Neutrino astronomy in the era of the Global Neutrino Network

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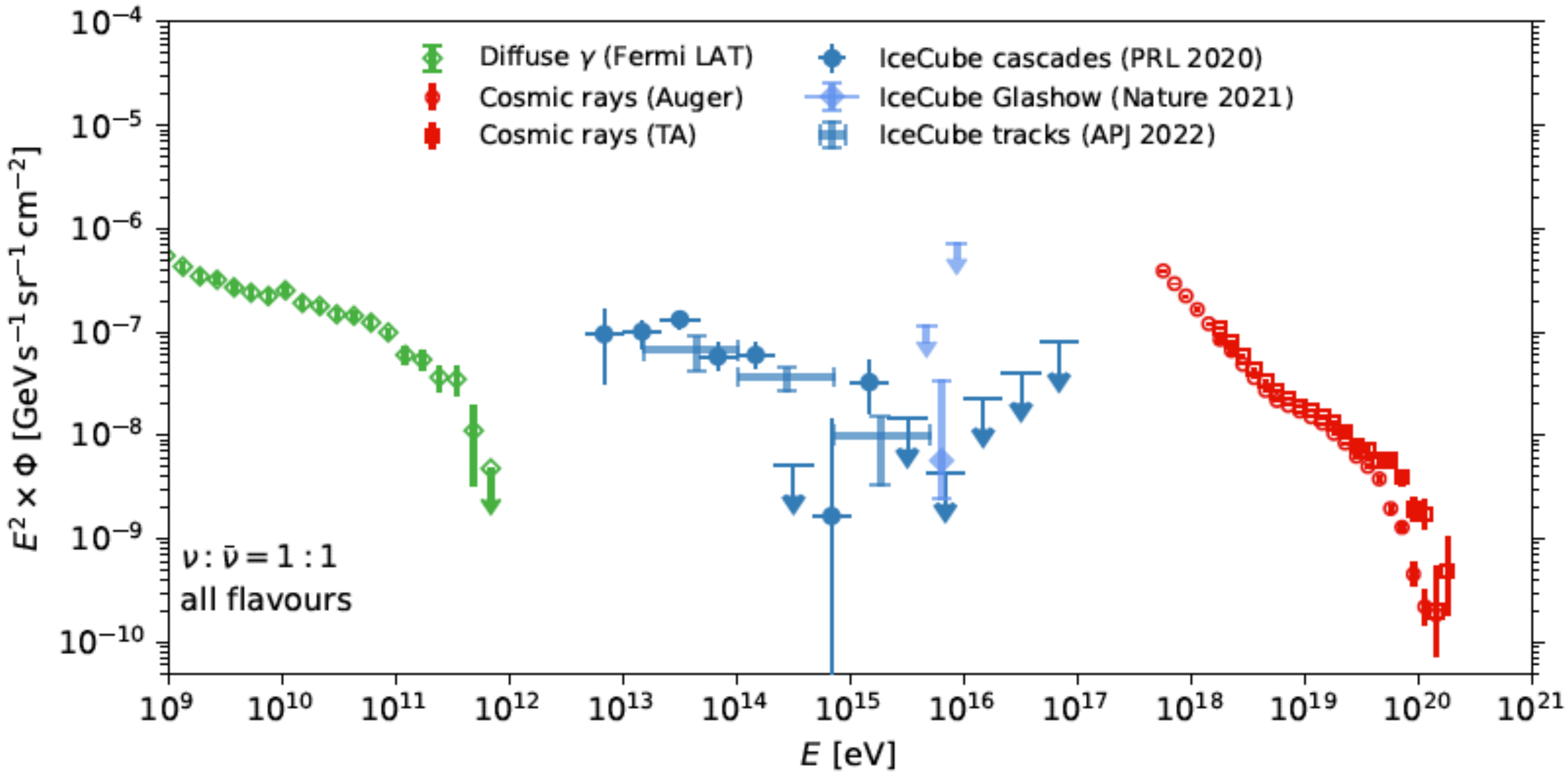
3rd Gravi Gamma Workshop, Volterra, 5-7/09/2022

Different ν data sets available

Different neutrino samples already indicated the observation of a "extraterrestrial" VHE neutrino flux at more than 10 σ



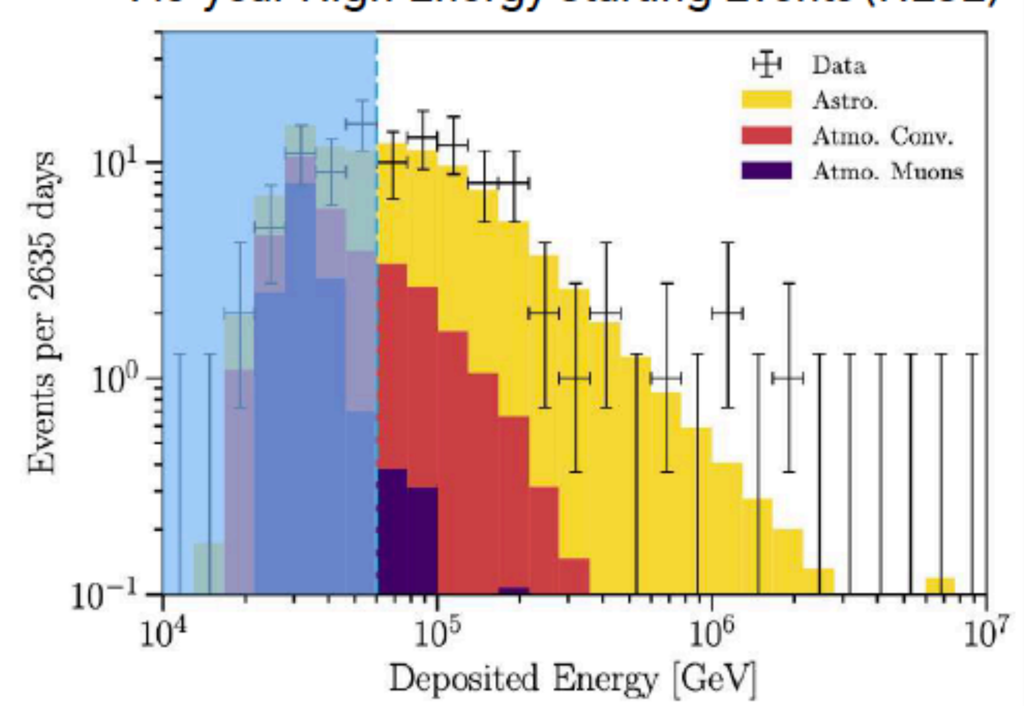
ν spectral features favors a multicomponent description "Reservoirs" + "Accelerators"

Single VHE neutrino events need a MM observations to become significants

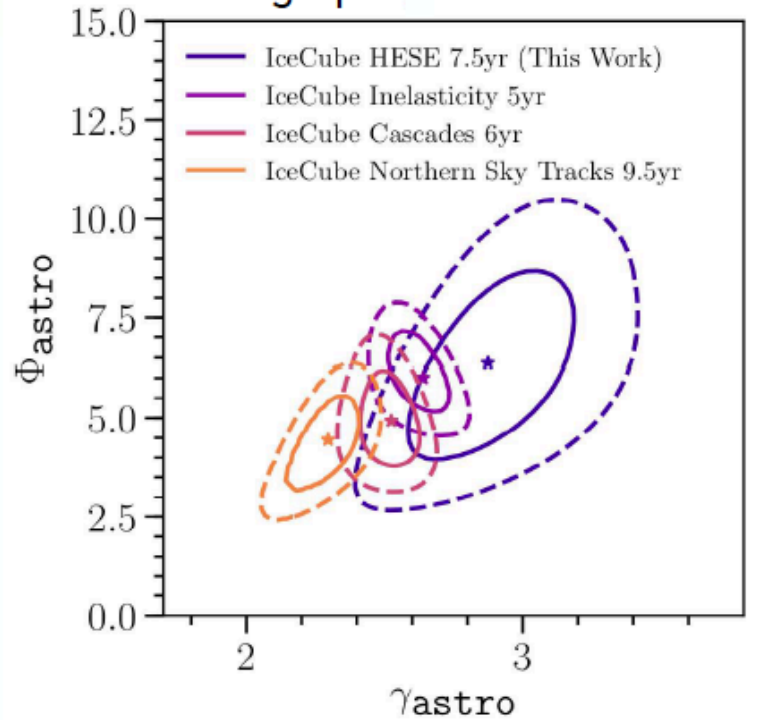
Astro ν Spectral properties

PRD 104 (2021)
IceCube

7.5-year High-Energy Starting Events (HESE)



Single power-law best-fit

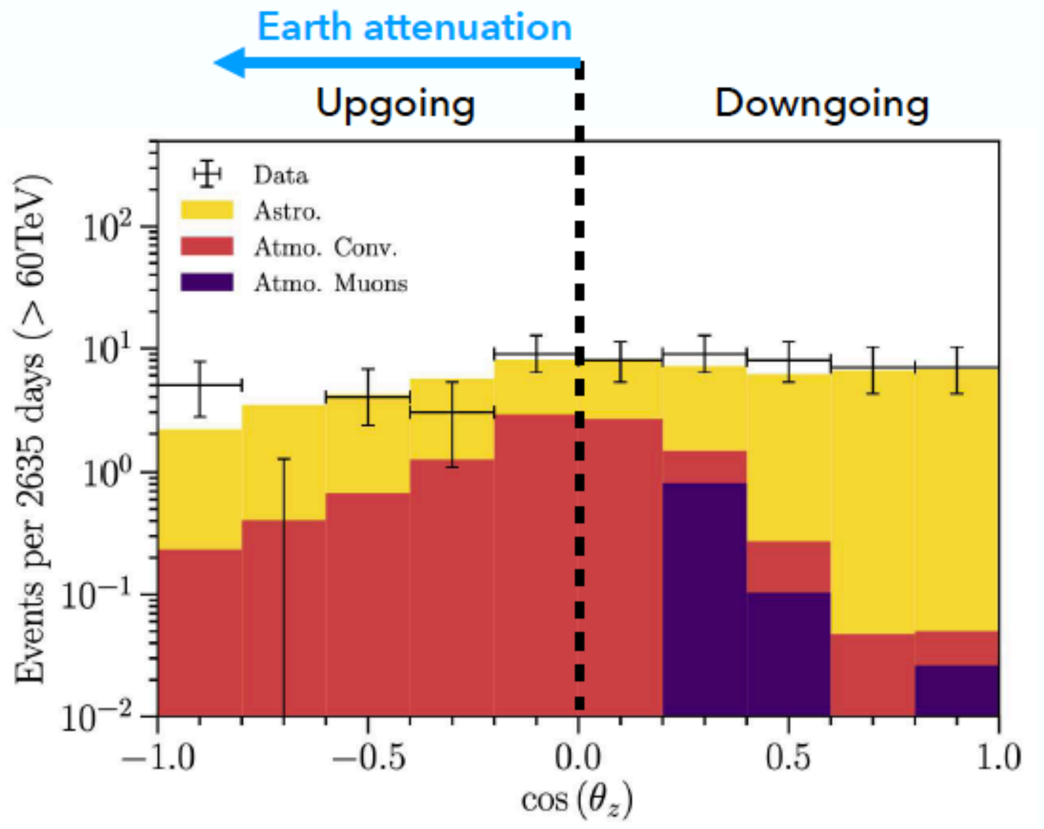


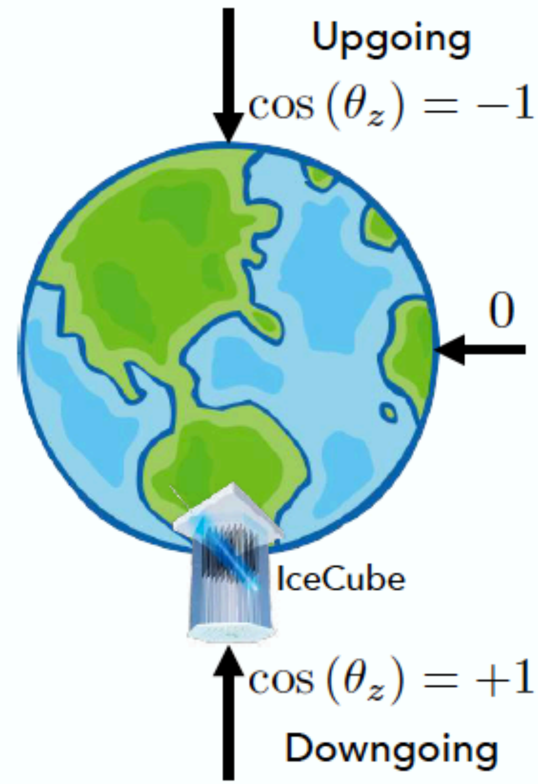
- ✦ 100+ neutrino events above 30 TeV since 2011
- ✦ Bkg-only hypothesis excluded at more than 7σ

$$\frac{d\Phi_{6\nu}}{dE} = \Phi_{\rm astro}\left(\frac{E_\nu}{100\,{\rm TeV}}\right)^{-\gamma_{\rm astro}} \cdot 10^{-18}\ {\rm GeV^{-1}cm^{-2}s^{-1}sr^{-1}}$$

ASTRO ν ARRIVAL DIRECTION

PRD 104 (2021)
IceCube





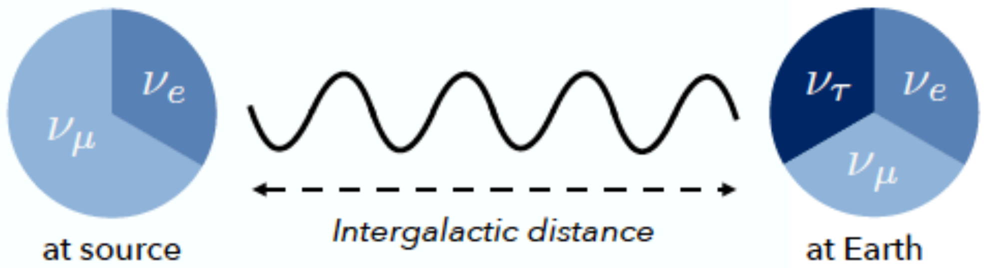
- ✦ The diffuse flux is isotropic

expected observation: Isotropy

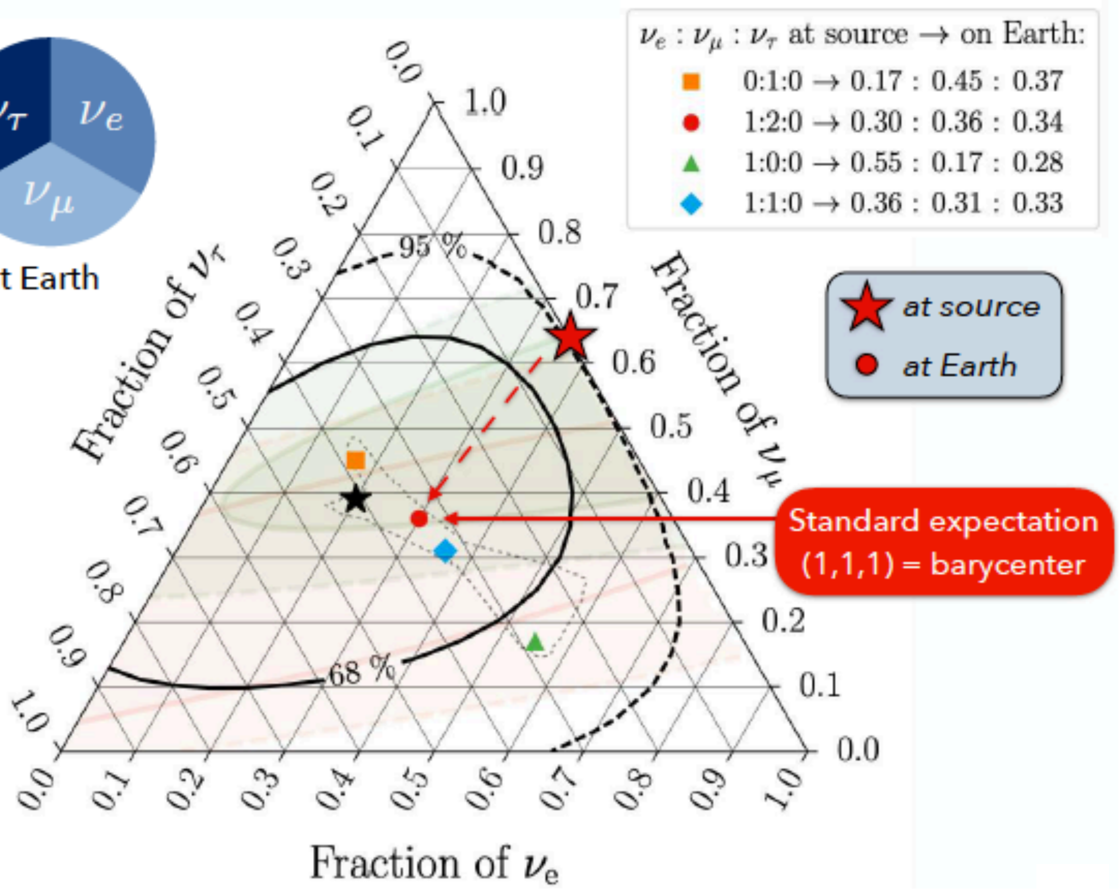
ν FLAVORS: ASTROPHYSICAL ORIGIN

ArXiv 2011:03561
IceCube

The different event topologies (tracks and showers) allow the study of flavor composition and oscillation

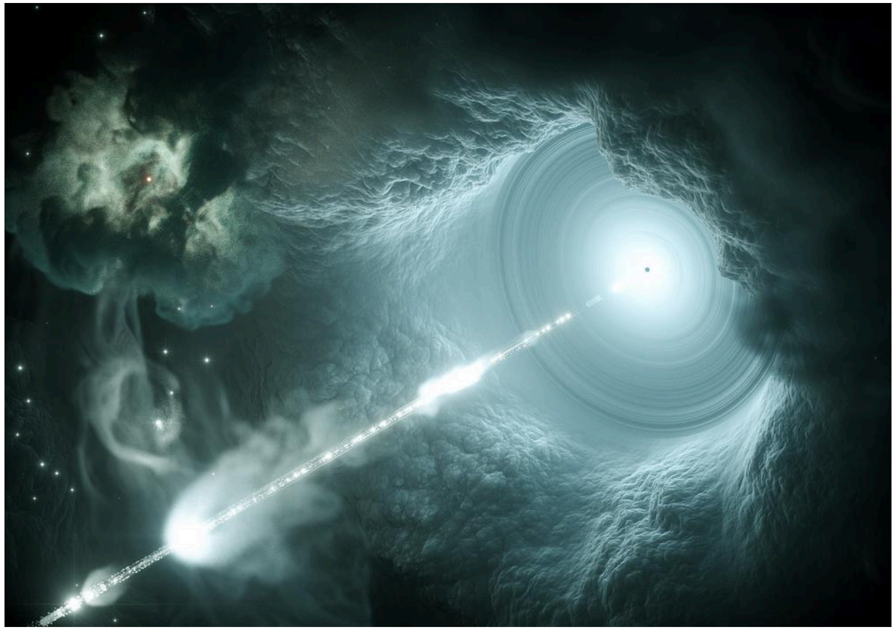


$$\nu_\alpha = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \to \nu_\alpha} \nu_\beta$$



- ✦ Unveiling the astrophysical neutrino production
- ✦ Probing standard and non-standard neutrino oscillation probabilities thanks to high energies and large distances

LOOKING FOR QUITE STABLE ν EMITTERS & LONG TIME VARIABLE ν EMITTERS (>1 DAY)



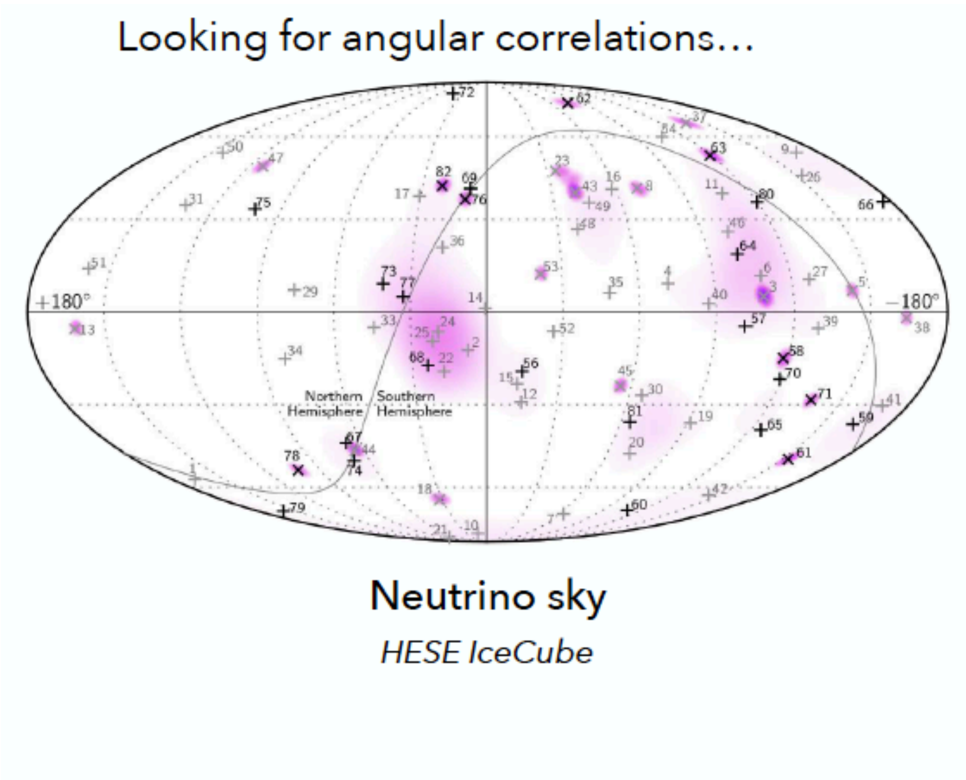
Blazar, artist view
DESY, science Comm. Lab

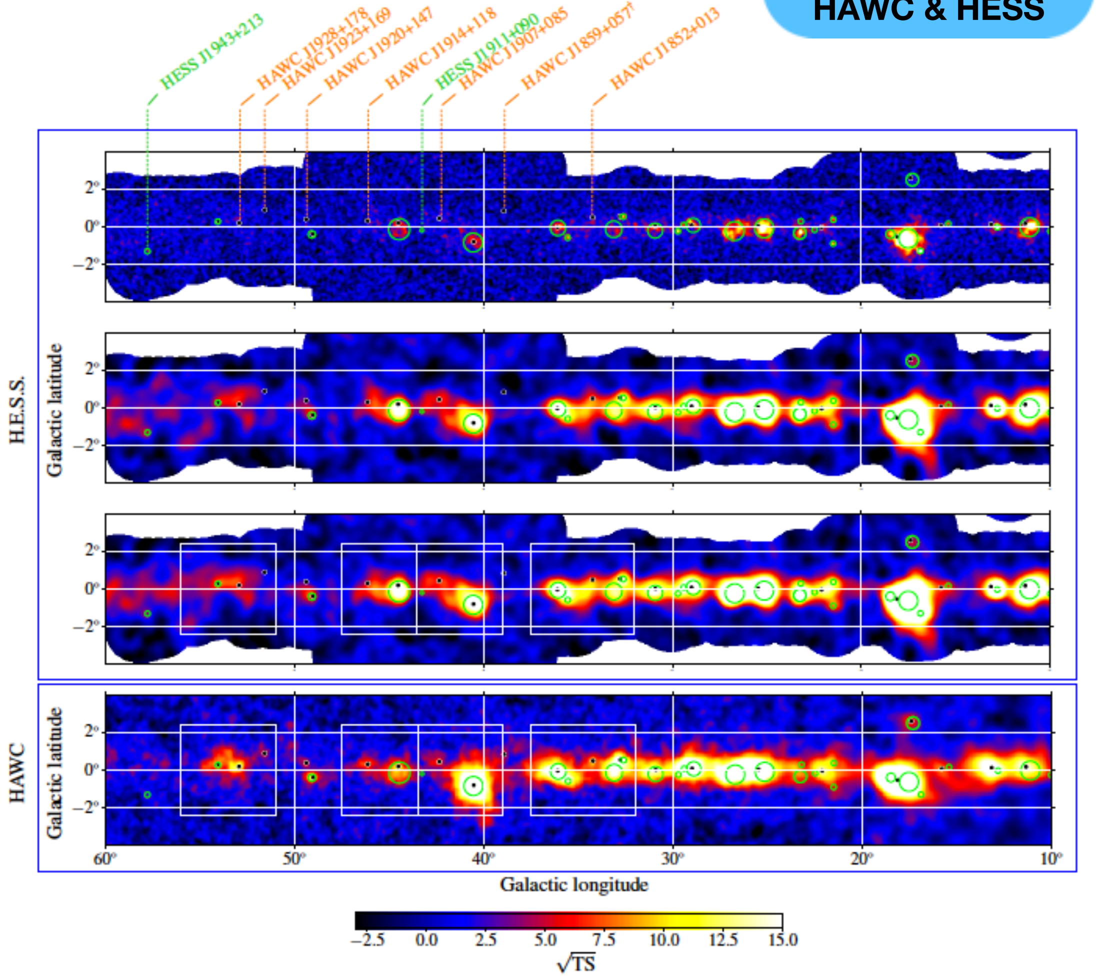
Starburst Galaxy M82
NASA, ESA, and The Hubble heritage Team (STScI/AURA)

Correlation with galactic sources

ApJ 849 (2017)
IceCube

ApJ 917:6 (2021)
HAWC & HESS



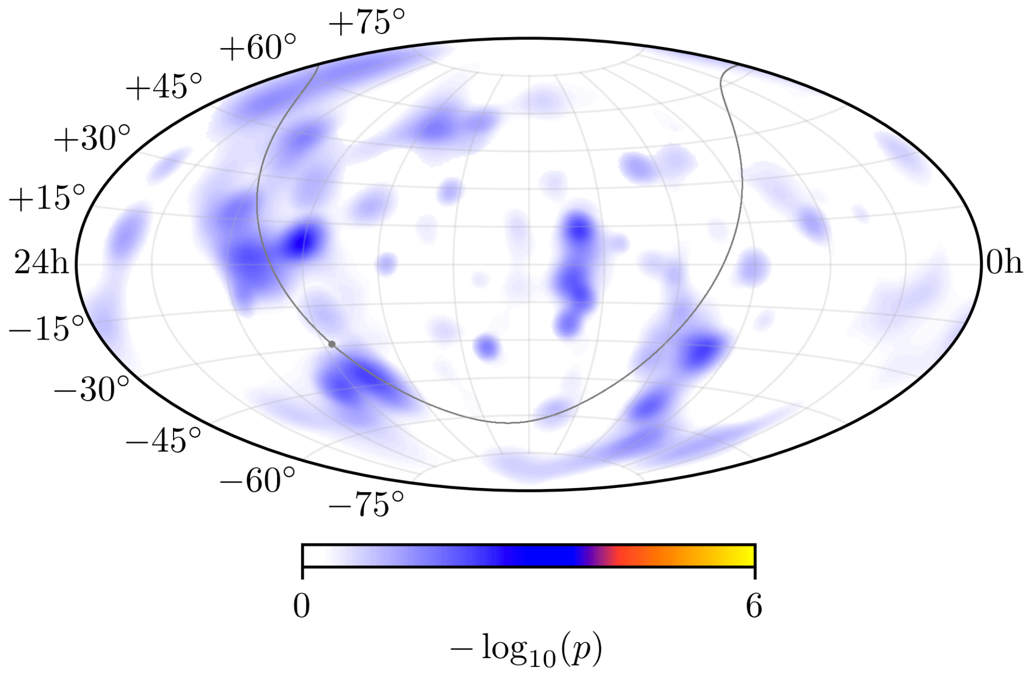


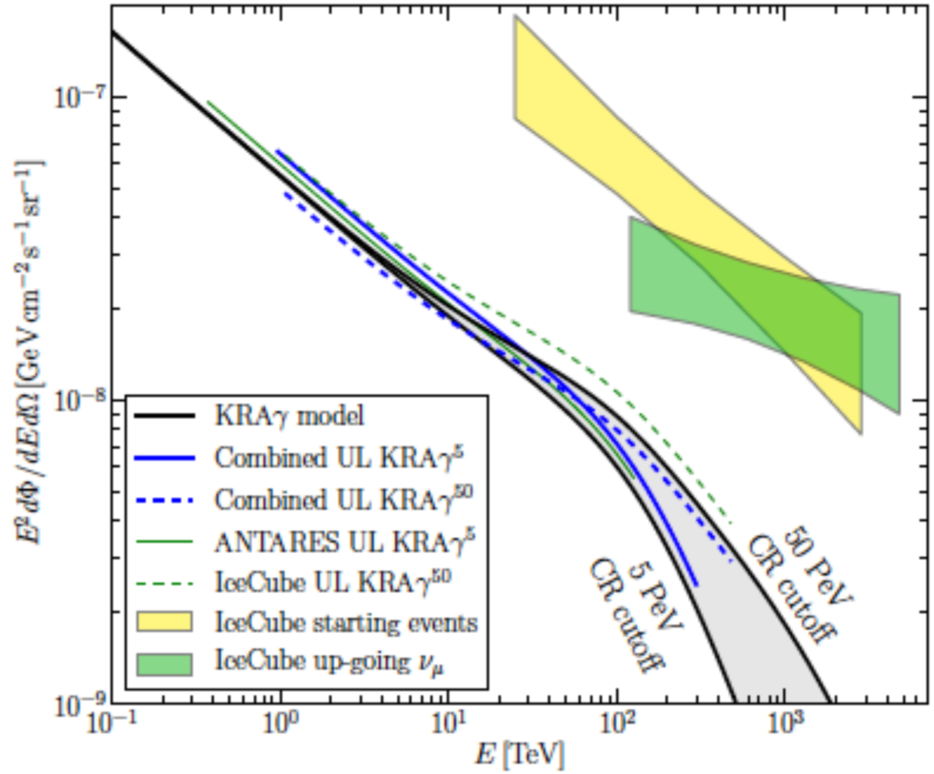
No significant association with the HAWC and H.E.S.S. observed Galactic sources

Galactic diffuse component

ApJ 920 (2019)
IceCube

Gaggero,Grasso, A.M, Urbano, Valli APJL (2015)
PRD IceCube +Antares (2017)





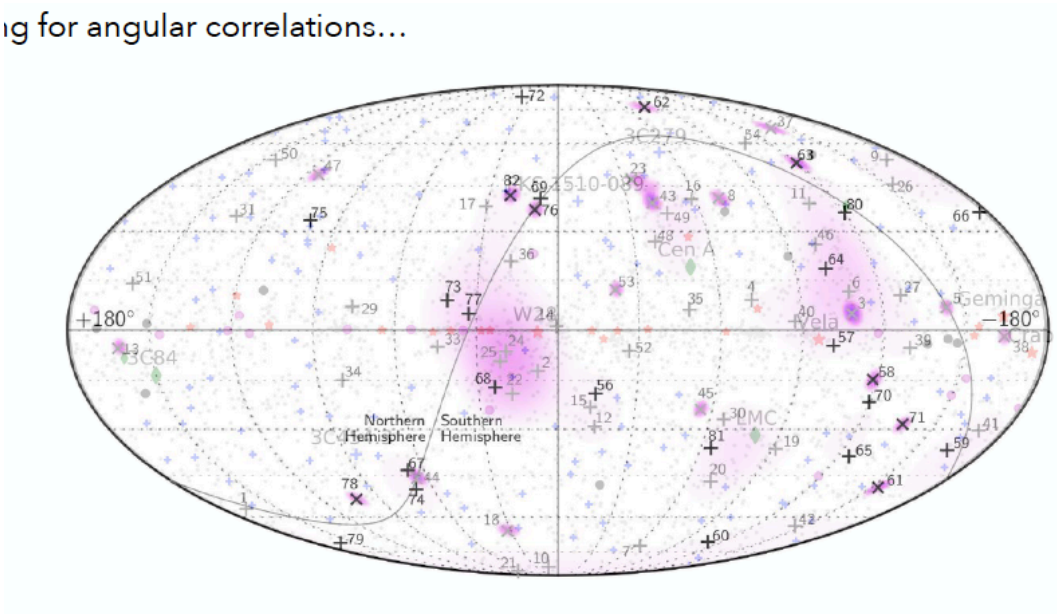
Evidence of galactic diffuse component at 2.2 sigma

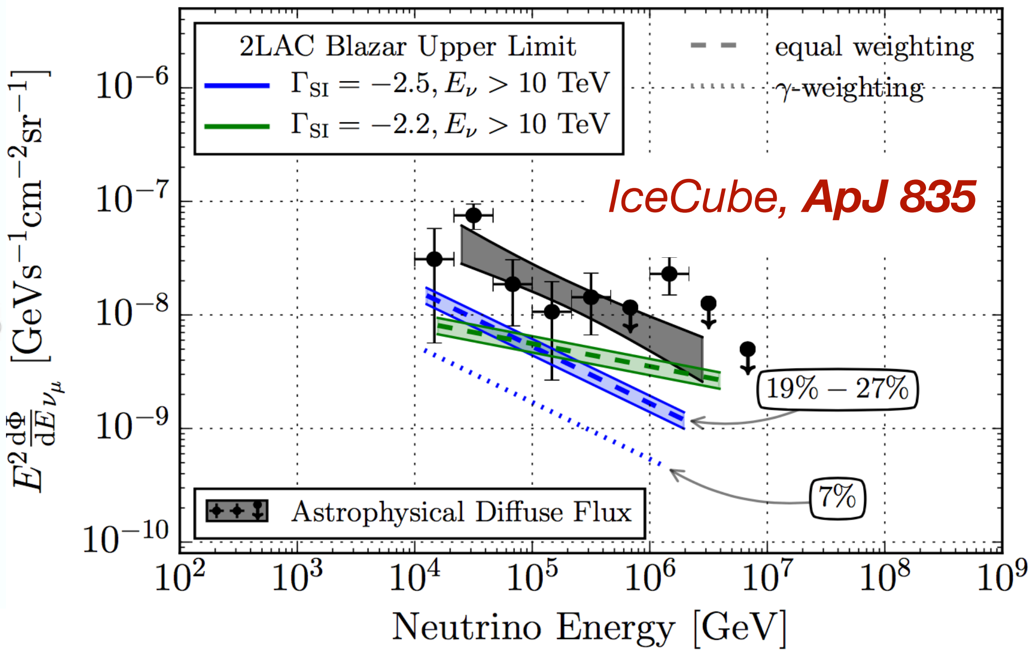
Galactic diffuse component less than 10% of total astrophysical flux measured by IceCube

Blazars neutrino stacking limit

More about that in the Sara Buson talk

ApJ 835 (2017)
IceCube





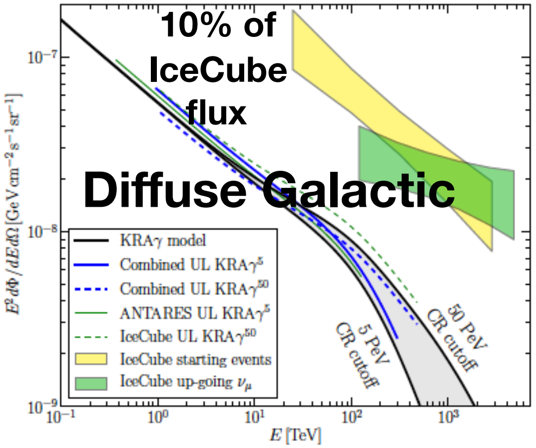
IceCube stacking limit: blazars can contribute at most 19% - 27% of the diffuse neutrino flux

$(E_\nu > 10$ **TeV**$)$

MULTICOMPONENT FIT OF THE ICECUBE DATA

- High energy part of IceCube SED can be described through **photo-hadronic** neutrino production of blazars (in the plot calibrated with TXS 0506+056 observations).

Gaggero,Grasso, A.M, Urbano, Valli APJL (2015); PRD IceCube +Antares (2017)



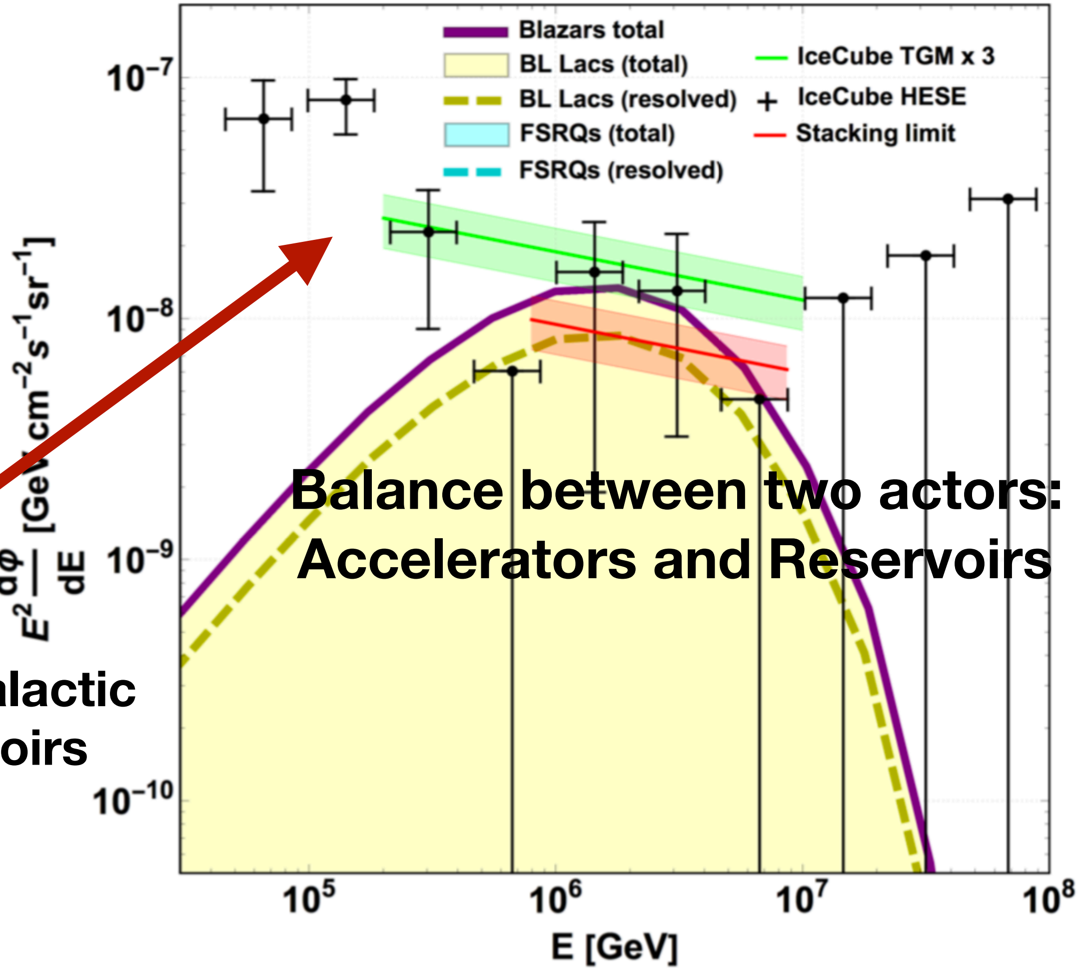
10% of IceCube flux

Diffuse Galactic

+

Extra Galactic reservoirs

*Palladino et al., **ApJ 871** (2019)*



Balance between two actors: Accelerators and Reservoirs

Possible description of "reservoir" components: Starforming + Starburst galaxies

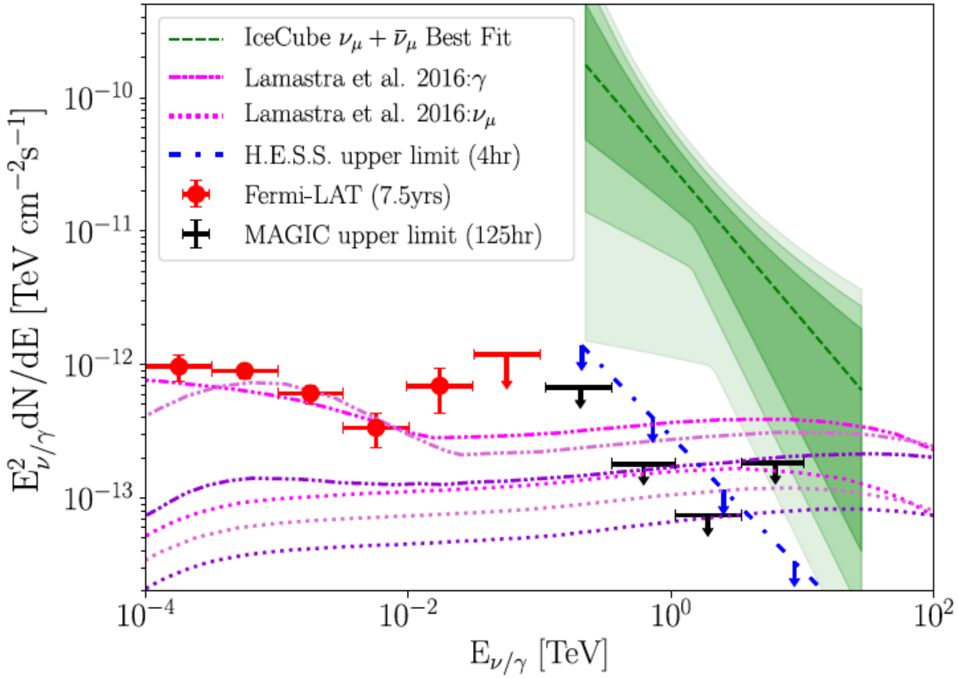
MNRAS 503 4032 (2021) Ambrosone, Chianese, Fiorillo, A.M., Miele, Pisanti

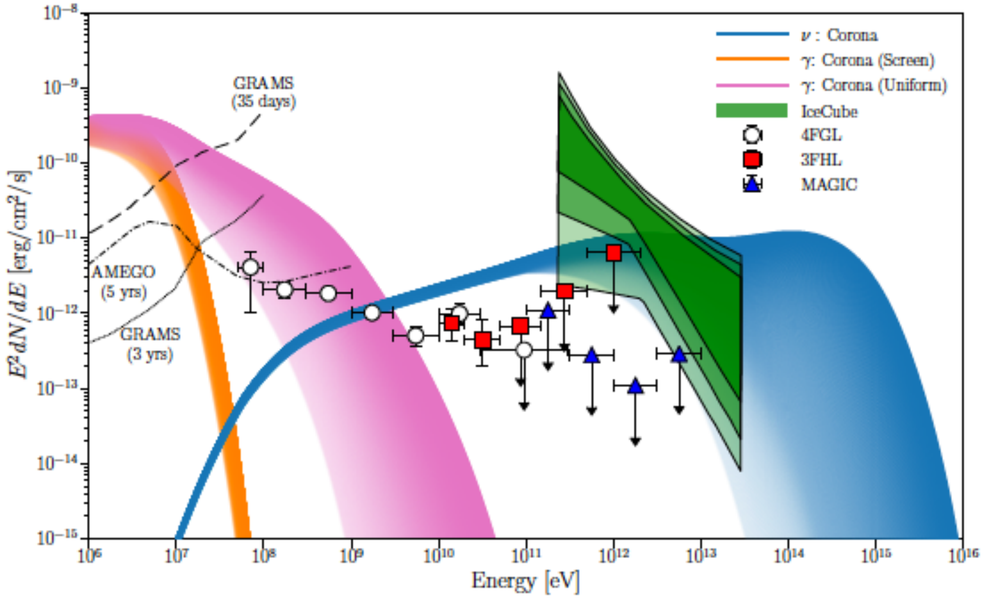
THE CASE OF NGC 1068

PRL 124 (2020) IceCube

The IceCube Collaboration has found a 2.9σ excess into the 10-year data

APJL 891 (2020) Inoue et al.
PRL 125 (2020) Murase et al.

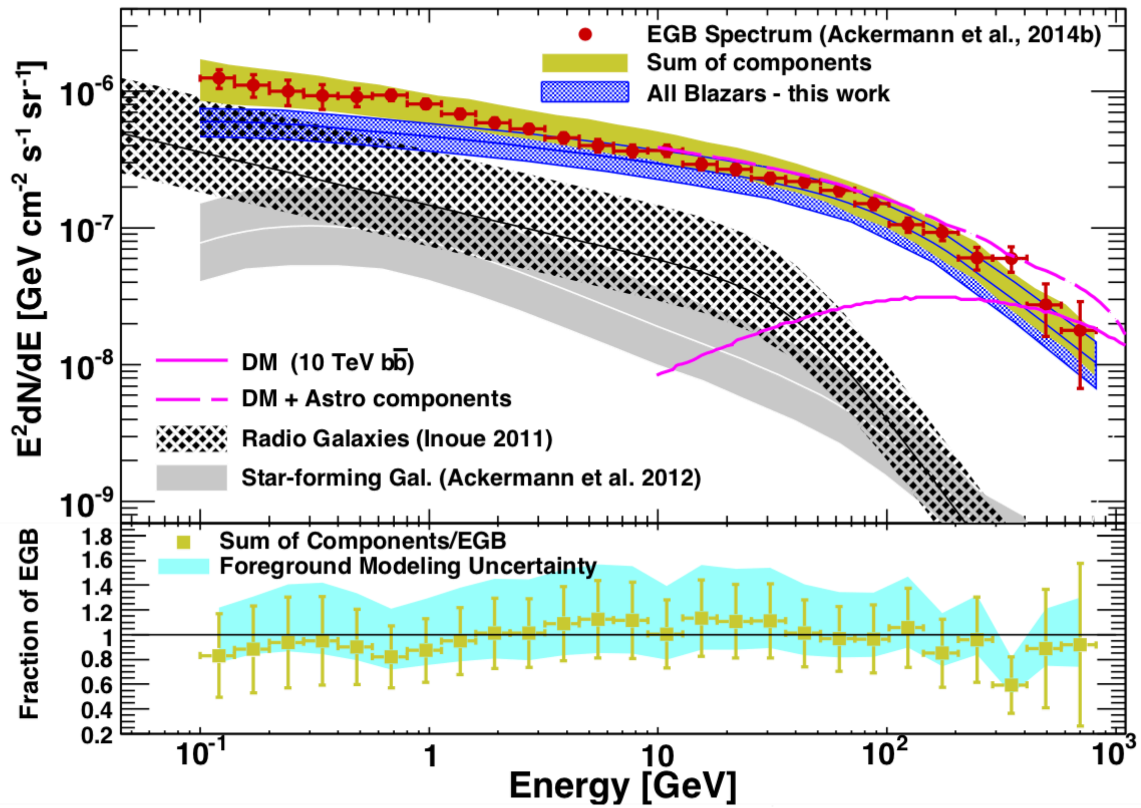




One of the most significant spot in the northern sky observed by IceCube need a better understanding: only starburst emission or additional emission components related to the AGN activity?

EXTRAGALACTIC GAMMA-RAY BACKGROUND

Ajello et al., APJL 800 (2015)



- Fermi-LAT resolved many individual sources belonging to different classes, Blazars dominates the EG samples.
- Limit on PS above 50 GeV varies from 68% (Lisanti et al. 2016) to 86% (Ackermann et al. 2016) of the EGB

Starforming and Starburst galaxies gamma-ray component needs a better definition due to the small number of resolved ones at HE

Hadronic production in the SBGs

p-p interaction is likely to occur when
density of gas higher than density of radiation
(for example in Starburst Galaxies)

Properties of SBGs

- **~100 Myr phase** in the life of a Galaxy
- High Star Formation Rate **(10-100 times higher than Milky Way)**
- They are abundant **(~10^4 — 10^5 Gpc^{-3})**
- Strong Magnetic field **10^2-10^3 μG**
- Not very brilliant in gamma-rays **(only a few currently observed)**

The Starburst Galaxy M82

SEMI-ANALYTIC PARAMETRIZATION OF SBGs

All the SBGs are considered with the same properties of a ***prototype*** galaxy with "known" parameters

- In the calorimeter scenario, three main parameters:

parameter	value
$p_{p,\max}$	10^2 PeV
α	4.2
R	0.25 kpc
D_L	3.9 Mpc
$\xi_{\rm CR}$	0.1
$\mathcal{R}_{\rm SN}$	0.06 yr^{-1}
B	200 μG
$n_{\rm ISM}$	100 cm^{-3}
$v_{\rm wind}$	700 km/s
$U_{\rm rad}$	2500 $\mathrm{eV/cm}^3$

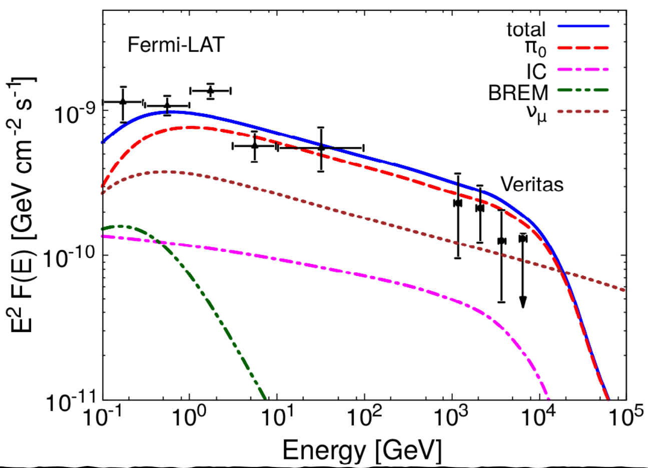
- Cut-off energy
- Spectral index
- Rate of Supernova explosions → **The Star Formation Rate**

Tloss > Tesc in the core

Leaky-box-like model for CR transport

$$f(p)\left(\frac{1}{\tau_{\rm loss}(p)}+\frac{1}{\tau_{\rm adv}(p)}+\frac{1}{\tau_{\rm diff}(p)}\right)=Q(p)$$

CR injected and accelerated by SNRs



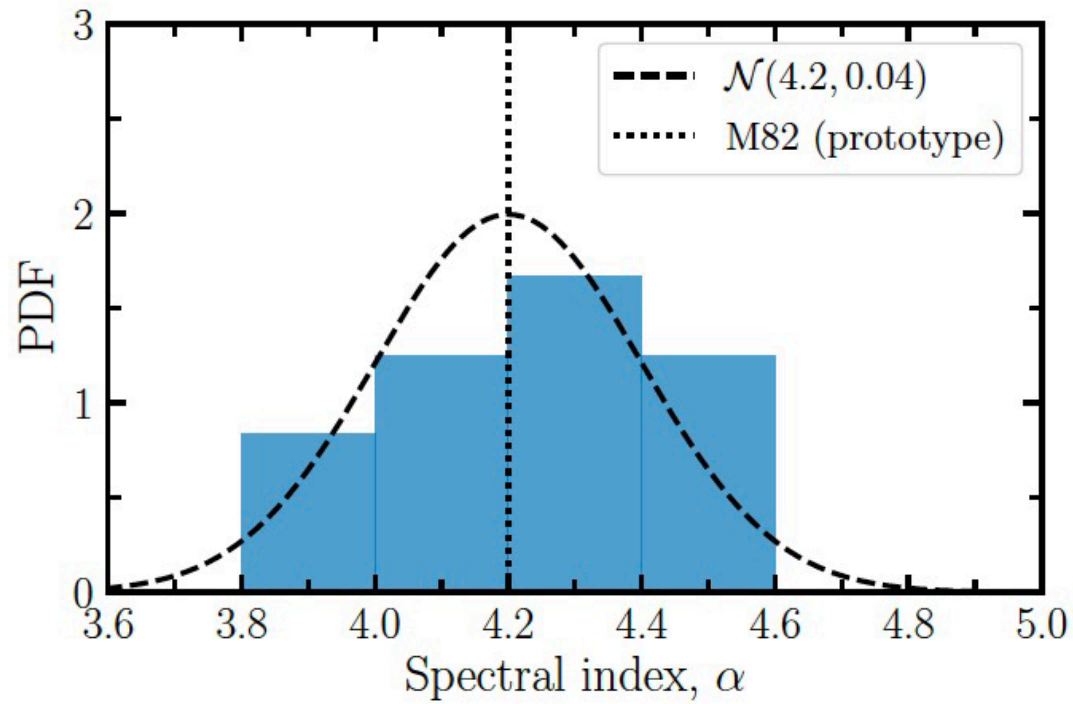
M82 as prototype

BLENDING OF SPECTRAL INDEXES USED

- We allow each starburst galaxy to have different a different spectral index

$$\left\langle \phi_{\nu,\gamma}(E|p^{\max},\alpha) \right\rangle_\alpha = \int \mathrm{d}\alpha\, \phi_{\nu,\gamma}(E|p^{\max},\alpha)\, p(\alpha)$$

MNRAS 503 4032 (2021) Ambrosone, Chianese, Fiorillo, A.M., Miele, Pisanti



- 12 SFGs and SBGs have been resolved in gamma-rays

Ajello et al., ***arXiv:2003.05493***

↓

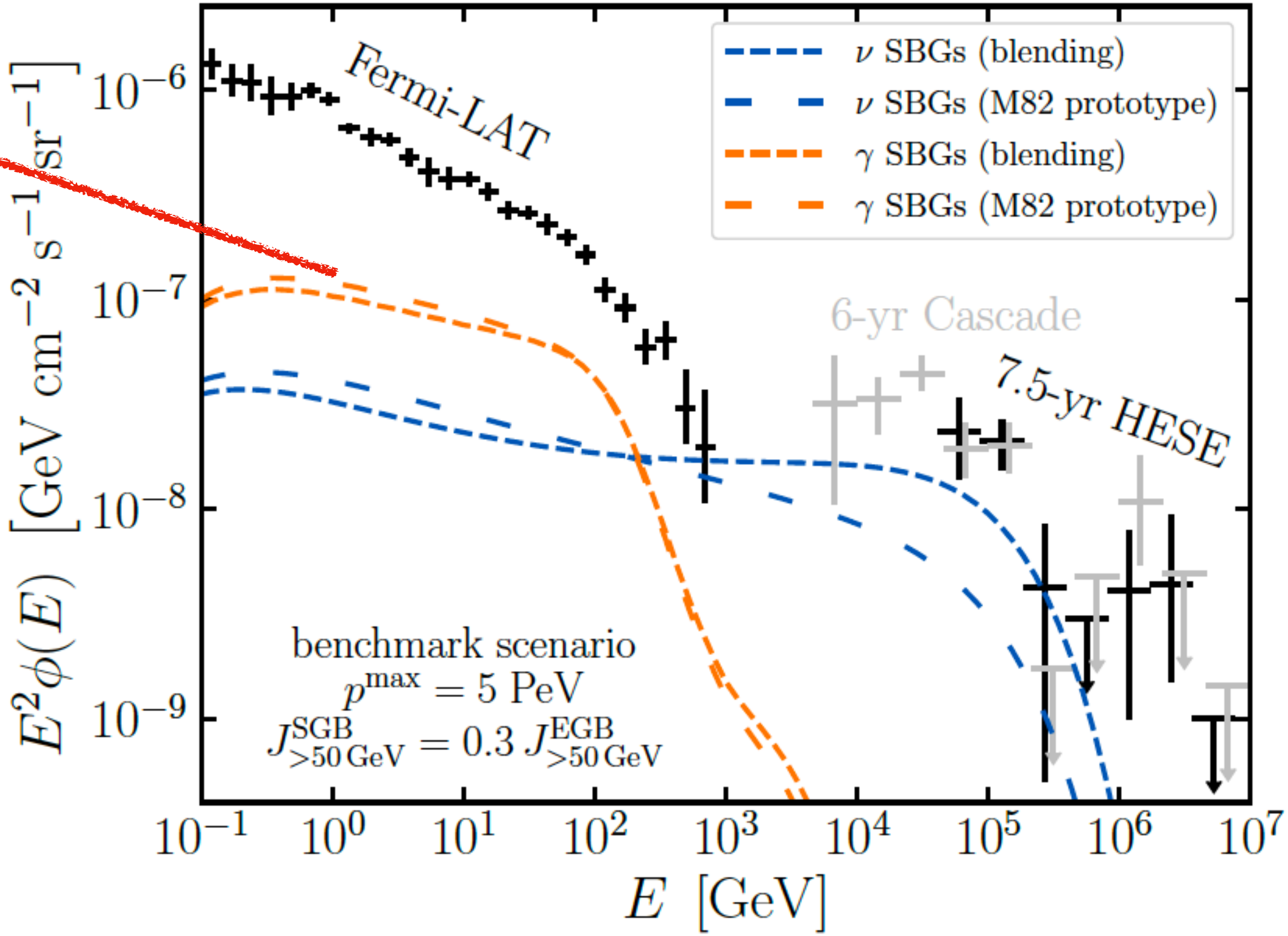
$$p(\alpha) = \mathcal{N}(\alpha|4.2, 0.04)$$

BLENDING VERSUS PROTOTYPE SCENARIO

Diffuse emission considering SFR modified Schecter function up to z=4.2 (based on IR+UV)

MNRAS 503 4032 (2021) Ambrosone, Chianese, Fiorillo, A.M., Miele, Pisanti

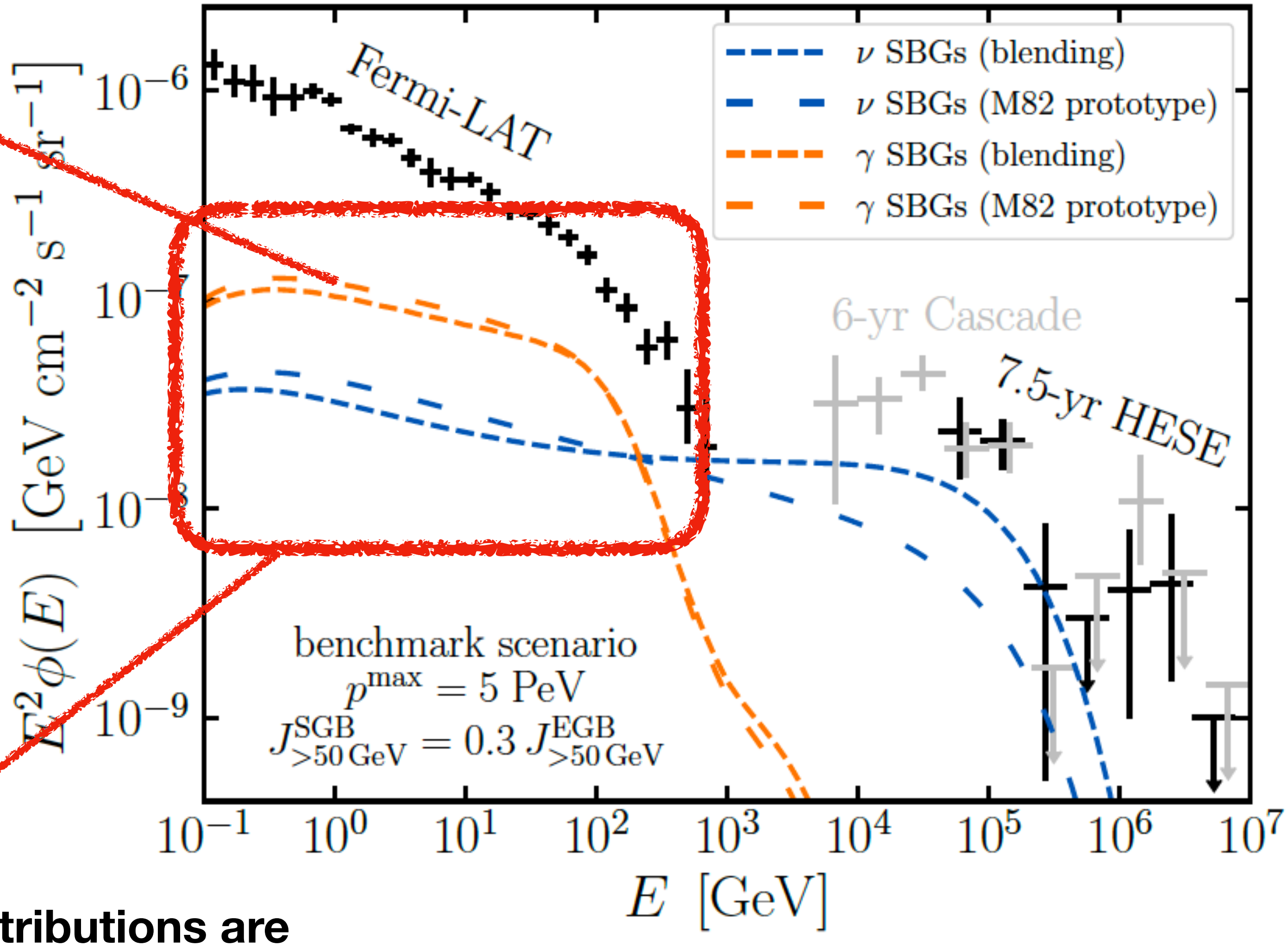
Direct + electromagnetic cascades gamma-ray flux



BLENDING VERSUS PROTOTYPE SCENARIO

MNRAS 503 4032 (2021) Ambrosone, Chianese, Fiorillo, A.M., Miele, Pisanti

Direct + electromagnetic cascades gamma-ray flux EBL taken into account

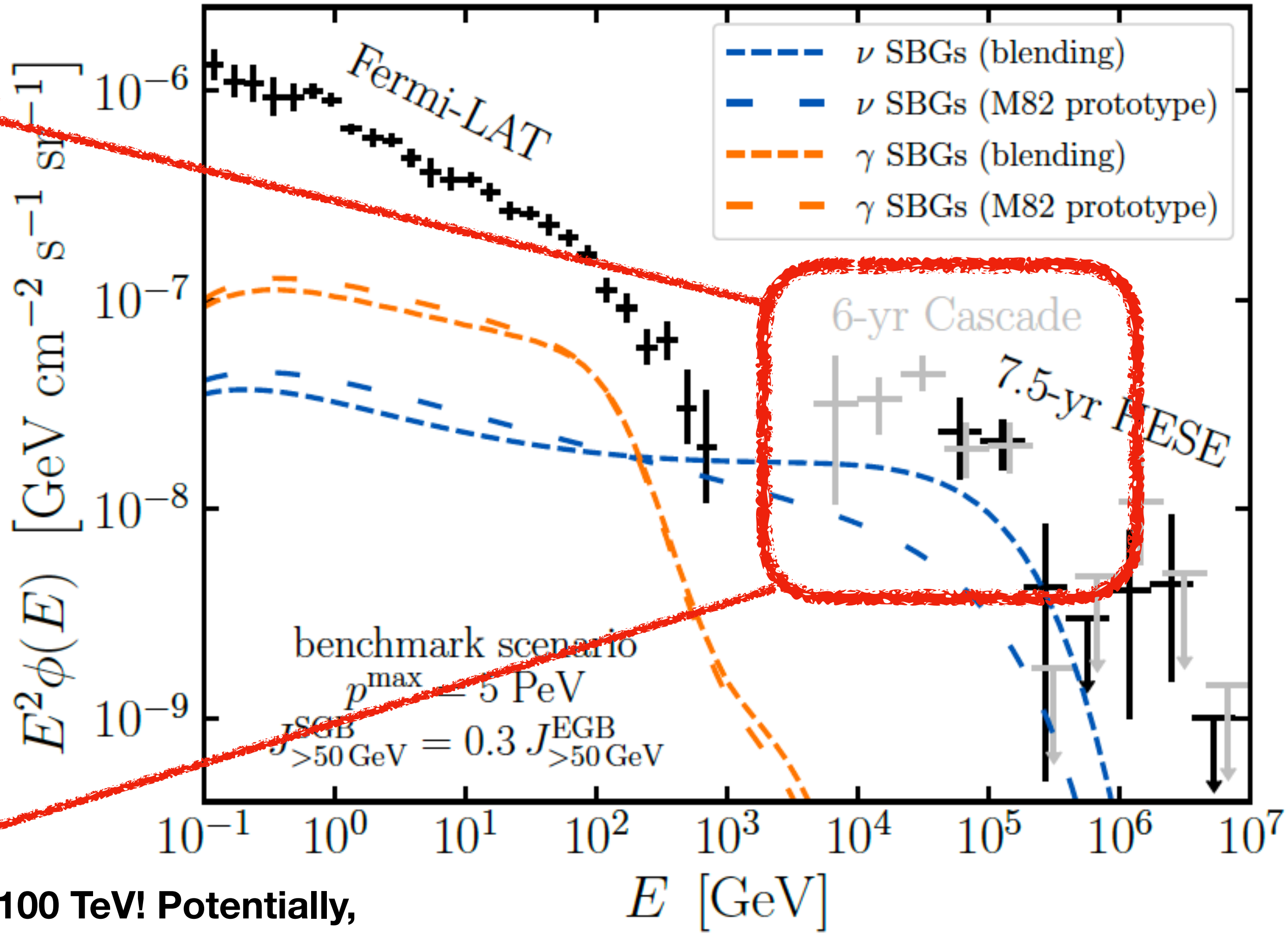


The diffuse gamma contributions are almost the same!

BLENDING VERSUS PROTOTYPE SCENARIO

MNRAS 503 4032 (2021) Ambrosone, Chianese, Fiorillo, A.M., Miele, Pisanti

With $p^{\max} = \mathcal{O}(\mathrm{PeV})$ it is possible to obtain a significant nu contribution at around 100 TeV

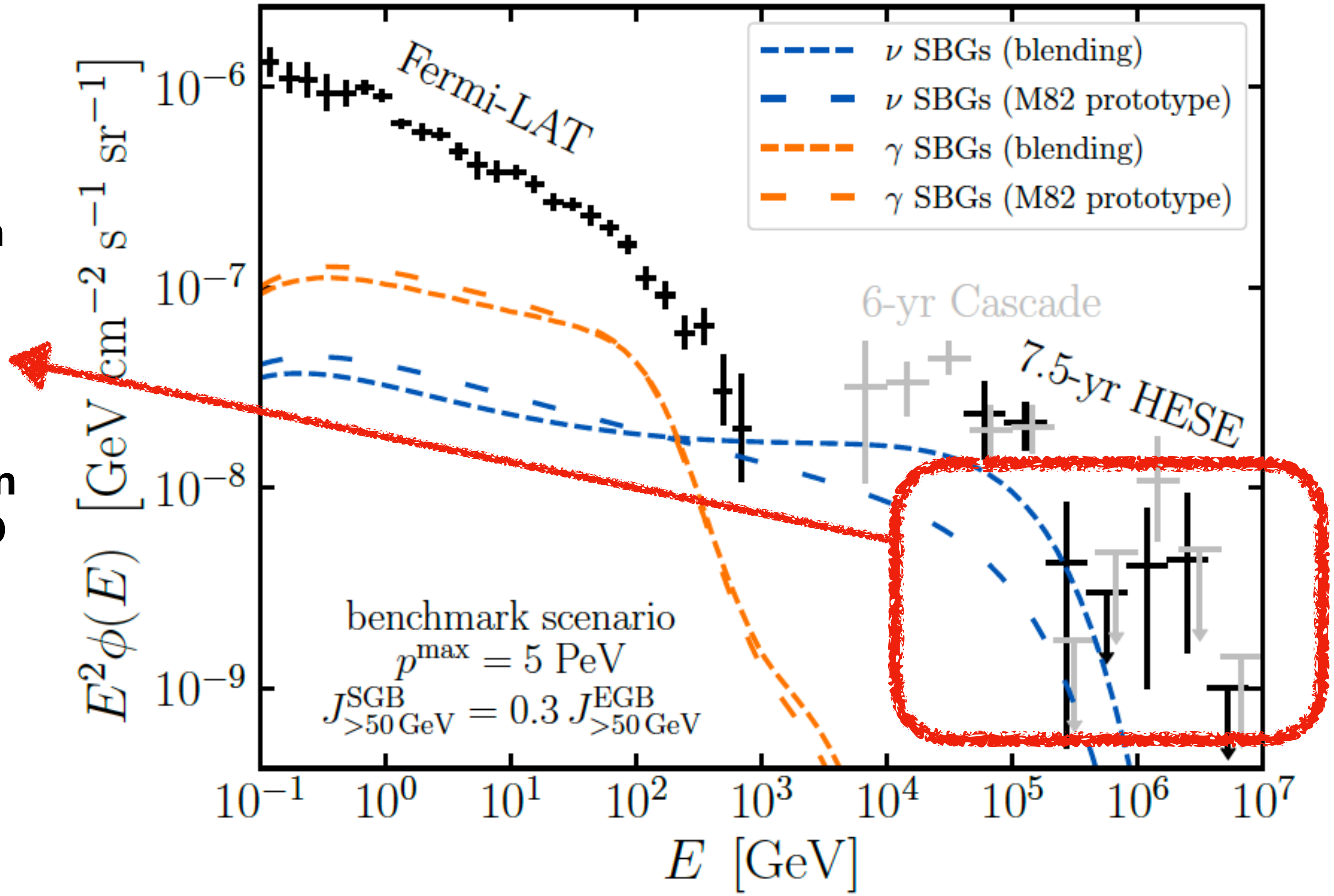


Larger contribution around 100 TeV! Potentially,
It could alleviate the tension between neutrino and gamma-ray data when using hadronic scenarios to explain IceCube observations.

BLENDING VERSUS PROTOTYPE SCENARIO

MNRAS 503 4032 (2021) Ambrosone, Chianese, Fiorillo, A.M., Miele, Pisanti

A possible contribution at higher energies from Blazar?
A interplay between reservoirs and accelerators can explain the whole IceCube SED



THE PROPOSED MULTIMESSENGER FIT

The Gamma-Ray Contributions:
1. **SBGs**
2. **Blazar + Electromagnetic Cascades**
3. **Radio Galaxies**

For Blazars and Radio Galaxies, we used the estimations given by Ajello et al. 2015 **(ArXiv: 1501.05301)**

The Neutrino Contributions:
1. **SBGs**
2. **Blazars**

For Blazars, we used the estimations given by Palladino et. Al 2019 **(ArXiv:1806.04769)**

MNRAS 503 4032 (2021) Ambrosone, Chianese, Fiorillo, A.M., Miele, Pisanti

Observational Samples Used

Extragalactic gamma-ray Background (EGB)

1. **7.5 years HESE**
2. **6 years Cascades**

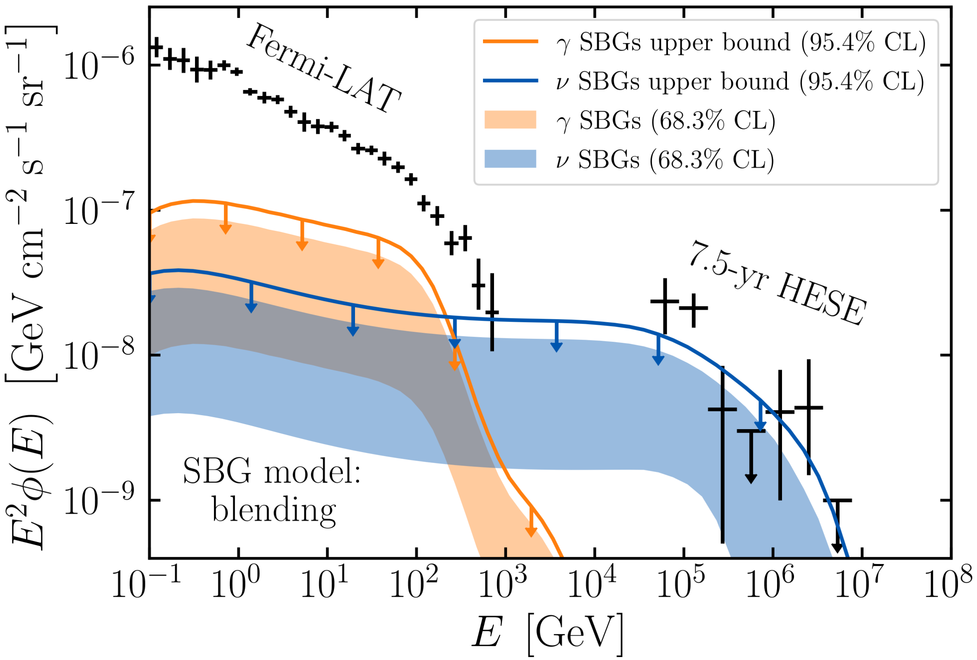
$$\chi^2_{\nu+\gamma}(N_{SBG}, N_{RG}, N_{Blazars}, p^{max}) = \chi^2_\nu + \chi^2_\gamma + \left(\frac{N_{Blazars}-1}{0.26}\right)^2 + \left(\frac{N_{RG}-1}{0.65}\right)^2 + \left(\frac{N_{Blazars}-0.80}{0.11}\right)^2$$

They come from uncertainties of the Non-SBG components

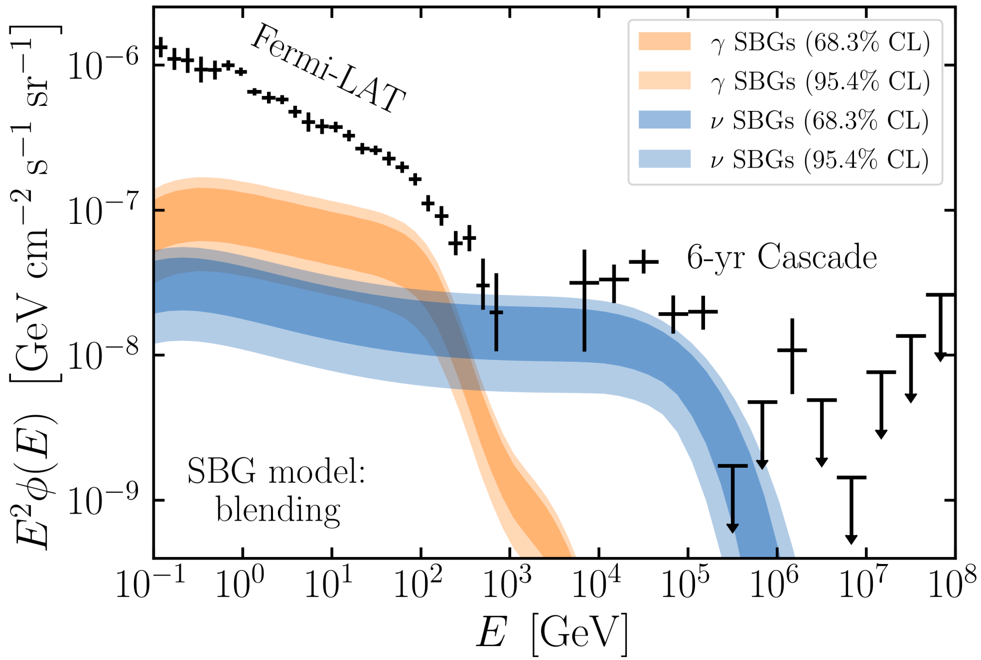
It comes from the positional limit of Point Sources above 50 GeV (Lisanti et al. 2016)

THE PROPOSED MULTIMESSENGER FIT

MNRAS 503 4032 (2021) Ambrosone, Chianese, Fiorillo, A.M., Miele, Pisanti



2 sigmas allowed SED considering Fermi-LAT EGB and IceCube HESE data

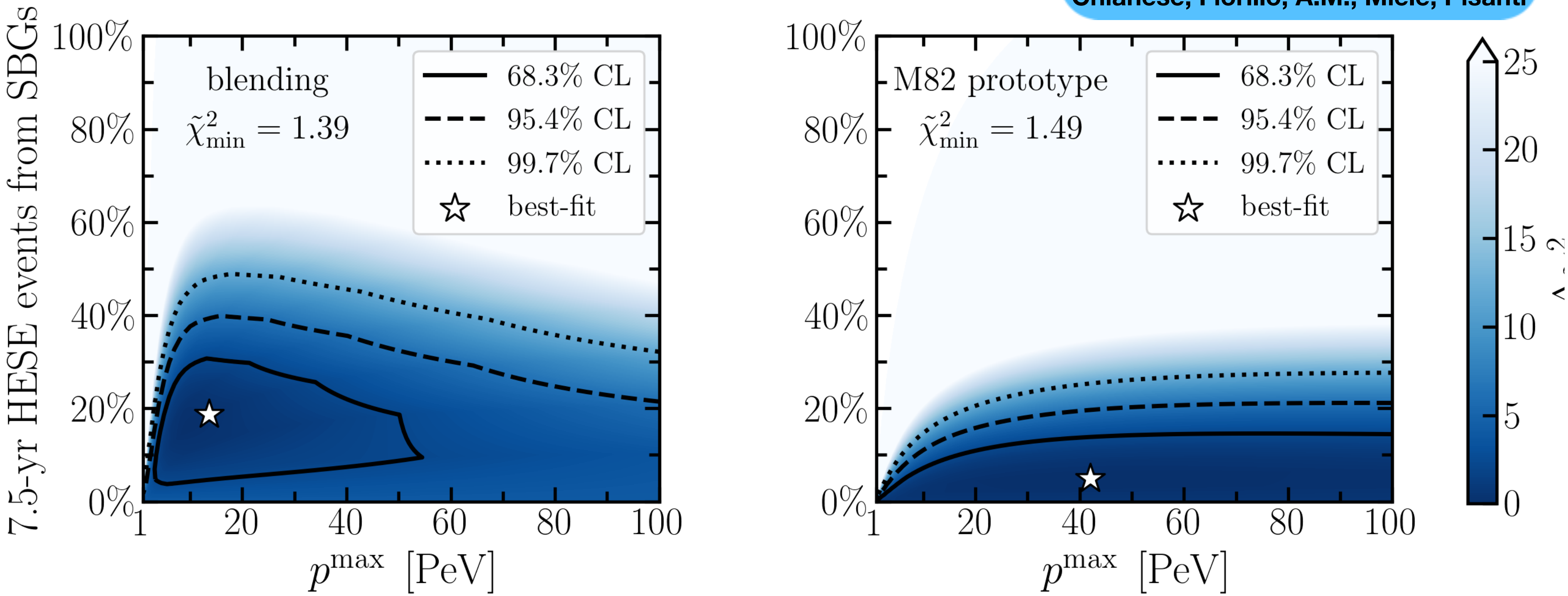


2 sigmas allowed SED considering Fermi-LAT EGB and IceCube CASCADE data

THE PROPOSED MULTIMESSENGER FIT

MNRAS 503 4032 (2021) Ambrosone, Chianese, Fiorillo, A.M., Miele, Pisanti

Redshift interval: $0 \leq z \leq 4.2$



At 2 sigma level the "blending" scenario can account up to 40% of IceCube HESE measured flux, moreover at 1 sigma a Pmax up to 50 PeV is permitted, however a cutoff ~ 10 PeV is favored.

LOOKING AT CLOSE KNOWN SBGs

The gas density and the star formation rate have been linked through this relation:

$$n_{\rm ISM} = 175 \left(\frac{\dot{M}_*}{5\ {\rm M}_\odot\ {\rm yr}^{-1}} \right)^{2/3} {\rm cm}^{-3}$$

(Kennicutt 1998 ; Inoue et al. 2000 ; Hirashita et al. 2003 ; Yuan et al. 2011 ; Kennicutt & Evans 2012 ; Kennicutt & De Los Reyes 2021

While the star formation rate is expected to be proportional to infra red observations through:

$$U_{\rm rad} = 2500 \left(\frac{\dot{M}_*}{5\ {\rm M}_\odot\ {\rm yr}^{-1}} \right) {\rm eV\ cm}^{-3}$$

APJL 919 (2021) Ambrosone, Chianese, Fiorillo, A.M., Miele

Source	Uniform prior	Most-likely values	68% credible intervals		χ^2/dof
	$\dot{M}_*$	$(\dot{M}_*, \Gamma)$	$\dot{M}_*$	Γ	
M82	3.0 – 30	(4.5, 2.30)	[4.3, 4.6]	[2.27, 2.33]	1.24
NGC 253	1.4 – 17	(3.3, 2.30)	[3.14, 3.40]	[2.28, 2.32]	1.32
ARP 220	60 – 740	(740, 2.66)	[492, 740]	[2.51, 2.68]	1.52
NGC 4945	0.35 – 4.15	(4.15, 2.30)	[4.05, 4.15]	[2.23, 2.32]	1.52
NGC 1068	5 – 93	(16, 2.52)	[13, 20]	[2.45, 2.65]	0.65
NGC 2146	3 – 57	(15, 2.50)	[9, 27]	[2.44, 2.88]	0.50
ARP 299	28 – 333	(28, 2.15)	[28, 200]	[1.40, 1.90] ∪ [2.77, 3.00]	0.18
M31	0.09 – 0.90	(0.34, 2.40)	[0.31, 0.40]	[2.29, 2.61]	0.52
M33	0.09 – 0.90	(0.44, 2.76)	[0.19, 0.56]	[2.57, 2.96]	0.44
NGC 3424	0.4 – 5.4	(5.4, 2.22)	[2.5, 5.4]	[1.92, 2.67]	1.63
NGC 2403	0.1 – 1.2	(0.75, 2.12)	[0.58, 0.96]	[1.92, 2.36]	0.38
SMC	0.008 – 0.090	(0.038, 2.14)	[0.037, 0.039]	[2.13, 2.16]	1.90
Circinus Galaxy	0.1 – 8.1	(6.6, 2.32)	[6.2, 7.8]	[2.15, 2.45]	0.92

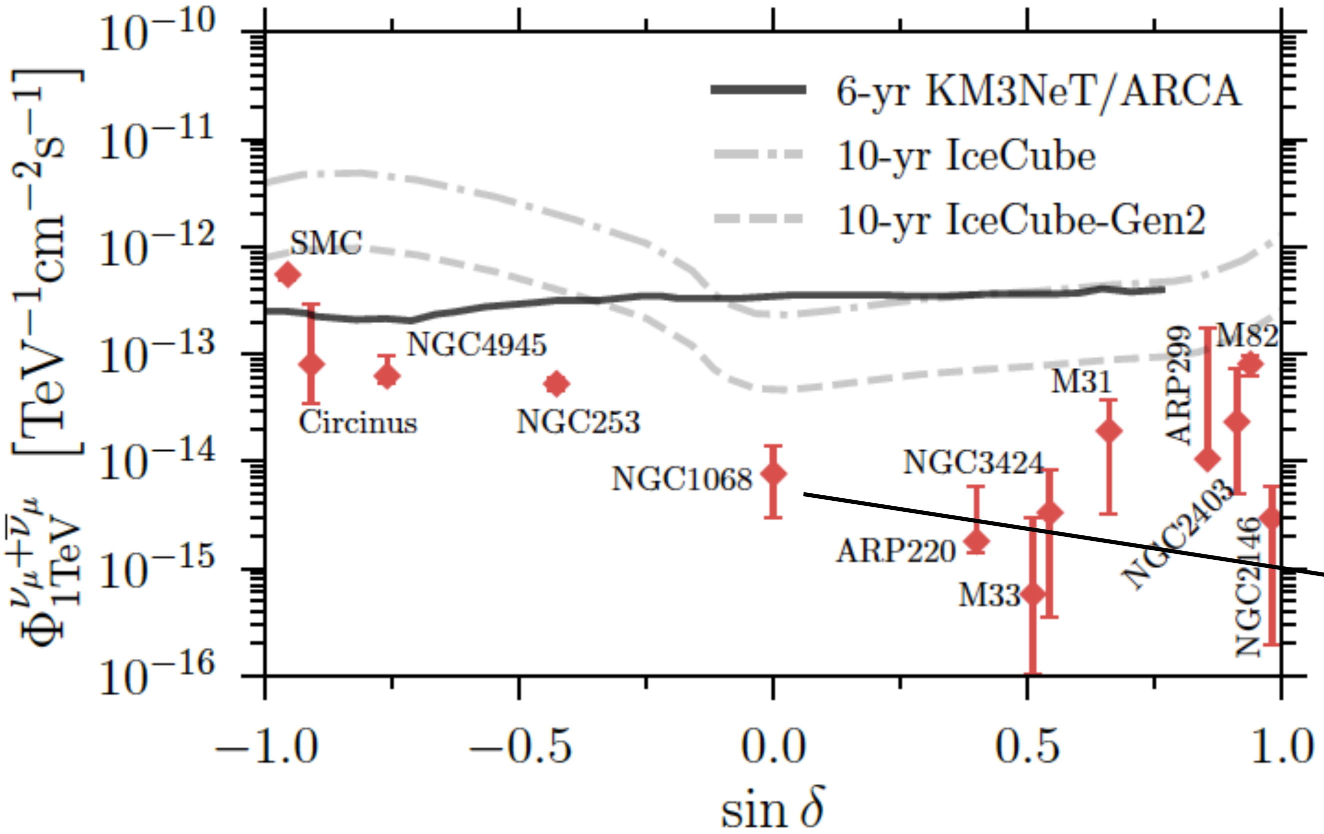
NOTE—The star formation rate $\dot{M}_*$ is in units of ${\rm M}_\odot\ {\rm yr}^{-1}$.

For each SBG we check if the fitting of gamma rays assuming a "calorimetric" scenario does not produce a tension between the gas needed and the IR observations

NEUTRINO EXPECTATIONS FROM KNOWN SBGs

The neutrino normalizations obtained for the 13 SBGs considered have been compared to the expected point-like sensitivities of KM3NeT and IceCube observatories.

APJL 919 (2021) Ambrosone, Chianese, Fiorillo, A.M., Miele



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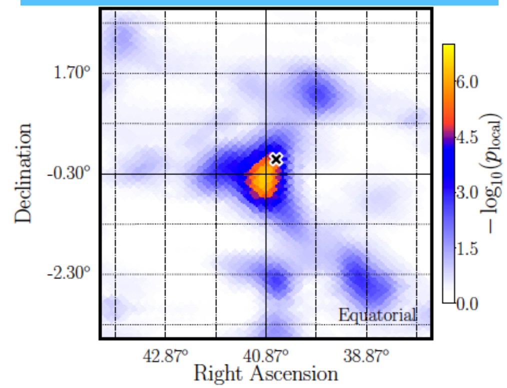
To describe the neutrino excess observed from NCG1068 additional AGN components are needed.

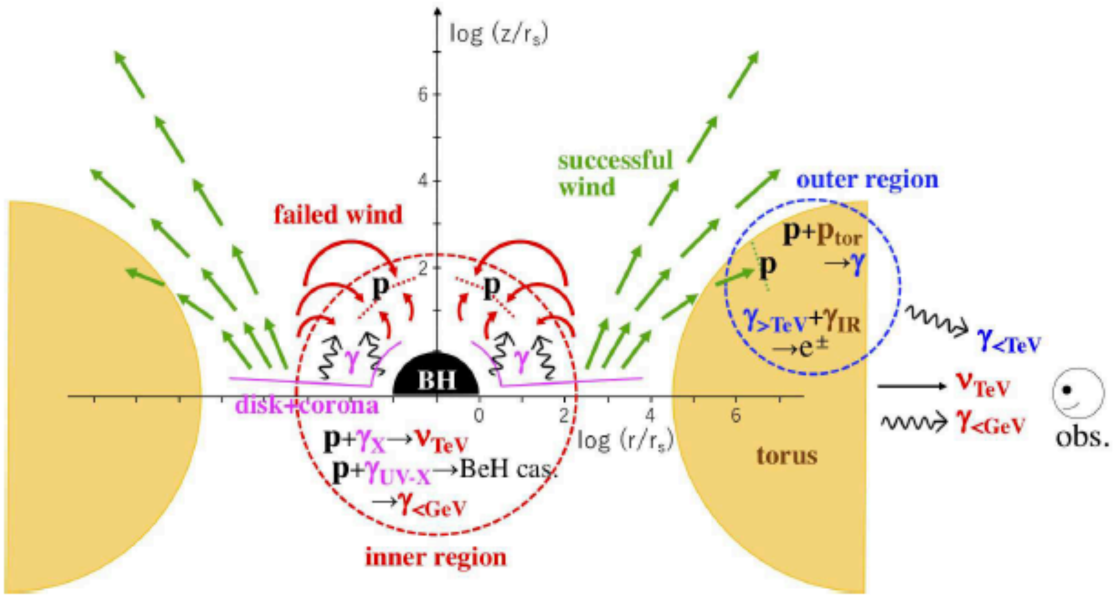
IceCube coll. PRL 2020

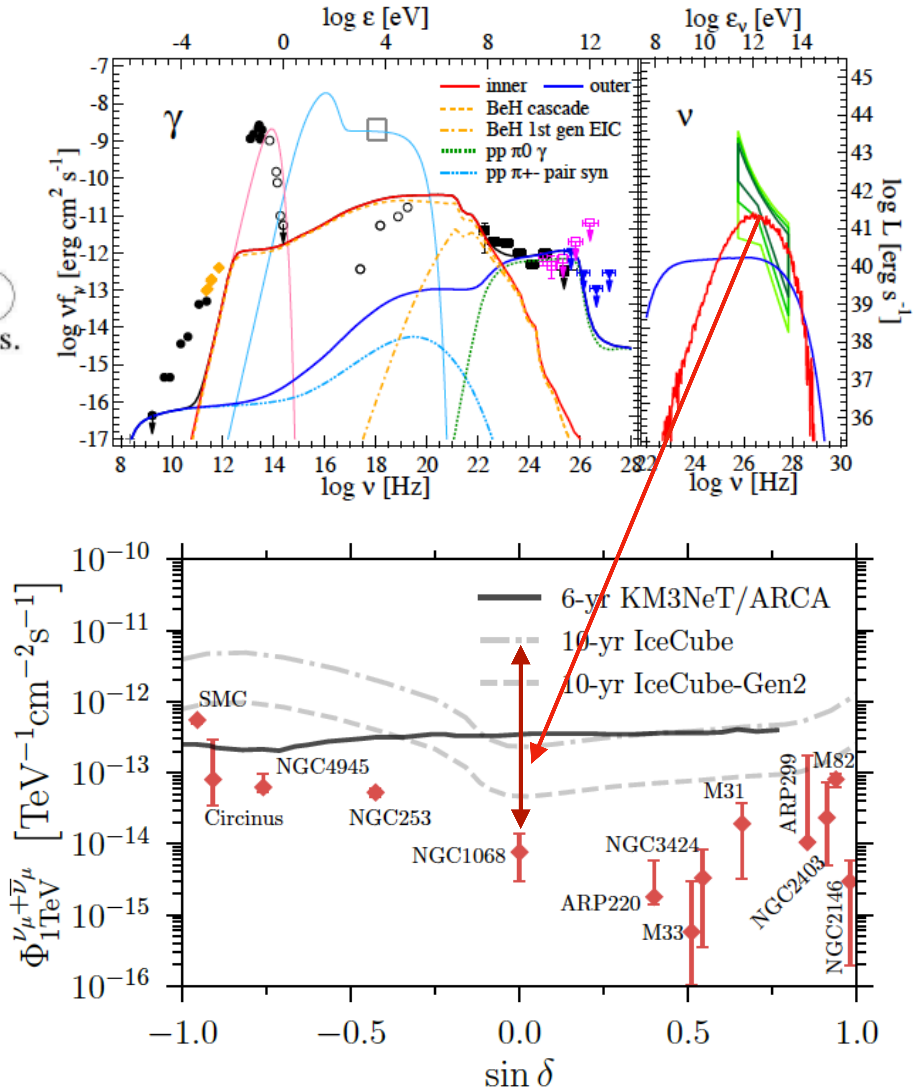


Few SBGs have the possibility to be observed by neutrino telescopes only considering the starburst neutrino production, however some of them can produce VHE neutrinos through the activity related to the supermassive black holes hosted (AGN).

ADDITIONAL AGN ν COMPONENT

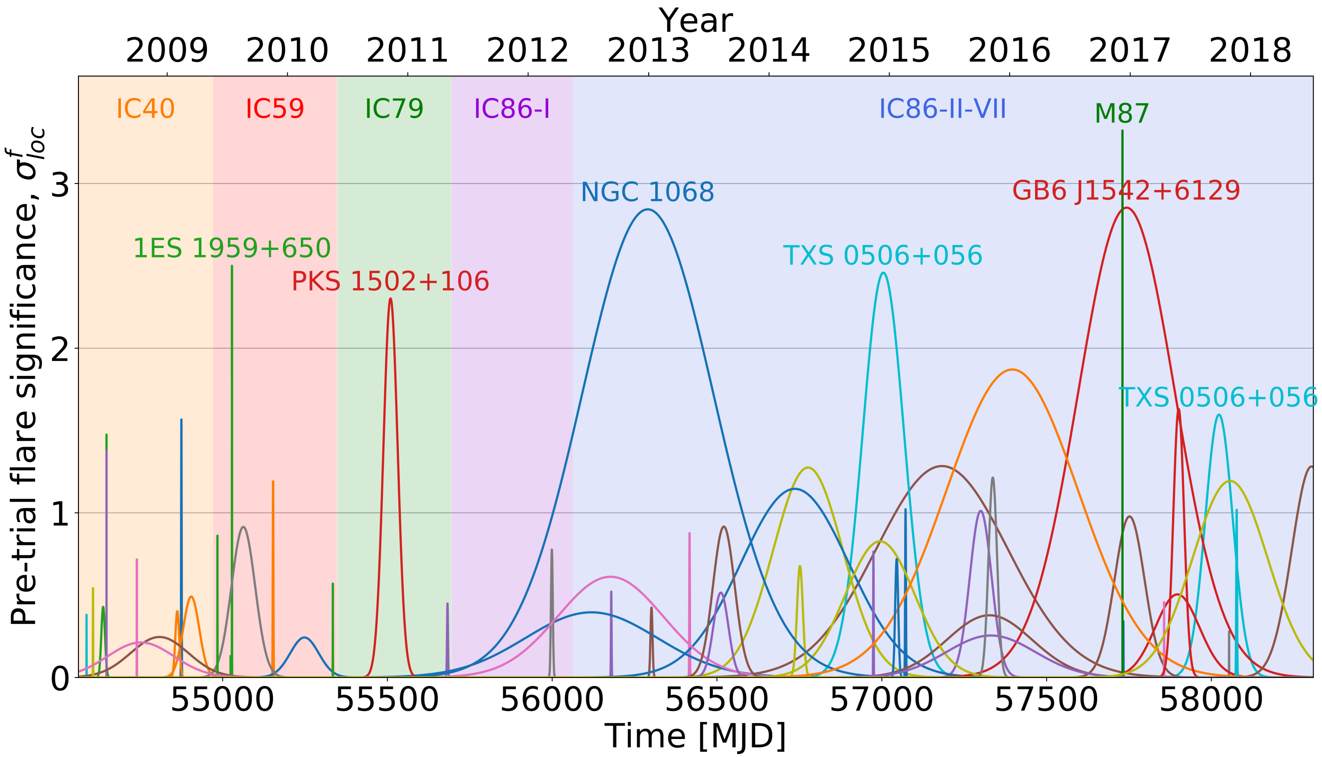
ArXiv: 2207.02097
Inoue et al.





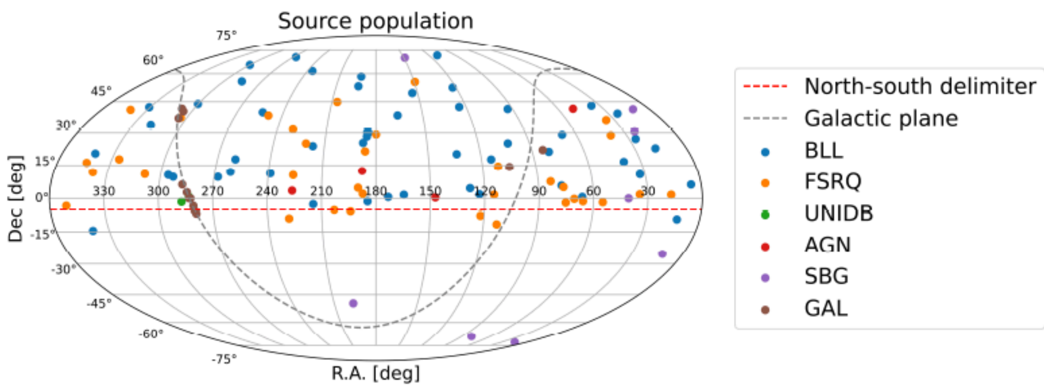
Additional components (to the neutrino emitted by the star forming region) due to the wind in hot corona can explain the IceCube excess

THE IMPORTANCE OF ν "LIGHT CURVE"



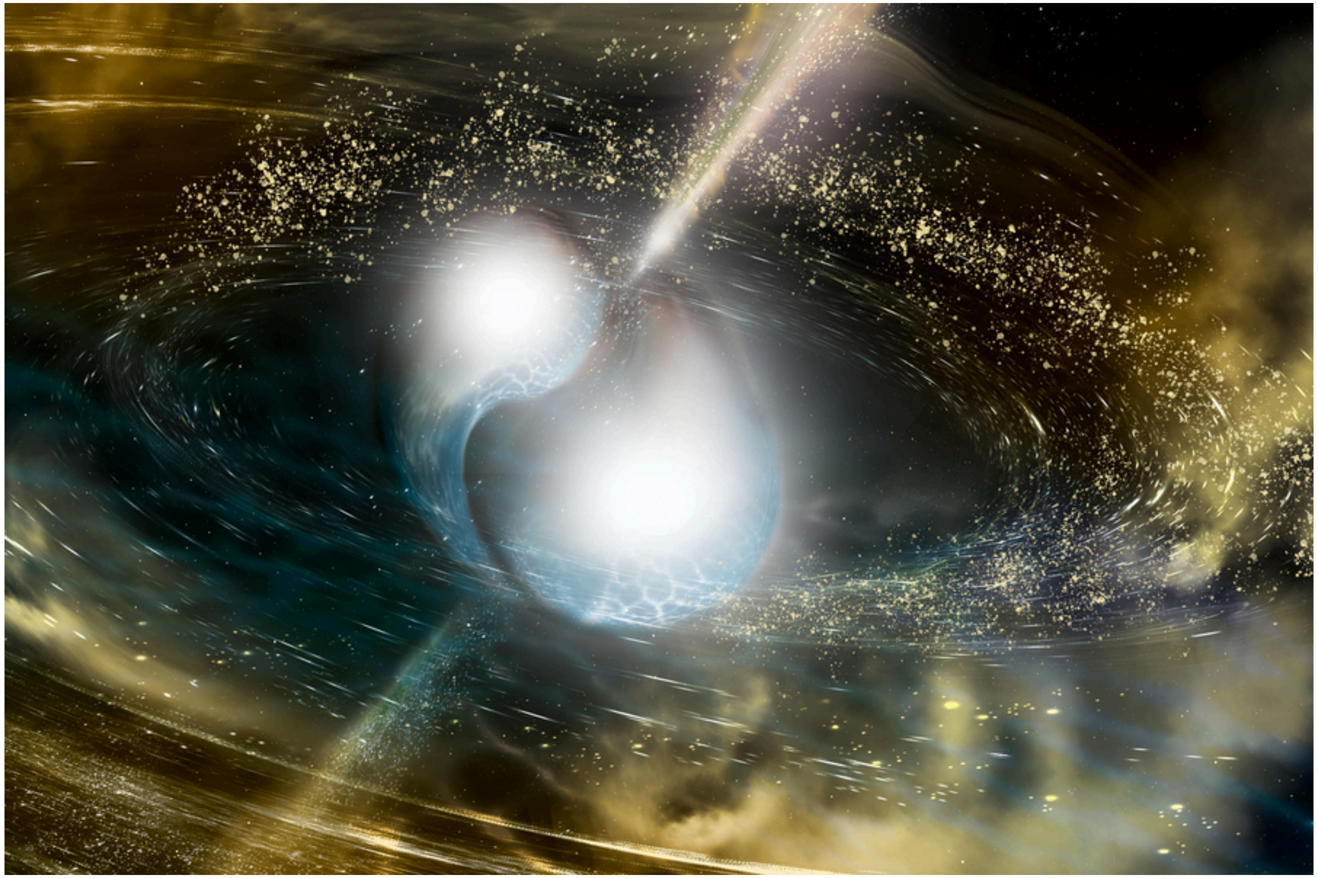
ApJ letter 2021
IceCube coll.

"lightcurve" can help to better understand cases like NGC1068



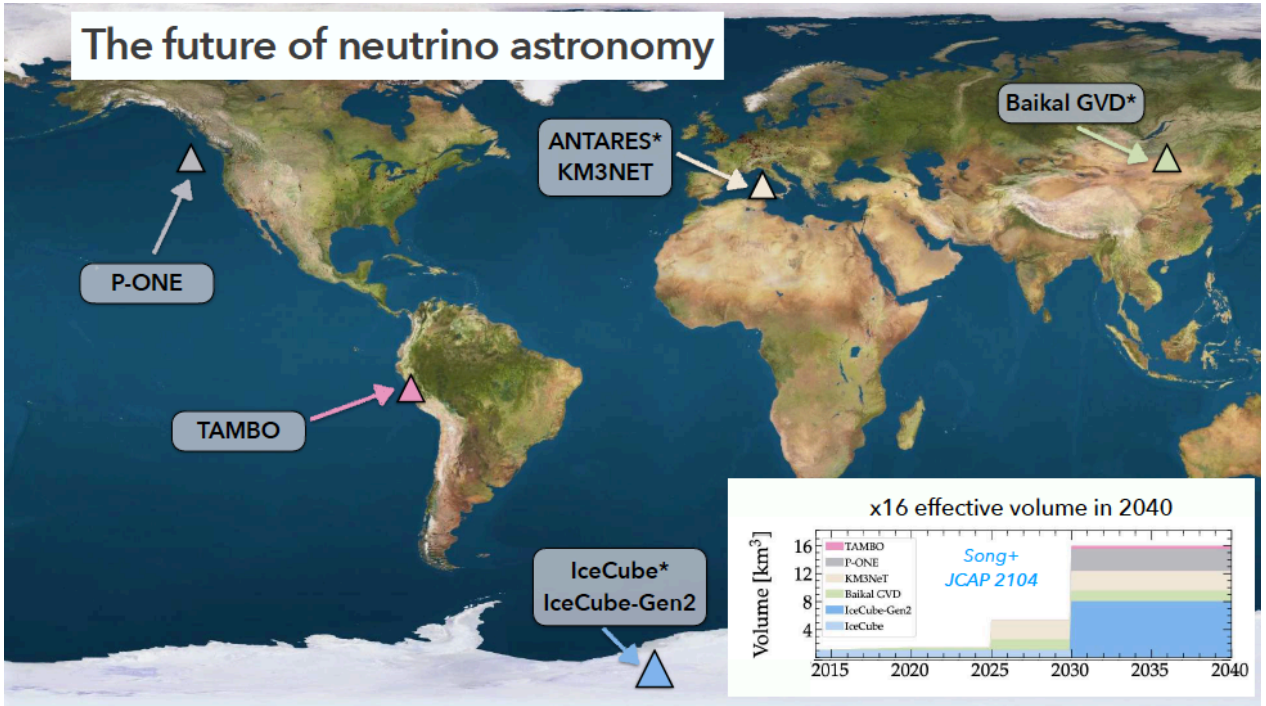
The variability of neutrino flux can help to disentangle a possible activity related to the supermassive black hole from the CR interaction inside the hosting galaxy

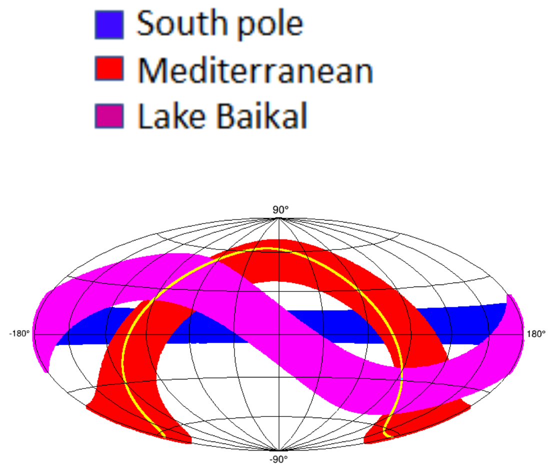
LOOKING FOR SHORT TIME TRANSIENT PHENOMENA AND NEUTRINO TELESCOPES FOLLOW-UP CAPABILITIES



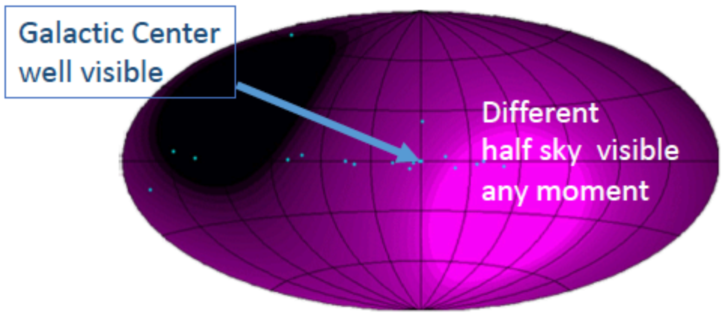
Credit: National Science Foundation/LIGO/Sonoma State University/A. Simonnet, edited by MIT News

complementarity between neutrino telescopes

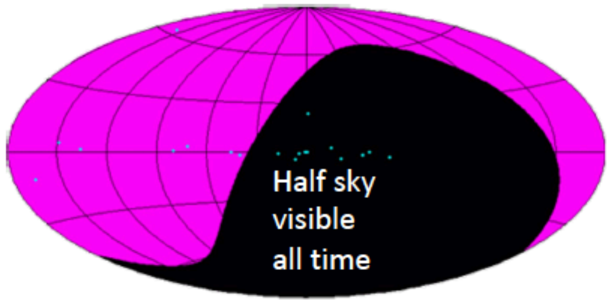




Instantaneous field of view with horizontal tracks



Mediterranean Sea (~43deg North)

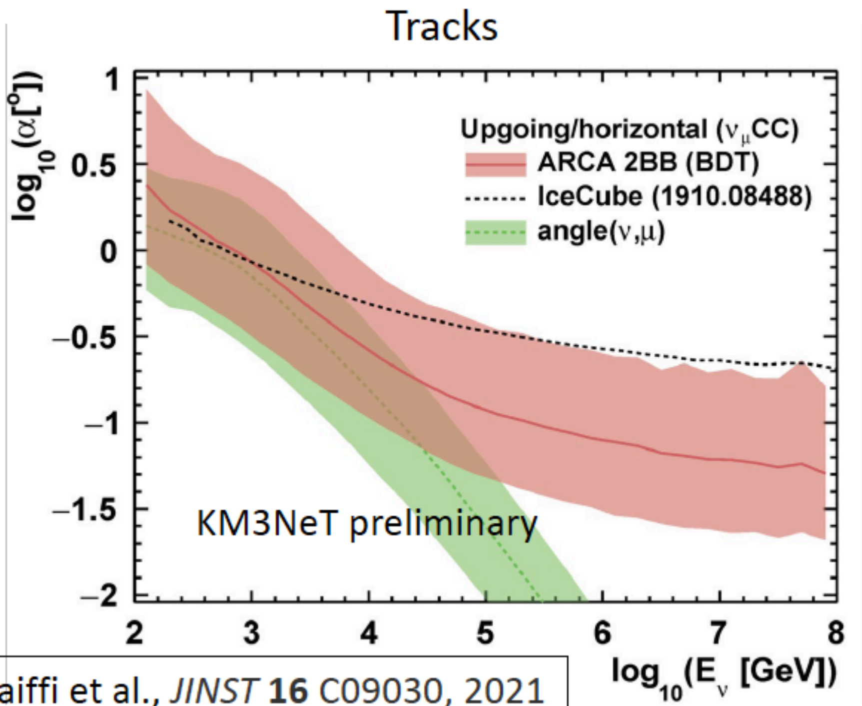


South Pole

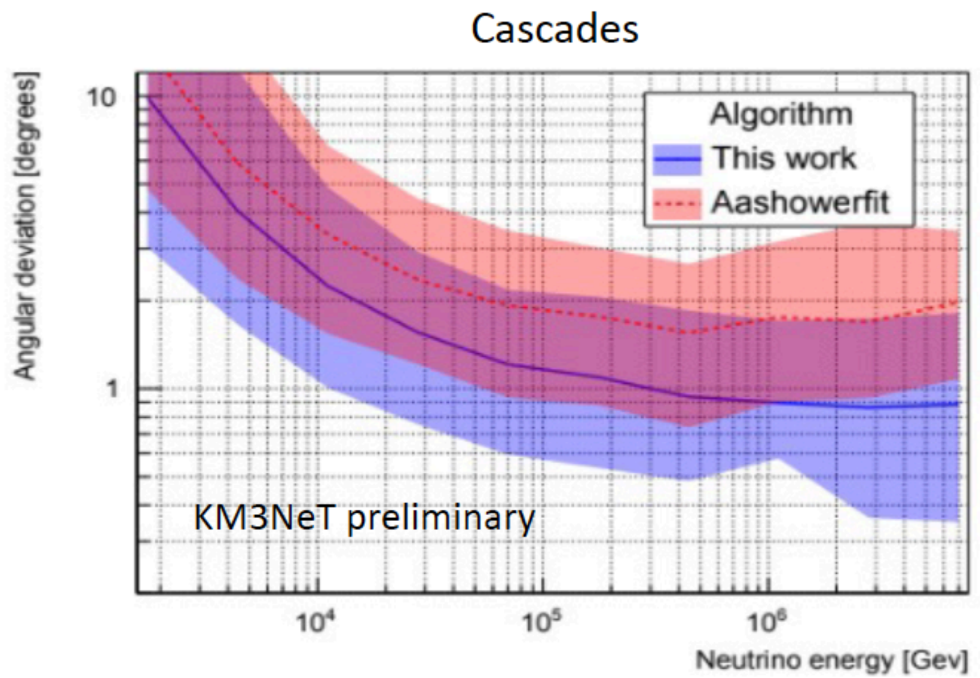
ν TELESCOPES ANGULAR RESOLUTION

Moving from large volume Ice detectors to large volume water detectors we can gain on medium transparency and better scattering properties:

Excellent angular resolution for track-like and shower-like events (considering all flavors)



Caiffi et al., *JINST* **16** C09030, 2021



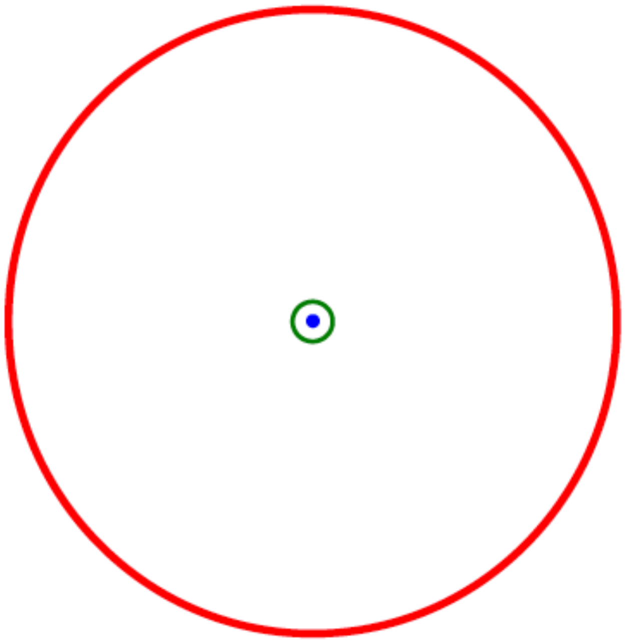
ν TELESCOPES ANGULAR RESOLUTION

The angular resolution reached by large volume water Cherenkov telescopes with track-like events is comparable with VHE gamma-ray atmospheric Cherenkov

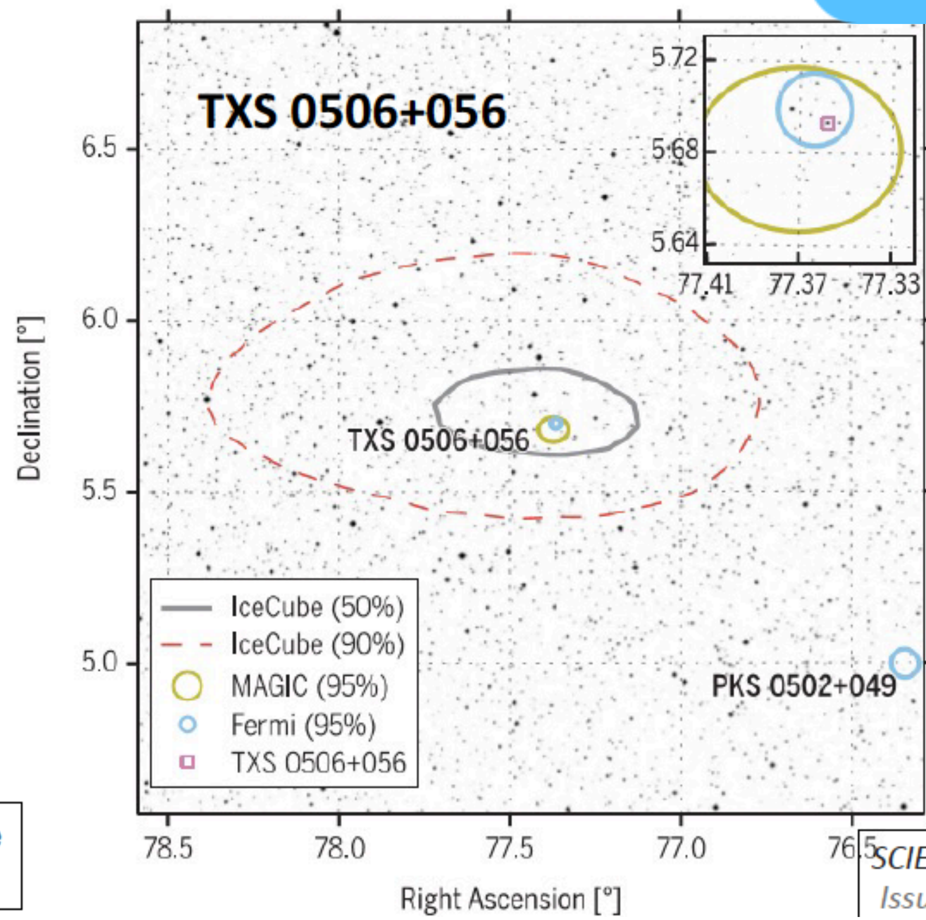
KM3NeT resolution

Science 2018
Vol361

KM3NeT/ARCA expected intrinsic resolution for high energy (>=PeV) tracks/cascades



Morphology of extended sources can be explored (track events)

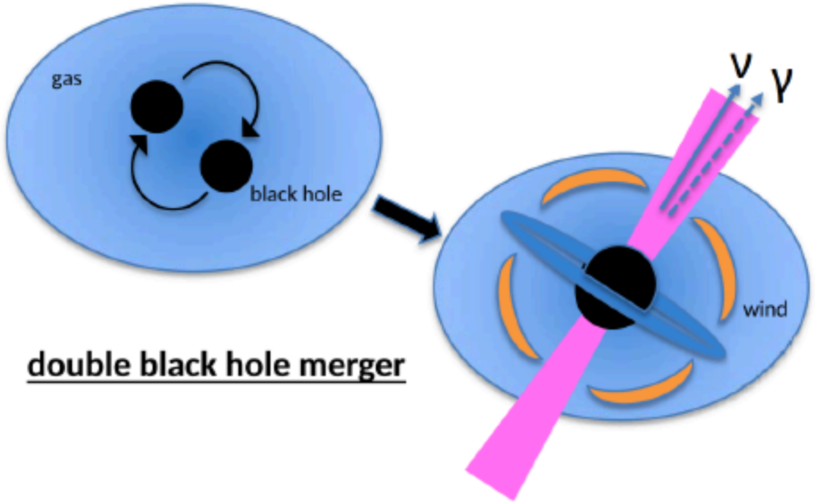


SCIENCE Vol 361, Issue 6398, 2018

Possible ν from Binary Mergers

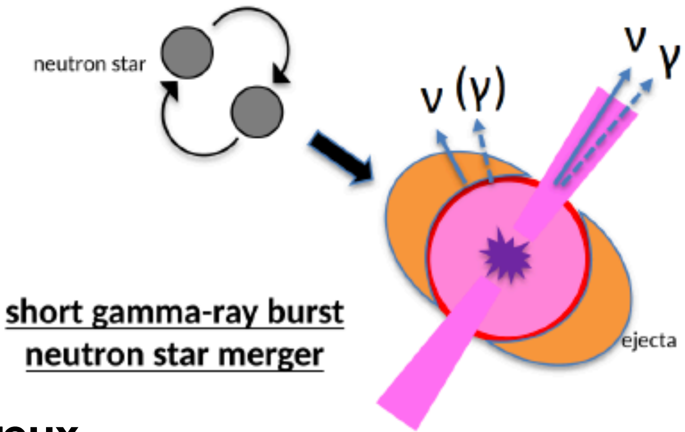
Phys. Rev D 93, 044019
Phys. Rev D 93, 123015

Mergers of compact objects
(Neutron Stars -NS-, Black Holes -BH-)
are established gravitational wave (GW) emitters.



- **BNS** (NS+NS) or **NSBH** (NS+BH): may produce short Gamma-Ray Bursts with neutrino production
- **BBH** (BH+BH): neutrinos may be produced in the accretion disks of the BHs

Spectrum	$E^{-\gamma}$ often considered in searches and MeV/GeV emission?
Shape	isotropic (not realistic at high energy) or presence of directional jet?
Timing	GW170817 + GRB170817A observation hints to prompt signal for BNS

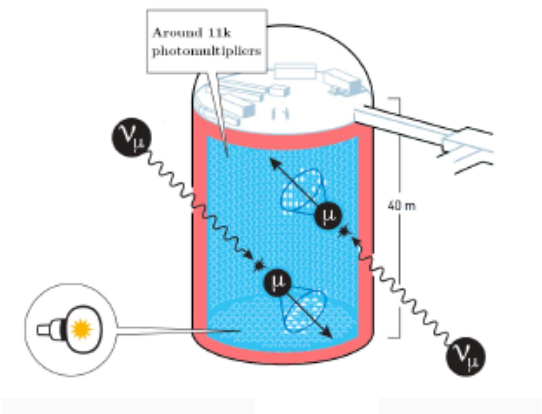
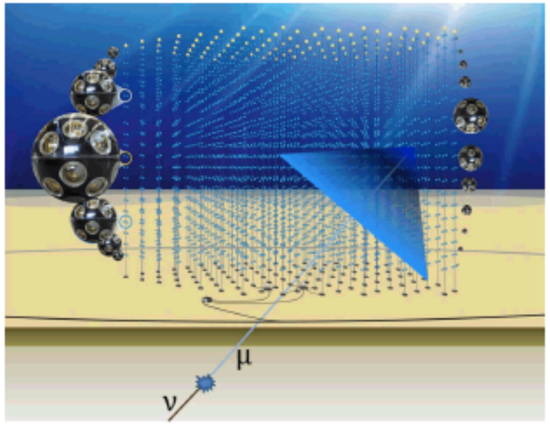
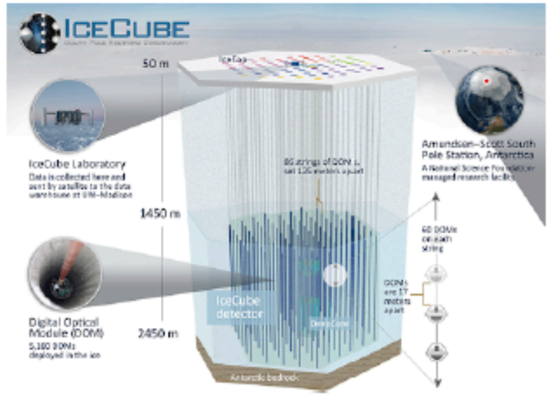


From Methieu Lamoureux
(KM3NeT Town Hall)

ν TELESCOPES: CURRENT SITUATION

Large volume water detectors instrumented with PMTs using Cherenkov techniques to see the products of neutrino interactions

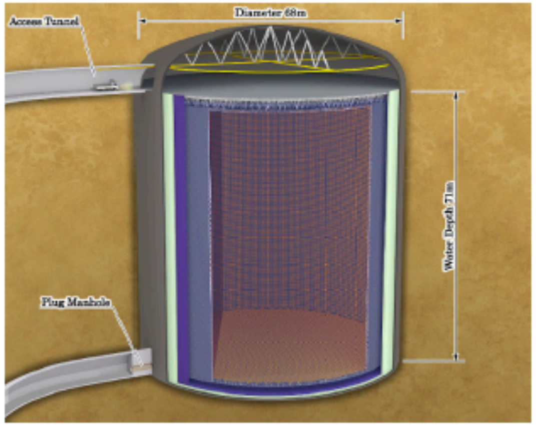
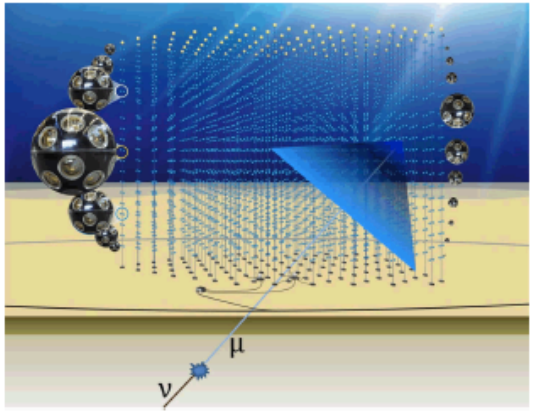
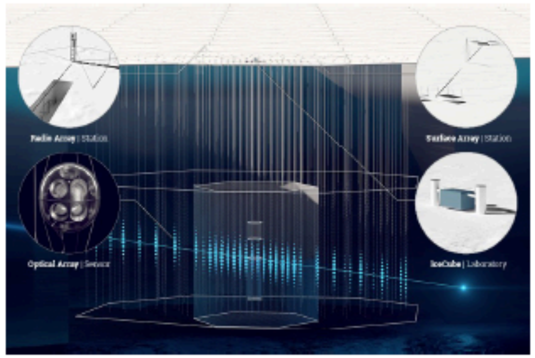
Covered energy range: from MeV to PeV

	Super-Kamiokande	KM3NeT	IceCube
			
Where?	mine in Japan	deep in Mediterranean sea	deep in South Pole ice
When?	1996 – running	2019 –	2011 – running
How?	11k PMTs on the walls	now: 11 lines (ORCA)	86 strings
	50 kt	now: 21 lines (ARCA)	1 Gt

From Methieu Lamoureux (KM3NeT Town Hall)

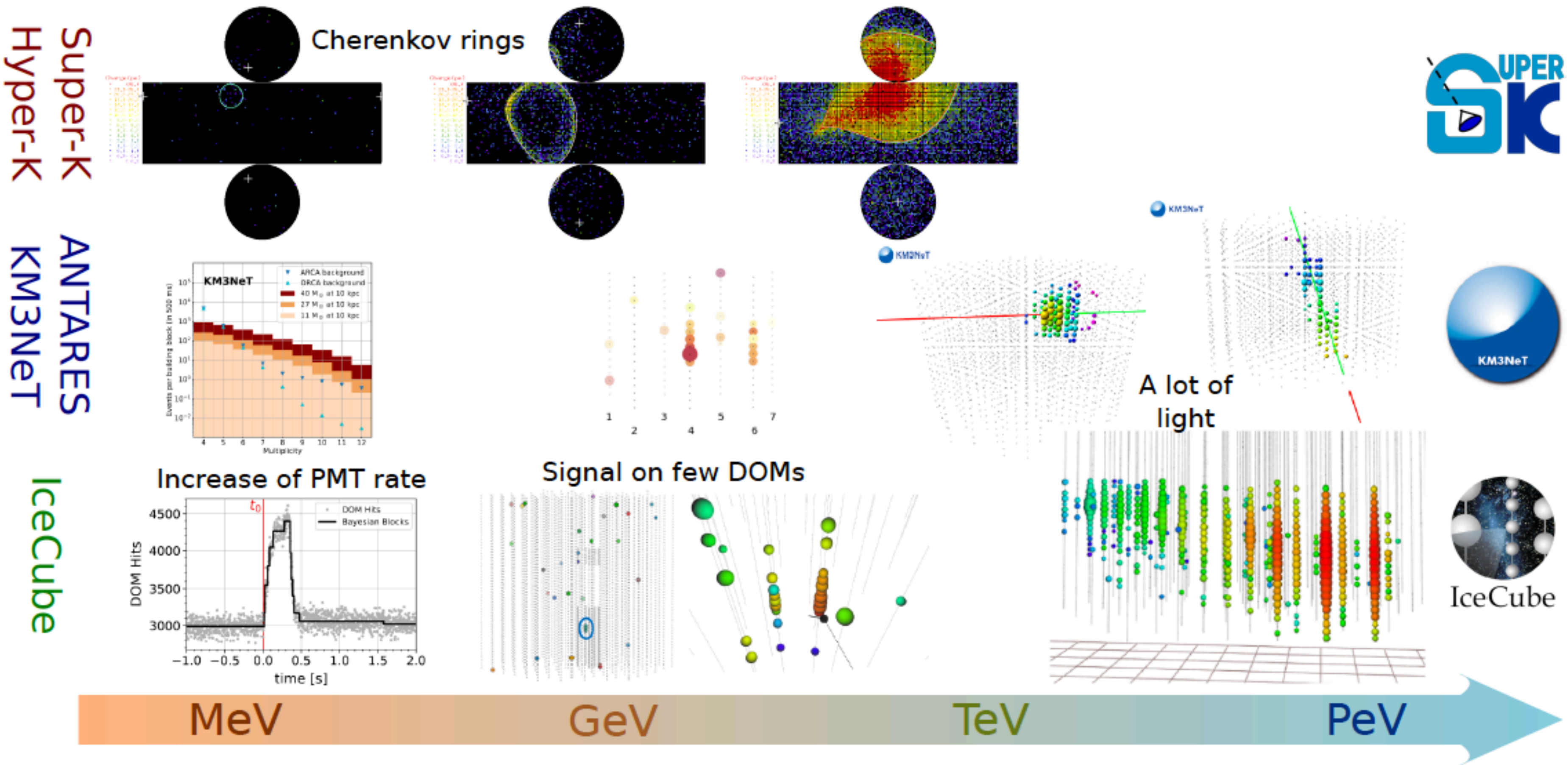
ν TELESCOPES: CURRENT & FUTURE

Large volume water/Ice detectors instrumented with PMTs using Cherenkov techniques to see the products of neutrino interactions

	Hyper-Kamiokande	KM3NeT	IceCube-Gen2
			
Where?	mine in Japan	deep in Mediterranean sea	deep in South Pole ice
When?	end of 2020s	under construction	2030s
How?	20k+ PMTs	3×115 lines	+120 strings
	50 kt	$10\,\text{Mt} + 2 \times 0.5\,\text{Gt}$	10 Gt

ν ENERGY RANGES

GW follow up through HE neutrino searches span from MeV up to PeV energy and beyond if we consider also UHE ν studies with atmospheric shower detectors



Different neutrino data semples to be used for the GW follow-up events with a time window of +/- 500 s around the GW detection

Type	Super-Kamiokande	ANTARES & KM3NeT	IceCube (+DeepCore)	Others
Energy range	7 – 100 MeV 0.1 GeV – TeV	5 – 30 MeV GeV – TeV TeV – PeV	0.5 – 5 GeV 5 GeV – TeV TeV – PeV	KamLAND: $\bar{\nu}_e$ 1.8-111 MeV, 1000 s NOvA: MeV – TeV, 1000 s and 0-45 s
Time window	1000 s	1000 s	1000 s + 3 s	AUGER: > 0.1 EeV, 24 h
Flavours	$\bar{\nu}_e$/all	all	all/ν_μ	
Online	Under study	Yes	Yes	
Published	O1+O2, O3a	O1, O2, O3	O1, O2, O3	Baikal-GVD: TeV-PeV
Ready soon	O3b	O3b (ANTARES)	-	

GW FOLLOW-UP RESULTS WITH ν ANALYSIS

APJ 918 (2021) 2, 78
Super-K coll.

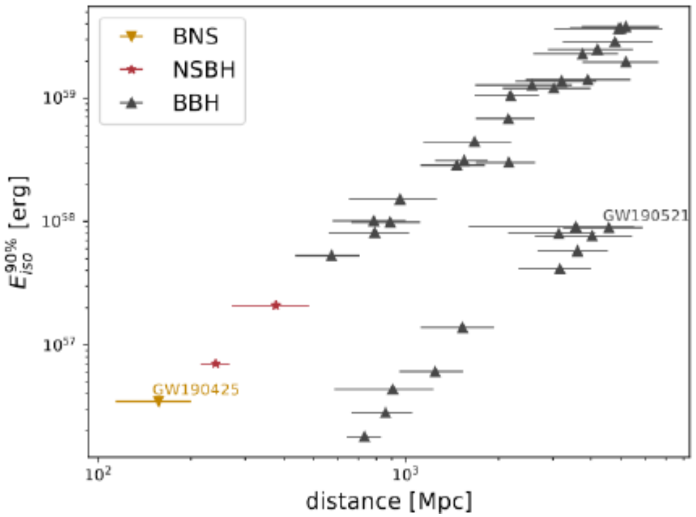
Eur.Phys.J.C 80 (2020) 5, 487
Poster @ Neutrino 2022

PoS ICRC2021, 939
arXiv:2208.09532

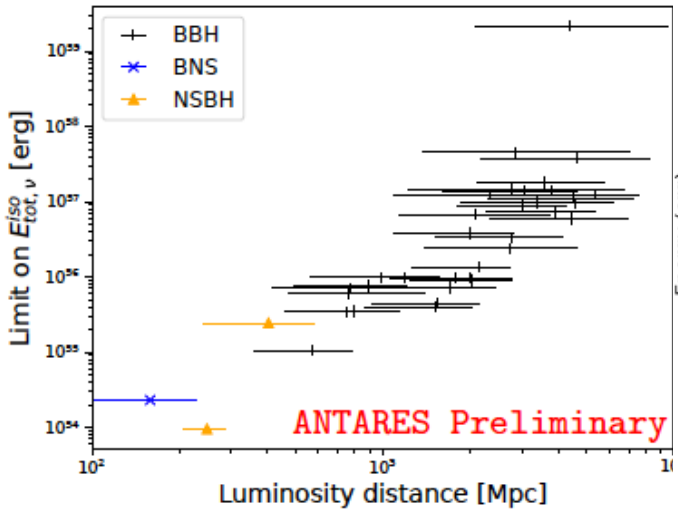
Bkg: ~ 0.1 event $/1000\,\mathrm{s}$

Bkg: $2.7 \times 10^{-3}/1000\,\mathrm{s}$

Super-K

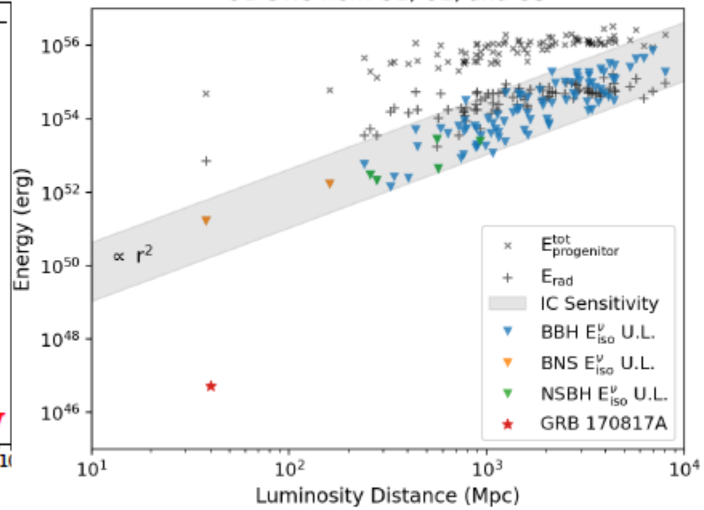


Antares



IceCube

91 GWs from O1, O2, and O3



Limits (E^{-2}, all-flavour):
$30 - 2000\,\mathrm{GeV\,cm^{-2}}$
$2 \times 10^{56} - 4 \times 10^{59}$ erg

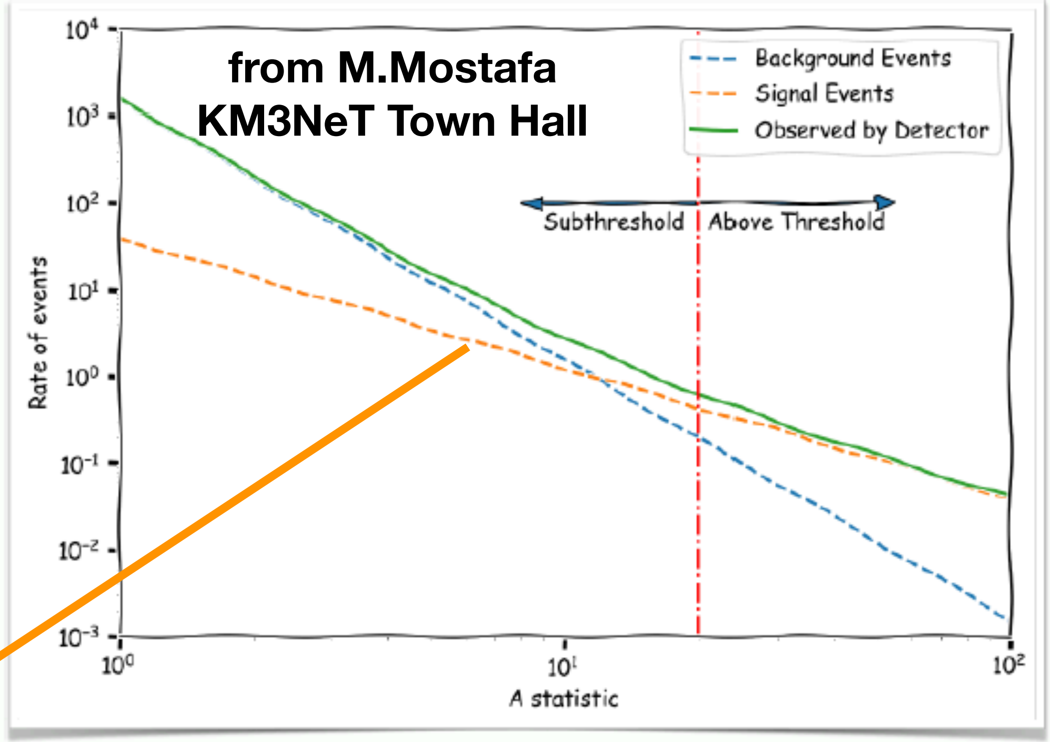
Limits (E^{-2}, all-flavour):
$4 - 600\,\mathrm{GeV\,cm^{-2}}$
$10^{54} - 10^{59}$ erg

Limits (E^{-2}, per flavour):
$0.03 - 1\,\mathrm{GeV\,cm^{-2}}$
$10^{51} - 10^{55}$ erg

SUB THRESHOLD ν USE FOR MM

AMON provides the **framework** for:

- **Real-time** and near real-time sharing of *subthreshold* data among *multimessenger* observatories
- Real-time and archival searches for any **coincident** (in time and space) signals.
- Prompt distribution of **alerts** for follow-up observations



For ν we already use these events for point-like searches, up-going track-like events spatially and/or temporally correlated with other messengers. Energy lower limit up to hundreds of GeVs for Kilometer telescopes.

SUMMARY

- Astrophysical neutrino flux observed by IceCube detector favors a multicomponent scenario

- A considerable contribution (up to 40-50%) of the astrophysical neutrino signal measured by IceCube with E > tens of TeV can be attributed to stable "reservoir" neutrino emitters

- More indications about transient phenomena are expected through MM observations (ν + EM + GW)

- Good perspectives for O4 follow up programs considering the Global Neutrino Network, excellent angular resolution reached with track-like and shower-like neutrino events and the complete sky coverage.


UV
Thank you
for the
attention
https://www.rankred.com/catalogue-of-star-forming-galaxies/