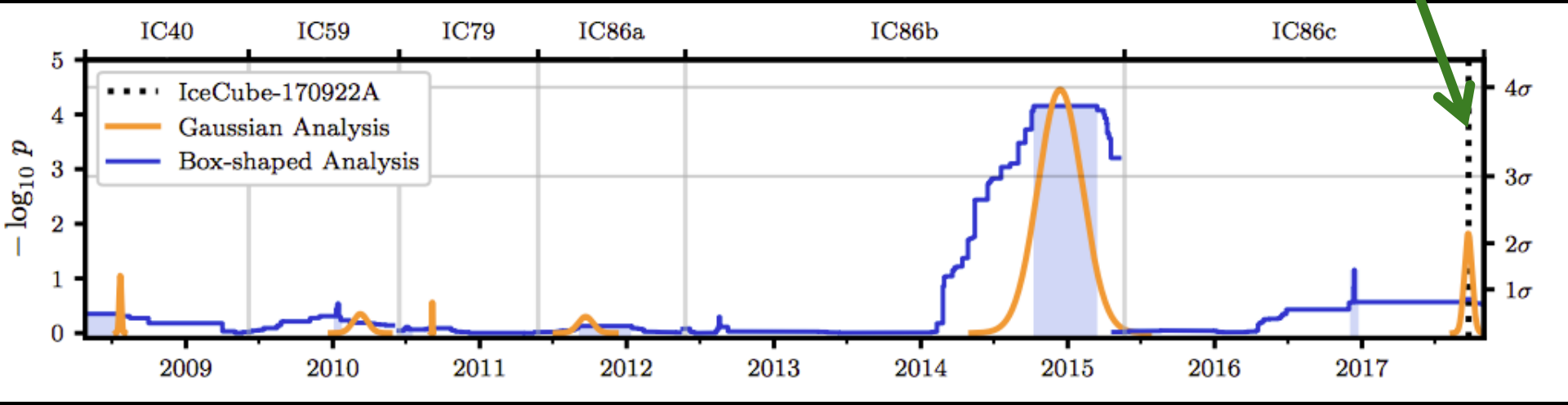


Significance for the overlap: 3σ

Neutrino Energy: 290 TeV (>180 TeV, 90% CL)
RA: 77.43° (-0.65°/+0.95° 90% CL)
Dec: 5.72° (-0.30°/+0.50° 90% CL)

Archival search

IceCube170922A



- Search for a point source in a time-dependent analysis in the direction of TXS
- Excess of 13 ± 5 neutrinos in 2014-2015 over 110 days
- Significance defined using similar searches in random directions : 3,5σ

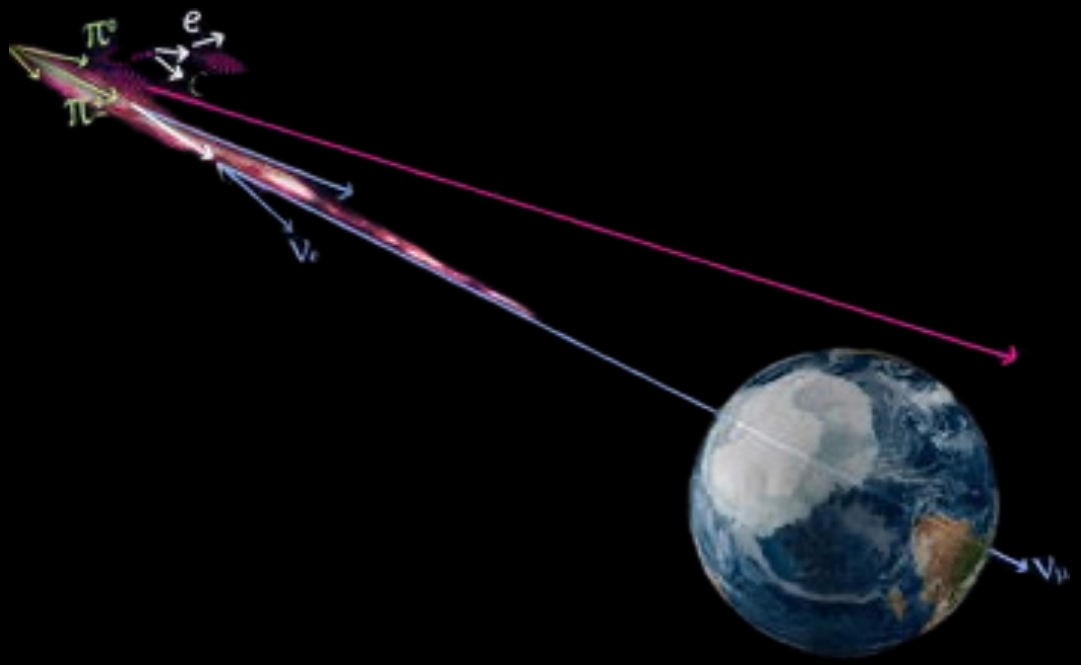
Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert

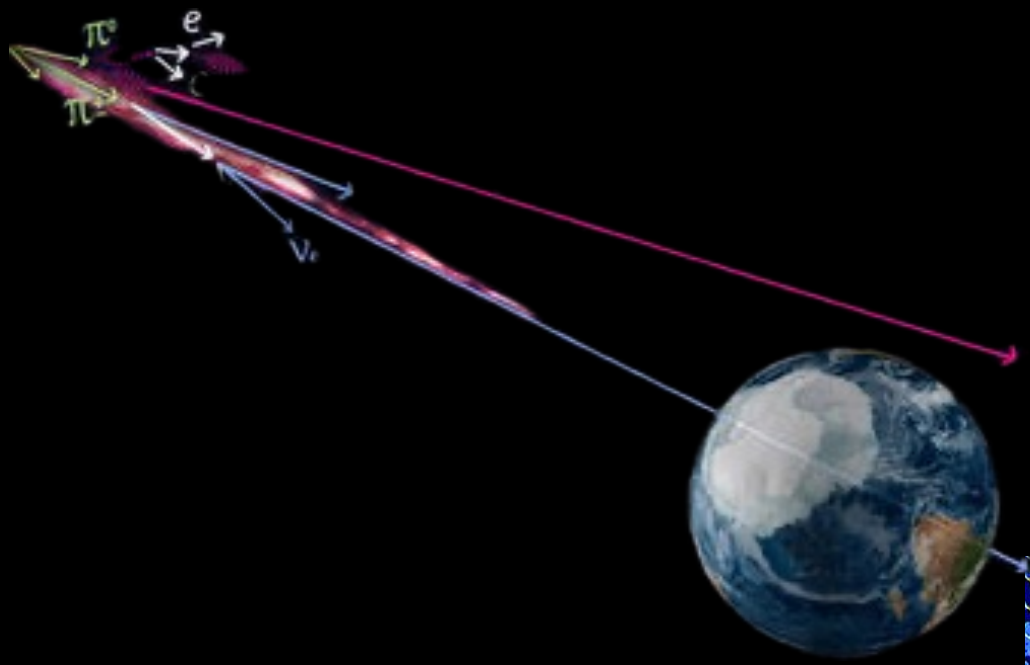
13 Jul. 2018

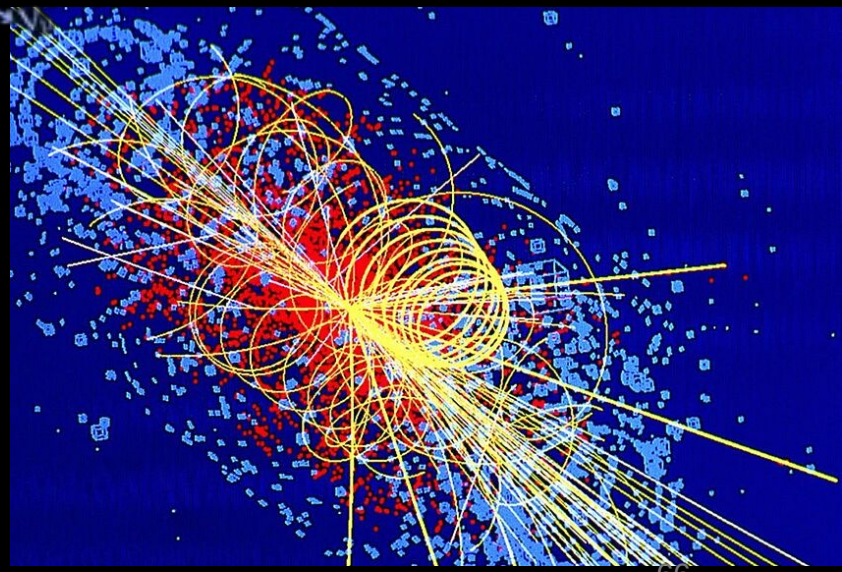
Can we learn more from neutrino astronomy?

Can we learn more from neutrino astronomy?



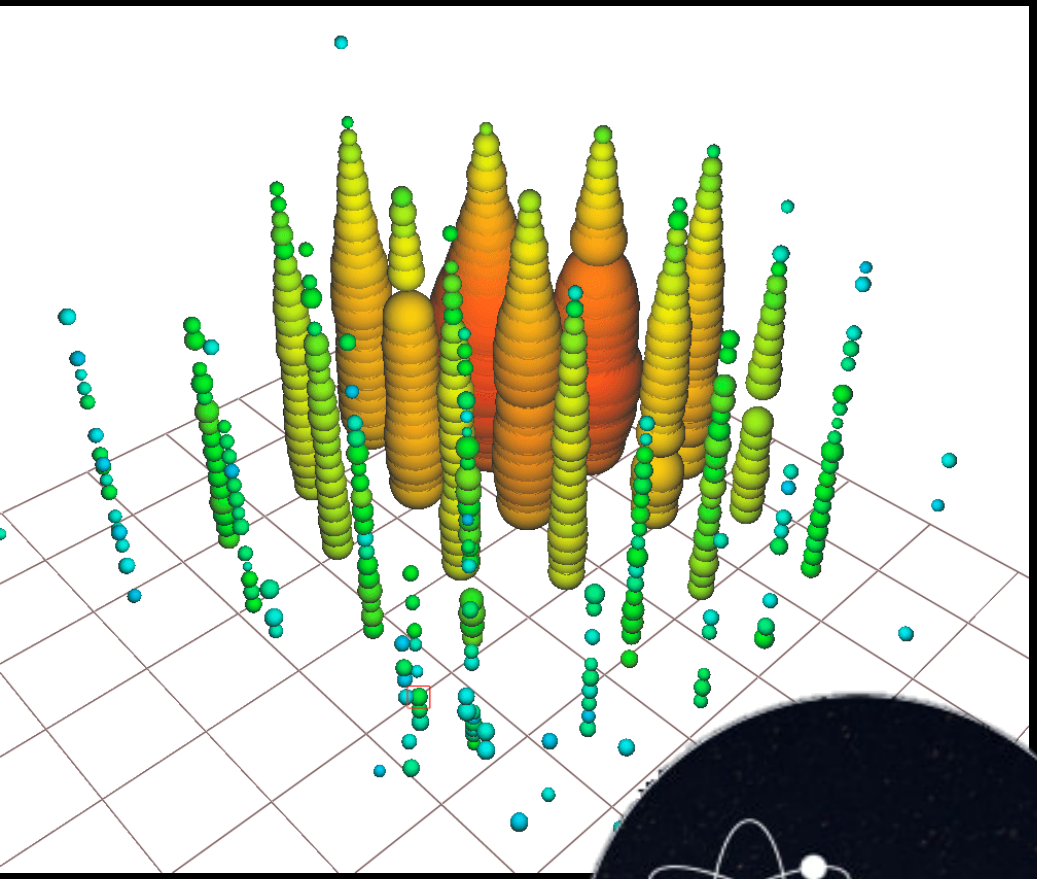
Can we learn more from neutrino astronomy?

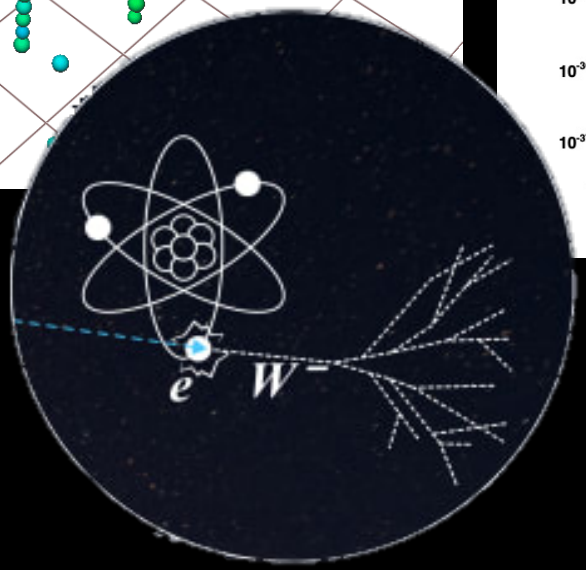


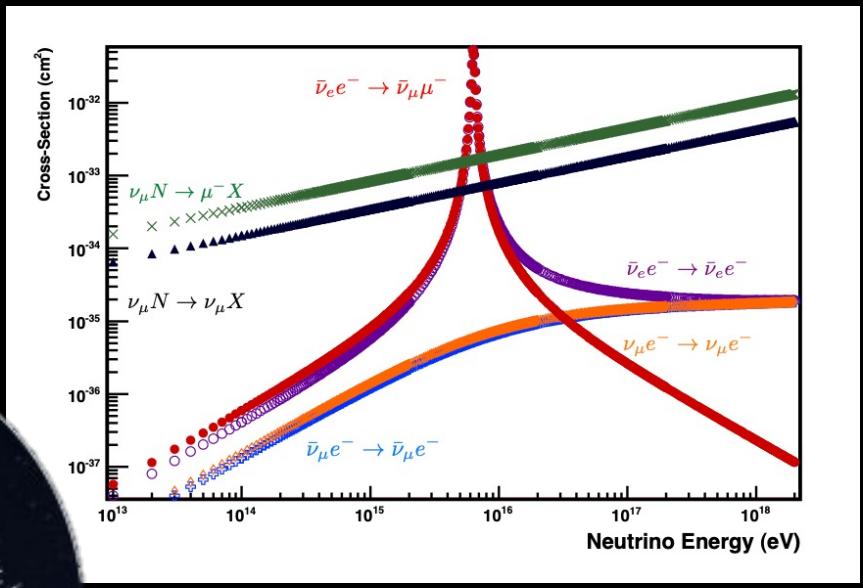


First observation of a Glashow resonance event

Detection of a shower with an energy of 6.05 ± 0.72 PeV

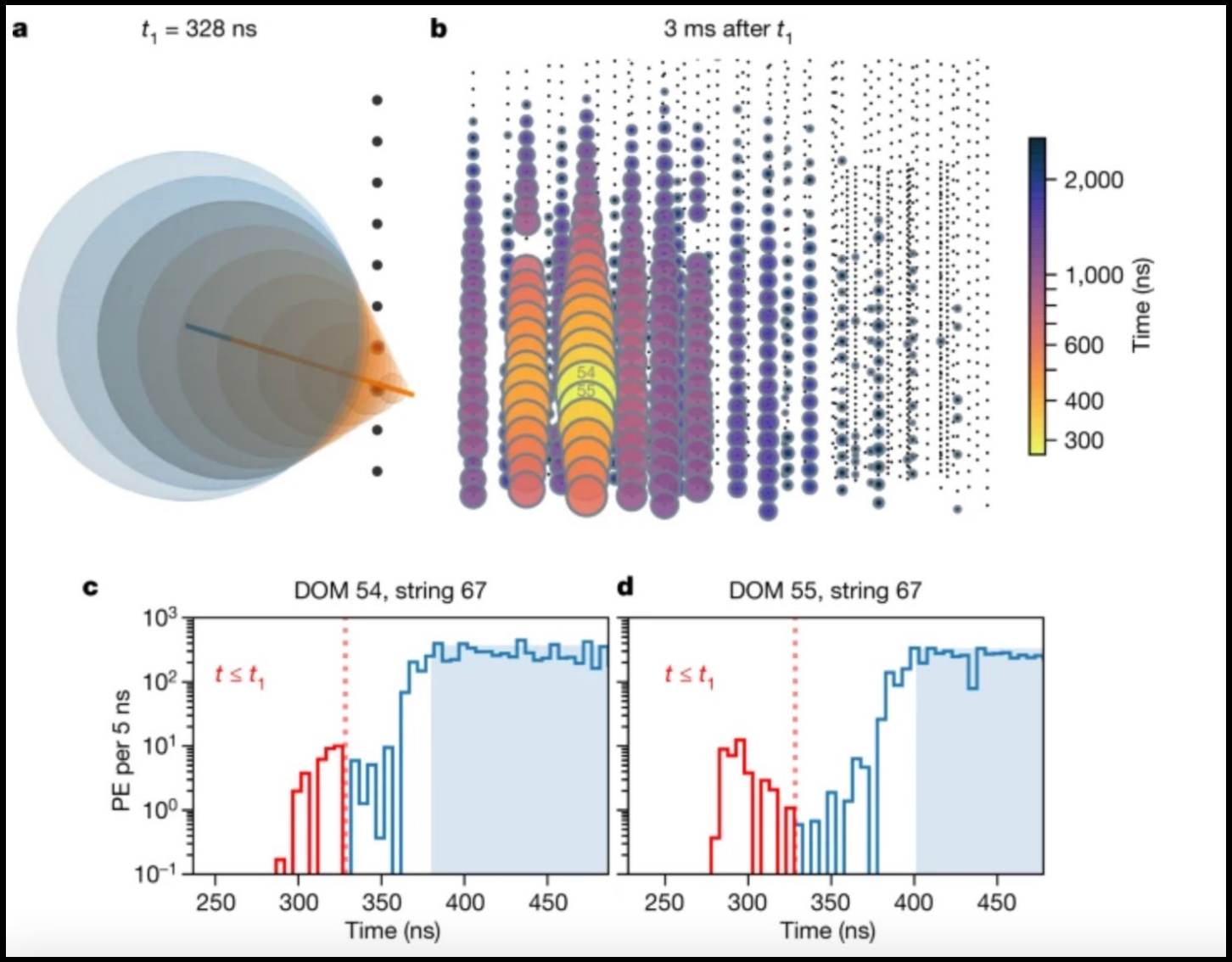






https://www.nature.com/articles/s41586-021-03256-1

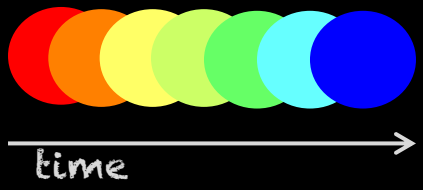
First observation of a Glashow resonance event

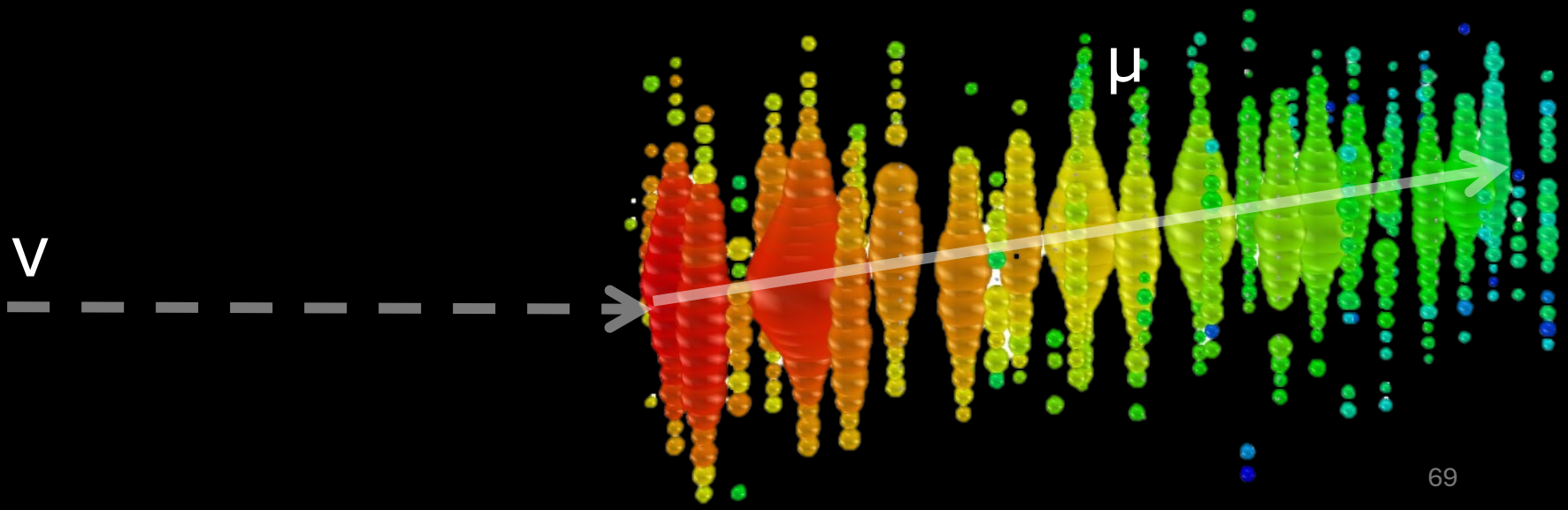


https://www.nature.com/articles/s41586-021-03256-1

Detection strategy

- Amount of light-> Energy
- Timing -> Direction
- Topology -> Flavor





Cascades + Tracks + Double cascades

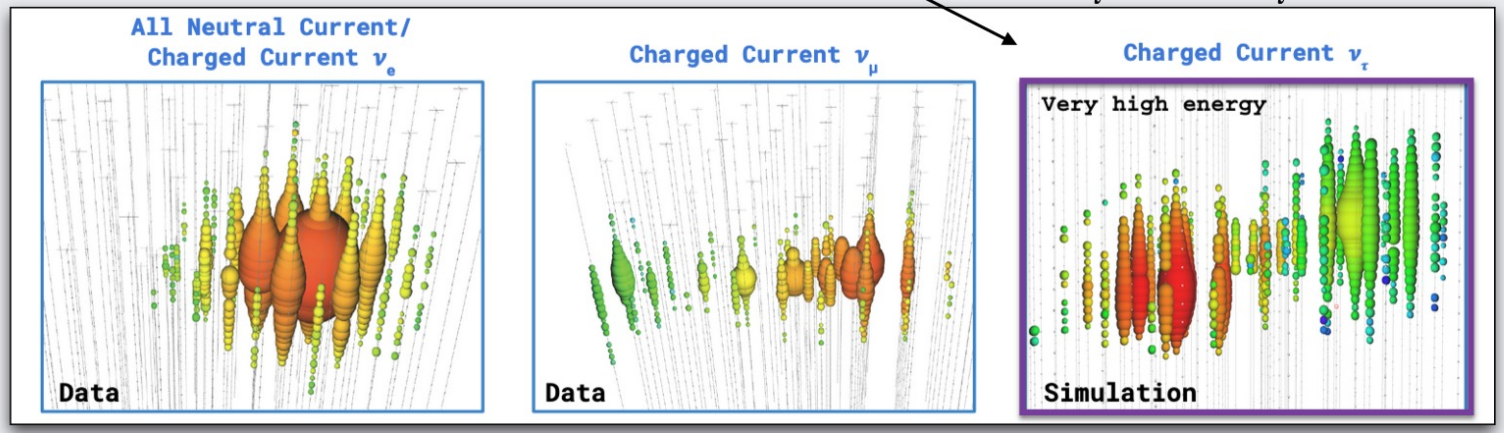
ν_τ^{astro}: Signatures

Spheres: DOMs
White: recorded no light
Color: recorded light
Size: light collected

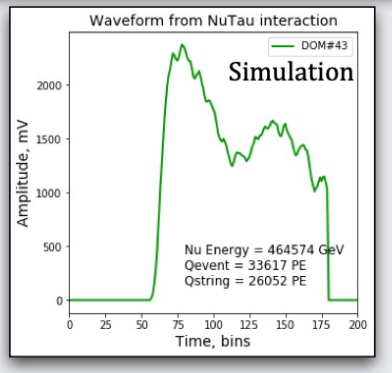
Color shows time information:
Early — Late

At high energies: "Double Bang."
Unfortunately, very rare.

$L_\tau \simeq 50\text{m} \cdot E_\tau\ /\text{PeV}$



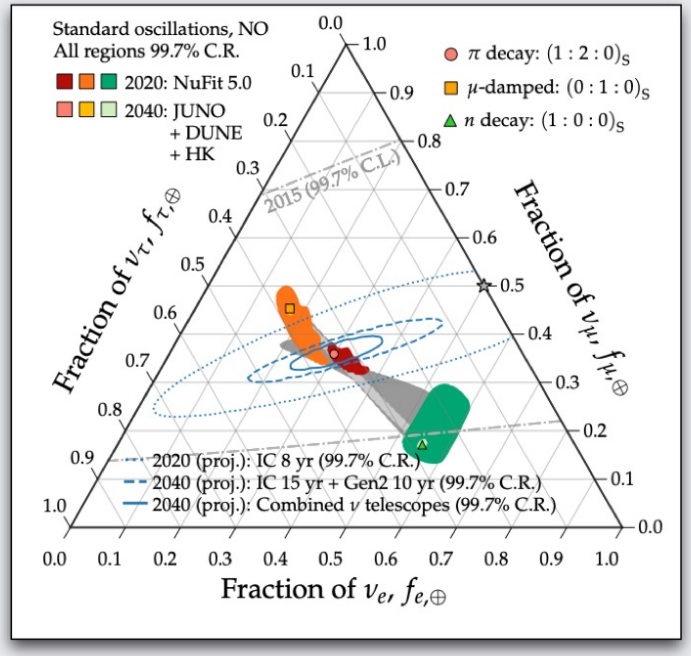
More flux at lower energies!
Look for subtler signature(s)
in one or more modules.



Cascades + Tracks + Double cascades

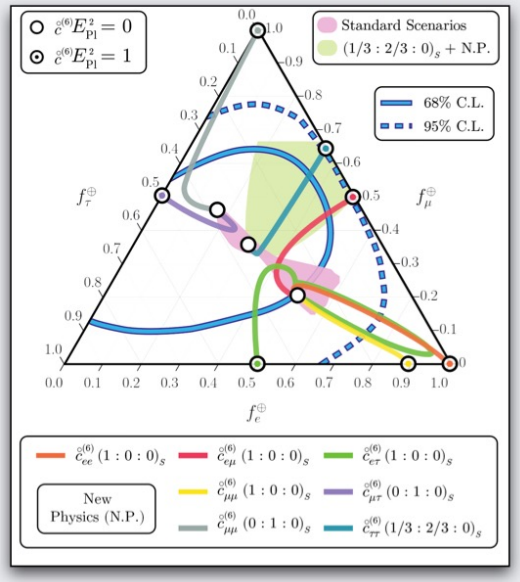
Importance of Flavor ID for ν^{astro}

At Earth, $\nu_e : \nu_\mu : \nu_\tau$ could tell us about the source…



https://arxiv.org/abs/2012.12893

…while strong deviations from 1:1:1 could mean new physics.



https://arxiv.org/abs/2111.04654v1

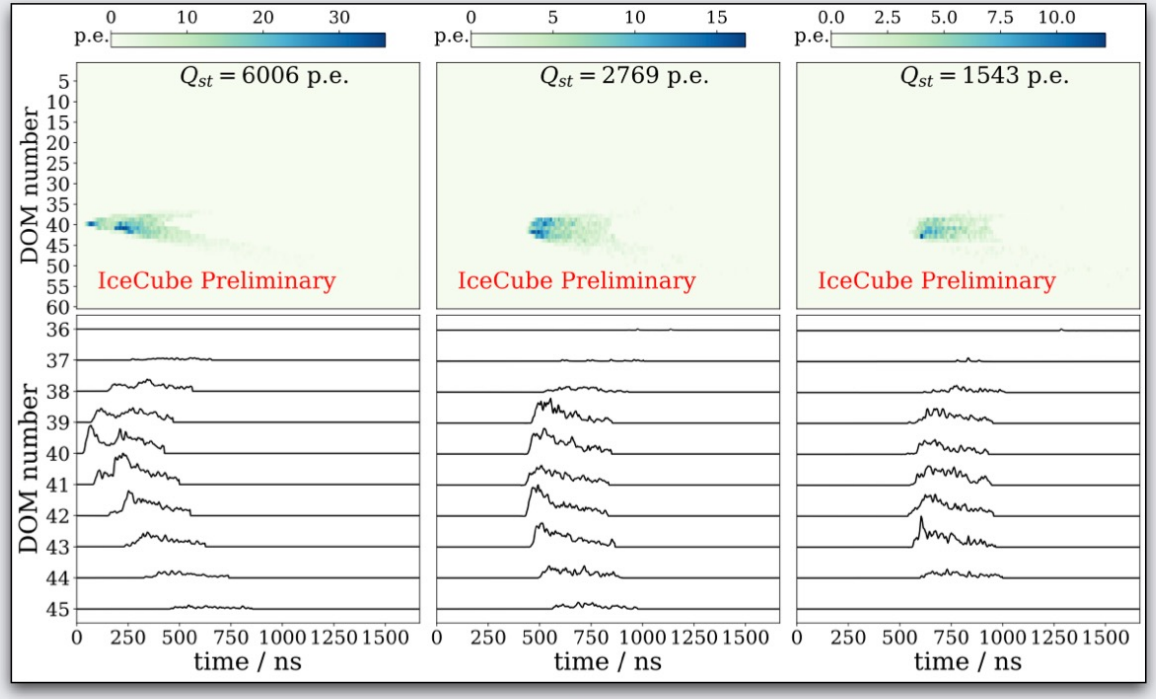
Example: Effect of quantum gravity.

For more examples, see Refs. 22-59 in IceCube, PRD 104, 022002 (2021).

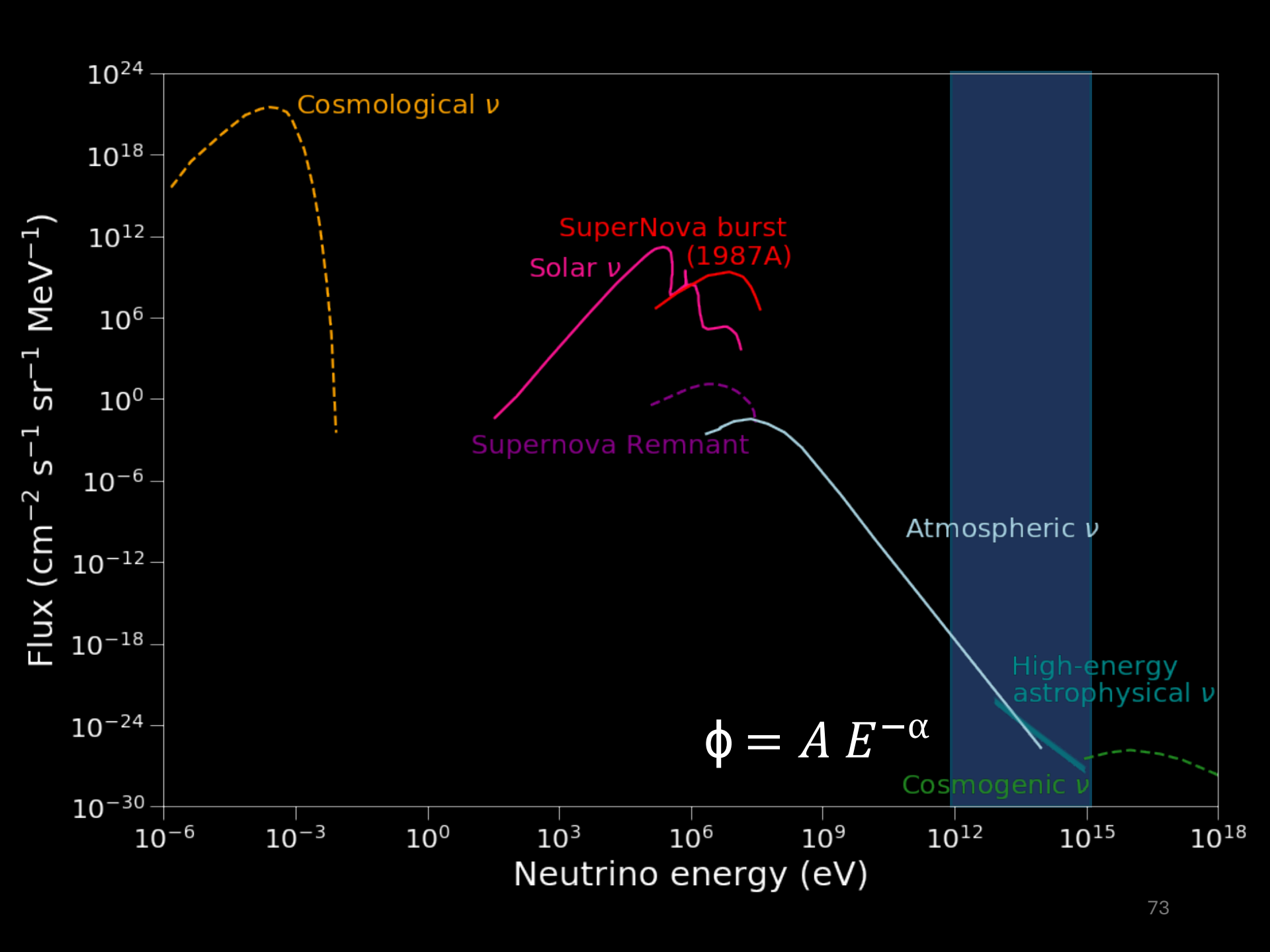
Cascades + Tracks + Double cascades

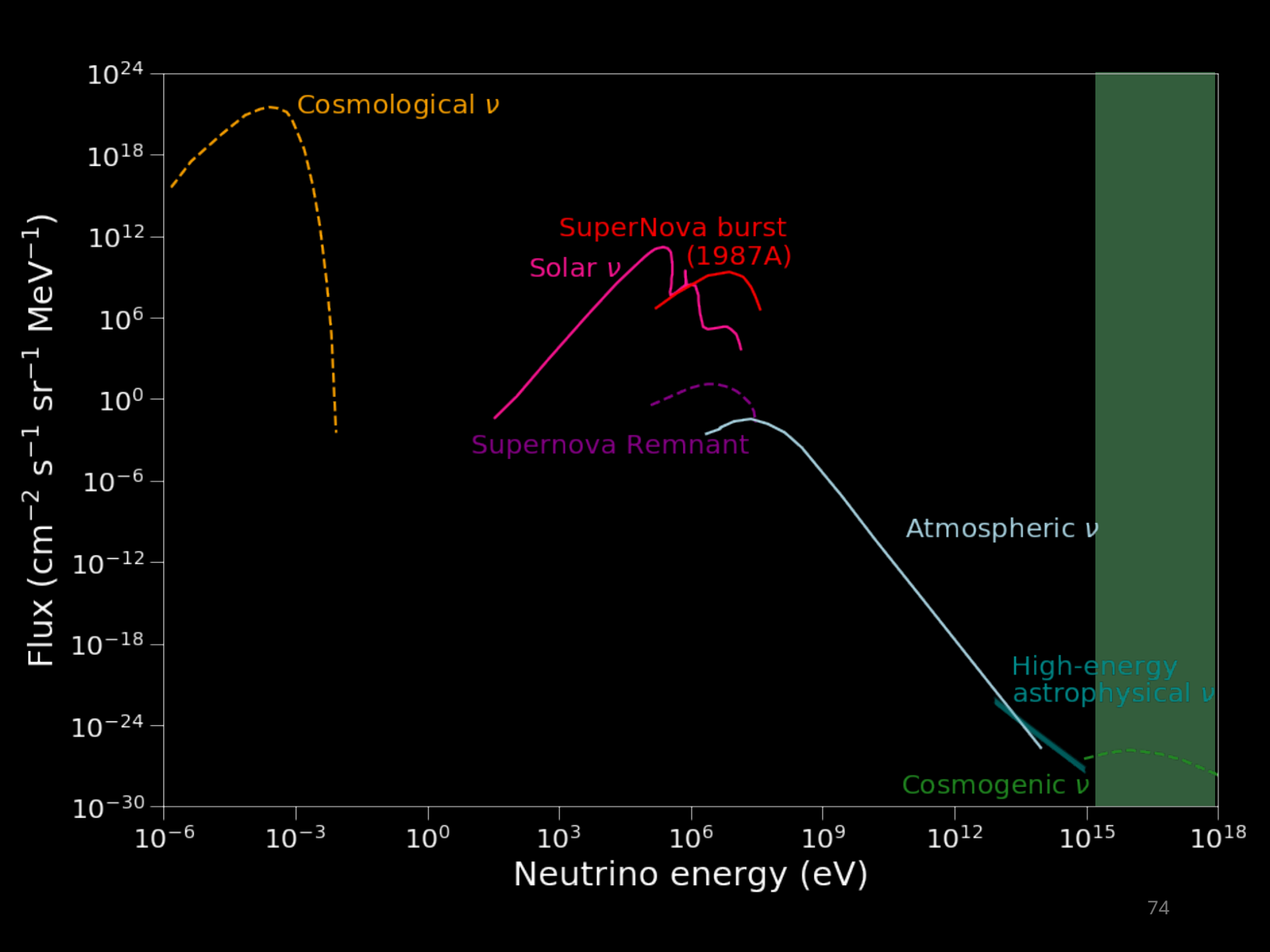
ν_τ^{astro} Candidate Event Pics

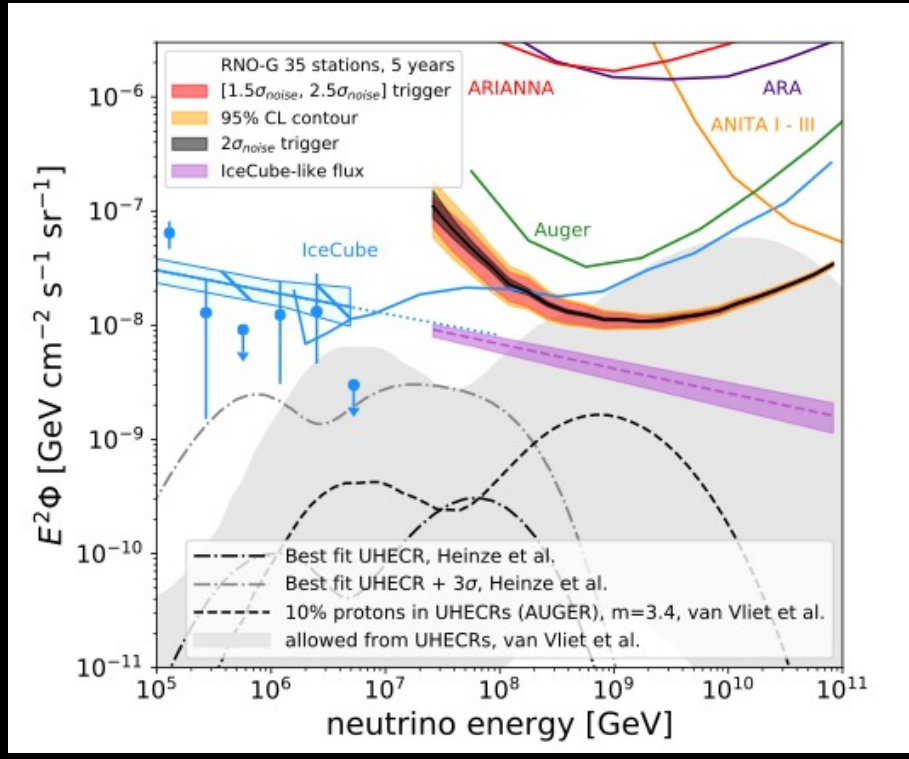
Here's "Scarlet Macaw," a new event:

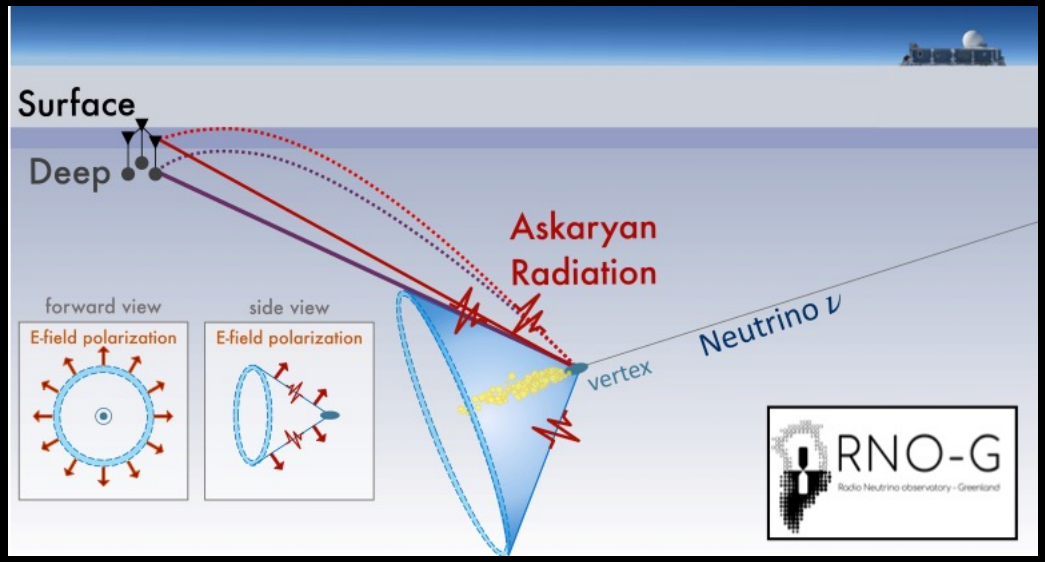


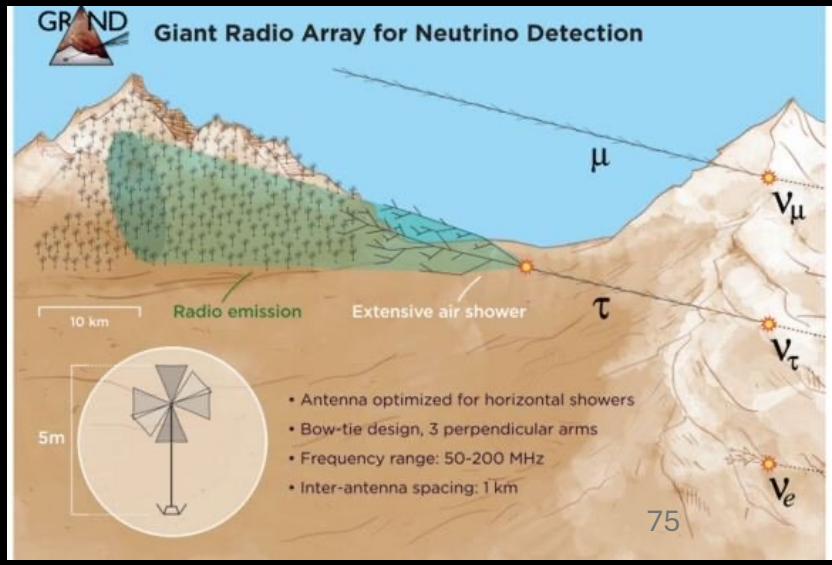
Clear ν_τ signature. Detected in 2019 (too recent for previous analyses to have seen).


Cosmological ν
SuperNova burst
(1987A)
Solar ν
Supernova Remnant
Atmospheric ν
High-energy
astrophysical ν
Cosmogenic ν
$\phi = A\,E^{-\alpha}$
Flux (cm^{-2} s^{-1} sr^{-1} MeV^{-1})
Neutrino energy (eV)
10^{24}
10^{18}
10^{12}
10^{6}
10^{0}
10^{-6}
10^{-12}
10^{-18}
10^{-24}
10^{-30}
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
10^{18}


Cosmological ν
SuperNova burst
(1987A)
Solar ν
Supernova Remnant
Atmospheric ν
High-energy
astrophysical ν
Cosmogenic ν
Flux (cm^{-2} s^{-1} sr^{-1} MeV^{-1})
Neutrino energy (eV)
10^{24}
10^{18}
10^{12}
10^{6}
10^{0}
10^{-6}
10^{-12}
10^{-18}
10^{-24}
10^{-30}
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
10^{18}

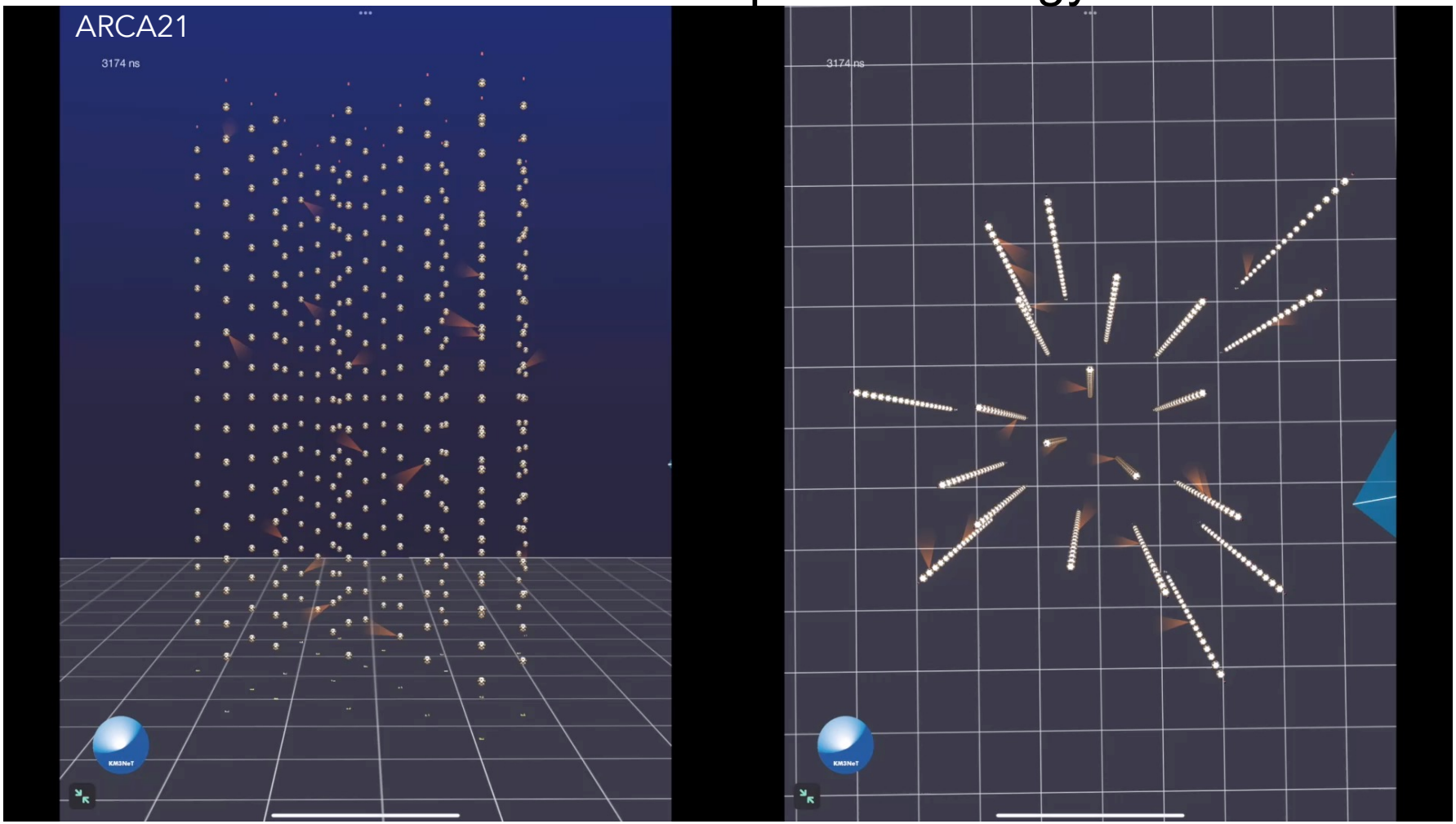

RNO-G 35 stations, 5 years
[1.5σ_{noise}, 2.5σ_{noise}] trigger
95% CL contour
2σ_{noise} trigger
IceCube-like flux
ARIANNA
ARA
ANITA I - III
Auger
IceCube
Best fit UHECR, Heinze et al.
Best fit UHECR + 3σ, Heinze et al.
10% protons in UHECRs (AUGER), m=3.4, van Vliet et al.
allowed from UHECRs, van Vliet et al.
$E^2\Phi$ [GeV cm^{-2} s^{-1} sr^{-1}]
neutrino energy [GeV]


Surface
Deep
Askaryan Radiation
forward view
E-field polarization
side view
E-field polarization
vertex
Neutrino ν
RNO-G
Radio Neutrino observatory - Greenland


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

The most energetic neutrino ever…

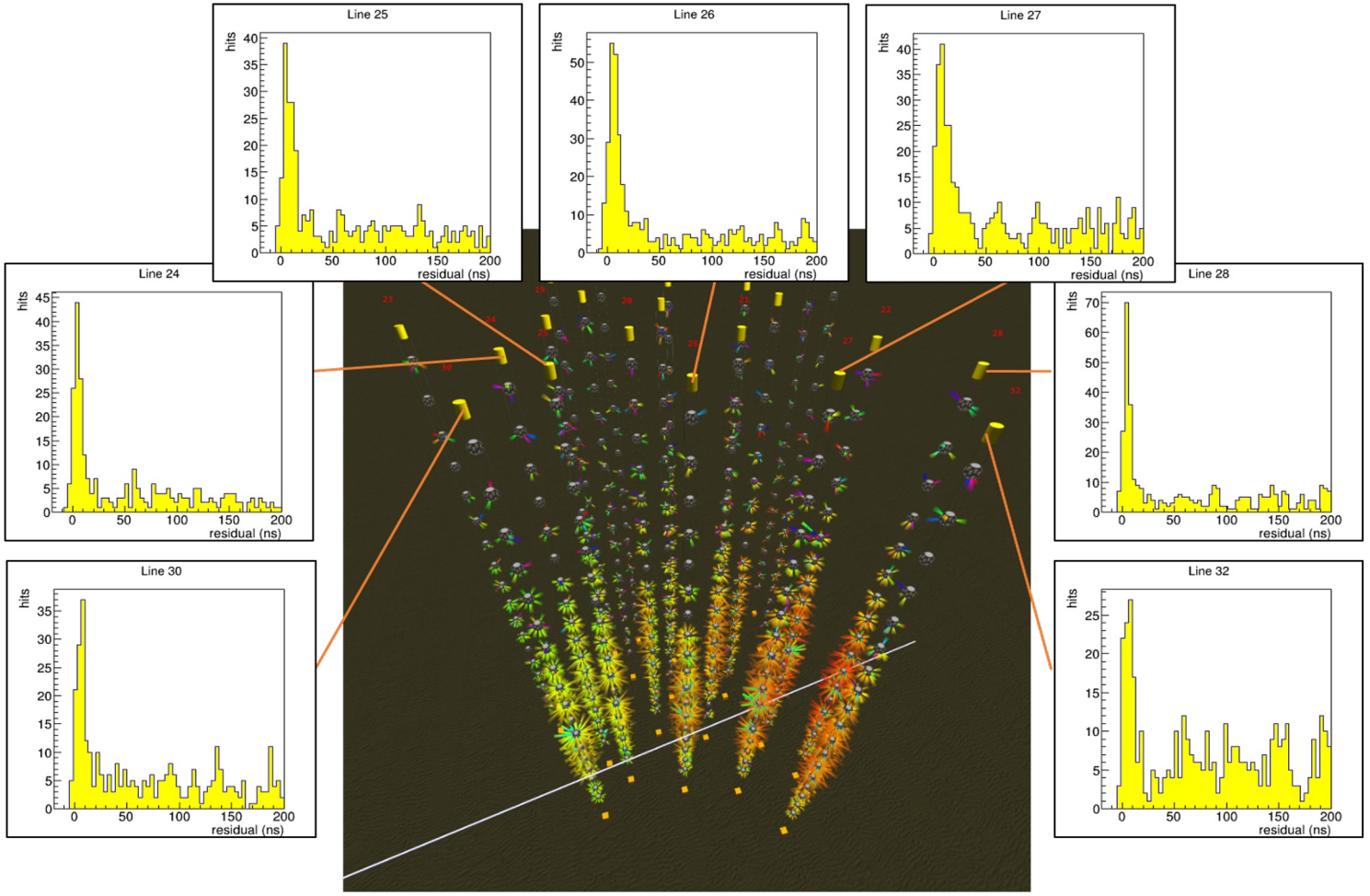
With a deposited energy above 10 PeV !



Possibly the first detection of a cosmogenic neutrino

The most energetic neutrino ever...

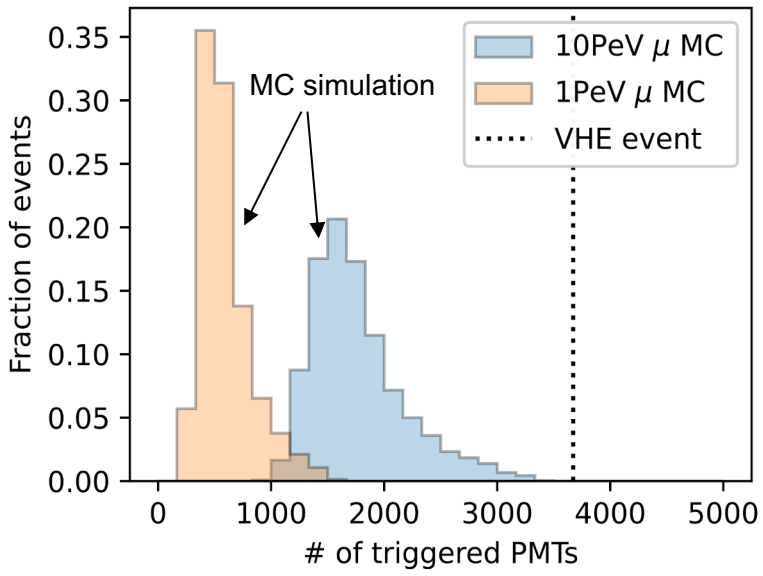
The event is well reconstructed as a track (cf. time residuals)
1° above the horizon

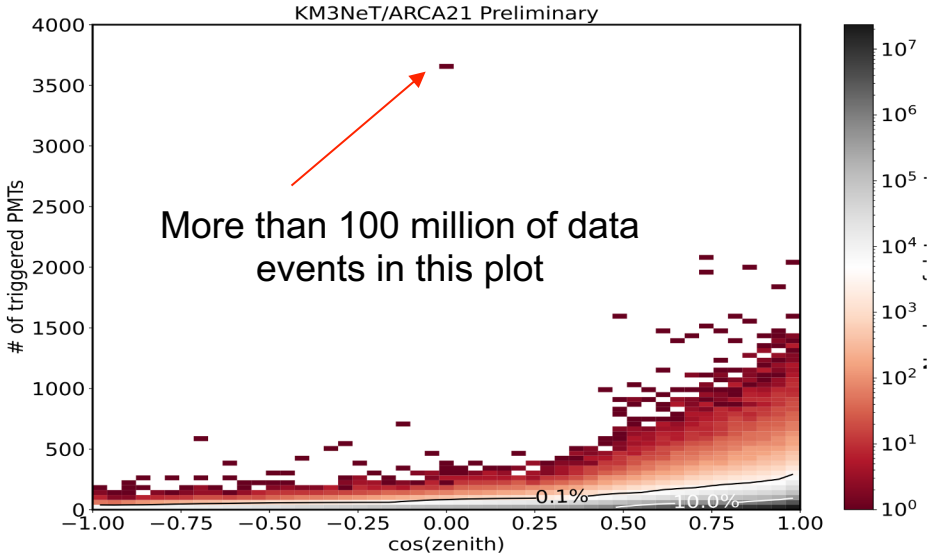


The most energetic neutrino ever...

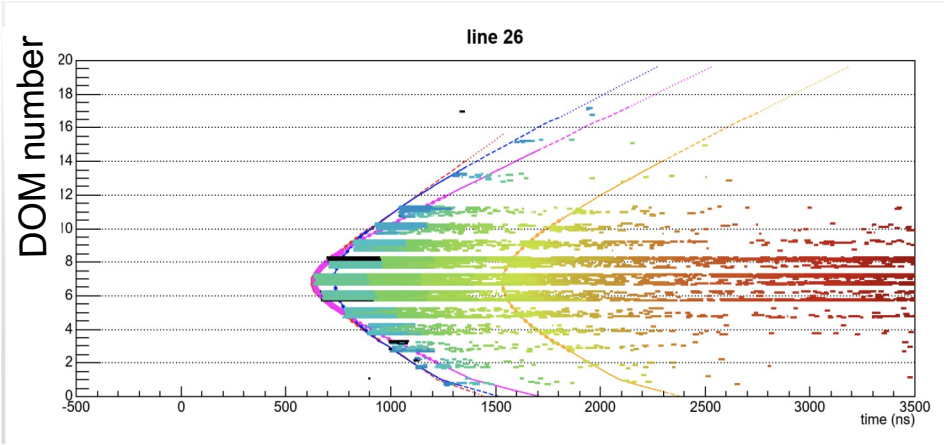
With a deposited energy above 10 PeV !

Huge amount of light detected -> 35% of the total number of PMTs were triggered





The most energetic neutrino ever...

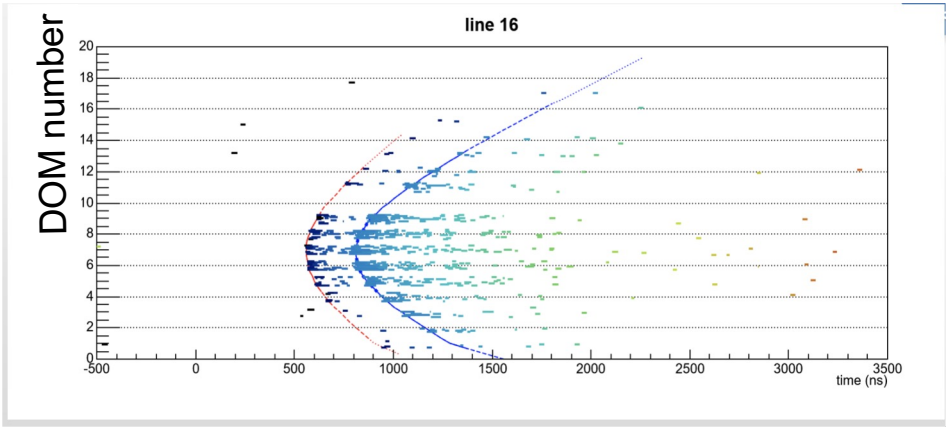


From the track and shower reconstructions

👇

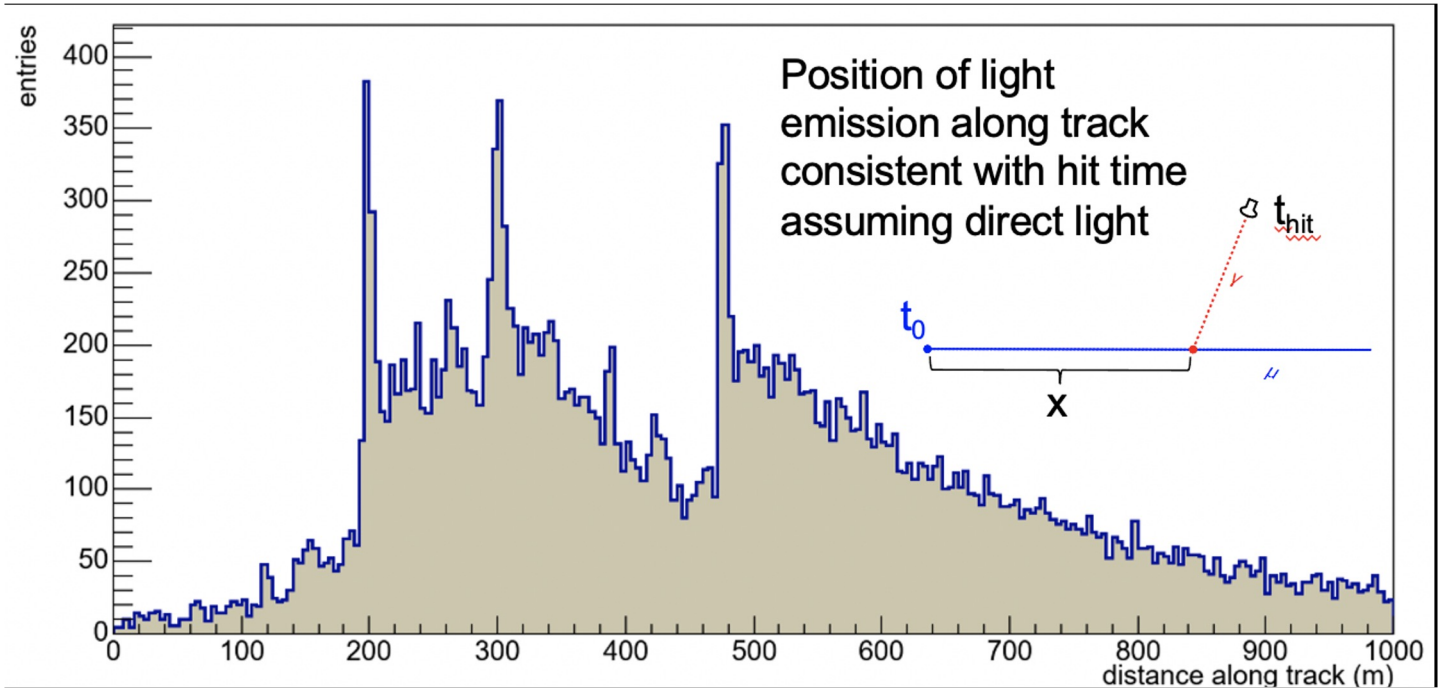
A muon track and three showers detected

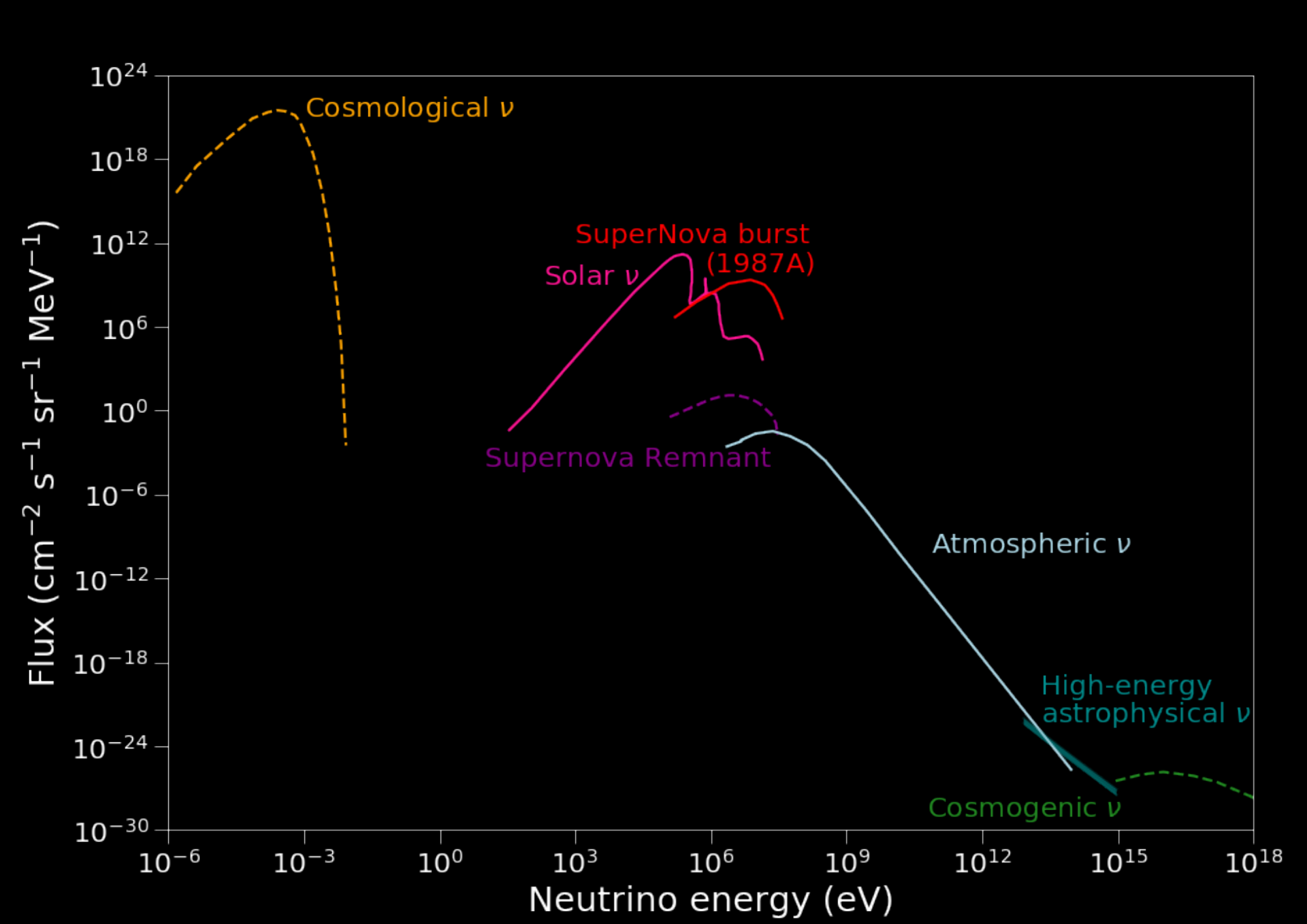
Hit times are fully consistent with photons from Cherenkov emission



The most energetic neutrino ever...

Hit times consistent with the emission from three points along the track -> stochastic light emission




Cosmological ν
SuperNova burst
(1987A)
Solar ν
Supernova Remnant
Atmospheric ν
High-energy
astrophysical ν
Cosmogenic ν
Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
Neutrino energy (eV)
10²⁴
10¹⁸
10¹²
10⁶
10⁰
10⁻⁶
10⁻¹²
10⁻¹⁸
10⁻²⁴
10⁻³⁰
10⁻⁶
10⁻³
10⁰
10³
10⁶
10⁹
10¹²
10¹⁵
10¹⁸

Impact of the environment

Impact of the environment

- Find an example and how to mitigate the impact

Impact of the environment

- Find an example and how to mitigate the impact
- Why is it an issue?

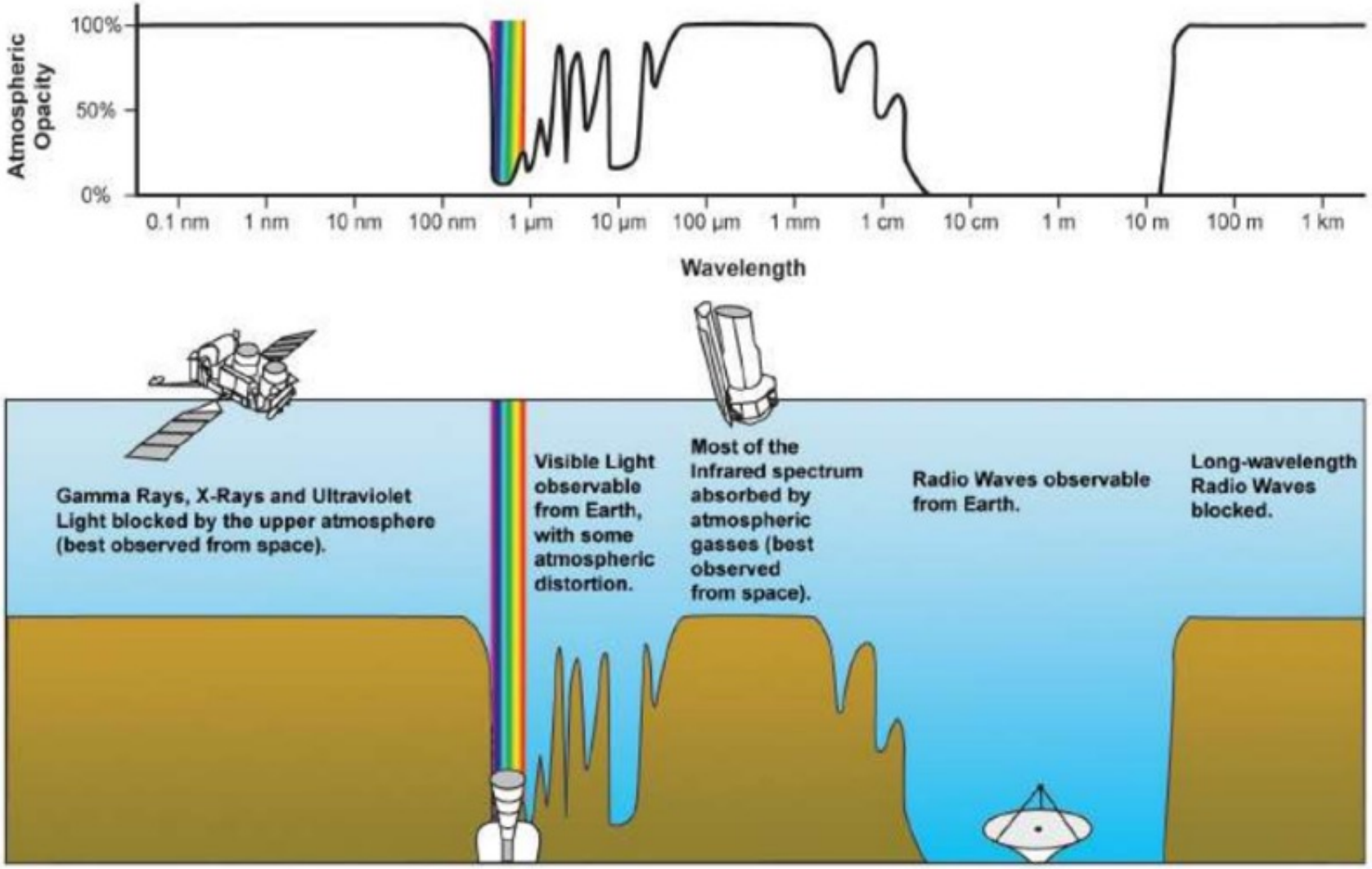


Fig. 1.3 The atmosphere opacity as a function of the wavelength is presented in the *upper part*. Opacity is represented by the percentage of electromagnetic radiation, which does not reach the ground. Space experiments are widely used to detect electromagnetic radiation that does not reach the Earth's surface. Note that the scale is in terms of the logarithm of the wavelength, so the energy scale decreases from left to right. Credit: NASA

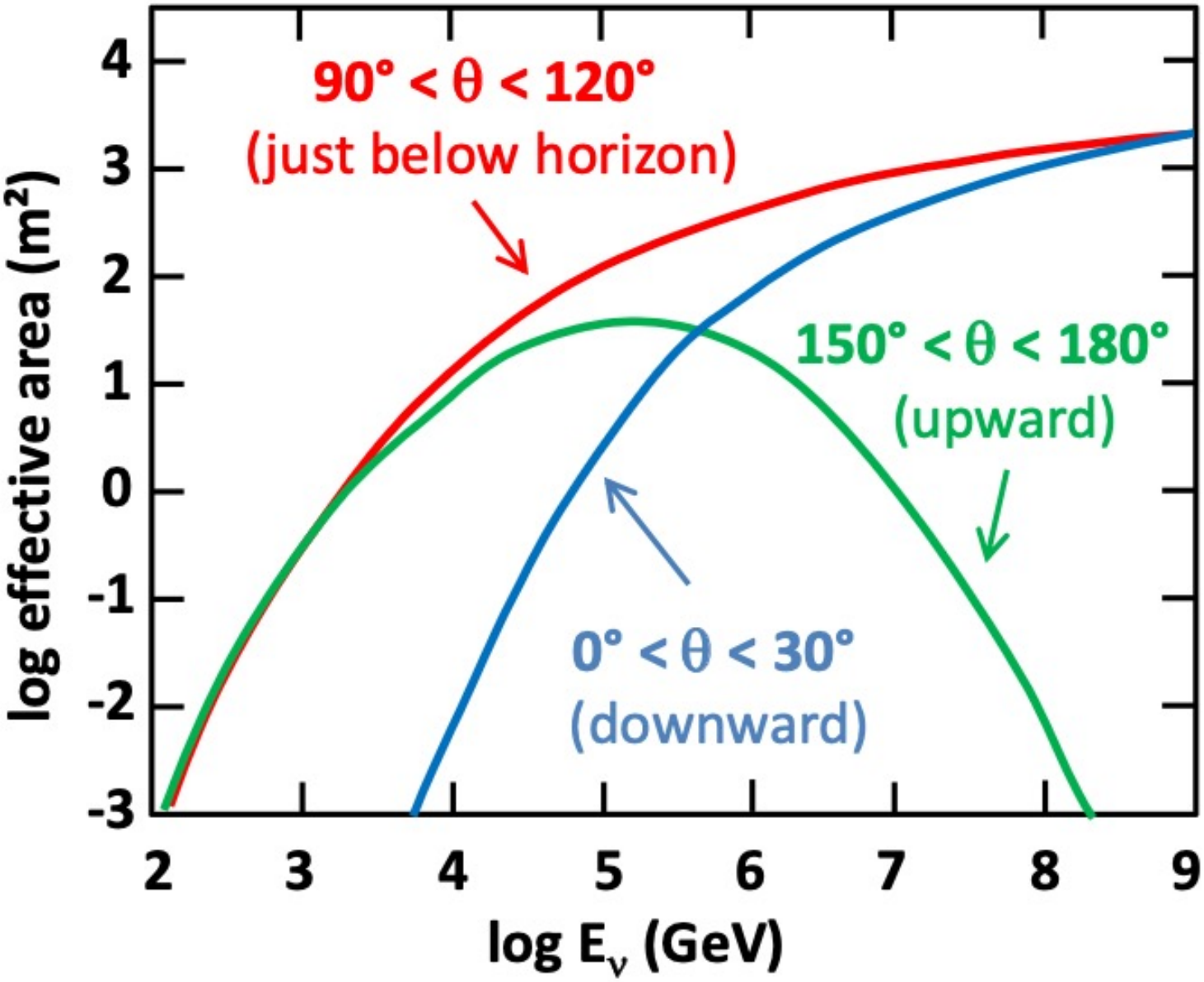
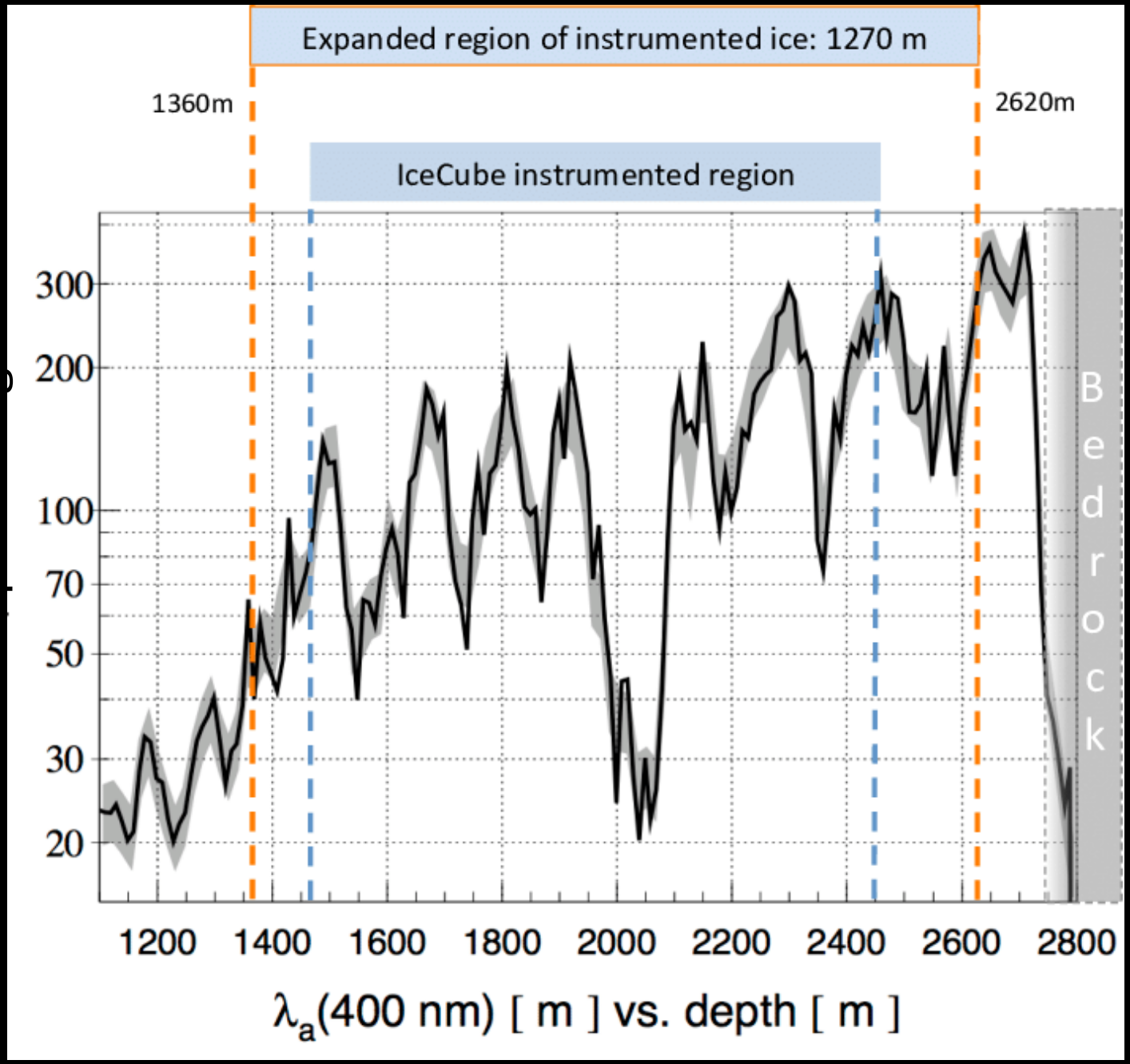
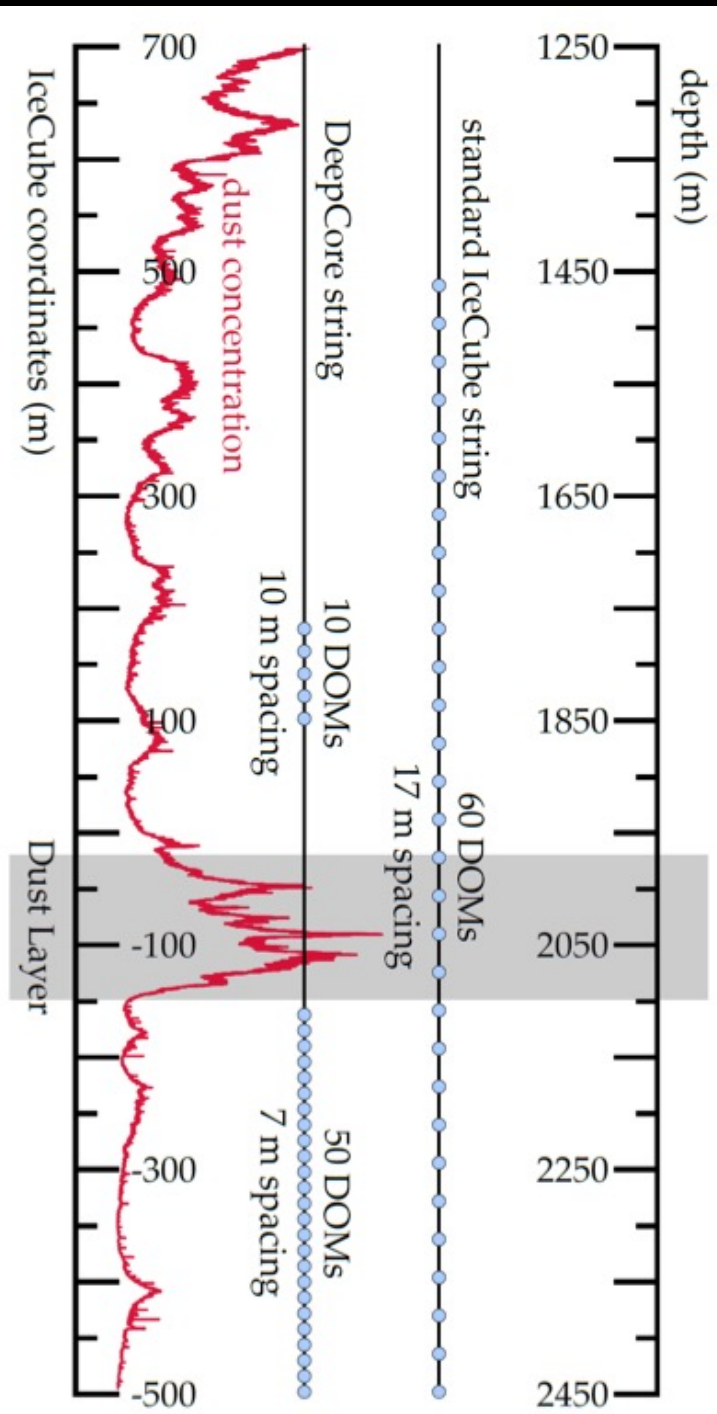
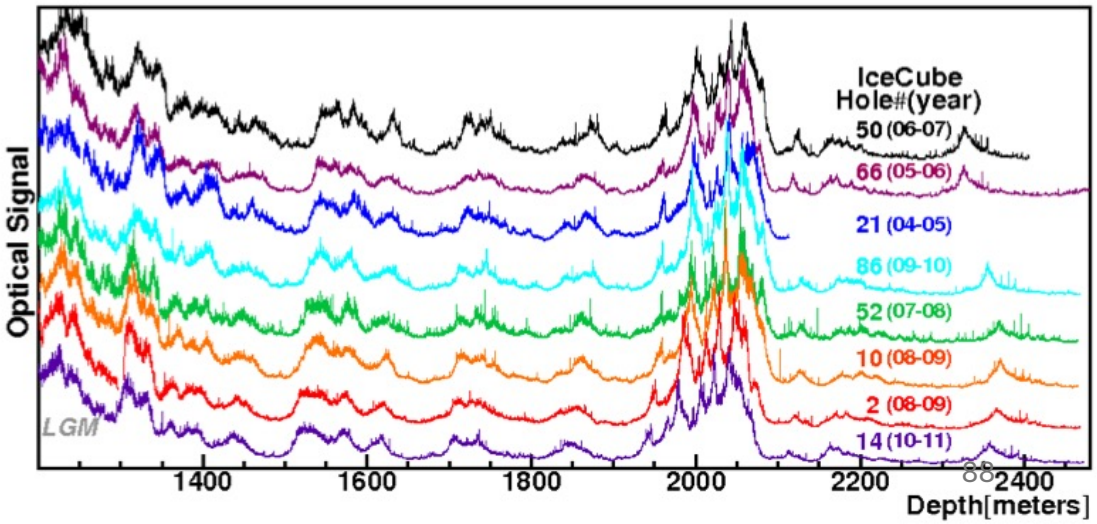


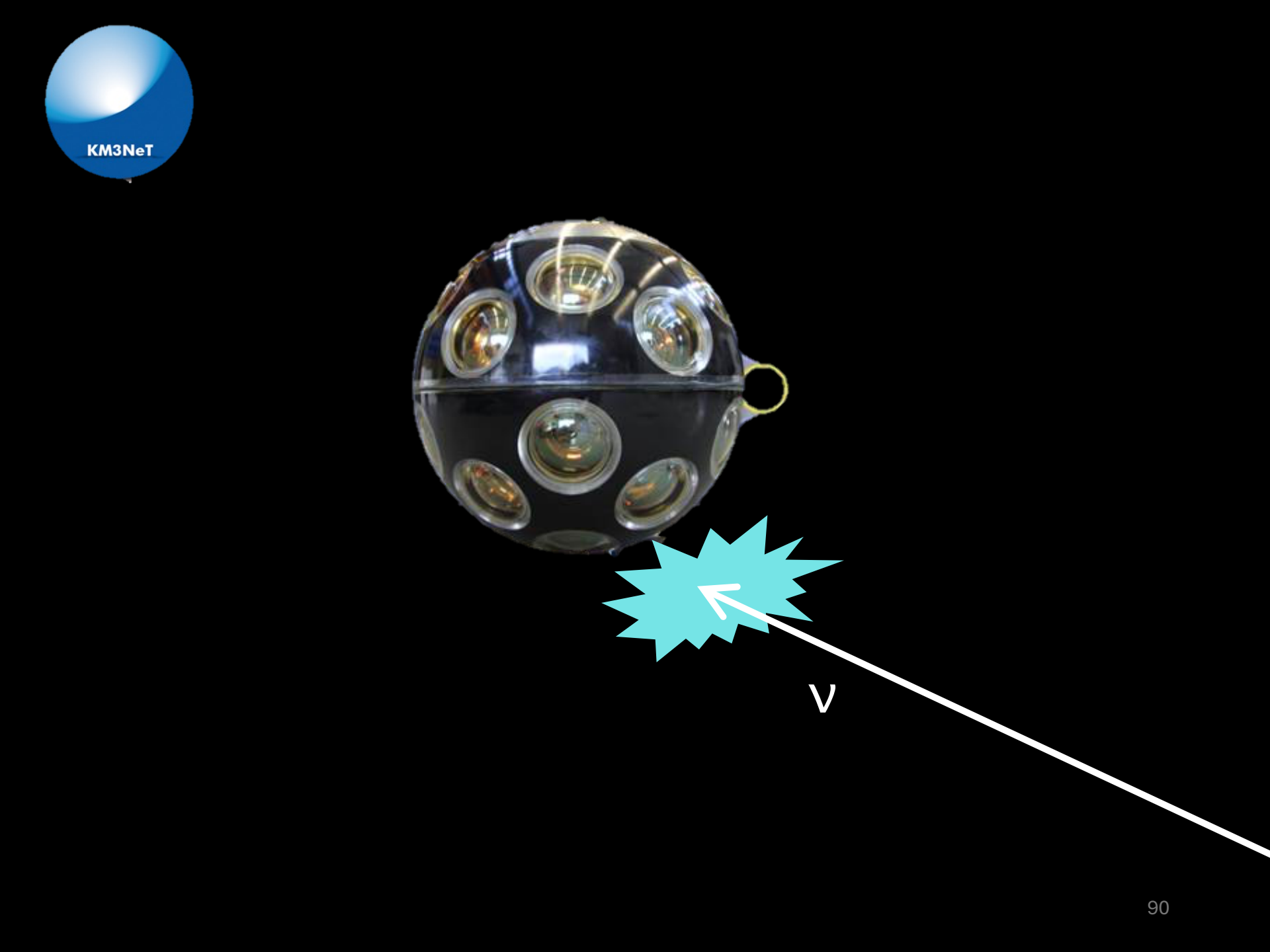
Figure 36.5: Effective $\overline{\nu}_\mu$ area for IceCube as an example of a cubic-kilometre NT, as a function of neutrino energy for three intervals of the zenith angle θ. The values shown here correspond to a specific event selection for point source searches.

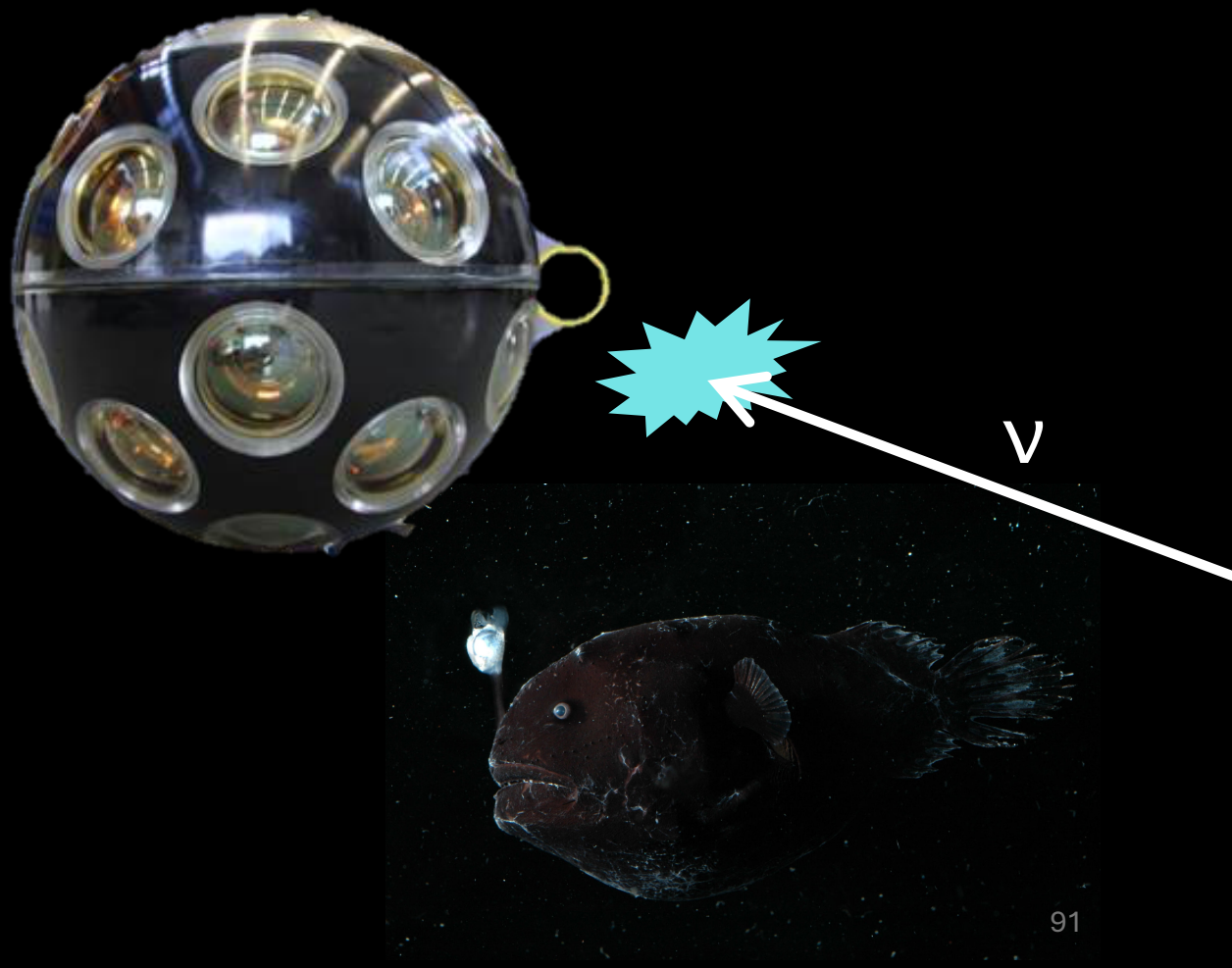

Expanded region of instrumented ice: 1270 m
1360m
2620m
IceCube instrumented region
300
200
100
70
50
30
20
Bedrock
1200
1400
1600
1800
2000
2200
2400
2600
2800
λa(400 nm) [m] vs. depth [m]


IceCube coordinates (m)
700
500
300
100
-100
-300
-500
dust concentration
DeepCore string
10 m spacing
10 DOMs
17 m spacing
50 DOMs
7 m spacing
standard IceCube string
60 DOMs
depth (m)
1250
1450
1650
1850
2050
2250
2450
Dust Layer

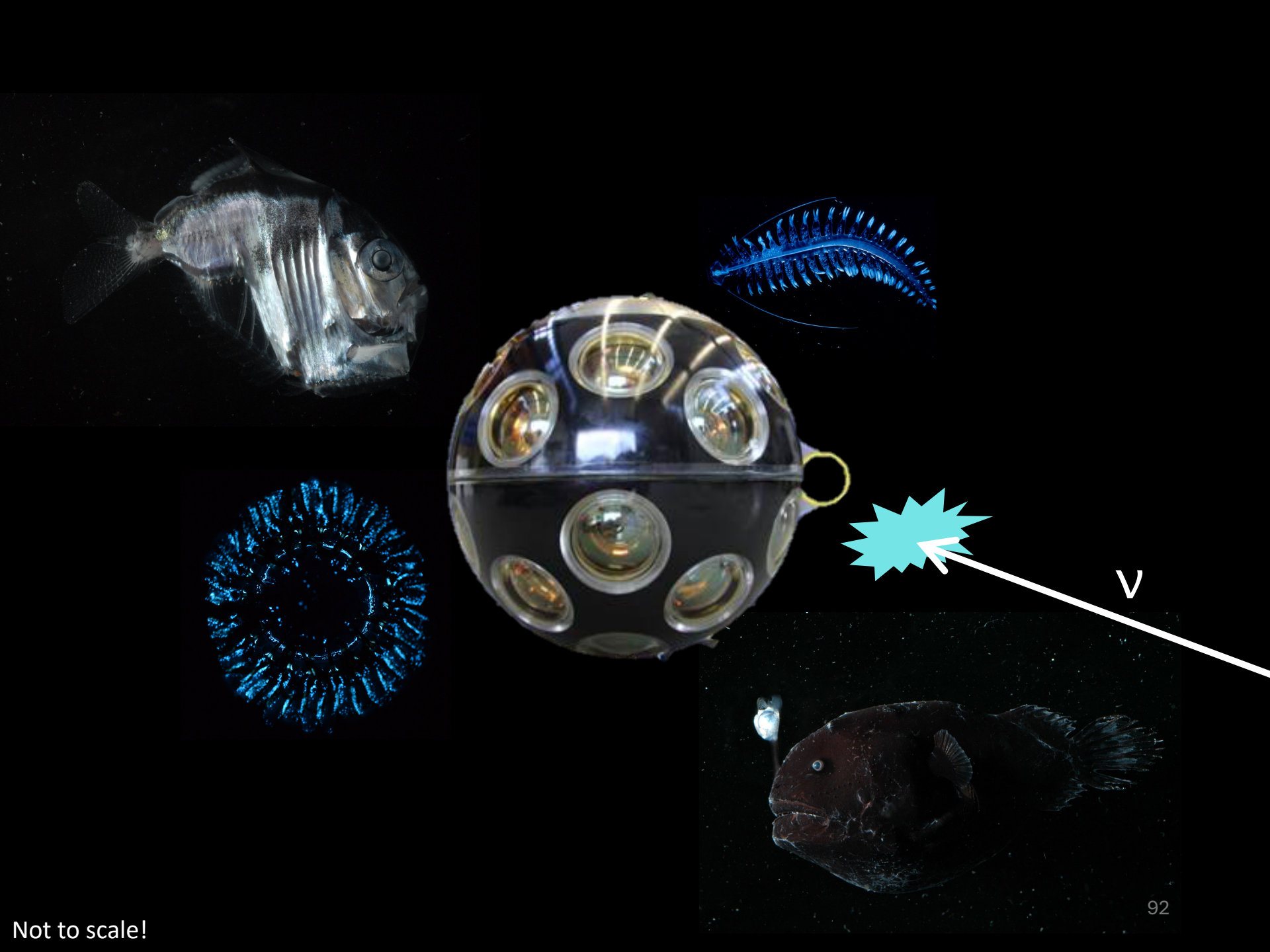

Optical Signal
IceCube
Hole#(year)
50 (06-07)
66 (05-06)
21 (04-05)
86 (09-10)
52 (07-08)
10 (08-09)
2 (08-09)
14 (10-11)
LGM
1400
1600
1800
2000
2200
2400
Depth[meters]


L 3 2702 18 166 1 0 1.4
01:08:24 04/01/17 337 901


KM3NeT
ν

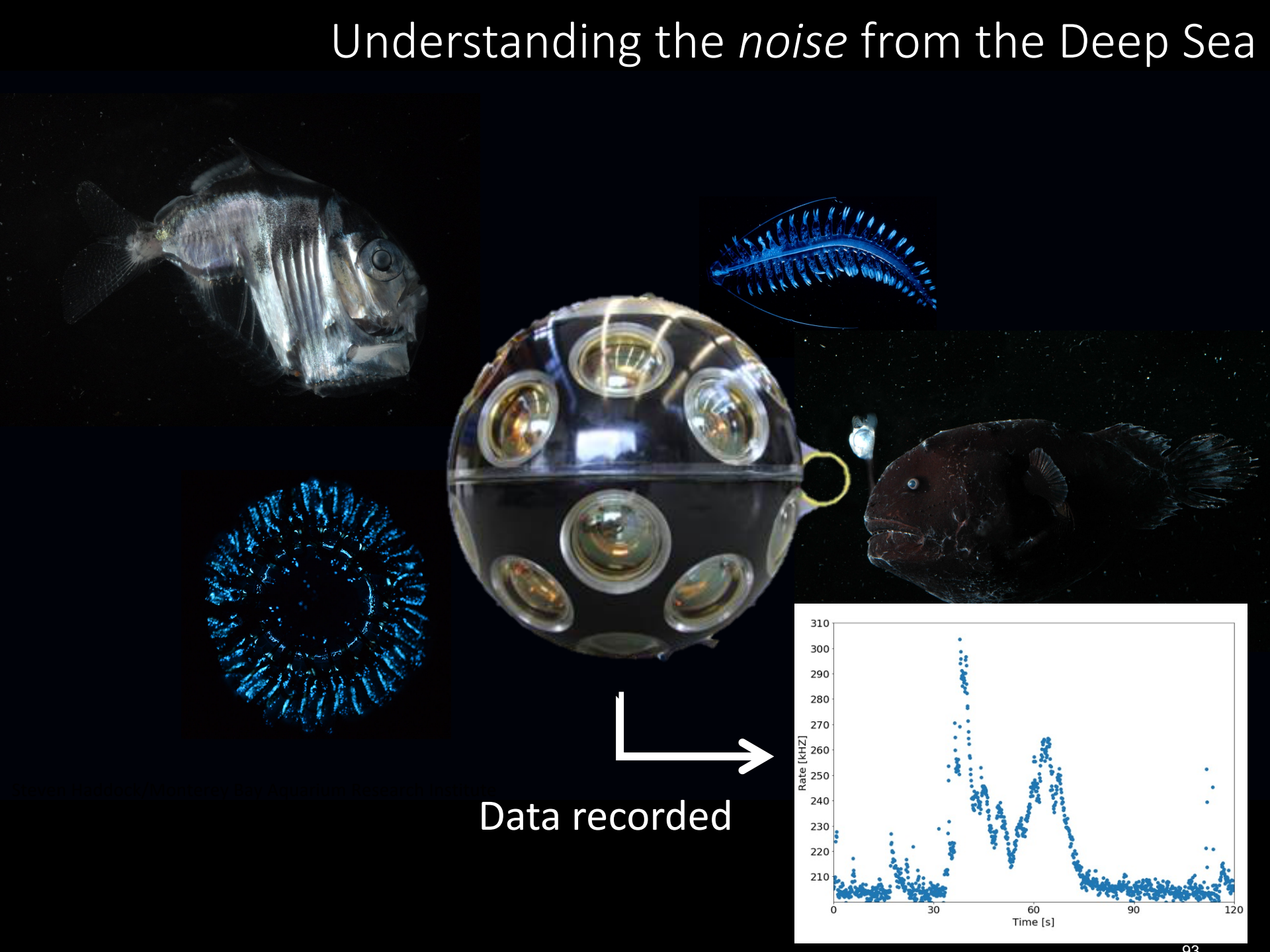


Not to scale!

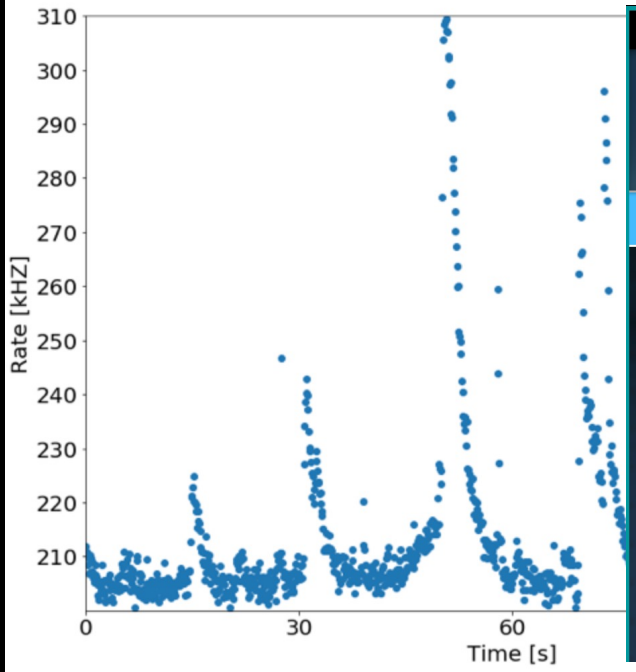


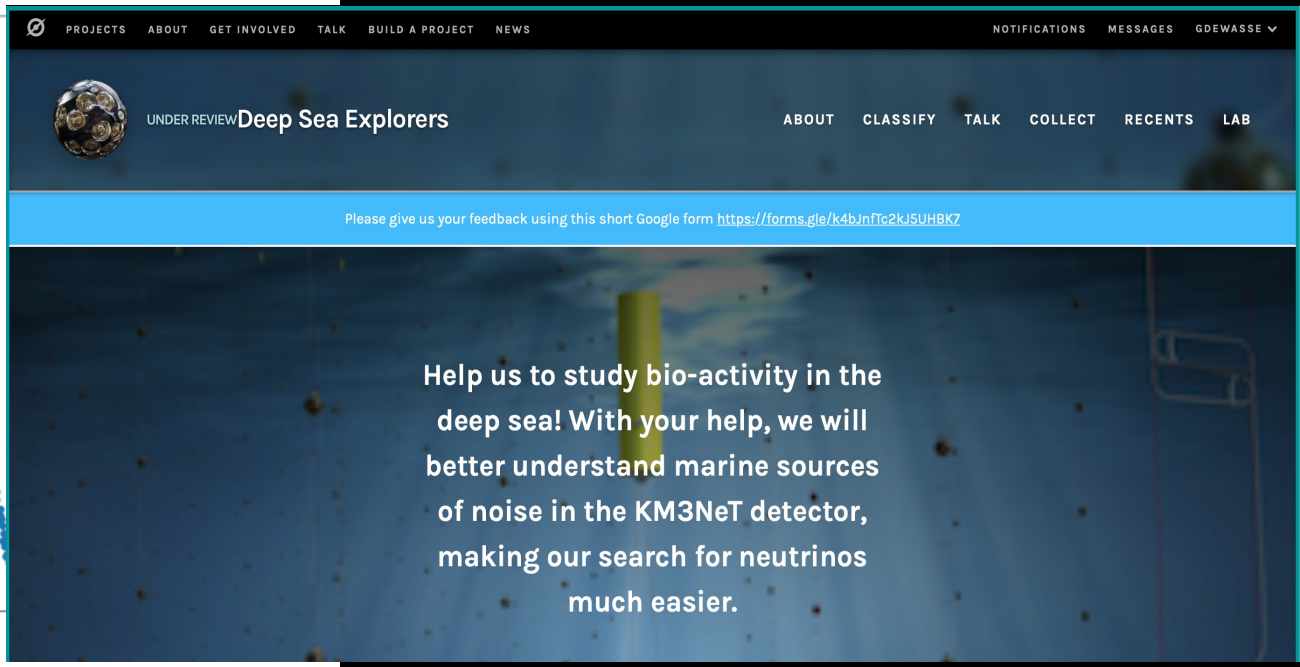
Not to scale!

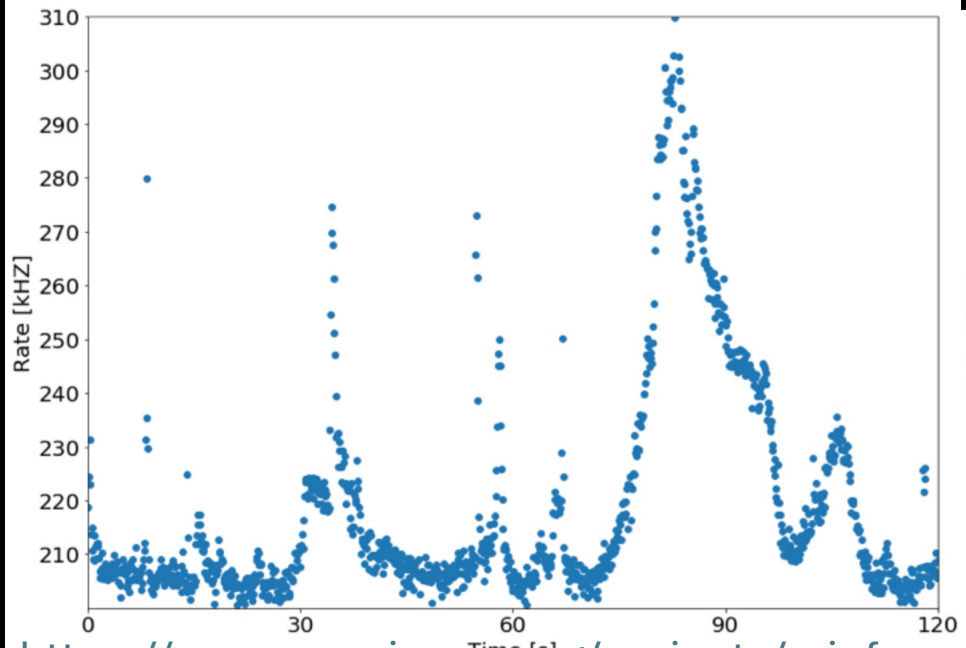
Understanding the *noise* from the Deep Sea

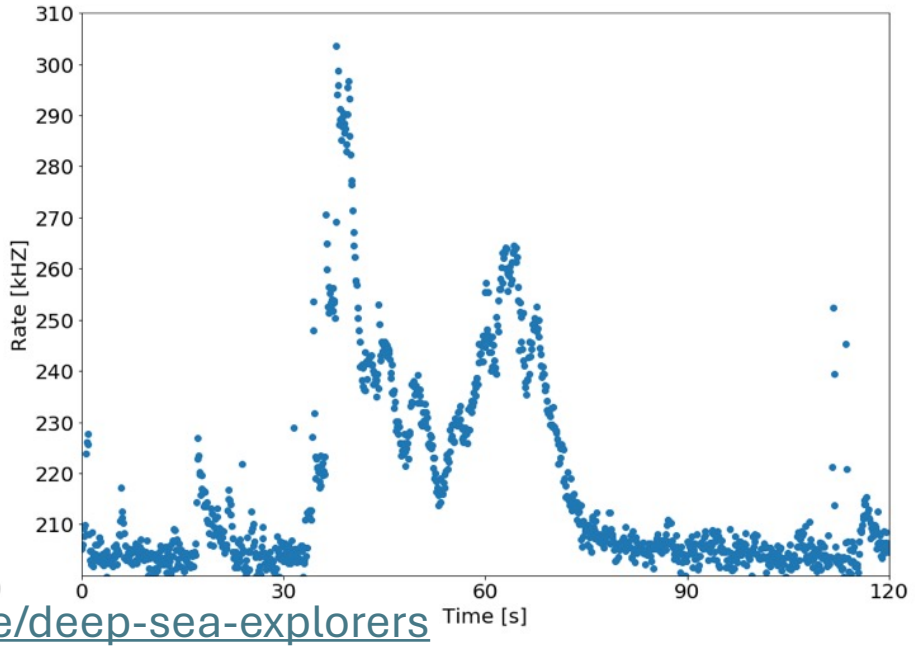


Data recorded

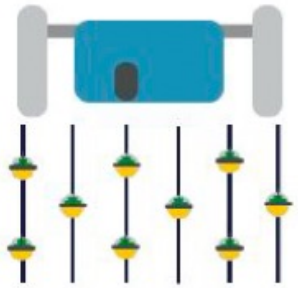






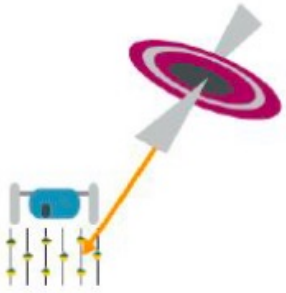


https://www.zooniverse.org/projects/reinforce/deep-sea-explorers

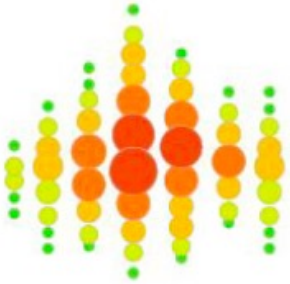


IceCube completion

Diffuse astro flux



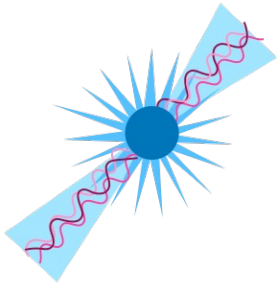
TXS0506+056



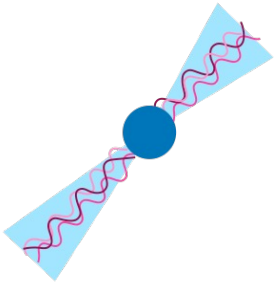
Glashow event

NGC1068

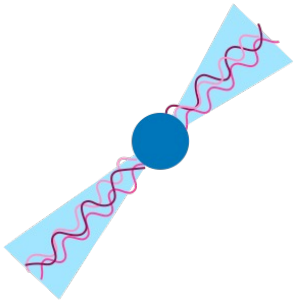
GW150914



GW170817



IACT's GRBs



GRB221009A

2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022

Master

PhD study

Postdoc

Professor


Neutrino
astronomy


Neutrino
astronomy
110


Neutrino
astronomy
110

Speeding up

Cascades vs tracks	Cascades + Tracks + Double cascades
Upgoing track searches	All-sky all-flavour searches
1 km^3 detector	At least 3 km^3 detectors around the globe
Seeing the diffuse flux	Resolving sources

Towards Multi-Detector and Multi-Energy
neutrino astronomy
in the Multi-Messenger Era!