Astronomía de neutrinos

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AAE @ INAOE - Tonantzintla
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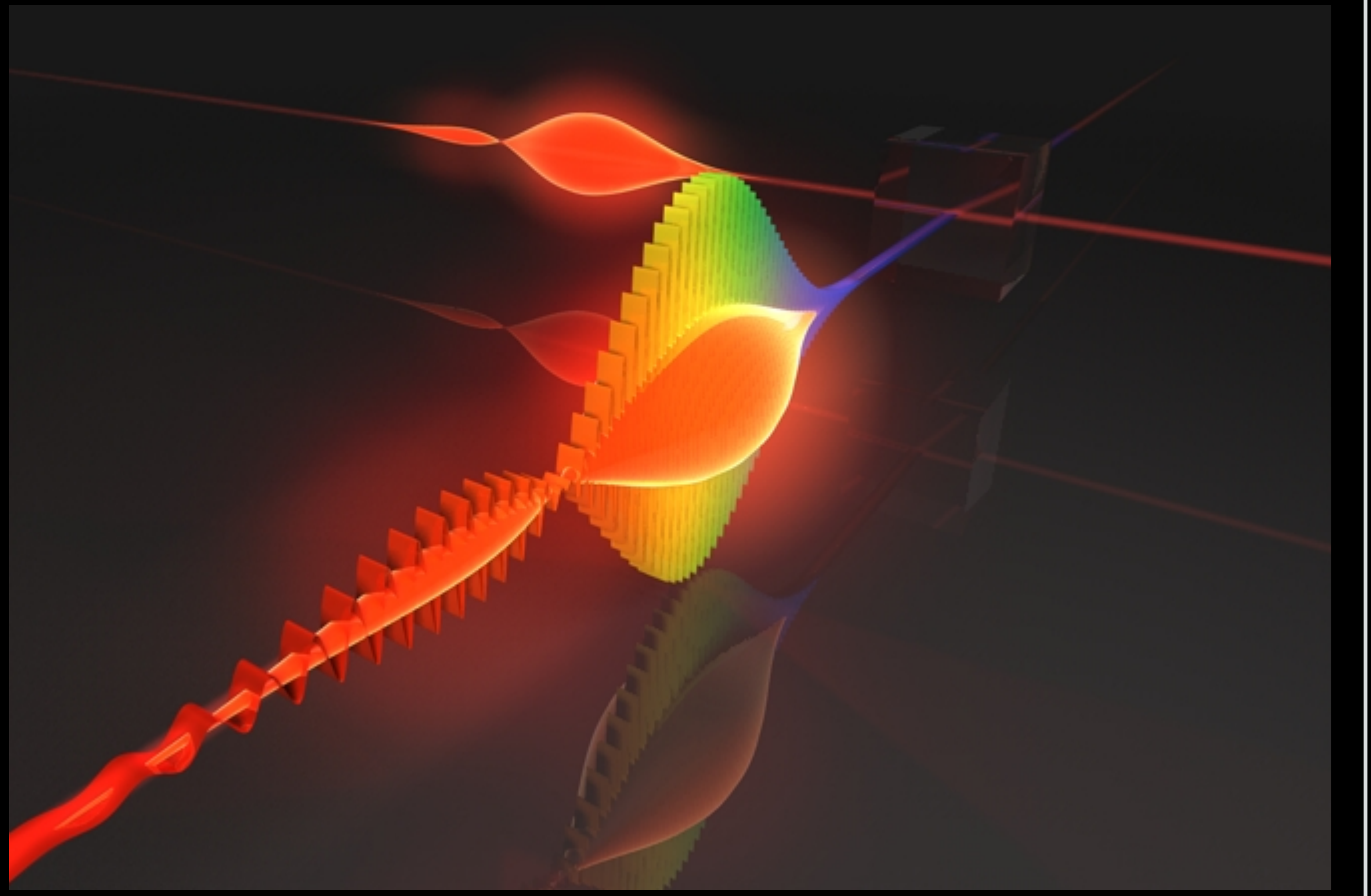
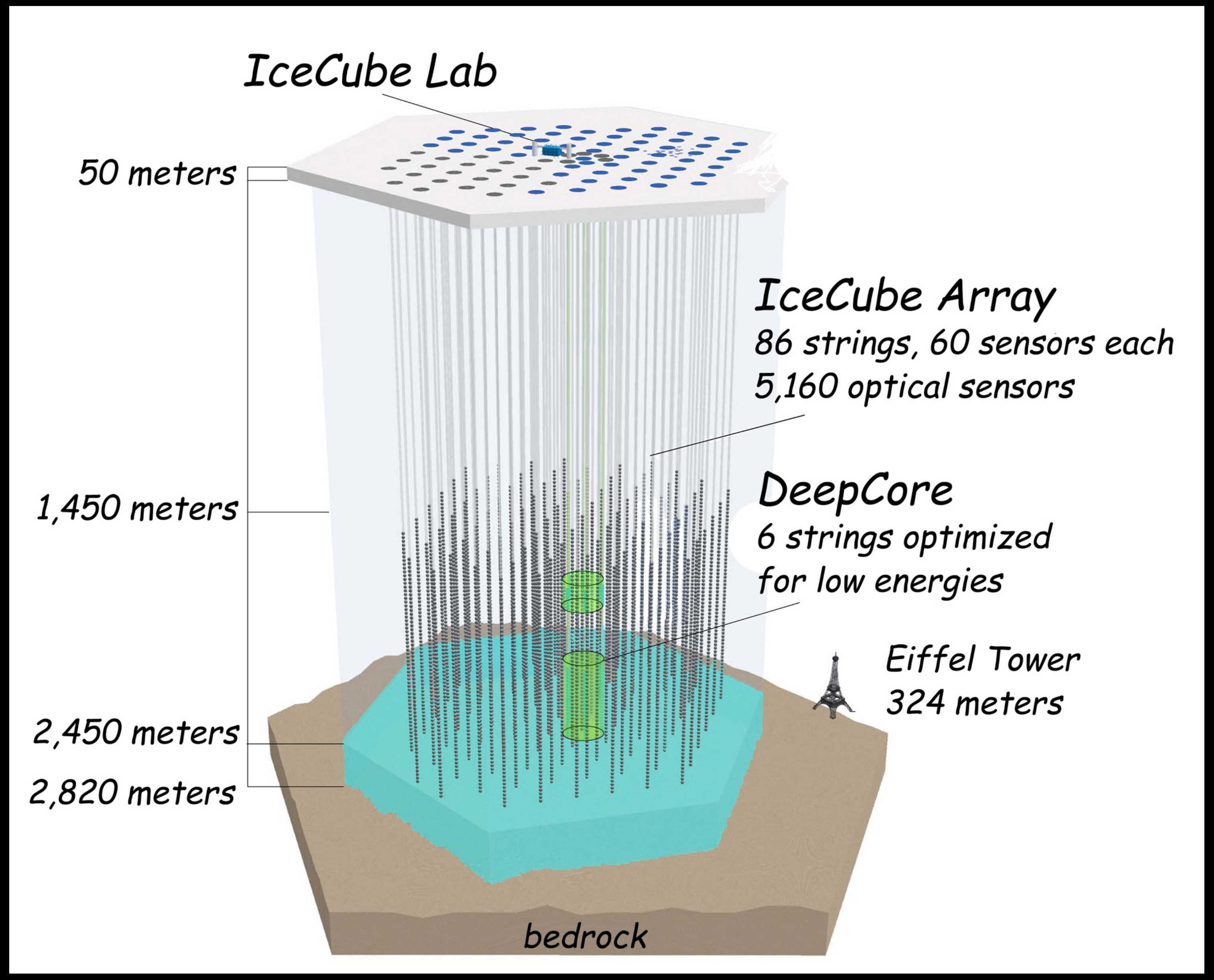
Luz y ondas electromagnéticas



Partículas cósmicas

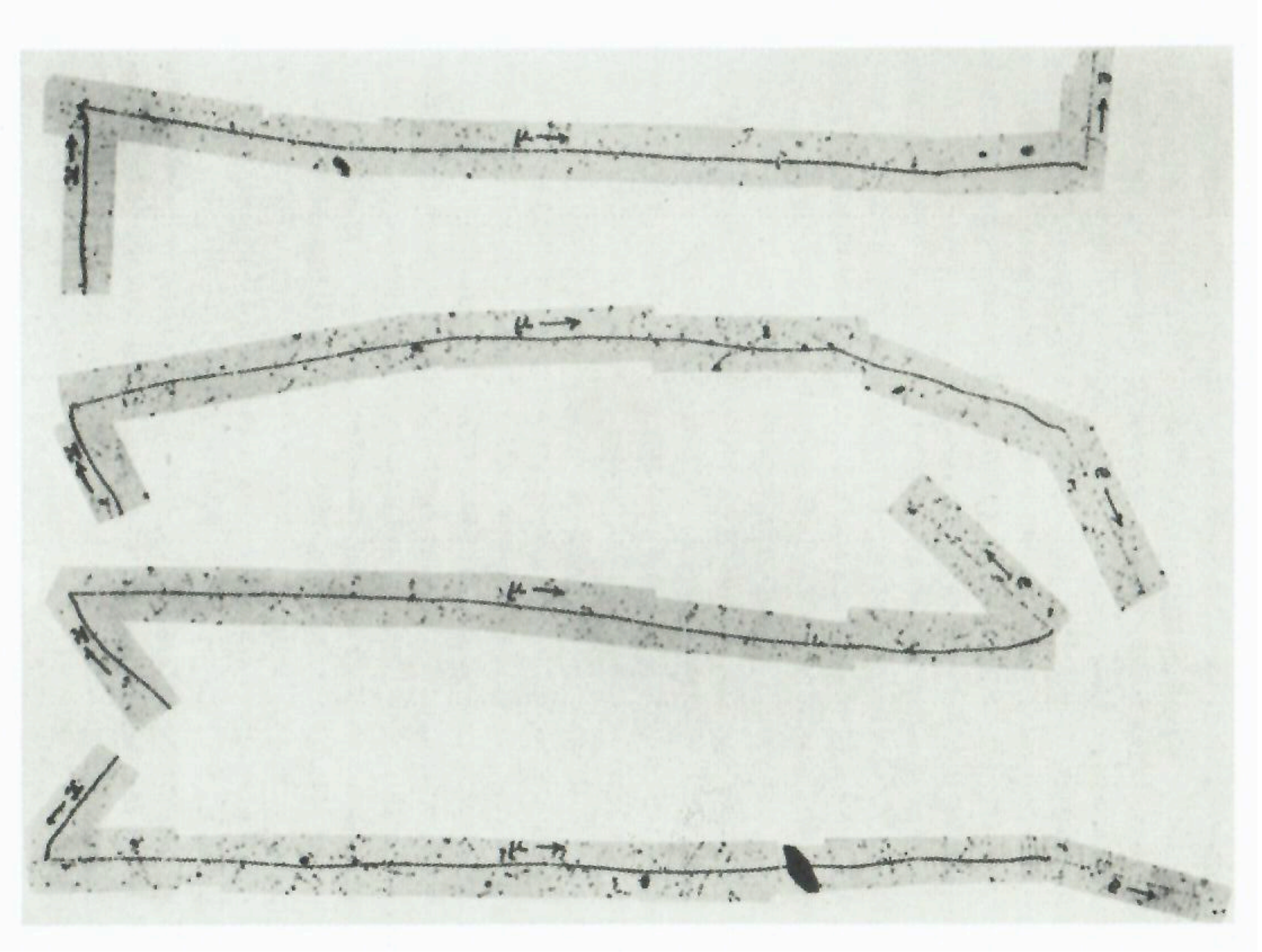
Neutrinos



Ondas gravitacionales

Astronomía de neutrinos

1. El decaimiento β y el neutrino
2. Neutrinos solares y oscilaciones
3. SN 1987A
4. Detectores de gran volumen
5. Astrofísica con IceCube
6. Próxima generación de detectores



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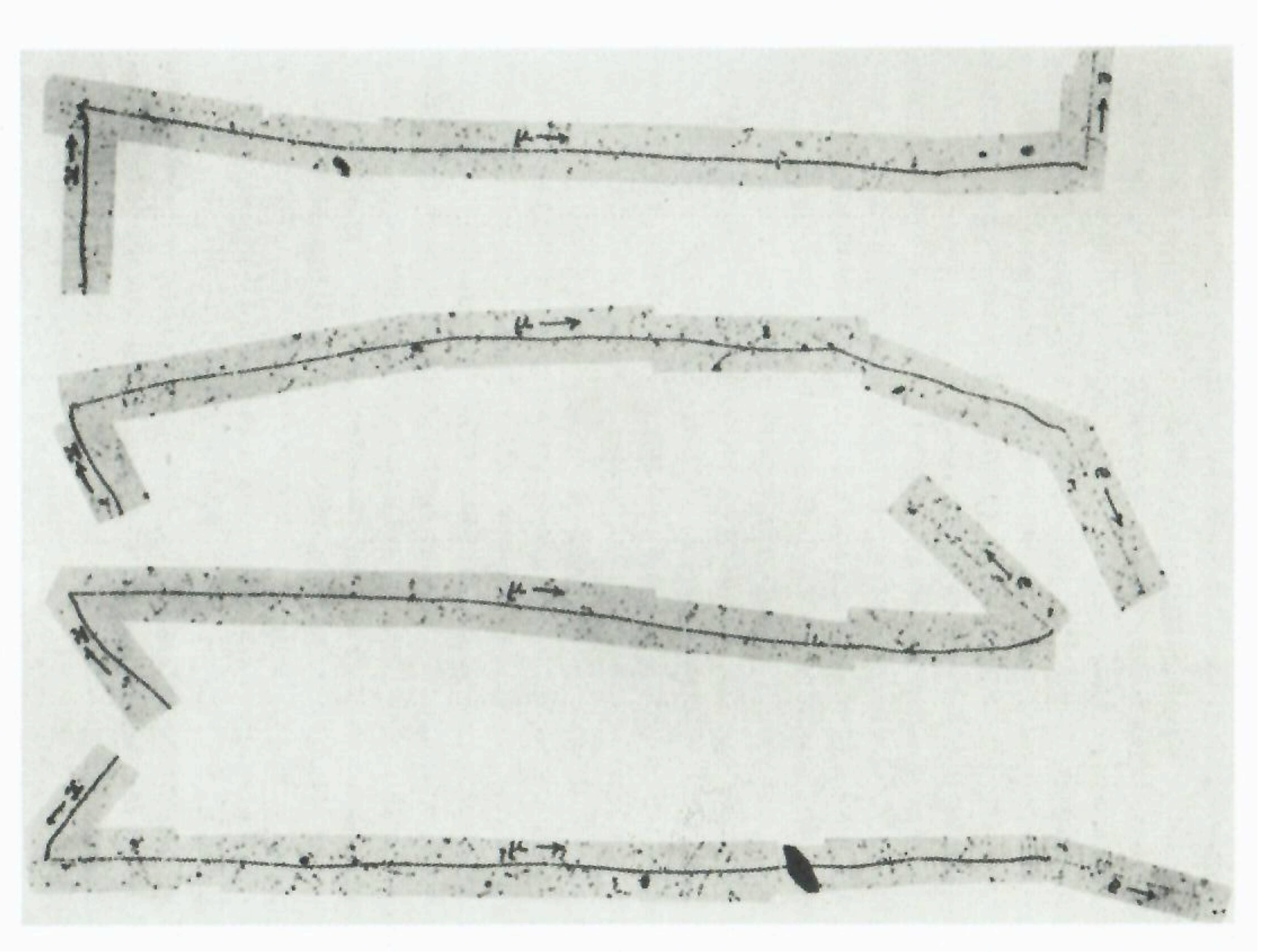


El decaimiento β

- El decaimiento β es una de las tres formas de radioactividad descubiertas a finales del siglo XIX.
- Consiste en la emisión de un electrón o positrón por un núcleo, conservando la masa atómica A pero modificando $Z \to Z \pm 1$.
- Se observa en isótopos inestables. Por ejemplo:

$$ {}^{14}_{6}\mathrm{C} \to {}^{14}_{7}\mathrm{N} + e^- + \bar{\nu}_e \,, \quad {}^{3}_{1}\mathrm{H} \to {}^{3}_{2}\mathrm{He}^+ + e^- + \bar{\nu}_e \,, \quad {}^{23}_{12}\mathrm{Mg} \to {}^{23}_{11}\mathrm{Na} + e^+ + \nu_e \,. $$

- El decaimiento β aparece como la emisión de un electrón o positrón, en aparente contradicción con la conservación de energía y momento, dado el espectro continuo para la energía del electrón.

El decaimiento del neutrón

- El decaimiento espontáneo del neutrón, descrito originalmente como $n \to p^+ + e^-$, requiere por conservación de energía y momento,

$$\begin{pmatrix} m_N \\ 0 \end{pmatrix} = \begin{pmatrix} \gamma_p m_p + \gamma_e m_e \\ \gamma_p \vec{\beta}_p m_p + \gamma_e \vec{\beta}_e m_e \end{pmatrix},$$

lo que implica, para $m_N = 939.566\,\mathrm{MeV}$, $m_p = 938.272\,\mathrm{MeV}$, $m_e = 0.511\,\mathrm{MeV}$,

$$\gamma_e m_e = \frac{m_N^2 - m_p^2 + m_e^2}{2m_N} \simeq 1.29\,\mathrm{MeV}.$$

- El espectro de energías observado es un continuo que *termina* en 1.29 MeV.

“Introduction to elementary particles”, Griffiths

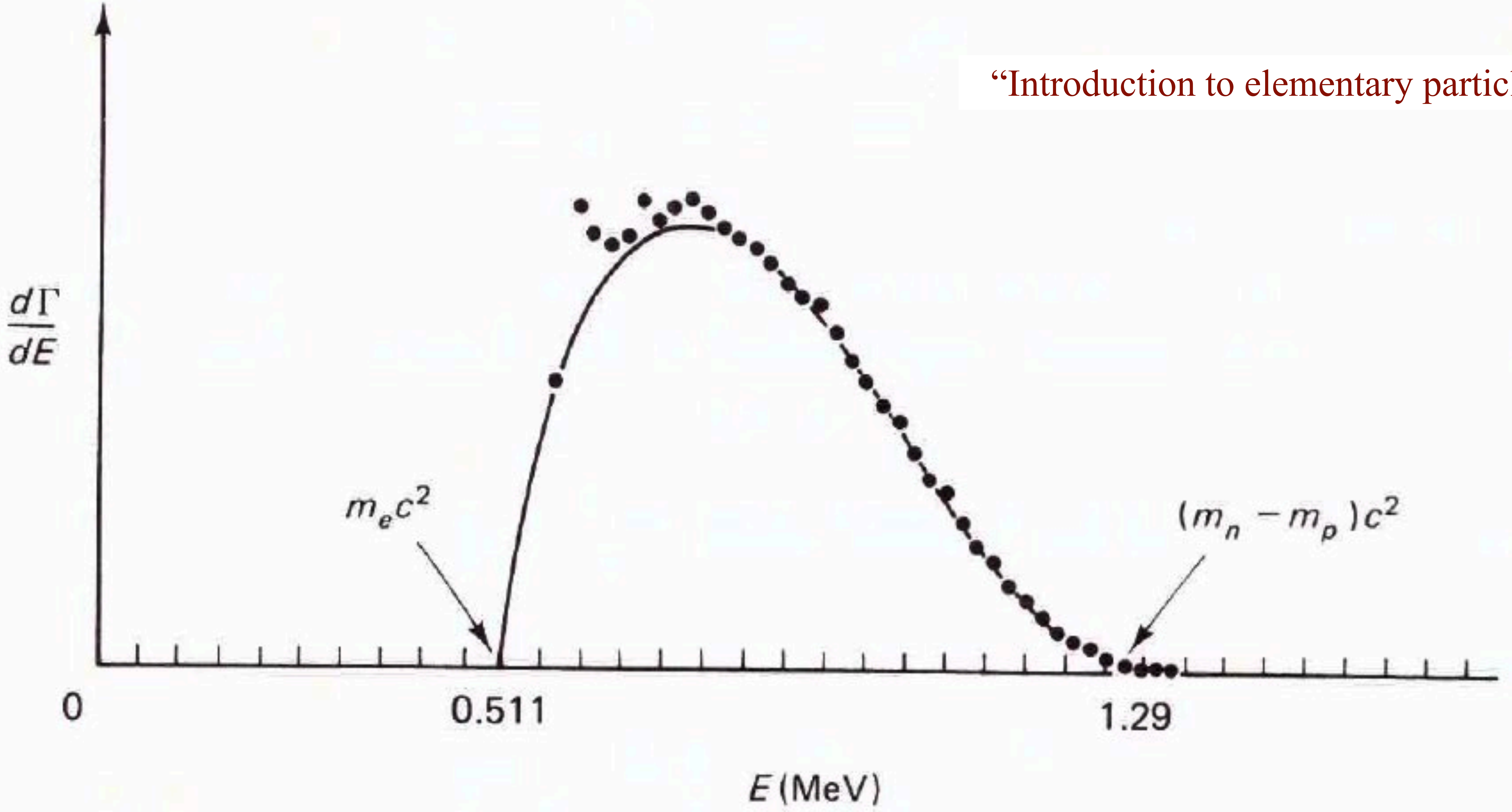


Figure 10.2 Electron energy distribution from neutron beta decay. (Solid line is the theoretical curve; dots are experimental data.) [*Source:* C. J. Christensen et al., *Phys. Rev.* **D5**, 1628 (1972), Figure 4.]

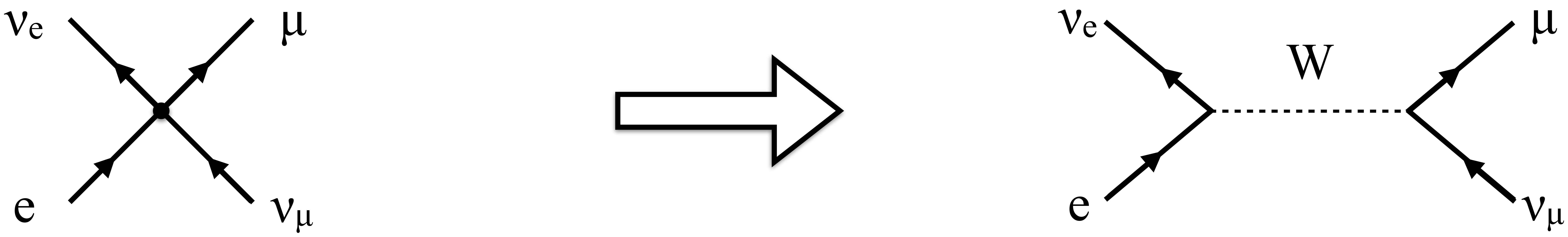
El neutrino

- Para mantener el principio de conservación de energía, Pauli postula la existencia del neutrino ν, partícula sin carga y sin masa,

$$n \rightarrow p^+ + e^- + \bar{\nu}.$$

- La primera teoría de la interacción débil fue presentada por Fermi (1934).
- Majorana (1937) sugiere que el neutrino y el antineutrino podrían ser la misma partícula $\Rightarrow$ si además tiene masa, debe ser posible el decaimiento β doble,

$$(Z, A) \rightarrow (Z+2, A) + 2\mathrm{e}^- + 2\bar{\nu}_e.$$



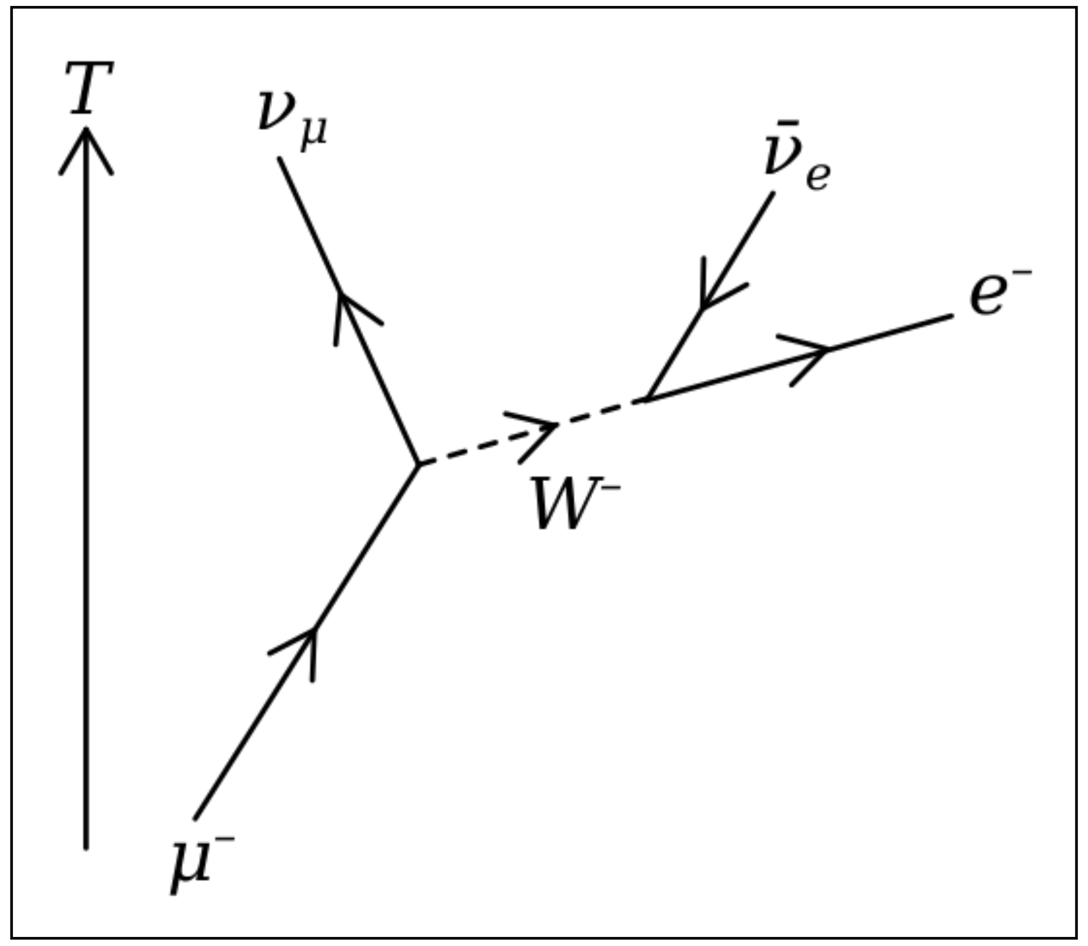
El decaimiento β

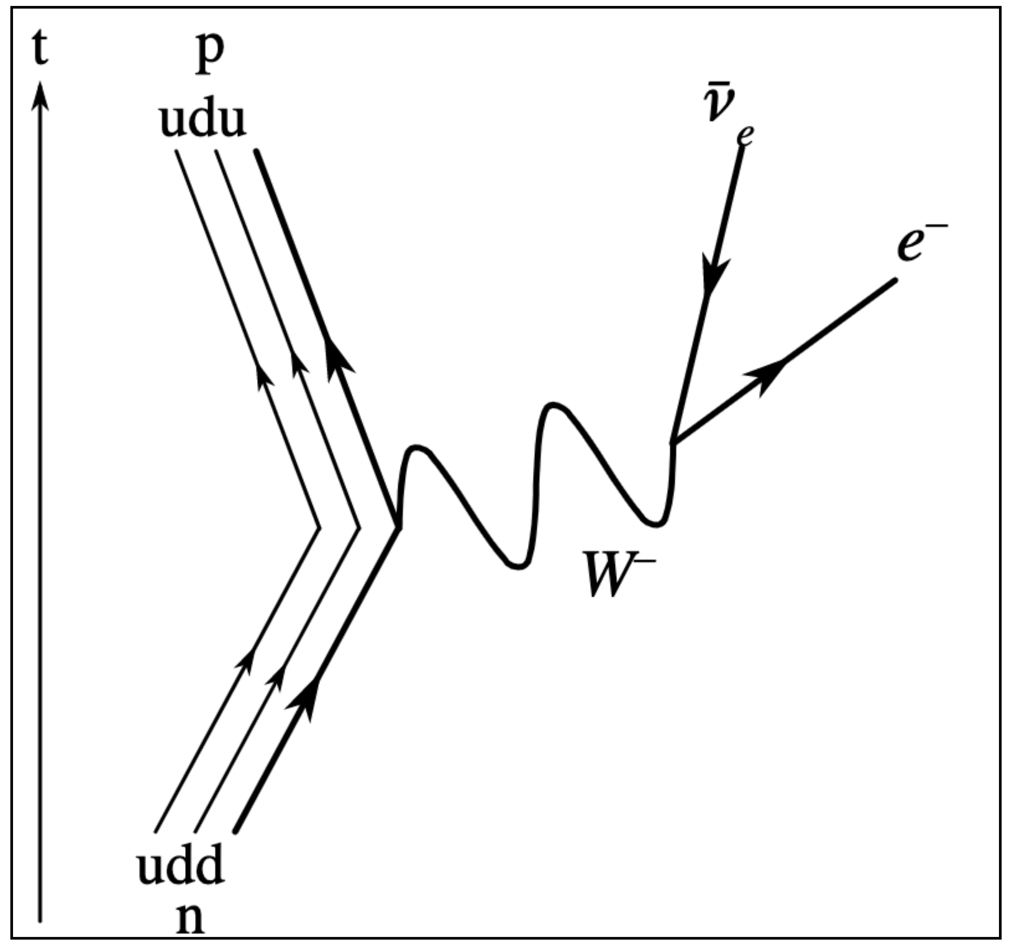
- Se observa tanto en leptones,

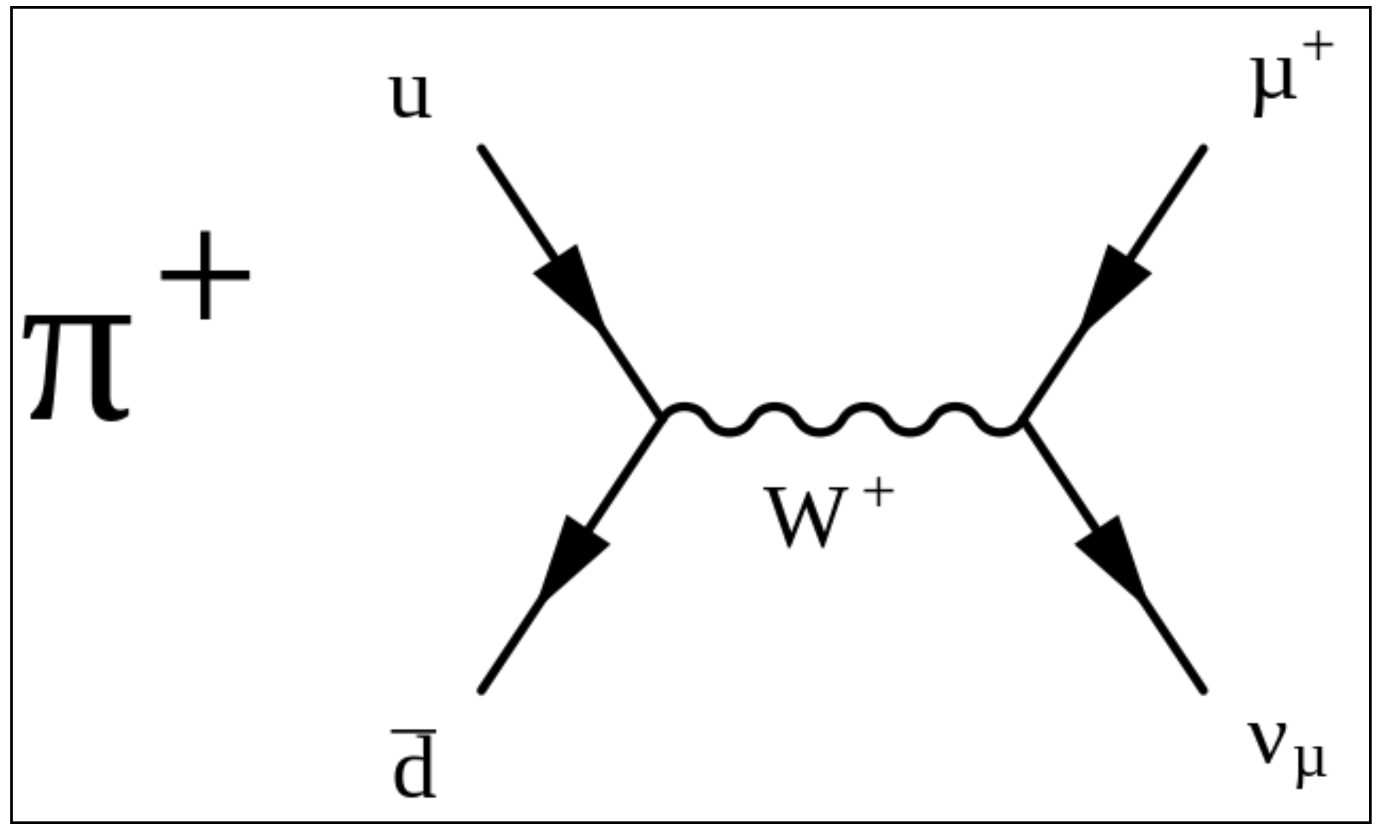
$$\mu^- \rightarrow \mathrm{e}^- + \bar{\nu}_e + \nu_\mu,$$

como en hadrones, tanto el decaimiento del neutrón, como,

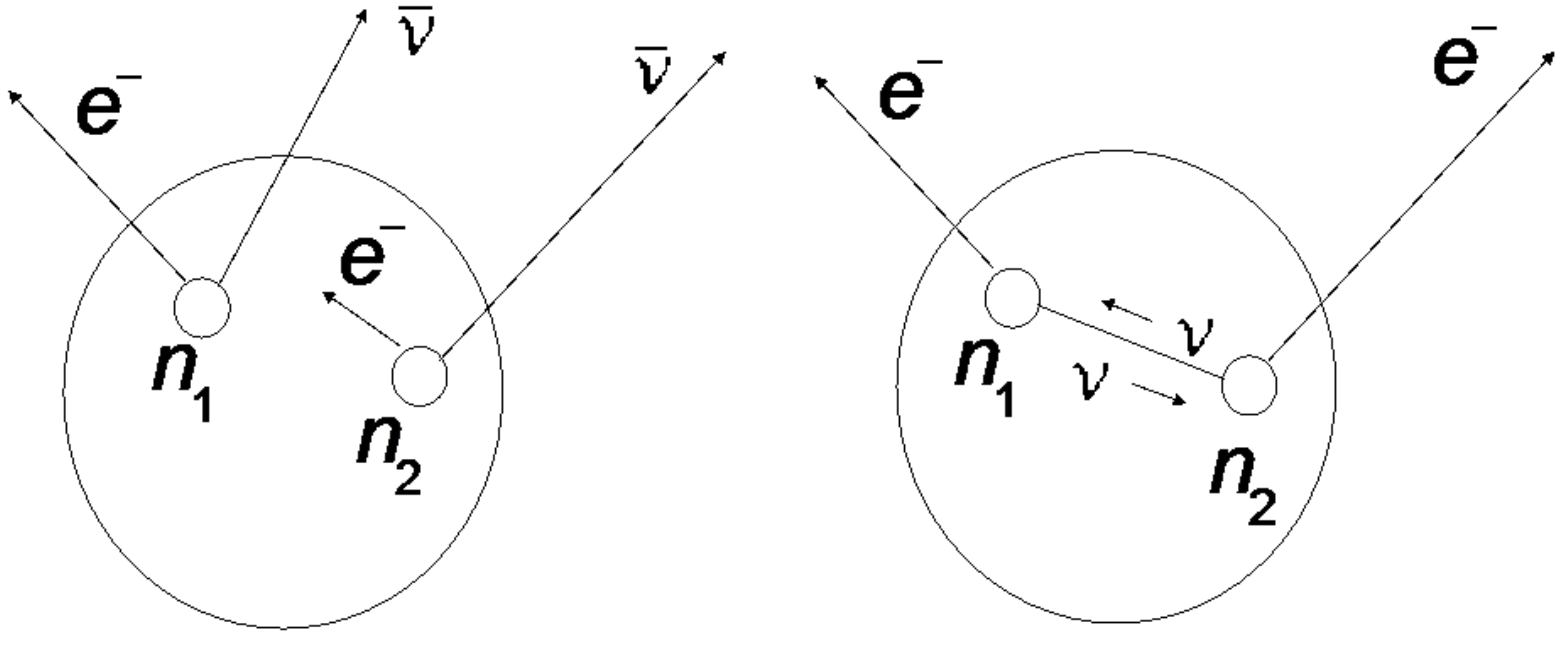
$$\pi^- \rightarrow \mu^- + \nu_\mu.$$



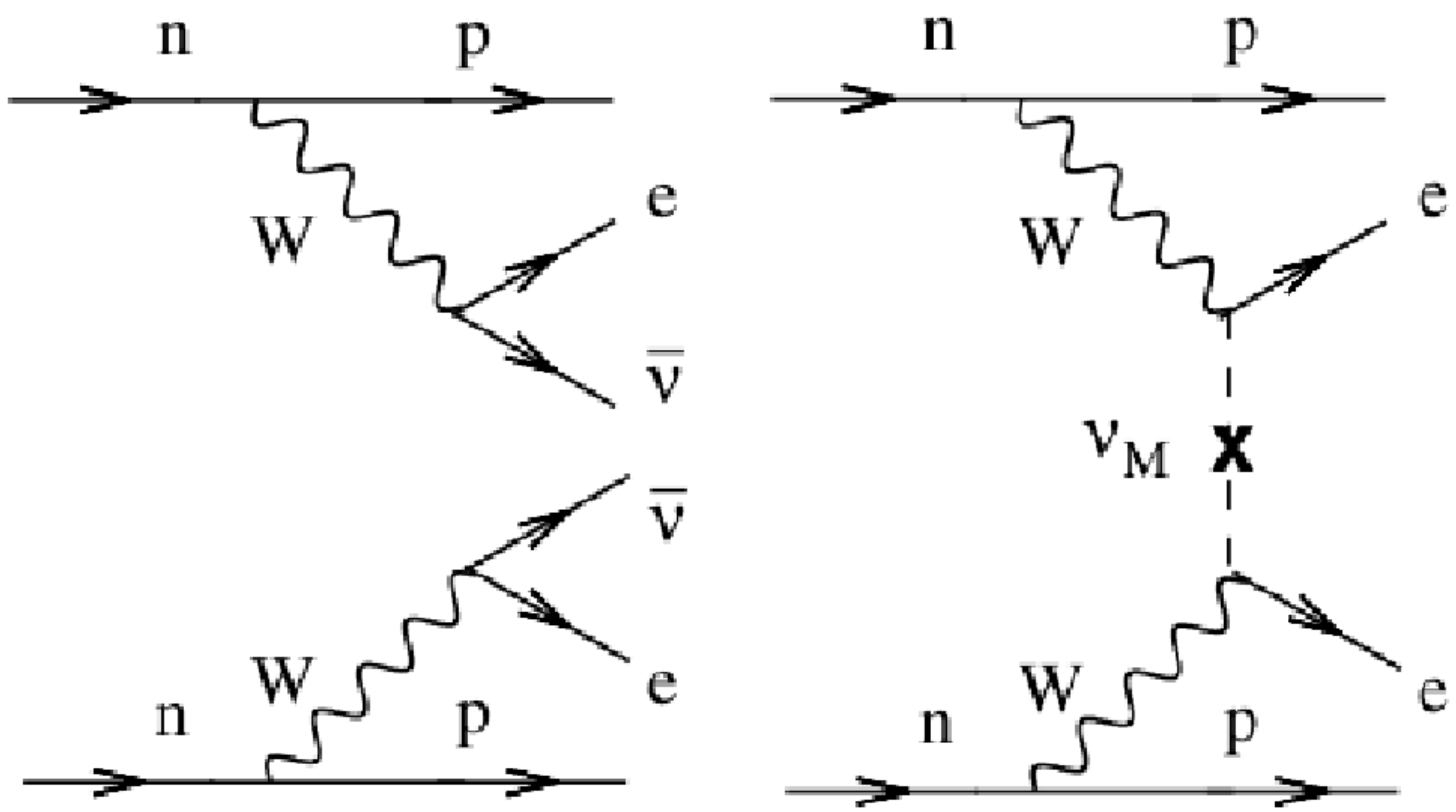




Decaimiento β doble

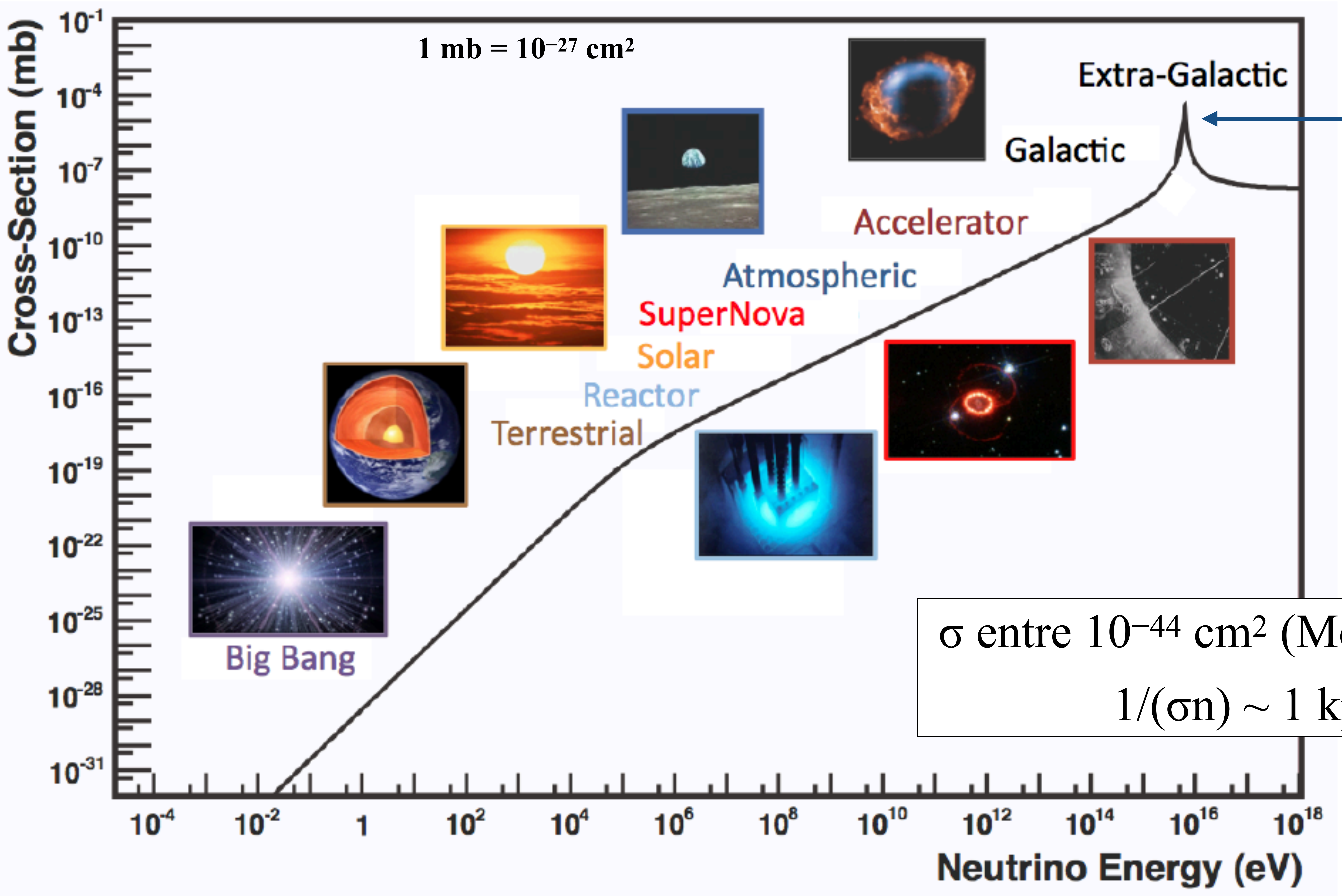


2νββ 0νββ



Detección del neutrino

- Cowan & Reines (1955) detectan por primera vez neutrinos provenientes de reactores nucleares.
- Raymond Davis instala en 1955 el primer prototipo de un detector de neutrinos solares.
  - En 1966-67 inicia la búsqueda de neutrinos solares.
  - Davis et al. (1968, PRL) primeros límites; detección hacia 1971.
- Detección de neutrinos μ con energías de GeV por Schwartz, Lederman & Steinberger (1962).



Resonancia de Glashow @ 6.3 PeV

σ entre 10^{-44} cm² (MeV) y 10^{-37} cm² (TeV)

$1/(\sigma n) \sim 1$ kpc en agua…

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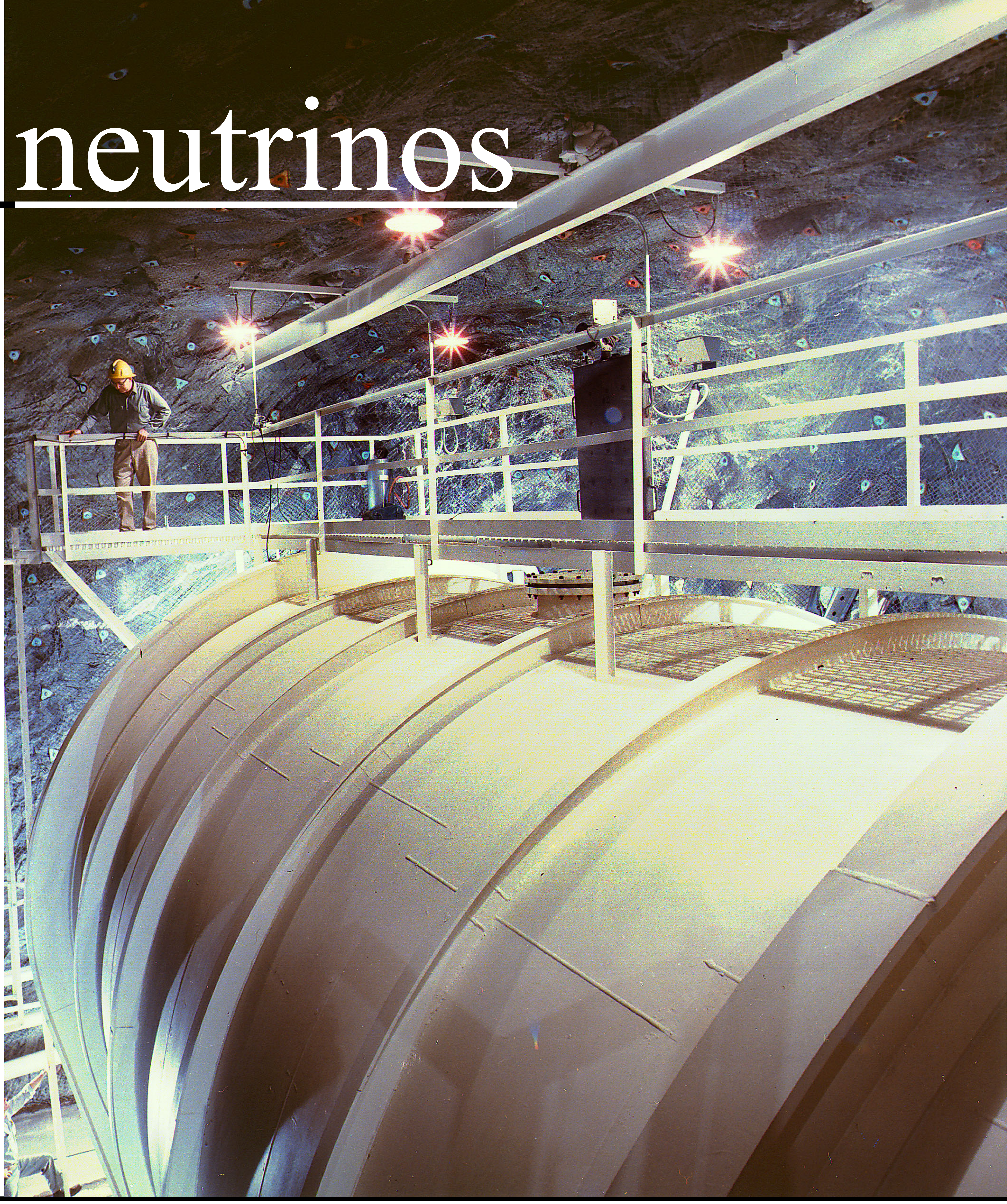


Detección de neutrinos solares

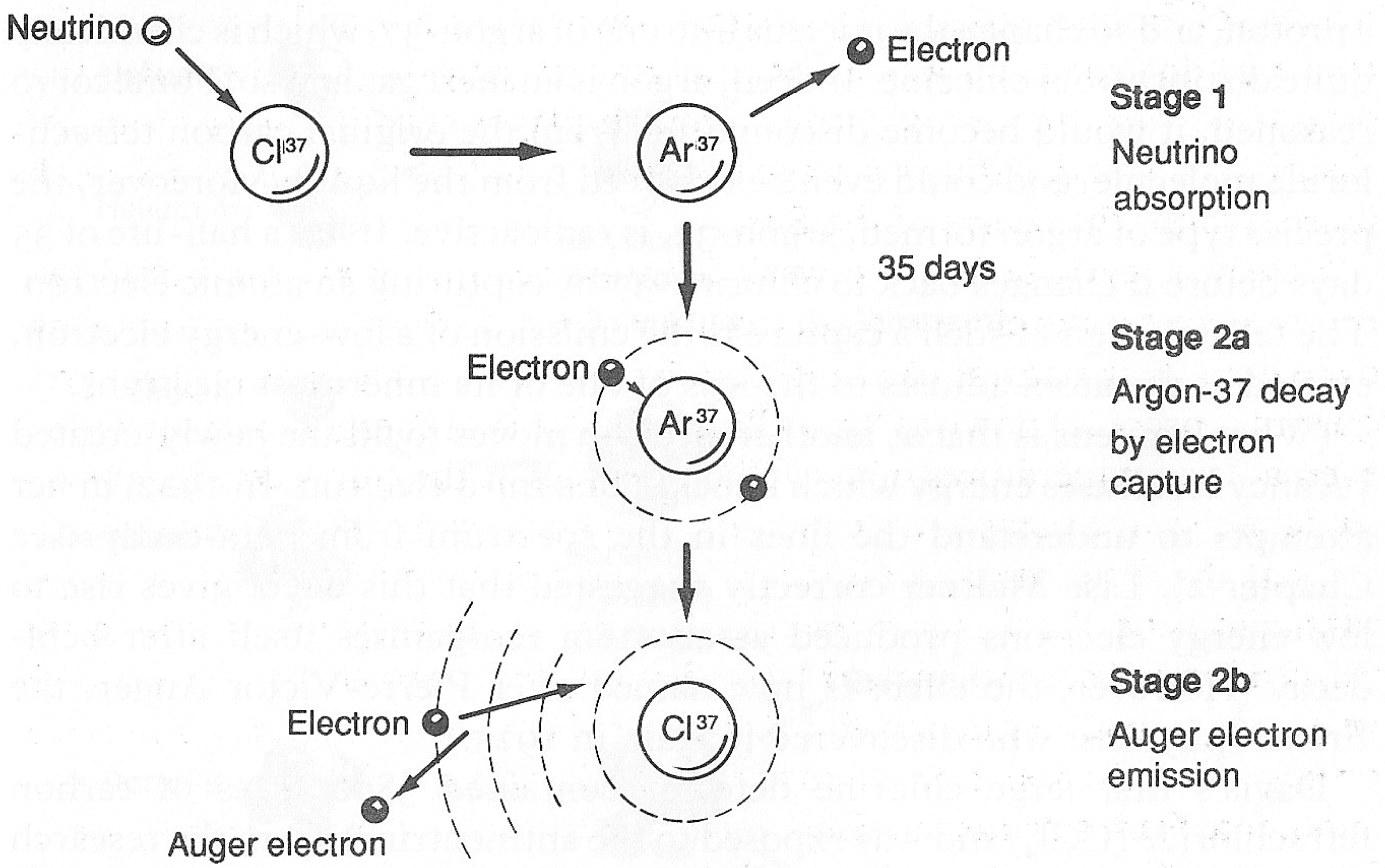
- Raymon Davis Jr. instala un tanque con 100,000 galones de C_2Cl_4 en mina de Homestake, SD (1970-1994). Reacción,

$$\nu_e + \,^{37}_{17}\mathrm{Cl} \longrightarrow \,^{37}_{18}\mathrm{Ar} + e^- \ ,$$

  con umbral $E_\nu \geq 0.82\ \mathrm{MeV}$. Un átomo de argón producido cada dos o tres días. Modelo solar estándar predice 7.9 SNU, con 1 SNU$=10^{-36}$ reacciones por átomo por segundo; tasa observada $= 2.23 \pm 0.26\ \mathrm{SNU}$.
- Gallex (1991-1997) y SAGE (1997-) emplean la reacción,

$$\nu_e + \,^{71}_{31}\mathrm{Ga} \longrightarrow \,^{71}_{32}\mathrm{Ge} + e^-$$

  con umbral $E_\nu \geq 0.23\ \mathrm{MeV}$.
- Kamiokande y SK emplean emisión Cherenkov de e^- dispersados por neutrinos. Umbral $E_\nu \geq 5\ \mathrm{MeV}$.



The chlorine experiment

"Spaceship neutrino", C. Sutton

Neutrinos solares

La producción de neutrinos solares depende de las formas de quemado de hidrógeno (Bahcall 1989 y otros papers):

Cadena protón-protón

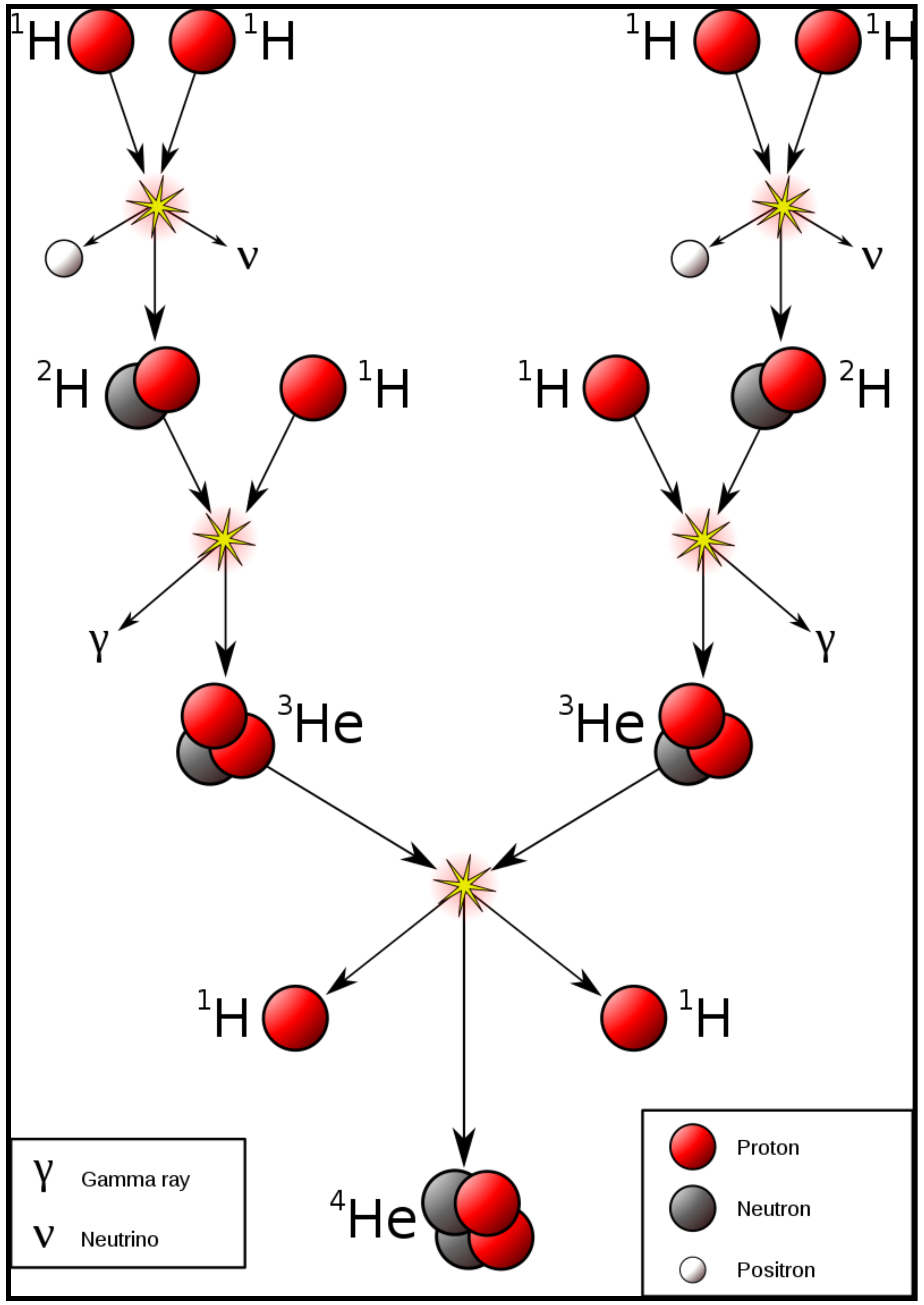
(I) ${}^1_1\mathrm{H} + {}^1_1\mathrm{H} \rightarrow {}^2_1\mathrm{H} + e^+ + \nu_e,\ {}^2_1\mathrm{H} + {}^1_1\mathrm{H} \rightarrow {}^3_2\mathrm{He} + \gamma,\ {}^3_2\mathrm{He} + {}^3_2\mathrm{He} \rightarrow\ {}^4_2\mathrm{He} + {}^1_1\mathrm{H} + {}^1_1\mathrm{H}.$
(II) ${}^3_2\mathrm{He} + {}^4_2\mathrm{He} \rightarrow {}^7_4\mathrm{Be} + \gamma,\ {}^7_4\mathrm{Be} + e^- \rightarrow {}^7_3\mathrm{Li} + \nu_e,\ {}^7_3\mathrm{Li} + {}^1_1\mathrm{H} \rightarrow {}^4_2\mathrm{He} + {}^4_2\mathrm{He}.$
(III) ${}^7_4\mathrm{Be} + {}^1_1\mathrm{H} \rightarrow {}^8_5\mathrm{B} + \gamma,\ {}^8_5\mathrm{B} \rightarrow {}^8_4\mathrm{Be} + e^+ + \nu_e,\ {}^8_4\mathrm{Be} \rightarrow {}^4_2\mathrm{He} + {}^4_2\mathrm{He}.$

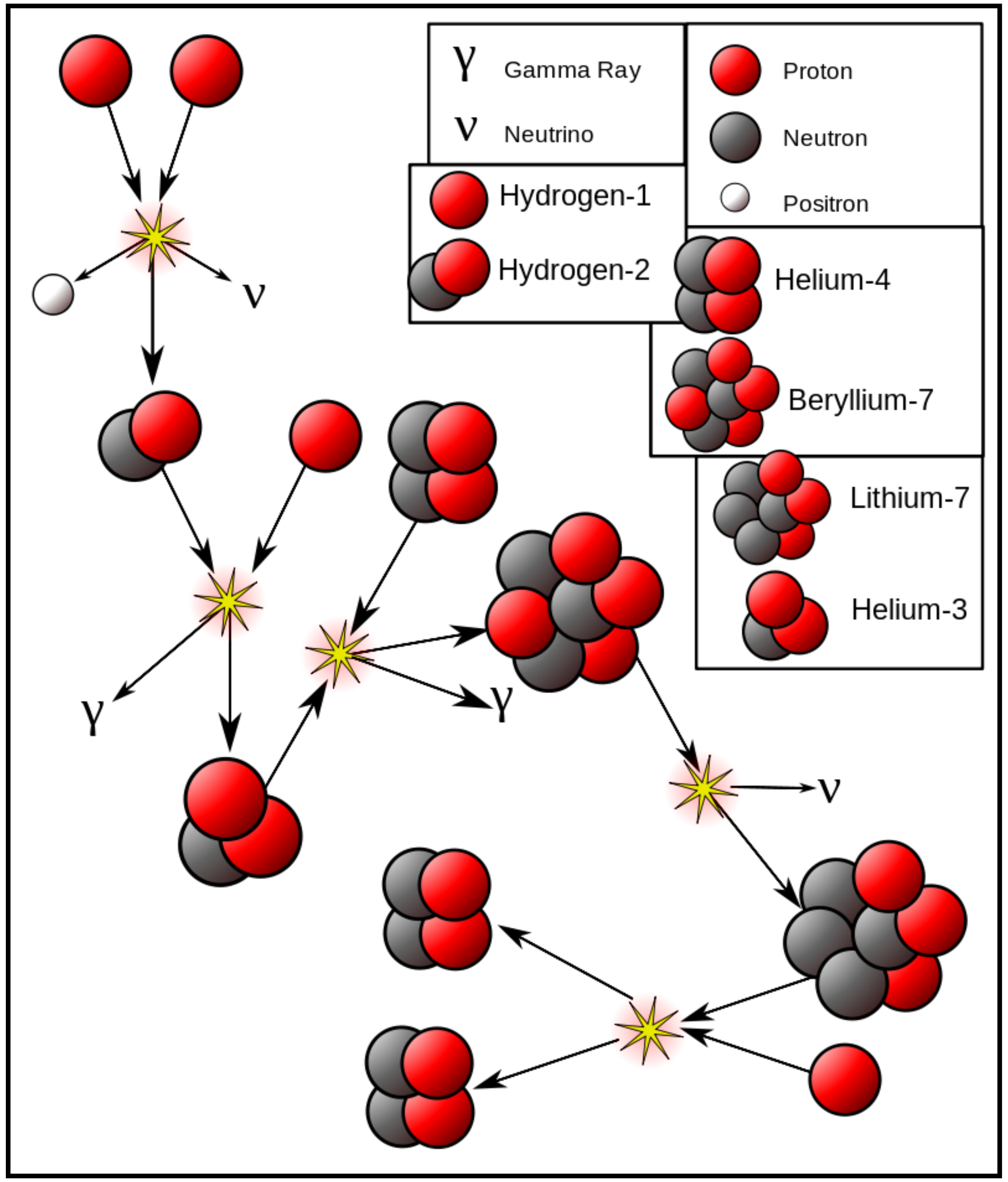
Las reacciones,

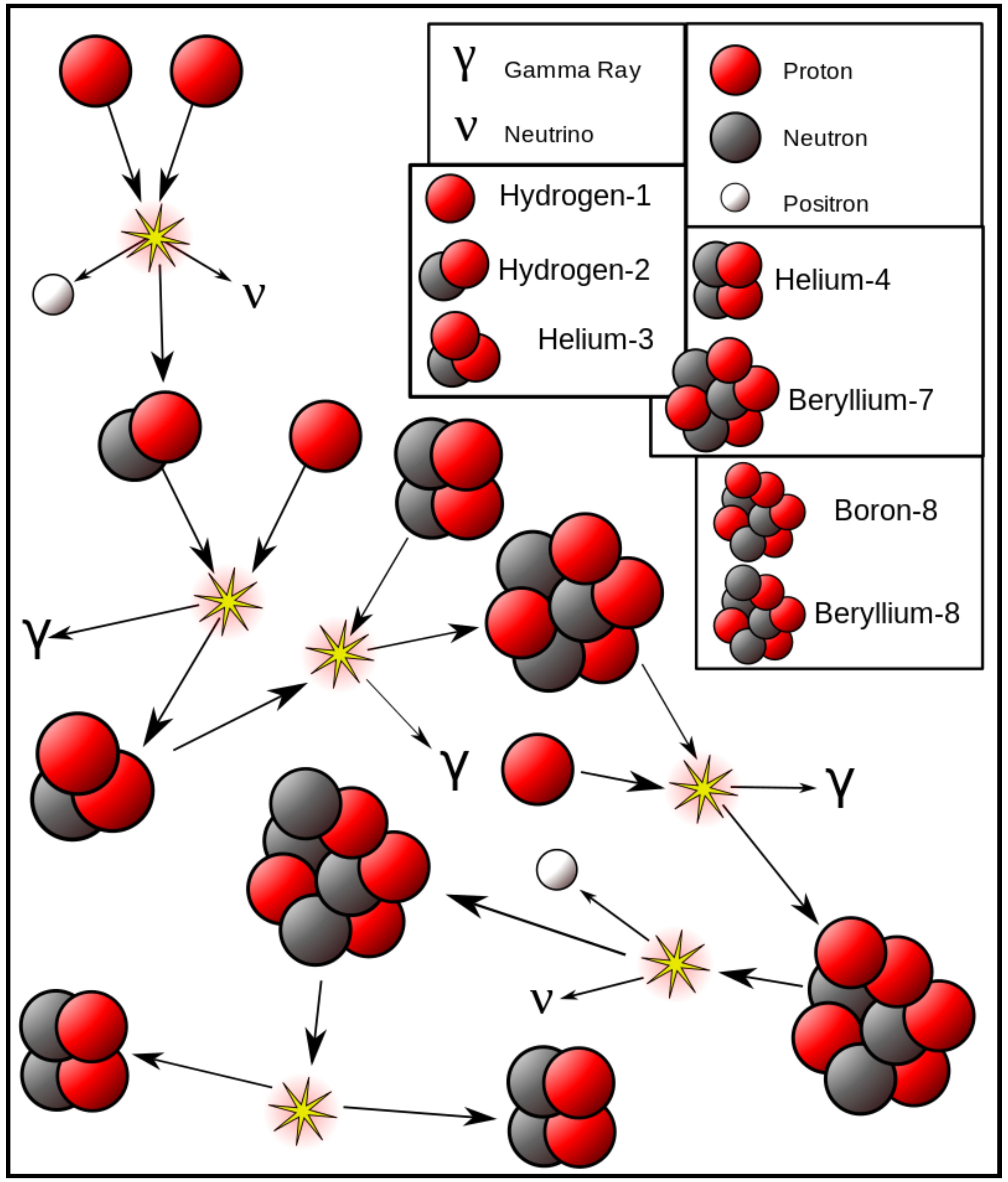
pep: ${}^1_1\mathrm{H} + {}^1_1\mathrm{H} + e^- \rightarrow {}^2_1\mathrm{H} + \nu_e$, hep: ${}^3_2\mathrm{He} + {}^1_1\mathrm{H} \rightarrow {}^4_2\mathrm{He} + e^+ + \nu_e$

El ciclo CNO

${}^{12}_6\mathrm{C} + {}^1_1\mathrm{H} \rightarrow {}^{13}_7\mathrm{N} + \gamma,\quad {}^{13}_7\mathrm{N} \rightarrow {}^{13}_6\mathrm{C} + e^+ + \nu_e,\quad {}^{13}_6\mathrm{C} + {}^1_1\mathrm{H} \rightarrow {}^{14}_7\mathrm{N} + \gamma,$
${}^{14}_7\mathrm{N} + {}^1_1\mathrm{H} \rightarrow {}^{15}_8\mathrm{O} + \gamma,\quad {}^{15}_8\mathrm{O} \rightarrow {}^{15}_7\mathrm{N} + e^+ + \nu_e,\quad {}^{15}_7\mathrm{N} + {}^1_1\mathrm{H} \rightarrow {}^{12}_6\mathrm{C} + {}^4_2\mathrm{He}.$







By Sarang - Own work, Public Domain, https://commons.wikimedia.org/w/index.php?curid=51118538

{^{1}H, ^{2}H, ^{3}He, ^{4}He, ^{7}Li, ~~^{7}Be~~, ~~^{8}Be~~, ~~^{8}B~~}

Ciclo del carbono

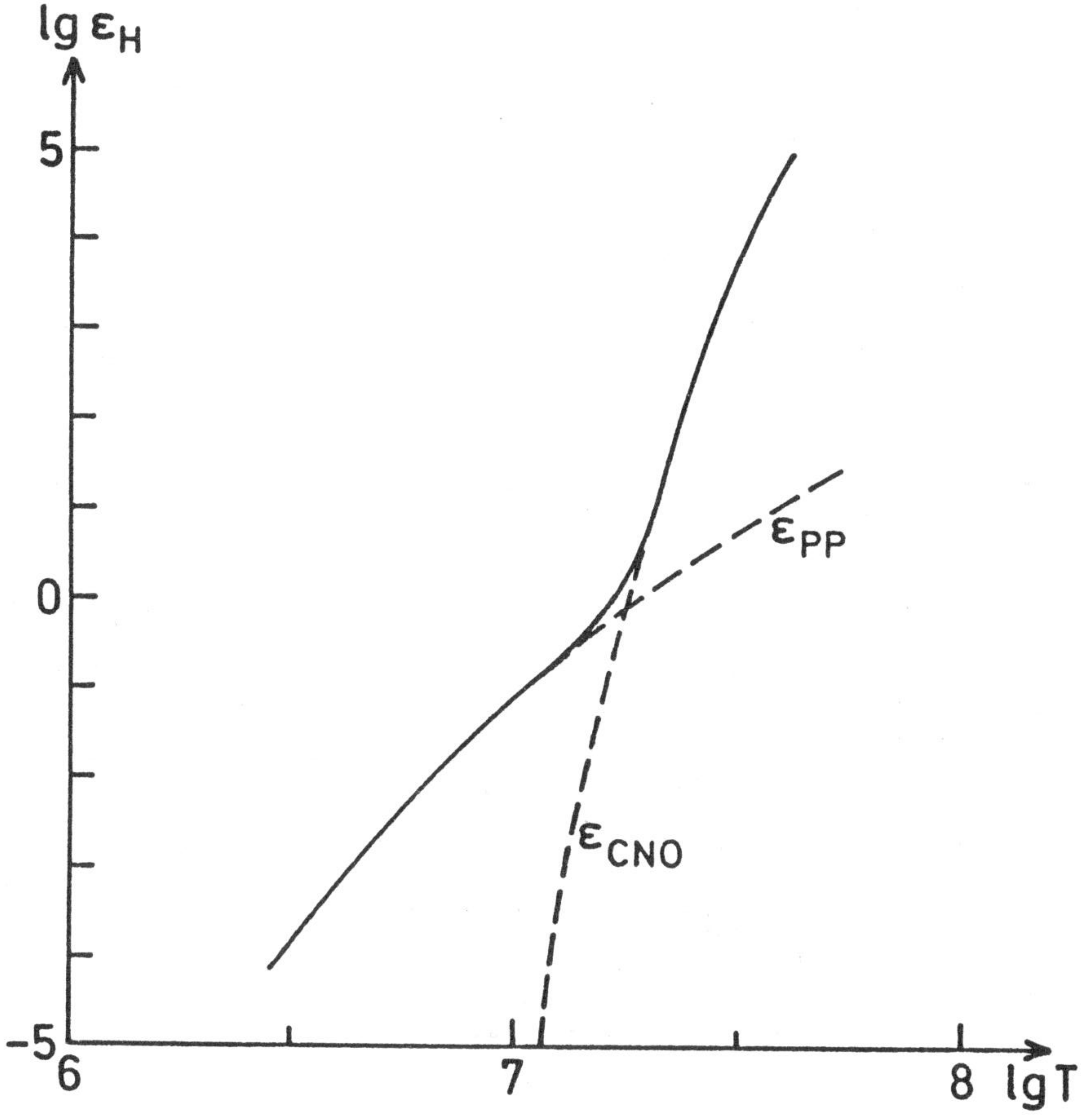
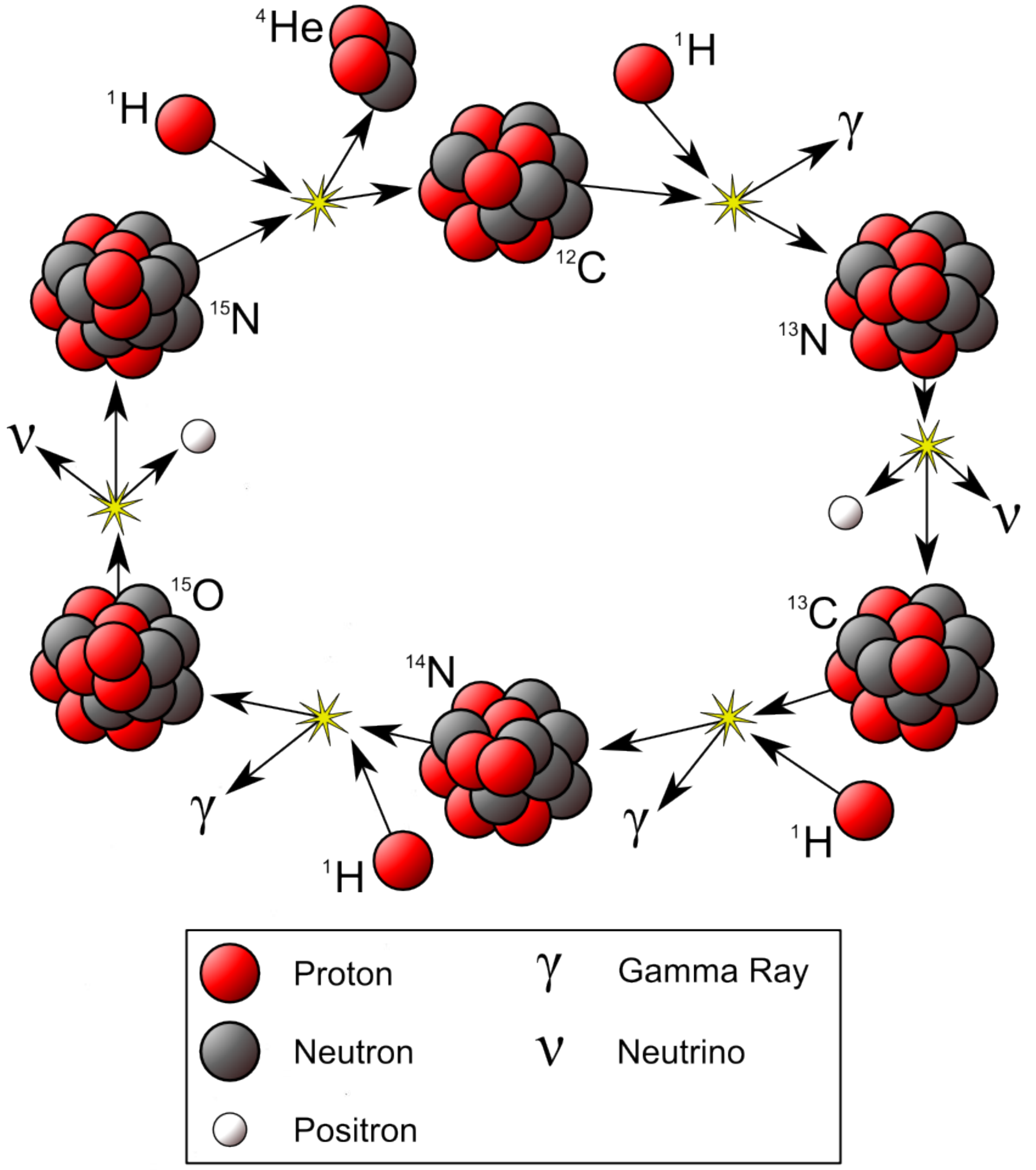
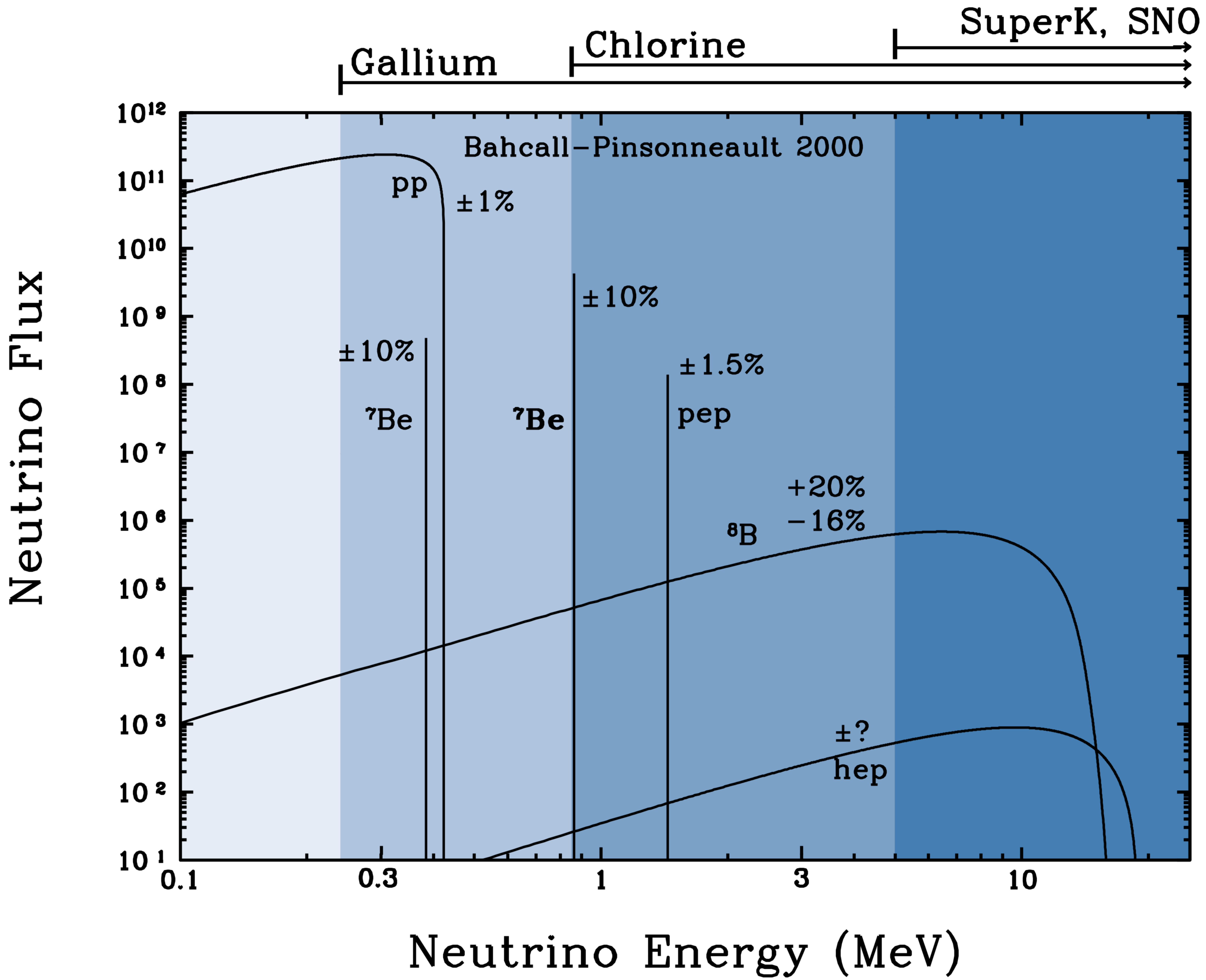


Fig. 18.8. Total energy generation rate ε_H (in erg g^{-1} s^{-1}) for hydrogen burning (*solid line*) over the temperature T (in K), for $\varrho = 1$ g cm^{-3}, $X_1 = 1$, $X_{CNO} = 0.01$. The contributions of the *pp* chain and the CNO cycle are dashed





Gallium
Chlorine
SuperK, SNO
Bahcall–Pinsonneault 2000
pp
±1%
±10%
±10%
±1.5%
7Be
7Be
pep
+20%
−16%
8B
±?
hep
Neutrino Flux
Neutrino Energy (MeV)
0.1
0.3
1
3
10

TABLE 8

Solar Neutrino Rates

Experiment	BP2000	Measured	Measured/BP2000
Chlorine	$7.6^{+1.3}_{-1.1}$	2.56 ± 0.23	0.34 ± 0.06
GALLEX+GNO	128^{+9}_{-7}	$74.1^{+6.7}_{-7.8}$	0.58 ± 0.07
SAGE..........................	128^{+9}_{-7}	$75.4^{+7.8}_{-7.4}$	0.59 ± 0.07
^{8}B-Kamiokande	$5.05[1.00^{+0.20}_{-0.16}]$	$2.80[1.00 \pm 0.14]$	0.55 ± 0.13
^{8}B-Super-Kamiokande	$5.05[1.00^{+0.20}_{-0.16}]$	$2.40[1.00^{+0.04}_{-0.03}]$	0.48 ± 0.09
hep-Super-Kamiokande......	9.3	$11.3(1 \pm 0.8)$	~ 1

Note.—Theory vs. experiment. The units are SNU (10^{-36} interactions atom^{-1} s^{-1}) for the radiochemical experiments: chlorine, GALLEX+GNO, and SAGE. The units for the ^{8}B and *hep* fluxes are, respectively, 10^{6} and 10^{3} cm^{-2} s^{-1}. The errors quoted for measured/BP2000 are the quadratically combined uncertainties for both BP2000 and the measured rates. For simplicity in presentation, asymmetric errors were averaged. Refer
given in the text and in Lande 2001, Bellotti et al. 2001, G
Suzuki 2001 for the chlorine, GALLEX+GNO, SAGE, K
results.

- ¿el experimento está mal?
- ¿el modelo estándar del Sol está mal?
- ¿la física de neutrinos está mal?

Raymond Davis, Jr.: A half

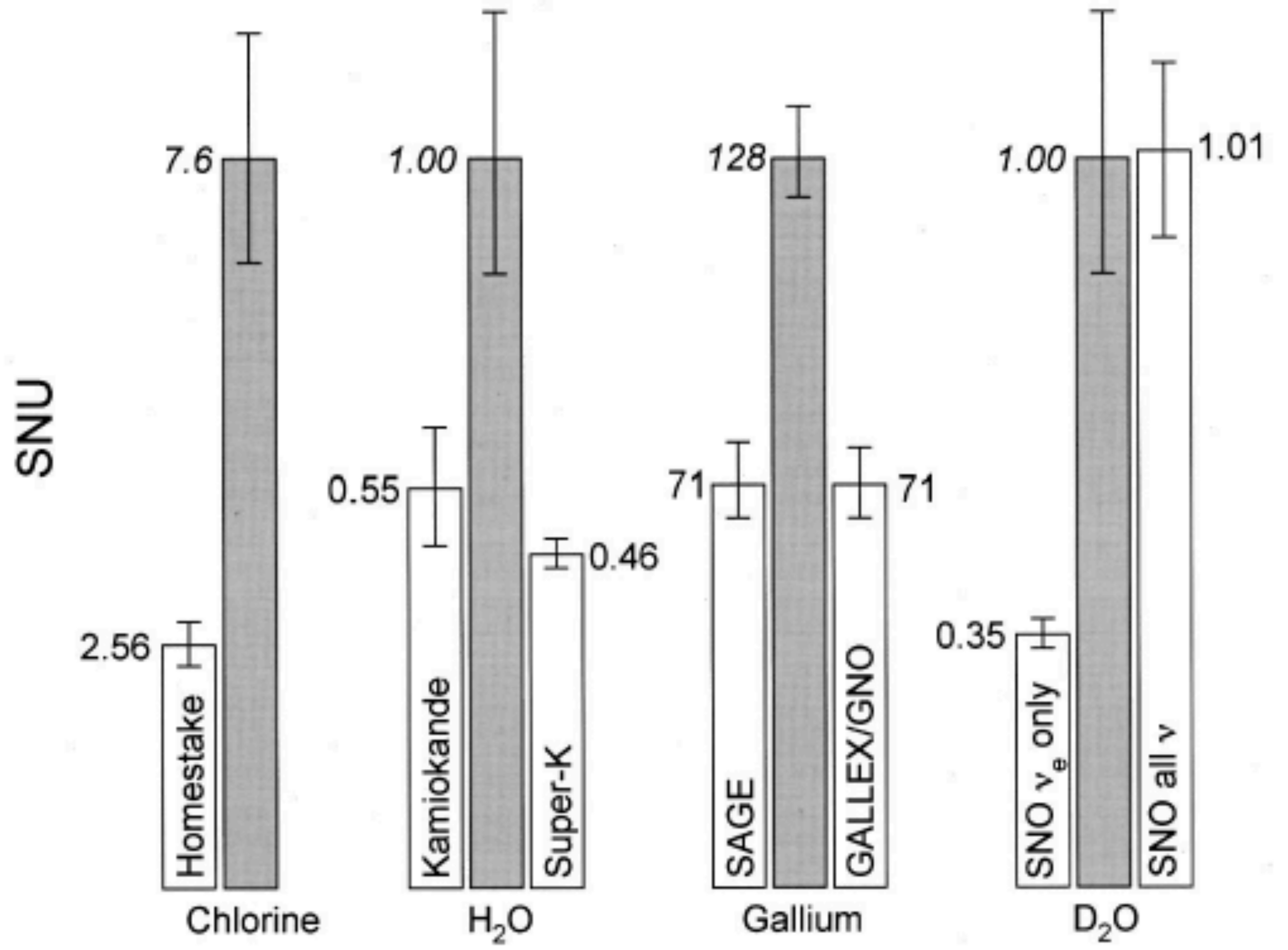


FIG. 16. A comparison of measured solar neutrino flux from the chlorine experiment, two gallium experiments (SAGE and GALLEX/GNO), two water Cerenkov experiments (Kamiokande and Super-Kamiokande) and the SNO D_2O experiment with theoretical predictions of Bahcall *et al.* (2001). The

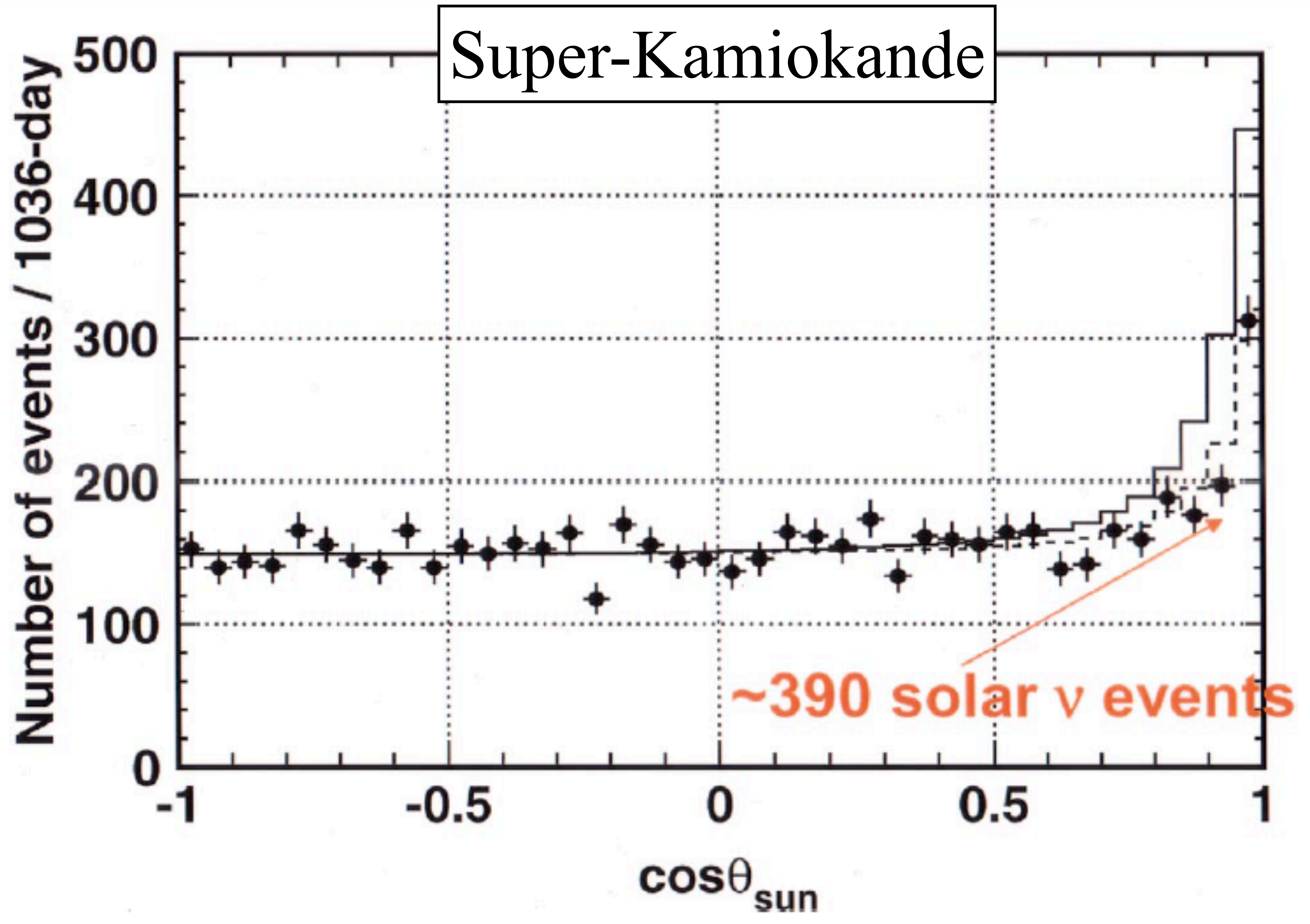


FIG. 7. (Color in online edition) The directional observation of solar neutrinos.

Oscilaciones de neutrinos

- Los neutrinos que se observan ("sabores") son superposiciones de estados de masa,

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix},$$

  con θ el ángulo de mezclado entre los estados 1 y 2.
- El desarrollo resulta en

$$\mathrm{Prob}(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(1.27 L_{\mathrm{km}}\,\Delta m^2_{\mathrm{eV}}/E_{\mathrm{GeV}}\right),$$

  con $\Delta m^2 = |m^2_\alpha - m^2_\beta|$ en el vacío.
- La presencia de materia altera L.

La masa del neutrino

- Acotada experimentalmente por debajo de 1 eV.

Experimento	Cota
Mediciones cosmológicas:	$m_\nu = \sum_i m_{\nu_i} < 120\,\mathrm{meV}$.
→ Futuros exp	$\sigma(m_\nu) = 17\,\mathrm{meV}$.
Neutrino-less double β decay:	$m_{\beta\beta} = 120 - 250\,\mathrm{meV}$.
→ Futuros exp	$m_{0\nu\beta\beta} = 25\,\mathrm{meV}$.
Decaimiento β directo:	$m_{\nu_e} = 200\,\mathrm{meV}$.

Mertens (arxiv 1605.01579).

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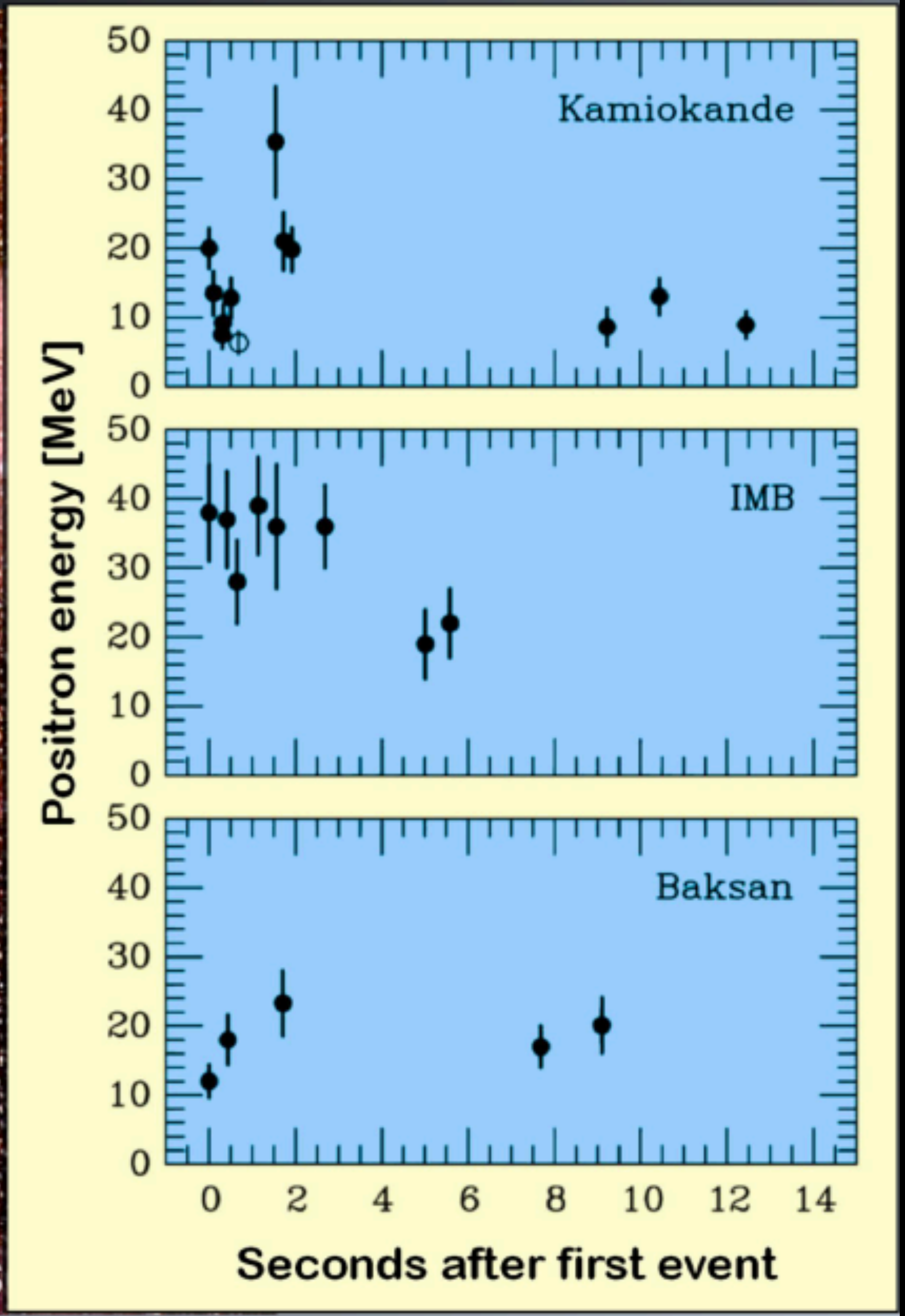
HST - oct 2011

Rangos espectrales

the birth of neutrino astronomy: supernova 1987A

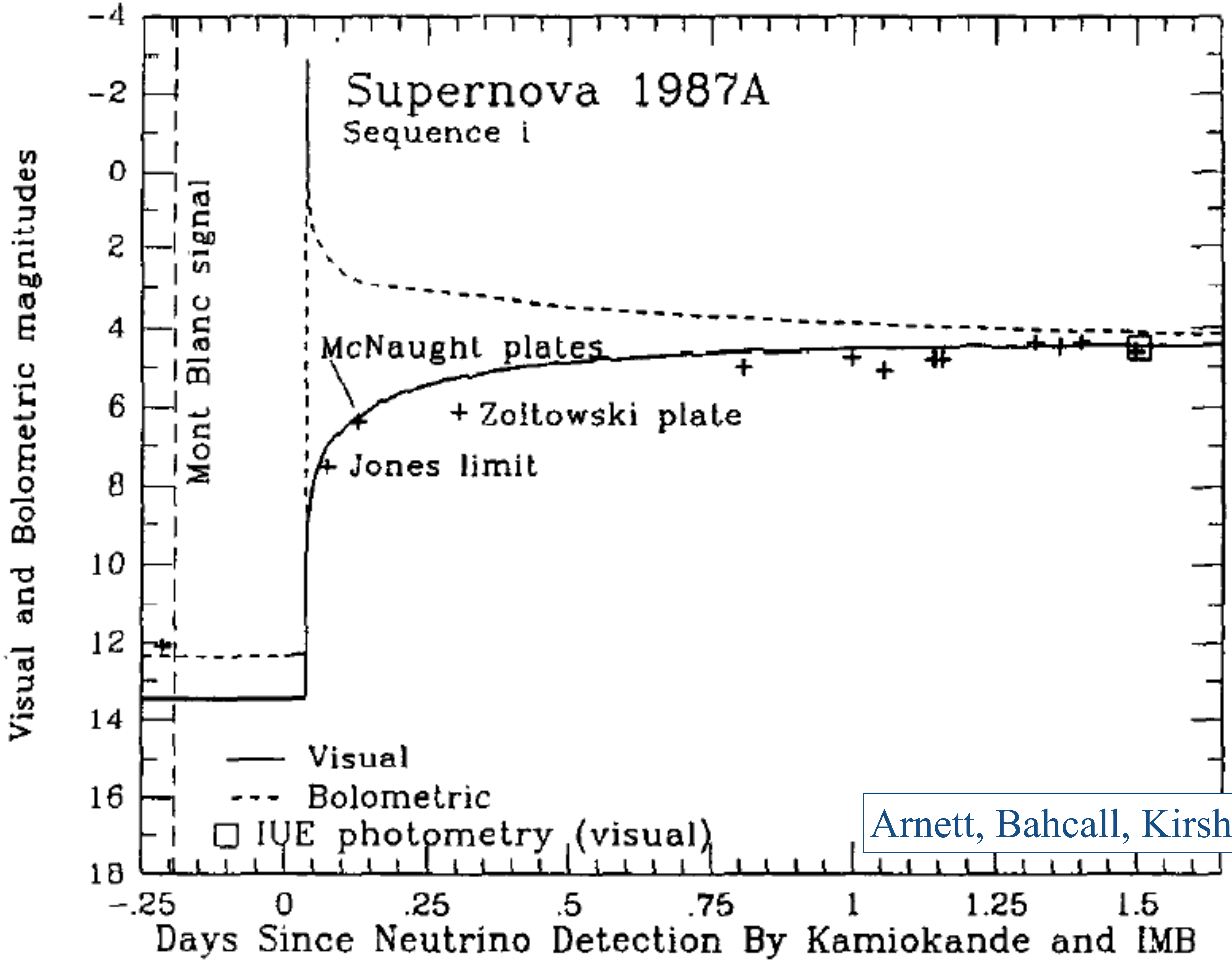


Halzen @ ICRC 2019

3. SN 1987A

- El 23 de febrero de 1987 explotó en la LMC la supernova más brillante observada en 383 años (+ otros 35…). Reportada visualmente el 23.44 Feb.
- Líneas de Balmer en absorción con velocidades de 30,000 km/s (0.1c): SN tipo II, sub-luminosa.
- Identificación previa de la progenitora de la supernova (siendo el segundo caso): Sk −69º202, tipo B3I, estrella azul de 20 $M_\odot$.
- La detección de neutrinos aportó la primera evidencia observacional de la formación de una estrella de neutrones por colapso estelar.

Arnett, Bahcall, Kirshner, Woosley - ARAA 27, 629 (1989).



Arnett, Bahcall, Kirshner, Woosley - ARAA 27, 629 (1989).

SN 1987A

Table 1 Burning stages in the evolution of a 20-$M_\odot$ star

Fuel	ρ_c (g cm^{-3})	T_c (10^9 K)	τ (yr)	L_{phot} (erg s^{-1})	L_ν (erg s^{-1})
Hydrogen	5.6(0)	0.040	1.0(7)	2.7(38)	—
Helium	9.4(2)	0.19	9.5(5)	5.3(38)	<1.0(36)
Carbon	2.7(5)	0.81	3.0(2)	4.3(38)	7.4(39)
Neon	4.0(6)	1.7	3.8(−1)	4.4(38)	1.2(43)
Oxygen	6.0(6)	2.1	5.0(−1)	4.4(38)	7.4(43)
Silicon	4.9(7)	3.7	2 days	4.4(38)	3.1(45)

Núcleo estelar de He de 5 a 7 $M_\odot$.

Arnett, Bahcall, Kirshner, Woosley - ARAA 27, 629 (1989).

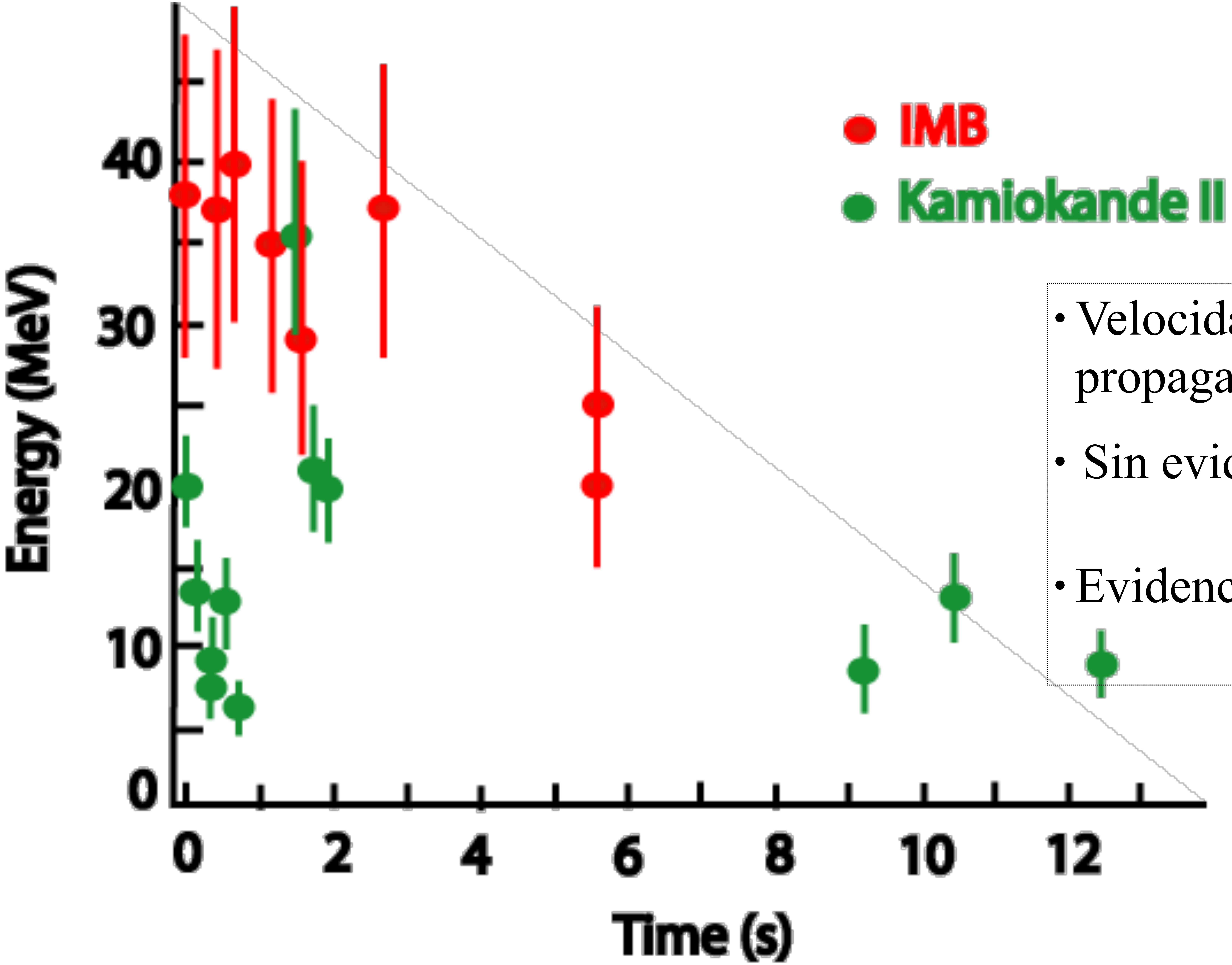
Explosión de SN 1987A

- Primera evidencia observacional de la formación de una estrella de neutrones por colapso estelar.
- $E_\nu \simeq 2.7 \times 10^{53}$ erg $\simeq 0.15\ M_\odot c^2$

  1% rebote (20 ms) y 99% enfriado térmico con temperatura $T \simeq 4.2(+1.2\ ,-0.8)$ MeV;

  enfriamiento exponencial con $\tau \simeq 4.5\ (+1.7\ ,\ -2.0)$ s.
- Al mes la curva de luz mostró comportamiento característico de ^{56}Co. Evidencia posterior de ^{44}Ti.
- Límite a la masa del e-neutrino de alrededor de ~11 eV.

Arnett, Bahcall, Kirshner, Woosley - ARAA 27, 629 (1989).



- Velocidad consistente con c a 10^{-8}; propagación sobre la misma geodésica.
- Sin evidencia de la estrella de neutrones
  arXiv 1805.04526
- Evidencia de la estrella de neutrones!?
  Cygan et al. (2020)

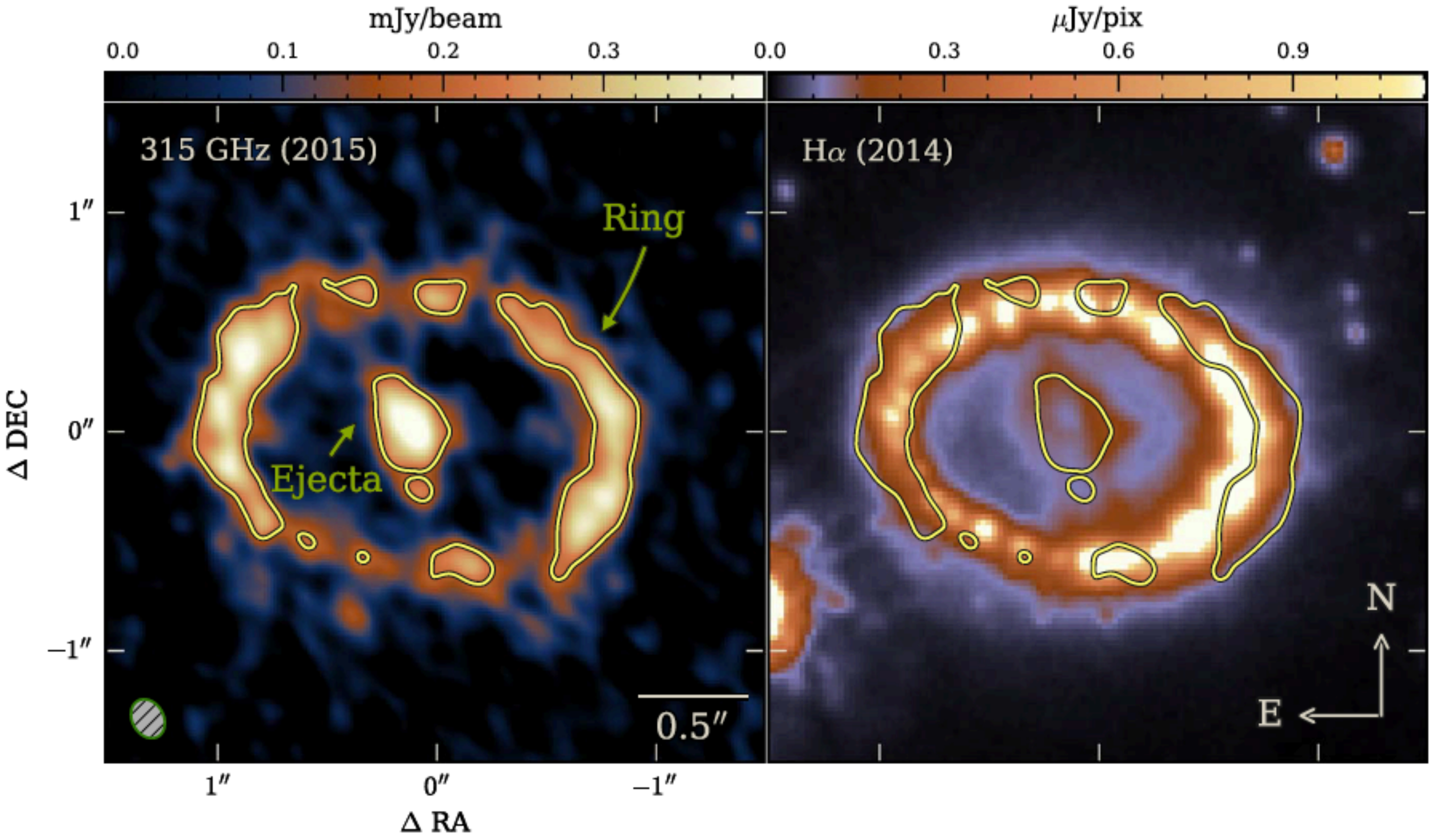


Figure 2. ALMA 315 GHz (with beam) and 2014 *HST* F625W band image (Fransson et al. 2015), which includes Hα. The yellow contours display 315 GHz emission at 0.2 mJy beam^{-1}. The 315 GHz continuum in the inner ejecta originates from thermal dust emission, while in the ring it is due to synchrotron emission. The 18 mas uncertainty on the relative alignment due to Band 7 astrometric error (12 mas) and *HST* image registration based on fitting the ring (6 mas) is of order 1 pixel in these images.

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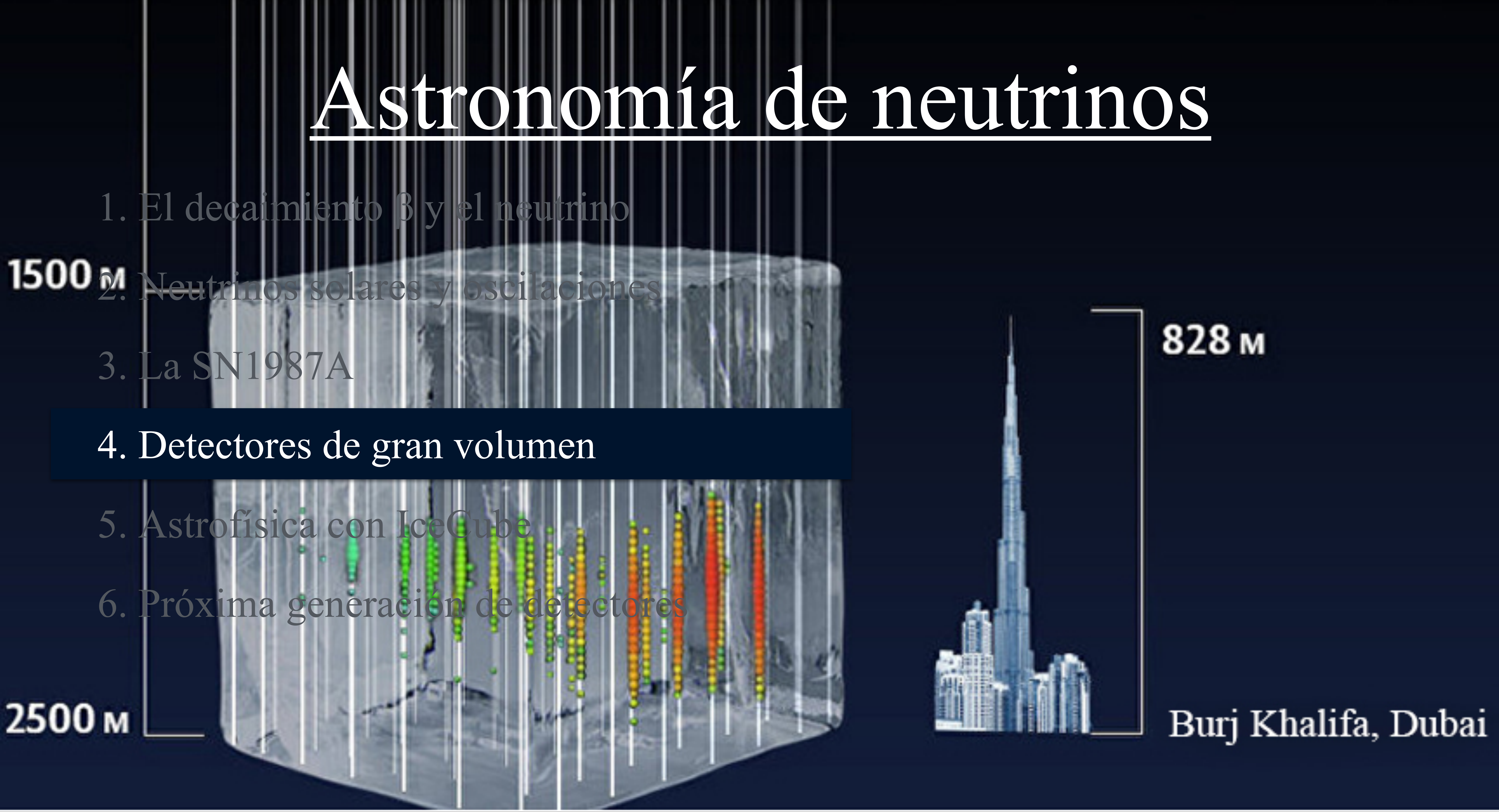
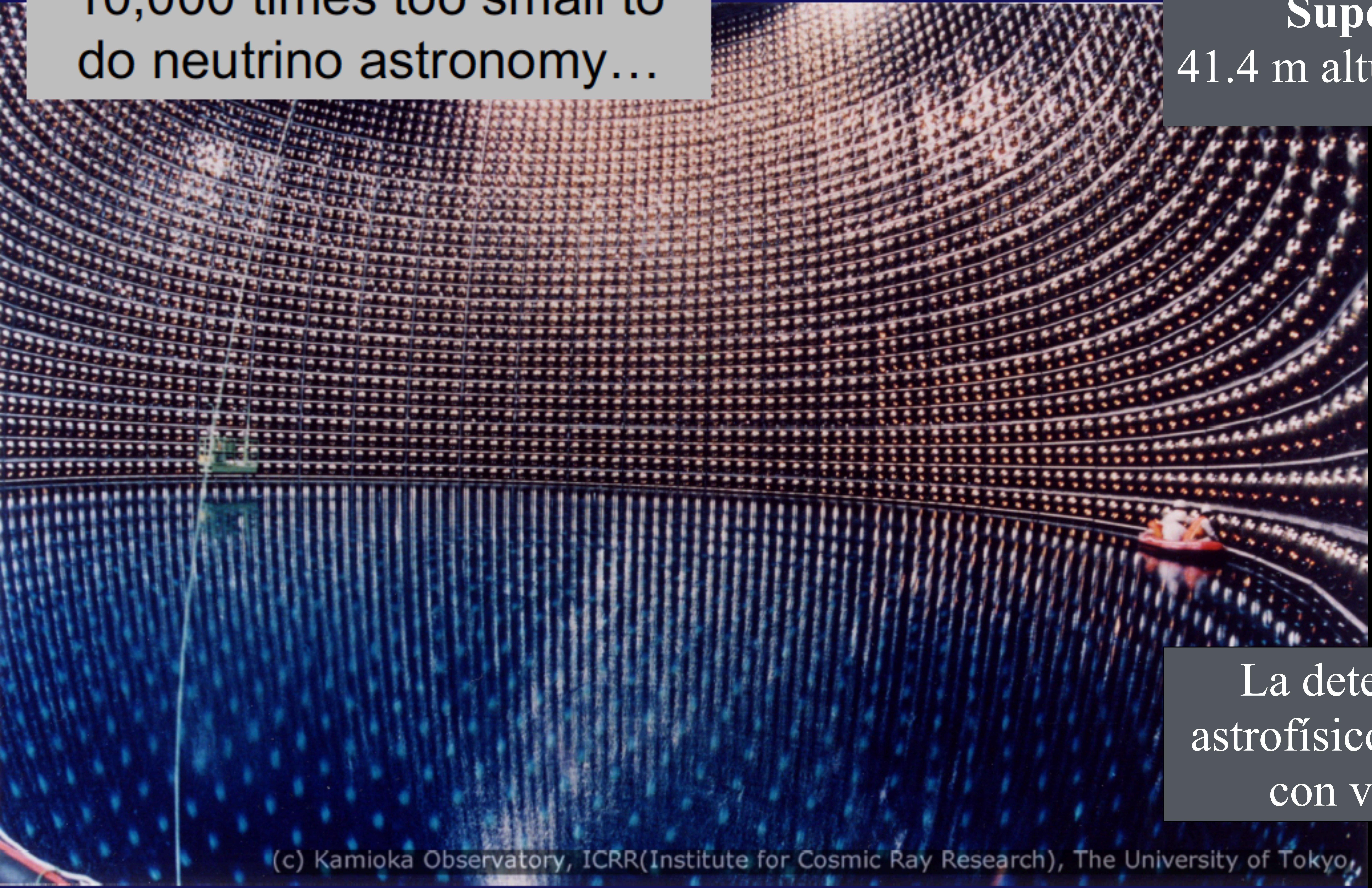


10,000 times too small to do neutrino astronomy…

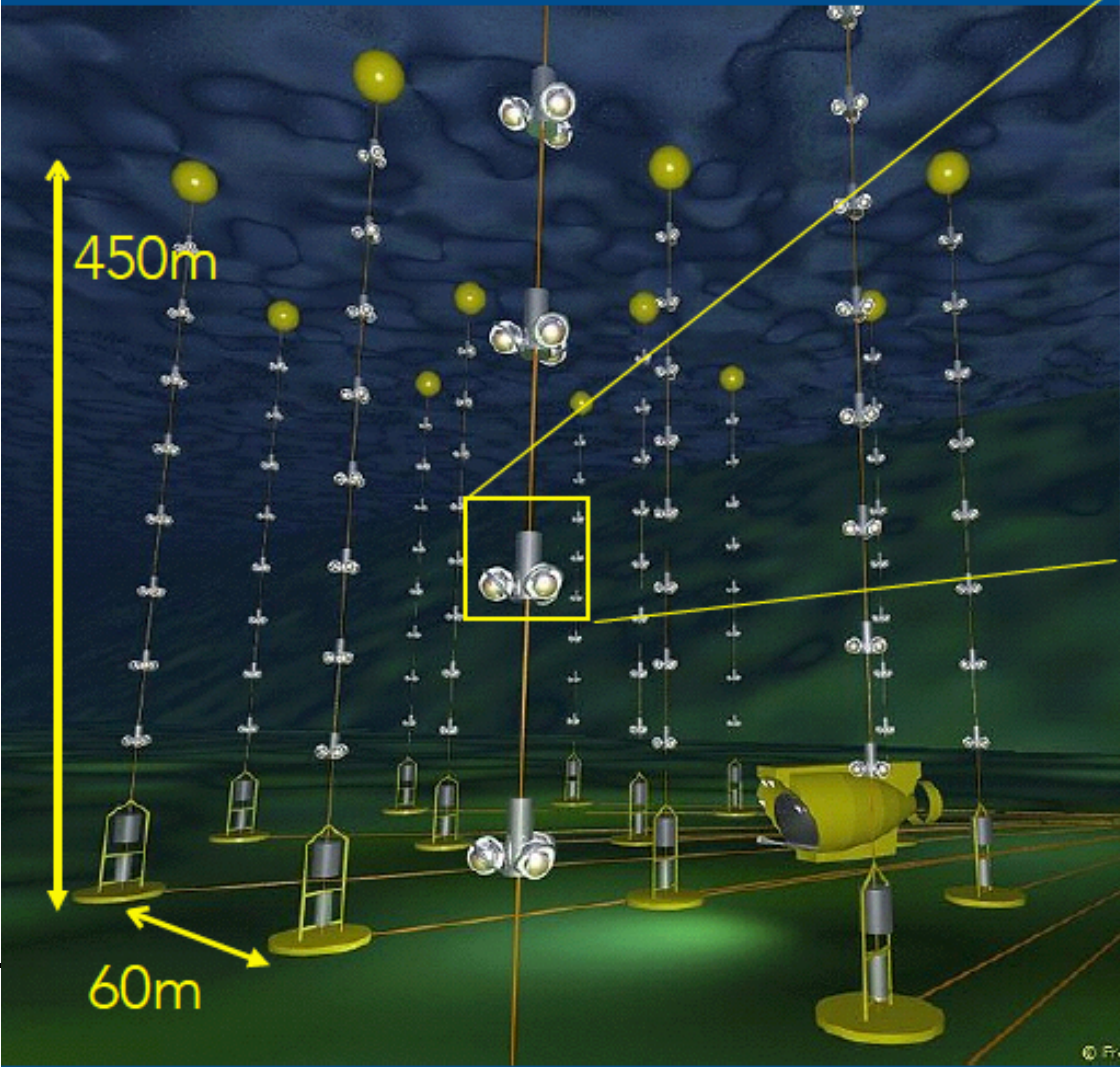
Super-Kamiokande
41.4 m altura × 39.3 m diámetro



La detección de neutrinos astrofísicos requiere detectores con volúmenes de km^3

Lake Baikal experiment observes atmospheric neutrinos

THE ANTARES DETECTOR



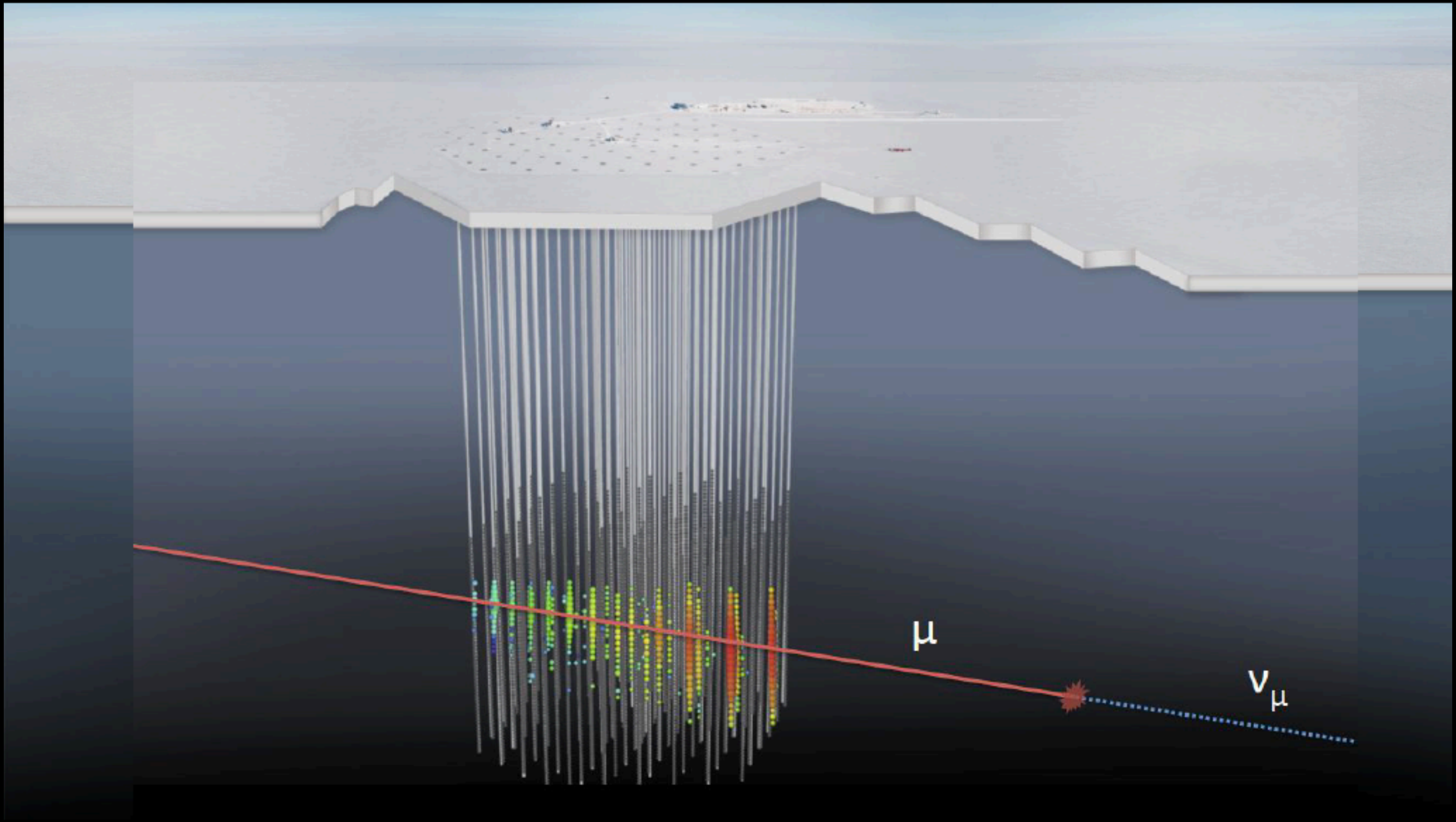
Optical sensor
1 PMT of 10 inches

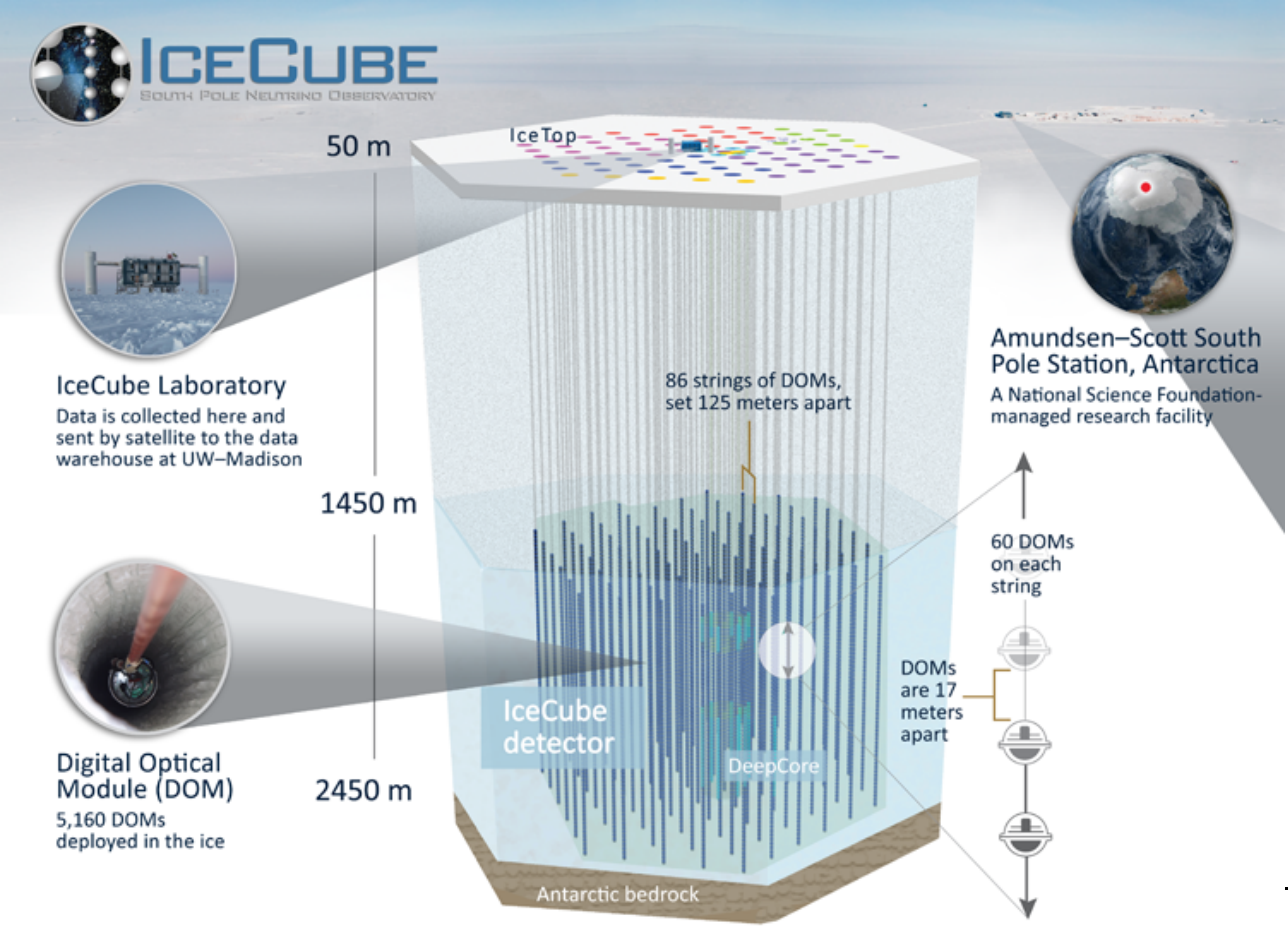
Depth 2475m

- 12 lines of 75 PMTs
- 1 line for Earth and Marine sciences
- 25 storeys / line
- 3 PMTs / storey
- 885 PMTs
- **Volume 0.01 km³**

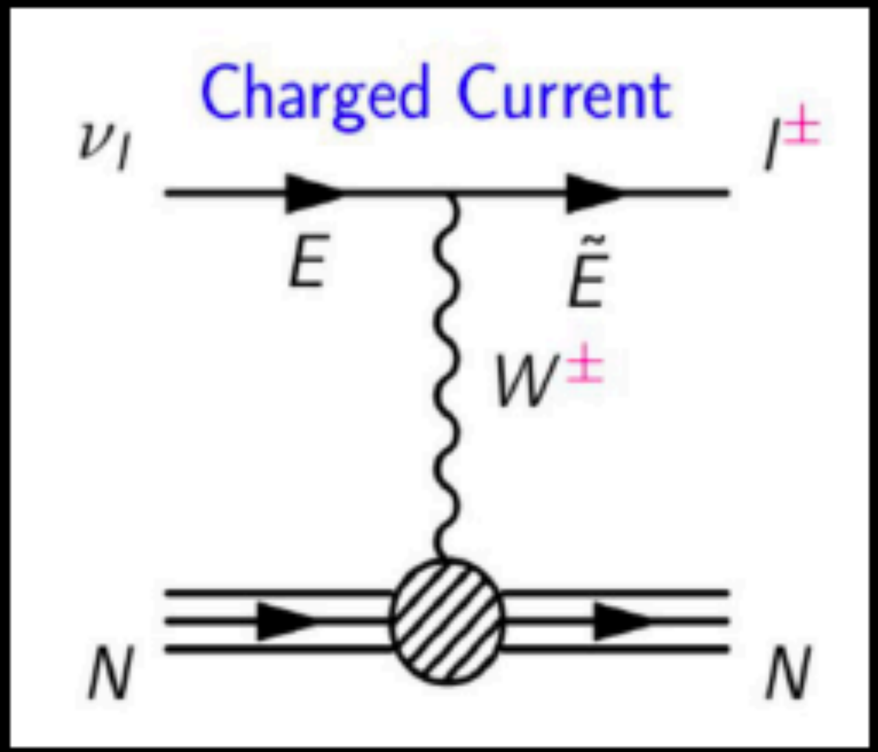
Detector completed in 2008
Taking data since 11 years
with a duty cycle of ~95%

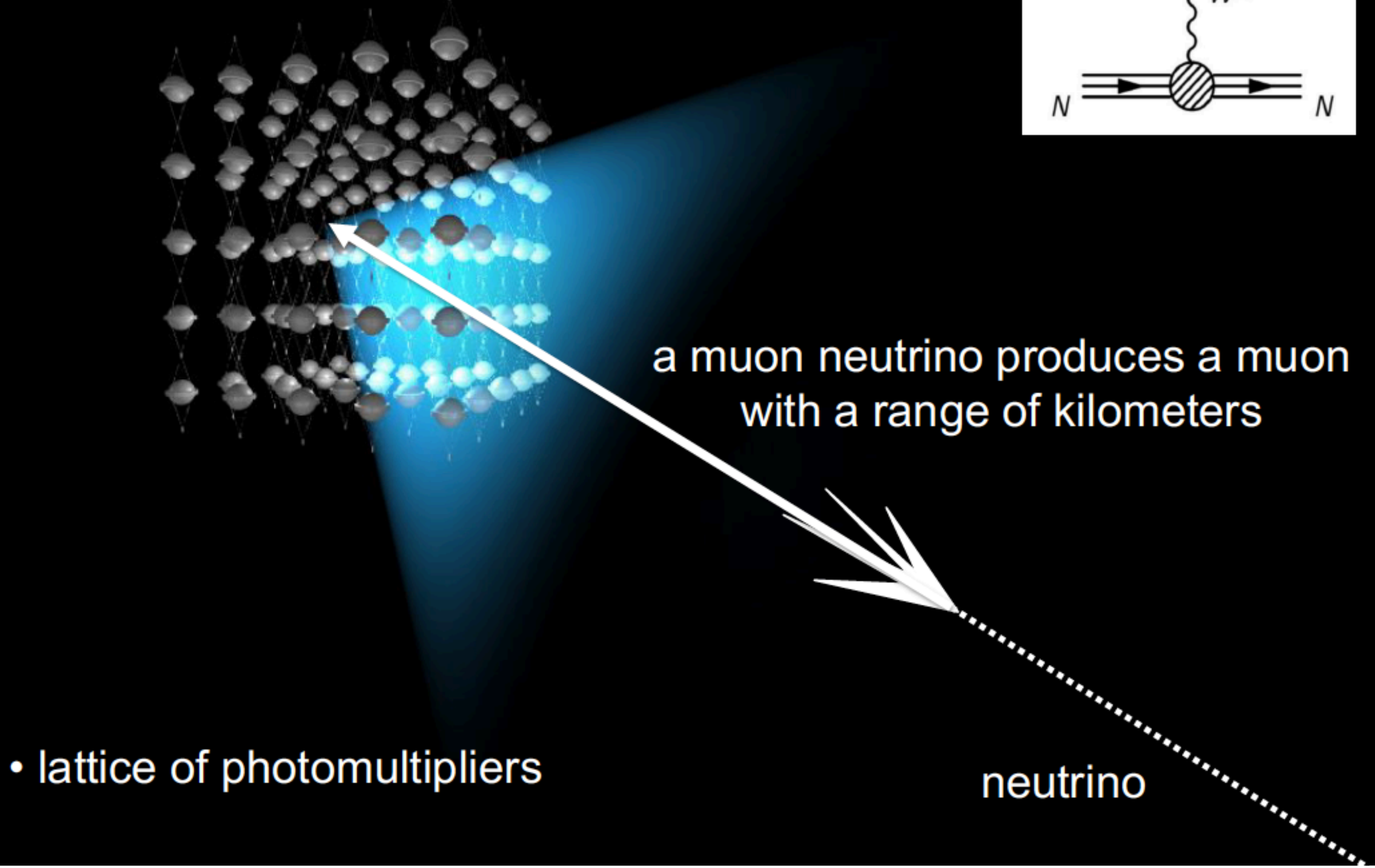
instrument 1 cubic kilometer of natural ice below 1.45 km



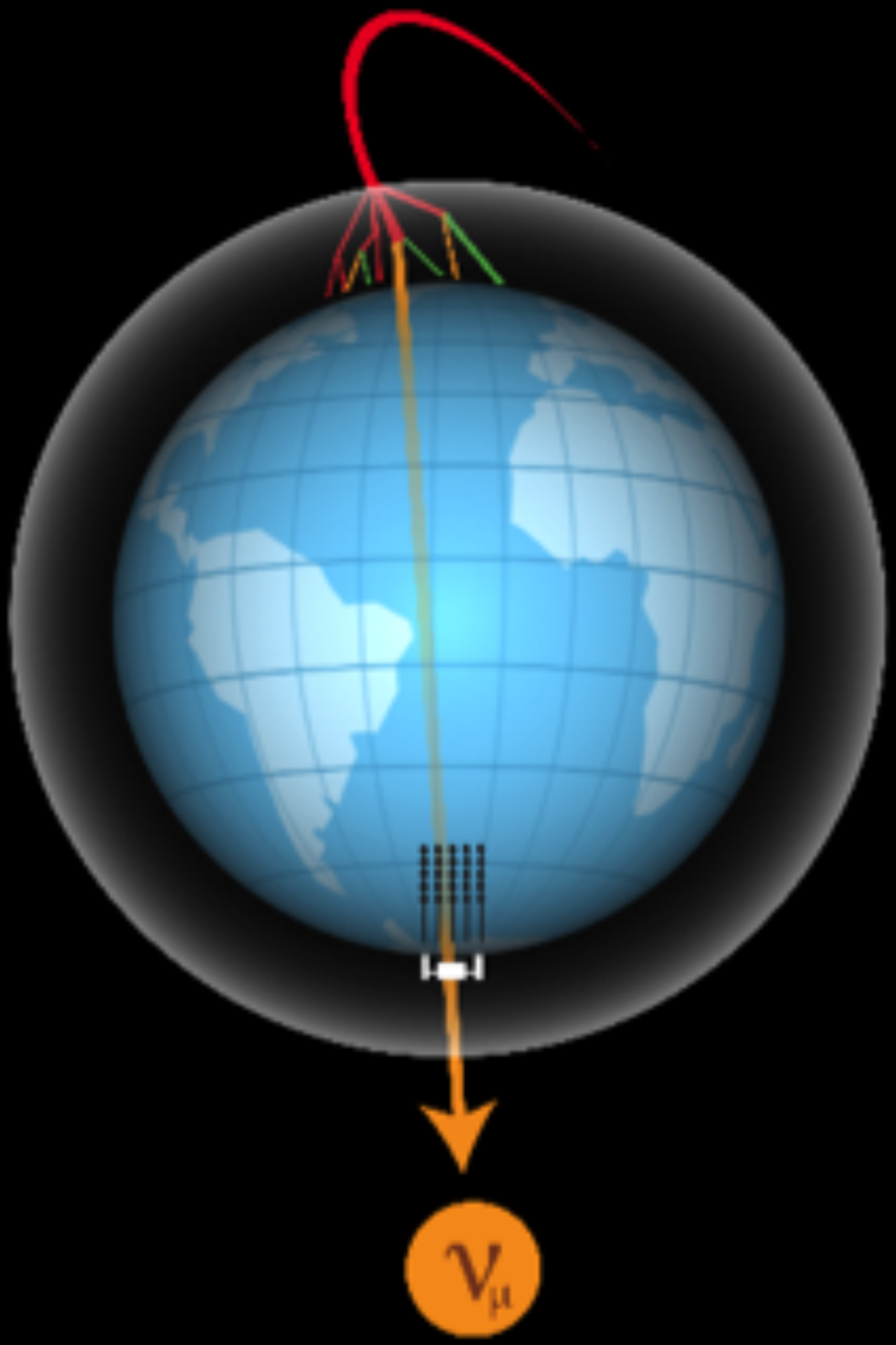

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
IceTop
50 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
1450 m
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
2450 m
86 strings of DOMs, set 125 meters apart
IceCube detector
DeepCore
Antarctic bedrock
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
60 DOMs on each string
DOMs are 17 meters apart

Halzen, ICRC 2019

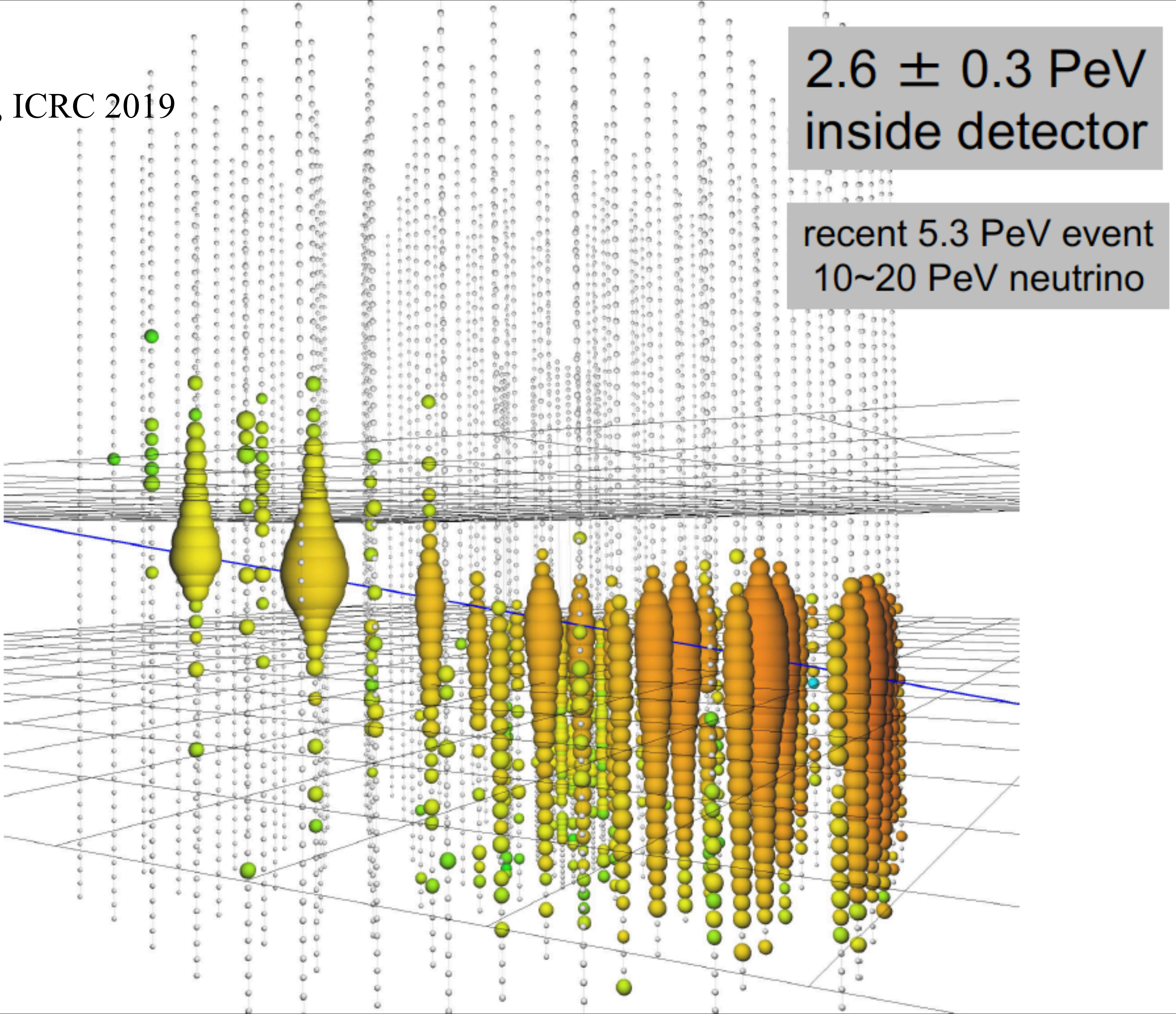




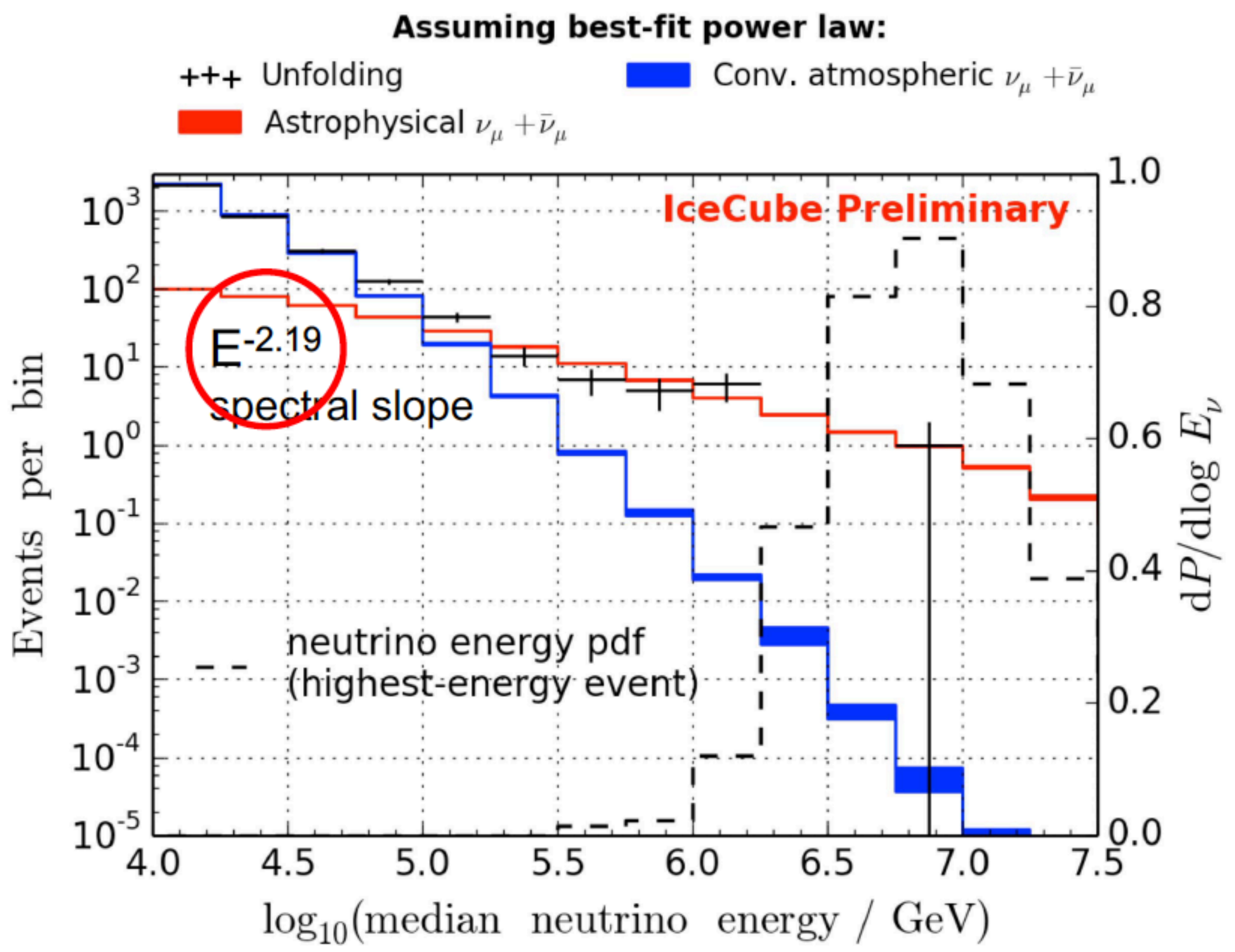
Halzen, ICRC 2019



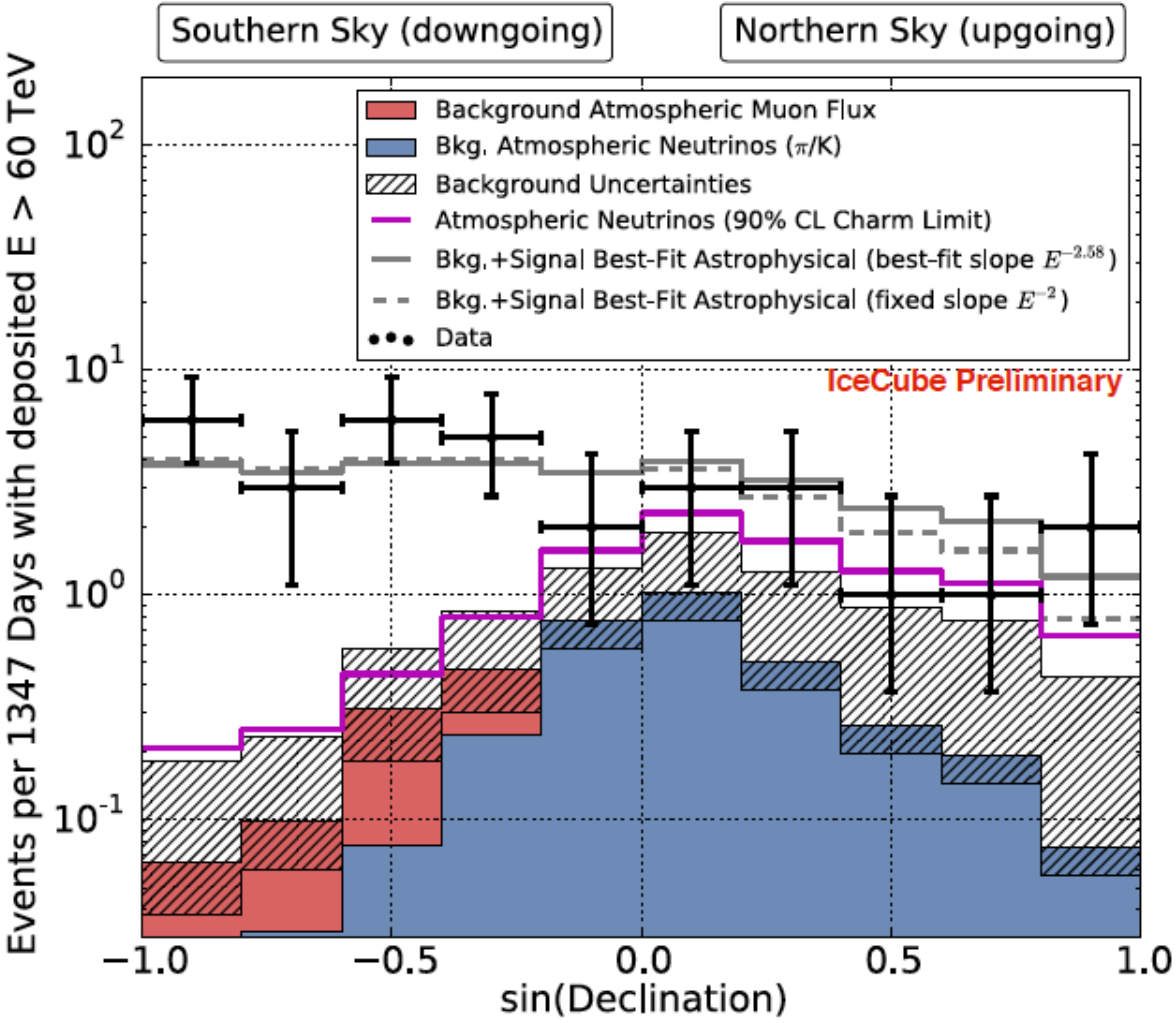
Halzen, ICRC 2019



~ 550 cosmic neutrinos in a background of ~340,000 atmospheric
atmospheric background: less than one event/deg^2/year

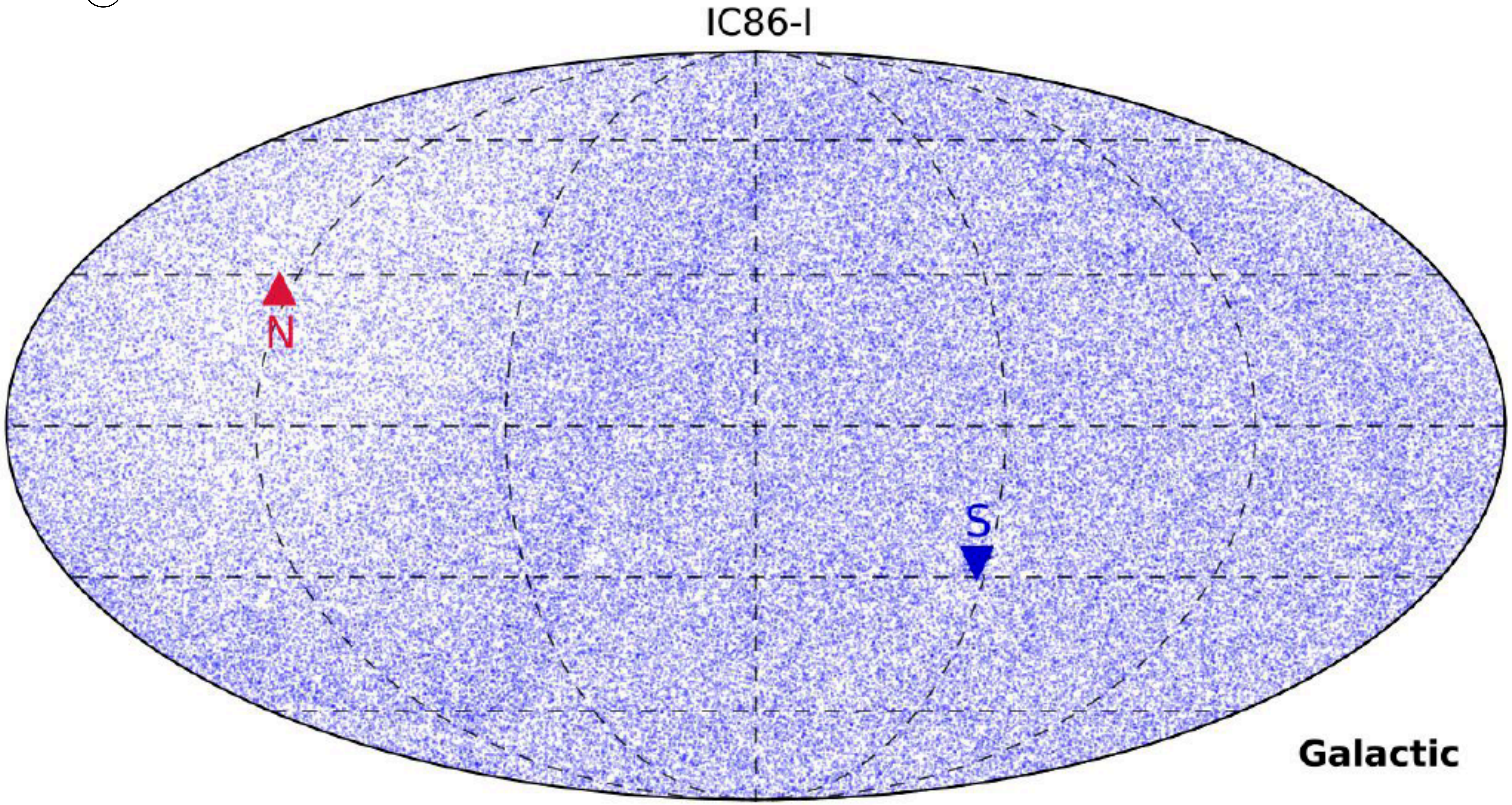


Halzen, ICRC 2019



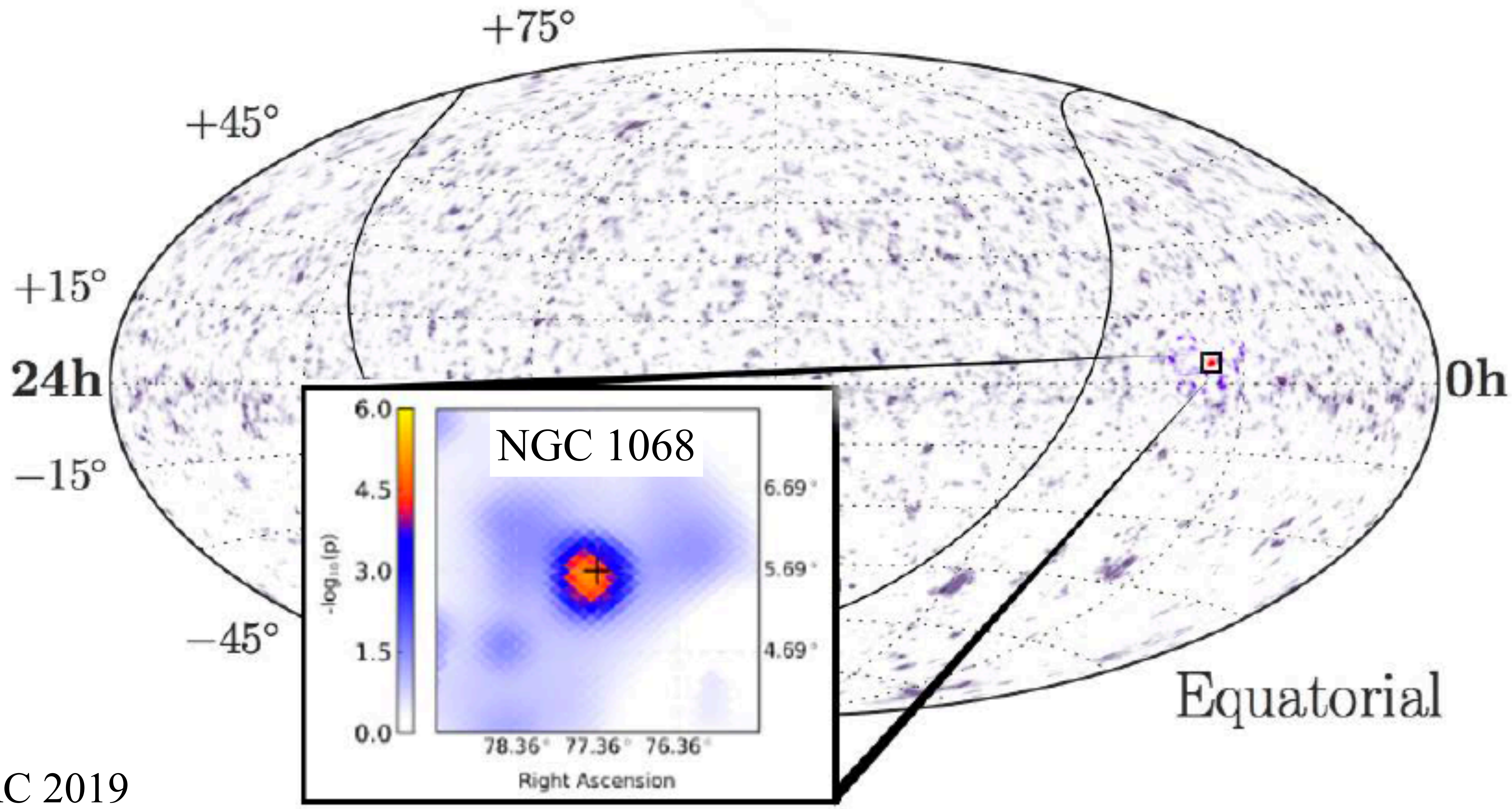
arXiv 1510.05223

Halzen @ ICRC 2019



138322 neutrino candidates in one year
120 cosmic neutrinos
~12 separated from atmospheric background with E>60 TeV
structure in the map results from neutrino absorption by the Earth

10 years of IceCube data: evidence for non-uniform skymap, mostly resulting from 4 source candidates



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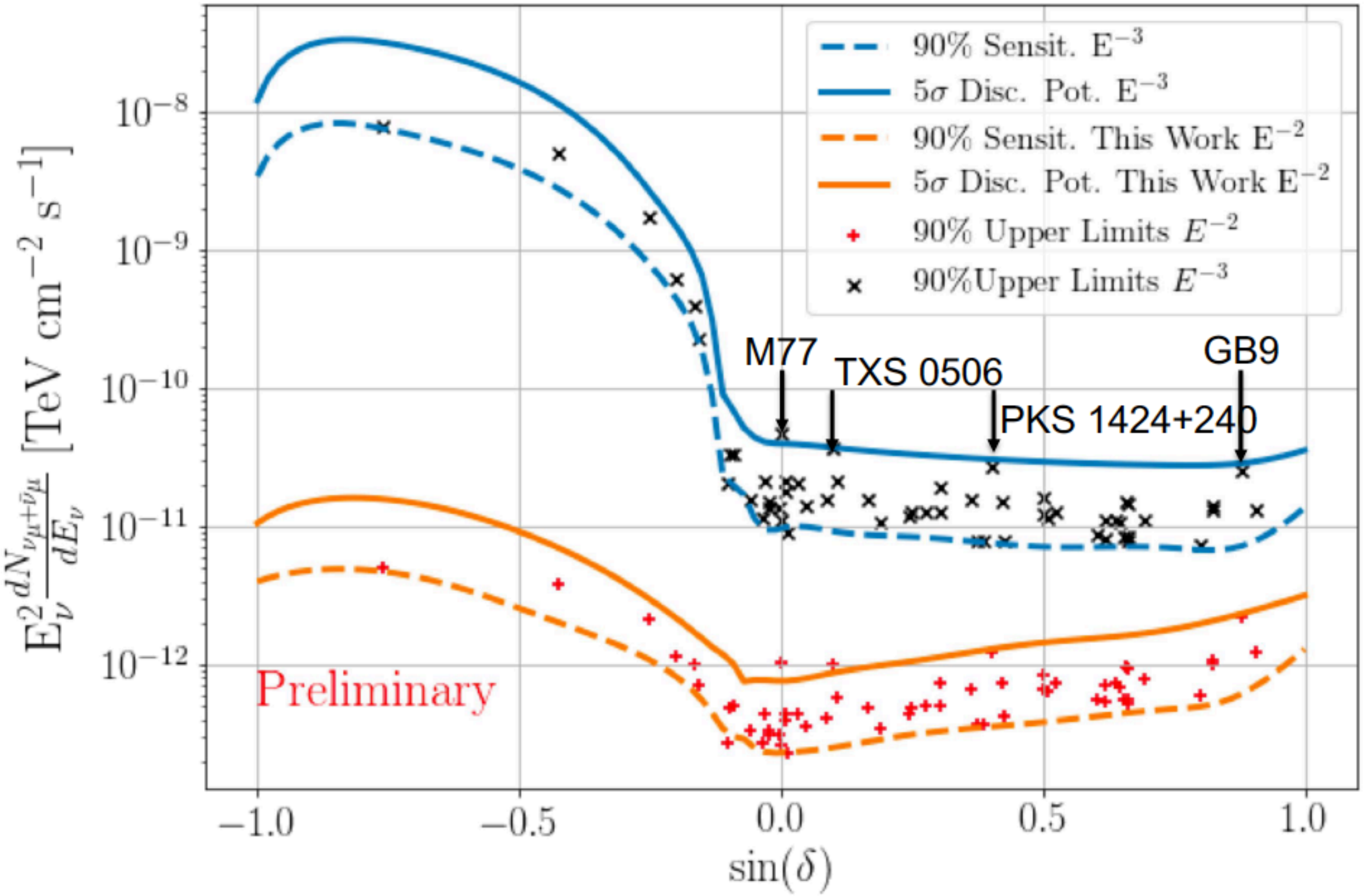
limits and fluctuations(?)



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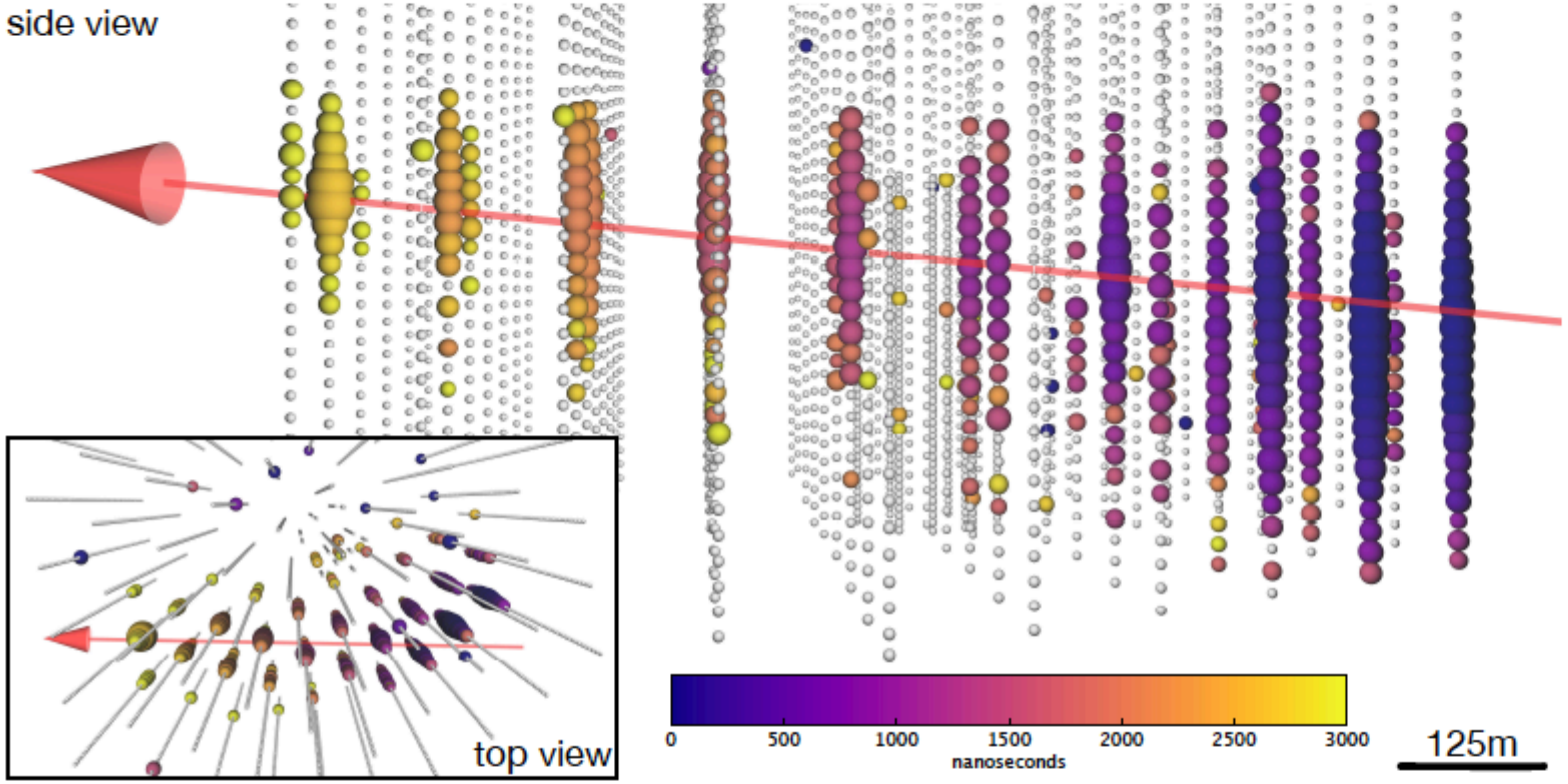
this is the case for larger detectors with better angular resolution!

IceCube-170922A

Evento del 22 septiembre 2017 reconstruido por IceCube con E_ν = 290 TeV (E_ν > 183 TeV, Prob 90%).



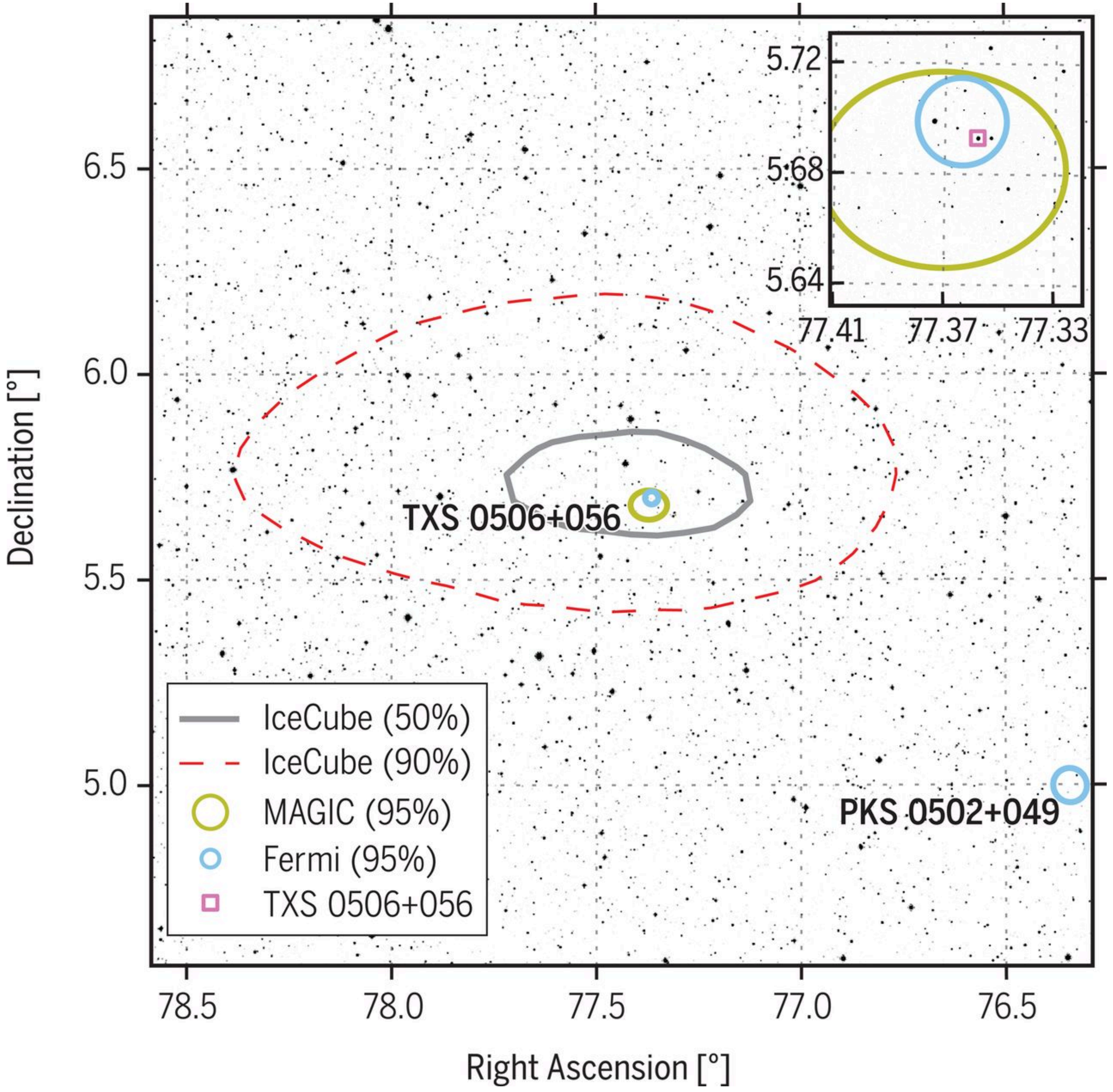
Aartsen et al. (2018) Science & 1807.08816

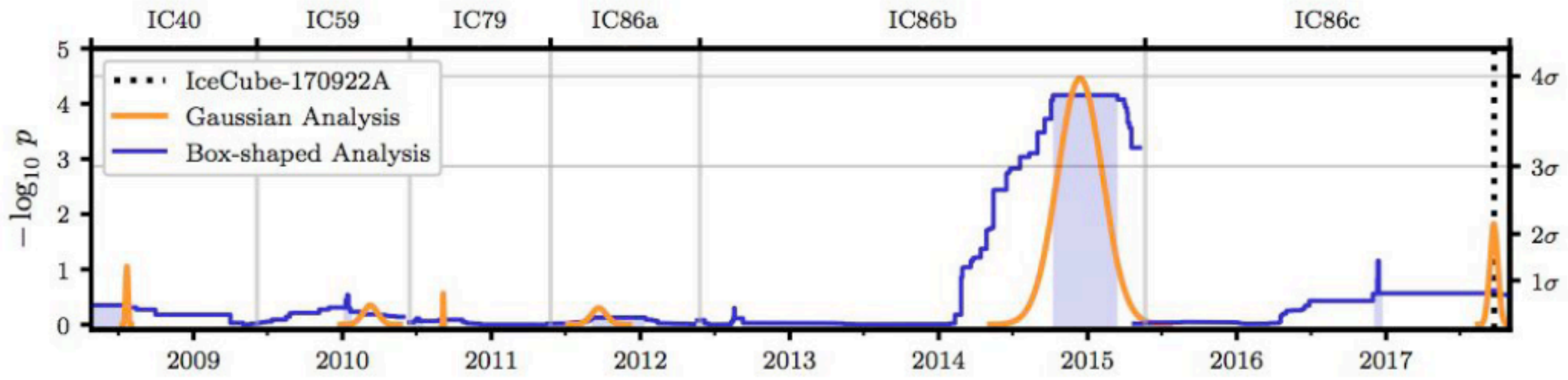
Figure 1: **Event display for neutrino event IceCube-170922A.** The time at which a DOM

Follow-up detections of IC170922 based on public telegrams

Texas 0506+056

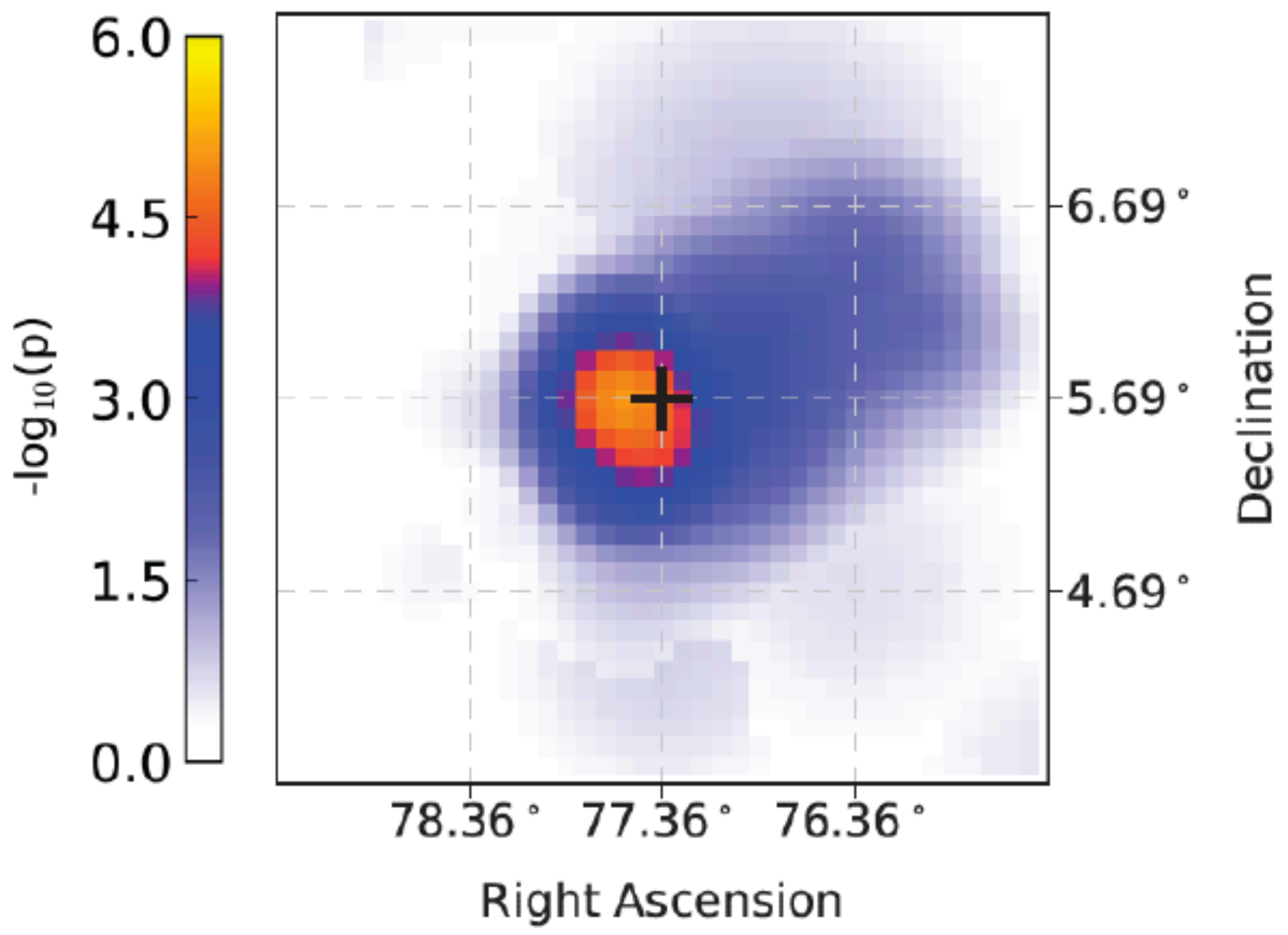
- IC-170922A coincide con 3FGL J0509.4+0541 (1FGL; EGR; 3FHL J0509.4+0542) asociado al BL Lac TXS 0506+056.
- TXS 0506+056 activo en Fermi; MAGIC lo detecta en VHE.
- GTC → z = 0.3365.





search in archival IceCube data:

- 150 day flare in December 2014 of 19 events (bkg <6)
- 2.10^{-5} bkg.probability
- spectrum $E^{-2.1}$



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Understanding neutrinos from TXS 0506+056

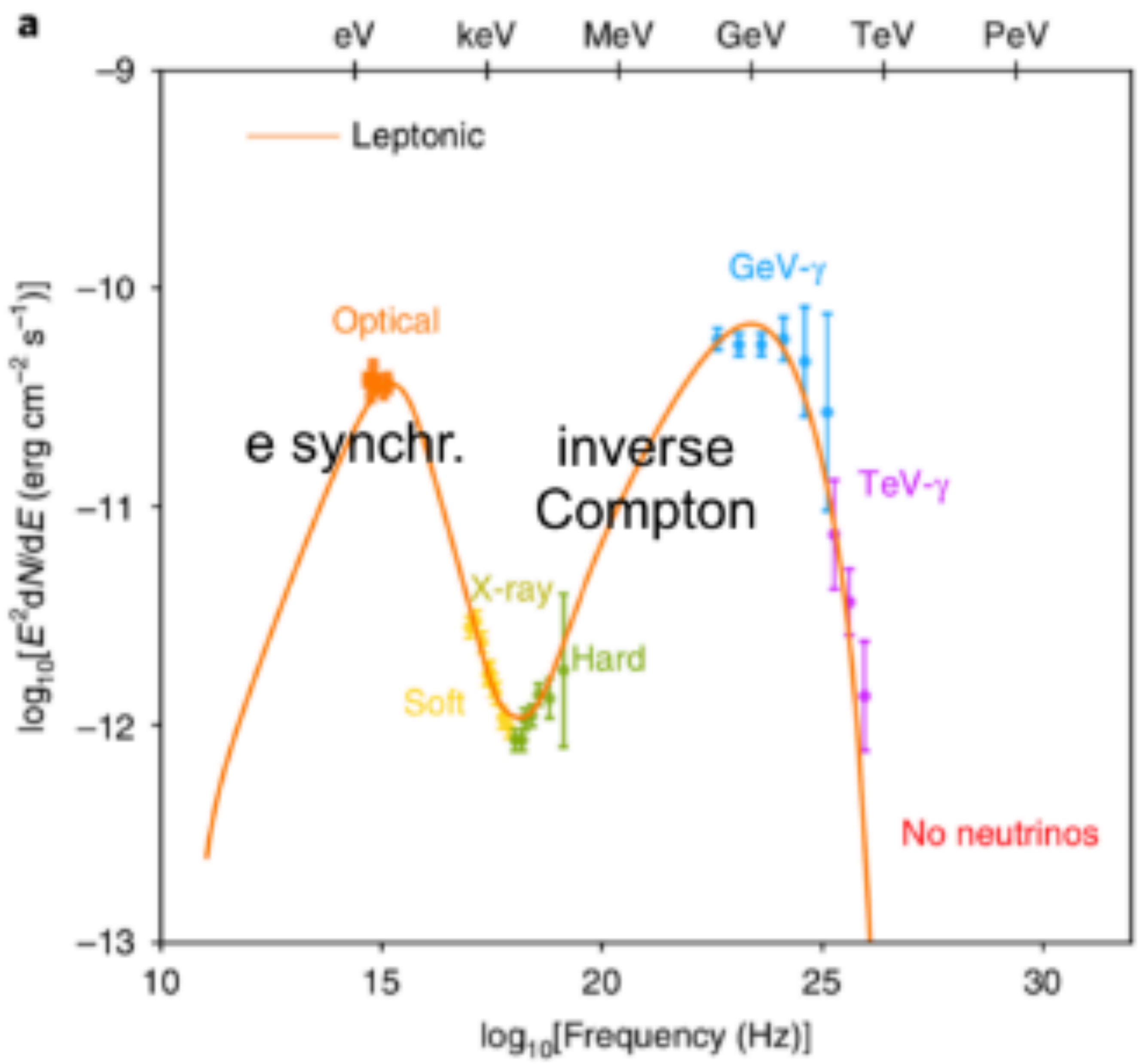
PoS(ICRC2019)1032 (Walter Winter)

One zone model results (2017 flare)

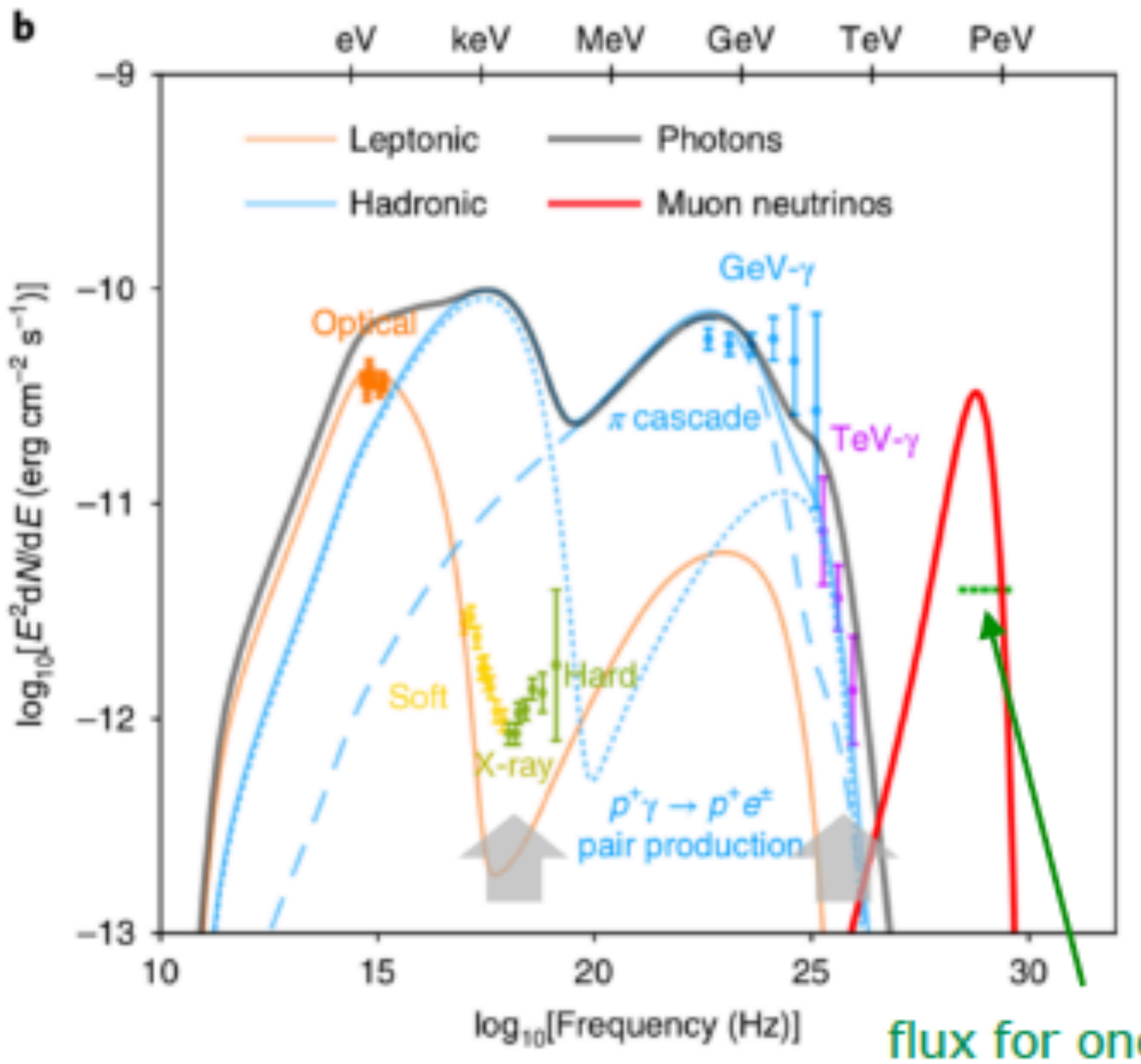
Fewest assumptions

R'

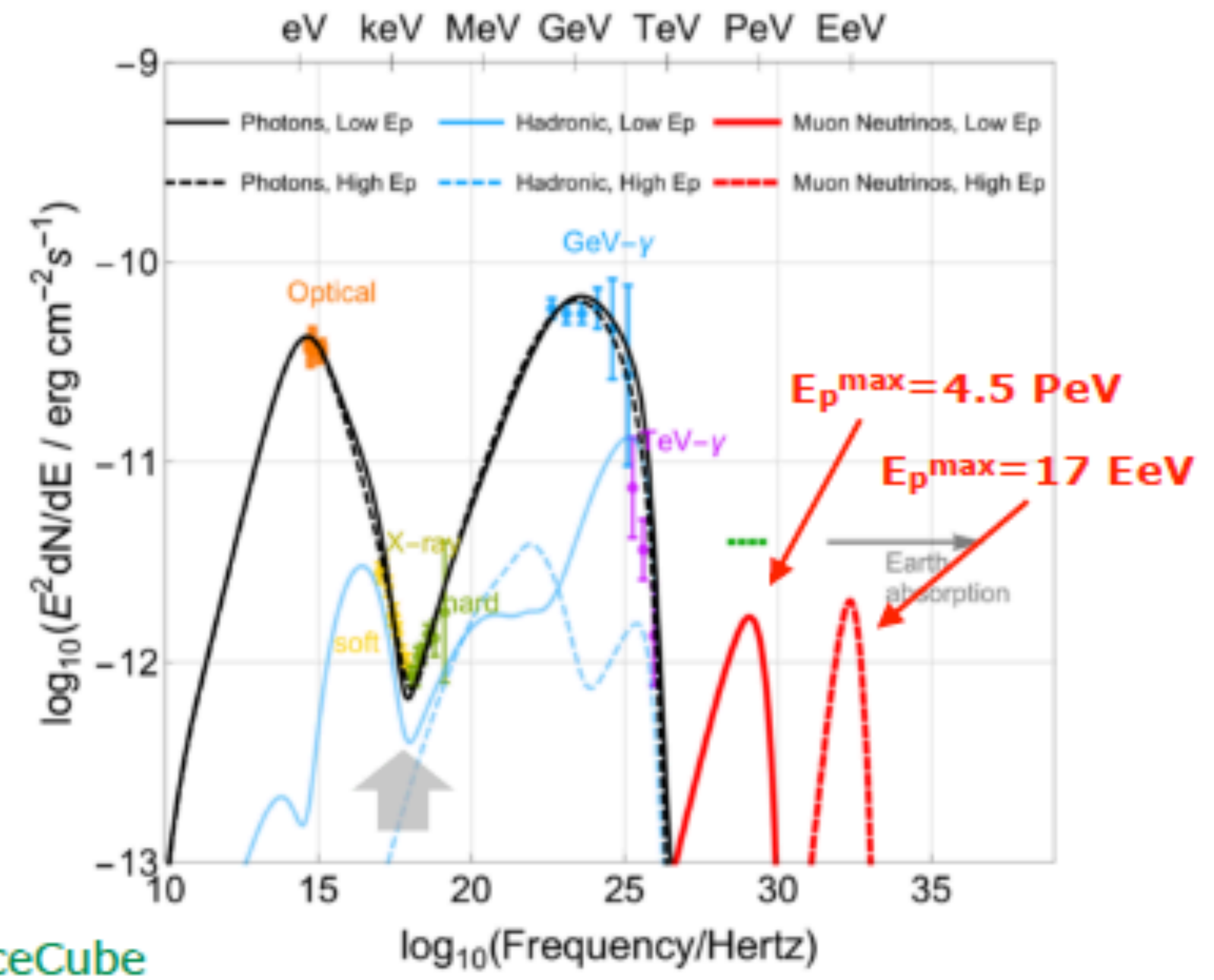
Leptonic models



Hadronic (π cascade) models



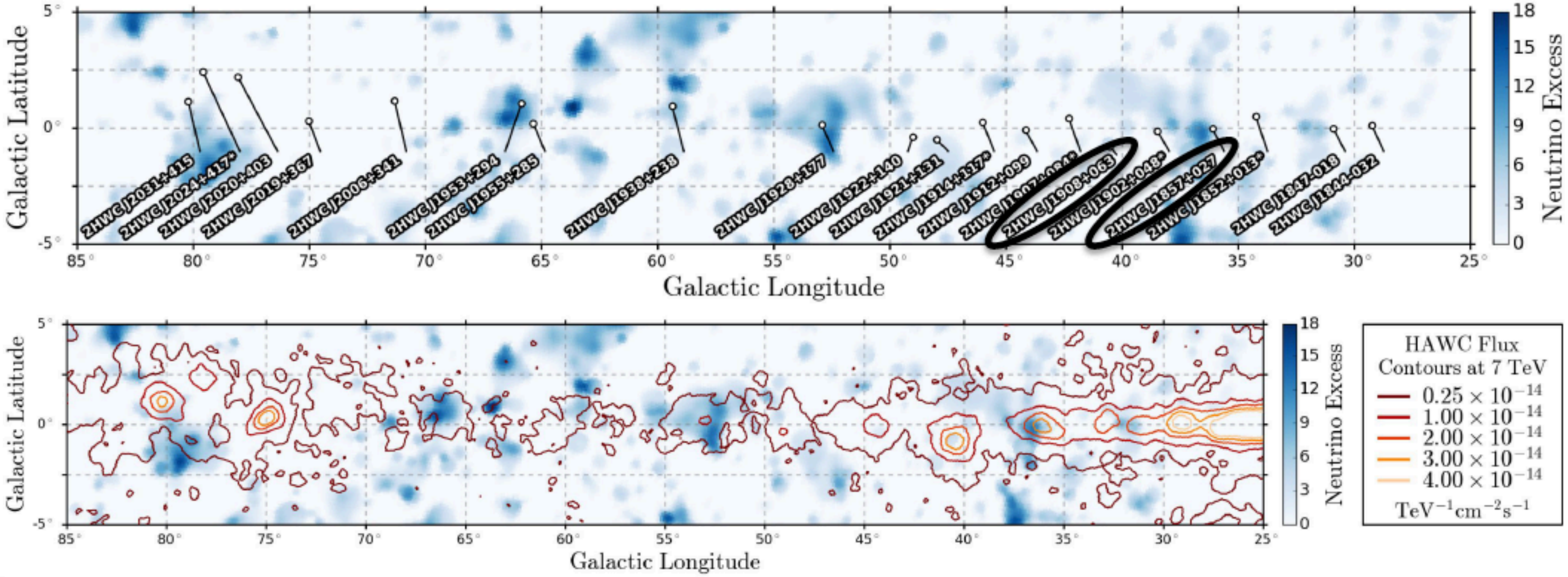
Hybrid or p synchrotron models



- No neutrinos
- Violate X-ray data
- Violate energetics (L_{edd}) by a factor of a few hundred or significantly exceed ν energy

X-ray (and TeV γ-ray) data indicative for hadronic origin

En la Galaxia



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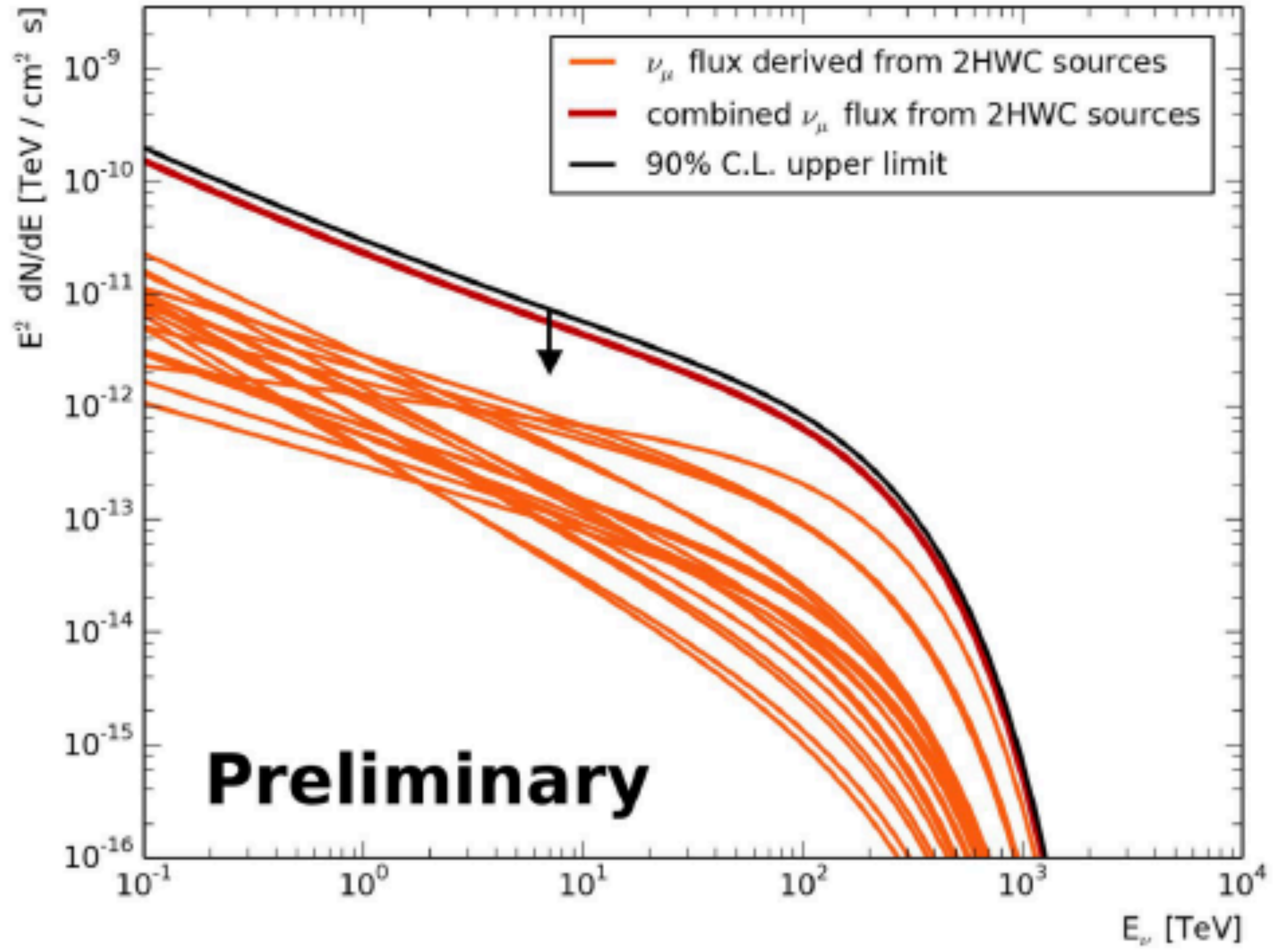
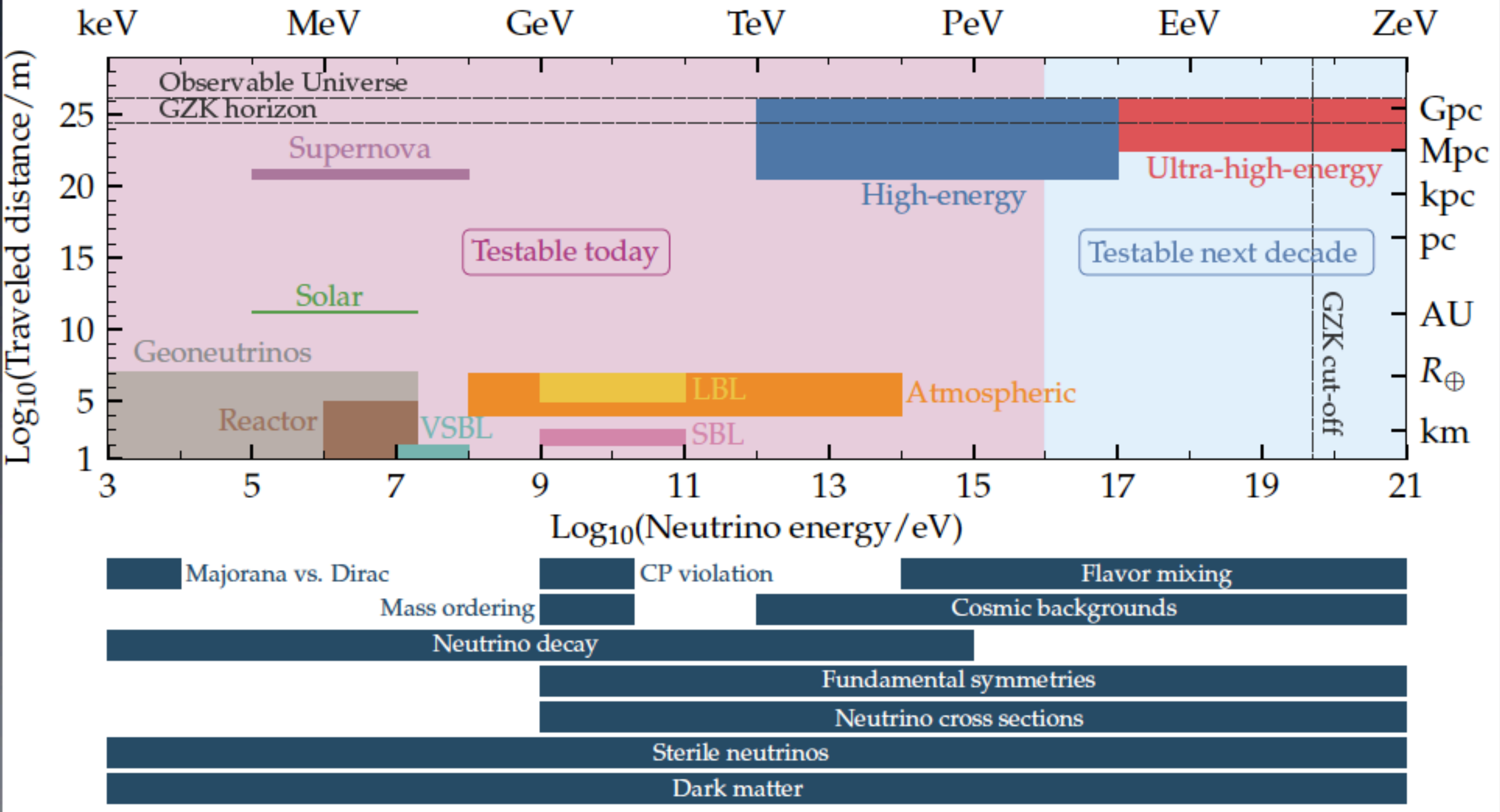
HAWC photons and IceCube neutrinos

neutrino flux at the level predicted, but not significant yet



Probing a Wide Range of Fundamental Physics



M. Bustamante, from arXiv:1903.04333, Astro2020 Science Whitepaper

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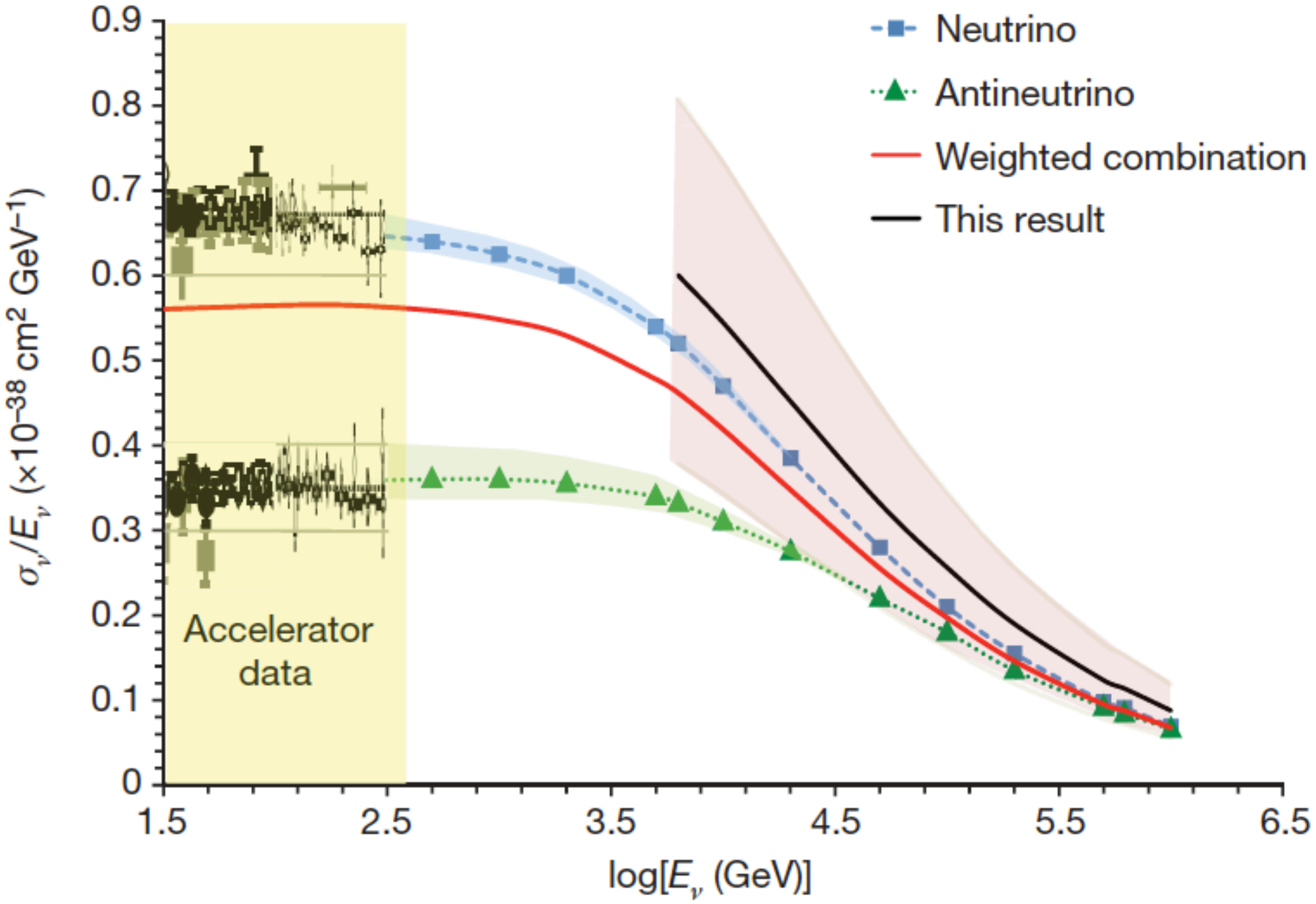
4

Measurement of the multi-TeV neutrino interaction cross-section with IceCube using Earth absorption

The IceCube Collaboration*



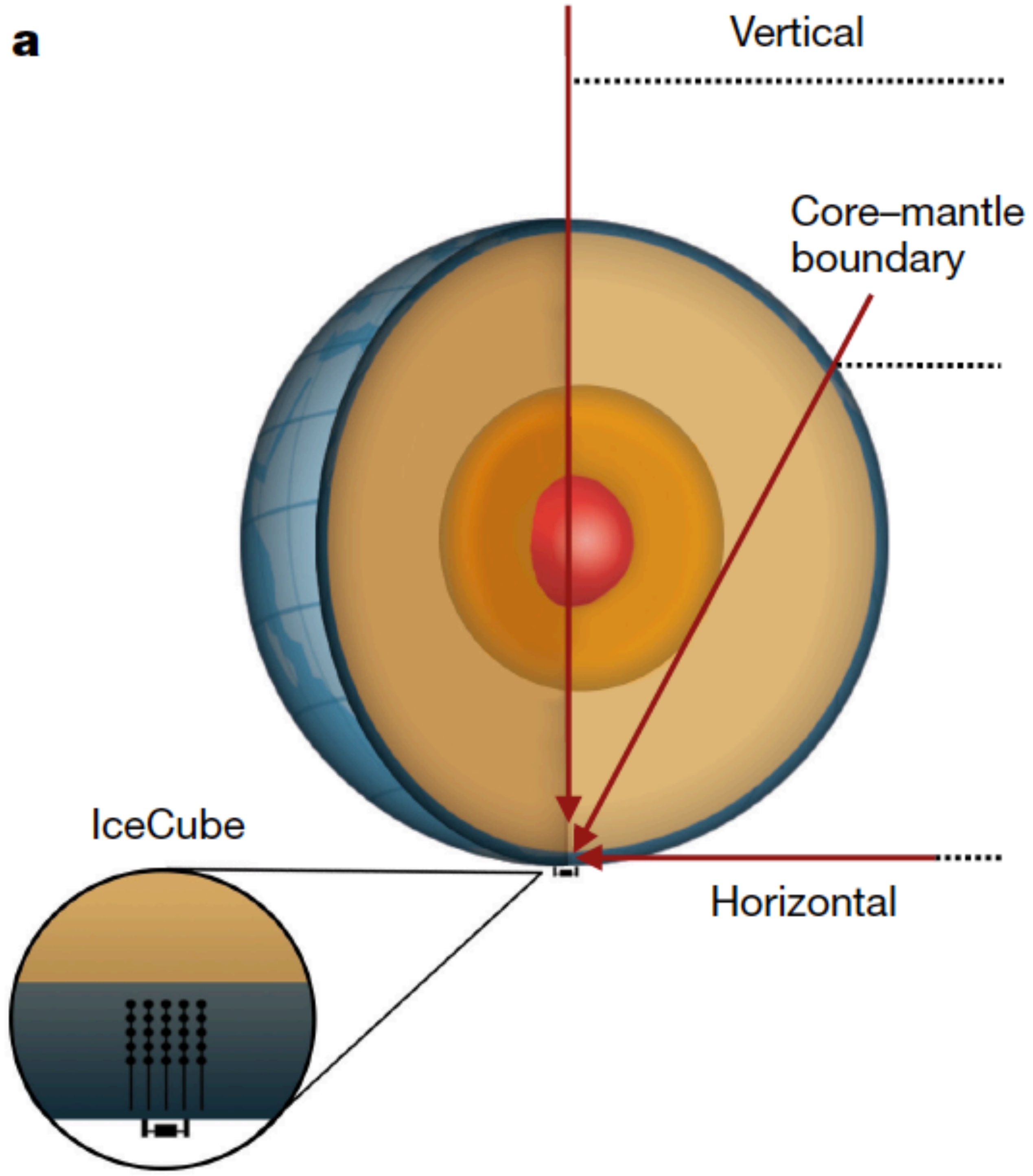


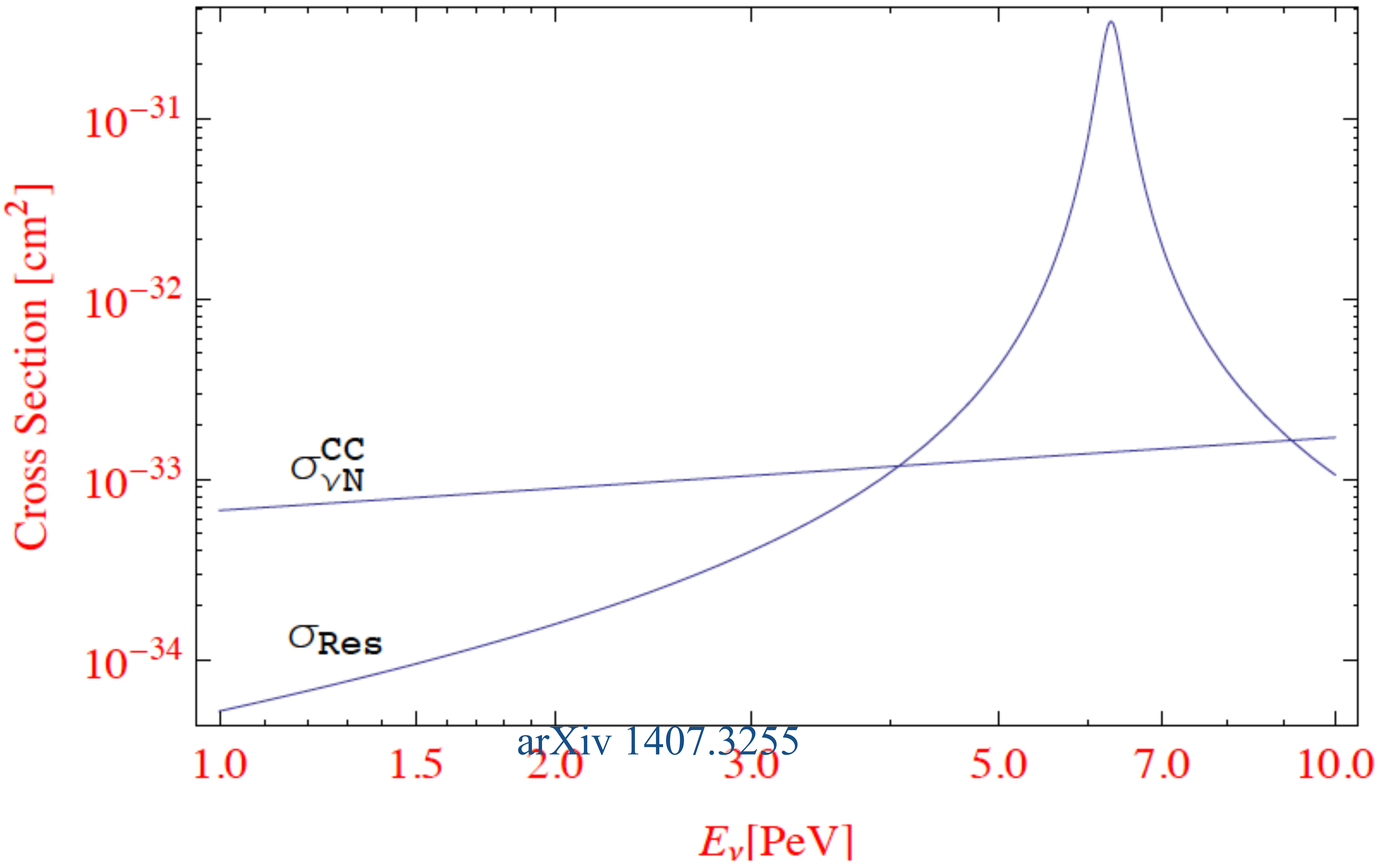
Figure 1 | Neutrino cross-section measurements. Measured neutrino charged-current interaction cross-sections σ_ν, divided by the neutrino energy E_ν, from accelerator experiments are shown, along with error bars

Nature, 22 de noviembre 2017

Resonancia de Glashow

$\bar{\nu}_e + e^- \rightarrow W^- \rightarrow X$

Proceso resonante a
$E_\nu = 6.3$ PeV

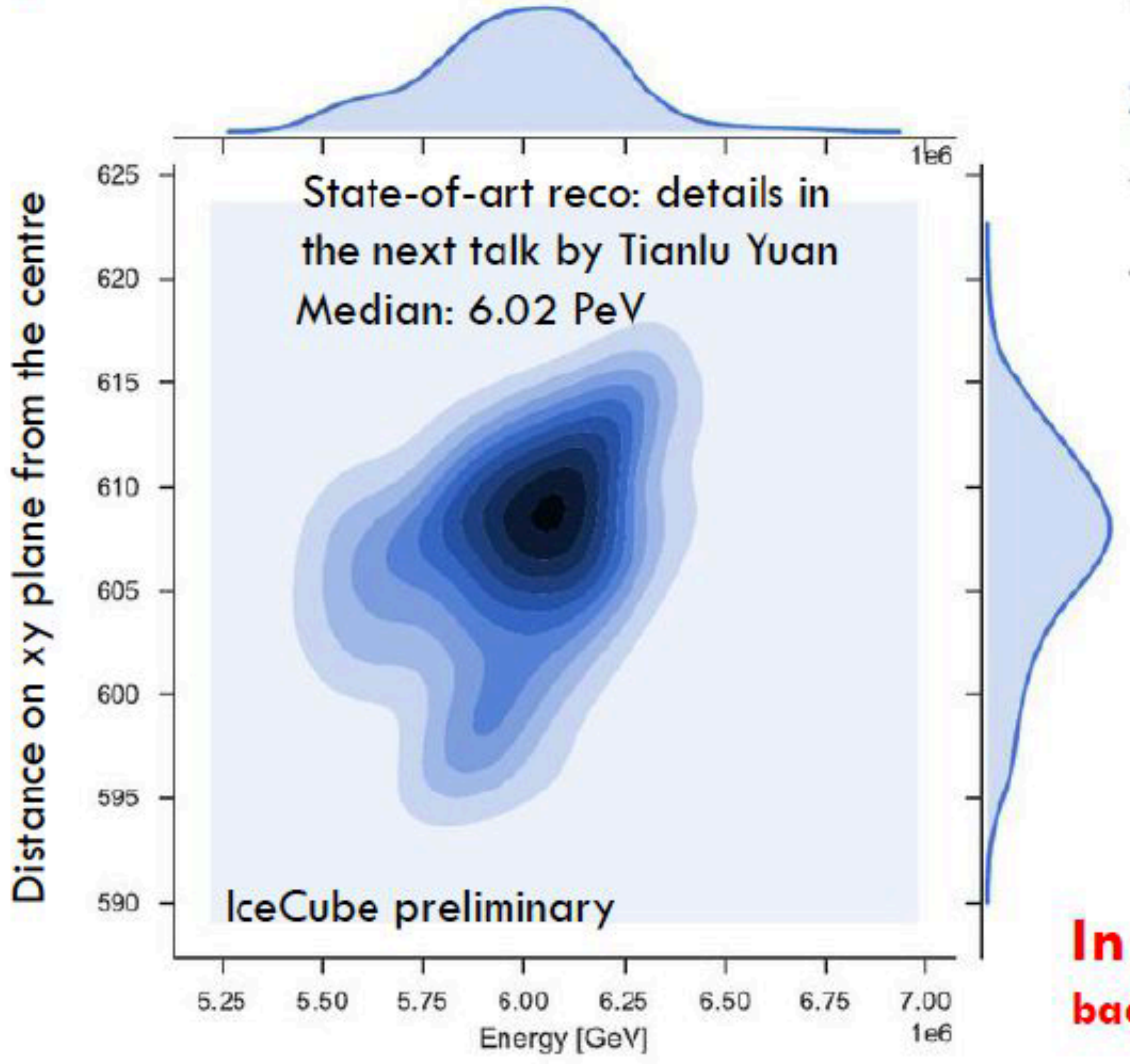


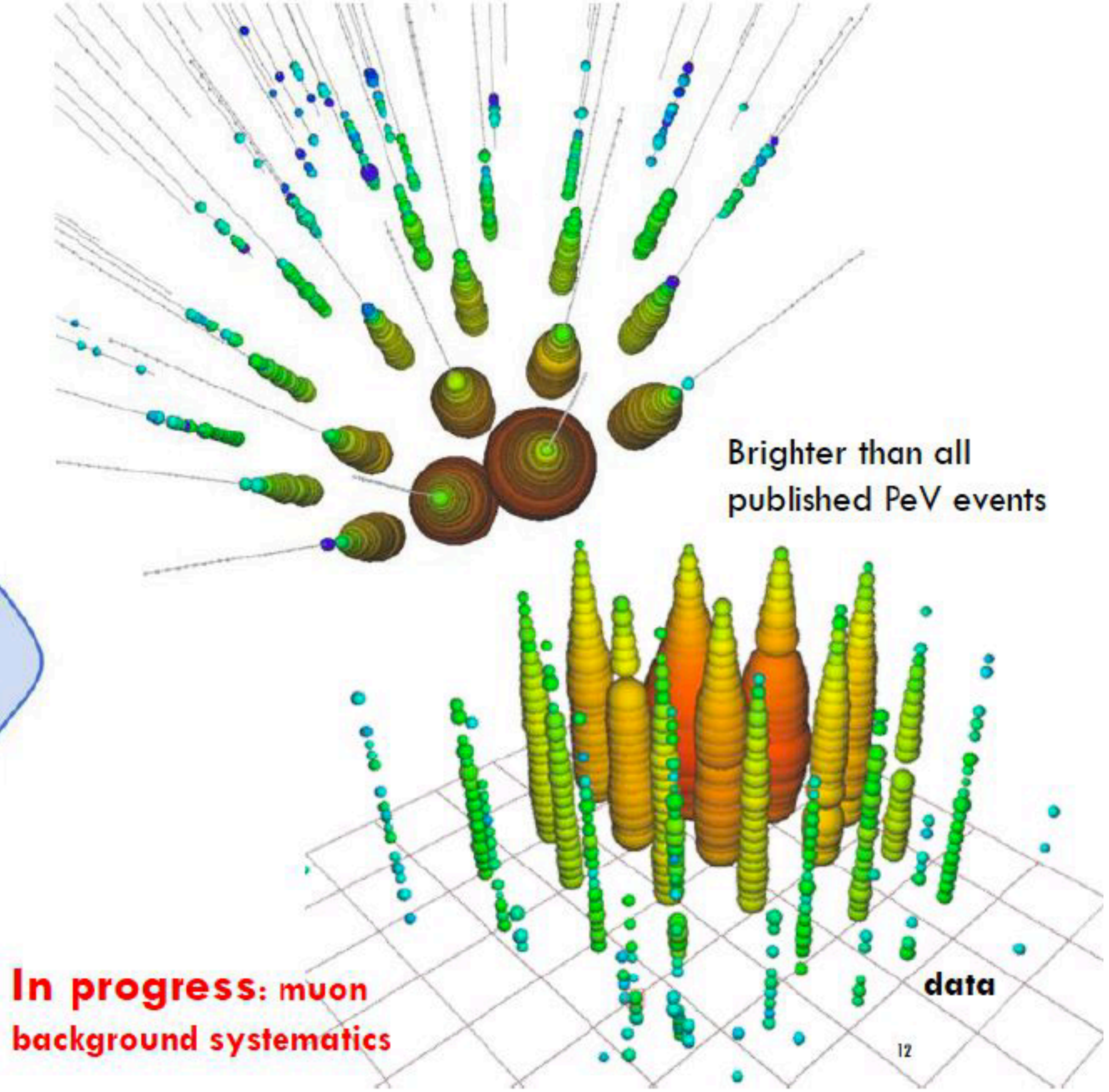
arXiv 1407.3255

FIG. 1: Cross sections for the resonant process, $\bar{\nu}_e + e^- \rightarrow W^- \rightarrow$ hadrons, and the non-resor
process, $\nu_e + N \rightarrow e^- +$ hadrons, in the 1–10 PeV region.

partially contained event with energy of 6.3 PeV

HIGHEST-ENERGY NEUTRINO CANDIDATE





Neutrino Production: The GZK Process

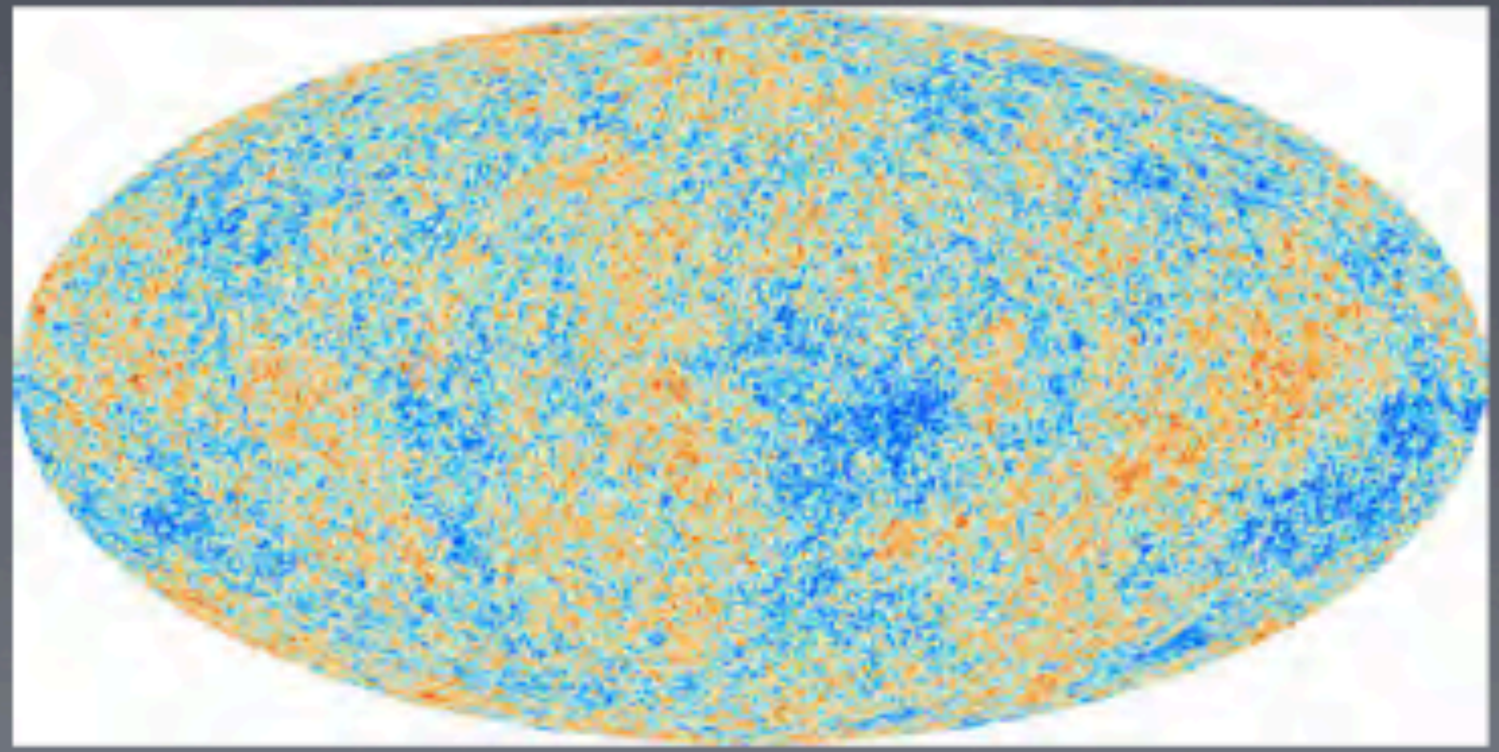
GZK process: Cosmic ray protons (E> $10^{19.5}$ eV) interact with CMB photons

$$p + \gamma_{cmb} \rightarrow \Delta^{+} \rightarrow n + \pi^{+}$$
$$\rightarrow \mu^{+} + \boxed{\nu_{\mu}}$$
$$\rightarrow e^{+} + \boxed{\bar{\nu_{\mu}} + \nu_{e}}$$

Cosmic Rays

+

CMB



= Neutrino Beam!

Discover the origin of high energy cosmic rays and neutrinos?

What is the high energy cutoff of our universe?

What is(are) the acceleration mechanism(s)?

5

Astronomía de neutrinos

1. El decaimiento β y el neutrino
2. Neutrinos solares y oscilaciones
3. La SN1987A
4. Detectores de gran volumen
5. Astrofísica con IceCube
6. Próxima generación de detectores

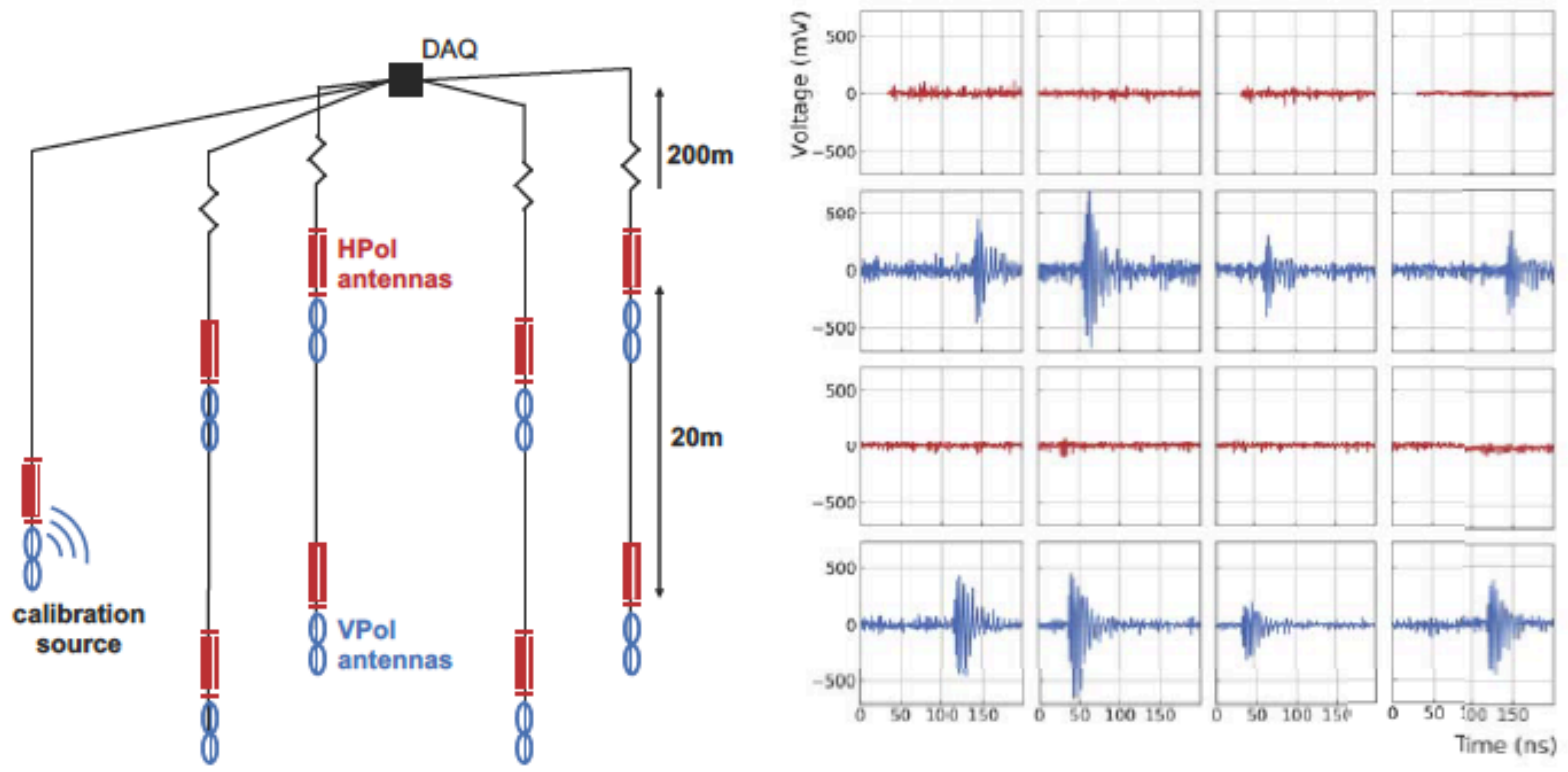
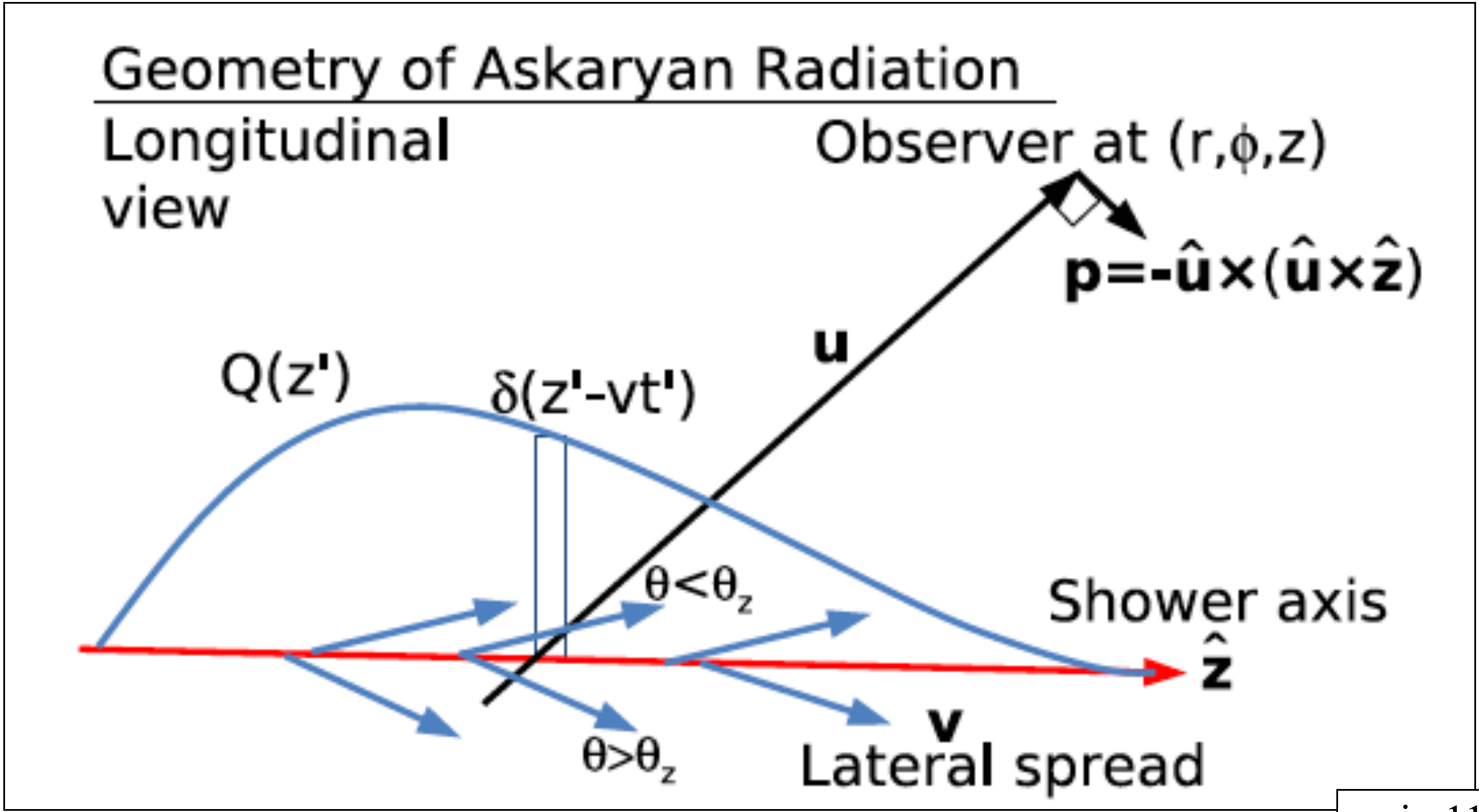


Figure 2: (Left) A drawing of the ARA stations as it is deployed in the ice, showing the cubical lattice of VPol and HPol antennas, as well as the calibration pulser system. (Right) A display of the sixteen waveforms recorded by the array for a typical calibration event.

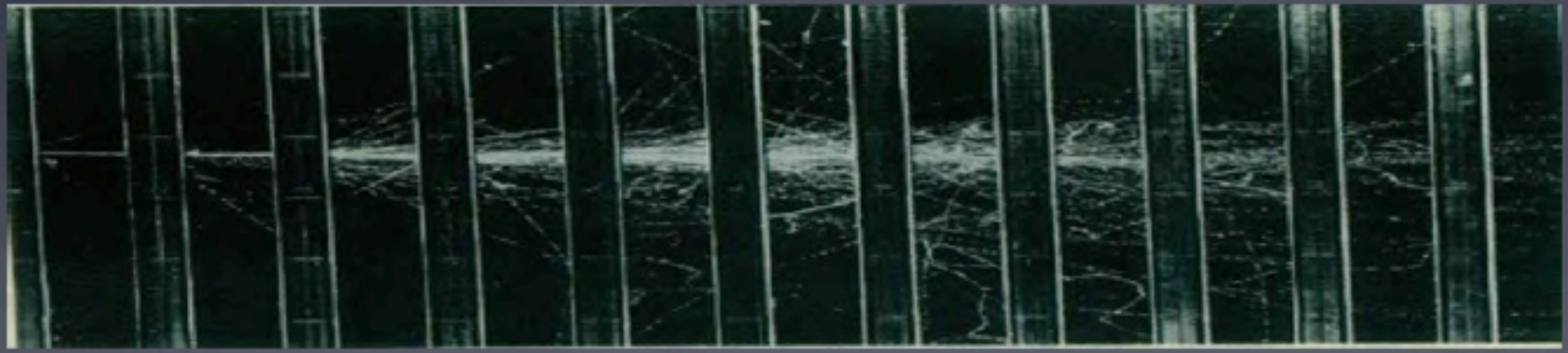


arxiv 1106.6283

Method 1: Radio emission from neutrino interactions in dense material

- EM shower in dielectric (ice, sand) → moving negative charge excess
- Coherent radio Cherenkov radiation ($P \sim E^2$) if λ > Moliere radius

e^+, e^-, γ →

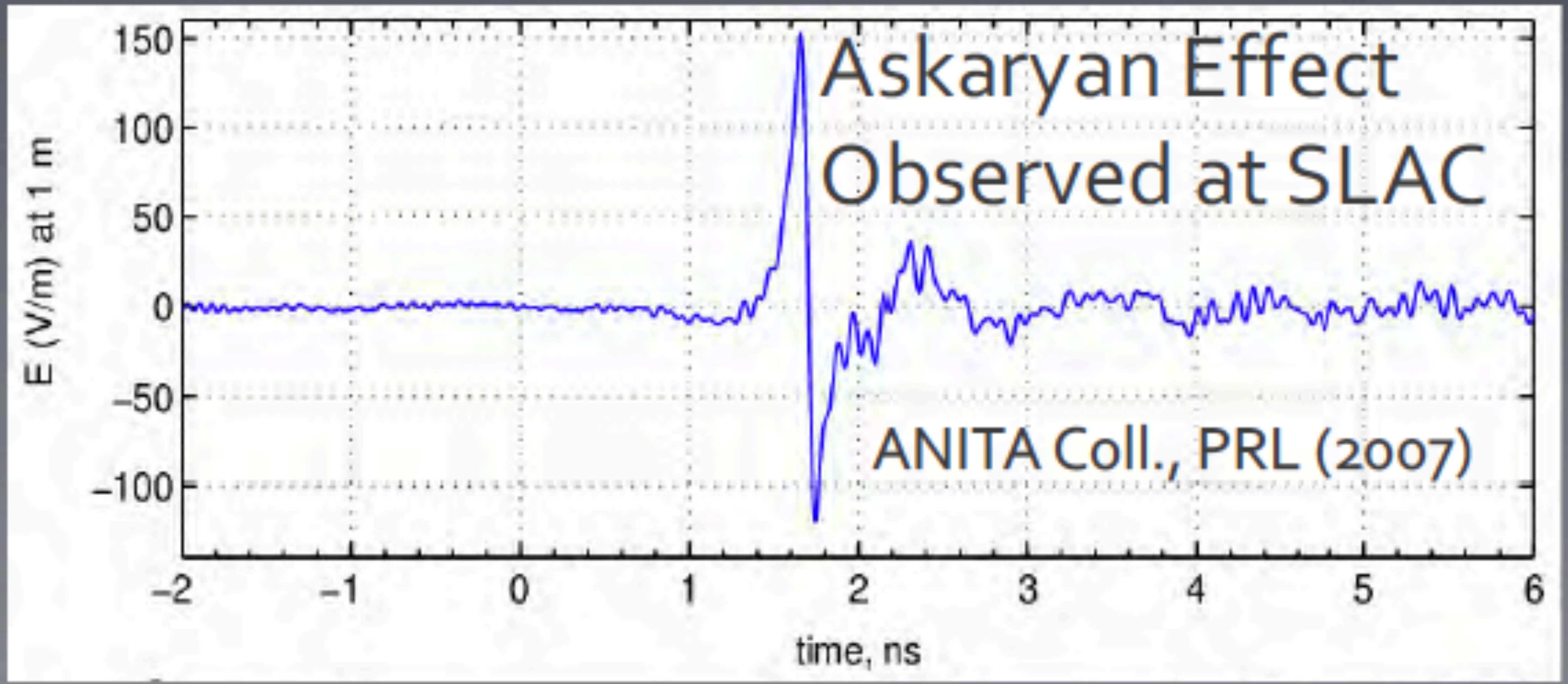


Typical Dimensions:

$L \sim 10$ m

$R_{moliere} \sim 10$ cm

→ Radio Emission is stronger than optical for UHE showers



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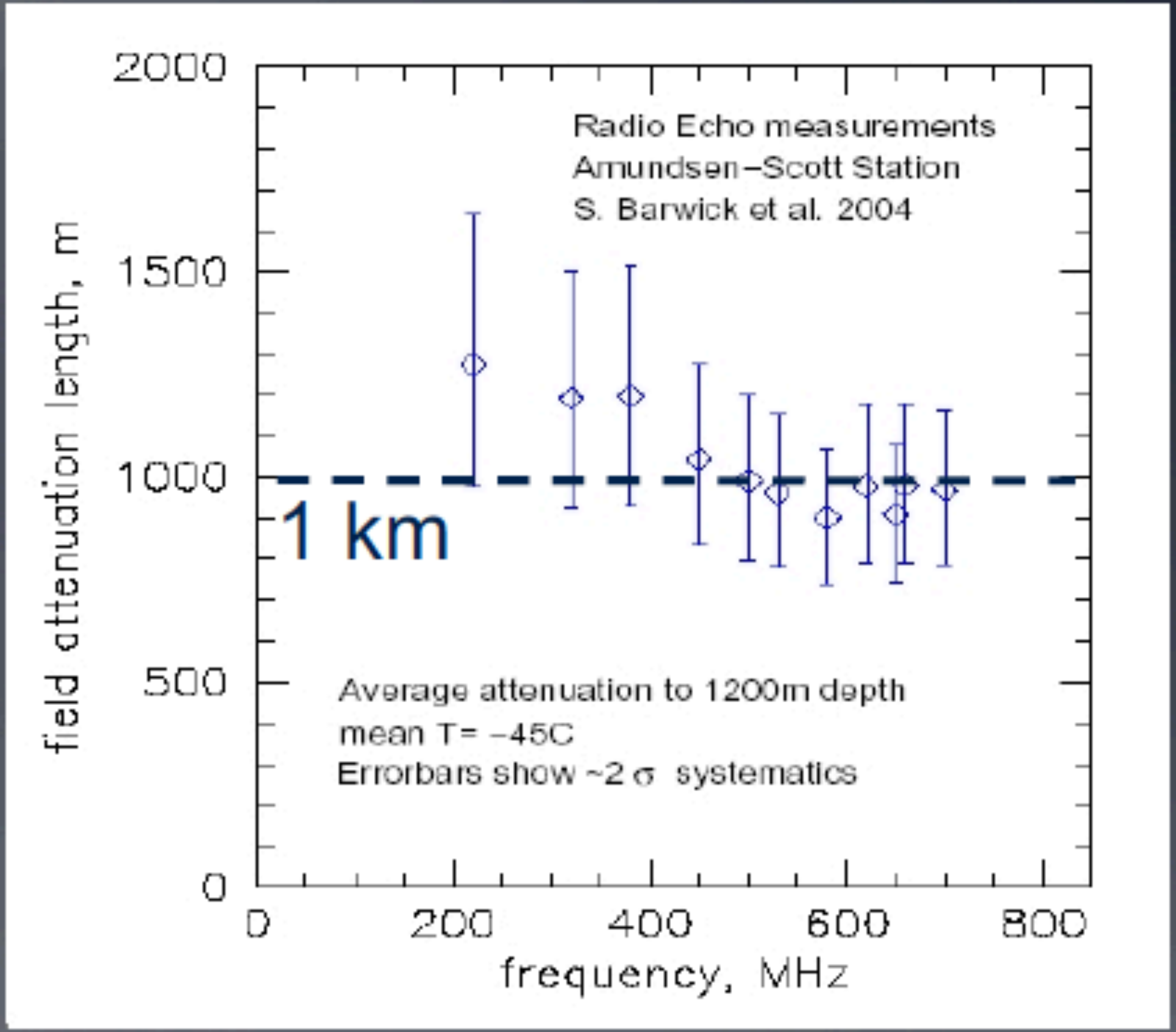
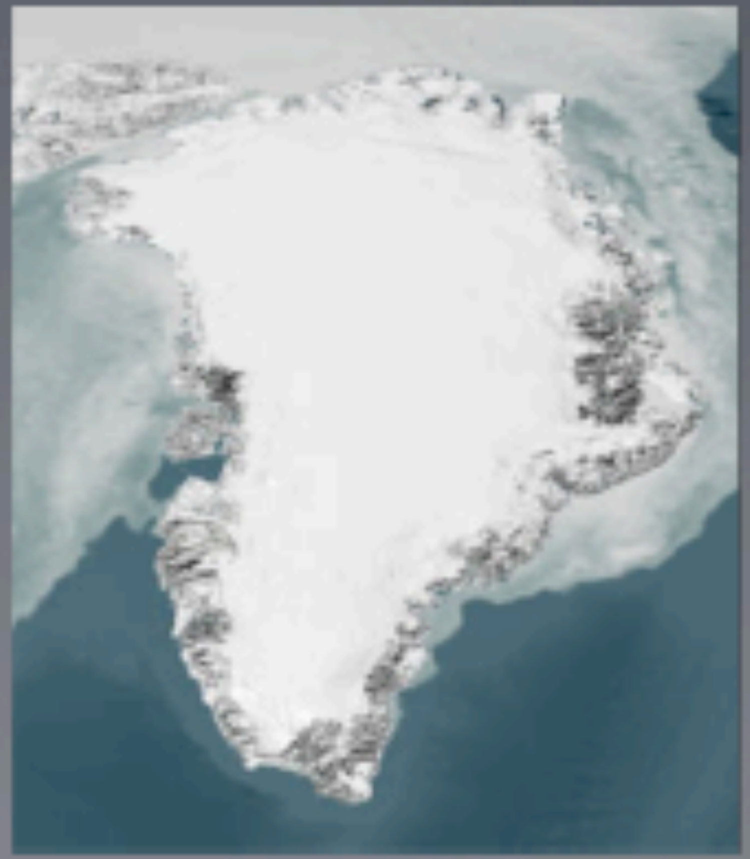
Askaryan Neutrino Detector Requirements

- 1 UHE neutrino/km²/year
- L_{int} ~ 300 km for ice
  → 0.003 neutrinos/km³/year
- Need a huge (> 1000 km³), radio-transparent detector
- Long radio attenuation lengths in ice
  - 1 km for RF
- → Ice is good for radio detection of UHE neutrinos!





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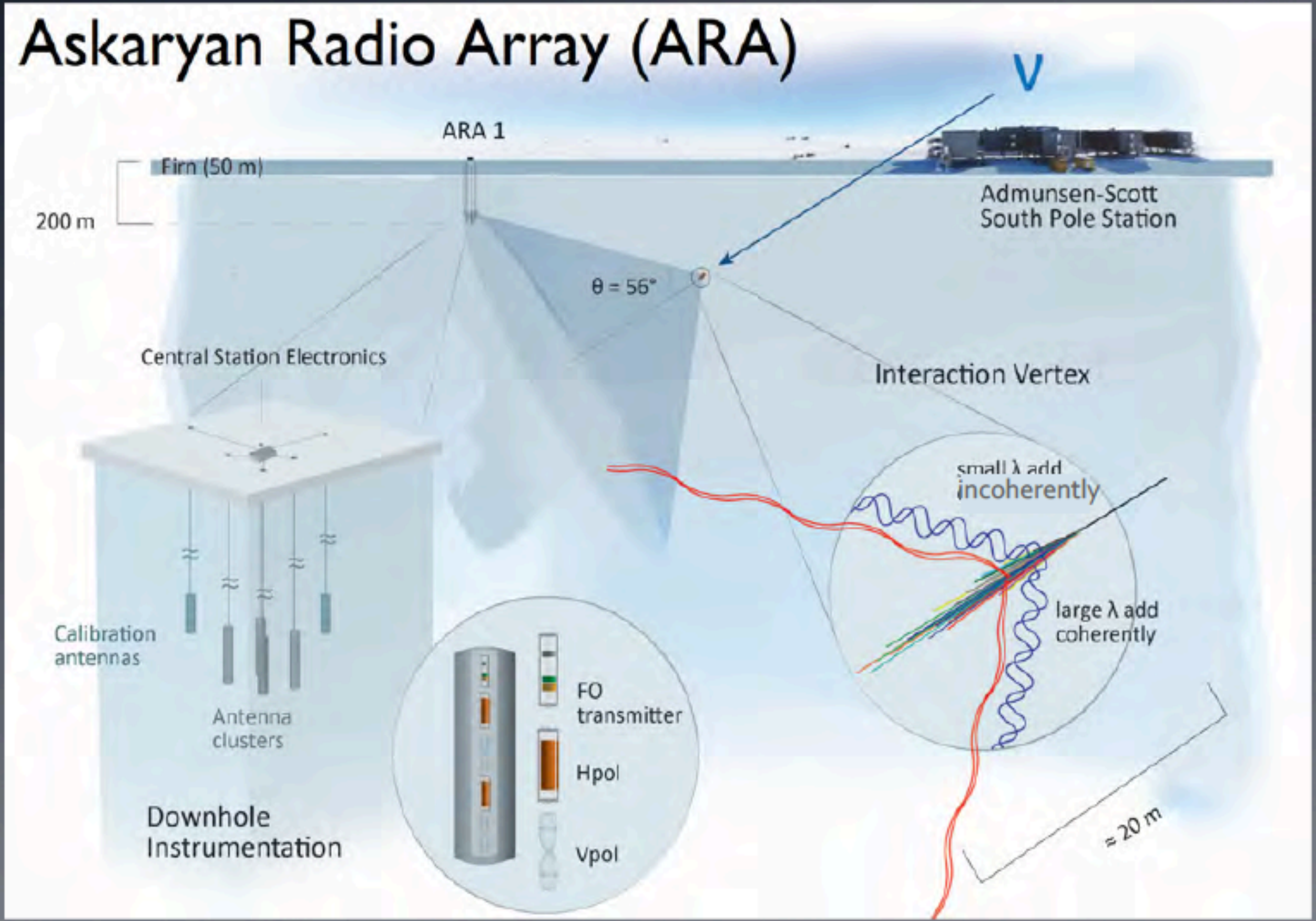
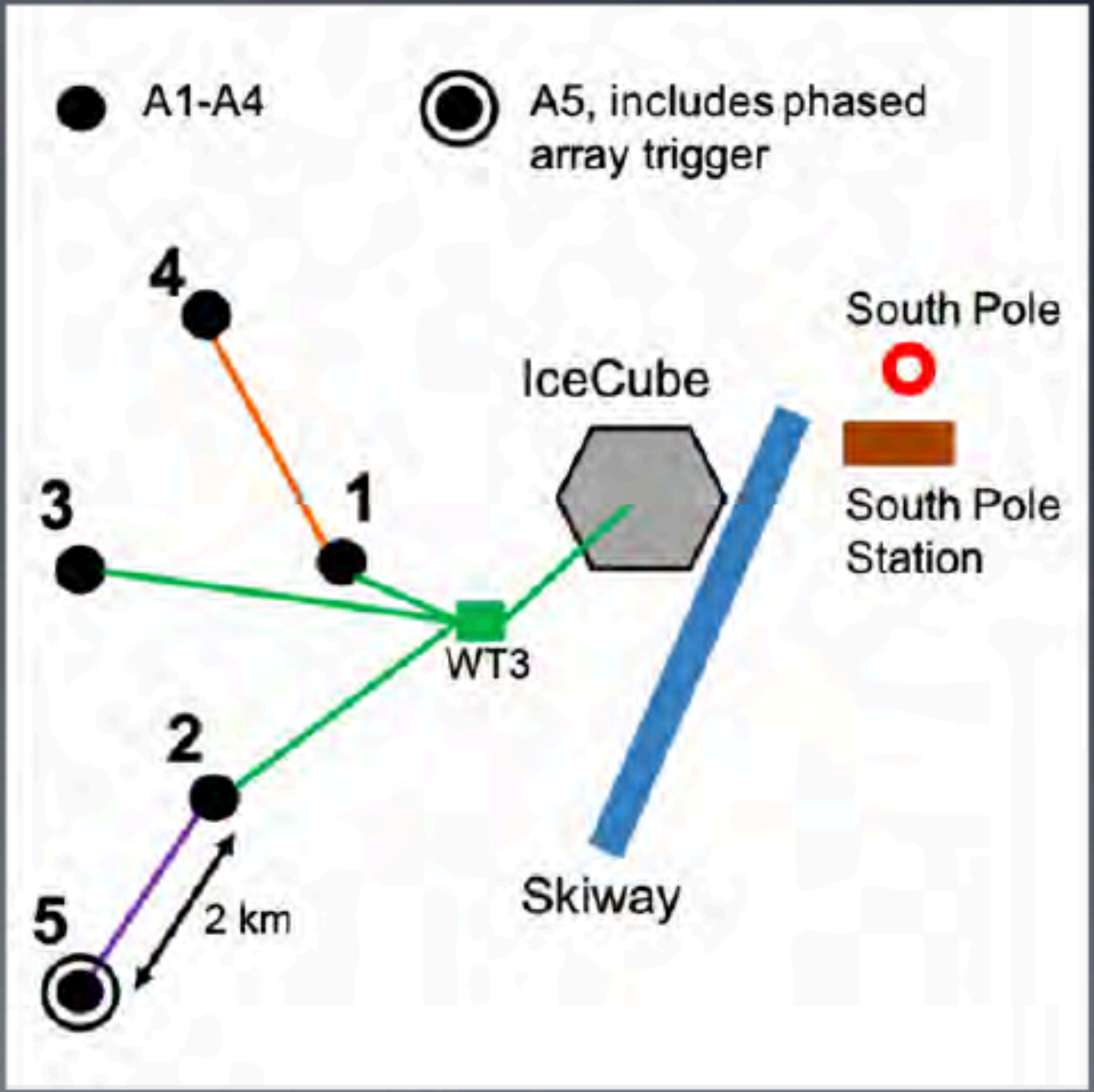
ARA: In-Ice Radio Detector at South Pole





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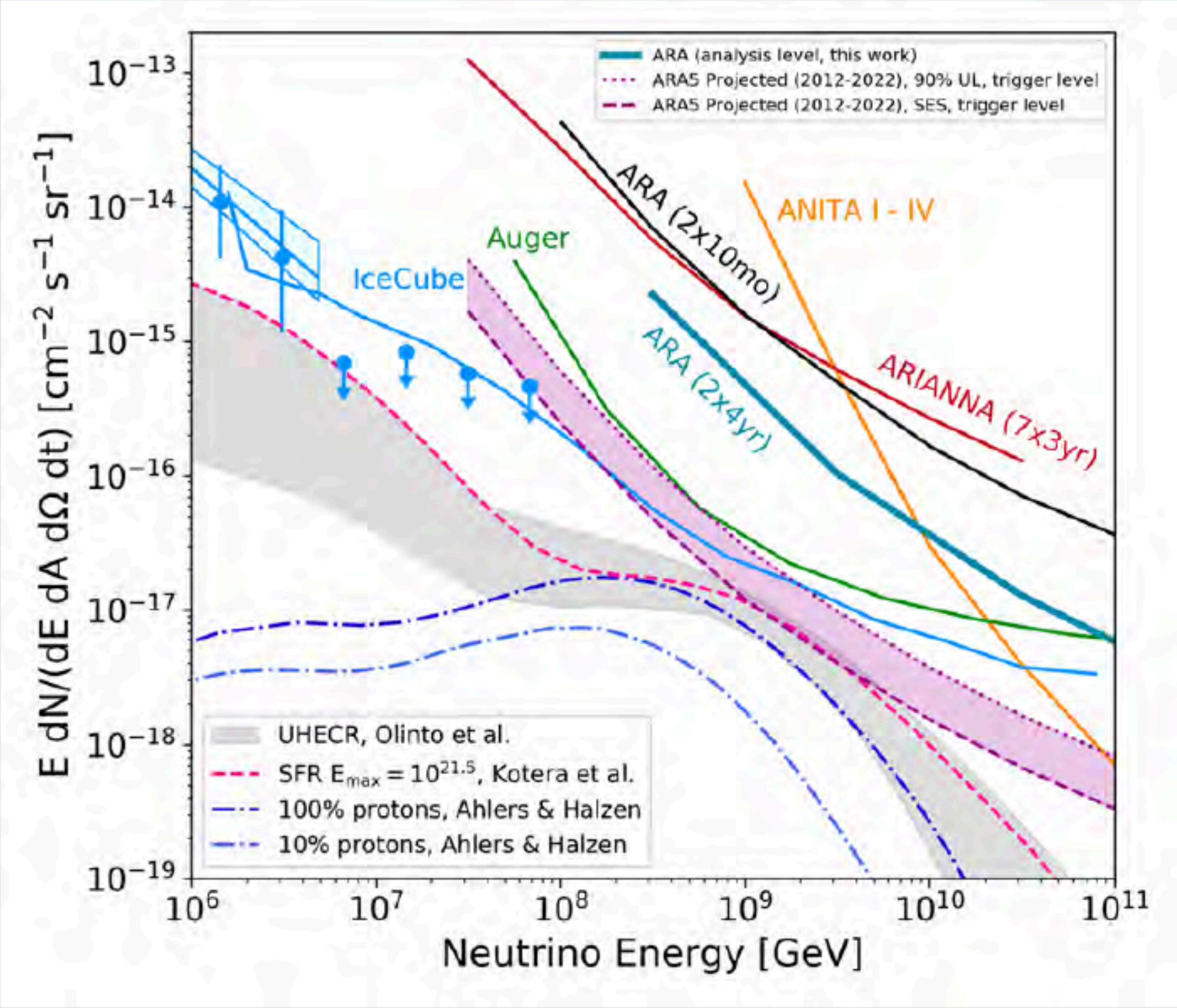
ARA Sensitivity and Analysis Status

- 8 station-year analysis nearing unblinding
- 5 stations are now running, all with high livetimes over the last few years
- Projected sensitivity of data in the can by 2022 is shown in pink



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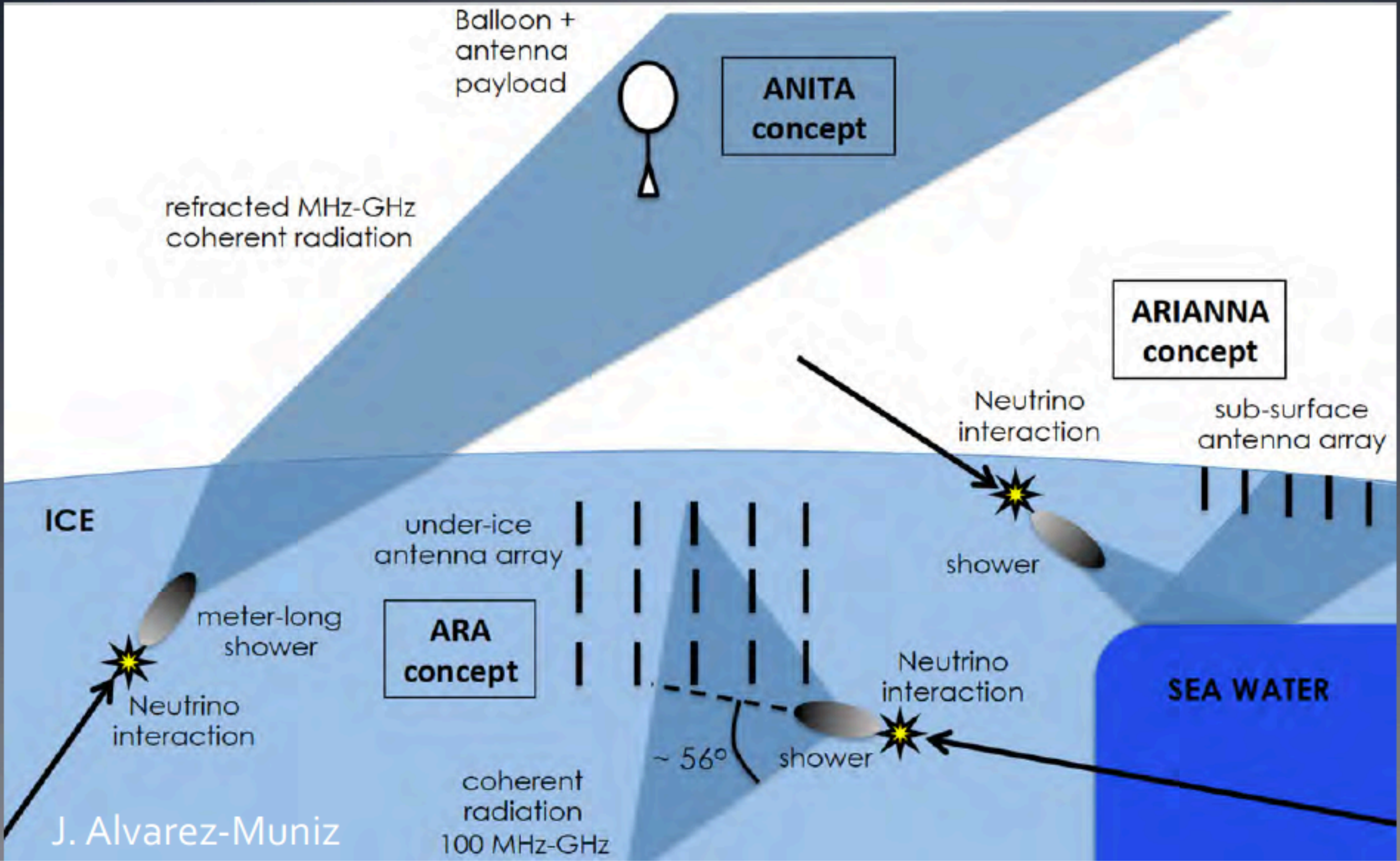
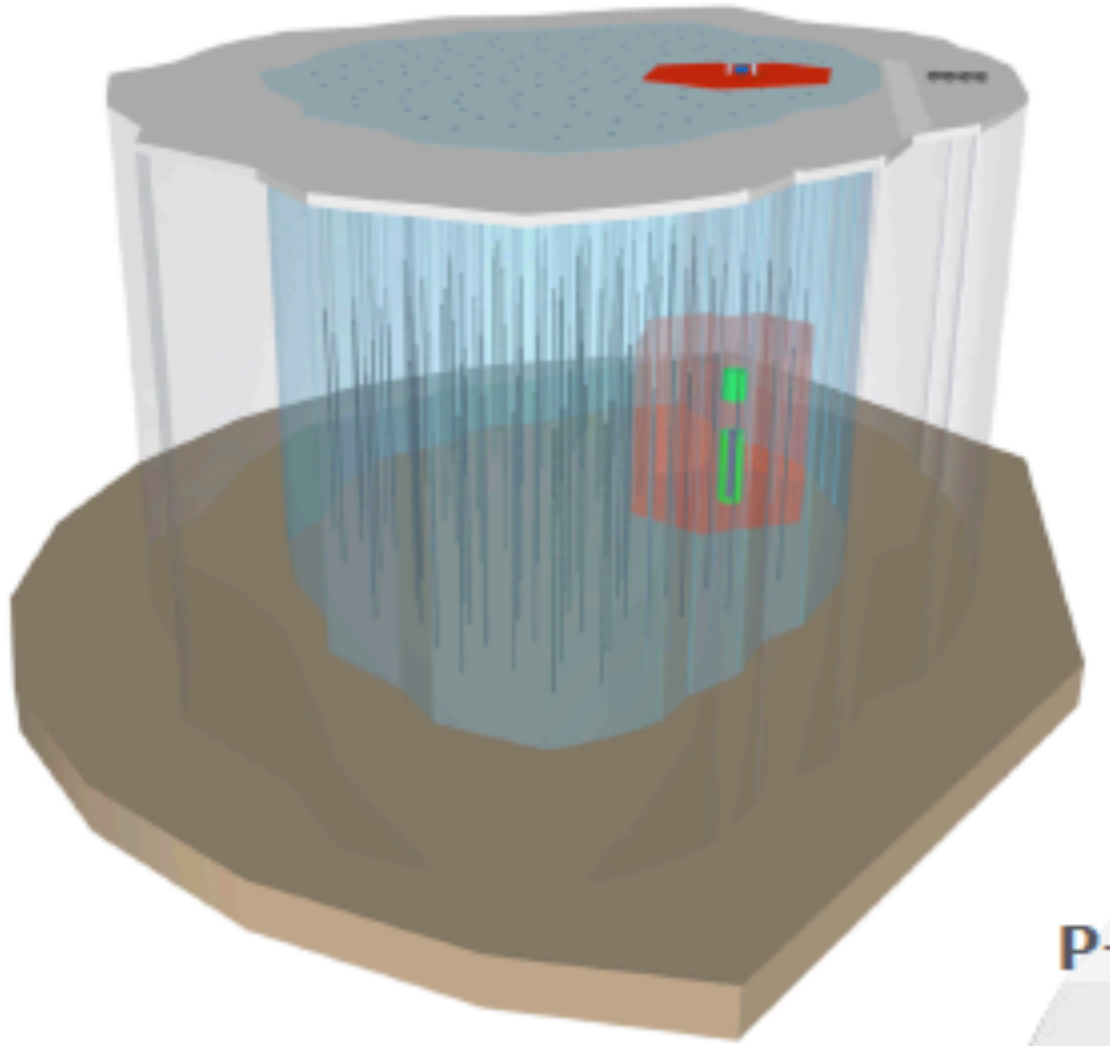
See A. Connolly Talk

Ongoing Efforts in Radio Detection in Dense Media

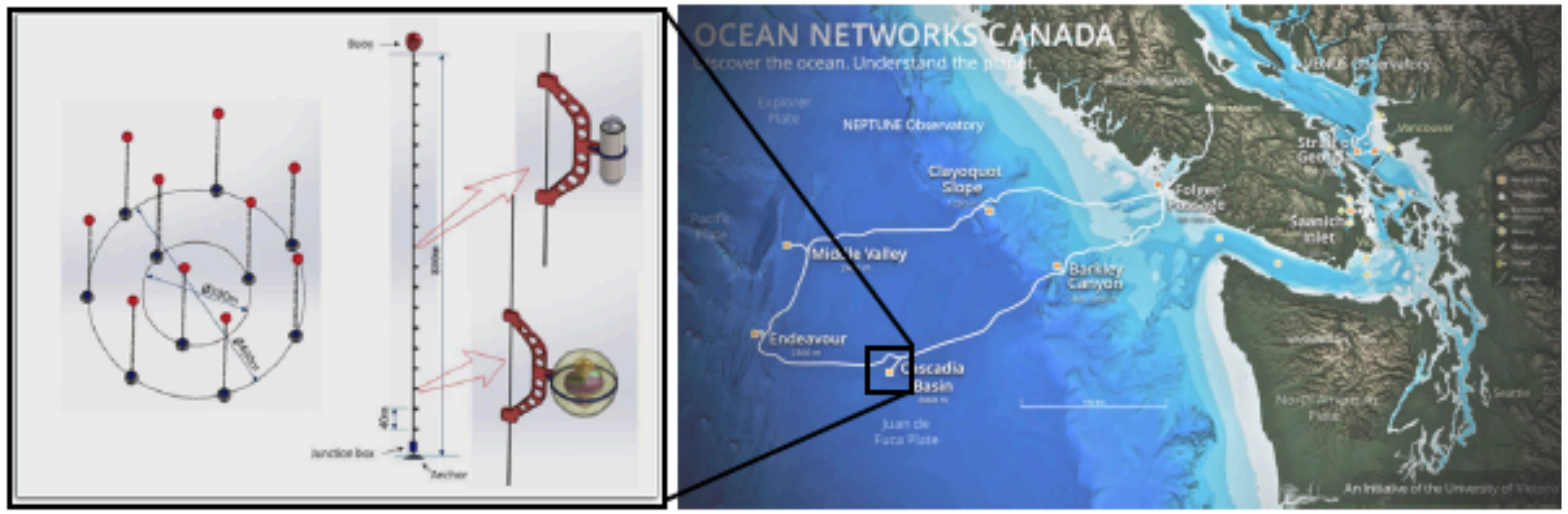


Future neutrino telescopes

IceCube-Gen2

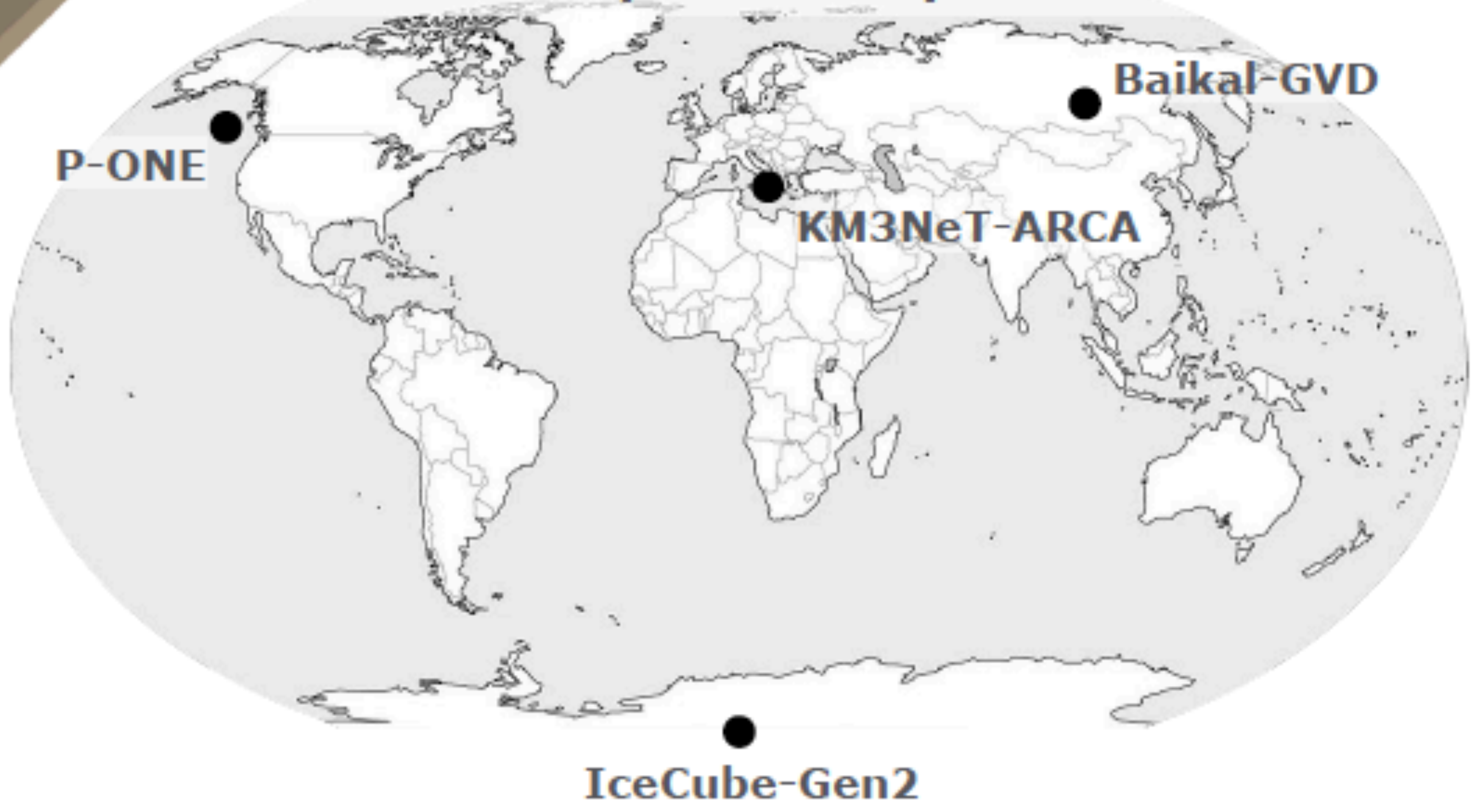


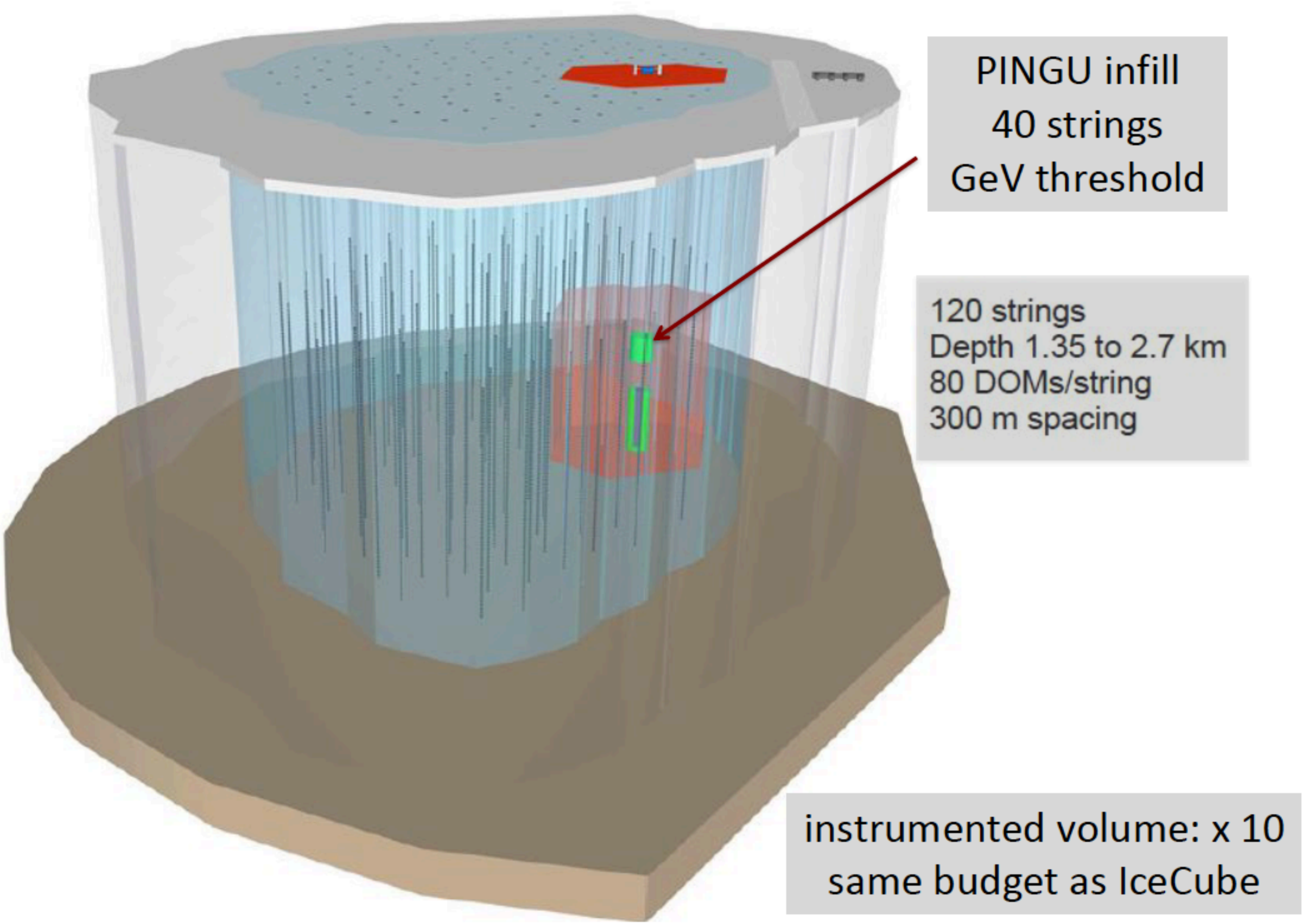
P-ONE (E. Resconi) — New kid on the block



- In conceptual phase
- Up to 500 strings optimized for horizontal HE muon tracks
- STRAW pathfinder mission successfully operating (PoS(ICRC2019)890)

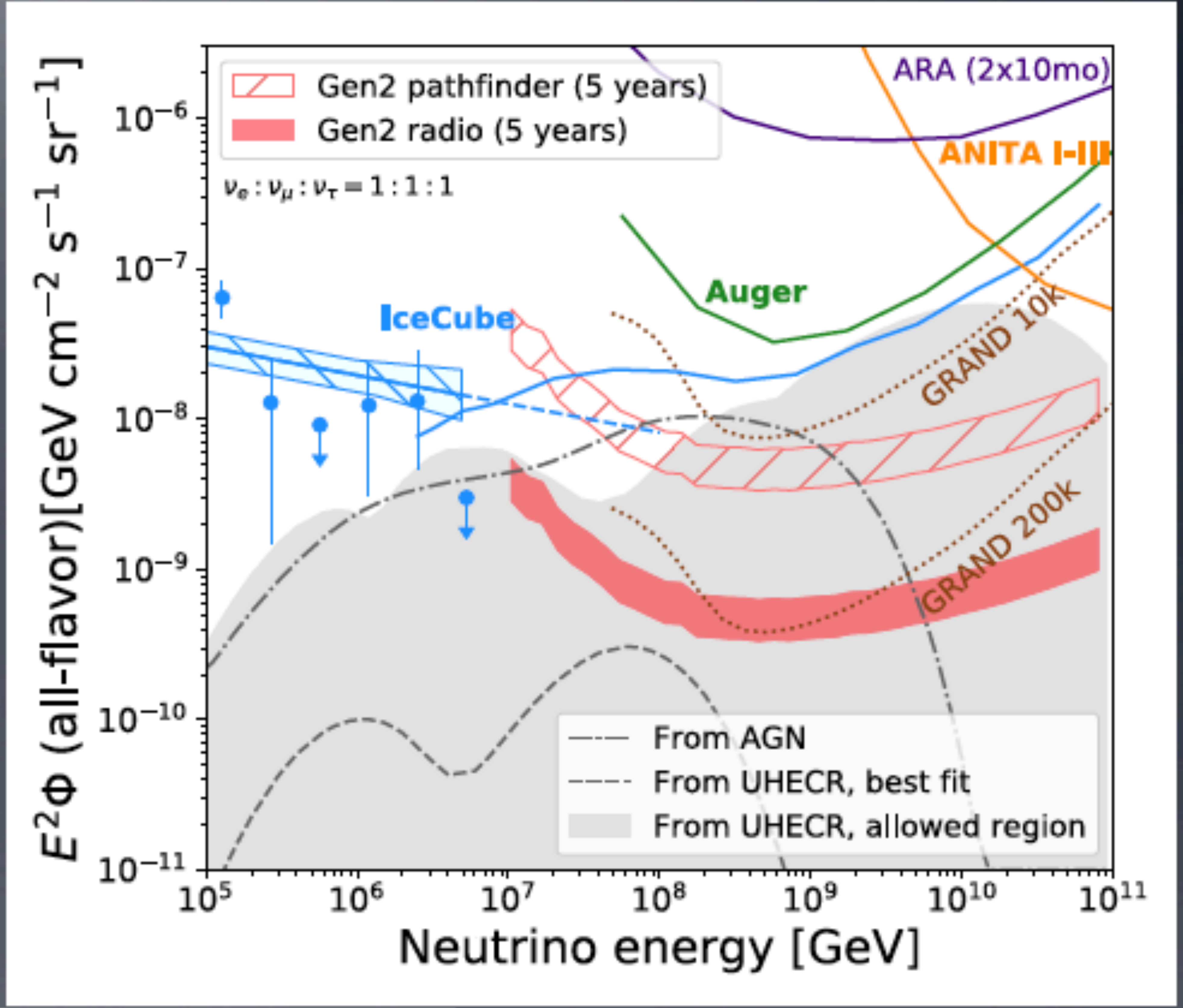
Neutrino telescope landscape in 2025–30

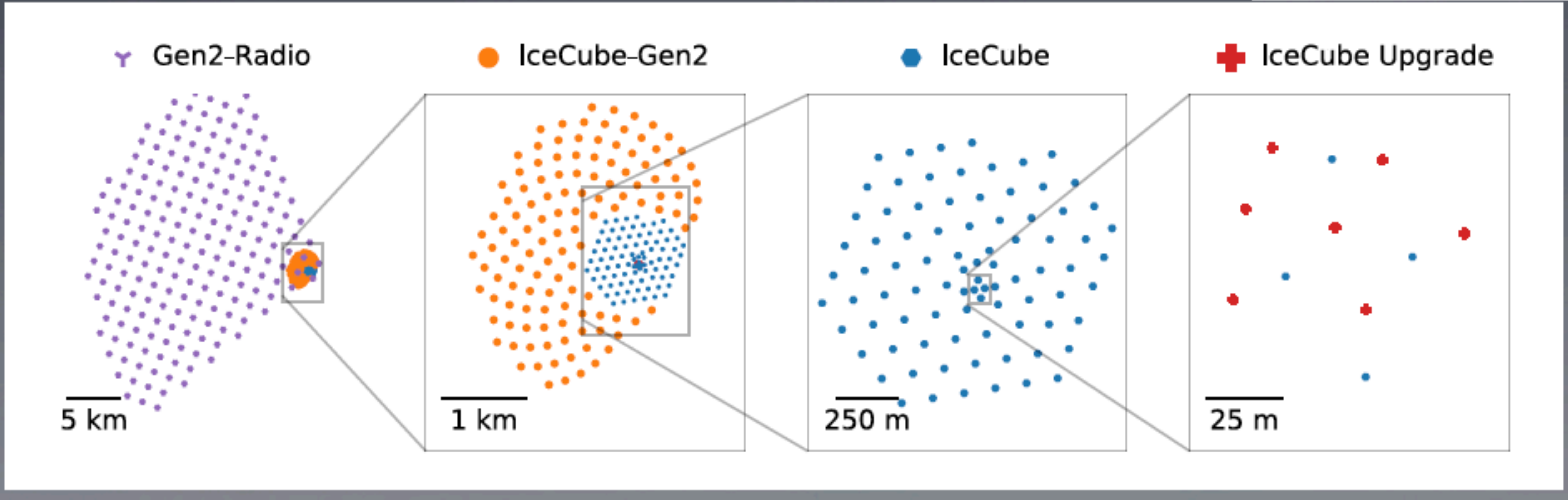



PINGU infill
40 strings
GeV threshold
120 strings
Depth 1.35 to 2.7 km
80 DOMs/string
300 m spacing
instrumented volume: x 10
same budget as IceCube

Toward IceCube Gen2

- IceCube Gen2: a multi-component facility to reach the broadest range of energies.





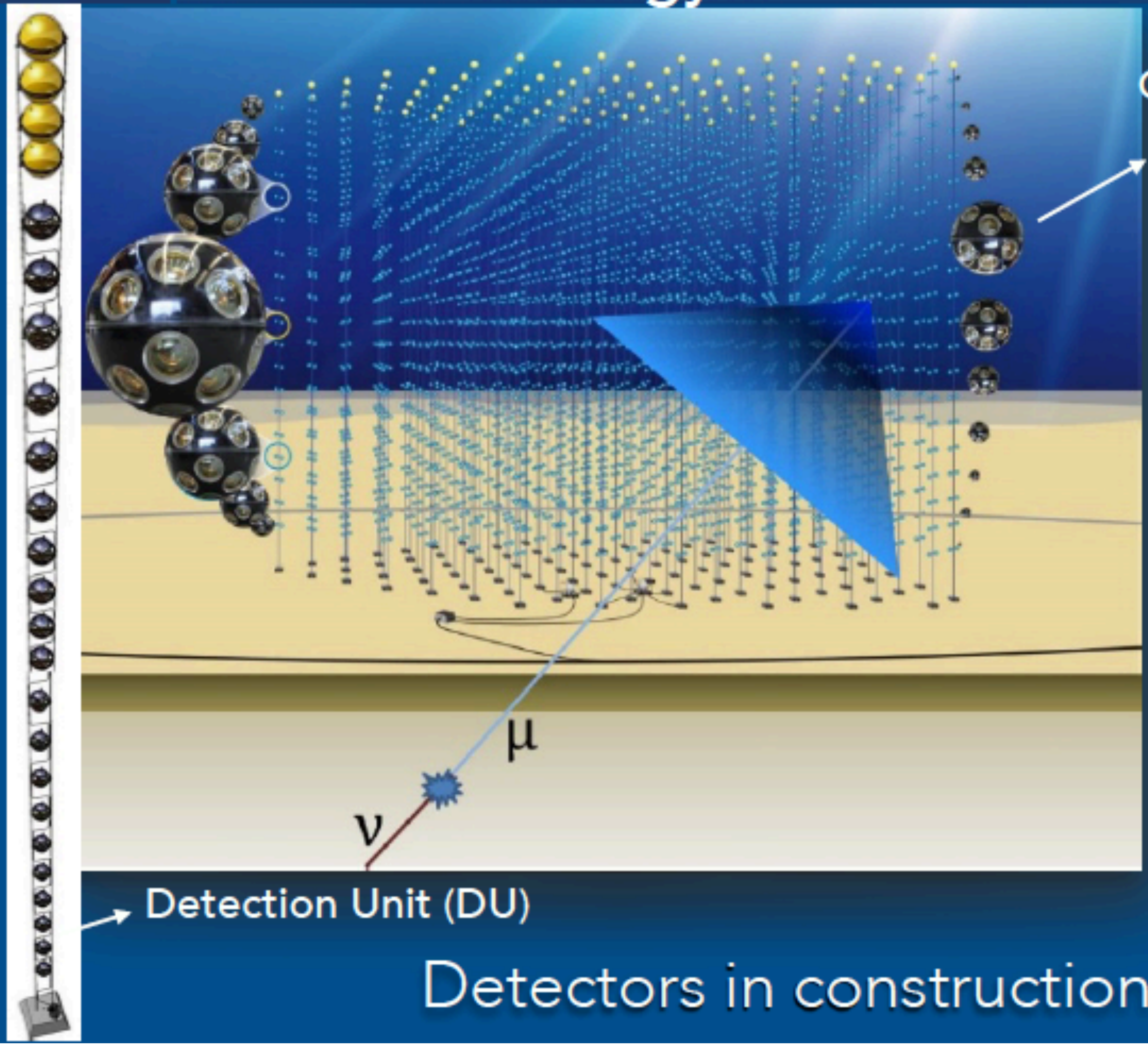
A. Nelles, from Astro2020 Whitepaper

Vieregg @ ICRC 2019

THE KM3NET DETECTORS

Coniglione @ ICRC 2019

Same technology for the two detectors



Optical sensor (DOM)
31 PMTs of 3 inches

Detection Unit (DU)

Detectors in construction

ORCA

- Depth ~2500 m
- One block of 115 Detection Units
- Average distance between Detection Units ~20 m
- Average vertical distance between DOMs ~9 m
- **Volume ≈ 8 Mton**

ARCA

- Depth ~3500 m
- Two blocks of 115 Detection Units each
- Average distance between Detection Units ~90 m
- Vertical distance between DOMs ~36 m
- **Volume (0.5 × 2) km^3 ≈1 Gton**

Finding UHEν — Current/planned experiments, and new ideas

Air showers

- Radio (*interferometric*)
  - ***ANITA*** PoS(ICRC2019)867
  - *TAROGE* PoS(ICRC2019)967
  - *BEACON* PoS(ICRC2019)1033
  - GRAND PoS(ICRC2019)233
- Particles
  - **Auger** PoS(ICRC2019)979
- Cherenkov
  - **Ashra-1**, NTA (also fluorescence) PoS(ICRC2019)976
  - TRINITY PoS(ICRC2019)970
  - POEMMA PoS(ICRC2019)378

In-ice showers

running, planned

- Radio
  - **ARA**, ARA5 PoS(ICRC2019)858
  - **ARIANNA**, ARIA PoS(ICRC2019)980
  - RNO PoS(ICRC2019)913
- Radar PoS(ICRC2019)986