Astroparticle Physics
Lecture 19

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Recall

- Introductory astro and particle physics
- Detectors and FOMs
- Detector descriptions
- Gamma Ray Astronomy
- Gravitational Waves

This lecture and next

Other CR detectors

Multi messenger astronomy

Statistics for astroparticle physics

The existing detectors

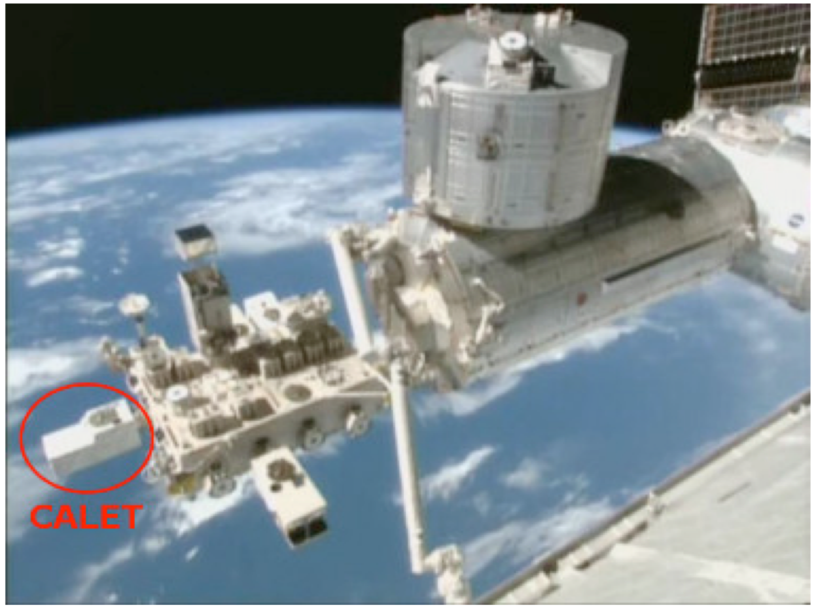
7 ton payload onboard the ISS
Permanent magnet and 8 detectors. TOF detector from scintillation counters, Silicon strip detectors, Ring Imaging Cherenkov Detector, Electromagentic Calorimeter (alternating layers of scintillator fibers and lead foil)
Caliberated in an accelerator beam at CERN

Few antihelium/antihelium-3 events claimed.

Calorimetric detector, no magnet (calibrated in Orbit using the Earth's magnetic field). Order of magnitude higher detection range than AMS-02

DAMPE :
China+Italy+Switzerland

The existing detectors (contd)

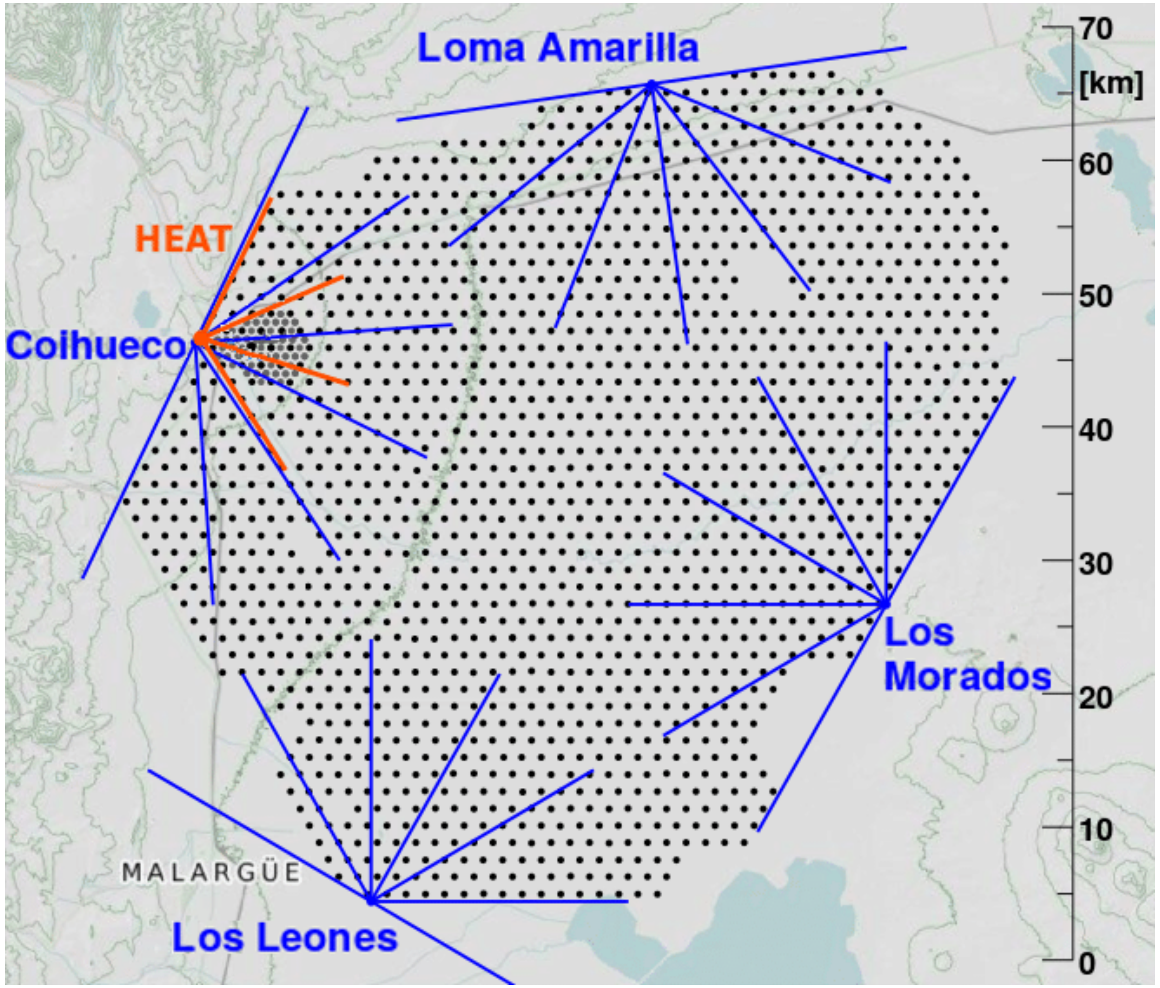


Also on the ISS, 650 kg (JEM Kibo)
Calorimetric, charge identifying detector made of plastic scintillators
3 radiation length thick imaging calorimeter with Tungsten and scintillating fiber layers. Lead Tungstanate Hodoscope. Optimized to measure electron spectrum.

All recent measurements have been made at orbits very close to Earth

Instrument	Weight (kg)	Orbit	Mission duration (years)
AMS-02 (ISS)	6717	Lower Earth	10+
DAMPE	1400	Sun Synchronous	3 (P), 6+
CALET (ISS -JEM Kibo)	650	Lower Earth	6+

Pierre Auger Observatory



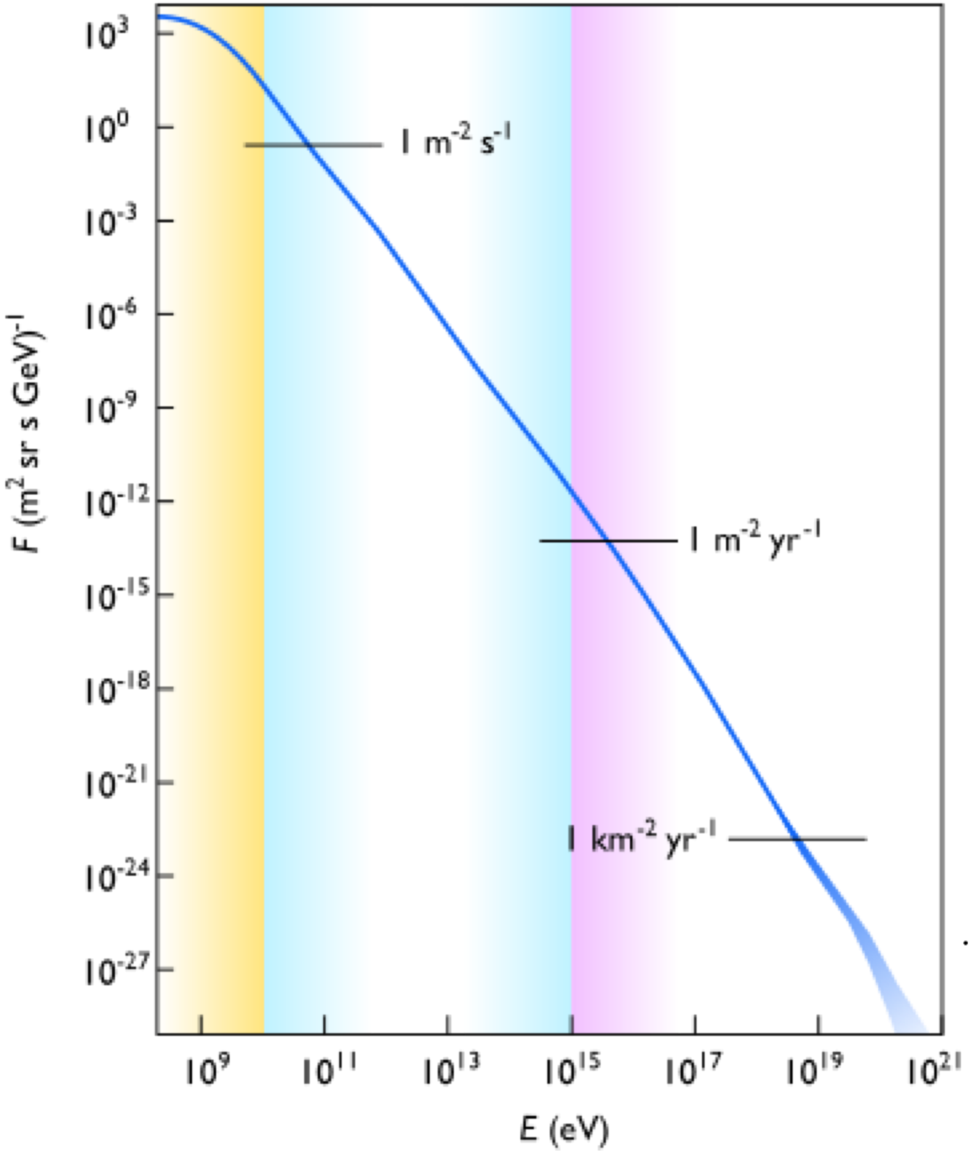
$3000\ km^2$

Surface detectors (Water tank)

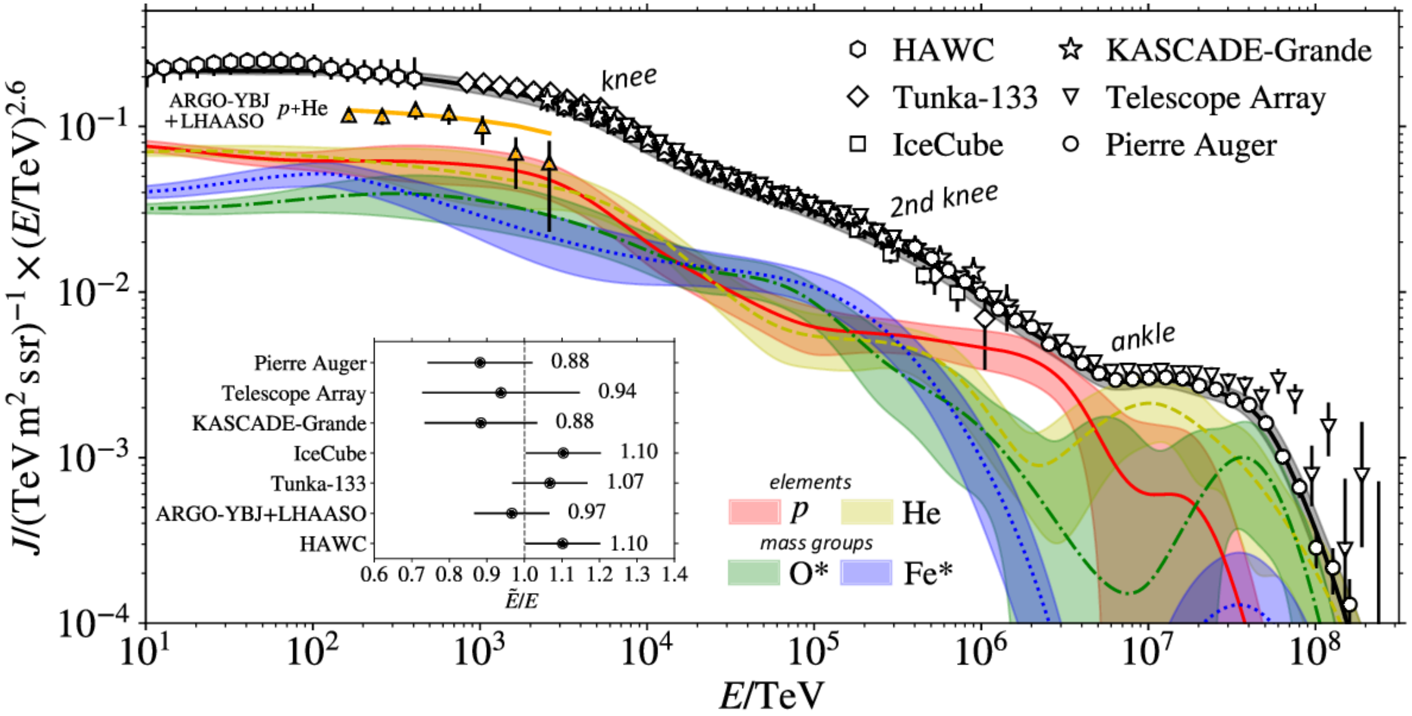
Fluorescence detector

Fly's Eye technique

Taking data since construction (2004) completed in 2008



F (m^2 sr s GeV)^-1
10^3
10^0
10^-3
10^-6
10^-9
10^-12
10^-15
10^-18
10^-21
10^-24
10^-27
1 m^-2 s^-1
1 m^-2 yr^-1
1 km^-2 yr^-1
10^9
10^11
10^13
10^15
10^17
10^19
10^21
E (eV)



J/(TeV m^2 s sr)^-1 × (E/TeV)^2.6
E/TeV
HAWC
Tunka-133
IceCube
KASCADE-Grande
Telescope Array
Pierre Auger
knee
2nd knee
ankle
ARGO-YBJ +LHAASO p+He
Pierre Auger 0.88
Telescope Array 0.94
KASCADE-Grande 0.88
IceCube 1.10
Tunka-133 1.07
ARGO-YBJ+LHAASO 0.97
HAWC 1.10
Ẽ/E
elements
p
He
mass groups
O*
Fe*

Fermi Gamma ray space telescope

The LAT, a pair conversion instrument detecting photons between 20 MeV and ~300 GeV. 20% sky coverage

The GBM - 14 scintillator detectors with 150 keV to 30 MeV, full sky coverage

Low circular orbit with 95 minute period
Looks away from Earth
Covers the entire sky ~16 times per day.

Multi-messenger Astronomy

Photons

>1 cm ~1 mm ~10 µm ~1 nm <0.1 nm

10^{-6} eV 10^{-4} eV 10^{-1} eV ~1 KeV > 100 KeV

Pulsars, quasars, radio galaxies The Big Bang (CMB) Non thermal processes

Cosmic Rays

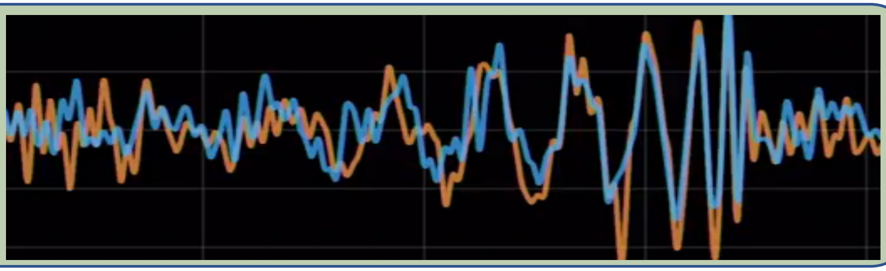
Electrons, protons, heavy nuclei : 10^{8} - 10^{20} eV – Origins unknown. Observed first by Victor Hess in 1912

Gravitational Waves

Predicted by General relativity – Observed first in 2015

BH-BH merger ~410 Mpc away.

Phys. Rev. Lett. 116 (6): 061102

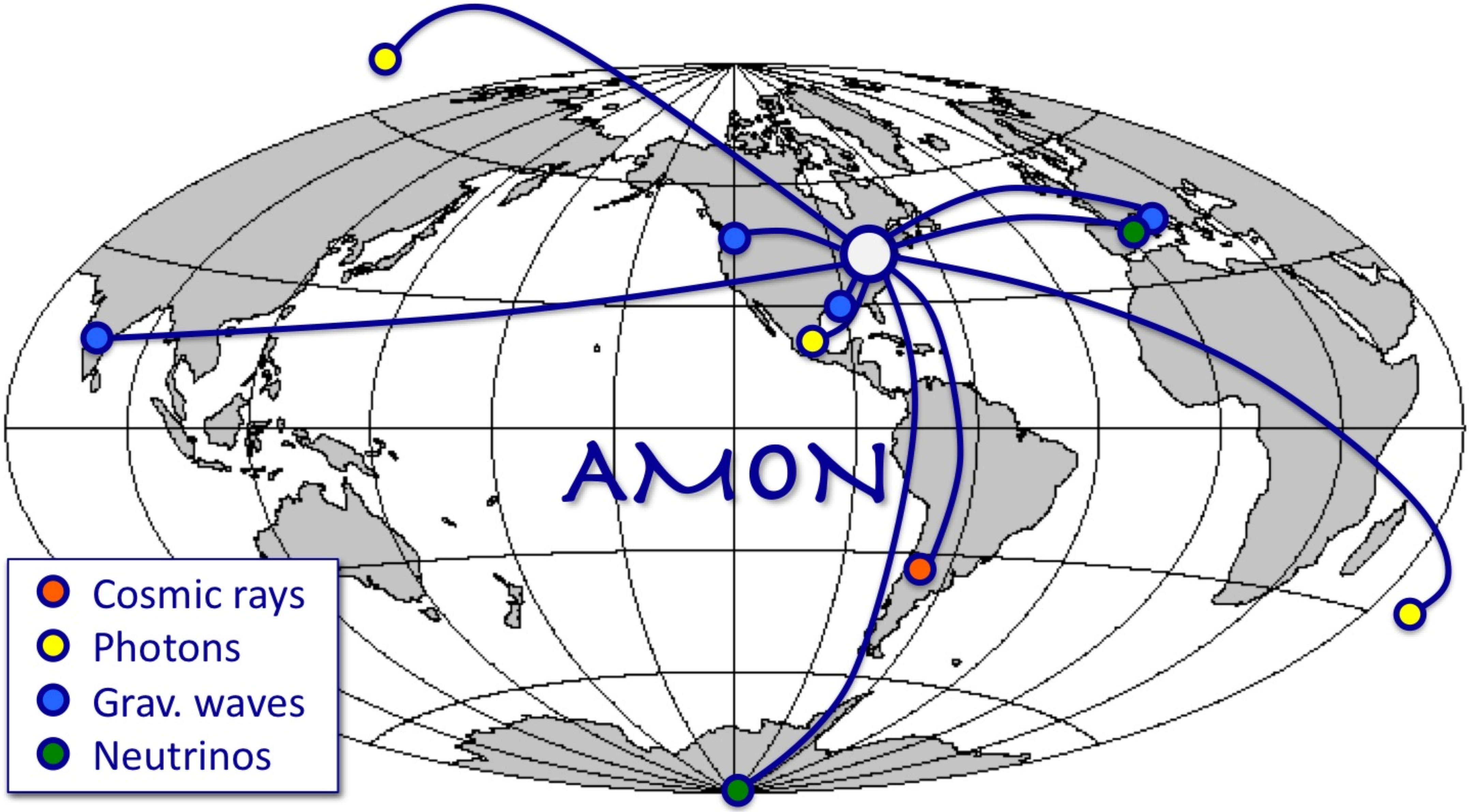


Neutrinos

Proposed by Pauli in 1931, detected by Reines and Cowan in 1959, neutral, weakly interacting.

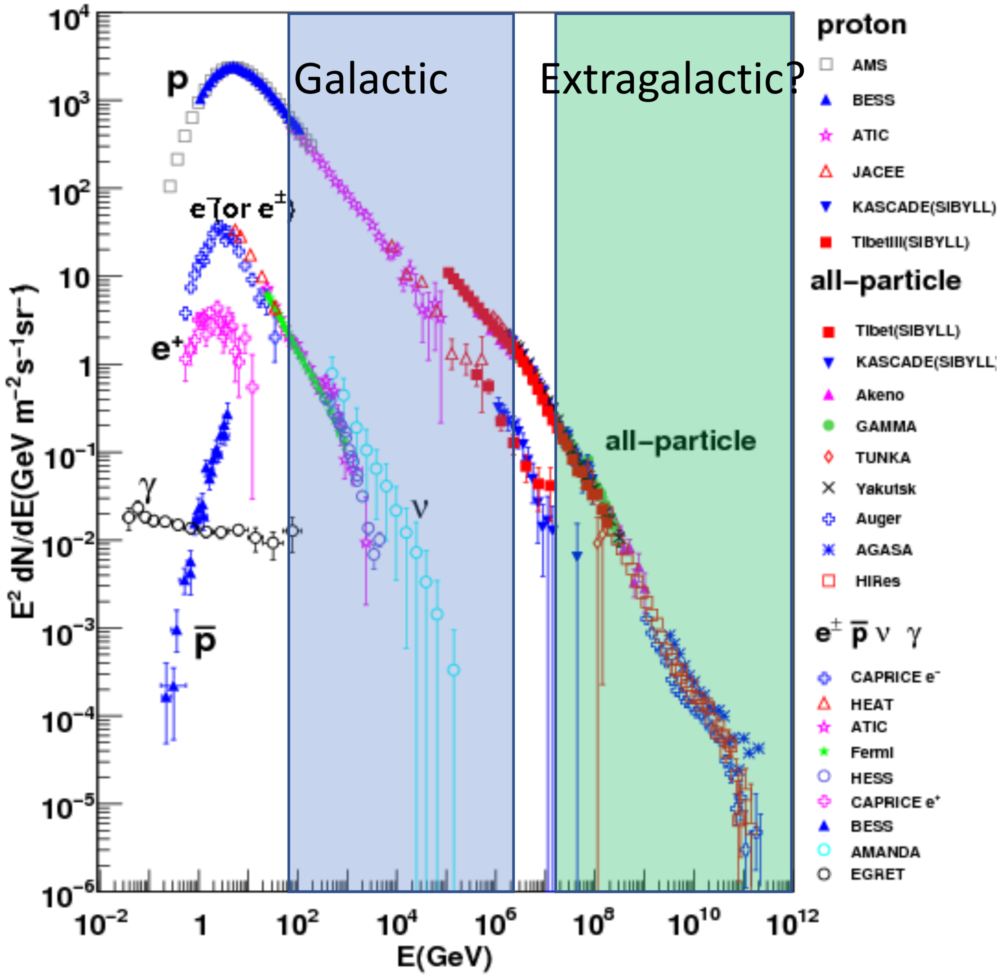
The Sun, SN1987 A – 10 MeV, TXS0506+056, NGC4096

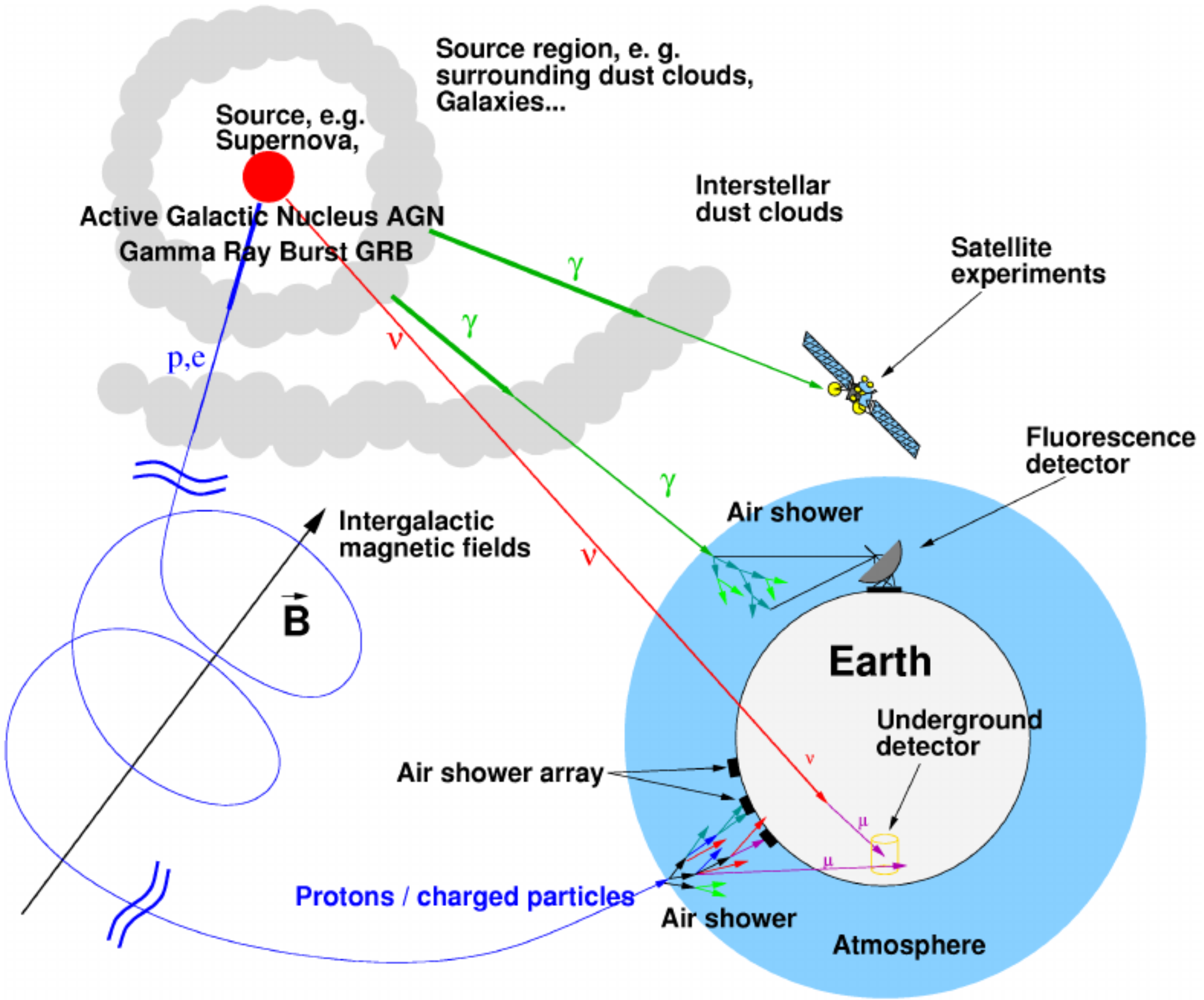
Diffuse astrophysical flux >50 TeV



https://www.amon.psu.edu/

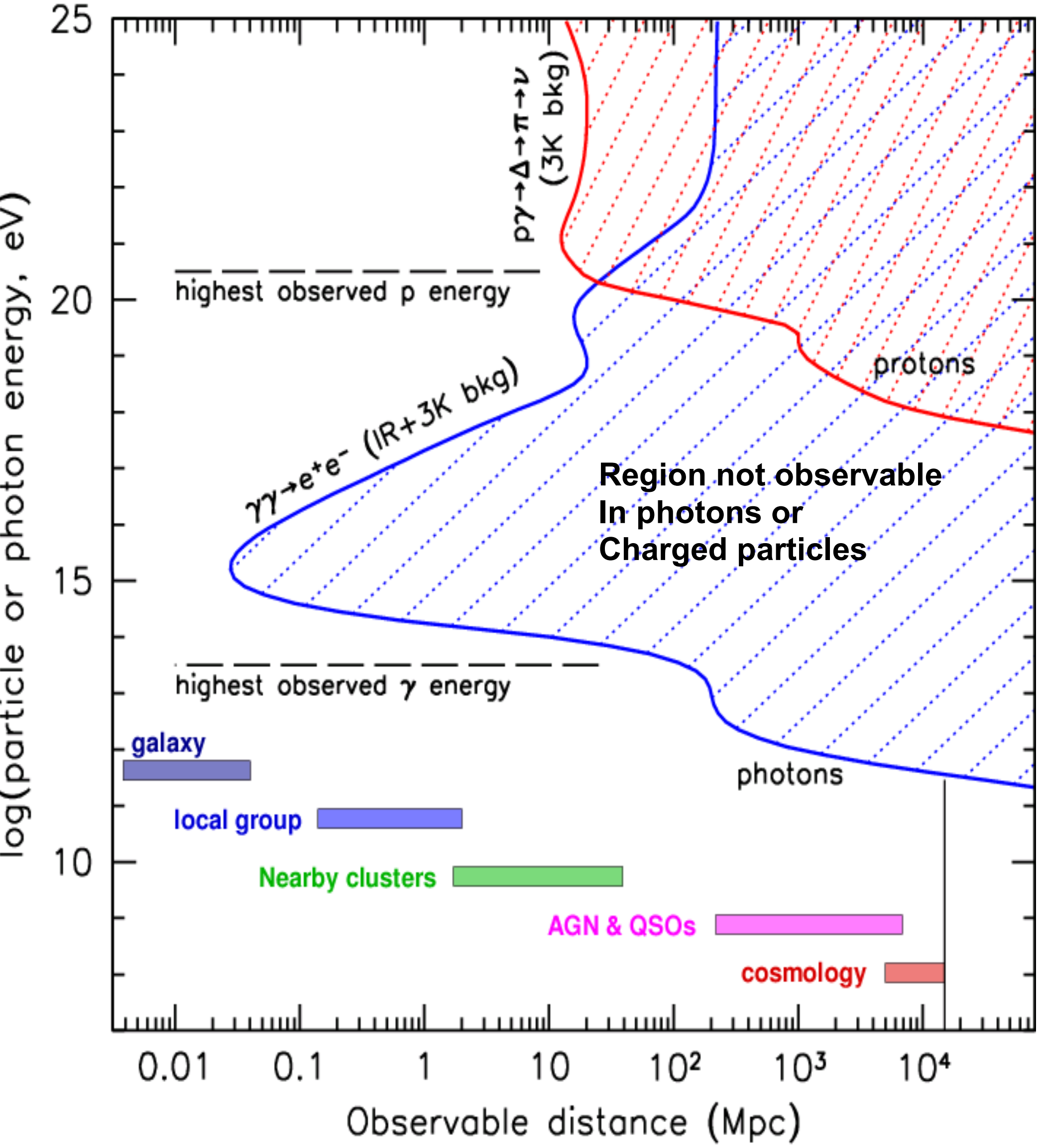
Multi messenger astronomy





Where do CRs come from? Neutrinos can tell

The messenger horizon



γ-rays do not travel too far

- 1 TeV : Closest AGNs

CRs cannot point back

- Deflection : few degrees at ~50 EeV
- Horizon ~100 MPc – interactions with CMB

The neutrino Neutral, undeflected

  – can point back

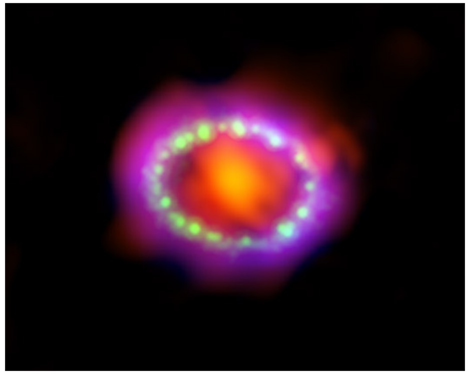
- Interacts only weakly

  – can travel Gpc distances

  – hard to detect

- We hope to see
  - The sites of CR acceleration
  - Dark Matter annihilation

Multimessenger observations so far



<u>The Sun</u>
photons – cosmic rays - Neutrinos

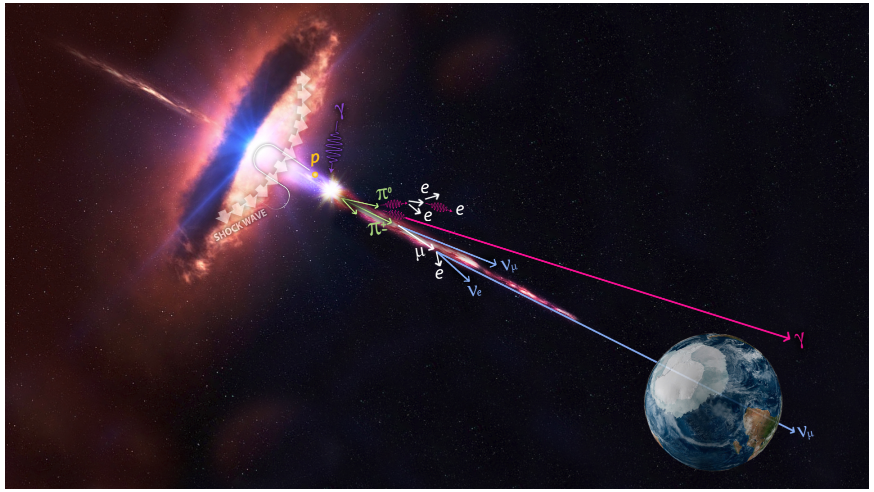
<u>The Moon</u>
Photons - CR deficit (moon shadow)

<u>SN1987A - Type 2 supernova in the Large Magellanic Cloud</u>
Photons, neutrinos (no directionality)

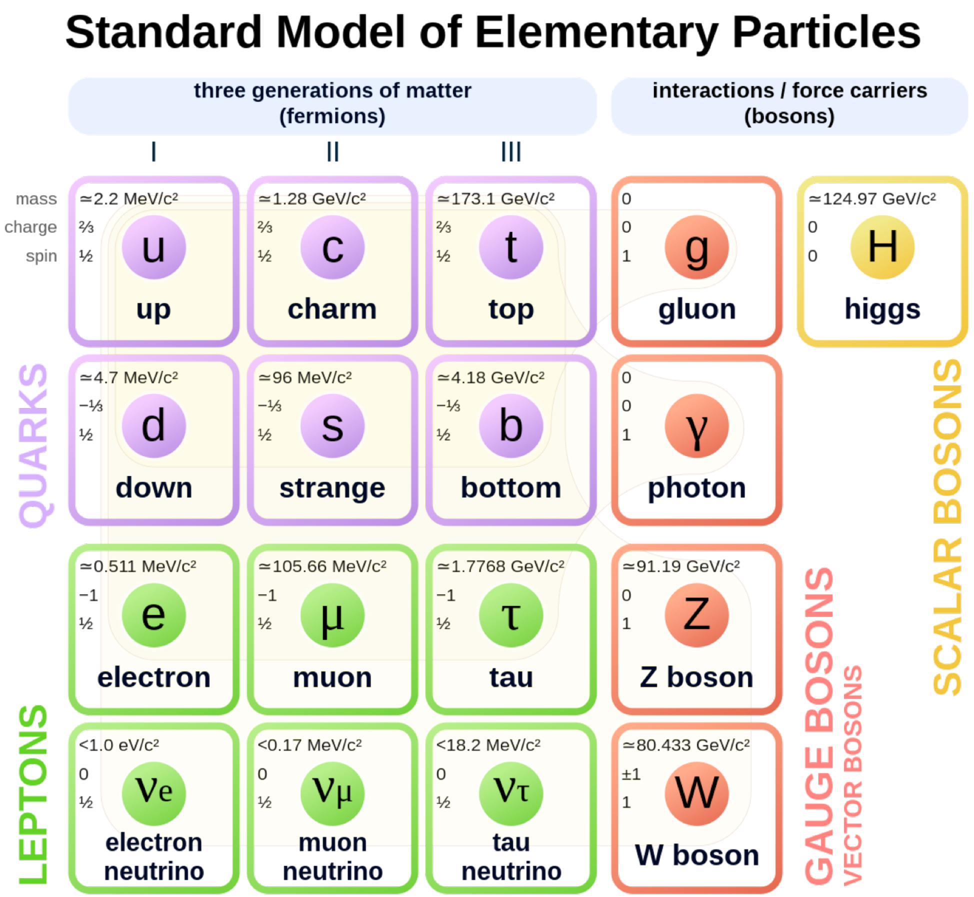
<u>Binary Neutron Star Merger on 17th August 2017</u>
Photons, Gravitational Waves

<u>TXS 0506+056 Blazar</u>
Photons, Neutrinos

NGC 1068, Active Galactic Nuclei
Photons, Neutrinos

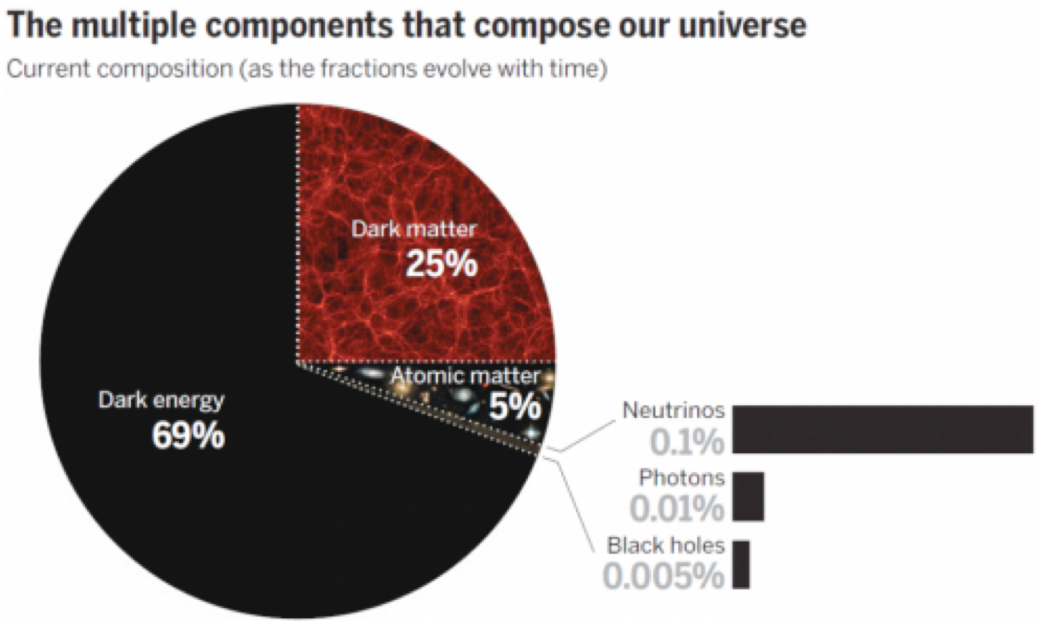


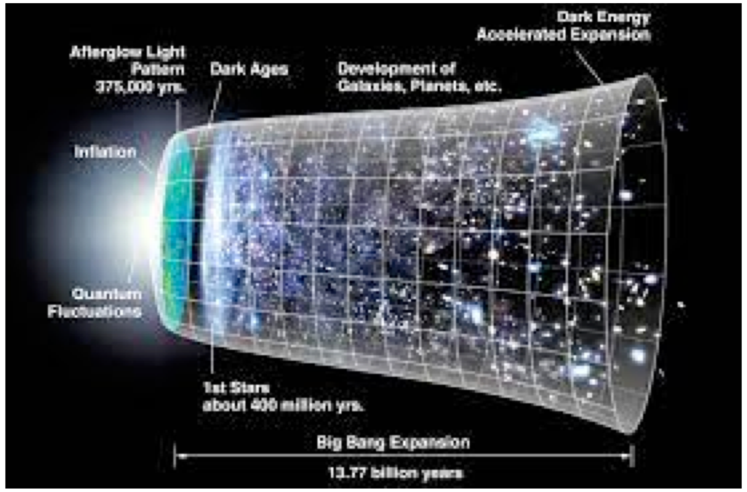
Some statistics



Frequentist statistics

Repeatable experiments





Bayesian statistics (Bayes theorem)

How statistics is used

Hypothesis testing

Point estimation

Confidence Interval estimation

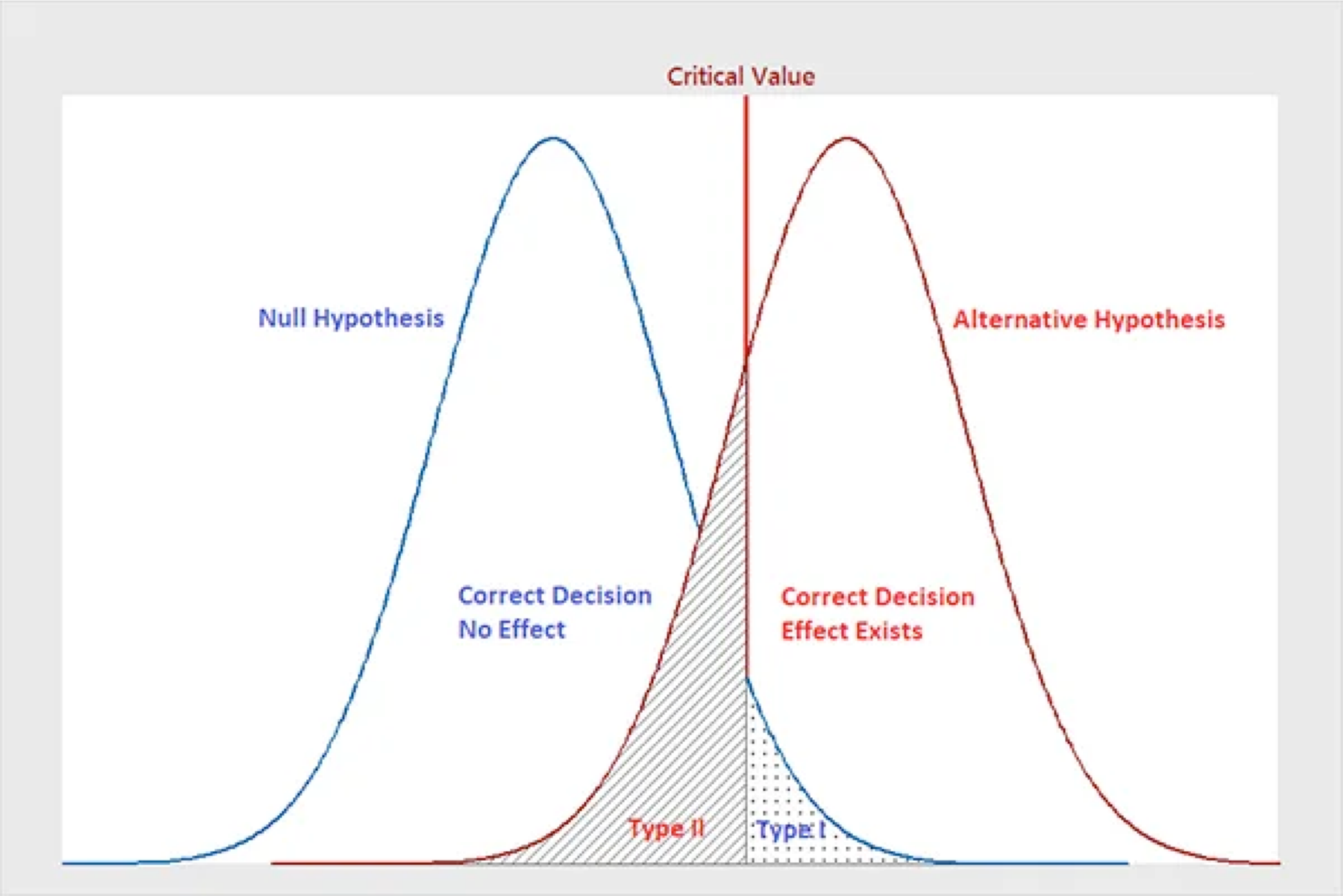
Goodness of fit testing

Model selection

Decision theory

Type I and Type II Error

Null hypothesis is ...	True	False
Rejected	Type I error False positive Probability = α	Correct decision True positive Probability = $1 - \beta$
Not rejected	Correct decision True negative Probability = $1 - \alpha$	Type II error False negative Probability = β


Critical Value
Null Hypothesis
Alternative Hypothesis
Correct Decision
No Effect
Correct Decision
Effect Exists
Type II
Type I

The Definition of the Probability

- For most of the talk: Define Probability P of X as

$$P(X) = N(X)/N \quad \text{for} \quad N \to \infty$$

  Examples: coins, dice, cards

- For continuous x extend to Probability Density

$$P(x \,\text{to}\, x + \mathrm{d}x) = p(x)\mathrm{d}x$$

  $p(x)$ is the *probability density function (pdf)*

- Examples:
  - Measuring continuous quantities ($p(x)$ often Gaussian, Poisson, ...)
  - Counting rates
  - Physical Quantities: Parton momentum fractions (proton pdfs) ...

- Alternative: Define Probability $P(X)$ as "degree of belief that X is true"

The Likelihood

- Probability distribution of random variable x often depends on some parameter a
- Joint function $p(x, a)$:
  - Considered as $p(x)|a$ this is the pdf.
  - Normalised: $\int p(x)\mathrm{d}x = 1$
  - Considered as $p(a)|x$ this is the Likelihood $L(a)$ (or $\mathcal{L}(a)$)
  - Not "likelihood of a" but "likelihood that a would give x"
  - Not normalised. Indeed, must never be integrated.
- This is going to be one of the central concepts/quantities for the rest of the talk
- If we want to know a parameter a, we are looking for the point where the likelihood that a would predict the data x is maximized
- If we want to test a Hypothesis H_0 against another one (H_1), we want to compare their likelihoods
- If we want to know what a cannot be, we want to know where $\mathcal{L}(a)|x$ is small

Frequentist Reasoning

It's pretty simple, I think:

- Probability of an event is the relative frequency of its occurrence
- Need something which (at least in a simulation) can in principle repeated indefinitely, otherwise there exists no probability
- Since the universe can't be repeated (we don't know how to simulate its genesis before the big bang): there exists no probability density in theory/parameter space
- Therefore, the only statements we can make are:
  If theory H is true (which we will *never* know), then the probability of the observed outcome D of our experiment $P(D|H)$ is . . .

Frequentist Reasoning: Examples

- Can't say
  "It will probably rain tomorrow."
  There is only one tomorrow. P is either 1 or 0
- Have to say
  "The statement 'It will rain tomorrow.' is probably true."
  Can then even quantify (meteorology).

Frequentist Reasoning: Examples for interpeting physics results

- Can't say
  "m_t has a 68% probability of lying between 171 and 175 GeV"
- Have to say "The statement 'm_t lies between 171 and 175 GeV' has a 68% probability of being true"
- Be aware:
  - In this context, a certain value of m_t has no probability. It is either true or false.
  - But the interval $[171, 175]$ depends on the data and does fluctuate. If you repeat the experiment, you will get different intervals each time, and 68% of them should cover the invariant true value.
- if you always say a value lies within its error bars, you will be right 68% of the time
- Say "m_t lies between 171 and 175 GeV" with 68% Confidence. Or 169 to 177 with 95% confidence.
- That is the Confidence Level CL

Bayesian Reasoning

- Mathematically, Bayes theorem is unquestioned and simple:

$$P(H|D) = \frac{P(D|H)}{P(D)} P(H)$$

$$P(D) = \sum_{i=1}^{i<n} P(D|H_i) P(H_i)$$

with

  - $P(H|D)$: "Posterior", belief in H given D
  - $P(D|H)$: "Likelihood", probability of D given H
  - $P(H)$: "Prior" belief in H, given nothing
  - $P(D)$: "Evidence": believe in D, given all possible hypotheses H

Bayesian Reasoning – oh, why?

- Given this – in my very personal view – philosophical mess: Why is it used by many people?

Stolen from Ben Farmer and Martin White

- $P(\text{ball under cup i}) = P(i) = 1/1000$
  Assume we looked under 999 cups. No ball found (D)!

$$P(1000|D) = \frac{P(D|1000)}{\sum_{i=1}^{i\leq 1000} P(D,i)P(i)} P(1000)$$

$$P(1000|D) = \frac{1}{999 \times 0 + 1 \times 1/1000} \times \frac{1}{1000} = 1$$

- In an "experiment" where the "theory" consists of a fixed number of individually testable basic theorems this is fine.

Bayesian Reasoning – why not?

- Can we apply this to the belief in the CMSSM parameter point x?

$$P(CMSSM\,x|D) = \frac{P(D|CMSSM\,x)}{\sum_{i=1}^{\infty} P(D|CMSSM\,i)P(CMSSM\,i)} P(CMSSM\,x)$$

  no, we clearly can't; We can't execute the sum, and we don't know anything about $P(CMSSM\,x)$, it does not exist for philosophical reasons! Our theories are *never* finite sums of basic theorems

- So can we apply it to answer the question: How unlikely did the CMSSM become relative to the SM, given that we found no SUSY?

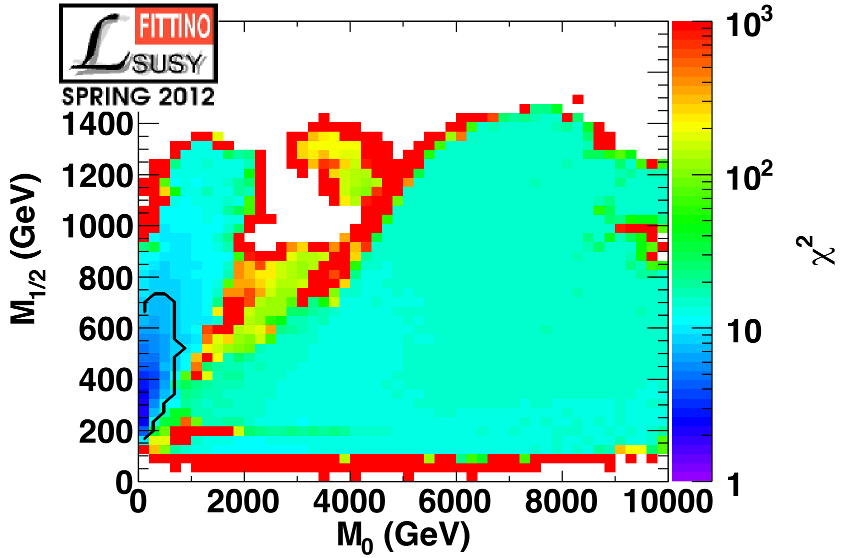
$$\frac{P(CMSSM|D)}{P(SM|D)} = \frac{P(D|CMSSM)}{P(D|SM)} \frac{P(CMSSM)}{P(SM)}$$

  It looks like we at least could say something about how the present data D modifies our prior belief in the CMSSM and the SM

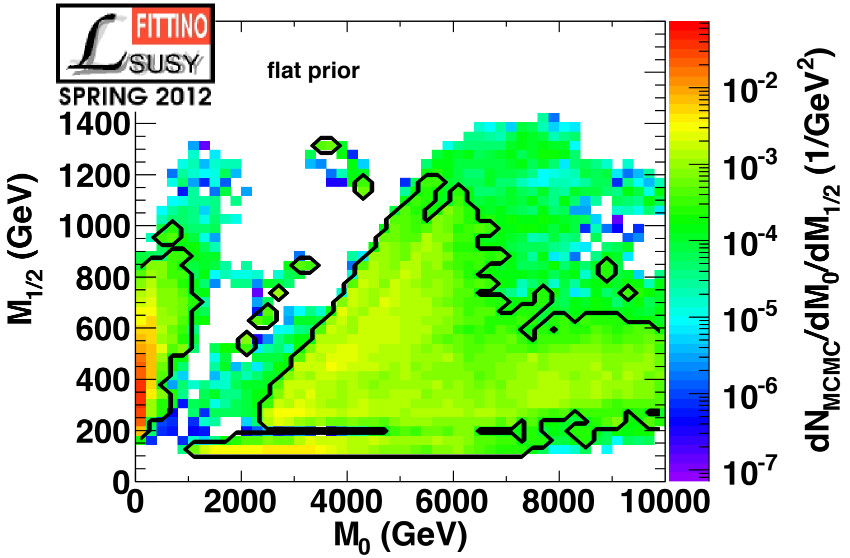
- Well, actually no:

$$P(D|CMSSM) = \prod_i \int_{\theta_i} P(D|CMSSM\,\theta_i)P(CMSSM\,\theta_i)\mathrm{d}\theta_i$$

Examples for Frequentist and Bayesian Interpretations



Frequentist Profile Likelihood



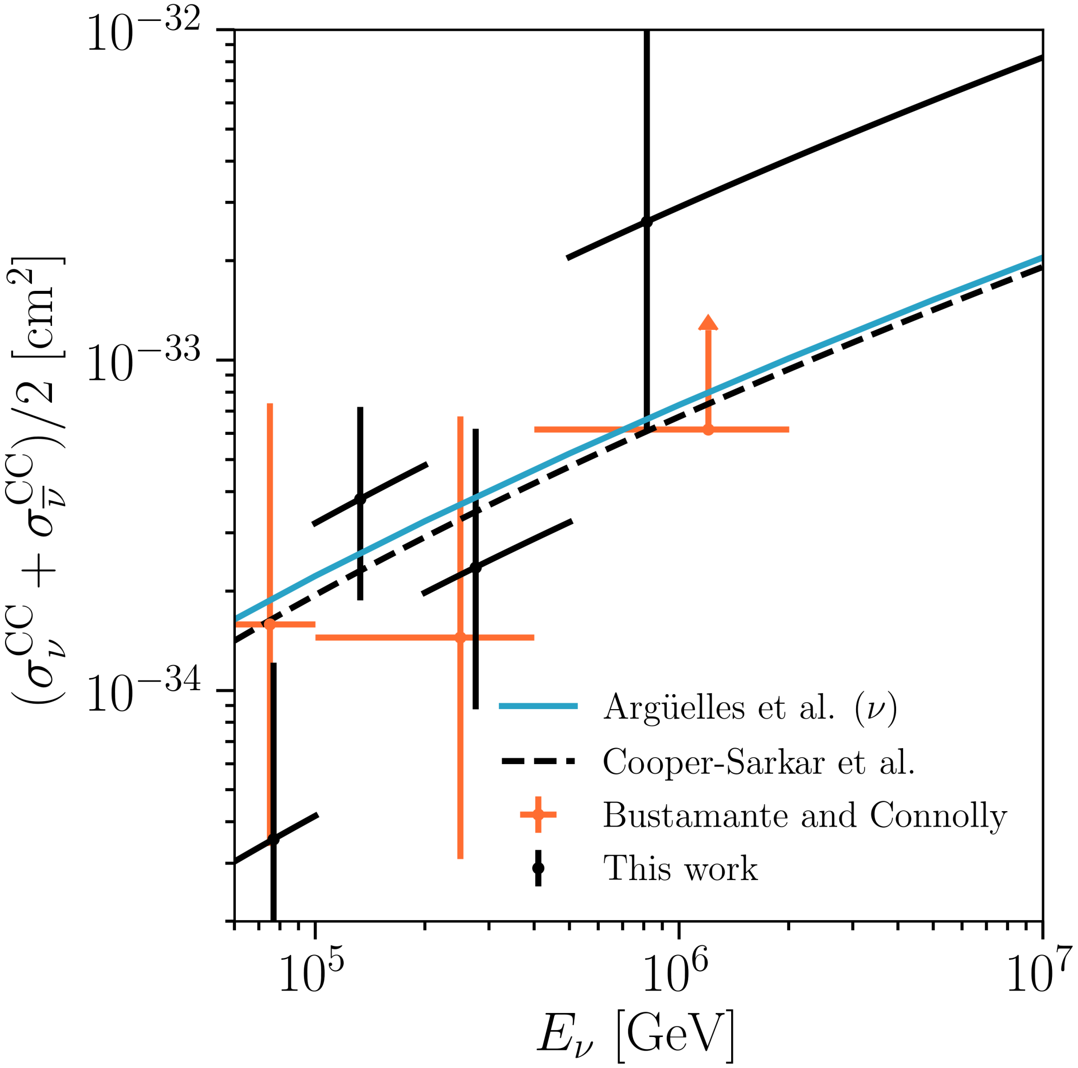
Bayesian, Flat prior

- Quantify the agreement between each model point and the data:

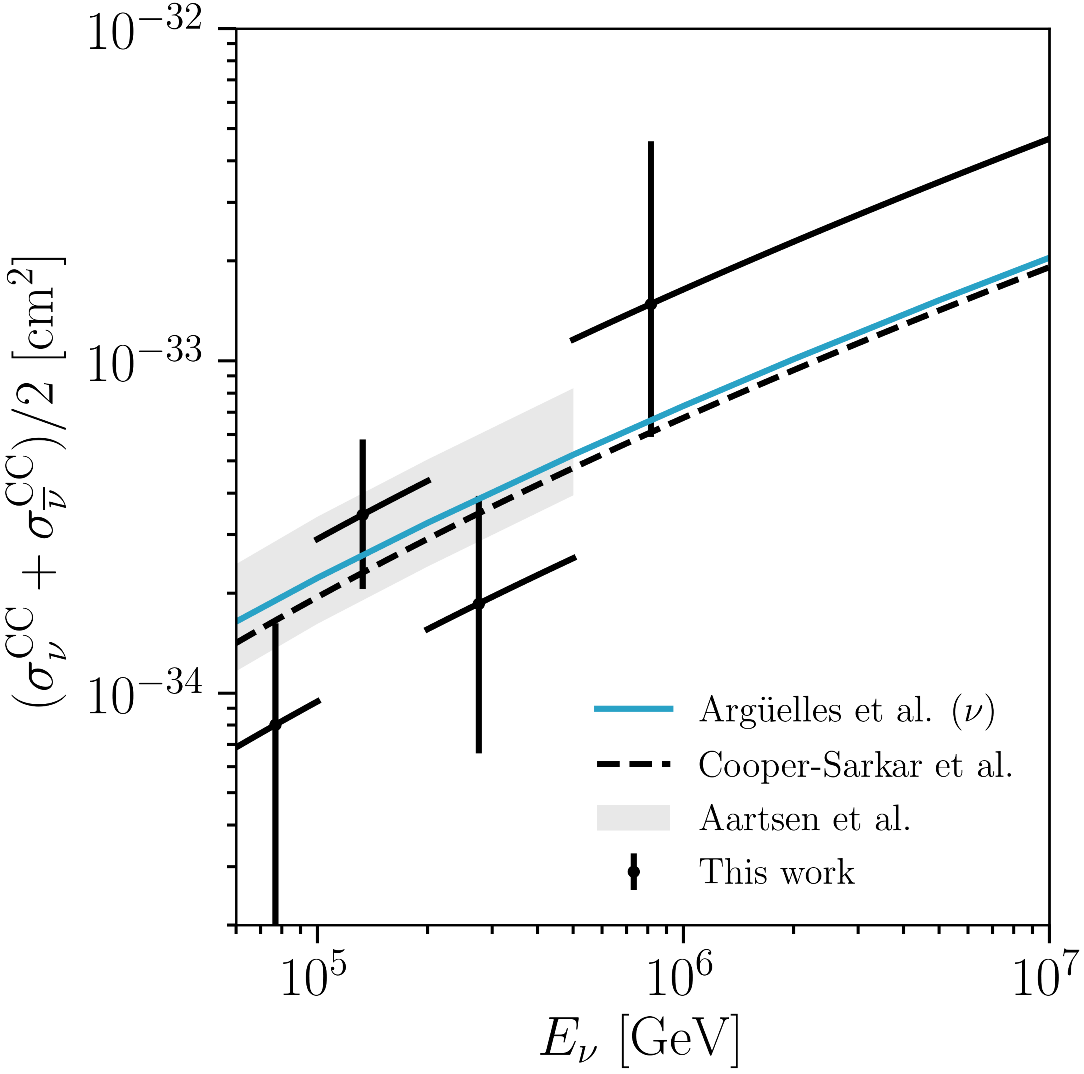
$$\chi^2 = \sum_{i=1}^{n_{Obs}} \frac{(M_i - O_i(\vec{P}))^2}{\sigma_i^2} + Constraints$$

- Advanced MCMC scans with automatically adapting proposal density width

Phys. Rev. D 104, 022001 (2021)



Bayesian higher posterior density credible interval



Frequentist confidence intervals

Neyman Construction

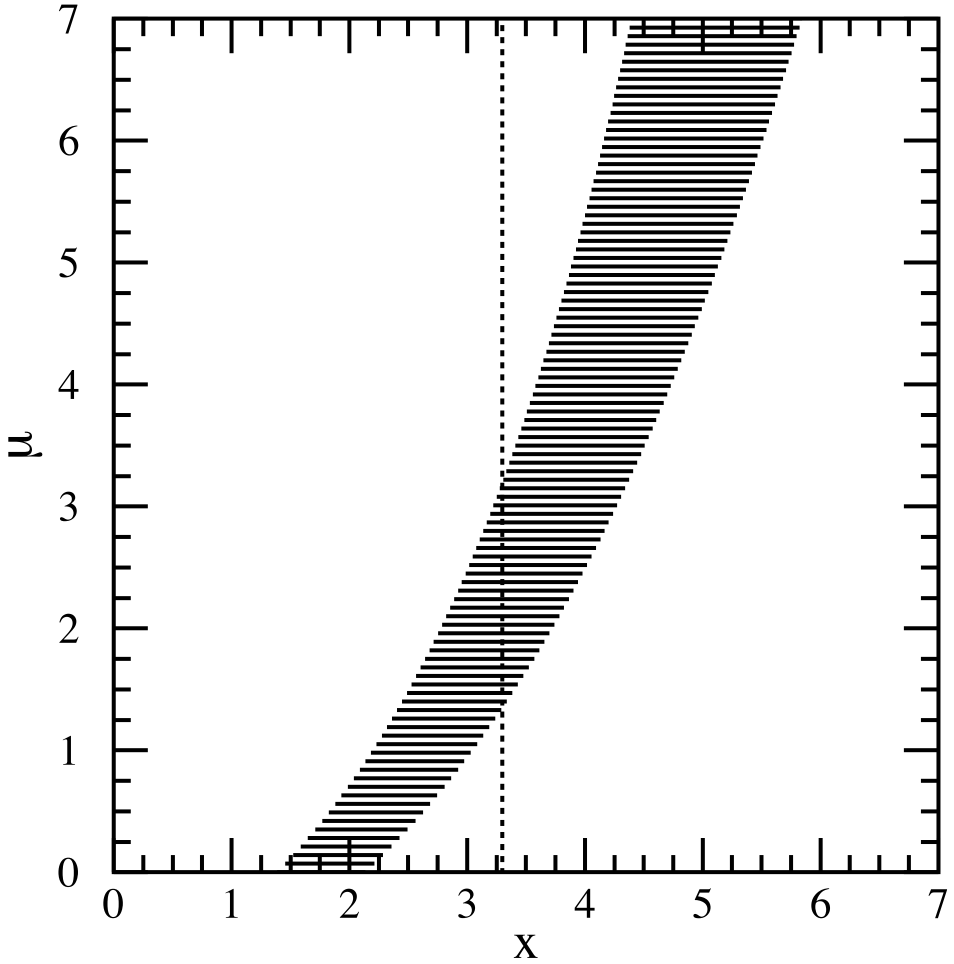


FIG. 1. A generic confidence belt construction and its use. For each value of μ, one draws a horizontal acceptance interval $[x_1, x_2]$ such that $P(x \in [x_1, x_2] \,|\mu) = \alpha$. Upon performing an experiment to measure x and obtaining the value x_0, one draws the dashed vertical line through x_0. The confidence interval $[\mu_1, \mu_2]$ is the union of all values of μ for which the corresponding acceptance interval is intercepted by the vertical line.

Gaussian case, we say that the intervals cover μ at the stated confidence

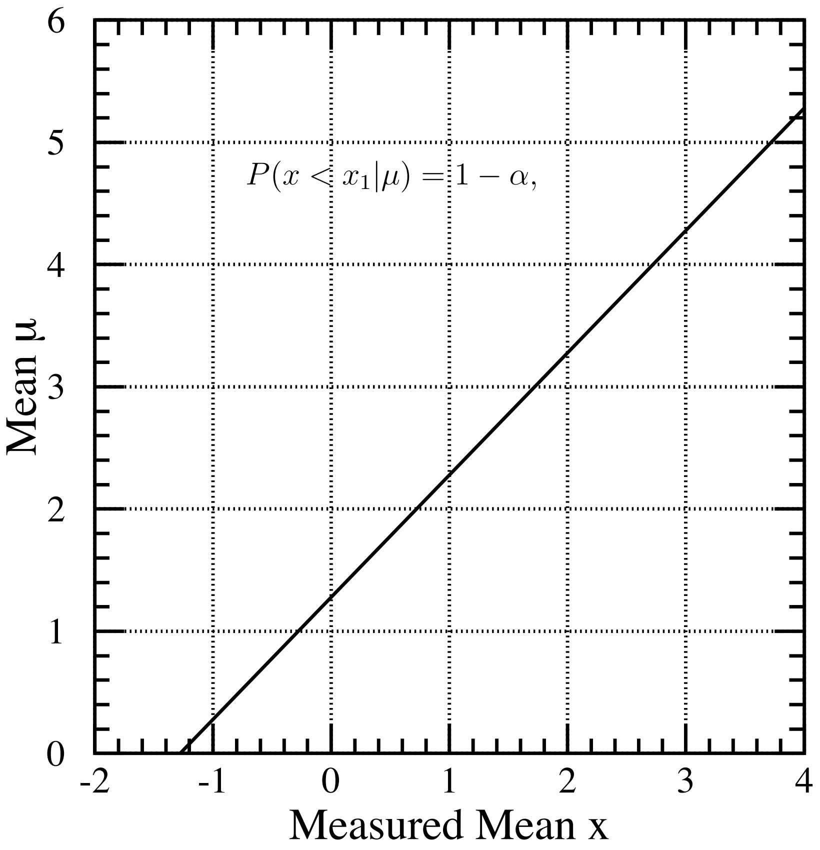


FIG. 2. Standard confidence belt for 90% C.L. upper limits for the mean of a Gaussian, in units of the rms deviation. The second line in the belt is at $x = +\infty$.

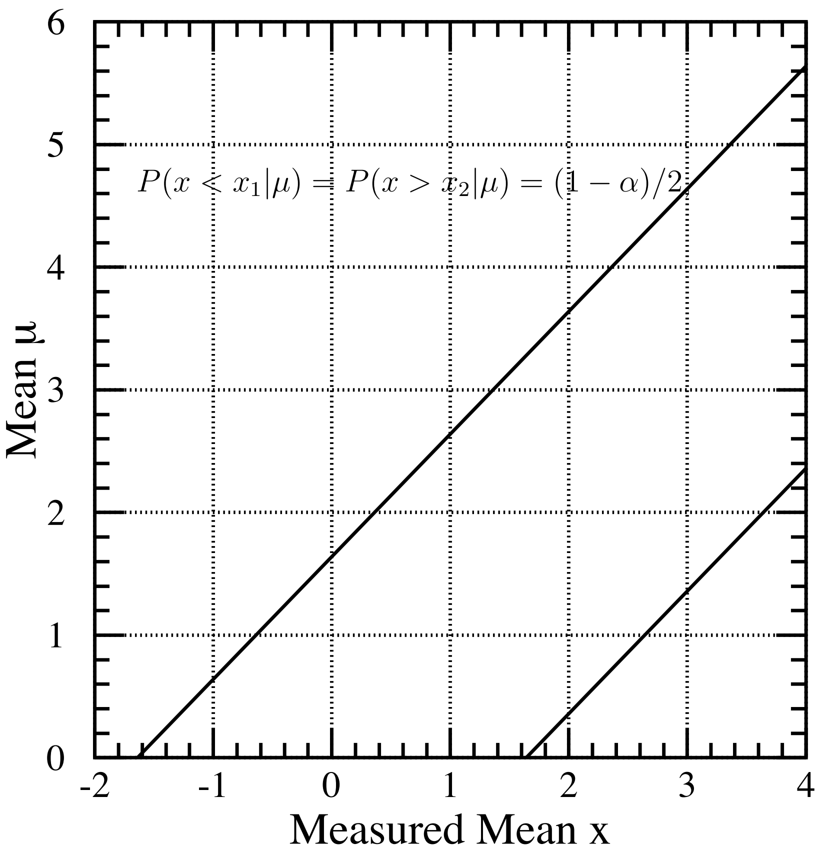


FIG. 3. Standard confidence belt for 90% C.L. central confidence intervals for the mean of a Gaussian, in units of the rms deviation.

When should you give a central interval and when an upper limit?

Let us suppose, for example, that Physicist X takes the following attitude in an experiment designed to measure a small quantity: "If the result x is less then 3σ, I will state an upper limit from the standard tables. If the result is greater than 3σ, I will state a central confidence interval from the standard tables." We call this policy "flip-flopping" based on the data. Furthermore, Physicist X may say, "If my measured value of a physically positive quantity is negative, I will pretend that I measured zero when quoting a confidence interval", which introduces some conservatism.

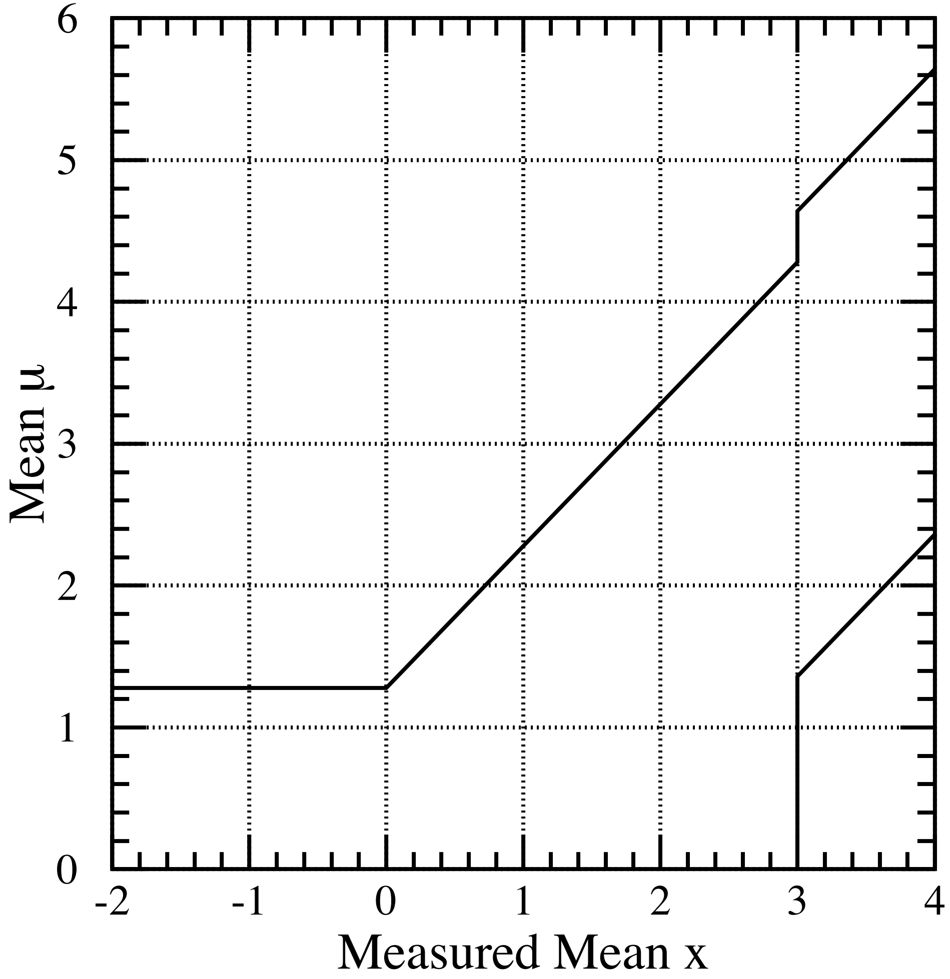


FIG. 4. Plot of confidence belts implicitly used for 90% C.L. confidence intervals (vertical intervals between the belts) quoted by flip-flopping Physicist X, described in the text. They are not valid confidence belts, since they can cover the true value at a frequency less than the stated confidence level. For $1.36 < \mu < 4.28$, the coverage (probability contained in the horizontal acceptance interval) is 85%.

We need an ordering principle

Feldman & Cousins ordering principle :

$$R = P(n|\mu)/P(n|\mu_{\ best})$$

A Unified Approach to the Classical Statistical Analysis of Small Signals

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(February 2, 2008)

Abstract

We give a classical confidence belt construction which unifies the treatment of upper confidence limits for null results and two-sided confidence intervals for non-null results. The unified treatment solves a problem (apparently not previously recognized) that the choice of upper limit or two-sided intervals leads to intervals which are not confidence intervals if the choice is based on the data. We apply the construction to two related problems which have recently been a battle-ground between classical and Bayesian statistics: Poisson processes with background, and Gaussian errors with a bounded physical region. In contrast with the usual classical construction for upper limits, our construction avoids unphysical confidence intervals. In contrast with some popular Bayesian intervals, our intervals eliminate conservatism (frequentist coverage greater than the stated confidence) in the Gaussian case and reduce it to a level dictated by discreteness in the Poisson case. We generalize the method in order to apply it to analysis of experiments searching for neutrino oscillations. We show that this technique both gives correct coverage and is powerful, while other classical techniques that have been used by neutrino oscillation search experiments fail one or both of these criteria.

PACS numbers: 06.20.Dk, 14.60.Pq

TABLE I. Illustrative calculations in the confidence belt construction for signal mean μ in the presence of known mean background $b = 3.0$. Here we find the acceptance interval for $\mu = 0.5$.

n	$P(n\|\mu)$	μ_{best}	$P(n\|\mu_{\mathrm{best}})$	R	rank	U.L.	central
0	0.030	0.	0.050	0.607	6		
1	0.106	0.	0.149	0.708	5	$\surd$	$\surd$
2	0.185	0.	0.224	0.826	3	$\surd$	$\surd$
3	0.216	0.	0.224	0.963	2	$\surd$	$\surd$
4	0.189	1.	0.195	0.966	1	$\surd$	$\surd$
5	0.132	2.	0.175	0.753	4	$\surd$	$\surd$
6	0.077	3.	0.161	0.480	7	$\surd$	$\surd$
7	0.039	4.	0.149	0.259		$\surd$	$\surd$
8	0.017	5.	0.140	0.121		$\surd$	
9	0.007	6.	0.132	0.050		$\surd$	
10	0.002	7.	0.125	0.018		$\surd$	
11	0.001	8.	0.119	0.006		$\surd$	

Values of n are added to the acceptance regionfor a given μ in decreasing order of R, until the sum of P(n|μ) meets or exceeds the desired C.L.

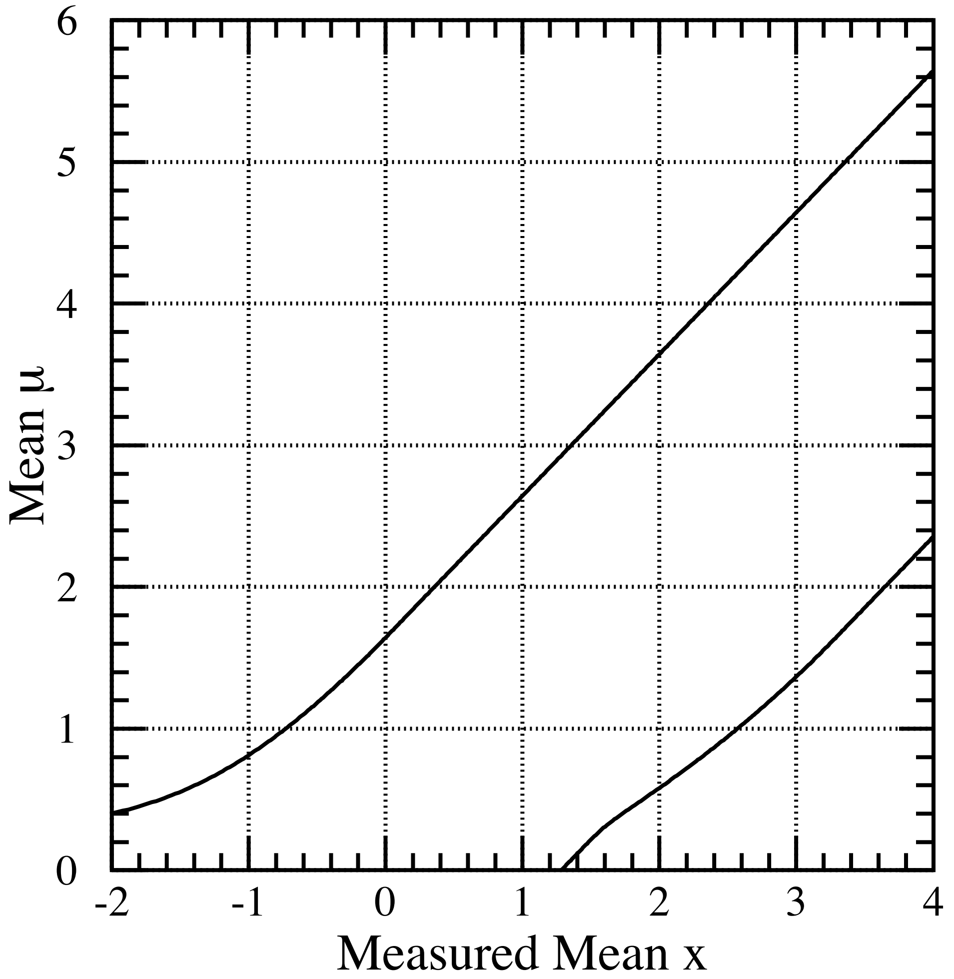


FIG. 10. Plot of our 90% confidence intervals for mean of a Gaussian, constrained to be non-negative, described in the text.

Conclusions

A Neyman construction is the most technically straightforward frequentist way to provide a confidence interval.

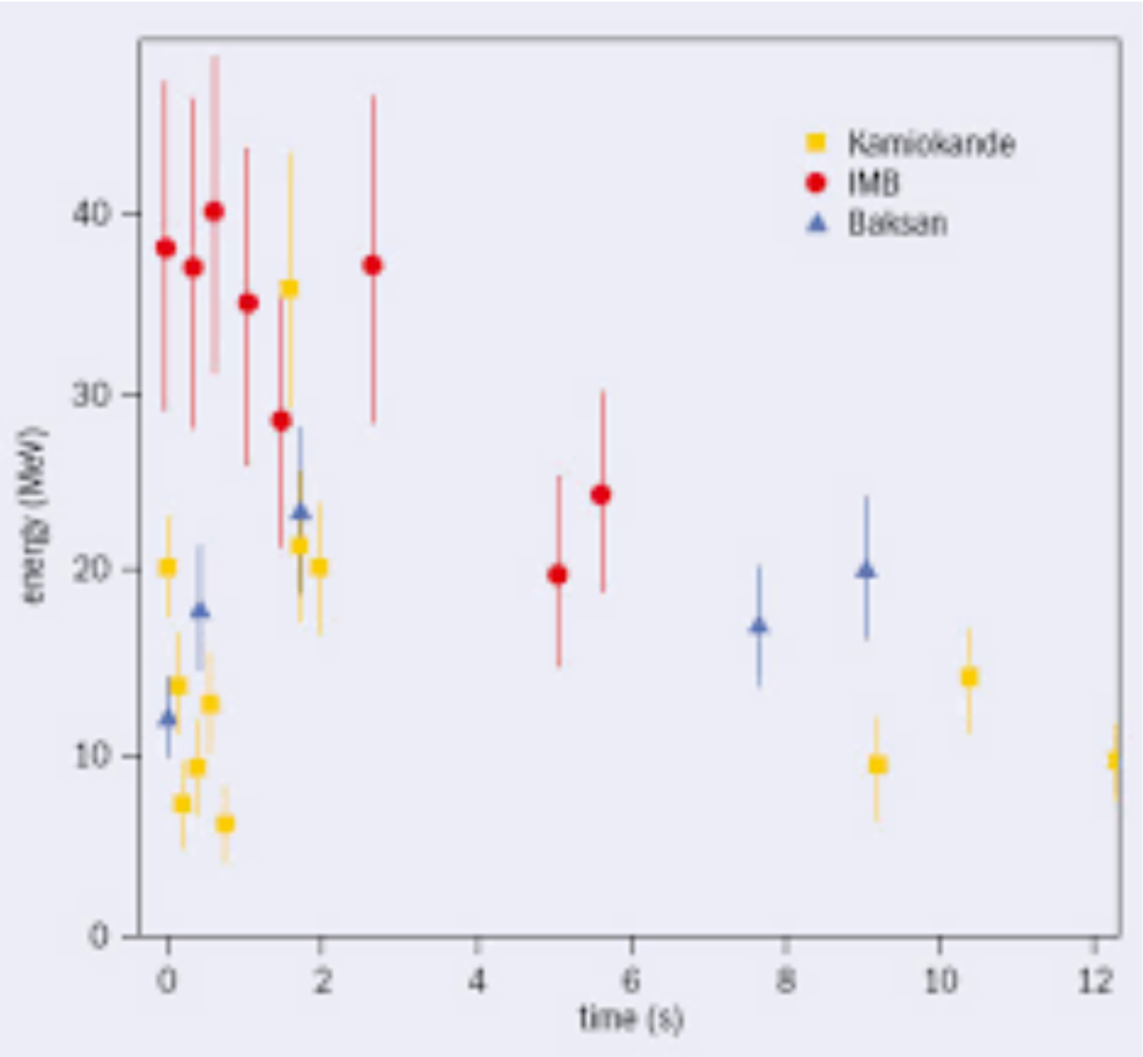
However it requires an ordering principle to ensure perfect coverage for small signals

The Neyman Pearson Lemma states that the likelihood ratio test is the most powerful test possible for a given α

Profile likelihoods are the currently best accepted frequentist techniques for handling nuisance parameter uncertainties.

To be continued

SN1987A



February 23, 1987

First SN studied in detail by modern astronomers

51.4 kpc away

The collapsed neutron star, discovered by ALMA in 2019 and Chandra and Nu-Star in 2021

Kamiokande II detected 12 antineutrinos
Irvine Michigan Brookhaven , 8 antineutrinos
Baksan 5 antineutrinos

Consistent with models of SN then

10^{58} neutrinos, 10^{46} joules

Upper bounds on neutrino mass and number of flavours

GW 170817 + GRB 170817

17 August 2017

NGC 4993 host galaxy

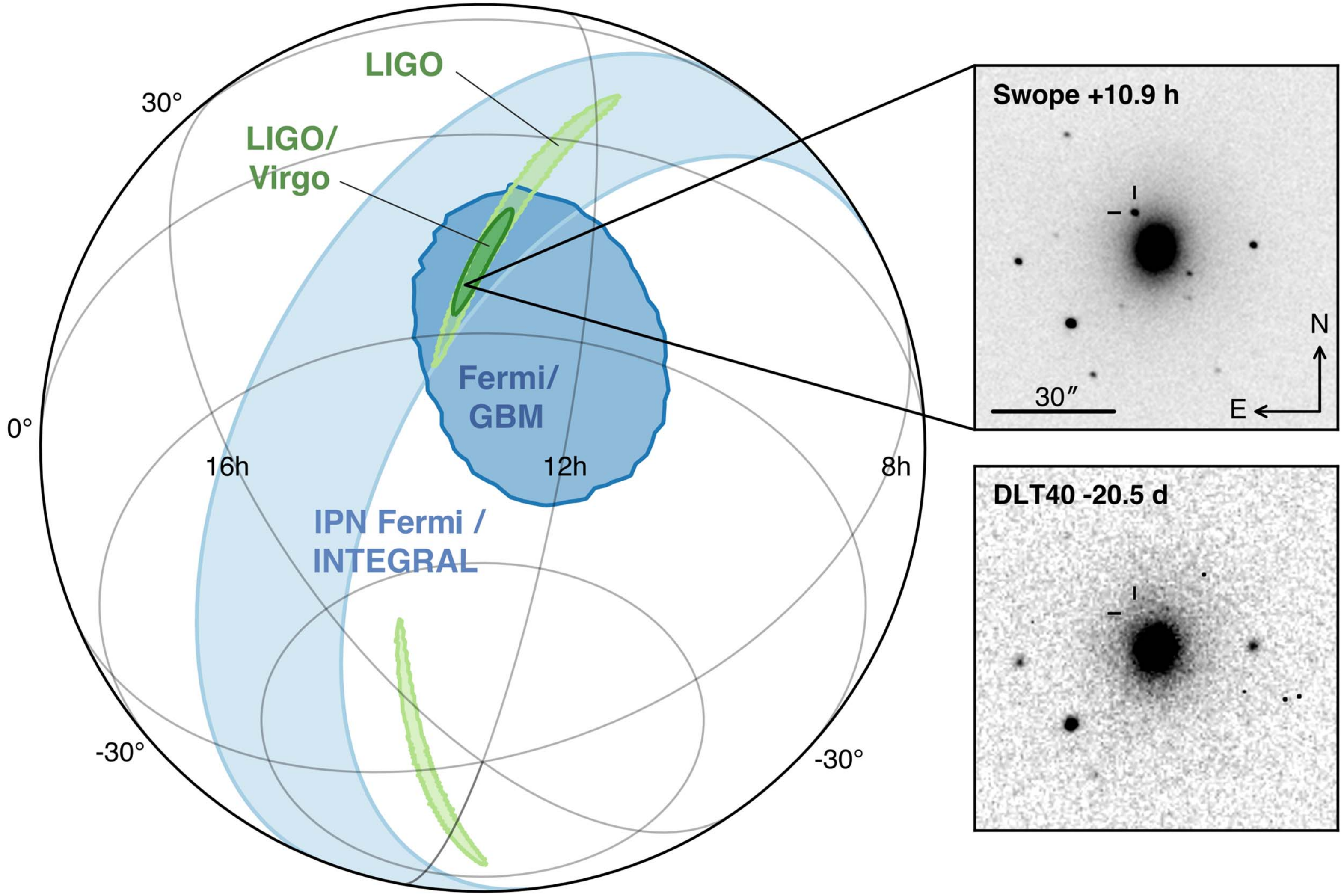
Kilonova Neutron star merger

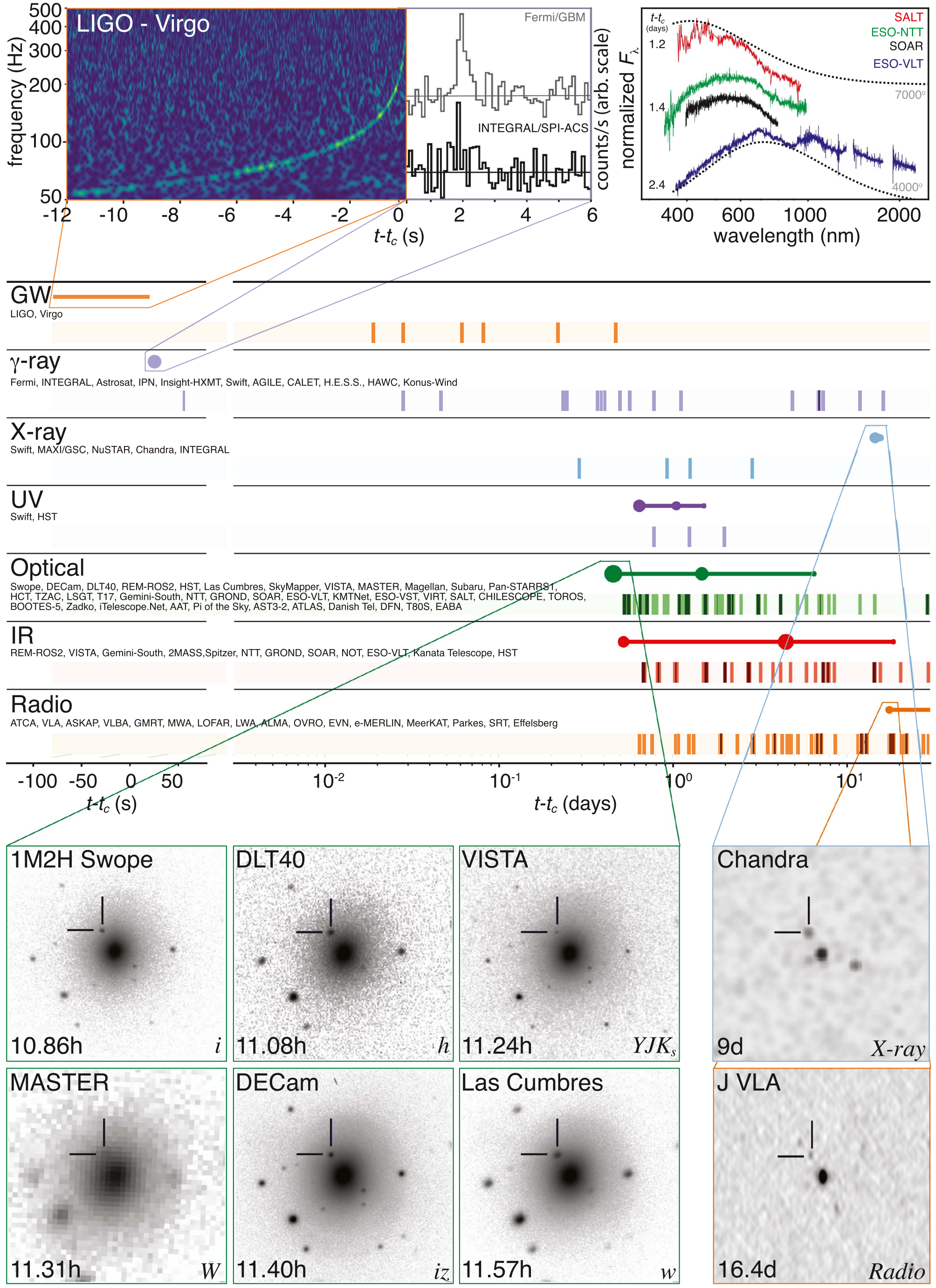
LIGO, Virgo (did not see it)

LIGO Livingston detector had a 'glitch', which then had to be interpolated.

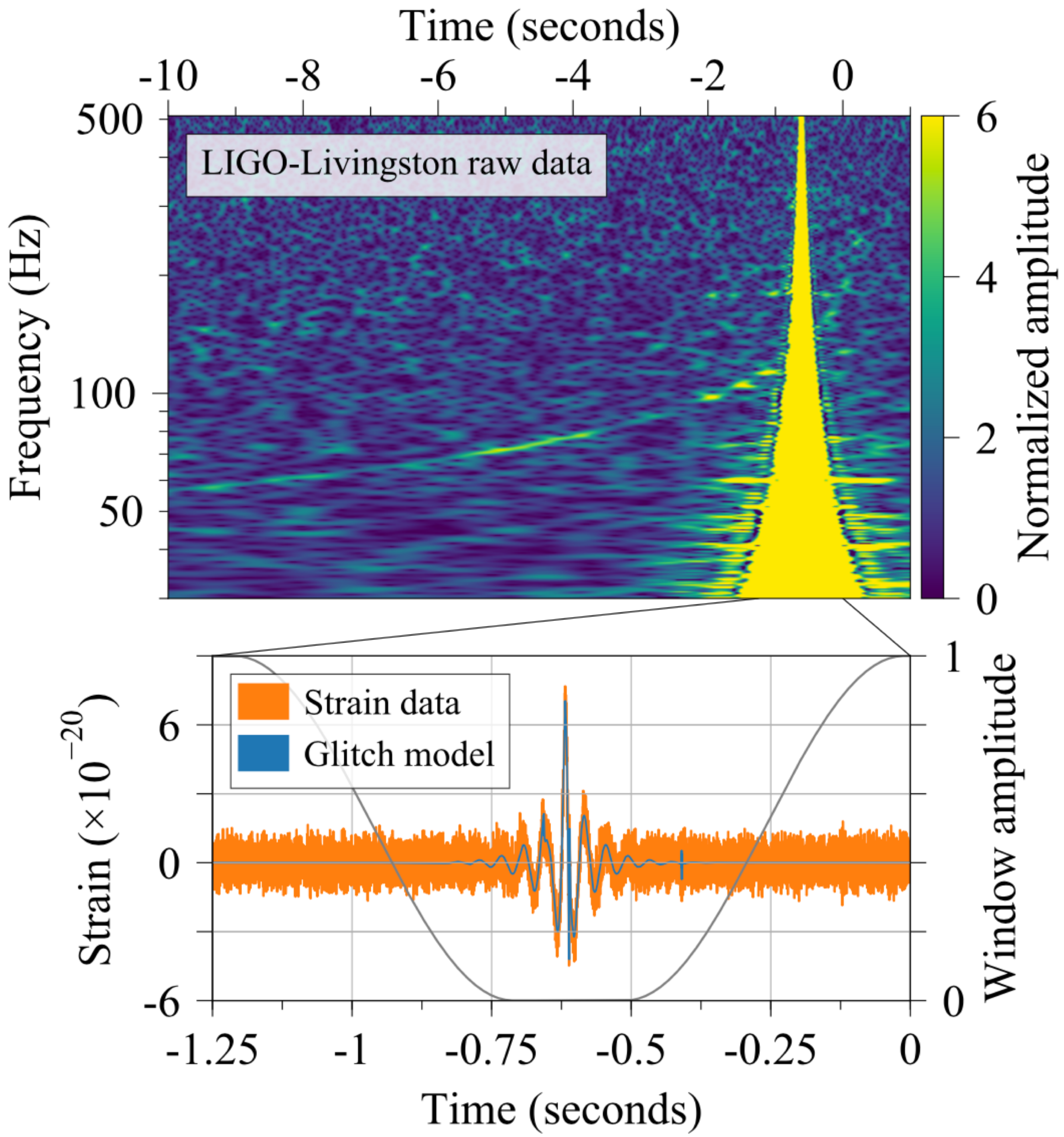
Alert timings are a posteriori.

Rapid neutron capture r process nucleosynthesis





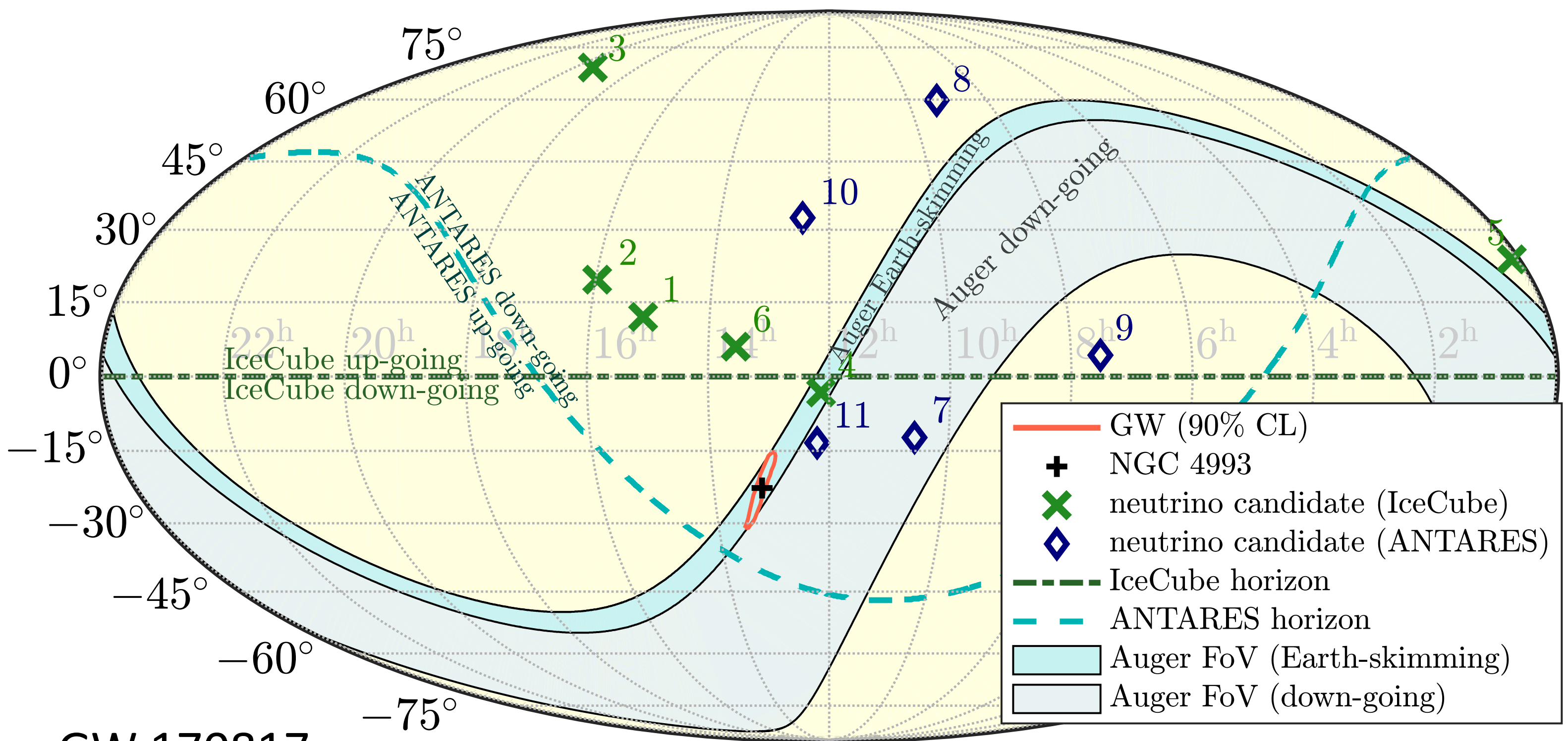
LIGO - Virgo
frequency (Hz)
Fermi/GBM
INTEGRAL/SPI-ACS
counts/s (arb. scale)
t-tc (s)
SALT
ESO-NTT
SOAR
ESO-VLT
normalized Fλ
wavelength (nm)
GW
LIGO, Virgo
γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind
X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
UV
Swift, HST
Optical
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1, HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS, BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN, T80S, EABA
IR
REM-ROS2, VISTA, Gemini-South, 2MASS,Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata Telescope, HST
Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
t-tc (s)
t-tc (days)
1M2H Swope
10.86h
i
DLT40
11.08h
h
VISTA
11.24h
YJKs
Chandra
9d
X-ray
MASTER
11.31h
W
DECam
11.40h
iz
Las Cumbres
11.57h
w
J VLA
16.4d
Radio



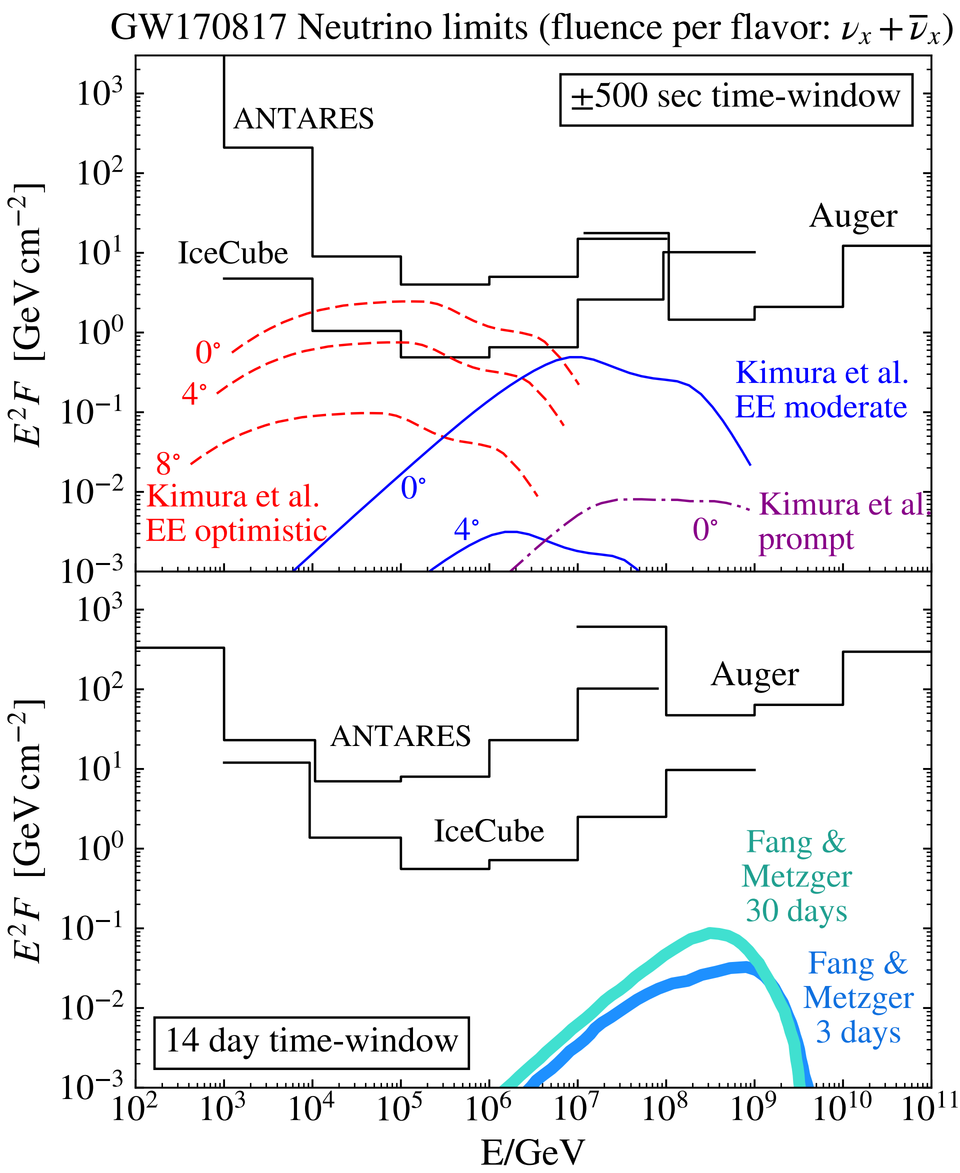
Time (seconds)
LIGO-Livingston raw data
Frequency (Hz)
Normalized amplitude
Strain data
Glitch model
Strain (×10^−20)
Window amplitude
Time (seconds)

Search for neutrinos in coincidence with gravitational waves

binary neutron star merger

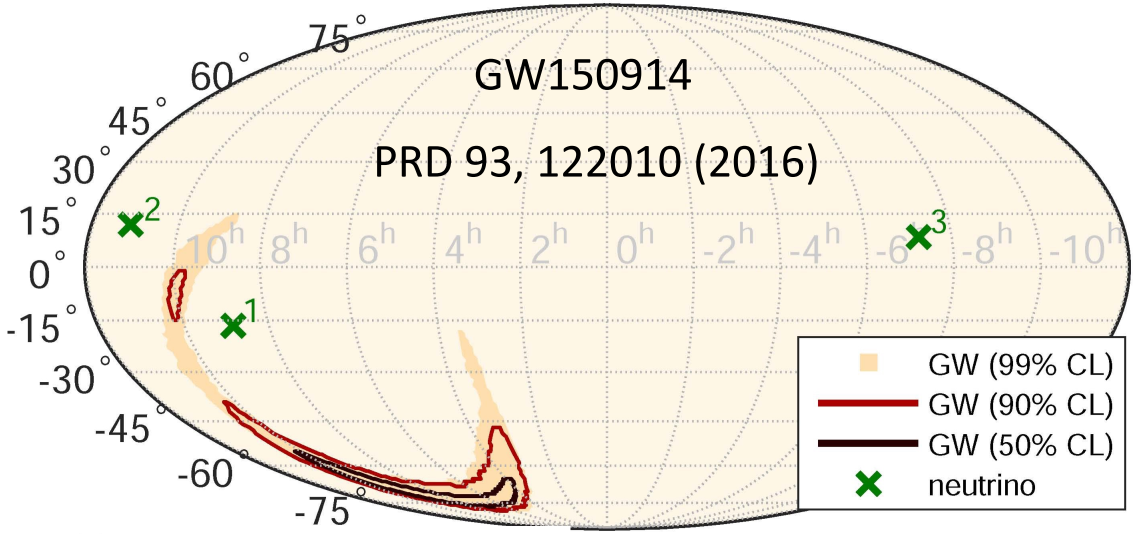


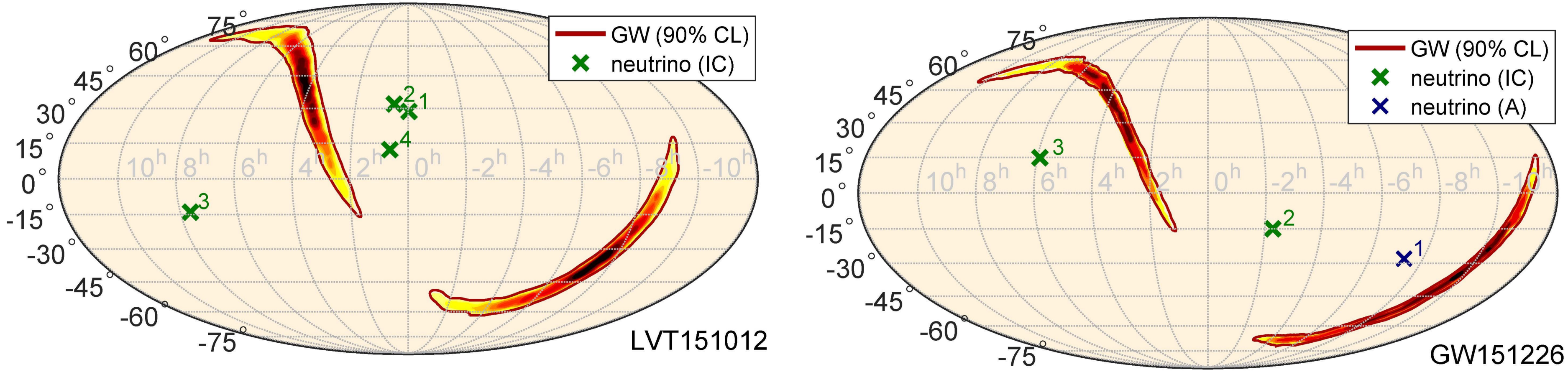
GW 170817



ANTARES, IceCube, Auger, LIGO/Virgo, ApJL 850:L35 (2017)
+ null results from binary black hole merger neutrino searches

ν from GWs? (contd)

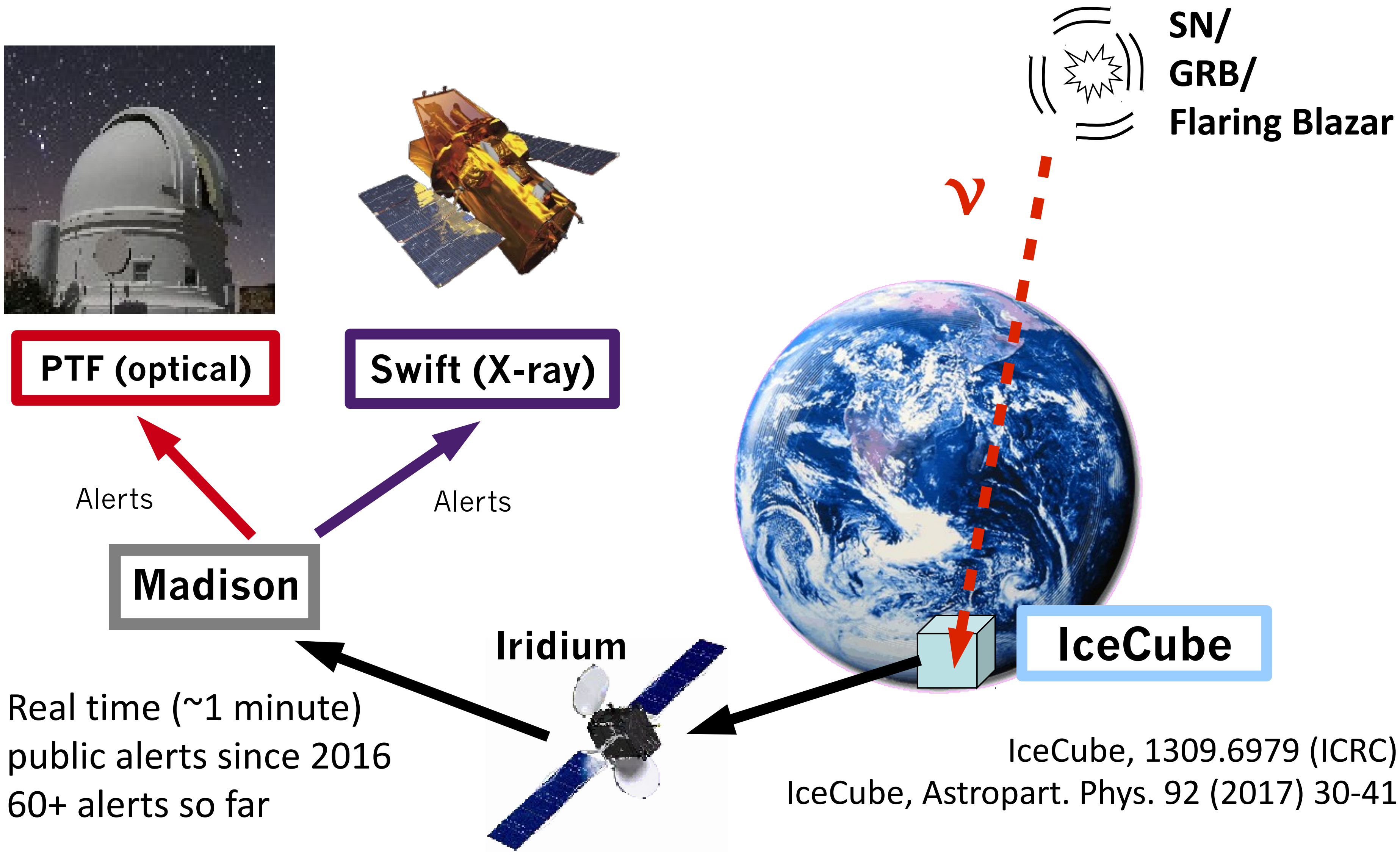




PRD 96, 022005 (2017)

ANTARES, IceCube, LIGO/VIRGO

Realtime Alerts from IceCube



Real time (~1 minute)
public alerts since 2016
60+ alerts so far

IceCube, 1309.6979 (ICRC)
IceCube, Astropart. Phys. 92 (2017) 30-41

Multi-messenger alerts: TXS 0506+056

On September 22, 2017, IceCube issued a neutrino alert:

- A muon track event created by a ~290 TeV neutrino (IceCube-170922A)
- Found to be spatially coincident with a known blazar (TXS 0506+056) that was in a flaring state
- Blazar was also detected by the MAGIC air-Cherenkov telescope in the days after the alert, with γ-rays up to 400 GeV.
- This launched a very active multi-messenger follow-up campaign that included observations from radio to γ-rays.

TITLE: GCN CIRCULAR
NUMBER: 21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino candidate event
DATE: 17/09/23 01:09
FROM: Erik Blaufuss a

Claudio Kopper (Univers
Maryland) report on bel
icecube.wisc.edu/).

On 22 Sep, 2017 IceCub
high probability of bein
the Extremely High En
was in a normal operat
interaction vertex that
the detector volume, a

Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration*
on 28 Sep 2017; 10:10 UT
Credential Certification: David J. Thompson (David.J.Thompson@nasa.gov)

Subjects: Gamma Ray, Neutrinos, AGN

Referred to by ATel #: 10792, 10794, 10799, 10801, 10817, 10830, 10831, 10833, 10838, 10840, 10844, 10845, 10861, 10890, 10942, 11419, 11430, 11489

Tweet Recommend 3

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817; *Razmik Mirzoyan for the MAGIC Collaboration*
on 4 Oct 2017; 17:17 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845, 10942

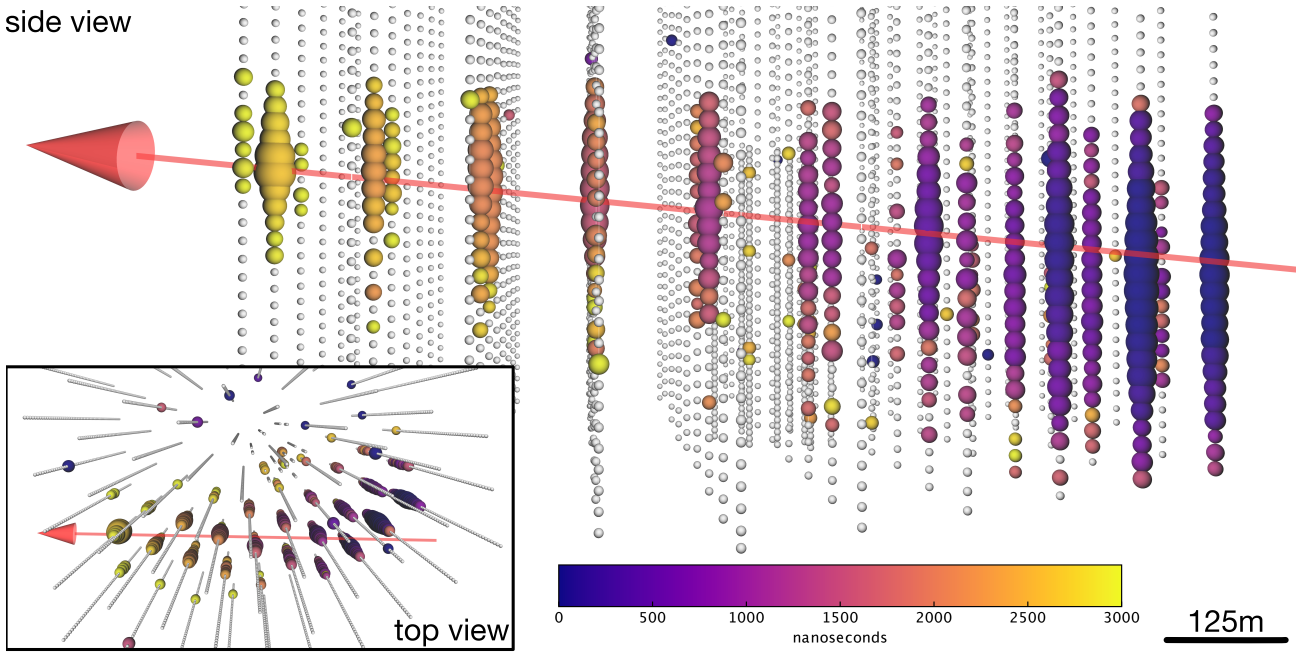
Tweet Recommend 449

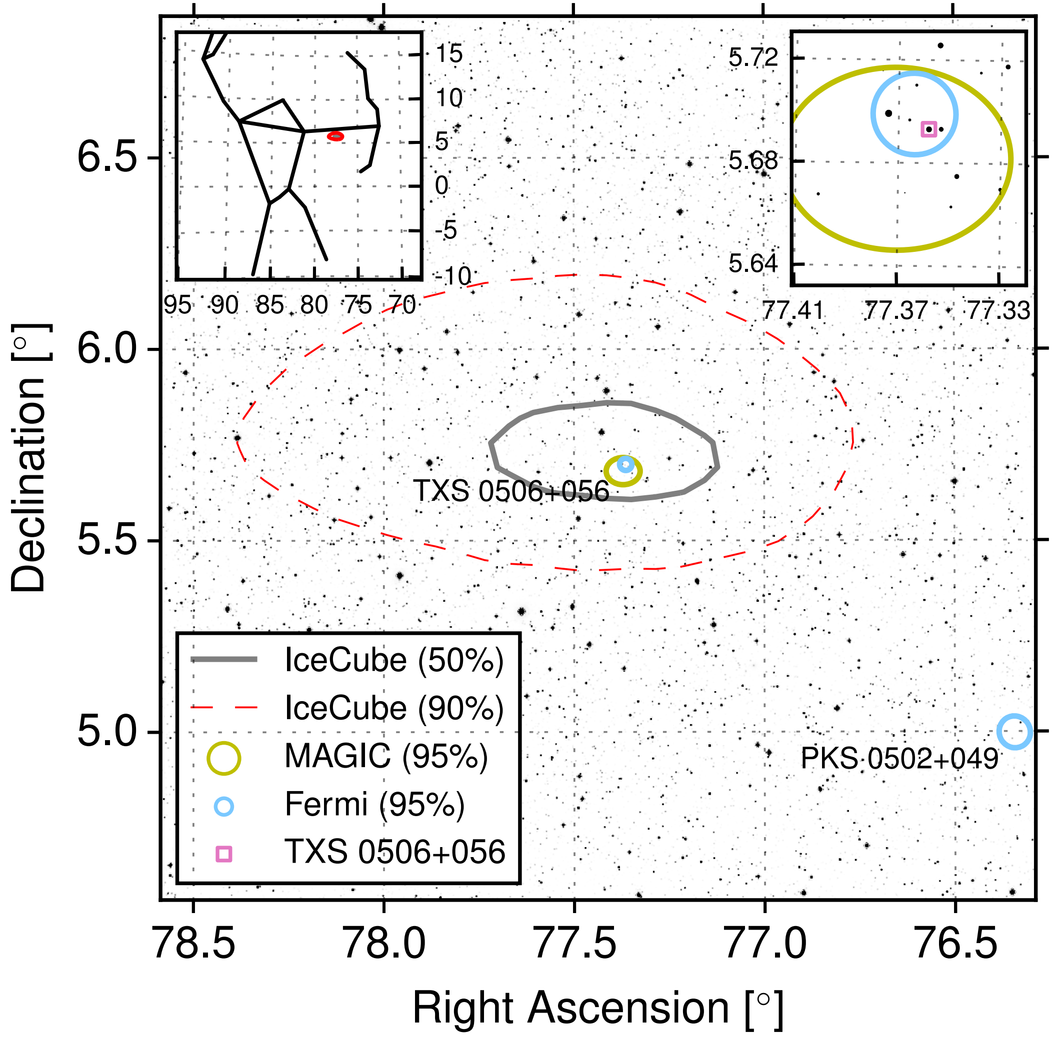
After the IceCube neutrino event EHE 170922A detected on 22/09/2017 (GCN circular #21916), Fermi-LAT measured enhanced gamma-ray emission from the blazar TXS 0506+056 (05 09 25.96370, +05 41 35.3279 (J2000), [Lani et al., Astron. J., 139, 1695-1712 (2010)]), located 6 arcmin from the EHE 170922A estimated direction (ATel #10791). MAGIC observed this source under good weather conditions and a 5 sigma detection above 100 GeV was achieved after 12 h of observations from September 28th till October 3rd. This is the first time that VHE gamma rays are measured from a direction consistent with a detected neutrino event. Several follow up observations from other observatories have been reported in ATels: #10773, #10787, #10791, #10792, #10794, #10799, #10801, GCN: #21941, #21930, #21924, #21923, #21917, #21916. The MAGIC contact persons for these observations are R. Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de) E. Bernardini (elisa.bernardini@desy.de), K.Satalecka (konstancja.satalecka@desy.de). MAGIC is a system of two 17m-diameter Imaging Atmospheric Cherenkov Telescopes located at the Observatory Roque de los Muchachos on the Canary island La Palma, Spain, and designed to perform gamma-ray astronomy in the energy range from 50 GeV to greater than 50 TeV.

Recently published in Science:
IceCube Coll. et al., Science 361 (2018)

Multi-messenger alerts: TXS 0506+056

Neutrino direction was well reconstructed
- Uncertainty of less than 1 sq. deg at 90% CL
- Positionally consistent with blazar TXS 0506+056
- ~290 TeV estimated neutrino energy





Multi-messenger alerts: TXS 0506+056

At detection time of IceCube-170922A, very little was known about blazar TXS 0506+056.

As part of the large community follow-up effort, the redshift has been measured
$z = 0.3365 \pm 0.0010$ (Pianno, et al. ApJ **854** (2018) 2)

But how often does this happen by chance?

- 2257 cataloged extragalactic Fermi-LAT sources
- Light curves above 1 GeV in monthly bins
- Likelihood ratio test comparing random coincidence (null hypothesis) to correlation between gamma-ray flux and neutrino flux for several models
  - Energy flux, Flux variability, VHE detection/detectability
  - 4.1σ preference for correlated emission
- Trials corrected:
  - 9 previous alerts + 41 additional events that *would* have generated alerts, had they been operational
  - **3.0σ** preference for correlated emission

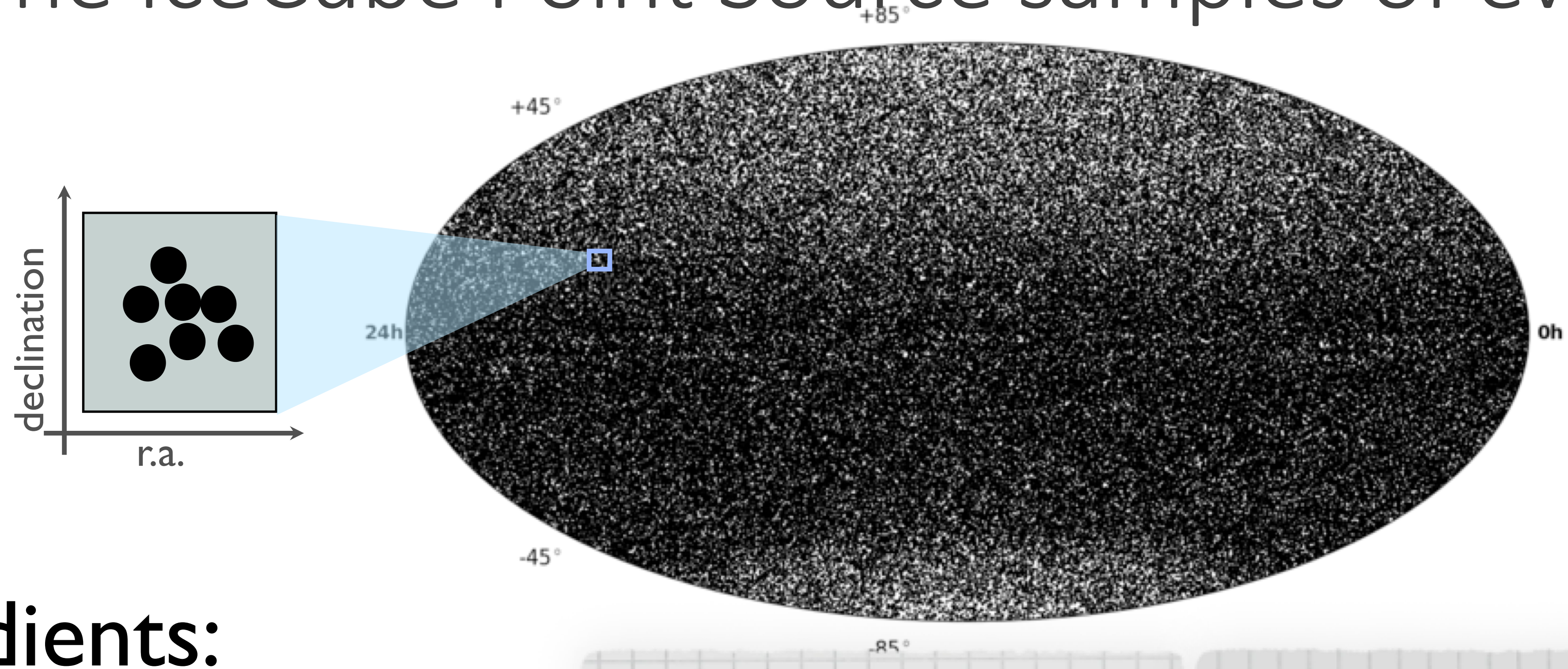
IceCube Coll. et al., Science 361 (2018)

The IceCube Point Source samples of events

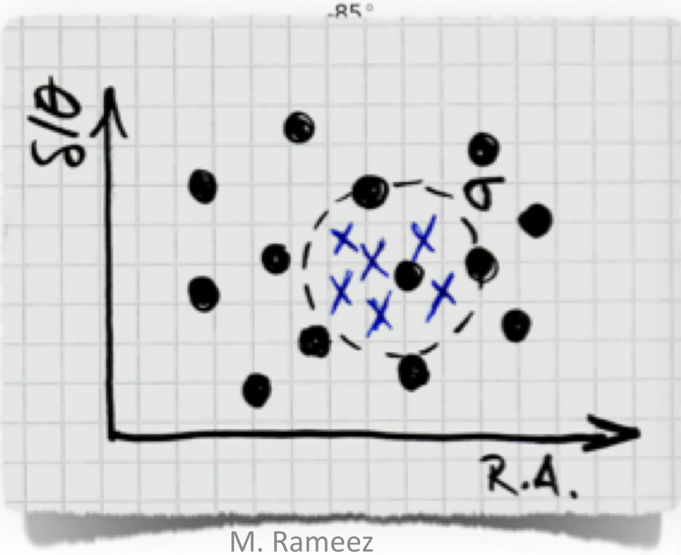
No Veto

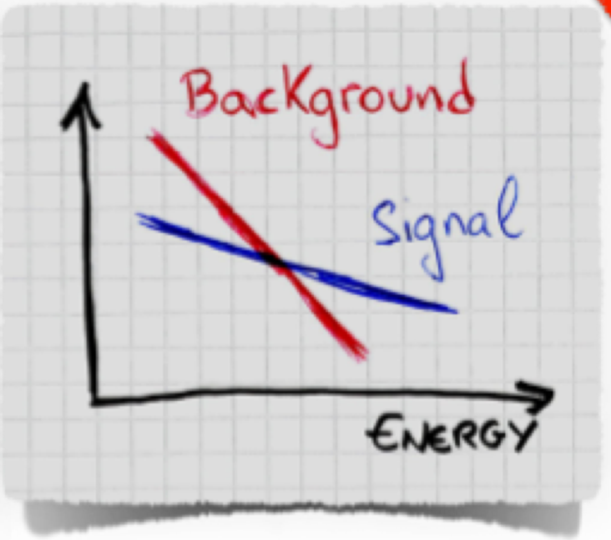
Lower Energy Threshold

Tracks



Ingredients:





For a given direction in the sky $\vec{r}_j$, the data can be described by two hypotheses:

H_0 **- The data consists of events from atmospheric muons and/or neutrinos only**: Under this hypothesis, all events are expected to be distributed uniformly within each declination band. The distribution of the values of the energy estimator E of these events can be indicated by $P(\delta_i, E|\phi_{atm})$ which also accounts for the declination dependence of the energy response of the detector. The background probability distribution can then be expressed as:

$$\mathcal{B}(\vec{r}_i, E_i) = B(\delta_i) \times P(\delta_i, E_i|\phi_{atm}) \tag{4.1}$$

and can be constructed in its entirety using real experimental data that has been randomized in right ascension (r.a.).

H_s **- The data is described by atmospheric muon and/or neutrino events as well as astrophysical neutrino events produced by a source of power law spectral index γ and a specific strength** : While the atmospheric neutrino and muon events are expected to follow the same distribution as in the case of H_0 - spatially and in energy, the additional events from an astrophysical source are expected to be clustered around the direction of the source according to the Gaussian distribution:

$$S_i^j = \frac{1}{2\pi(\sigma_i^2)} e^{-\frac{\theta^2_{|\vec{r}_i - \vec{r}_j|}}{2\sigma_i^2}} \tag{4.2}$$

where σ_i is the angular resolution of event i and $\theta_{|\vec{r}_i - \vec{r}_j|}$ is the angle between the direction $\vec{r}_i$ of event i and the direction $\vec{r}_j$ of source j. The distribution of the values of the energy estimator E of these astrophysical events can be indicated by $\mathcal{E}(\delta_i, E_i|\gamma)$ and can be constructed from Monte Carlo simulations of the signal. Thus the signal probability distribution for a source of power law spectrum of index γ is:

$$\mathcal{S}(\vec{r}_i, \vec{r}_j, E_i, \gamma) = S_i^j \times \mathcal{E}(\delta_i, E_i|\gamma) \tag{4.3}$$

For a sample of N events consisting of n_s signal events from a source j at $\vec{r}_j$ and $N - n_s$ background events, the likelihood can then be written as:

$$\mathcal{L}(\vec{r}_j, n_s, \gamma) = \prod_N (\frac{n_s}{N}\mathcal{S}_i + (1 - \frac{n_s}{N})B_i) \tag{4.4}$$

The log of the ratio of the likelihoods of obtaining the observed data under each of these hypothesis serves as the test statistic:

$$TS = -2 \times \log[\frac{P(\mathrm{Data}/H_0)}{P(\mathrm{Data}/H_S)}] \tag{4.5}$$

$$TS = 2 \times log[\frac{\mathcal{L}(\vec{r}_s, \hat{n}_s, \hat{\gamma})}{\mathcal{L}(\vec{r}_s, n_s = 0)}]$$

Energy PDFs

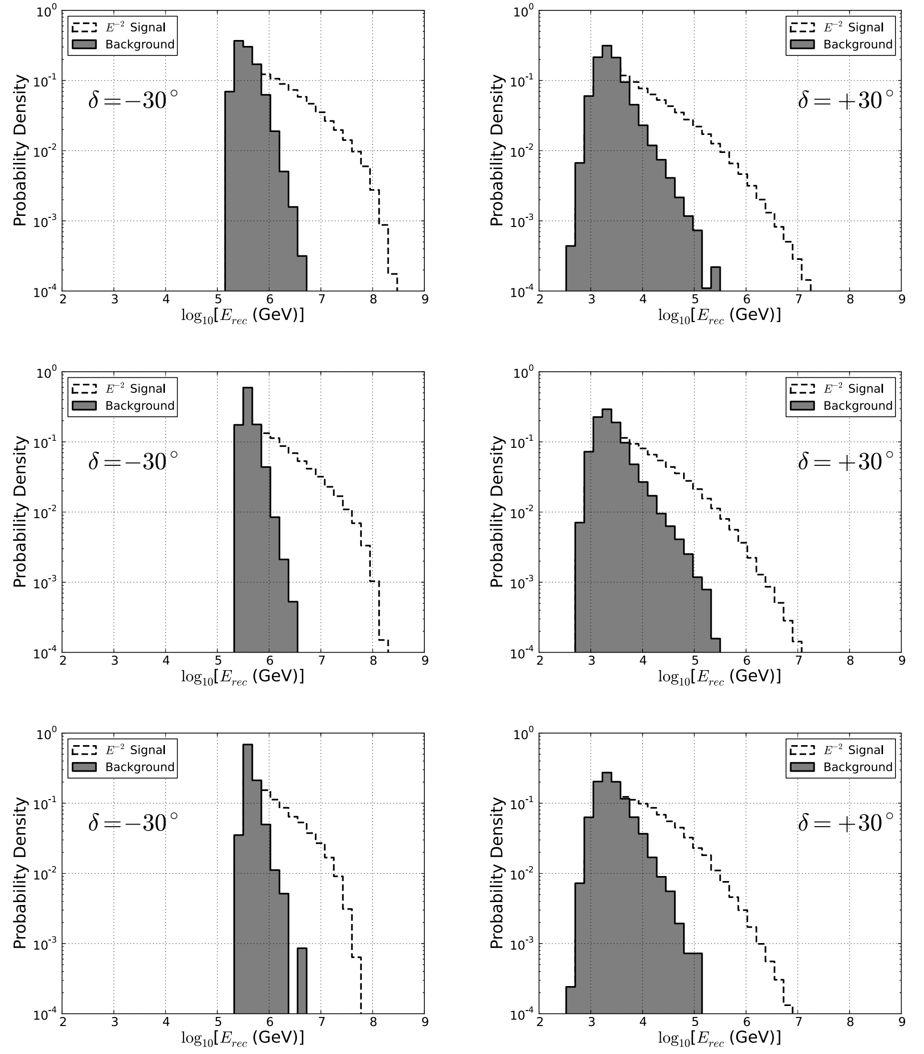
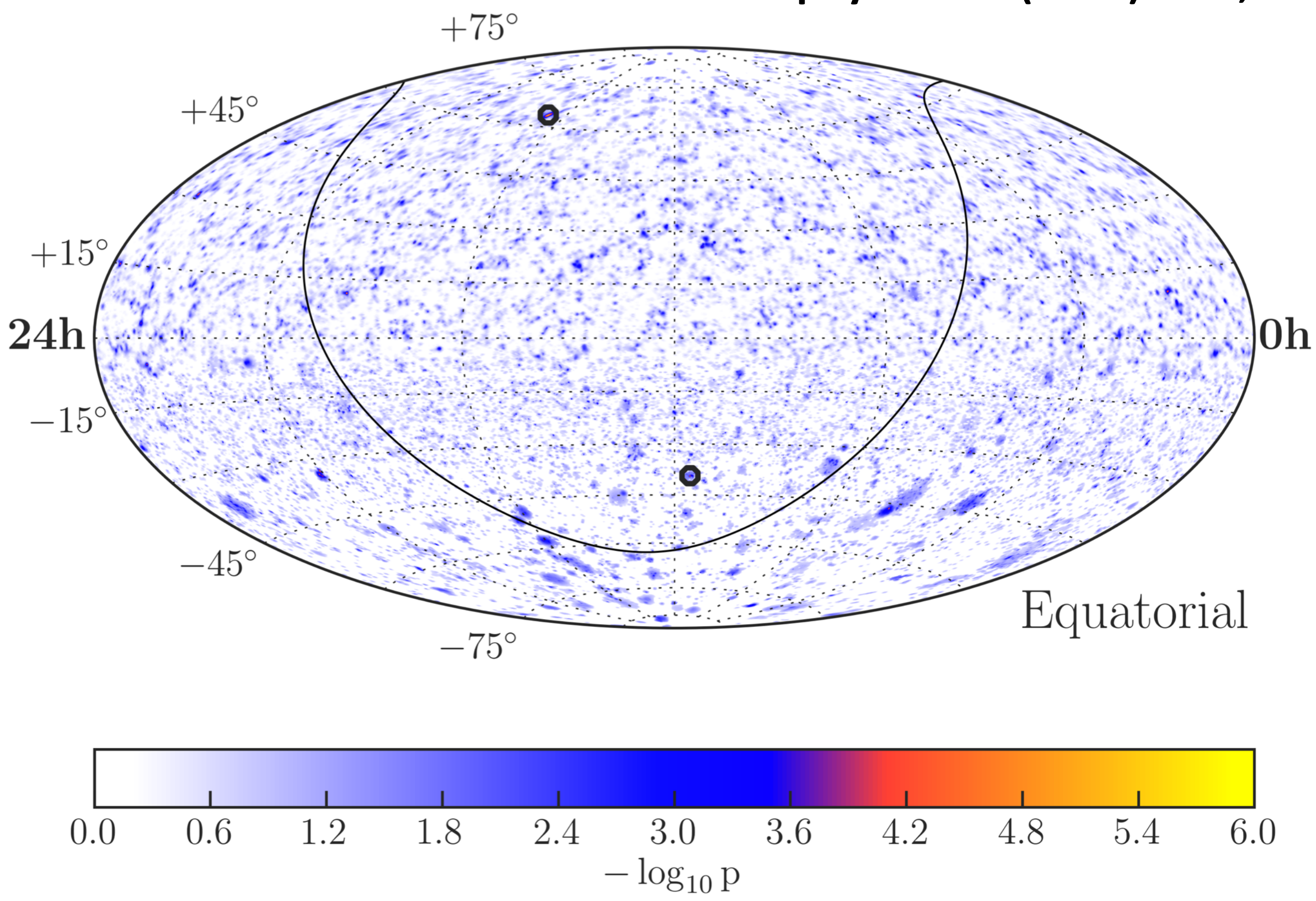


Figure 10: Energy p.d.f. given as $dN/d\log_{10} E_{rec}$ for two different declinations, $\delta = -30^\circ$ (left column) and $\delta = 30^\circ$ (right column) for background and an exemplary signal of an E^{-2} spectrum for the three different detector configurations, the 79-string configuration (top row), the 59-string configuration (middle row) and the 40-string configuration (bottom row).

All sky point source searches - 7 years

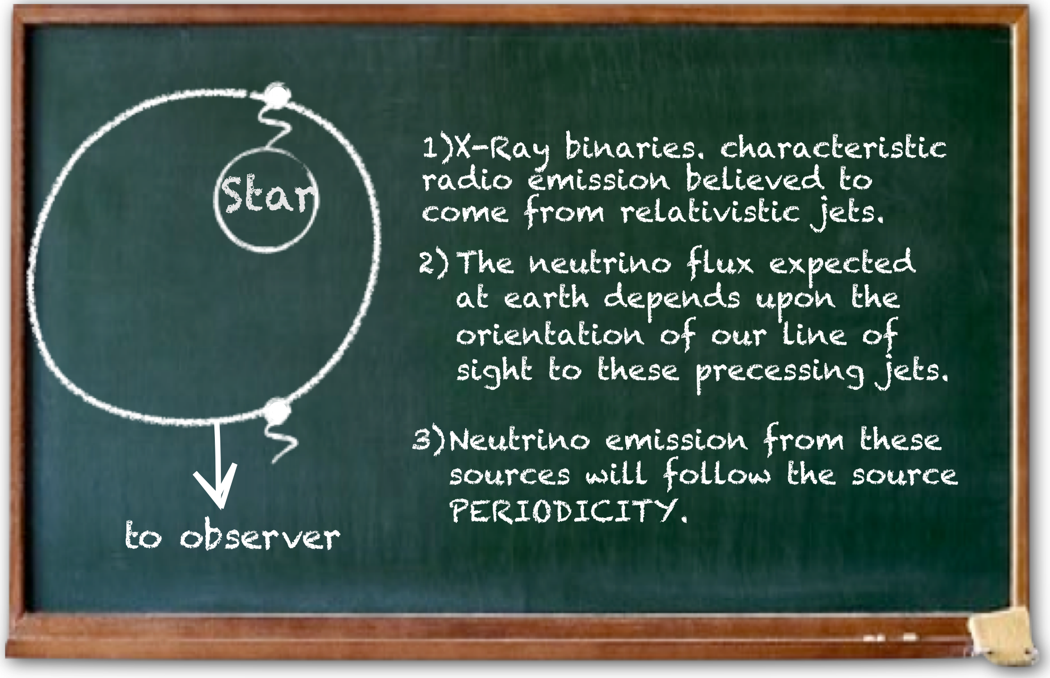
Astrophys.J. 835 (2017) no.2, 151

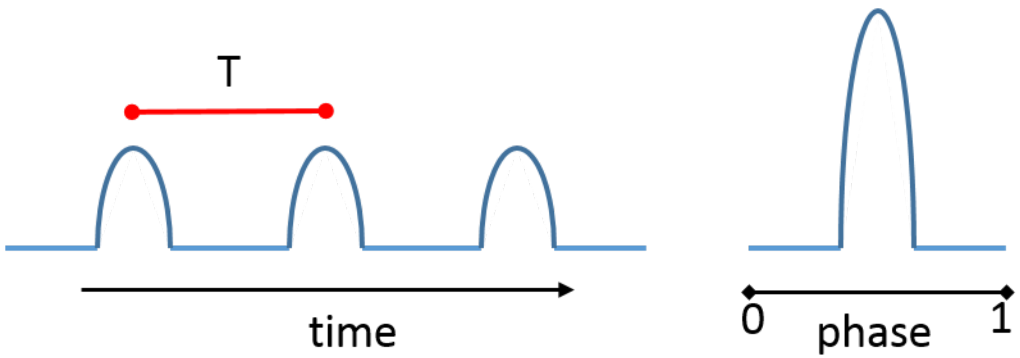


Northern sky p value : 5.75×10^{-6}

Southern sky p value : 4.68×10^{-6}

Time/Phase dependence

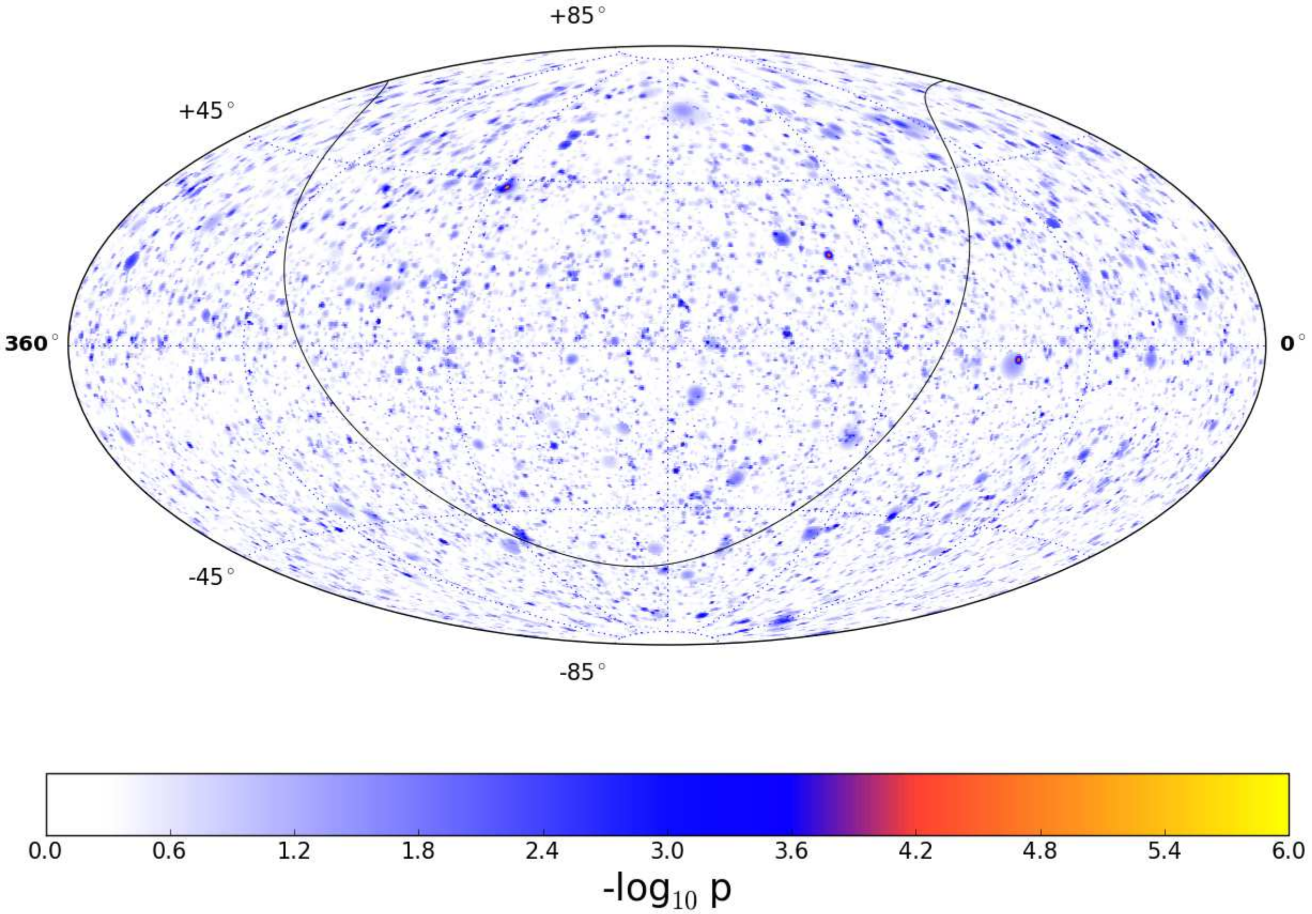


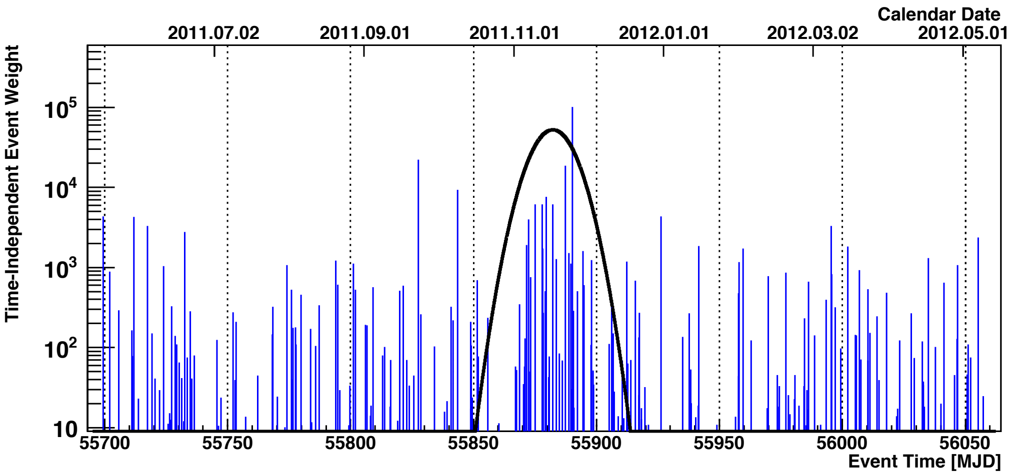


Method : Look for a directional excess of events also clustered also in time/phase.

$$\mathcal{P}_i^{\mathrm{signal}}(\Phi_j, \sigma_{\Phi,\mathrm{j}}) = \frac{1}{\sqrt{2\pi}\sigma_{\Phi_\mathrm{j}}} exp\left(-\frac{(\phi_i - \Phi_j)^2}{2\sigma_{\Phi,\mathrm{j}}^2}\right),$$

Scanning the entire sky induces a large number of trials



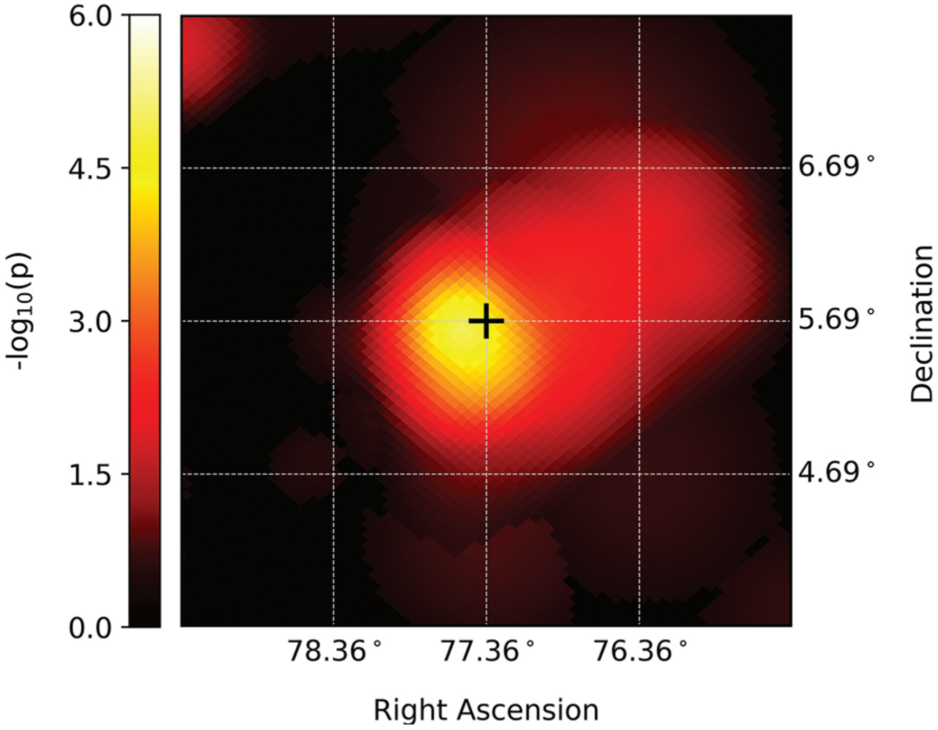


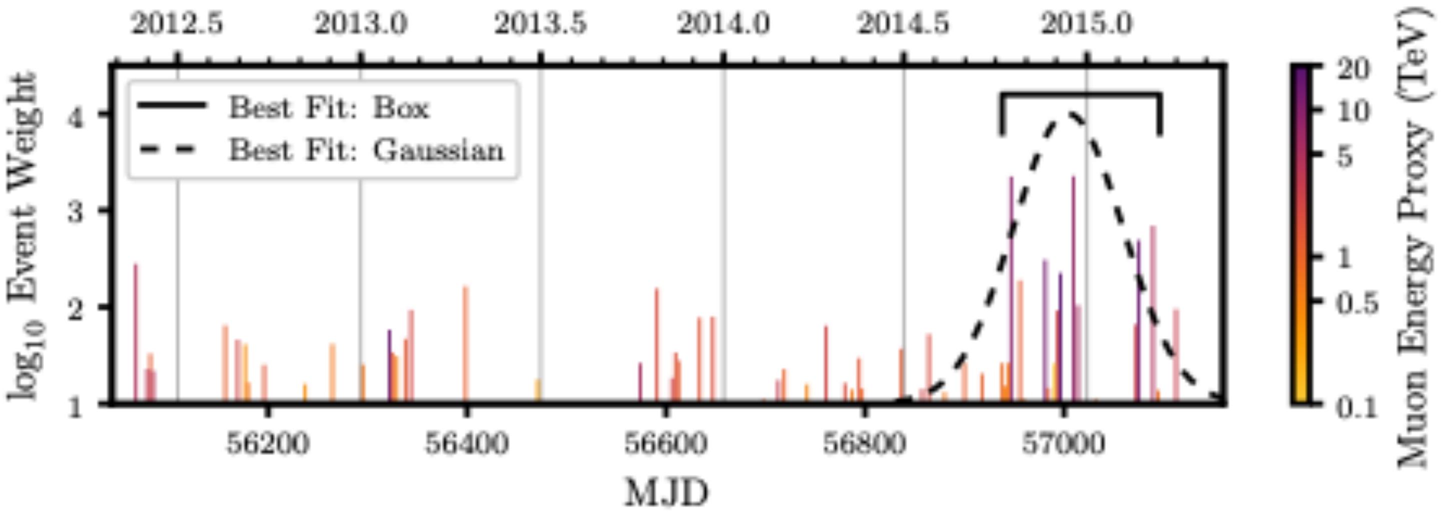
IceCube Archival Data

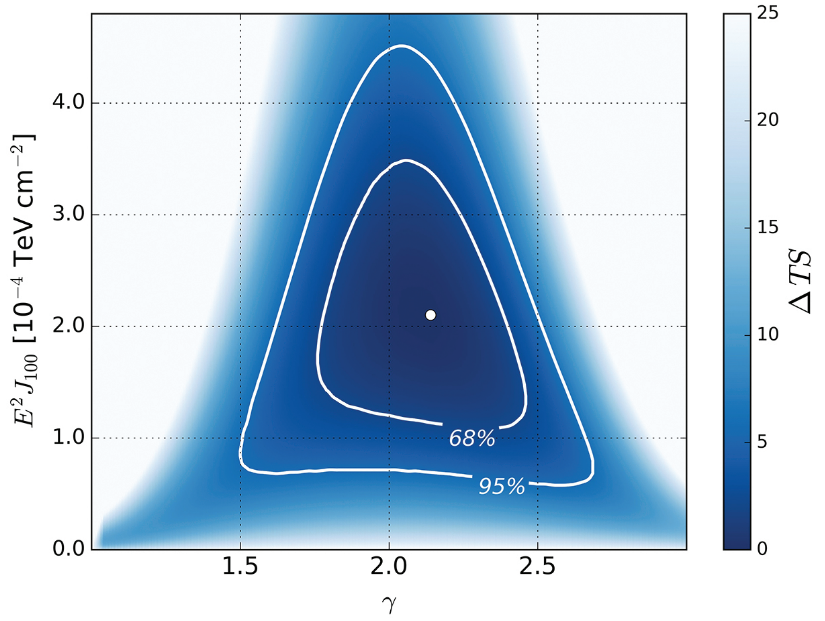
Evidence of time-dependent emissions is observed:

Independent of, and prior to neutrino alert
- September 2014 - March 2015
- 3.5σ excess over expected background
- 13 ± 5 events over background

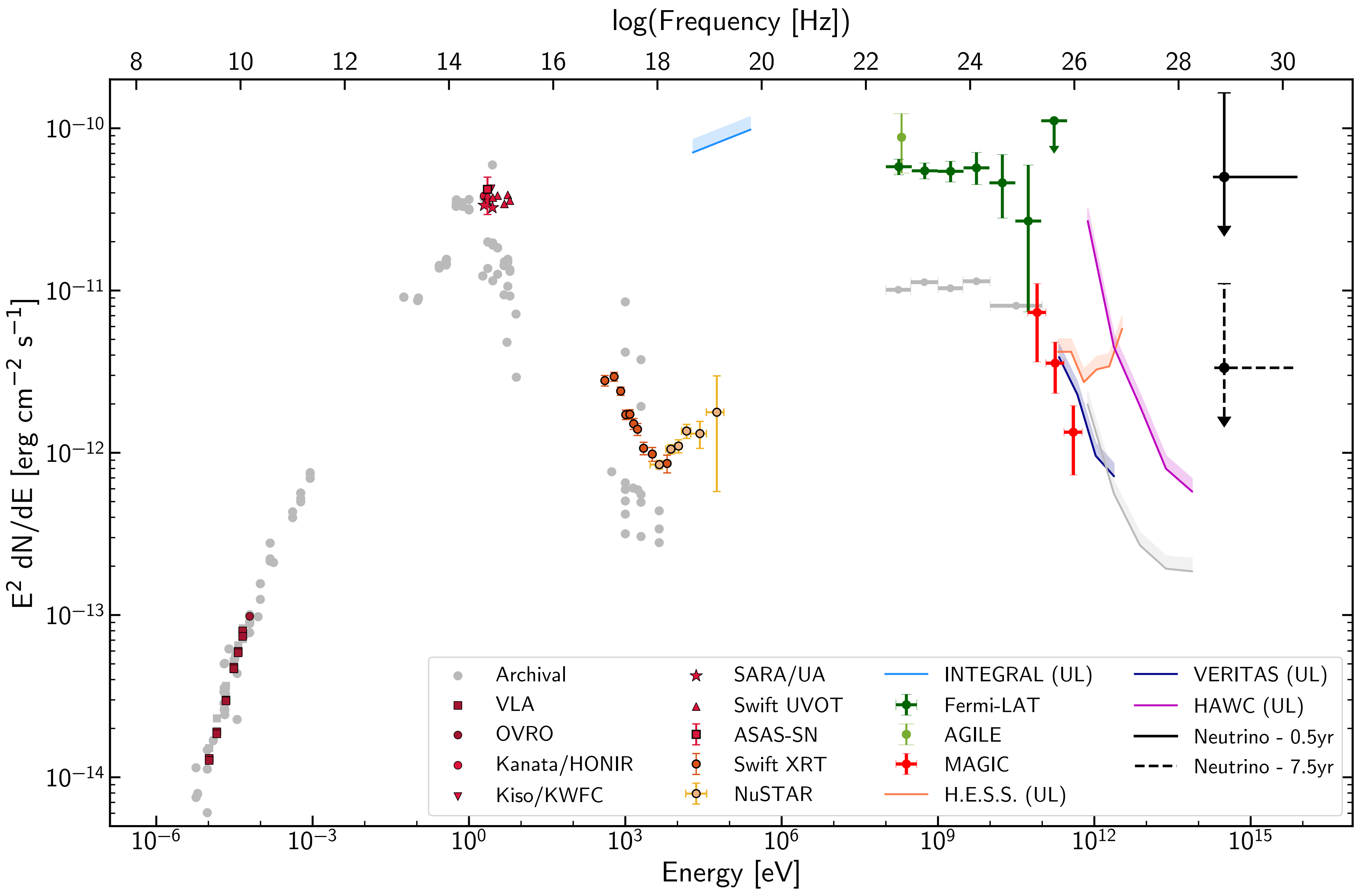
Science: IceCube Coll. Science 361 (2018) 147



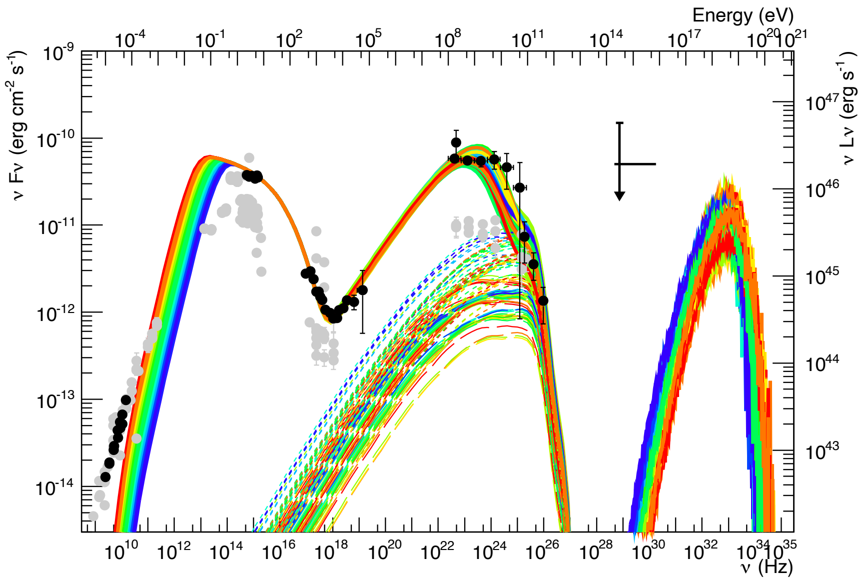




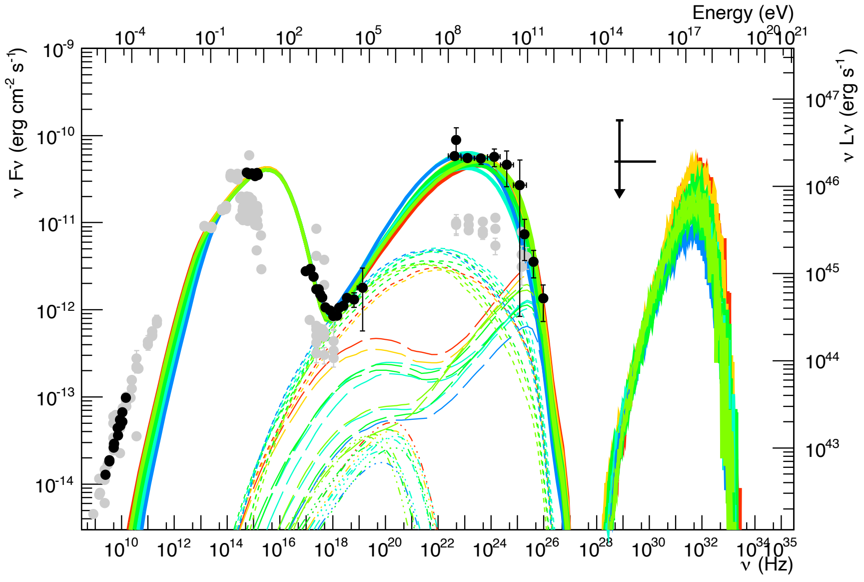
Spectral Energy Distribution



Models are quantified by how well they can fit the SED



(a) Proton synchrotron modeling of TXS 0506+056

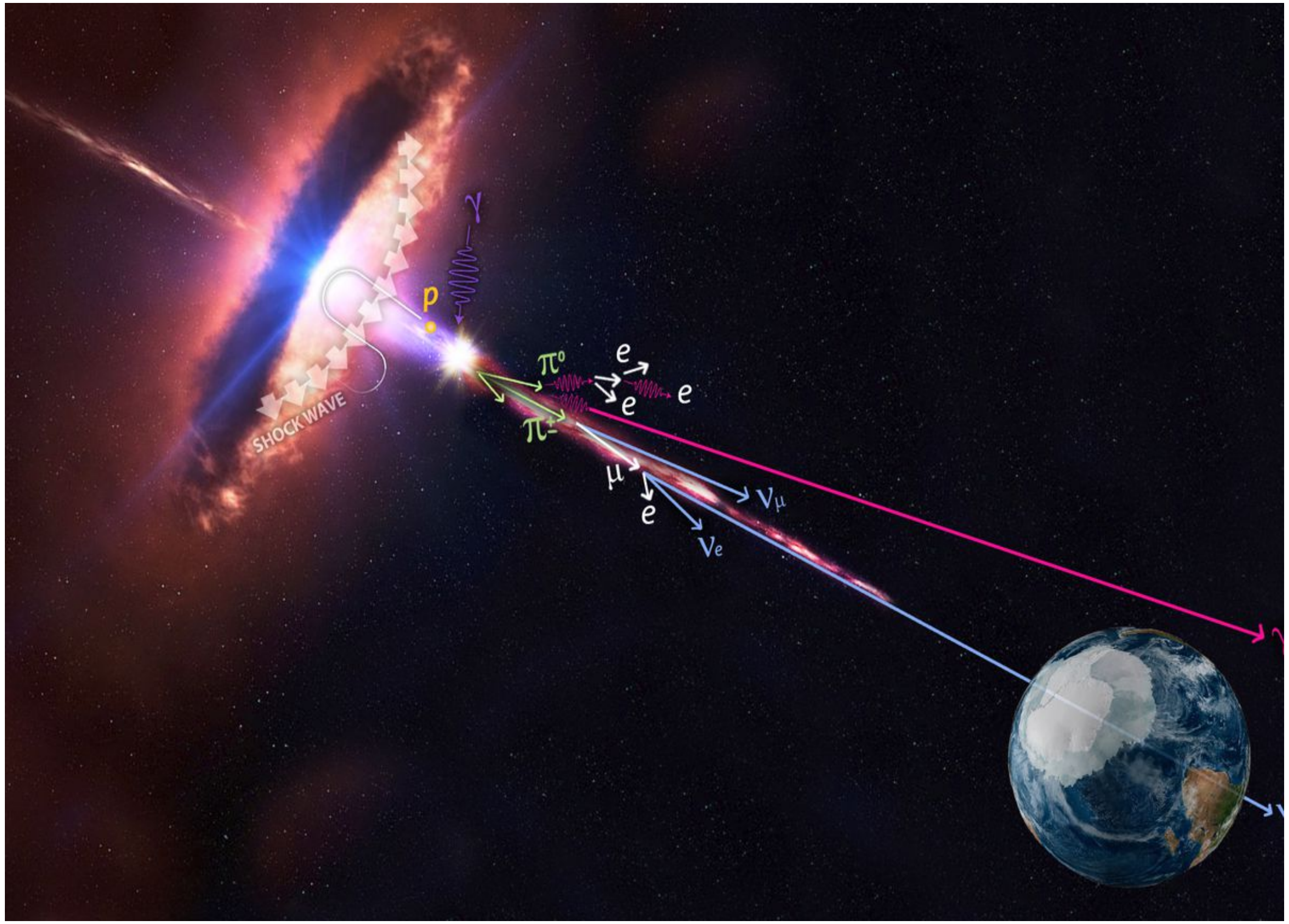


(b) Lepto-hadronic modeling of TXS 0506+056

Figure 1. Modeling of TXS 0506+056 for the proton synchrotron (1a) and lepto-hadronic (1b) scenarios. Black points are data from IceCube Collaboration et al. (2018b), while gray points are archival data. For each model, bold lines represent the total emission in photons (E < 100 TeV) and neutrinos (single flavour, E > 100 TeV); dashed lines the emission from pion cascades; dotted lines the emission from Bethe-Heitler cascades; dotted-dashed lines the proton synchrotron emission. Colours from red to blue represent increasing values of R.

MNRAS 000, 1–6 (2018)
arXiv: 1807.04335

Multi-messenger source: TXS 0506+056



Two analyses provide evidence that TXS 0506+056 is the first of the long-sought sources of astrophysical neutrinos.

When both results are considered together, this provides evidence that blazars, especially TXS 0506+056, is a site of high-energy cosmic ray acceleration, and blazars are a potential source of a sizable fraction of the IceCube diffuse neutrino flux.

Many question still remain:

- Why TXS 0506+056?
  - A distant (4 Bly) and very luminous blazar • Why not closer blazars?
  - Why did the archival flare not have an associated gamma ray flare?
- What other objects are out there like TXS 0506+056?
  - Ongoing investigations with partners to resolve
  - Continued alerts