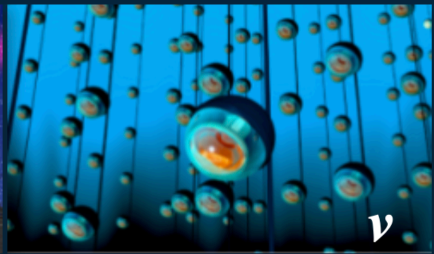
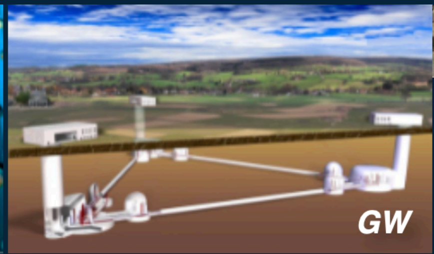
Multi-Messenger Astronomy

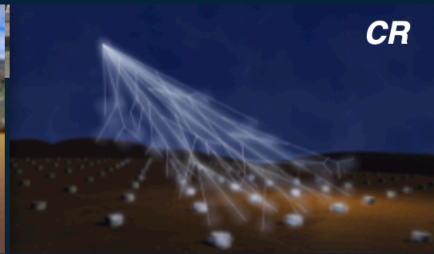
Teresa Montaruli

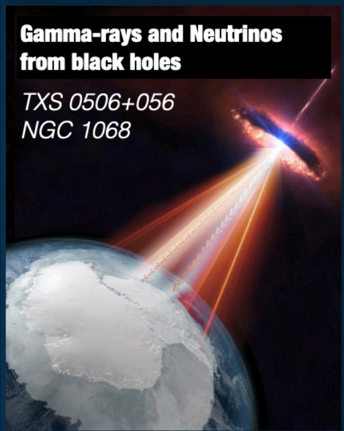
07.10.2022

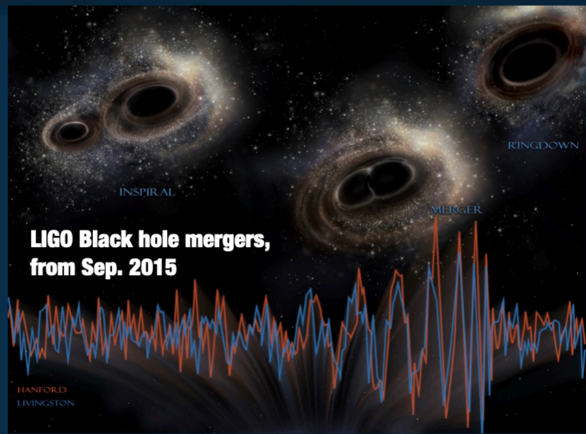
UNIVERSITÉ DE GENÈVE

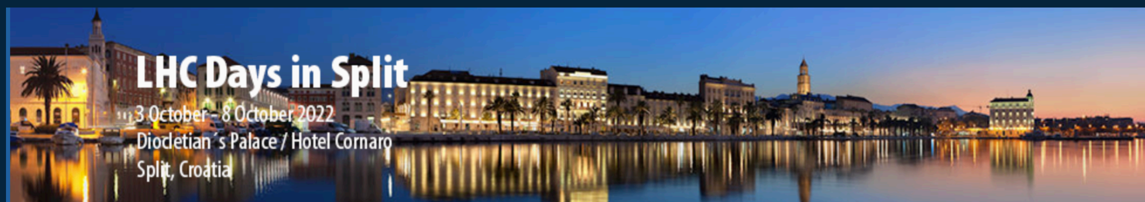










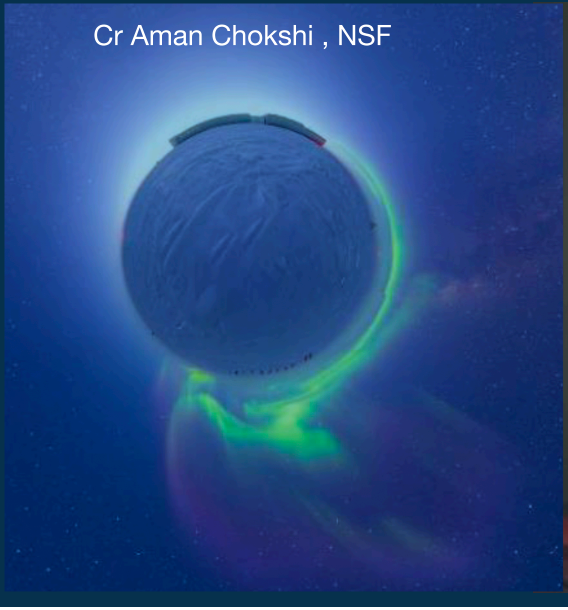


Contents

- The UHECR-neutrino connection: optically thin and calorimetric sources
- The origin of the > 100 TeV diffuse IceCube neutrino flux: Galactic Plane + extragalactic blazars and starburst galaxies, gamma-ray bursts

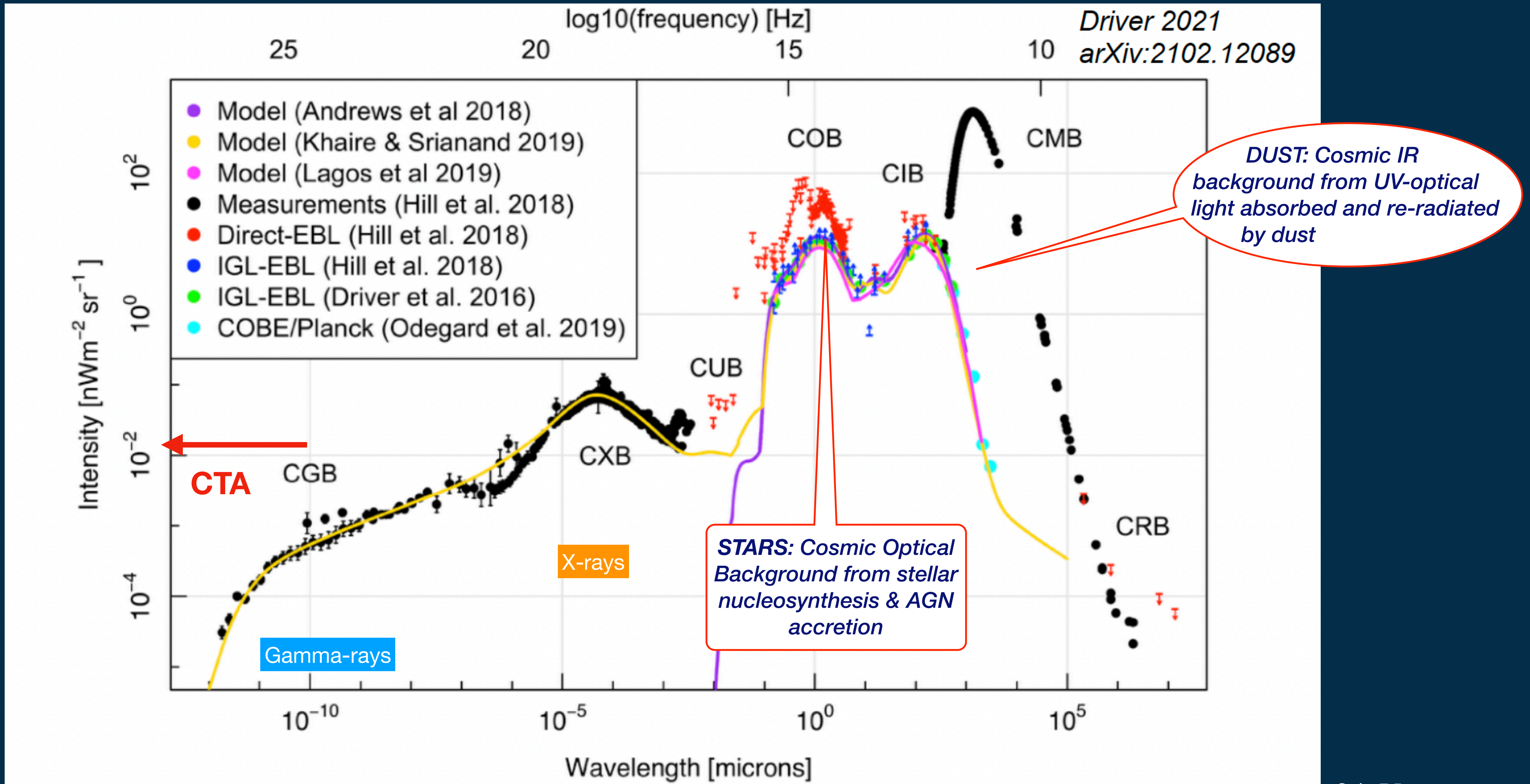
Cr. Akihiro Ikeshita

Cr Aman Chokshi , NSF



Cr Moreno Baricevic, NSF

Radiation spectrum from the universe

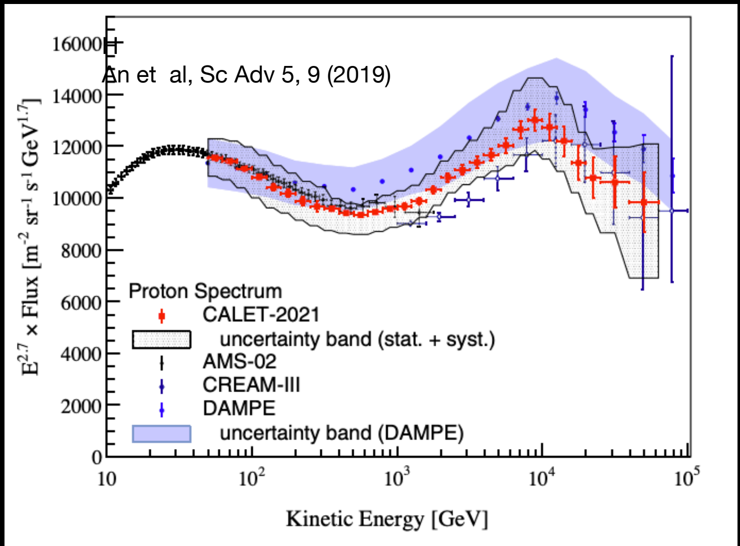


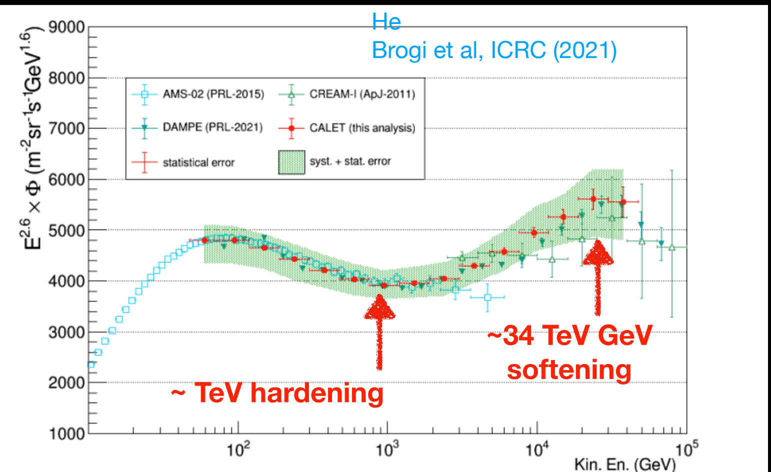
Non thermal processes

$$\lambda = \frac{c}{\nu} = \frac{h}{p} = \frac{hc}{E_\gamma} \Rightarrow E_\gamma(\text{eV}) = \frac{1.24\text{eV} \cdot \mu\text{m}}{\lambda(\mu\text{m})}$$

Astro-particle: Cosmic ray spectrum

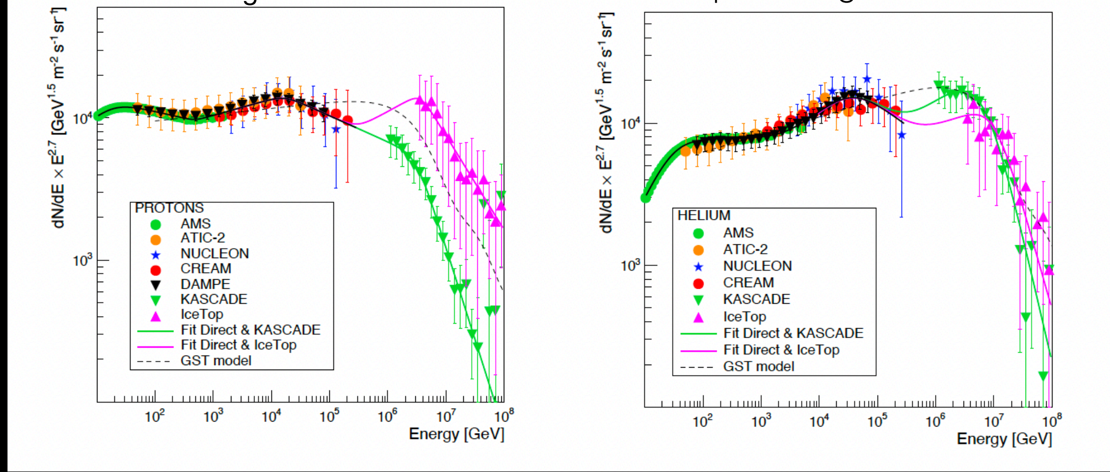
Space-based



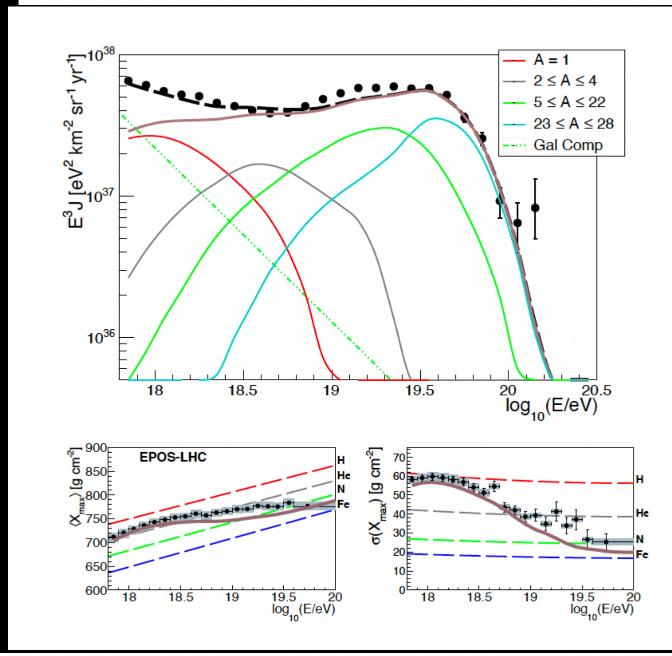


Space-based and ground-based

The knee with ground based detectors: for H Icetop flux is higher than KASCADE



Lipari & Vernetto 2018, ICRC2021

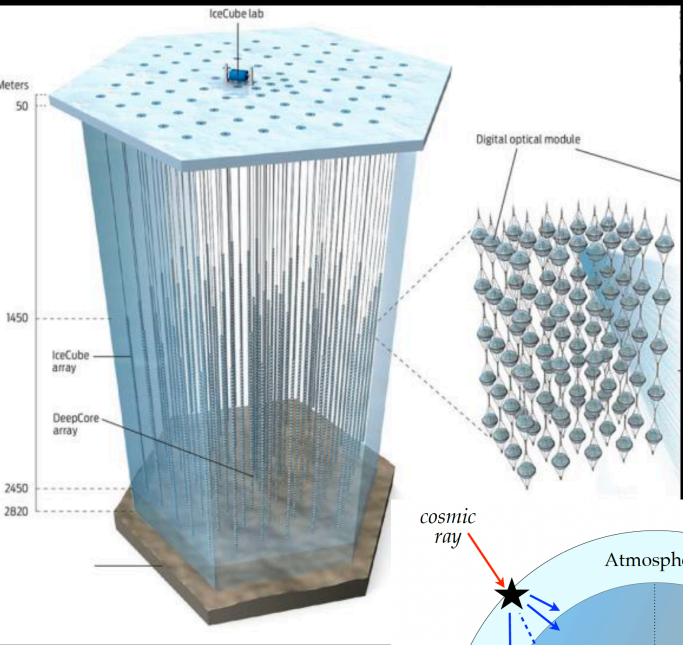


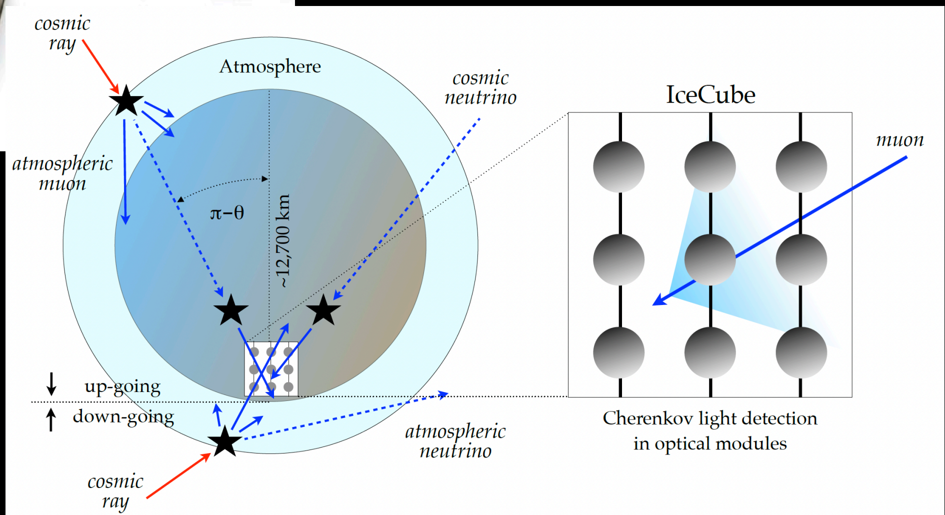
Heinze et al 2019

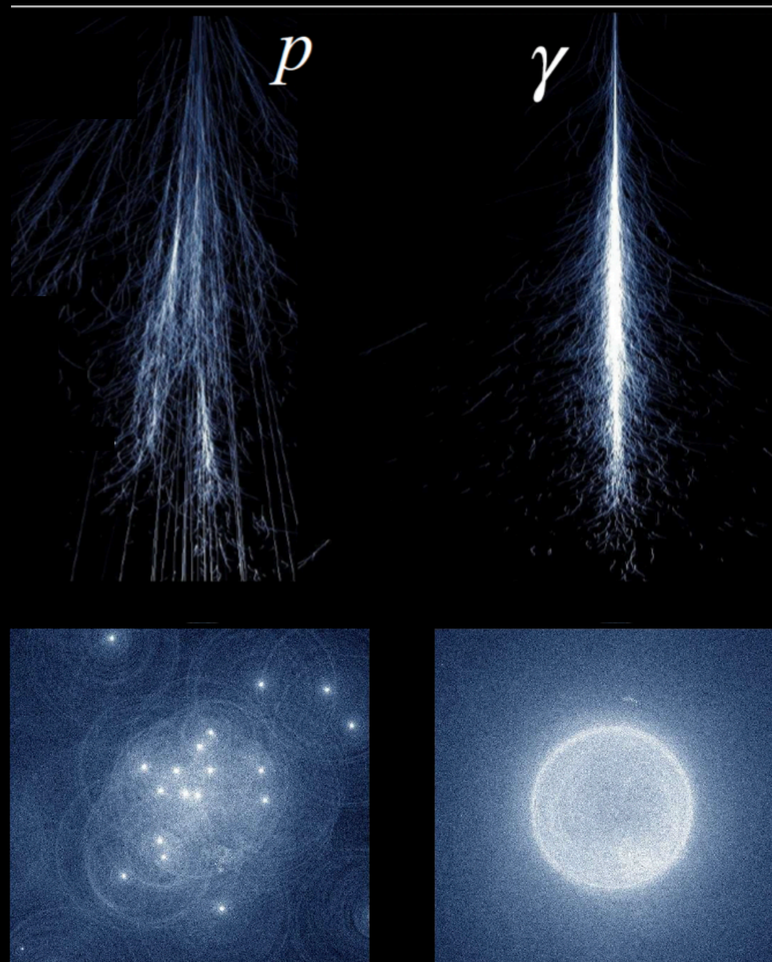
Condorelli et al, 2022

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.
For neutrino telescopes atmospheric neutrinos are undistinguishable unless energy, direction or time are used.

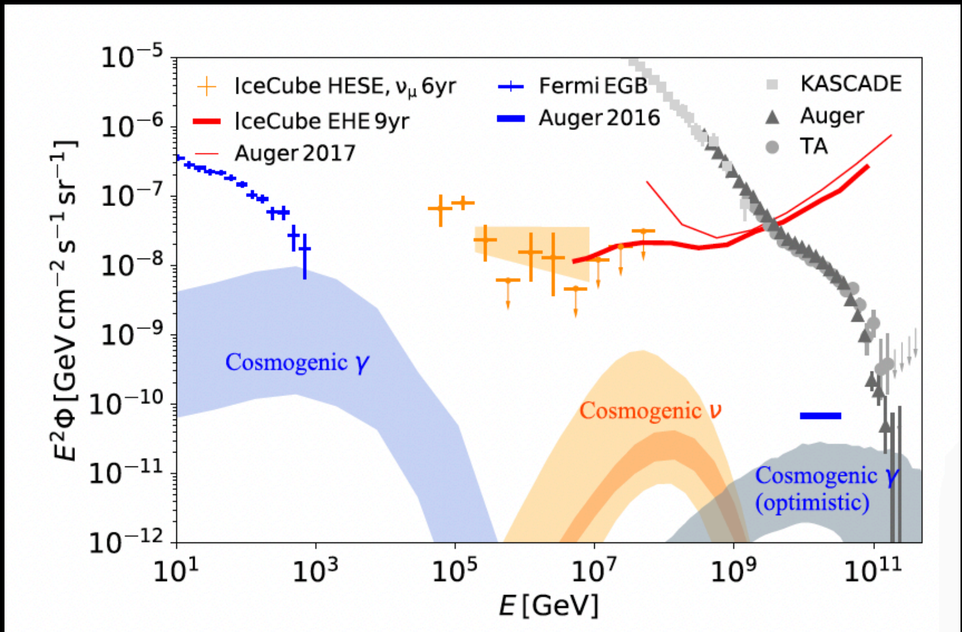






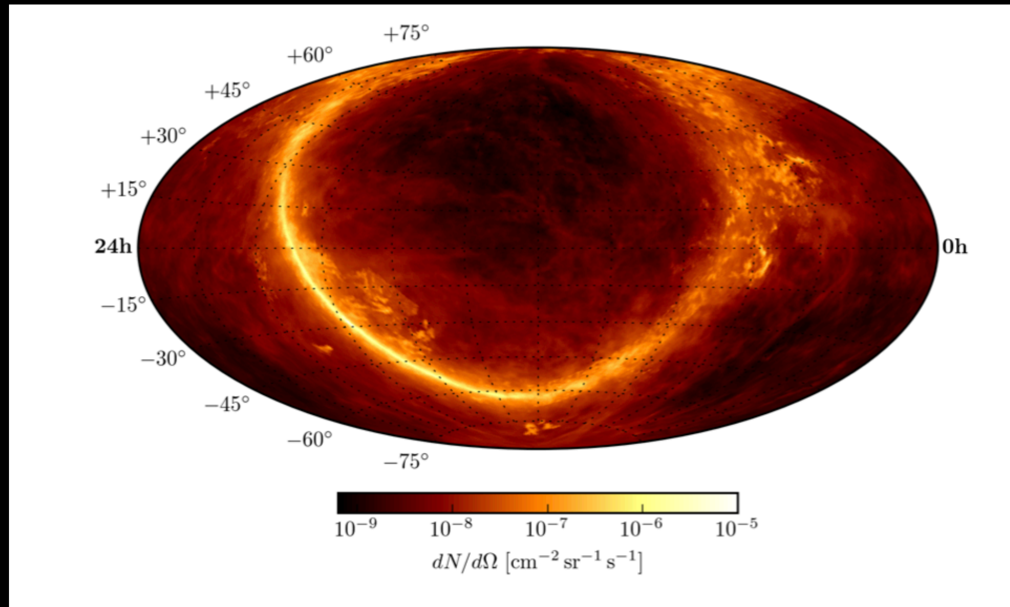
The granted Multi-Messenger diffuse fluxes

Extra-Galactic



Snowmass 2022 paper

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.

The multi-messenger galactic plane

Breuhaus et al , 2022; Ahlers et al, 2016

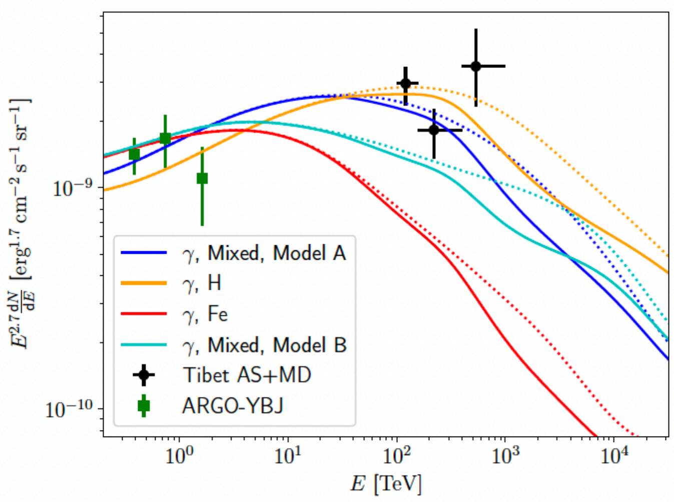
The composition is relevant to calculate neutrino and gamma-ray spectra

$$\frac{dN}{dE} = N_p \cdot \left(\frac{E}{E_0}\right)^{-\alpha_p} \exp\left(-\frac{E}{E_{cut,p} \cdot A}\right),$$

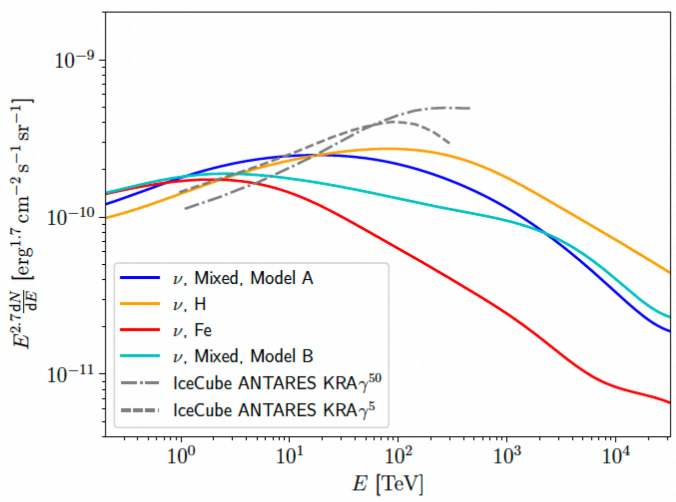
Neutrino limits touch KRA models of diffuse galactic emission from CRs interacting on ISM (Gaggero et al 2015, 2017). IceCube > 20 TeV diffuse muon flux and > 100 TeV diffuse flux contributes < 10% to it. Finding significant contributions from the Galactic Plane requires lowering the threshold in ν energy.

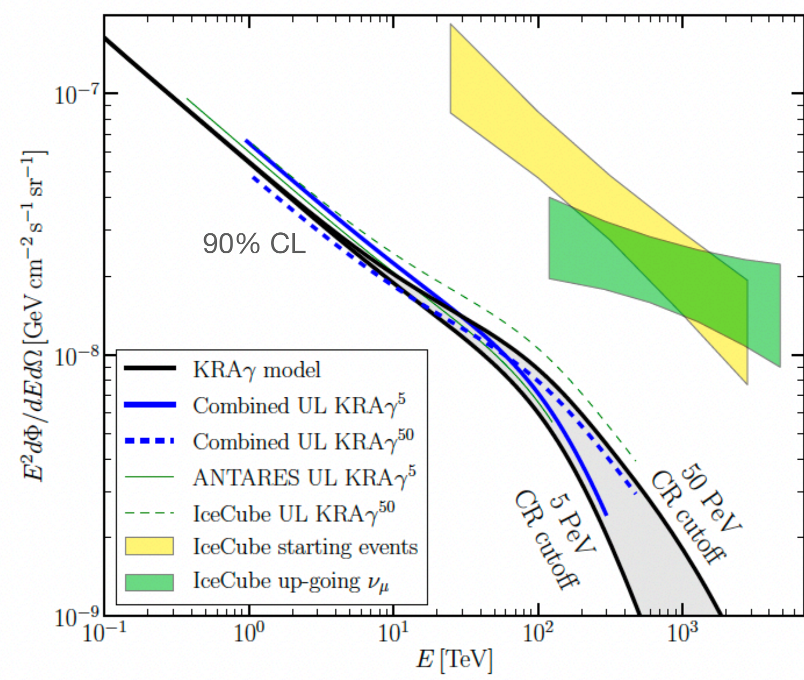
IceCube arXiv:1707.03416
ANTARES-IceCube arXiv:1808.03531

Gamma-rays



Neutrinos





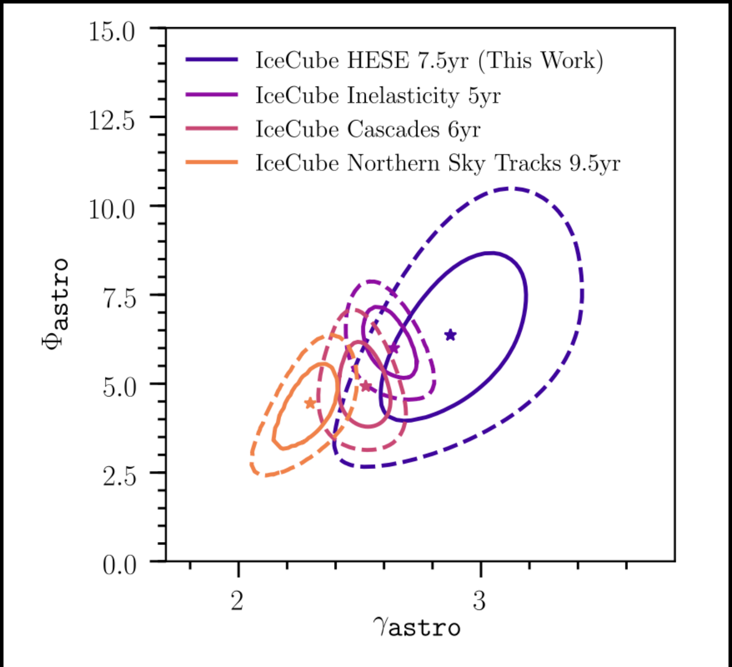
Tibet AS+MD data at 100 TeV do not favour pure Fe models.
Model A and Model B account for the disagreement of CREAM and NUCLEON on p and He fluxes and NUCLEON is in better agreement with gamma-ray data.
Mixed indicates 50% H, 50% O - ISM
Solid and dashed lines are with and wo absorption of gammas

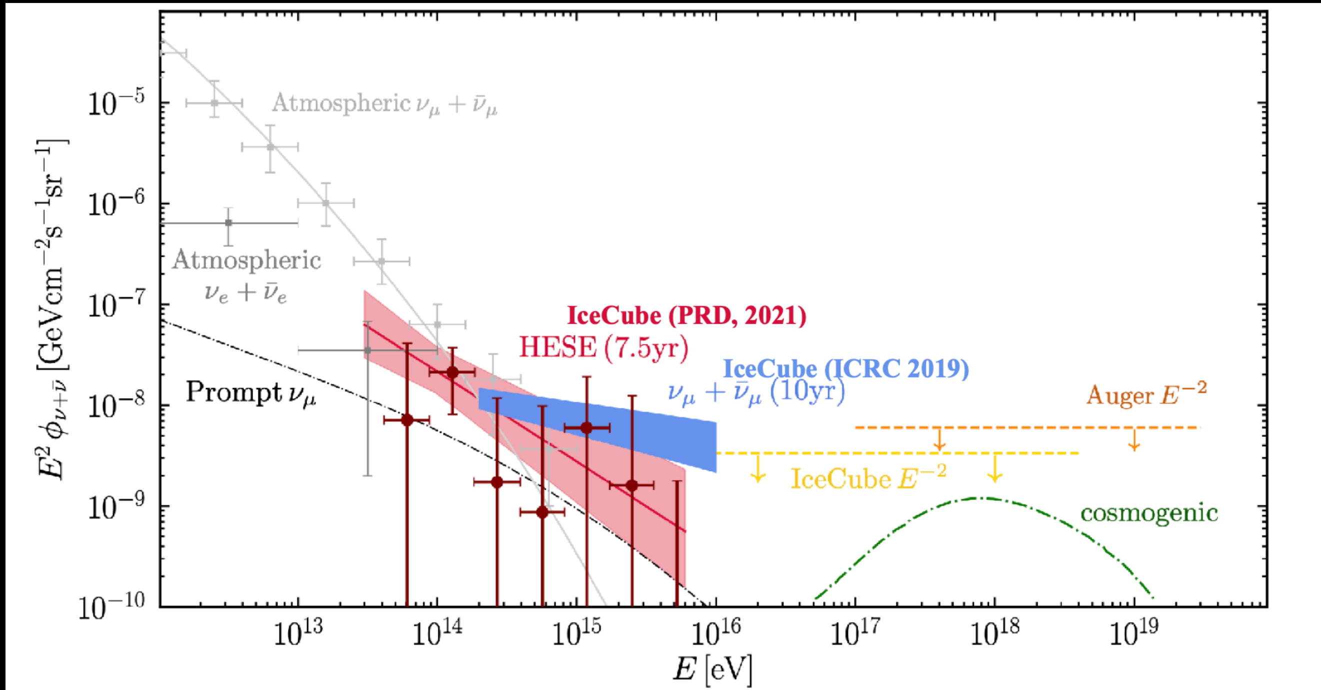
The IceCube diffuse fluxes

Impact of sys errors on
Cosmic power law flux

Tracks: IceCube Coll. ApJ 928 (2022) 50

HESE: IceCube, PRD 104 (2021)





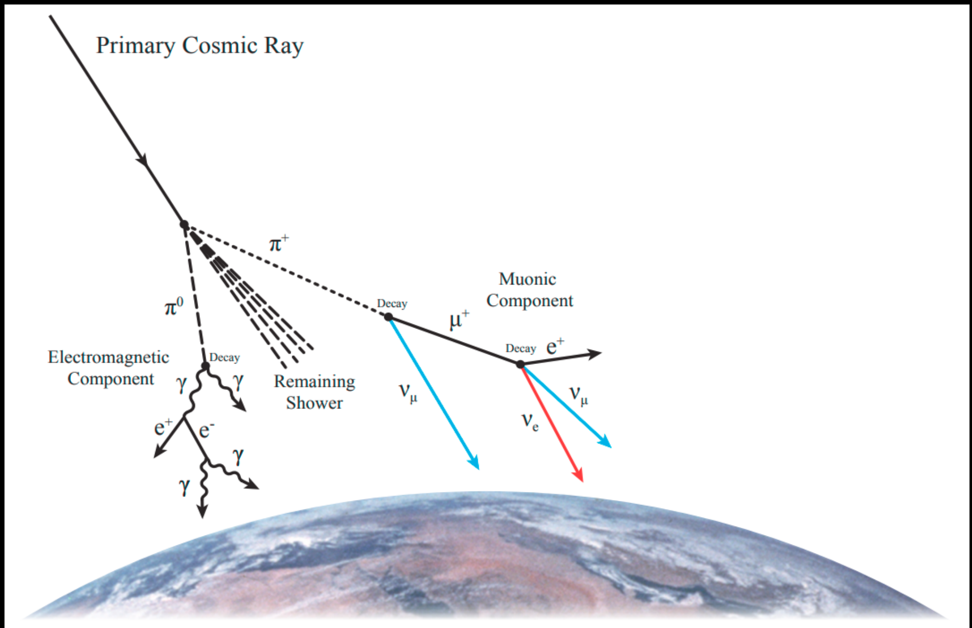
$$\Phi_{prompt} = 0.00\pm^{5.34}_{-0.00}$$

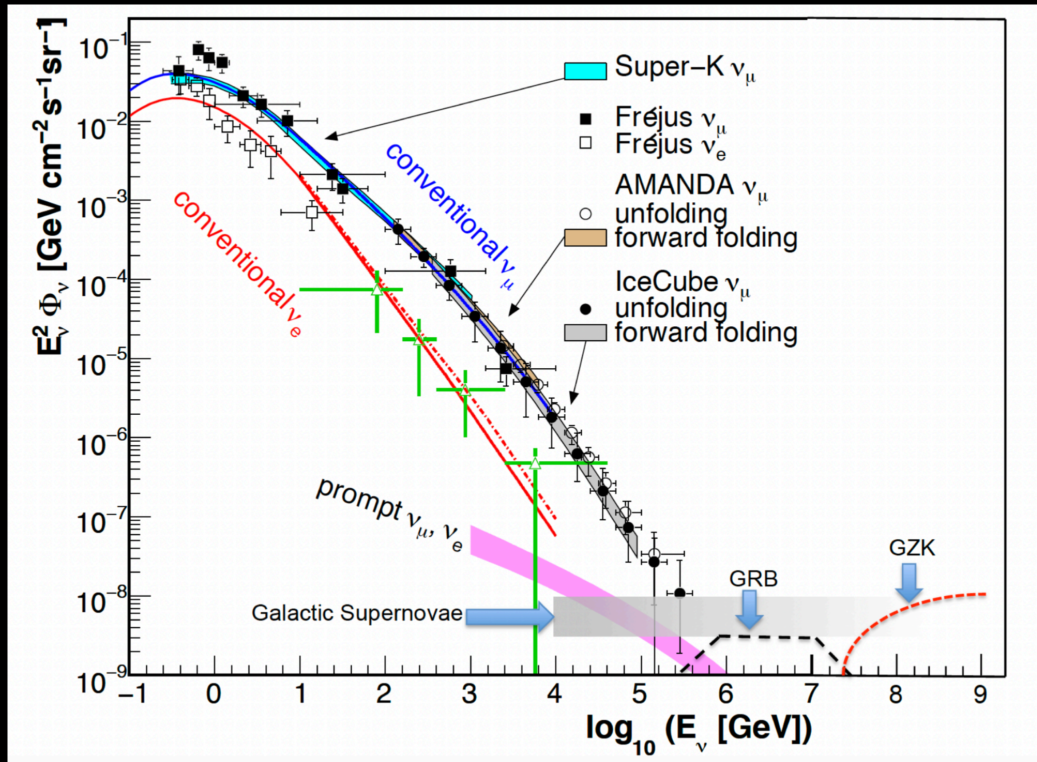
Excesses in diffuse flux are in ANTARES 10 yr data, GVD and KM3NeT will soon confirm

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

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

Astro-particle: the neutrino spectrum



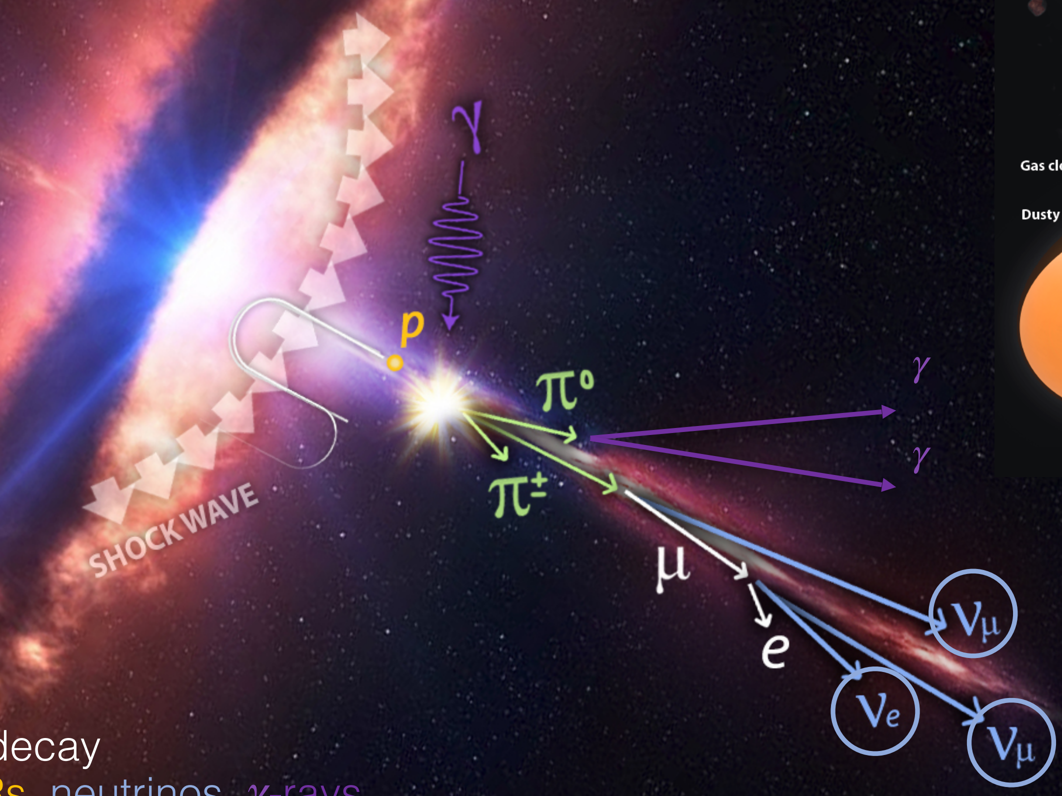


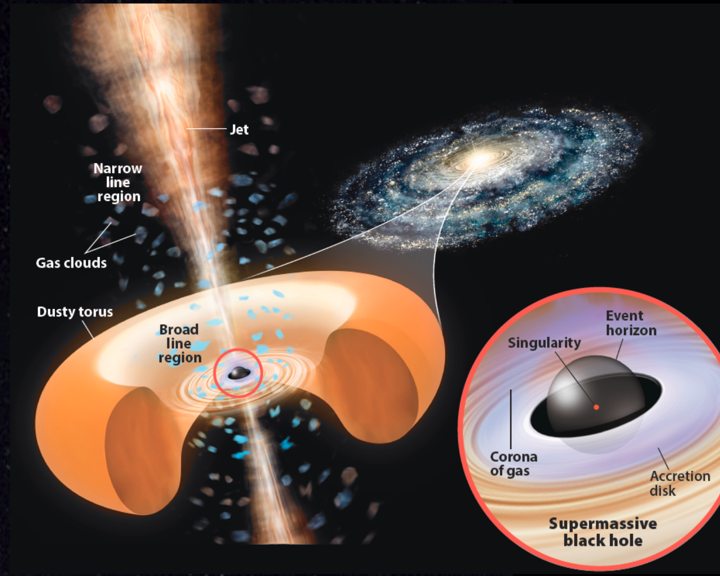
Cascades are an important tool to lower the threshold on neutrino telscopes and to tag neutrinos through their vertex

Multimessenger Production

CRs accelerated in shock fronts produced by astrophysical sources

Neutrinos originate from beam dump of accelerated CRs on ambient matter or radiation field and allow exploring the inner regions of sources



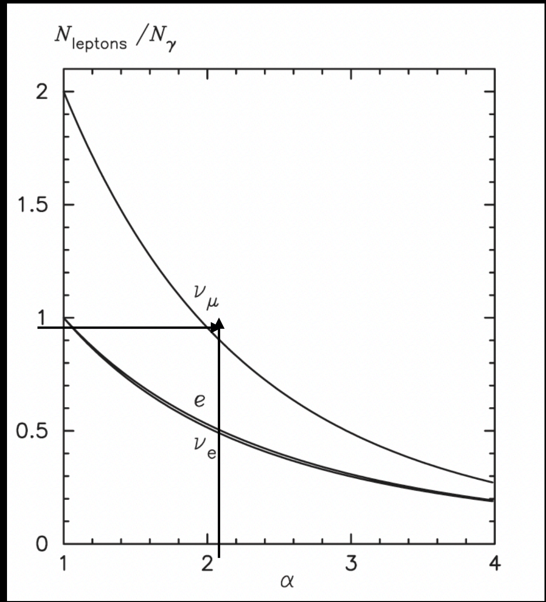


γ-rays emitted from π^0 decay
$\Rightarrow$ common origin of CRs, neutrinos, γ-rays

Multi-Messenger relations

Halzen & Kheirandish 2022

Kelner, Aharonian, Bugayov 2006



From SN shocks or Galacitc plane +ISM

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

$$\pi^+ \rightarrow \mu^+\nu_\mu \rightarrow e^+\nu_\mu\nu_e\bar{\nu}_\mu \qquad \pi^- \rightarrow \mu^-\bar{\nu}_\mu \rightarrow e^-\bar{\nu}_\mu\bar{\nu}_e\nu_\mu \qquad \pi^0 \rightarrow \gamma\gamma$$

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

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

$$\kappa = \frac{N_\pi E_\pi}{E_p}$$ = 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

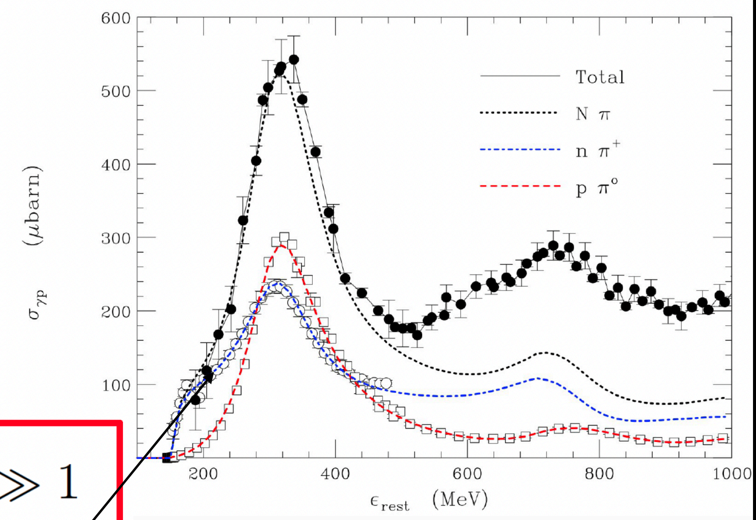
$$p+\gamma \rightarrow \Delta^{+} \rightarrow p+\pi^{0} \quad 2/3$$
$$p+\gamma \rightarrow \Delta^{+} \rightarrow n+\pi^{+} \quad 1/3$$

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

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 $p+\gamma \rightarrow$ 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 $p\gamma(pp)$

Cosmic ray/gamma-ray/neutrino consistency

Halzen & Kheirandish 2022
Waxman & Bahcall 1998
Yoshida and Murase 2020

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

Local Emission rate density to feed UHECRs

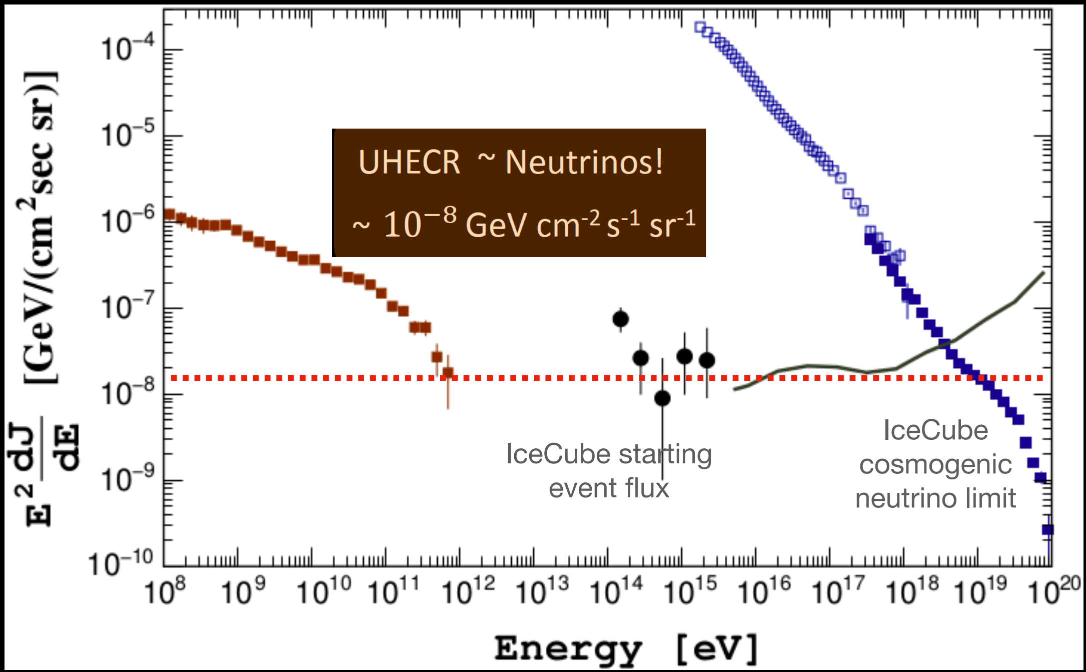
Relation between the neutrino flux per flavor and the CR rate density:

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

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

Target dimension

Target nucleon density



S. Yoshida at CRIS2022

UHECRs and ν's have a common origin in a Unified Picture when

- $0.1 \lesssim \tau_{p\gamma} \lesssim 0.6$: Optically thin sources
- $f_\pi = 1 - e^{-\tau_{p\gamma}} = 1$: Waxman & Bahcall upper limit
- $\tau_{p\gamma} >> 1$ 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)

The neutrino flux is at the level of the calorimetric limit!

Diffuse - single source fluxes

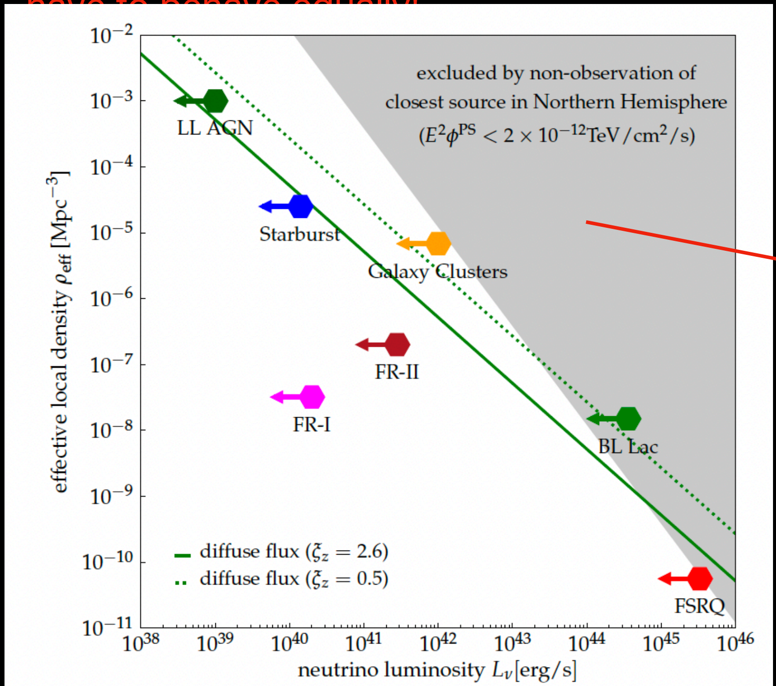
Relationship between a PS flux and diffuse flux

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

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!



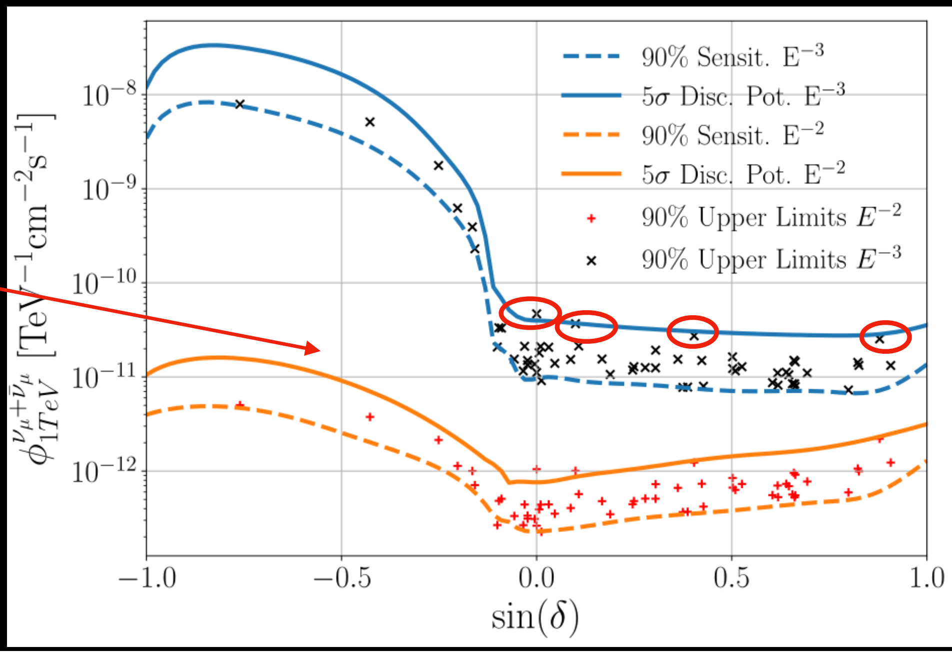
$$\xi_z = \int_0^\infty dz \frac{(1+z)^{-\Gamma}}{\sqrt{\Omega_\Lambda + (1+z)^3\Omega_m}} \frac{\rho(z)}{\rho_0}.$$

Evolution of the considered class of sources:

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

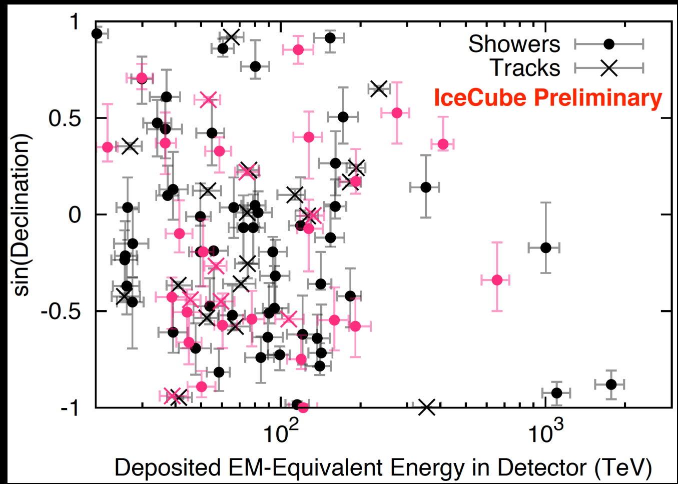
$\xi_z \sim 2.6$ for $\gamma = 2$, star formation evolution $\rho(z) = \rho_0\ (1+z)^3$ for $z < 1.5$, $(1+1.5)^3$ for $1.5 < z < 4$ and ρ_0 = effective source density

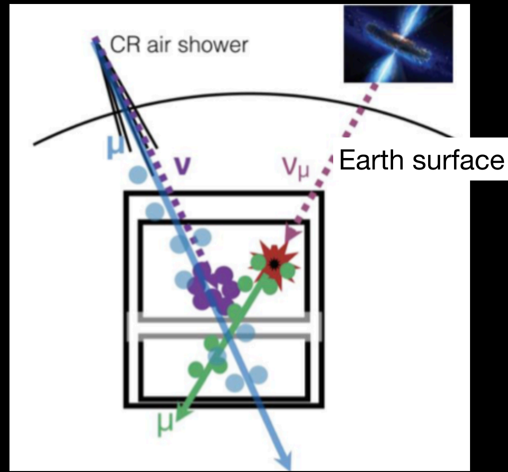
IceCube PhysRevLett.124.051103 Tessa Carver PhD thesis UNIGE

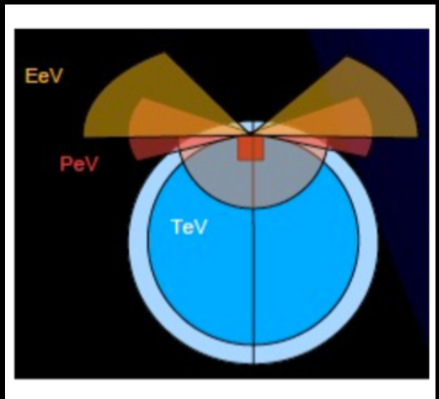


The > 100 TeV diffuse neutrino flux

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.

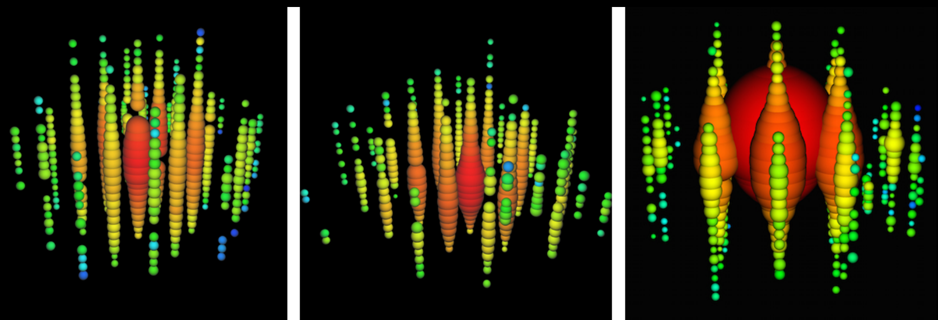


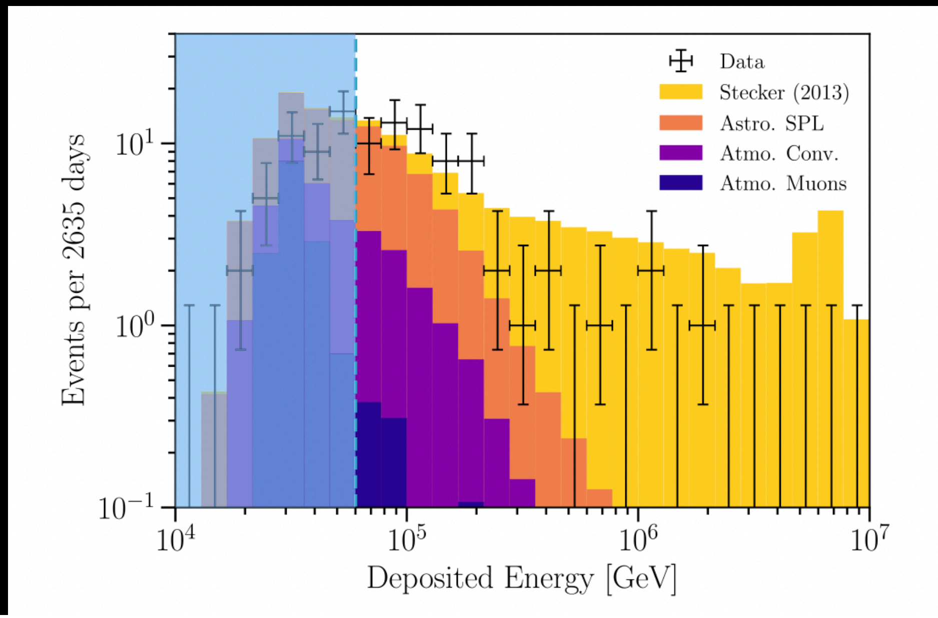




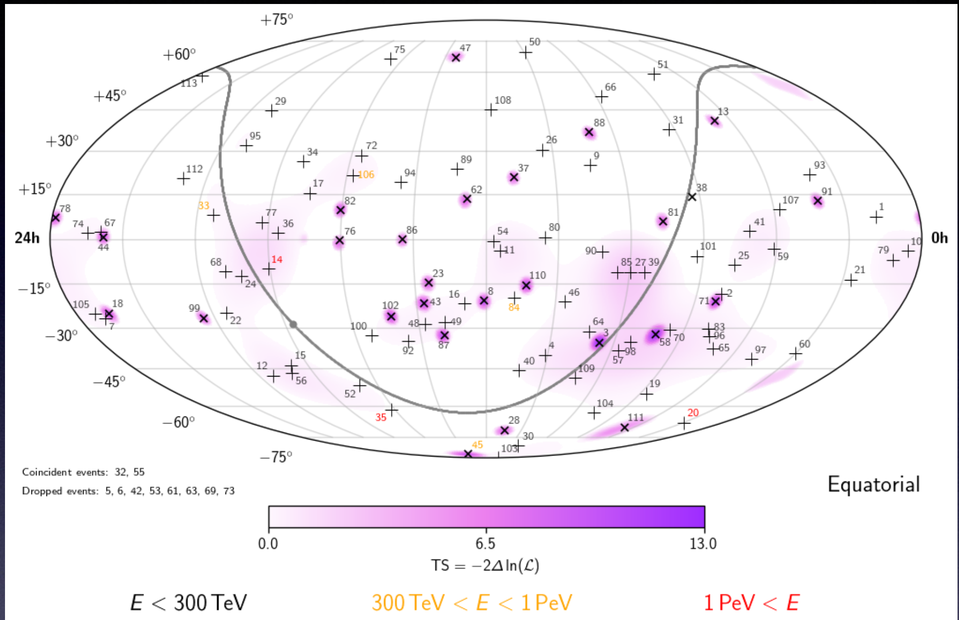
Astronomy beyond PeV is mostly horizontal!

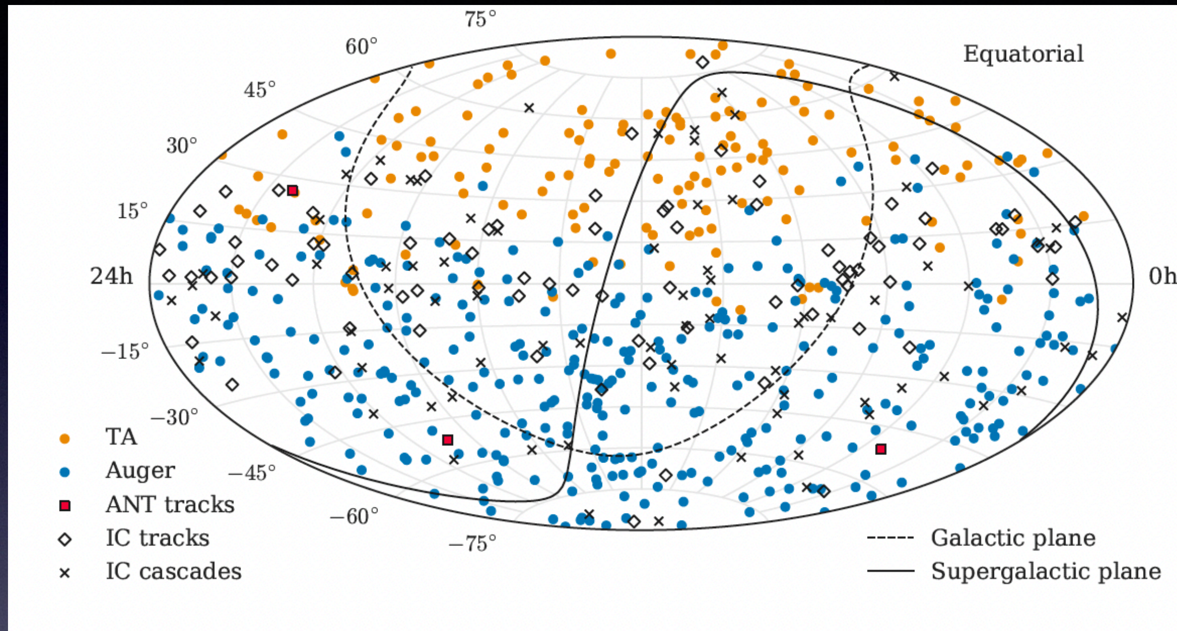
Vetoes are important!





The IceCube HESE directions and UHECR - ν correlation





Post.trial p-value ~1%

IceCube, ANTARES, PAO and TA, 2022

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

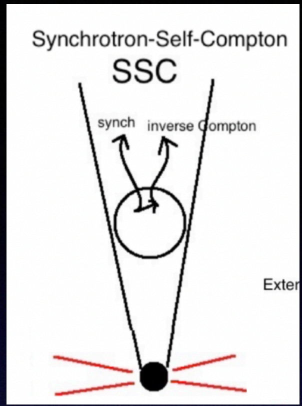
The absence of correlation with UHECRs > 50 EeV indicates that if the neutrinos are being injectected in the IceCube/ANTARES samples, their distance is beyond the UHECR accessible horizon or that magnetic deflections are larger than what considered.

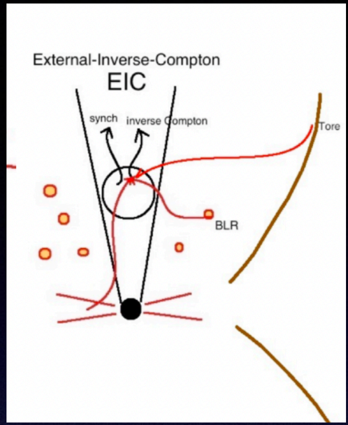
Blazars: BL Lacs and FSRQ

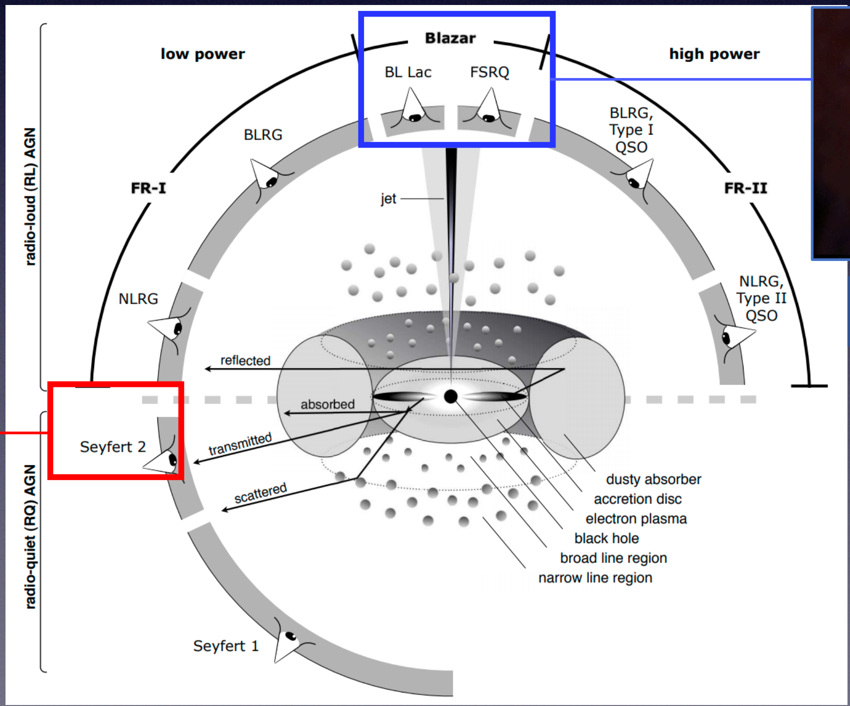
Cerruti RICAP 2022

Blazars: radio-loud AGNs: radiative emission dominates over thermal continuum with jet against us ~10% of galaxies.
Flat-spectrum-radio-quasars (FSRQ) : LBL blazar with optical/UV spectrum with broad emission lines from photo-excitation by a radiatively efficient accretion disk around SMBH -> External IC. At times lines are hidden by the torus -> masquerading FSRQ.
BL Lacertae objects : featureless optical/UV spectrum -> SSC

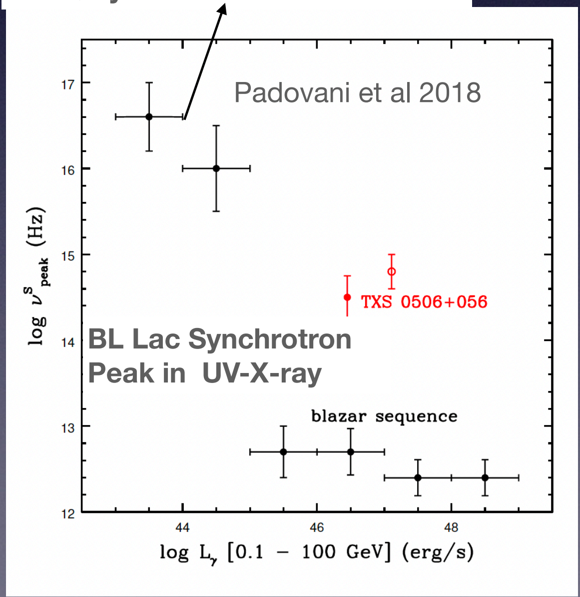
IceCube limit at 10 TeV-2 PeV on Fermi 2LAC blazar neutrino emission (ApJ 2016) assumes same spectra for ν's as γ's (ignoring variability) or some plausible spectra of neutrinos: 27% for $E^{-2.2}$ and 50% for $E^{-2.5}$







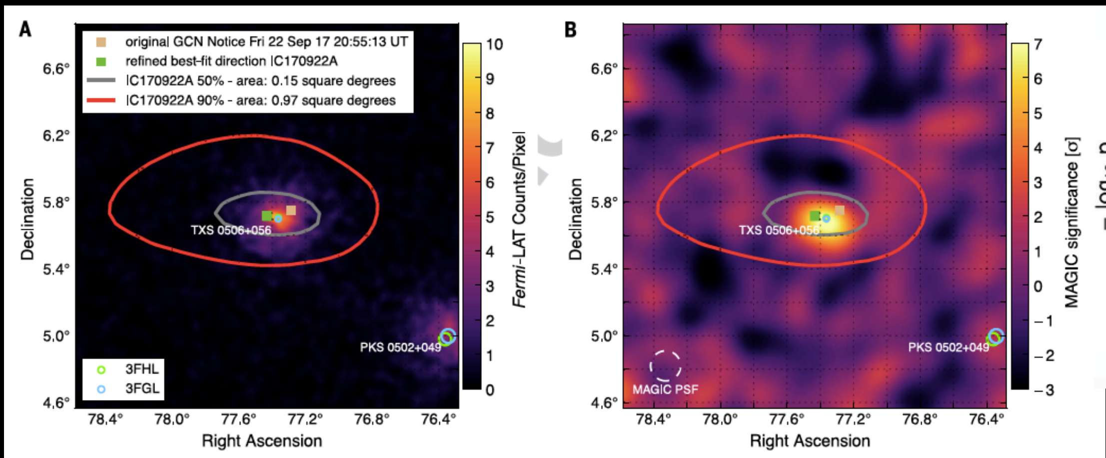
FSRQ Synchrotron Peak in IR

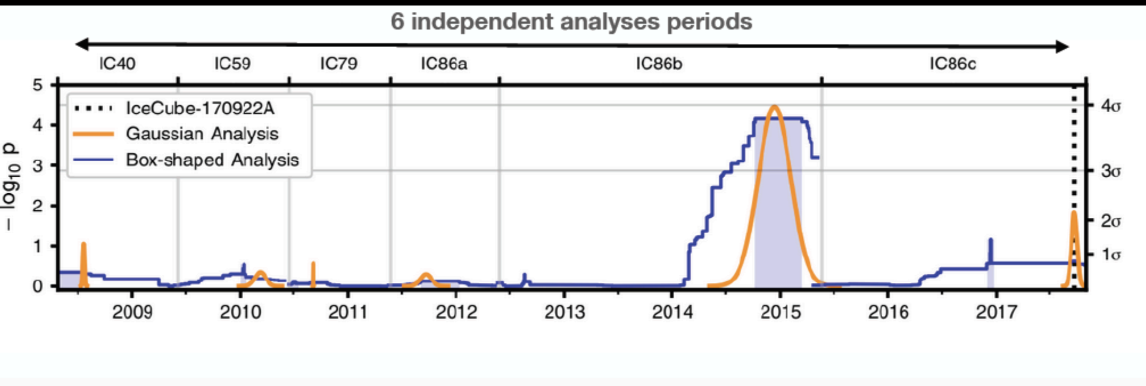


IC170922A and historical data of IceCube

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.

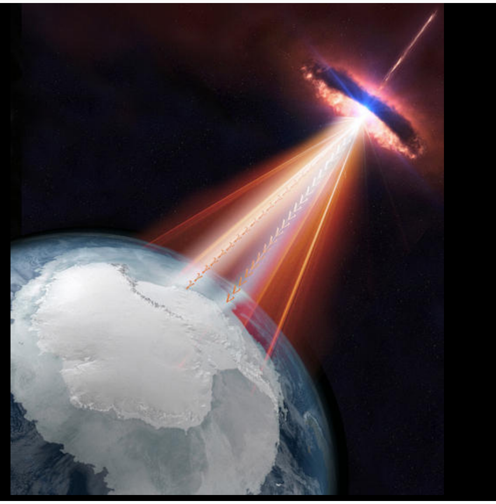
Variability up to x6 in 1 d. Among the top 3% most intense blaars in Fermi catalogue. z= 0.336.





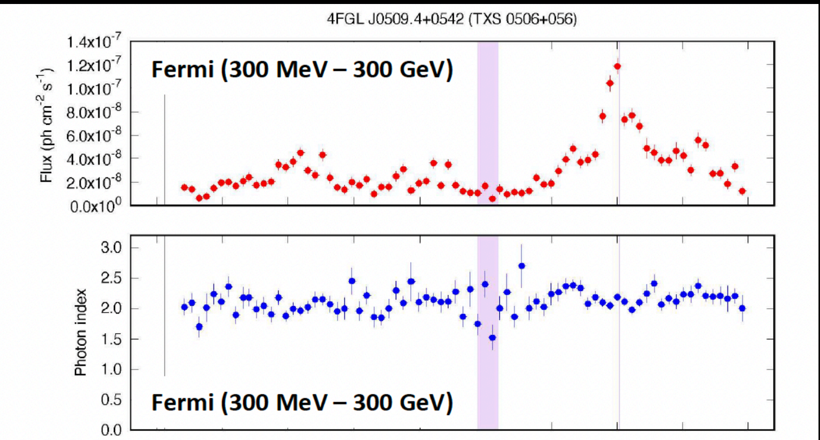
Science 361, 147-151 (2018)

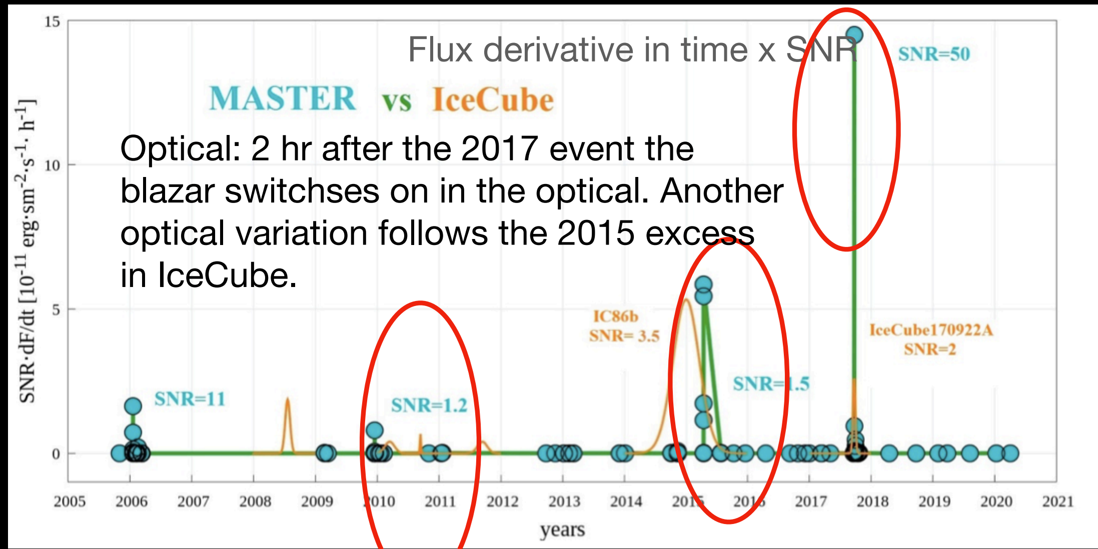
A. Christov thesis UNIGE archive



MAGIC @ Los Roche de los Muchachos, La Palma

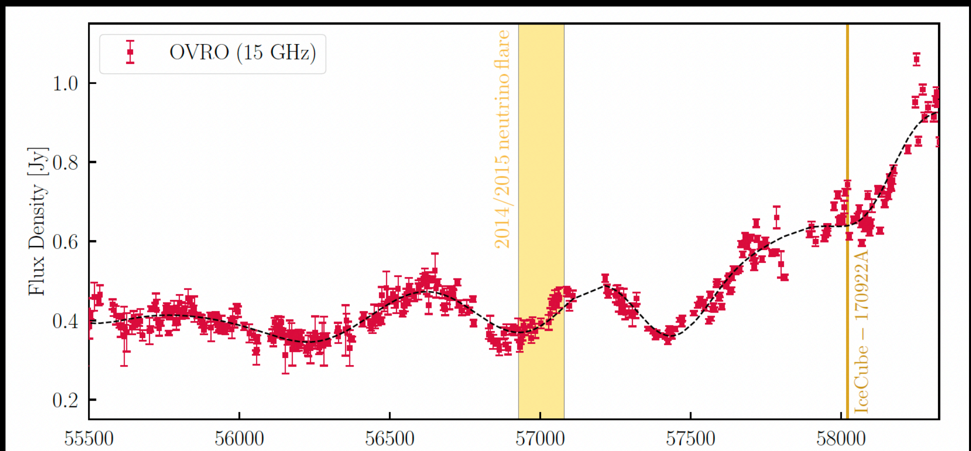
MWL observations of the 2014-2015 flare





A huge flare in Fermi-LAT for 2017 event, no activity for 2014-2015 flare

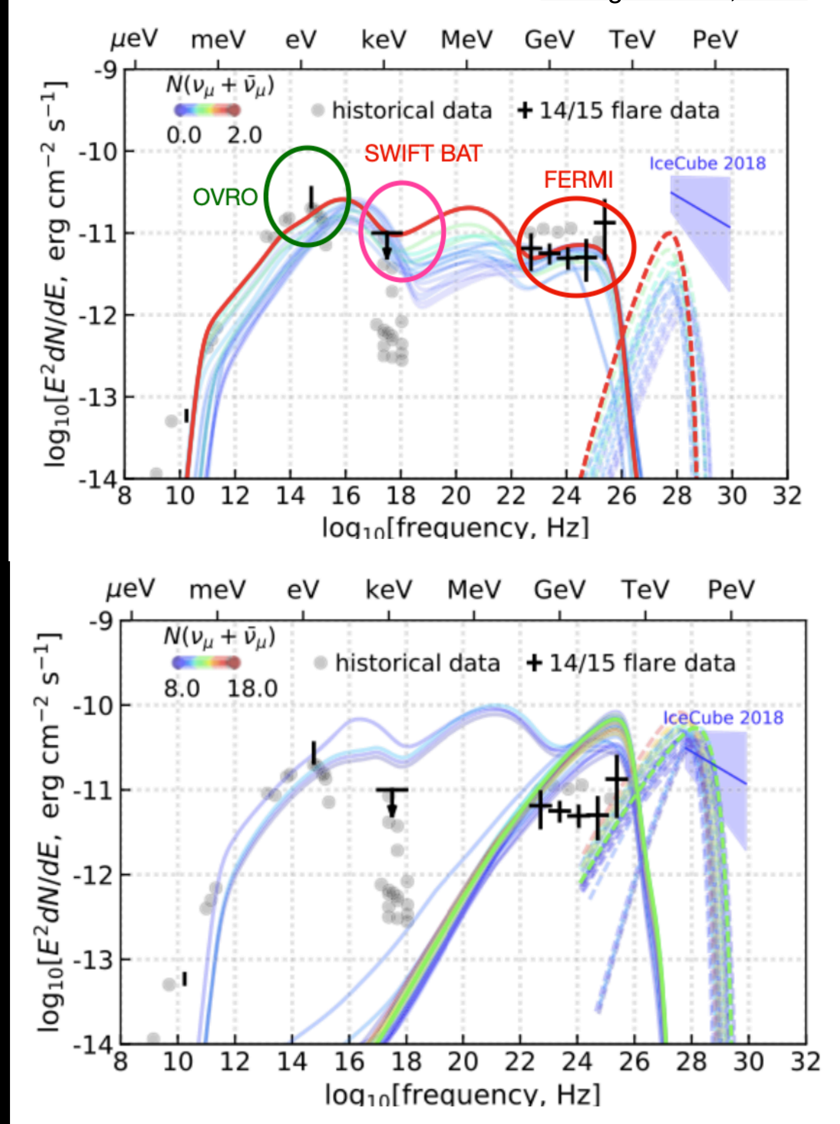
Radio emission is increasing in both cases

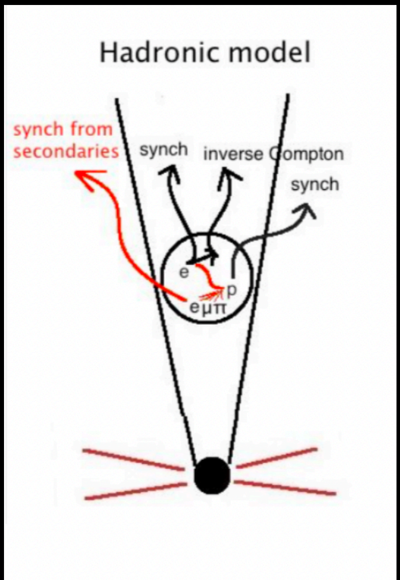


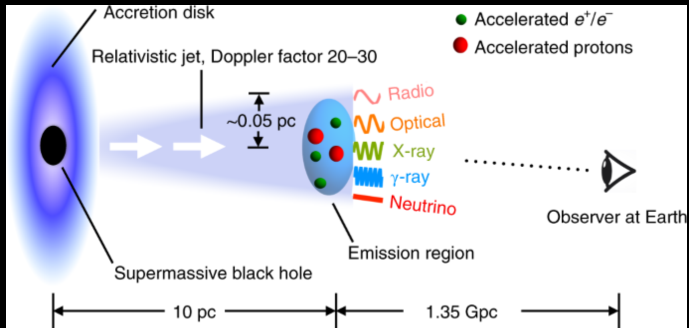
Phenomenological interpretation

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. Lepto-hadronic models or multiple zones can fit all data requiring high proton energetics and also resulting in low neutrino rates

Rodrigues et al, 2019







Keivani et al, 2019,
A. Reimer et al. ApJ 881 2019,
F. Halzen et al. ApJL 874 2019
See presentation of M. Cerruti at RICAP 2022 for a full review of all proposed models

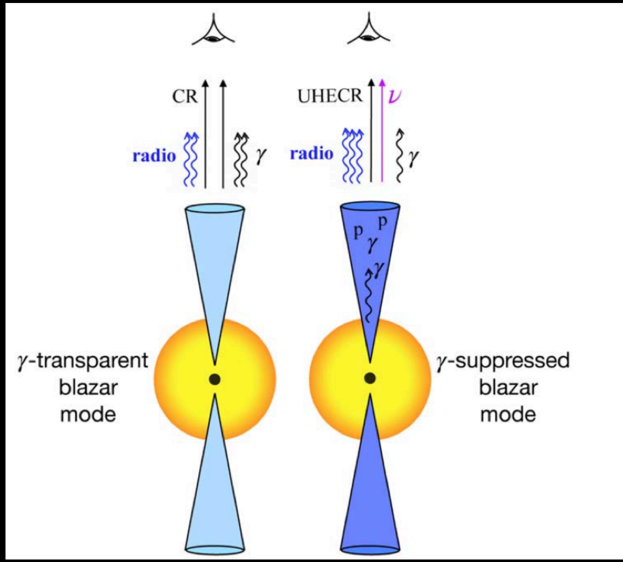
Gao et al. Nature Nov. 2018

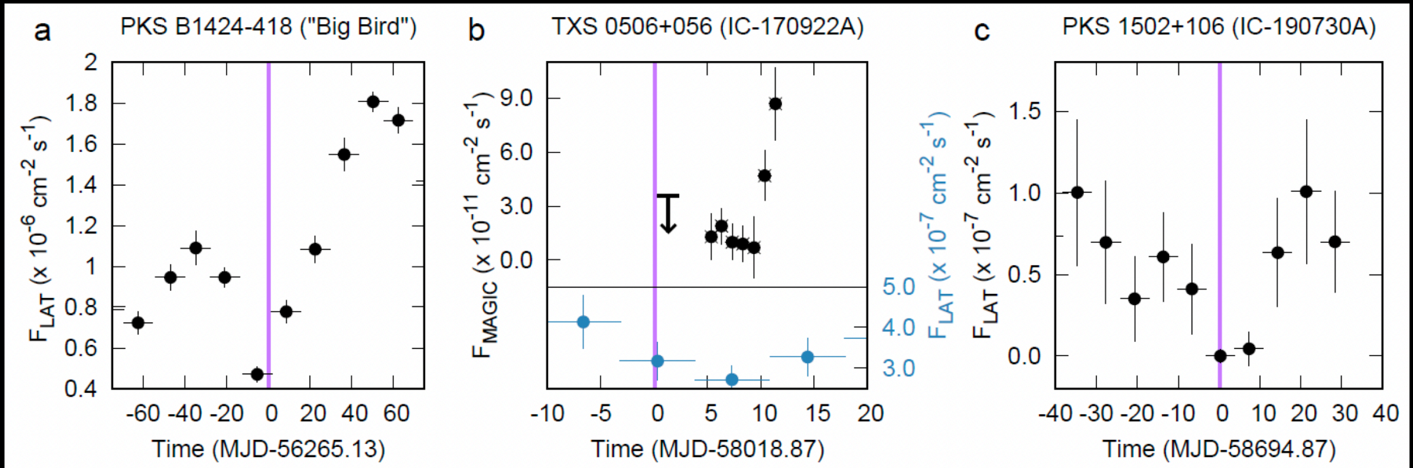
A special class of blazars?

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, $\tau_{p\gamma} \sim 0.4 \Rightarrow \tau_{\gamma\gamma} \sim O(100)$

Sahakyan 2022: all the blazars producing these events behave as masqueradin BL Lac



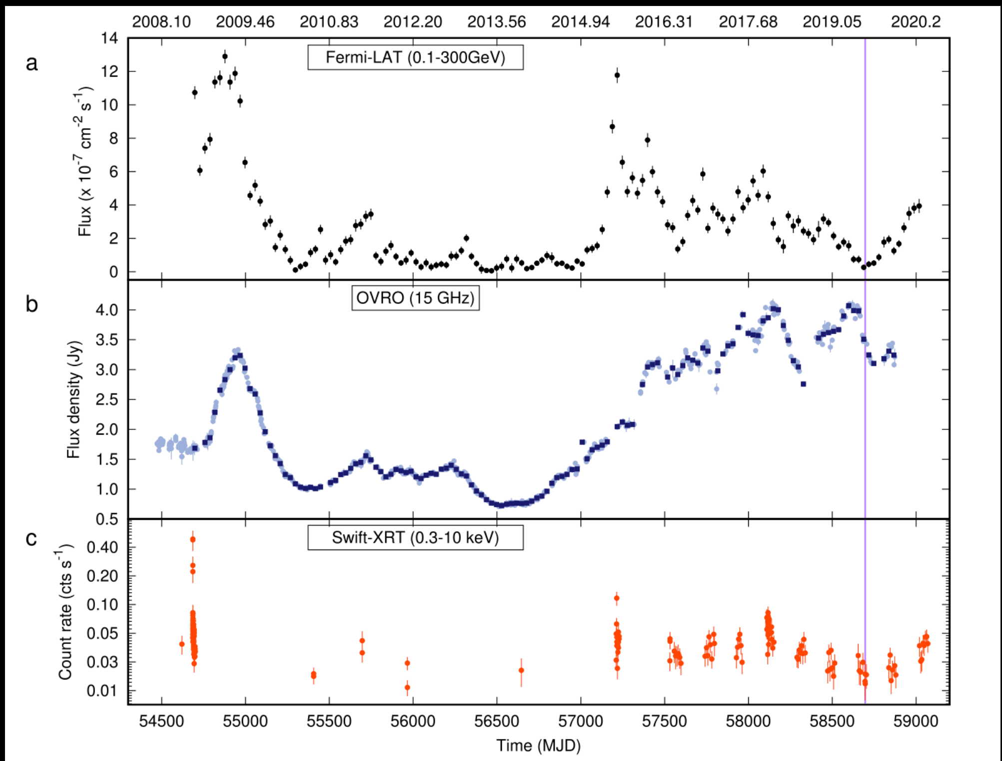


Kun, Bartos, JBT, Biermann, Halzen, Mez´´o ApJL (2021)

Other events from masquerading FSRQ?

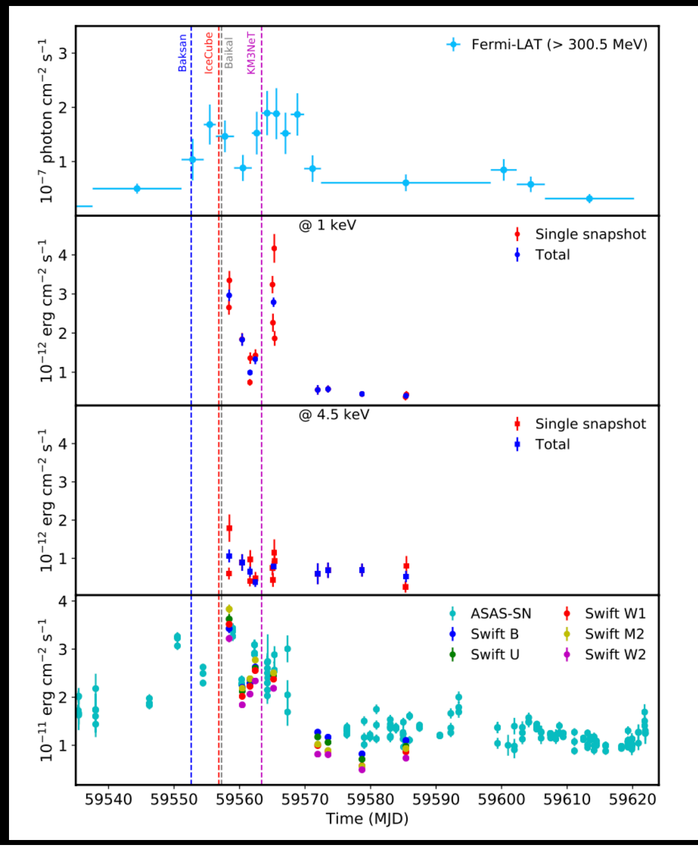
Another 300 TeV neutrino is observed in space-coincidence with PKS 1502+106 (z ~1.8) low-spectral peaked and highly polarized quasar (Stein et al GCN 25225).

Sumida et al 2021



In the next future multiplet searches more important with multiple neutrino telescopes and looking at radio as well, not only gammas (see PKS 0735+178 at z = 0.65 in).

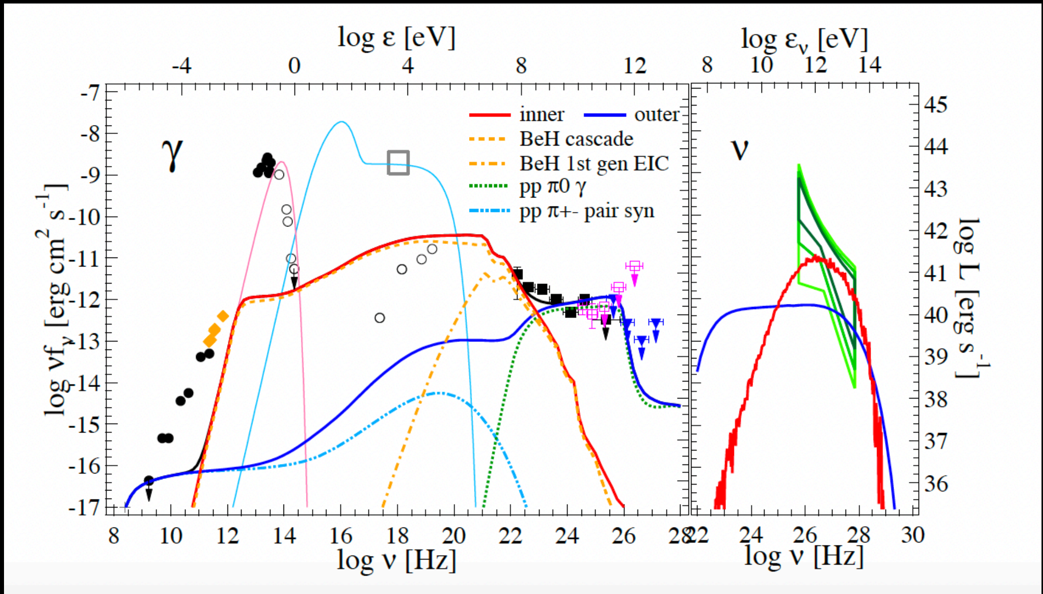
Sahakyan 2022: all the blazars producing these events behave as masqueradin BL Lac

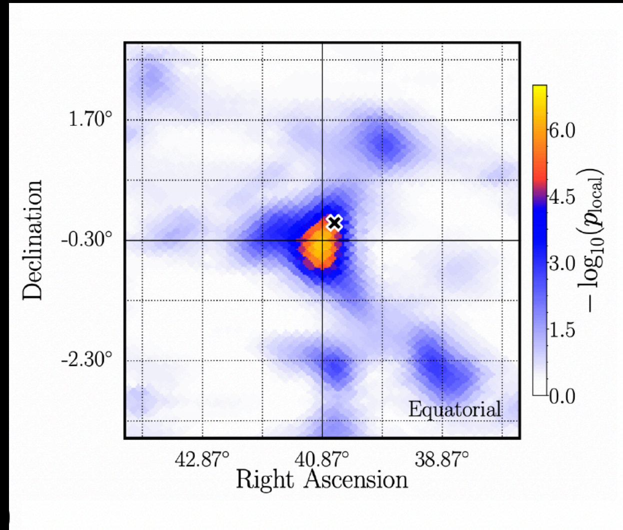


Non-jetted AGN Inner disk Winds

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

Inoue et al 2022   Eichmann et al 2022





2.9σ from a direction of NGC 1068 in a catalogue of 110 gamma-ray emitters with 8 starbursts

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

Gallimore et al (1996, 2004) detects in the radio a mildly relativistic jet extending several kpc with change of direction of 0.2” presumably due to an interaction with a molecular cloud. Additionally, near and mid-IR emission associated with inner radio jet as result of shock heating on the dust by passage of jet

Ultra-fast outflows (UFO) launched by accretion disk seen as UFO: UV and X-ray Ultra-Fast Outflows. If winds start from **inner part** of the disk they might fall back and DSA accelerated protons interact with photons from the disk and corona and TeV gamma absorbed (MAGIC limits). In the outer part, successful winds pp interactions pp with torus. gas. Other models Corona models Murase, Kimura, Meszaros 2020, Inoue et al. ApJL 891 (2020). See also Eichmann et al 2022.

A clear case for MAGIC+LST observations!

Diffuse flux from calorimetric sources : starburst galaxies (SGBs)

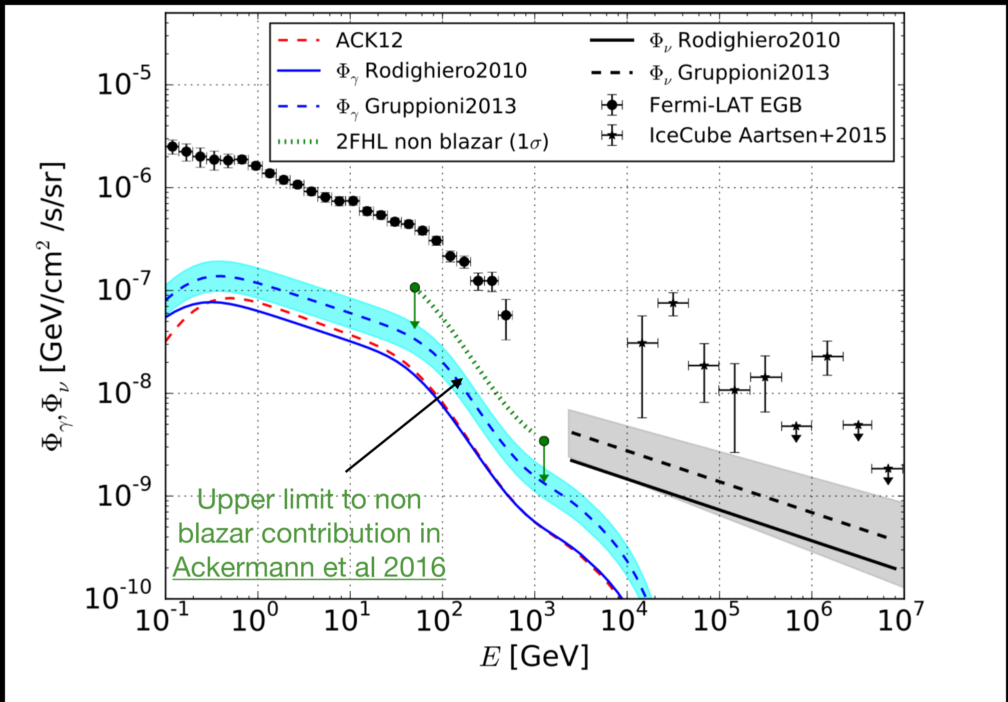
SGBs proposed as neutrino sources in Waxman & Loeb, 2006. Small scale anisotropy detected with PAO UHECRs with > 32 EeV σ 4.1cl (Abreu et al 2022). Some, like NGC 1068, host AGNs with weak jets, but starburst winds can accelerate to 100 PeV (Peretti et al, 2022).

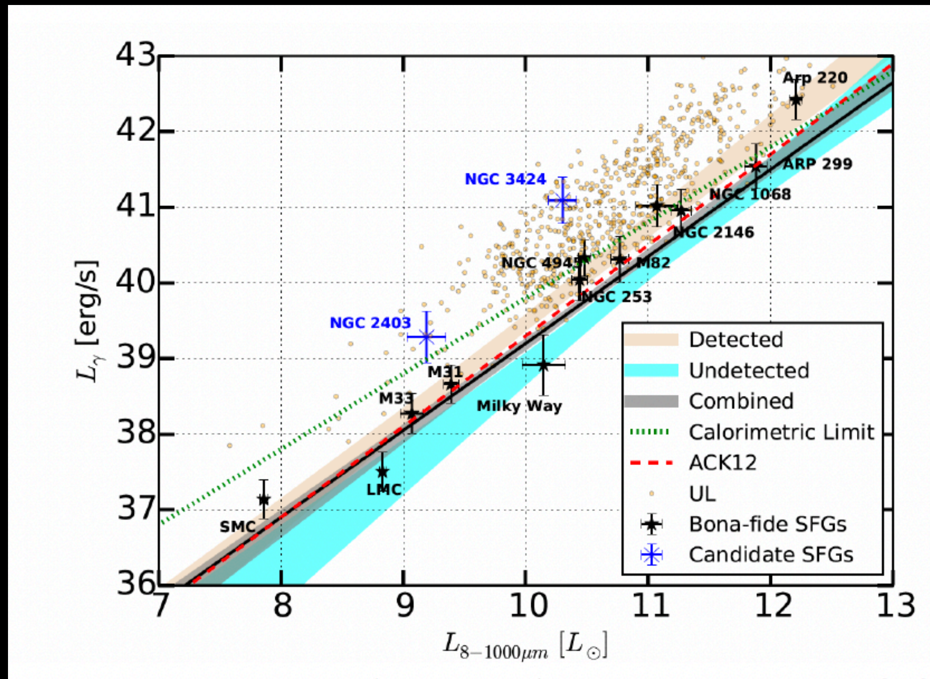
Ajello et al, 2020 : cumulative emission assuming from average spectrum of 13 SBG detected by Fermi cumulatively < 5% contribution to diffuse neutrino flux (1% in Tamborra 2014, Bechtol et al 2017)

SFR > 10-1000 $M_{\odot}/yr$

$L_{IR} > 10^3 eV\,\mathrm{cm}^{-3}$

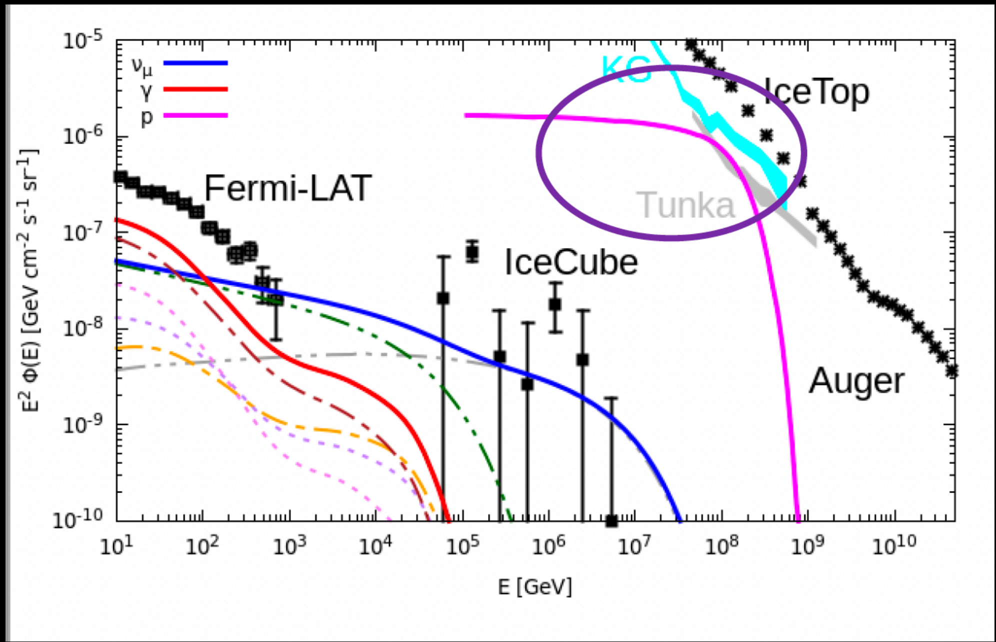
Strong turbolence $B > 10^2 \mu G$

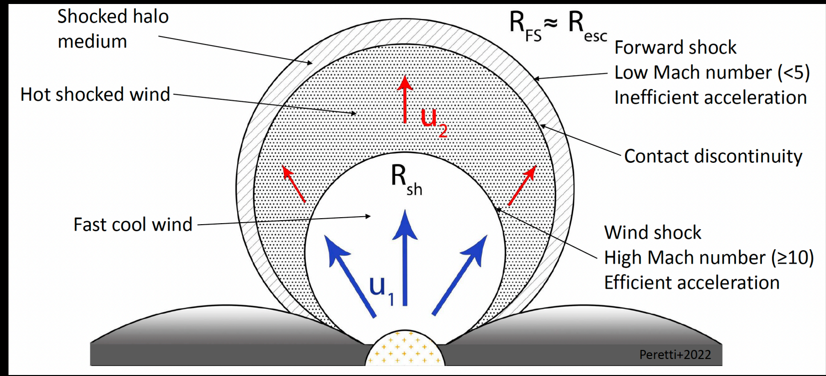




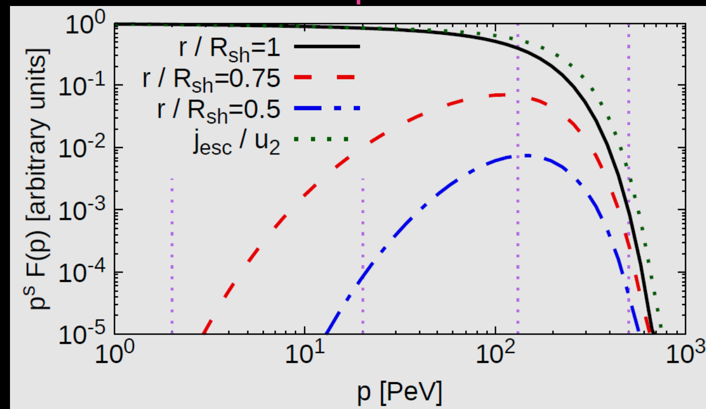
IceCube search for 75 ULIRG **Ultra-Luminous Infrared Galaxies**

Extragalactic and Galactic wind bubbles

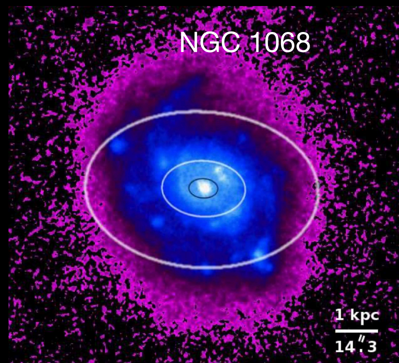




Transport in Starburst Nuclei : Emax up to 100 PeV (Peretti et al 2022)=> neutrinos up to 10 PeV

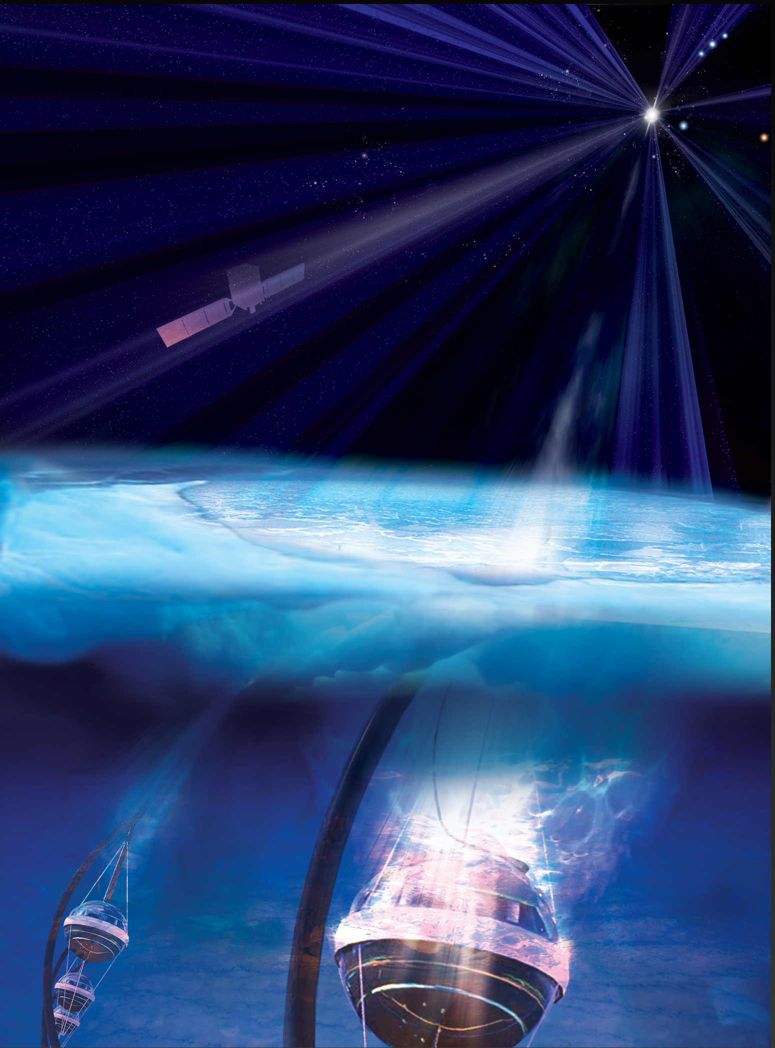


Pion production in Starburst galaxies: acceleration of protons in wind bubbles



Winds can be sustained ~100 Myr.

Conclusions


Credit: NASA/Fermi and Aurora Simonnet
Sonoma State University

Baikal → GVD

The diffuse flux of neutrinos at > 100 TeV has been discovered

Another granted flux from the galactic plane is at reach

Cascades have the power to beat the background of atmospheric neutrinos

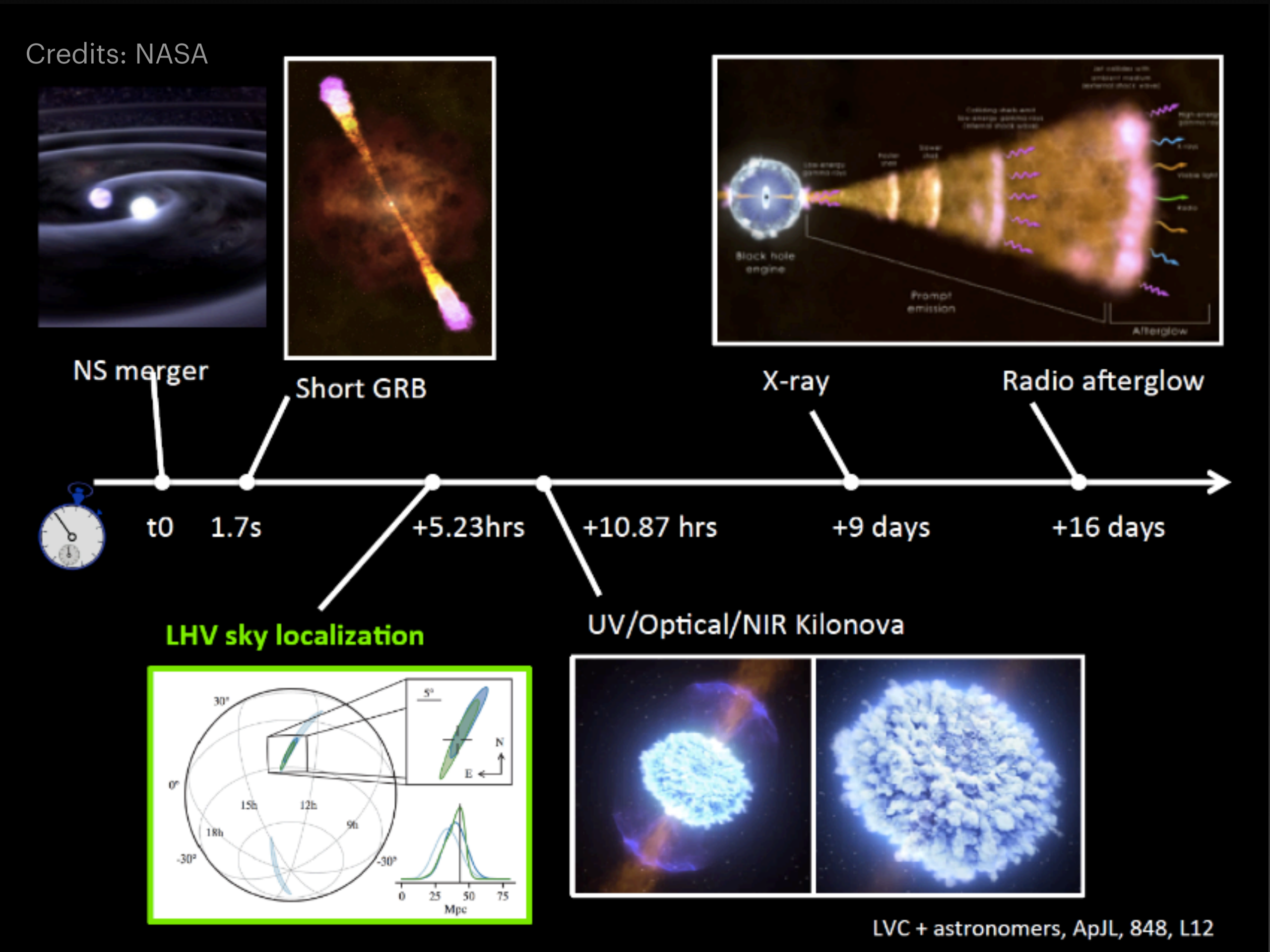
Lower thresholds are at reach of new methods (GNN,..) thanks to better Ice Modeling

Despite many multi-messenger coincidences are at 3σ level the modeling started for neutrino observations driven by multi-band. Now also multi-neutrino telescope multiplets.

Their continuation is a MUST => IceCube-Gen2, KM3NeT, GVD,…

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

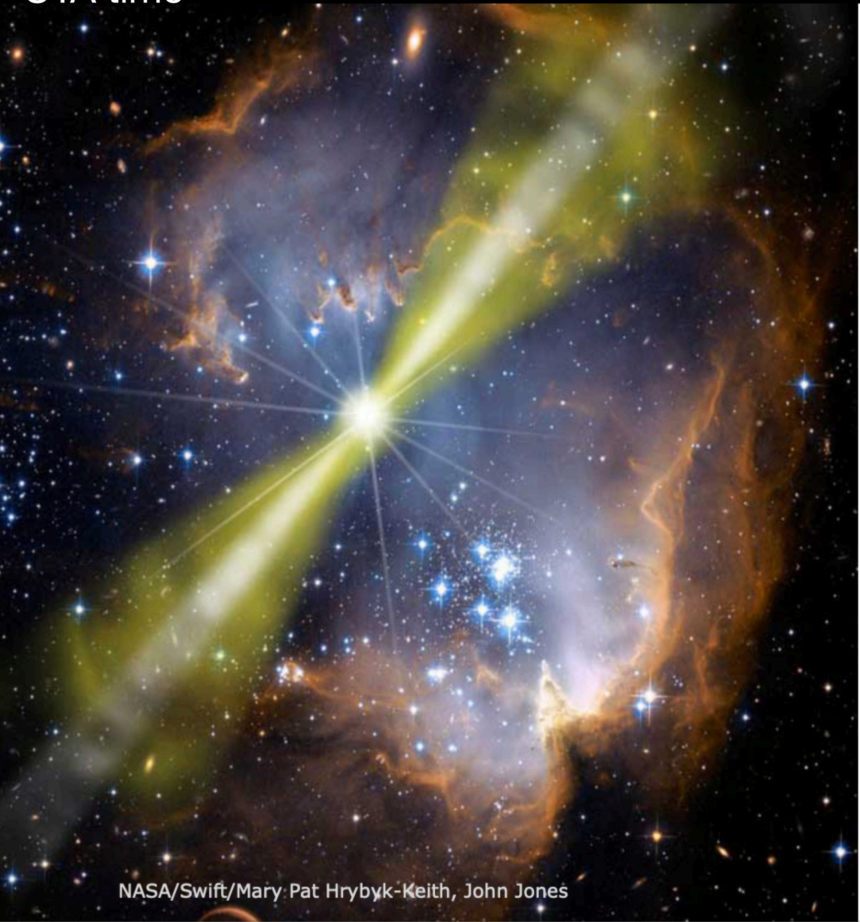
Detection of Inverse Compton from a kilonova event due to a long-lived lo power jet. Marica Branchesi's talk

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

PRD 96, 022005 (2017)

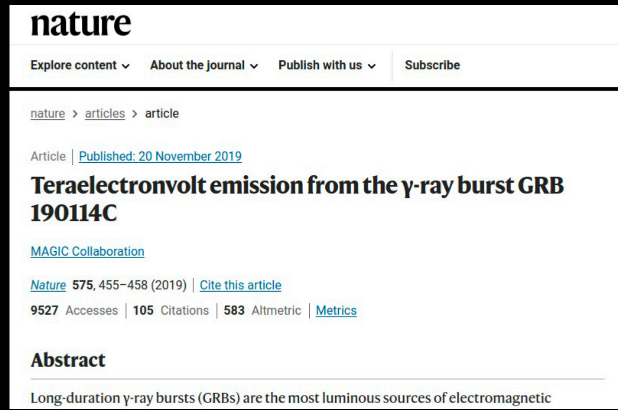
TeV gamma-ray bursts

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 >3σ
  - 3.5σ above 50 GeV
- **GRB 201216C** *(PoS ID 395, S.Fukami)*
  - long GRB 5σ
  - z=1.1
  - for 20' after T_0+56s
  - 6σ E<100 GeV

6


nature

Explore content ⌄ About the journal ⌄ Publish with us ⌄ Subscribe

nature > articles > article

Article | Published: 20 November 2019

Teraelectronvolt emission from the γ-ray burst GRB 190114C

MAGIC Collaboration

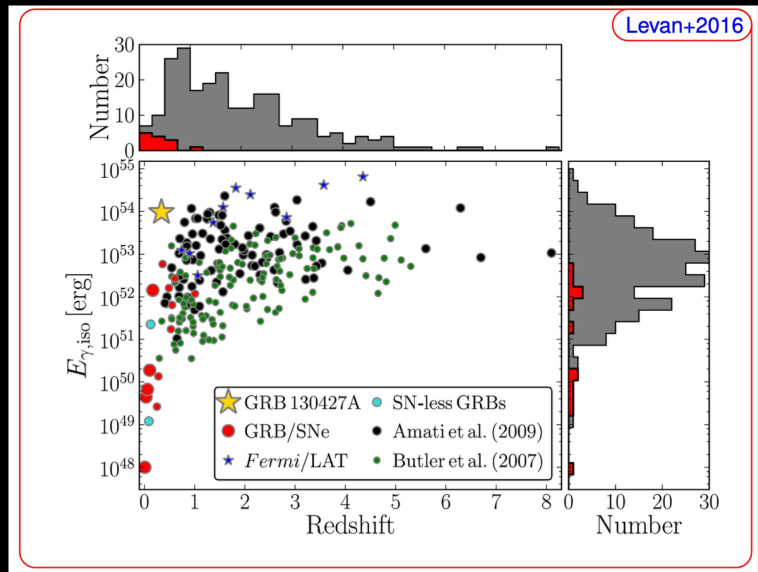
Nature **575**, 455–458 (2019) | Cite this article

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

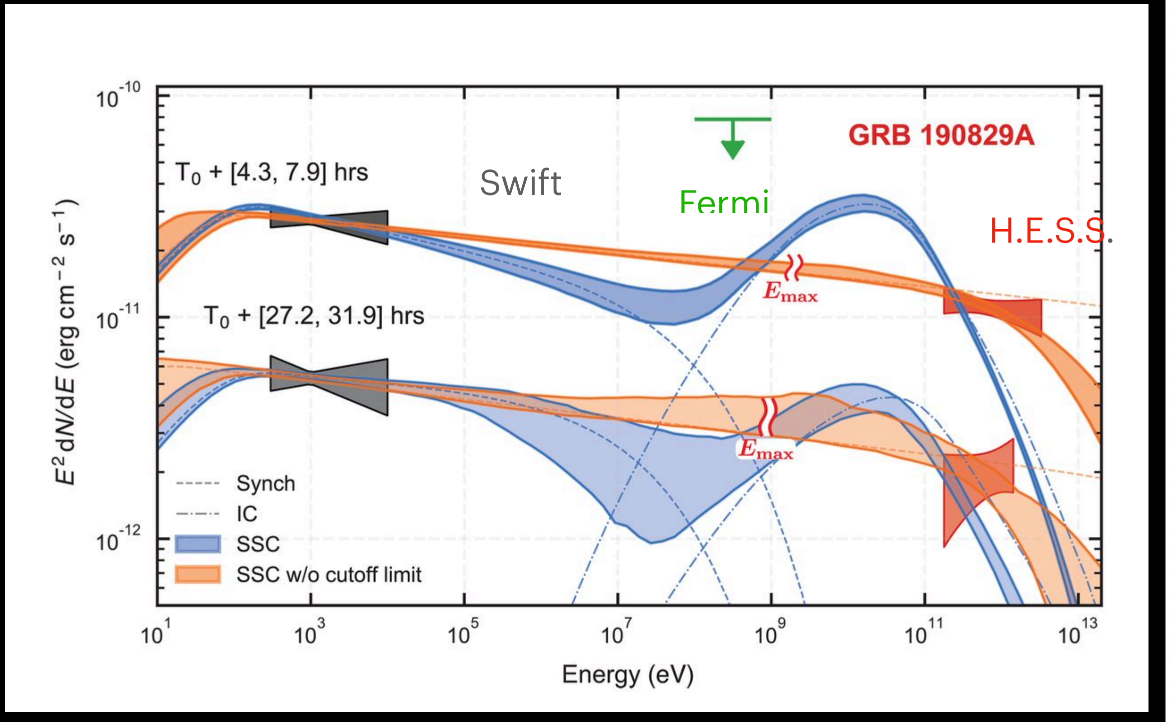
Abstract

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

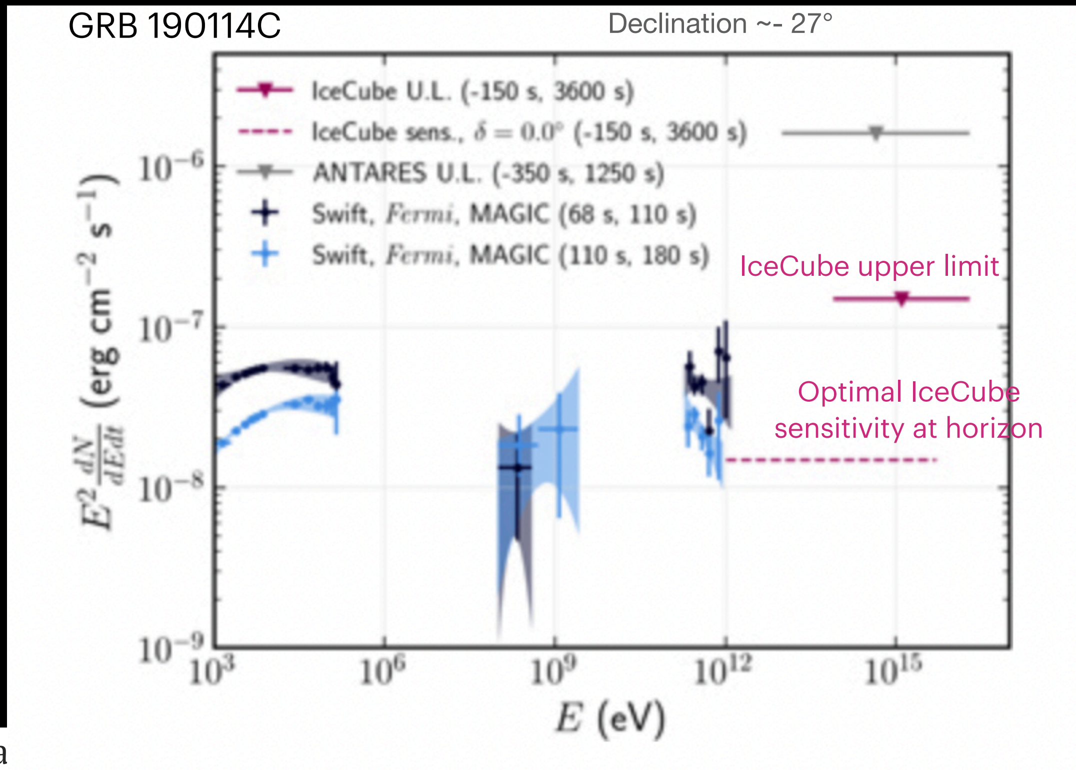


An unexpected afterglow spectrum



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

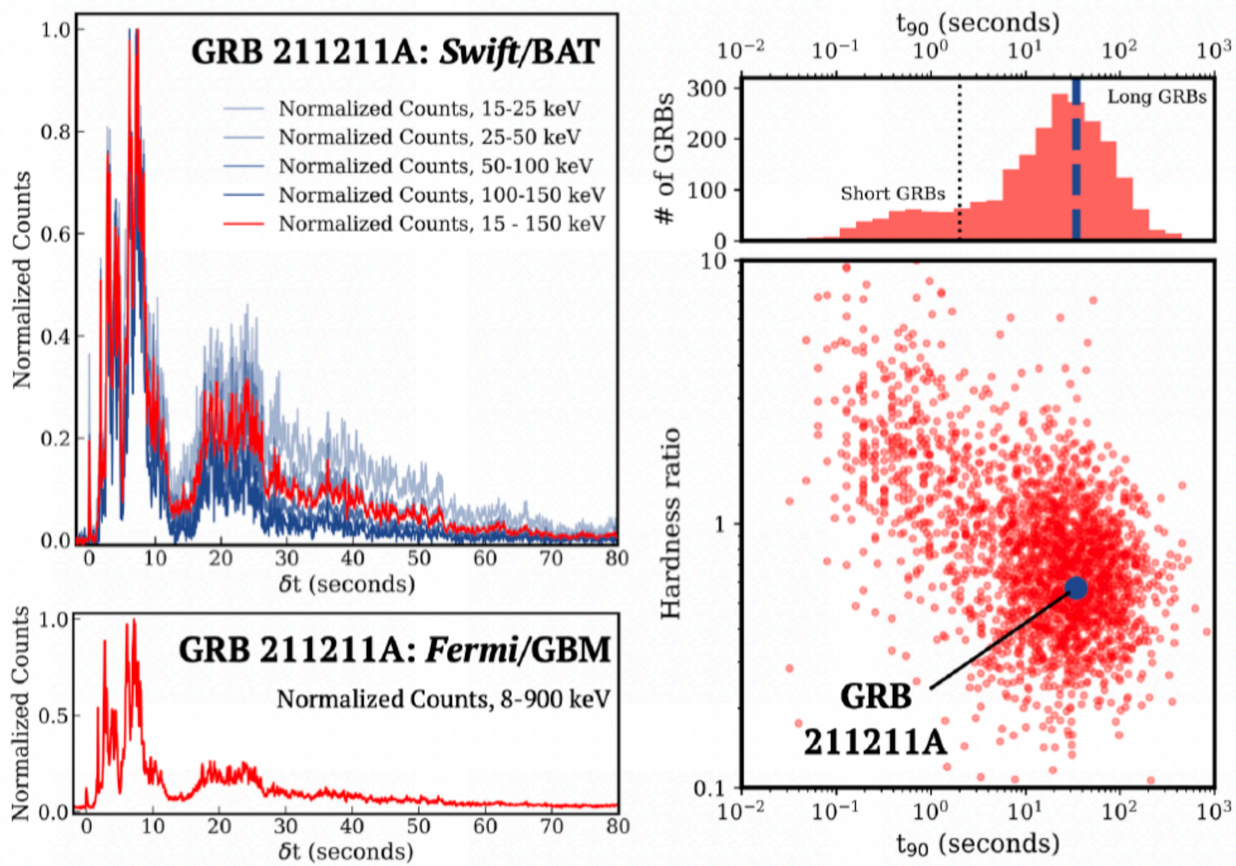
H.E.S.S. Science 372 (2021)



R. Abbasi et al 2021 ApJ 910 4

A paradigma on the origin of GRBs?

- GW170807 established sGRBs as originating from BNS mergers
- Kilonova are called **r-process SN** as ejecta host radioactive species decays forming heavy ions in their n-rich environments. It is expected that radiation in the optical is highly streched out over a long time scale of order of days and emitted in the nIR (Tanvir et al, 2013).
- Recent surprise! Swift 2022: during a long GRB a kilonova optical/NIR event observed at 350 Mpc (z = 0.0763), confirmed by HST
- Similar luminosty, duration, color that AT217gfo, the kilonova associated to the BNS merger GW170817
- The merger ejecta of $\sim 0.04 M_\odot$ are rich of r-processed heavy material ($\sim 0.03 M_\odot$ of lanthanide with velocity 0.3c) consistent with BNS with mass ~ $\sim 1.4 M_\odot$



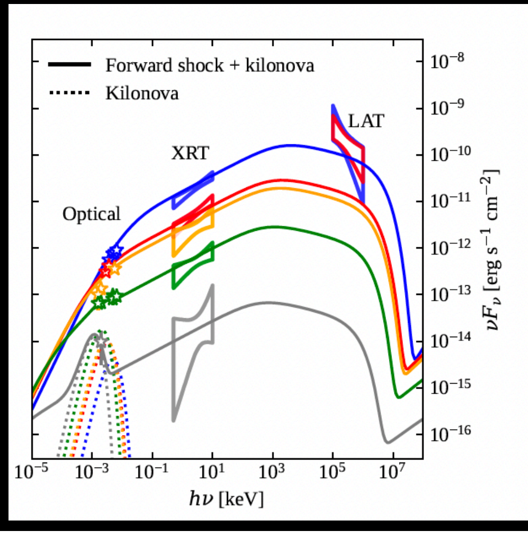
Swift-BAT gamma-ray light curve of GRB211211A

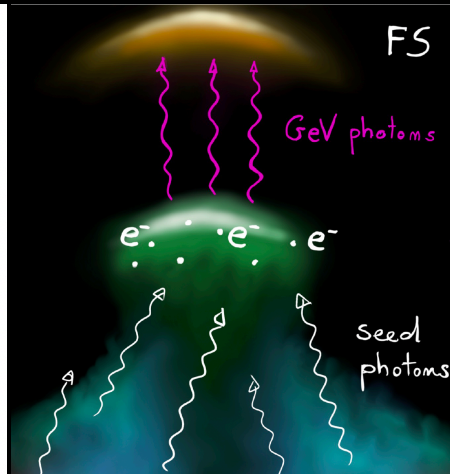
Inverse Compton from GRBs

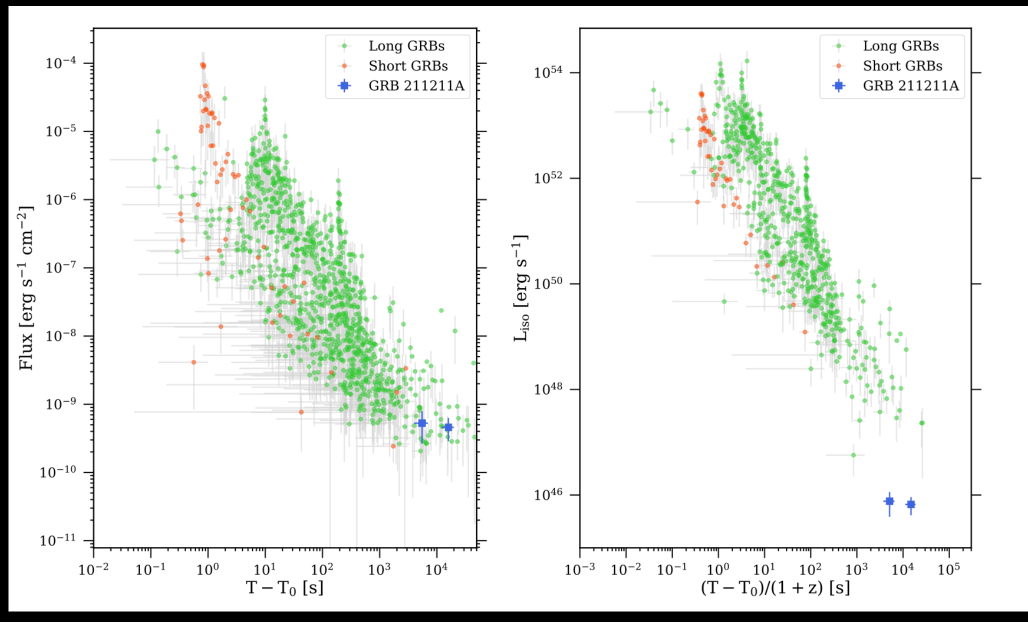
- Mei et al, 2022 report the discovery of a > 5σ transient-like emission in the high-energy Fermi-LAT γ-rays E> 0.1GeV starting 10^3 s after the burst. After an initial phase with a roughly constant flux ($\sim 5 \times 10^{-10}$erg s^{-1} cm^{-2}) lasting ~ 2×10^4 s, then decreasing.

- The fit of the multi-wavelength 'afterglow' emission observed at such late times is in excess with respect to synchrotron emission from a relativistic shock wave that arises as the GRB jet decelerates in the ISM. An IC emission scenario due to the interaction of a long-lived, low-power jet with seed photons emitted by kilonova ejecta is explored. Kilonova emission can provide the necessary seed photons for GeV emission in binary neutron star mergers.

- This observation opens new perspectives in detecting kilonova emission at high energies and GeV counterpart of GW signal from BNS.

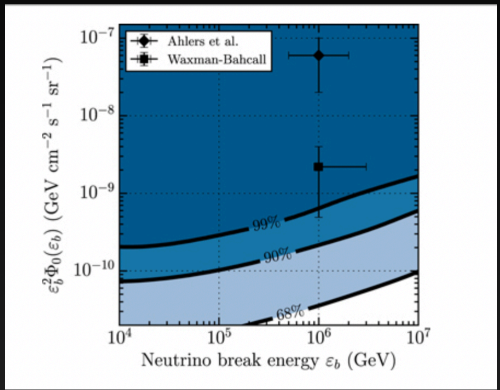


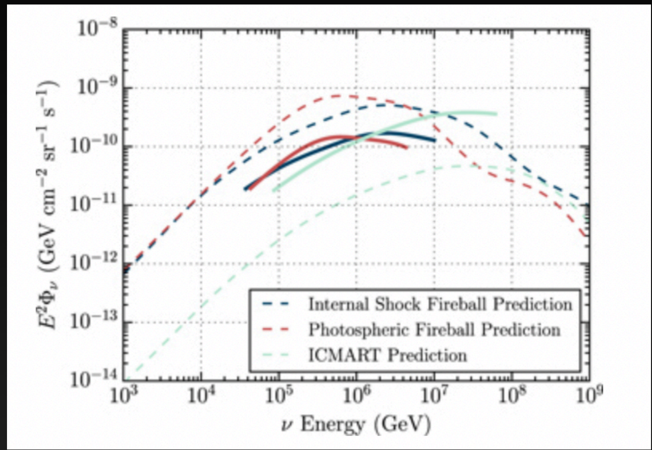




1172 GRBs and IceCube (2010-2015) tracks and cascades

IceCube 2017





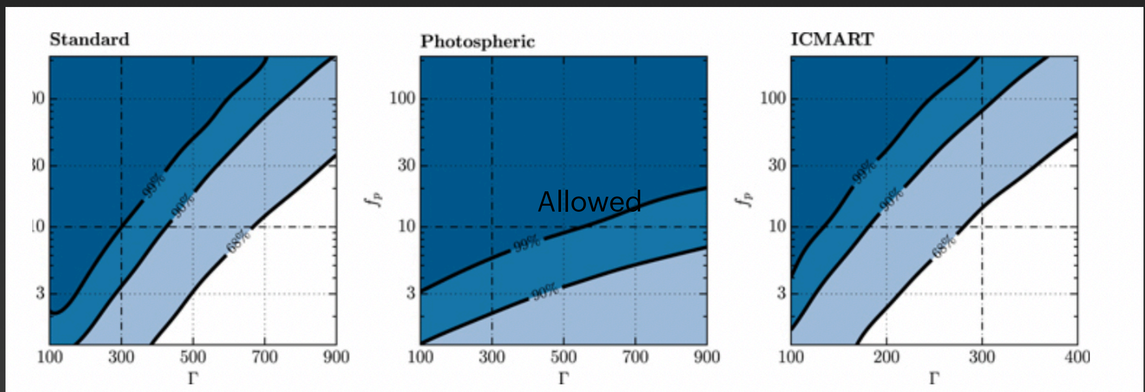
More recently a new paper has been submitted a new paper extending the window to 14 d after the prompt and for a catalogue of precursors (IceCube 2022)

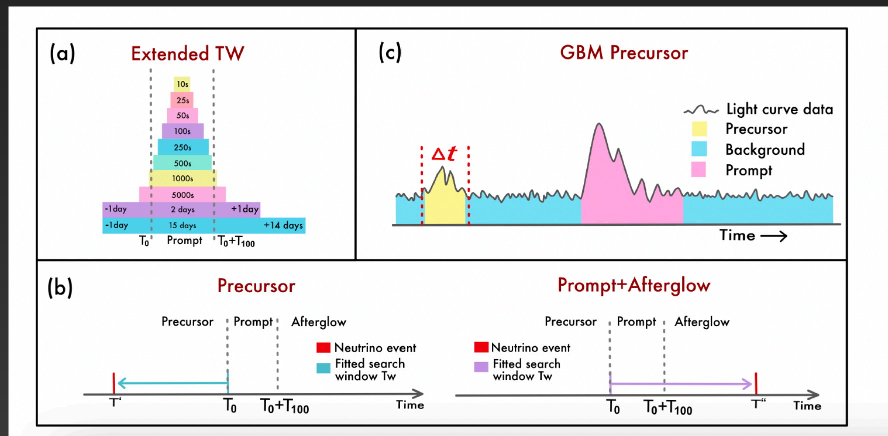
From per flavor burst g flux to diffuse

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

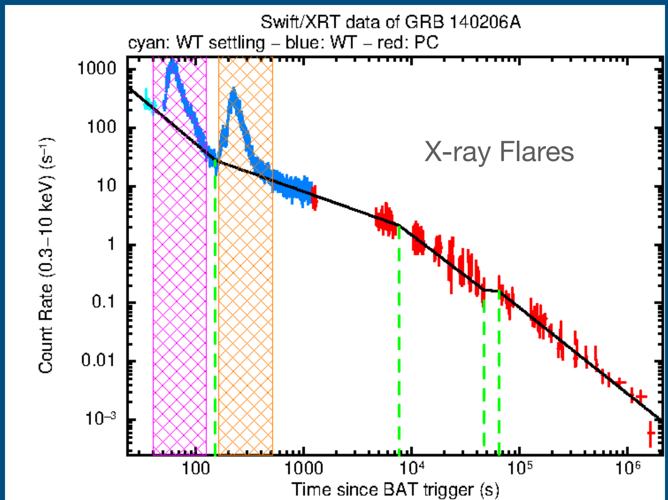
Assumed equal fluence at Earth

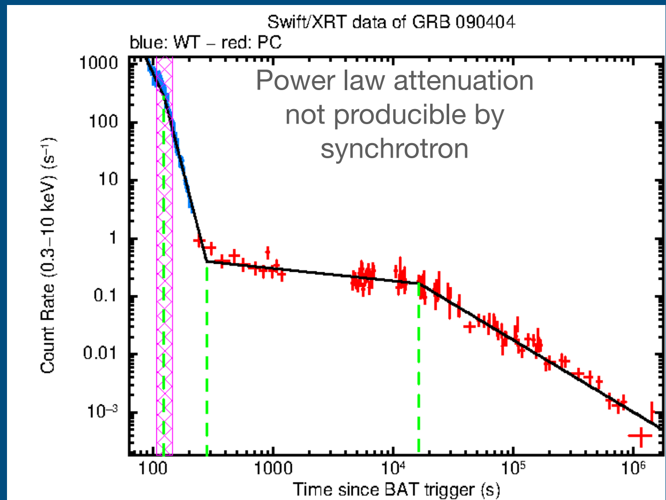
Allowed

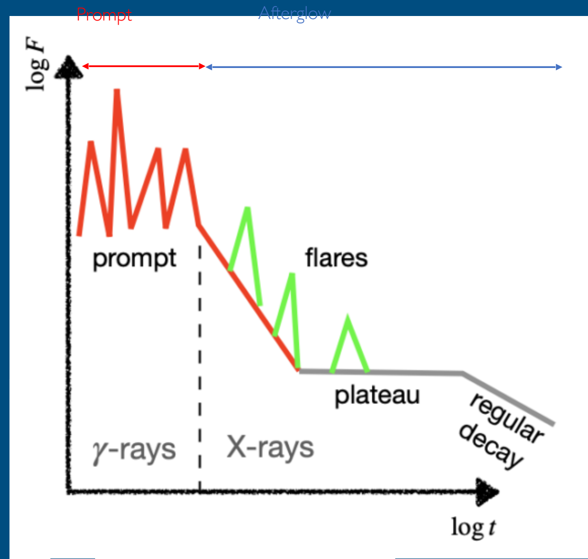




Selected GRBs for ν searches



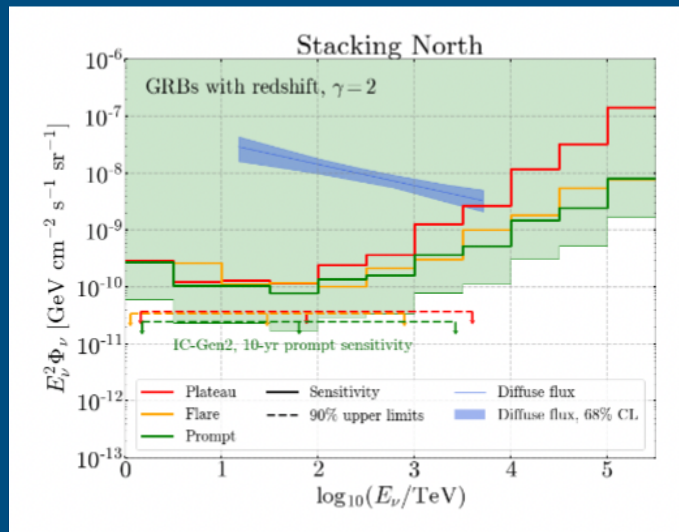




$$E^2_{\nu_\mu}\phi_{\nu_\mu} = \frac{1}{8}\xi_p f_p f_{p\gamma} f_\pi^{syn} f_\mu^{syn} S_{iso}$$

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)

F. Lucarelli, G. Oganesyan, M. Branchesi, T. Montaruli, Mei, Ronchini 2022

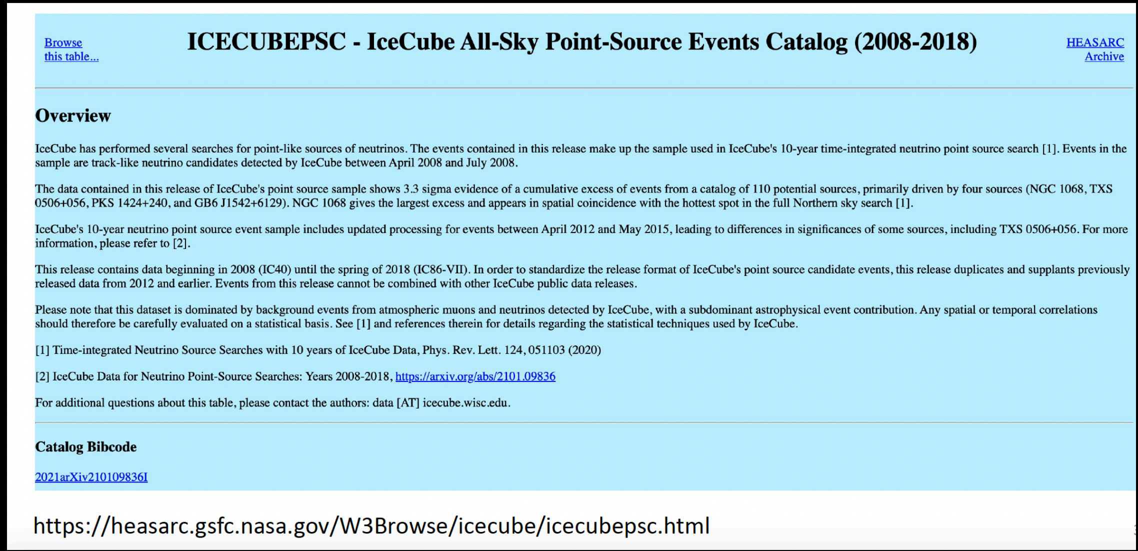


10 yr Data sample in HEASARC and open software for point-source searches

See: https://github.com/orgs/icecube/repositories

For point source analysis and transient sources
https://github.com/icecube/PSLab_PS_analysis
https://github.com/icecube/flarestack
https://github.com/icecube/skyllh
https://github.com/icecube/FastResponseAnalysis

FIRESONG to simulatie populations of neutrinmo sources



ICECUBEPSC - IceCube All-Sky Point-Source Events Catalog (2008-2018)

Browse this table...

HEASARC Archive

Overview

IceCube has performed several searches for point-like sources of neutrinos. The events contained in this release make up the sample used in IceCube's 10-year time-integrated neutrino point source search [1]. Events in the sample are track-like neutrino candidates detected by IceCube between April 2008 and July 2008.

The data contained in this release of IceCube's point source sample shows 3.3 sigma evidence of a cumulative excess of events from a catalog of 110 potential sources, primarily driven by four sources (NGC 1068, TXS 0506+056, PKS 1424+240, and GB6 J1542+6129). NGC 1068 gives the largest excess and appears in spatial coincidence with the hottest spot in the full Northern sky search [1].

IceCube's 10-year neutrino point source event sample includes updated processing for events between April 2012 and May 2015, leading to differences in significances of some sources, including TXS 0506+056. For more information, please refer to [2].

This release contains data beginning in 2008 (IC40) until the spring of 2018 (IC86-VII). In order to standardize the release format of IceCube's point source candidate events, this release duplicates and supplants previously released data from 2012 and earlier. Events from this release cannot be combined with other IceCube public data releases.

Please note that this dataset is dominated by background events from atmospheric muons and neutrinos detected by IceCube, with a subdominant astrophysical event contribution. Any spatial or temporal correlations should therefore be carefully evaluated on a statistical basis. See [1] and references therein for details regarding the statistical techniques used by IceCube.

[1] Time-integrated Neutrino Source Searches with 10 years of IceCube Data, Phys. Rev. Lett. 124, 051103 (2020)

[2] IceCube Data for Neutrino Point-Source Searches: Years 2008-2018, https://arxiv.org/abs/2101.09836

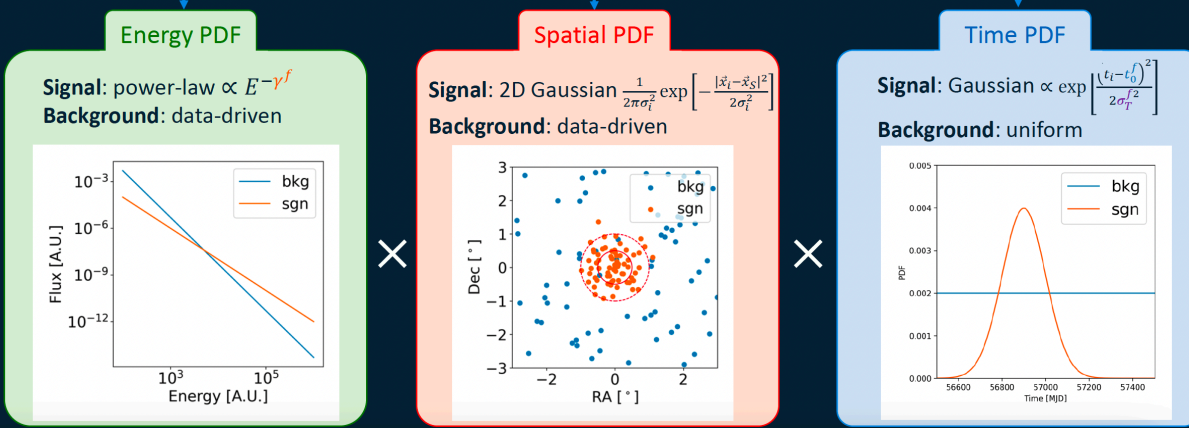
For additional questions about this table, please contact the authors: data [AT] icecube.wisc.edu.

Catalog Bibcode

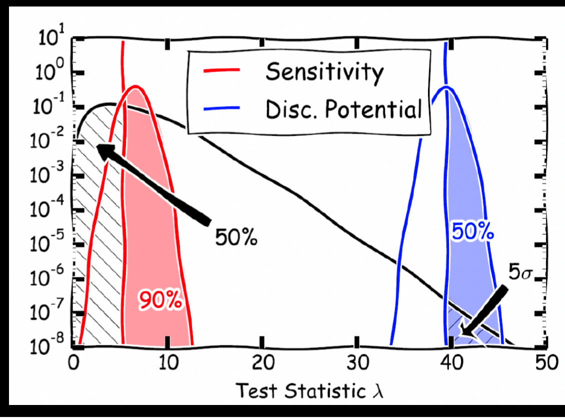
2021arXiv210109836I

https://heasarc.gsfc.nasa.gov/W3Browse/icecube/icecubepsc.html

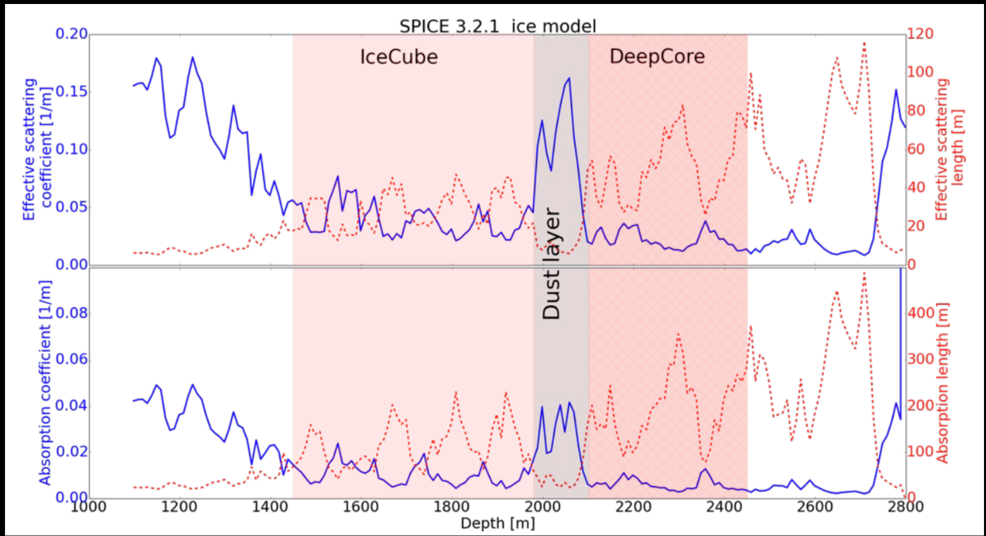
$$\mathcal{L}(\vec{n}_s,\vec{\gamma},\vec{t}_0,\vec{\sigma}_T) = \prod_{i=\text{events}} \left\{ \sum_{f=\text{flares}} \left[\frac{n_s^{(f)}}{N} S_i^{(f)}(\gamma^f, t_0^f, \sigma_T^f) \right] + \left(1 - \sum_f \frac{n_s^{(f)}}{N} \right) B_i \right\}$$



Phys. Rev. Lett. 124, 051103 (2020), arXiv:2101.09836v2

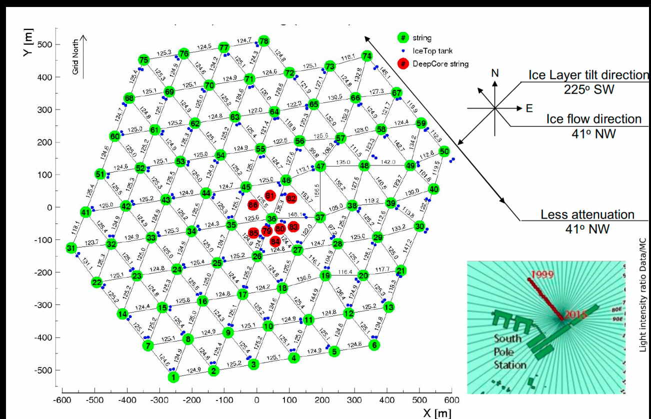


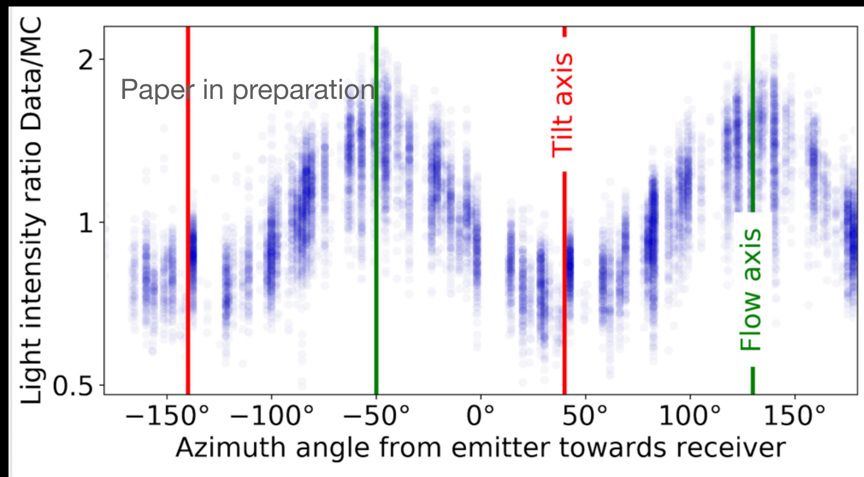
Knowing the detector and simulation: Environment and photon propagation



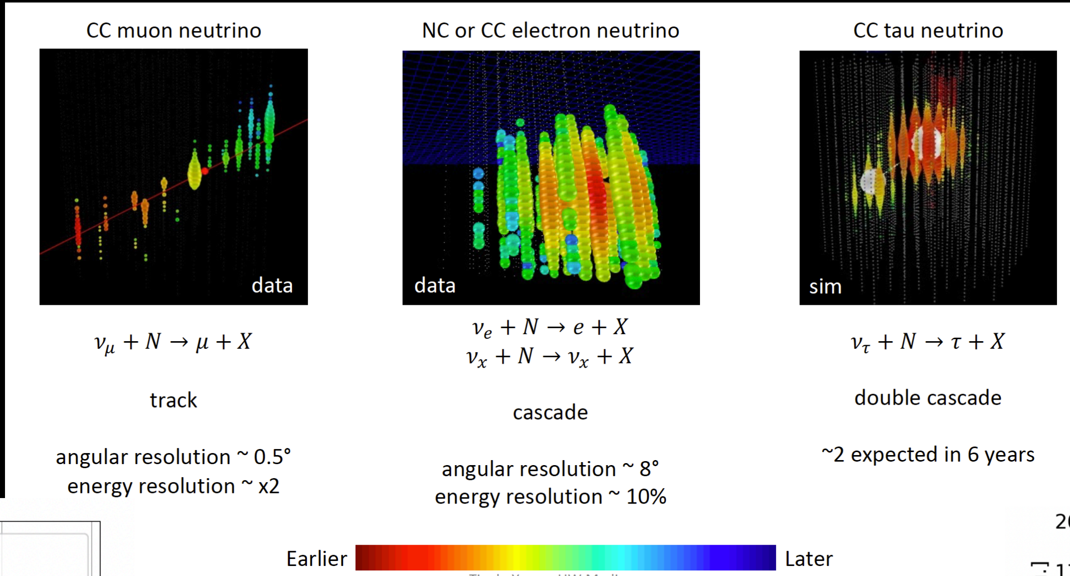
Photon propagation is ideally suited for GPUs
(see H. Schwanekamp et al, 2022) [NIM A711:73,2013]

Anisotropy in photon attenuation is linked to birefringence of ice polycristal deformation in a direction perpendicular to the crystal axis. This results in photons slowly being deflected towards the axis of the ice flow of 10 m/yr.
Larger diffusion for light propagation along the axis of the ice flow and smallest for light propagation along the perpendicular tilt direction.
The tilt is primarily an effect of the underlying, undulating bedrock having gradually been filled up to a flat ice surface as we see today. Tilt and flow are orthogonal because the river flows down the local topological gradient.
See D. Chirkin et al at SCAR 2022 and (Rongen and Chirkin et al ICRC2019)





The neutrino telescope signal signature



The improvement on the reconstruction of cascades has boosted IceCube results as atmospheric neutrinos are less than muon neutrinos and

Tianlu Yuan RICH 2022: accounting for birifrangence of ice crystals (Rongen and Chirkin et al ICRC2019)