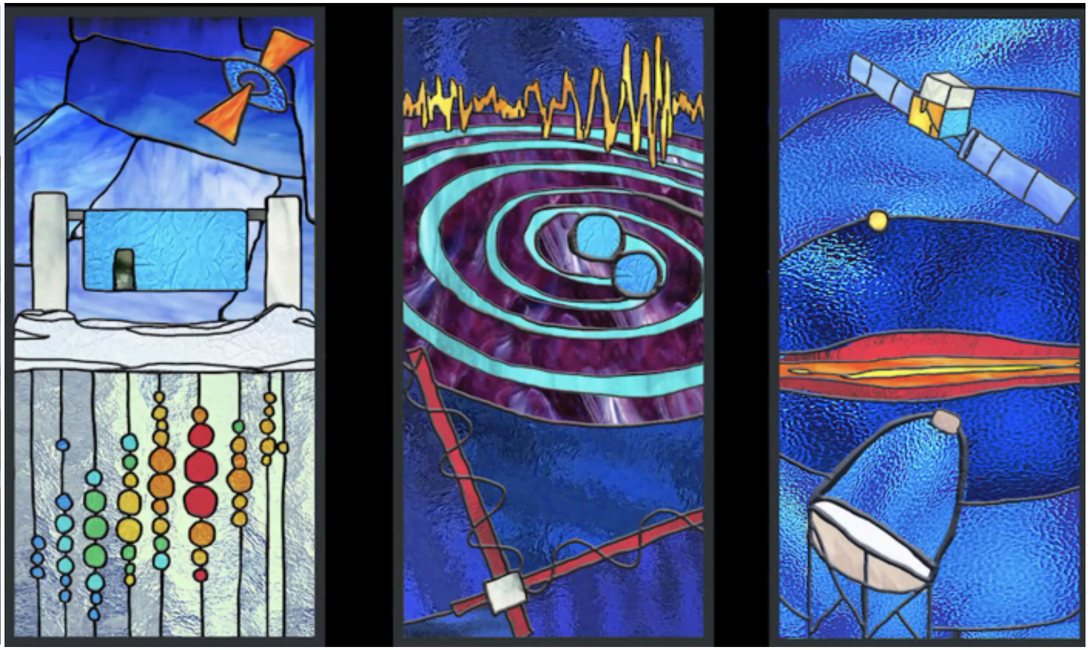
Some thoughts on `Neutrino Telescopes'



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UNIVERSITÉ
DE GENÈVE

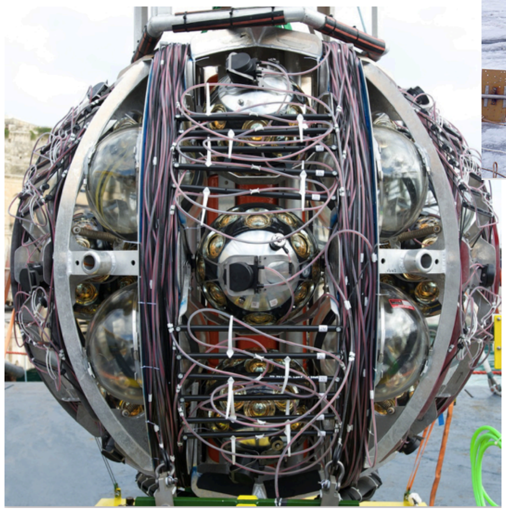
XIX International Workshop on Neutrino Telescopes 2021, 18-26 Feb. 2021

Disclaimer

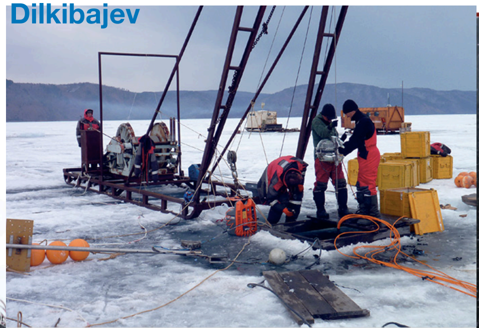
- This is not a summary of all what was discussed at the conference! Focus is on Neutrino Telescopes and **Multi-Messenger Astrophysics**.
- A collection of thoughts on what struck me during these days…hence it is clearly not objective. Not all suitable references are provided for each subject

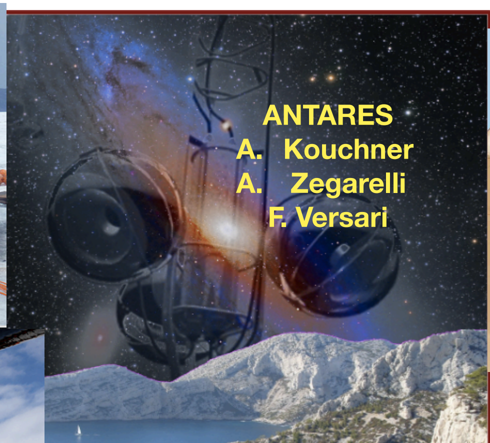
One first thought: For sure astroparticle physicists are not scared of thinking BIG!! Lots of techniques, lots of geographical exploration!

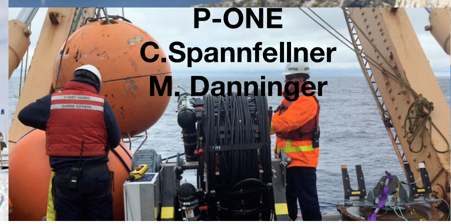
KM3NeT:
A. Hejboer
NRK Chowdhury

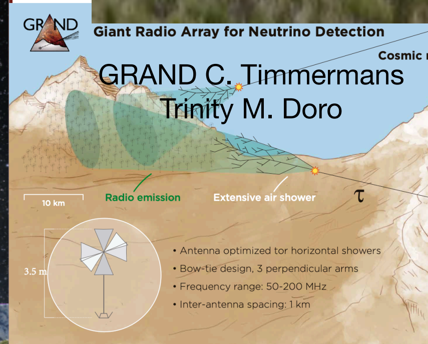


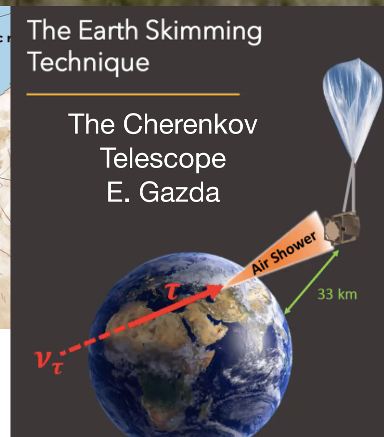
GVD
Dilkibajev

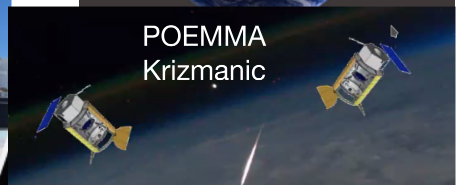


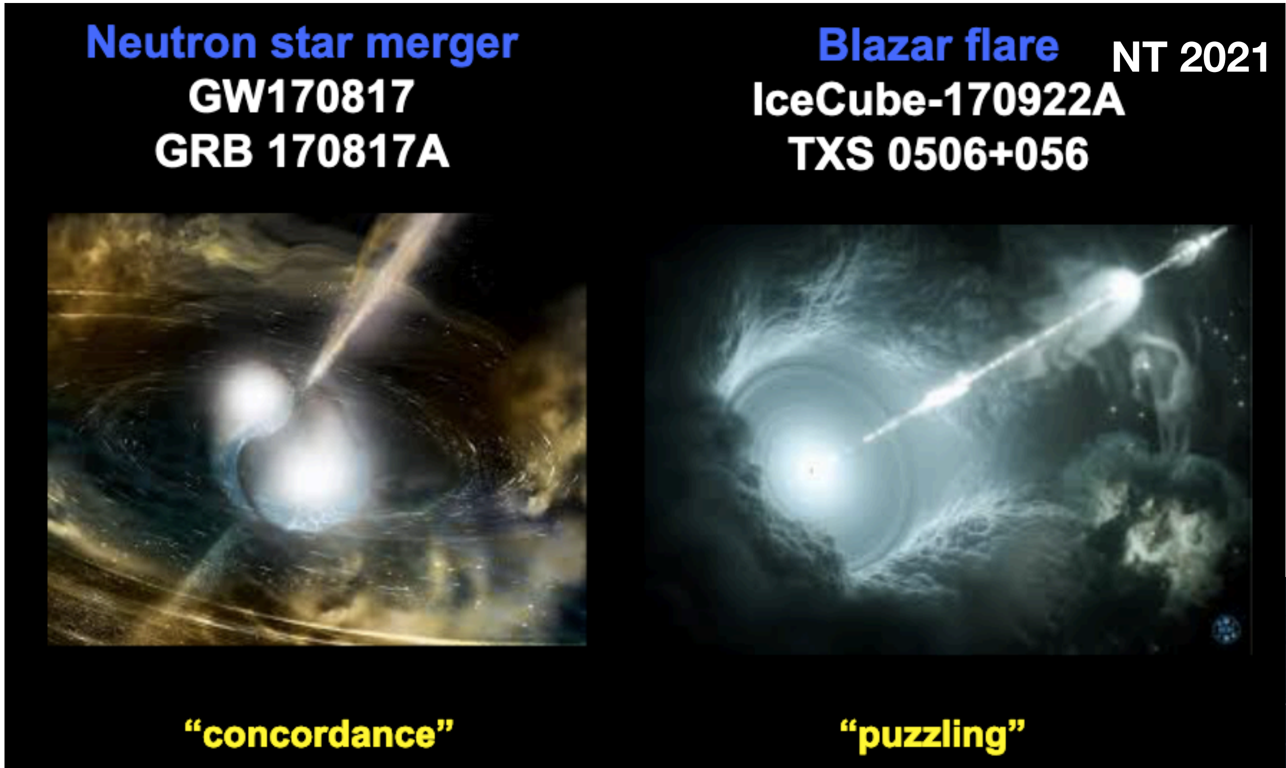






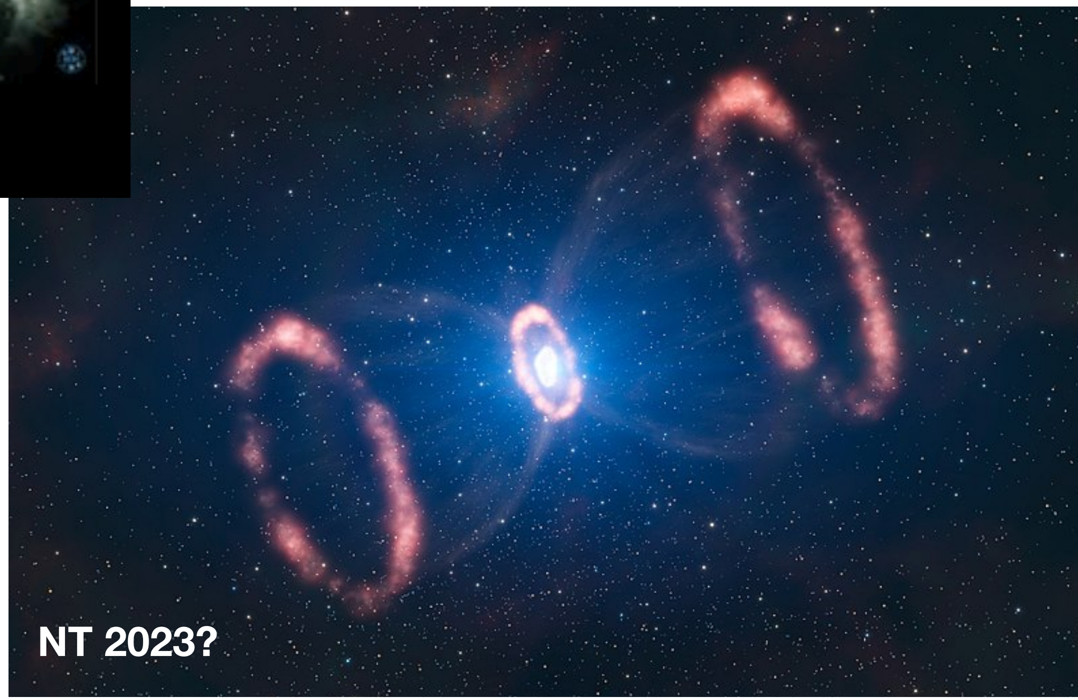






B. Barish: When will we make the Neutrino-Photon-GW connection?

Possible future coincident joint observation in GWs, neutrinos and radiation : **core collapse SN sufficiently close to us (stars > 8$M_{\odot}$)**, including MeV short GRB burst + emissions from the remnant which can form a jet if rapidly spinning, kilonova - short GRBs associated to BN-BN, periodic sources such as pulsars,…



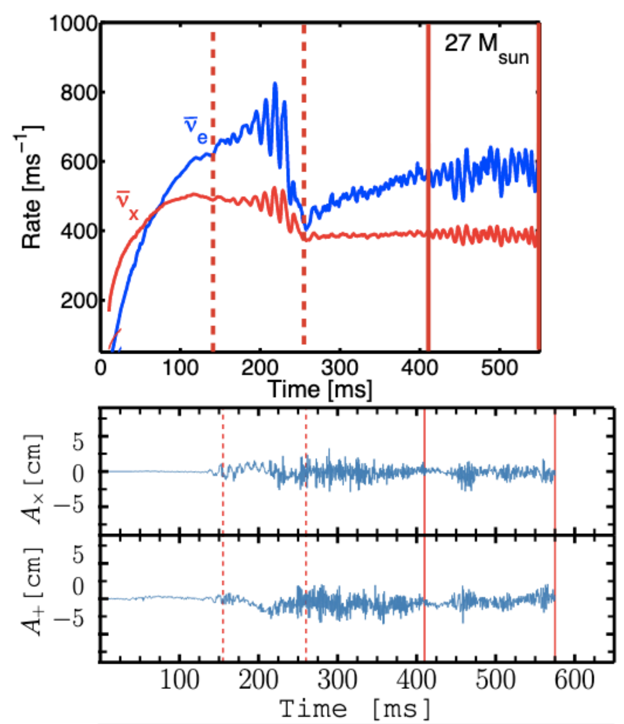
Borrowed from K. Murase’s exciting summary talk

Various searches for coincident ν-GW presented at this conference: SK ν-GW SK-O3 1.4σ post trial (M. Lamoureux’s), Pierre Auger (M. Shimp), ANTARES (A. Kouchner); NOVA! (M. Strait)

The supernova connection

SuperNova Early Warning System 2.0.

$\nu's$ and GWs can probe instants before BH formation in BH forming core collapse SN. Hydrodynamical instabilities produce modulations testable through $\nu's$ and GWs.



Neutrinos

Gravitational waves

Tamborra et al., PRL (2013), PRD (2014). Andresen et al., MNRAS (2017,2019). Walk, Tamborra et al., PRD (2018,2019).

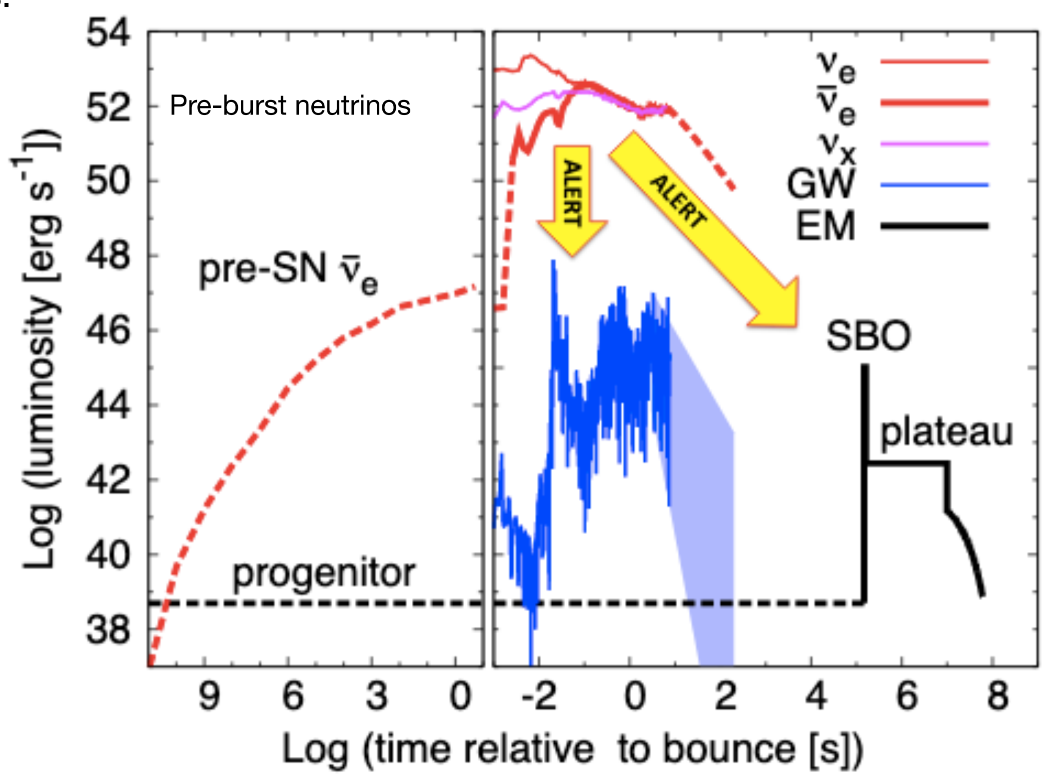
Walk et al, https://arxiv.org/abs/2011.00035

Irene Tamborra's talk

The core collapse SN multi-messengers: neutrinos can provide the early alert (up to 1 day before!)

Energy in each messenger:

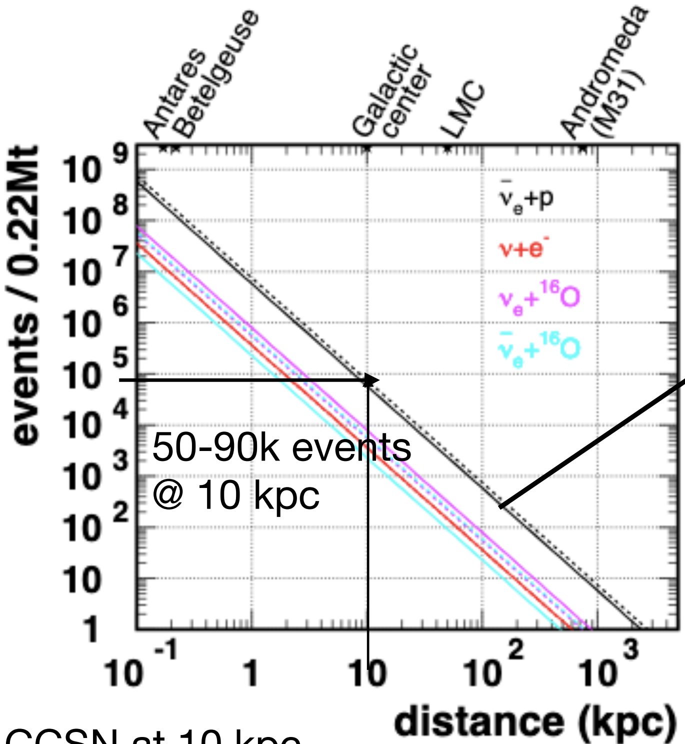
$\bar{\nu}_e \sim 6 \times 10^{52}\,\mathrm{erg}; \gamma \sim 4 \times 10^{49}; \mathrm{GWs} \sim 7 \times 10^{46}\mathrm{erg}$



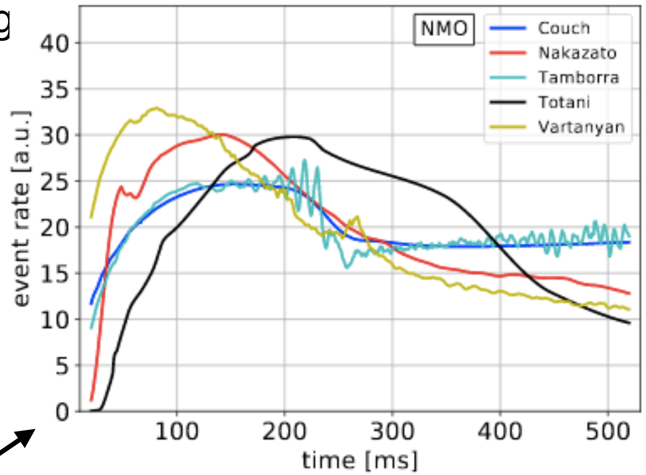
The Einstein Telescope will cover the full Milky Way, the current generation of interferometers cover some kpcs

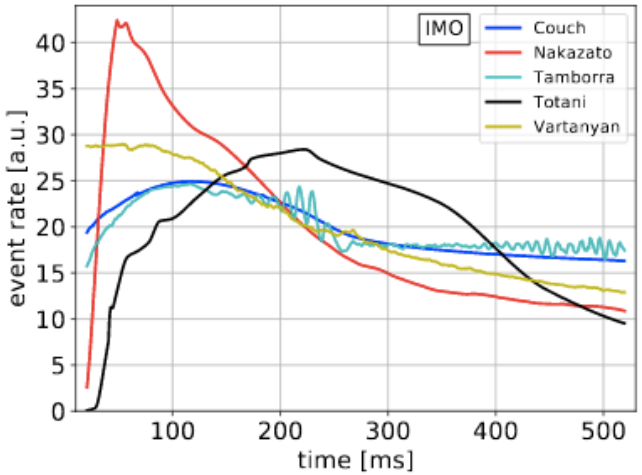
For NT 2027!

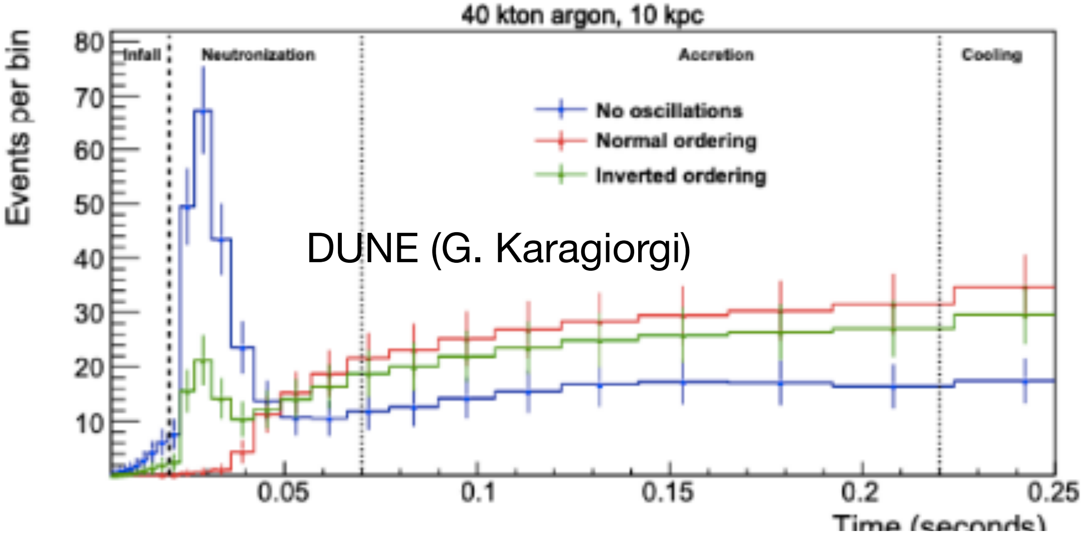
Hyper-Kamiokande (G. Catanesi & F. Di Lodovico's talk) : x 8 SK >20k PMTs 50 cm PMTs
50-90k events @ 10 kpc
For 300 events @ 60-100 kpc, considering
Ordering



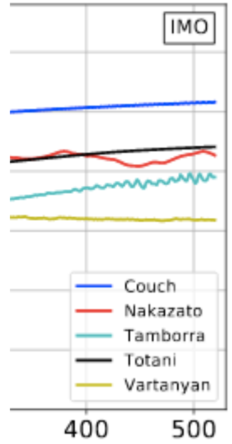
50-90k events
@ 10 kpc







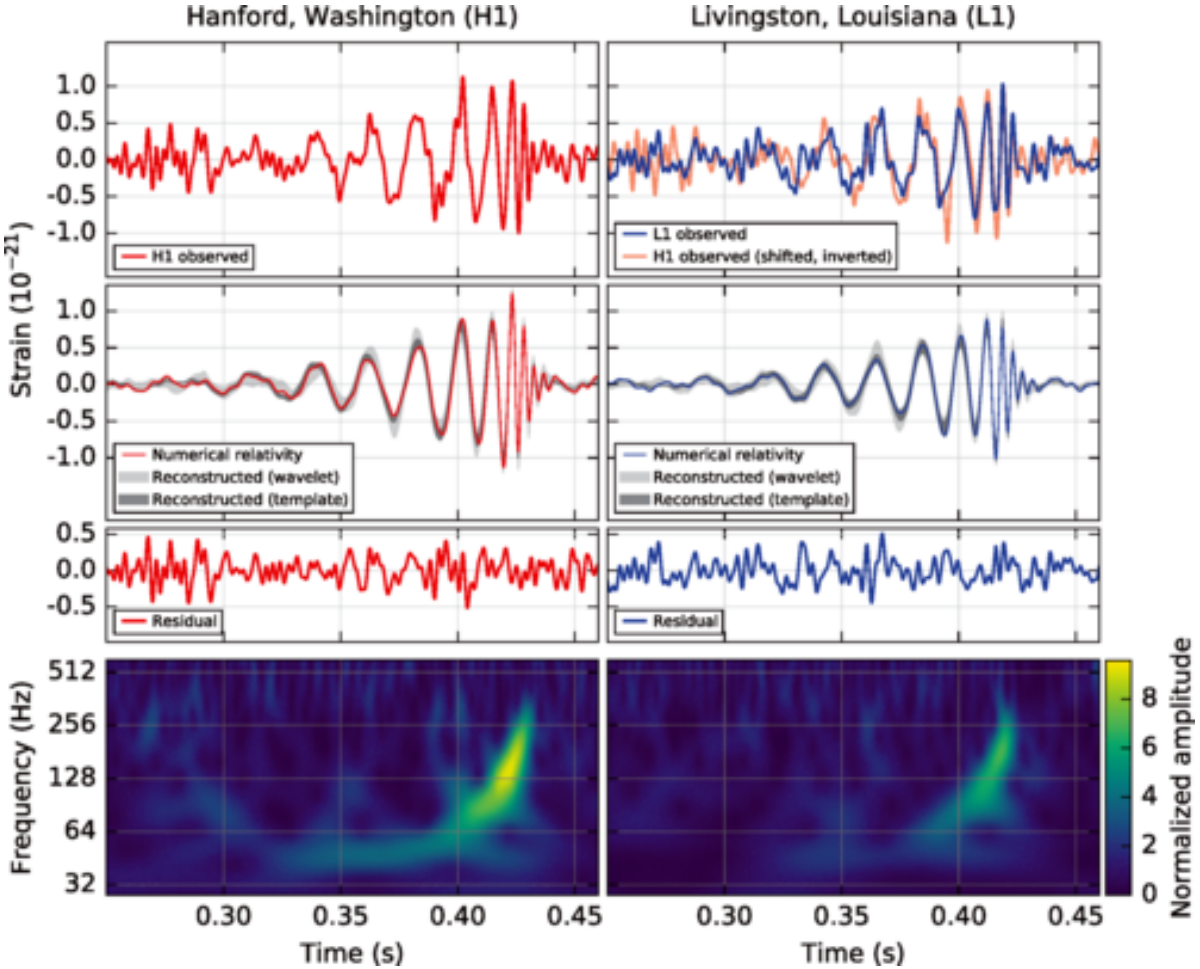
DUNE (G. Karagiorgi)



CCSN at 10 kpc
JUNO ~10k events (D. Xu)

The first GW telescope event of BH-BH merger

GW arrived first at L1 and then after 6.9–0.4+0.5 ms at H1



A direct detection : RAW DATA after pass band filter in 35–350 Hz!

https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.116.061102

Fit to simple formulas bring a lot of information!

At first order, the rate of change of the frequency is

$$\frac{df}{dt} = \frac{96\pi^{8/3}(G\mathcal{M})^{\frac{5}{3}} f^{\frac{11}{3}}}{5\,c^5},$$

And the chirp mass is related to the masses of mergers

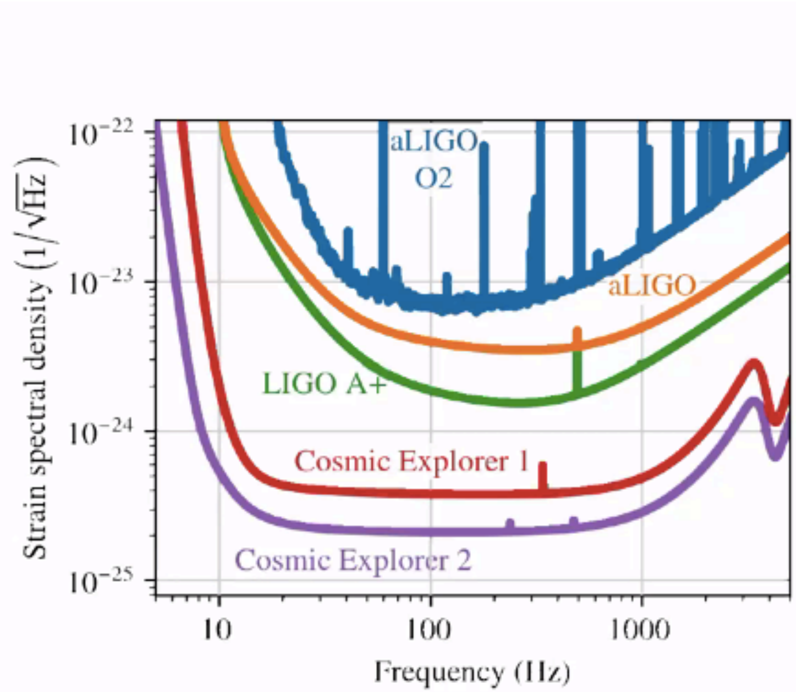
$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}.$$

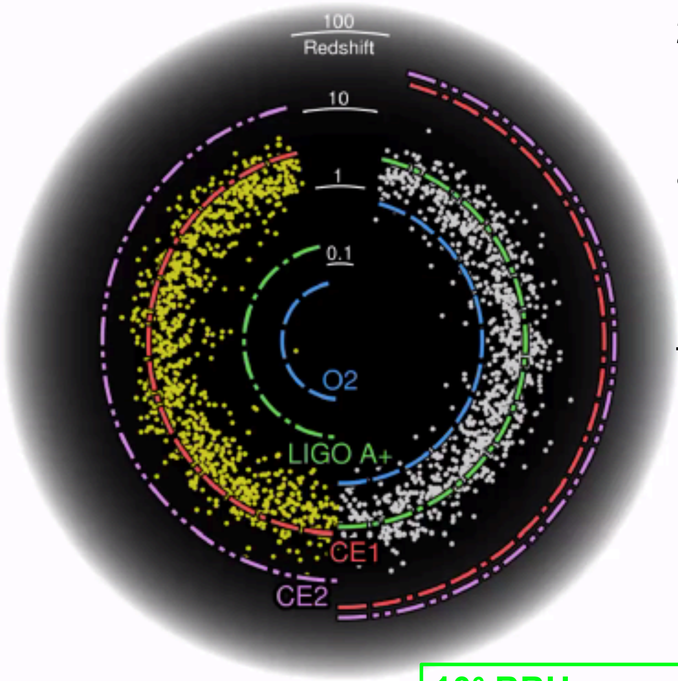
The polarization of the waves provides the angle of emission
And the distance is a multiple of the laser wavelength.
And also energy radiated, spin, inclination, localisation in sky…

A relevant difference: Neutrino Telescopes measure neutrinos from their secondaries (indirect technique). We know particle interactions with matter, but one needs a Monte Carlo (probability density distributions) to infer all relevant quantities.

…and this is a **challenge**! (N. Whitehorn)

GW telescopes: Current and future sensitivity and redshift horizon





2G has been successful realising interferometry with precision better than $\Delta L \sim 10^{-12}$ x the wavelength of light with arm lengths of L ~1000 km suitable to probe the change of position of 2 test masses by $h = \dfrac{\Delta L}{L} \sim 10^{-21} \Rightarrow 10^{-18} m$!

The future seeks for < 10^{-24}!

The future : cosmology with GWs!

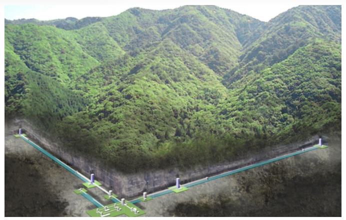
LIGO - WA

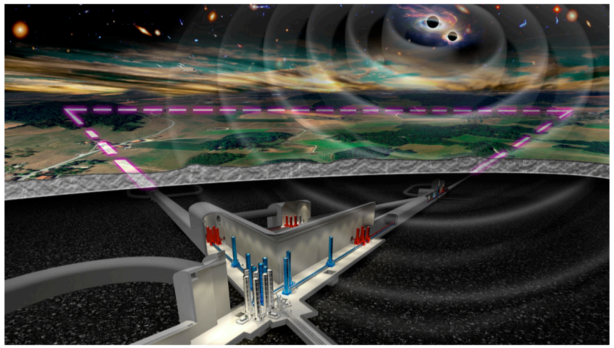
LIGO - LA

Virgo - I

GEO600 - D

KAGRA & LIGO India

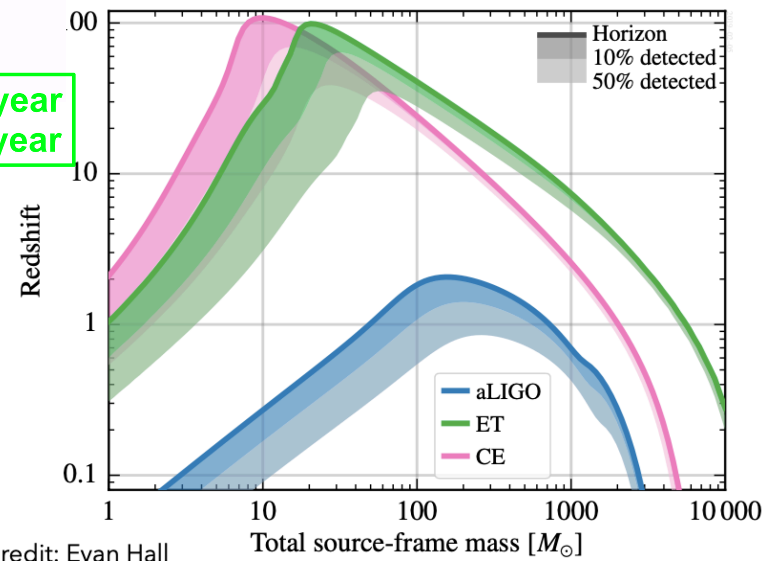




3G : Einstein Telescope in Europe
Cosmic Explorer North America

10^6 BBH per year
10^5 BNS per year

3G NETWORK SENSITIVITY



Credit: Evan Hall

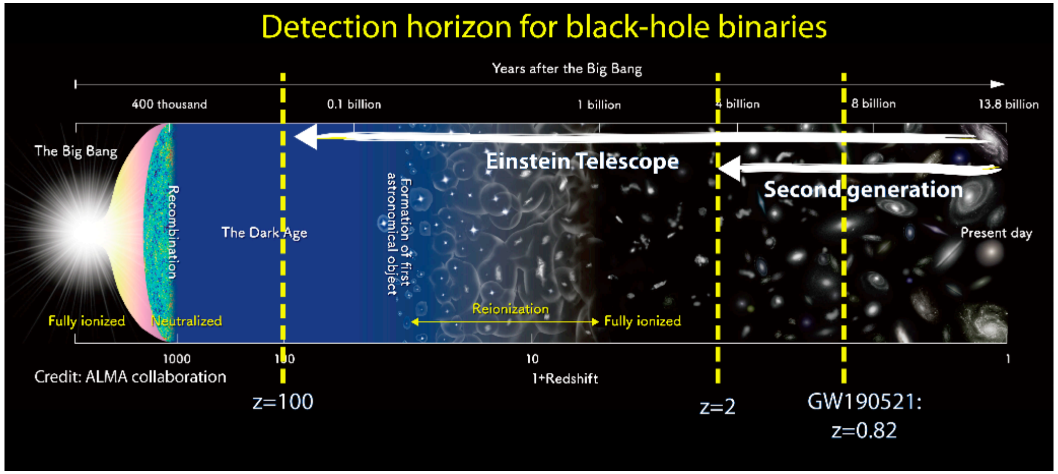
Cosmology with 3G

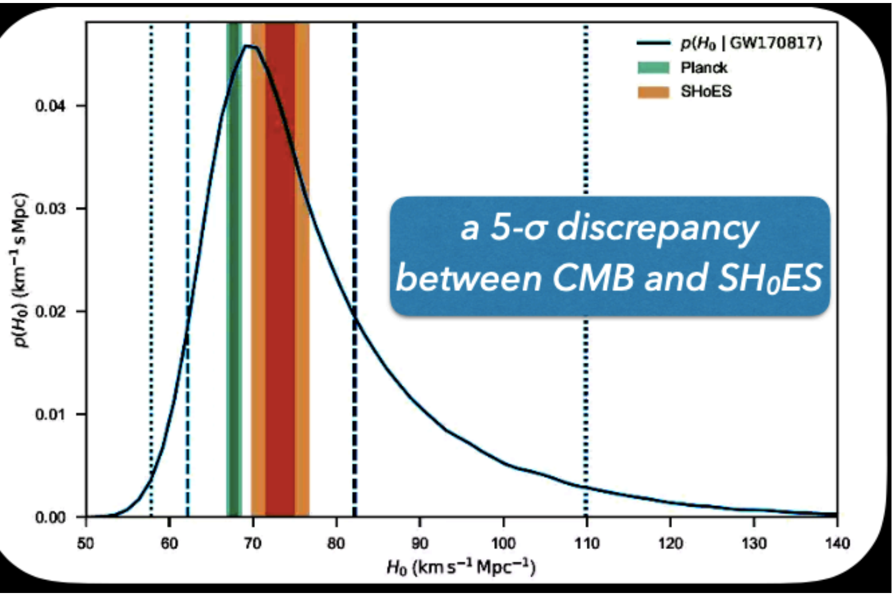
Standard sirens: Independent measurement of the Hubble constant: z from optical observations and luminosity distance D_L from GW signal from NS-NS merger GW170817

$$H_0 D_L = cz \Rightarrow H_0 = 70^{12.0}_{-8.0}\,\mathrm{km\,s^{-1}Mpc^{-1}}$$

Adding O1+O2: $H_0 = 68^{14.0}_{-7.0}\,\mathrm{km\,s^{-1}Mpc^{-1}}$.

The degeneracy of the inclination angle of the plane of the system will be removed measuring the 2 polarizations (Einstein Telescope)

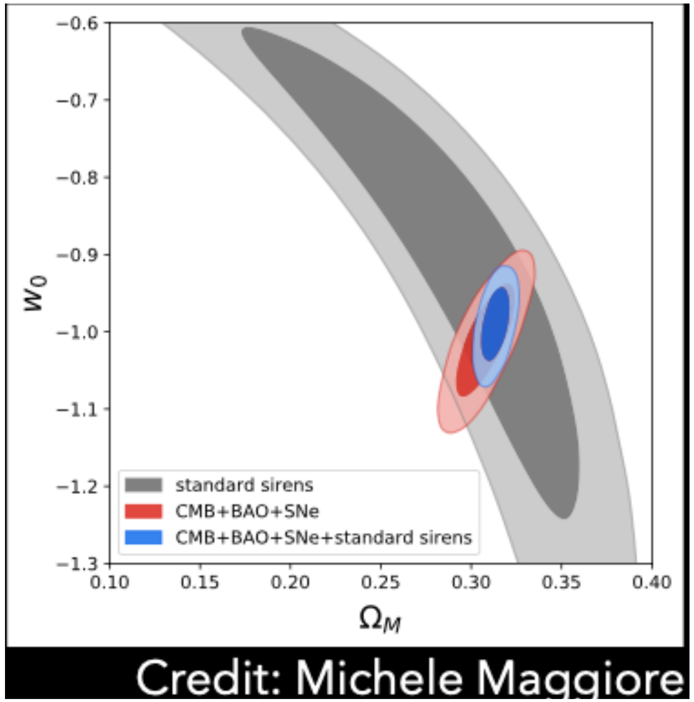




Abbott+, Nature (2017)

Hubble tension between early universe value (Planck) and from SNe : a cosmological constant all over the cosmic history, neutrino steriles?(M. Kamionkowski's, S. Hannestad's, Galli's talks).

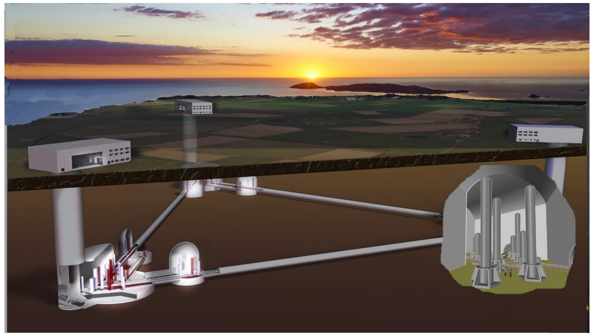
10^3 standard Sirens in ET: equation of state parameter vs matter energy density

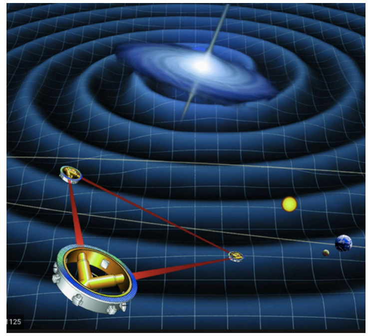


Sensitivity and sources

ESA LISA Mission 2.5 x 10^6 km arms
=> 8.3 s => 10^{-4}-10^{-2} Hz

3G: Einstein Telescope & Cosmic Explorer
10 km arms

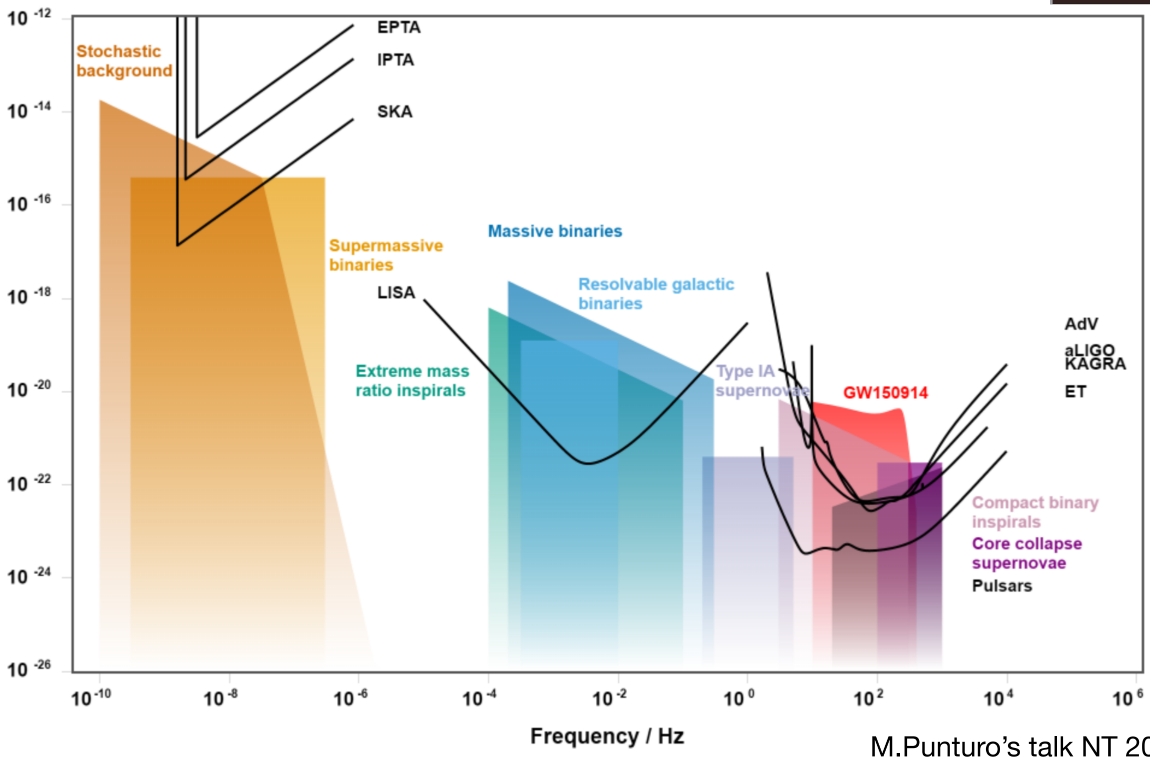




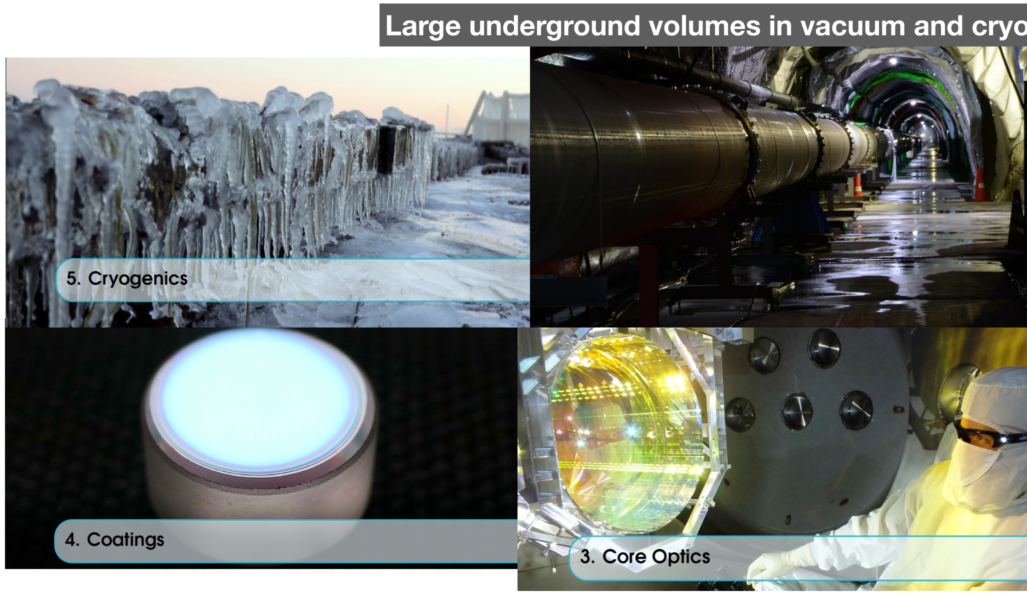
The future…cosmology with GWs!

Terrestrial: $f \in]1, few\times10^3]Hz \to \frac{M}{M_S} \in [NS, 4\times10^3]$

LISA: $f \in [10^{-4}, 10^{-2}]Hz \to \frac{M}{M_S} \in [10^5, 10^7]$



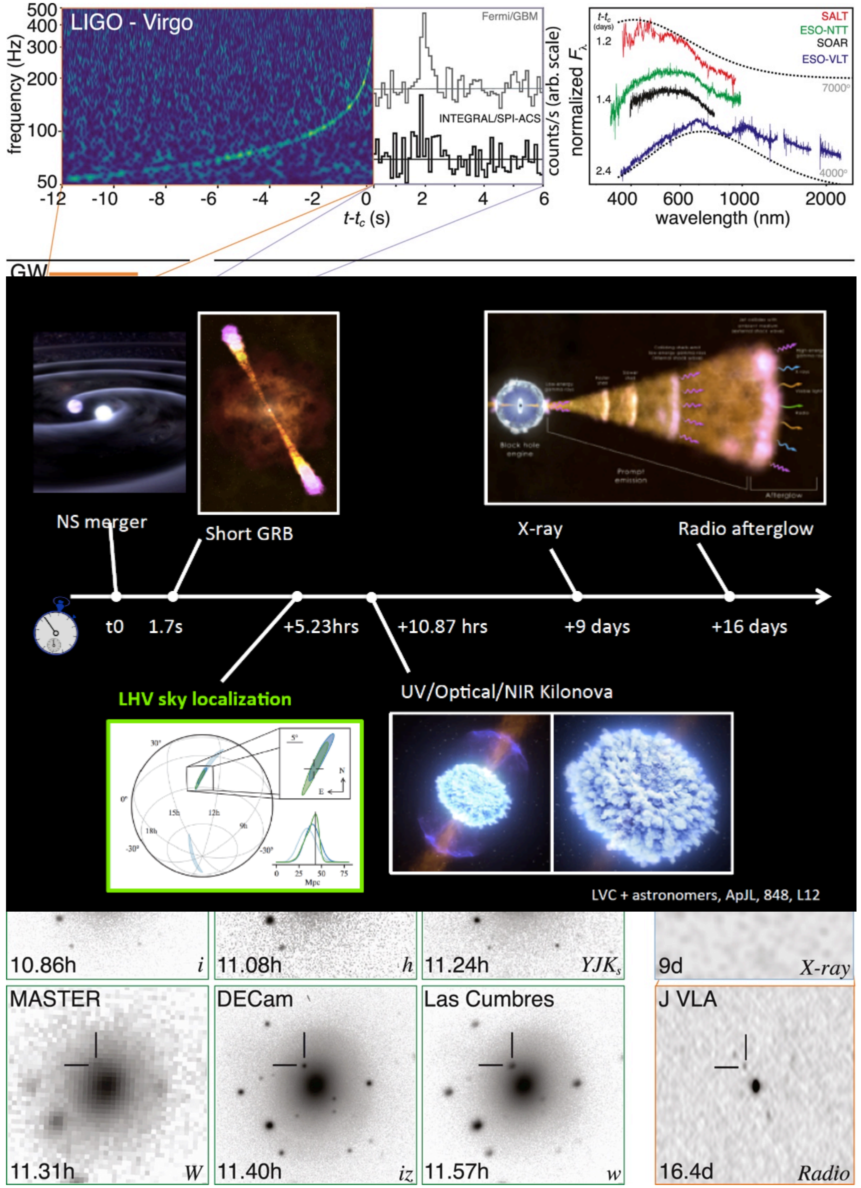
M.Punturo's talk NT 2019



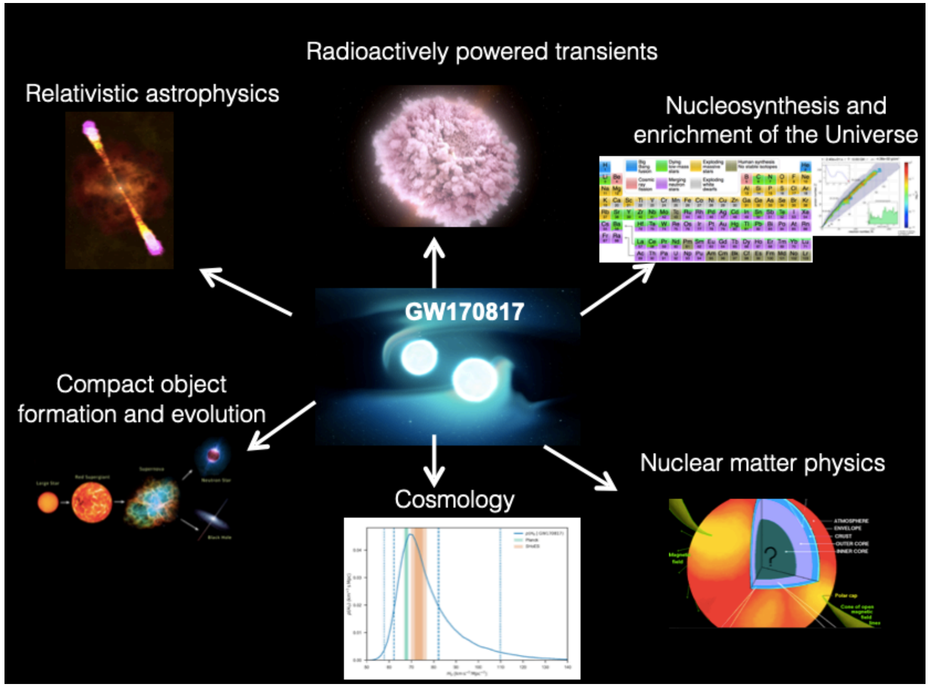
Abbott et al., ApJL., 848:L13 (2017)

GW 170817-photon connection

M. Branchesi's talk



SGRBs are explained by Kilonova and a lot of physics return!



In NGC 4993 at $D_L = 40^{8}_{-14}$ Mpc $\sim$ 130Mly $\Delta t = 1.7 \pm 0.5$ s

=> Stringent test of GW speed = to speed of light :

$$\frac{v_{GW} - c}{c} \sim \frac{c}{D_L}\Delta t \Rightarrow -3 \cdot 10^{-15} < \frac{v_{GW} - c}{c} < 7 \cdot 10^{-16}$$

For $D_{L,min} = 24$ Mpc

If sGRB emitted 10 s after GW

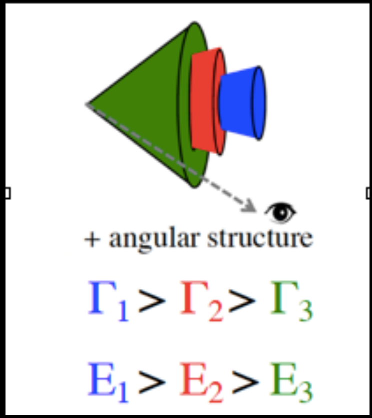
Multi-messenger observations pin down the structure of the jet!

While it is the closest of the GRBs observed by Fermi-GBM it has lower luminosity $L_{iso} \sim 3 \times 10^{47}\,\mathrm{erg/s}$ 2-6 orders of magnitude lower than all others.
Radio and X-rays 9-16 d after indicate 2 possible jet scenarios for the remnant: possible off-angle jet but in an unstructured jet scenario a luminosity decline was expected, while after 100 d the flux increased.
2 scenarios remain possible to explain the increase in the flux: a structured jet (where velocity changes with angle) or a chocked jet or cocoon.
The radio observations after 155 d of a 2.6 mas displacement of the source apparent positionsupports the structured jet scenario.

Ghirlanda et al. 2019, Science

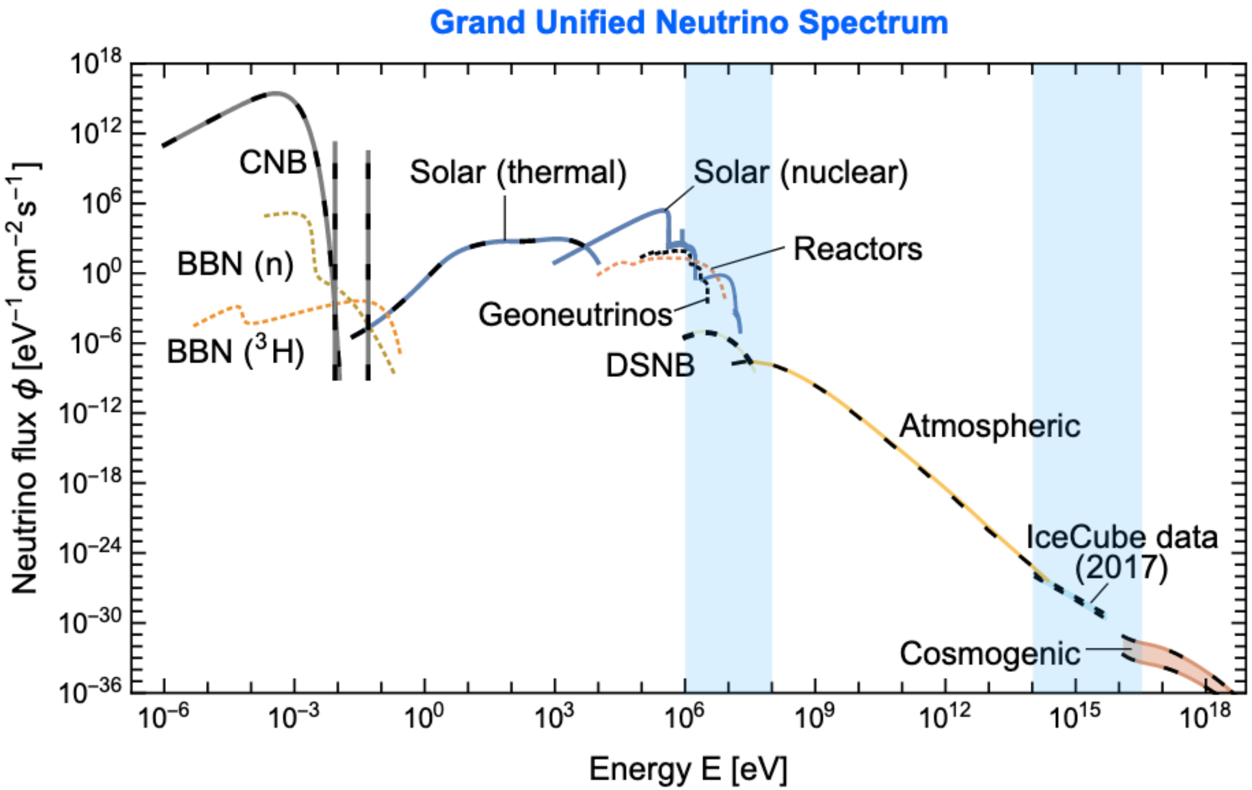
The radio observations are key to understand the jet

For GRBs and AGNs, structured jets seem to be favoured with more degrees of freedom are needed

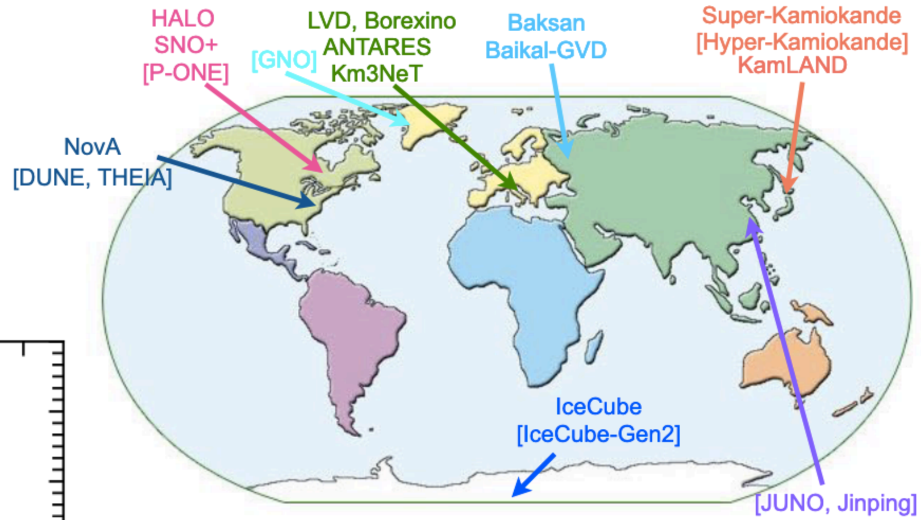


A relativistic energetic and narrowly-collimated jet successfully emerged from neutron star merger GW170817!

The Grand-Unified neutrino telescopes

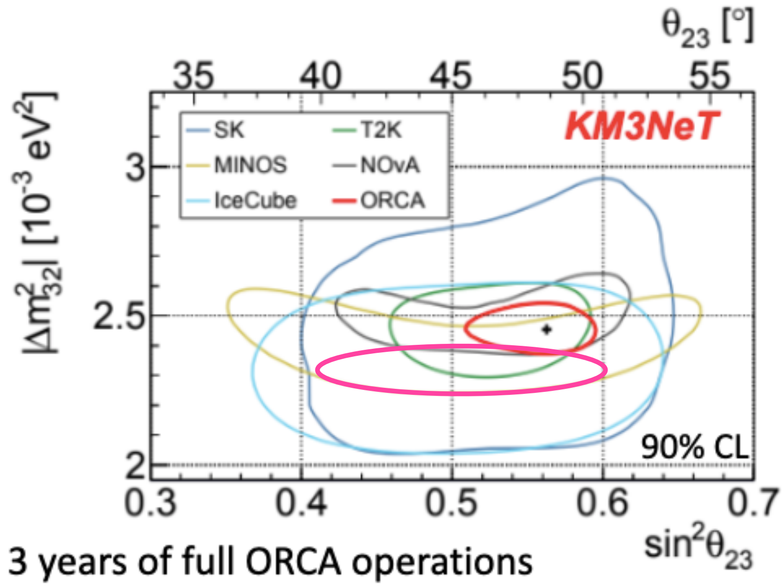


Vitagliano, Tamborra, Raffelt, Rev. Mod. Phys. (2020).



Many detectors / Big vetoed detectors

Next future prospect for atmospheric ν oscillations



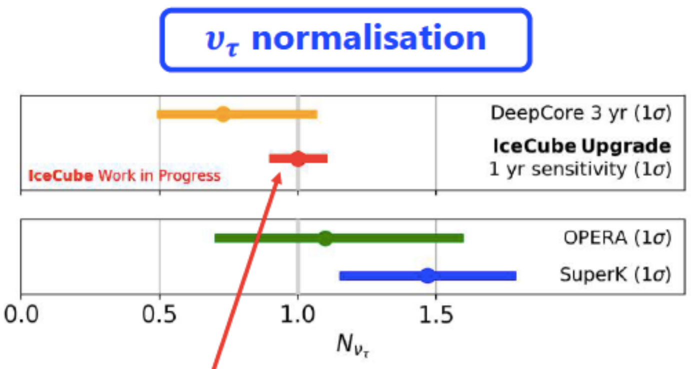
IceCube upgrade 3 yrs redrawn from T. Studdard's talk
DeepCore 2019 3 yr result best fit point assumed) different from KM3NeT

DeepCore: 2Mtons 250'000 atmospheric neutrinos (of which 11'000 ν_τ in 8 yr => IceCube Upgrade x4 vs DeepCore => 1ν/min X10 more efficient @10 GeV

6 KM3NeT/ORCA lines working since 12 months

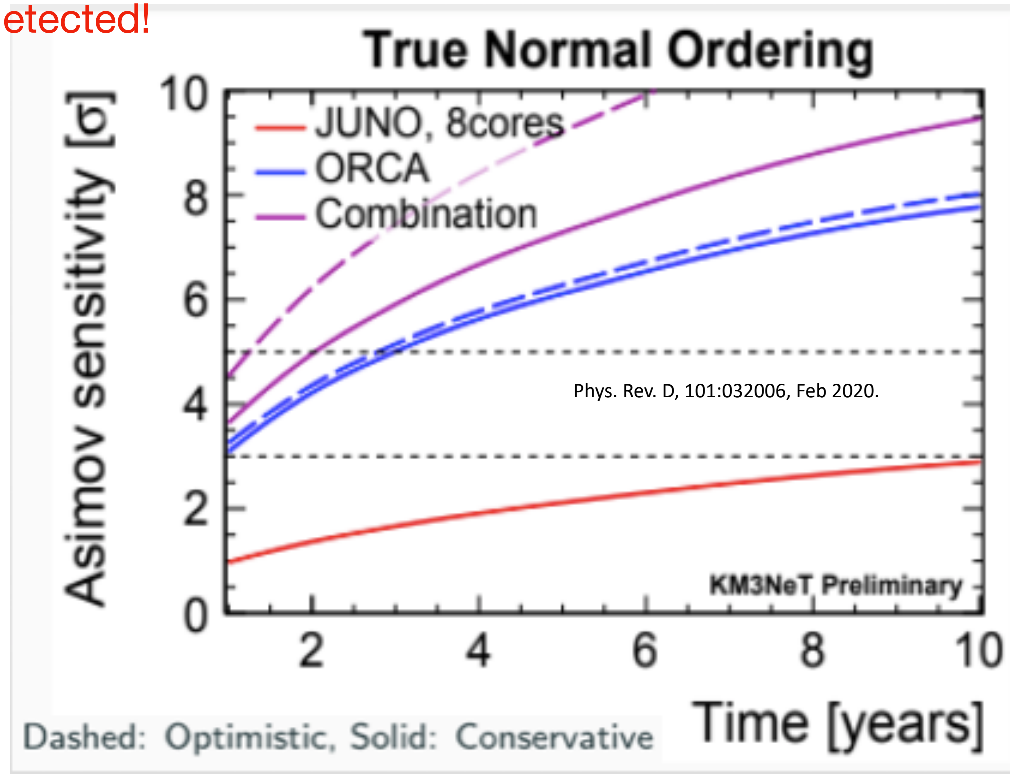
First neutrinos detected!

A. Heijboer, N. Chau



10% ν_τ norm in 1 yr (6% in 3 yrs)

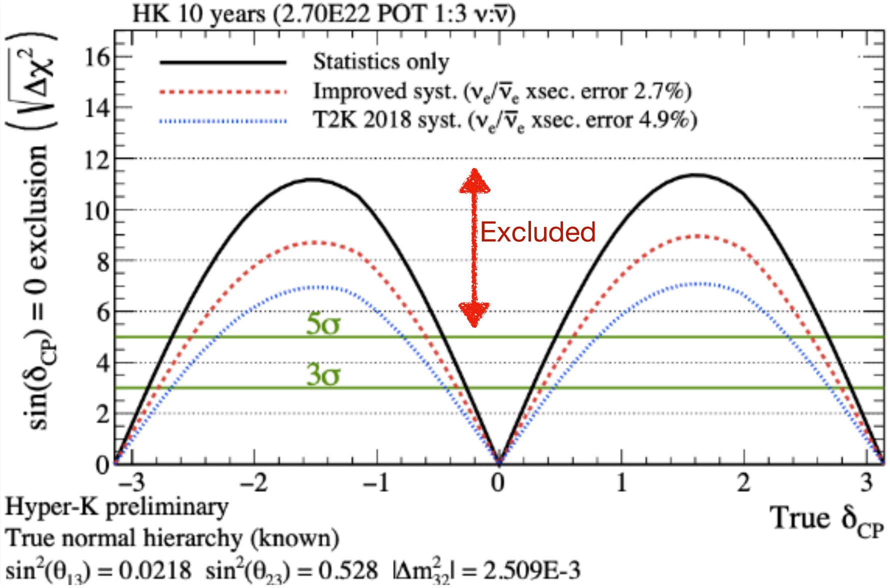
J. Lazar's talk
T. Stuttard' talk



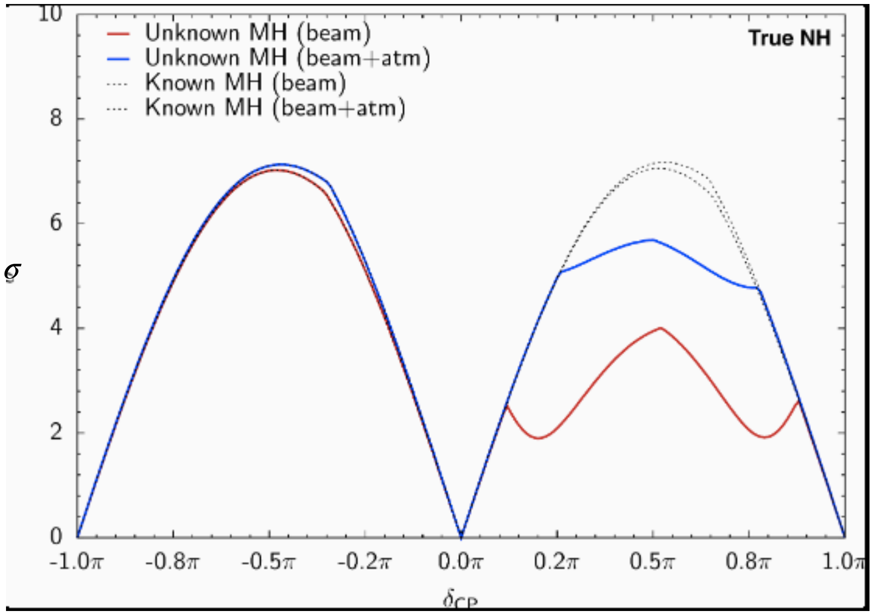
Complementary beam-atmospheric neutrinos for δ_{CP}

Is provided by difference between $\bar{\nu}_e$ and ν_e rates so statistics matters.

With longer baseline atmospheric neutrinos have good sensitivity to mass ordering (MO) and complement beam analysis in the case MO is known so to increase sensitivity above 5σ.

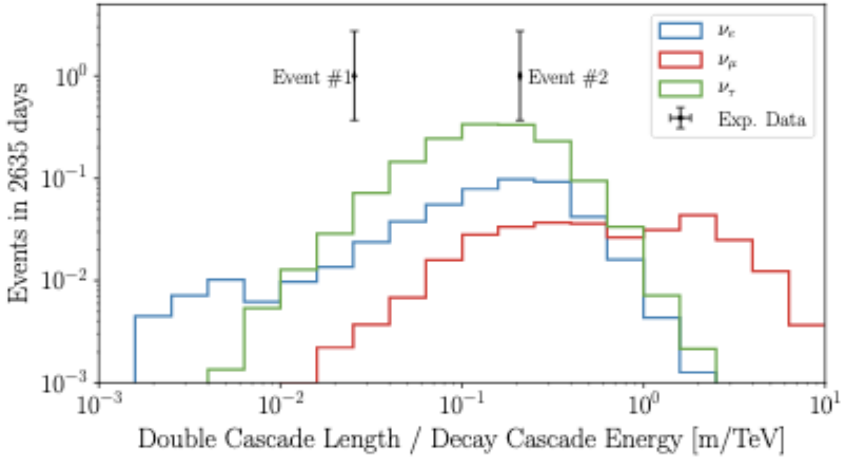


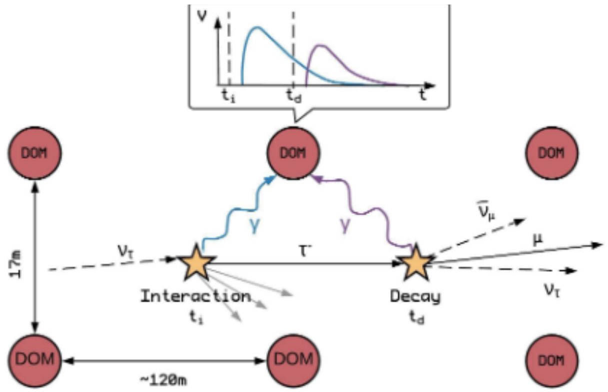
Number of σ



The flavor domain: Tau neutrinos probe new physics

No astrophysical origin of the tau neutrino flux disfavored at 2.8σ C.L.
2 events observed (**and they are what we expect!!**)

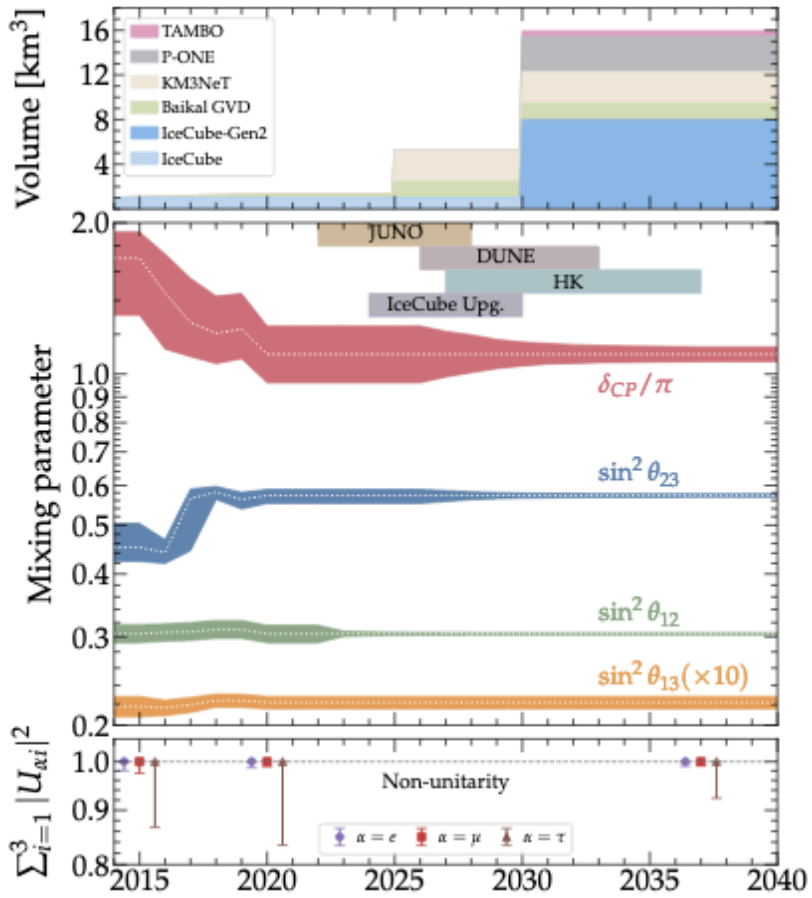




IceCube Coll. https://arxiv.org/pdf/2011.03561.pdf

Pankova & Fienberg's talk

Song et al, 20020 https://arxiv.org/pdf/2012.12893.pdf



Evidence of cosmic neutrinos neutrino oscillations from cosmic sources or non standard neutrino production in sources. By 2040 big detectors and large networks will explore oscillations of astro neutrinos.

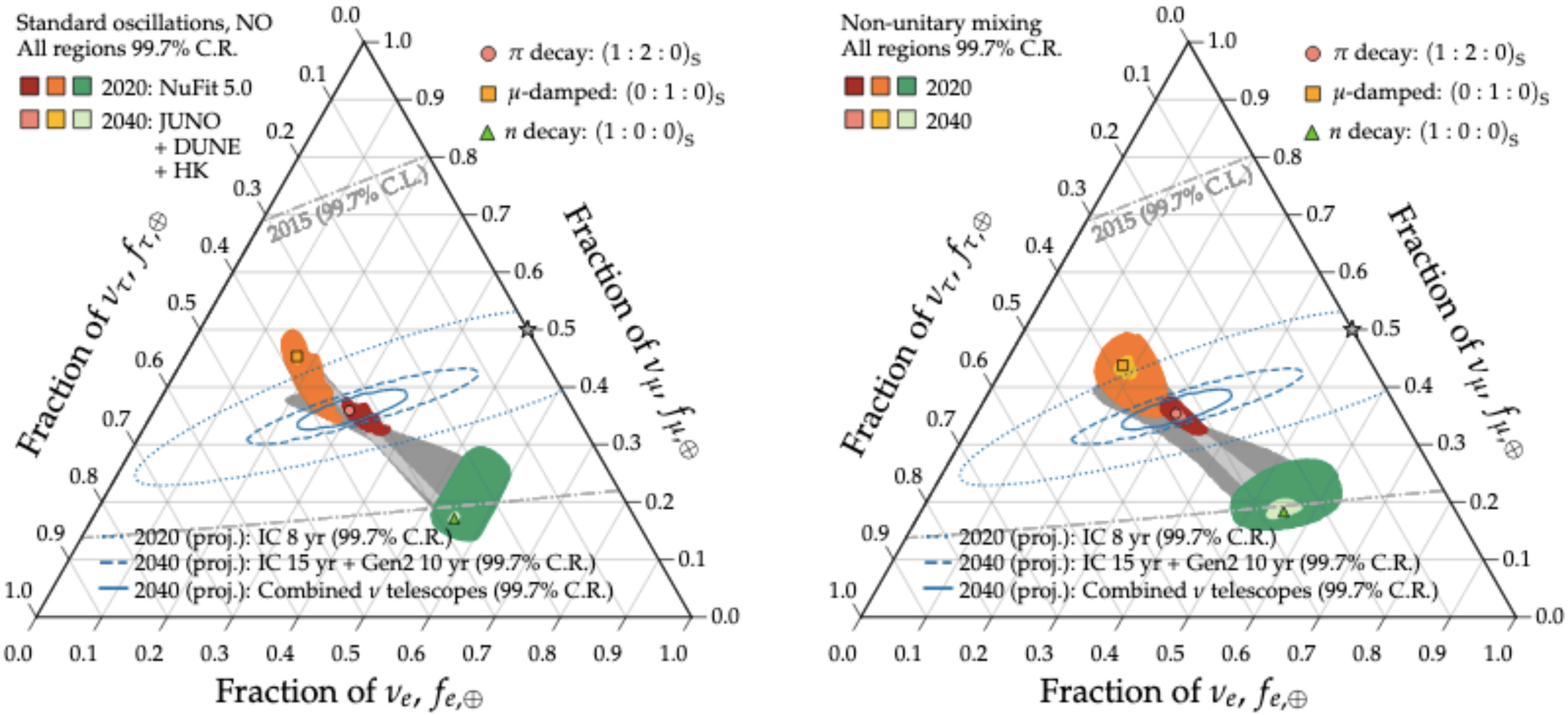
The flavor domain in the future

N. Song's talk

Song et al, 20020 https://arxiv.org/pdf/2012.12893.pdf
IceCube-Gen2: https://arxiv.org/pdf/2008.04323.pdf
N. Song et al https://arxiv.org/pdf/2012.12893.pdf

New Physics probe for processes:
In the source: sterile neutrino or non-standard tau neutrino production, dense matter new interactions, DM decays
Propagation effects: quantum decoherence, VLI, neutrino decay
Detection effects: NSI in the earth
Information in 2020 and in 2040 (with JUNE+DUNE+HK)

With Sterile neutrinos (non unitarity implies larger regions)



The Diffuse neutrino signal (or background to point source ν fluxes)

Category	$E < 60\,\mathrm{TeV}$	$E > 60\,\mathrm{TeV}$	Total
Total Events	42	60	102
Up	19	21	40
Down	23	39	62
Cascade	30	41	71
Track	10	17	27
Double Cascade	2	2	4

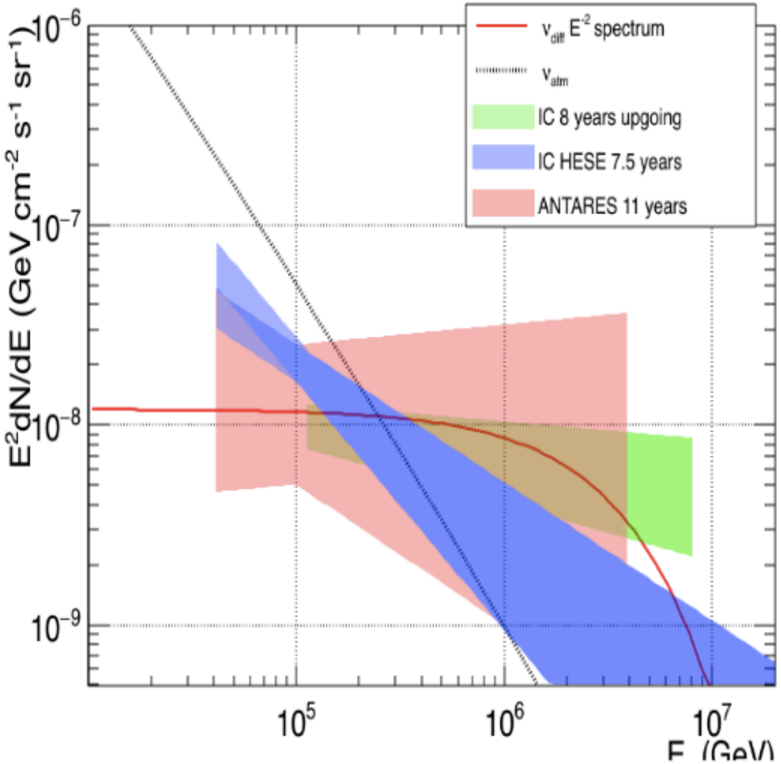
The astrophysical component dominates above 20 TeV, predominantly downgoing due to Earth absorption.

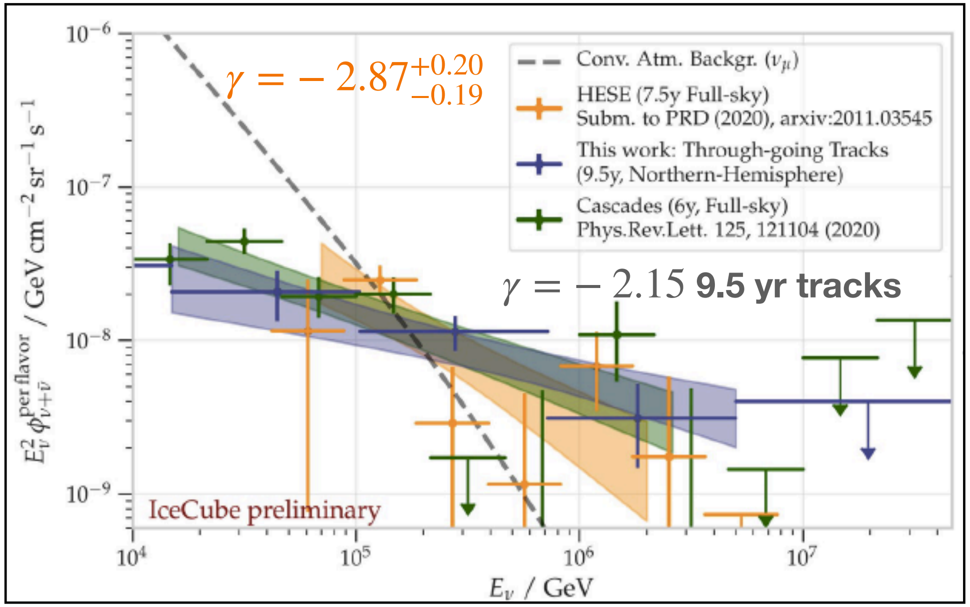
ANTARES 50 track events (36 from background)

$\gamma = -2.3 \pm 0.4$ for 11 yr !!

A. Kouchner's talk

First 2 > 100 TeV in 7 clusters of GVD!





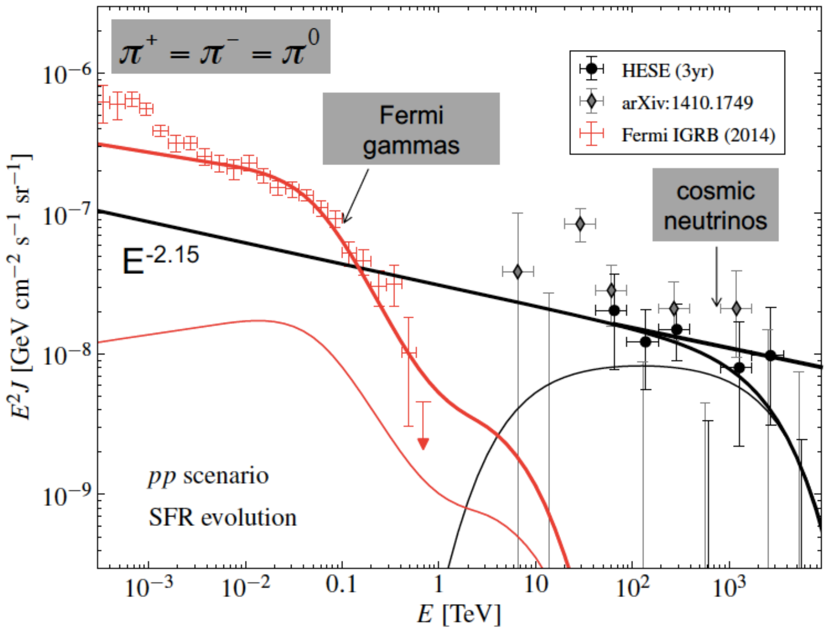
Some tension between HESE E^-2.15 with throughgoing muons. Notice error increases or softer spectra.

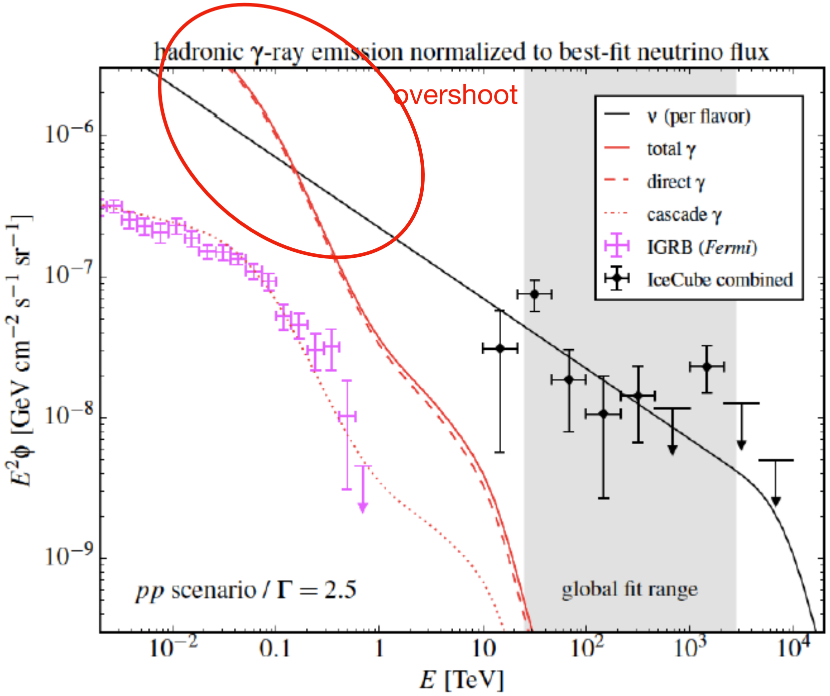
HESE 7.5 yr (N. Whitehorn's ta

https://arxiv.org/pdf/2011.03545

Energy in neutrinos and gamma-rays correspondence and opaque neutrino sources

F. Halzen's talk





Left: From diffuse IceCube flux for $E^{-2.15}$ infer gamma-rays => energy deposition in Fermi is compatible with the diffuse neutrino flux. Right: Since the HESE diffuse flux is steeper, e.g. $E^{-2.5}$ the estimated gamma-rays are more than what measured by Fermi. This means that the photons must loose energy in the source!

Connection to parent UHECRs:

Cosmic-ray Accelerators

Being a resonant effect no power low for secondary ν

$$p + \gamma \rightarrow N\pi + X$$

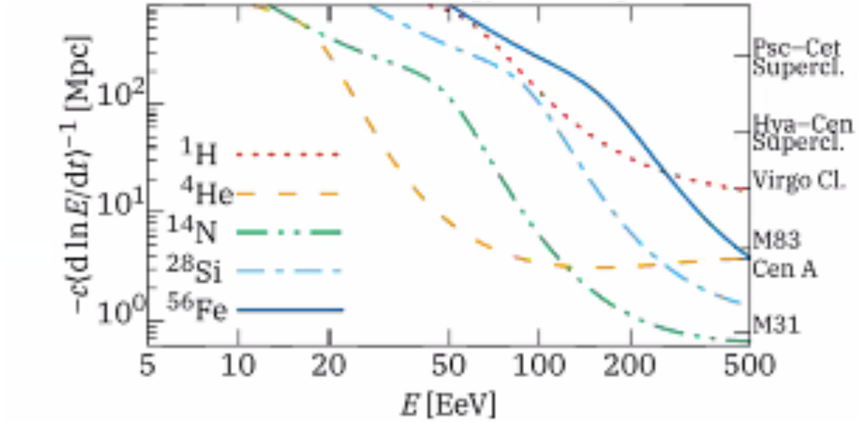
Cosmic-ray Reservoirs

$$p + p \rightarrow N\pi + X$$

Galaxy clusters (Kotera et al, 2009 Ap), K. Murase, Inoue, Nagataki 2008)
SBG consistent with PeV flux (Waxman & Loeb 2006)

UHECR anisotropies (P. Auger)

Having accounted for the UHECR horizon intermediate scale anisotropies



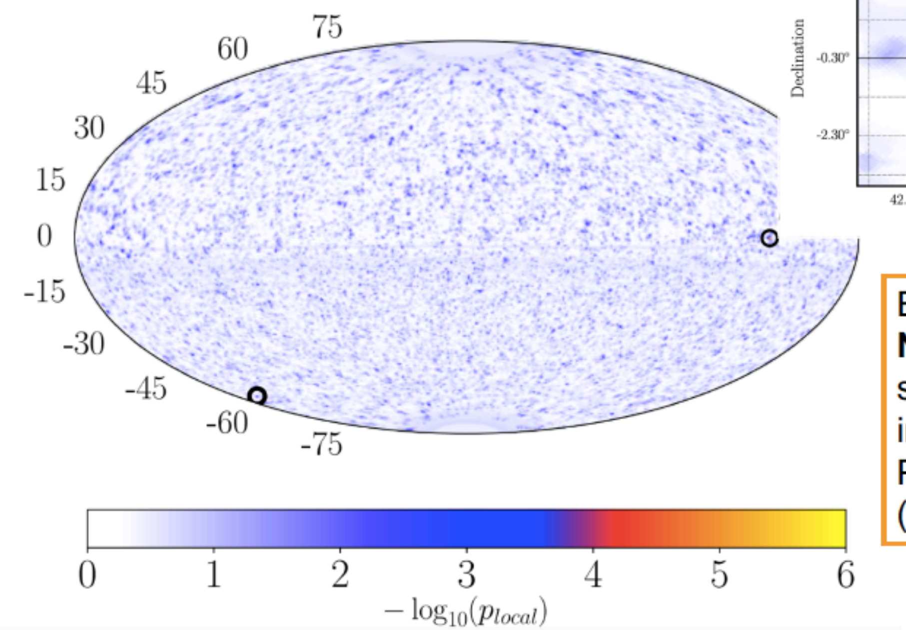
Catalog	E_{th}	θ	f_{aniso}	TS	Post-trial
Starburst	38 EeV	15^{+5}_{-4}°	11^{+5}_{-4}%	29.5	4.5 σ
γ-AGNs	39 EeV	14^{+6}_{-4}°	6^{+4}_{-3}%	17.8	3.1 σ
Swift-Bat	38 EeV	15^{+6}_{-4}°	8^{+4}_{-3}%	22.2	3.7 σ
2MRS	40 EeV	15^{+7}_{-4}°	19^{+10}_{-7}%	22.0	3.7 σ

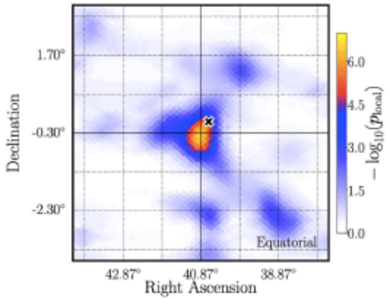
M. Unger’s talk

Time independent candidates

Tessa Carver at Neutrino Telescopes 2019

All sky analysis & **predefined source list**

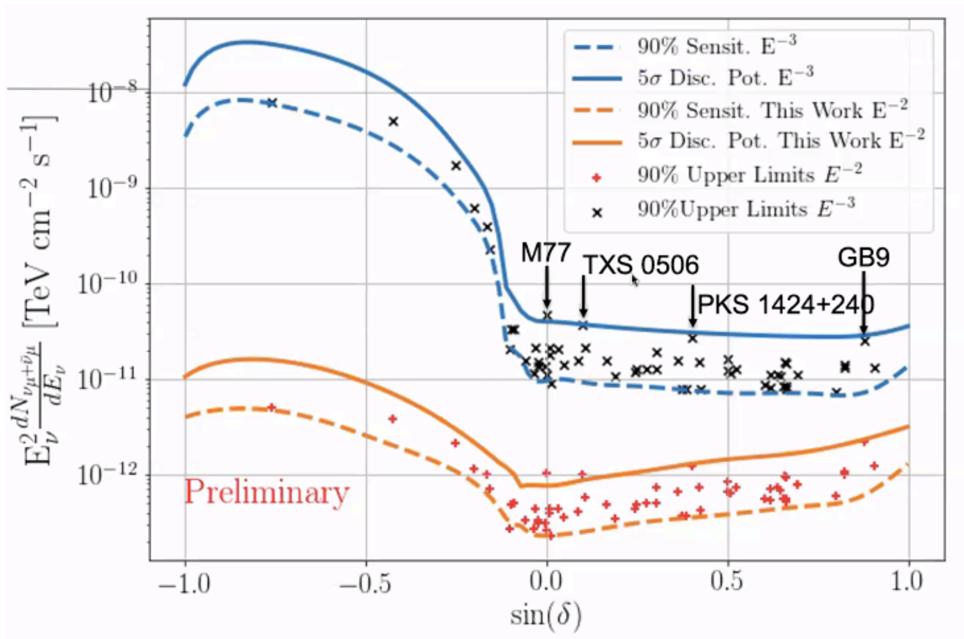




Excess close to **NGC 1068**, most significant source in predefined list: Post-trial: 2e-3 (**2.9 sigma**)

IceCube Coll. PRL 124 (2020)

- All sky hottest source: **NGC 1068** (2.9σ post-trial) from 51 soft spectrum neutrinos
- SBG models predict it as the strongest ν emitter (Loeb & Waxman 2006, Murase et al., A Ambrosone at this conference)
- Pierre Auger: (ApJ 835 2018) >39 EeV UHECR=> anisotropy 4σ post-trial from 9.7% of 23 SGB



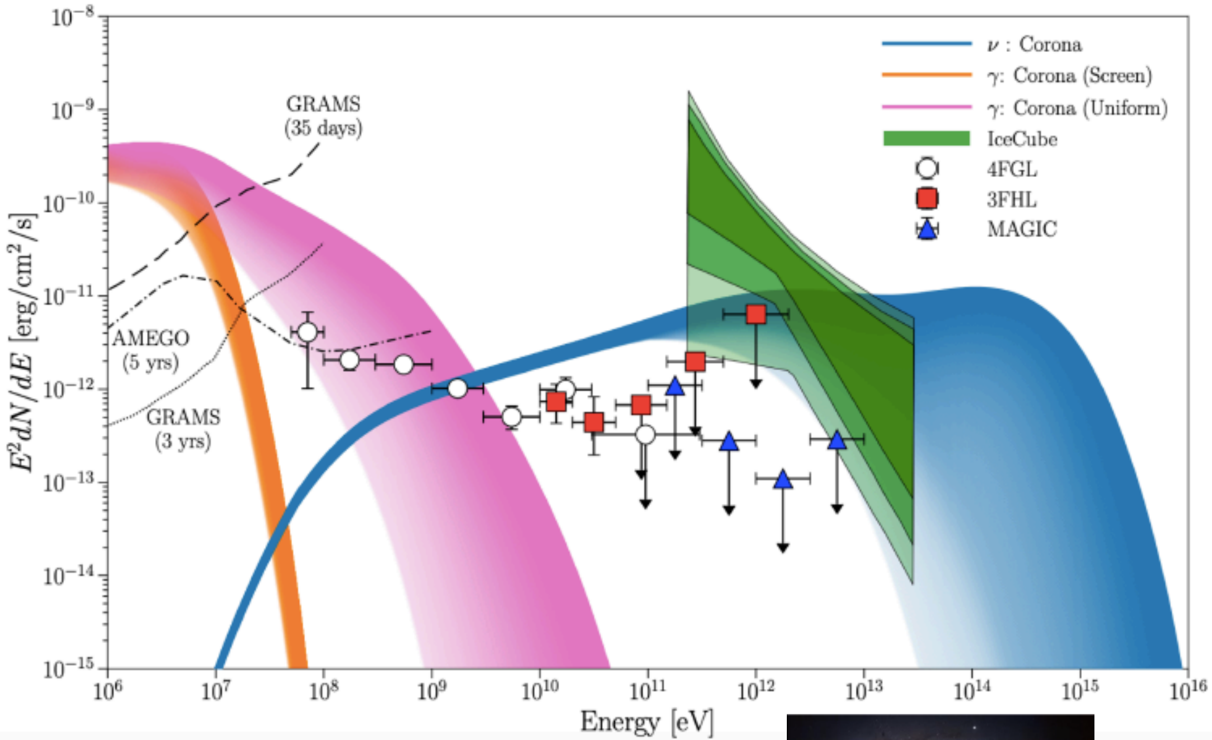
Sub-threshold population analysis for selected catalog of 110 sources: extragalactic sources with highest flux/sensitivity ratio Fermi-LAT 4FGL (FSRQ + BL Lacs + 8 starburst galaxies) + galactic sources from TeVCat and gamma cut with flux > 50% IceCube's sensitivity => 3.3σ due to 4 sources

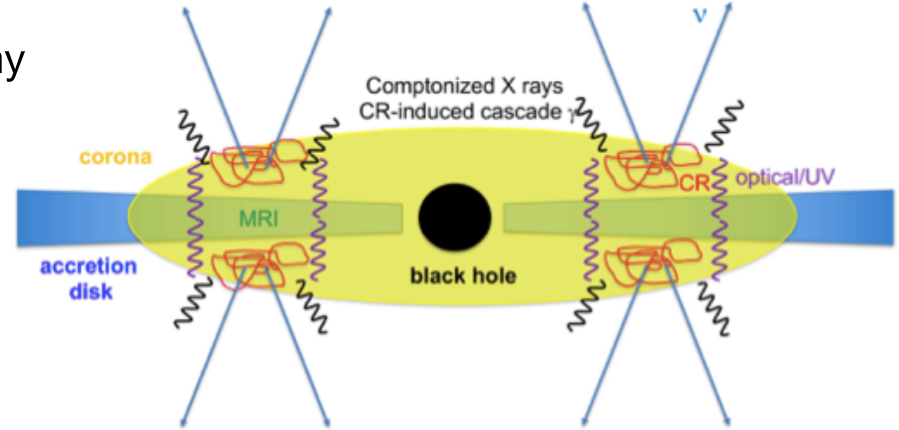
https://icecube.wisc.edu/science/data-releases/
https://arxiv.org/abs/2101.09836

Breaking the paradigma of transparent sources: AGN corona models

Dark sources or beam dumps are at the roots of neutrino astronomy

Murase, Kimura, Meszaros 2020, Inoue et al. ApJL 891 (2020)

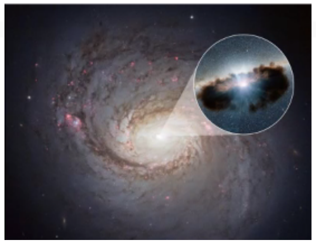




$$\tau \approx \frac{\sigma_{\gamma\gamma}}{4\pi c}\epsilon_X^{-1} L_X R^{-1} \simeq 10^5 \left(\frac{\epsilon_X}{1\ \mathrm{keV}}\right)^{-1} \frac{L_X}{L_{\mathrm{Edd}}} \frac{R_s}{R}$$

NGC 1068: tthe neutrino emission can be produced only in the vicinity of the supermassive black hole in the center of the galaxy, namely in the **corona, an optically thick environment.**

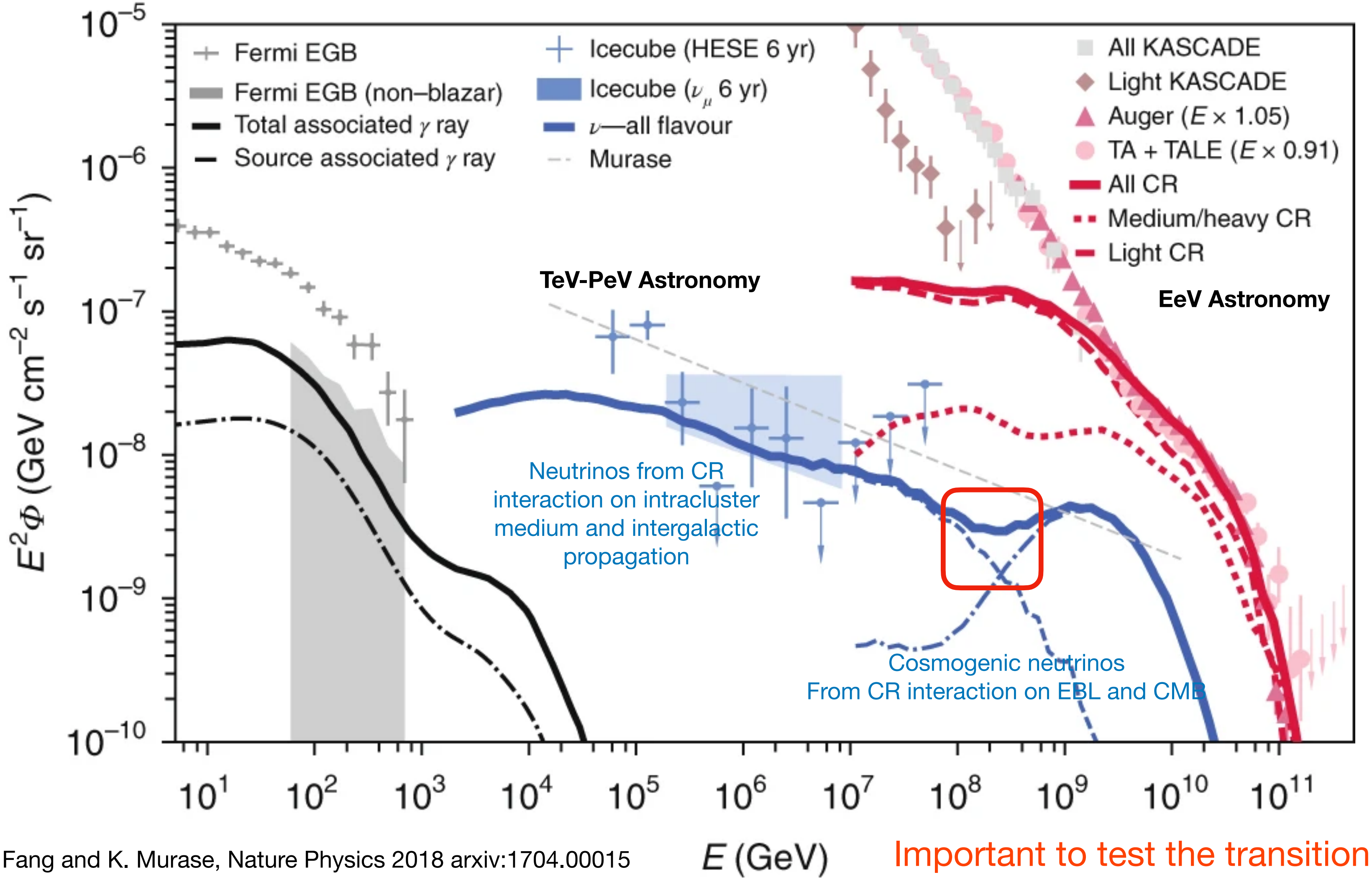
A large optical depth of gamma rays requires the presence of a **compact and dense** X-ray target of keV photons (it depends on the size of the emitting region in units of Schwarzchild radius $R_S = \dfrac{2GM}{c^2}$ and on the X-ray luminosity)



A. Kheirandish talk'
M. Petropolou's talk

Grand - Unified Multi-Messenger picture

Jets of AGNs in galaxy clusters with high radio loud of kpc-scale AGNs (lobe dominated) explain global observations. Normalization provided by Auger and IceCube measurements => compatible with Fermi extragalactic background from gamma-rays cascading down and escaping transparent sources

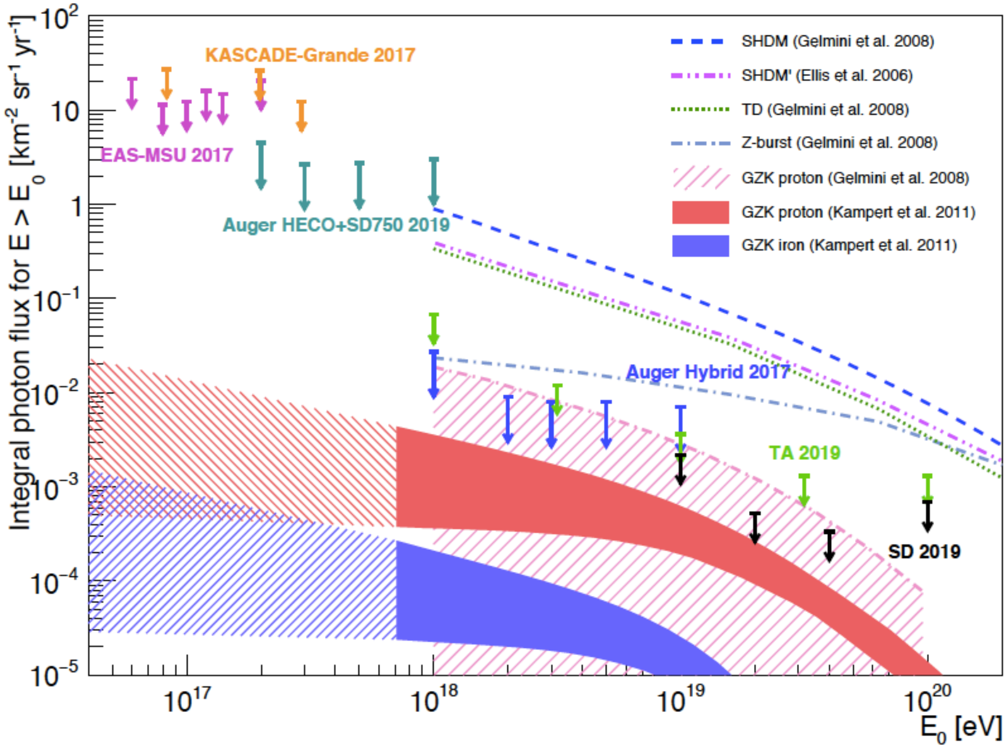


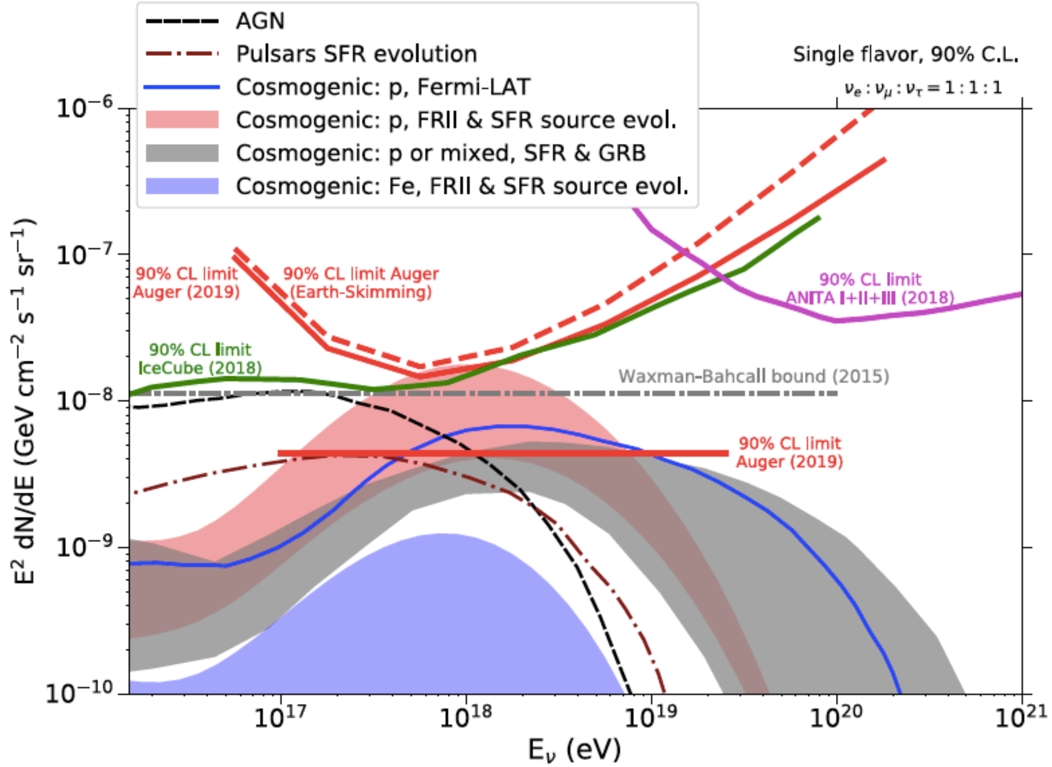
K. Fang and K. Murase, Nature Physics 2018 arxiv:1704.00015

Important to test the transition from PeV neutrinos to EHE!!

EeV astronomy:
Large detectors with vetoes (radio antennas, EAS), eg IceCube-Gen2,
or
Network of m**any** detectors: Network (TAMBO x20 IceCube by 2040) of all existing neutrino telescopes (IceCube, GVD, KM3NeT, P-ONE, GRAND, other radio detectors)(see talks at this conference)

Next to come…cosmogenic photons and neutrinos





Cosmogenic fluxes lower for mixed composition of UHECR and depend on the galactic-extragalactic transition

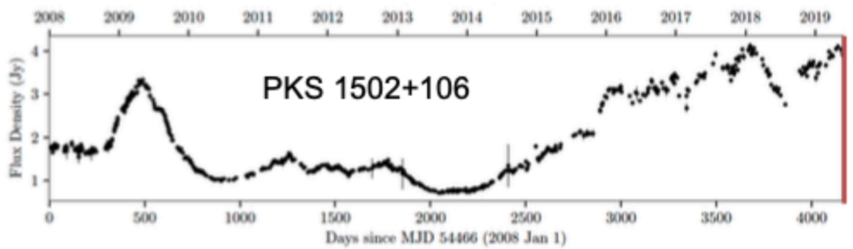
V. Scherini's talk

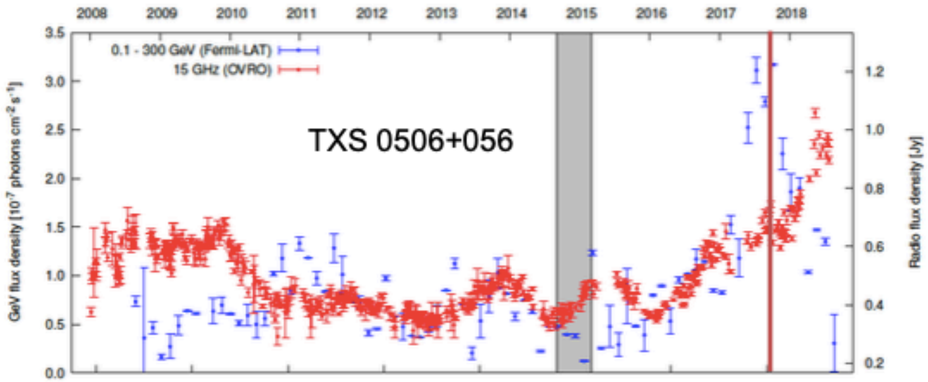
J. Rautenberg and F. Pedreira for P. Auger Collaboration ICRC 201

Time dependent candidates: Some suspect jetted candidates…

- F. Halzen: some percent of flaring blazers in coincidence with radio flares TXS 0506+056 sources would explain the HESE flux

the two highest energy (300 TeV ν_μ) IceCube neutrino alerts are coincident with radio flares (see also 2001.00930 [astro-ph.HE])

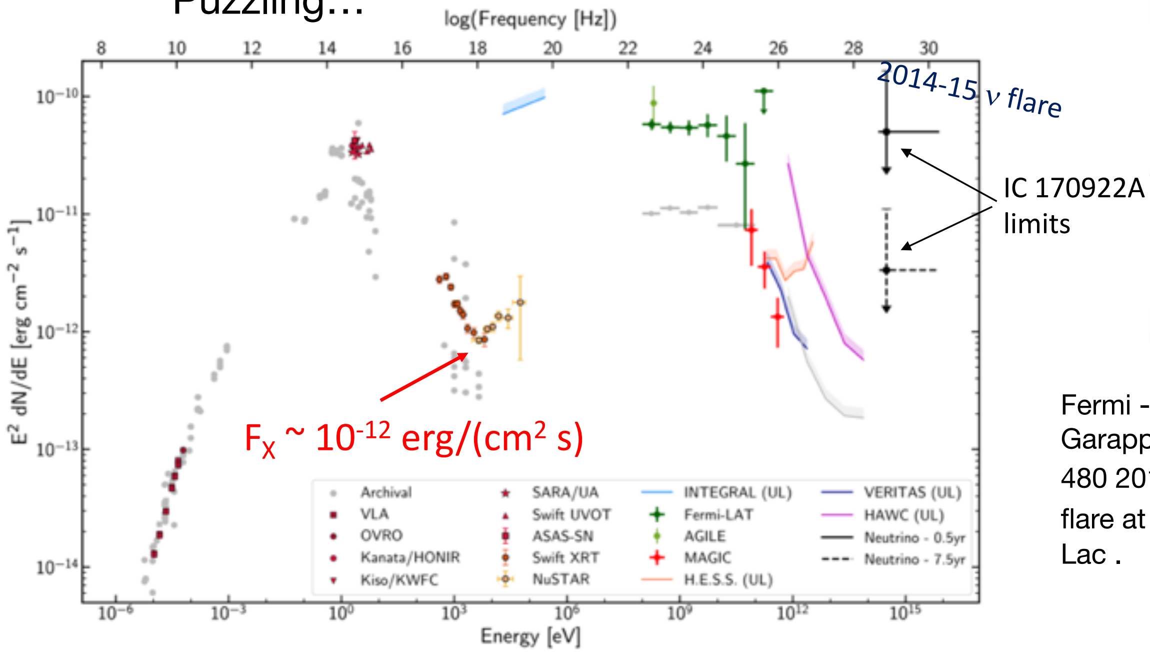


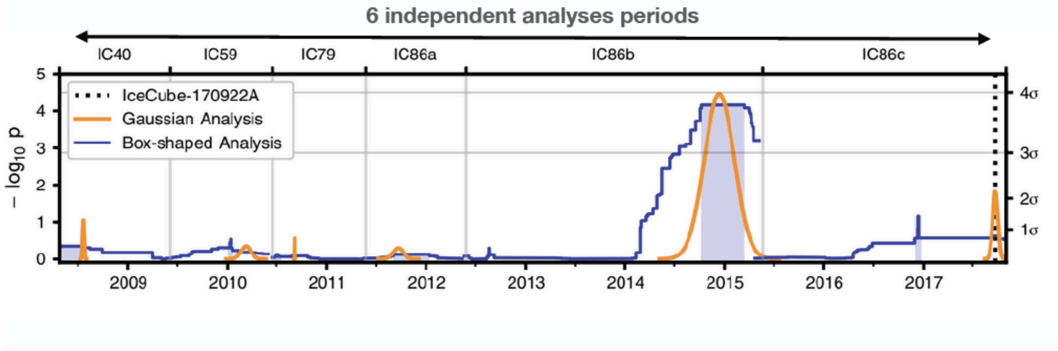


- A. Franckowiack & C. Lunardini's talk: 26% of the flux could be due to TDE (astro-ph:2005.05340). IC191001 coincident with TDE AT2019dsg (230 Mpc) seen 150 d after the ν.
- AT201dsg has highest X-ray luminosity of 4 TDE with X-ray emission exhibits also a mildly relativistic radio flow.
- The jet could form after accretion of stellar disrupted mass by the BH.
- 1 more neutrino after a year (IC200530A) + a new flare from a Seyfert I galaxy in coincidence with it. Neutrino energy is x 10 Black Body luminosity of the TDE
- The efficiency of pion production in p-γ depends on R_C^{-2}: a decreasing distance of the collision region results in higher efficiency $R_C = 2\Gamma^2 t$ (variability). A delay can be realised between the X-ray emission and the neutrino one.
- Model in https://www.nature.com/articles/s41550-021-01305-3

The SED of TXS 0506+056 in photons and neutrinos

Puzzling…





Fermi -LAT 300 MeV-1TeV
Garappa et al 2019: a low state in Fermi data but Padovani et al. MNRAS 480 2019 claimed a harder HE γray spectrum than during the 2017 γ-ray flare at 2σ level and advocate it is a FSRQ incorrectly classified as a BL Lac .

llaria Viale's talk on MAGIC follow ups

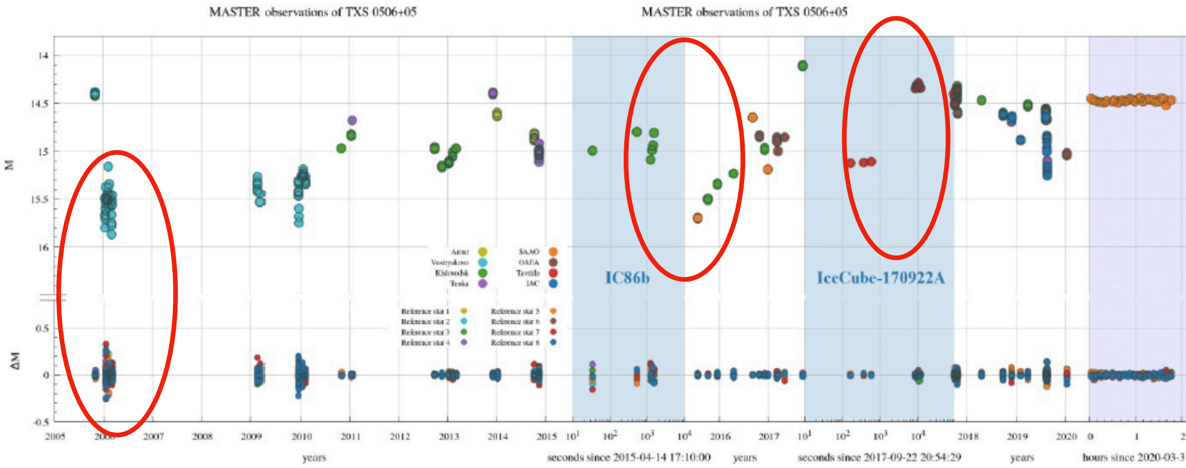
- The source during the flares is a **beam dump** or **opaque source** or **hidden source** not a BL Lac! At the maximum of their neutrino emitting efficiency, an **atypical blazar** may not be an efficient gamma-emitter.

- If few % of Fermi blazars are atypical dark flare emiters, such as TXS 0506+056, opaque to gamna-rays but efficient neutrino emitters ($\tau_{\gamma-\gamma} >> \tau_{p-\gamma} > 0.4$ - opacity of source to protons) they can explain the IceCube diffuse flux (F. Halzen's tale, A. Franckowiack's talk).

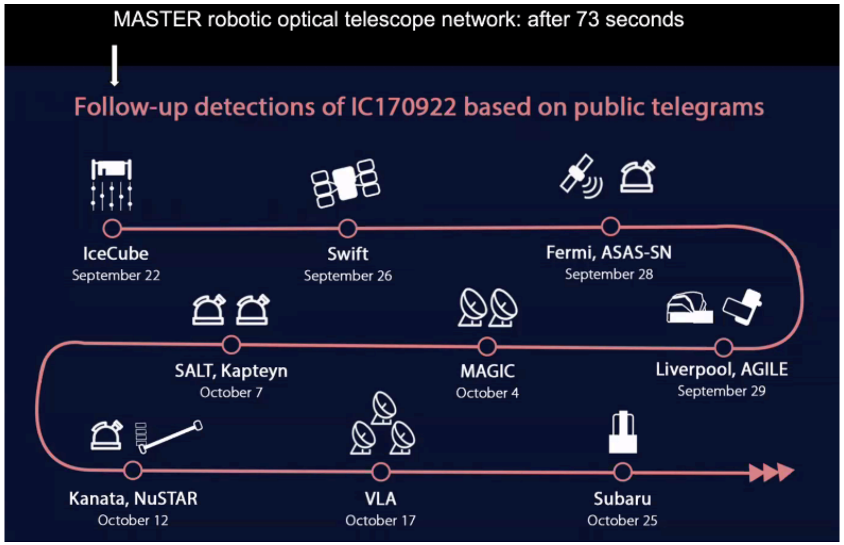
Interestingly…variability matters!

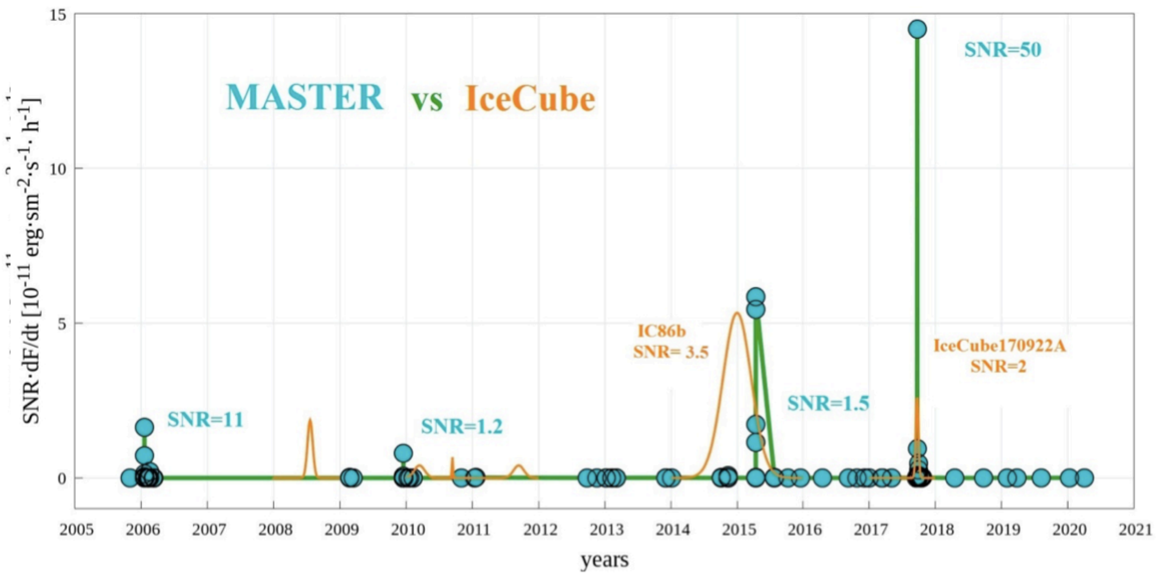
Lipunov et al. 2020, https://arxiv.org/pdf/2006.04918.pdf

3 high variability episodes (up to hour scale) : in 2006 (IceCube had 1 string), Apr. 2015 (IceCube flare 9/2014-3/2015) and 9/2017

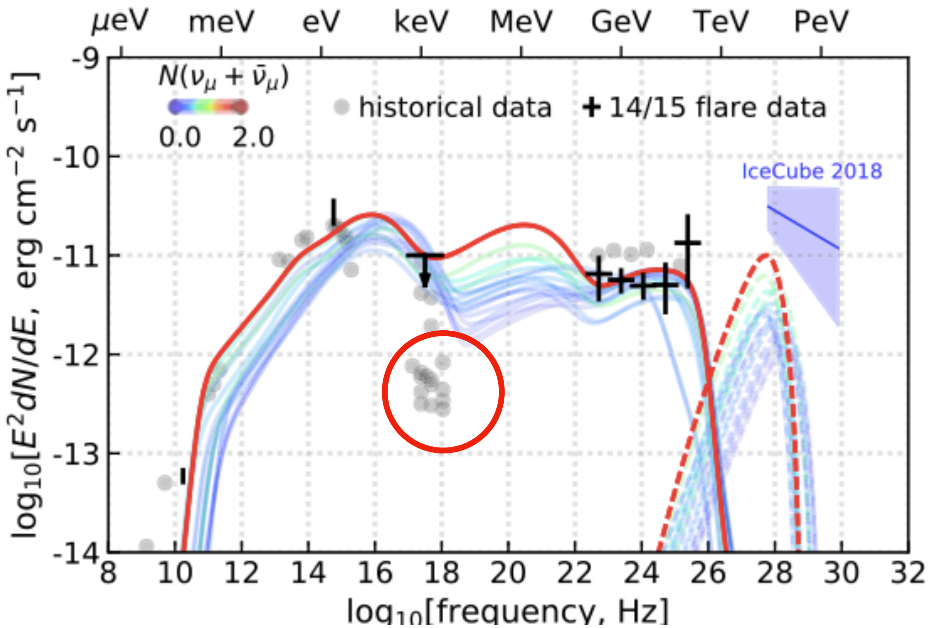


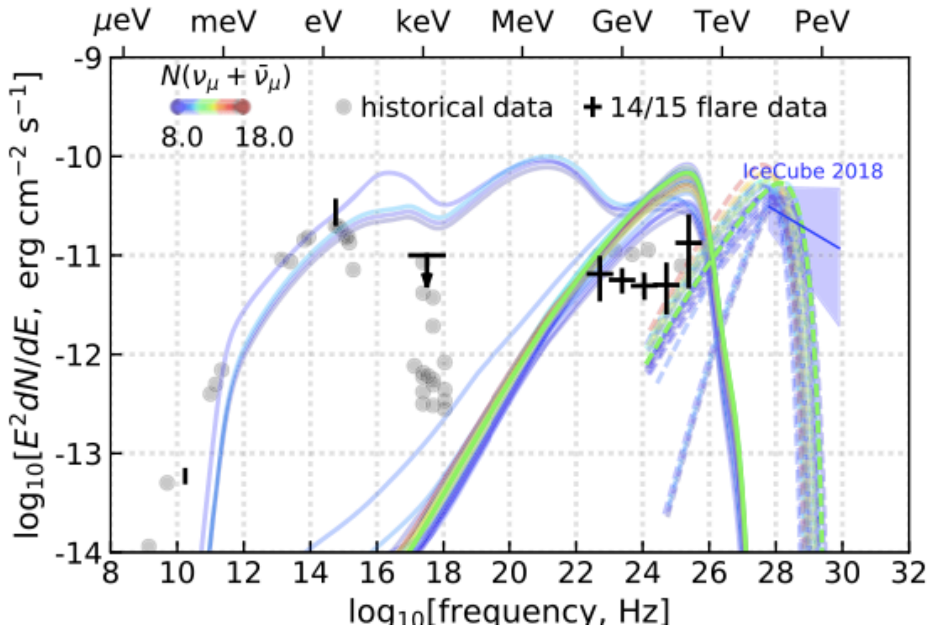
MASTER found the TXS 0506+056 in a quiet state 73 s after the IceCube 2017 event, but 2 hr after increase of optical flux at 50σ level (biggest variation since 2005!





Puzzling…not explained by single-zone models





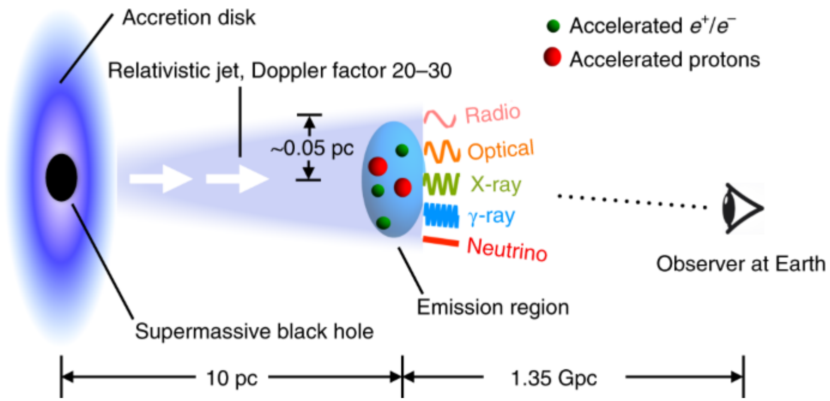
The 2014/15 ν flare poses problems to single-zone models:

- **Purely leptonic models** provide good fits but **cannot explain** νs

-**Hadronic models:** photons from π^0 and neutrinos from $\pi^\pm$

Left) if MWL data are considered, the SED cannot explain the observed high flux in the 2014/15 flare.

Right) if the parameters are tuned to fit theIceCube data, the X-ray flux at ~10^{-11-12} erg cm^{-2} s^{-1} is overshoot since an efficient em cascade and electron synchrotron emission is not preventable.



Rodrigues et al. ApJL 874 2019, A. Reimer et al. ApJ 881 2019,
F. Halzen et al. ApJL 874 2019 A. Frankowiack's talk

Gao et al. Nature Nov. 2018

Keivani et al. Nature Nov. 2018

Atypical blazar with structured jets or collisions with stars?

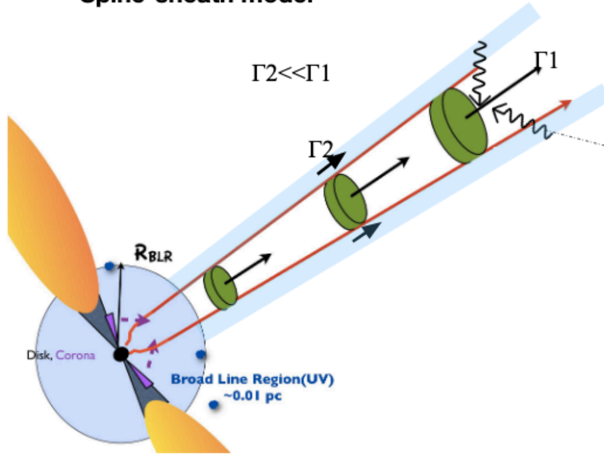
Models inferred from radio observations

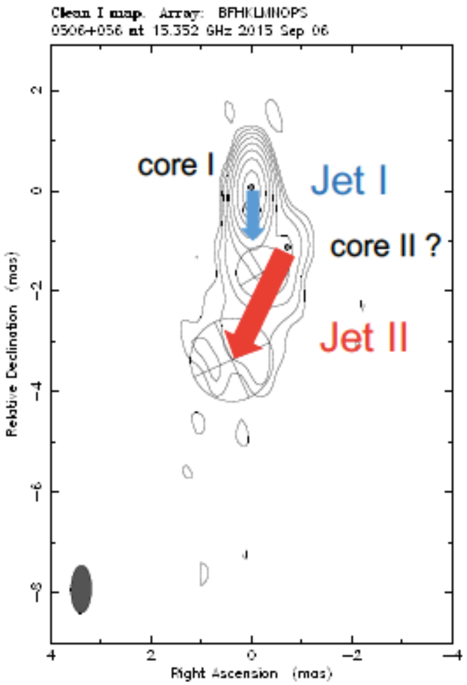
Britzen et al. A&A 630 (2019) and errata: evidence in VLBA 15 GHz observations from 2009-18 of strongly curved jet leading to 2 scenario interpretation for 2014-15 ν flare:

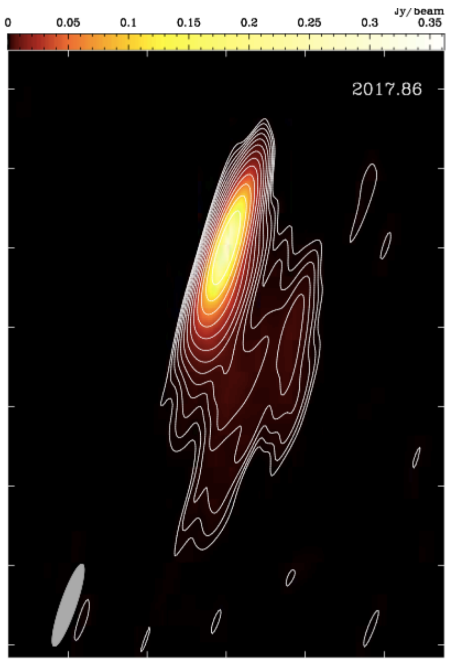
1) **precessing single jet** with 10 yr period, causing changes of speed and direction. 2017 falls in the bright precession phase.
2) **Cosmic collider!** collision of 2 jets: the spike could be the jet of another potential BH. Neutrinos could be produced in such colliding material.

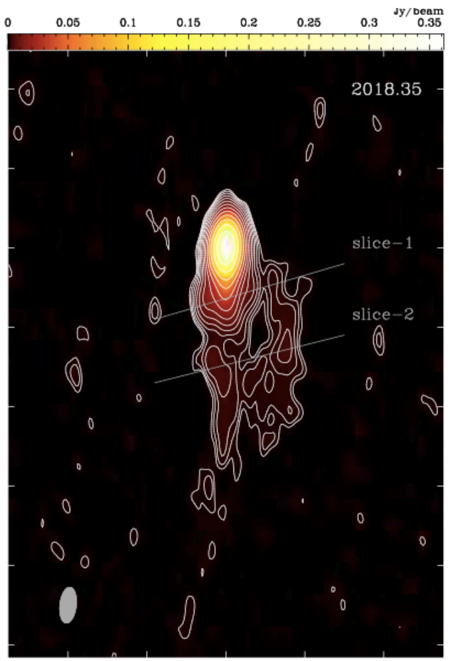
Ros et al A&A 633, 2020:
Nov. 2017 and May 2018 mm-VLBI radio 43 GHz observations indicate a compact core with highly collimated jet and a downstream jet showing a wider opening angle (slower) external sheat (loss of collimation of the jet beyond 0.5 mas). The slower flow serves as seed photons for $p-\gamma$ interactions producing neutrinos.

Structured jets
Spine-sheath model









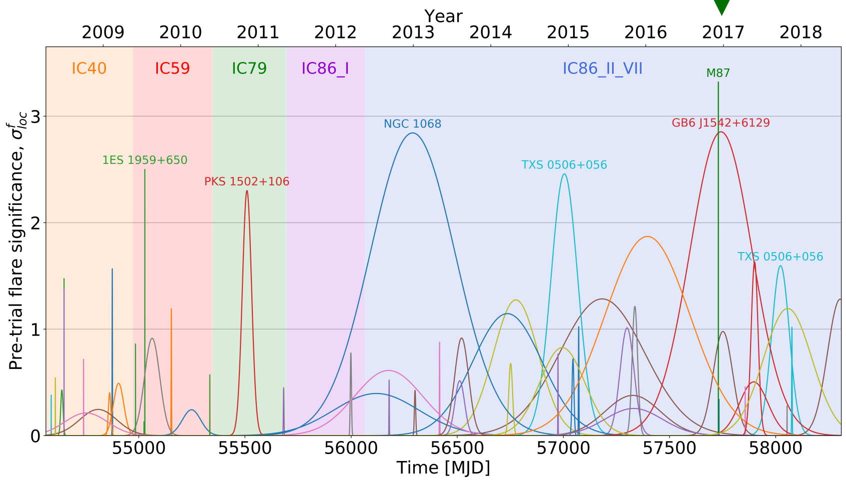
Spine-sheat models: predict large neutrino fluxes and compatible X-ray fluxes require:

- structured jets (spine-sheat Ghisellini, Tavecchio, Chiaberge 2015, Sikora, Rukowski, Begelman. 2015; Murase, Oikonomou, Petropoulou 2018). 2x model.

- stars in the jet?

Another interesting flaring hint

3 TeV neutrino events in ~15 min on 57730 from the region including M87
make it the hottest source but significance is marginal

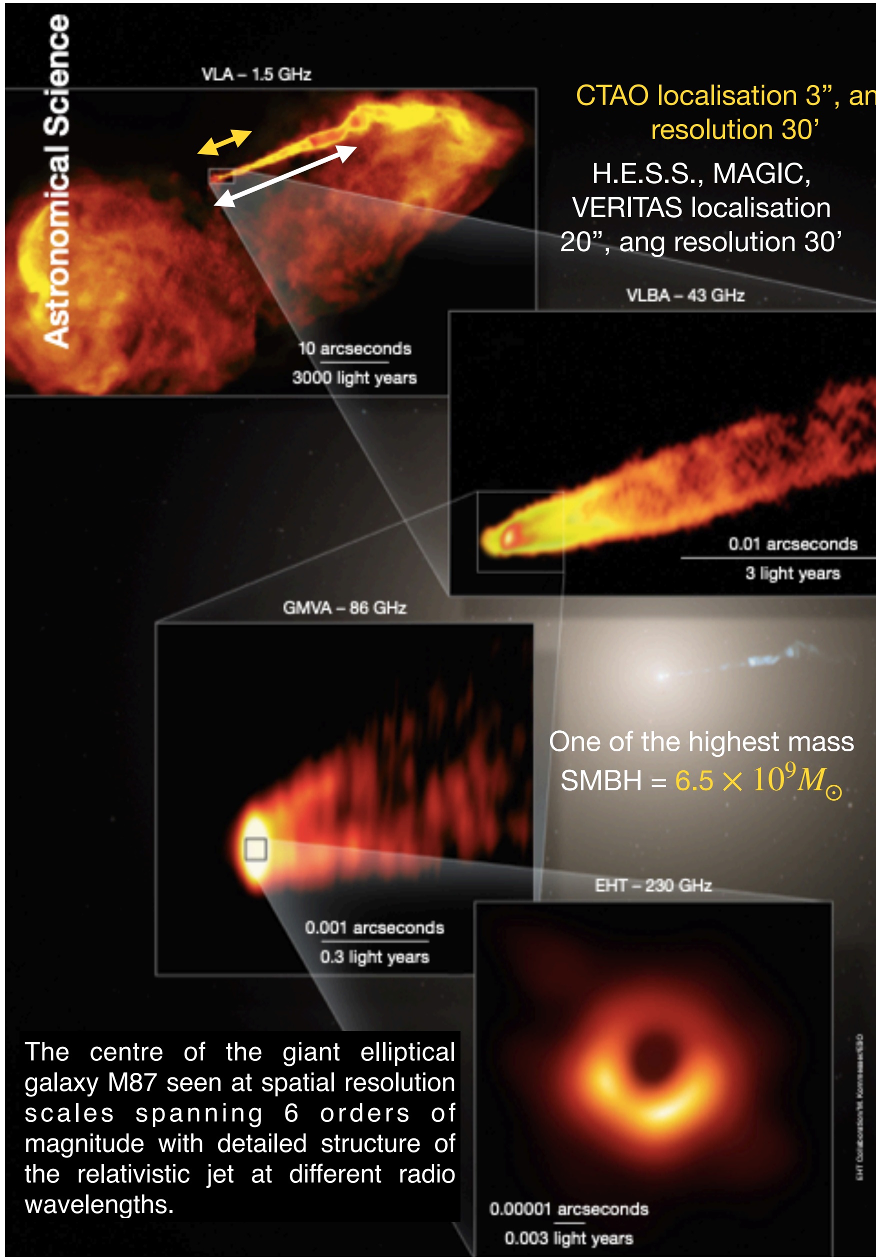


2 Tests: variability of the 110 sources in the catalogue and time-dependent population study which derives 3σ post-trial with main significance from M87 (1.7σ), confirms TXS 0506+056 2 flares.

Largest close by BH: $\sim 10^9 M_\odot$, jet with superluminal motion to 6c, 2d variability measured by H.E.S.S:
Also a structured jet (https://www.nature.com/articles/252661b0), spine - sheat model by Tavecchio & Ghisellini, 2018, 2005

CTAO will have an excellent sensitivity to short flares of minute-day-scale

F. Lucarelli's presentation



Multi-TeV-PeV gamma-ray astronomy

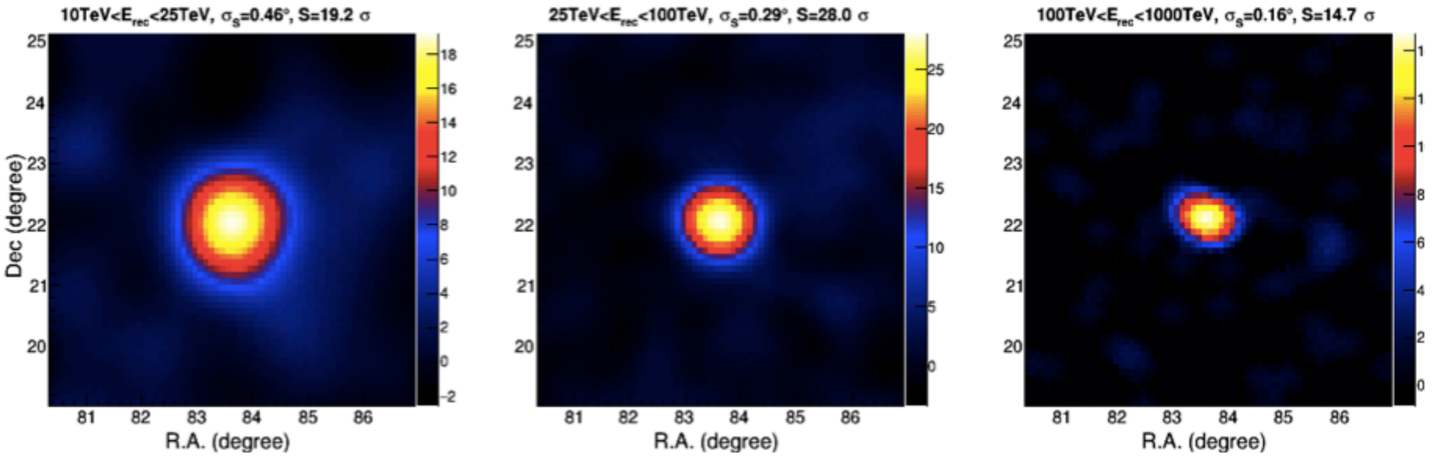
F. Aharonian's presentation

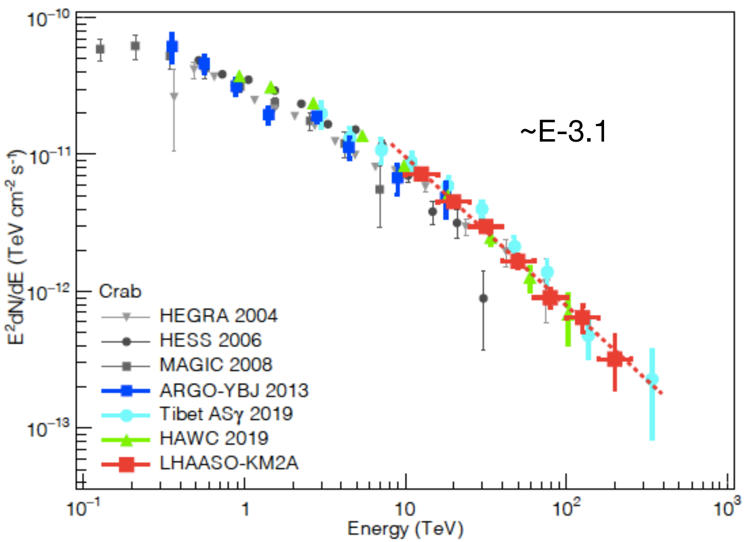
CTAO: the precision era of gamma-ray astronomy

Discovering the PeVatrons the new generation is already active and taking data: LHAASO

- Up to March 2020
- Crab 77 σ (E>1 TeV) by WCDA-1
- Pointing error <0.1°

Crab Nebula image from the KM2A of LHAASO





https://arxiv.org/abs/2010.06205

Crab Nebula a clear PeVatron with secondary gammas > 100 TeV (also HAWC and Tibet ASγ with no cut -off above 400 TeV indicating that primary electrons can reach above 0.1 PeV

LHAASO Collaboration, https://arxiv.org/pdf/2010.06205.pdf

Data share is happening!

- Lots of alerts from different messengers
- Major data samples are released and being analysed by independent scientists! Still far from the Fermi data model but already fostering the field
- Many analysis software open and licensed
- Next challenges : find a unified analysis approach! With respect to real telescopes Neutrino Telescopes, IACTs, EAS build up source images from probability densities of filtered events => time-dependent pixelized maps!

https://www.gw-openscience.org/catalog/

https://icecube.wisc.edu/science/data-releases

https://antares.in2p3.fr/publicdata.html

http://www.auger.org/opendata

http://opendata.magic.pic.es/

And many more!!

Multi-messenger stars!

- Thanks Mauro, Elisa, for maintaining this brilliant platform alive after Milla and even virtually! if the field grows like this Neutrino Telescope 2023 will be 2 weeks long and 10’000 people !

- Thanks Francis and Barry! Life of young scientists can be illuminated by more senior inspiring scientists! I wish to the young promising scientists that presented beautiful flash talks to find your stars!