VHE neutrino astronomy

Are we there yet…?

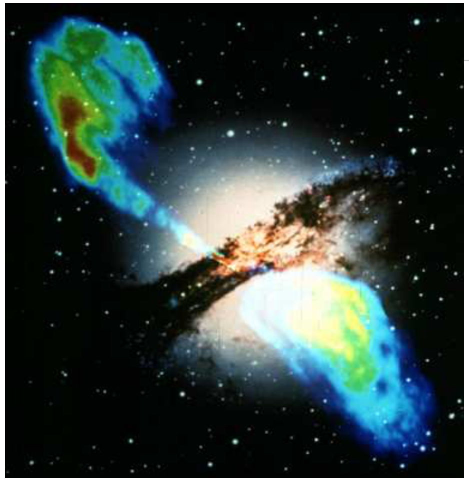
Konstancja Satalecka, DESY
Multimessenger Data, Sexten, 2019

Cosmic messengers

The multi messenger approach

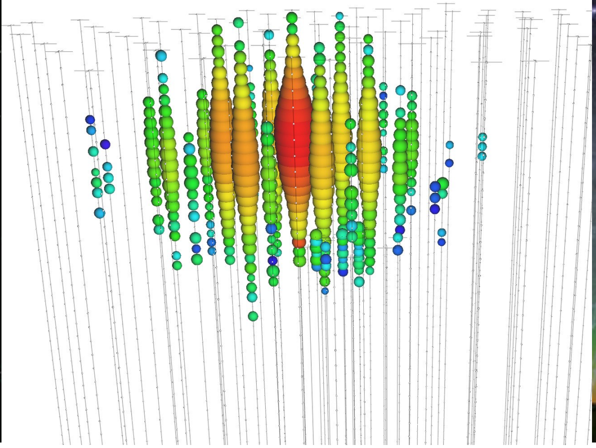
Coordinated observation and interpretation of distinct signals ("messengers") associated with two or more of the four fundamental forces:

photons



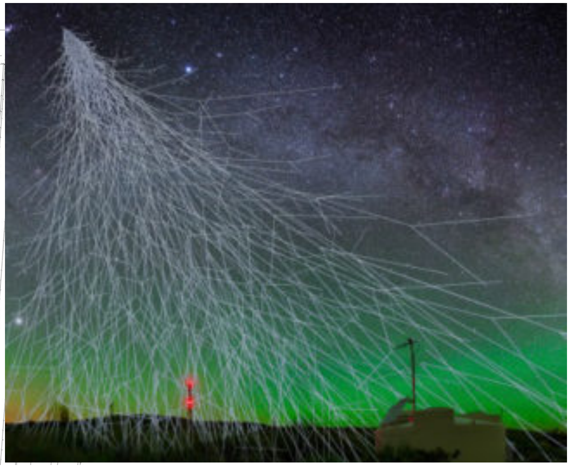
+ arcmin resolution
- absorption

neutrinos



- 1-10 deg resolution
+ no absorption

cosmic rays



- deflected in mag. fileds
- GZK cut-off

gravitational waves

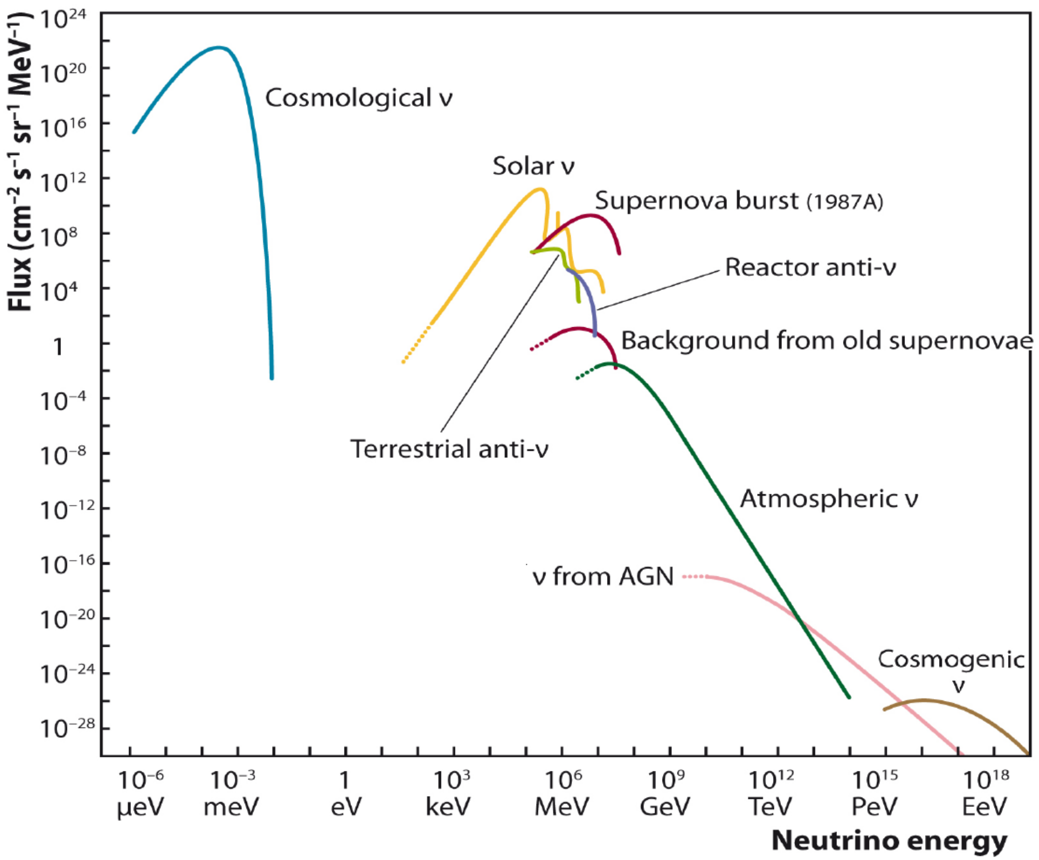
- localisation 100 deg^2
+ no-absorption

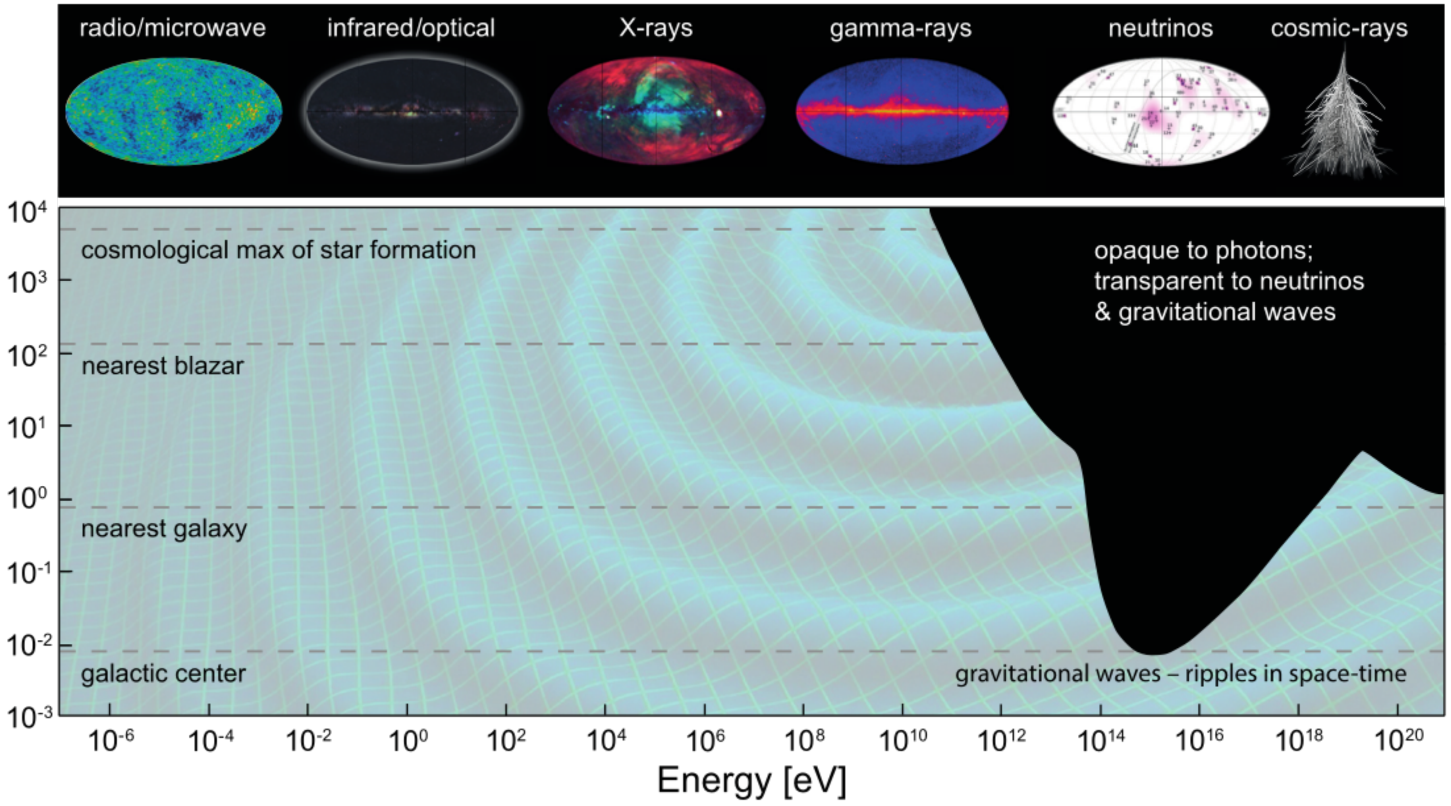
Cosmic messengers

The neutrino window to the Universe

Above ~PeV energies the Universe is opaque to photons due to absorption on EBL

$$\gamma + \gamma_{IR,CMB,radio} \to e^+ + e^-$$

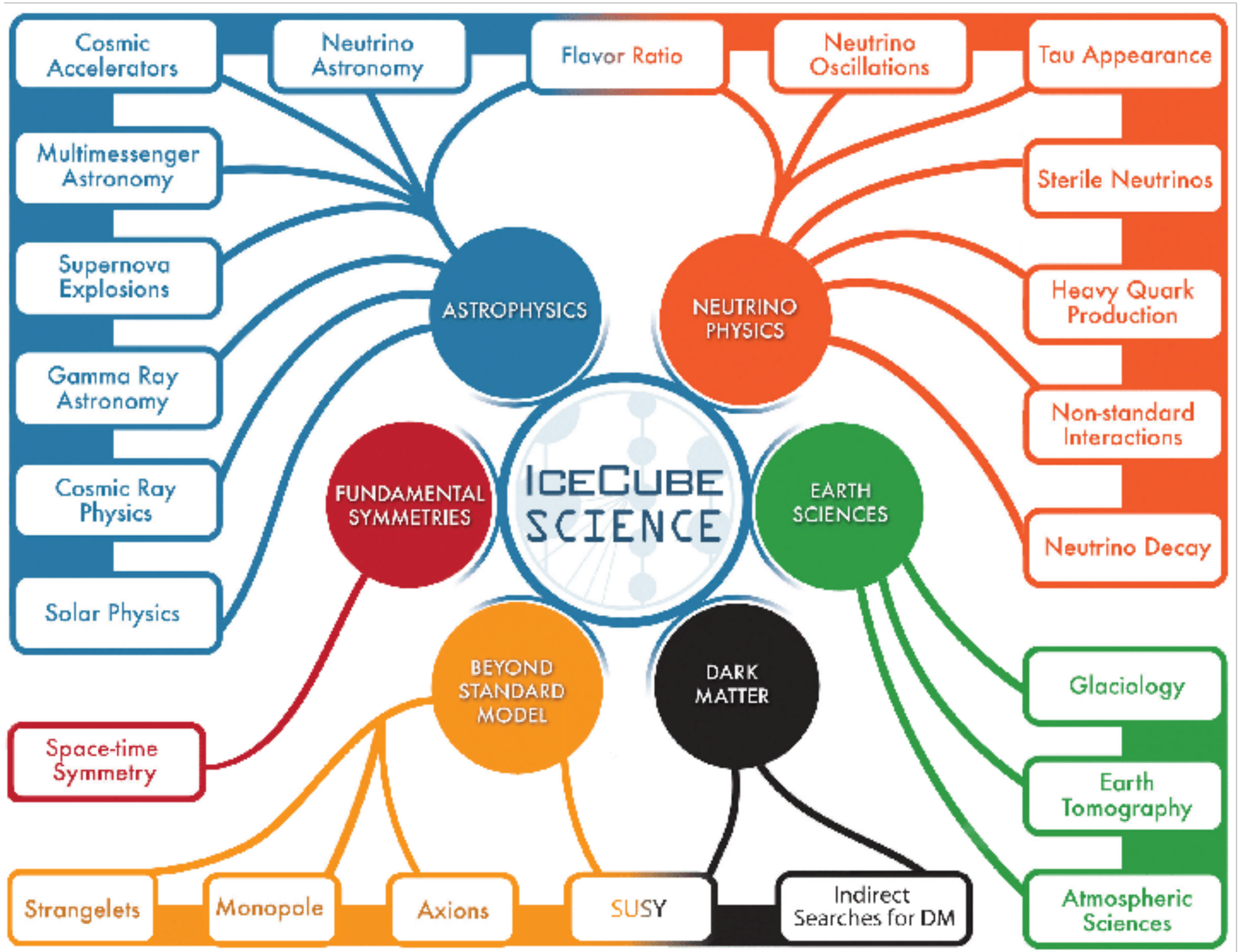




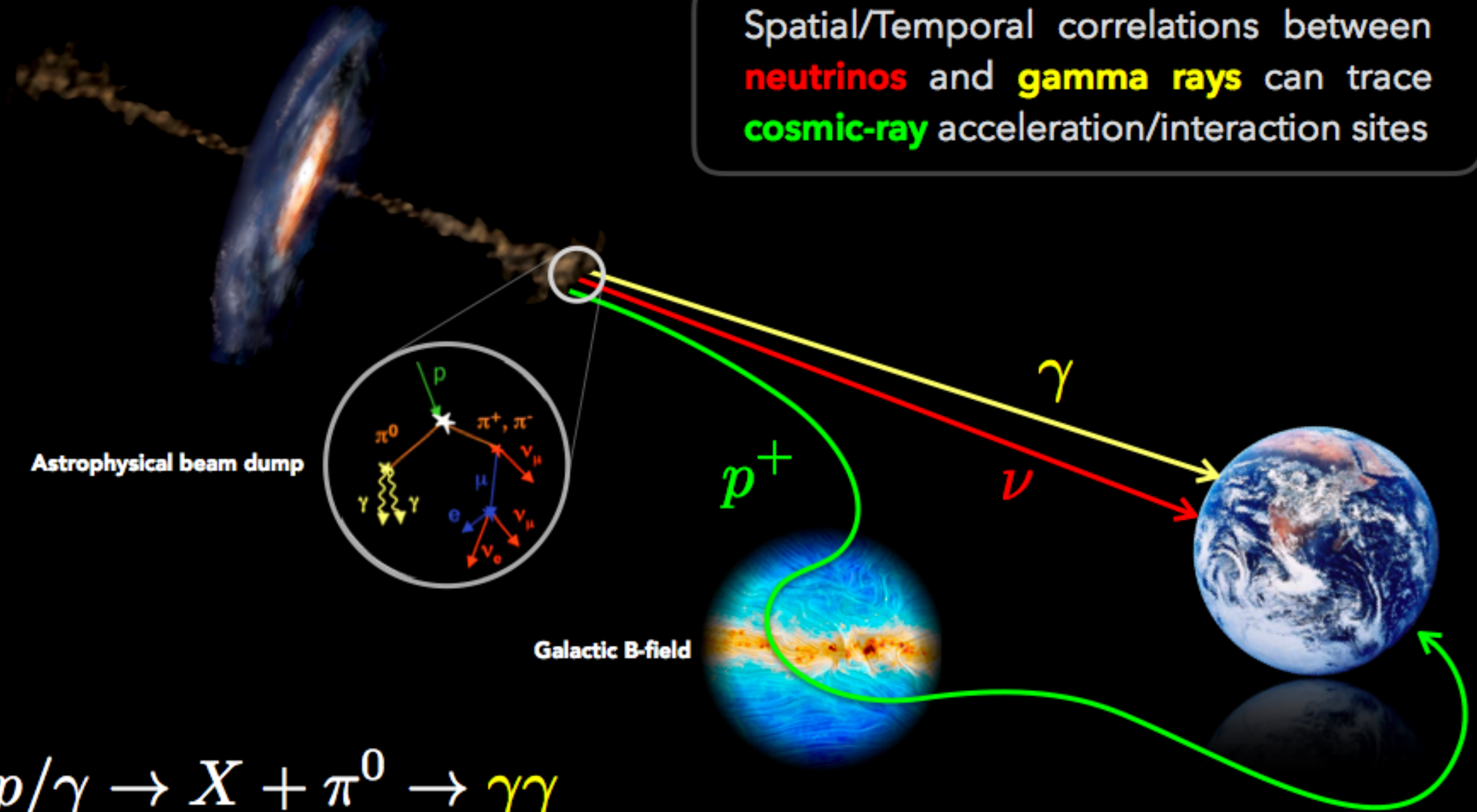
Neutrino

Multi-tasking particle

- Astrophysics is our main motivation, but once you invest all this money you can as well have a look at ➠

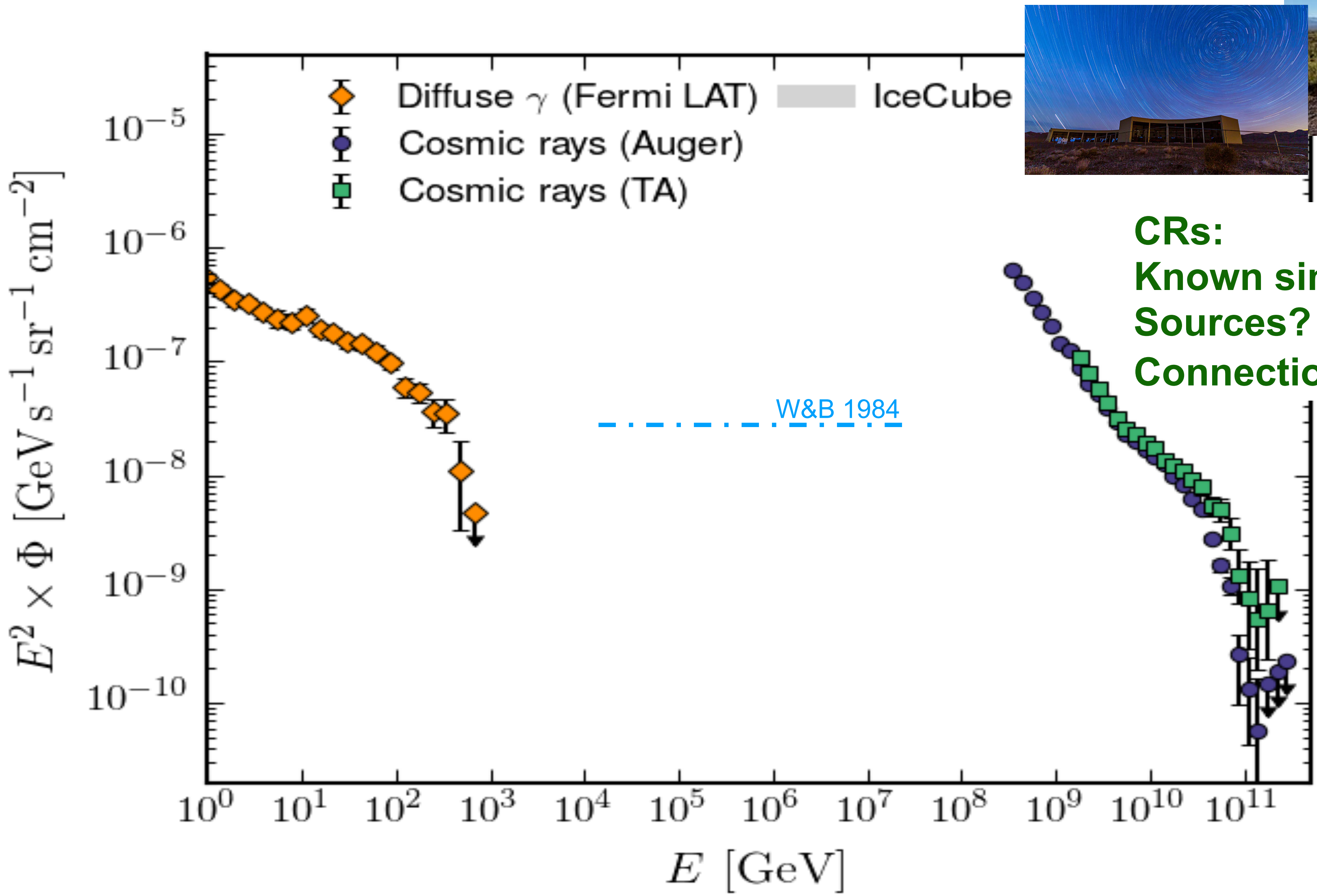


Spatial/Temporal correlations between **neutrinos** and **gamma rays** can trace **cosmic-ray** acceleration/interaction sites



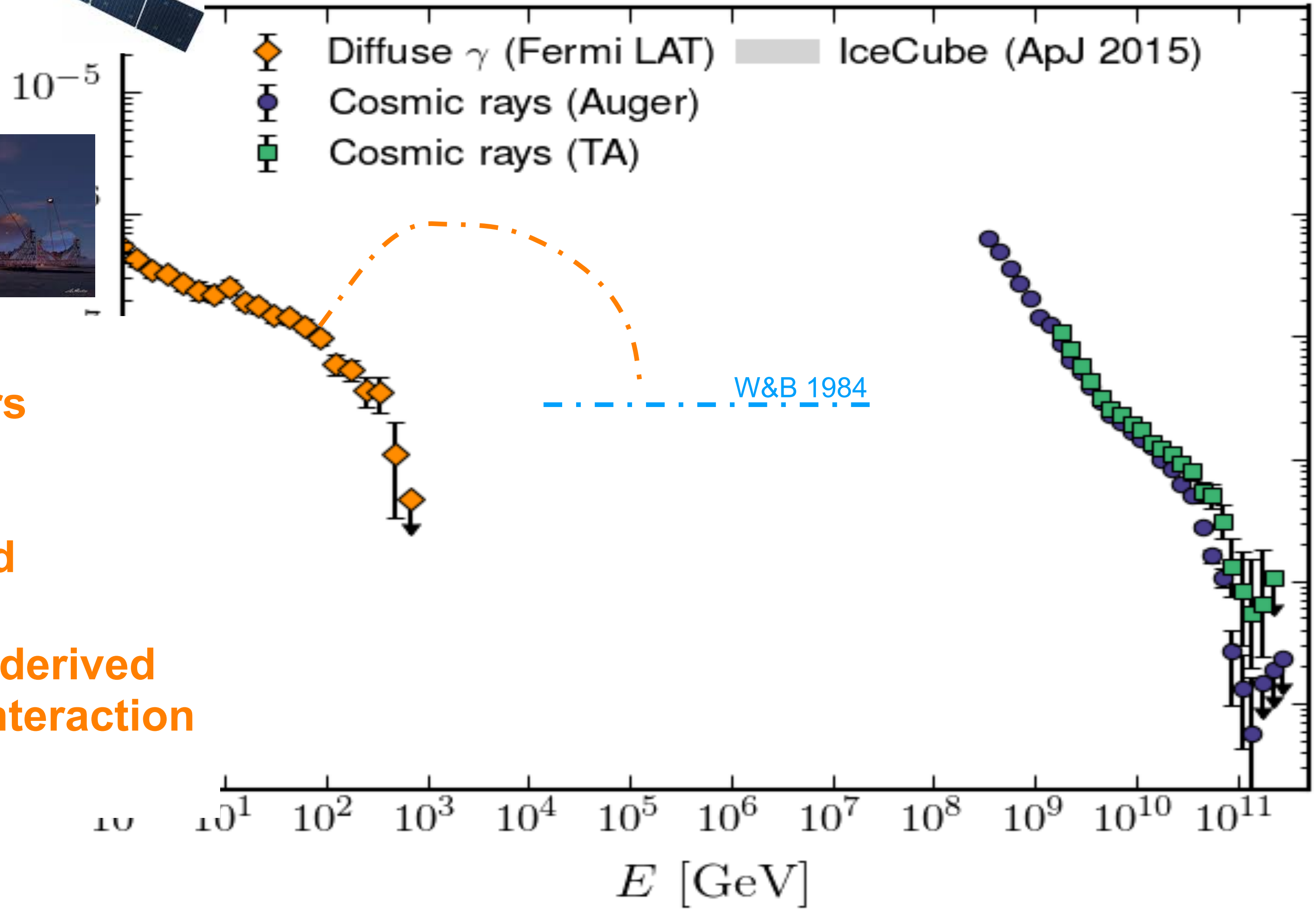
$$p + p/\gamma \rightarrow X + \pi^0 \rightarrow \gamma\gamma$$
$$\rightarrow X + \pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$ **(oscillates to ~1:1:1)**

Neutrinos, γ–rays & CRs



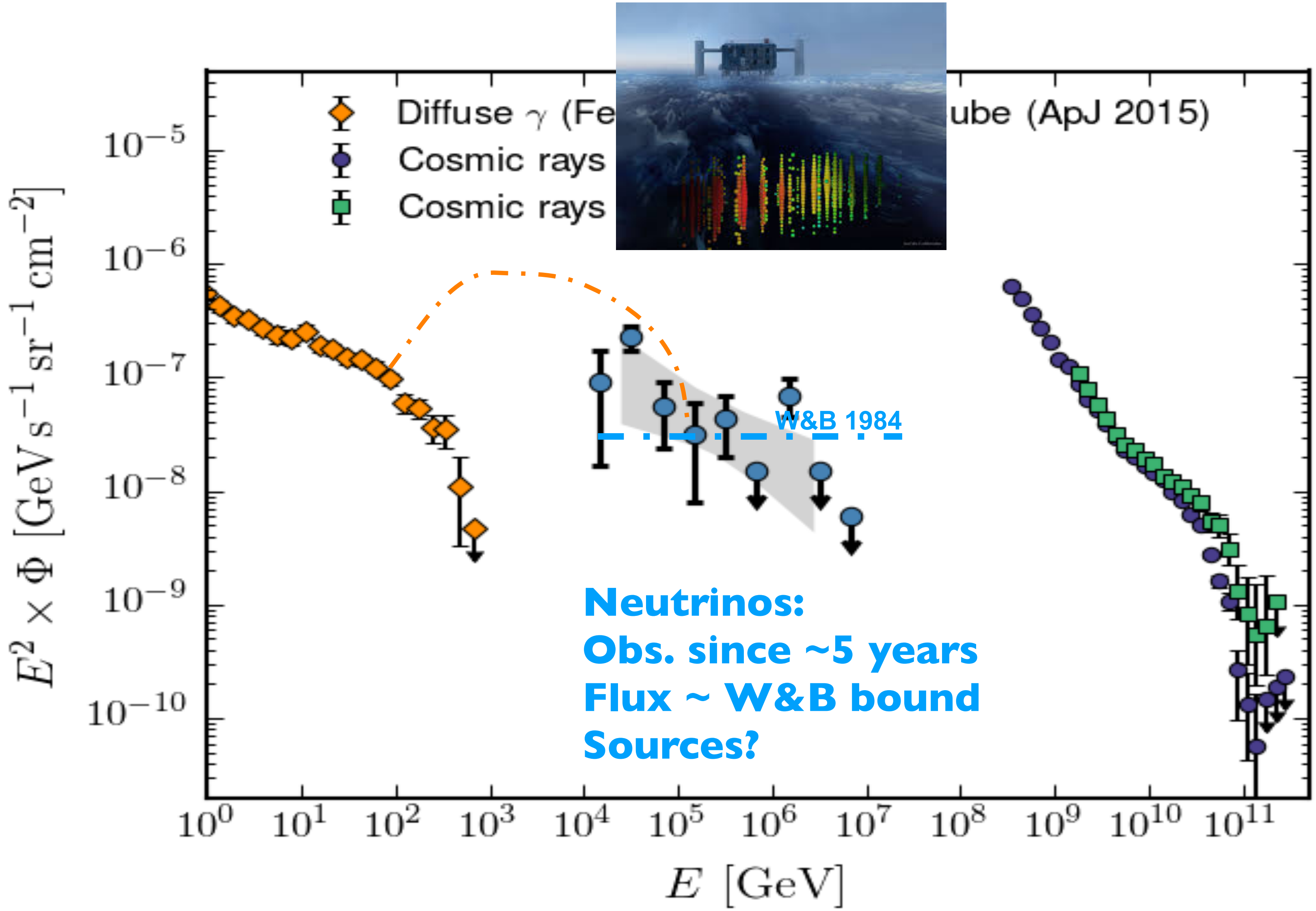
CRs:
Known since 100 yrs!
Sources?
Connection to ν?

Neutrinos, γ–rays & CRs

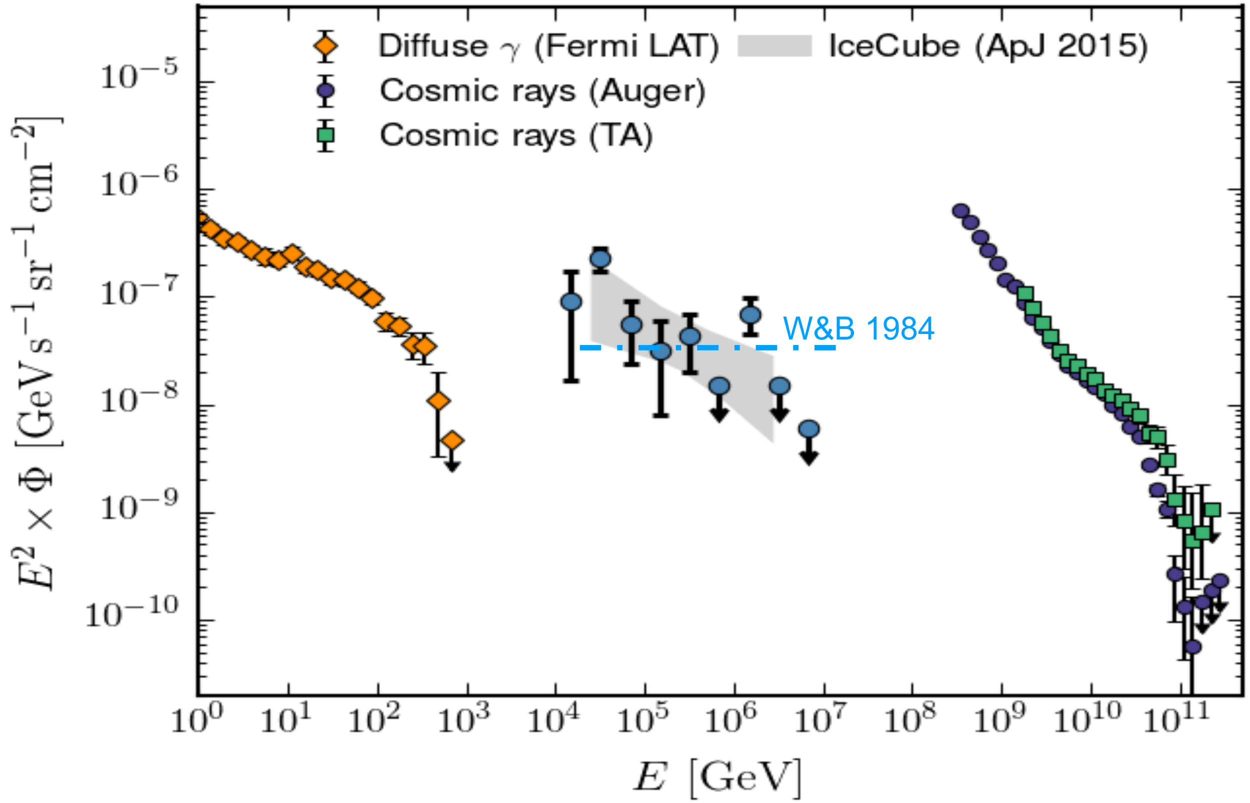


γ-rays:
Known since ~30 yrs
~3000 sources
> 100 TeV sources
Should be produced together with ν!
Constraints can be derived depending on the interaction type (pp or p/γ)

Neutrinos, γ–rays & CRs



Neutrinos, γ–rays & CRs



- How are the different messengers connected
- What are their sources?
- What are the acceleration/emission/propagation processes?
- Neutrino flux ~ W&B bound → real connection or accident?

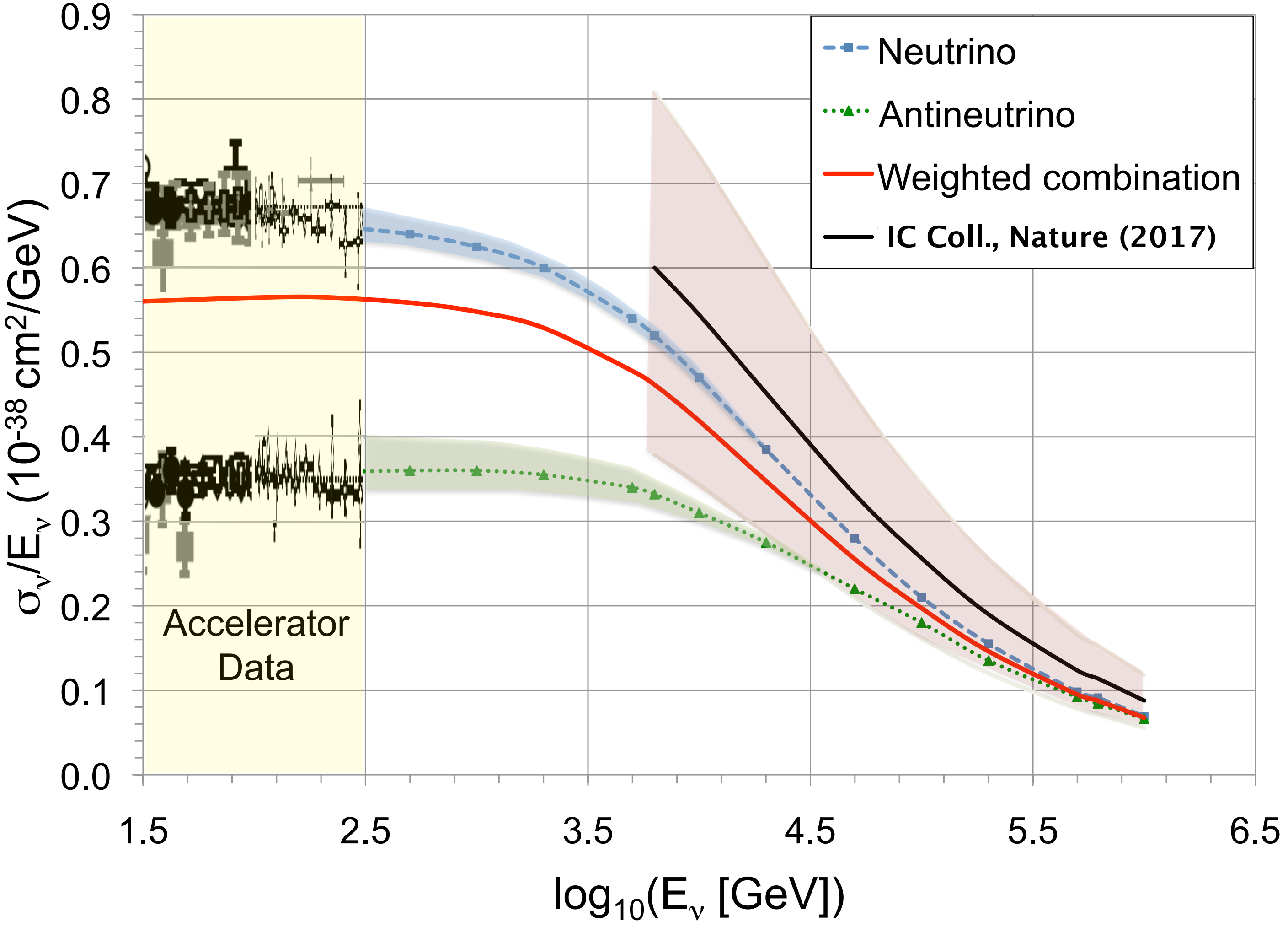
Very similar energy output for all three messengers!

Neutrino detection

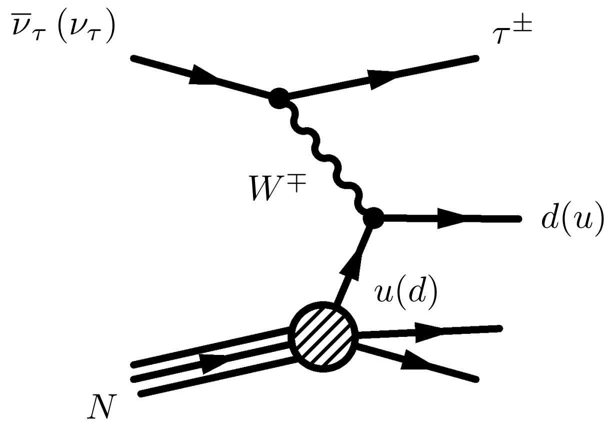
Low cross-sections, low fluxes, hopeless…?

Neutrino flux is extremely small

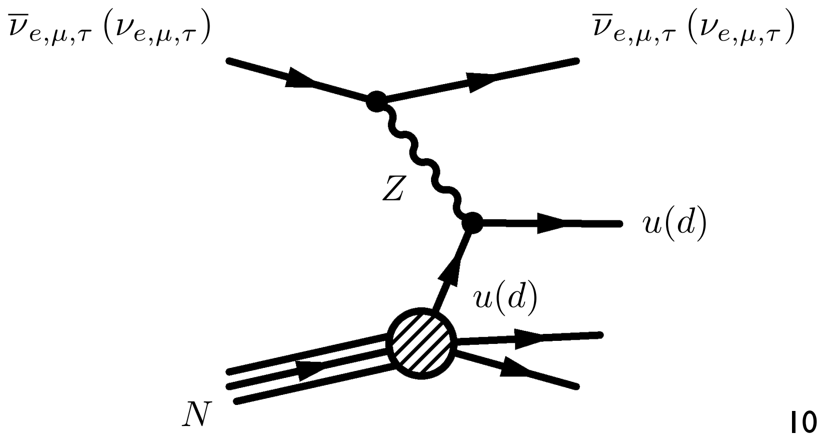
- At 10^{15} eV: 0.01 neutrinos per (year, km², sr)
- At 10^{18} eV: 10^{-10} neutrinos per (year, km², sr)



Charged-current (CC)



Neutral-current (NC)



Instruments: now

Instruments: now

ANTARES
0.01 km^3
Medium: water
2008 - 2019

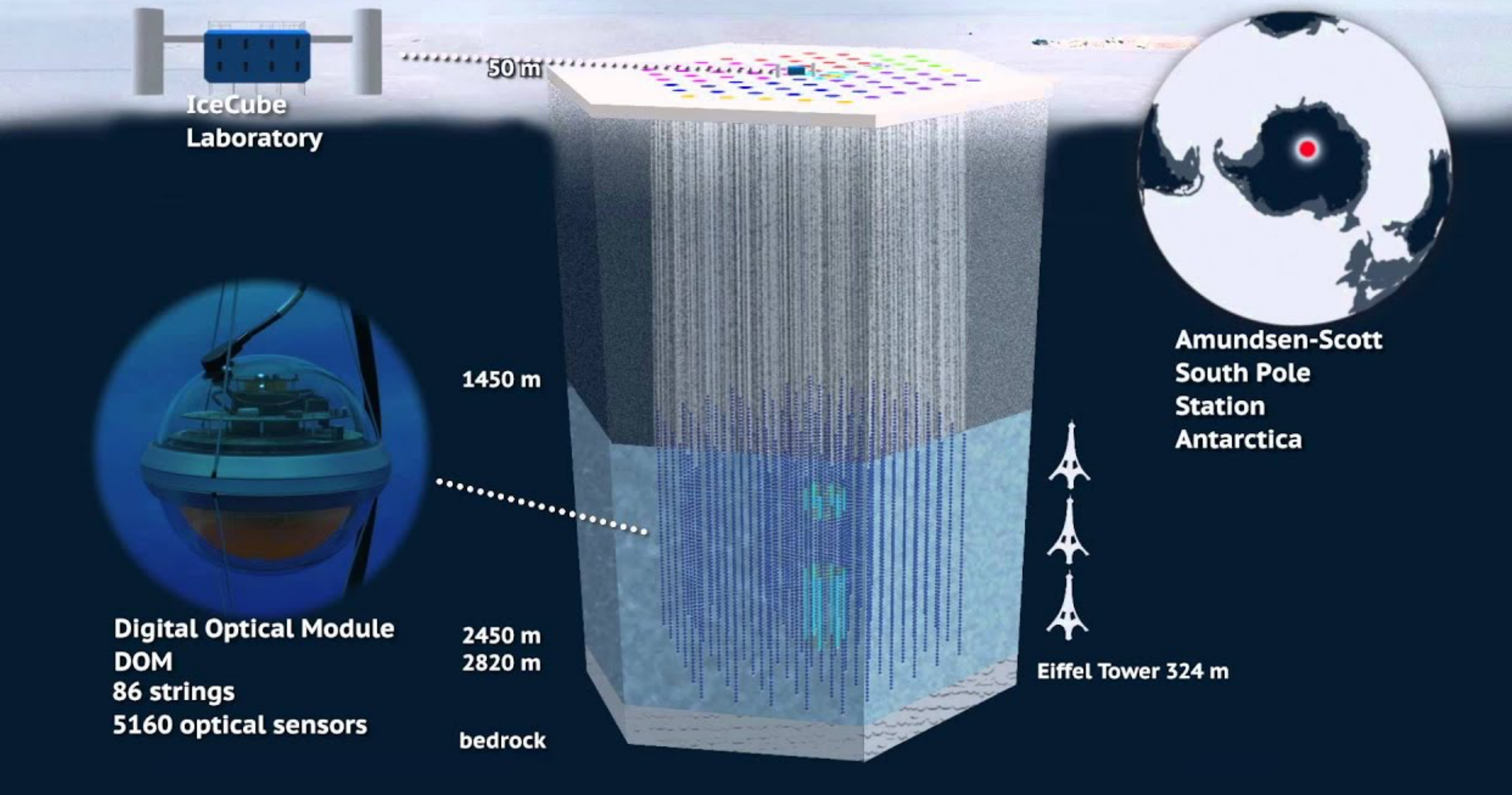
THE LAKE BAIKAL NEUTRINO TELESCOPE
0.02 km^3
Medium: water
1998 - …

Water:
Con: currents, corrosiveness of sea water, animals, ships, bioluminescence, …
Pro: Less scattering (better angular resolution), easier accessibility, different locations (wider field of view)

Ice:
Con: extreme cold, expensive drilling, scattering through dust, limited in location, unknown ice quality, borehole restricted sensors, …
Pro: stable configuration, no non-particle background light, …

ICECUBE
1 km^3
Medium: ice
2011- …

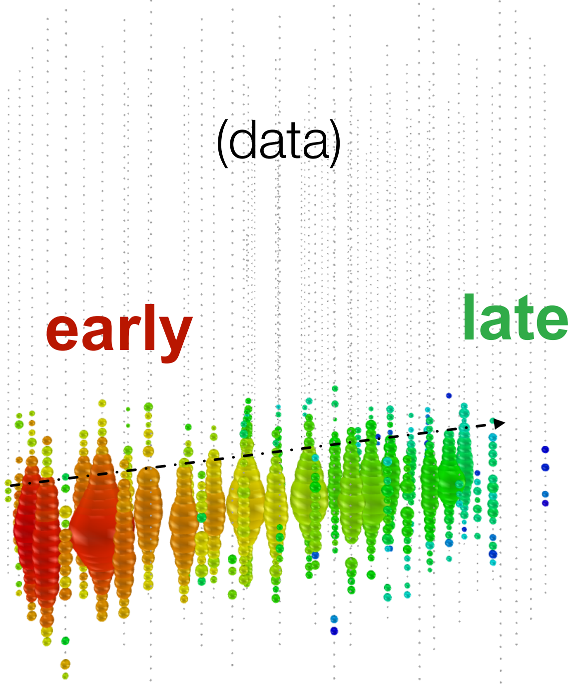
IceCube South Pole Neutrino Observatory



Neutrino detection

Event Signatures

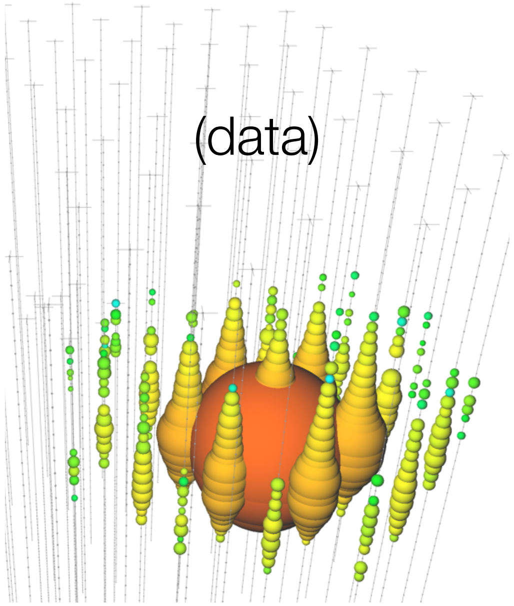
Charged-current ν_μ



Up-going track

Factor of ~2 E resolution
< 1 deg angular resolution

Neutral-current / ν_e

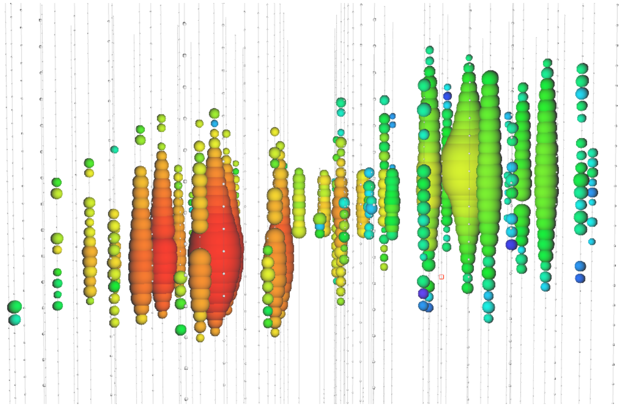


Isolated energy deposition **(cascade)** with no track

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

Charged-current ν_τ

(simulation)

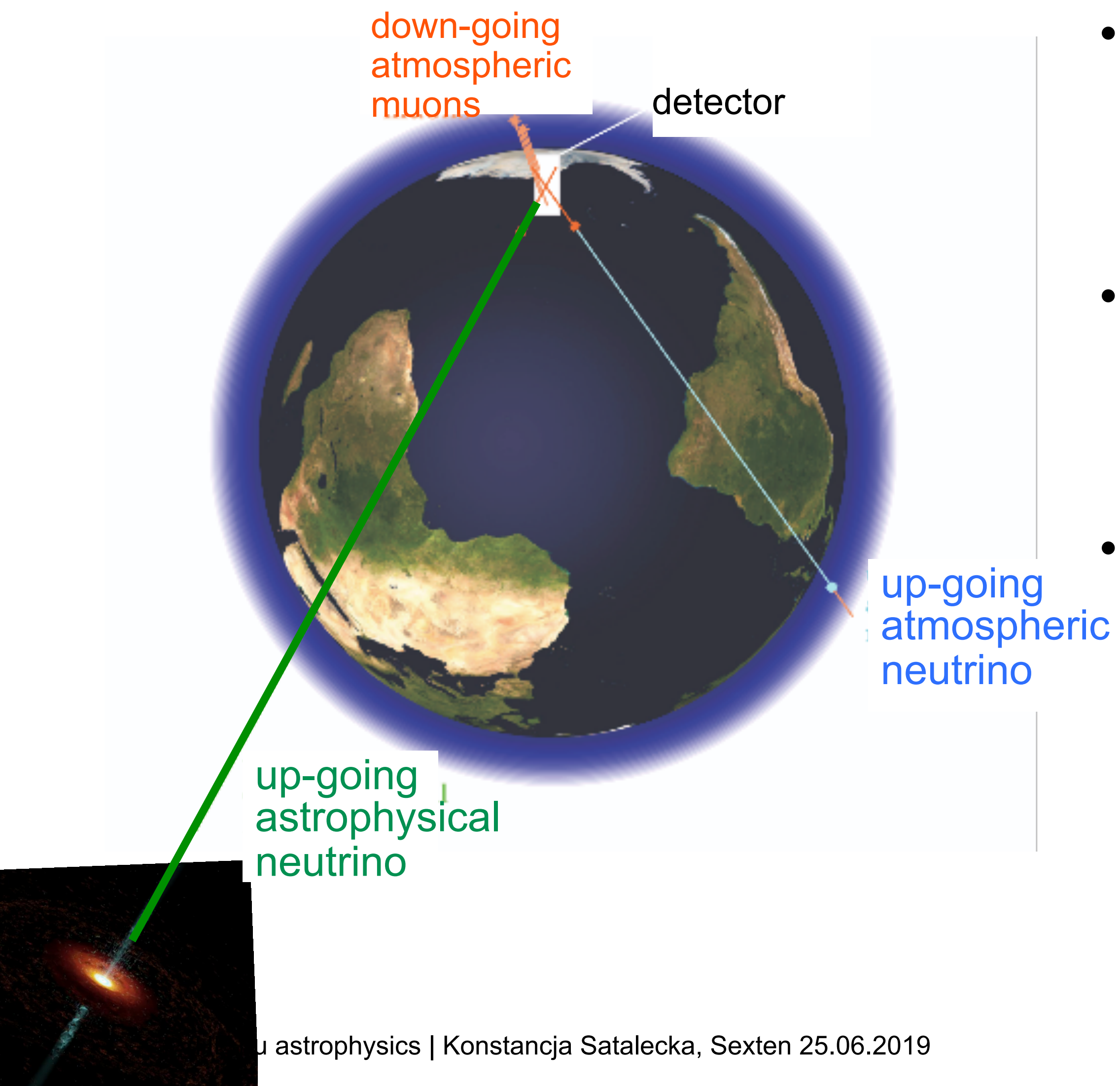


Double cascade

(resolvable above ~100 TeV deposited energy)

The three signal channels

Cosmic neutrinos are not all of the story….



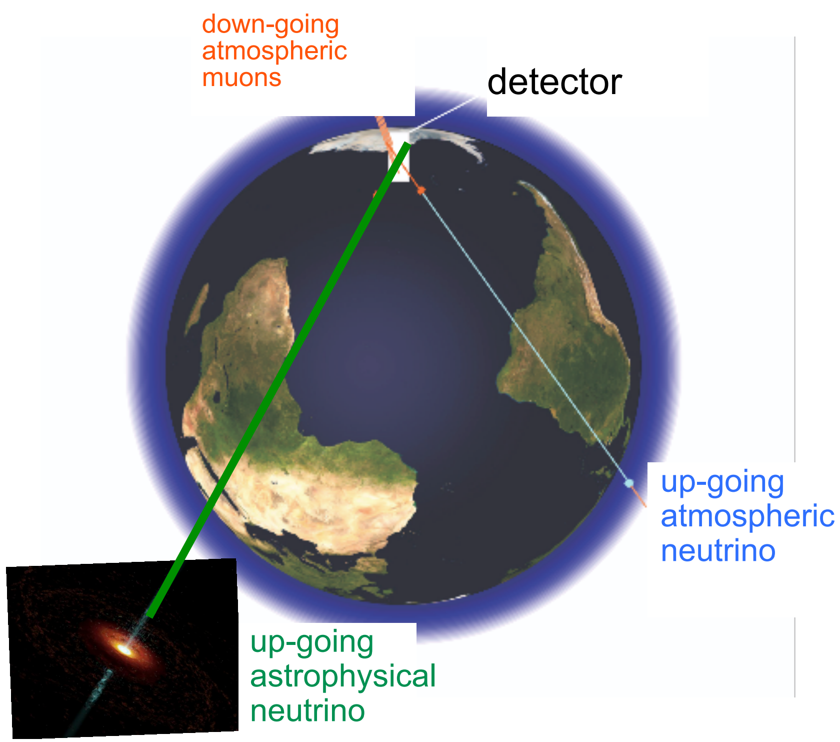
Event rates per year:

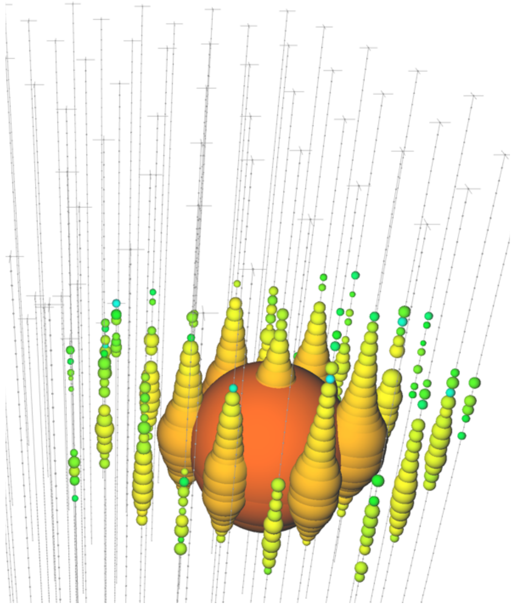
- Atmospheric μ (99.999% of triggered events) 7×10^{10} (2000/s)
  - CR Spectrum…YES
  - CR Anisotropy…YES
  - CR Composition…Soon
- Atmospheric ν (residual background) 5×10^4 (1/6 minutes)
  - Spectrum….YES
  - Oscillations…YES
  - Sterile ...Not yet
- Astrophysical neutrinos: ~ $O(10)$
  - Diffuse High Energy...YES
  - Multimessenger….YES
  - Source Catalog....Not yet

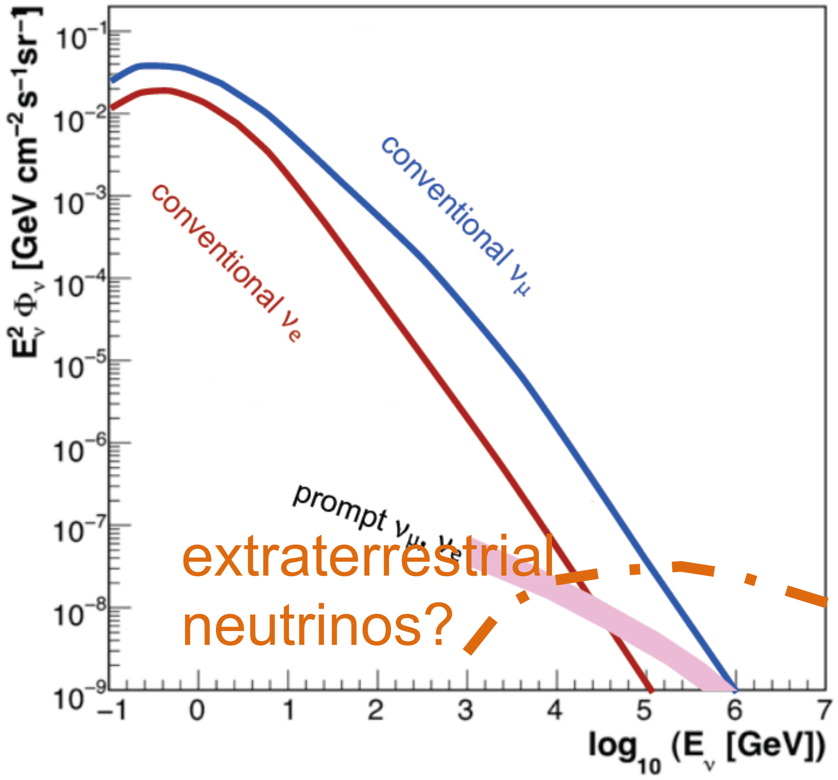
→ We need clever background rejection techniques!!

Neutrino detection

Background rejection





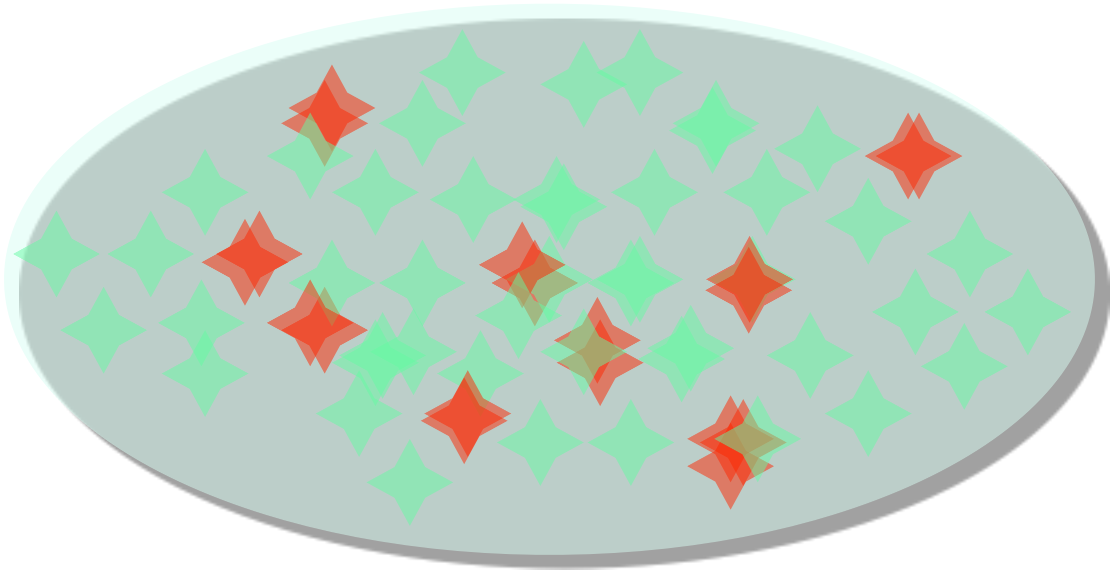


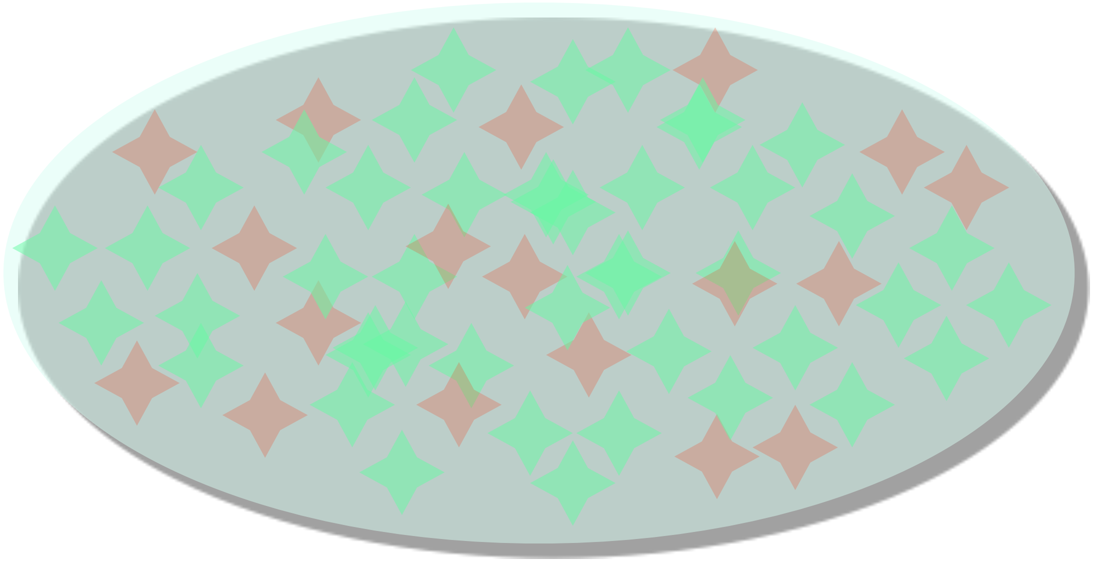
Background rejection:

- By direction: accept only events coming from North (up-going)
- By event type: cascades – only produced by NC and ne CC
- By energy: expected astrophysical flux harder than atmospheric - accept only high energy events

Neutrino detection

Background rejection - analysis tricks



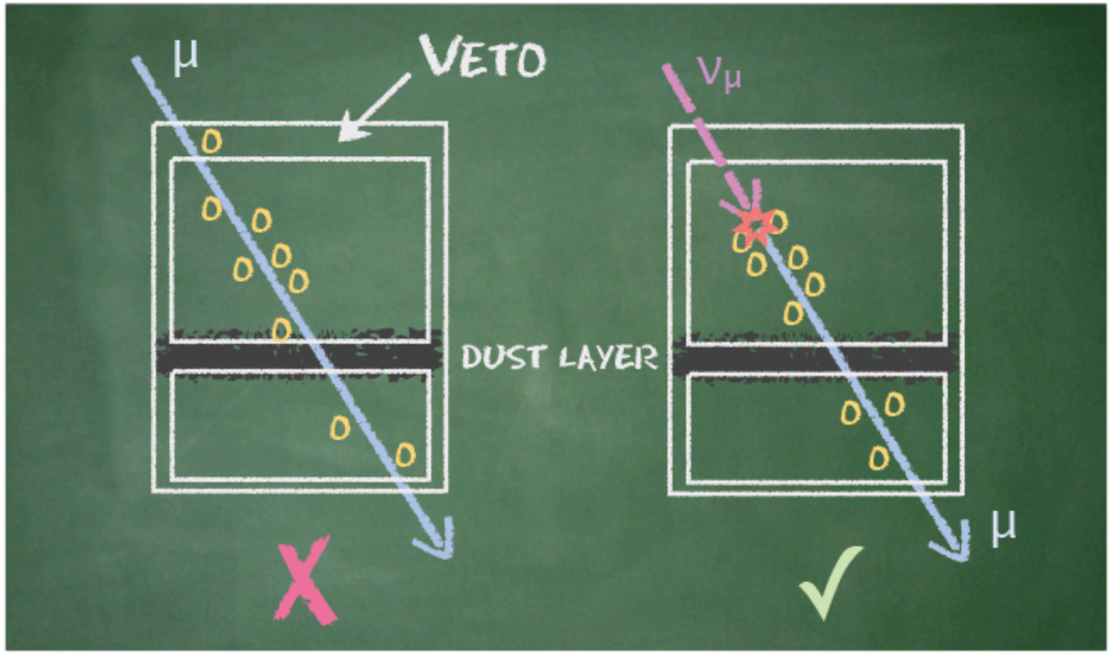


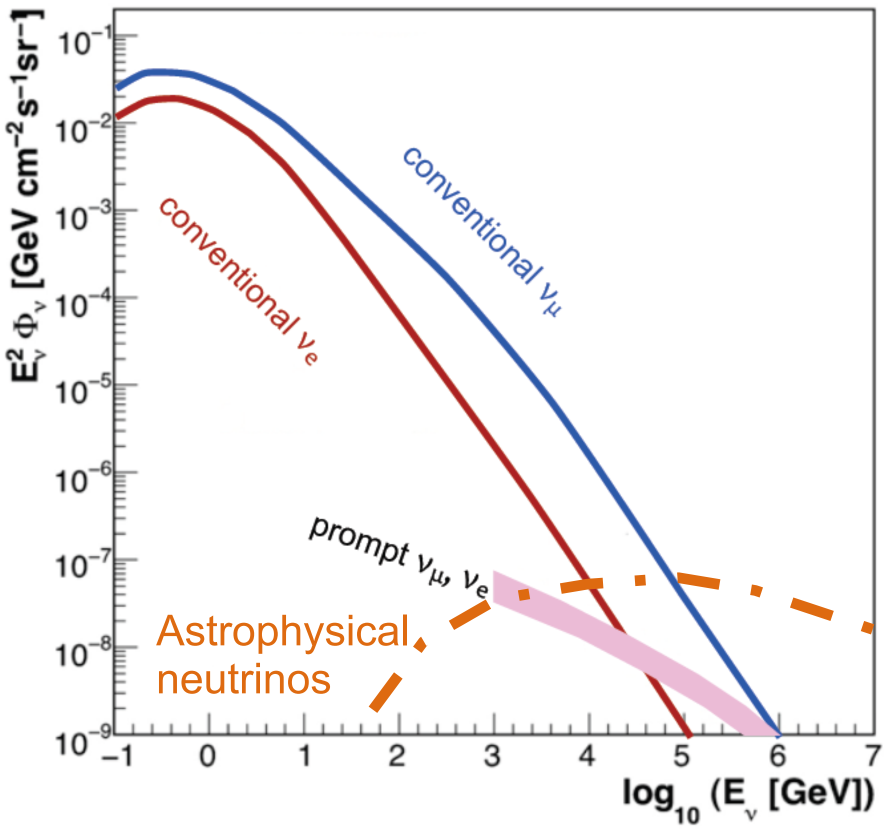
Point sources: search for excesses from few strong objects. Localised (in space and/or time)

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

High Energy Starting Events

The "golden channel" for astrophysical neutrino detection





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

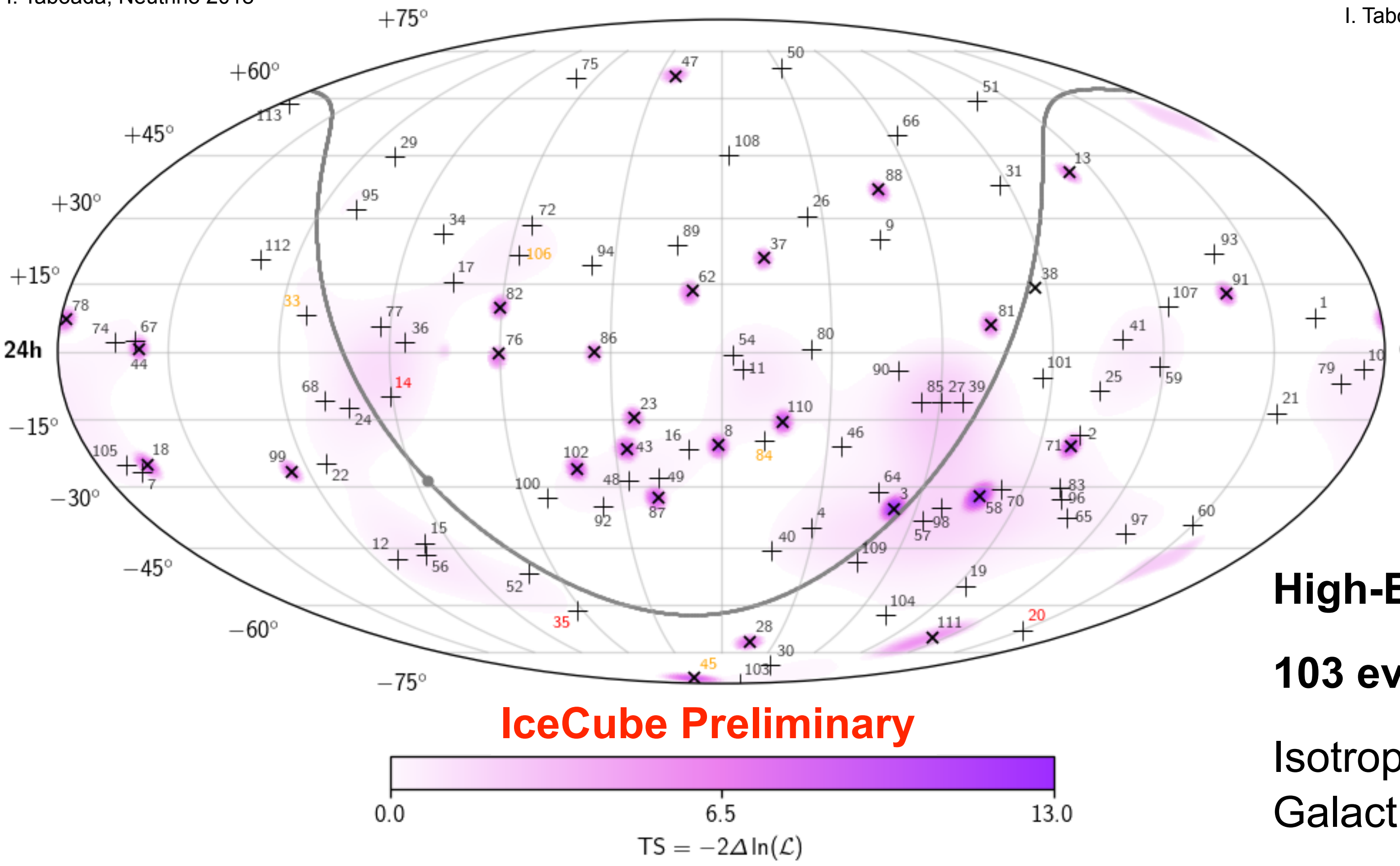
for atms. ν → reject tracks accompanied by air showers with muons, expected background: $4^{+3.6}_{-1.2}$ /year (detectable when coming from the Southern hemisphere)

+ charge cut (> few 1000 phe) to select very high energy events

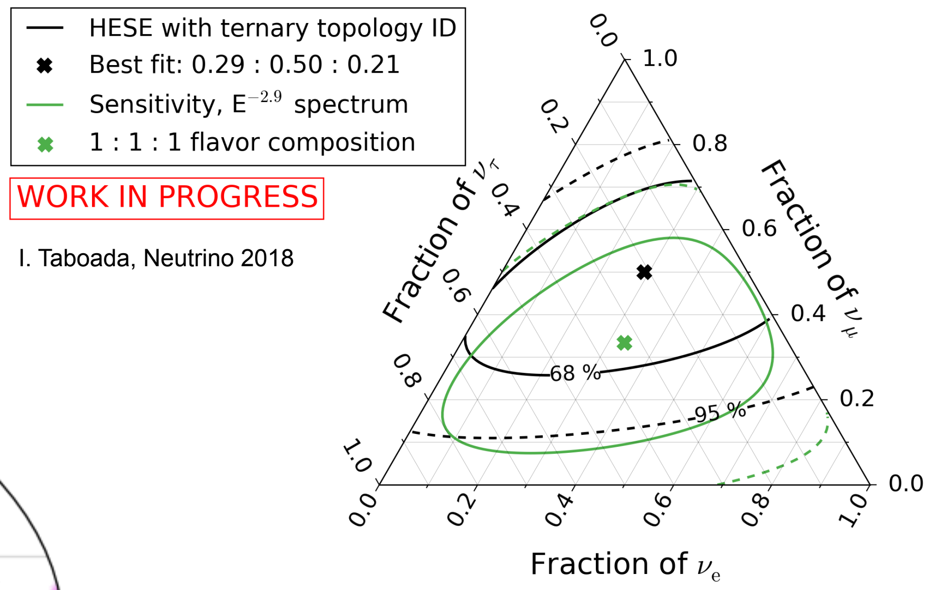
Astrophysical neutrinos

> 100 and counting…

I. Taboada, Neutrino 2018



$E < 300$ TeV 300 TeV $< E < 1$ PeV 1 PeV $< E$



Flavour ratio: **0.29:0.50:0.21**
(first tau neutrinos?!)
but 1:1:1 cannot be excluded…

High-Energy Starting Events (HESE) 7.5 yrs:

103 events, with 60 events > 60 TeV

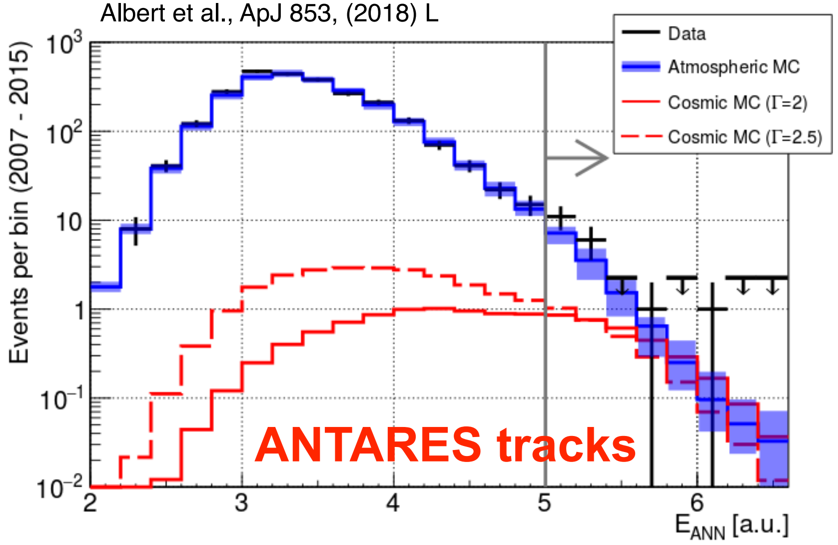
Isotropic, no clustering, no correlation with Galactic Plane → **Extragalactic (?)**

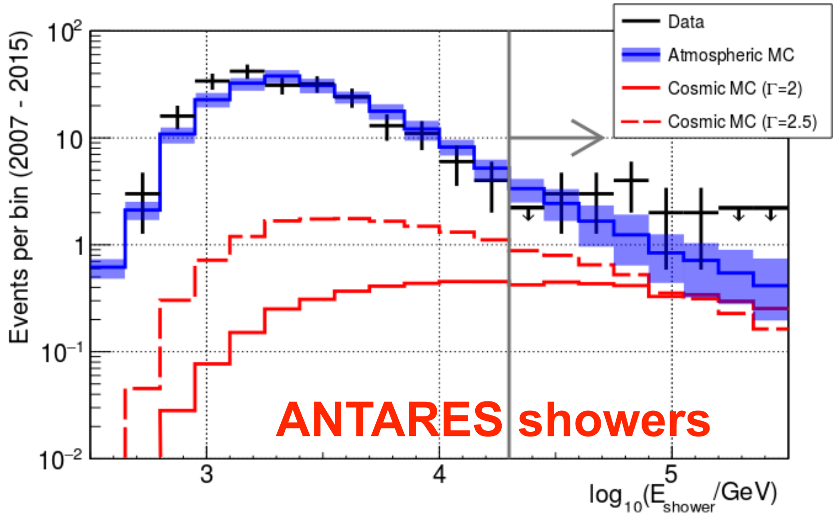
+33 events from ANTARES → →

Astrophysical neutrinos

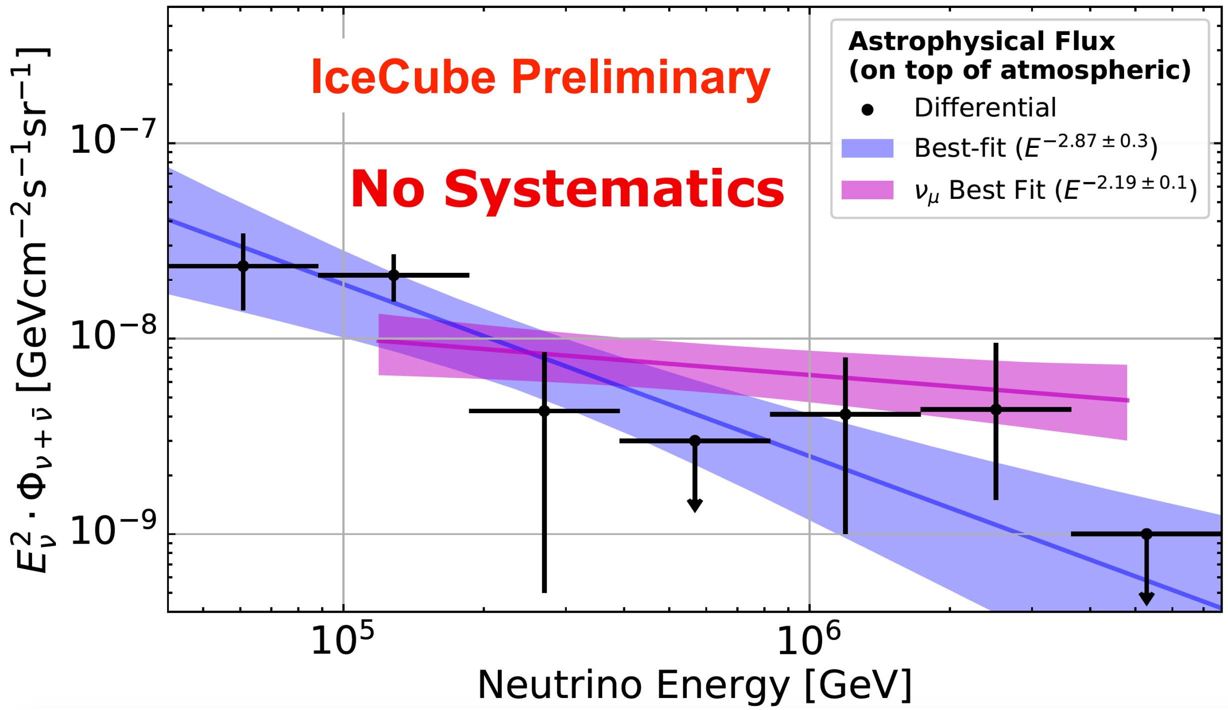
Diffuse flux

Albert et al., ApJ 853, (2018) L





I. Taboada, Neutrino 2018



IceCube HESE 7.5 yrs (2011-2017)

- All-flavour analysis compatible with the ν_μ-tracks only > 200 TeV
- Best fit: one-component power law (see legend)

ANTARES 9 yrs (2007-2015)

- All-flavour analysis (track+showers)
- Signal modeled according to the IceCube flux
- Φ_0 (100 TeV) = (1.7 ± 1.0) ×10^{-18} GeV^{-1} cm^{-2} s^{-1} sr^{-1}, spectral index Γ = 2.4 +0.5/-0.4
- 33 events (19 tracks + 14 showers) in data
- 24 ±7 (stat.+syst.) events background in MC
- **1.6 σ excess, null cosmic rejected at 85%**

Point sources…

…not yet.

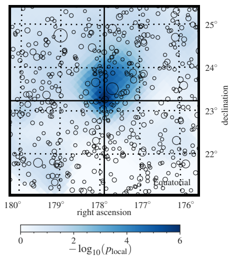
- Most recent results:
  - IC, 8 years
  - ANTARES 9 years
  - No significant clustering in space
  - No excess on selected source lists

- Previous off-line searches, spatial and temporal **did not revel any significant excess** neither…

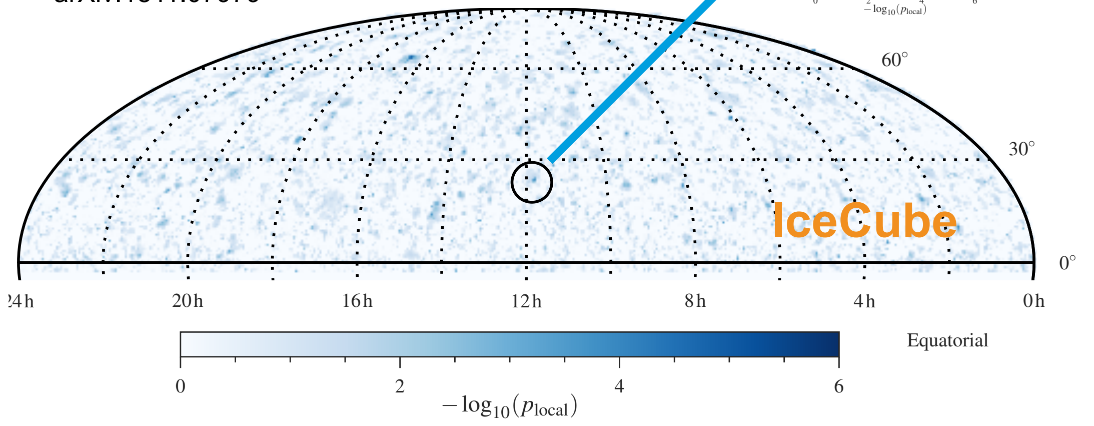
- IC + ANTARES: complimentary field of view

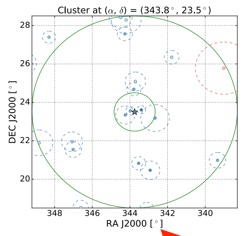
- Joined IC + ANTARES point-source search in preparation!

M.G. Aarsten et al. submitted to *EPJ-C*
arXiv:1811.07979



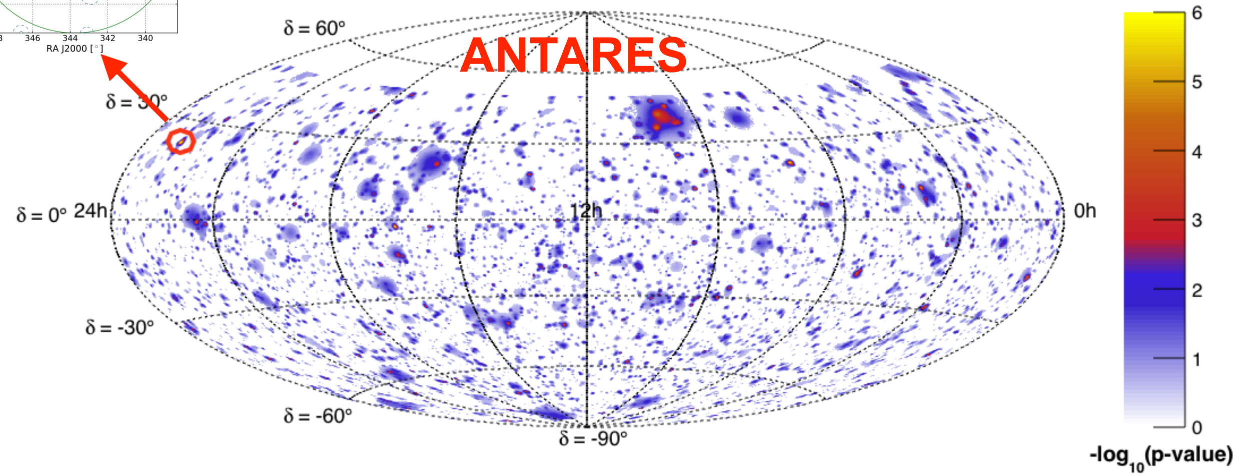
26.5%
post-trial
P-value





1.9σ
post-trial
significance

A.Albert et al.
Phys. Rev. D 96, 082001 (2017)

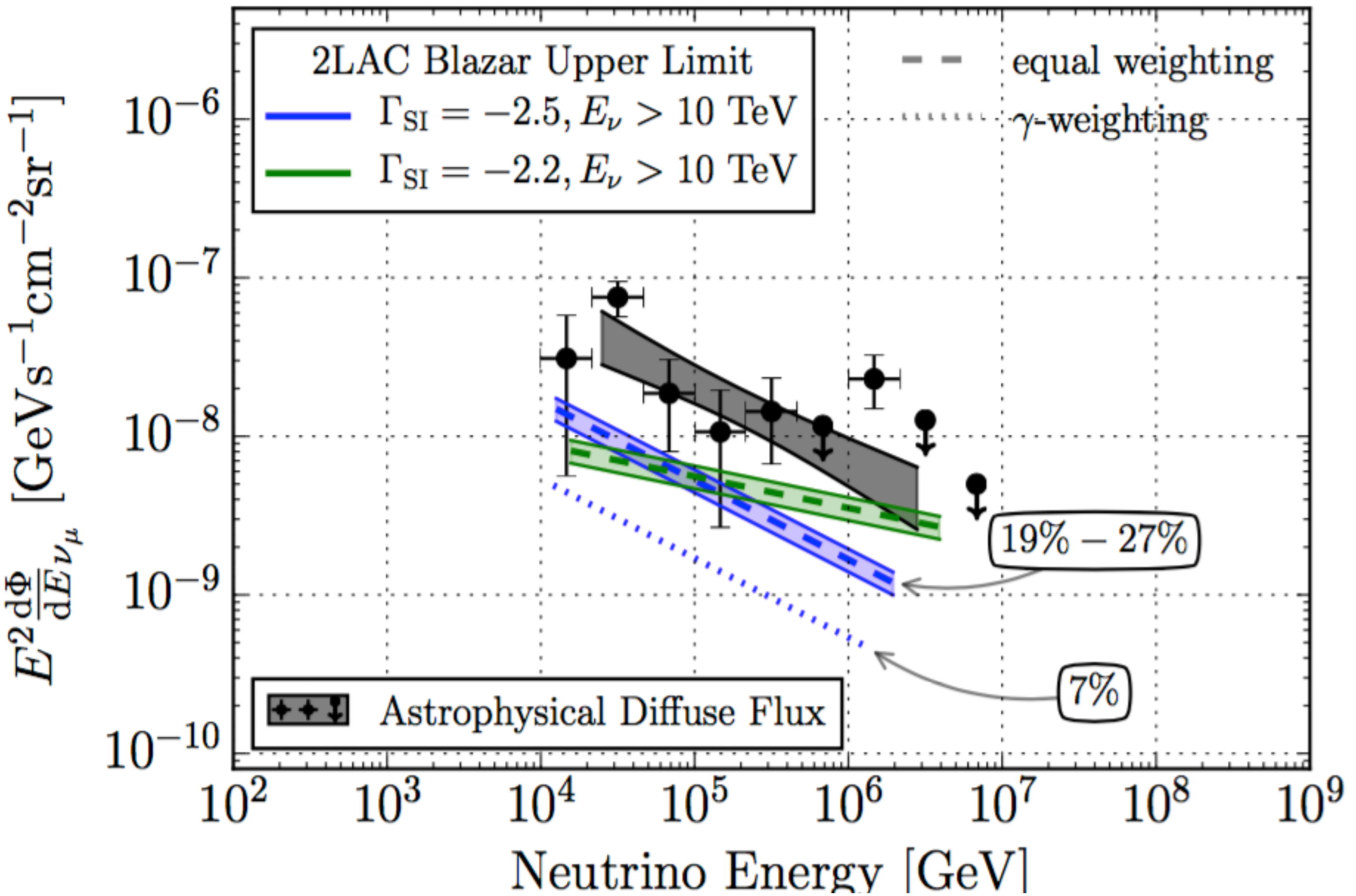


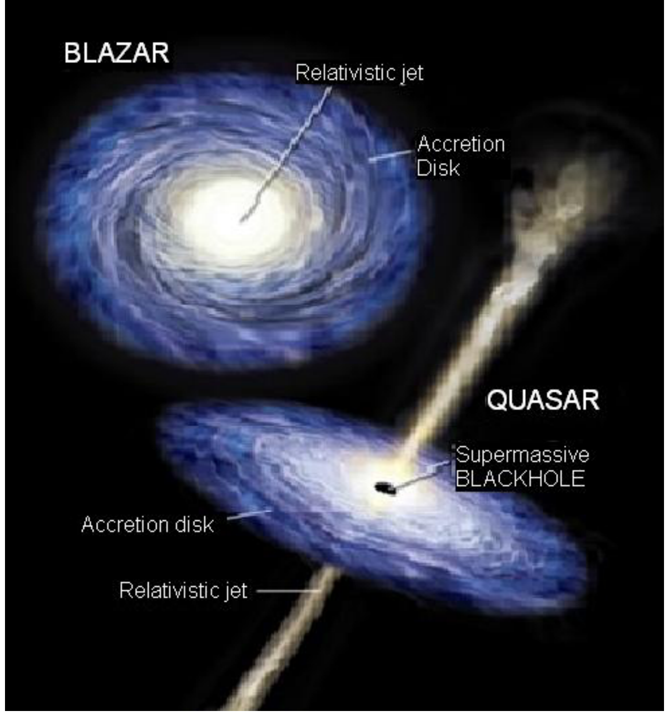
Population studies

Active Galactic Nuclei

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

M.G. Aarsten et al., ApJ 853 (2017) 1



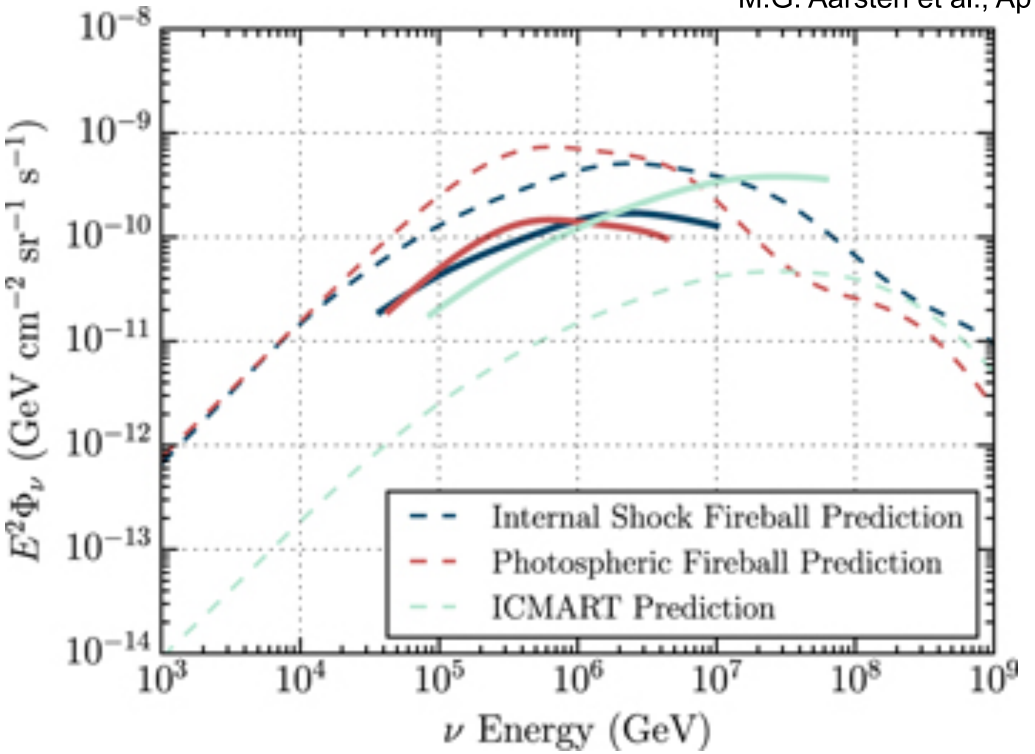


Blazars account for:
85% of extragalactic γ background,
but only < 27% of the neutrino flux

Population studies

Gamma-ray Bursts

M.G. Aarsten et al., Ap J 843 (2017) 2



Gamma-ray connection:
Detection of long GRBs by MAGIC & HESS
Great prospects for CTA! (see talk by E.Bissaldi)

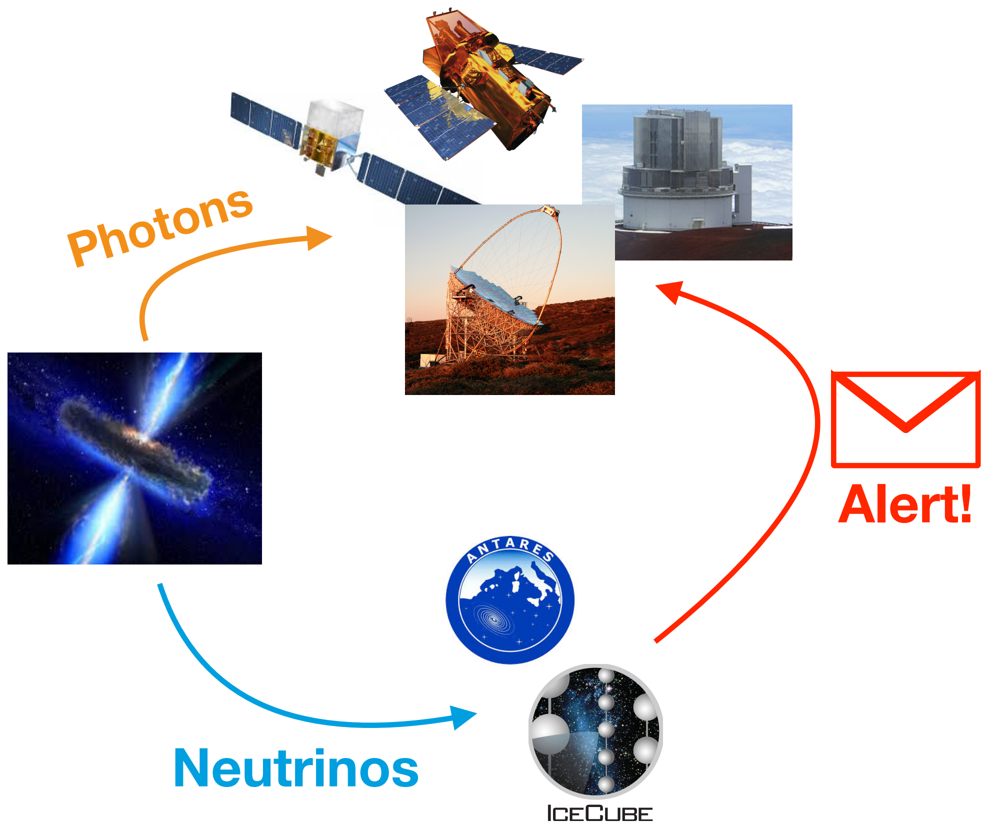
GW connection: production of neutrinos and g-rays in short-GRBs and GW events caused by mergers (NS-NS) (talk by G.A.Prodi)

- > 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"…

Real-time MultiMessenger

Catch them in the act!

- Key for understanding neutrino source emission: **simultaneous MWL data**
- Alerts → make sure we get them when nu telescope sees something interesting!
- **IC alerts**:
  - Public: single high energy events > 60 TeV (via AMON, since 2016)
  - Private: event clusters, specific programs aimed at gamma-ray and optical telescopes (since 2012)
- **ANTARES alerts**:
  - Only private
  - Optical, X-ray, gamma-ray follow-up
  - Single events & doublets

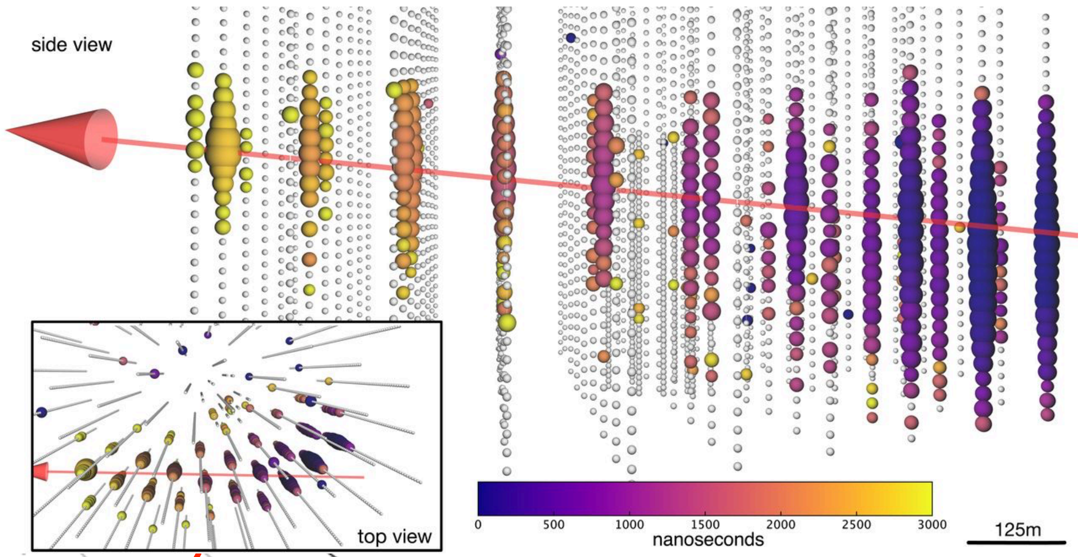


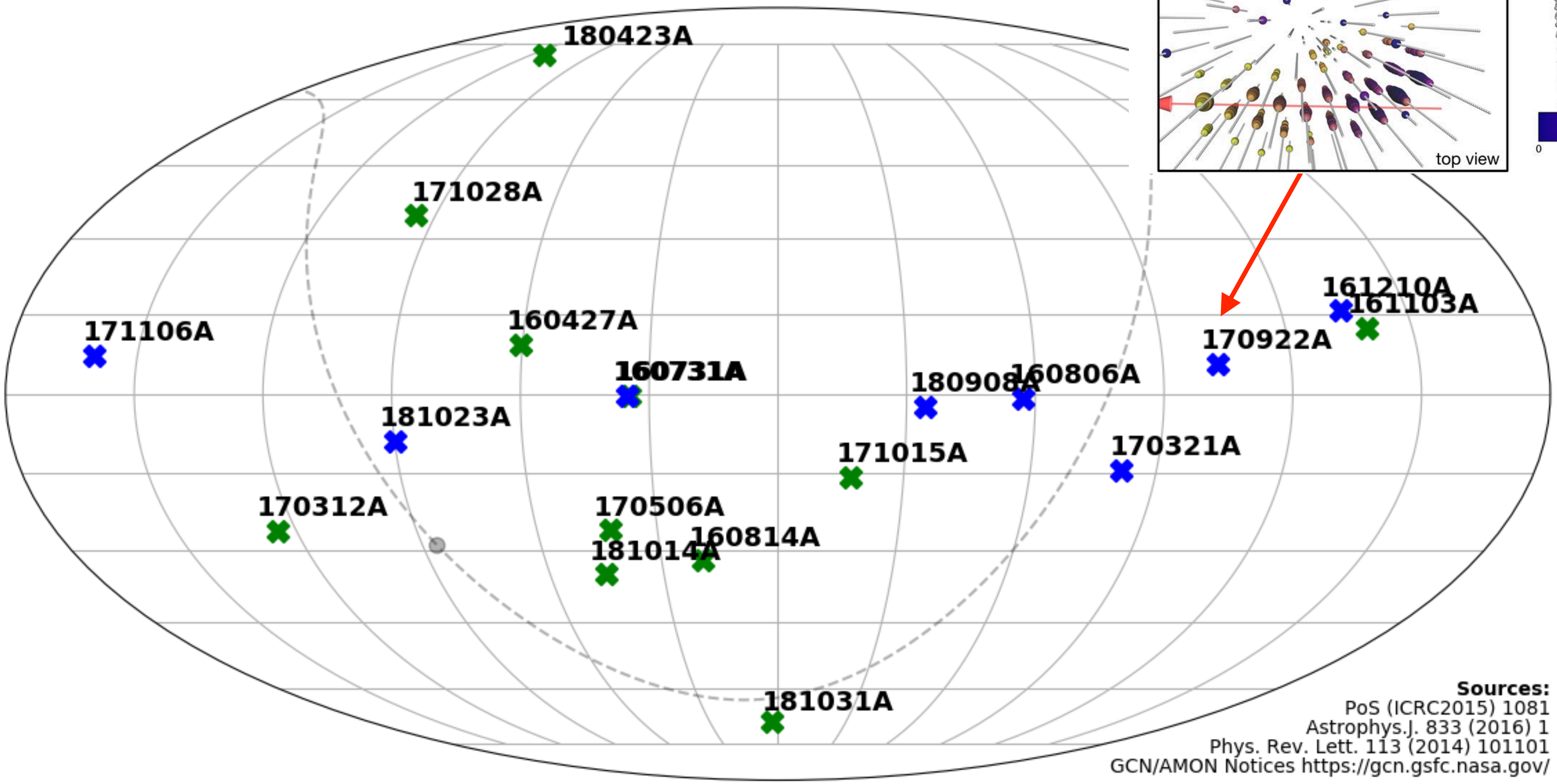
IceCube: M.G. Aartsen et al., Astropart. Phys. 92 (2017) 30-41s
ANTARES: S. Adrián-Martínez et al., JCAP 02 (2016) 062

Real-time MultiMessenger

First evidence for a neutrino source!

The IceCube, 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.
***Science* 361, eaat1378 (2018)**





Sources:
PoS (ICRC2015) 1081
Astrophys.J. 833 (2016) 1
Phys. Rev. Lett. 113 (2014) 101101
GCN/AMON Notices https://gcn.gsfc.nasa.gov/

3σ correlation of IC-170922A (~300 TeV) with the flaring blazar TXS 0506+056

TXS 0506+056

Neutrino blazar…?

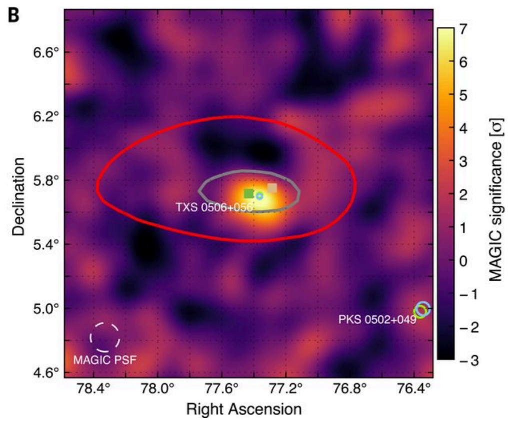
- Texas survey of radio sources, discovered in 1983
- Classified as ISP-type BL Lac object, a subclass of blazars, but recently considered as a “hidden FSRQ” (Padovani et al, MNRAS 484(1):L104-L108 2019)
- Among the brightest 5% of blazars detected in g-rays
- Redshift z=0.3365, ~4 billion light years
- One of the most luminous objects known up to this distance

Real-time MultiMessenger

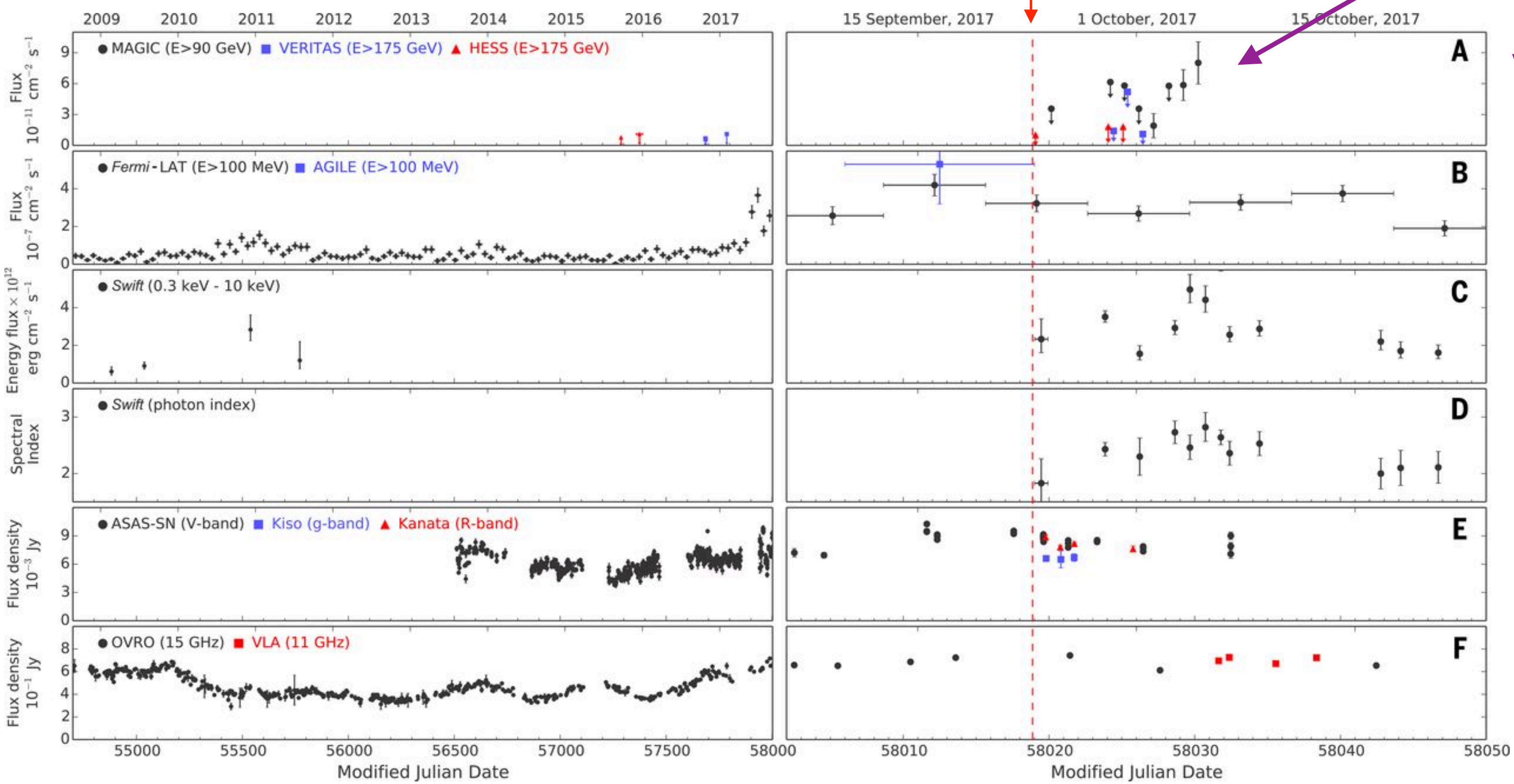
First evidence for a neutrino source!

The IceCube, 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.
Science 361, eaat1378 (2018)

Fast MWL response over all EM spectrum!



IC-170922A



VHE γ rays: MAGIC discovery
Day-scale variability

HE γ rays: flare

X-ray: day-scale variability

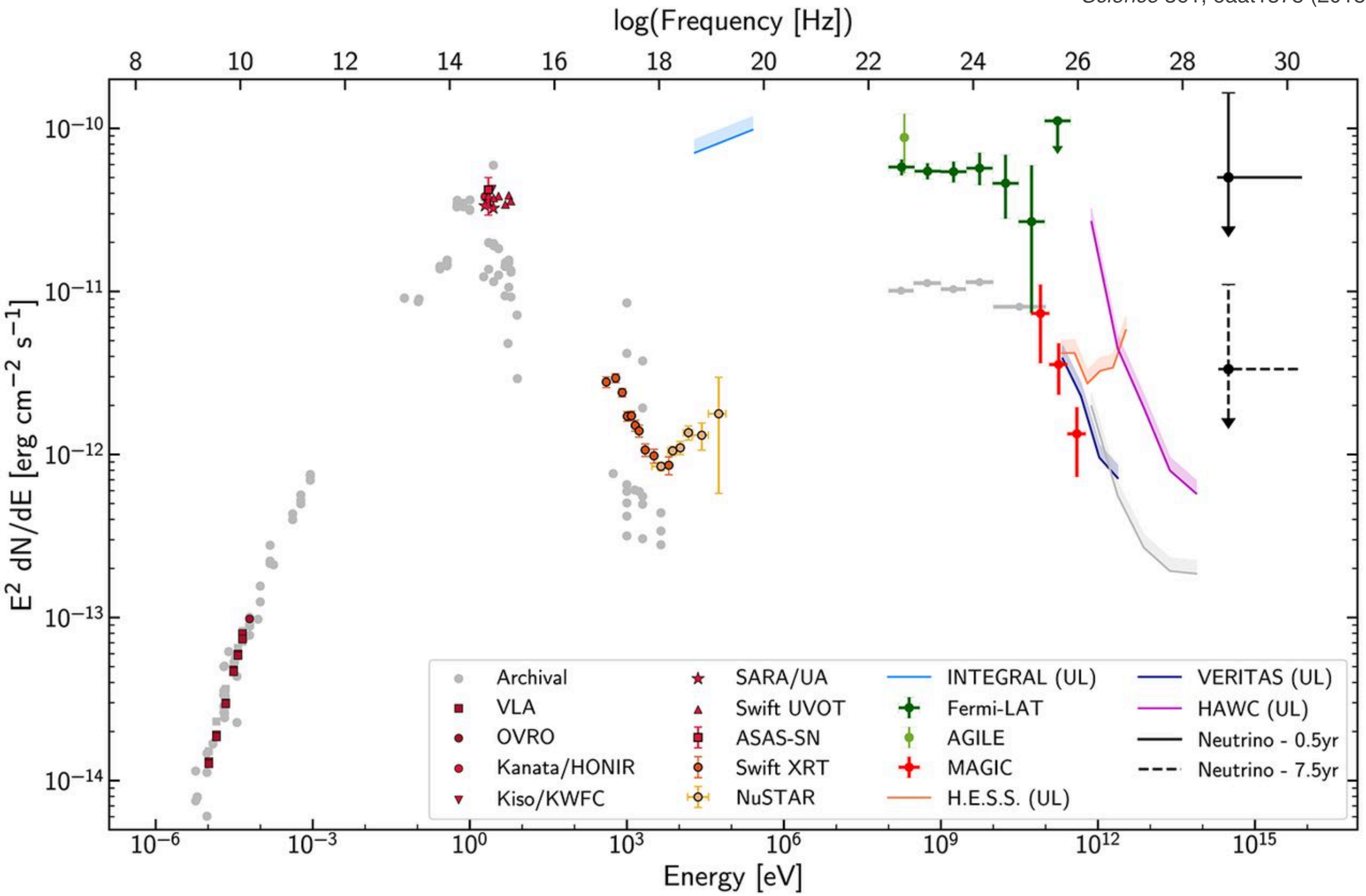
Optical: enhanced emission

Radio: enhanced emission

Real-time MultiMessenger

First evidence for a neutrino source!

The IceCube, 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. *Science* 361, eaat1378 (2018)

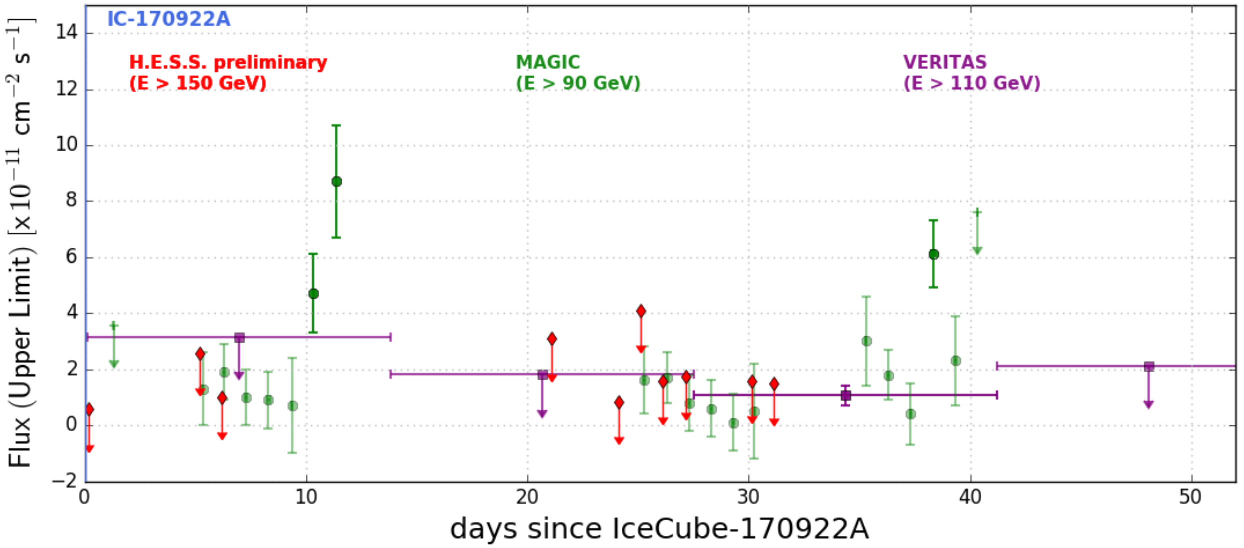


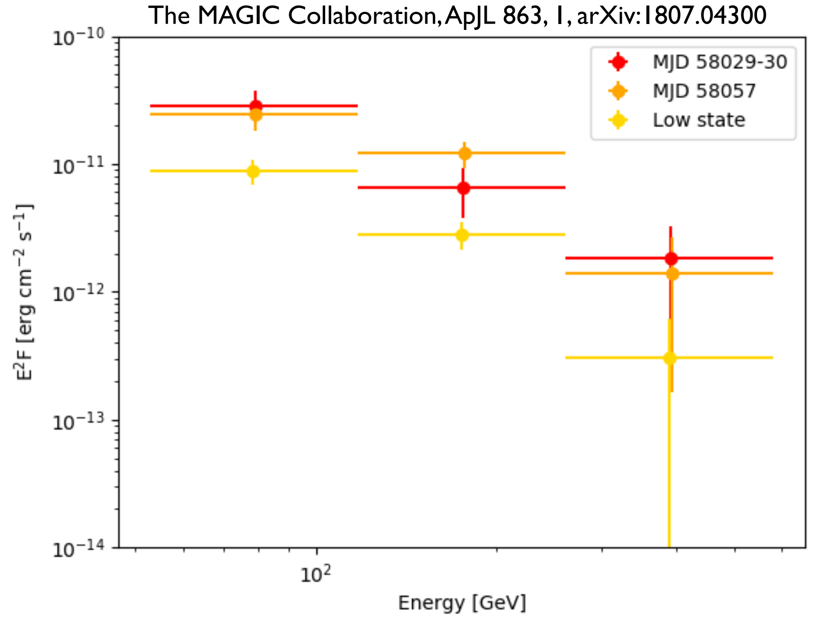
First MultiMessenger SED → bounty of theoretical interpretations!
(see talks by Ch. Righi and S.Cutini)

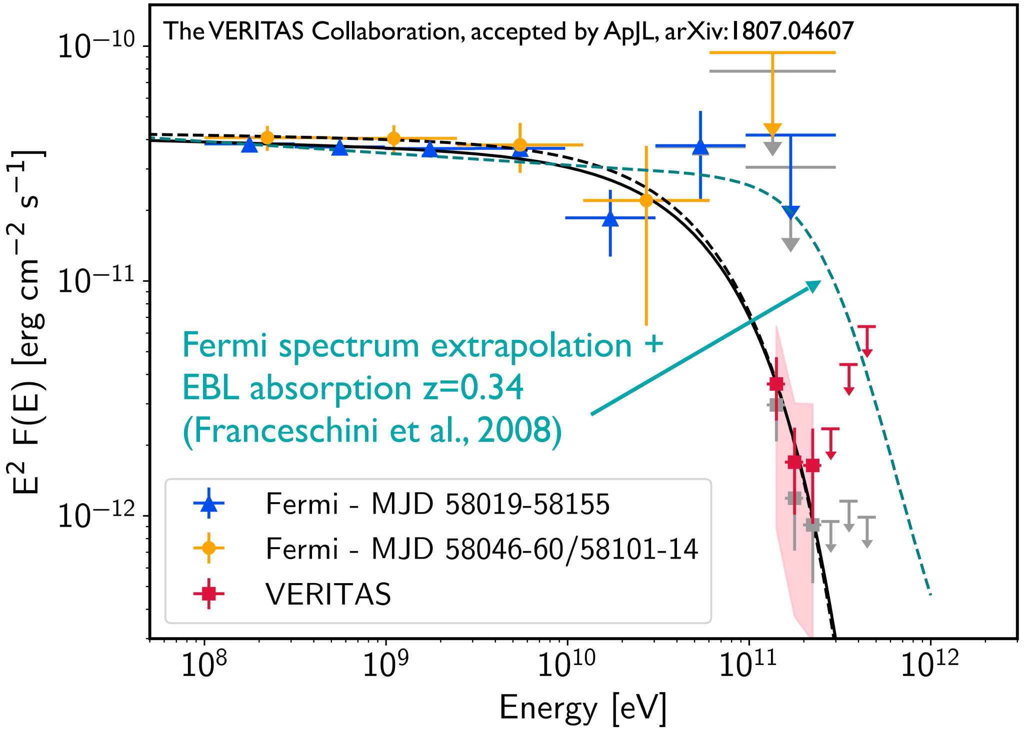
TXS 0506+056

The IACT perspective

Credit: F. Schüssler







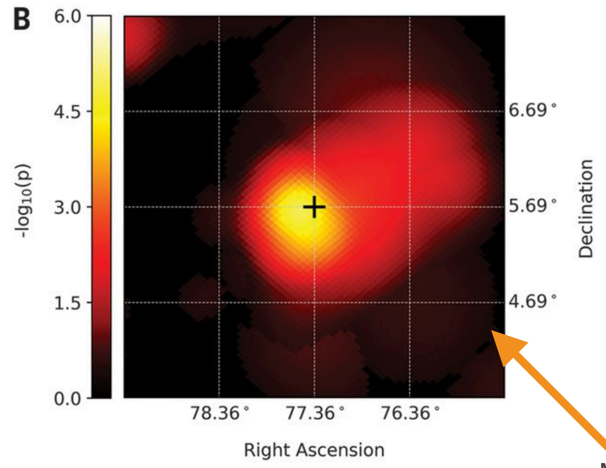
- MAGIC: 2 flares + lower state, but no spectral index variability measured
- MAGIC+VERITAS: simple PL, index much softer than Fermi-LAT (~ 4.0)

→ clear spectral curvature, apart from EBL effect: internal absorption, primary particle spectral break, production inefficiency…?

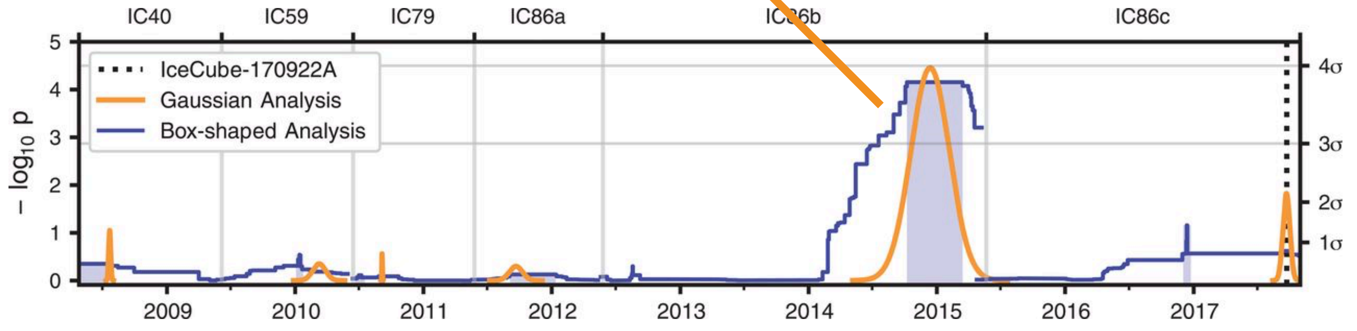
- Task for CTA: detailed spectral measurements, look out for hints of hadronic emission signature

The neutrino past of TXS 0506+056

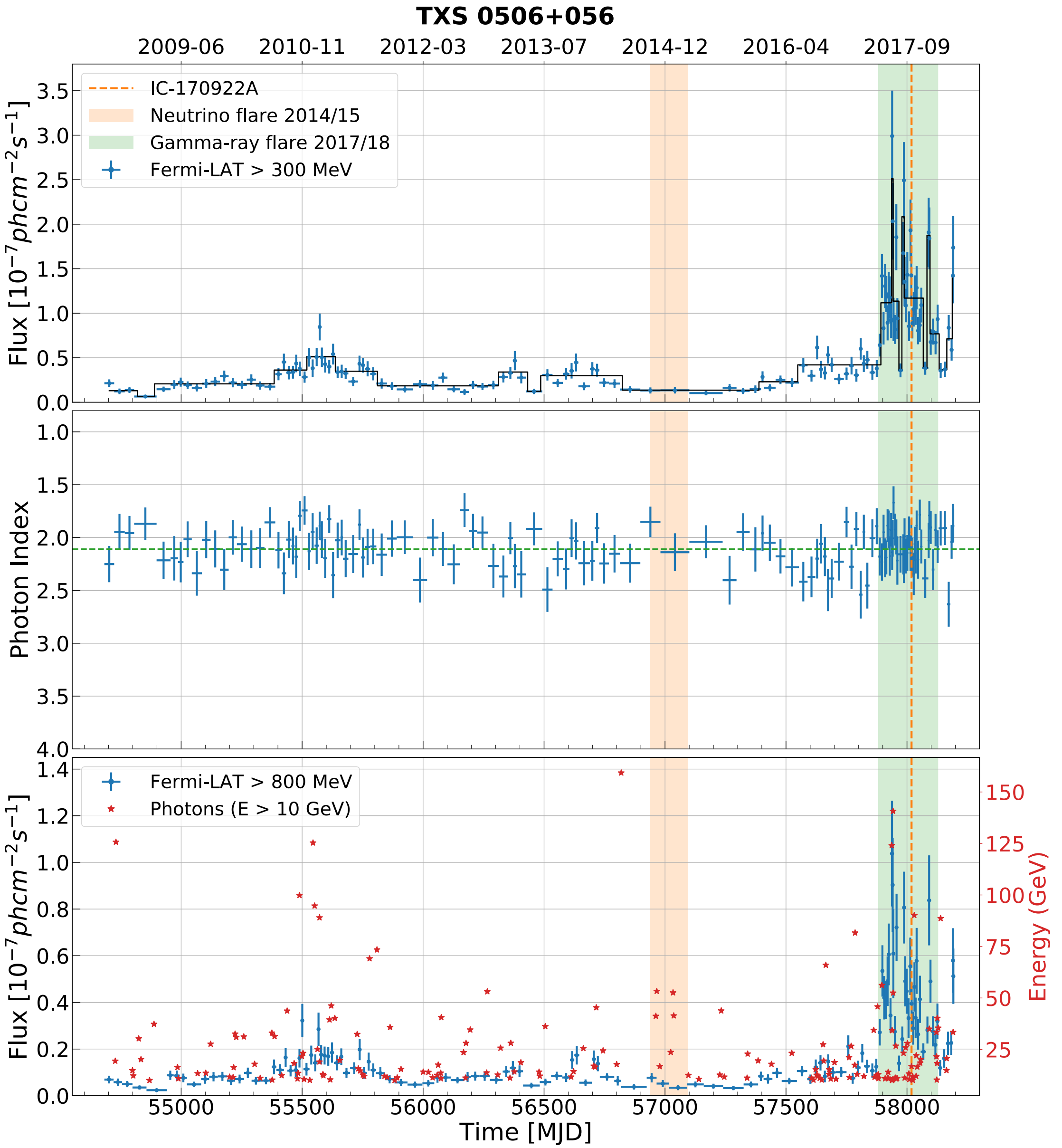
Another evidence for a neutrino source!



M.G. Aartsen et al. *Science* 361, 147-151 (2018)



Fermi, ASAS_SN and IC: https://arxiv.org/abs/1901.10806



Looking into IC past data: excess of HE neutrino events, between Sep 2014 and Mar 2015, from TXS 0506+056, another **3.5σ evidence**.

TXS 0506+056 2014-2015 neutrino flare

What about CTA?

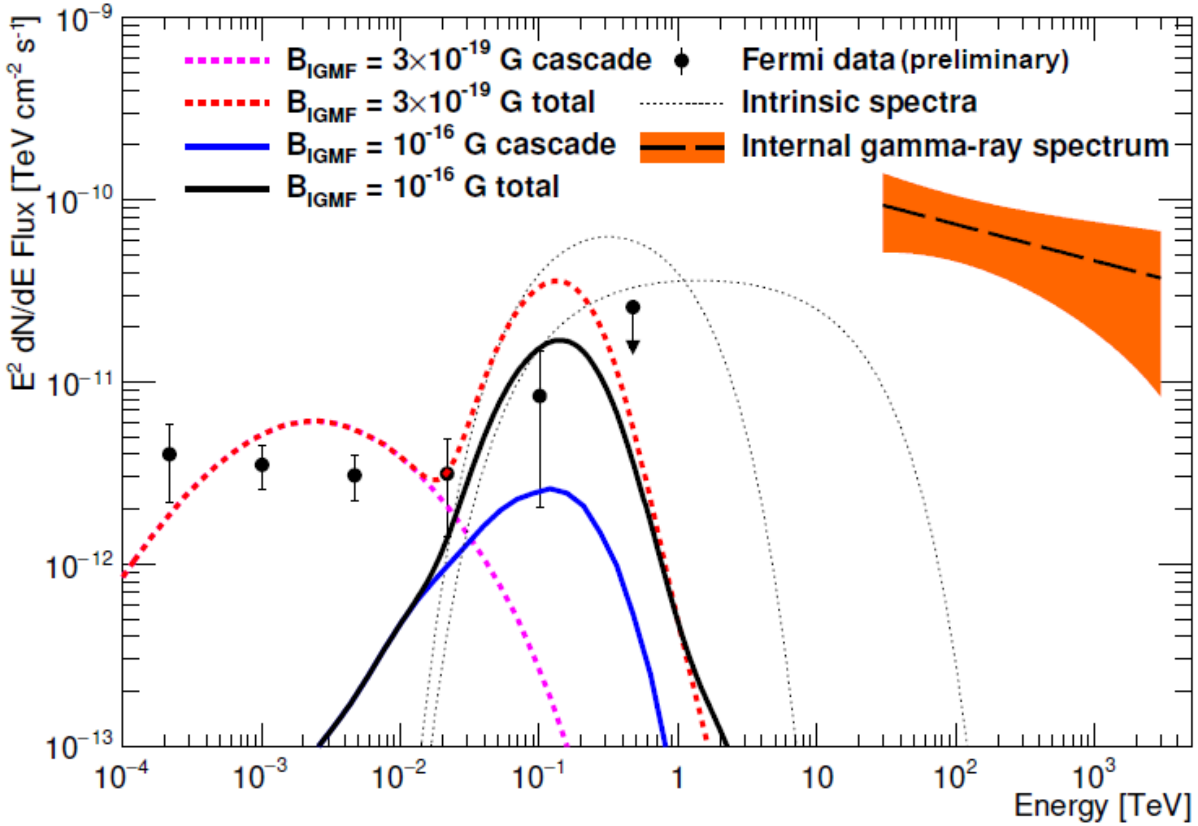
- Assume that diffuse neutrino flux is produce by "TXS 0506+056-like" sources
- Special class of blazars that undergo 110-day duration flares like TXS0506+056 once every ~10 years
- Gamma-ray flux is parametrized as PL with LE and HE cut-offs (A - norm. related to nu flux):

$$\frac{dN}{dE} = AE^{-2}e^{-E_L/E-E/E_H}$$

- FIRESONG code used for neutrino sources and alert simulations (https://github.com/ChrisCFTung/FIRESONG):
- Simulations for flaring sources fraction:

F = 0.5%, 1%, 5%, 10%

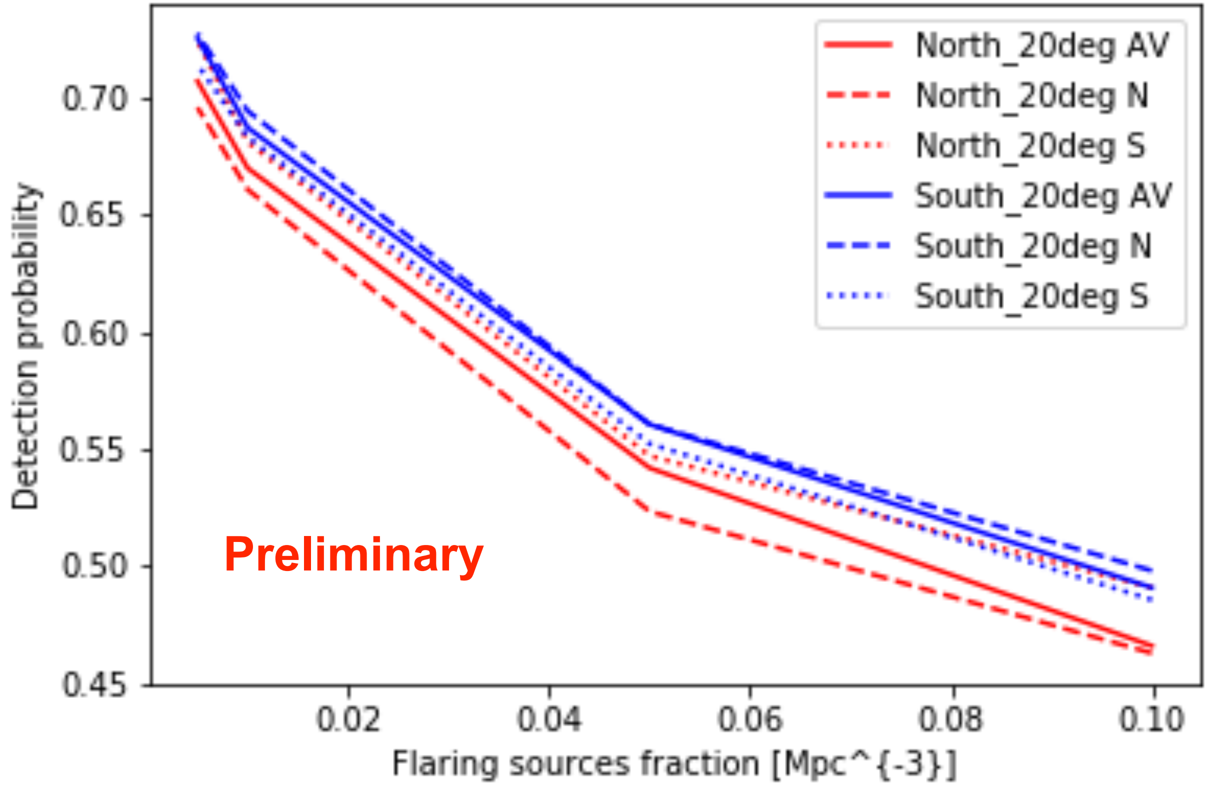
Halzen et al, ApJL, Volume 874, Issue 1, article id. L9, 5 pp. (2019)



TXS 0506+056 2014-2015 neutrino flare

What about CTA?

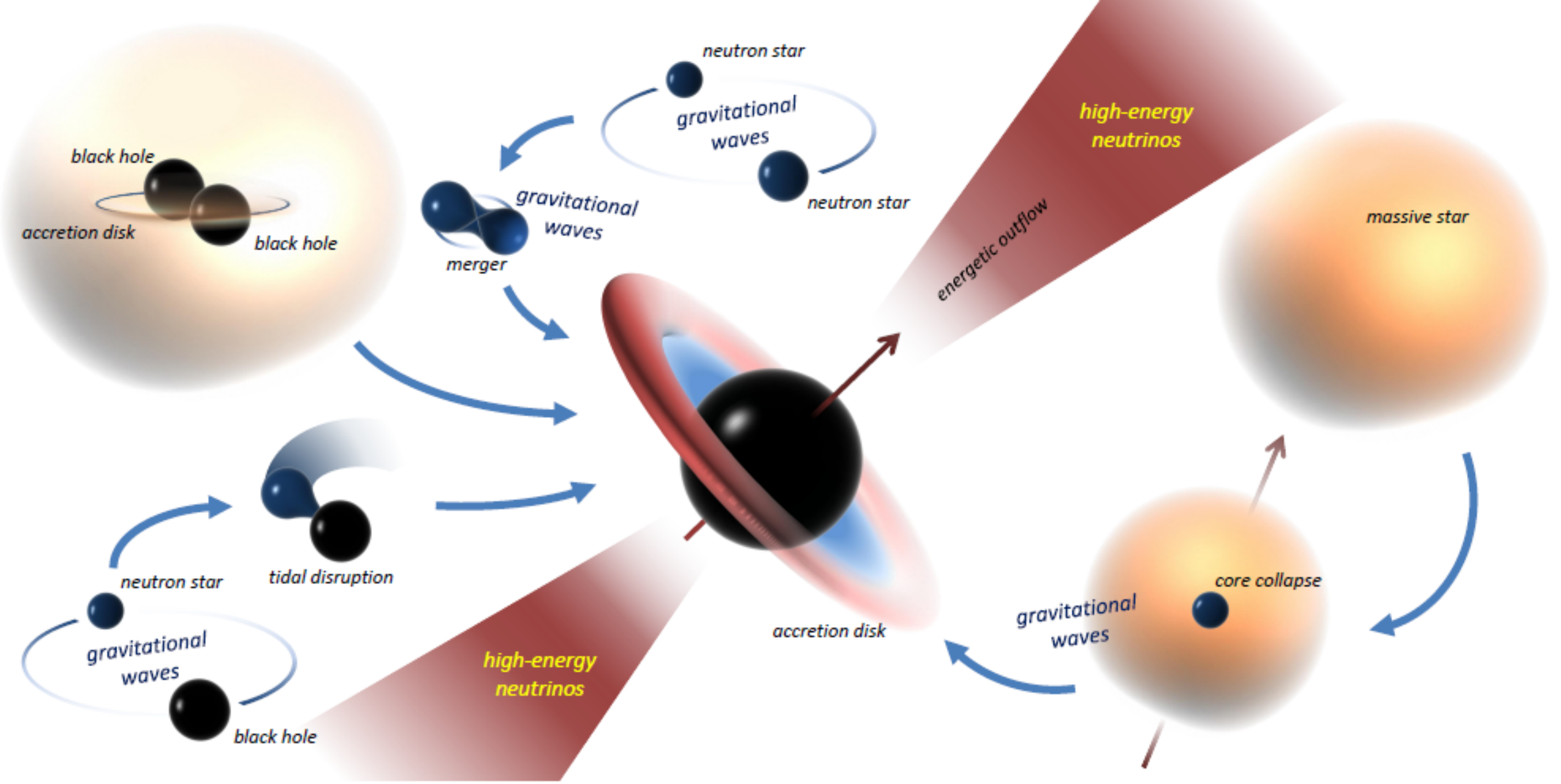
- FIRESONG simulations for flaring sources fraction:
- F = 0.5%, 1%, 5%, 10%
- CTA IRFs used to calculate the detection probability
- 10 min of observations
- NOTE: IC alerts have ~50% signal purity (divide by 2!)
- NOTE: CTA duty cycle & source visibility



- We can do the same exercise for different source populations, e.g. transients, stable sources
- Prediction: detection/constraints of g-ray flux from neutrino sources depending on local source density
- Work in-progress within the CTA KSP Neutrino Follow-up→ join the CTA Neutrino Team! :)

Connection to GW

GW+EM+nu…?!

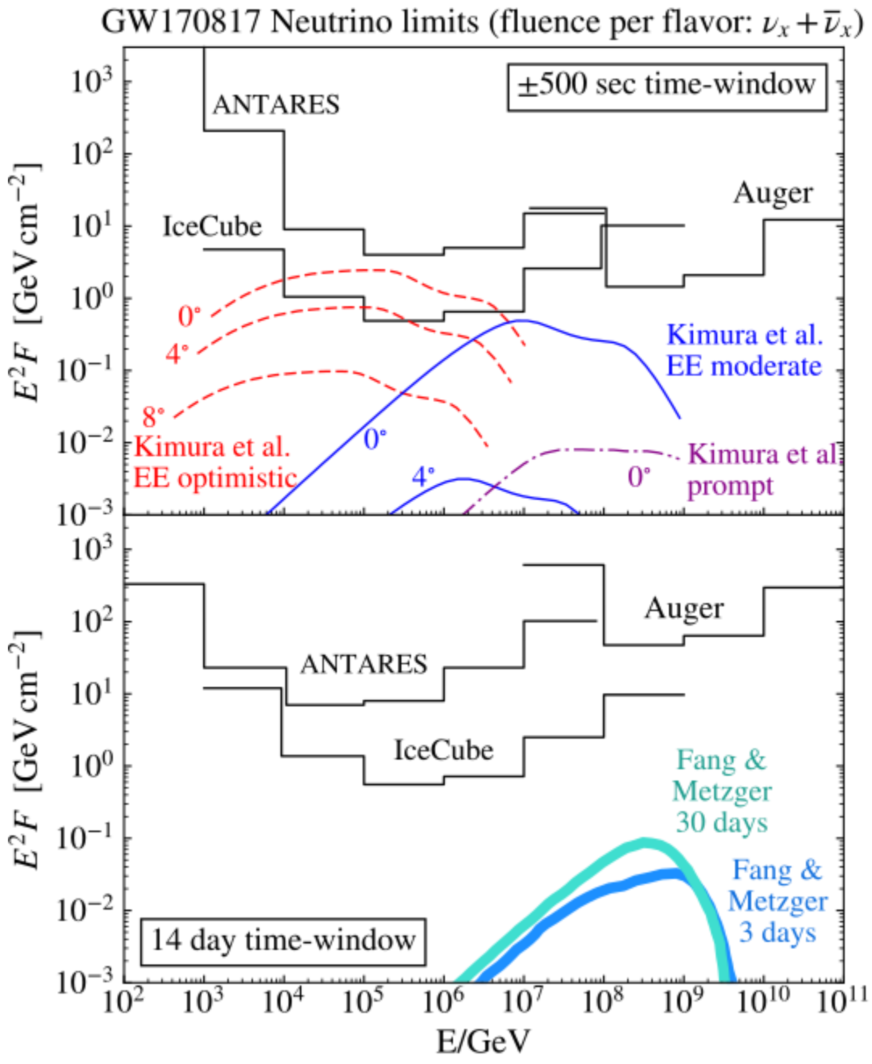


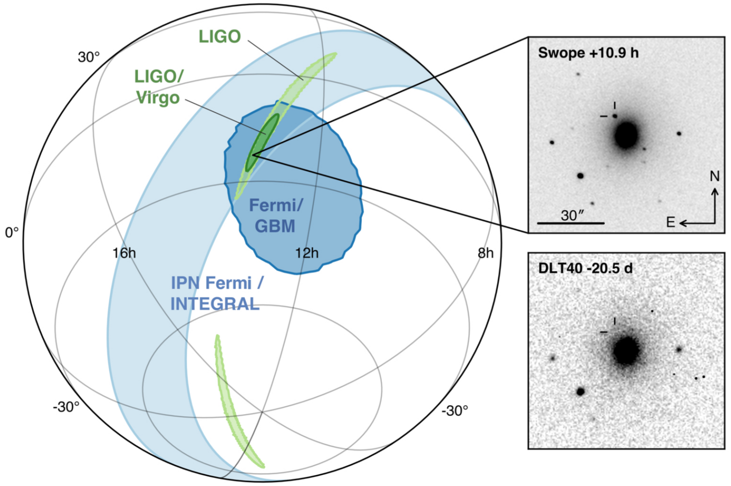
- BH-BH mergers probably no EM or nu (depends on environment)
- MeV neutrinos from stellar core collapse
- HE neutrinos + gamma-rays from non-thermal processes (BH+acc. disc → jets?!)
- Chocked GRBs - only neutrinos and GW!
- Timing of signals from different messengers → progenitor
- EM emission → localization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

- IC performs an automated analysis +/-500s around each GW alert -> neutrino event list with p-value

GW-170817 and neutrinos

NS-NS megrger, short GRB, kilonova





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)

So…

…are we there yet…?

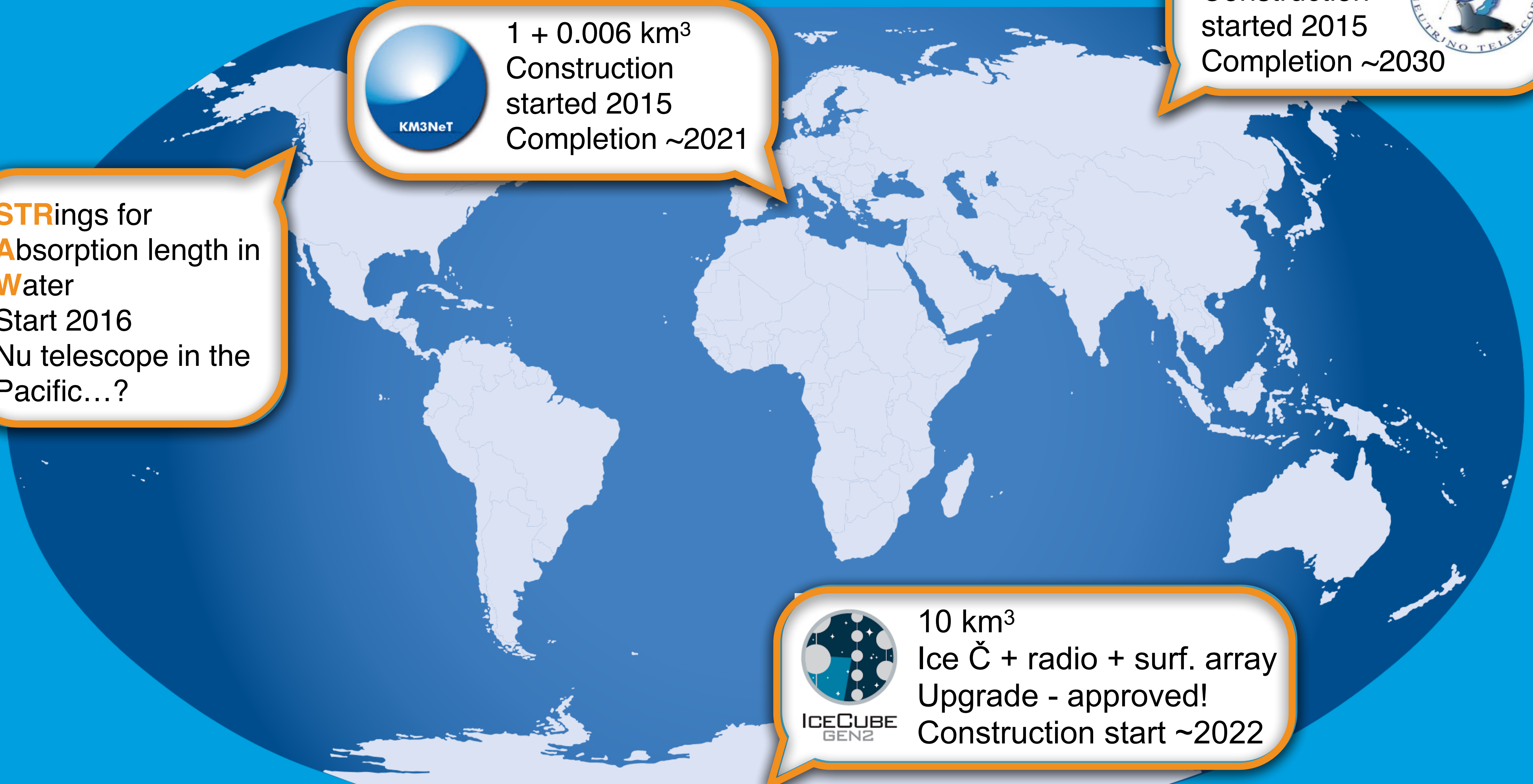
- Astrophysical neutrinos - YES!
- Tau neutrinos - maybe…
- Point sources - not yet…
- TXS 0506+056 - first compelling evidence of a neutrino source?
- Most probably:
    - Many different source populations contribute to the diffuse flux
    - Large number of faint sources

- Real-time alerts and MultiMessenger approach of high interest to the whole astro-community

How to get there?

- More statistics → bigger detectors
- Extended energy range → bigger detectors
- Full sky coverage with high sensitivity → bigger detectors on both hemispheres

Instruments: future



1 + 0.006 km^3
Construction started 2015
Completion ~2021

>1 km^3
Construction started 2015
Completion ~2030

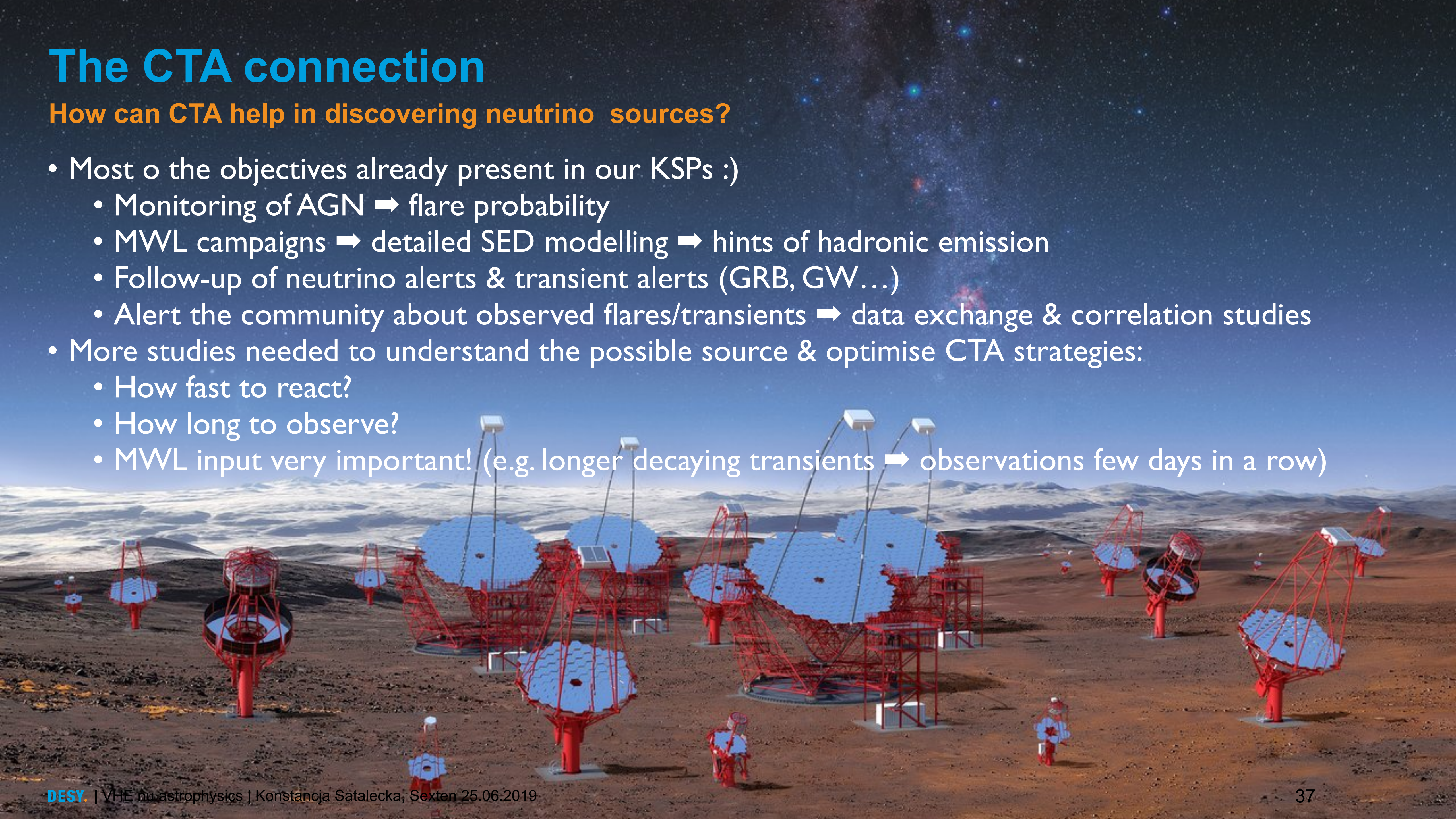
STRings for **A**bsorption length in **W**ater
Start 2016
Nu telescope in the Pacific…?

10 km^3
Ice Č + radio + surf. array
Upgrade - approved!
Construction start ~2022

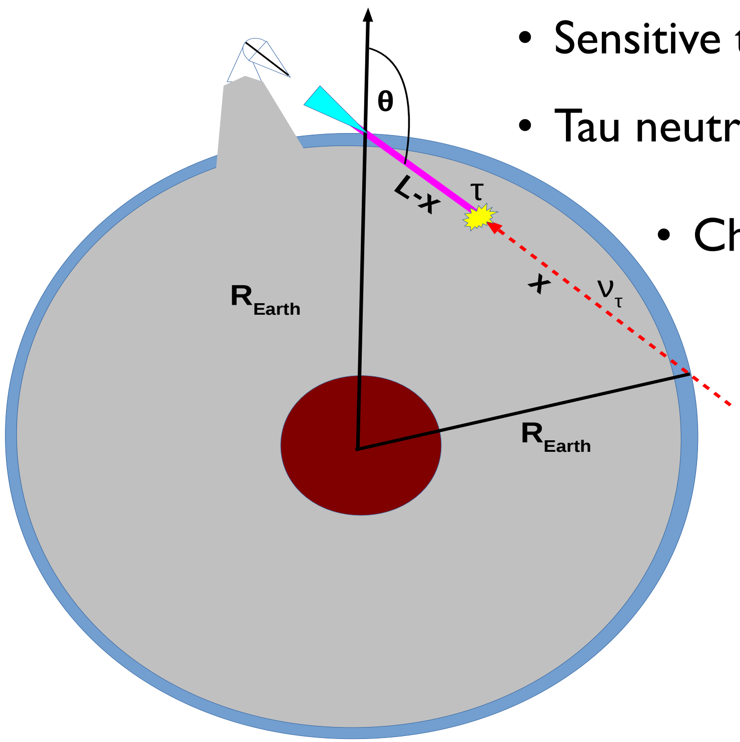
The CTA connection

How can CTA help in discovering neutrino sources?

- Most o the objectives already present in our KSPs :)
  - Monitoring of AGN ➡ flare probability
  - MWL campaigns ➡ detailed SED modelling ➡ hints of hadronic emission
  - Follow-up of neutrino alerts & transient alerts (GRB, GW…)
  - Alert the community about observed flares/transients ➡ data exchange & correlation studies
- More studies needed to understand the possible source & optimise CTA strategies:
  - How fast to react?
  - How long to observe?
  - MWL input very important! (e.g. longer decaying transients ➡ observations few days in a row)

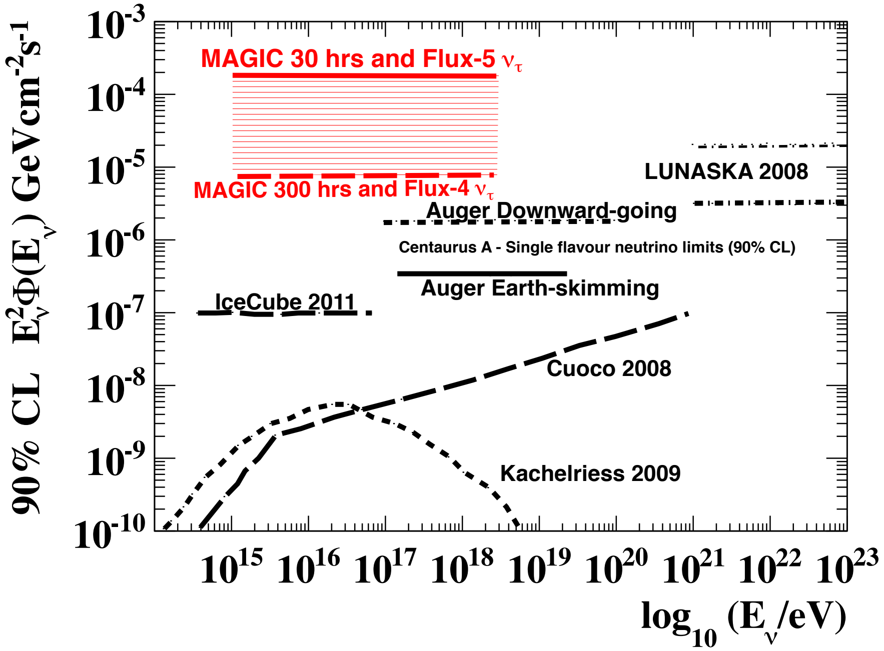


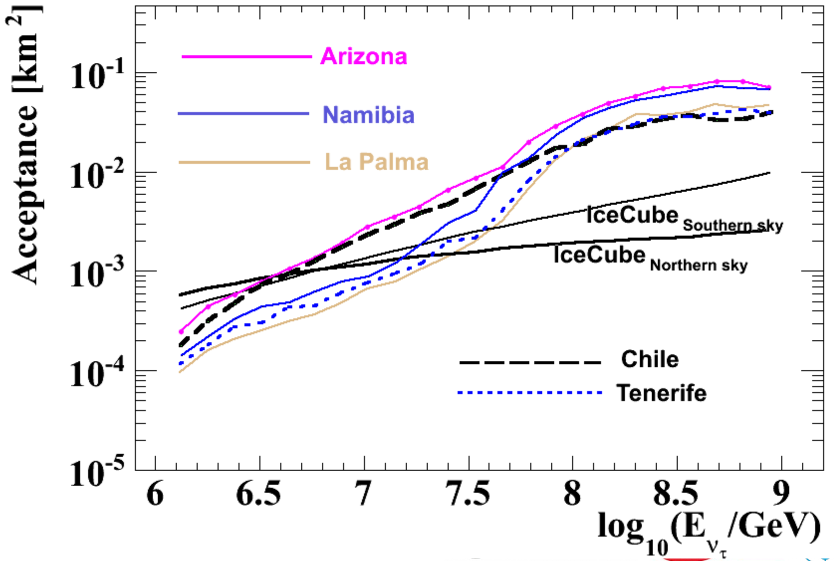
BONUS: IACTs as neutrino detectors!



- Look for tau induced showers from the see/rock
- Sensitive to tau of PeV-EeV energies
- Tau neutrinos HAVE TO be astrophysical!!!
- Cheap observation time (cloudy weather)
- Diffuse or point-source observations
- Most optimistic models for high luminosity transient events: GRBs, AGN flares

MAGIC Coll., *Astroparticle Physics* **102**, 77-88, 2018





- Feasibility studies with MAGIC – for long observations ULs ~ AUGER can be set
- CTA: event rates comparable or higher than for IC

Thank you!


Dist. by Universal Udick
are we there yet?
here
almost
t
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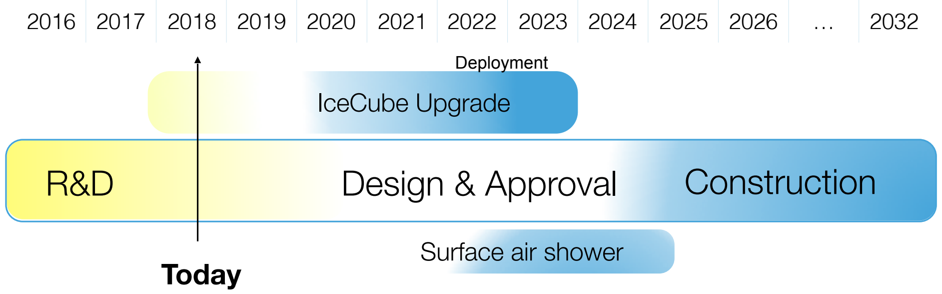
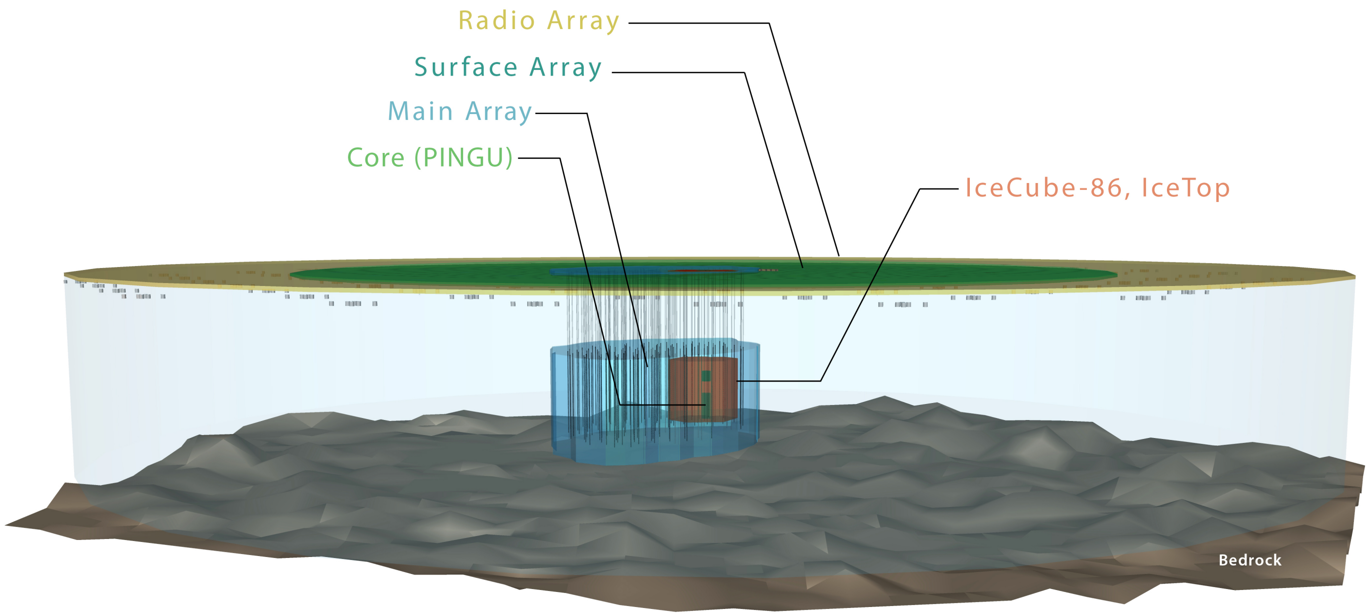
Back-up

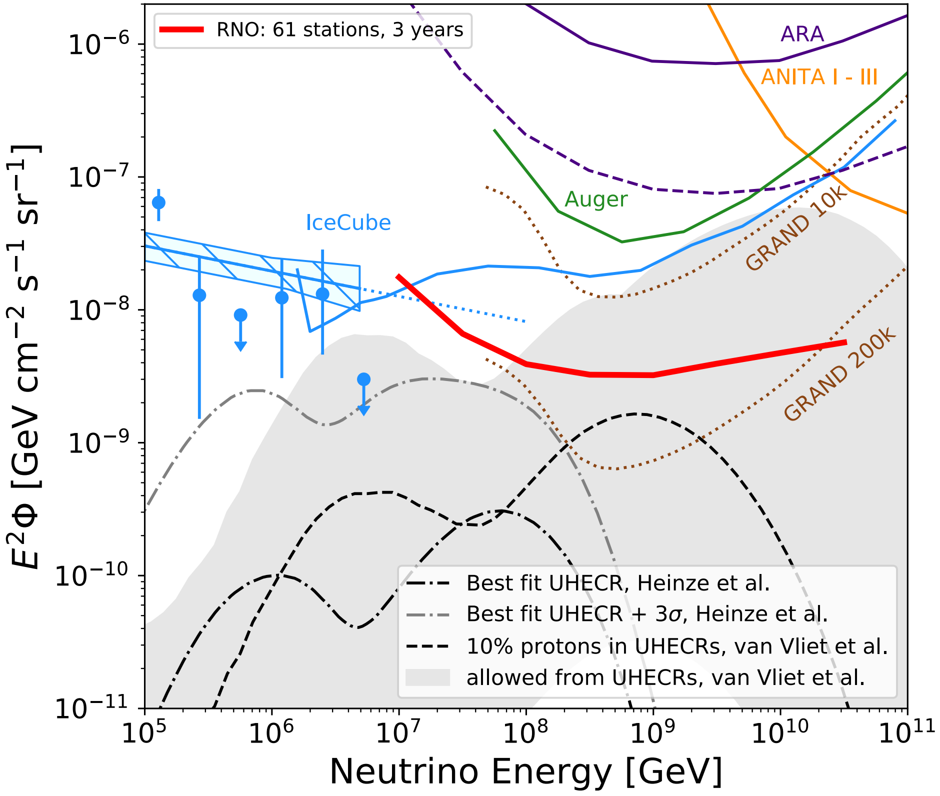
IC/Gen2

The next generation neutrino observatory



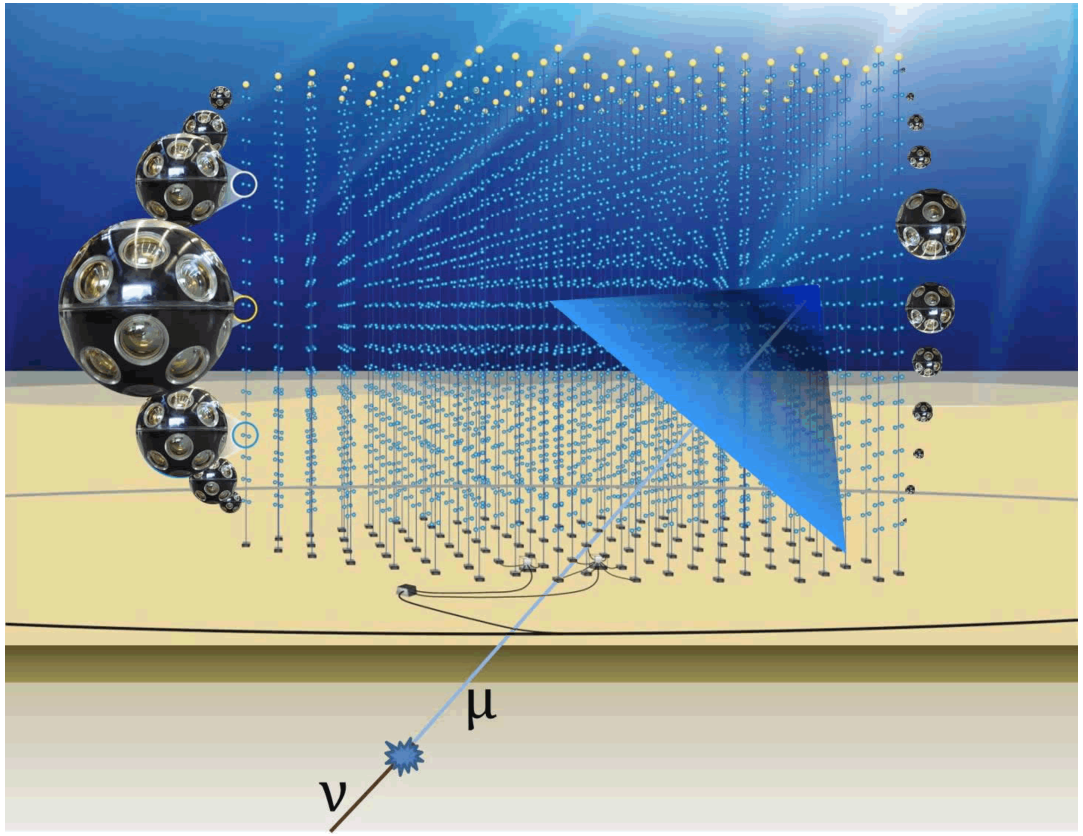
- Hybrid design: optical sensors, radio antennas, surface array, maybe IACTs…
- Extension of IC energy range: 100 MeV - EeV
- Wide science coverage from oscillations to cosmogenic (GZK) neutrinos
- Upgrade: 7 strings, test devices 2022/23
- IC/Gen2: construction start ~2025



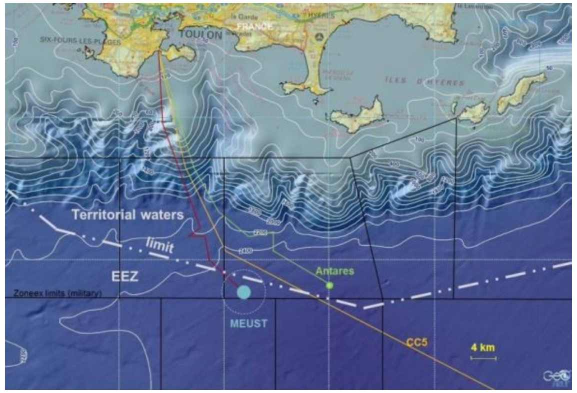


KM3Net

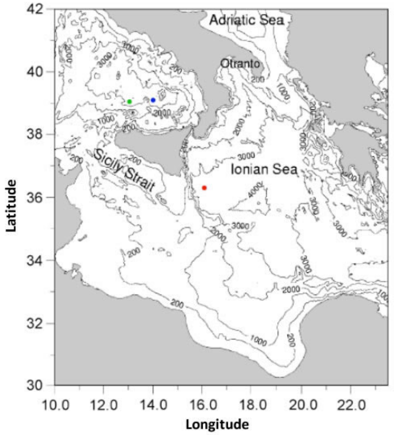
The next generation neutrino observatories



Multi-cubic km size neutrino telescope in Mediterranean Sea



- ORCA: neutrino oscillations
  - Fist string deployed in 2017
  - Completion ~2021

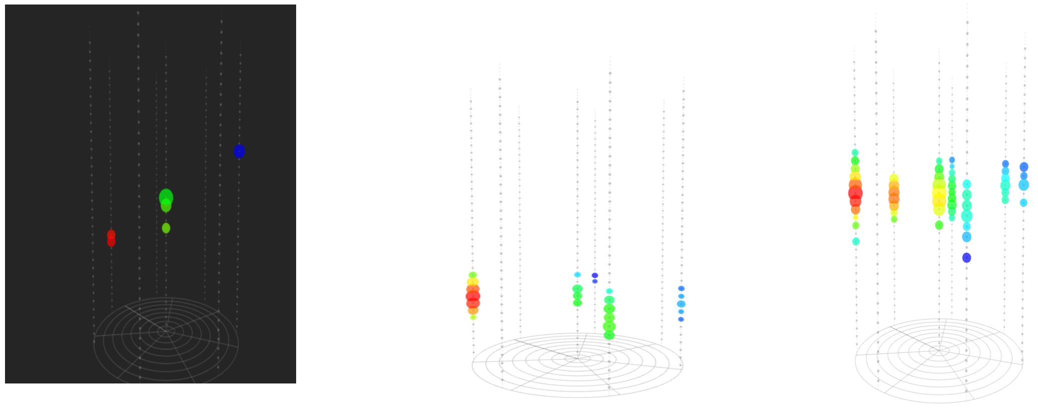


- ARCA: TeV - PeV astrophysical neutrinos (Galactic Center!)
  - First two DU deployed successfully 2016/2017
  - Completion ~2022

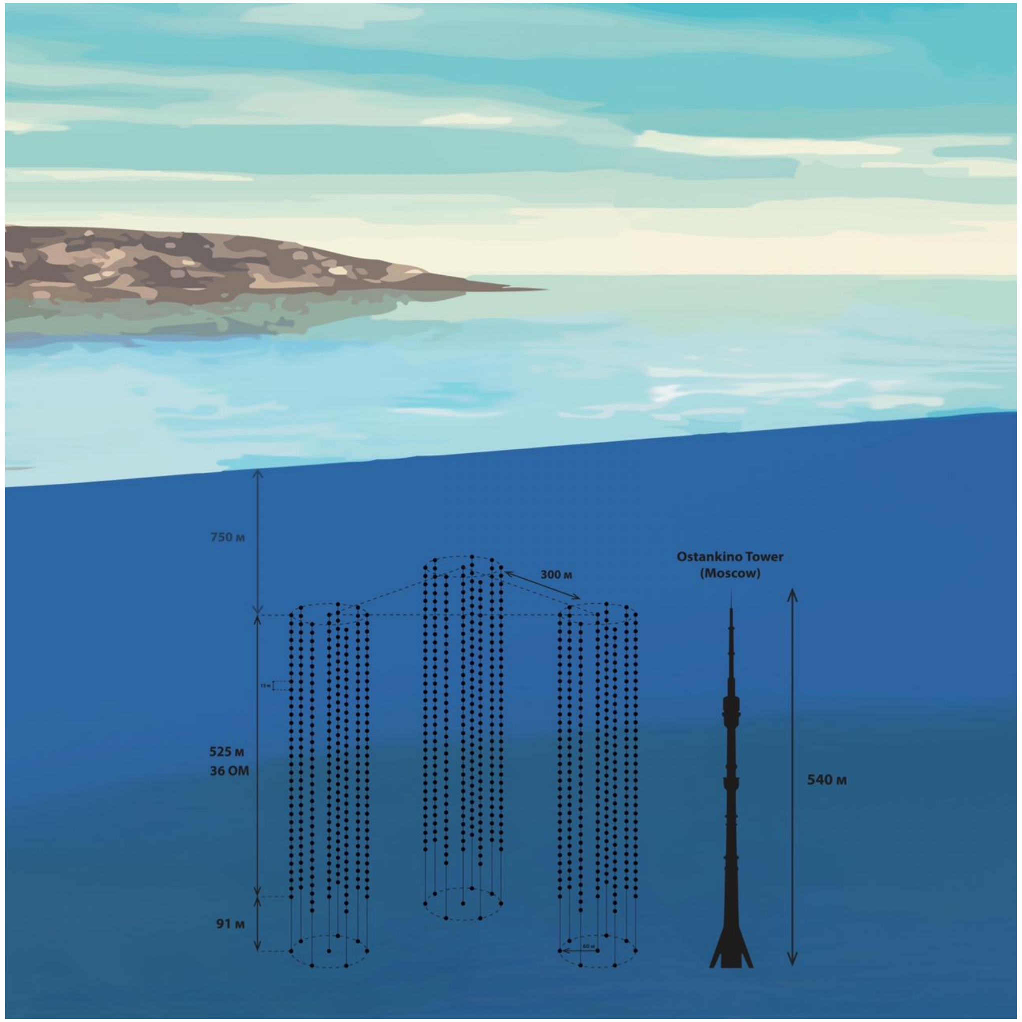
Baikal-GVD

The next generation neutrino observatories

- Under construction since 2015
- Now: 3 clusters with 288 OMs each
- Phase-1 Baikal-GVD: 8 clusters, deployed by 2020-2021
- Goal: ~2 km^3 with 10.000 OMs ~2030
- First muon neutrino and cascade events detected!



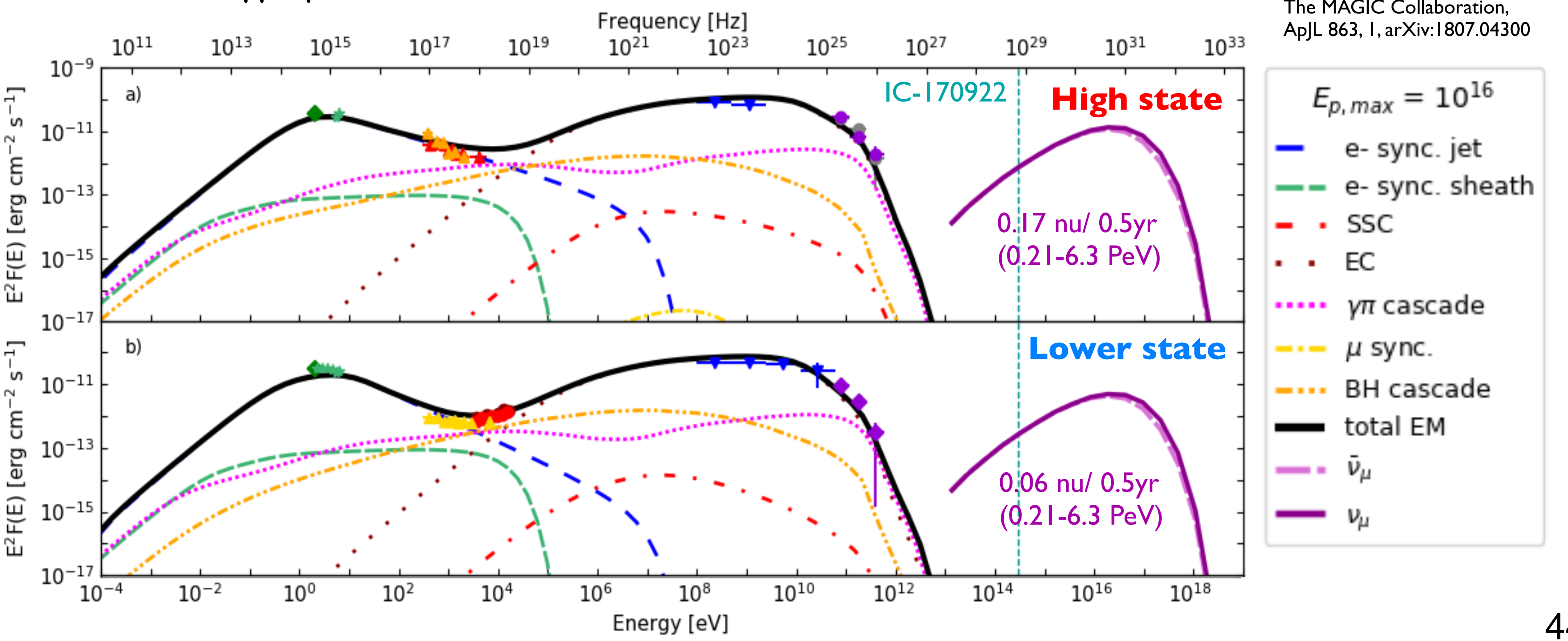
A.D. Avrorin et al., arXiv:1808.10353



TXS 0506+056 and IC-170922A

Interpretation: jet-sheath model

- Jet-sheath model (Ghisellini G., Tavecchio F., Chiaberge M., 2005, A&A, 432, 401)
- Components: leptonic (synchrotron, SSC, EC) + hadronic (photo-meson casc., BH casc., synch. rad. from pi and mu)
- Day-scale variability → Size of emitting region ~10^{16} cm
- Internal absorption: $\tau_{\gamma\gamma}(E_\gamma \sim 100$ GeV$)\sim 1$ consistent with the observed spectral break



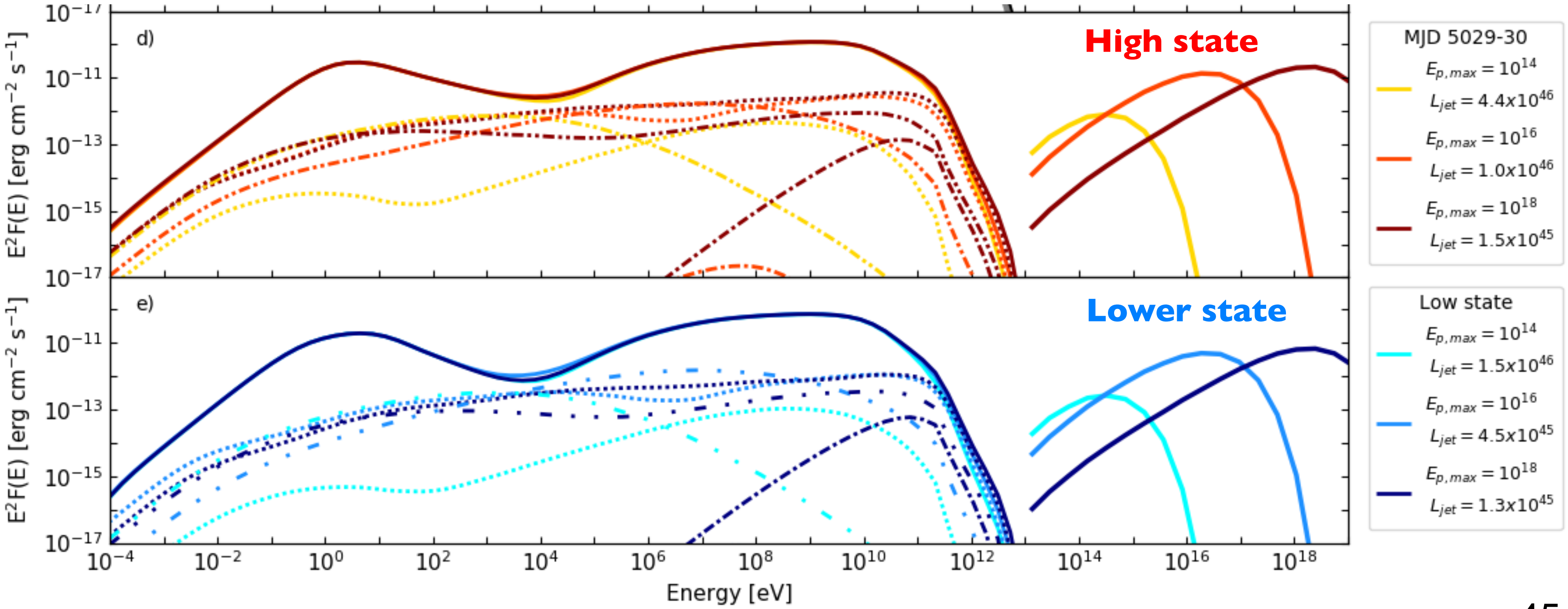
The MAGIC Collaboration, ApJL 863, 1, arXiv:1807.04300

TXS 0506+056 and IC-170922A

Interpretation: jet-sheath model

- X-ray and VHE gamma-ray data set tight constraints on max. proton energy $E_{p,max}$
- Scan of $E_{p,max}$: 10^{14}-10^{18} eV (co-moving frame)
- → TXS 0506+056 able to accelerate CR to UHE!

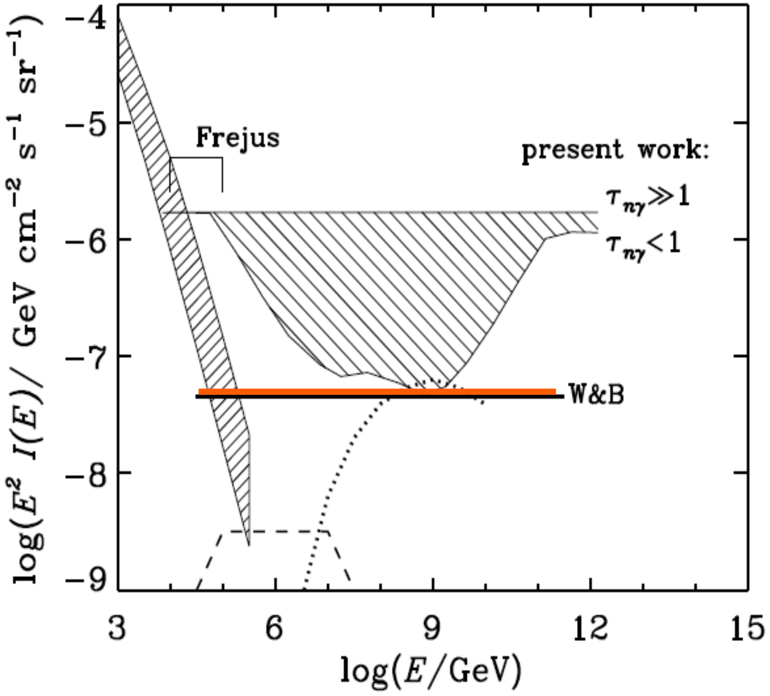
The MAGIC Collaboration,
ApJL 863, 1, arXiv:1807.04300



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?

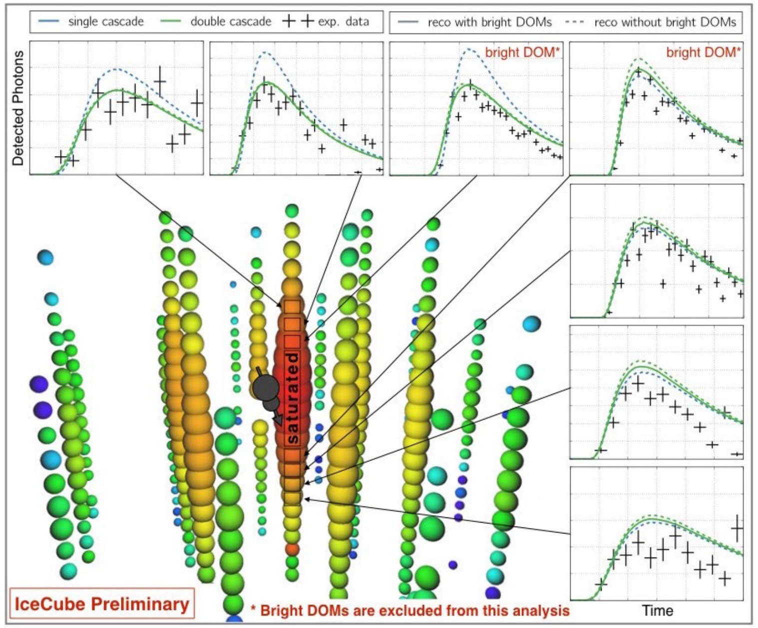
K. Mannheim, et al. (2001)

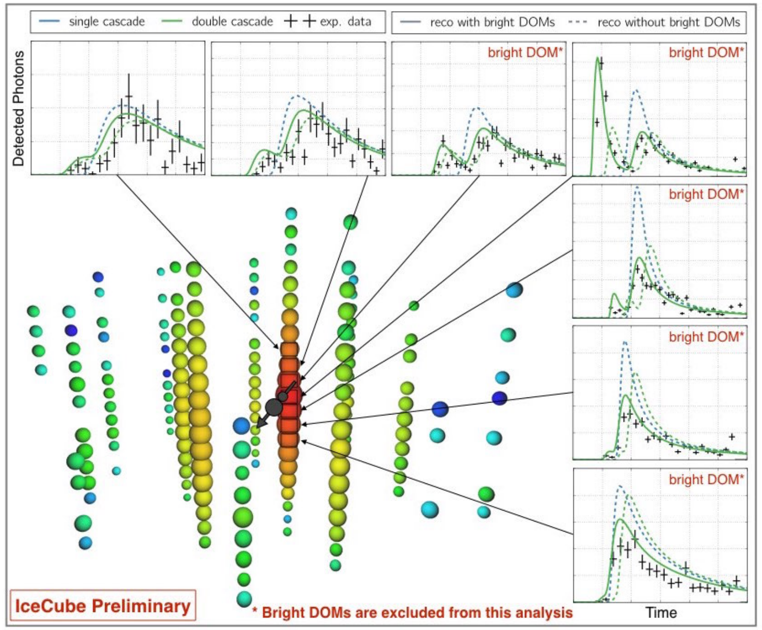


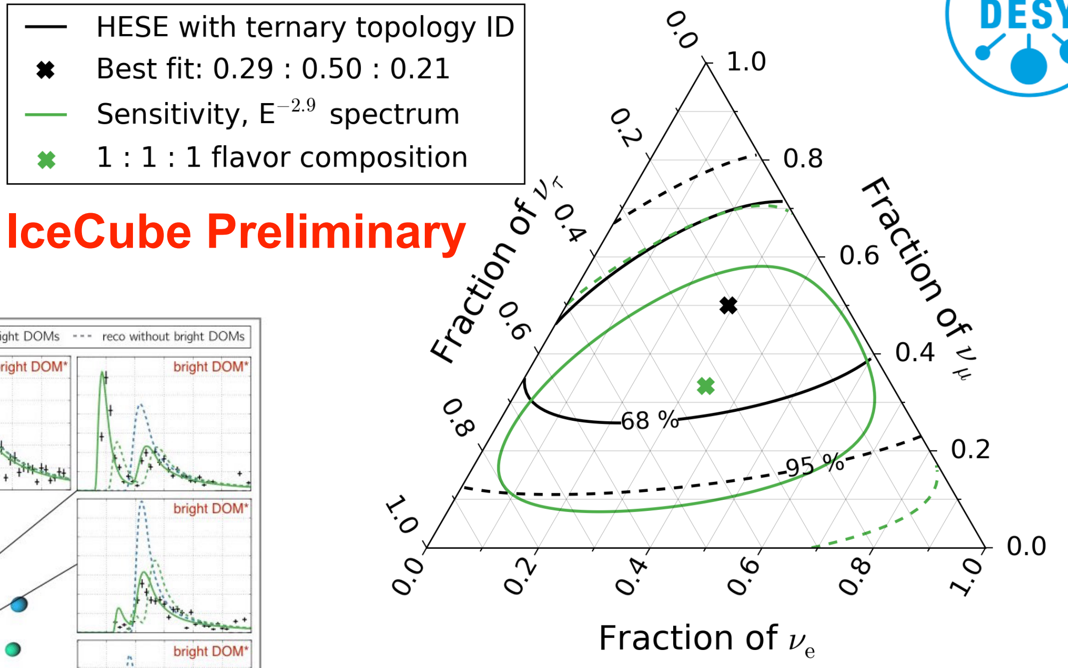
$$E^2\Phi < 3 \times 10^{-8}\,\mathrm{GeV\,s^{-1}\,sr^{-1}\,cm^{-2}}$$

Astrophysical neutrinos

All flavours?!







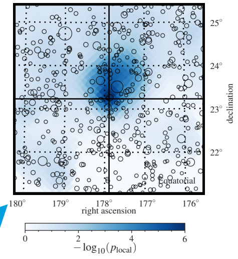
I. Taboada, J. Stachurska Neutrino 2018

First IceCube tau neutrinos?!

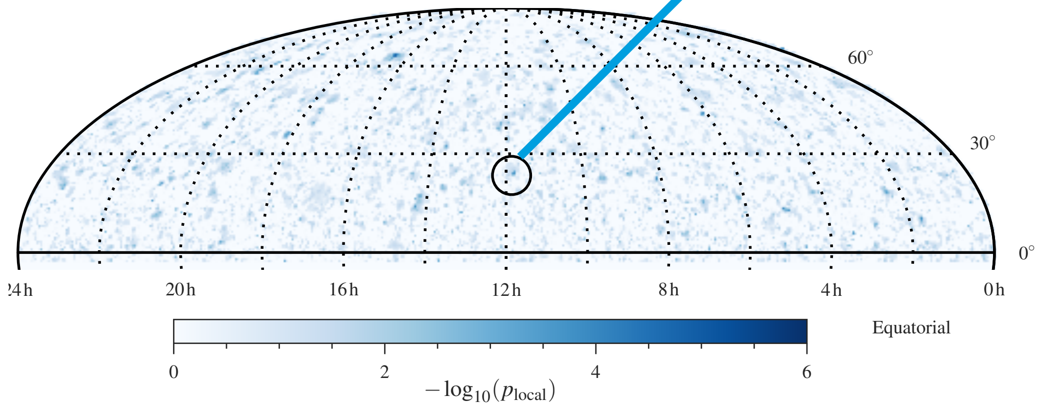
- Two double cascade events have been identified
- In one of these two events, the observed light arrival time favours the double cascade hypothesis
- Double cascades can arise from atmospheric and astrophysical backgrounds
- Further study of the tauness of double cascade events is ongoing, as well as independent double pulse analyses
- Best fit flavour composition is 0.29:0.50:0.21 but zero tau cannot be excluded

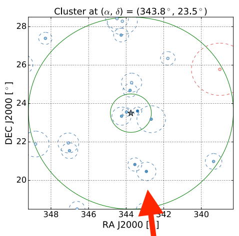
Point sources…

…not yet.



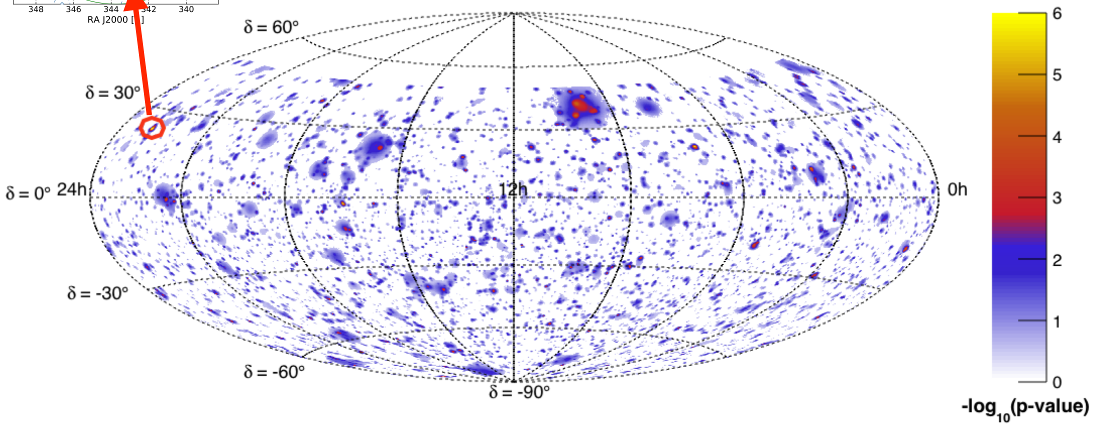
26.5%
post-trial
P-value

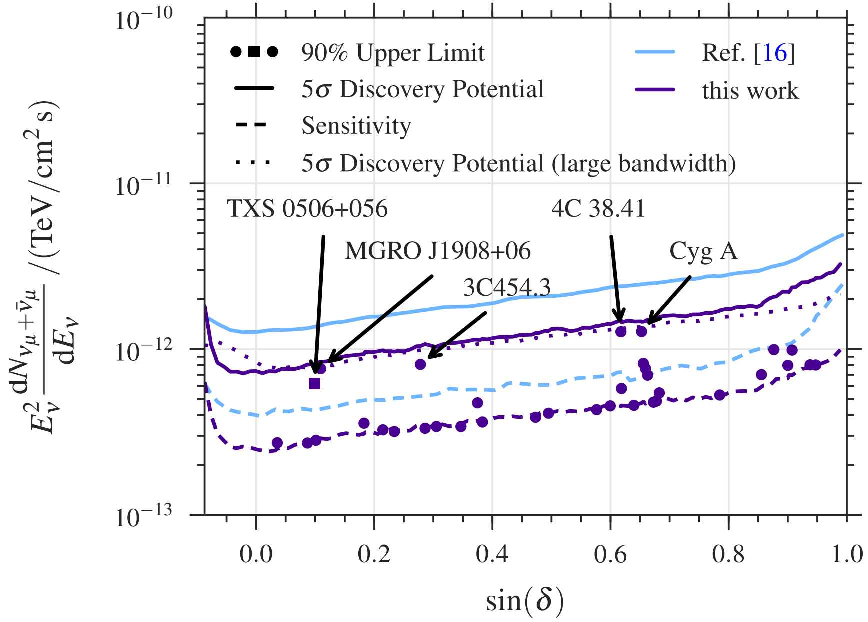




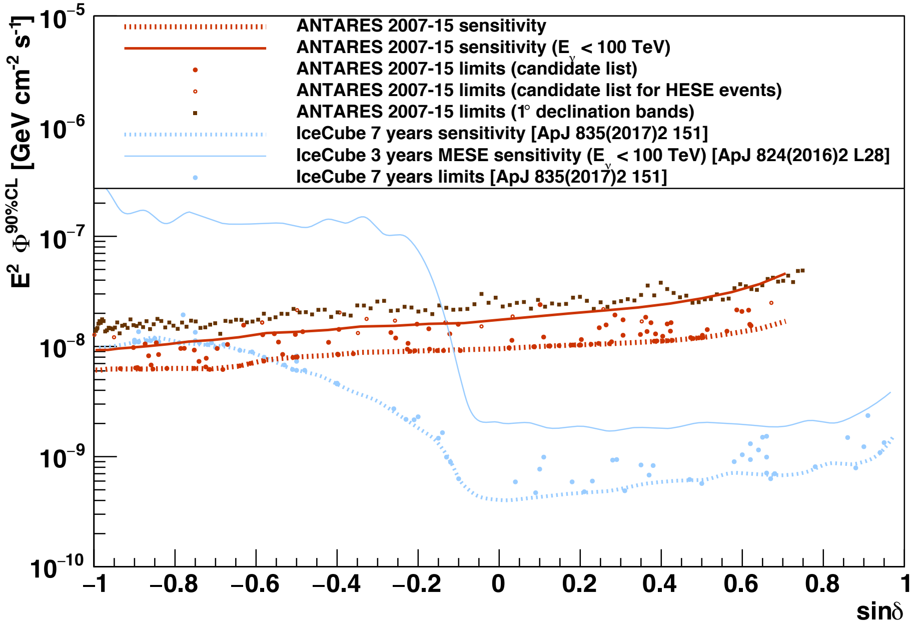
1.9σ
post-trial
significance

A.Albert et al.
Phys. Rev. D 96, 082001 (2017)





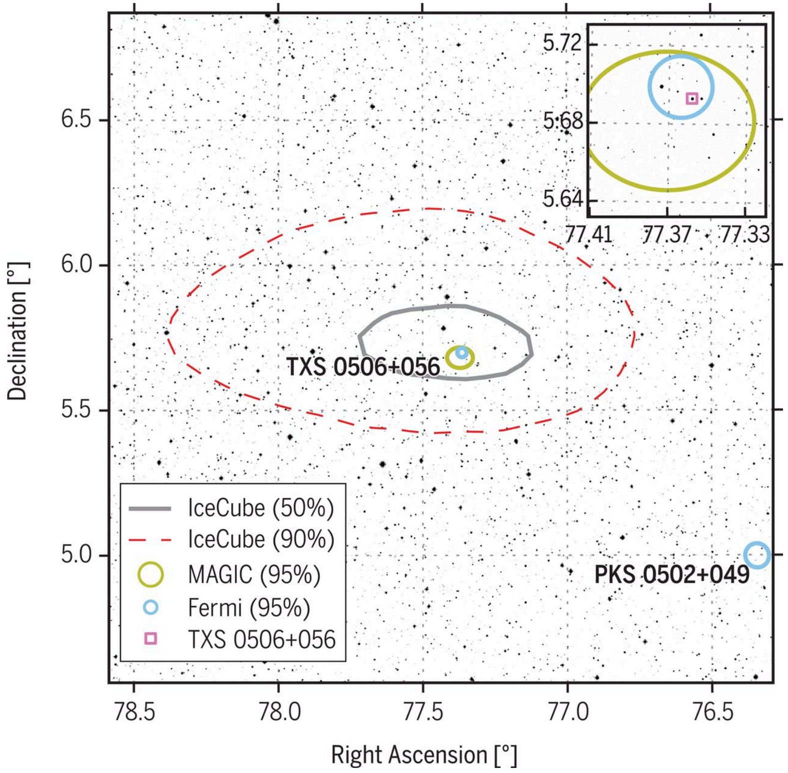
M.G. Aarsten et al.
submitted to *European Phys. J. C*
arXiv:1811.07979



Real-time MultiMessenger

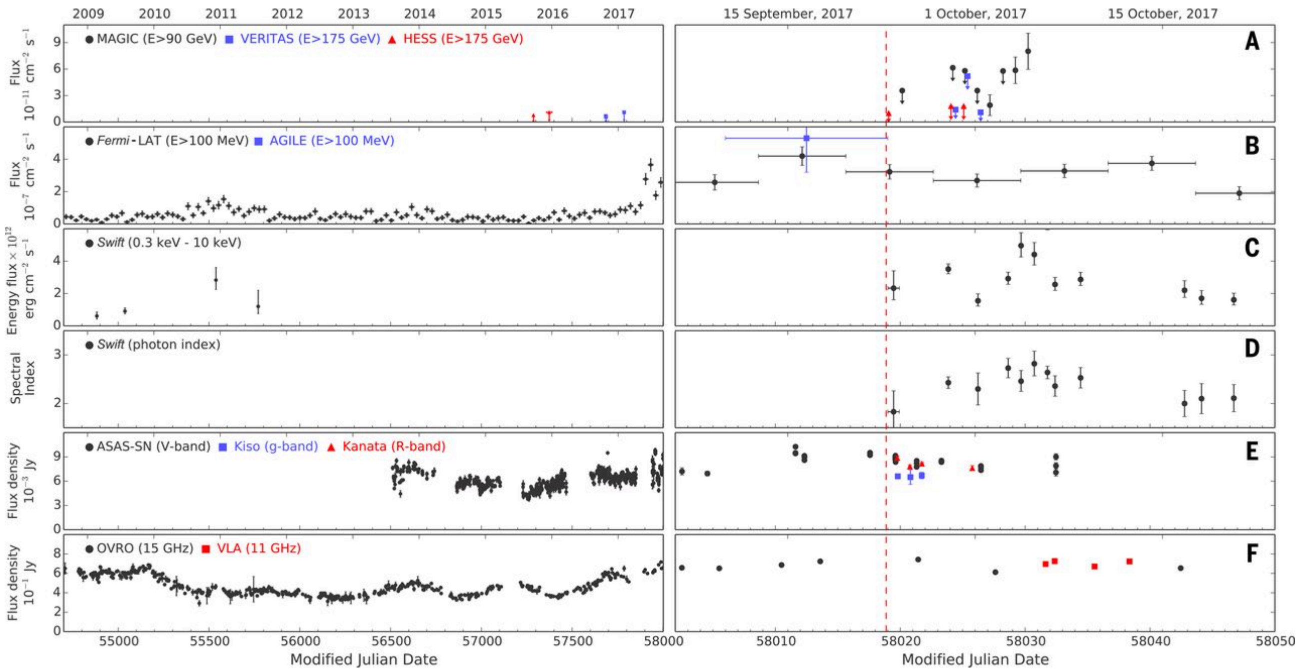
First evidence for a neutrino source!

The IceCube, 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. *Science* 361, eaat1378 (2018)



3σ correlation of IC-170922A (~300 TeV) with the blazar TXS 0506+056 flare

Fast MWL response over all EM spectrum!



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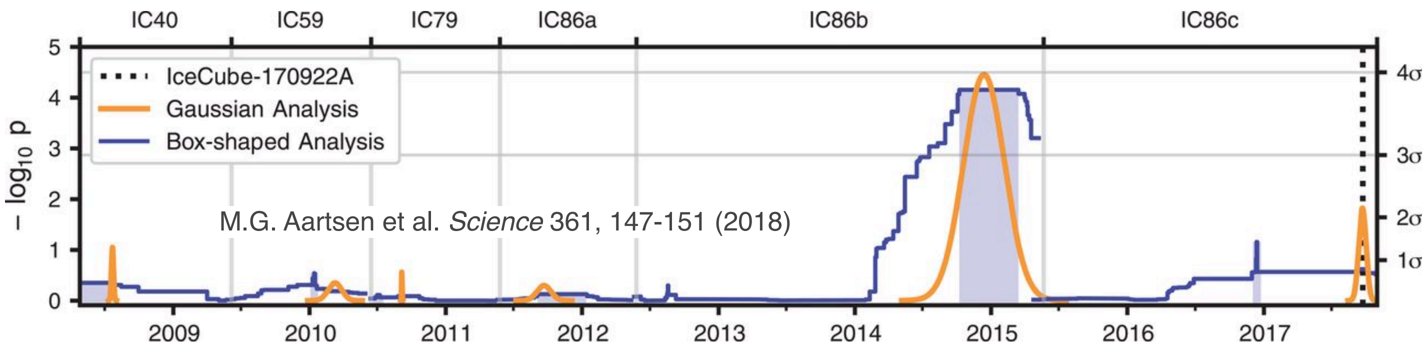
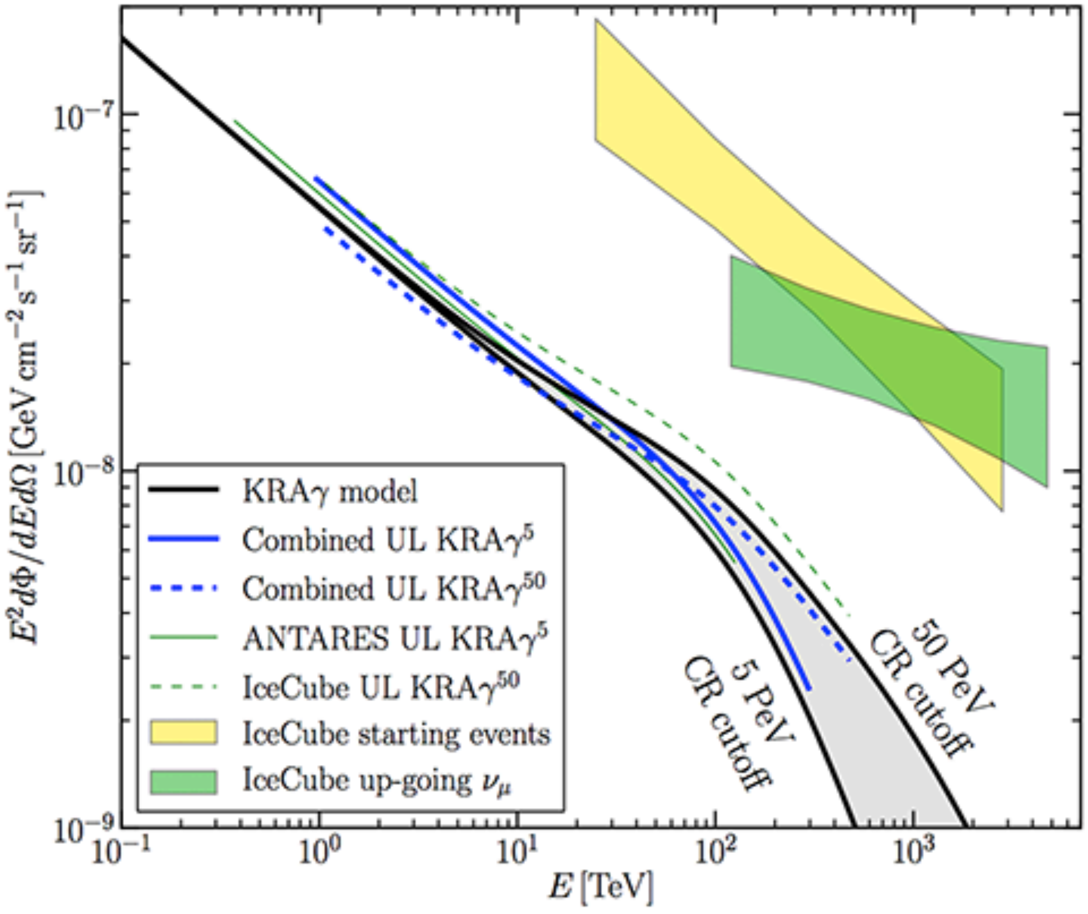
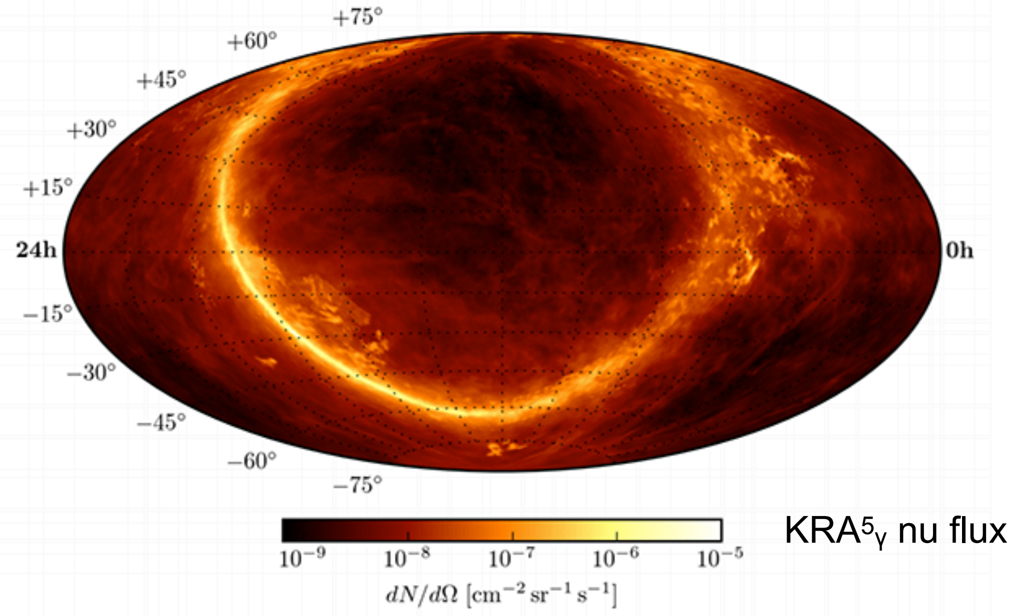


Galactic Plane

Join forces!

The ANTARES and IceCube Collaborations:
Albert et al. *The Astrophysical Journal Letters* 868 (2018), arxiv.org/abs/1808.03531.





KRA$^5_\gamma$ nu flux prediction

IceCube 7 yrs + ANTARES 9 yrs

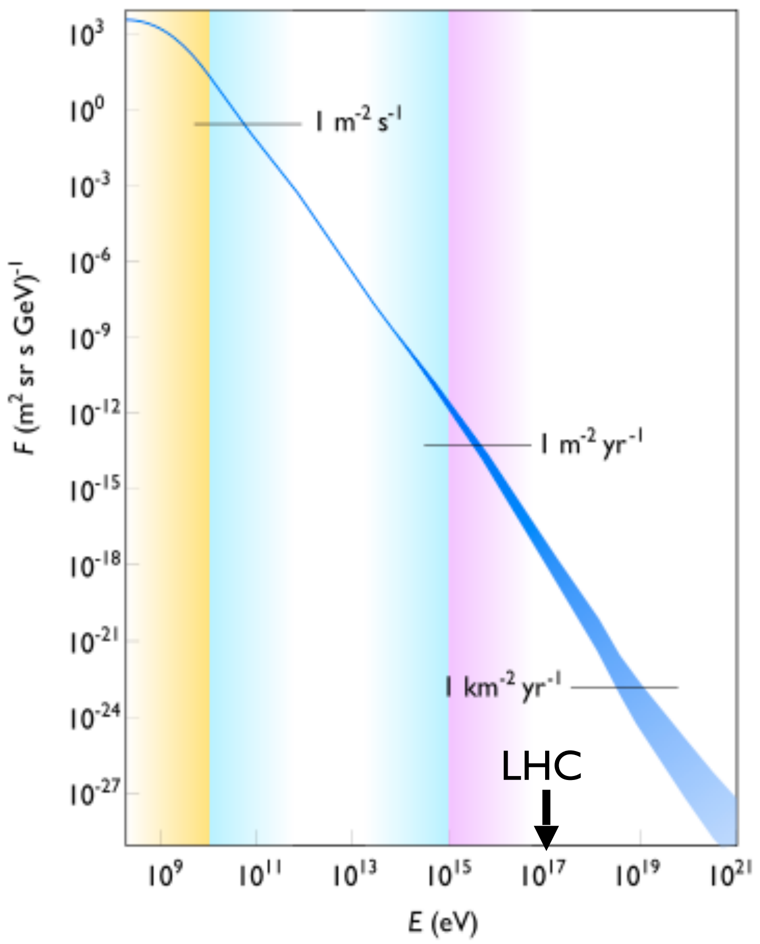
- Galactic cosmic rays propagate in the interstellar medium producing γ-rays and neutrinos.
- Gamma-ray: increasing flux and spectral hardening at the Galactic ridge with increasing γ-ray energy
- Neutrinos: flux increasing with energy, follow γ-ray spatial pattern
- Combined UL in agreement with KRA model, preference for 5 PeV CR spectrum cut-off
- **Galactic contribution to IC astrophysical nu flux < 8.5%**

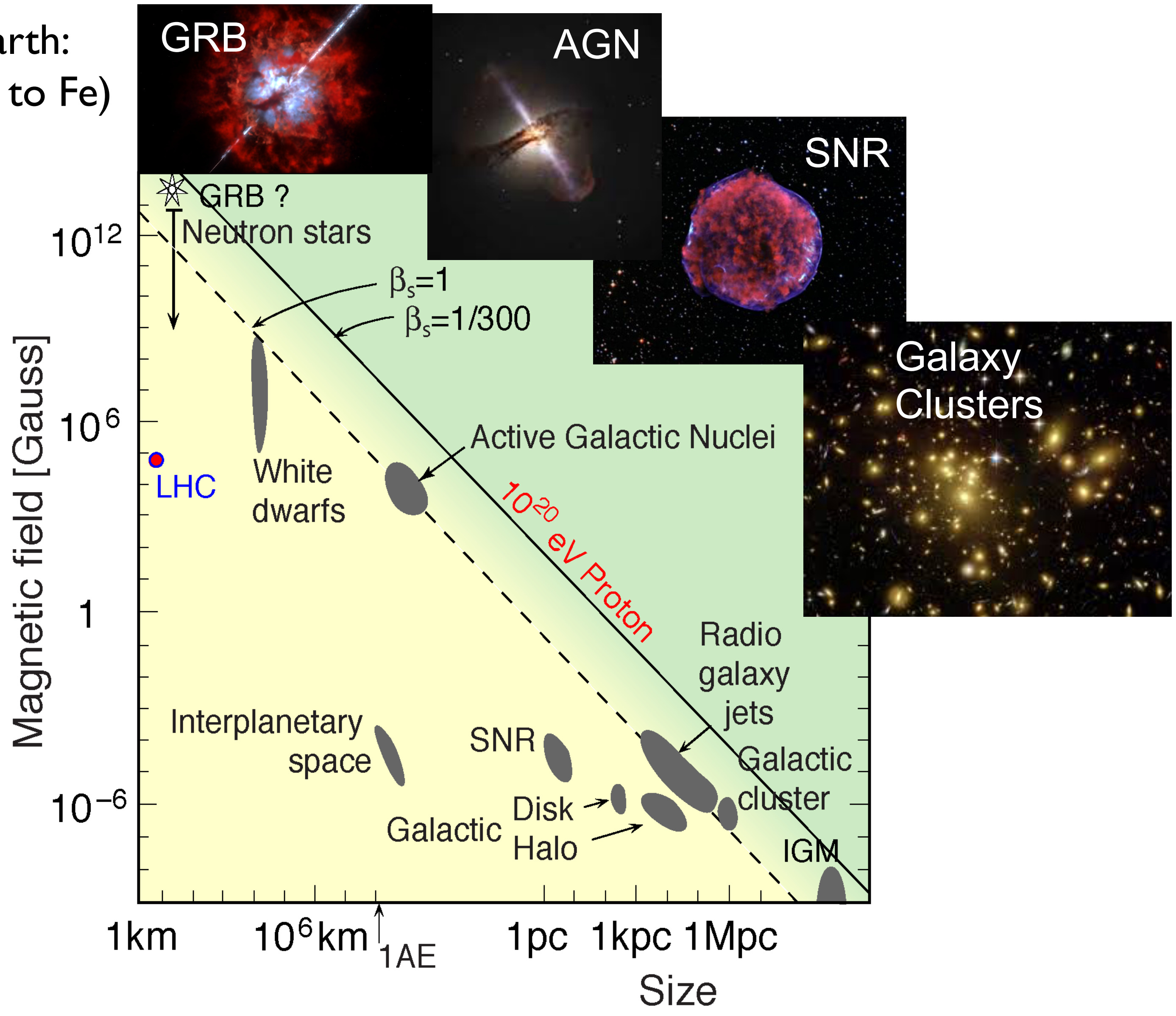
Neutrinos: cosmic messengers

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

The multi messenger approach

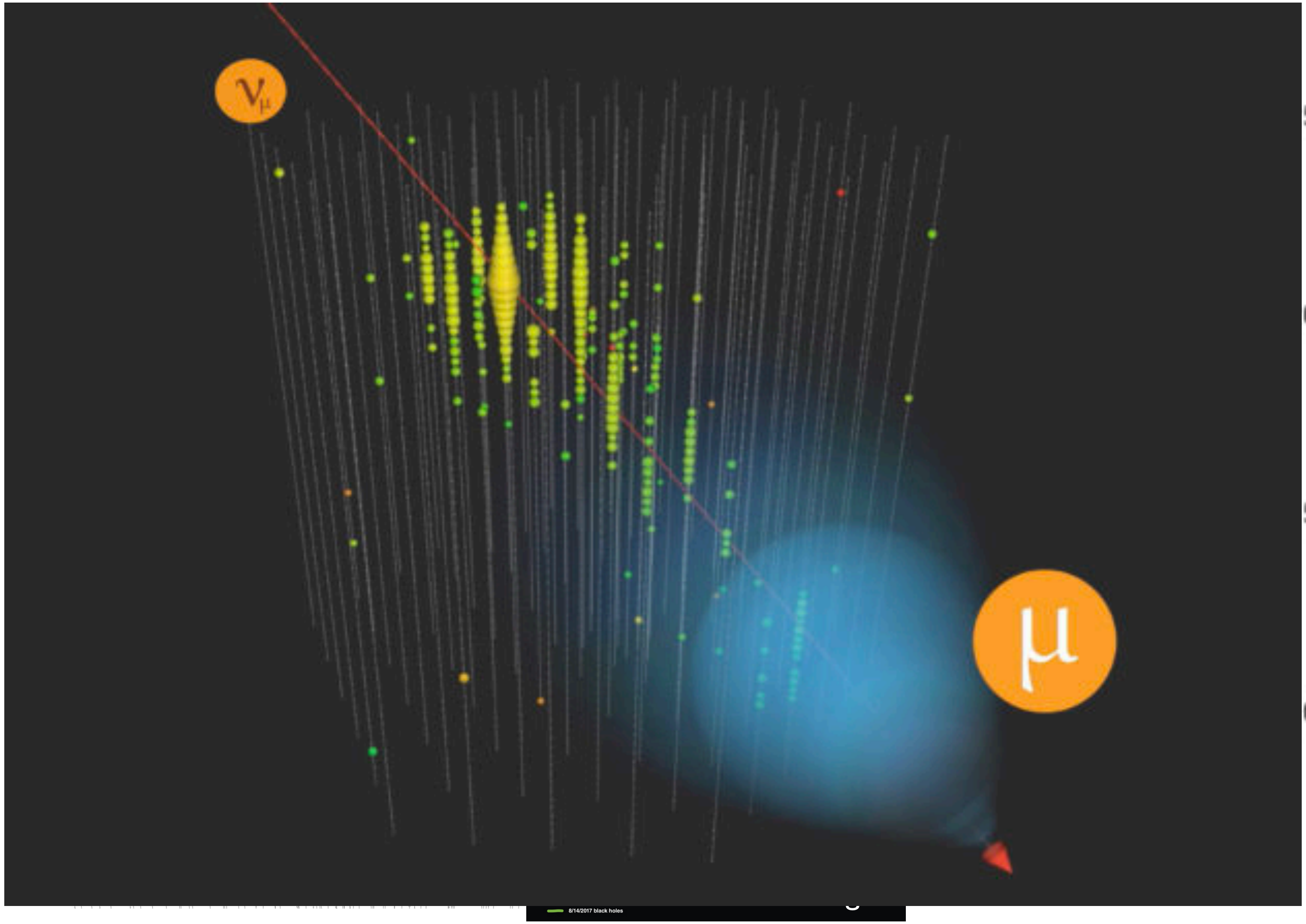
Highest energy particles observed on Earth:
cosmic rays (protons nuclei from He up to Fe)



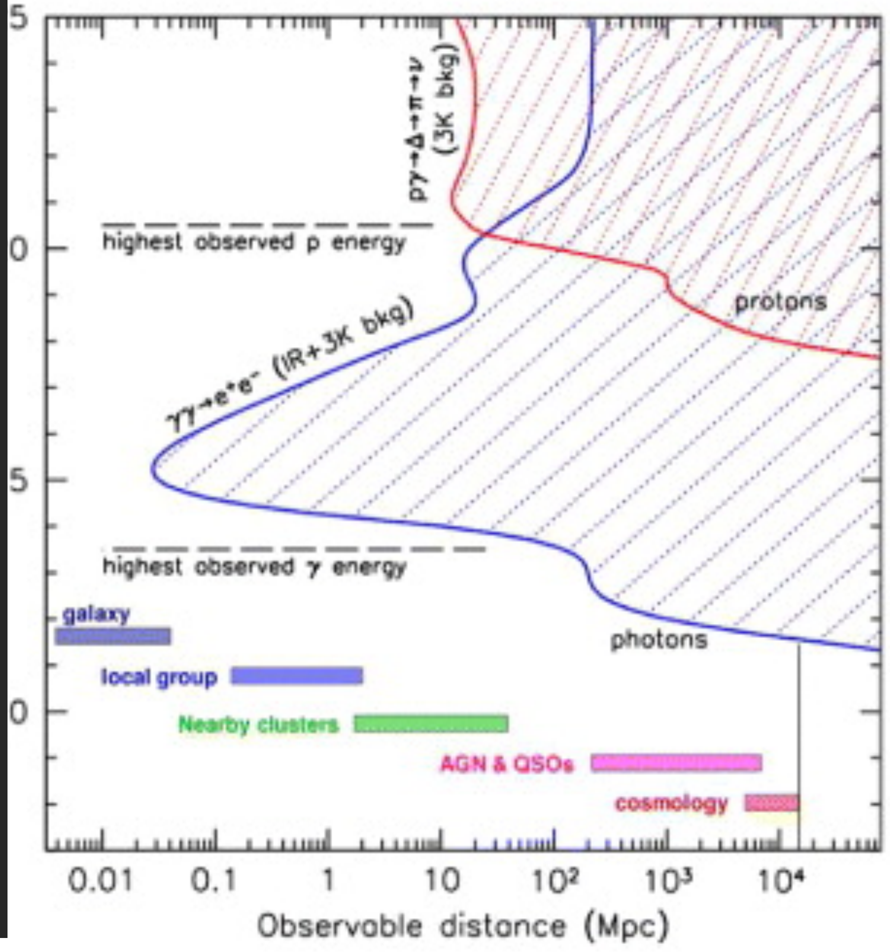


Cosmic messengers

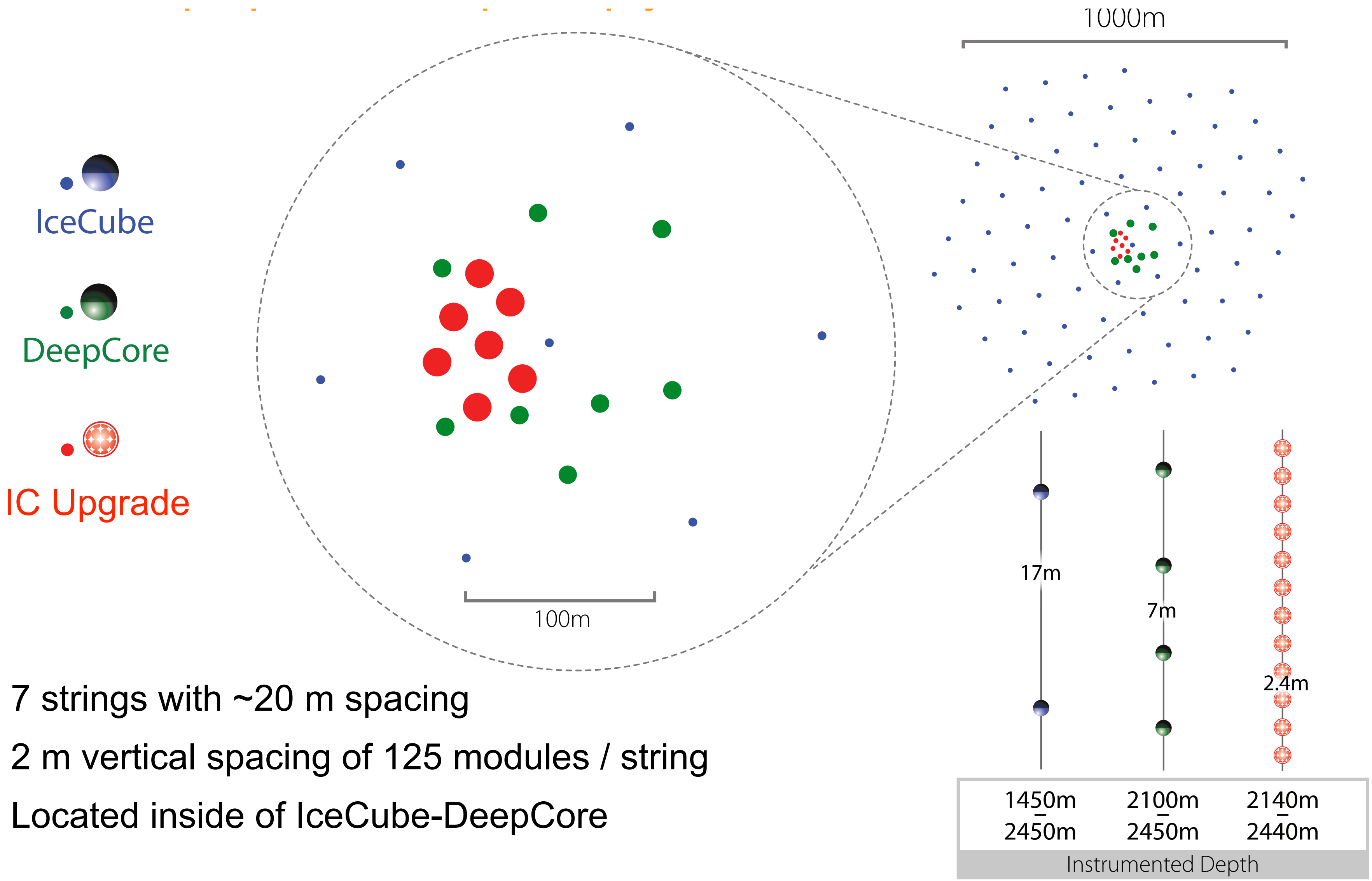
Each of the messengers has its special qualities…



Proton/photon free path in the Universe

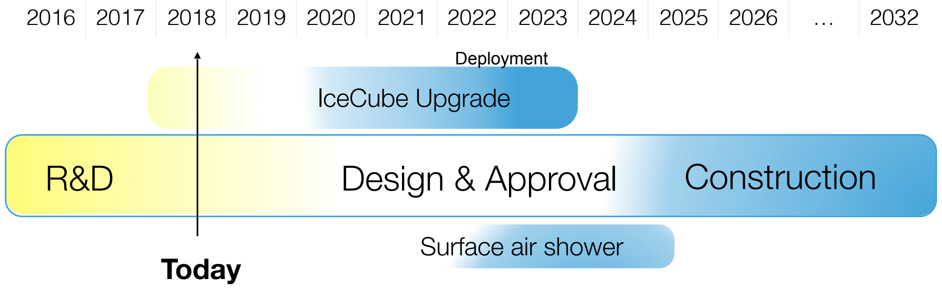


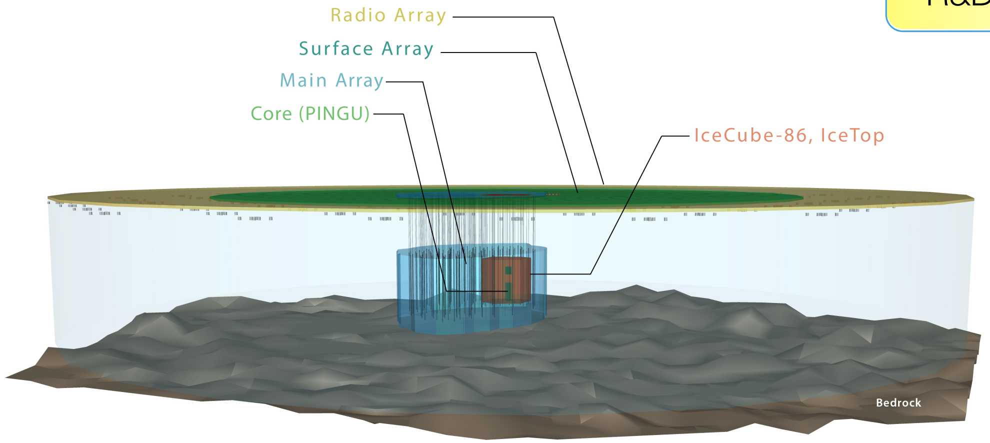
IceCube upgrade

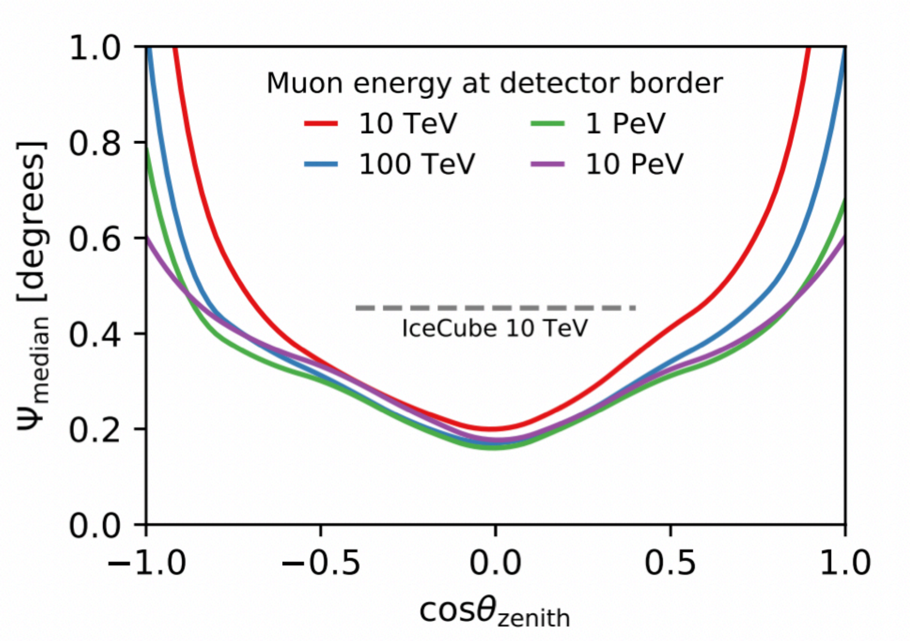


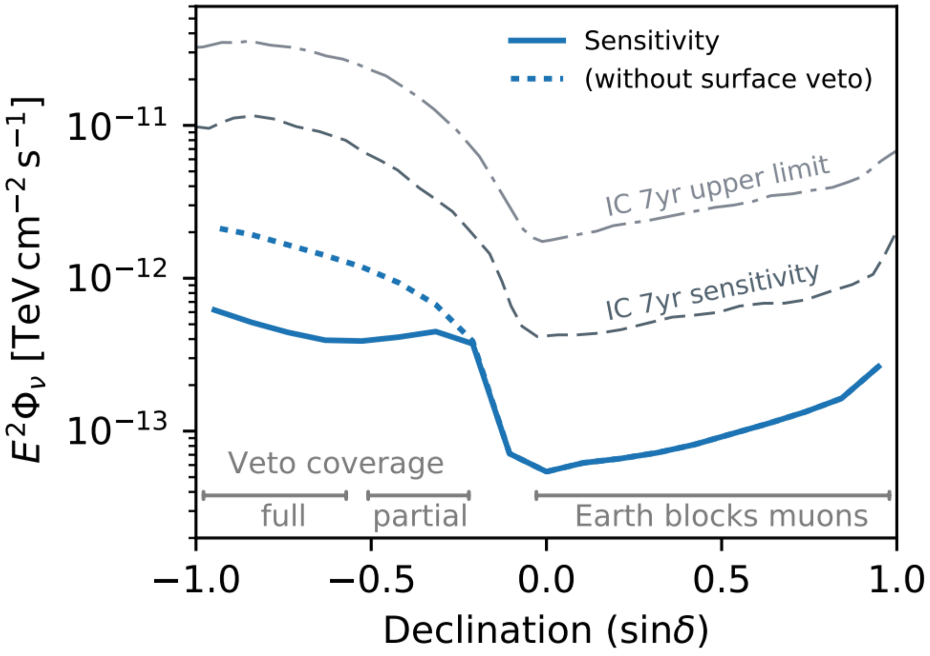
- 7 strings with ~20 m spacing
- 2 m vertical spacing of 125 modules / string
- Located inside of IceCube-DeepCore

Future: IceCubeGen2

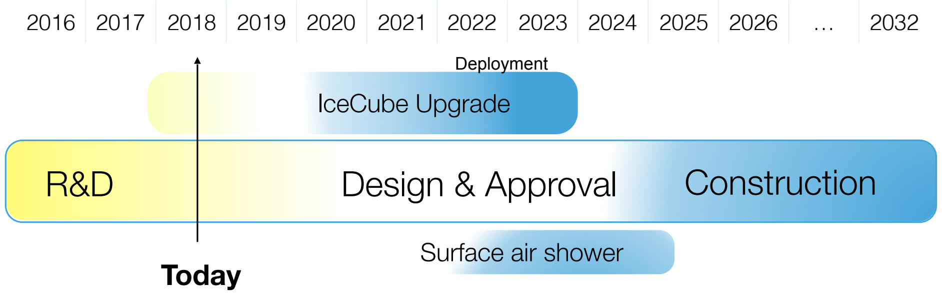


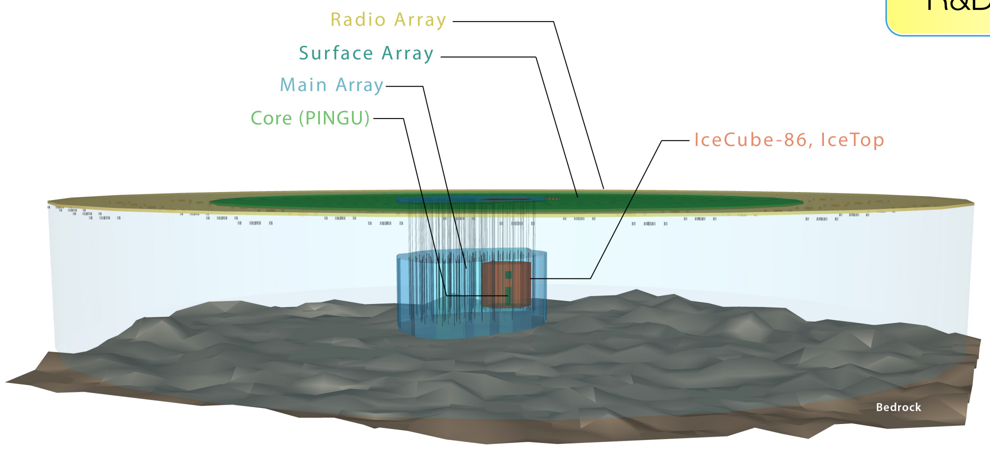


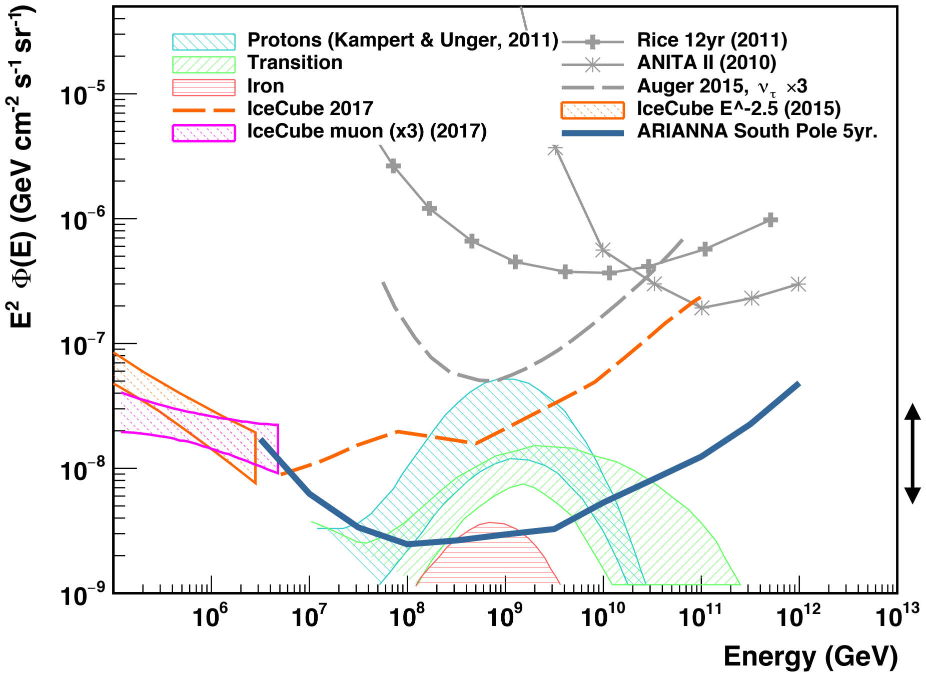


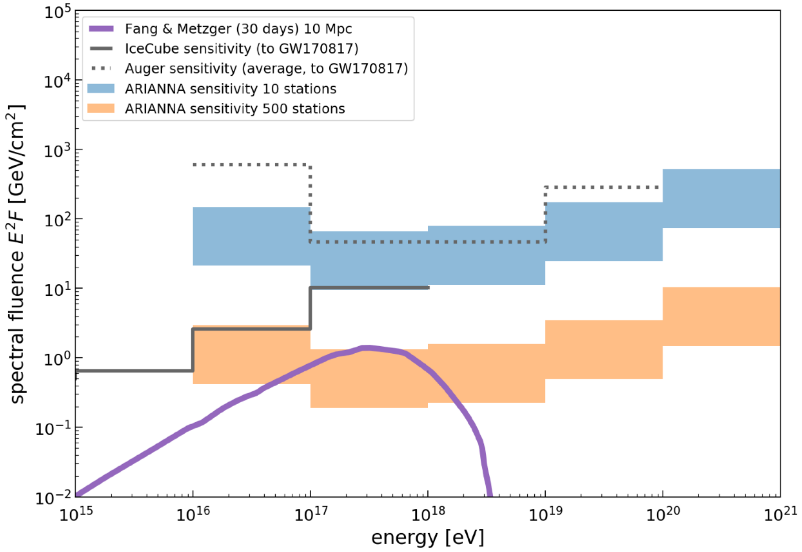


Future: IceCubeGen2









Scales linearly with number of stations

300 stations