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Neutrino Astronomy

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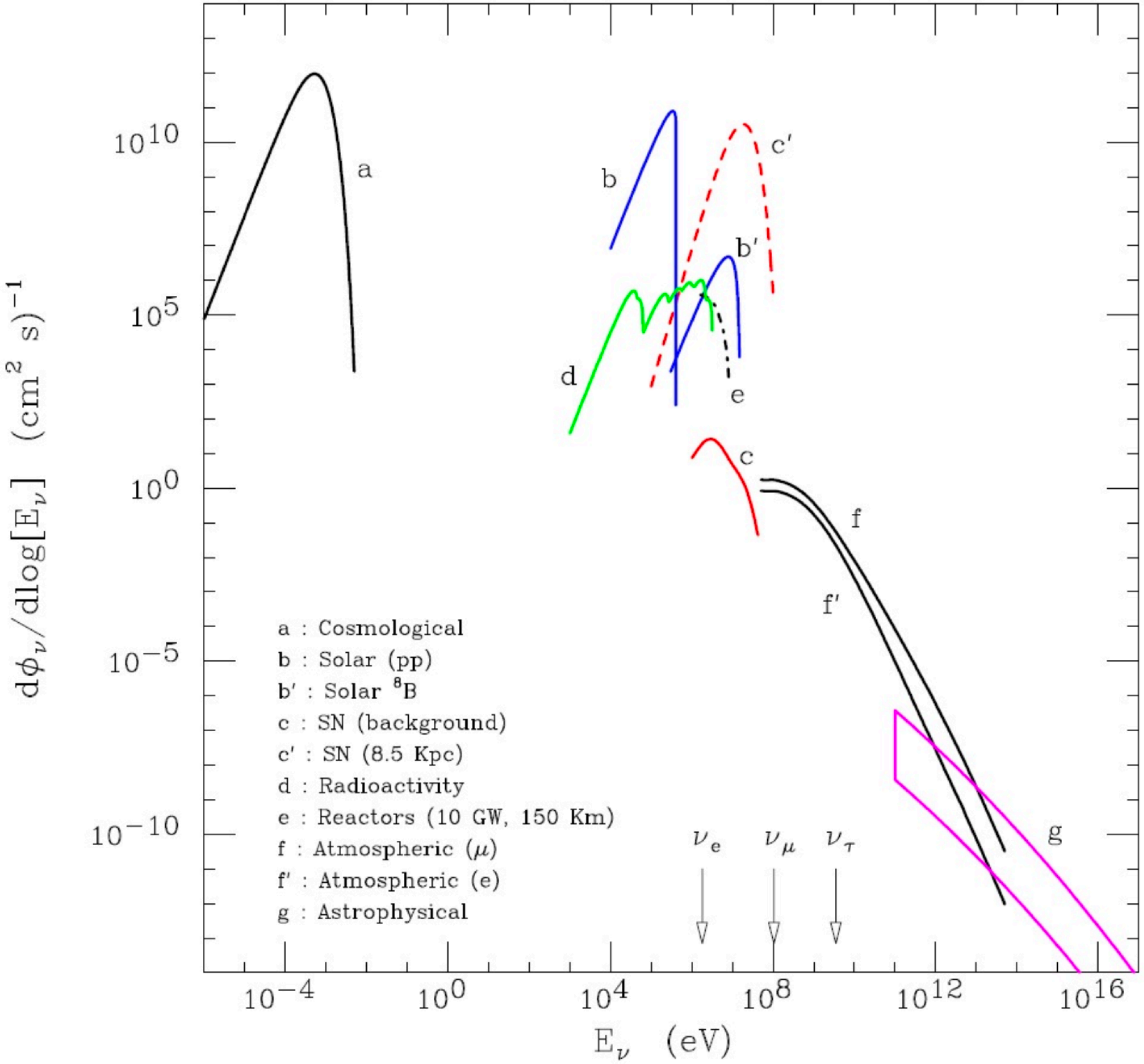
Overview

1. Why neutrino astronomy?
2. Stellar evolution and solar neutrinos
    - Solar neutrino detection & experiments
3. Supernova neutrinos
4. High energy cosmic neutrinos & neutrino telescopes
    - Galactic & Extragalactic sources

1. Why neutrino astronomy?

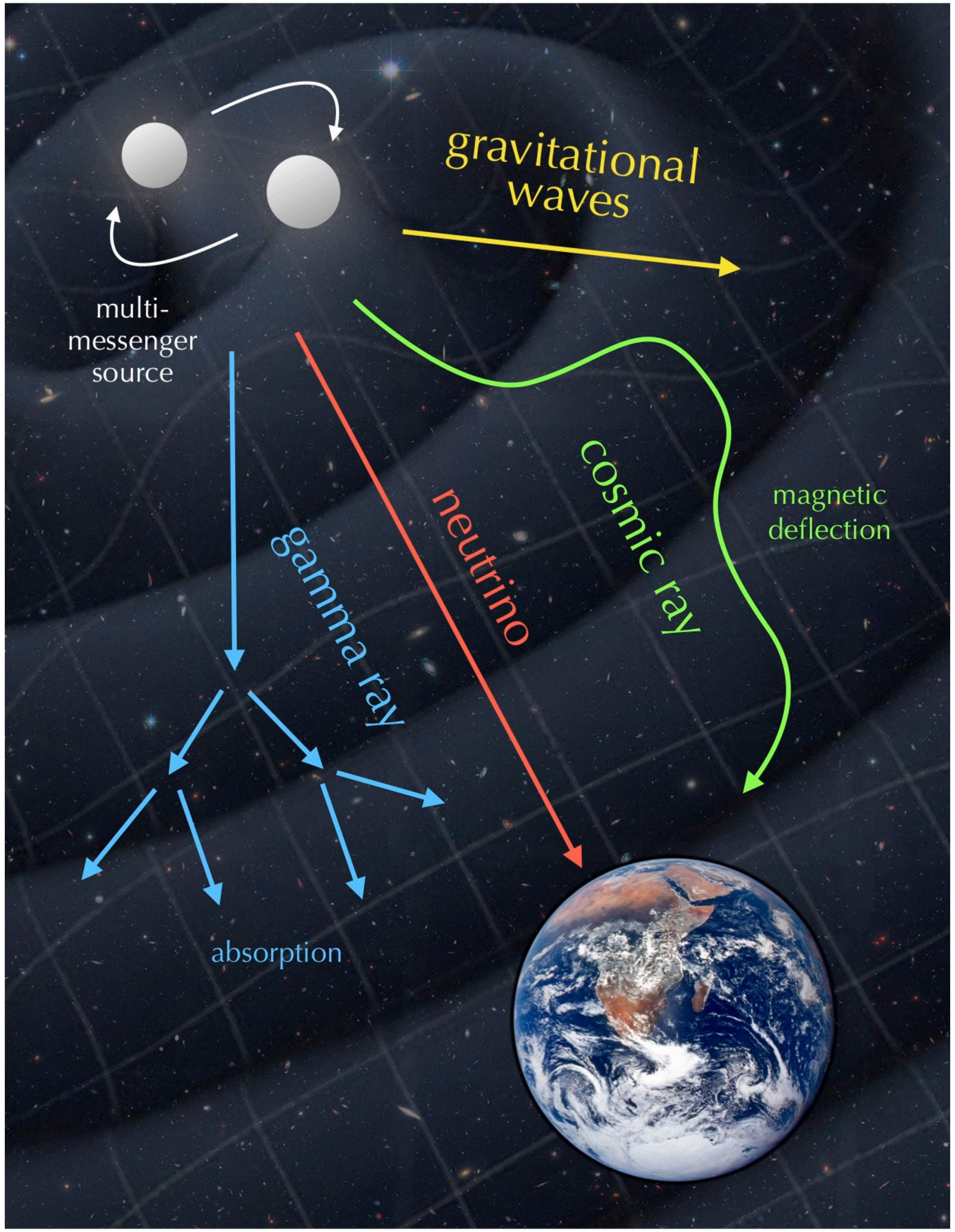
Why neutrino astronomy?

- Messengers of the Universe: protons, heavier nuclei, electrons, γ-rays, and neutrinos.
- Neutrinos are *elusive particles*, but they are abundant in the Universe.



Why neutrino astronomy?

- **Advantages:**
  - Photons: they interact with CMB (r~10 kpc @100 TeV) and other radiation fields and matter.
  - Protons: interact with CMB and deflected by magnetic fields.
  - Neutrons: are not stable.
- **Disadvantages:**
  - Due to small cross section, large detectors are needed.



2. Stellar evolution and solar neutrinos

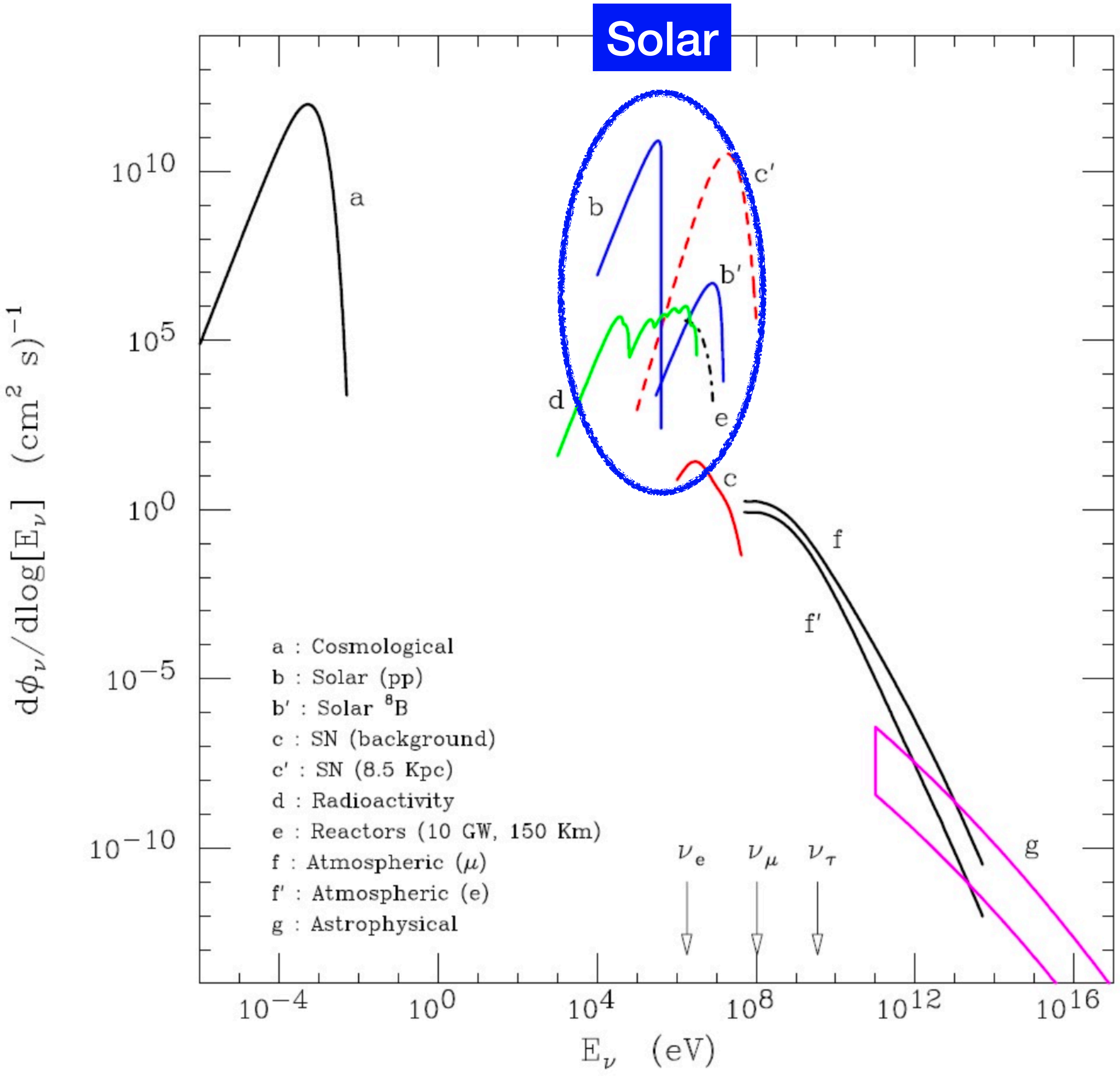
Solar Neutrinos

The solar neutrinos, i.e., the neutrinos emitted by the Sun, are of physical interest for:

1. they tell us how the Sun works, which is important on its own and also for the stellar physics at large;

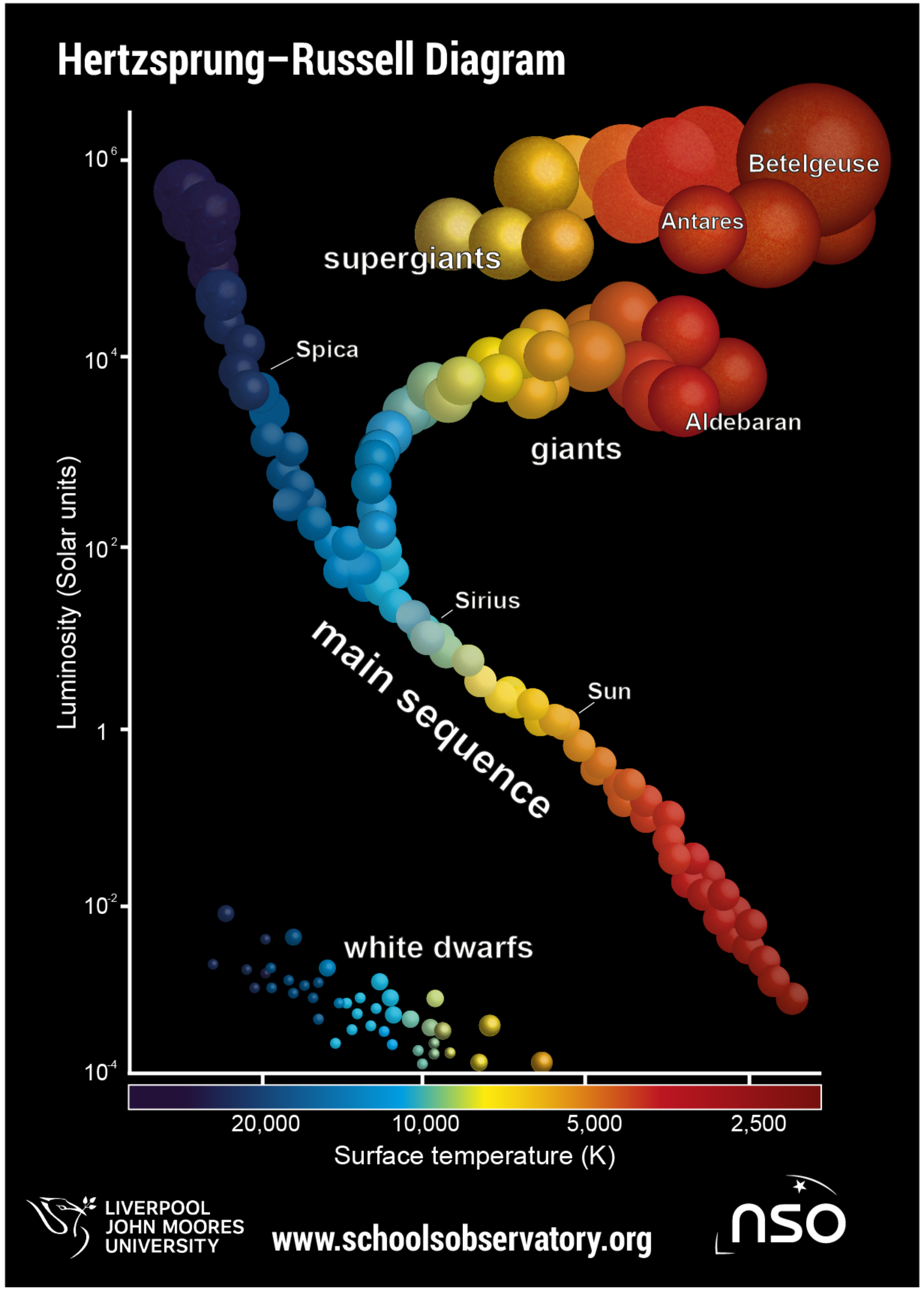
2. neutrinos escape from the Sun in about 2 seconds, rather than some 100000 years as the photons do: they are real-time messengers from the Sun;

3. the measurements of solar-neutrino flavor-oscillations give clear evidence of physics beyond the standard model of particle physics.

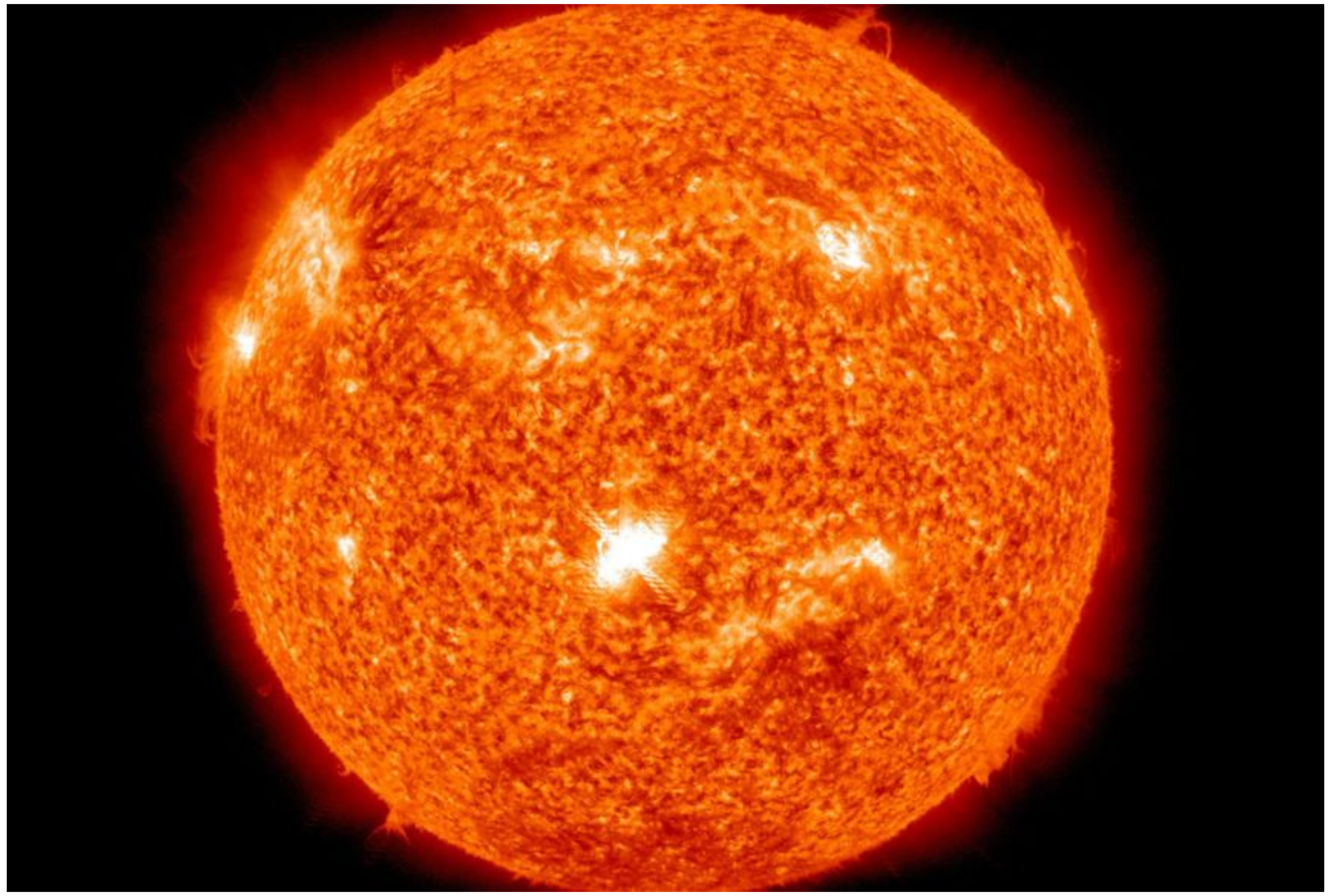


Stellar evolution

- Star: a system in equilibrium between pressure due to gravity and pressure due to radiation produced by fusion reactions in the core.
- Stellar evolution: theory of how stars evolve.
- It relies on **observations** on many stars with different masses, colors, ages, and chemical composition.
- Every **star** goes through specific evolutionary stages dictated by its mass, internal structure and how it produces energy -> change in the temperature and luminosity of the star -> **astronomers** can know a star's internal structure and evolutionary stage simply by determining its position in the diagram.

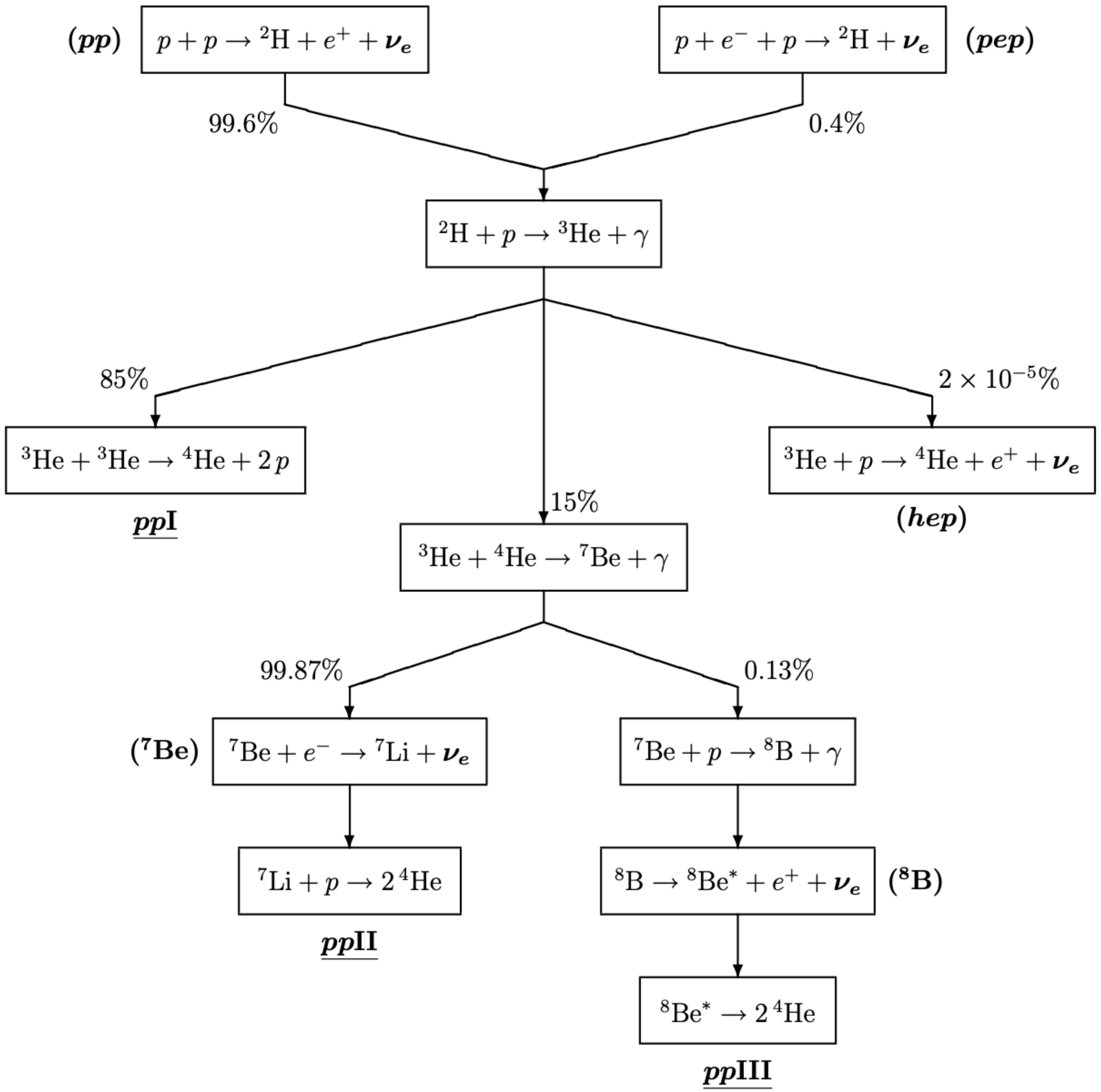


Sun



- The Sun, through the Standard Solar Model (SSM), is the only star for which the stellar evolution theory can be deeply tested.
- The neutrinos emitted from various thermonuclear processes in the Sun are extremely useful in testing theoretical predictions.
- The Sun is powered by the two groups of thermonuclear reactions known as the pp chain and the CNO cycle.

pp chain



(*pp*) $p + p \rightarrow {}^{2}\mathrm{H} + e^{+} + \boldsymbol{\nu_e}$

$p + e^{-} + p \rightarrow {}^{2}\mathrm{H} + \boldsymbol{\nu_e}$ **(*pep*)**

99.6%

0.4%

${}^{2}\mathrm{H} + p \rightarrow {}^{3}\mathrm{He} + \gamma$

85%

15%

$2 \times 10^{-5}\%$

${}^{3}\mathrm{He} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + 2\,p$

<u>*pp*I</u>

${}^{3}\mathrm{He} + p \rightarrow {}^{4}\mathrm{He} + e^{+} + \boldsymbol{\nu_e}$

(*hep*)

${}^{3}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{7}\mathrm{Be} + \gamma$

99.87%

0.13%

(^{7}Be) ${}^{7}\mathrm{Be} + e^{-} \rightarrow {}^{7}\mathrm{Li} + \boldsymbol{\nu_e}$

${}^{7}\mathrm{Be} + p \rightarrow {}^{8}\mathrm{B} + \gamma$

${}^{7}\mathrm{Li} + p \rightarrow 2\,{}^{4}\mathrm{He}$

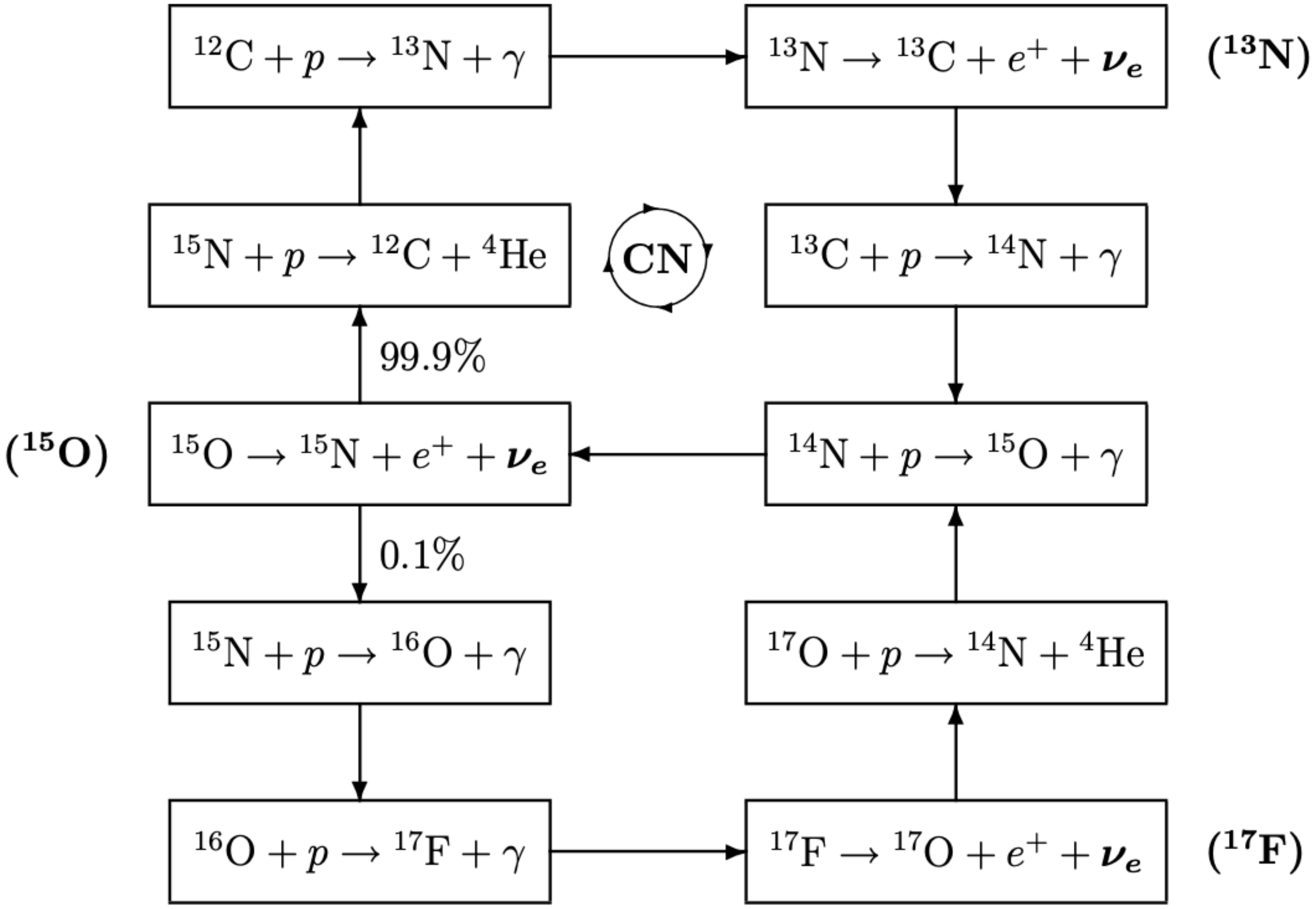
<u>*pp*II</u>

${}^{8}\mathrm{B} \rightarrow {}^{8}\mathrm{Be}^{*} + e^{+} + \boldsymbol{\nu_e}$ **(^{8}B)**

${}^{8}\mathrm{Be}^{*} \rightarrow 2\,{}^{4}\mathrm{He}$

<u>*pp*III</u>

CNO cycle



${}^{12}\mathrm{C} + p \rightarrow {}^{13}\mathrm{N} + \gamma$

${}^{13}\mathrm{N} \rightarrow {}^{13}\mathrm{C} + e^{+} + \boldsymbol{\nu_e}$ **(^{13}N)**

${}^{15}\mathrm{N} + p \rightarrow {}^{12}\mathrm{C} + {}^{4}\mathrm{He}$

CN

${}^{13}\mathrm{C} + p \rightarrow {}^{14}\mathrm{N} + \gamma$

99.9%

(^{15}O) ${}^{15}\mathrm{O} \rightarrow {}^{15}\mathrm{N} + e^{+} + \boldsymbol{\nu_e}$

${}^{14}\mathrm{N} + p \rightarrow {}^{15}\mathrm{O} + \gamma$

0.1%

${}^{15}\mathrm{N} + p \rightarrow {}^{16}\mathrm{O} + \gamma$

${}^{17}\mathrm{O} + p \rightarrow {}^{14}\mathrm{N} + {}^{4}\mathrm{He}$

${}^{16}\mathrm{O} + p \rightarrow {}^{17}\mathrm{F} + \gamma$

${}^{17}\mathrm{F} \rightarrow {}^{17}\mathrm{O} + e^{+} + \boldsymbol{\nu_e}$ **(^{17}F)**

pp chain & CNO cycle

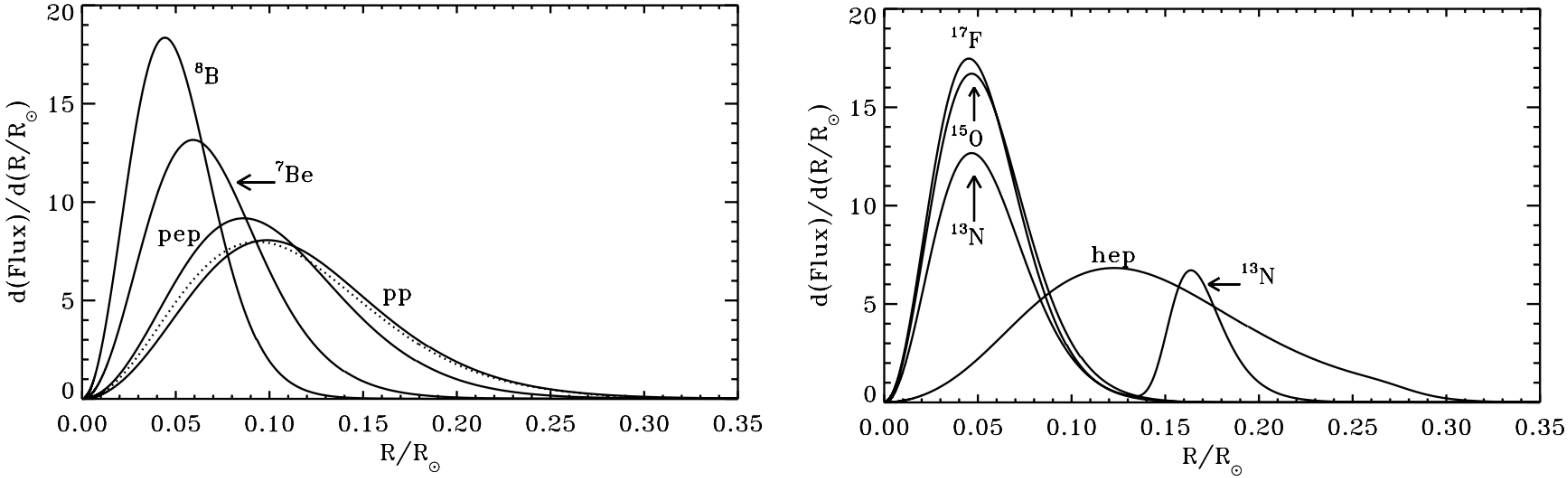


FIG. 10.5. Distribution of the neutrino production as a function of radius for each of the solar neutrino fluxes in the BSB(GS98) SSM [154]. The dotted line close to the distribution for the *pp* flux represents the distribution of the production of the solar luminosity.

Sun

- The result of both the pp chain and the CNO cycle is the conversion of four protons and two electrons into a ^{4}He nucleus plus two electron neutrinos:

$$4\,p + 2\,e^- \to {}^4\mathrm{He} + 2\,\nu_e + Q\,,$$

- where the energy release (Q) is given by (m_e = 0.511 MeV is the mass of the electron)

$$Q = 4\,m_p + 2\,m_e - m_{^4\mathrm{He}} = B(4,2) + 2\,m_e - 2\,(m_n - m_p) = 26.731\,\mathrm{MeV}\,.$$

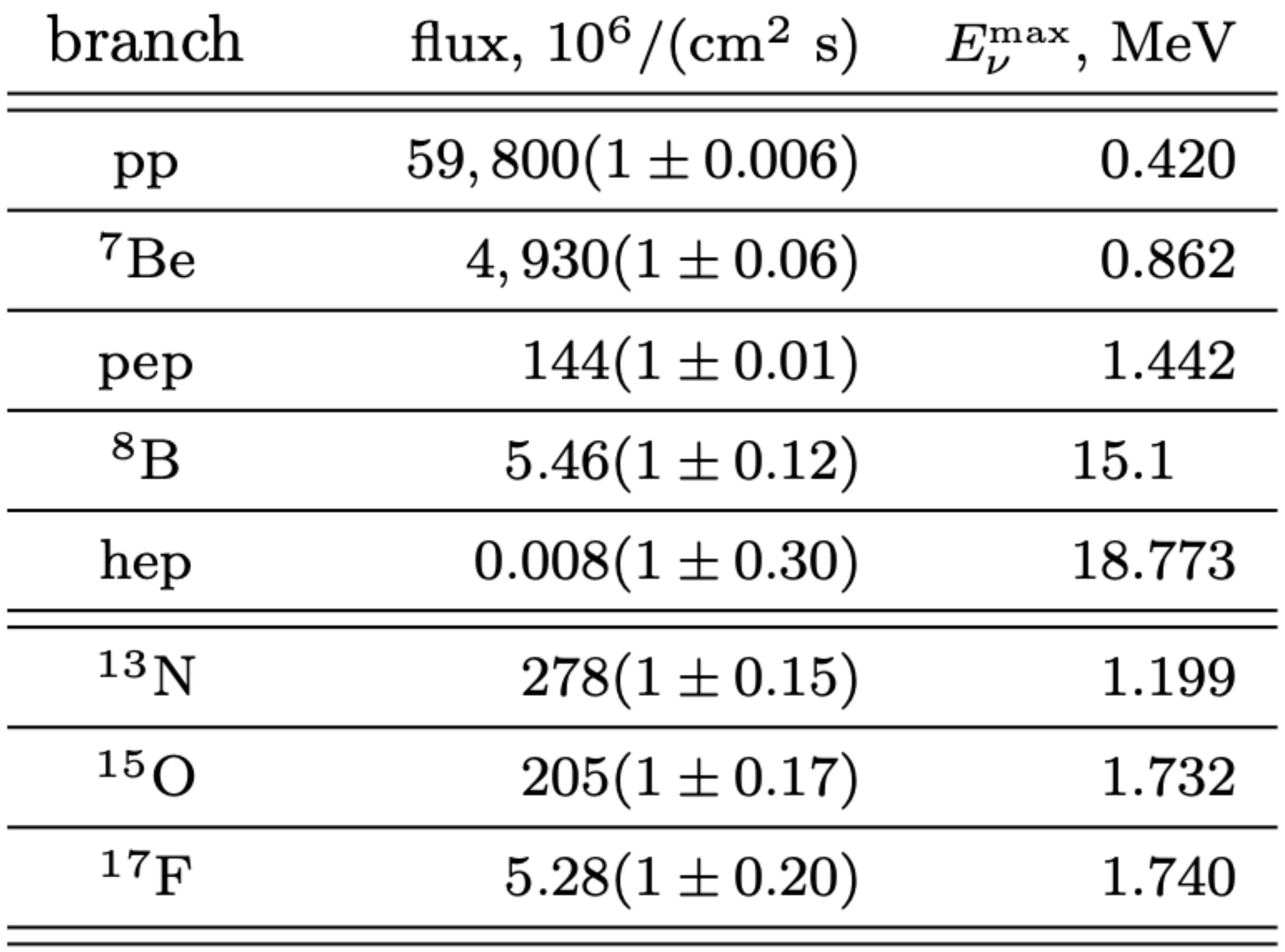
- This energy is released in the form of photons or kinetic energy of the neutrinos.
- The electron neutrinos producedin the core of the Sun can be detected on the Earth -> They provide a unique direct probe of the interior of the Sun.

Standard Solar Model and Neutrinos

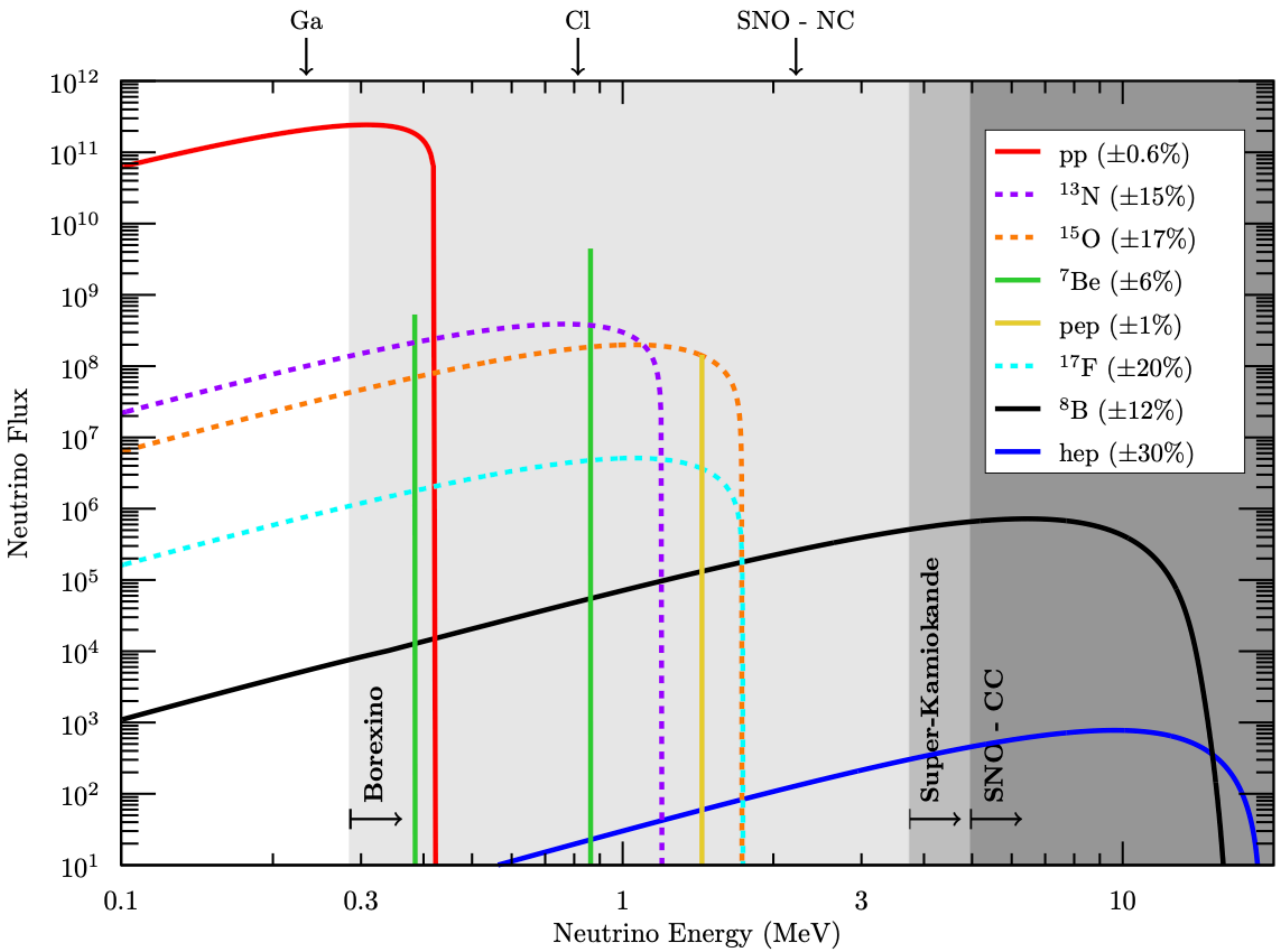
- Several experiments have tested the SSMs by measuring pressure-mode oscillations of the Sun.
- The science that studies these oscillations is called **helioseismology**: it gives detailed information on the sound speed and matter density in the interior of the Sun.
- Measurements and analysis of Doppler shifts of photospheric absorption lines show that the Sun's surface oscillates with amplitudes ~30 m and velocities ~0.1 m s^{-1}, reflecting a variety of interior modes.
- This function depends on the same quantity used in the SSM to derive the neutrino fluxes, namely the Sun quasi-static pressure, density, temperature, entropy, gravitational potential, and nuclear energy generation profiles that are all functions of the radial coordinate r.

Standard Solar Model and Neutrinos

- In order to study the physics of solar neutrinos, it is convenient to treat separately the neutrino fluxes produced by the individual thermonuclear reactions of the pp chain and the CNO cycle.



branch	flux, $10^6/(\mathrm{cm}^2\ \mathrm{s})$	E_ν^{max}, MeV
pp	$59,800(1 \pm 0.006)$	0.420
^{7}Be	$4,930(1 \pm 0.06)$	0.862
pep	$144(1 \pm 0.01)$	1.442
^{8}B	$5.46(1 \pm 0.12)$	15.1
hep	$0.008(1 \pm 0.30)$	18.773
^{13}N	$278(1 \pm 0.15)$	1.199
^{15}O	$205(1 \pm 0.17)$	1.732
^{17}F	$5.28(1 \pm 0.20)$	1.740



Solar neutrino detection

- The detection of low-energy neutrinos is extremely challenging.
- MeV-scale neutrinos interact mainly via quasi-elastic scattering

$$\nu_e + n \rightarrow p + e^- \qquad (1)$$

- or through elastic scattering (ES) on electrons, with a much smaller cross section.
- The problem of eq. (1) is that free neutrons do not exist in nature. Only neutrons bound in nuclei can be used in reactions

$$\nu_e + {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^- \qquad (2)$$

- By changing the number of protons, ν_e capture transforms the nuclide into a new element.
- (2) requires an additional energy with respect to (1) due to the difference of the nuclear binding energies between the nucleus *X* and *Y*.

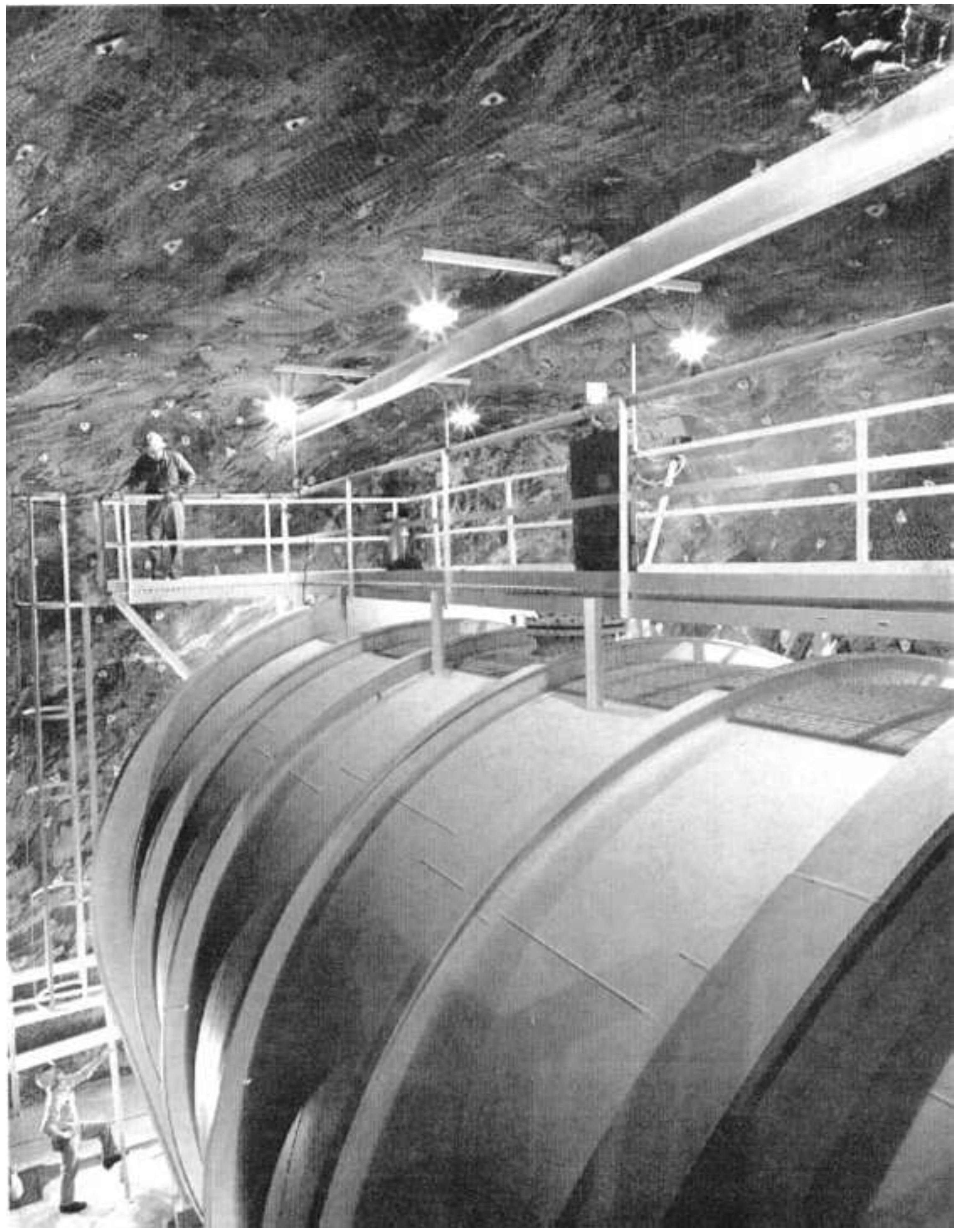
Solar neutrino detection

Reaction (2) can be used to detect solar neutrinos only if the very few *Y* atoms produced by the weak-interaction process can be separated from the huge number of *X* target atoms of the detector using *chemical extraction* techniques.

Only few elements *X* are thus suitable to be effectively used. The production rate of the *Y* atoms can be easily measured if the *Y* isotope is *radioactive* and, moreover, if the lifetime is neither too short nor too long. In this case, when extracted, the decay rates can be counted. The combination of these techniques gives rise to the so-called *radiochemical* experiments.

Chlorine radiochemical experiment

Homestake



- Radiochemical detection of neutrinos using ^{37}Cl in was suggested by Pontecorvo in 1946.
- The construction of an experiment with the scale necessary for solar neutrino detection (tank with 390,000 l of C_2Cl_4) began on the Homestake mine (South Dakota) in 1965, at a depth of 2438 m.
- The first results were announced in 1968 and the measurements continued until 2002, when the mine closed.
- ^{37}Ar is produced with a threshold energy of 0.814 MeV in the reaction

$$\nu_e + {}^{37}_{17}\mathrm{Cl} \rightarrow {}^{37}_{18}\mathrm{Ar} + e^- .$$ (3)

Chlorine radiochemical experiment

Homestake

- The average solar neutrino reaction rate in the tank was 0.48 counts/day, above an estimated background of 0.09 counts/day.
- Ar is a noble gas that does not interact chemically, and it can be extracted with high efficiency (estimated as ~95%) from large volumes of organic liquid.
- In addition, the ^{37}Ar isotope has a half-life of 35 days, long enough to allow to build up their concentrations in the tank over a saturation time of about two months.
- After extraction of ^{37}Ar nuclei from the tank, they decay via the capture of one orbital electron (usually from the K shell) returning to ^{37}Cl via the inverse reaction of (3) .
- The newly formed ^{37}Cl, is in an excited state with a missing electron in the inner shell. An outer shell electron will fill the empty inner level thereby dropping to a lower state -> emit an *X*-ray of 2.82 keV
- Miniaturized gas proportional counters were used for counting such decays.
- The chlorine experiment counted ~25 Ar nuclei per year.

Chlorine radiochemical experiment

Homestake

- Capture rate: $\langle\sigma\Phi\rangle \equiv \int dE \frac{d\Phi_{\nu_e}}{dE}\sigma(E) \quad [\mathrm{s}^{-1}]$

- The final measurement was $\boxed{\langle\sigma\Phi\rangle_{Cl} = 2.56 \pm 0.16_{\mathrm{stat}} \pm 0.16_{\mathrm{sys}}\ \mathrm{SNU}}$

(1 SNU ≡ 1 Solar Neutrino Unit = 10^{-36} captures per second)

- which is **about a factor of three below the SSM best values**: 8.00 ± 0.97 SNU.

- This result represents the beginning of the *solar neutrino problem*, a major discrepancy between measurements of the numbers of neutrinos reaching the Earth and theoretical predictions, lasting from the early results of the chlorine experiment to about 2002.

Gallium experiments

SAGE, GALLEX/GNO

- Another possible element for reaction (2) is gallium through the reaction

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

- With a low neutrino energy threshold: $E_\nu^{\mathrm{th}} = 0.233\,\mathrm{MeV}$
- The Soviet-American Gallium Experiment (SAGE) and the Gallium Experiment (GALLEX) (successively: Gallium Neutrino Observatory (GNO)) began solar neutrino measurements in December 1989 and May 1991, respectively, exploiting the above reaction.
- SAGE, located at the Baksan Neutrino Observatory in the Caucasus mountains in Russia and uses a target of 50 tons of Ga under the form of a molten metal at a temperature of 30 $^\circ$C.

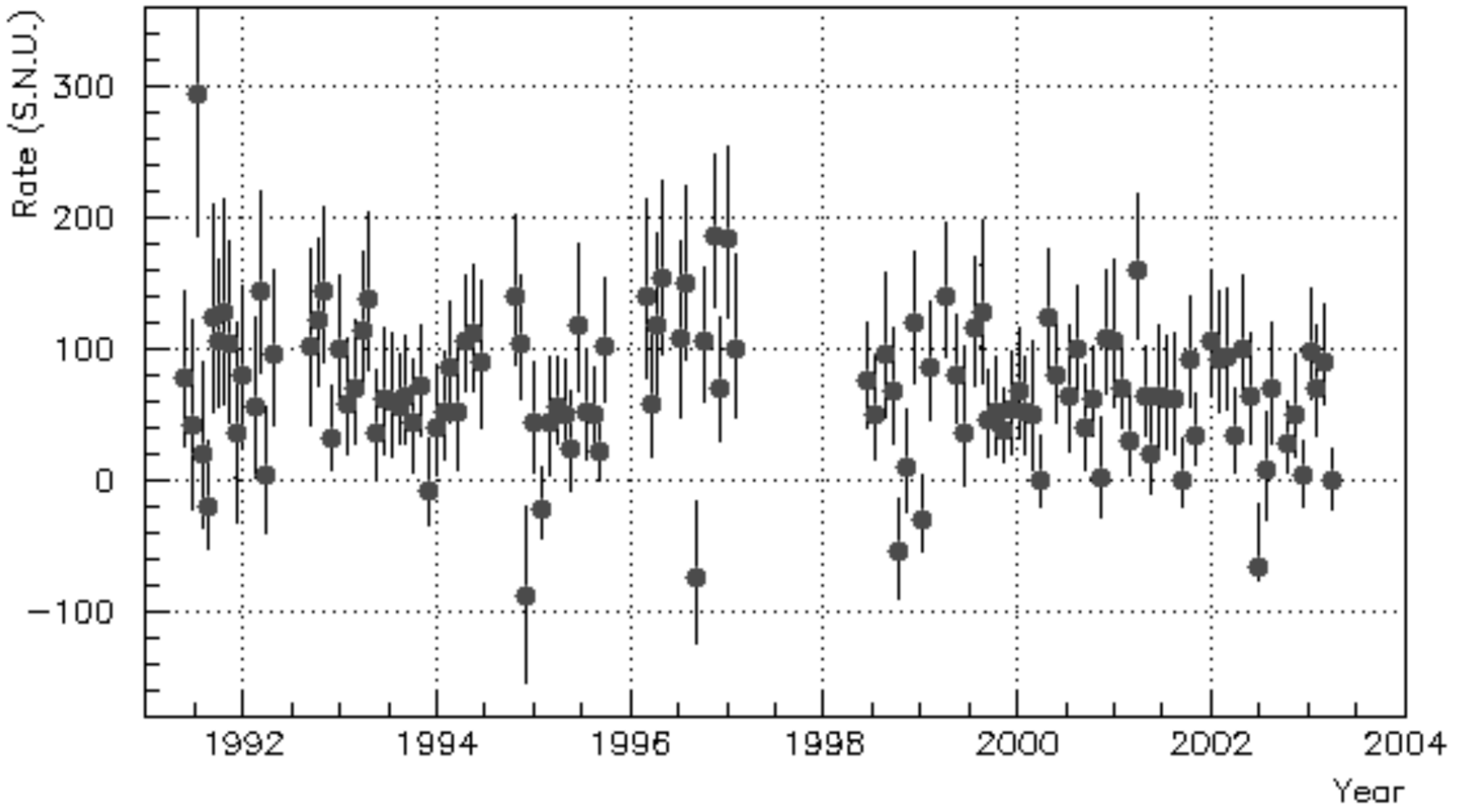
Gallium experiments

GALLEX/GNO, SAGE

- GALLEX, which used 30 tons of Ga in the form of a $GaCl_3$ solution, ran between 1991 and 1997 at the Gran Sasso Laboratory (LNGS) in Italy.
- A number of improvements in Ge extraction procedures, electronics, counter efficiency calibrations, and radon event characterizations were incorporated into the follow-up experiment GNO, who continued through 2003.
- After many years of operations, the weighted average of SAGE (65.4 ± 5 SNU), GALLEX (73.1 ± 7 SNU), and GNO (62.9 ± 6 SNU) results is

$$\boxed{\langle\sigma\Phi\rangle_{Ga} = 66.1 \pm 3.1 \mathrm{SNU}}$$

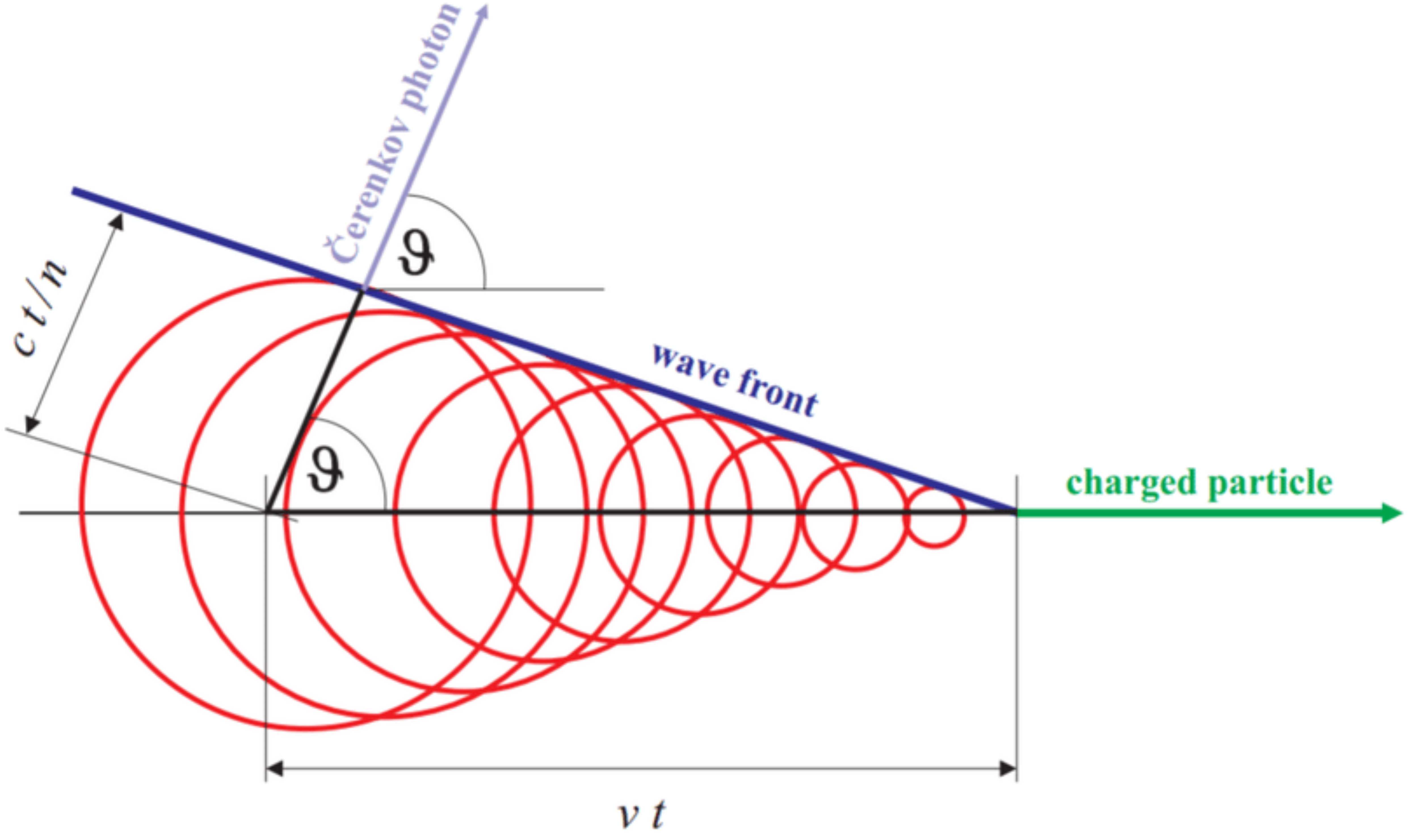
- **while the expected SSM rate is** 126.6 ± 4.2 SNU.



Results of the 123 extraction runs of GALLEX/GNO from May 1991 to April 2003

Water Cherenkov detectors

- Water Cherenkov detectors allow the detection of neutrinos in real time by observing the tracks of the ultrarelativistic charged leptons produced by neutrino interactions.
- Cherenkov effect: when a charged particle passes with velocity v > 1/n through a medium with index of refraction n, the particle emits Cerenkov light in a cone around the direction of motion.

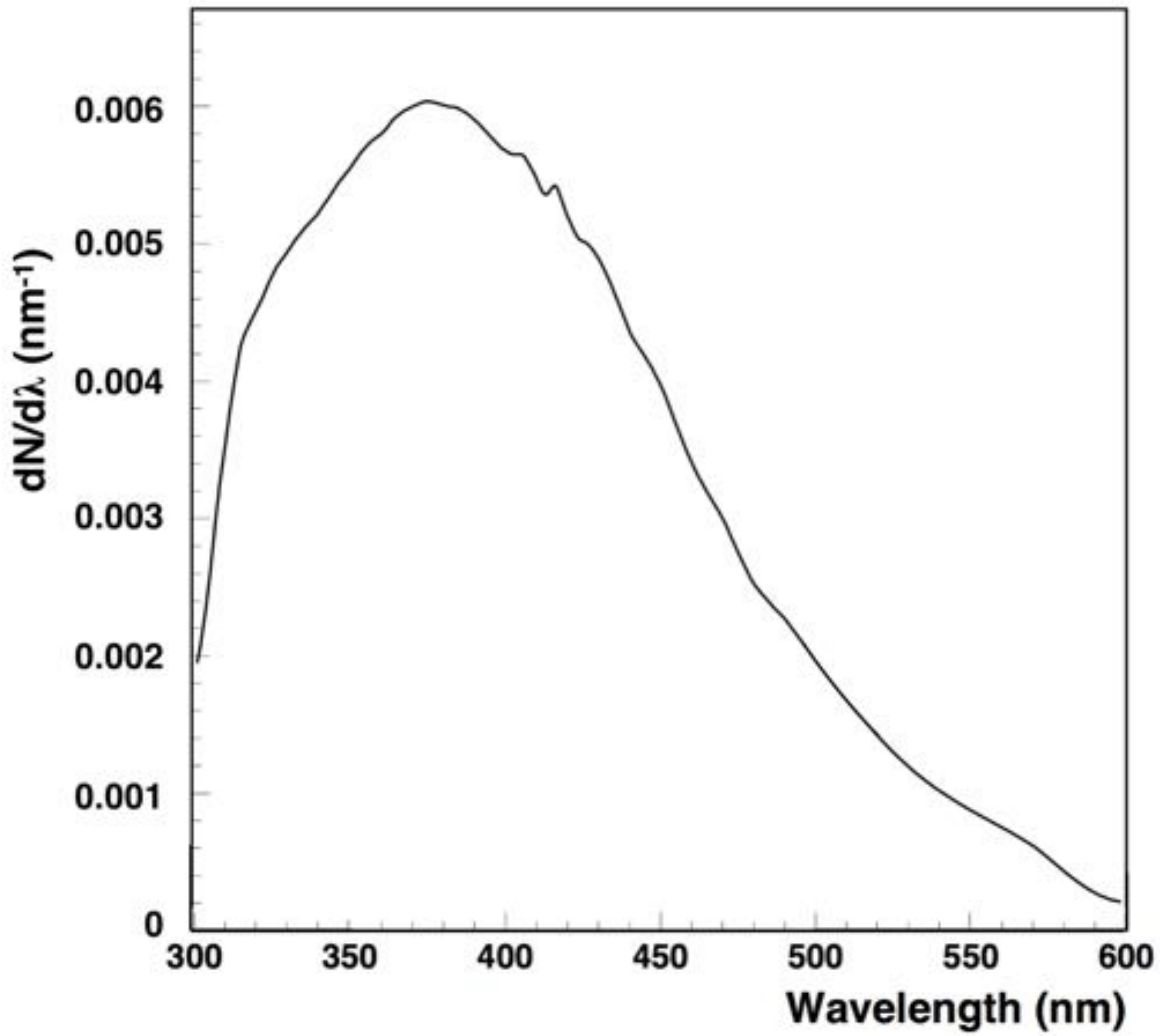


Water Cherenkov detectors

- Cherenkov effect: the spectrum is given by

$$\frac{\mathrm{d}N}{\mathrm{d}\lambda\,\mathrm{d}x} = 2\pi\alpha\left[1 - \left(\frac{1}{nv}\right)^2\right]\lambda^{-2},$$

where N is the number of photons, λ is the wavelength, and x is a coordinate along the track.



Water Cherenkov detectors

- Water has an index of refraction $n \simeq 1.33$, leading to $\theta \simeq 41^\circ$ for relativistic particles.
- For every cm of track length about 340 photons are produced in the wavelength range between 300 and 600 nm, which is appropriate for detection by photomultiplier tubes (PMT).
- Through observation of these photons, with a precise determination of the arrival time at each PMT, it is possible to determine the neutrino interaction point, the direction of the track of the produced charged lepton and its energy.

Water Cherenkov detectors

Kamiokande and Super-Kamiokande

- Neutrinos interacting via elastic scattering on electrons

$$ES: \quad \nu e^- \rightarrow \nu e^-$$

- were detected in a large water tank. This reaction does not have an energy threshold, however it is detectable above the natural radioactivity background only when the final state electron has a sufficiently high energy. This method can only reveal the highest energy neutrinos coming from the ^{8}B.

- Kamiokande: used a ~2.2 kt tank filled with purified water and viewed by 948 20" photomultiplier, providing ~20 % surface coverage. The innermost 0.68 kt of the detector served as the fiducial volume for solar neutrino detection. The energy threshold varied from the initial 9 MeV to 7 MeV after subsequent detector improvements. The outer portion of the detector was instrumented with 123 PMTs to serve as a muon veto, and additional water was added to shield against γ-rays from the surrounding rock.

Water Cherenkov detectors

Kamiokande and Super-Kamiokande

- The first result of Kamiokande was based on a livetime of 450 days through May 1988. The number of measured events was (46±15)% with respect to the SSM prediction.

- Kamiokande was the first experiment to record solar neutrinos event by event, since it could establish their solar origin through a correlation with the direction to the Sun, and to provide direct information on the ^{8}B energy spectrum.

- A more accurate measurement of solar ν_e is due to Super-Kamiokande: measured neutrino flux was ~50 % smaller than expected from the SSM

Results of all experiments

- All the above results indicate that there are “missing” neutrinos from the Sun, when data are compared to the SSM.
- Because neutrino oscillations were already observed in atmospheric neutrinos, they represented a natural explanation for the problem.
- However, none of the those experiments could prove that the lack of solar electron neutrinos was not connected with a combination of experimental problems, or to shortcomings of the theory -> They were all ν_e *disappearance experiments*.
- Oscillations produce neutrino of different flavors but conserve the total number. Neutrino *appearance experiments* should be able to observe neutrinos of flavor different from ν_e.
- The problem was solved by the SNO experiment, which measured the fraction of $\nu_\mu + \nu_\tau$ in the neutrino flux from the Sun using their neutral current (NC) interactions.

Water Cherenkov detectors

SNO

- The Sudbury Neutrino Observatory (SNO) in Canada recorded data from 1999 until 2006.
- It was able to detect Cherenkov light emitted by charged particles crossing the detector.
- The detector was a 12-m diameter spherical acrylic vessel viewed by an array of 9,500 20-cm PMTs, covering 56% of the spherical surface.
- It was filled with 1,000 tons of heavy water (D_2O) contained in the inner volume, and surrounded by 1,500 tons of normal water used for screening purpose.
- D_2O is used as both a moderator and a heat transfer agent.

Water Cherenkov detectors

SNO

- The reactions that occur in heavy water are:
  - elastic scattering (ES) on electron
  - ν_e CC interaction on the proton of the deuteron *d* = (*pn*): $CC: \quad \nu_e + d \to e^- + p + p$

    which only occurs for ν_e through a $W^{\pm}$ exchange.
  - deuterium dissociation through a Z^0 exchange: $NC: \quad \nu_f + d \to \nu_f + p + n, \quad \nu_f = \nu_e, \nu_\mu, \nu_\tau.$
- A ~2.2 MeV photon is emitted as a result of the *d* dissociation in *p* + *n*.
- Result clearly indicates that $\Phi_{\nu_\mu + \nu_\tau} = \Phi_{\nu_f} - \Phi_{\nu_e}$ is nonzero, providing a definitive proof that 2/3 of the ^{8}B solar electron neutrinos, on their way to the Earth, changed flavor.

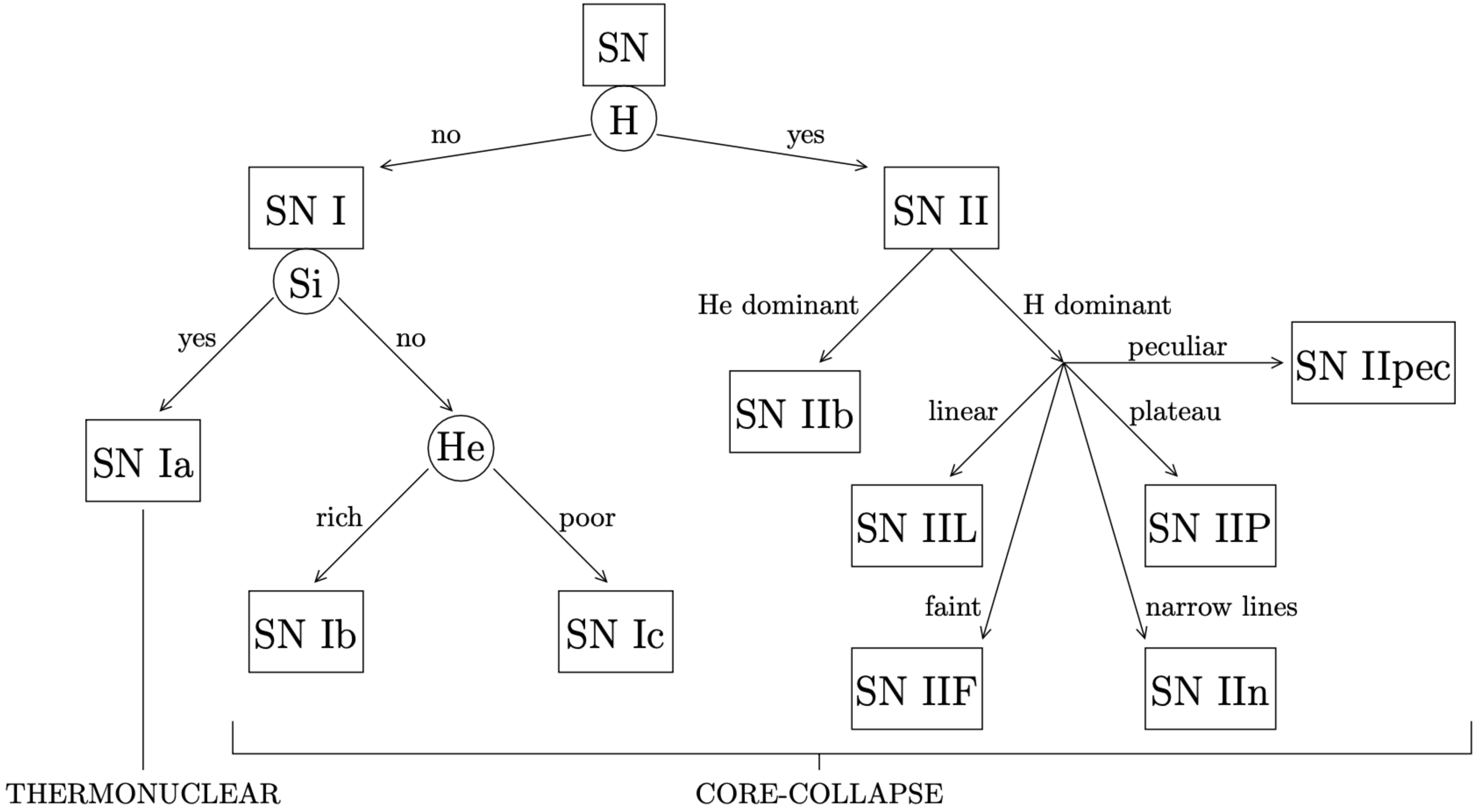
Summary on solar neutrino astronomy

- SK + KamLAND + BOREXINO have allowed to **precisely measure solar neutrino fluxes.**
- This has allowed to improve our understanding of solar physics since SSM prediction for solar neutrino fluxes are related to:
    - solar metallicity.
    - ratio $R_{I/II}$ between the ^{3}He–^{4}He and the ^{3}He–^{3}He fusion rates, which quantifies the relative intensity of the two primary terminations of the *pp* chain, a critical probe of the solar fusion.
    - the total power generated by nuclear reactions in the Sun's core.
    - ^{7}Be flux seasonal modulation: the flux of solar neutrinos at Earth is not constant in time, but is instead modulated due to Earth's movement around the Sun on an elliptical trajectory. Borexino was able to measure the annual modulation of solar neutrinos with high significance, confirming the solar origin of the measured ^{7}Be signal.

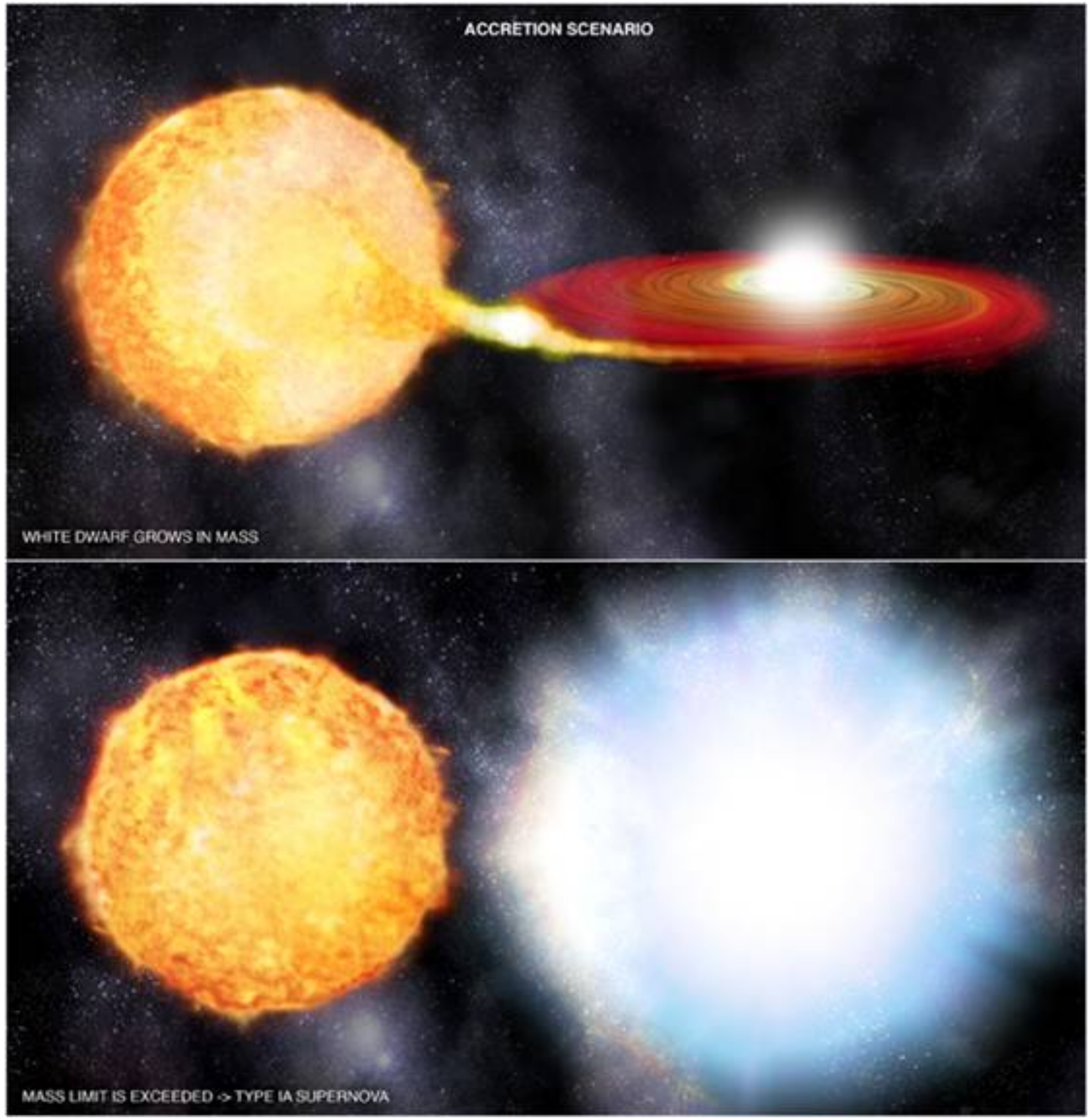
3. Supernova neutrinos

Supernova types

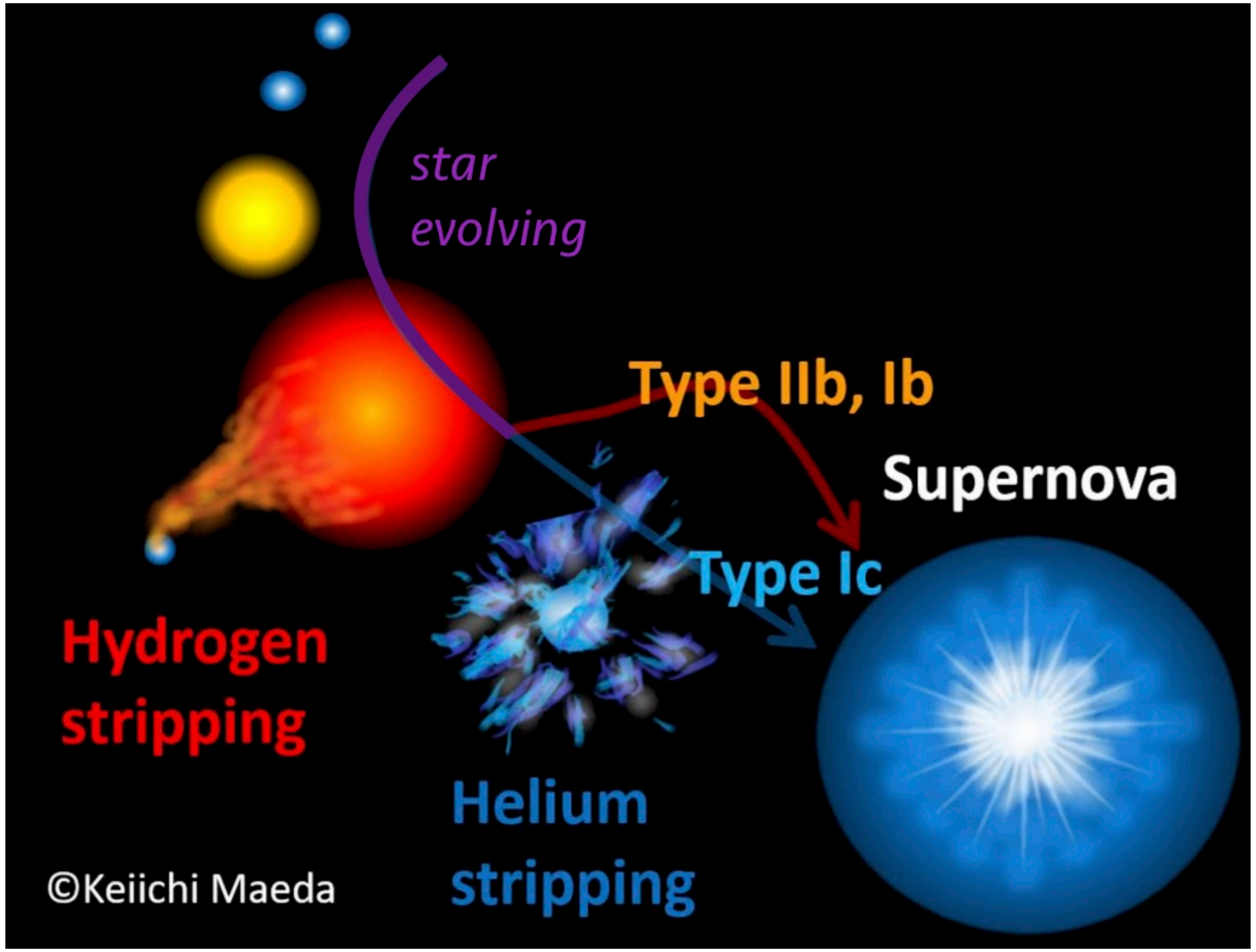
- SNe are divided into different types characterized by their spectroscopic characteristics near maximum luminosity and by the properties of the light curve, which depend on the composition of the envelope of the SN progenitor star
- The two wide categories called type I and type II are characterized by the absence or presence of hydrogen lines.
- However, the most important physical characteristic is the **mechanism that generates the supernova,** which distinguishes SNe of type Ia from SNe of type Ib, Ic and II.



Supernova Ia



Supernova Ib, Ic, II



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Supernovae

- When a massive star has exhausted hydrogen, it evolves by producing energy through the fusion of heavier elements up to the iron.
- Neutrinos produced during such reactions escape from the stellar material and more and more intense nuclear burning is needed to replace the huge amount of energy carried away.
- Once the inner region of a star becomes primarily iron, further compression of the core does not ignite nuclear fusion anymore; the star collapses to form a compact object such as a neutron star or a black hole.
- A prominent prediction from theoretical models of the core-collapse of a massive star is that 99 % of the gravitational binding energy of the resulting remnant is converted to neutrinos with a energies of a few tens of MeV over a timescale of 10 s.
- Neutrinos were observed from the celebrated 1987A supernova (SN1987A) in the Large Magellanic Cloud, 50 kpc away from the Earth,

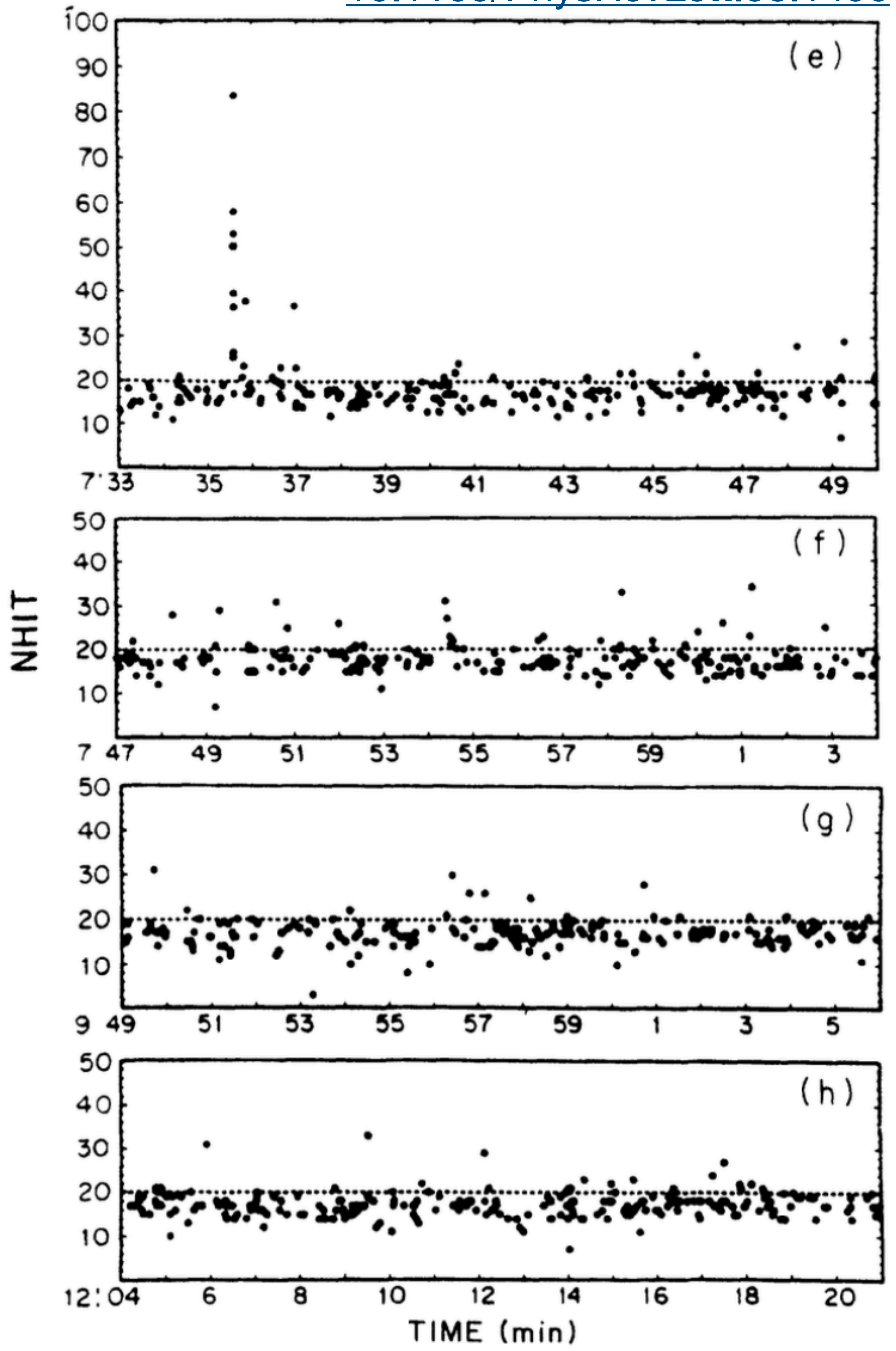
Supernova neutrinos

- From the point of view of neutrino physics, type Ib, Ic, and II SNe are much more interesting than type Ia SNe, simply because they produce a huge flux of neutrinos of all types.
- The astrophysics is much more complicated than that of solar neutrino emission, the associated uncertainties are large and the theorists involved in the study of this type of events are still unsure whether their computer simulations include all the relevant physics.
- 30 years ago we had a successful observation of the neutrinos from one supernova, called SN 1987 A, that has been recognized by the 2002 Nobel prize in physics to the Koshiba, the leader of the Kamiokande experiment.

Kamiokande observation of SN 1987 A

- Observation of a single neutrino burst on 27 February 1987 at 7:35:35 UT.

- “The nature of the single, observed neutrino burst coincides remarkably well with the elements of the current model of type-II supernovae and neutron-star formation. This is the first direct observation in neutrino astronomy”.



10.1103/PhysRevLett.58.1490

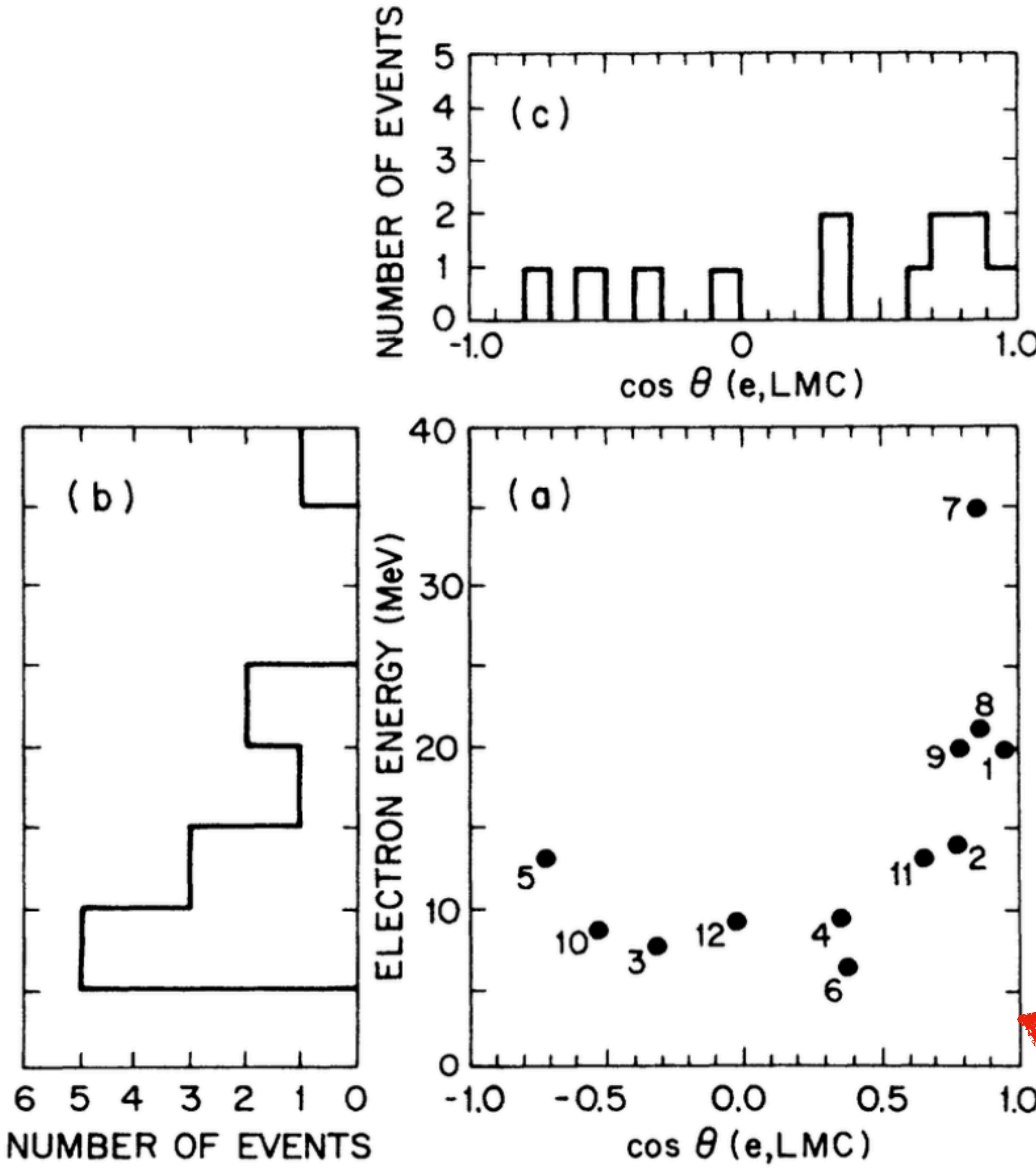
Kamiokande observation of SN 1987 A

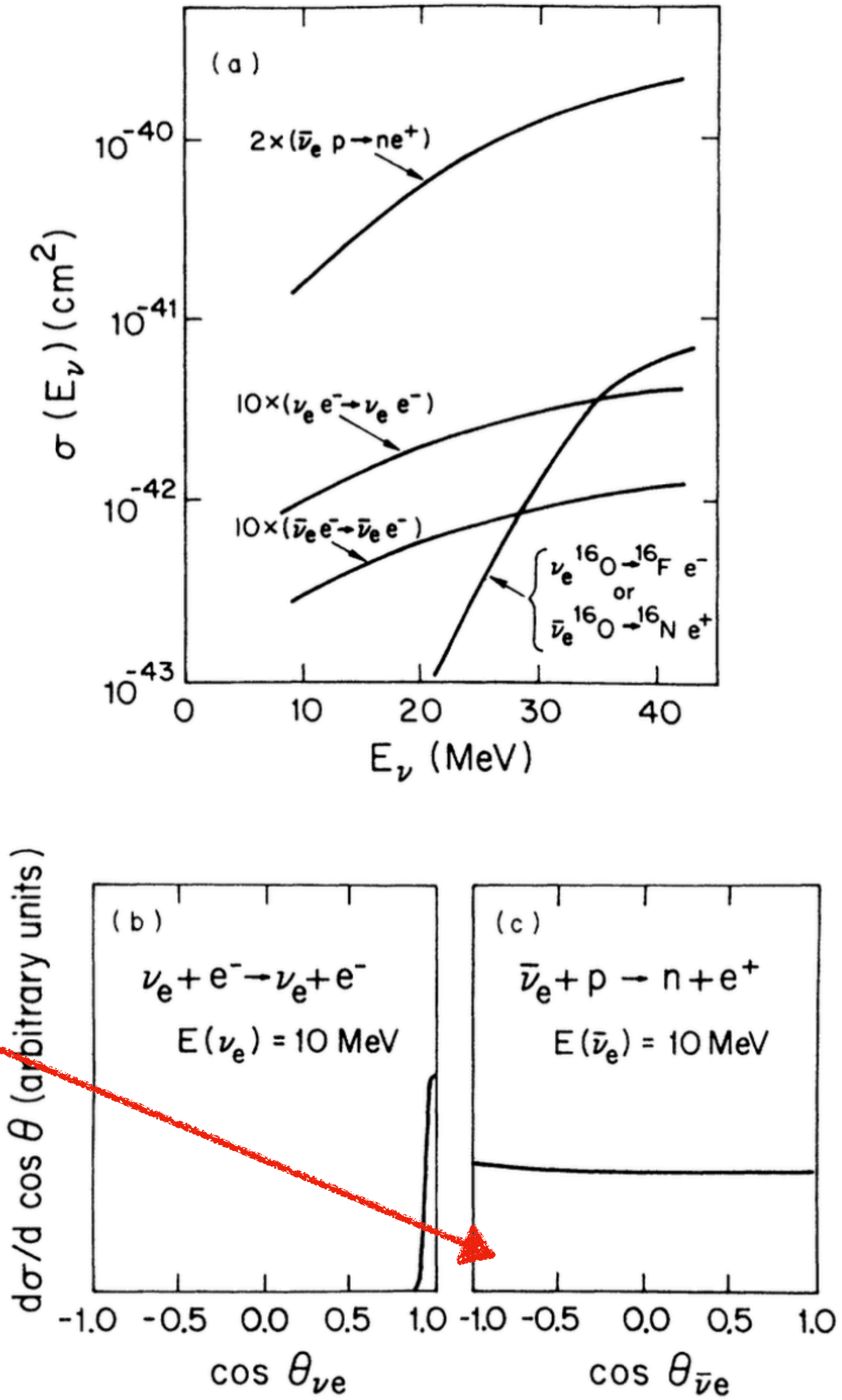
- The angular distribution was consistent with an isotropic distribution of the electrons relative to the Large Magellanic Cloud (LMC).

- This was consistent with the energy dependence of the neutrino cross sections: the dominant cross section is

$$\sigma(\bar{\nu}_e p_{\text{free}} \rightarrow e^+ n)$$

- with isotropic angular distribution.





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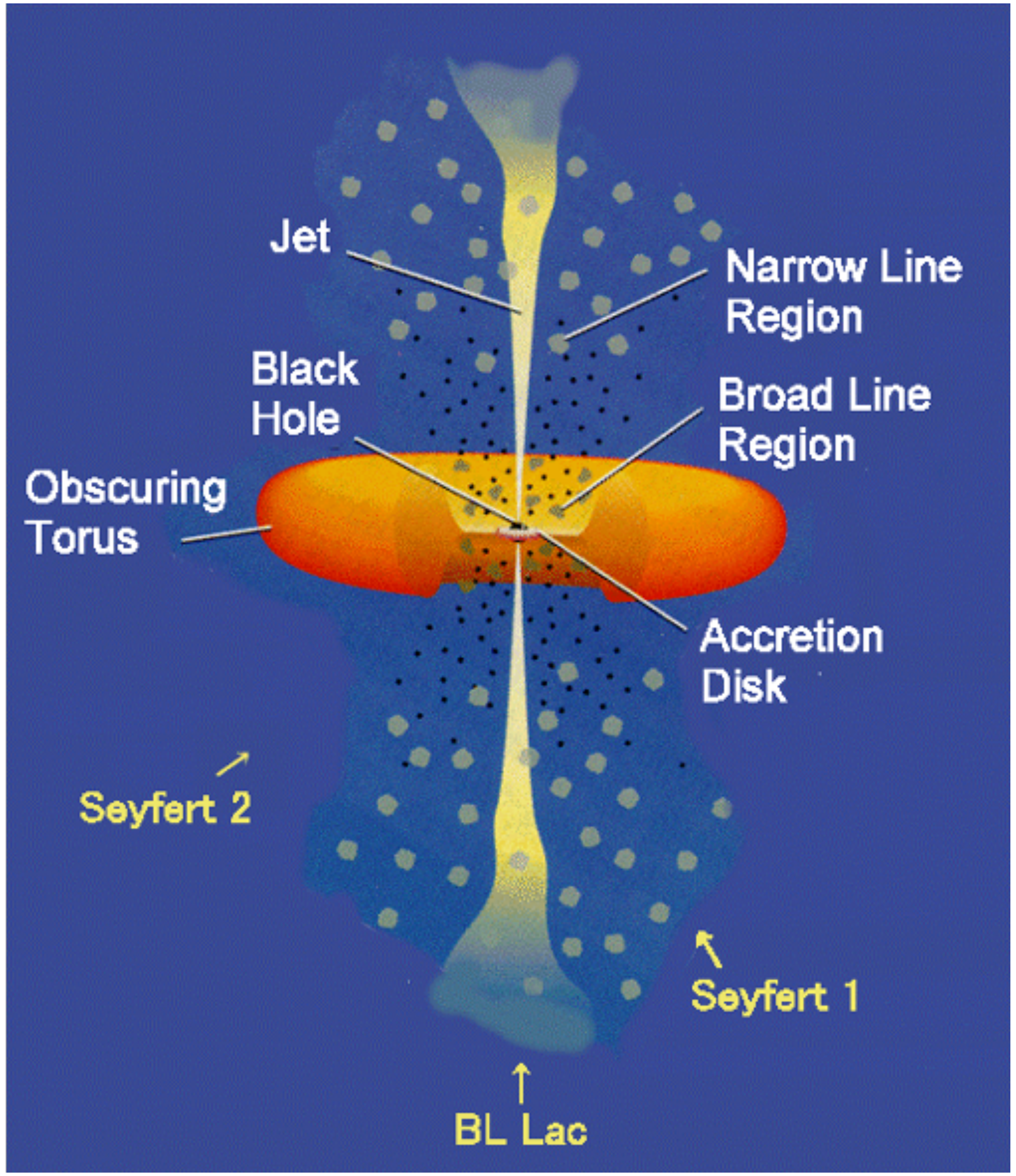
4. High energy cosmic neutrinos

Sources of cosmic neutrinos

- Although we do not have yet a clear theoretical idea on which the sources of cosmic neutrinos are and how intense they are, there are several options:
  - Extragalactic sources
  - Galactic sources

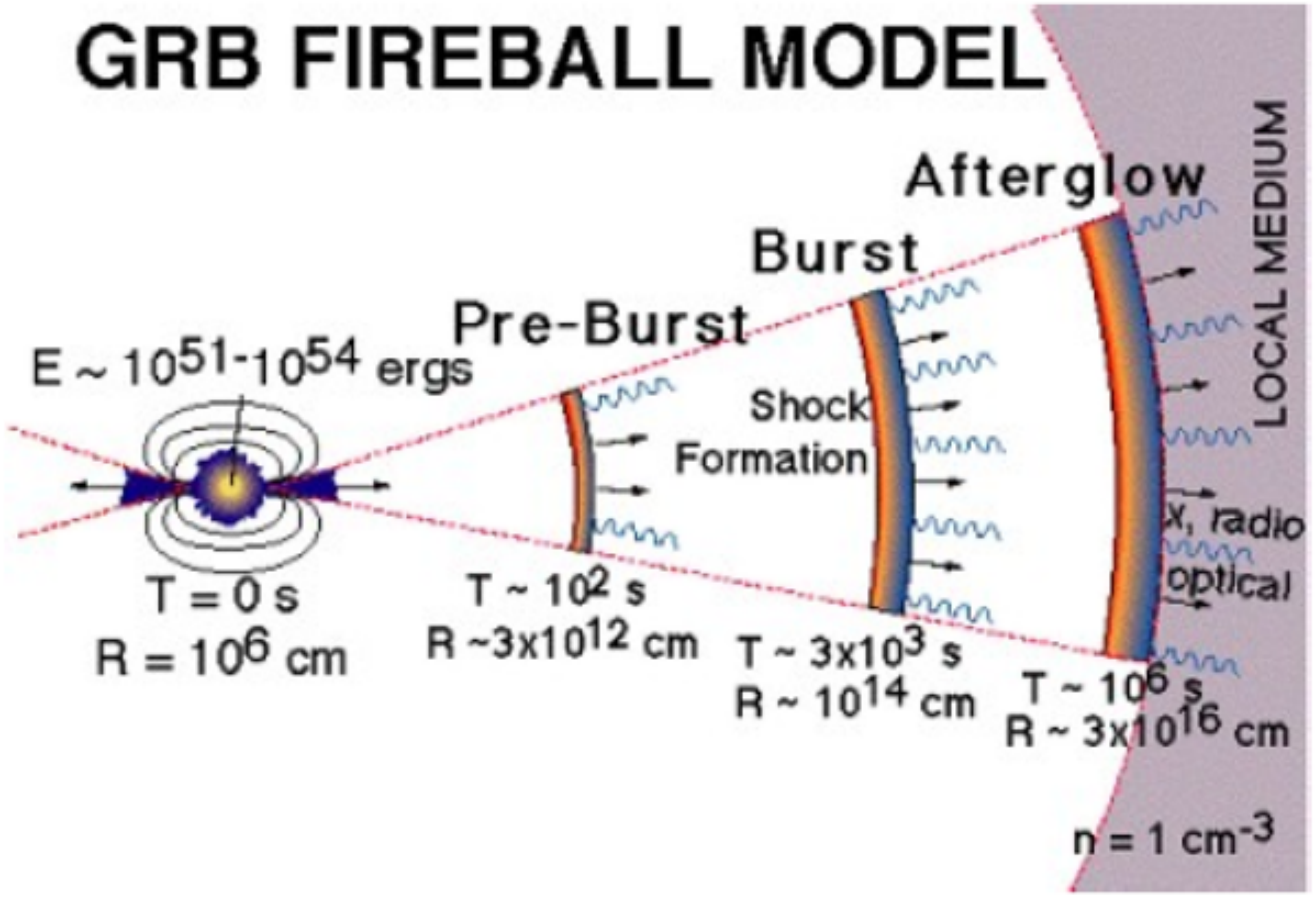
Extragalactic sources

- Extragalactic sources are believed to give the dominant contribution to the high energy neutrino flux.
- AGNs: Active Galactic Nuclei include Seyferts, quasars, radio galaxies and blazars.
  - Standard model: a super-massive (10^6-10^8 M_o) black hole towards which large amounts of matter are accreted.



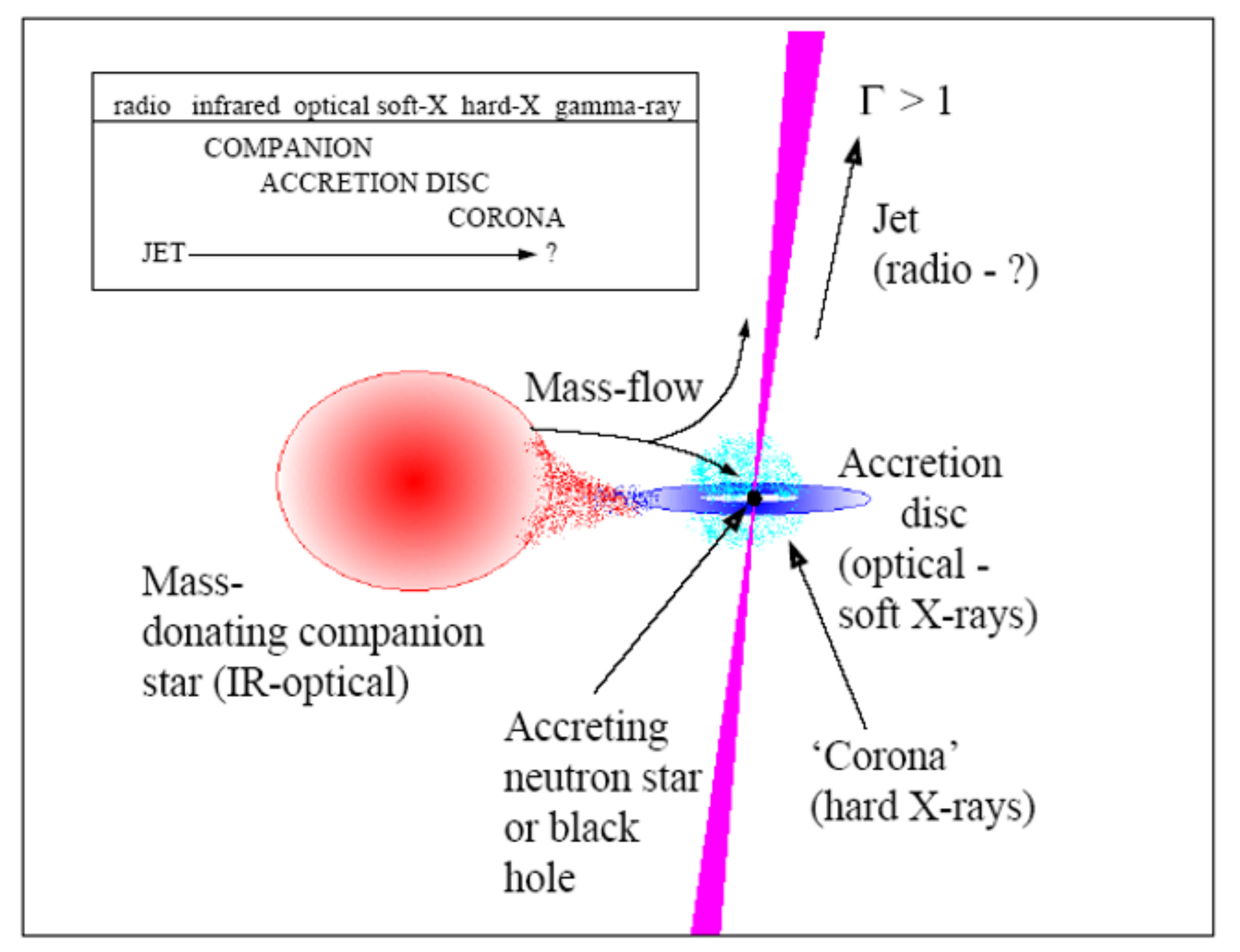
Extragalactic sources

- Extragalactic sources are believed to give the dominant contribution to the high energy neutrino flux.
- AGNs.
- GRBs: brief explosions of ɣ rays (often + X-ray, optical and radio).
  - In the fireball model, matter moving at relativistic velocities collides with the surrounding material. The progenitor could be a collapsing super-massive star.
  - <u>Time correlation</u> enhances the neutrino detection efficiency.



Galactic sources

- Near objects (few kpc) so the luminosity requirements are much lower.
- Micro-quasars: compact object (BH or NS) towards which a companion star is accreting matter. Neutrino beams could be produced in the Micro-quasar jets.

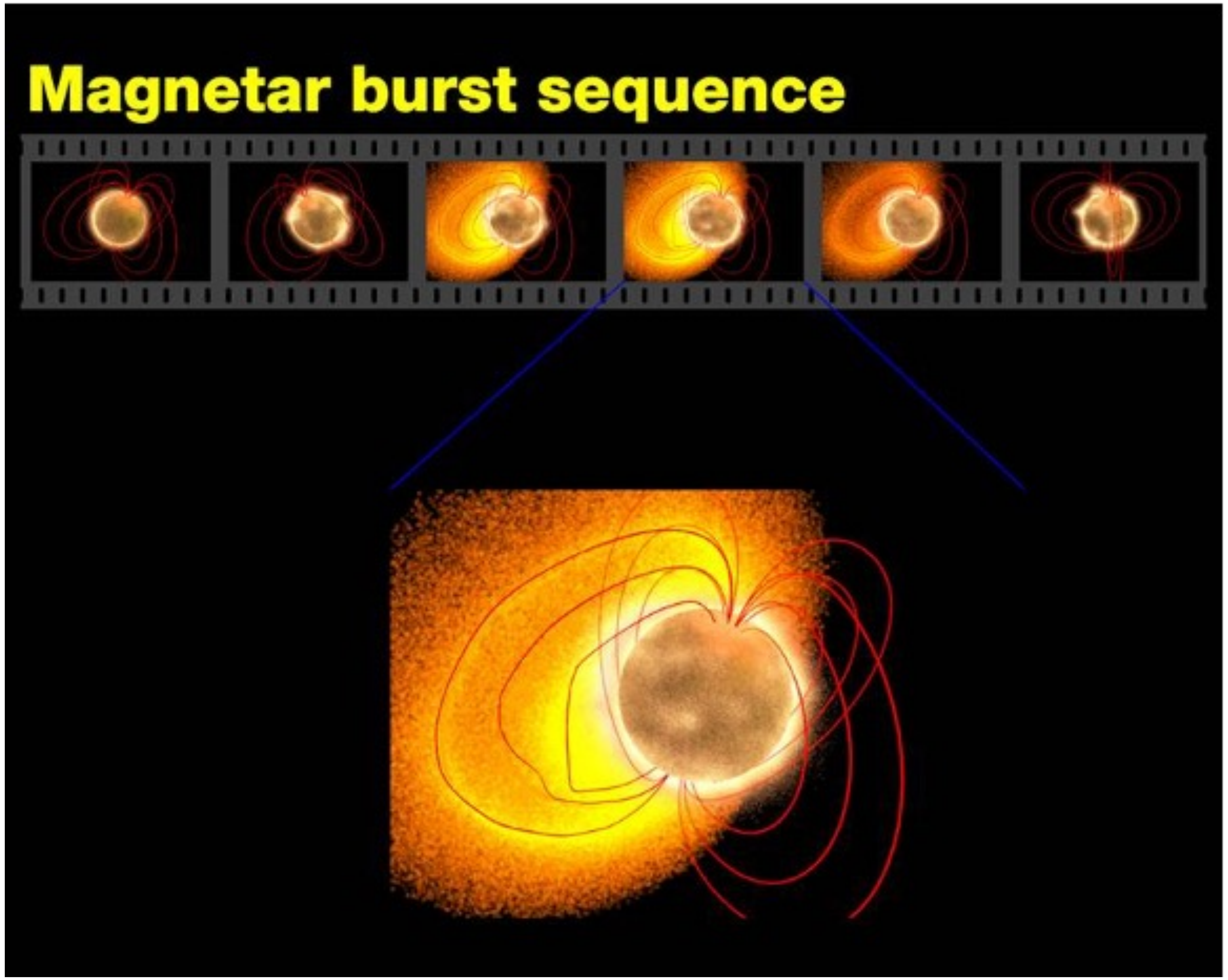


Galactic sources

- Near objects (few kpc) so the luminosity requirements are much lower.
- Micro-quasars.
- Supernova remnants.

Galactic sources

- Near objects (few kpc) so the luminosity requirements are much lower.
- Micro-quasars.
- Supernova remnants.
- Magnetars: Isolated neutron stars with surface dipole magnetic fields ~10^{15} G, much larger than ordinary pulsars.
  - Seismic activity in the surface could induce particle acceleration in the magnetosphere.

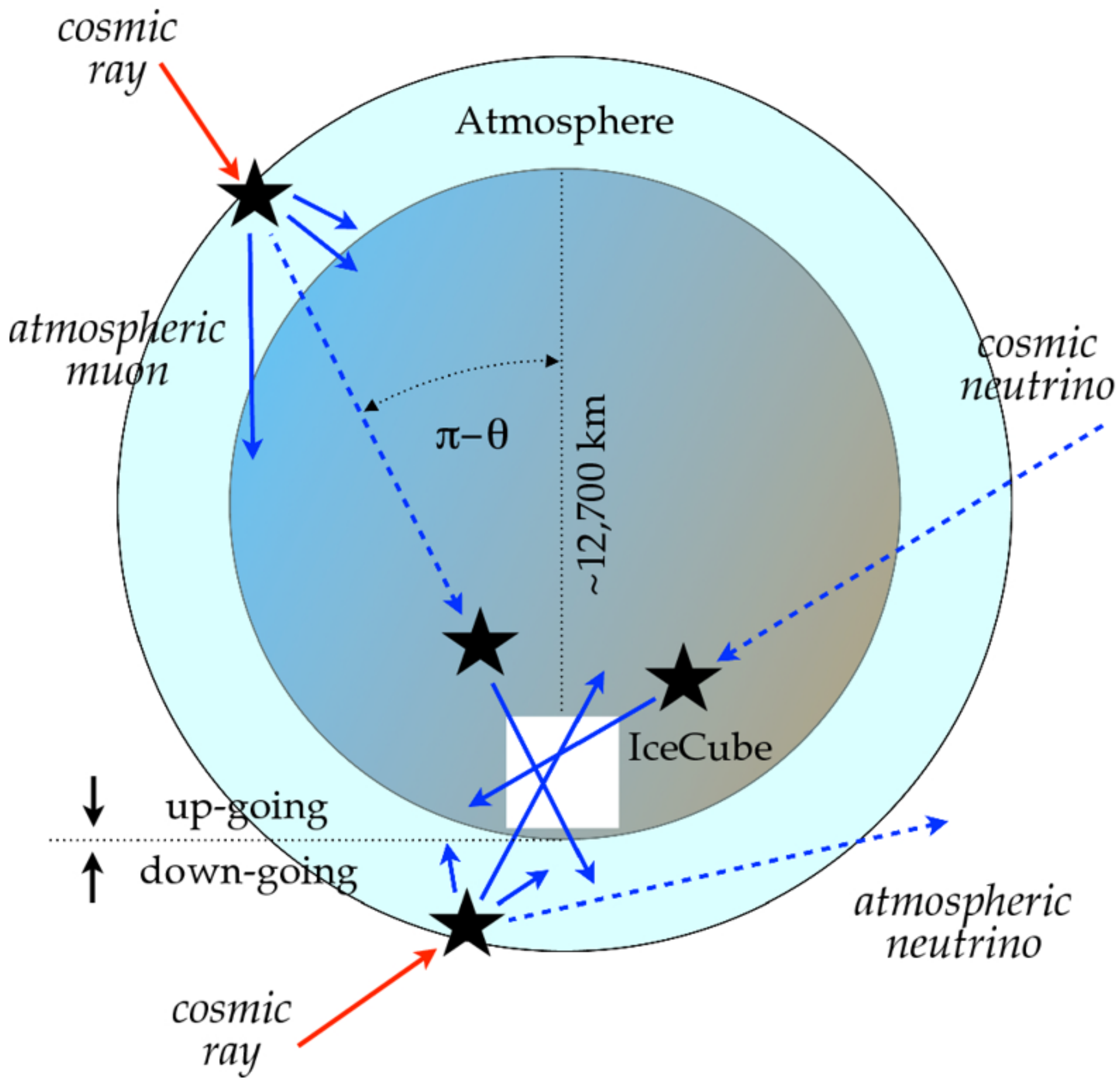


Galactic sources

- Near objects (few kpc) so the luminosity requirements are much lower.
- Micro-quasars.
- Supernova remnants.
- Magnetars.
- Galactic Ridge.

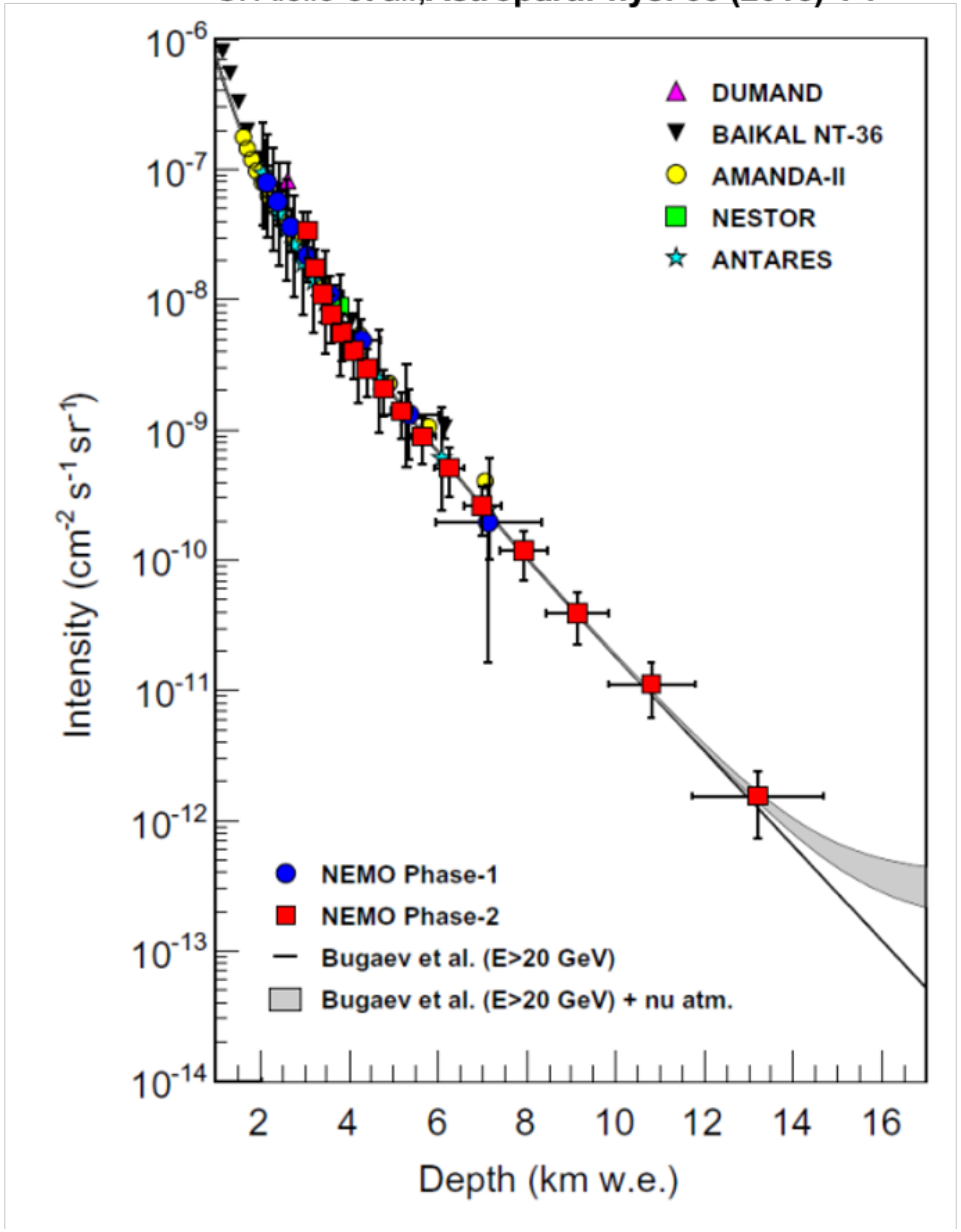
Background

- Atmospheric neutrinos: high energy neutrinos (up to >TeV) produced by interactions of primary cosmic rays with the Earth atmosphere. They can travel through the whole Earth up to the neutrino detector.
- Atmospheric muons: produced by interactions of primary cosmic rays with the Earth atmosphere. Being charged, they get by the atmosphere and by volumes of rock/water/ice.
- Muons cannot cross more than » 15 km.w.e.
- At 3 km.w.e. the flux is reduced by about 6 order of magnitude



Neutrino telescopes

- Built deep in water or ice:
  - large (and inexpensive) target for n interaction
  - transparent radiators for Cherenkov light;
  - large deep: protection against the cosmic-ray muon background


S. Aiello et al.,**Astropart.Phys. 66 (2015) 1-7**

Water vs ice

Cherenkov photons can reach one (or many) **PMT(s)** in an **Optical Module (OM)** and produce a signal.

Water/ice characterized by two quantities (depending on photon wavelength λ)

- ***absorption length, a(λ)***, of the order of 50 m (ice better than water). The absorption reduces the number of photons arriving on OMs.
- ***scattering length, b(λ)***, (water better than ice). The scattering reduces the number of photons arriving in time. It worsening the reconstruction capability.

- Usually, instruments measure the ***absorption*** and the ***attenuation*** length c(λ) (the combination of scattering and absorption), where

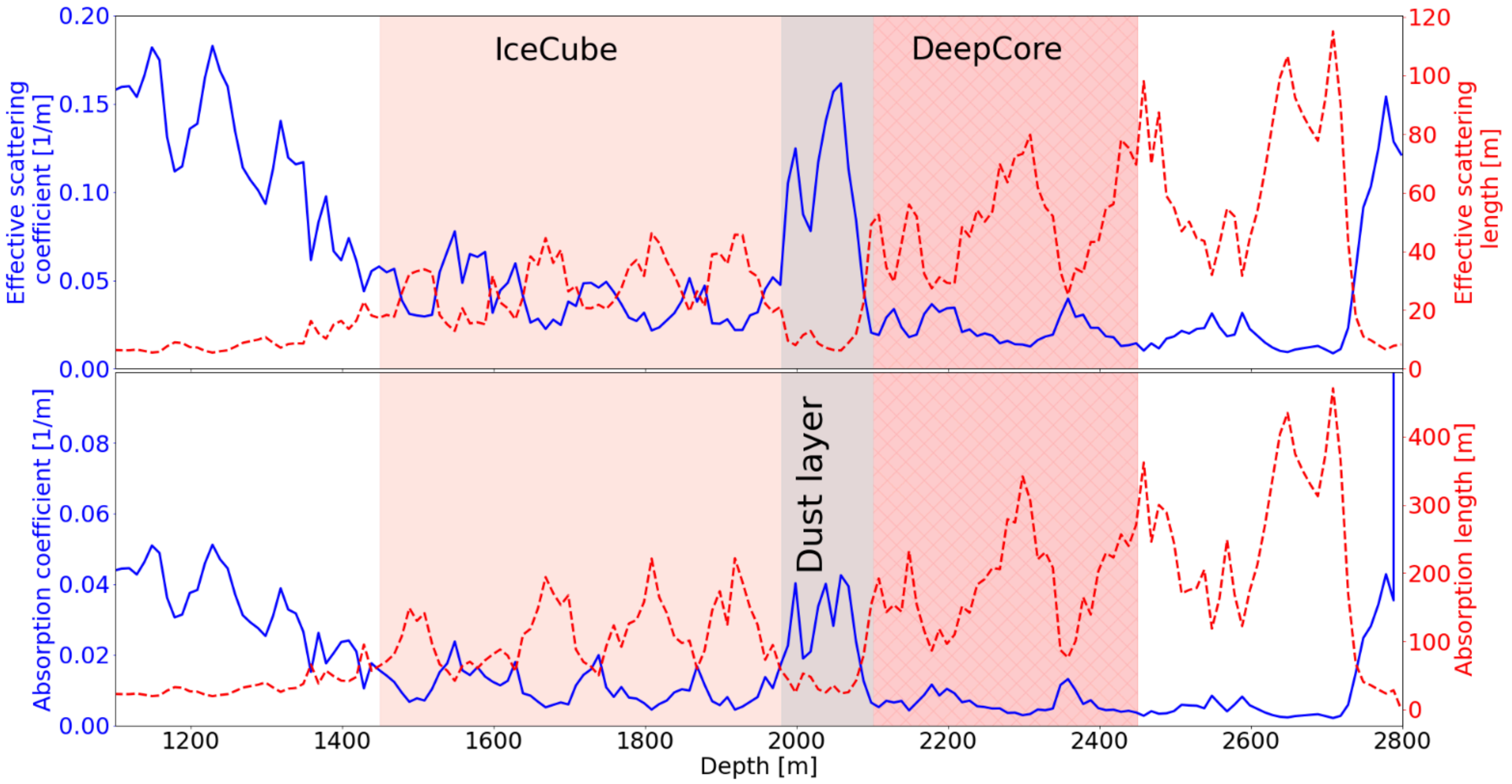
$$c(\lambda) = a(\lambda) + b(\lambda) \ \ [m^{-1}]$$

- The attenuation at a distance x is thus:

$$\mathrm{I}(x, \lambda) = I_o e^{-\, x \cdot c(\lambda)}$$

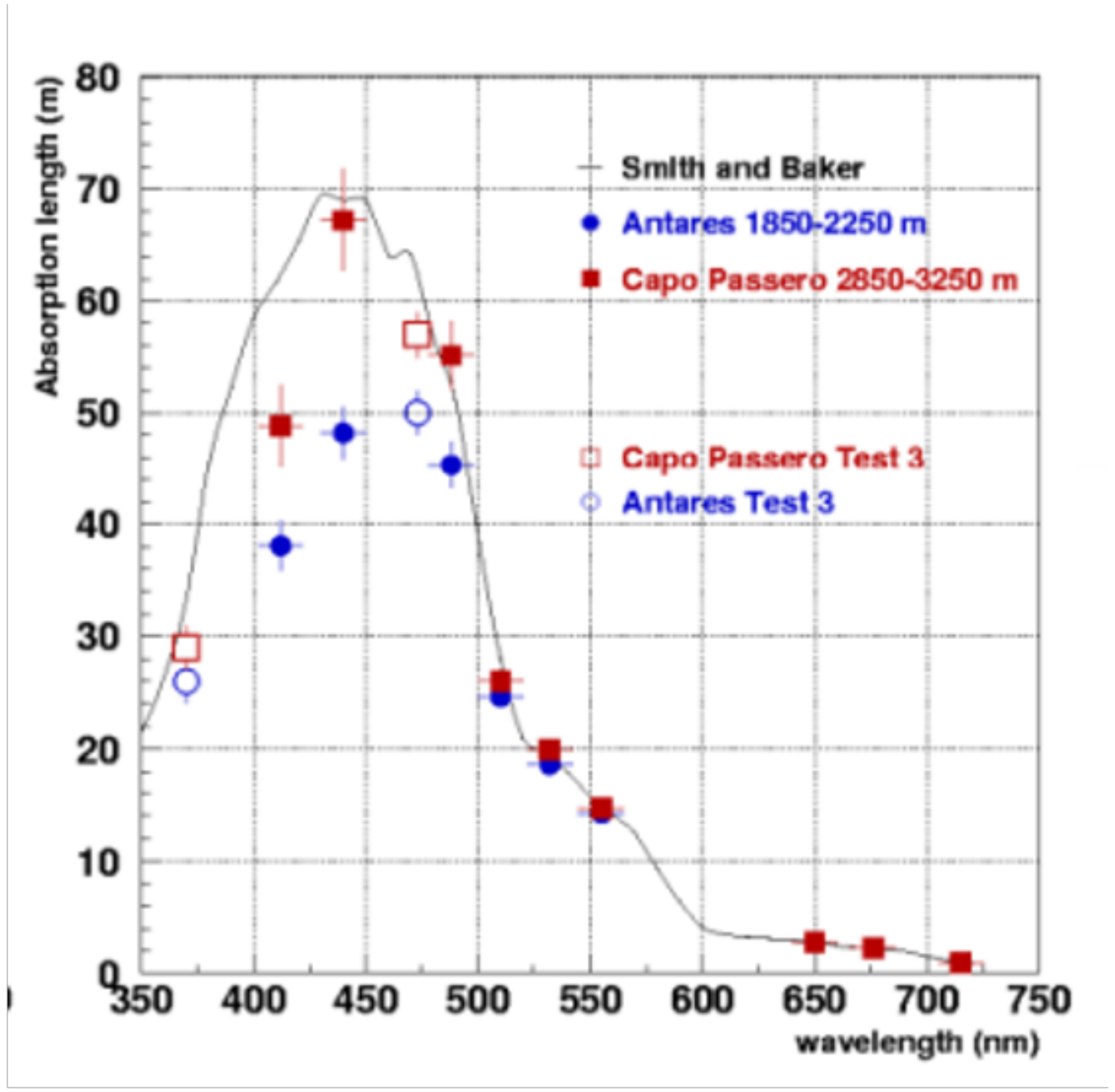
Water vs Ice

Ice



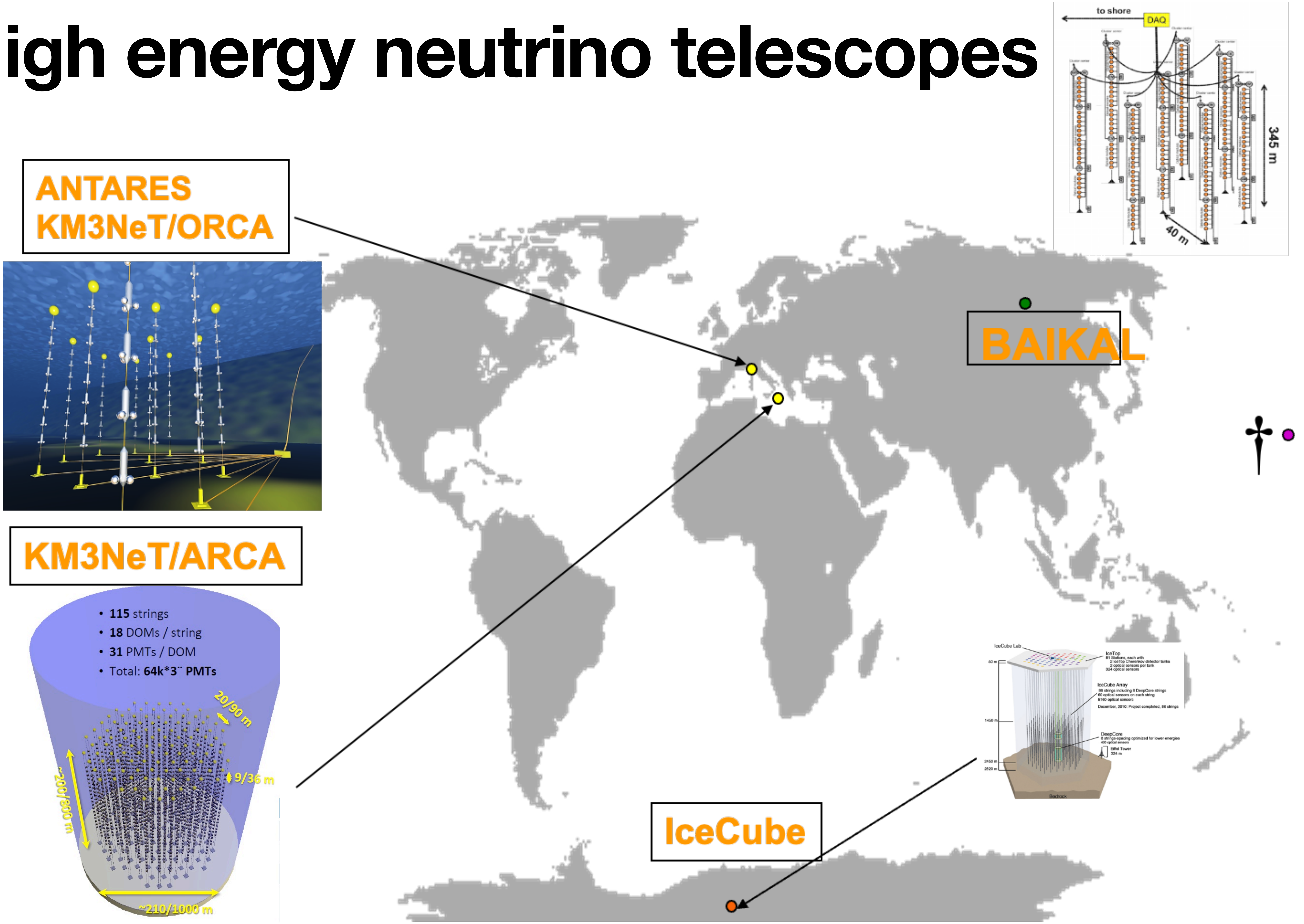
Martin Rongen, IceCube ice tilt, ICRC 2023, Japan

Water



$a^{-1}(\lambda)$ vs. wavelength for different sites (ANTARES, KM3/ARCA)

High energy neutrino telescopes



ANTARES
KM3NeT/ORCA

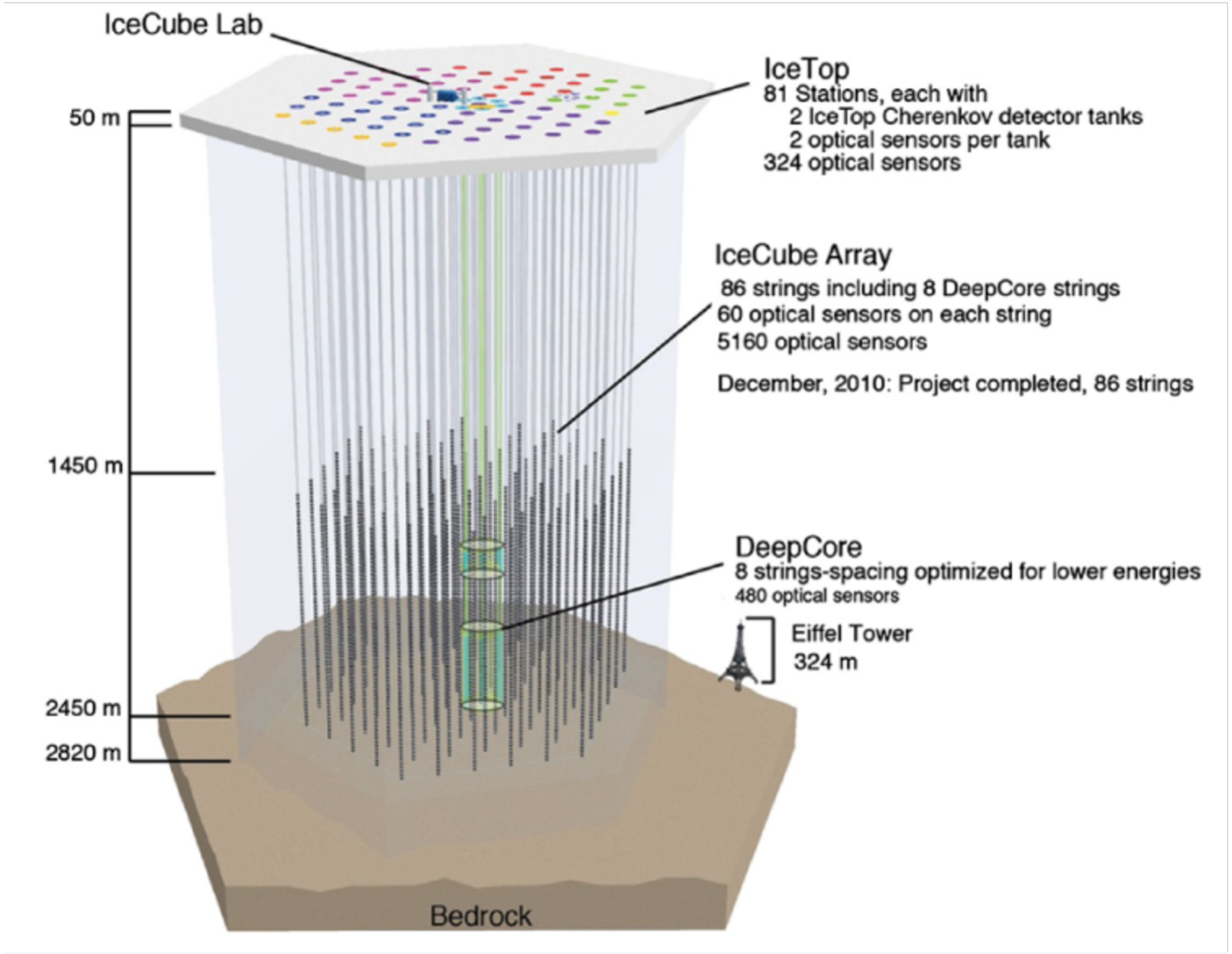
KM3NeT/ARCA

- **115** strings
- **18** DOMs / string
- **31** PMTs / DOM
- Total: **64k*3¨ PMTs**

BAIKAL

IceCube

IceCube at South Pole



IceTop
81 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
324 optical sensors

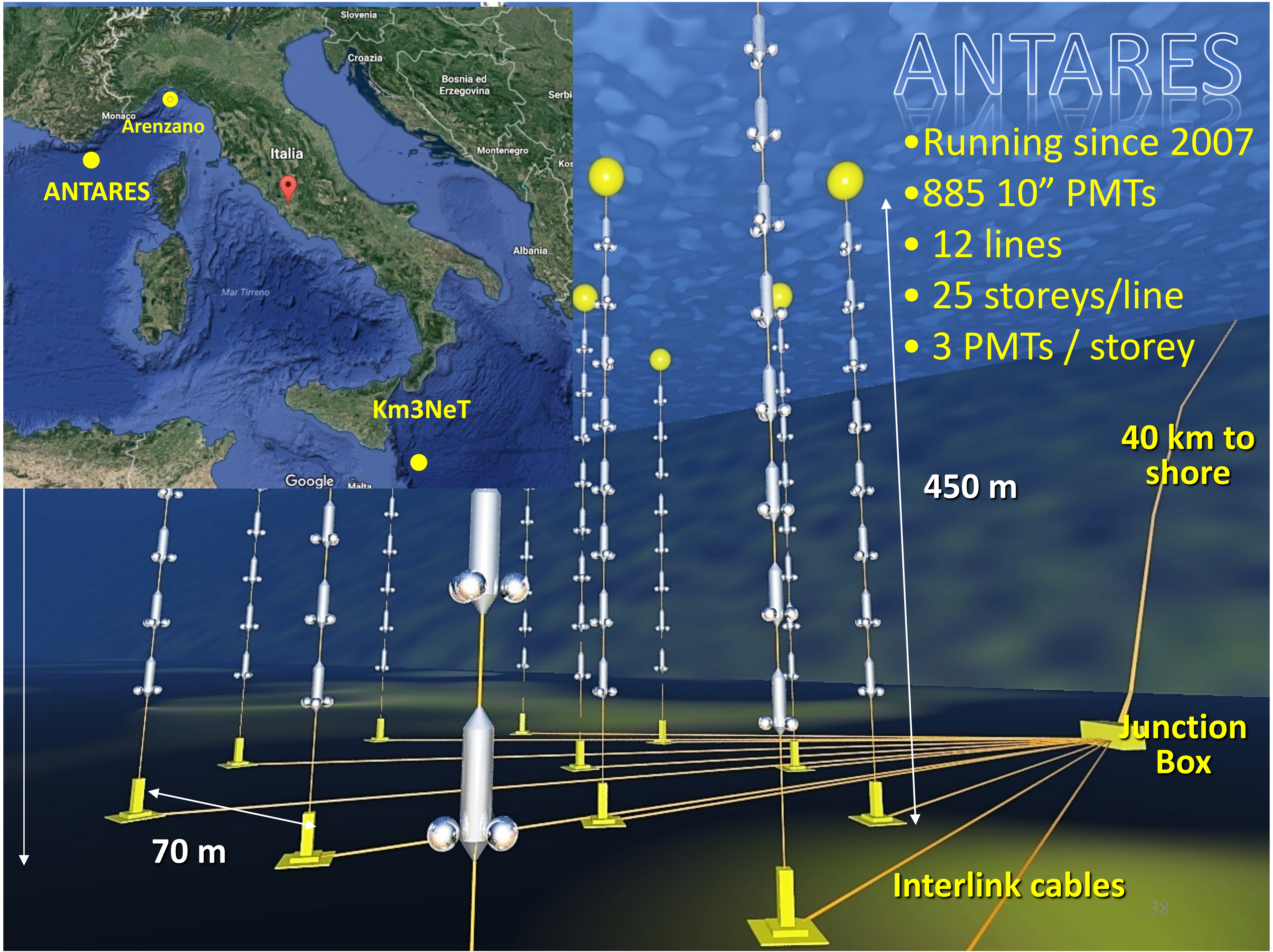
IceCube Array
86 strings including 8 DeepCore strings
60 optical sensors on each string
5160 optical sensors

December, 2010: Project completed, 86 strings

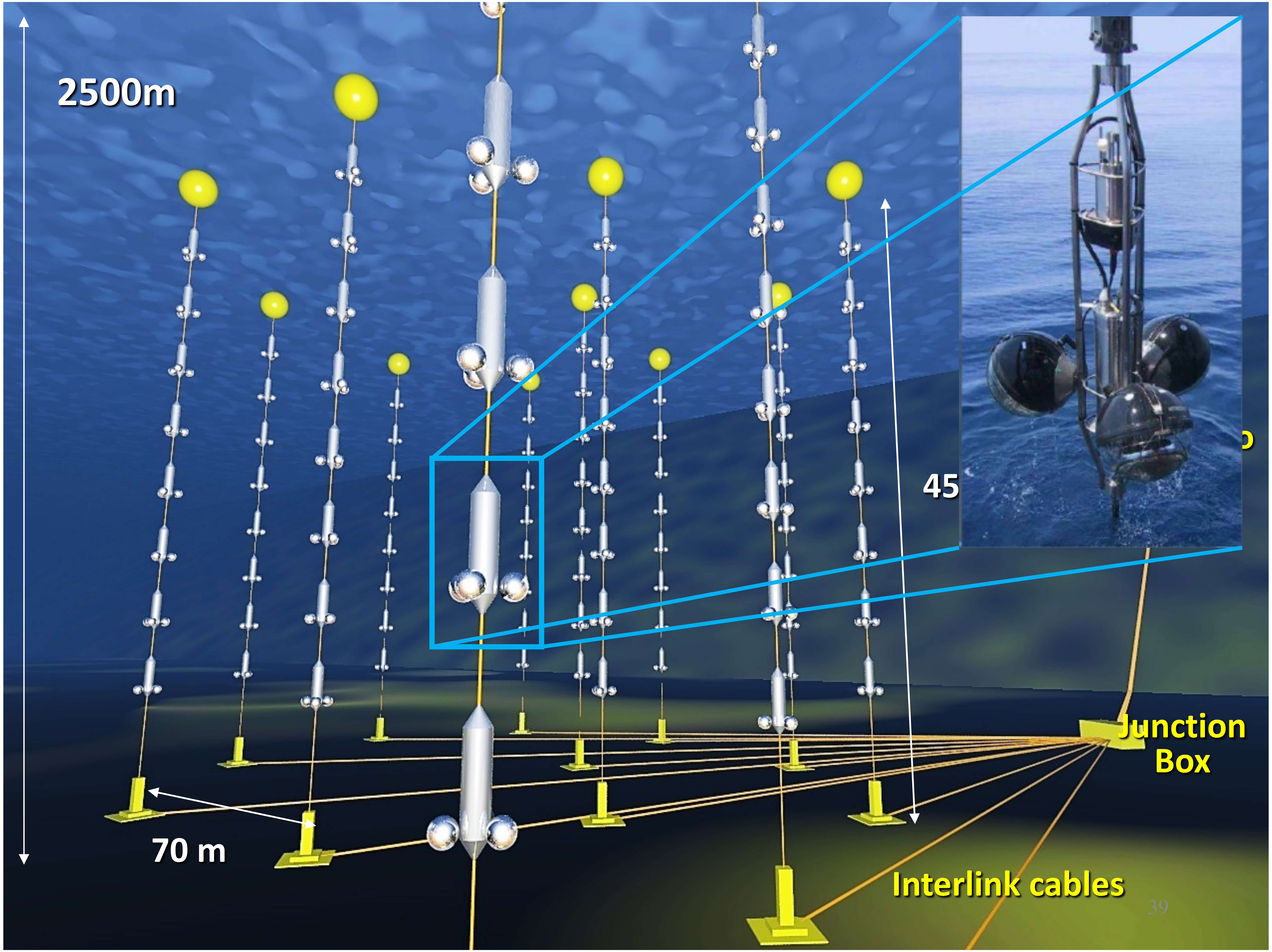
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors

Eiffel Tower
324 m

ANTARES

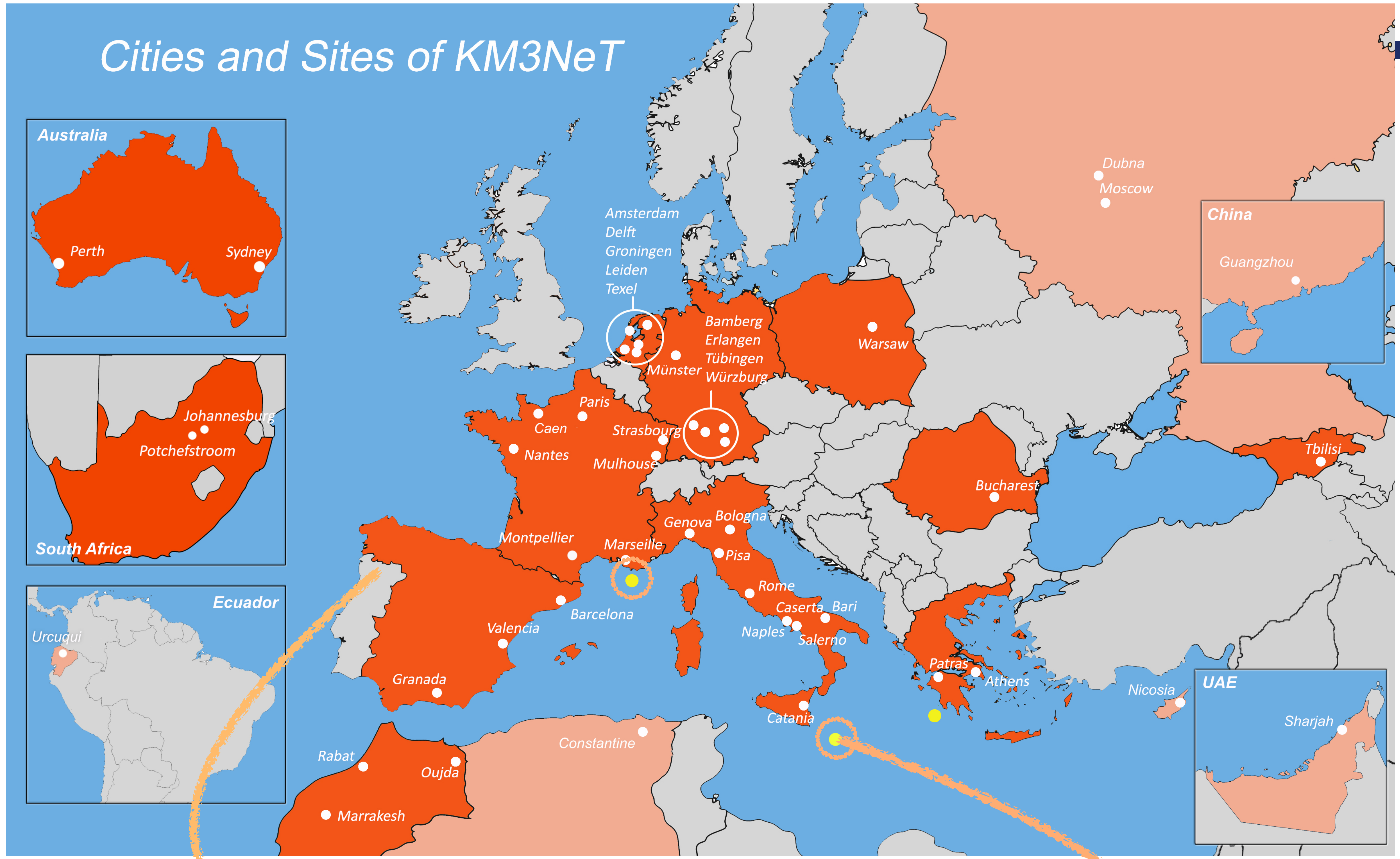


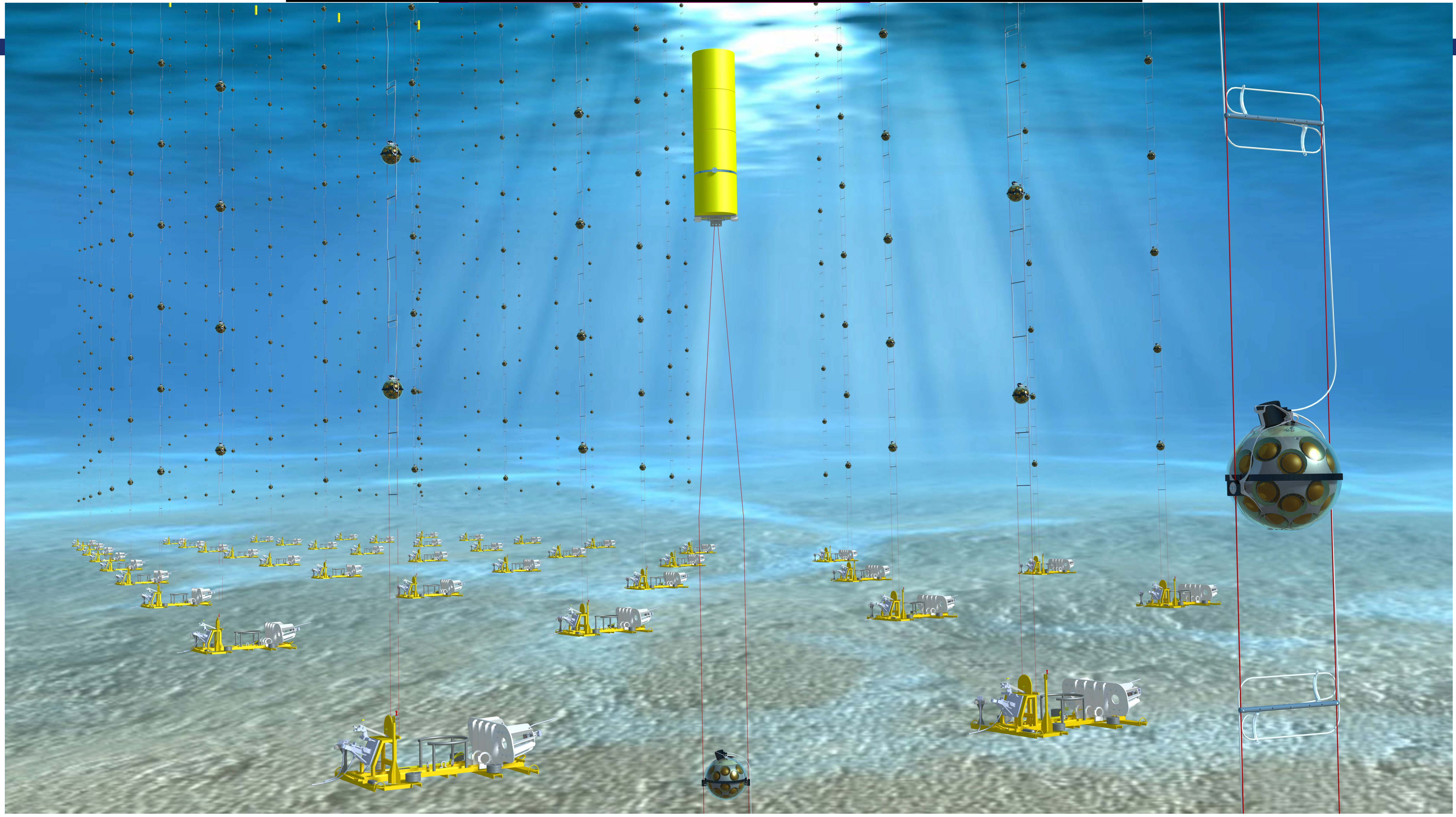
- Running since 2007
- 885 10” PMTs
- 12 lines
- 25 storeys/line
- 3 PMTs / storey


2500m
45
70 m
Junction Box
Interlink cables
39

KM3NeT

18 DOMS with 31 3″ PMTs FOR EACH LINE

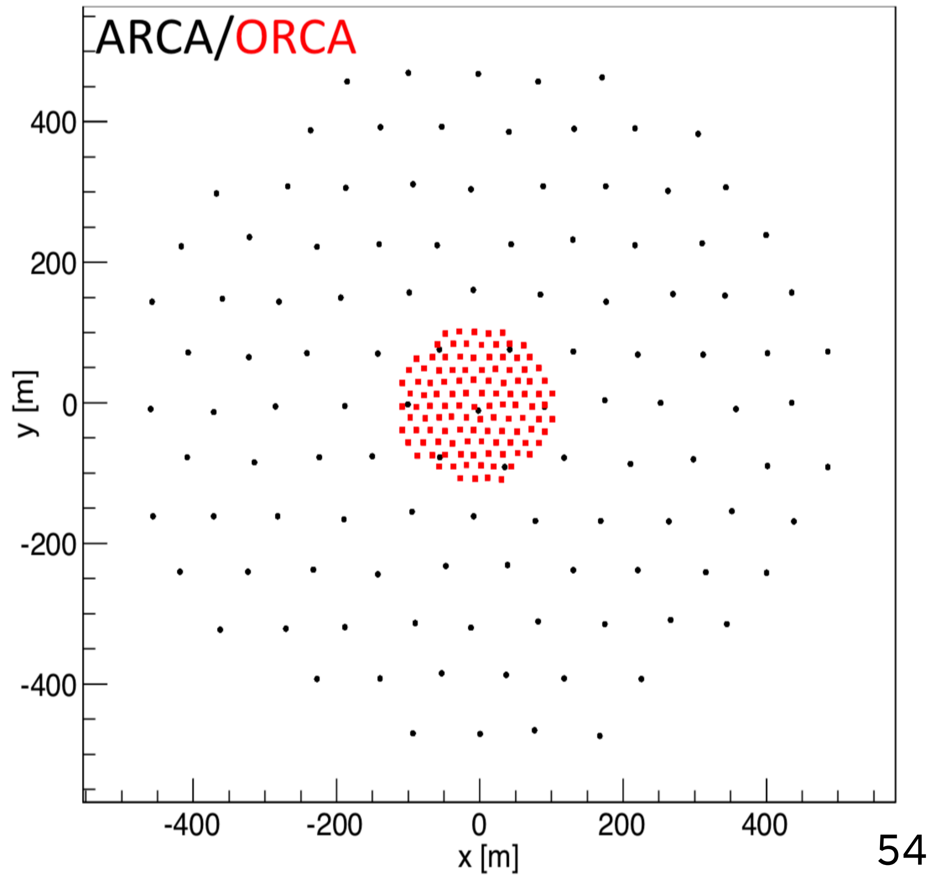




ORCA:
1 dense Building Block
optimised for intermediate energies (1-100 GeV)

ARCA:
2 sparse Building Blocks optimised for high energies (>1 TEV)

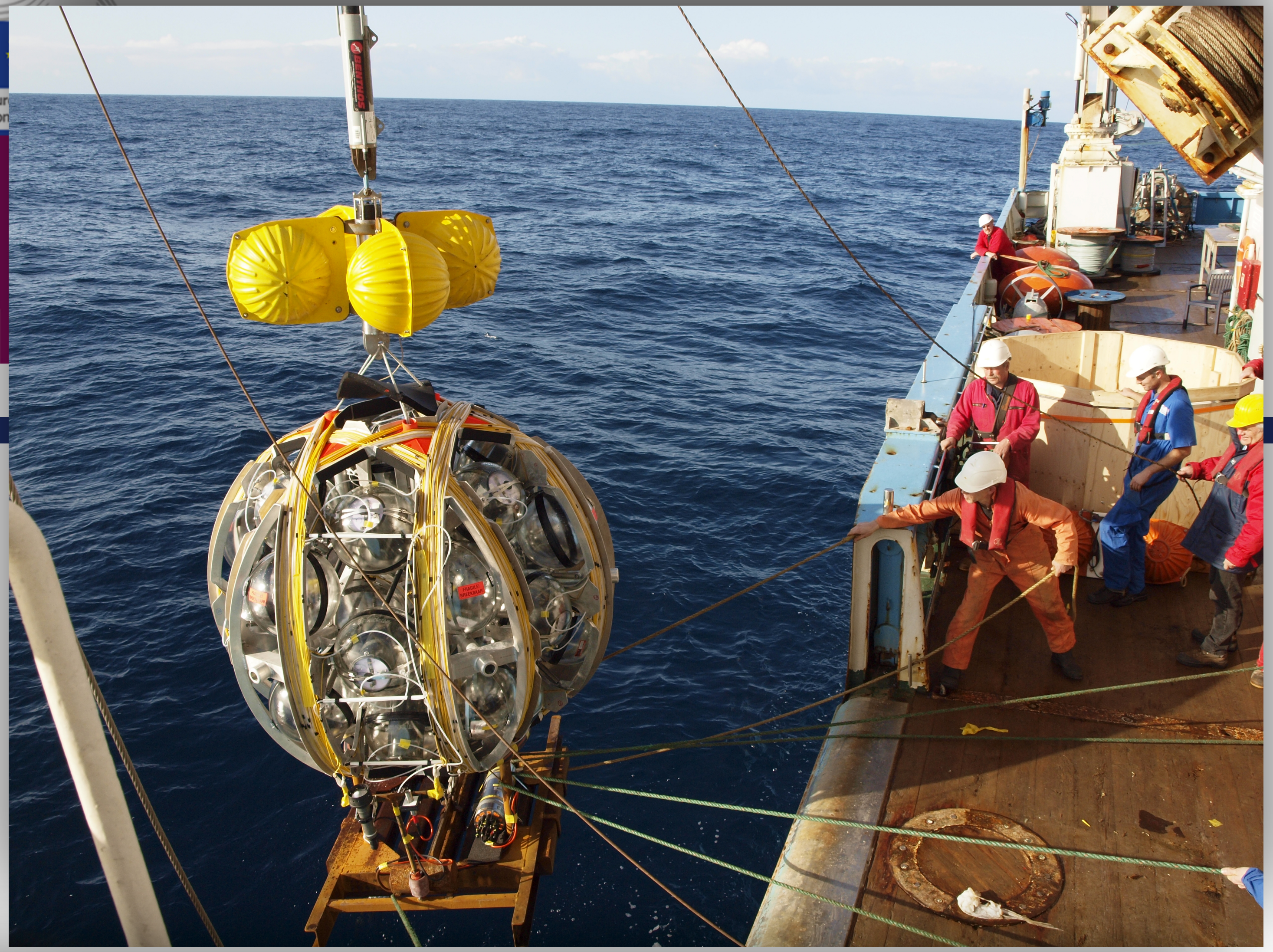
	ORCA	ARCA
String spacing	20 m	90 m
Vertical spacing	9 m	36 m
Depth	2470 m	3500 m

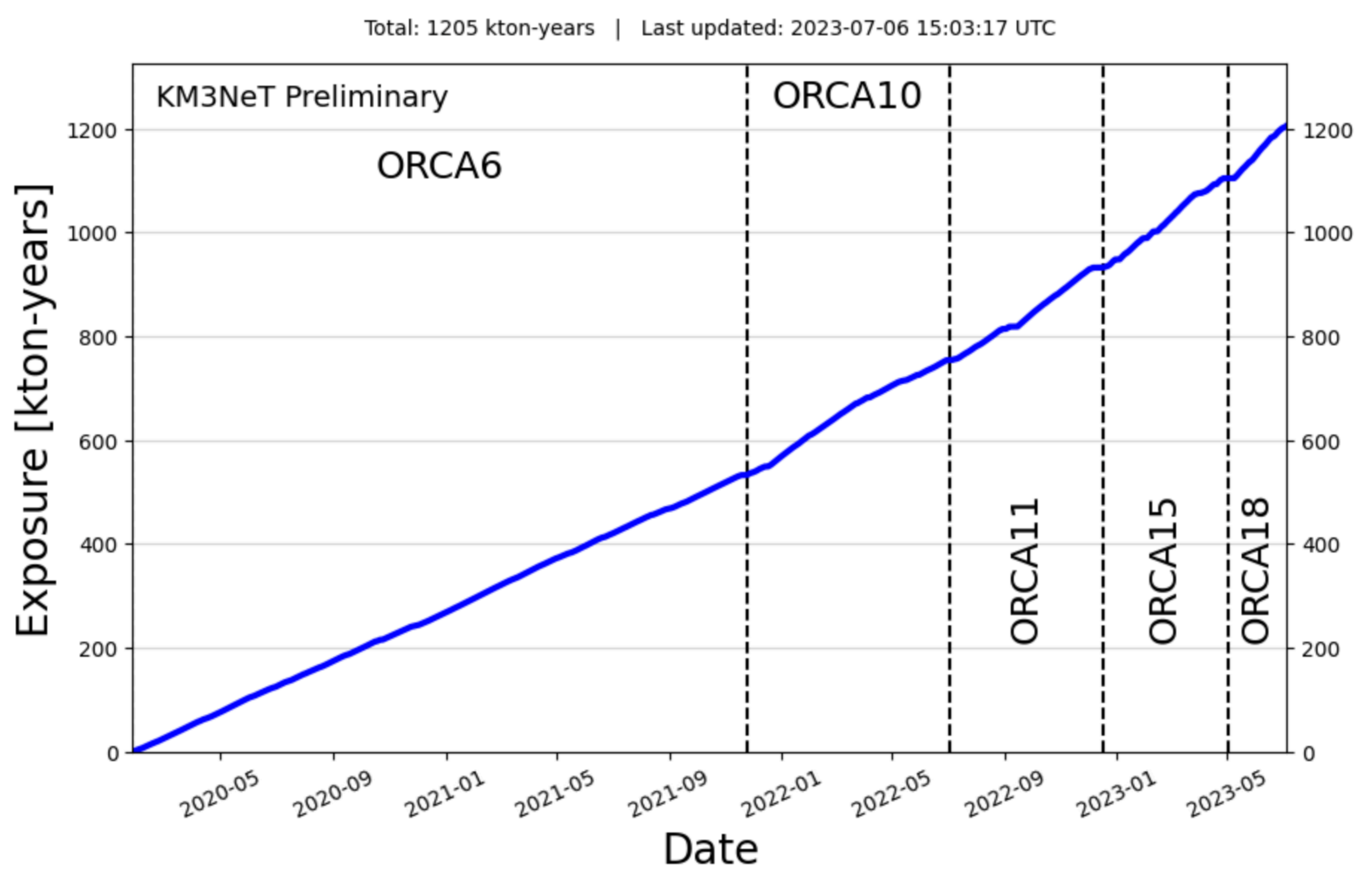


KM3NeT

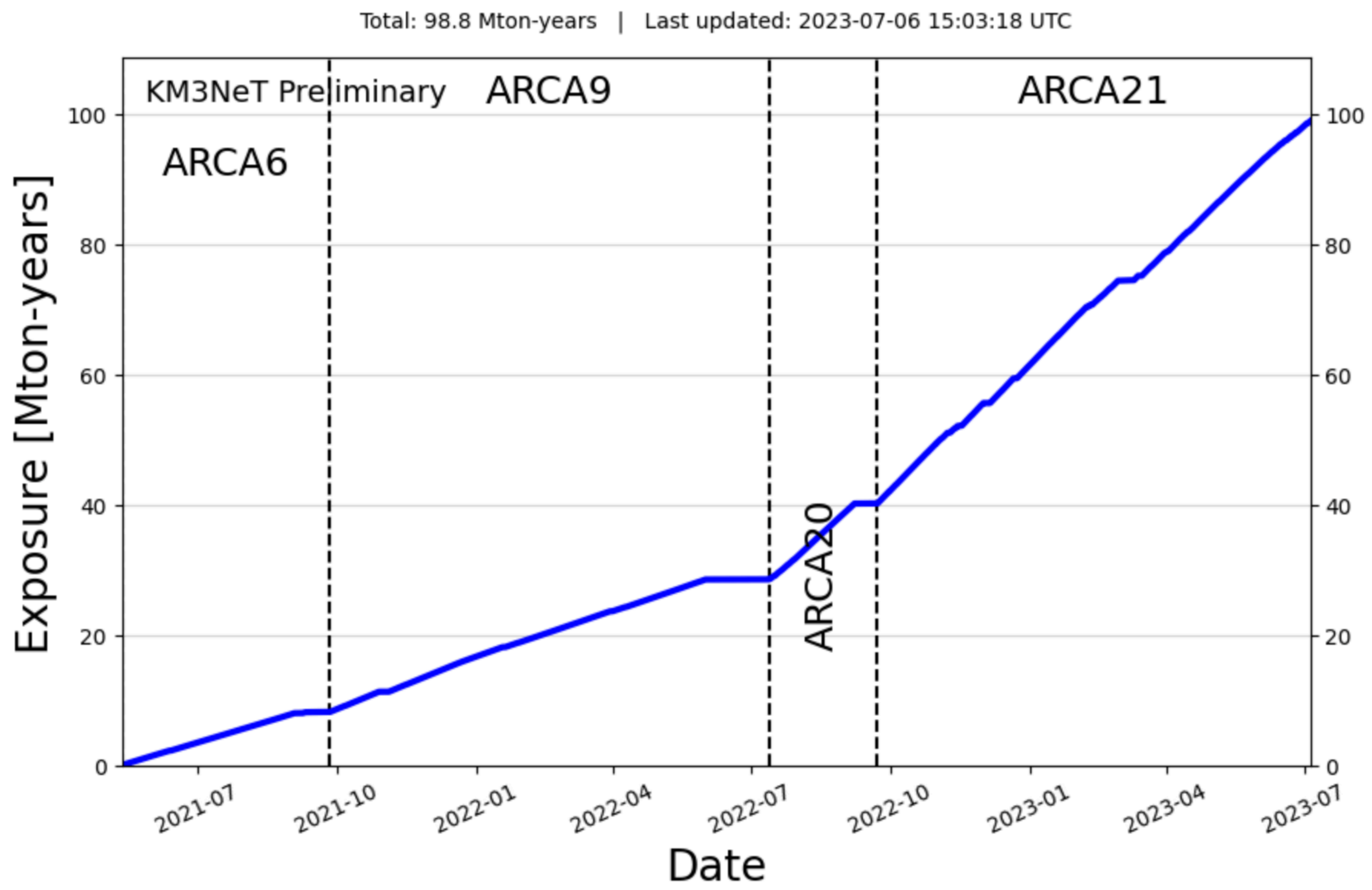
Modular deployment.

18 ORCA-DUs and 21 ARCA-DUs currently taking data!





Cumulative instrumented exposures of ORCA in kton-years.



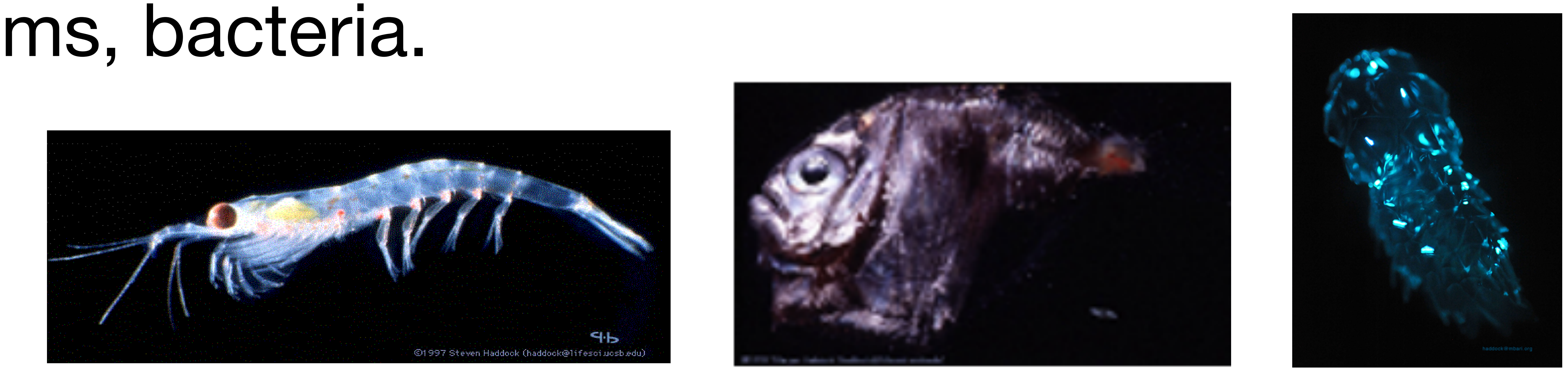
Cumulative instrumented exposures of ARCA in Mton-years.

Optical background in water

- a K40 decay: most abundant radioactive isotope in sea water.

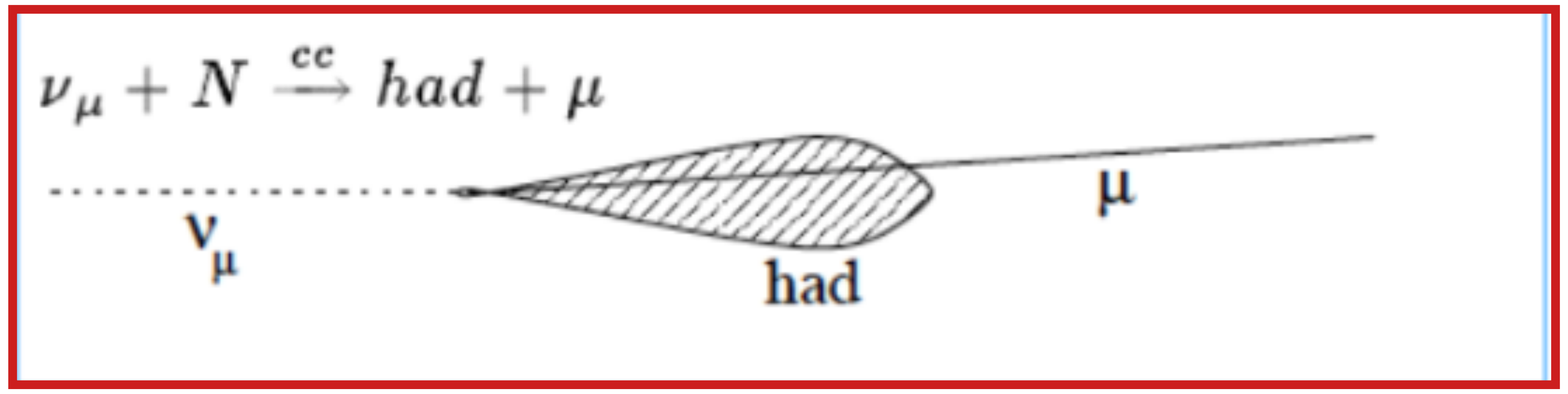
$$
\begin{aligned}
&{}^{40}K \rightarrow {}^{40}Ca + e^- + \overline{\nu}_e && (89.3\%) \\
&{}^{40}K + e^- \rightarrow {}^{40}Ar^* + \nu_e && (10.7\%) \\
&\qquad\qquad \hookrightarrow {}^{40}Ar + \gamma &&
\end{aligned}
$$

- Bioluminescence: macro organisms, bacteria.

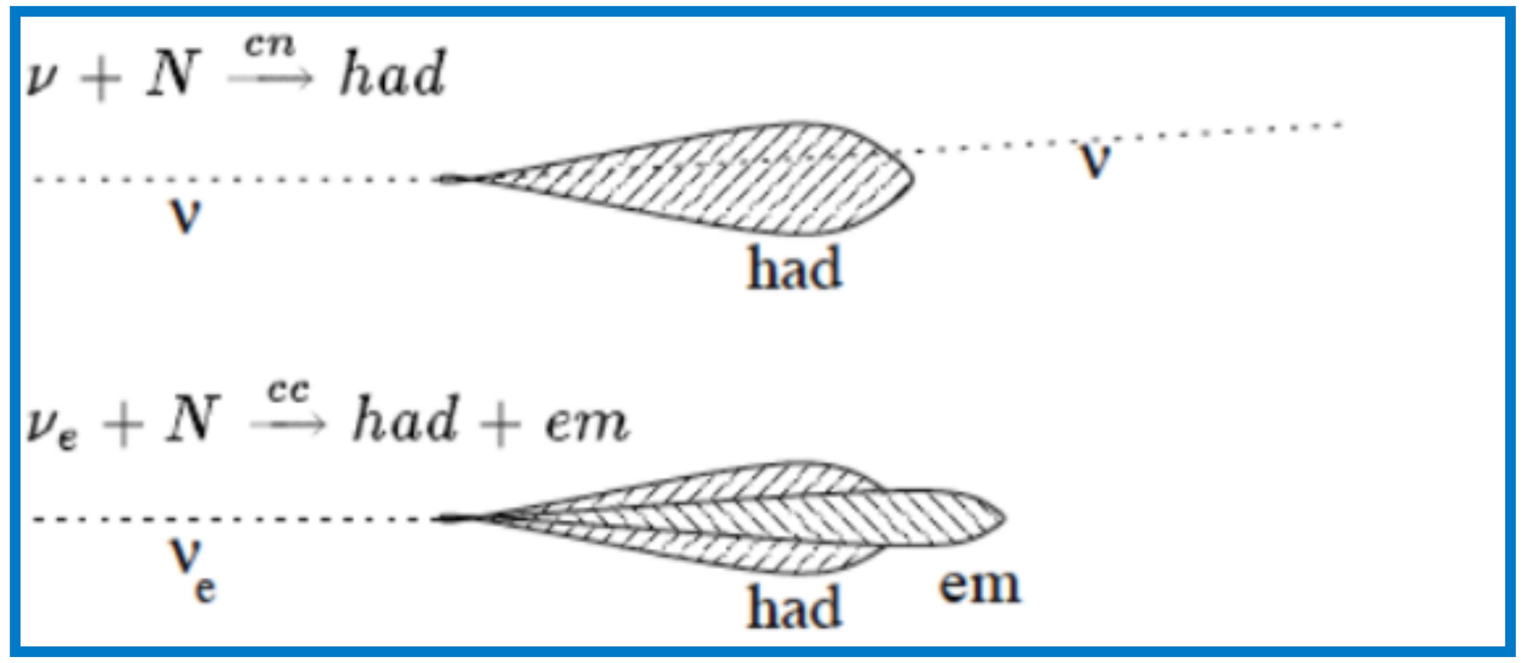


High energy event topologies

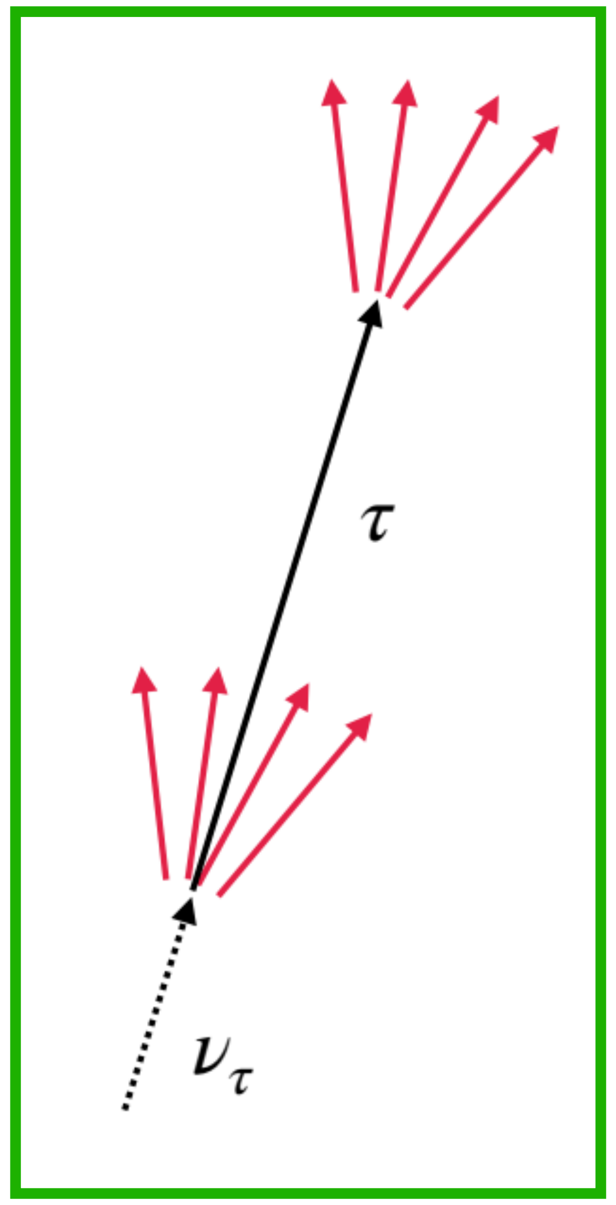
Tracks: ν_μCC, ν_τCC ($\tau \to \mu$)

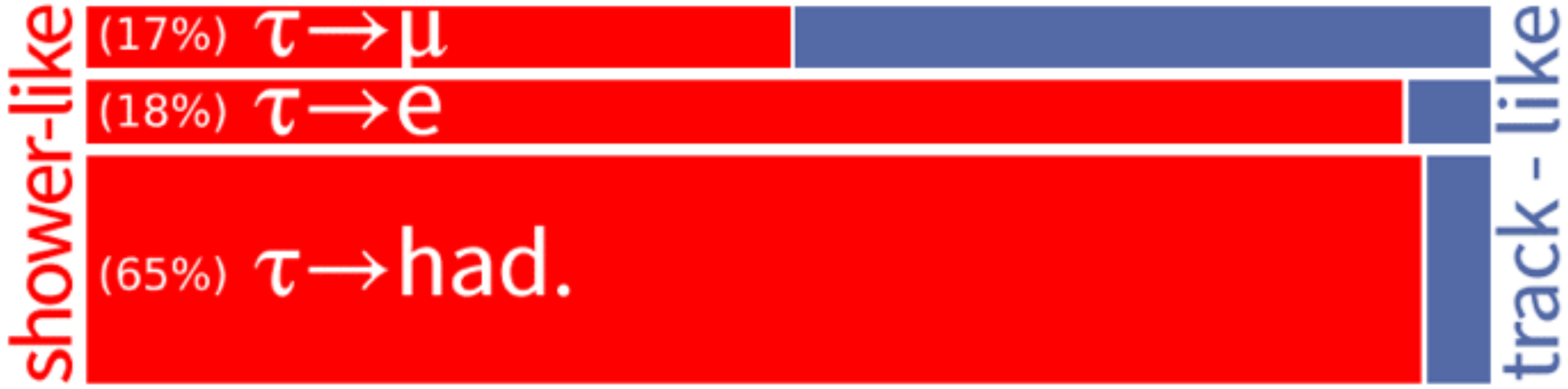


Showers: ν_eCC, νNC, ν_τ



Double showers: ν_τ





Cosmic neutrino detection

Method 1) Measuring an excess of events from a given direction (point-sources).

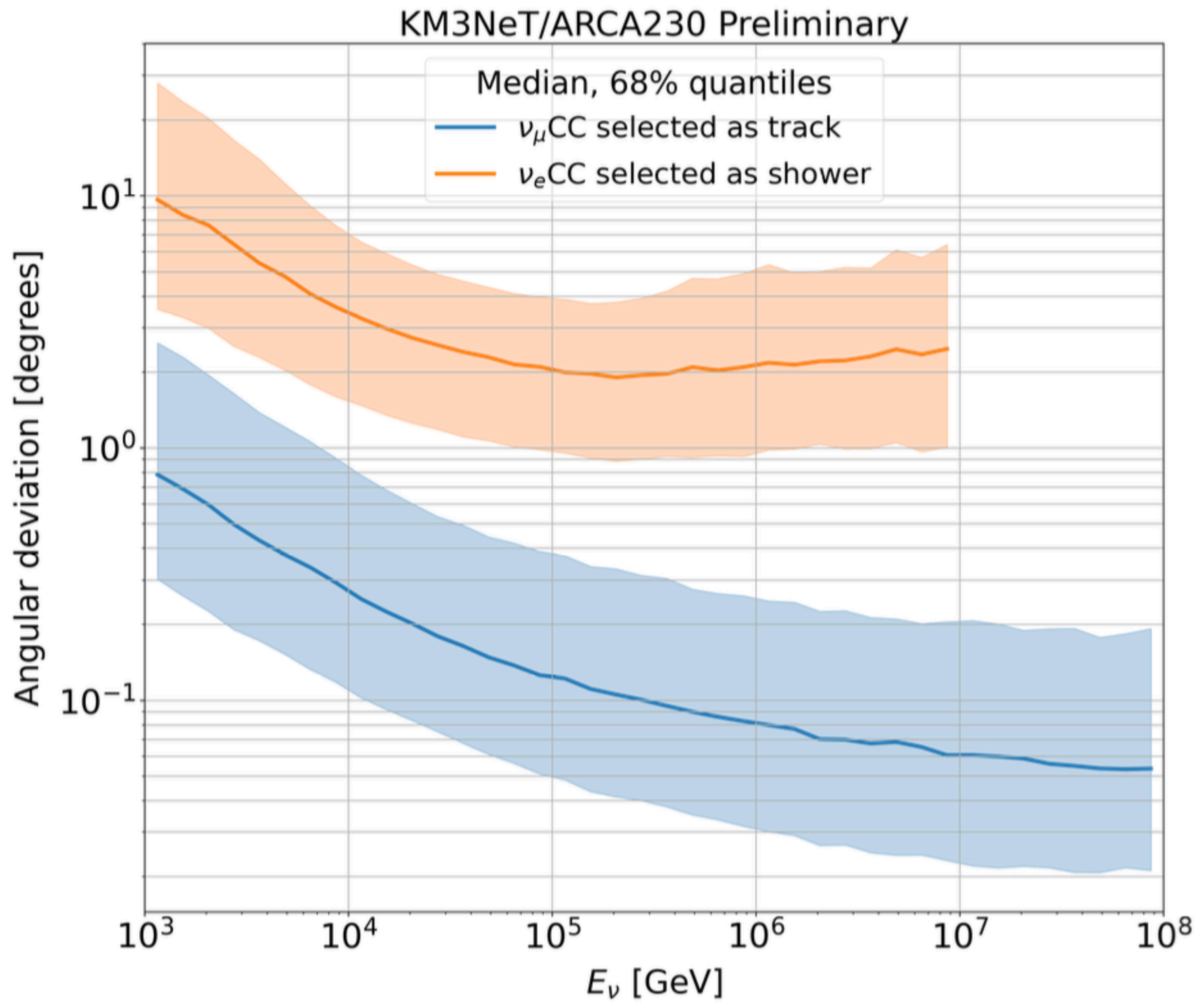
- Mainly ν_μ and upgoing events

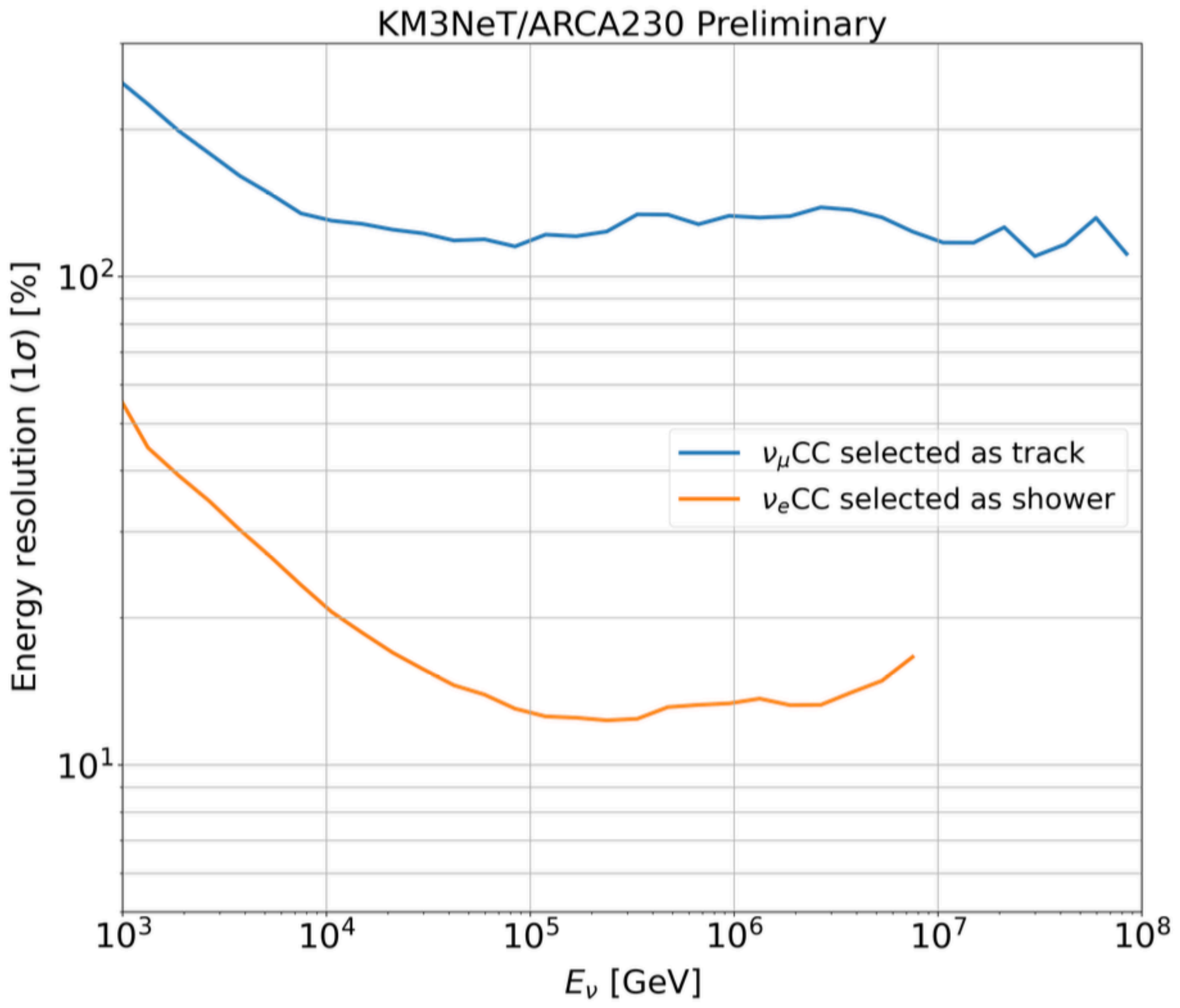
Method 2) Measure an excess of high-energy events with respect to the background (diffuse).

- All flavors. Tracks, showers and partially contained events.

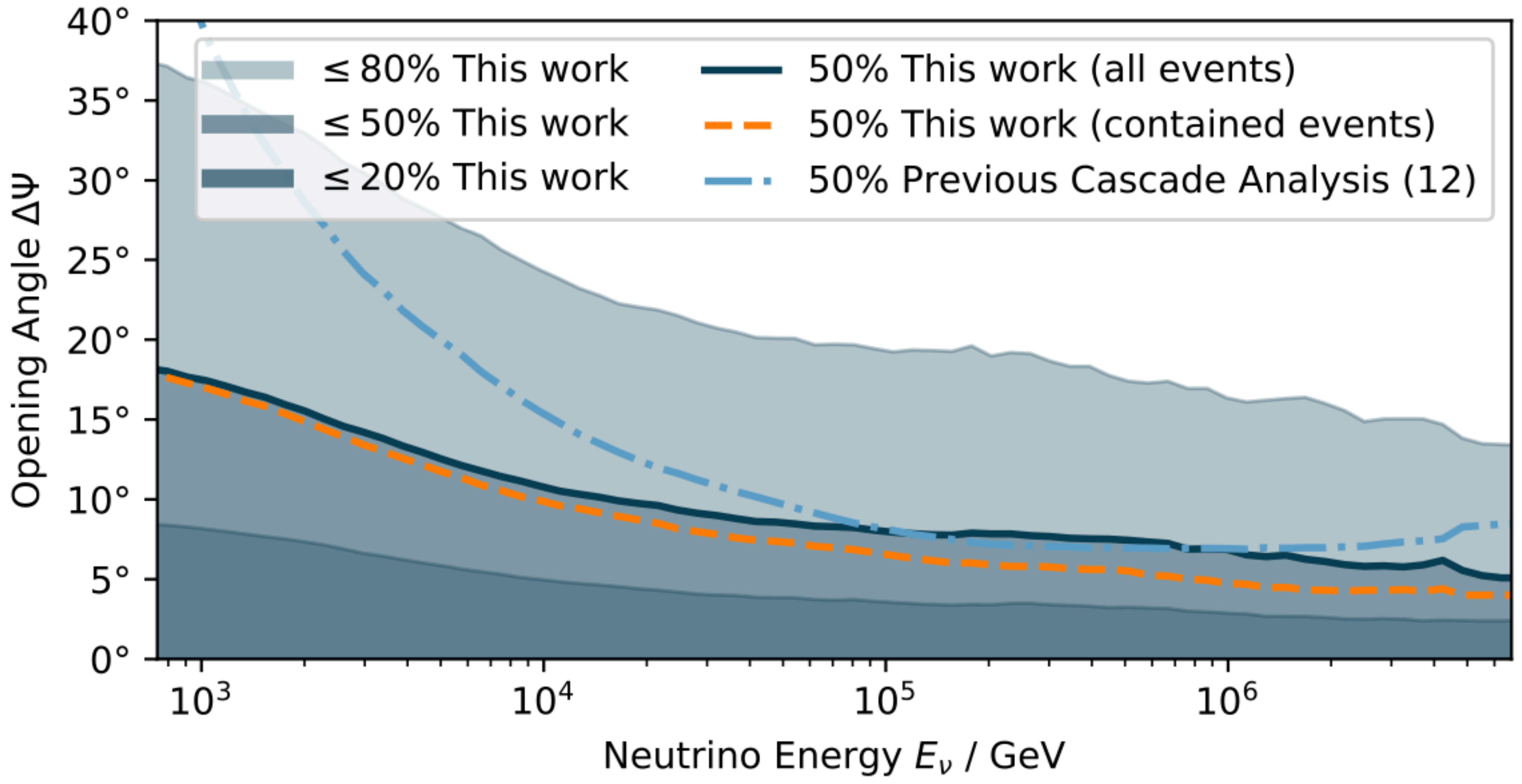
Angular & energy resolution important!

KM3NeT/ARCA

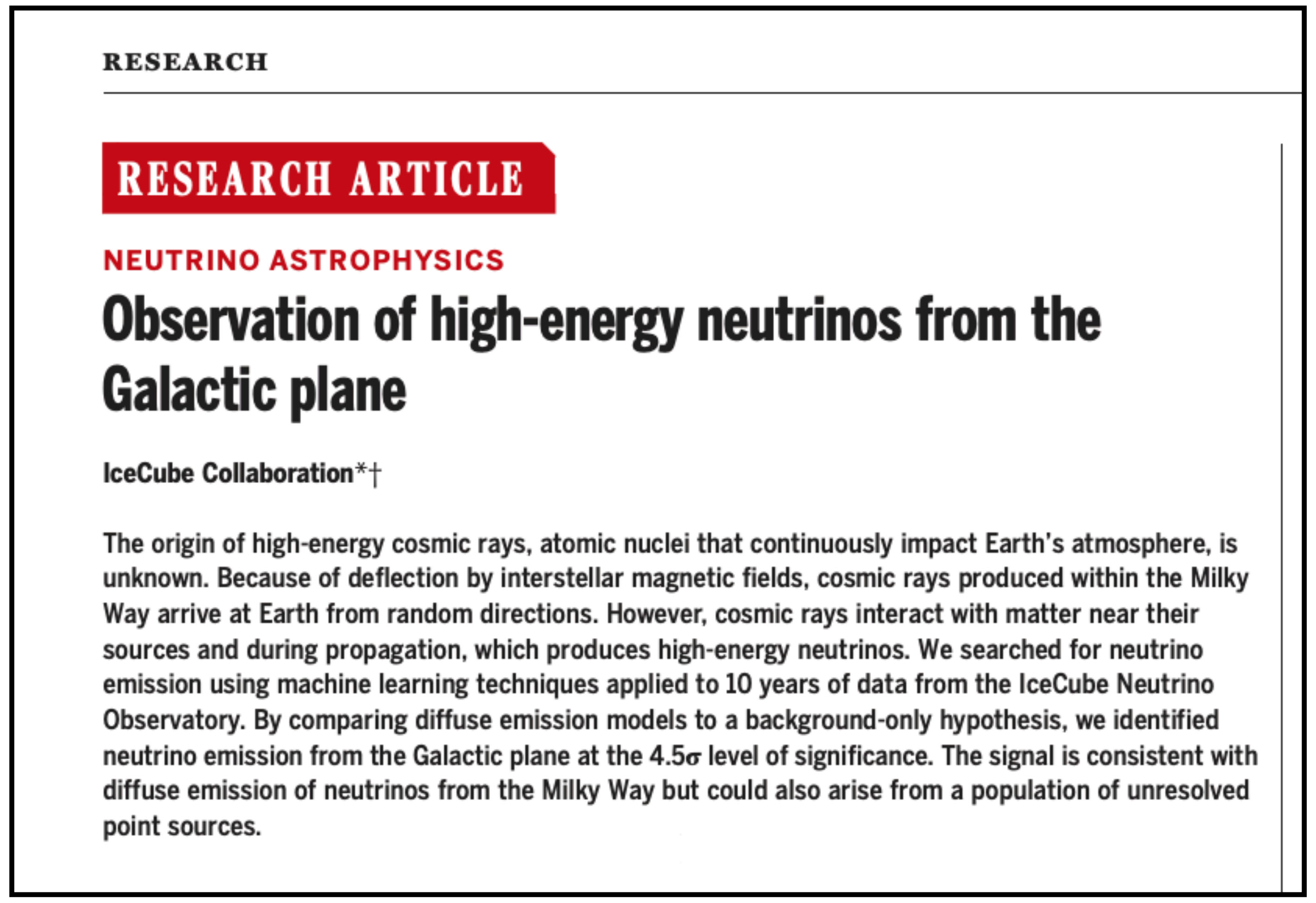




ICECUBE



… Improved angular resolution brings to important discoveries!



RESEARCH

RESEARCH ARTICLE

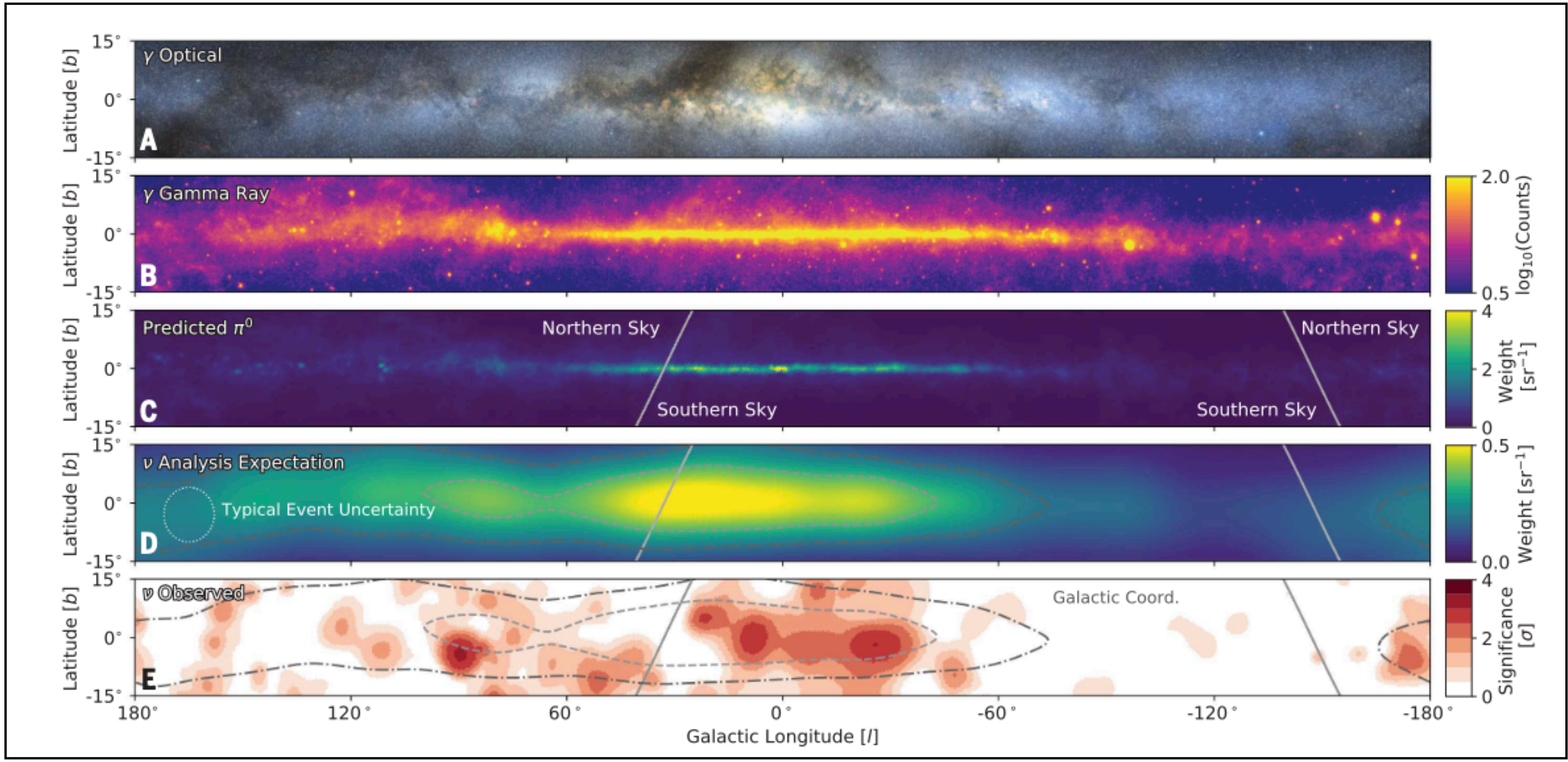
NEUTRINO ASTROPHYSICS

Observation of high-energy neutrinos from the Galactic plane

IceCube Collaboration*†

The origin of high-energy cosmic rays, atomic nuclei that continuously impact Earth's atmosphere, is unknown. Because of deflection by interstellar magnetic fields, cosmic rays produced within the Milky Way arrive at Earth from random directions. However, cosmic rays interact with matter near their sources and during propagation, which produces high-energy neutrinos. We searched for neutrino emission using machine learning techniques applied to 10 years of data from the IceCube Neutrino Observatory. By comparing diffuse emission models to a background-only hypothesis, we identified neutrino emission from the Galactic plane at the 4.5σ level of significance. The signal is consistent with diffuse emission of neutrinos from the Milky Way but could also arise from a population of unresolved point sources.

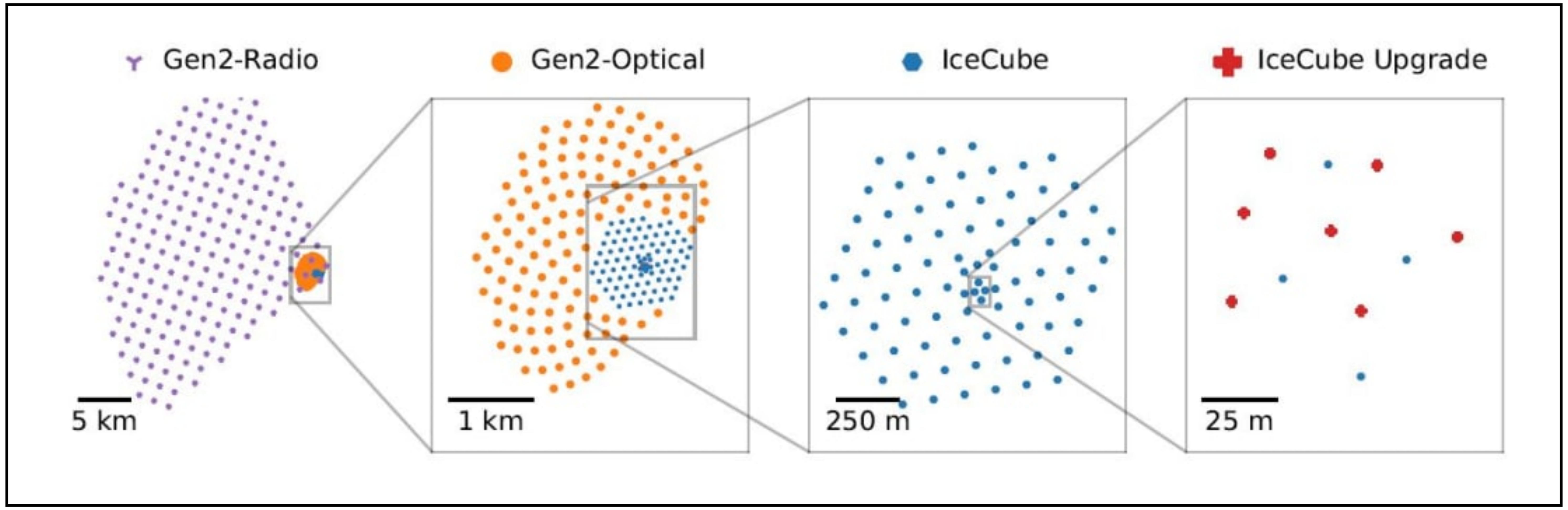
30 June 2023 - IceCube Collaboration,
Science 380, 1338-1343 (2023)



- High energy neutrinos from the Milky Way observed for the first time by IceCube thanks to an improvement in angular resolution due to machine learning.

Summary & Conclusions

- The elusive nature of neutrino makes them ideal sources for astronomy and fundamental physics searches.
- Neutrino astronomy has proven to be very powerful in improving our understanding of the Universe.
- Astrophysics with neutrino telescope is still a young, growing discipline in its discovery phase.
- Plans for increasing current detectors in order to observe even higher energy events (IceCube-Gen2).
- Neutrino radio-detection also possible.



References

- **Books:**
  - Carlo Giunti, Chung W. Kim - Fundamentals of Neutrino Physics and Astrophysics-Oxford University Press, USA (2007).
  - Maurizio Spurio, Particles and Astrophysics: A Multimessenger approach - Springer (2015).
- **Papers/reviews:**
  - Review on results from BOREXINO and implications on SSM: https://doi.org/10.3390/universe7070231
  - J. A. Formaggio and G. P. Zeller, *From eV to EeV: Neutrino cross sections across energy scales,* Rev. Mod. Phys. **84**, 1307 (2012).