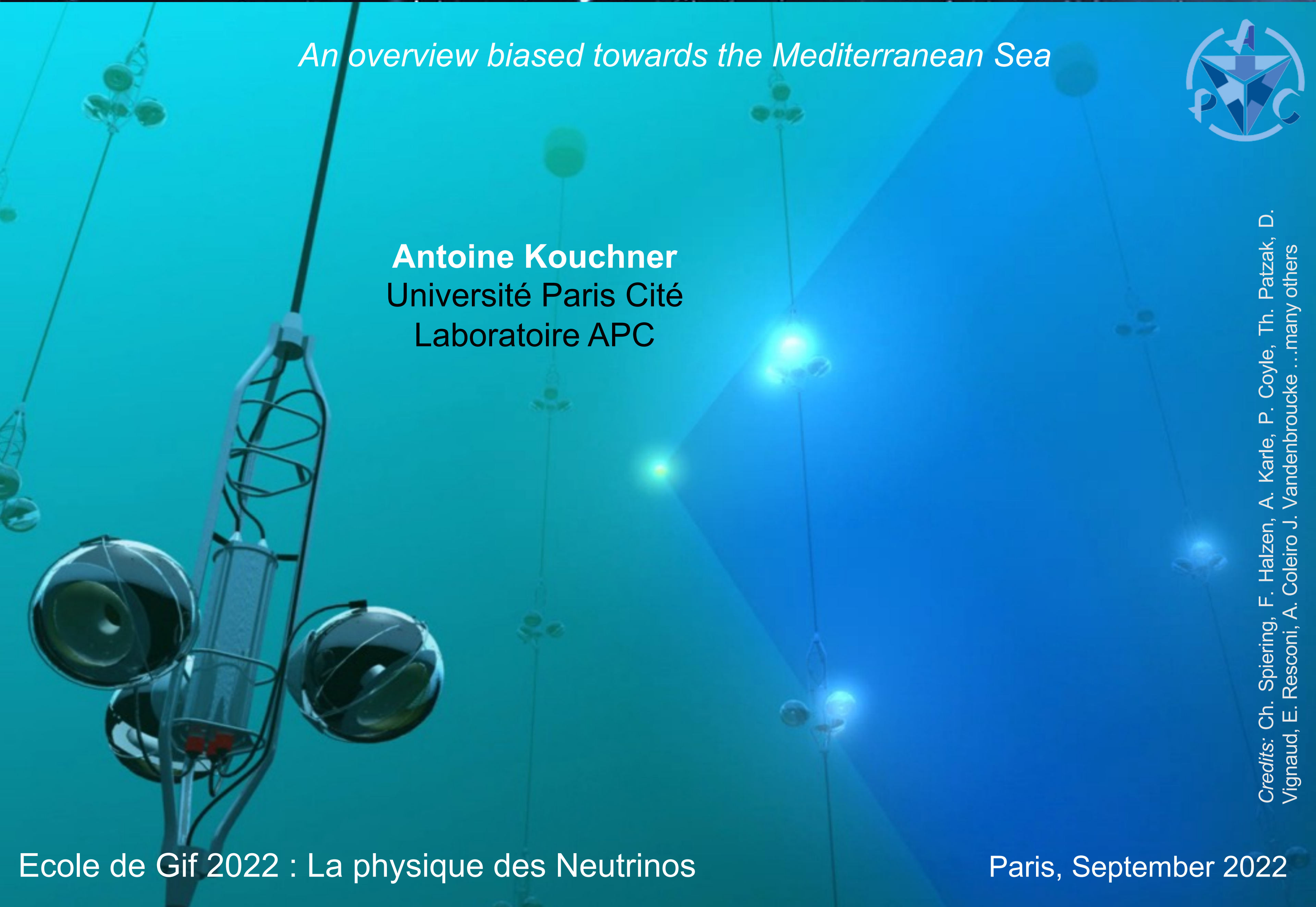
Astrophysique des neutrinos et multi-messagers

An overview biased towards the Mediterranean Sea



Antoine Kouchner
Université Paris Cité
Laboratoire APC

Credits: Ch. Spiering, F. Halzen, A. Karle, P. Coyle, Th. Patzak, D. Vignaud, E. Resconi, A. Coleiro J. Vandenbroucke …many others

Ecole de Gif 2022 : La physique des Neutrinos

Paris, September 2022

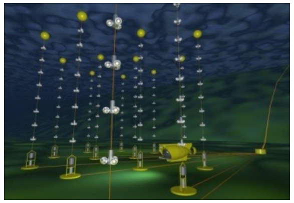
Outline

Neutrino astronomy

Scientific motivations

Historical aspects

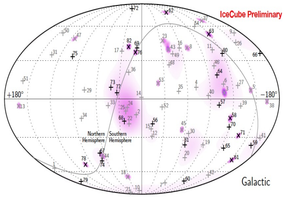
Cosmic neutrino sources



Neutrino telescope

Detection principles

Current telescopes



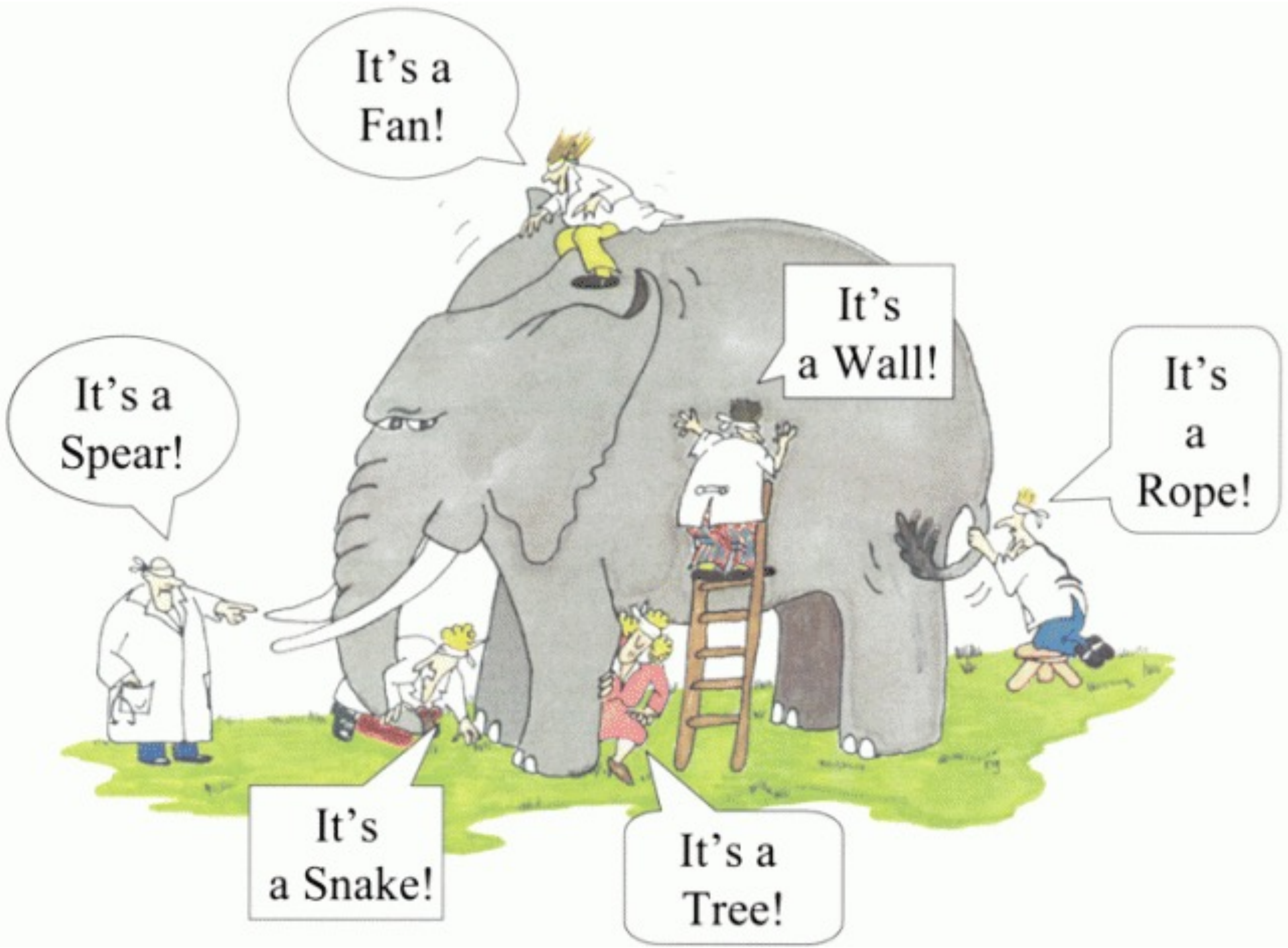
Selected results

Diffuse Flux, point sources

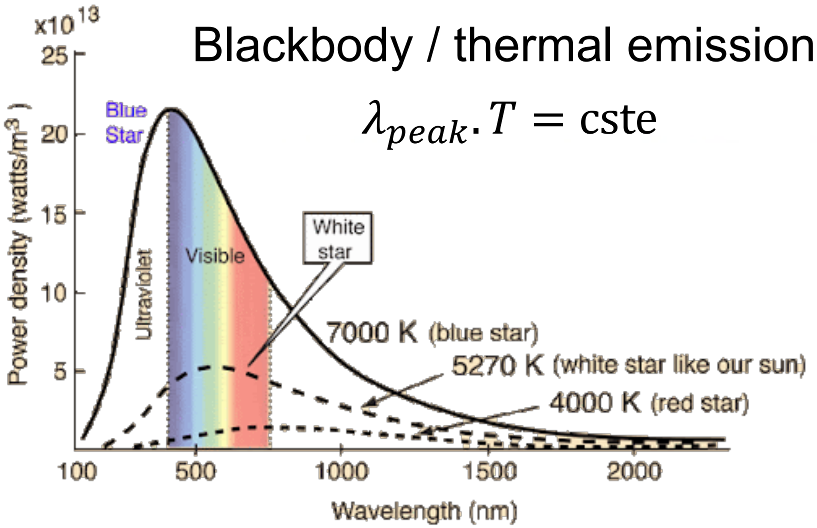
Multi-messenger search

ORCA prospects

Why Multi-wavelength/messenger ?



Multi-wavelength Astronomy



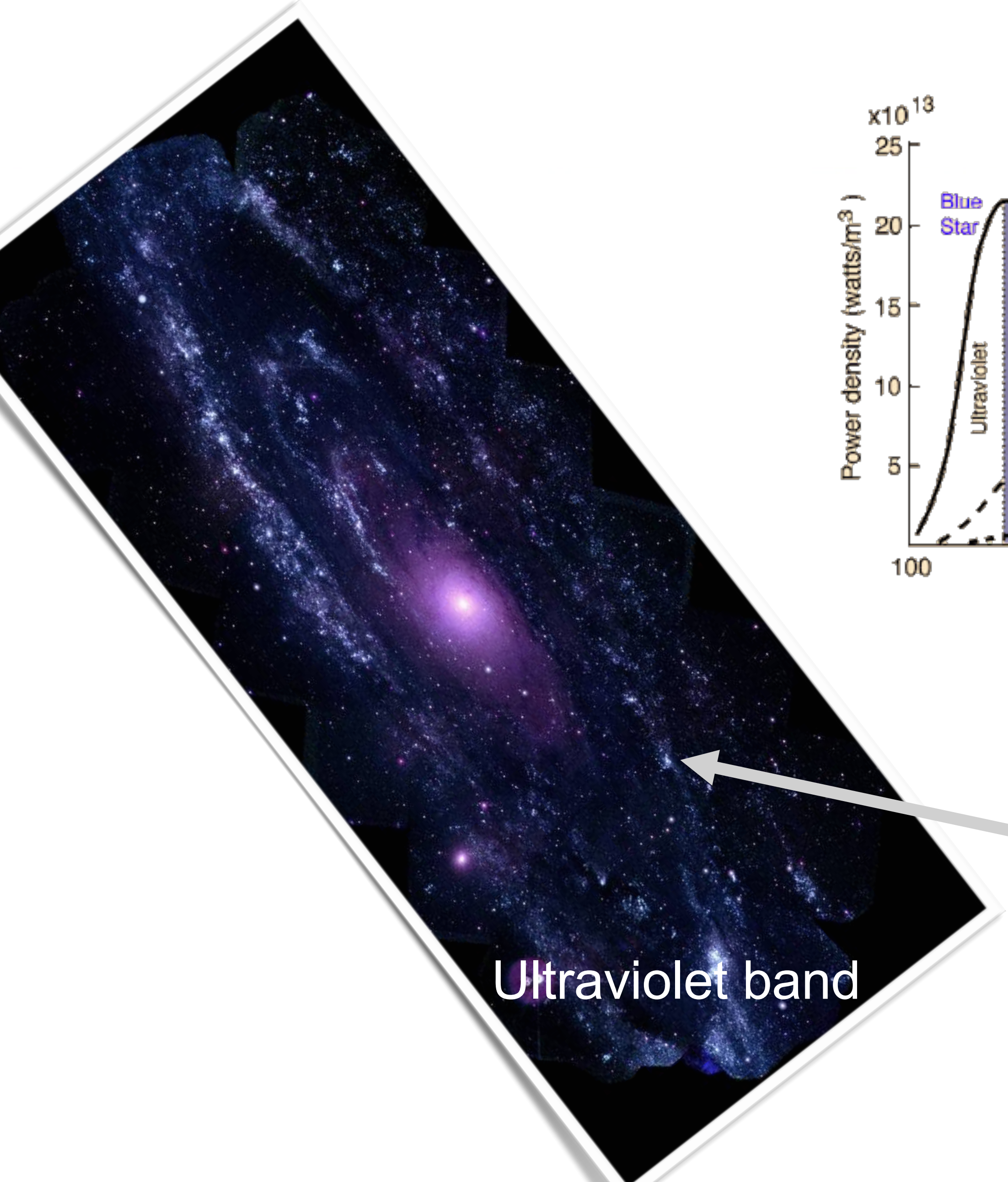
Blackbody / thermal emission:

$$\lambda_{peak}.T = \text{cste}$$

Thermal emission of stars in other galaxies or galaxy clusters

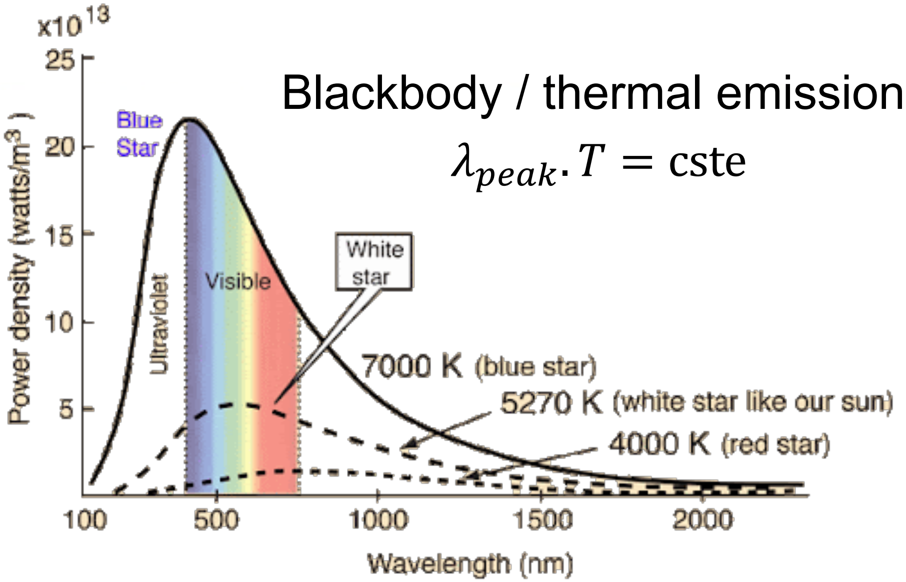
Thermal emission of stars in the Milky Way or in M31

Multi-wavelength Astronomy



Blackbody / thermal emission:

$$\lambda_{peak}.T = \mathrm{cste}$$



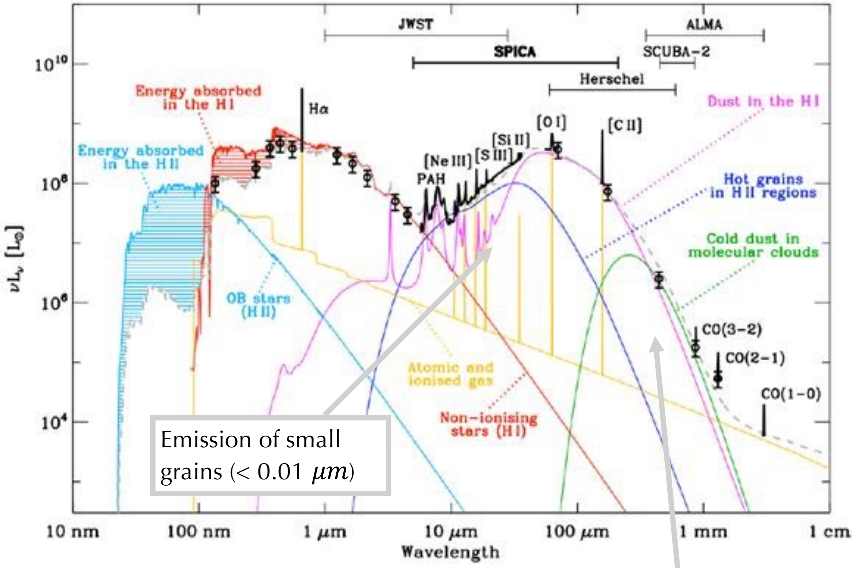
Thermal emission of massive stars in the galaxy

Multi-wavelength Astronomy

Andromeda galaxy

Infrared band

Different dust composition radiate at different energies:

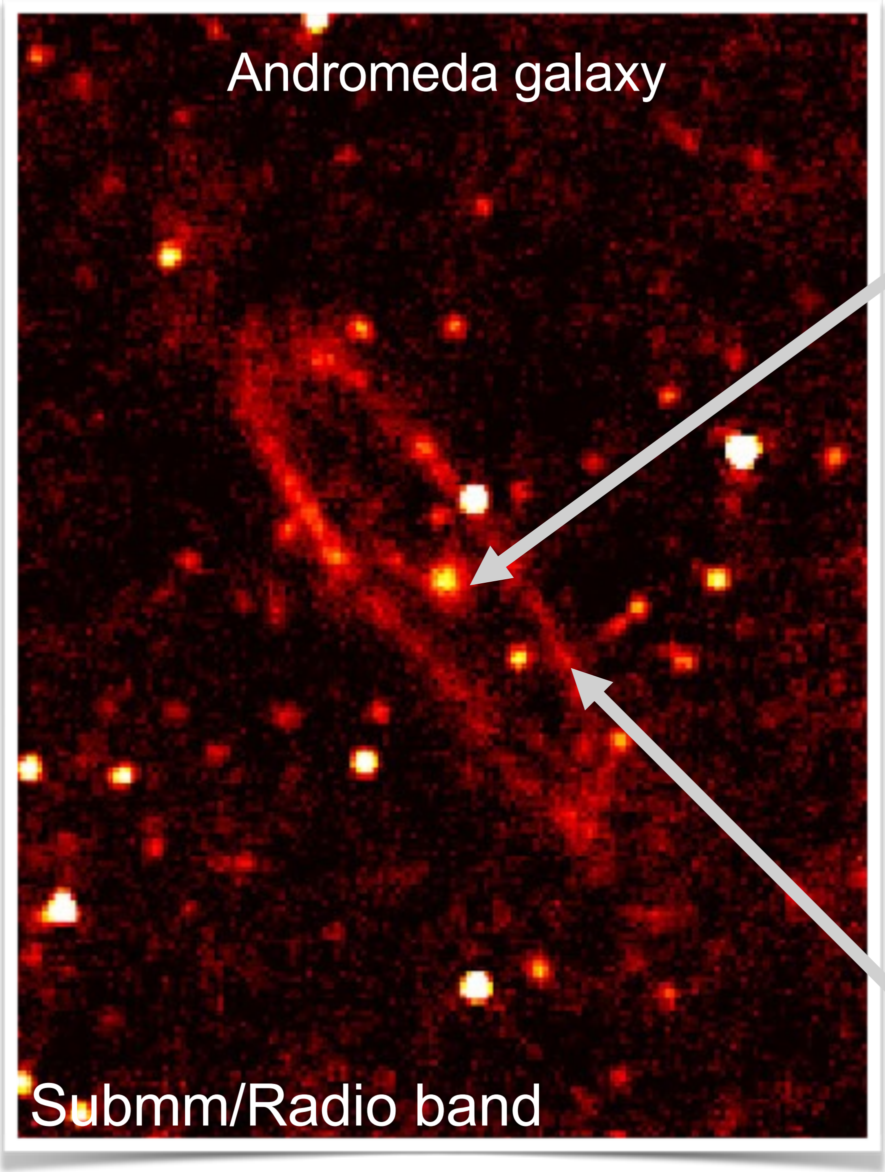


Emission of small grains (< 0.01 μm)

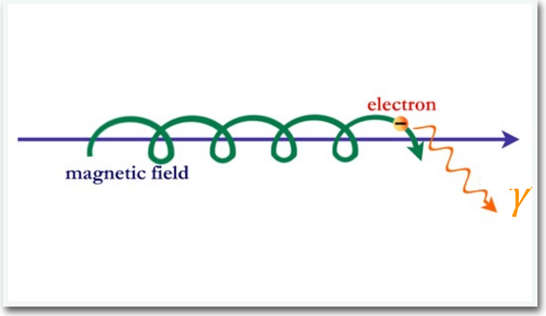
Emission of large grains (> 0.01 μm)

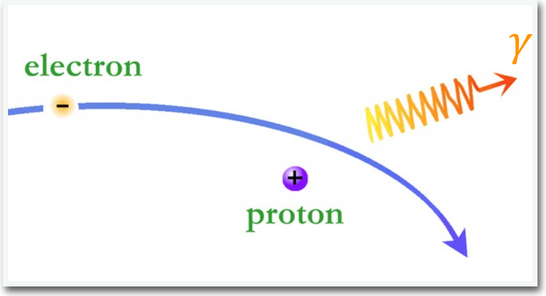
Dust in Molecular clouds: dense gas concentrations hosting star formation sites

Multi-wavelength Astronomy



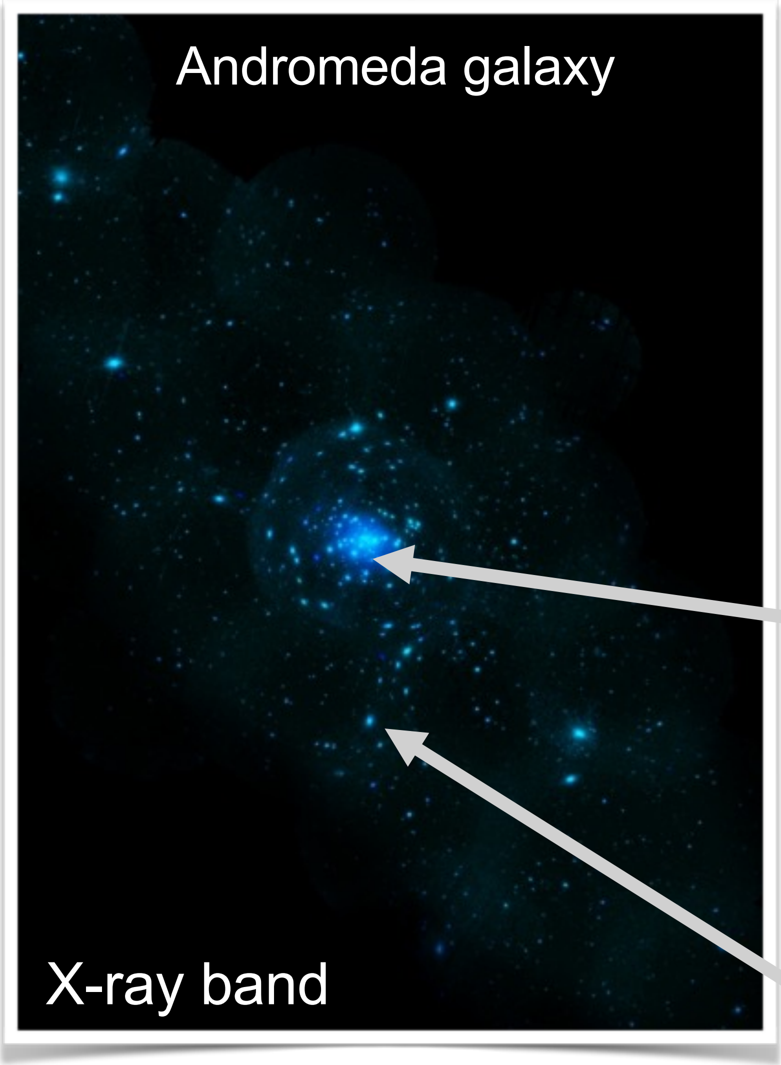
Synchrotron (non-thermal) + bremsstrahlung emission (star forming regions)

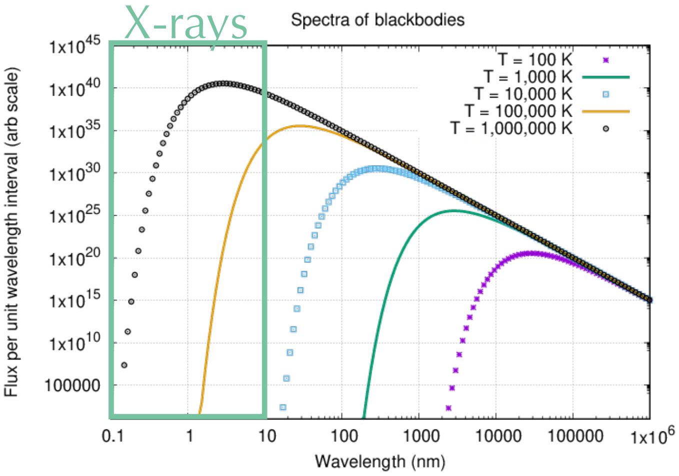




Gas in Molecular clouds: dense gas concentrations hosting star formation sites

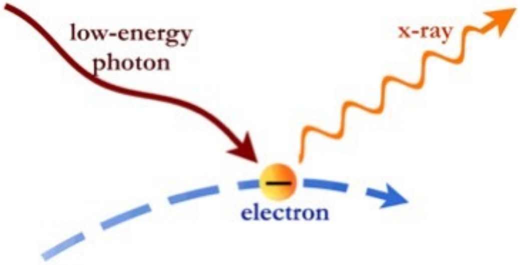
Multi-wavelength Astronomy





Thermal emission (blackbody + bremsstrahlung):
- *gas in galaxy clusters ($T \sim 10^7$ K)*
- *accretion onto compact object (potential energy converted to kinetic energy + radiation)*

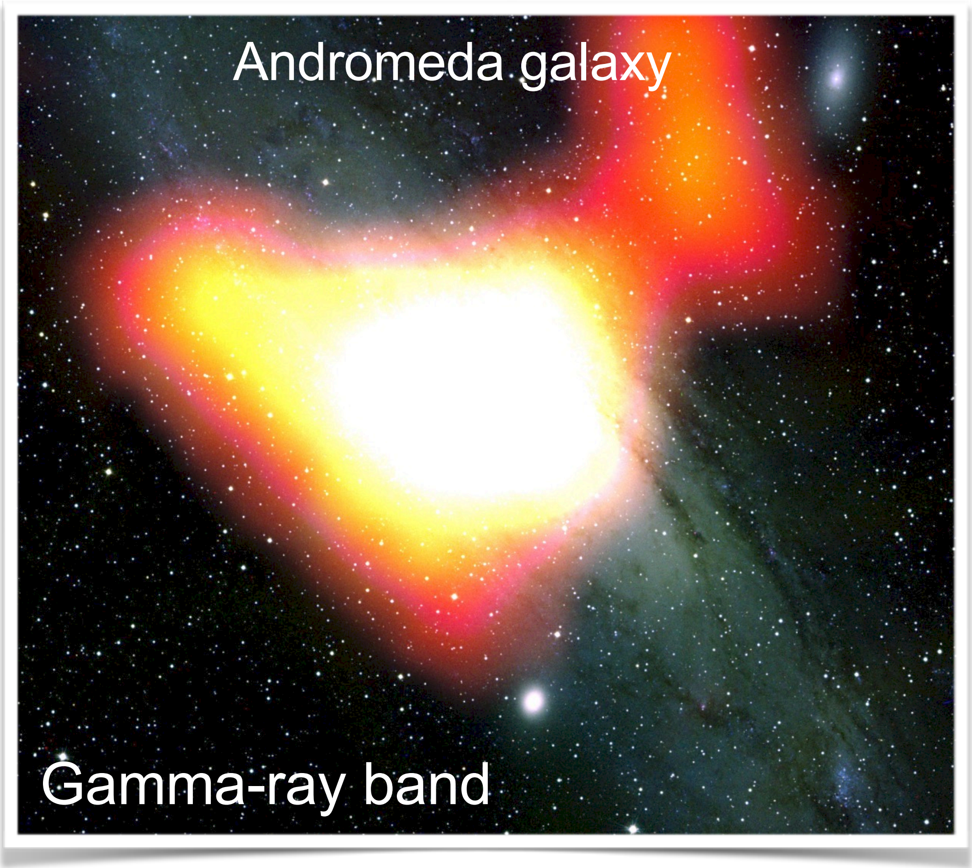
Non-thermal emission:
- *synchrotron*
- *inverse Compton*



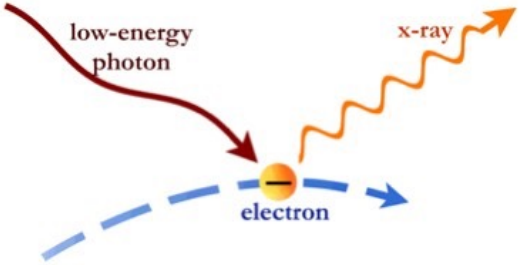
Multi-wavelength Astronomy

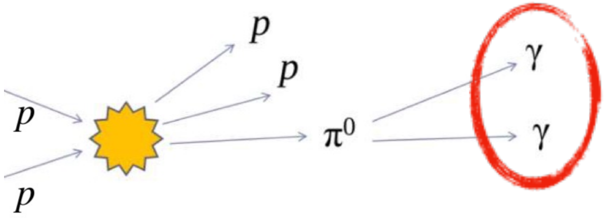
Non-thermal processes:

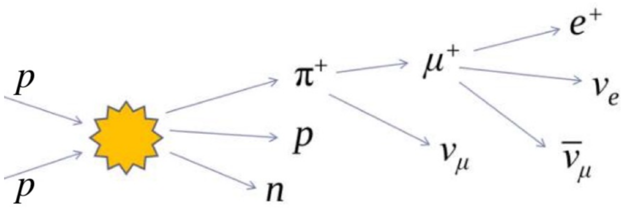
- *inverse Compton (leptonic origin)*
- *Interaction of high-energy protons with interstellar gas (hadronic origin)*
- *Unknown sources (dark matter) ?*



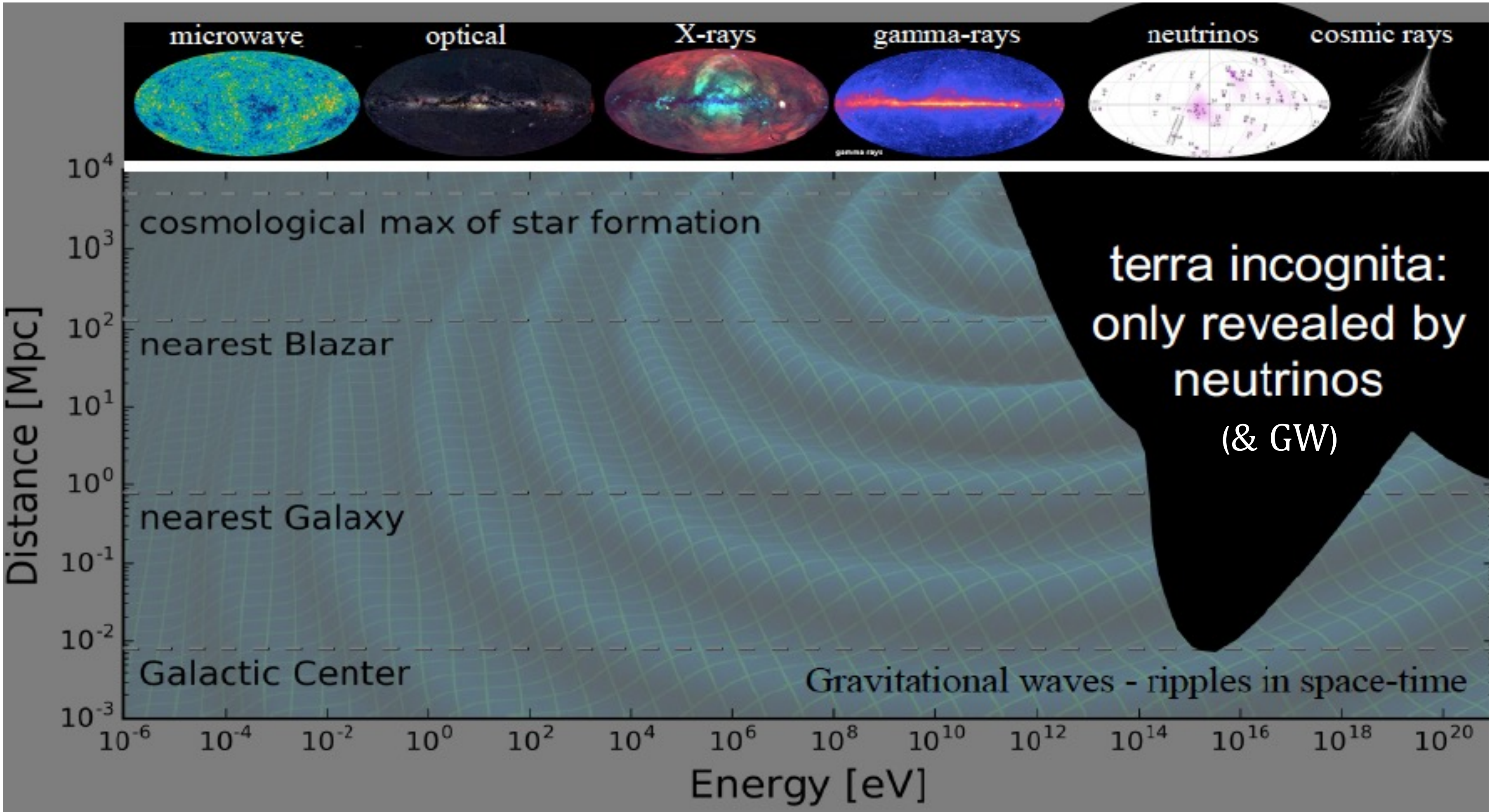
Angular resolution: ~1° (70 000 lower than in optical)







Multi-messenger astronomy



From F. Halzen

Neutrinos

✓Transient sources ✓Core of astrophysical bodies

✓ Point source ✓Cosmological distance

⇒ Signature of hadronic acceleration

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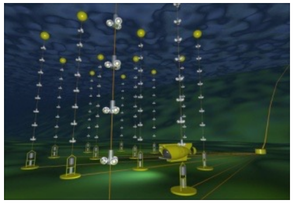
Historical aspects

Cosmic neutrino sources



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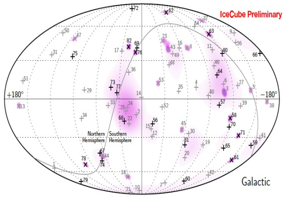

Selected results

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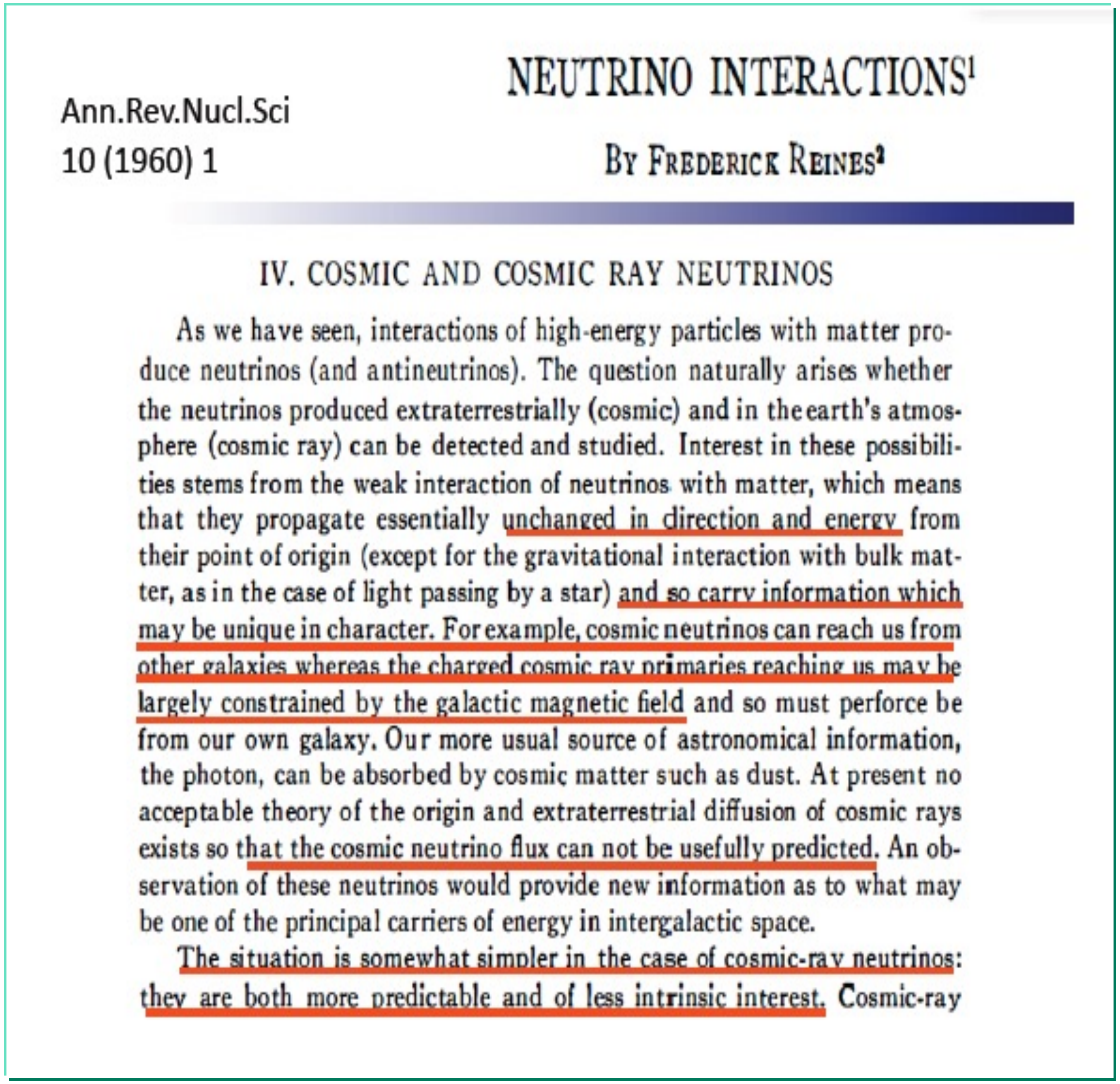
First ideas early 60’s…science



Ann.Rev.Nucl.Sci
10 (1960) 1

NEUTRINO INTERACTIONS[1]

By Frederick Reines[2]

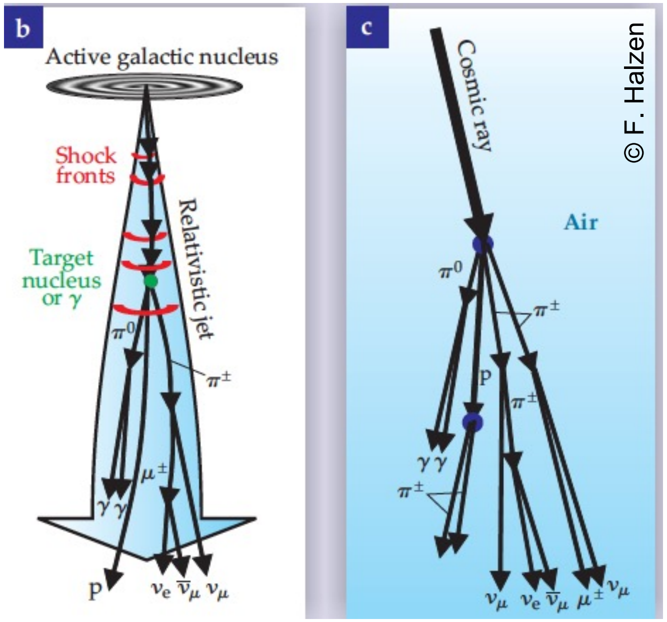
IV. COSMIC AND COSMIC RAY NEUTRINOS

As we have seen, interactions of high-energy particles with matter produce neutrinos (and antineutrinos). The question naturally arises whether the neutrinos produced extraterrestrially (cosmic) and in the earth's atmosphere (cosmic ray) can be detected and studied. Interest in these possibilities stems from the weak interaction of neutrinos with matter, which means that they propagate essentially unchanged in direction and energy from their point of origin (except for the gravitational interaction with bulk matter, as in the case of light passing by a star) and so carry information which may be unique in character. For example, cosmic neutrinos can reach us from other galaxies whereas the charged cosmic ray primaries reaching us may be largely constrained by the galactic magnetic field and so must perforce be from our own galaxy. Our more usual source of astronomical information, the photon, can be absorbed by cosmic matter such as dust. At present no acceptable theory of the origin and extraterrestrial diffusion of cosmic rays exists so that the cosmic neutrino flux can not be usefully predicted. An observation of these neutrinos would provide new information as to what may be one of the principal carriers of energy in intergalactic space.

The situation is somewhat simpler in the case of cosmic-ray neutrinos: they are both more predictable and of less intrinsic interest. Cosmic-ray

Greisen, 1960, Proc. Int. Conf on Instrum for HE physics

One may even anticipate eventual high-energy neutrino astronomy, since neutrino travel in straight lines, unlike the usual primary cosmic rays, and the neutrinos will convey a new type of astronomical information quite different from that carried by visible light and radio waves

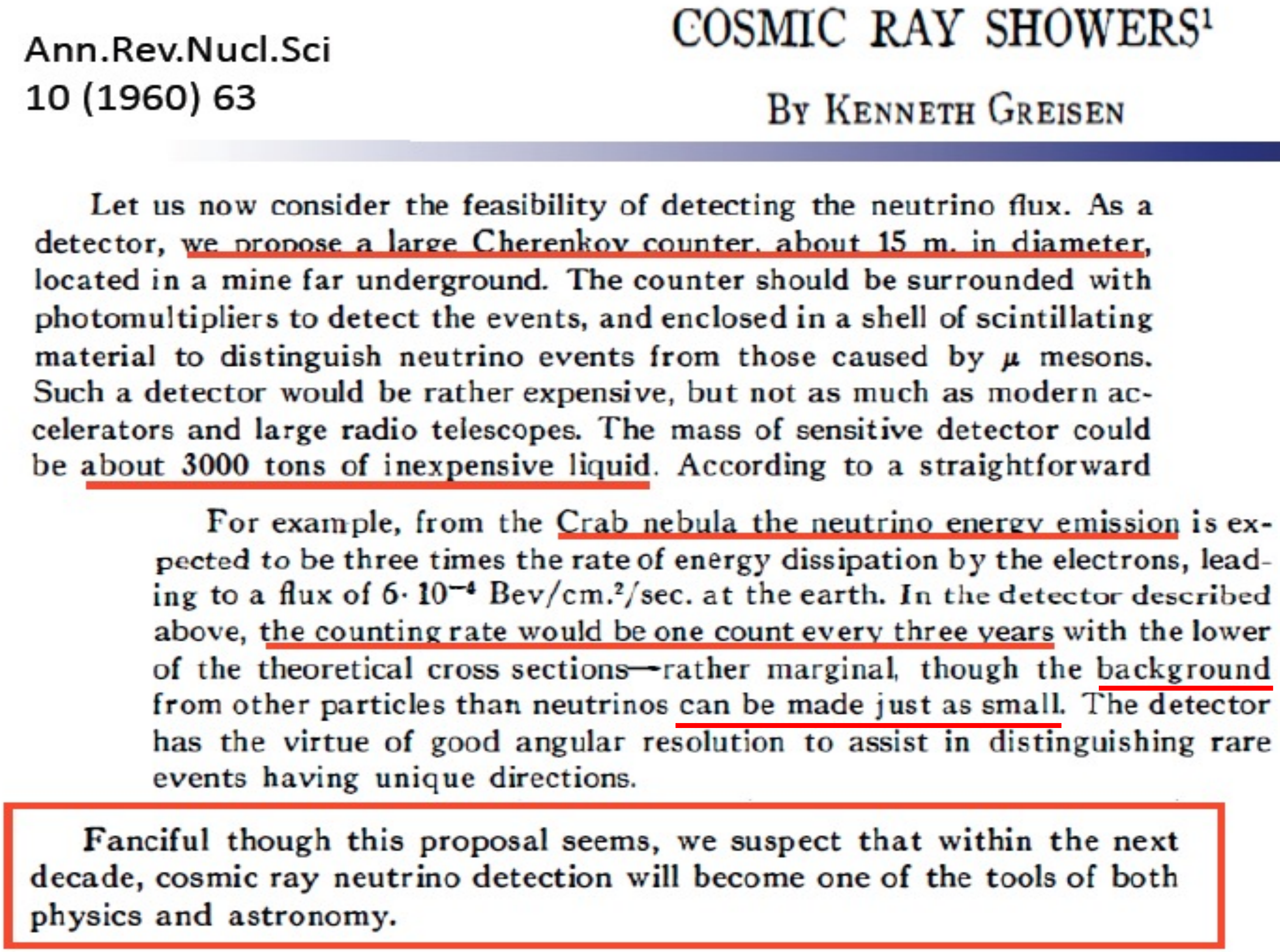


© F. Halzen

Courtesy: Ch. Spiering

First ideas early 60's…method

Ann.Rev.Nucl.Sci
10 (1960) 63



COSMIC RAY SHOWERS[1]

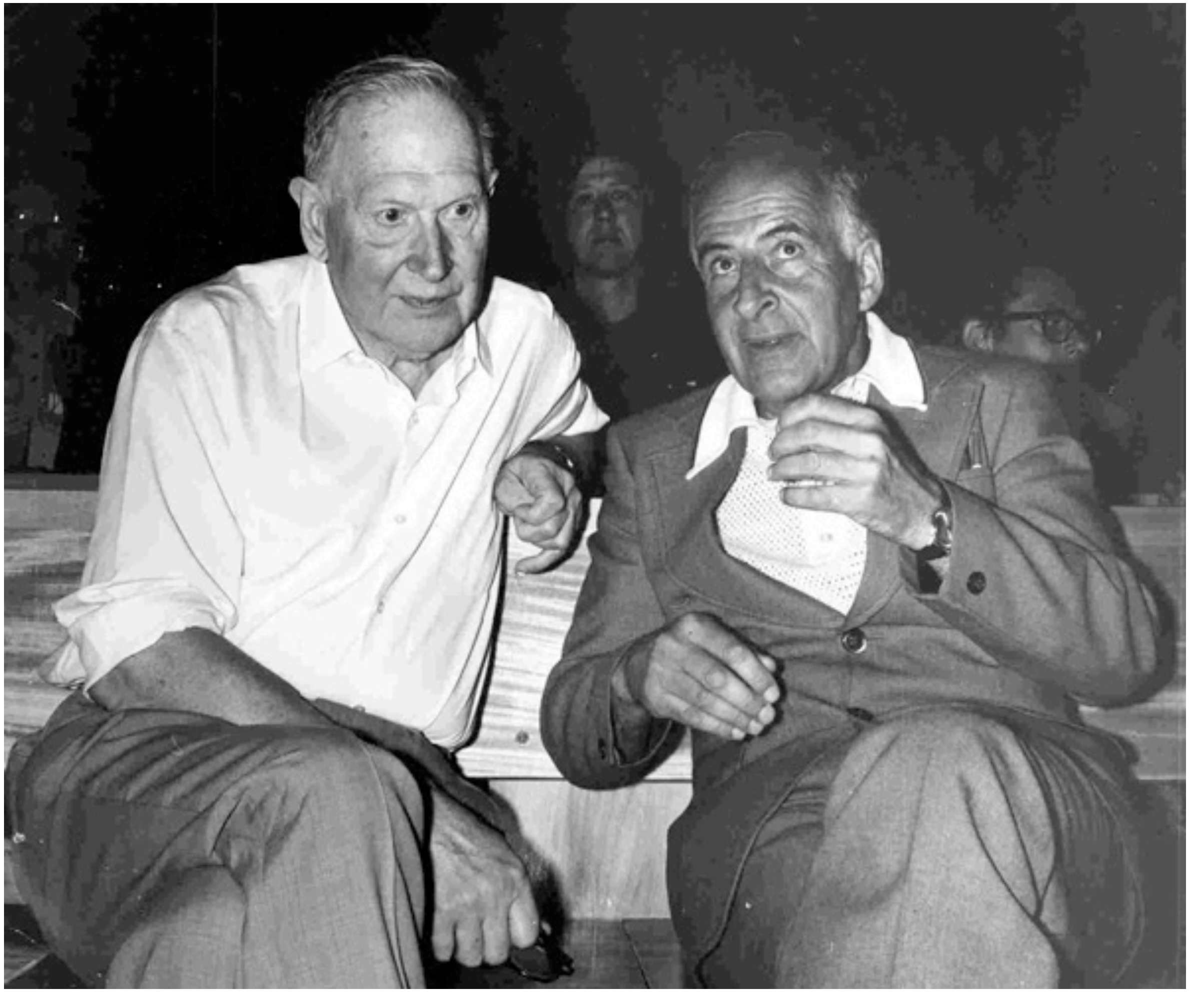
By Kenneth Greisen

Let us now consider the feasibility of detecting the neutrino flux. As a detector, we propose a large Cherenkov counter, about 15 m. in diameter, located in a mine far underground. The counter should be surrounded with photomultipliers to detect the events, and enclosed in a shell of scintillating material to distinguish neutrino events from those caused by μ mesons. Such a detector would be rather expensive, but not as much as modern accelerators and large radio telescopes. The mass of sensitive detector could be about 3000 tons of inexpensive liquid. According to a straightforward

For example, from the Crab nebula the neutrino energy emission is expected to be three times the rate of energy dissipation by the electrons, leading to a flux of $6\cdot 10^{-4}$ Bev/cm.^{2}/sec. at the earth. In the detector described above, the counting rate would be one count every three years with the lower of the theoretical cross sections—rather marginal, though the background from other particles than neutrinos can be made just as small. The detector has the virtue of good angular resolution to assist in distinguishing rare events having unique directions.

Fanciful though this proposal seems, we suspect that within the next decade, cosmic ray neutrino detection will become one of the tools of both physics and astronomy.

Recipes for a Neutrino Telescope (NT)



M. Markov:
"*We propose to install detectors deep in a lake or in the sea and to determine the direction of the charged particles with the help of Cherenkov radiation*"

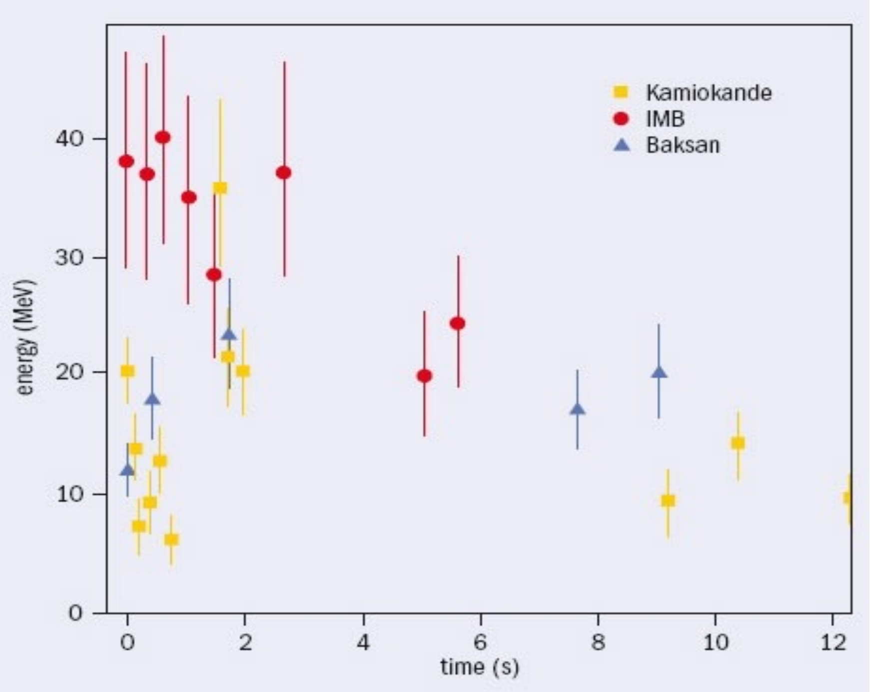
1960, Rochester Conference

M.A. Markov and B.M. Pontecorvo at the International conference on neutrino physics and astrophysics. Baksan canyon, Cheget, the Caucasus, 1977

First extraterrestrial neutrinos : SN

- **1987:** Observation of a neutrino burst from the supernova SN1987A in the Large Magellanic Cloud

Tarantula nebula: D ~ 51,4 kpc



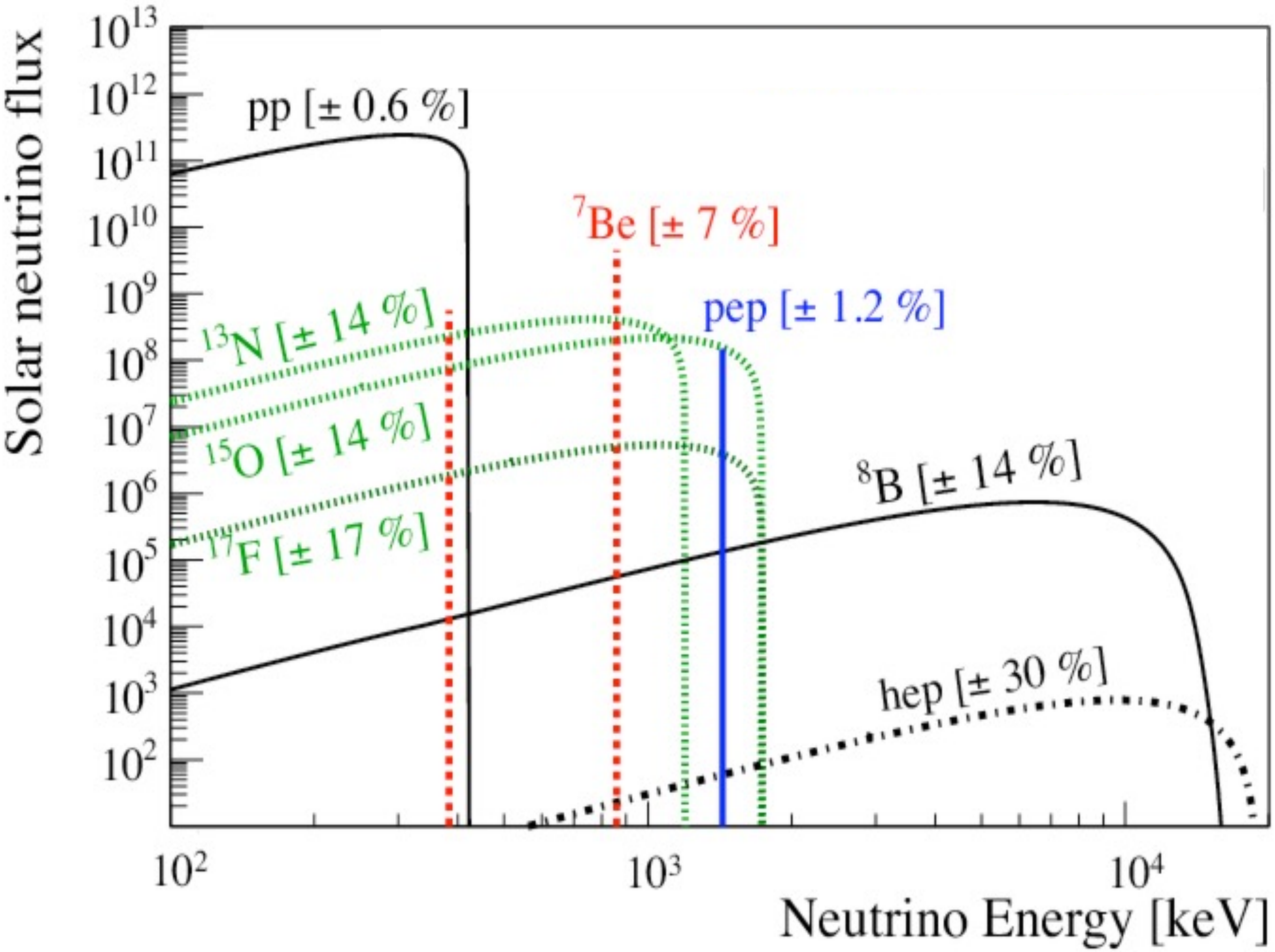
24 neutrinos detected in ~10 seconds
about 3 hours before the electromagnetic emission
Typical energy ~10 MeV

Cf. Lectures by C. Volpe

Solar Neutrinos

Cf. Lectures by D. Franco

Continuous spectra in /cm²/s/MeV
Discrete spectra in n /cm²/s



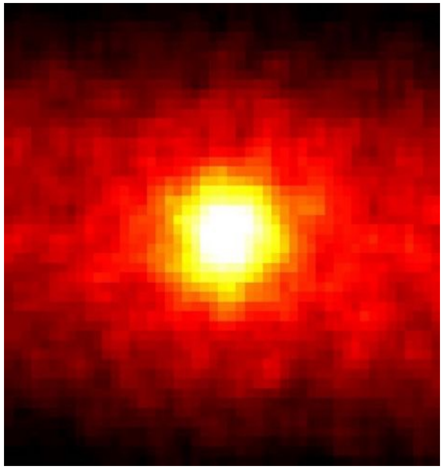
2 experimental approaches

Radiochemical experiments

Real-time detection

Real-time detection: water Cherenkov

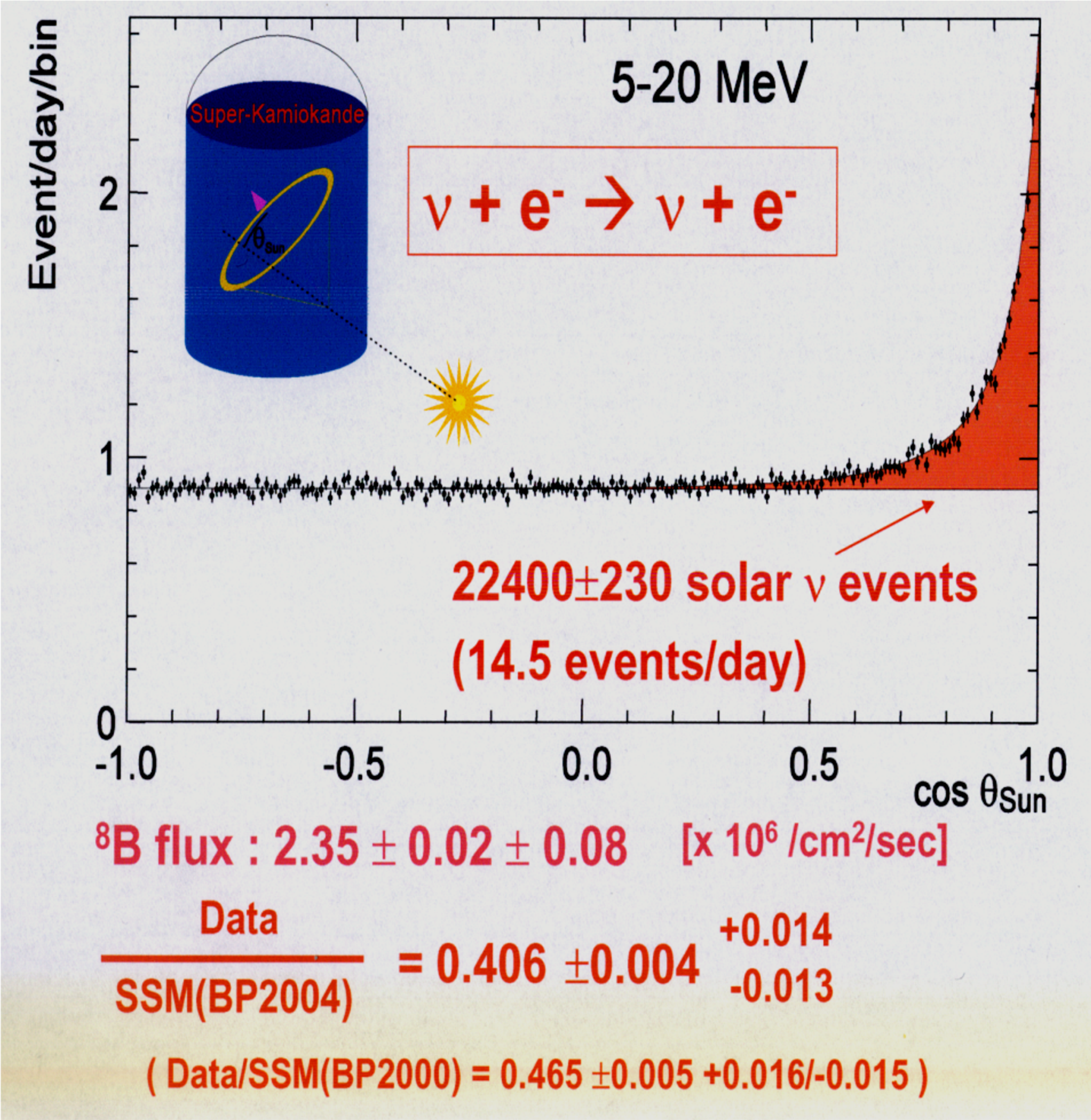
❖ **1998: Superkamiokande provides first picture of the Sun in neutrinos !**



- directionality performances allow to unambiguously identify neutrinos from the Sun

- 1500 days of data taking:
  22000 events detected
  48000 predicted by the SSM

→ Confirmation of deficit of ν_e already observed in radiochemical experiments



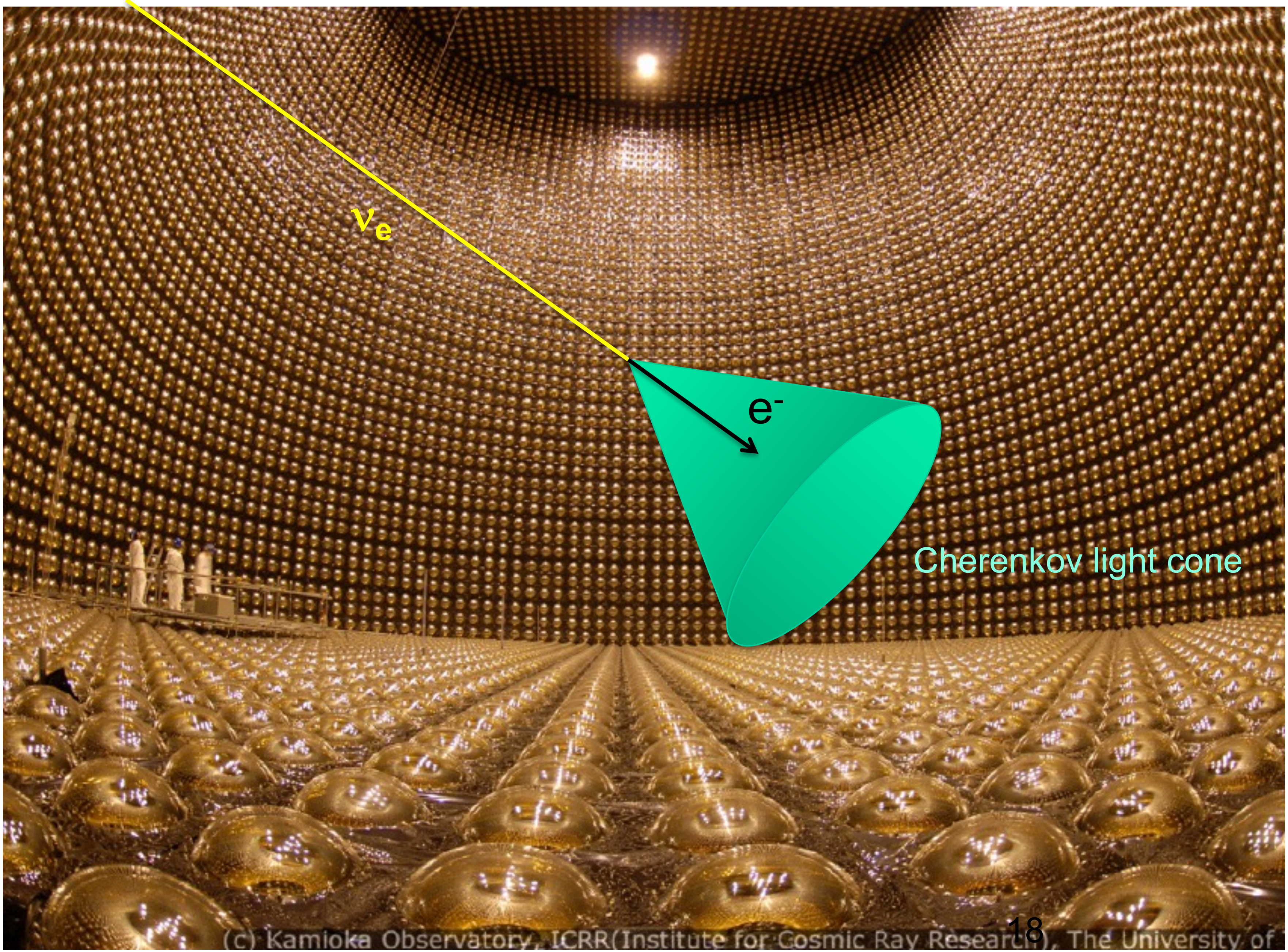
$\nu + e^- \rightarrow \nu + e^-$

^{8}B flux : $2.35 \pm 0.02 \pm 0.08$ [x 10^6 /cm^2/sec]

$$\frac{\text{Data}}{\text{SSM(BP2004)}} = 0.406 \pm 0.004 \, ^{+0.014}_{-0.013}$$

(Data/SSM(BP2000) = 0.465 ±0.005 +0.016/-0.015)

Real-time detection: water Cherenkov



Neutrinos from space: the long quest

The Nobel Prize in Physics 2002

"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"

Raymond Davis Jr.	Masatoshi Koshiba	Riccardo Giacconi
1/4 of the prize	1/4 of the prize	1/2 of the prize
USA	Japan	USA
University of Pennsylvania Philadelphia, PA, USA	University of Tokyo Tokyo, Japan	Associated Universities Inc Washington, DC, USA
b. 1914	b. 1926	b. 1931 (in Genoa, Italy)

Solar neutrinos

(MeV energies)

Davis et al. 1955 – 1978
Koshiba et al., 1987 – 1988

Presence of cosmic neutrinos E > GeV?

Galactic
Extragalactic

« These neutrino observations are so exciting and significant that I think we're about to see the birth of an entirely new branch of astronomy: neutrino astronomy.»

J.Bahcall
New York Times (3 Apr 1987)

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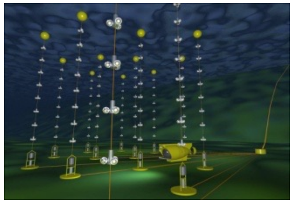

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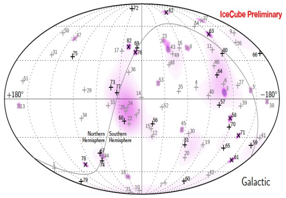

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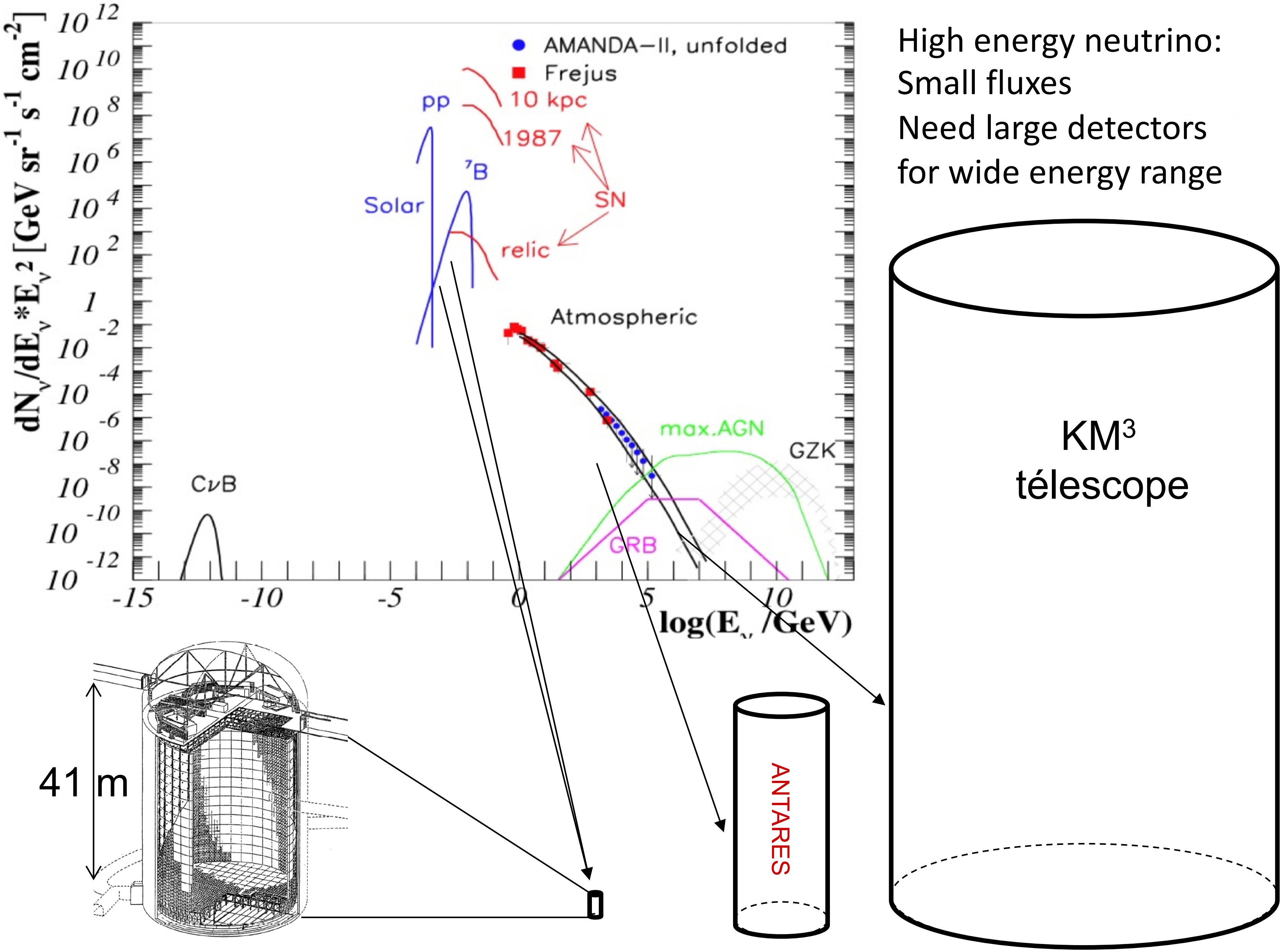
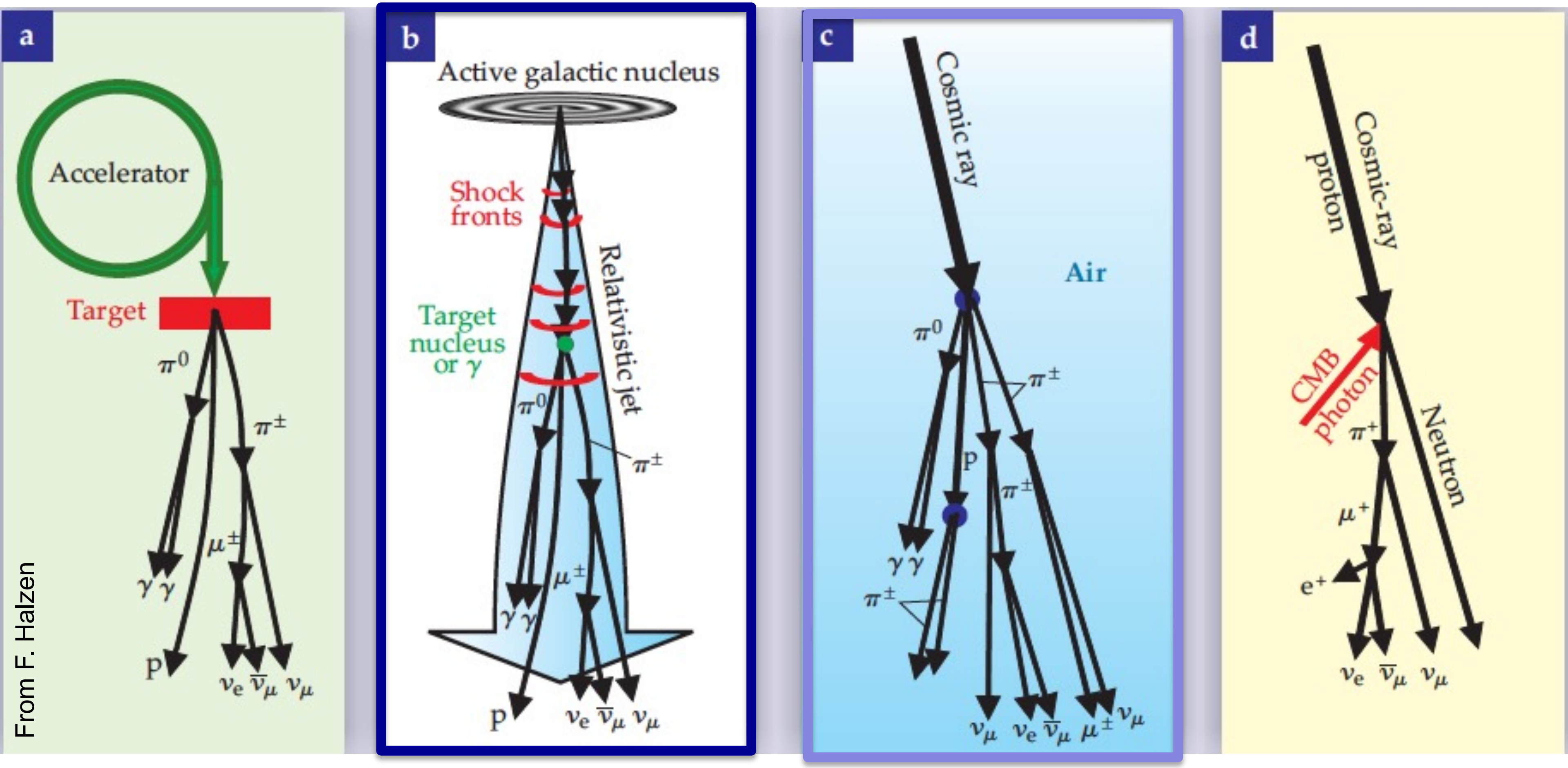
From MeV ν to PeV ν



High energy neutrino:
Small fluxes
Need large detectors
for wide energy range

Common production mechanism



Neutrino beam cosmic neutrinos atmospheric neutrinos cosmogenic ν (GZK)

→ Guaranteed source of >100 PeV neutrinos
→ Provide information on the composition of primaries
→ Alternative techniques (e.g Radio)

Not covered here

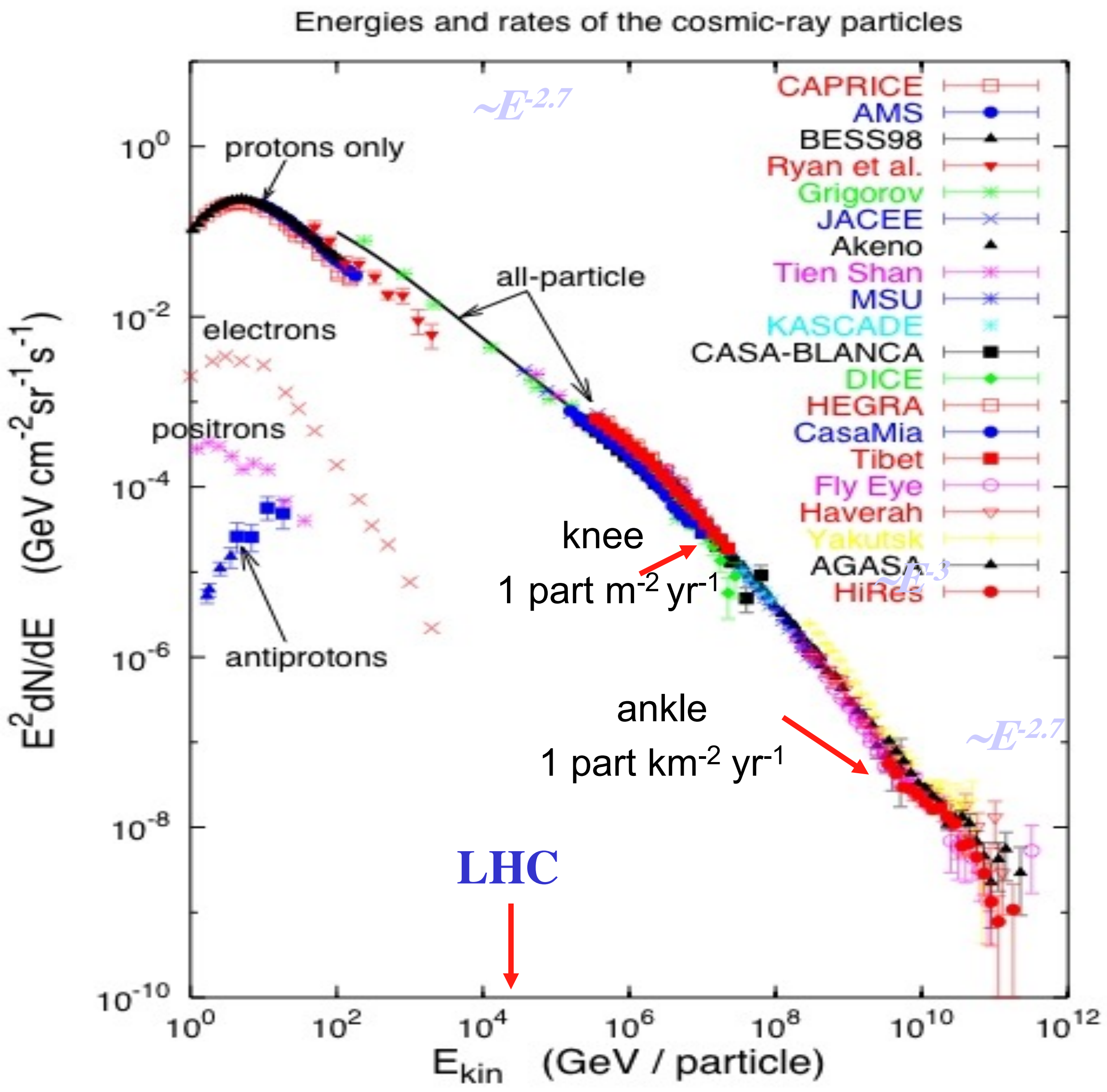
Neutrinos tracing UHE cosmic rays

Nature accelerates particles 10^7 times the energy of LHC!

Cutoff now confirmed
But…

where?

how?

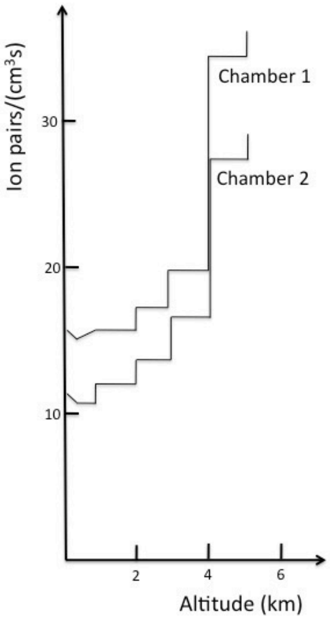


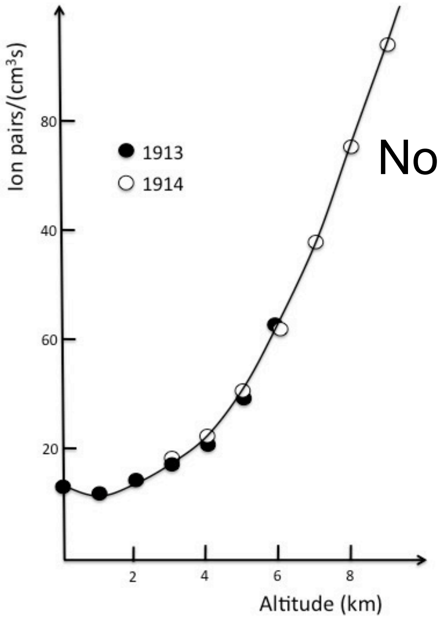
Cosmic rays

Cosmic rays are charged nuclei coming from outside the atmosphere

Discovered by V. Hess in 1912, through the detection of increase of the ionization rate with the altitude.

« The results of the observations seem most likely to be explained by the assumption that radiation of very high penetrating power enters from above into our atmosphere. »

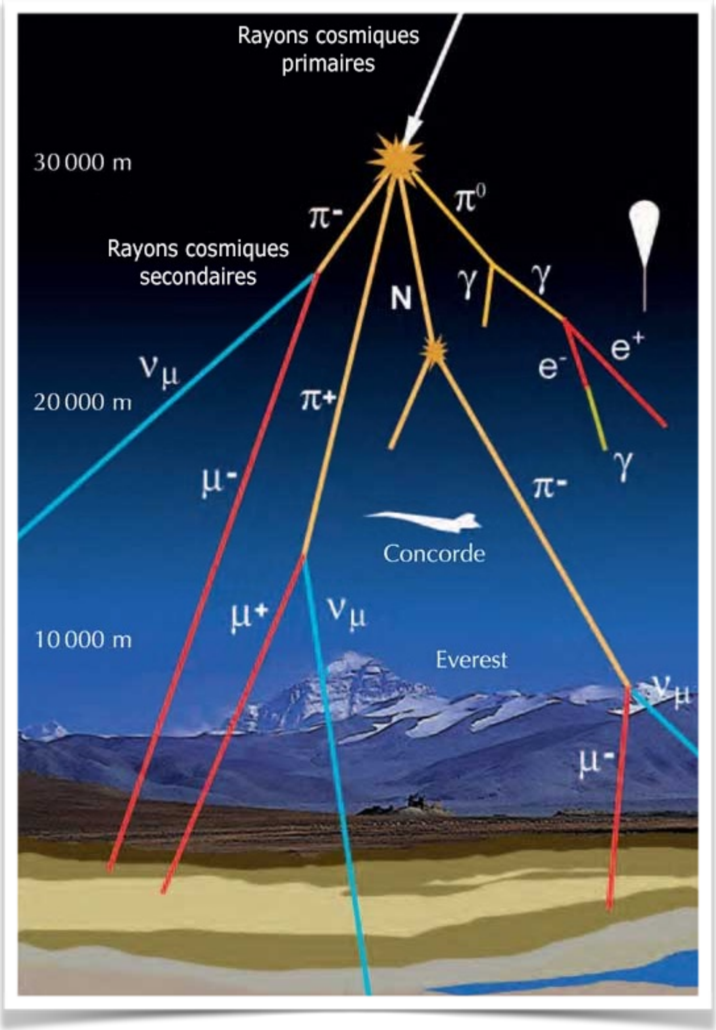




Nobel Prize in Physics - 1936

Cosmic rays

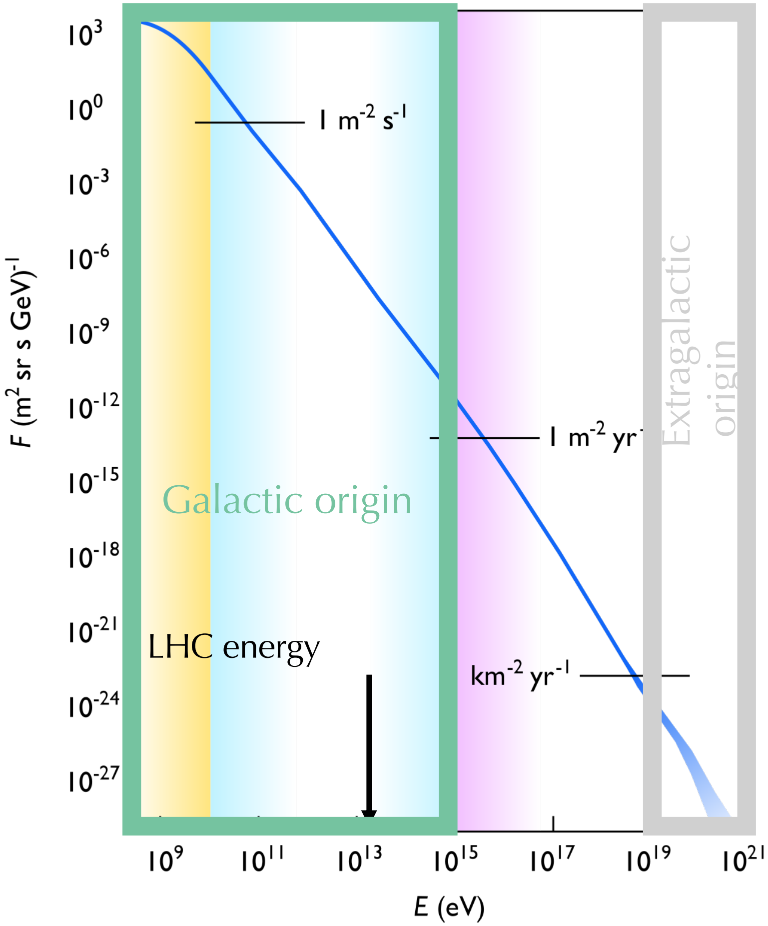
V. Hess' observations: secondary particles produced by the interaction of high-energy particles with the atmosphere.



From 1950: first direct observations using satellites and stratospheric ballons.

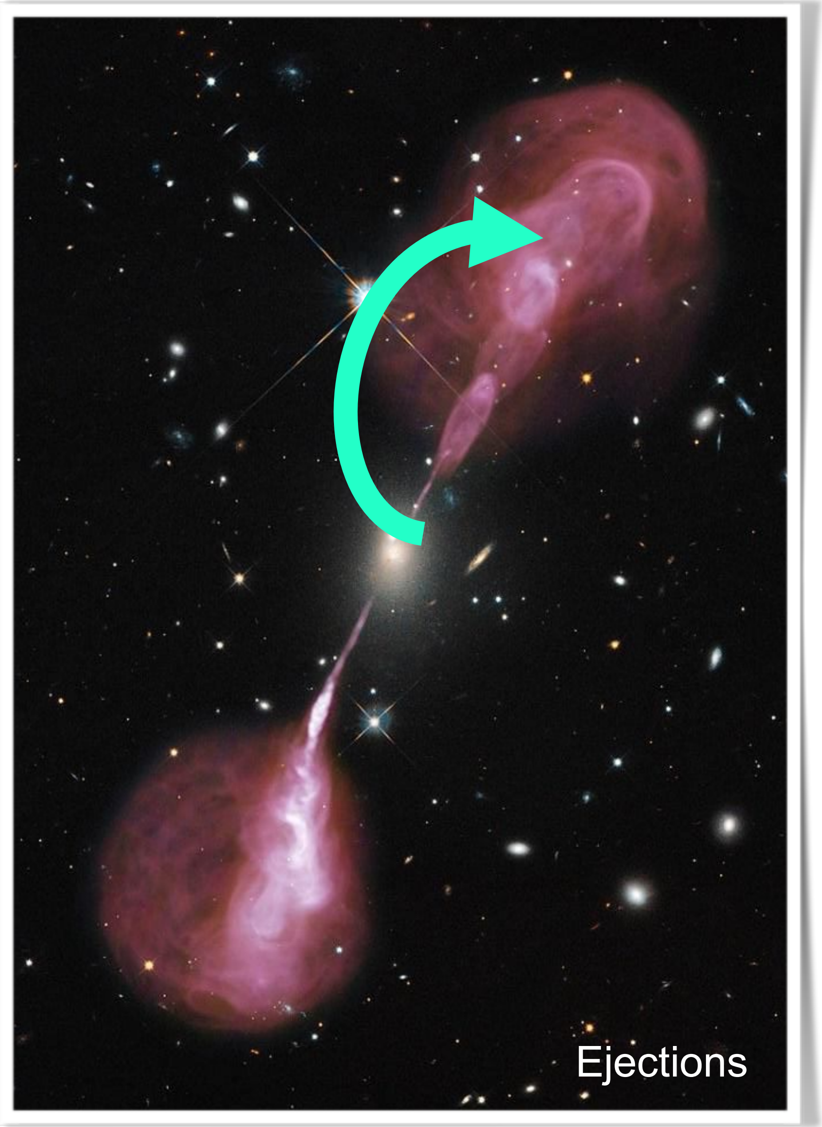
⇒ cosmic ray **composition**: 88% of protons, 9% of He nuclei, + électrons, heavier nucleons, … + **spectrum**

Nb of particles with energy $\in [E; E + dE]$, crossing a surface dS, with an observing direction $d\Omega$, in a time interval dt



High-energy processes

Physical processes taking the energy at small scale and redistribute it at larger scale



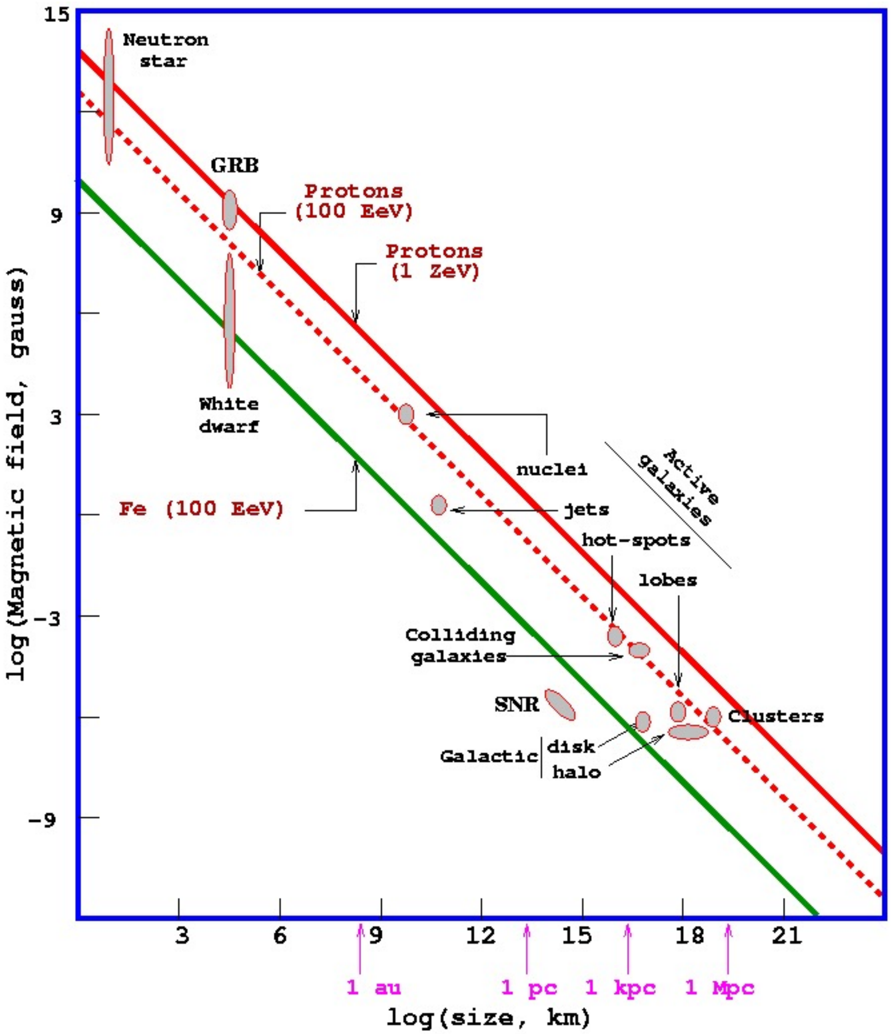
What astrophysical objects?

The Hillas Plot

$$E^{\mathrm{max}} \simeq Z\beta \cdot \left(\frac{B}{\mu\mathrm{G}}\right) \cdot \left(\frac{L}{\mathrm{kpc}}\right) \quad [\mathrm{EeV}].$$

- The equation defines the Hillas criterion for CR sources
- Several possible galactic and extragalactic acceleration sources are considered. Among them:
  - AGN
  - Gamma Ray Bursts (GRBs)
  - …

Acceleration of CRs up to a given energy requires magnetic fields and sizes above the respective line.
Some source candidates are still controversial

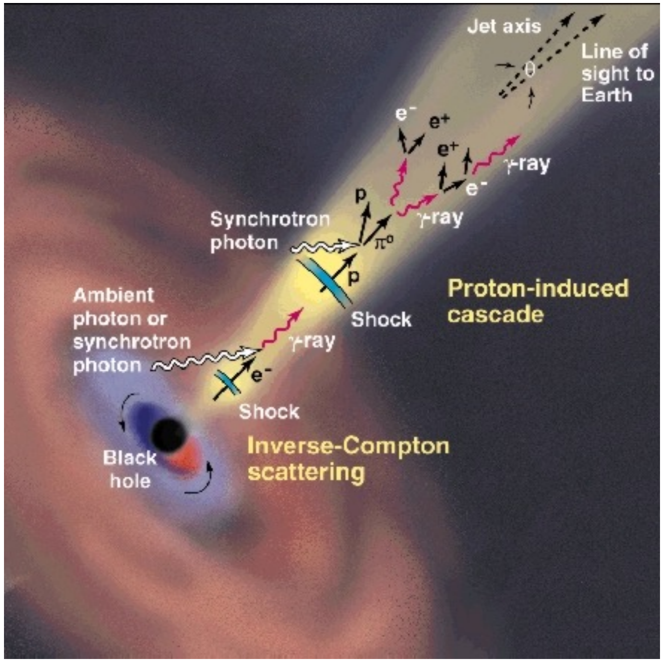


Potential extragalactic sources

Active Galactic Nuclei (AGN)

Steady (though flaring) sources

Observed luminosities $10^9 - 10^{15}\ L_\odot$

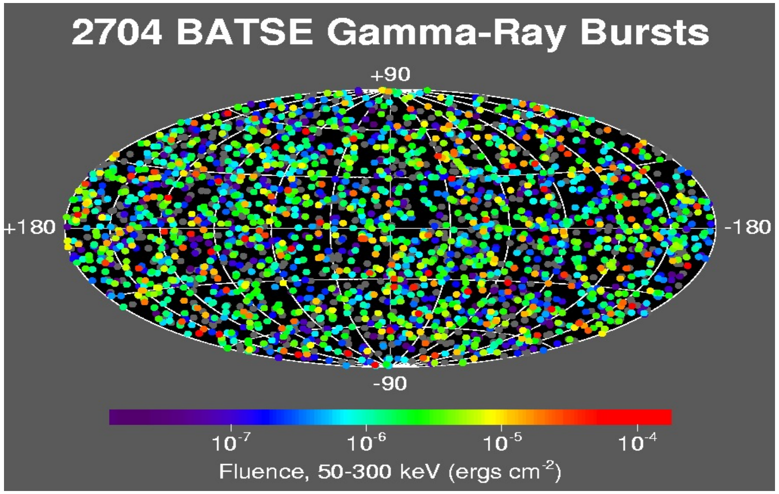


Gamma Ray Bursters (GRB)

Short emissions (~1s)
Very bright ~ $10^{18} \times L_\odot$

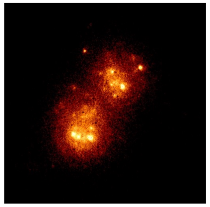
Counterparts : z up to 8.3

BATSE : 1 burst/day

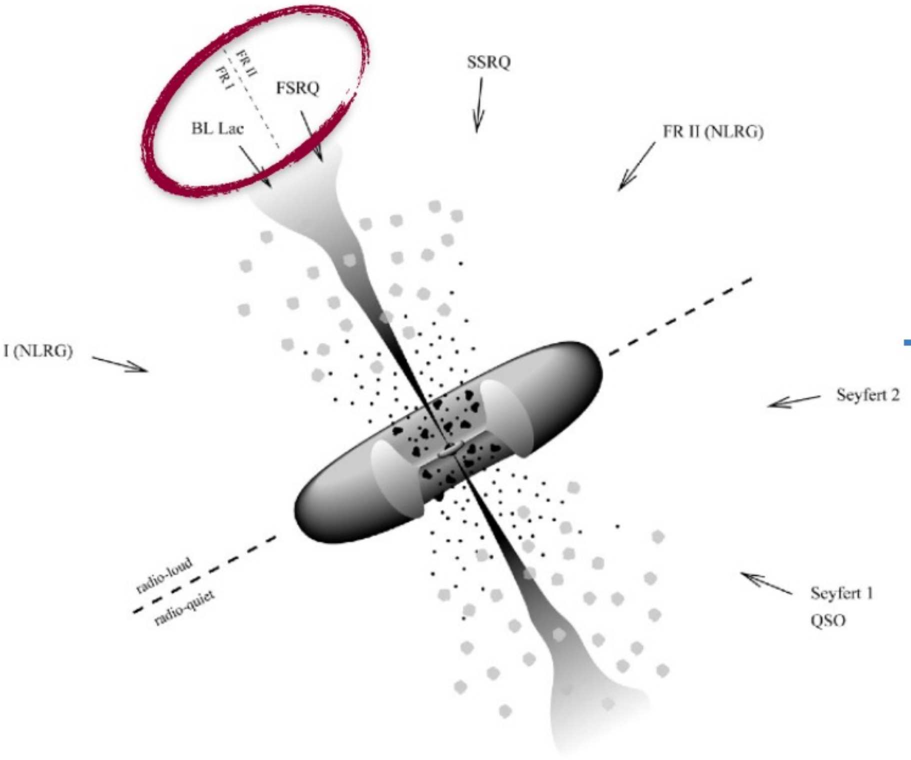


Starburst Galaxies

supernovae -> cosmic rays + dense gas -> pions



Blazars



Blazar: radio-loud AGN whose relativistic jet points towards the observer

→ Radiative emission from the jet dominates over all other components (non-thermal emission from radio to gamma-rays and fast variability)

Flat-spectrum-radio-quasars : optical/UV spectrum with broad emission lines

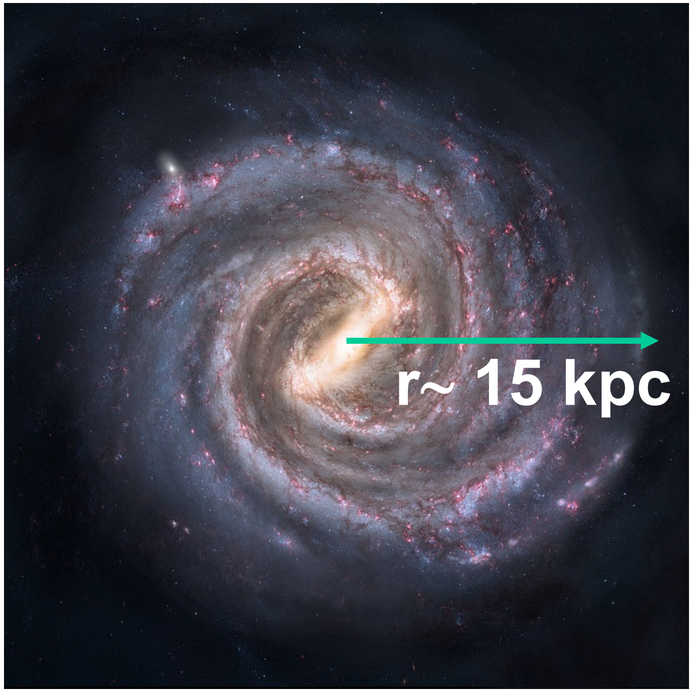
BL Lacertae objects : featureless optical/UV spectrum

Source : M. Cerruti, TeVPA22

The Physical Properties of the Galaxy

- **CR propagate in the Galaxy**
- The Milky Way is very similar to the spiral galaxies that we observe in the Universe.
- Thin disk (200-300 pc) & radius of 15 kpc
- The Sun is about 8.5 kpc from the center.

$$\boxed{1\ \mathrm{pc} = 3.086 \times 10^{18}\ \mathrm{cm}\,.}$$

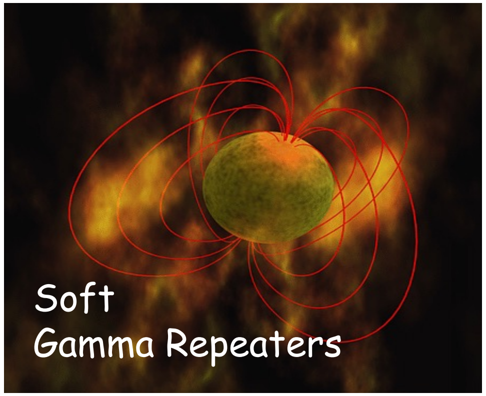


- The galactic volume, assuming a flat disk

$$\mathscr{V}_G = [\pi(15 \times 10^3)^2 \times 300] \times (3 \times 10^{18})^3 = 5 \times 10^{66}\ \mathrm{cm}^3\,.$$

- The Milky way hosts about 100 billion of stars and a supermassive black hole in its center

Potential Galactic sources



Microquasars X-ray binaries with compact object (neutron star or black hole) accreting matter and re-emitting it in relativistic jets (intense radio & IR) flares.

→ HEN from jets

SGRs X-ray pulsars with a soft γ-ray bursting activity.
Magnetar model: highly magnetized neutron stars whose outbursts are caused by global star-quakes

→ HEN from GRB-like flares

Galactic Center
seen with TeV photons

- *Supernovae remmants*
  pulsars, neutron stars

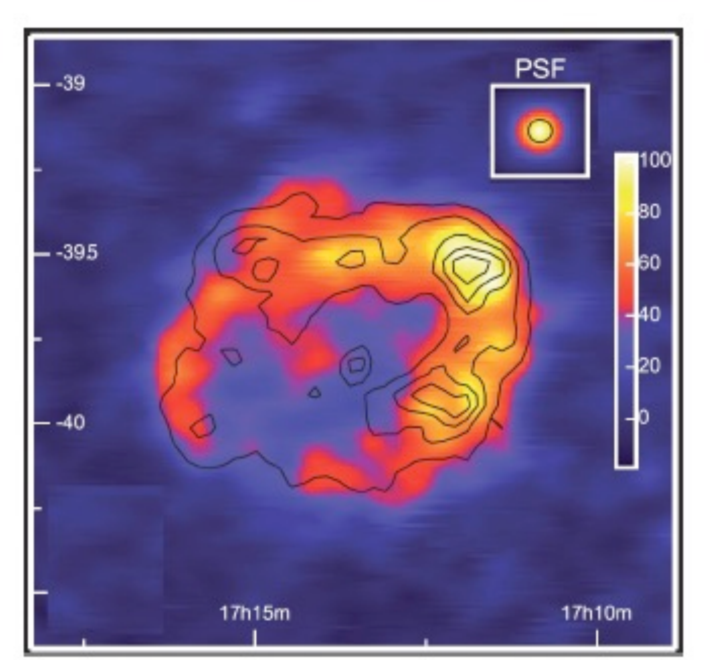
- *Dense regions*
  Sun , Galactic Centre, Interstellar medium

→ Mosty seen by Northern Hemisphere neutrino telescopes

About the Identification of Galactic CR Sources

- The Diffusive Shock Acceleration model predicts the production CRs in SNRs up to PeV.
- The amount of relativistic particles present in the acceleration region increases with time as the SNR passes through its free expansion phase, and reaches a maximum in the early stages of the so-called *Sedov phase*.
- Correspondingly, the peak in γ-ray luminosity typically appears some 10^3–10^4 years after the supernova explosion.
- Thanks to the HESS survey of the galactic plane, we know that acceleration sites up to $\sim$ 100 TeV are spatially superimposed with regions of non-thermal X-ray emission.

- This has strengthened the hypothesis that galactic CRs up to the knee are accelerated in SNRs.
- Figure shows the morphological structure of the RX J1713.7-3946 SNR. This shows a correlation of TeV emission with non-thermal X-rays.
- Even if radio and X-ray data suggest that SNRs are indeed the sources of CR electrons, **no compelling evidence for the acceleration of protons in SNRs up to the PeV energies has been found.**



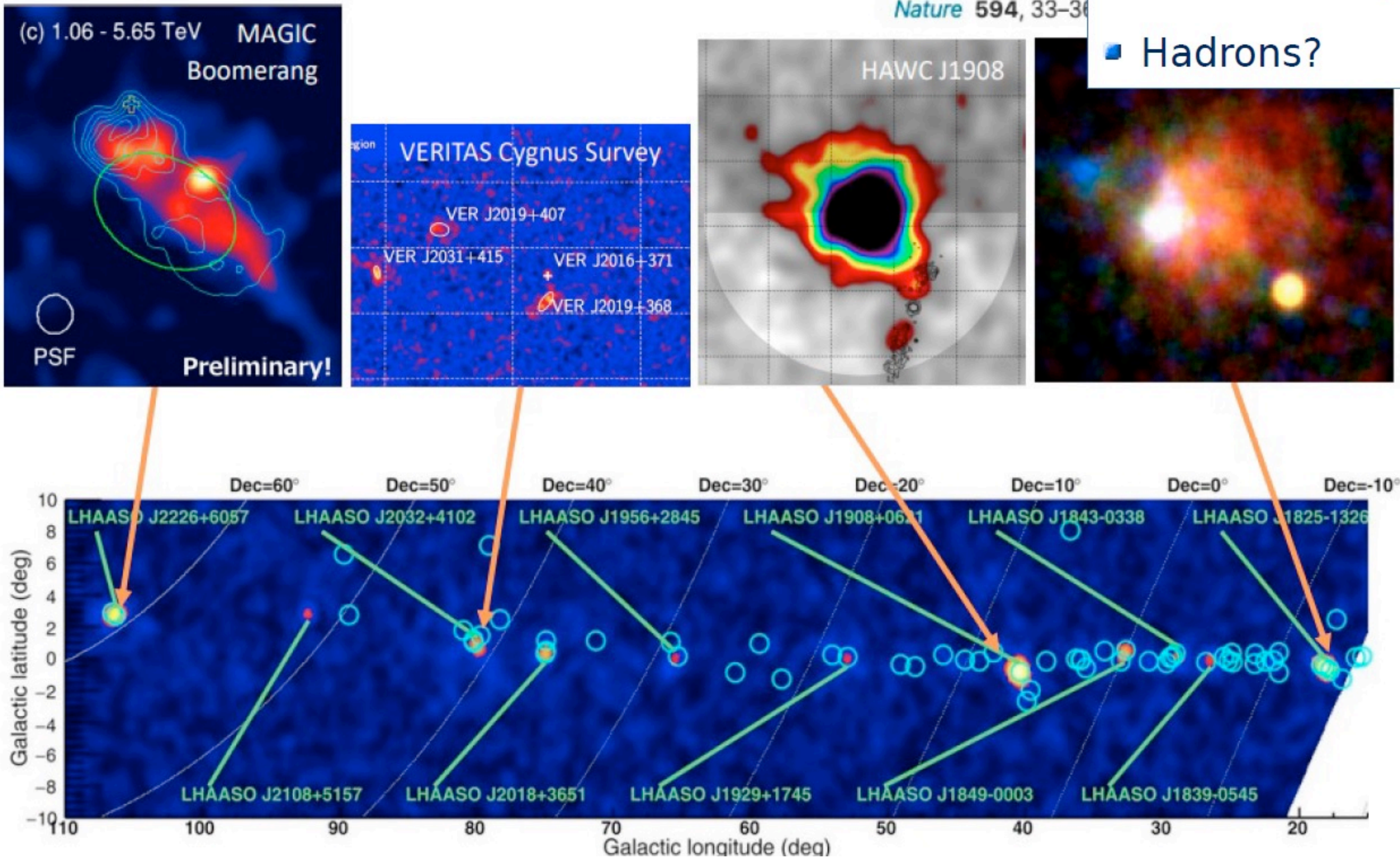
(2021) LHAASO first PeVatrons

Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources

Zhen Cao, F. A.

Nature **594**, 33–3

- 1y, KM2A
- E > 100 TeV, >7σ
- Hadrons?



Challenging for electrons

And more…

- Star-forming galaxies
- Galaxy clusters
- Galactic diffuse emission
- Discrete Galactic sources
- Binary black hole or neutron star mergers
- Novae
- Tidal disruption events
- Fast radio bursts
- Dark Matter
- Exotic heavy particles
- ???

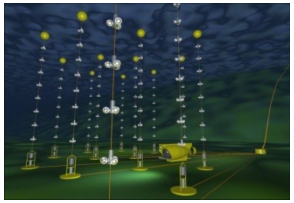
Outline

Neutrino astronomy

Scientific motivations

Historical aspects

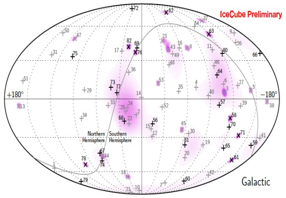
Cosmic neutrino sources



Neutrino telescope

Detection principles

Current telescopes



Selected results

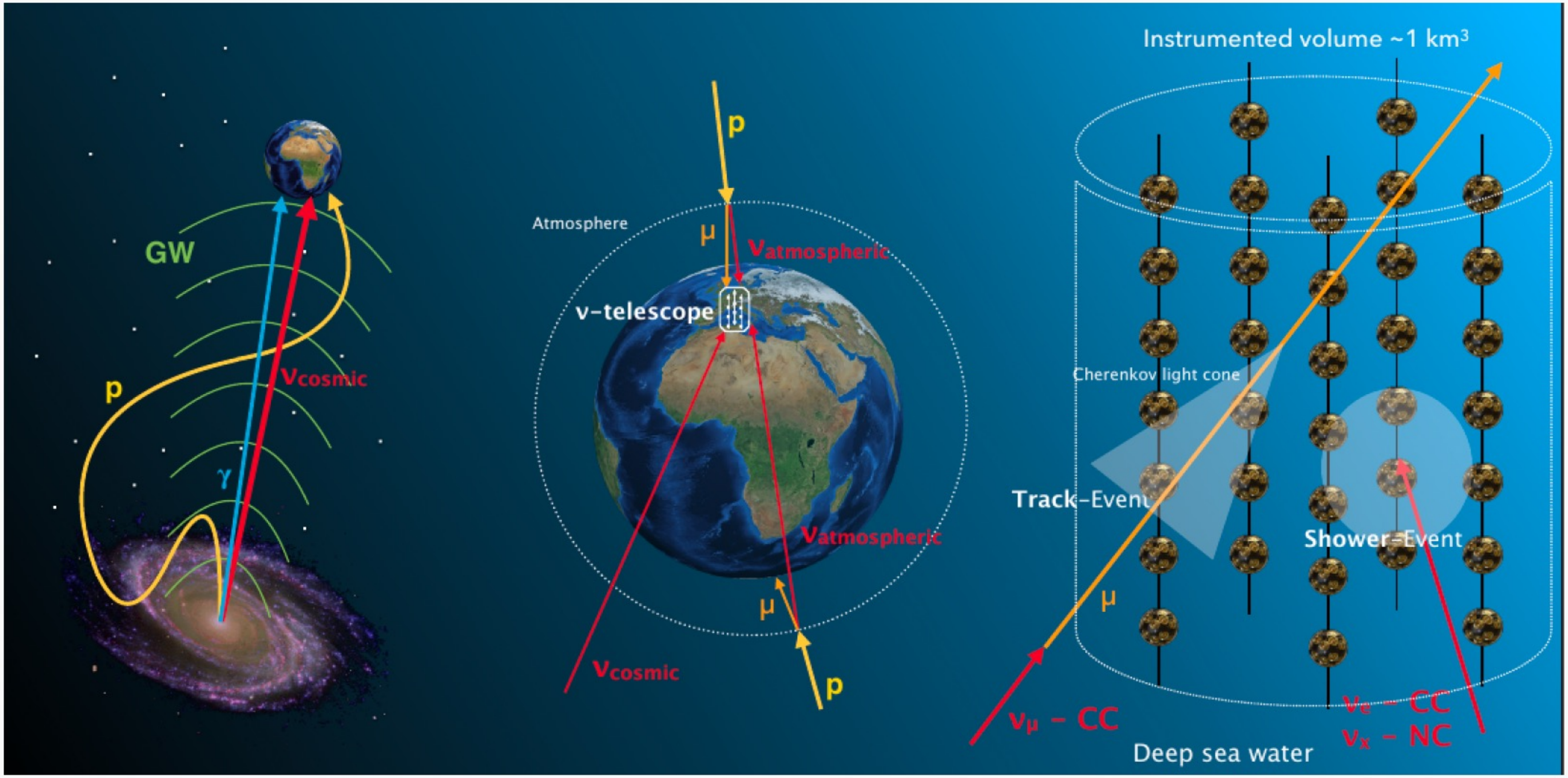
Diffuse Flux, point sources

Multi-messenger search

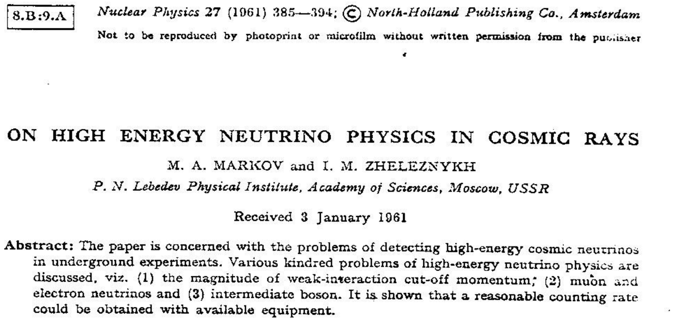
KM3NeT

ORCA prospects

In short


GW
p
ν_{cosmic}
γ
p
Atmosphere
μ
ν atmospheric
ν-telescope
ν atmospheric
μ
ν cosmic
p
Instrumented volume ~1 km³
Cherenkov light cone
Track-Event
Shower-Event
μ
νμ - CC
νe - CC
νx - NC
Deep sea water

Markov’s idea: muon neutrino



8.B:9.A

Nuclear Physics 27 (1961) 385—394; © *North-Holland Publishing Co., Amsterdam*

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ON HIGH ENERGY NEUTRINO PHYSICS IN COSMIC RAYS

M. A. MARKOV and I. M. ZHELEZNYKH

P. N. Lebedev Physical Institute, Academy of Sciences, Moscow, USSR

Received 3 January 1961

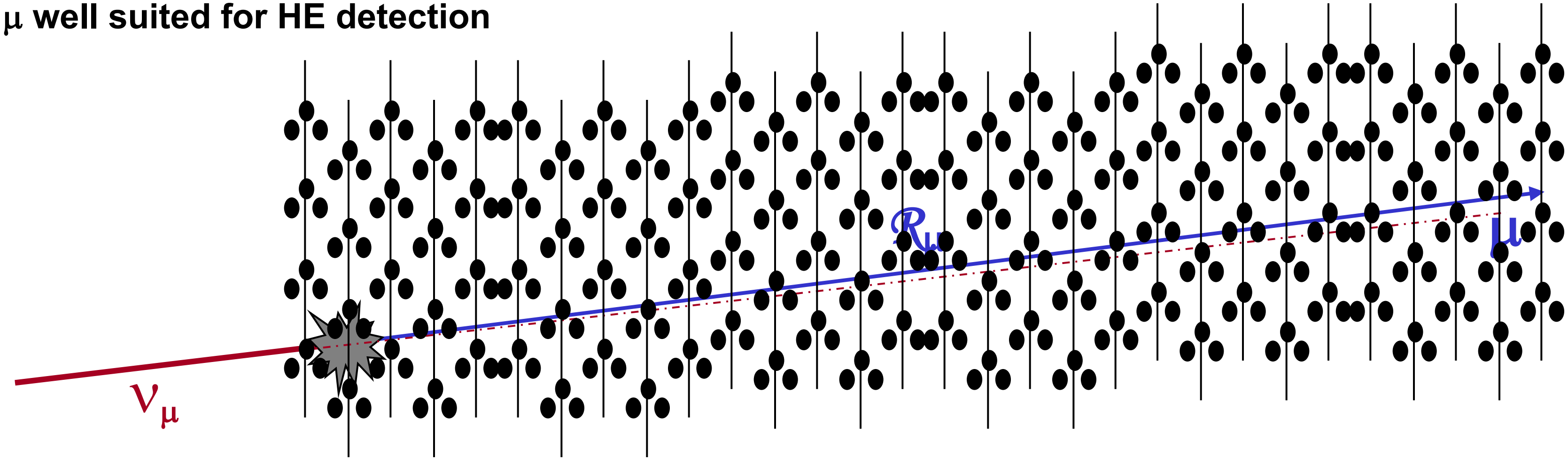
Abstract: The paper is concerned with the problems of detecting high-energy cosmic neutrinos in underground experiments. Various kindred problems of high-energy neutrino physics are discussed, viz. (1) the magnitude of weak-interaction cut-off momentum; (2) muon and electron neutrinos and (3) intermediate boson. It is shown that a reasonable counting rate could be obtained with available equipment.

In Water

R_μ (1 TeV) = 3 km

R_μ (1 PeV) > 10 km

μ well suited for HE detection



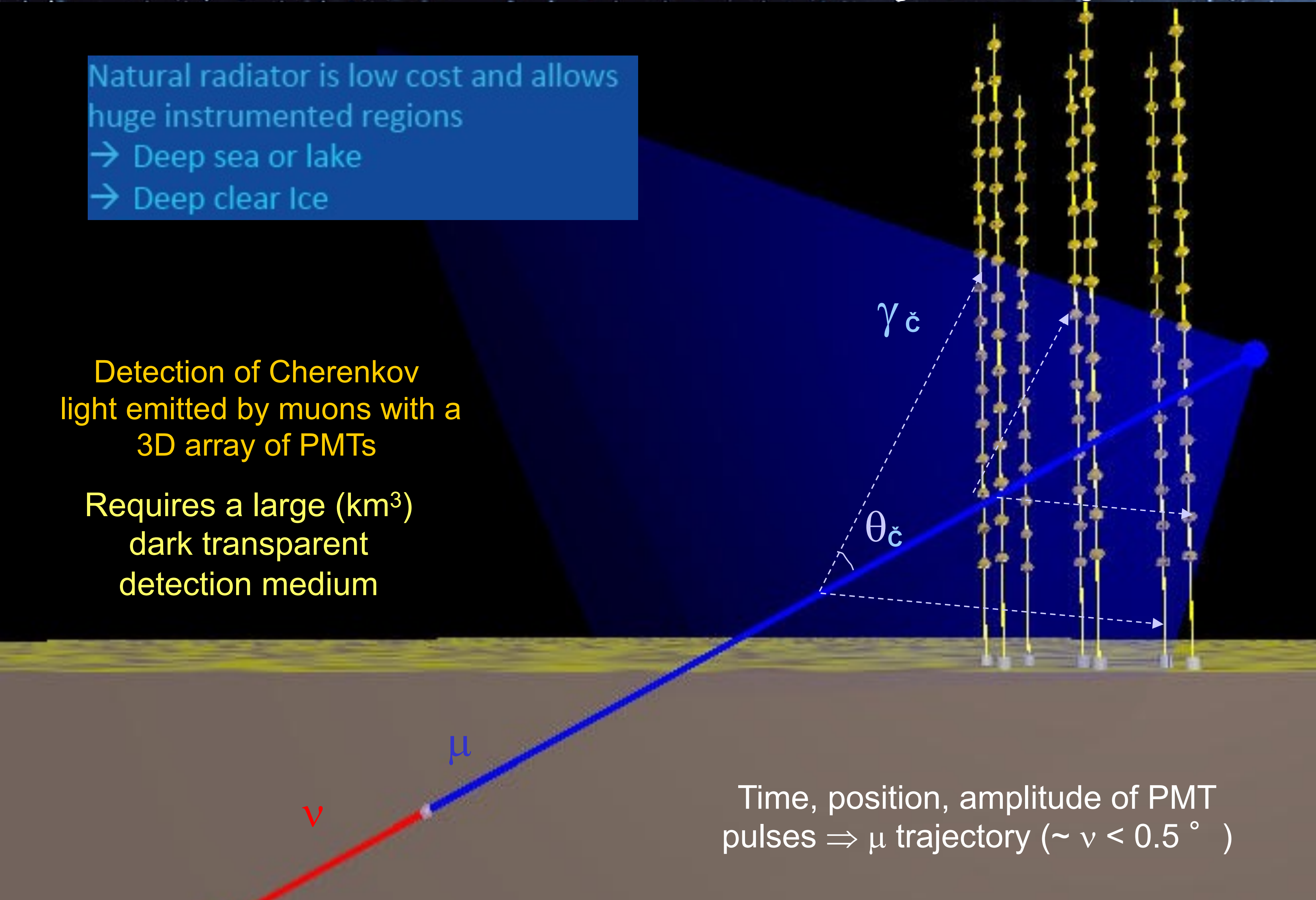
- Detection effective volume increases with E_ν
- Angle between ν and μ decreases with E_ν
- Interaction cross section increases with E_ν

Detection of HE muon neutrinos is favoured

Reconstruction of muon trajectory

Natural radiator is low cost and allows huge instrumented regions

- → Deep sea or lake
- → Deep clear Ice



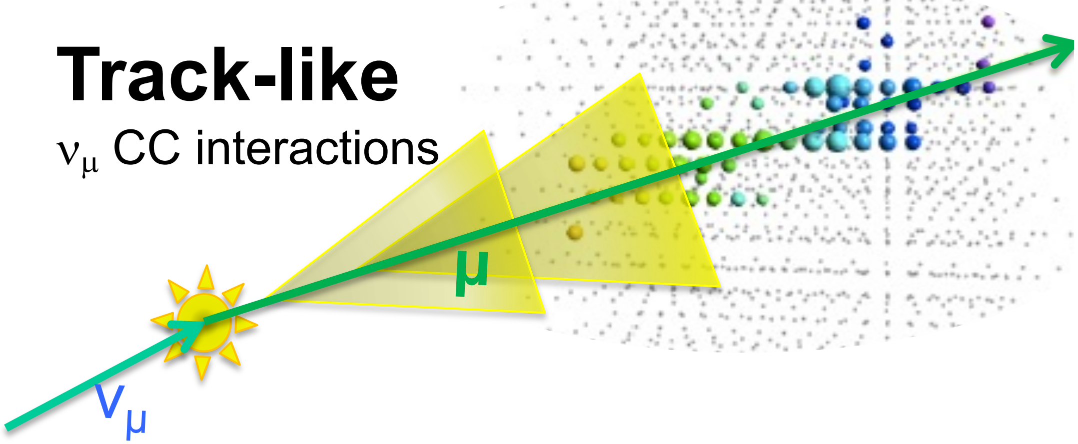
Detection of Cherenkov light emitted by muons with a 3D array of PMTs

Requires a large (km^3) dark transparent detection medium

Time, position, amplitude of PMT pulses ⇒ μ trajectory (~ ν < 0.5 °)

Shower- and track-like events

- **ν_e,ν_τ, neutral currents: <u>showers</u> in the detector**
  - Better energy measurement (energy dissipated in the detector)
- **ν_μ <u>tracks</u> in the detector**
  - Better direction estimate (the muon collinear with the neutrino)

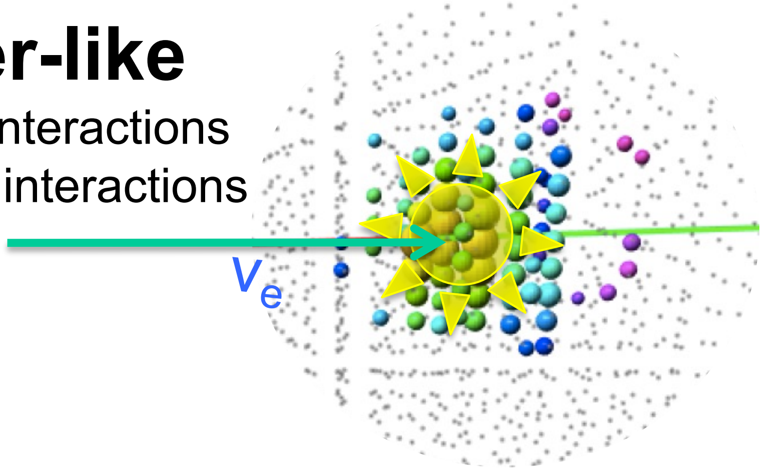


Track-like

ν_μ CC interactions

Shower-like

ν_e , ν_τ CC interactions
ν_X NC interactions



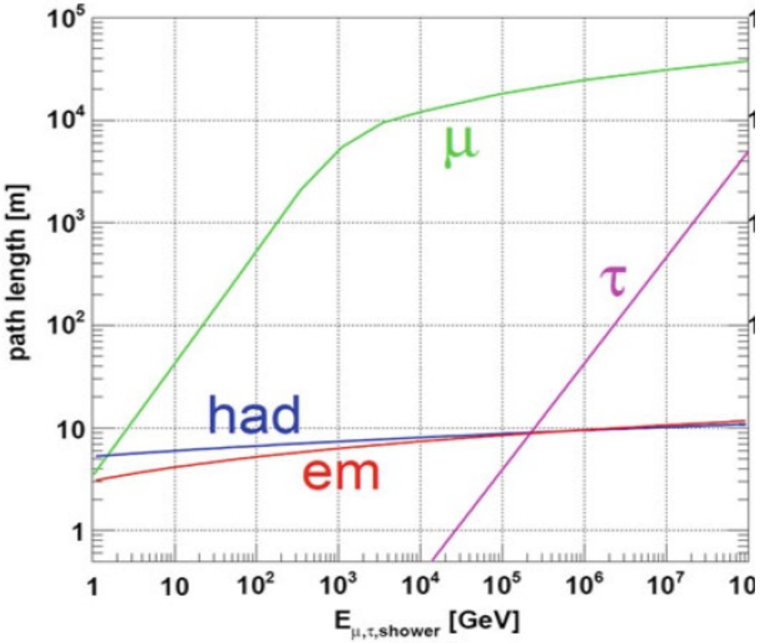
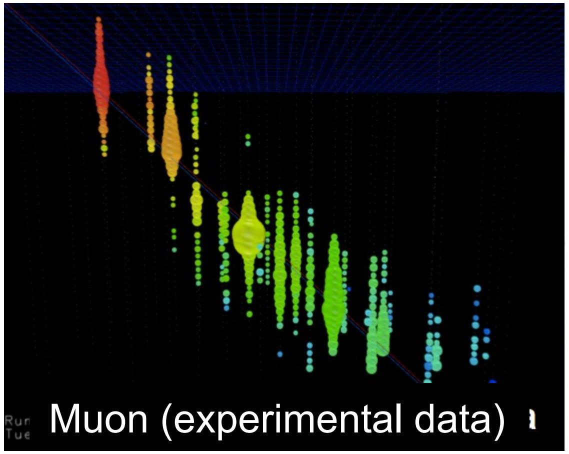


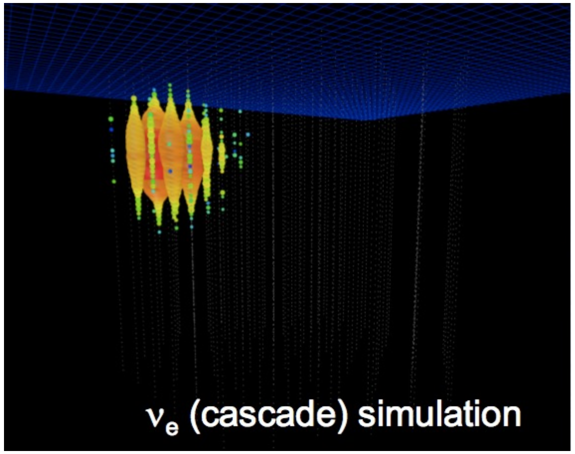
Figure: *Path length (m) of particles produced by different neutrino flavors and interactions in water versus their respective energy.*

Interaction channels and topologies

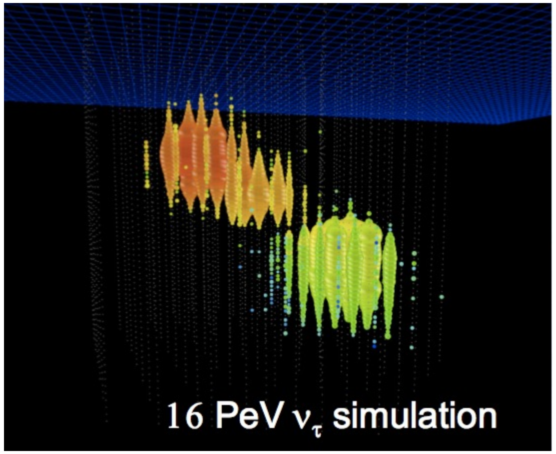
$\nu_e:\nu_\mu:\nu_\tau$ =1:2:0 at source $\xrightarrow{\textit{oscillation}}$ $\nu_e:\nu_\mu:\nu_\tau$ =1:1:1 at Earth !



Muon (experimental data)



ν_e (cascade) simulation



16 PeV ν_τ simulation

Muon neutrino

+ Straight track, points to neutrino source, angular resolution ~1°
- Cosmic-ray muon background

Electron neutrino

+ Good energy resolution
- Cascade, ideally in detector
- Poor angular resolution

Tau neutrino

+ Double bang signature, low background
+ Pointing capability
- Low rate

- Tracks: ~0.5° (ice) ~0.1° (water)
- Cascades/showers: ~10° (ice) ~1° (water)

ν absorption in the Earth

- The interaction length is:

$$\lambda = \frac{1}{n\sigma}\ [cm]$$

- n=number density (nucleons) that depends on the mass M, density of the material

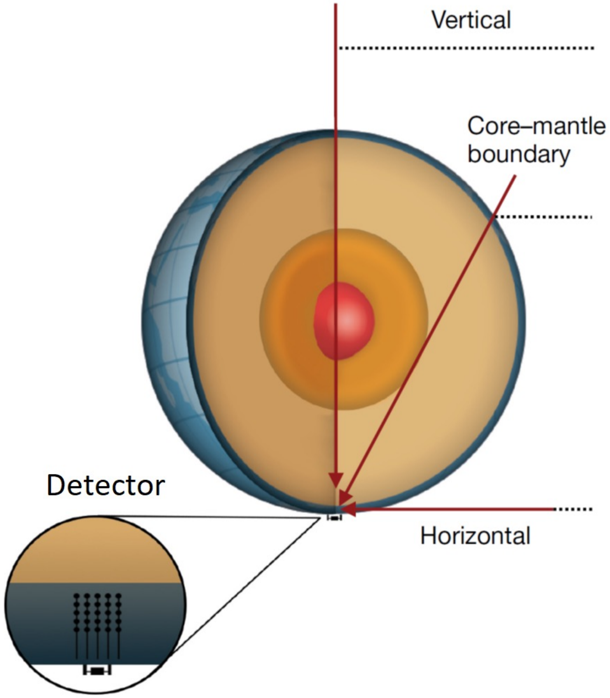
$$n = \frac{N_A}{M}\rho\ \ [cm^{-3}]$$

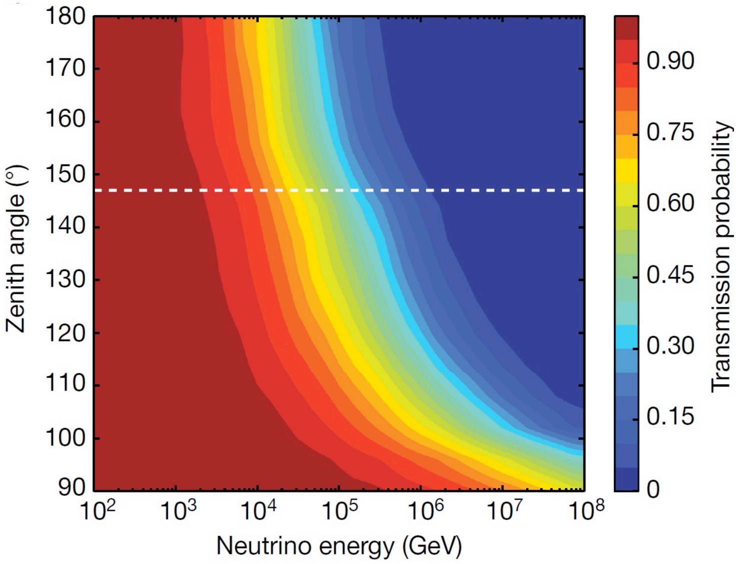
- Due to the interaction length, the surviving fraction of particles is:

$$N(x) = N_o e^{-x/\lambda}$$

  - A γ-ray of 1 TeV has an interaction length (in water) λ = 42 cm;
  - a ν of 1 TeV has λ~ $2\text{x}10^9$ m.

- The increase of the σ_ν with energy is such that the Earth absorption becomes not negligible at E_ν > 100 TeV.



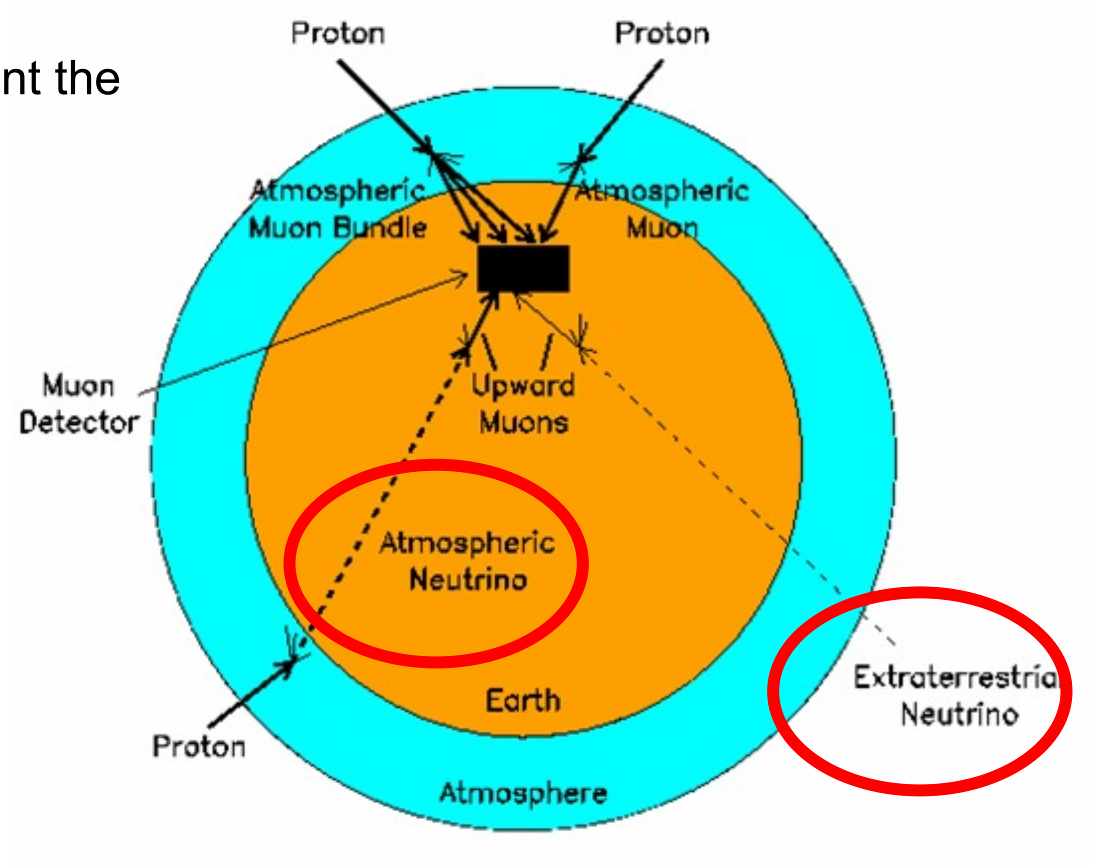


The background in neutrino telescopes

- **Down- and up-going hemisphere**: atmospheric neutrinos
- **Downgoing hemisphere**: atmospheric μ's dominate by many order of magnitude the muons induced by neutrinos
- Only upward-going particles are candidate for extraterrestrial ν .

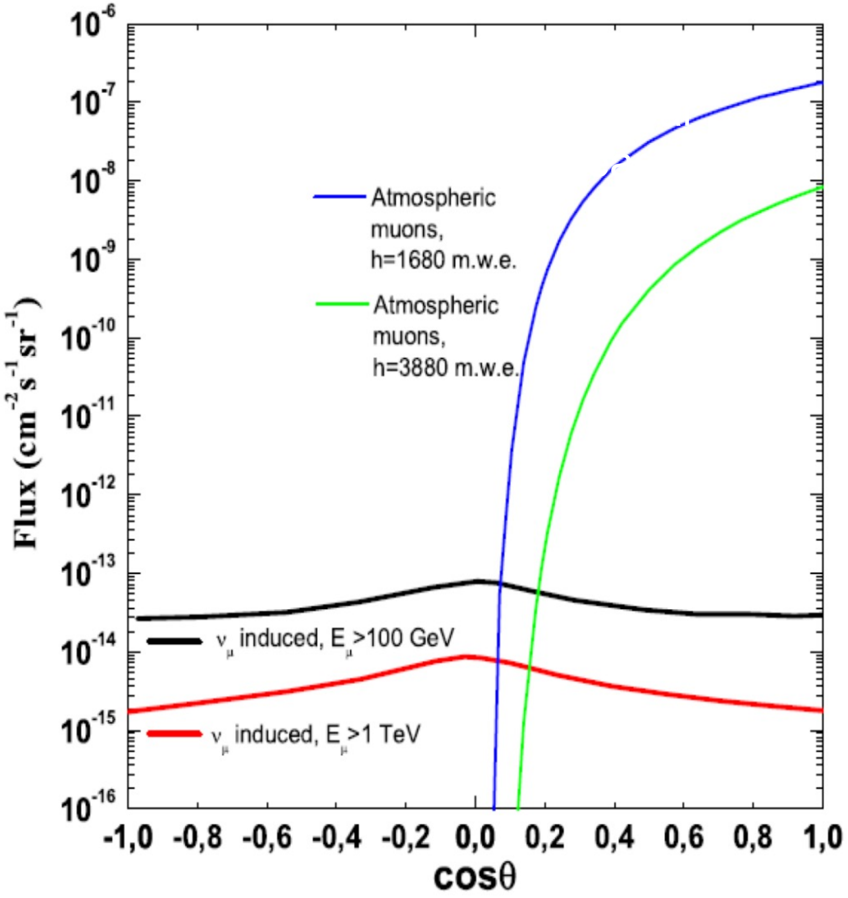
- Atmospheric neutrinos represent the irreducible background for nu-telescopes

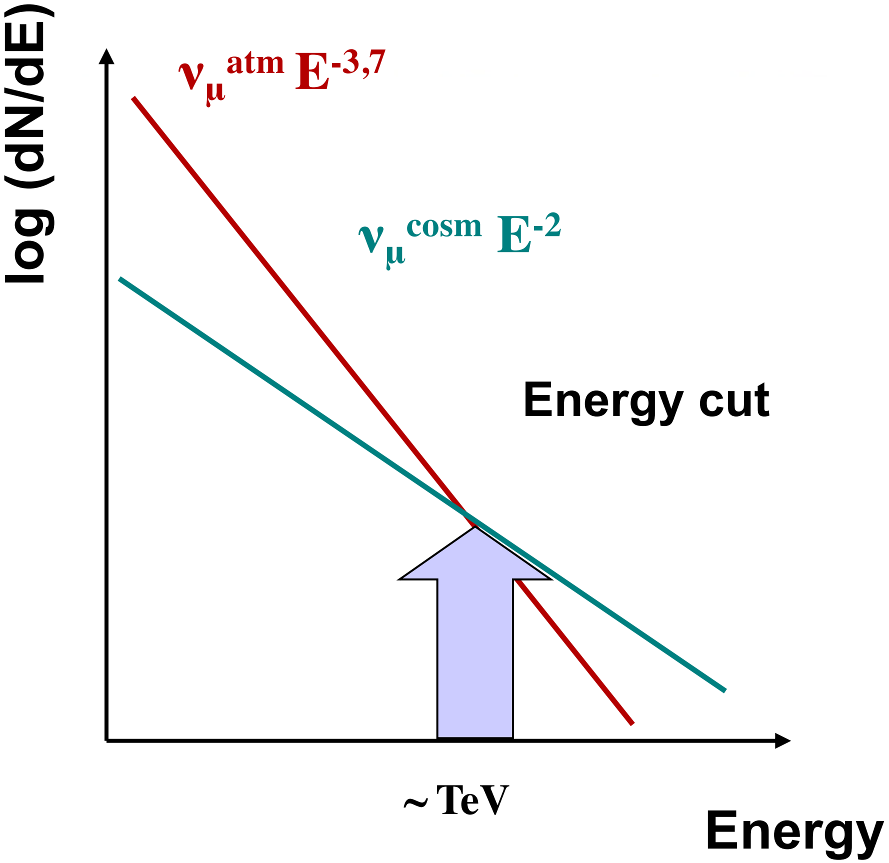
Upward-going muons (or horizontal muons) if correctly reconstructed ARE neutrino-induced!



Atmospheric background vs cosmic ν’s

Atmospheric muons: shield detector & define signal as upward muons





Atmospheric neutrinos: search for

- An excess at High Energy
- Anisotropies
- Time / space coincidence with other cosmic probes

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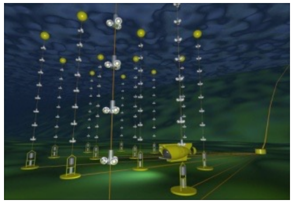
Historical aspects

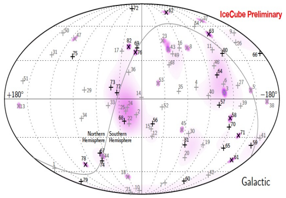
Cosmic neutrino sources



Neutrino telescope

Detection principles

Current telescopes



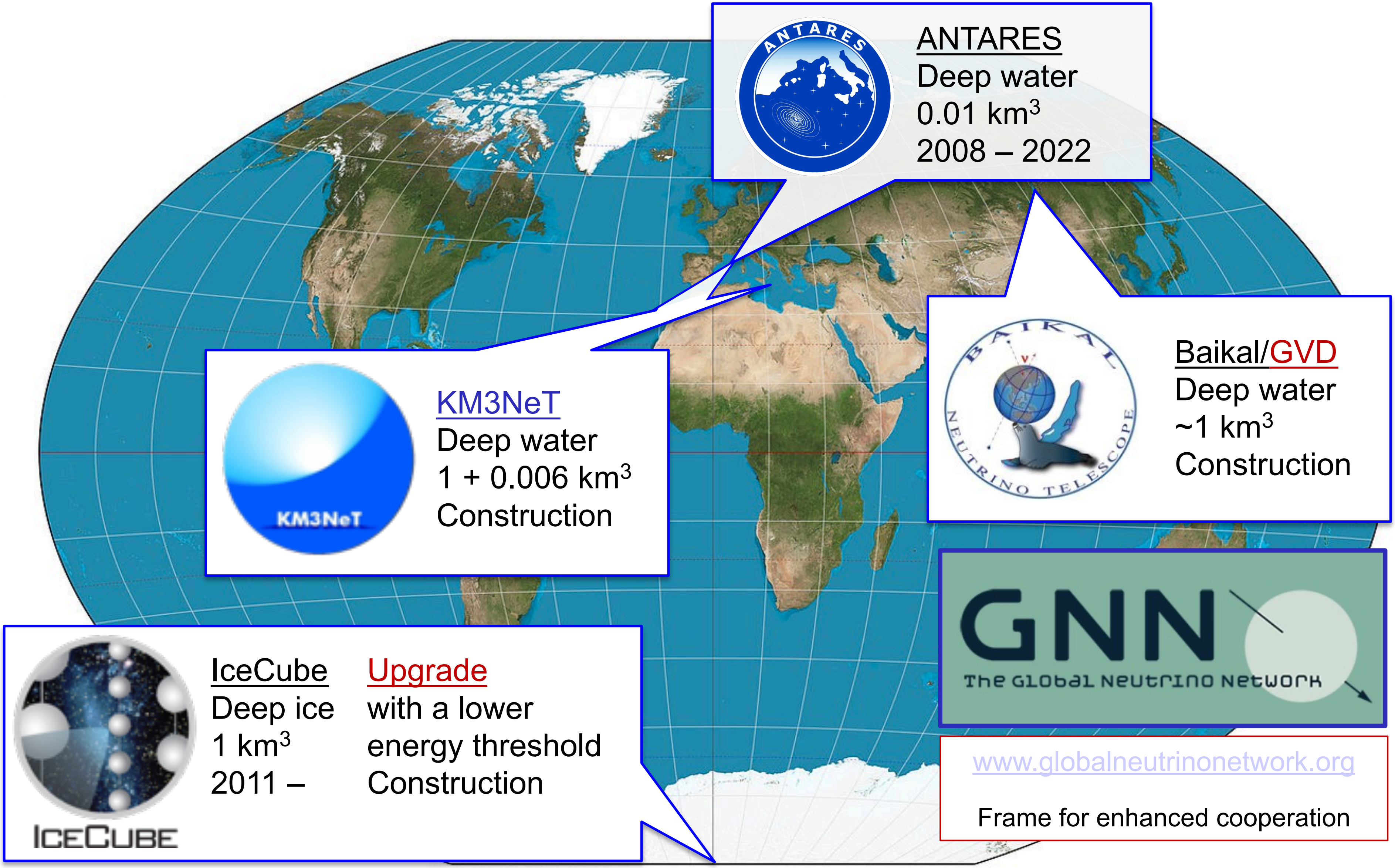
Selected results

Diffuse Flux, point sources

Multi-messenger search

ORCA prospects

The neutrino telescope world map 2022



ANTARES
Deep water
0.01 km^3
2008 – 2022

KM3NeT
Deep water
1 + 0.006 km^3
Construction

Baikal/GVD
Deep water
~1 km^3
Construction

IceCube
Deep ice
1 km^3
2011 –

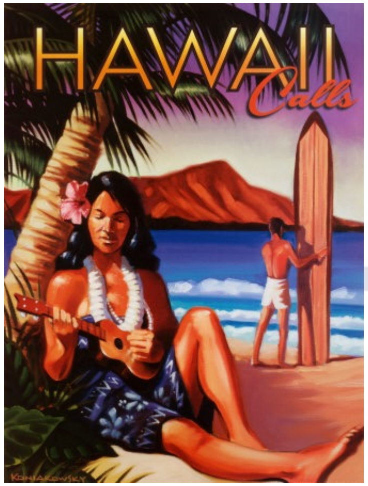
Upgrade
with a lower
energy threshold
Construction

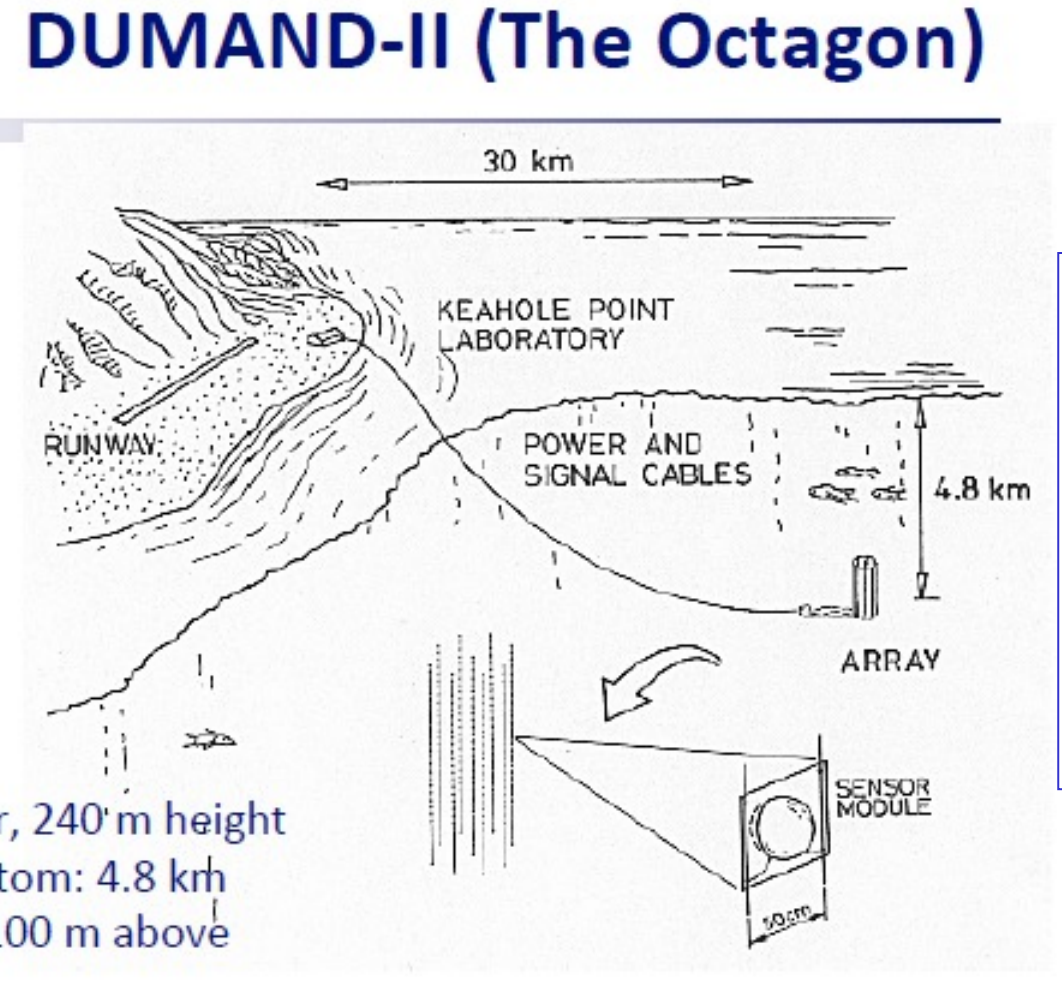
GNN
The Global Neutrino Network

www.globalneutrinonetwork.org

Frame for enhanced cooperation

Years 80’s : the first project





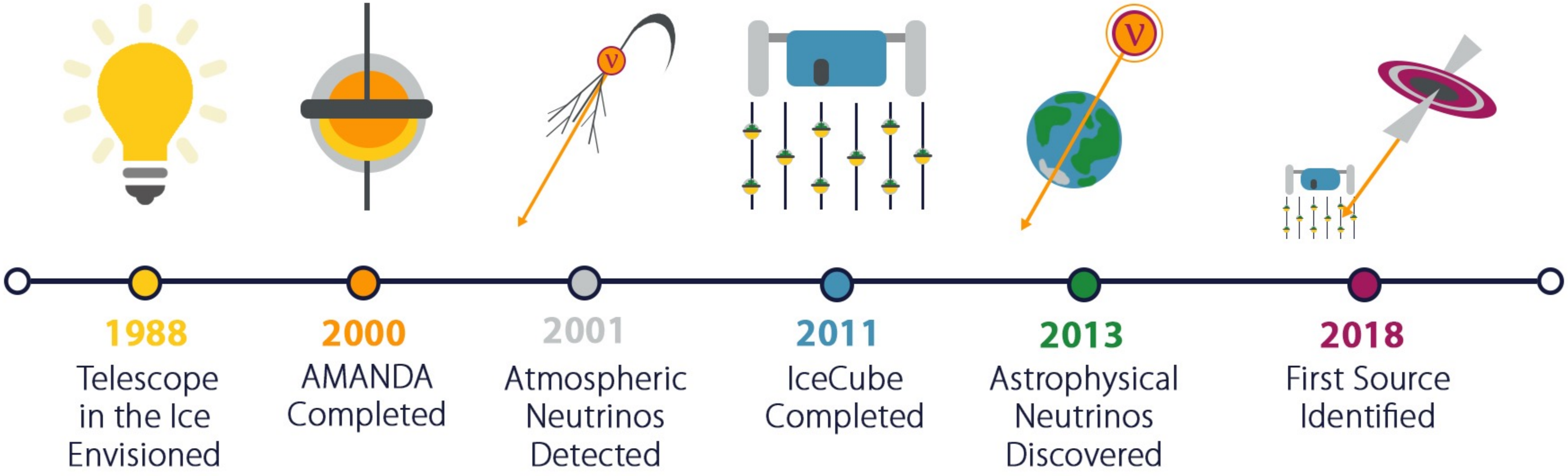
DUMAND-II (The Octagon)

- 9 strings
- 216 OMs
- 100 diameter, 240 m height
- Depth of bottom: 4.8 km
- Lowest OM 100 m above bottom

“At first, when we talked about DUMAND our accelerator friends laughed and said we were crazy. Now they ask why have you not got it operating yet !”
J G Learned (1992)

Project canceled in 1995

Historical steps in Antarctica



1988 Telescope in the Ice Envisioned

2000 AMANDA Completed

2001 Atmospheric Neutrinos Detected

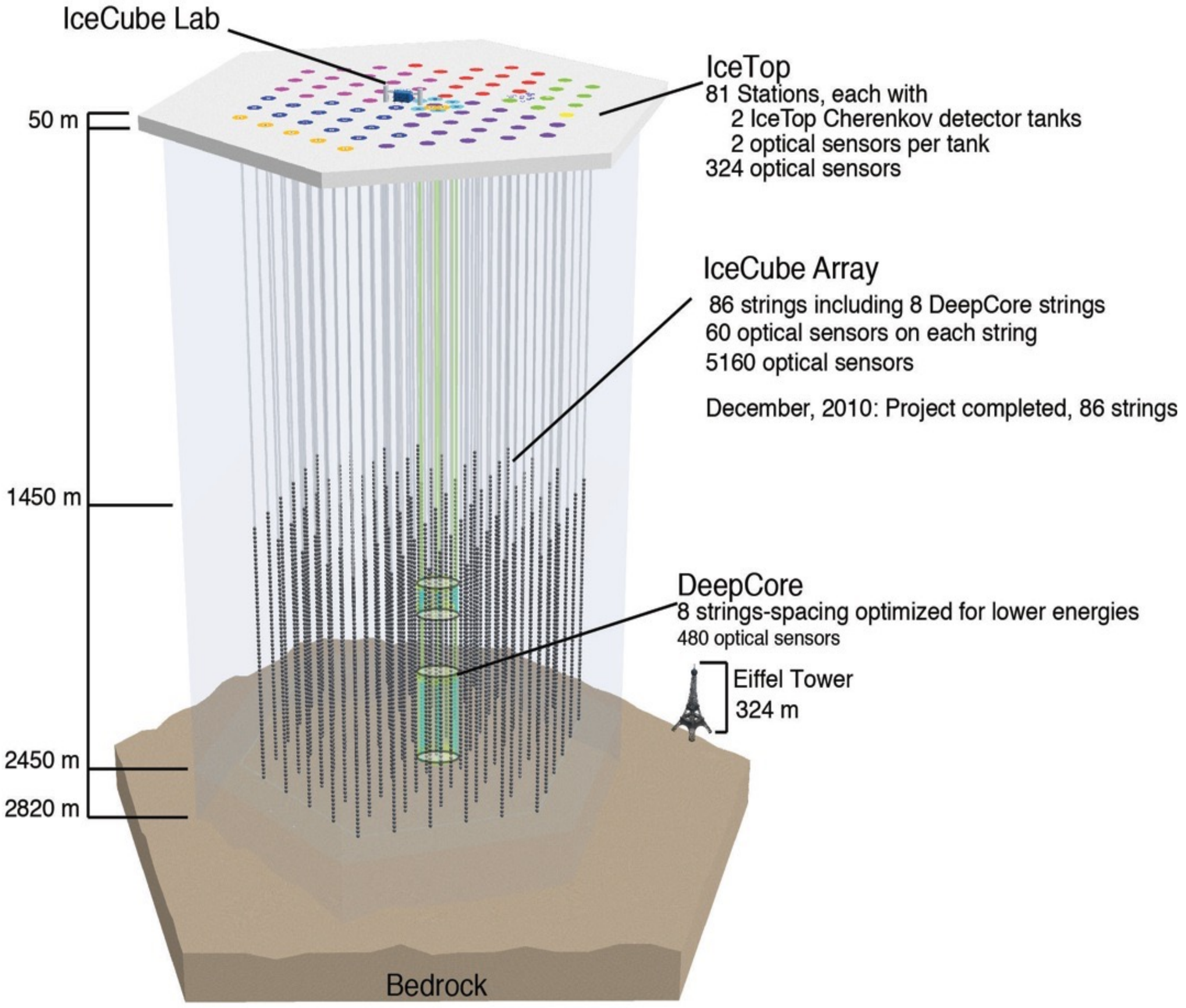
2011 IceCube Completed

2013 Astrophysical Neutrinos Discovered

2018 First Source Identified

IceCube : the biggest NT in the world

Completed since December 2010.

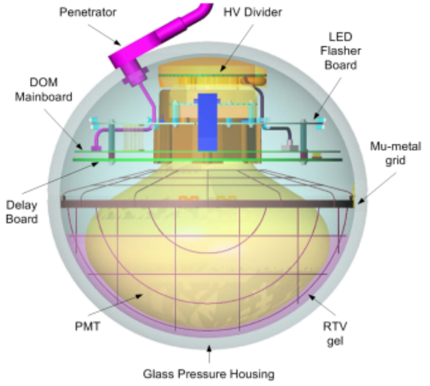


IceTop
81 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
324 optical sensors

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

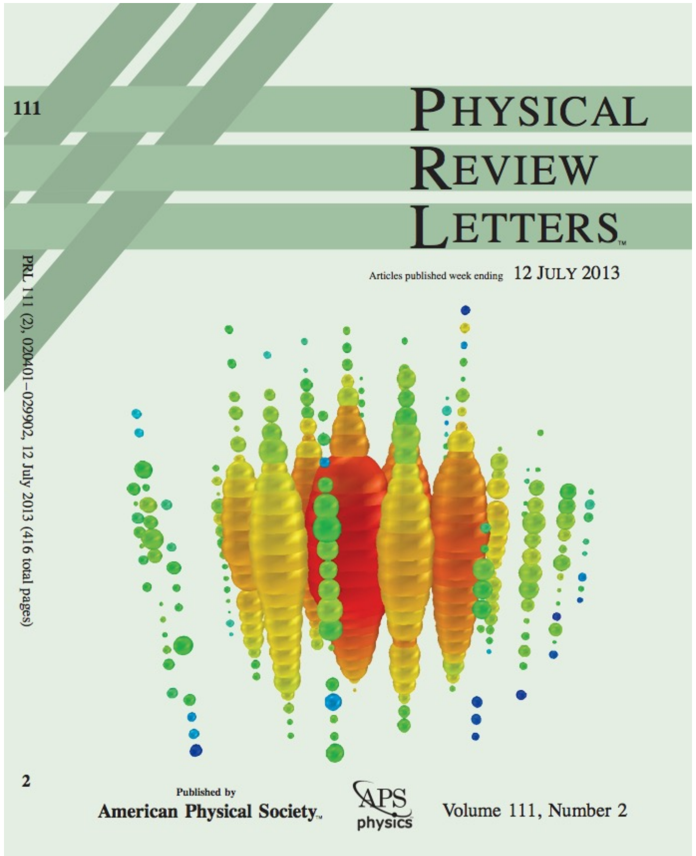
December, 2010: Project completed, 86 strings

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



Discovery of the diffuse astrophysical

2013


111

PHYSICAL
REVIEW
LETTERS

Articles published week ending 12 JULY 2013

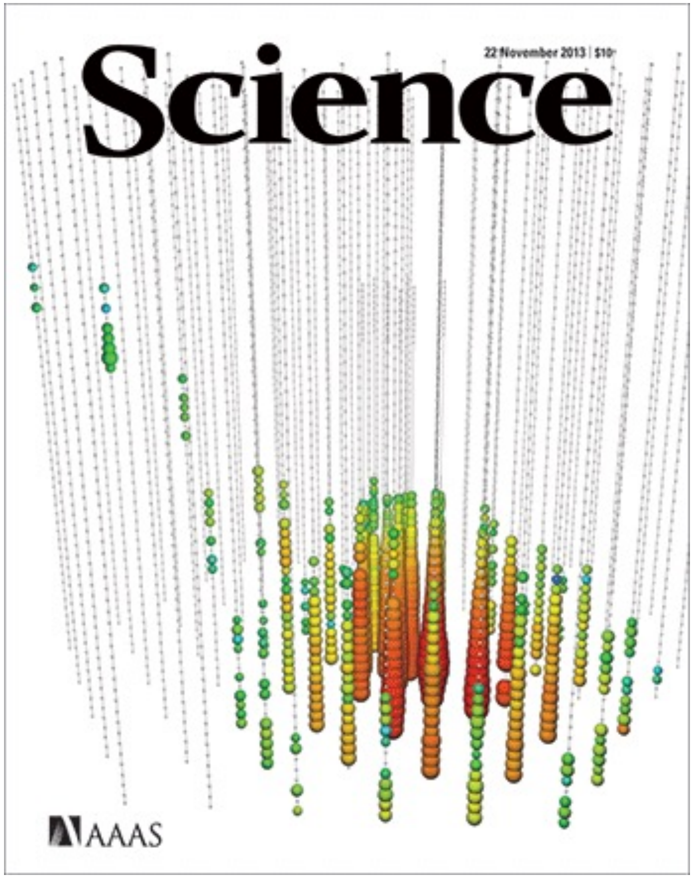
PRL 111 (2), 020401–029902, 12 July 2013 (416 total pages)

2

Published by
American Physical Society

APS physics

Volume 111, Number 2


22 November 2013 | $10

Science

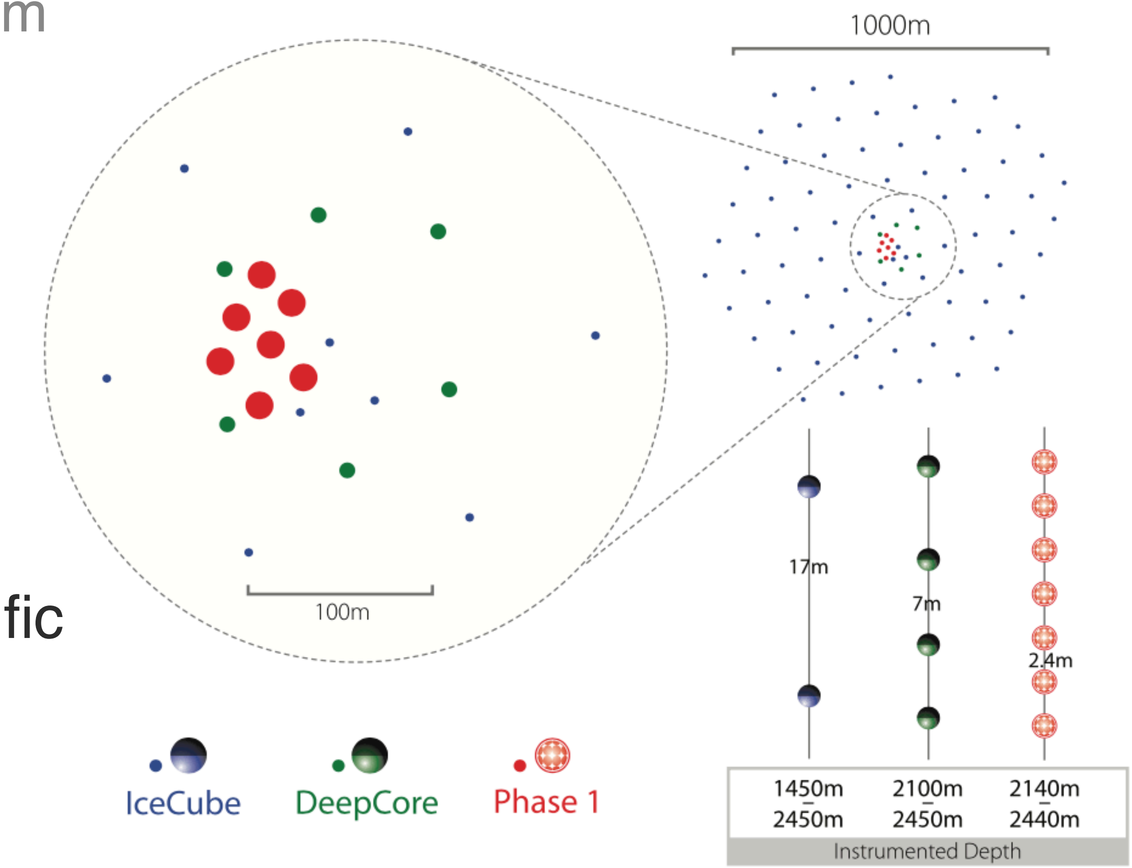
AAAS

IceCube, PRL 111, 021103 (2013)
IceCube, PRL 113, 101101 (2014)

IceCube, Science 342, 1242856 (2013)
IceCube, PRD 104, 022002 (2021)

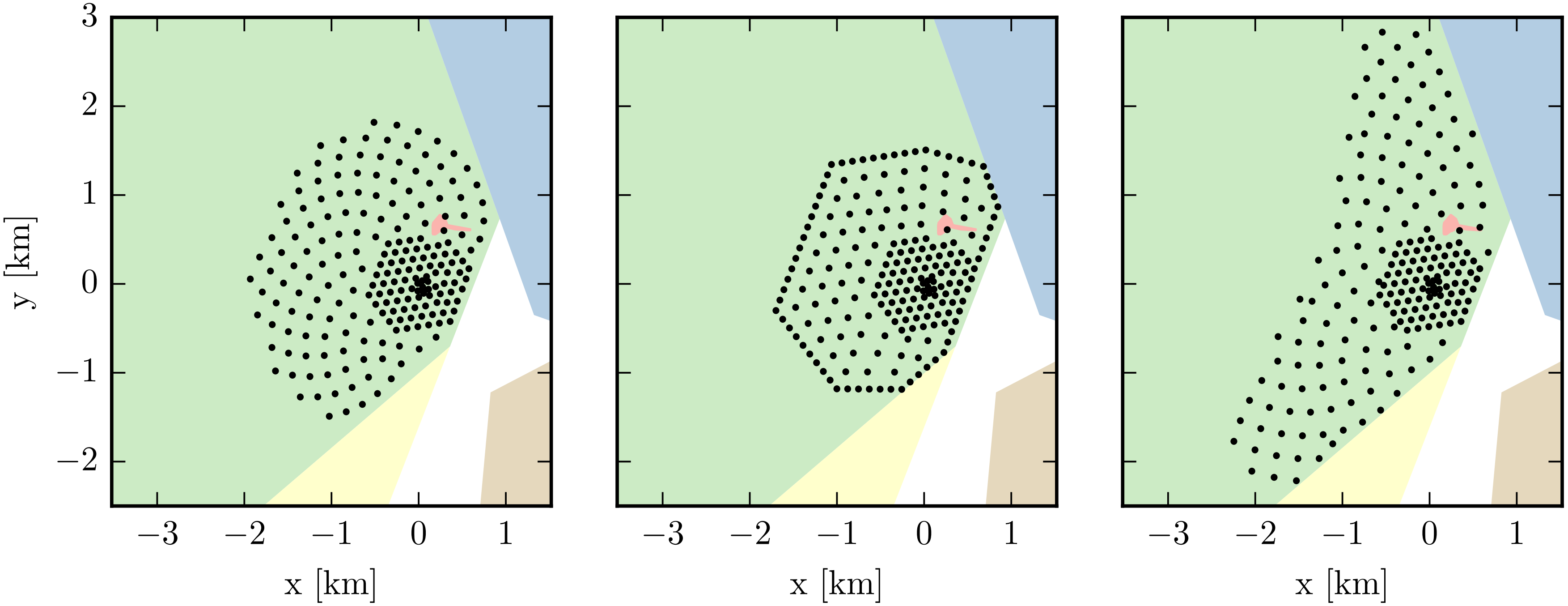
IceCube Upgrade (first step toward Gen 2):

- Seven new strings of multi-PMT mDOMs in the DeepCore region
  - Inter-string spacing of ~22 m
- New calibration devices, incorporating lessons learned from a decade of IceCube calibration efforts
- Enhance IceCube's scientific capabilities at both high and low energy



Target tau neutrino oscillation physics

IceCube Gen 2: the next generation



- High energy extension: Instrument ~10 km^3 (sparsely with ~120 new strings) to increase sensitivity to high energy (0.1-10 PeV) muon and cascade events
- Surface array for increased southern sky sensitivity and cosmic-ray physics
- Identify neutrino sources and study them with multiple messengers
- Dense inner core for neutrino physics including mass hierarchy
- Radio Neutrino Observatory for 10^{18} eV neutrinos

IceCube, 1412.5106 (LOI)
IceCube, 1510.05228 (ICRC)

Why the Mediterranean Sea?

- Long (homogeneous) scattering length

  Good pointing accuracy

- Deep sites: 2500→5000m

  Shielding from downgoing muons

- Logistically attractive

  Close to shore (deployment / repair)

- Complementarity to IceCube South Pole

  Excellent view of Galaxy

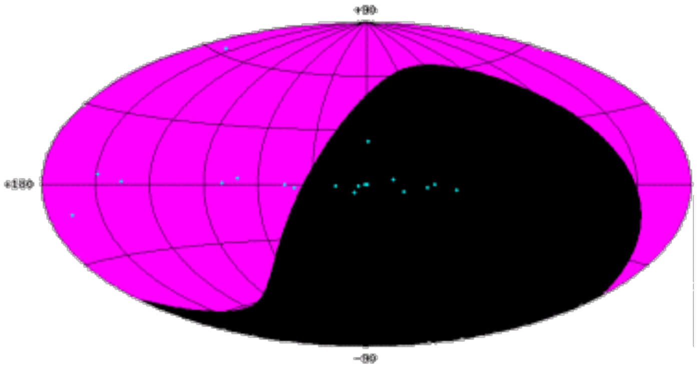
- Mild Latitude

  On/off studies → Background control

- K40 optical background

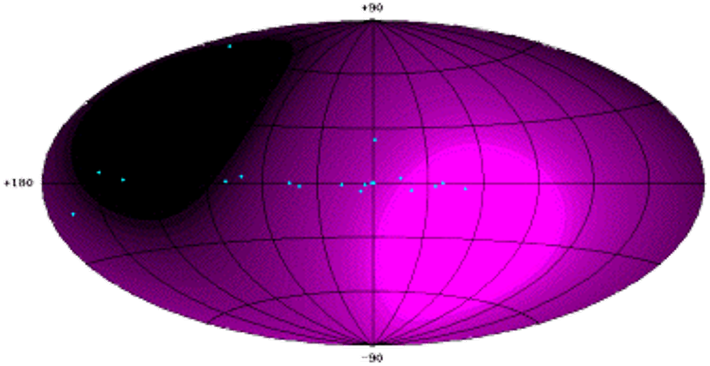
  Useful calibration, but requires causality filters

South Pole visible sky

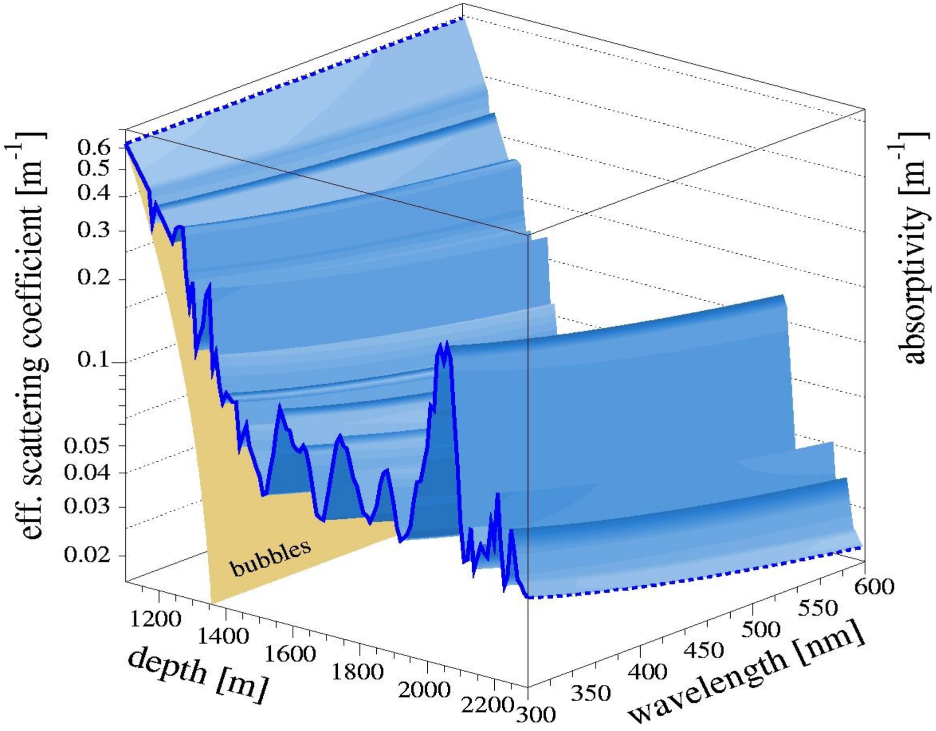


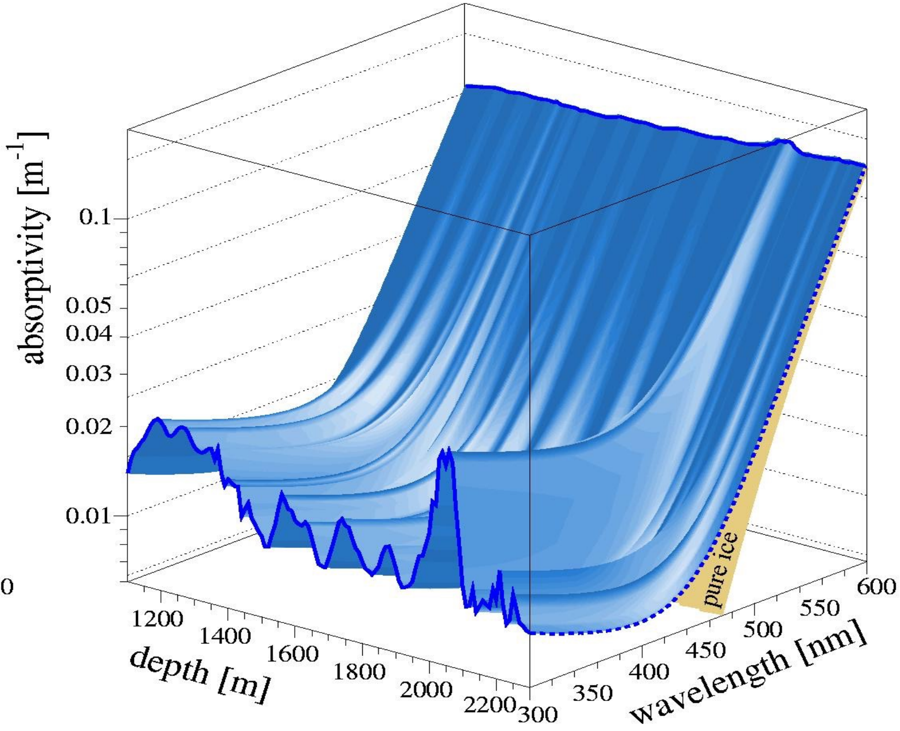
Most of the HESS TeV Sources visible by Northern NT

Mediterranean visible sky



The Ice optics





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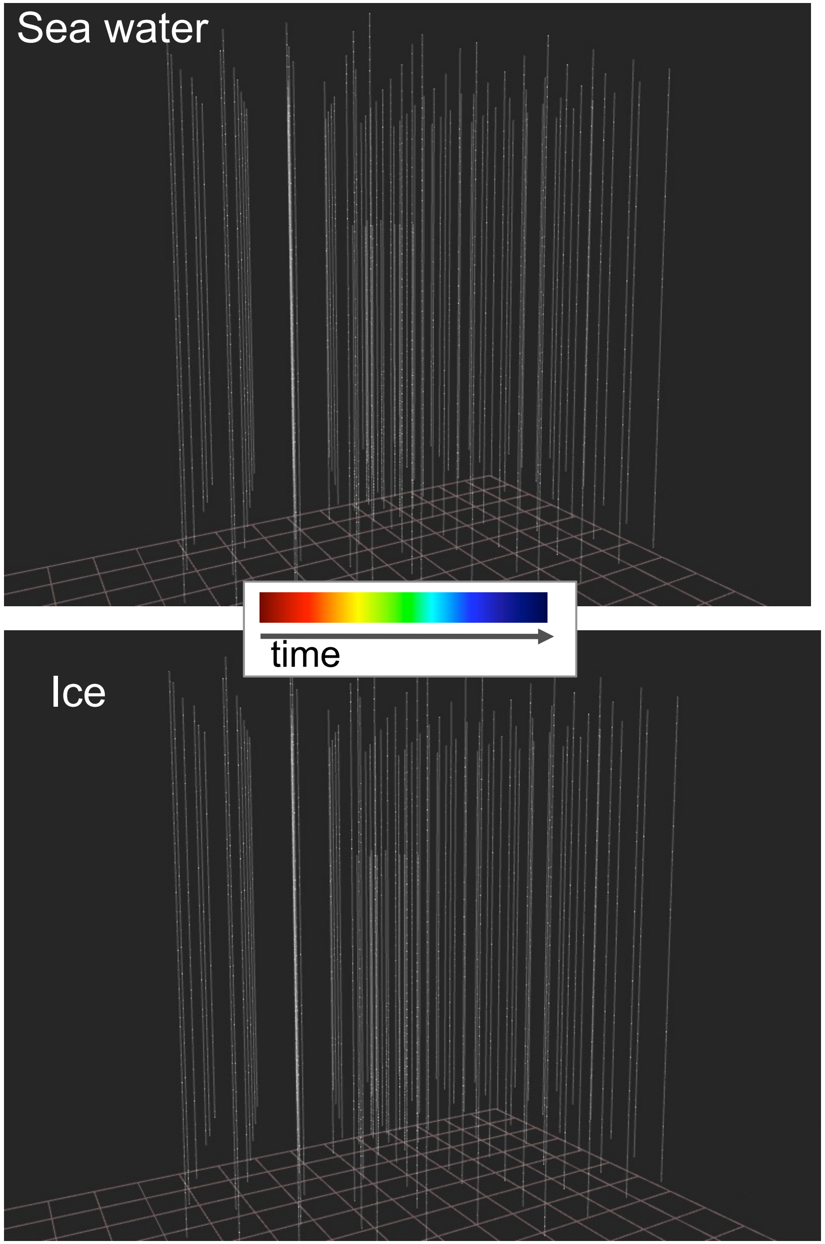
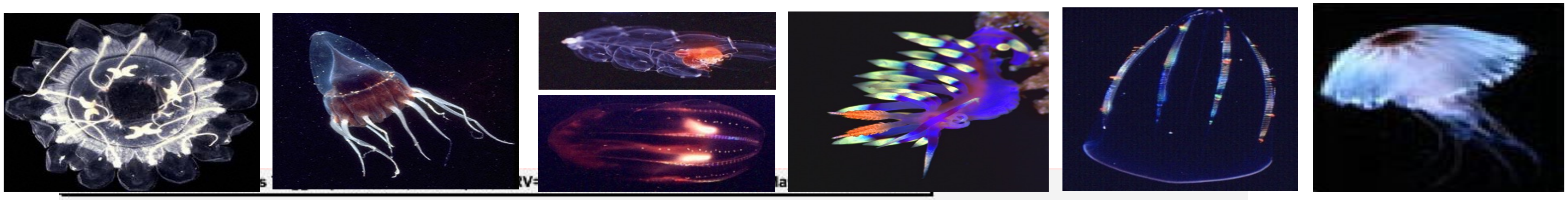
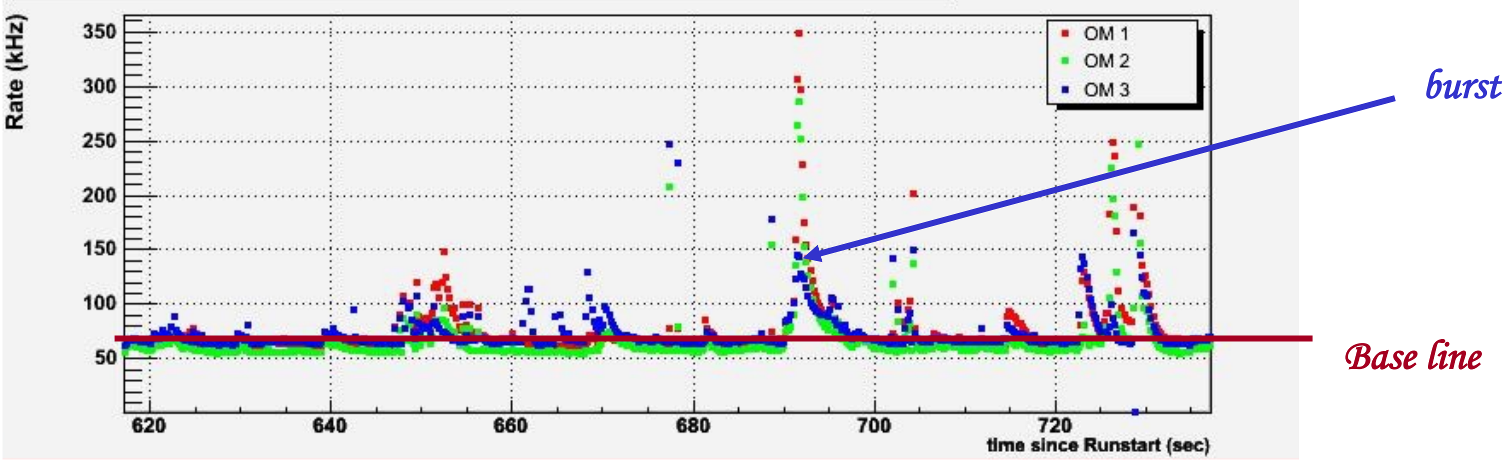


ANTARES Optical background

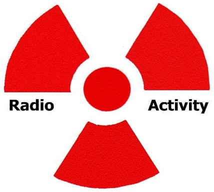




Base line

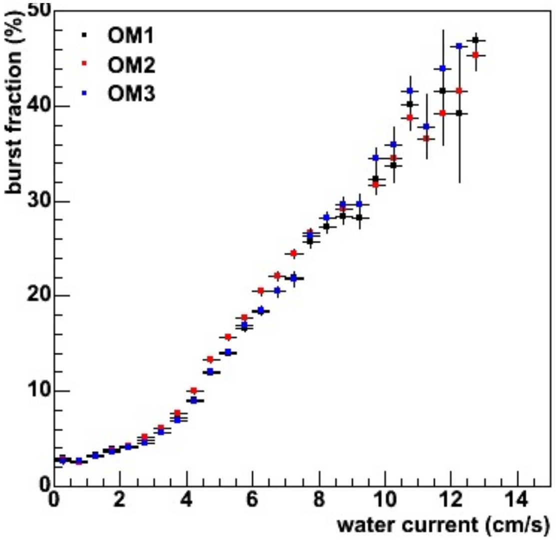
^{40}K

Bio-luminescence

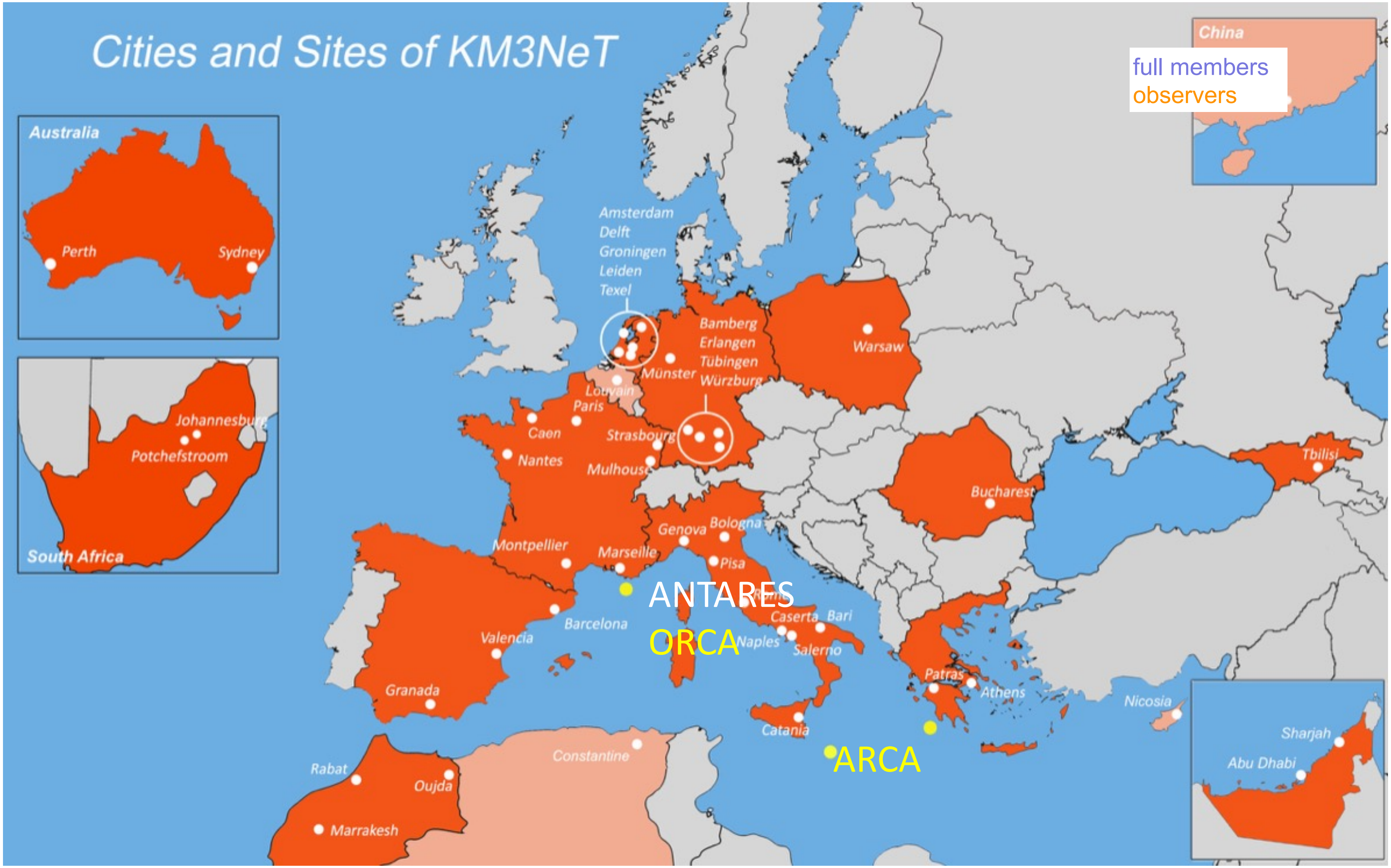


Bio-luminescence burst:

photo-emitter animals



ANTARES & KM3NeT

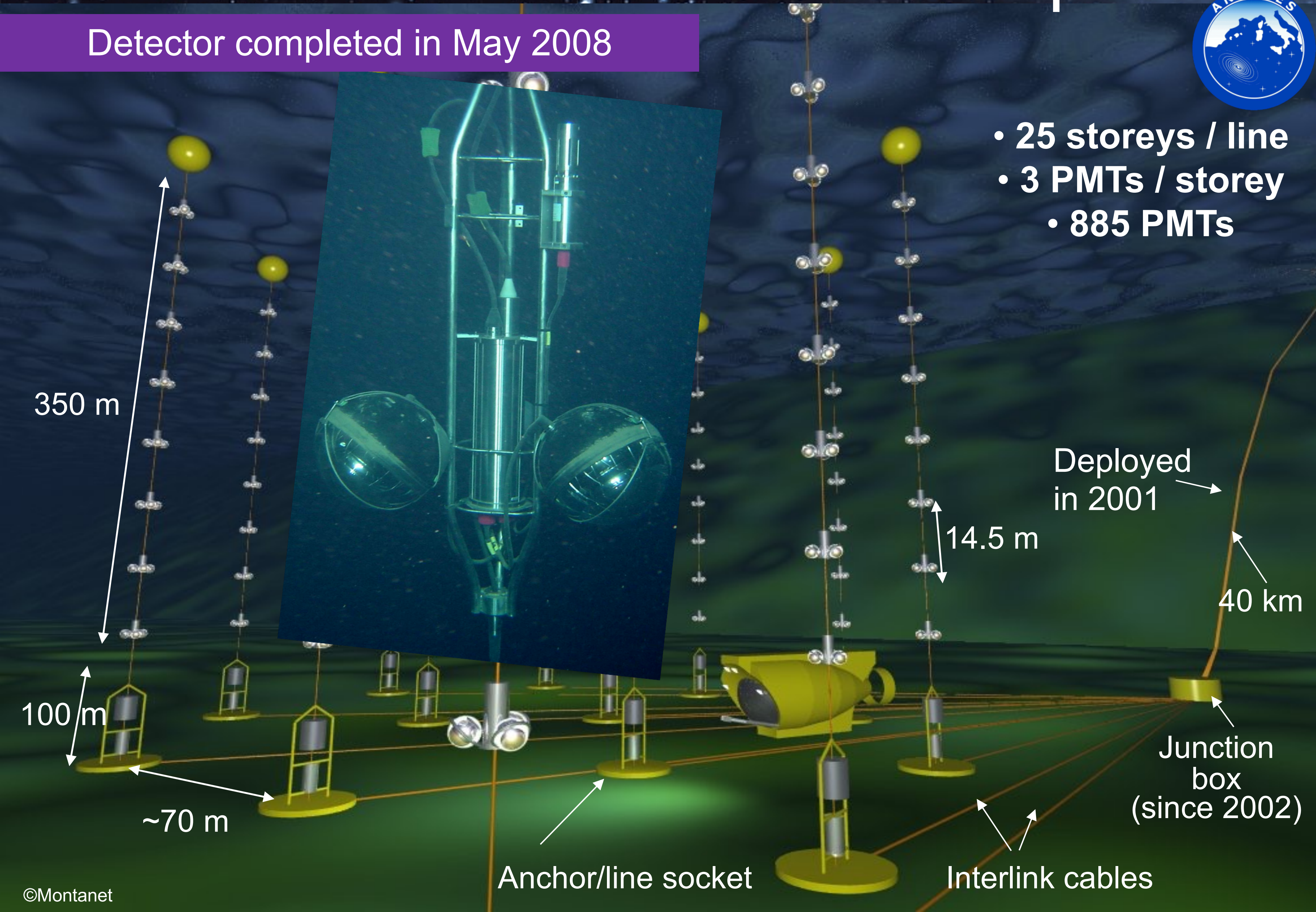


Toulon
M.Pacha
Antares
Electro-optical
Cable of
40 km
42 50'N, 6 10'E
Google
© 2008 Cnes/Spot Image
Image © 2008 DigitalGlobe
Image NASA
N

The ANTARES neutrino telescope

Detector completed in May 2008

- **25 storeys / line**
- **3 PMTs / storey**
- **885 PMTs**



350 m

100 m

~70 m

14.5 m

Deployed in 2001

40 km

Junction box (since 2002)

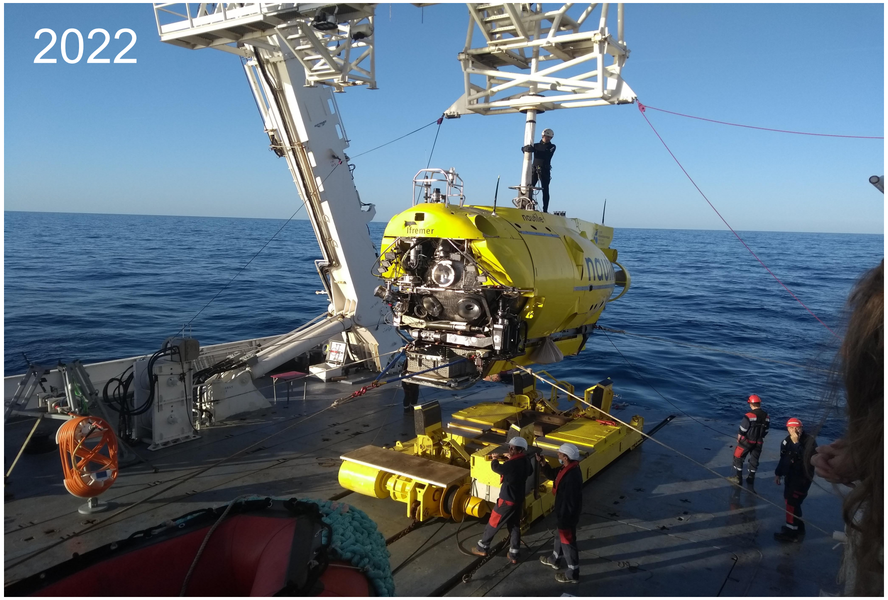
Anchor/line socket

Interlink cables

©Montanet

ANTARES 2001-2022

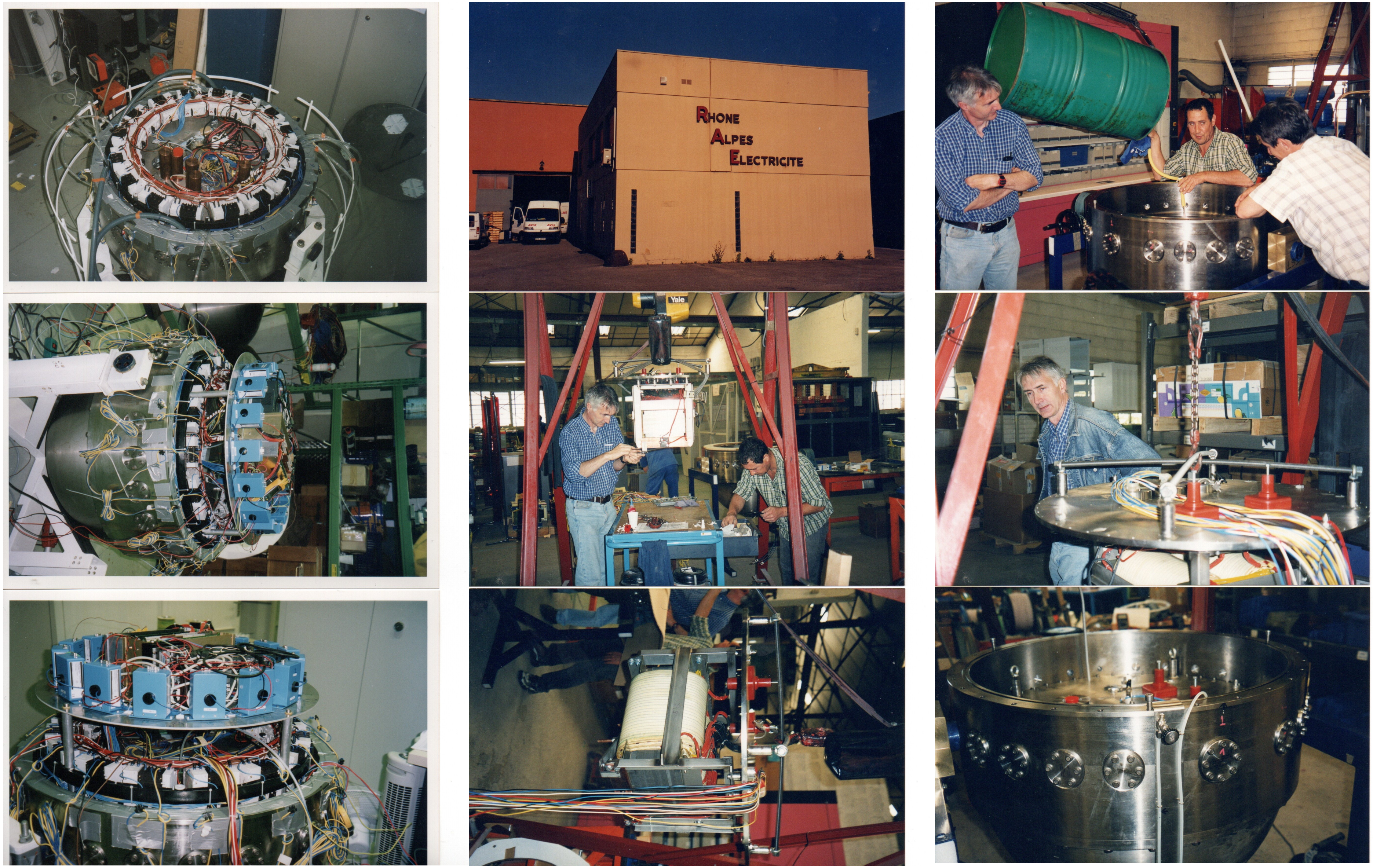

2001


2022

2001 Main Electro-Optical Cable
2002 Junction box
2003 Prototype Sector Line
2005 Mini Instrumentation Line with OMs
2006 First complete detector line
2008 Detector with 12 lines completed
2016 Running (almost) without common funds
2022 Data taking terminated & Recovery

Main Electro-Optical Cable - 2001

Junction Box 2002 – Construction



Junction Box 2002 – Deployment

Junction Box 2002

Worked reliably for 20 years

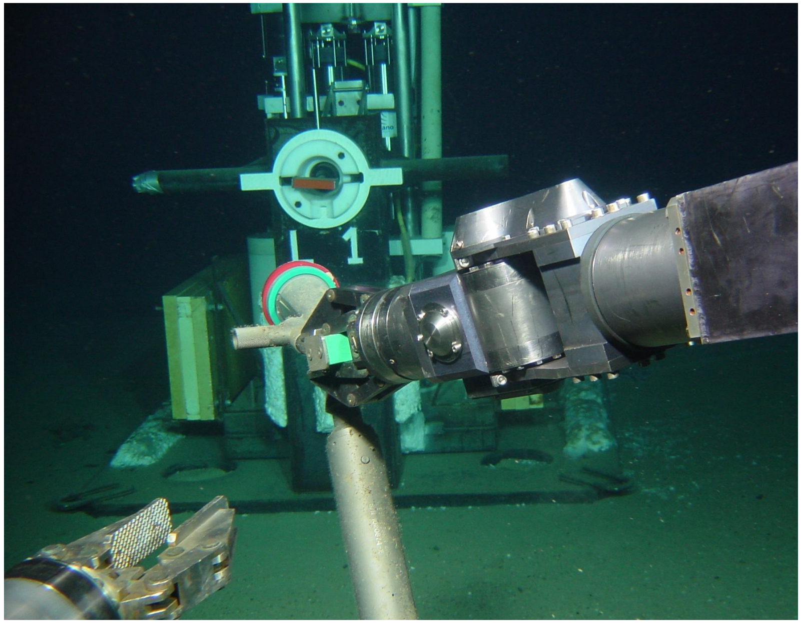
No failure, no repair needed

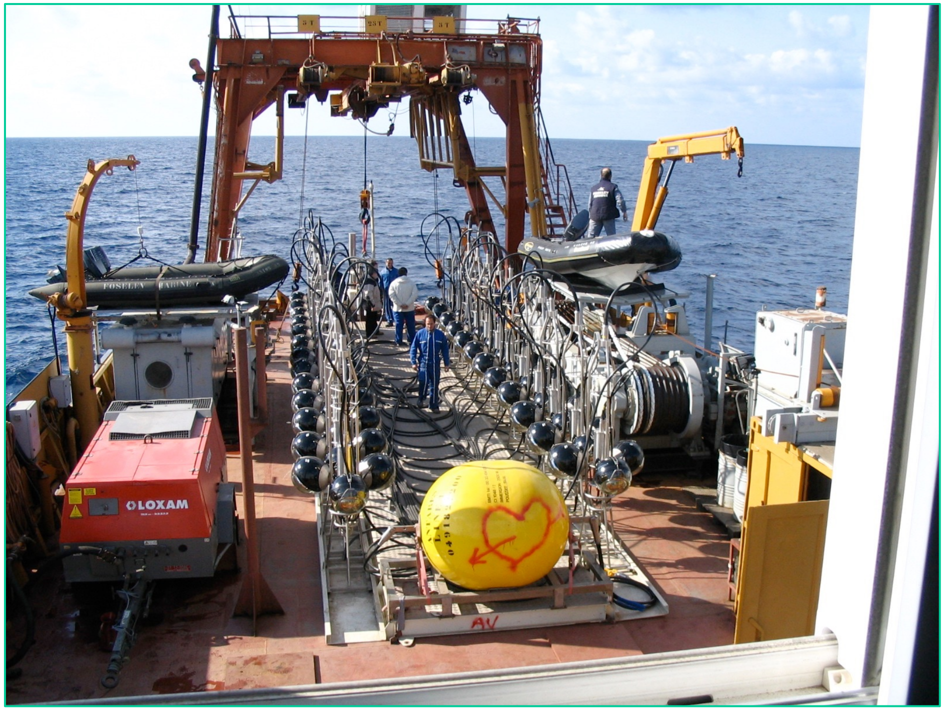
Waiting for recovery and potential second life?

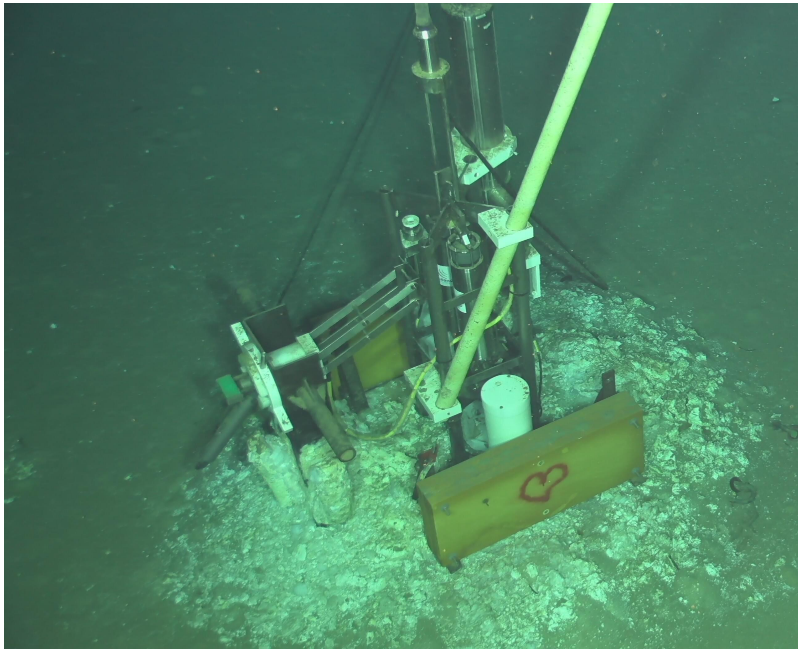
First complete detector line - 2006

First complete detector line – 2006 - 2022

Deployment 14/02/2006
Connection March 2006
Disconnection February 2022







Recovery completed

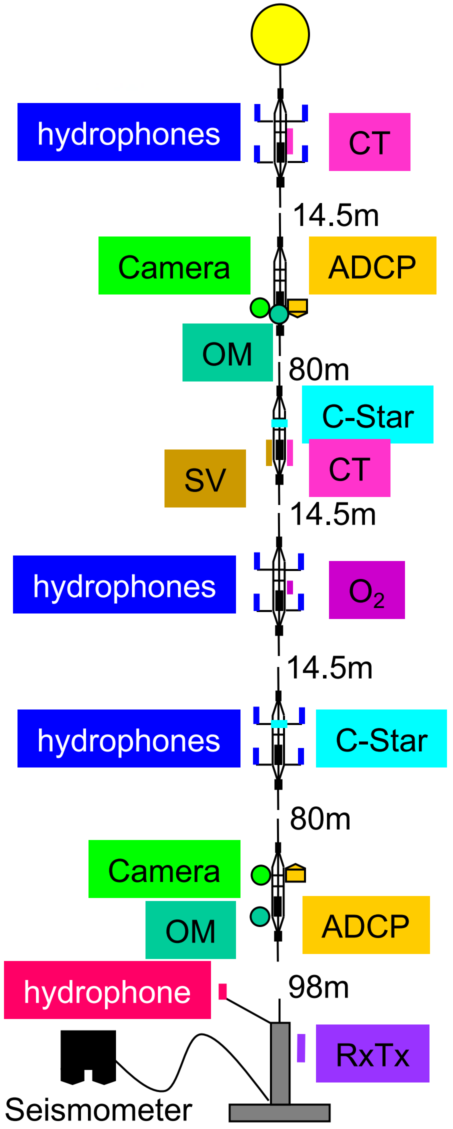
Picture from dismantling operation

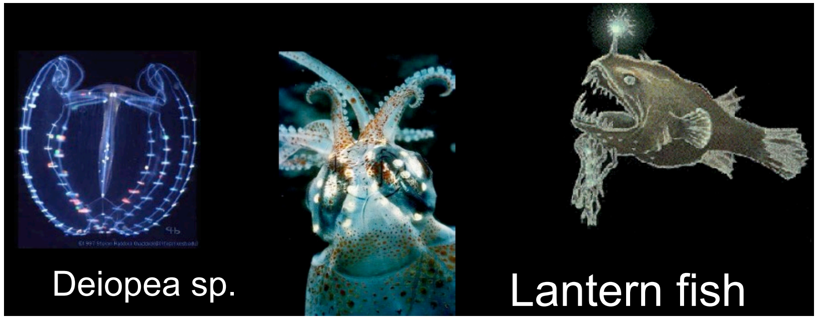
Recovery completed

Including Line 1, 16 years after…

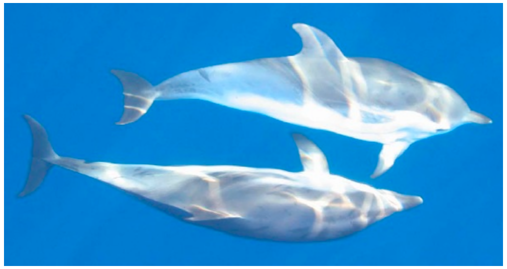
Sea science and Earthquakes

Instrumentation Line

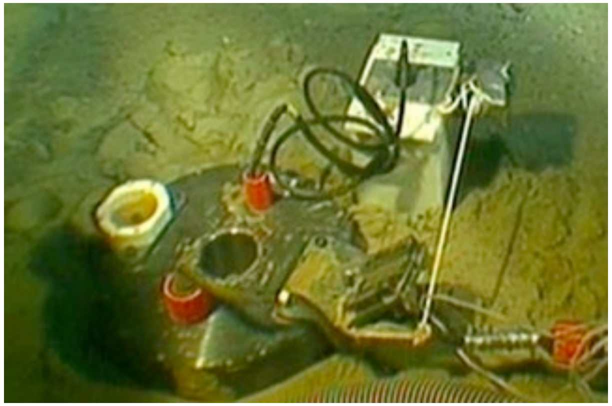




Acoustic noises



seismometer



Video-monitoring

ANTARES : a multidisciplinary observatory

Deep-Sea Cabled observatories

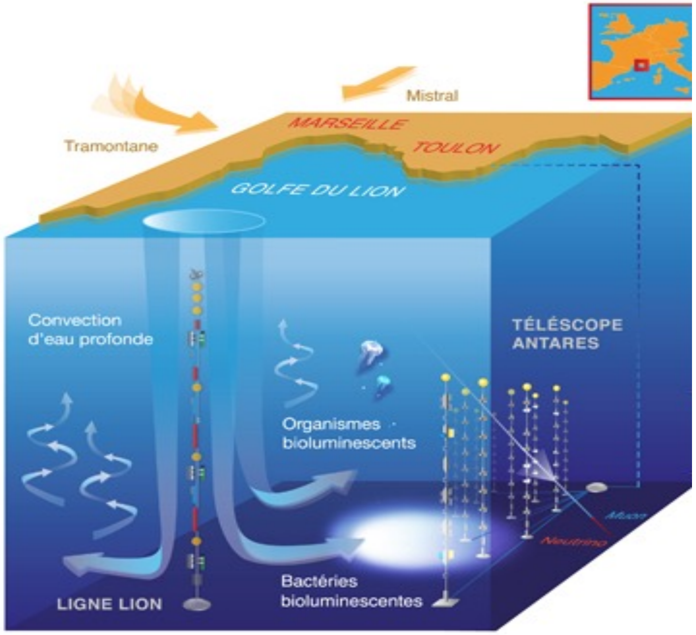
More and more important in the context of a rapid climate change

- Real-time
- High power
- High bandwidth, High frequency
- Multiple sensors in same location
- Continuous, Long term
- Trigger for studies with other sensors
- Oceanography (water circulation, climate change):
  - Current intensity and direction, water temperature, water salinity, oxygen, radionuclides...
- Geophysics (geohazard):
  - Seismic phenomena, low frequency passive acoustics, magnetic field variations,...
- Biology (micro-biology, cetaceans,...):
  - Passive acoustics, biofouling, bioluminescence, video, water samples analysis,...

Earth and Sea Sciences

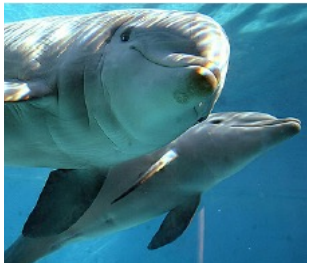
🕮 PLoS ONE 8 (7) 2013
Deep-sea bioluminescence blooms after dense water formation at the ocean surface

🕮 *Journal of Geophysical Research: Oceans, Vol 122, 3, 2017*
Deep sediment resuspension and thick nepheloid layer generation by open-ocean convection



🕮 Deep-Sea Research I 58 (2011) 875–884
Acoustic and optical variations during rapid downward motion episodes in the deep North Western Mediterranean

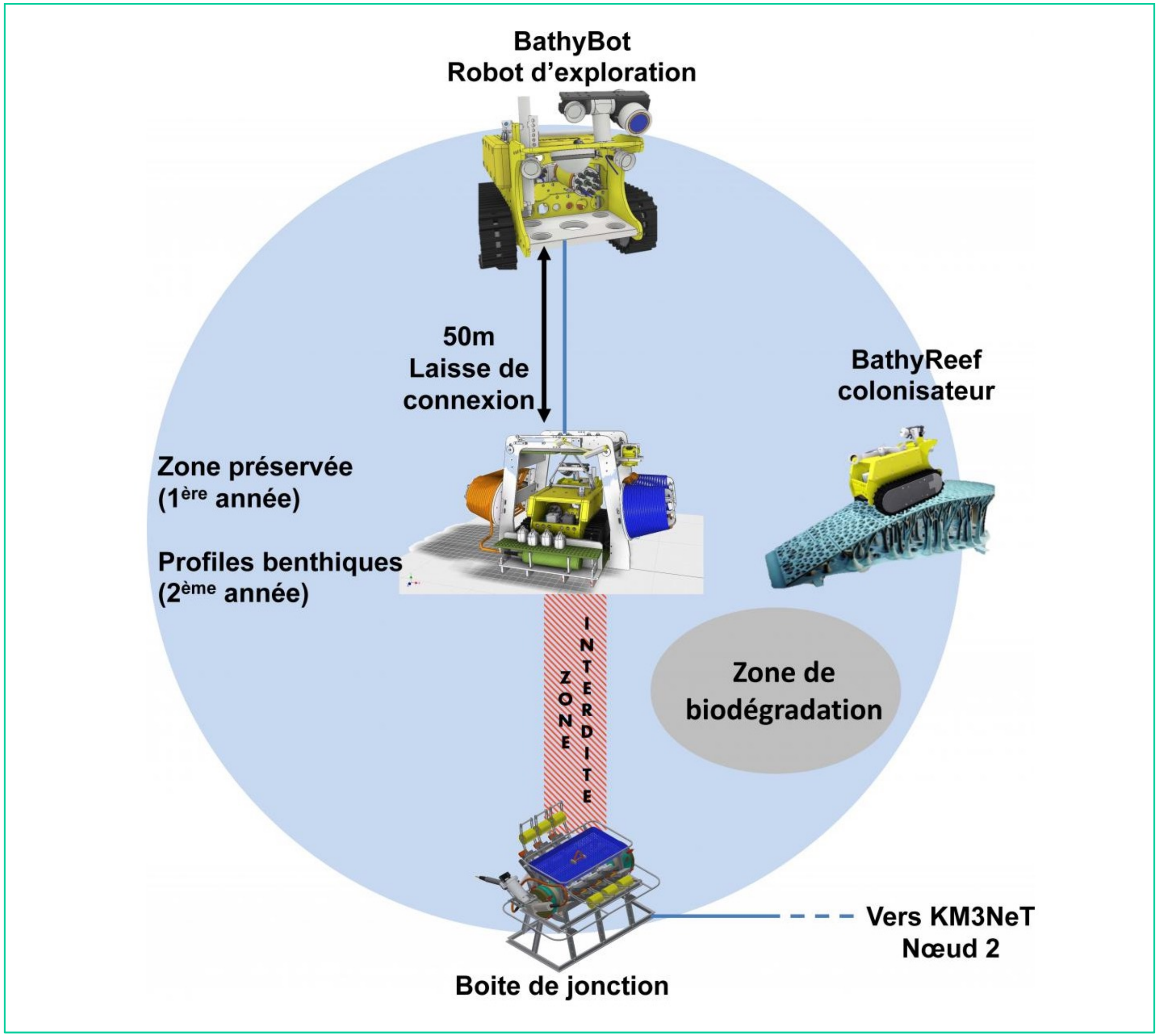
🕮 *Sci. Rep. 7 (2017) 45517*
Sperm whale diel behaviour revealed by ANTARES, a deep-sea neutrino telescope



🕮 Ocean Dynamics, April 2014, 64, 4, 507-517
High-frequency internal wave motions at the ANTARES site in the deep Western Mediterranean

New infrastructure for Sea Sciences

Recently installed at ORCA site!

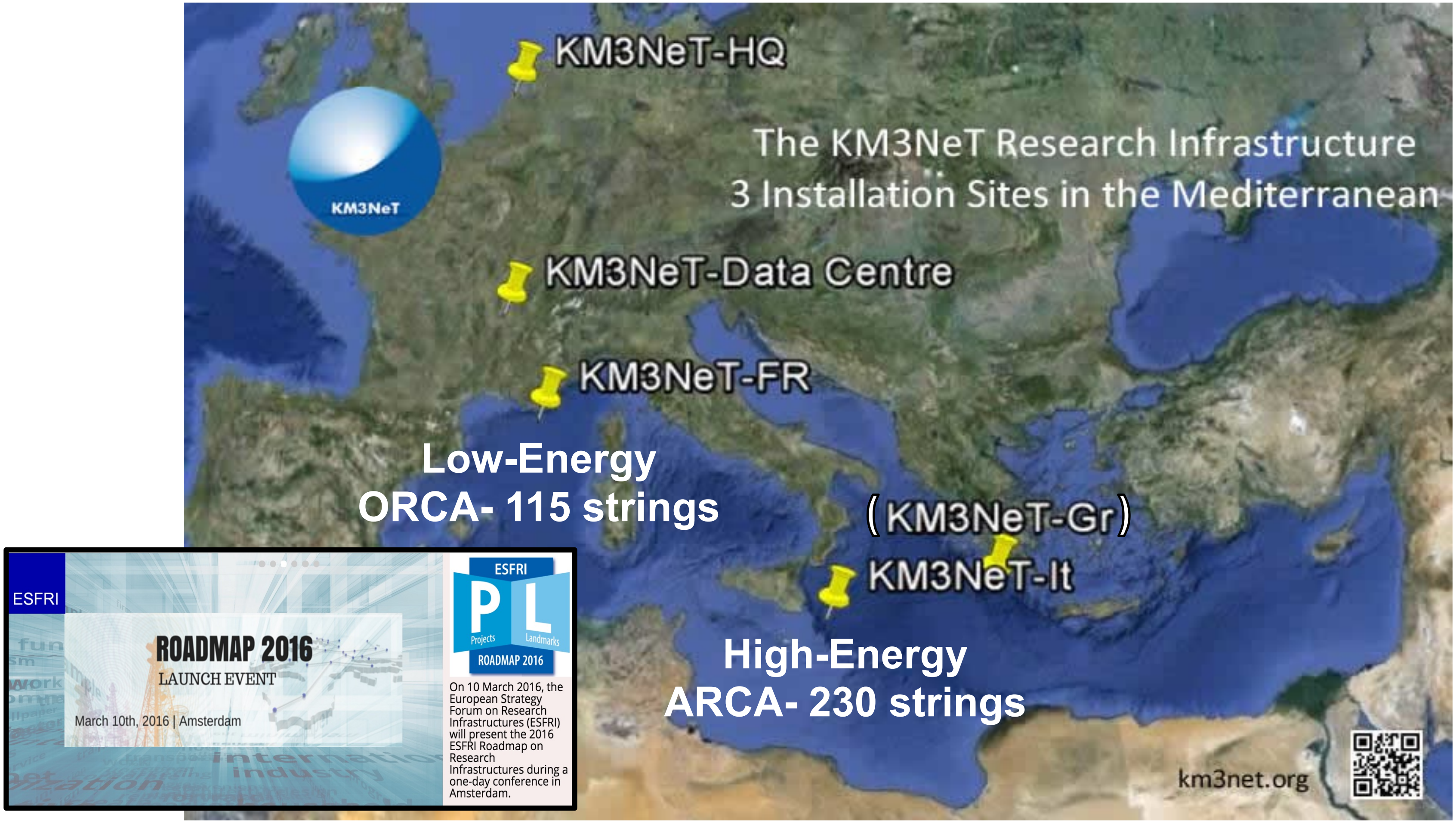


KM3NeT: Next gen. Med. detectors

KM3NeT is a distributed research infrastructure with <u>2 main physics topics</u>:

Low-Energy studies of atmospheric neutrinos – High-Energy search for cosmic neutrinos

Single Collaboration -- Single Technology



Low-Energy
ORCA- 115 strings

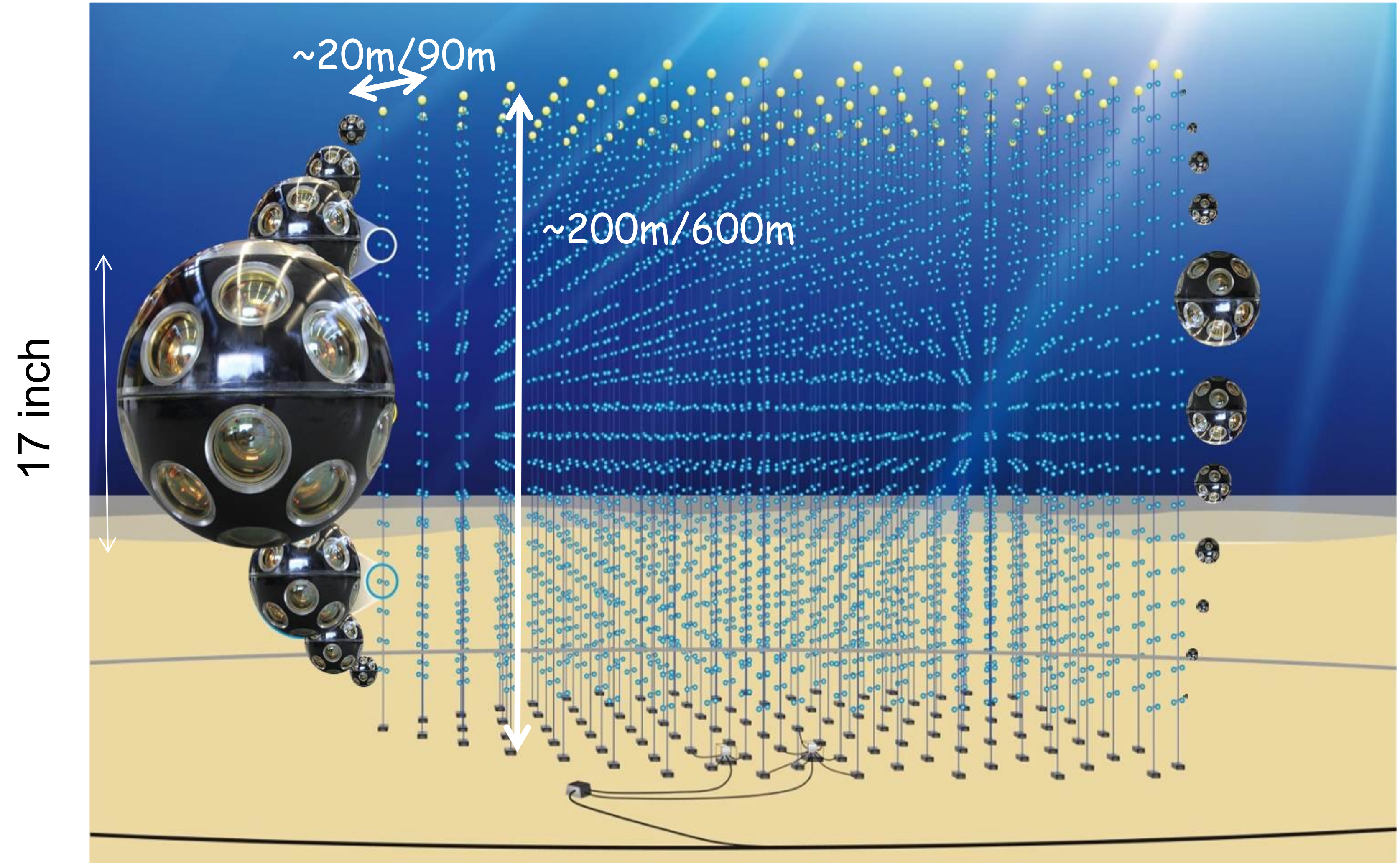
High-Energy
ARCA- 230 strings

ROADMAP 2016
LAUNCH EVENT
March 10th, 2016 | Amsterdam

ROADMAP 2016

On 10 March 2016, the European Strategy Forum on Research Infrastructures (ESFRI) will present the 2016 ESFRI Roadmap on Research Infrastructures during a one-day conference in Amsterdam.

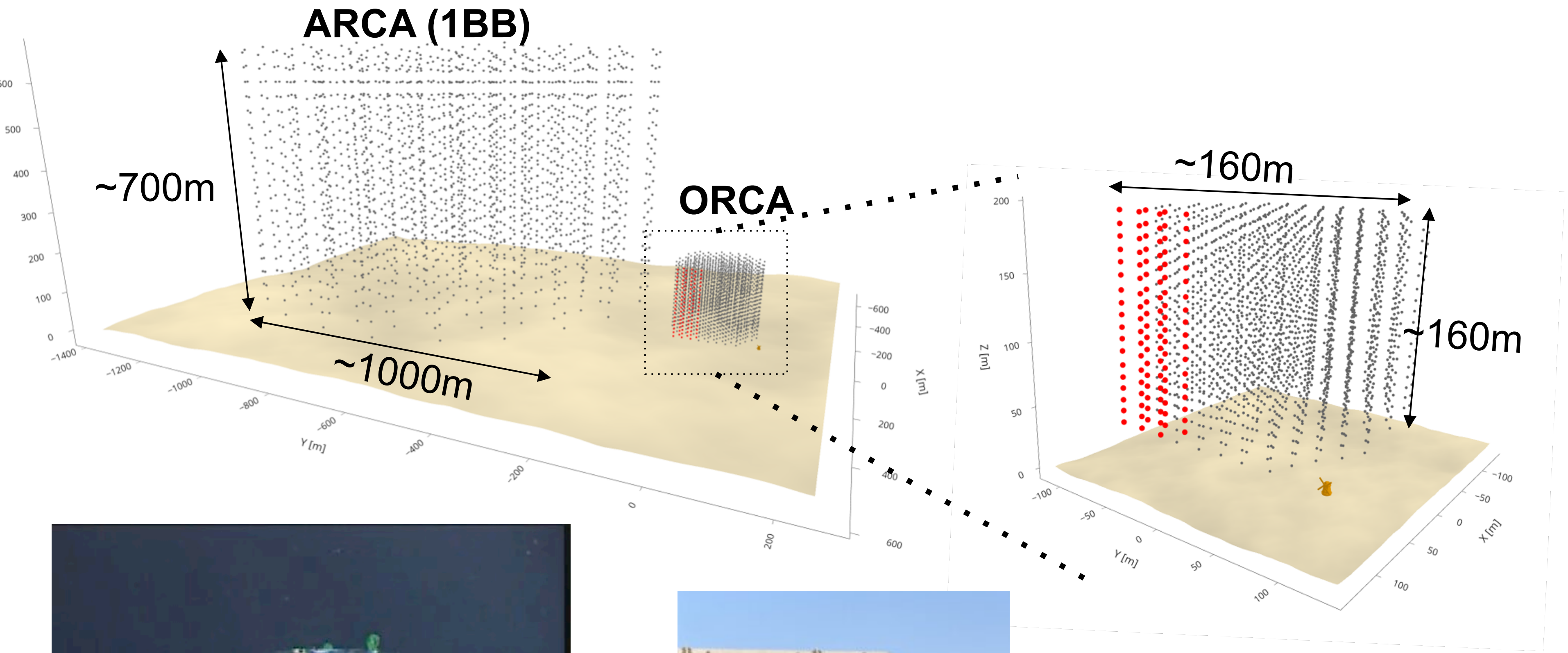
Detector technology

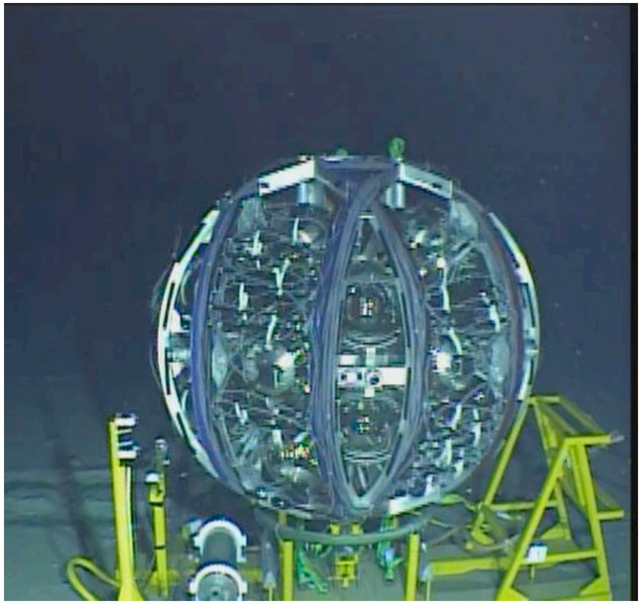


- 31 3” PMTs
- Digital photon counting
- Directional information

- Wide angle of view
- More photocathode than 1 ANTARES storey
- Cost reduction wrt ANTARES

KM3NeT ramping up





Compacting allows for several deployments at once
Unfurling from sea bed

KM3NeT ramping up

- ORCA : 10 Detection Units deployed
- ARCA : 19 Detection Units deployed

  2-weeks campaign was performed in June
    - 2 new junction boxes
    - 11 new detection units
    - → Speed record established: 7 DUs unfurled in less than 48hrs!

- NEW (yesterday)
  - 2 more ORCA DUs yesterday
  - One more Junction Box on ARCA site deployed

- Finances 67 M€ budget approved in Italy. Complete first block and start second one + Upgrade/realization new laboratories for DOM /DU/BM integration

- Completion ? :

ORCA : ½ BB Jan 24, Full Jan 2026
ARCA : First BB Jan 25,
Second BB Jan 2027

Fast developments !

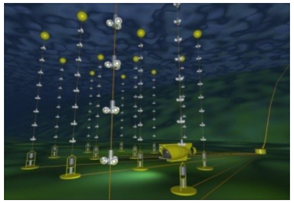
Outline

Neutrino astronomy

Scientific motivations

Historical aspects

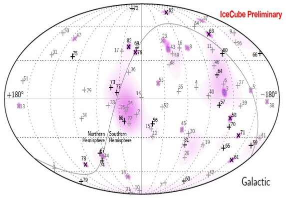
Cosmic neutrino sources



Neutrino telescope

Detection principles

Current telescopes



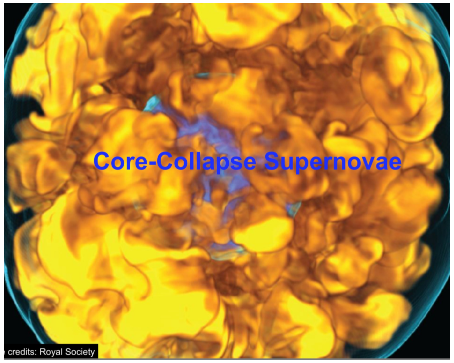
Selected results

Diffuse Flux, point sources

Multi-messenger search

ORCA prospects

Neutrino telescopes: science scope



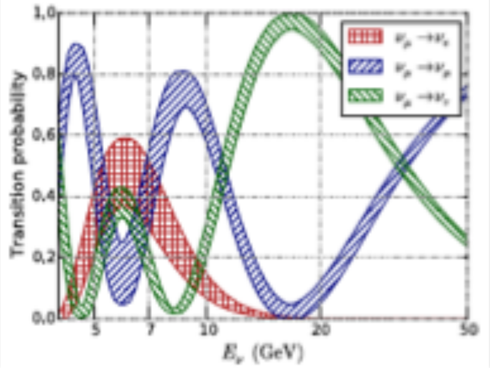
credits: Royal Society

MeV Energy
No reco. in HE NT

CCSNe

Full Galactic coverage
All mass progenitors
Triangulations
⬇
Localisation
Coleiro et al., Eur. Phys. J. C 80, 856 (2020)

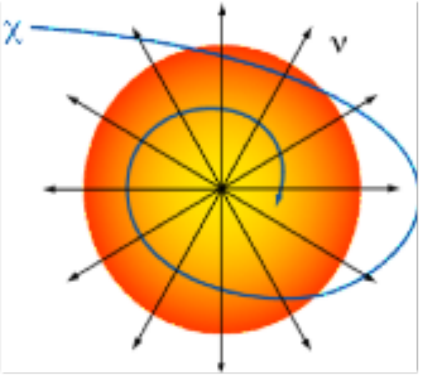
Ask Isabel ☺



Low Energy
GeV < E < 50 GeV

Oscillation

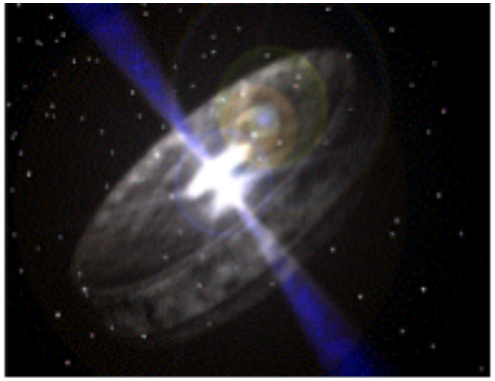
Focus at the very end of these lectures ?



Medium Energy
10GeV < E < 1 TeV

Dark Matter

Not covered
here



High Energy
E > 1 TeV

HE Astrophysics

Focus here

\+ Exotics (Monopoles, Nuclearites, etc.)

Not covered
here

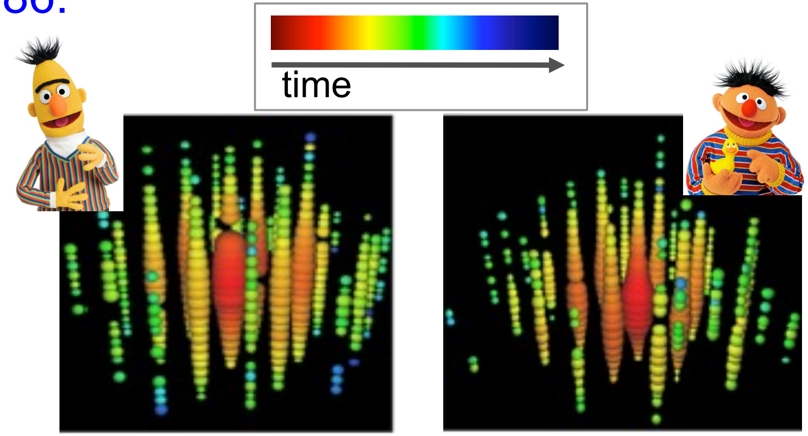
IceCube Discovery of HE neutrinos

- Two interesting cascade events found in IC79/IC86:

  analysis targeting GZK neutrinos (~EeV)

  significance 2.8σ (expected 0.08±0.05)

  📖 Phys. Rev. Lett. 111, 021103 (2013)



1.0 +/- 0.2 PeV

1.1 +/- 0.2 PeV

- Re-tuned on high-energy starting events:

  total deposited charge > 6000 p.e.

  track-like + shower-like events

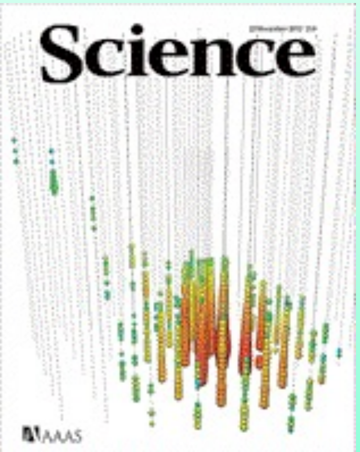
  outer layer used as veto against μ_{atm} & ν_{atm}

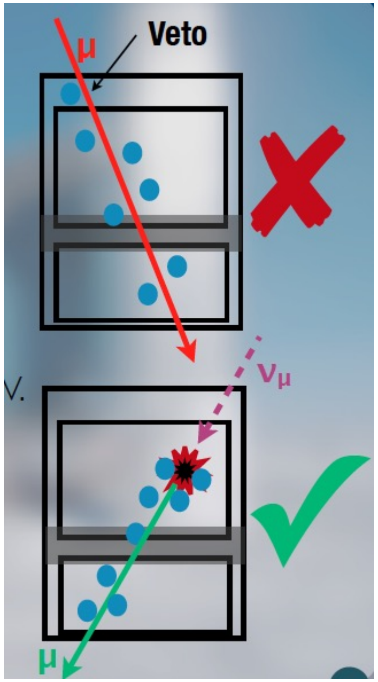
28 events selected (2-year data sample)
11 expected from μ_{atm} & ν_{atm} background:

4.1σ statistical significance

PhysicsWorld
2013 Breakthrough

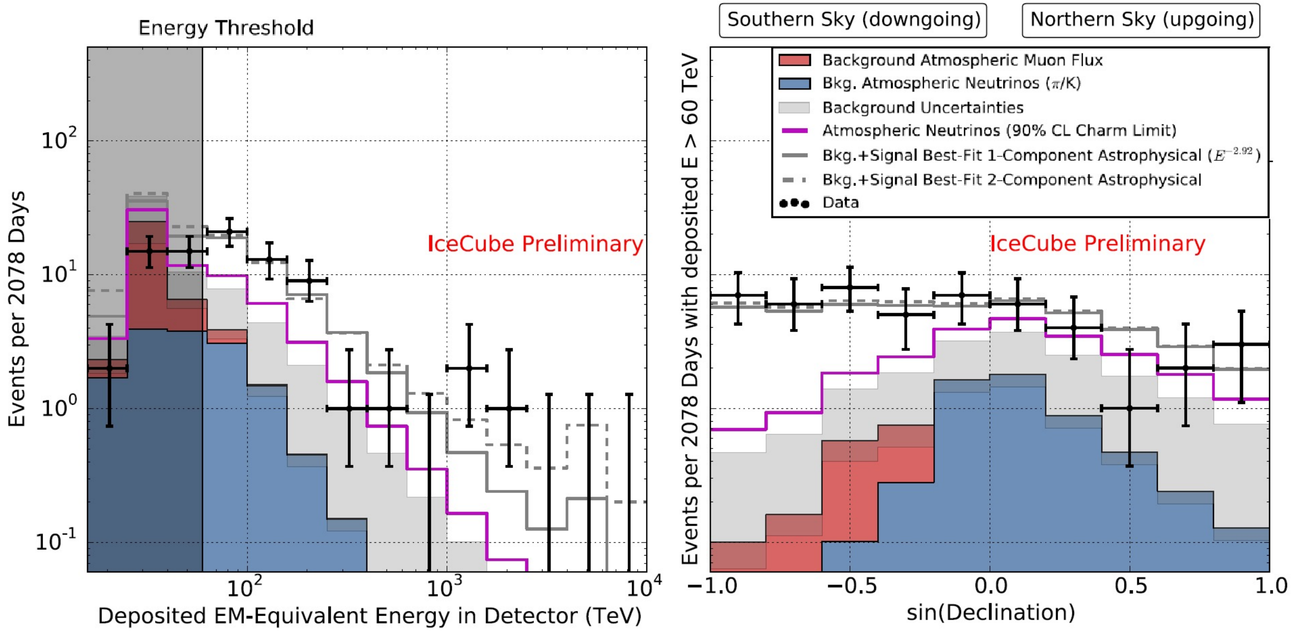
High Energy Starting Events (HESE)





Excess of HESE events over background

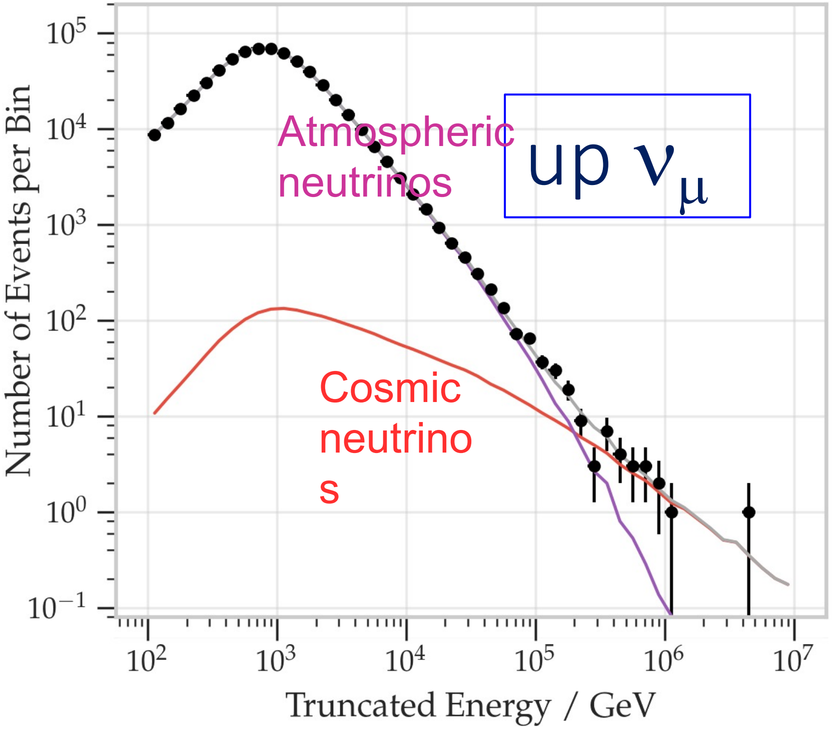
- **High Energy Starting Events** (**HESE**) in IceCube
- Events selected in a restricted fiducial volume (SK-like)
- Mostly showers with poor angular determination (>10°)
- Excess fitted with a power-law: $\boldsymbol{\Phi_\nu = \Phi_o E^{-\Gamma}}$



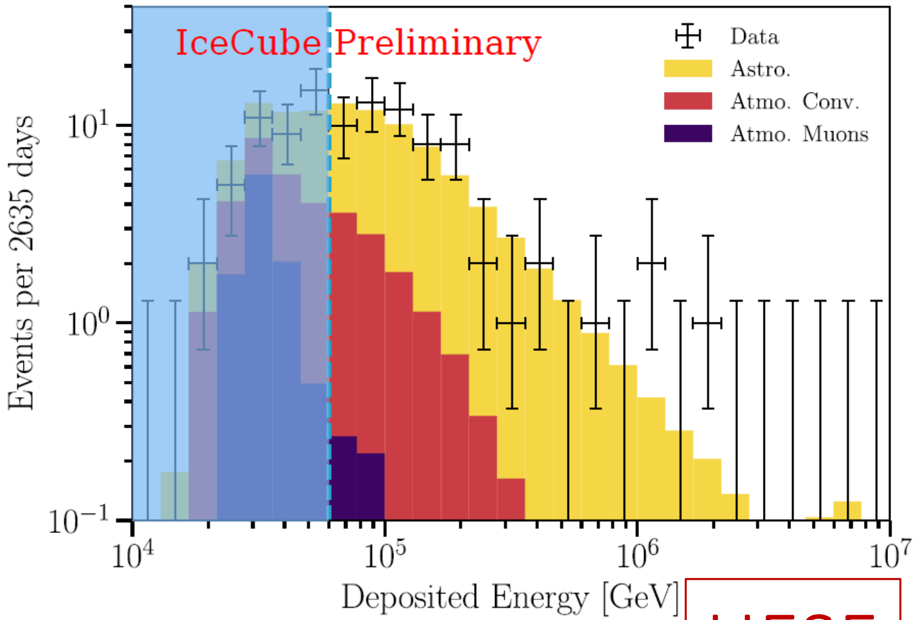
- Atmospheric muons
- Atmospheric neutrinos
- **Signal= excess of HE events**

*Deposited energies E_{dep} **(left)** and arrival directions **(right)** of IceCube events (crosses), 6 years. The hashed region shows uncertainties on the sum of all backgrounds, due to atmospheric muons and atmospheric neutrinos. The contribution of an astrophysical (v + v) flux for E_{dep} > 60 TeV is signal-background.*

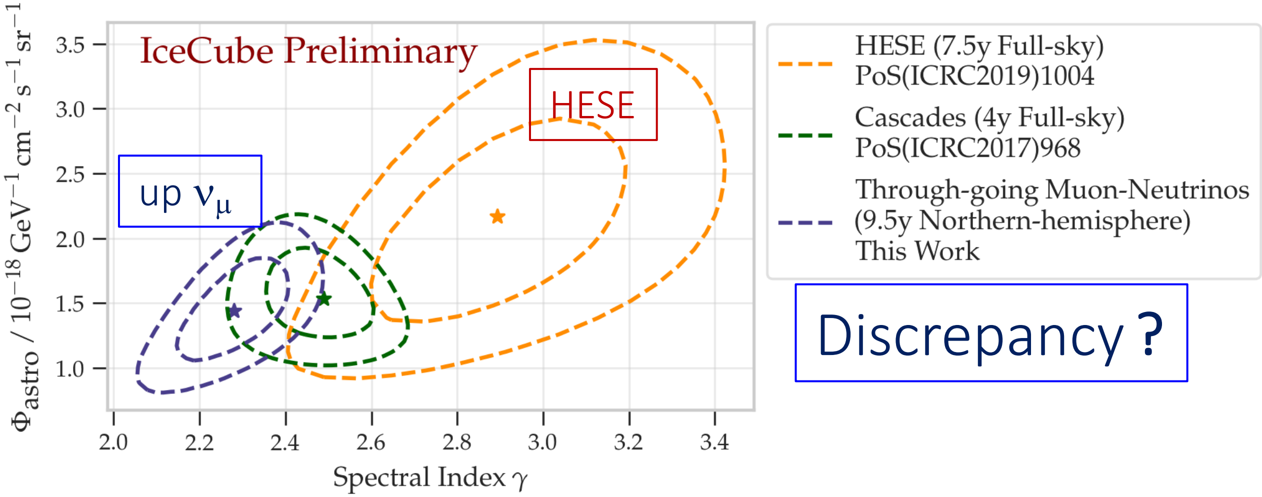
Excess of HE neutrinos in IceCube:



up ν_μ



HESE



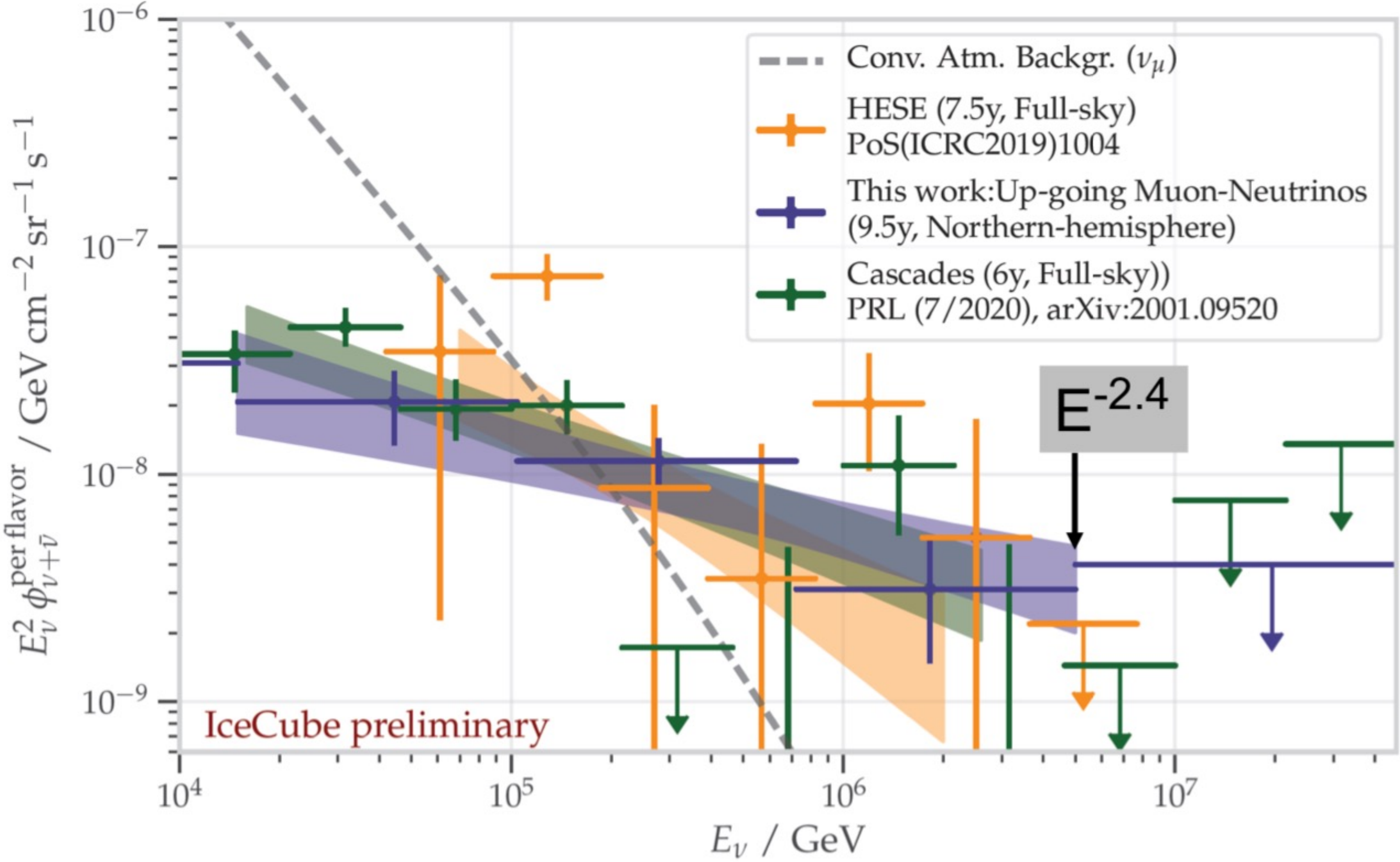
Discrepancy ?

$$\frac{d\Phi_\nu}{dE} = \Phi_{astro} \cdot E^{-\gamma}$$

Summary of recent IC results

The single power-law paradigm

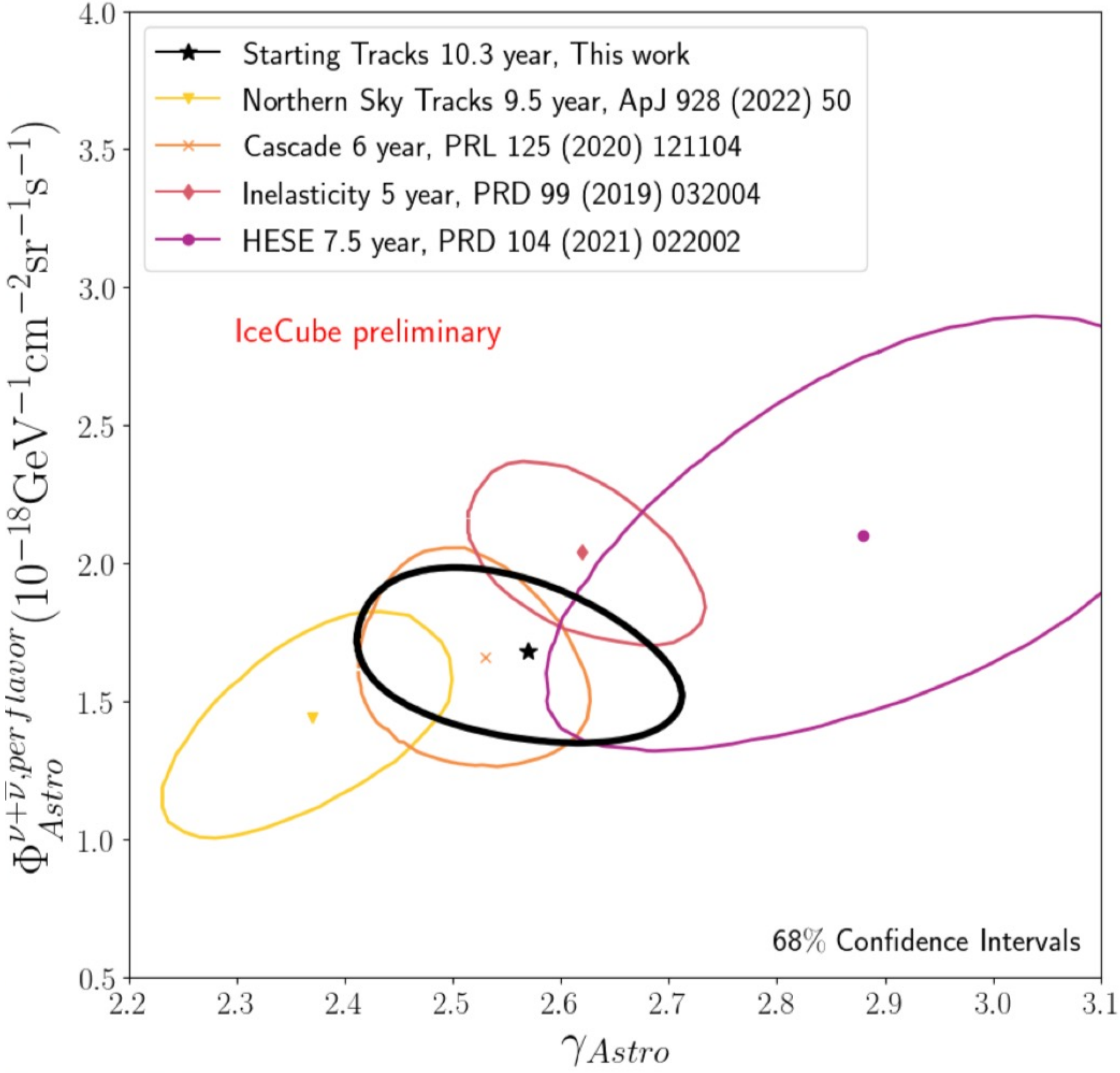
Halzen, NT conference 2021



Indication of spectral break (different energy thresholds) ?

Indication of galactic and extra-galactic contributions (different hemispheres) ?

Summary of recent IC results



What can ANTARES say?

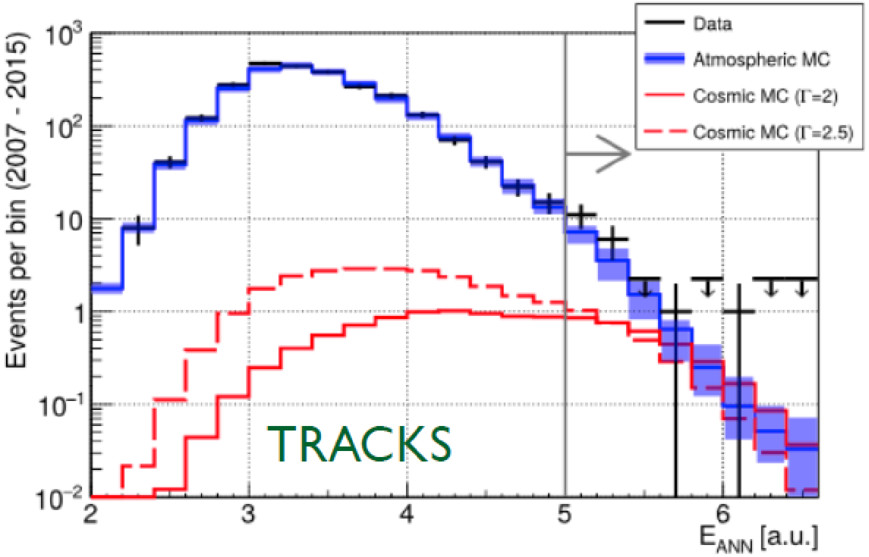
Sample:
- 2007 – 2015; livetime 2450 days
- All-flavour analysis (track+showers)

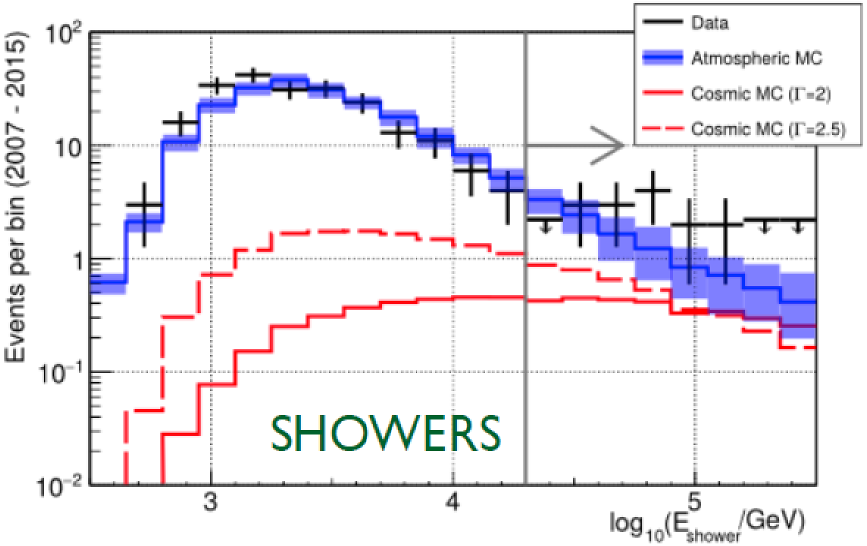
Event selection chain + energy-related cut applied to
- obtain a high-purity neutrino sample
- maximise sensitivity

Signal modeled according to the IceCube flux

Result:
33 events (19 tracks + 14 showers) in data
24 ±7 (stat.+syst.) events background in MC

1.6σ excess, null hyp. rejected at 85% CL

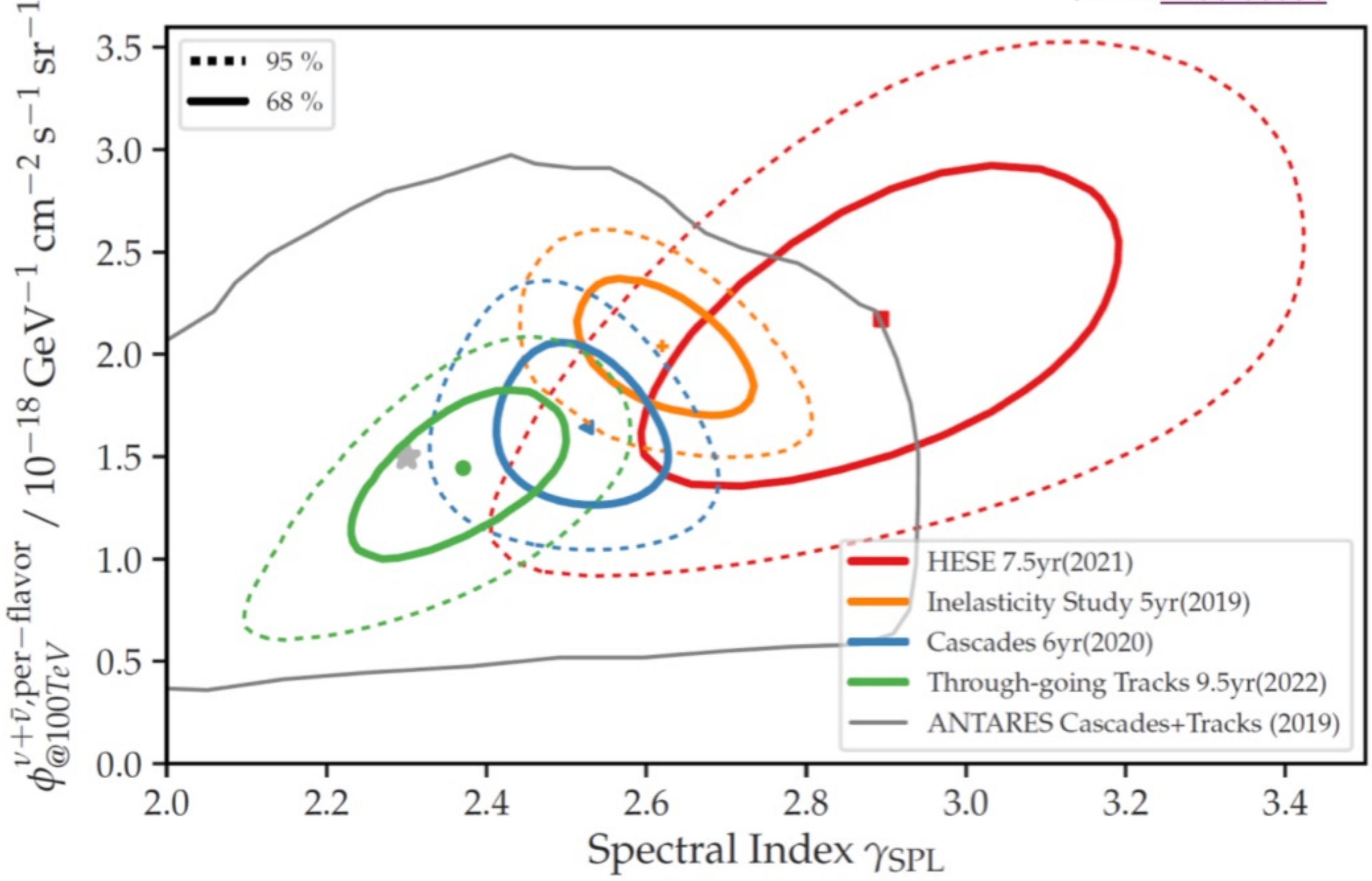




Results not really constraining… but fully compatible with IceCube

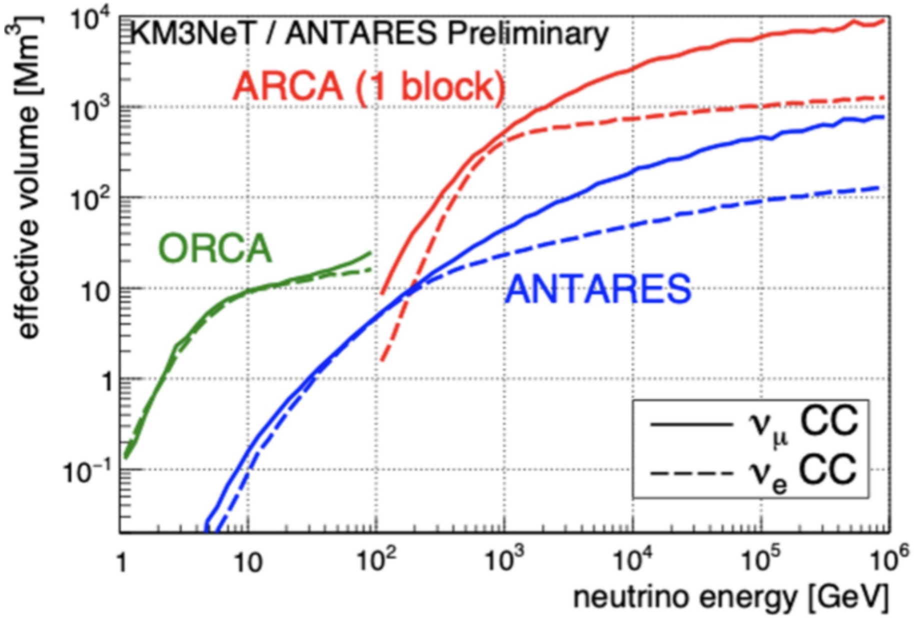
Diffuse flux – Single Power low

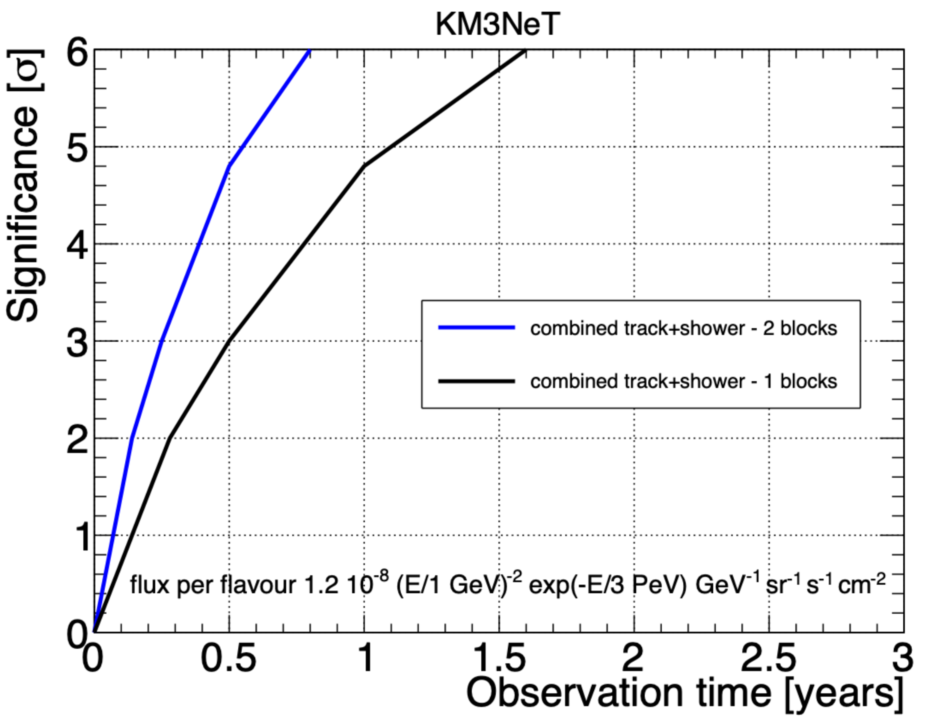
arXiv: 2203.08096



Results not really constraining… but fully compatible with IceCube

KM3NeT-ARCA sensitivity





📖 Astrop. Phys. 111 (2019) 100 -110

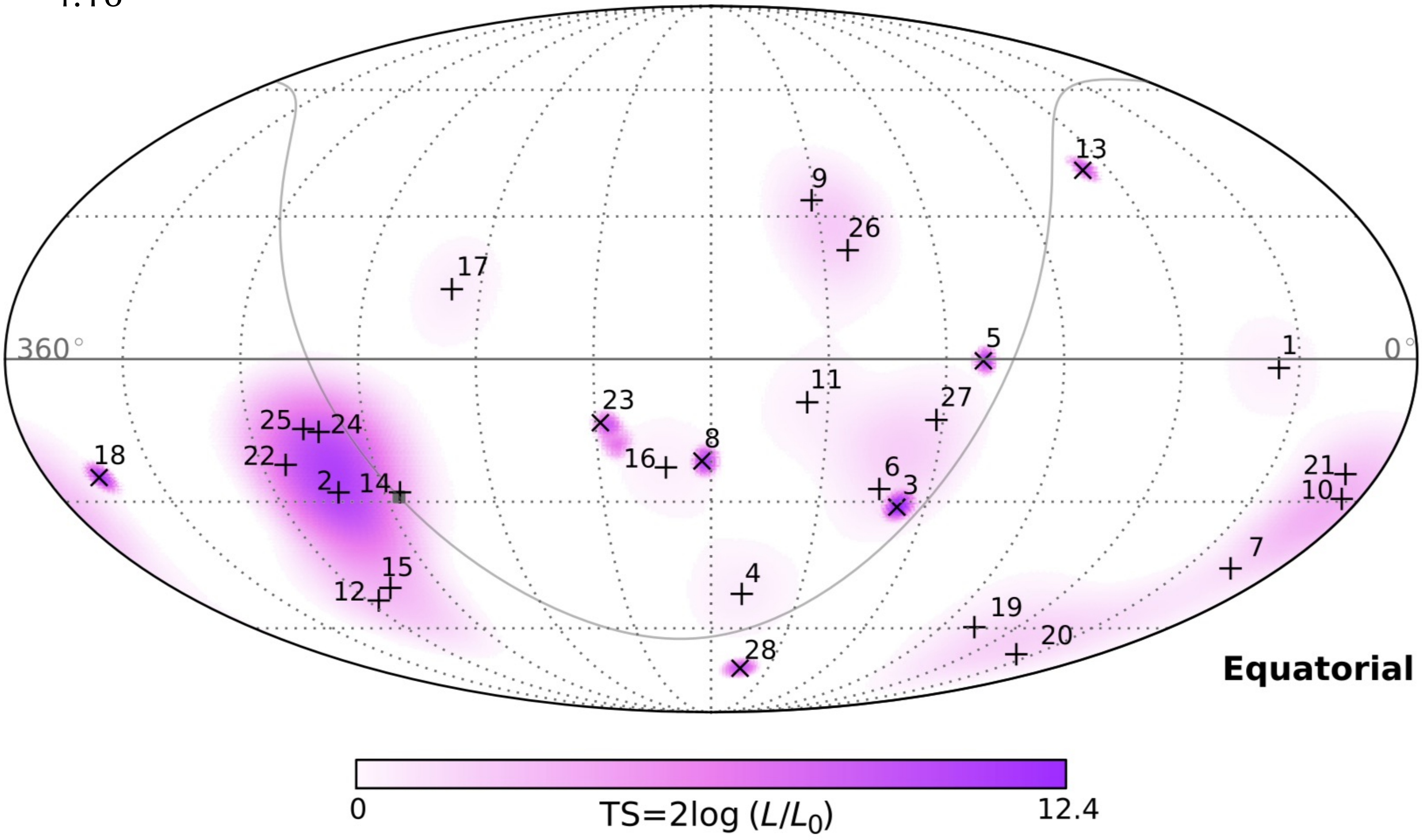
KM3NeT can observe (3σ) IceCube signal in 3 months and confirm it (5σ) in six months

High resolution follow-up and e.g. flavour composition

Diffuse neutrino flux (>TeV)

2-year data sample
4.1σ

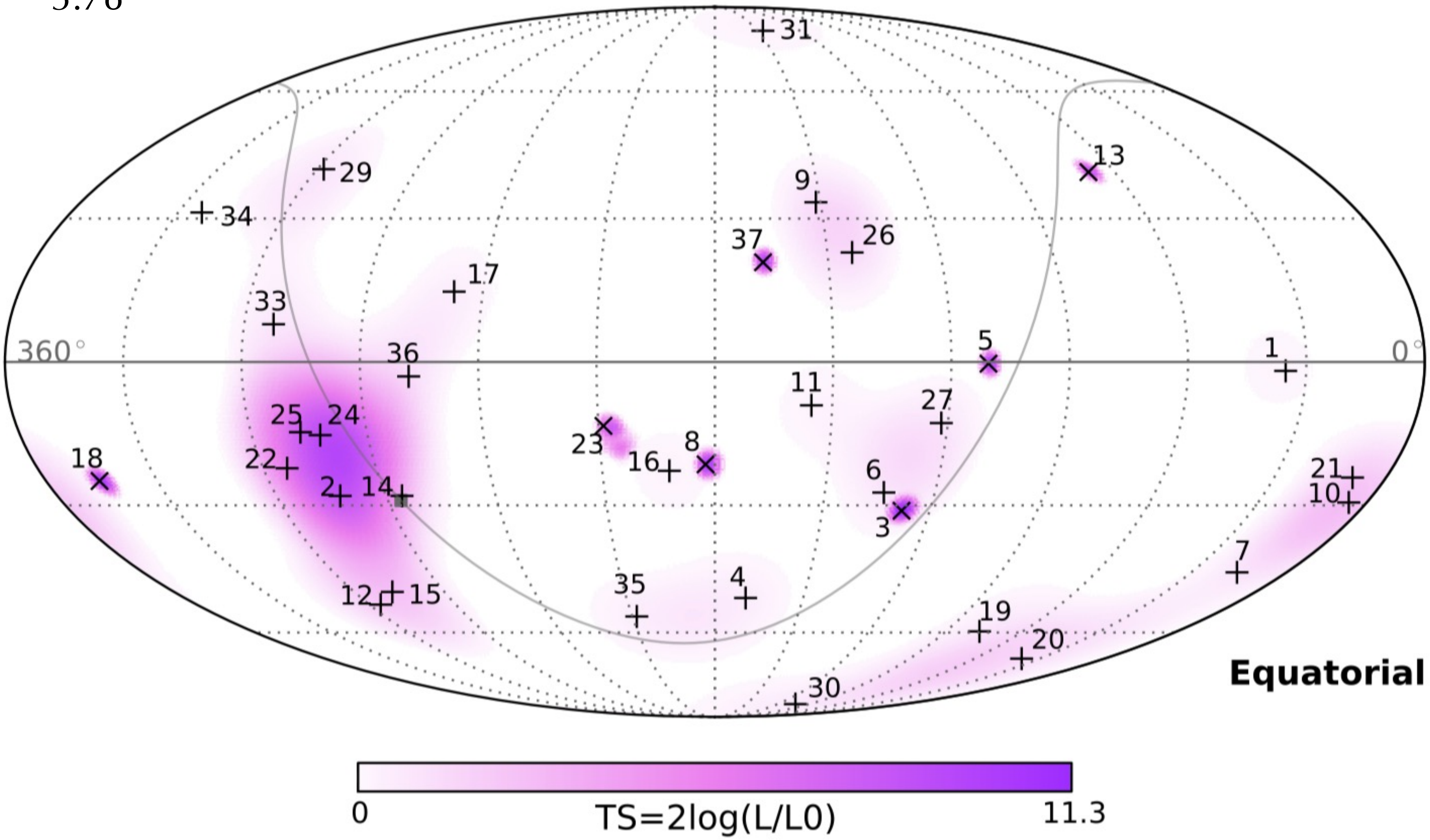
IceCube coll., ICRC 2017



Diffuse neutrino flux (>TeV)

3-year data sample
5.7σ

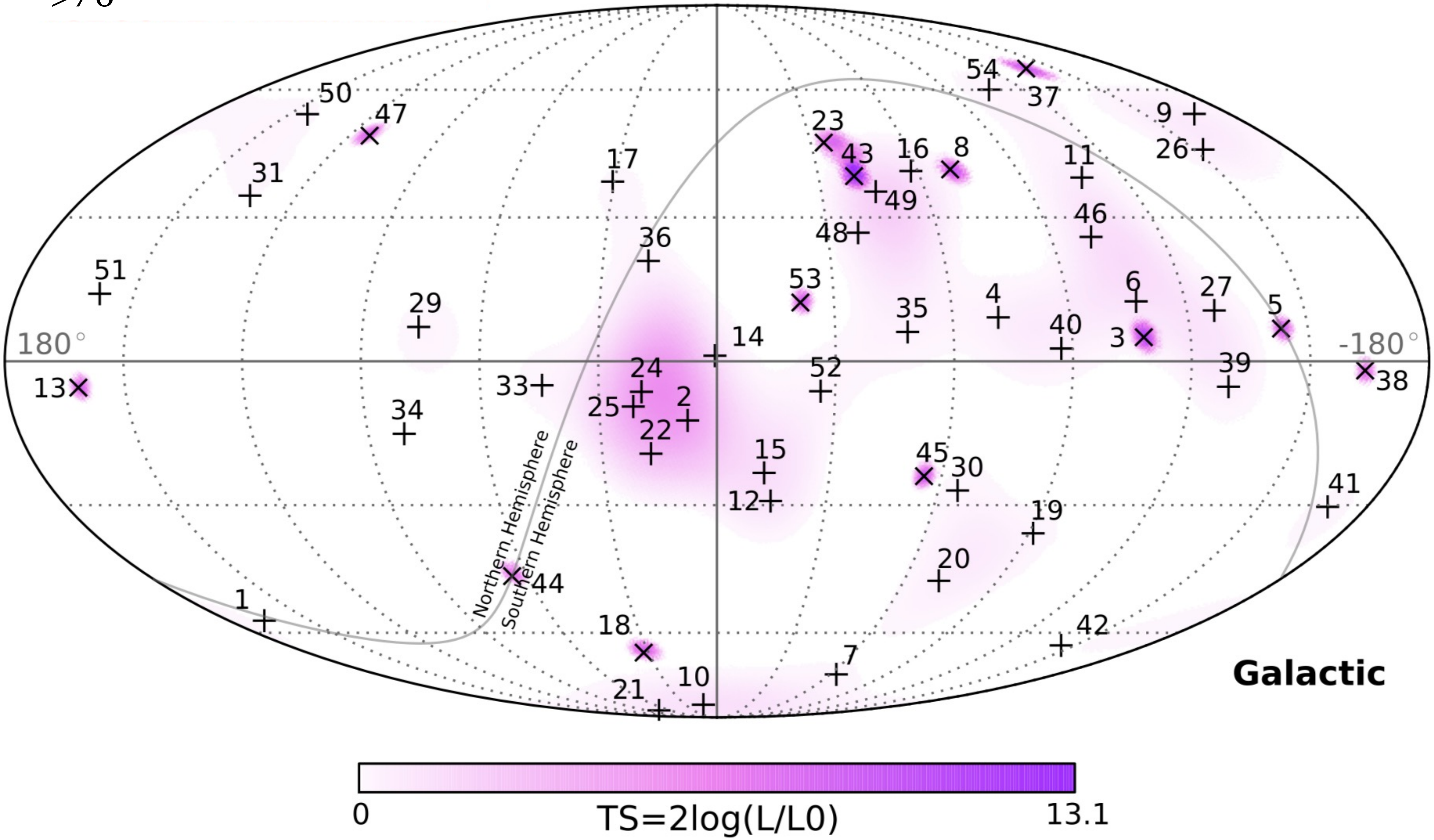
IceCube coll., ICRC 2017



Diffuse neutrino flux (>TeV)

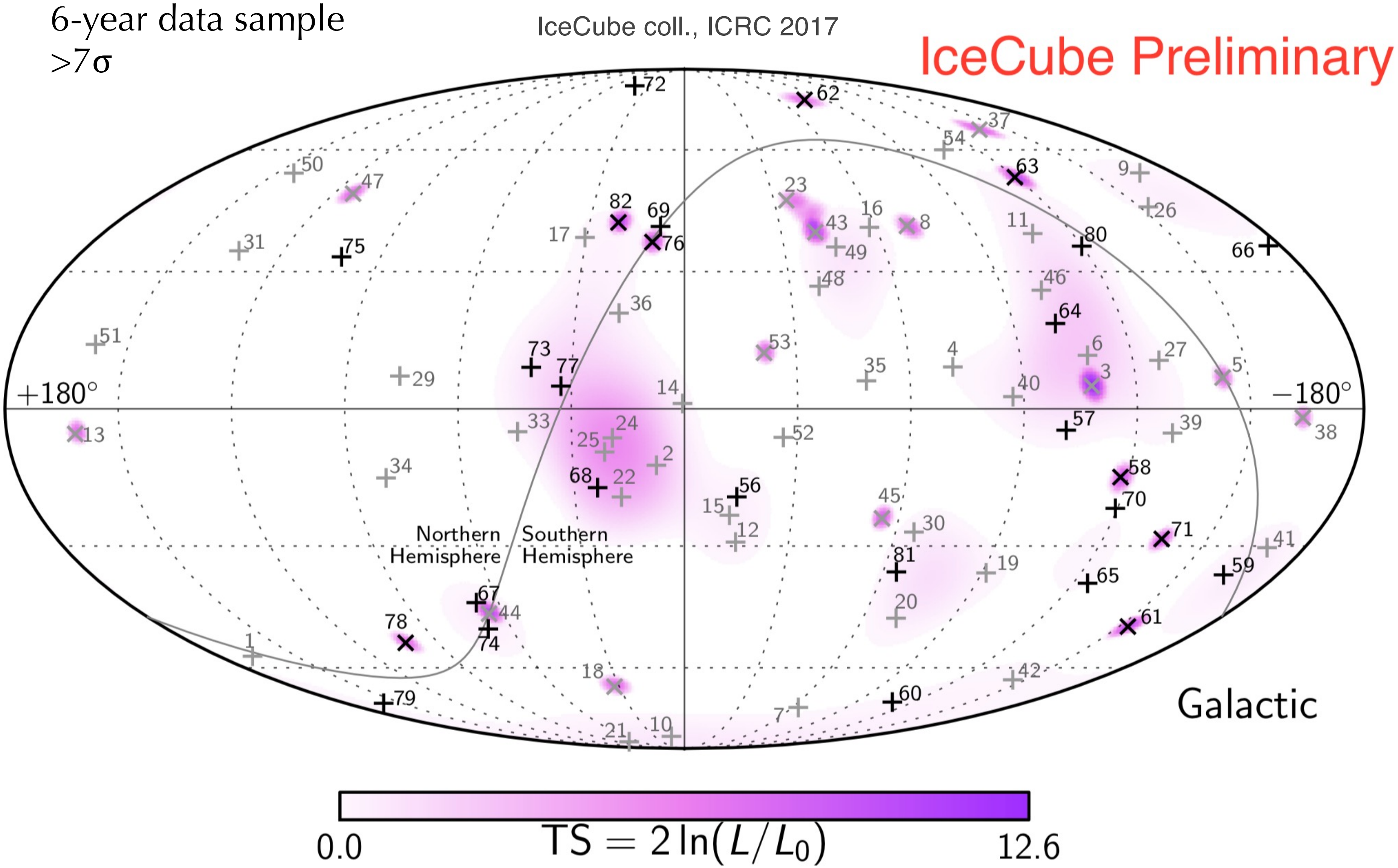
4-year data sample
>7σ

IceCube coll., ICRC 2017



Diffuse neutrino flux (>TeV)

6-year data sample
>7σ



IceCube coll., ICRC 2017

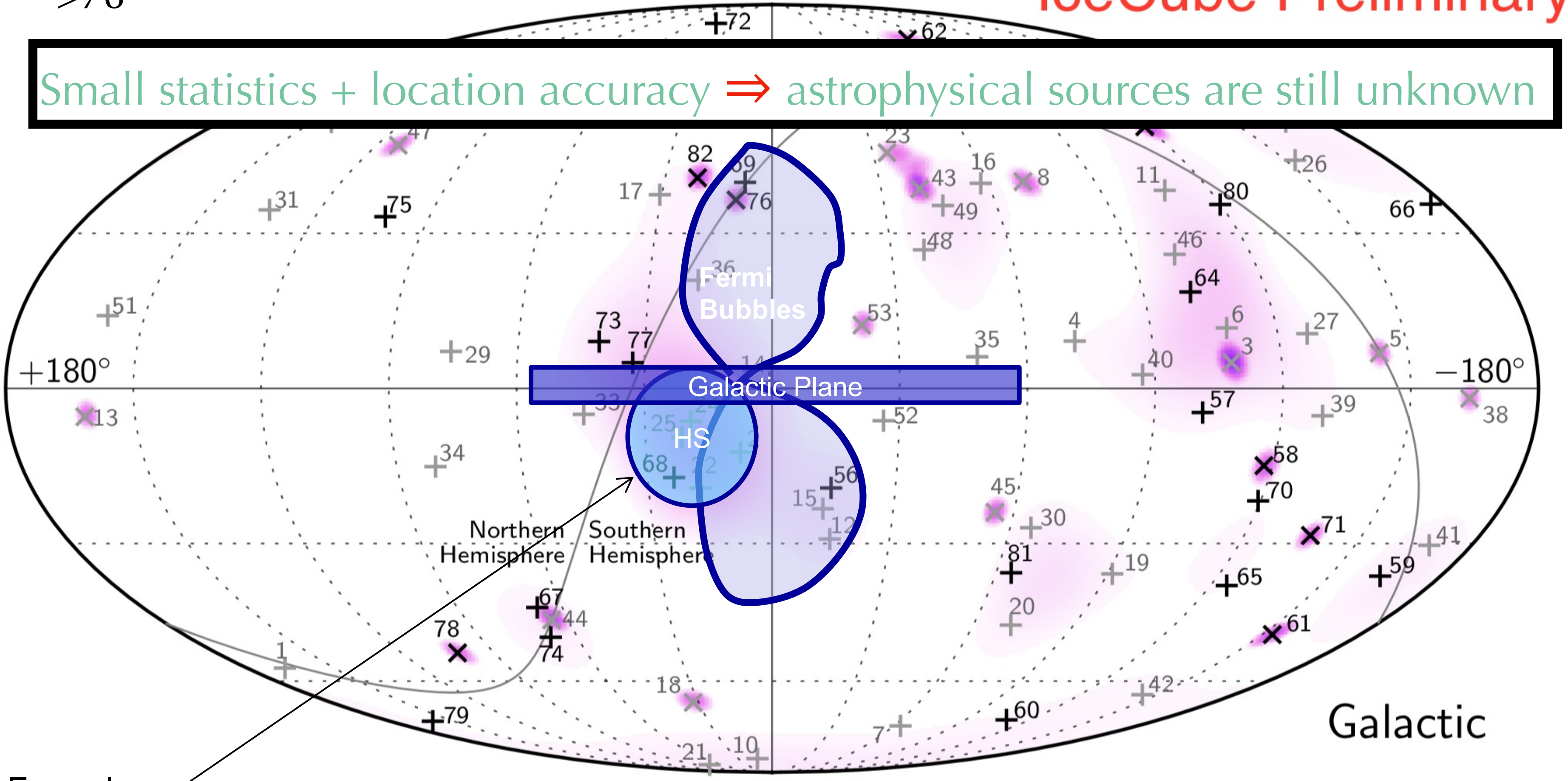
Reducing the search window

6-year data sample
>7σ

IceCube coll., ICRC 2017

IceCube Preliminary

Small statistics + location accuracy ⇒ astrophysical sources are still unknown

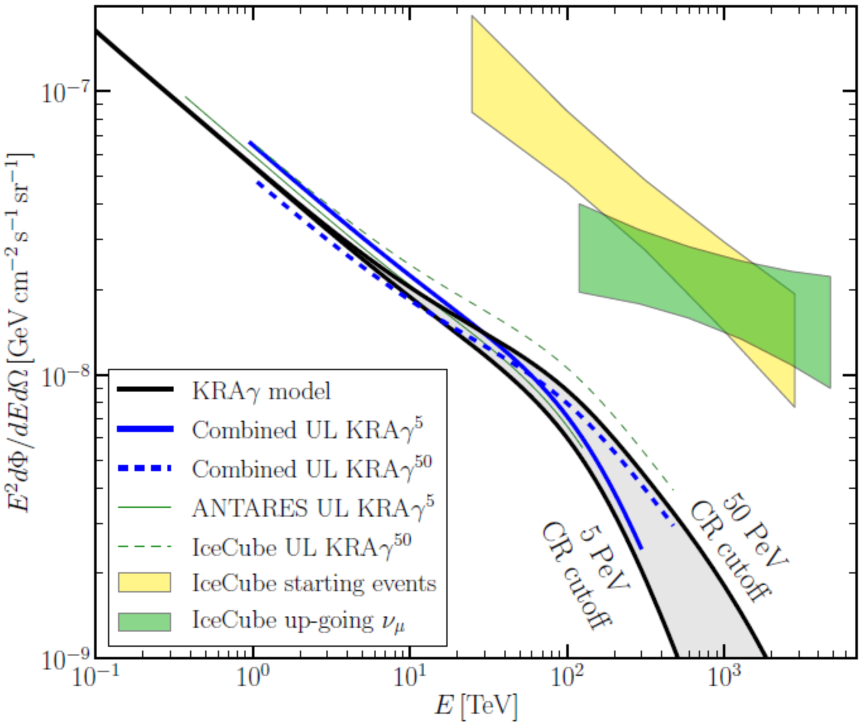


Example
ANTARES rules out any single PS close to the GC with spectral index of -2.5 as having a flux corresponding to more than 2 HESE…
📖 Astrophys. J. Lett. 786:L5 (2014)

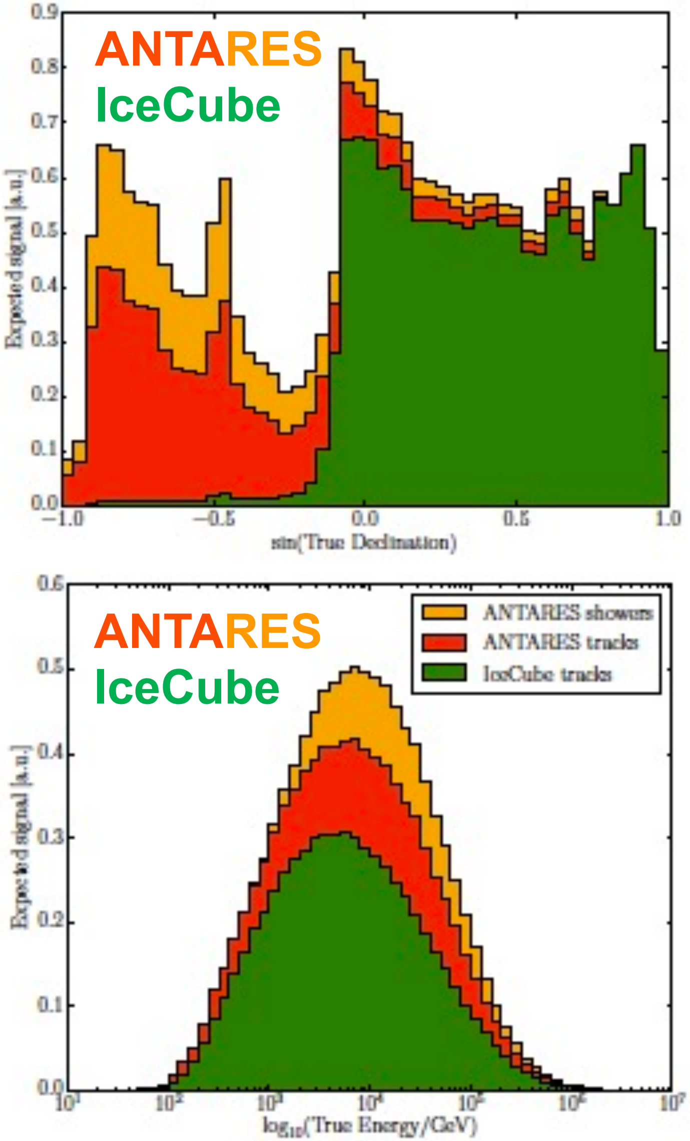
Hypothesized in literature:
Fermi Bubbles
Galactic Ridge
Galactic (point-like) source
…

Focus on the Galactic Plane

Combined U.L. at 90% CL (blue line) on the 3-flavor neutrino flux of the KRAγ model (5-50 PeV cutoff)



Stacked expected signal vs. δ (top) and energy (bottom). Colors relative contribution to the sensitivity



Result: total flux contribution of **diffuse Galactic neutrino** emission <9 % *of the total diffuse IC astrophysical signal (E_ν> 30 TeV)*

Phys. Rev. D 96, 062001

ANTARES+IC, in prep.

Recent article – IC public data

Astronomy & Astrophysics manuscript no. neutgalaxy
August 18, 2022

LETTER TO THE EDITOR

Galactic contribution to the high-energy neutrino flux found in track-like IceCube events

Yuri Y. Kovalev[1,2,3], Alexander V. Plavin[1], and Sergey V. Troitsky[4,⋆]

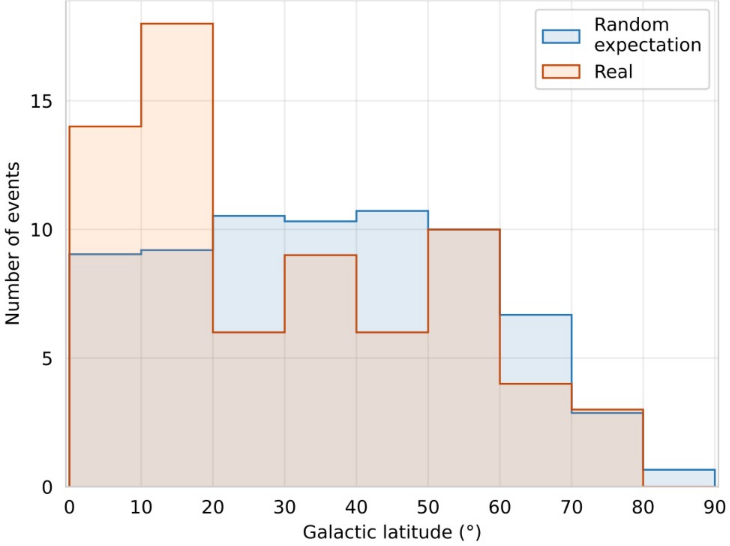


Fig. 3. Distributions of real (orange) and simulated (blue) events in the Galactic latitude of their arrival directions. The expected number of scrambled events in each bin is estimated by averaging 10^5 random samples.

We found 4.1σ evidence (p-value of 4×10^{-5}) for the existence of an anisotropic component of the neutrino flux above 200 TeV, coming from low Galactic latitudes. It constitutes about one third of the total astrophysical flux at these energies. The estimated Galactic diffuse neutrino flux agrees with multimessenger expectations for the Galactic diffuse gamma-ray flux above 400 TeV found recently by Tibet-ASγ (Amenomori et al. 2021). Future studies with huge neutrino telescopes are needed to unambiguously pinpoint the origin of the Galactic-disk high-energy neutrinos found in the present work. At least two components, Galactic (this study) and extragalactic (from blazars, e.g. Plavin et al. 2020, 2021), are found to significantly contribute to the observed neutrino flux. The neutrino sky may well be even more complex, like the electromagnetic one.

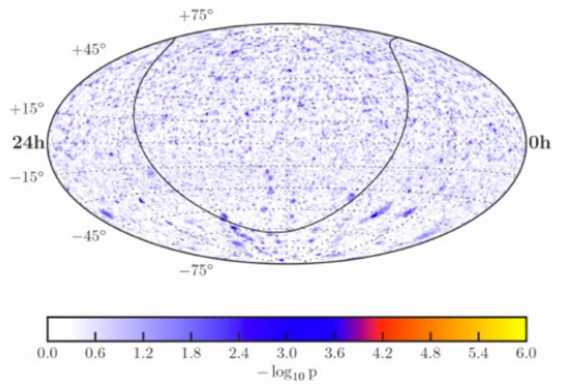
Stay tuned – New results from ANTARES – KM3NeT and IceCube ahead

Search for discrete sources

- Three main approaches:

Illustration : ANTARES

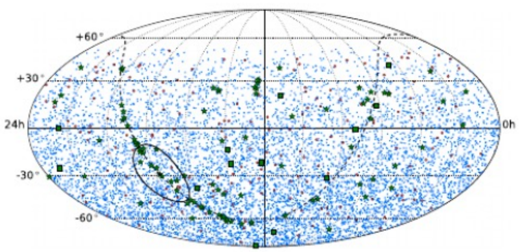
All-sky search



- Sky divided into a grid with a finer spacing than the typical event reconstruction uncertainty
- TS evaluated in each bin of the grid
- Cluster with largest TS → all-sky hotspot

- **Advantage**: unbiased by EM observations (no prior assumptions regarding directions in the sky)
- **Disadvantage**: large trial factor

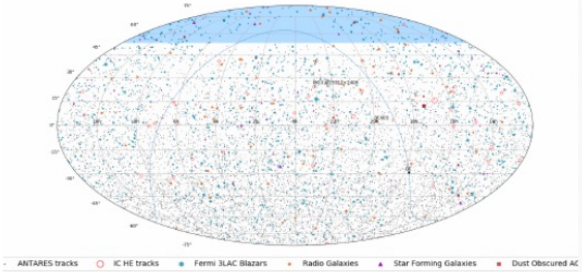
Source list search



- Investigated directions: location of selected γ-ray sources
- TS evaluated for each source

- **Advantage**: reduced trial factor
- **Disadvantage**: biased (the brightest ν sources may differ from the brightest γ-ray sources)

Stacking search / Population search

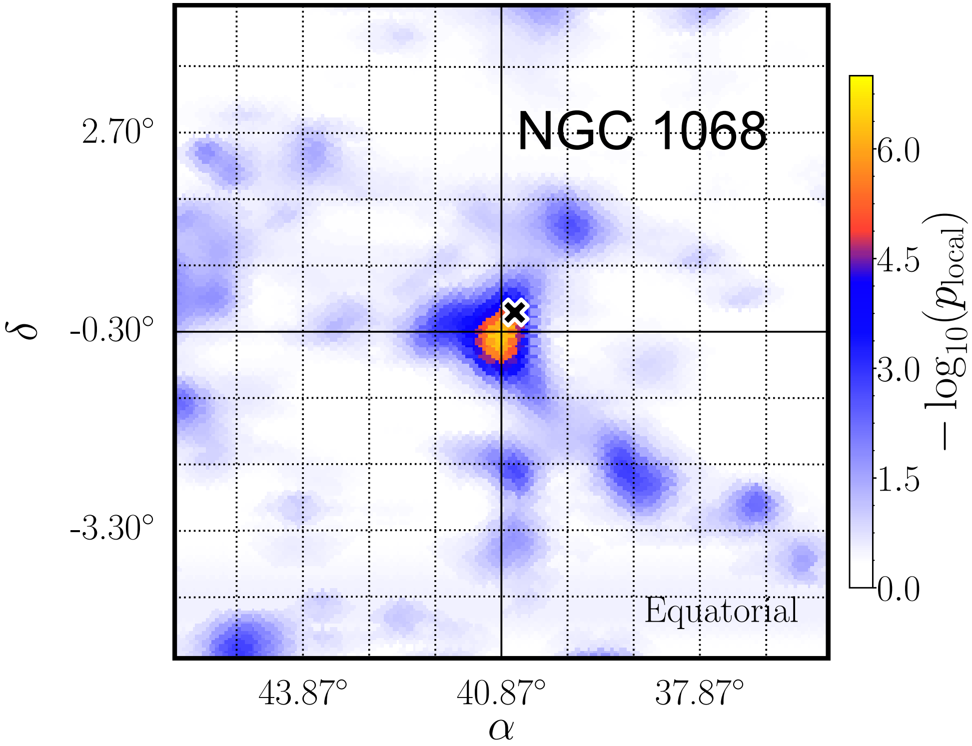


- Search for an excess from several sources
- Stacking: all the sources in the catalog analysed together → one TS per catalog
- Population: TS given by the sum of the individual TS

- **Advantage**: sensitive to individually weak sources that produce a significant cumulative signal
- **Disadvantage**: biased

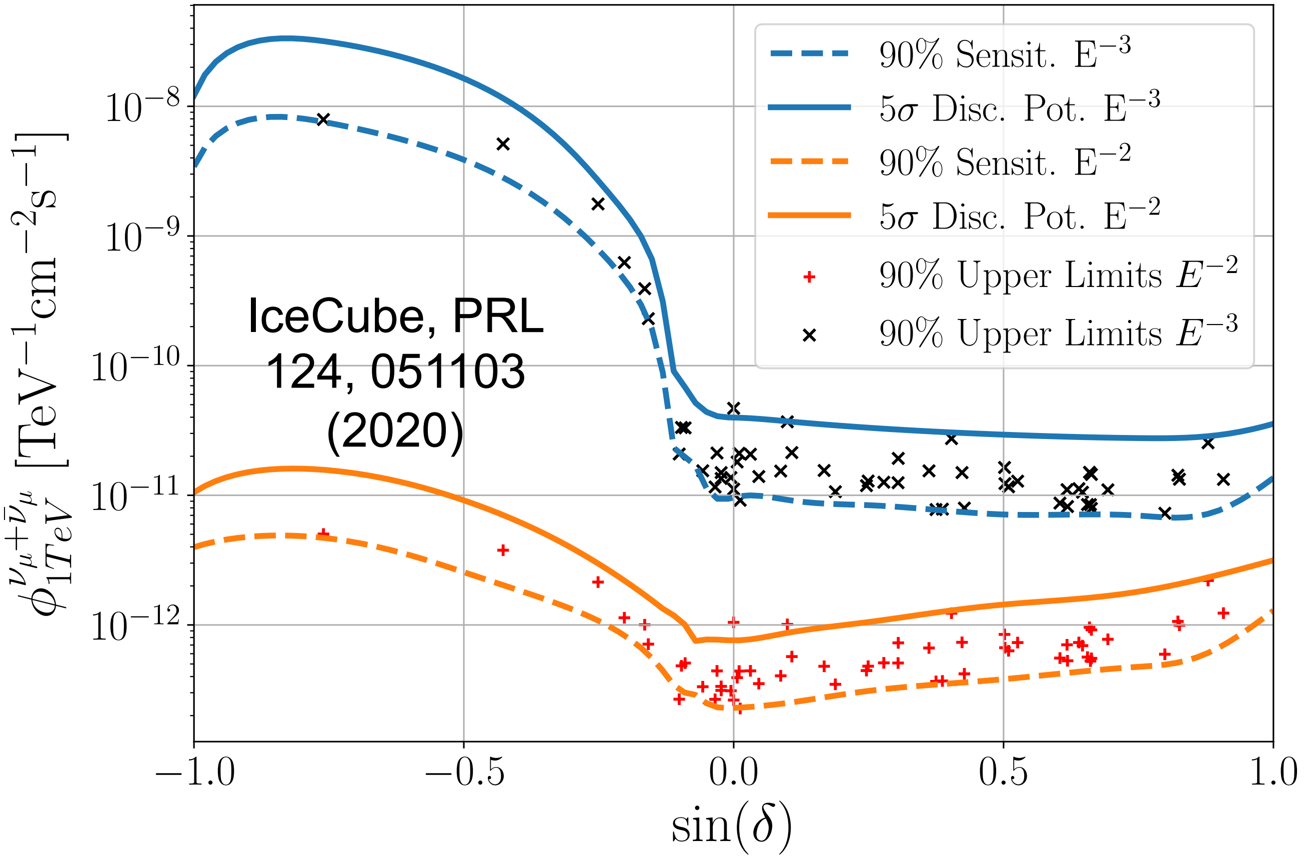
All-sky search for discrete neutrino sources

IceCube, PRL 124, 051103 (2020)



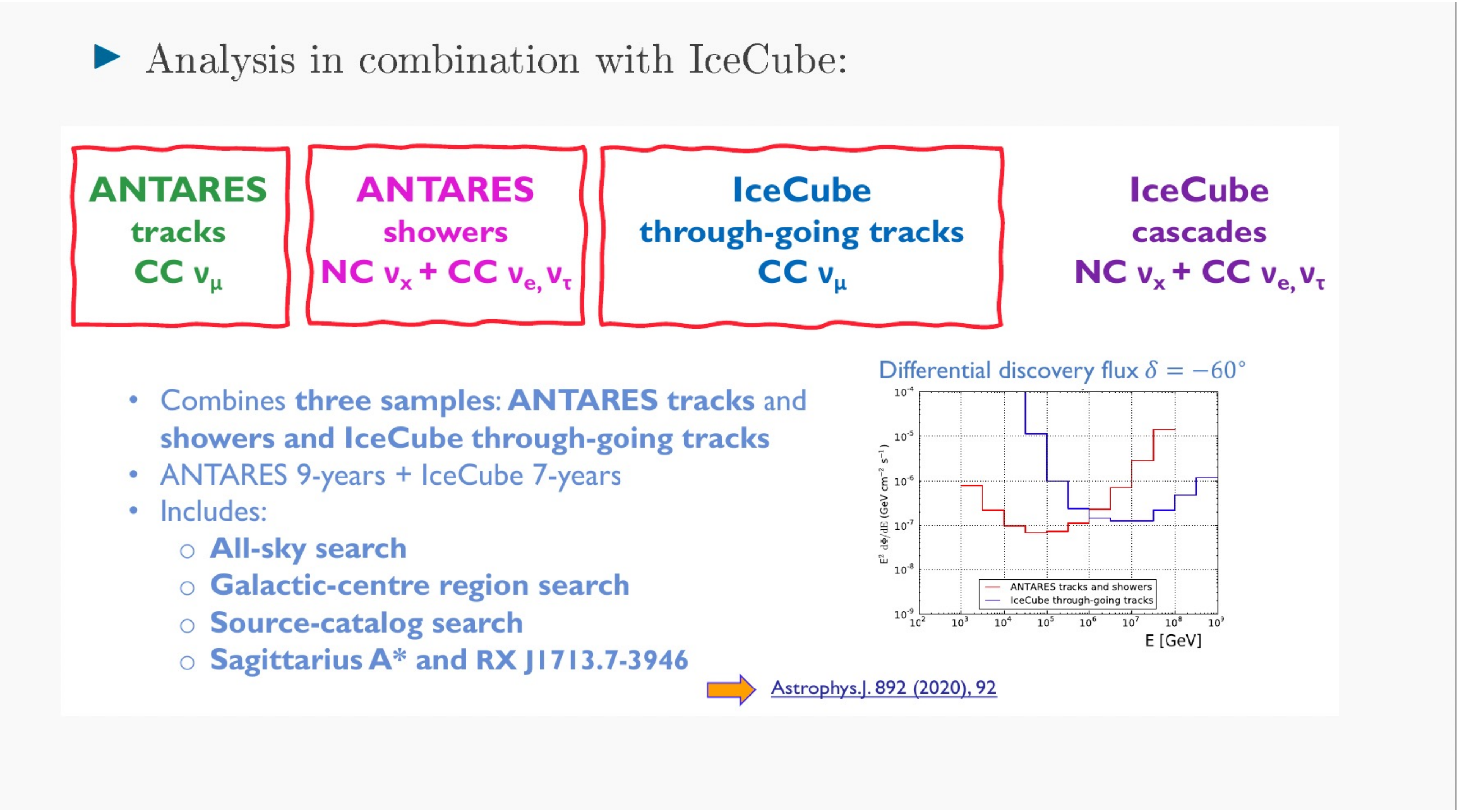
- Analysis (1) all-sky (4π) search
- Analysis (2) source list search: 110 gamma-selected objects
- Most significant candidate source coincides with most significant all-sky search: NGC 1068 / M 77 (a Seyfert II galaxy)
- (Nothing significant seen by ANTARES)

All-sky search for discrete neutrino sources



- Population analysis (search for excess of weak sources): 3.3 σ post-trials, for combination of 4 sources each with p<0.01 in source list search: NGC 1068 and 3 blazars (TXS 0506+056, PKS 1424+240, GB6 J1542+6129)
- Excluding TXS 0506+056: 2.3 σ post-trials; NGC 1068 alone: 2.9 σ post-trials (4.1 σ pre-trials)

Search for discrete sources



- Analysis in combination with IceCube:

ANTARES
tracks
CC ν_μ

ANTARES
showers
NC ν_x + CC ν_e, ν_τ

IceCube
through-going tracks
CC ν_μ

IceCube
cascades
NC ν_x + CC ν_e, ν_τ

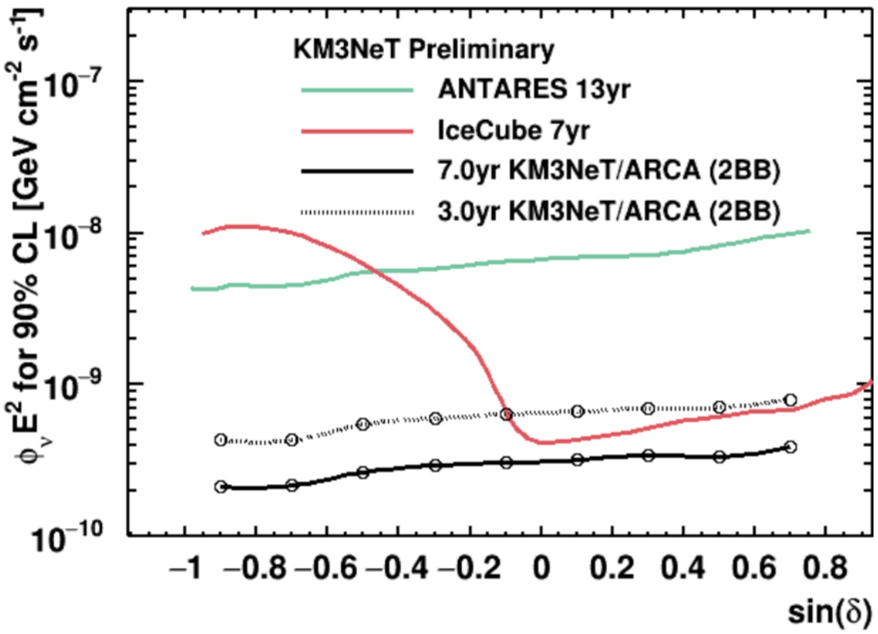
- Combines **three samples: ANTARES tracks** and **showers and IceCube through-going tracks**
- ANTARES 9-years + IceCube 7-years
- Includes:
  - **All-sky search**
  - **Galactic-centre region search**
  - **Source-catalog search**
  - **Sagittarius A* and RX J1713.7-3946**

Differential discovery flux $\delta = -60°$

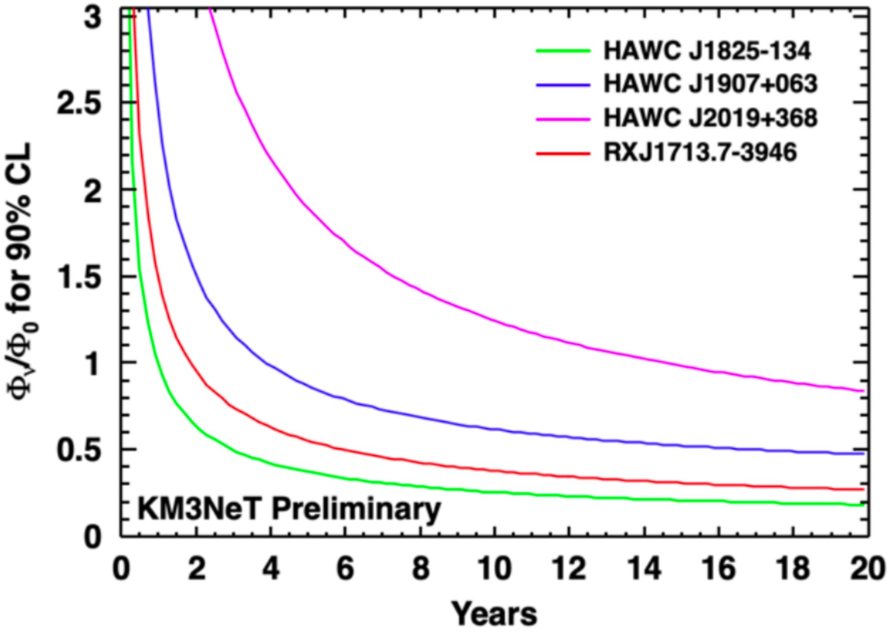
Astrophys.J. 892 (2020), 92

No excess reported – Improved (x2) sensitivity in Southern Sky for hard spectra

Prospects for KM3NeT-ARCA



E^{-2} neutrino flux 90% CL sensitivity



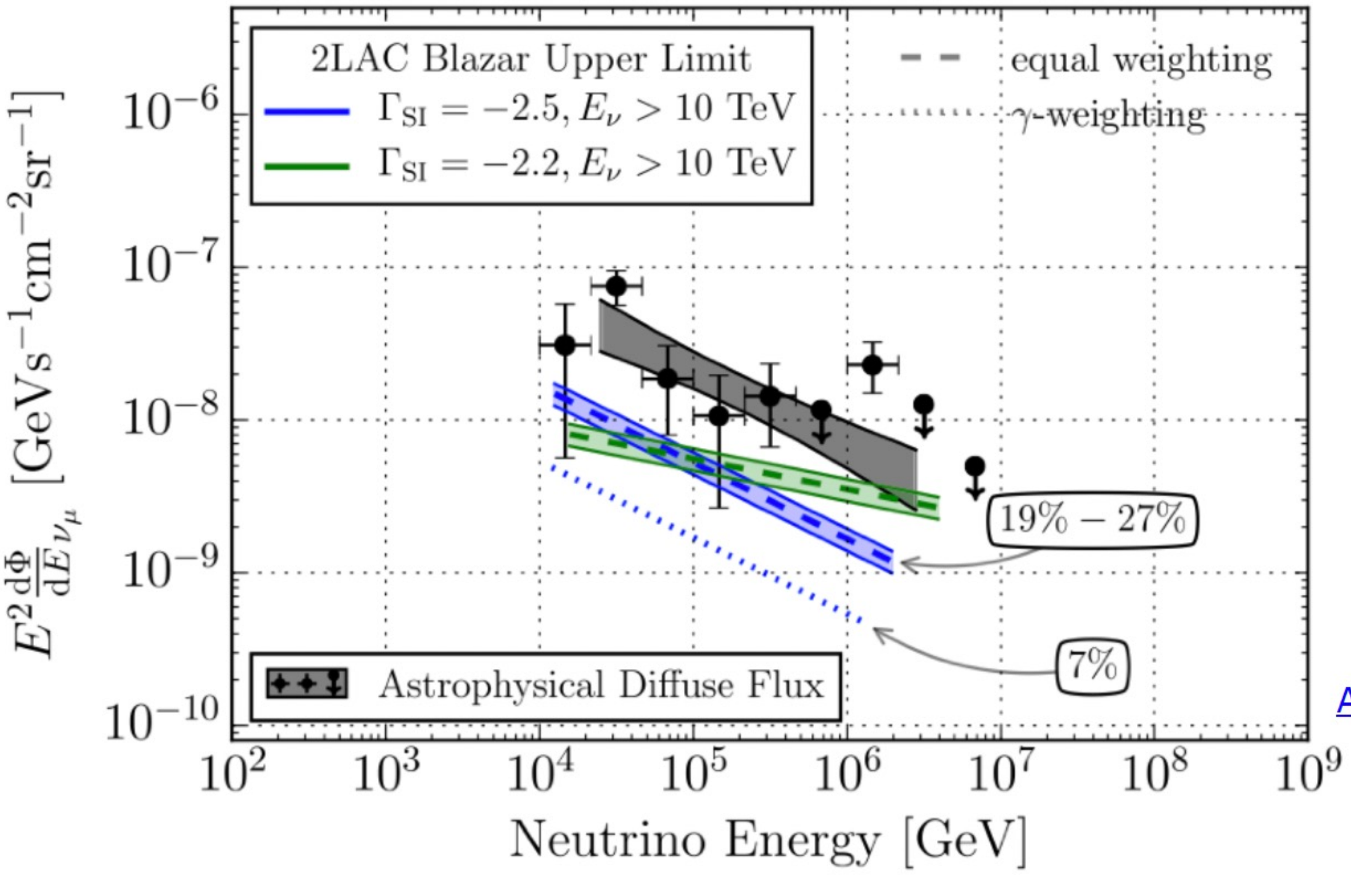
90% CL sensitivity for several candidate sources

More than order of magnitude improvement in Southern Hemisphere

Directly constrain (or discover) hadronic scenario in galactic TeV gamma sources

Population searches – Fermi blazars

Contribution of Fermi-LAT blazars to the IceCube diffuse neutrino spectrum

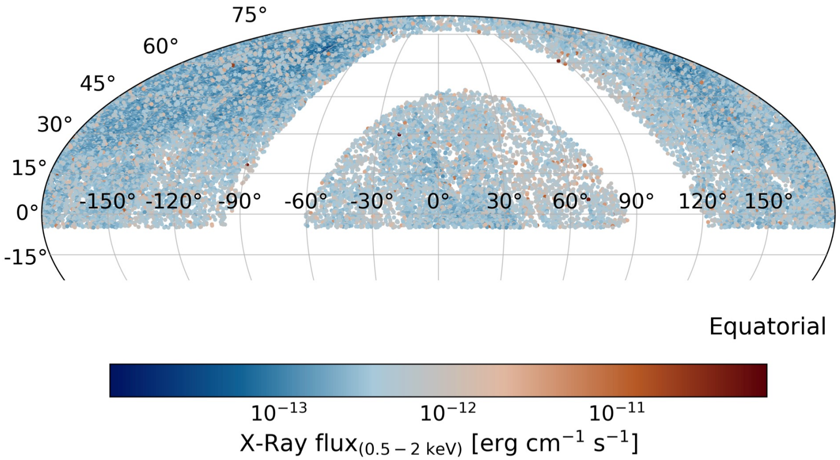


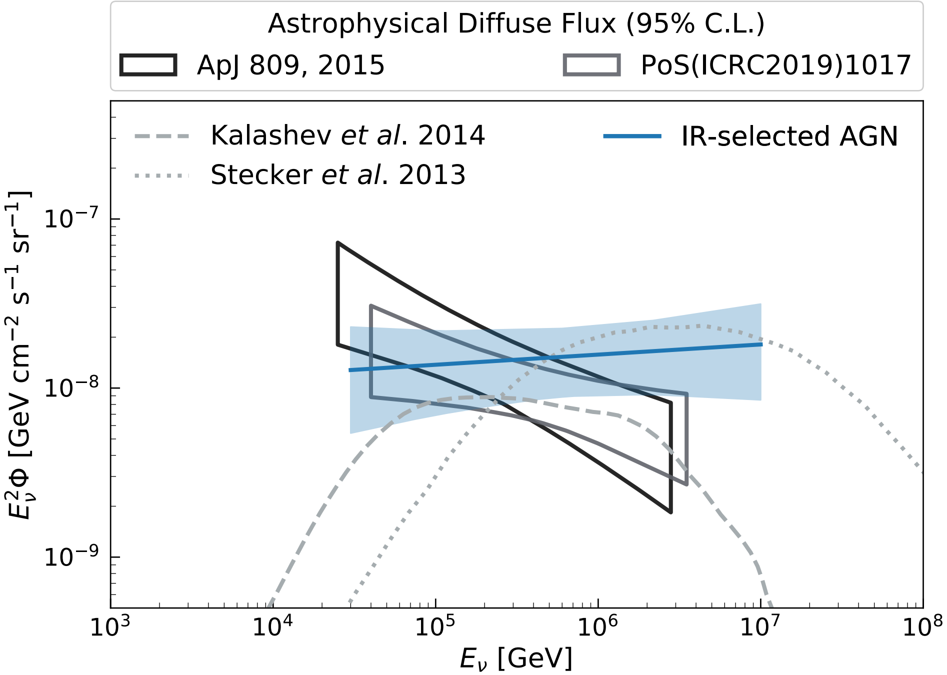
Aartsen et al. 2017

Cannot contribute to more than ~20%

Population searches – AGNs

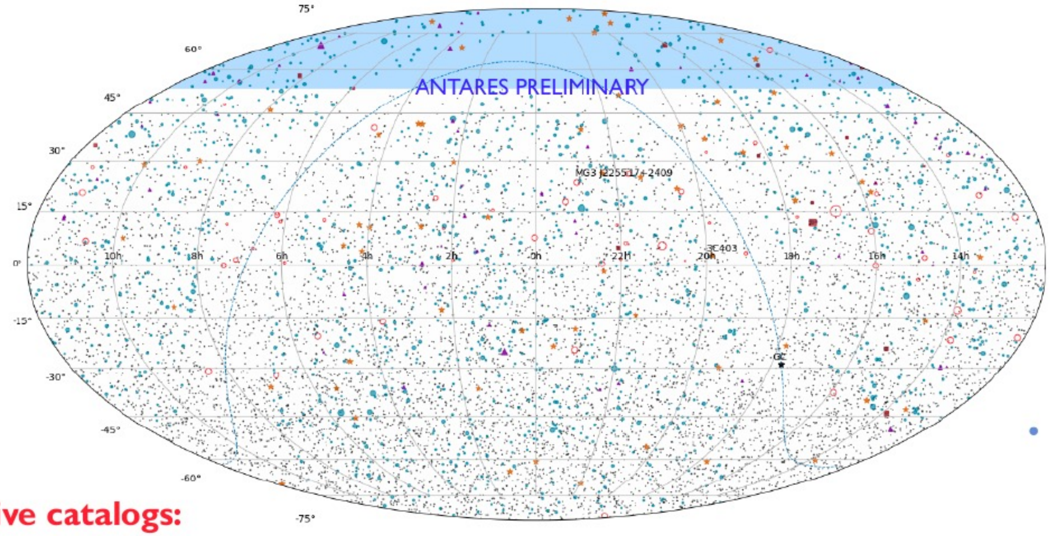
- Analysis of 32,249 AGN selected based on their infrared emission
- 2.60 σ excess
- Could produce 100% of the astrophysical neutrino signal at 100 TeV





Population sources with ANTARES

- Population search : evaluate the global degree of correlation with all the sources in different catalogs:



Two types of **source weights** in likelihood implemented:

- **Flux weight:** $w \propto \Phi_{\gamma,X,IR}$
- **Equal weight:** $w = 1$

Five catalogs:

· ANTARES tracks ○ IC HE tracks ● Fermi 3LAC Blazars ★ Radio Galaxies ▲ Star Forming Galaxies ■ Dust Obscured AGN

ANTARES data set: 8754 tracks

55 IceCube HE tracks (through-going and HESE)

[IceCube collaboration, ICRC 2017]

1255 Blazars detected in the 1-100 GeV range by Fermi

[Ackermann et al. ApJ 2015]

53 Radio Galaxies selected in soft γ-ray

[Bassani et al. MNRAS 2016]

54 Star Forming Galaxies observed in γ by Fermi

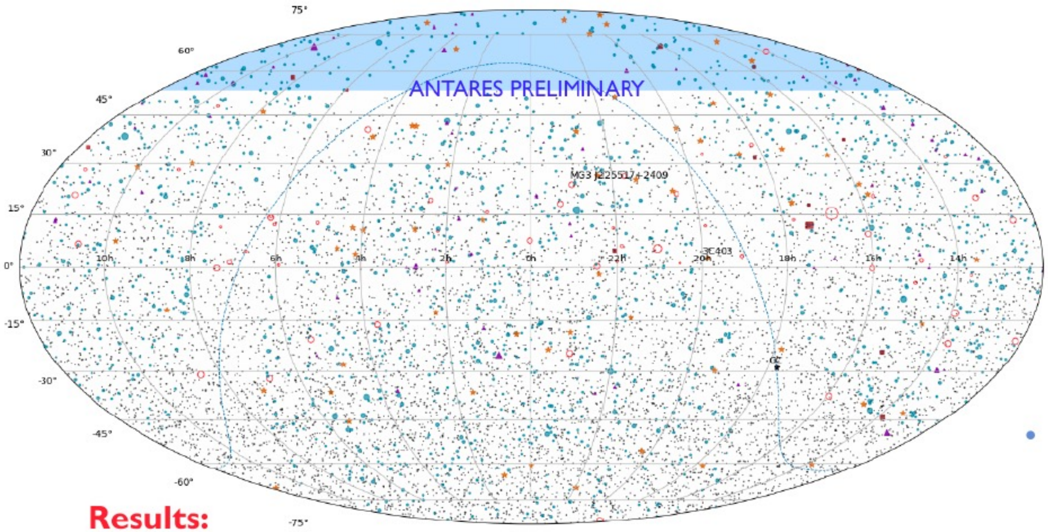
[Ackermann et al. ApJ 2012]

10 Dust Obscured AGNs selected in X-rays

[Maggi et al. PhysRevD 2016]

Population sources with ANTARES

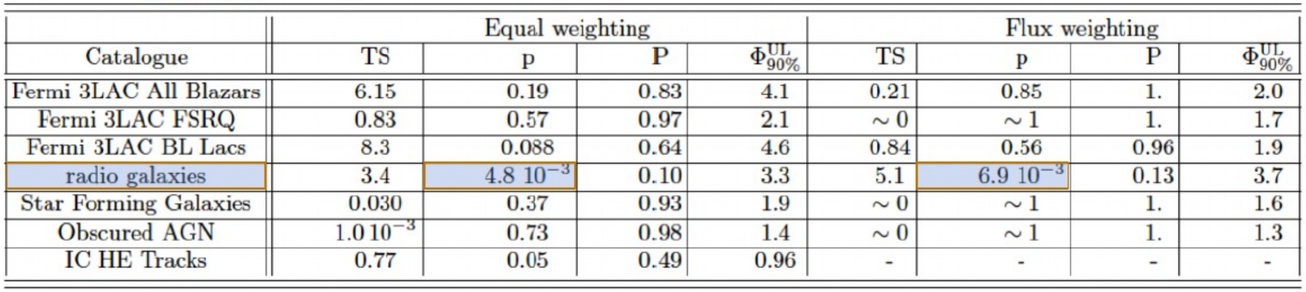
- Hint of excess for the radiogalaxies:



Two types of **source weights** in likelihood implemented:

- **Flux weight:** $w \propto \Phi_{\gamma,X,IR}$
- **Equal weight:** $w = 1$

Results:



	Equal weighting				Flux weighting			
Catalogue	TS	p	P	$\Phi^{UL}_{90\%}$	TS	p	P	$\Phi^{UL}_{90\%}$
Fermi 3LAC All Blazars	6.15	0.19	0.83	4.1	0.21	0.85	1.	2.0
Fermi 3LAC FSRQ	0.83	0.57	0.97	2.1	~ 0	~ 1	1.	1.7
Fermi 3LAC BL Lacs	8.3	0.088	0.64	4.6	0.84	0.56	0.96	1.9
radio galaxies	3.4	$4.8\ 10^{-3}$	0.10	3.3	5.1	$6.9\ 10^{-3}$	0.13	3.7
Star Forming Galaxies	0.030	0.37	0.93	1.9	~ 0	~ 1	1.	1.6
Obscured AGN	$1.0\ 10^{-3}$	0.73	0.98	1.4	~ 0	~ 1	1.	1.3
IC HE Tracks	0.77	0.05	0.49	0.96	-	-	-	-

Best catalog
2.8σ pre-trial
1.6σ post-trial

90% U.L given in equivalent E^{-2} diffuse flux
(10^{-9} GeV^{-1} cm^{-2} s^{-1} sr^{-1})

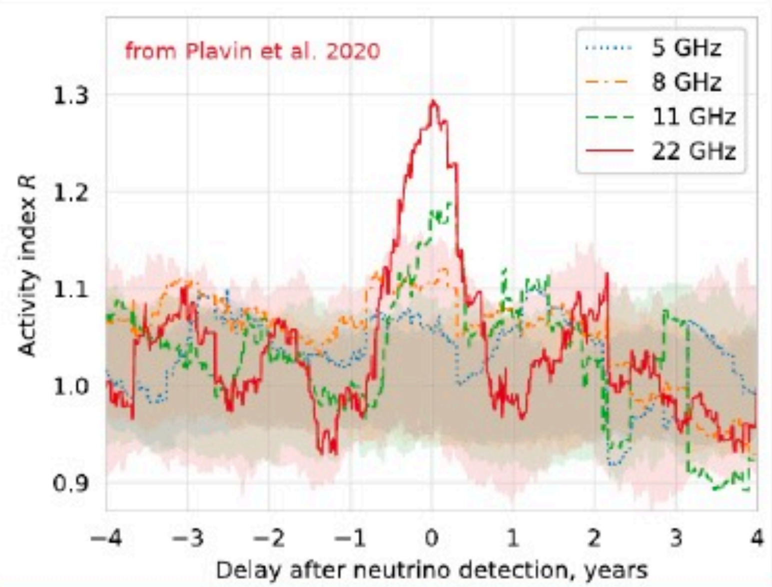
Correlation with radio-blazars ?

Recent evidence for Radio Blazars- IC neutrinos association

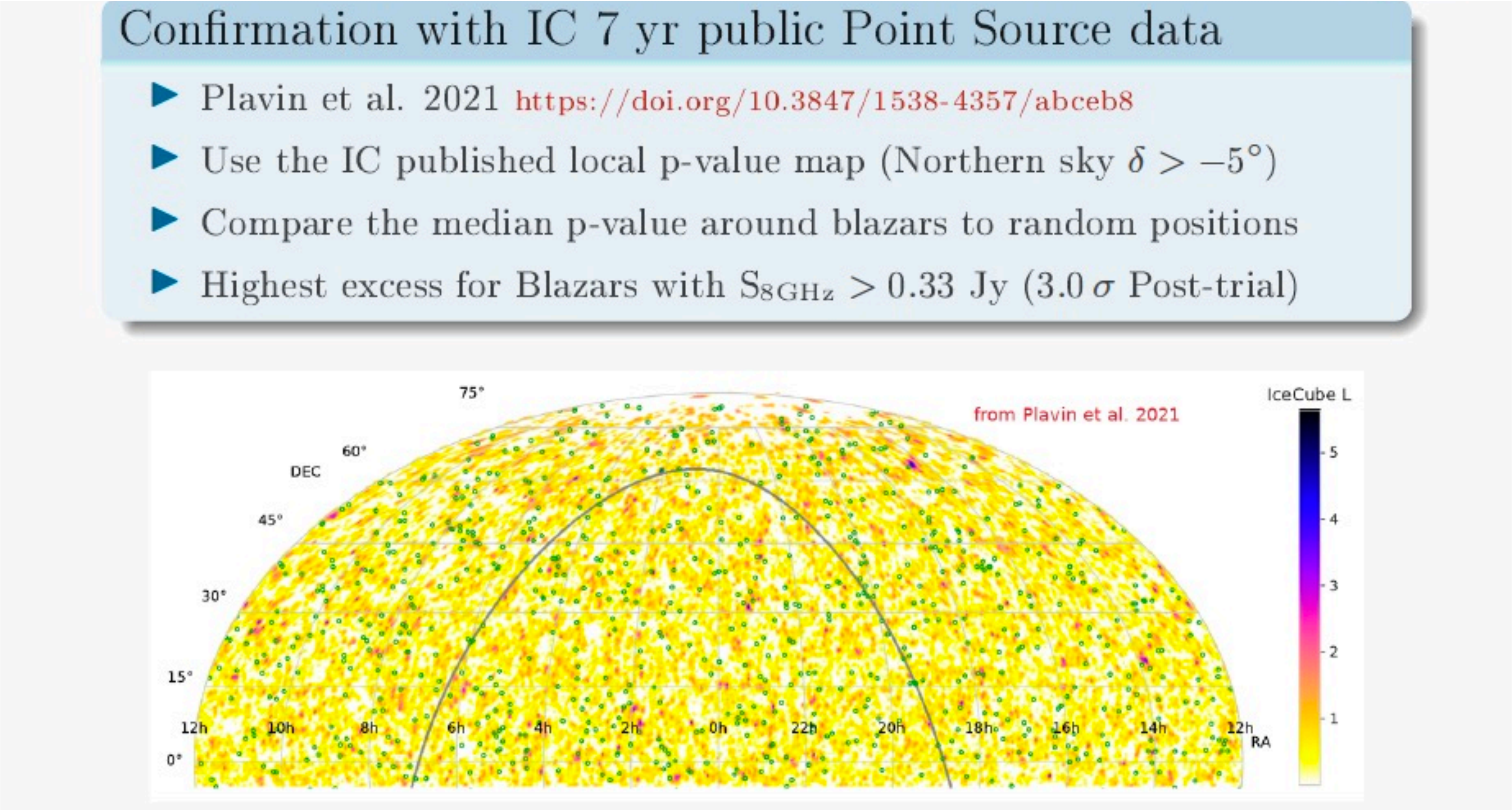
- Plavin et al. 2020 https://doi.org/10.3847/1538-4357/ab86bd
- Neutrinos: 56 IceCube tracks with E > 200 TeV (33 from EHEA + 23 from HESE, HESEA, MUONT)
- Blazars: 3388 objects selected in the 8 GHz band from VLBI observations (parsec-scale resolution of the AGN core)

Time correlation study

- Use RATAN-600 AGN monitoring data 2009-2019
- Higher radio activity observed @11 GHz and 22 GHz for ∼ months around neutrino detection



Correlation with radio-blazars ?



Confirmation with IC 7 yr public Point Source data

- Plavin et al. 2021 https://doi.org/10.3847/1538-4357/abceb8
- Use the IC published local p-value map (Northern sky $\delta > -5°$)
- Compare the median p-value around blazars to random positions
- Highest excess for Blazars with $S_{8\mathrm{GHz}} > 0.33$ Jy ($3.0\,\sigma$ Post-trial)

from Plavin et al. 2021

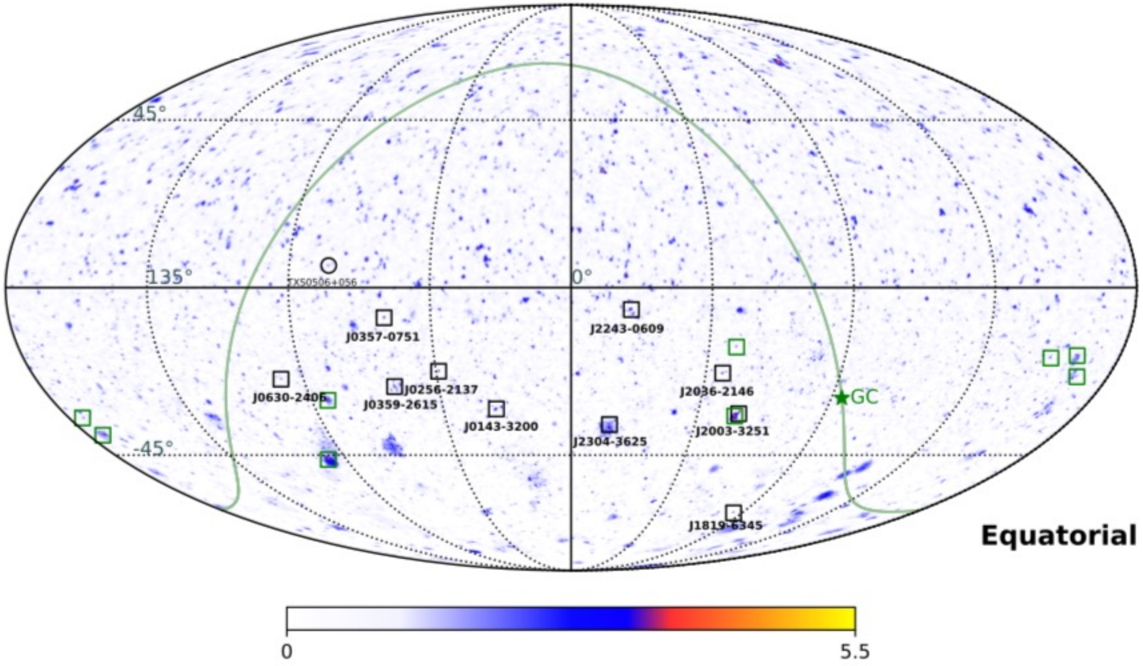
Recent article - IC public data

📖 Buson et al. 2022, ApJL , 933, 43;

Beginning a journey across the Universe: the discovery of extragalactic neutrino factories

Sara Buson[1], Andrea Tramacere[2], Leonard Pfeiffer[1], Lenz Oswald[1], Raniere de Menezes,[1]
Alessandra Azzollini[1] and Marco Ajello[3]

blazars, and others putting into question such relation. In this work we show that blazars are unambiguously associated with high-energy astrophysical neutrinos at unprecedented level of confidence, i.e. chance probability of 6×10^{-7}. Our statistical analysis provides the observational evidence that blazars are astrophysical neutrino factories and hence, extragalactic cosmic-ray accelerators.



Sky region	5BZCat	Hotspots	Matches	pre-trial p-value	post-trial p-value
Southern sky ($L \geq 4$)	1177	19	10	3×10^{-7}	6×10^{-7}

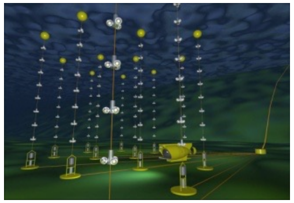
Outline

Neutrino astronomy

Scientific motivations

Historical aspects

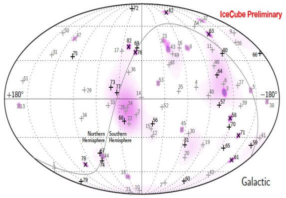
Cosmic neutrino sources



Neutrino telescope

Detection principles

Current telescopes



Selected results

Diffuse Flux, point sources

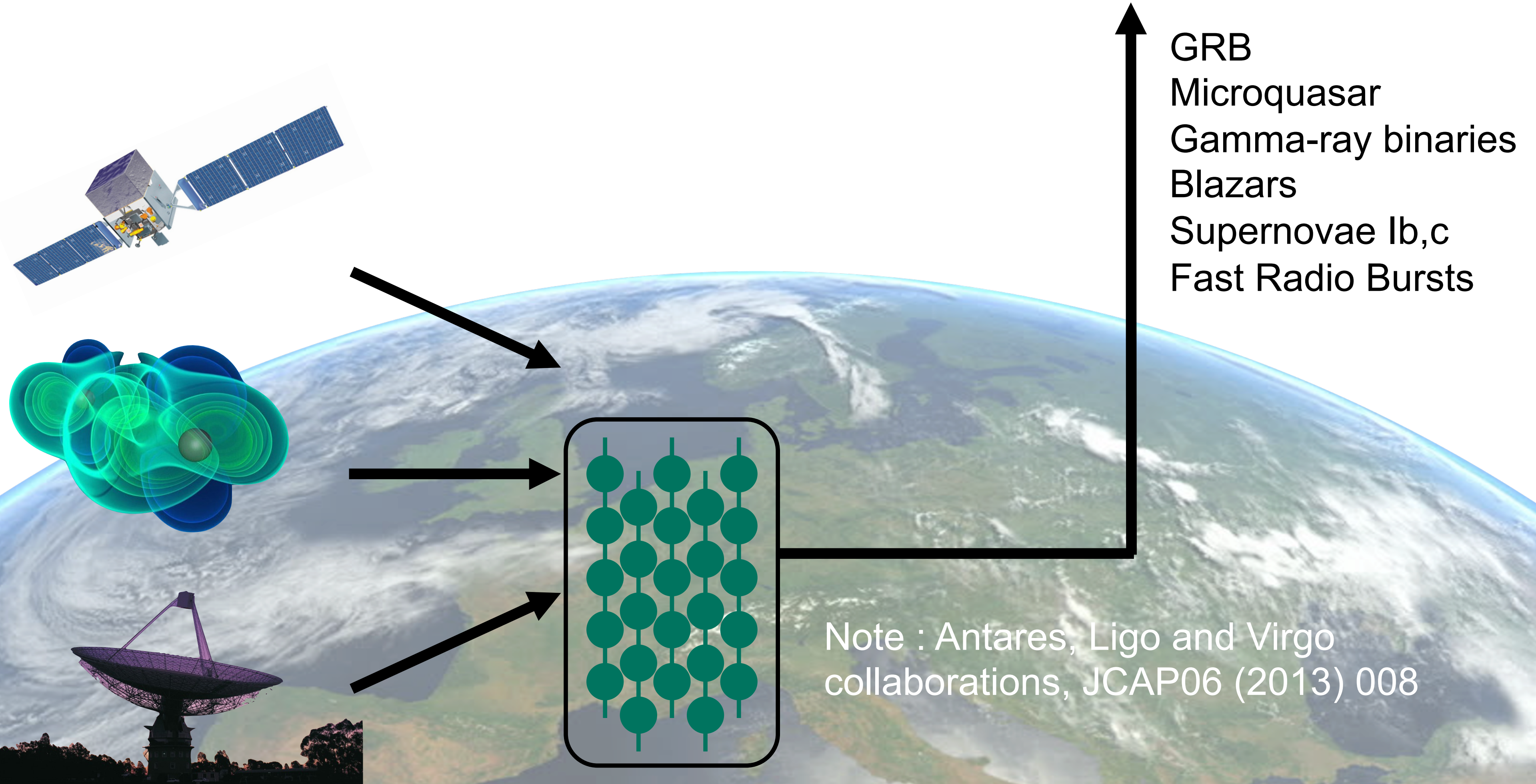
Multi-messenger search

KM3NeT

ORCA prospects

The multi-messenger program

1ST APPROACH:

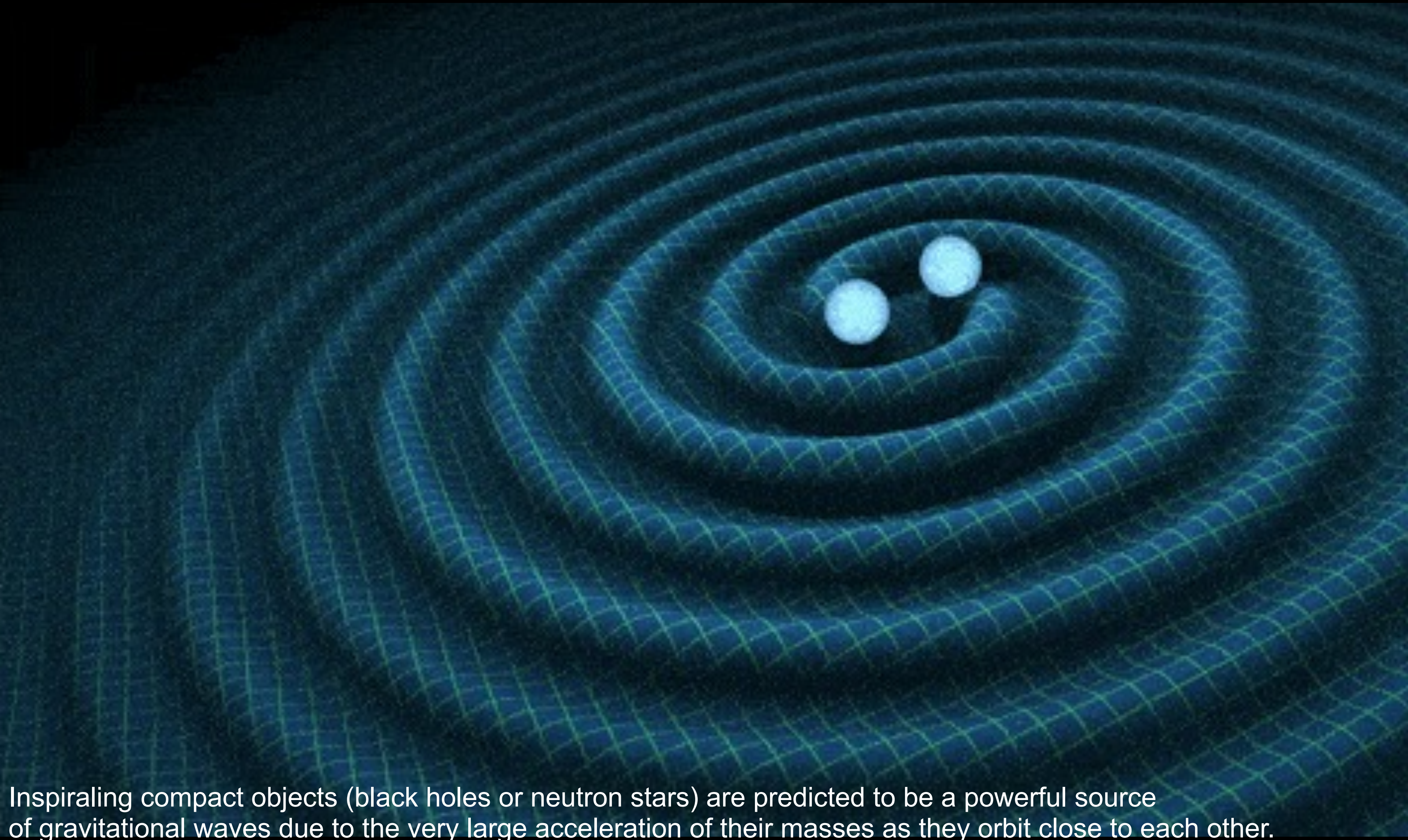


Time dependent searches

GRB
Microquasar
Gamma-ray binaries
Blazars
Supernovae Ib,c
Fast Radio Bursts

Note : Antares, Ligo and Virgo collaborations, JCAP06 (2013) 008

Gravitational Waves

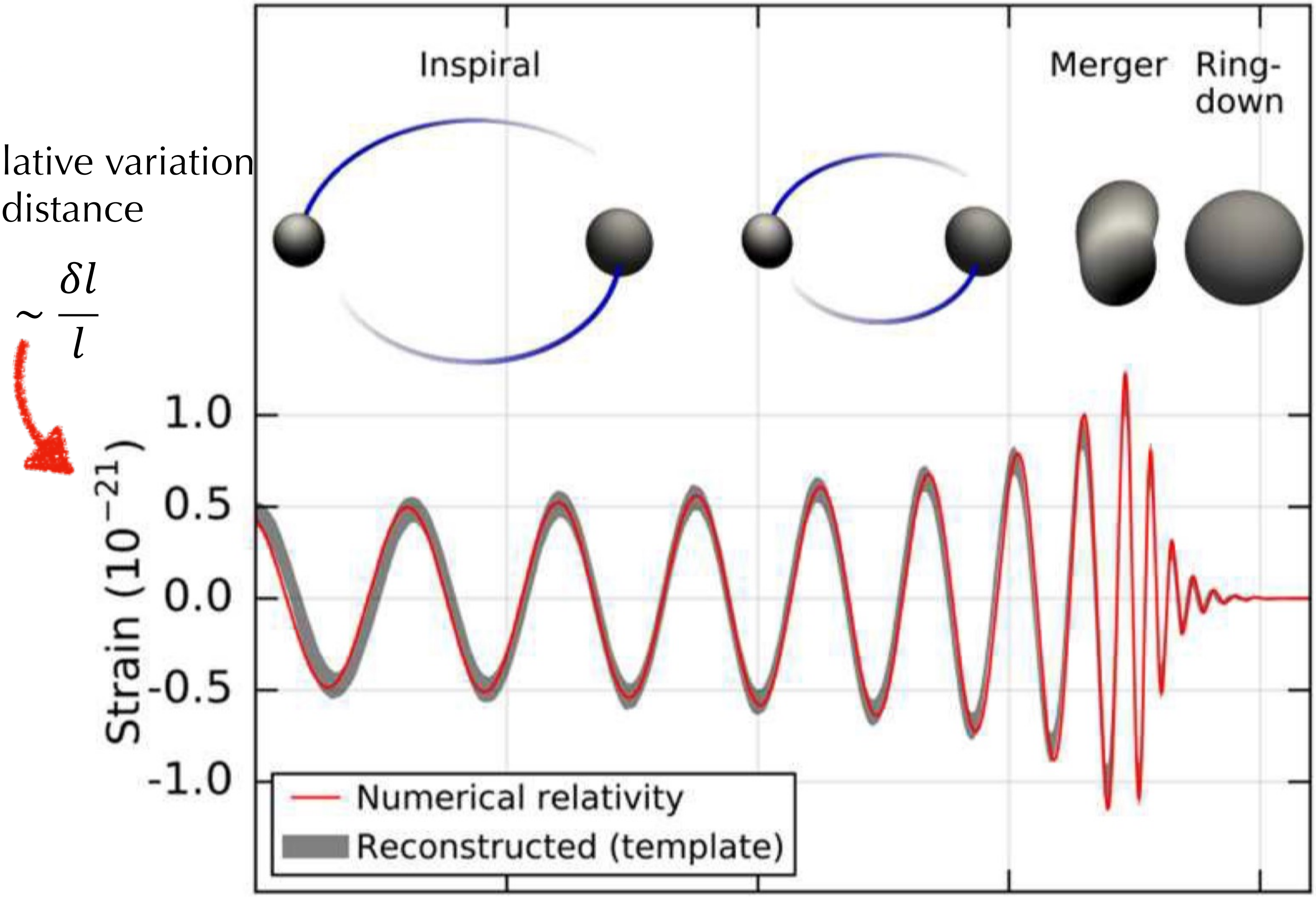


Inspiraling compact objects (black holes or neutron stars) are predicted to be a powerful source of gravitational waves due to the very large acceleration of their masses as they orbit close to each other.

Gravitational Waves

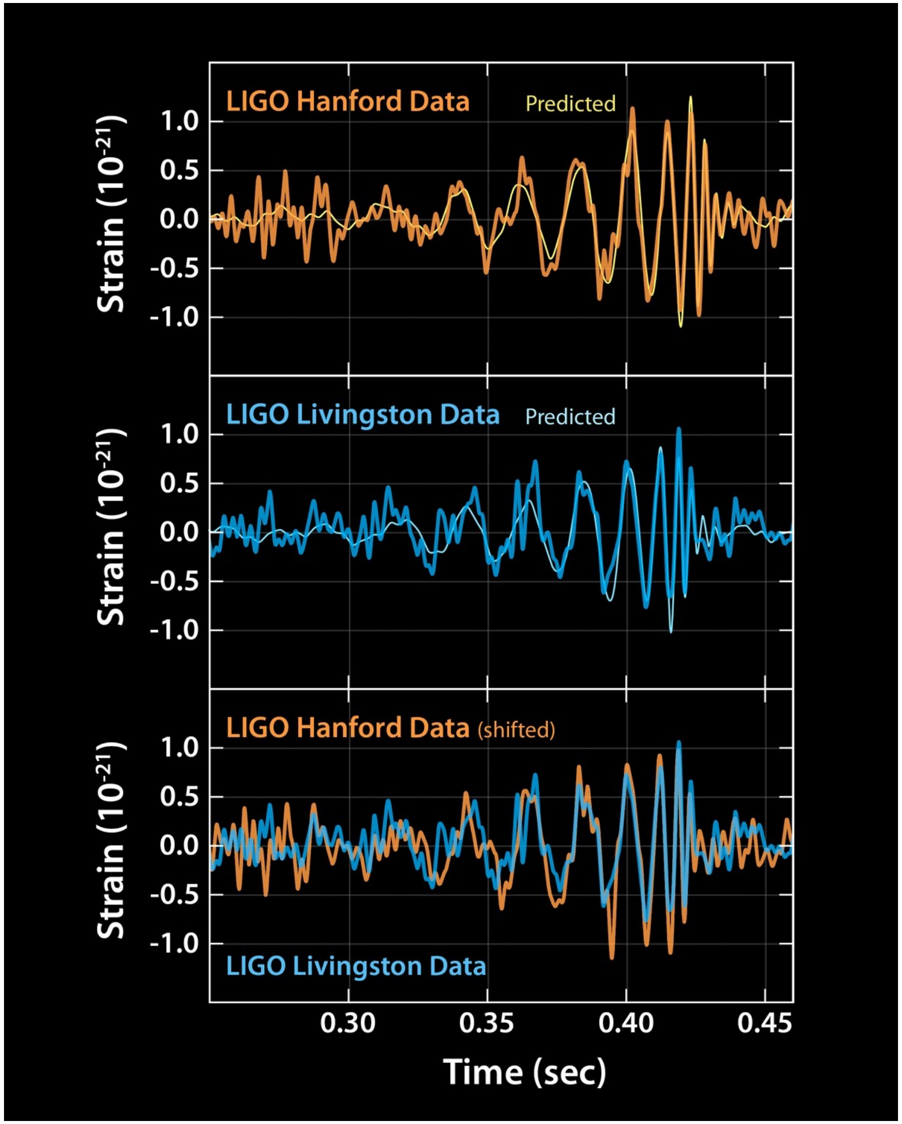
Relative variation of distance

$$\sim \frac{\delta l}{l}$$

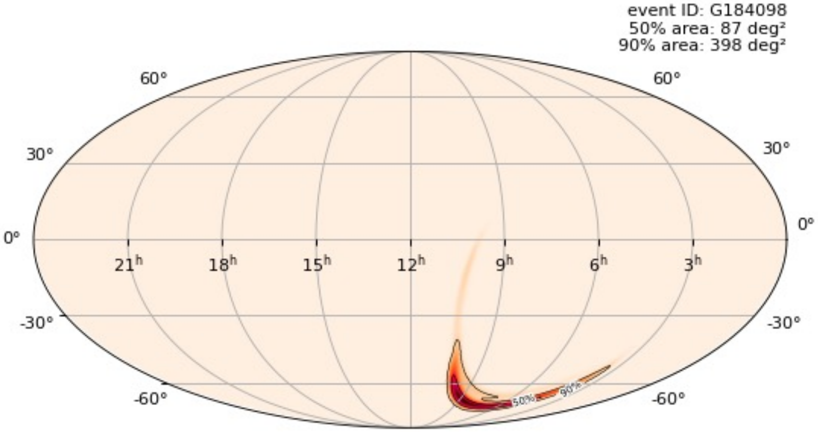


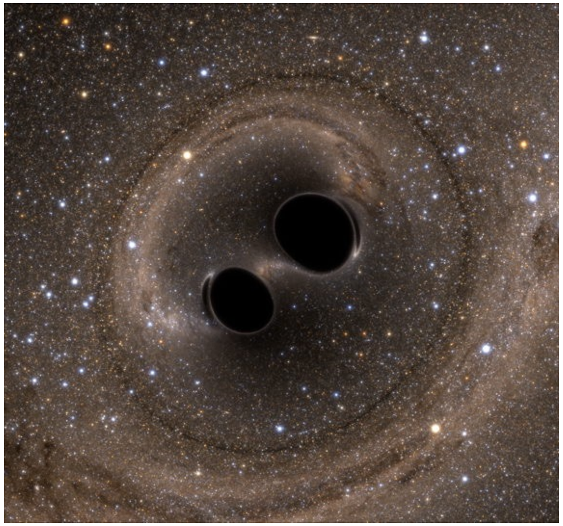
First detection: GW150914

September 14, 2015



GW150914: Coalescence of two black holes of 36 and 29 $M_\odot$ respectively



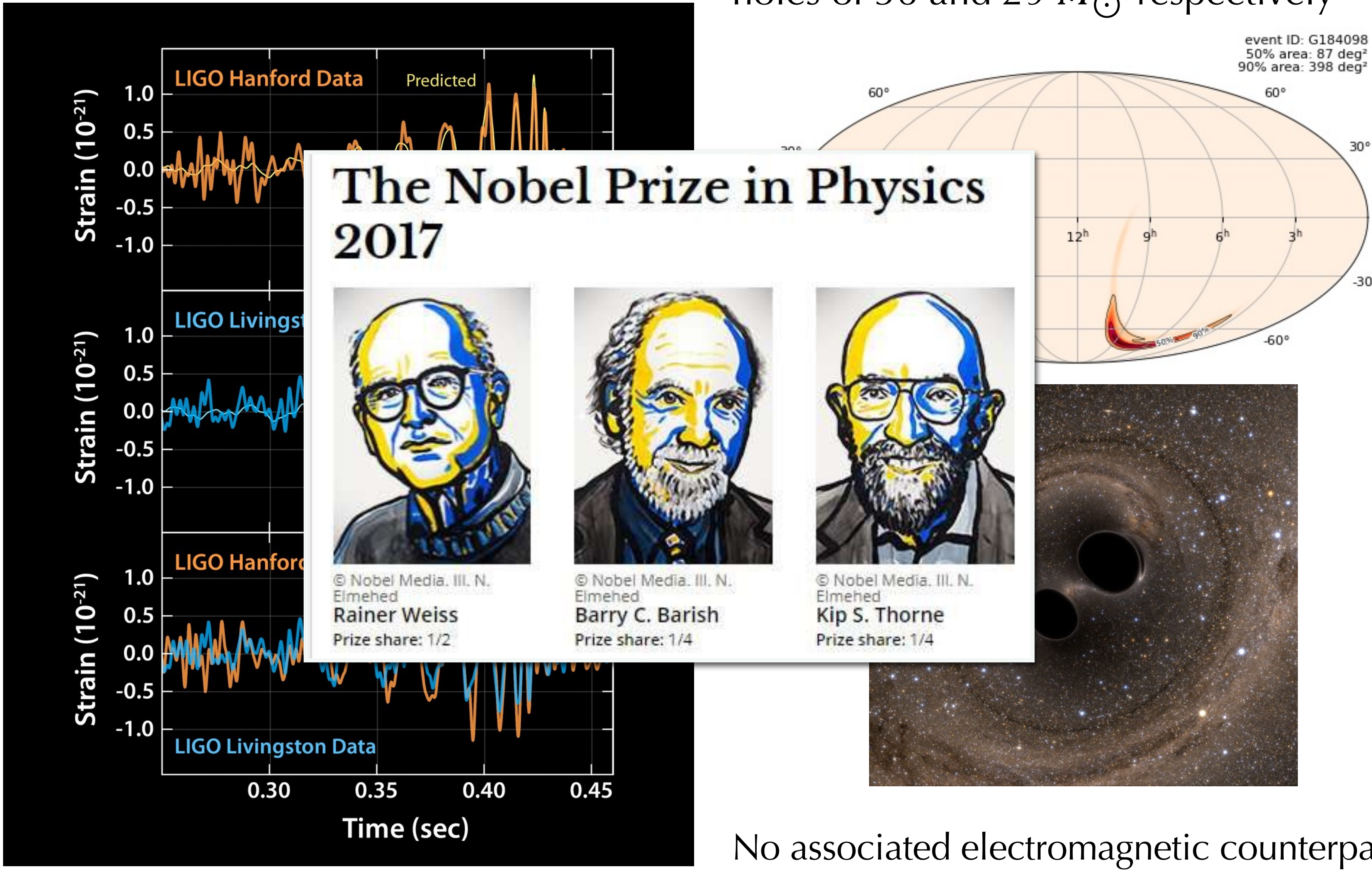


No associated electromagnetic counterpart…

First detection: GW150914

September 14, 2015

GW150914: Coalescence of two black holes of 36 and 29 $M_\odot$ respectively



The Nobel Prize in Physics 2017

© Nobel Media. Ill. N. Elmehed
Rainer Weiss
Prize share: 1/2

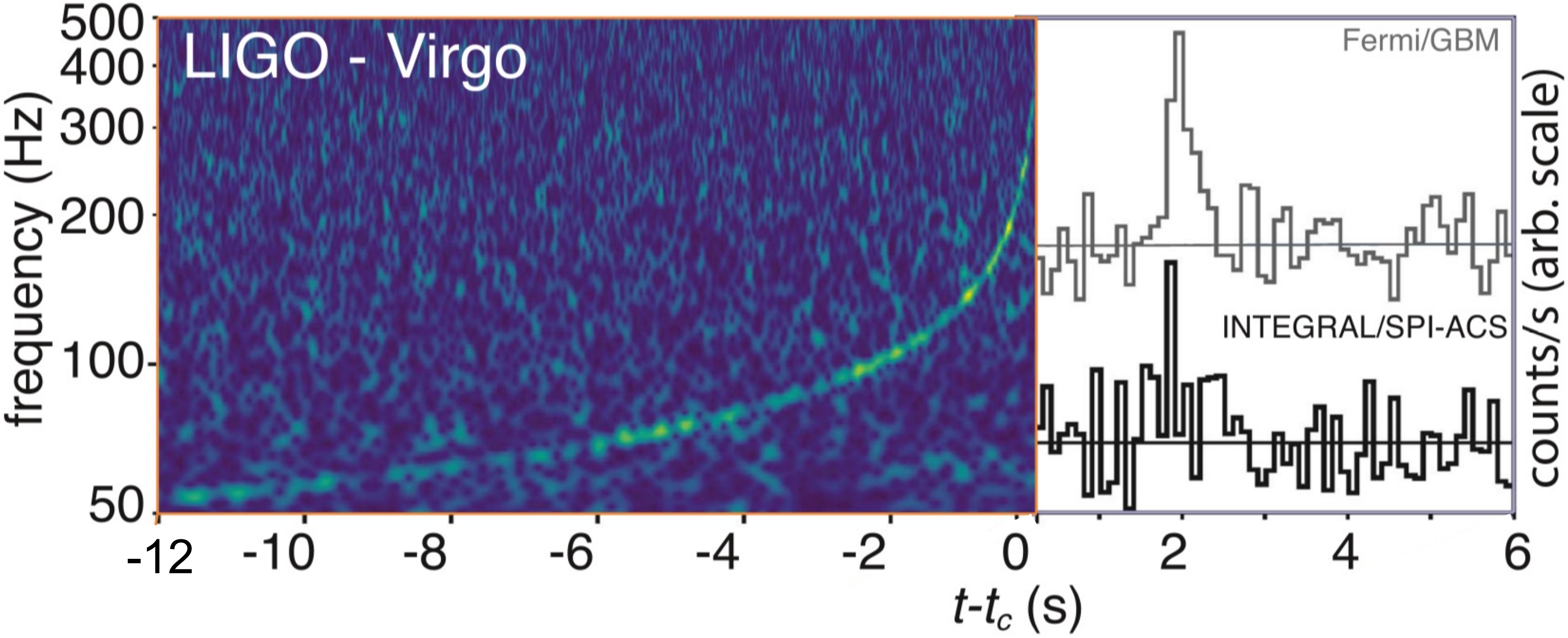
© Nobel Media. Ill. N. Elmehed
Barry C. Barish
Prize share: 1/4

© Nobel Media. Ill. N. Elmehed
Kip S. Thorne
Prize share: 1/4

No associated electromagnetic counterpart…

Gravitational wave signal GW170817

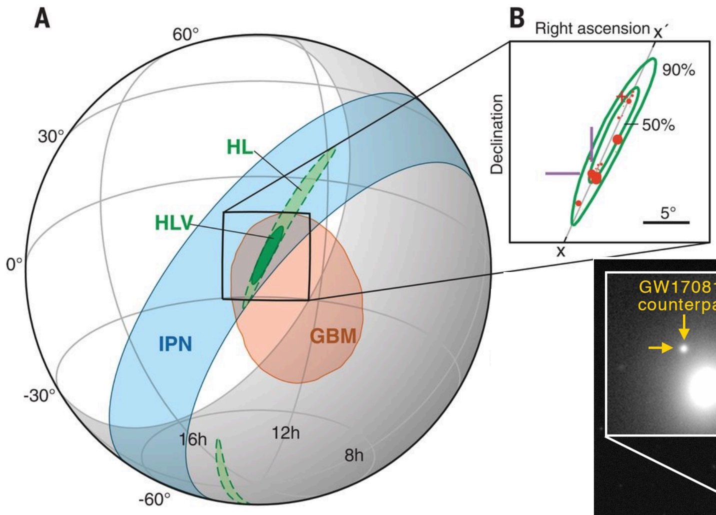
August 17, 2017 at 14h41m04s



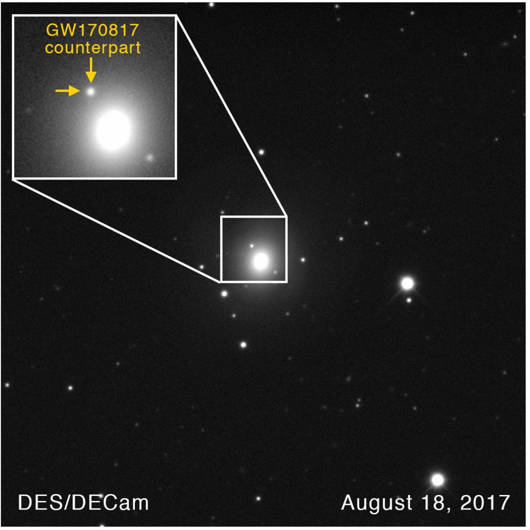
Gravitational wave signal GW170817

+2s Short GRB
GRB 170817A

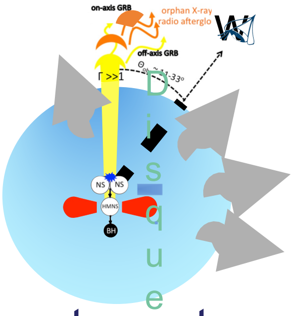
+5h Location
(30° ^{2}, 42 Mpc)

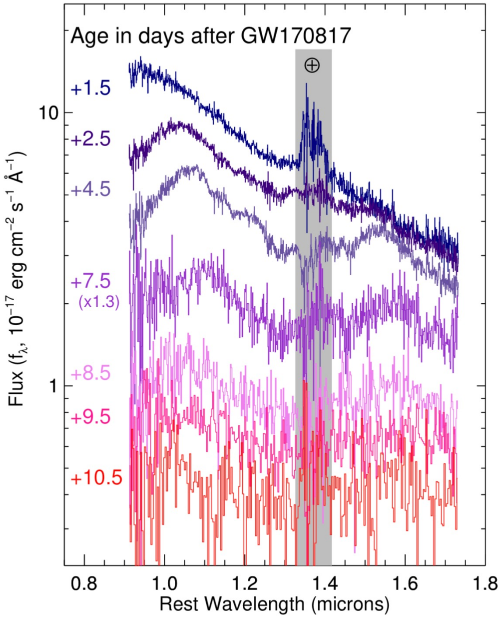


+11h Optical counterpart
AT2017gfo / NGC4993



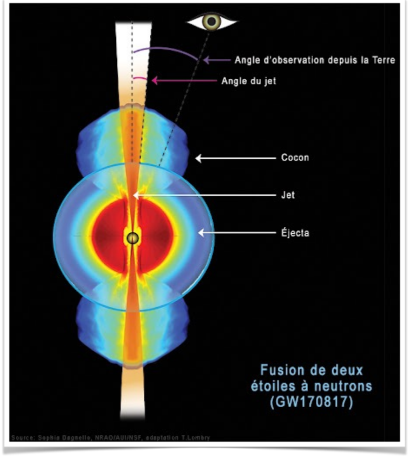
+1.2j Kilonova spectrum





+9j X-ray counterpart

+16j Radio counterpart

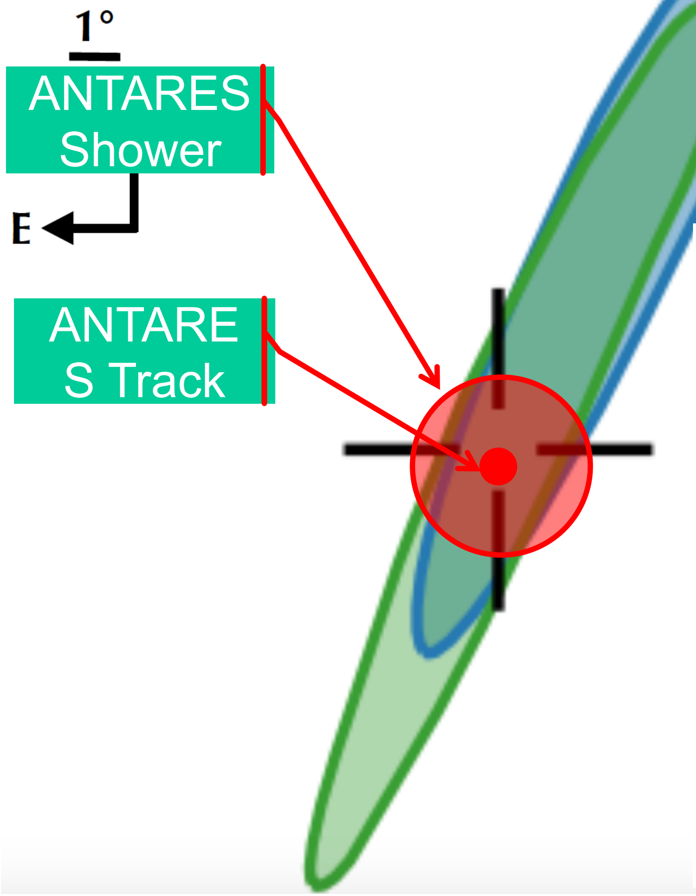


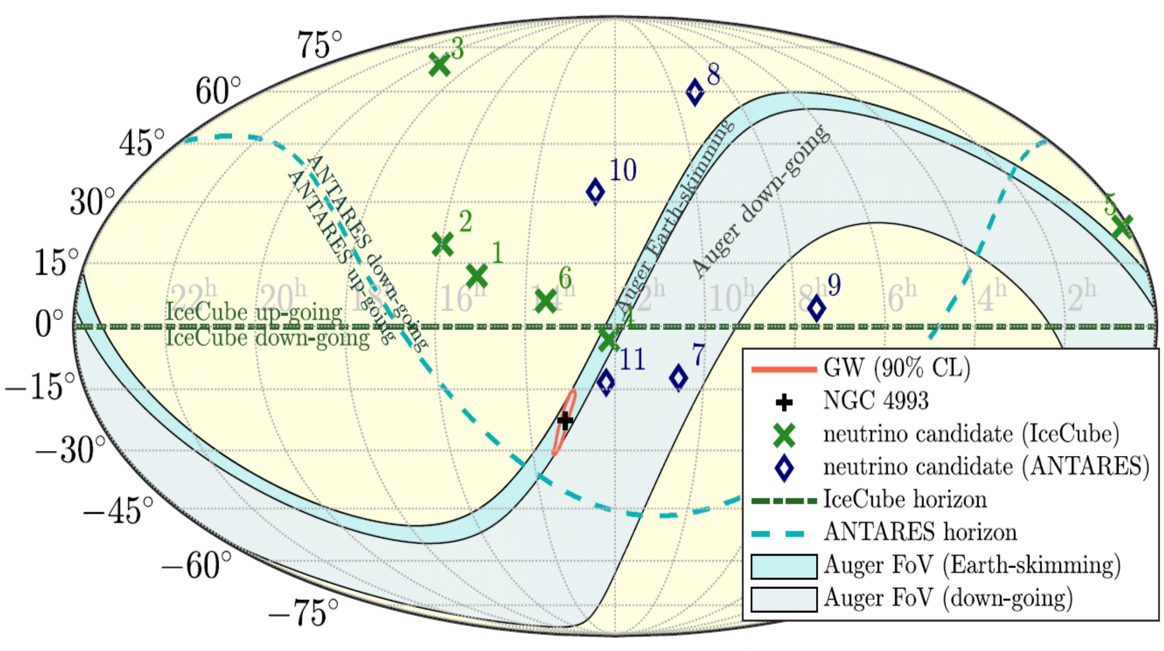
GW170817 Neutrino follow-up

NT:
field of view 2π-4π

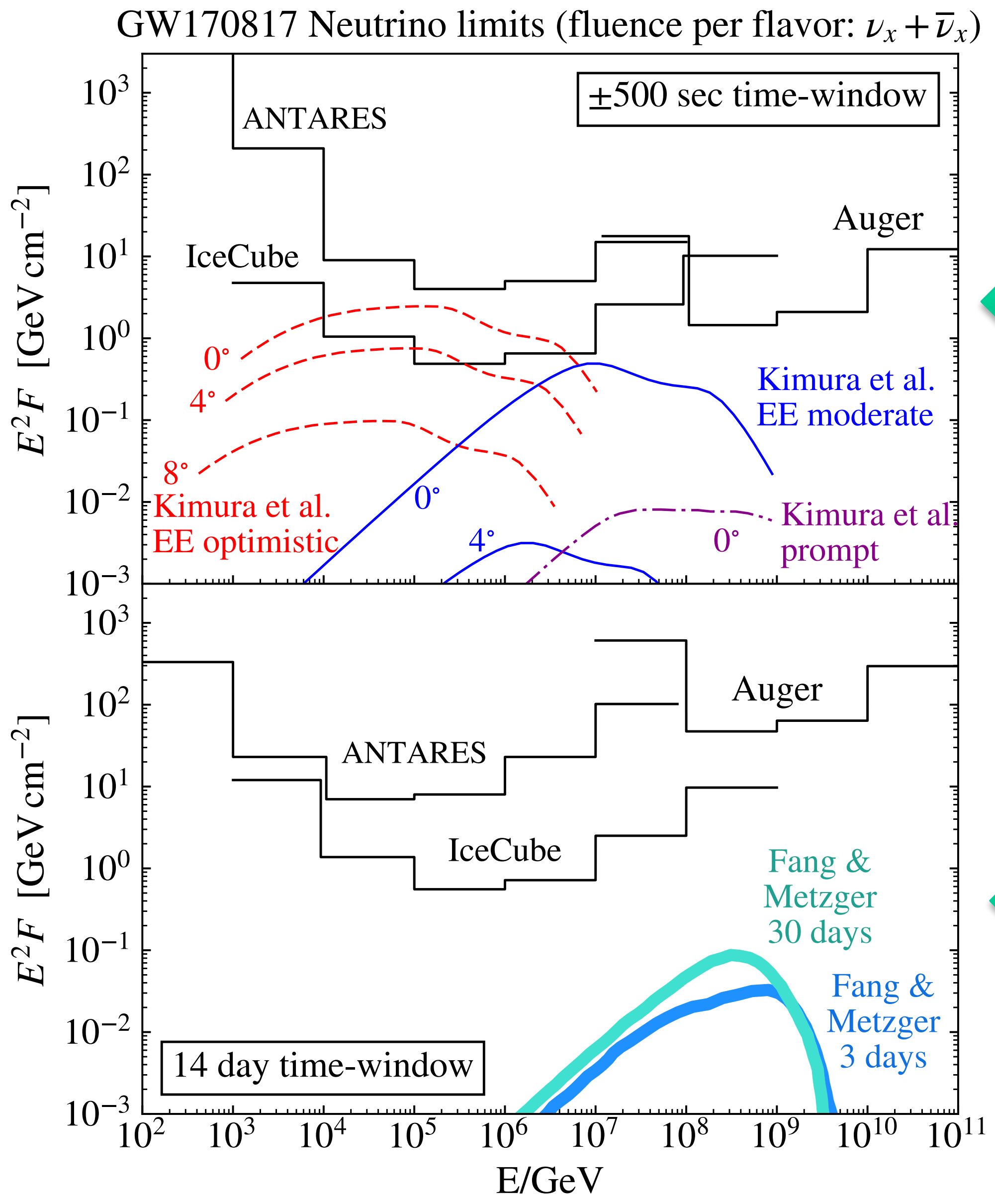
ApJL 850:L35 (2017)

(multimessenger): ApJL 848 L12 (2017)





GW170817 Neutrino follow-up



📖 ANTARES, IceCube, Pierre Auger,
LIGO Scientific and Virgo Collaborations
ApJL 850 L35 (2017)

Non-detection consistent with expectation from short GRB observed at large off-axis angle

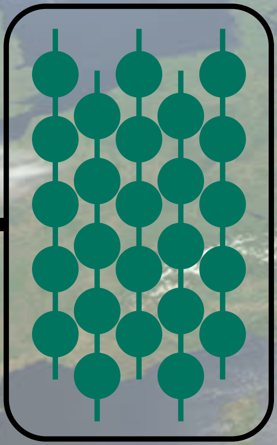
Model prediction:
Kimura et al. ApJL 848, L4

No detection during extended time period of 14 days after the GRB

Model prediction:
Fang, K., & Metzger, B. D. 2017, arXiv:1707.04263

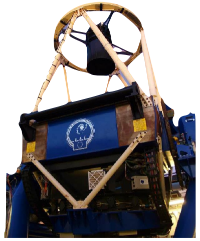
The multi-messenger program

2ND APPROACH:

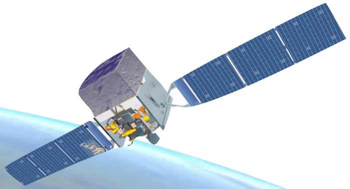


Real-time analysis

Alert triggering



H.E.S.S.

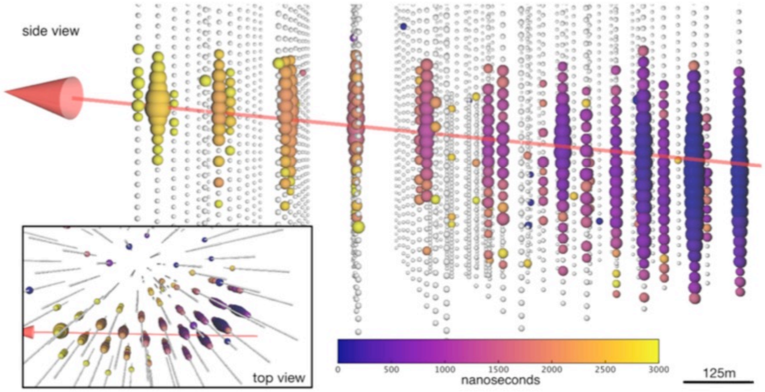


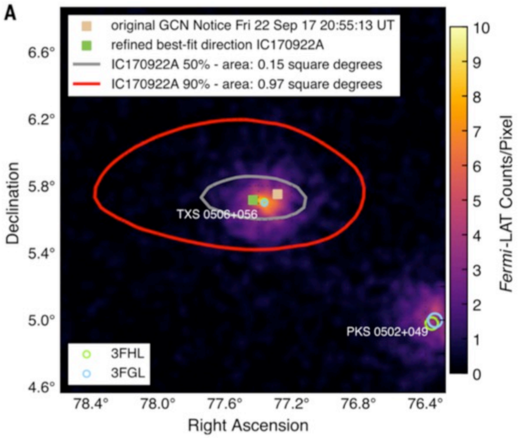
+ …

- Time to send an alert: ~5 s
- First optical image <20 s
- Median angular resolution: ~0.3°
- Triggers: single HE, preferred direction multiplets

Neutrinos from blazar TXS0506+056

Sept. 22, 2017:
A neutrino in coincidence with a blazar flare





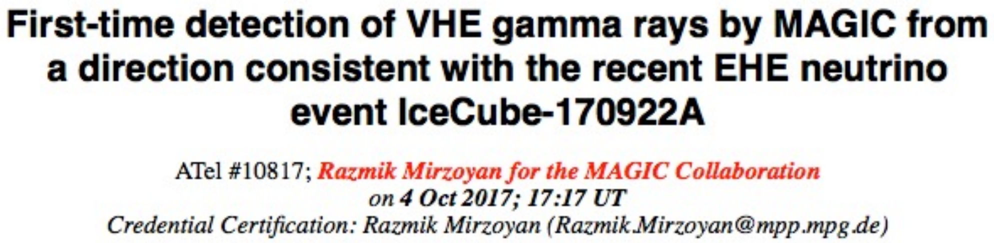
Observed by Fermi-*LAT* and MAGIC

Significance for correlation: 3σ

Science 361 (2018) no. 6398, eaat1378

- An **electromagnetic follow-up** campaign of the event IceCube-170922A* indicated that this event came from the direction of a known AGN blazar named TXS 0506+056.
- TXS 0506+056 is a BL Lac object, found at redshift $z=0.3365\pm0.0010$
- It was at that time flaring at multiple wavelengths.
- In particular, TXS 0506+056 was monitored by FERMI-LAT and observed by MAGIC after the IC trigger

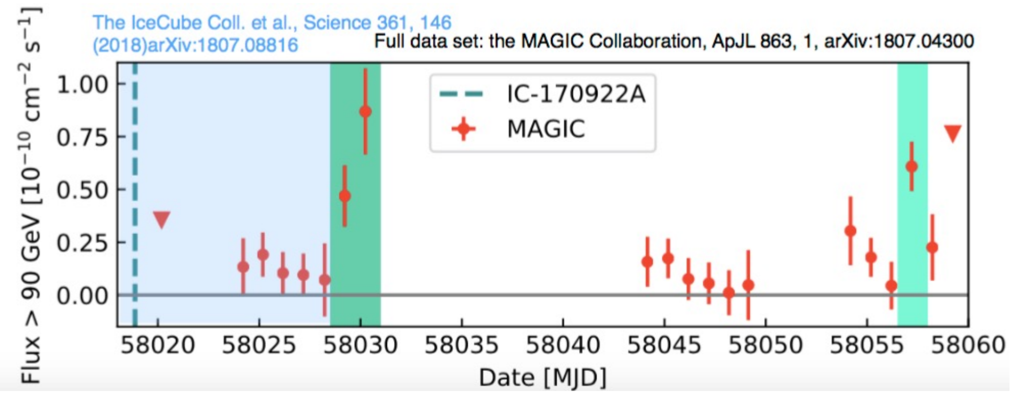
ICECUBE-170922 & Follow-ups



First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

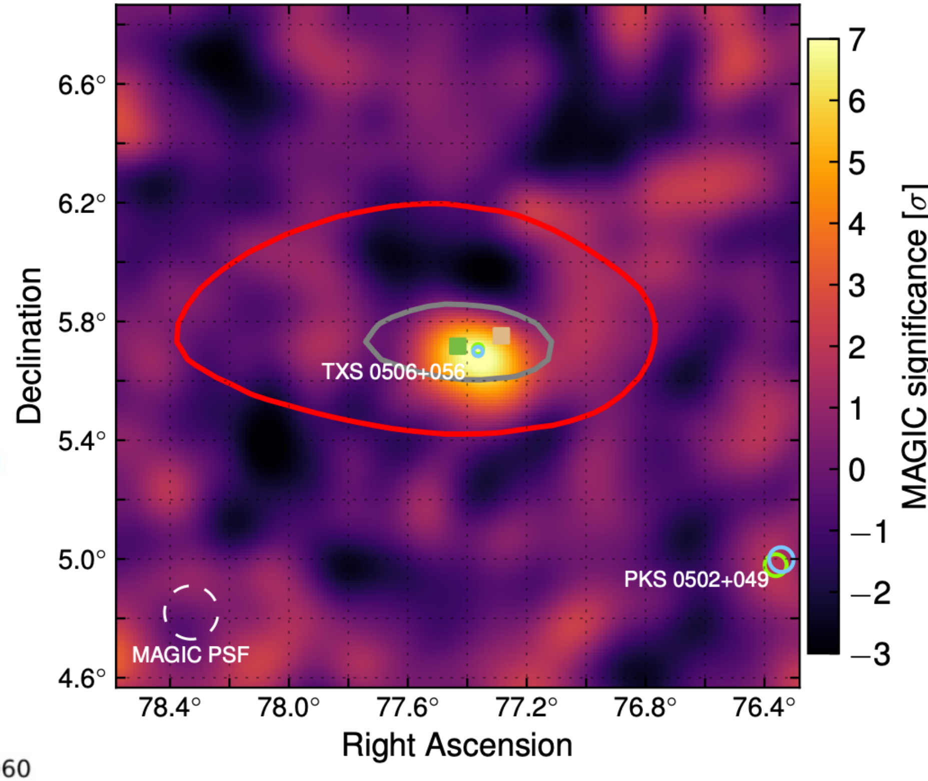
ATel #10817; *Razmik Mirzoyan for the MAGIC Collaboration*
on 4 Oct 2017; 17:17 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

- Detection up to ~400 GeV
- Clear variability on daily timescale
- Spectral index raging from -4.0 to -3.5



The IceCube Coll. et al., Science 361, 146 (2018)arXiv:1807.08816

Full data set: the MAGIC Collaboration, ApJL 863, 1, arXiv:1807.04300

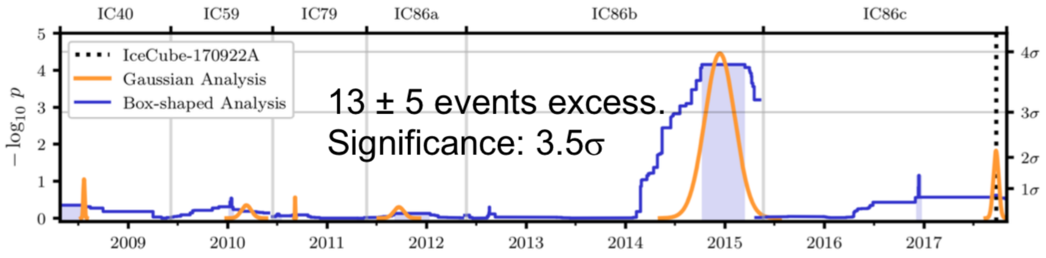


Pre-trials p-value = 4.1σ. 10 public alerts + 41 archival events → post-trials p-value = 3.0σ

Significant result due to « simultaneous » detection in neutrinos and gamma-rays !

Neutrinos from blazar TXS0506+056

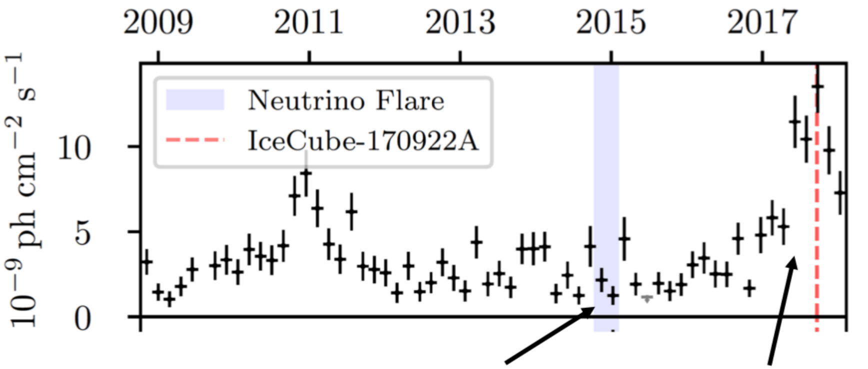
2014-2015: A (orphan) neutrino flare found from the same object in historical data



13 ± 5 events excess.
Significance: 3.5σ

Science 361 (2018) no. 6398, eaat2890

Fermi-*LAT* data; Padovani et al, MNRAS 480 (2018) 192



At 2014-15 neutrino flare

The 2017 flare

Page 2

- A further analysis of **archival IceCube data** revealed that this blazar was emitting neutrinos before;
- Within Oct. 2014-March 2015 an excess of 13±5 events over background was found.
- During this period, there was no significant EM flaring activity
- No simple theoretical interpretation

IceCube conclusion: **Compelling evidence** of a HE ν from a blazar

Blazars models

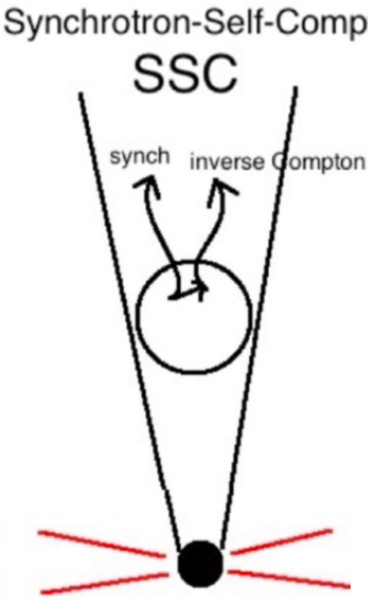
The low-energy SED component is synchrotron emission by electrons

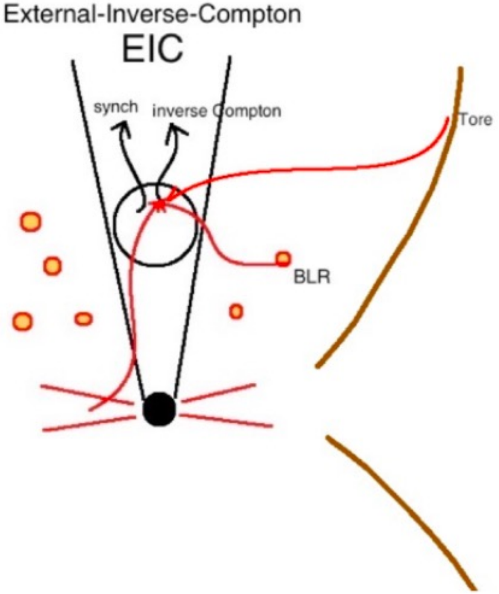
High-energy emission?

Leptonic models: inverse Compton

Same leptons that radiate synchrotron
 + their own synchrotron photons (SSC)
 + external photon fields (EIC)

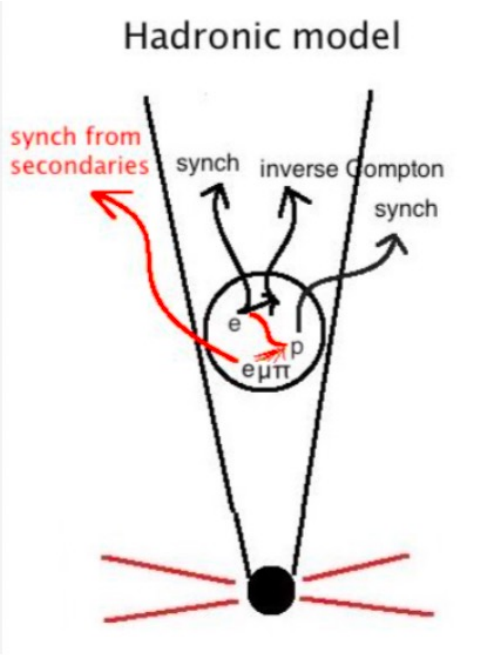
State-of-the-art models:
 HBLs → SSC
 LBLs / FSRQs → EIC





Source : M. Cerruti, TeVPA22

Blazars models



Proton-photon interactions complicate the modeling

Photo-meson

$$p + \gamma = p' + \pi^0 \rightarrow p' + 2\gamma$$
$$p + \gamma = n + \pi^+$$
$$p + \gamma = p' + \pi^+ + \pi^-$$
$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu \rightarrow e^\pm + \nu_\mu + \bar{\nu}_\mu + \nu_e$$

Bethe-Heitler pair production

$$p + \gamma = p' + e^+ + e^-$$

Injection of secondary leptons in the emitting region, triggering synchrotron supported pair-cascades

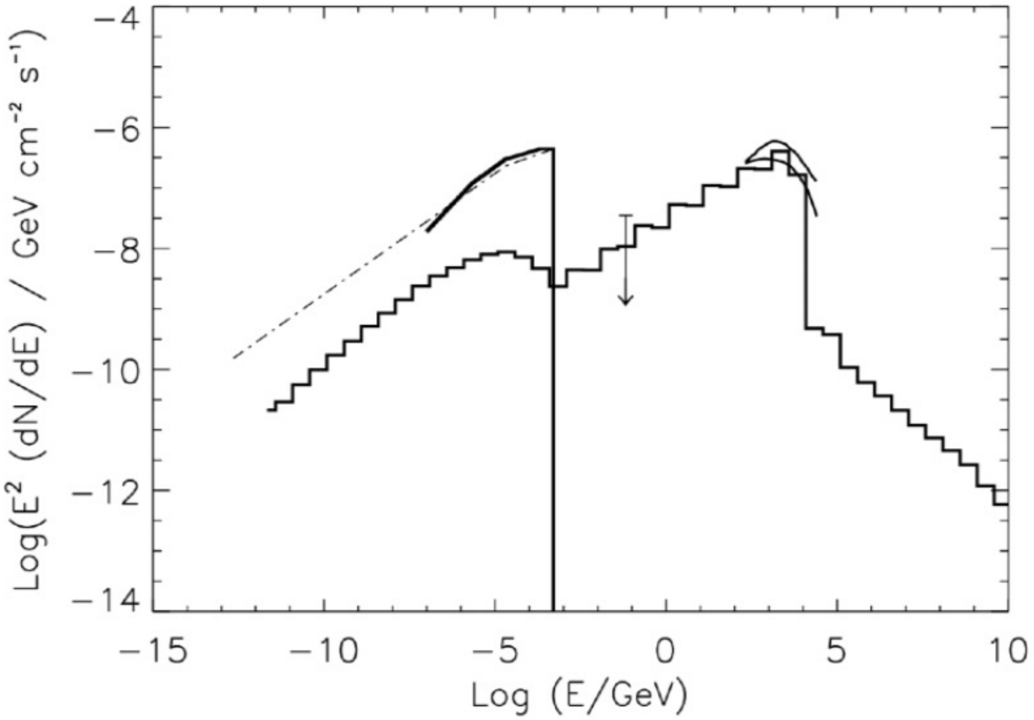
Synchrotron emission by muons can be important

Hadronic models

Simplest hadronic model:

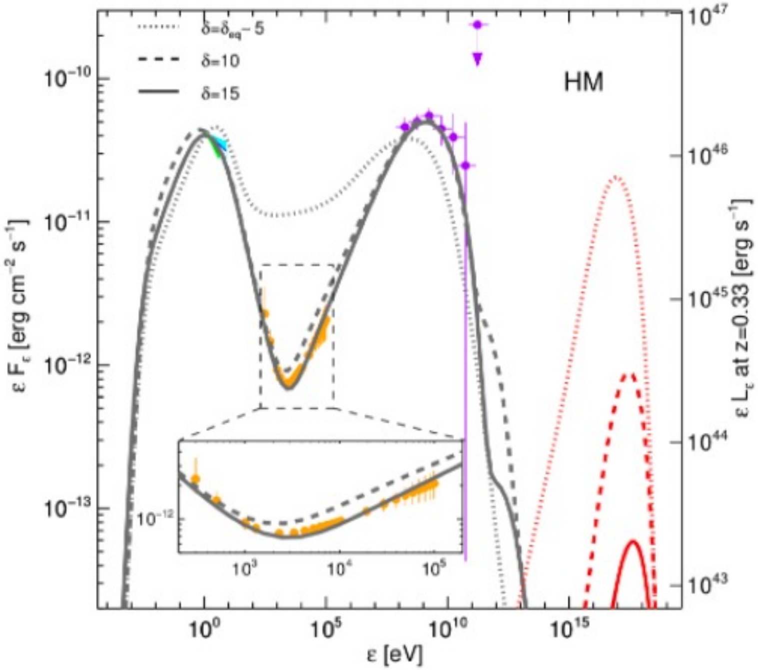
The high-energy component is proton synchrotron radiation

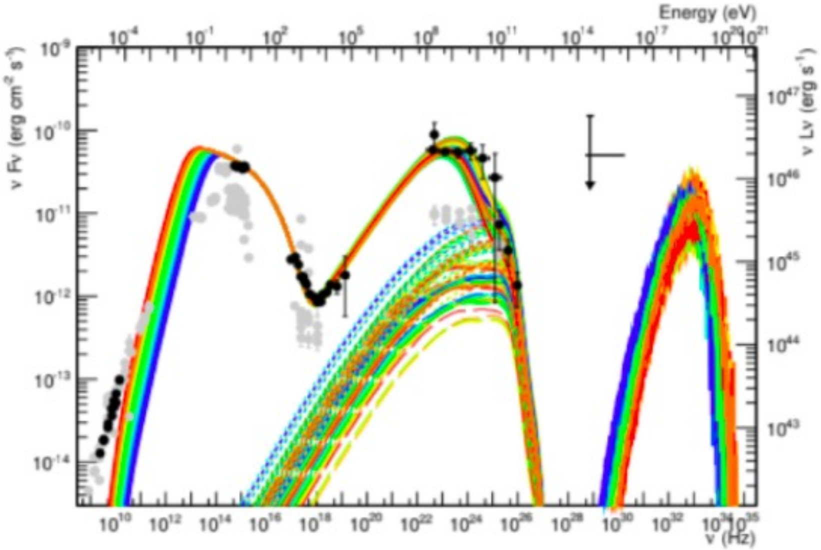
(Mannheim 1993, Aharonian 2000, Mucke & Protheroe 2001)



Mucke & Protheroe 2001

TXS 0506+056 2017 flare





(a) Proton synchrotron modeling of TXS 0506+056

Cerruti et al. 2019

$$\nu = 10^{-5} - 10^{-3}\ yr^{-1}$$

Keivani et al. 2018

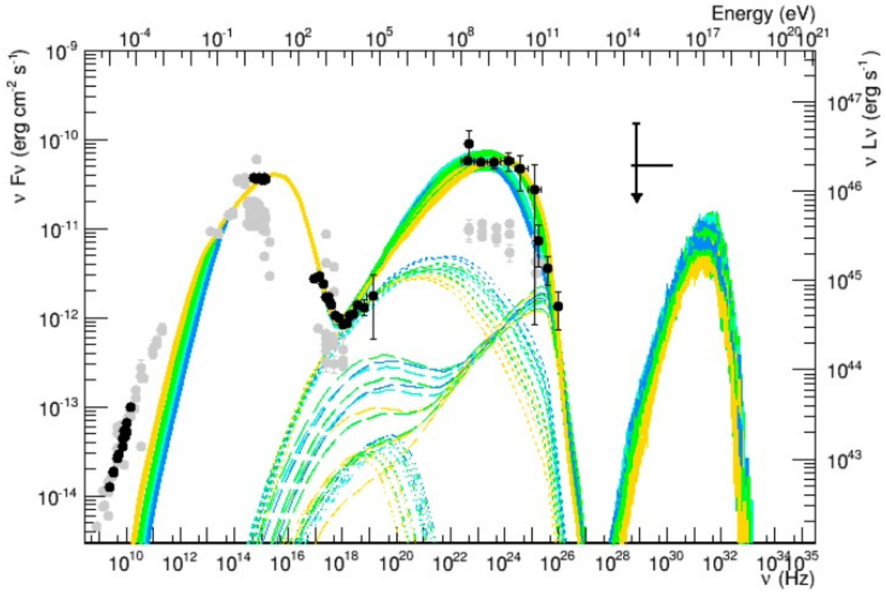
$$\nu \simeq 10^{-5}\ yr^{-1}$$

Proton synchrotron solutions exist,
but the expected neutrino rate is very low

Source : M. Cerruti, TeVPA22

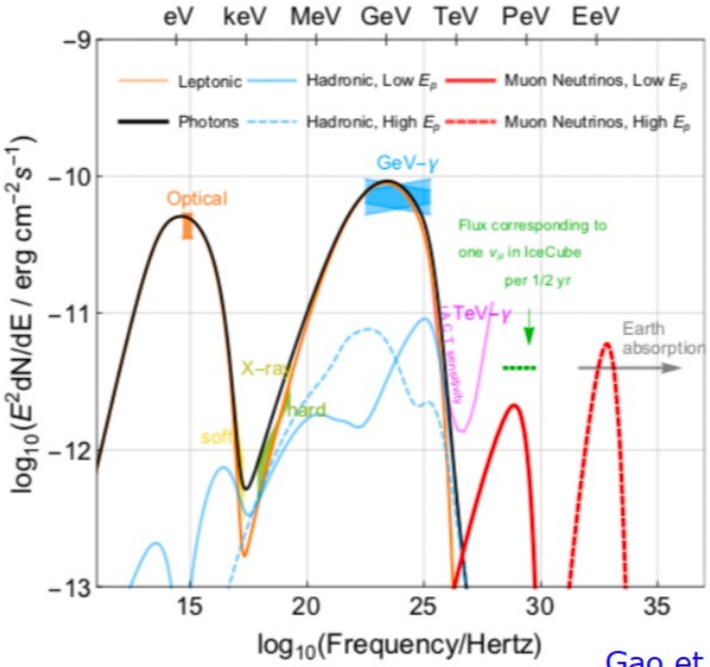
TXS 0506+056 2017 flare

Lepto-hadronic solutions



Cerruti et al. 2019

$L_{jet} = (9 - 60) \times 10^{47} erg/s$
$\nu = 0.01 - 0.06\ yr^{-1}$



Gao et al. 2018

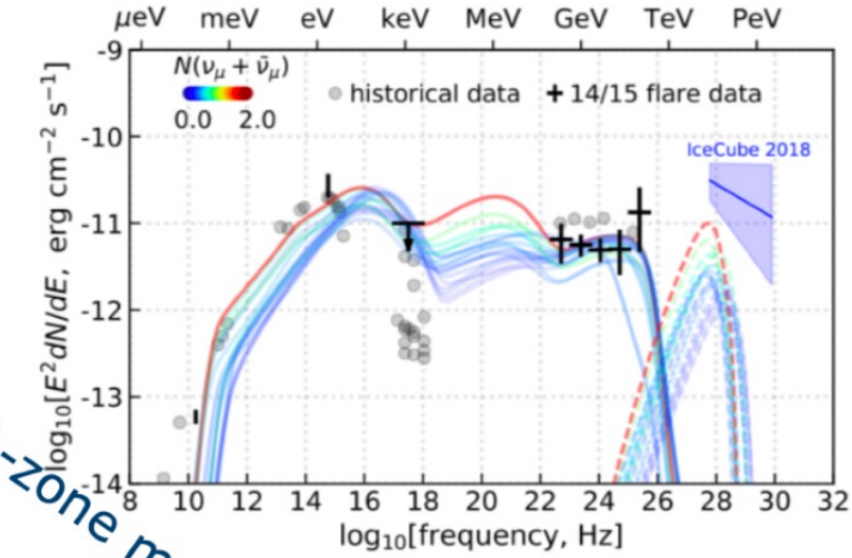
$L_{jet} \simeq \times 10^{50} erg/s$
$\nu = 0.3\ yr^{-1}$

They can work: neutrino rates of the order of 0.1 / yr

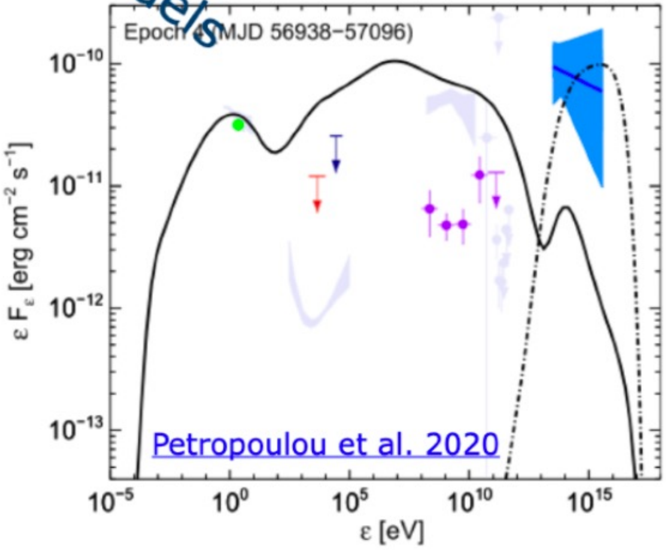
But rather high energetic requirement : $L_{jet} \gg L_{Edd} \simeq \times 10^{46-47}\ erg/s$

Source : M. Cerruti, TeVPA22

TXS 0506+056 2014/2015 ν flare



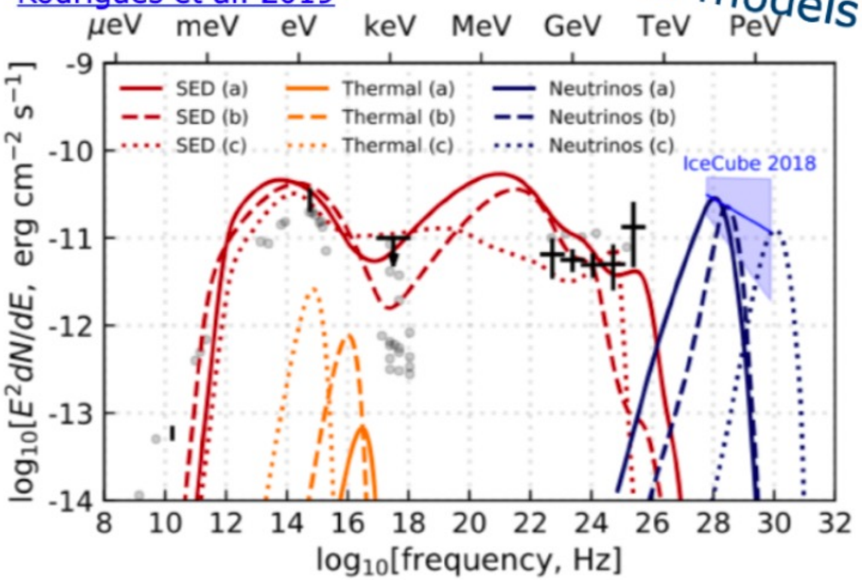
1-zone models

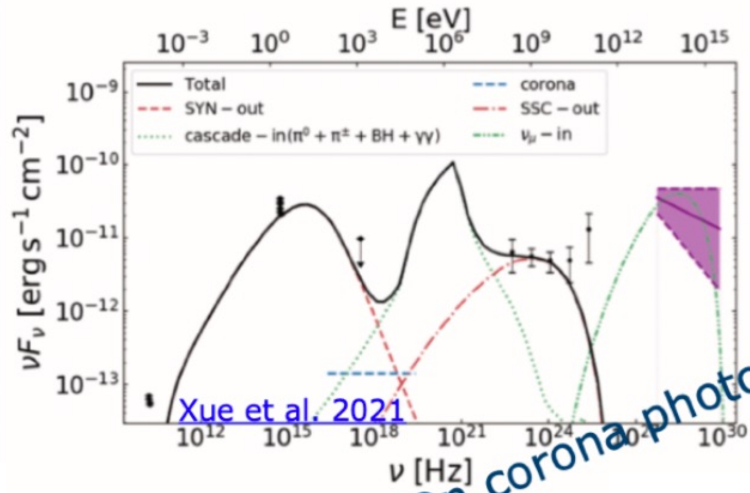


Petropoulou et al. 2020

External field models

Rodrigues et al. 2019





Xue et al. 2021

On corona photons

Source : M. Cerruti, TeVPA22

More neutrinos from blazars ?

PKS 1502+106 (FSRQ@z=1.83) and IC190730A:

Spatial association but no flaring activity during the neutrino event

3HSPJ095507.9+355101 (Extreme HBL @ z=0.56) and IC200107A:

Spatial association (1.7% prob.) but no flaring activity (Fermi hardening?)

IBL@z=0.65? (>0.42) and IC211208A:

- Neutrino in IC with false alarm rate of 1.2 /yr (GCN)
- LAT source 2.2deg away (slightly beyond the 90% contour)

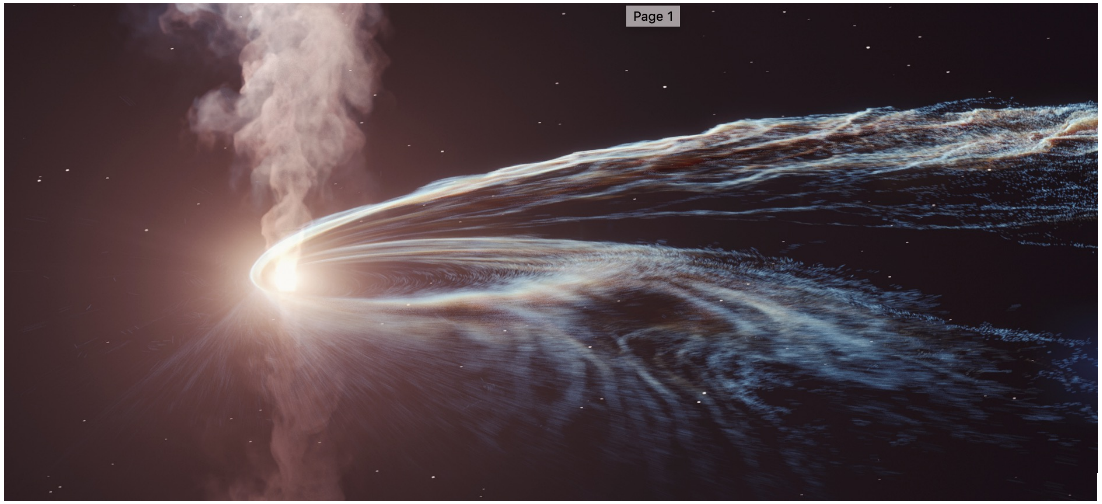
- Neutrino in Baikal (4h later). Chance coincidence prob. 2.85σ (ATel)
- Neutrino in KM3Net on Dec.15, p-value of 14% (ATel)
- Neutrino in Baksan on Dec.4, p-value of 0.2% (ATel)
- Flaring in Fermi-LAT, optical, X-rays

Different blazars

Stay tuned !

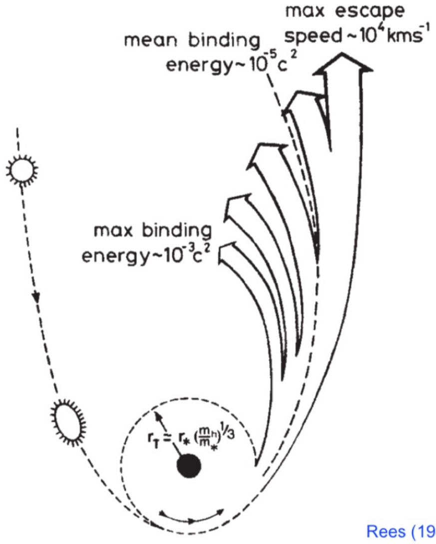
Neutrinos to Tidal Disruption Events ?

Lunardini, TeVPA22



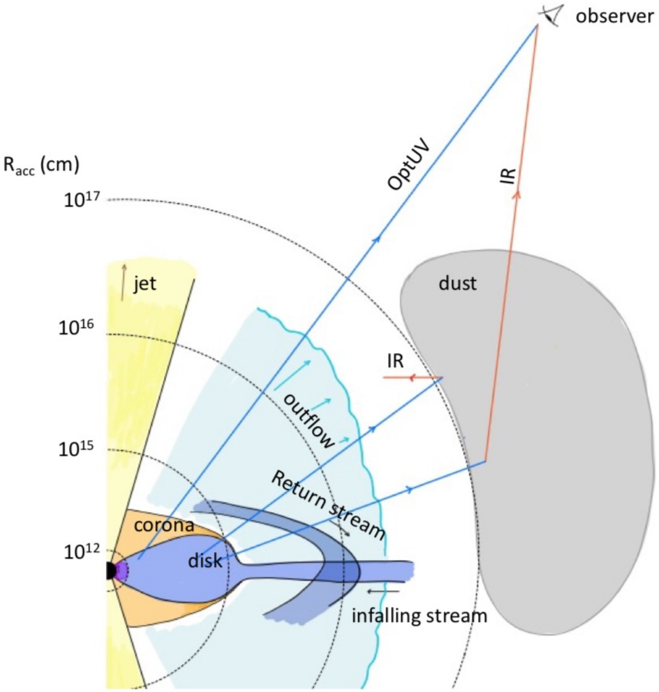
- possible sites: jet, corona, accretion disk, colliding streams, …

ν



Rees (1988)

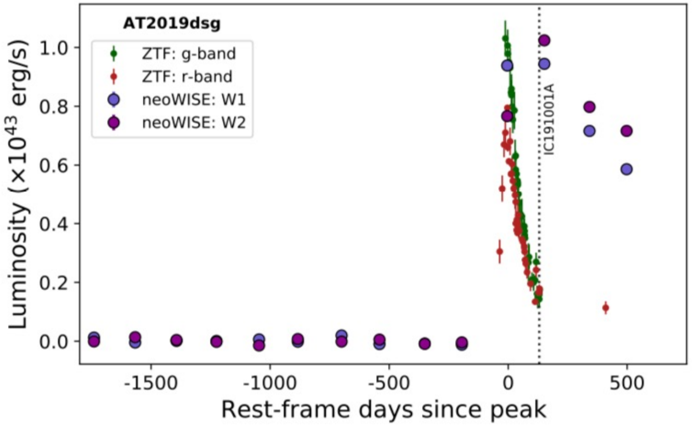
- masses:
  $m \sim (0.1 - 2)\ M_\odot$,
  $M \sim (10^4 - 10^8)\ M_\odot$
- $\sim m/2$ remains bound, falls back onto the SMBH
- mass accretion powers flare



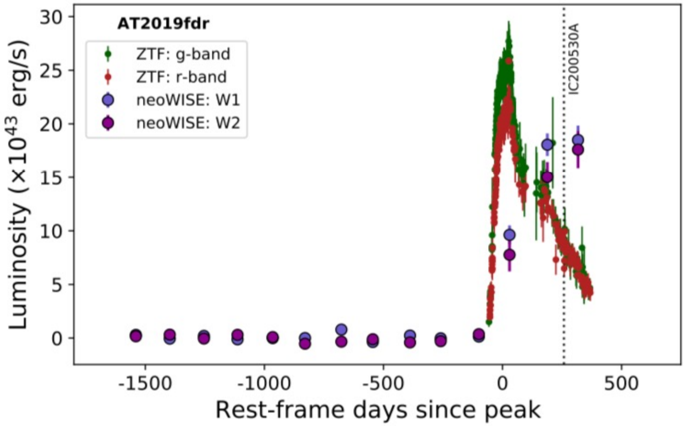
Neutrinos to Tidal Disruption Events ?

Lunardini, TeVPA22

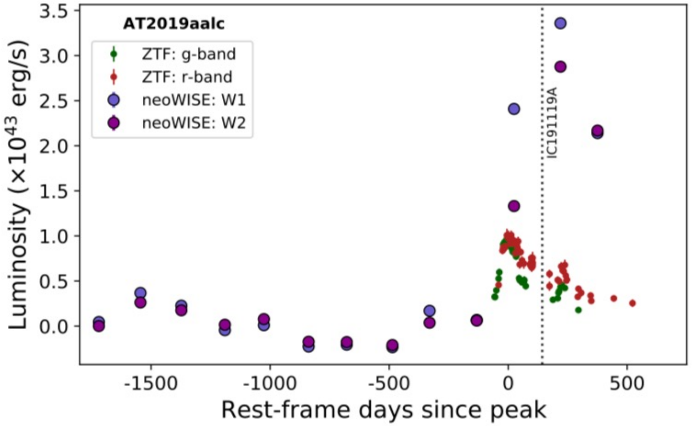
AT2019dsg :



AT2019fdr :



AT2019aalc :



Looking for **special** features:

- late neutrino arrival time
- unusually bright in X-rays
- unusually bright dust echo

No significant counterpart in ANTARES
📖 2021 ApJ 920 50

figs: van Velzen et al., arXiv:2111.09391; small dots: OptUV; large dots: IR. Also observed in X-rays, Radio

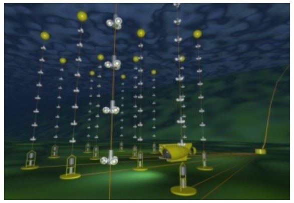
Outline

Neutrino astronomy

Scientific motivations

Historical aspects

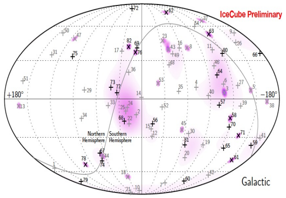
Cosmic neutrino sources



Neutrino telescope

Detection principles

Current telescopes



Selected results

Diffuse Flux, point sources

Multi-messenger search

KM3NeT

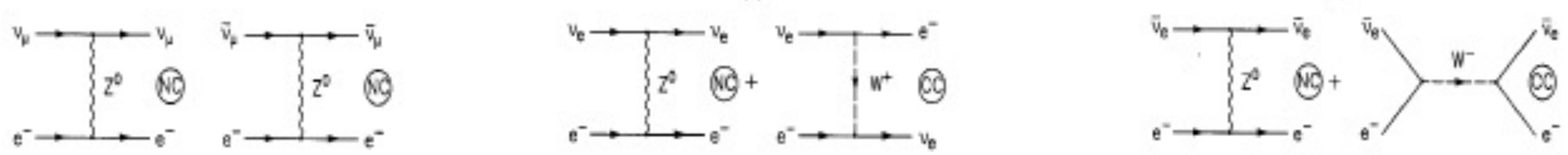
ORCA prospects

Sensitivity to Mass Ordering

- « Standard approach » :probe $\nu_\mu \leftrightarrow \nu_e$ governed by Δm^2_{13}

$$P_{\mu e} = \sin^2\theta_{23}\boxed{\sin^2 2\theta_{13}}\sin^2\left(\frac{\Delta m^2_{13}L}{4E}\right) + \text{“subleading”}$$

- Insensitive to the sign of Δm^2_{13} at leading order.
- Matter effects (MSW) come to the rescue
- Earth density variations also affect the oscillations
- Different effect for neutrinos and antineutrinos
- Atmospheric neutrinos: effect measurable $\sigma(\nu) \approx 2\,\sigma(\bar{\nu})$

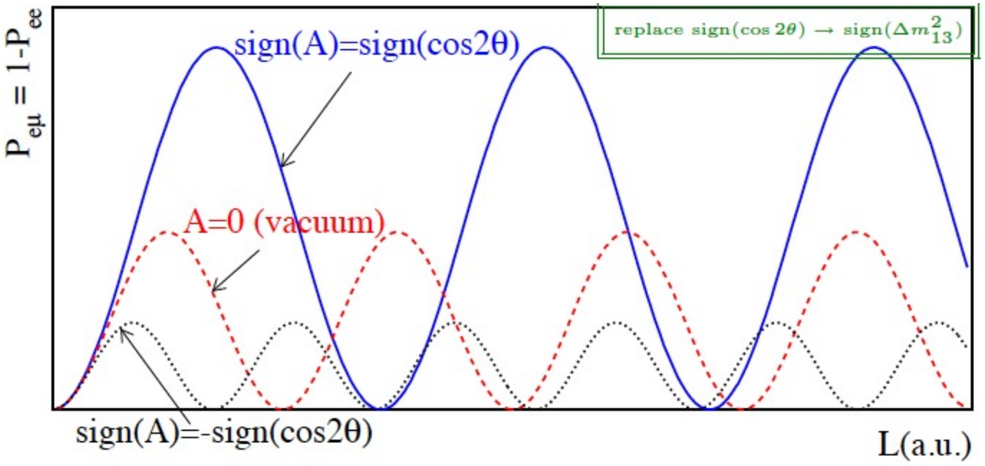


(Constant density) Matter effects

$$P_{\mu e} \simeq P_{e\mu} \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}^{\rm eff}\sin^2\left(\frac{\Delta_{13}^{\rm eff}L}{2}\right),$$

$$\sin^2 2\theta_{13}^{\rm eff} = \frac{\Delta_{13}^2\sin^2 2\theta_{13}}{(\Delta_{13}^{\rm eff})^2},$$

$$\Delta_{13}^{\rm eff} = \sqrt{(\Delta_{13}\cos 2\theta_{13} - A)^2 + \Delta_{13}^2\sin^2 2\theta_{13}},$$



$A \equiv \pm\sqrt{2}G_F N_e$ is the matter potential.

>0 for neutrinos
<0 for anti-neutrinos

Requirements:

Δ_{13} ~ A matter potential must be significant not overwhelming
L large enough – matter effects are absent near the origin

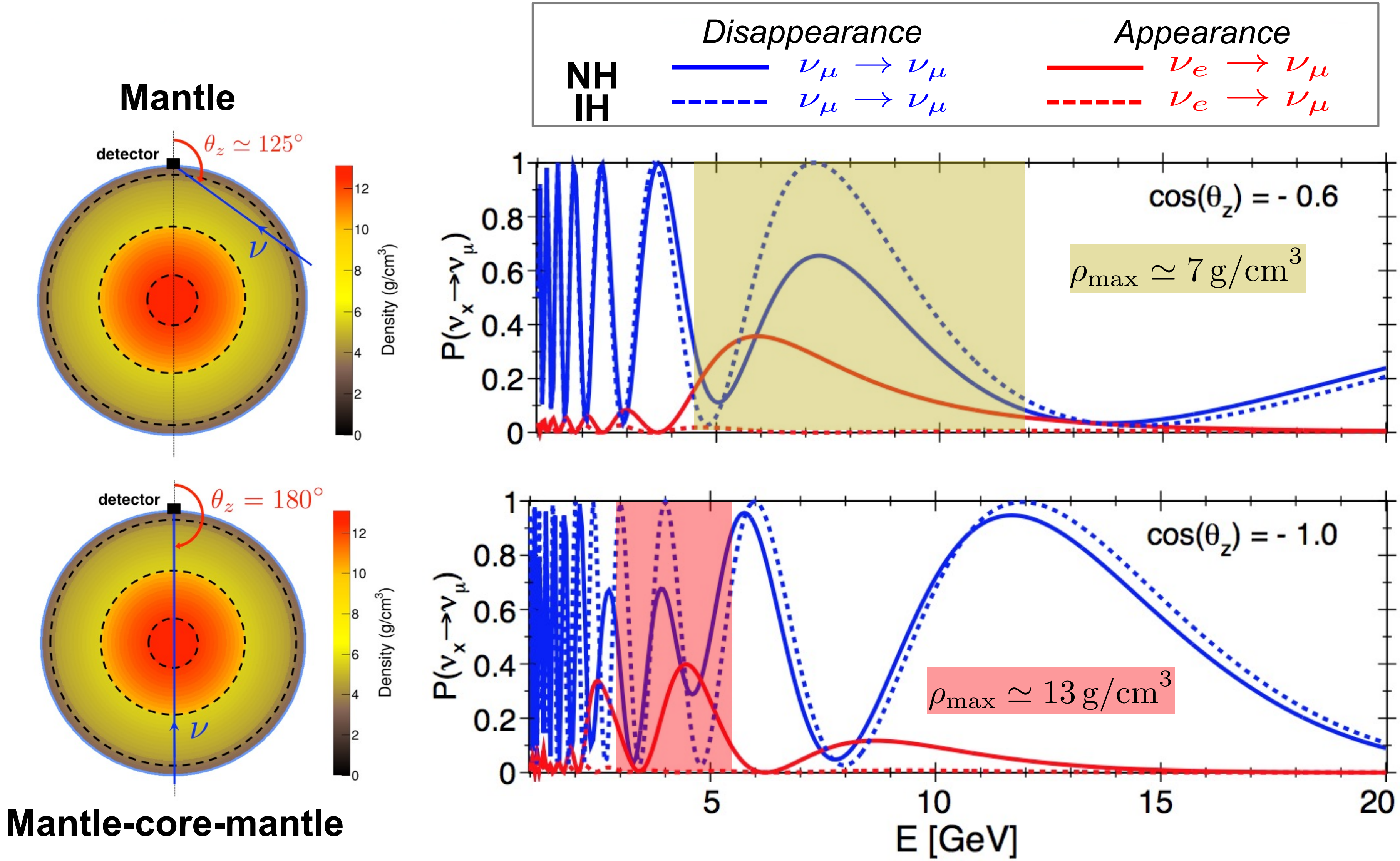
Matter resonance: A ➔ $\Delta_{13}\cos 2\theta_{13}$
In this case:
- Effective mixing maximal
- Effective osc. frequency minimal

Resonance energy:

$$E_{\rm res}\,[\mathrm{GeV}] \sim 13\,200\ \cos 2\theta\,\frac{\Delta m^2\,[\mathrm{eV}^2]}{\rho\,[\mathrm{g/cm}^3]}$$

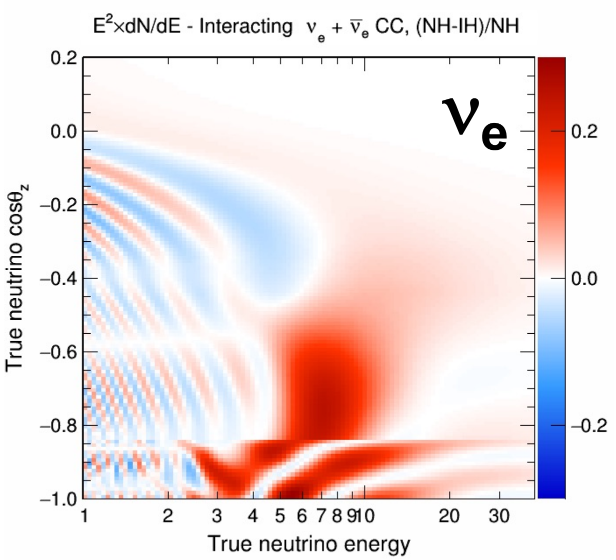
Mass hierarchy with atmospheric neutrinos

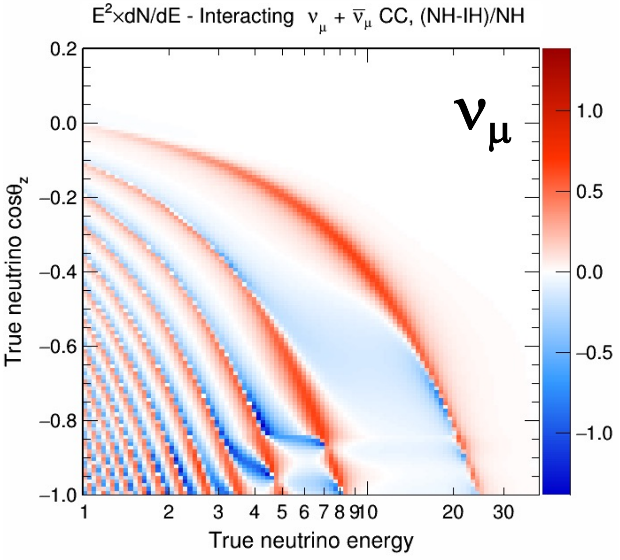
The MSW resonance depends on matter density
→ appears in different regions of neutrino energy & zenith angle



Mass hierarchy with atmospheric neutrinos

Expected signal in the E-zenith plane: (NH - IH)/NH

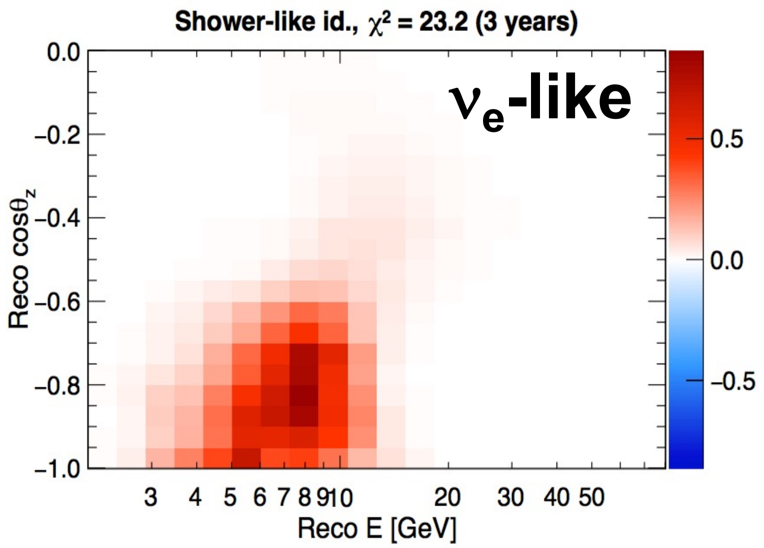


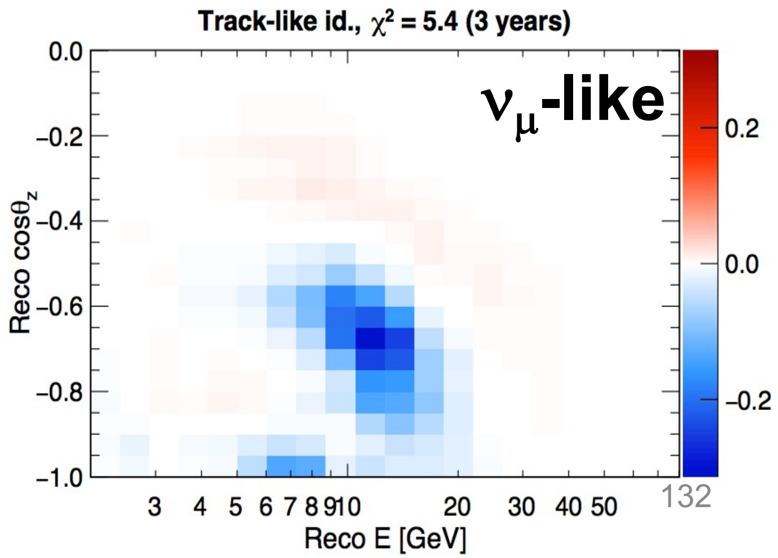


Large statistics…

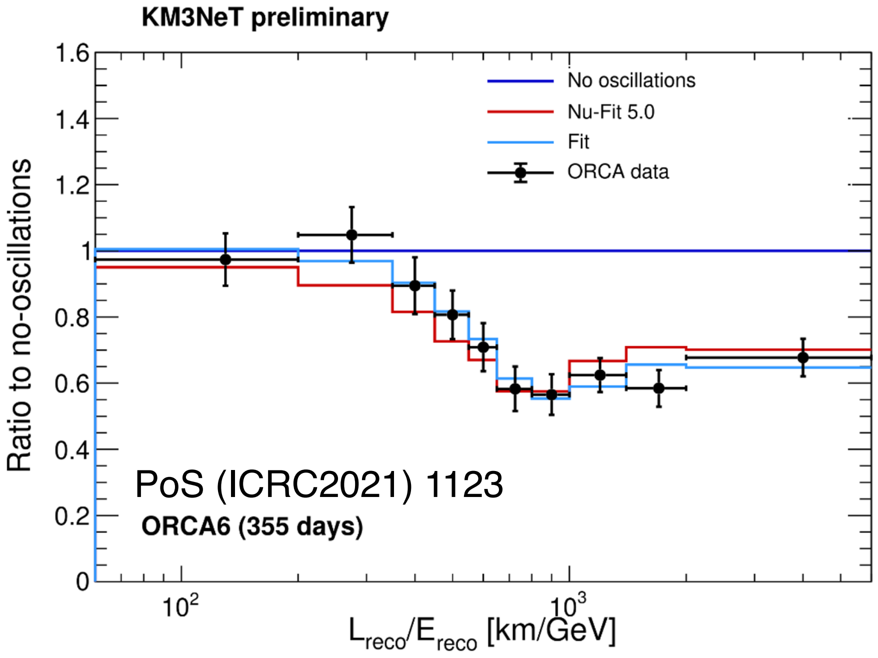
Challenge: overcome detector limited resolutions!

Observable signal

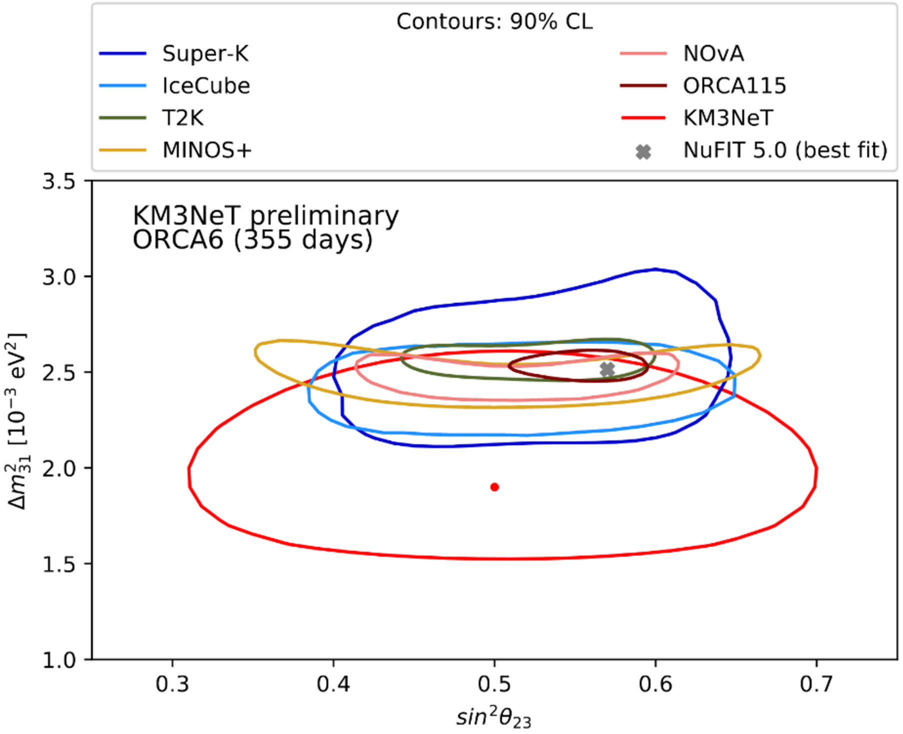




Oscillation studies

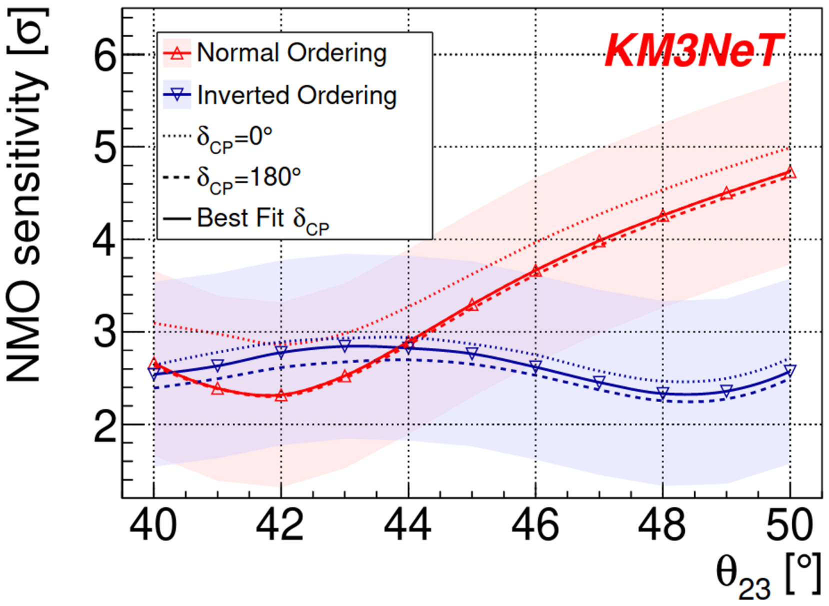


Strong oscillation signal
with only 6 DU

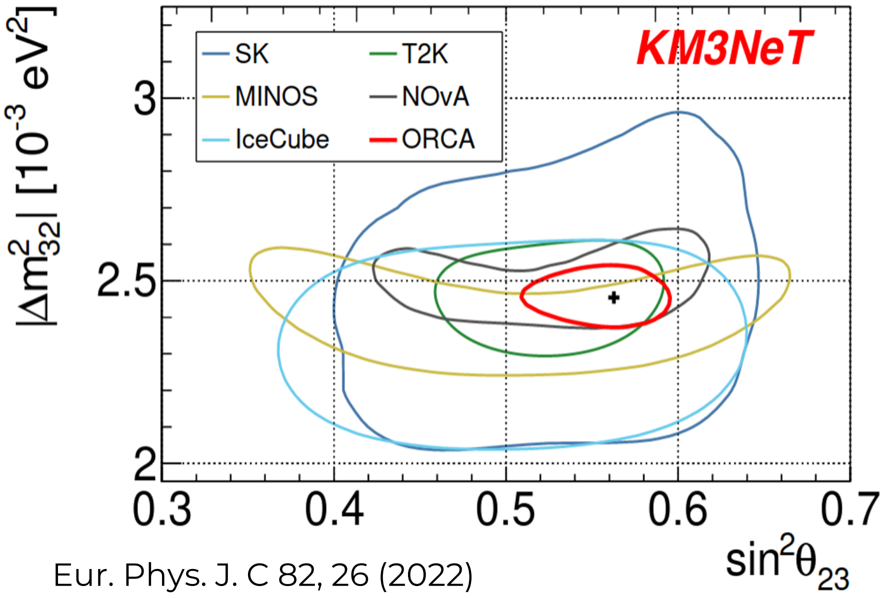


Data has a preference to oscillation
of 5.9σ

Prospects for the Mass Ordering



Expected results for 3 years exposure, full detector.



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Competitive sensitivity to Δm^2_{32}, θ_{23}

Thanks for your attention

Multi-messenger astronomy into space but also…under water !