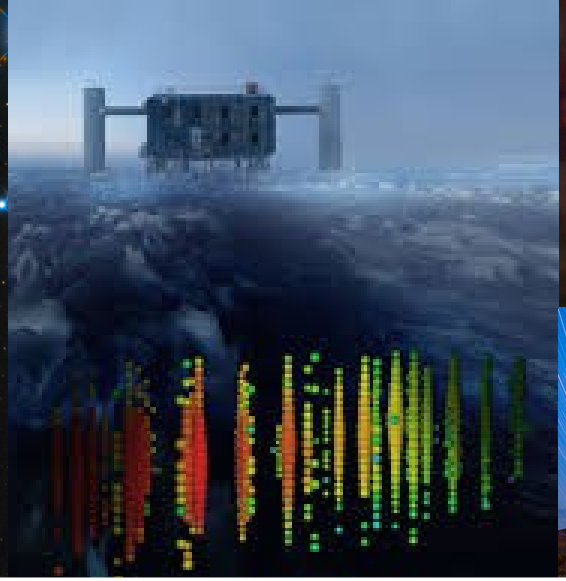
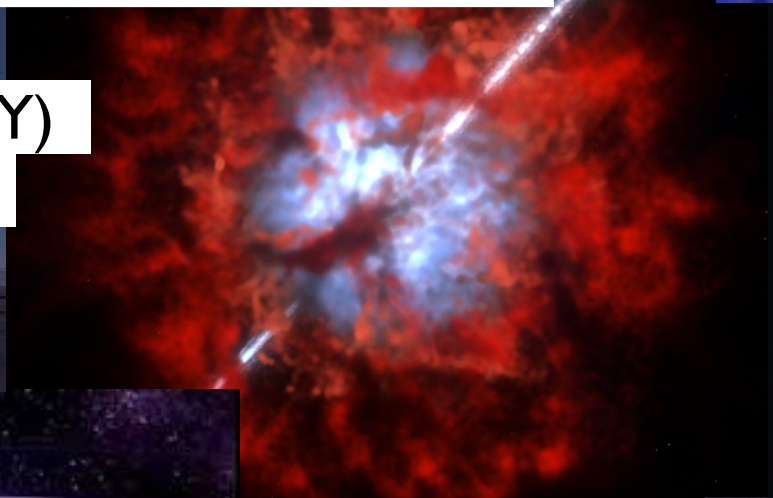
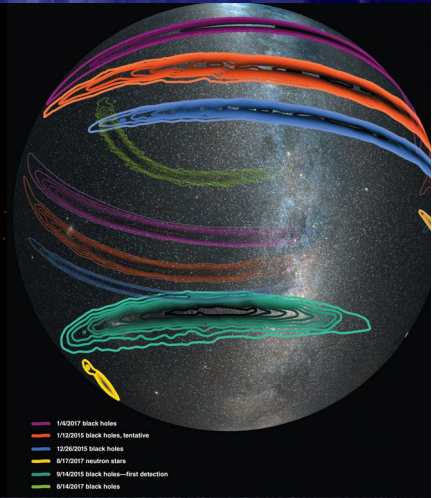
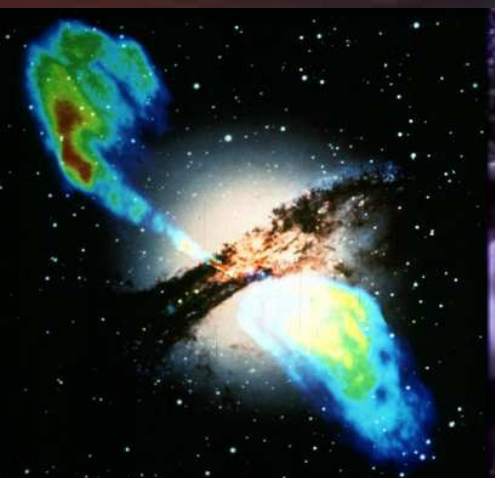




MultiMessenger astrophysics

Konstancja Satalecka (DESY)

Rencontres de Blois 2018

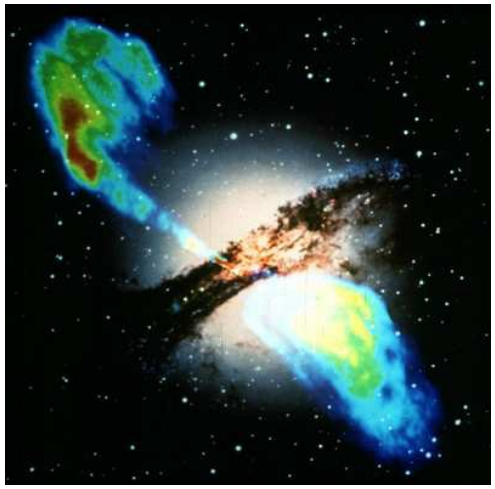







MultiMessenger

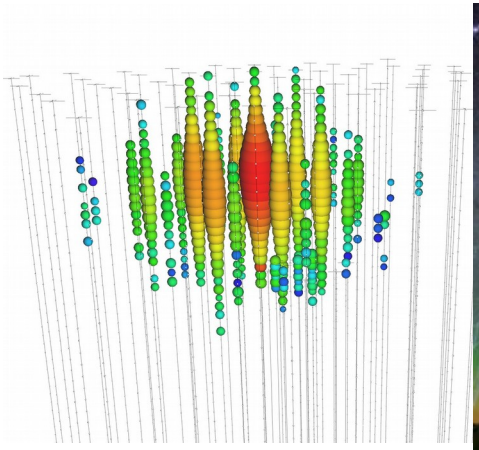
Coordinated observation and interpretation of distinct signals ("messengers") associated with two or more of the four fundamental forces:

photons

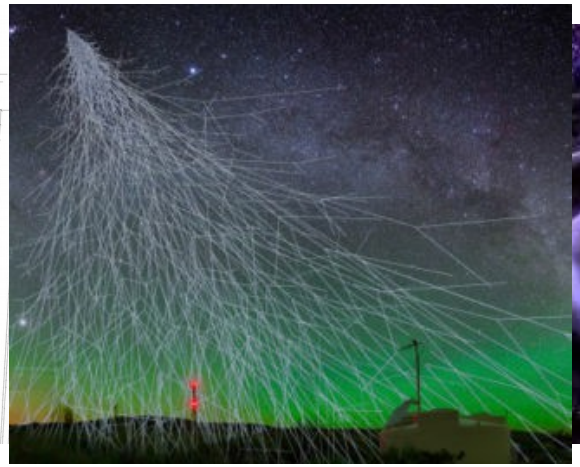


Heide Constantini
VHE g-rays, Fri @9:00

neutrinos



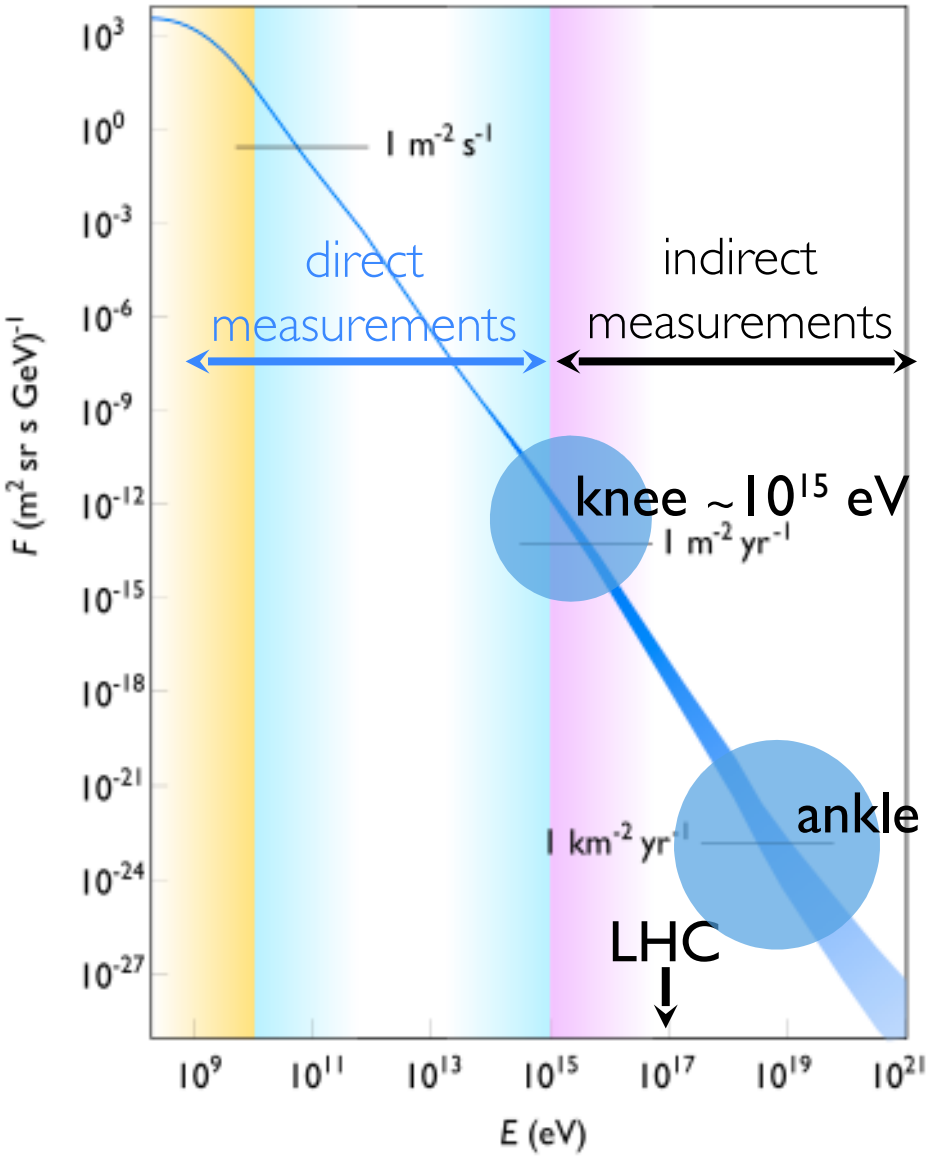
cosmic rays



gravitational waves

Ed Porter
GWs, Mon @10:15

Astrophysical messengers: cosmic rays



- protons, nuclei from He up to Fe

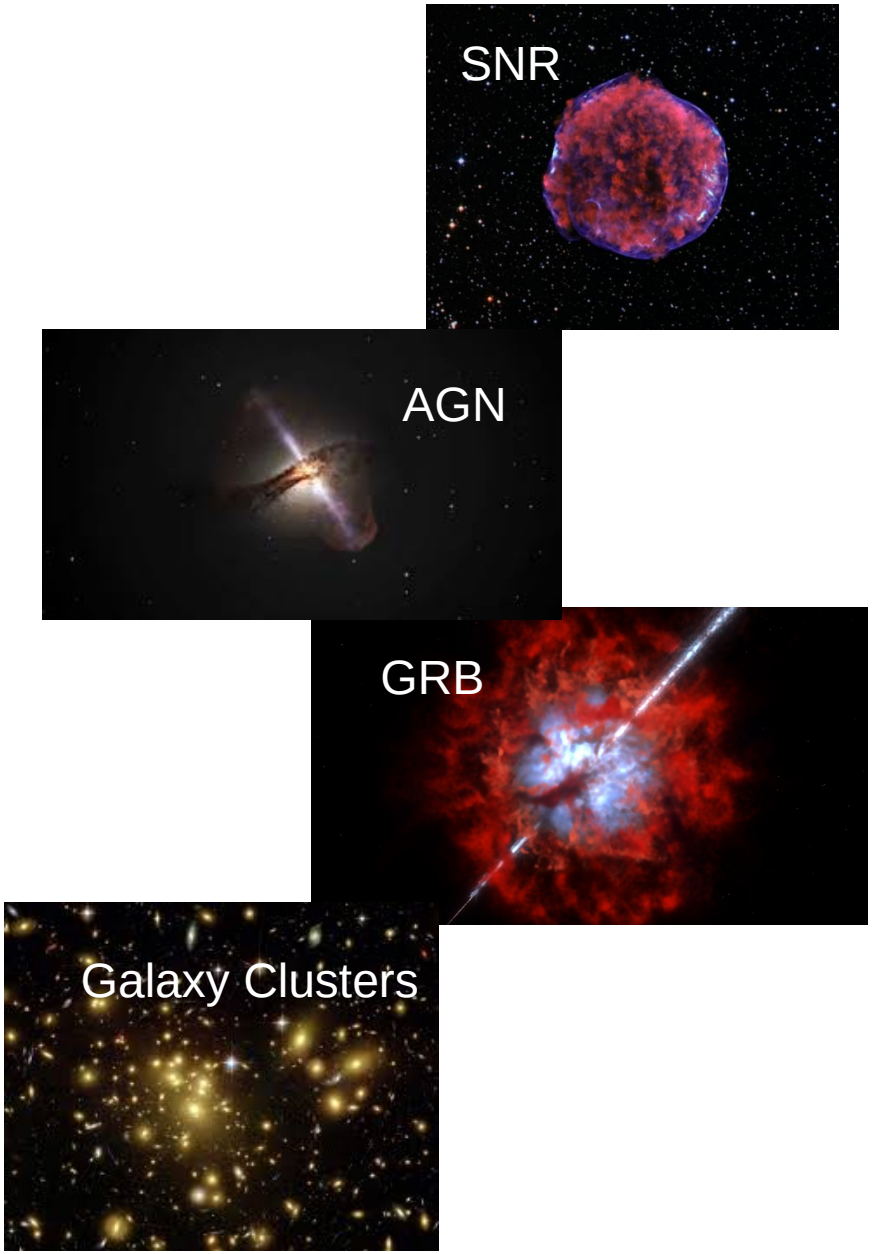
- CR interact with atmosphere
produce hadronic cascades
→ atmospheric neutrinos

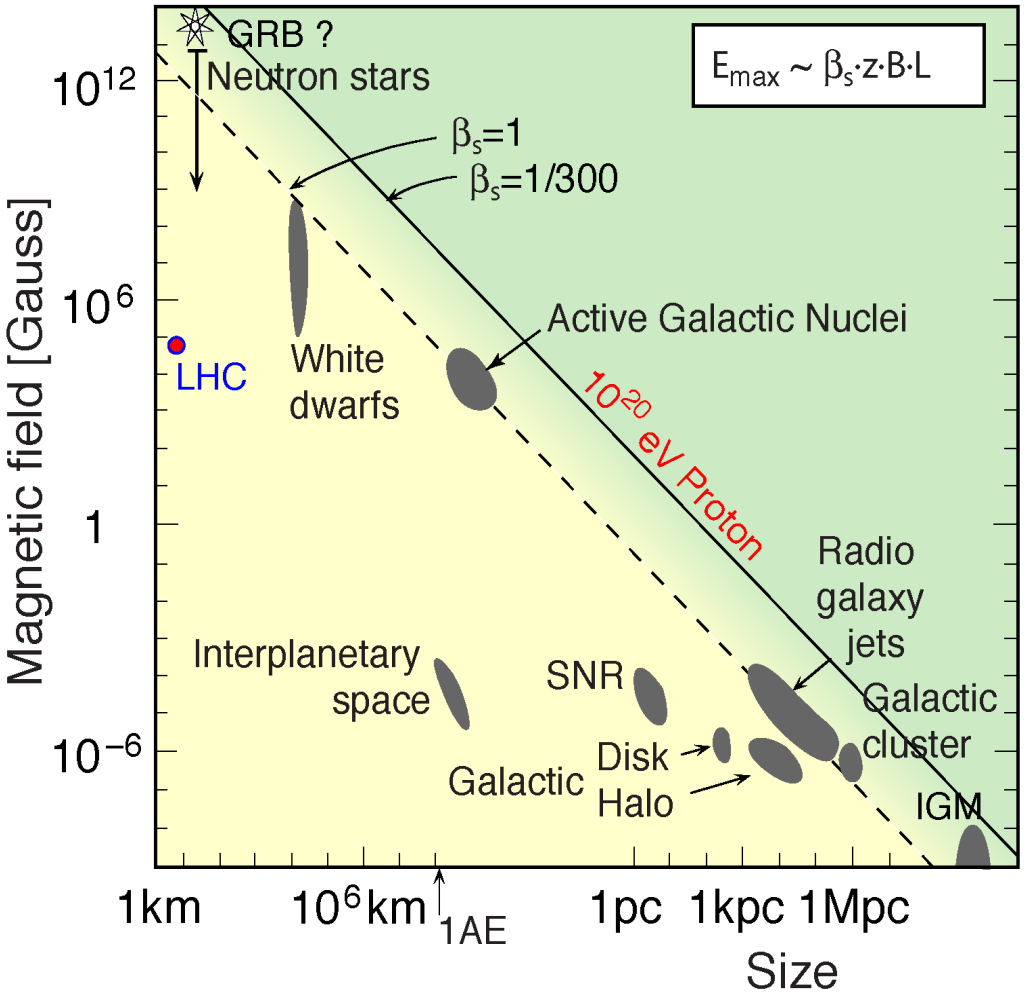
- power-law spectrum

- transition form galactic to extragalactic sources ~10^{15} eV (knee)

- GZK cutoff at ~10^{20} eV
$p+\gamma_{CMB} \rightarrow \Delta^{+} \rightarrow p+\pi^{0}$ or $n+\pi^{+}$
$\pi^{\pm} \rightarrow \mu^{\pm}\nu_{\mu} \rightarrow e^{\pm}\nu_{\mu}\,\nu_{e}$
guaranteed source of UHE neutrinos!

Cosmic rays: acceleration sites?

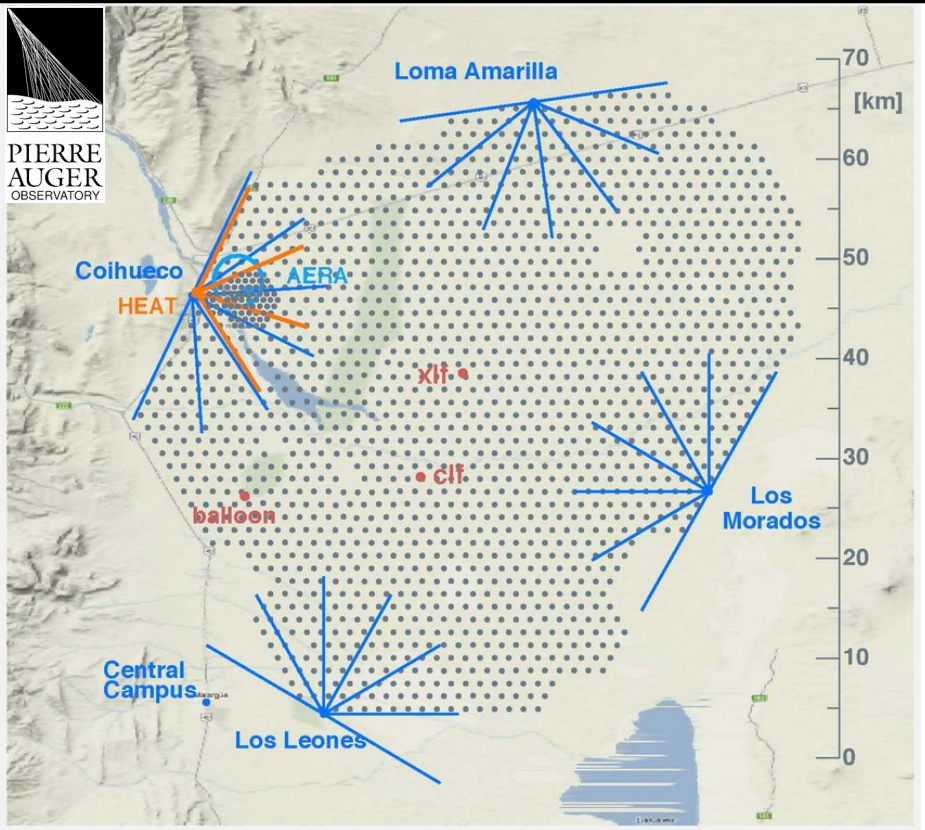




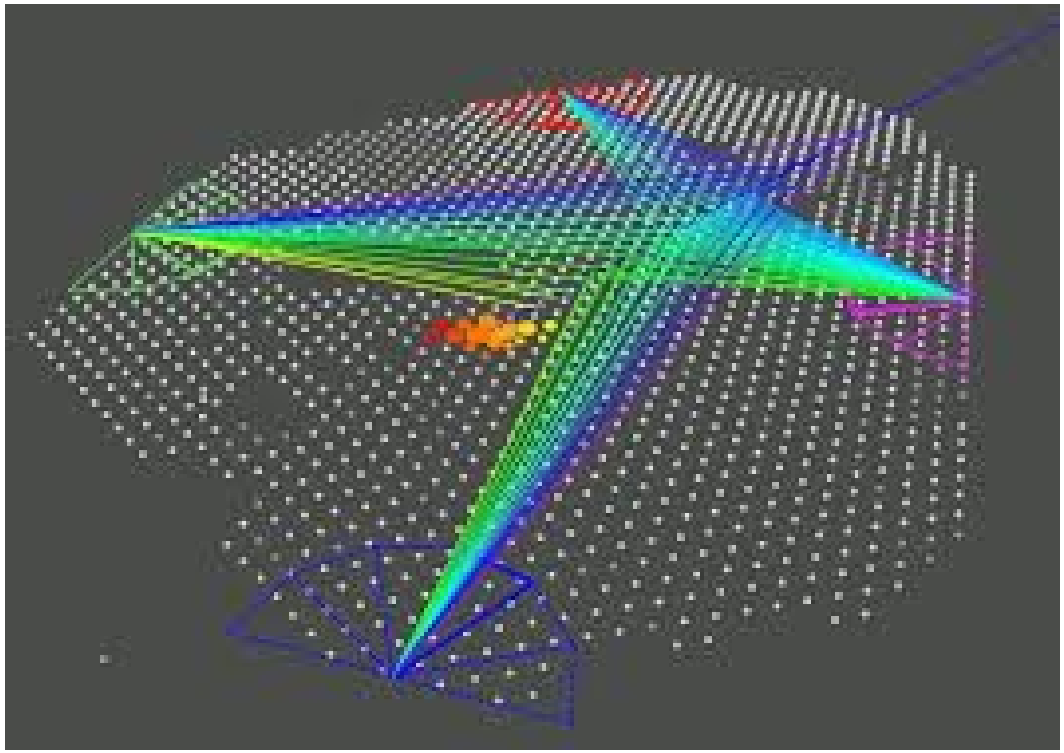
- Hillas criterium (1984):
  $E_{max} \simeq 10^{18}$eV $Z\,\beta$ (R/kpc)(B/μG)

Astrophysical messengers: cosmic rays

Ruben Conceicao
AUGER, Wed@18:50

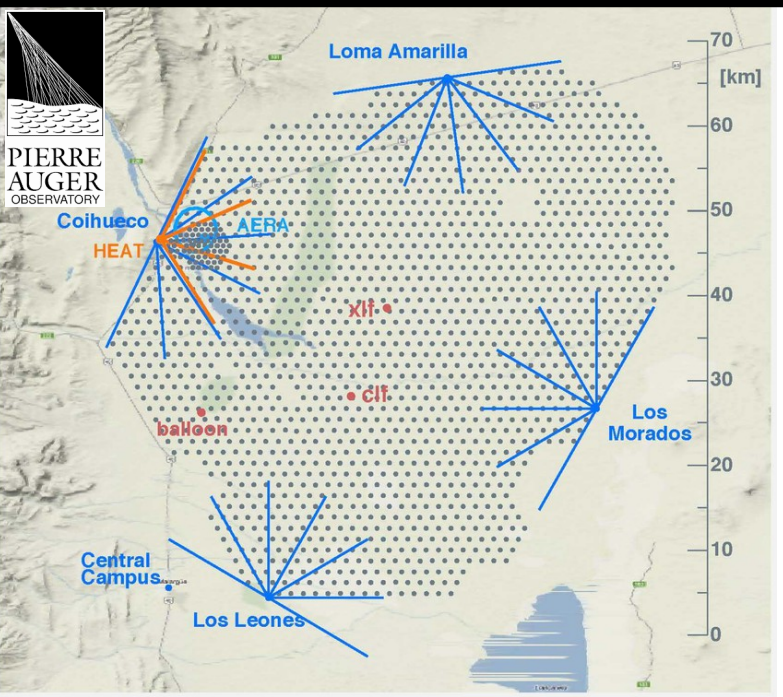


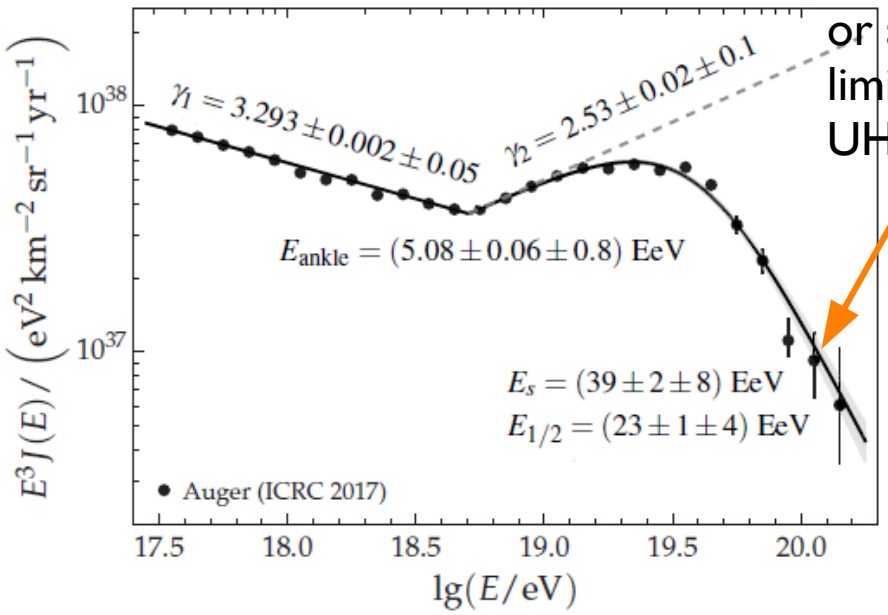
- Located in Argentina
- 3,000 km2 area
- Hybrid: 1600 water-Cherenkov tanks + 4 fluorescent detectors
- Detects CR of energy > 10^{17} eV (0.1 EeV)



Astrophysical messengers: cosmic rays

Ruben Conceicao
AUGER, Wed@18:50

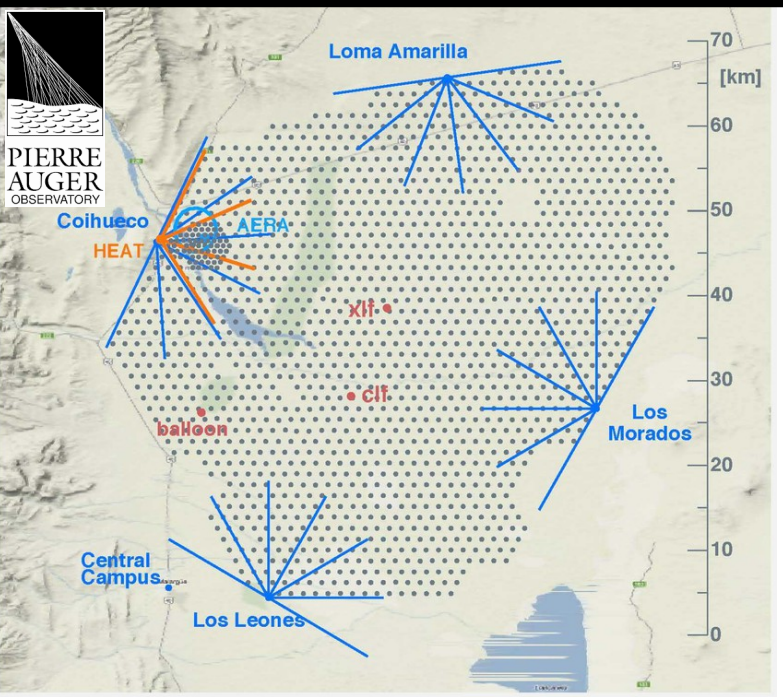


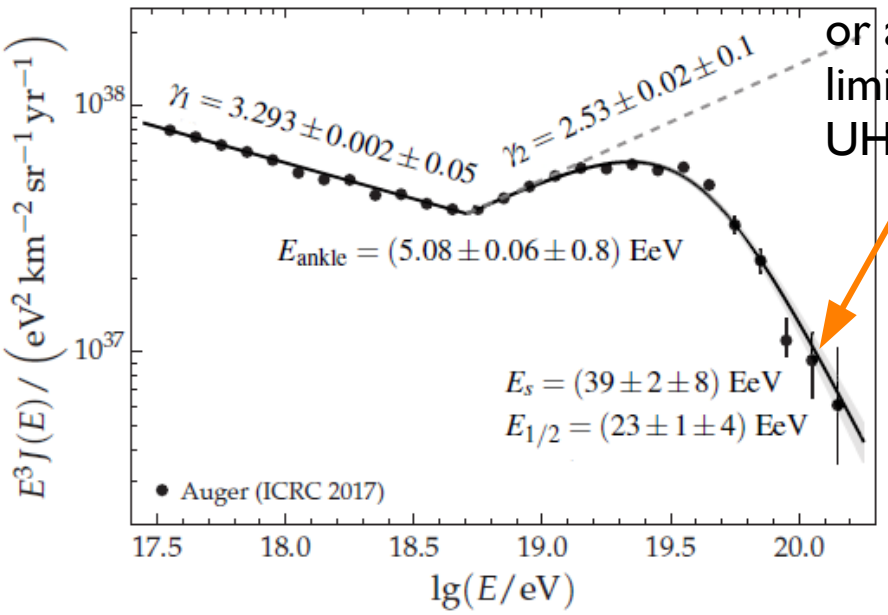


GZK cut-off
or acceleration
limits?
UHE neutrinos?

Astrophysical messengers: cosmic rays

Ruben Conceicao
AUGER, Wed@18:50





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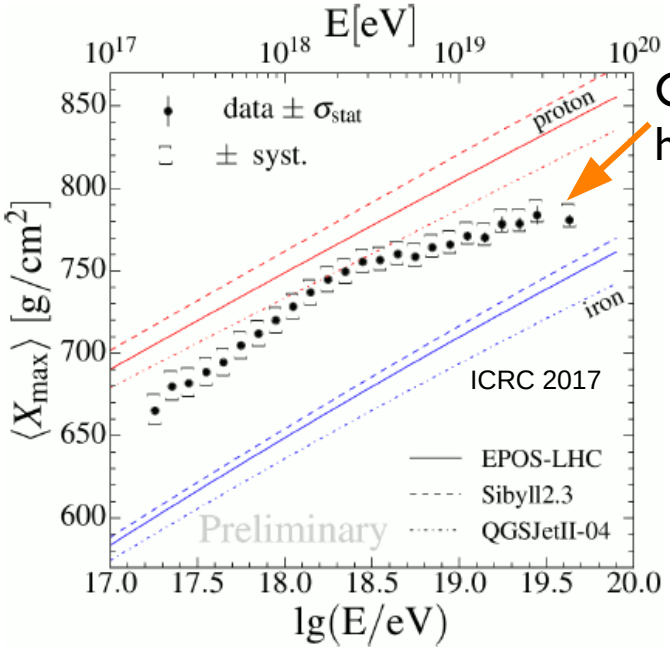
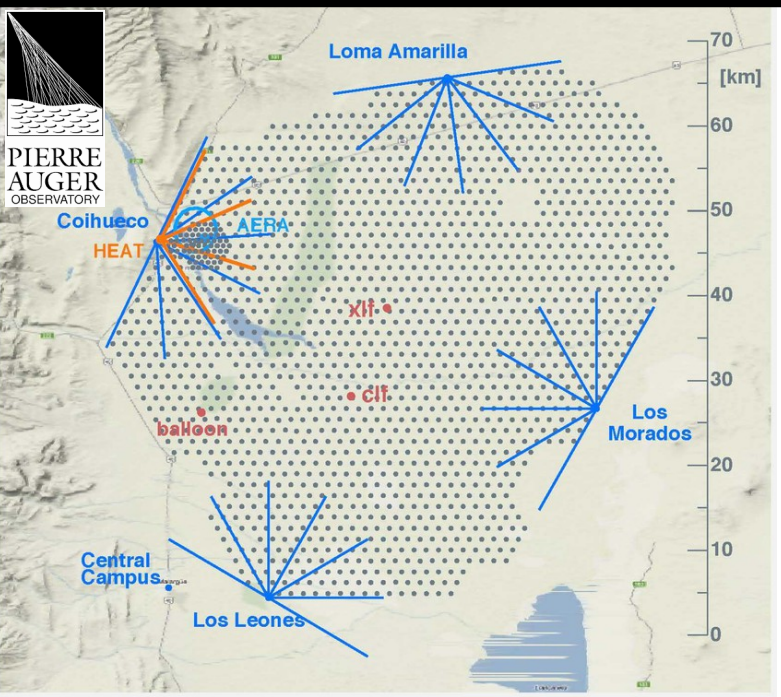
UHE neutrinos?

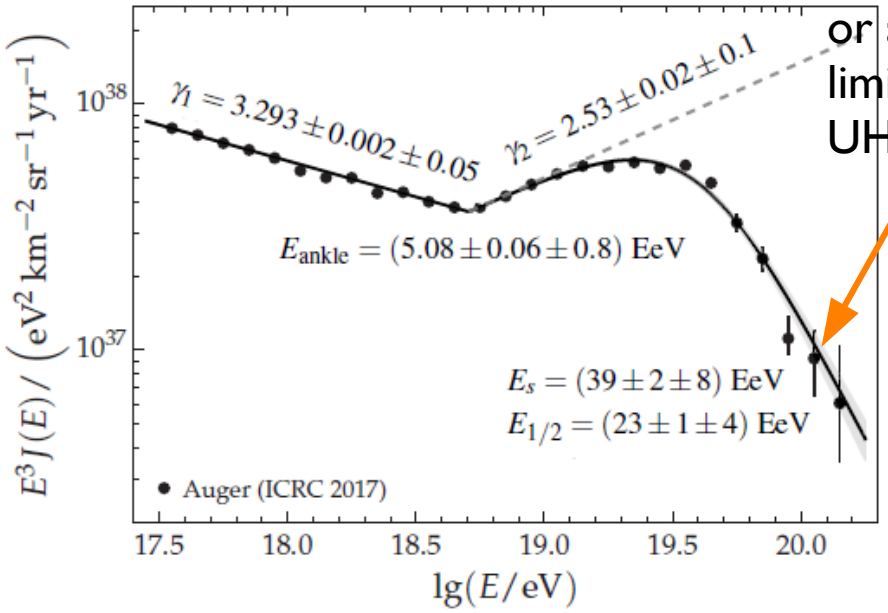


Composition:
heavier @ higher E

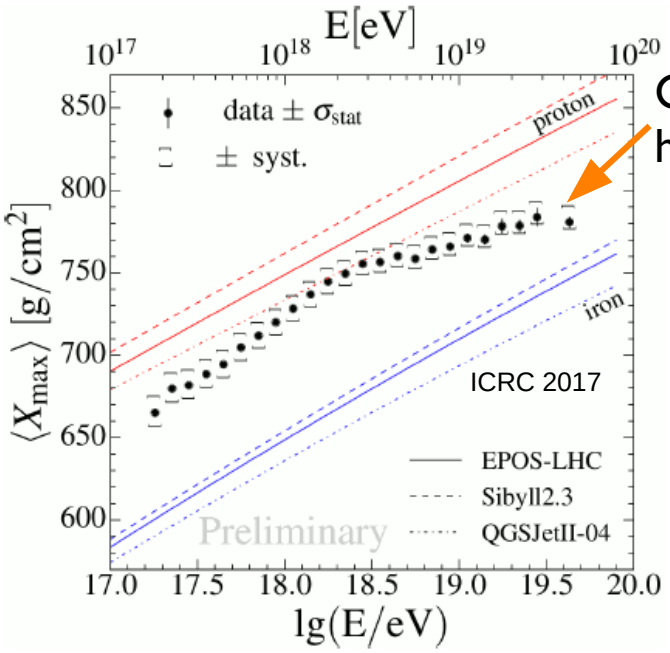
Astrophysical messengers: cosmic rays

Ruben Conceicao
AUGER, Wed@18:50



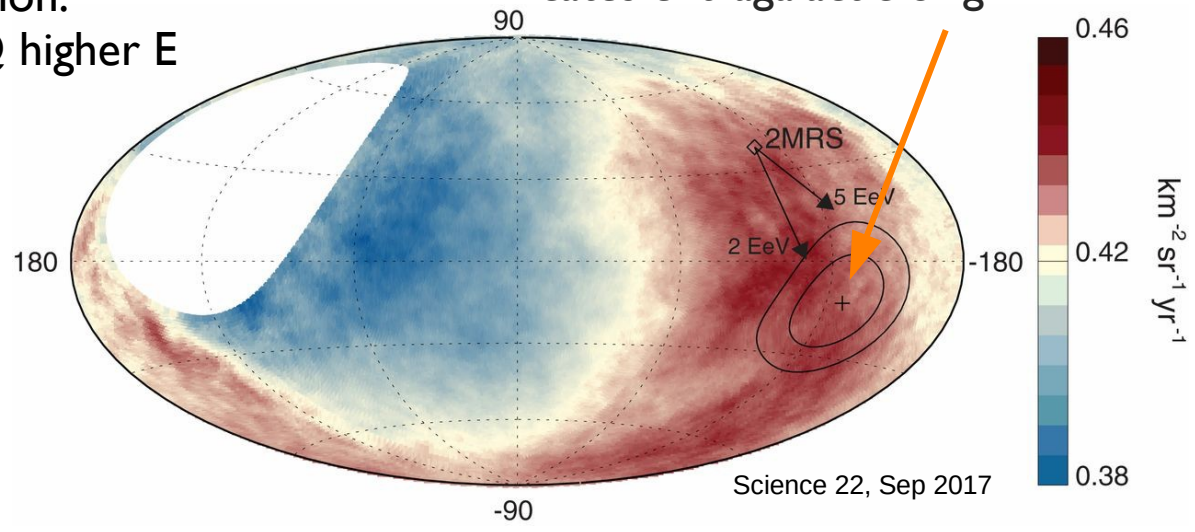


GZK cut-off
or acceleration
limits?
UHE neutrinos?



Composition:
heavier @ higher E

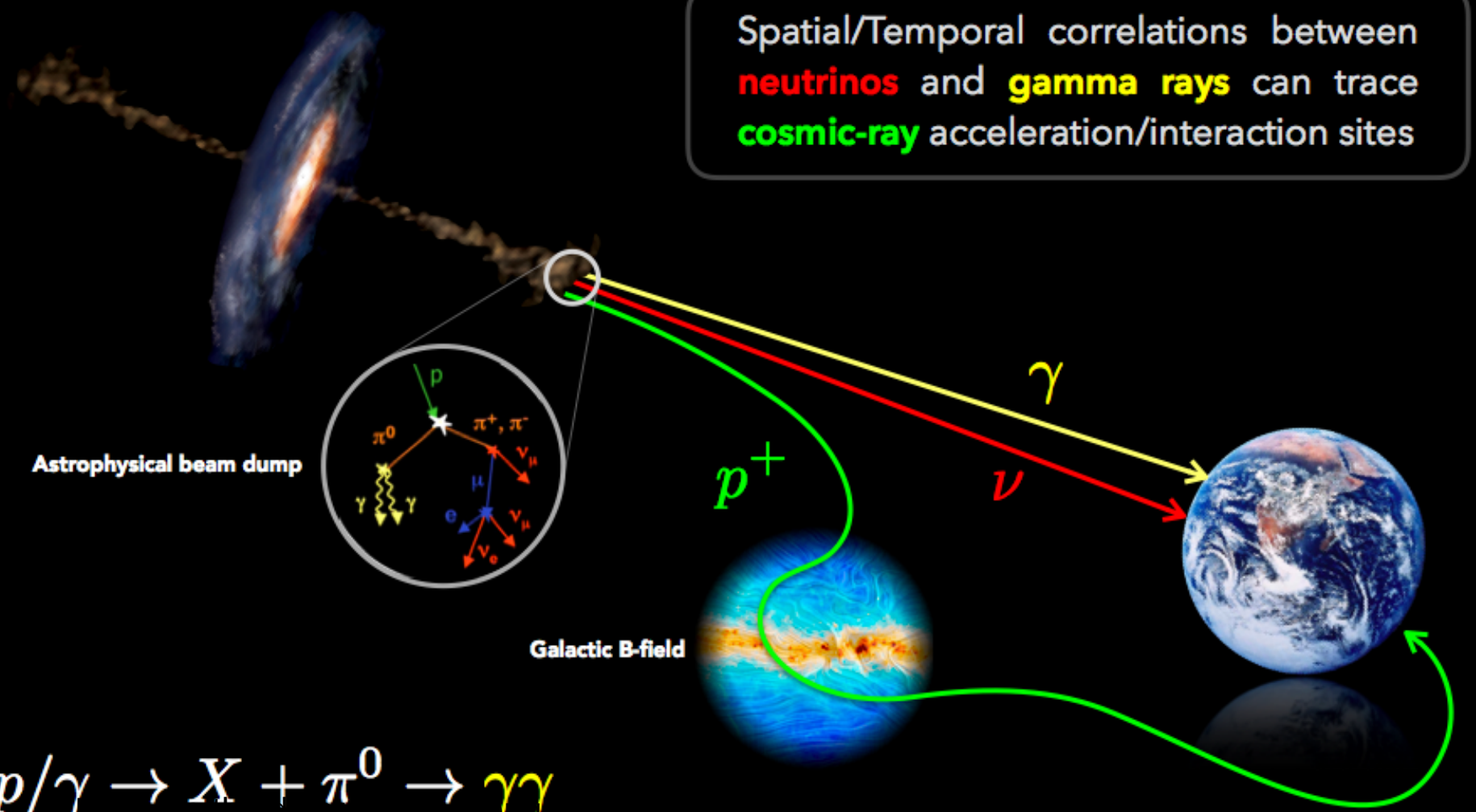
Large-scale anisotropy >8×10[18] eV
indicates extragalactic origin



Science 22, Sep 2017

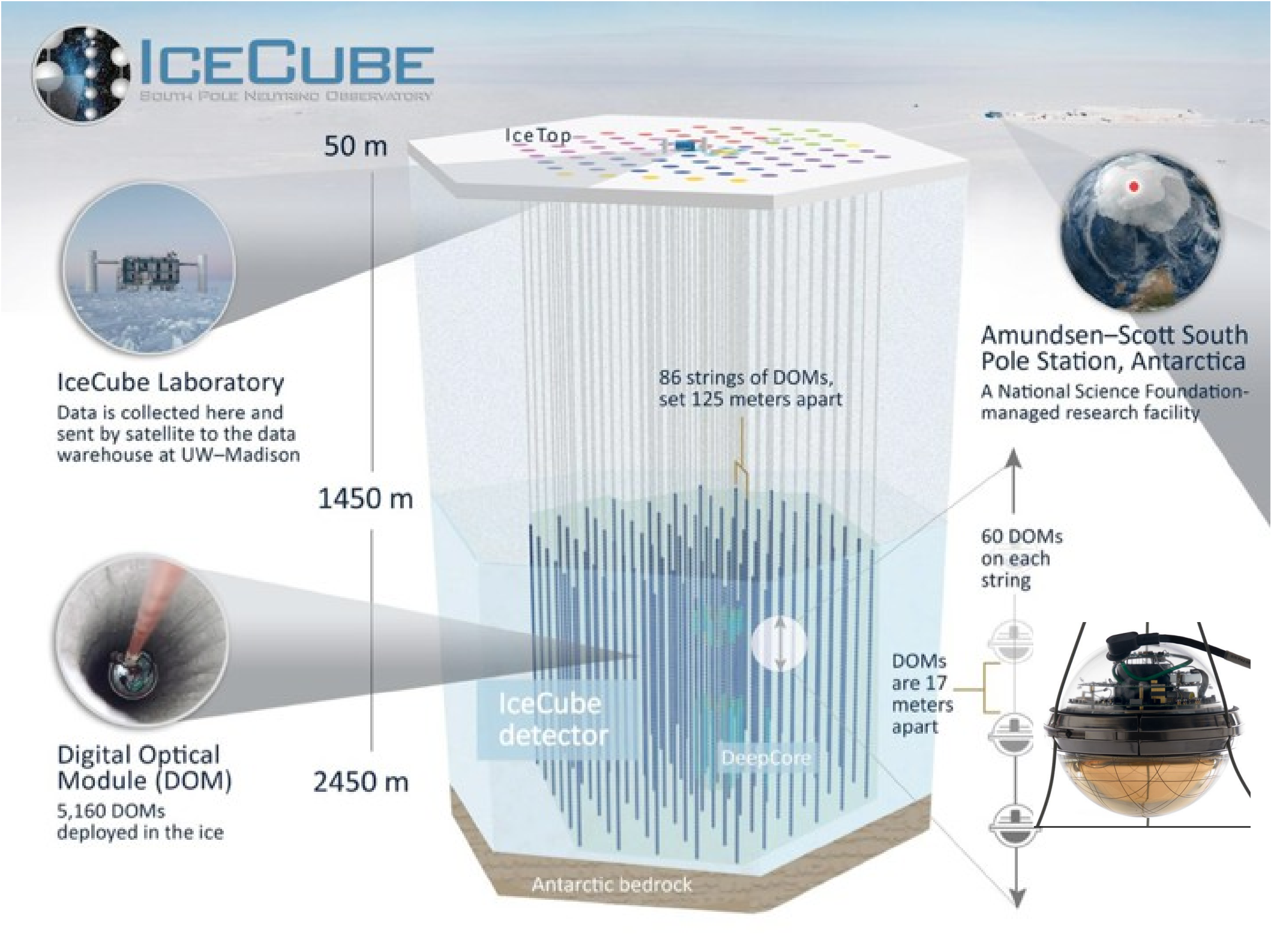
Neutrinos, γ–rays & CRs

Spatial/Temporal correlations between **neutrinos** and **gamma rays** can trace **cosmic-ray** acceleration/interaction sites



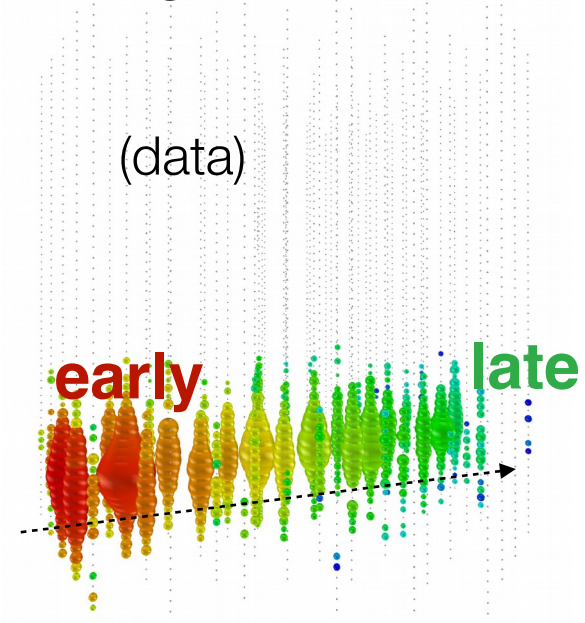
$$p + p/\gamma \rightarrow X + \pi^0 \rightarrow \gamma\gamma$$
$$\rightarrow X' + \pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

At source: 1:2:0
(oscillates to ~1:1:1)


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

Neutrino detection: event signatures

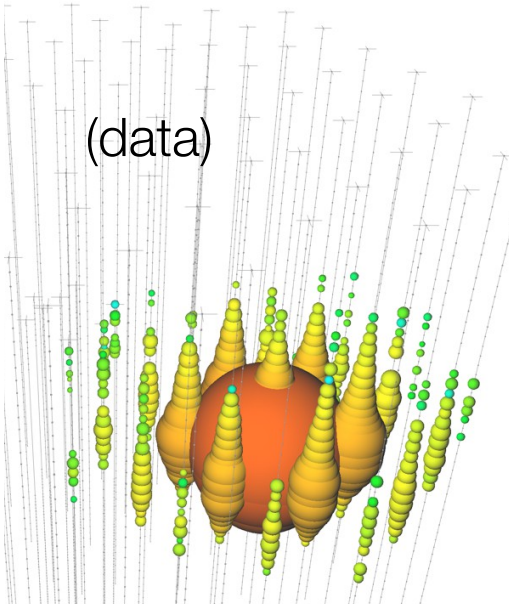
Charged-current ν_μ



Up-going track

Factor of ~2 E resolution
< 1 deg angular resolution

Neutral-current / ν_e

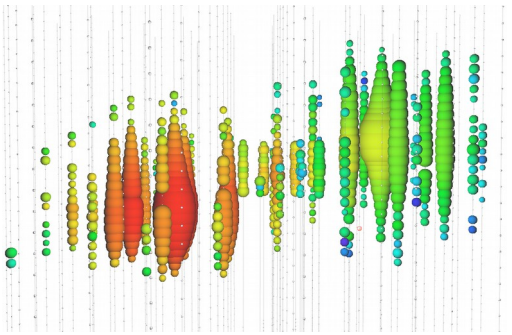


Isolated energy deposition (cascade) with no track

15% deposited E res.
~10-20 deg ang. res.

Charged-current ν_τ

(simulation)

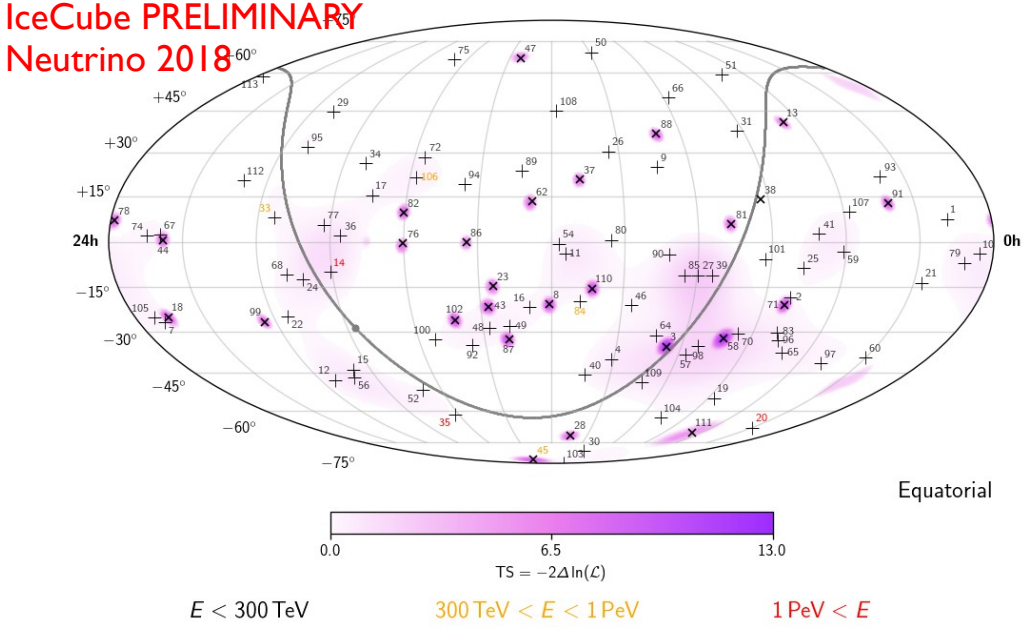


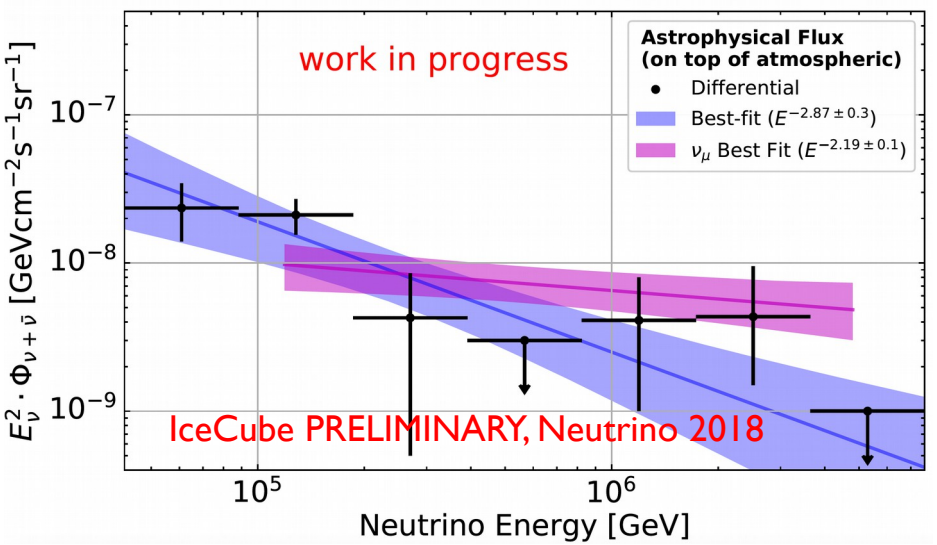
Double cascade

(resolvable above ~100 TeV deposited energy)

7.5 years of astrophysical neutrinos

M. Bustamante
Astro. neutrinos
Thu@15:00





First detection: 2013

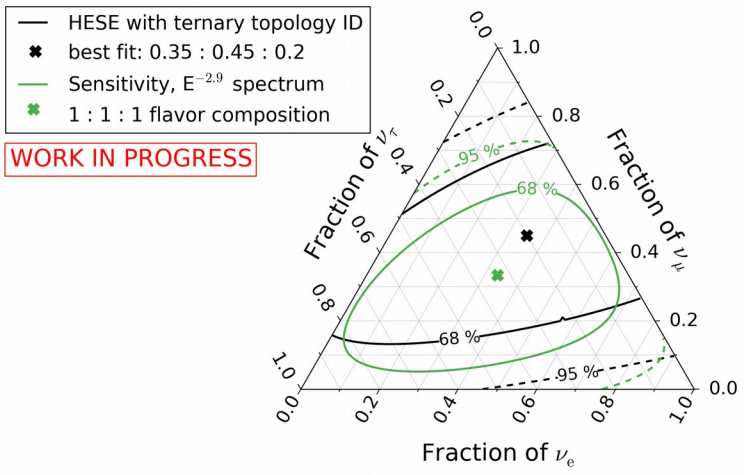
> 100 astrophysical events!

No significant event clustering

Energy spectrum: unbroken power law with $\gamma_{astro} \sim 2.9$

Flavor ratio – consistent with 1:1:1

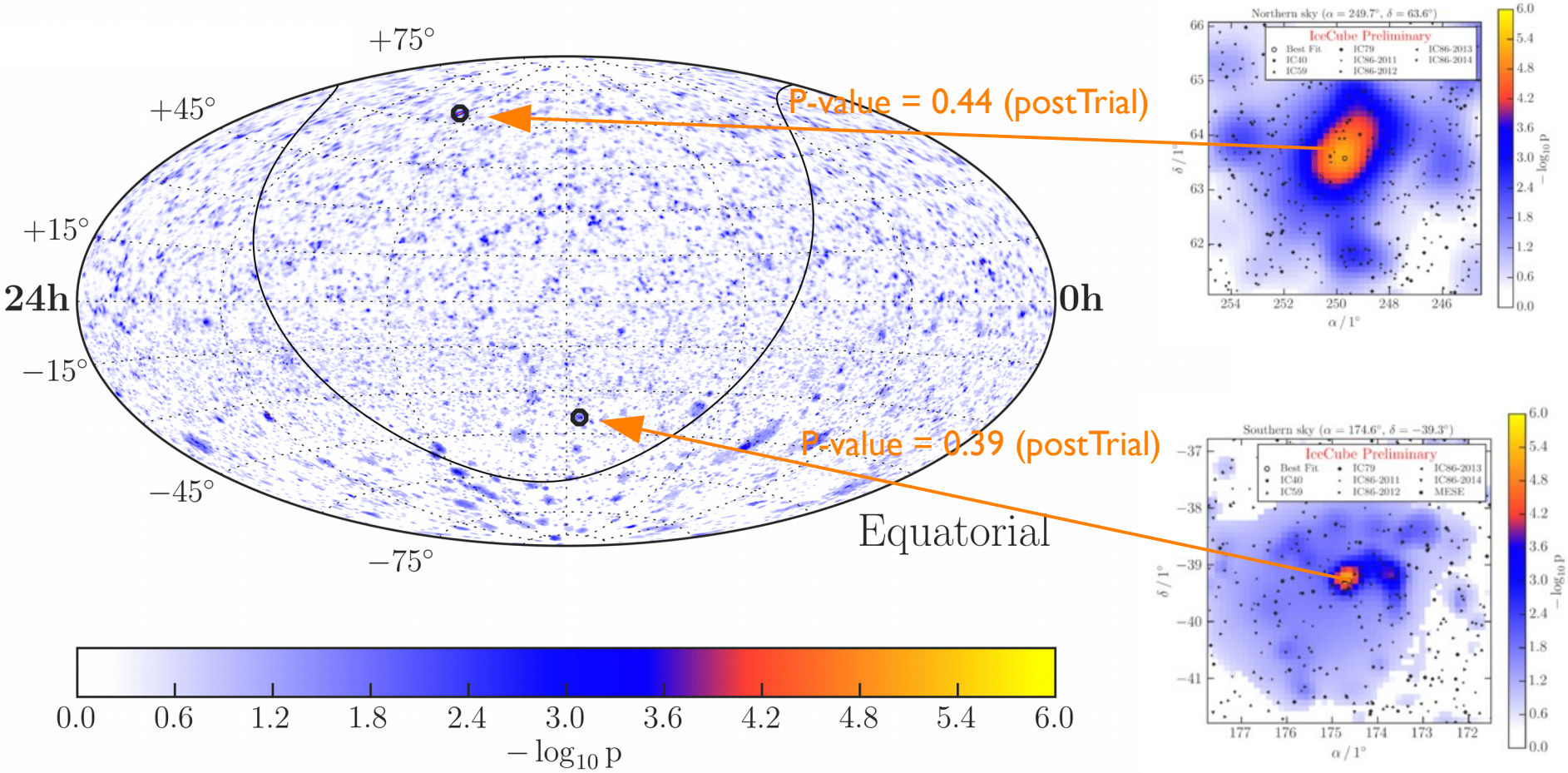
Mostly isotropic → extragalactic (?)



IceCube PRELIMINARY, Neutrino 2018

Neutrinos: search for point-sources

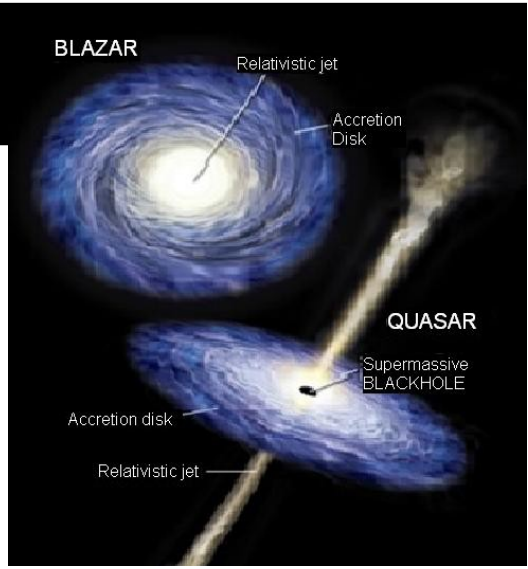
Stephanie Bron
IC PS search,
Wed@18:10



IceCube muon tracks > 1 TeV, all-sky, time independent analysis (7 years)

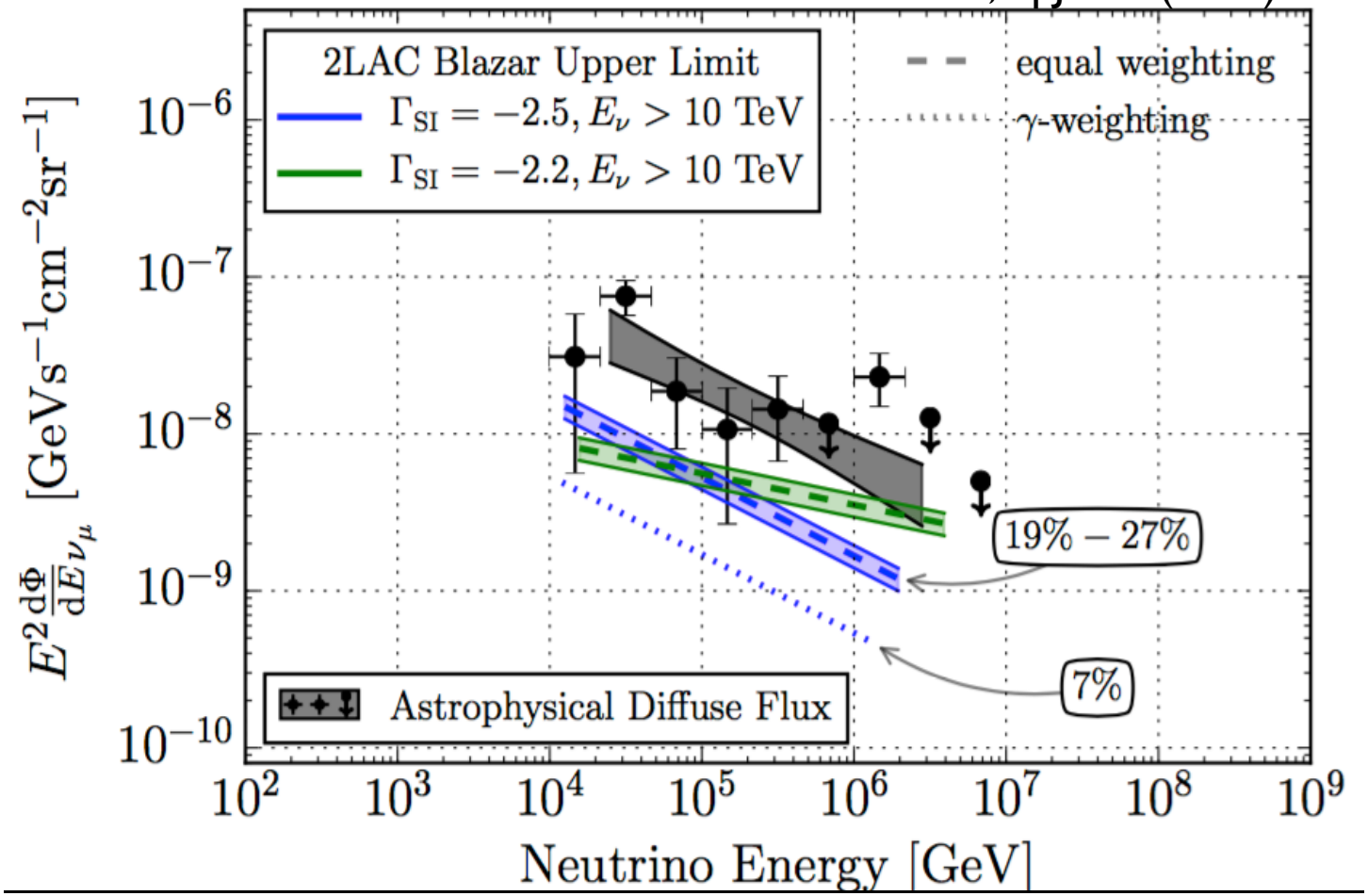
No significant event clustering in space, no point sources identified so far

Neutrino sources: blazars…?



Correlation of 7 years of IceCube neutrino events with > 860 blazars from 2LAC (Fermi/LAT)

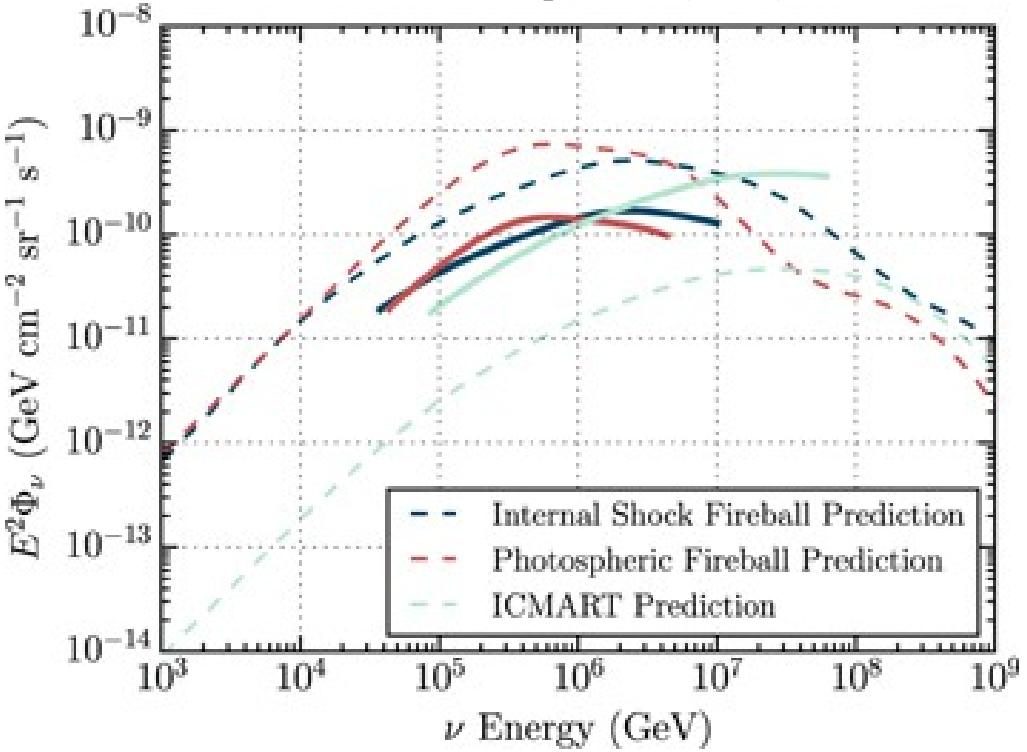
IC Coll., ApJ 853 (2017) 1



Blazars account for: 85% of extragalactic γ background, but only < 27% of the neutrino flux

Neutrino sources: GRBs…?

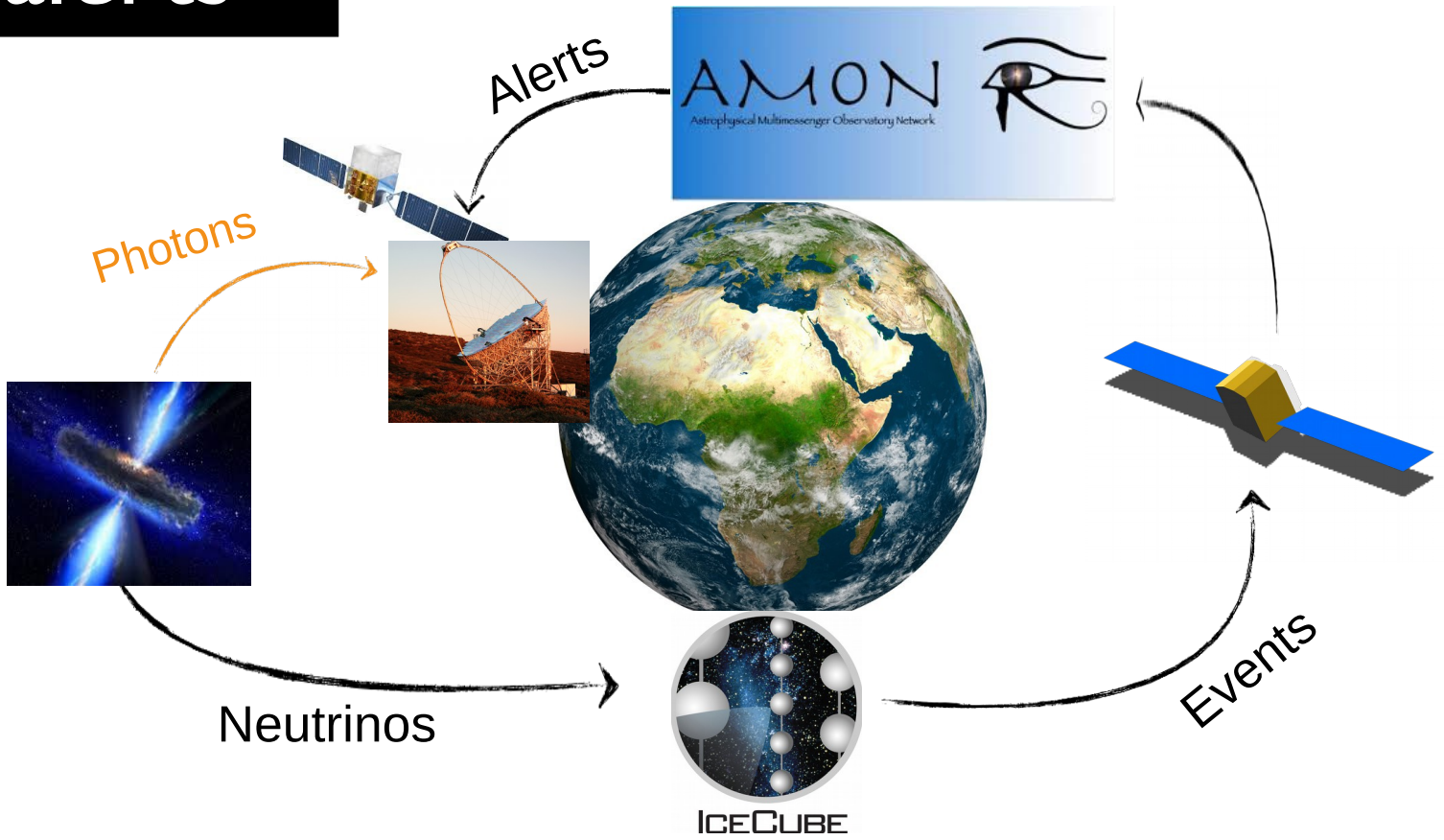
IC Coll., Ap J 843 (2017) 2



Exciting GW connection: production of neutrinos and g-rays in short-GRBs and GW events caused by mergers (NS-NS) [Bartos et al. (2013)]

- > 1100 GRBs correlated with IceCube data
- GRBs contribute less than 1% to observed diffuse neutrino flux
- Most popular neutrino emission models excluded (production in prompt phase)
- NOT excluded: production in precursor or after-glow phase, multi zone models, “chocked GRBs”…

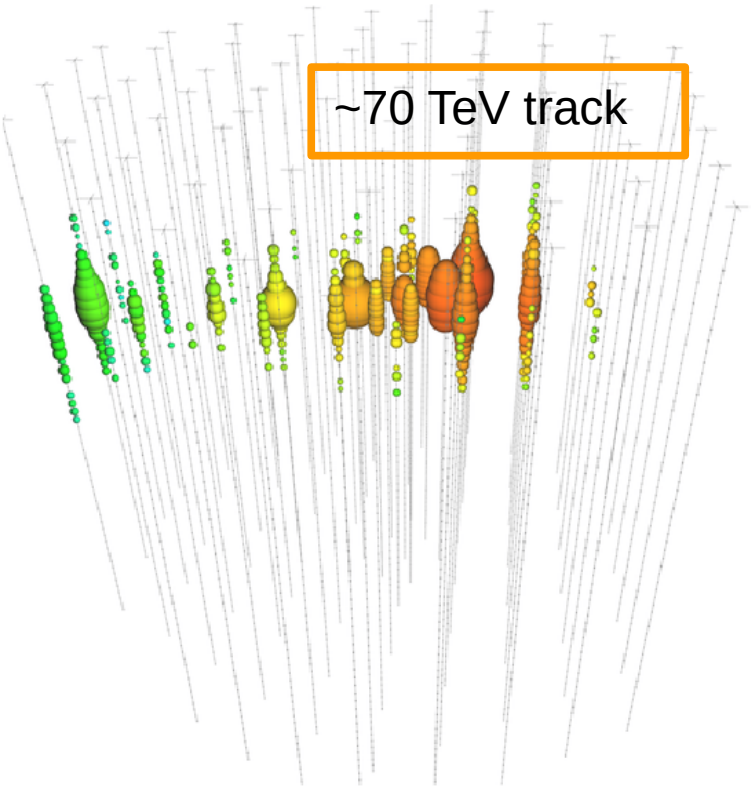
IceCube alerts



- Key for understanding neutrino source emission: simultaneous MWL data
- Alerts → make sure we get them when IC sees something interesting!
- IC alerts:
  - Public: single high energy events > 60 TeV (via AMON)
  - Private: event clusters, specific programs aimed at gamma-ray and optical telescopes

IC real-time system: M.G. Aartsen et al., Astropart. Phys. 92 (2017) 30-41s

IceCube public alerts

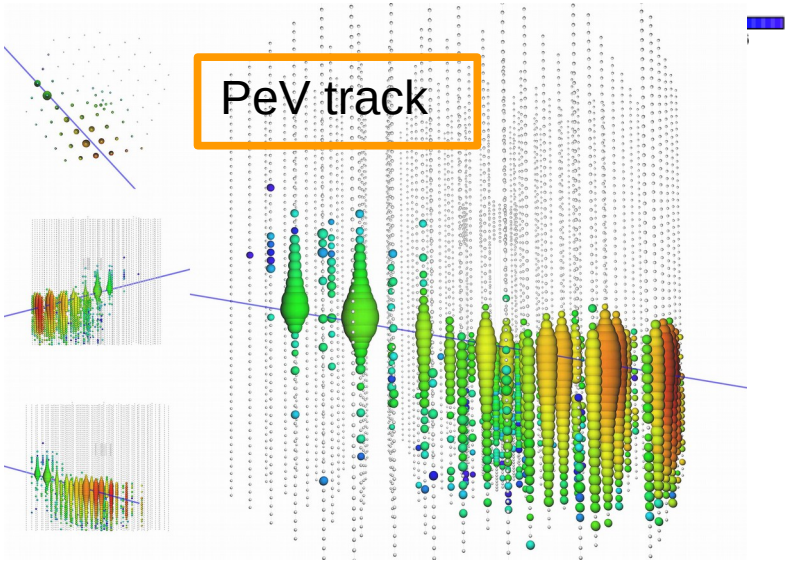


HESE = High Energy Starting Event (since Apr 2016):

- Muon track starting inside the detector
- E_{th} ~ 60 TeV
- median angular resolution 0.4-0.6 deg
- expected rate: 4/yr all-sky (50% signal probability)

EHE = Extremely High Energy (since Jun 2016):

- Muon track going through the detector
- E_{th} ~ 100 TeV
- median angular resolution 0.22 deg
- expected rate: 4/yr all-sky (75% signal probability)



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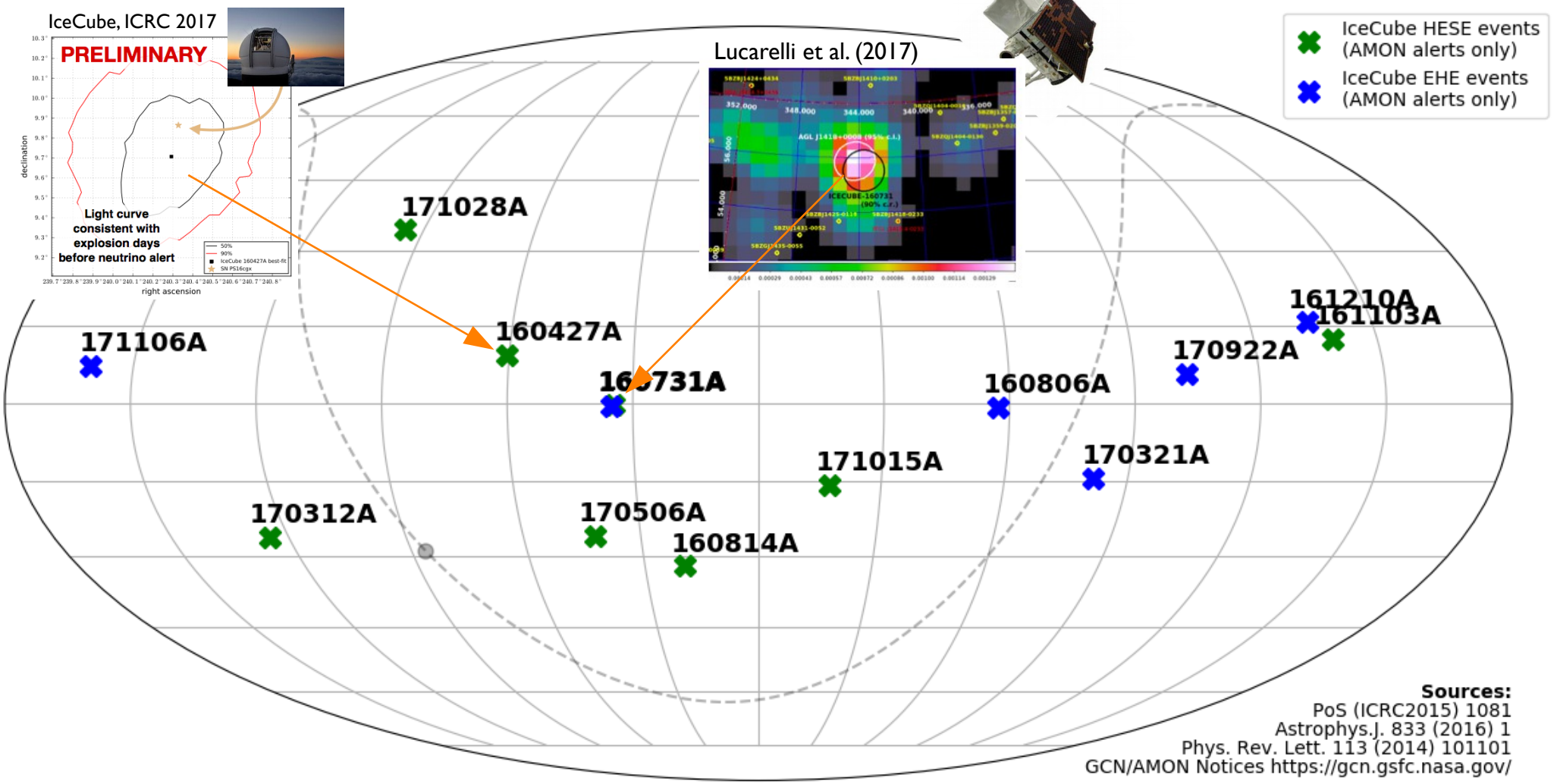
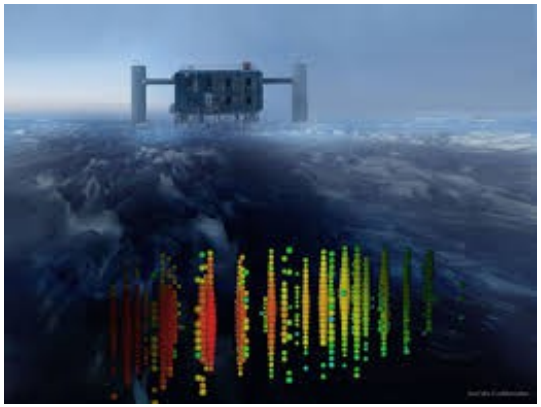
IceCube public alerts



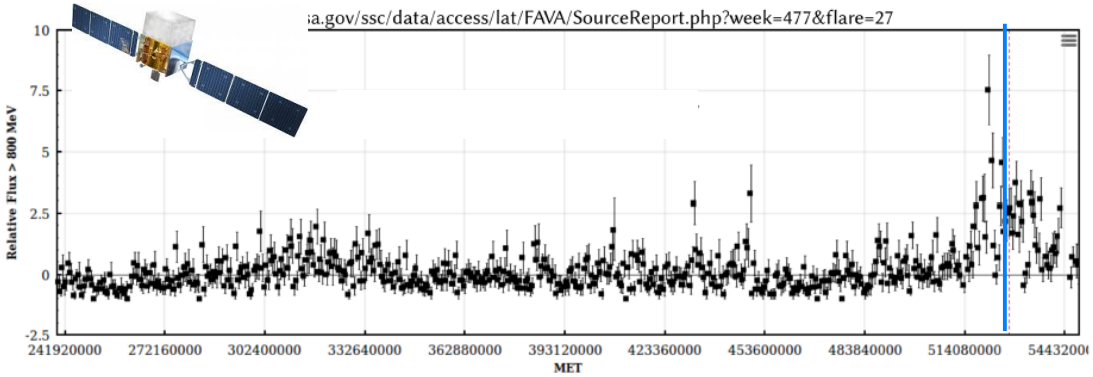
12 alerts sent so far. No firm source identification.

Planned extensions: all-sky neutrino event clusters + upgrade of single events streams (lower E threshold)

Alerts: IC-170922A



GCN #21916
Sep 22nd, 2017 @20:54:30.43 UTC
IceCube detects a high-energy muon track with a high probability of being of astrophysical origin (EHE)
RA: 77.43 deg (-0.80 deg/+1.30 deg, 90% PSF)
Dec: 5.72 deg (-0.40 deg/+0.70 deg, 90% PSF)
14 arcmin away from blazar TXS 0506+056!



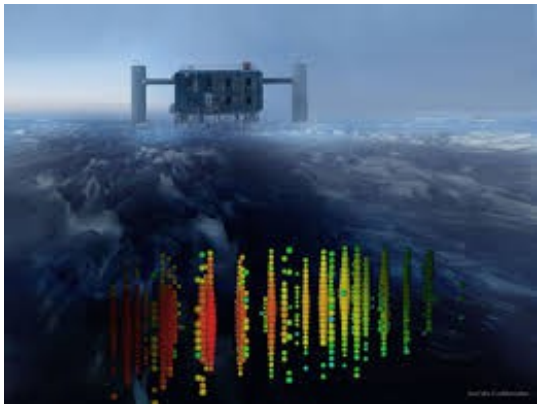
ATel #10791
Sep 27th, 2017
Fermi/LAT detection of an **increased gamma-ray activity of TXS 0506+056**

ATel #10817
Oct 4th, 2017
MAGIC: 12h of observations Sep 28th-Oct 3rd
Detection > 5 sigma > 100 GeV
First time detection of TXS 0506+056 in VHE gamma-rays

Related

10845 Joint Swift XRT and NuSTAR Observations of TXS 0506+056
10844 Kanata optical imaging and polarimetric follow-ups for possible IceCube counterpart TXS 0506+056
10840 VLT/X-Shooter spectrum of the blazar TXS 0506+056 (located inside the IceCube-170922A error box)
10838 MAXI/GSC observations of IceCube-170922A and TXS 0506+056
10833 VERITAS follow-up observations of IceCube neutrino event 170922A
10831 Optical photometry of TXS0506+056
10830 SALT-HRS observation of the blazar TXS 0506+056 associated with IceCube-170922A
10817 First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A
10802 HAWC gamma ray data prior to IceCube-170922A
10801 AGILE confirmation of gamma-ray activity from the IceCube-170922A error region
10799 Optical Spectrum of TXS 0506+056 (possible counterpart to IceCube-170922A)
10794 ASAS-SN optical light-curve of blazar TXS 0506+056, located inside the IceCube-170922A error region, shows increased optical activity
10792 Further Swift-XRT observations of IceCube 170922A
10791 Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.
10787 H.E.S.S. follow-up of IceCube-170922A
10773 Search for counterpart to IceCube-170922A with ANTARES

Alerts: IC-170922A



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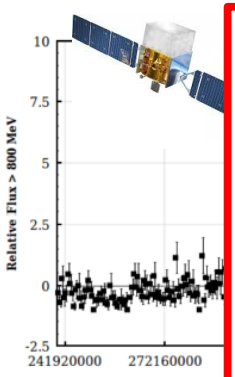
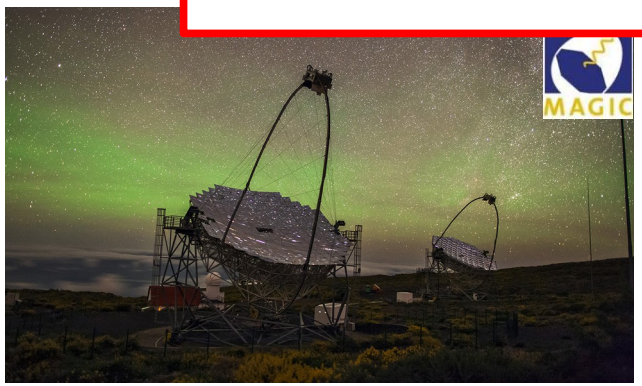
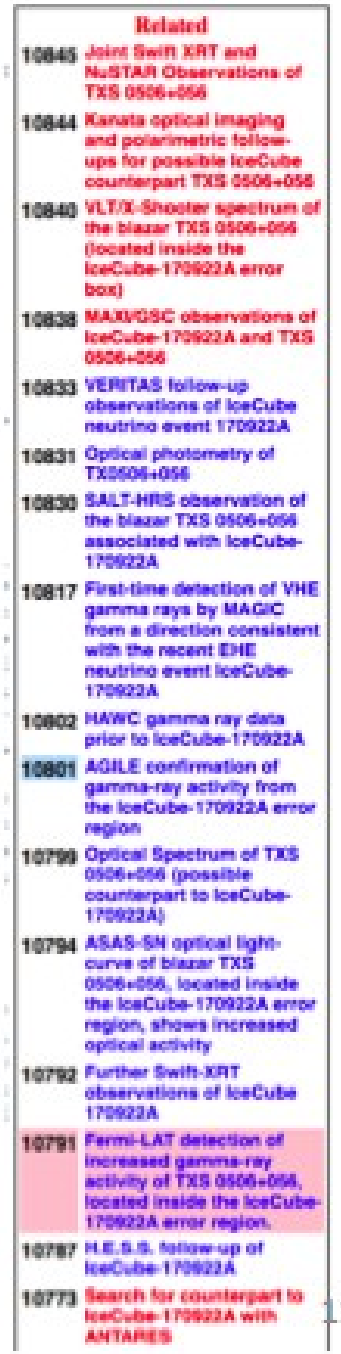


HE neutrino event observed from
a direction consistent with a gamma-ray emitter!

Publication coming soon!



Atel #10817
Oct 4th, 2017
MAGIC: 12h of observations Sep 28th-Oct 3rd
Detection > 5 sigma > 100 GeV
First time detection of TXS 0506+056 in VHE gamma-rays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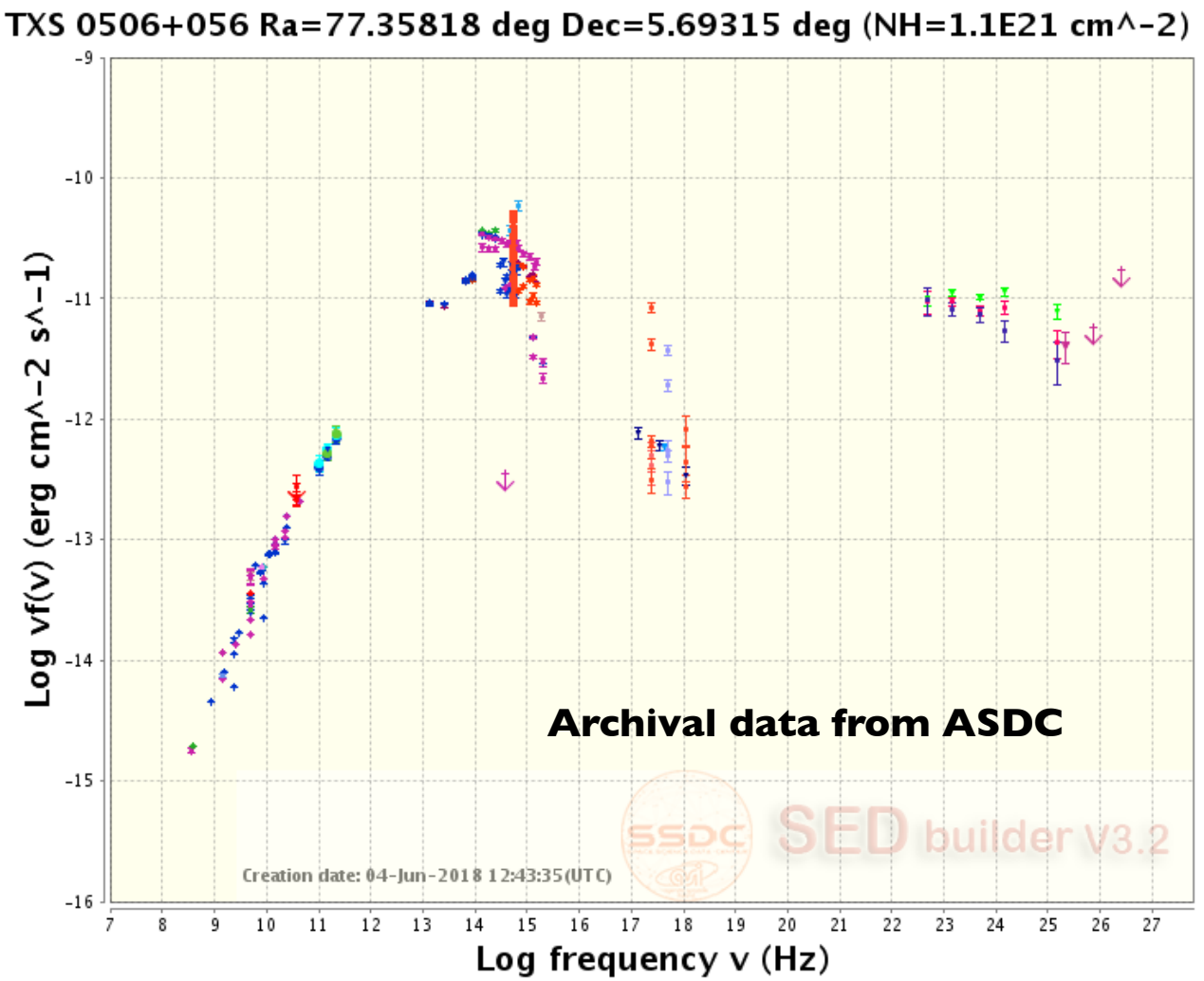
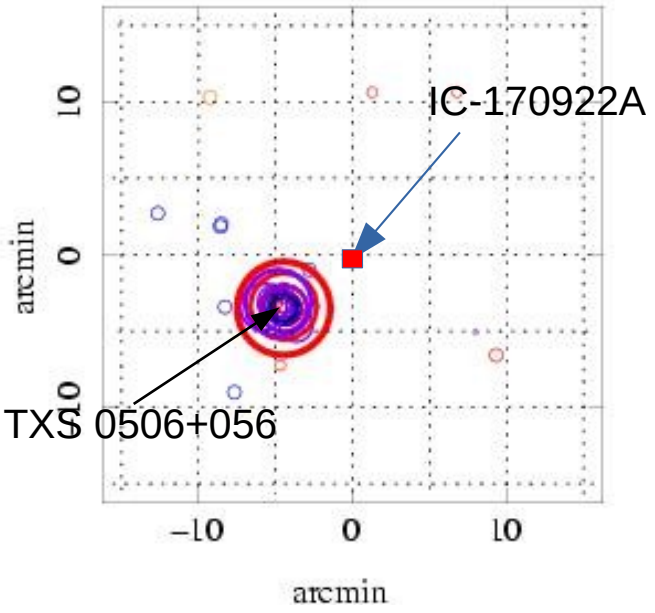
10844 Kanata optical imaging and polarimetric follow-ups for possible IceCube counterpart TXS 0506+056
10840 VLT/X-Shooter spectrum of the blazar TXS 0506+056 (located inside the IceCube-170922A error box)
10838 MAXI/GSC observations of IceCube-170922A and TXS 0506+056
10833 VERITAS follow-up observations of IceCube neutrino event 170922A
10831 Optical photometry of TXS0506+056
10830 SALT-HRS observation of the blazar TXS 0506+056 associated with IceCube-170922A
10817 First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A
10802 HAWC gamma ray data prior to IceCube-170922A
10801 AGILE confirmation of gamma-ray activity from the IceCube-170922A error region
10799 Optical Spectrum of TXS 0506+056 (possible counterpart to IceCube-170922A)
10794 ASAS-SN optical light-curve of blazar TXS 0506+056, located inside the IceCube-170922A error region, shows increased optical activity
10792 Further Swift-XRT observations of IceCube 170922A
10791 Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.
10787 H.E.S.S. follow-up of IceCube-170922A
10773 Search for counterpart to IceCube-170922A with ANTARES

TXS 0506+056

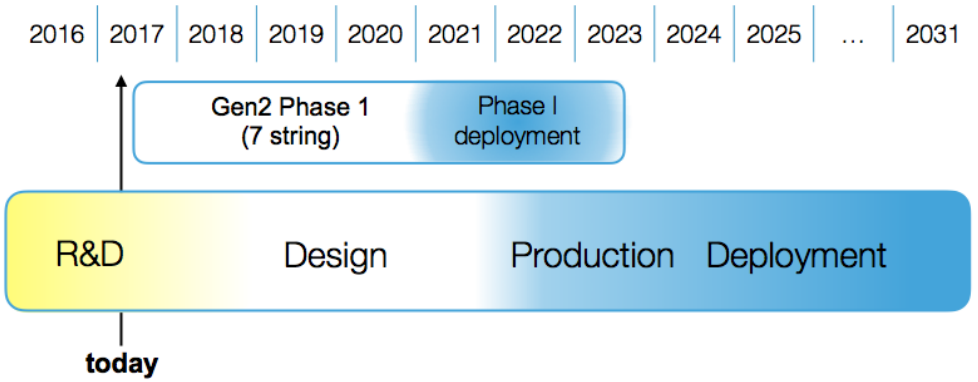




Typical blazar of BL Lac type
z= 0.34 (Paiano et al., 2018)
10% brightest in HE g-rays

After alert: dense MWL coverage + neutrino?! → Exciting prospects for modeling!

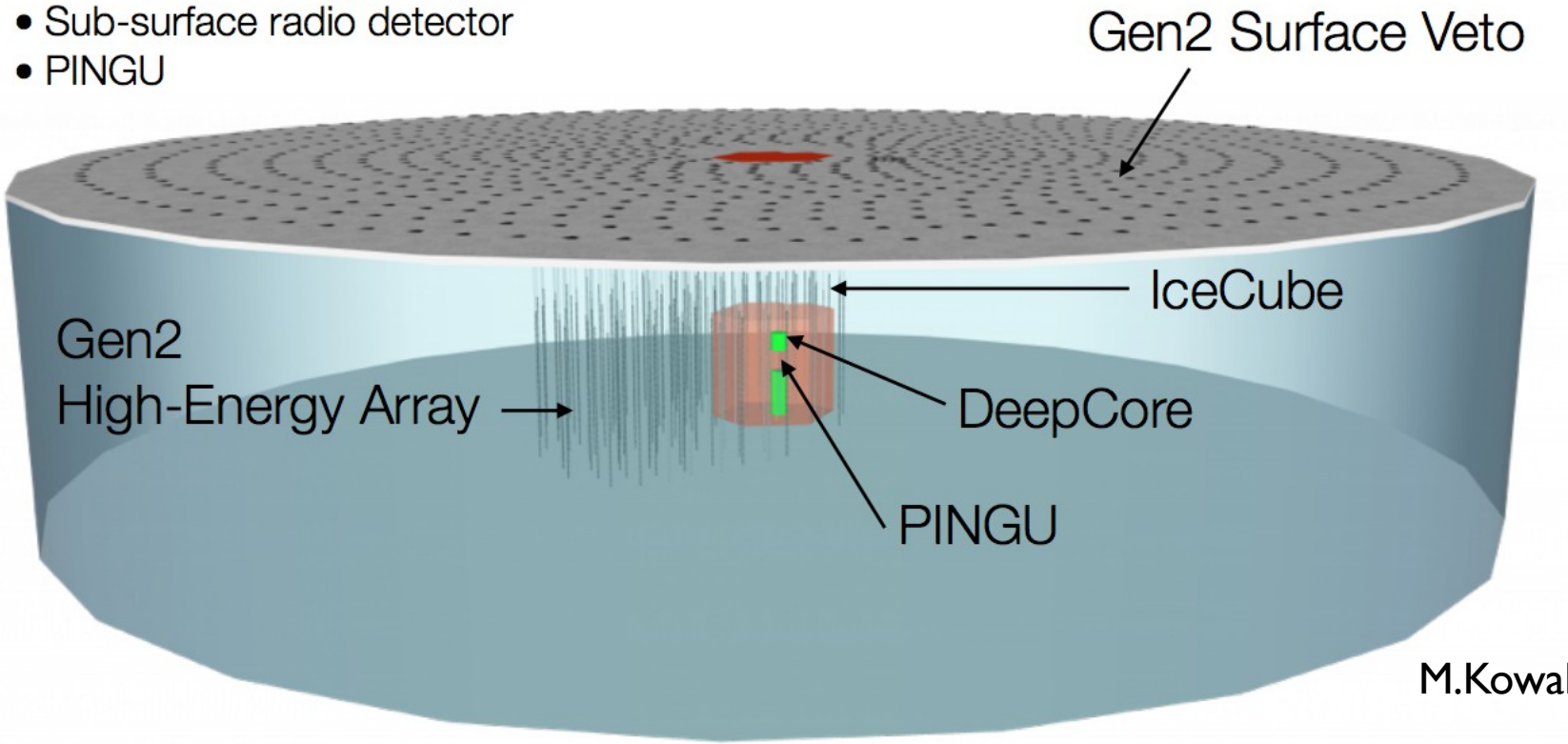
Future: IceCubeGen2



A wide band neutrino observatory (MeV – EeV) using several detection technologies – optical, radio, and surface veto – to maximize the science

Multi-component observatory:

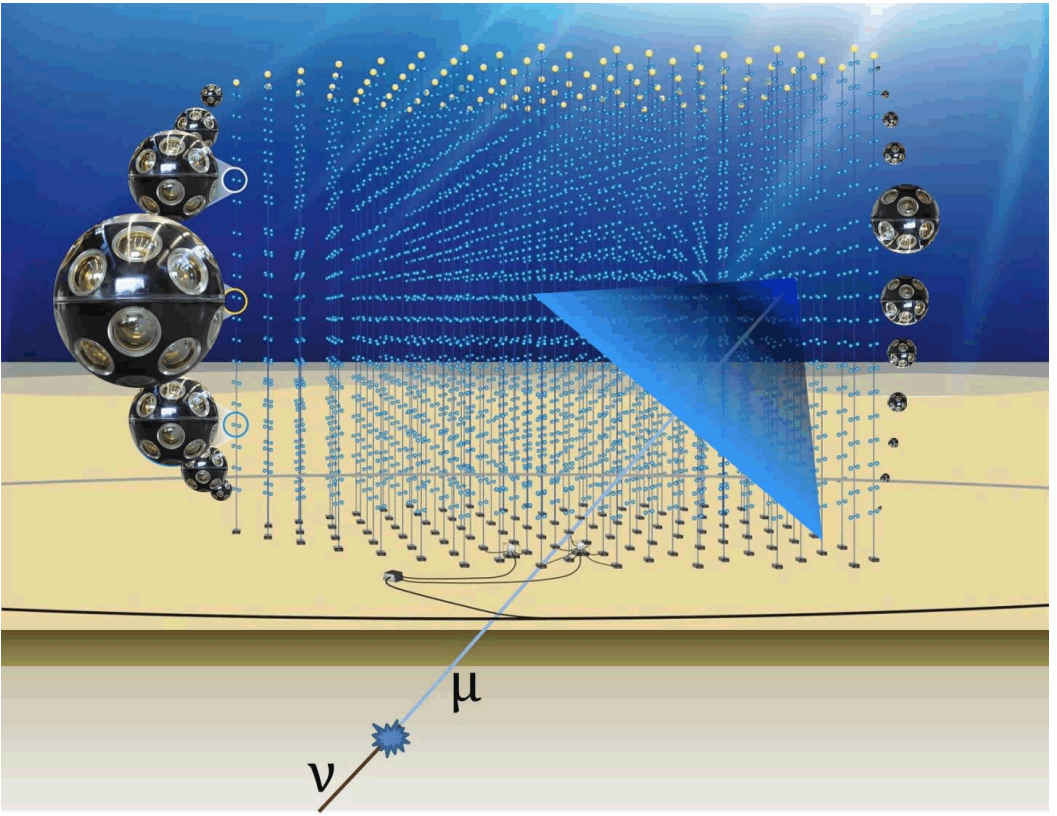
- Surface air shower detector
- Gen2 High-Energy Array
- Sub-surface radio detector
- PINGU



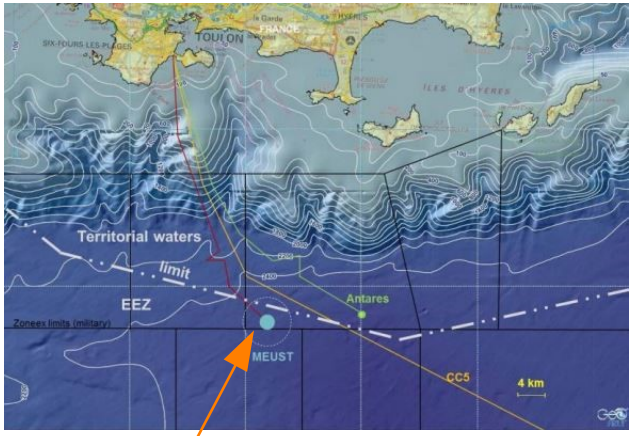
M.Kowalski TeVPA 2017

Future: KM3NeT

G.Ferrara, Wed@17:50
ANTARES+KM3Net

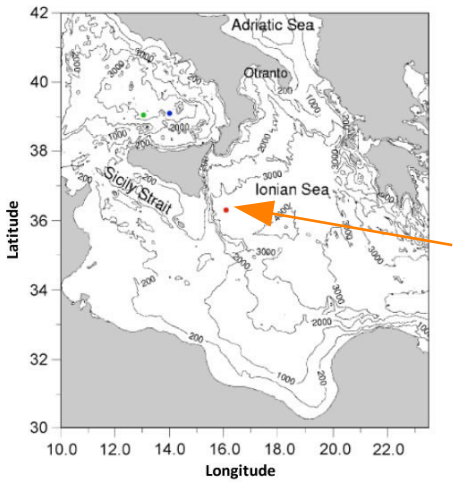


Multi-cubic km size neutrino telescope in Mediterranean Sea



ORCA: neutrino oscillations

- Fist string deployed in 2017
- Completion ~2021

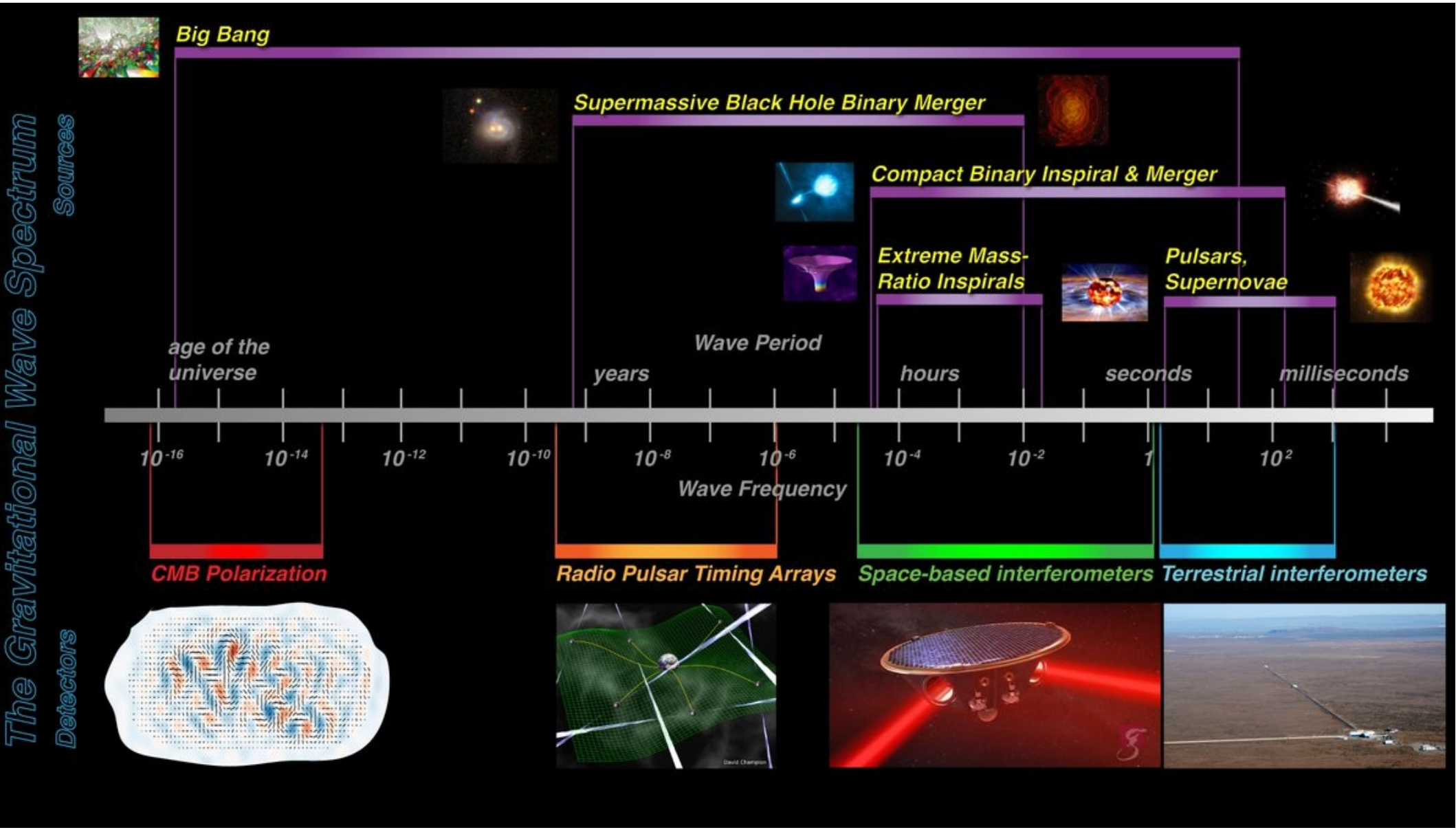


ARCA: TeV - PeV astrophysical neutrinos (Galactic Center!)

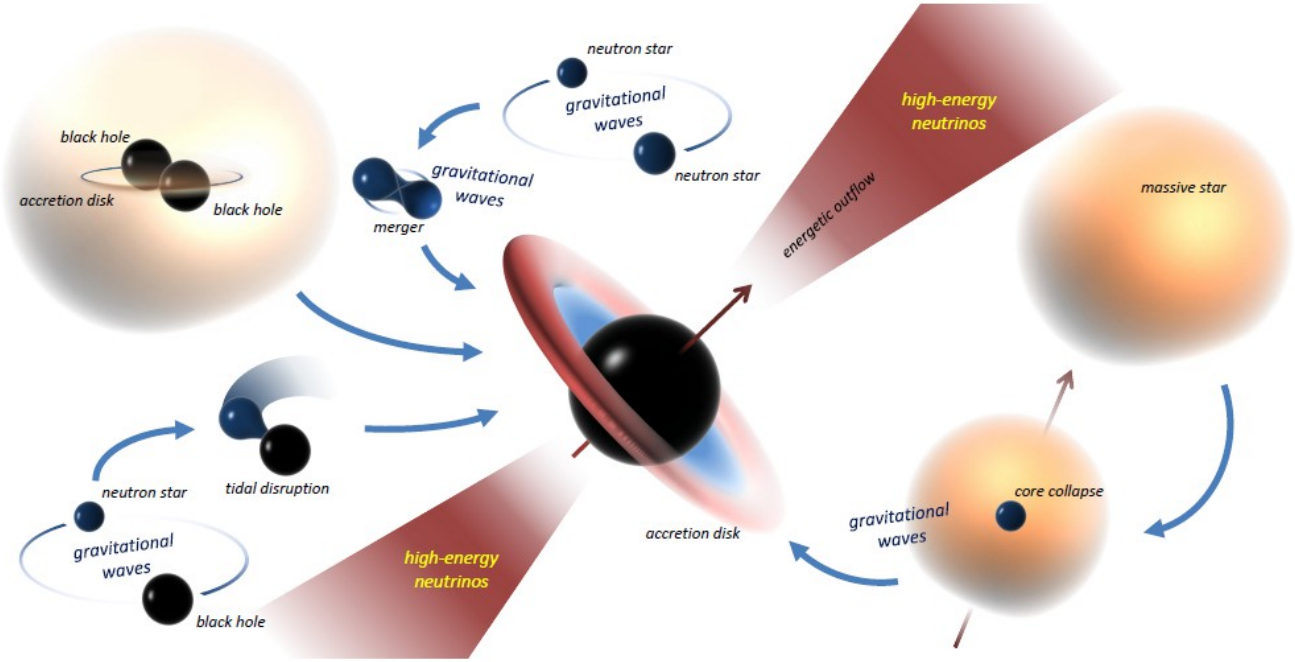
- First two DU deployed successfully 2016/2017
- Completion ~2022

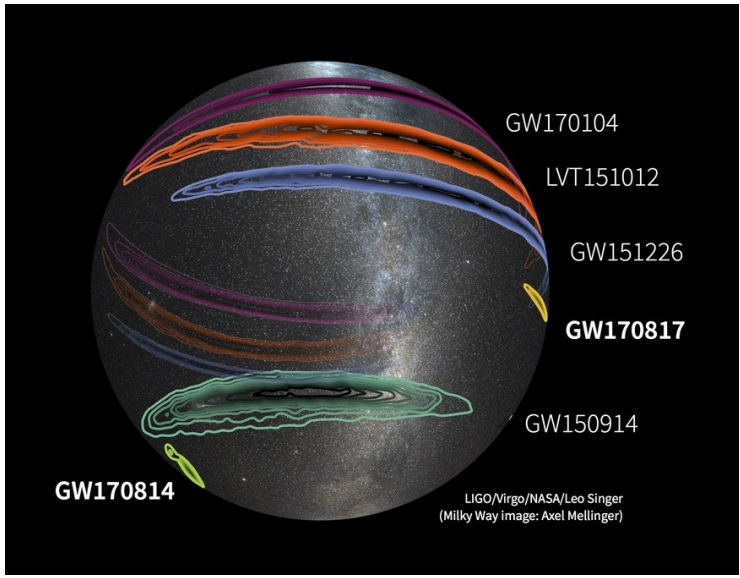
Gravitational Waves

See talk by E.Porter
Mon@10:15



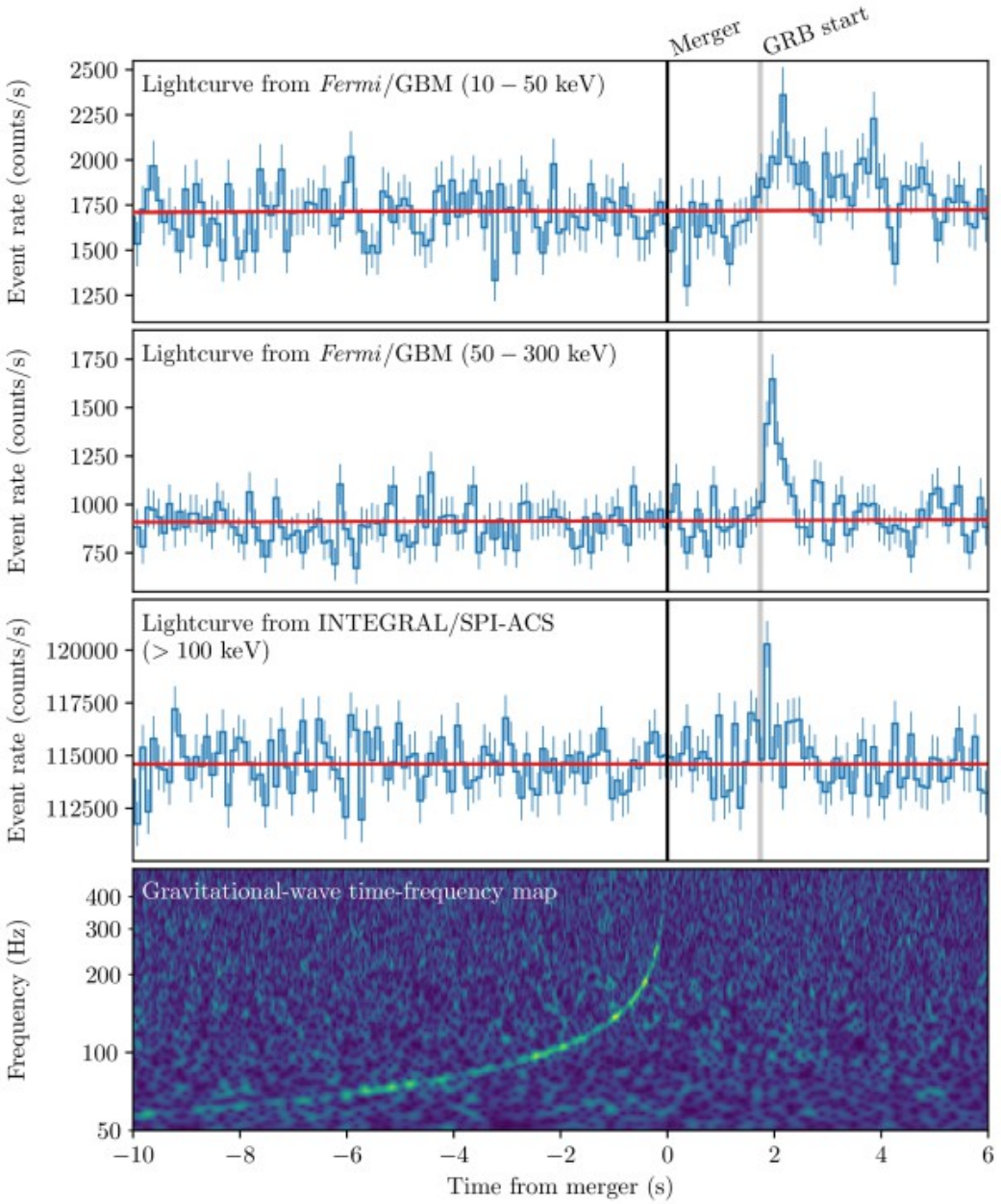
GW + EM + neutrinos...?

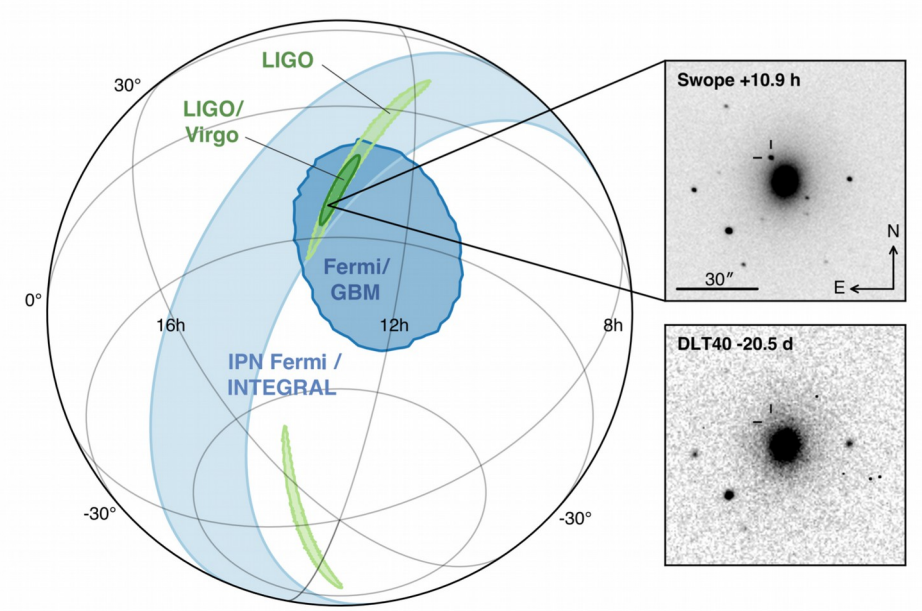




- BH-BH mergers probably no EM or nu (depends on environment)
- MeV neutrinos from stellar core collapse
- HE neutrinos + gamma-rays from non-thermal processes (BH+acc. disc → jets?!)
- chocked GRBs - only neutrinos and GW!
- Timing of signals from different messengers → progenitor
- EM emission → localization + redshift

GW-170817

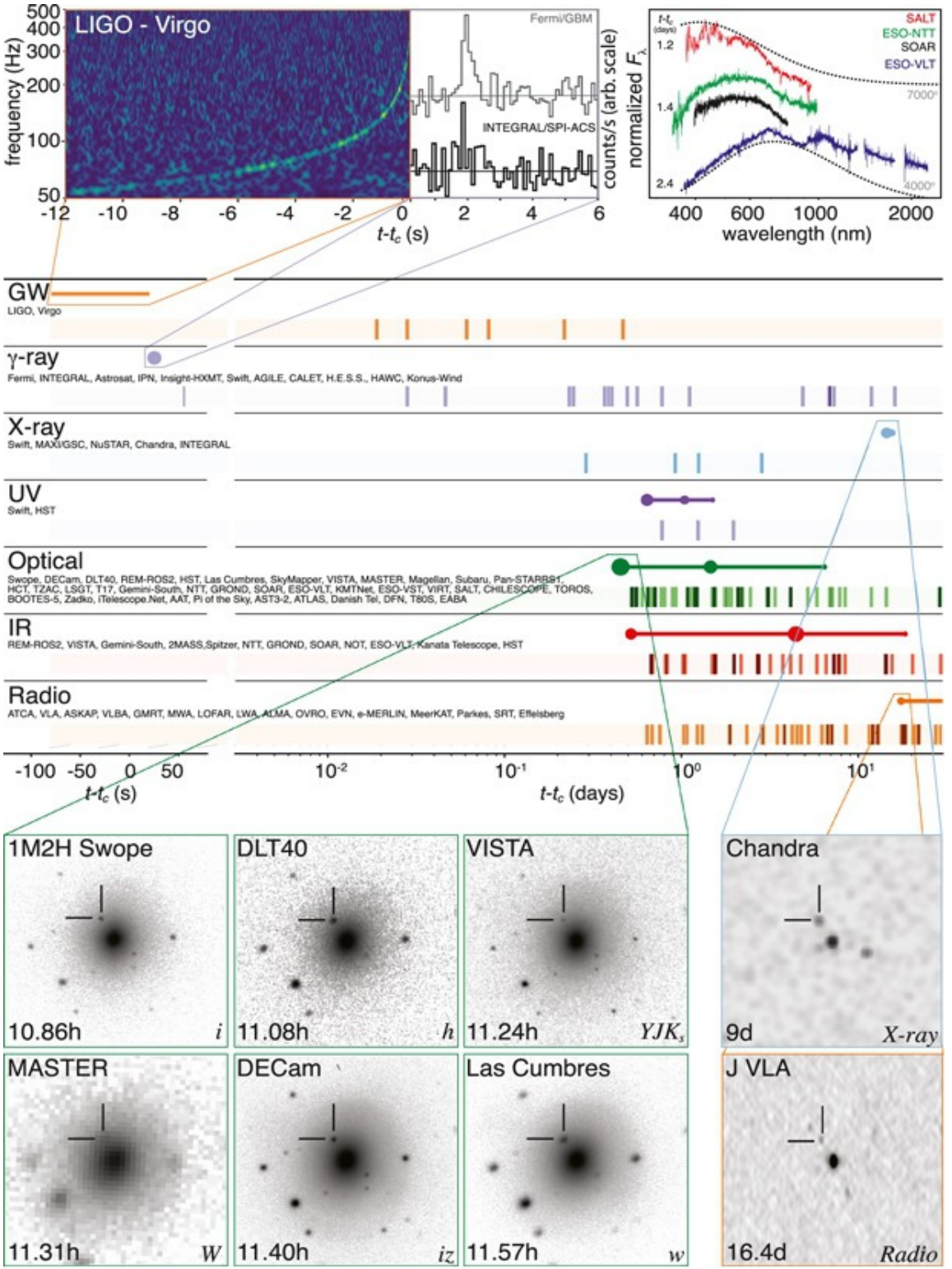




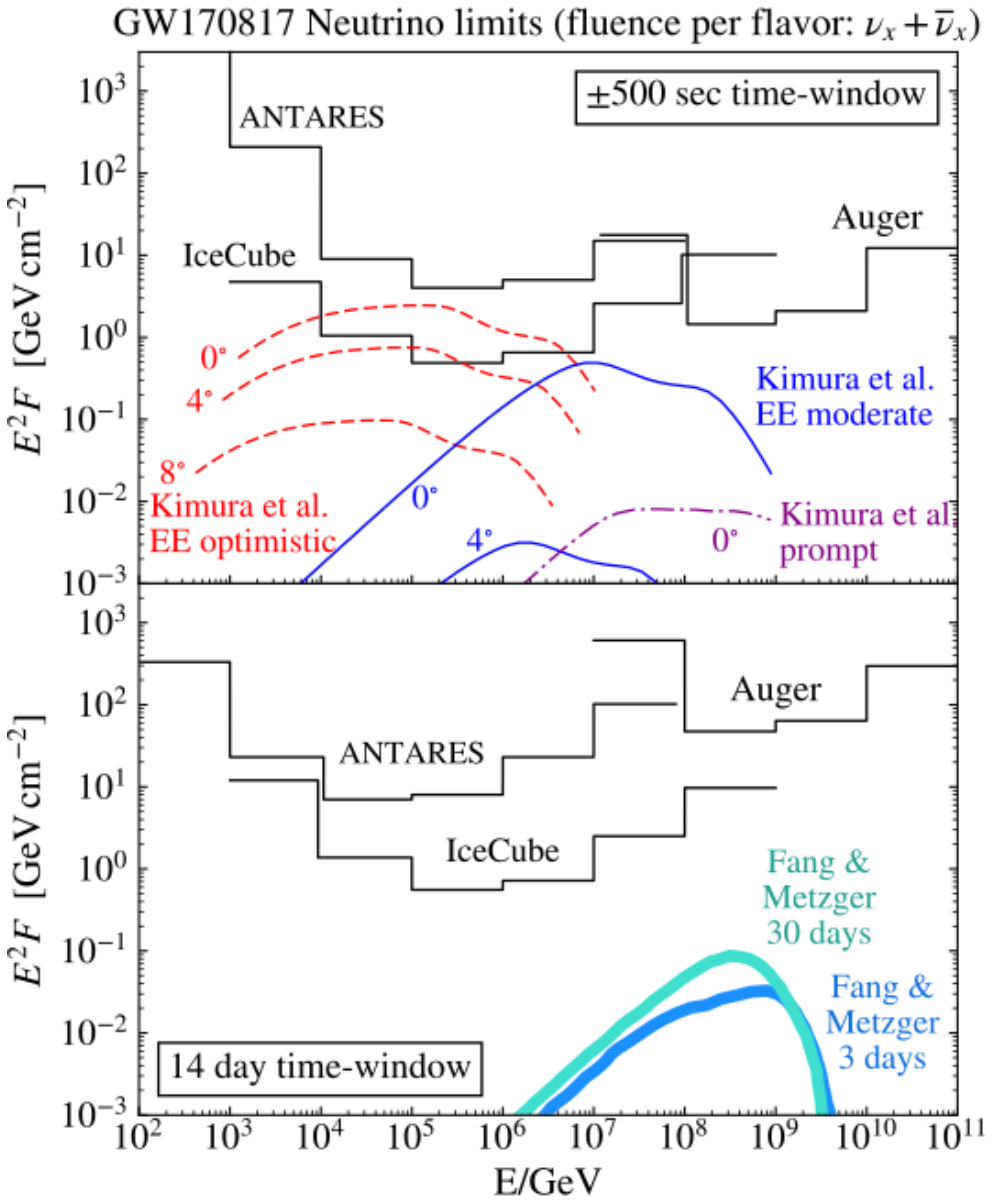
- GW emission duration ~100 s, typical NS-NS pattern, localization ~28 deg2
- Fermi/GBM: independent detection of GRB 170817A, t_0+1.74±0.05 s, duration ~ 2 seconds (faint! "chocked GRB"?)
- ~t_0+11 h Swope SN Survey identified the nearest galaxy as NGC 4993 → localization error 0.0001 deg
- Distance: 40 Mpc (z=0.0099)

GW-170817

- 70 observatories on all seven continents and in space
- NS-NS → kilonova = sGRB + longer afterglow due to decay of heavy r-process nuclei (strongest evidence for NS-NS as sGRB progenitors!)
- No neutrinos detected (jet ~30 deg off-axis?)
- Limit on c_{EM} - c_{GW}
- "Standard siren": an independent measurement of $H_0 = 70.0^{+12.0/-8.0}$ (km/s)/Mpc



GW-170817 + neutrinos



Observed isotropic-equivalent energy of $E_{iso} \approx 4 \times 10^{46}$ erg, (Fermi-GBM) → faint!

Maximum jet misalignment:

$\theta_{obs} \leq 36^\circ$ at 90%

Typical opening half-angles for short GRBs: $\theta_j \approx 3^\circ - 10^\circ$

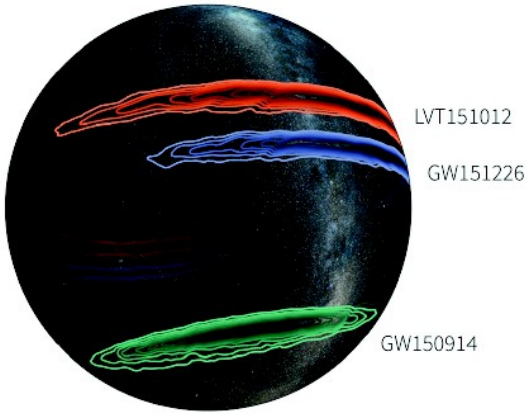
Prompt and extended emission models tested for +/- 500 s and +/- 14 days

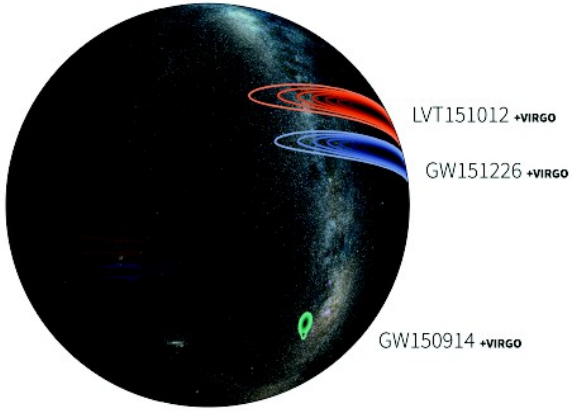
Most optimistic predictions for small jet viewing angle constrained

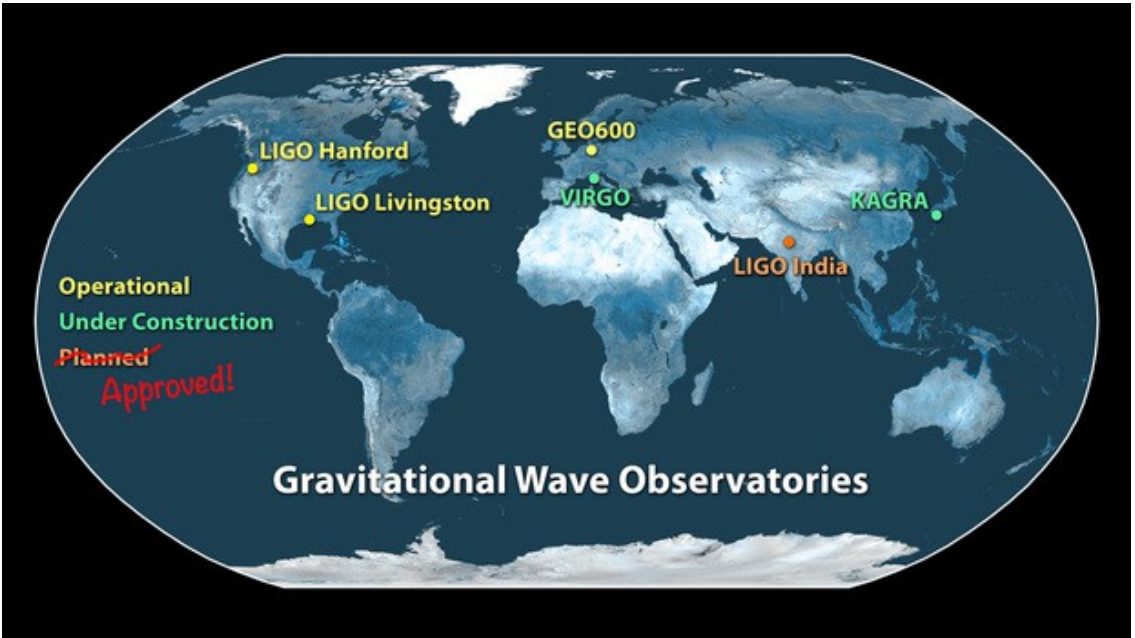
(in agreement with measurements)

Gravitational Waves – the future

- Detectors improving, especially at lower frequencies
- Increasing observation time
- Better progenitor localization
- Public alerts
- Expected rate for O3:
  - ~ 1/week BH-BH
  - ~ 1/month NS-NS







Looking forward to (O3) !!!

Summary

2017 – exciting year for MM!

Precise measurement of CR spectrum at UHE
CR composition seem to shift towards heavier nuclei with higher energies
UHE CR origin extragalactic

Astrophysical neutrinos sample growing steadily
Low contribution of bright g-ray sources → "hidden accelerators"…?

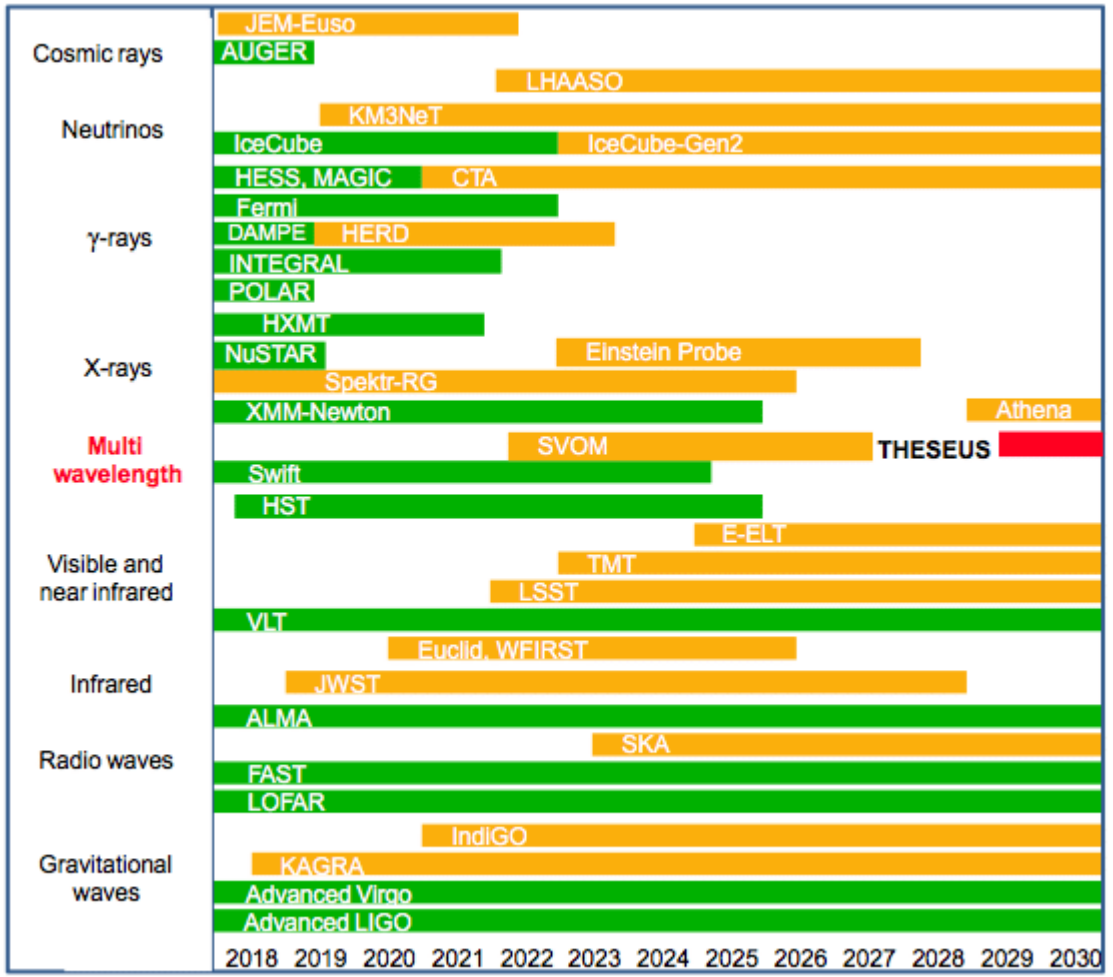
IC-170922A HE neutrino coming from a direction consistent with flaring gamma-ray blazar

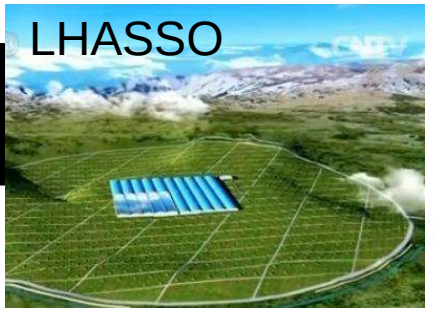
GW-170817A first high energy MM source (GW+EM)

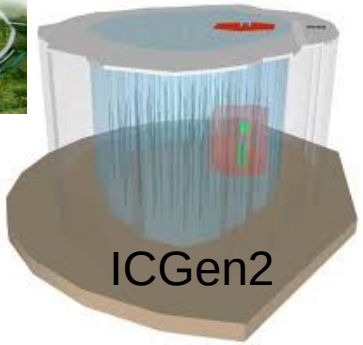
Significant progress towards resolving the fundamental MM questions: acceleration/emission/propagation…? sources…?

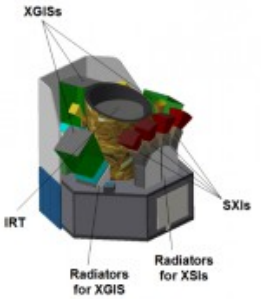
The future is MultiMessenger

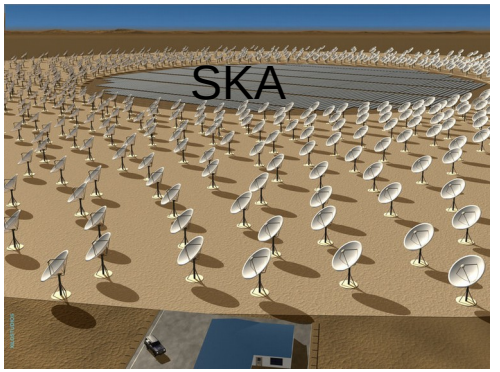
THESEUS, MMA paper, arXiv: 1712.08153



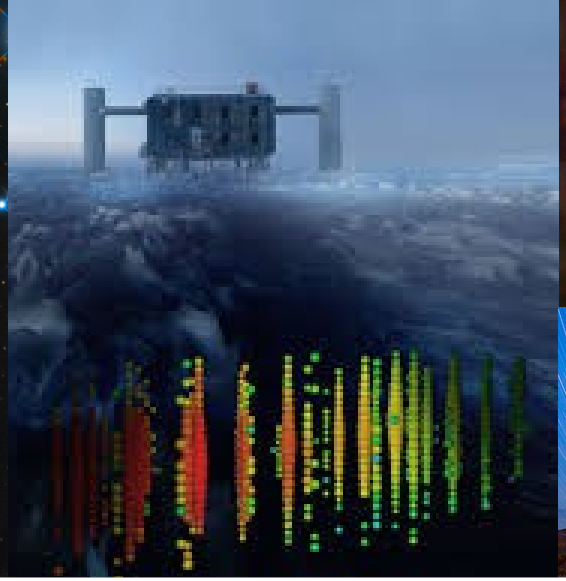


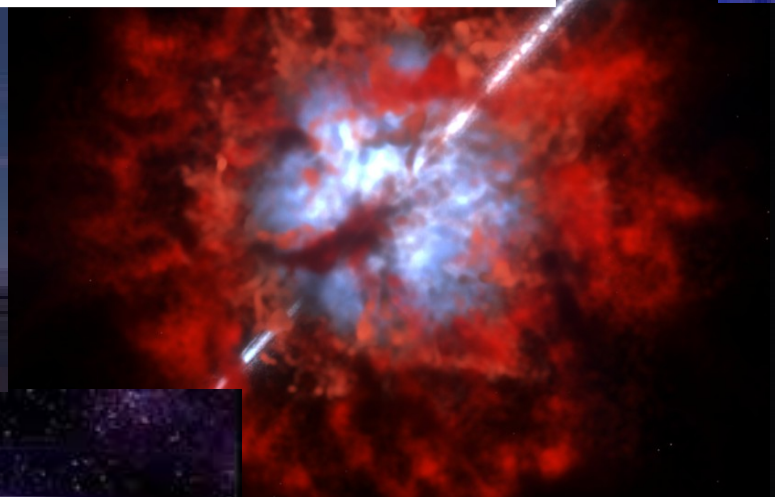


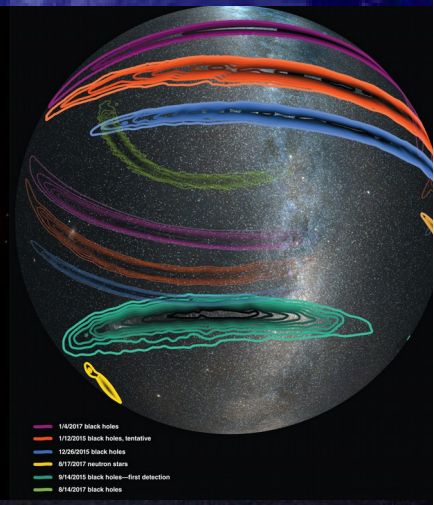


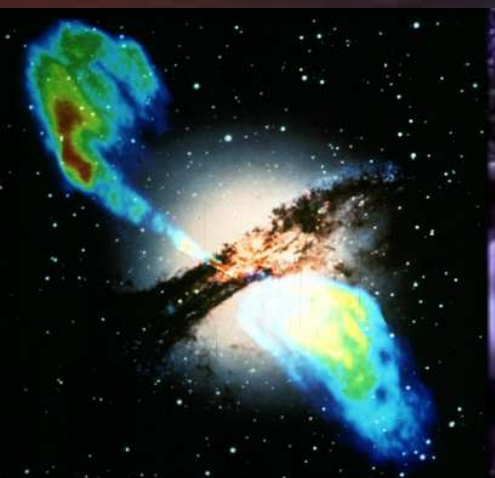


Back-up






1/4/2017 black holes
1/12/2015 black holes, tentative
12/26/2015 black holes
8/17/2017 neutron stars
9/14/2015 black holes—first detection
8/14/2017 black holes

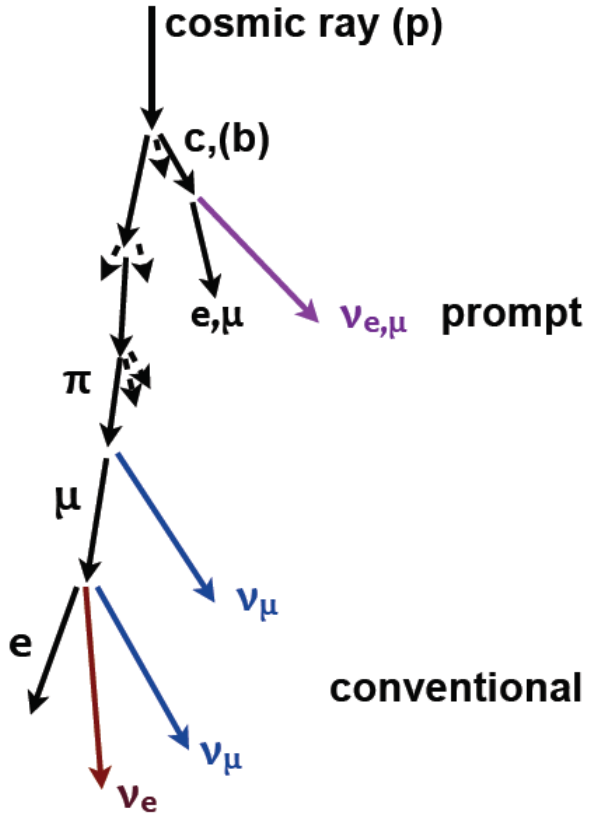


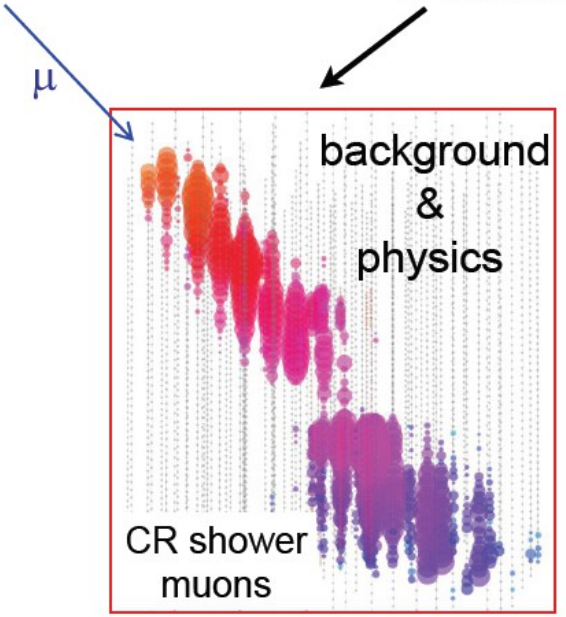
Neutrino detection: BACKGROUND

Event rates:

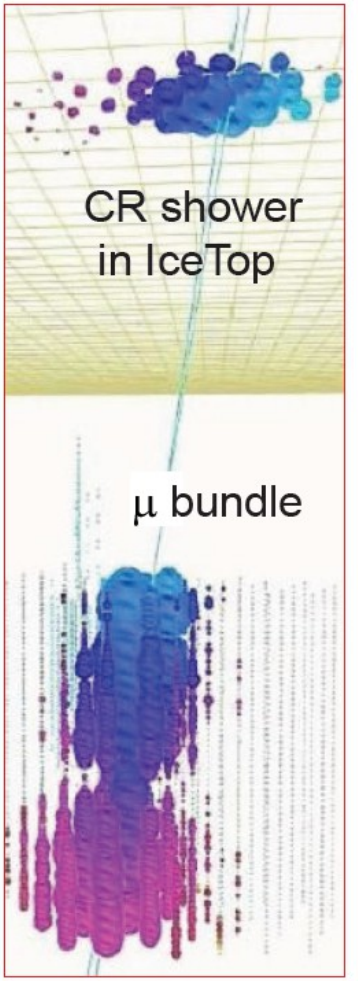
- atmospheric μ (99.999% of triggered events) 7 x 10^{10} (2000 per second)
- atmospheric ν (residual background) 5 x 10^{4} (1 every 6 minutes)
- astrophysical neutrinos: ~ *O*(10) per year

→ We need clever background rejection techniques!!



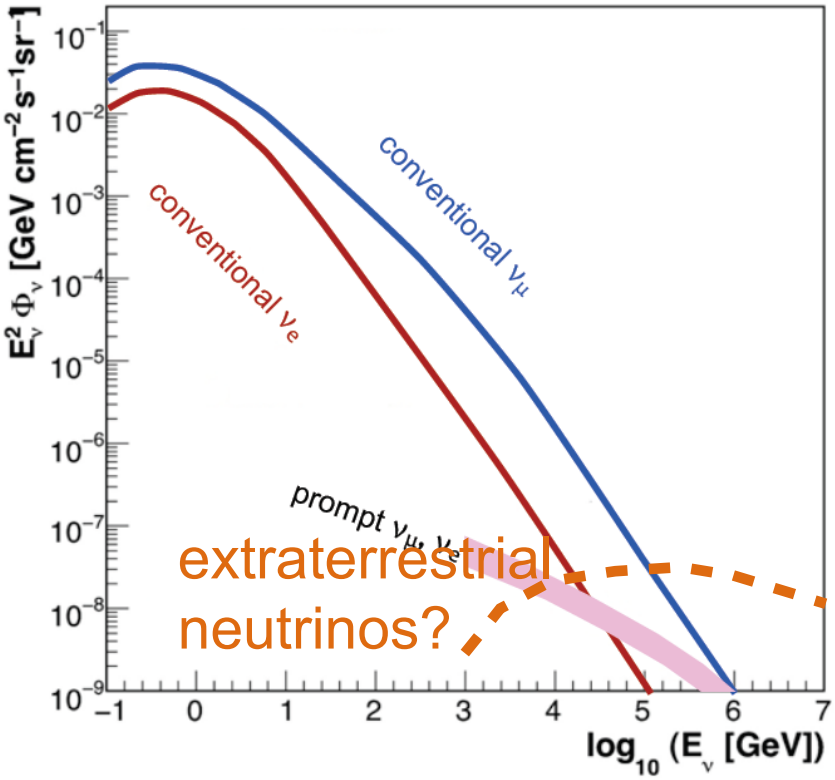


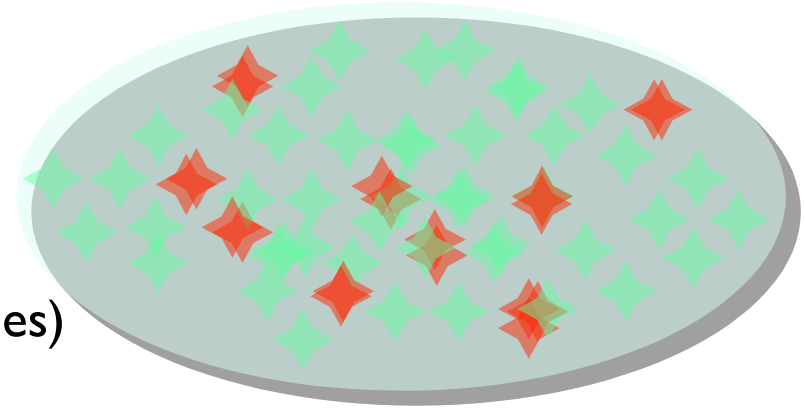
99.9999%
of all events



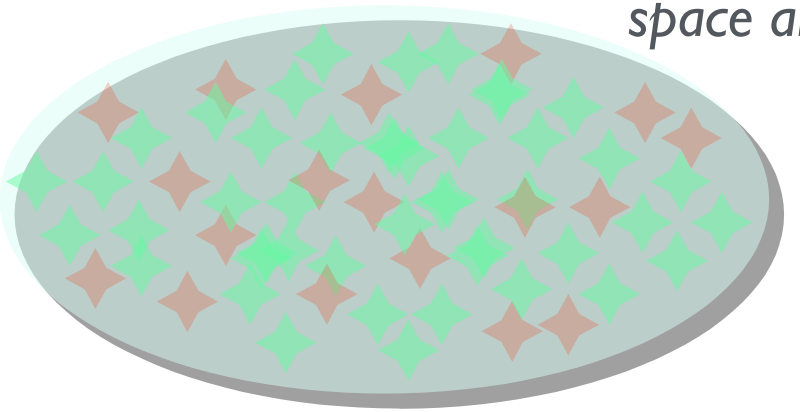
SERACH FOR COSMIC Nu SIGNAL

- The signal is expected to exhibit a differed spectrum compared to atmospheric neutrinos
- Search for deviations from background
  - in energy (diffuse-like searches)
  - in energy and direction (look for individual sources)



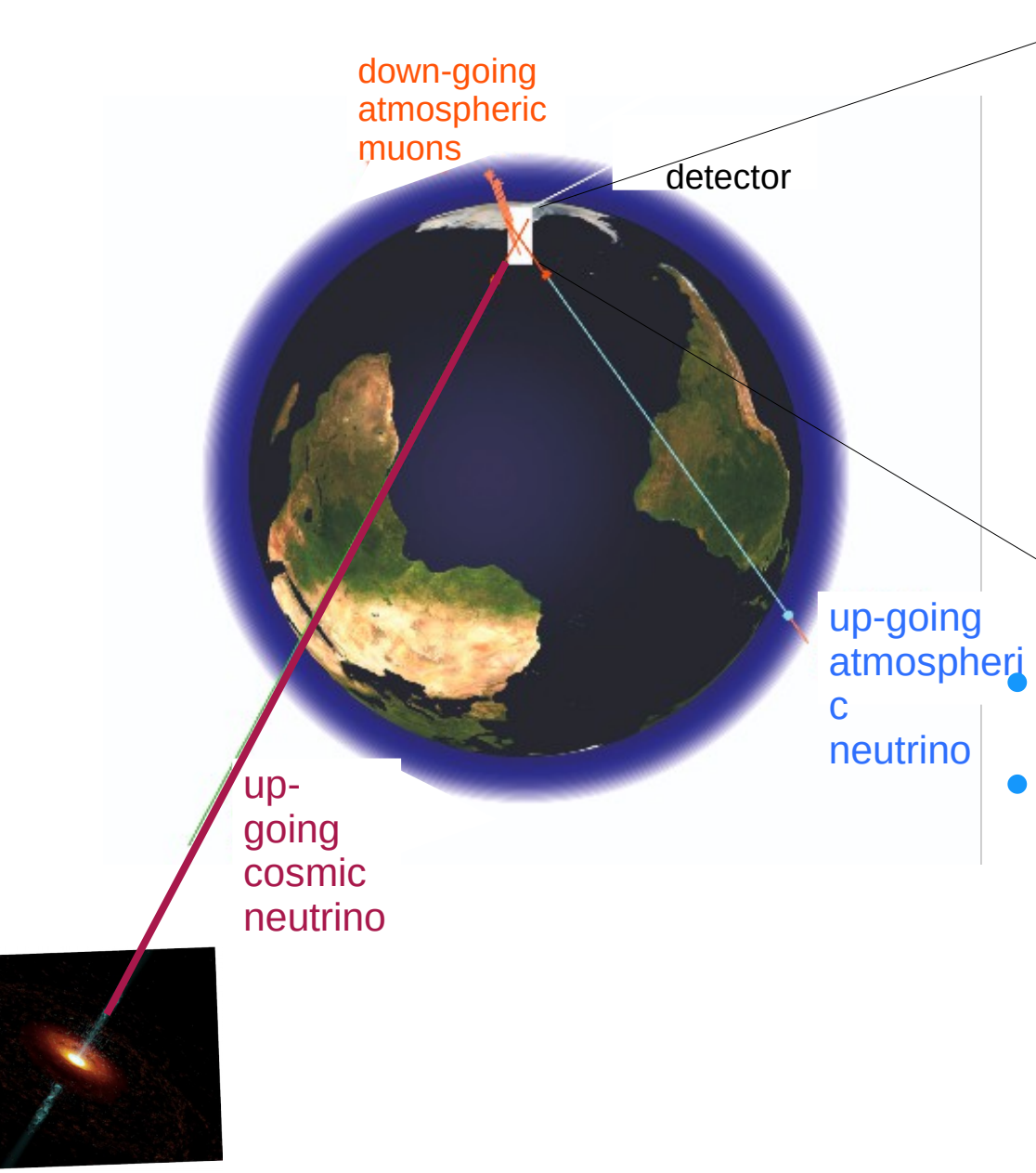


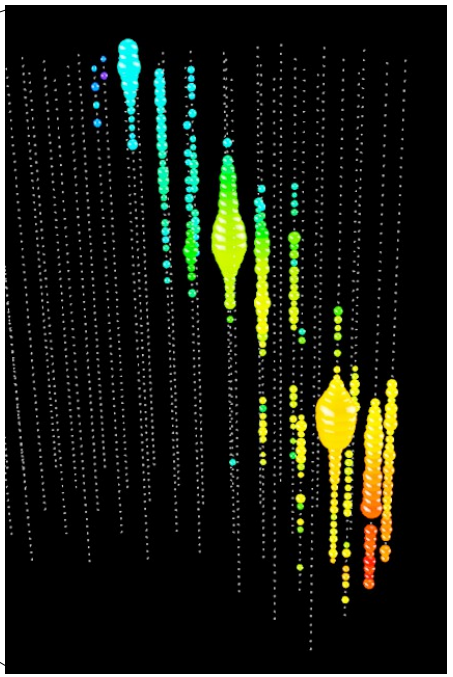
Individual sources: search for excesses from few strong objects. Localised (in space and/or time)



Diffuse searches: search for an overall excess from an ensemble of many weak sources. Deviation in energy spectrum

BACKGROUND SUPPRESSION: DIRECTION

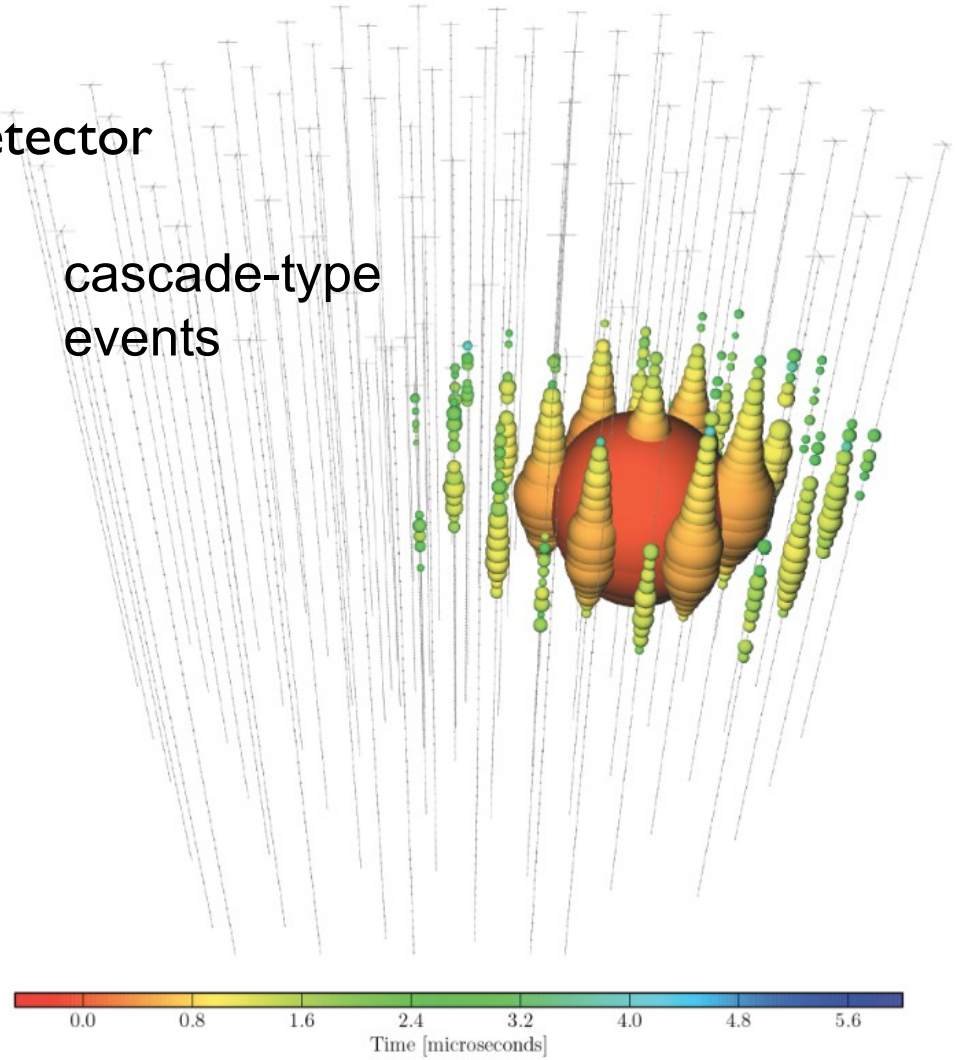




- Earth stops penetrating muons from below
- Apply direction cuts (select up-going)
  - Effective volume larger than detector
  - E > O(100 GeV)
  - Sensitive to ν_μ only
  - Sensitive to "half" the sky (the North)

BACKGROUND SUPPRESSION: EVENT TYPE

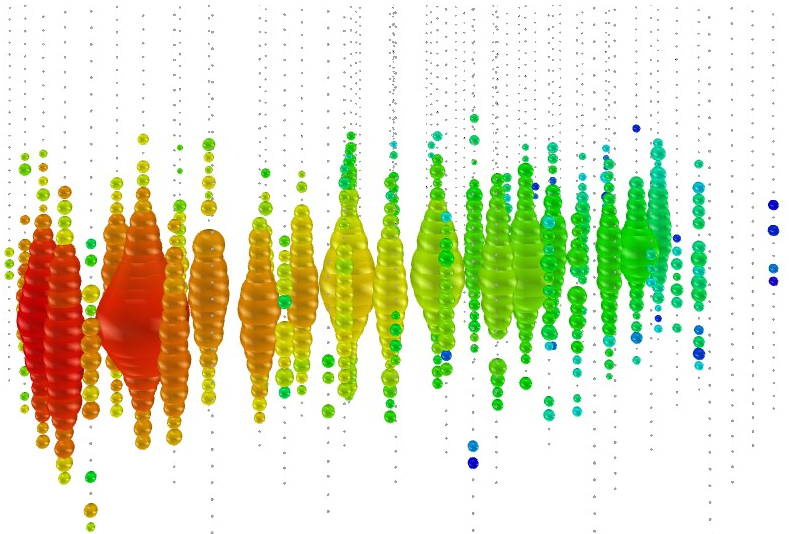
- Looking for cascades
  - Effective volume smaller than detector
  - E > *O*(30 TeV)
  - Sensitive to all flavours
  - Sensitive to full sky
  - almost background-free!



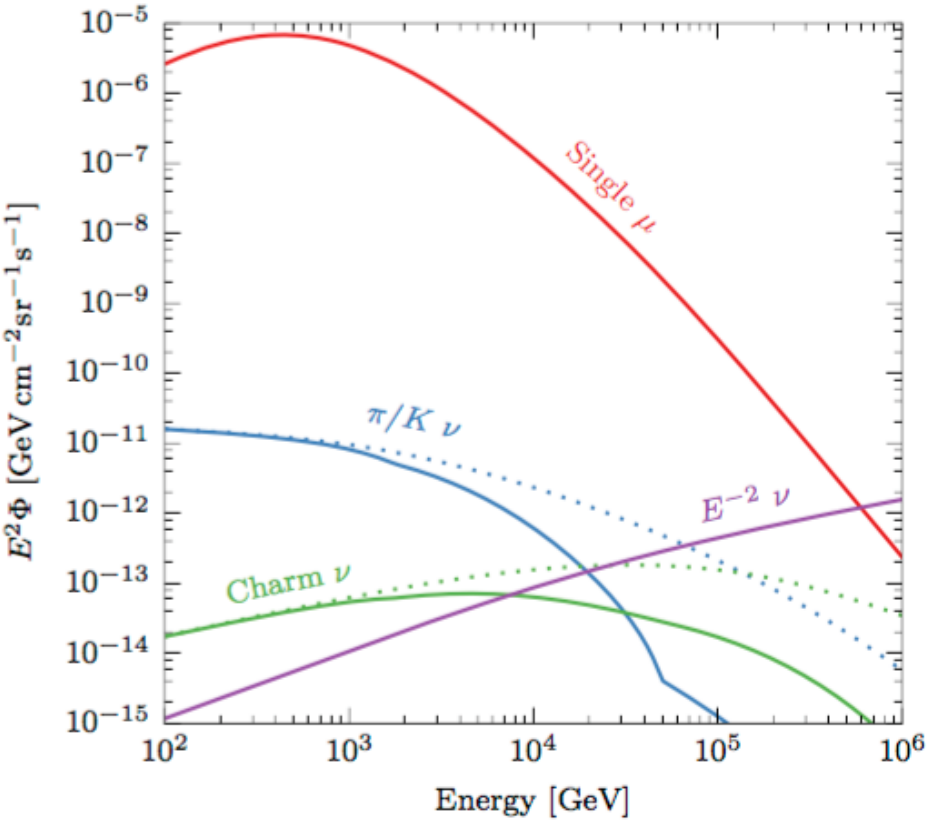
BACKGROUND SUPPRESSION: ENERGY

- Energy spectrum looks different for background and signal
- Select high-energy events:

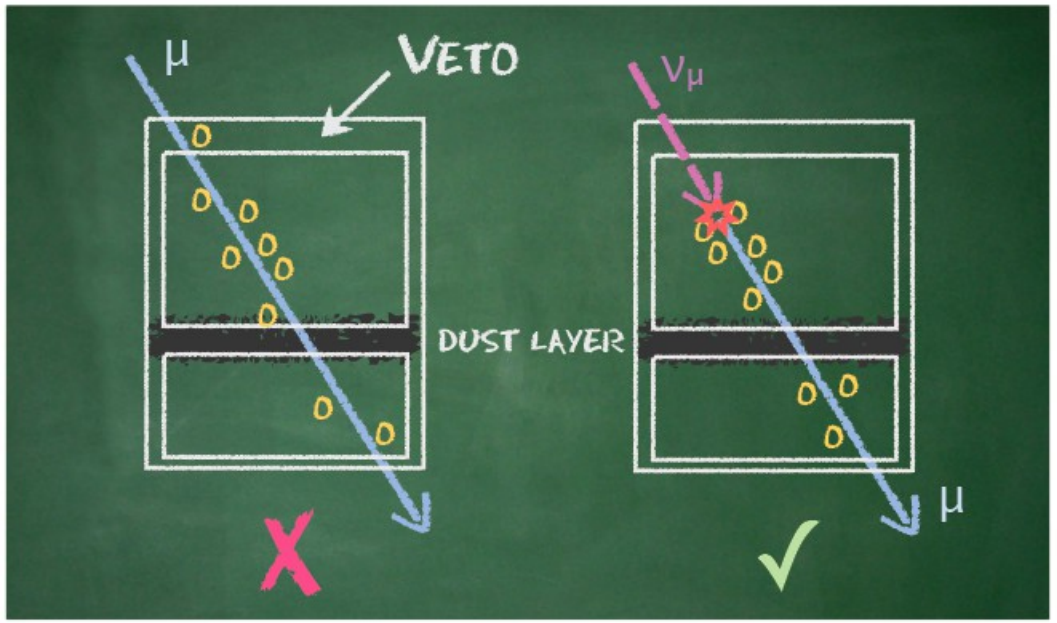
  - reject atmospheric μ
  - reject atmospheric ν_μ
  - requires strong energy cuts
  - mostly sensitive at the horizon

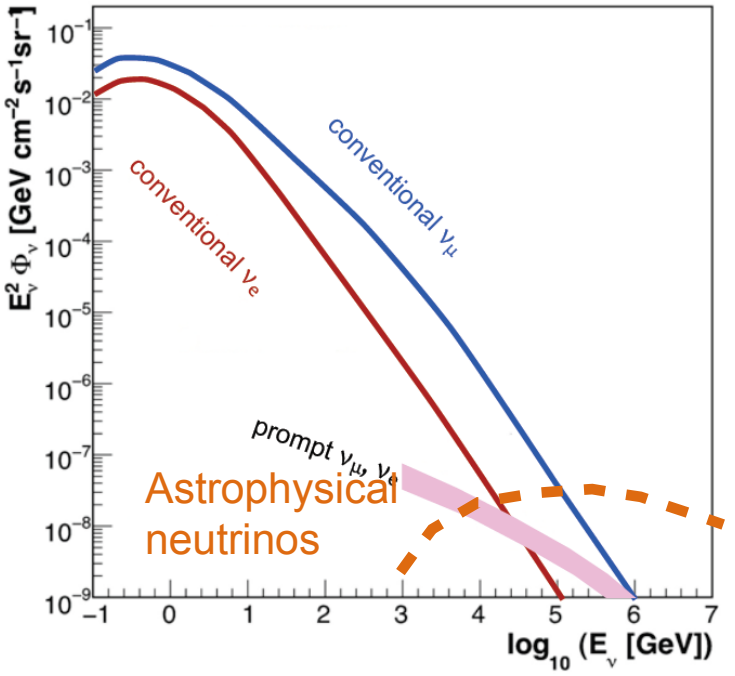


IceCube Coll. Phys. Rev. D 91, 022001 (2015)



Astrophysical neutrinos





for atms. μ
→ reject tracks entering the detector from outside, expected background: 6±3.4 /year

for atms. ν
→ reject tracks accompanied by air showers with muons, expected background: $4^{+3.6}_{-1.2}$ /year
(detectable when coming from the Southern hemisphere)

+ charge cut (> 4000 phe) to select very high energy events
→ "golden channel": High Energy Starting Events (HESE)

CR & ν: COSMOGENIC NEUTRINOS

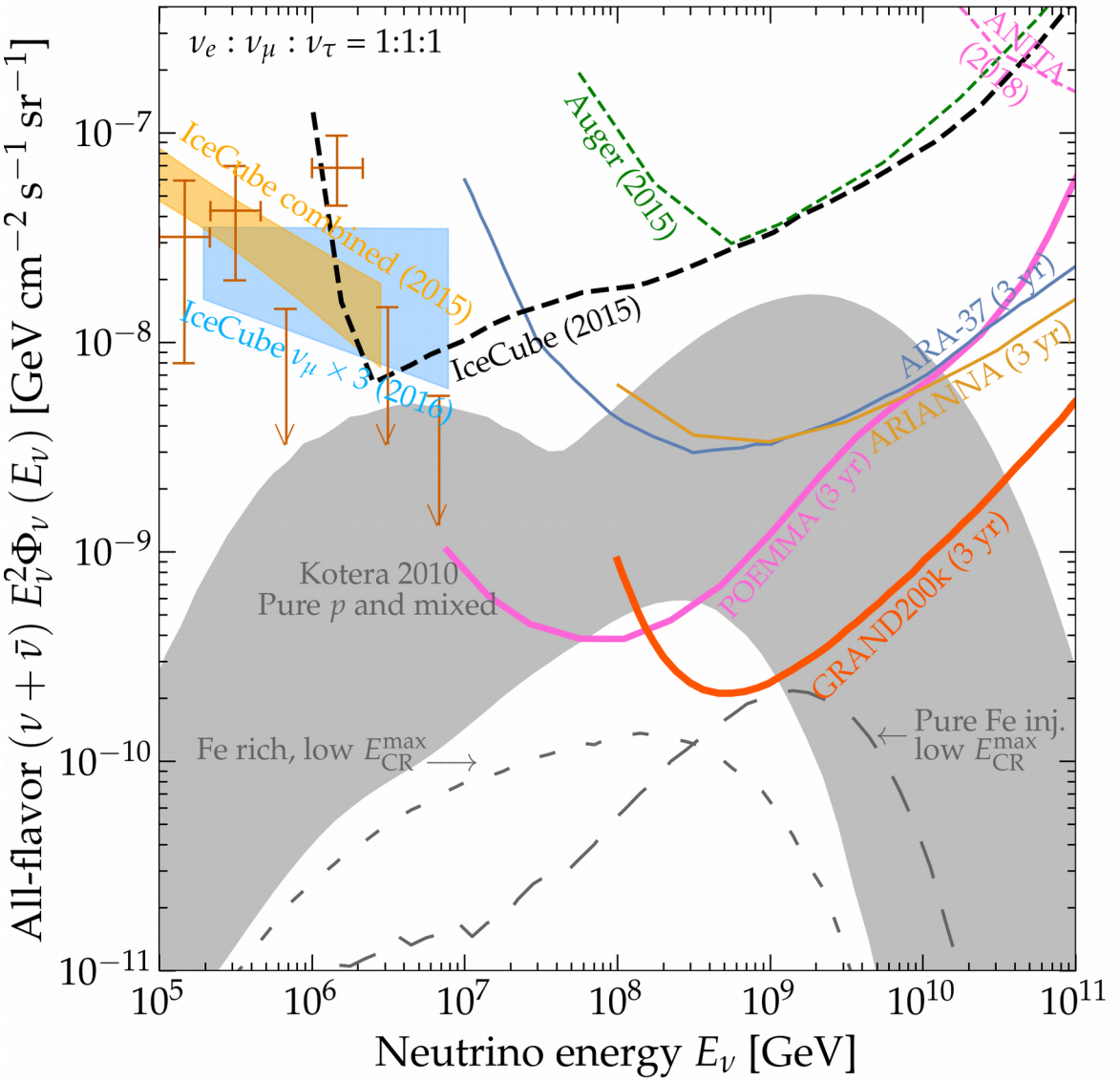
- Protons with energies exceeding 10^{19} eV interact with the cosmic microwave background photons:
  $p+\gamma_{CMB} \rightarrow \Delta^{+} \rightarrow p+\pi^{0}$ or $n+\pi^{+\pm}$.
  $\pi^{\pm} \rightarrow \mu\ \nu_{\mu} \rightarrow e^{\pm} \nu_{\mu}\ \nu_{e}$
  guaranteed source of UHE neutrinos!

- No such neutrino has been observed so far..

- "Two mysterious ANITA events"

  (see talk by L. Cremonesi

  Wed @18:30)

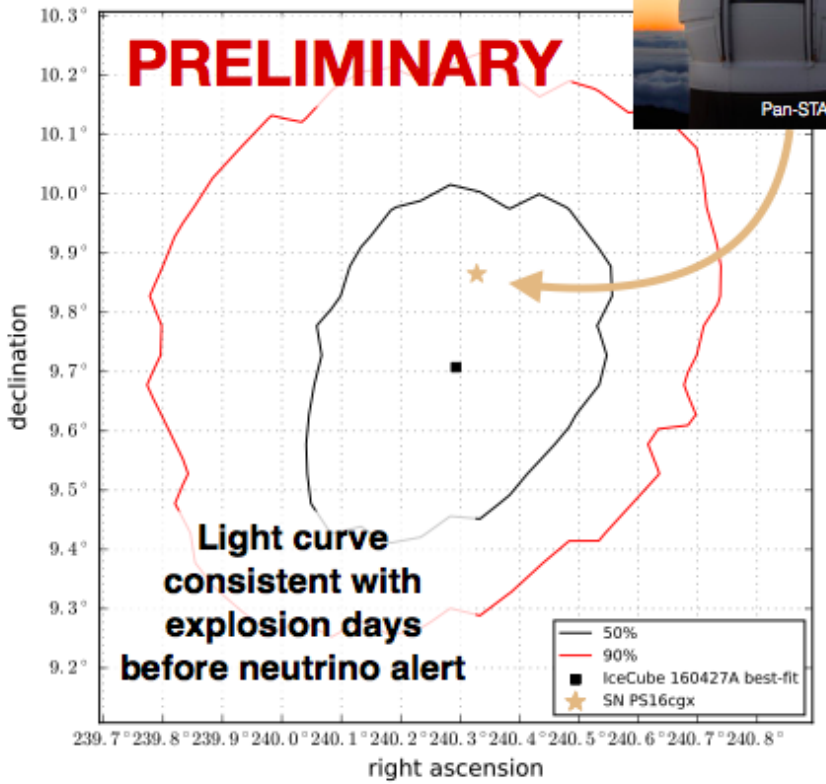


Credit: M.Bustamante

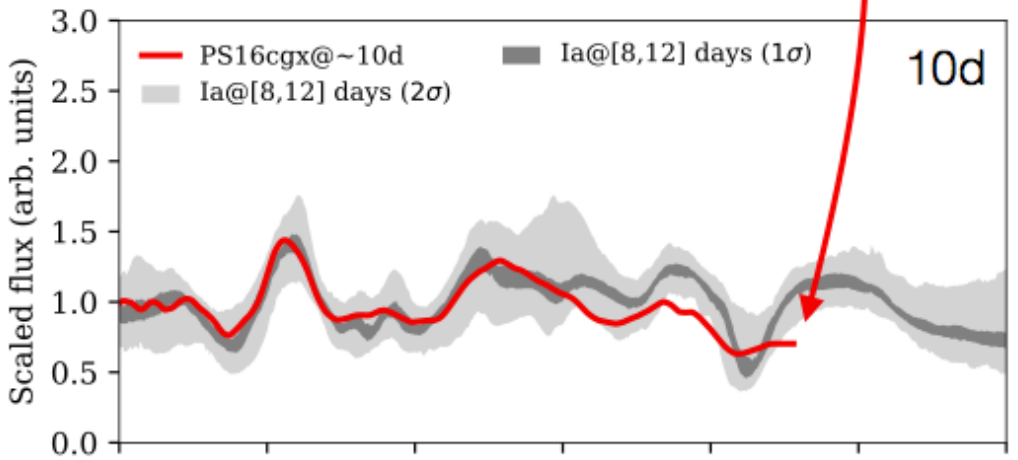
Alerts: HESE-160427A

Jacob van Santen ICRC 2017

PAN-Starrs followed up IceCube HESE alert on 2016-04-27 and found a recent supernova at z=0.3:



Optical spectroscopy 10, 20 days post-peak



Features atypical for SNIa, but not sufficient to exclude

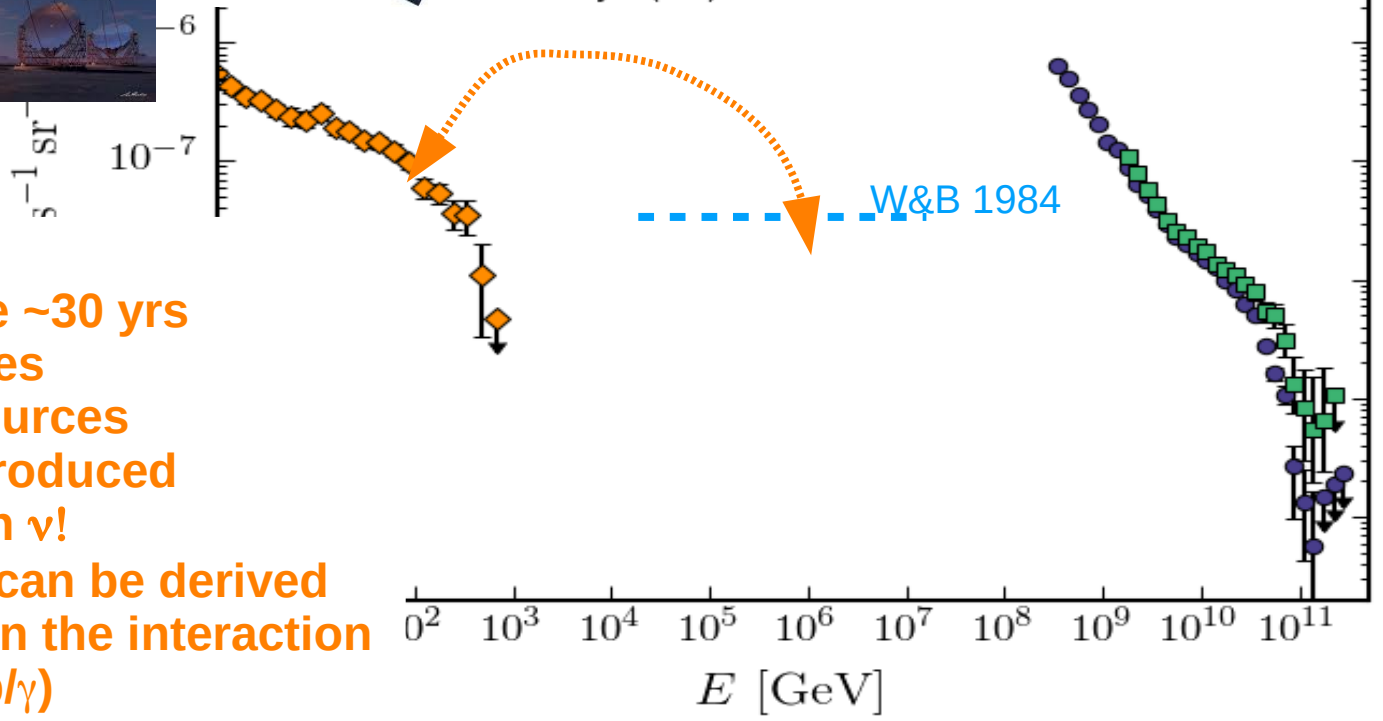
Chance probability { if **Ic** (associated with GRBs): **<1%**
if **Ia** (no HE neutrinos expected): **<10%**

Neutrinos, γ–rays & CRs

CRs:
Known since 100 yrs!
Sources?
Connection to ν?

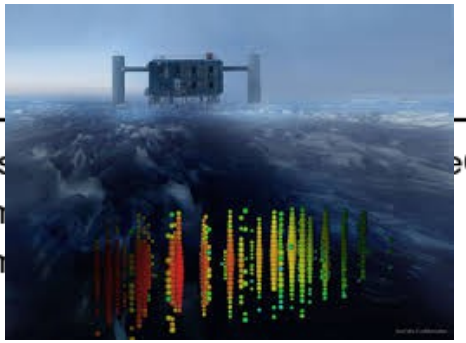
Heide Constantini
VHE g-rays, Fri @9:00

Neutrinos, γ–rays & CRs



γ-rays:
Known since ~30 yrs
~3000 sources
> 100 TeV sources
Should be produced together with ν!
Constraints can be derived depending on the interaction type (pp or p/γ)

Neutrinos, γ–rays & CRs



Mau
Nu
+ Wed Astro+Cosmo
es, Fri @8:30

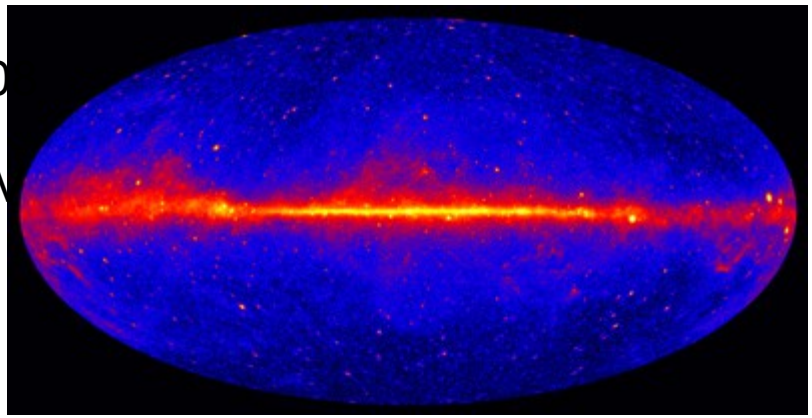
Neutrinos:
Obs. since ~few years
Flux ~ W&B bound
Sources?

Very similar energy output for all three messengers!

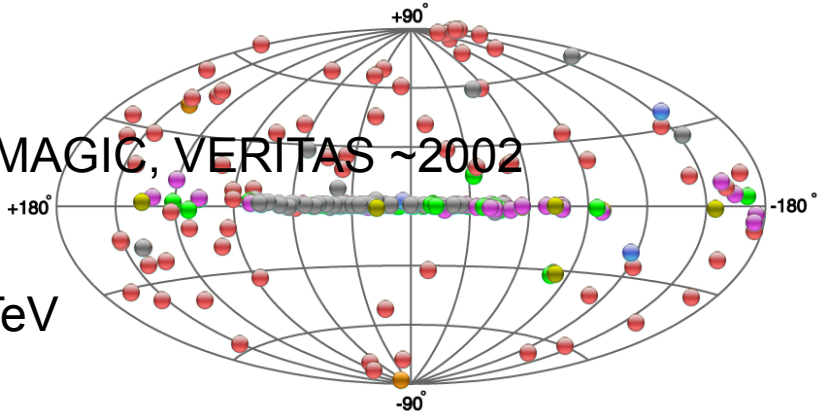
Astrophysical messengers: photons

See talk by xxxx
Fri @9:00

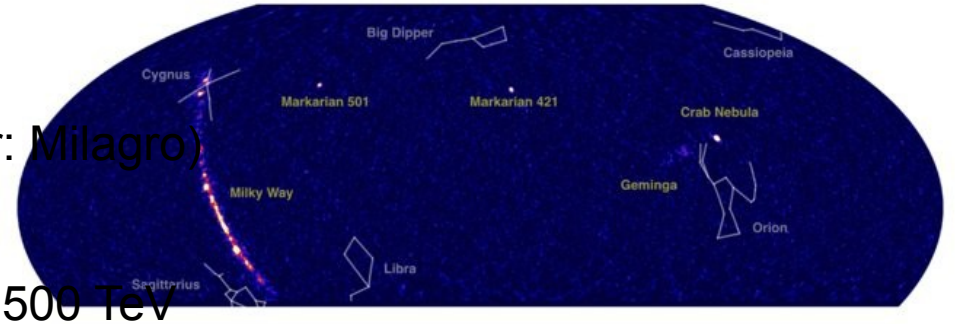
Fermi-LAT satellite:
Surveying the whole sky since 200
> 3000 sources detected
Energy range: 100 MeV – 300 GeV



IACTs
Current generation H.E.S.S, MAGIC, VERITAS ~2002
Pointing instruments
> 200 sources detected
Energy range: 50 GeV – 50 TeV

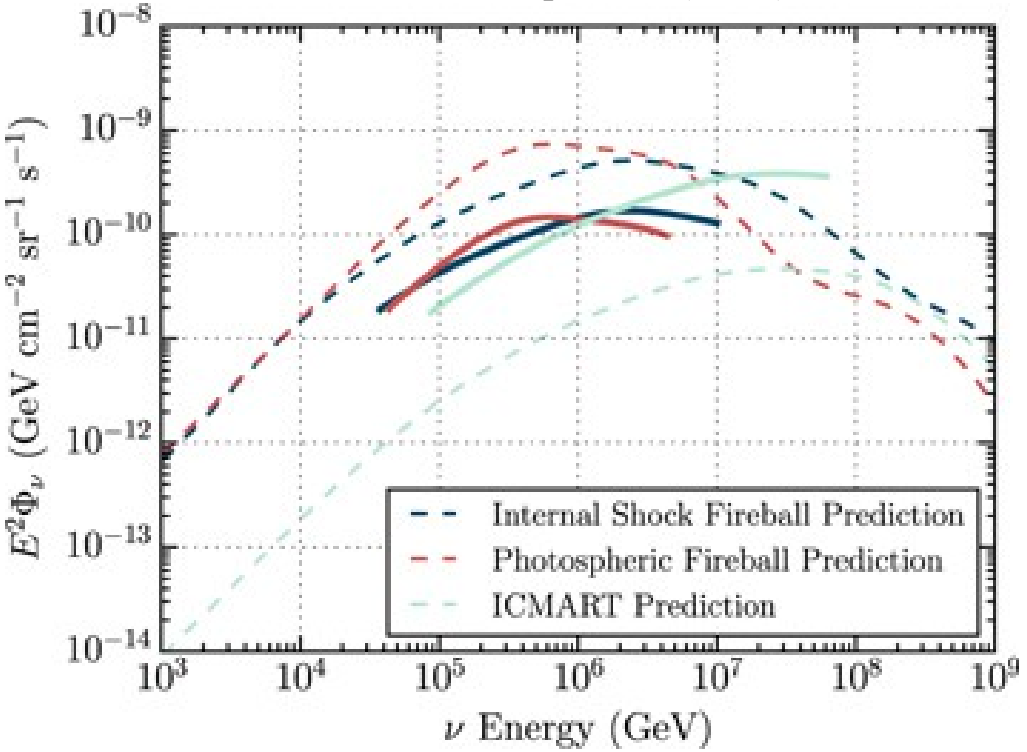


Water Cherenkov arrays
HAWC 2015 (predecessor: Milagro)
FoV: 2 sr
> 20 sources detected
Energy range: 500 GeV – 500 TeV



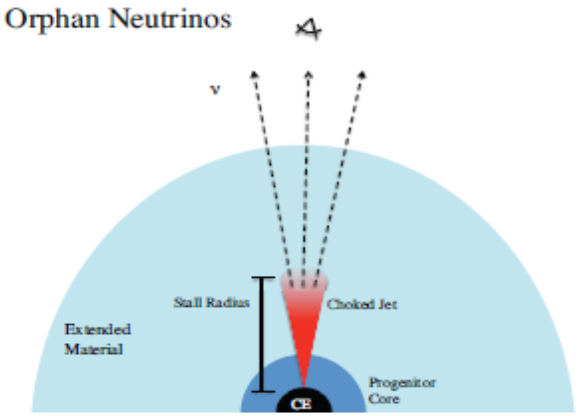
Neutrino sources: GRBs…?

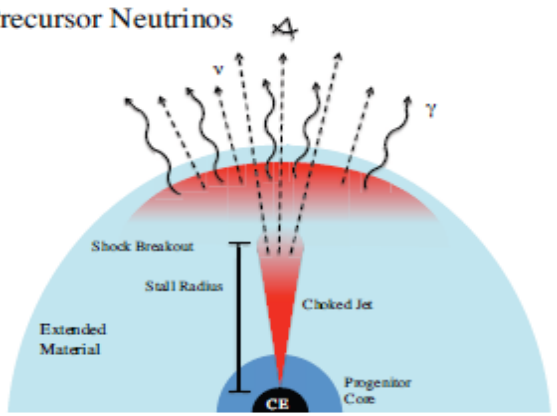
IC Coll., Ap J 843 (2017) 2

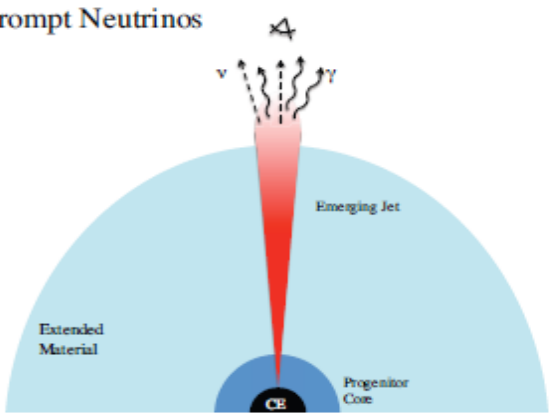


Exciting GW connection: production of neutrinos and g-rays in short-GRBs and GW events caused by mergers (NS-NS) [Bartos et al. (2013)]

Senno, Murase, Mészáros, (2016) PRD,93,083003

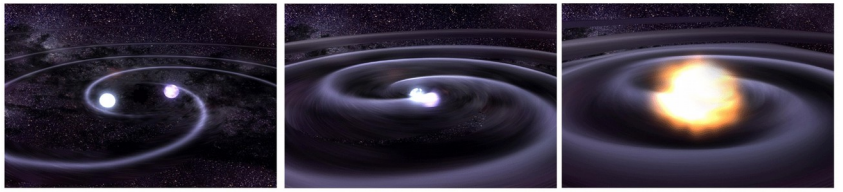




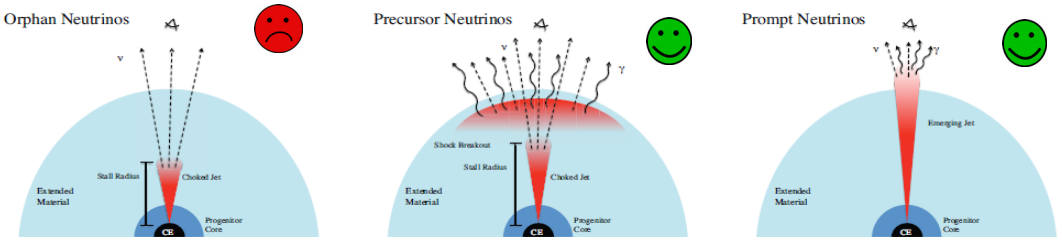


Neutrino sources: transients…?

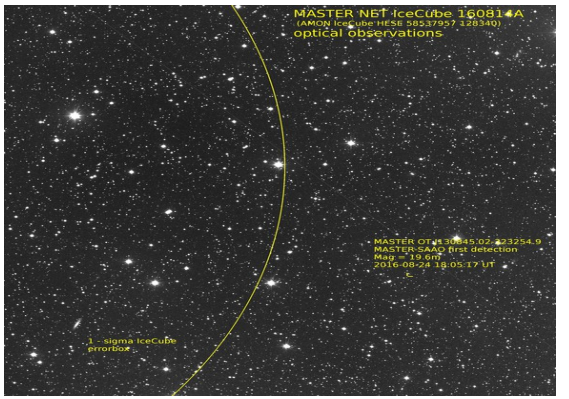
- Possible connection of ν and γ-rays in short-GRBs and GW events caused by mergers (NS-NS) [Bartos et al. (2013)]



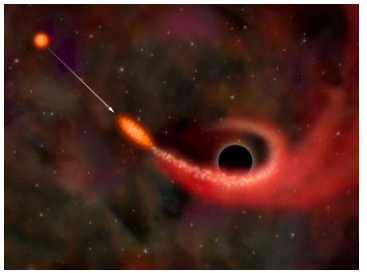
- GRBs with jets "choked" in surrounding medium [Senno et al. (2016)]: explains hypernovae and Low Luminosity GRBs (rate ~100-1000 $Gpc^{-3}yr^{-1}$), predicts neutrino & γ-ray emission



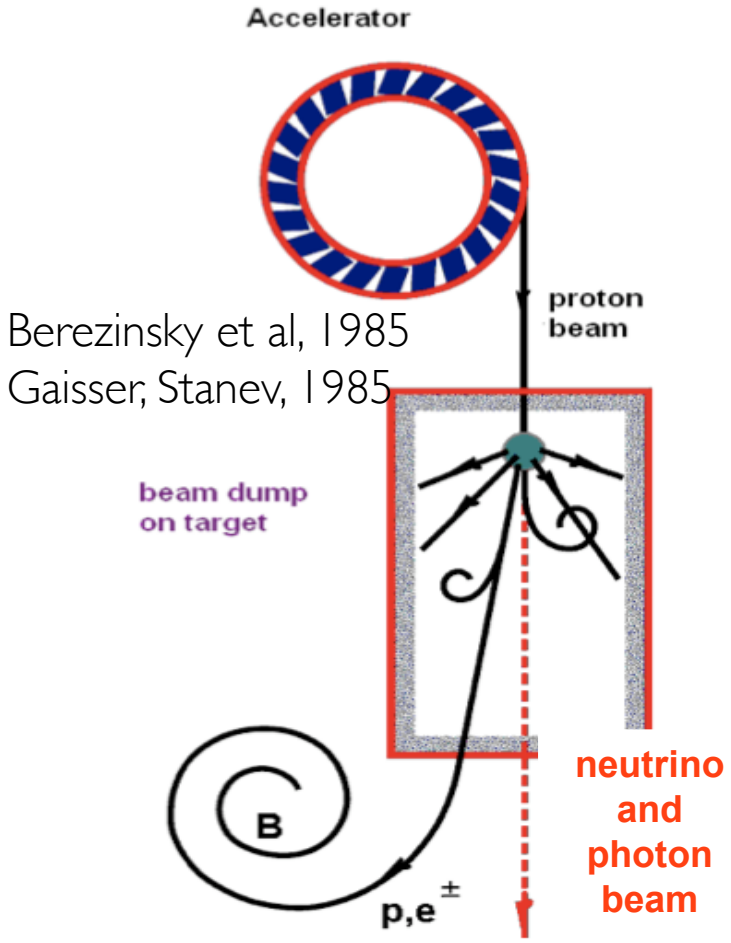
- GCN#19888, MASTERS follow-up of IC alert, reports a delayed optical transient in FoV → white dwarf in binary system or other cataclismic variable?! Possible prompt γ-ray emission: see models by [Bednarek&Pabich (2010)] and refs in GCN#19888

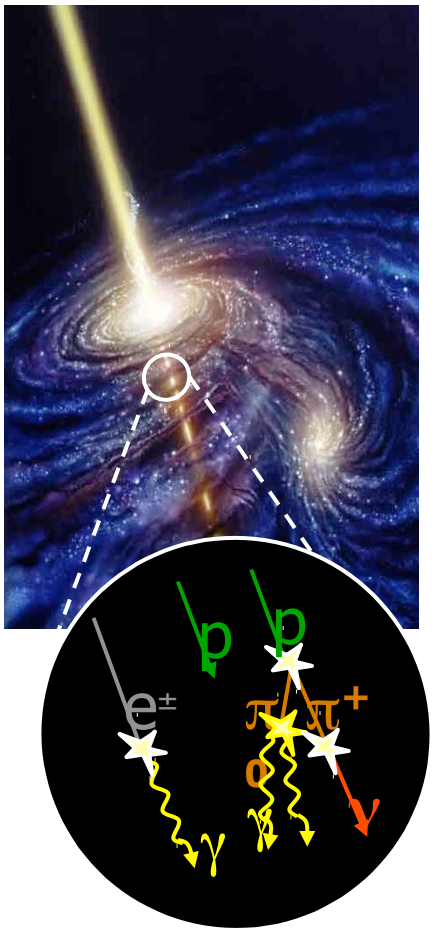


- Tidal Disruption Events (BH eating a star) → jet + surrounding material → ν? γ-ray? [Lunardini&Winter (2016)]



Cosmic “beam dump”





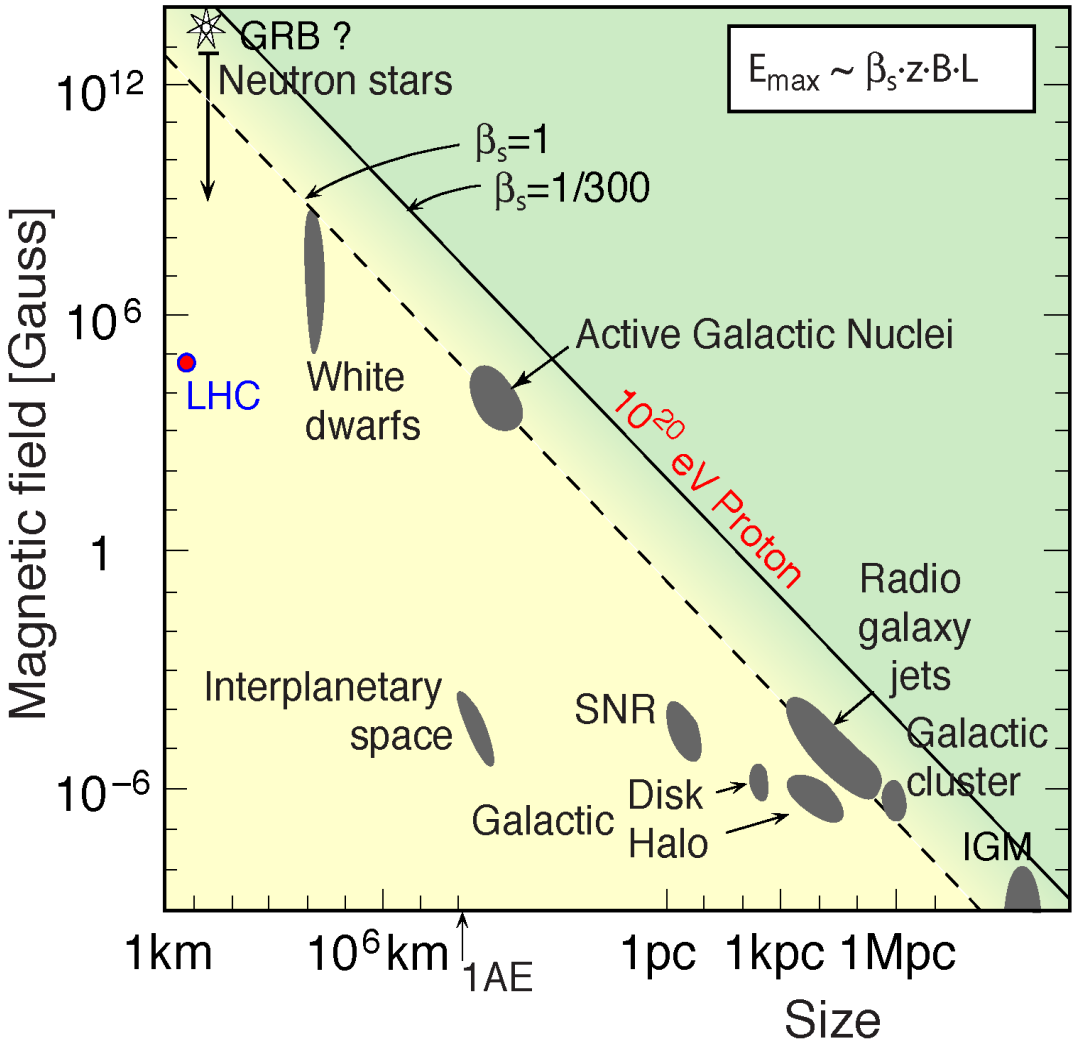
Neutral particles should trace the production sites of CRs!

Potential sources of cosmic rays

- In 1984 Hillas did a back-of-an-envelope calculation that in order for a source to accelerate CR to high energies, the size of the acceleration region must be > 2 x Larmor radius

- The formula is:
  $E_{max} \simeq 10^{18} \text{eV}\, Z\, \beta\, (R/\text{kpc})(B/\mu\text{G})$

→ By looking at the size and magnetic field of different objects one can find many CR accelerator candidates

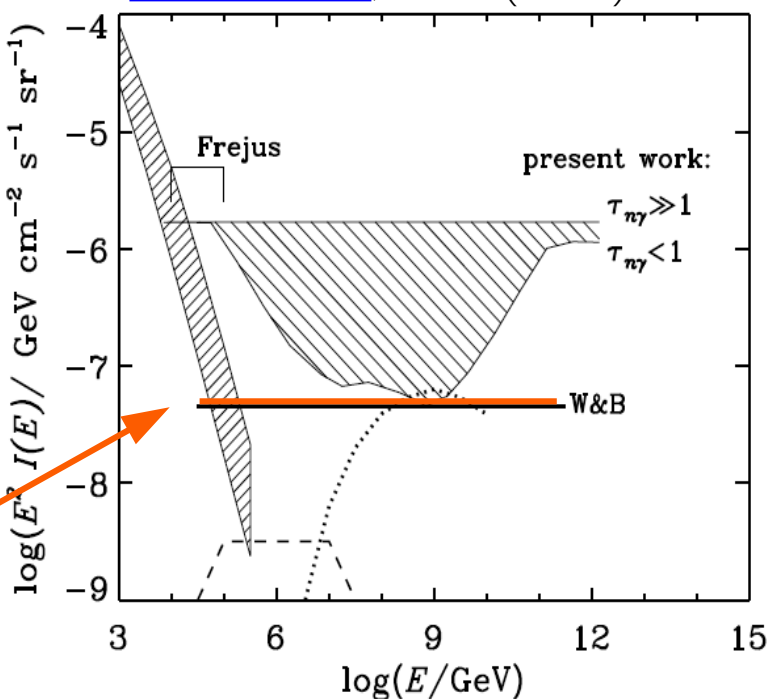


CR & ν: WAXMANN BAHCALL BOUND

- Starting from the observed CRs with energies >10^{19} eV a limit was derived on the neutrinos produced within the same sources assuming:
  1. Protons are accelerated at the sources with a power-law index 2
  2. All protons undergo photo-hadronic interactions giving neutrons, neutrinos and g-rays
  3. The sources are optically "thin" to neutrons, which escape and decay into protons giving the observed CRs
  4. The luminosity evolution of far away sources (whose CR we do not observe) is not stronger than any class we know
- Mannheim Protheroe and Rachen (MPR) showed that different CR spectra can considerably weaken the limit
- The observed flux is very close to WB limit: a coincidence or a deeper multi-messenger connection?

$$E^2\Phi < 3\times10^{-8}\,\mathrm{GeV\,s^{-1}\,sr^{-1}\,cm^{-2}}$$

K. Mannheim, et al. (2001)



G-RAY FOLLOW-UP PROGRAM RESULTS

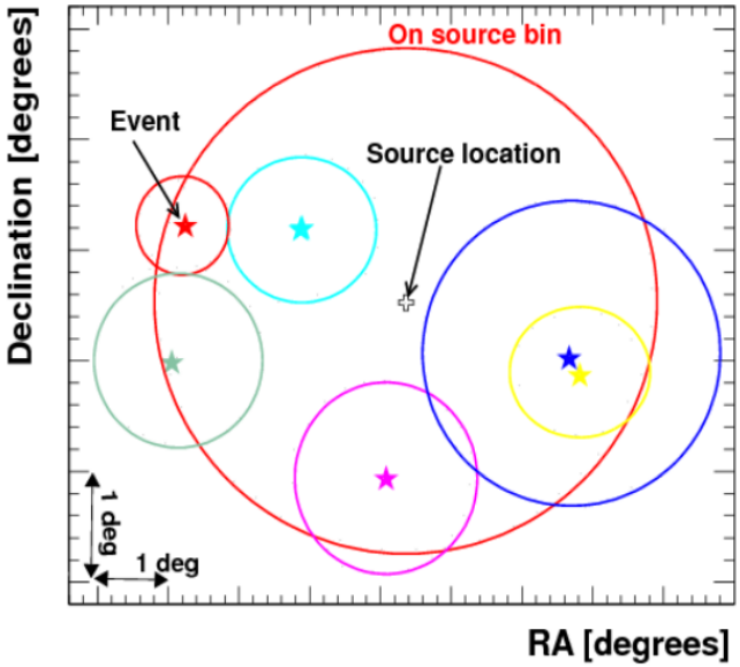
- Time-dependent point-source analysis within 21 days
- Pre-agreed upon source list
- Rate threshold

  MAGIC (1 alert / year)

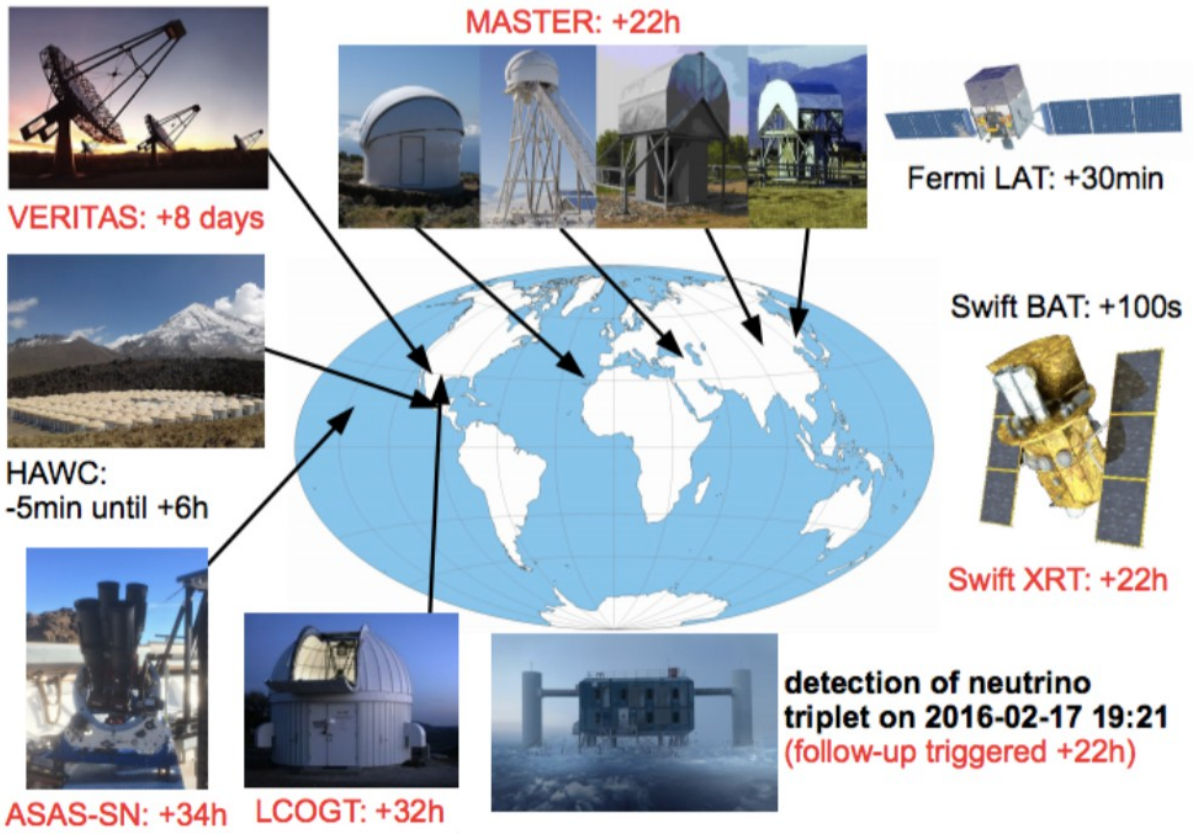
  VERITAS (3 alerts / year)

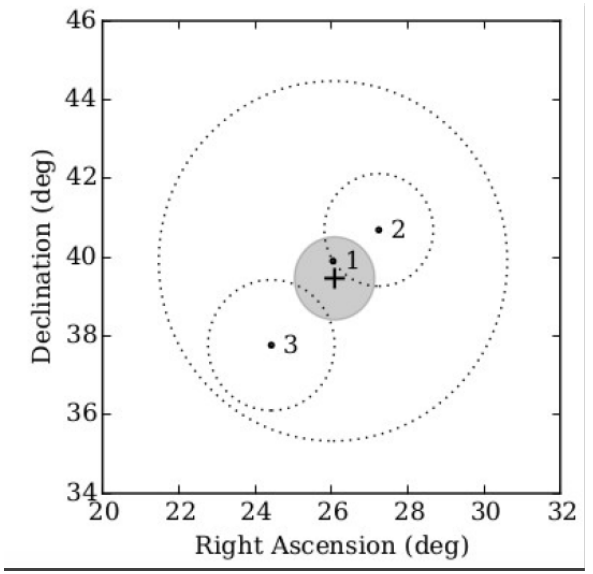
- Most significant alert on 09.11.2012
- 6 events in 4.2 days
- Alert forwarded to VERITAS → no signal
- Planned extension: North+South, all-IACTs + Fermi + HAWC

IceCube arXiv: 1610.01814



OPTICAL FOLLOW-UP PROGRAM: RESULTS

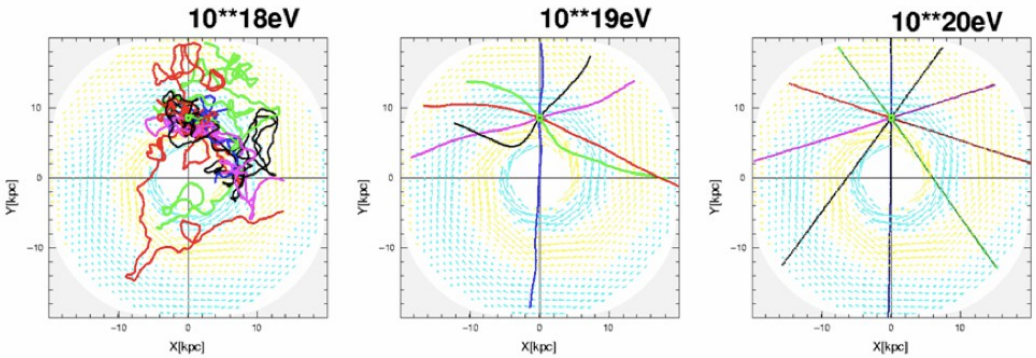




- Three neutrino candidates within 100 sec from the same direction
- Once every 14 years from background
- No optical counterpart found close-by supernova ruled out

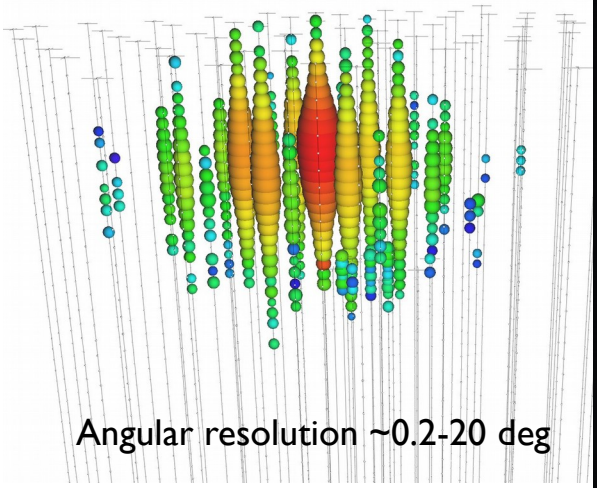
MultiMessenger

Each of the messengers has its special qualities...

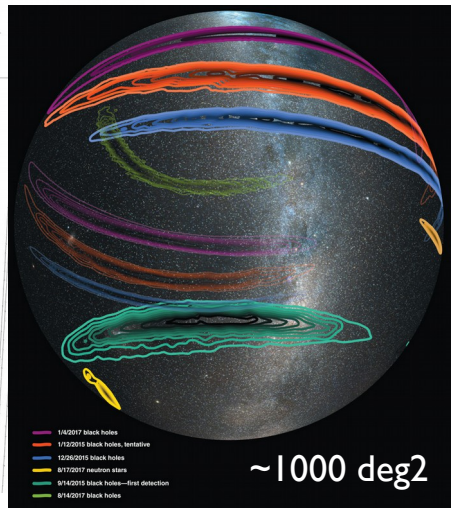


Proton deflection in Galactic magnetic field

Instrumental limitations...

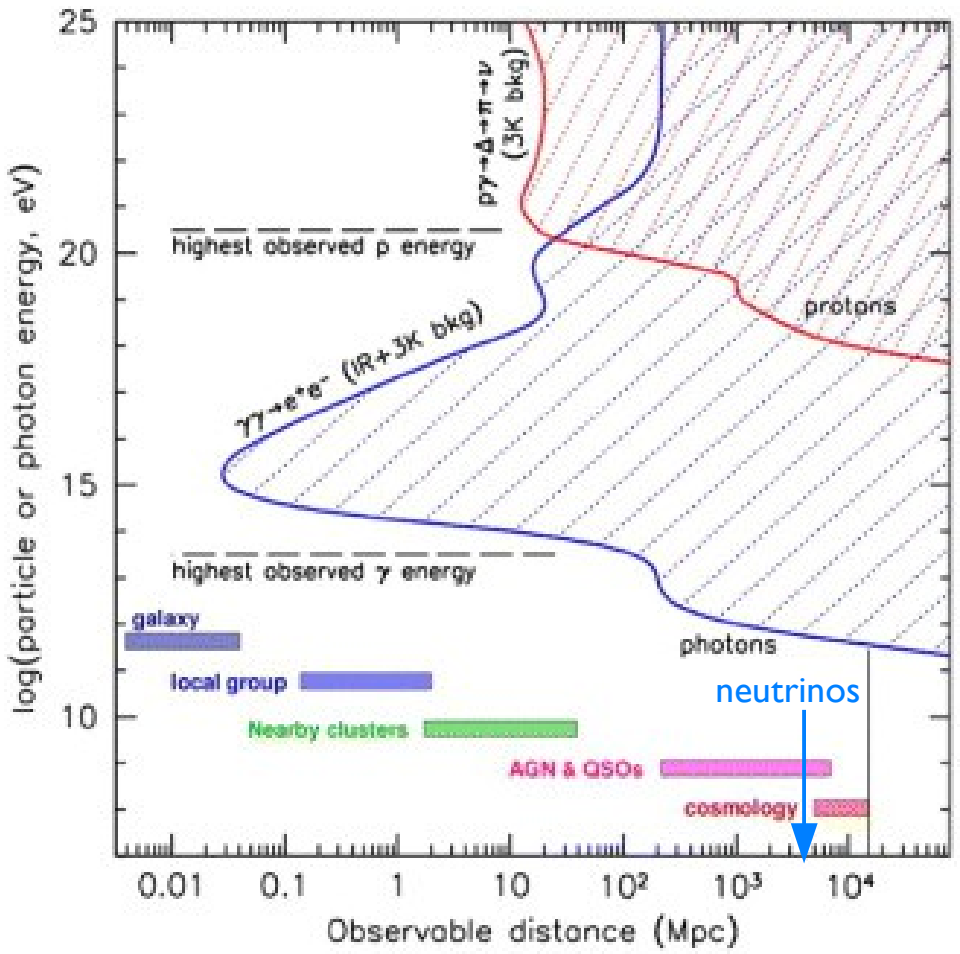


Angular resolution ~0.2-20 deg



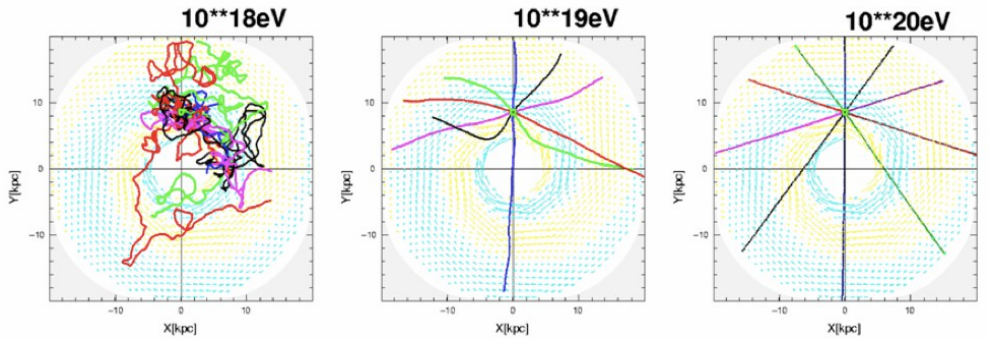
~1000 deg2

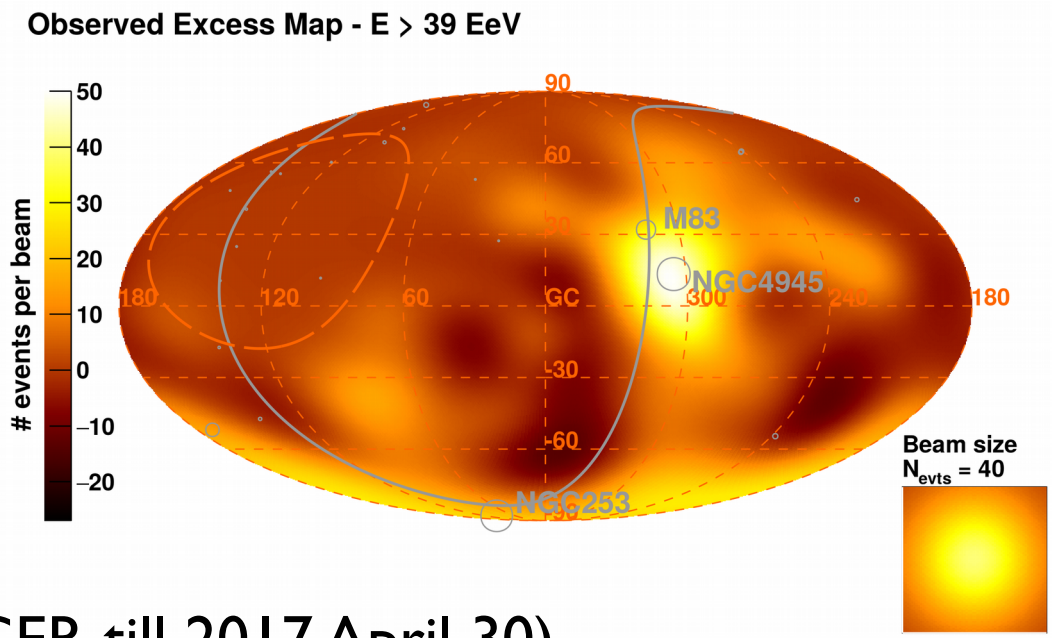
Proton/photon free path in the Universe



Potential sources of cosmic rays

Ruben Conceincao
AUGER, Wed@18:50





- Data: 5514 events, E>20 EeV (AUGER till 2017 April 30)
- Test: 4 anisotrophy models based on active galactic nuclei (AGNs) and starburst galaxies (SBGs) from Fermi-LAT, Swift-BAT and 2MRS catalogues
- Result: starburst model fits the data better than the hypothesis of isotropy with a statistical significance of 4.0σ (alternative models ~2.7−3.2σ)