Multimessenger (MM) Astronomy

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IGFAE Instituto Galego de Fisica de Altas Enerxias

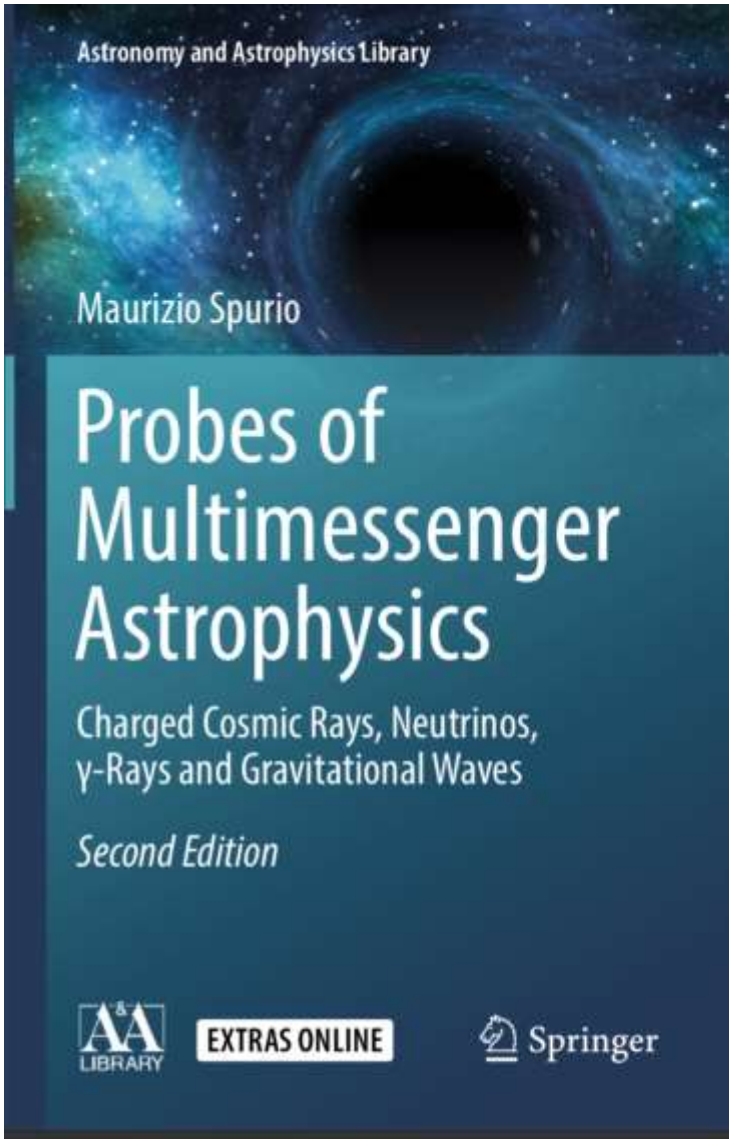
XUNTA DE GALICIA

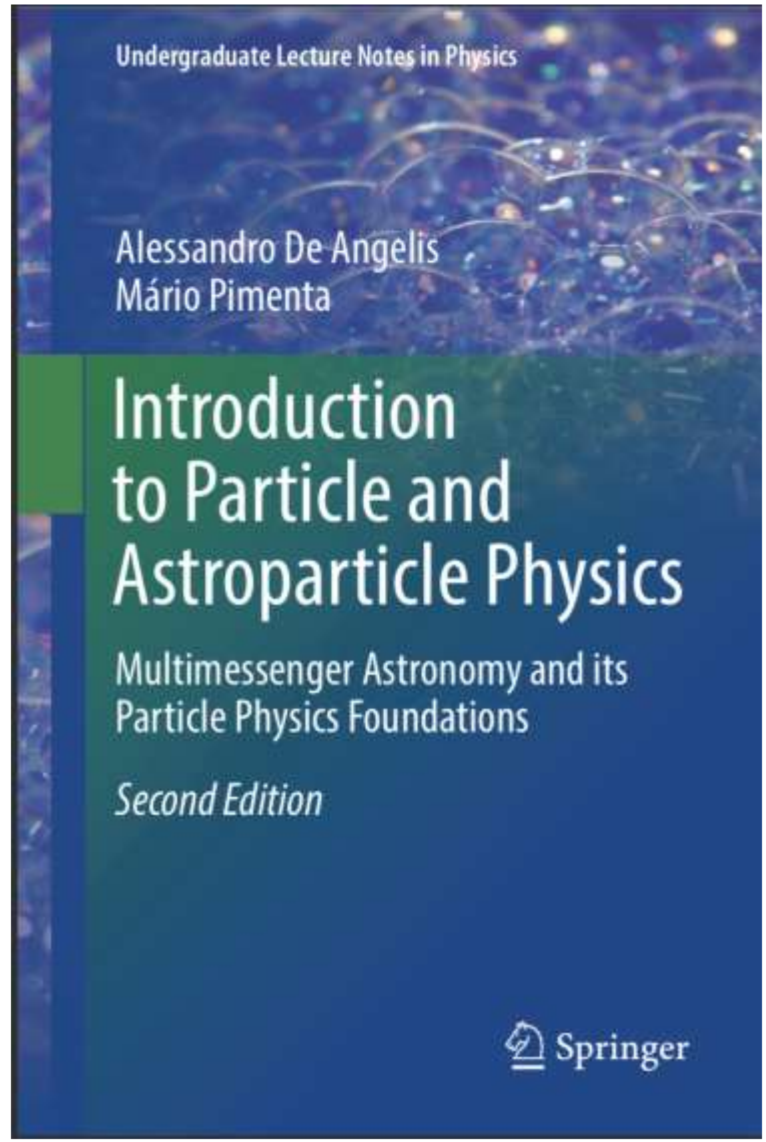
USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Contents

- What is Multimesssenger (MM) Astronomy?
- The messengers of MM Astronomy:
  - Who are they?
  - How do we detect them?
  - What are the most important questions?
- Milestones in MM Astronomy
- Conclusions

Two books on MM Astronomy





What is Multimessenger (MM) Astronomy?

- *Exploration of Universe through the combination of information from a multitude of cosmic messengers:*
  - *Electromagnetic radiation*
  - *Gravitational Waves*
  - *Neutrinos*
  - *Cosmic-Rays*

- **Key point:** these messengers are created by different astrophysical processes, and thus reveal different & complementary information about their sources.

- MM Astronomy is the natural extension of the traditional (optical photons) & multi-wavelength astronomy.

Multimessenger Astronomy:

“the event of a lifetime” (in words of F. Halzen)

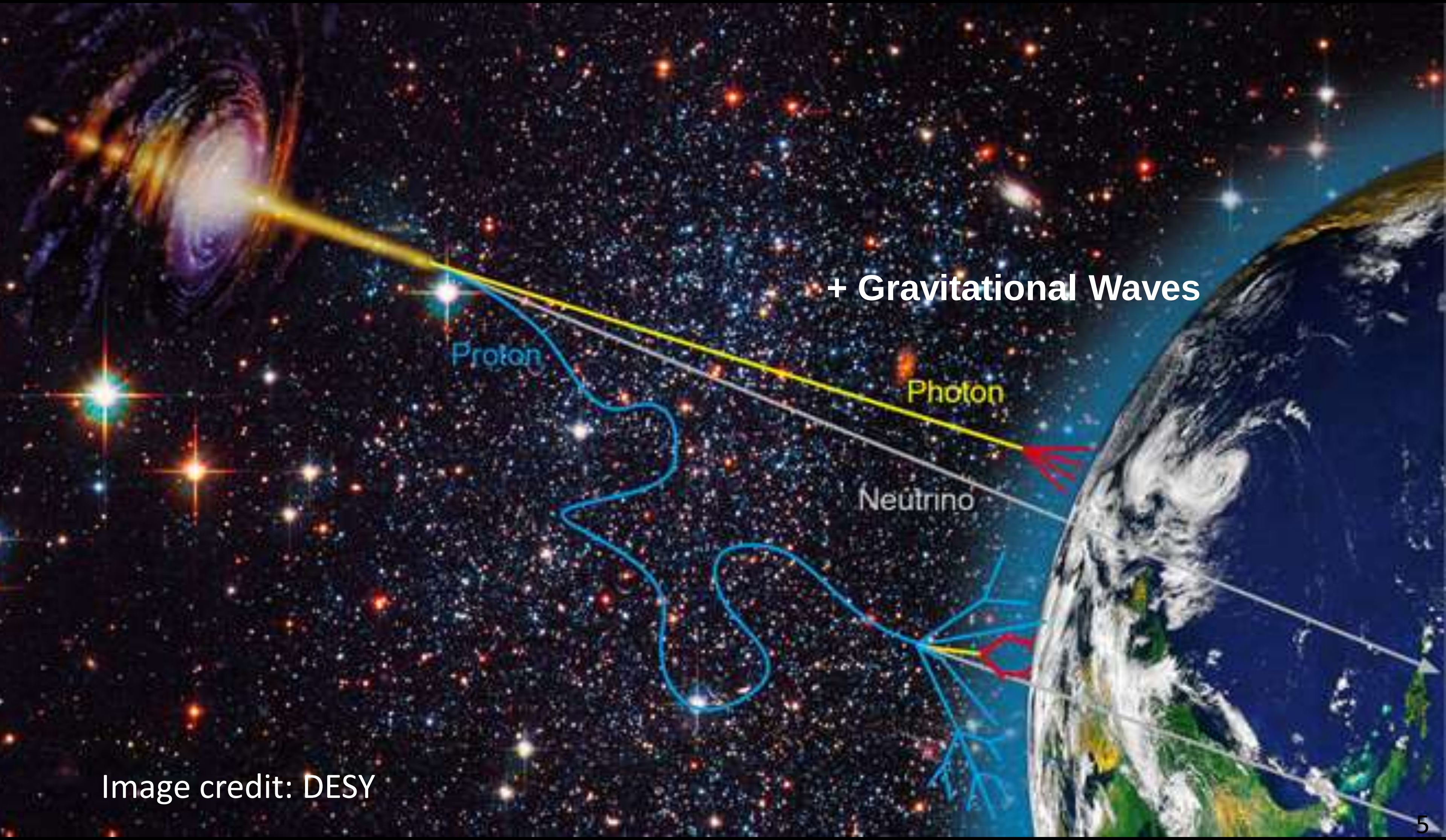


Image credit: DESY

The ideal messenger of the Universe

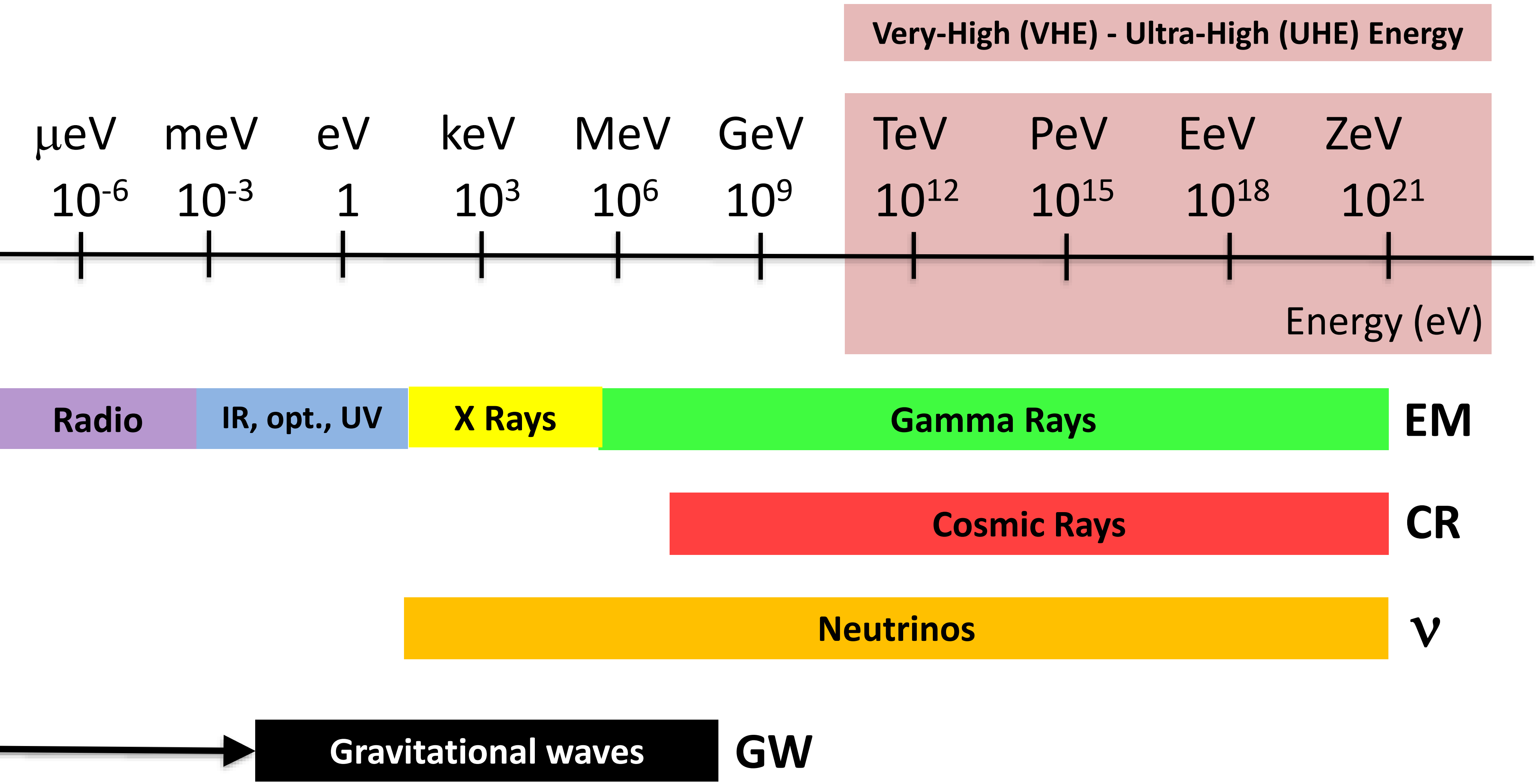
- **Large horizon distance**:
  - Can reach earth from cosmological distances
- **Neutral**:
  - Not deflected by galactic & extra-gal. magnetic fields. Points back to the source => Astronomy
- **Easy** (& if possible cheap) **to detect**

There is NO ideal messenger of the Universe

Messengers

- Cosmic Rays
- Electromagnetic radiation
- Neutrinos
- Gravitational Waves

Energy range of messengers



This talk: concentrate on Very-High (VHE) to Ultra-High (UHE) Energy regime + GW

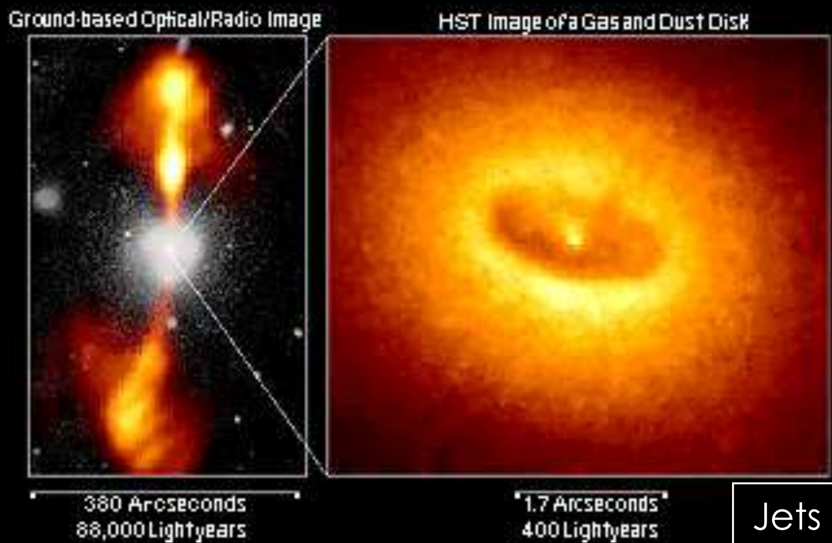
There is much Physics in the sky

Multimessenger Astronomy allows access to physics across multiple aspects/fields:

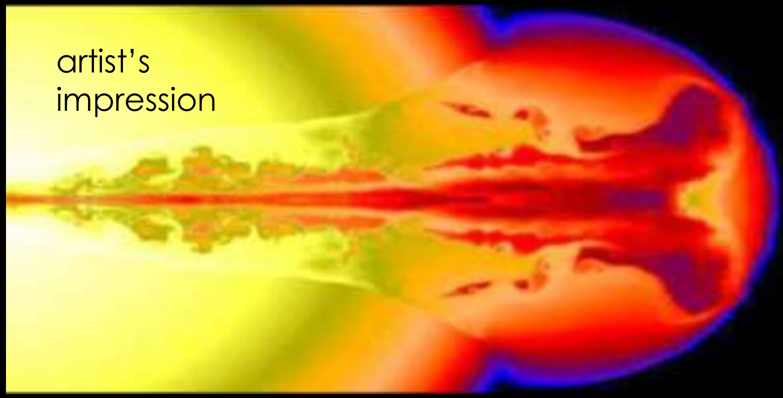
- **Astroparticle Physics:** particle acceleration & production,…
- **Astrophysics:** compact objects, black holes, neutron stars,…
- **Particle Physics:** neutrino oscillations, beyond SM physics,..
- **General Relativity:** gravitational waves, black holes,…
- **Cosmology:** early Universe,…
- **Nuclear Physics:** r-process & heavy element production,…

A whole new Universe at VHE - UHE

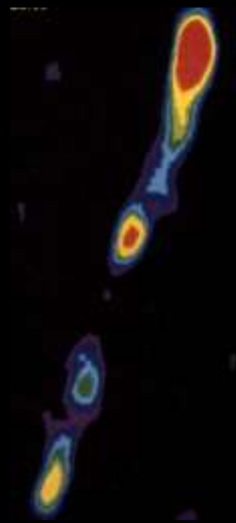
Accretion in supermassive black holes



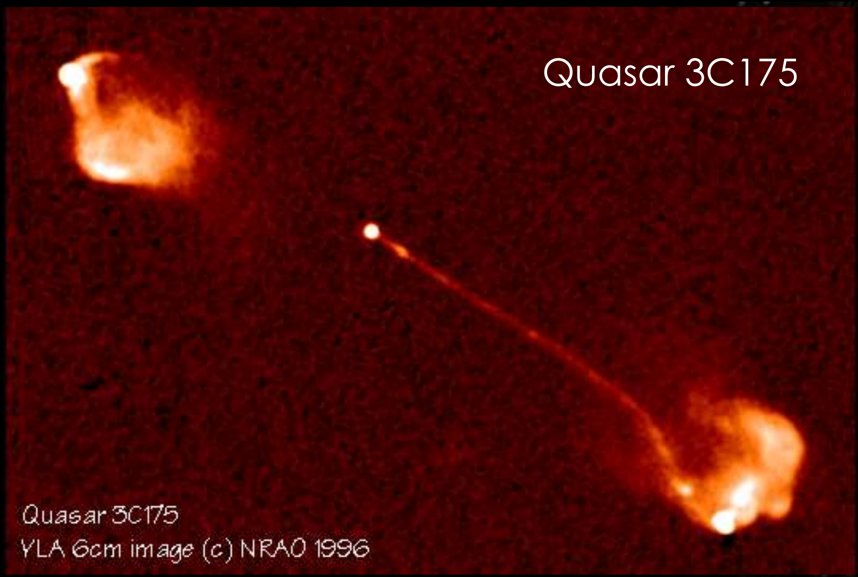
Gamma Ray Bursts

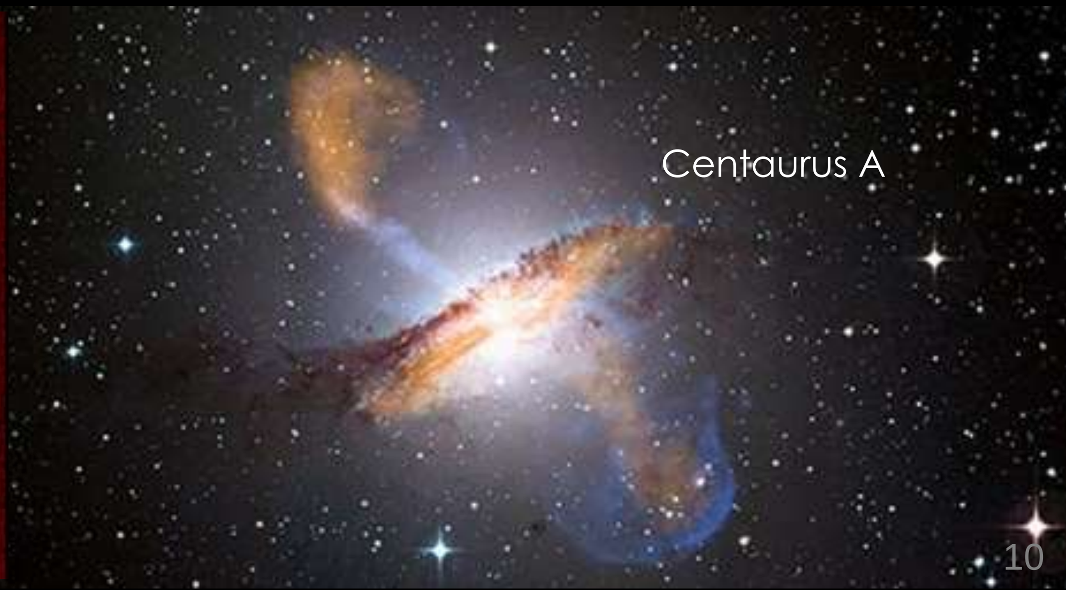


micro-quasars



Jets of Active Galactic Nuclei

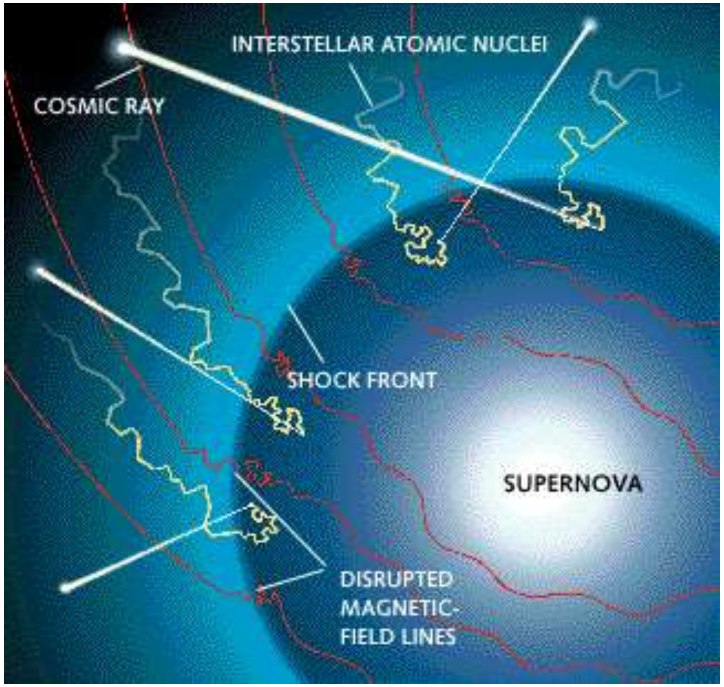




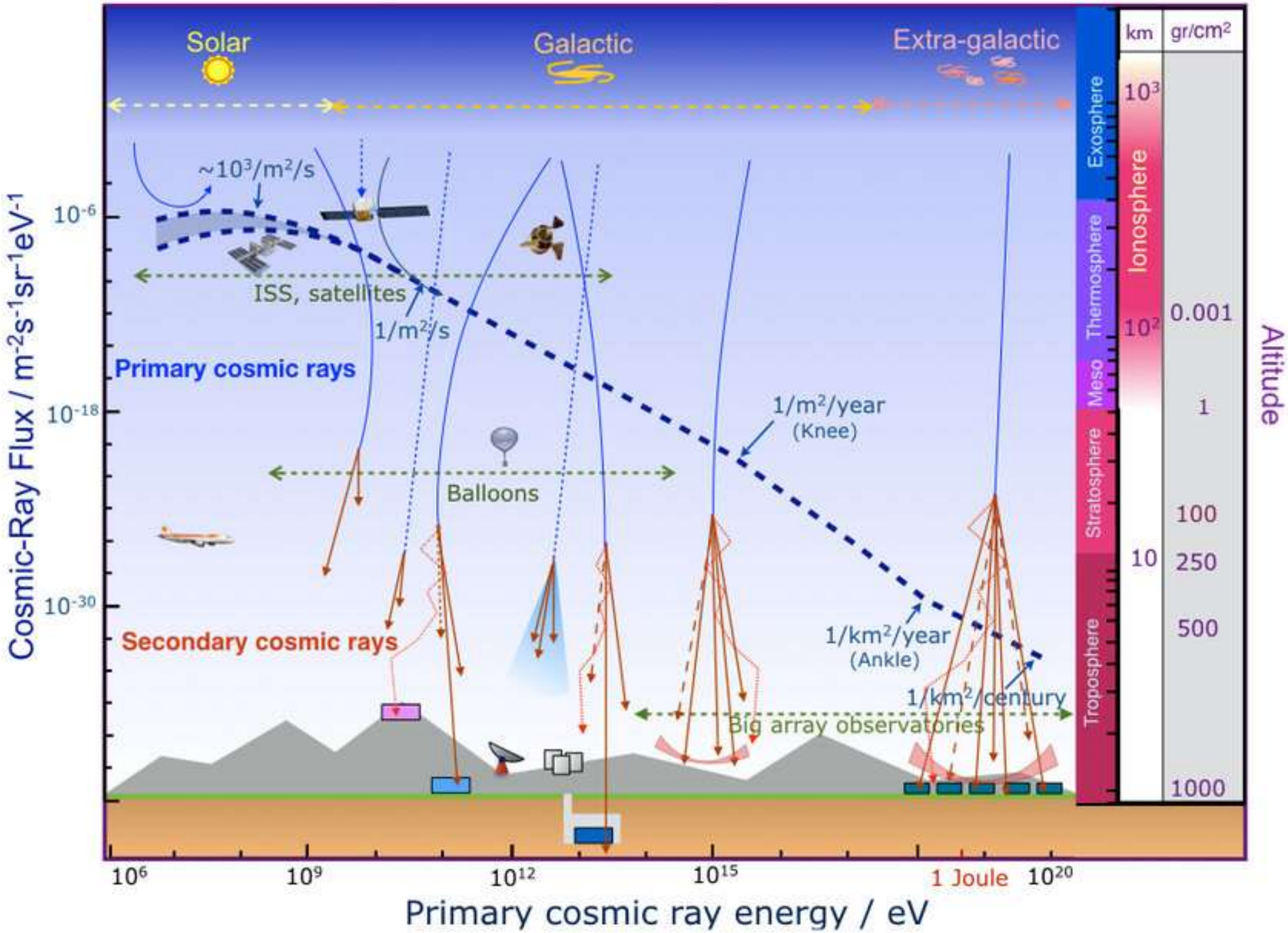
The messengers

Cosmic Rays

- Earliest known messengers (V. Hess, 1912)
- Mainly fully ionized protons & nuclei up to iron
  - Also electrons, positrons, photons & neutrinos
- Extraterrestrial radiation:
  - produced by acceleration in astrophysical sources.
  - bombard Earth continuously
  - interact in atmosphere & do not directly reach ground



Cosmic Rays: energy spectrum



Credit: J.A. Garzon (IGFAE, USC)

Cosmic Rays as messengers

✗ **Charged:** deflected by Galactic/inter-gal. B-fields:

- Do not point back to sources where they were produced.
  - Deflections are small at highest energies (if protons) -> Astronomy?
- Accumulate time delays – not useful to observe transient sources

Cosmic Rays as messengers

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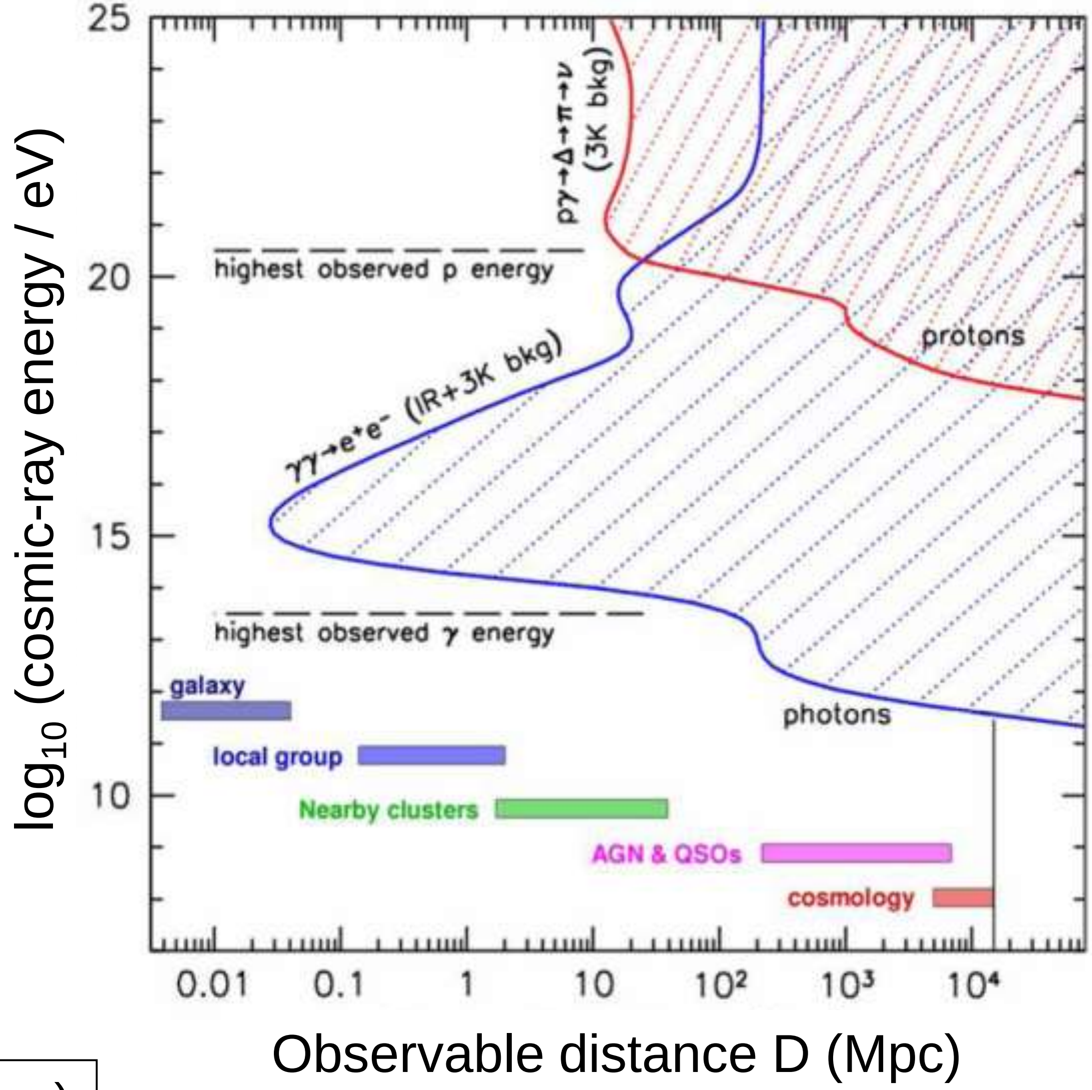
✓ **Travel unimpeded** along cosmological distances:

- except at energies above ~ 4 10^{19} eV when interactions with CMB limit their source distances to < 100 Mpc (so-called GZK effect).
- can produce **secondary photons & neutrinos** at sources or during propagation through Universe

$$p + \gamma \longrightarrow n + \pi^+$$
$$\hookrightarrow \pi^+ \longrightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow \mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$
$$\hookrightarrow n \longrightarrow p + e^- + \bar{\nu}_e$$

$$p + \gamma \longrightarrow p + \pi^0$$
$$\hookrightarrow \pi^0 \longrightarrow \gamma + \gamma$$

Horizons in the Universe: Cosmic Rays



z ~ 0.01 (D / 46 Mpc)

Cosmic Rays as messengers

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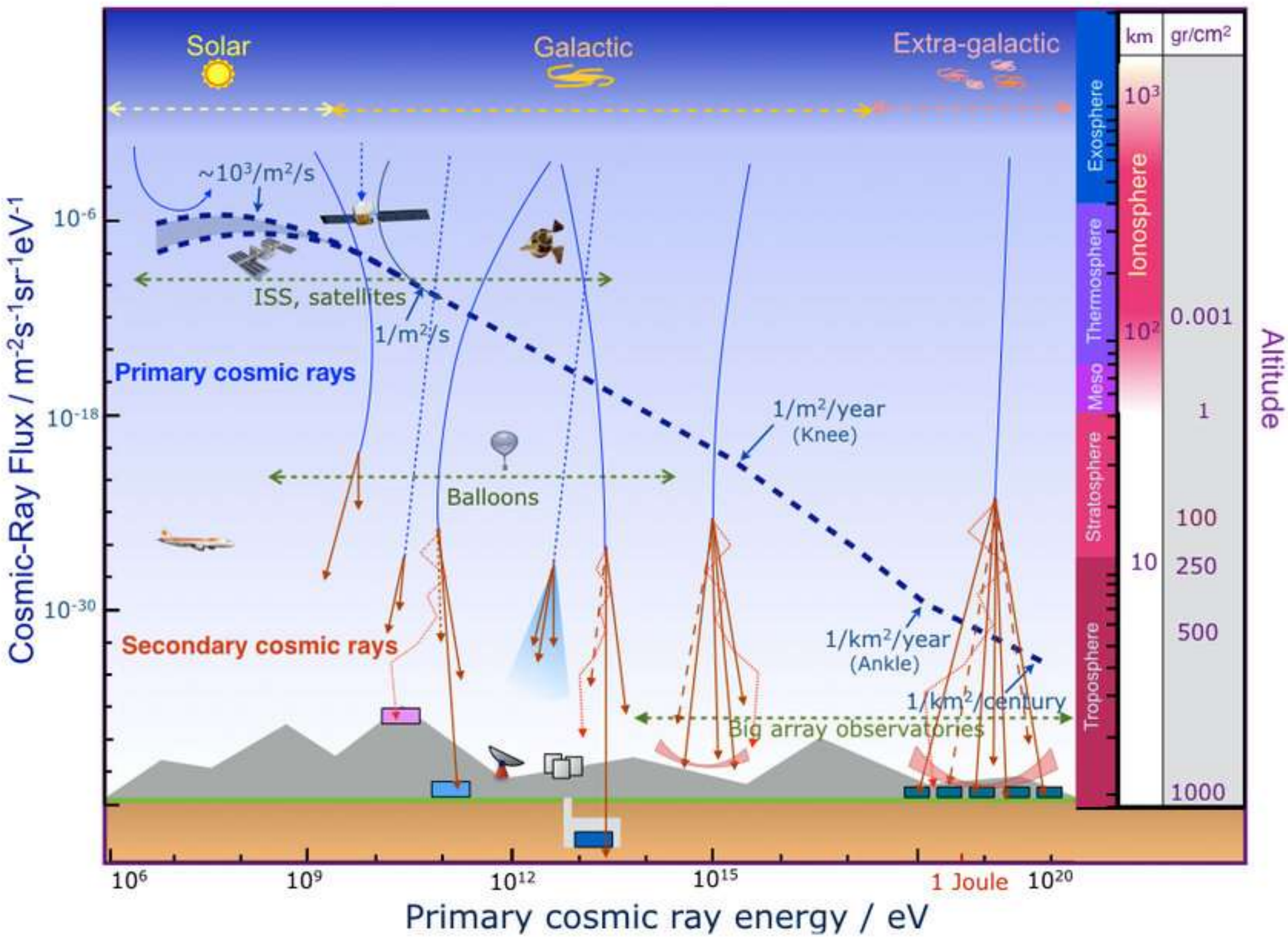
- Accumulate time delays w.r.t. optical transient sources

✓ **Travel unimpeded** along cosmological distances

- except at energies above $\sim 4\ 10^{19}$ eV when interactions with CMB limit their source distances to < 100 Mpc (GZK effect).
- Must produce secondary photons & neutrinos

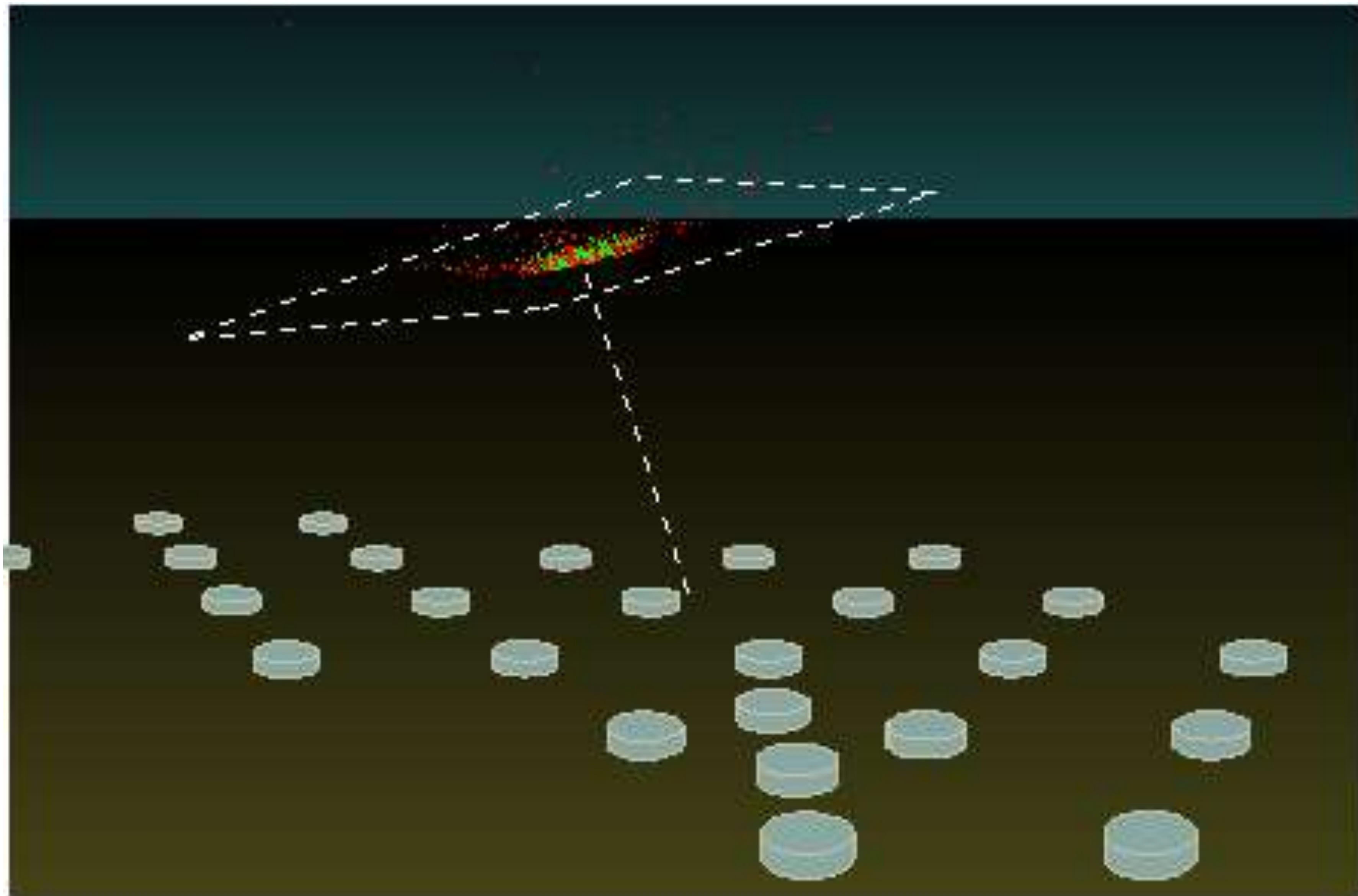
✓ **Relatively easy to detect**

Cosmic Rays: detection techniques



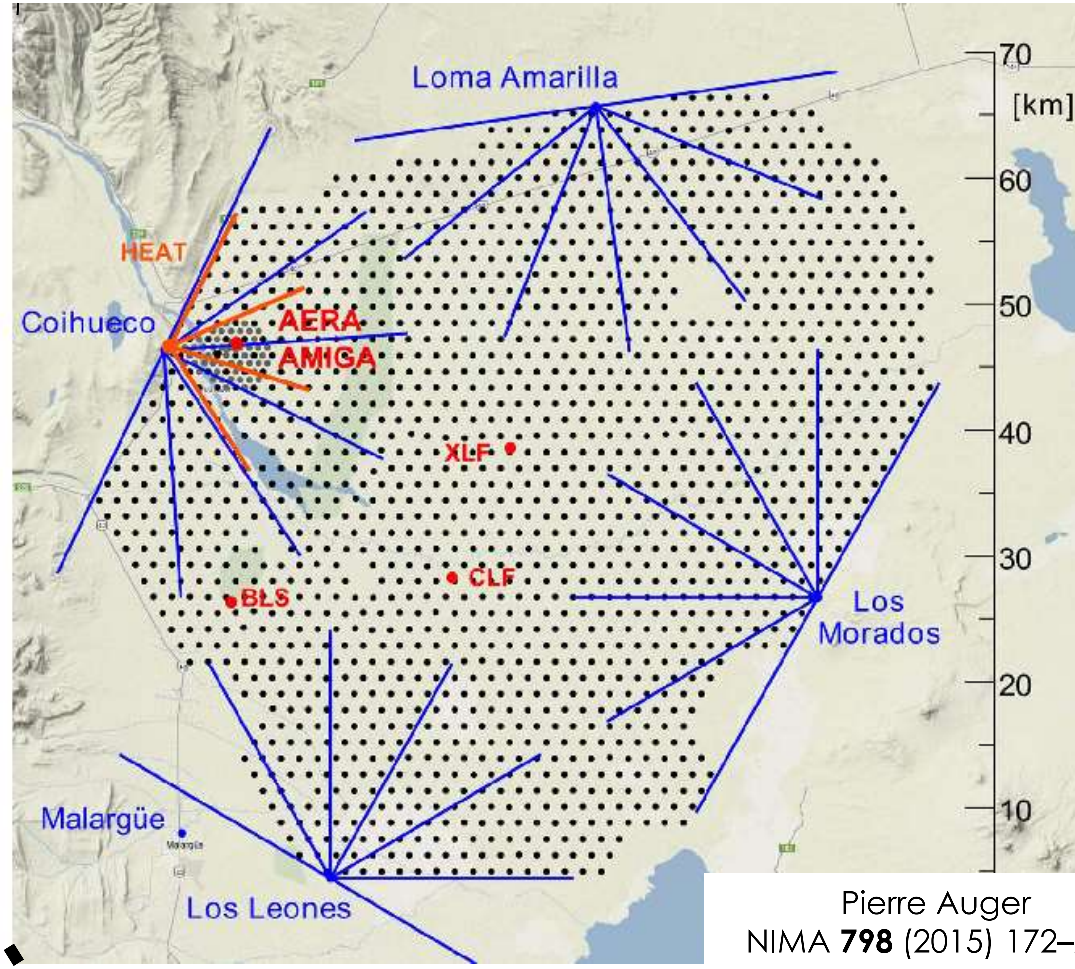
Credit: J.A. Garzon (IGFAE, USC)

Extensive air showers



The Pierre Auger Observatory

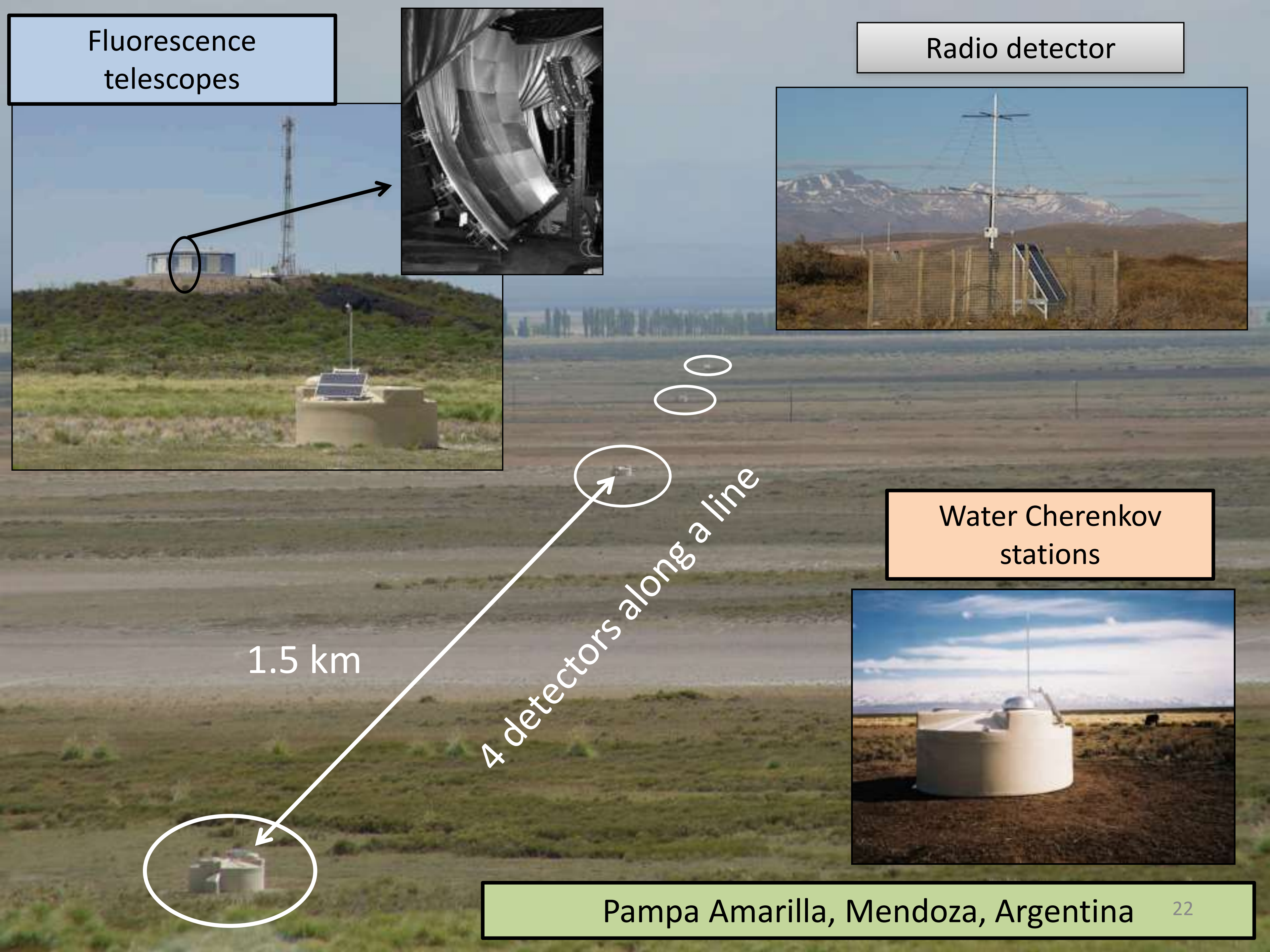
Malargüe, Mendoza, Argentina
35.5º S, 69.3º W
1400 m a.s.l.
880 g cm^{-2}



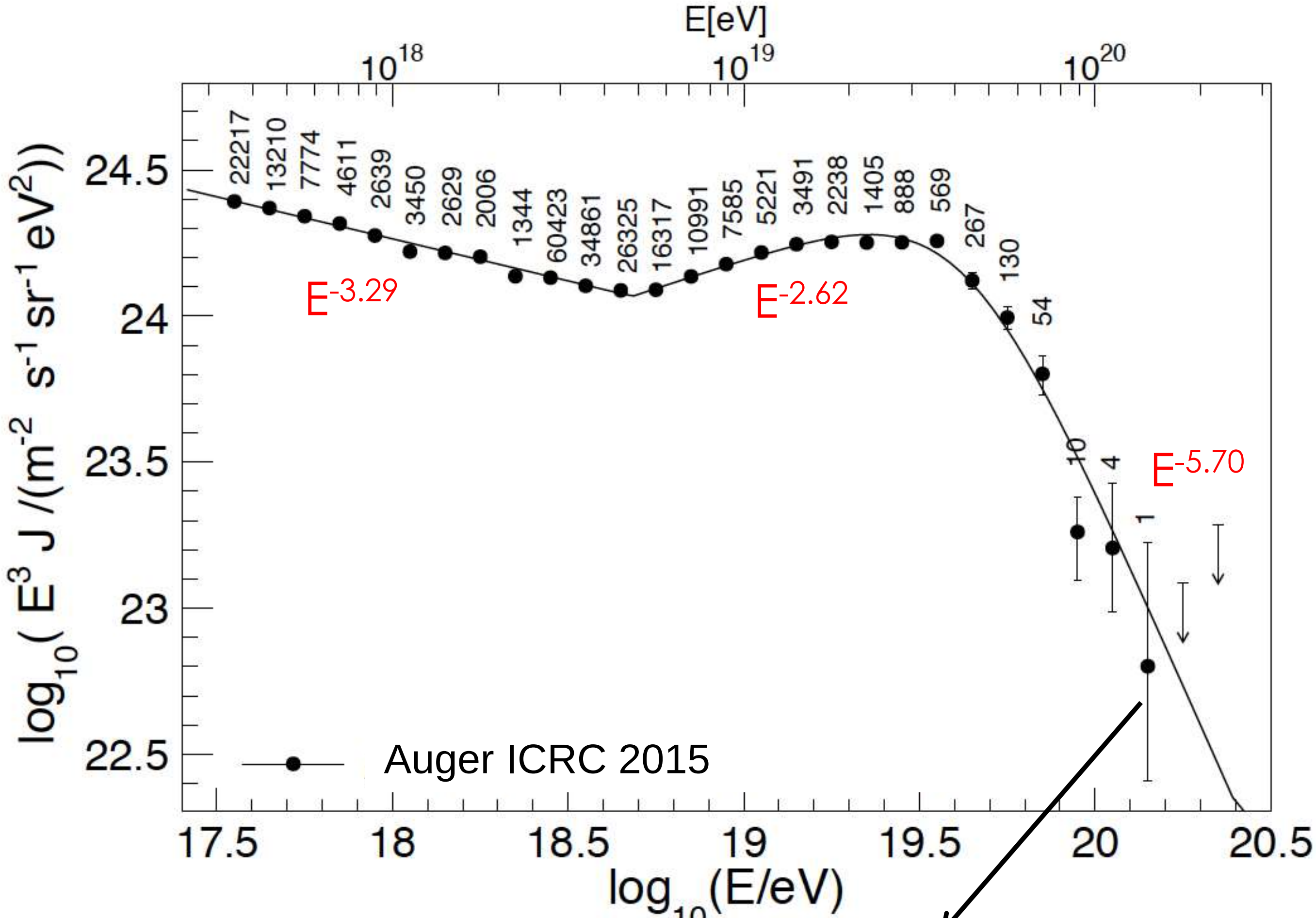
Pierre Auger
NIMA **798** (2015) 172–213

- ✓ **SD 1500 = Array of 1600 Water-Cherenkov stations (3000 km²)**
- ✓ **4 Fluorescence Detectors + HEAT (high-elevation FD)**
- ✓ **SD 750 (infill array) = 61 water Cherenkov stations (25 km²)**
- ✓ **AERA = Array of 153 antennas (17 km²)**
- ✓ **AMIGA = Array of 7 buried muon detectors**

If the center of Auger was in Santiago de Compostela...


Fluorescence telescopes
Radio detector
Water Cherenkov stations
1.5 km
4 detectors along a line
Pampa Amarilla, Mendoza, Argentina

Ultrahigh-Energy Cosmic-Ray (UHECR) Flux



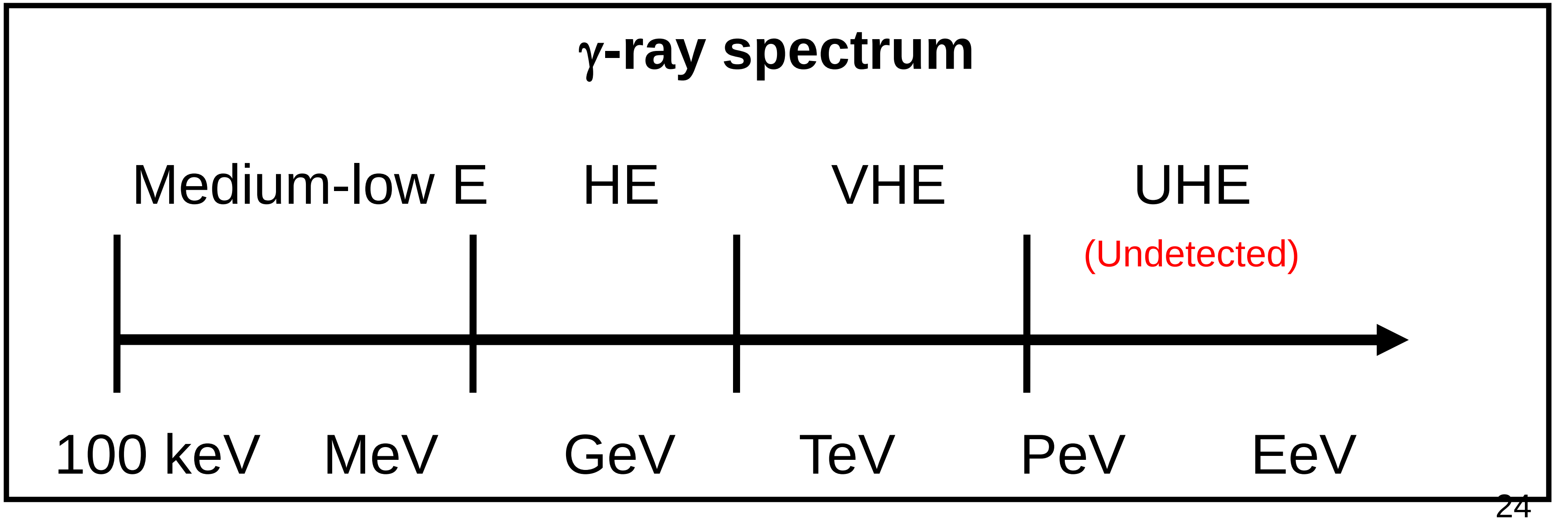
Pierre Auger Observatory

Cosmic-ray energies up to 10^{20} eV (~ 16 Joule) observed !! …but…

- What are the sources? What is their Nature (protons, heavier nuclei,…)?
- What is causing flux suppression? Interaction with CMB ($p\gamma \longrightarrow p\ \pi^0$ or $n\ \pi+$ - GZK-effect), sources run out of power to accelerate?

Gamma Rays

- Most energetic form of electromagnetic radiation:
  - E > 100 keV (X-ray to γ-ray borderline).
  - No upper limit to their energy (can reach up to E $\sim 10^{20}$ eV)

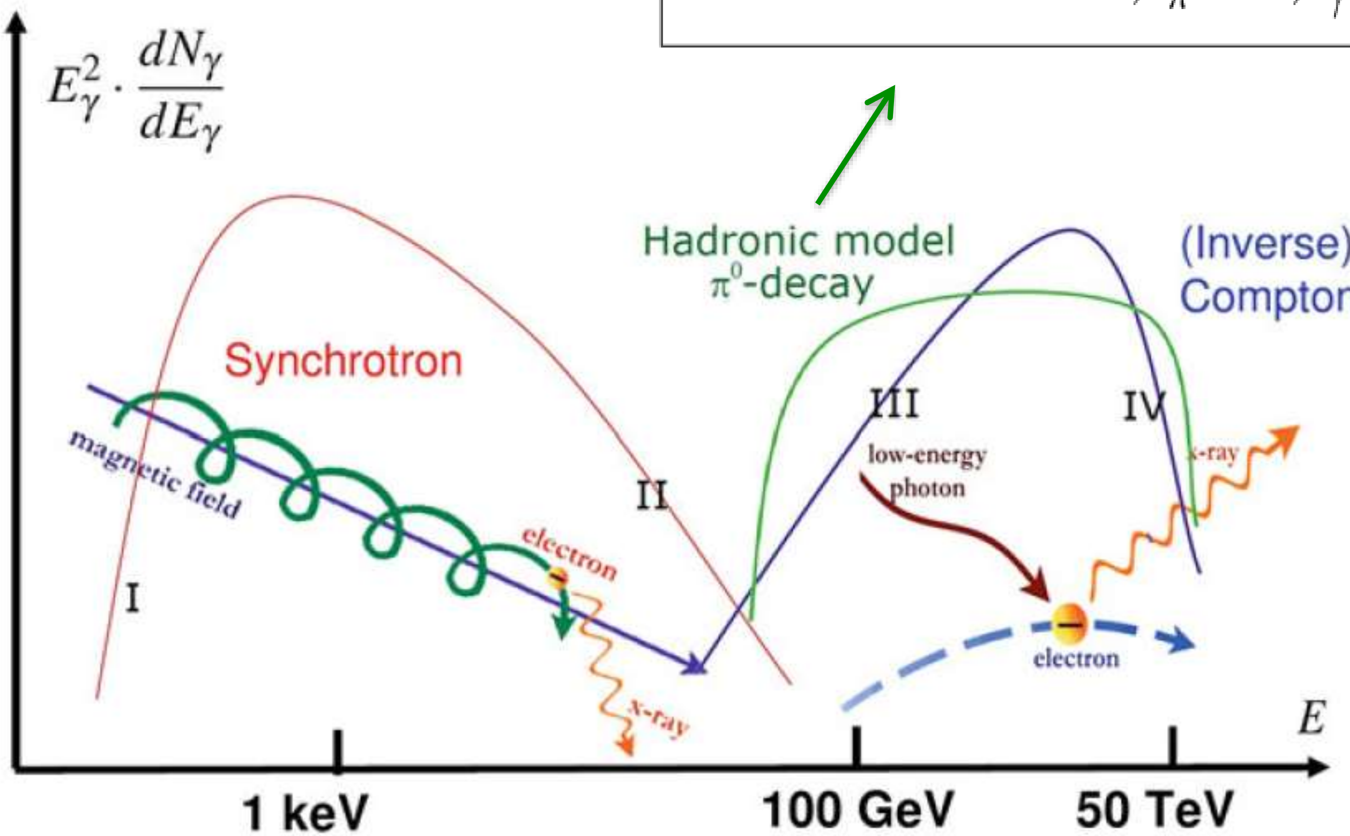


Gamma Rays: production

Produced in interactions of electrons and/or cosmic-rays at their sources

$$p + p \longrightarrow p + n + \pi^0 + \pi^\pm + \ldots$$
$$\hookrightarrow \pi^0 \longrightarrow \gamma + \gamma$$

$$p + \gamma \longrightarrow p + \pi^0$$
$$\hookrightarrow \pi^0 \longrightarrow \gamma + \gamma$$



Gamma Rays as messengers

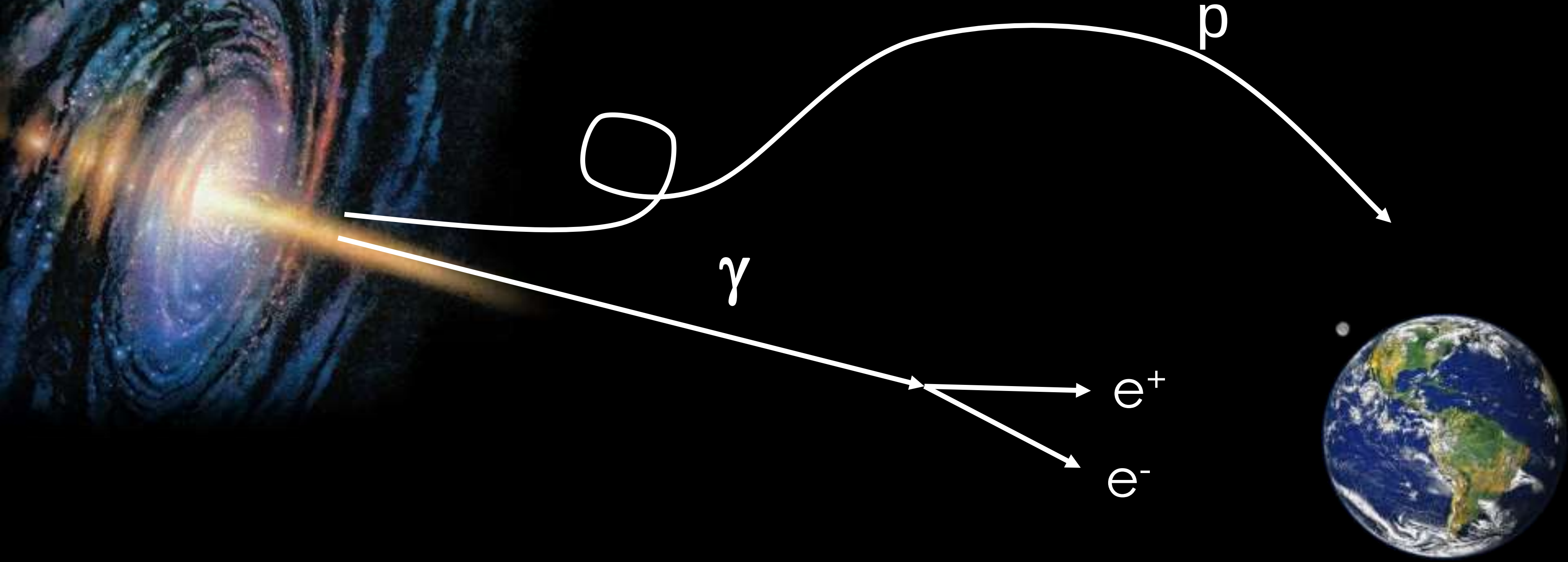
✓ **Not deflected** by Galactic/inter-gal. B-fields:

- Point back to sources where they were produced
- No time delays w.r.t. optical transient sources

✗ **Horizon distance is limited:**

- $\gamma\,\gamma_{background} \rightarrow e^+e^-$ cause a horizon for γ-ray astronomy.
- Backgrounds: Cosmic Microwave Background, infraRed & starlight

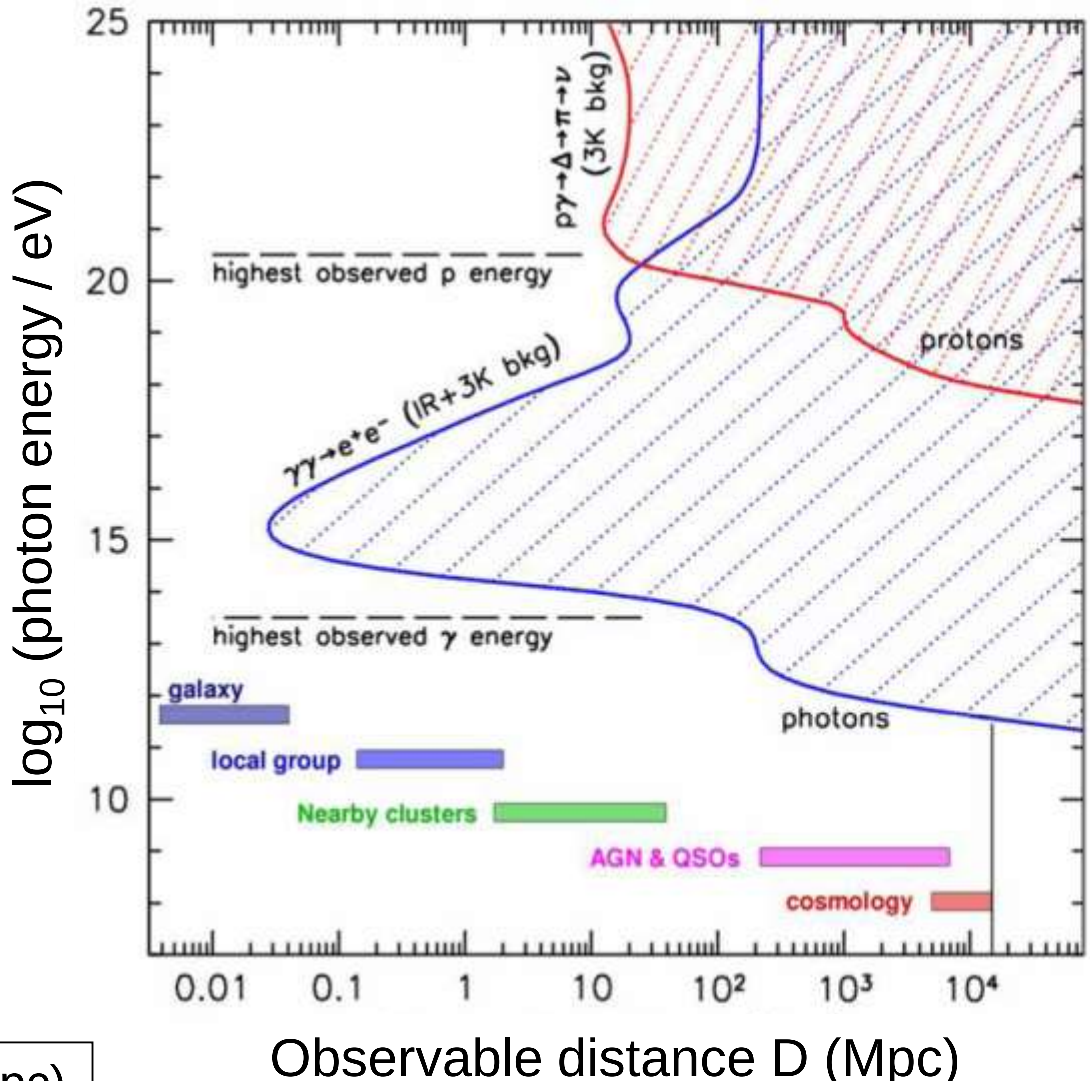
The opaque Universe



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

PeV photons interact with microwave photons ($411/cm^3$) before reaching earth

Horizons in the Universe



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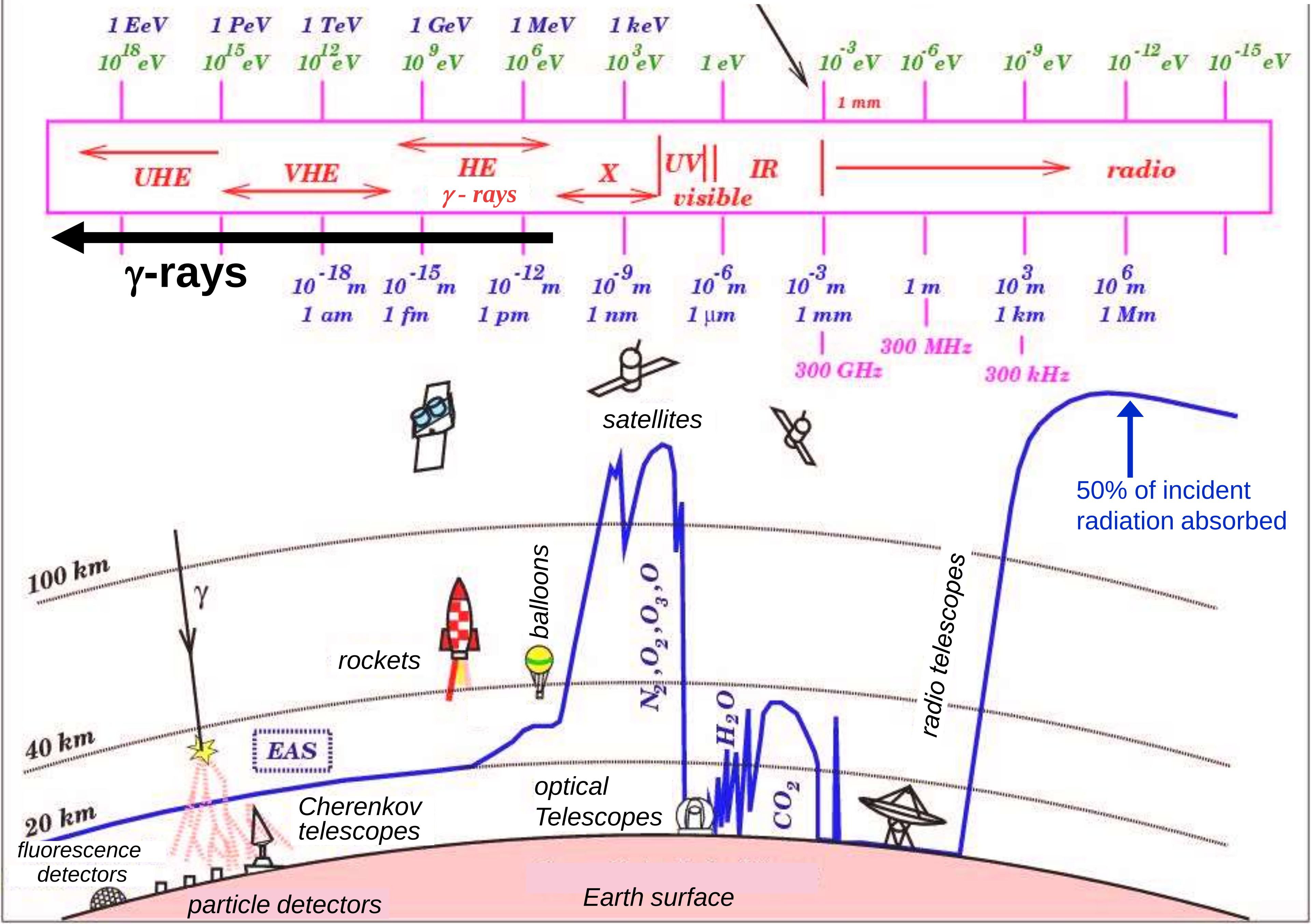
Windows of electromagnetic Astronomy



Gamma Rays: detection

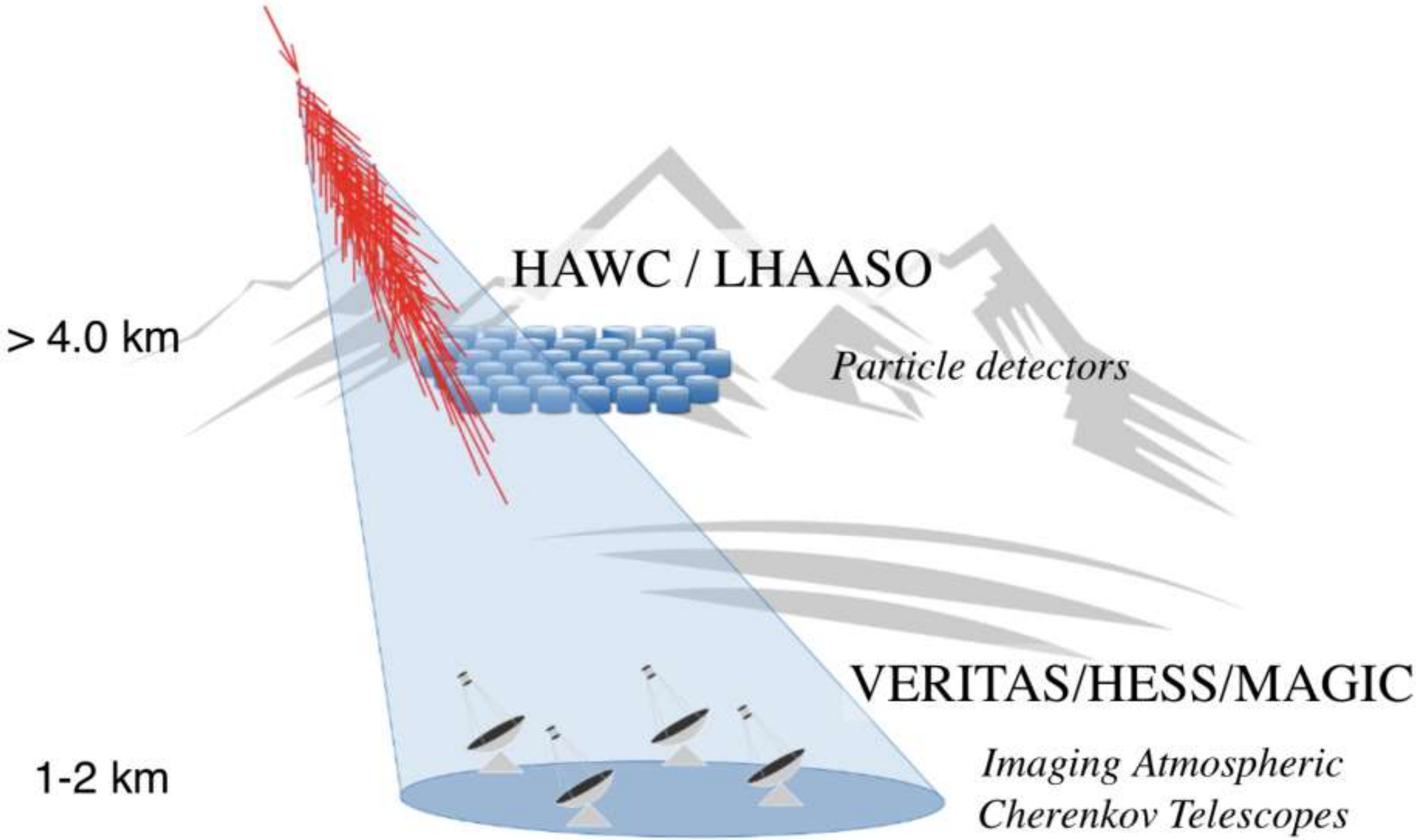
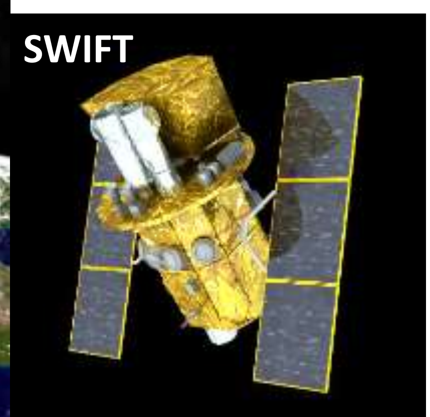


image credit: A. Jardin-Blicq

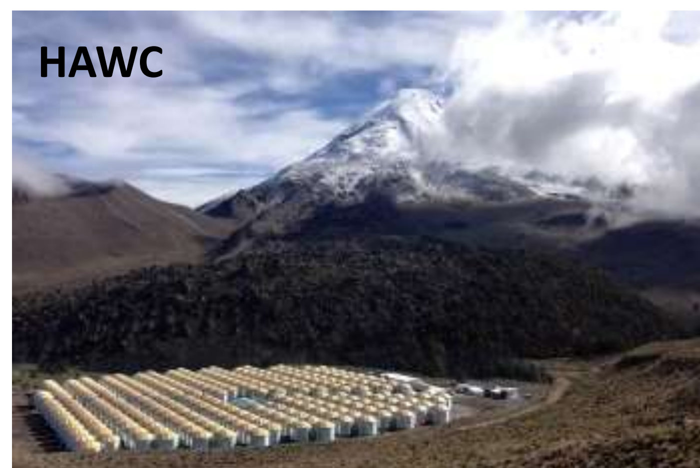
Gamma Rays: detectors

Satellites



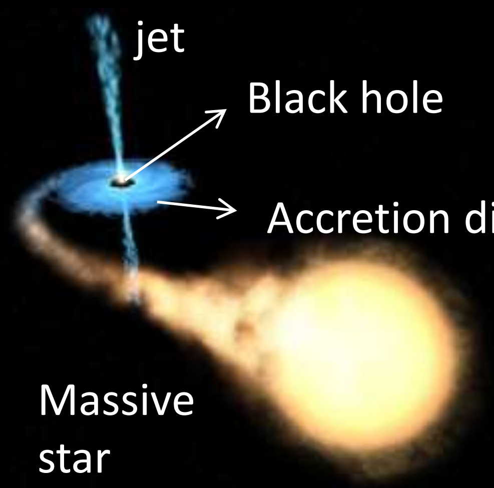
Imaging Air Cherenkov Telescopes

Ground Arrays

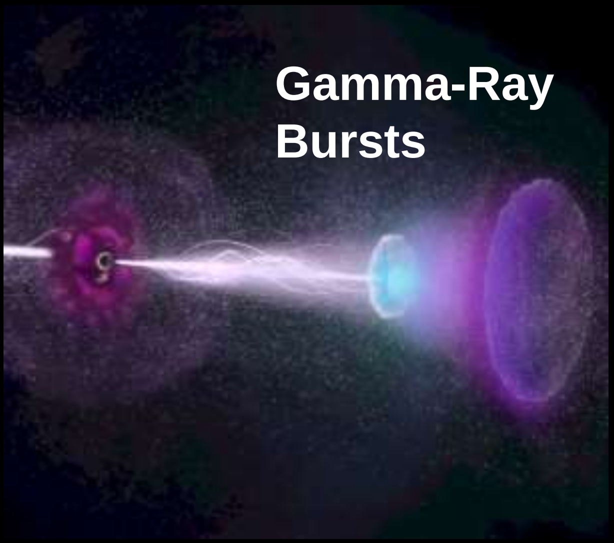


Gamma Rays: sources

Micro-quasars



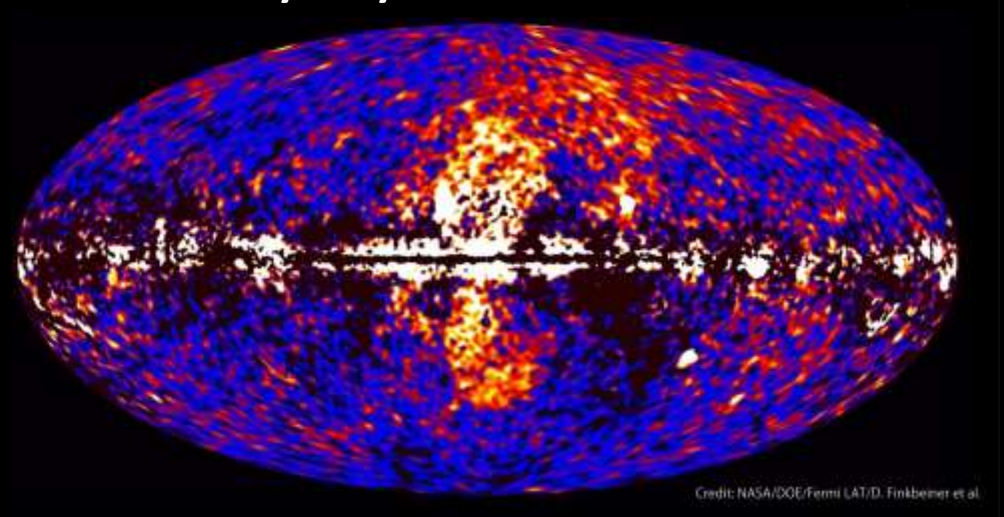
Pulsars
Pulsar Wind Nebulae



EXTRAGALACTIC SOURCES

GALACTIC SOURCES

Jets in Milky Way



High-Energy Neutrinos

✓ **Not deflected** by Galactic/inter-gal. B-fields:

- Point back to sources where they were produced

✓ **Travel unimpeded** along cosmological distances

- Only messengers of high-redshifted Universe at UHE

✓ **Can escape** from dense cores of astrophysical objects

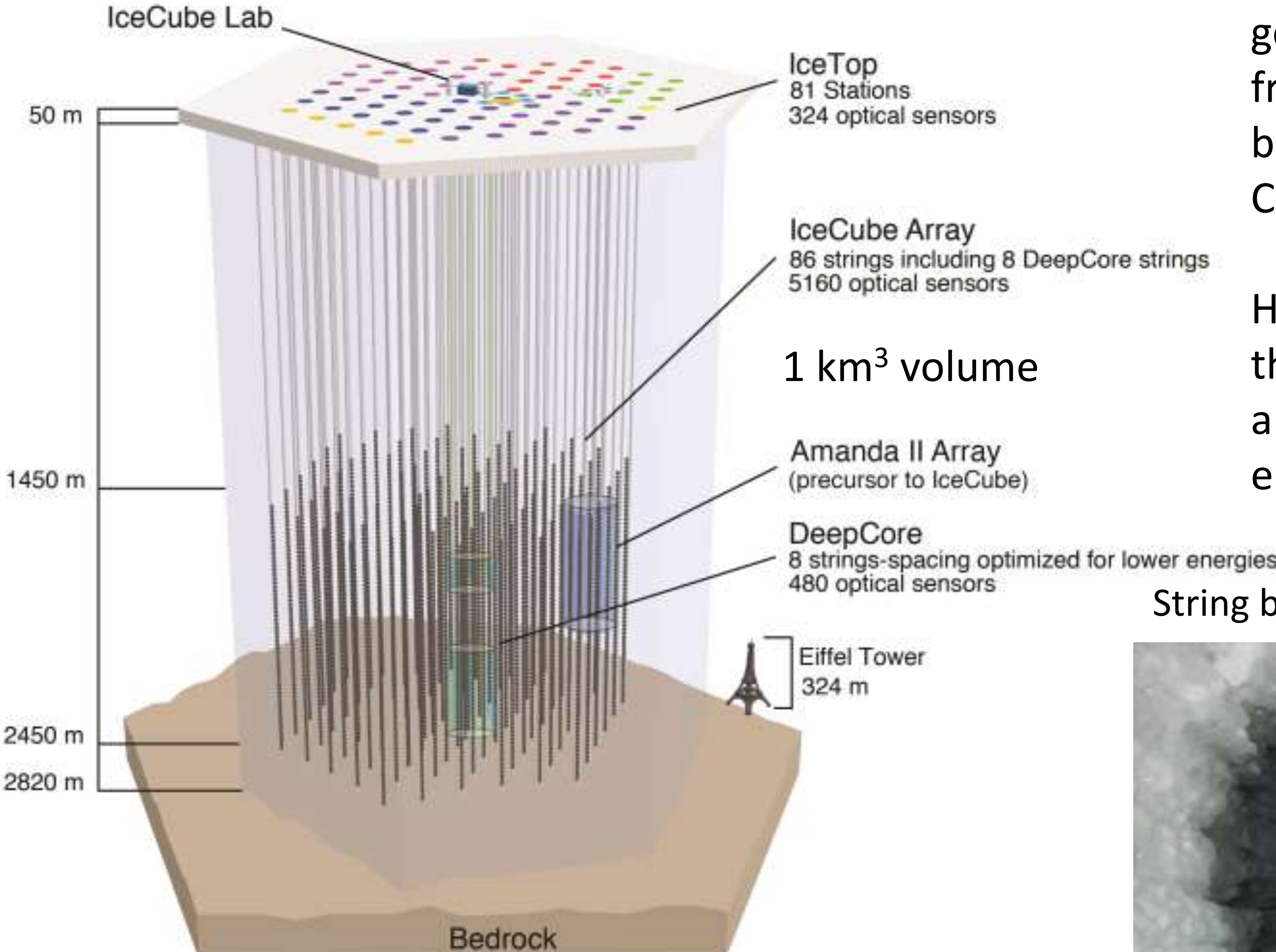
- Probe the inner workings of sources

✗ **Difficult to detect:**

- Require the instrumentation of enormous volumes of target material such as natural ice or the entire atmosphere

IceCube Neutrino Observatory

South Pole - Antarctica

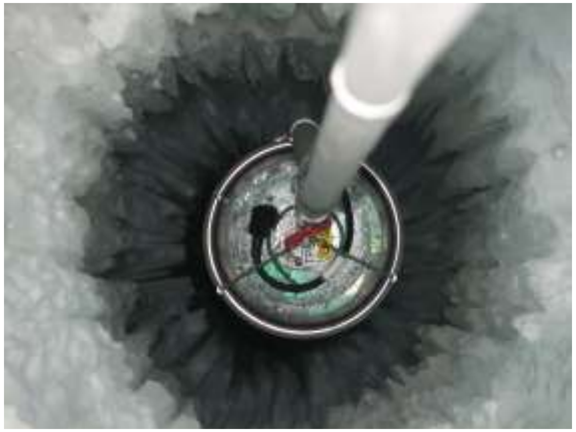


1 km^3 volume

Neutrino telescopes must go underground to shield from the particle background produced by CR showers in atmosphere.

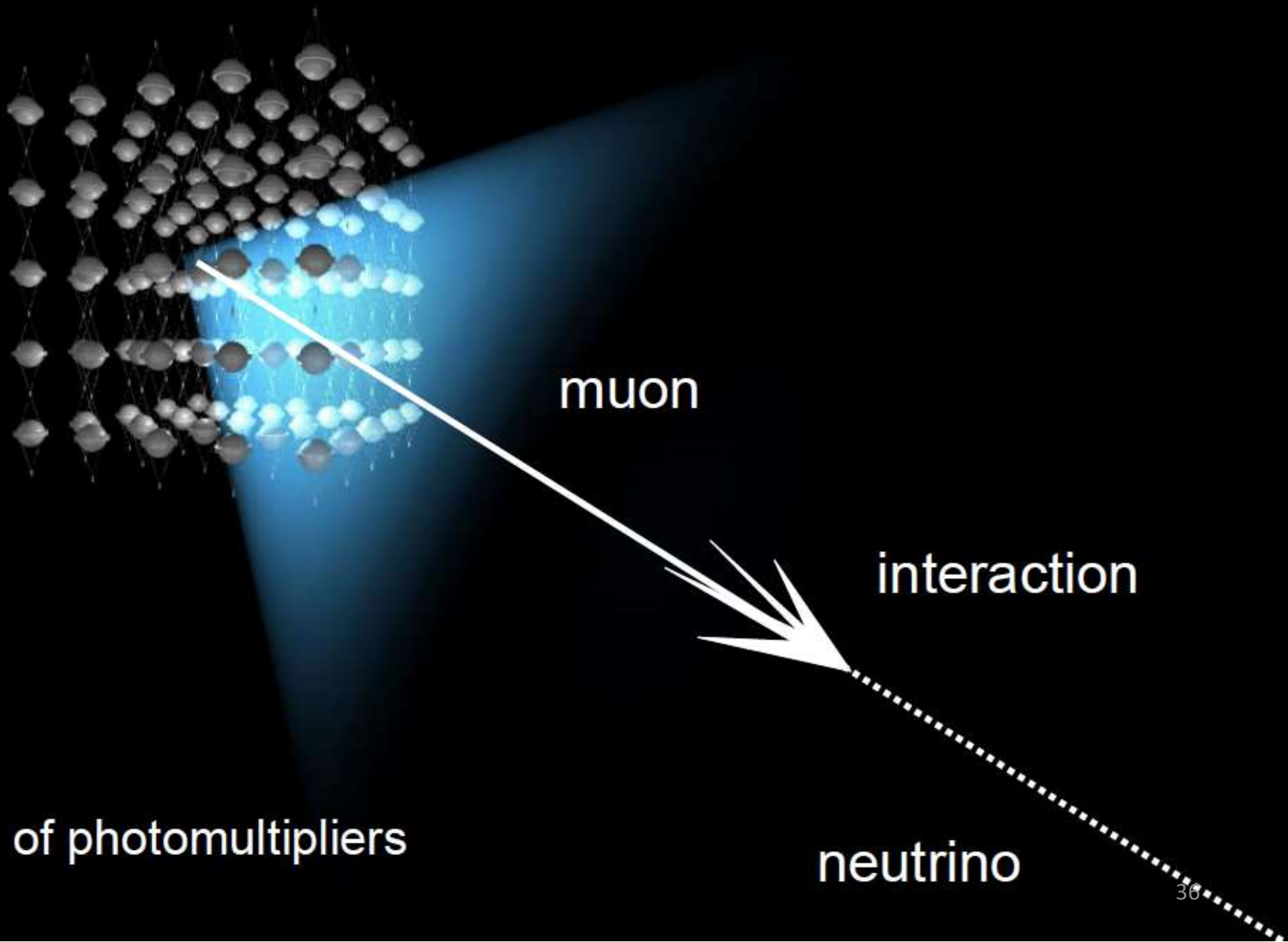
Have to look for neutrinos that passed through Earth, a filter that lets nothing else through.

String being buried into the ice



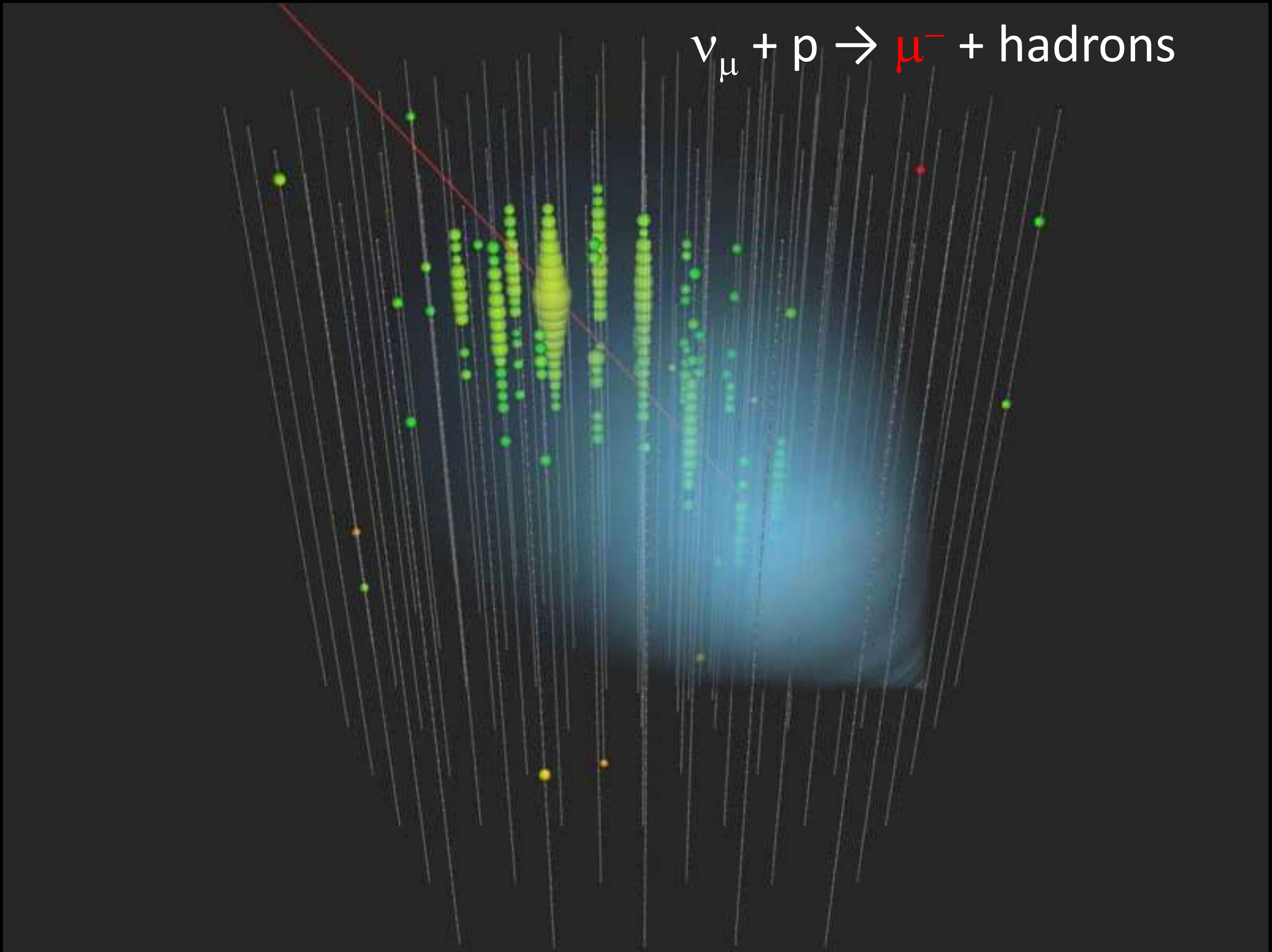
https://icecube.wisc.edu/

Principle of detection of neutrino Cherenkov telescopes



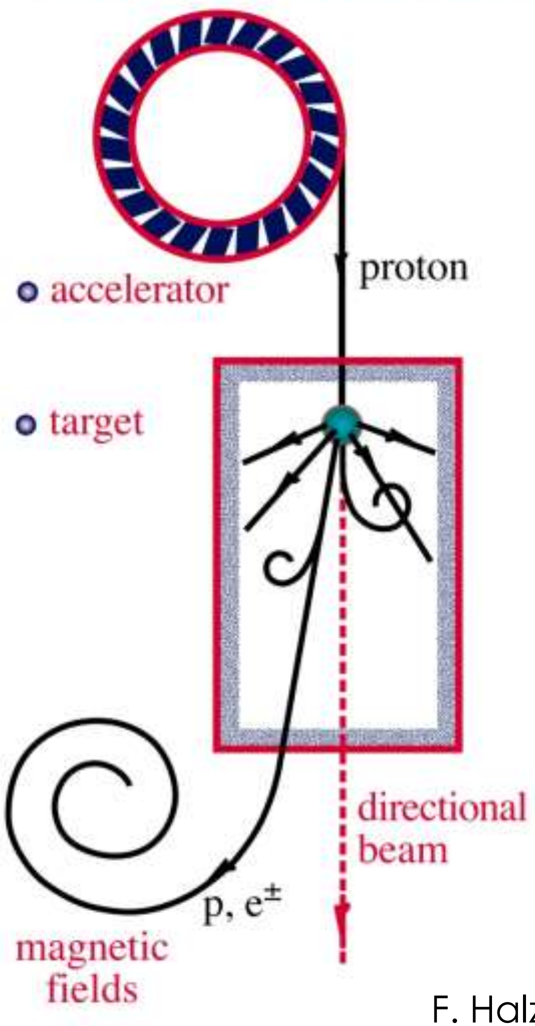
- lattice of photomultipliers

A muon track in IceCube



Neutrino beams: Earth & Heaven

Earth



F. Halzen

"Standard model" of neutrino production:

Cosmic Ray acceleration (Fermi mechanism?)

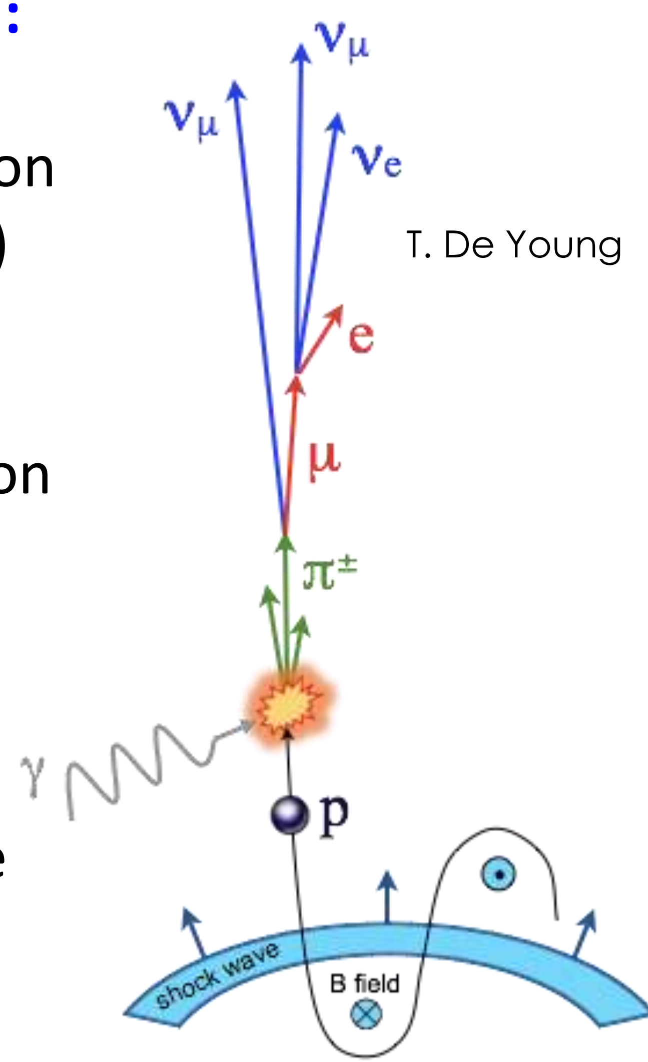
+

interaction with matter and/or radiation in/around source

and/or

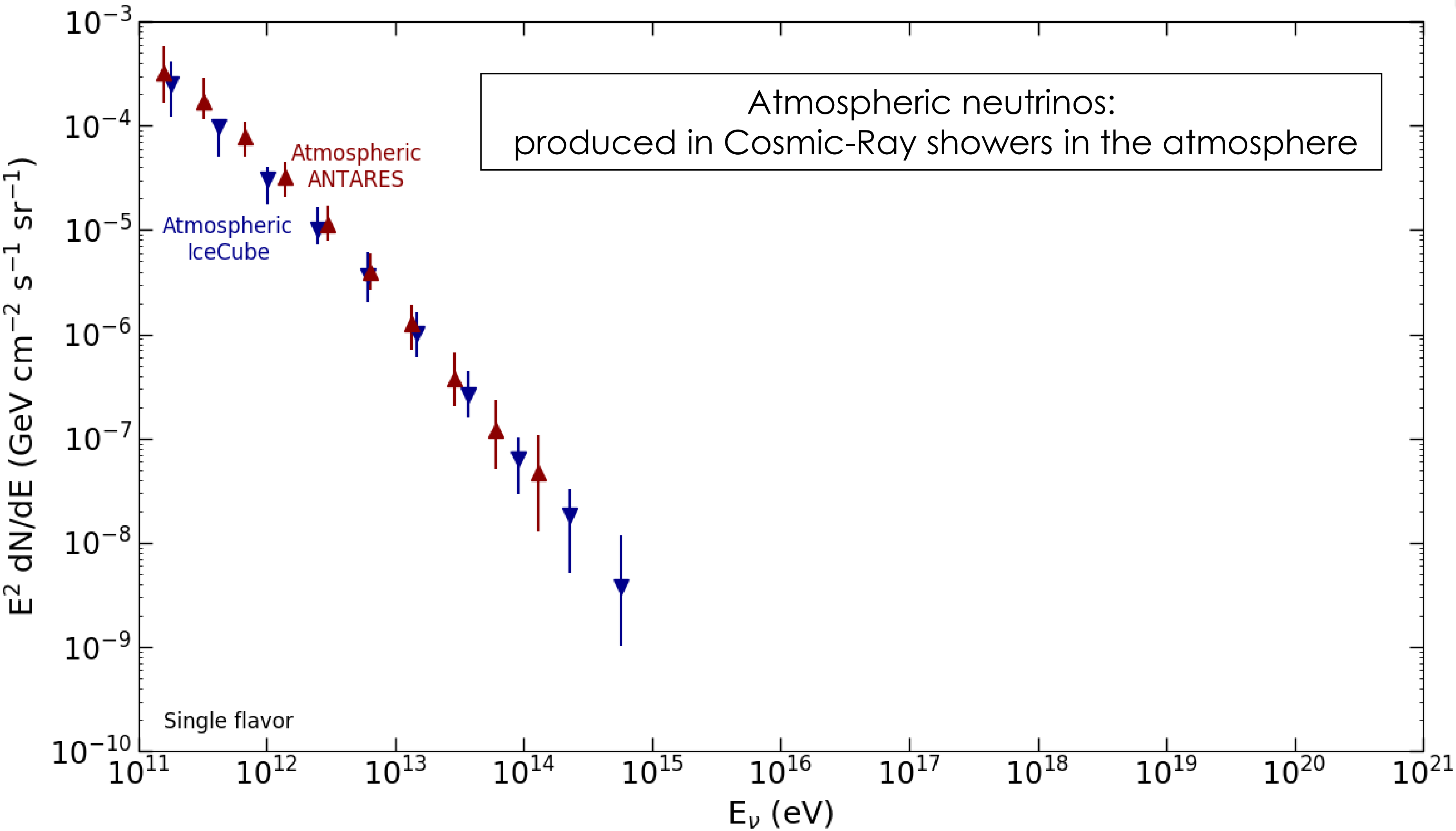
while CRs propagate through Universe

Heaven

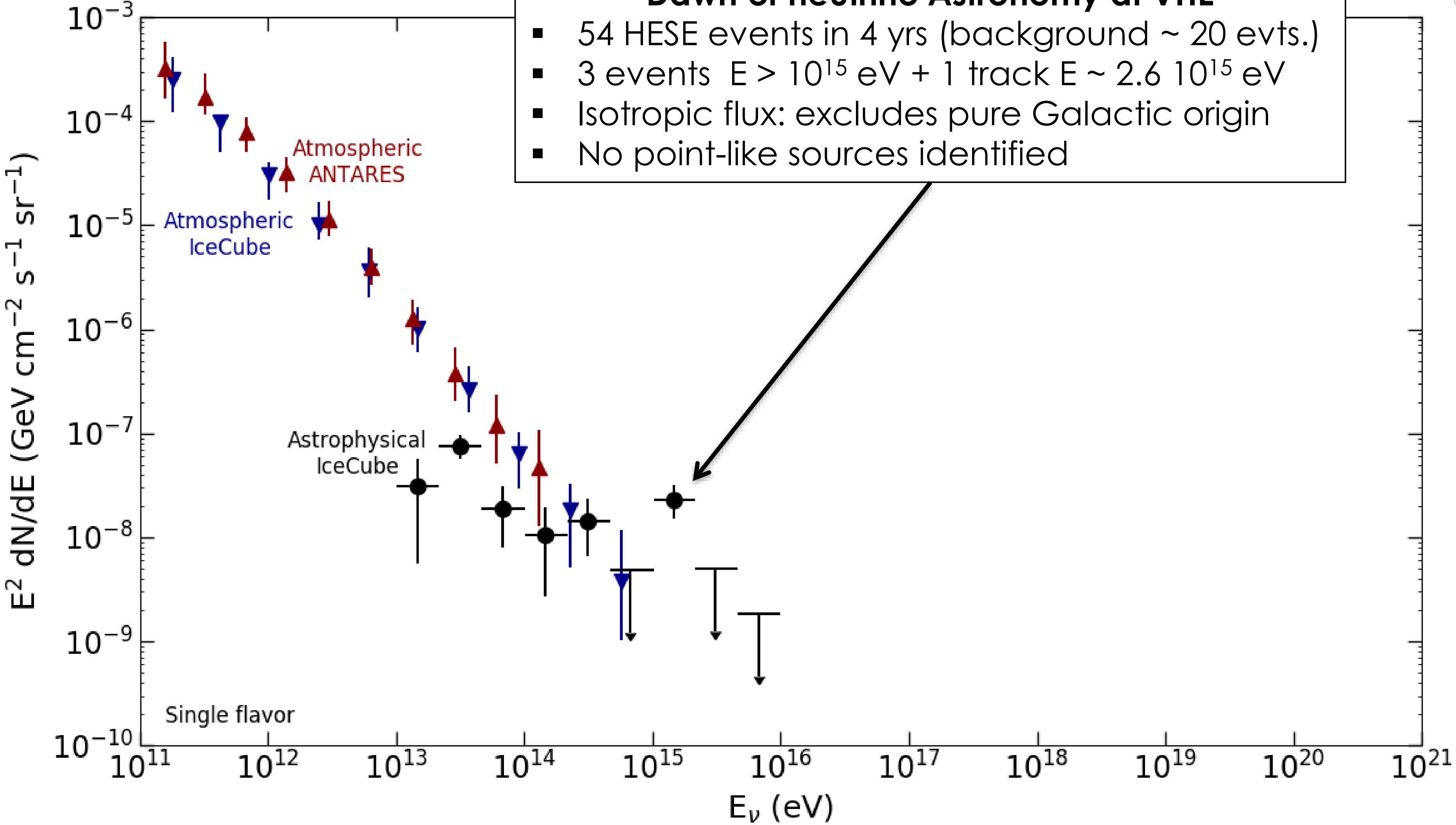


T. De Young

Atmospheric neutrinos: IceCube/ANTARES



Astrophysical neutrinos: IceCube

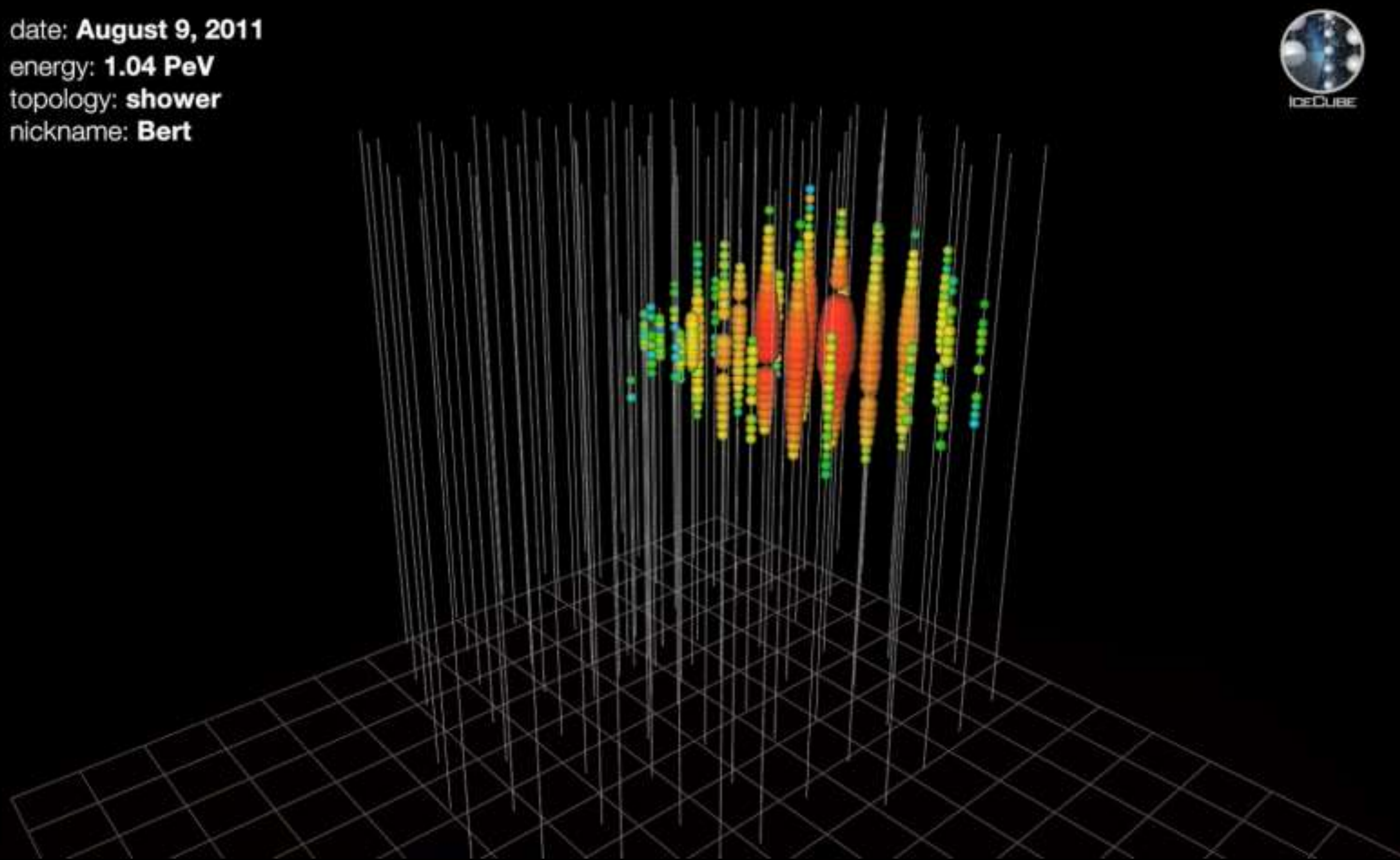


Dawn of neutrino Astronomy at VHE

- 54 HESE events in 4 yrs (background ~ 20 evts.)
- 3 events E > 10^{15} eV + 1 track E ~ 2.6 10^{15} eV
- Isotropic flux: excludes pure Galactic origin
- No point-like sources identified

Update: 80 events in 6 yr of IceCube data in a bkg. ~ 40 (C. Kopper, ICRC2017)

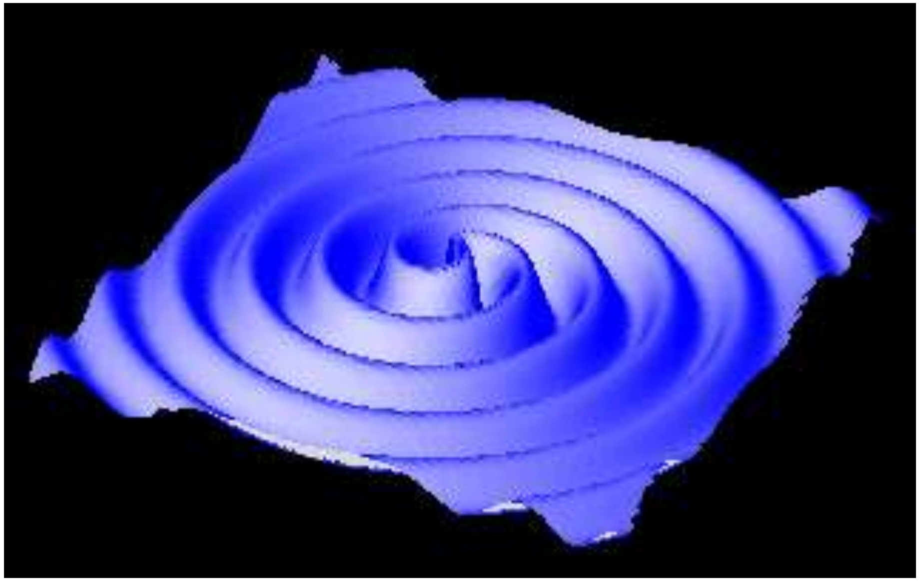
A cosmic neutrino interacts INSIDE the detector: it is too energetic to be produced in the atmosphere

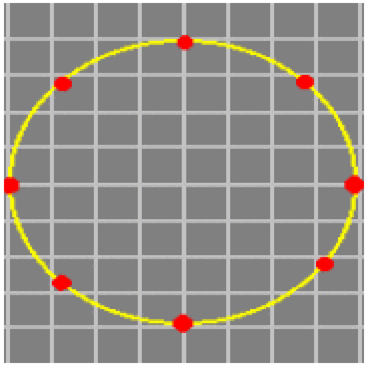


> 300 optical sensors; > 100,000 photons; 2 ns time resolution

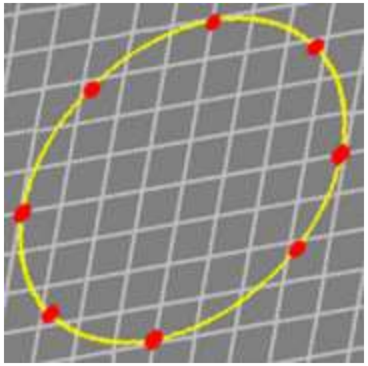
Gravitational Waves

- Rapid variations of curvature of space due to motion of objects => curvature ripples = Gravitational Waves (GW)
- Propagate at speed of light
- Radiate energy
- Two polarizations "+" and "x"





+



x

GW as messengers

✓ **Not deflected** by Galactic/inter-gal. B-fields:

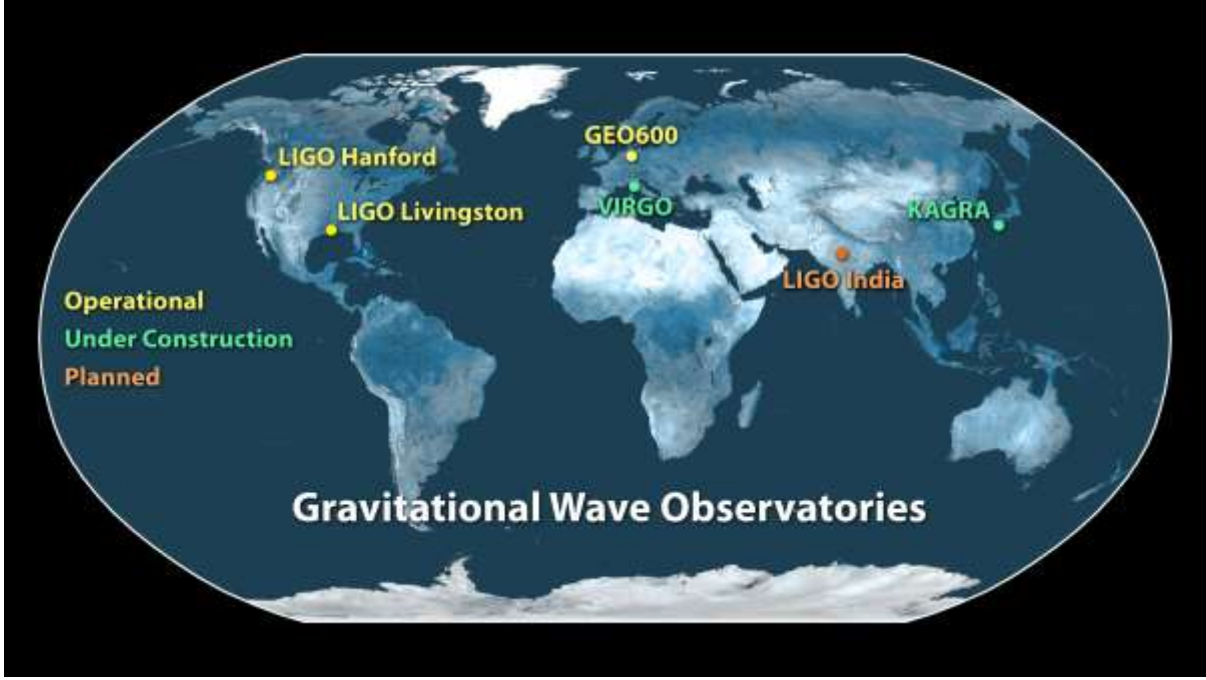
- Point back to sources where they were produced
- No time delays w.r.t. optical transient sources

✓ **Horizon distance NOT limited:**

- Can come from cosmological distances (> Gpc)

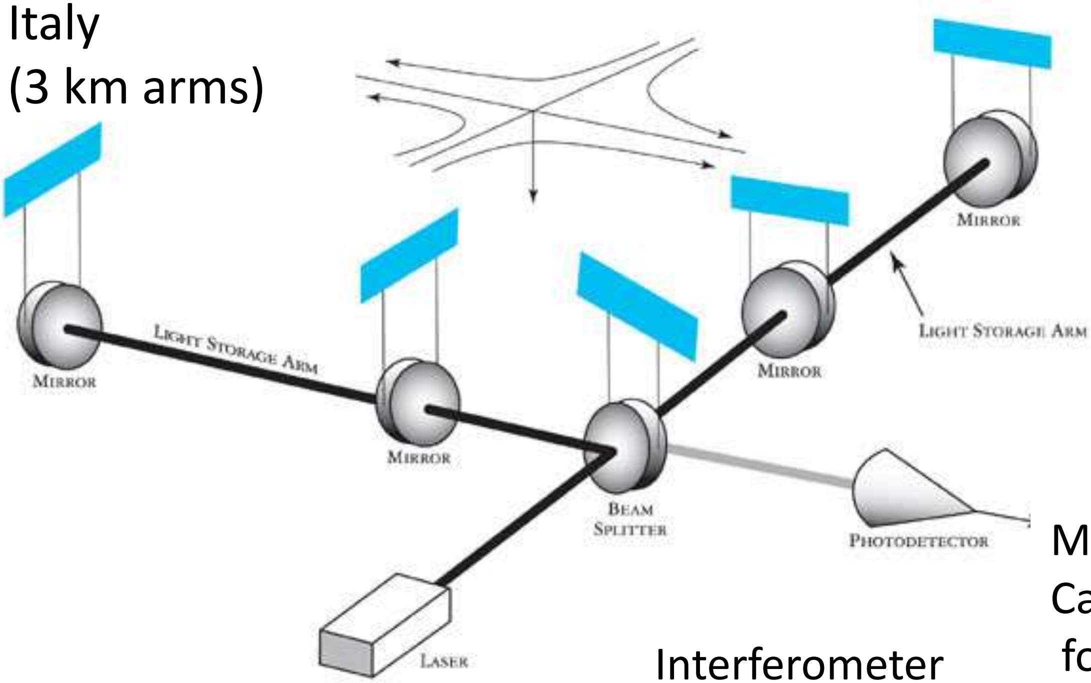
- **Not so easy (& not so cheap) to detect**

Laser Interferometer Gravitational Wave Observatory



LIGO:
Hanford WA, USA
Livingston LA, USA
(4 km arms)

Virgo:
Italy
(3 km arms)



Interferometer

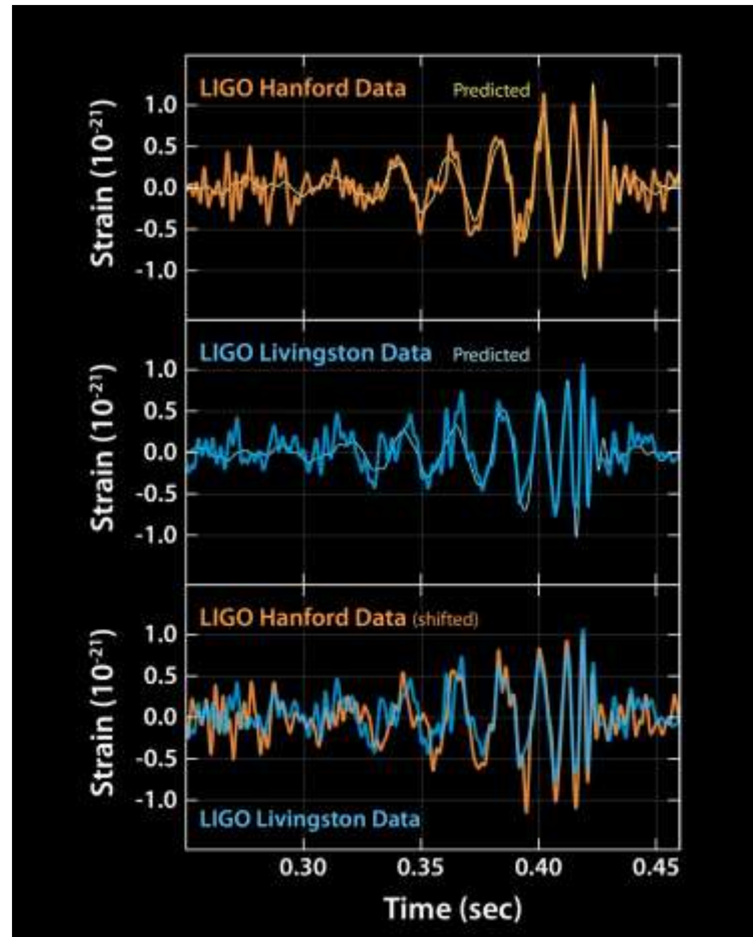
LIGO Hanford WA, USA

Most precise “ruler” in the World.
Capable of measuring $\Delta L/L = h(t) \sim 10^{-21}$
for $L = 4$ km $\Rightarrow \Delta L \sim 10^{-3}$ fm

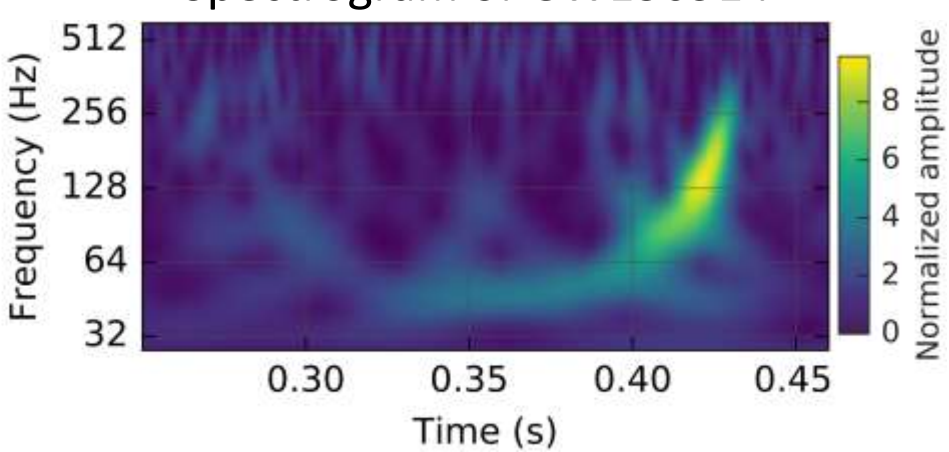
1^{st} detection: GW150914

14 September 2015, detection of merger of a binary black-hole (BBH) system:
D ~ 430 Mpc, $M_1 \sim 35.6$ & $M_2 \sim 30.6$ solar masses
~ 3.1 solar masses radiated in GW

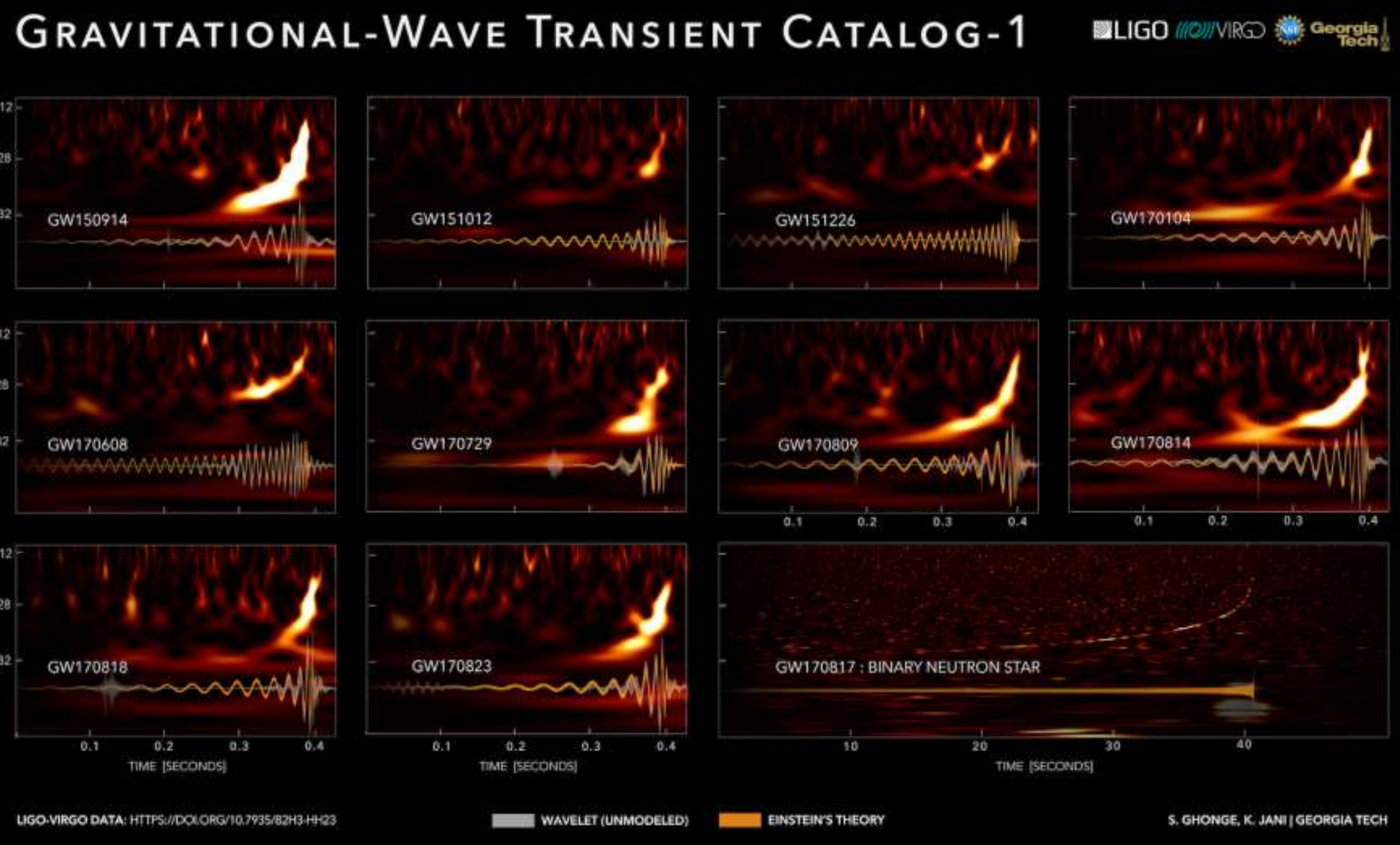
h(t) Strain vs time



Spectrogram of GW150914

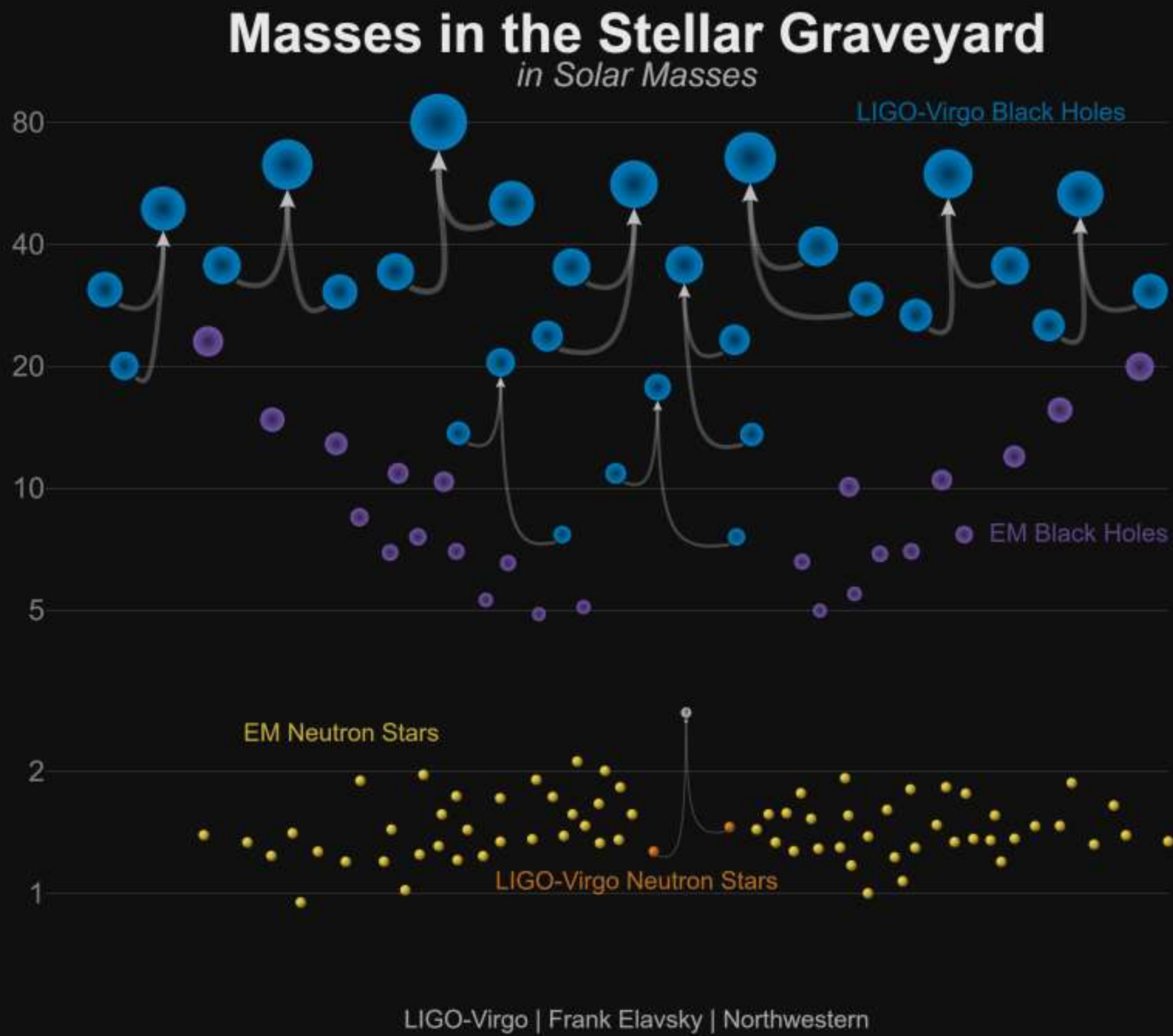


1st catalog of GW: 10 BBH + 1 BNS



arXiv:1811.12907 [astro-ph.HE]

Mass (solar mass units)



Milestones in MM Astronomy

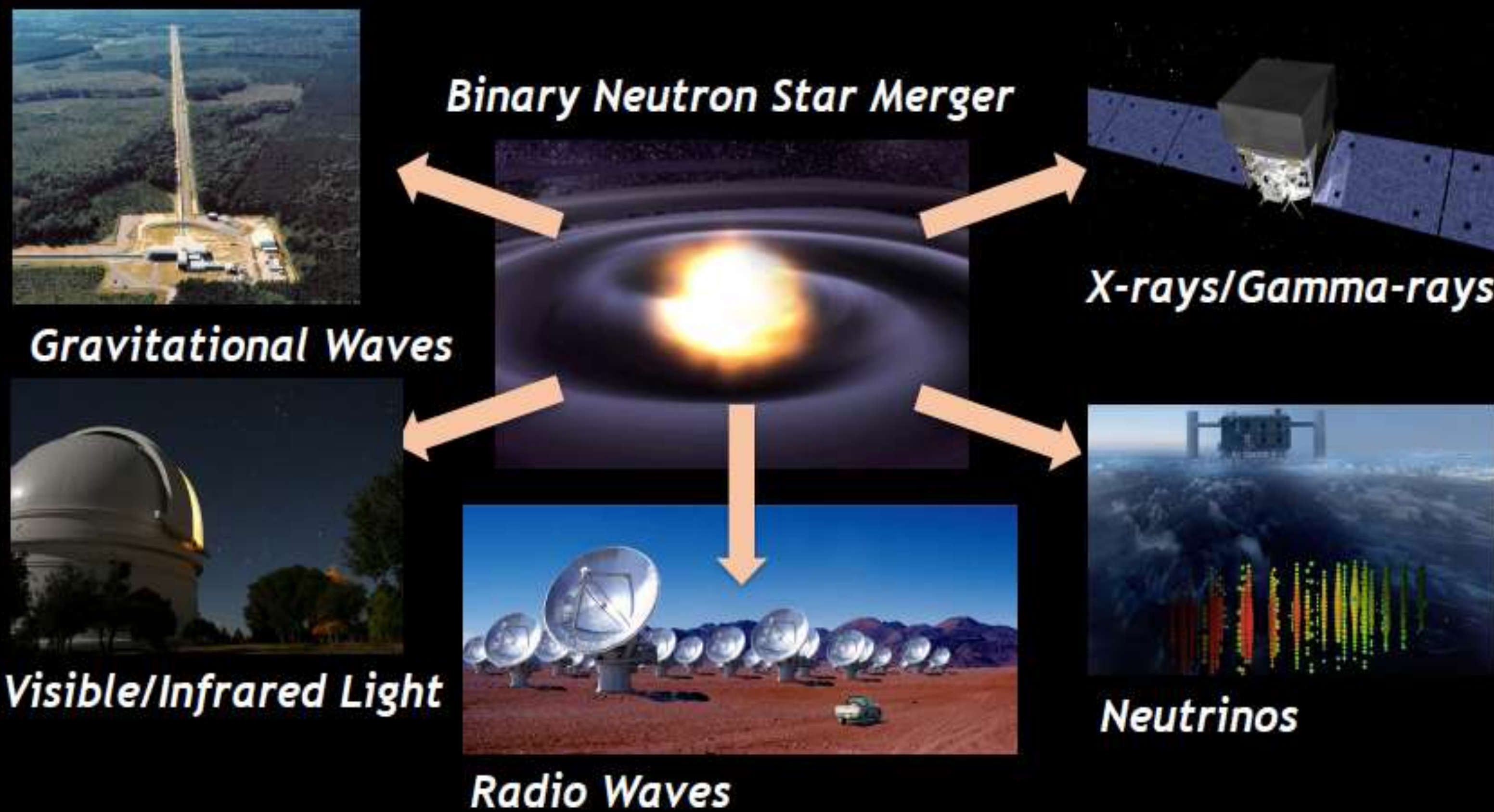
1. **The Sun:** electromagnetic + cosmic-rays
2. **The Sun:** electromagnetic + low-Energy (MeV) neutrinos
3. **Supernova 1987A:** low-E (MeV) neutrinos + electrom.
4. **GW170817 Binary Neutron Star:** GW + electrom.
5. **TXS 0506+056:** high-E neutrinos + electrom.

(only **4** and **5** will be discussed in this talk)

17 August 2017, GW170817

observation of a Binary Neutron Star (BNS) merger

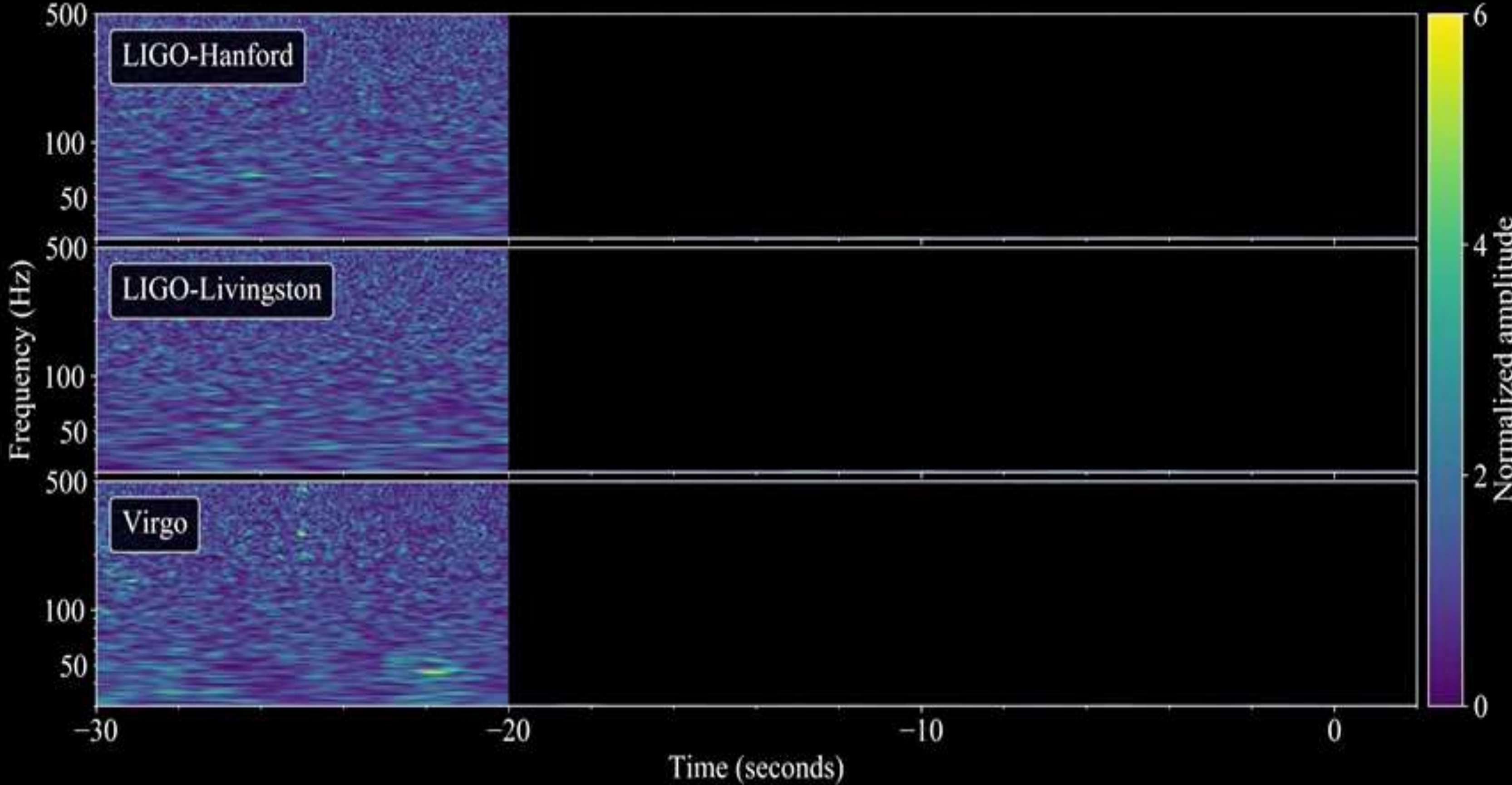
Multi-messenger Astronomy with Gravitational Waves



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

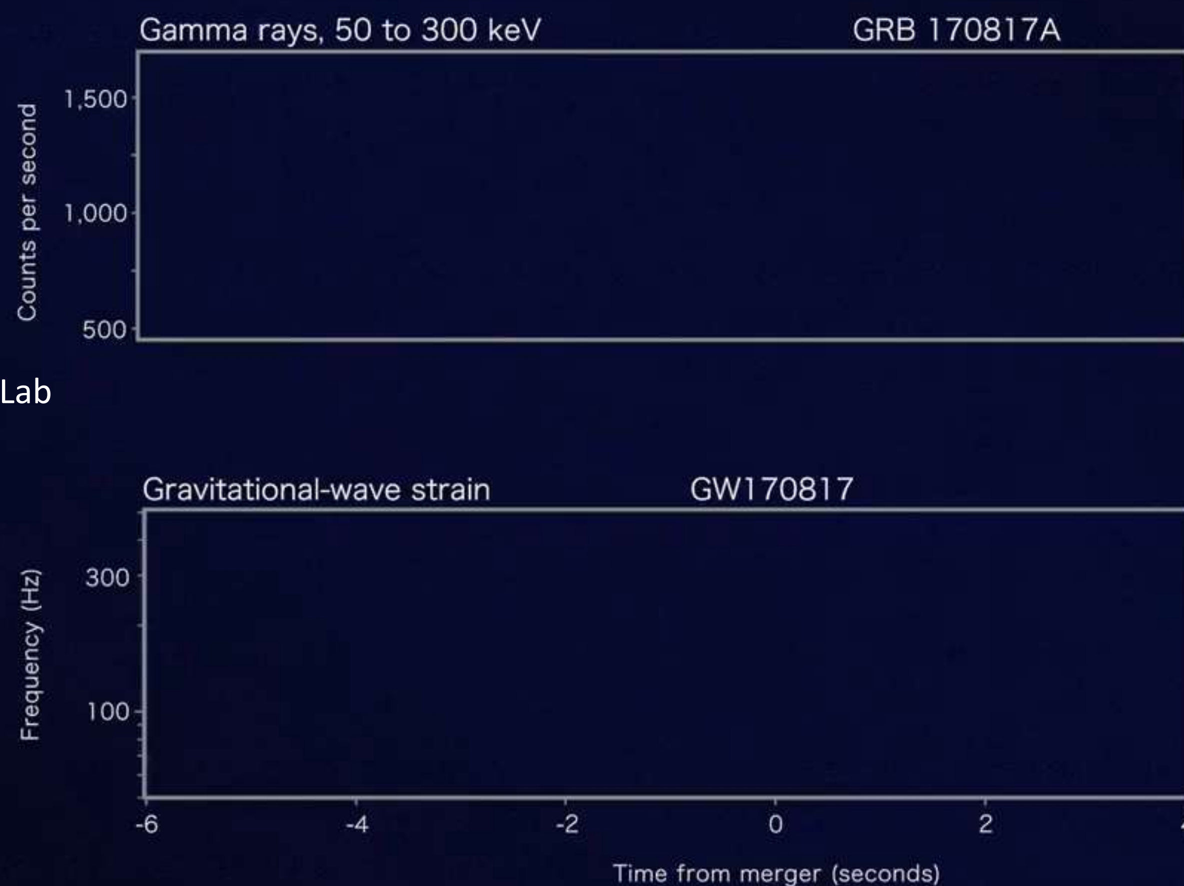
GW170817



In 2017 August 17 a binary neutron star coalescence with merger time 12:41:04 UTC was observed through gravitational waves by the Advanced LIGO and Advanced Virgo detectors.

Gamma-Rays from Binary Neutron Star

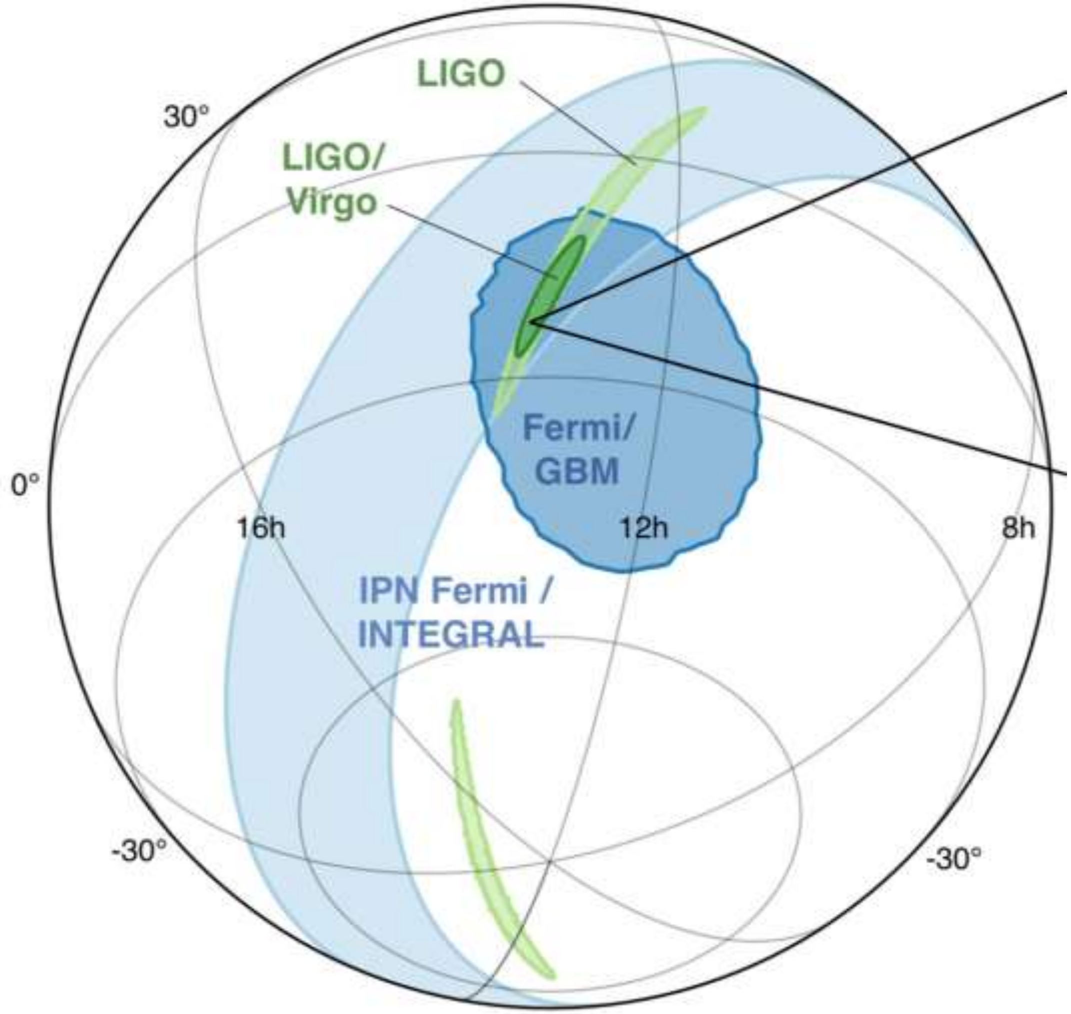
1.7 seconds later Fermi detected a short gamma-ray burst*



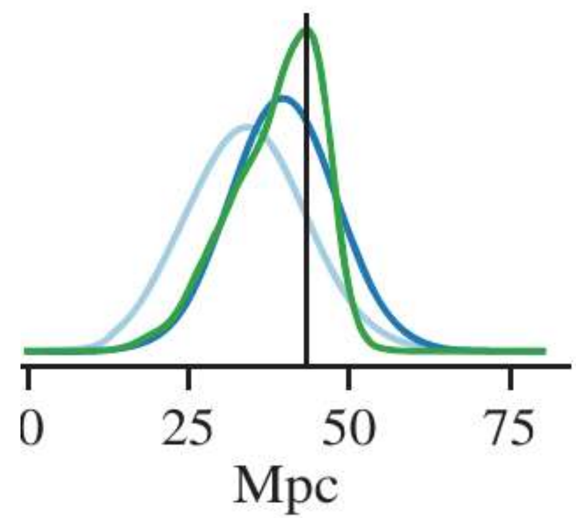
Credit: NASA GSFC & Caltech/MIT/LIGO Lab

*short GRB: < 2 s burst of keV-MeV γ-rays produced by Binary Neutron Star merger

GW170817 localization in the sky



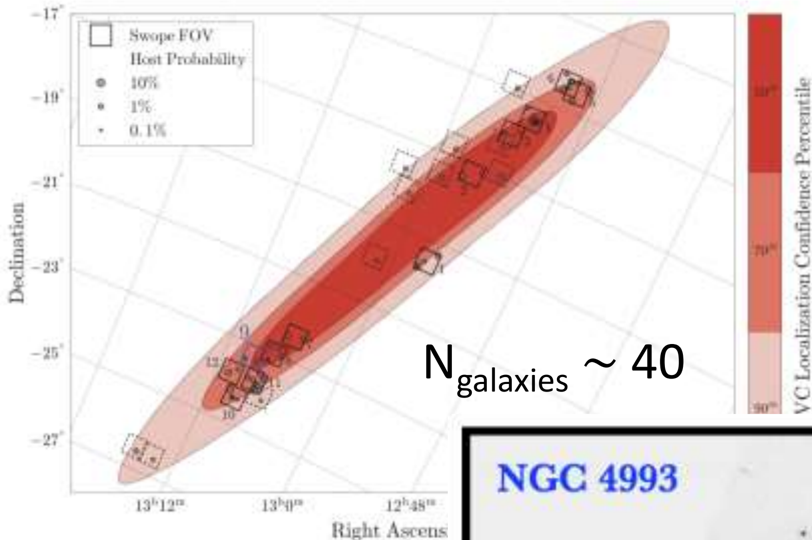
Localization & distance using GW & gamma-ray observations



LVC et al. 2017 ApJ 848 12; ApJ 848 13; PRL 119 1101

Optical follow-up

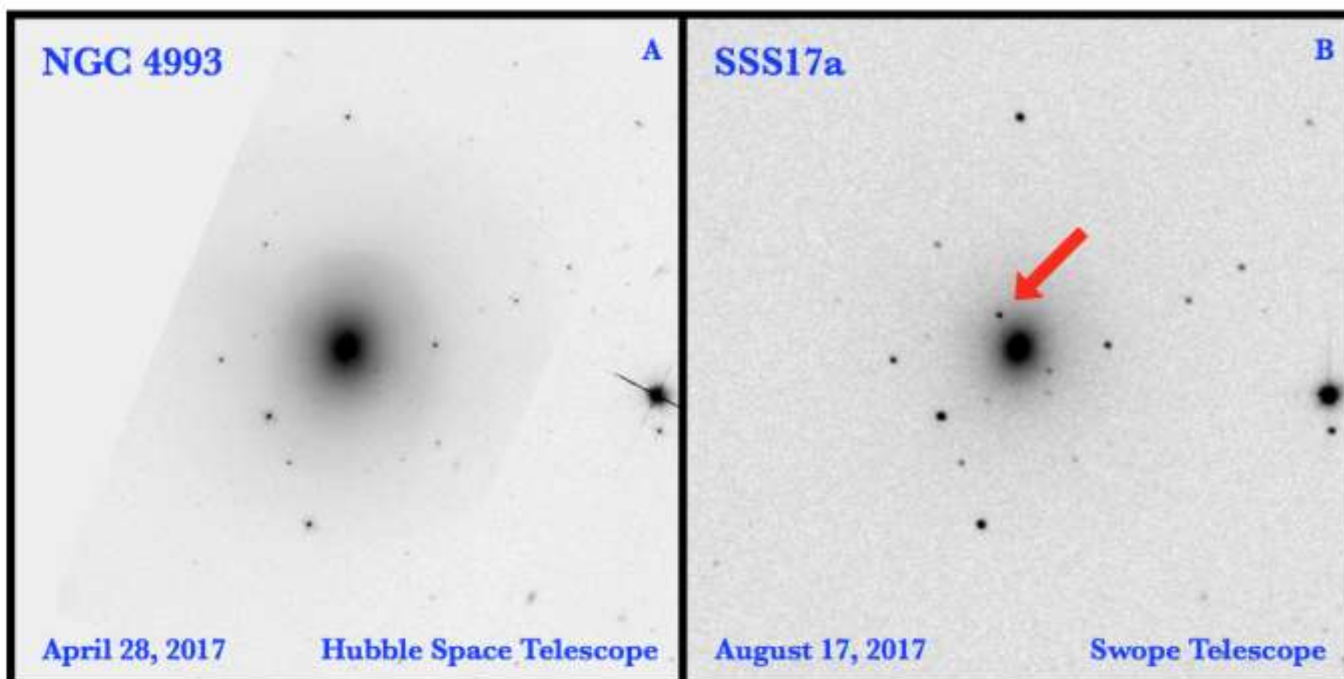
Swope telescope, Cerro Las Campanas, Chile



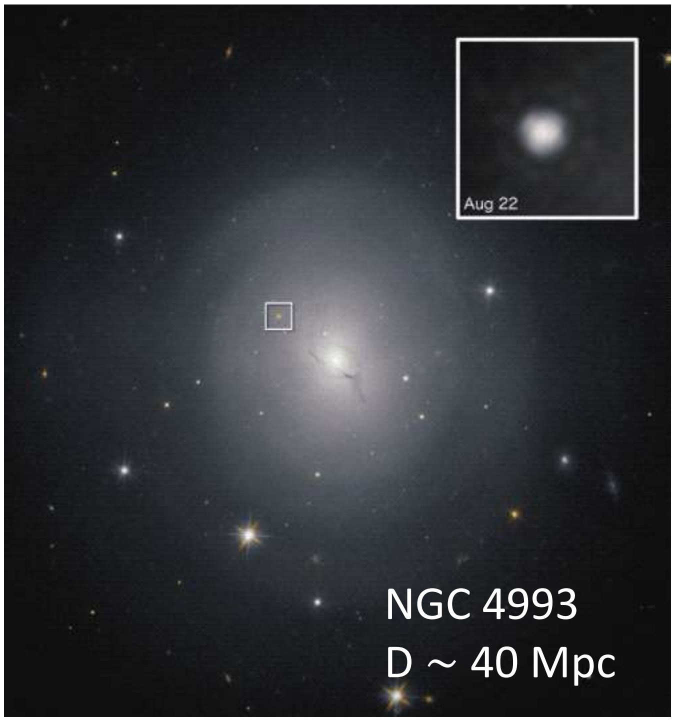
$N_{galaxies} \sim 40$

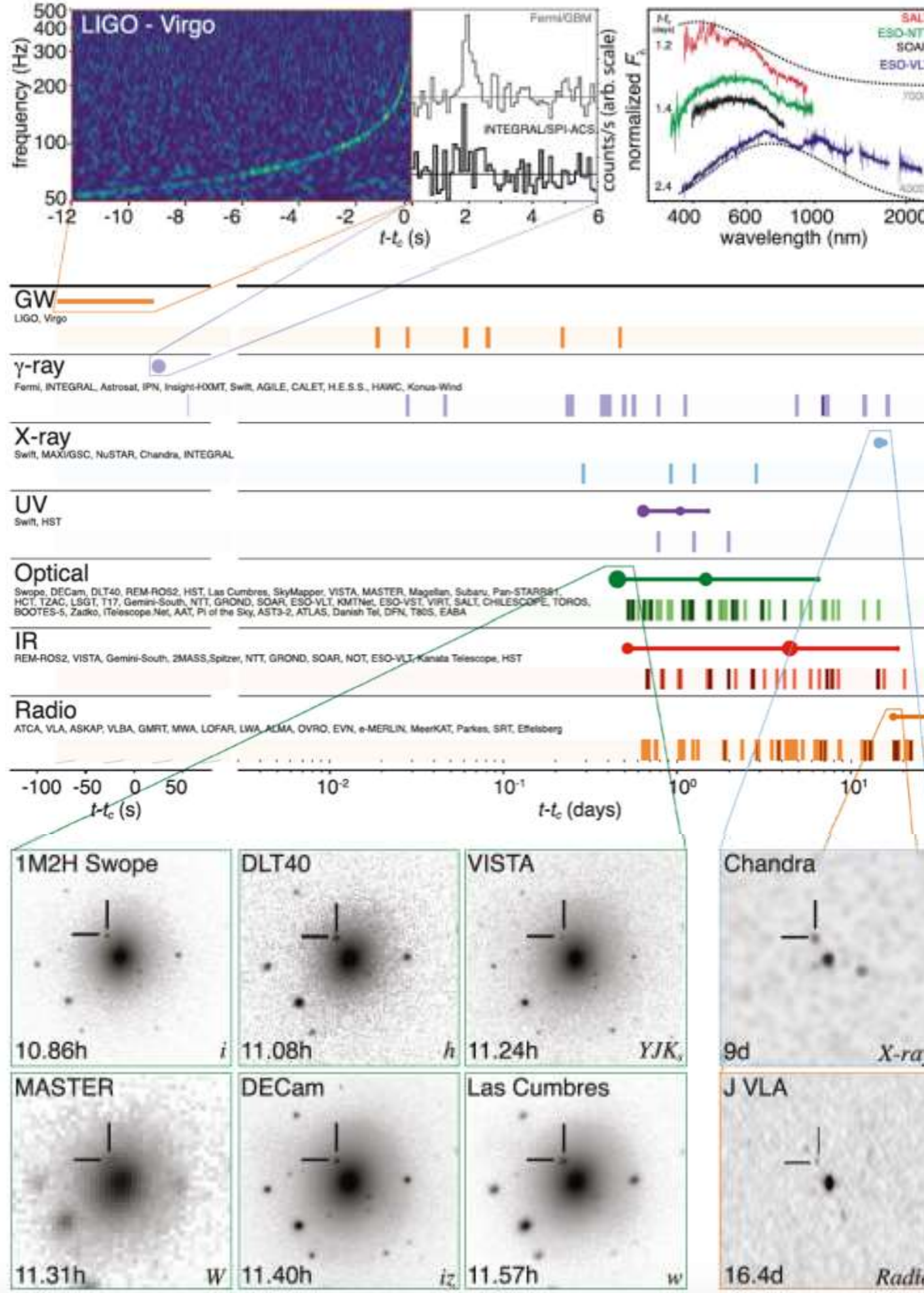
Coulter et al. 2017

- ~ 10 hours AFTER the GW170817 it was dark night in Chile
- Optical telescopes began observing the localization region established with GW + gamma-rays
- An optical transient was found in the outskirts of galaxy NGC 4993, D ~ 40 Mpc



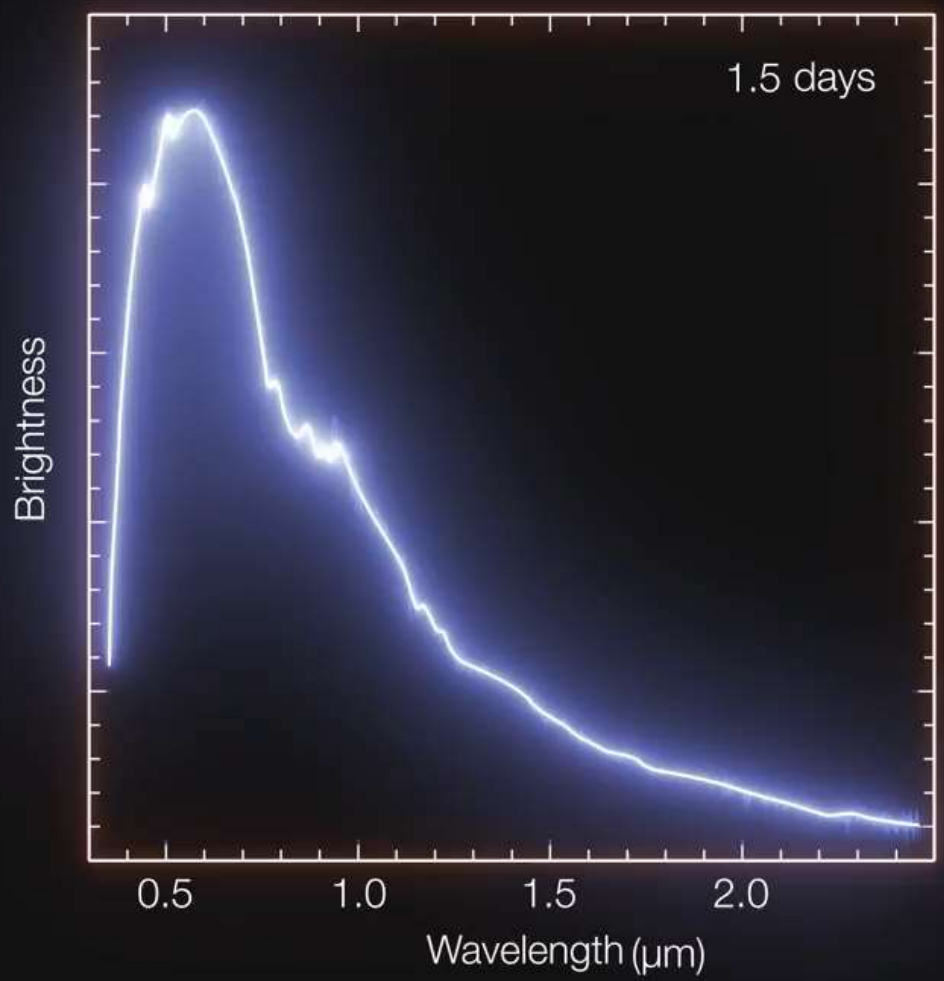
Observations Across the Electromagnetic Spectrum





Abbott, et al. ,LIGO Scientific Collaboration and Virgo Collaboration, “Multi-messenger Observations of a Binary Neutron Star Merger” Astrophys. J. Lett., 848:L12, (2017)

Counterpart brightness



a **kilonova** was found

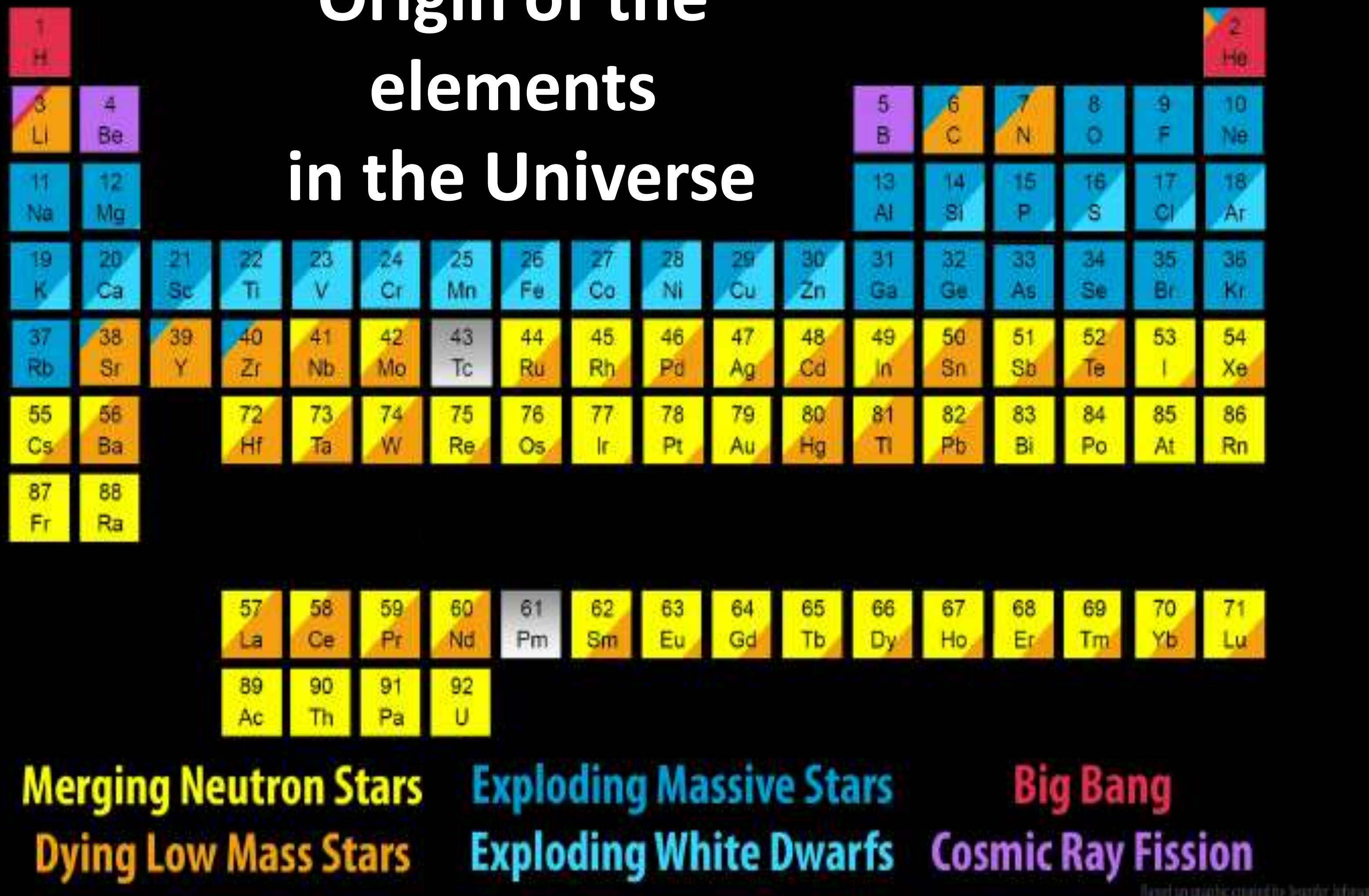
transient source emitting in:

- Ultraviolet
- Optical
- Infrared

They are due to radioactive decay of heavy elements formed by rapid neutron capture in the dense neutron environment provided by the BNS.

Credits: European Southern Observatory (ESO)

Origin of the elements in the Universe



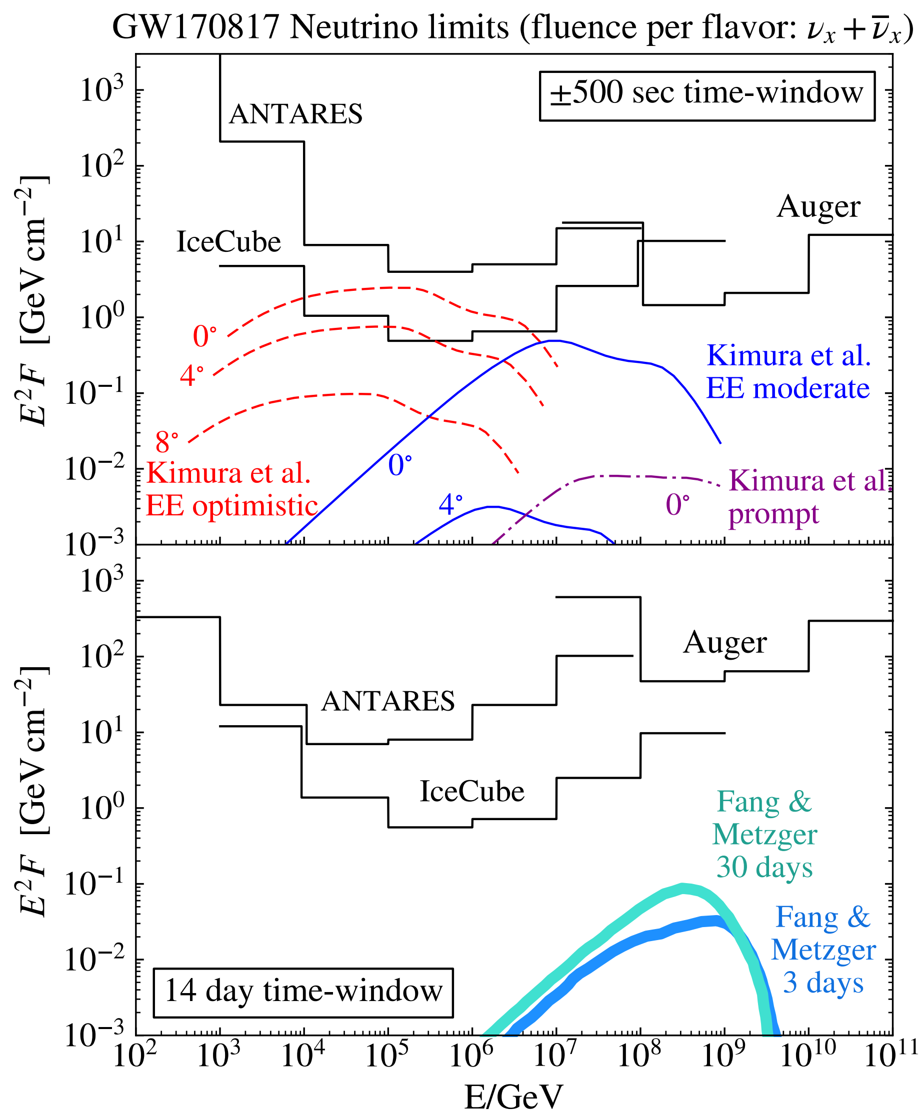
- Kilonovae are candidates for production of half the chemical elements heavier than iron in the Universe.
- 16,000 times the mass of the Earth in heavy elements
- Ten Earth masses just of the two elements gold and platinum

Limits to ν from BNS event GW170817

ANTARES, IceCube & Pierre Auger Observatory

- Neutrino limits based on non-observation in ± 500 sec & +14 days-time windows

- Lack of neutrino detection consistent with expectations from a short GRB viewed at a large off-axis angle ≳ 20° (in agreement with LIGO/Virgo & GRB observations)



ANTARES, IceCube, Auger, LIGO & Virgo Astrophys. J. Lett. **850**, L35 (2017)

What have we learnt ?

- **Binary Neutron Star (BNS) mergers** are strong sources of Gravitational Wave emission.
- **Short gamma-ray bursts** are produced by BNS mergers.
- **Kilonovas** are associated to BNS mergers => responsible for heavy elements that are not produced in Supernovae.
- And also:
  - Independent measurement of **Hubble constant**:

    H_0 = 70 (+12, - 8) km/s/Mpc
  - Constraints on the **speed v_{GW} of gravitational waves**:

    $-3 \times 10^{-15} < (v_{GW} - c)/c < 7 \times 10^{-16}$
  - Constraints on **equation of state (EoS) of Neutron Stars**:

    Consistent with “soft” EOS => more compact NS

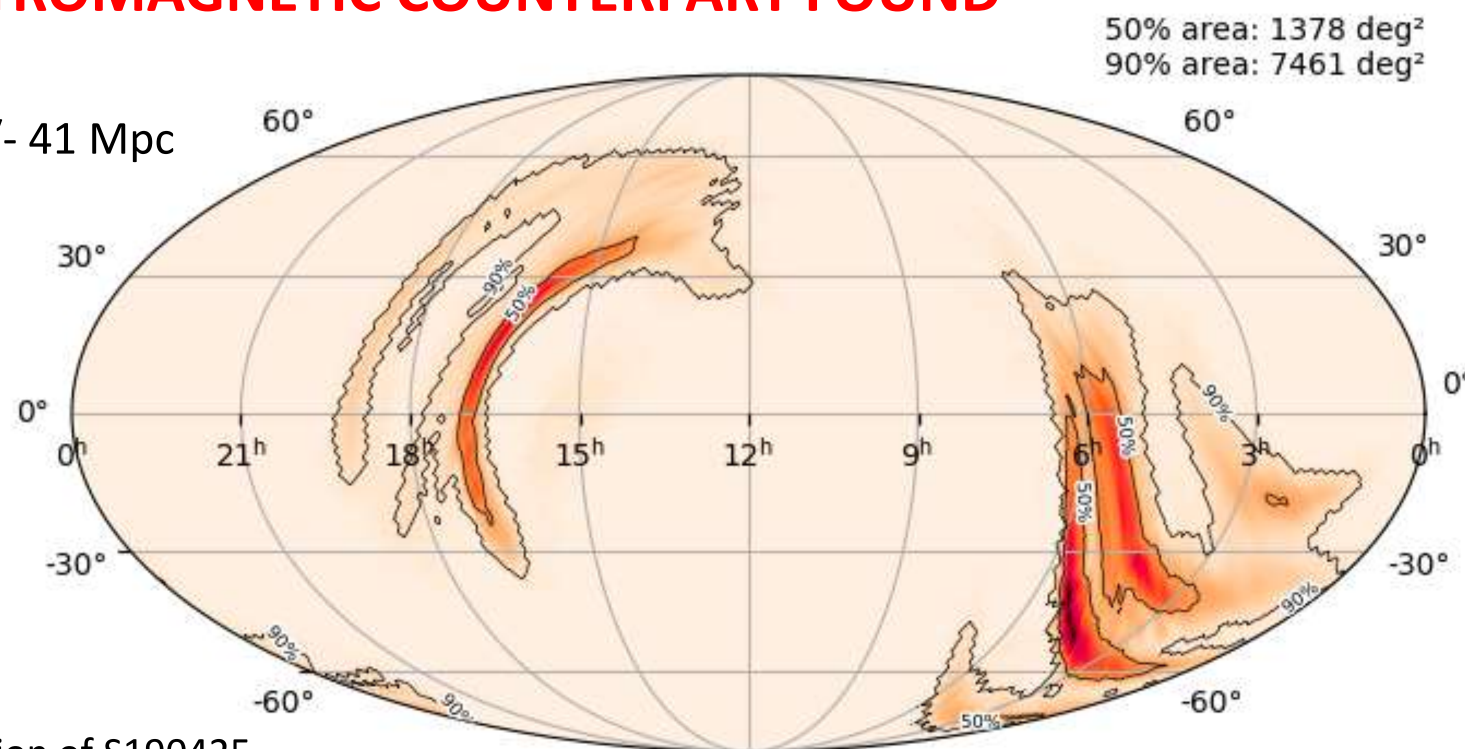
25 April 2019: another Binary Neutron Star candidate !

Detected in GW by LIGO – alert sent immediately to many observatories BUT...
... poor localization in a region of area ~ 18% of the sky:

- Only 1 LIGO observatory detected the GW event.
- No GRB detected by Fermi (50% coverage) or other gamma-ray satellites.
- Optical telescopes had to search a region in which there are 49,354 galaxies !!

NO ELECTROMAGNETIC COUNTERPART FOUND

D = 156 +/- 41 Mpc



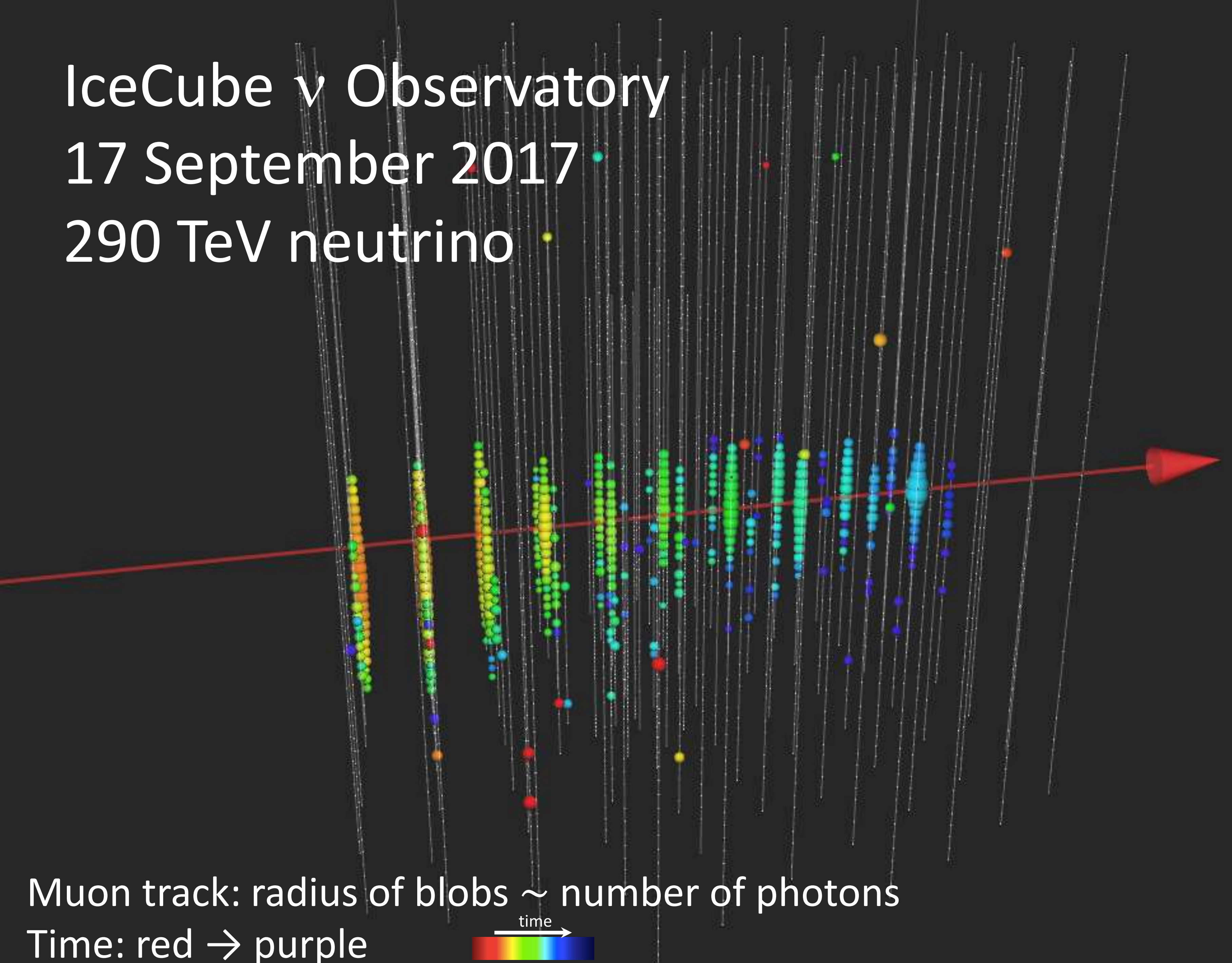
LIGO localization of S190425

What have we learnt ?

Multimessenger Astronomy is a simple idea,

but it is not easy !

IceCube ν Observatory
17 September 2017
290 TeV neutrino



Muon track: radius of blobs ~ number of photons

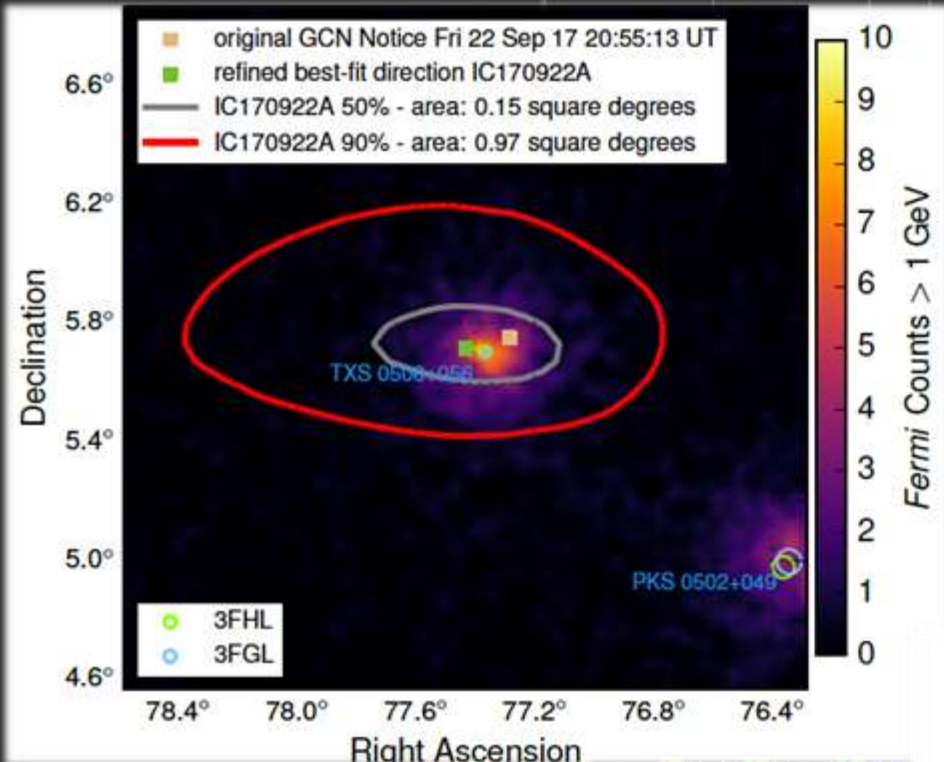
Time: red → purple

IceCube alerts other observatories

43 seconds after IceCube trigger, a 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]
```

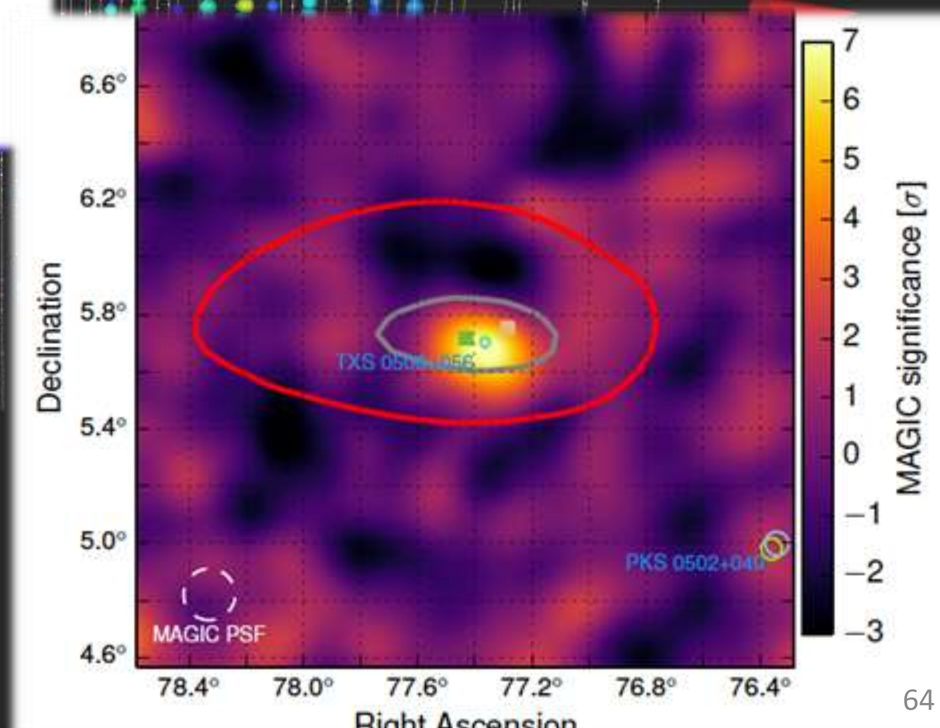
Electromagnetic follow-up of IC17



28 September 2017

Fermi γ-ray satellite detects a flaring blazar* within 0.1^o of IceCube neutrino

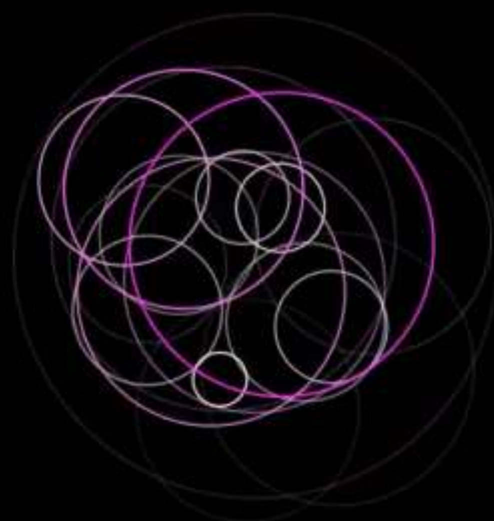
MAGIC Cherenkov telescope detects emission of TeV γ-rays



* blazar = extragalactic radio, optical, X-ray, gamma-ray sources with jets pointing at us

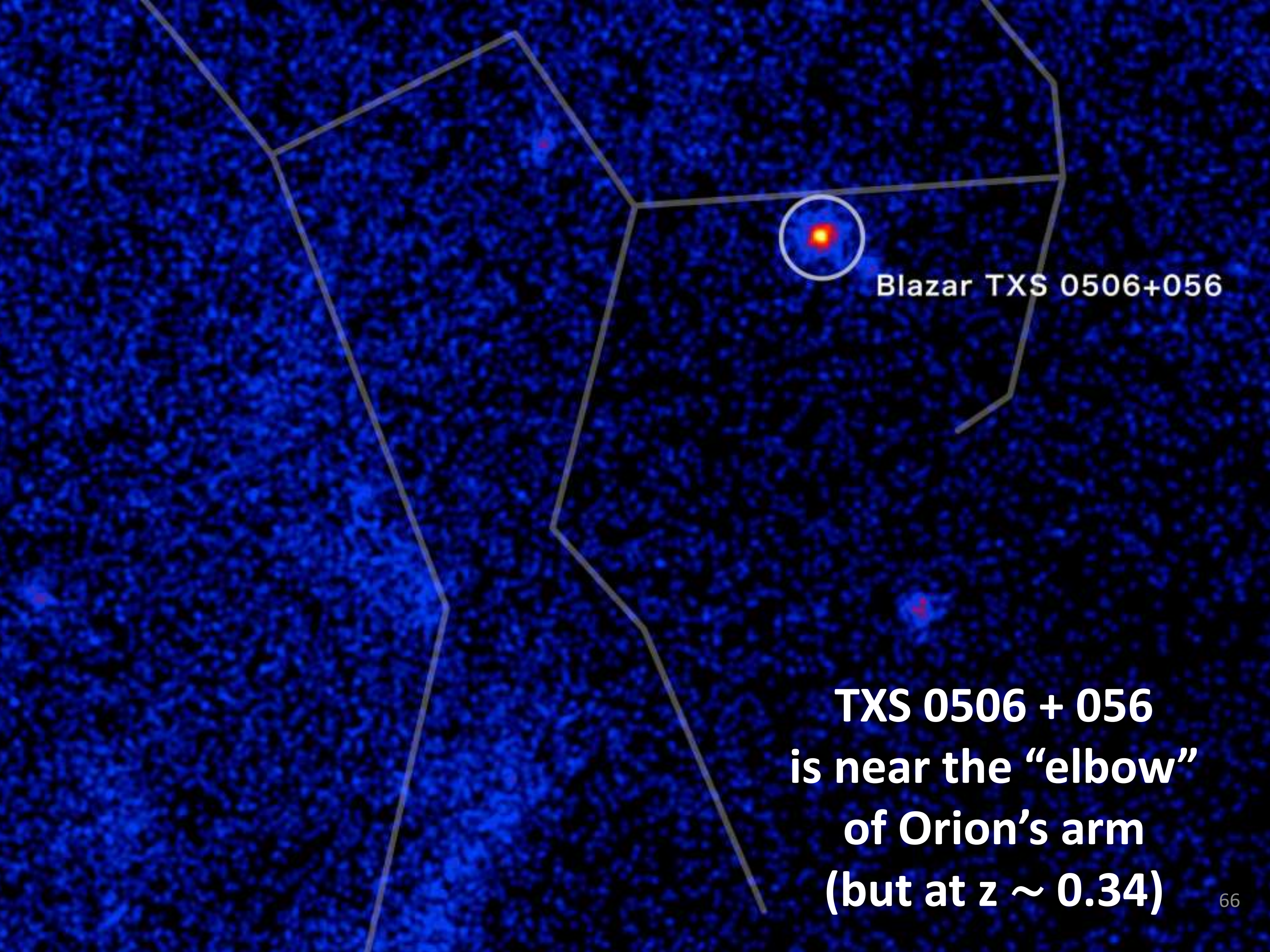
γ-ray flare from TXS 0506 + 056 blazar seen by Fermi satellite

22 Sep 2008



Size of circle and tone of sound matched to γ-ray energy

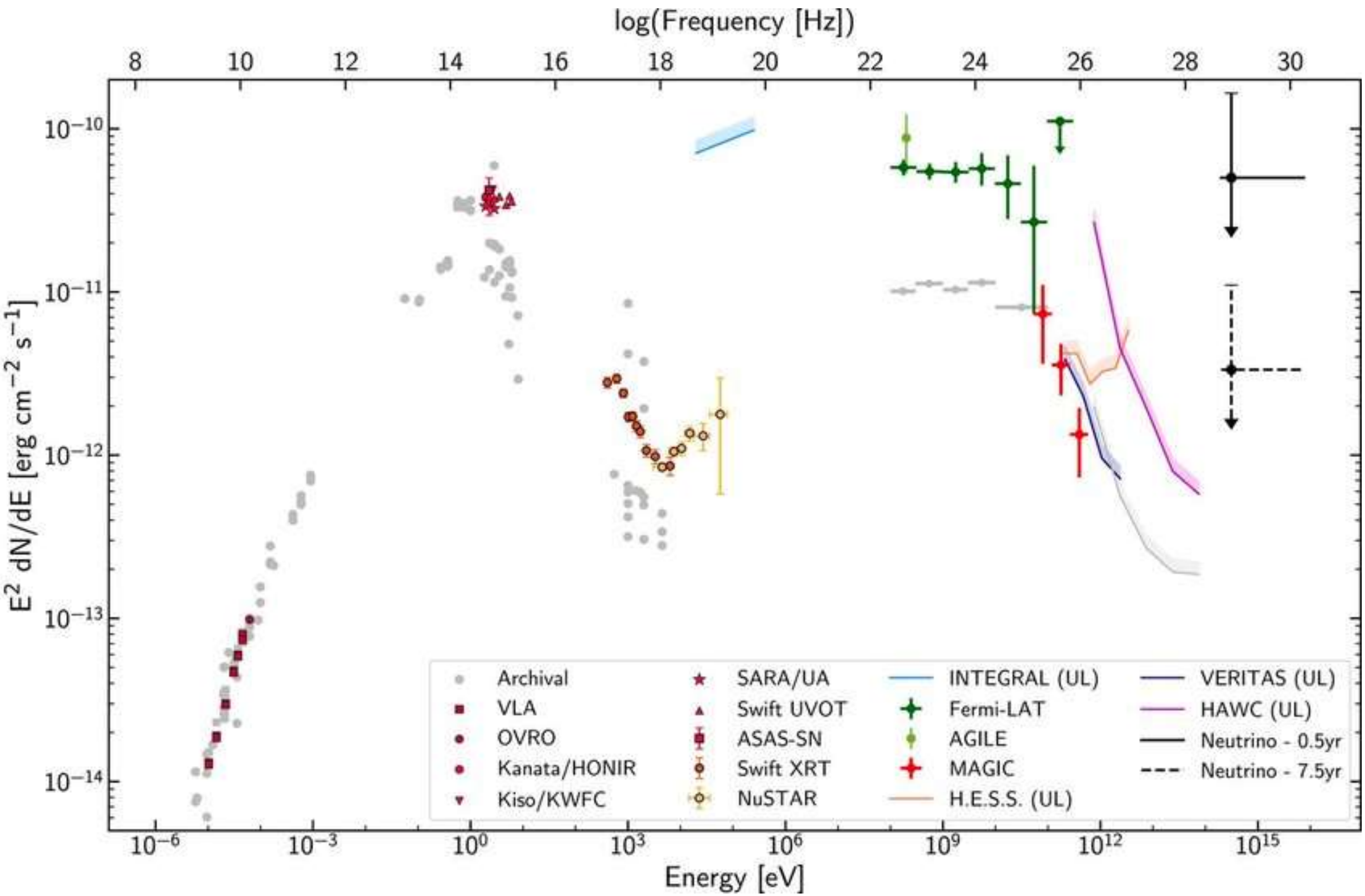
Credit: NASA/DOE/Fermi LAT Collaboration., Matt Russo and Andrew Santaguida/SYSTEM Sounds



TXS 0506 + 056
is near the “elbow”
of Orion’s arm
(but at $z \sim 0.34$)

Electrom. & ν spectrum of TXS 0506+056

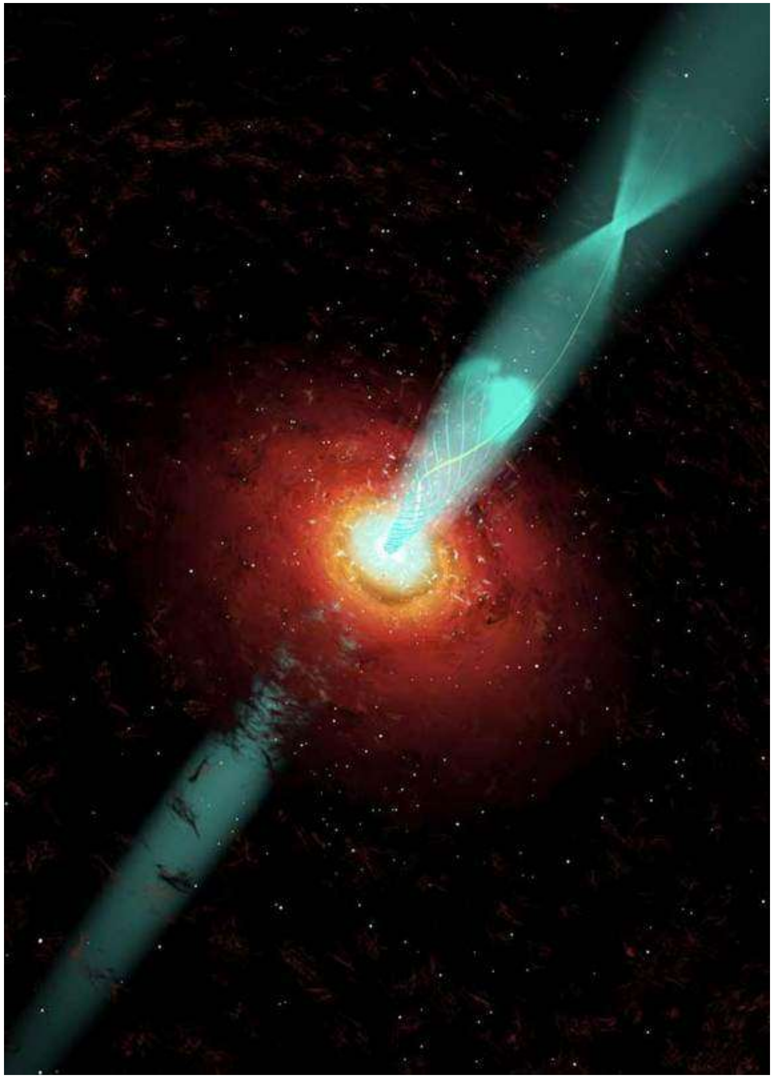
1st association of High-E ν & γ-ray source



Science 361 (2018) no.6398, eaat1378

What have we learnt ?

- Blazar jets may accelerate cosmic-rays: they may be one of the long-sought sources of cosmic-rays.
- Blazars can produce γ-rays and neutrinos in interactions of cosmic-rays with ambient matter and/or radiation in/around blazar.
- Blazars may be responsible for a fraction of IceCube astrophysical neutrino flux of unknown origin.



Conclusions

- Multi-Messenger Astronomy is now & is exciting !

- Observations of the same source with different messengers provide a wealth of information not accessible with single messengers alone.

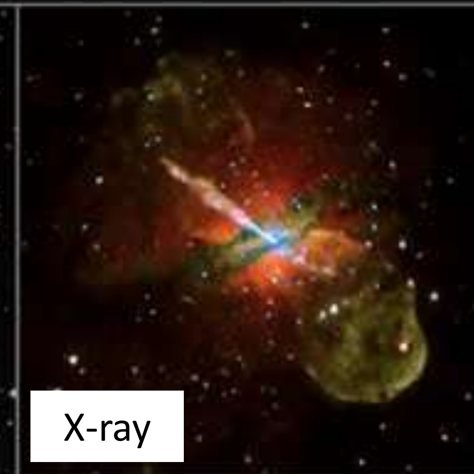
- The future will bring more MM observations:

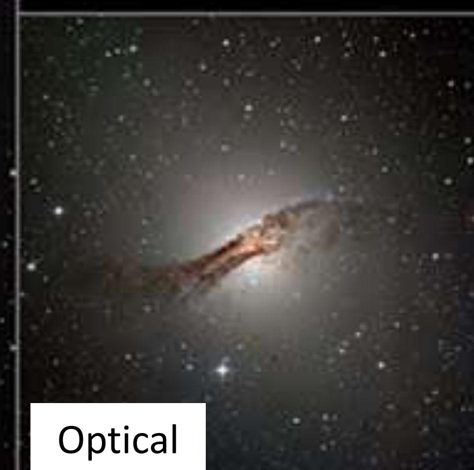
F. Halzen's "event of a lifetime" (observation of GW, electromagnetic radiation, cosmic-rays & neutrinos) might be around the corner...

muito obrigado !

Backup

Multi-wavelength Astronomy





Multi-Messenger: origins

University of Wisconsin - Madison MADPH-03-1320

January 2003

MULTI-MESSENGER ASTRONOMY: COSMIC RAYS, GAMMA-RAYS AND NEUTRINOS

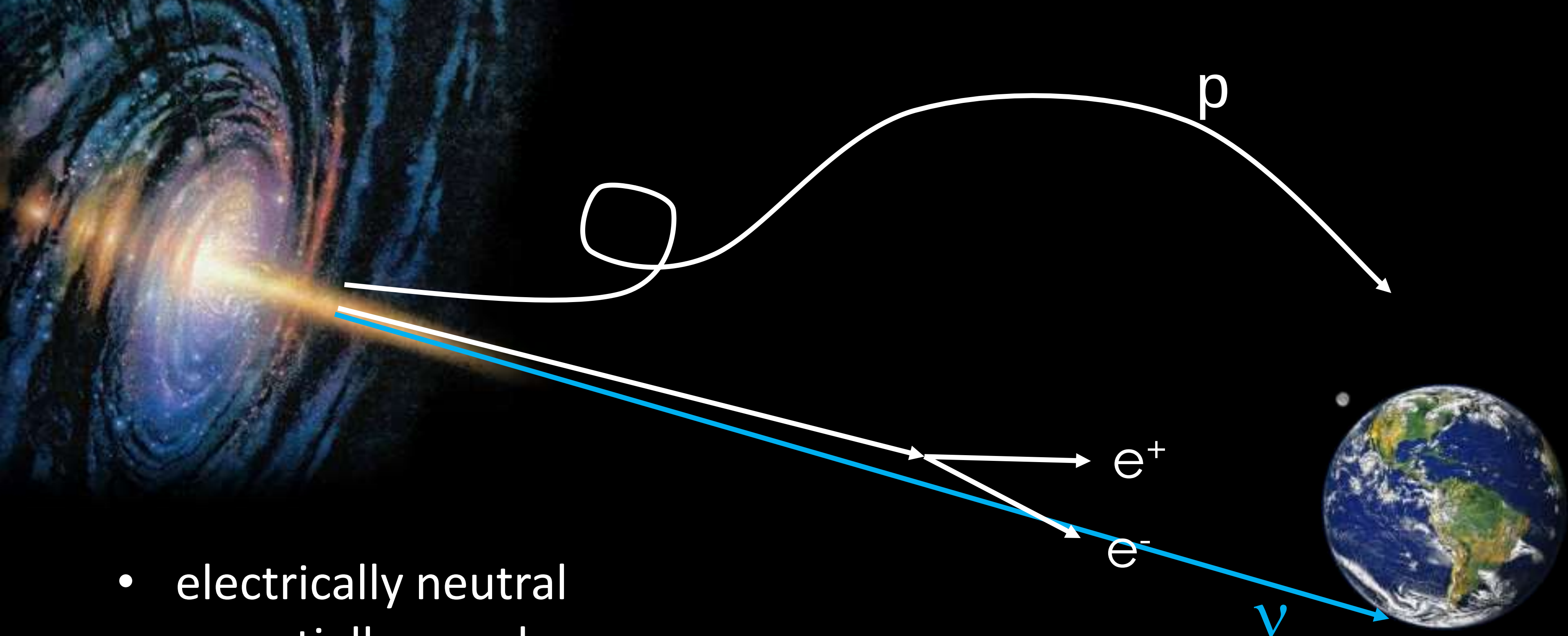
FRANCIS HALZEN

Department of Physics, University of Wisconsin, Madison, WI 53706, USA

Although cosmic rays were discovered a century ago, we do not know where or how they are accelerated. There is a realistic hope that the oldest problem in astronomy will be solved soon by ambitious experimentation: air shower arrays of 10,000 kilometer-square area, arrays of air Cerenkov telescopes and kilometer-scale neutrino observatories. Their predecessors are producing science. We will review the highlights:

- Cosmic rays: the highest energy particles and the GZK cutoff, the search for cosmic accelerators and the the Cygnus region, top-down mechanisms: photons versus protons?
- TeV-energy gamma rays: blazars, how molecular clouds may have revealed proton beams, first hints of the diffuse infrared background?
- Neutrinos: first results and proof of concept for technologies to construct kilometer-scale observatories.

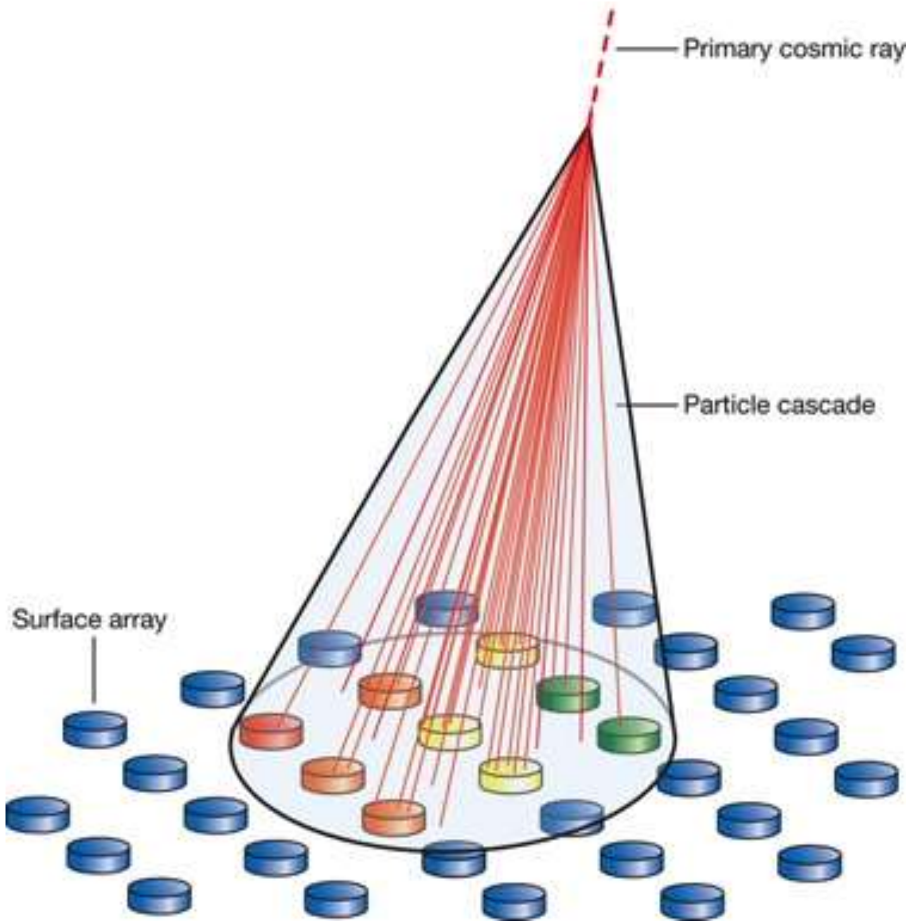
Neutrinos? Perfect Messenger



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

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

Extensive air showers



10^{15} eV => 10^{6} particles in 10^{4} m^{2}
10^{20} eV => 10^{11} particles in10 km^{2}

Cascade of particles initiated by cosmic rays (CR) interacting in atmosphere: **multiplicative** process

Particles reach ground level, spreading laterally over large area (~100 m - few km radius)

Detection possible by instrumenting small fraction of large area on ground => compensates low CR flux

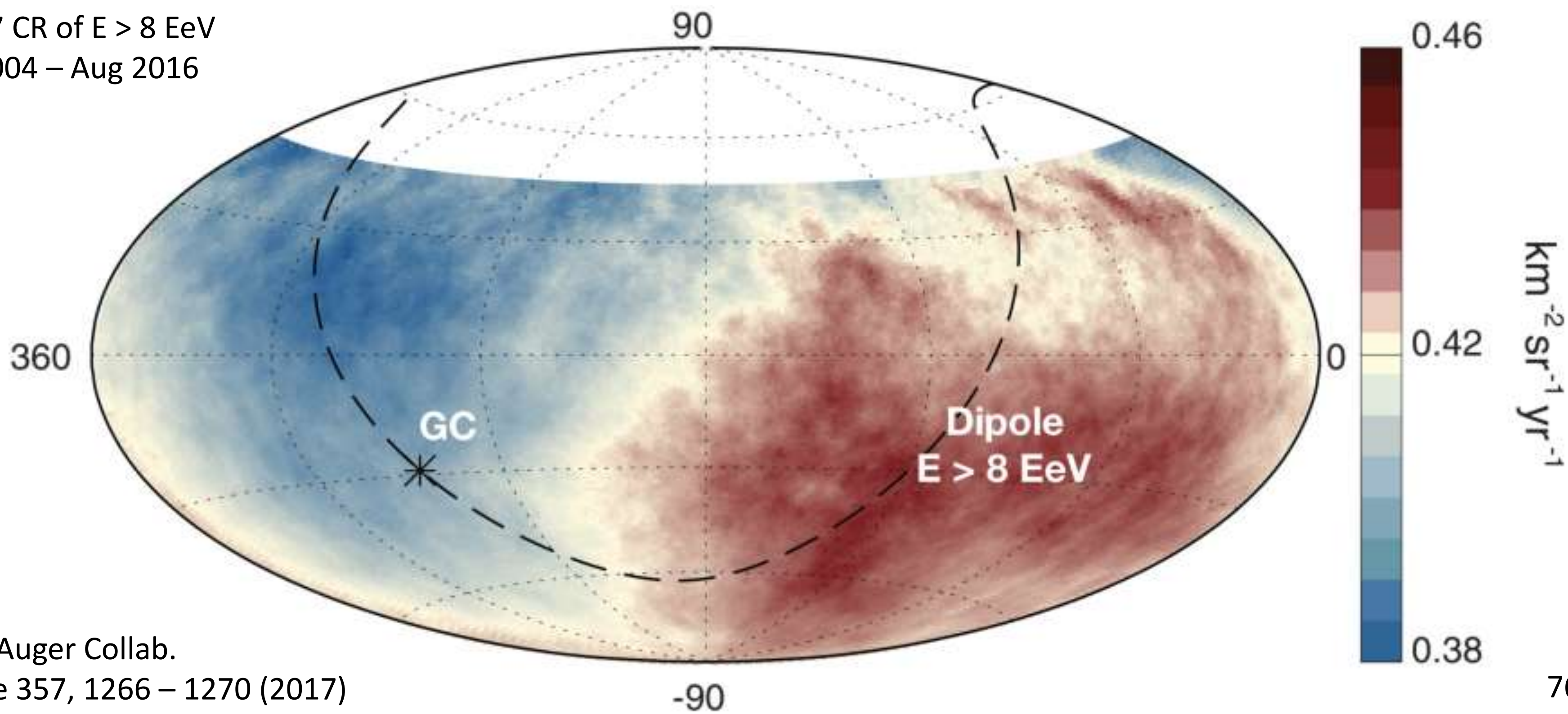
Information on primary initiating shower can be retrieved (energy, direction, mass,…)

Extragalactic origin of UHECR @ E > 8 10^{18} eV

- Dipolar anisotropy in arrival direction of UHECR with E> 8 EeV.
  - Amplitude 6.5%
  - Direction pointing ~ 125° away from Galactic Center.
- Supports hypothesis of extragalactic origin for UHECR, rather than sources within Galaxy.

Flux map above 8 EeV in equatorial coordinates

32,187 CR of E > 8 EeV
Jan 2004 – Aug 2016

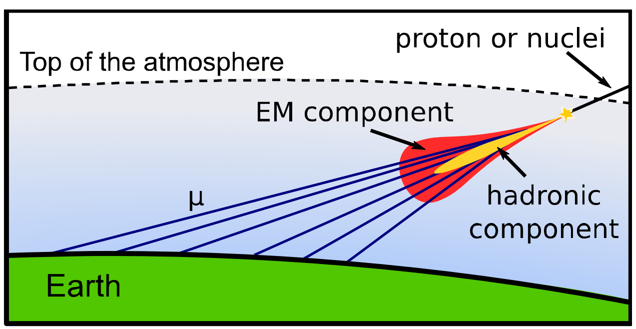


Pierre Auger Collab.
Science 357, 1266 – 1270 (2017)

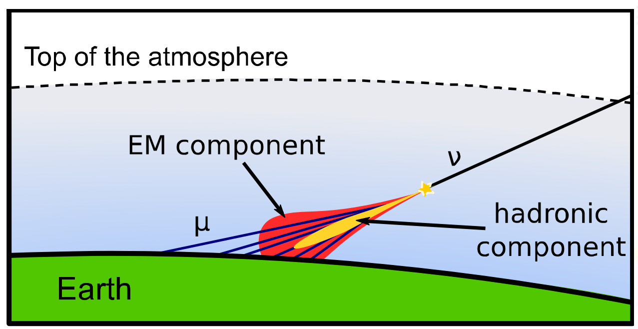
Search for UHEν at Pierre Auger Observatory

- **Pierre Auger is not a dedicated neutrino observatory but…**
- **UHE neutrinos** induce extensive air showers that **can be distinguished** from background charged CR showers:

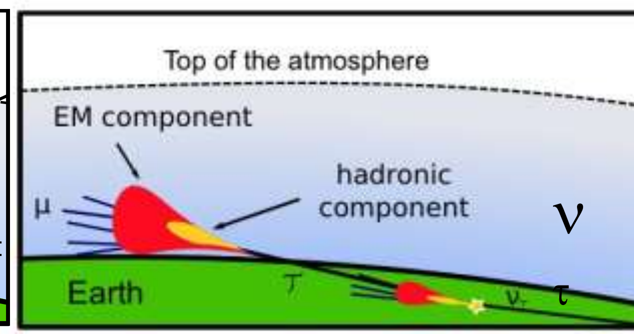
Cosmic Ray



Downward-going neutrino



Upcoming tau neutrino

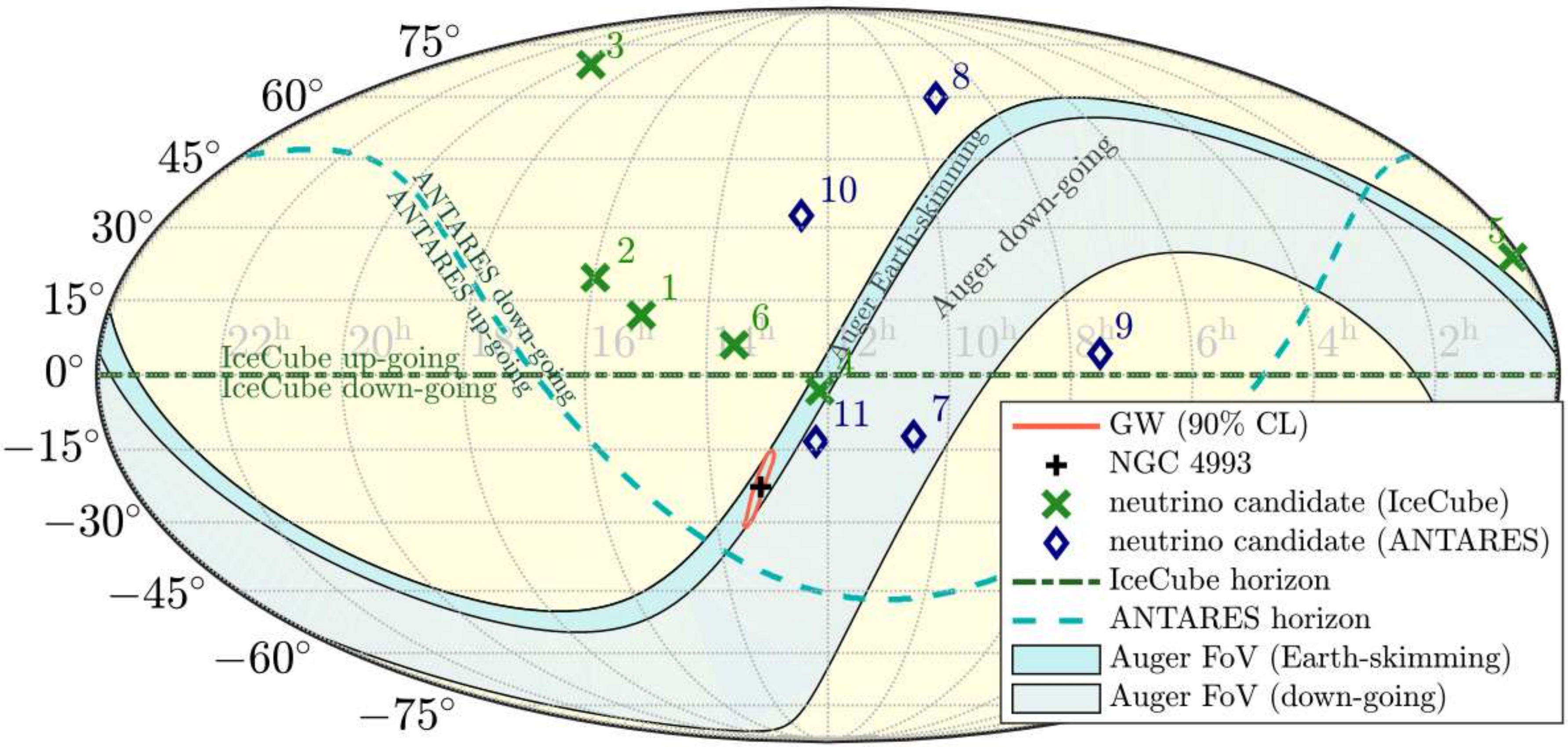


Neutrino signature ⇒ **inclined showers** that develop close to ground

Pierre Auger Collaboration, Phys. Rev. D 91, 092008 (2015), arXiv:1906. [astro-ph.HE]

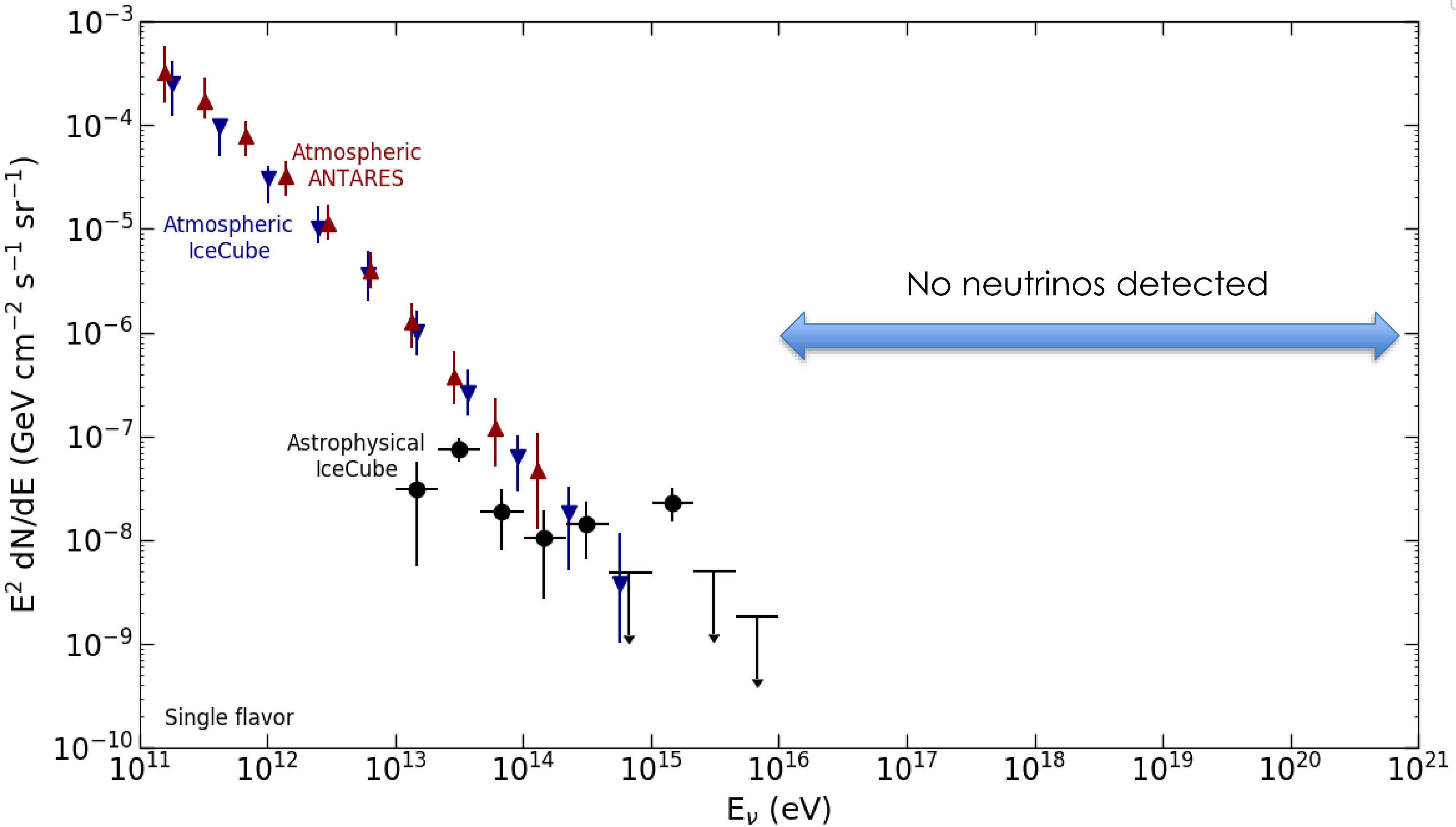
No neutrinos from BNS GW170817

ANTARES, IceCube and Pierre Auger did not see neutrinos in coincidence with GW170817



The NS-NS merger was in an **optimal position** for the detection of UHE tau neutrinos from Auger at the instant of emission of GW170817

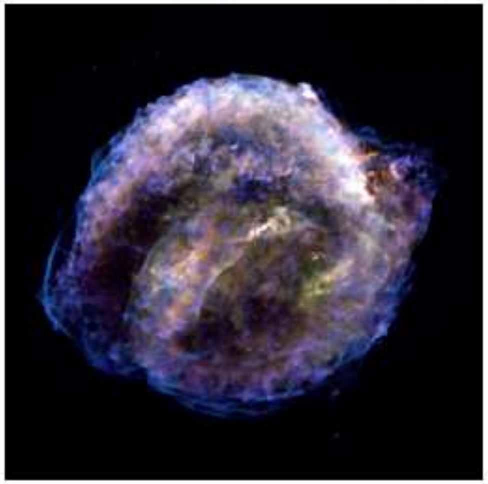
UHE neutrinos ($E \gtrsim 10^{17}$ eV): no data



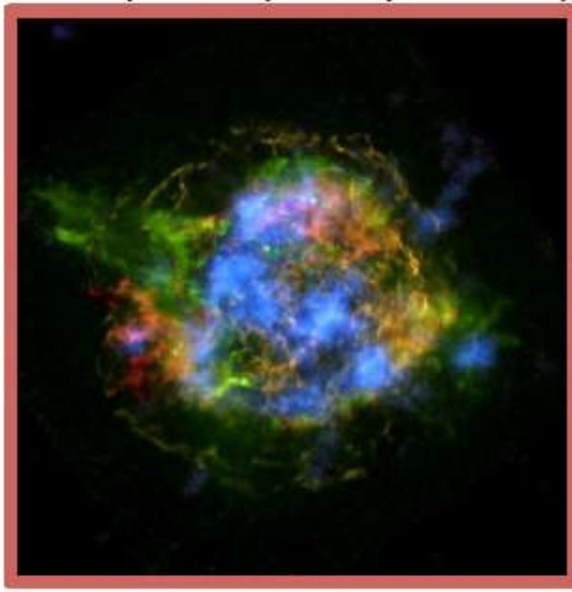
Historical Supernovae

SN1006: Chandra/ESA

Kepler, SN1604 Chandra

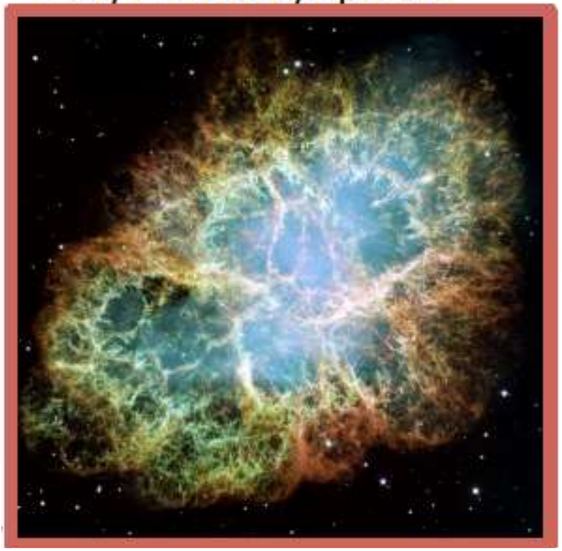


Cassiopeia A (~350 years old)

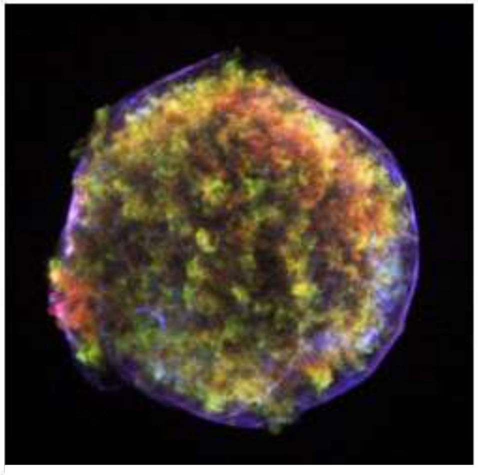


Chandra/NuSTAR

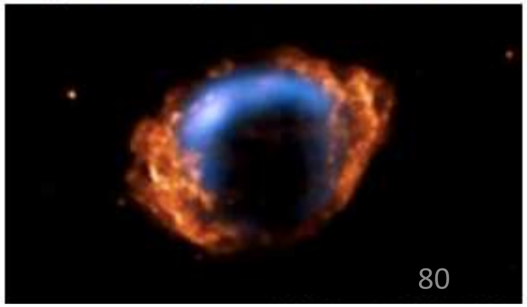
Crab SNR: SN 1054
HST/Chandra/Spitzer



Tycho, SN1572 Chandra



G1.9+0.3
150 years old, only discovered
10 years ago. VLA/Chandra



Types of Supernovae

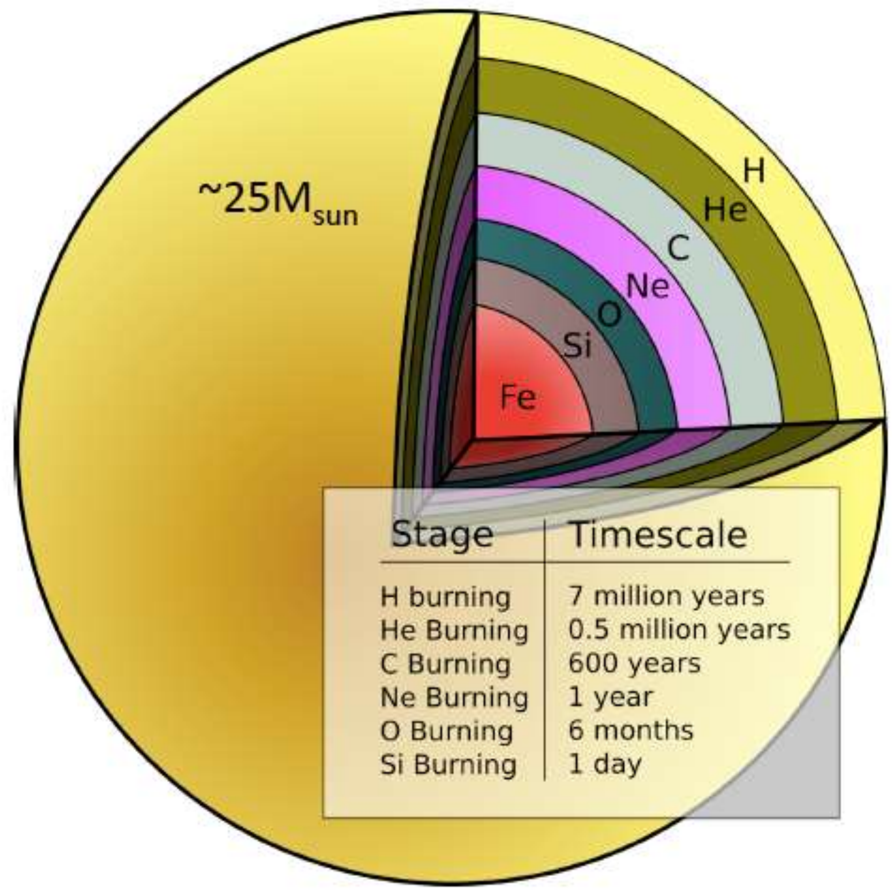
- Thermonuclear Supernovae: Type Ia
  - caused by runaway thermonuclear burning of white dwarf fuel to Nickel
  - roughly of 10^{51} ergs released
  - very bright, used as standard candles
  - no remnant

- Core-Collapse Supernovae: Type II, Ib, Ic
  - result from the collapse of an iron core in an evolved massive star ($M_{ZAMS} > 8\text{-}10M_{sun}$)
  - Few x 10^{53} ergs released in gravitational collapse, most (99%) radiated in neutrinos
  - Spread stellar evolution elemental products throughout galaxy
  - neutron star or black hole remnant

SN2011fe (PTF; Byrne Observatory)

Massive Stars: Burning stages

- Stars spend most of their lives burning hydrogen.
- The product – helium – settles in the core and will burn when temperatures increase sufficiently.
- For massive stars ($M > 8\text{-}10M_{sun}$), the process continues through carbon, oxygen, … , up to iron.
- This process does not continue past iron as iron is one of the most tightly bound nuclei.
- Iron core builds up in center of star.

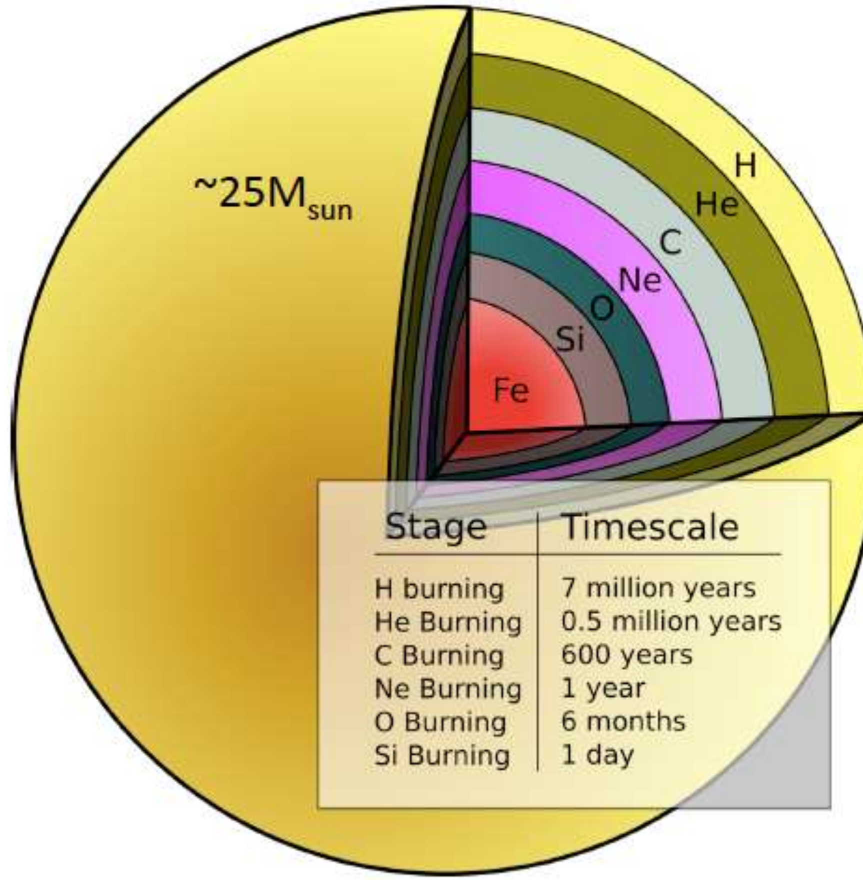


Stage	Timescale
H burning	7 million years
He Burning	0.5 million years
C Burning	600 years
Ne Burning	1 year
O Burning	6 months
Si Burning	1 day

A. C. Phillips, *The Physics of Stars*, 2nd Edition (Wiley, 1999).

Massive Stars: End Stage

- Stars are, for the majority of the time, in hydrostatic equilibrium because the radiation pressure of the photons from nuclear reactions balance gravity.
- Iron cores however are supported by electron degeneracy pressure, much like a white dwarf, there is a maximum mass that electron degeneracy pressure can support.



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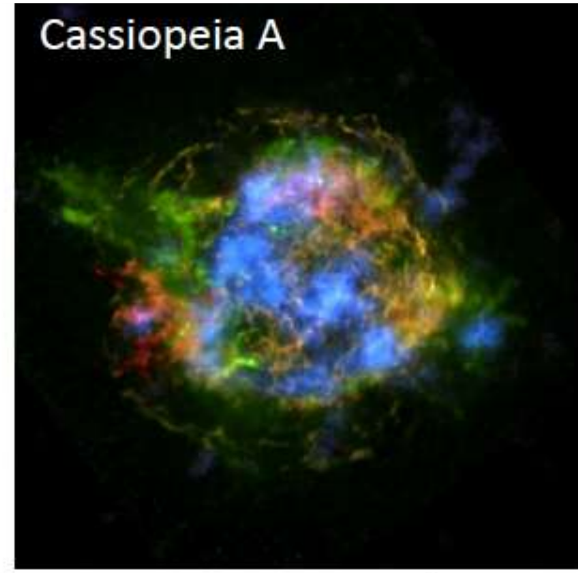
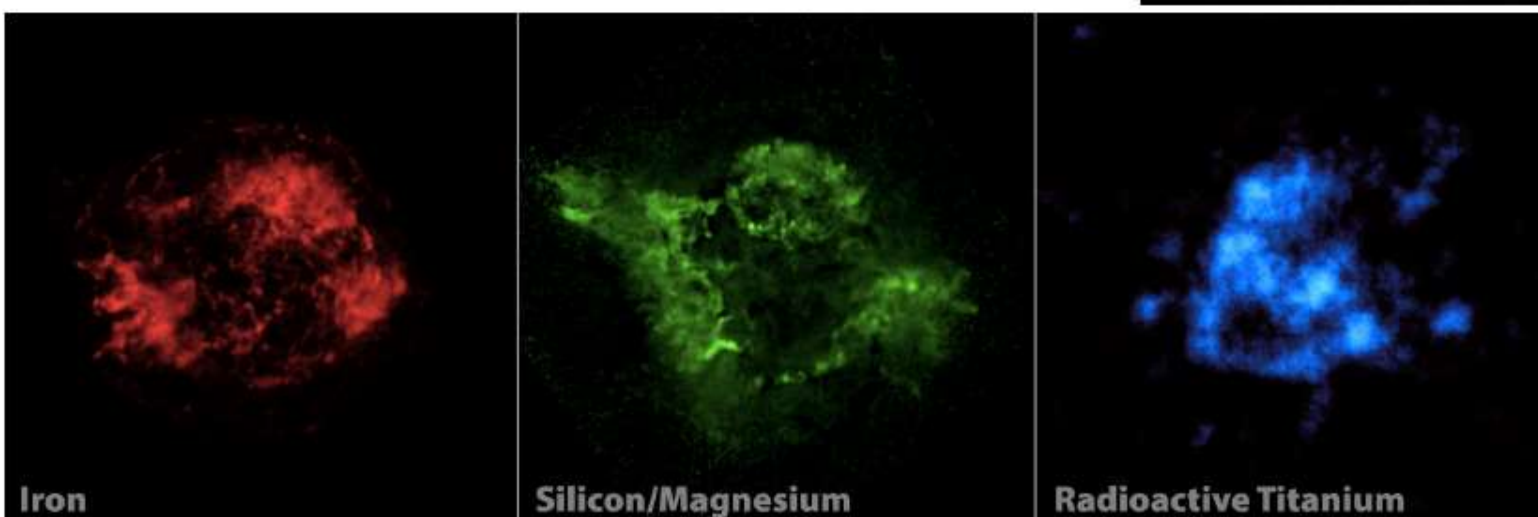
A. C. Phillips, *The Physics of Stars*, 2nd Edition (Wiley, 1999).

Products of Supernovae

- Core-Collapse Supernovae are responsible for unbinding and spreading the elemental products of stellar evolution through the galaxy
- They are the birth sites of neutron stars and black holes

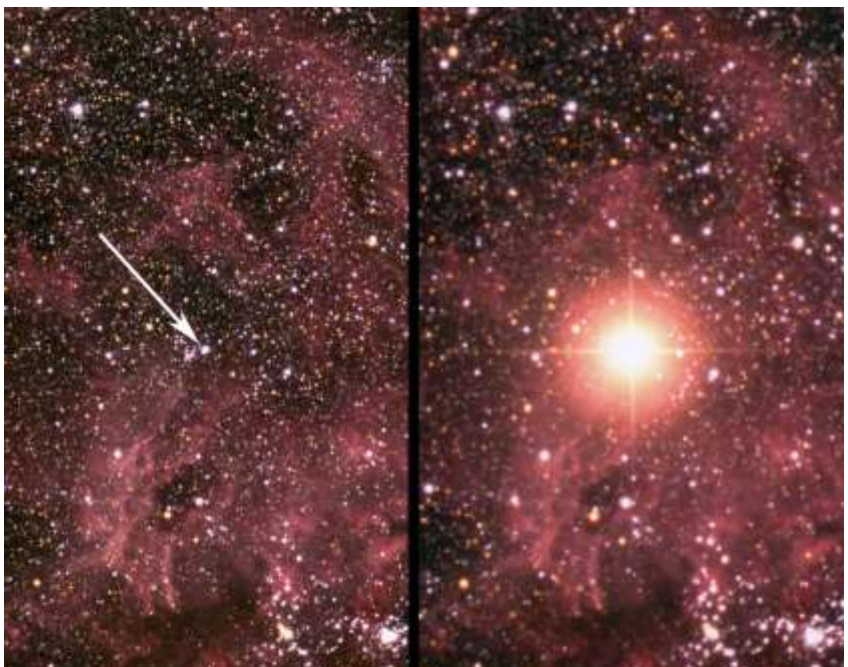




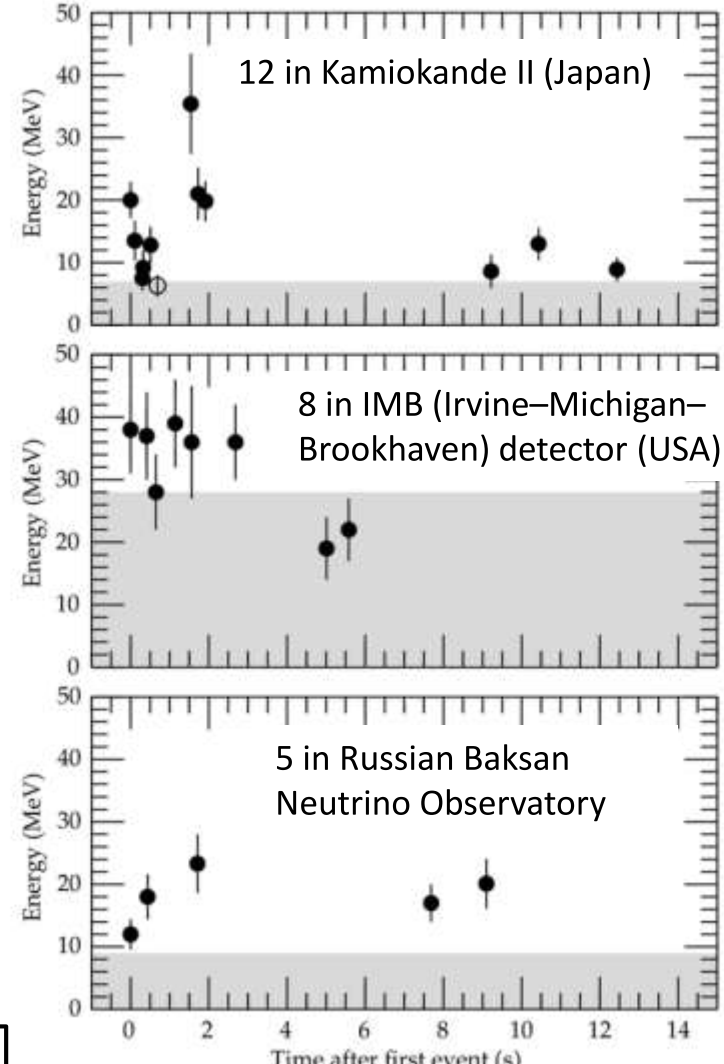
JPL; Chandra/NuSTAR

Supernova SN1987A

- Type II SN in Large Magellanic Cloud (51.4 kpc)
- Detected in optical on 23 Feb 1987.
- Approx. 2 - 3 hours **before** light from SN 1987A reached earth, a burst of 25 neutrinos of MeV energy was observed



MeV neutrinos



Death of a Star ⇒ Birth of Neutrino Astronomy

Are Gravitons Massless?

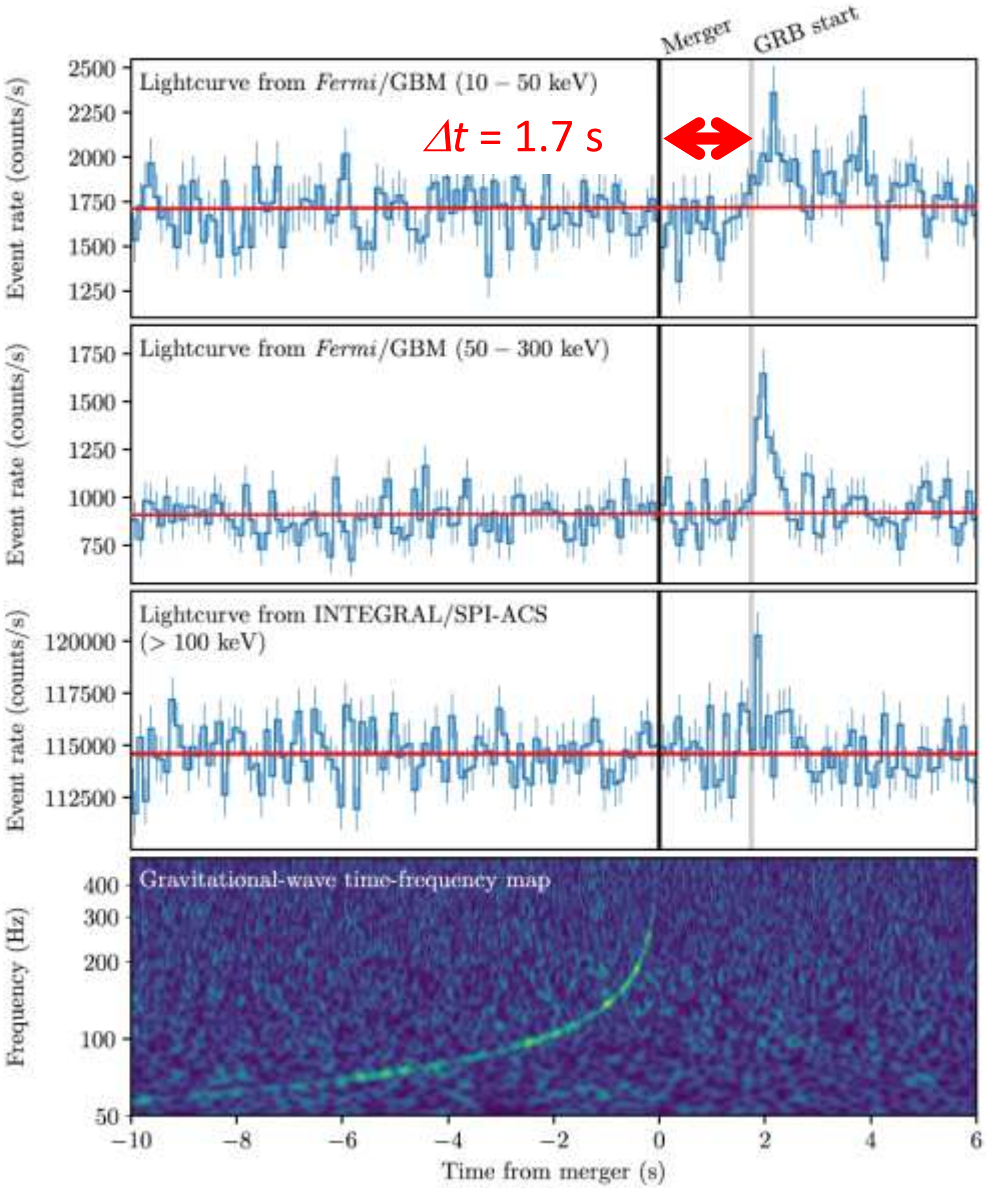
- GW170817 provides a stringent test of the speed of gravitational waves

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

- Δt =1.74 +/- 0.05 s
- $D \approx$ 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



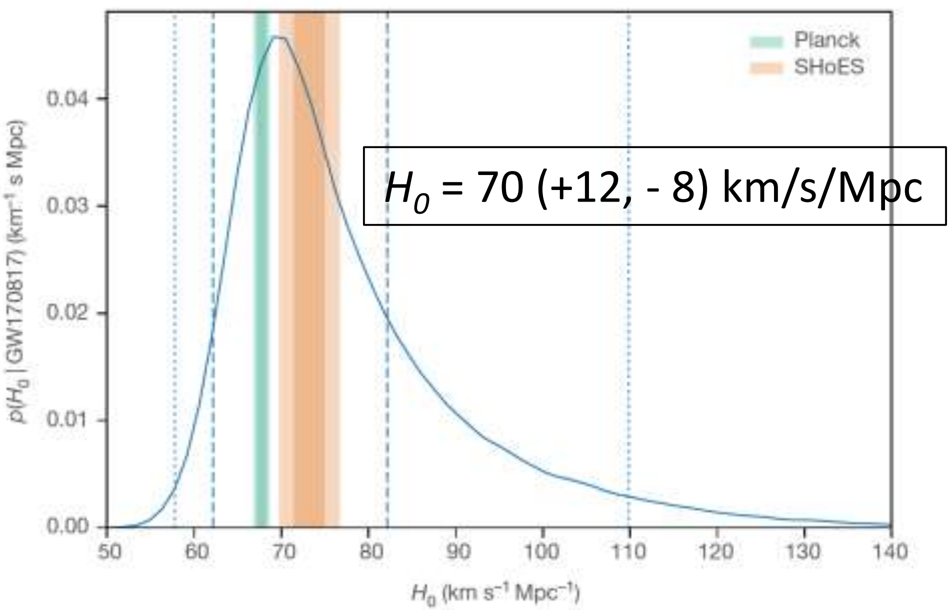
LIGO Scientific Collaboration and Virgo Collaboration, Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A" Astrophys. J. Lett., 848:L13, (2017)

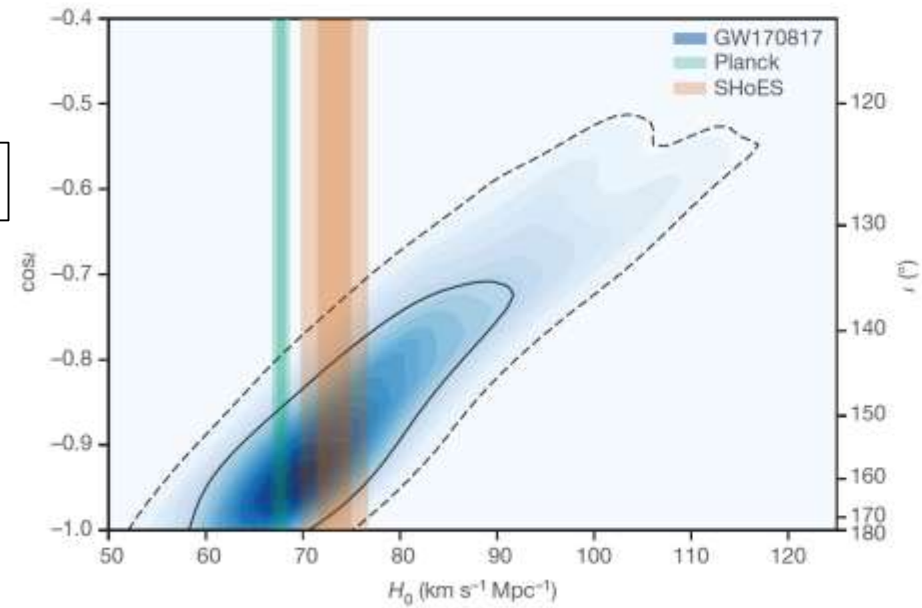
A gravitational-wave standard siren measurement of the Hubble constant

- 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!





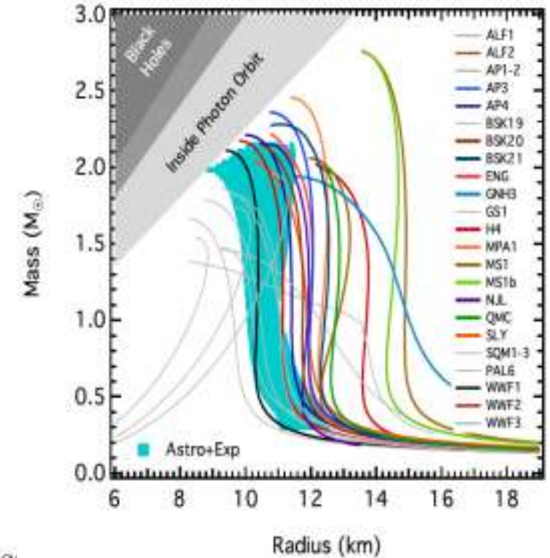
Abbott, et al., LIGO-Virgo Collaboration, 1M2H, DeCAM GW-EM & DES, DLT40, Las Cumbres Observatory, VINRO UGE, MASTER Collaborations, A gravitational-wave standard siren measurement of the Hubble constant”, *Nature* 551, 85–88 (2017).

Constraining the Neutron Star Equation of State

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

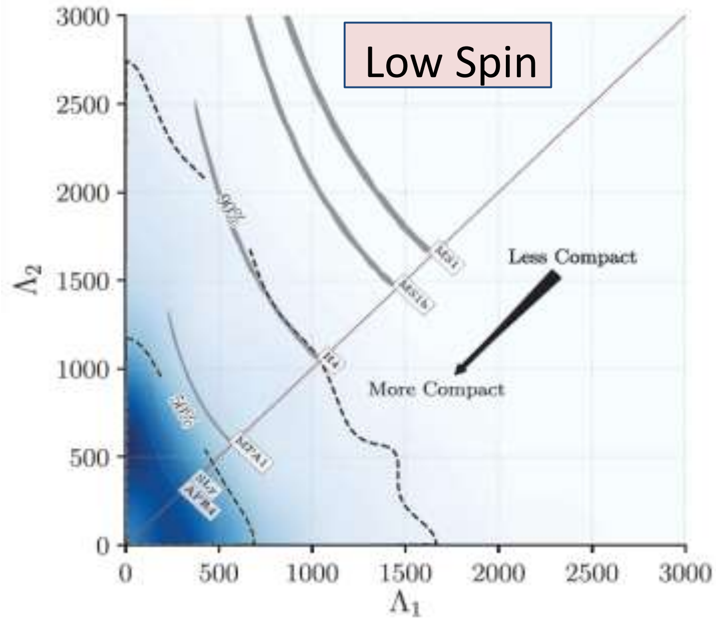
$$\Lambda = \frac{2}{3} k_2 \left(\frac{R}{M} \right)^5$$

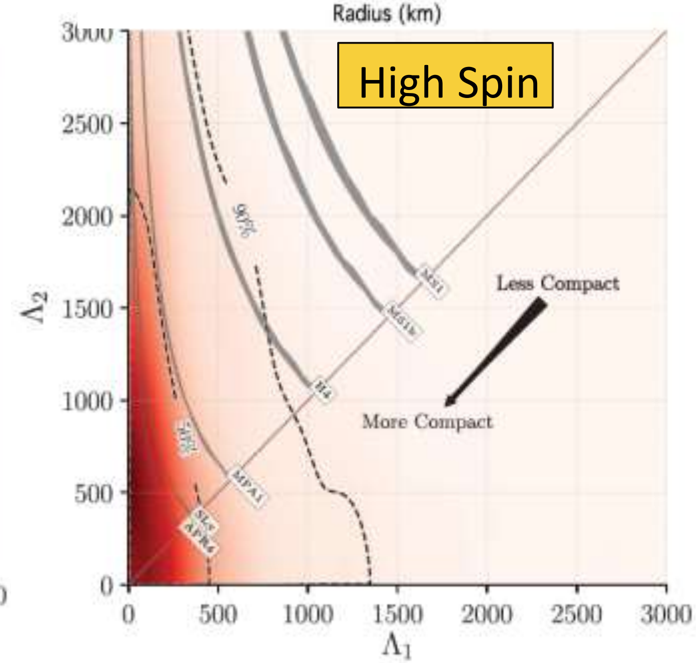
- GW170817 data consistent with softer EOS → more compact NS



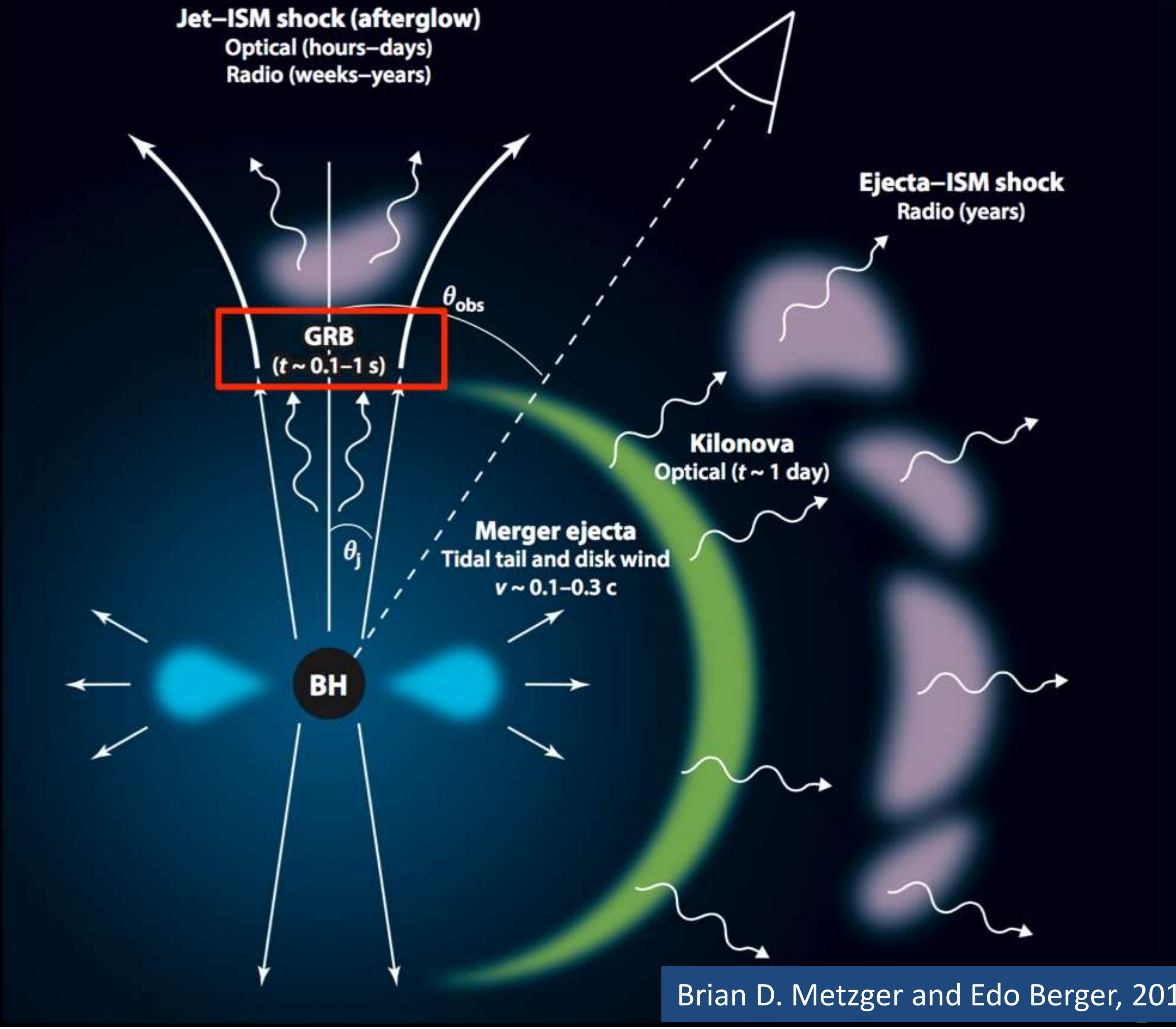
Ozel and Friere (2016)

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)





Electromagnetic Counterparts of NS Mergers



Brian D. Metzger and Edo Berger, 2012