(Very/Ultra) High Energy Astrophysics
IV – Multi-Messenger Astronomy

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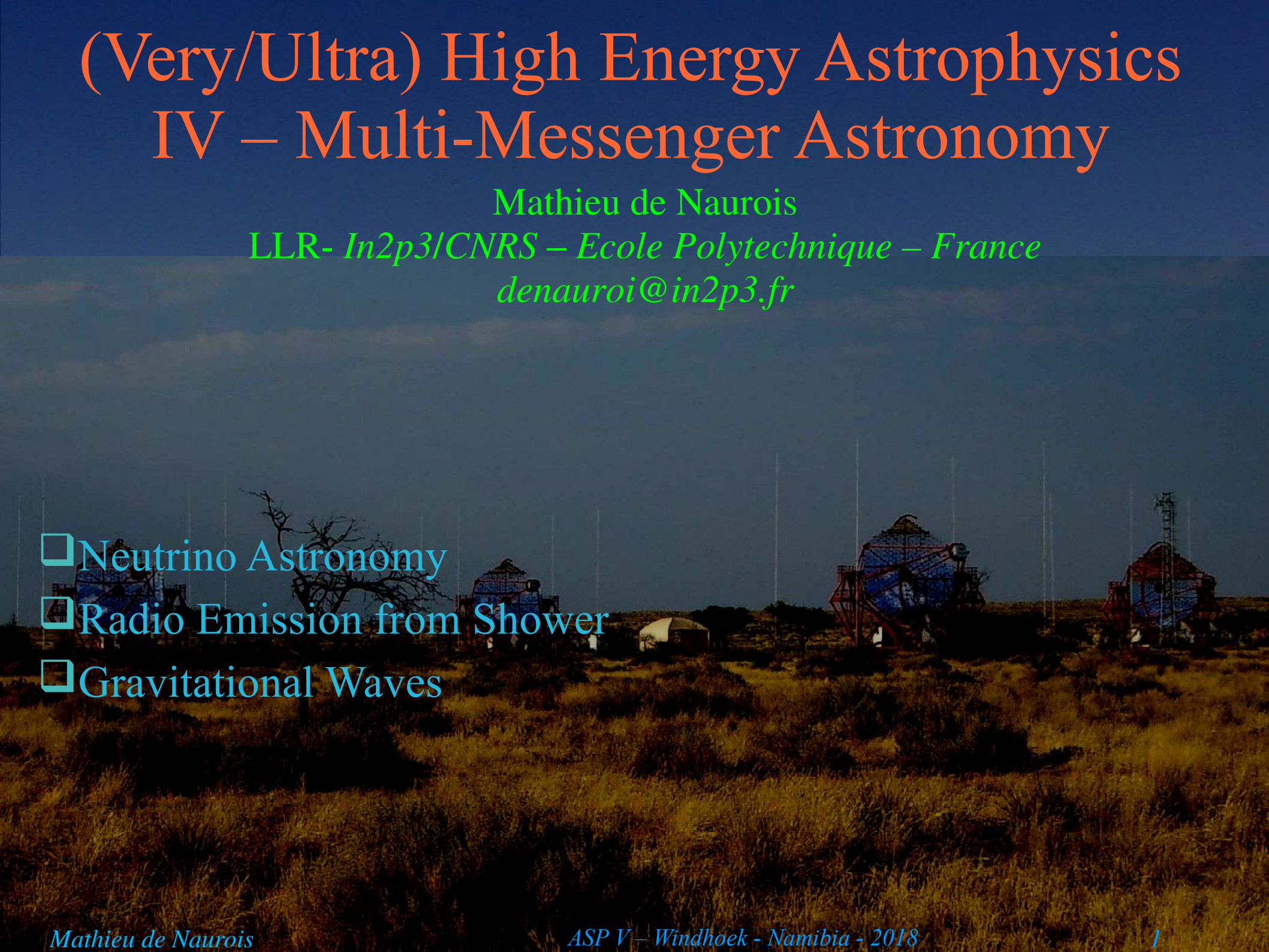
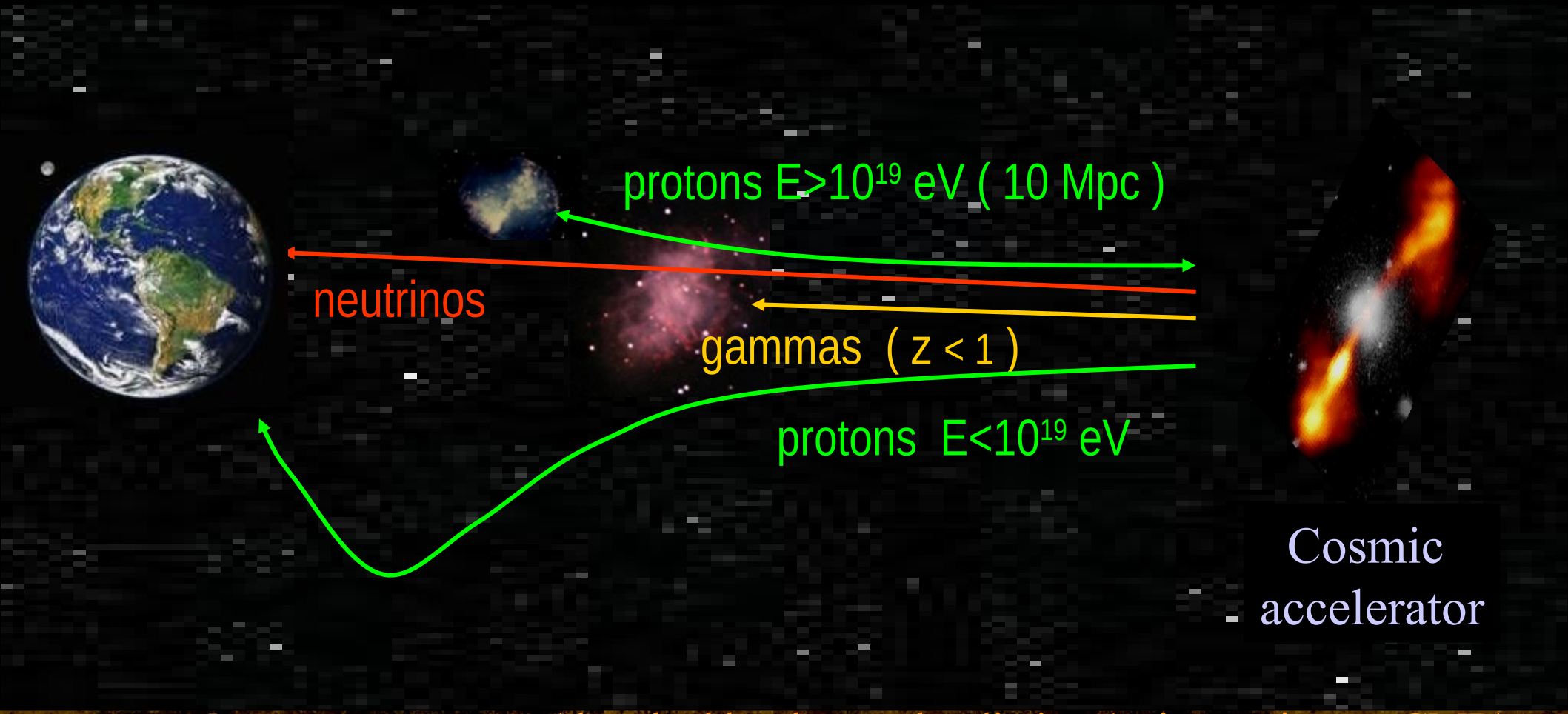


- Neutrino Astronomy
- Radio Emission from Shower
- Gravitational Waves

Multi-messenger observations of the Cosmos



photons: Absorbed by dust and radiation (pair creation on CMB)

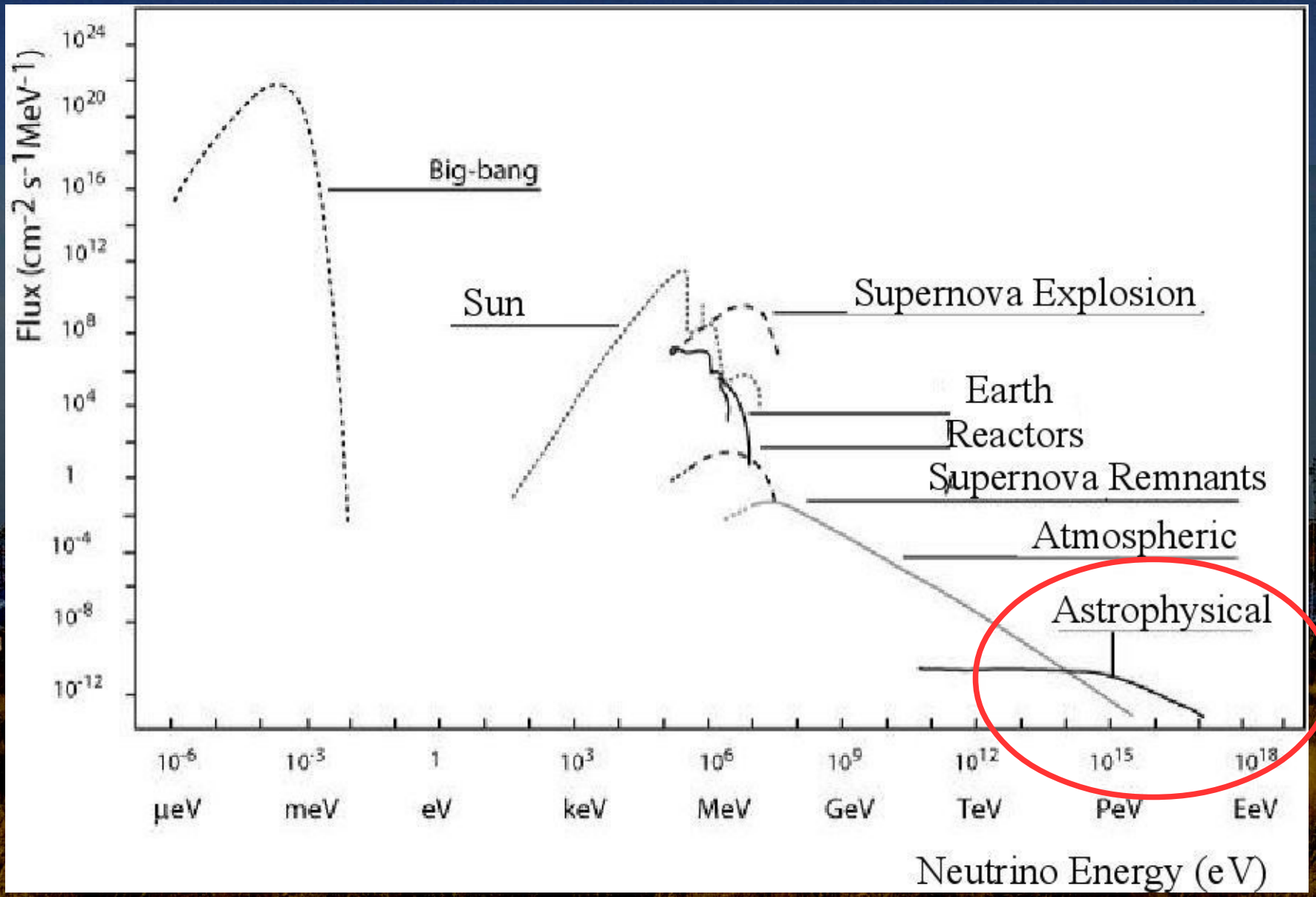
protons/nuclei: Deviated by B field, absorbed by CMB (GZK effect)

neutrinos: Difficult to detect

⇒ **Three "astronomies" possible...**


Neutrinos

Flux of cosmic neutrinos

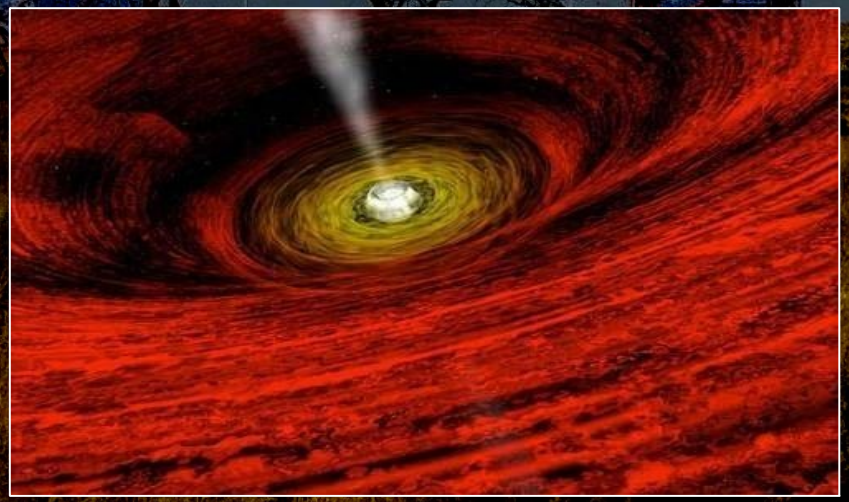


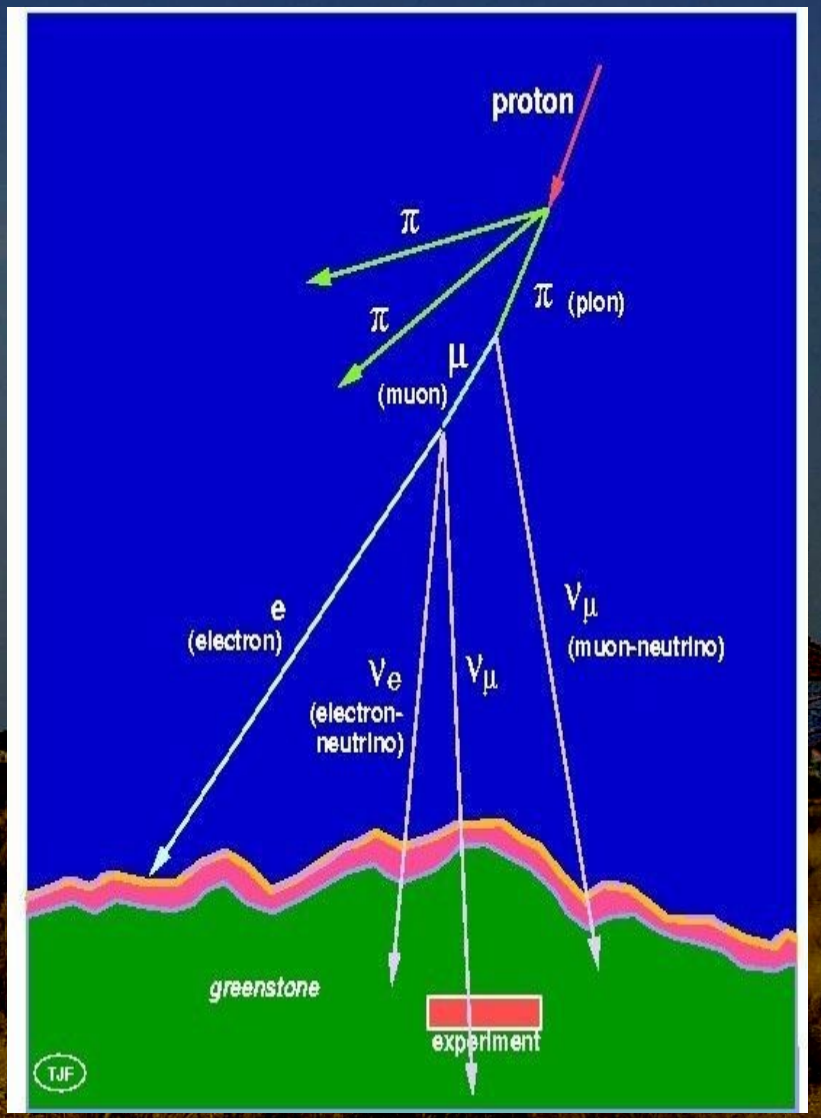
High Energy Neutrinos

- Atmospheric neutrinos
  - Neutrinos produced in hadronic showers

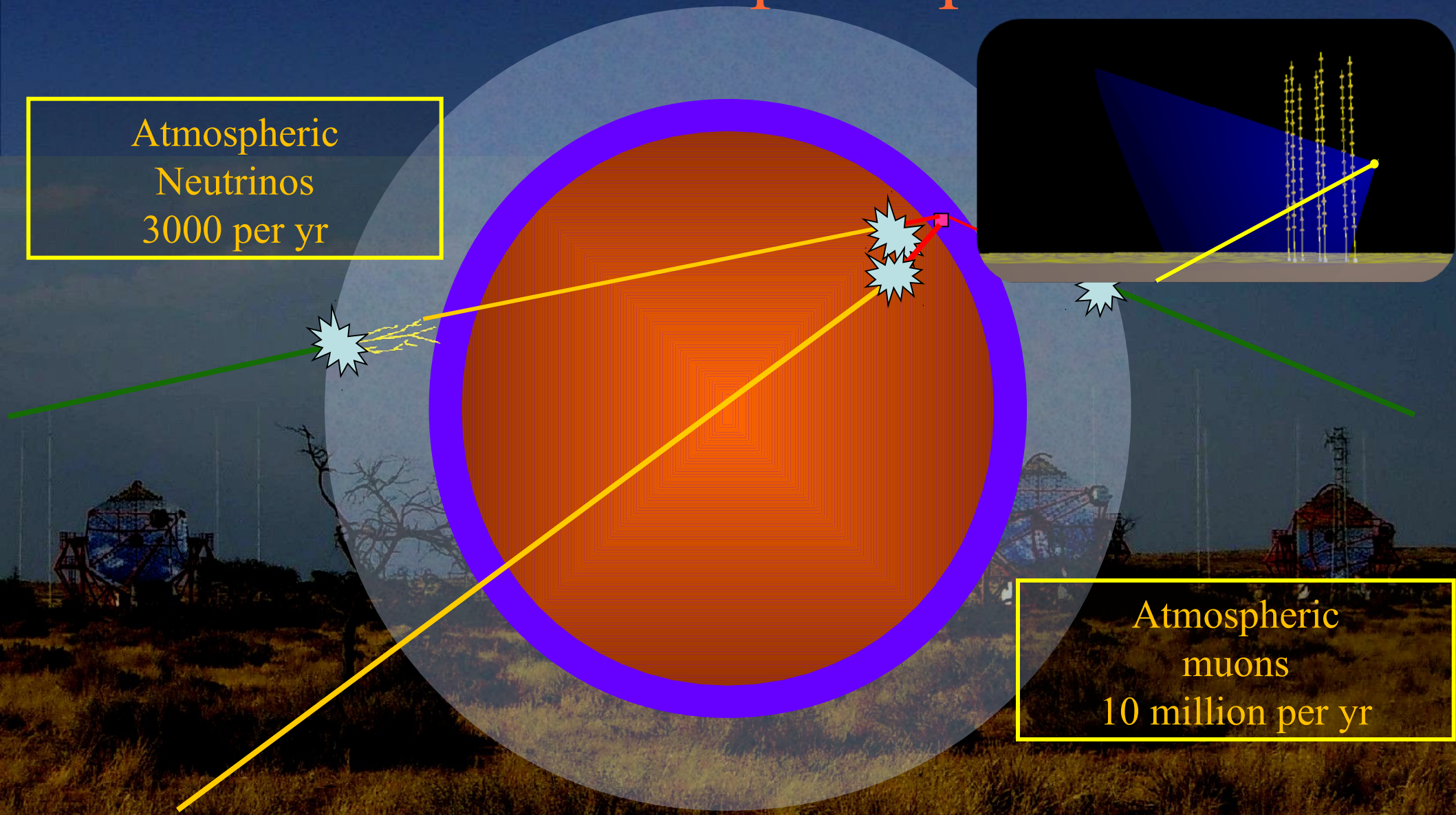
$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu \rightarrow e^- \bar{\nu}_e \nu_\mu \bar{\nu}_\mu$$

  - Ratio $\nu_\mu / \nu_e \sim 2$
- Astrophysical neutrinos (AGN, GRB, SNRs, ...)



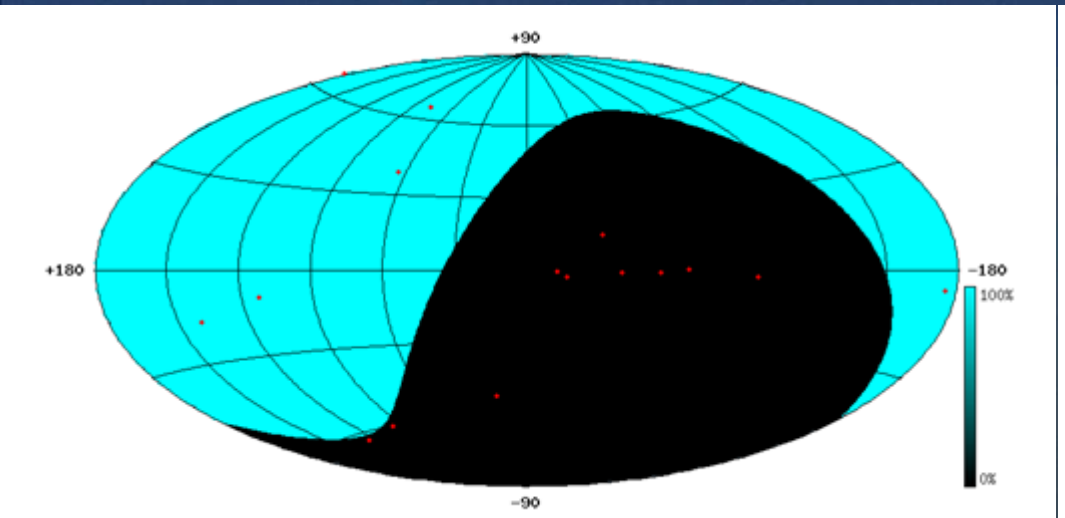


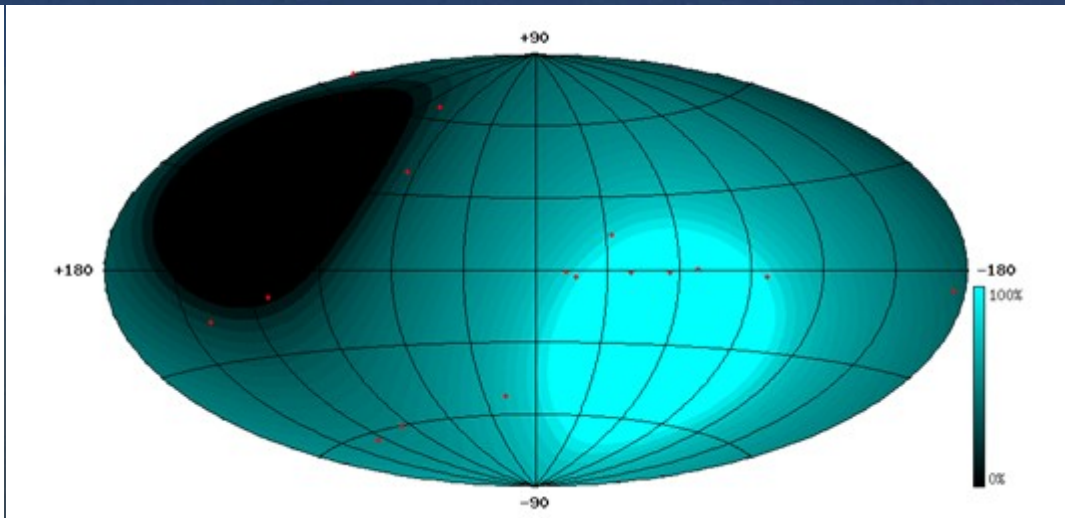
Detection principle

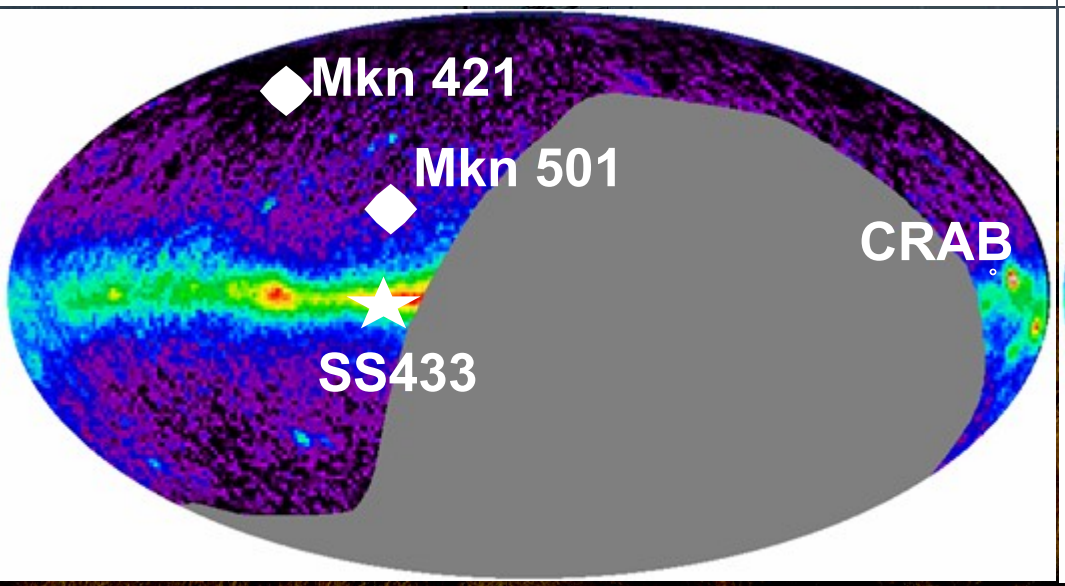


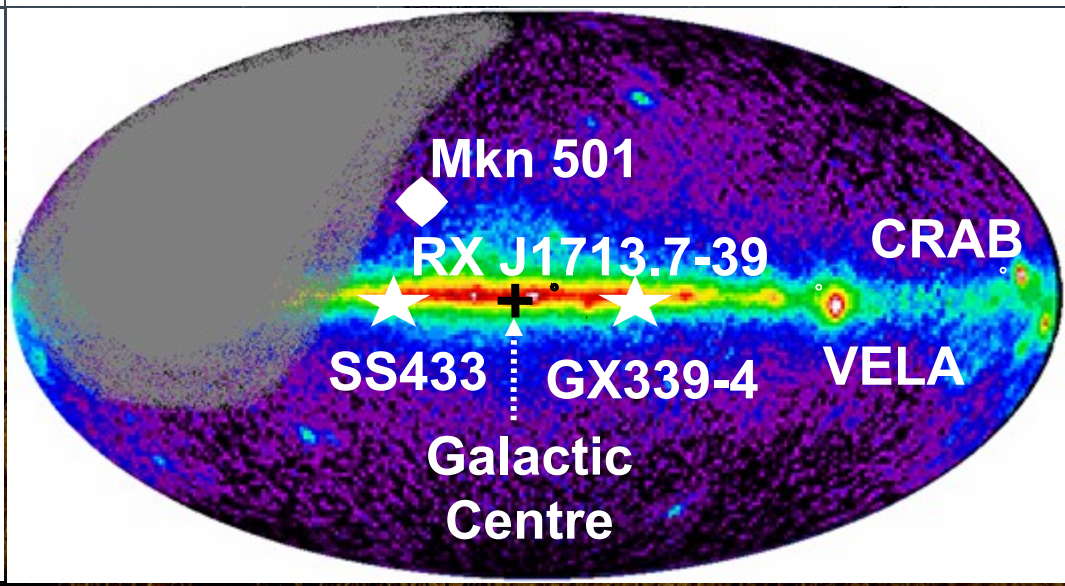
High Energy Neutrino Sky

AMANDA (South Pole) **ANTARES (43° North)**









+ Baikal, Nemo, Nestor

Comparison of media

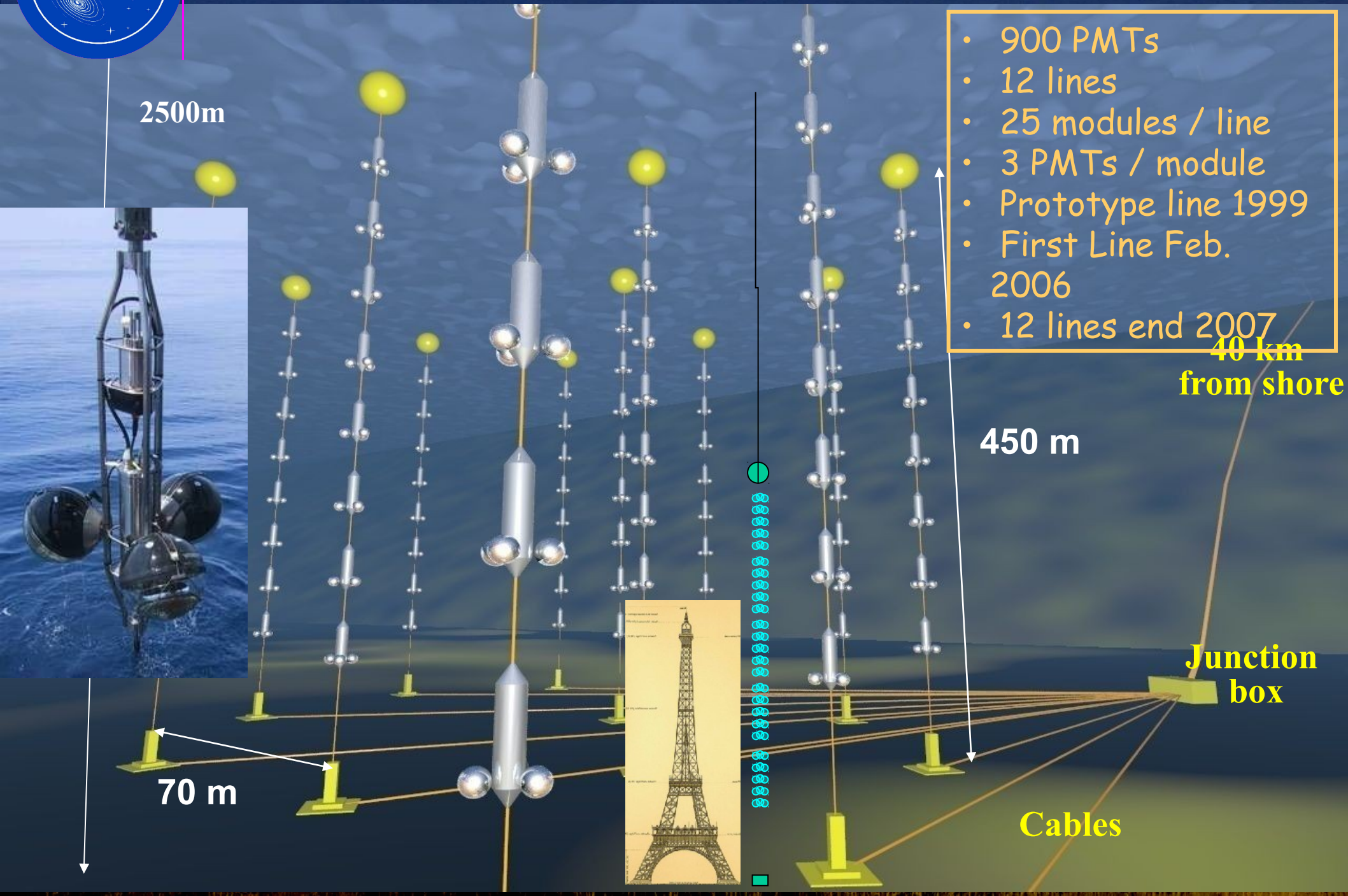
ICE

- Stable, easy drilling
- ~350 Hz noise (40K), sterile
- Large absorption length ~100 m
- Low diffusion length 20-25 m (degraded angular resolution)
- Max Depth 2500 m

WATER

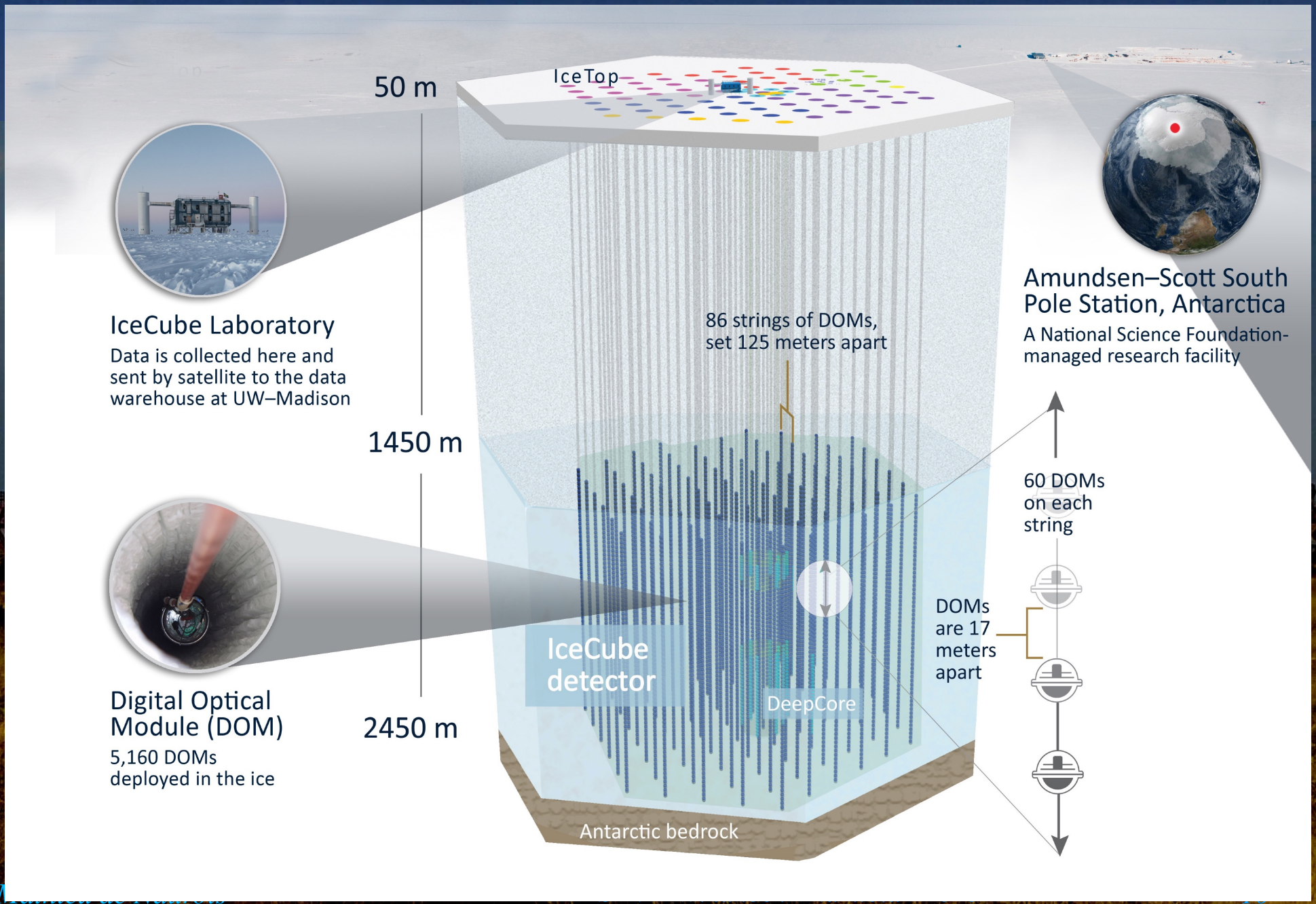
- High pressure, corroding
- 30-60 kHz noise, bioluminescence
- Low absorption length 25-60 m
- Large diffusion length >100 m
- Max Depth 3800 m

Antares



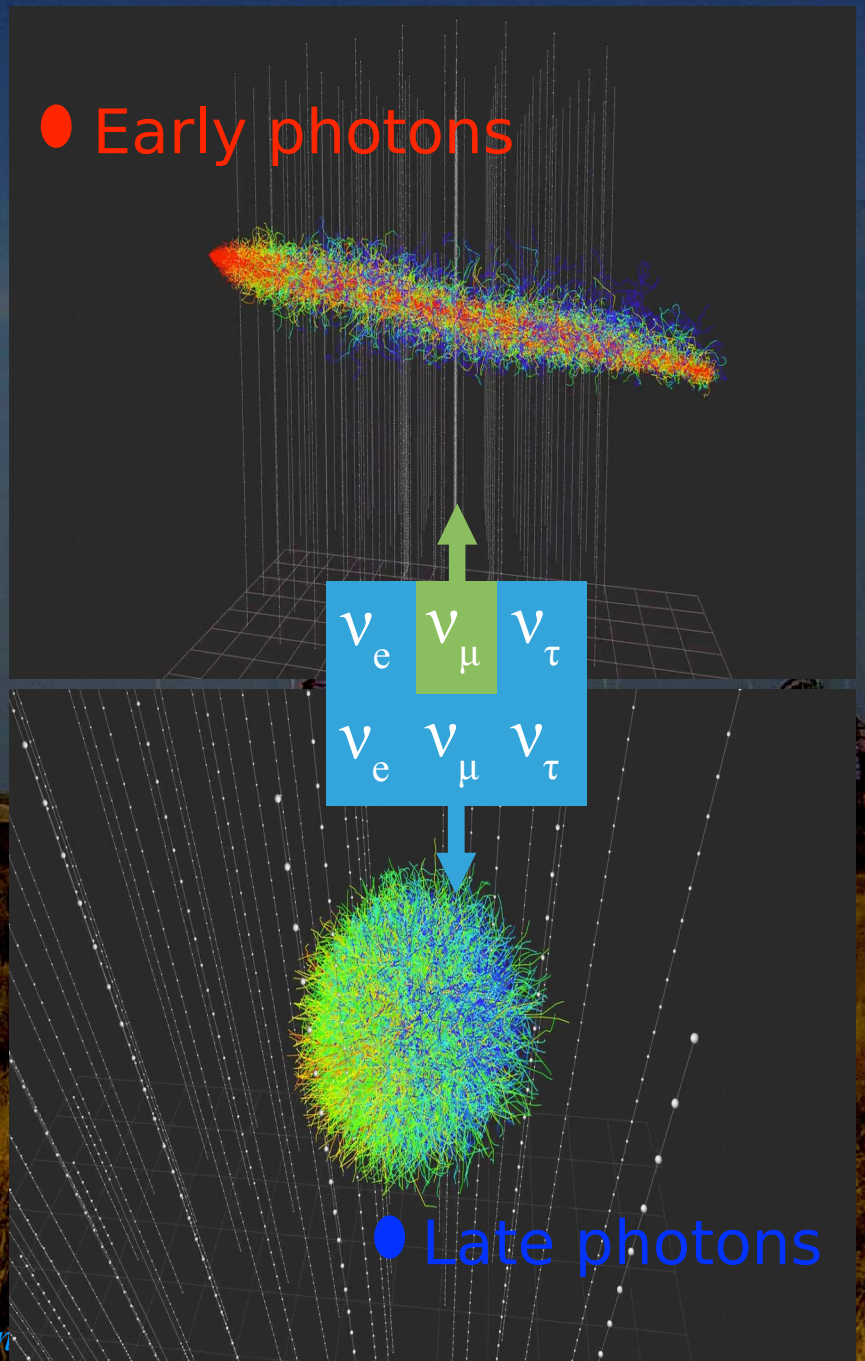
- 900 PMTs
- 12 lines
- 25 modules / line
- 3 PMTs / module
- Prototype line 1999
- First Line Feb. 2006
- 12 lines end 2007

Ice Cube


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

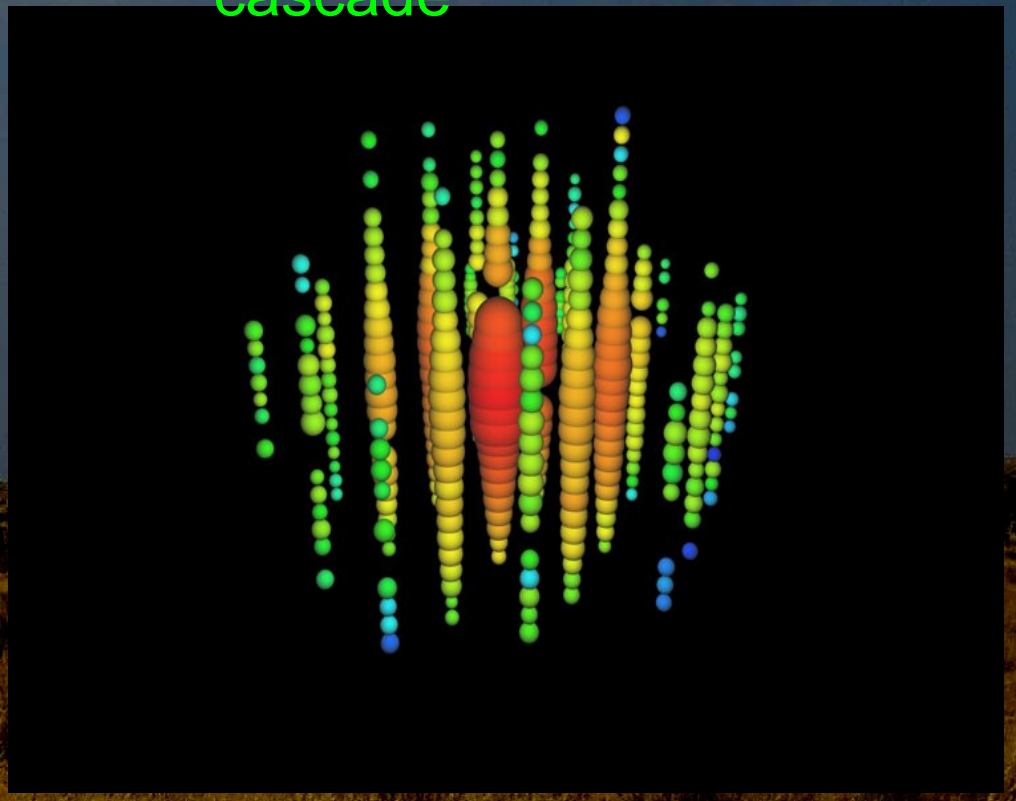
Signatures

- "Track" events
  - Only ν_μ
  - Good angular resolution ($\leq 1°$)
    → Neutrino astronomy
  - Vertex outside detector
    → Bad energy resolution
- "Shower" events
  - All flavours
  - Bad angular resolution (~10°)
  - But fully calorimetric
    → Energy Resolution ~ 15%



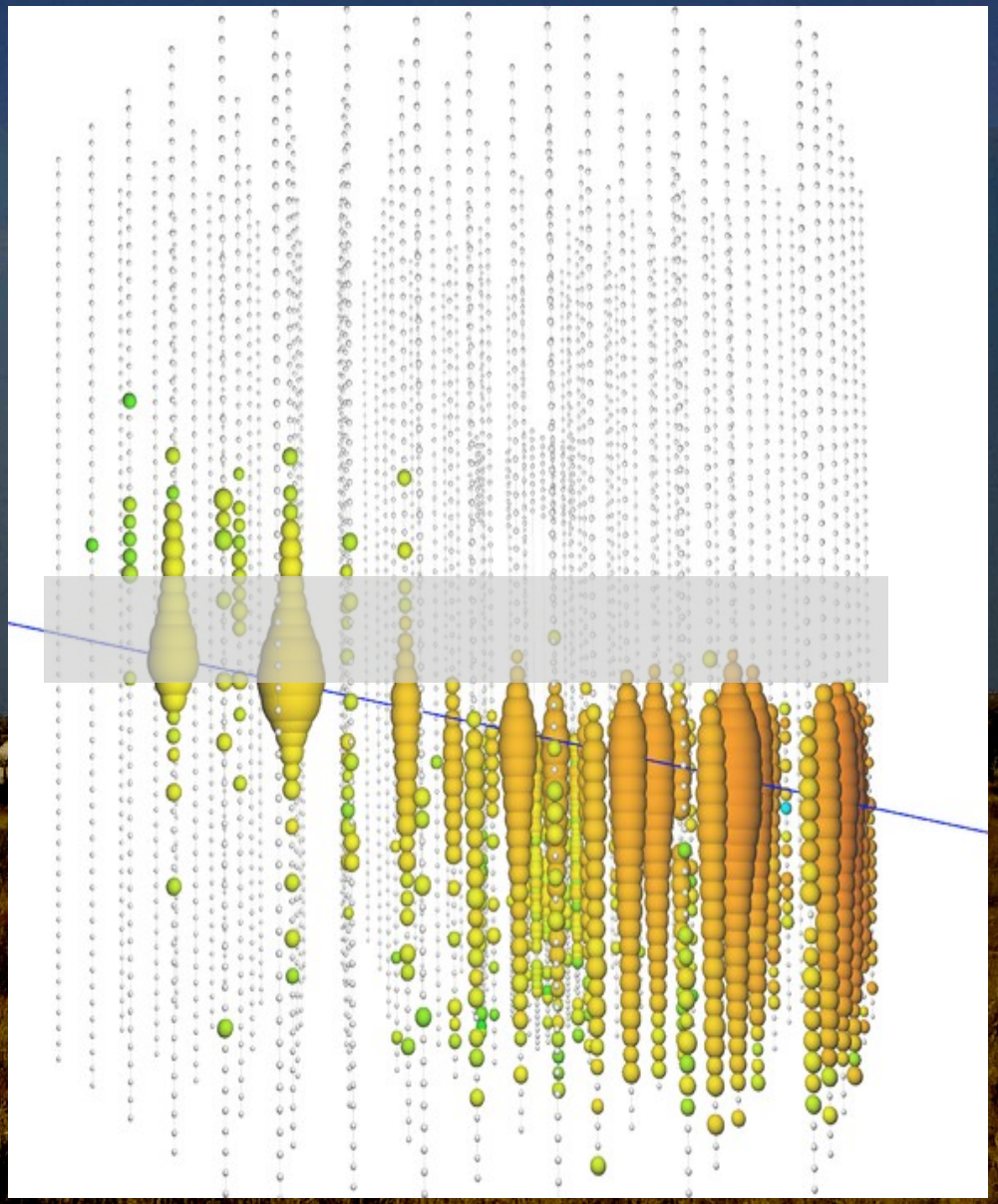
PeV neutrinos

- Summer 2012: 2 PeV neutrinos announced (Bert and Ernie)
- 1.04 ± 0.16 and 1.14 ± 0.17 PeV
- 2.8 sigma above expected atmospheric background
- First indication of astrophysical neutrinos
- gamma-ray burst appear as good candidates
- AGN could also
- GZK neutrinos should be at higher energies
- 3rd event detected November 27, 2013



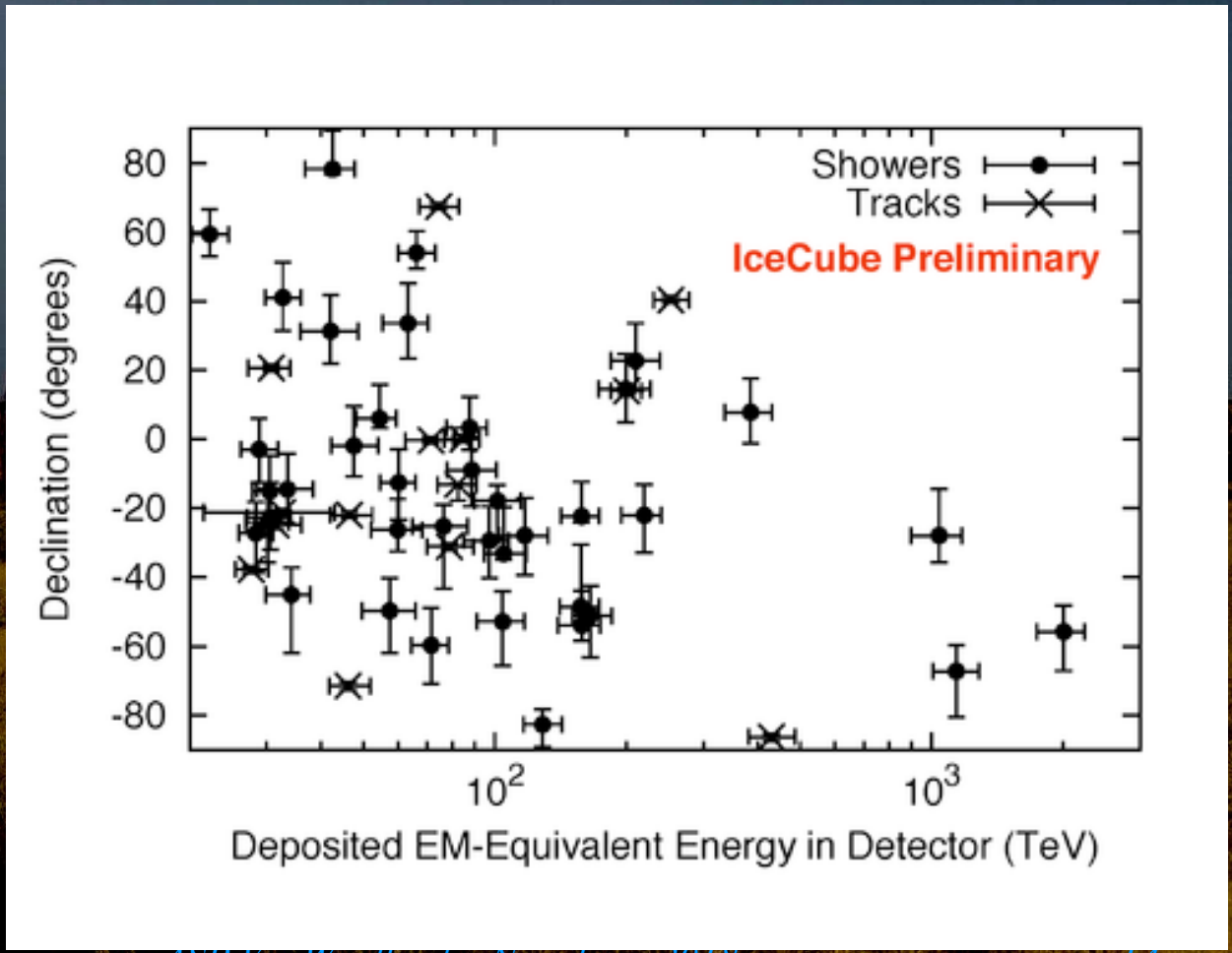
PeV Track Event

- Multi-PeV track event
  - June 11, 2014
  - deposited energy: 2.6±0.3 PeV
  - No counterpart found



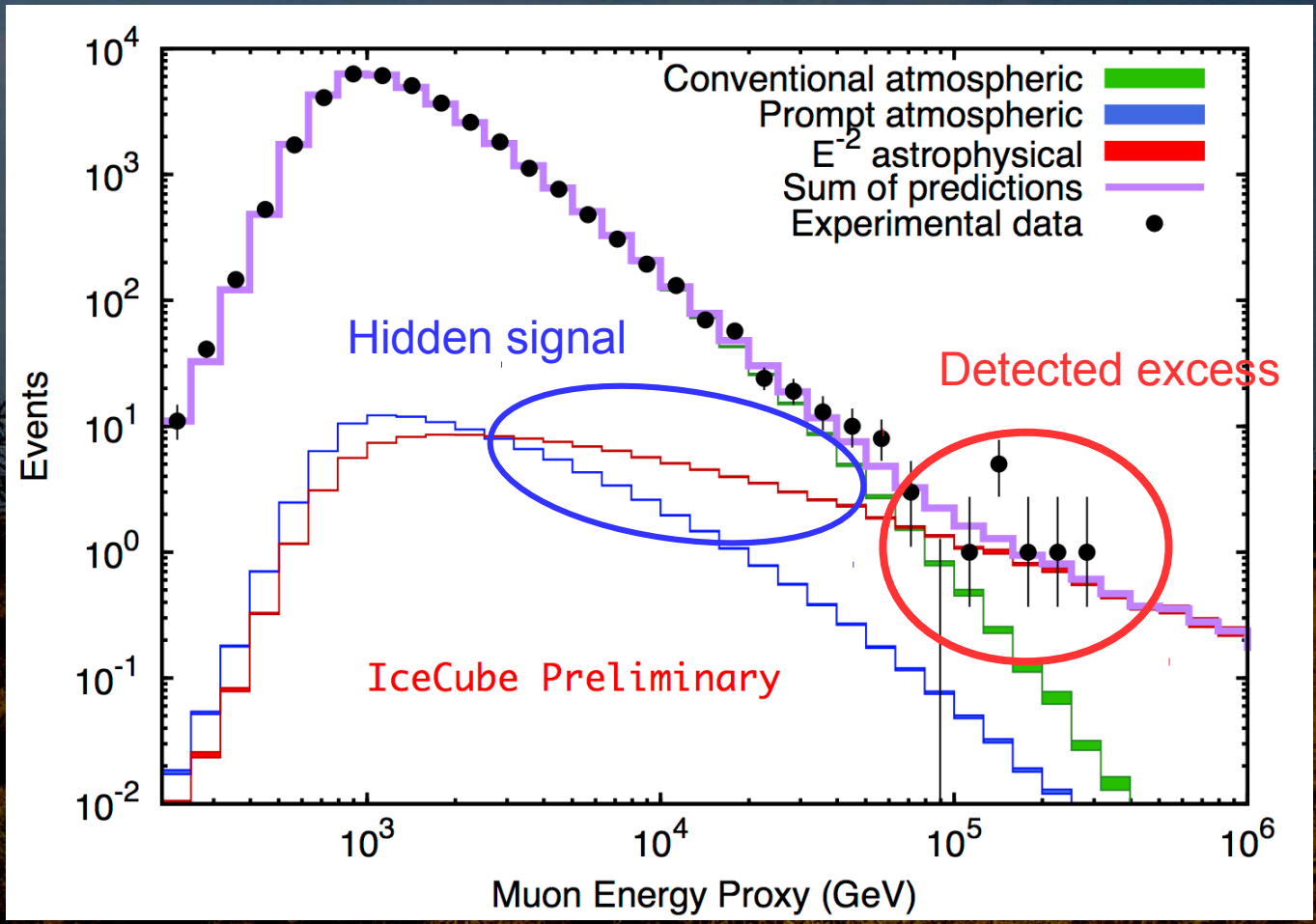
Multi-TeV neutrinos

- 53 TeV neutrinos detected (above ~ 30 TeV)
- Expected background:
  - 9 atmo. υ
  - 12 atmo. μ
- 6.5 σ evidence for astrophysical neutrinos! (2016)



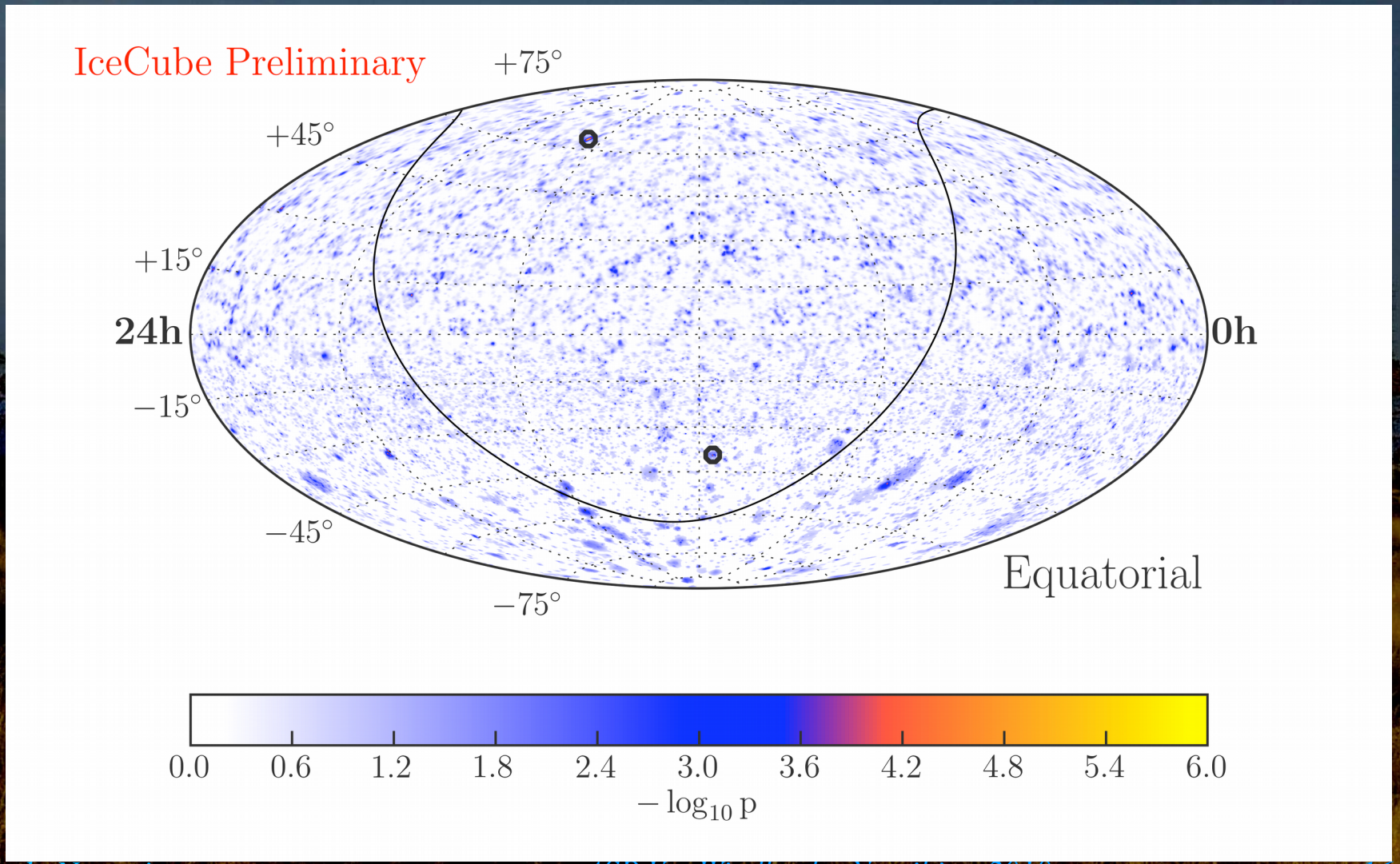
Astrophysical Neutrinos

- Tons of astrophysical neutrinos hidden by the background below ~ 60 TeV



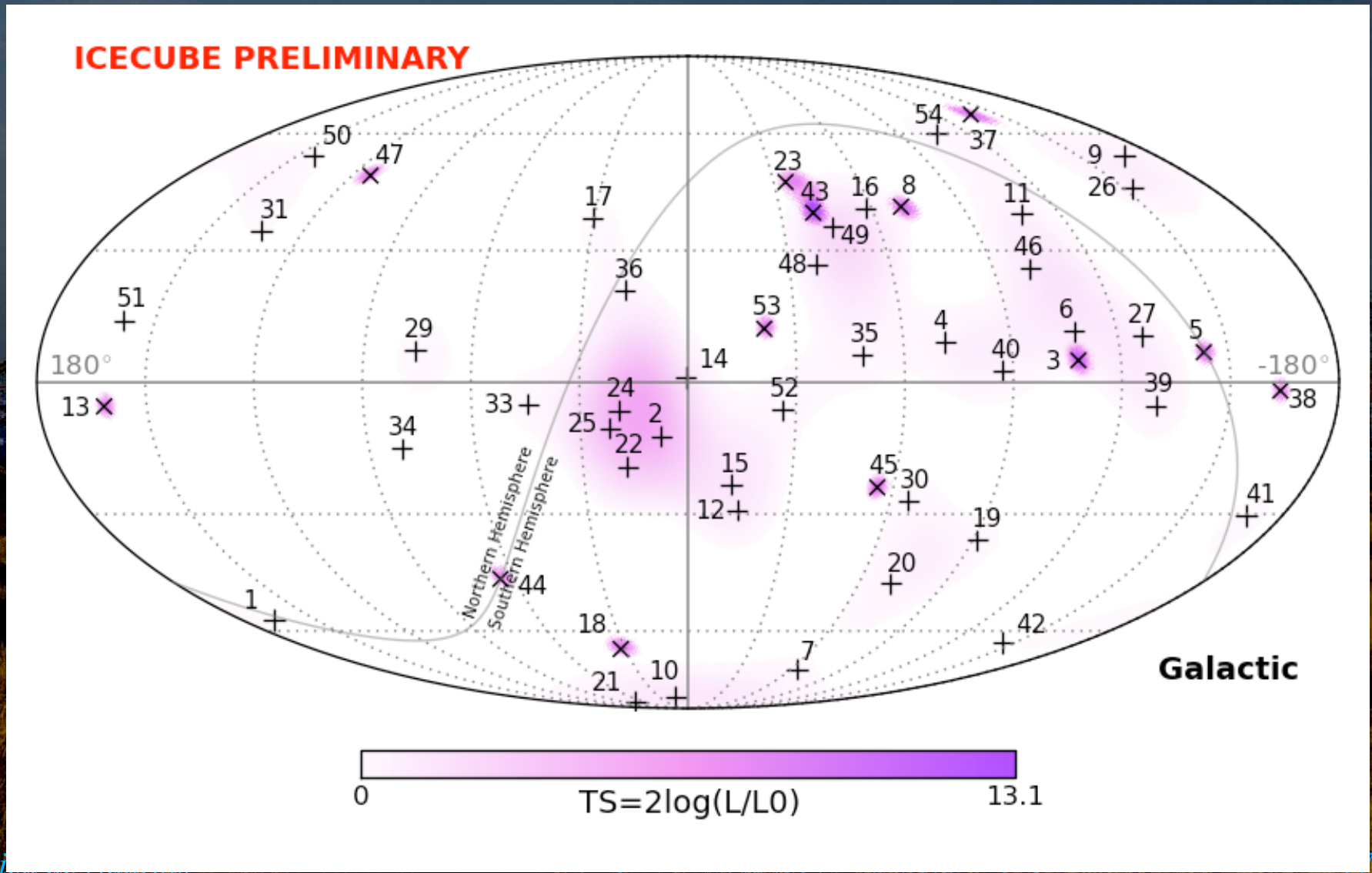
Sources

- Full data sample: no evidence for sources



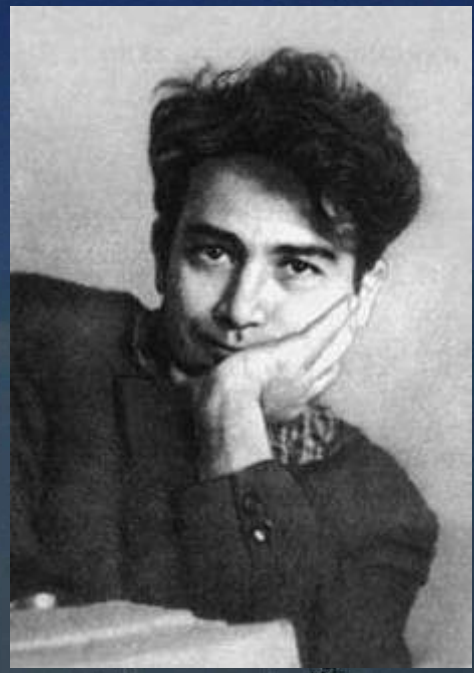
Sources

- High Energy: vague indication of clustering toward Gal. Centre

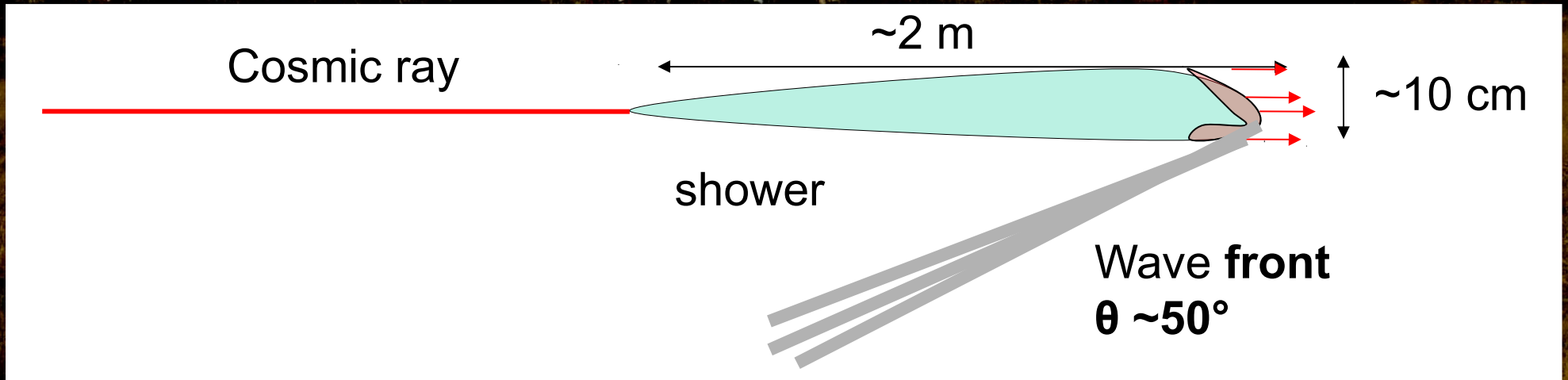


Radio detection

Askaryan Effet (1928-1997)

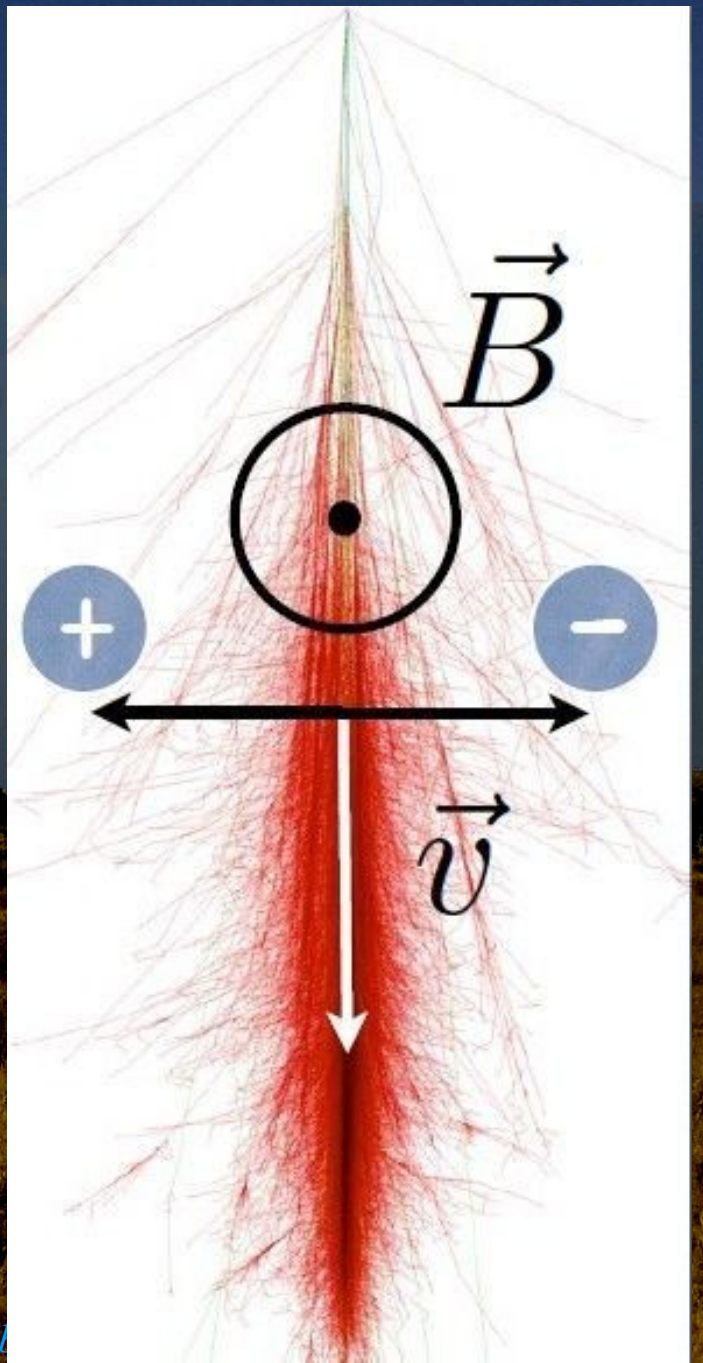


- Small e+/e- asymmetry in showers:
  - Positron Annihilation
  - Compton scattering
- Coherent Cherenkov forward emission, (2~5 GHz), emitted in matter (ice, salt, rocks) showers
- Confirmed in 2000 at SLAC
- Well adapted for neutrinos (emerging shower)
- Many experiments: FORTE, RICE, SALSA, GLUE



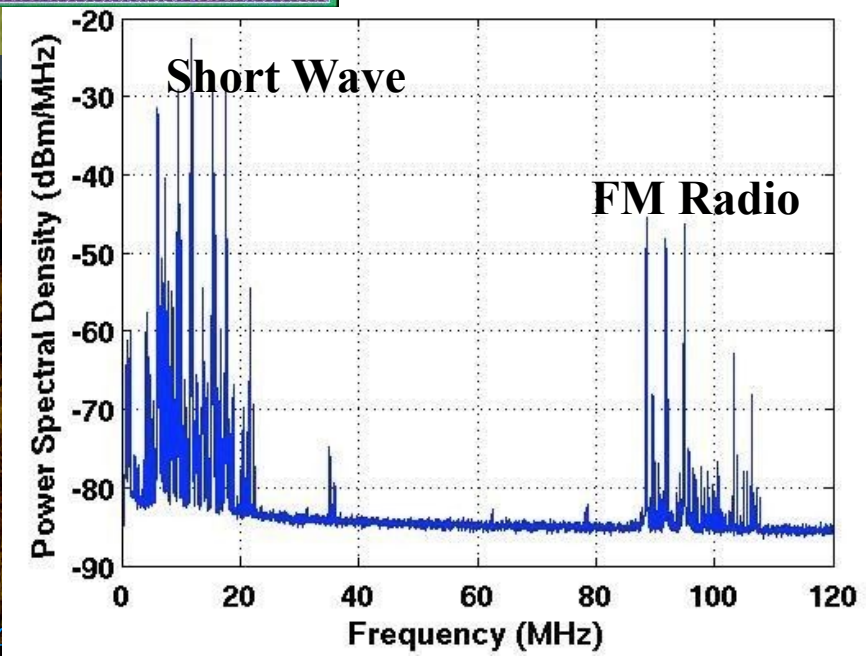
Sources of radio emission

- Charge excess in relativistic motion
- Geomagnetic effect:
  - Earth magnetic fields separates electrons and positrons apart
  - Dipole in relativistic motion...
- Synchrotron emission of electrons
- Emission from the current
- ...
- Frequency band [1-200] MHz
  - Noise from human activities
- Complex morphology of signal
- By ~calorimetric



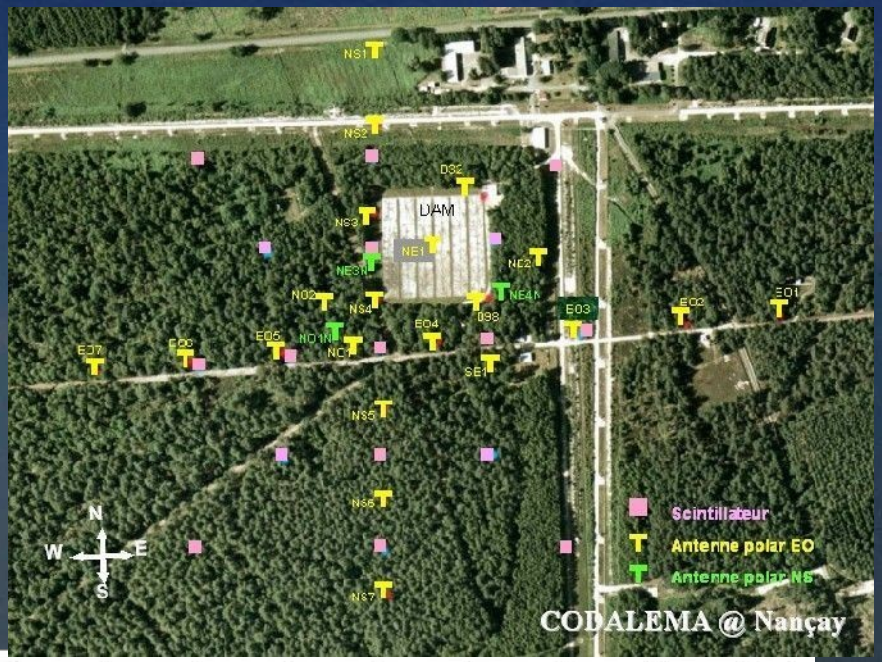
Why is radio interesting ?

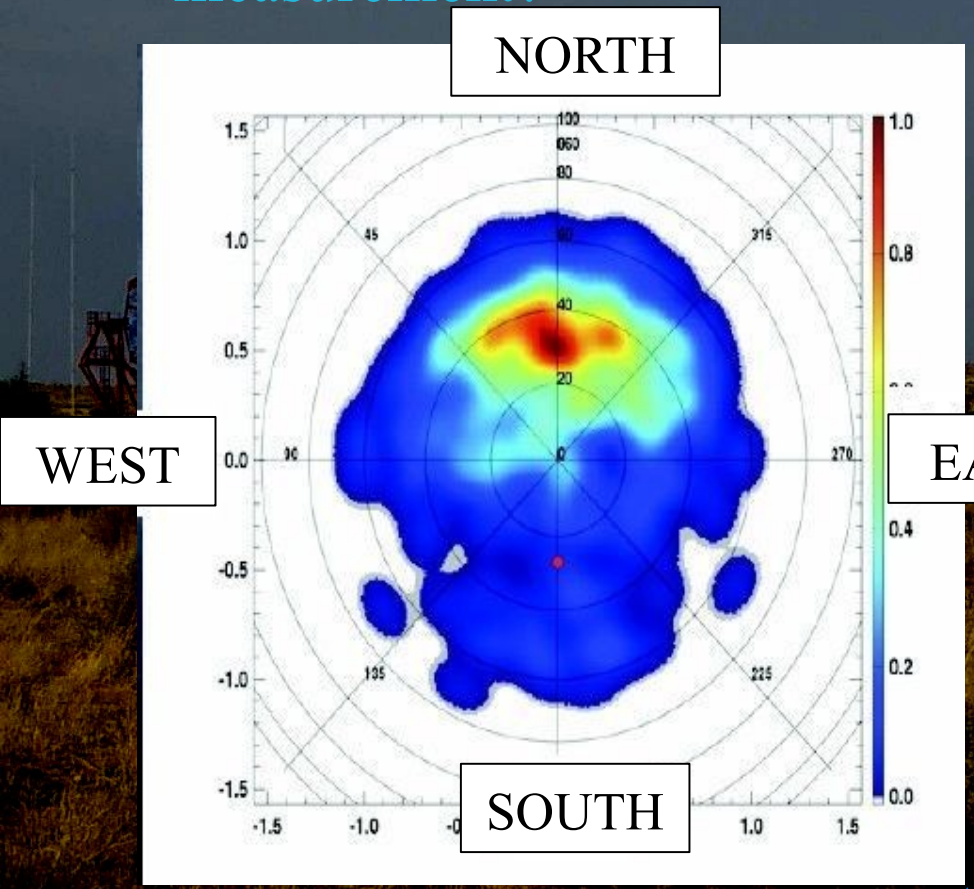
- Pretty inexpensive equipment
  - Active Dipolar antenna
    ~1 m × 10 cm
    Frequency band [1-200] MHz
  - Low noise amplifier (ASIC)
  - Fast ADC (300 MHz)
  - Cost ~ 4000 Euros
- Duty cycle ~100 %
- Efficiency ~100 %
- Calorimetric Measurement
- Timing and lateral distribution allow reconstruction of shower
- 25 – 85 MHz region pretty empty

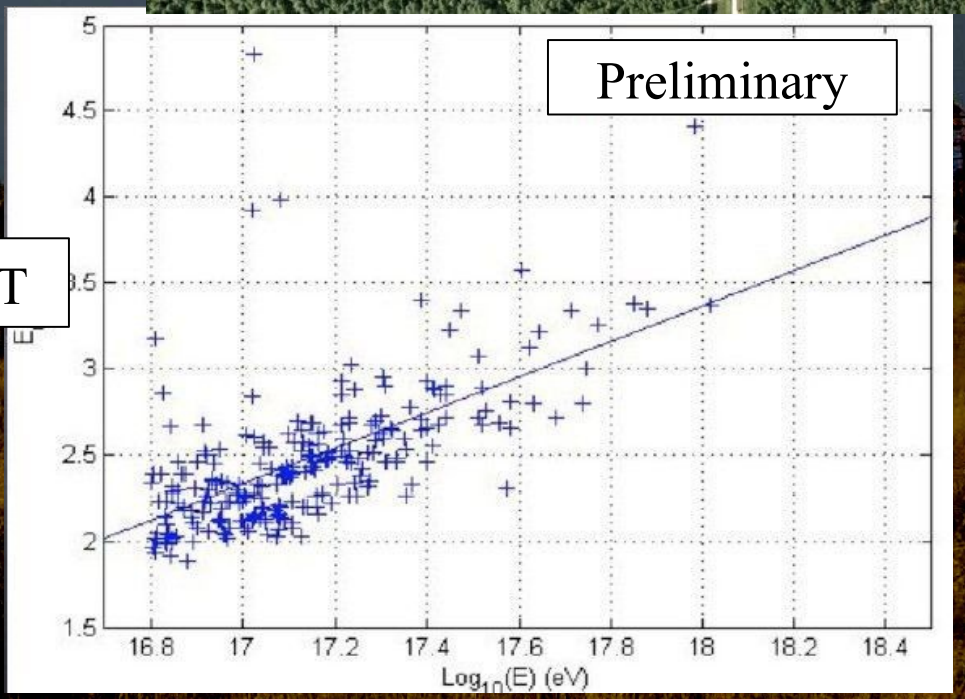


Radio detection of showers: CODALEMA

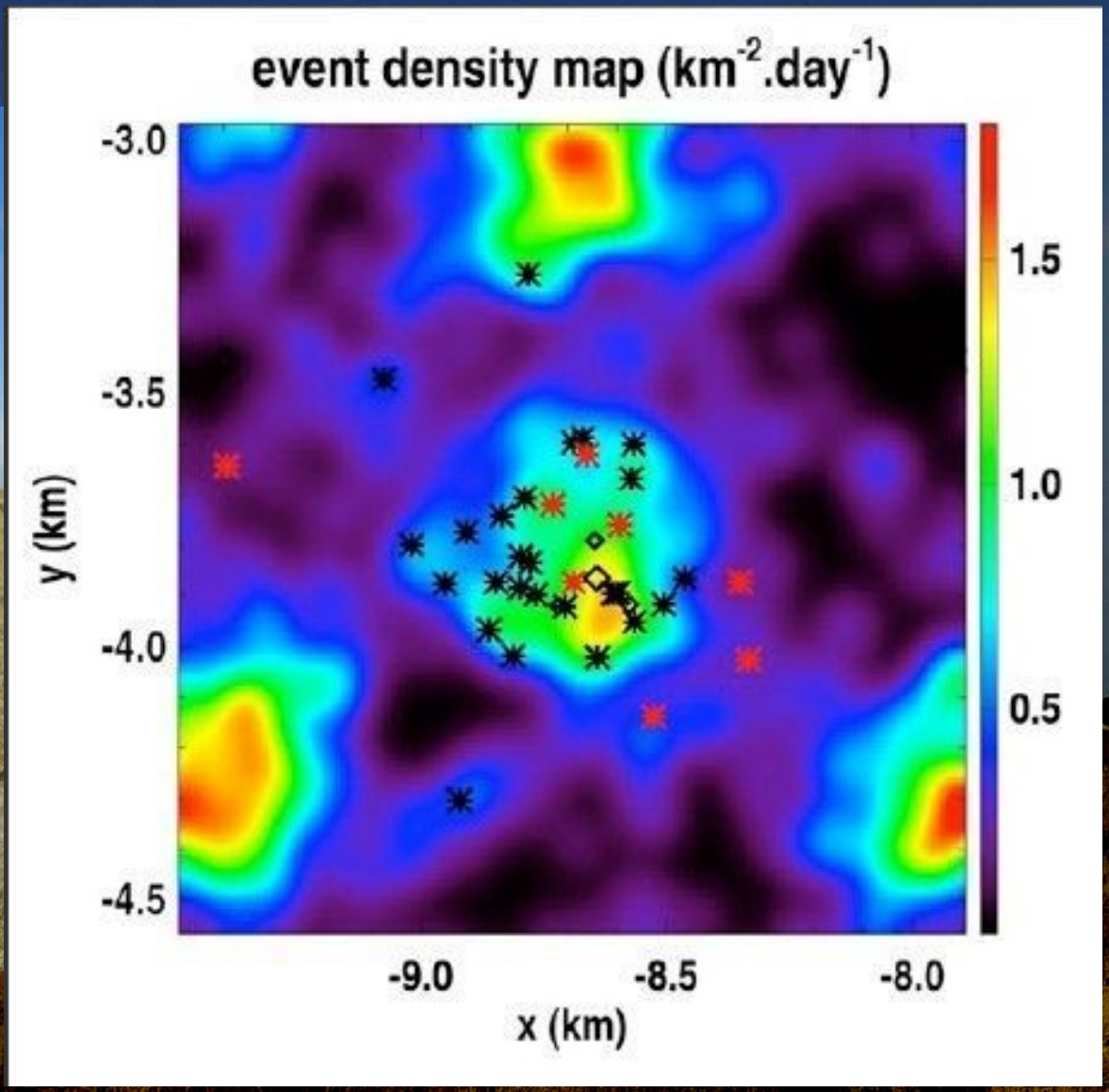
- Clear asymmetry in arrival directions
- Unambiguous proof for geomagnetic effect
- Electric field amplitude proportional to energy ⇒ calorimetric measurement?



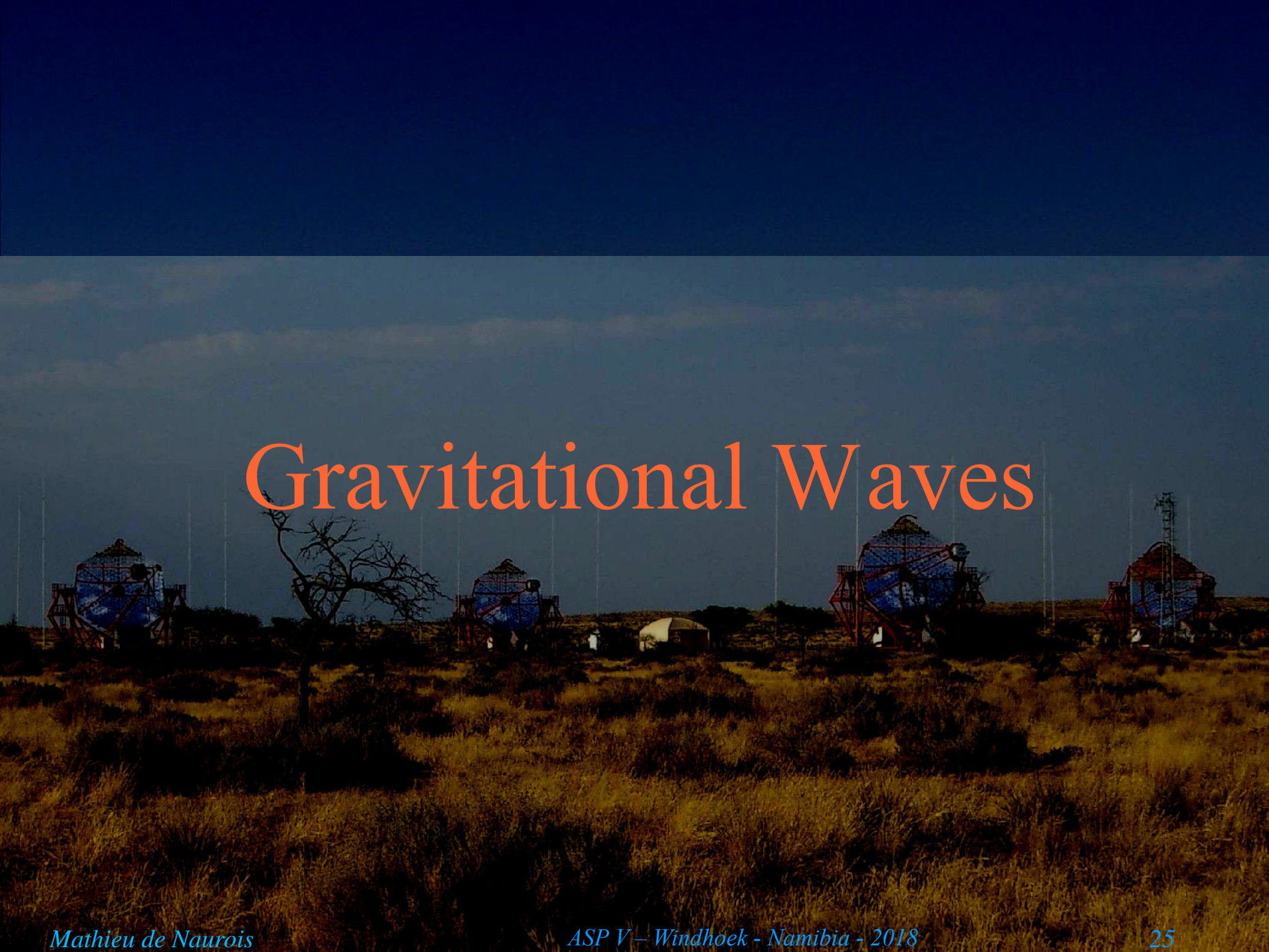




Radio Detection @ Auger

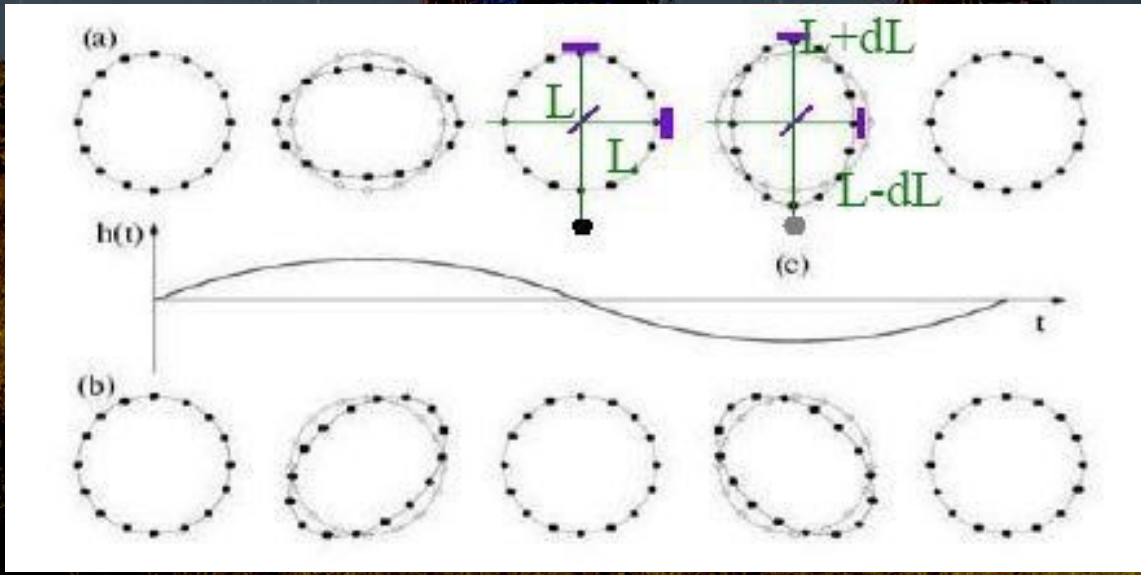


- Autonomous prototype installed @ AUGER
- First detection: July 2007
- 39 events in coincidence with Auger SD (SD trigger)
- First self-trigger announced recently
- Radio detection seems to work up to 1 km away from antennas
- Radio detection seems to work for horizontal showers


Gravitational Waves

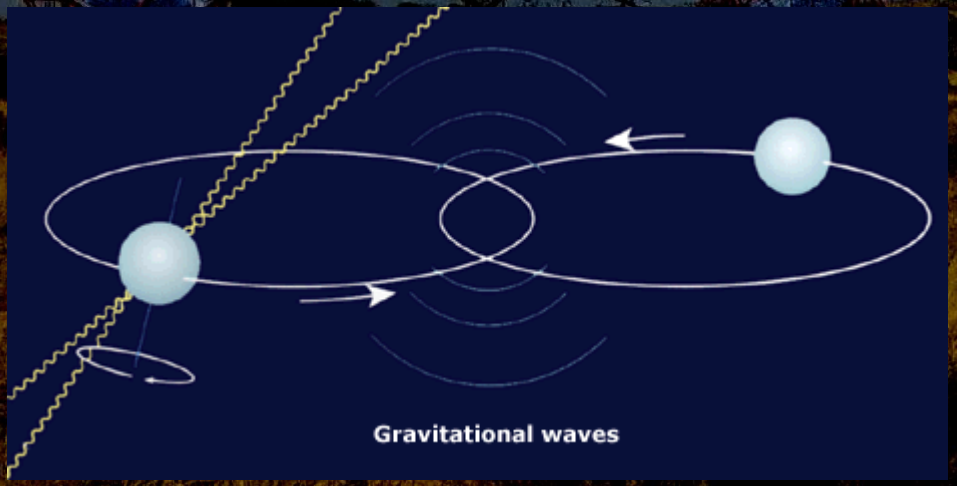
Gravitational waves

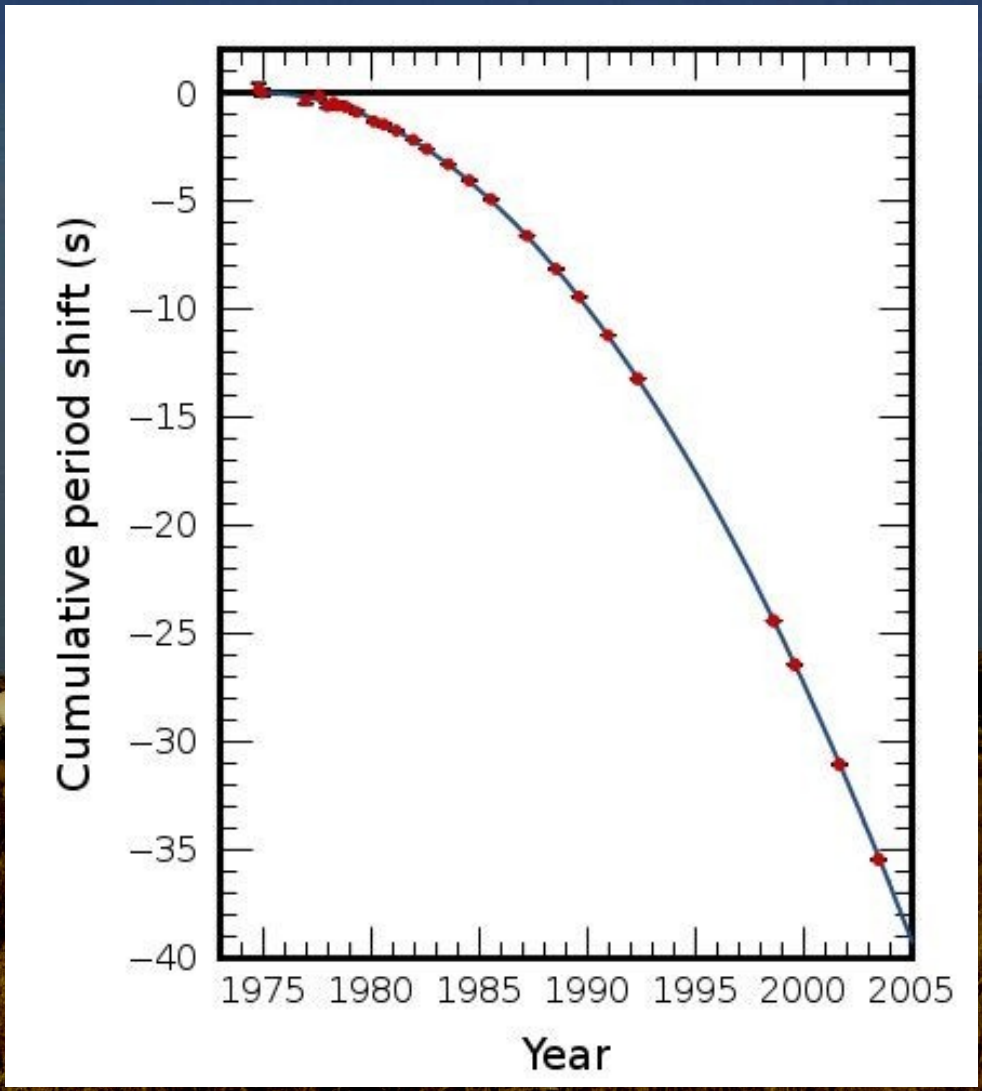
- General Relativity predicts propagation gravitational waves (deformation of space-time)
- Bursts
  - Supernovae
  - Black Holes disexcitation
- Spiralling binary systems
  - Neutron stars, black holes
- Periodic sources
  - Pulsars
- Other? (new physics)



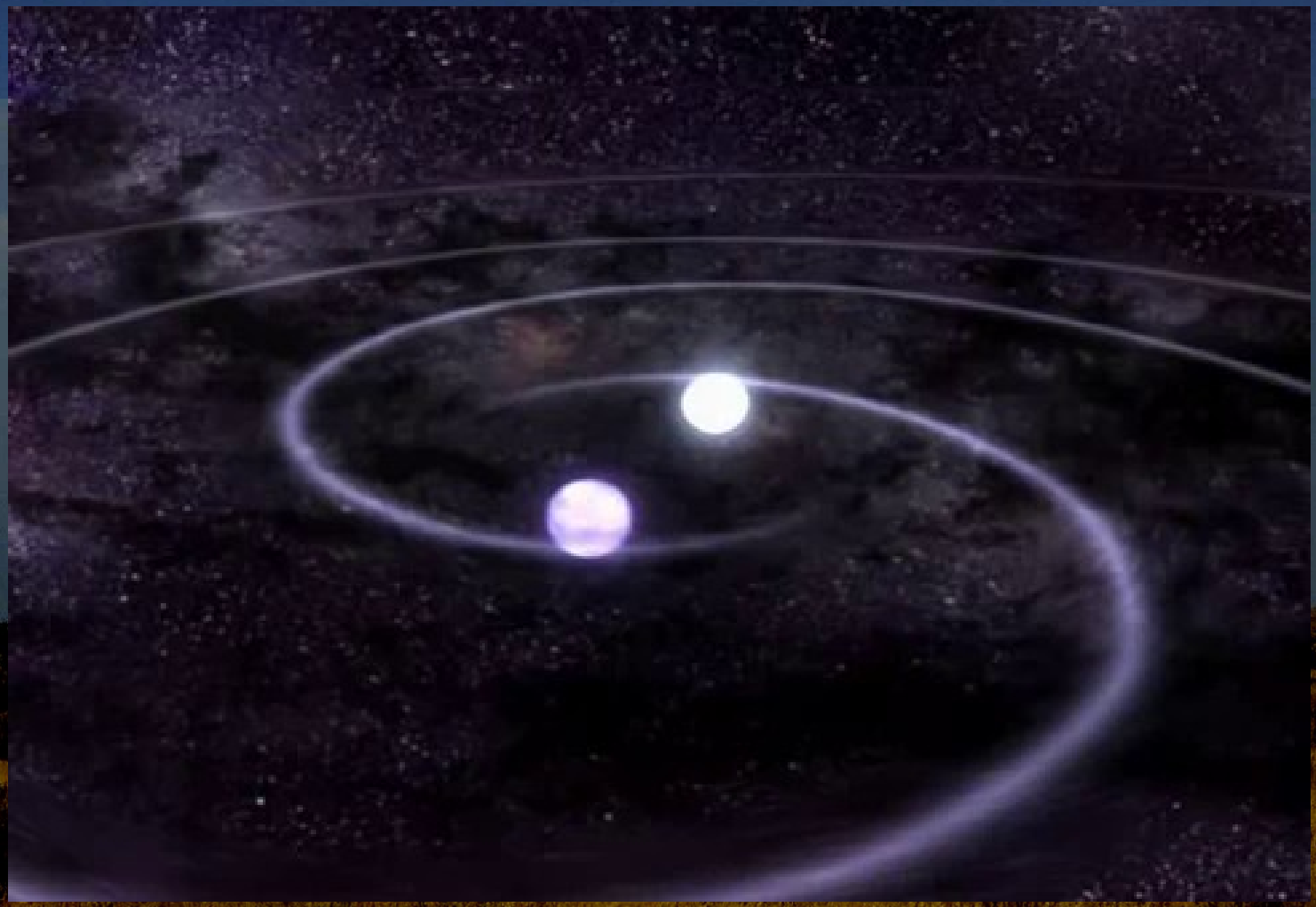
Proof of existence: PSR B1913+16

- Binary pulsar PSR B1913+16
  - Orbital period of 8h
  - Decay measured in 1974
- Agreement with GR (energy loss due to GW)
- Hulse & Taylor's Nobel prize (1993)



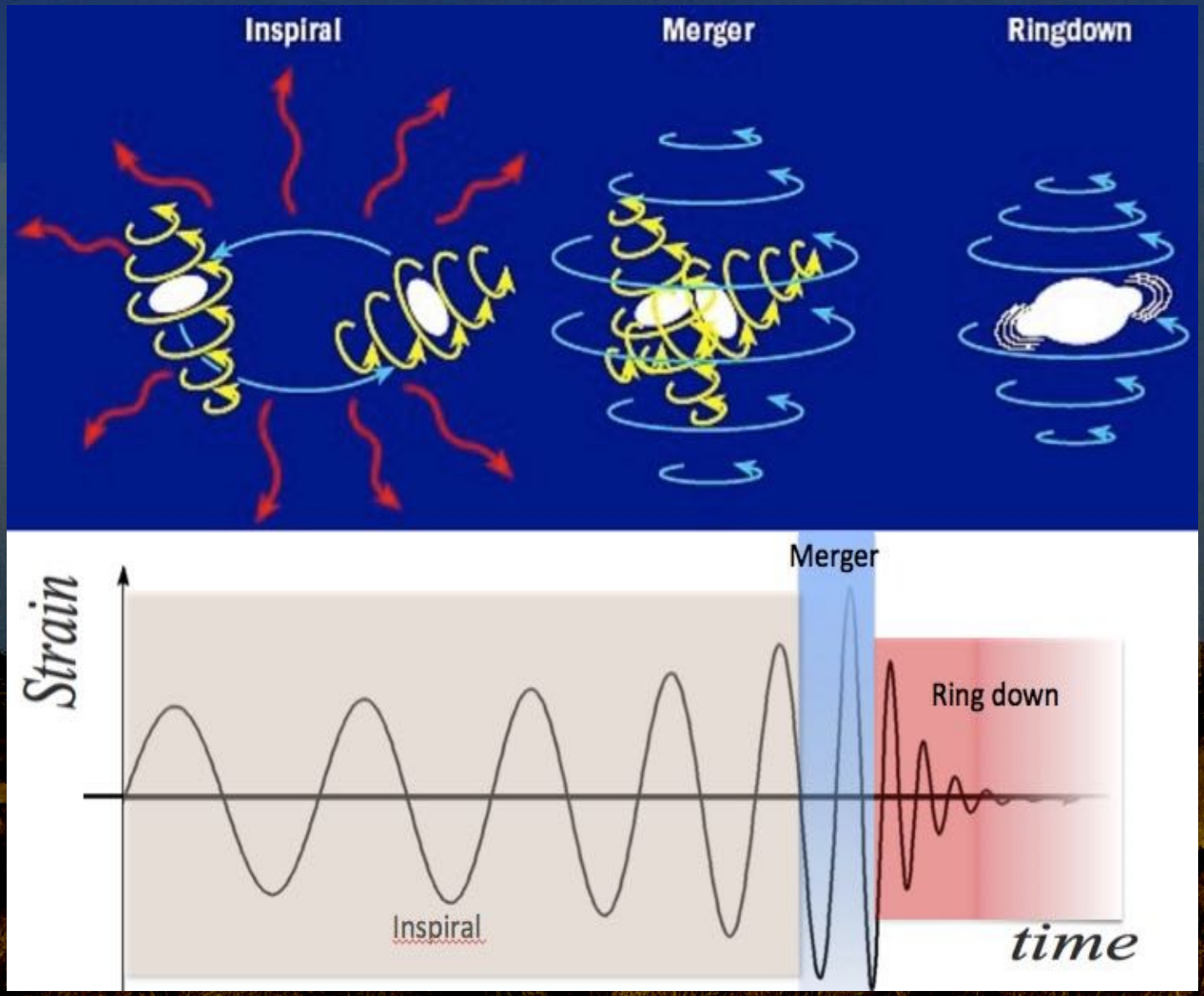


Neutron stars merger



Artist's view

Signal shape

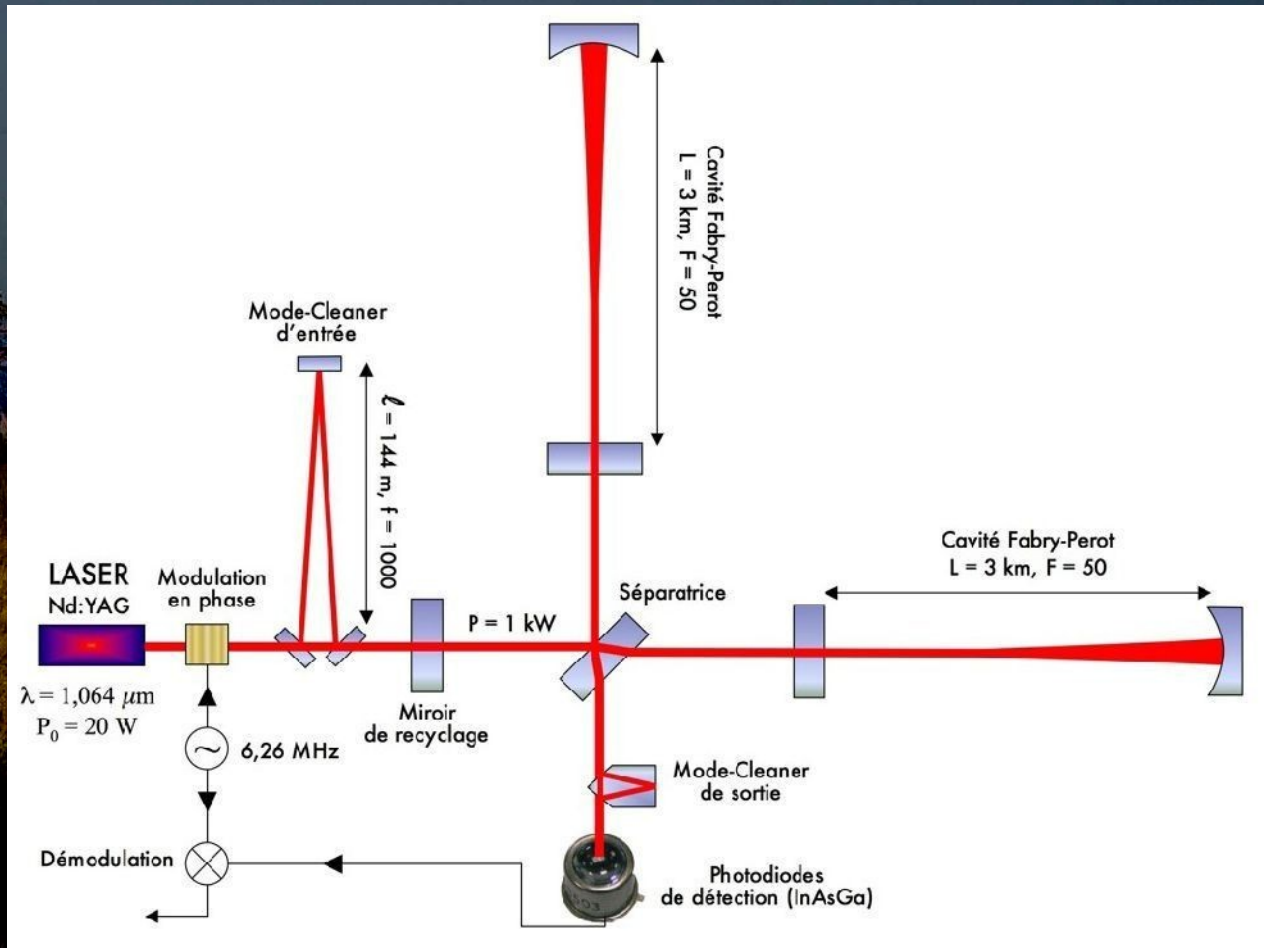


Easy to compute

Challenging

Detection Principles

- Basic idea: giant interferometer
- Fabry Perrot cavities in each arms multiply path length and increases sensitivity
- Challenges:
  - Typical amplitude: $\Delta L/L \sim 10^{-21}$, $\Delta L \sim 10^{-18}$,
  - Mechanic Noise (vibrations, ...)
    ⇒ Multi-stage filters
    ⇒ Ultra high vacuum
  - Quantum Noise
    ⇒ High laser intensity, stabilized



Current Detectors

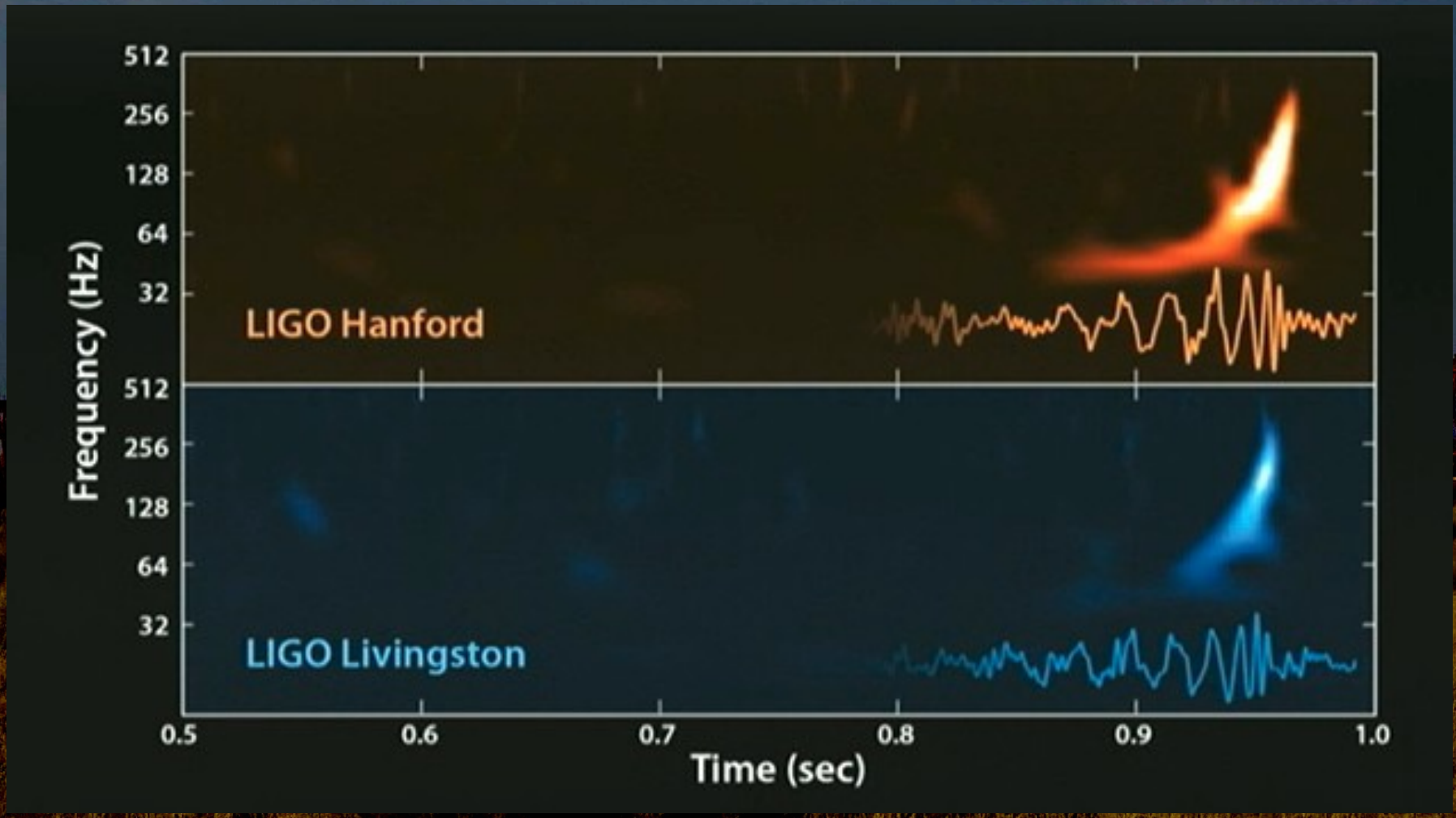
- VIRGO (name after the Virgo cluster)
- 1 site in Italy

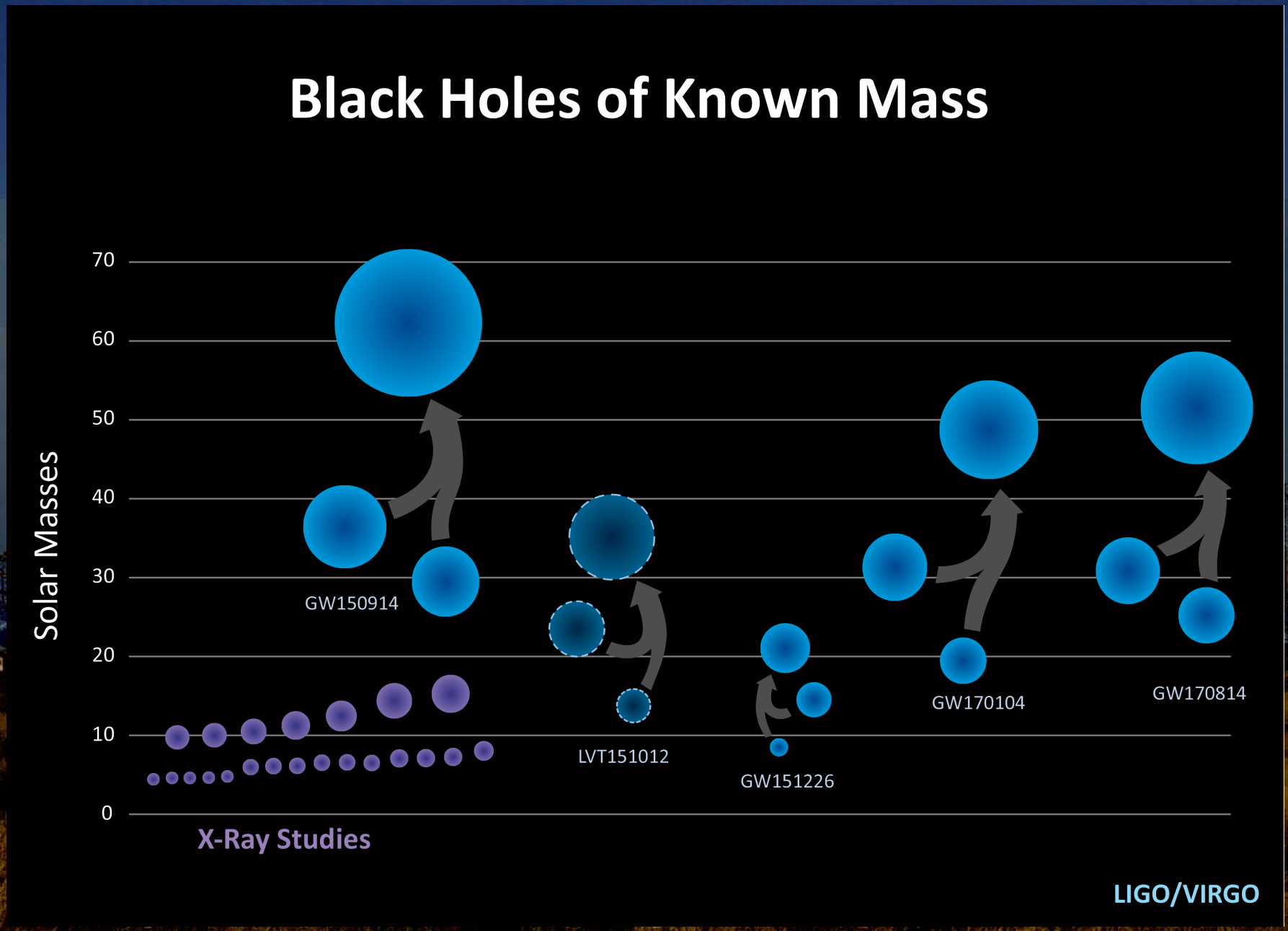
- LIGO: Laser Interferometer Gravitational wave Observatory
- 2 sites 3030 km away:
  - H1 (Washington)
  - L1 (Louisiana)

Hanford (Washington): 2 interferometers
Livingston (Louisiana) : 1 interferometer (4 km)

First Detection – September 14th 2015

- Announced February 11th 2016
- Second detection announced June 15th, 2016



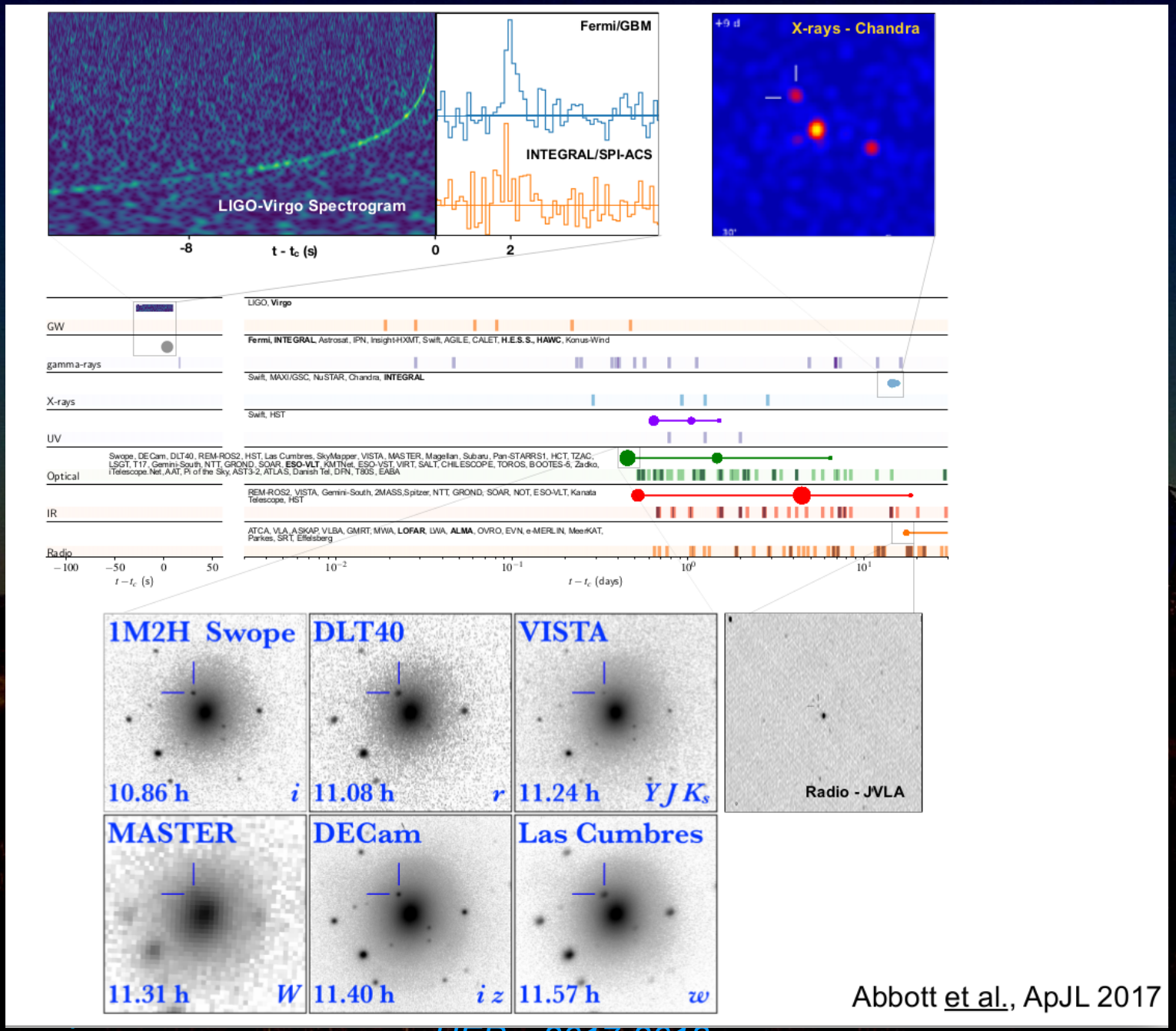

Black Holes of Known Mass
Solar Masses
70
60
50
40
30
20
10
0
GW150914
LVT151012
GW151226
GW170104
GW170814
X-Ray Studies
LIGO/VIRGO

Formation Scenarii

- Massive BHs (> 25 $M_\odot$) form from:
  - Direct collapse of very massive stars in metal-poor environment (isolated binary)
  - Mergers of lower mass BHs or BH-star favoured in Globular Cluster/Young Star Cluster (3 body encounters)

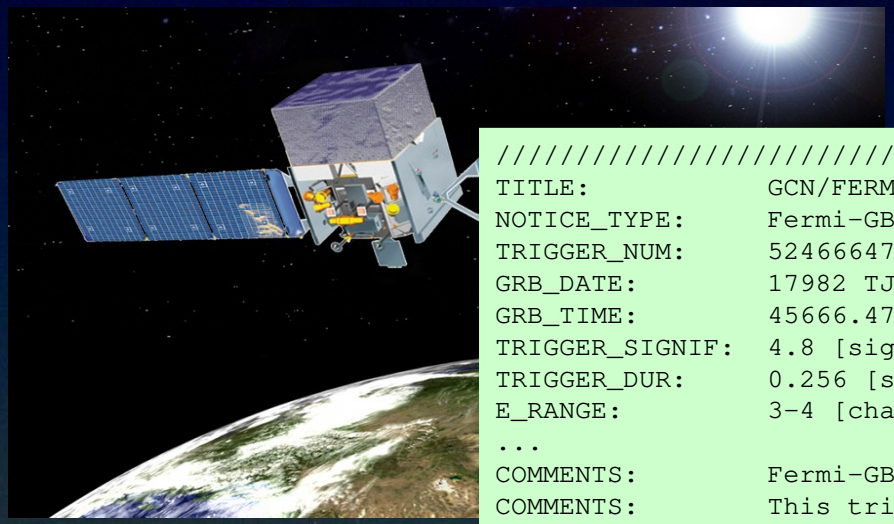
- Counterparts not easy at all to identify (No EM counterpart from the merger itself)
  - EM counterpart could come from accreting material
  - Or B Field structure

Neutron Star Merger – August 17th 2018



Abbott et al., ApJL 2017

What Happened?



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////////////////////////////////////////////////////////////////////////
TITLE:            GCN/FERMI NOTICE NOTICE_DATE:     Thu 17 Aug 17 12:41:20 UT
NOTICE_TYPE:      Fermi-GBM Alert RECORD_NUM:      1
TRIGGER_NUM:      524666471
GRB_DATE:         17982 TJD;   229 DOY;   17/08/17
GRB_TIME:         45666.47 SOD {12:41:06.47} UT
TRIGGER_SIGNIF:   4.8 [sigma]
TRIGGER_DUR:      0.256 [sec]
E_RANGE:          3-4 [chan]   47-291 [keV]
...
COMMENTS:         Fermi-GBM Trigger Alert.
COMMENTS:         This trigger occurred at longitude,la
   The LC_URL file will not be created until ~15 min af
////////////////////////////////////////////////////////////////////////
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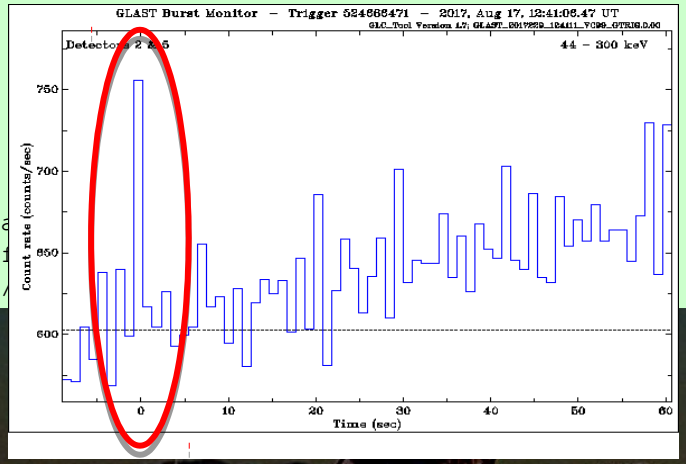
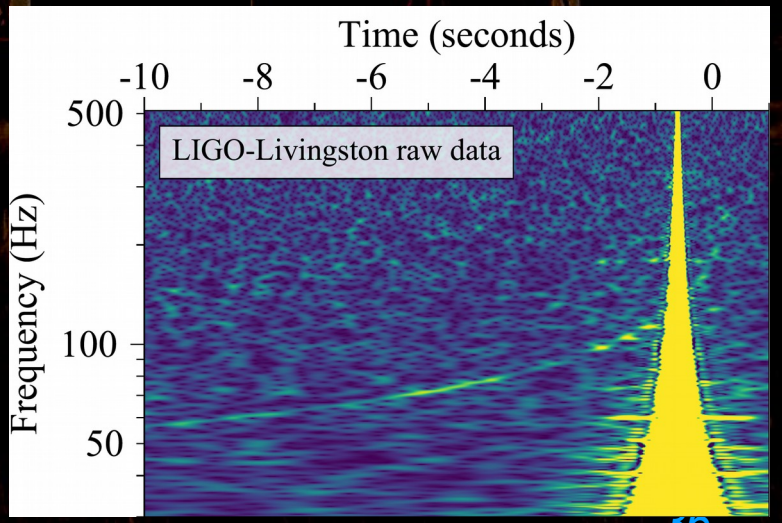
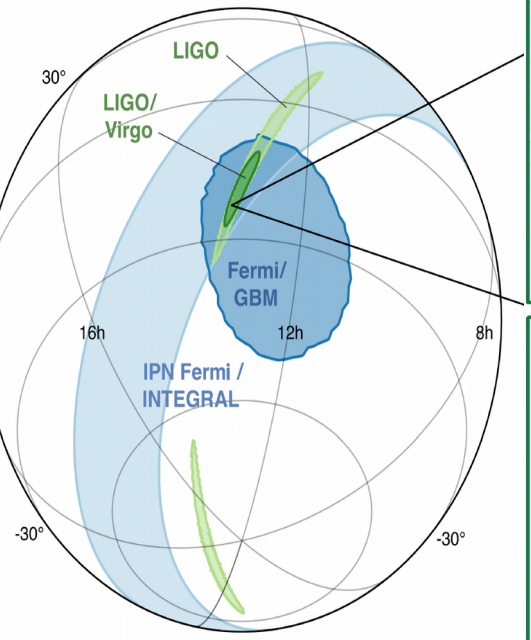
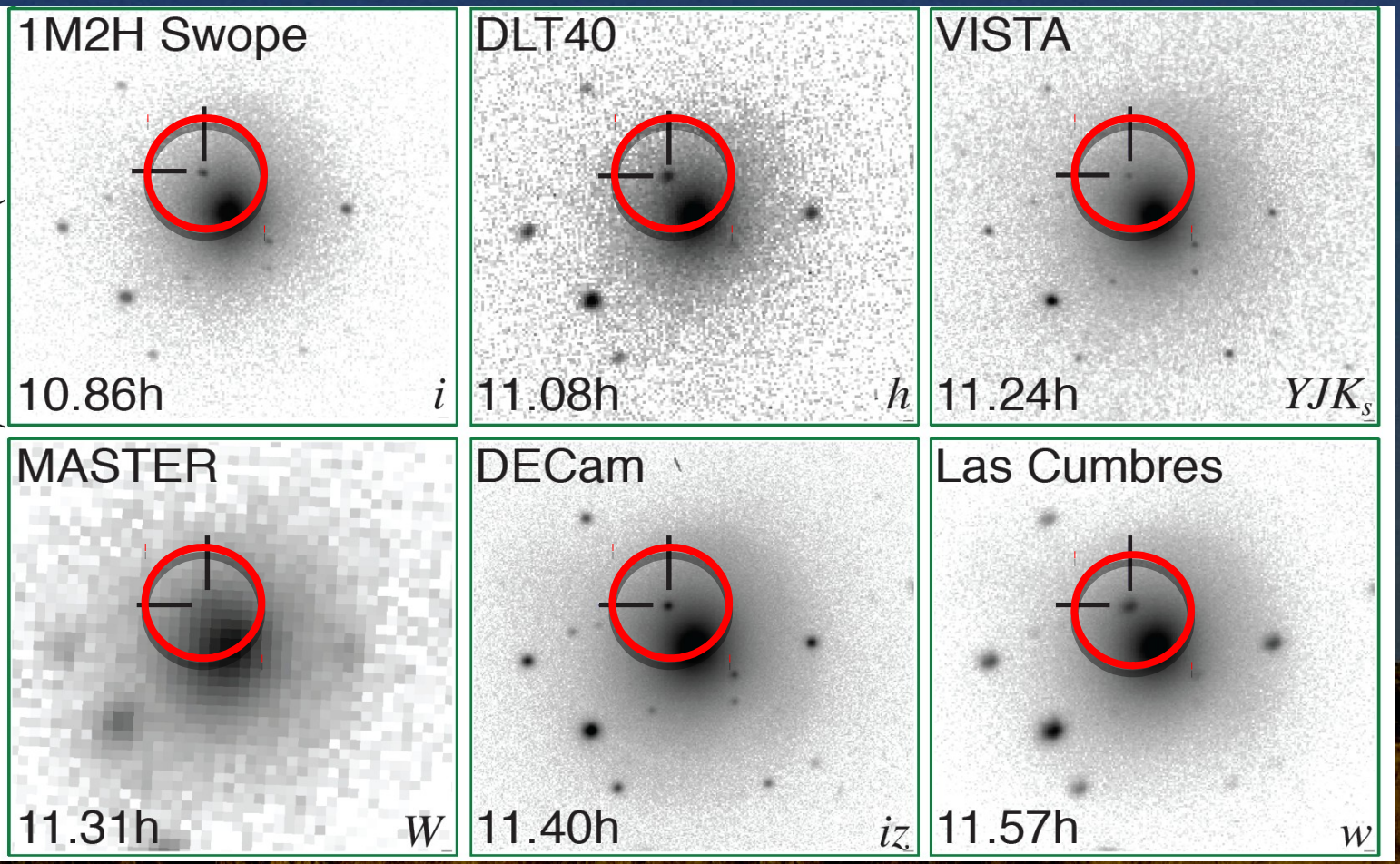


- 14h41: Short gamma-ray burst of low intensity
- 14h47: Internal LIGO alert, strong signal, but parasitic signal
- 19h54: signal corrected, alert sent



Rush to the source

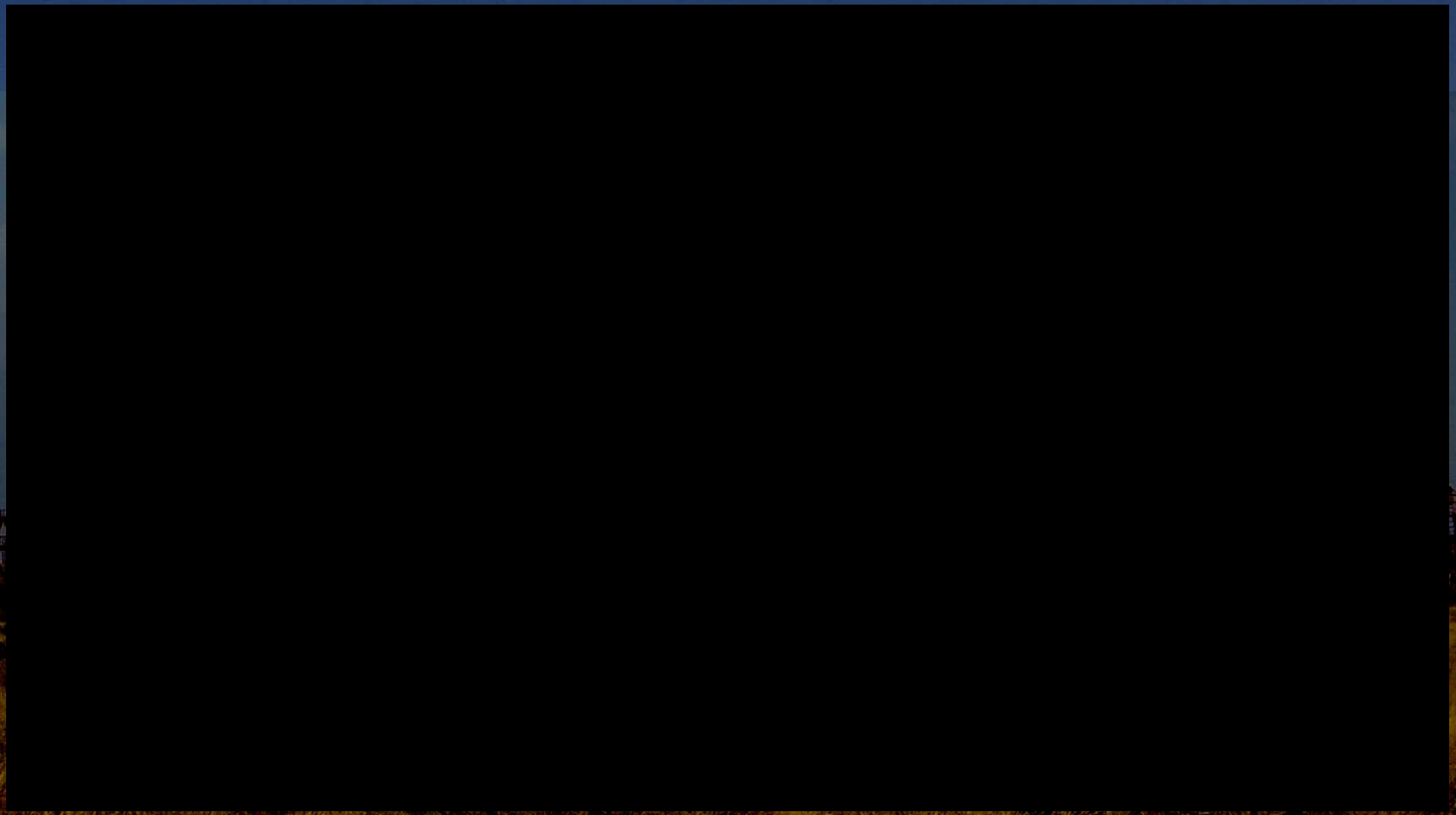




- 70 observatories pointed to the source
- HESS was on target 37seconds after alert (no VHE signal)

Neutron Star Merger – KiloNova

Animation: NASA's Goddard Space Flight Center

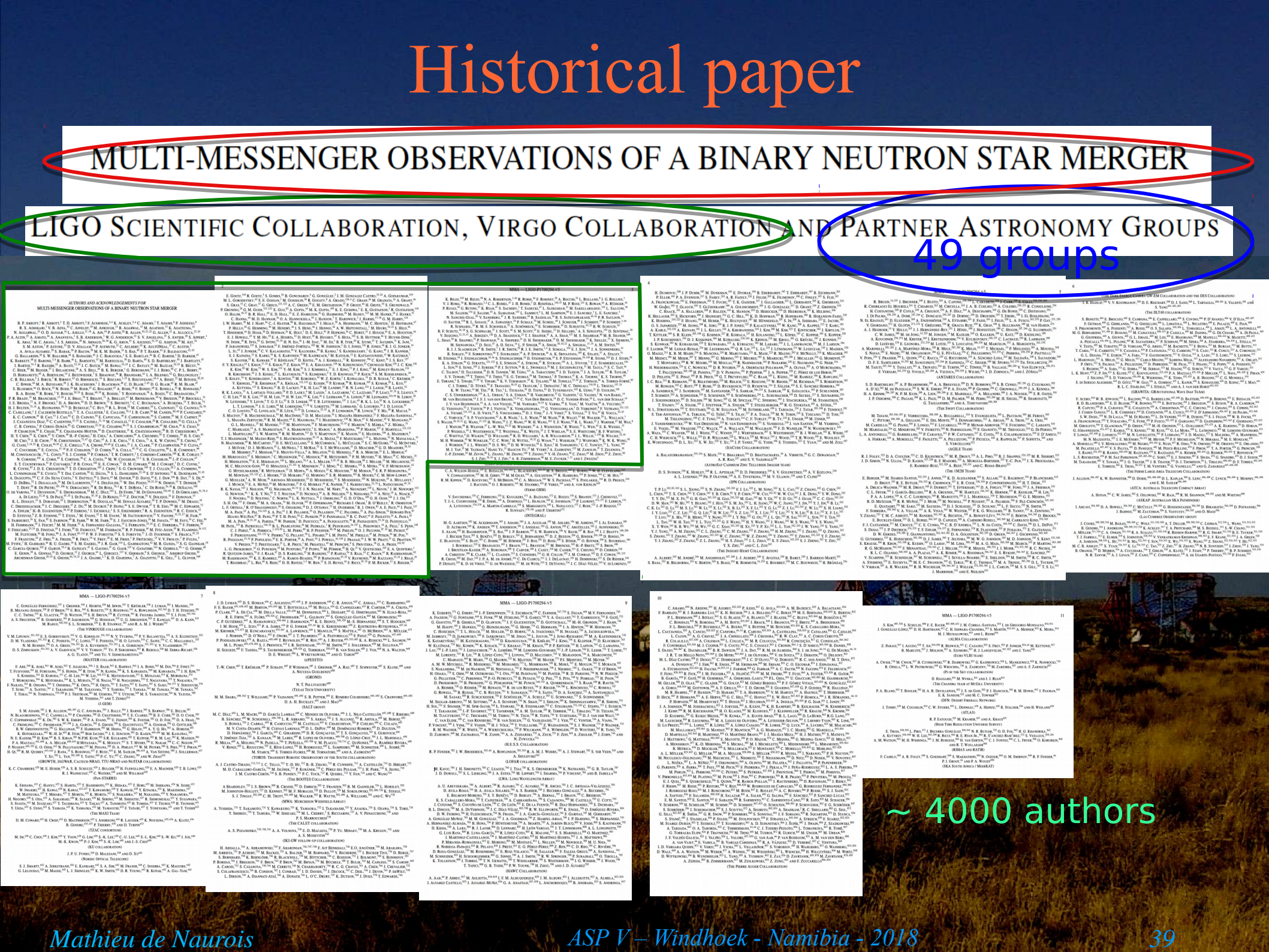


Historical paper

MULTI-MESSENGER OBSERVATIONS OF A BINARY NEUTRON STAR MERGER

LIGO Scientific Collaboration, Virgo Collaboration and Partner Astronomy Groups

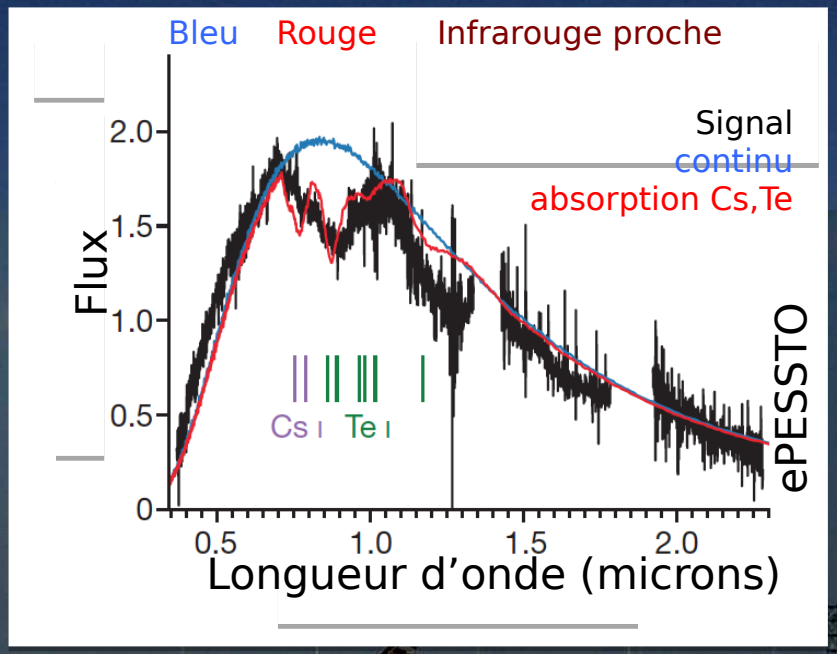
49 groups

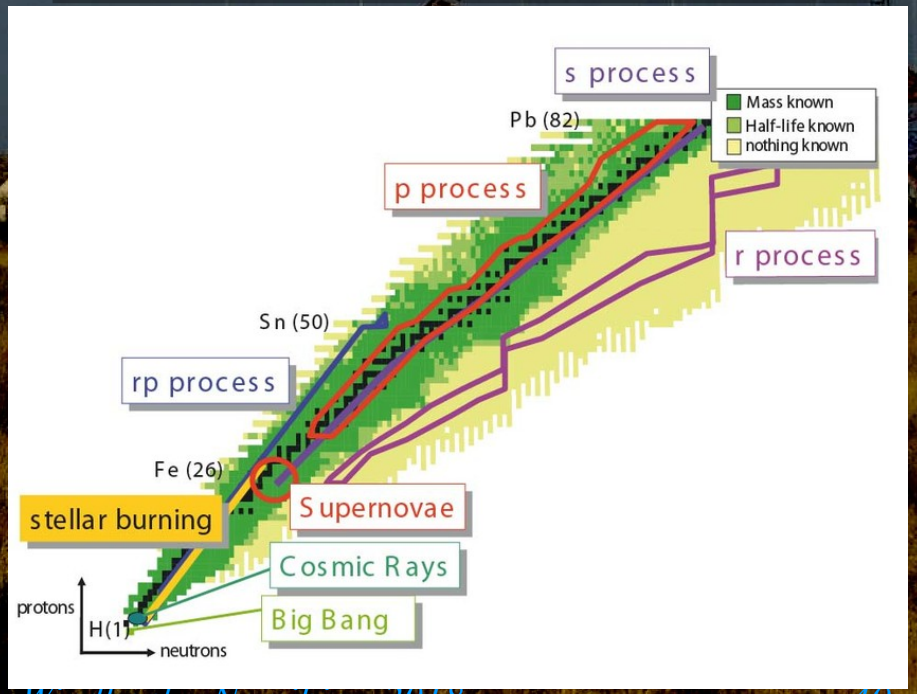


~ 4000 authors

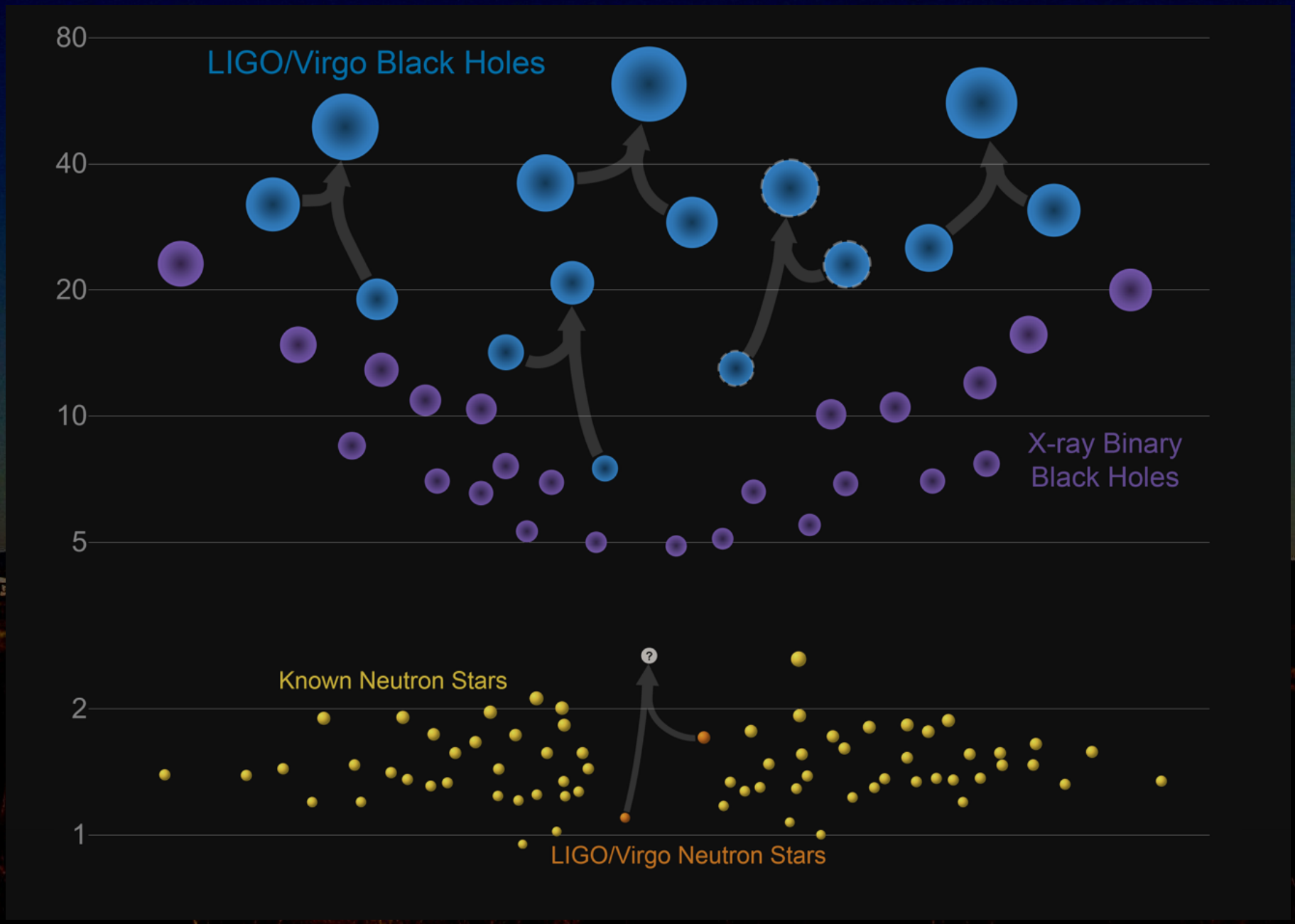
What have we learnt?

- GW travel at speed of light ($\Delta t < 2s$)
- Measurement of distance → Direct measurement of Hubble constant: $h = 70_{-8}^{+12}$ km/s/Mpc
- Spectroscopic measurement: Heavy elements (gold, etc) are most likely produced in kilonova through the "R process": absorption of neutrons followed by beta decay





Updated Mass Chart



Conclusion

- Gravitational Astronomy has started.
- Worldwide collaboration effort
  - First experiments demonstrated proof of principle:
    ability to beat the noise and reach expected sensitivity
  - First detection came as a surprise: intermediate mass BH mergers
  - Next generation of instruments coming online with larger statistics
  - Space experiments will increase frequency range

High Energy Astrophysics, aka Astroparticles...

- Is a very various field:
- Multimessenger:
  - Cosmic rays
  - Gamma-rays
  - Neutrinos
  - Gravitational Waves
- Multiwavelength: from 10^6 to 10^{20} eV: 14 decades in energy!
- Great variety of technologies and instruments
  - satellites, balloon, ground based, underground , ...
  - particle physics detector, radio detection, acoustic, ...
- Great variety of physics subjects: phenomenology of cosmic rays, astronomy, cosmology (structure formation), dark matter search, fundamental physics (Lorents invariance, ...)
- Exciting future, many projects (AMS, Auger North, Radio detection, Neutrinos, CTA, Virgo+, ET, LISA, ...)