Multi-Messenger High-Energy Results

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UNIVERSITÉ DE GENÈVE

γ 2022
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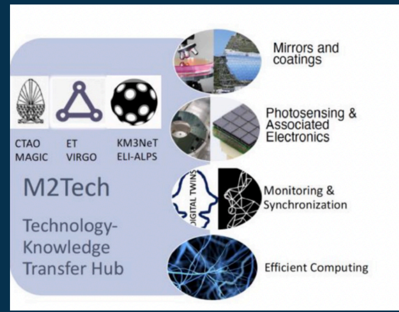
High Energy Gamma-Ray Astronomy
Barcelona, July 4-8 2022

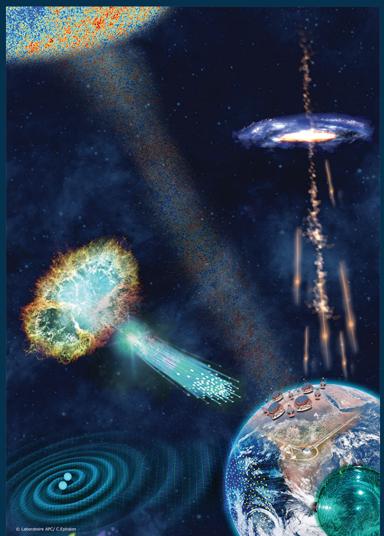
Cr. Akihiro Ikeshita

Contents

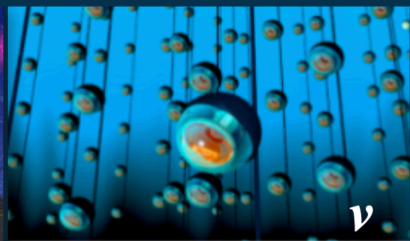
M2TeCH CTAO, ET, MAGIC, Virgo, KM3NeT, INFRA-TECH

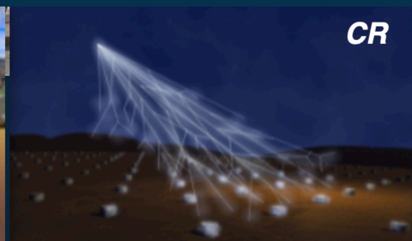


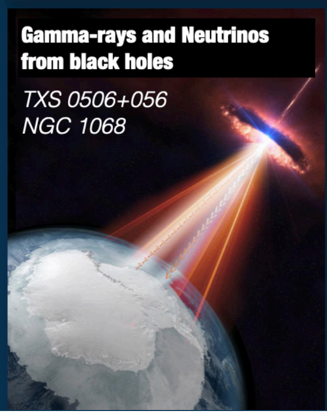
- During the talk I will refer to some (not all) instruments active in multimessenger
- The origin of the multi-messenger diffuse fluxes: 50 TeV - PeV measured flux: blazars and GRBs (time domain) ; starburst winds and Fermi Bubbles
- Diffuse granted fluxes: Cosmogenic, Galactic Plane
- Cosmological studies: PTA and H_0

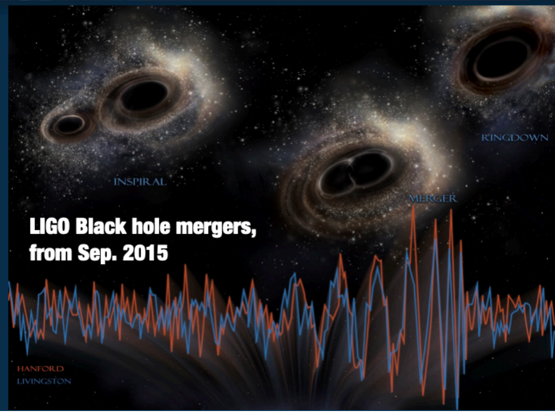


APPEC



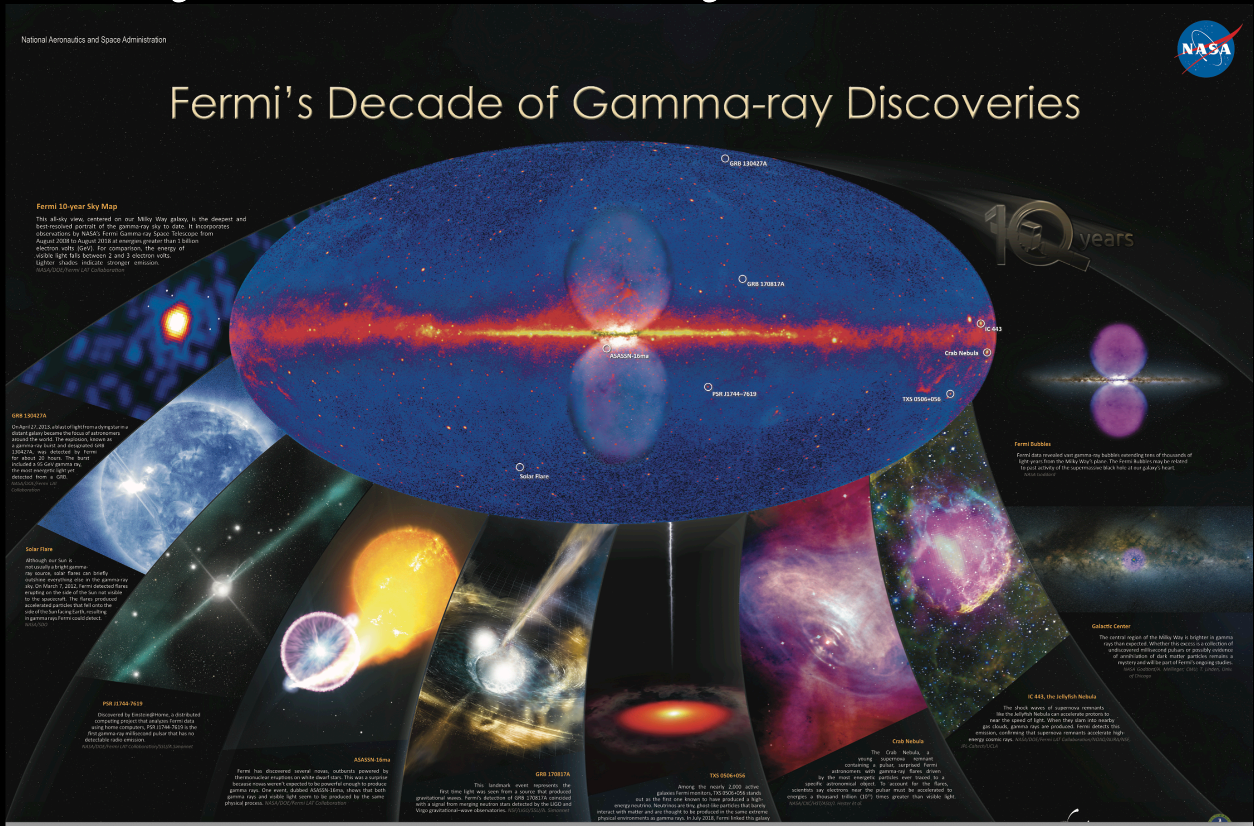






A future mission for 10 MeV-300 GeV?

Gamma-rays are pivotal in the study of every major physics question in the coming decade. The lack of planned funding for this photon band, in addition to ultra high-energy neutrinos, cosmic rays and low frequency gravitational waves, which are probed through pulsar timing arrays, should be truly alarming to those who have borne witness to the magnitude of recent multimessenger discoveries. *Snowmass MultiMessenger paper 2022*



Fermi-LAT 12 yr catalogue (4FGL-DR3) 50 MeV - 1 TeV.

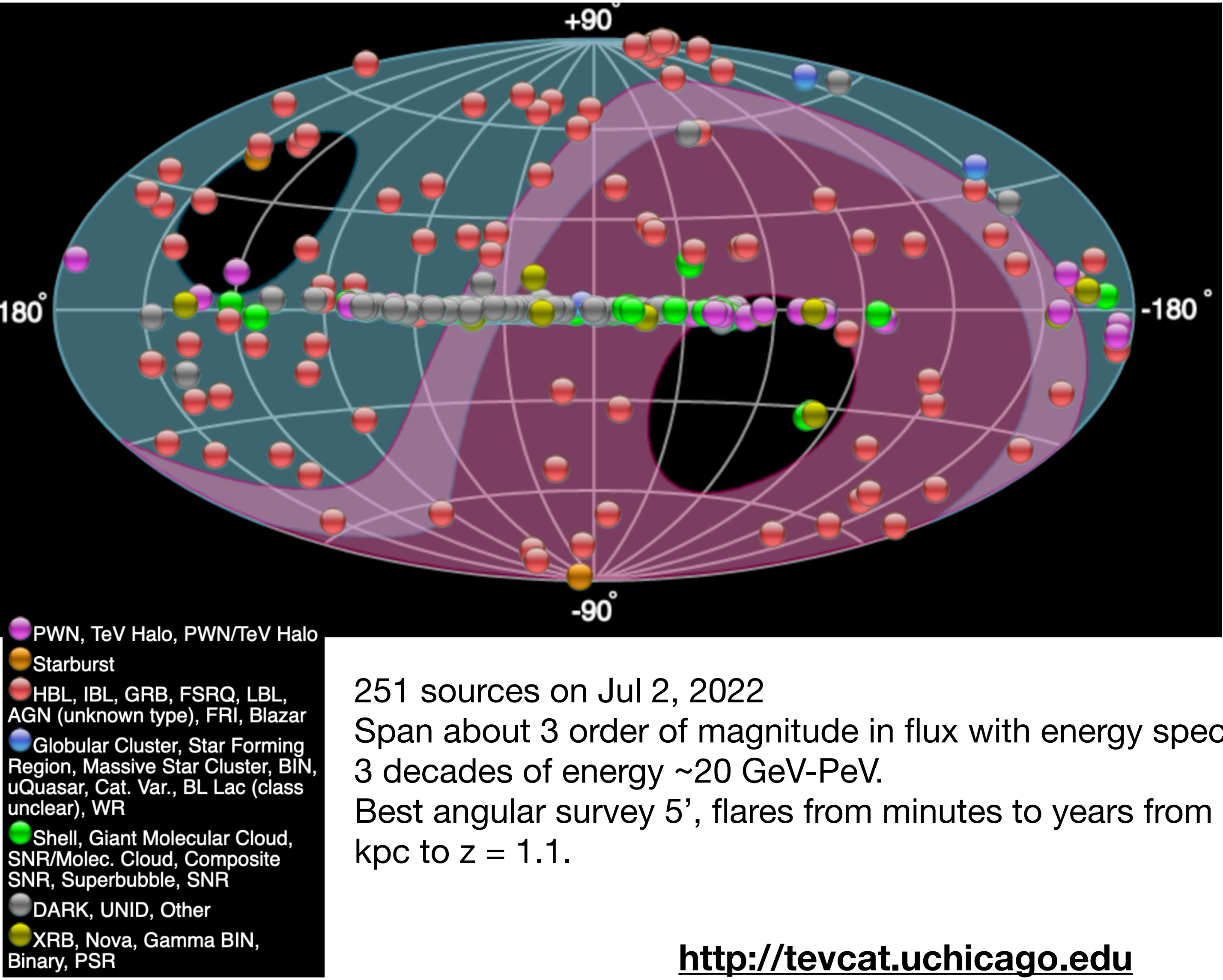
6658 sources: 25% are highly variable, 32.4% are unassociated, 78 sources are extended!

Galactic source: ~ 4% are pulsar, 19 PWN associated to LAT sources, 35 globular clusters, 43 SNRs.

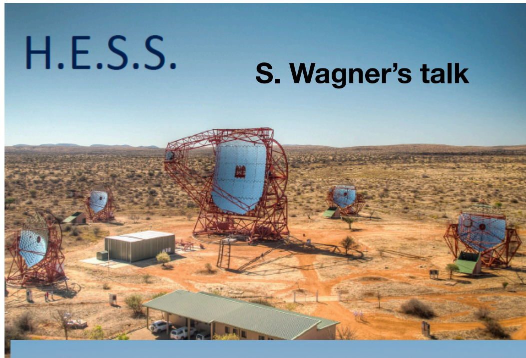
Extragalactic radio-loud sources: the largest sample is blazars (**2251** (~34%) identified or associated to BL Lacs and FSRQs) and **1493** unclassified blazars.

Future missions: HERD (geometrical acceptance x3 Fermi, x6 X_0, ang res <0.1° @ 100 GeV, AMEGO-X?

Ground-based gamma-ray sources



CTAO
LHAASO
and
SWGO in
the future

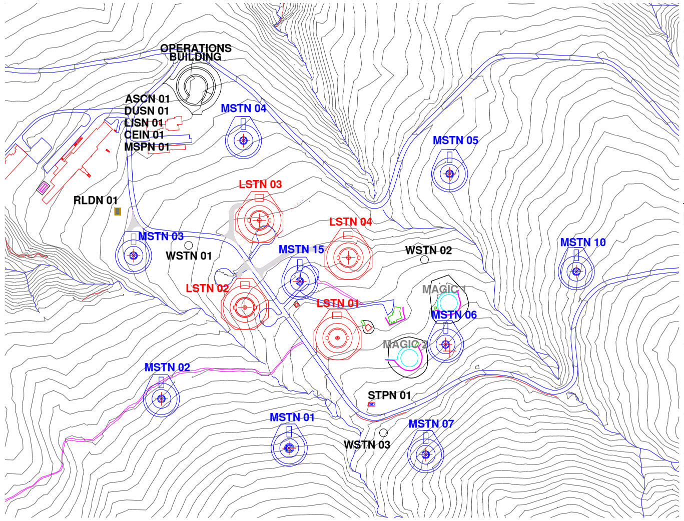


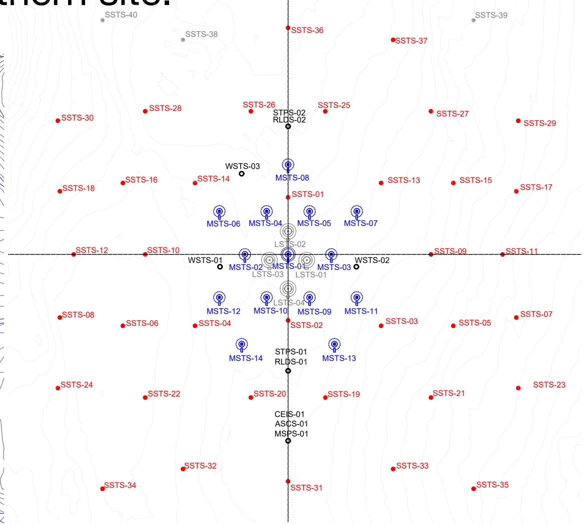
251 sources on Jul 2, 2022
Span about 3 order of magnitude in flux with energy spectra in 3 decades of energy ~20 GeV-PeV.
Best angular survey 5', flares from minutes to years from 0.2 kpc to z = 1.1.

http://tevcat.uchicago.edu

The Cherenkov Telescope Array Observatory

Alpha configuration in the approved Costbook (Jun 2021).
Beta configuration in preparation: PNRR financed INAF for 56 M€ for 3 additional LSTs and SSTs in the Southern site.





Tomorrow's talks

CTAO Northern Array

- **4 LSTs + 9 MSTs**
- 0,25 km^2 footprint
- focus on extra-Galactic science

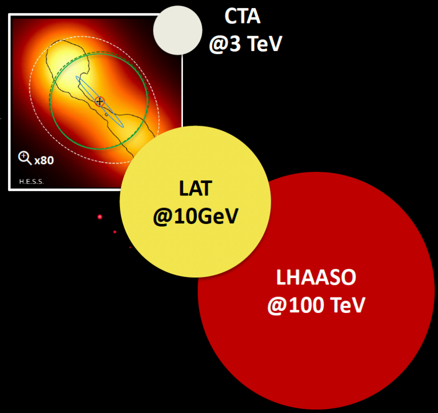
Talk of J. Cortina's on first results of LST-1

CTAO Southern Array

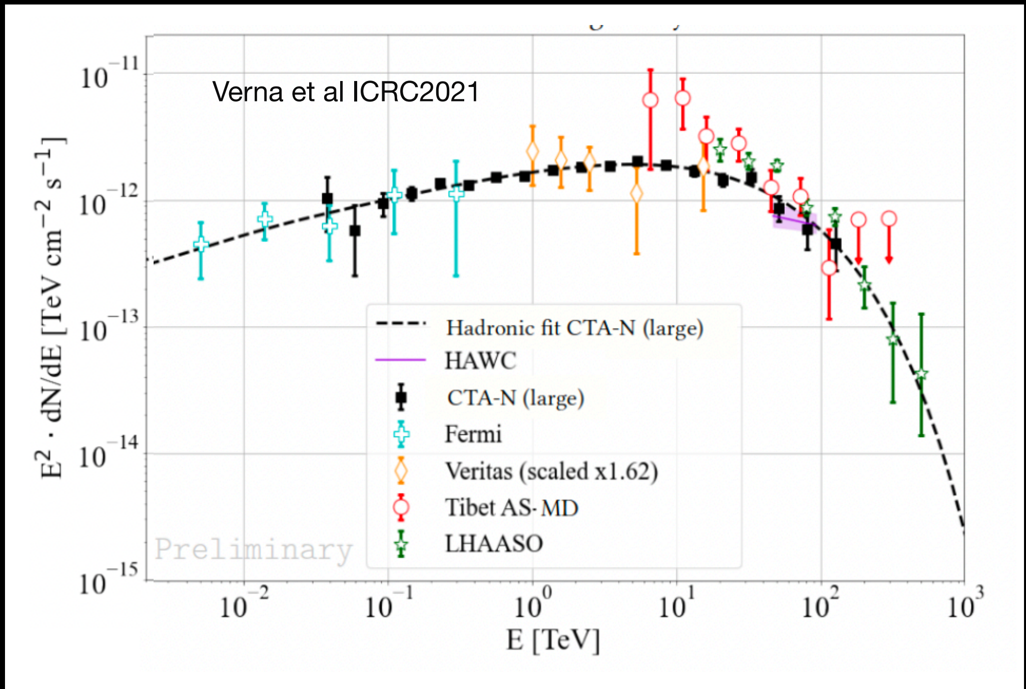
- **14 MSTs + 37 SSTs**
- 3 km^2 footprint
- focus on Galactic science

+ 4 excavations for LSTs + 3 extra foundations for SSTs

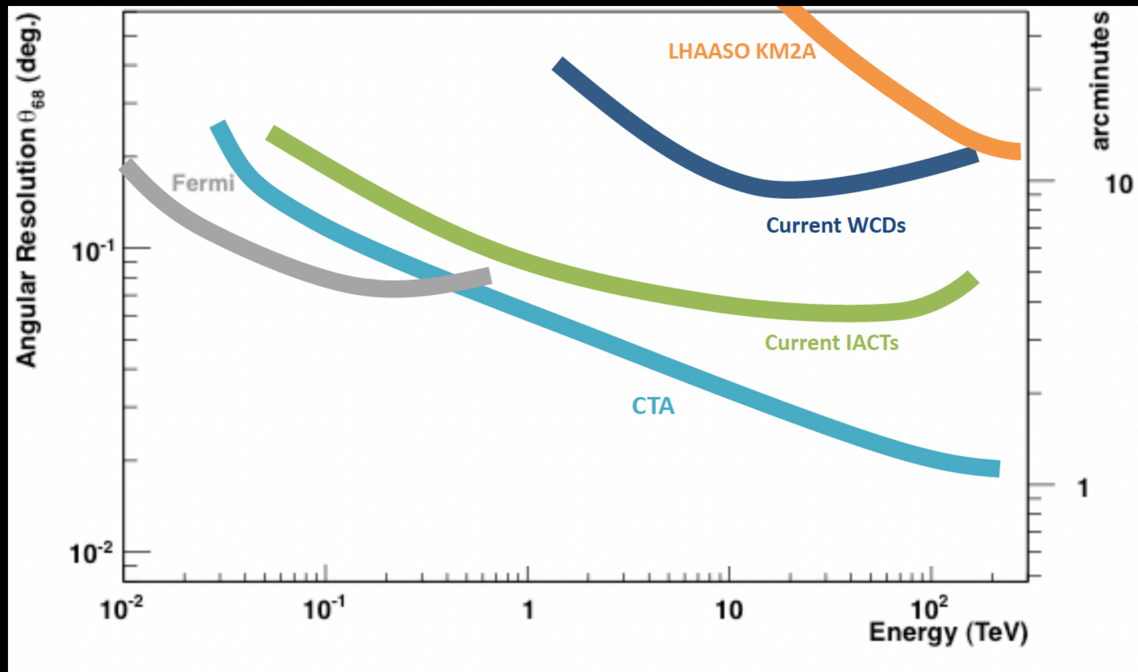
The precision era from 20 GeV to 1 PeV



- CTA will bring the angular resolution for point sources to 0.01° (arcmin)
- Extend the energy range down to 20 GeV and up to ~300 TeV with x10 better sensitivity
- Will have wider FoV for faster surveys: sensitivity to 2-4 mCrab; 10°x10° around Galactic Centre to 2 mCrab, unbiased extragalactic survey 25% of sky to 5 mCrab, LMC 1-2 mCrab.
- CTA has wider energy coverage and better satistics for morphology and spectra, important for model fitting



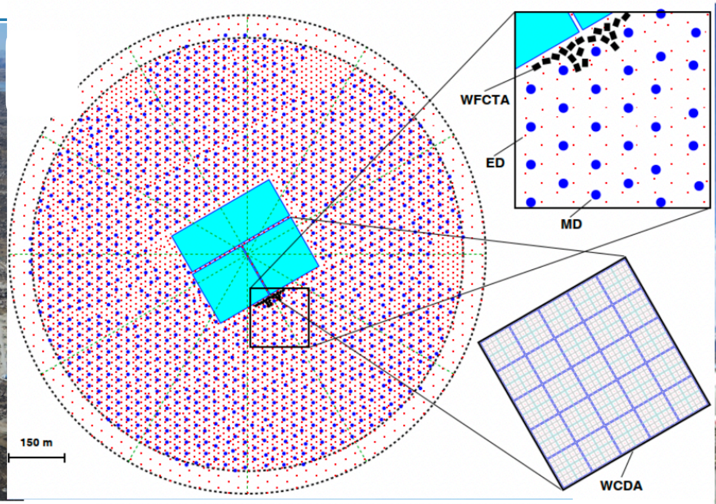
R. Zanin ICRC2021

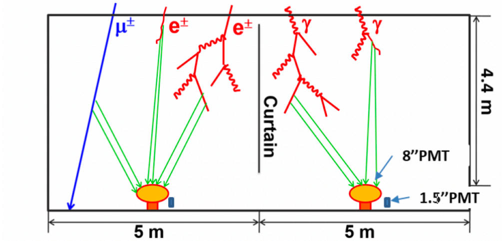


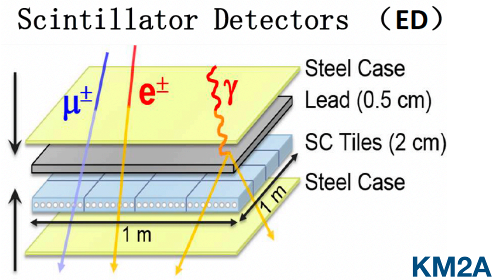
LHAASO: Large High Altitude Air Shower Observatory

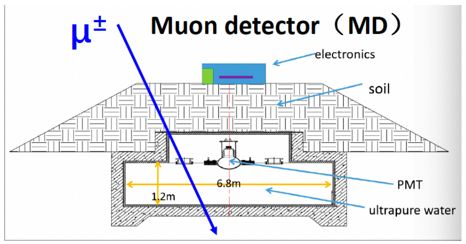
Z. Cao's talk

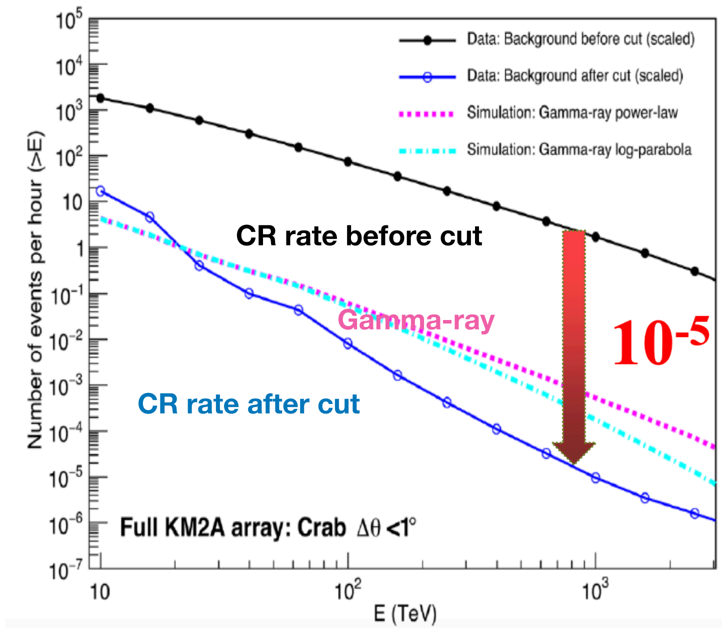
Aerial photograph of LHAASO (Image by IHEP)











WCDA: 78’000m^2 water pools, with 3120 units of 5x5 m^2 cells with 2 size PMTs (1.5”+8” WCDA-1, 20”+3”WCDA2,3). Energy range: ~200 GeV-20 TeV

KM2A 5195 EM surface scintillator detectors + 1188 underground water tanks for muons.

Energy range: > 10 TeV. Operation of full array 2021/7.

WFCTA: 18 wide-FoV IACTs and fluorescence telescopes.

The SST-1M project

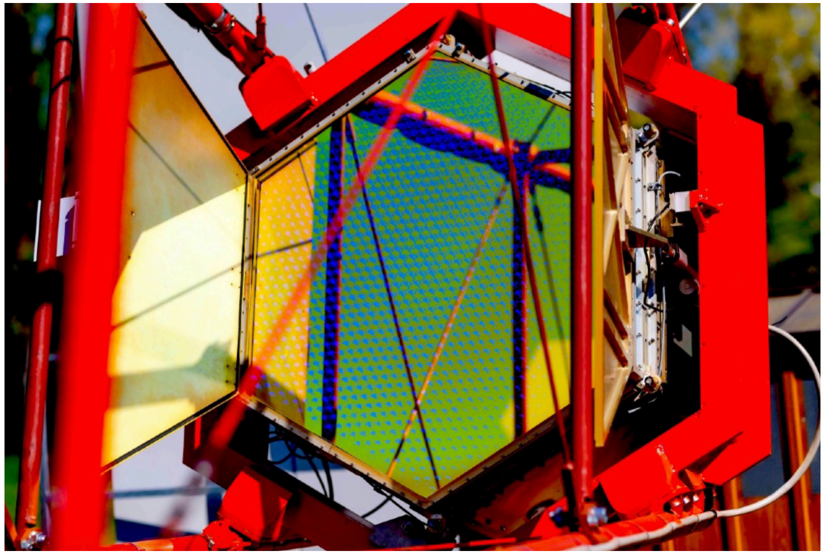
Initially proposed to implement 70 small size telescopes at CTAO Southern site

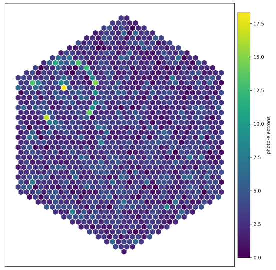
- UNIGE: Design, Coordination, System management, camera (DPNC), software (ASTRO)
- With Polish and Czech Consortia involved countries with 52 people (and about 27 FTE)

LHAASO and CTAO Advanced LSTs benefit for SST-1M development.

A mini-array of two telescopes for monitoring of sources, alerts and tests at the Ondrejov site.

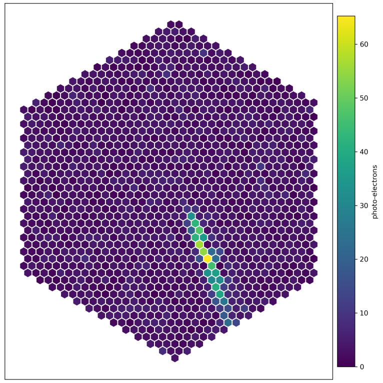
Jacek Niemic's talk





Muon - like event

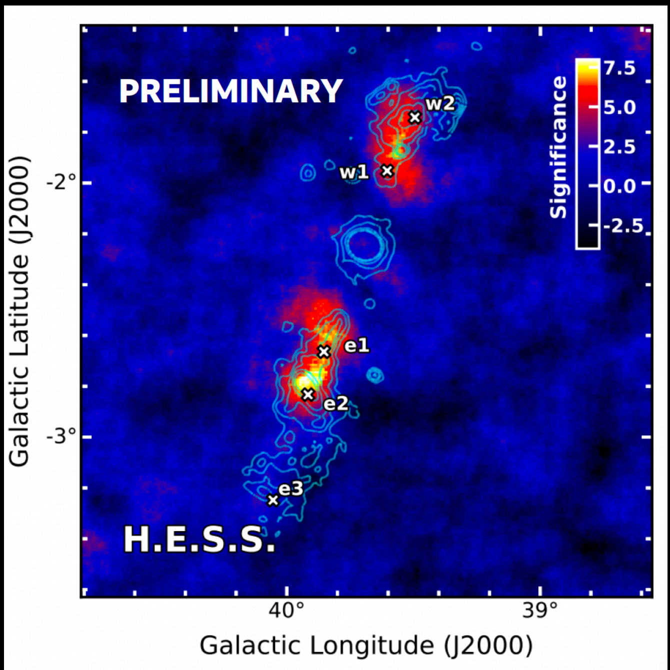
Gamma-ray - like event



Precision era for galactic sources has started!

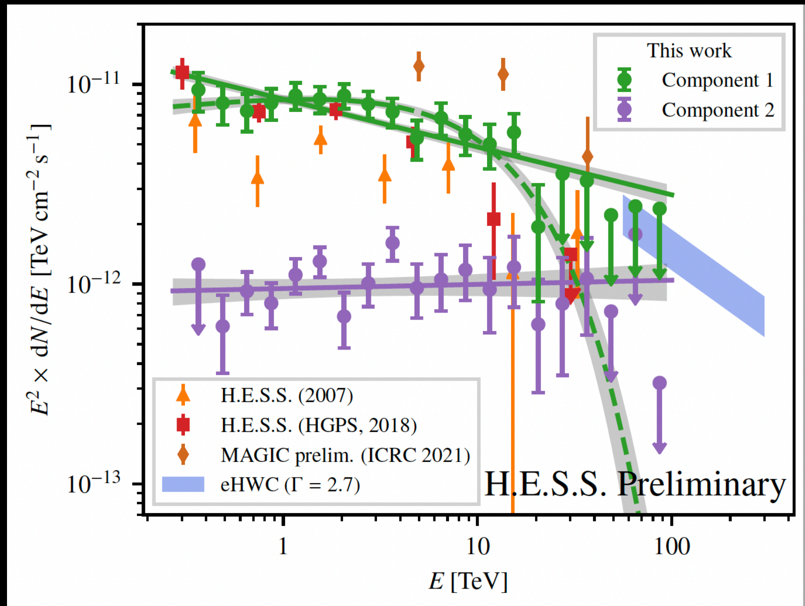
At this conference:

SS433 Olivera-Nieto's talk

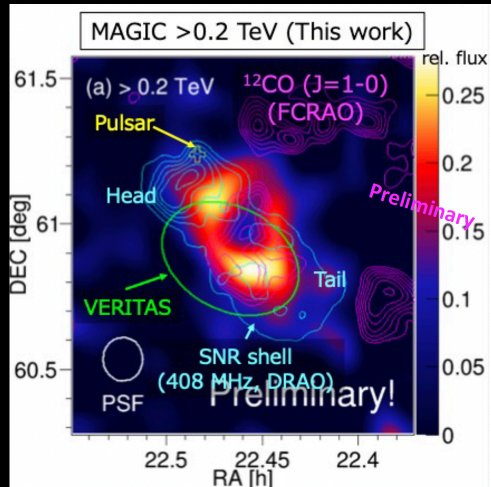


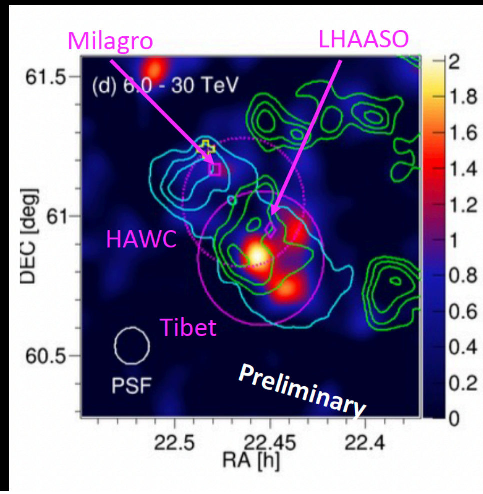
Fermi reveals a periodic source which is difficult to reconcile (see P. Bordas' talk)

HESS 1809-193 L. Mohrmann
Component 1 Halo of electrons remnants of Vela X
Component 2 molecular cloud/shell SNR/PWN



Saito's talk: the head & tail of Boomerang





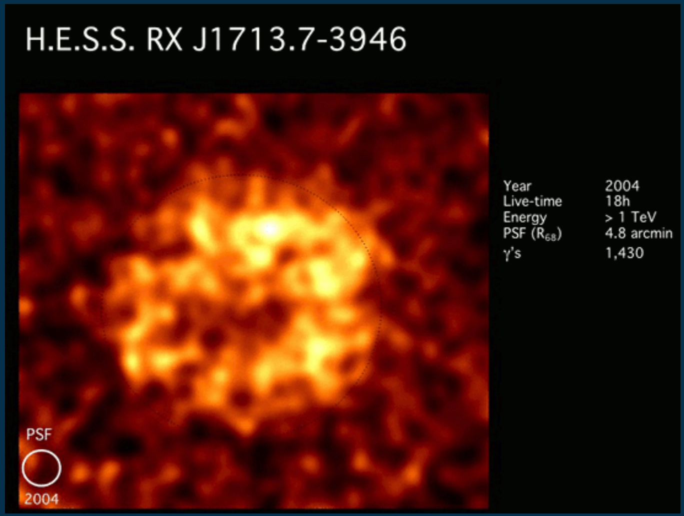
Indirect detections

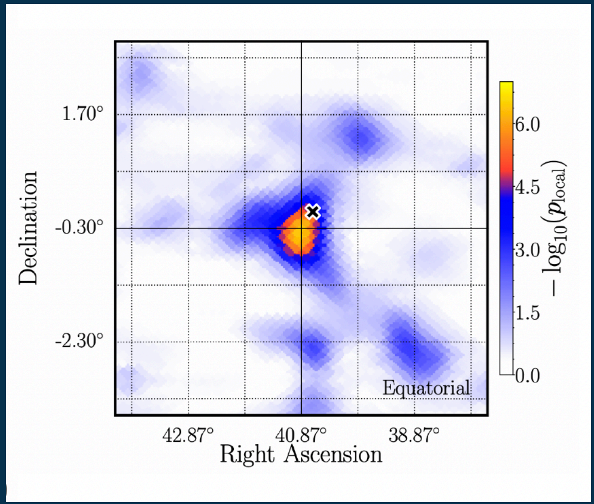
- Neutrino Telescopes (E. Resconi, TM)
- Gamma-ray ground-based infrastructures (many…)
- UHECRs (A. Olinto's presentation)
- No distance of messenger source unlike for GWs (M. Branchesi)

H.E.S.S 2018: angular resolution of 0.036° for E> 2 TeV probing scales of 0.6 pc!

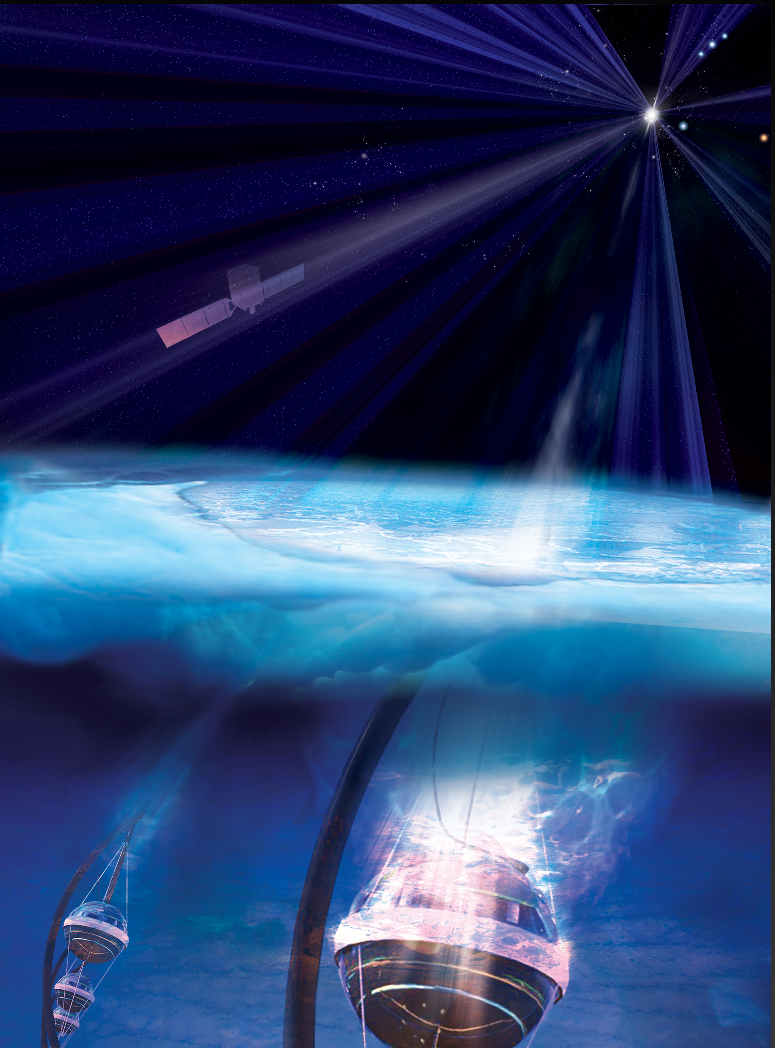
First image of NGC 1068 in neutrinos (IceCube PRL 124 (2020))

The primary is converted in secondaries of which the emitted Cherenkov light is directional. Imaging on a statistical basis.
Not at the statistical level for neutrino morphology…but gamma-rays achieved this potential for galactic sources.



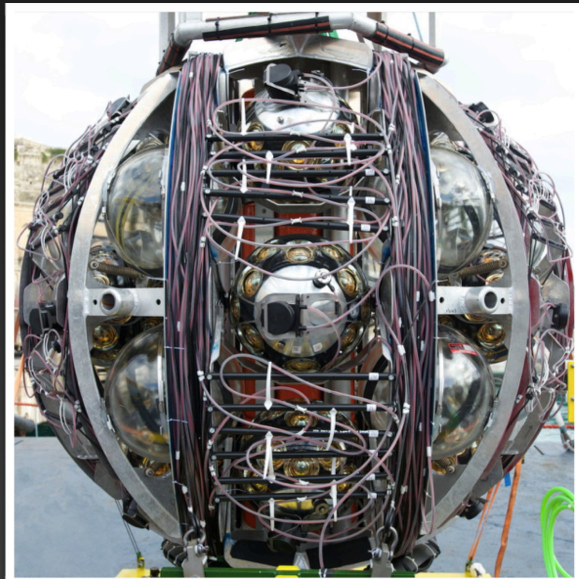


The challenge of the neutrino giants



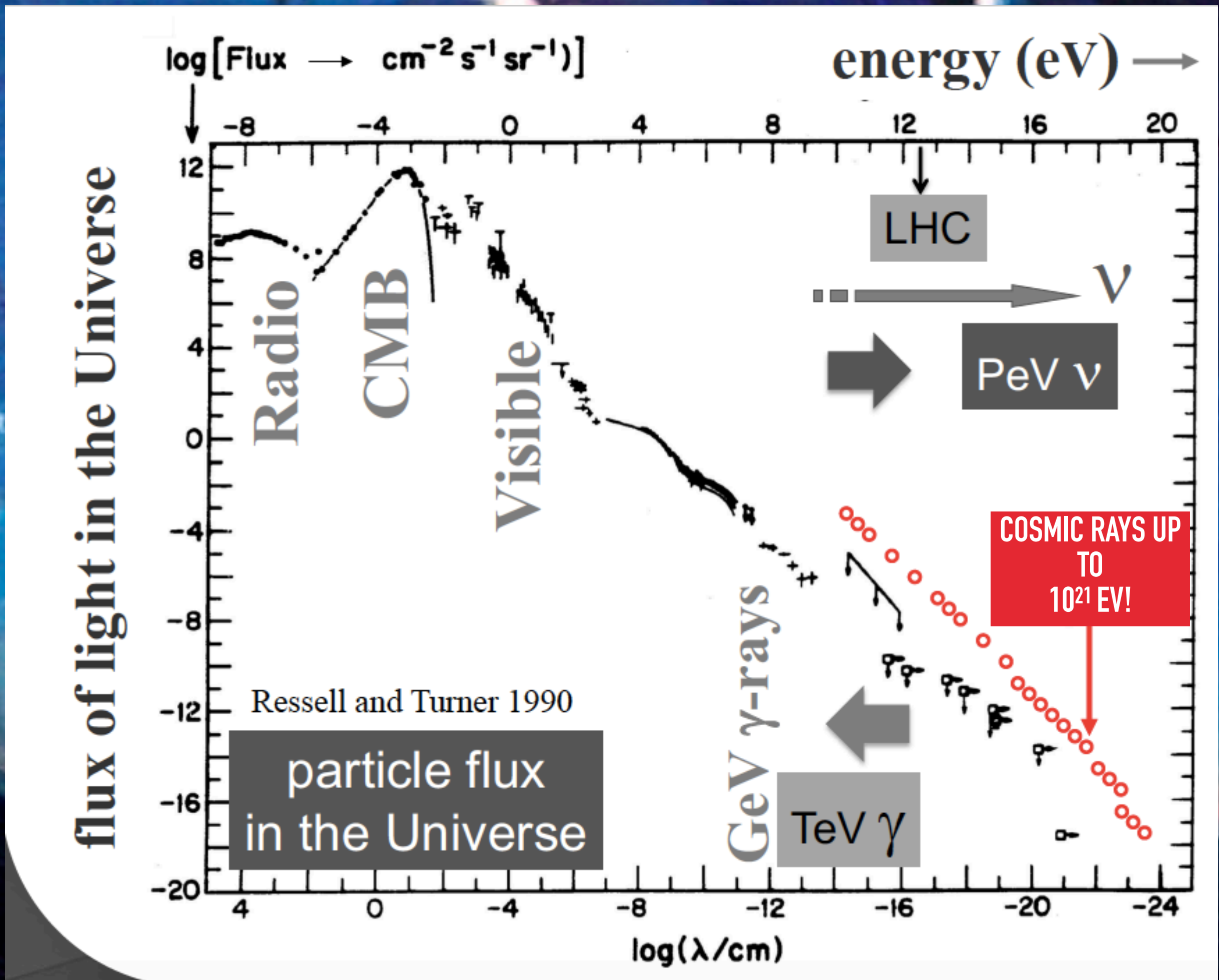
Credit: NASA/Fermi and Aurora Simonnet
Sonoma State University

ANTARES → KM3NeT : ORCA+ARCA



The grand unified spectrum : radiation and charged particles

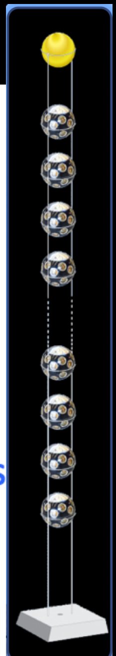
Ressel & Turner 1990



In the Mediterranean sea: KM3NeT

Oscillation Research with Cosmics In the Abyss

Astroparticle Research with Cosmics In the Abyss

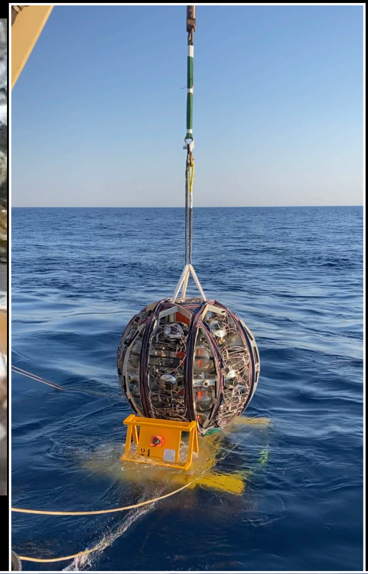


	ARCA	ORCA
Location	Italy	France
DU distance	90 m	20 m
DOM spacing	36 m	9 m
DU height	~ 800 m	~ 200 m
Instrumented mass	2*500 Mton	7 Mton
Depth	3500 m	2500 m

The Detection Unit (DU)

1 Buoy
2 Dyneema ropes
18 DOMs
1 Anchor
Electro-optical backbone:

ARCA= 2 BB = 230 DUs
ORCA= 1 BB

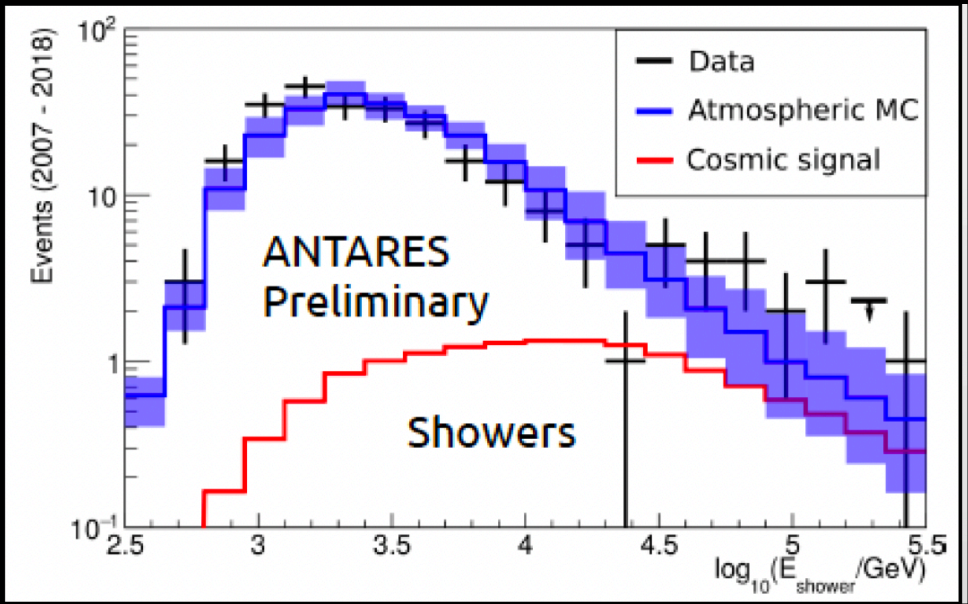


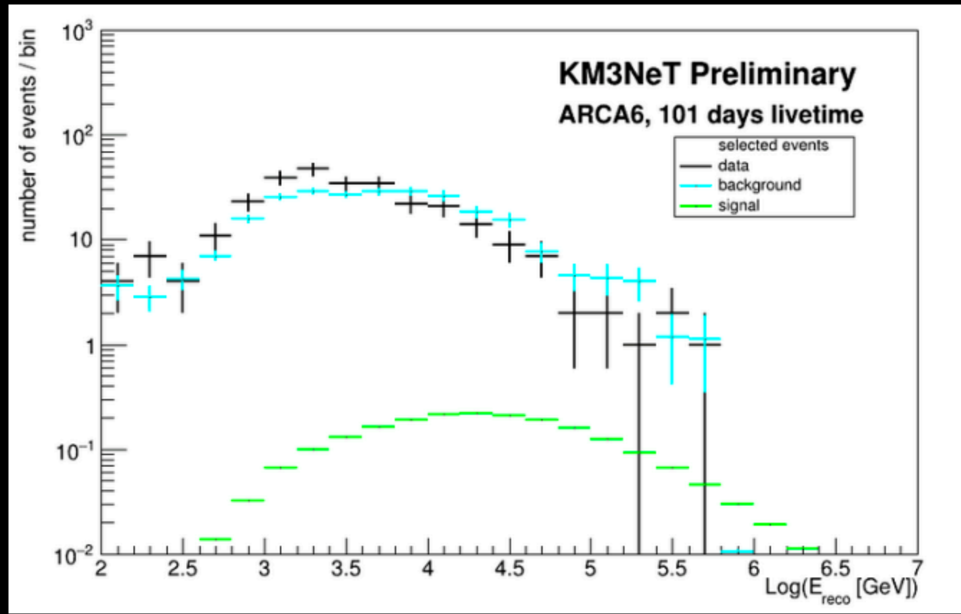
Congratulations to the team of KM3NeT for the conclusion of the campaign on Jun 14! In two weeks two new junction boxes and 11 new lines add to 8 lines existing (ARCA19). Photocathode area ~ 1.5 x ANTARES!

A new era of exploration of the Galactic Centre is starting!

Combined analysis of ORCA with JUNO leads to determination of neutrino hierarchy at 5σ ≤ 6 yr for any value of oscillation parameters (Aiello et al, 2022)

Diffuse flux of neutrinos from sea detectors





- Data: 50 events (27 tracks + 23 showers)
- Background : 36.1 ± 8.7

ARCA 6, 101 days
- Sample dominated by muons
- No high-E excess due to neutrinos
- Results compatible with background

Neutrino 2022 A. Heijboer

In Lake Baikal : GVD

Dzhilkibaev, Neutrino 2022

Construction start 2016. 2022: 10 clusters until now,
5 laser station

Year	Number of clusters	Number of OMs
2022	10	2880
2023	12	3456
2024	14	4032
2025	16	4608
2026	18	5184

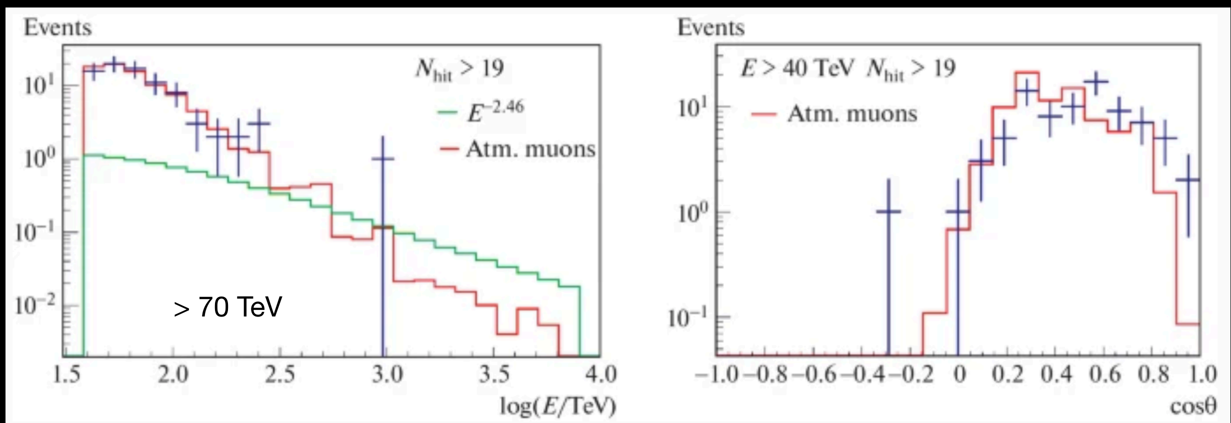
Cluster: 288 OMs
- 24 Sections on 8 strings,
- Cluster DAQ center
- Shore cable: 6 - 7 km
- Depths from 750 to 1275 m

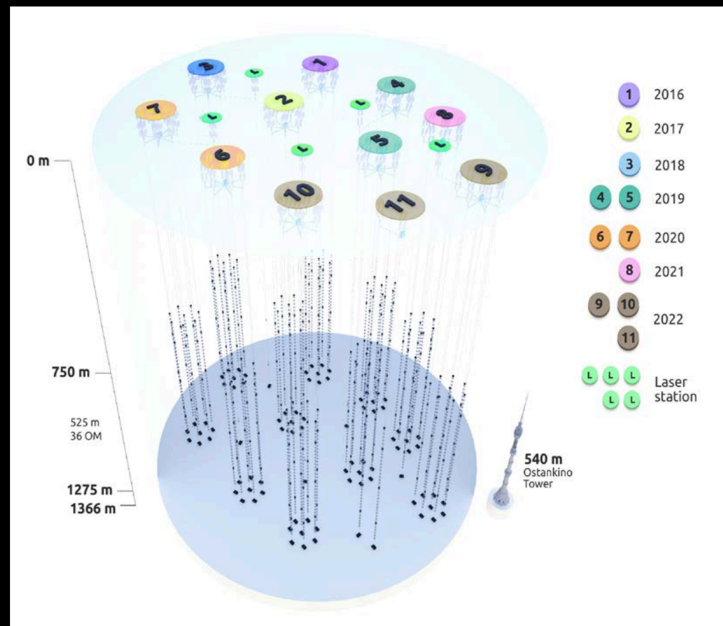
High energy cascades from April to 2018-2021, 5522 d; GVD 2022
Processing neutrino alerts: IceCube, ANTARES, 3 min processing time of HE alerts

Probability for the background-only hypothesis (stat. errors only):
P-value=0.033 or 2.13σ

16 data events have been selected
8.7 events from atm. muons
0.8 events from atm. neutrinos
7.8 events are expected from IC $E^{-2.46}$ astrophysical flux

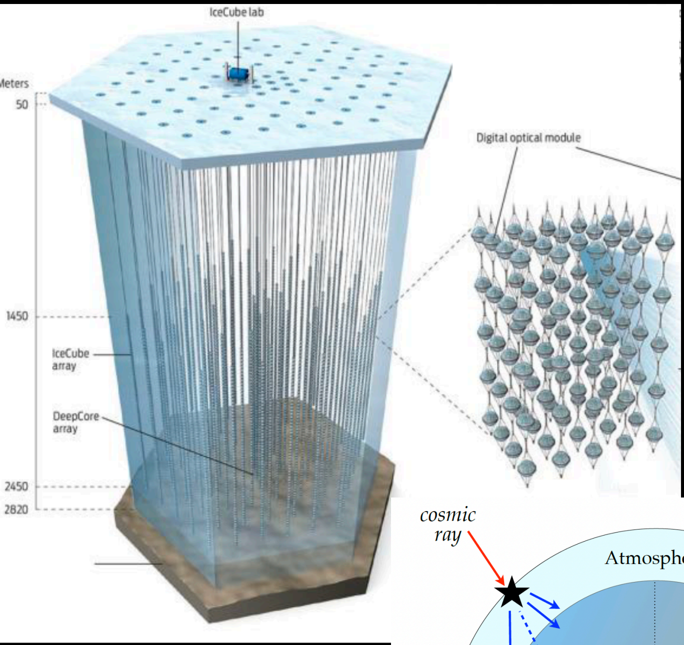
News at Neutrino 2022:
Adding upward events > 15 TeV 3σ evidence confirms IceCube Astrophysical flux.
But watch out for more checks on agreement with atmospheric backgrounds in 15 TeV region given the shallower depth.

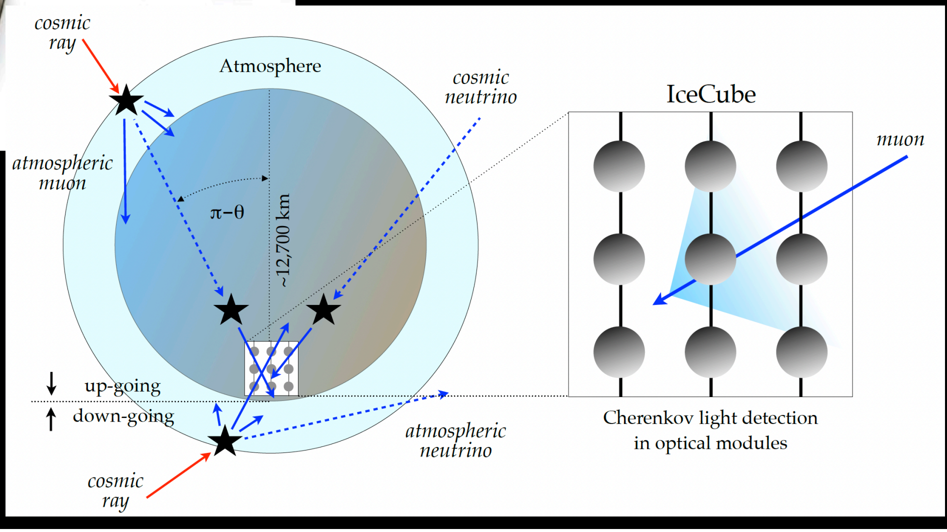


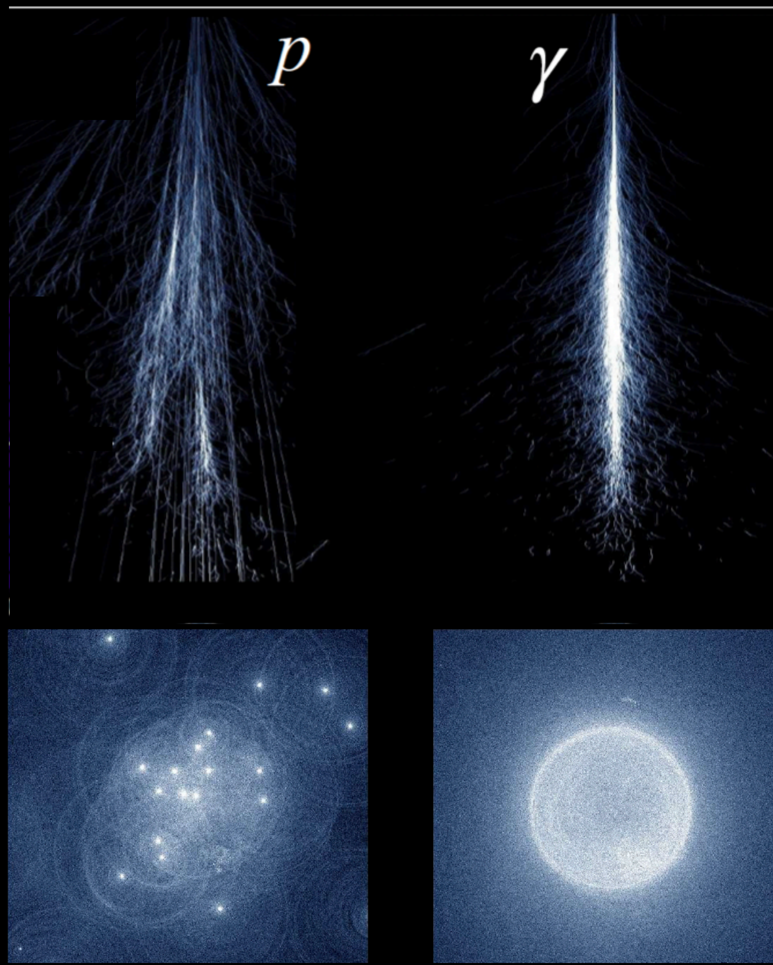


Indirect detection of neutral messengers and backgrounds

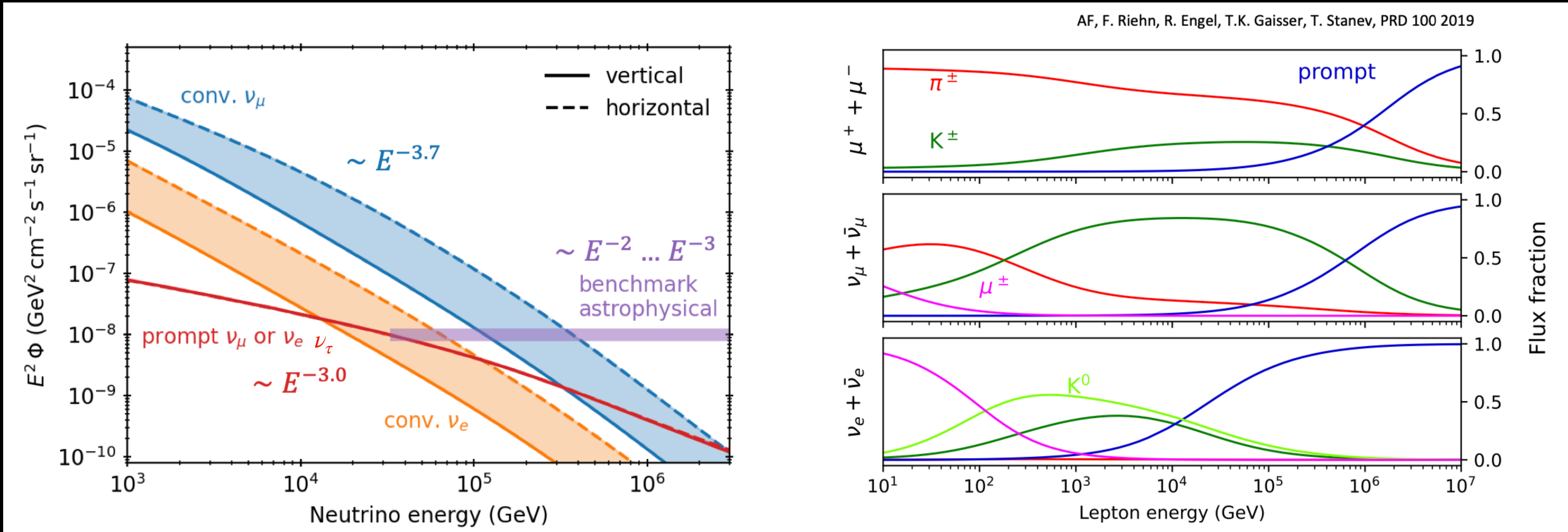
For IACTs cosmic ray background is ~10^5 orders of magnitude than gamma-ray signal and electrons are undistinguishable.R
For neutrino telescopes atmospheric neutrinos are undistinguishable unless energy, direction or time are used.







Steeply falling atmspheric neutrino flux

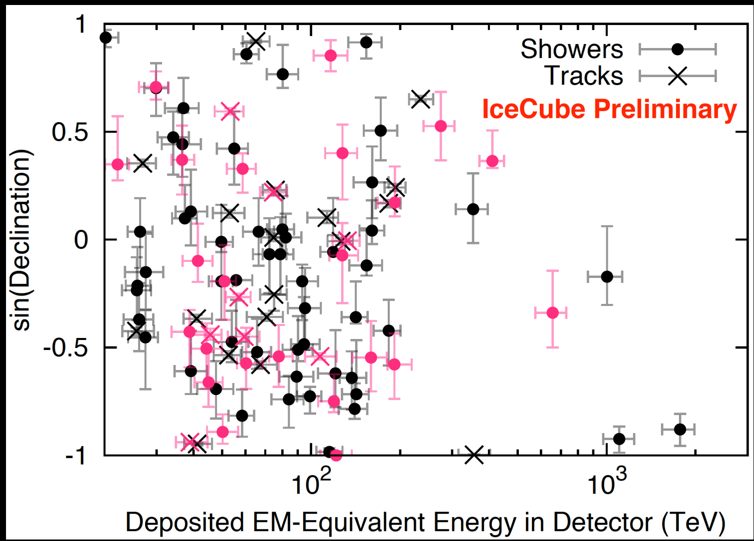


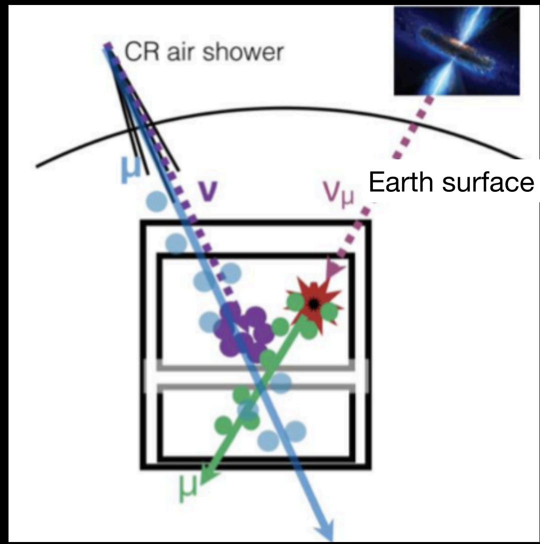
Cascade events are dominantly dominantly produced by ν_e and ν_τ less copiously produced by the atmosphere though their angular resolution is about ~10 larger than muon events. Prompt neutrinos and muons dominate > 1 PeV (muon events) and > 10 TeV for ν_e .

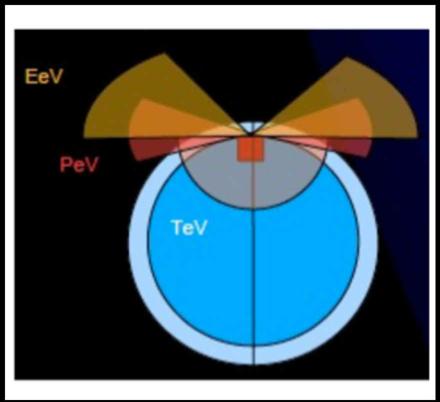
A. Fedynitch Neutrino 2022

A vetoed neutrino astronomy: IceCube

Discovery in 2013, PRD 104 (2021) : 102 High Energy Starting Events neutrino events in 7.5 yr, atmospheric $\nu's$ disfavored at 5σ. Cascades are mostly due to ν_e, ν_τ and beyond 100 TeV mostly of astrophysical origin.

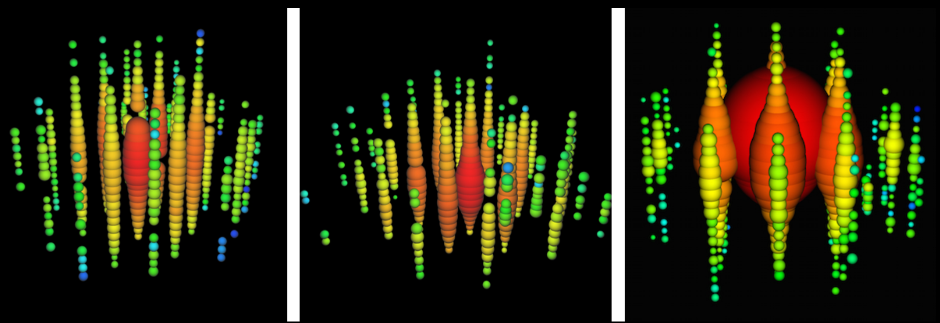


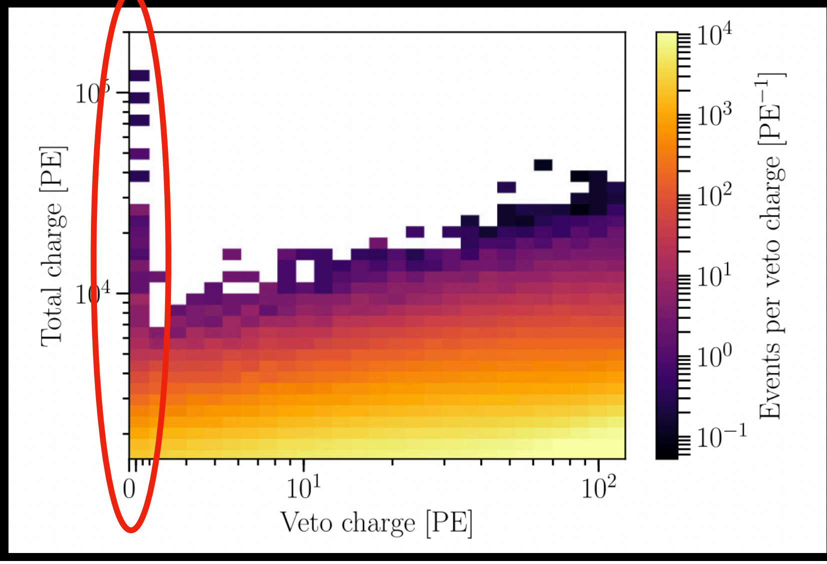




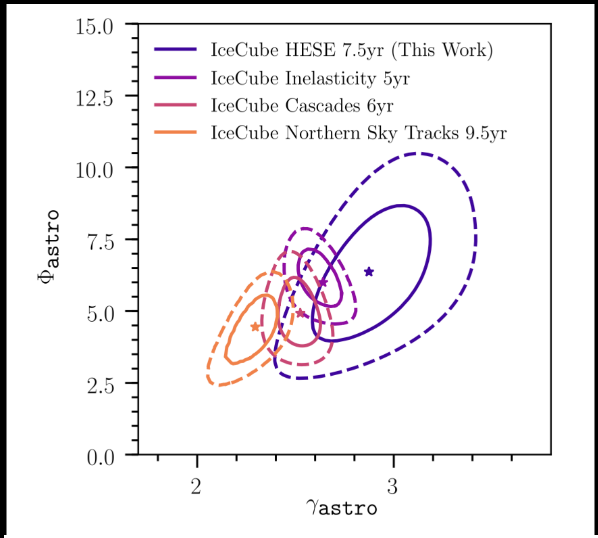
Astronomy beyond PeV is mostly horizontal!

Vetoes are important!





The IceCube diffuse fluxes



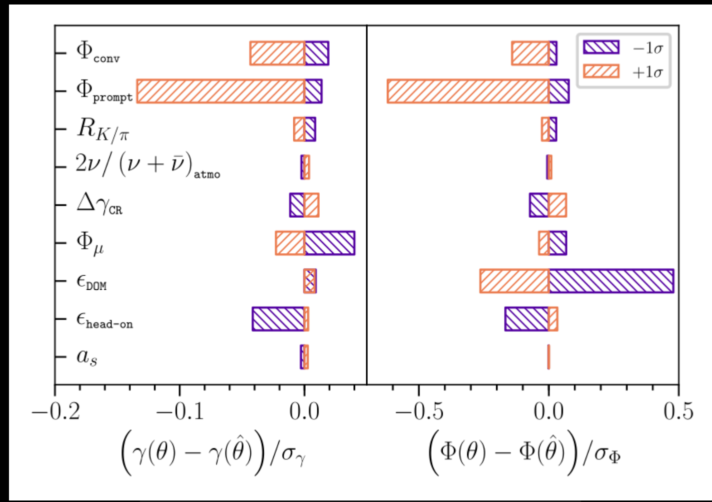
$$\Phi_\nu = \phi \times (E_\nu / 100\,\mathrm{TeV})^{-\gamma}$$

$$\gamma^{7.5\ \mathrm{years}}_{\mathrm{astro}} = 2.87^{+0.20}_{-0.19}$$

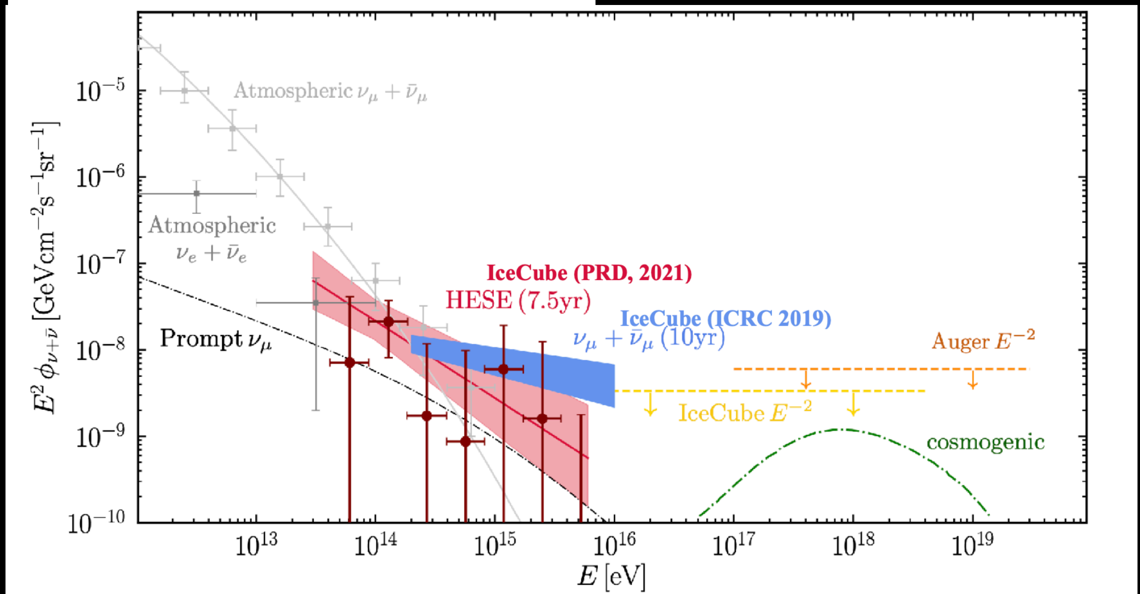
$$\Phi_{prompt} = 0.00 \pm^{5.34}_{-0.00}$$

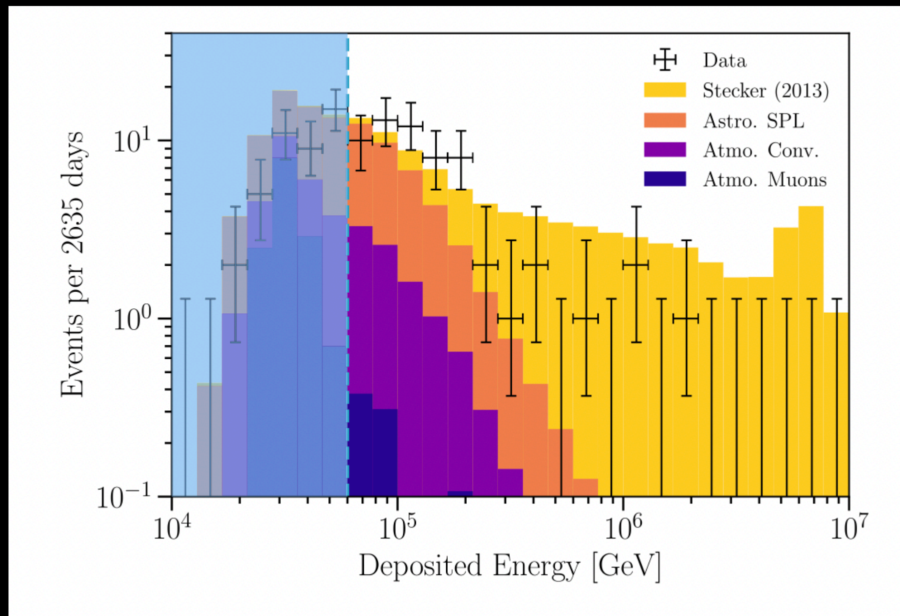
E. Resconi's talk

Impact of sys errors on Cosmic power law flux

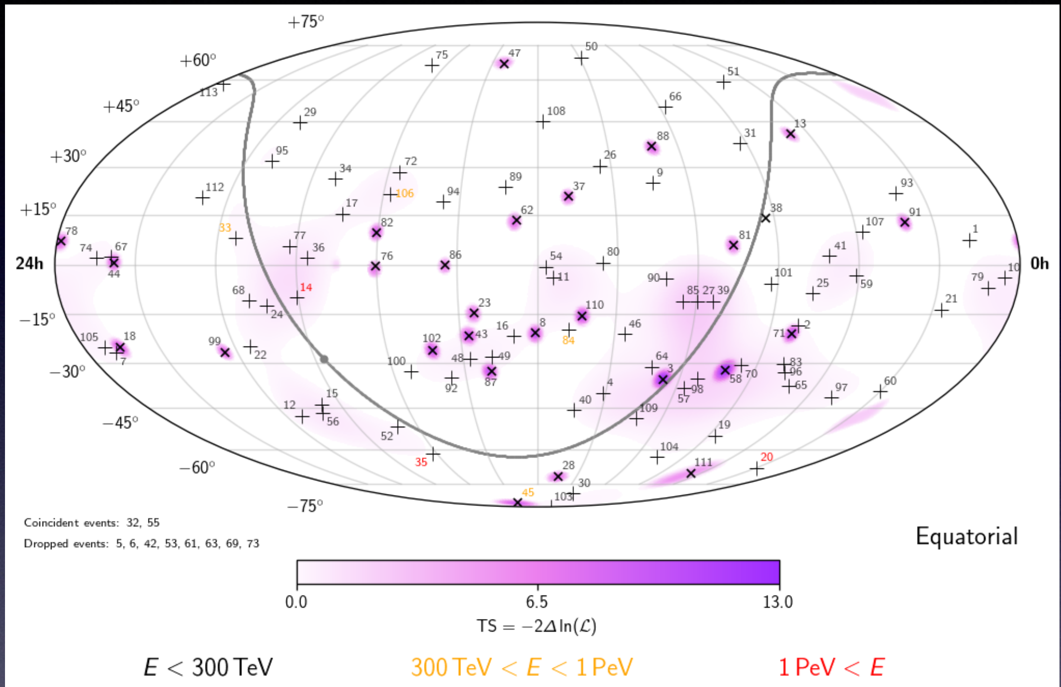


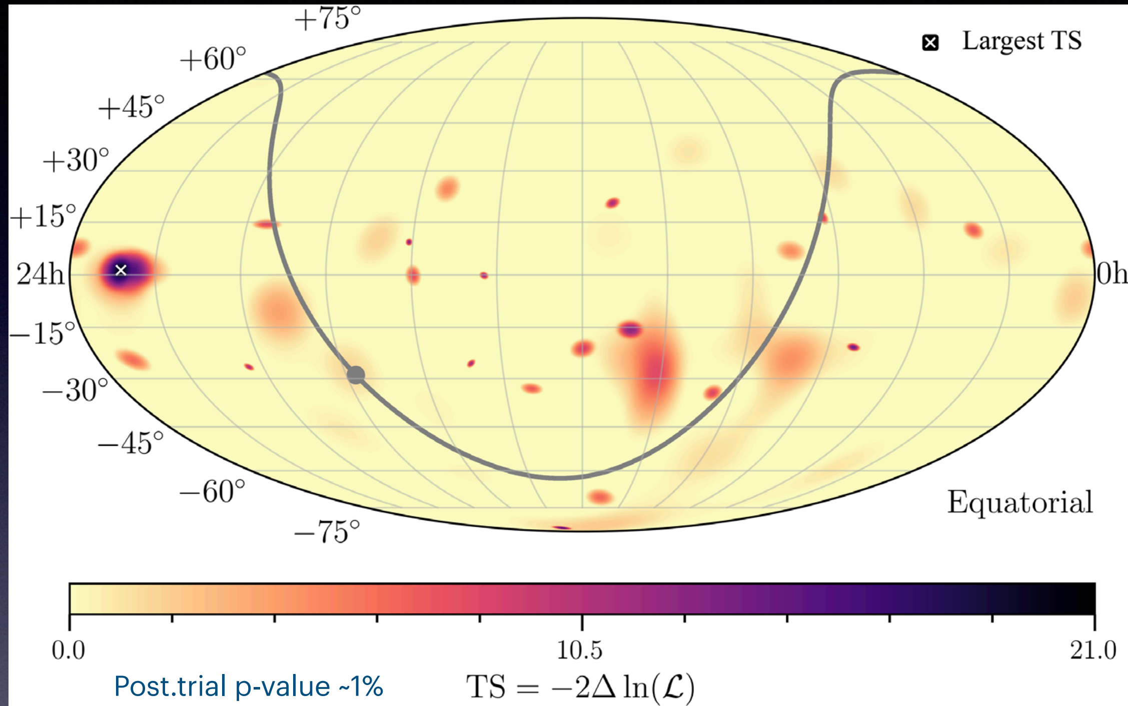
IceCube, PRD 104 (2021)





The IceCube HESE directions

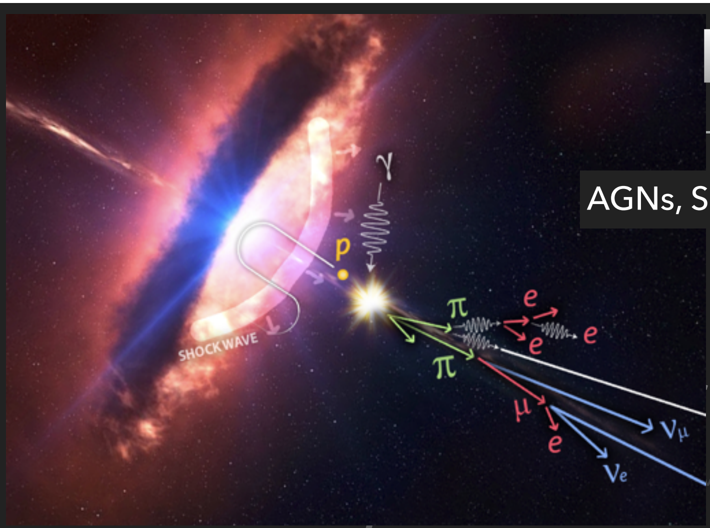




Subdominant contribution from galactic plane ⇒ Mostly extragalactic sources but 10% galactic contribution cannot be excluded

IceCube (ApJ 2016) set an upper limit of about 30% (50%) to the blazar contribution to the diffuse ν flux between 10 TeV- PeV which nonetheess assumes all blazars produce similar power law spectra with spectral index -2.5 (-2.2). Assuming that all sources in a class are identical ignores the role of host environments and different characteristics of accelerators.

Multi-messenger high-energy astrophysics



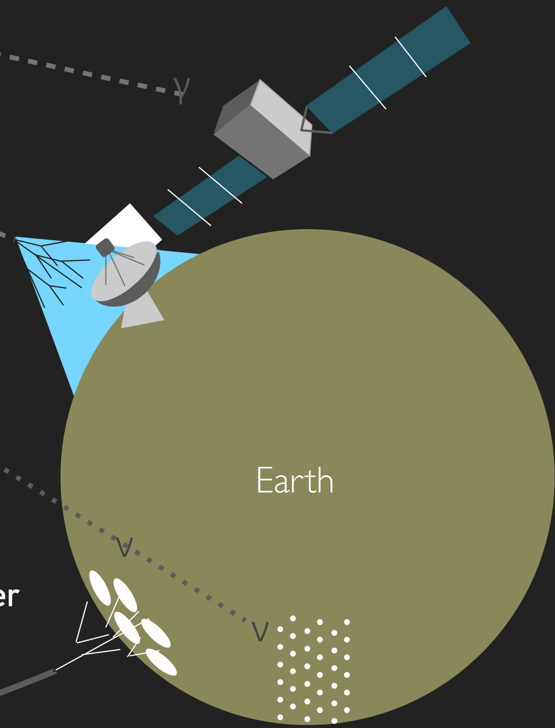
AGNs, SNRs, GRBs….

GAMMA-RAYS point to their sources but are absorbed and have multiple emission mechanisms.Also produced by leptonic acceleration, inverse Compton and synchrotron emission

Gravitational Wave connection is established with EM emission not yet established with neutrinos and cosmic rays

NEUTRINOS
They are neutral and weak particles: point to the source carrying information from the deepest parts.

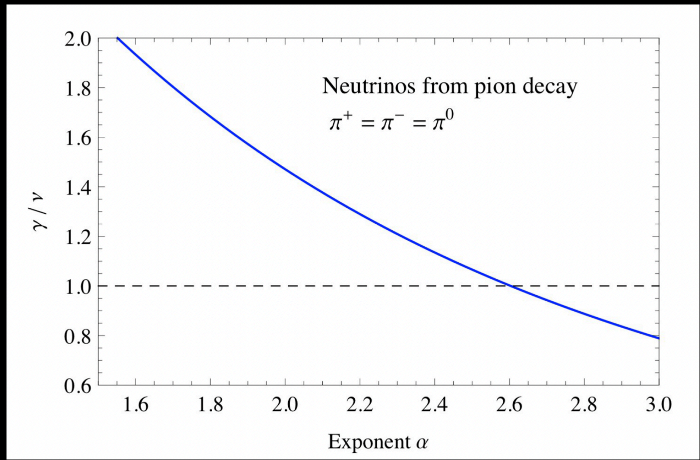
COSMIC RAYS
Deflected by magnetic fields (E < 10^{19} eV)



Multi-Messenger relations

Halzen & Kheirandish 2022

Kelner, Aharonian, Bugayov 2006



From SN shocks or Galacitc plane +ISM

$$p + p \rightarrow N_\pi(\pi^+ + \pi^- + \pi^0) + X$$

$$\mu^+\nu_\mu \quad \mu^-\bar{\nu}_\mu \quad \gamma\gamma$$

$$e^+\nu_\mu\nu_e\bar{\nu}_\mu \quad e^-\bar{\nu}_\mu\bar{\nu}_e\nu_\mu$$

1 neutral pion and 2 charged pions in ~same number with multiplicity N_π, each carrying the fraction of proton energy

$$x_\pi = \frac{\kappa}{N_\pi} = <\frac{E_\pi}{E_p}> \sim 0.2$$

$\kappa = \dfrac{N_\pi E_\pi}{E_p}$ = inelasticity or energy of proton taken by pions

$$x_\nu = <\frac{E_\nu}{E_p}> = \frac{x_\pi}{4} \sim \frac{1}{20} \Rightarrow dE_\nu = x_\nu dE_p$$

$$x_\gamma = <\frac{E_\gamma}{E_p}> = \frac{x_\pi}{2} \sim \frac{1}{10} \Rightarrow dE_\gamma = x_\gamma dE_p$$

$$\frac{dN_\nu}{dE} \sim \frac{dN_\gamma}{dE} \text{ for pp}$$

$\pi^+ \approx \pi^- \approx \pi^\circ$

$\pi^0/\pi^\pm \approx 1/2$

$\gamma/\nu \approx 1$

$\pi^+/\pi^- \approx 1$

$\nu/\bar{\nu} \approx 1$

Multi-Messenger relations: proton-γ

Halzen & Kheirandish 2022

Kelner & Aharonian 2008

Higher energy threshold: in AGNs, GRBs. Target photon density vs energy influences the spectral shape of secondaries

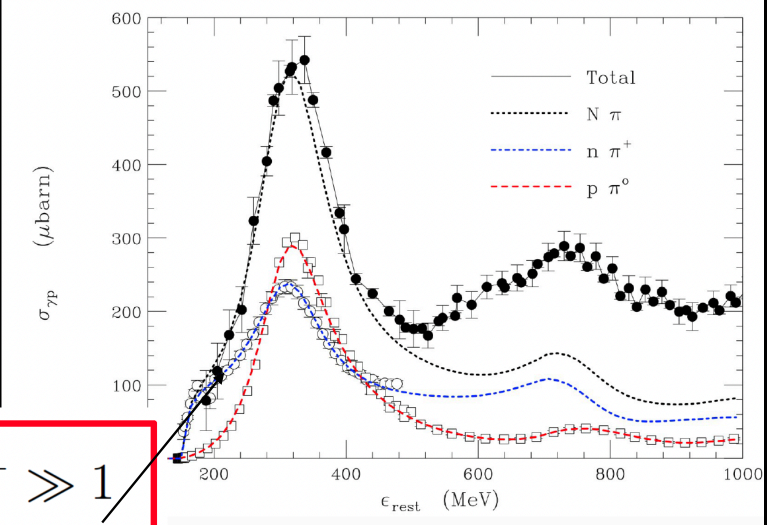
$$p+\gamma \to \Delta^+ \to p+\pi^0 \quad 2/3$$
$$p+\gamma \to \Delta^+ \to n+\pi^+ \quad 1/3$$

$$\pi^0 \to \gamma+\gamma$$
$$\pi^+ \to \mu^+ + \nu_\mu \to (e^+\nu_e\bar{\nu}_\mu) + \nu_\mu$$

branching ratios

	$p\pi^+$	$p\pi^0$	$p\pi^-$	$n\pi^+$	$n\pi^0$	$n\pi^-$
Δ^{++}	1					
Δ^+		2/3		1/3		
Δ^0			1/3		2/3	
Δ^-						1

Cross section $p+\gamma \to$ hadrons



Ahlers & Halzen, 2017: the BR are changed into about 1/2 due to the contribution of non resonant pion production at the resonance energy

$$\frac{dN_\nu}{dE} \sim \frac{1}{2}\frac{dN_\gamma}{dE} \text{ for p} - \gamma$$

$$\pi^+/\pi^- \gg 1$$
$$\pi^0/\pi^+ \approx 1$$
$$\gamma/\nu \approx 2$$
$$\nu/\bar{\nu} \approx 2$$

In summary, for each ν flavor

$$\frac{1}{3}\sum_\alpha E_\nu \frac{dN_\nu}{dE_\nu dt}(E_\nu) \sim \frac{K_\pi}{2}\frac{dN_\gamma}{dE_\gamma dt}(E_\gamma)$$ with $K_\pi \sim 1{,}2$ for $p\gamma(pp)$

Diffuse - single source fluxes

Relationship between a PS flux and diffuse flux

$$\frac{1}{3}\sum_{\alpha} E_\nu^2 \phi_{\nu_\alpha}(E_\nu) \simeq \frac{c}{4\pi}\frac{\xi_z}{H_0}\rho_0 \frac{1}{3}\sum_{\alpha} E_\nu^2 Q_{\nu_\alpha}(E_\nu)$$

One could infer from the diffuse measured neutrino flux

$$E^2\phi_\nu \simeq 10^{-8}\ \mathrm{GeV cm^{-2} s^{-1} sr^{-1}}$$

a single source upper limit but all sources have to behave equally!

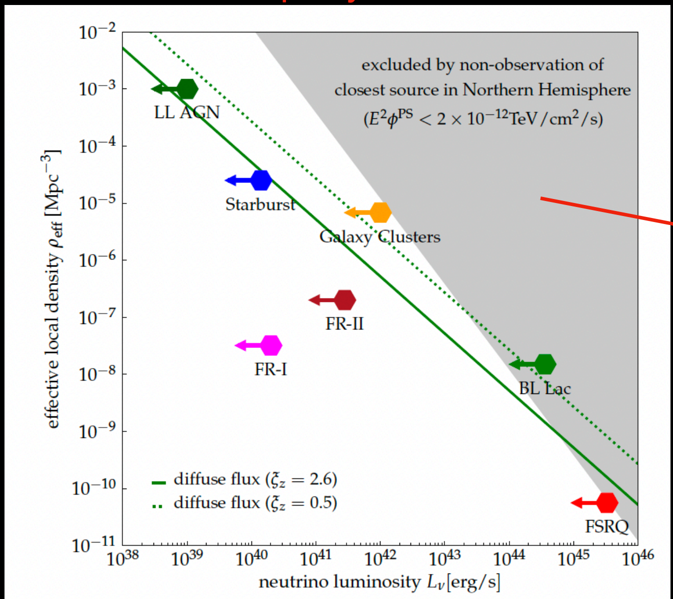
$$\xi_z = \int_0^\infty \mathrm{d}z \frac{(1+z)^{-\Gamma}}{\sqrt{\Omega_\Lambda + (1+z)^3\Omega_\mathrm{m}}} \frac{\rho(z)}{\rho_0}\,.$$

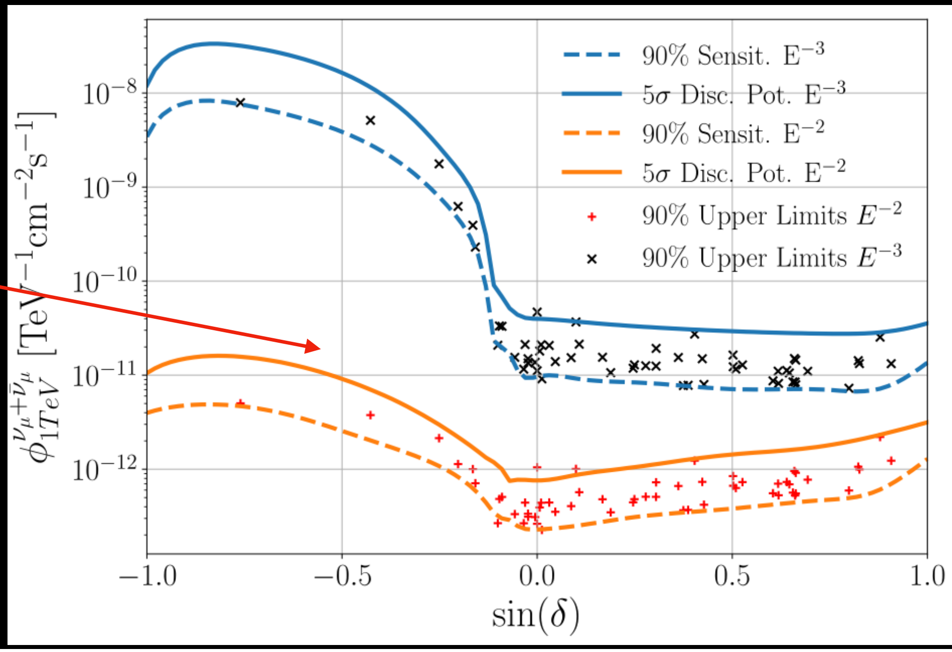
Evolution of the considered class of sources:

$\xi_z \sim 0.5$ for $\gamma = 2$, no evolution $\rho(z) = \rho_0$ and z<2

$\xi_z \sim 2.6$ for $\gamma = 2$, star formation evolution $\rho(z) = \rho_0 \ (1+z)^3$ for $z < 1.5$, $(1+1.5)^3$ for $1.5 < z < 4$ and ρ_0 = effective source density

IceCube PhysRevLett.124.051103 Tessa Carver PhD thesis UNIGE





Cosmic ray/gamma-ray/neutrino connection

Halzen & Kheirandish 2022
Waxman & Bahcall 1998

$$\left[E_p^2 Q_p(E_p)\right]_{10^{19.5}\mathrm{eV}} \sim (0.5 - 2.0) \times 10^{44} \mathrm{erg/Mpc^3/yr}$$

Local Emission rate density to feed UHECRs

Relation between the neutrino flux per flavor and the CR rate density:

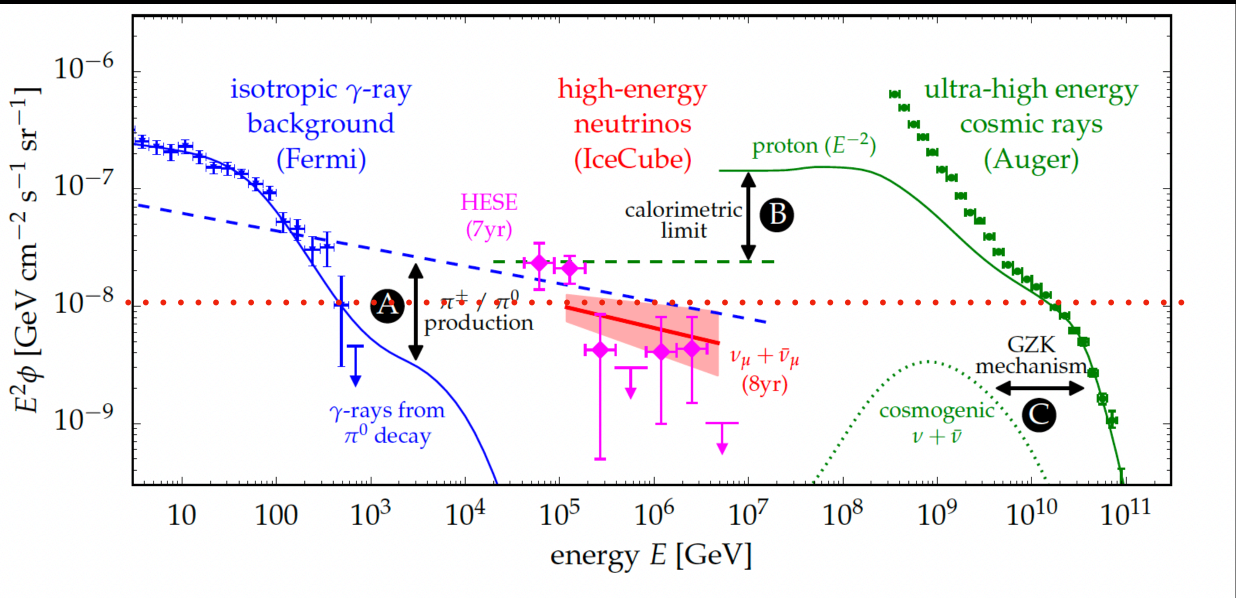
$$\frac{1}{3}\sum_\alpha E_\nu^2 \phi_{\nu_\alpha}(E_\nu) \simeq 3 \times 10^{-8} f_\pi \left(\frac{\xi_z}{2.6}\right)\left(\frac{\left[E_p^2 Q_p(E_p)\right]_{E_p=10^{19.5}\mathrm{eV}}}{10^{44}\,\mathrm{erg/Mpc^3/yr}}\right)\frac{\mathrm{GeV}}{\mathrm{cm^2\,s\,sr}}.$$

f_π = efficiency of pion production from CRs = $1 - e^{-\tau_{p\gamma}}$

With $\tau_{pp,p\gamma} = \kappa \ell \sigma_{pp,p\gamma} n$

Target nucleon density

Target dimension



(A) common origin of γ's and ν's from π production

(B) CRs and ν's have a common origin

$f_\pi \to 1$ calorimetric limit(e.g. starburst galaxies)
$\tau = \kappa\ell\sigma n >> 1$ CRs are trapped and their total energy is converted into gamma and neutrinos (e.g. starbursts, galaxy clusters)
$f_\pi < 1$ Optically thin sources : Waxman & Bahcall upper limit

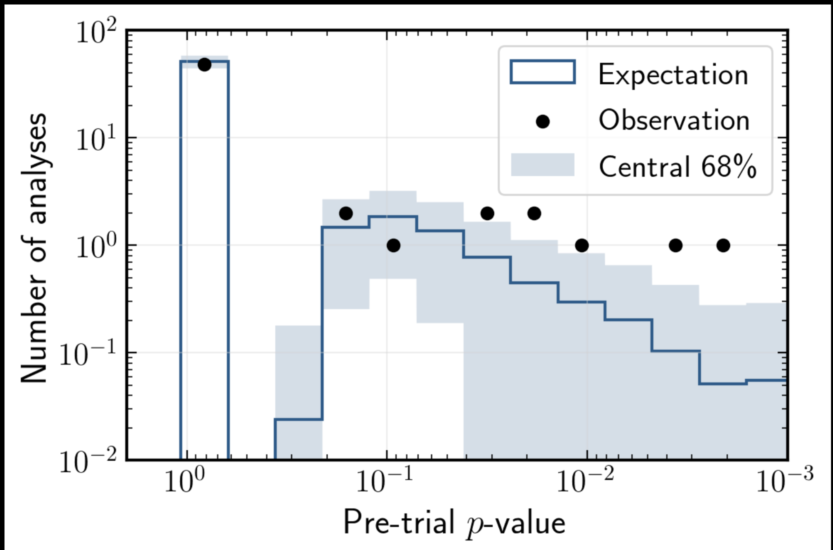
(C) CRs and cosmogenic ν's

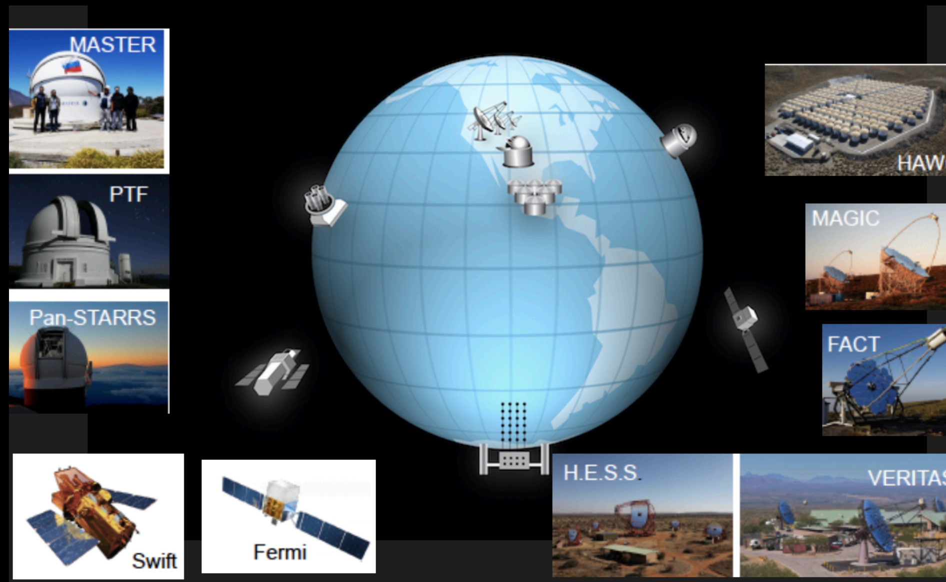
The origin of the extragalactic component of the IceCube diffuse neutrino flux Blazars and starbursts

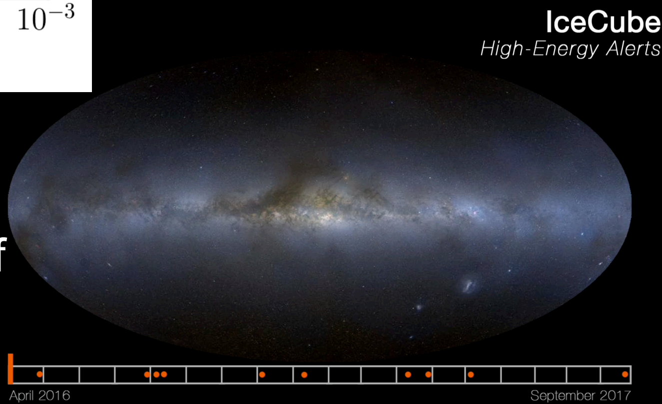
Post.trial p-value ~1%

The first IceCube real-time public alerts

58 alerts followed up by a Fast Response Analysis:
the obtained p-values is compared to pseudo-experiments with background only

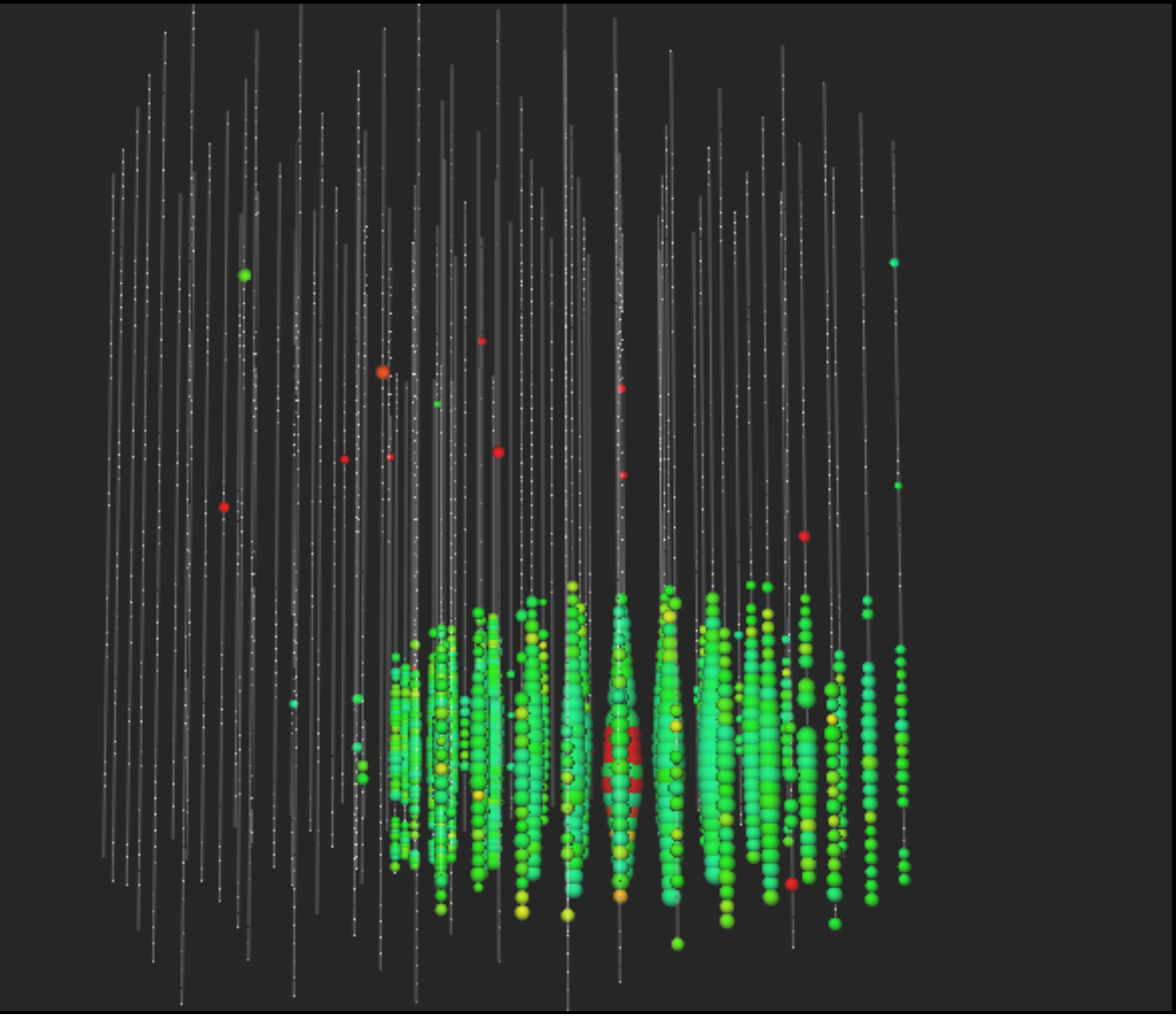






20-30 alerts per year since 2016, with <1 minute latency
One of them triggered the activity of a network of multi-band telescopes
E. Blaufuss et al, 2019

Neutrino event of 480 TeV: stay tuned



IceCube-220625A - IceCube observation of a high-energy astrophysical neutrino candidate event

ATel #15472; ***Marcos Santander (Univ of Alabama) for the IceCube Collaboration***
*on **25 Jun 2022; 17:32 UT***
Credential Certification: Marcos Santander (jmsantander@ua.edu)

Subjects: Neutrinos

Tweet

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

On 2022-06-25 at 14:14:38.53 UT IceCube detected a cascade-like event with a high probability of being of astrophysical origin (p ~ 0.9). The event was selected by the ICECUBE_CASCADE alert stream. The IceCube detector was in a normal operating state at the time of detection.

The online reconstruction of the event yields the following directional information (in J2000 coordinates):
RA: 179.39 deg
Dec: -4.16 deg
Localization uncertainty radius (at 90% containment): 5.86 deg

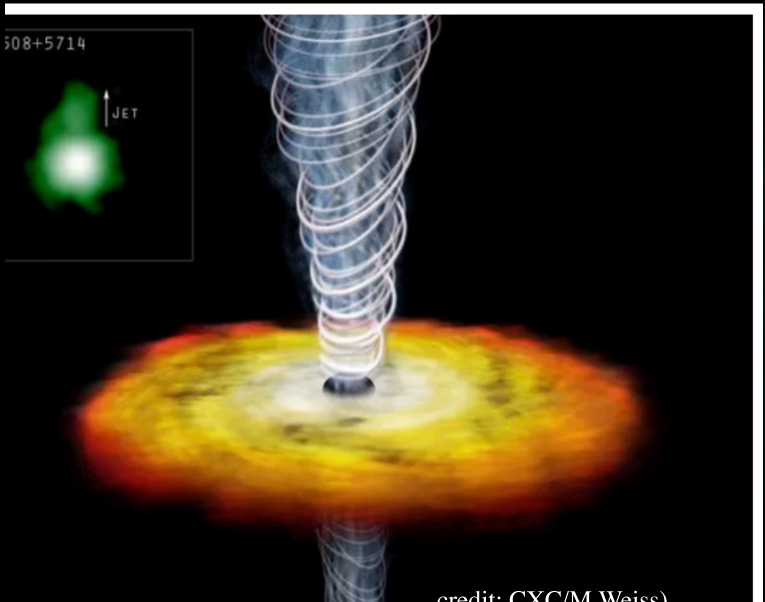
Additional information regarding this alert is provided in the initial GCN Notice and a HEALPix localization skymap is available in the GCN IceCube Cascade Alert webpage. The high energy of this candidate neutrino event (preliminary estimate: 480 TeV) makes it one of the highest energy cascade events detected by IceCube in recent years. We therefore encourage follow-up by ground and space-based instruments to help identify a possible astrophysical source for the candidate neutrino.

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

Extra-galactic sources: Blazars (jetted AGNs)

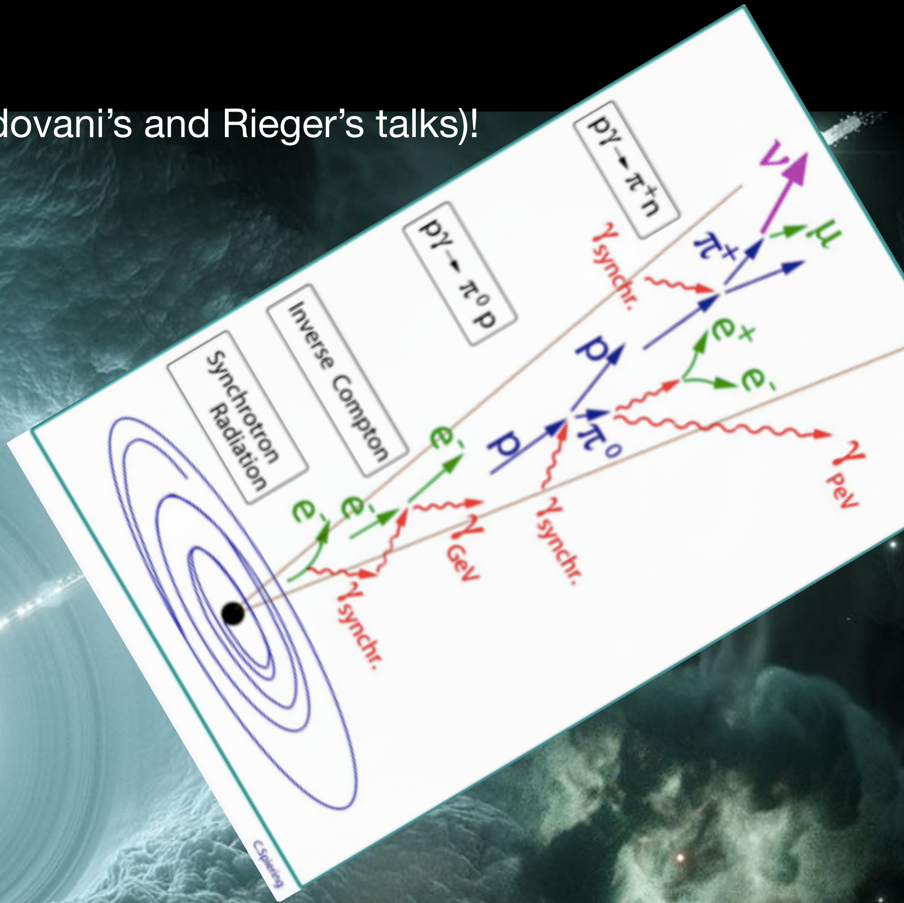
Where does acceleration occurs and how? It may occur at the termination shocks of the jets in intergalactic space or at distances of 100 Mpc where the material is reduced and consequently neutrino production.
Where/When does production of neutrinos occur? in the corona near the BH or in collisions of accelerated particles diffusing in the magnetic field of the host galaxy of the BH.

IceCube limit at 10 TeV-2 PeV with Fermi 2LAC blazars (ApJ 2016) assumes same spectra for ν's as γ's (ignoring variability) or some plausible spectra of neutrinos 27% for $E^{-2.2}$ and 50% for $E^{-2.5}$



credit: CXC/M.Weiss)

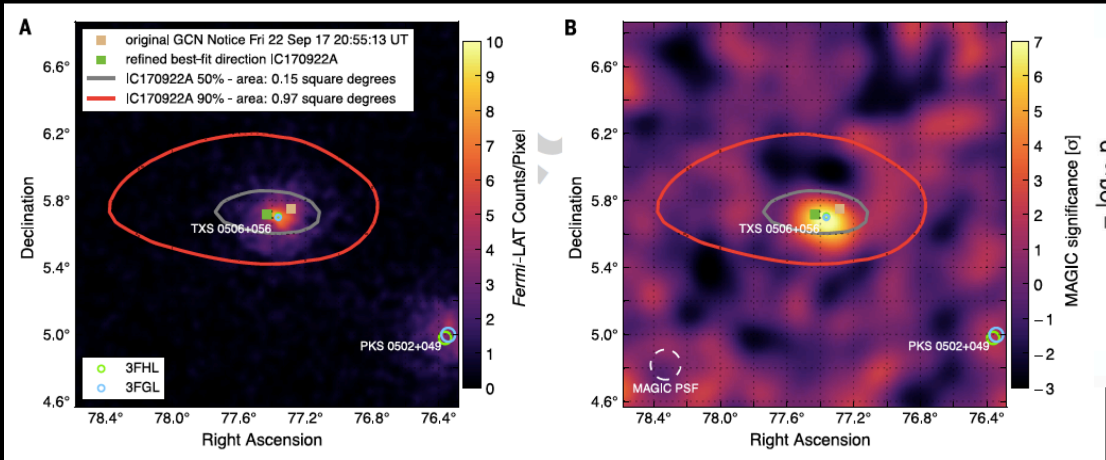
Many unknowns (see Padovani's and Rieger's talks)!

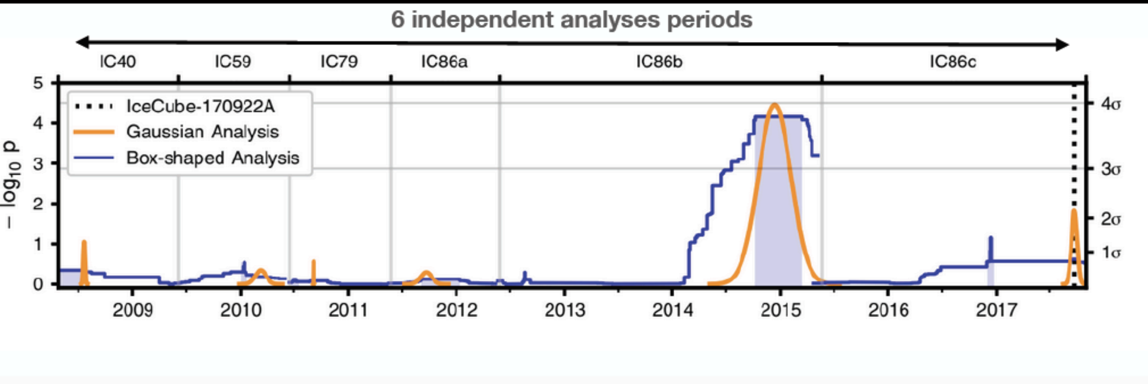


The follow ups of IC170922A and historical data of IceCube

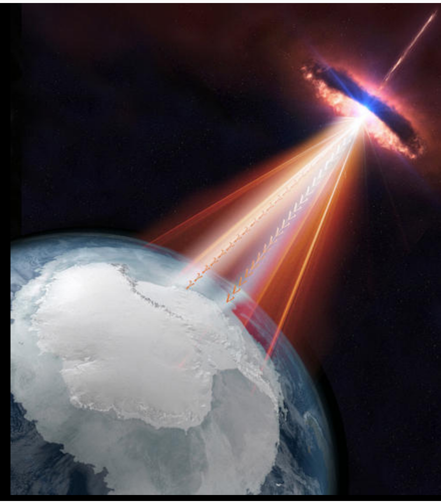
IceCube sent an alert including the direction of a muon neutrino event of ~ 3 x 10^{14} eV in only 43 s. Shortly after, Fermi (20 MeV-300 GeV) discovered a blazar, TXS 0506+056 at 0.06° distance from the IceCube event in a flaring state (ATel#10791). In a follow up from 1.3-40 d, MAGIC detected gamma rays of > 300 GeV energy from the source with >6.2σ (ATel#10817, MAGIC 2018). The probability that this is not a casual coincidence is 3σ post-trial. IceCube found a 2nd flare from the source in 2014-15 with higher significance of 3.5σ post-trial.

Variability up to x6 in 1 d. Among the top 3% most intense blaars in Fermi catalogue. z= 0.336.





Science 361, 147-151 (2018)
A. Christov thesis UNIGE archive



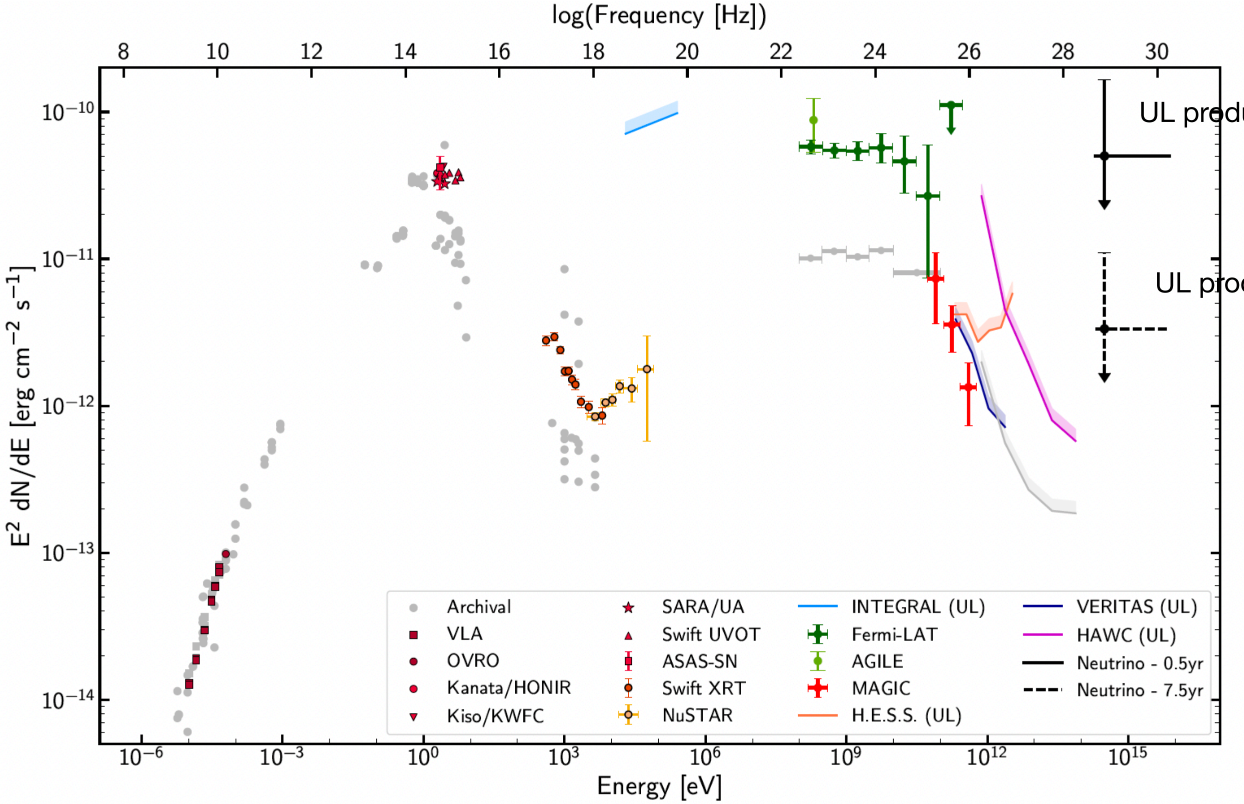
MAGIC @ Los Roche de los Muchachos, La Palma

The first SED with hadronic guesses: TXS 0506+056

Leptonic scenarios:

Synchrotron Self-Compton (SSC): seed photons for IC scattering are synchrotron photons produced by nonthermal electron–positron pairs accelerated in the jet.

Emission or external inverse-Compton (EIC) : the seeds for Compton scattering are provided by external radiation fields, such as scattered accretion disk radiation, broadline/dust emission, and soft radiation from the sheath region of a structured jet.

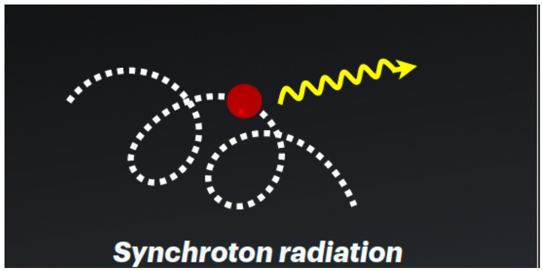


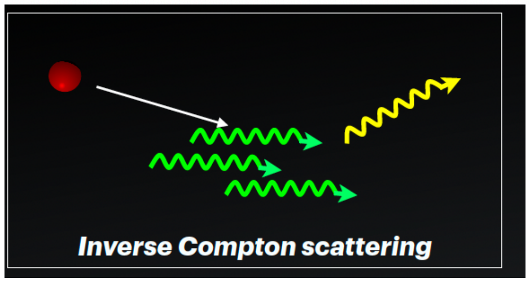
UL producing one detection as IC170922A in 0.5 yr
Assuming E^{-2}

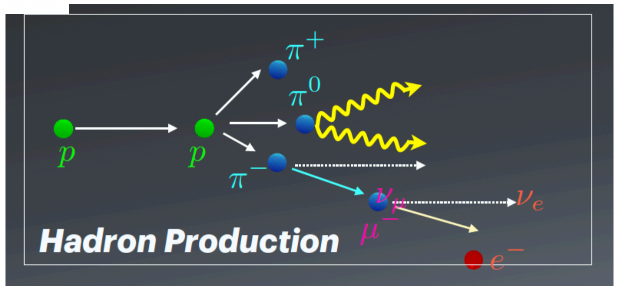
UL producing a detection as IC170922A in 7.5 yr

Data and limits on observed UV/X-ray flux of $F_x \sim 10^{-12}$ erg cm^{-2} s^{-1} for TXS 0506+056 constrain the target photon luminosity and required proton power

Hadronic scenarios:





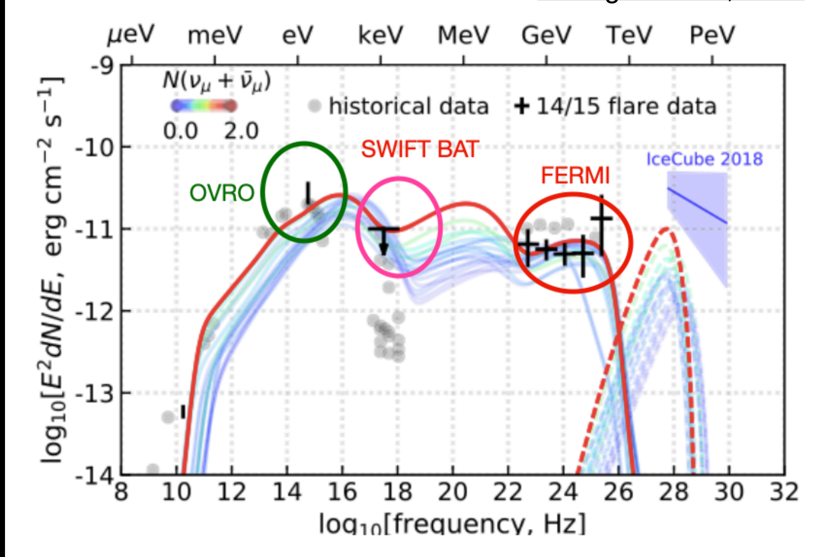


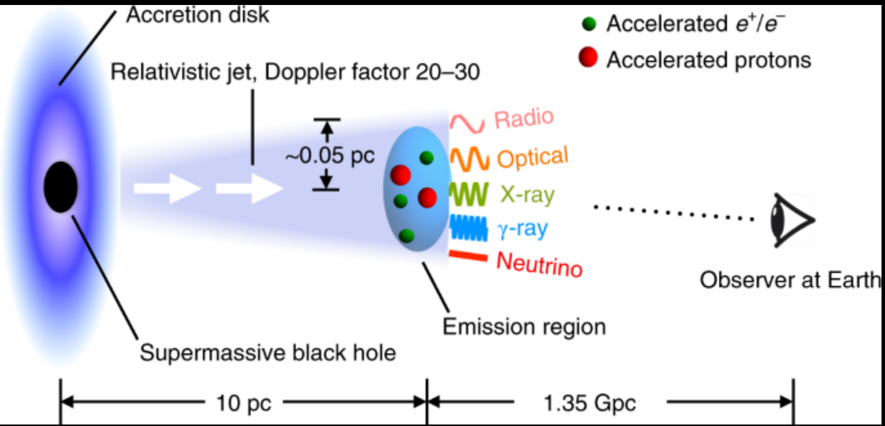
Phenomenological interpretation

Protons can efficiently be accelerated in blobs/sheets of matter traveling in the jet with $\Gamma \sim 10$ and the duration of the burst is linked to the blob size $\Gamma c \Delta t \sim 10^{-2} pc$ in the observer frame.

The 2014/15 ν flare challenges **single-zone hadronic models.** If MWL data are fit, due to X-ray limit by Swift at ~10^{-11} erg cm^{-2} s^{-1} the SED cannot explain the observed high ν flux in the 2014/15 flare. If model parameters are tuned to also fit IceCube data, the X-Swift upper limit during the flare is overshoot since an efficient em cascade and electron synchrotron emission is not preventable.

Rodrigues et al, 2019

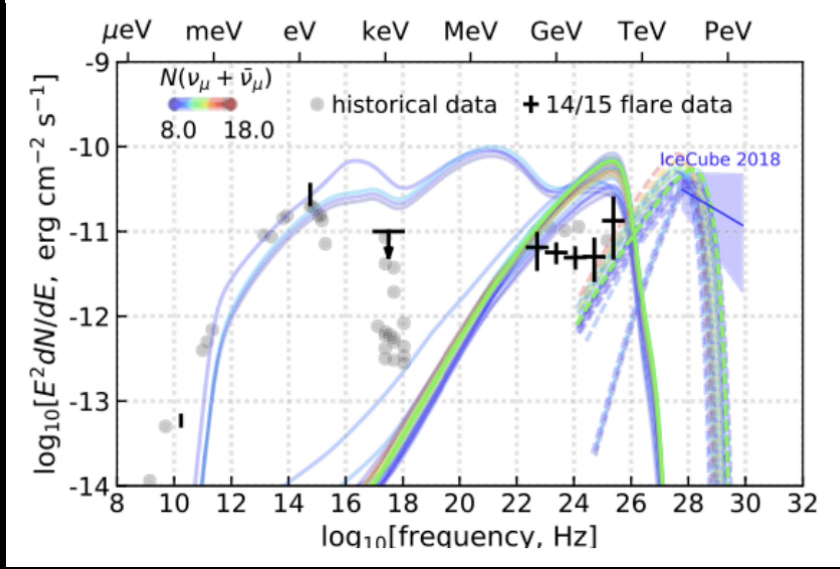




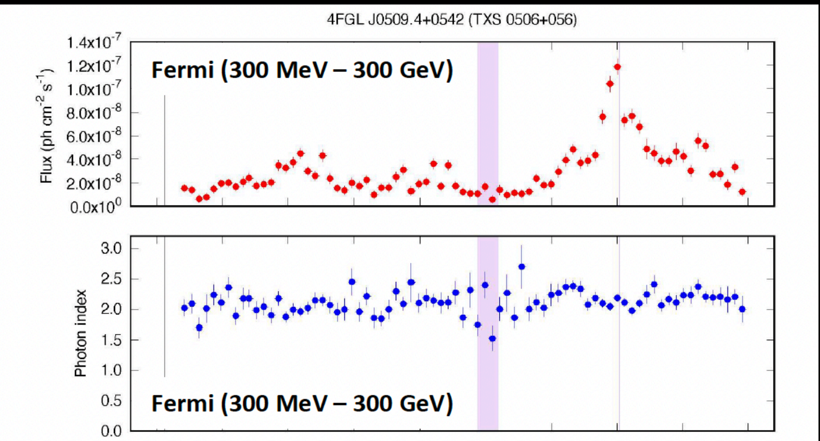
Gao et al. Nature Nov. 2018

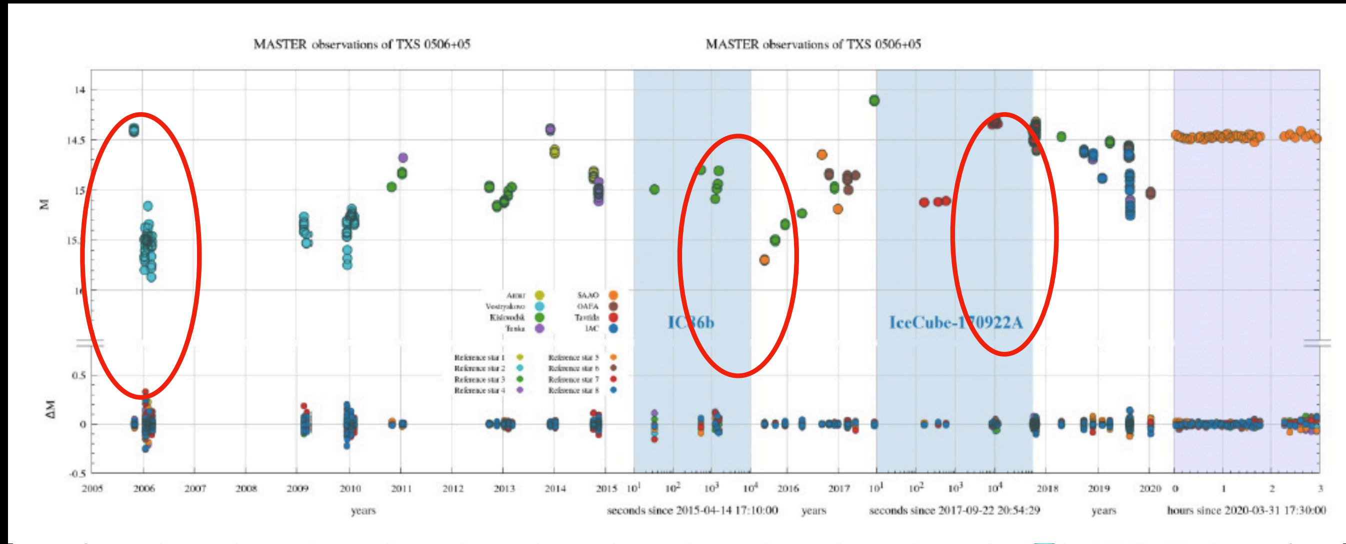
Keivani et al, 2019,

A. Reimer et al. ApJ 881 2019,
F. Halzen et al. ApJL 874 2019

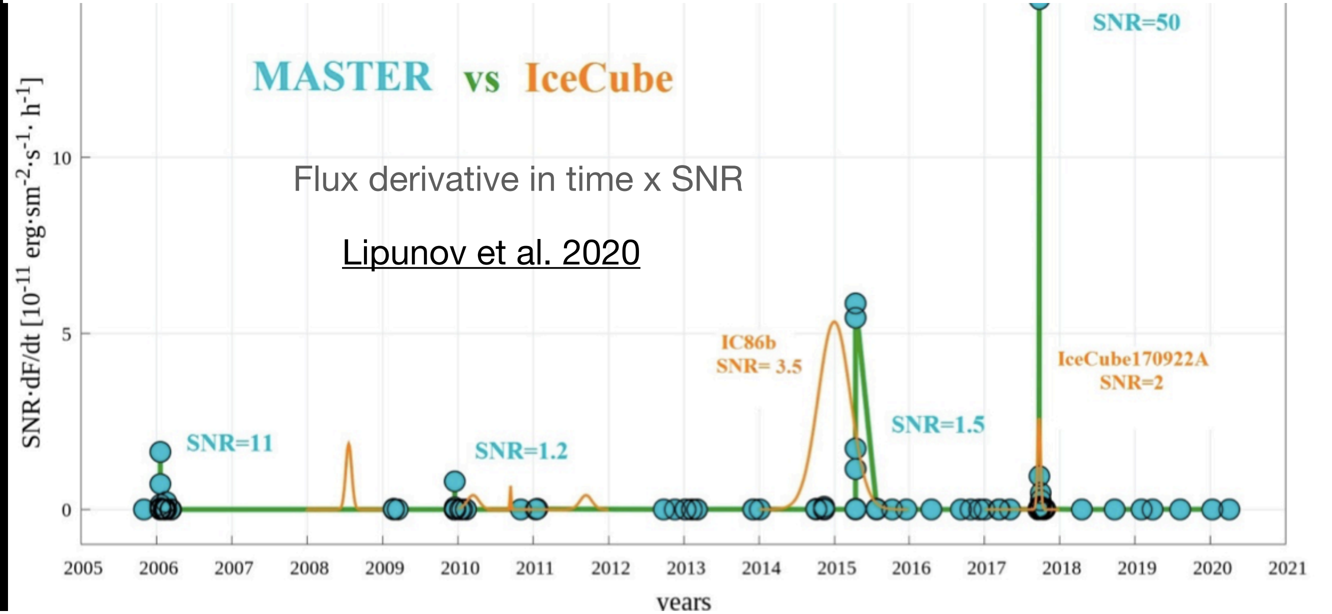


MWL observations of the 2014-2015 flare



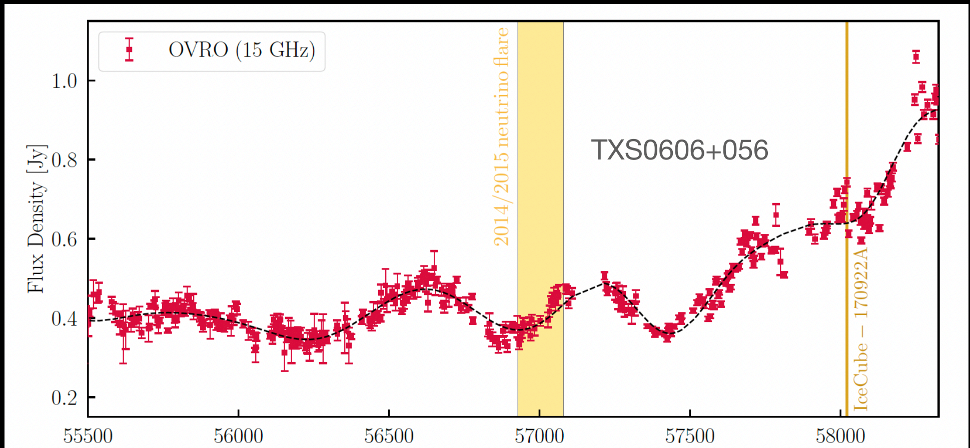


A huge flare in Fermi-LAT for 2017 event, no MWL activity aside from an optical flare reported by MASTER in 2014-2015 but some possible hardening of spectrum.



Optical matters: 2 hr after the 2017 event the blazar switchses on in the optical. Another optical variation follows the 2015 excess in IceCube.

Another event?



IceCube Another 300 TeV neutrino is observed in space-coincidence with PKS 1502+106 (z ~1.8) low-spectral peaked and highly polarized quasar (Stein et al GCN 25225).

[Previous | Next | ADS]

Neutrino candidate source FSRQ PKS 1502+106 at highest flux density at 15 GHz

ATel #12996; *S. Kiehlmann (IoA FORTH, OVRO), T. Hovatta (FINCA), M. Kadler (Univ. WÃ¼rzburg), W. Max-Moerbeck (Univ. de Chile), A. C.S. Readhead (OVRO)*

on ***7 Aug 2019; 12:31 UT***

Credential Certification: Sebastian Kiehlmann (skiehlmann@mail.de)

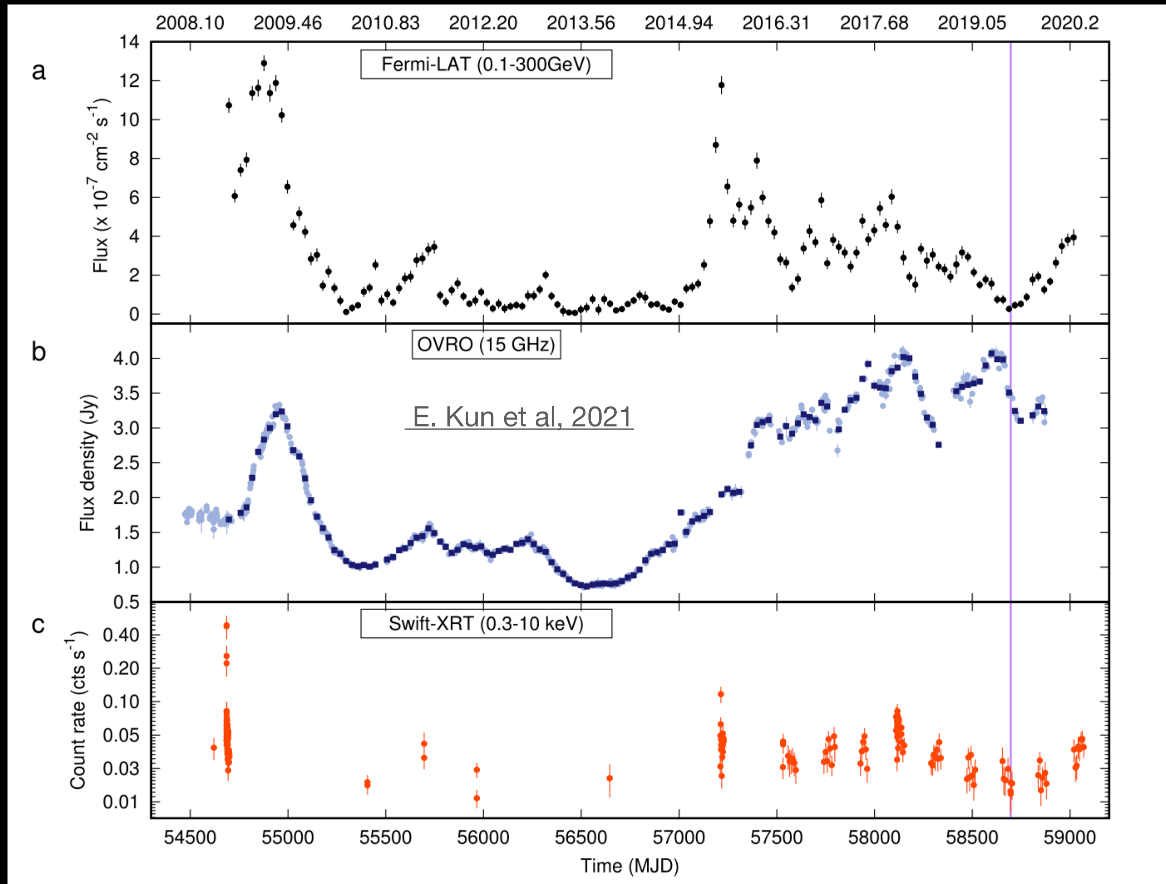
Subjects: Radio, Neutrinos, AGN, Blazar, Quasar

Tweet

On 2019/07/30.86853 UT IceCube detected a high-energy astrophysical neutrino candidate (Atel #12967). The FSRQ PKS 1502+106 is located within the 50% uncertainty region of the event. We report that the flux density at 15 GHz measured with the OVRO 40m Telescope shows a long-term outburst that started in 2014, which is currently reaching an all-time high of about 4 Jy, since the beginning of the OVRO measurements in 2008. A similar 15 GHz long-term outburst was seen in TXS 0506+056 during the neutrino event IceCube-170922A.

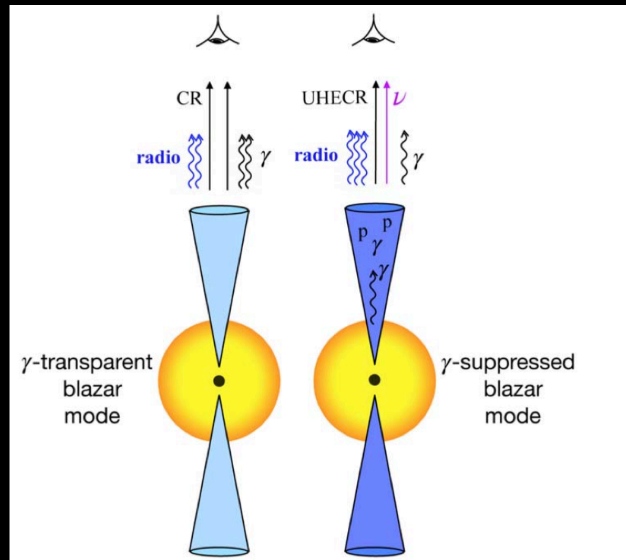
Related

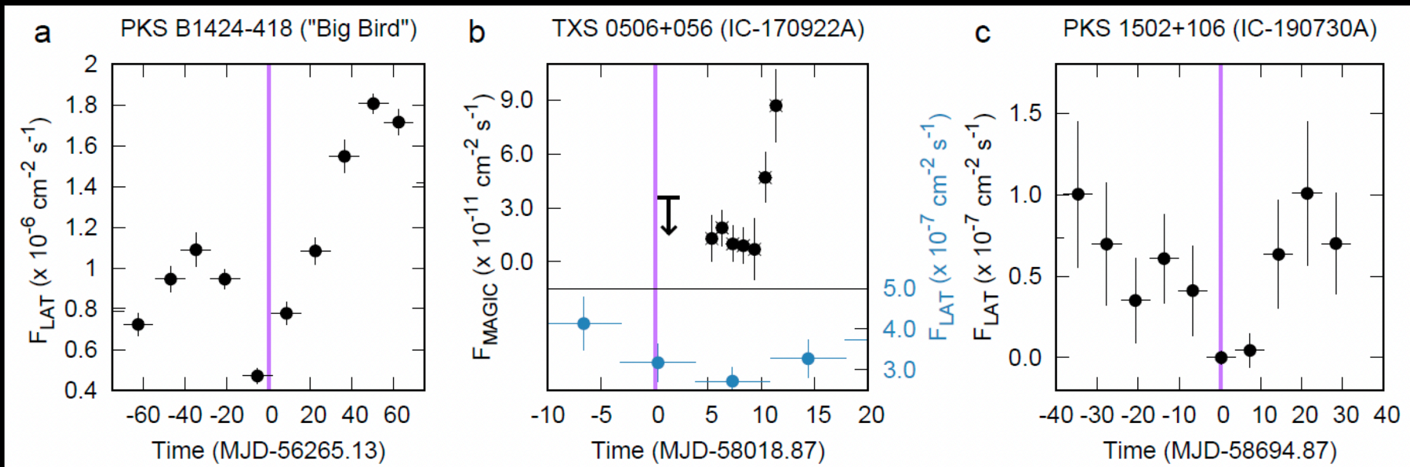
12996	Neutrino candidate source FSRQ PKS 1502+106 at highest flux density at 15 GHz
12985	IceCube-190730A: Swift XRT and UVOT Follow-up and prompt BAT Observations
12983	Optical fluxes of candidate neutrino blazar PKS 1502+106
12981	ASKAP observations of blazars possibly associated with neutrino events IC190730A and IC190704A
12974	Optical follow-up of IceCube-190730A with ZTF
12971	IceCube-190730A: MASTER alert observations and analysis
12967	IceCube-190730A an astrophysical neutrino candidate in spatial coincidence with FSRQ PKS 1502+106
12926	VLA observations reveal increasing brightness of 1WHSP J104516.2+275133, a potential source of IC190704A



A special class of blazars?

A sub-class of blazars with TXS 0506+056 luminosity and flaring for ~100 d, representing 5% of blazars, are very efficient accelerators when VHE photons are more absorbed can explain IceCube diffuse flux. For TXS 0506+056, $\tau_{p\gamma} \sim 0.4 \Rightarrow \tau_{\gamma\gamma} \sim O(100)$





Kun, Bartos, JBT, Biermann, Halzen, Mez´´o ApJL (2021)

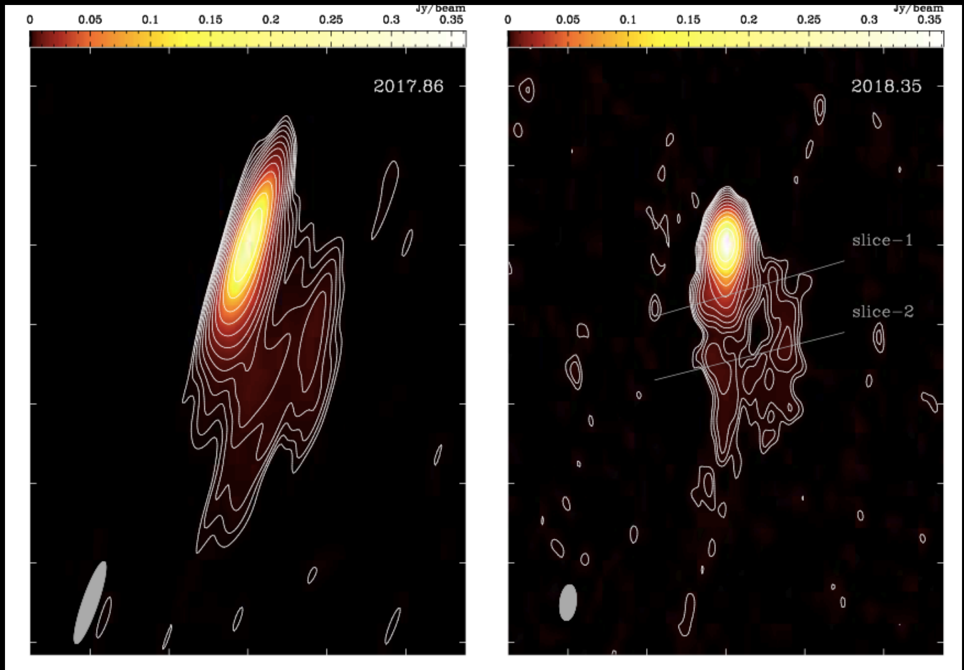
Structured or multiple jets?

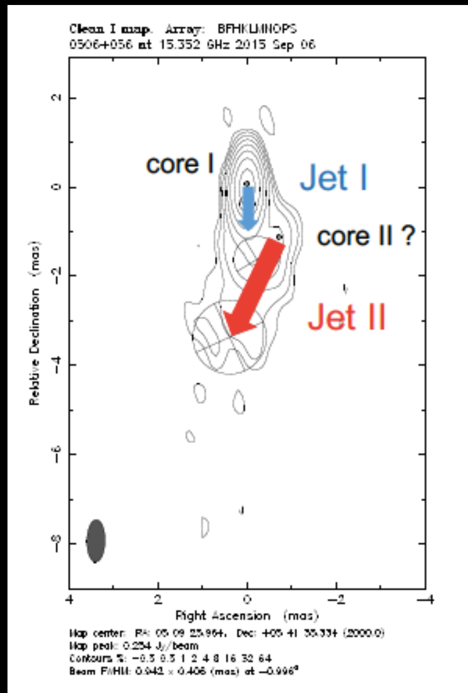
Ros et al A&A 633, 2020:
Nov. 2017 and May 2018 mm-VLBI radio 43 GHz observations indicate a compact core with highly collimated jet and a downstream jet showing a wider opening angle (slower) external sheat (loss of collimation of the jet beyond 0.5 mas). The slower flow serves as seed photons for $p-\gamma$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

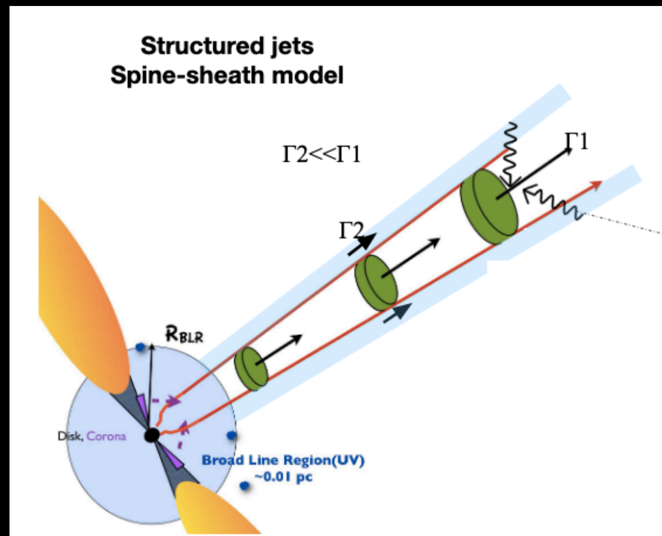
Britzen et al. A&A 630 (2019): VLBA 15 GHz observations from 2009-18 indicate a strongly curved jet leading to 2 scenario interpretation for 2014-15 ν flare:

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 and ν's can be produced in such colliding material.

Spine-sheat models: predict large neutrino fluxes and compatible X-ray fluxes. Protons may collide with a slower moving and denser region of jetted photons in the , structured jets (spine-sheat Ghisellini, Tavecchio, Chiaberge 2015, Sikora, Rukowski, Begelman. 2015; Murase, Oikonomou, Petropoulou 2018).



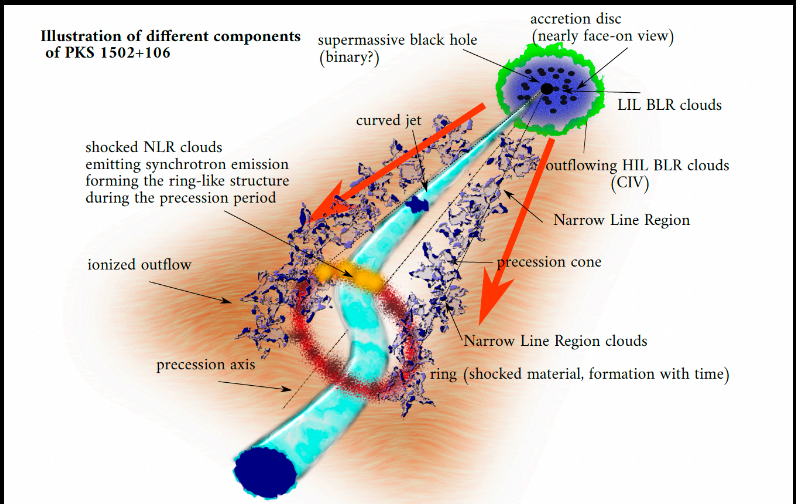




Radio observations

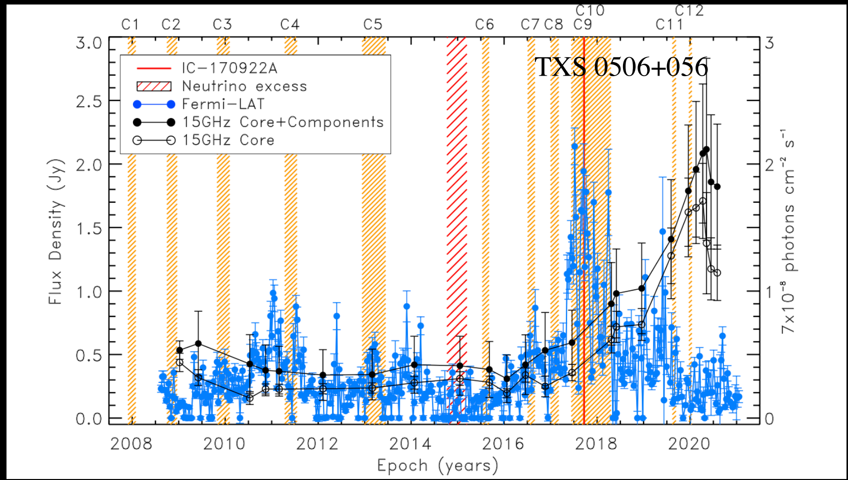
PKS1506+106: Precessing curved jet interacting with the NLR clouds at distance of 330 pc and a ring-like and arc like configuration developing right before the neutrino emission and not present at all times. The ring is offset from the jet axis

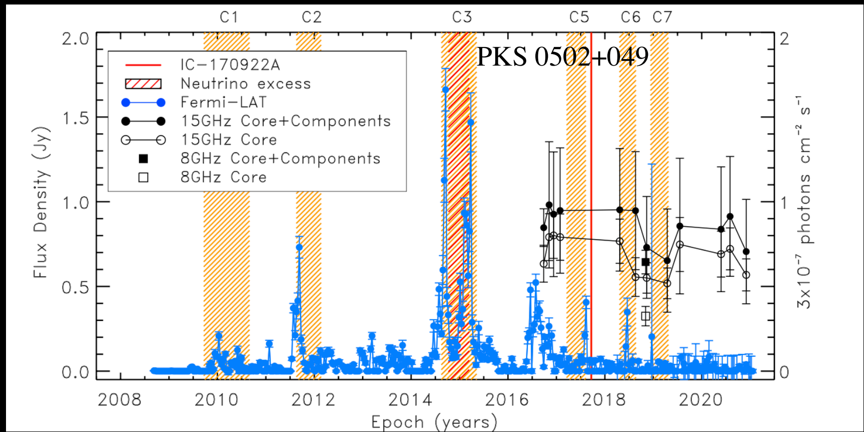
Brizen et al 2021



Identified in VLBI data a radio core and jet extending up to 4 mas with superluminal components of the jets. The emergence of these components coincides with gamma flares and two seem correlated to neutrino events.

Sumida et al 2021

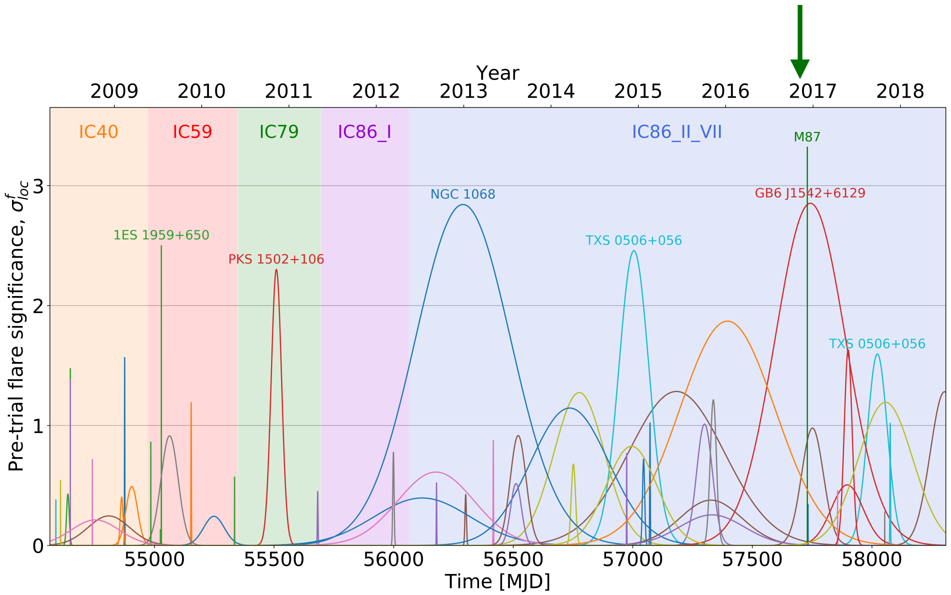




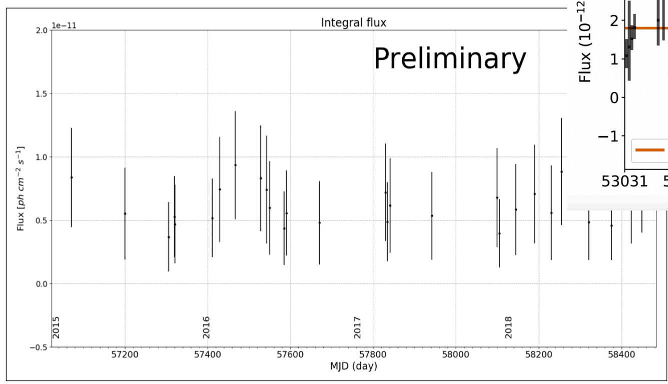
Synergy IceCube-Gen2, CTAO, SKAO!

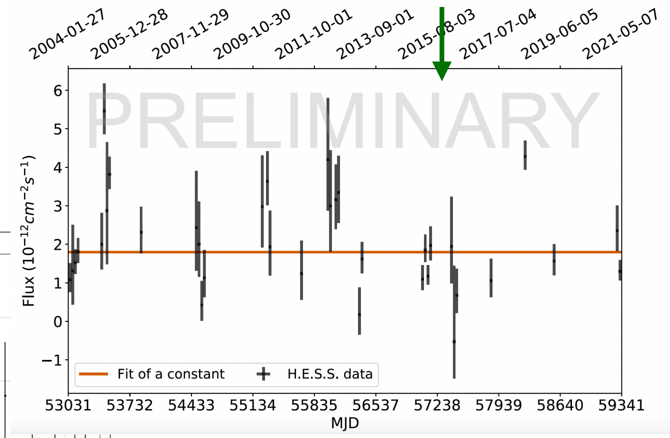
IceCube Multi-flare search on 10 yr data

3 TeV neutrino events in ~15 min on 57730 (Dec. 8, 2016) from the region including M87 make it the hottest source but significance is marginal.



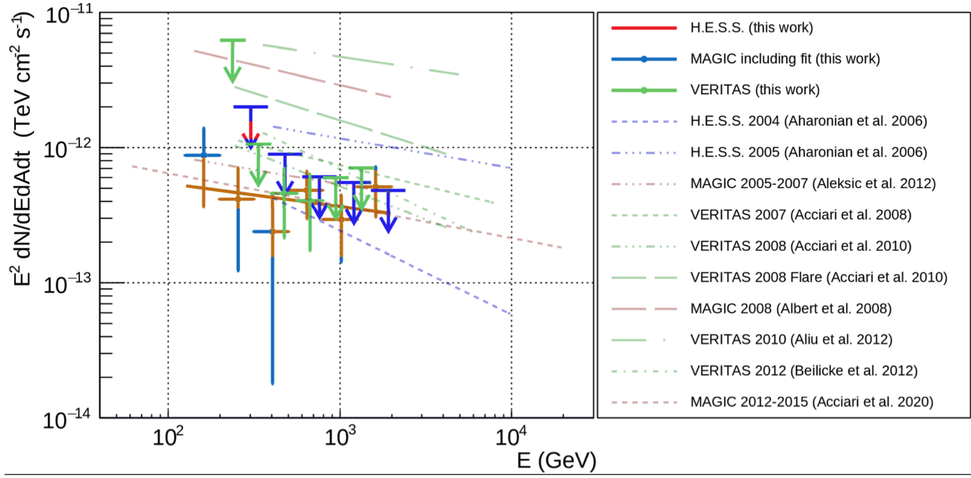
M87 HAWC (J. Goodman's talk)





HESS M87 morphology

Probable low state in Dec 2016?



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. (IceCube PRL 2021)

Largest close by BH: $\sim 10^9 M_\odot$, jet with superluminal motion to 6c
Also a structured jet (Wilkinson 1974), spine - sheat model by Tavecchio & Ghisellini, 2018, 2005
CTAO will have an excellent sensitivity to short flares of minute-day-scale

F. Lucarelli UNIGE

Other possible contributors: starbursts, AGN winds

NGC 1068: the hottest spot in 10 yr IceCube data

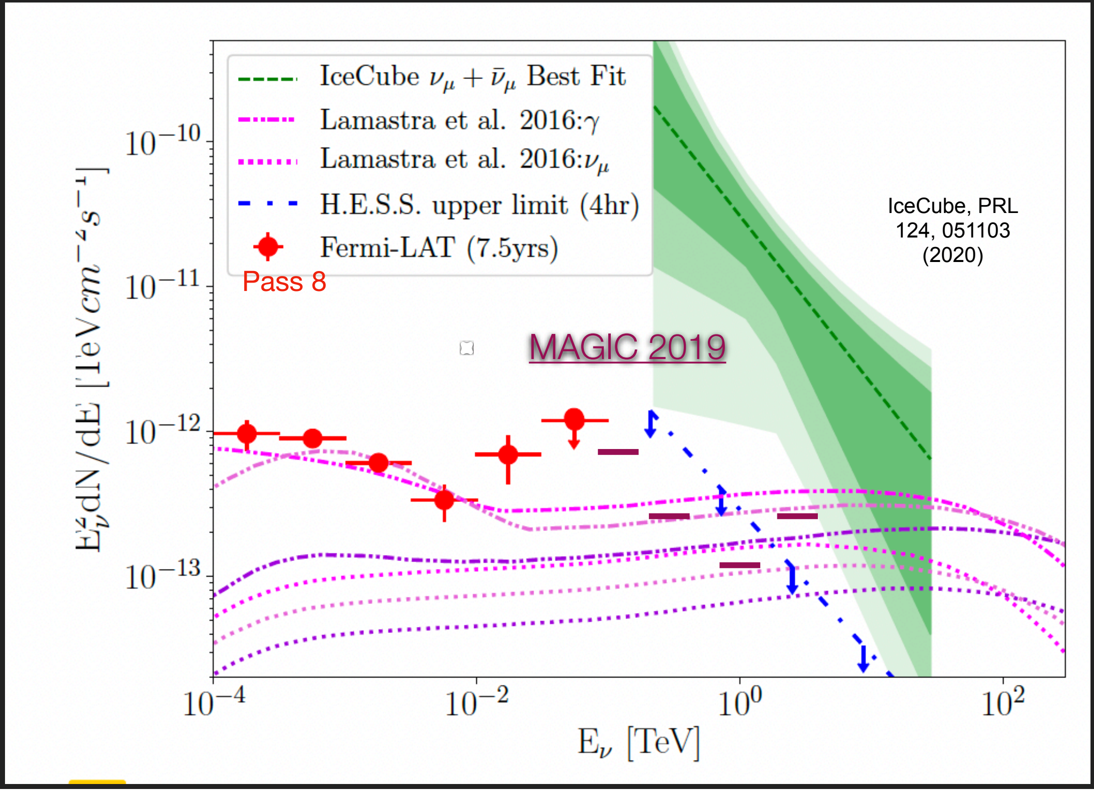
Hottest spot in all sky scan + catalogue of brightest Fermi sources convolved with IceCube sensitivity + 8 galaxies with sturburst activities with 10 yr IceCube data => 2.9σ from a direction compatible to NGC 1068 offset ~0.35°. Offset consistent with simulated tests for a soft flux from a point source with E^-3.3 spectrum as resulting from fit.

Starburst proposed long ago as neutrino sources (Waxman & Loeb, 2006). Small scale anisotropy detected by PAO UHECRs but the role of starburst as UHECRs sources is yet controversial (Lunardini et al. 2019). Some, like NGC 1068, host AGNs with weak jets, but starburst winds can accelerate to 100 PeV (see Peretti's talk, Peretti et al, 2022).

No correlation neutrinos - UHECRs.

Good candidate for LST-1-MAGIC observations to unerstand role of the winds and jets in acceleration of hadrons.

Excess of 3.3σ from the population study of the catalogue dominated by NGC 1068, TXS 0506+056, PKS 1424+240,GB6 J1542+6129.



Close - by jets in intense star formation regions

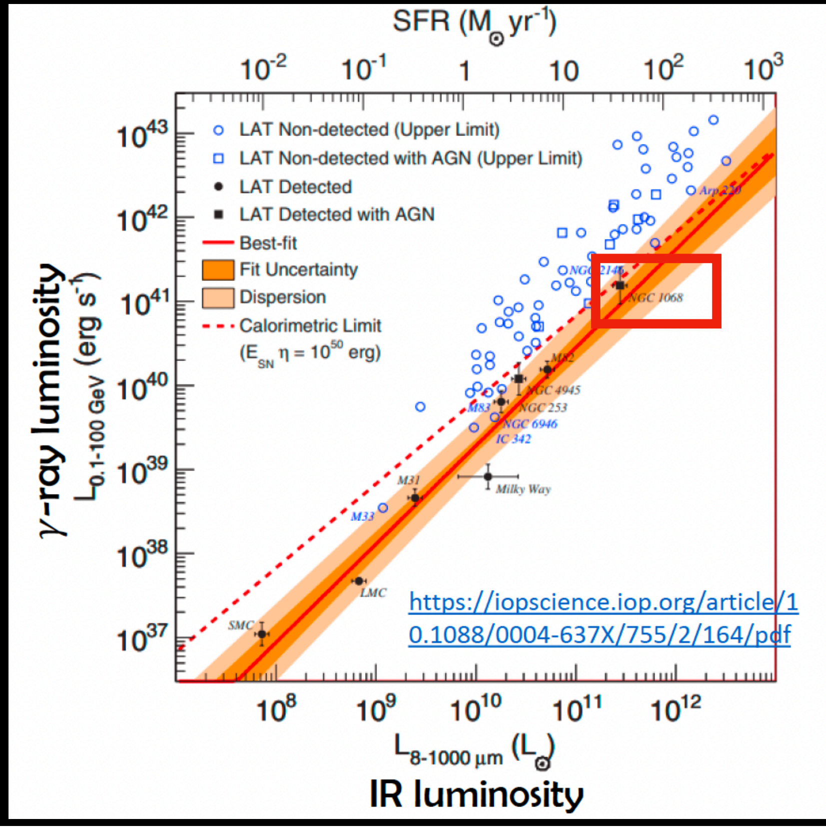
NGC 1068 is one of the closest Seiyfert II galaxy at 14.4 Mpc and one of the brightest starburst in the Fermi sample, with non thermal contribution from their core from a jet.
Column density ~10^{25} cm$^{-2,}$ intense star formation, bright in X-rays and < 10 GeV gamma rays but not in > 100 GeV gamma-rays due to absorption. Can be an interesting target for LST-1 + MAGIC to understand the interplay between the AGN, star winds and star formation is indicated by high NIR and FIR stellar formation. Stellar winds and dusts can contribute to the neutrino flux.

COSMIC RAYS FROM ACTIVE GALACTIC NUCLEI AND IN METAGALACTIC SPACE

M. M. SHAPIRO[1, 2] AND R. SILBERBERG[2]

Received 1982 March 29; accepted 1982 May 26

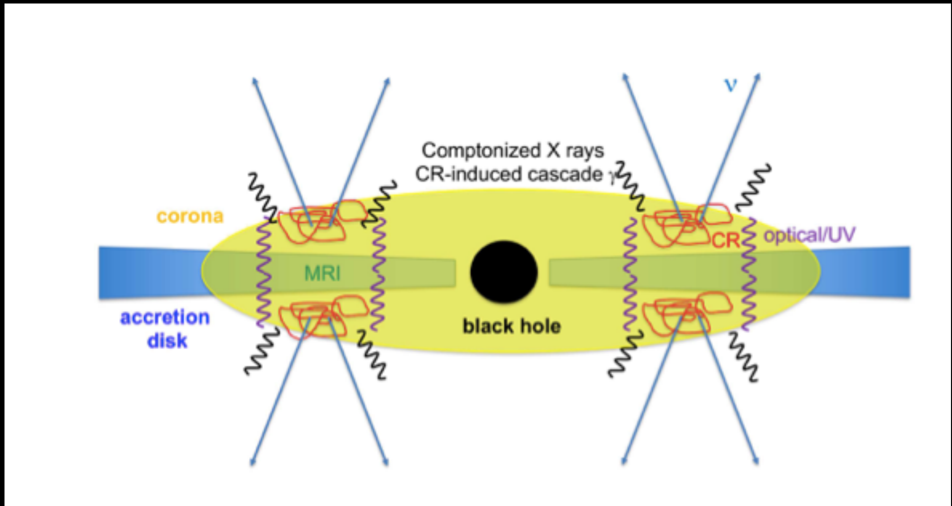
Supercluster is $\sim 10^{43}$ ergs s^{-1}. The rate of nonthermal energy output of radio galaxies in the supercluster region (from Cen A, Virgo, and Fornax) is also about 10^{43} ergs s^{-1}. On the other hand, the power output of Seyfert galaxies is of the order of 2×10^{45} ergs s^{-1}, within ~ 15 Mpc, mainly from NGC 4151 and NGC 1068 (Kafatos, Shapiro, and Silberberg 1981, and references therein). For a cosmic-ray confinement time of 10^9 years in the supercluster, the Seyfert galaxies alone could support $\sim 10^{-4}$ eV cm^{-3}, and for a 10^{10} year confinement, $\sim 10^{-3}$ eV cm^{-3}. (For $E \gtrsim 10^{19}$ eV, the confinement time is $\sim 10^8$ years, as discussed at the end of this section.) These values are consistent with the intergalactic energy density of cosmic rays ($\sim 10^{-4\pm1}$ eV cm^{-3}) calculated above; thus, in principle, the Seyfert galaxies can satisfy the cosmic-ray power requirement in metagalactic space within the supercluster. Normal galaxies and radio galaxies, on the other hand, fall short of this requirement by two orders of magnitude.



Neutrinos from the core of AGNs

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

IceCube 2021



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

selection:

- X-ray catalogues 2RXS + XMMSL2
- IR WISE catalogue: X-rays associated with the core produce infrared light on dust at the center of the galaxy

correlation between cores of active galaxies and cosmic neutrinos

(γ = -2.03; 2.6σ post trial)

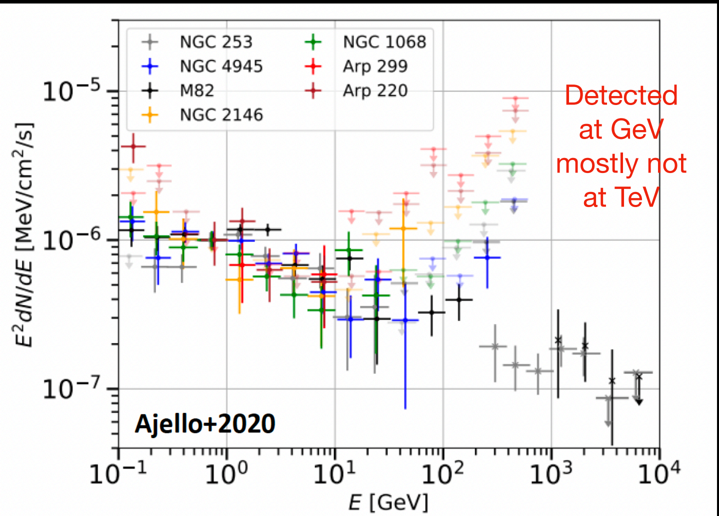
The neutrino emission is assumed to be proportional to the accretion disk luminosity estimated from the soft X-ray flux. Next to the observed soft X-ray flux, the objects for the three samples have been selected based on their radio emission and infrared color properties.

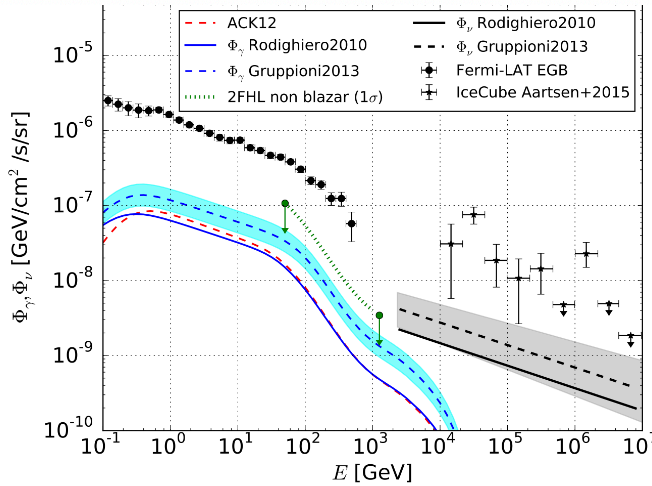
NGC 1068: tthe neutrino emission can be produced in the vicinity of the supermassive BH in the center of the galaxy, namely in the **corona, an optically thick environment.** A large optical depth requires the presence of a **compact and dense** X-ray target of keV photons (it depends on the size of the emitting region in units of Schwarzchild radius $R_S = \dfrac{2GM}{c^2}$ and on the X-ray luminosity)

IceCube search for ULIRG **Ultra-Luminous Infrared Galaxies**

Diffuse flux from starbursts

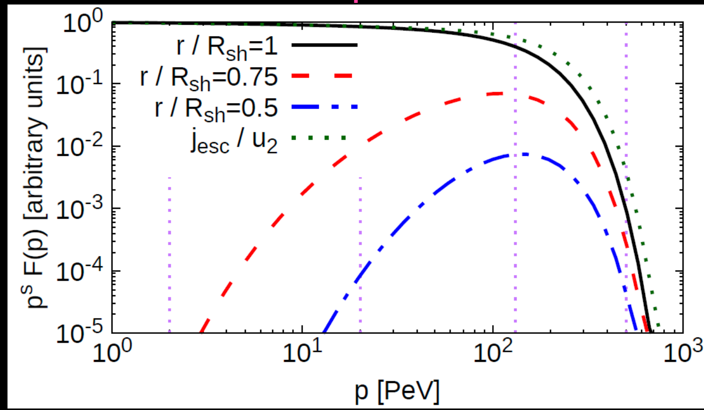
Ajello et al, 2020 : cumulative emission assuming average spectrum from 13 SBG detected by Fermi cumulatively.



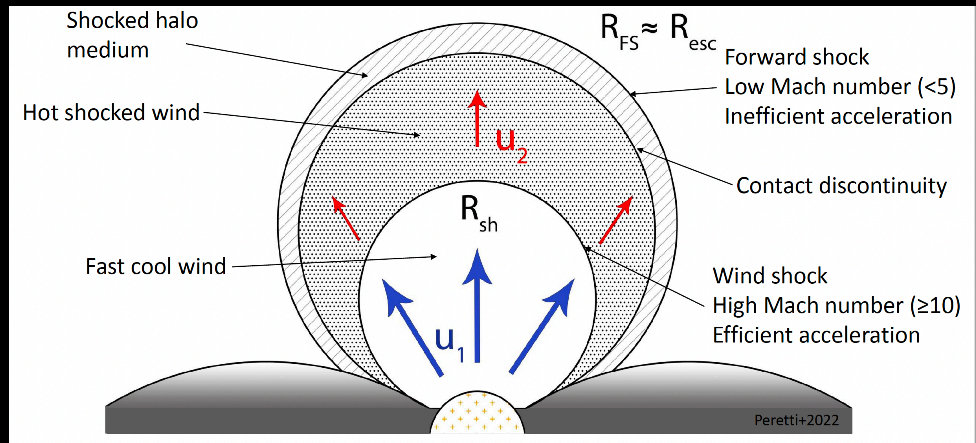


5% contribution to IceCube diffuse flux. Previously < 1% (Tamborra 2014, Bechtol et al 2017)

Transport in Starburst Nuclei : Emax up to 100 PeV (Peretti's talk)=> neutrinos up to 10 PeV

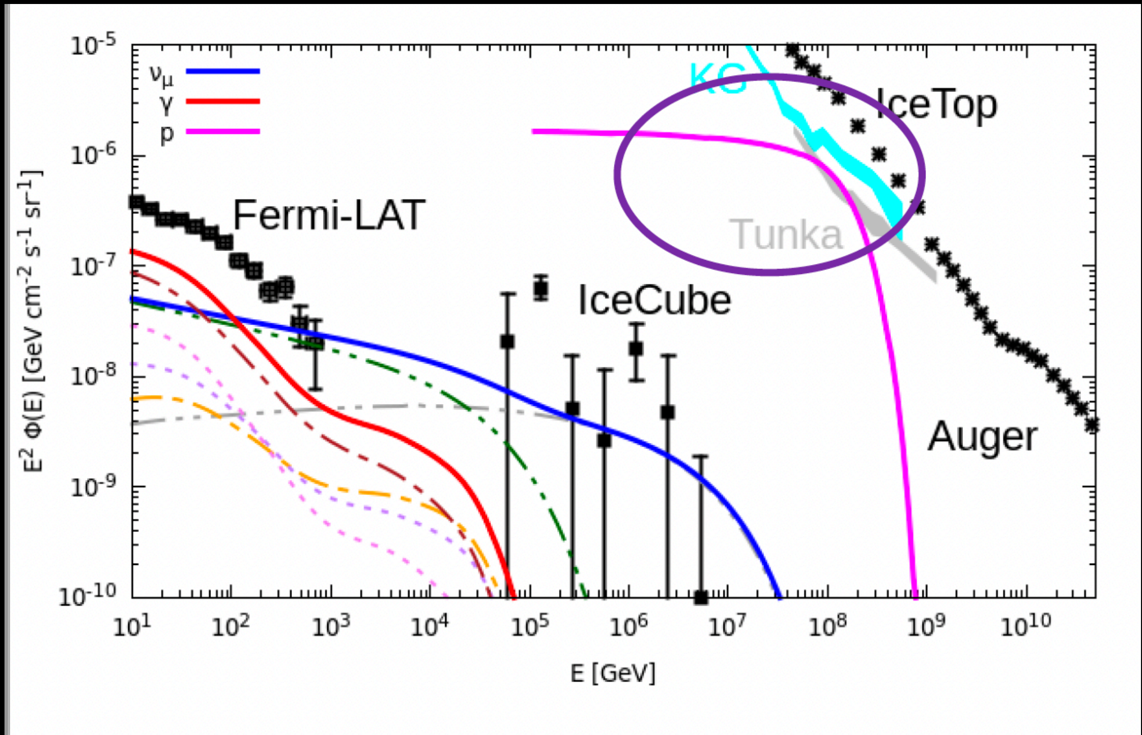


Winds can be sustained ~100 Myr.



Extragalactic and Galactic wind bubbles

One of the most intriguing neutrino candiate producer. LHAASO 1.4 PeV gamma



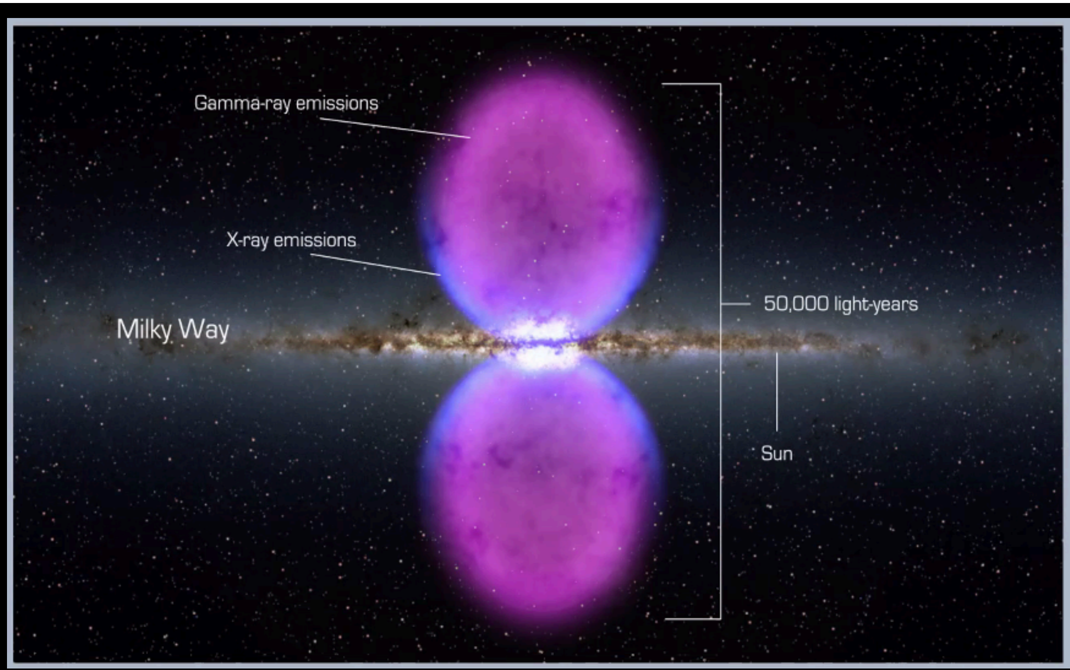
The galactic extende flux: Fermi Bubbles

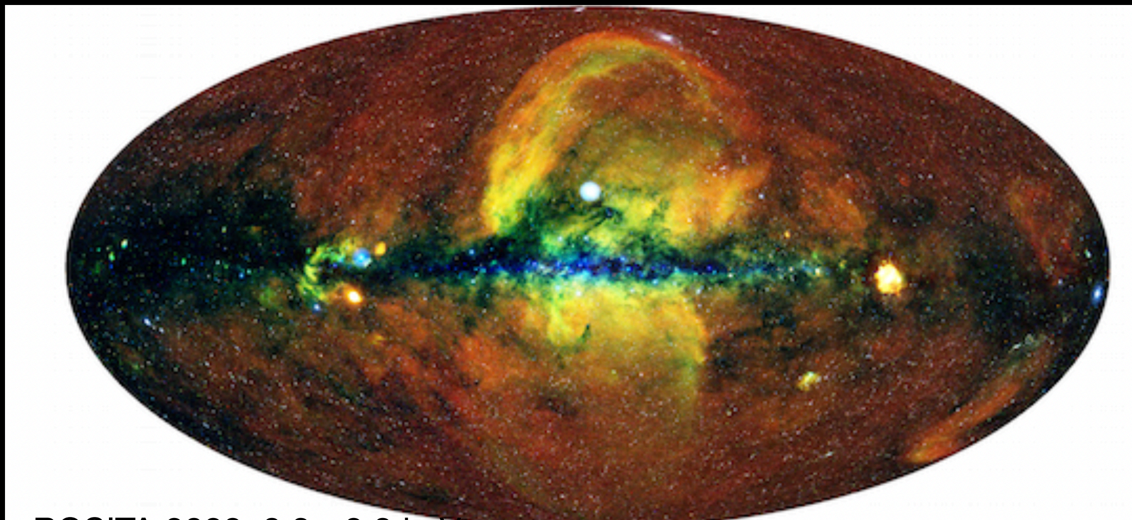
WMAP Haze (Finkbeiner 2004); discovery in gamma-rays (Su et al 2010). ROSAT in X-ray map at 1.5-2 keV (Snowden et al 1997), and X-rays are more extended than γ-rays.

γ emission is of leptonic or hadronic origin? Constrain from hard spectrum $E^{-2.1}$:

- hadronic models: protons have to be transported by starburst or AGN winds that do not easily cool (hadronic models). For hadrons cooling takes > 25-100 Myr (Crocker & Aharonian 2011, protons and ions injected by longtime scale processes & star formation and winds).
- Leptonic jet models : electrons quickly transported in AGN jets before they cool. Due to short TeV-electron cooling predict several Myr ;
- In situ acceleration models : CRs accelerated in situ by shocks or turbulence near the shock front.

Many components: γ-rays from CRs+ISM; electron synchrotron in B-field + IC of electrons on CMB, starlight, IR from dust (GALPROP); contamination from many extra-galactic sources and mis-classified charged particle; point sources; FB; GC excess, Sun, Moon, extended sources as LMC, Cygnus, giant radio Loop, DM? (Fermi 2017)





eROSITA 2022: 0.3 - 2.3 keV

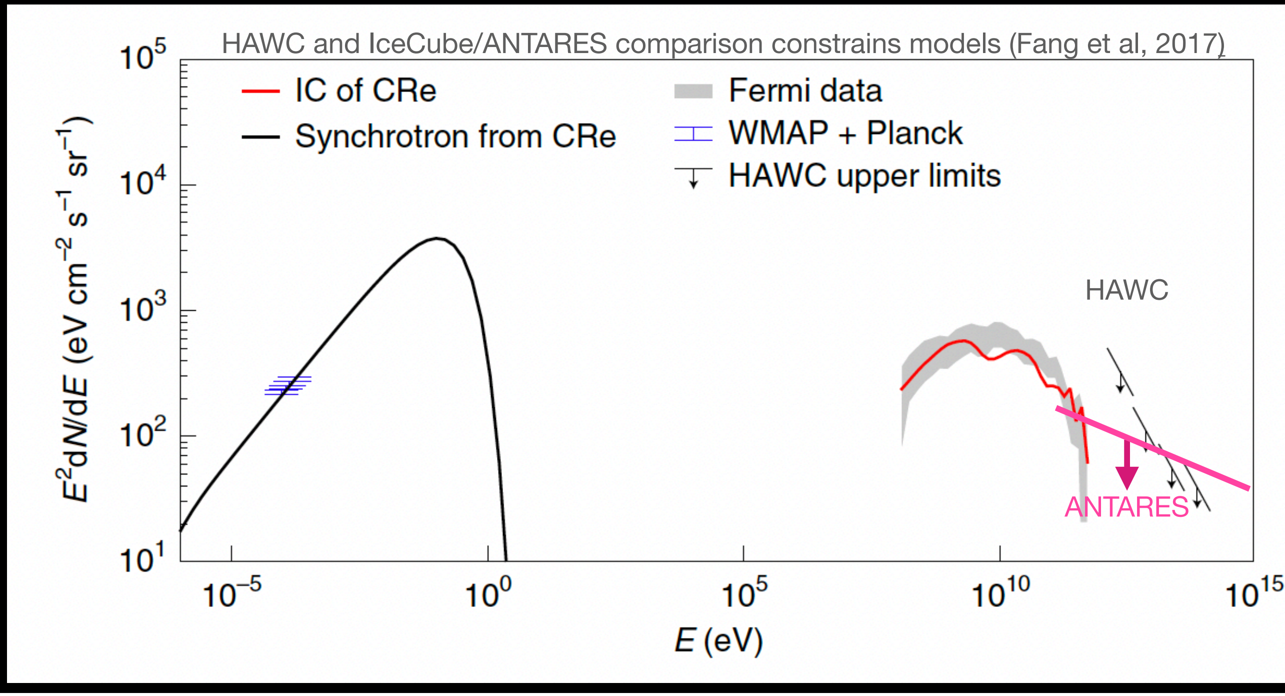
The FB after eROSITA: leptonic jet models

- Leptonic models:

  - Zhang & Guo 2020: (pre-eROSITA model) in situ shock-acceleration model of CRs. The hydrodinamic simulation of a collimated relativistic jet of **Sgr A* with forward shock moving at ~2000 km/s (edge of bubbles) generated when the jet punches the ambient gas**. After ~5 Myr ago, for an injected energy of 10^{55} erg, the bubble takes the measured dimensions. The model does not explain eROSITA observations due to the larger X-ray region than gamma-rays.

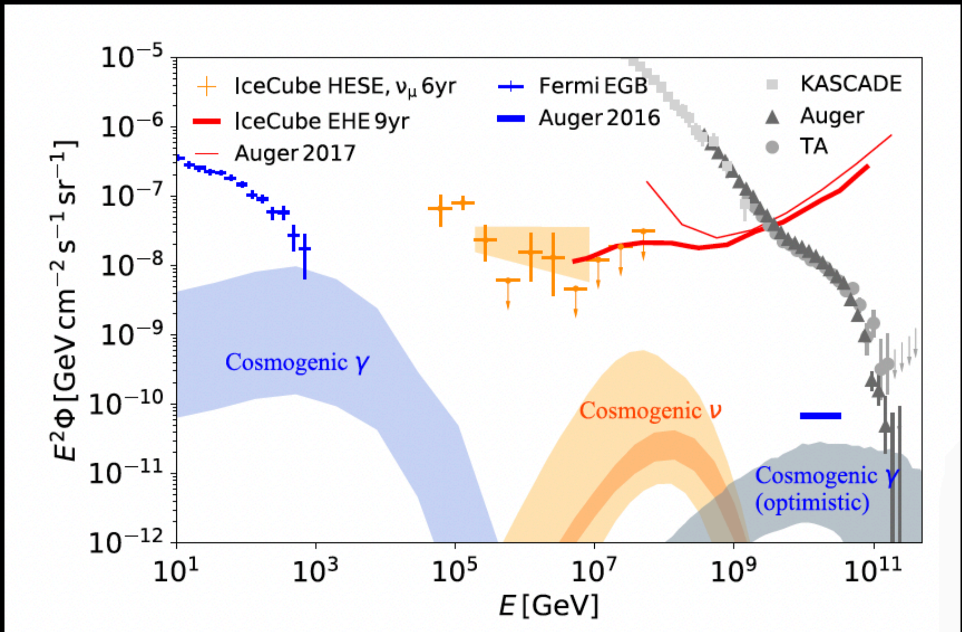
- Yang, Ruszkowski & Zweibel, Nature 2022: jet model, in which the surface of the eROSITA is the forward shock (~11 kpc away from Galactic plane and width ~14 kc) and **Fermi bubbles the contact discontinuity**. Within the contact discontinuity there is under-dense of thermal gas with CRs. Their separation **constrains the duration of the jet** due to a single event 2.6 Myr ago with acceleration phase of CR electrons in the AGN jet lasting **0.1 Myr**. The region between the two edges is compressed to electron number densities of ~10^{-3} cm^{-3} and $T_{shock} \sim 10^7 K$.

- The MWL SED is emodeled satisfying the HAWC limits and IceCube/ANTARES limits (see also Fang et al 2017)



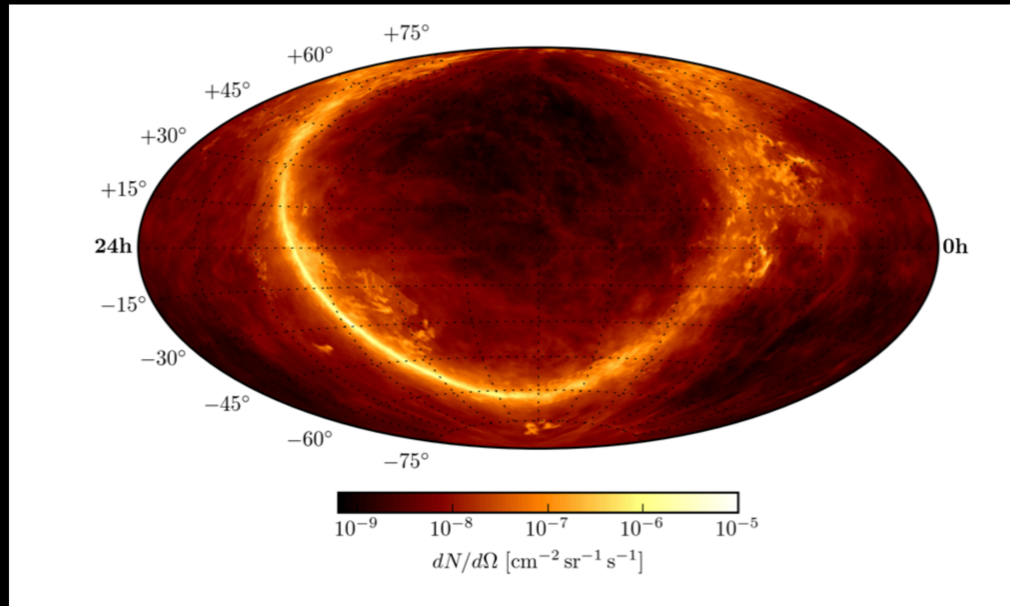
The granted Multi-Messenger diffuse fluxes

Extra-Galactic



A. Olinto's presentation, Snowmass 2022 paper, Heinze et al 2019

Galactic

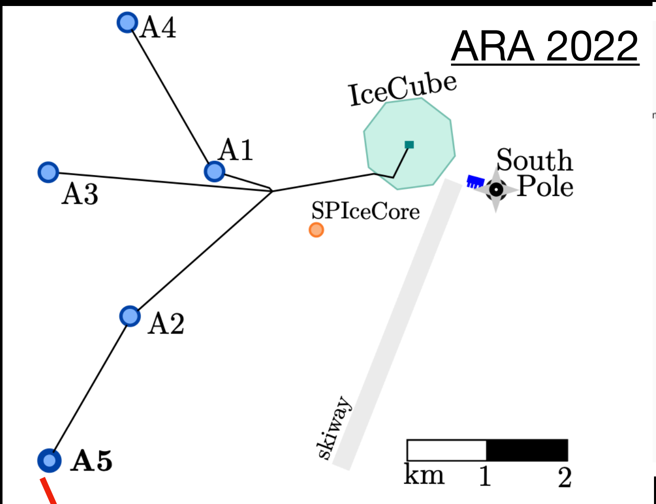


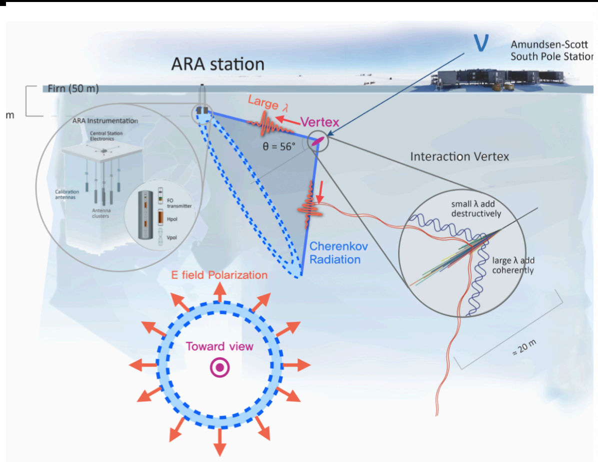
Gamma-ray emission from the galactic plane from KRA models (Gaggero et al 2015) of CRs interacting with ISM for a CR spectrum cut-off at 5 PeV/nucleon.

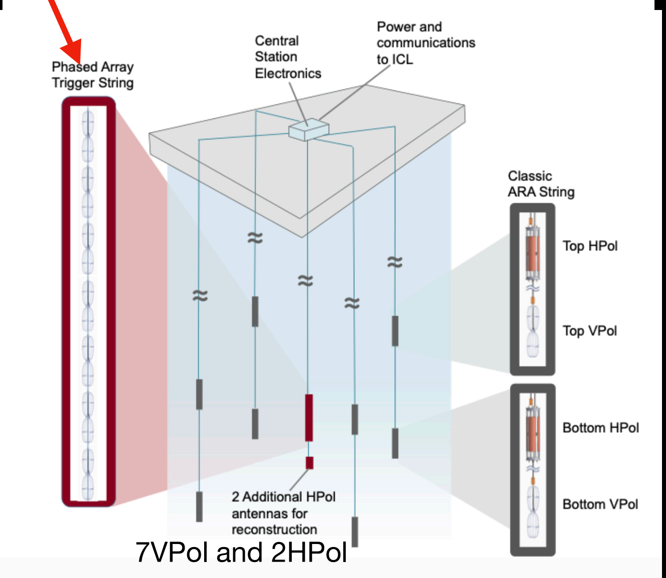
Fermi emission < 10 GeV is well reproduced by GALPROP. At higher energies KRA models include a CR diffusion coefficient scaling with rigidity according to an exponent with linear dependence on the galactocentric radius.

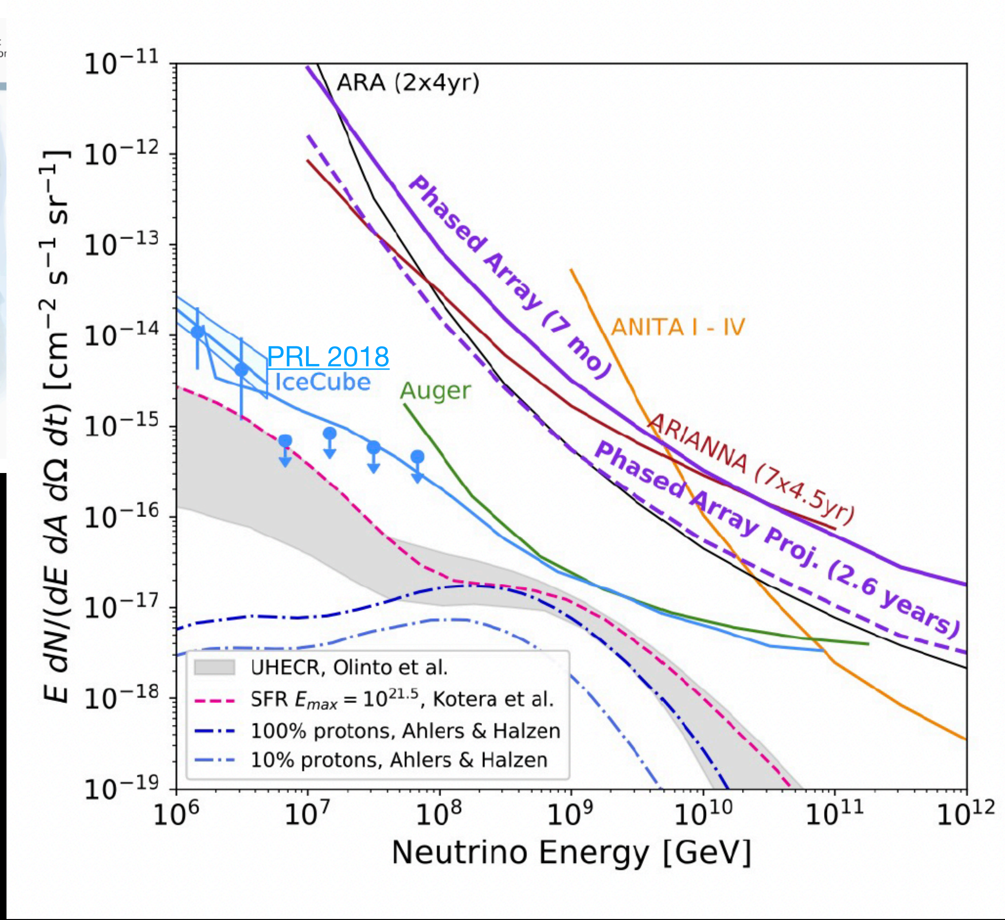
radius of the propagated CR spectral indexon energy and on the Galactic radius (Gaggero et al. 2015, 2017).

EHE flux and the radio technique: UHECRs-neutrino connection





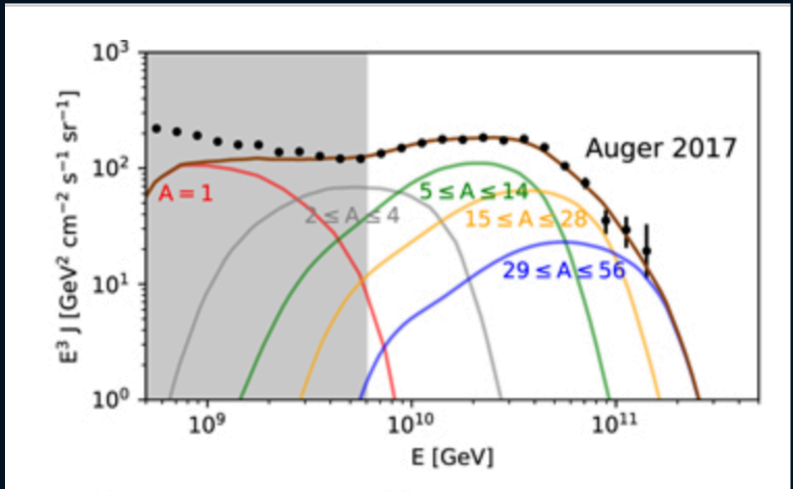


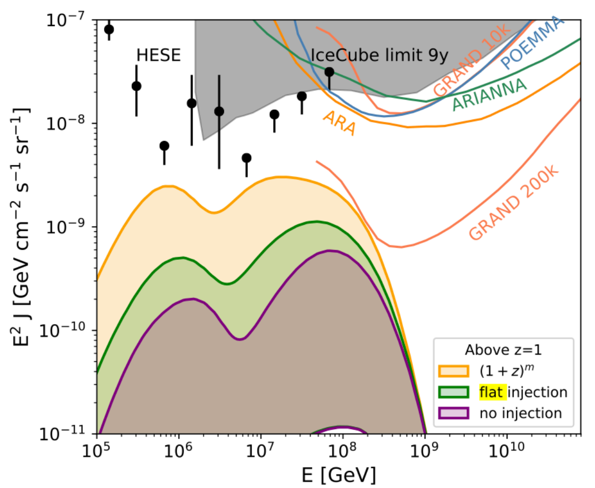


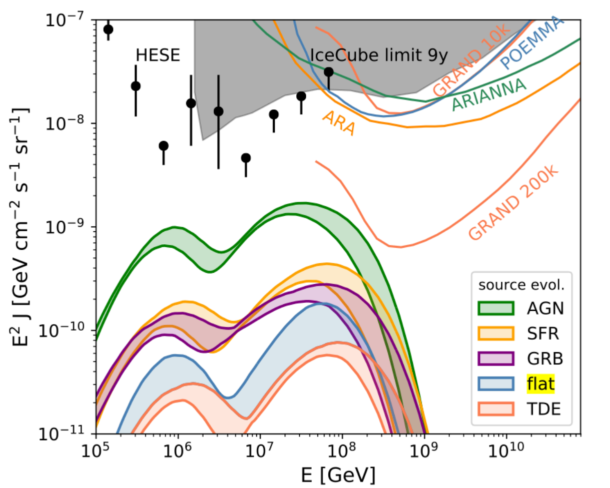
Radio detection at IceCube Gen2

Neutrino-induced showers develop O(20%) negative charge excess due to scattering with the electrons in the medium, and shower positrons annihilating with electrons in matter. The negative charge causes 2 types of radiation: bremsstrahlung, due to transient nature of the net charge, and Cherenkov radiation, due to net charge with v>c/n. The radiation is coherent for λ> apparent lateral width of the shower (Molière radius of the material at the viewing angle),

UHECRs- Cosmogenic ν diffuse flux

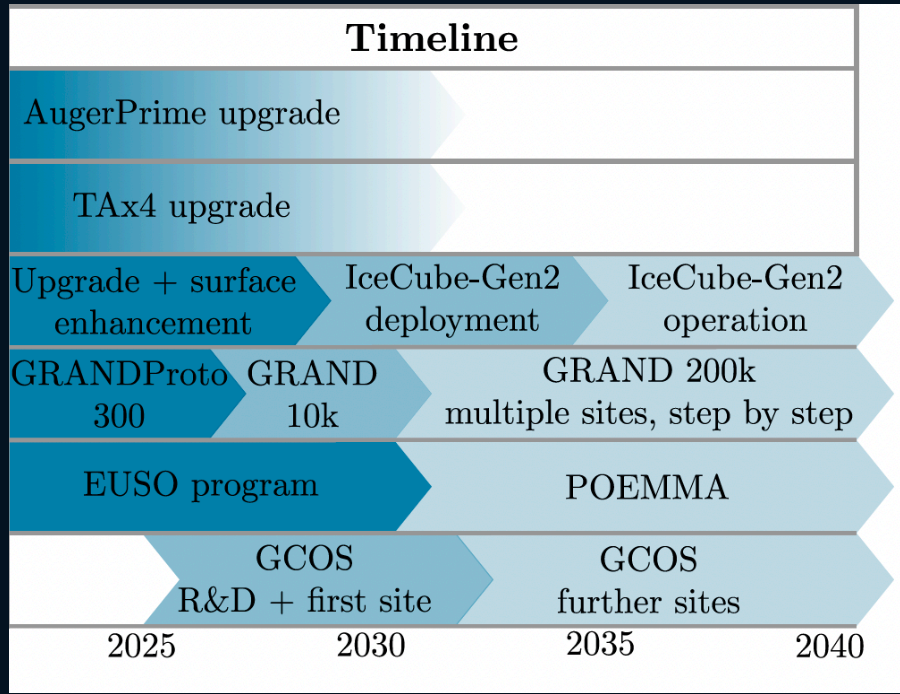






A. Olinto's presentation, Snowmass 2022 paper, Heinze et al 2019

Experiments searching for UHE neutrinos and photons in the coming future



Recommendations
- Current giant EAS operation to 2032
- Future Global Cosmic Ray Observatory (GCOS)
- GRAND
- From space: POEMMA

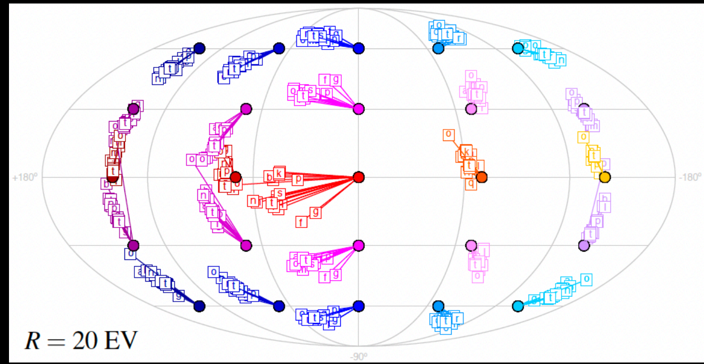
Correlations UHECRs-neutrinos

IceCube, ANTARES, PAO and TA, 2022

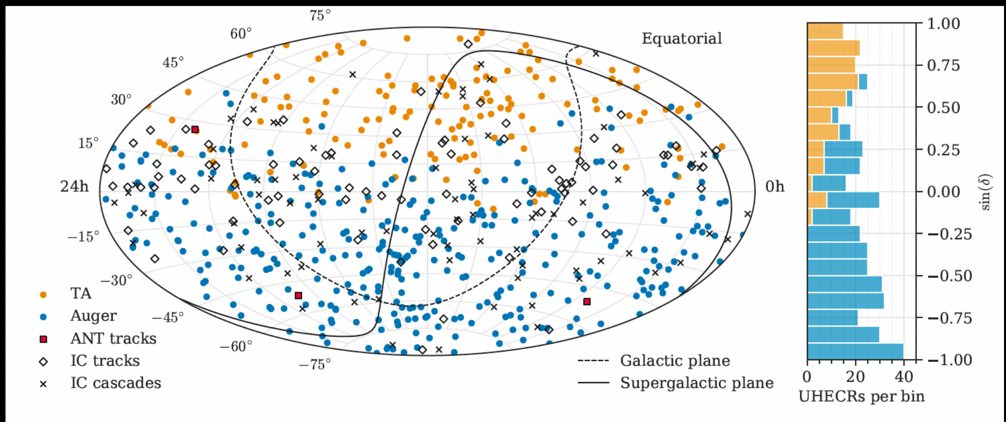
Three analysis hypothesis:

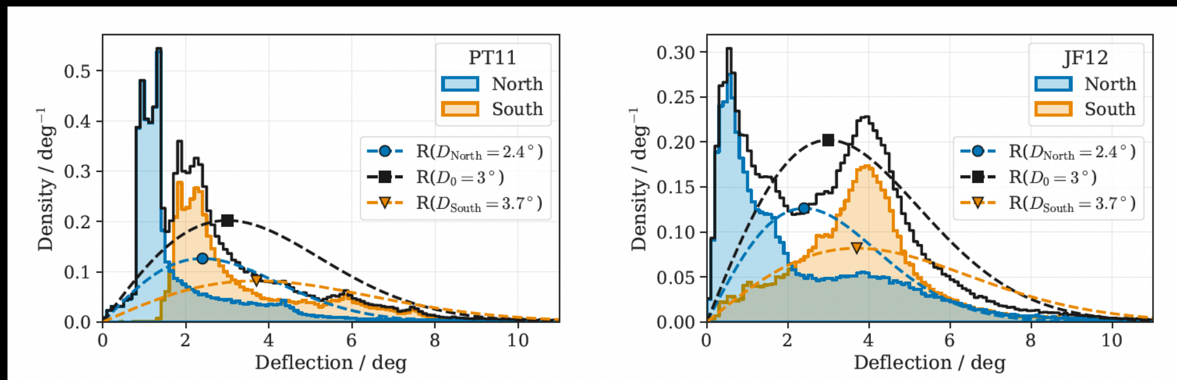
1) neutrino souces spatially correlated with UHECR directions within a region derived from their estimated deflection using a sample
2) Stacking search assuming that the UHECR sources are in the neutrino direction against the isotropic assumption of UHECRs weighted by the exposure of the PAO or TA
3) Two point correlation function

The absence of correlation can indicates that if the neutrinos are being injectected in the IceCube/ANTARES samples, their distance is beyond the UHECR accessible horizon or that magnetic deflections are larger than what considered.

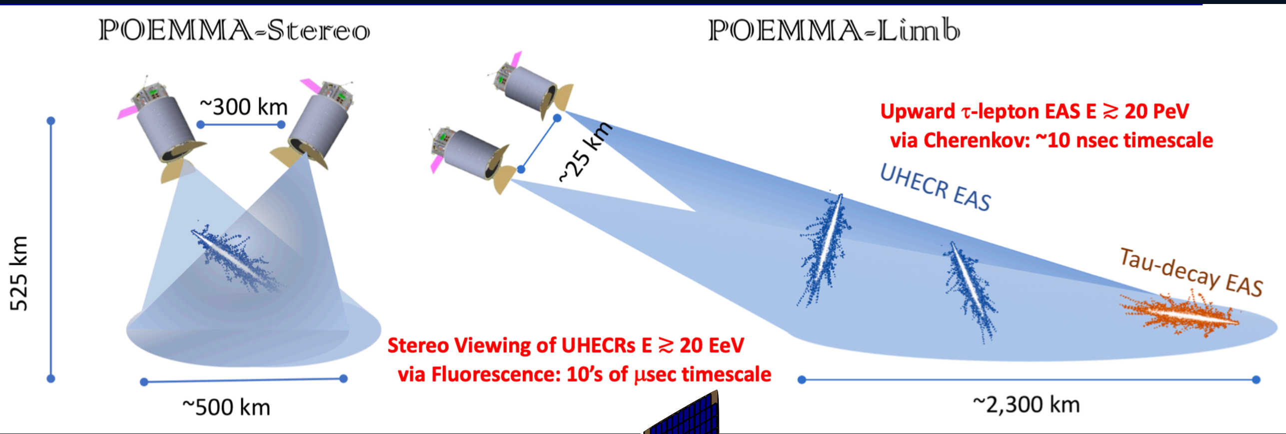


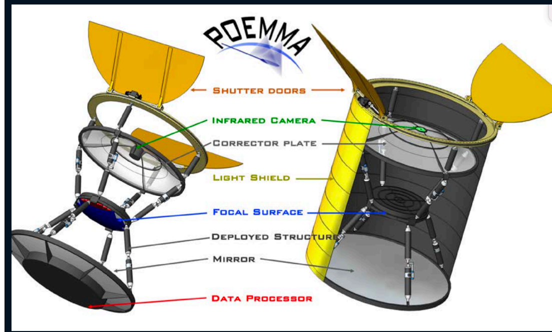
Farrar & Unger 2018, 2019: backtracing of charged particles at 20 EV
Determination of the GMF: radio obervation of Faraday rotation, polarized synchrotron emission of electrons in the Galaxy (WMAP, Planck synchrotron maps). The resulting direction ouside the galaxy is indictaed by squares
CRPropa software

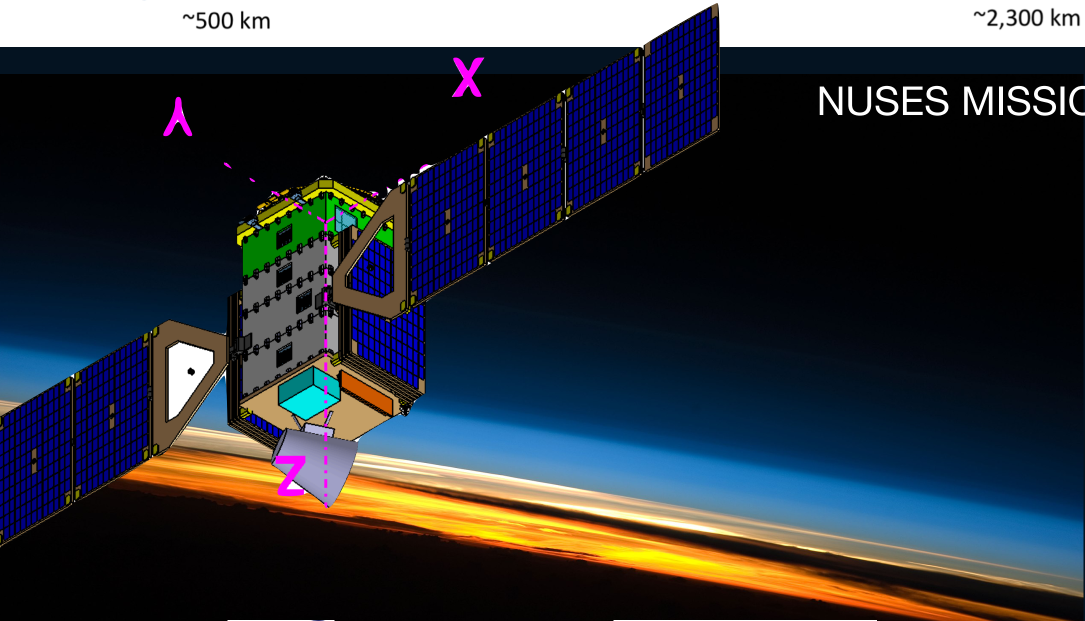




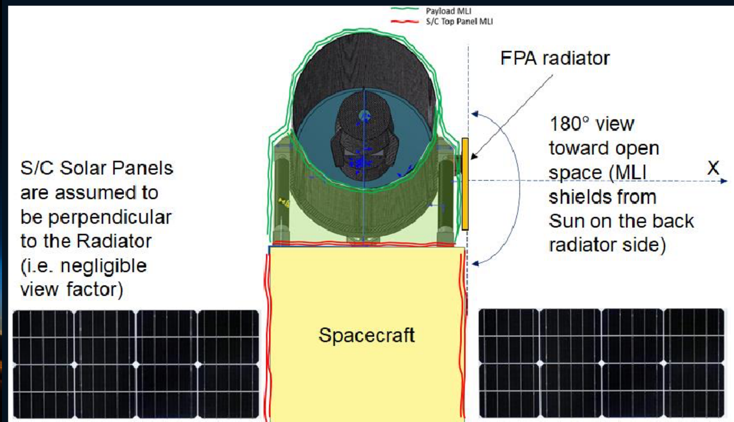
A prototype for Cherenkov light detection from space

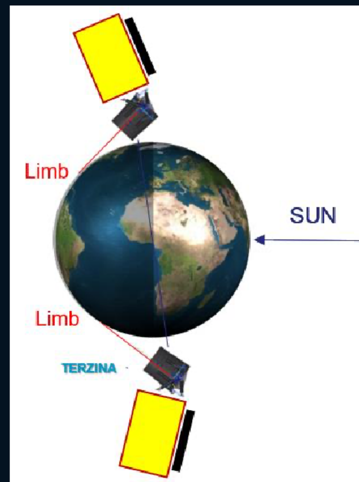






NUSES MISSION: Date of start of activities 06/04/2021. LAUNCH in 3 yrs





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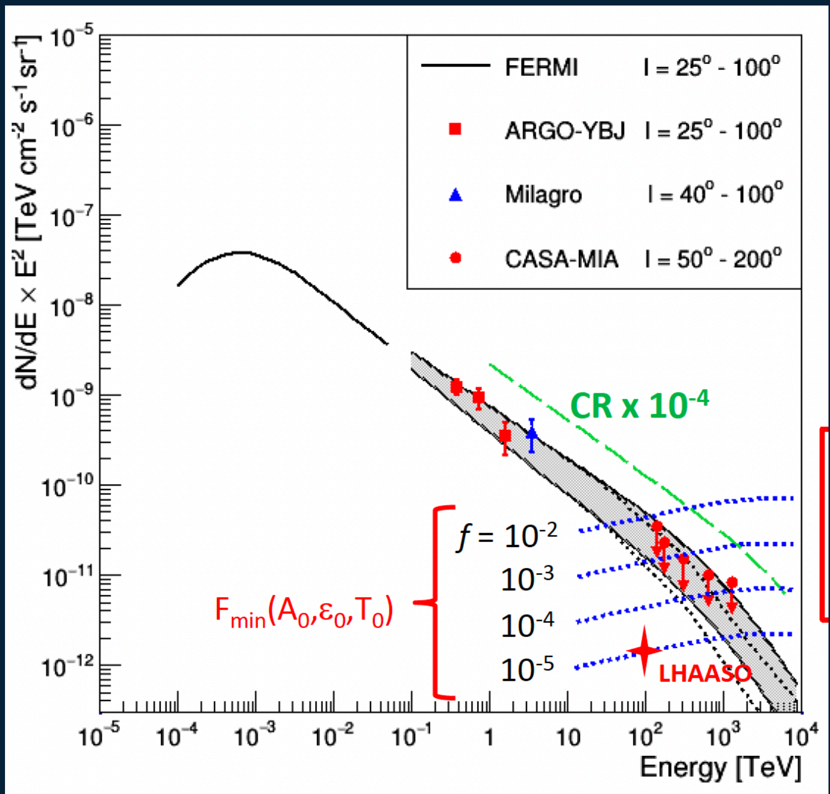
Diffuse gamma-ray - neutrino flux

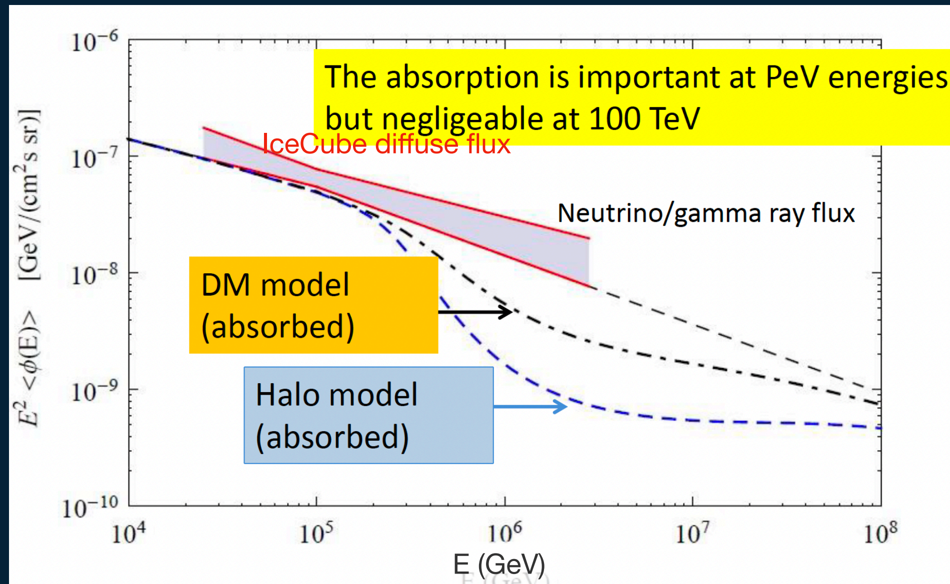
Components of the flux: 1.point-like or extended sources; 2. an isotropic flux of extragalactic origin; 3. Diffuse flux from interactions of CRs with a spectrum of $\sim E^{-(2.6\div2.8)}$ on ISM emitting gamma-rays and neutrinos from pion decay.
Below 10 GeV GALPROP models fit Fermi data. E> 10 GeV in the galactic bulge < 3 kpc Ferrière et al 2007

Unlike for the co-produced νs, γ-rays can be absorbed > 10^5 GeV.

Lipari & Vernetto 2018, 2021; RICAP 2016

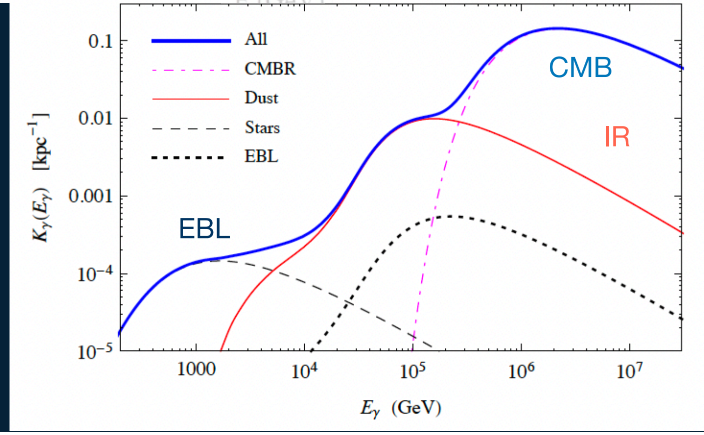


Photon diffuse background in the in proximity to solar system



Extrapolation of the Fermi spectrum with and wo absorption (pair production on photon background) Currently only upper limits exist. LHAASO with CR background rejection of 10^{-5} in the gamma-ray sample is promising

Optical



The multi-messenger galactic plane

Breuhaus et al , 2022; Ahlers et al, 2016

The composition is relevant to calculate neutrino and gamma-ray spectra

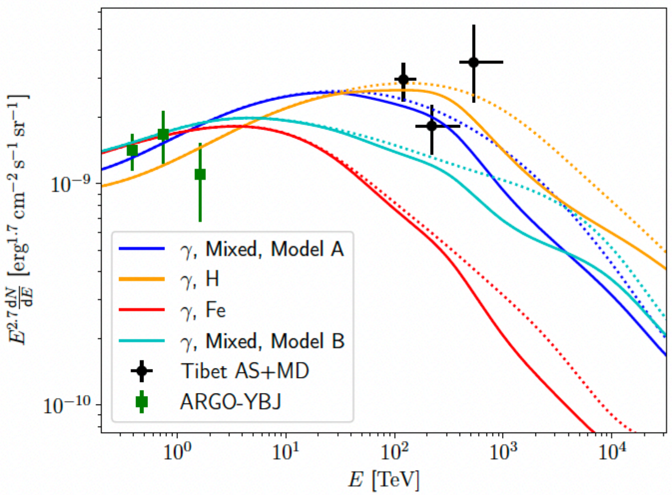
$$\frac{\mathrm{d}N}{\mathrm{d}E} = N_{\mathrm{p}} \cdot \left(\frac{E}{E_0}\right)^{-\alpha_{\mathrm{p}}} \exp\left(-\frac{E}{E_{\mathrm{cut,p}} \cdot A}\right),$$

Neutrino limits touch KRA models of diffuse galactic emission from CRs interacting on ISM (Gaggero et al 2015, 2017). IceCube > 20 TeV diffuse muon flux and > 100 TeV diffuse flux contributes < 10% to it. Finding significant contributions from the Galactic Plane requires lowering the threshold in ν energy.

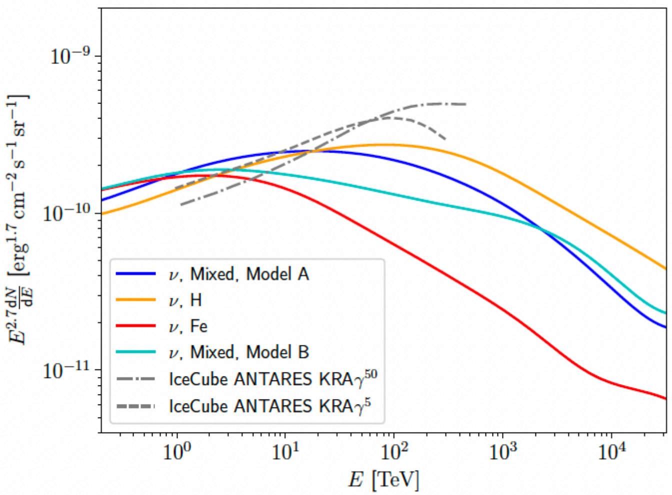
IceCube arXiv:1707.03416

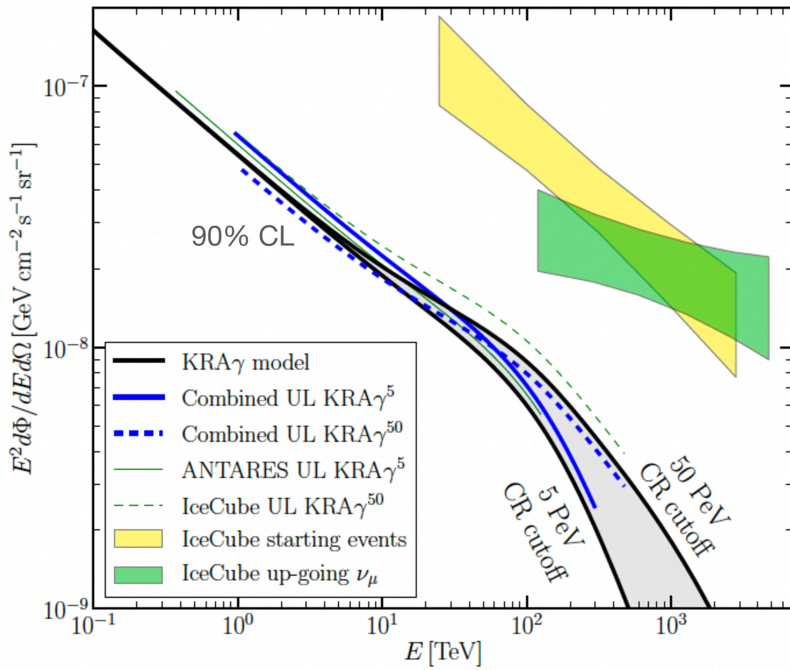
ANTARES-IceCube arXiv:1808.03531

Gamma-rays



Neutrinos

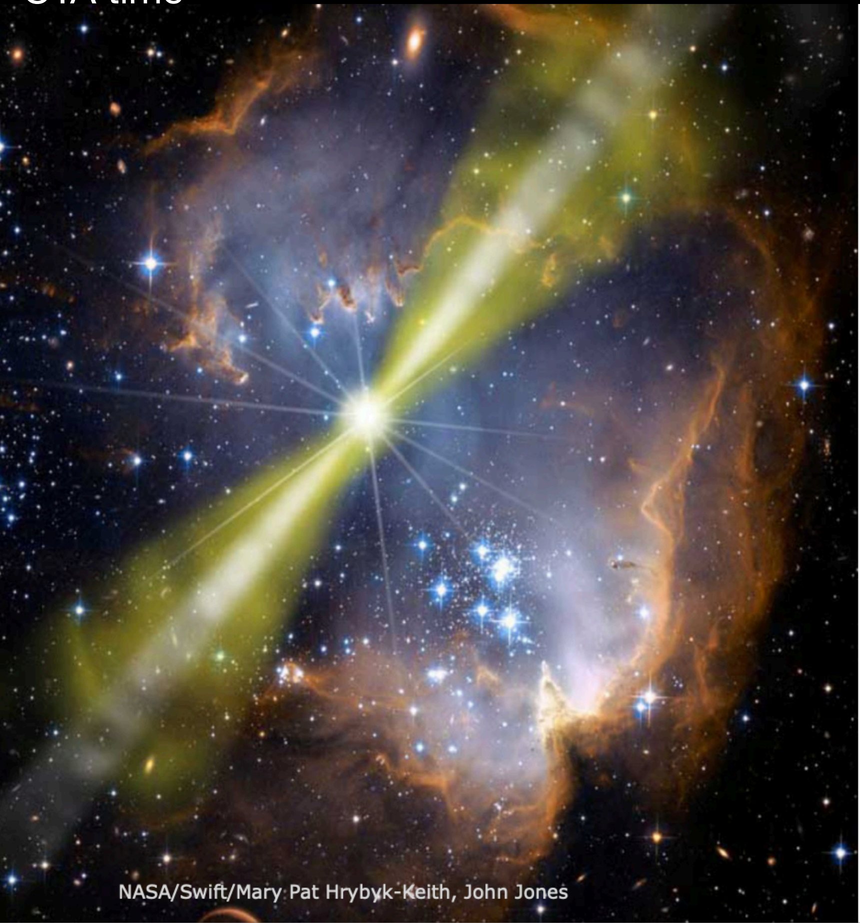




Tibet AS+MD data at 100 TeV do not favour pure Fe models.
Model A and Model B account for the disagreement of CREAM and NUCLEON on p and He fluxes and NUCLEON is in better agreement with gamma-ray data.
Mixed indicates 50% H, 50% O - ISM
Solid and dashed lines are with and wo absorption of gammas

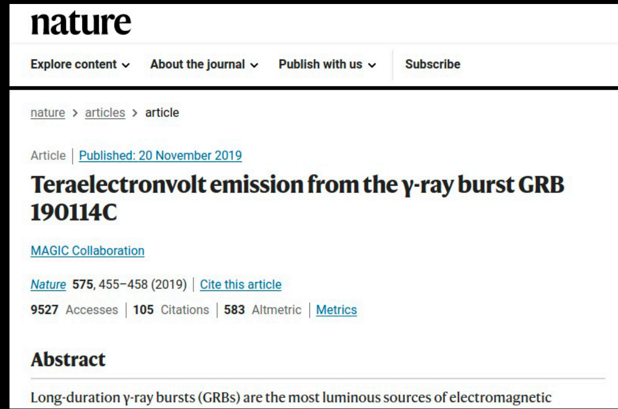
TeV gamma-ray bursts

Banerijee’r talk
With ET precursor alerts to CTA will be possible to detect 20-50 sources following ET pre-alerts of 5 min with 100 sq deg localization with only 1-2% CTA time



- **GRB 190114C** *(MAGIC Coll., Nature, 2020)*
  - long GRB
  - z = 0.42
  - for 40’ after T0 +60 s
  - 0.2 -1 TeV 50σ
- **GRB 180720B** *(H.E.S.S. Coll., Nature, 2020)*
  - long GRB
  - z = 0.65   < 440 GeV 5σ 10 hr
  - after T_0 + 10..
- **GRB 190829A** *(H.E.S.S. Coll., Science)*
  - long GRB
  - z = 0.078 20σ
  - for 3 nights after T_0 + 4,3h
  - 0.18-3.3 TeV
- **GRB 160821B** *(MAGIC Coll. ApJL 2021)*
  - short GRB 3σ ?
  - z =0.162   Kilonova?
  - 3σ @ E>500 GeV
  - for 4h after T_0+24s   20 s response
- **GRB 201015A** *(PoS ID 305, Y.Suda)*
  - long GRB
  - z=0.42
  - for 3,4 h after T_0+40s $>3\sigma$
  - 3.5σ above 50 GeV
- **GRB 201216C** *(PoS ID 395, S.Fukami)*
  - long GRB   5σ
  - $\boxed{z=1.1}$
  - for 20’ after T_0+56s
  - 6σ E<100 GeV

6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Article | Published: 20 November 2019

Teraelectronvolt emission from the γ-ray burst GRB 190114C

MAGIC Collaboration

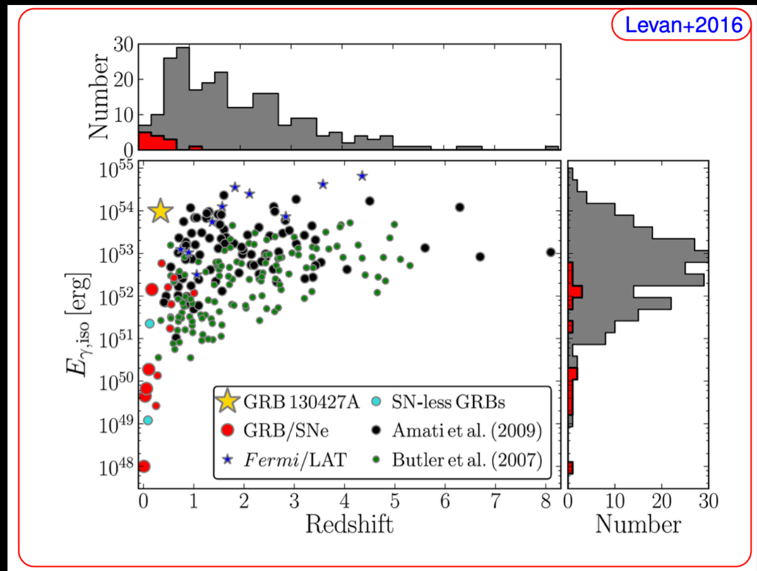
Nature **575**, 455–458 (2019) | Cite this article

9527 Accesses | **105** Citations | **583** Altmetric | Metrics

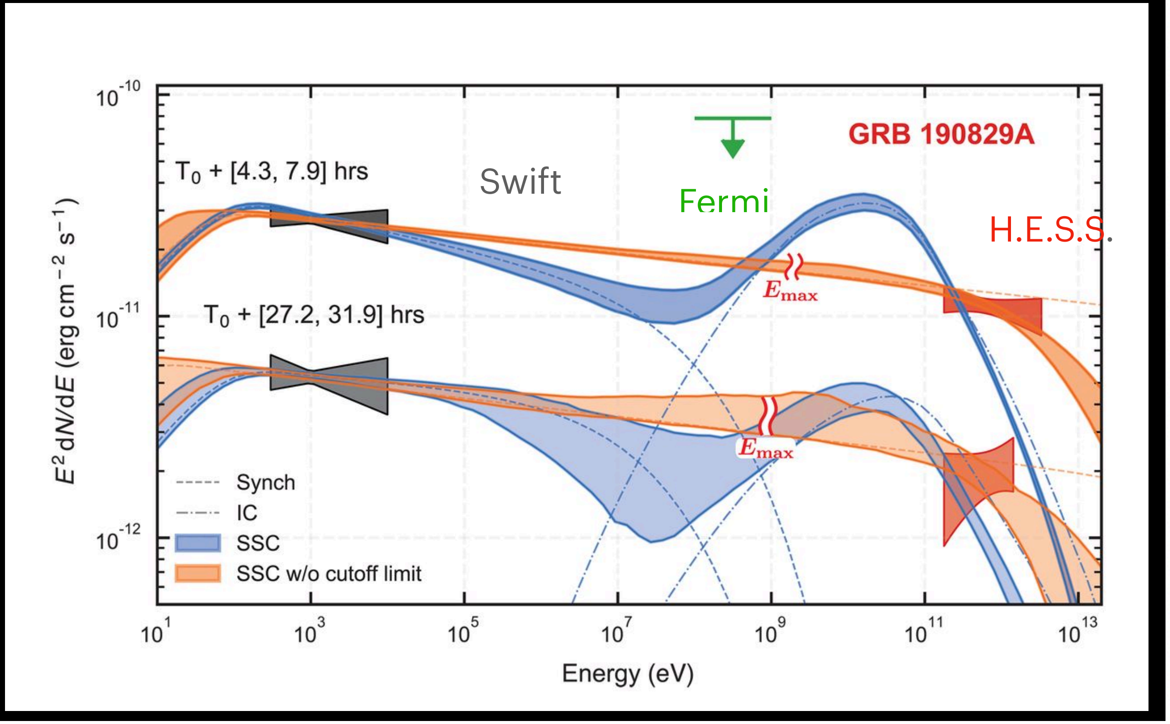
Abstract

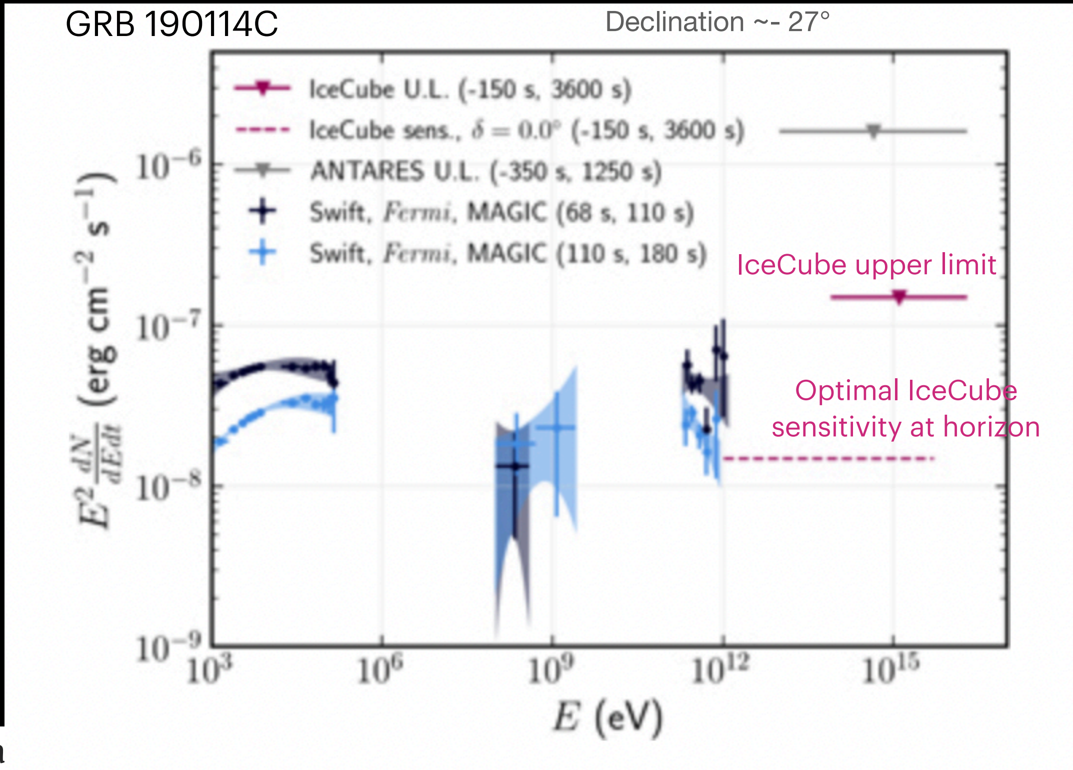
Long-duration γ-ray bursts (GRBs) are the most luminous sources of electromagnetic

Another component in afterglow phase: Synchrotron self Compton? A composite lightcurve, K-N effects need to be considered See Piran’s presentation and Yamasaki & Piran, 2021



An unexpected afterglow spectrum





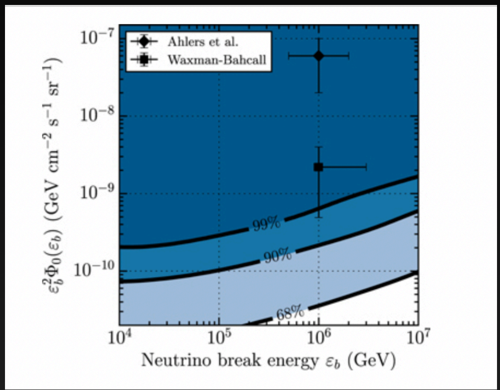
The spectral steepening predicted in the VHE range implies that HESS data of 2 nights of observations cannot reproduce the observations with a simple one-zone Synchrotron-Self Compton model

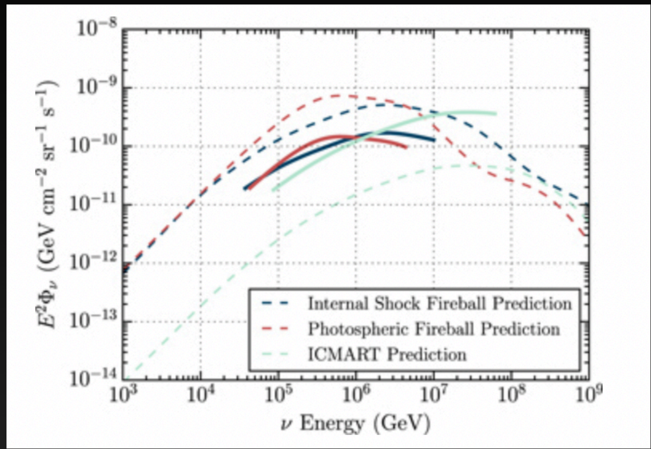
R. Abbasi et al 2021 ApJ 910 4

H.E.S.S. Science 372 (2021)

1172 GRBs and IceCube (2010-2015) tracks and cascades

IceCube 2017





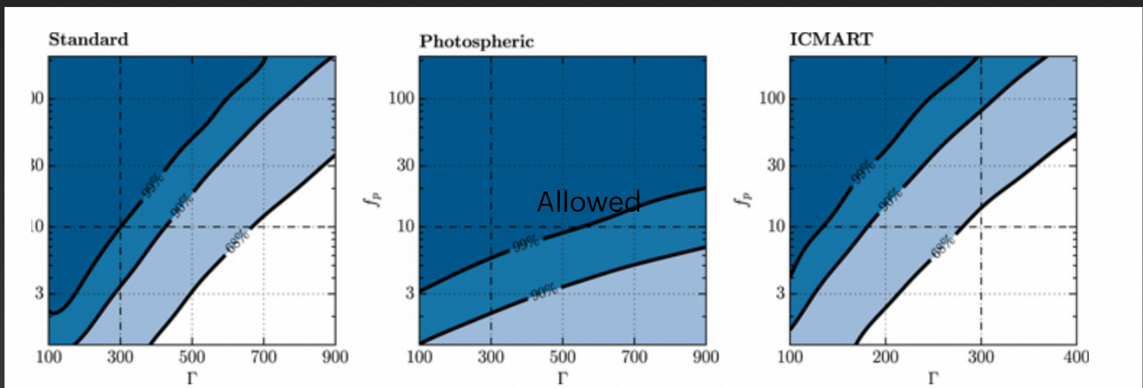
From per flavor burst g flux to diffuse

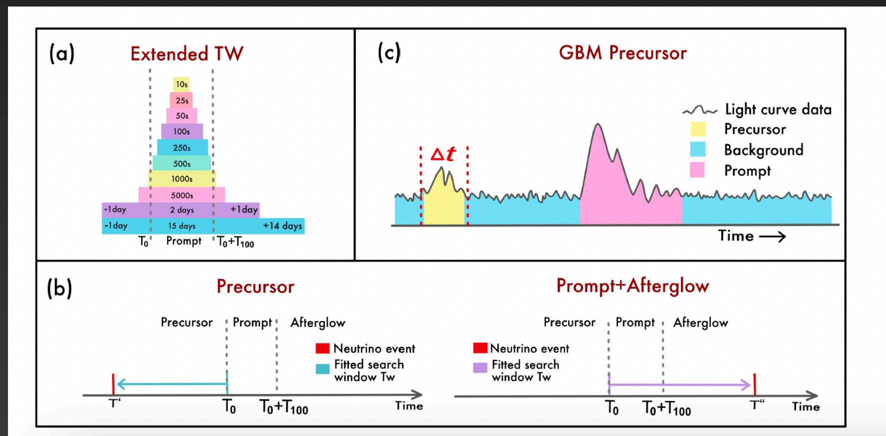
$$\Phi_{\Gamma,f_p}(E_\nu) = \left[\sum_g F_{g;\Gamma,f_p}(E_\nu)\right] \times \left(\dot{N}_{\mathrm{GRB}}/N_{\mathrm{obs}}\right) \times (4\pi\ \mathrm{sr})^{-1}$$

Assumed equal fluence at Earth

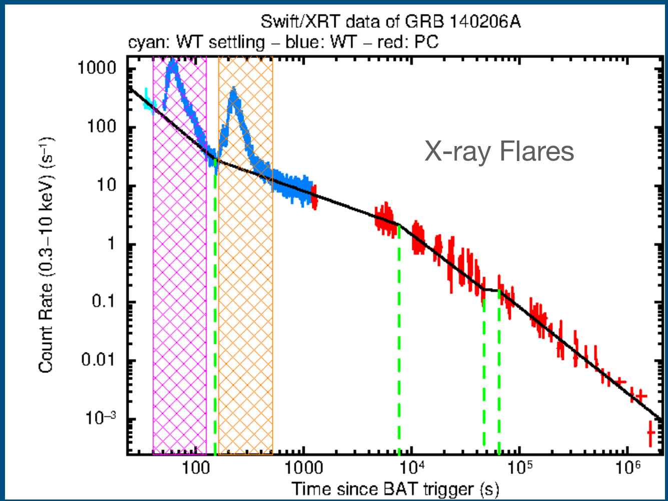
More recently a new paper has been submitted a new paper extending the window to 14 d after the prompt and for a catalogue of precursors (IceCube 2022)

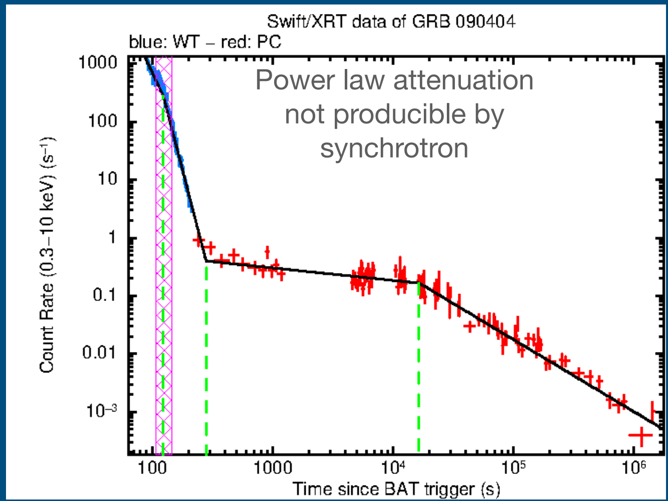
Allowed





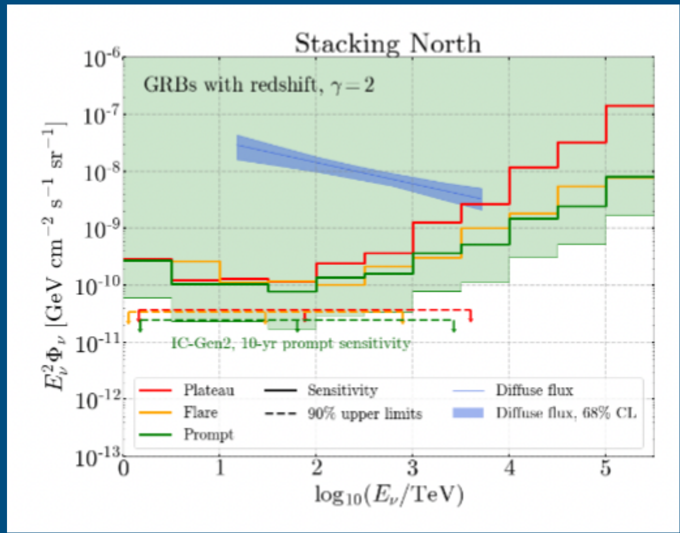
Selected GRBs for ν searches





$$E_{\nu_\mu}^2 \phi_{\nu_\mu} = \frac{1}{8} \xi_p f_p f_{p\gamma} f_\pi^{syn} f_\mu^{syn} S_{iso}$$

GRB catalog	North (with redshift)	South (with redshift)
Prompt	963 (73)	796 (51)
X-ray plateau	141 (63)	119 (54)
X-ray flare	117 (43)	83 (45)

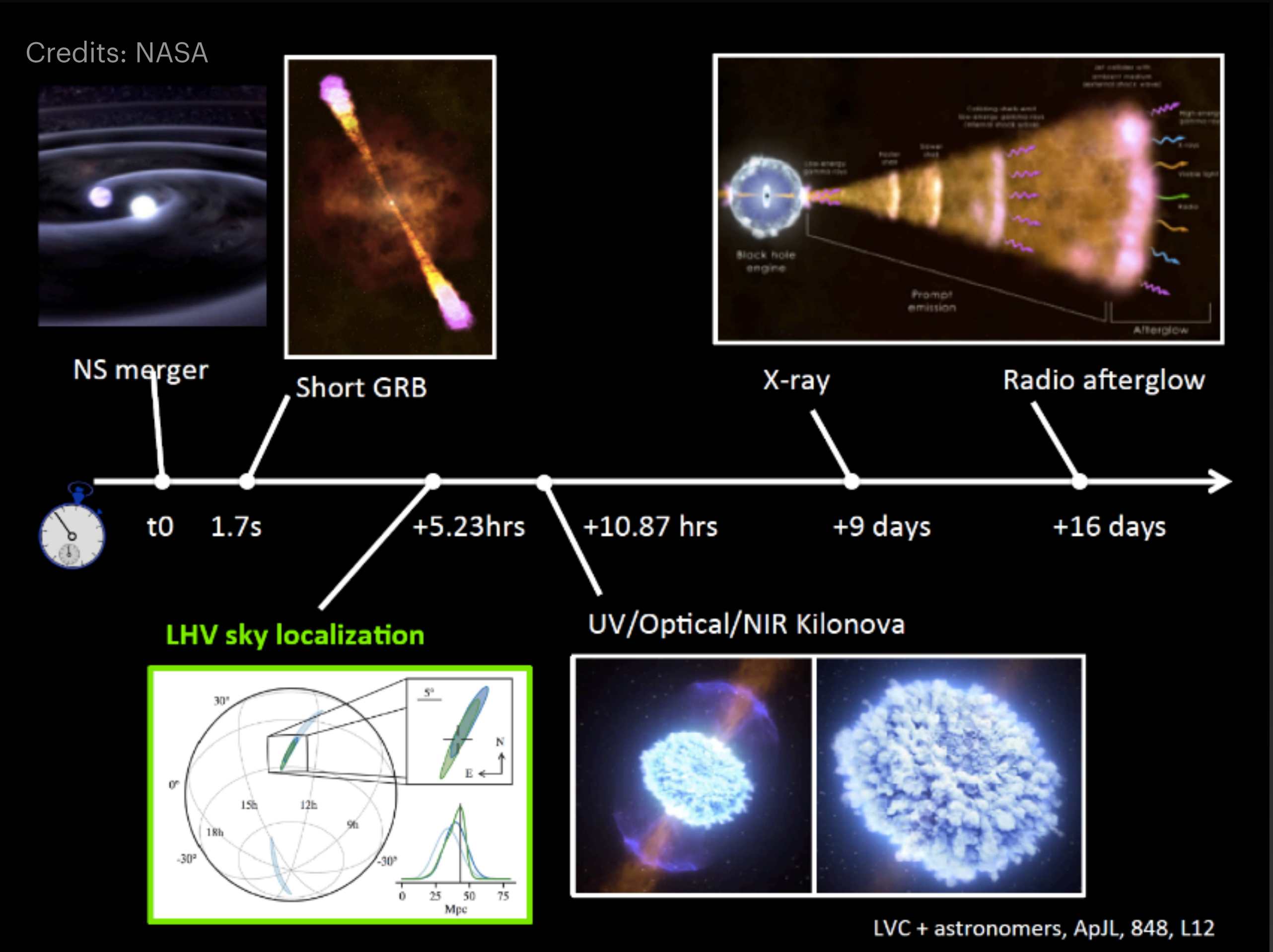


Gor Oganesyan's talk

F. Lucarelli, G. Oganesyan, M. Branchesi, T. Montaruli, Mei, Ronchini in preparation

Short GRBs and GW-EM joint observations

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



A GRB event detected by Fermi-LAT, 1.7 s after…sGRBs link to kilonovas?

Swift observation of GRB211211A: during a long GRB a kilonova optical/ NIR event observed at 350 Mpc (z = 0.0763), confirmed by HST

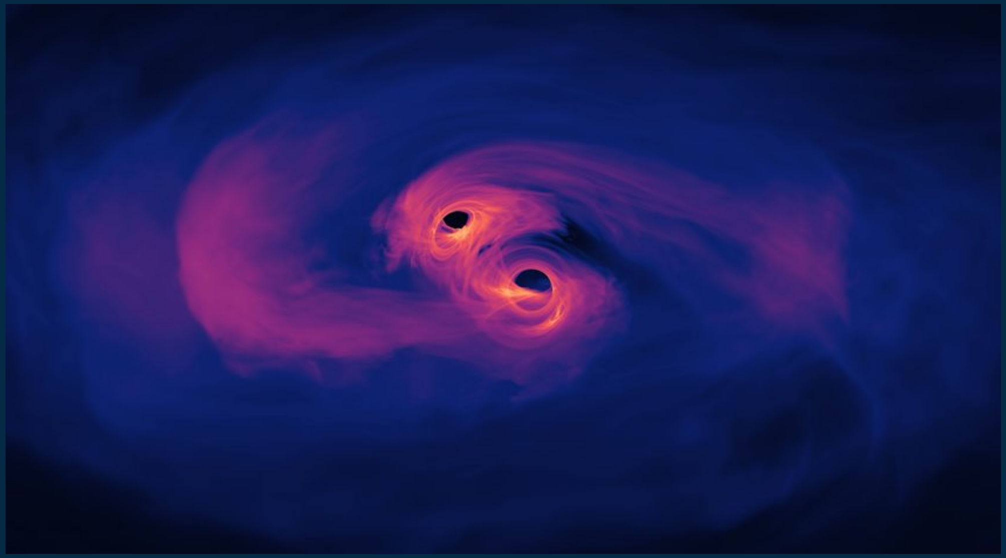
Detection of Inverse Compton from a kilonova event due to a long-lived lo power jet. Marica Branchesi's talk

No neutrinos from binary neutron stars yet, (GW 170817)

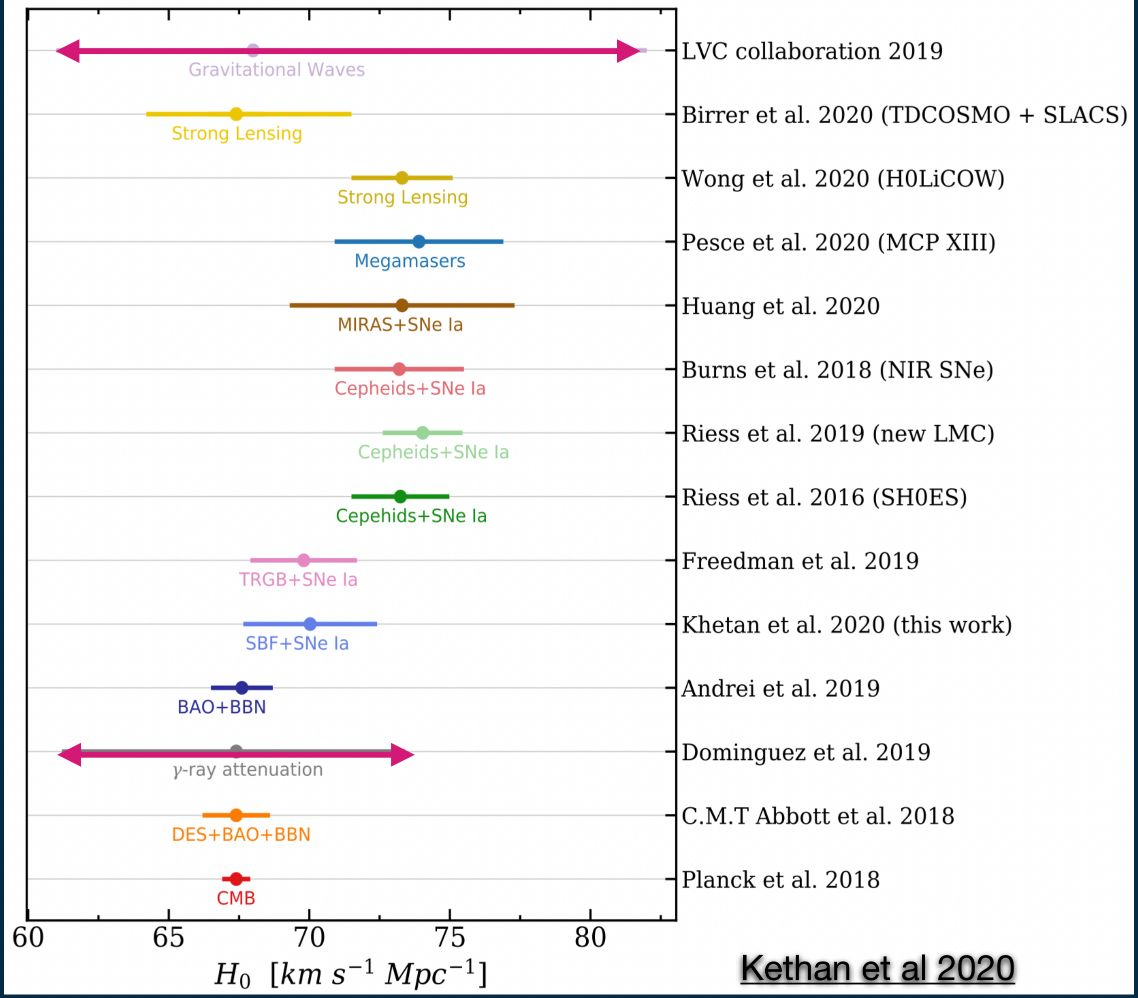
PRD 96, 022005 (2017)

Cosmology related multi-messenger studies

nHz Astrophysics



Fermi 2022

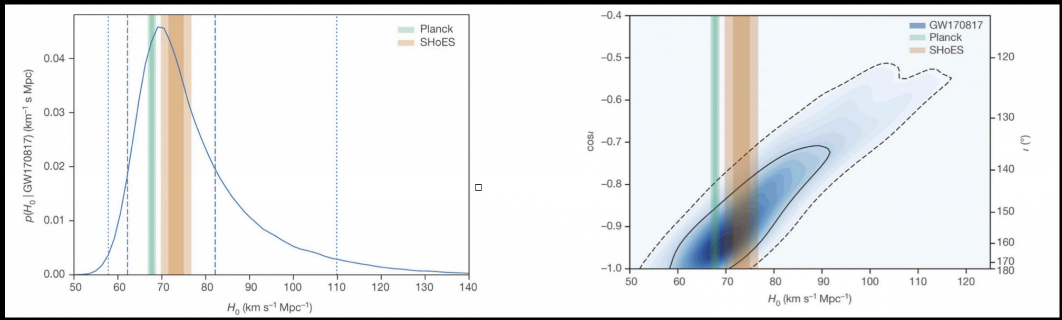


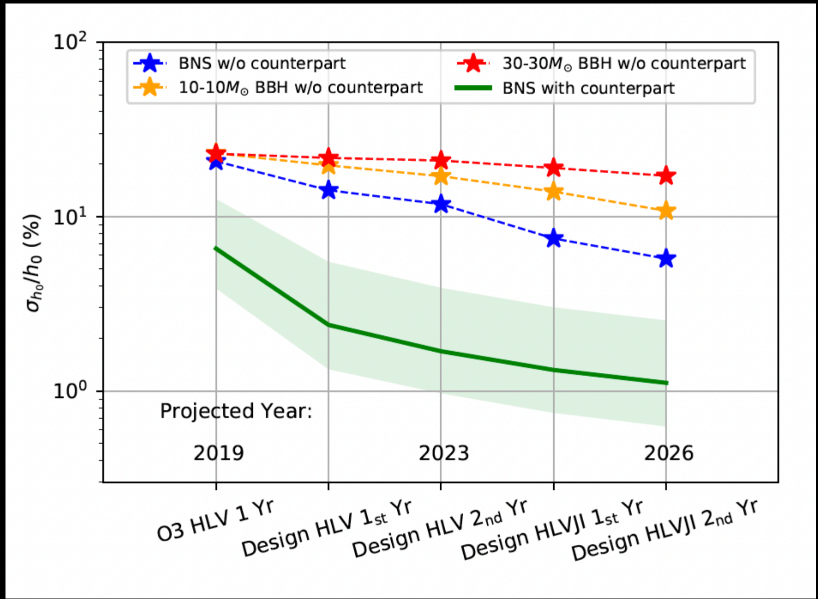
Kethan et al 2020

H_0 (late universe) from standard sirens and perspectives

LIGO/Virgo can constrain H_0 at 2% level in ~5 yr

Chen et al; Nature 2017,





Sirens because the absolute distance to the source can be determined from the GW measurement. The error comes from degeneracy between distance measurement and inclination of the system.

$H_0 D_L = cz$ from NS-NS merger GW170817

$H_0 = 70.0^{+12.0}_{-8.0} \mathrm{km s^{-1} Mpc^{-1}}$ (1σ) Abbott et al., Nature, 24471 (2017)

Another updated estimate is from the superluminal motion of the jets (Nature Astron. (2019). 1806.10596)

In the absence of a counterpart, the error on H_0 increases with the number of potential host galaxies in the localization volume. Galaxy clustering can mitigate this, e.g. for GW170817, the optical counterpart was found in NGC 4993 but without a counterpart there are about 20 galaxies in its cluster, all of which have an equivalent Hubble recessional velocity.

Extragalatic Background Light optical depth evolution with z

Extragalactic source spectrum

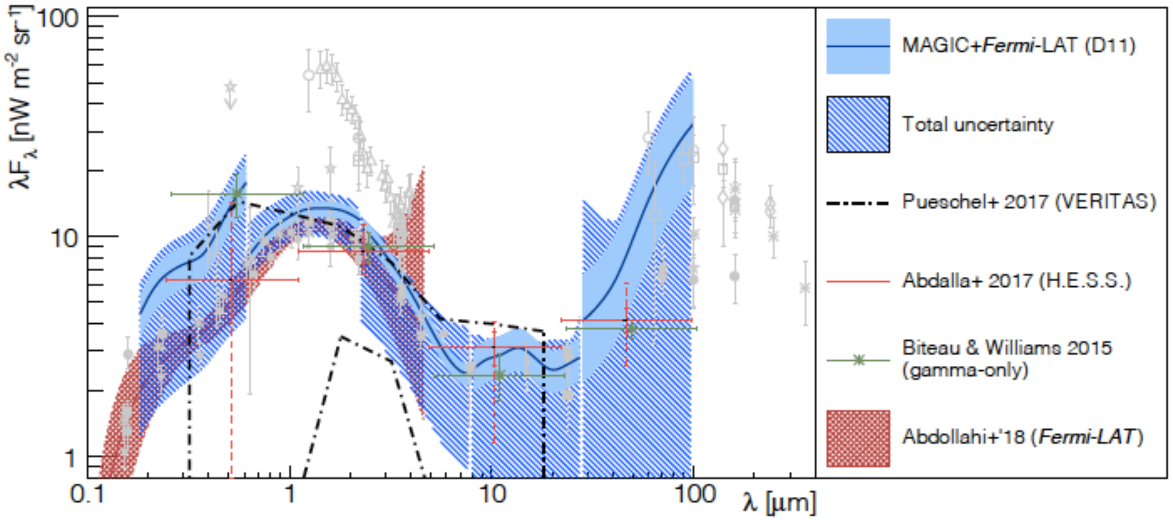
$$\left(\frac{\mathrm{d}N}{\mathrm{d}E}\right)_{\mathrm{obs}} = \left(\frac{\mathrm{d}N}{\mathrm{d}E}\right)_{\mathrm{int}} \exp\left[-b \cdot \tau_{\gamma\gamma}(E, z)\right]$$

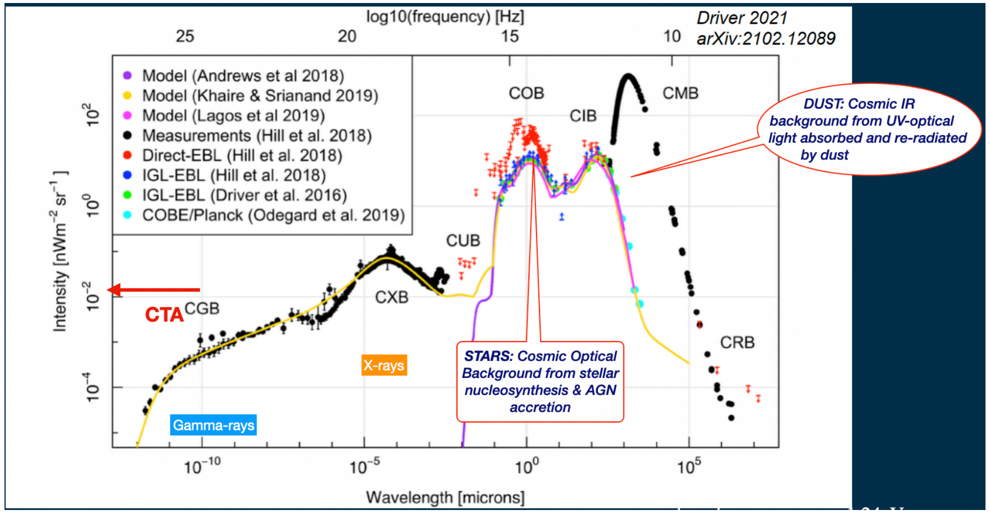
b = 0 no attenuation

b=1 attenuation accordng to EBL model (e.g. Finke 2010 or Gilmore 2012, Domingez 2011…)

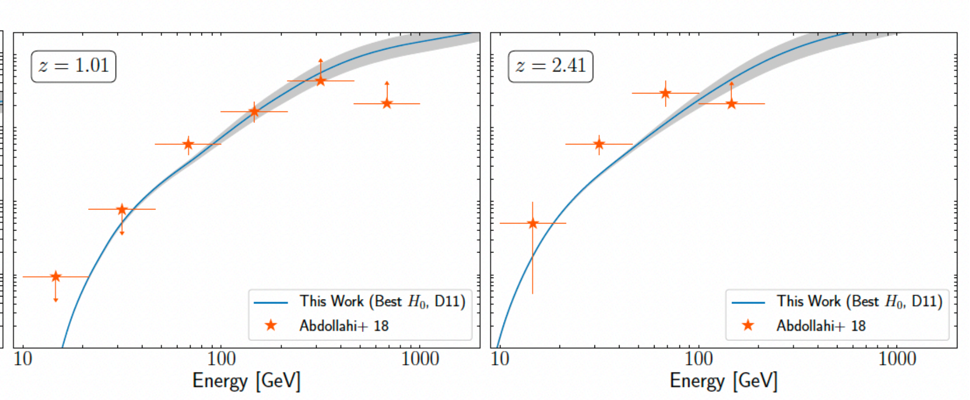
At this conference on EBL: Zieberman EBL from M87

MAGIC arXiv:1904.00134 Fermi Collaboration, 2018





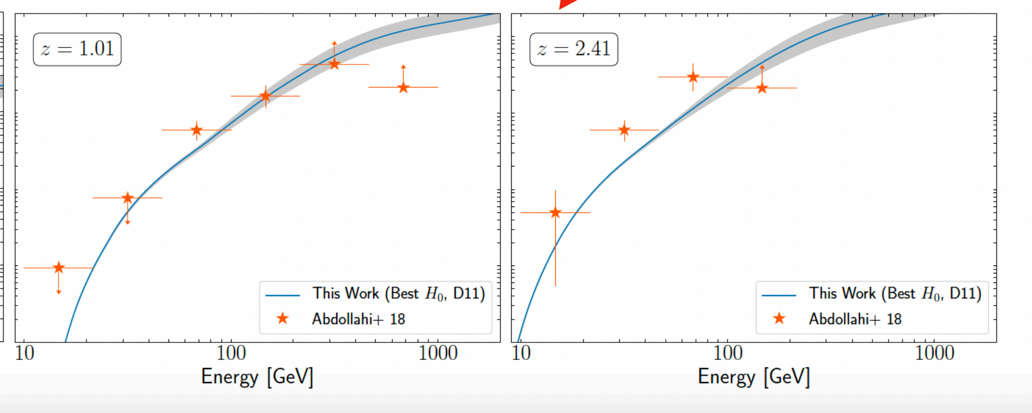
EBL evolution with z

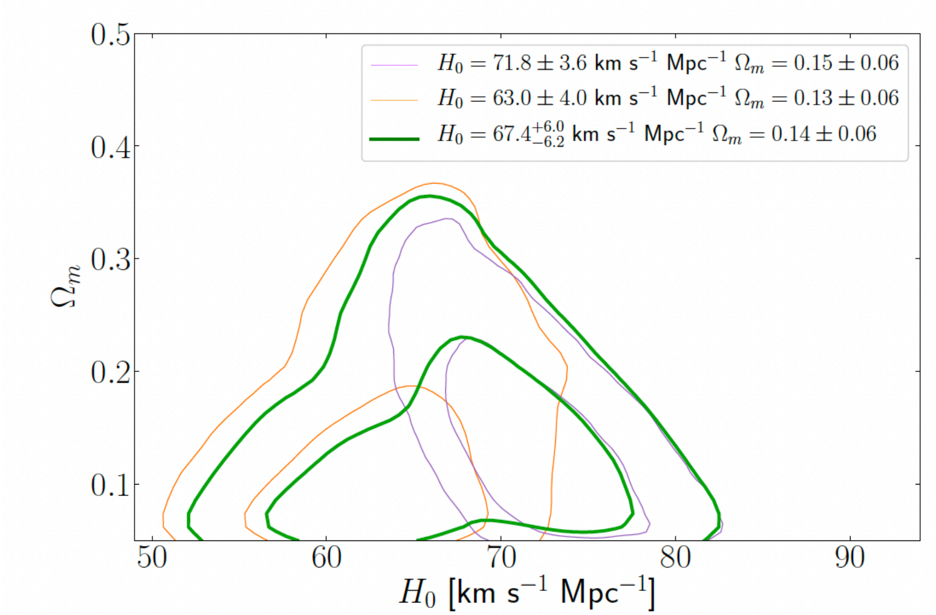


Optical depth vs energy for z = 1.01, and 2.41, ***fixing Ω_m = 0.32 and varying*** *H_0 between 40 -92 km s-1 Mpc-1 assuming the EBL model by Dominguez et al.2011*

Optical depth vs energy for z = 1.01, and 2.41, fixing H_0 to the most likely values and varying Ω_m = 0.05 (upper bound) - 0.6 (lower bound) assuming the EBL model by Finke et al 2010.

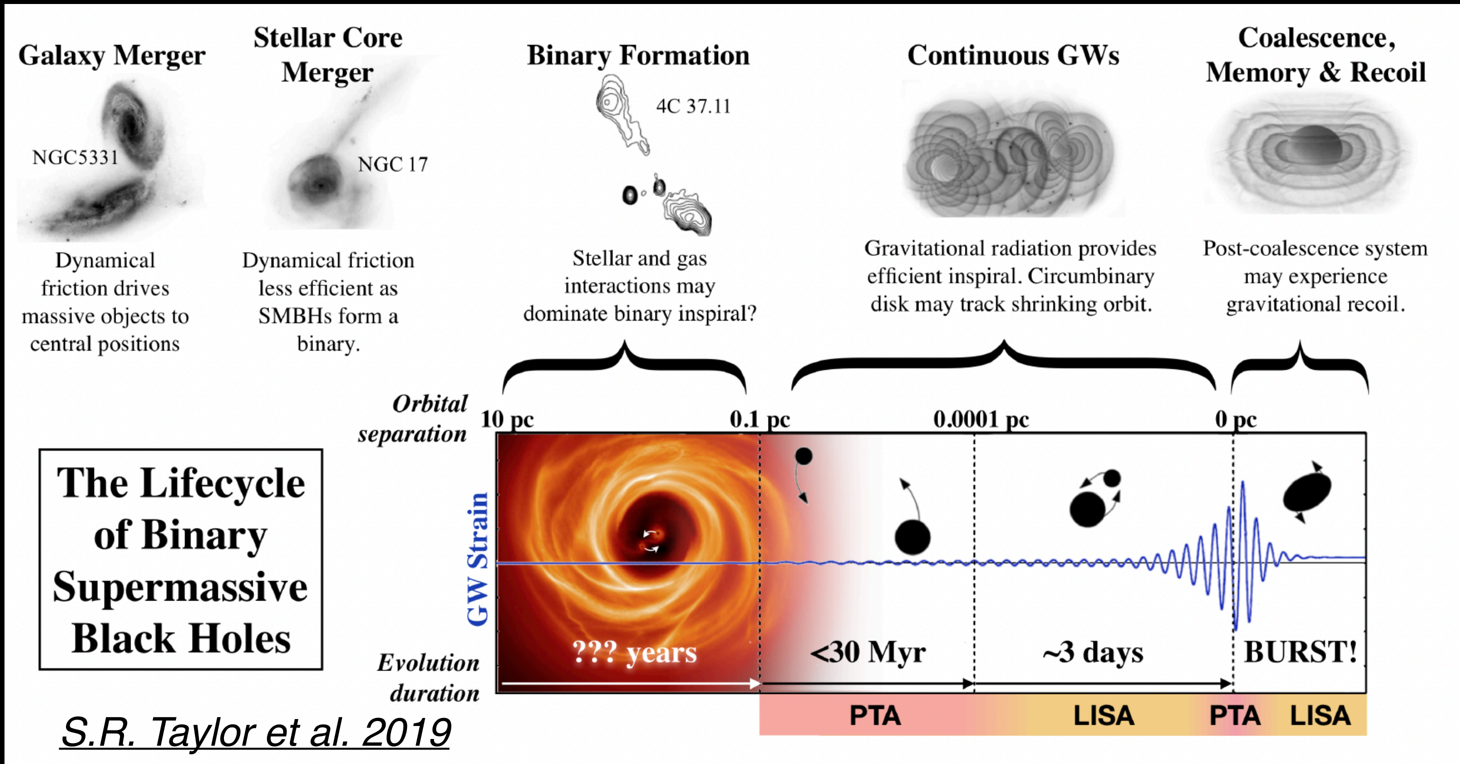
Dominguez et al 2019





Zeng & Yan, 2019 fit EBL > 10 GeV (dominated by blazars) to obtain H_0 and Ω_m

Galaxy mergers and the stochastic GW background



- Mergers of galaxies can originate SMBH binaries during building up hierarchical structures in ΛCDM generating the Stochastic Gravitational Wave Background (SGWB).
- For orbital separatiom of the SMBH <0.01 pc, the orbits decay due to GW emission at nHz, produced as a consequence of dynamical friction
- Pulsar Timing Arrays measure the times-of-arrival (TOA) of radio pulses from ms pulsars as a mean of measuring the local space-time curvature, and thus signs of passing GWs produced by SMBH binary mergers, while LVC uses pairs of perpendicular laser arms.
- NANOGrav in 12.5 yr a sample of 45 ms pulsars

PTAs may have potentially poorer parameter estimation than interferometers because PTAs typically observe an early portion of the binary inspiral, and only have a glimpse of this phase over the 1-2 decade observational timespans.

Gamma-rays as PTAs

- Gamma-rays represent a complementary approach to PTA in the radio, being at higher frequency and are not as affected by the ISM and solar wind.

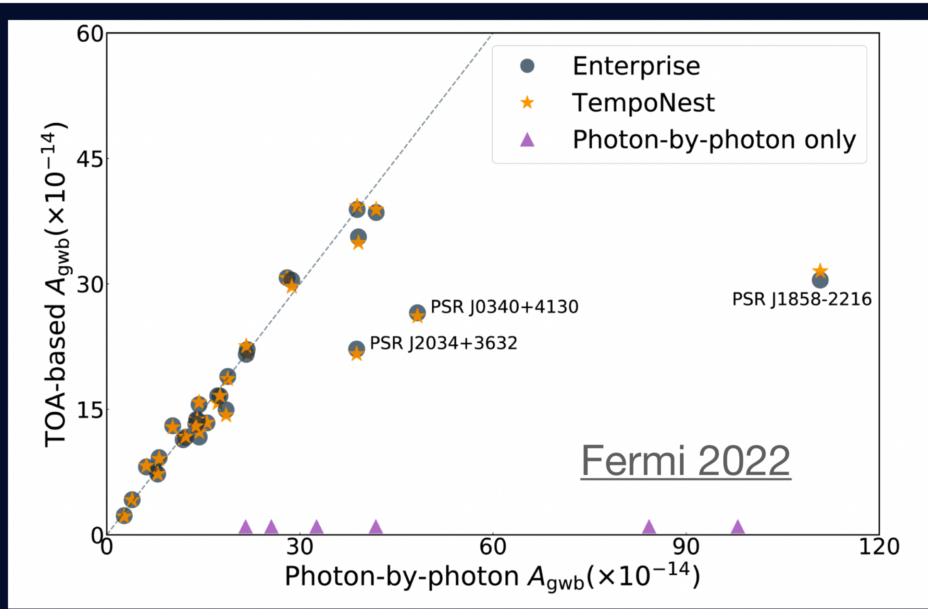
- Gamma-ray observations Fermi covers the full sky in 3 hr with time precision < 300 ns so enabling pulsar timing and measurement of time of arrival of pulsar signal (TOA).

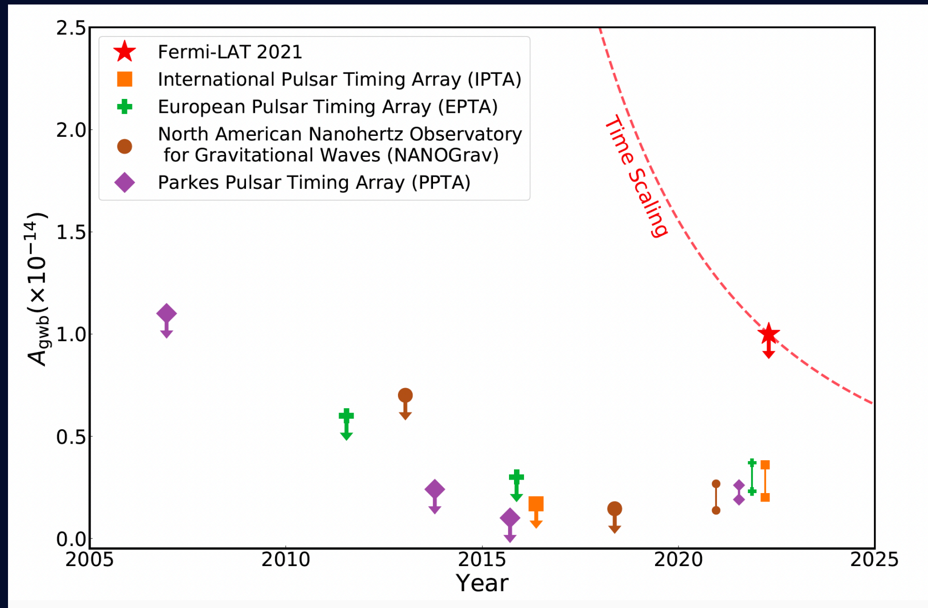
- The **GW strain from the superposition of all GWs emitted by SMBH binaries** with distance <0.01 pc follows a power law: $h_c(f) = A_{GWB} \left(\frac{f}{\text{year}^{-1}} \right)^{\alpha}$, where $\alpha = -\frac{2}{3}$ for binary inspirals.

- A_{GWB} depends on the distribution of SMBH masses and the dynamical evolution of binary systems.

- 35 brightest stable ms pulsars of Fermi-LAT sets a limit on the GWB at characteristic strain of 1×10^{-14} at a frequency of 1 yr^{-1} (96% CL). 29 have sufficiently long time-scale signals for achieving good sensitivity.

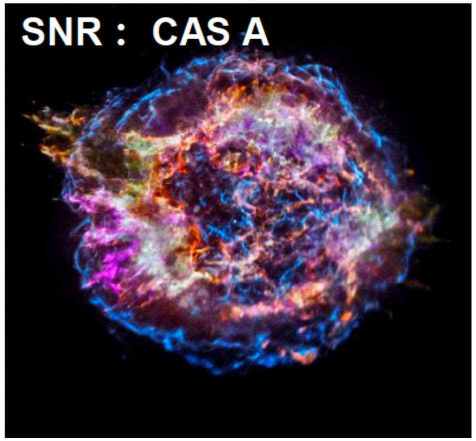
Synergy of CTAO with SKAO!





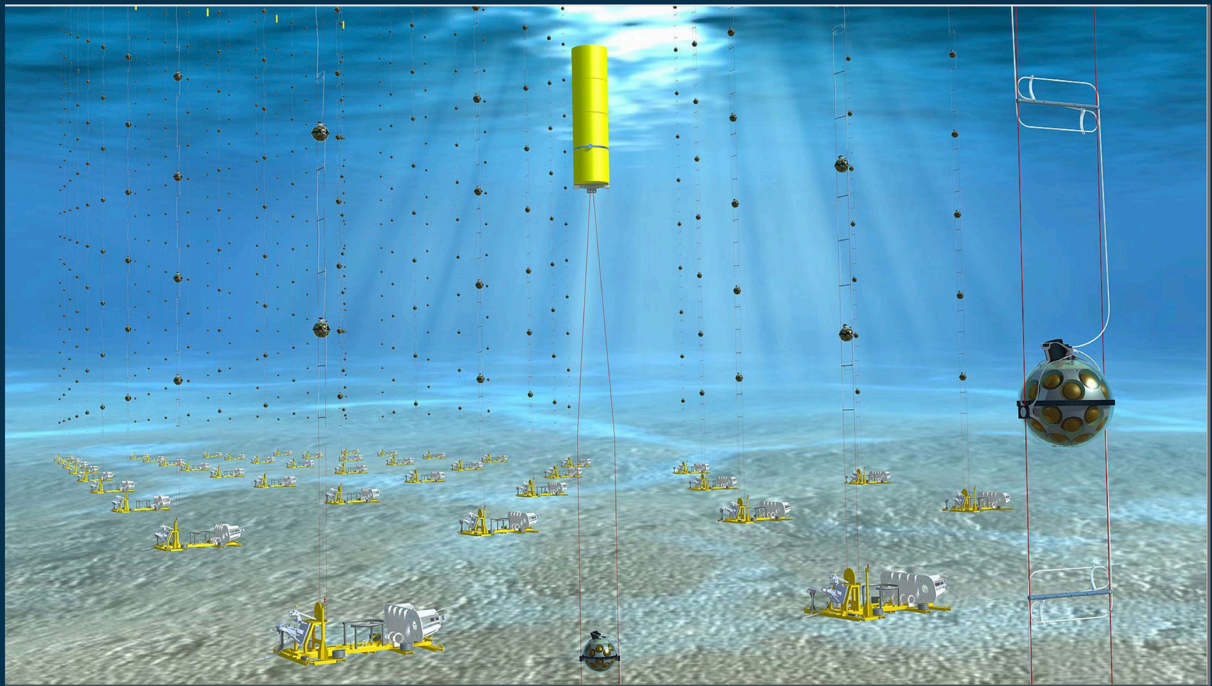
Galactic sources

- Naturally multi-messengers: CRs-γ's- $\nu's$
- Suitable candidate galactic sources must explain:
    - The power budget in CRs to the knee
    - How do they accelerate particles of mixed composition to $E_{max} \sim Ze \times 1\mathrm{PeV}$? PeVatron candidates
    - Spectral features and the transition to extra-galactic sources.
- Molecular clouds, pulsar halos and clusters
- Morphology of shocks
- The serendipetous bubbles
- The diffuse emission from the galactic plane



Conclusions

- A bright future of Multimessengers is ahead because of current generation having reached maturity and precision level: fast responses, morphology domain, high statistics of gamma-rays
- In the future Vera Rubin, CTAO, SKAO, ET, LISA, WFIRST, EUCLID!
- Future space mission replacing Fermi is needed, HERD is on the way but



Ma sedendo e mirando, interminati
Spazi di là da quella, e sovrumani
Silenzi, e profondissima quiete
Io nel pensier mi fingo; ove per poco
Il cor non si spaura.

L'infinito di G. Leopardi