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

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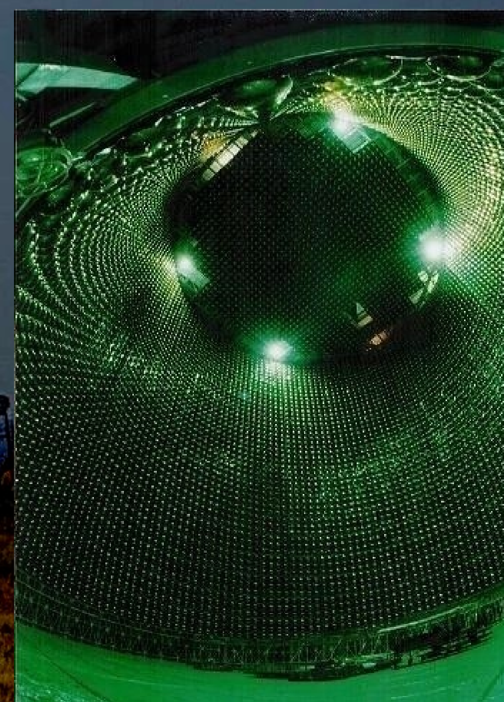
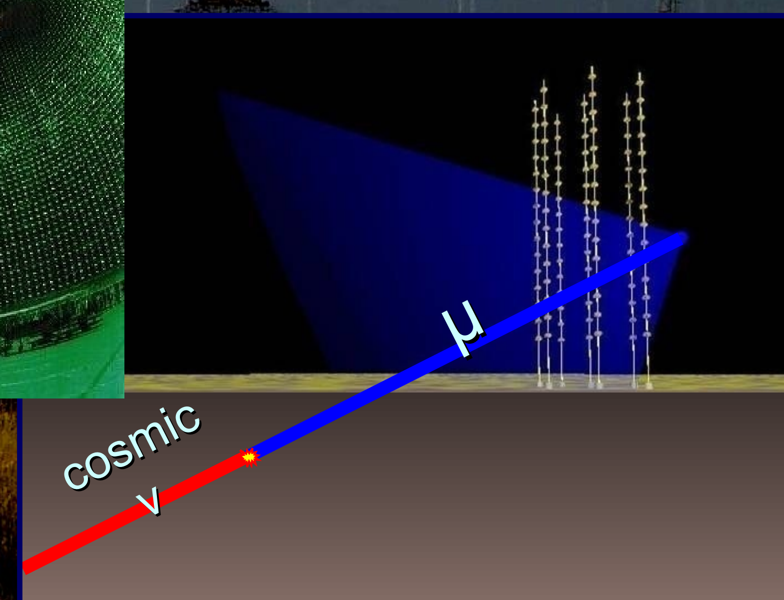
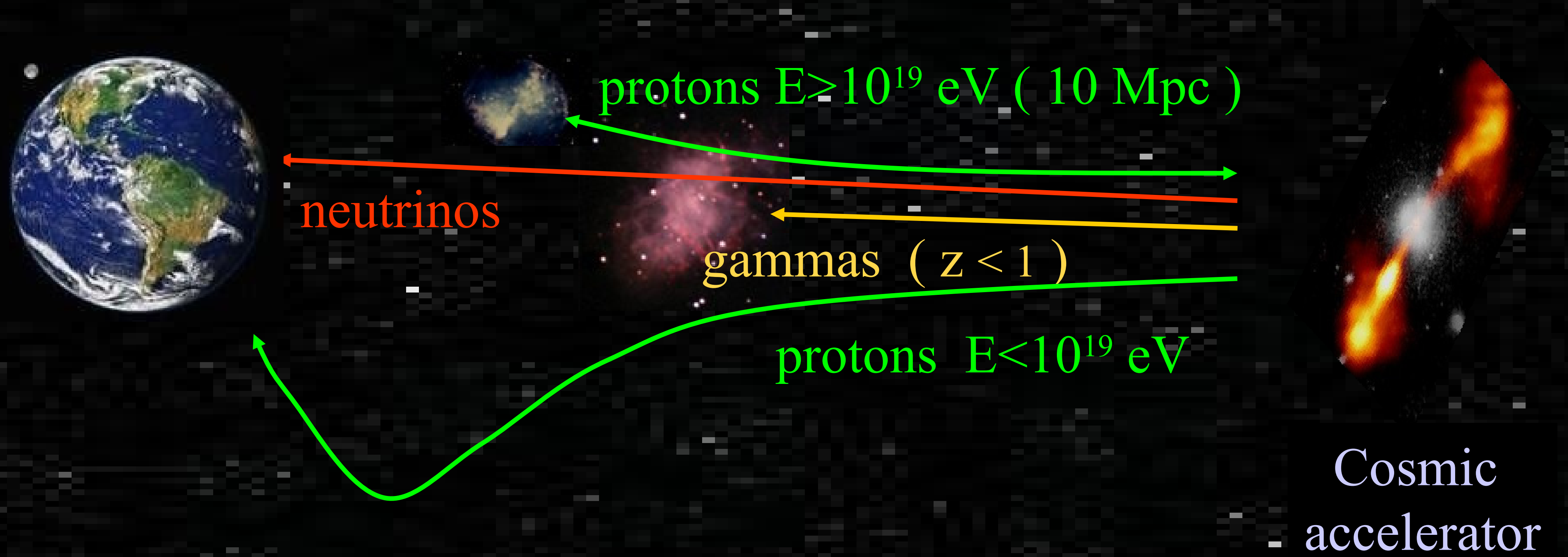


- ❑ Neutrino Astronomy
- ❑ Gravitational Waves



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
- **gravitational waves:** Emerging

⇒ **Four "astronomies" possible...**

Which neutrinos?

- Neutrino arise mostly from:
  - β^- decays produce **anti-neutrinos**: $n \rightarrow p + e^- + \bar{\nu}_e$
    Occurring in neutron rich environment, i.e. from heavy elements (nuclear fission – nuclear reactors)
  - β^+ decays produce **neutrinos**: $p \rightarrow n + e^+ + \nu_e$
    Occurring in proton rich environment, i.e. nuclear fusion (stars)
  - Thermal emission produce both **neutrinos** and **anti-neutrinos** in same quantities, e.g. $e^- + e^+ \leftrightarrow \gamma + \gamma \leftrightarrow \nu_e + \bar{\nu}_e$
    Occurring in hot & very dense environment, i.e. supernova explosion
  - Hadronic interaction, leading to **$\pi^\pm$ production** and subsequent decay, e.g. **atmospheric showers**

Neutrino oscillation

- **Hamiltonian** Eigenstates (i.e. energy/mass levels) differ from **Flavour** Eigenstates

  ⇒ 3×3 mixing matrix (PMNS Matrix) connects the two bases

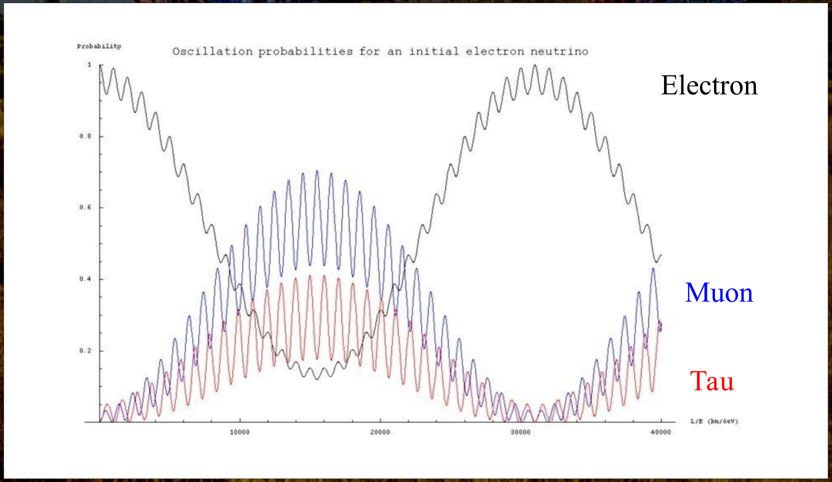
  e/μ/τ propagate as a mixture of different mass eigenstates and can oscillate ⇒ different flavour at Earth
- Can lead to CP violation

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

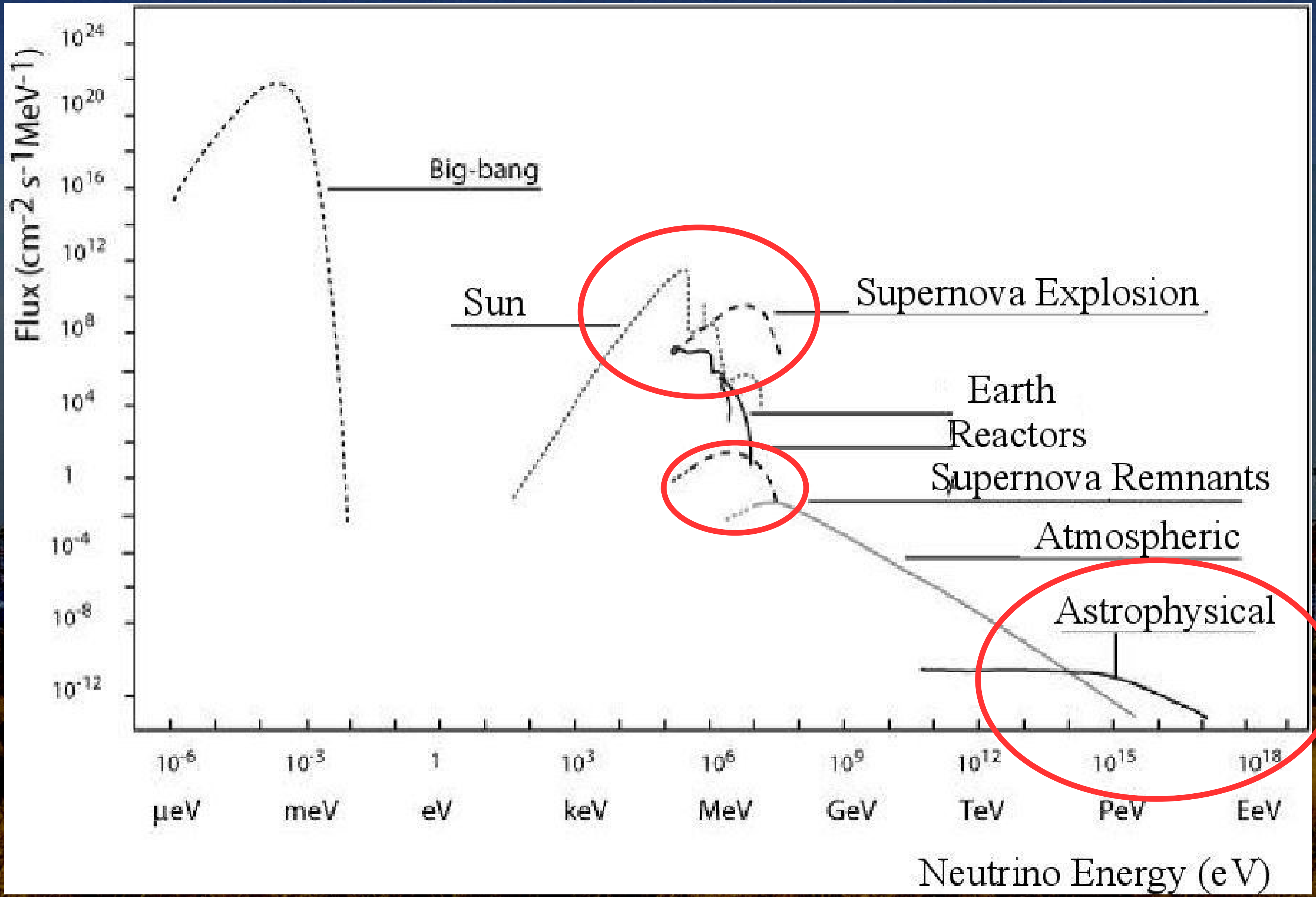
$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$\nu_\mu \rightarrow \nu_\tau$ $\quad$ $\nu_e \rightarrow \nu_\tau$ $\quad$ $\nu_e \rightarrow \nu_\mu$

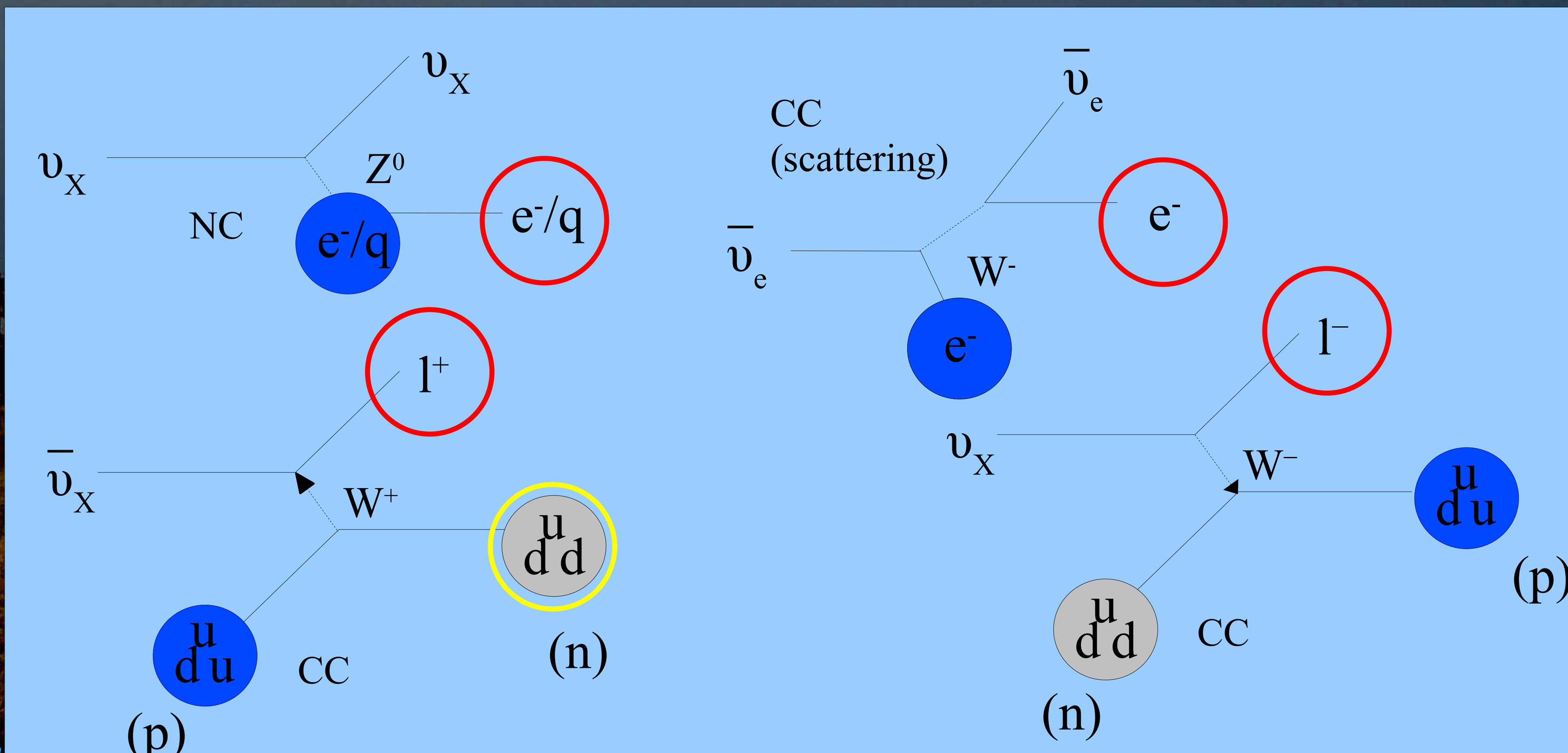


Flux of cosmic neutrinos



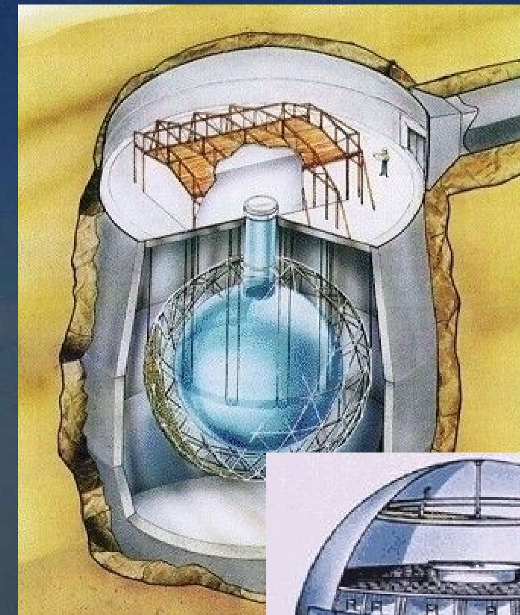
Interaction of neutrinos

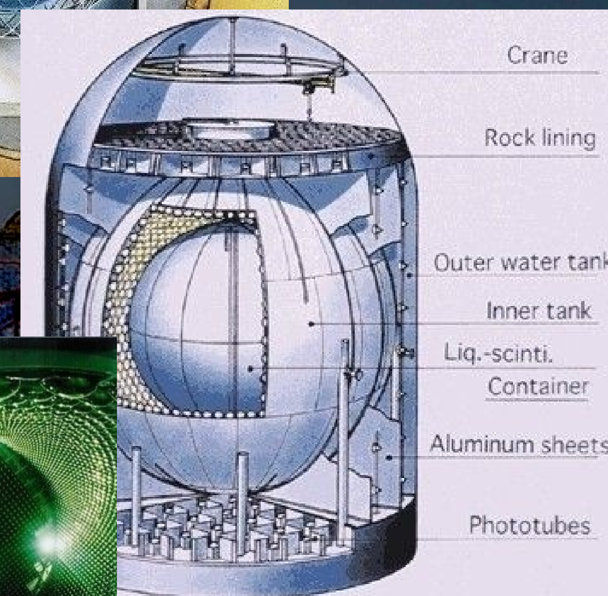
- Weak interaction (neutral & charged currents)
- Detection of outgoing lepton/neutron capture/change of chemical composition

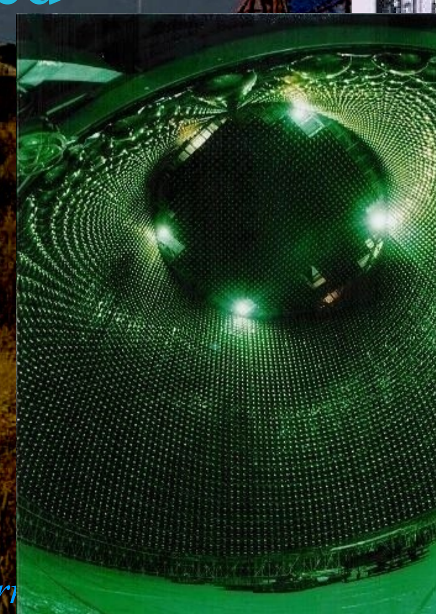


Low energy (MeV – GeV) Neutrinos

- Cherenkov emission of lepton (SNO, Kamiokande)
- Scintillation of lepton (KamLAND, Borexino)
- Neutron capture (favoured by Boron, Gadolinium, …) (SNO, Kamiokande)
- Heavy water D_2O sometimes used to limit neutron capture
- Physics:
  - Solar & Reactor neutrinos
  - Neutrino Oscillations

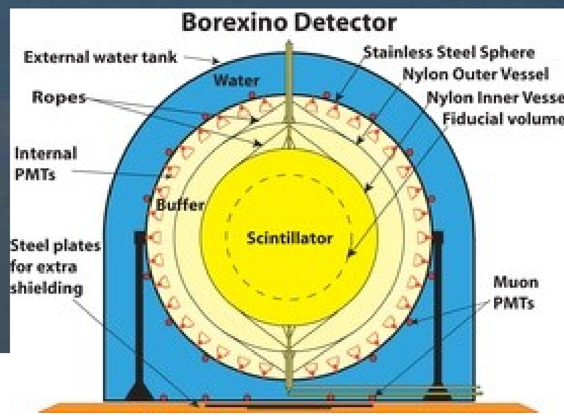


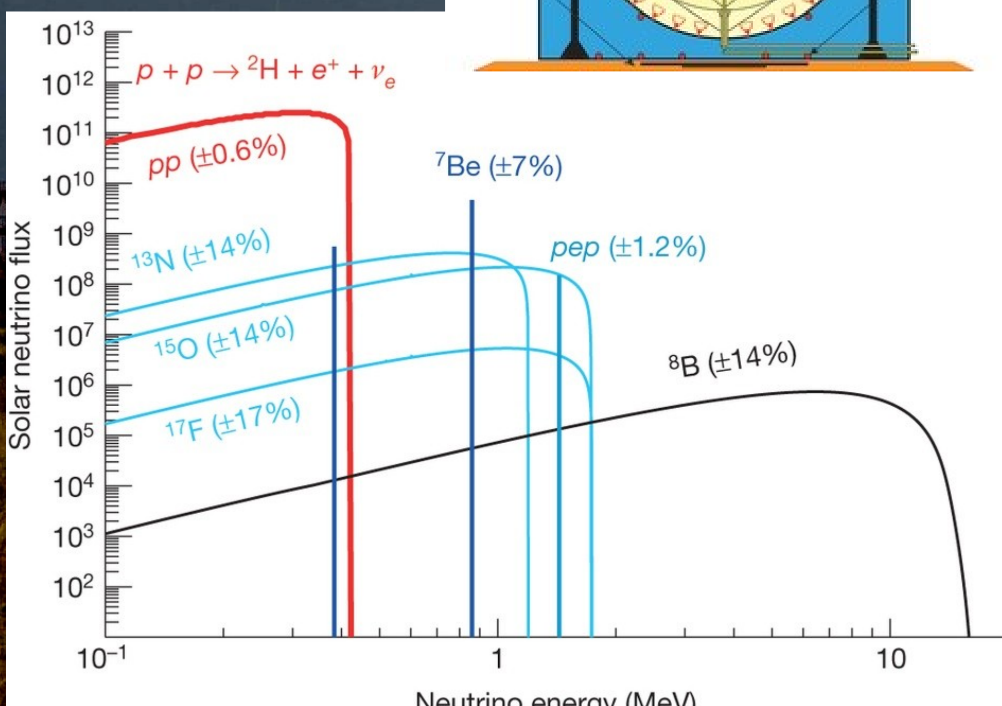


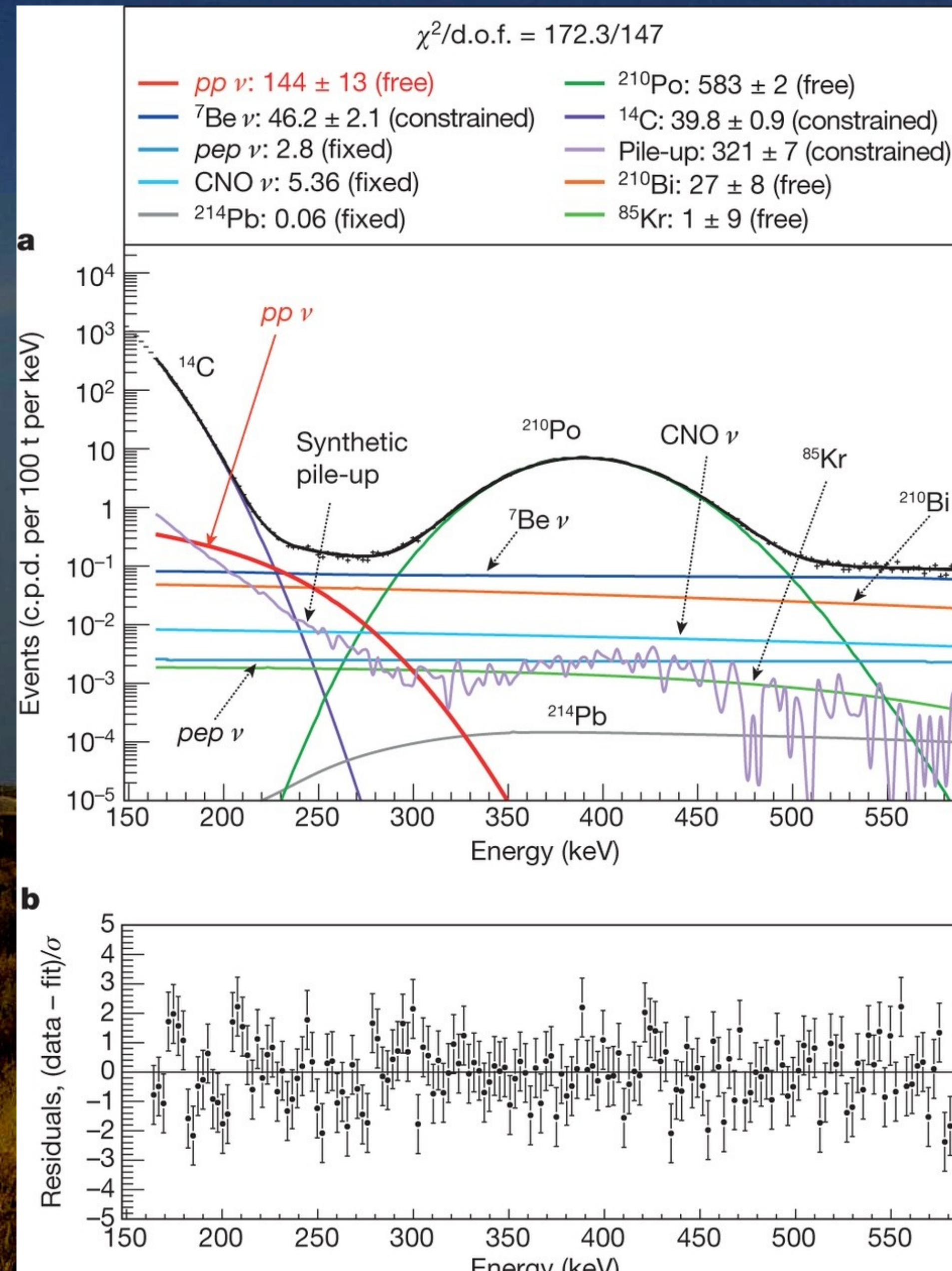


Validation of solar model

- Borexino Collaboration Nature, 2014







Solar Neutrinos

$p + p \rightarrow {}^2H + e^+ + \nu_e$ (ν_e - pp) $\langle E_\nu \rangle = 0.27$ MeV — 99.6 %

$p + e^- + p \rightarrow {}^2H + \nu_e$ — 0.4 % (ν_e - pep) $E_\nu = 1.44$ MeV

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

85 %: ${}^3He + {}^3He \rightarrow {}^4He + 2p$

pp I **loss ~ 2%**

15 %: ${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

$2.\ 10^{-5}$ %: ${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$ (ν_e - hep) $E_\nu = 9.63$ MeV

99.87 %: ${}^7Be + e \rightarrow {}^7Li + \nu_e$ (ν_e - ${}^7Be$) $E_\nu = 0.39, 0.86$ MeV

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

pp II **loss 4%**

0.13 %: ${}^7Be + p \rightarrow {}^8B + \gamma$

${}^8B \rightarrow {}^8Be + e^+ + \nu_e$ (ν_e - ${}^8B$) $\langle E_\nu \rangle = 6.74$ MeV

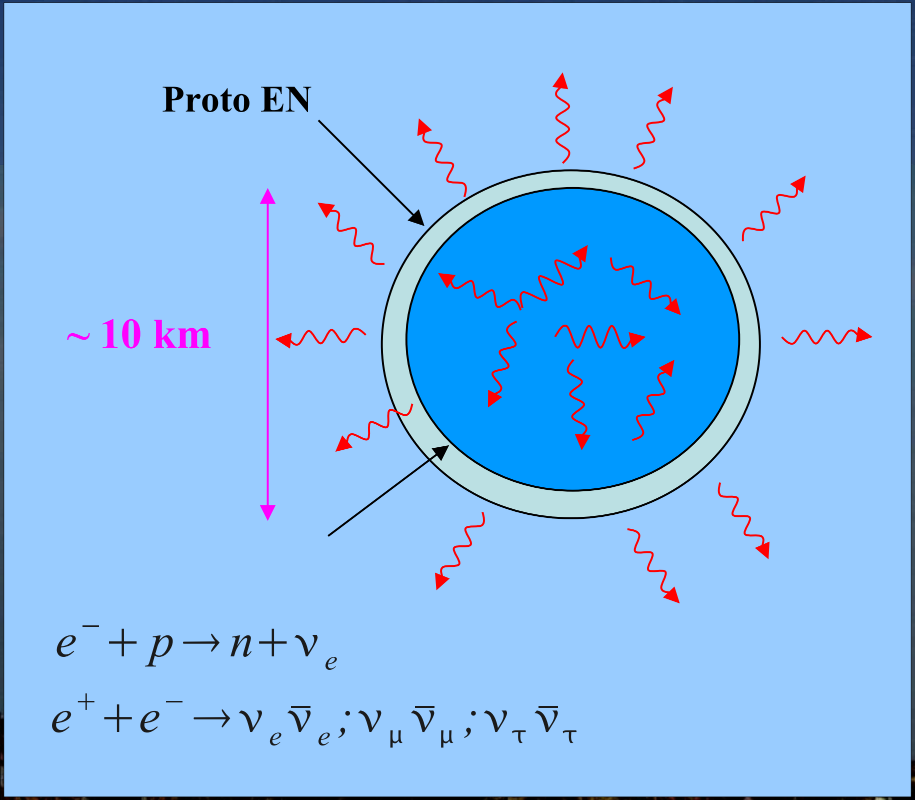
${}^8Be \rightarrow 2\ {}^4He$

pp III **loss 28%**

Total loss 2.3 %

$N\nu \sim 2\ 10^{38}\ s^{-1}$

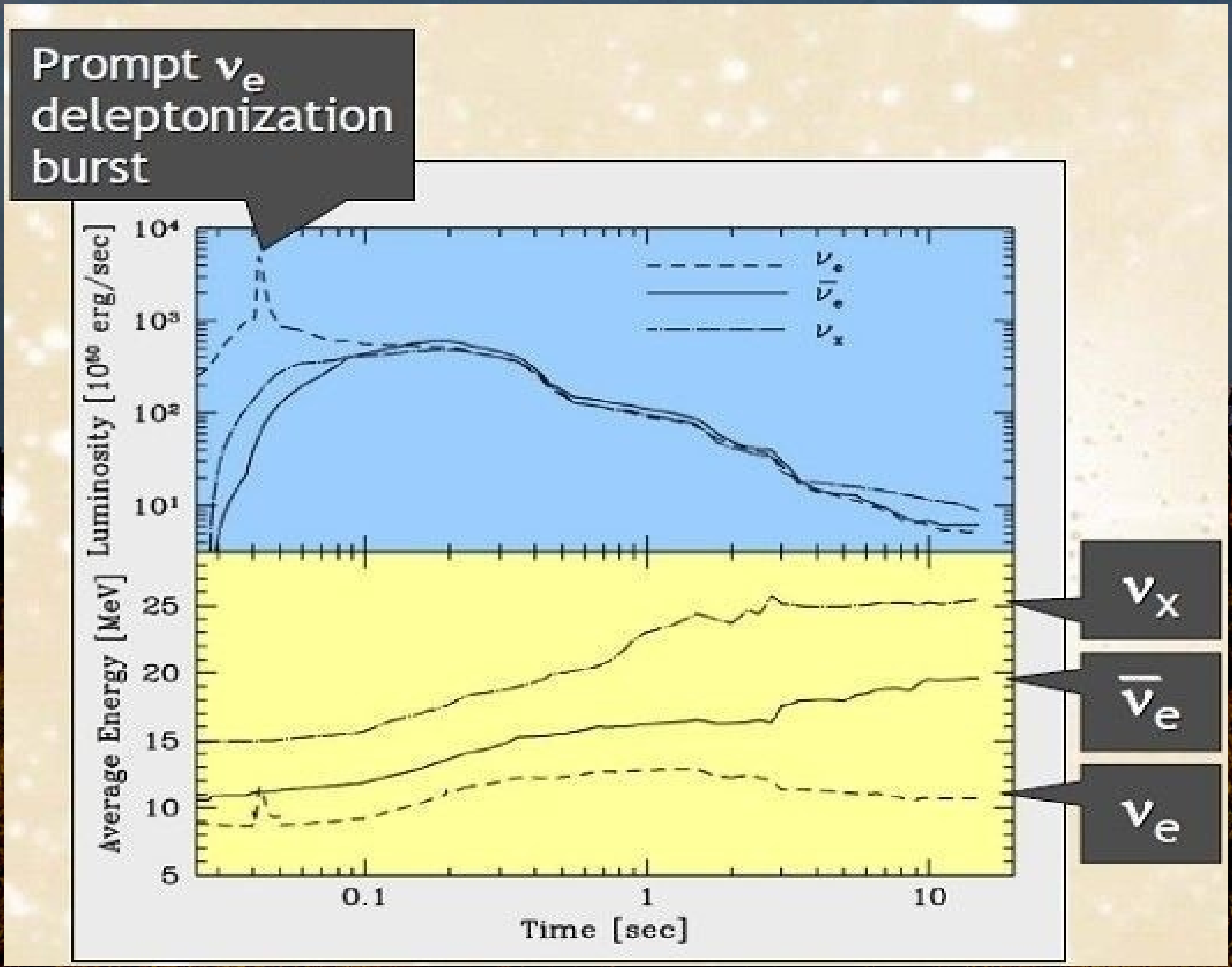
Neutrinos from Supernovae



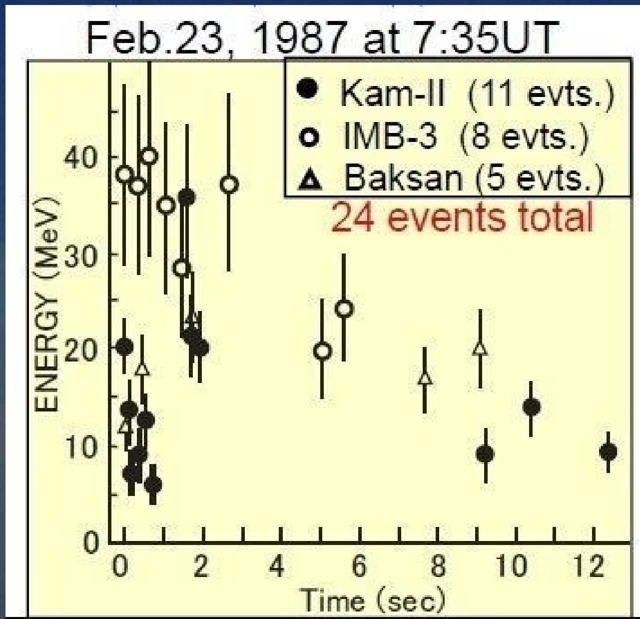
- Density $\rho \sim 10^{14}$ g /cm^3
- Coherent Scattering of neutrinos:
  $\lambda \sim 1/\rho\sigma \sim 300$ cm
  - Diffusion time $\tau \sim 1$s
  - Collapse time $\tau \sim 0{,}1$ s
  - Neutrinos are dynamically trapped
- Burst of neutrinos during the explosion

Neutrinos from Supernovae

- Large uncertainties in estimations
- Around 10^{53} erg in neutrinos



Neutrinos from Supernovae



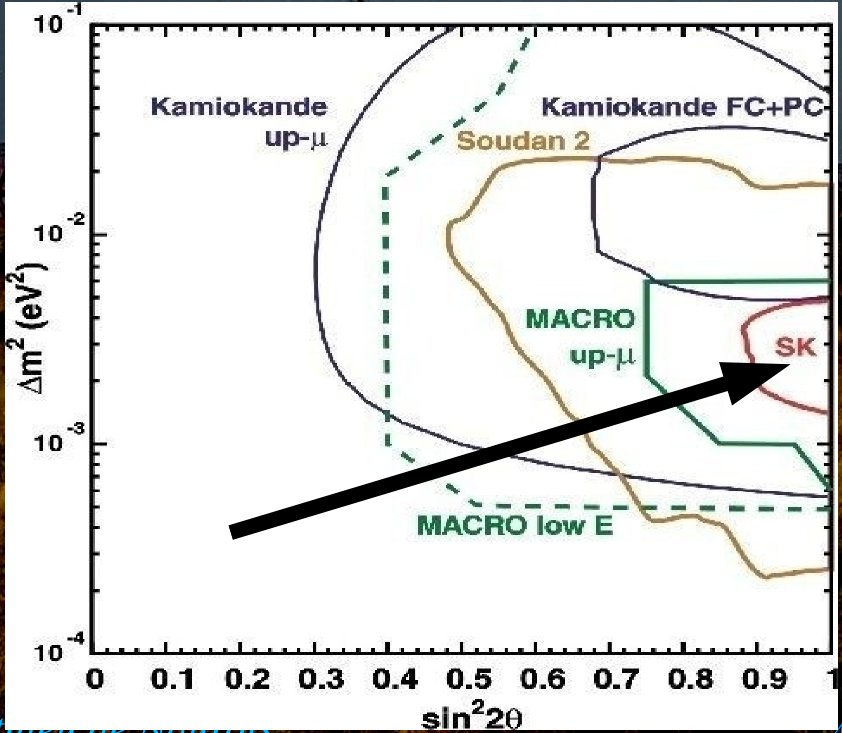
Neutrino

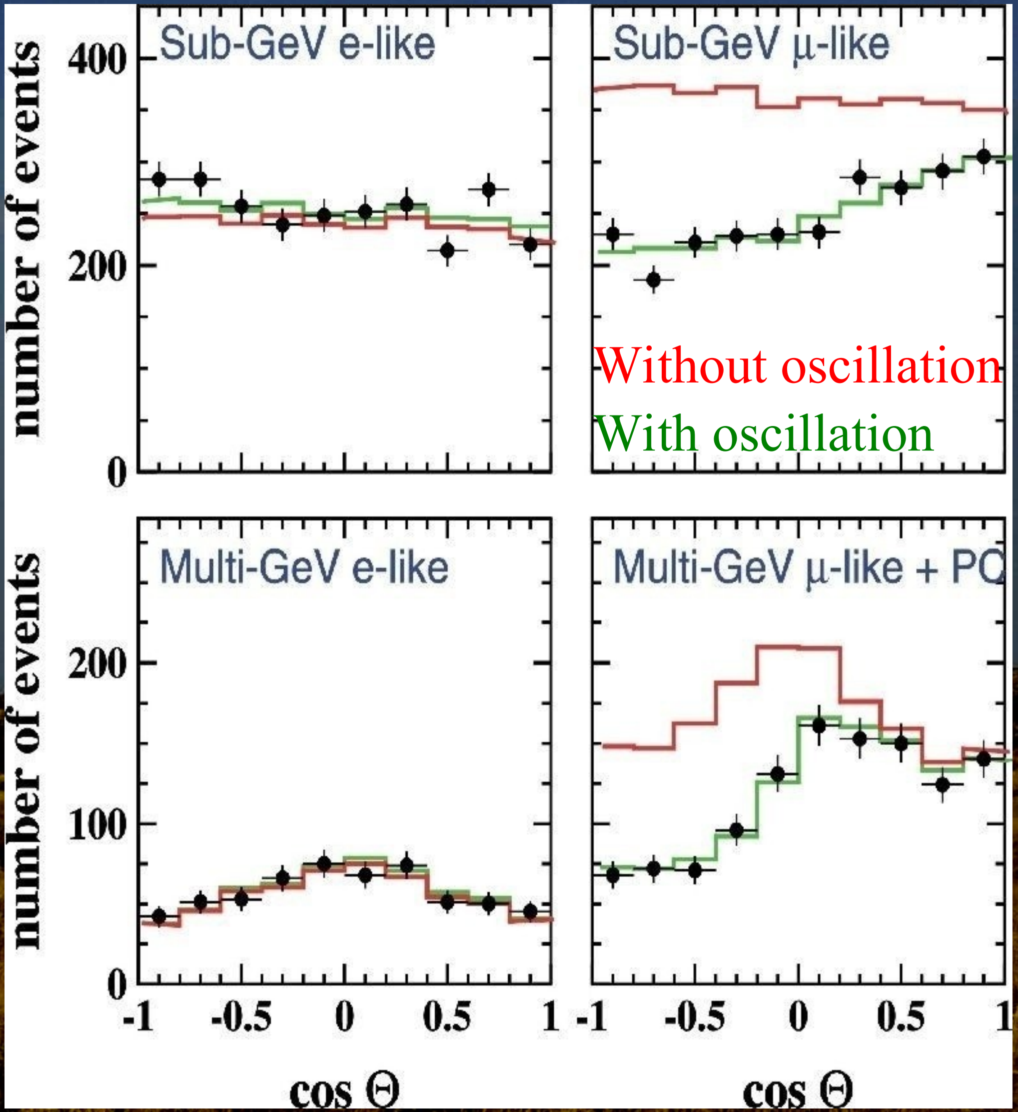
Visible

- Confirmation of SN explosion mechanism; 10^{53} erg (99% neutrinos, $\langle E_\nu \rangle \sim 10$ MeV, optical precursor, …)
- Limits on the physics of neutrinos (mass, magnetic moment, life-time, ...)
- Confirmation of Shapiro effect (gravitational time delay)
- Waiting for next nearby (but not too close!) supernova

Physics of atmospheric Neutrinos

- Disappearing of muon neutrinos ν_μ due to oscillations in earth: $\nu_\mu \leftrightarrow \nu_\tau$
- Points toward max. mixing.



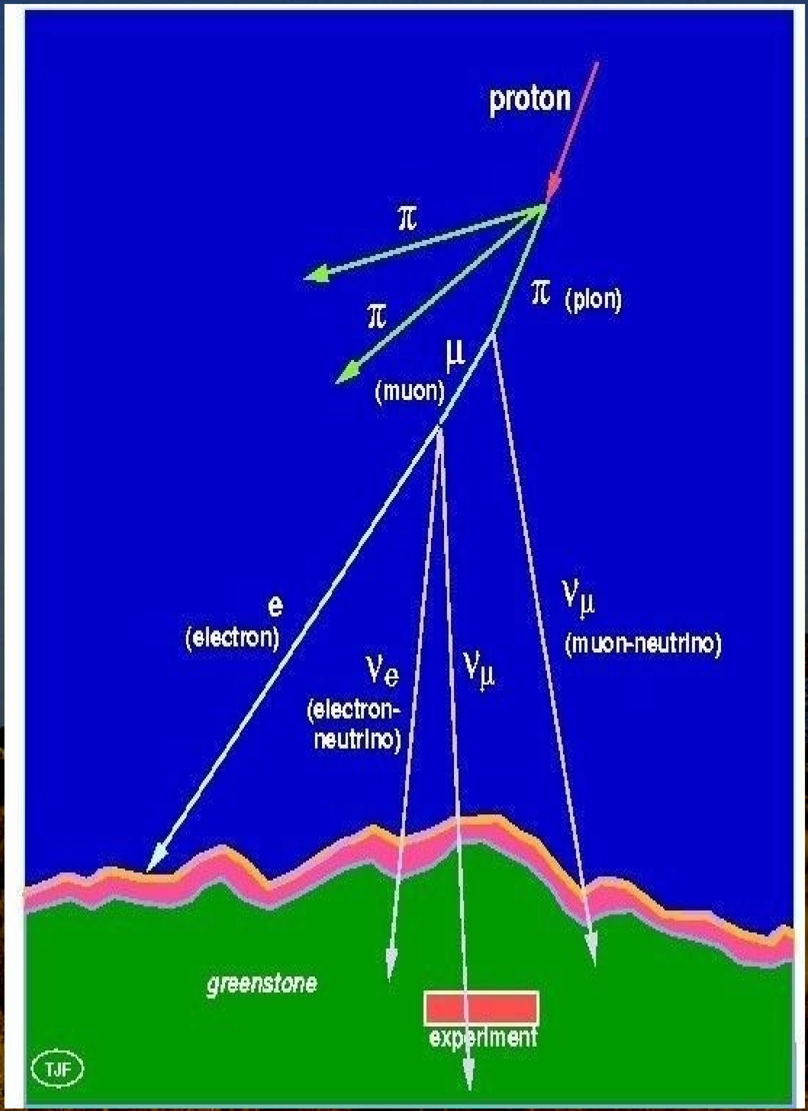


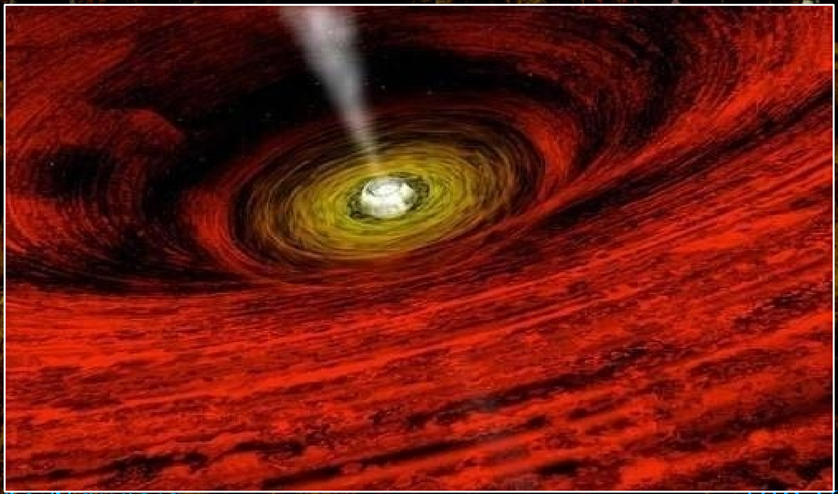
High Energy Neutrinos

- Atmospheric neutrinos
  - Neutrinos produced in hadronic showers

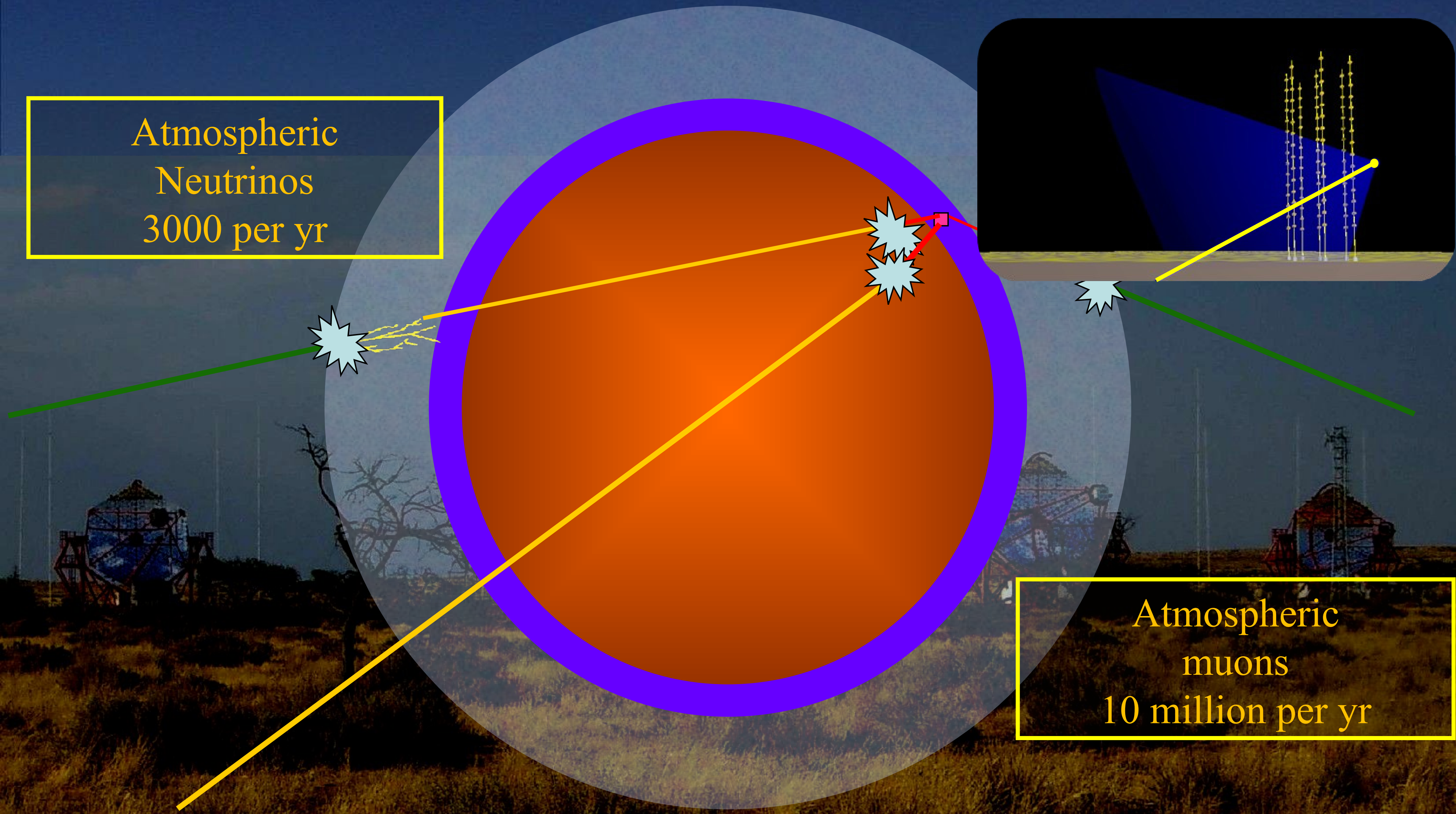
$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu \rightarrow e^- \bar{\nu}_e \nu_\mu \bar{\nu}_\mu$$

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





Detection principle



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Comparison of media

ICE

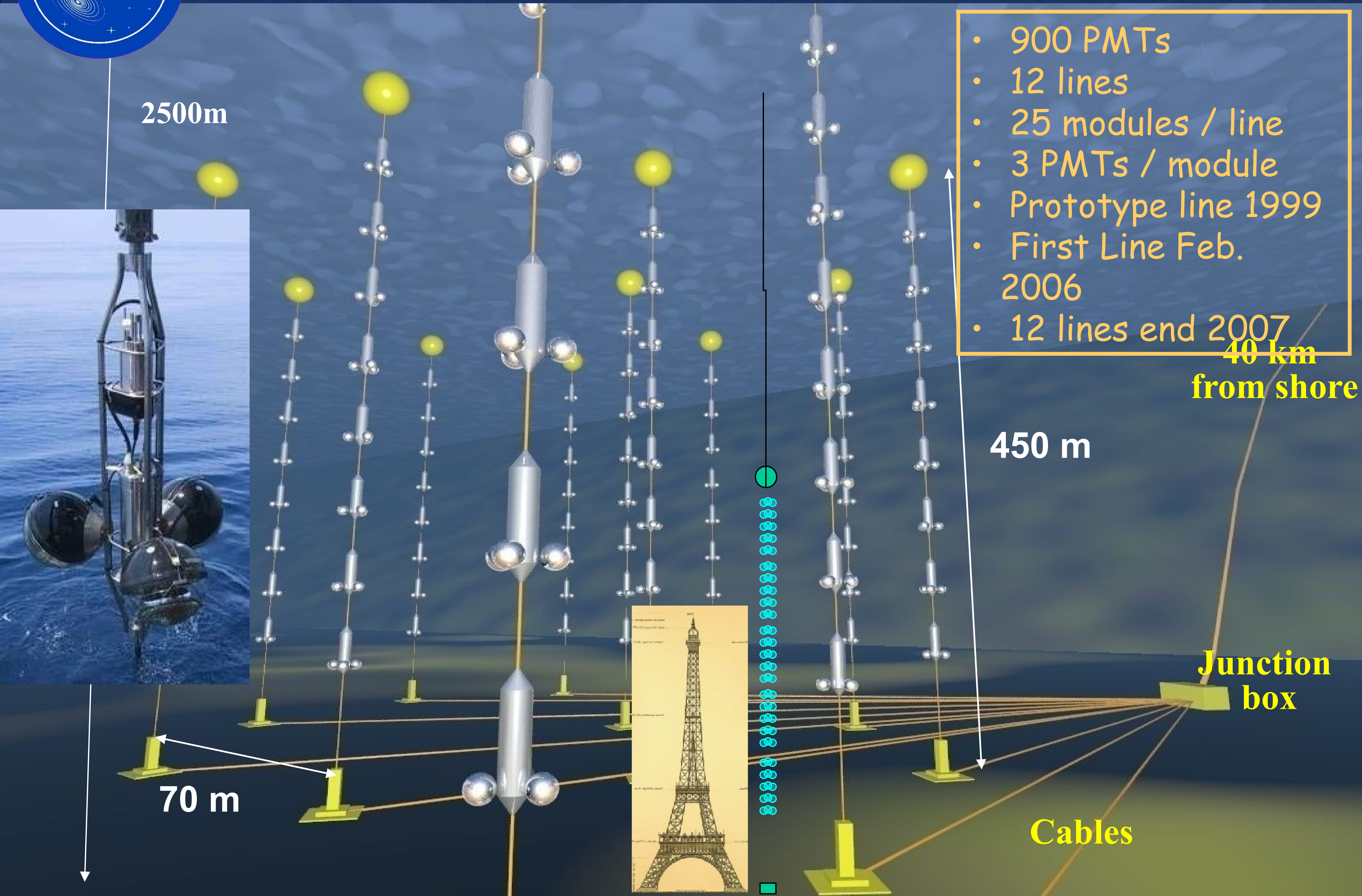
- Stable, easy drilling
- ~350 Hz noise (40K), sterile
- Large absorption length ~100 m
- Low diffusion length 20-25 m (degraded angular resolution)
- Max Depth 2500 m

WATER

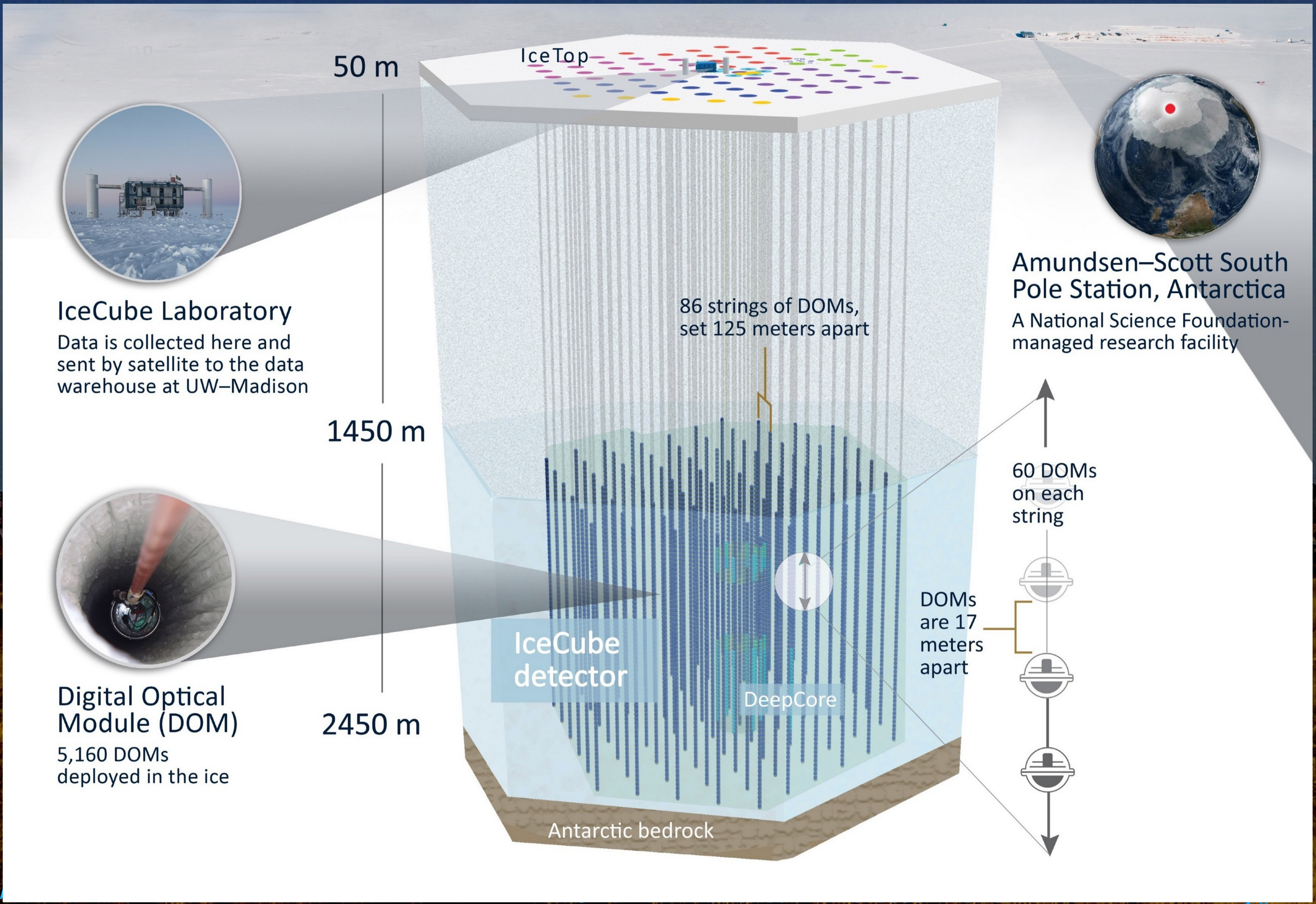
- High pressure, corroding
- 30-60 kHz noise, bioluminescence
- Low absorption length 25-60 m
- Large diffusion length >100 m
- Max Depth 3800 m

Antares

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

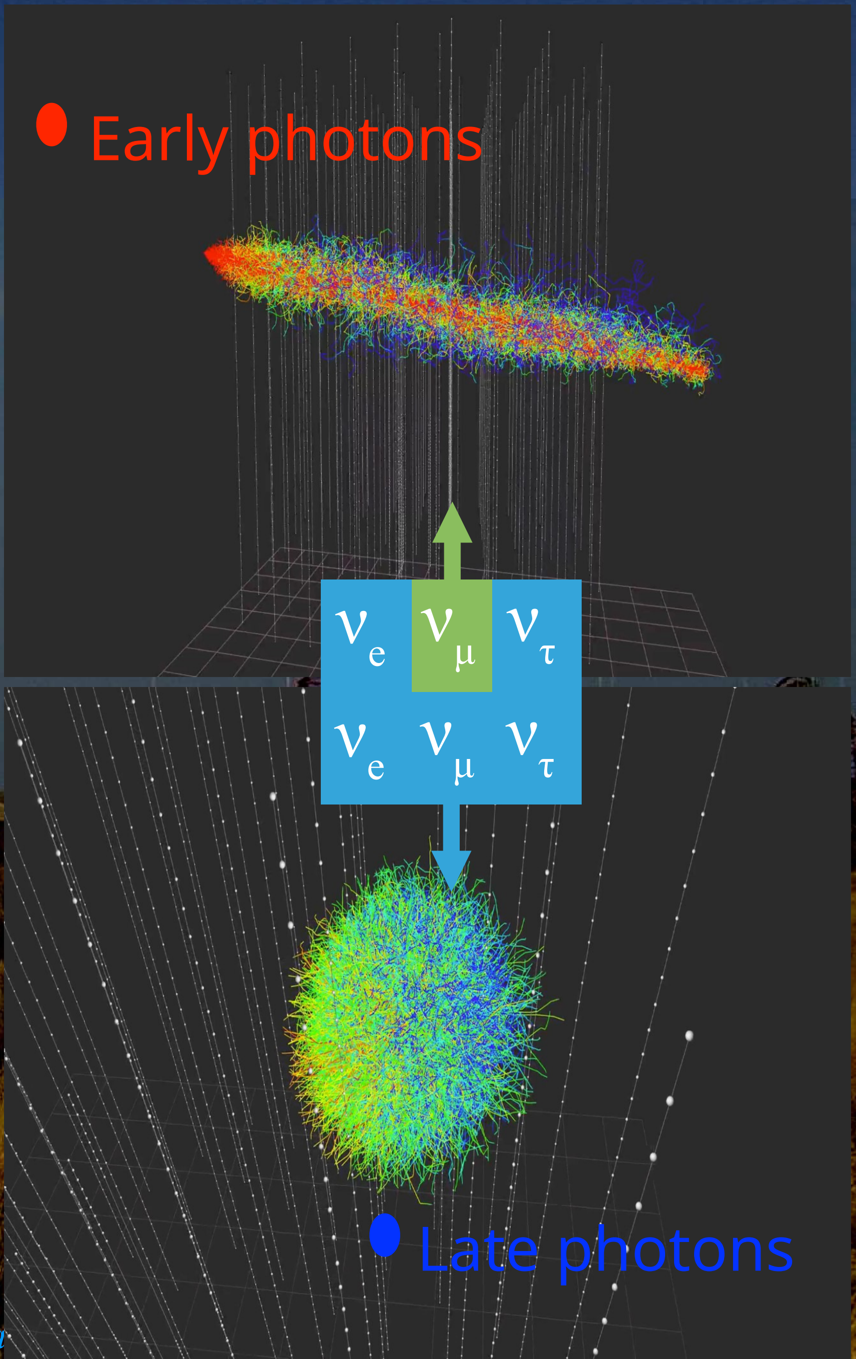


Ice Cube


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

Signatures

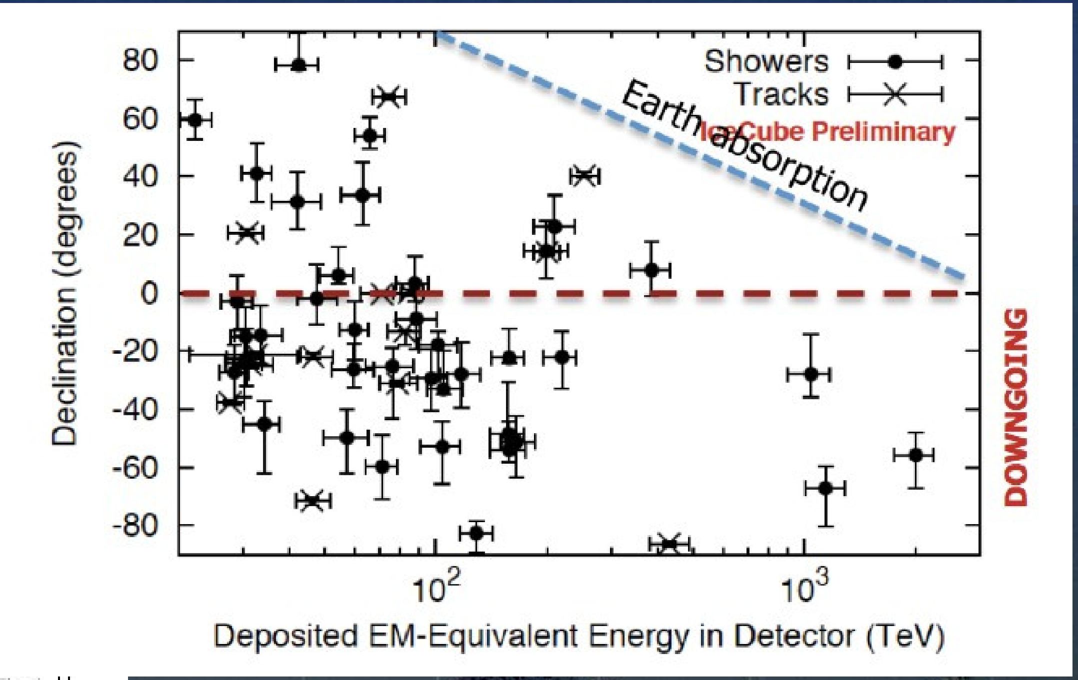
- "Track" events
  - Only ν_μ
  - Good angular resolution ($\leq 1°$)
    → Neutrino astronomy
  - Vertex outside detector
    → Bad energy resolution

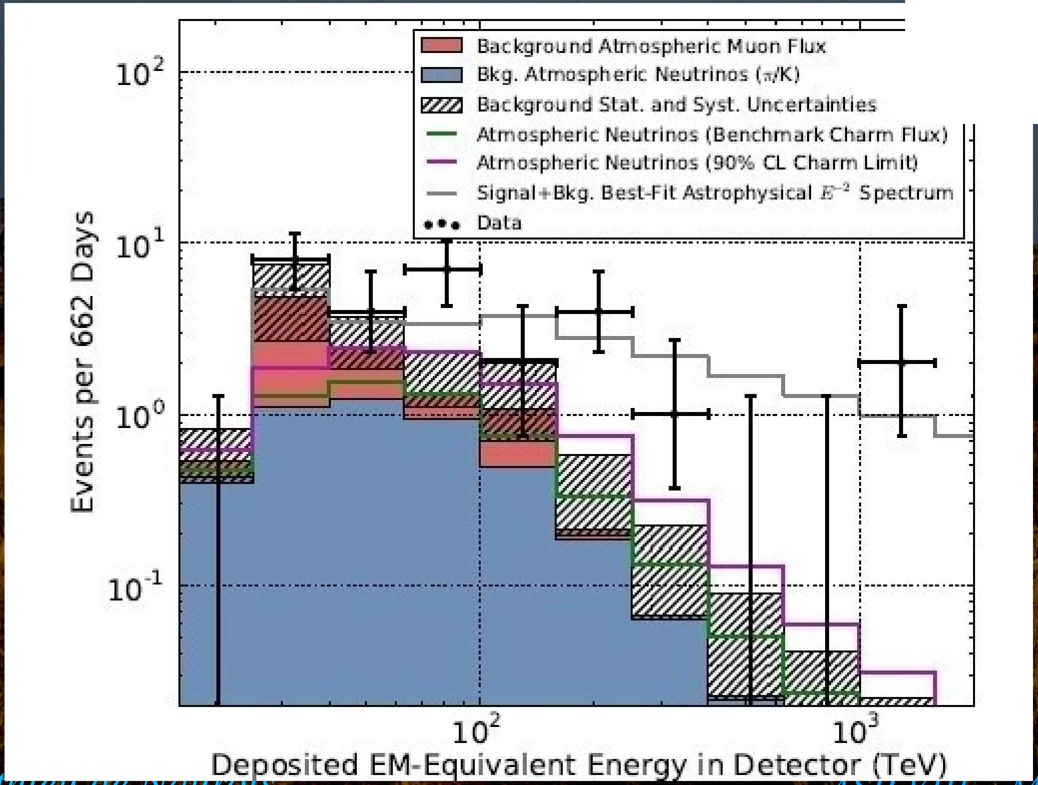


- "Shower" events
  - All flavours (e^- scattering)
  - Bad angular resolution (~10°)
  - But fully calorimetric
    → Energy Resolution ~ 15%

TeV Neutrinos

- 53 TeV neutrinos detected (above ~ 30 TeV)
- Well above atmospheric background (6.5 σ)
- First astrophysical signal!

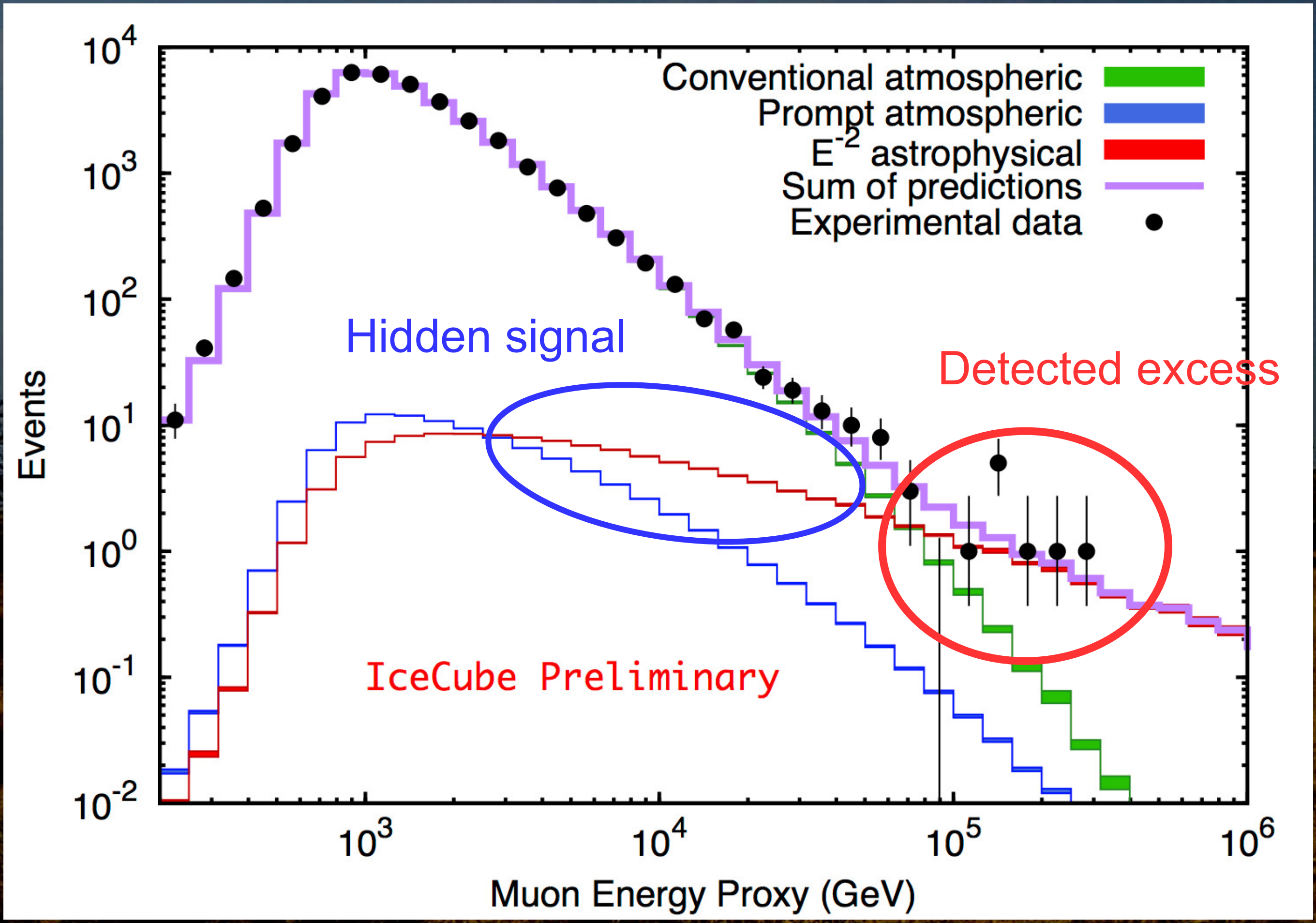




- Some are muon neutrinos ⇒ good angular resolution [~ 1°]
- Showers ⇒ ~ 15°

Astrophysical Neutrinos

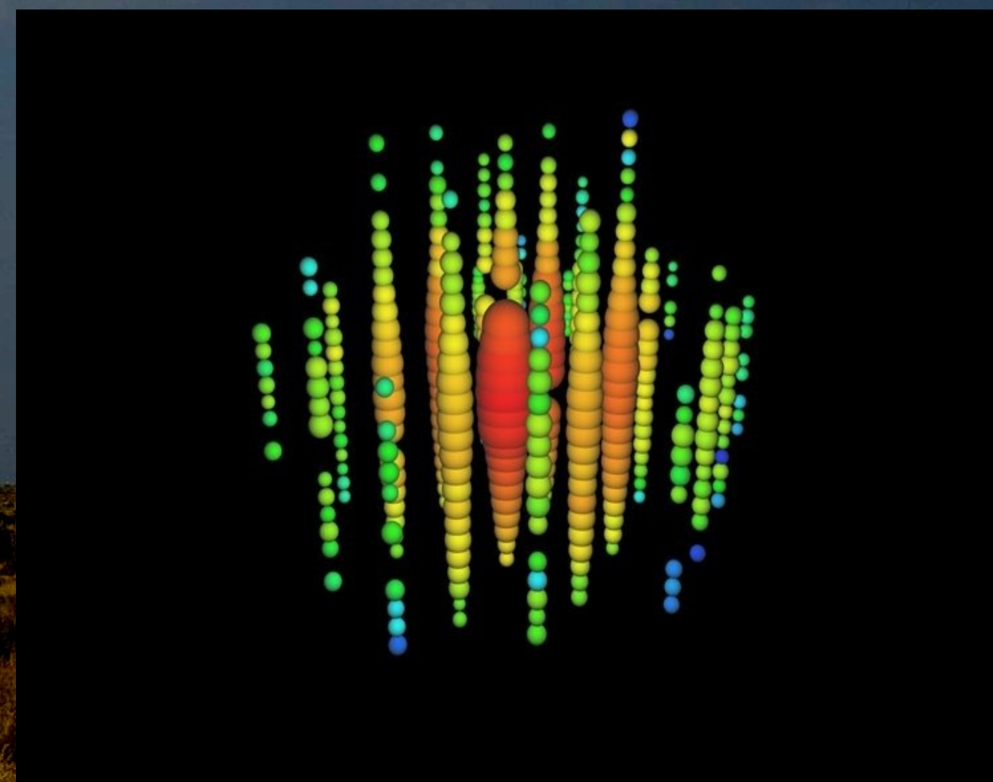
- Tons of astrophysical neutrinos hidden by the background below ~ 60 TeV



PeV neutrinos

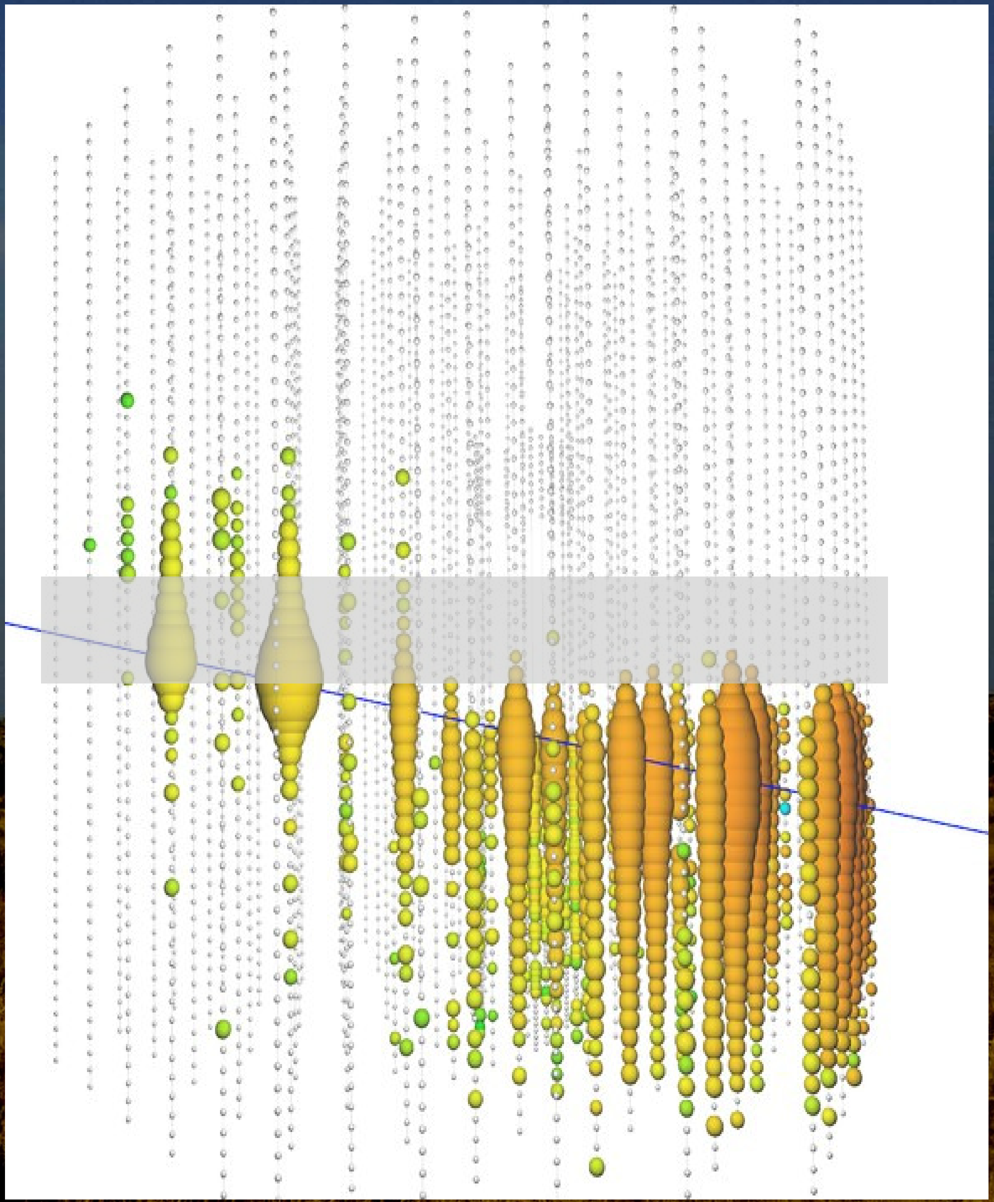
- Summer 2012: 2 PeV neutrinos announced (Bert and Ernie)
- 1.04 ± 0.16 and 1.14 ± 0.17 PeV
- 2.8 sigma above expected atmospheric background
- Could be produced by AGN or GRBs
- More events (~10) accumulated since then

neutrino induced cascade



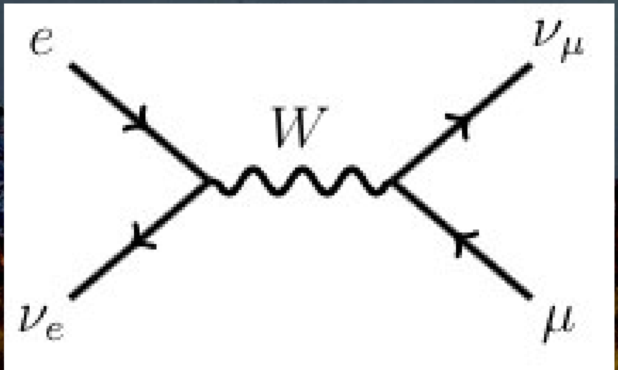
PeV Track Event

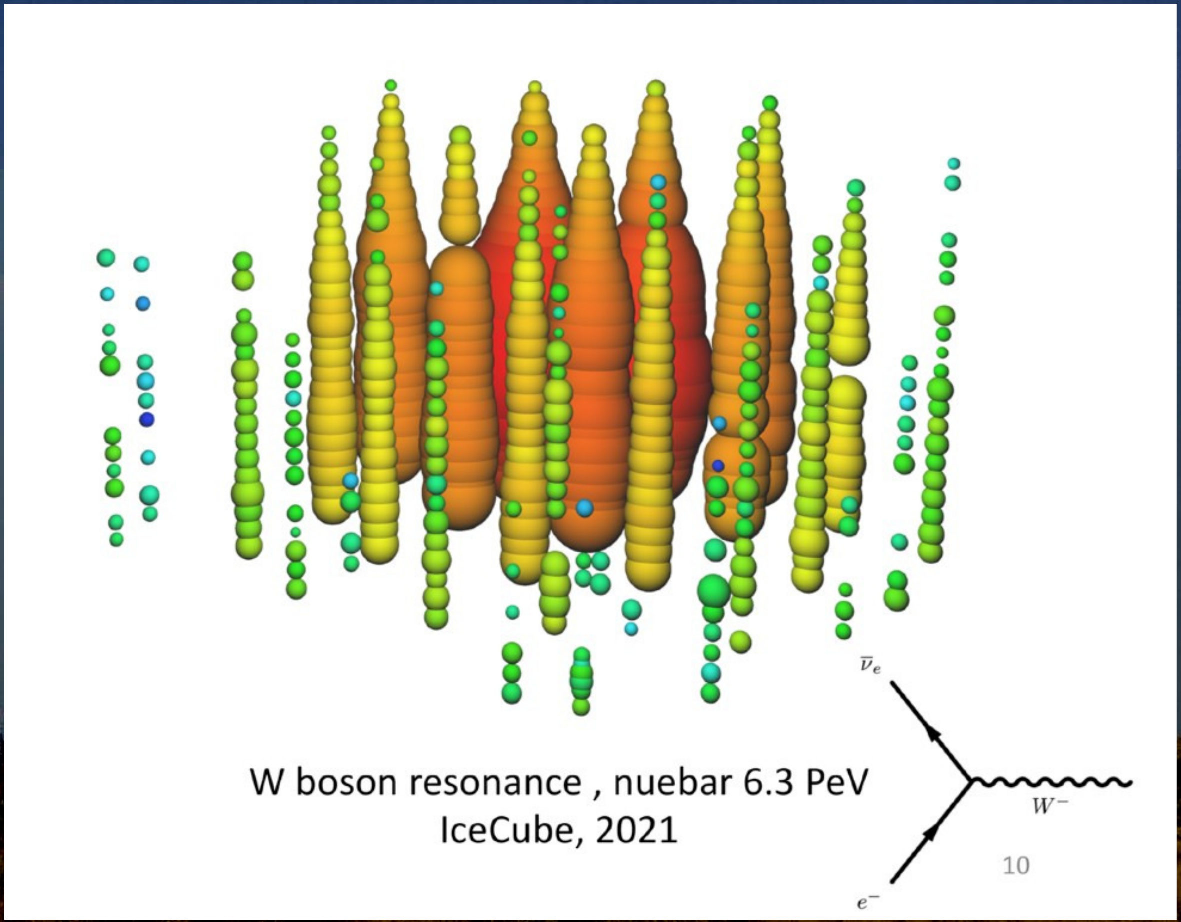
- Multi-PeV track event
  - June 11, 2014
  - deposited energy: 2.6±0.3 PeV
  - No counterpart found



Record-breaking

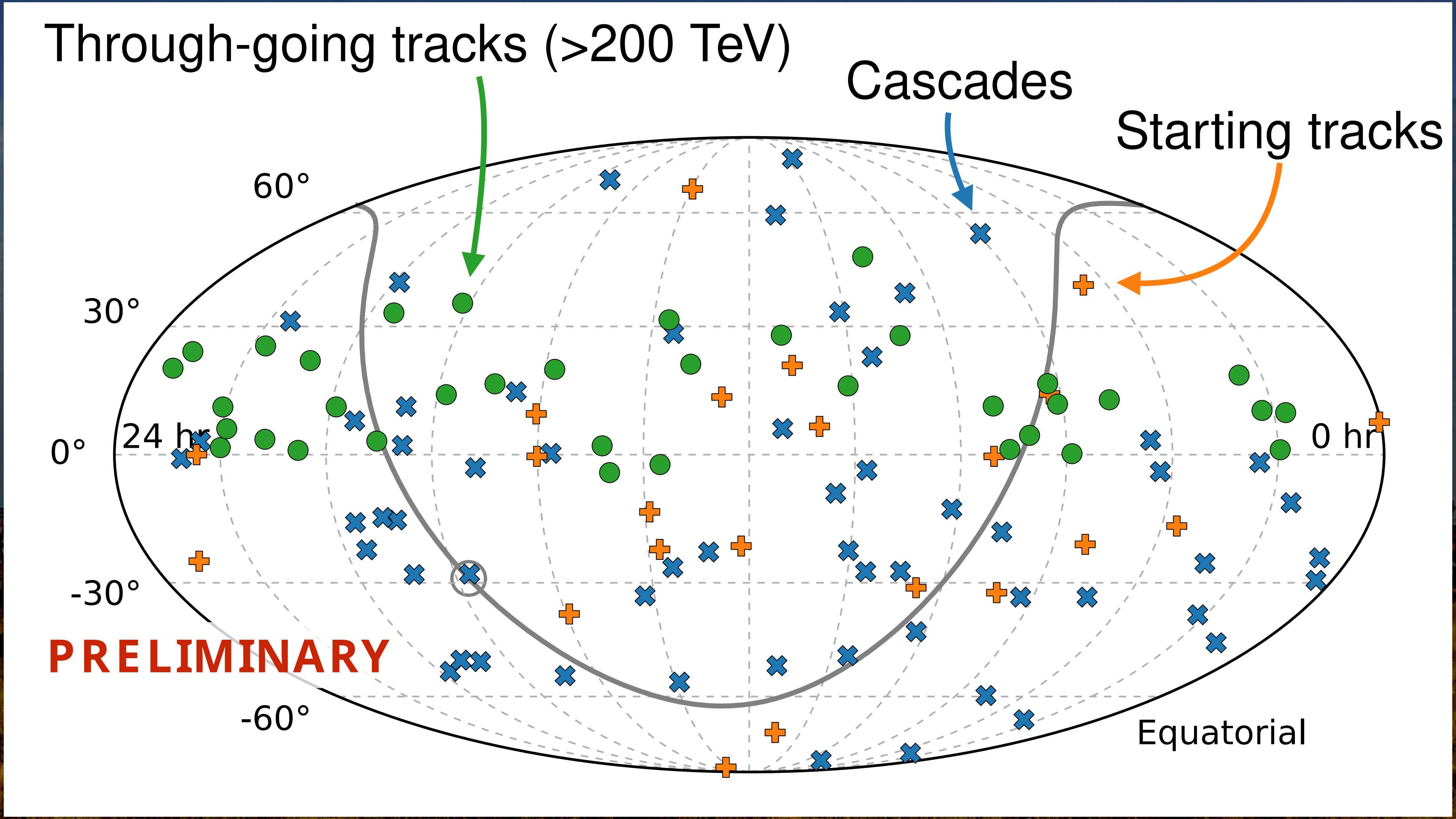
- Highest energy neutrino so far: 6.02 PeV
- First Glashow resonance event:
  $\bar{\upsilon}_e + e^- \rightarrow W^-$ @ 6.3 PeV





Nature 591, 220–224 (2021)

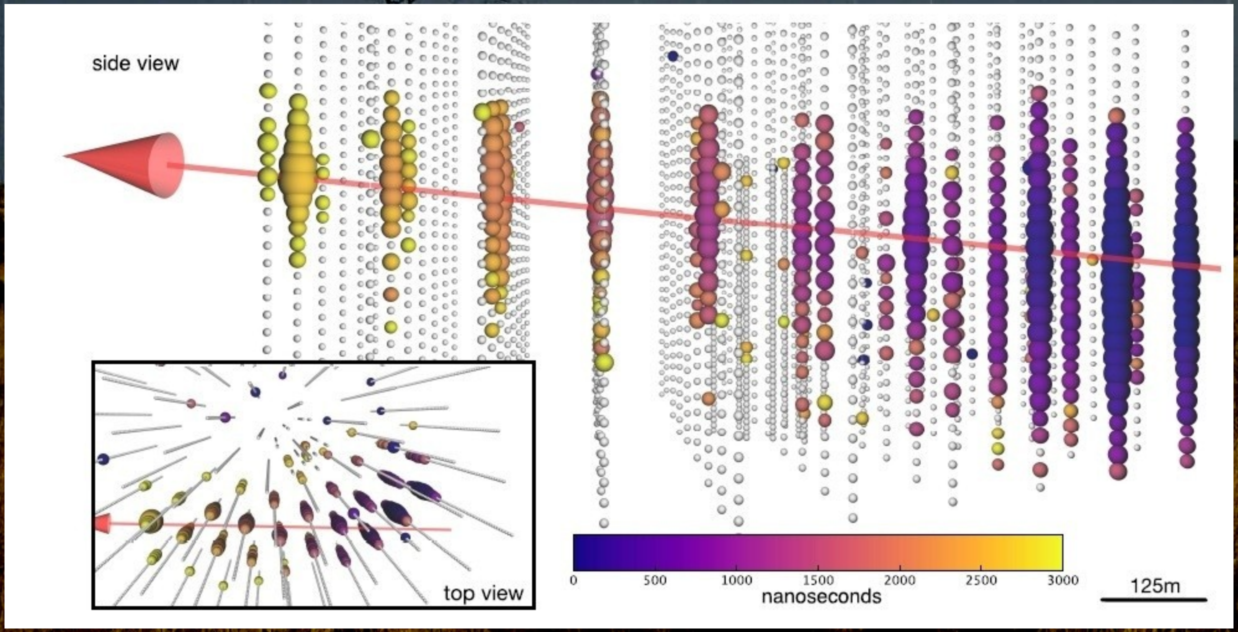
Angular distribution (2017)

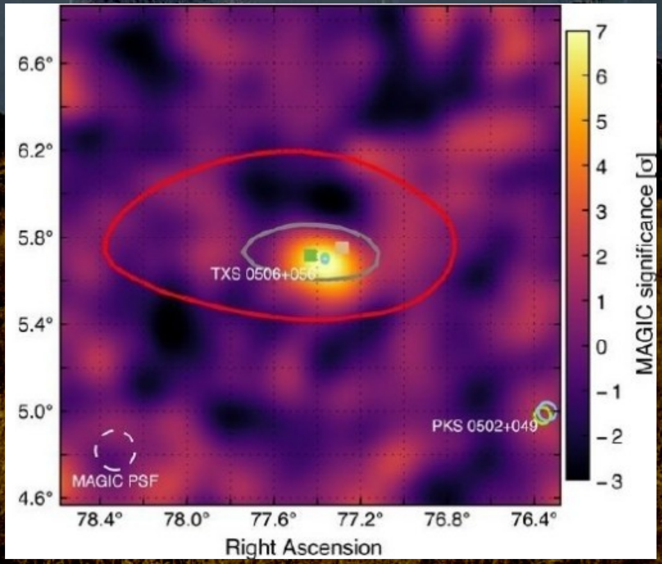


Which Sources?

- Up-going muon track (5.7° below horizon) observed on September 22, 2017 (E ~ 300 TeV)

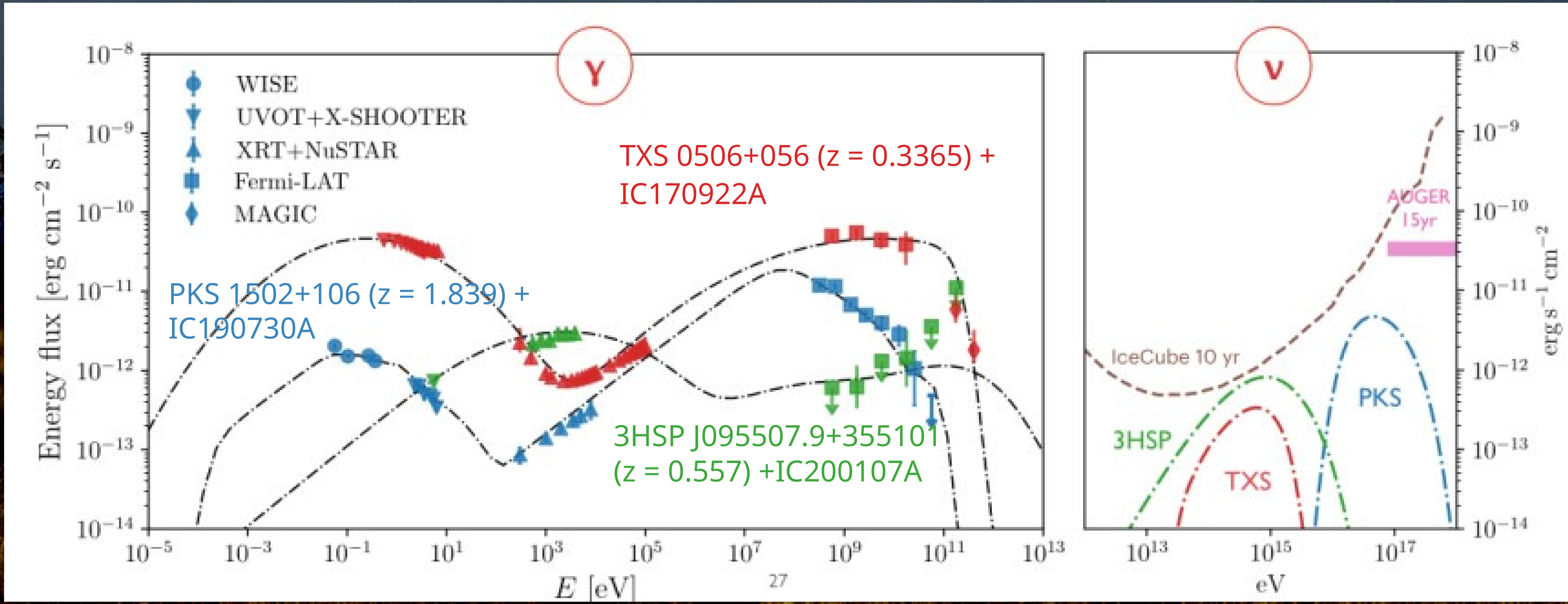
  ⇒ IceCube EHE ("extremely-high energy") alert IC-170922A
- Coincident with Flaring Blazar TXS 0506+056 (~3σ)
- Detected by MAGIC above 90 GeV ~32 hours after alert
- 3.5 σ evidence, not a detection





Recent Blazar Associations

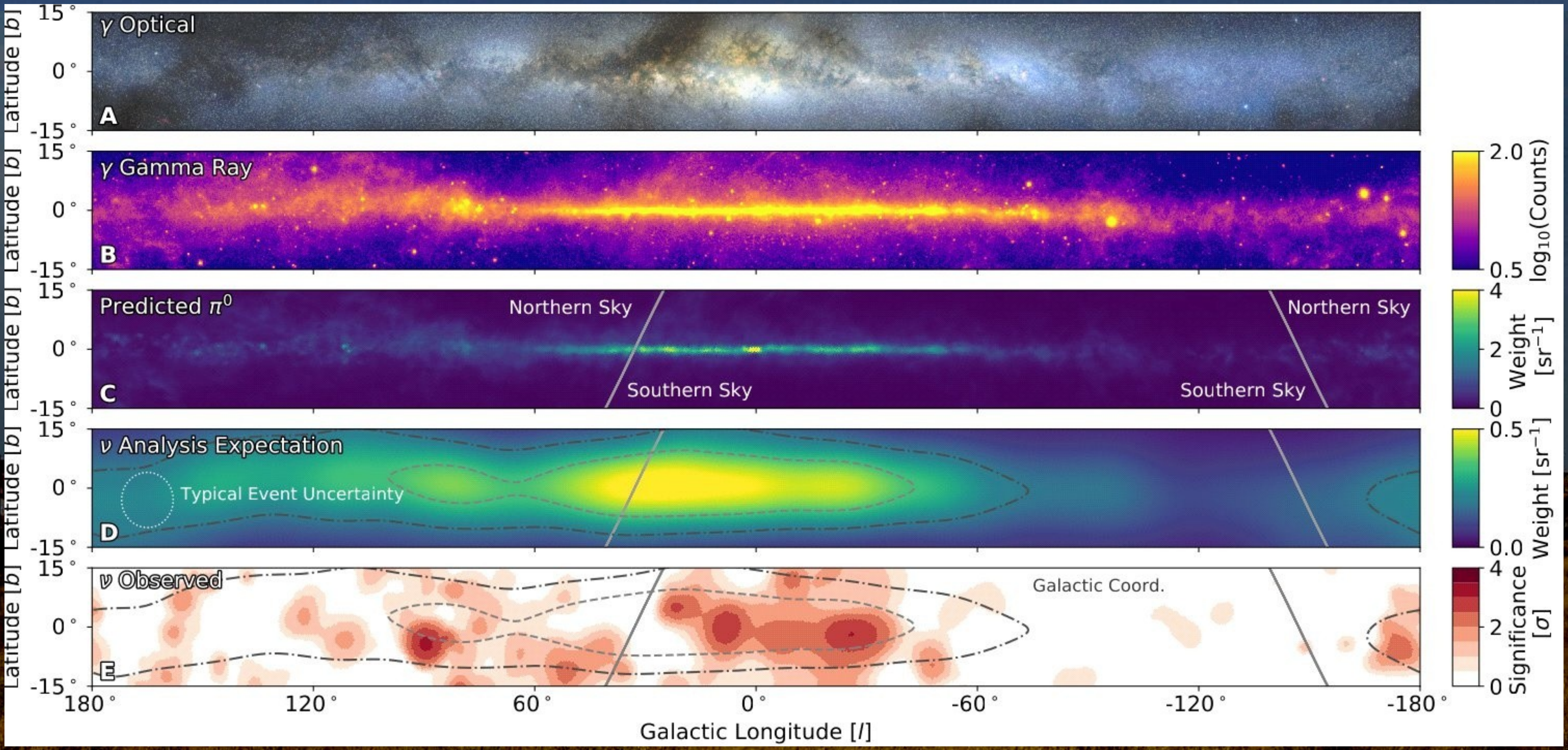
- IC 190730A ⇒ PKS 1502+106 (15th brightest GeV Blazar, with strong radio flare)
- IC 200107A ⇒ BZB / 3 HSP J0955+3551 (strong X-ray flare)
- Growing evidences that Blazars contribute to neutrino flux!



Foteini Oikonomou, ICRC 2021

2023 - Diffuse Neutrinos from the Galactic Plane

- Using Cascade events ⇒ 4.5 σ correlation with Gal. Plane

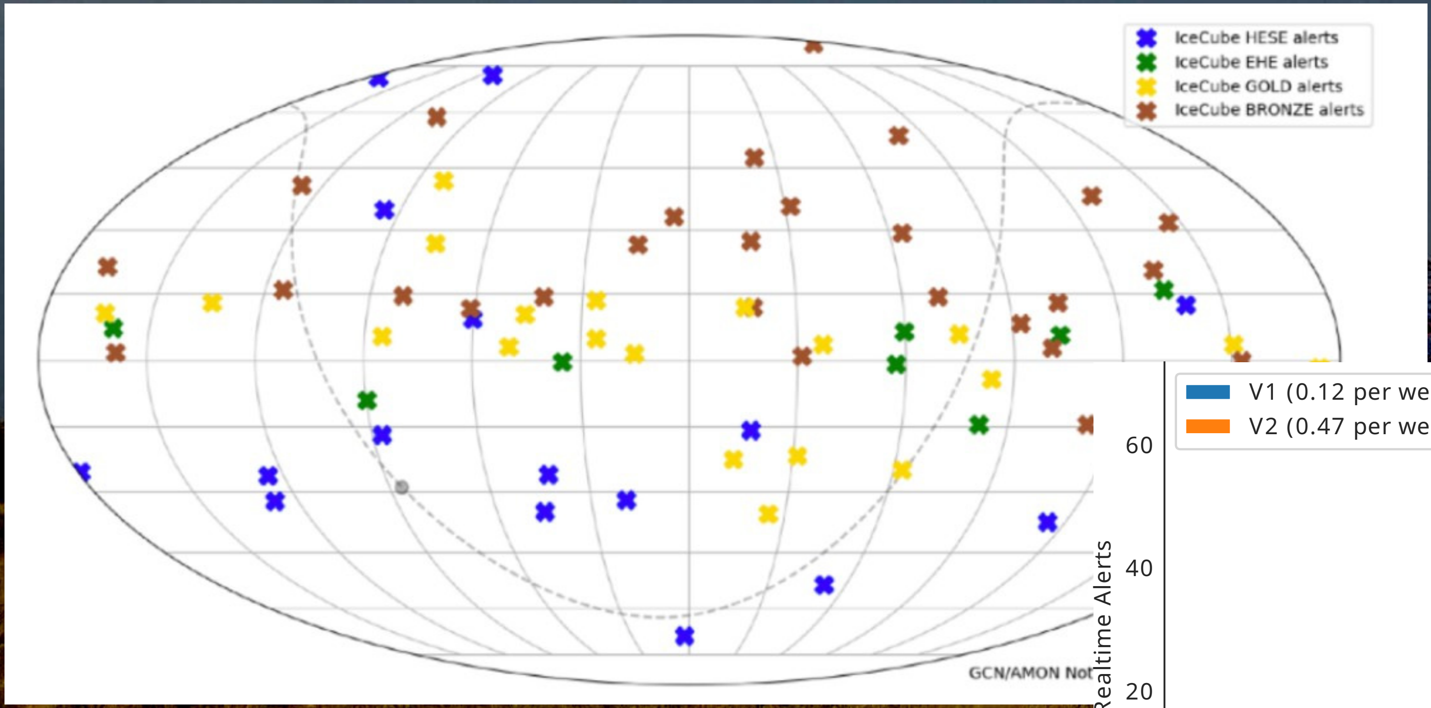


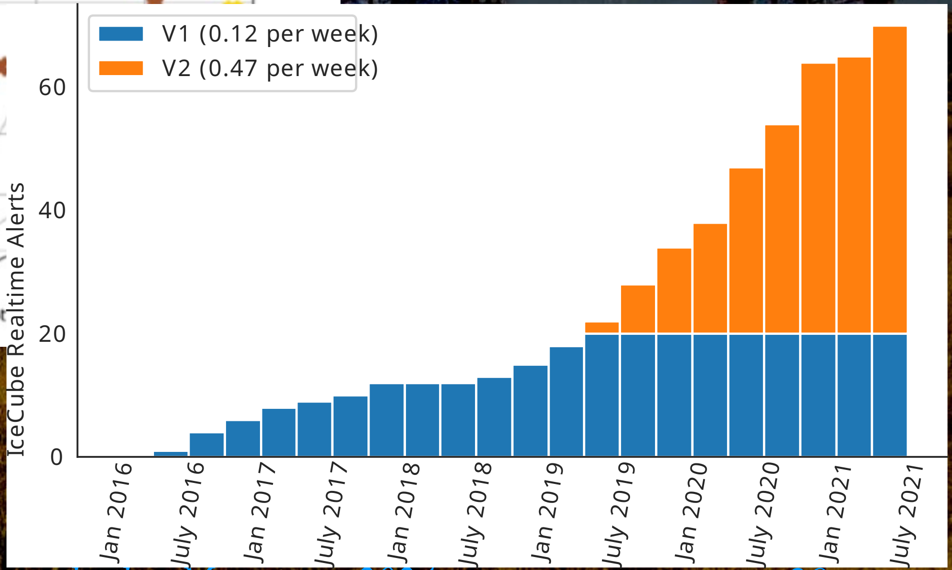
Science 380 (2023) 1338

Follow-up program

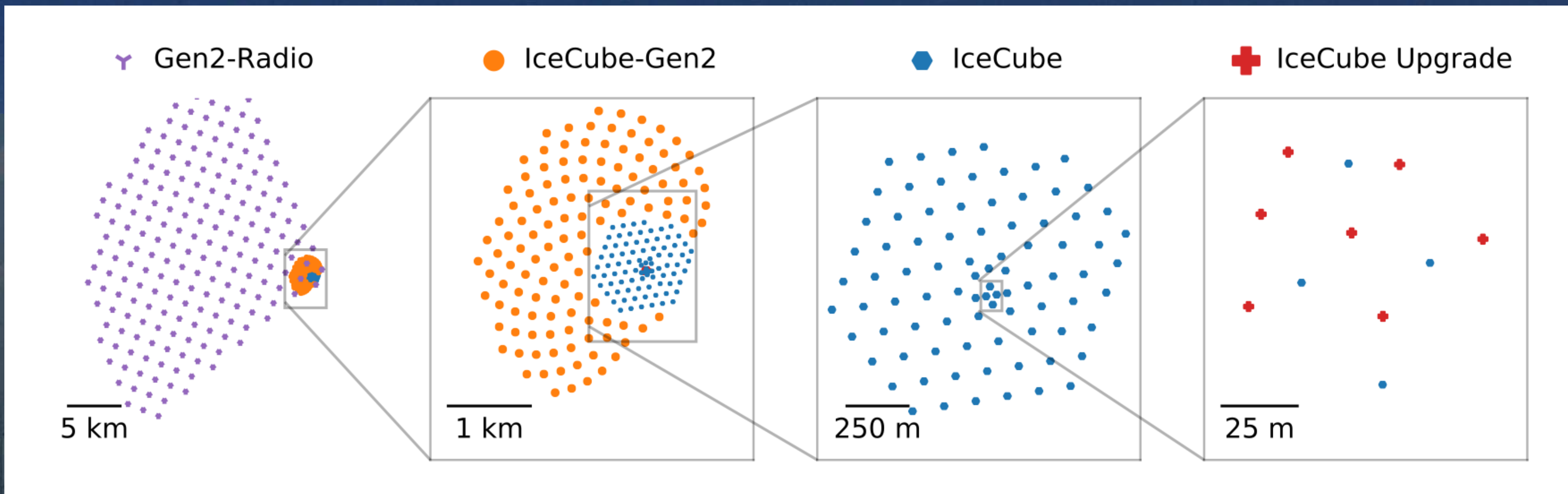
- Multi-messenger program mandatory
- Real-time stream running since april 2016

  > 80 alerts so far, followed by major instruments worldwide

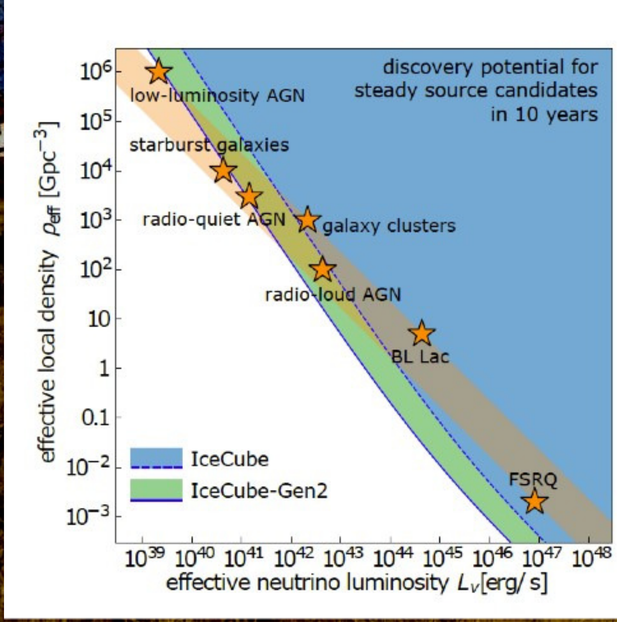




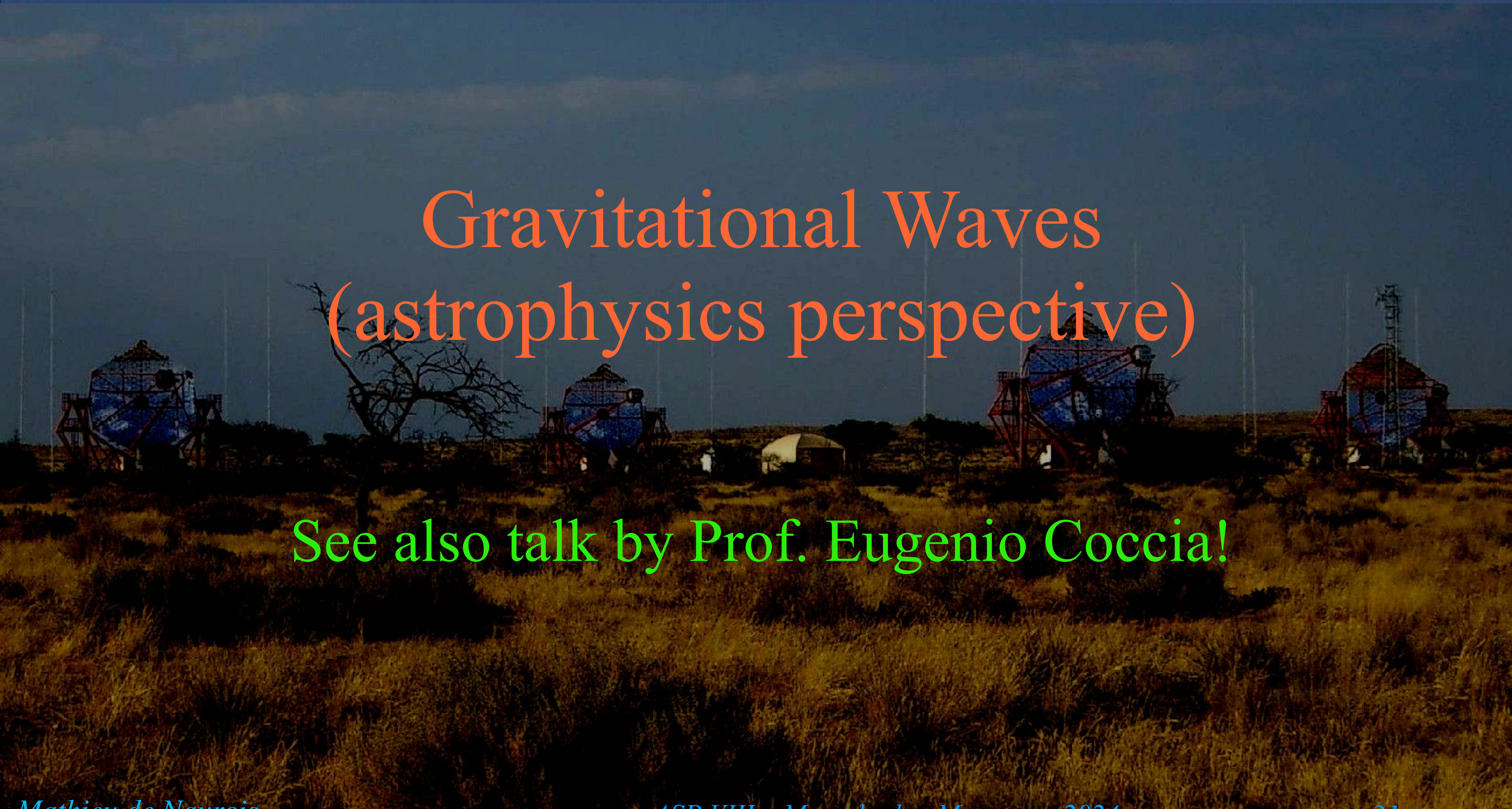
The Future – IceCube-Gen2



- Multiscale detector from 10^9 to 10^{20} eV
- IceCube-Gen2 planed construction: 2024 – 2032
- Expected ~ 10× in the number of sources
- First phase funded.



Gen2 white paper: 2008.04323

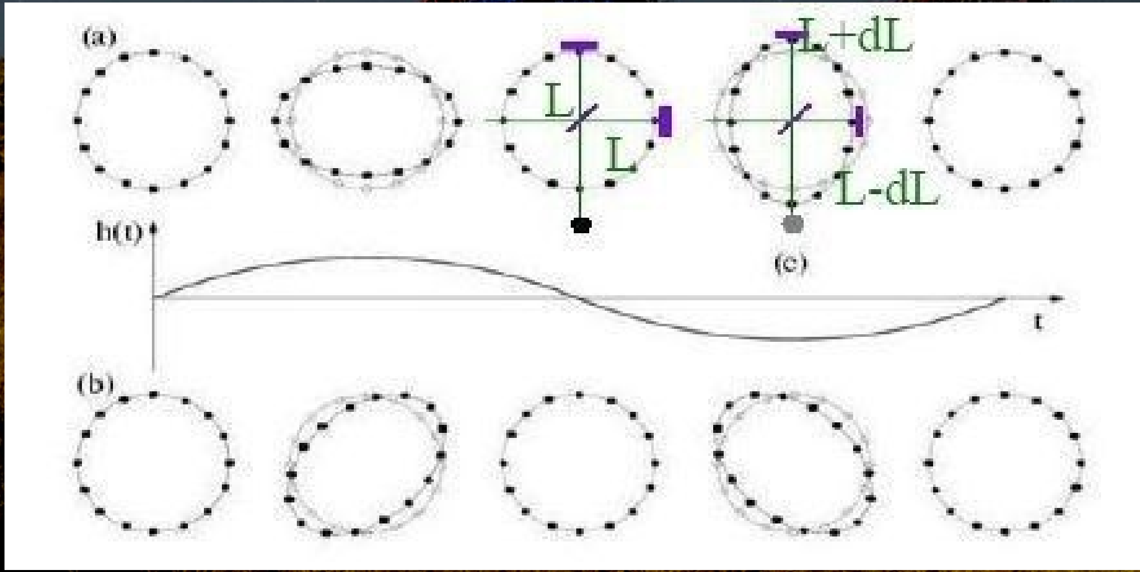


Gravitational Waves (astrophysics perspective)

See also talk by Prof. Eugenio Coccia!

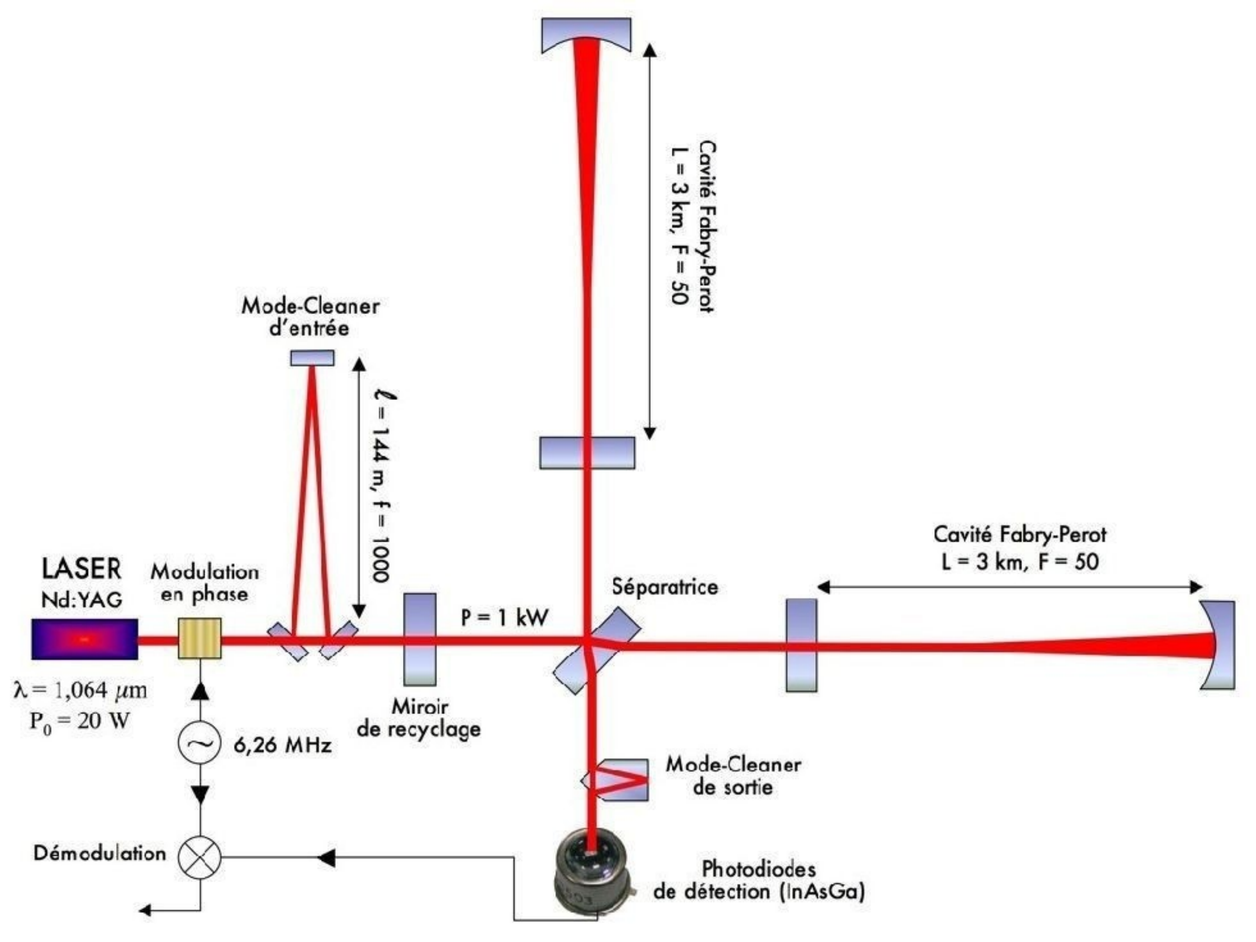
Gravitational waves

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



Detection Principles

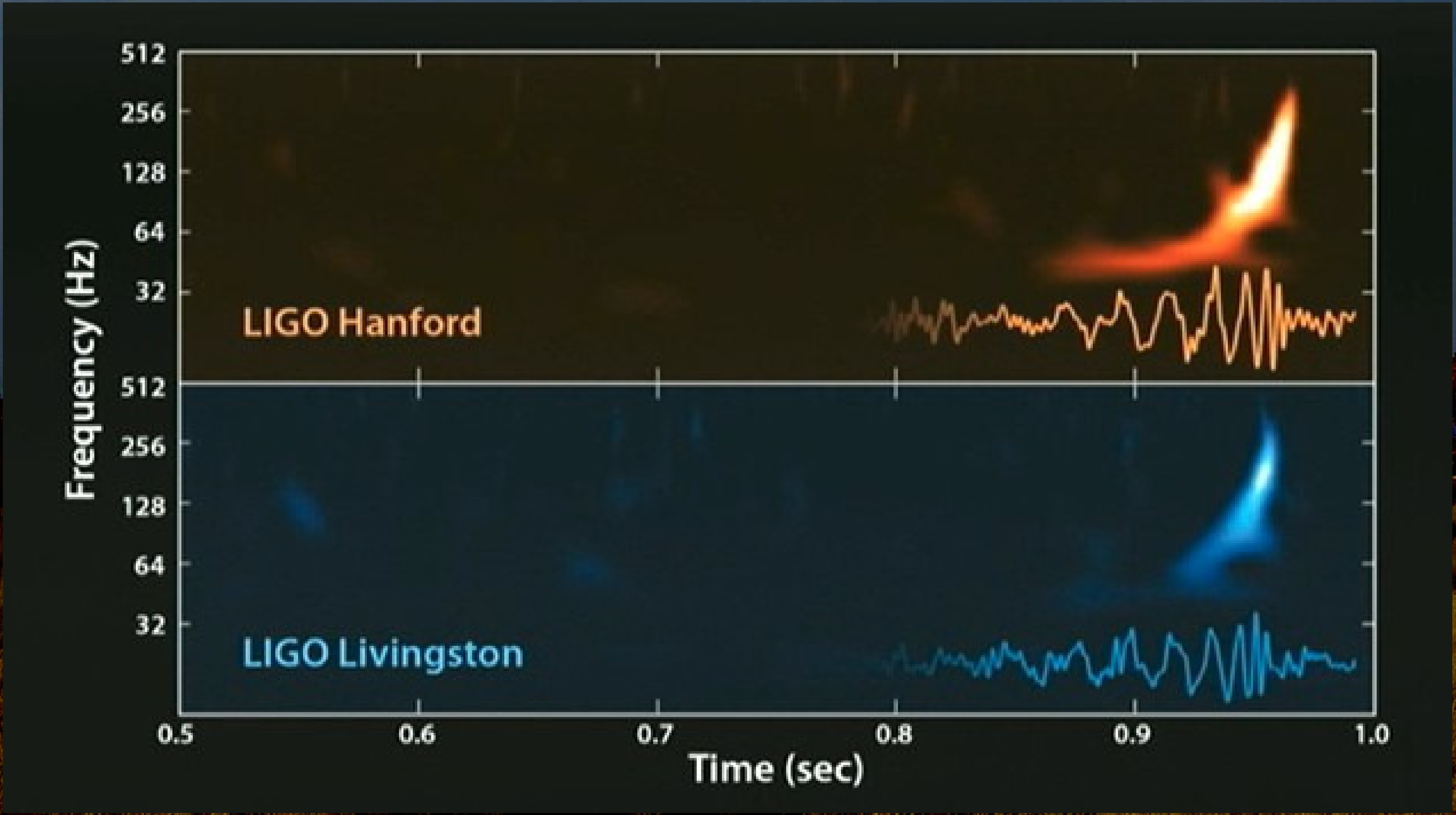
- Basic idea: giant interferometer
- Fabry Perrot cavities in each arms multiply path length and increases sensitivity
- Crazy technical challenges:
  - Typical amplitude:
    $\Delta L/L \sim 10^{-21}$,
    $\Delta L \sim 10^{-18,}$
  - Mechanic Noise (vibrations, ...)
    ⇒ Multi-stage filters
   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



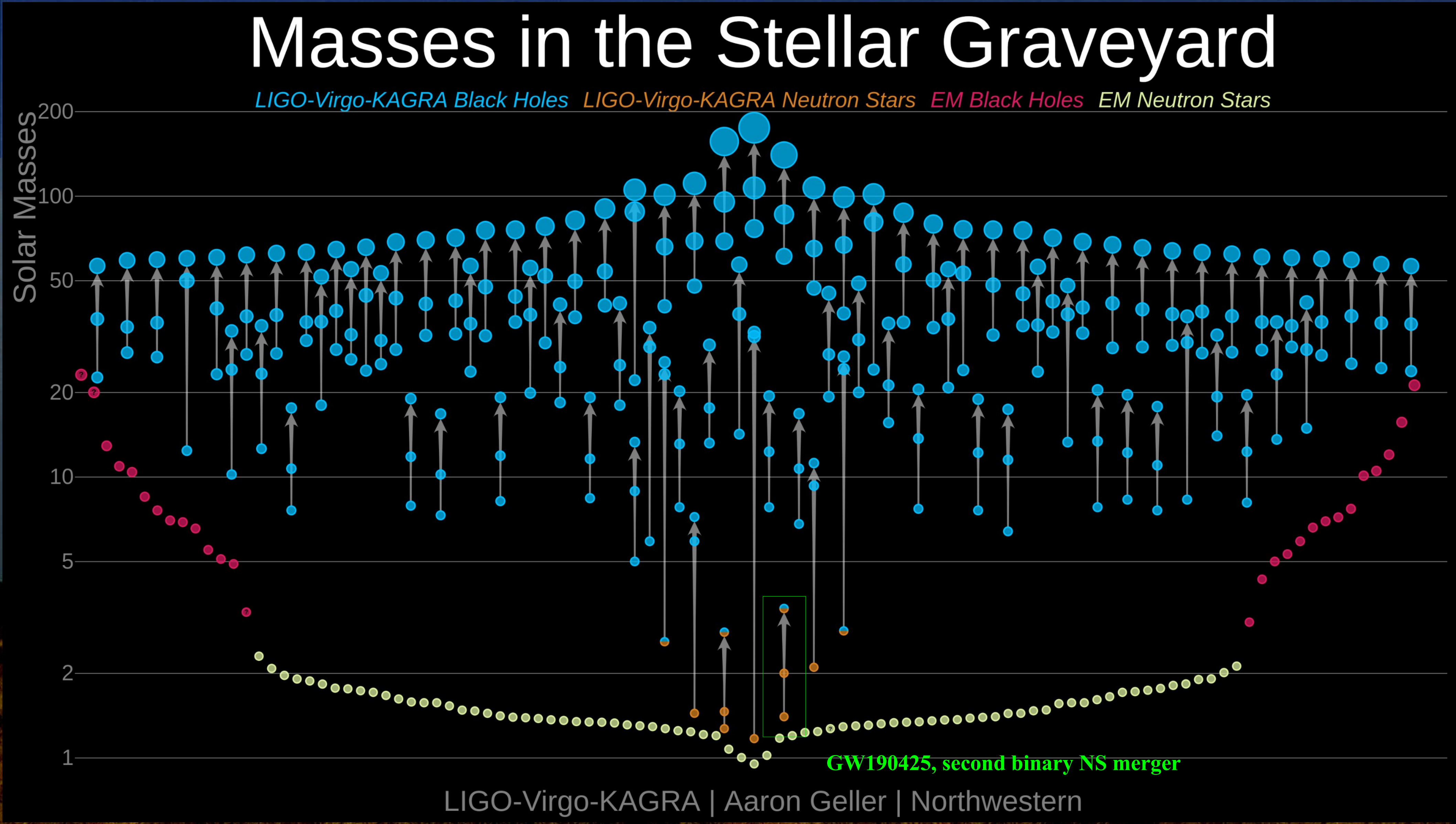
Mathieu de Naurois

First Detection – September 14th 2015

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



Final O3B Mass Plot



Released November 7, 2021

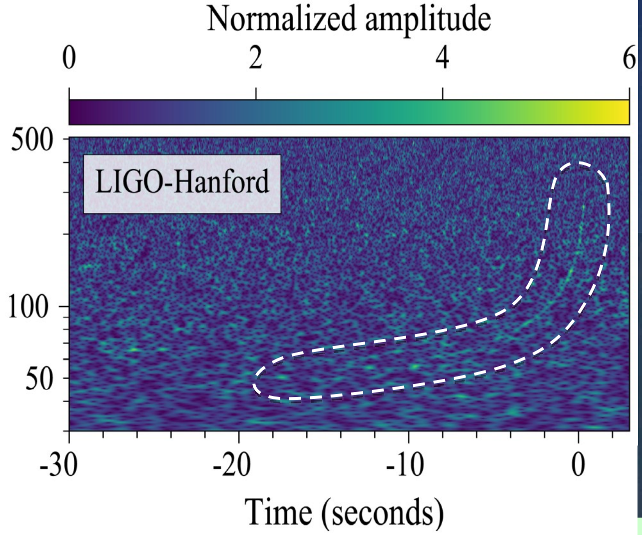
Formation Scenarii

- Major suprise: merger of intermediate mass black holes are common!
- 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

GW170817 – Neutron Star Merger

- 14h47 (CET): Automatic internal alert
- Simultaneous with a faint GRB
- First ever electromagnetic counterpart
- 15h21: First joint LIGO-Virgo alert
- Massive, worldwide, MWL observation campaign (from radio to TeV), ~90 observatories




```
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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 trigg                                        , 3.9
[deg].    COMMENTS:          T                                        5 mi
after the trigger.
///////////////////////////                                          /
```
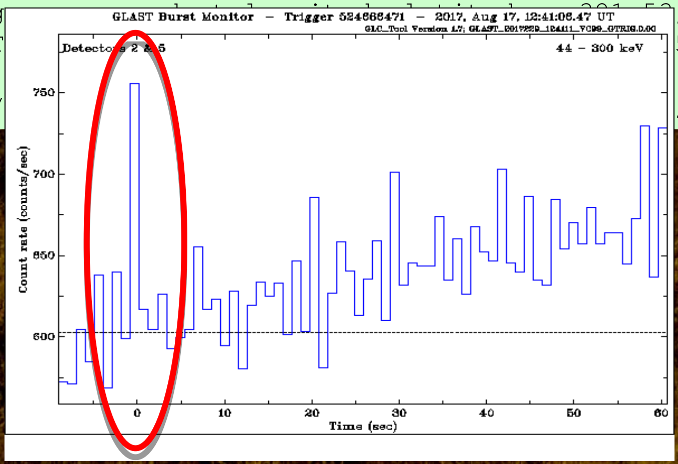
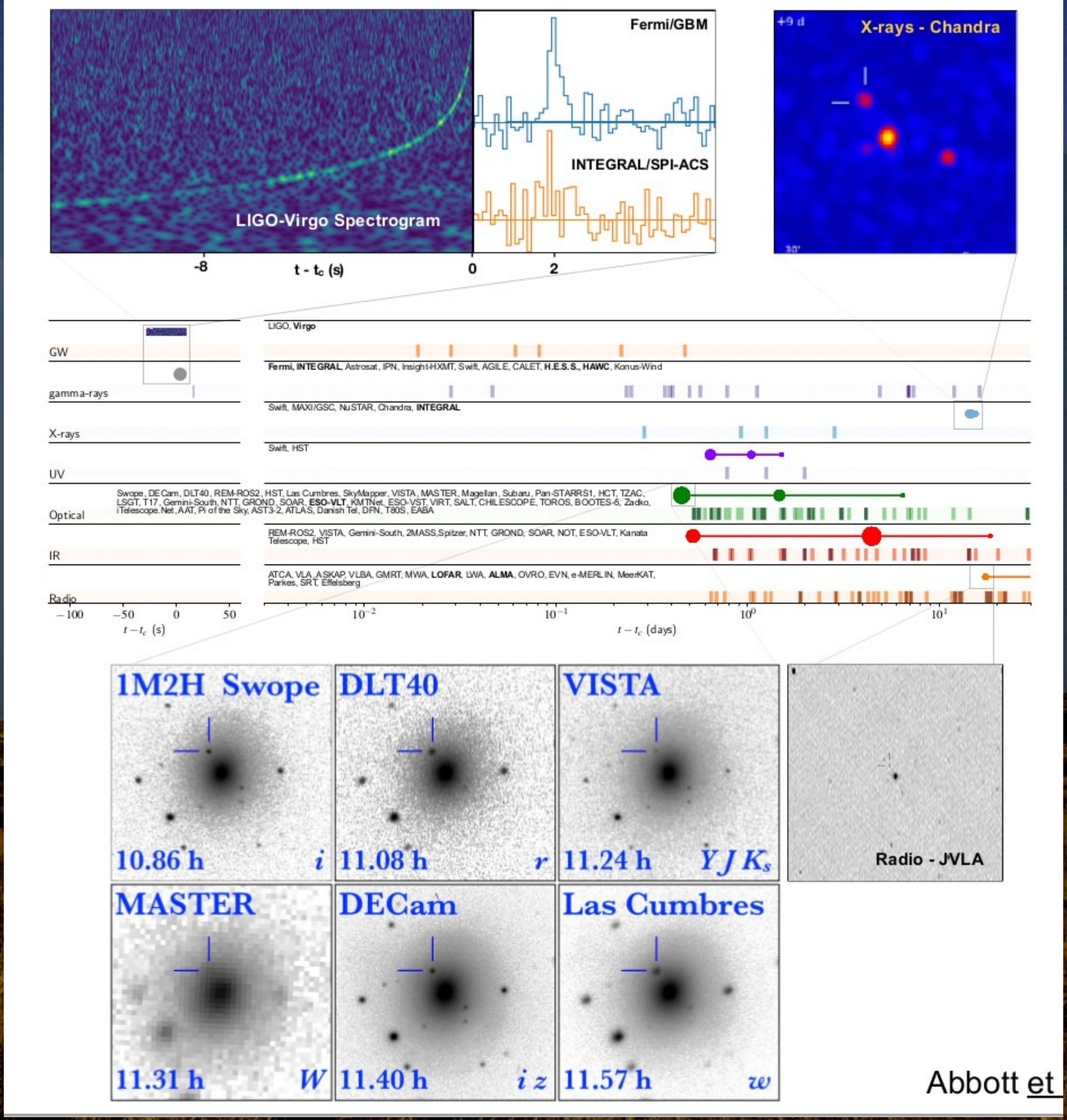



GW170817 - Neutron Star Merger

- 14h47 (CET): Automatic internal alert
- Simultaneous with a faint GRB
- First ever electromagnetic counterpart
- 15h21: First joint LIGO-Virgo alert
- Massive, worldwide, MWL observation campaign (from radio to TeV), ~90 observatories



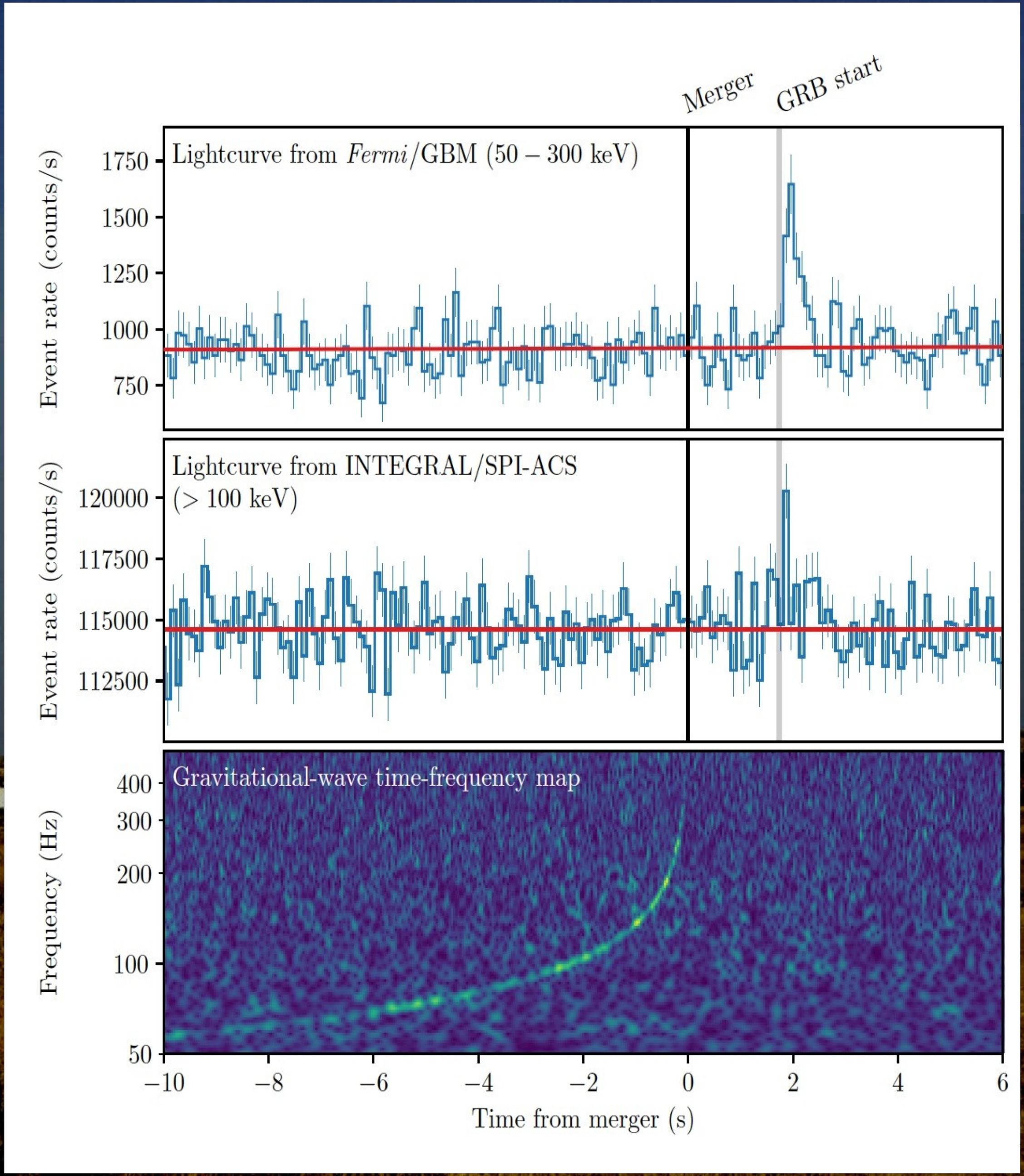
Timing

- GW & GRB almost simultaneous ($\Delta t \sim 2s$)
  - GRB slightly delayed (emitted after) due to opacity of fireball
- Travel time 130×10^6 y

  → GW propagate at c

  → Independent measure of Hubble constant (distance from GW, redshift from electromagnetic)

$$h_0 = 70.0^{+12.0}_{-8.0}\ \mathrm{km s^{-1} Mpc^{-1}}$$



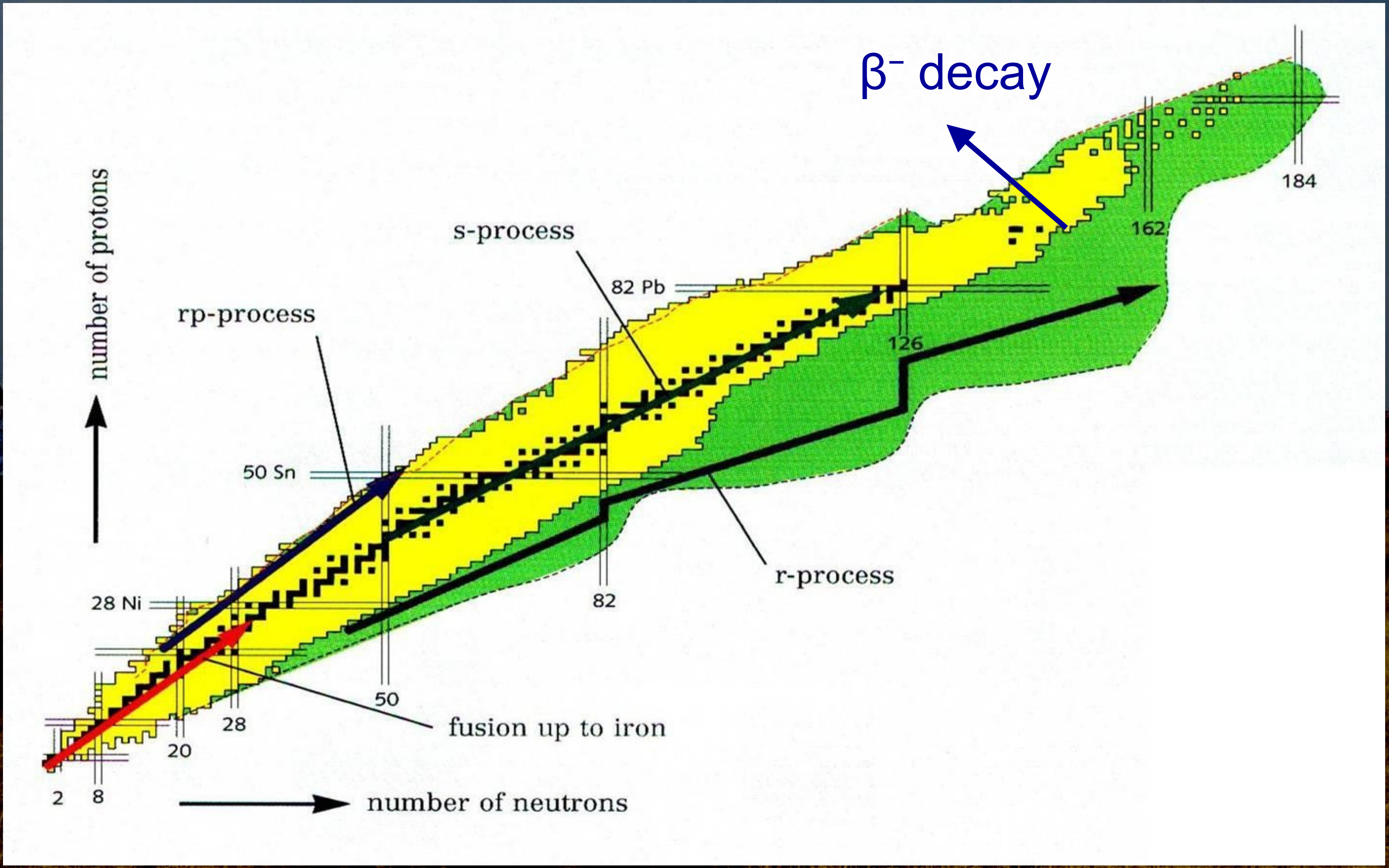
Neutron Star Merger – KiloNova

- Confirmation of the “kilonova mechanism”
- Formation of heavy elements by massive neutron flux on nuclei

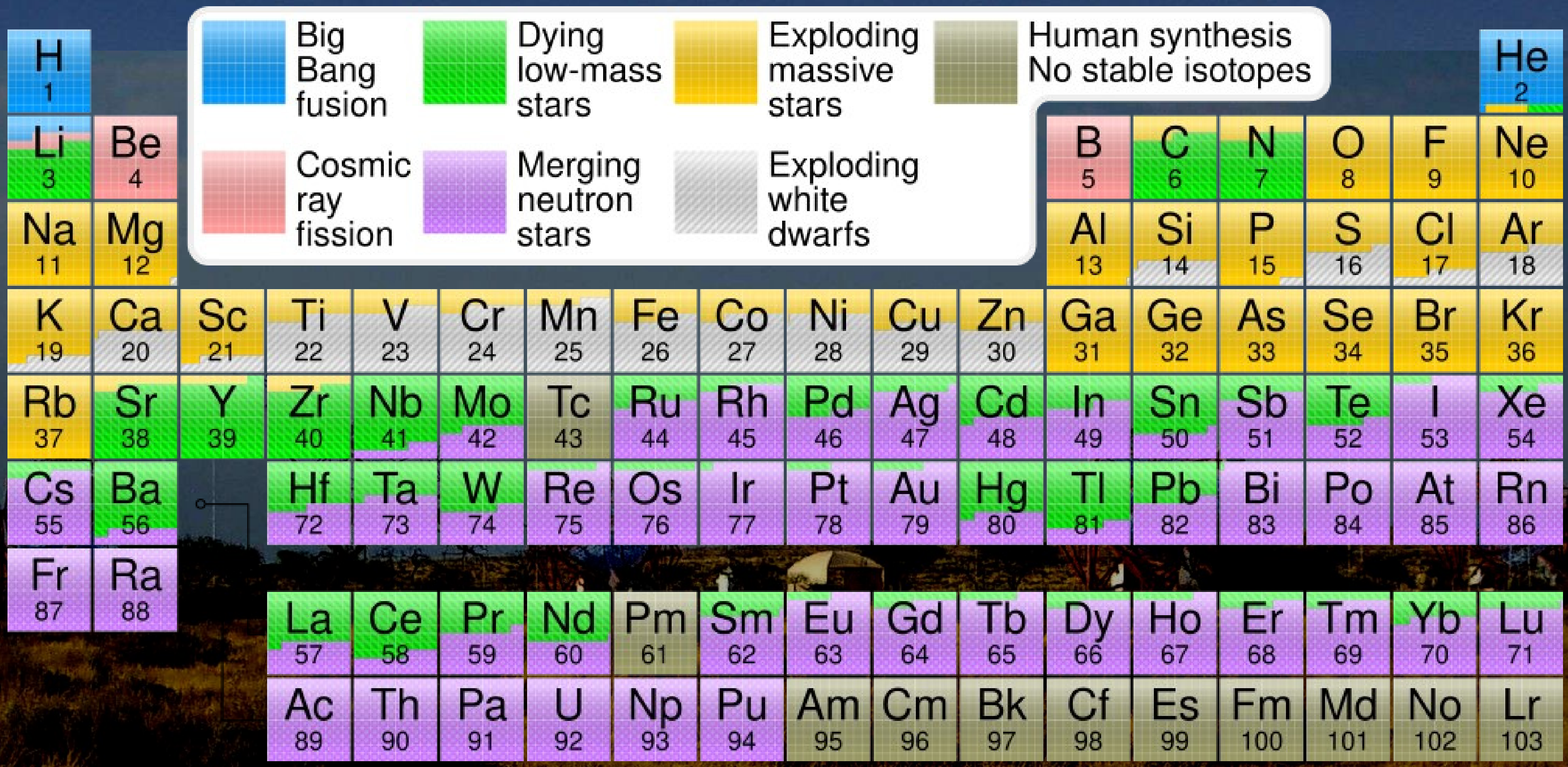
Animation: NASA's Goddard Space Flight Center

R-proces – the path to heavy elements

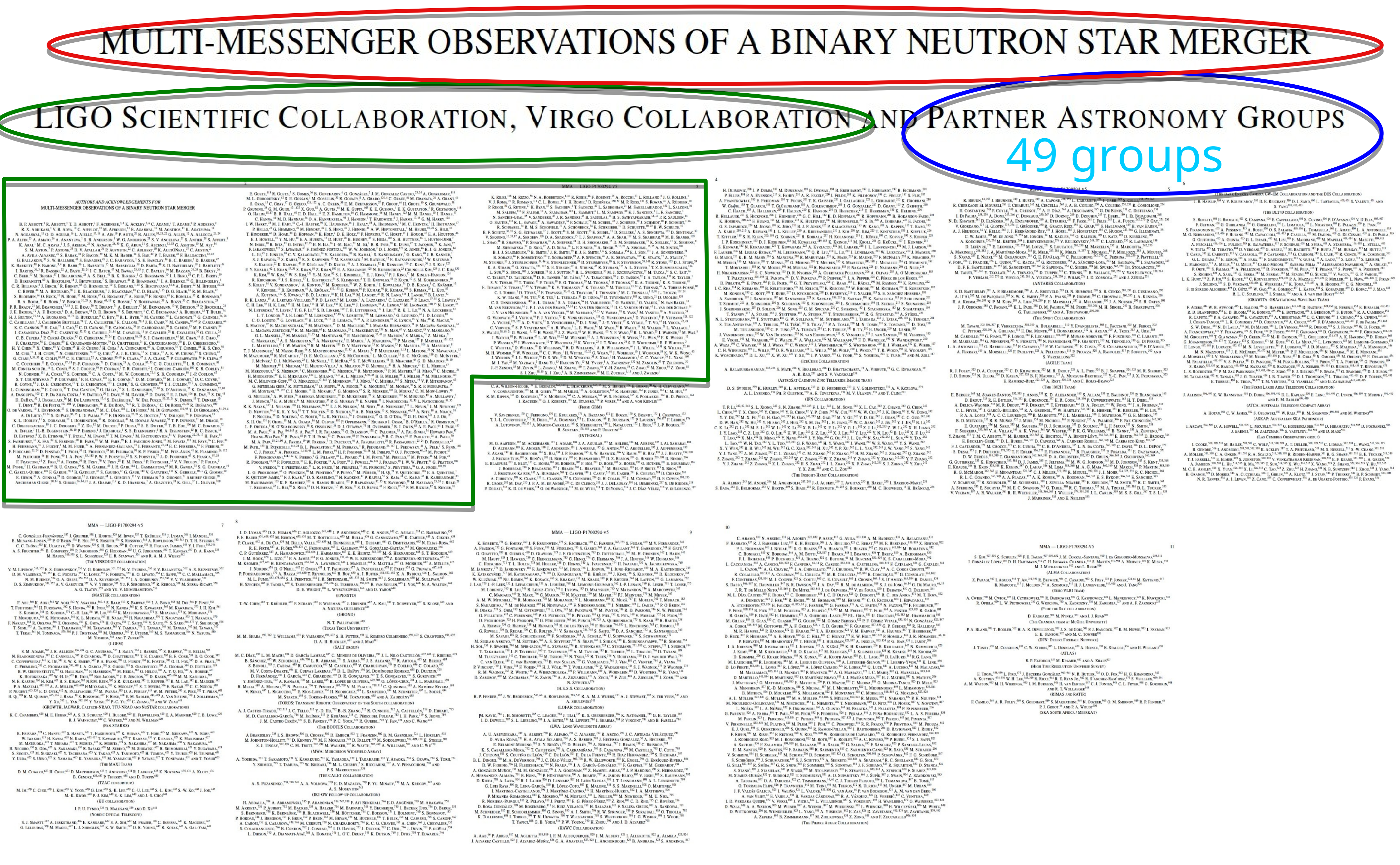
- "rapid neutron-capture process" followed by β^- decays
- Needs a neutron rich environment



Heavy Elements



Historical Article ~ 4000 authors


MULTI-MESSENGER OBSERVATIONS OF A BINARY NEUTRON STAR MERGER

LIGO SCIENTIFIC COLLABORATION, VIRGO COLLABORATION AND PARTNER ASTRONOMY GROUPS

Conclusion

- First evidences of astrophysical counterparts of high energy neutrinos
- Large number of intermediate mass binary BH-BH coalescence, came as a real surprise, not trivial to explain
- First EM counterpart of a NS-NS merger confirmed the kilonova scenario
- Birth of cosmology with gravitational waves

- Real birth of long-awaited multiwavelength-multimessenger astronomy!

Backup

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)