Multi-messenger science

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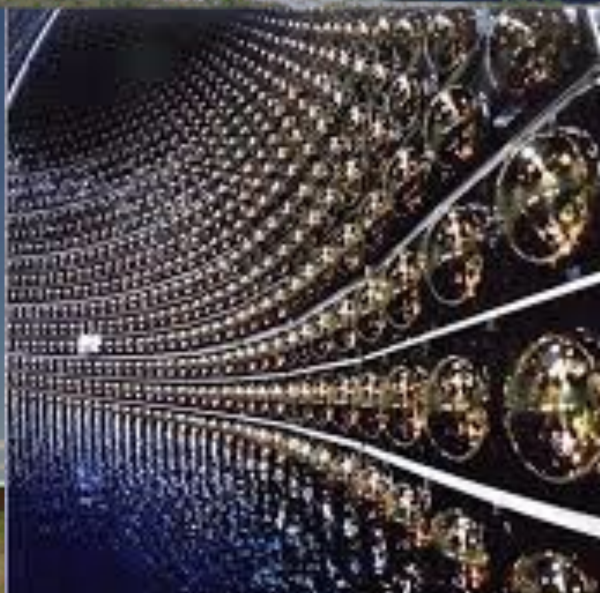
Summer Institute 2019



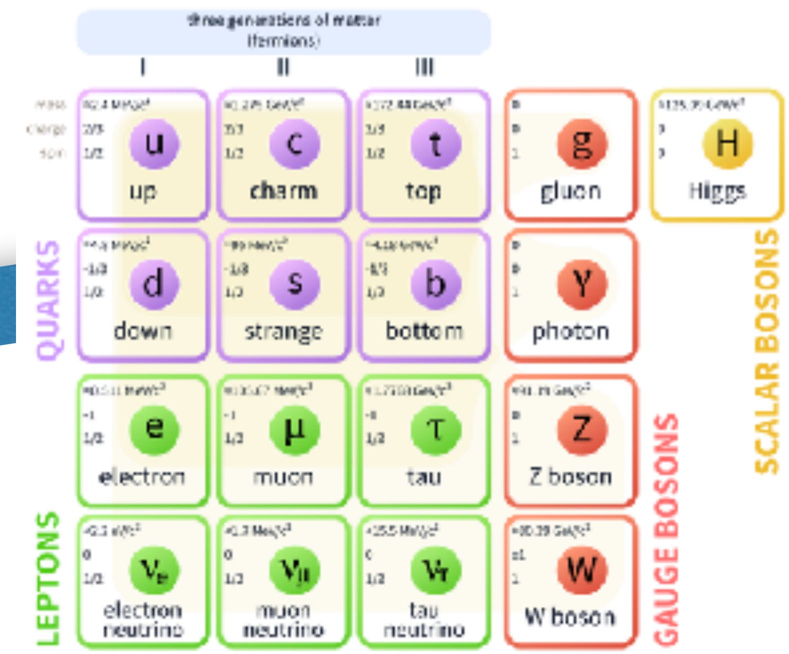
Motivation

- There is no such thing as too much information in astroparticle physics
- The more we can explore and examine the full range of particles at large in the cosmos – and the more we can link our discoveries and findings together – the better we can understand the Universe, its most extreme characteristics and its most fascinating and awe-inspiring phenomena.

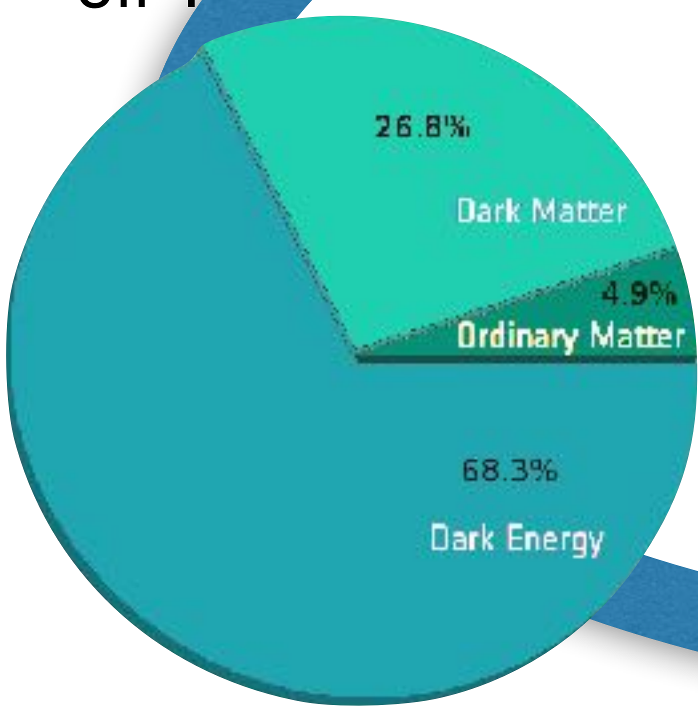
APPEC European Astroparticle Physics Strategy 2017-2026

The big questions of our time

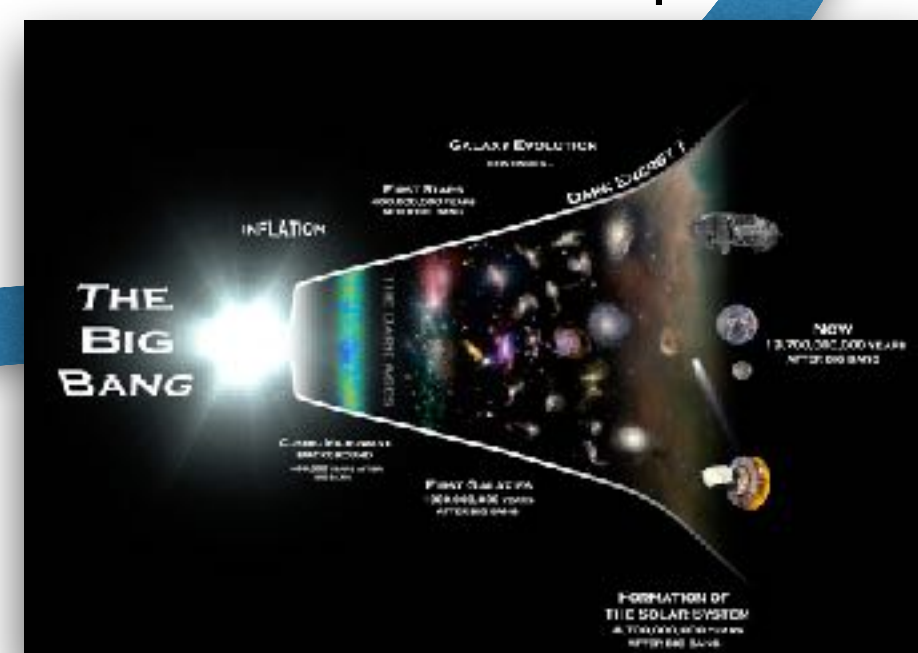
What are the fundamental particles



What is the Universe made off ?



How did the Universe come to be and how will it develop ?



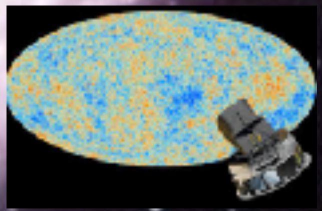
ASTROPARTICLE PHYSICS

ASTRONOMY

Dark energy

Gravitational waves

Cosmic Microwave Background



HE neutrinos

Gamma-rays

Cosmic rays

Dark matter

Neutrino properties

SM Model tests

PARTICLE PHYSICS

Some of the most pressing questions we hope to make progress during the next decade (~2017-2026)

A very bright future

Over the past decades, astroparticle physics has established itself as an important scientific discipline – just as particle physics, astronomy and cosmology have done. Like those sister disciplines, it has generated knowledge and insights with potential to generate spin-off benefits: for example, innovative technologies for low-level light sensors and high-precision seismic sensors, and revolutionary imaging concepts using cosmic-ray muons.

This emergence of astroparticle physics as a core scientific discipline is reflected by a string of Nobel Prizes awarded in this field since the turn of the century:

- 2002: for work on '... detection of cosmic neutrinos...';
- 2006: for work on '...anisotropy of the cosmic microwave background...';
- 2011: for work on the '...accelerating expansion of the Universe ...'; and
- 2015: for the '...discovery of neutrino oscillations...'.

The Nobel Prize in Physics 2017 was divided, one half awarded to Rainer Weiss, the other half jointly to Barry C. Barish and Kip S. Thorne "for decisive contributions to the LIGO detector and the observation of gravitational waves."

Tiny particles, huge questions

Astroparticle physics is a dynamic, interdisciplinary research field. Consequently, its precise scope can be hard to define; indeed, definitions vary slightly from country to country. Nevertheless, a general consensus surrounds the fundamental questions that astroparticle physics aims to address. More than that, generating an answer to any of these questions will almost certainly constitute nothing less than a major breakthrough in our understanding of the Universe. For example:

- *What is Dark Matter?*
- *What is Dark Energy?*
- *What caused our Universe to become dominated by matter and not anti-matter?*
- *Can we probe deeper into the earliest phases of our Universe's existence?*
- *What are the properties of neutrinos?*
- *Can we identify the sources of high-energy neutrinos?*
- *What is the origin of cosmic rays?*
- *Do protons decay?*
- *What do gravitational waves tell us about General Relativity and cosmology?*
- *What will multi-messenger astronomy teach us?*

Windows on the Universe: The Era of Multi-messenger Astrophysics

10 Big Ideas for Future NSF Investments

We have arrived at a special moment in our quest to understand the universe. For years, we have been making observations across the known electromagnetic spectrum -- from radio waves to gamma rays -- and many great discoveries have been made as a result. Now, for the first time, we are able to observe the world around us in fundamentally different ways than we previously thought possible. Using a powerful and synthetic collection of approaches, we have expanded the known spectrum of understanding and observing reality. Just as electromagnetic radiation gives one view of the universe, particles such as neutrinos and cosmic rays provide a different view. Gravitational waves give yet another.

v.3.2. 19.07.29

SI 2019 Schedule

	8/18 (Sun)	8/19 (Mon)	8/20 (Tue)	8/21 (Wed)	8/22 (Thu)	8/23 (Fri)	
9:00		D.L. - Morimitsu Tanimoto **[L] C. Rott 1**	D.L. - Ki-Young Choi **[L] M.Sasaki 1**	D.L. - Deog Ki Hong **[L] C. Shin 2**	D.L. - Koichi Hamaguchi **[L] T.Lin 3**	D.L. - Taichiro Kugo **[L] M. Sasaki 3**	9:00
10:00		D.L. - Morimitsu Tanimoto **[L] T. Lin 1**	D.L. - Ki-Young Choi **[L] T. Lin 2**	D.L. - Deog Ki Hong **[L] M. Sasaki 2**	D.L. - Koichi Hamaguchi **[L] C.Rott 3**	D.L. - Taichiro Kugo **[L] C. Shin 3**	10:00
11:00		Coffee	Coffee	Coffee	Coffee	Thanksgiving & Closing	11:00
		D.L. - X.G. He **[L] C.Shin 1**	D.L. - Matthew Baumgart **[L] C. Rott 2**	D.L. - Cheng Wei Chiang **[F] T.Kugo** **[F] Cologain**	D.L. - Seodong Shin **[F] YJKwon** **[F] X.G.He**		
12:00							12:00
12:30		Lunch	Lunch	Excursion	Lunch		12:30
13:00							13:00
14:00							14:00
15:00							15:00
16:00	Check-in & Welcoming	D.L. - Hyun Min Lee **[F] DKHong** **[F] Baumgart** **[F] JHyuck Park**	D.L. - Hyung Do Kim **[F] CWChiang** **[F-S] KBan, SMChoi** **[F] Y.Omura**		D.L. - Youngjoon Kwon **[F] Hamaguchi** **[F] JHSong** **[F] FPHuang**		16:00
17:00							17:00
17:30	Reception	Dinner	Dinner		Dinner		17:30
18:00							18:00
19:00		D.L. - Yuji Omura **[F] HDKim** **[F] SHYun**	**Parallel A, B**	Banquet	**Parallel C, D**		19:00
	D.L. - Pyungwon Ko **[Colloquium 1]** **H.Murayama**						
19:30							19:30
20:00		Coffee					20:00
	Free discussion	D.L. - Pyungwon Ko **[Colloquium 2]** **H.Murayama**	**Poster Session**		**Poster Session**		
			Free discussion		Free discussion		
21:00							21:00

Lectures

- Day 1
    - Overview
    - Multi-messenger Science Introduction
    - Cosmic ray mystery / cosmic rays
    - Recent Breakthroughs in Multi-messenger Science
    - Outlook
- Day 2
    - Observatories for Multi-messenger astroparticle physics
    - High-energy Neutrinos and Multi-messenger Science
- Day 3
    - Real time / follow-up / Alert programs
    - Future perspectives

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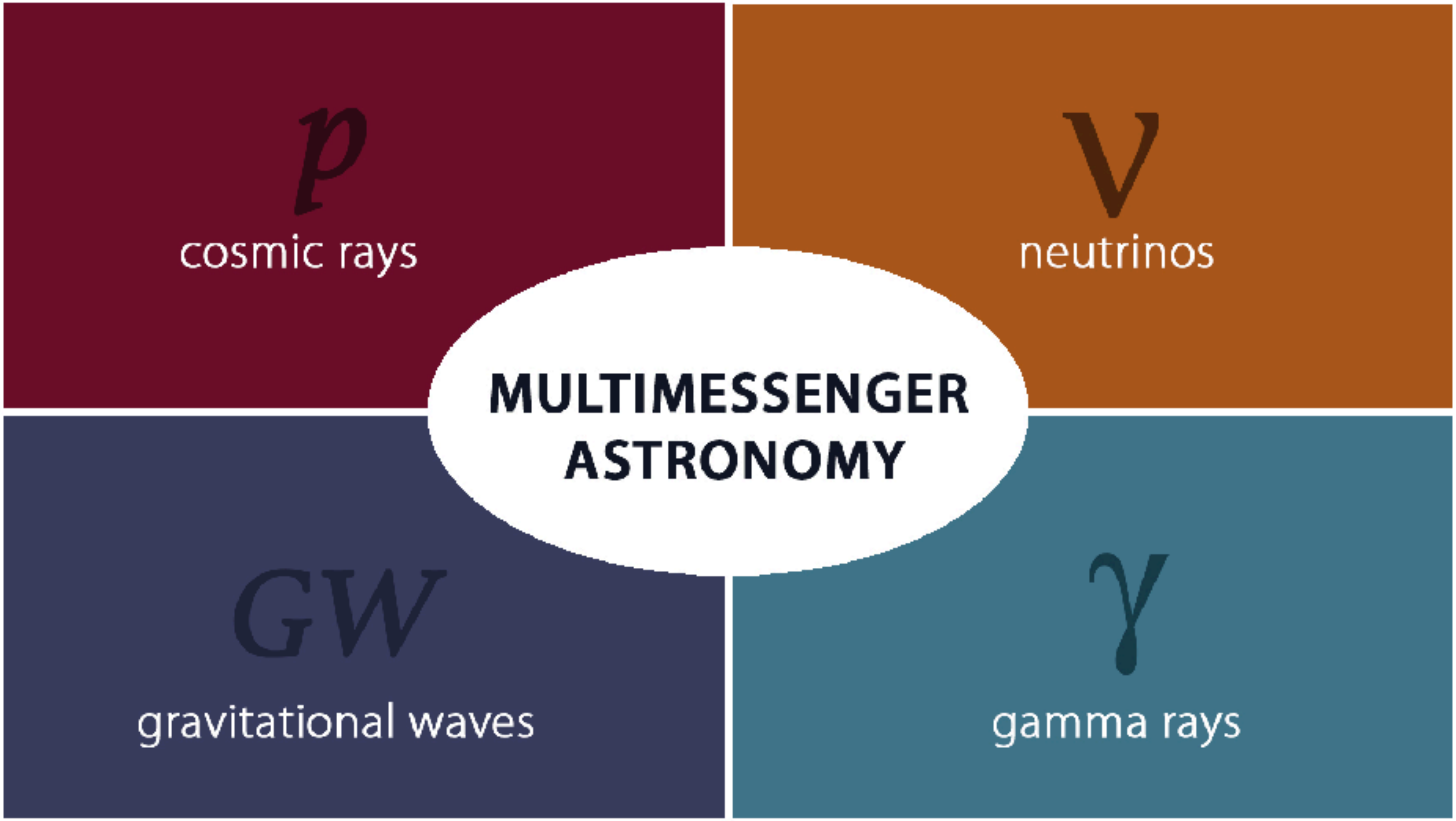
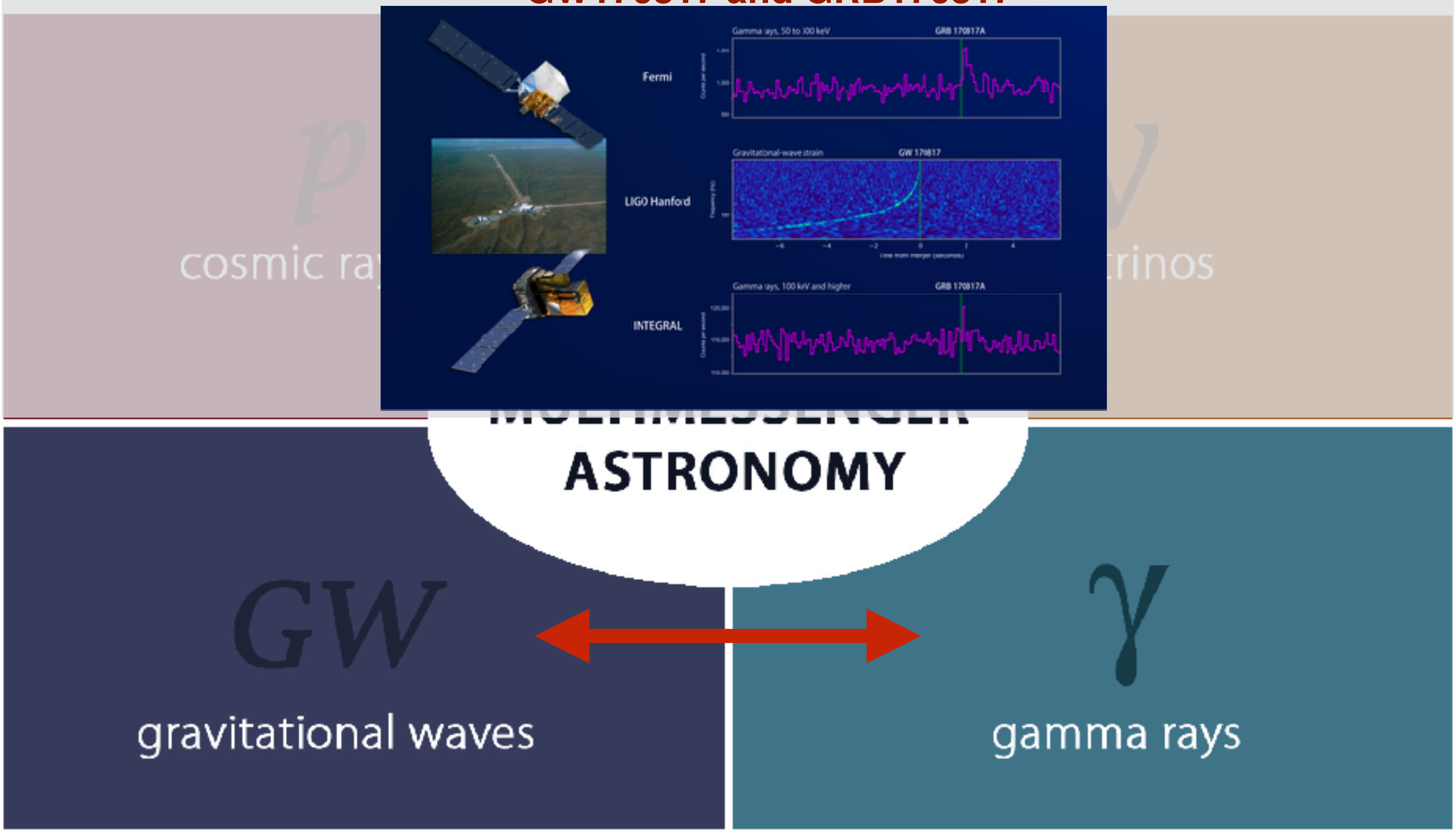
Multimessenger Astronomy

Multi-Messenger Astrophysics



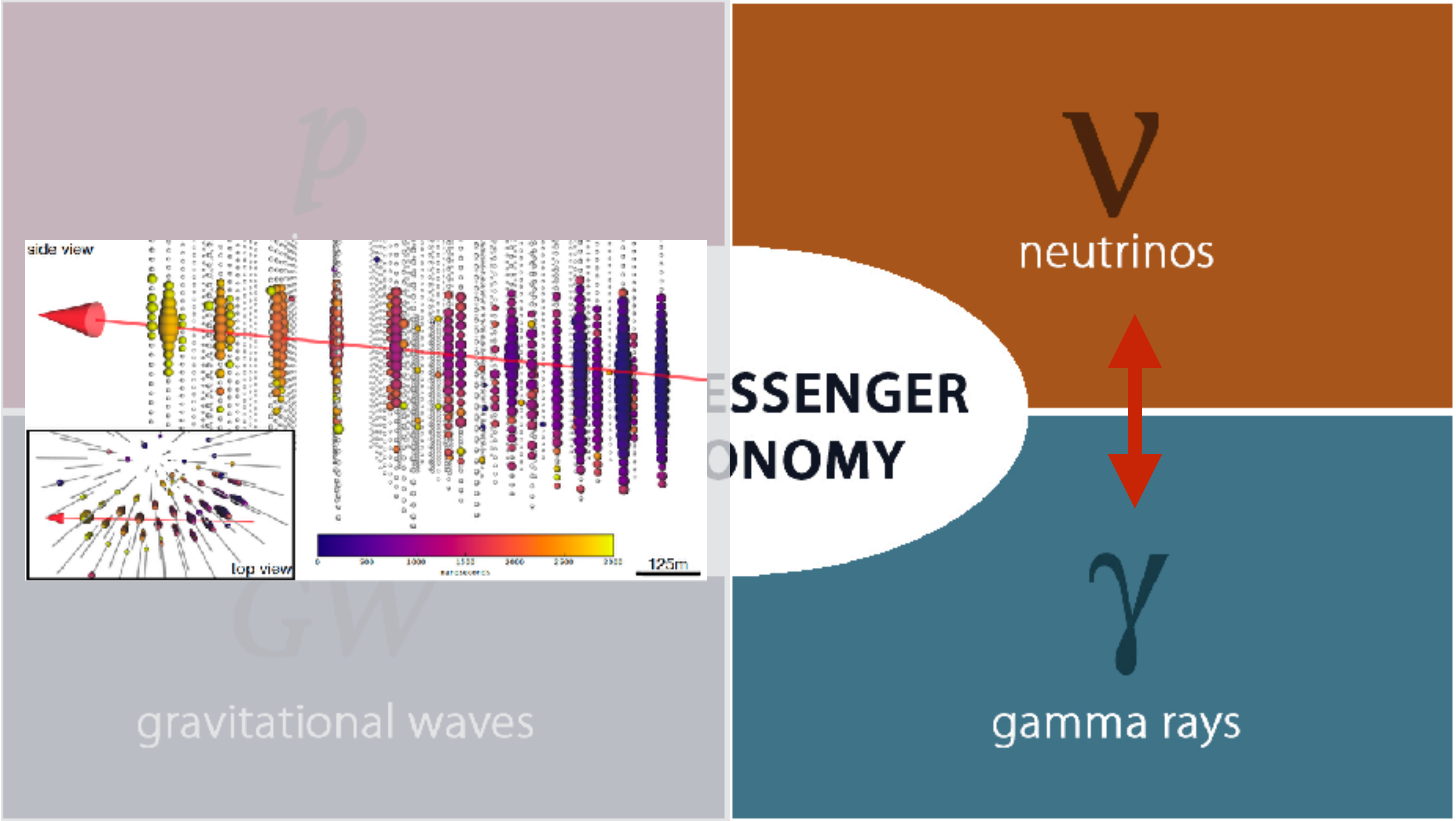
Multi-Messenger Astrophysics

GW170817 and GRB170817



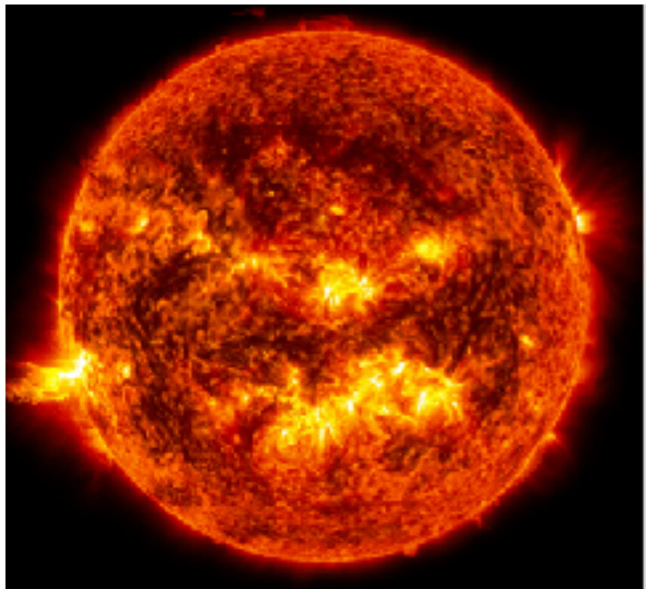
Multi-Messenger Astrophysics

Icecube-170922A and TXS 0506+056

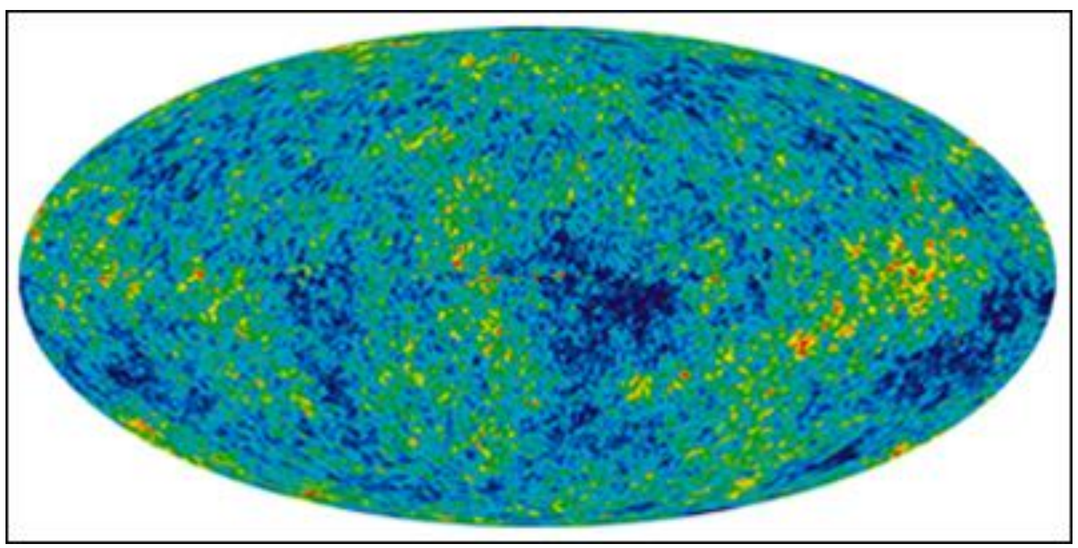


The non-thermal Universe

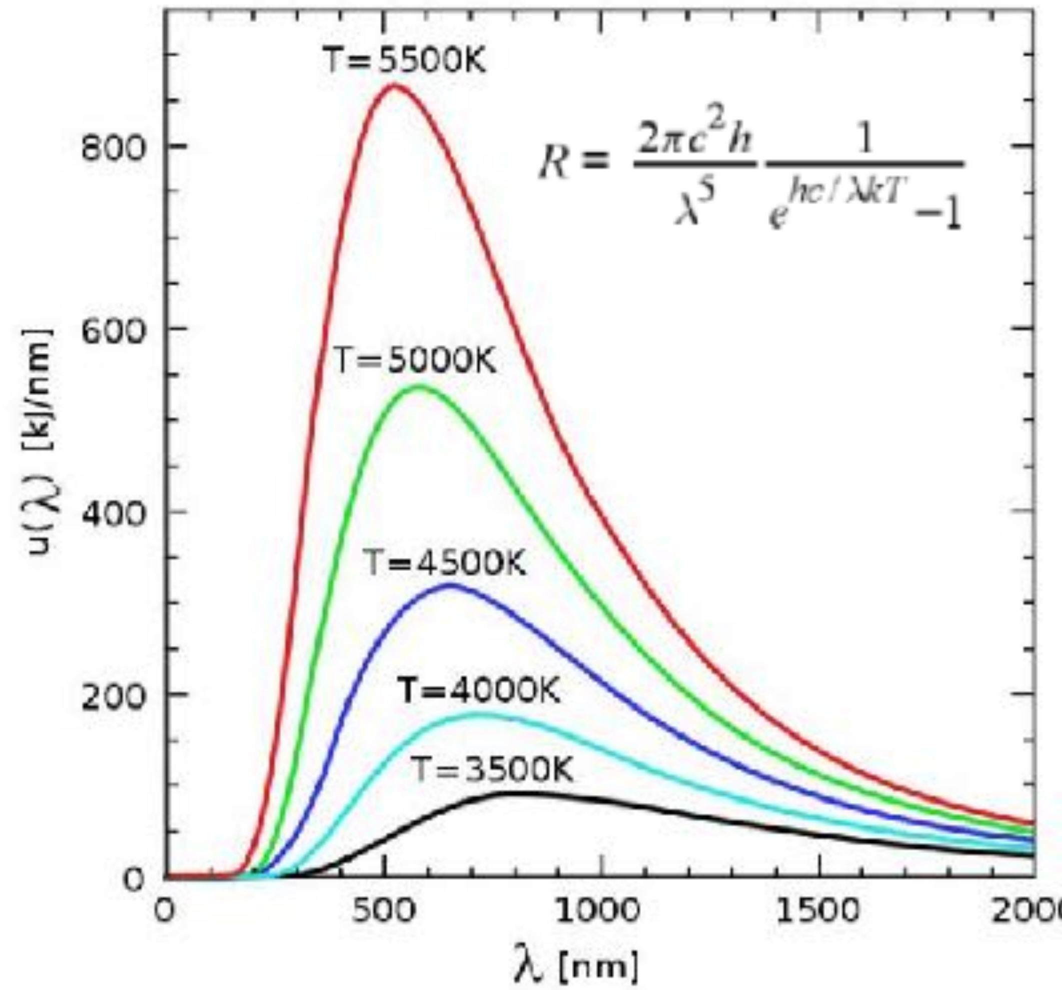
Sun



CMB



Planck's law of black-body radiation



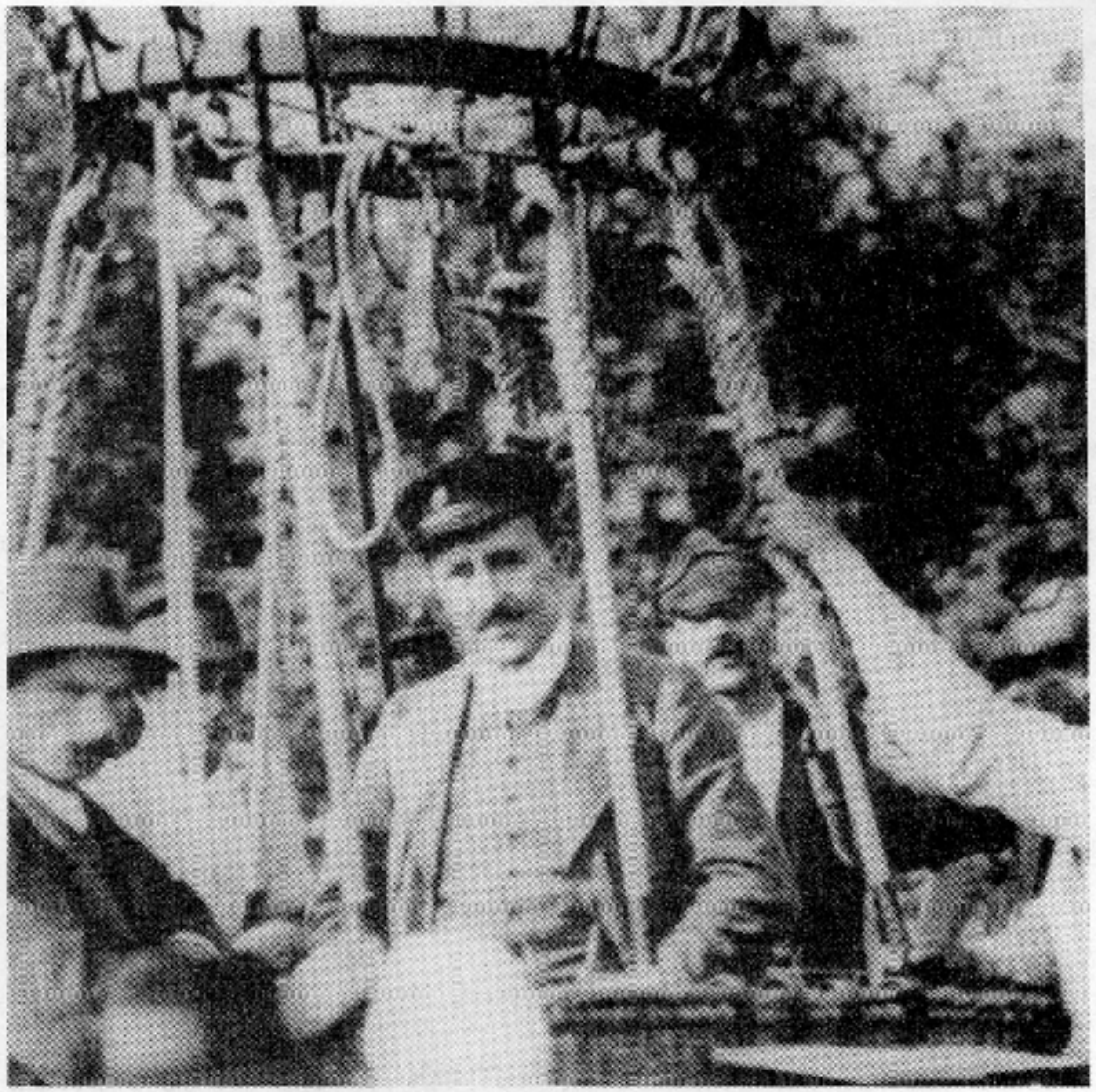
- Most of the visible light and other electromagnetic radiation we observe from the Universe is emitted by objects in near-thermal equilibrium

Exploring the non-thermal Universe

- High-energy cosmic rays cannot be explained by thermal processes
  - With the exception of BigBang no object in the Universe can attain the temperatures required to emit particles with energy as occasionally observed in cosmic rays
- Origin of ultra-relativistic particles
  - Astrophysical sources
    - Example - aftermath of a cataclysmic event such as a supernova explosion
  - Exotic sources:
    - Decay of super-heavy unknown particles
  - More exotic
    - Particles produced as a result of mechanisms that are as yet entirely unknown and unexpected …

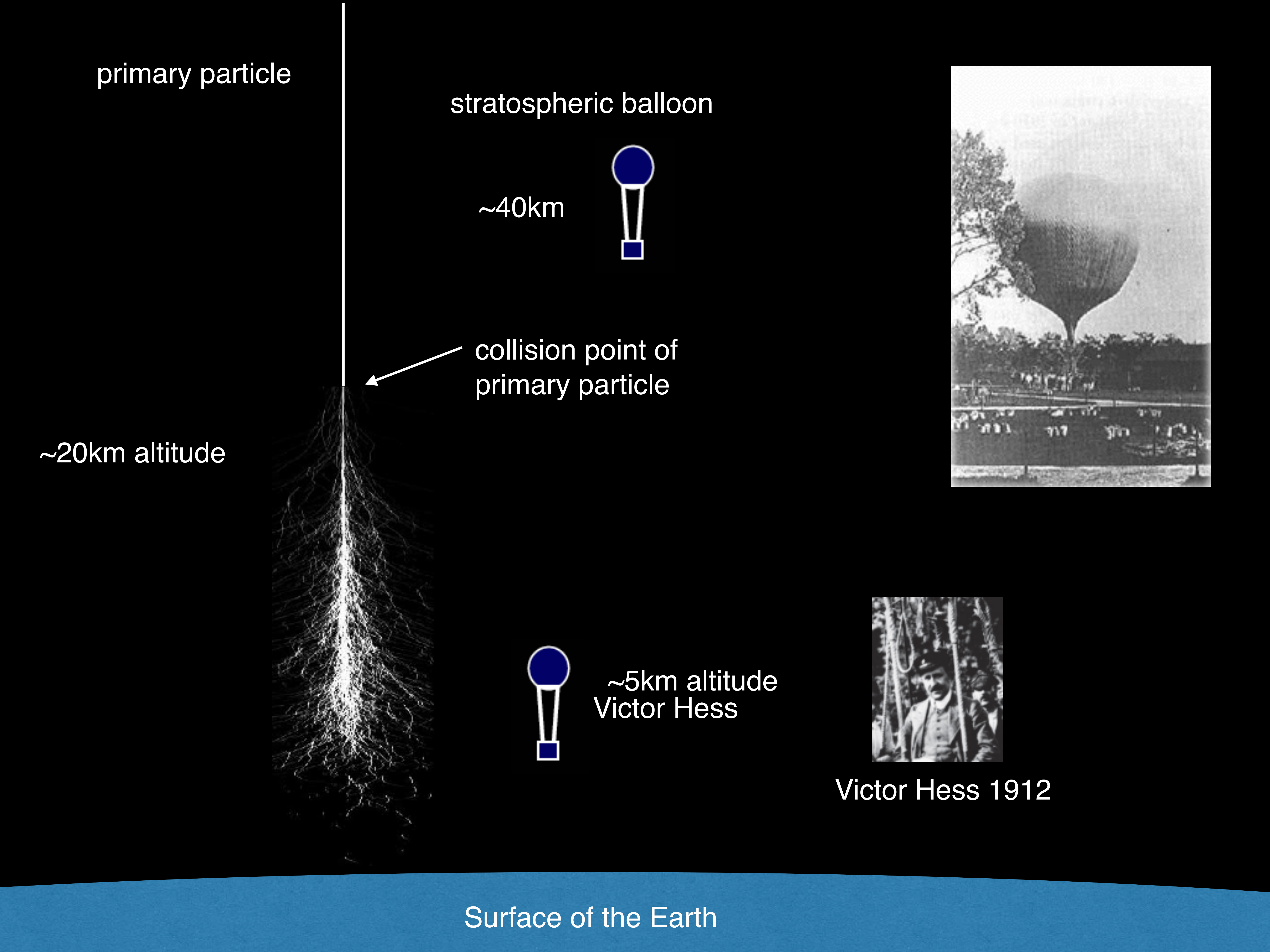
The Cosmic Ray Mystery

Victor Hess

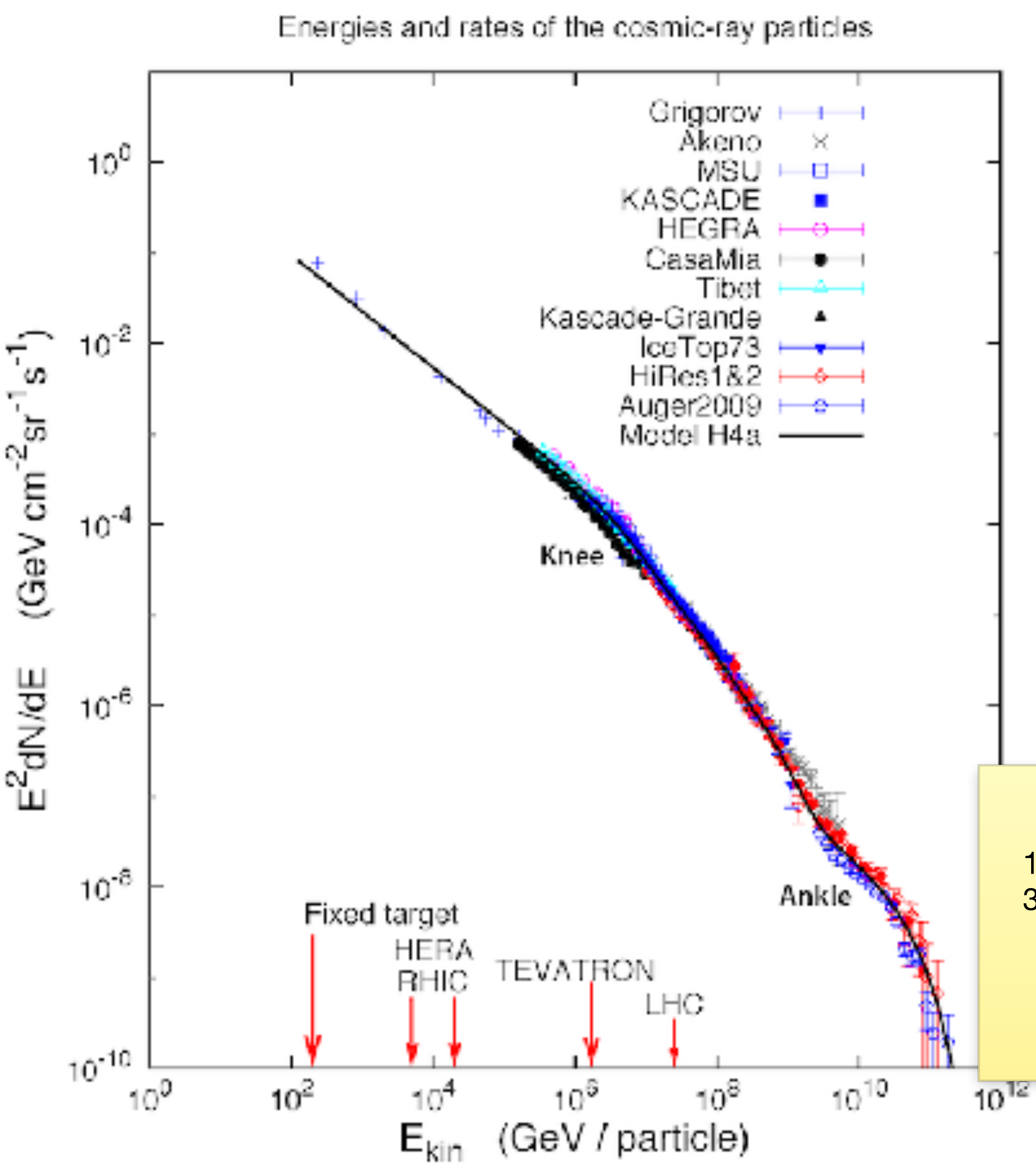


Courtesy ALPHONZ WEBER, FORDHAM UNIVERSITY

Victor Hess surrounded by Austrian peasants after landing from one of his ascensions a few weeks before his record breaking ascent in the Böhmen.


primary particle
stratospheric balloon
~40km
collision point of
primary particle
~20km altitude
~5km altitude
Victor Hess
Victor Hess 1912
Surface of the Earth

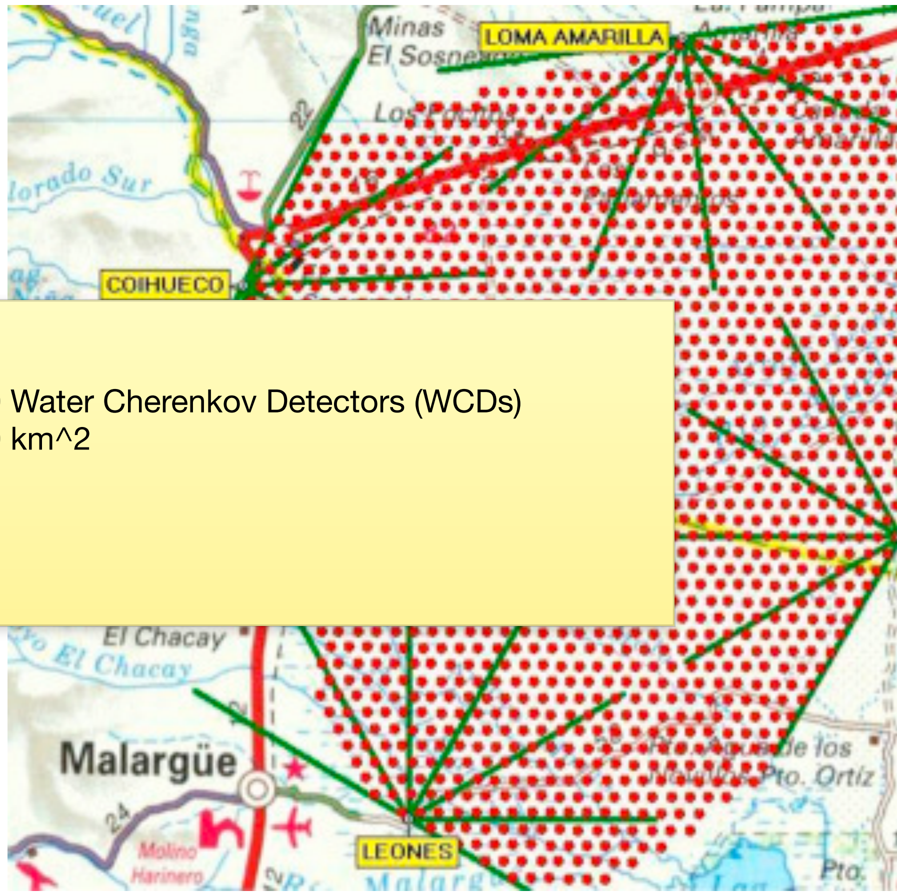
Cosmic rays



Cosmic rays have been observed with energies up to 10^{20}eV (100EeV) or 10^{7} LHC beam energies

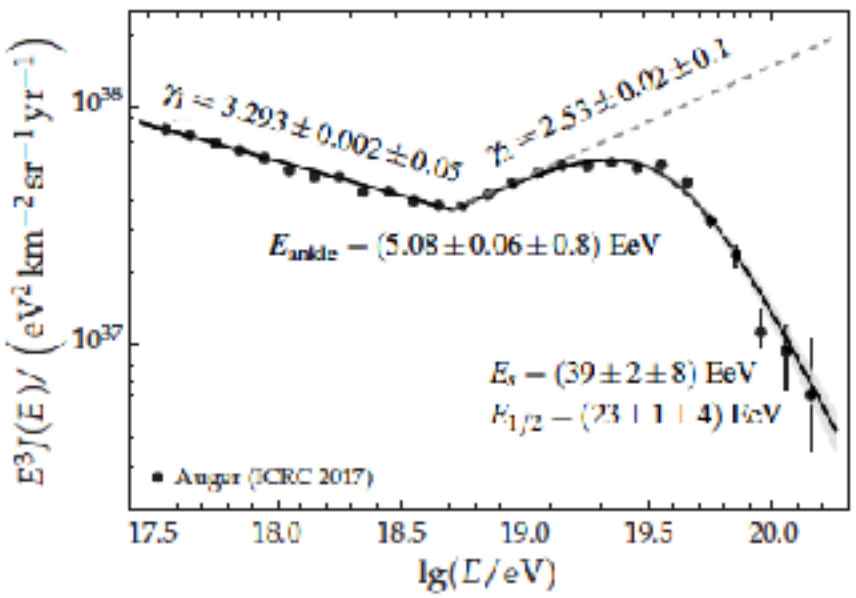
AUGER

Malargüe, Mendoza

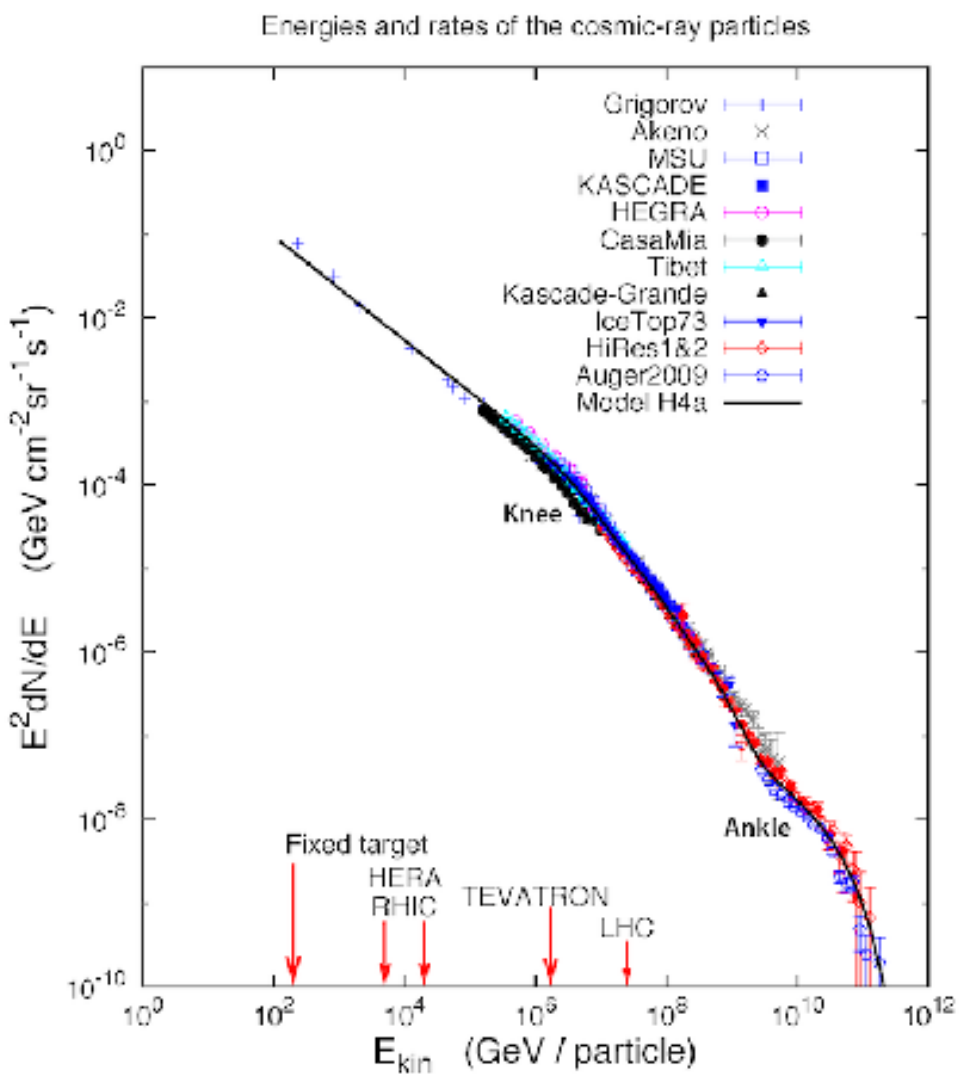


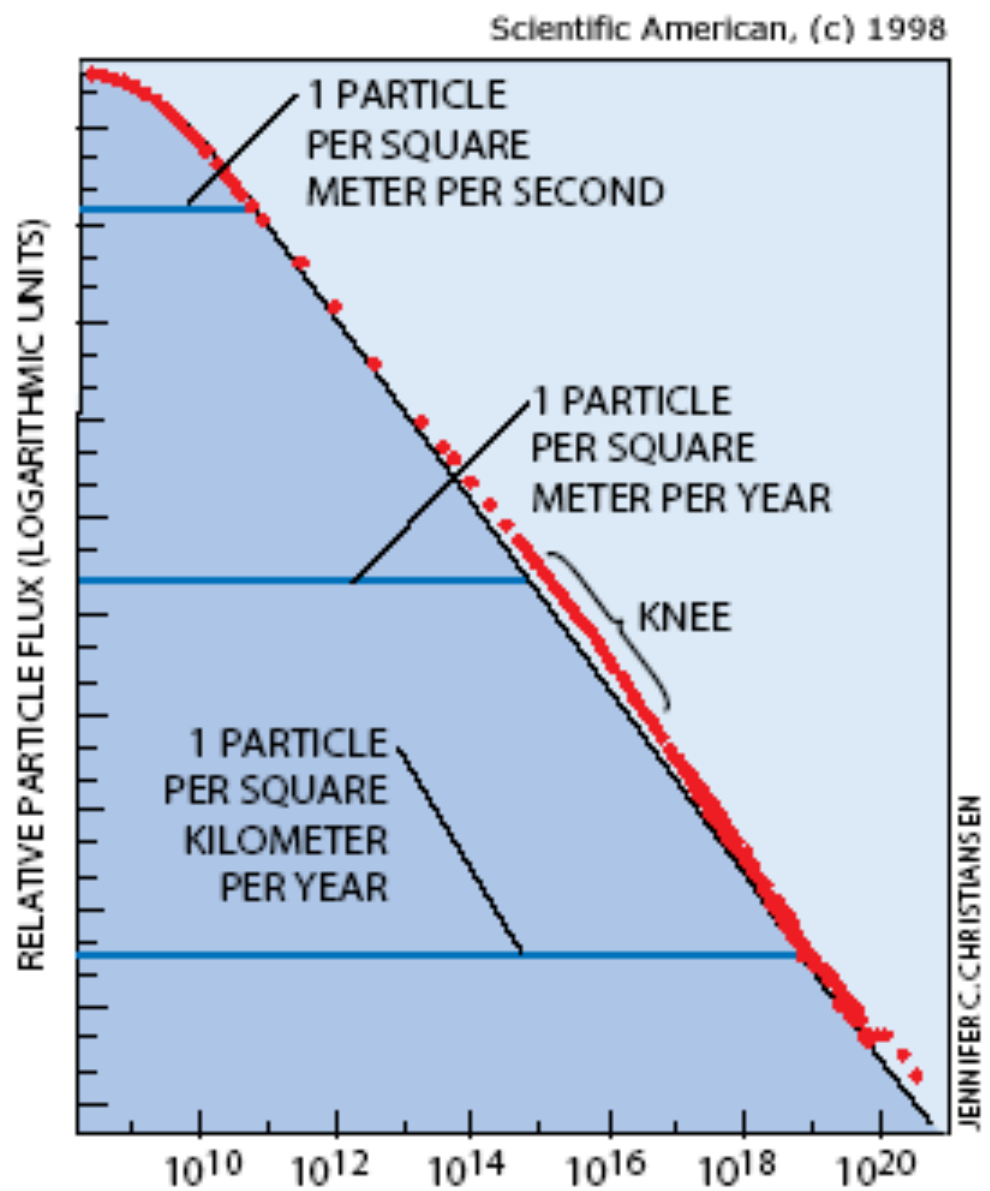
1600 Water Cherenkov Detectors (WCDs)
3000 km^2

AUGER Collaboration ICRC2017



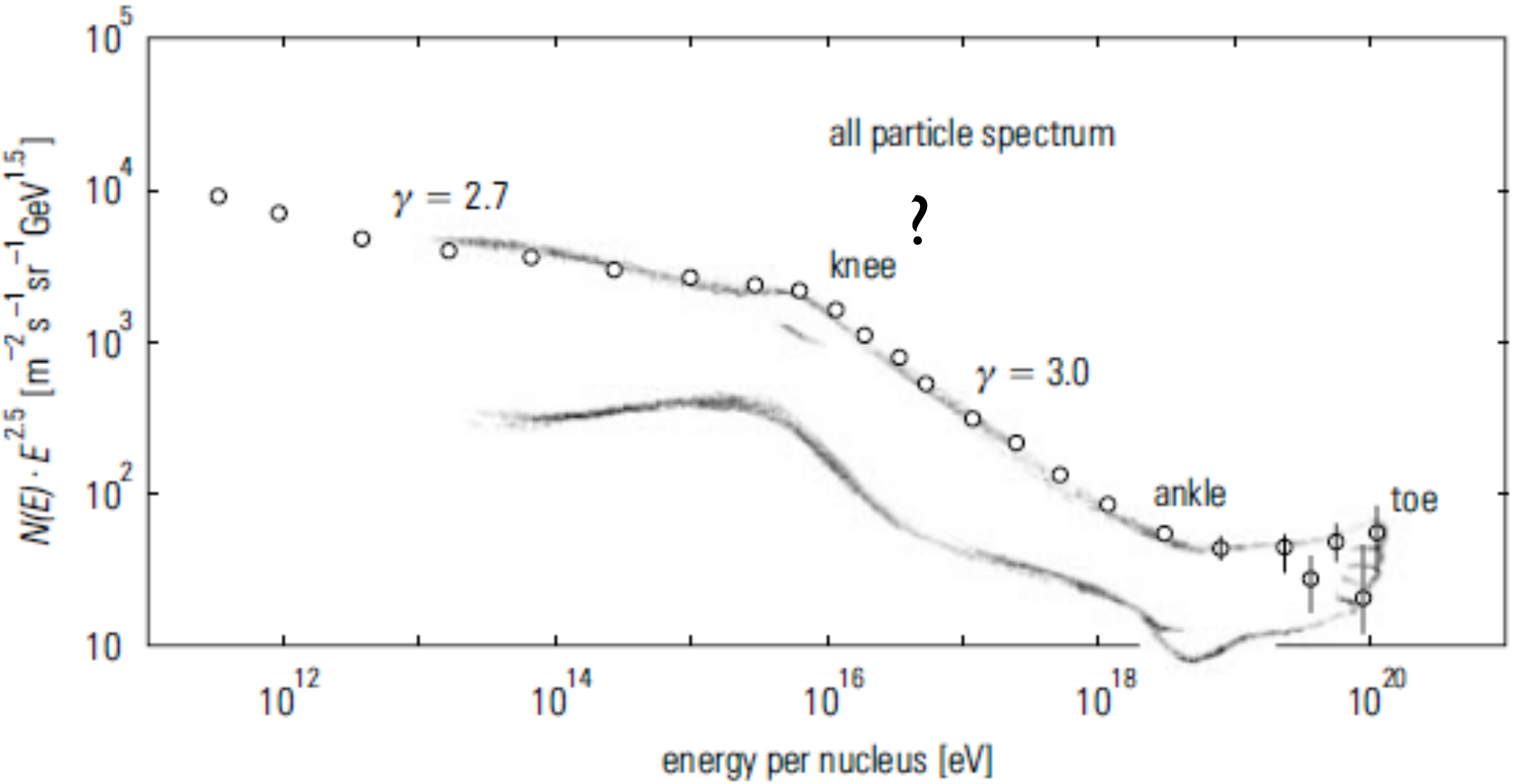
- Cosmic ray spectrum extremely well measured (TA, Auger, …)
- Where are they coming from ?
- What cosmic sources accelerate these particles to energies well beyond that reached at LHC ?



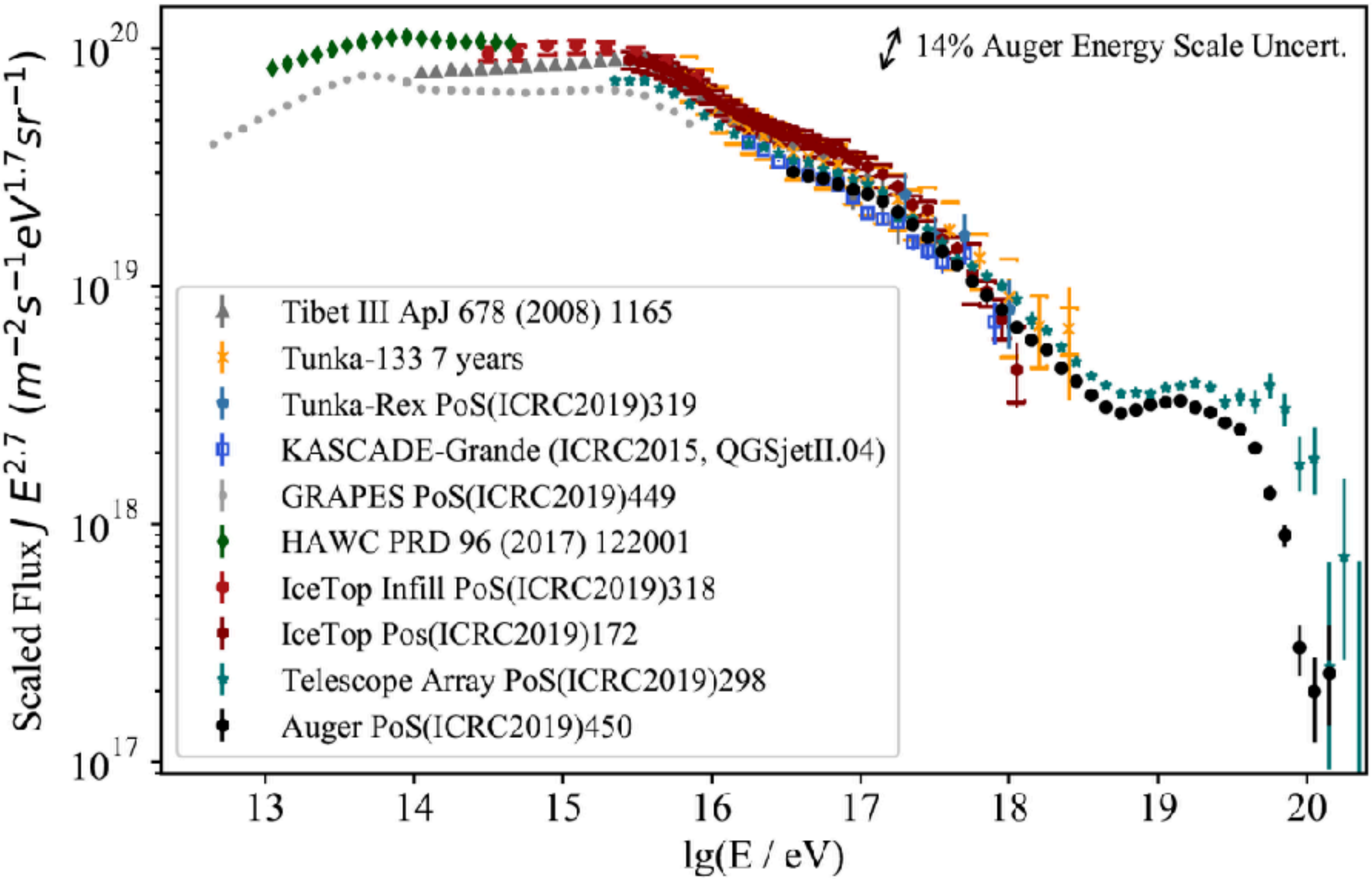


- Where are they coming from ?
- What cosmic sources accelerate these particles to energies in the EeV range ?

Nomenclature



All-particle Energy Spectrum by Air-Shower Arrays



The Knee

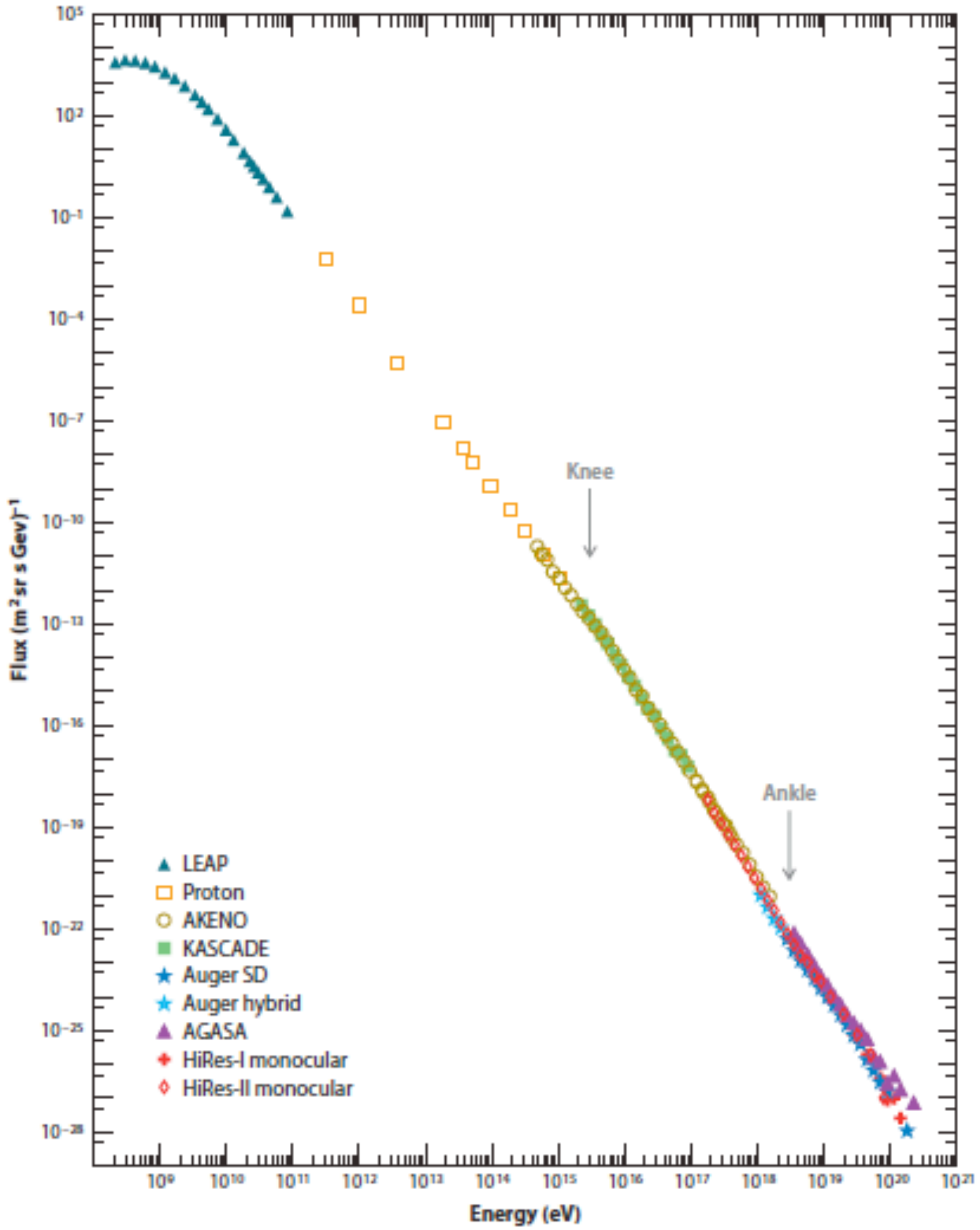


Figure 1

Overview of the cosmic ray spectrum. Approximate energies of the breaks in the spectrum commonly referred to as the knee and the ankle are indicated by arrows. Data are from LEAP (4), Proton (5), AKENO (6), KASCADE (7), Auger surface detector (SD) (8), Auger hybrid (9), AGASA (10), HiRes-I monocular (11), and HiRes-II monocular (11). Scaling of LEAP proton-only data to the all-particle spectrum follows (12).

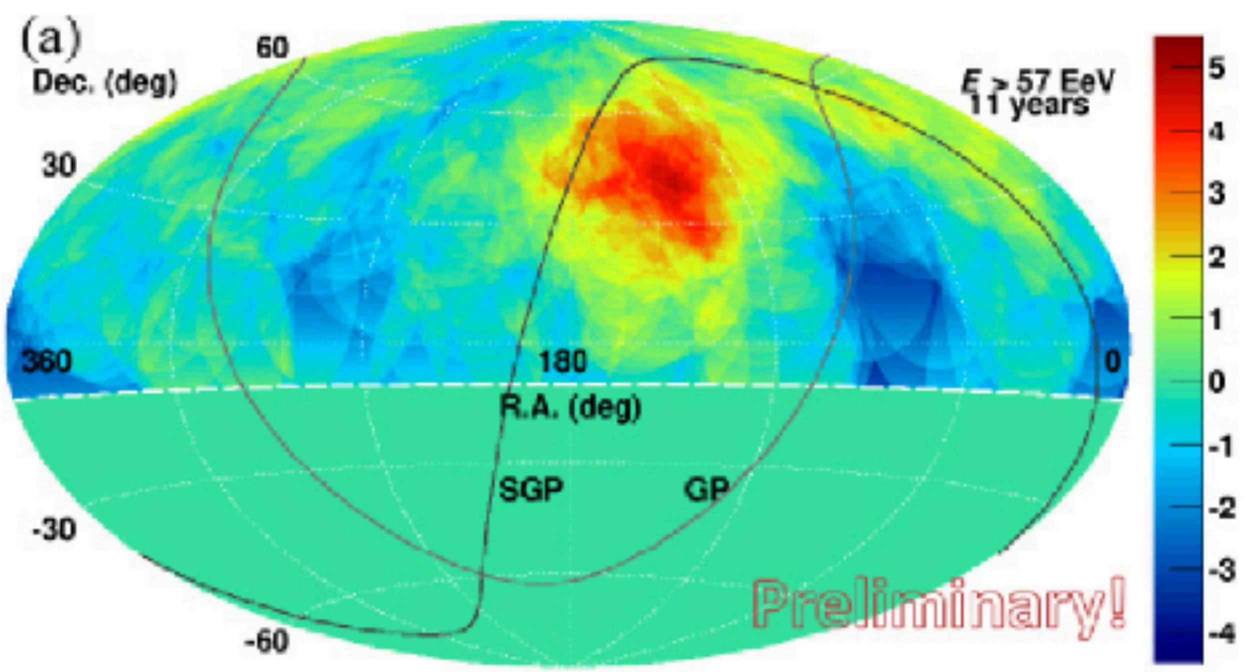
- The reason for the steepening of the spectrum at ~2PeV (knee) is not understood
  - (1) Cosmic rays escape from the Milky Way
  - (2) Galactic Accelerators can only accelerate up to about ~ PeV
  - (3) Interaction cross section changes

Anisotropy

Telescope Array - Hotspot

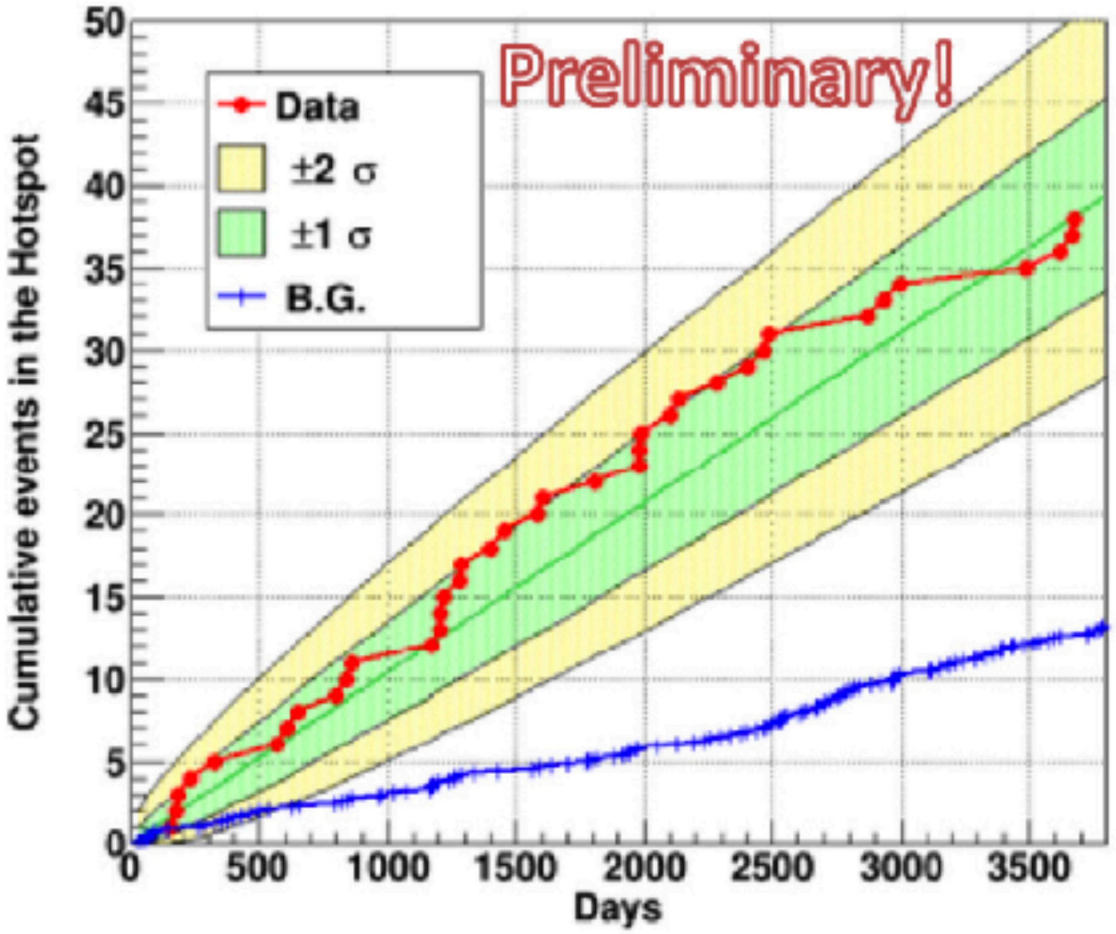
K. Kawata (TA Coll.)
PS3-173 - PoS 310

- number of events grows slightly slower than in the past, but still grows faster than background rate

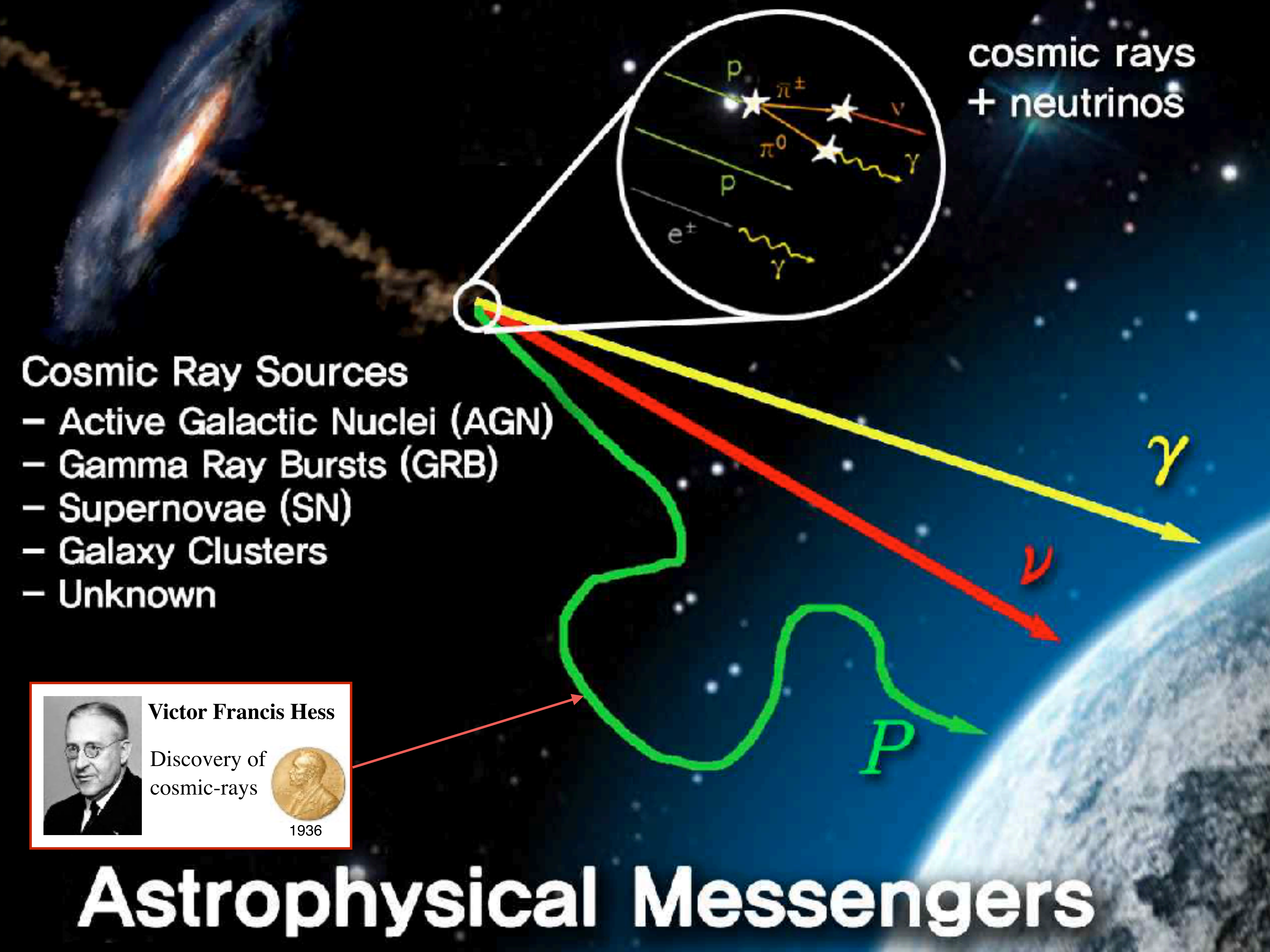


Hotspot from 11 years of TA SD data, from May 11, 2008 to May 11, 2019

E > 57 EeV, in total 168 events
38 events fall in Hotspot (α=144.3°, δ=40.3°, 25° radius, 22° from SGP), expected=14.2 events
local significance = 5.1 σ, chance probability → 2.9σ
25° over-sampling radius shows the highest local significance (scanned 15° to 35° with 5° step)



20 of 53 | 01 August 2019 ICRC, Madison, WI, USA | RP3: Cosmic Ray Indirect | fgs@udel.edu frank.schroeder@kit.edu


cosmic rays
+ neutrinos
p
π±
ν
π0
γ
p
e±
γ
Cosmic Ray Sources
– Active Galactic Nuclei (AGN)
– Gamma Ray Bursts (GRB)
– Supernovae (SN)
– Galaxy Clusters
– Unknown
γ
ν
P
Victor Francis Hess
Discovery of
cosmic-rays
1936
Astrophysical Messengers

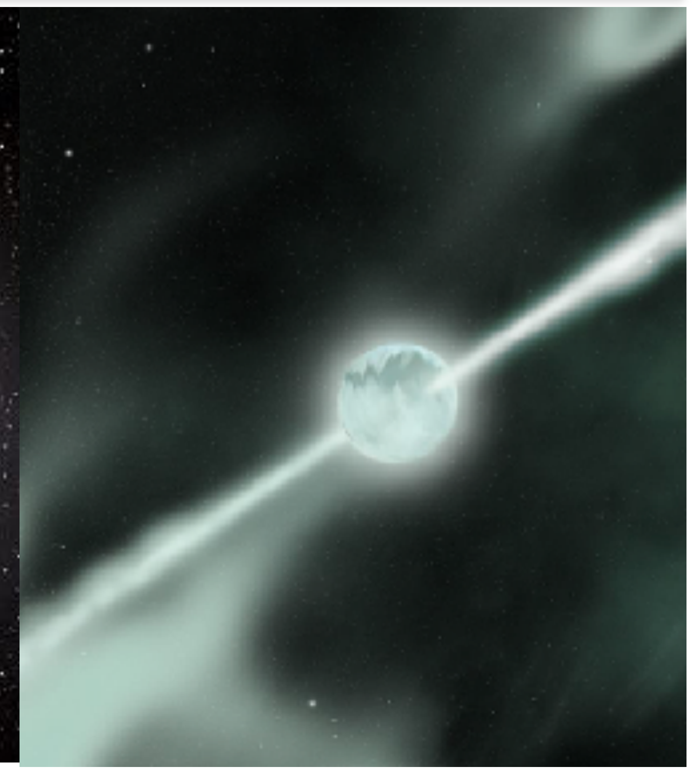
Potential sources of high-energy neutrinos

Galactic sources

Supernova remnants

Extragalactic sources

Active Galactic Nuclei

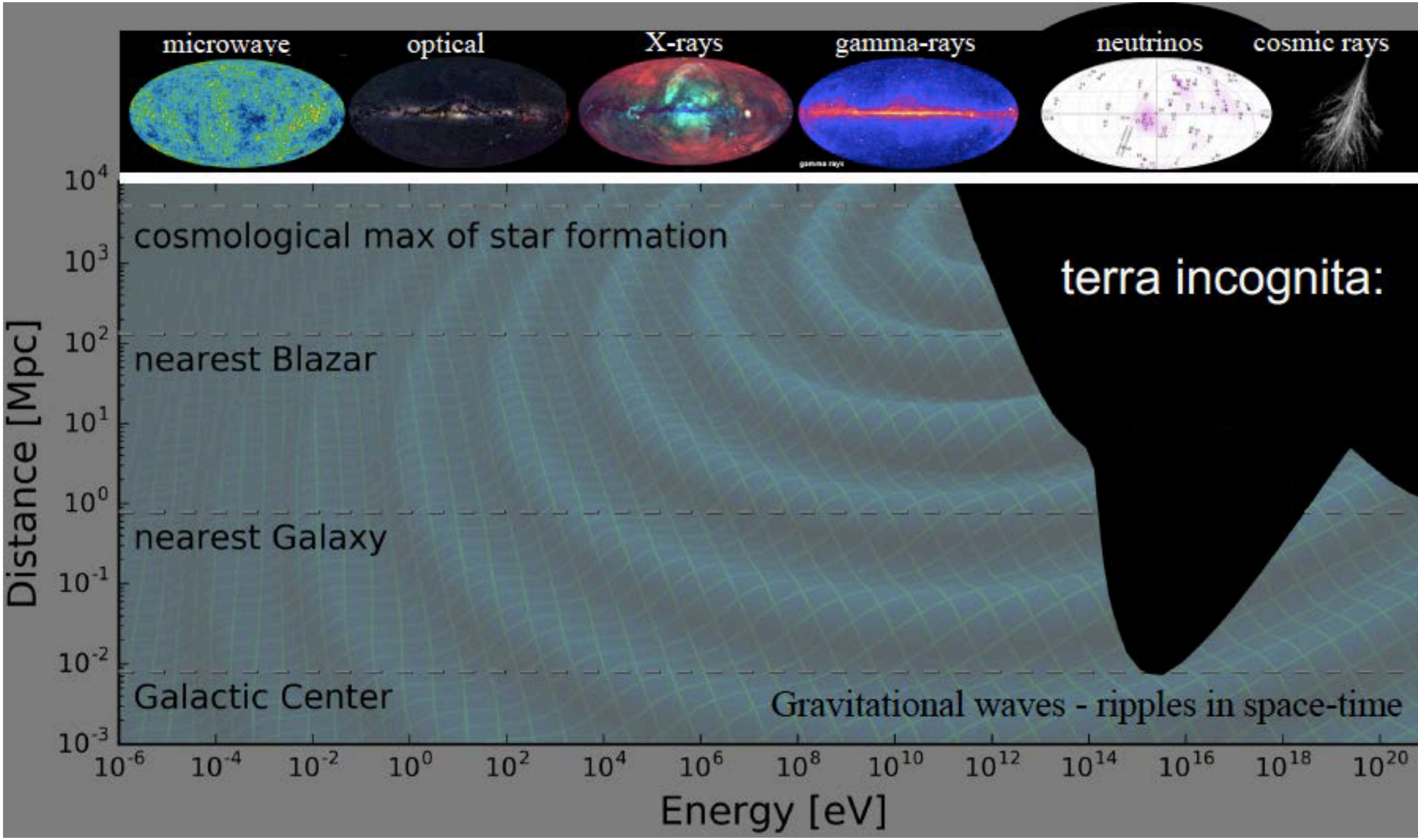


Gamma-ray bursts

Exotic

Something unexpected

Multimessenger Horizon



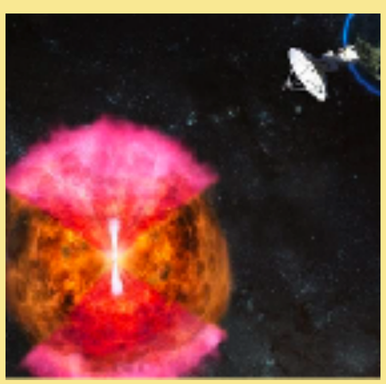
- Non-thermal Universe powered by cosmic accelerators
- Probed only by gravity waves, neutrinos and cosmic rays

Energetic Universe

Potential extragalatic Sources

Explosions of massive stars

Gamma ray bursts (GRBs)



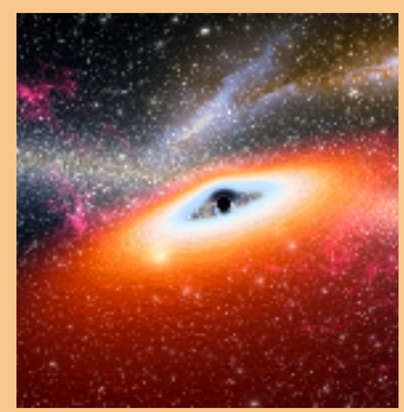
Choked GRBs

Supernovae IIn

Accreting supermassive black holes

Blazars

Tidal disruption events (TDEs)



Active Galactic Nuclei (AGN)

Calorimetric sources

Starburst galaxies

Clusters of Galaxies

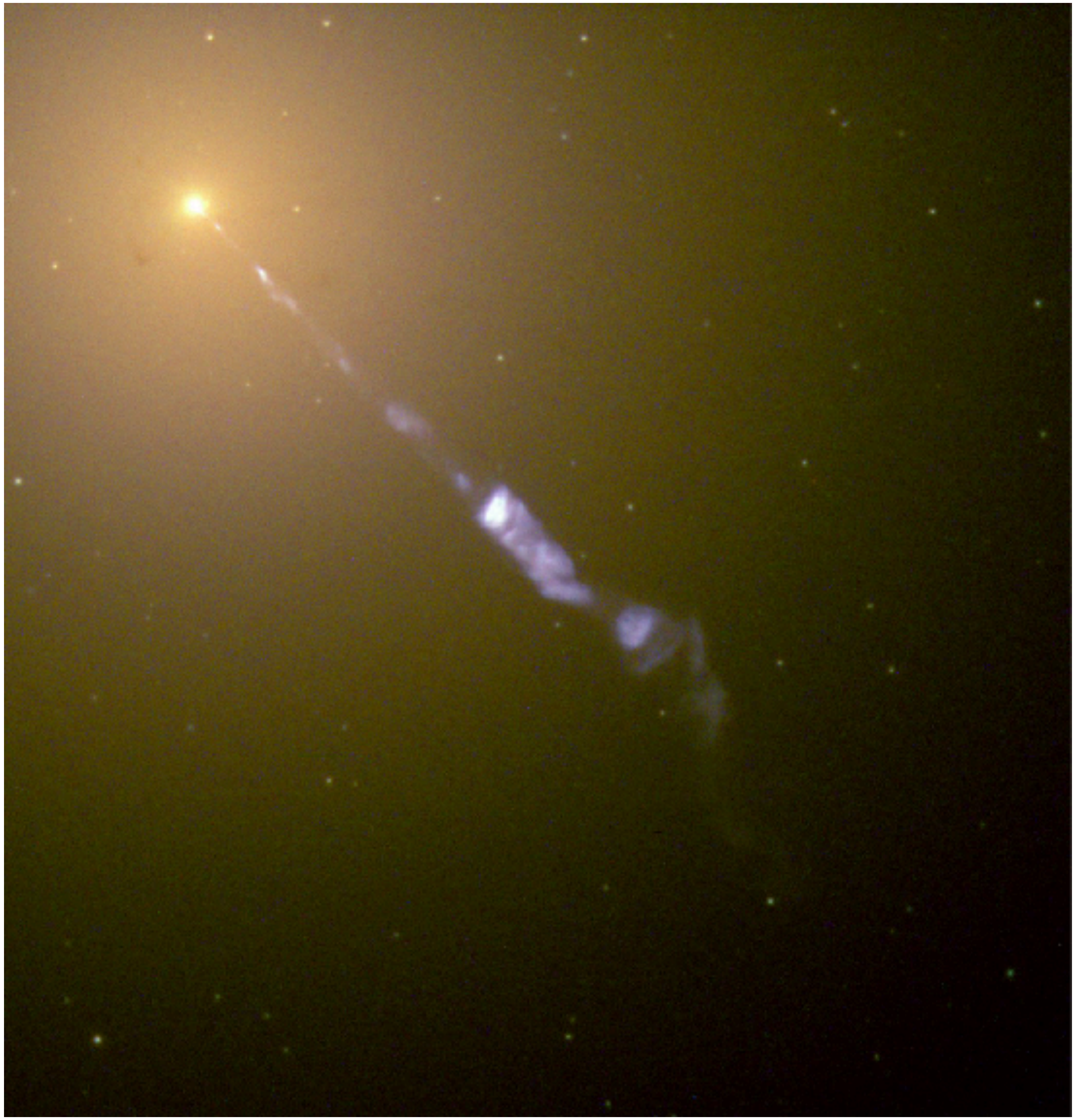
seconds — weeks — month — continuous

		Expected emission:	Opt. peak mag.:	Duration:
GRBs		γ-rays, X-rays, UV, **optical** rarely: VHE γ-rays	-24th	~100 s
choked or ll-GRBs		**optical** maybe: γ-rays, X-rays, late radio	SN: -19th	ν: ~100 s em.: ~30 d
type IIn SNe		**optical** rarely: γ-rays, X-rays	-18th (-21th if superl.)	~100 days
jetted TDEs		**optical**, UV, X-rays	-20th	~100 days
blazars		all wavelengths	-26th	minutes - months

Nora Linn Strotjohann | Optical emission from neutrino sources | 2019-05-21 | Page 14

Active Galactic Nuclei (AGN)

- Supermassive backholes with relativistic outflows in jets at the center of large galaxies
- Observational characteristics change depending on the alignment of the jets and observer



Unified Scheme of AGNs

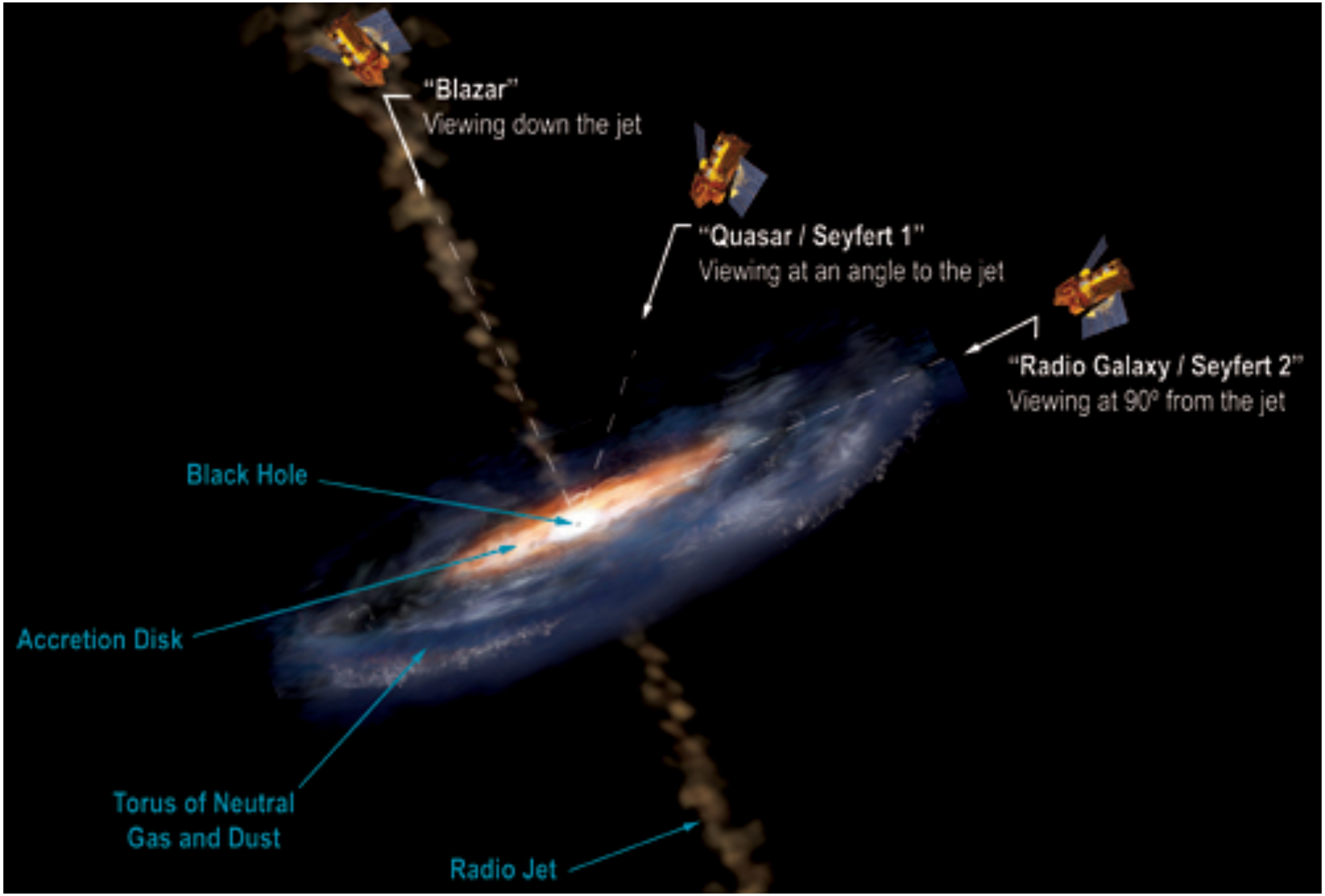


Image above: This illustration shows the different features of an active galactic nucleus (AGN), and how our viewing angle determines what type of AGN we observe. The extreme luminosity of an AGN is powered by a supermassive black hole at the center. Some AGN have jets, while others do not. **Image credit:** Aurore Simonnet, Sonoma State University.

Blazar - An AGN with the jet pointing towards us

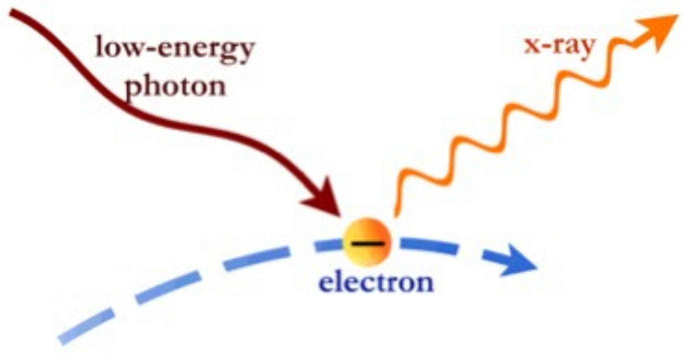
- Energy spectrum shows two characteristic bumps
  - Between IR / X-ray
    - Believed to be from synchrotron radiation from relativistic electrons
  - γ-ray
    - Could be attributed to inverse Compton scattering

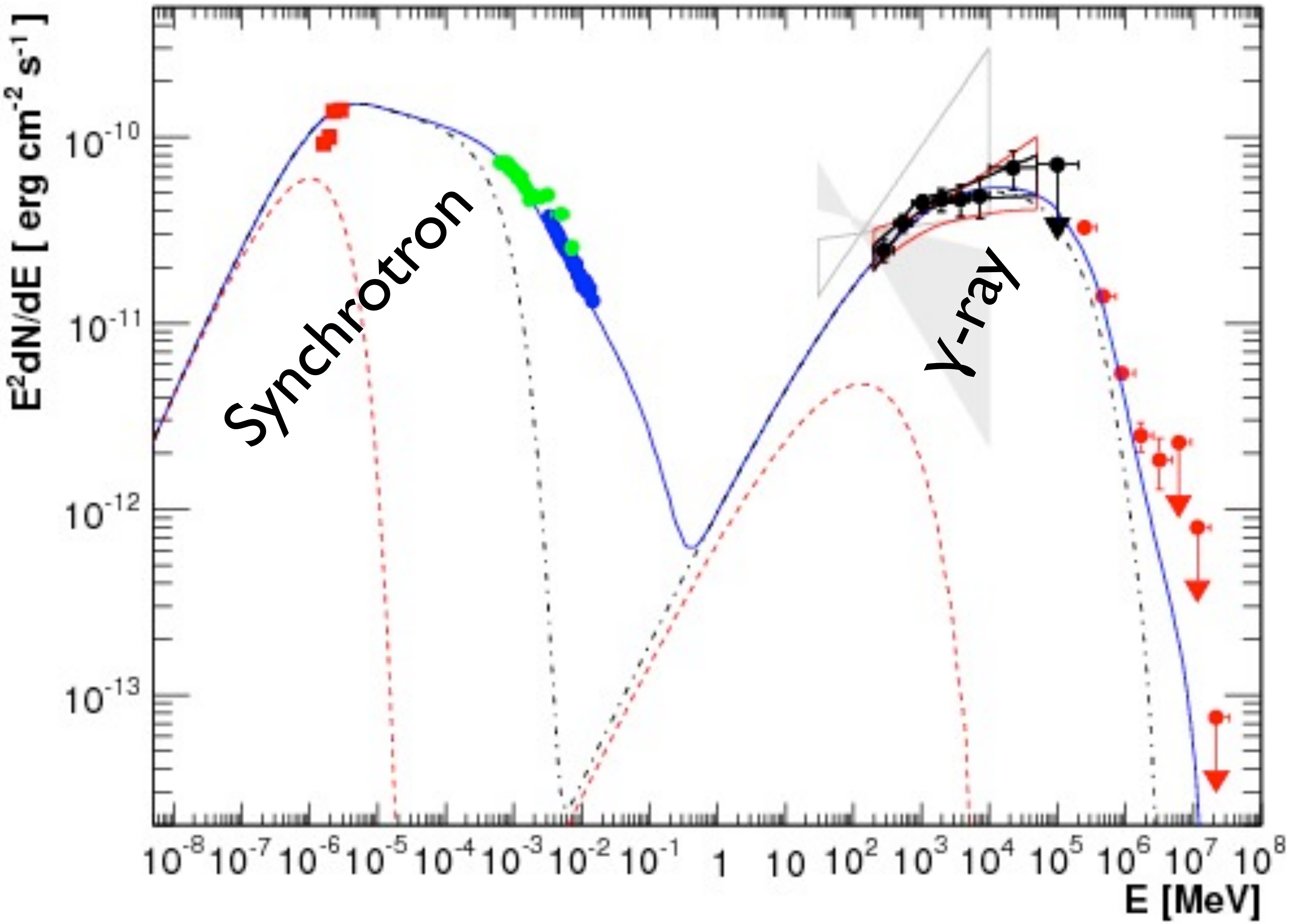
Synchrotron radiation:

$$P_{cl} = \frac{2}{3}\alpha m^2 \left(\frac{p_\perp}{m}\frac{cB}{m^2}\right)^2$$

$dE/dt \sim m^{-4}$

Inverse Compton:




E²dN/dE [erg cm⁻² s⁻¹]
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³
Synchrotron
γ-ray
10⁻⁸ 10⁻⁷ 10⁻⁶ 10⁻⁵ 10⁻⁴ 10⁻³ 10⁻² 10⁻¹ 1 10 10² 10³ 10⁴ 10⁵ 10⁶ 10⁷ 10⁸
E [MeV]

Blazars

- subdivided into different types based on the location of the synchrotron peak (low-energy) - SED (Spectral energy distribution)

SED component. Low-synchrotron-peaked (LSP) blazars, consisting of flat-spectrum radio quasars and low-frequency peaked BL Lac objects (LBLs), have their synchrotron peak in the infrared regime, at $\nu_s \leq 10^{14}$ Hz. Intermediate-synchrotron-peaked (ISP) blazars, consisting of LBLs and intermediate BL Lac objects (IBLs) have their synchrotron peak at optical – UV frequencies at 10^{14} Hz $< \nu_s \leq 10^{15}$ Hz, while High-synchrotron-peaked (HSP) blazars, almost all known to be high-frequency-peaked BL Lac objects (HBL), have their synchrotron peak at X-ray energies with $\nu_s > 10^{15}$ Hz

Blazars

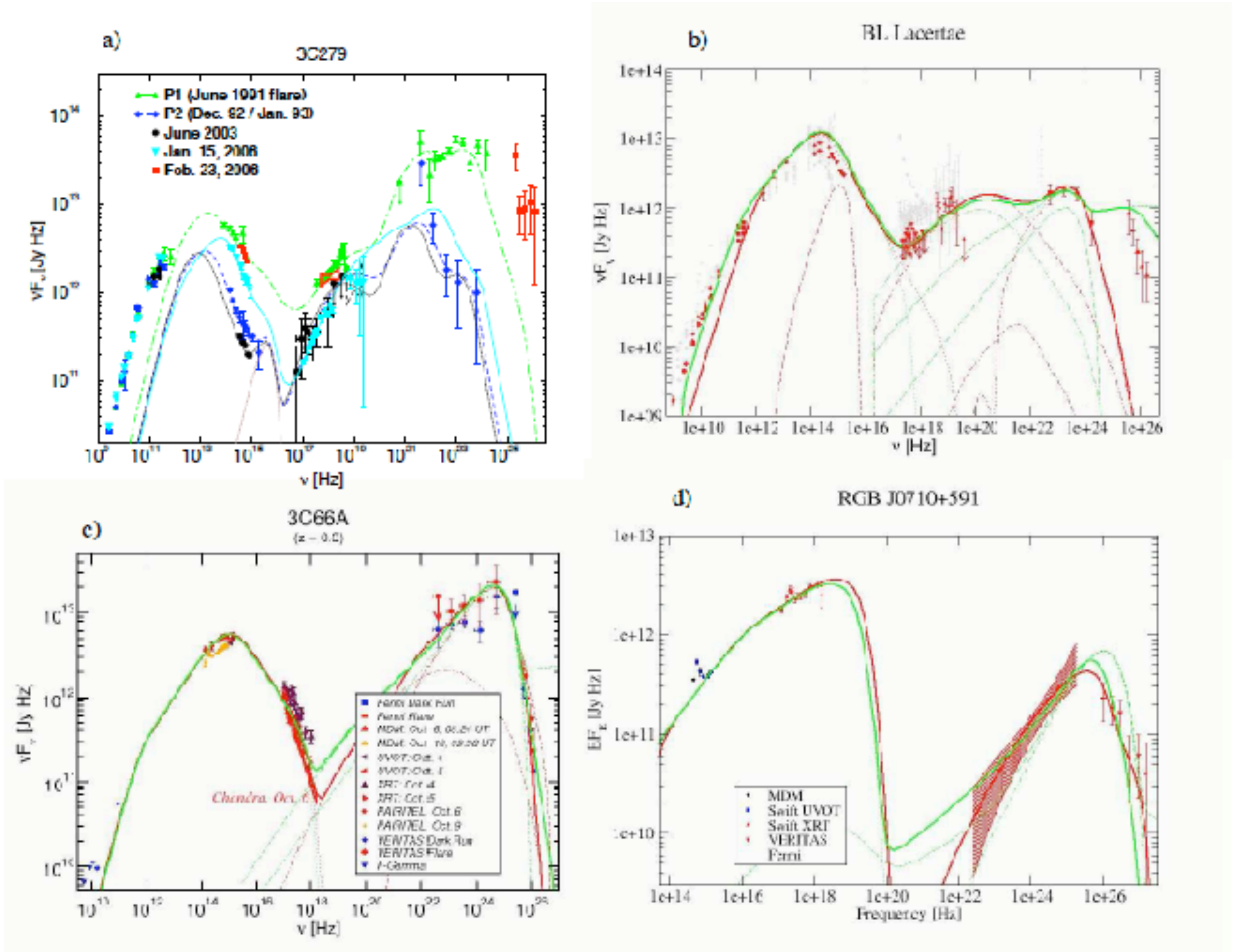


Fig. 1. Spectral energy distributions of four sub-classes of blazars: a) the FSRQ 3C279 (from Collmar et al. (2010)), b) the LBL BL Lacertae, (data from Abdo et al. (2010b)), c) the intermediate BL Lac 3C66A (data from Acciari et al. (2010c)), and d) the HBL RGB J0710+591 (data from Acciari et al. (2010b)). In Panel a) (3C279), lines are one-zone leptonic model fits to SEDs at various epochs shown in the figure. In all other panels, red lines are fits with a leptonic one-zone model; green lines are fits with a one-zone lepto-hadronic model.

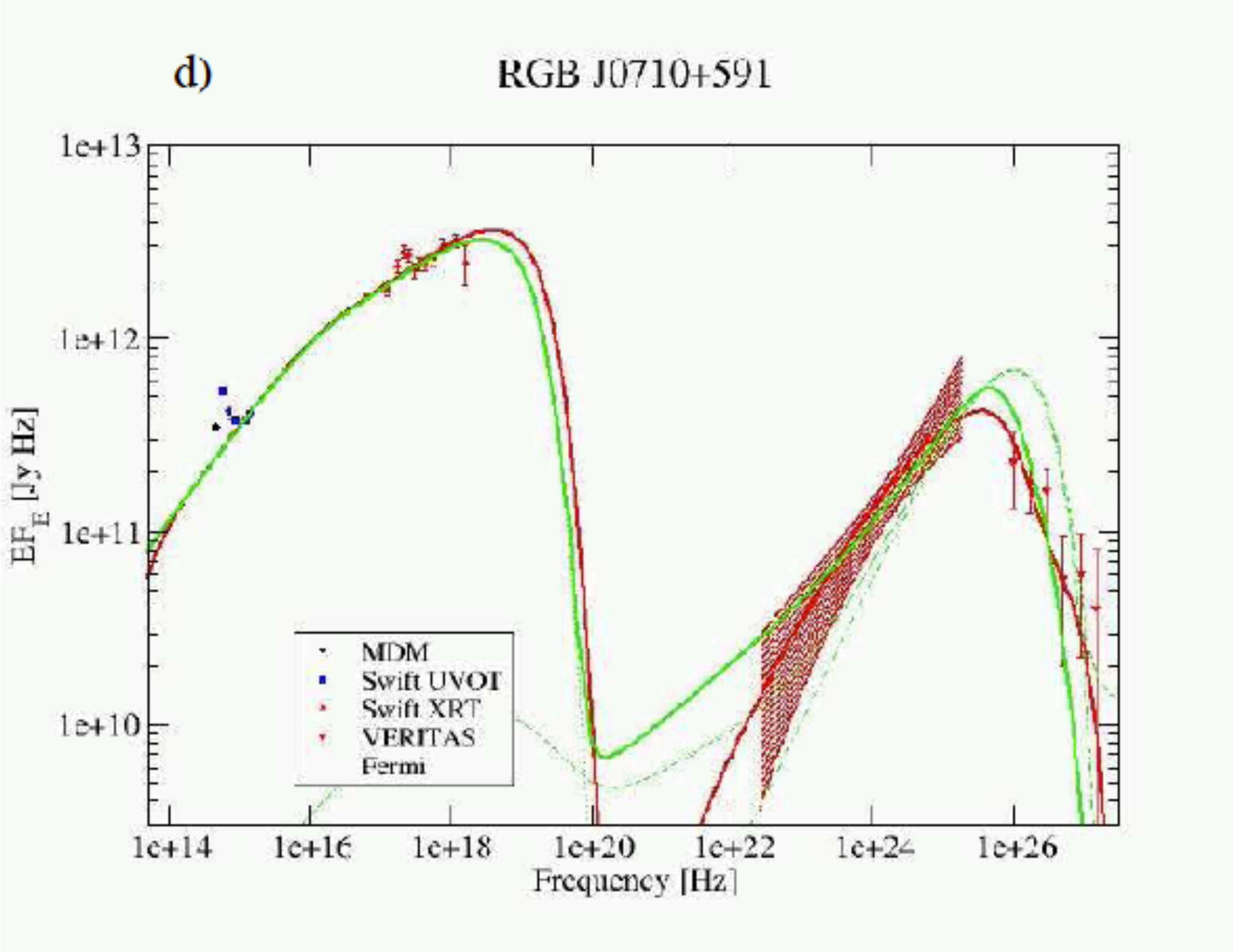
Blazars

- The electron-synchrotron origin of the low-frequency emission is well established.
- However: Two fundamentally different approaches concerning the high-energy emission:
  - **Leptonic:** Emission from ultra-relativistic electrons
  - **Lepto-hadronic:** Emission from cascades initiated by pγ

Blazars

M. Boettcher arXiv:1006.5048v1

- Leptonic models are difficult to distinguish from lepto-hadronic models by γ-ray observations alone



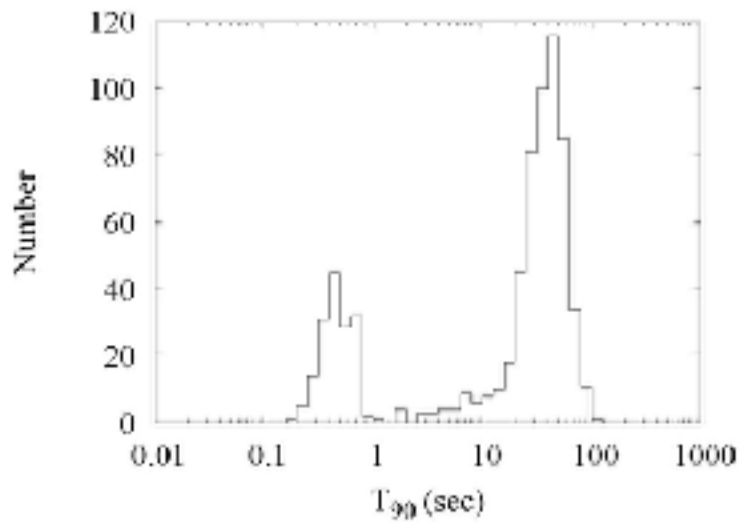
1) lepto-hadronic models assume that the high-energy emission is dominated by decays of pions produced in pγ interactions or synchrotron radiations from protons, pions, and muons.

2) leptonic models assume that the dominant cause of the high-energy emission is through ultra-relativistic electrons, while protons are not accelerated to sufficiently high energies to reach the pion production threshold or to few of them reach such energies.

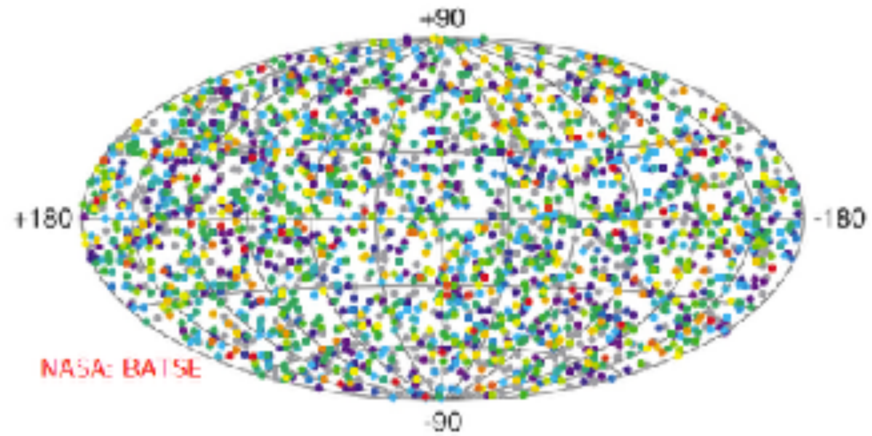
Gamma Ray Bursts (GRBs)

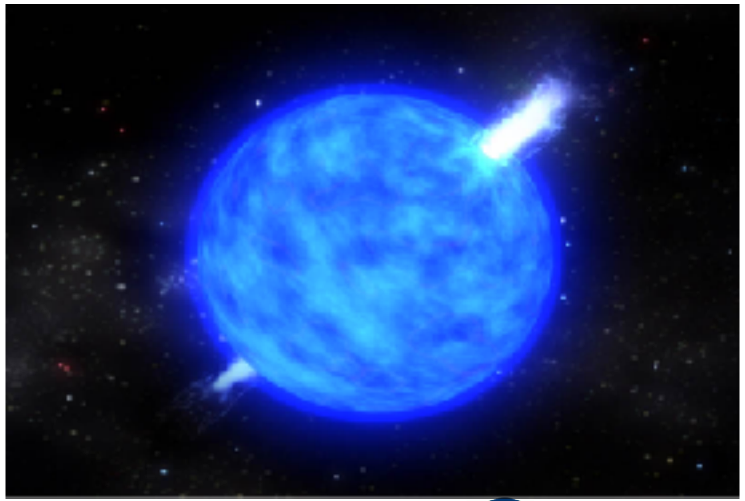
Gamma Ray Bursts

- Observation
  - Bursts last from milliseconds to tens of seconds and show great variety. Clearly bimodal
    - We distinguish between **long (>2s)** and **short (<2s)** bursts
  - Isotropic distribution
    - Cosmic origin
  - highest redshift burst z=9.4 (GRB 090429B)
    - Energy output too high to be spherically radiated, hence must be highly beamed
  - Frequency ~ 1/day
    - Actual rate suspected to be much higher due to beaming



2704 BATSE Gamma-Ray Bursts





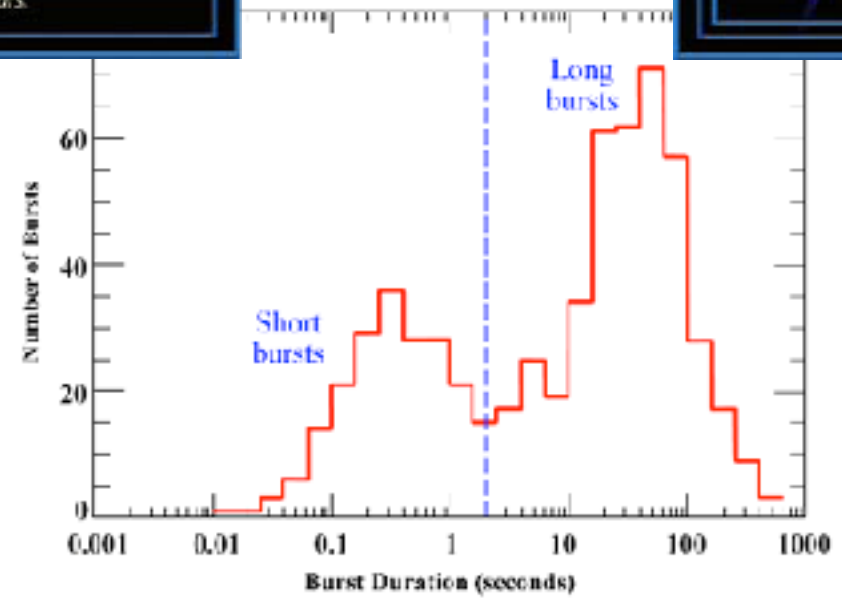
GRB Models

- There is a consensus that the GRB phenomenon is caused by the death of a massive star and involves:
    - Unusually large amount of angular momentum
        - $j \sim 10^{16} - 10^{17} cm^2 s^{-1}$
    - Unusually large magnetic fields
        - $\sim 10^{15}$ Gauss

Long and Short GRBs

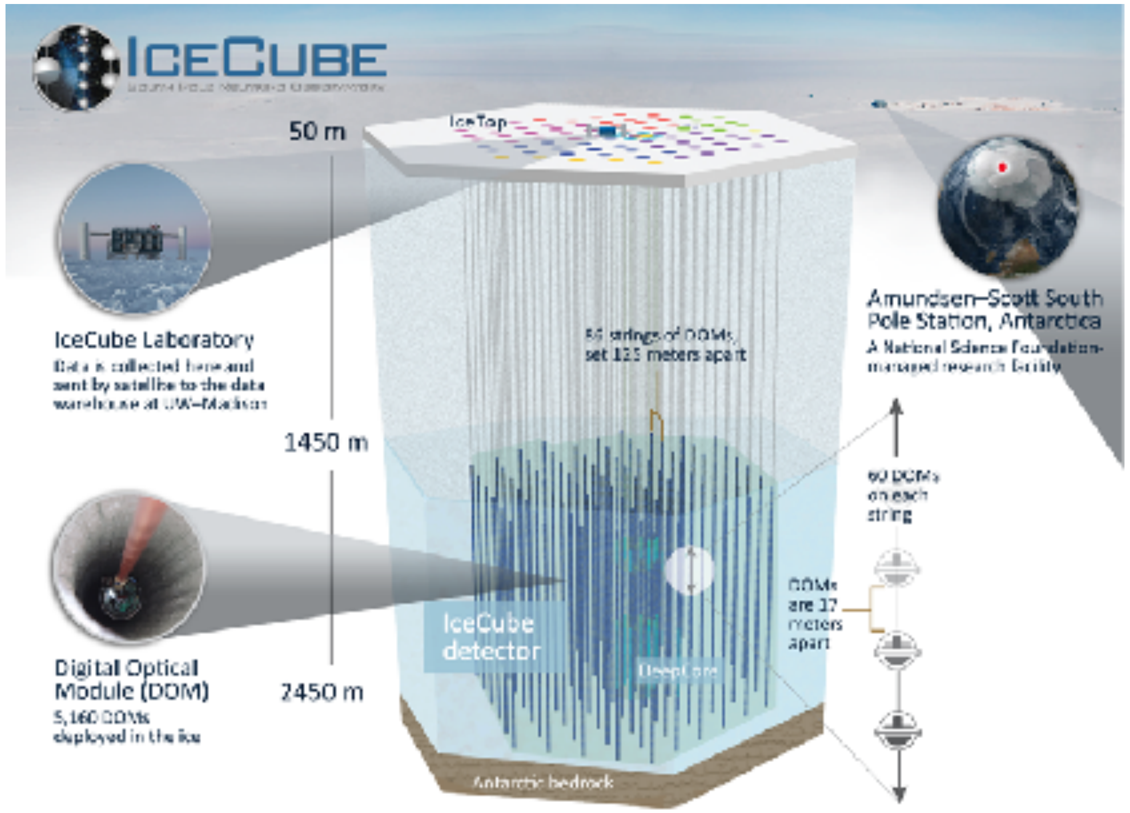
- Long bursts (>2s)
  - Can often be associated with a galaxy with rapid star formation
  - Some long GRBs are linked to supernovae
  - Brightest Supernovae are associated with relatively faint GRBs
- Short bursts (<2s)
  - Several short GRB (X-ray) afterglows have been associated with centers of large galaxy clusters or large elliptical galaxies, both regions of little or no star formation
  - No Supernova link established

short bursts tend to be dimmer by a factor of 10 and have more highly-energetic (hard) gamma rays than their long burst counterparts



Observatories

Observatories



IceCube Neutrino Observatory is a Gigaton detector at the South Pole designed to detect cosmic neutrinos!

LIGO/Virgo observatories designed to detect cosmic gravitational waves by measuring the ripples in spacetime

Multi-messenger Science

Multi-messenger events

Recent events

- Neutrino observed in coincidence with Gravitational wave !
  … but significance from this event alone is not very high

TITLE: GCN CIRCULAR
NUMBER: 25192
SUBJECT: LIGO/Virgo S190728q: One neutrino candidate from IceCube search
DATE: 19/07/28 10:06:18 GMT
FROM: Raamis Hussain at IceCube <raamis.hussain@icecube.wisc.edu>

IceCube Collaboration (http://icecube.wisc.edu/) reports:

A search for track-like muon neutrino events detected by IceCube consistent with the sky localization of gravitational-wave candidate S190728q in a time range of 1000 seconds [1] centered on the alert event time (2019-07-28 06:36:50.529 UTC to 2019-07-28 06:53:30.529 UTC) has been performed. During this time period IceCube was collecting good quality data. The search is a maximum likelihood analysis which searches for a generic point-like neutrino source coincident with the given GW skymap [2].

One track-like event is found in spatial and temporal coincidence with the gravitational-wave candidate S190728q calculated from the map circulated in the 4-Initial notice. This represents an overall p-value of 0.03 (1.84 sigma).

An earlier search (GCN 25185) based on preliminary information of S190728q yielded no significant p-values for the worse GW localization [3].

Properties of the coincident events are shown below.

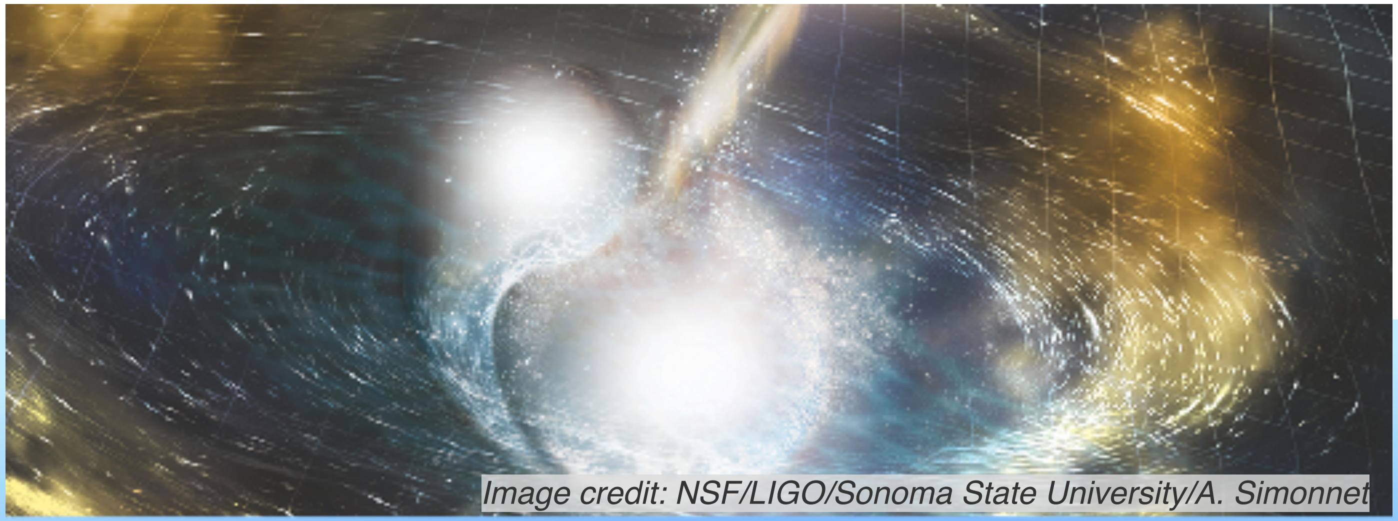
dt	ra (deg)	dec (deg)	Angular Uncertainty(deg)	p-value(generic transient)
-360	312.87	5.85	4.81	0.039

where:
dt = Time offset (sec) of track event with respect to GW trigger.
Angular uncertainty = Angular uncertainty of track event: the radius of a circle representing 90% CL containment by area.
p-value = the p-value for this specific track event
RA & Dec = Right ascension and declination in degrees quoted in J2000 epoch

The IceCube Neutrino Observatory is a cubic-kilometer neutrino detector operating at the geographic South Pole, Antarctica. The IceCube realtime alert point of contact can be reached at roc@icecube.wisc.edu

[1] Baret et al., Astroparticle Physics 35, 1 (2011)
[2] Braun et al., Astroparticle Physics 29, 299 (2008)
[3] GCN 25185: https://gcn.gsfc.nasa.gov/gcn3/25185.gcn3

https://gcn.gsfc.nasa.gov/gcn3/25192.gcn3



GW170817 -
GRB 170817A

1. **GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral**
(2327) LIGO Scientific and Virgo Collaborations (B.P. Abbott (LIGO Lab., Caltech) *et al.*). Oct 16, 2017. 18 pp.
Published in **Phys.Rev.Lett. 119 (2017) no.16, 161101**
LIGO-P170817
DOI: 10.1103/PhysRevLett.119.161101
e-Print: **arXiv:1710.05832** [gr-qc] | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; Link to PRESSRELEASE; Link to LiveScience.com article; Link to New York Times article; Link to Space.com article; Link to Symmetry Magazine article; Link to Fulltext
Detailed record - Cited by 2327 records 1000+

2. **Multi-messenger Observations of a Binary Neutron Star Merger**
(926) LIGO Scientific and Virgo and Fermi GBM and INTEGRAL and IceCube and IPN and Insight-Hxmt and ANTARES and Swift and Dark Energy Camera GW-EM and DES and DLT40 and GRAWITA and Fermi-LAT and ATCA and ASKAP and OzGrav and DWF (Deeper Wider Faster Program) and AST3 and CAASTRO and VINROUGE and MASTER and J-GEM and GROWTH and JAGWAR and CaltechNRAO and TTU-NRAO and NuSTAR and Pan-STARRS and KU and Nordic Optical Telescope and ePESSTO and GROND and Texas Tech University and TOROS and BOOTES and MWA and CALET and IKI-GW Follow-up and H.E.S.S. and LOFAR and LWA and HAWC and Pierre Auger and ALMA and Pi of Sky and DFN and ATLAS Telescopes and High Time Resolution Universe Survey and RIMAS and RATIR and SKA South Africa/MeerKAT Collaborations and AstroSat Cadmium Zinc Telluride Imager Team and AGILE Team and 1M2H Team and Las Cumbres Observatory Group and MAXI Team and TZAC Consortium and SALT Group and Euro VLBI Team and Chandra Team at McGill University (B.P. Abbott (LIGO Lab., Caltech) *et al.*). Oct 16, 2017. 59 pp.
Published in **Astrophys.J. 848 (2017) no.2, L12**
LIGO-P1700294, VIR-0802A-17, FERMILAB-PUB-17-478-A-AE-CD
DOI: 10.3847/2041-8213/aa91c9
e-Print: **arXiv:1710.05833** [astro-ph.HE] | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; CERN Document Server; OSTI.gov Server; Fermilab Library Server (fulltext available); Link to Fulltext; Link to Physics World Breakthrough of the Year
Detailed record - Cited by 926 records 500+

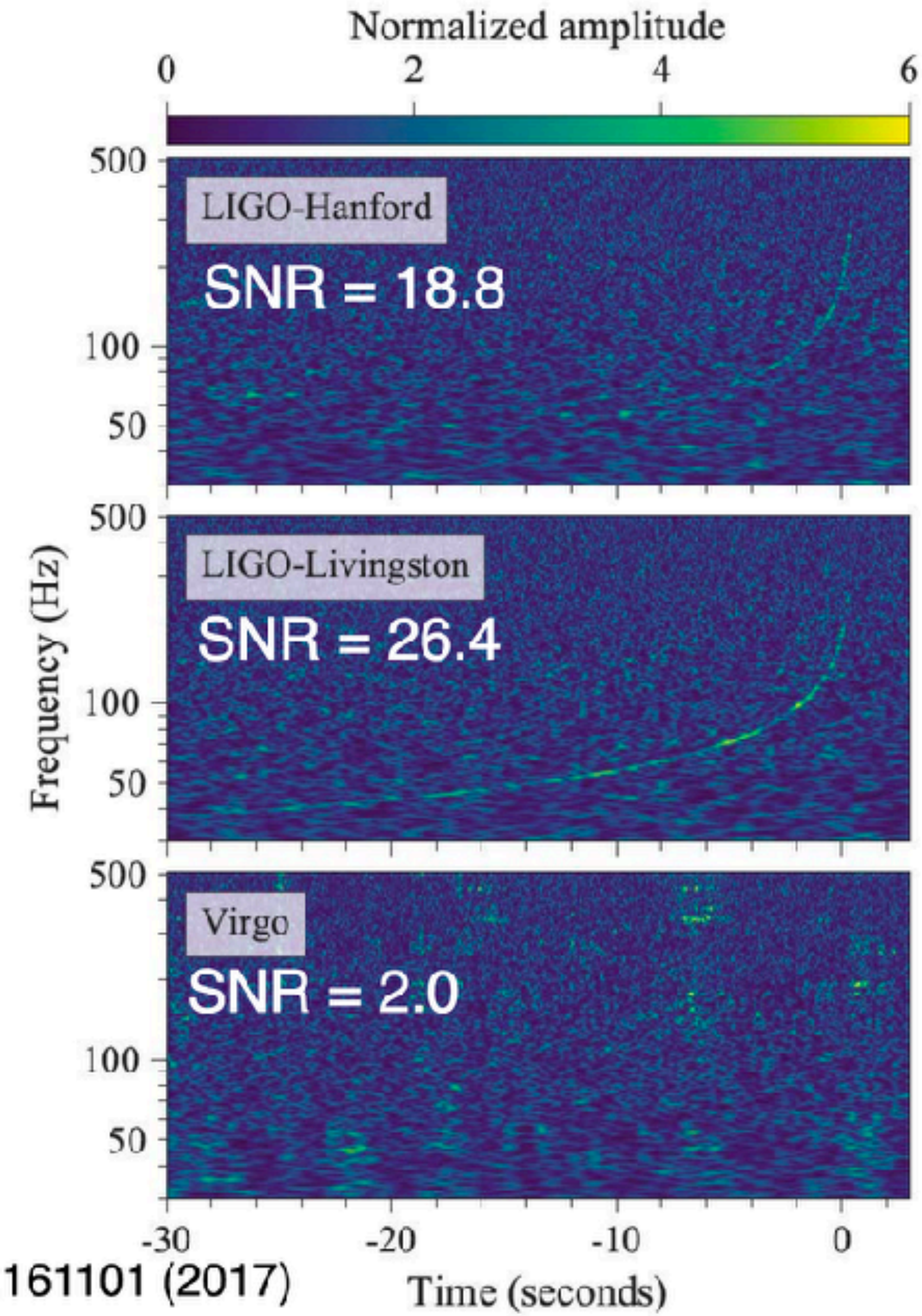
3. **Gravitational Waves and Gamma-rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A**
(854) LIGO Scientific and Virgo and Fermi-GBM and INTEGRAL Collaborations (B.P. Abbott (LIGO Lab., Caltech) *et al.*). Oct 16, 2017. 27 pp.
Published in **Astrophys.J. 848 (2017) no.2, L13**
LIGO-P1700308
DOI: 10.3847/2041-8213/aa920c
e-Print: **arXiv:1710.05834** [astro-ph.HE] | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record - Cited by 854 records 500+

GW170817

- August 17, 2017, the LIGO-Virgo detector network observed a gravitational-wave signal from the inspiral of two low-mass compact objects consistent with a binary neutron star (BNS) merger
- Gamma-ray Burst (GRB 170817A) was observed in coincidence with this event
- Multi-messenger observations and EM follow ups observations support the hypothesis that GW170817 was produced by the merger of two neutron stars in NGC4993 followed by a short gamma-rayburst (GRB 170817A) and a kilonova/macronova powered by the radioactive decay of r-process nuclei synthesized in the ejecta

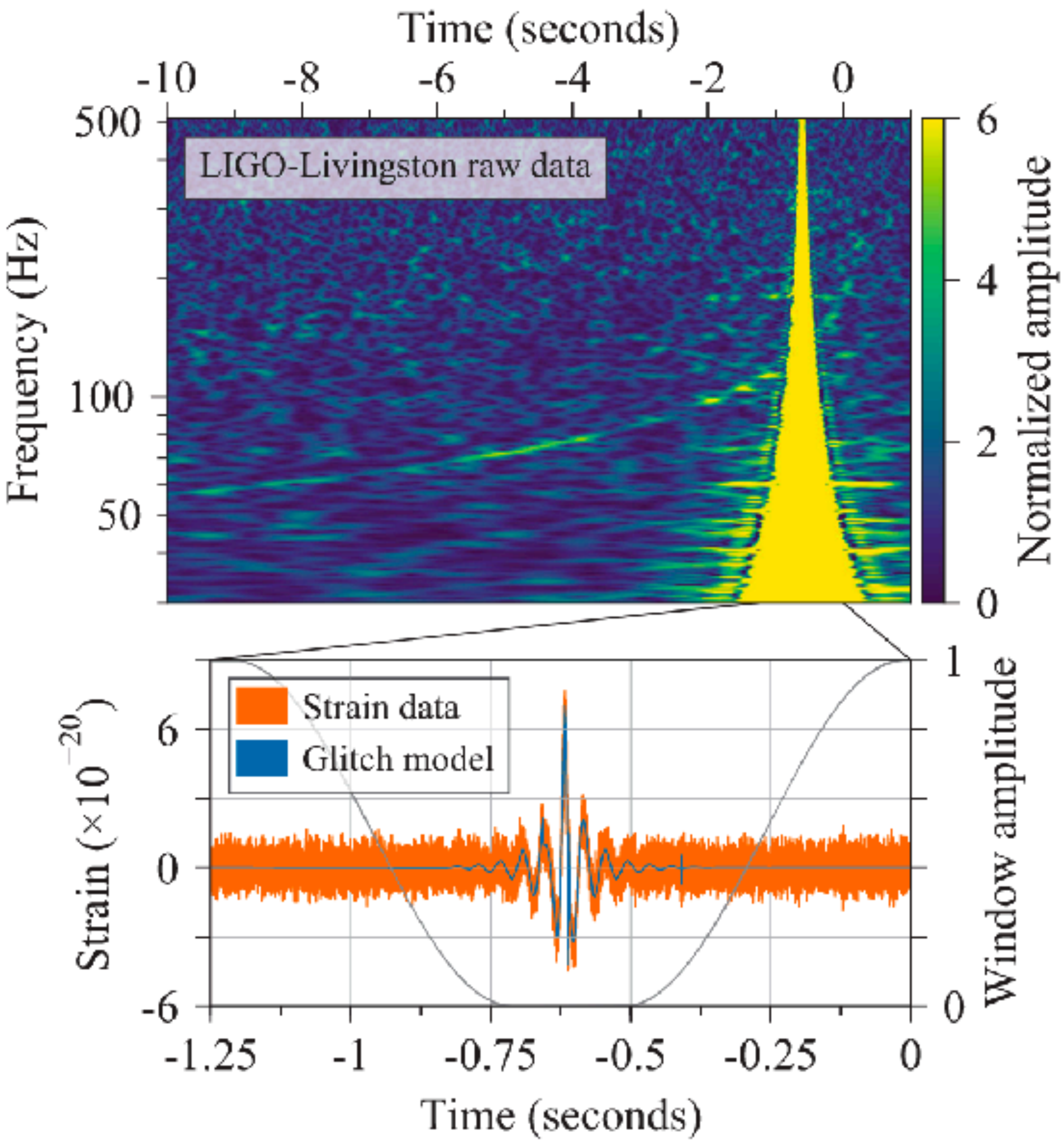
GW signal from GW170817

- Slower waveform evolution than all BBH systems we observed
  - Implies much lower chirp mass
- Clear signals in LIGO detectors, not obvious in Virgo
- Signal spends ~100 sec in the LIGO sensitive band (>20 Hz)
- BNS horizon distances (Mpc) 218 (L1), 107 (H1), 58 (V1)
- In Virgo's blind spot, however triangulation is still possible
- Total Signal-to-noise ratio SNR: 32.4
  - Loudest GW signal detected!

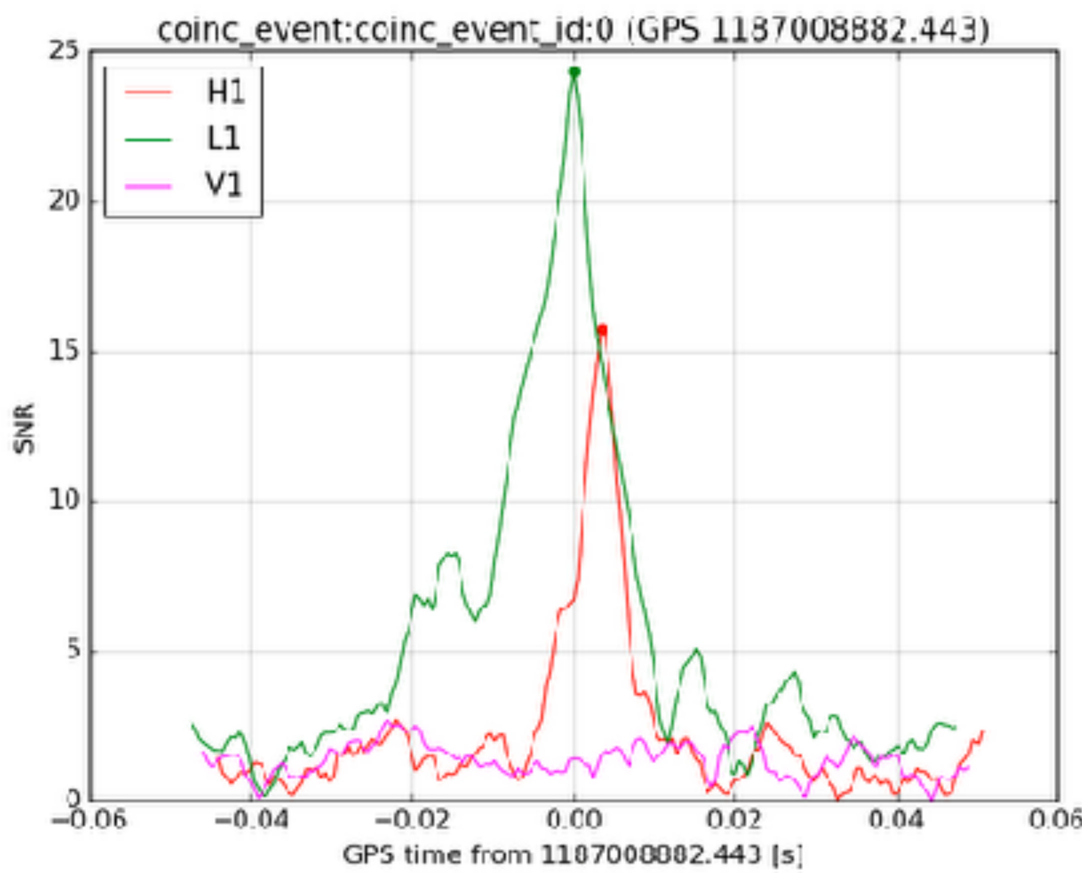


PRL119,161101 (2017)

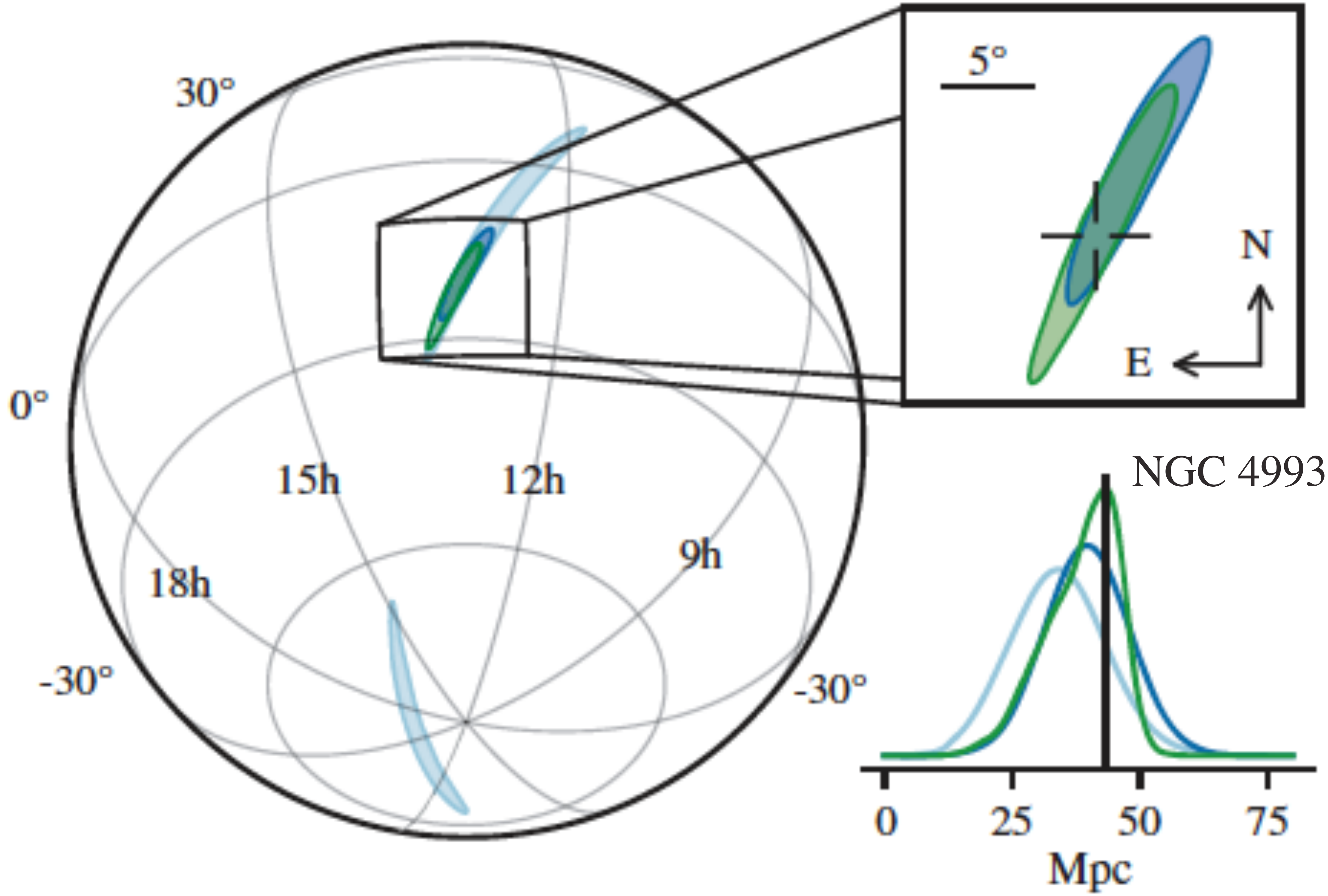
Triangulation and Glitch removal



- Data quality: contained loud transient (glitch) in LIGO-Livingston Observatory (LLO)
- To mitigate the glitch in the rapid reanalysis that produced the localization skymap, a window amplitude was applied

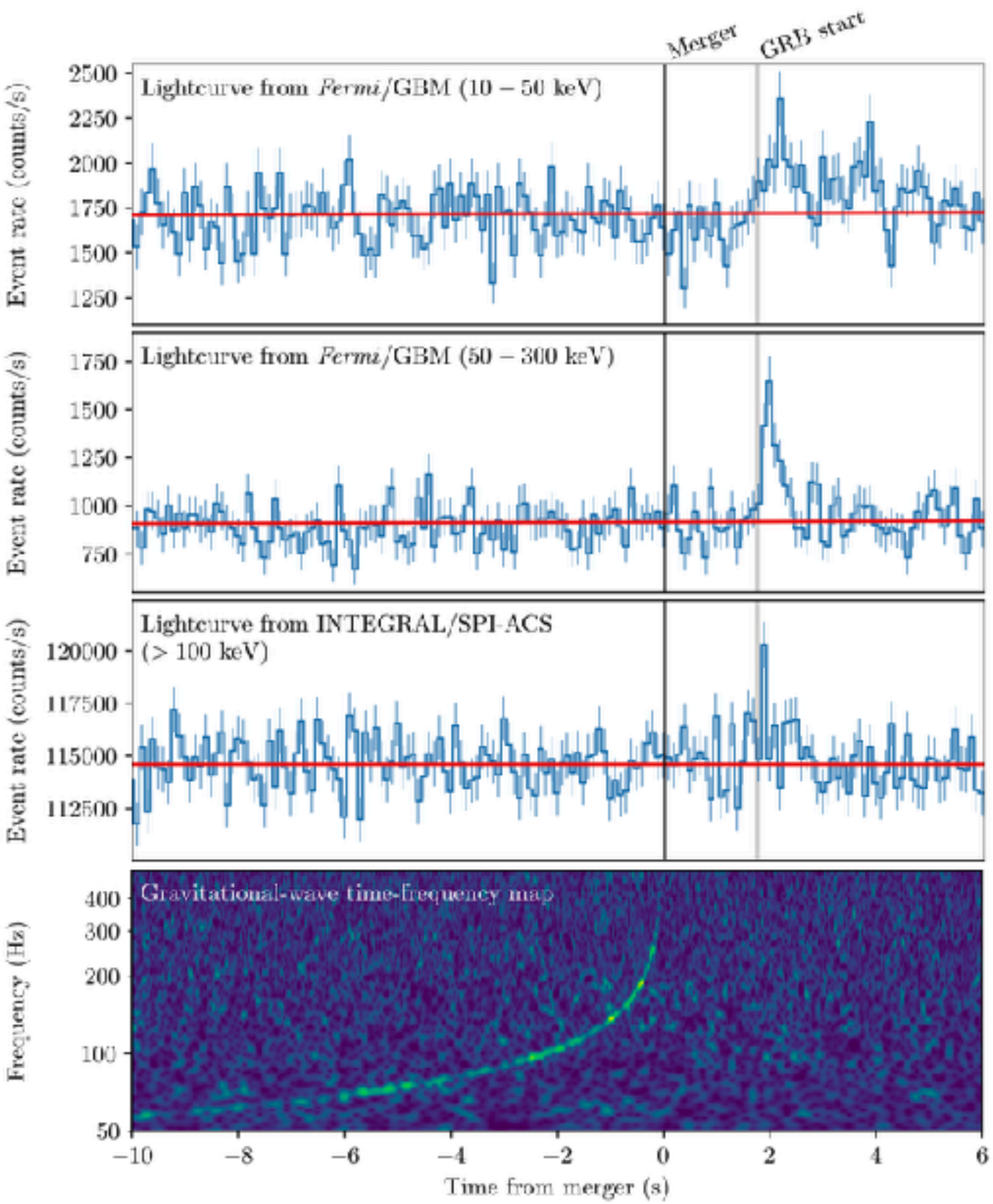


Sky localization

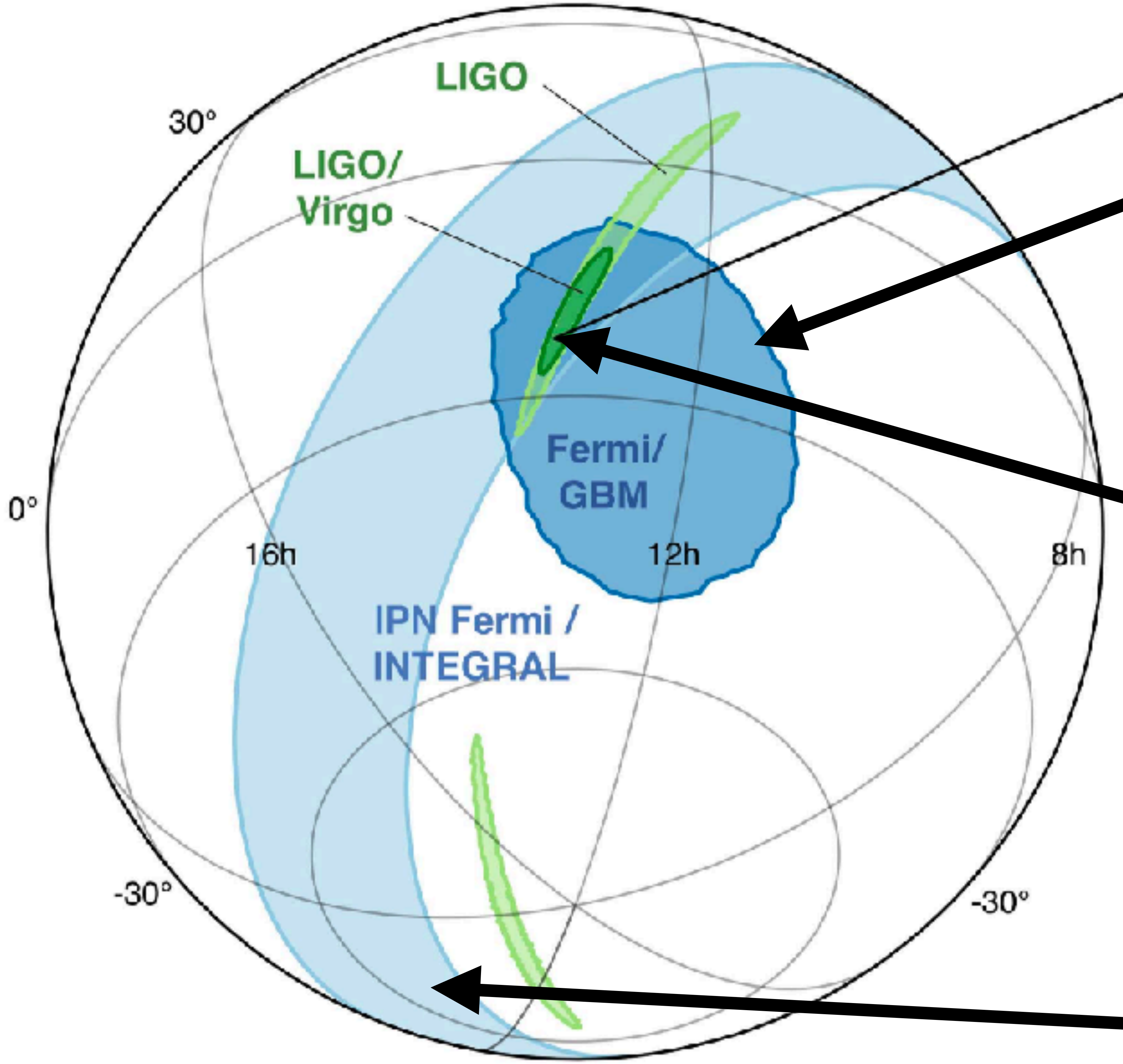


GammaRayBurst detection

- Fermi GBM: 90% of burst fluence observed over T_{90} = 2.0 ± 0.5 s
- Signal shape
  - Fast main pulse
    - ~0.5 sec long
    - Comptonized spectrum (power law + exponential)
    - peak energy 185 ± 62 keV
  - Followed by a weak tail
    - ~1 sec long
    - 10 keV
    - blackbody spectrum
- Overall observation indicates
  - 3:1 odds for 'short' vs. 'long' GRB



Sky localization



GBM map from directional sensitivity

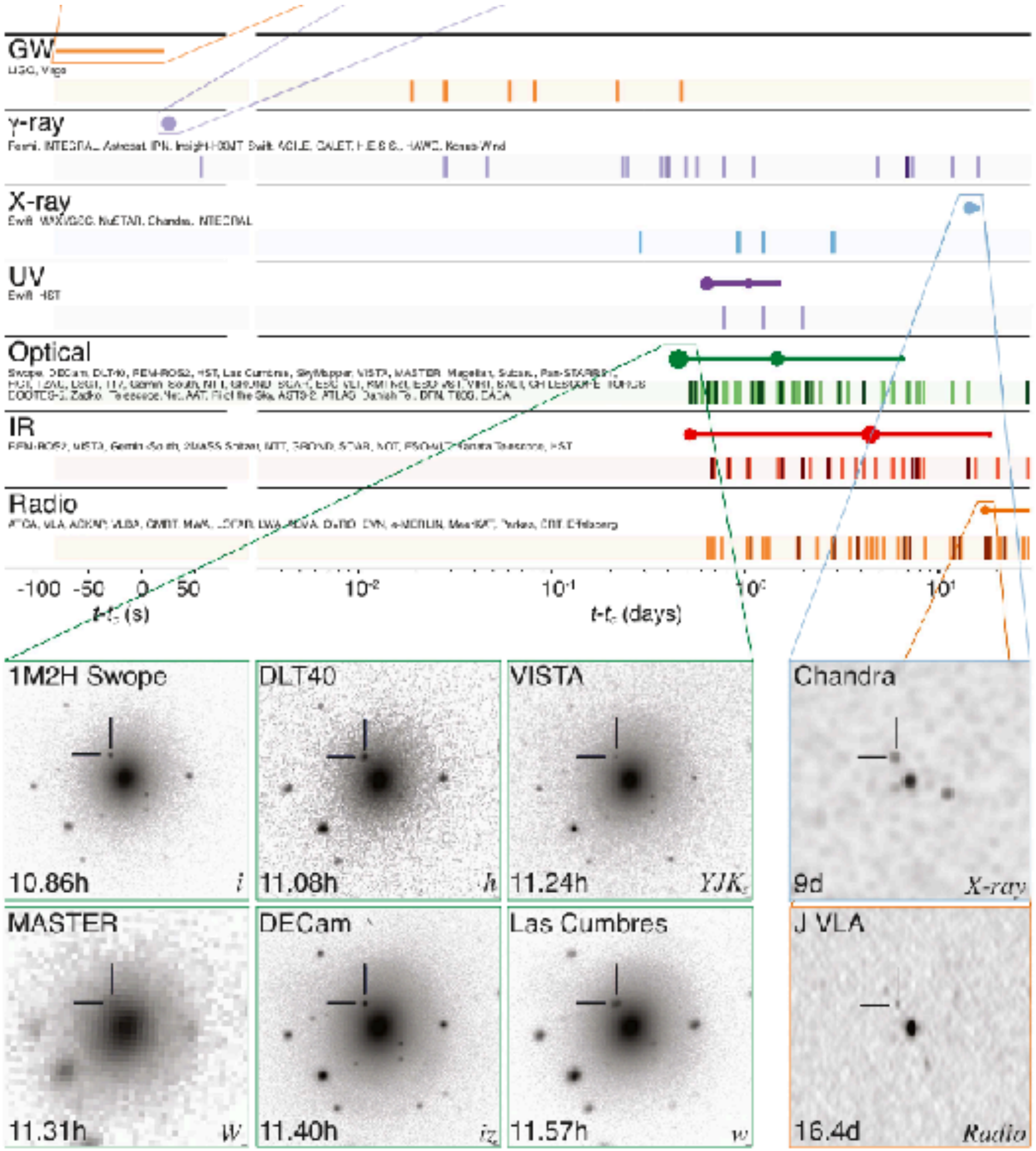
GW map uses H–L time delay and H/L/V signal amplitudes

Fermi/Integral band from time delay

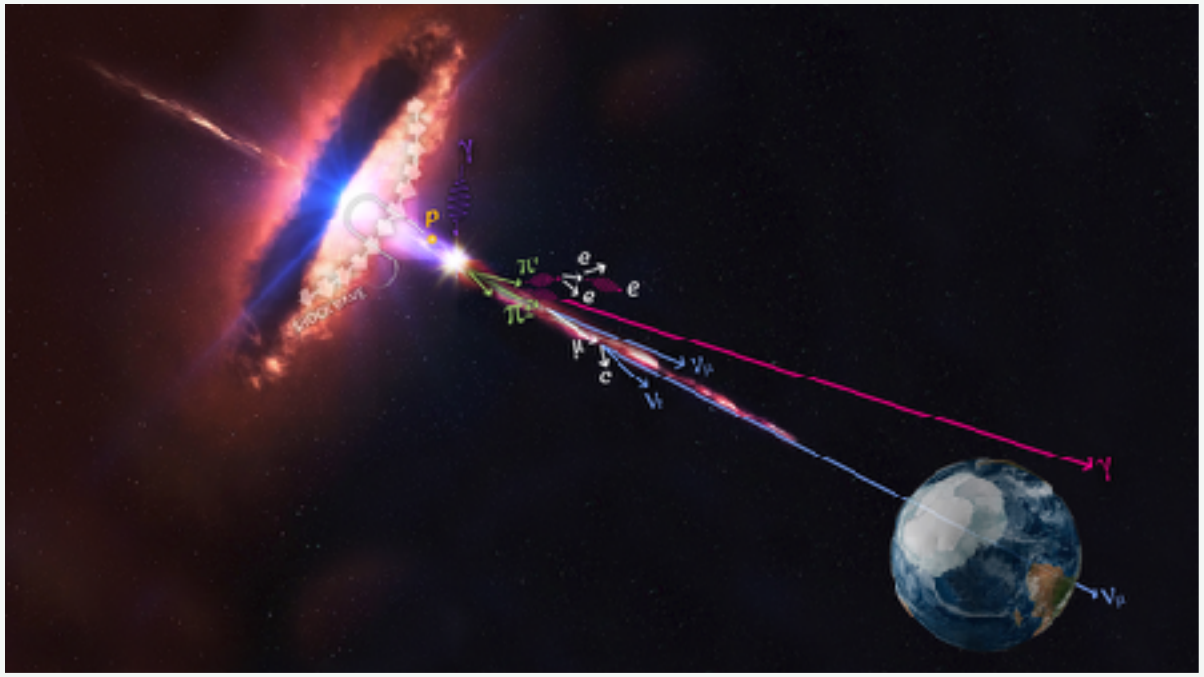
Probability of chance coincidence

- Rate of sGRBs detected by GBM ~0.1/day
- Probability that unrelated sGRB detected with peak within ±1.74 ~ $5x10^{-6}$
- Probability that GW/Fermi–GBM sky maps are as consistent for unrelated sGRB ~ 0.01
- . Chance probability for both time and direction :
- $5x10^{-8}$ ~ "5.3 σ"
- ⇒ Clear association of BNS merger with (one) sGRB

Identification of optical counterpart and host galaxy

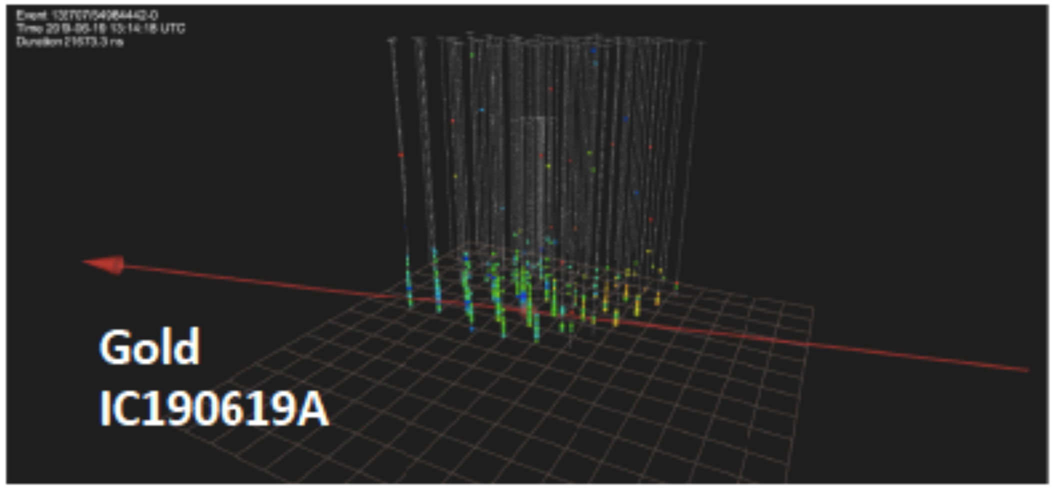


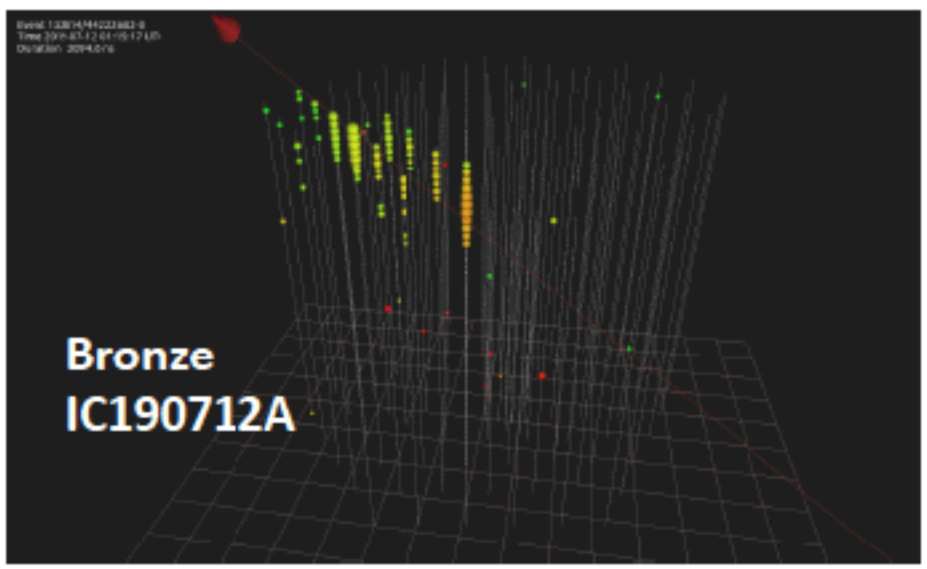
- Follow up campaigns by dozens of observatories
- New source was found within hours
- NGC 4993 identified as host galaxy
    - Distance ~40Mpc
    - Redshift z = 0.0097



Multi-messenger Neutrino Astronomy and IceCube-170922A

IceCube Realtime Alerts



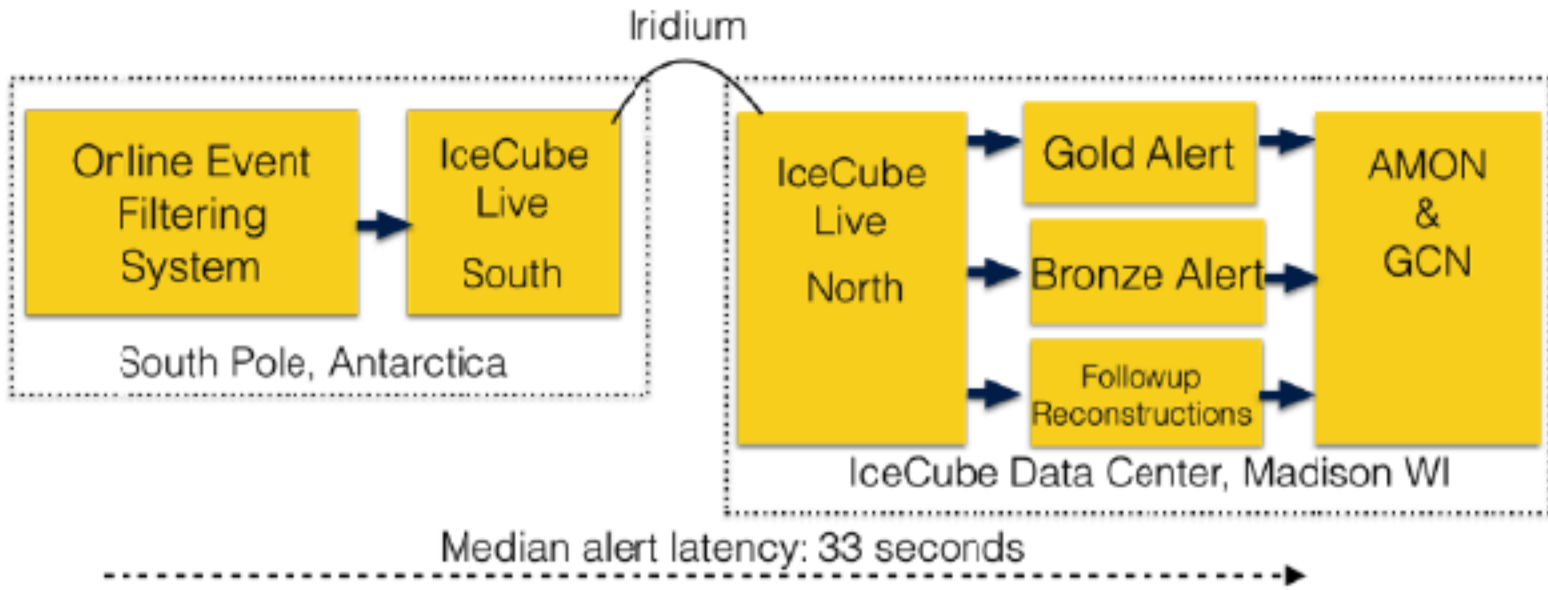


IceCube sending alerts since April 2016
Updated alerts as of June 2019

Initial GCN Notice followed by GCN Circular with updated reconstruction

C. Tung NU9b

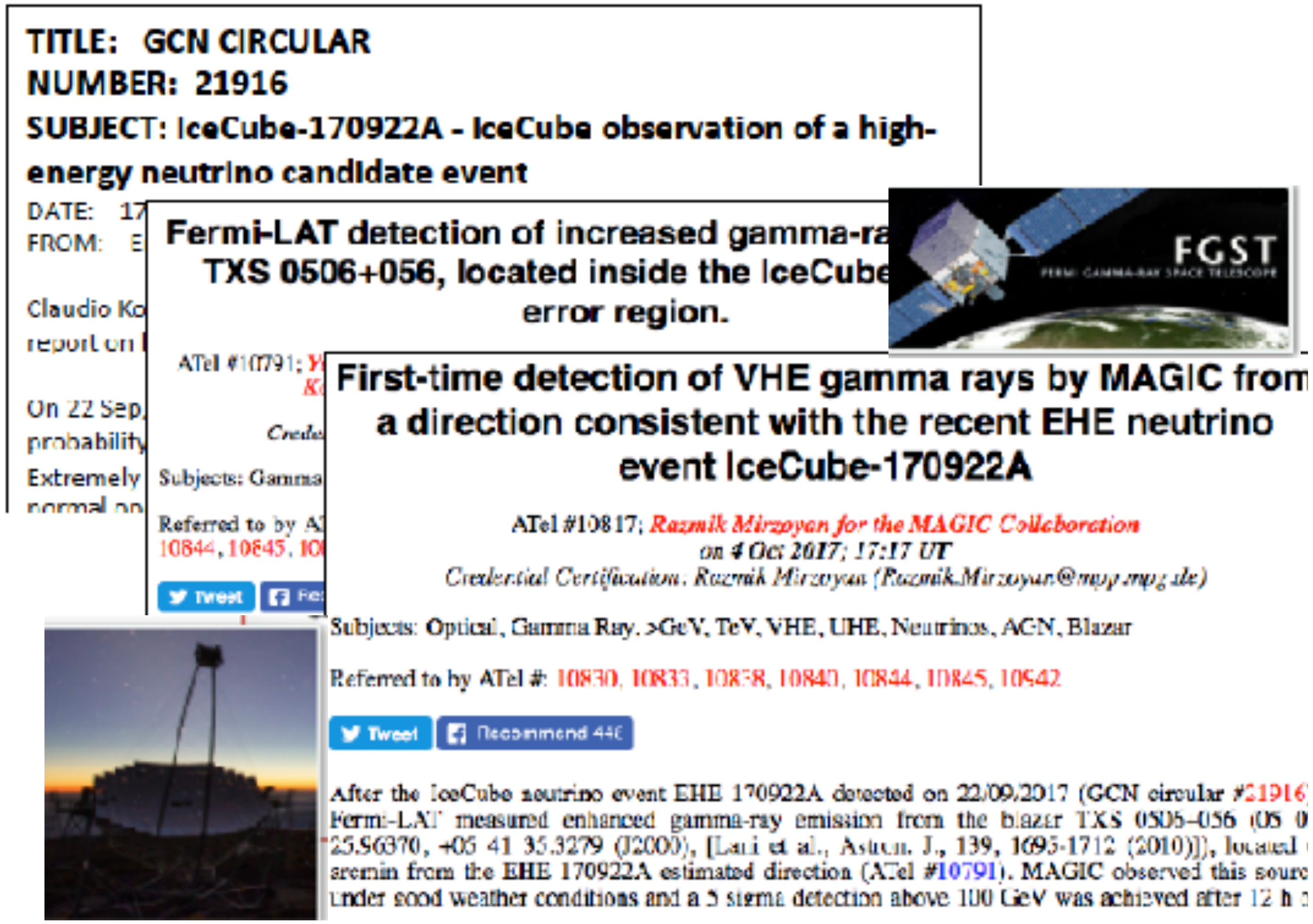
Updated alerts	Gold	Bronze
Signalness	> 50%	>30%
Expected signal/yr	6.6	2.8
Expected bkgd/yr	6.1	14.7



Astropart. Phys. 92 (2017) 30

A&A 607 (2017) A115

IceCube-170922A & TXS 0506+056



Declination [°]

- September 22, 2017: a neutrino alert issued by IceCube
- Fermi-LAT and MAGIC identify a spatially coincident flaring blazar (TXS 0506+056)
- Very active multi-messenger follow-up from radio to γ-rays

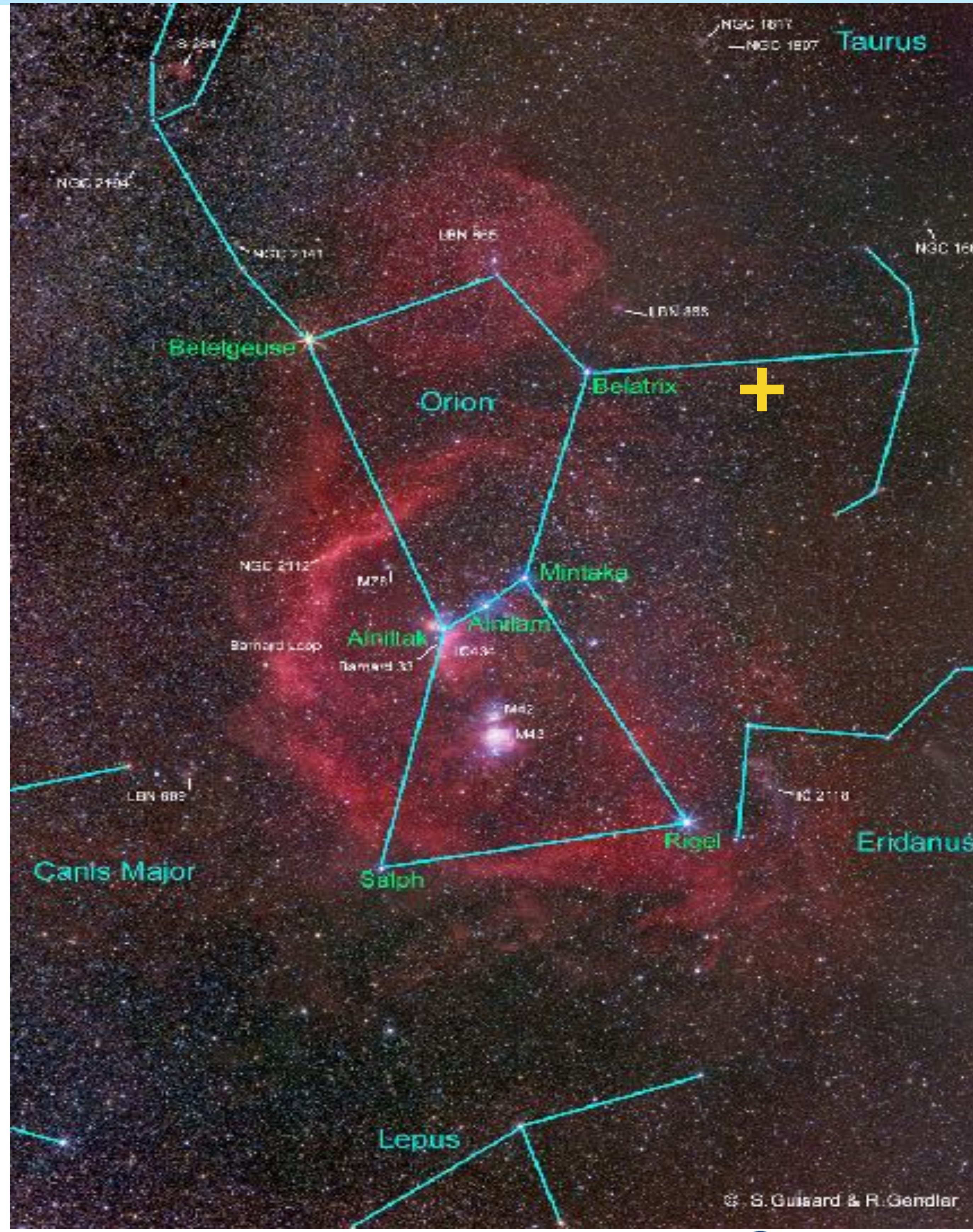
(Science 361, eaat1378 (2018))

IceCube-170922A

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

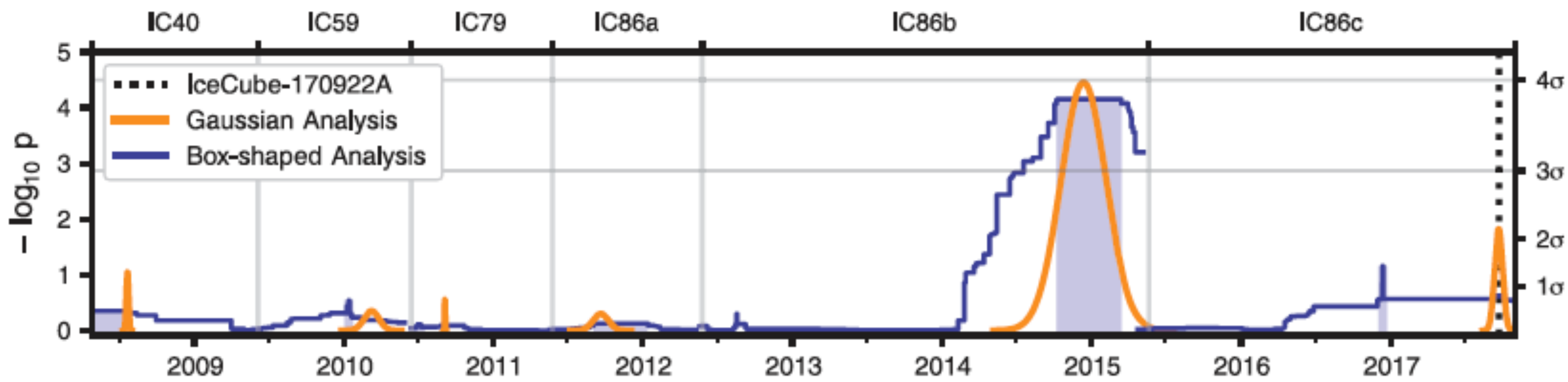
The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift*/*NuSTAR*, VERITAS, and VLA/17B-403 teams*†

- Chance probability of a Fermi-IceCube coincident observation: ~3σ (determined based on the historical IceCube sample and known Fermi-LAT blazars)
- Time-integrated neutrino spectrum is approximately $E^{-2.1}$
- TXS 0506+056 redshift determined to be z=0.3365 (S. Paiano et al. ApJL 854.L32(2018))
- Time-average luminosity about an order of magnitude higher than Mkn 421, Mkn 501, or 1ES 1959+605

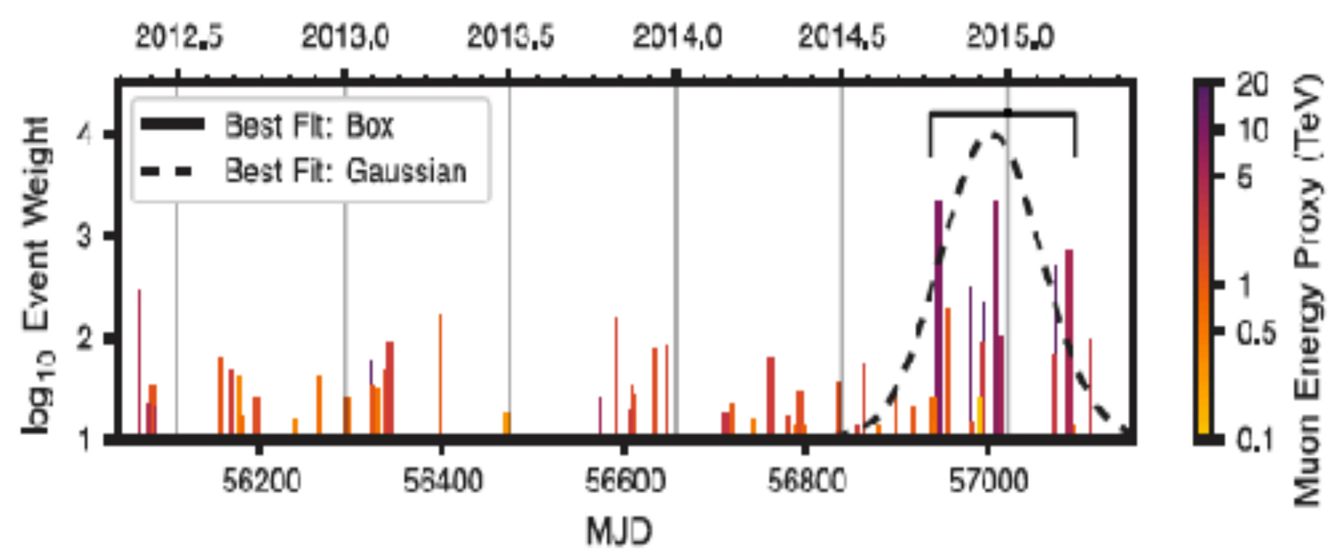


Science 361 (6398), 147-151.

IceCube-170922A



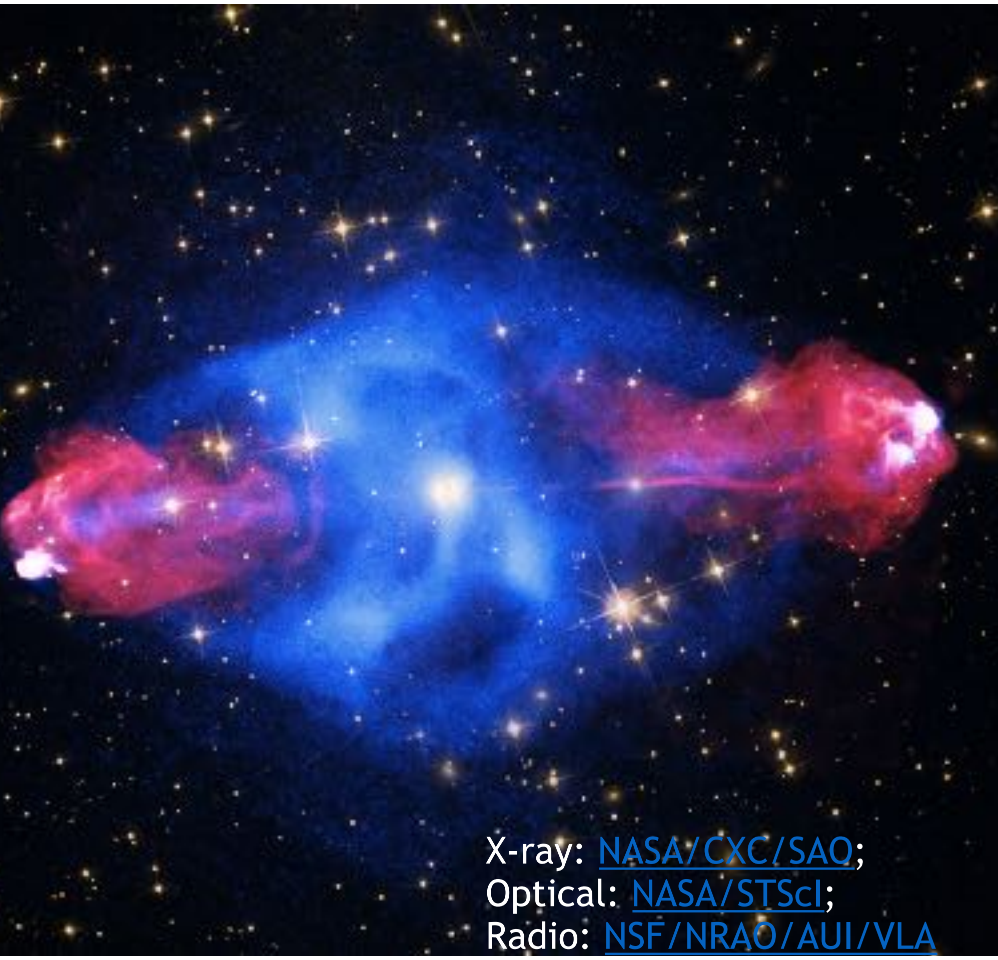
- 9.5 years of archival data was evaluated in direction of TXS 0506+056
- An excess of 13±5 events above background was observed during Sep 2014 - March 2016
- Inconsistent with background only hypothesis at **3.5σ** level (independently of the **3σ** associated with IceCube-170922A alert)

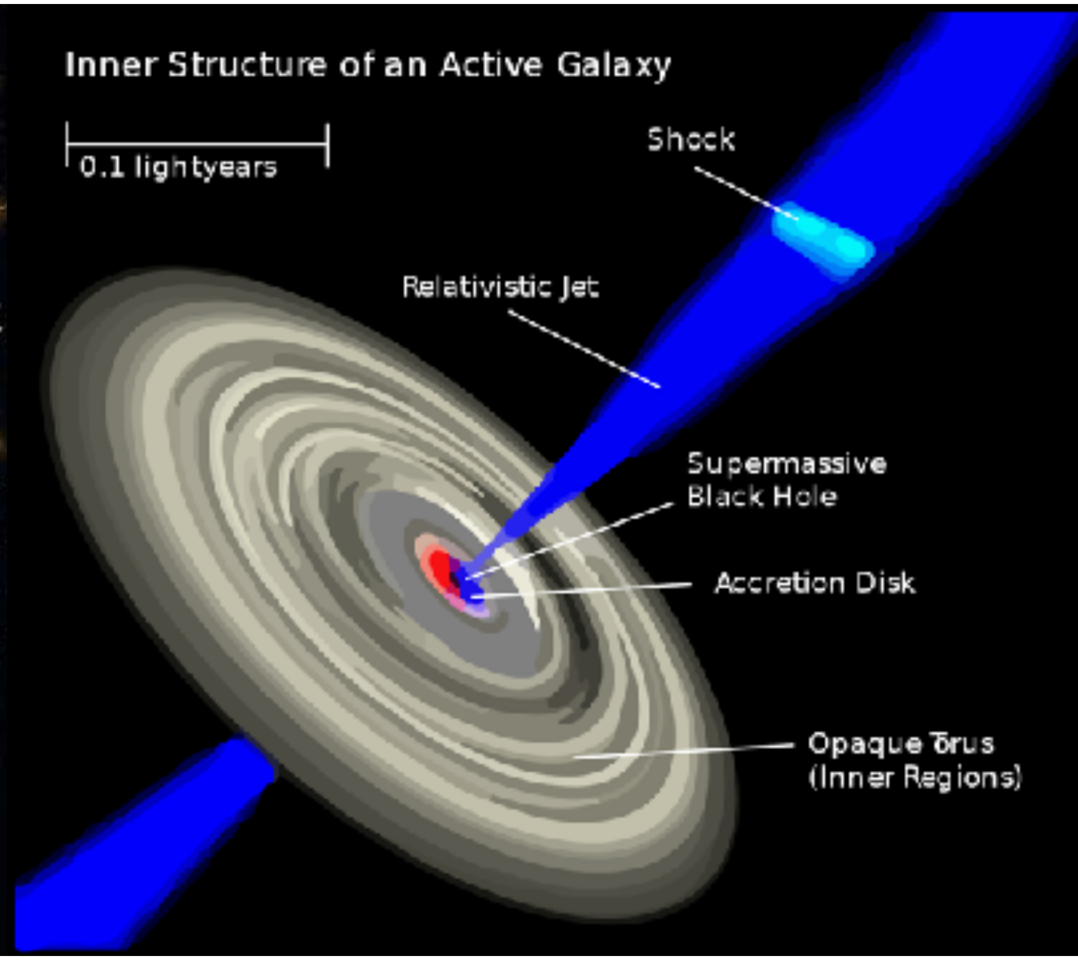


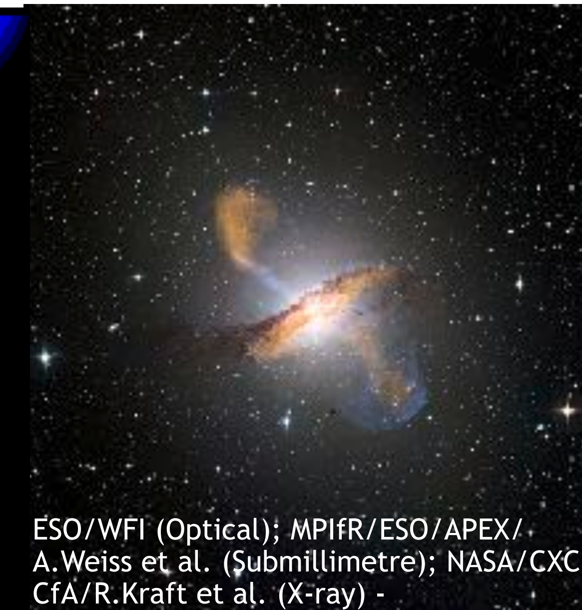
Time-independent weight of individual events during the IC86b period.

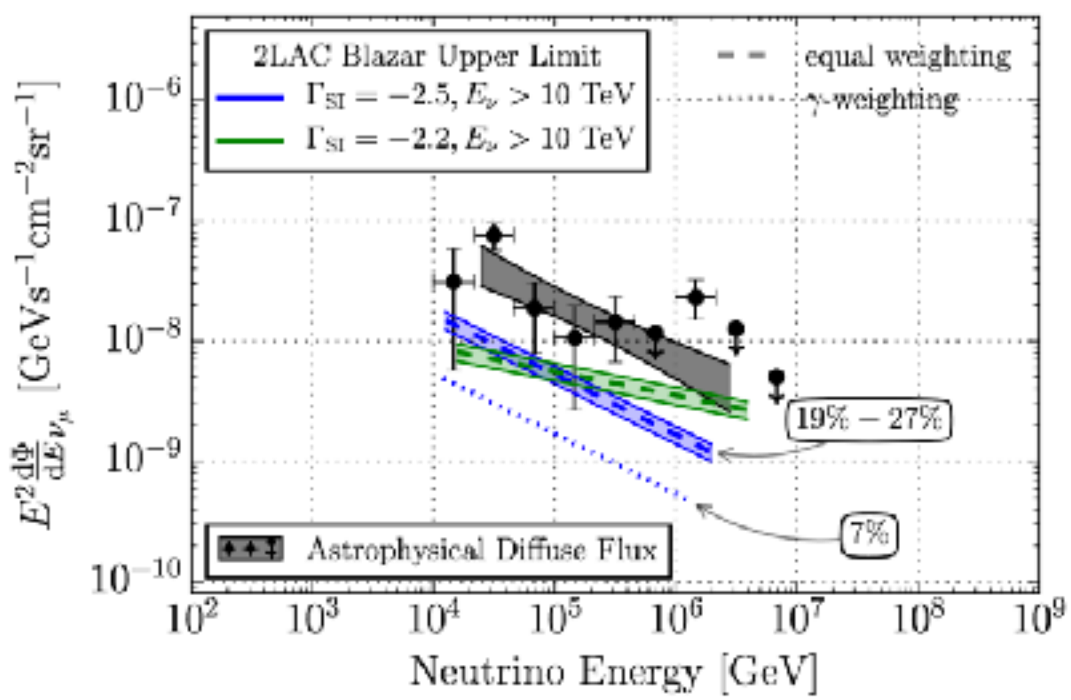
However: Maximum contribution of the 2LAC blazars to the observed astrophysical neutrino flux to be 27% or less between around 10 TeV and 2 PeV [IceCube Astrophys.J. 835 (2017) no.1, 45]

Active Galactic Nuclei: Cosmic Accelerators?









However: Maximum contribution of the 2LAC blazars to the observed astrophysical neutrino flux to be 27% or less between around 10 TeV and 2 PeV [IceCube Astrophys.J. 835 (2017) no.1, 45]

Conclusions/Summary

- We are now able to observe the Universe in fundamentally new ways (using Gravitational Waves, High-energy Neutrinos, Gamma-rays, …)
- Astroparticle and Multi-messenger science has seen dramatic progress over the last years
- Coincidence observation of GW170817 with a GRB
- First compelling evidence of high-energy neutrinos with electromagnetic counterparts (TXS 0506+056)
- Opportunities to discover new phenomena beyond the SM (probe physics at the highest energy scales)
- Entering golden age of multi-messenger astroparticle physics