AMALDI
RESEARCH CENTER

High Energy astrophysical neutrino detection in a multimessenger scenario

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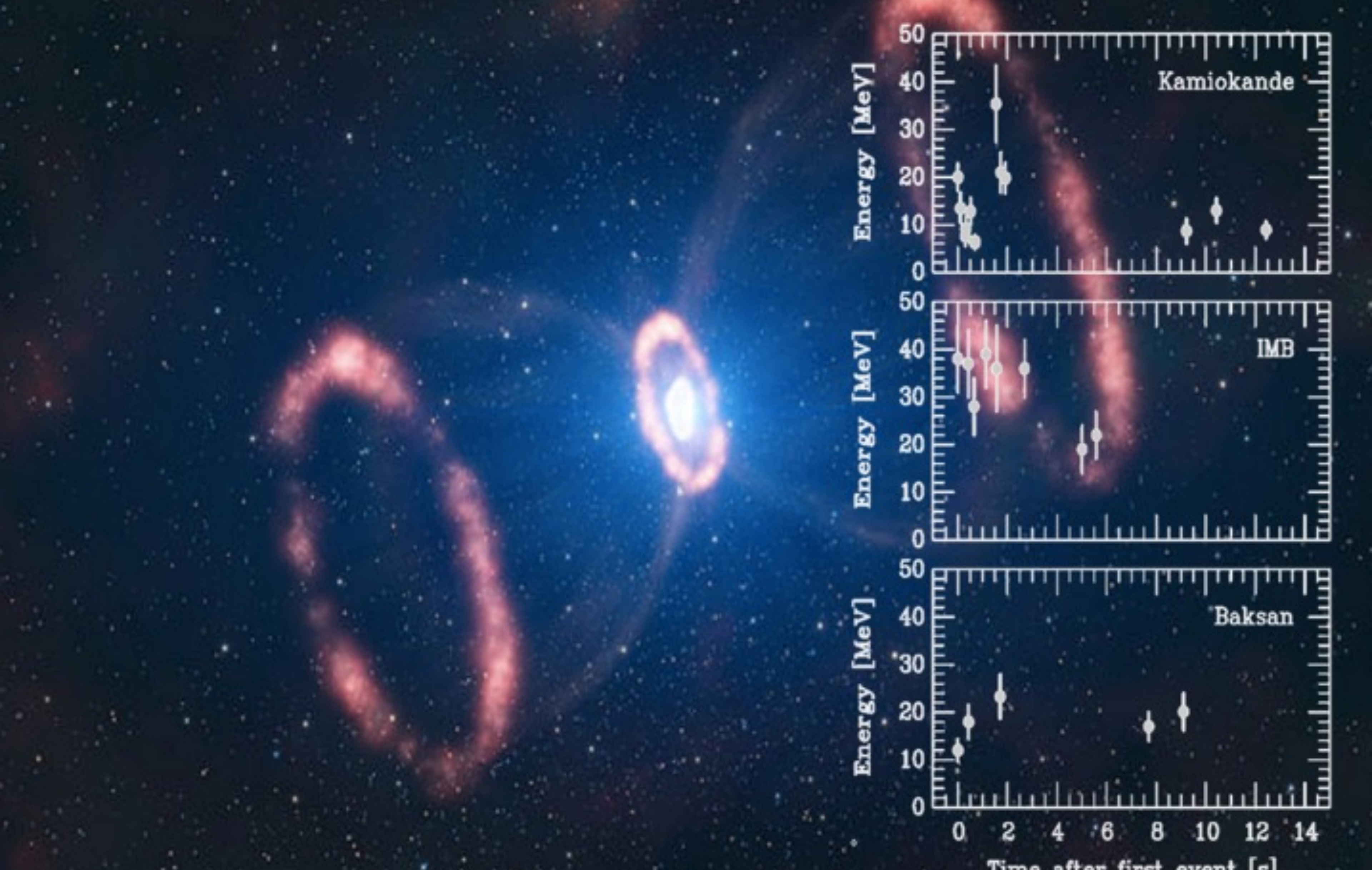
STVDIVM VRBIS

INFN

- **The New era of Gravitational Wave: GW170817 - crucial milestone in multimessenger astrophysics**
- The complementary messenger: the neutrino
  - ✓ IC170922
  - ✓ NGC 1068
- The future challanges

MeV Neutrinos from SN1987A

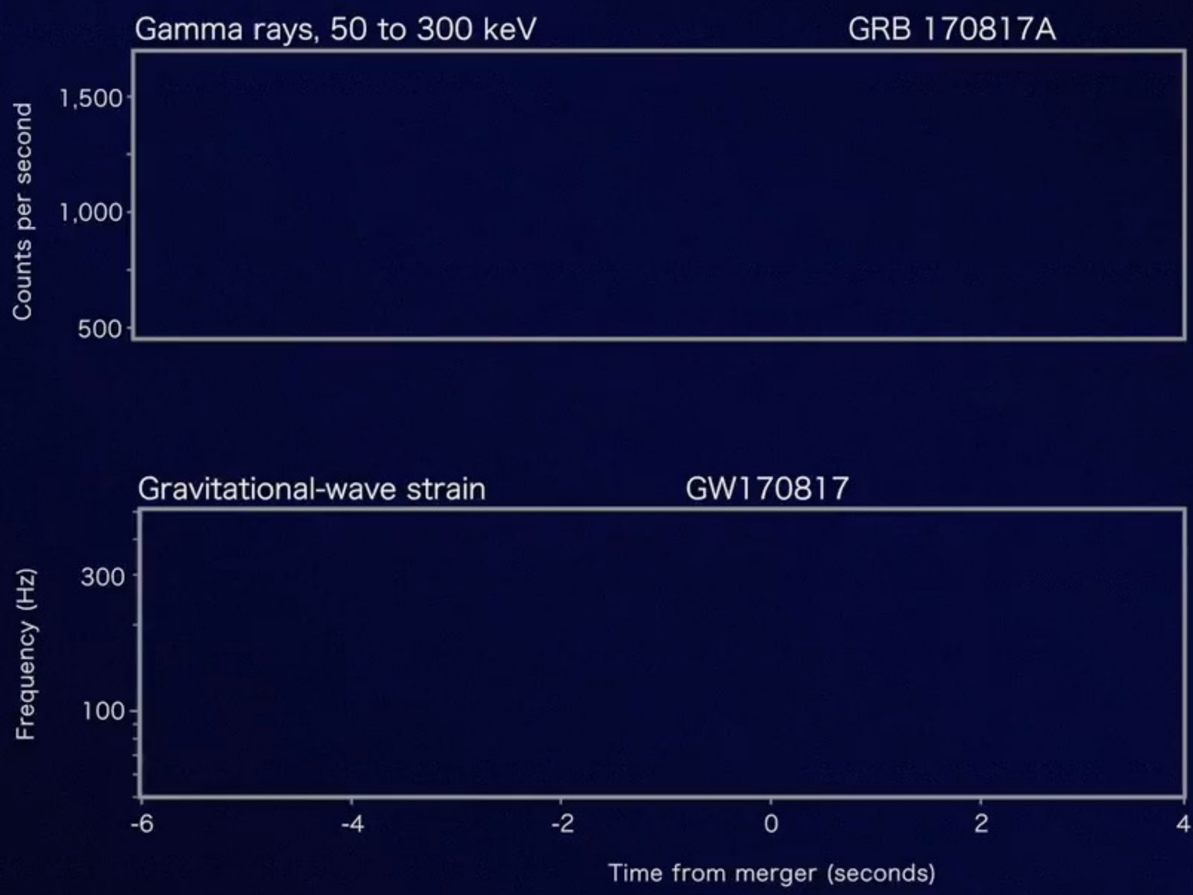


February 23, 1987.

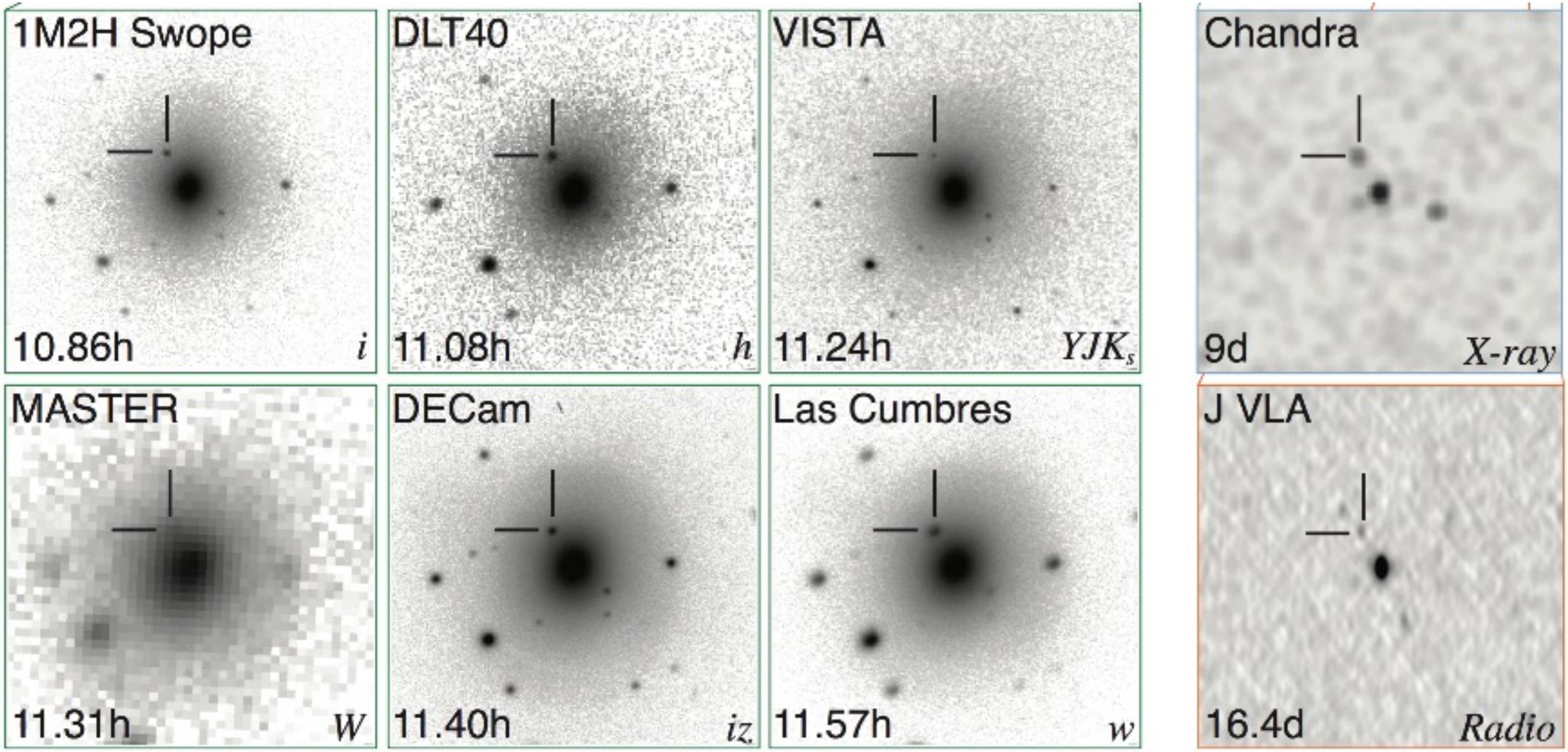
GW170817 and GRB170817A

Fermi

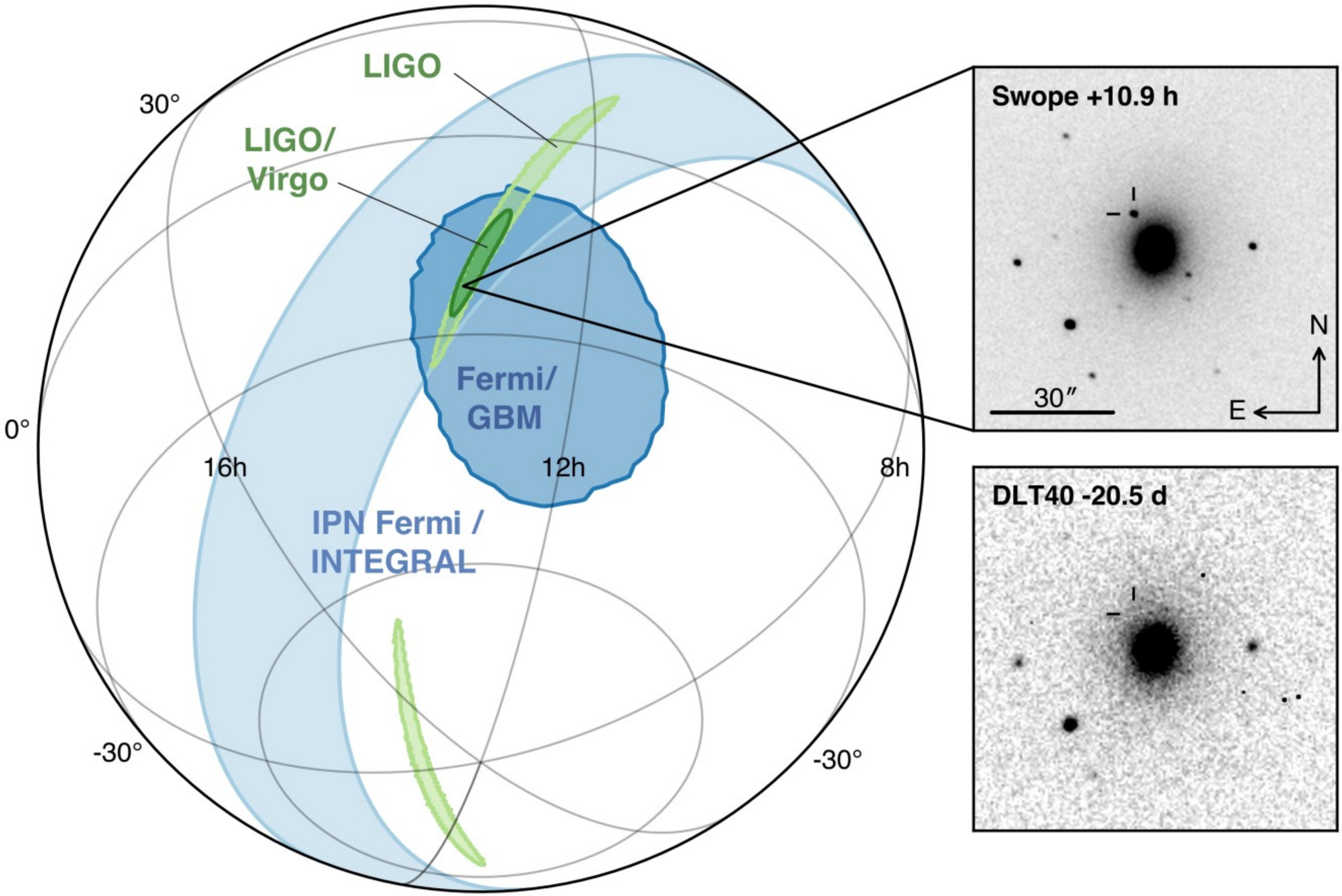
LIGO



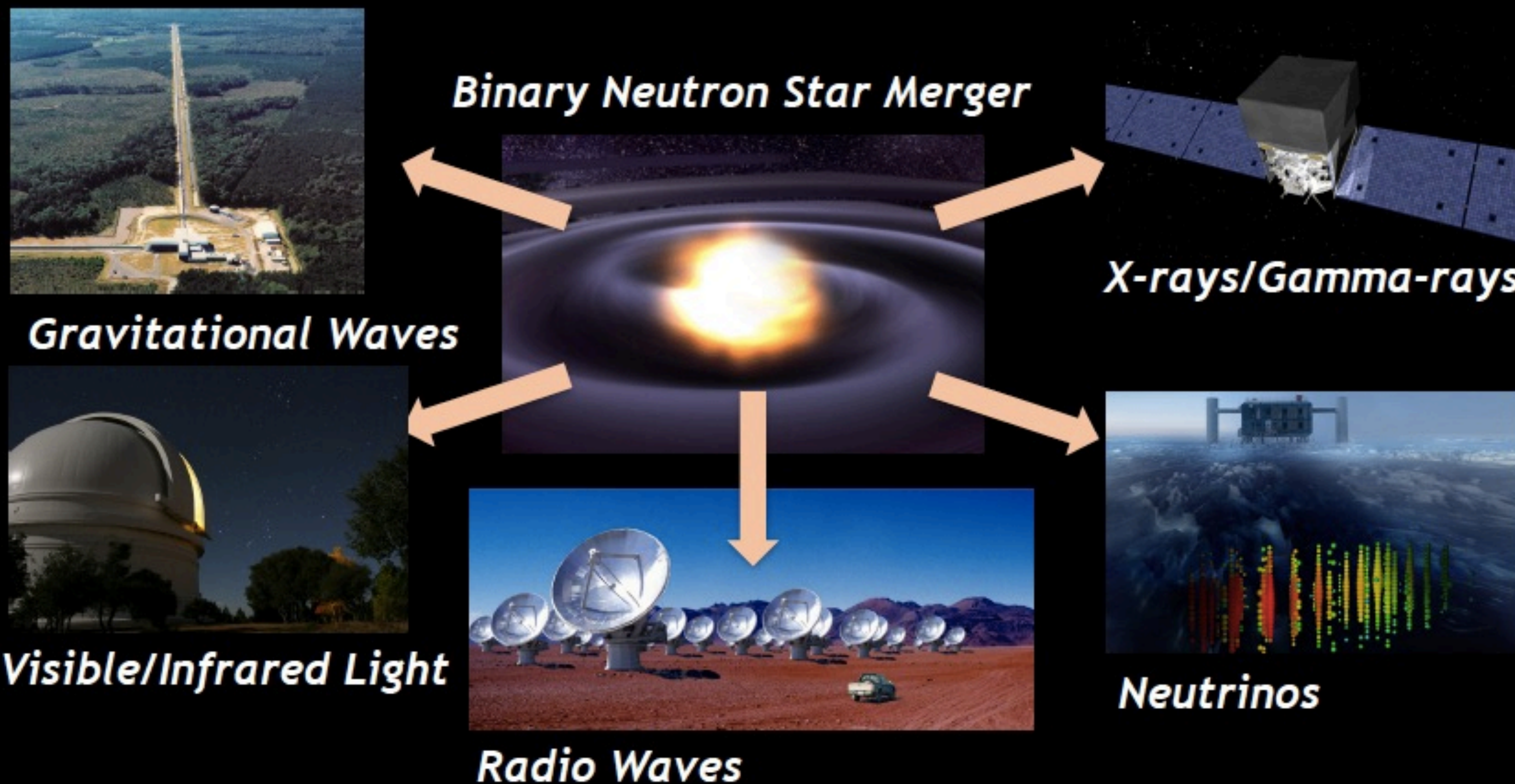
Credit: NASA GSFC & Caltech/MIT/LIGO Lab



Shown here are 8 images of the aftermath of the BNS merger (designated SSS17a/AT2017gfo). On the left are six optical images taken between 10 and 12 hours after the merger by different telescopes. On the right are images constructed from x-ray and radio observations. The x-ray image was taken 9 days after the merger by NASA's Chandra X-ray Observatory. 16 days after the merger NRAO's Jansky Very Large Array (VLA) captured the radio image. In all 8 images the galaxy NGC 4993 is seen in the middle and SSS17a/AT2017gfo is marked by two lines.

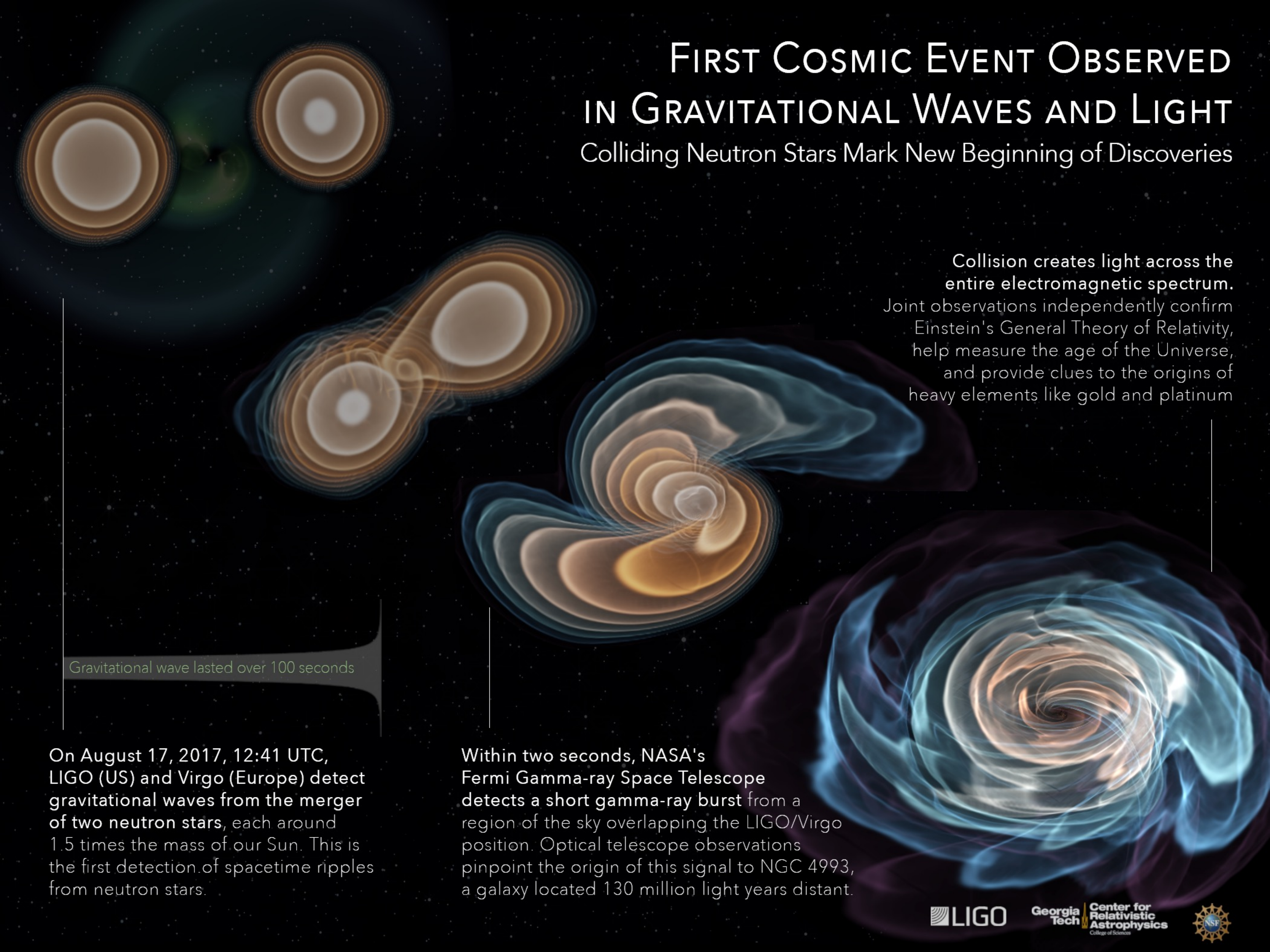

LIGO
LIGO/
Virgo
30°
0°
16h
12h
8h
-30°
-30°
Fermi/
GBM
IPN Fermi /
INTEGRAL
Swope +10.9 h
N
E
30″
DLT40 -20.5 d

Multi-messenger Astronomy with Gravitational Waves



LIGO and Virgo signed agreements with 95 groups for EM/neutrino followup of GW events

- ~200 EM instruments - satellites and ground based telescopes covering the full spectrum from radio to very high-energy gamma-rays
- Worldwide astronomical institutions, agencies and large/small teams of astronomers

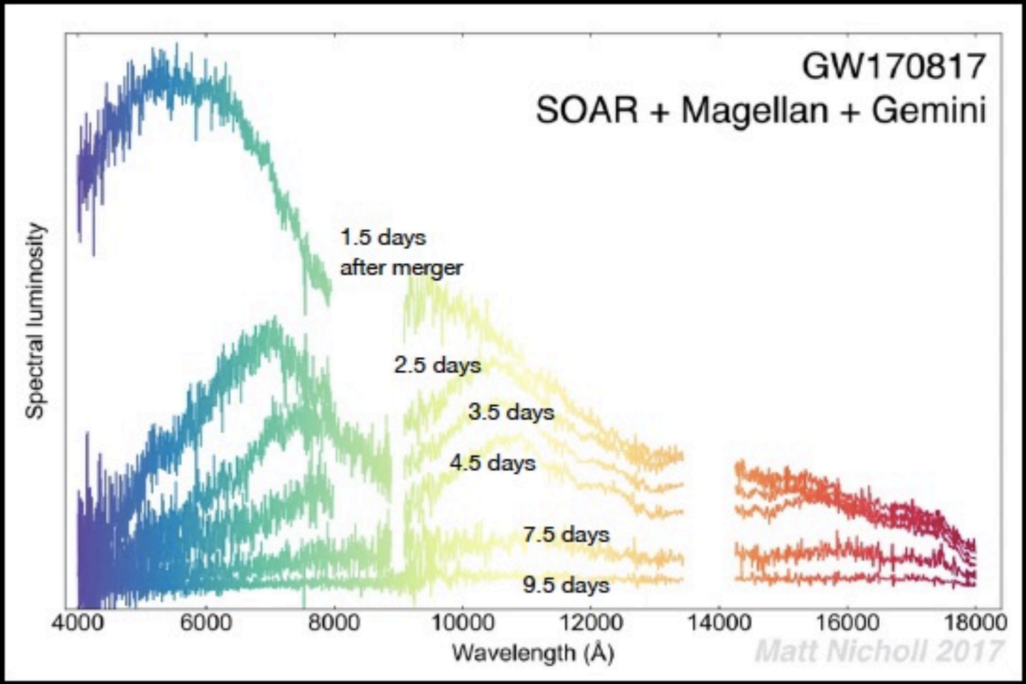


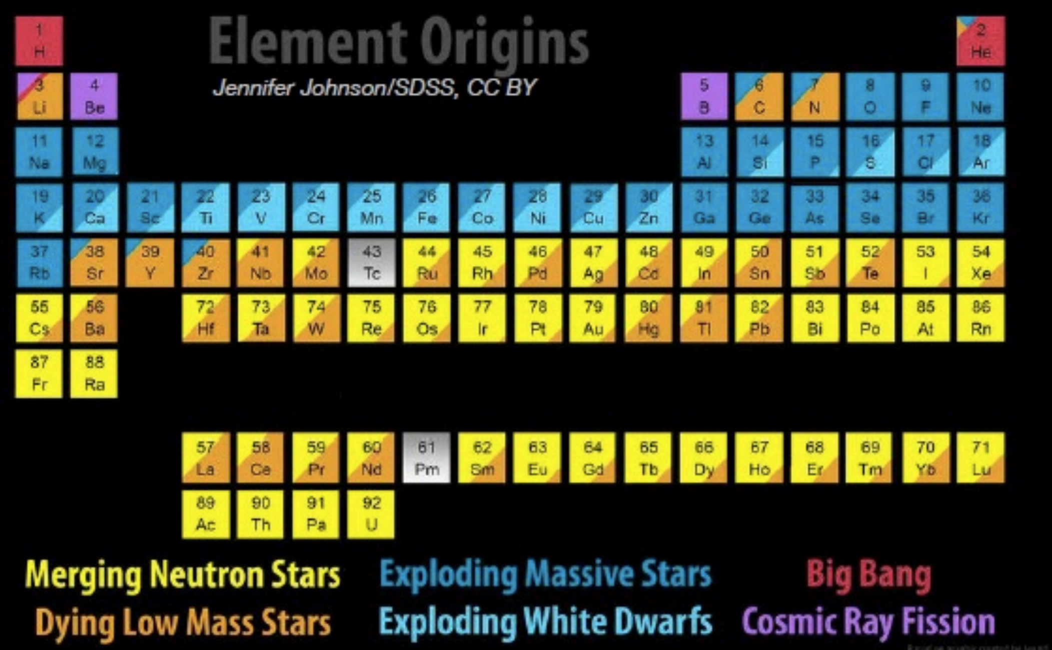
FIRST COSMIC EVENT OBSERVED
IN GRAVITATIONAL WAVES AND LIGHT
Colliding Neutron Stars Mark New Beginning of Discoveries
Collision creates light across the entire electromagnetic spectrum.
Joint observations independently confirm Einstein's General Theory of Relativity, help measure the age of the Universe, and provide clues to the origins of heavy elements like gold and platinum
Gravitational wave lasted over 100 seconds
On August 17, 2017, 12:41 UTC, LIGO (US) and Virgo (Europe) detect gravitational waves from the merger of two neutron stars, each around 1.5 times the mass of our Sun. This is the first detection of spacetime ripples from neutron stars.
Within two seconds, NASA's Fermi Gamma-ray Space Telescope detects a short gamma-ray burst from a region of the sky overlapping the LIGO/Virgo position. Optical telescope observations pinpoint the origin of this signal to NGC 4993, a galaxy located 130 million light years distant.
LIGO
Georgia Tech
Center for Relativistic Astrophysics
College of Sciences
NSF

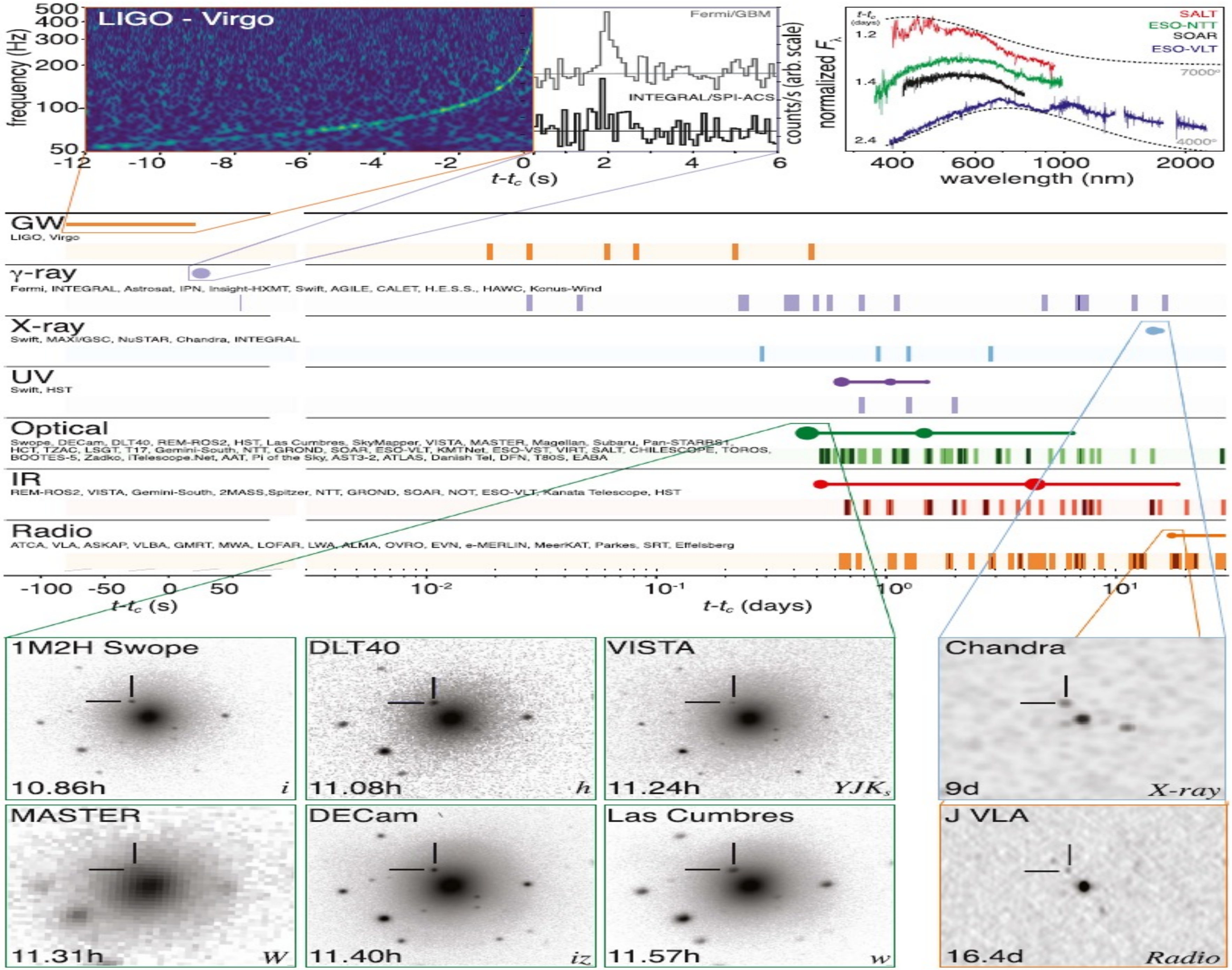
Kilonova

SSS17a

Swope & Magellan Telescopes






LIGO - Virgo
frequency (Hz)
500
400
300
200
100
50
-12 -10 -8 -6 -4 -2 0 2 4 6
t-t_c (s)
Fermi/GBM
INTEGRAL/SPI-ACS
counts/s (arb. scale)
normalized F_λ
t-t_c (days)
1.2
1.4
2.4
SALT
ESO-NTT
SOAR
ESO-VLT
7000°
4000°
400 600 1000 2000
wavelength (nm)
GW
LIGO, Virgo
γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind
X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
UV
Swift, HST
Optical
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1, HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS, BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN, T80S, EABA
IR
REM-ROS2, VISTA, Gemini-South, 2MASS, Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata Telescope, HST
Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
-100 -50 0 50
t-t_c (s)
10⁻² 10⁻¹ 10⁰ 10¹
t-t_c (days)
1M2H Swope
10.86h
i
DLT40
11.08h
h
VISTA
11.24h
YJK_s
Chandra
9d
X-ray
MASTER
11.31h
W
DECam
11.40h
iz
Las Cumbres
11.57h
w
J VLA
16.4d
Radio

Are Gravitons Massless?

- GW170817 provides a stringent test of the speed of gravitational waves

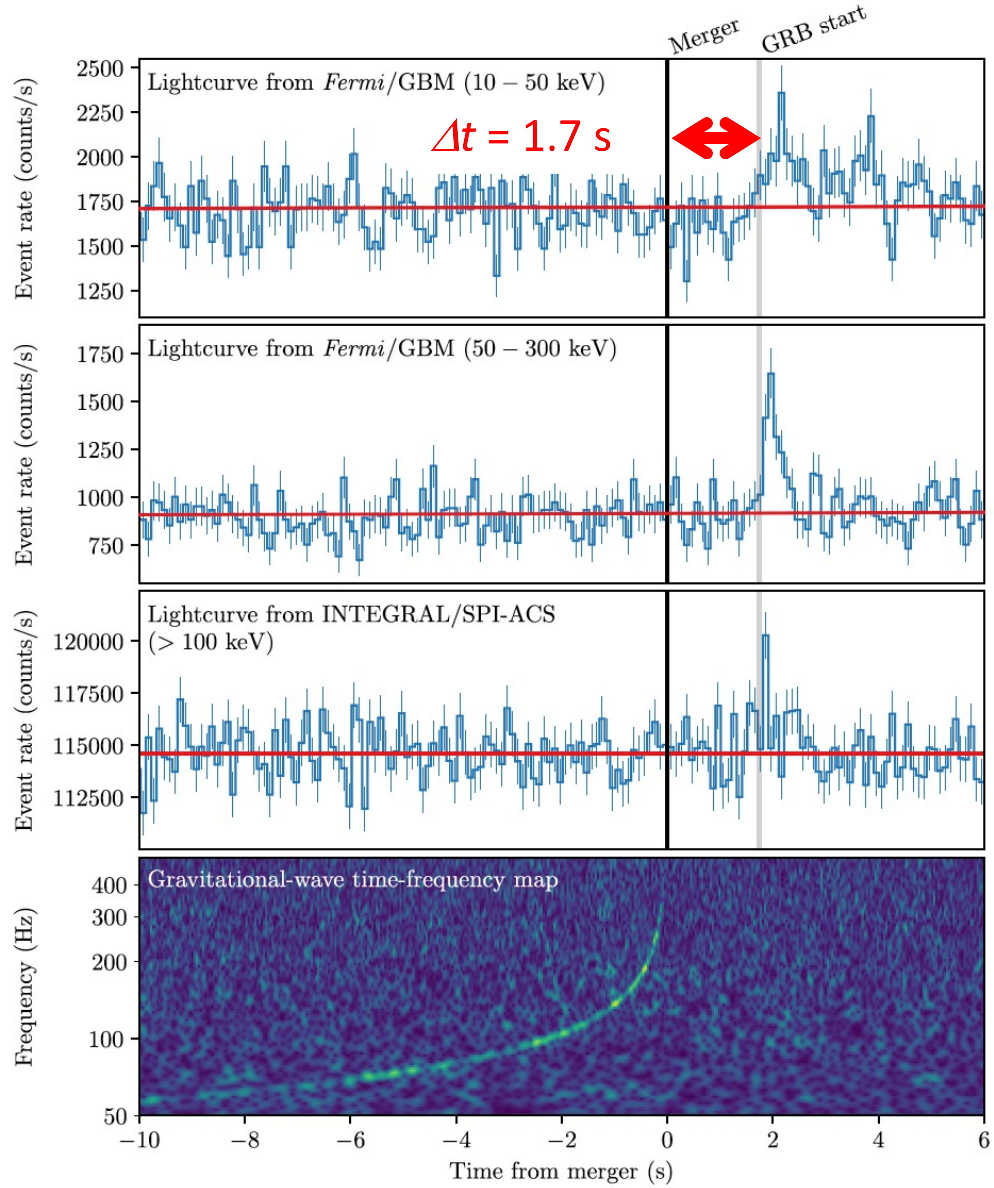
$$\frac{v_{GW} - c}{c} \approx \frac{c\Delta t}{D}$$

- Δt =1.
- $D \approx 26$ Mpc
  - Conservative limit – use 90% confidence level lower limit on GW source from parameter estimation

$$-3 \times 10^{-15} \leq \frac{v_{GW} - c}{c} \leq +7 \times 10^{-16}$$

- GW170814 also puts limits on violations of Lorentz Invariance and Equivalence Principle

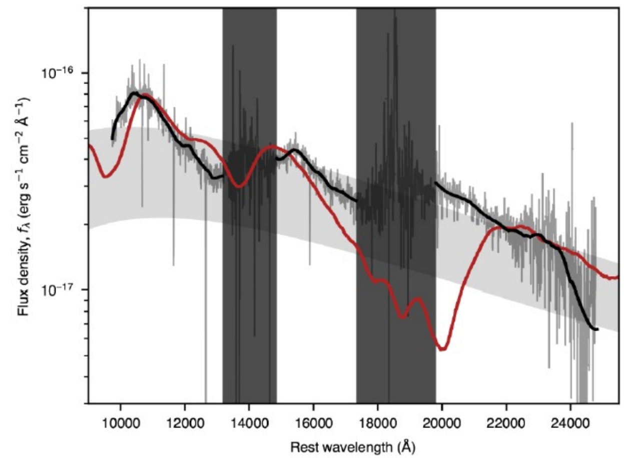
LIGO Scientific Collaboration and Virgo Collaboration, Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A" Astrophys. J. Lett., 848:L13, (2017)



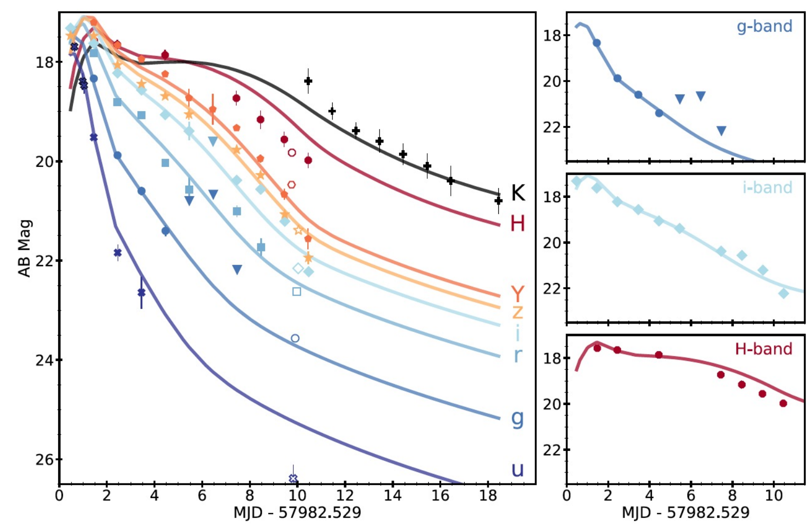
Binary Neutron Star Mergers Produce Kilonovae

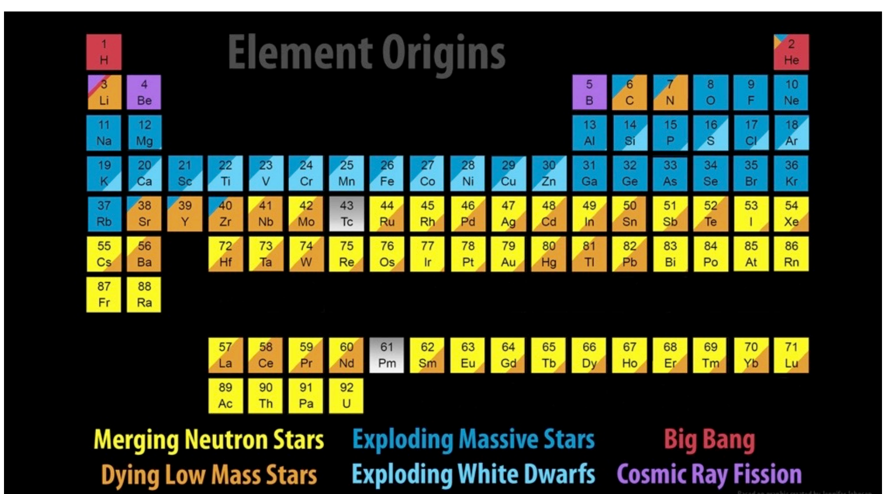
- Electromagnetic follow-up of GW170817 provides strong evidence for kilonova model
  - kilonova - isotropic thermal emission produced by radioactive decay of rapid neutron capture (‘r-process’) elements synthesized in the merger ejecta
- Spectra taken over 2 week period across all electromagnetic bands consistent with kilonova models
  - “Blue” early emission dominated by Fe-group and light r-process formation; later “red” emission dominated by heavy element (lanthanide) formation
- Recent radio data prefers ‘cocoon’ model to classical short-hard GRB production!

Kasliwal et al. 2017,
Science, DOI: https://doi.org/10.1126/science.aap9455



Cowperthwaite, et al. 2017,
Ap. J. Lett. DOI: https://doi.org/10.3847/2041-8213/aa8fc7



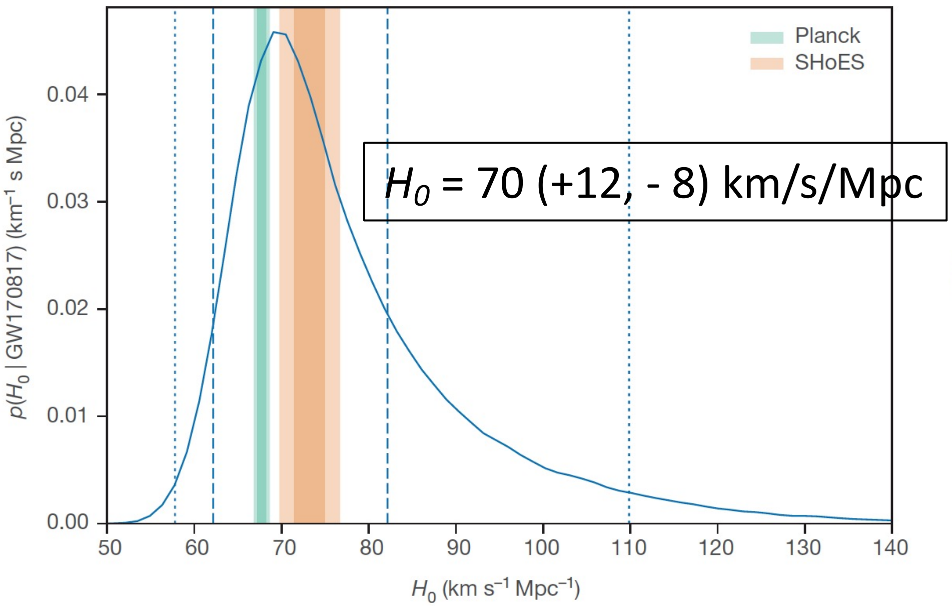


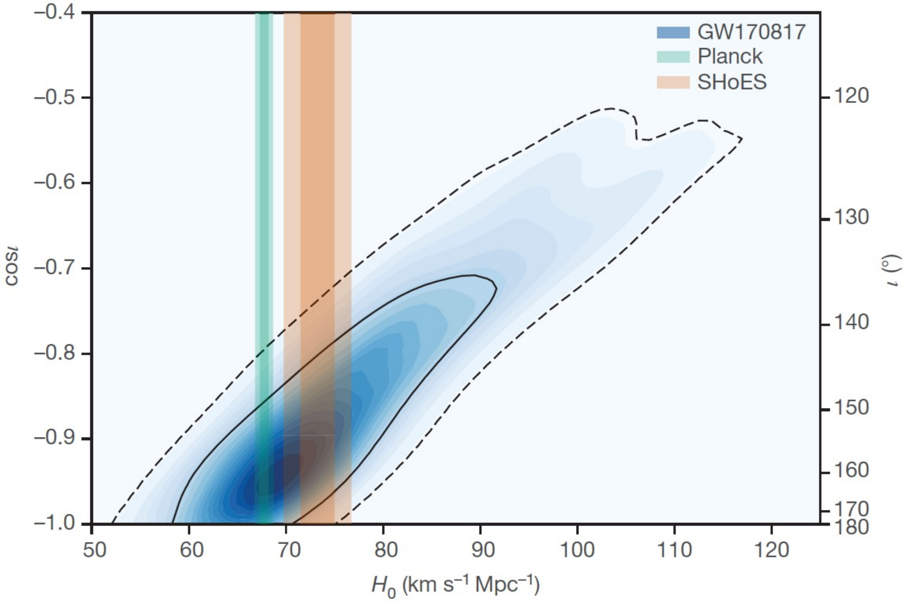
A gravitational-wave standard siren measurement of the Hubble constant

- Gravitational waves are ‘standard sirens’, providing absolute measure of luminosity distance d_L
- can be used to determine H_0 directly if red shift is known:

$$c\, z = H_0\, d_L$$

- … without the need for a cosmic distance ladder!





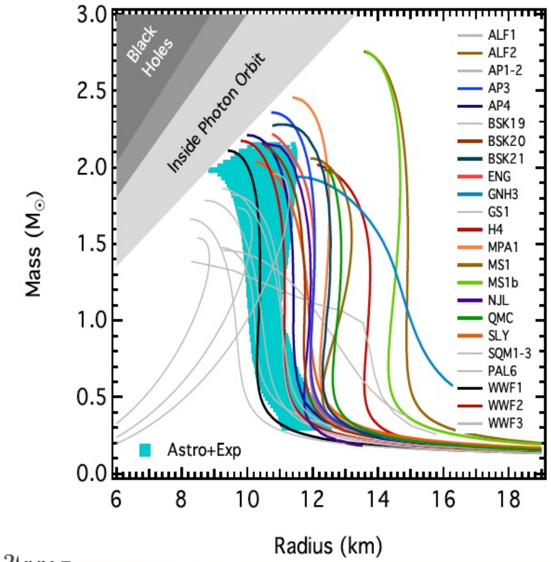
Abbott, et al., LIGO-Virgo Collaboration, 1M2H, DeCAM GW-EM & DES, DLT40, Las Cumbres Observatory, VINRO UGE, MASTER Collaborations, A gravitational-wave standard siren measurement of the Hubble constant”, *Nature* 551, 85–88 (2017).

Constraining the Neutron Star Equation of State with GW170817

- Gravitational waveforms contain information about NS tidal deformations → allows us to constrain NS equations of state (EOS)
- Tidal deformability parameter:

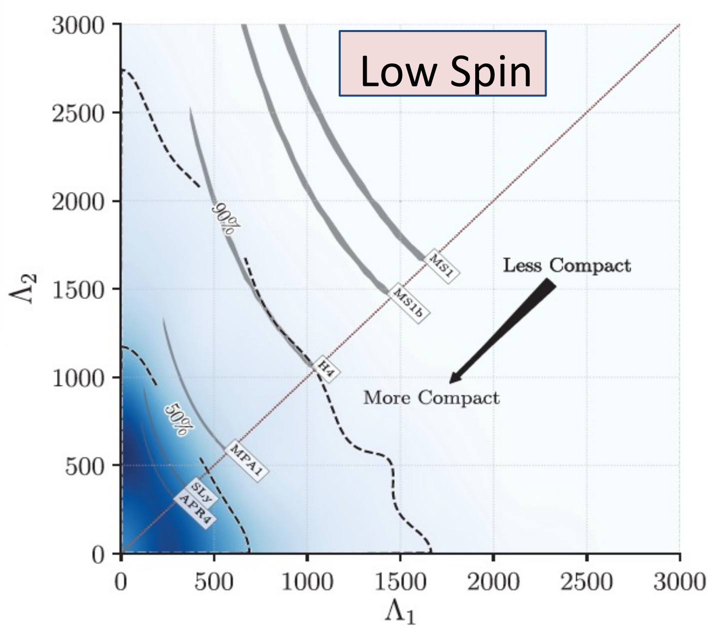
$$\Lambda = \frac{2}{3} k_2 \left(\frac{R}{M} \right)^5$$

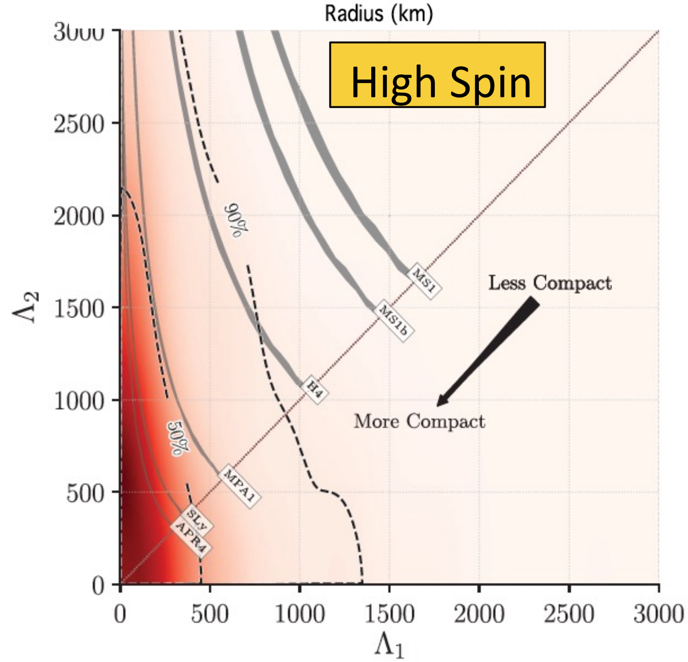
- GW170817 data consistent with softer EOS → more compact NS



Ozel and Friere (2016)

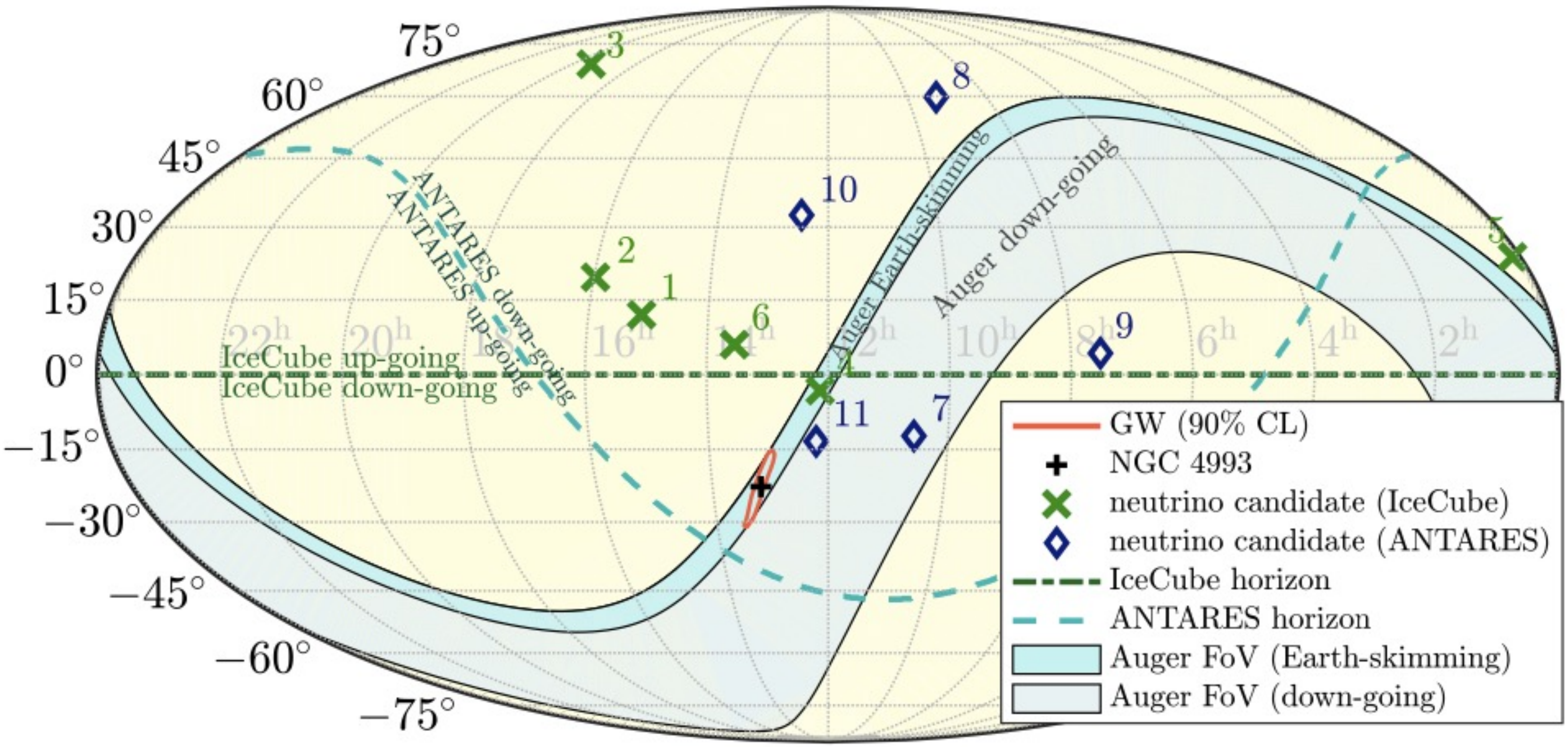
Abbott, et al. ,LIGO Scientific Collaboration and Virgo Collaboration, "GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral" Phys. Rev. Lett. 161101 (2017)





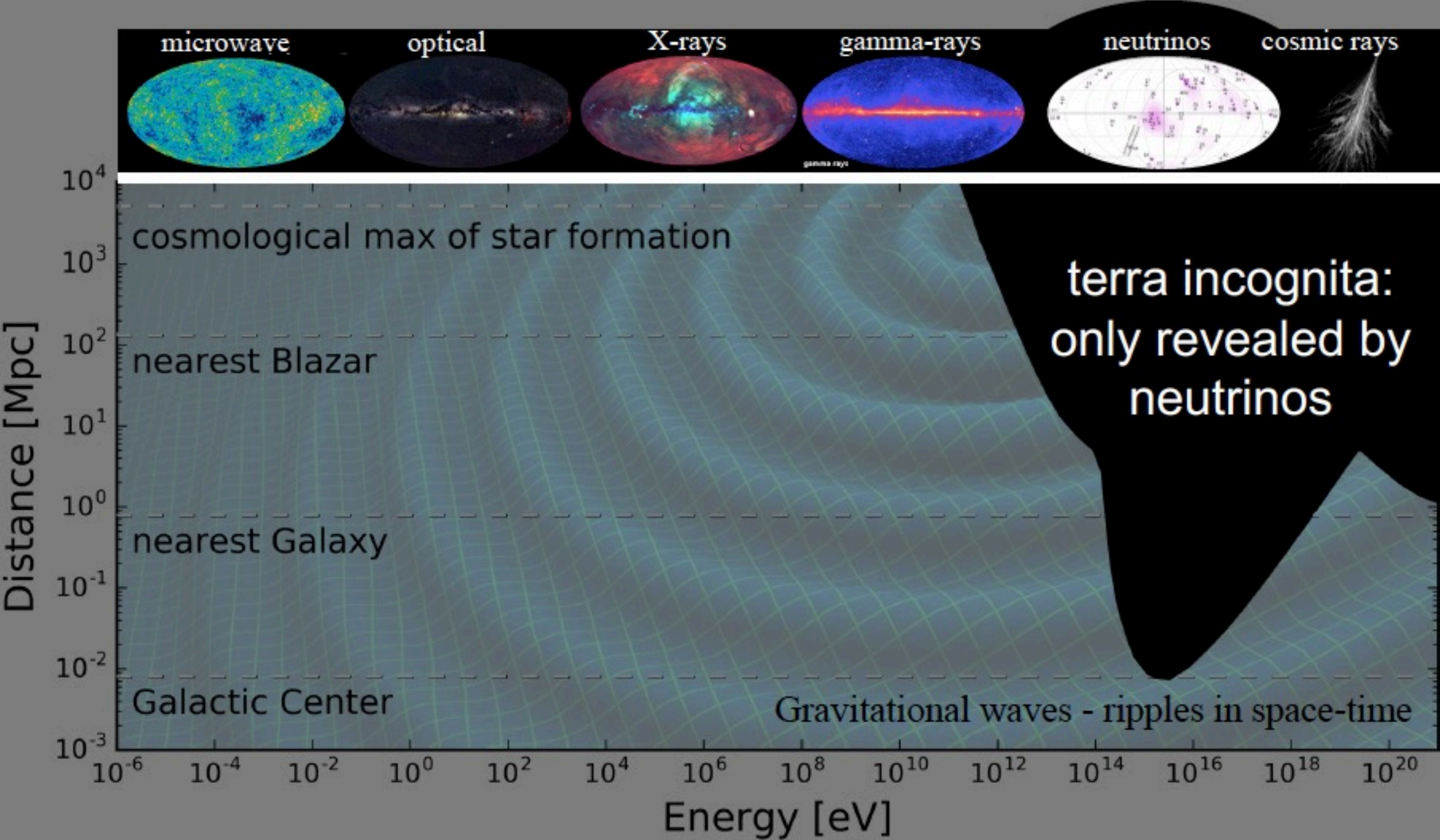
Neutrino Search from GW170817

ANTARES/IceCube/Ligo/Virgo/Auger "follow-up" analysis



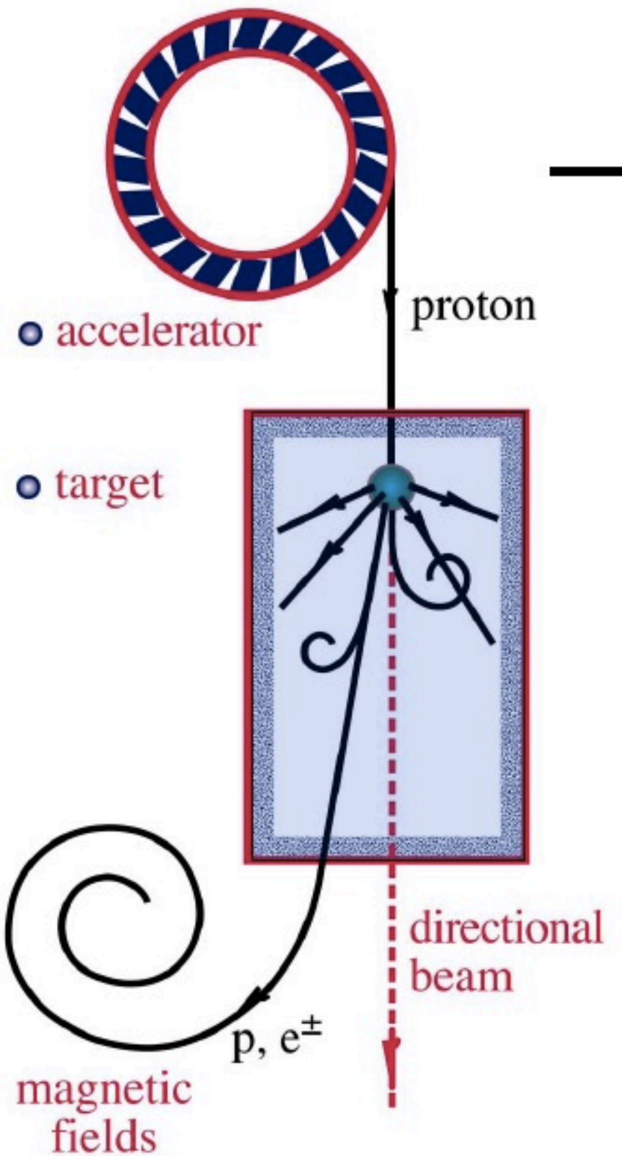
The Astrophysical Journal Letters, 850:L35, 2017

- The New era of Gravitational Wave: GW170817 - crucial milestone in multimessenger astrophysics
- **The complementary messenger: the neutrino**
  - ✓ **IC170922**
  - ✓ **NGC 1068**
- The future challanges



- 20% of the Universe is opaque to the EM spectrum
- non-thermal Universe powered by cosmic accelerators
- probed by gravitational waves and neutrinos

ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

black hole
neutron star

radiation and dust

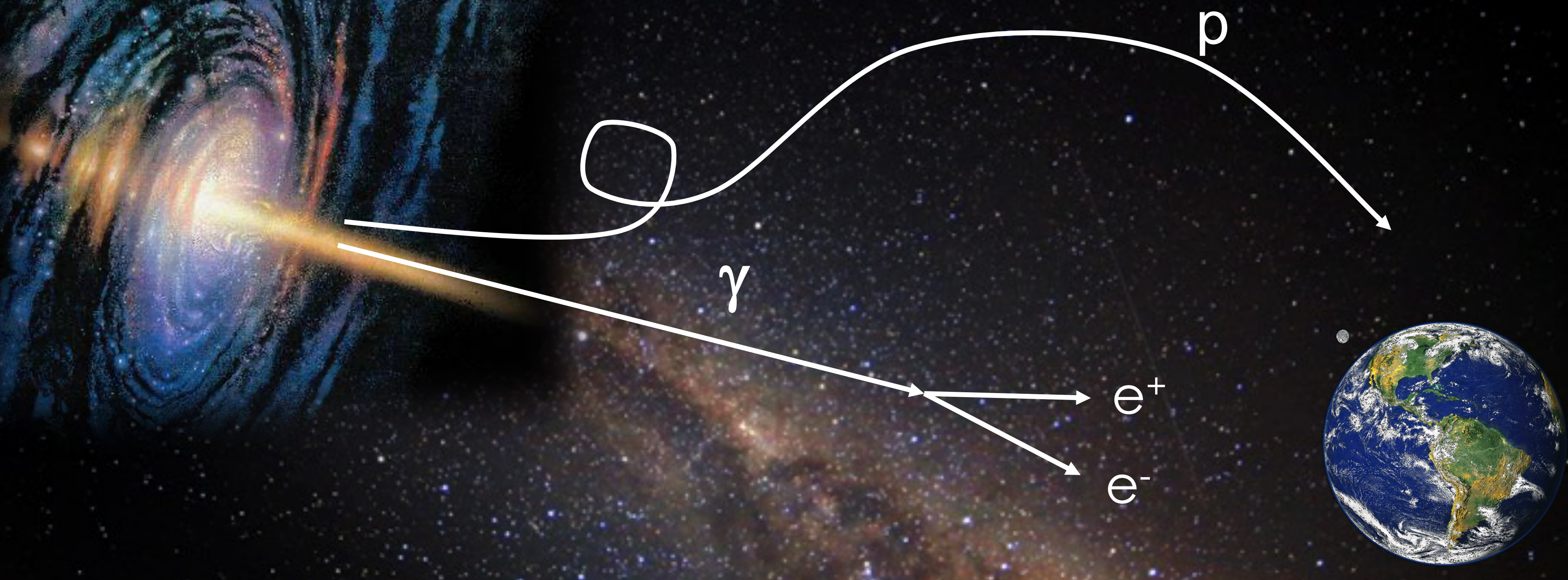
$$p + \gamma \rightarrow n + \pi^+$$

~ cosmic ray + neutrino

$$\rightarrow p + \pi^0$$

~ cosmic ray + gamma

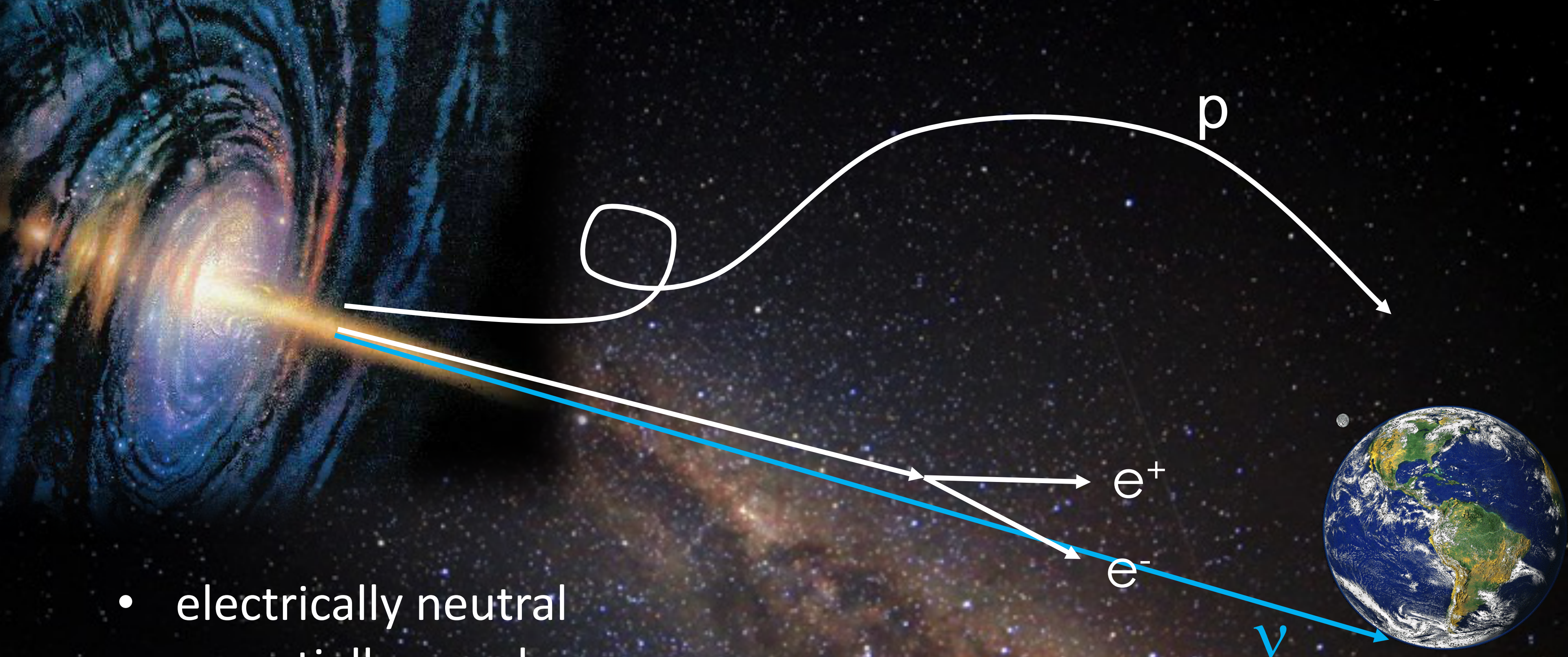
The opaque Universe



$$\gamma + \gamma_{CMB} \rightarrow e^{+} + e^{-}$$

With 10^3 TeV energy, photons do not reach us from the edge of our galaxy because of their small mean free path in the microwave background.

Neutrinos? Perfect Messenger



- electrically neutral
- essentially massless
- essentially unabsorbed
- tracks nuclear processes
- reveal the sources of cosmic rays

- … but difficult to detect: how large a detector?

Looking downward

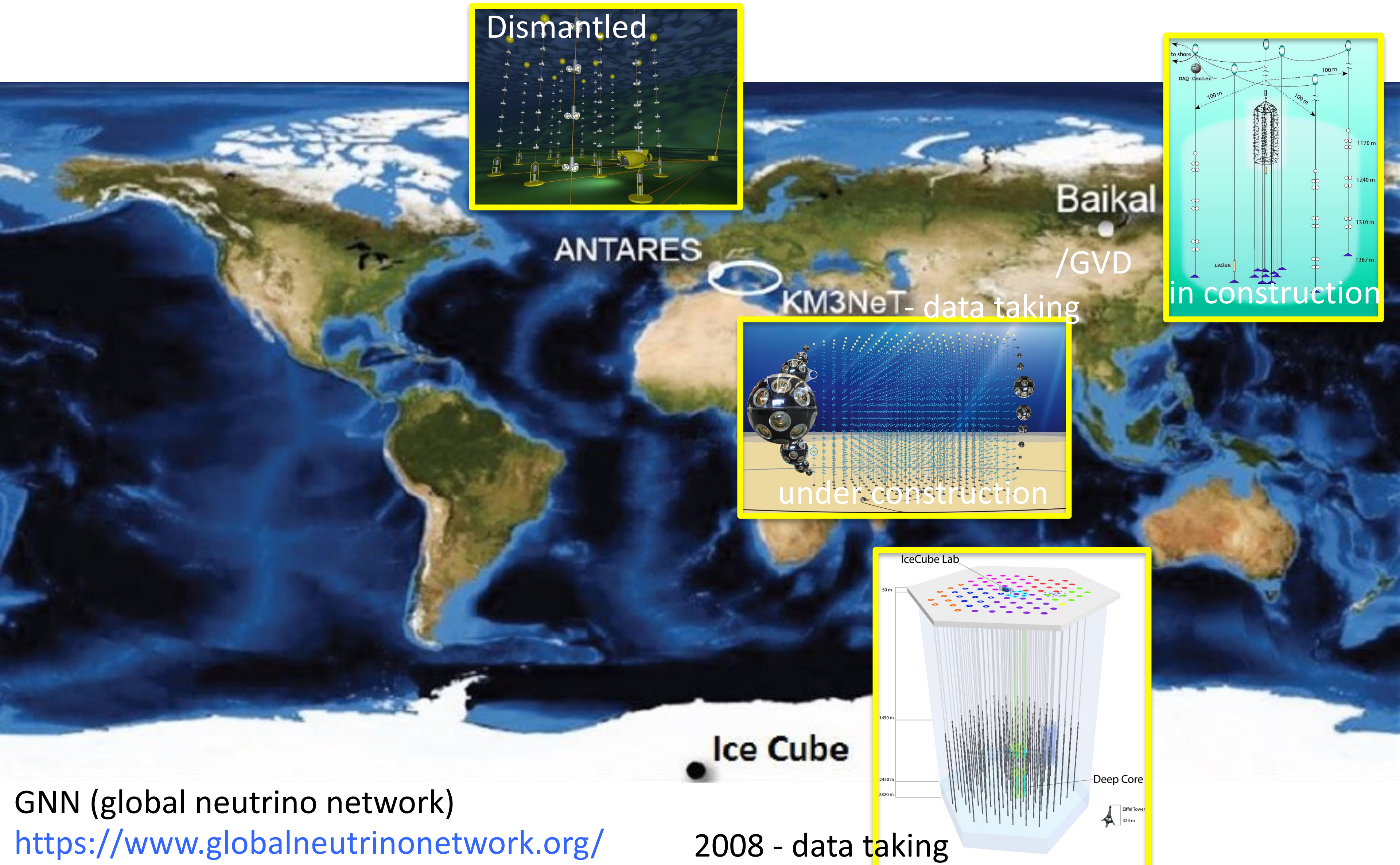
- At Earth's surface, cosmic-ray air showers produce a huge background of charged particles in particle detectors. Therefore, neutrino telescopes attempting to see beyond the atmosphere must go underground.

- Looking upward from even the deepest mineshaft, one would have to contend with a non-negligible flux of muons from cosmic-ray showers.

- Neutrino telescopes have to look for neutrinos that passed through the entire Earth, which serves as a filter that lets nothing else through.

- Neutrino telescopes seek out upward-moving muons created in collisions between high-energy muon neutrinos (ν_μ) from below and material within the detector or its surroundings.

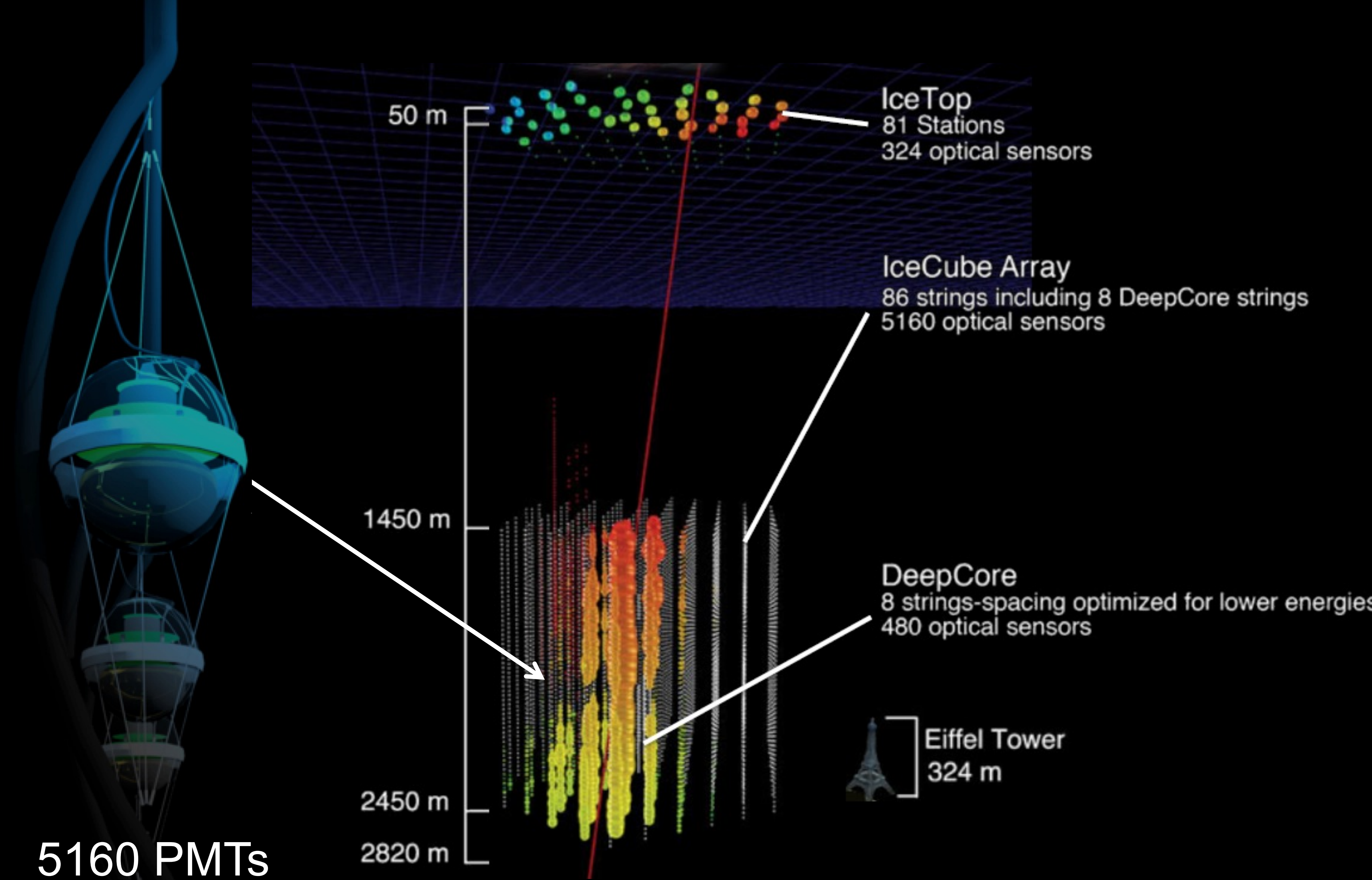
Large neutrino telescopes on Earth



GNN (global neutrino network)
https://www.globalneutrinonetwork.org/

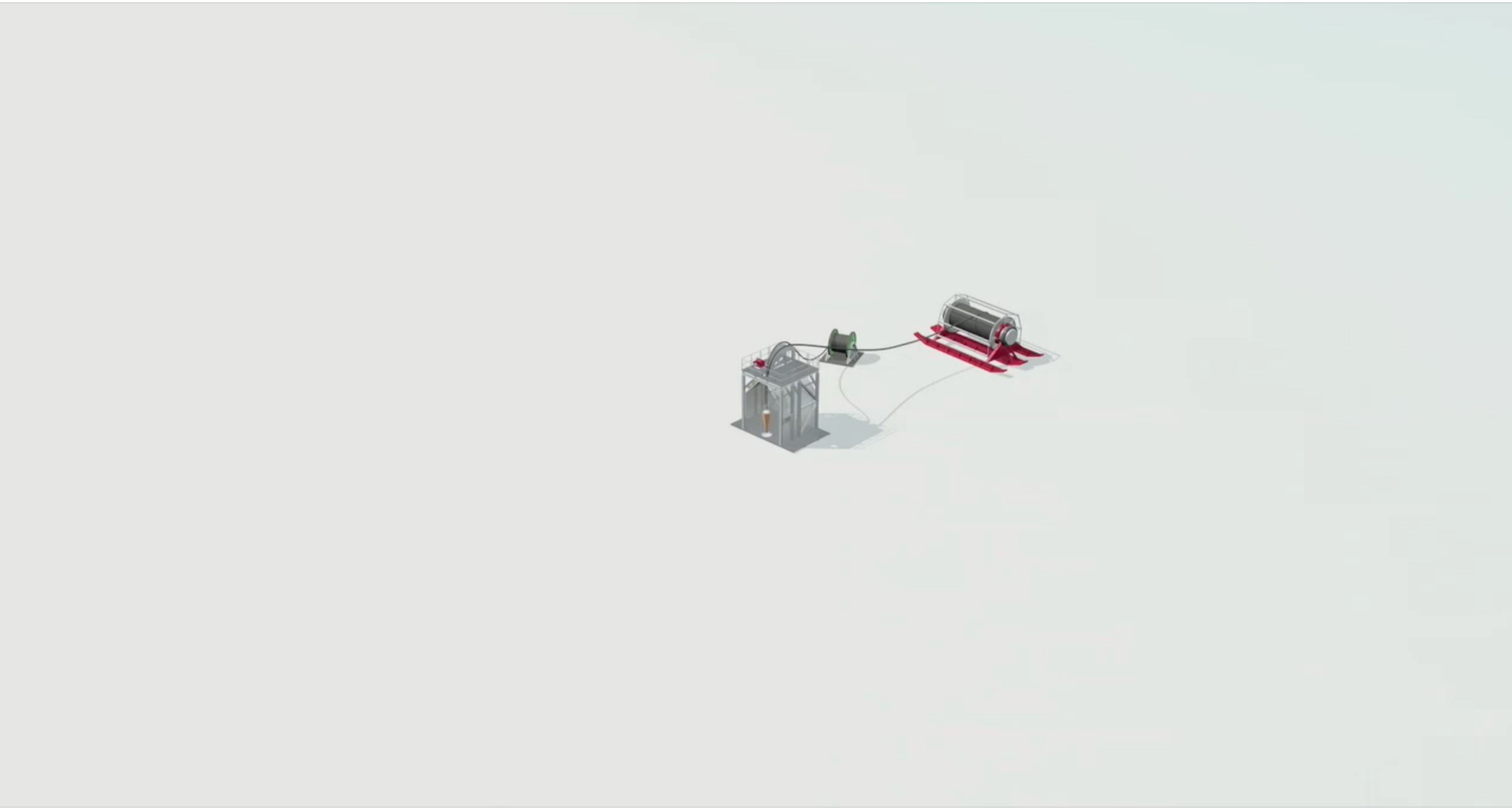

ultra-transparent ice below 1.5 km

IceCube



5160 PMTs
in 1 km^3

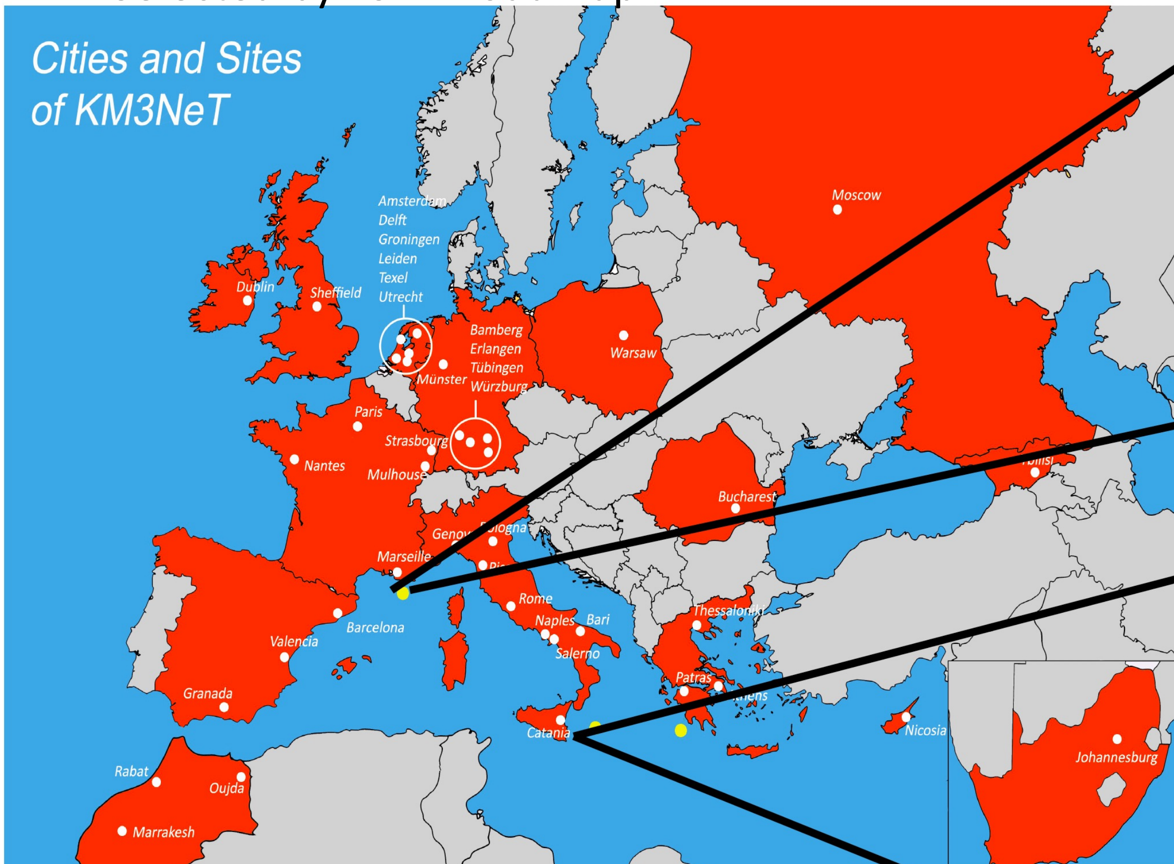
IceCube

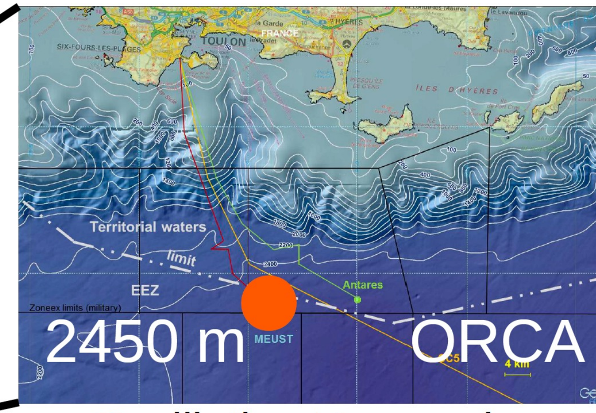


Courtesy of IceCube Collaboration

KM3NeT detector

- Multi-site, deep-sea neutrino telescope
- Selected by ESFRI roadmap





Oscillation Research
with Cosmics In the Abyss

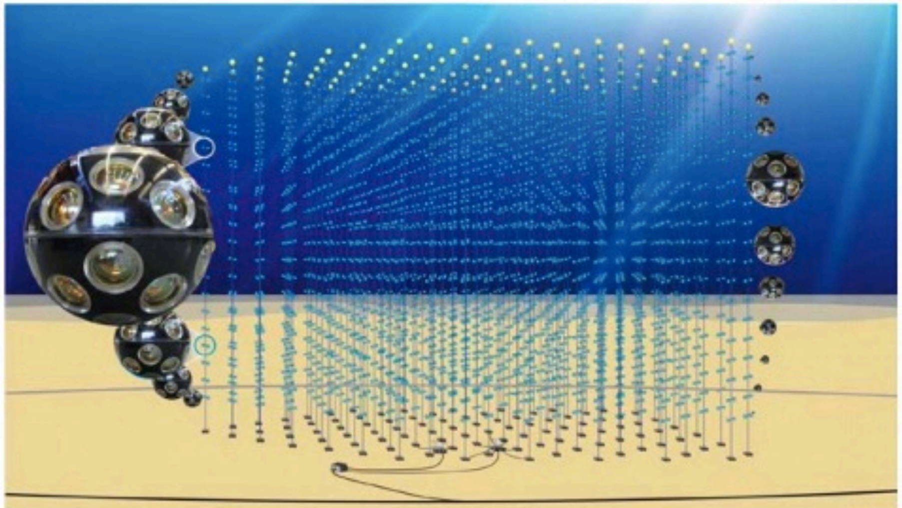
Astroparticle Research
with Cosmics In the Abyss

* KM3NeT = **km^3 N**eutrino **T**elescope

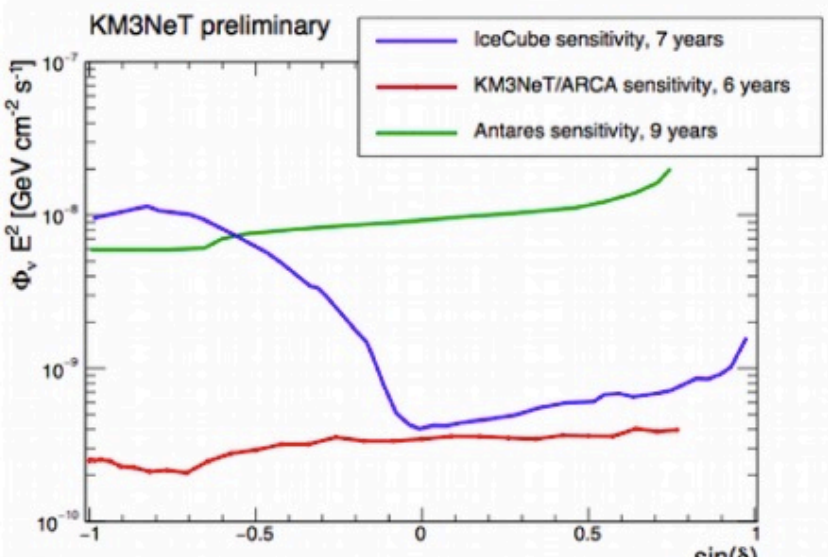
Single Collaboration, Single Technology

KM3NeT, Journal of Physics G: Nuclear and Particle Physics, 43 (8), 084001, 2016

KM3NeT:ARCA



Volume : 1 Gt



2 x 115 strings
18 DOMs / string
31 PMTs / DOM
Total: **128 000 PMTs (3”)**

Vertical spacing: 36 m
Horizontal spacing: 90 m

Mission: neutrino astronomy

Angular resolution ~ 0.2 deg
(tracks, E > 10 TeV)

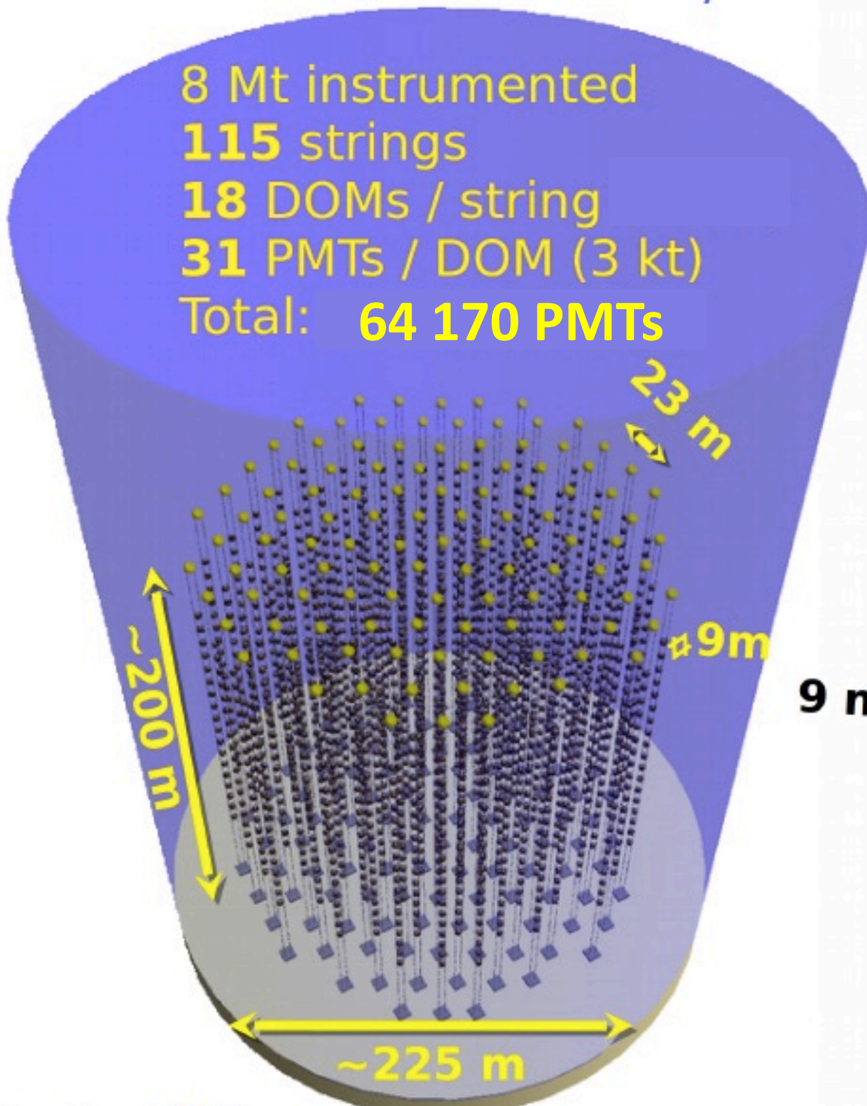
Energy resolution up to 5%
(cascades)

Sensitivity similar to IceCube,
but covering both sky hemispheres

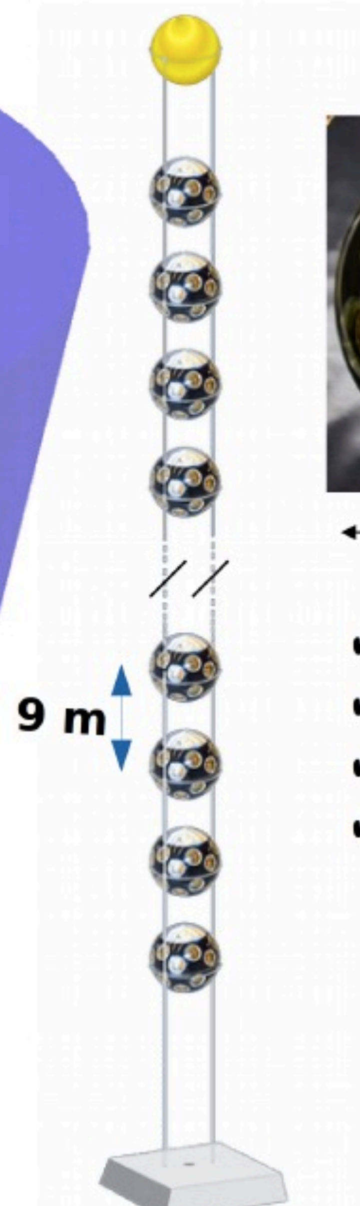
KM3NeT, Journal of Physics G: Nuclear and Particle Physics, 43 (8), 084001, 2016

KM3NeT:ORCA

Mission: neutrino mass hierarchy



Depth=2450 m



Digital Optical Module

← 17” →

- 31 x 3” PMTs
- PMT HV
- LED & piezo
- FPGA readout
- DWDM

✔ Uniform angular coverage
✔ Directional information
✔ Digital photon counting
✔ All data to shore

photocathode area similar to a 17” PMT

Optical background (mainly ^{40}K): 5-10 kHz/PMT

KM3NeT, Journal of Physics G: Nuclear and Particle Physics, 43 (8), 084001, 2016

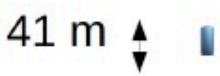
Instrumented volume comparison

Smaller but denser instruments are best for low energies (low amount of light)

Larger but sparser instruments are best for high energies (low fluxes)

IceCube & Baikal-GVD have similar size

SuperK
11100 PMTs
50 kt



MeV - GeV

Solar & atm. ν

operating for 25 yr

KM3NeT-ORCA
2000 OMs
(64000 PMTs)
8 Mt

E > 3 GeV

atm. ν

under construction

ANTARES
885 PMTs
15 Mt

E > 20 GeV

astrophysical and atm. ν

operating for 14y

KM3NeT-ARCA
4000 OMs (128 000 PMTs)
1 Gt

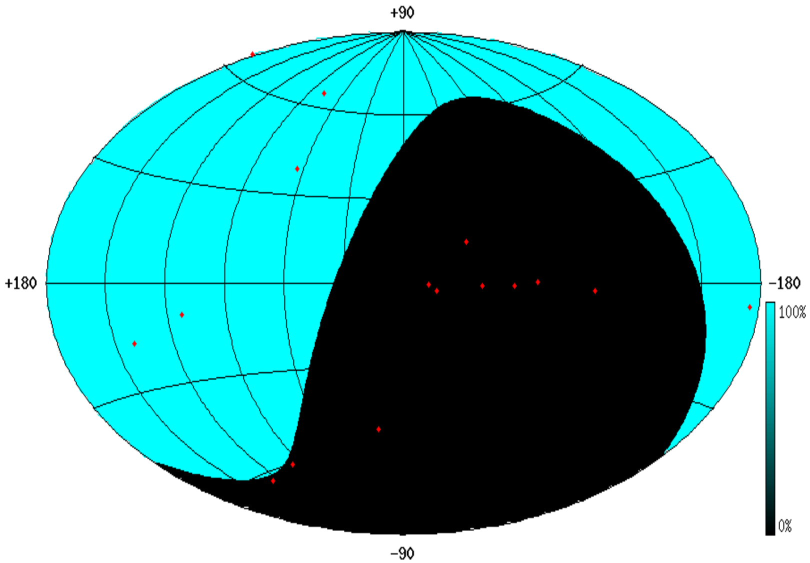
E > 100 GeV

astrophysical ν

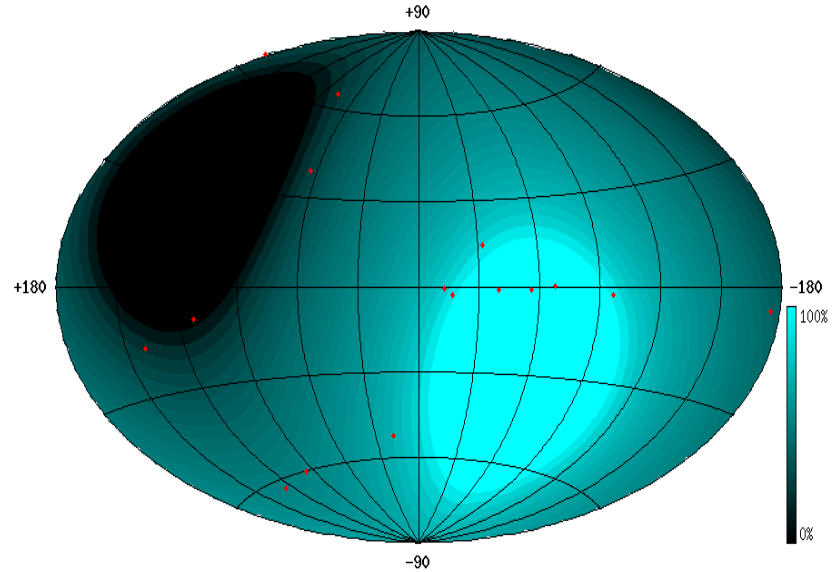
under construction

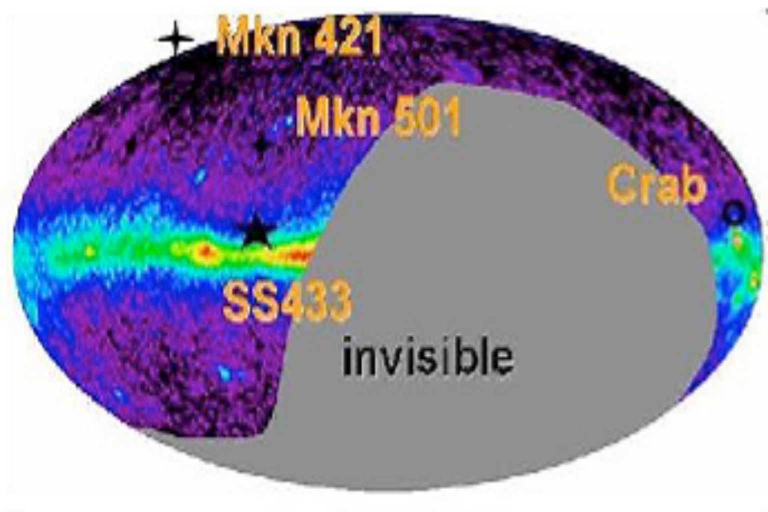
Complementarity with IceCube

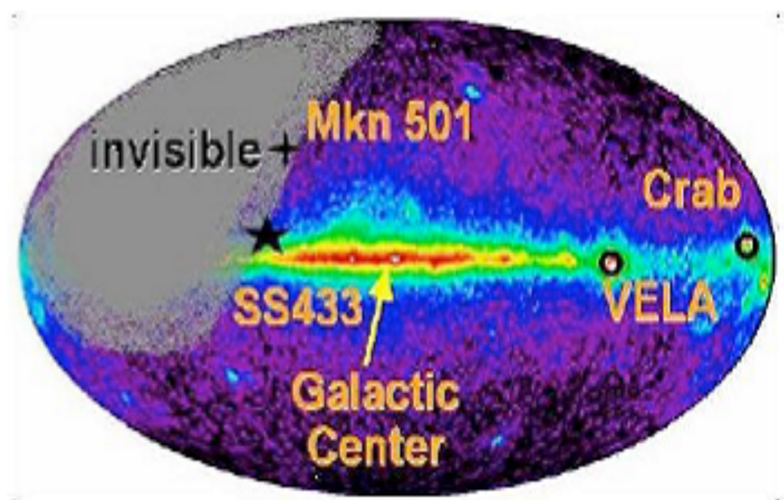
South Pole **IceCube**

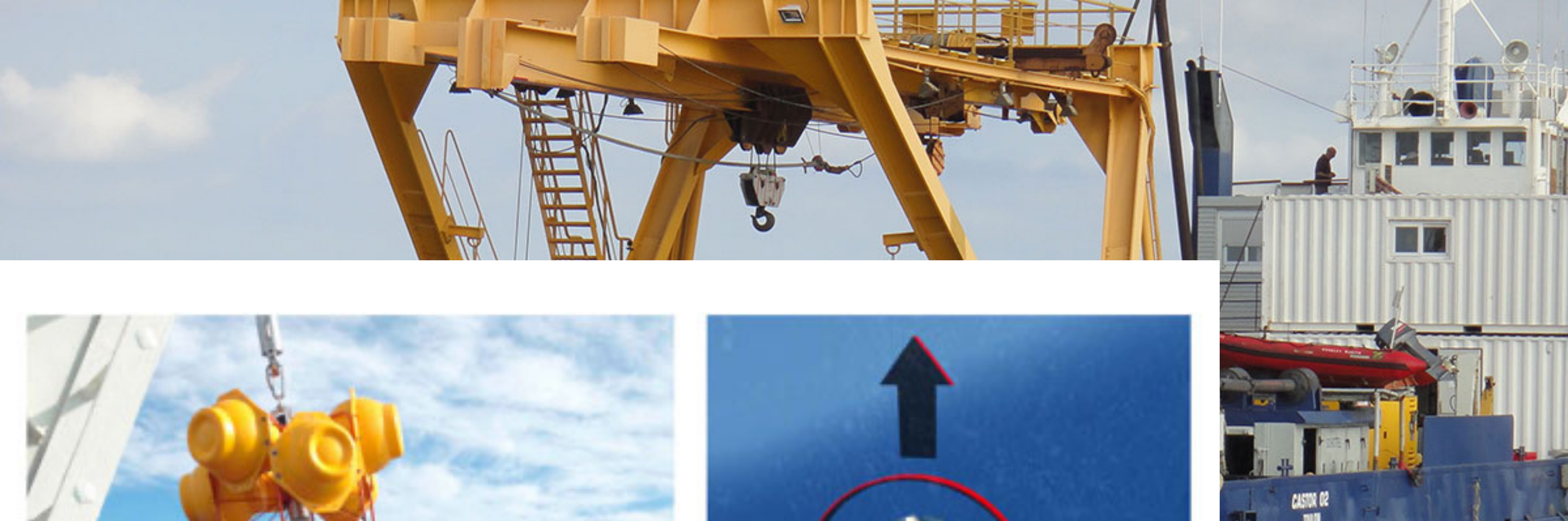


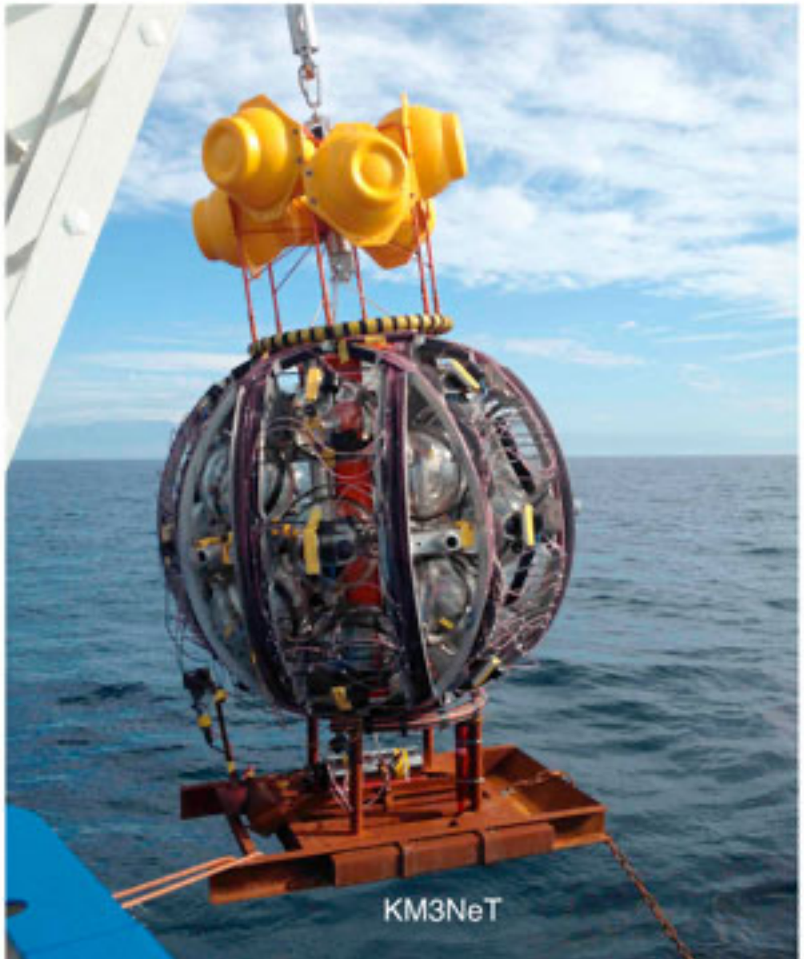
Mediterranean Sea **ARCA**

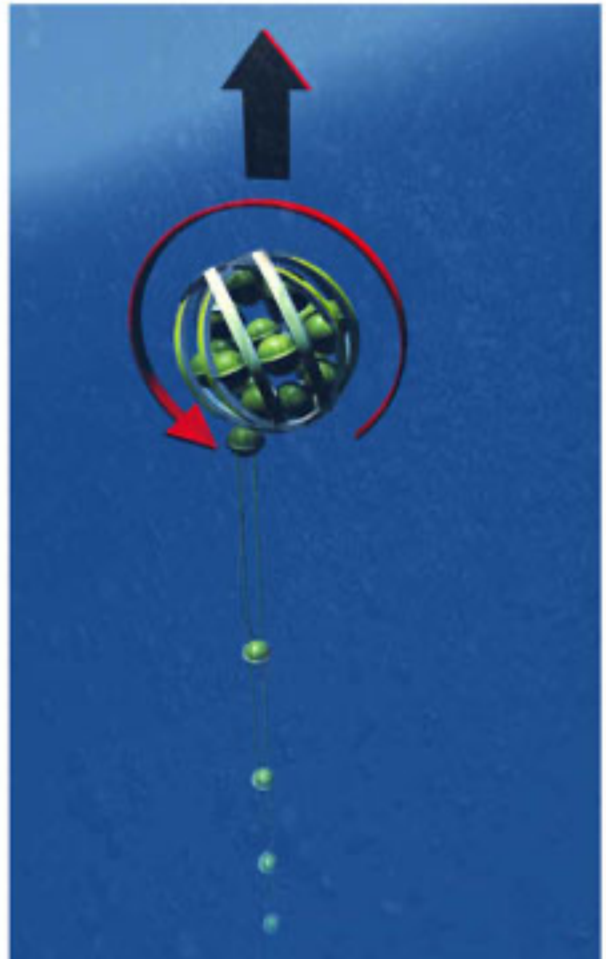






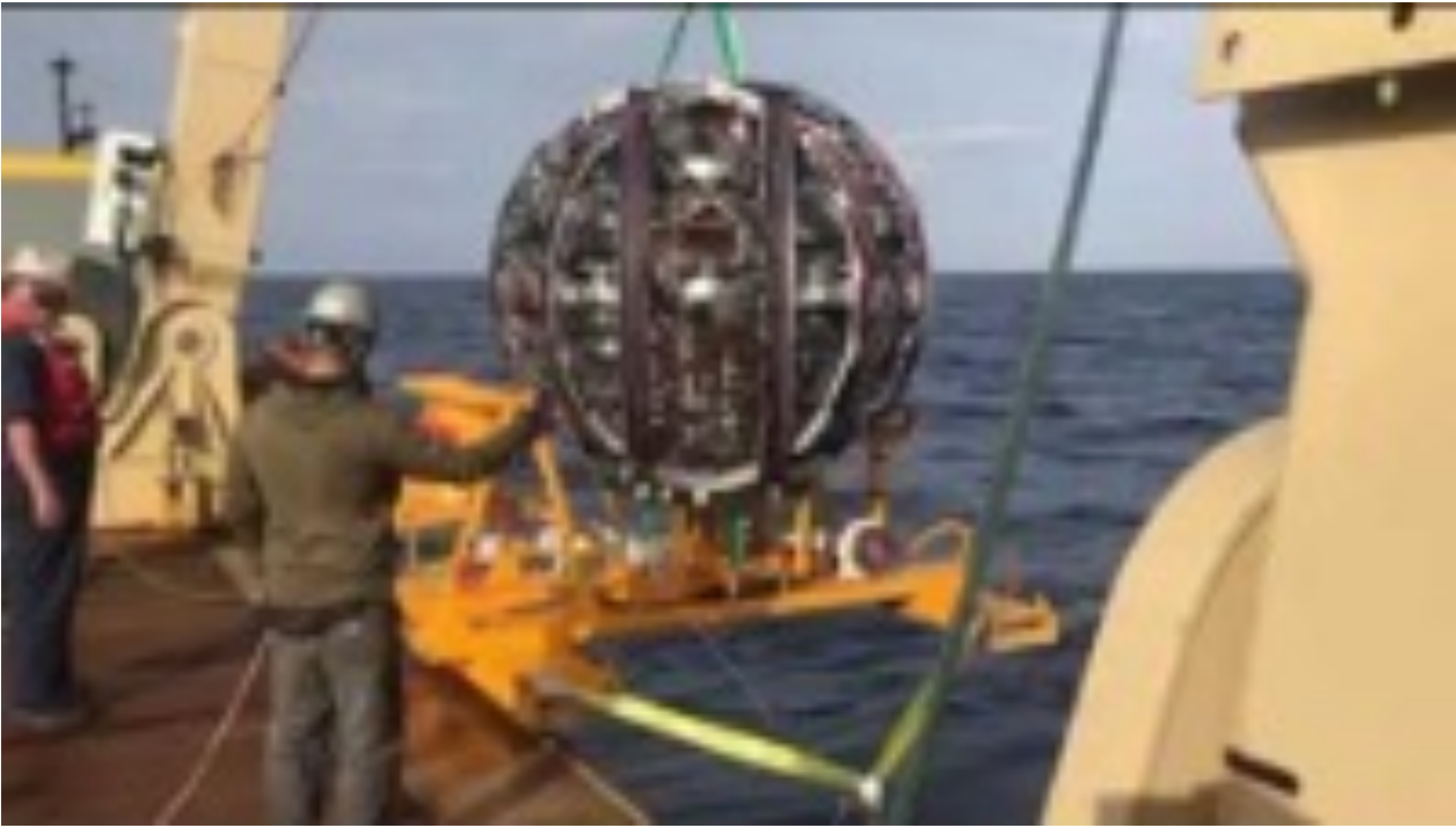

CASTOR 02


KM3NeT

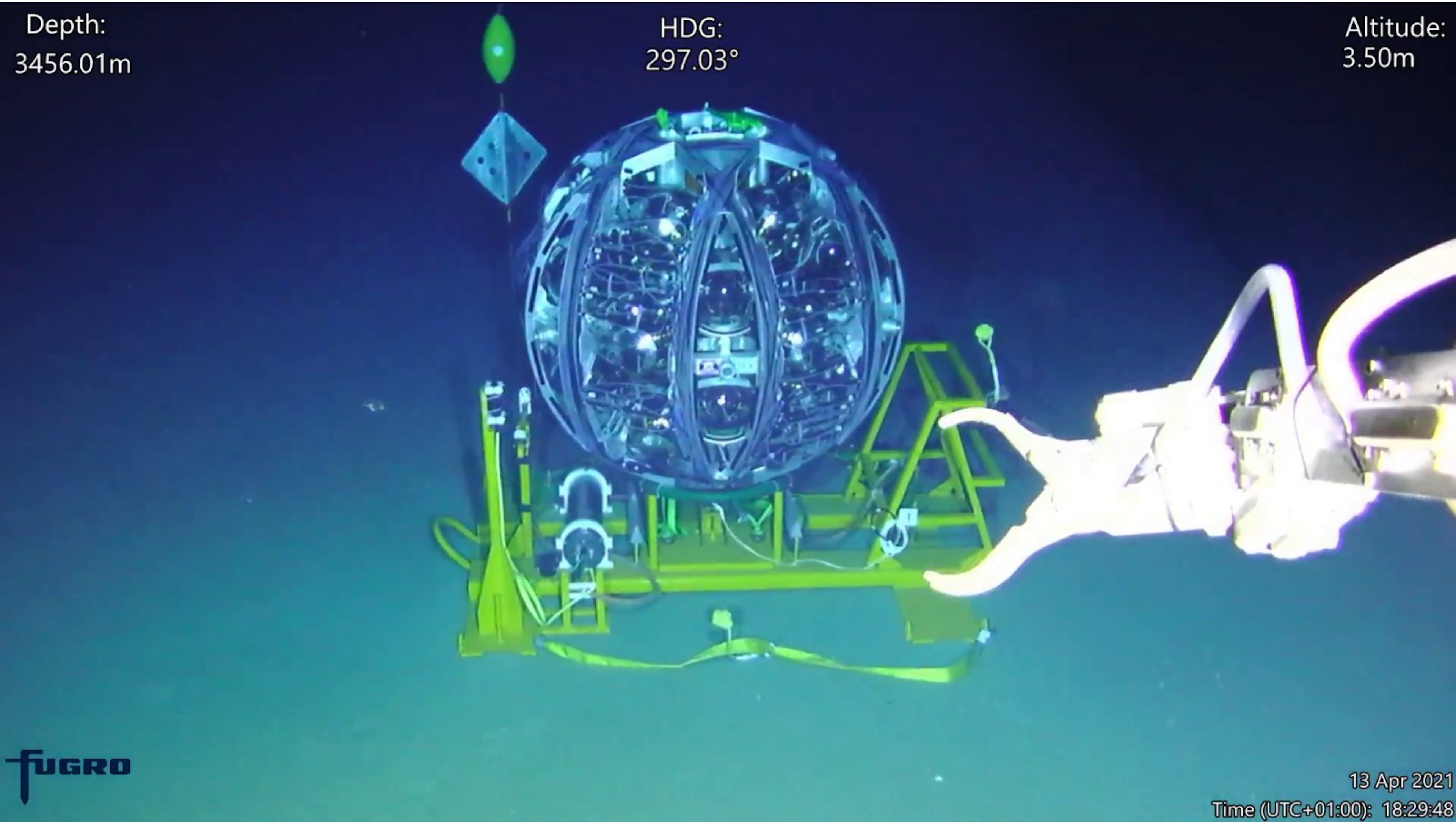


Deployment of the new Junction Box

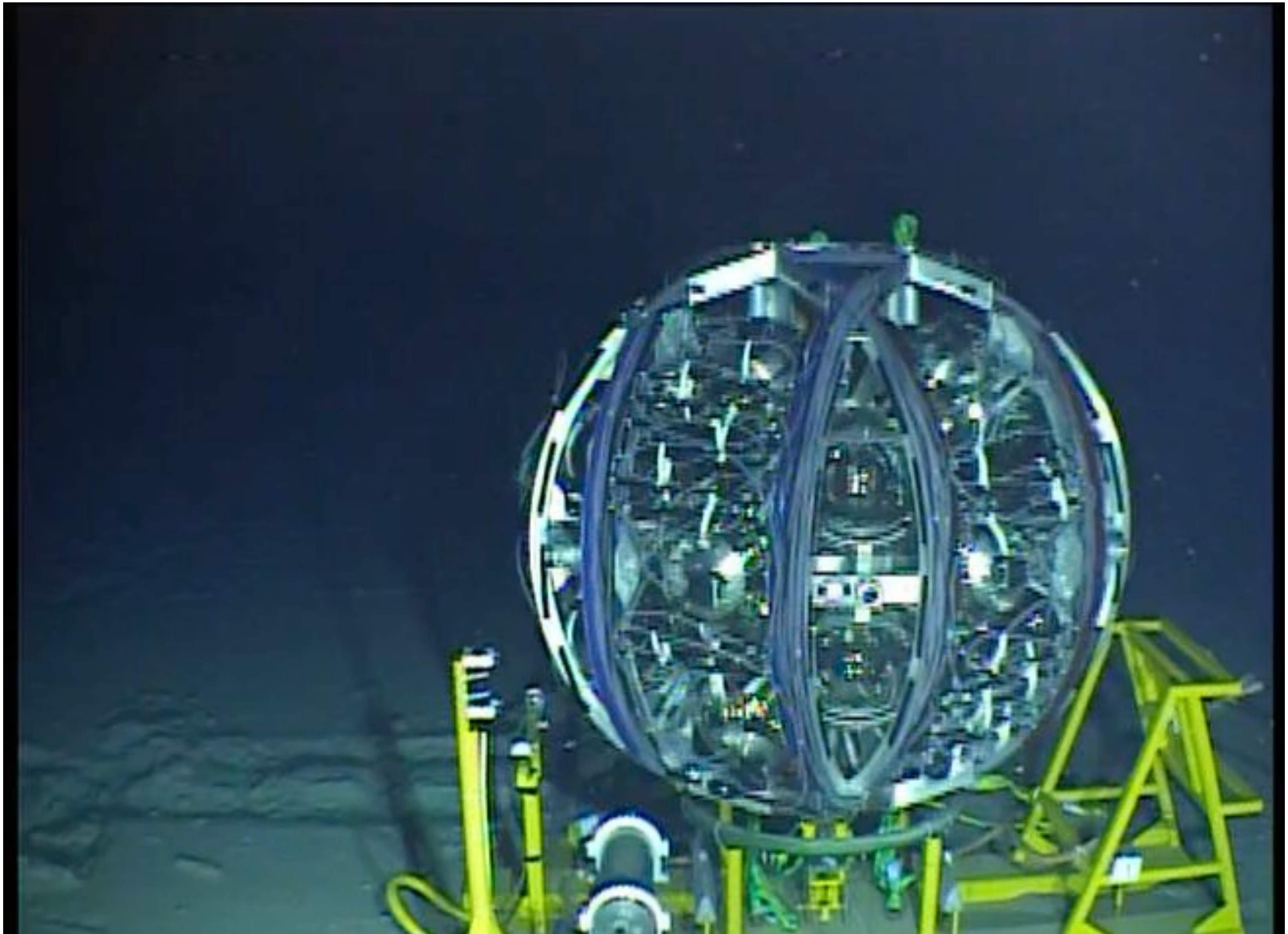
The Detector Unit deployment



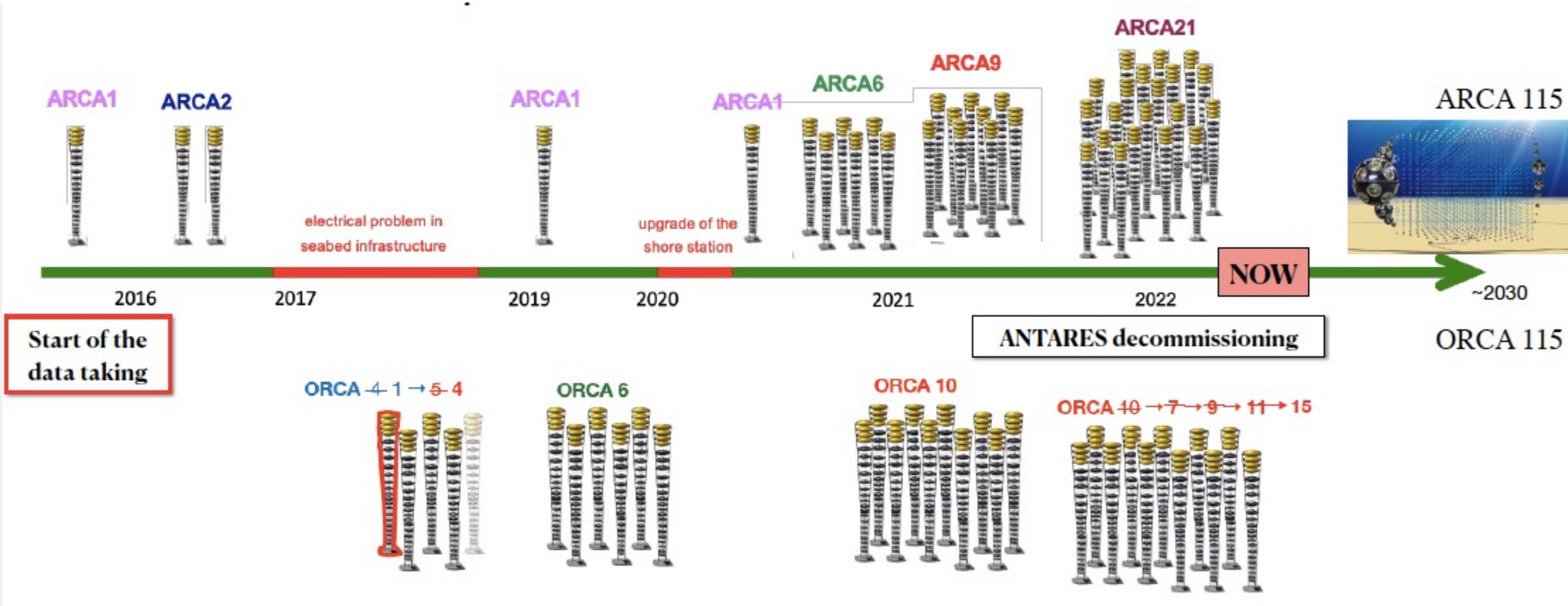
The Detector Unit deployment



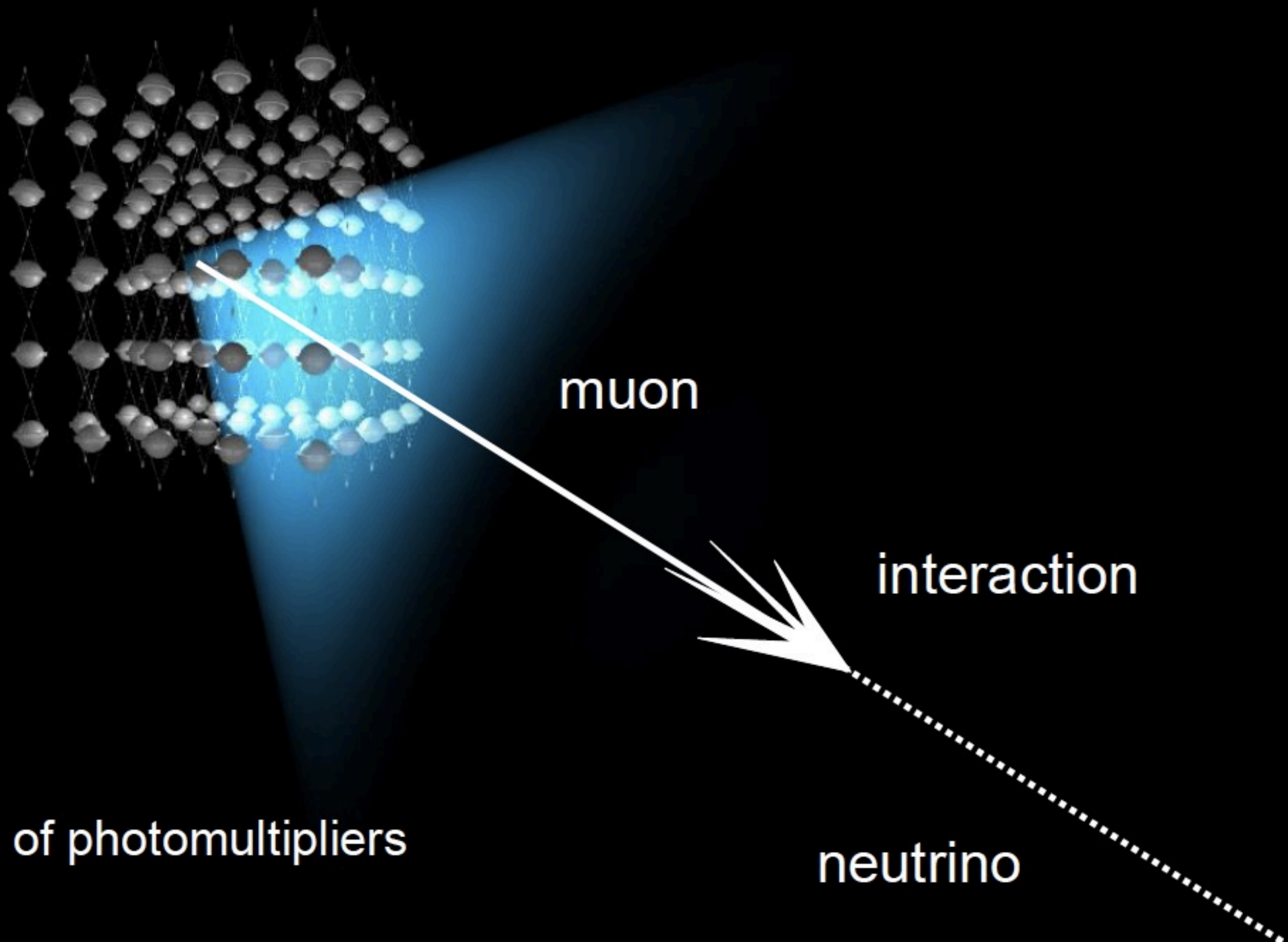
The unfurling mechanism



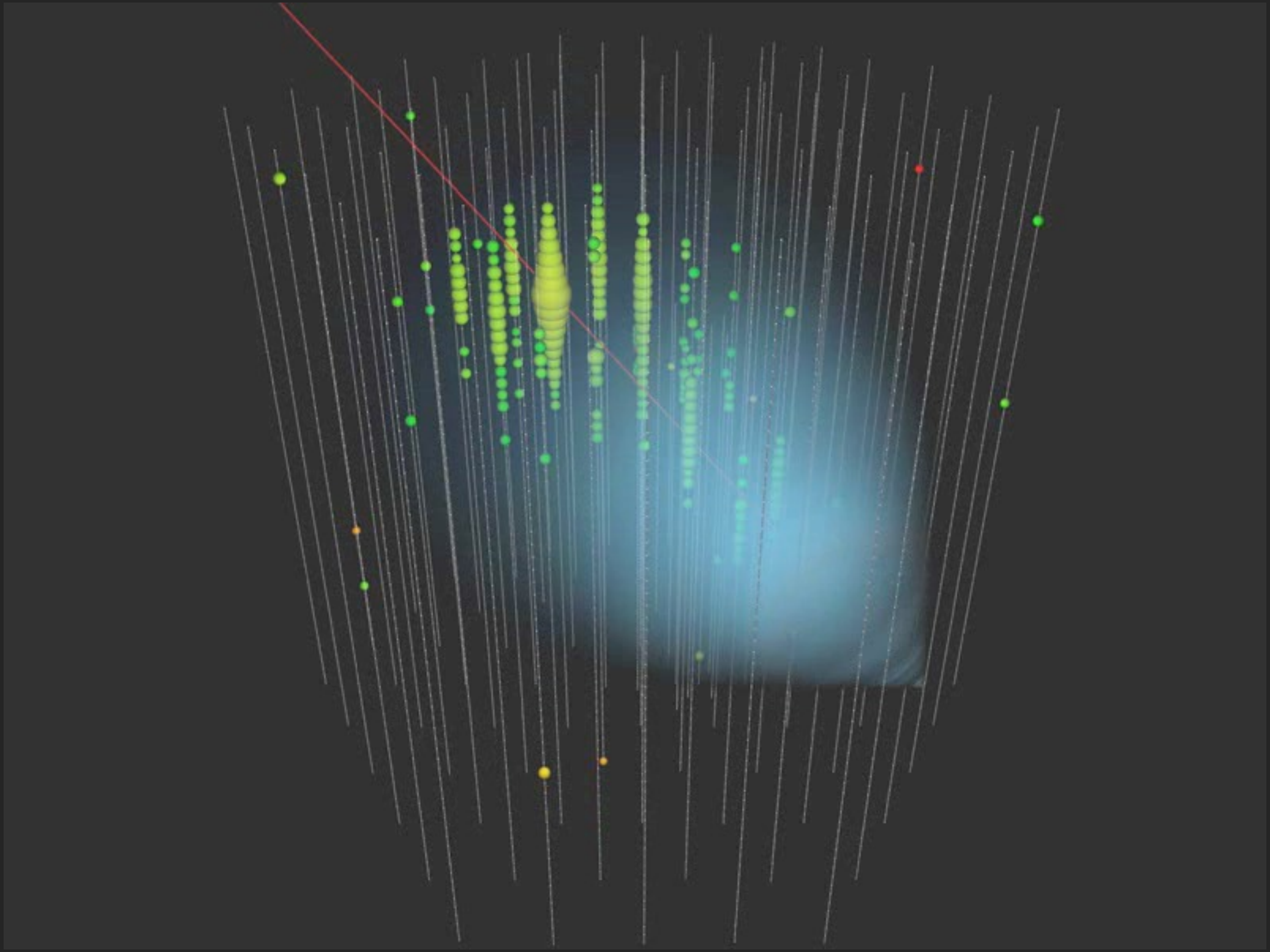
KM3NeT: current status



KM3NeT, Journal of Physics G: Nuclear and Particle Physics, 43 (8), 084001, 2016



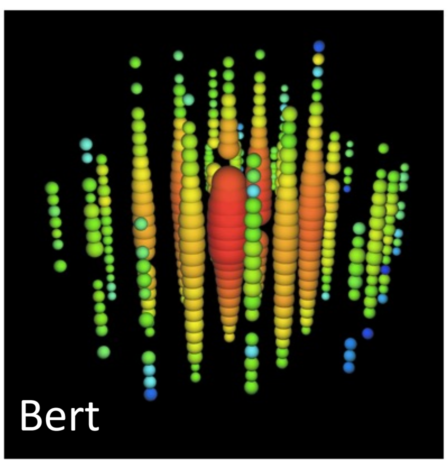
- lattice of photomultipliers

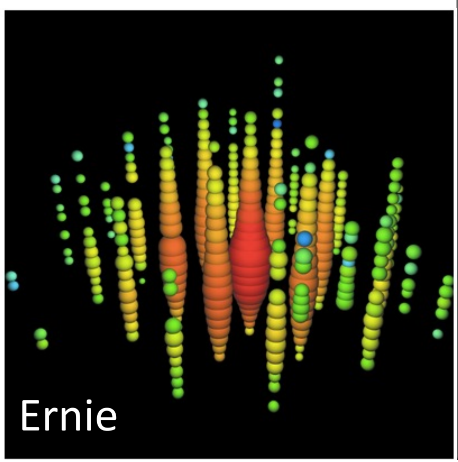


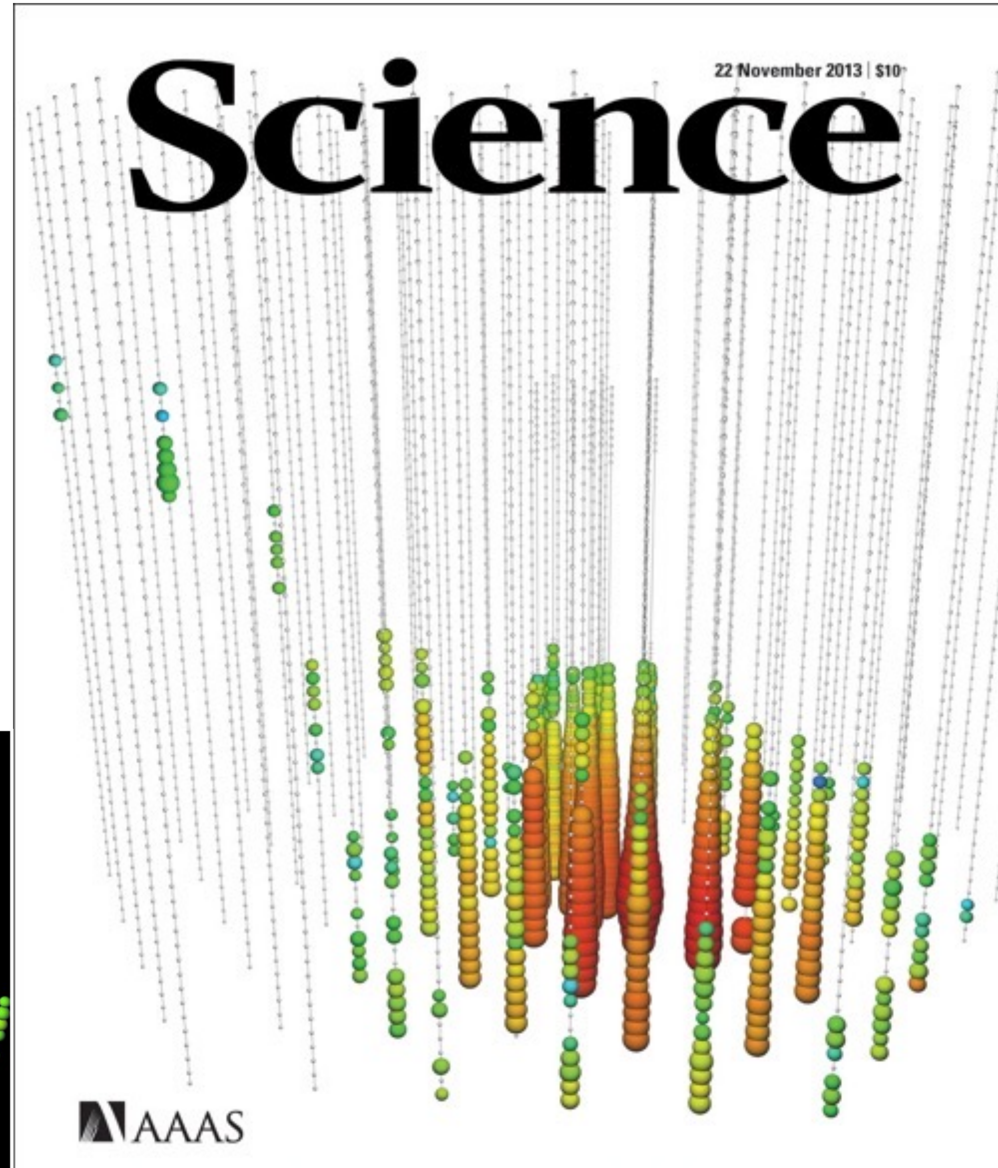
Muon track: color is time; number of photons is energy

Evidence of the ν diffuse flux

28 events, which include the highest energy neutrinos ever observed, have flavors, directions, and energies inconsistent with those expected from the atmospheric muon and neutrino backgrounds. These properties are, however, consistent with generic predictions for an additional component of extraterrestrial origin.

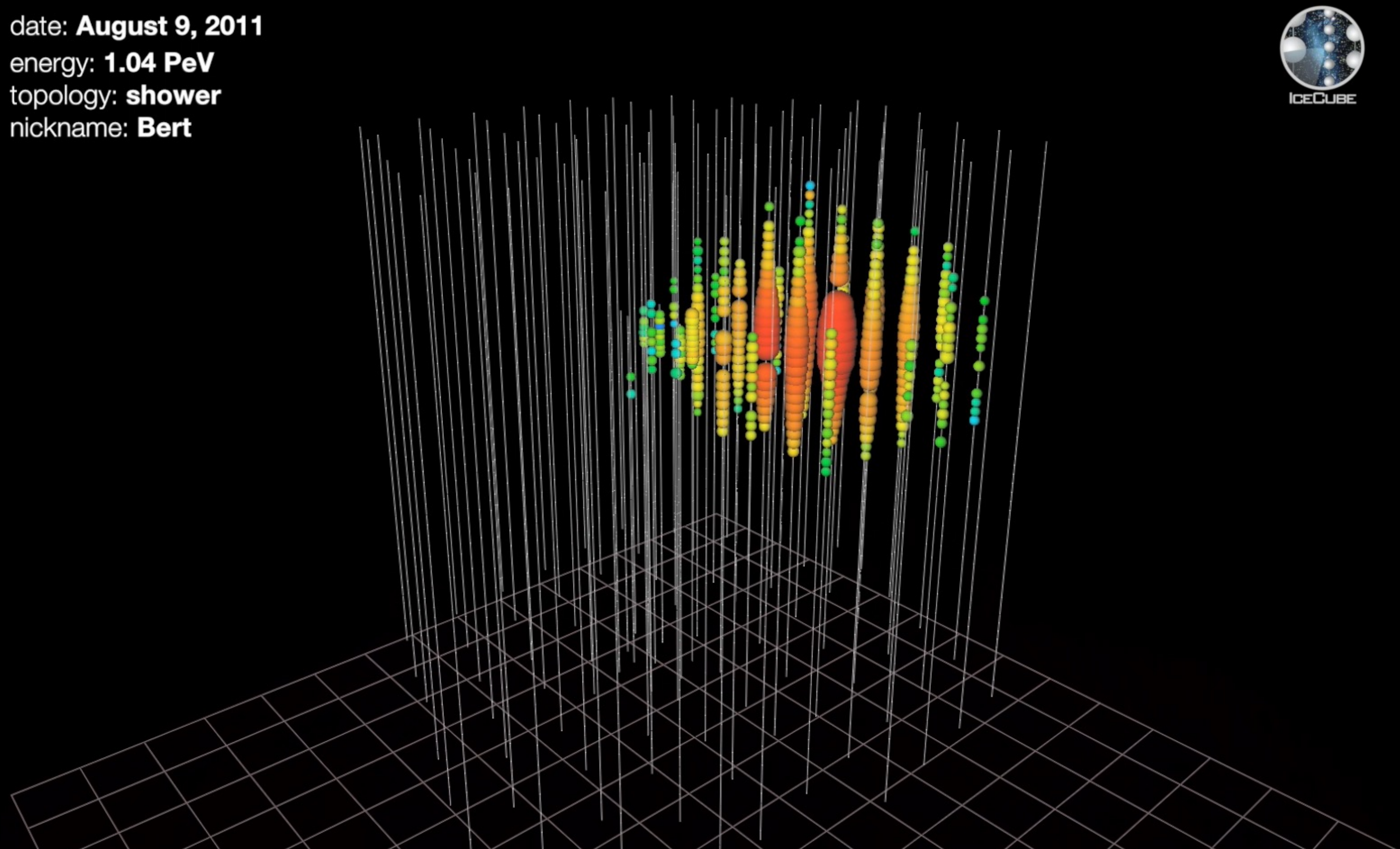




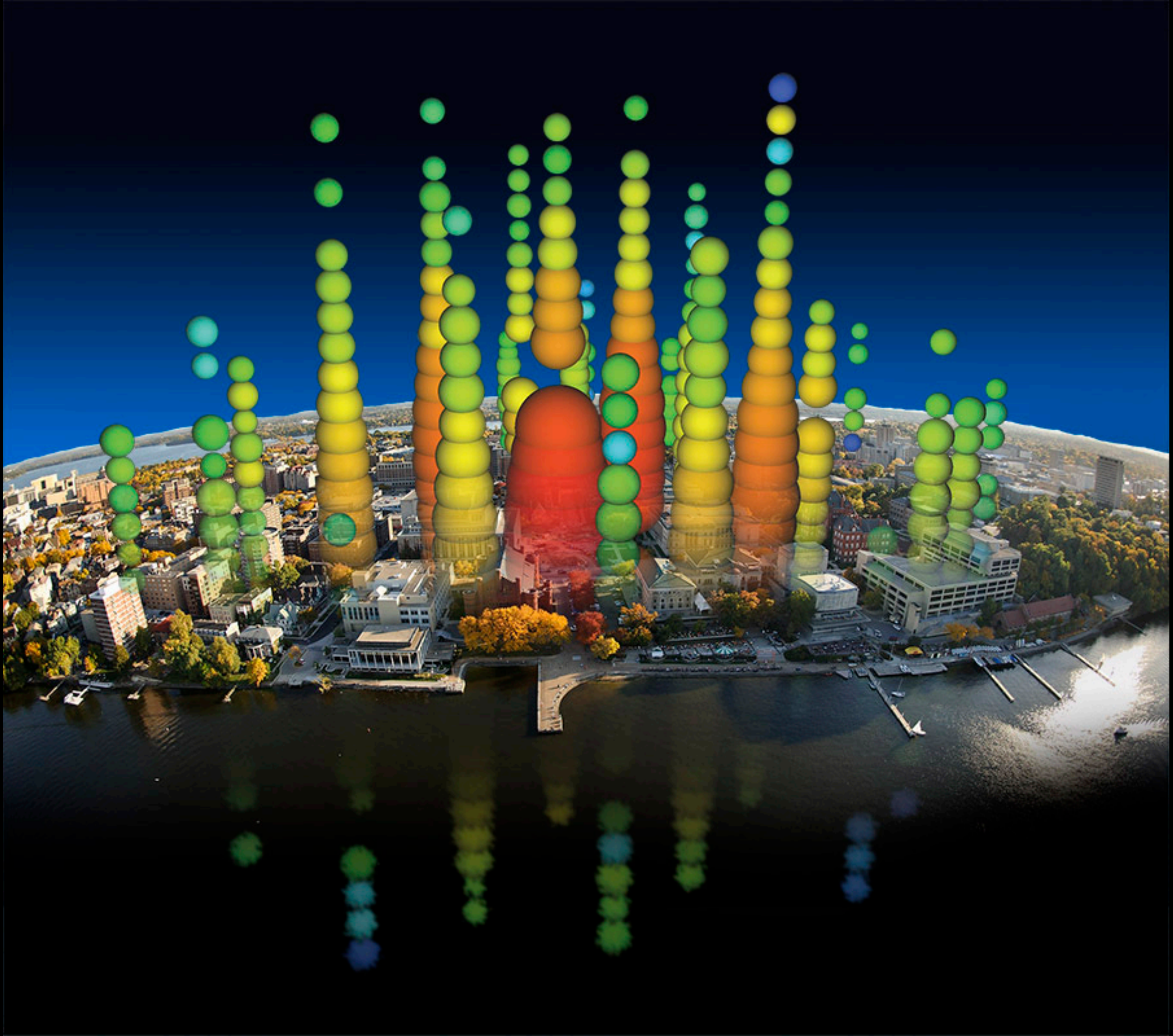


2-year analysis: ***Science 342, 1242856 (2013)***

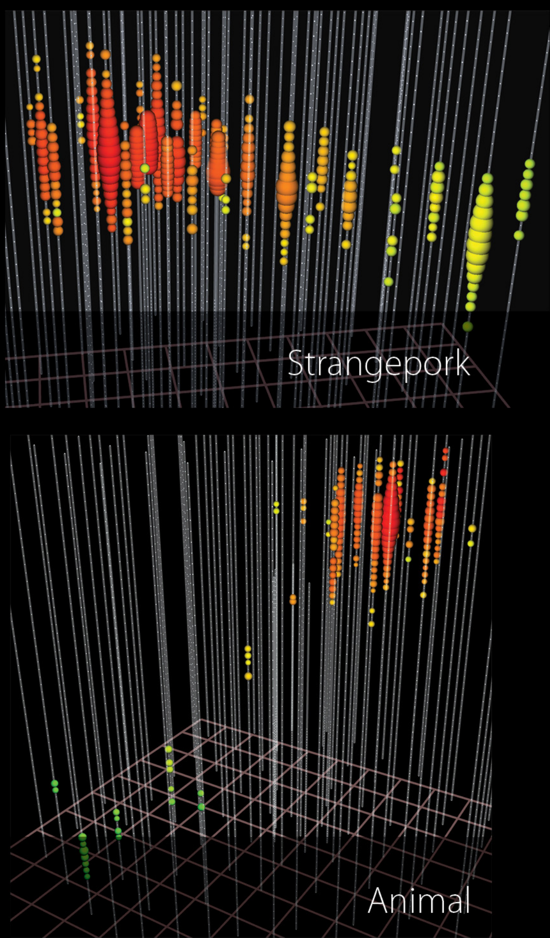
A cosmic neutrino interacts INSIDE the detector: it is too energetic to be produced in the atmosphere

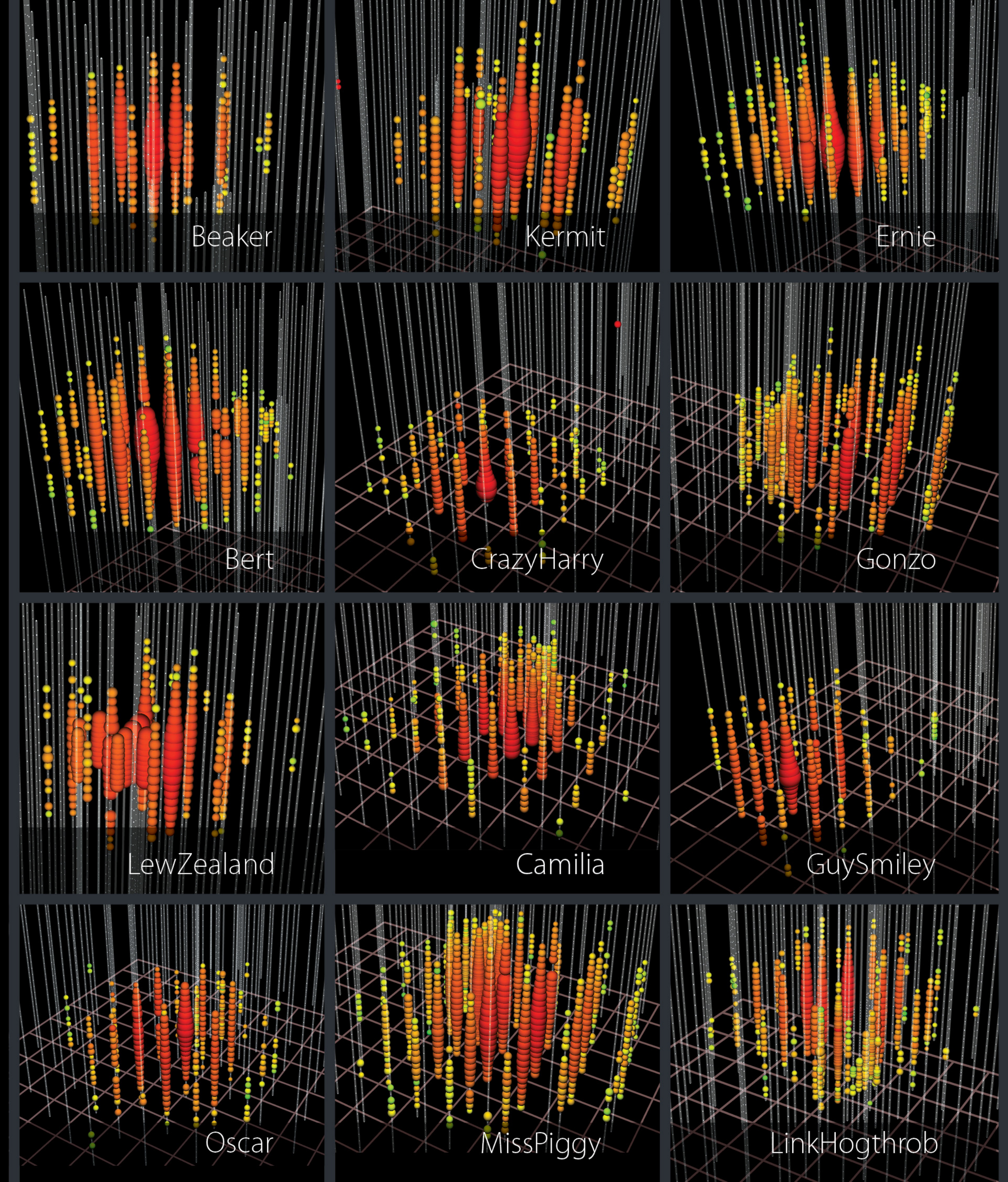


> 300 optical sensors; > 100,000 photons; 2 nanosec time resolution

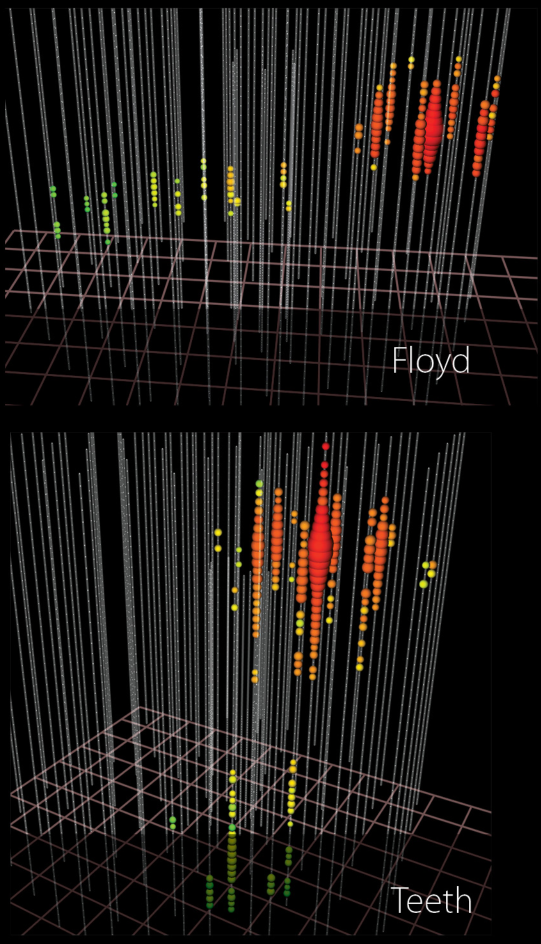


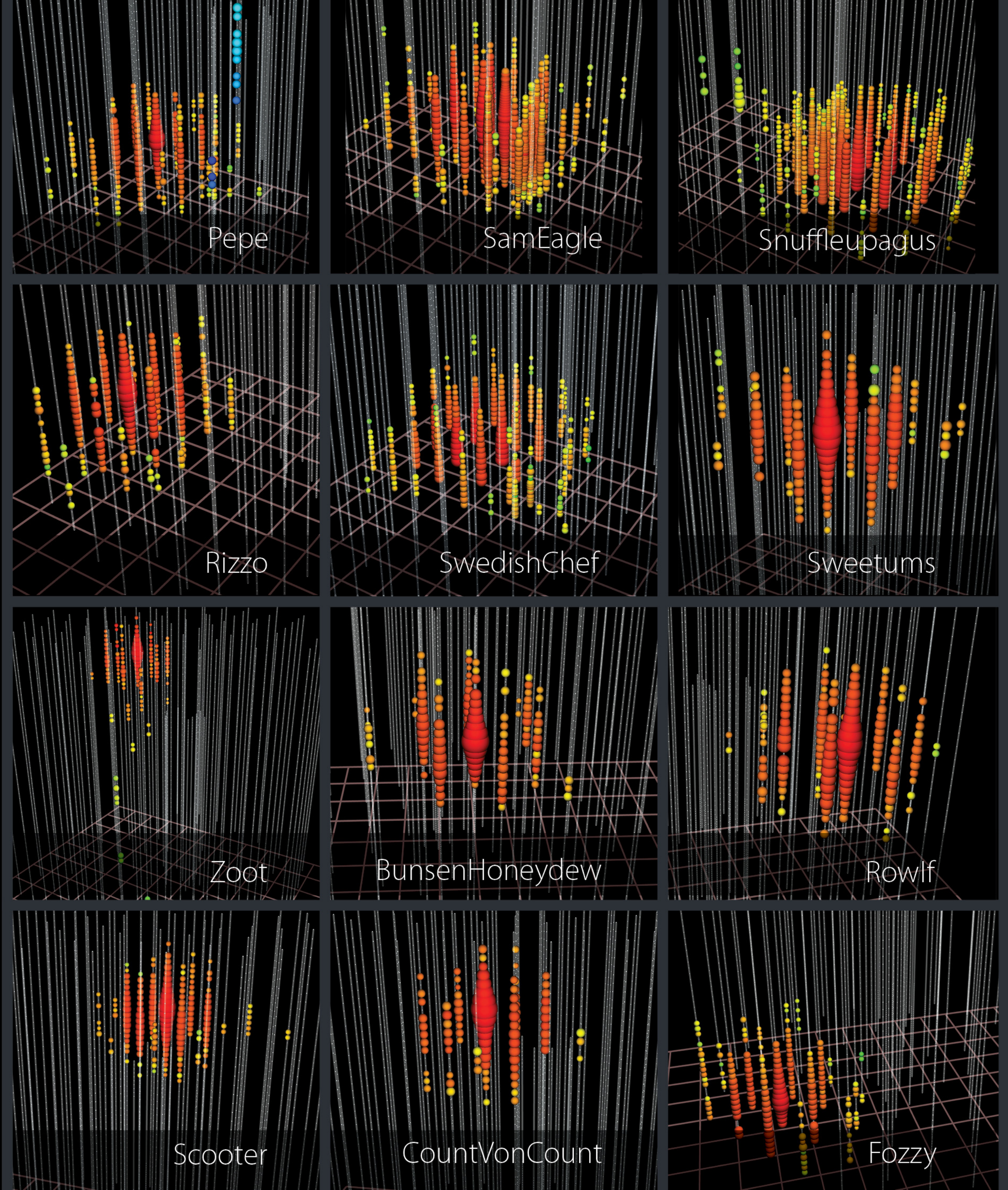
28 High Energy Events





28 High Energy Events





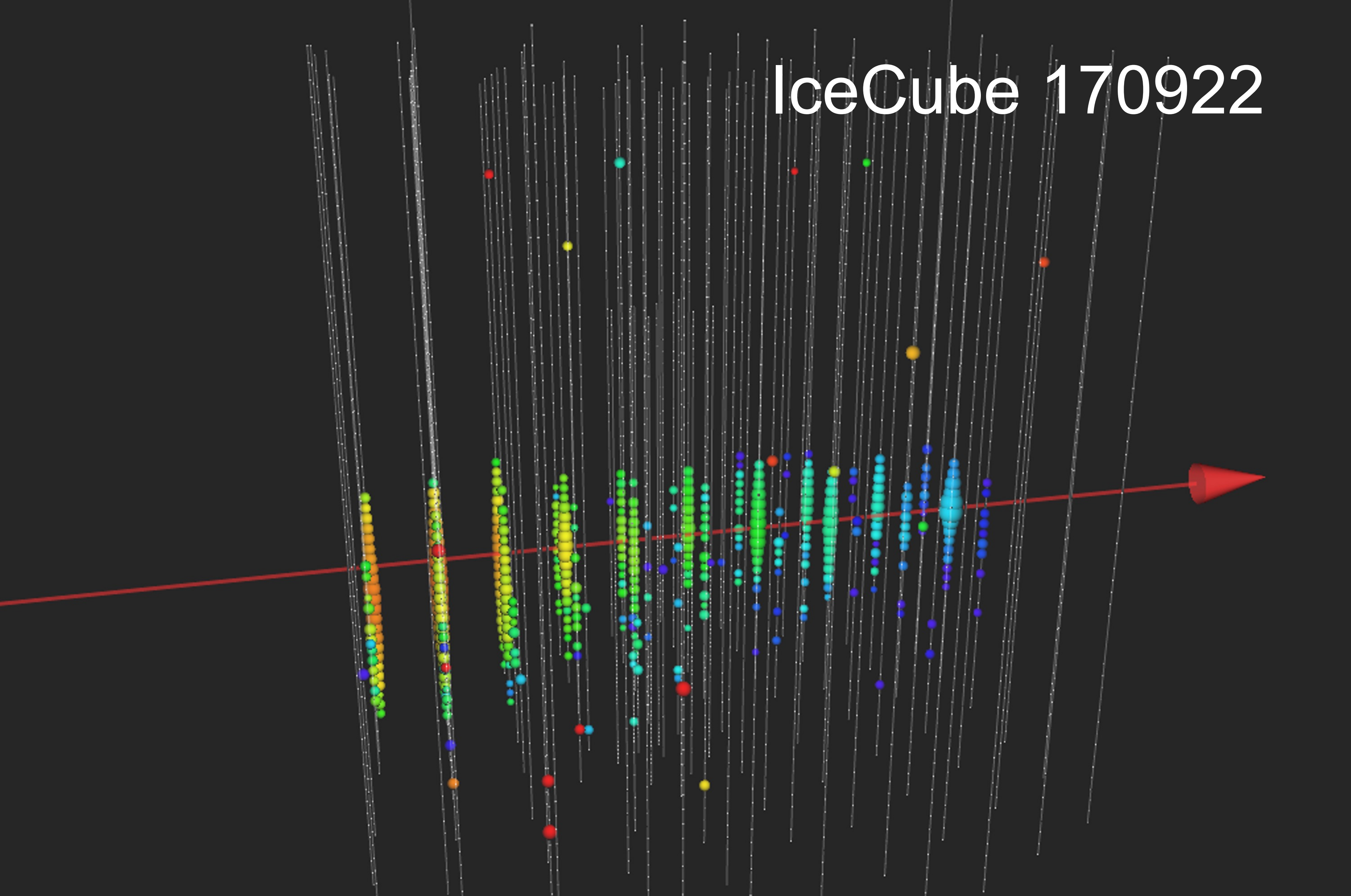
IC170922, Sep. 22, 2017

IceCube Trigger

43 seconds after trigger, GCN notice was sent

```
//////////////////////////////////////////////////////////////////////
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Fri 22 Sep 17 20:55:13 UT
NOTICE_TYPE:      AMON ICECUBE EHE
RUN_NUM:          130033
EVENT_NUM:        50579430
SRC_RA:            77.2853d {+05h 09m 08s} (J2000),
                   77.5221d {+05h 10m 05s} (current),
                   76.6176d {+05h 06m 28s} (1950)
SRC_DEC:           +5.7517d {+05d 45' 06"} (J2000),
                   +5.7732d {+05d 46' 24"} (current),
                   +5.6888d {+05d 41' 20"} (1950)
SRC_ERROR:        14.99 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE:   18018 TJD;   265 DOY;   17/09/22 (yy/mm/dd)
DISCOVERY_TIME:   75270 SOD {20:54:30.43} UT
REVISION:         0
N_EVENTS:         1 [number of neutrinos]
STREAM:           2
DELTA_T:          0.0000 [sec]
SIGMA_T:          0.0000e+00 [dn]
ENERGY :          1.1998e+02 [TeV]
SIGNALNESS:       5.6507e-01 [dn]
CHARGE:           5784.9552 [pe]
```

IceCube 170922

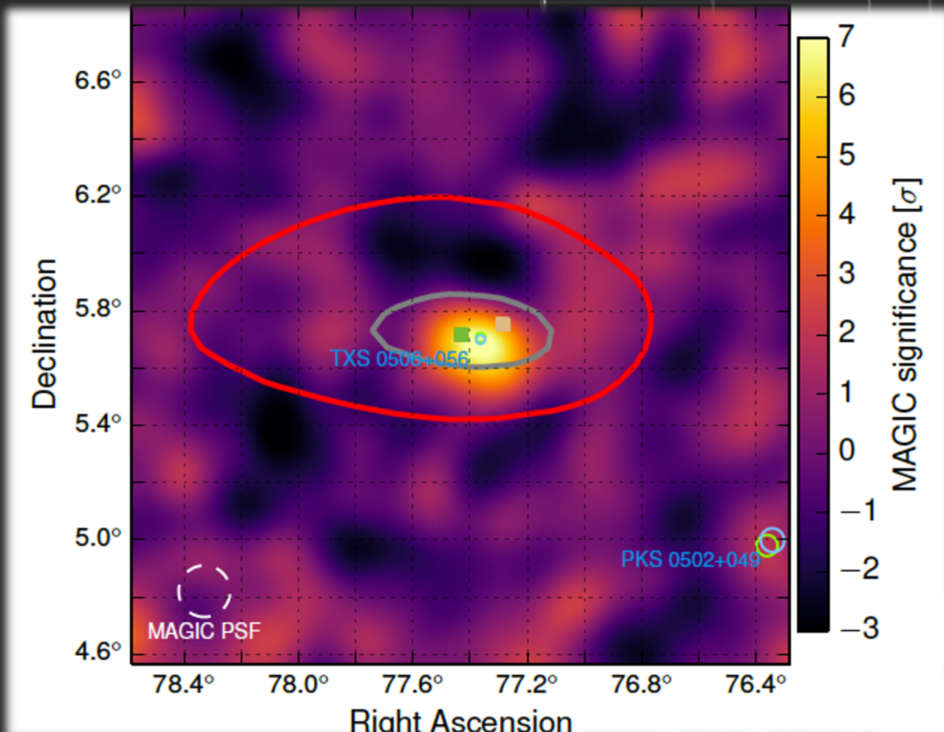


Muon track; radius ~ number of photons

time ~ red → purple

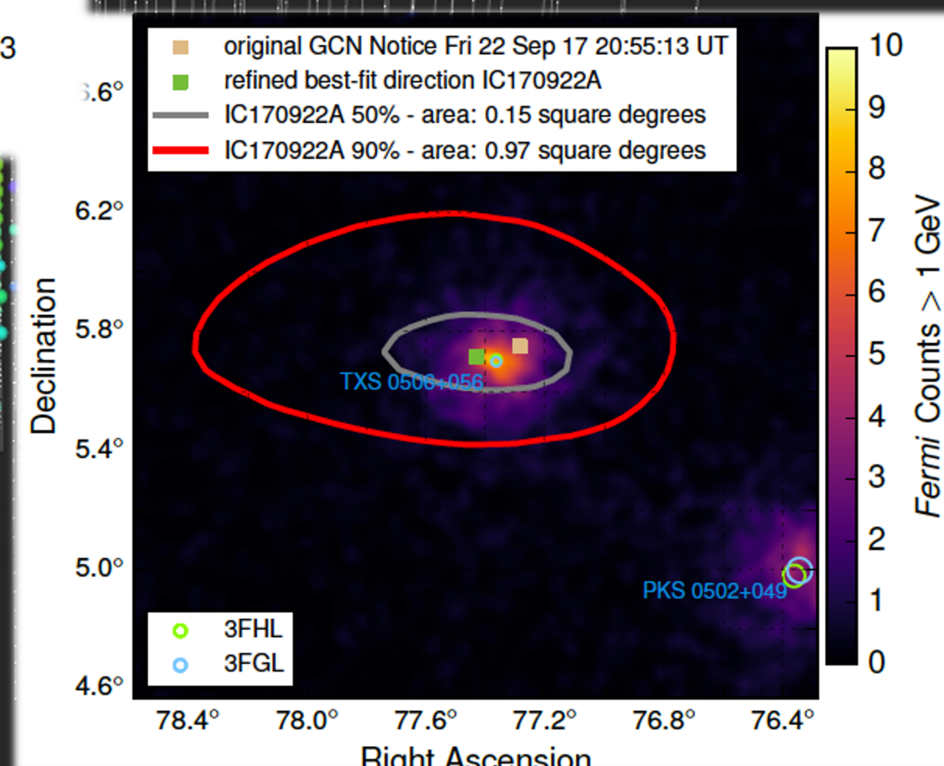
Follow-up detections of IC170922 based on public telegrams

IceCube 170922

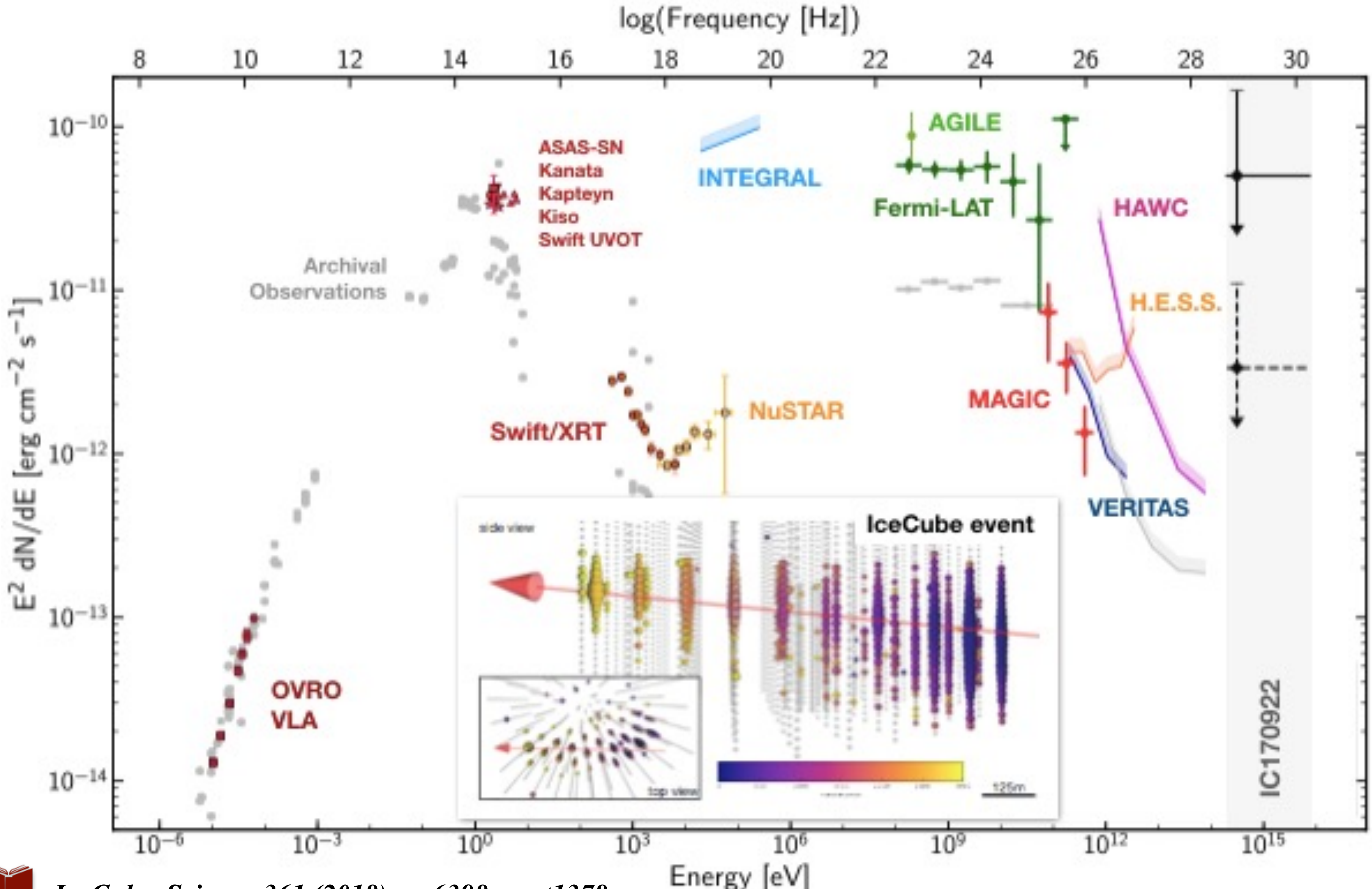


Fermi
detects a flaring
blazar within 0.1°

MAGIC
detects emission of
TeV gammas



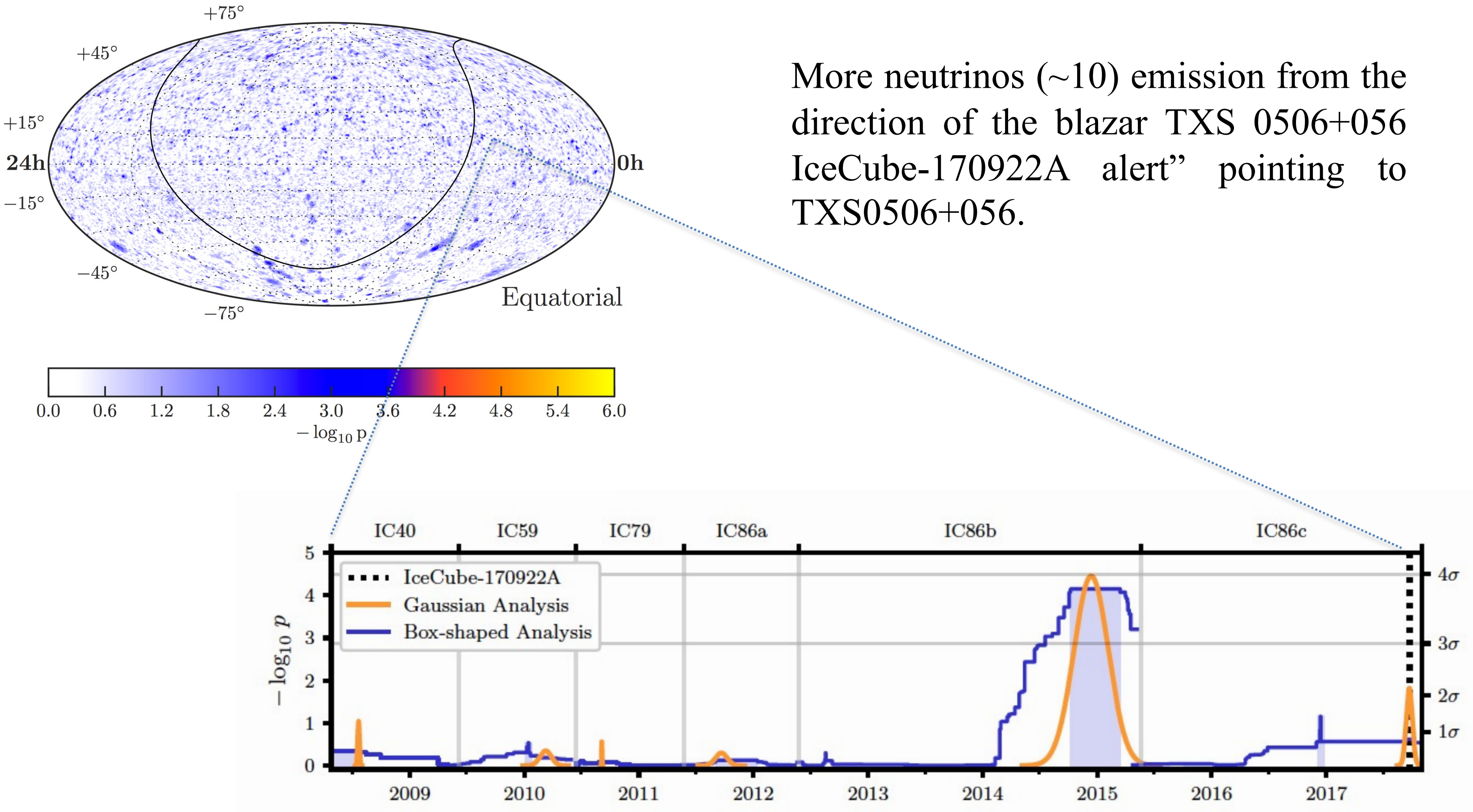
Observational spectrum of TSX 0506+056



IceCube, Science 361 (2018) no.6398, eaat1378

TSX 0506+056

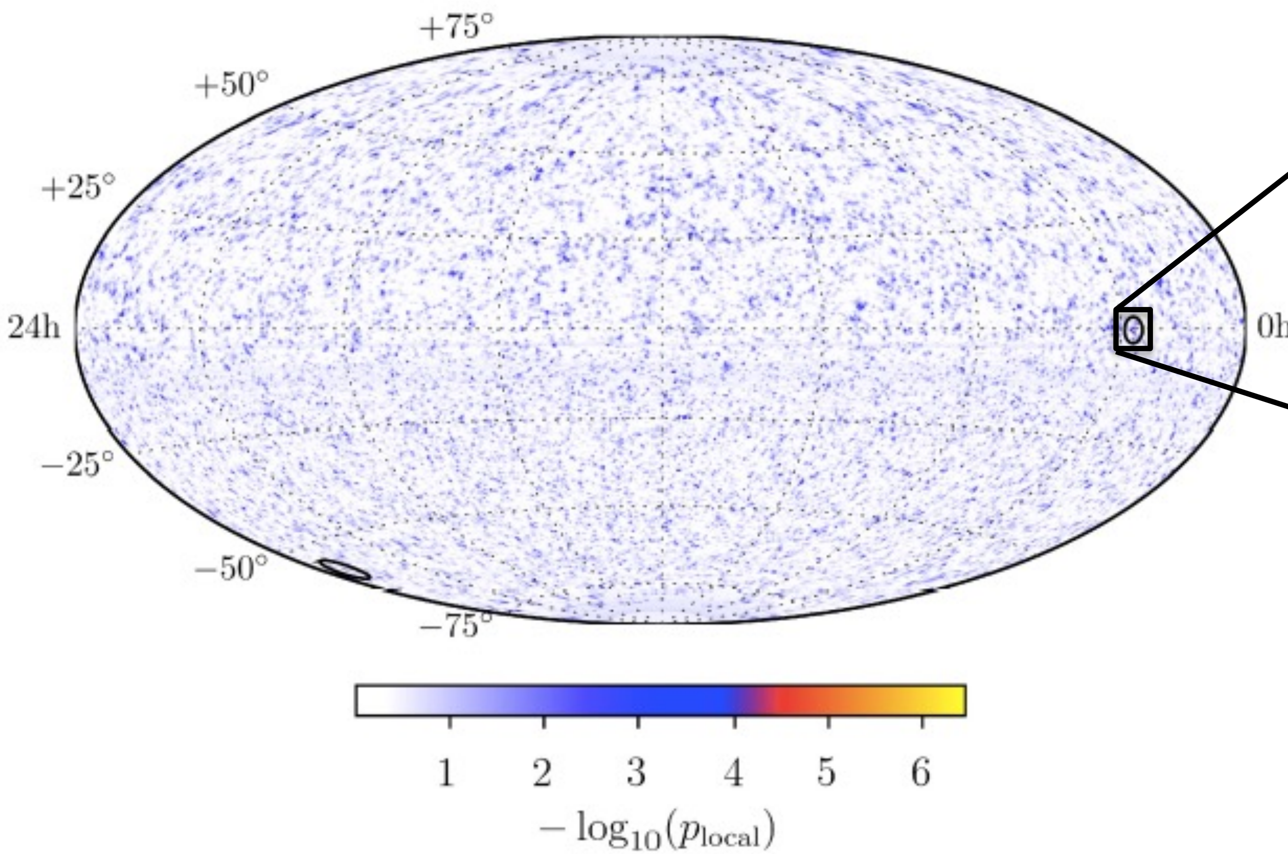
More neutrinos (~10) emission from the direction of the blazar TXS 0506+056 IceCube-170922A alert" pointing to TXS0506+056.

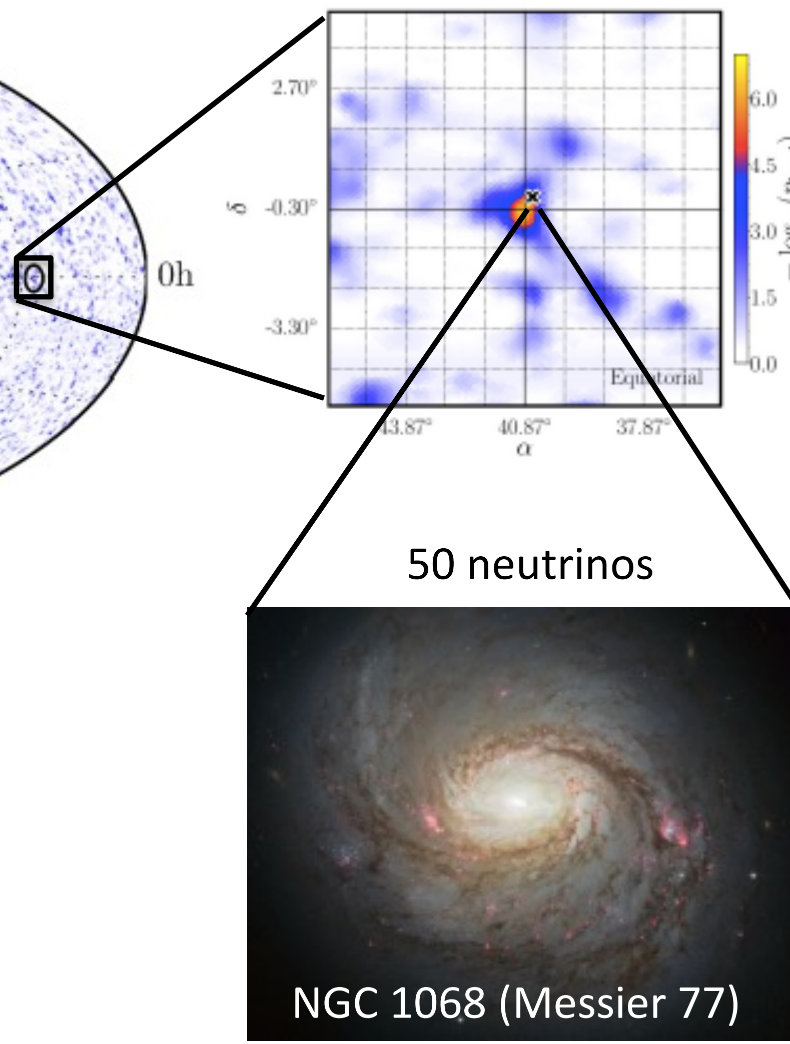


3.5σ evidence (a-priori following predefined tests procedures)

IceCube Collaboration: M.G. Aartsen et al. Science 361, 147-151 (2018)

2020 skymap: Most significant position on sky consistent with NGC 1068 (Messier 77), a Seyfert II galaxy (2.9 σ)



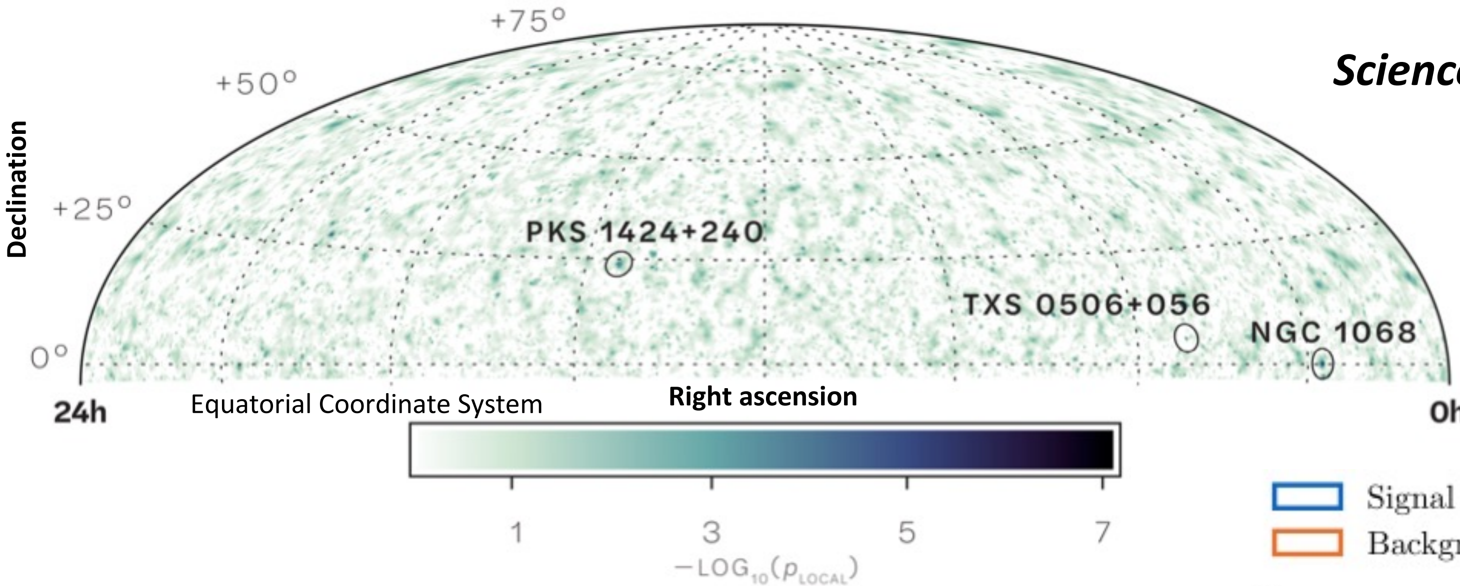


Per year:
90 billion atmospheric muons
80 thousand atmospheric neutrinos

IceCube, PRL 124, 051103 (2020)

Evidence for neutrino emission from the nearby active galaxy NGC 1068 (M 77)

Science — Nov. 4, 2022



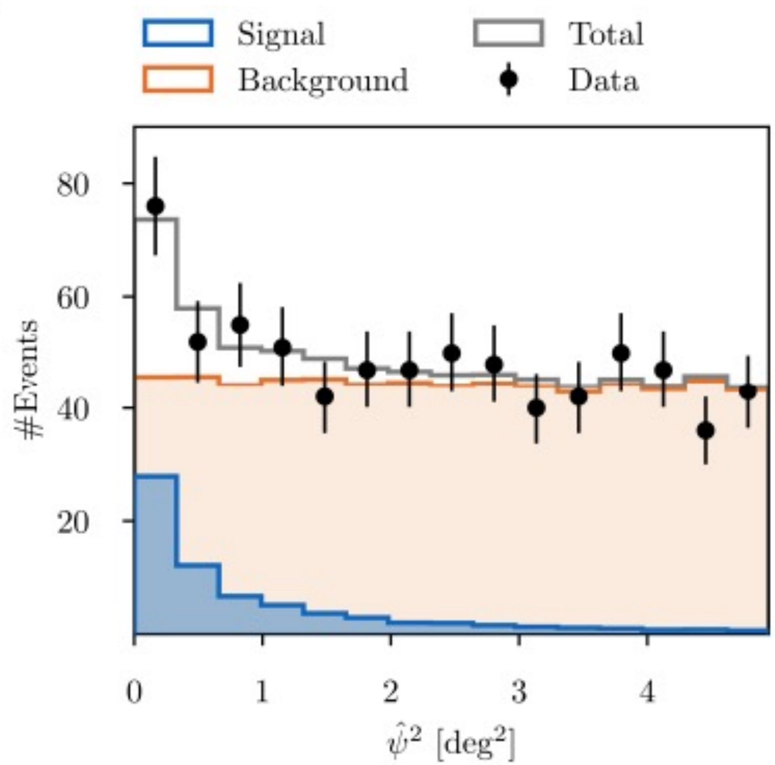
Analysis with improved calibrations

At the NGC 1068 location:

Astrophysical neutrino events = 79^{+22}_{-20}

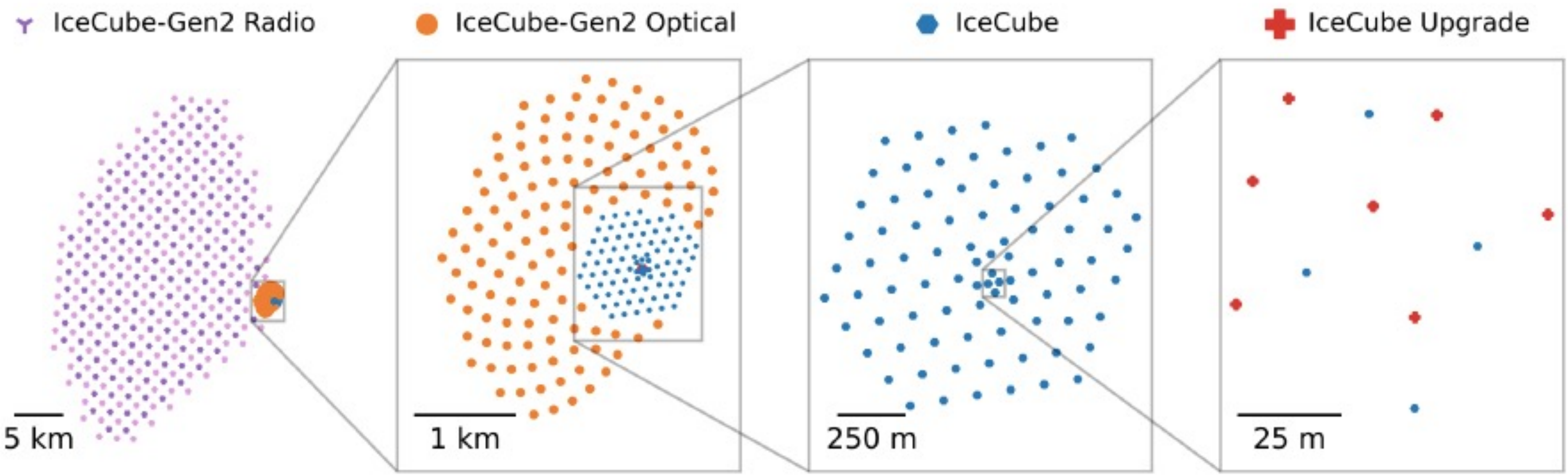
Spectral index = 3.2 ± 0.2

... significance **4.2σ**



IceCube, Science 378, 6619, 538-543 (2022)

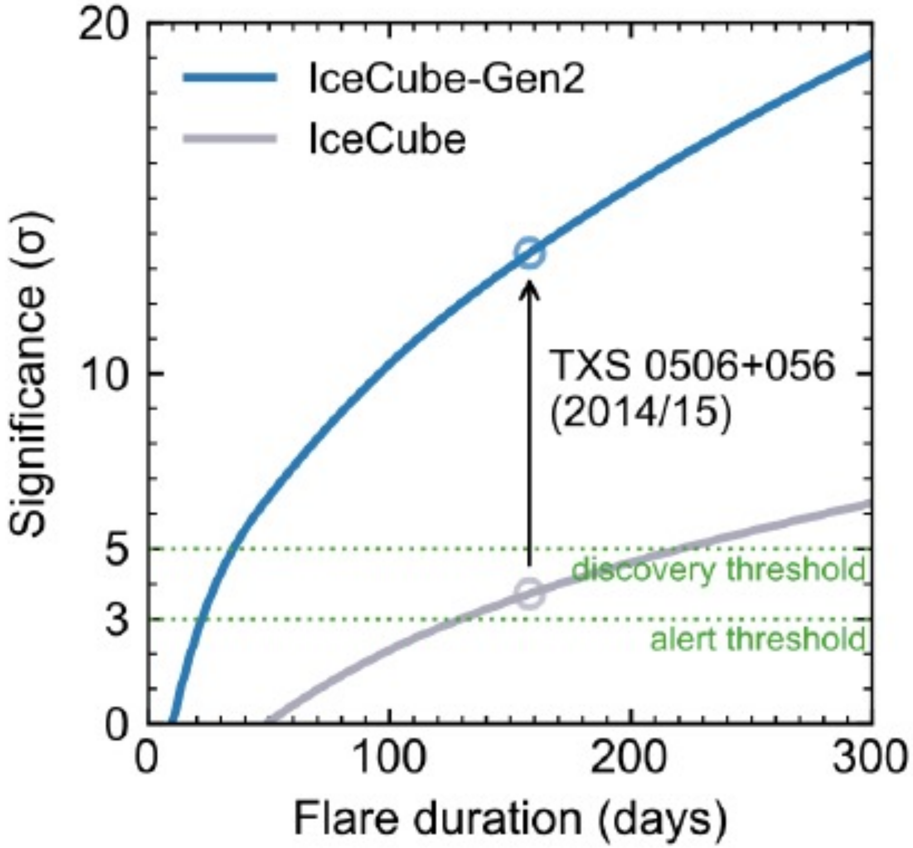
IceCube and IceCube-Gen2 : scales and energy ranges

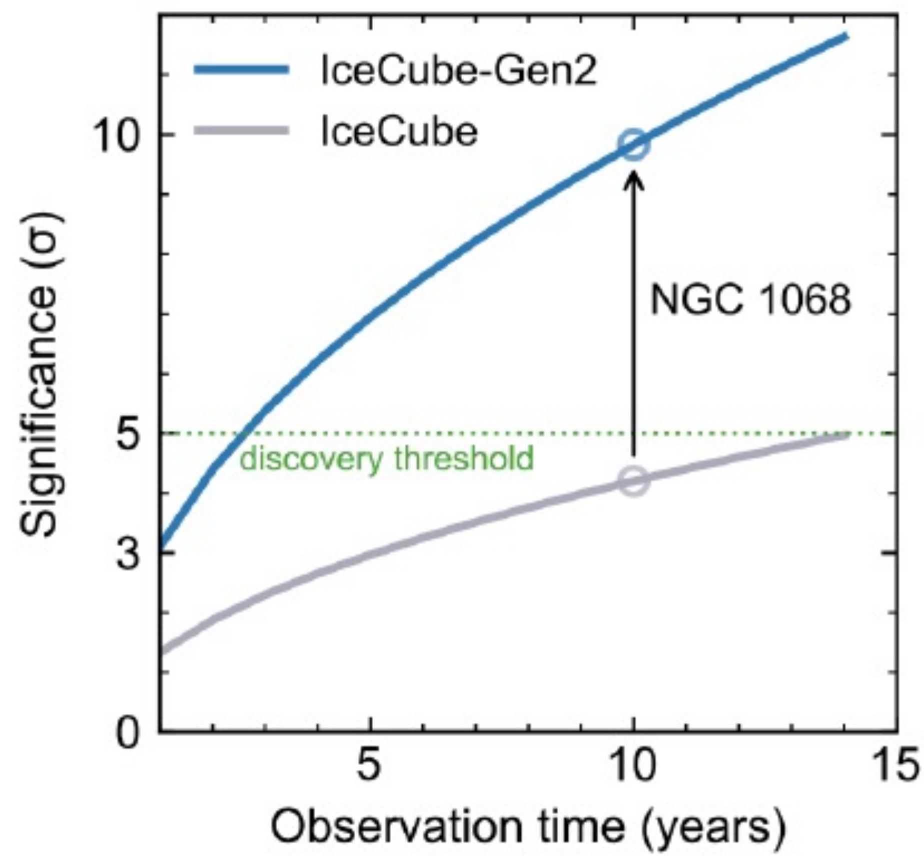


>10 PeV | > 5 TeV | > 0.5 TeV | few GeV

IceCube-Gen2 sensitivity: Point sources

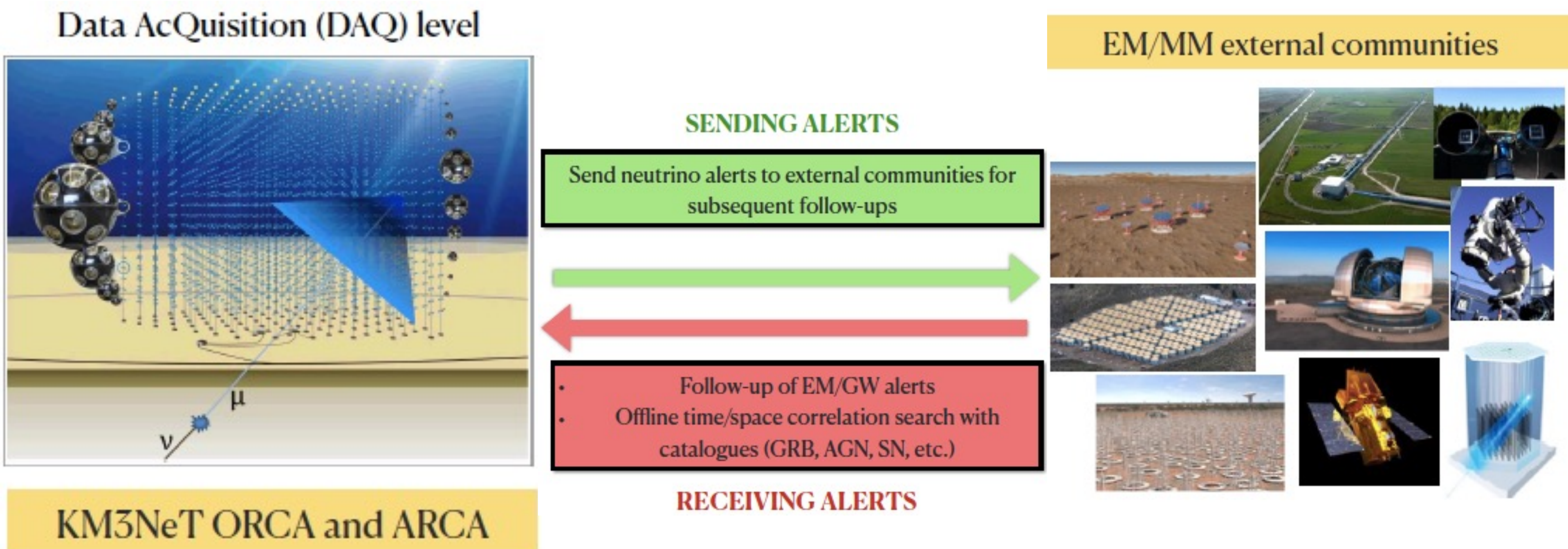
How would TXS and NGC look in Gen2?





- The New era of Gravitational Wave: GW170817 - crucial milestone in multimessenger astrophysics
- The complementary messenger: the neutrino
  - ✓ IC170922
  - ✓ NGC 1068
- **The future challanges**

KM3NeT: the multimessenger program

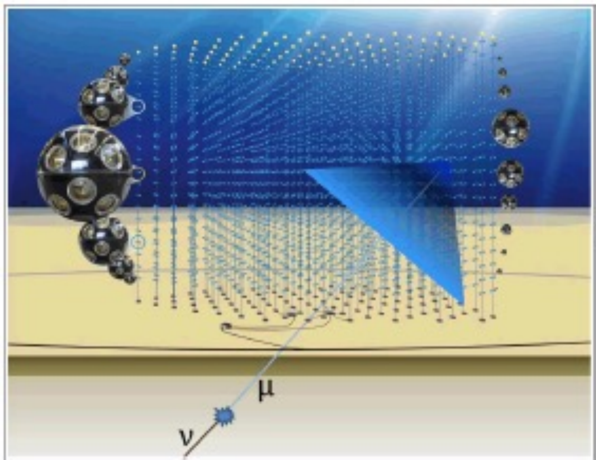


Courtesy of A. Zegarelli

KM3NeT, VLVNT2021 conference proceedings, arXiv:2107.13908

KM3NeT: the multimessenger program

Data AcQuisition (DAQ) level

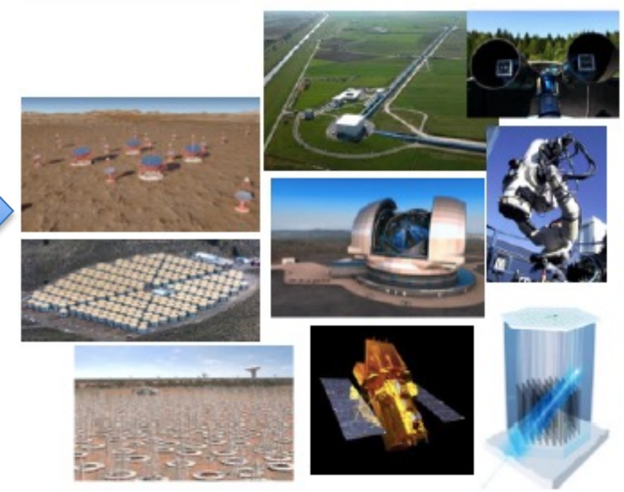


KM3NeT ORCA and ARCA

ARCA:
Portopalo di Capo Passero (Sicily)

ORCA:
Toulon (France)

EM/MM external communities



1) Neutrino induced events inside the detectors

2) All data are immediately sent to the shore stations

3) All the events are reconstructed, selected and classified

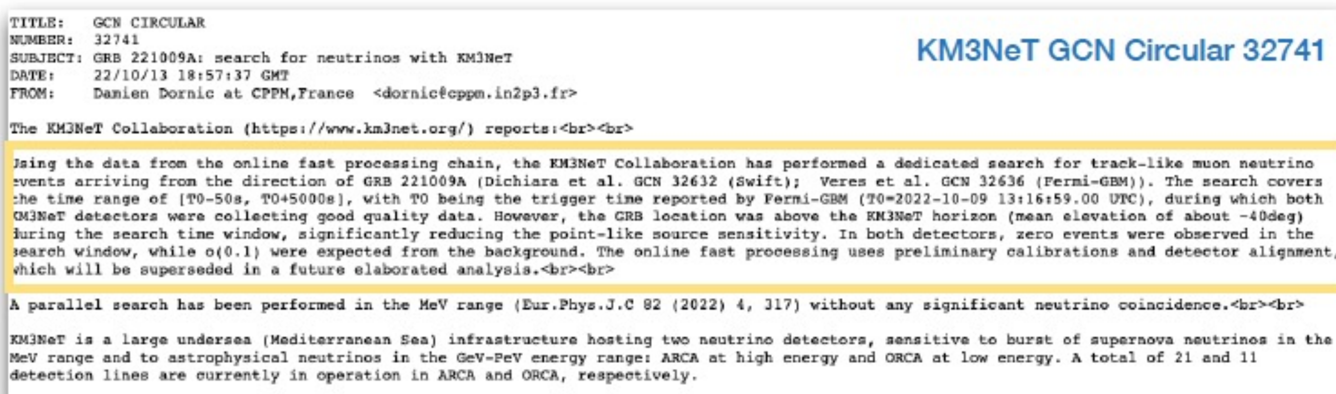
4) Interesting events are sent to other multi-messenger instrumentations

Courtesy of A. Zegarelli

KM3NeT, VLVNT2021 conference proceedings, arXiv:2107.13908

KM3NeT real-time analysis: the recent case of GRB 221009

- ~ 3 months ago the **brightest long GRB** ever detected was observed, relatively close to us (z~0.15, corresponding to 2.4 billion light-years away), at 13:16.59 UT
- This event produced the **most energetic GRB photon ever seen by Fermi LAT** (ATel #15656), that of **99 GeV**
- LHAASO during 2000 sec after the GRB trigger detected **photons up to 18 TeV, highest energies ever detected from a GRB** (GCN #32677)



TITLE: GCN CIRCULAR
NUMBER: 32741
SUBJECT: GRB 221009A: search for neutrinos with KM3NeT
DATE: 22/10/13 18:57:37 GMT
FROM: Damien Dornic at CPPM,France <dornic@cppm.in2p3.fr>

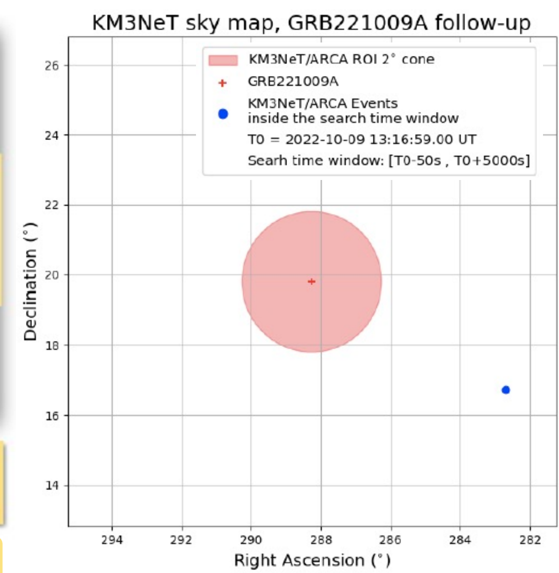
KM3NeT GCN Circular 32741

The KM3NeT Collaboration (https://www.km3net.org/) reports:

Jsing the data from the online fast processing chain, the KM3NeT Collaboration has performed a dedicated search for track-like muon neutrino events arriving from the direction of GRB 221009A (Dichiara et al. GCN 32632 (Swift); Veres et al. GCN 32636 (Fermi-GBM)). The search covers the time range of [T0-50s, T0+5000s], with T0 being the trigger time reported by Fermi-GBM (T0=2022-10-09 13:16:59.00 UTC), during which both KM3NeT detectors were collecting good quality data. However, the GRB location was above the KM3NeT horizon (mean elevation of about -40deg) during the search time window, significantly reducing the point-like source sensitivity. In both detectors, zero events were observed in the search window, while o(0.1) were expected from the background. The online fast processing uses preliminary calibrations and detector alignment, which will be superseded in a future elaborated analysis.

A parallel search has been performed in the MeV range (Eur.Phys.J.C 82 (2022) 4, 317) without any significant neutrino coincidence.

KM3NeT is a large undersea (Mediterranean Sea) infrastructure hosting two neutrino detectors, sensitive to burst of supernova neutrinos in the MeV range and to astrophysical neutrinos in the GeV-PeV energy range: ARCA at high energy and ORCA at low energy. A total of 21 and 11 detection lines are currently in operation in ARCA and ORCA, respectively.



No events found in the signal region. More elaborated analysis ongoing!

KM3NeT started to play a crucial role in the field of real-time multimesseger astronomy!

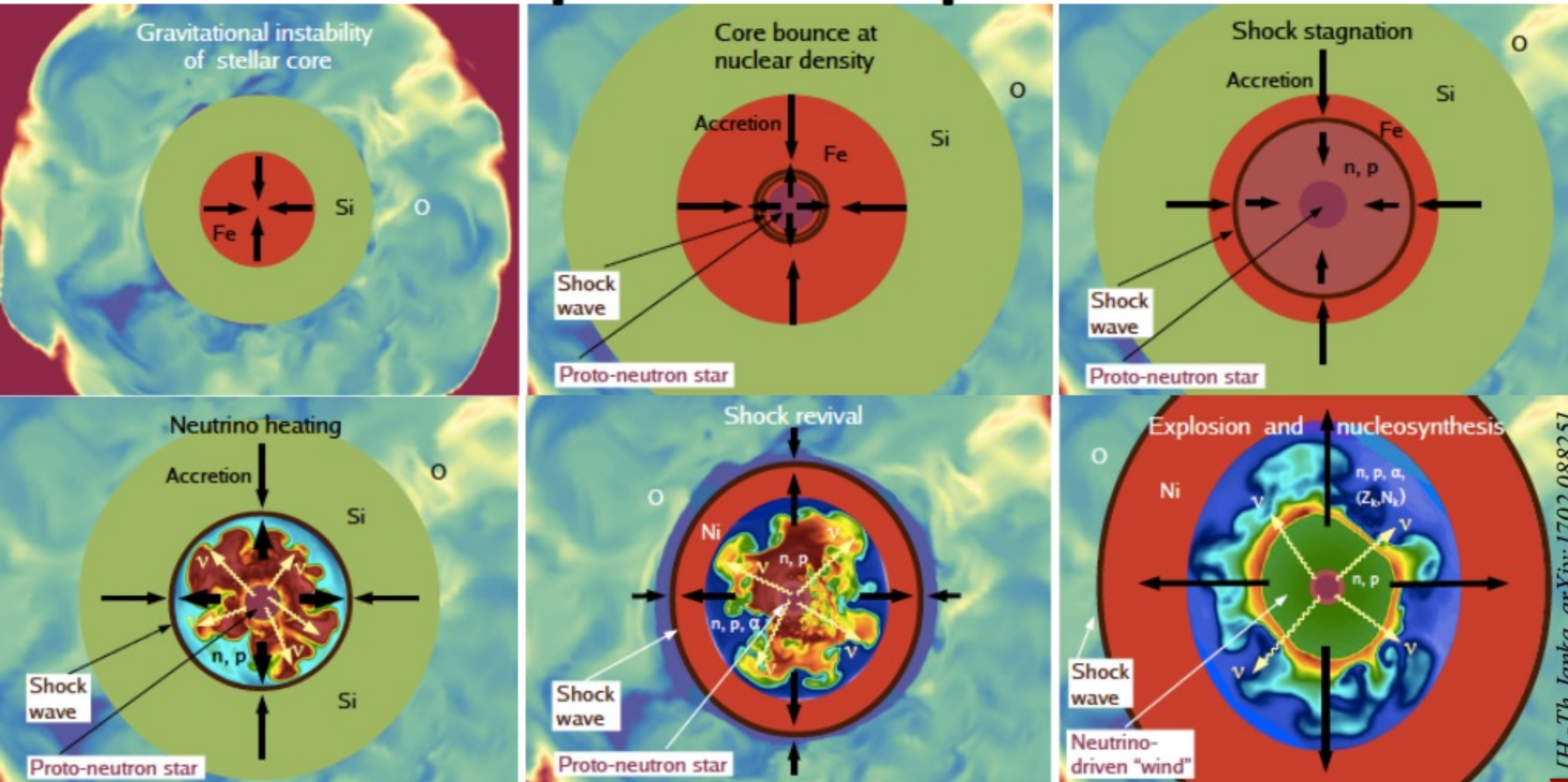
Courtesy of A. Zegarelli

SNEWS 2.0

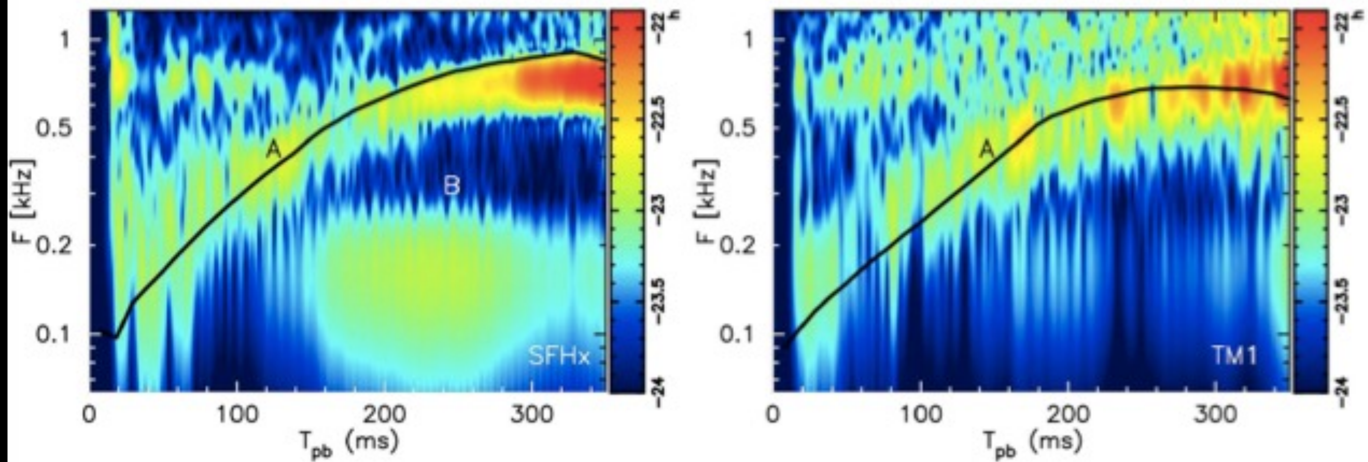
The SuperNova Early Warning System (SNEWS) is a global network of neutrino experiments sensitive to supernova neutrinos. The goal of SNEWS is to provide the astronomical community with a prompt alert of an imminent Galactic core-collapse event. This will allow for complete multi-messenger observations of the supernova across the electromagnetic spectrum, in gravitational waves, and in neutrinos.

S. Al Kharusi et al, New J. Phys. 23 031201 (2021)

Dynamical phases of stellar core collapse and explosion

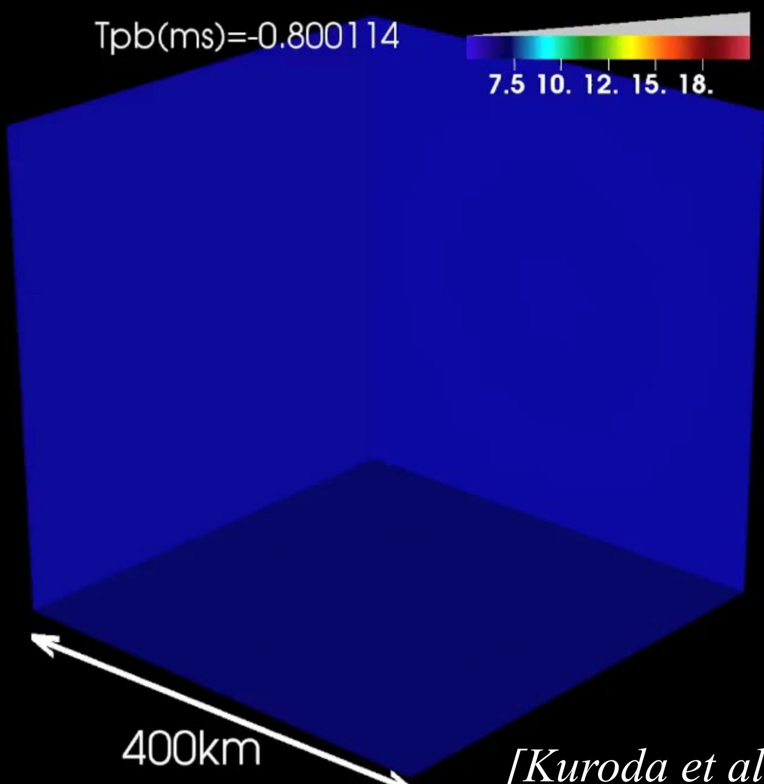


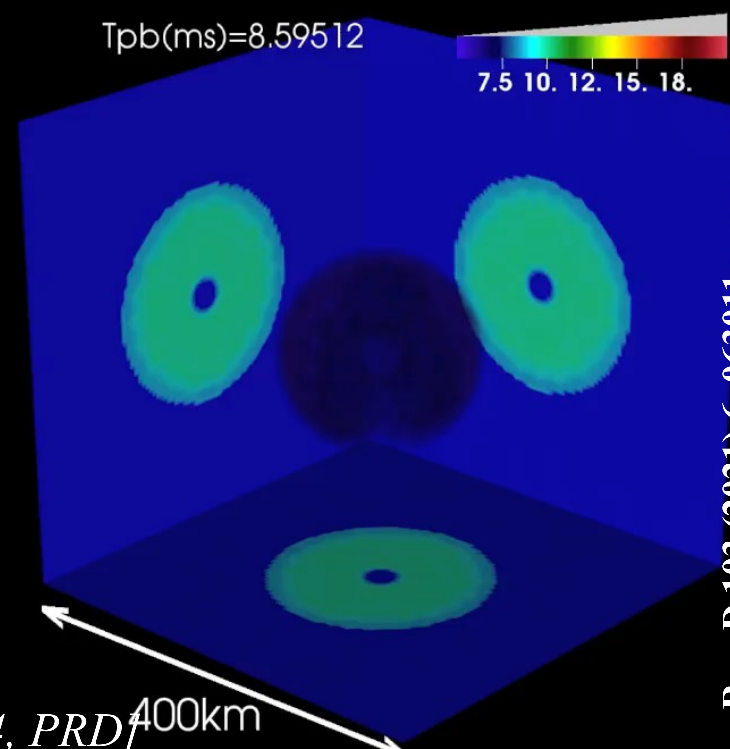
- When the radiation pressure doesn't balance gravity anymore the collapse starts.
- The implosion of the inner core is stopped abruptly when nuclear saturation density is reached at the center.
- The inner core bounces back and its expansion creates pressure waves.
- The newly formed shock begins to propagate outwards in radius as well as in mass.
- Shortly after core bounce neutrino emission carries away energy from the postshock layer.
- If the heating by neutrinos is strong enough, the shock can be pushed outwards and the SN explosion can be launched.



SFHx :softer

TM1 :stiffer





[Kuroda et al 2016, ApJL, 2014, PRD]

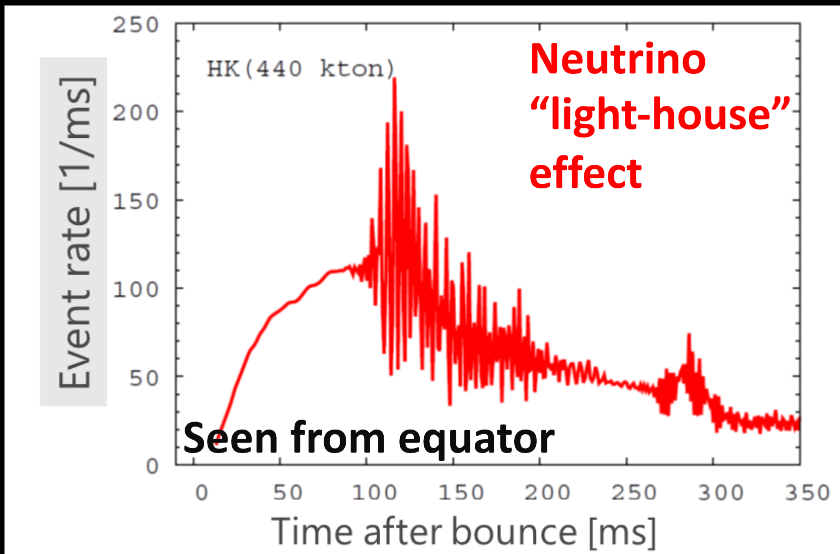
Phys.Rev. D 103 (2021) 6, 063011

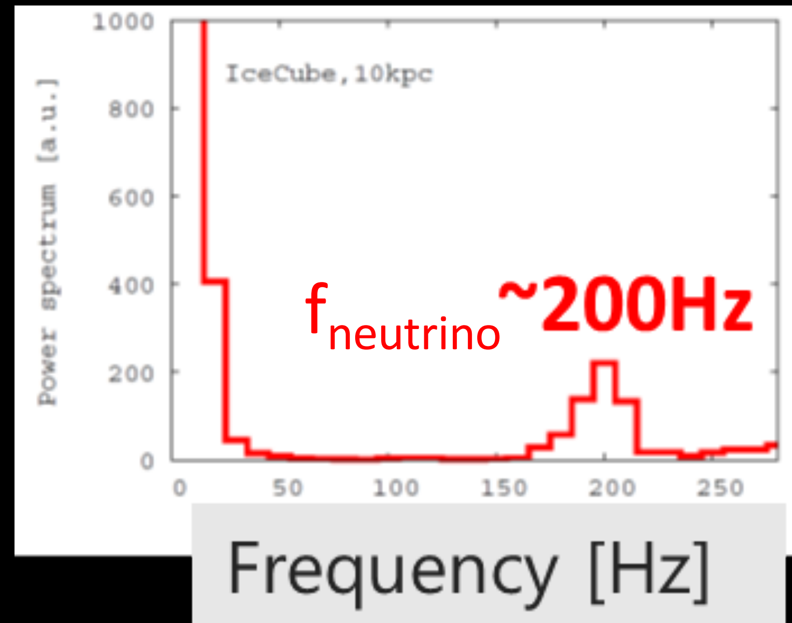
✓ **SASI activity higher for softer EOS** (due to high growth rate, e.g., Foglizzo et al. ('06)).

Correlation of ν and GW signals from a rapidly rotating 3D model

Takiwaki, KK, Foglizzo, (2021)

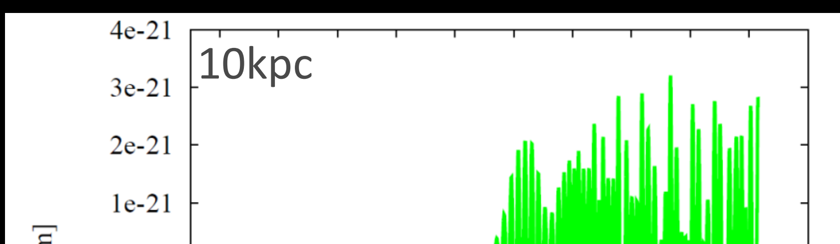
Neutrino event rate (27 M_{sun}, Ω_0 = 2rad/s)

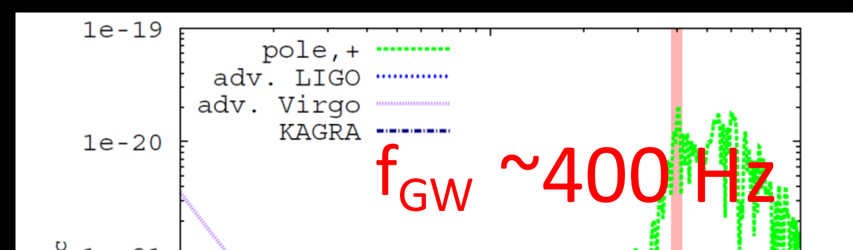




Courtesy of K. Kotake

Gravitational waveform





- ✓ Peak frequency of the GW signals (f_{gw}) is twice of the neutrino modulation freq ($f_{neutrino}$) ! due quadrupole GW emission)
- ✓ Also the case for non-rotating progenitor, $f_{neutrino, SASI}$~80 Hz, QUIZ f_{gw} ~80 or 160 Hz
- ✓ Coincident detection between GW and ν : smoking gun signature of rapid core rotation !