Outline:

Session 1:
- Introduction: The Cosmic High Energy Frontier
- Sources, messengers and goals
- Charged Cosmic rays

Session 2:
- Neutrino Telescopes
- Neutrino properties with Neutrino Telescopes
- Gravitational Waves

Session 3:
- VHE Gamma Rays
- Multi-messengers
- Outlook

SESSION 2

HE NEUTRINO ASTRONOMY

WINDOW OPENED, LANDSCAPE UNCHARTED

Moisej Markov

1960

Fred Reines

1965

Cosmic Neutrinos

- Only neutrinos from extraterrestrial origin detected until a couple of years ago:

  Sun and SN 1987A

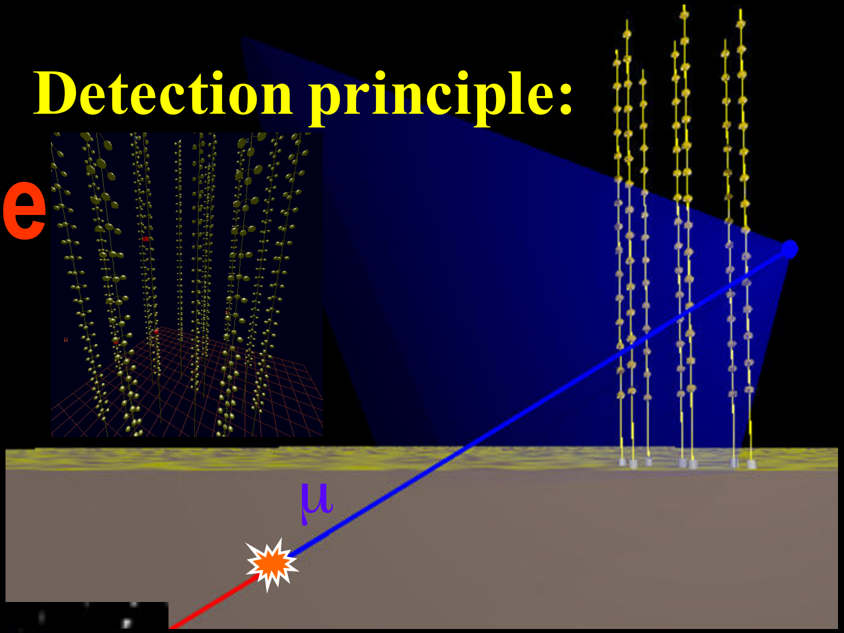
- Very, very, very weak interaction ->

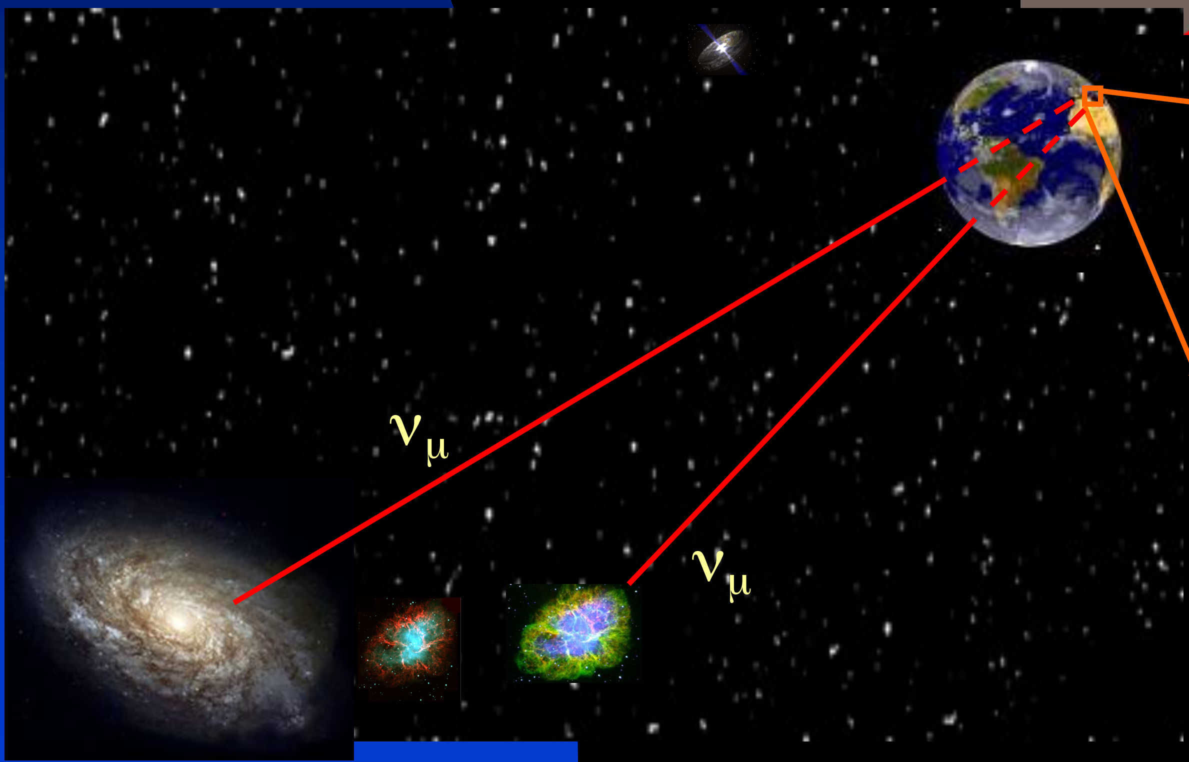
  1 light/year (10^{13} Km) of lead needed to absorb 50% of a neutrino beam

  => To build a "neutrino telescope" the whole earth is used as detector, and the Cherenkov light from the secondary muons produced by the neutrino interaction is used as the signal

ANTARES Telescope

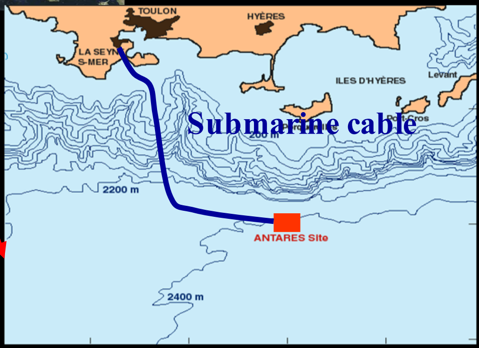
Detection principle:



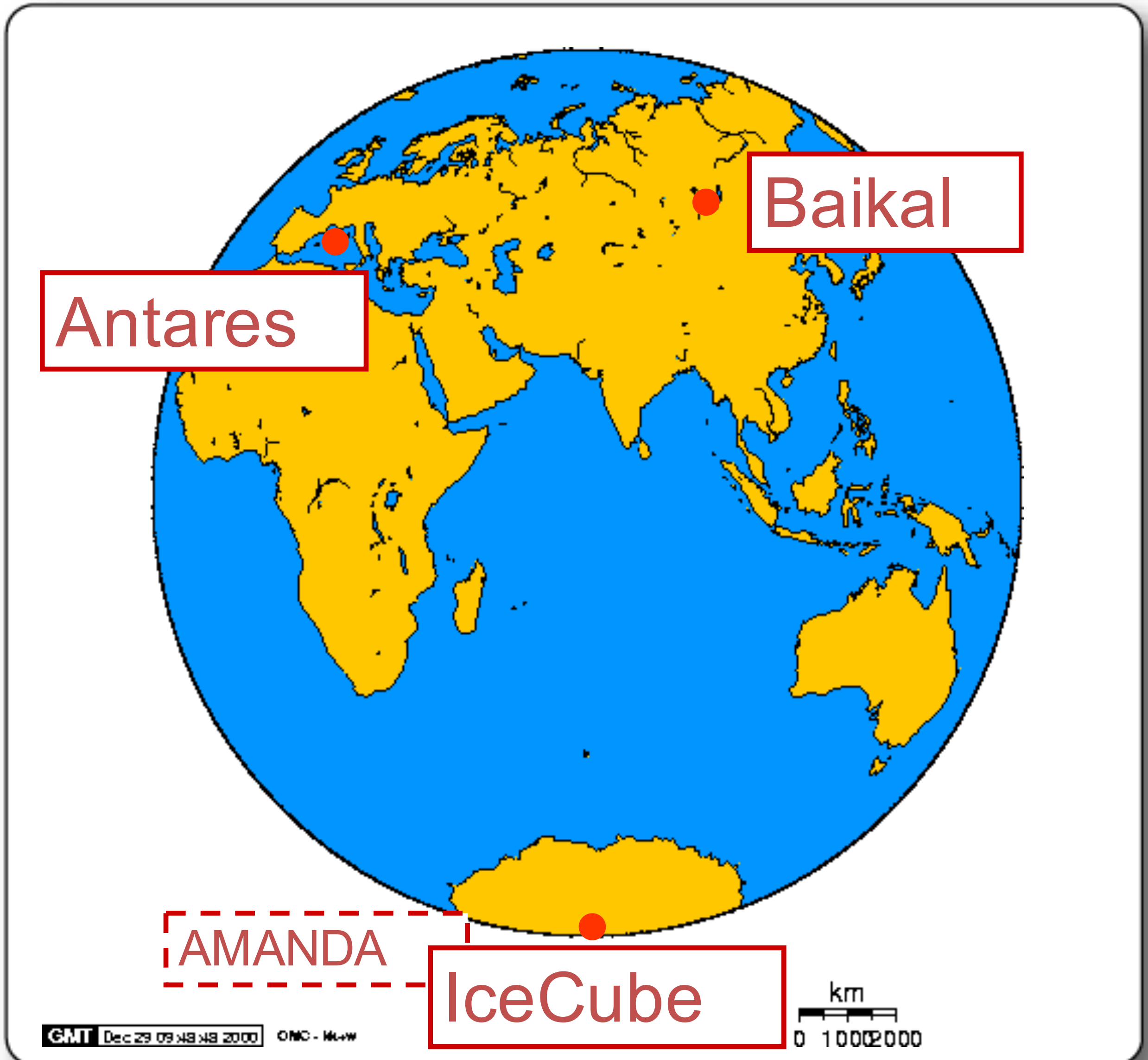


Location:

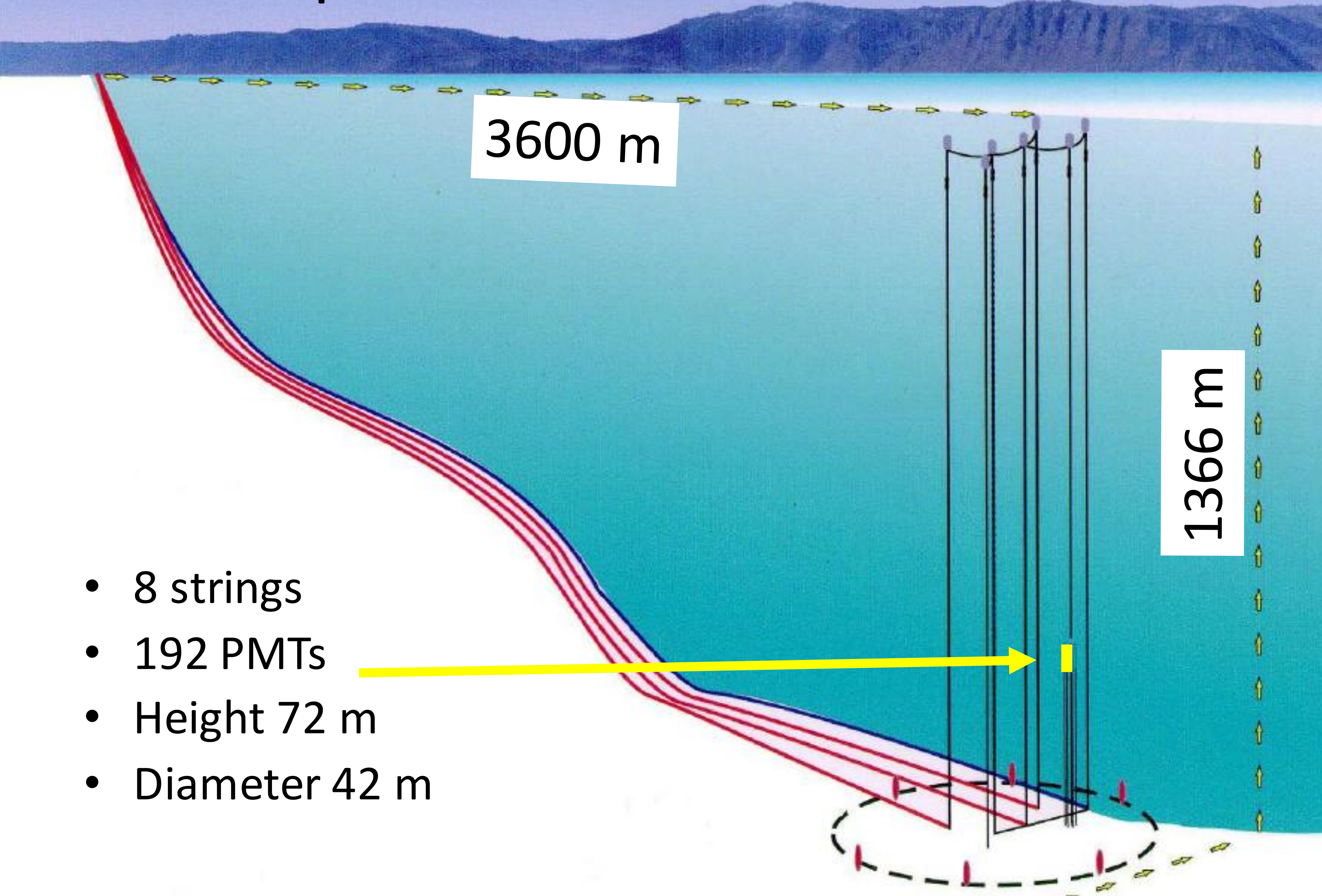
42º50'N, 6º10'E) a 2500 m depth, 40 km off-shore Toulon (France)



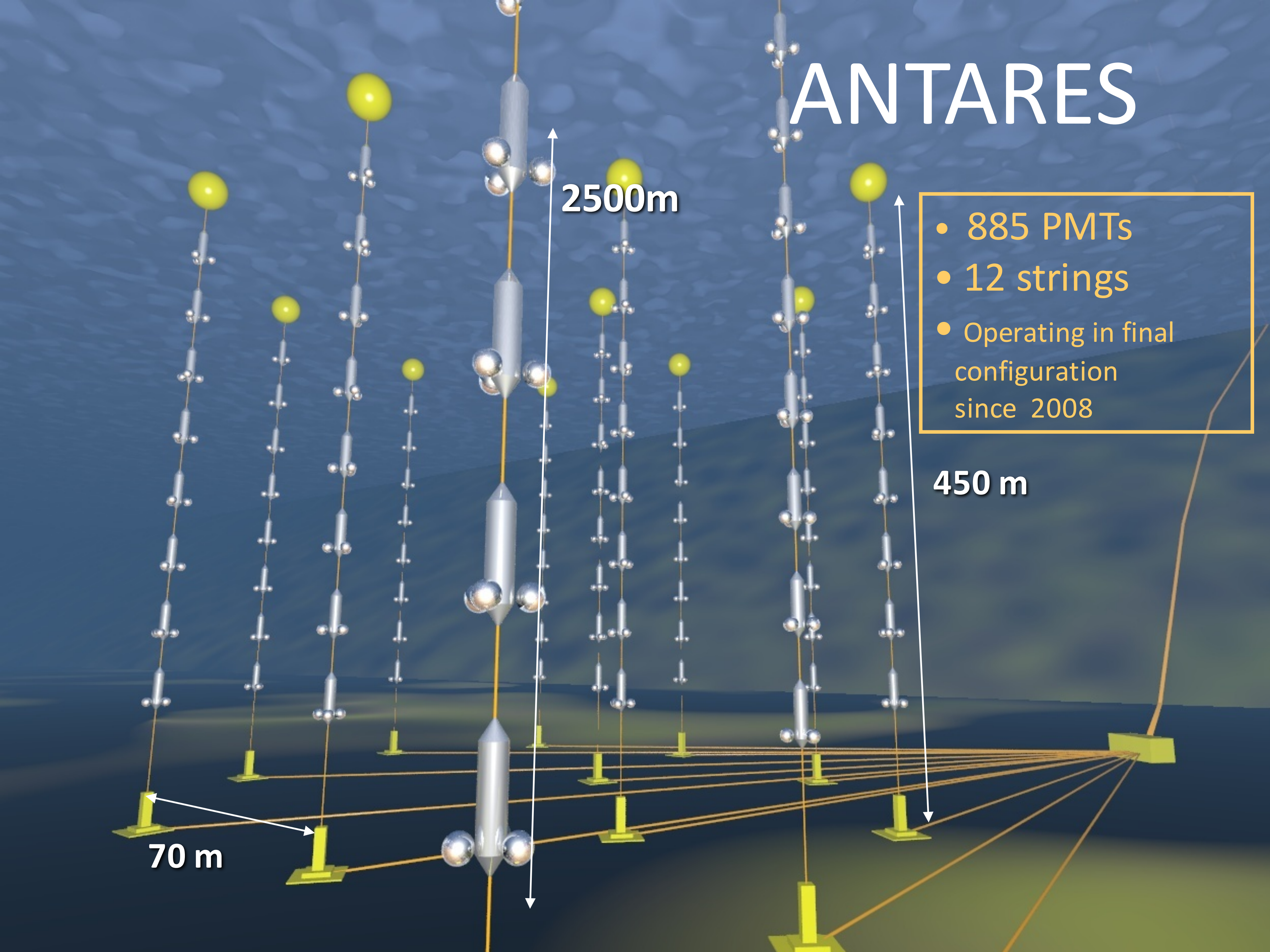
The devices



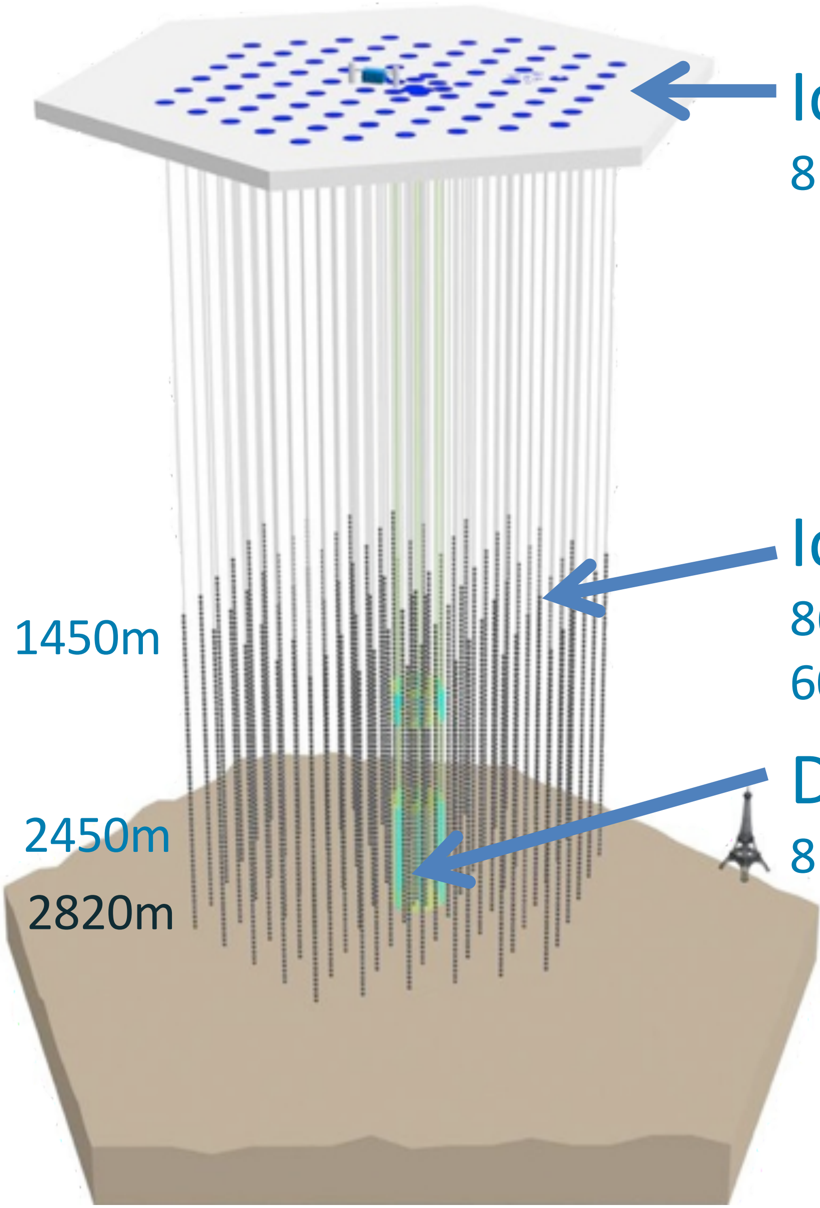
The pioneer: NT200 in Lake Baikal



- 8 strings
- 192 PMTs
- Height 72 m
- Diameter 42 m


ANTARES
• 885 PMTs
• 12 strings
• Operating in final configuration since 2008
2500m
450 m
70 m

IceCube Neutrino Observatory



IceTop air shower detector

81 pairs of water Cherenkov tanks

IceCube

86 strings including 8 Deep Core strings
60 PMT per string

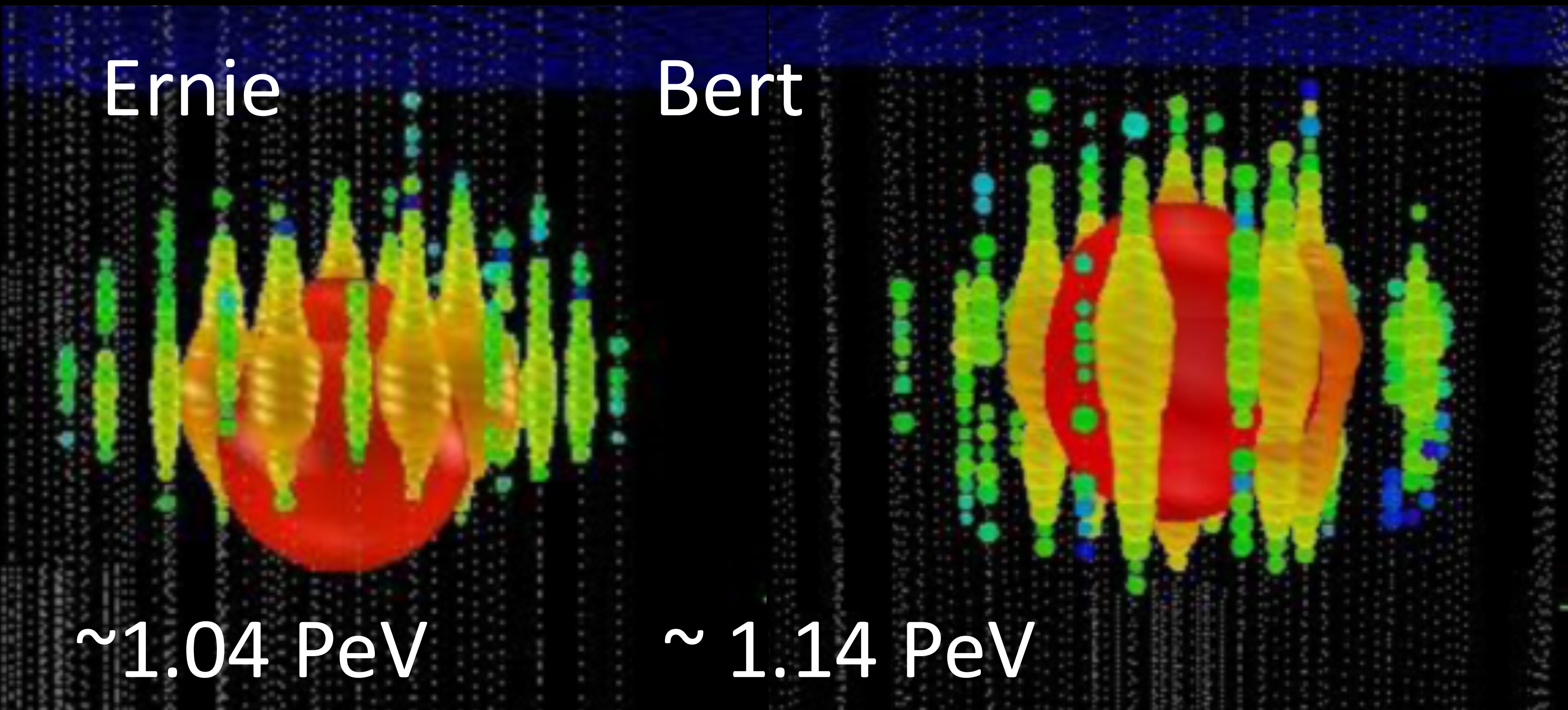
DeepCore

8 closely spaced strings

- ~220 /day
- Threshold
  - IceCube ~ 100 GeV
  - DeepCore ~10 GeV

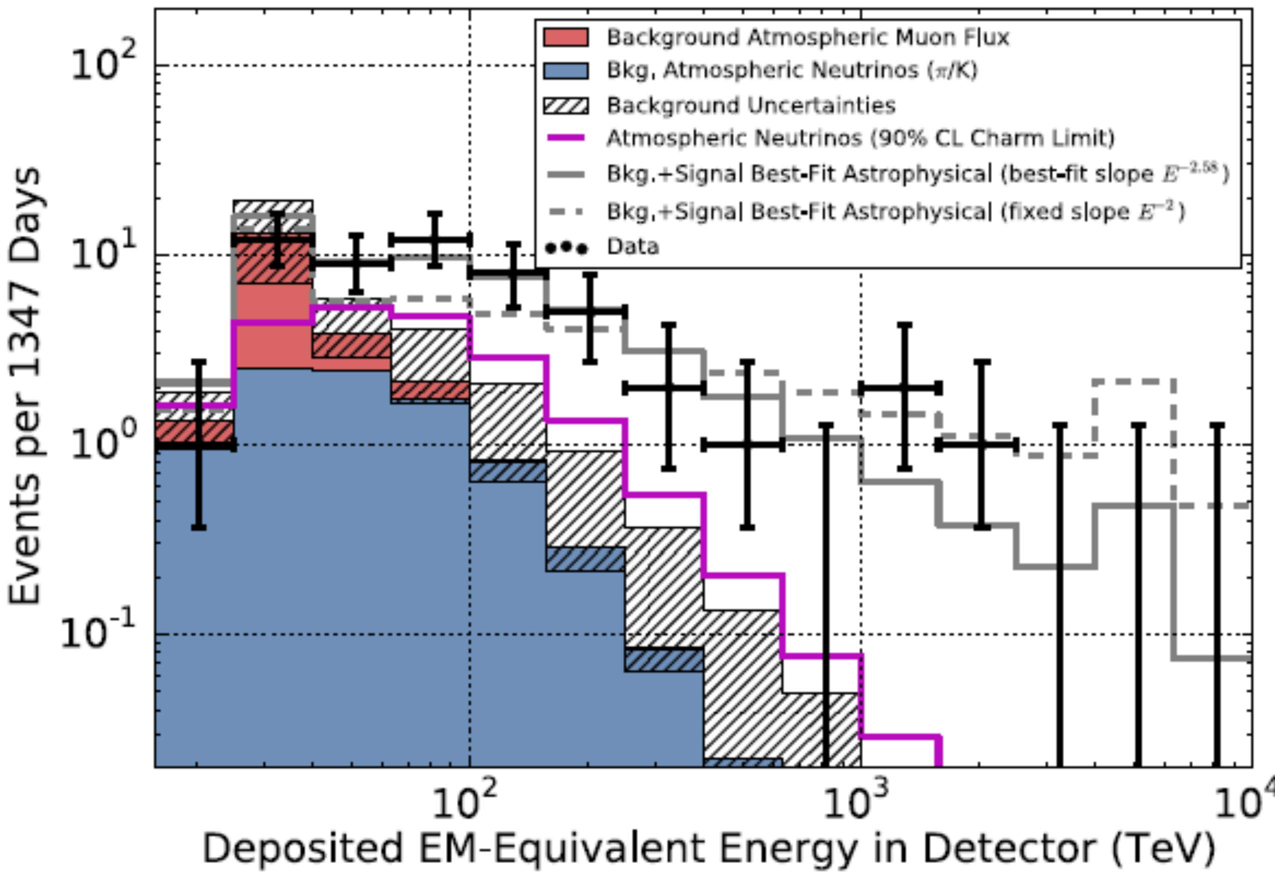
Special search for neutrinos with E > 500 TeV

IC79/IC86 2.8



Follow-up Analysis: HESE (High Energy Starting Event)

First evidence for an extra-terrestrial h.e. neutrino flux



2 yrs data, 28 evts 4.1

Science 342 (2013)

3 yrs data, 37 evts 5.9

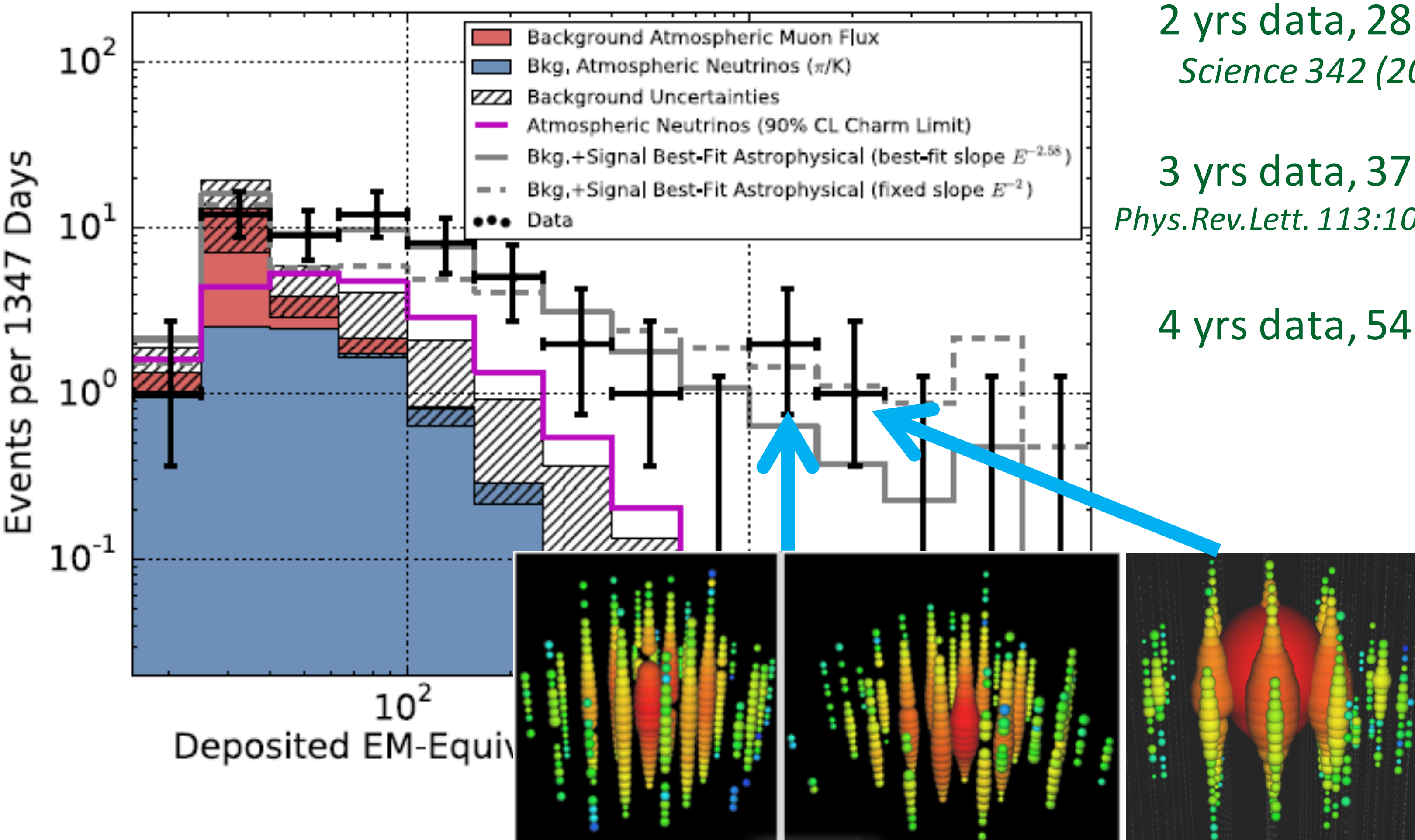
Phys.Rev.Lett. 113:101101 (2014)

4 yrs data, 54 evts ~ 7

Threshold ~ 30 TeV

Follow-up Analysis: HESE (High Energy Starting Event)

First evidence for an extra-terrestrial h.e. neutrino flux



2 yrs data, 28 evts 4.1

Science 342 (2013)

3 yrs data, 37 evts 5.9

Phys.Rev.Lett. 113:101101 (2014)

4 yrs data, 54 evts ~ **<u>7</u>**

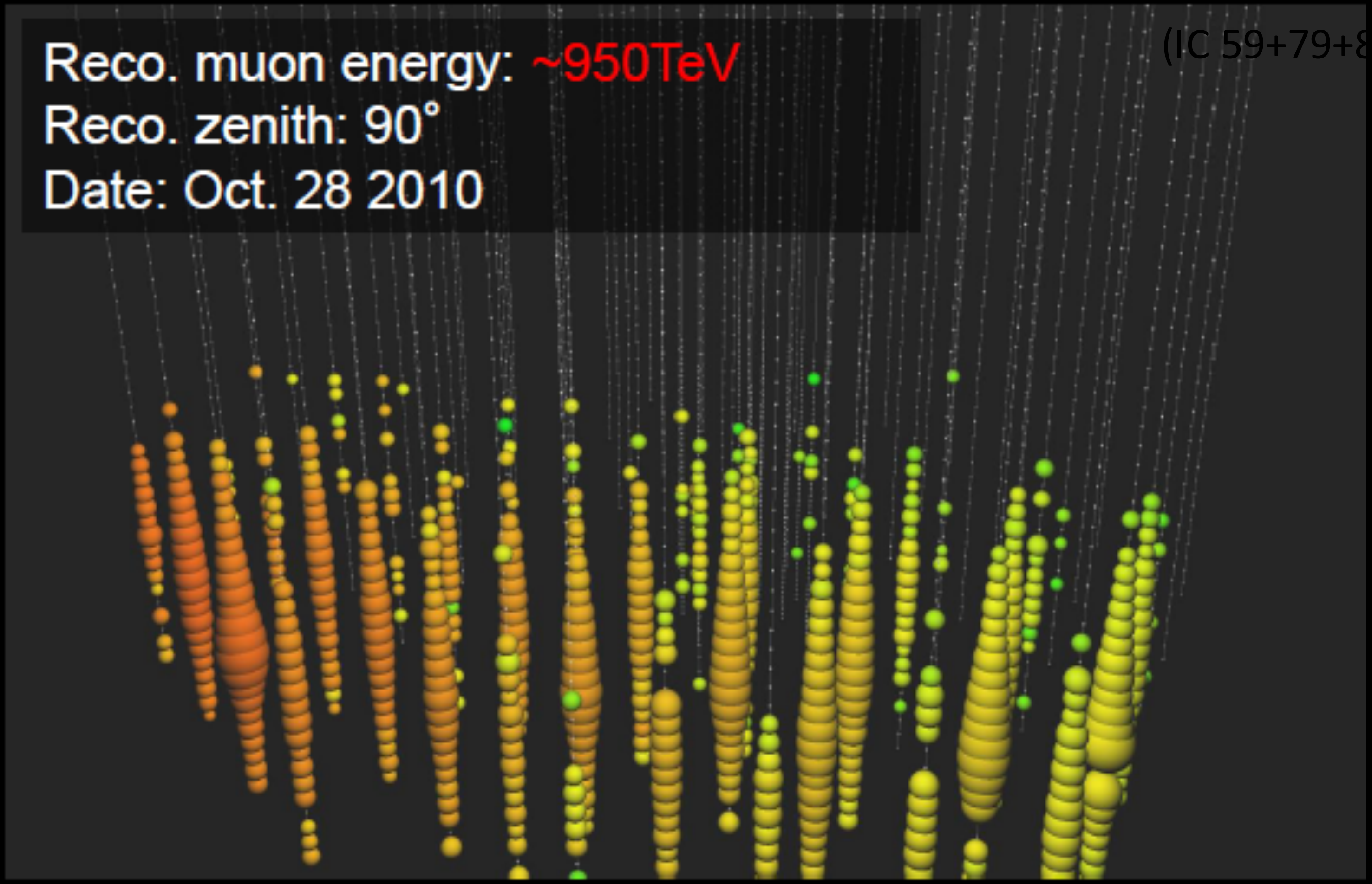
"Bert"
1.04 PeV
Aug. 2011

"Ernie"
1.14 PeV
Jan. 2012

"Big Bird"
2 PeV
Dec. 2012

3 years through-going muons

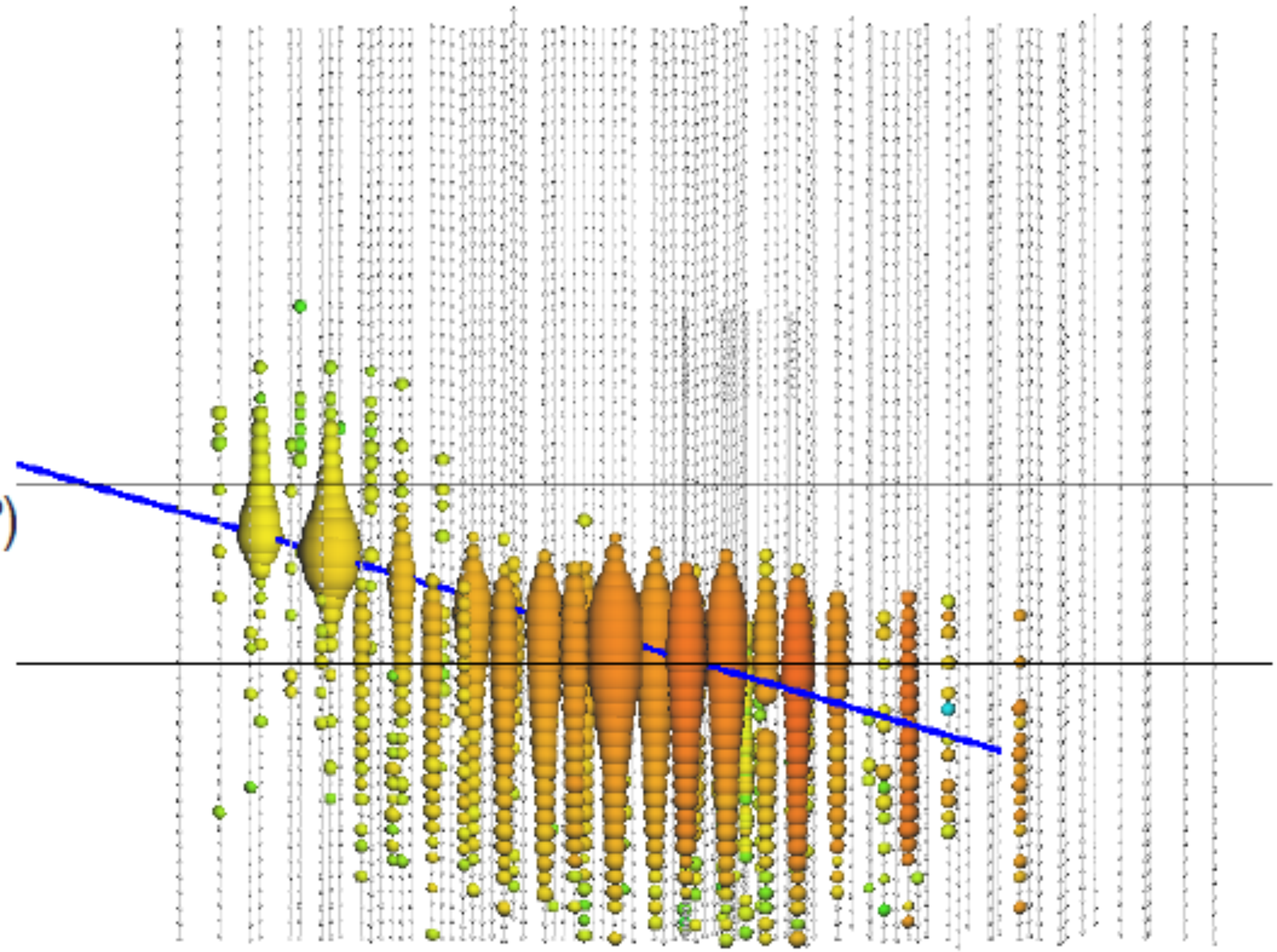
The highest energy muon in 2009-12



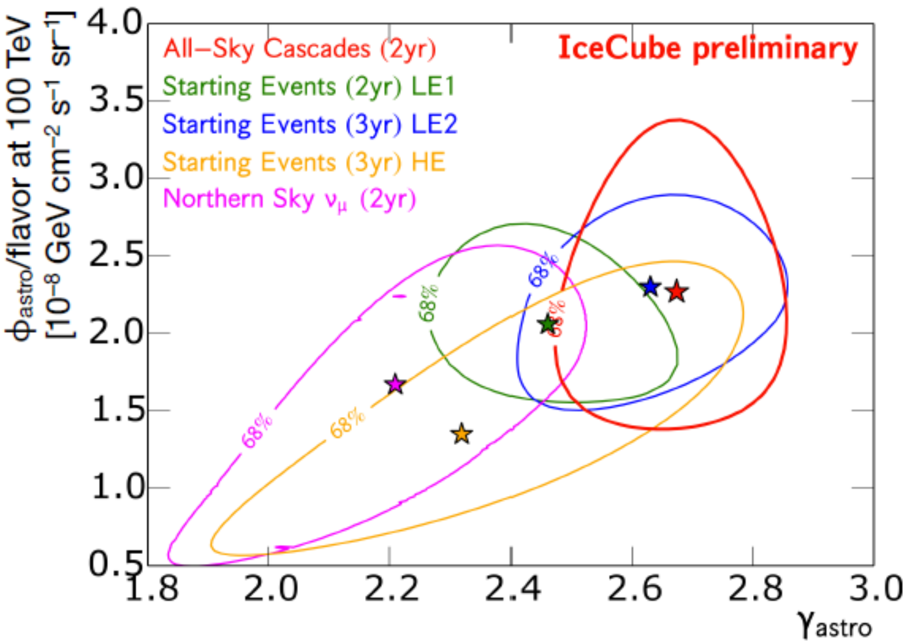
(IC 59+79+8

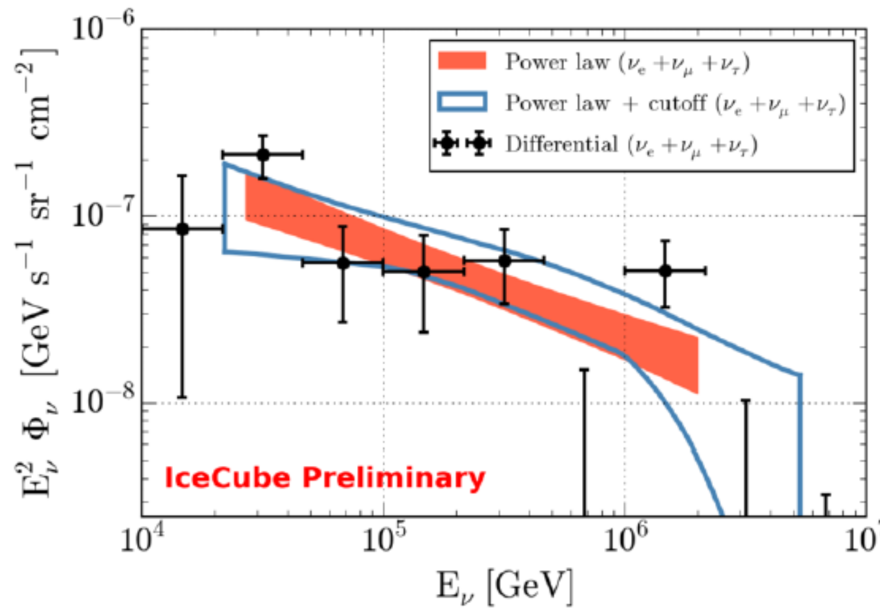
New: The highest energy of all !

- Reconstructed with 2.6±0.3 PeV *deposited* energy
  - Lower limit on neutrino energy
- Up-going muon neutrino (decl. 11.5°)
  - June 11, 2014



Energy spectrum = $_0$ E





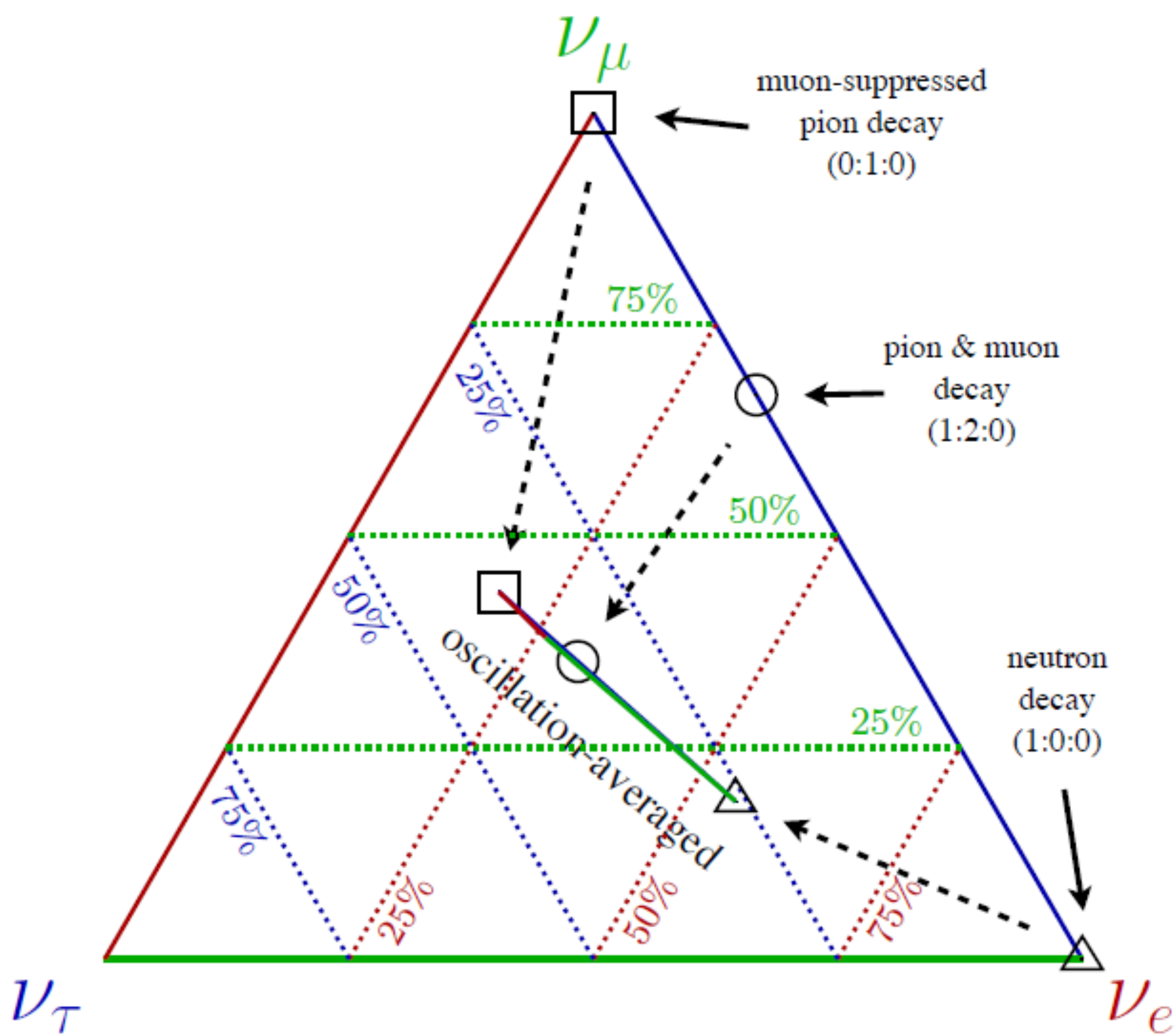
Different analyses find different (but statistically compatible) spectral indices

need more statistics

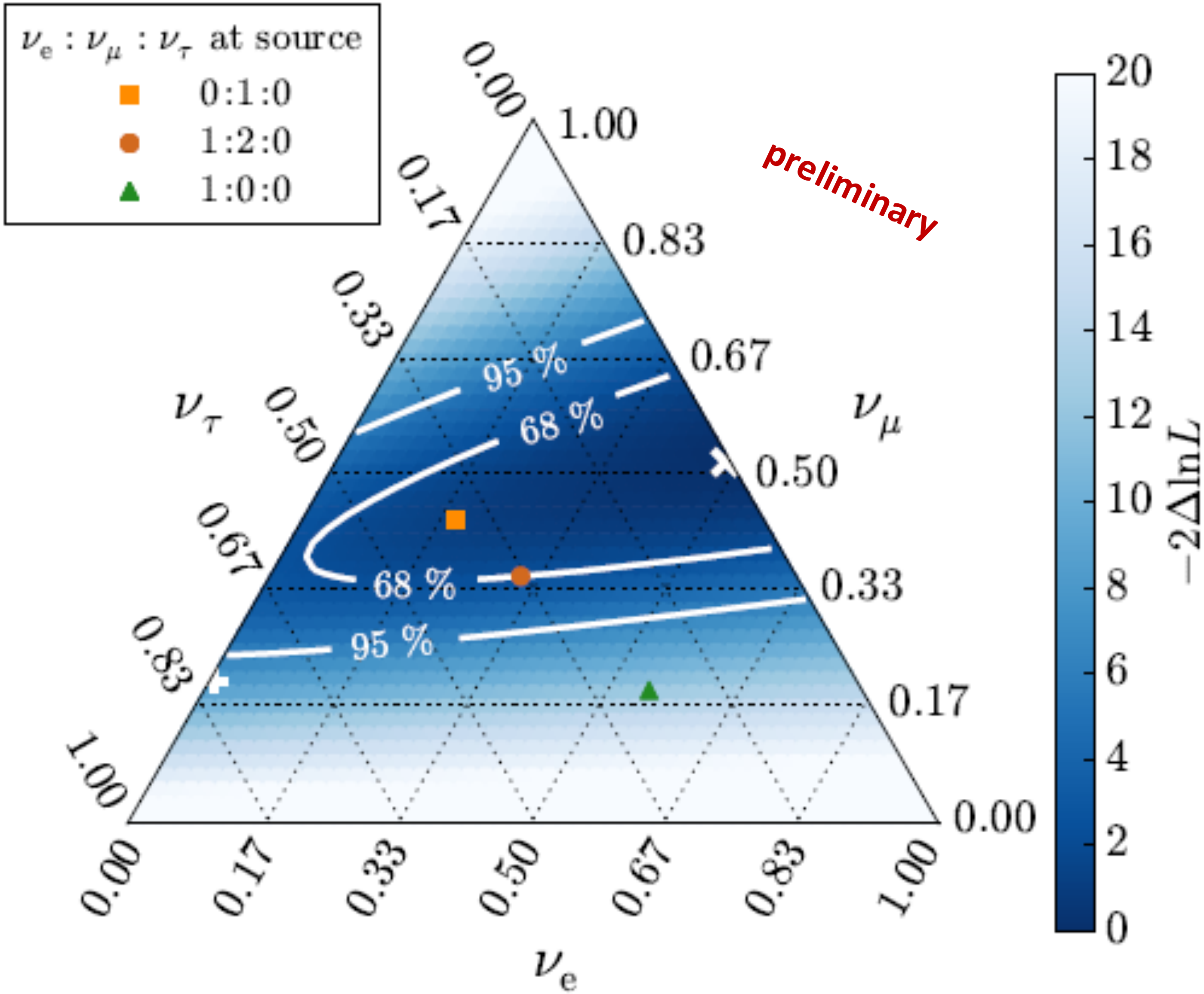
need independent measurement with different systematics

need KM3NeT and Baikal-GVD!

Flavour composition: what do we expect?



Flavour comp.: what do we measure?

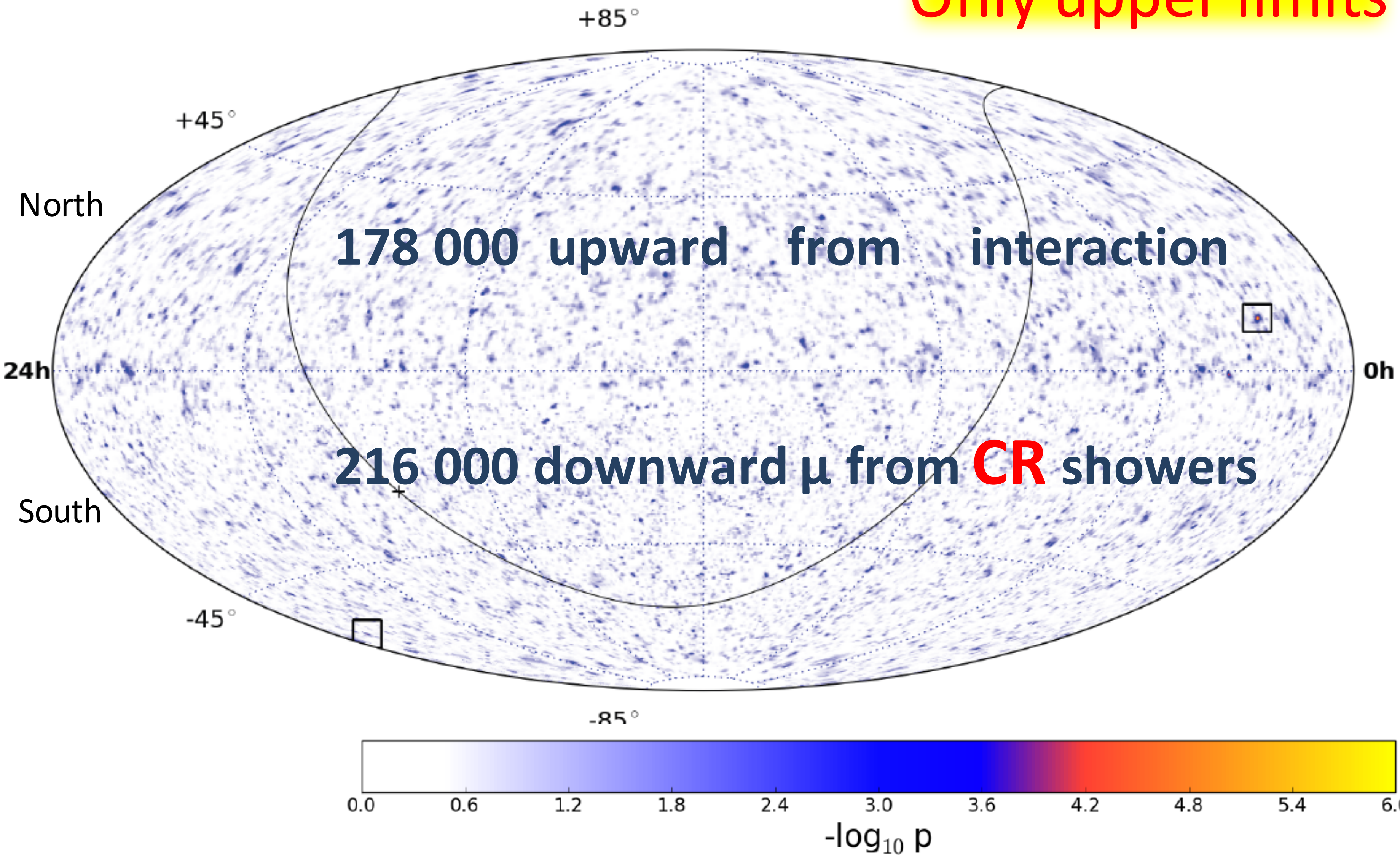


the best fit flavor composition disfavors 1:0:0 at source at 3.6

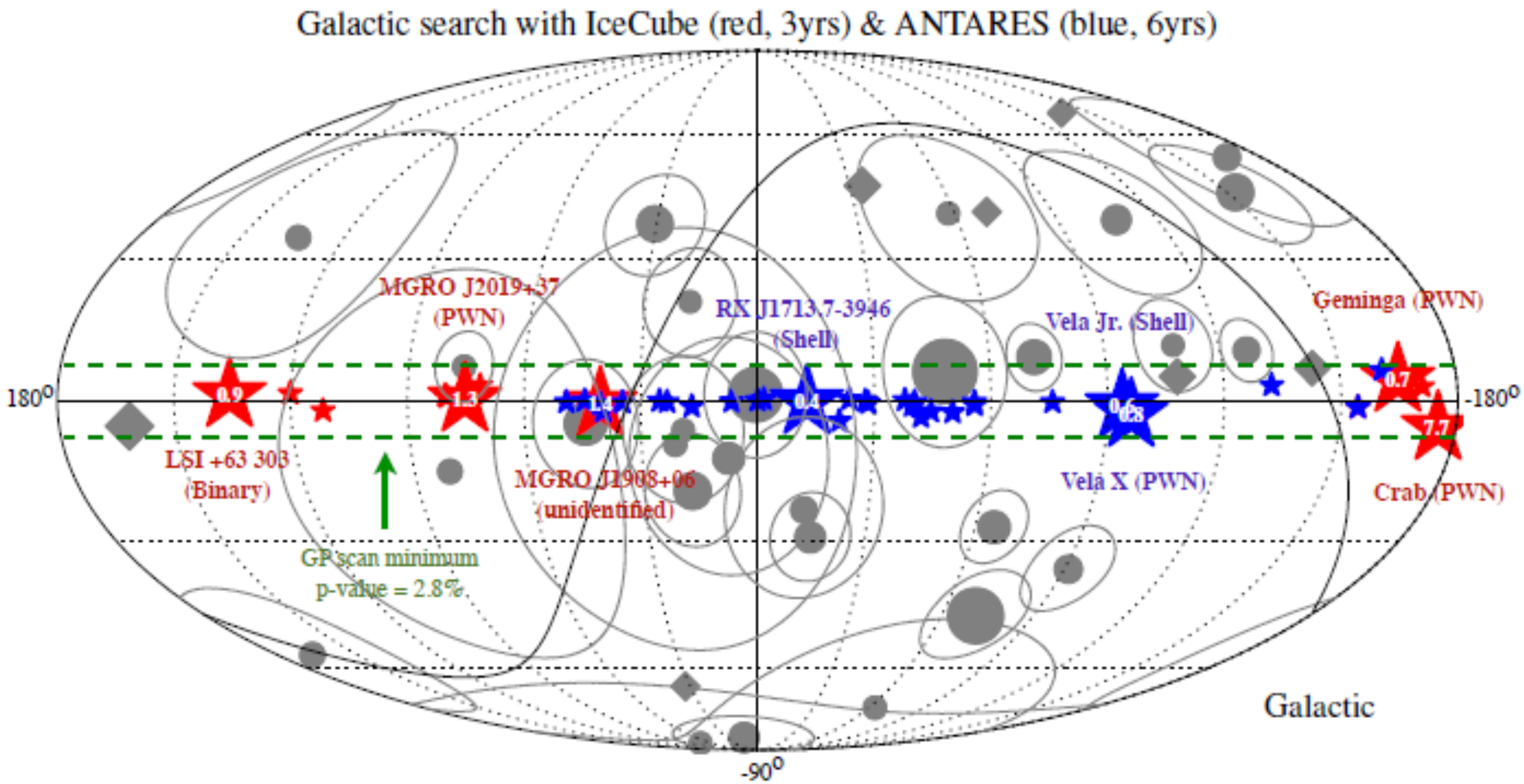
IceCube 4 years

pre-trial significance skymap

Only upper limits



But may be we are close!



- relative strength of neutrino limits assuming hadronic TeV γ-ray emission (only shown for selected strong sources):

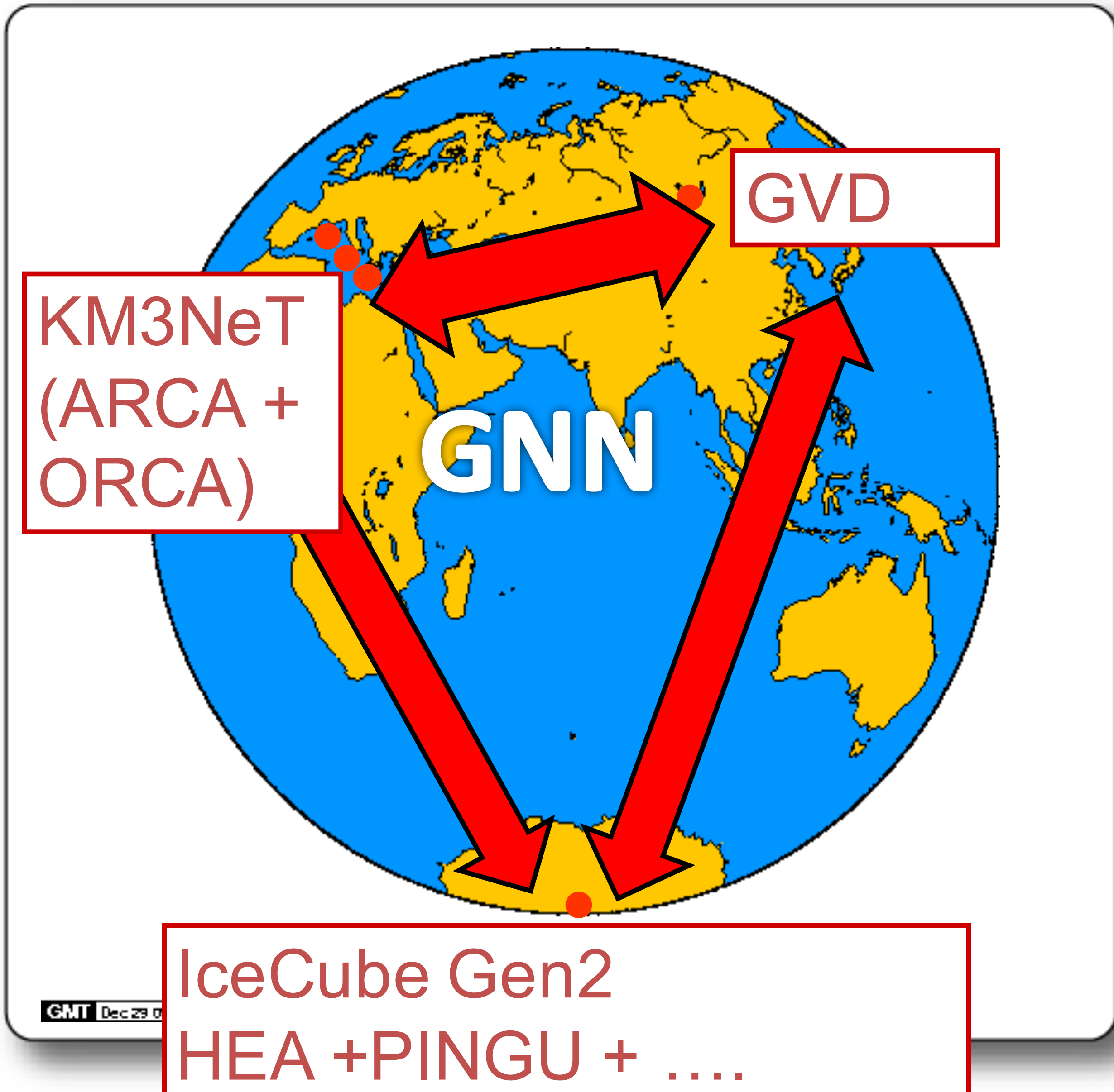
$$F_\gamma(E_\gamma > E_{\rm th})/F_\nu^{90CL}(E_\nu > E_{\rm th}/2)$$

✘ **caveats:** soft spectra, low energy cutoffs and extended emission

Markus Ahlers
VLVNT 2015

The future of high-energy neutrino astronomy

Baikal, Mediterranean Sea, South Pole



GIGATON VOLUME DETECTOR

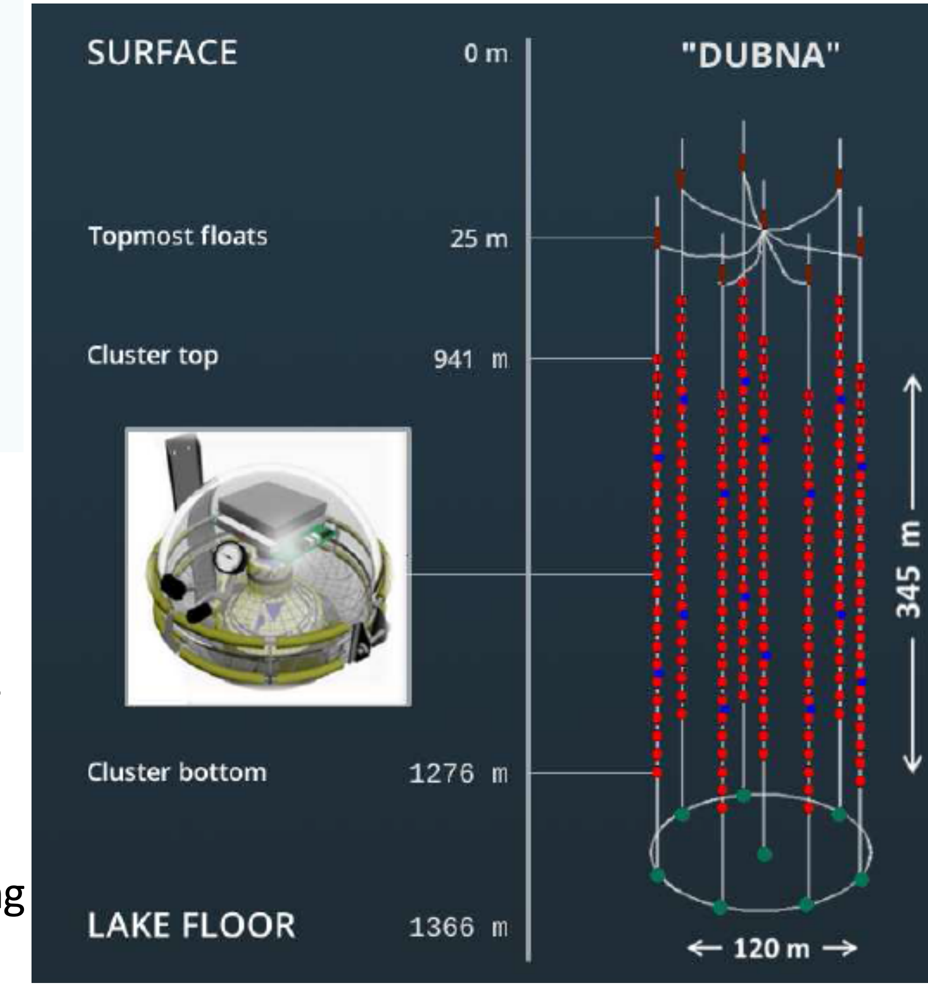
BAIKAL GVD

GVD: Phase 1 (2020) and Phase 2 (~2025)

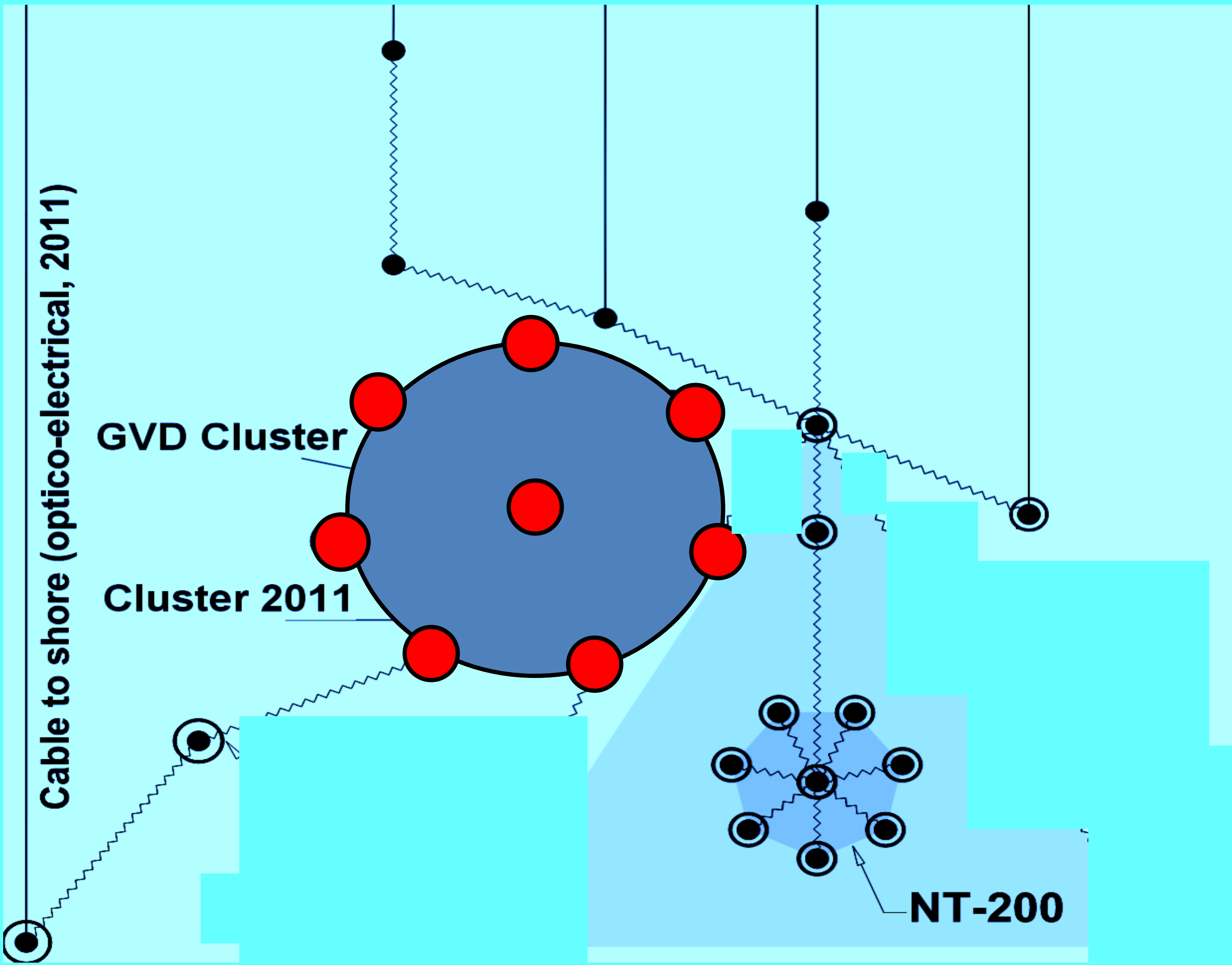
GVD-1: 0.4 km^3

- 12 clusters with 8 strings each
- Cluster diameter 120 m
- Height 520 m
- 36 OMs per string

GVD-2: ~ 1.5 km^3



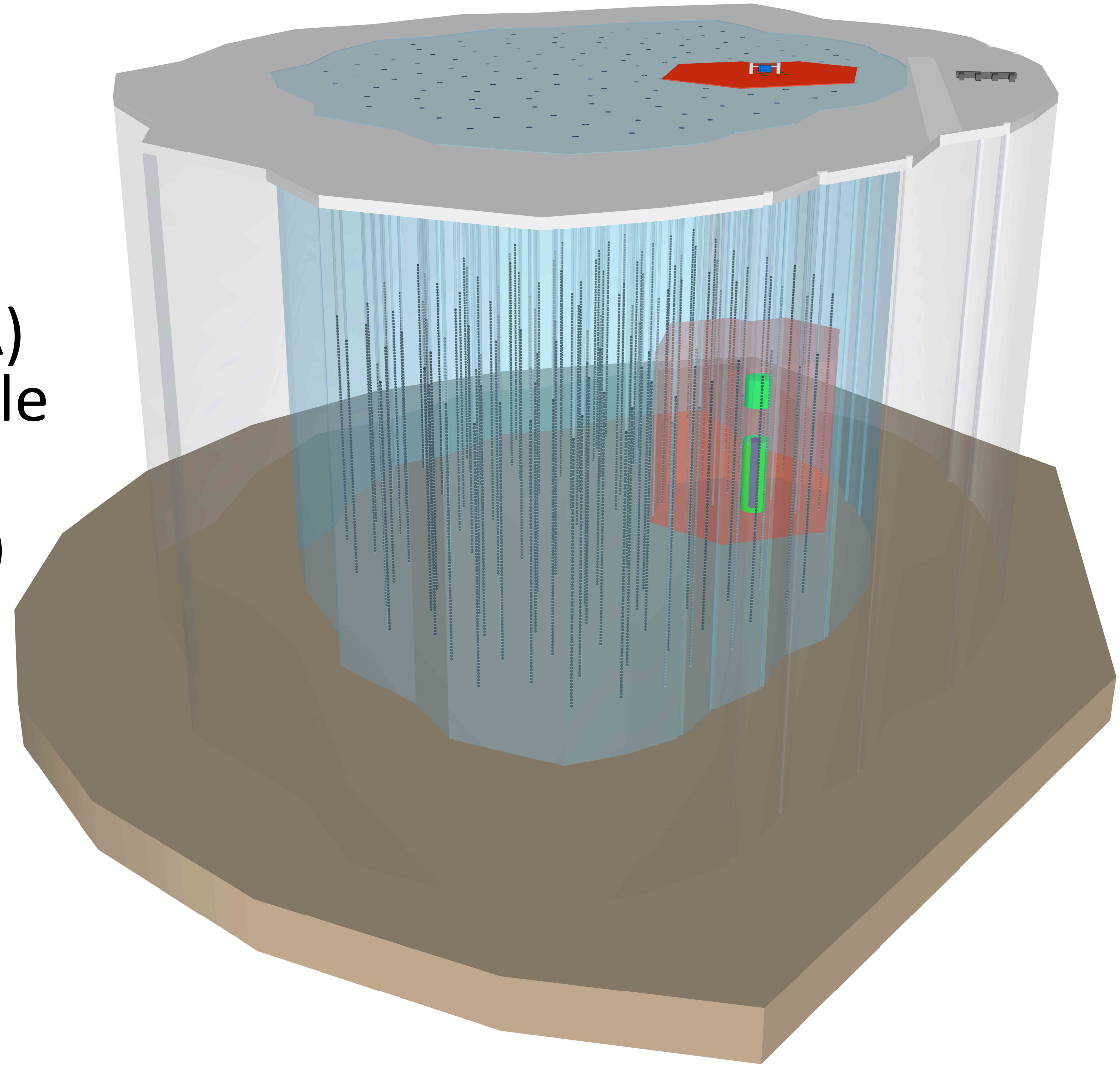
2015: First cluster of GVD versus NT200



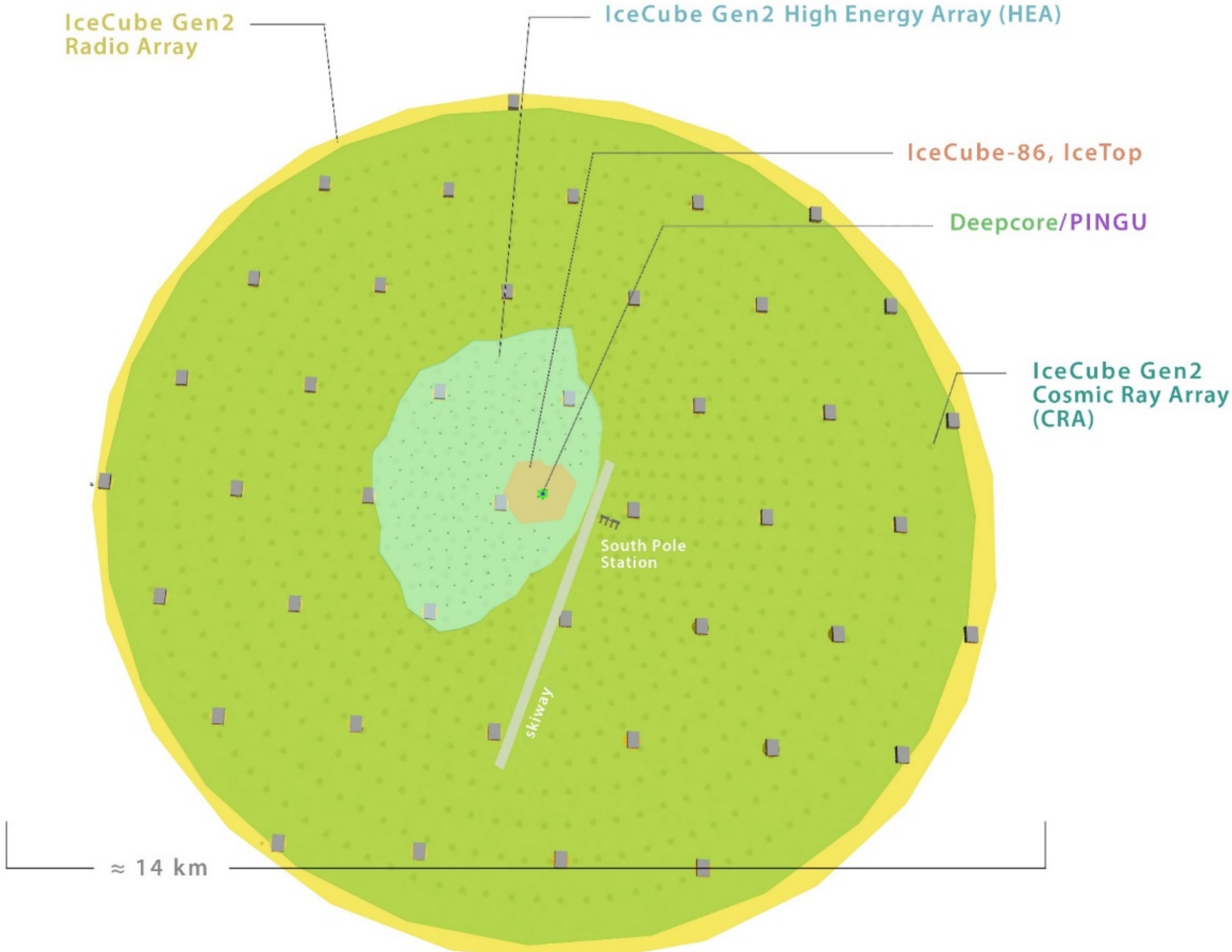
IceCube GEN2

The IceCube Gen2 facility: conceptual drawing

- PINGU : low energy, mass hierarchy
- High Energy Array (HEA)
  - 100 TeV- PeV scale neutrinos
- Cosmic Ray Array (CRA)
  - veto array for HEA
  - cosmic ray physics
- Radio Array (RA)
  - \> 100 PeV
  - BZ (GZK) neutrinos



The IceCube Gen2 facility: conceptual

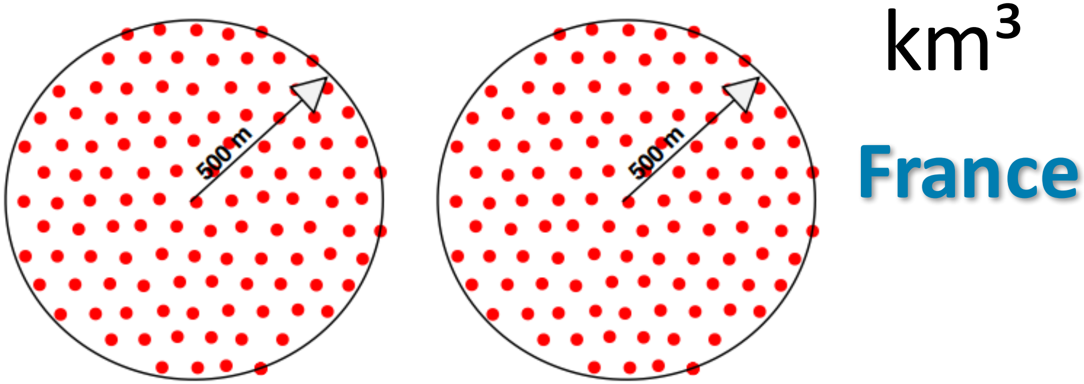


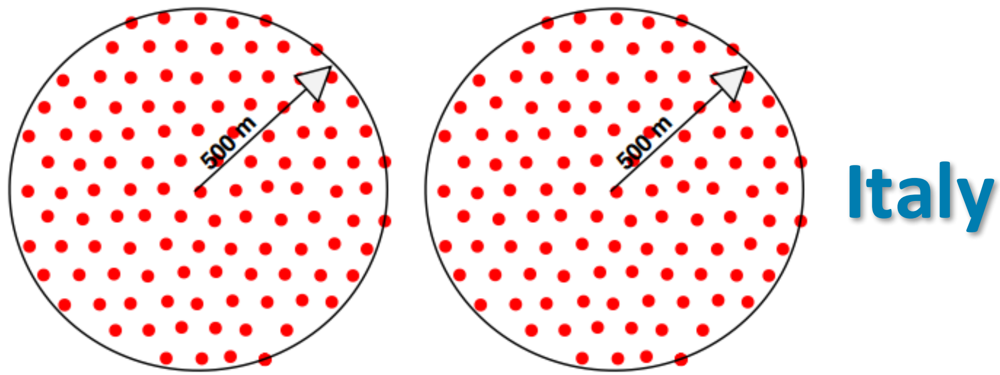
KM3NET

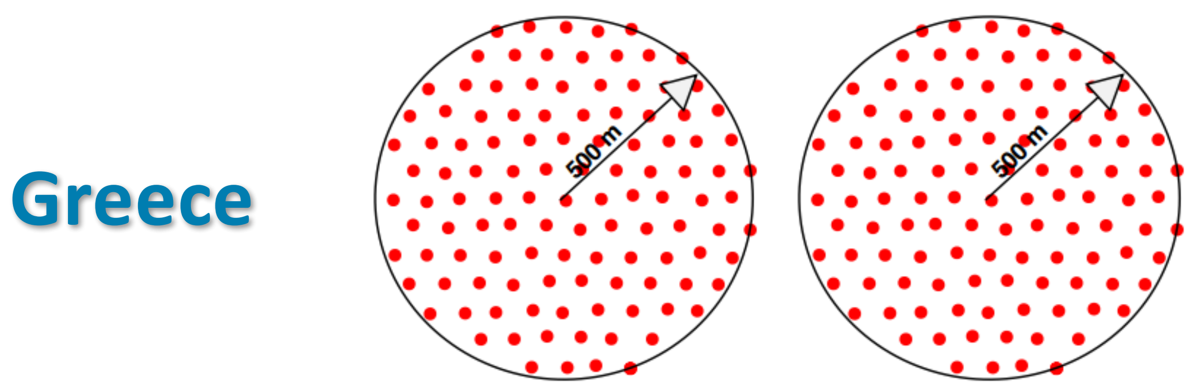
ESFRI

Original idea: 6 blocks at 3 locations: 6 x 0.6 km^3

115 strings per block
18 DOMs per string
31 PMTs per DOM



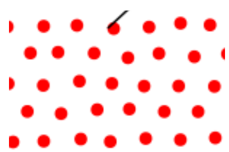




Phase 1 (2017):

France

7 strings, small spacing
- Feasibility test for ORCA

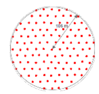


Italy

24 strings, 124 m spacing
- Demonstrate principle
- Physics on the 3-4 times Antares scale

Phase 2: ORCA and ARCA

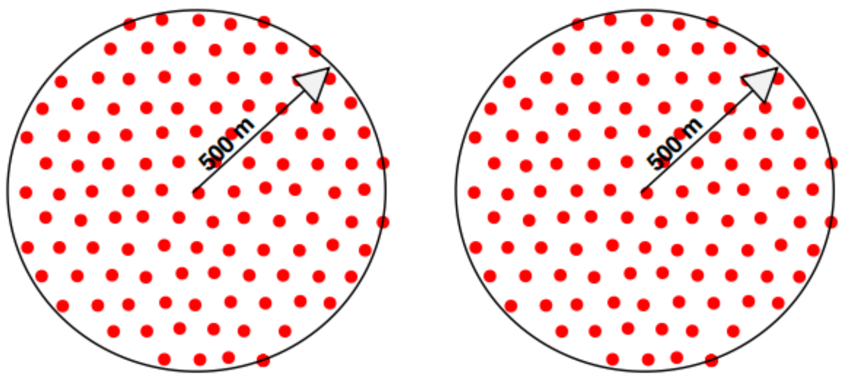
(2020?)



France

ORCA

ARCA



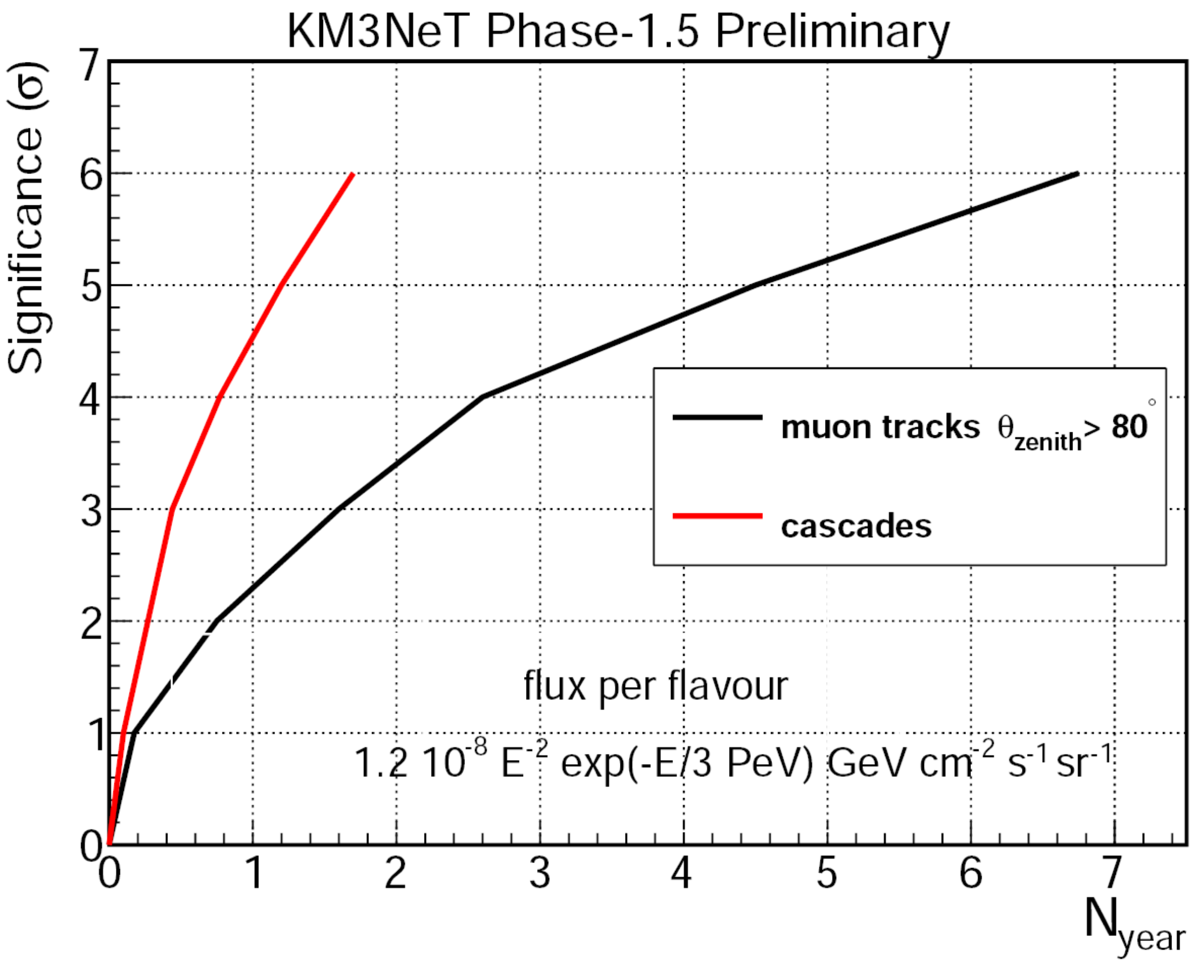
Italy

ORCA: determination of the Neutrino Mass Hierarchy (NMH)

ARCA: IceCube physics, but with better angular resolution and from the Northern hemisphere

KM3NeT Phase 2: diffuse fluxes

Sensitivity to IceCube HESE signal

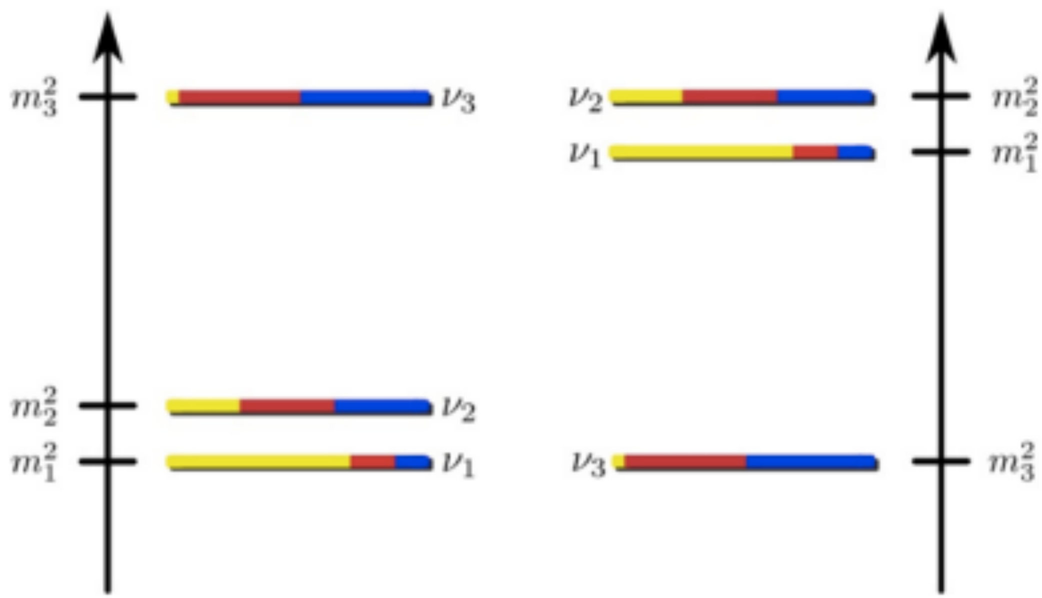


... plus first galactic sources ?

NEUTRINO PROPERTIES WITH NEUTRINO TELESCOPES

A WINDOW OF OPPORTUNITY

- Neutrino Mass Hierarchy (NMH) can be experimentally determined via matter effects in from oscillation pattern of atmospheric neutrinos passing through earth by measuring two-dimensional arrival pattern (energy and zenith angle) in the energy regime of about 3-20 GeV.

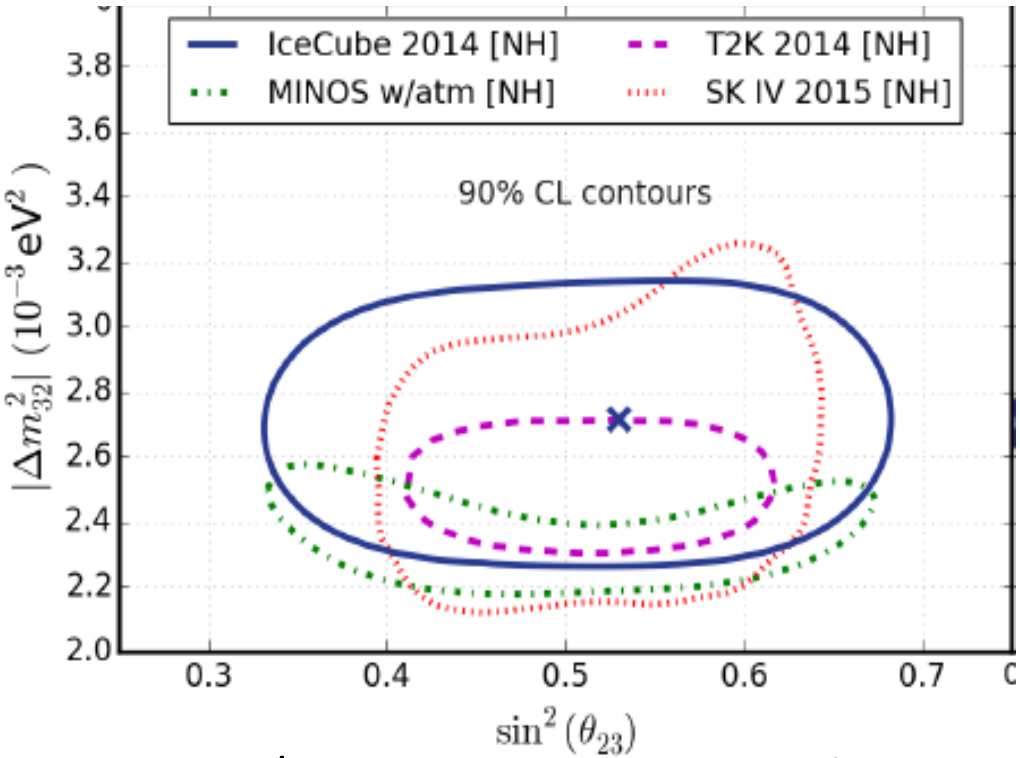


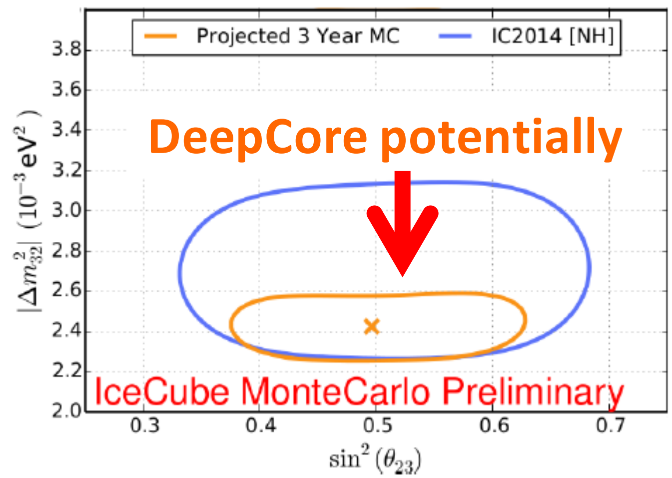
Normal Hierarchy

Inverted Hierarchy

ORCA/PINGU: neutrino mass hierarchy

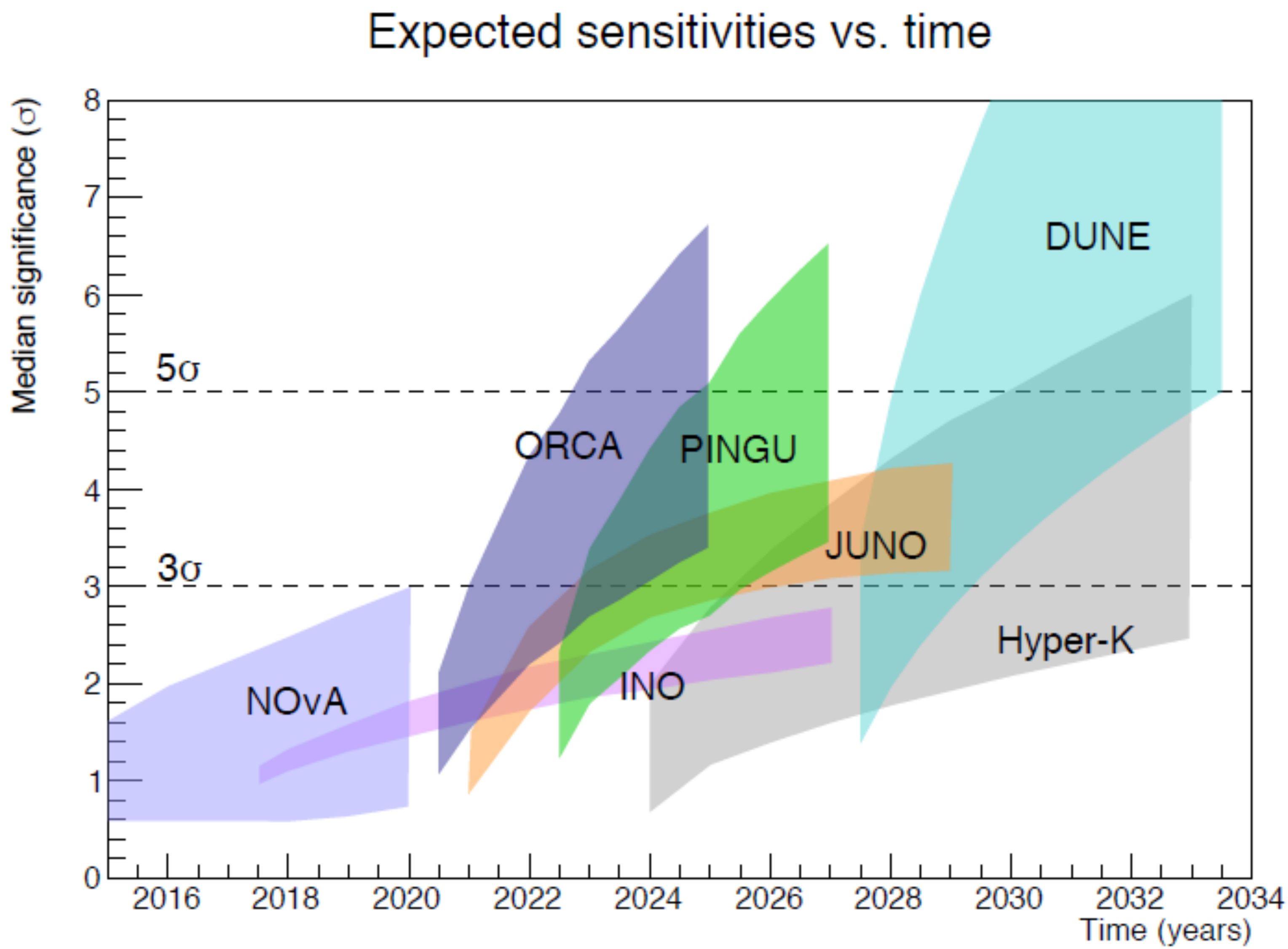
- Deep Core has proven that neutrino telescopes in natural media can do precision neutrino physics. Threshold ~10 GeV.



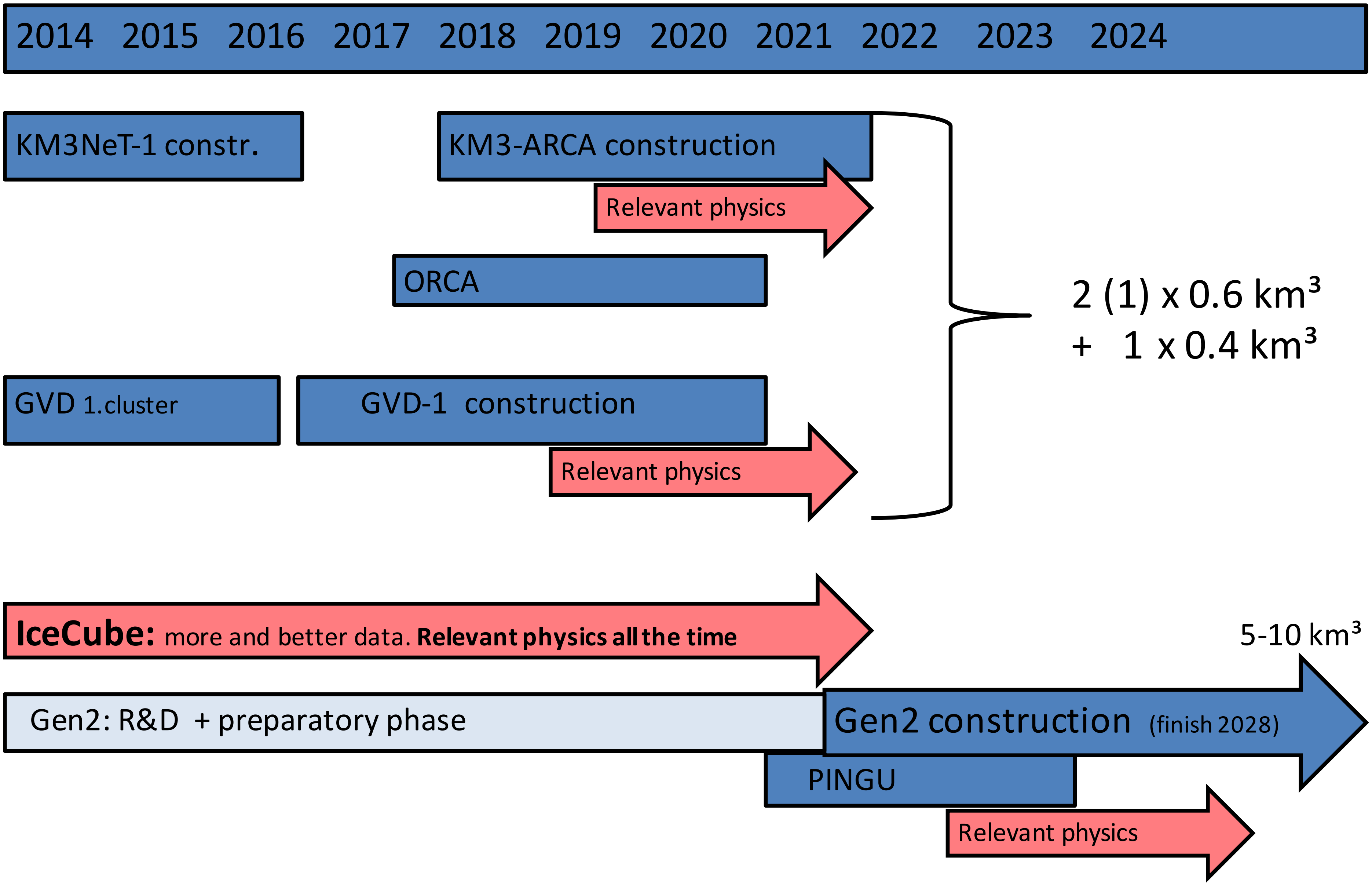


- PINGU/ORCA: measure NMH with atmospheric neutrinos via effects of matter oscillations. Need threshold ~ 3 GeV

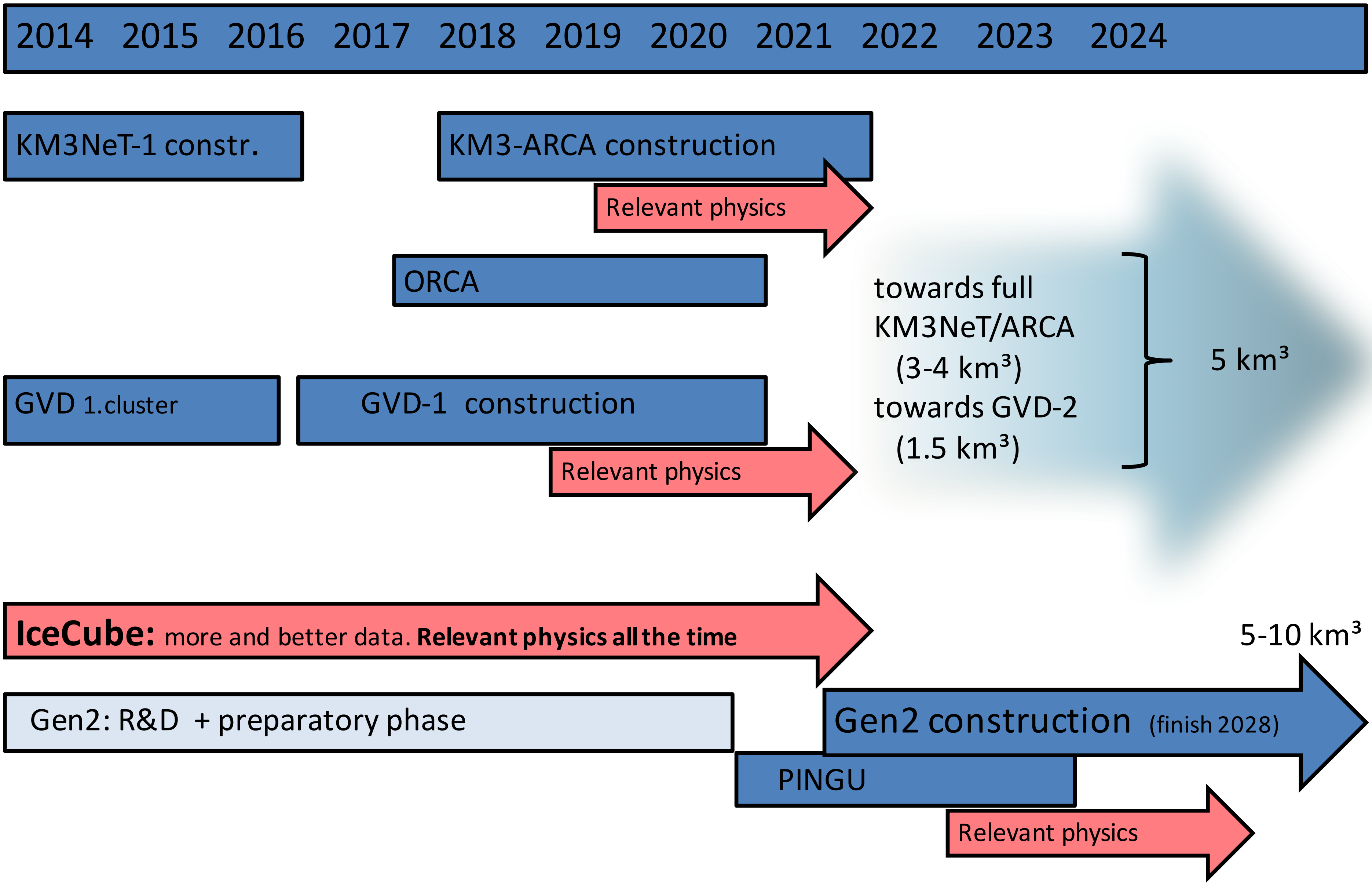
ORCA/PINGU: neutrino mass hierarchy



Global timeline



Global timeline



Conclusions HE neutrinos

- Cosmic high-energy discovered !
- Opened new window, but landscape not yet charted:
  no point sources identified up to now
- Remaining uncertainties on spectrum and flavour composition
- Point sources in reach!
- Need larger detectors, also with different systematics <u>and</u> at the Northern hemisphere.
- Next logical step: KM3NeT$_{\text{Phase2}}$ + GVD$_{\text{Phase1}}$
- Next logical step on NMH: ORCA (later PINGU)
- ~2028: A Global Neutrino Observatory (KM3NeT-GVD-IceCube-Gen2,) full sky with > 5 km^3

GRAVITATIONAL WAVES

BREAKTHROUGH IN 2015/2016

Albert Einstein

1918

Joseph Weber

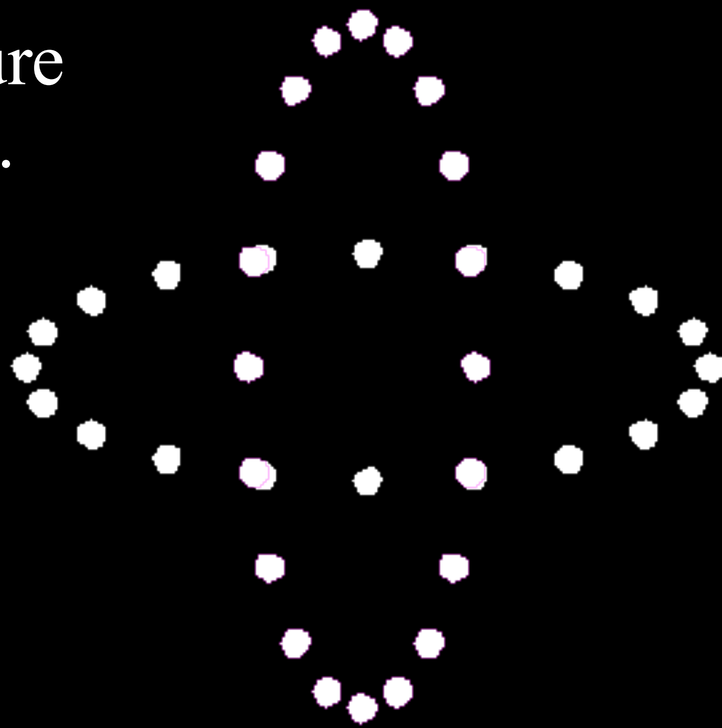
1958

Gravitational waves

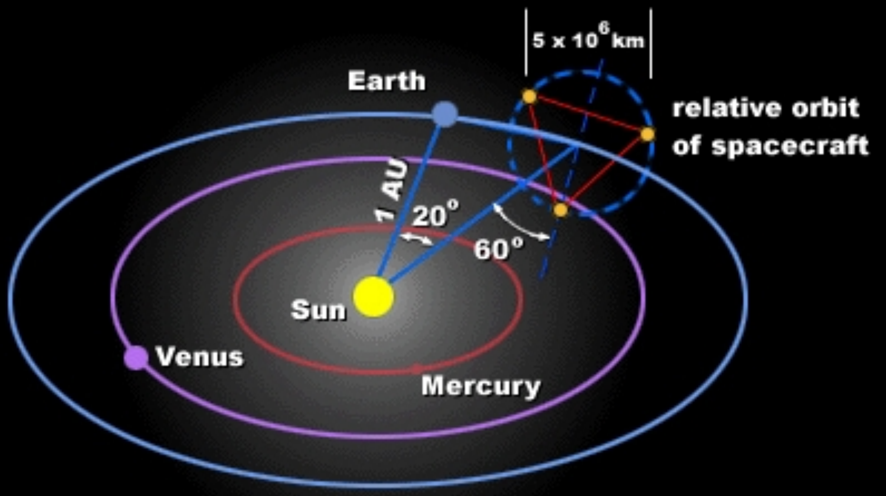
Fluctuations of the space-time curvature
that propagate in the form of waves.

Strain=dh/h ~ 10^{-20}

Age of the Universe ~ 10^{18} s



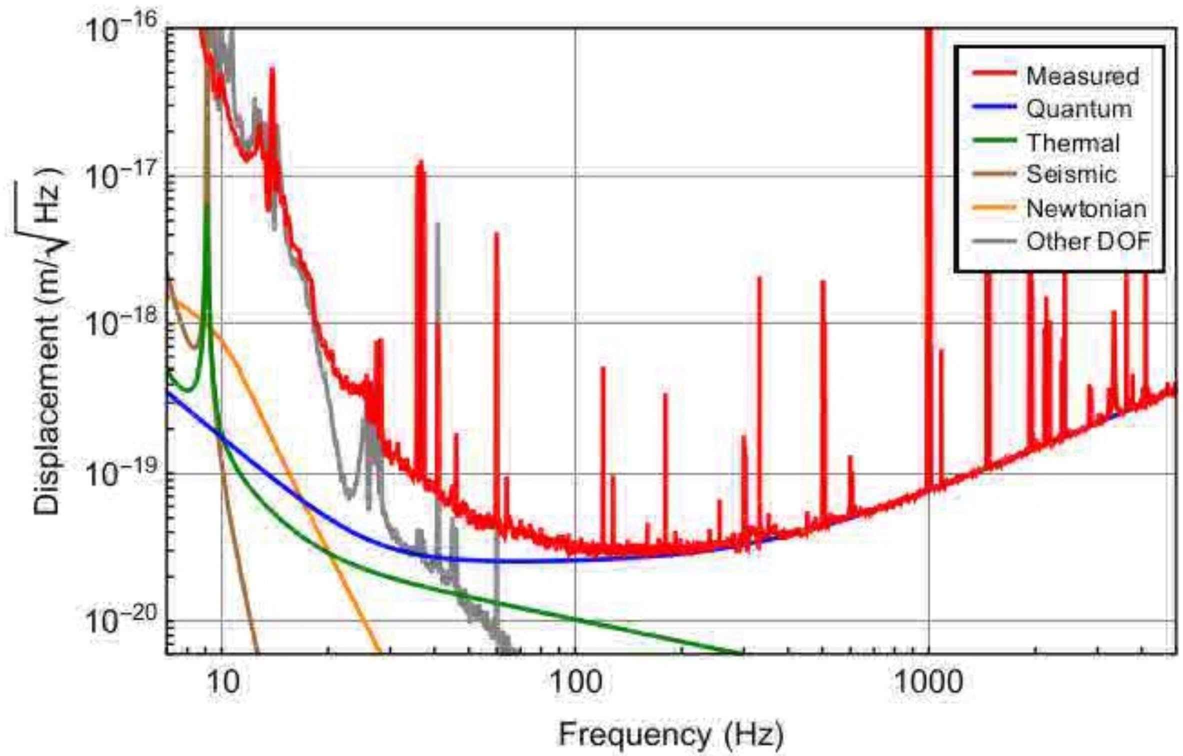
Virgo Interferometric Observatory



Lisa Space Mission

Technical challenges

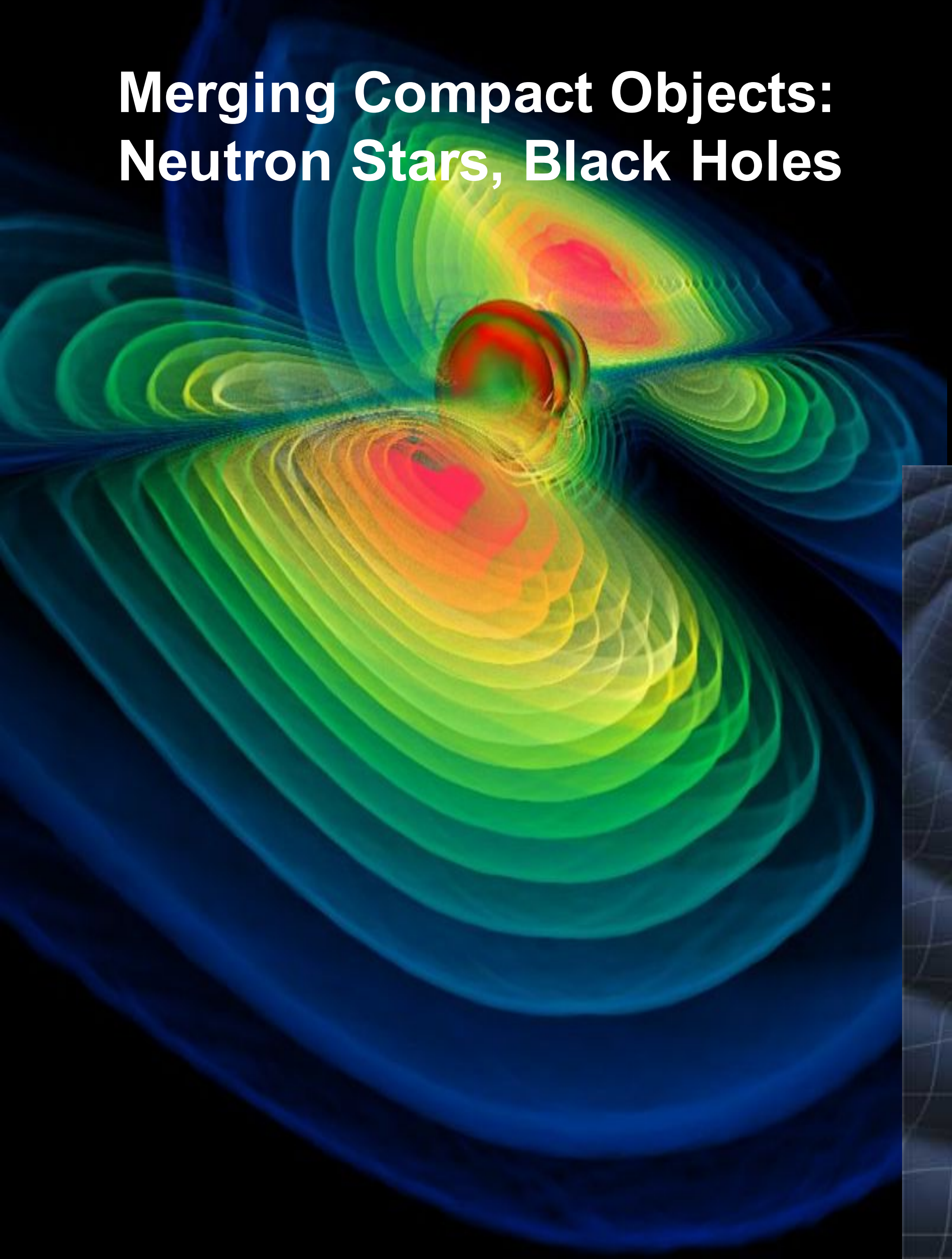
- Seismic isolation
- Vacuum system
- High power lasers
- Thermal noise
- Quantum fluctuations

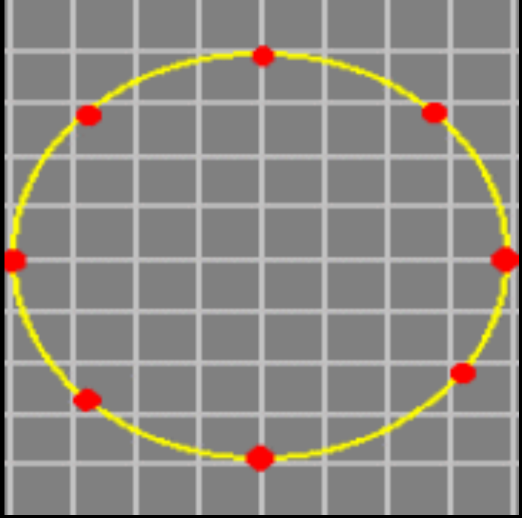


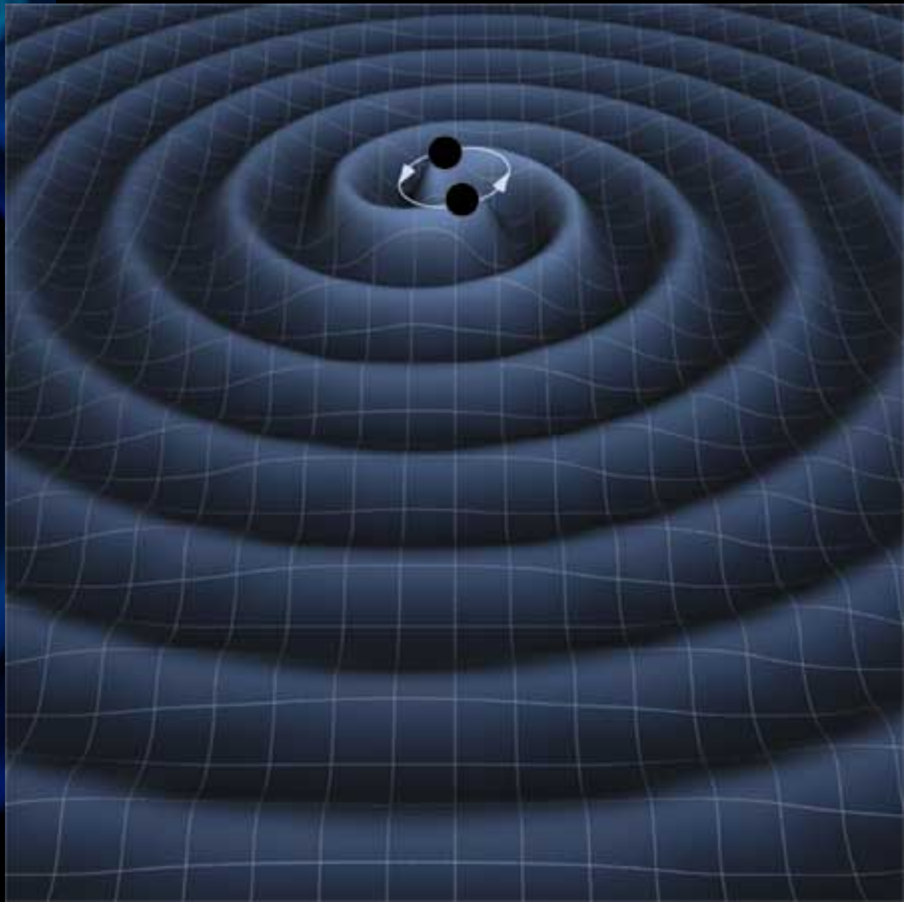
Abbott et al 2016

Also – newtonian noise, magnetic noise

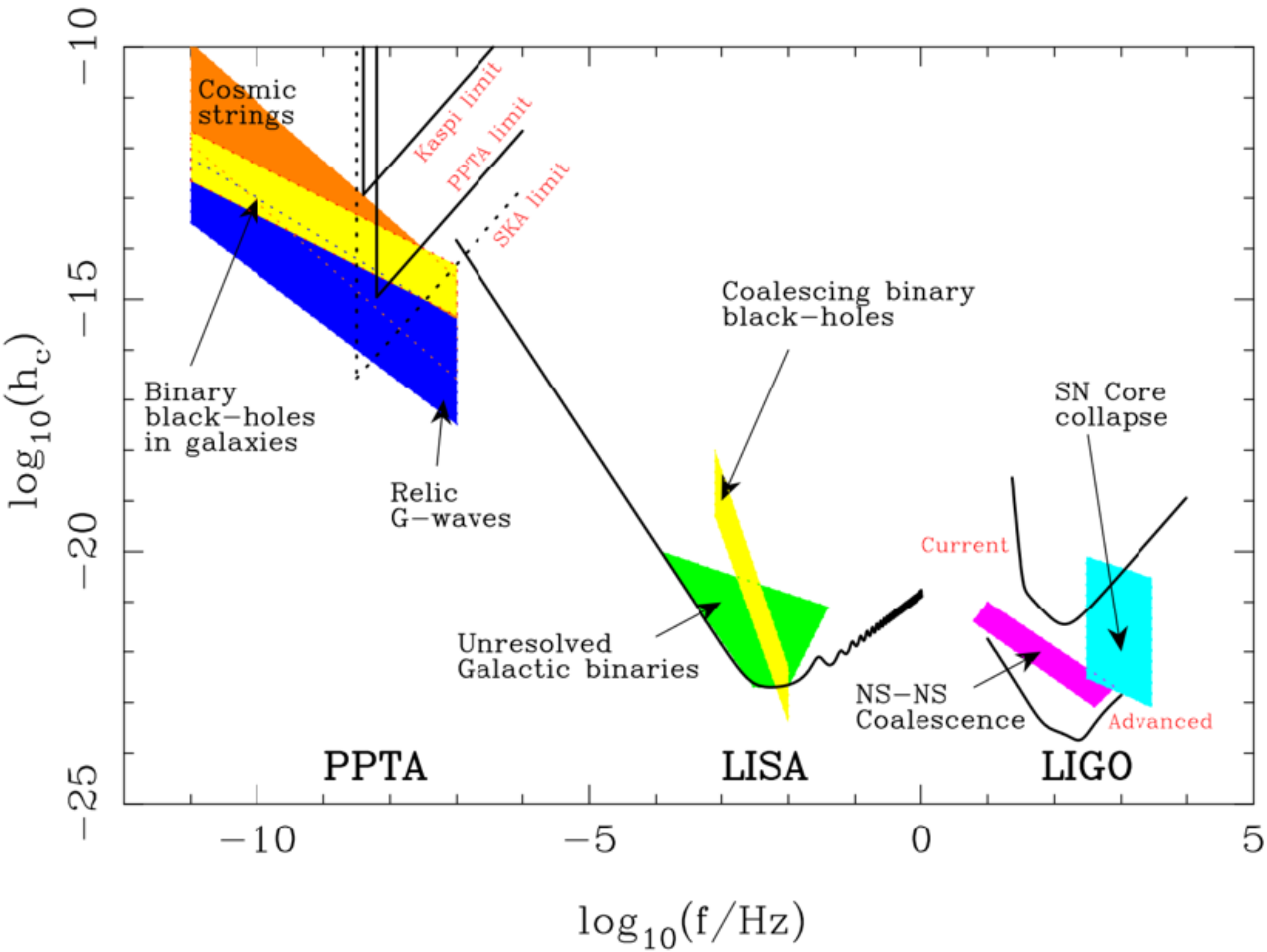
Merging Compact Objects: Neutron Stars, Black Holes





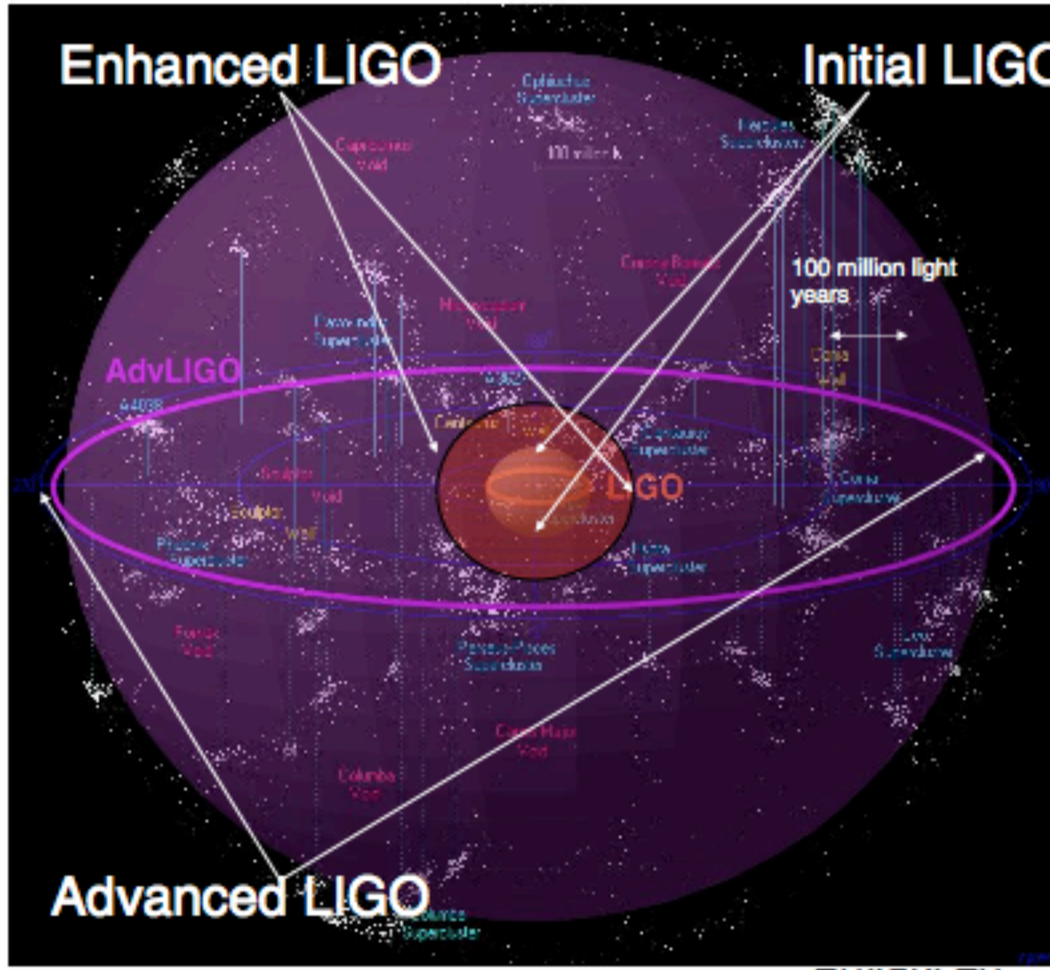


The GW spectrum (credit NASA)

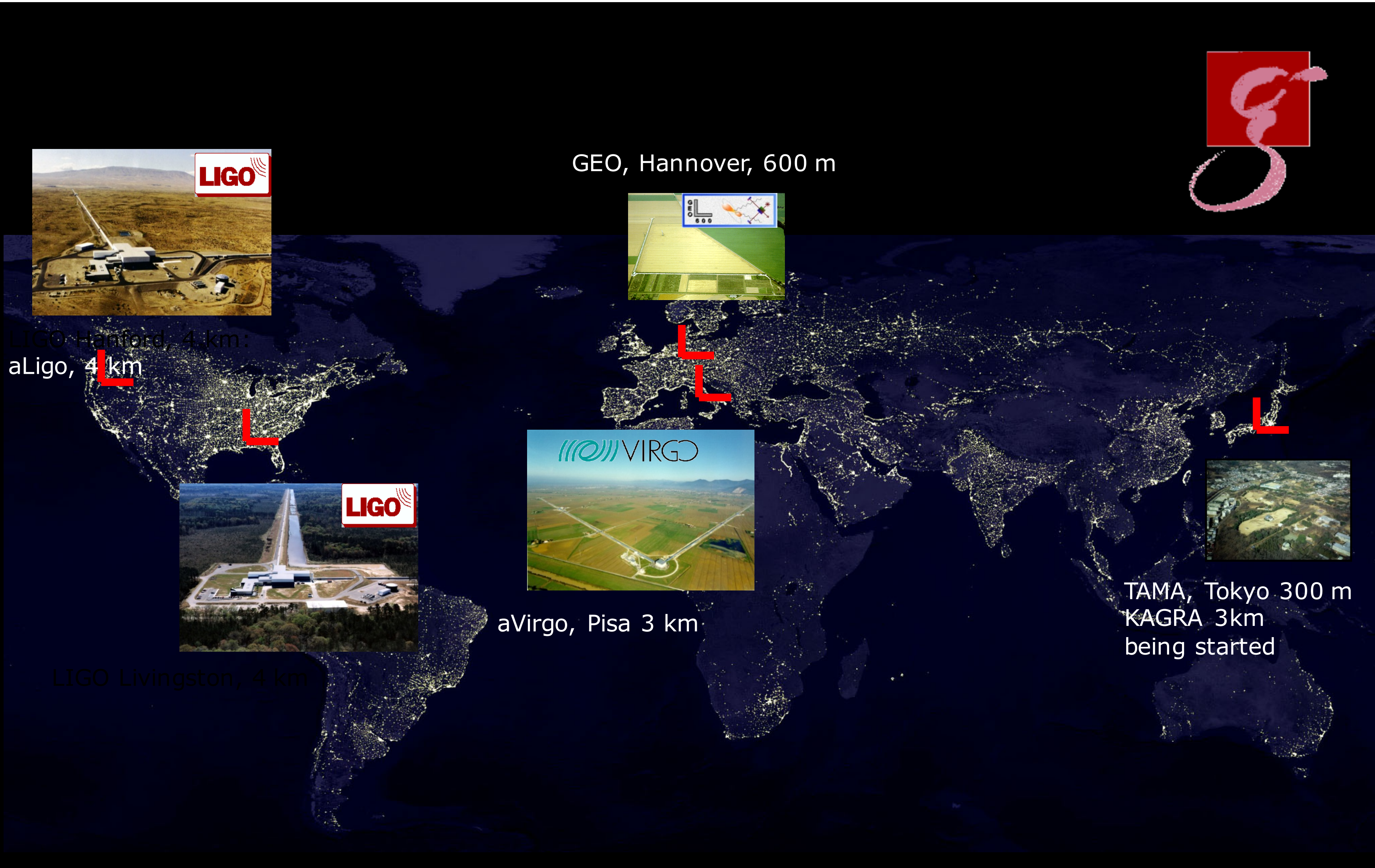


Advanced LIGO

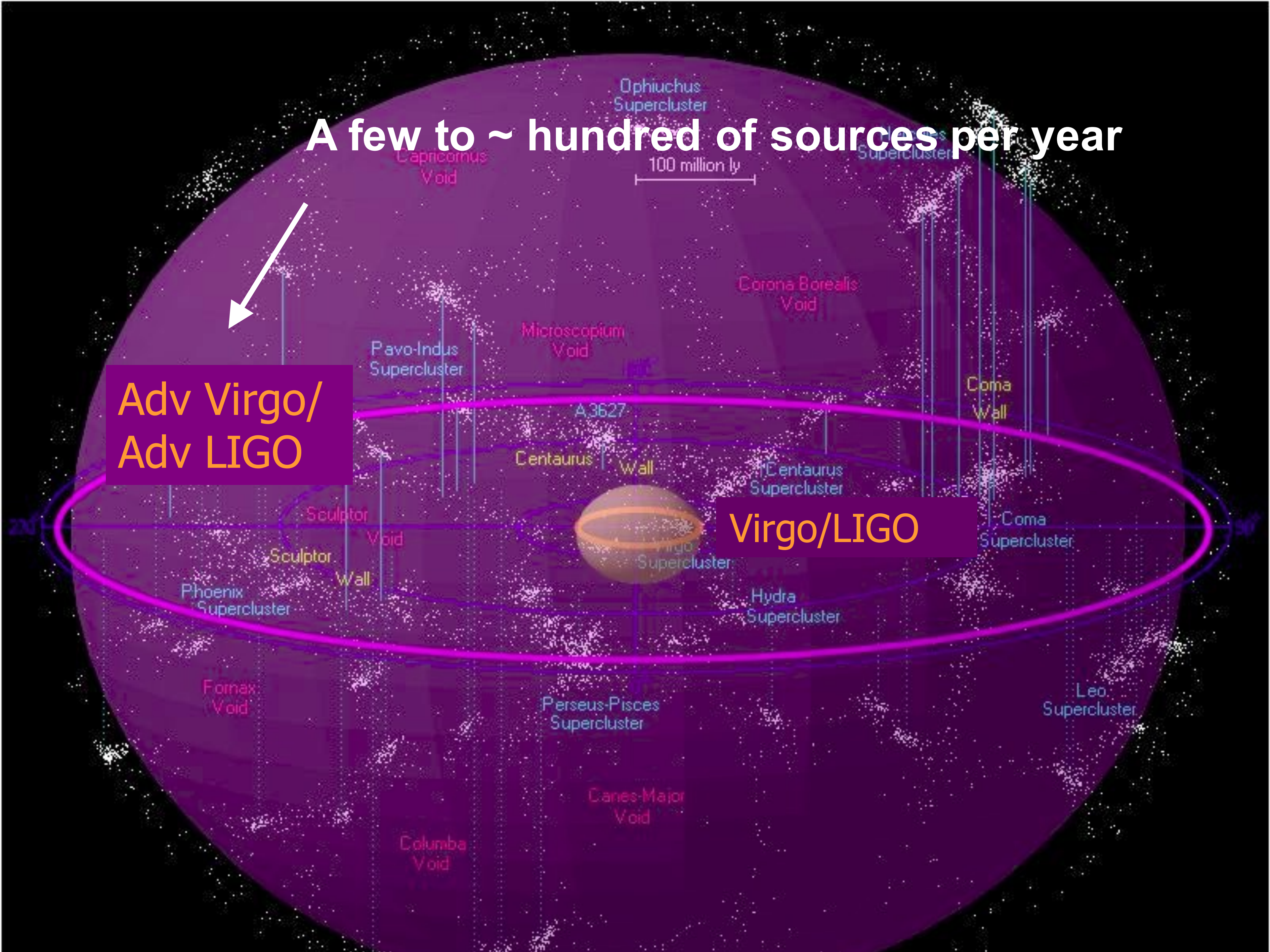
- Factor 10 improvement in sensitivity
- Better low frequency response
- More than 1000 times more sources within reach
- Signal predictions go from ~1 per 10 years (iLIGO) to **~1 per week** (aLIGO)
- (See talk from Francesco Fidecaro for discussion of science goals of the network)



The current GW network of interferometers

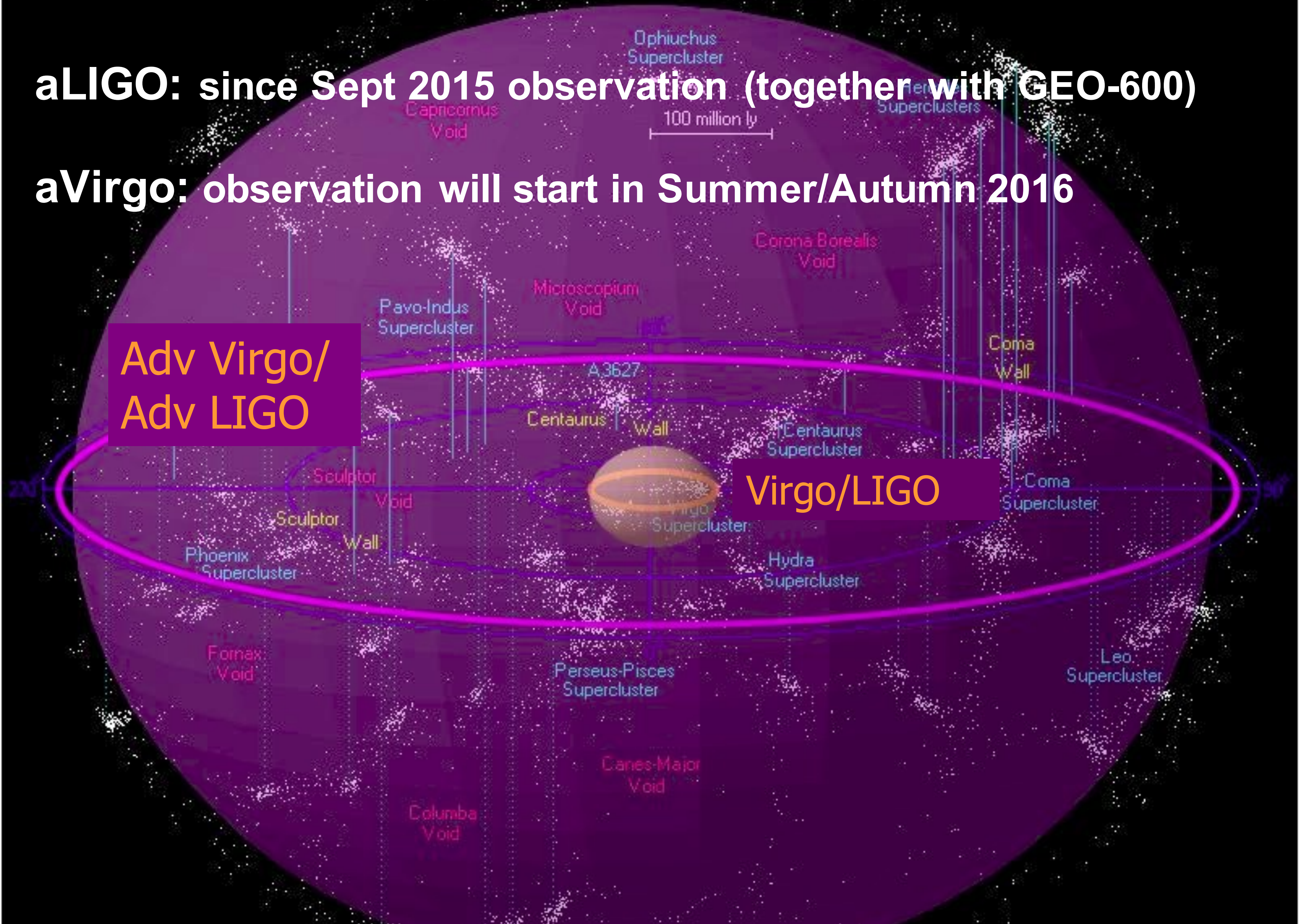


A few to ~ hundred of sources per year



aLIGO: since Sept 2015 observation (together with GEO-600)

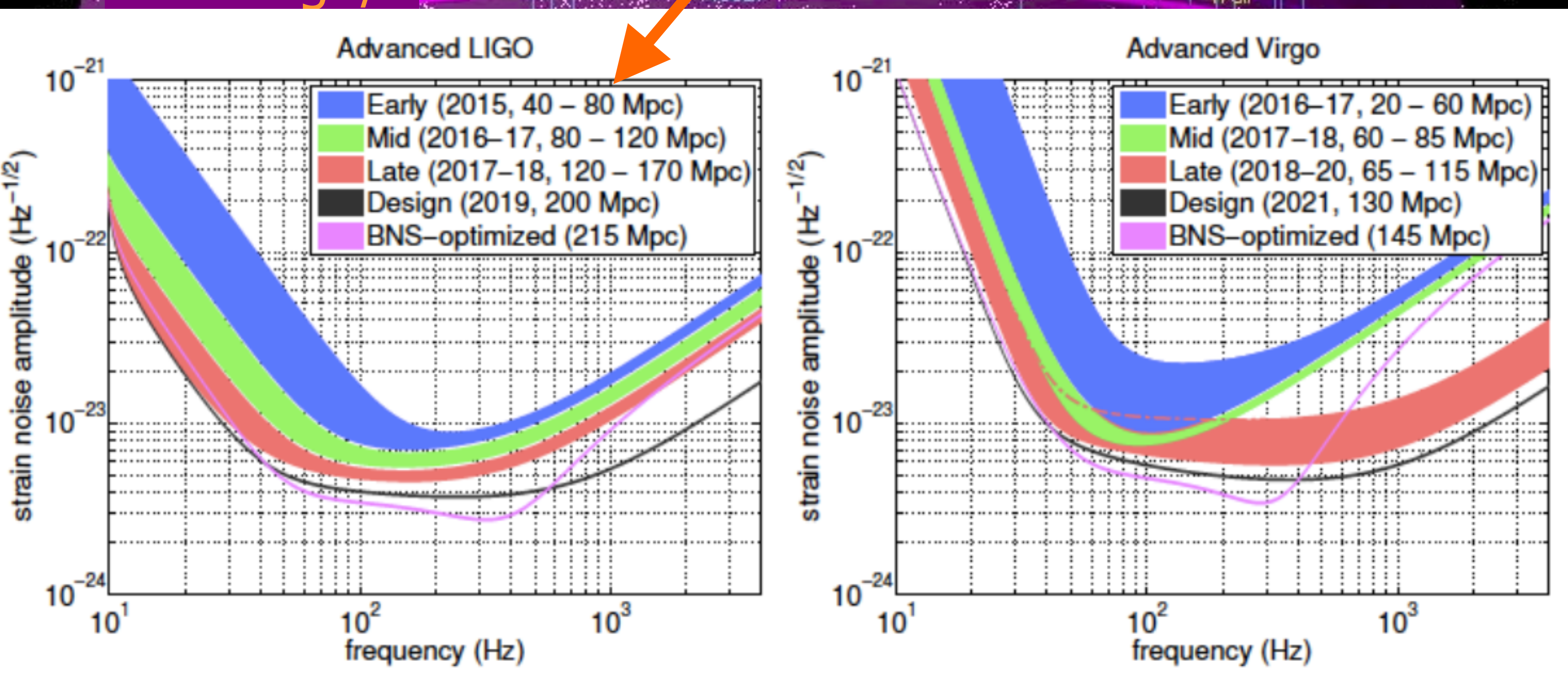
aVirgo: observation will start in Summer/Autumn 2016



aLIGO should reach 80 Mpc sensitivity for BH-BH mergers !

0.01-10 mergers per year

Adv Virgo/



And, luckily, it happened immediately

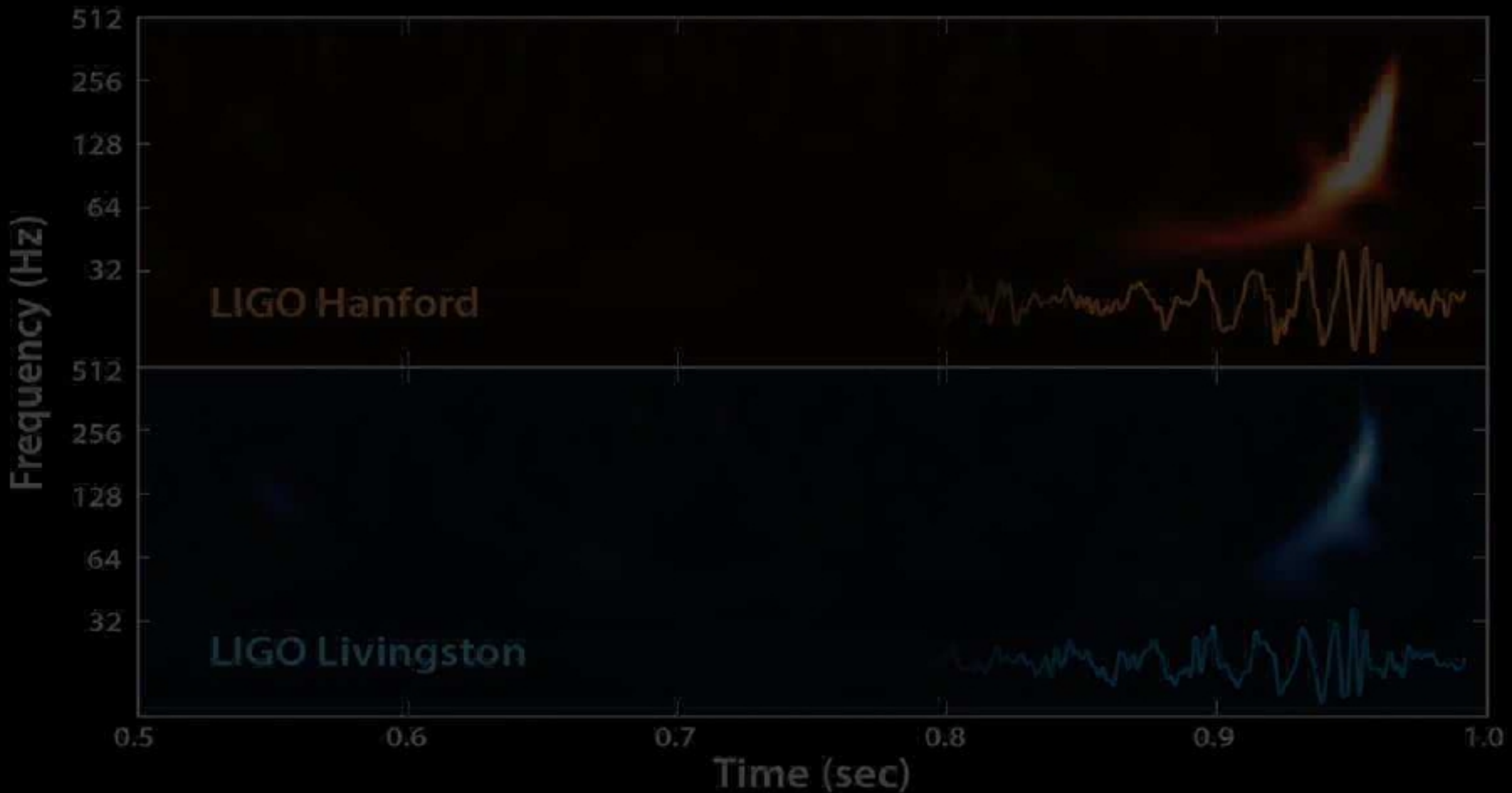
(after 100 years of General Relativity) !!!:

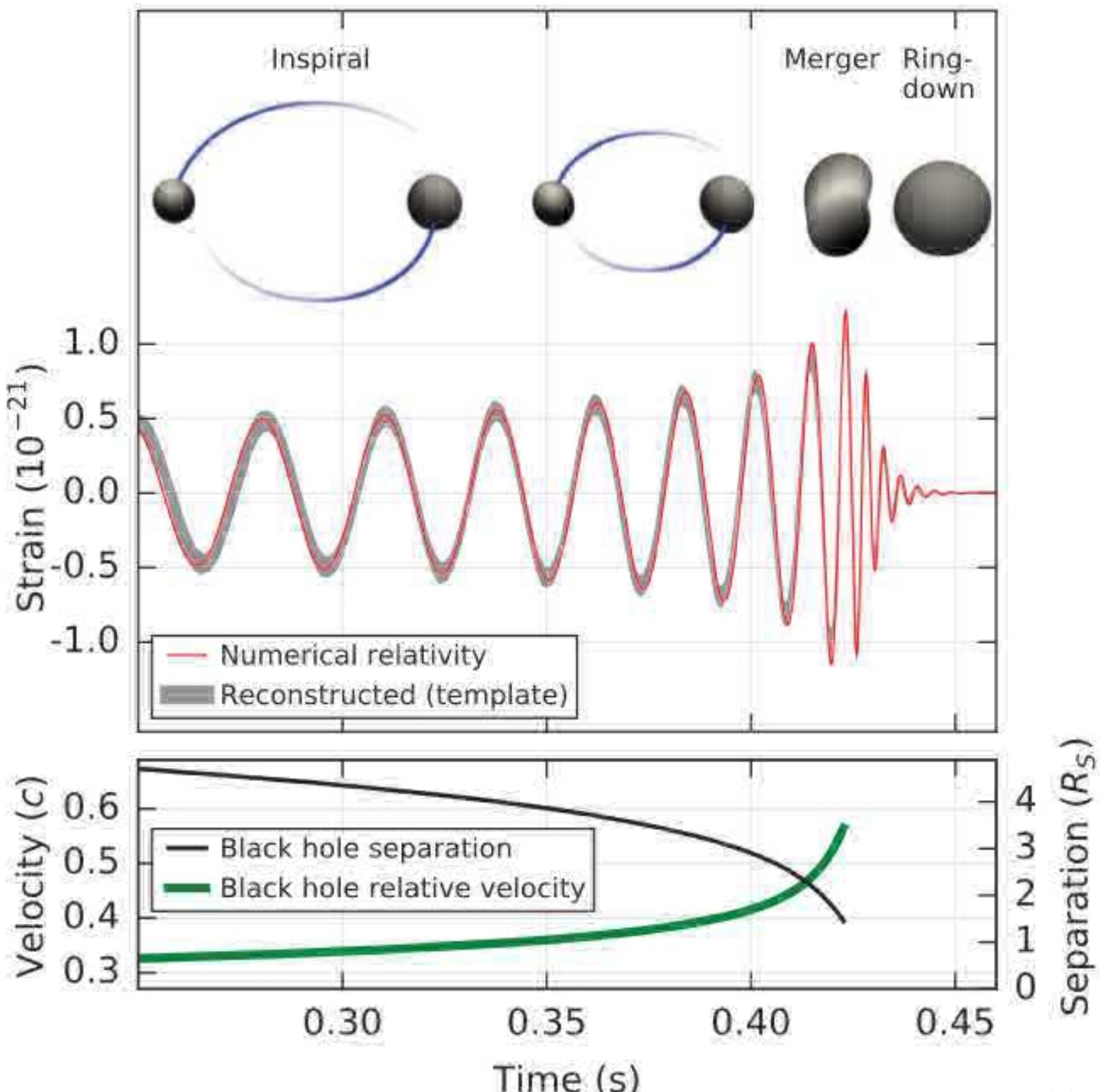
GW150914

The first direct detection of gravitational waves

The detection on Sep 14th, 2015

https://youtu.be/QyDcTbR-kEA

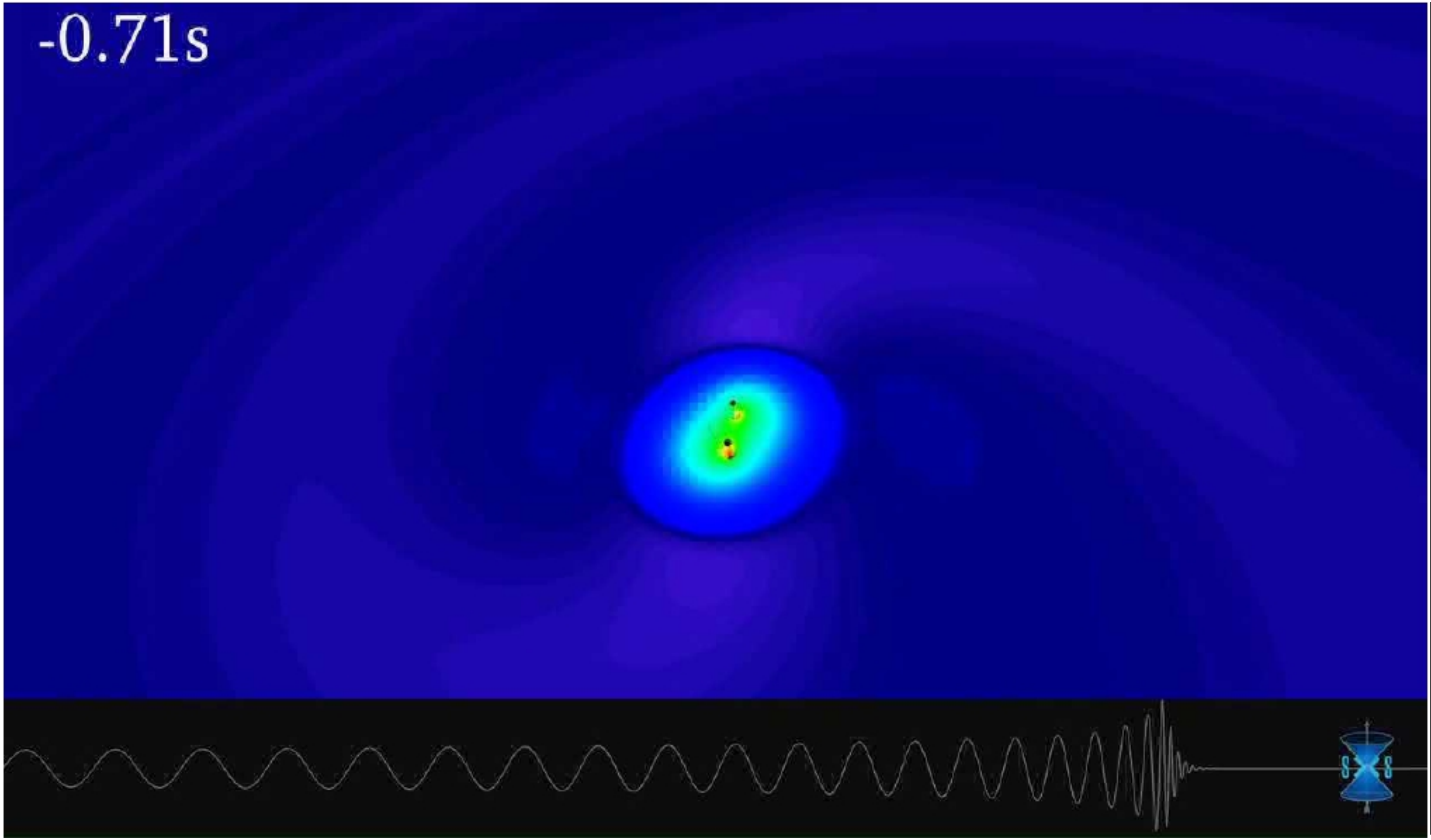




Abbott et al 2016

How does the merger look?

https://youtu.be/1agm33iEAuo



What is it?

- A binary black hole!

Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

A list of breakthroughs

- Detection of gravitational waves
- Detection of a black hole (?)
- Detection of black hole binary
- Evidence for BHs with masses of 30 and and up to 60 solar masses
- Possibility to test General Relativity
- The brightest source ever seen in the sky:

$$L_{GW} = 200^{+30}_{-20} \mathrm{M}_{\odot} s^{-1} = 3.6^{+0.5}_{-0.4} \times 10^{56} \mathrm{erg\ s}^{-1}$$

What after discoveries ?

First discoveries with LIGO (VIRGO) will impact

- R&D for further upgrades
- Detectors in India and Australia
- Search strategy for astrophysical sources & GW network strategy
- Worldwide funding situation for GW science

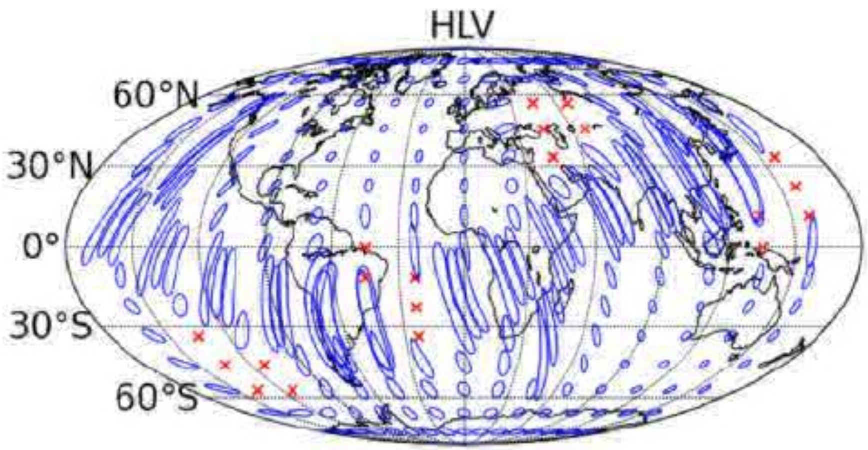
  … in particular

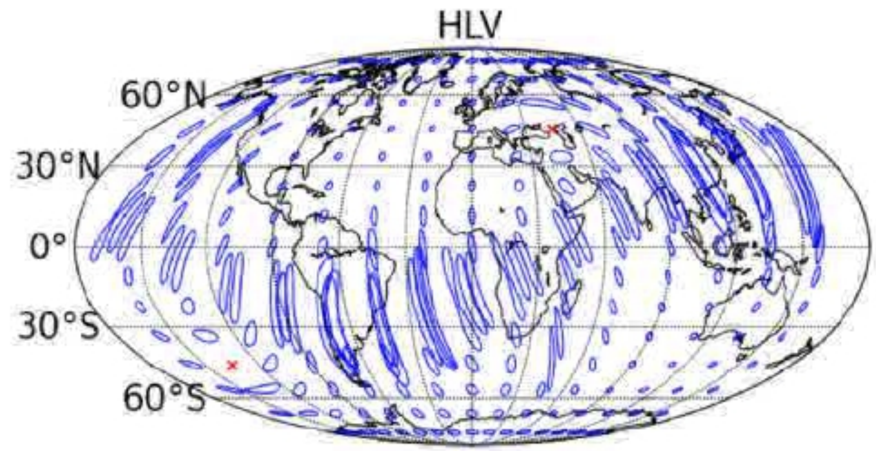
Einstein Telescope (ET)

eLISA

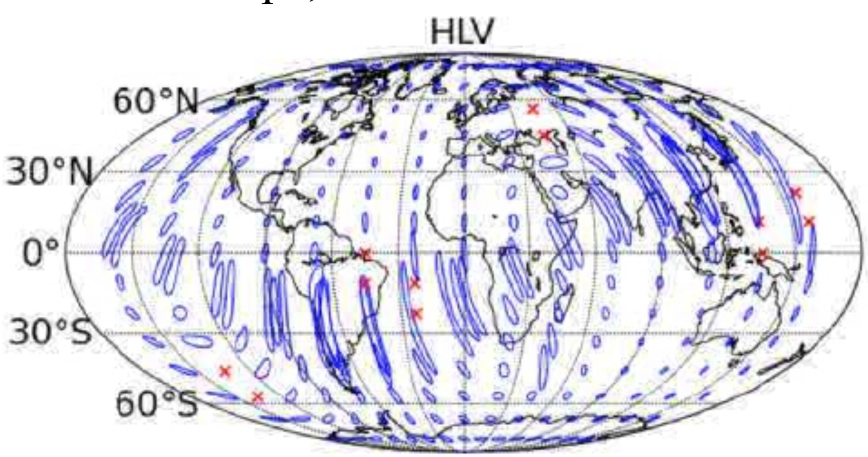
Expected sky localizations

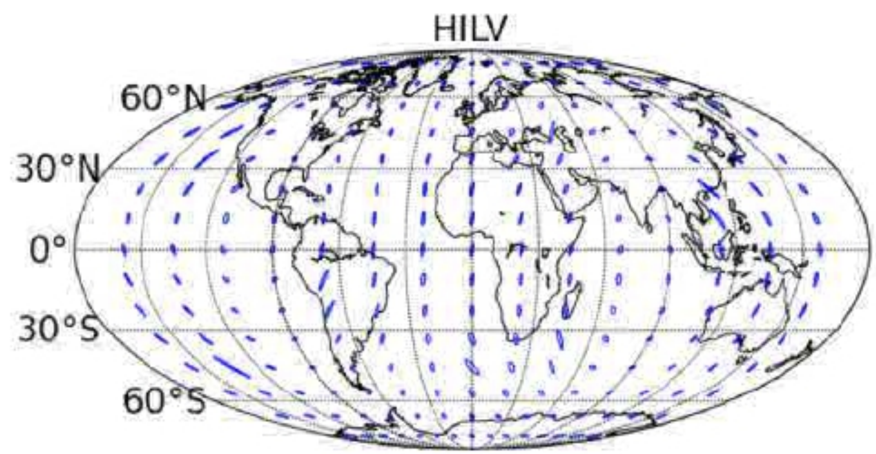
BNS at 80Mpc 2017 2019





BNS at 160Mpc, 2019+



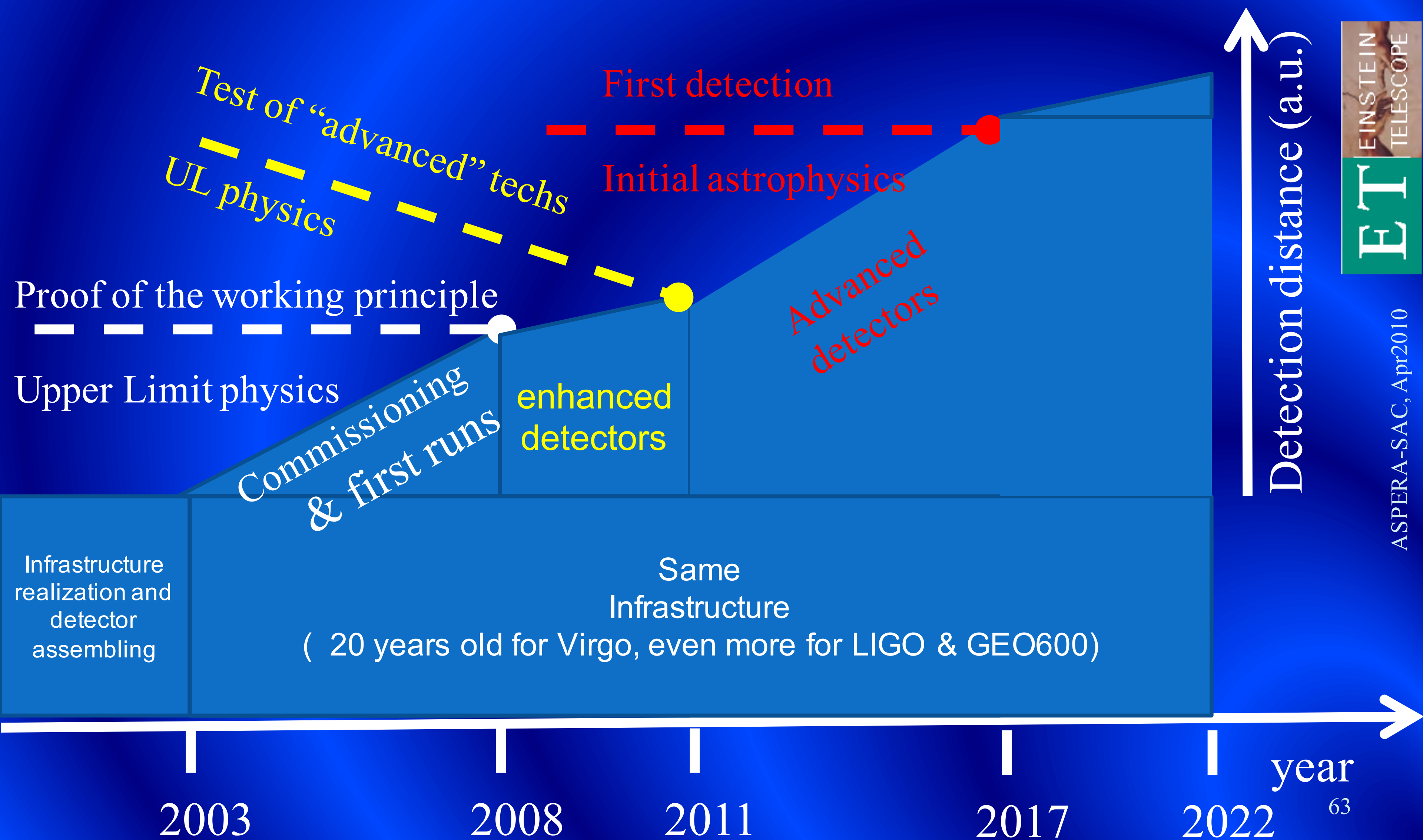


Typical errorbox size – 10 deg square

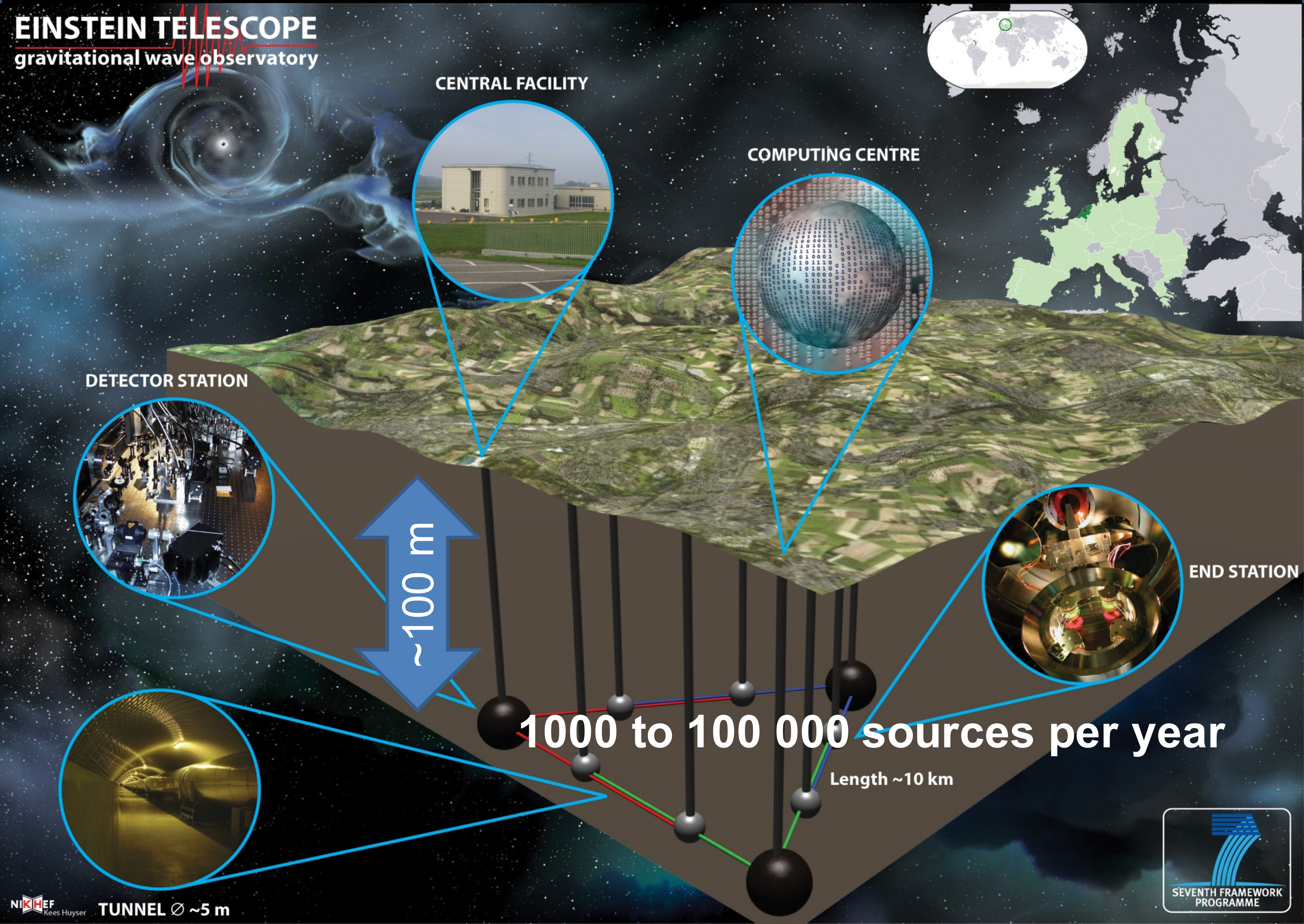
The GW network in 4-5 years

3rd generation: Why ?

- Evolution of the GW detectors (Virgo example):



> 2025


EINSTEIN TELESCOPE
gravitational wave observatory
CENTRAL FACILITY
COMPUTING CENTRE
DETECTOR STATION
END STATION
~100 m
1000 to 100 000 sources per year
Length ~10 km
TUNNEL ∅ ~5 m
NIKHEF
Kees Huyser
SEVENTH FRAMEWORK PROGRAMME

LISA

Lisa Pathfinder reached LP at January 22

Testrun started in March 3

eLISA 2034

(just a funding question, technically it could start 2028)