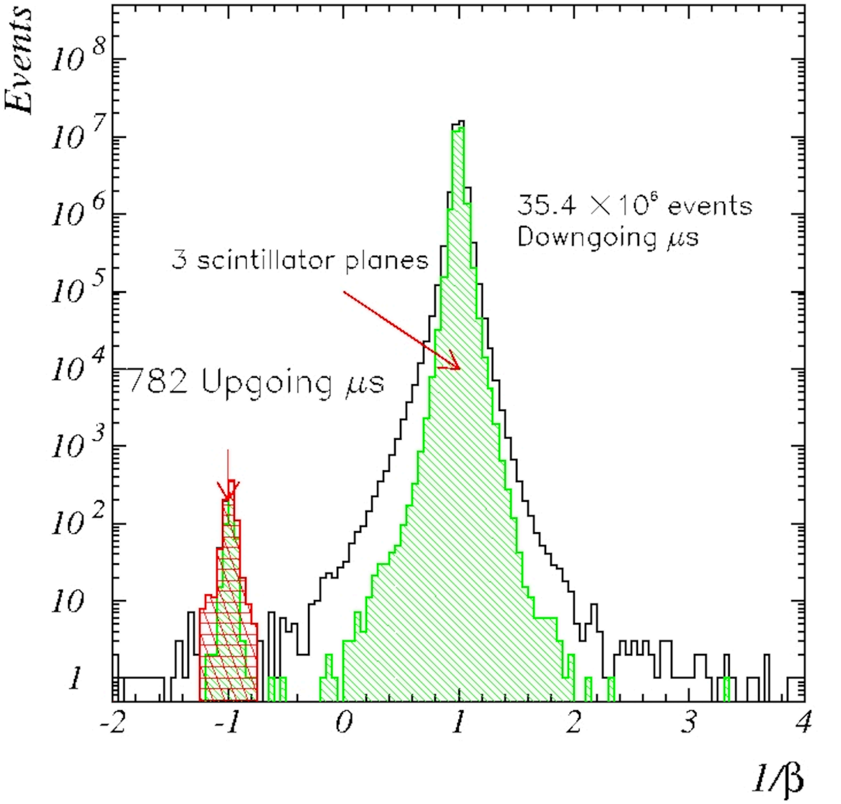
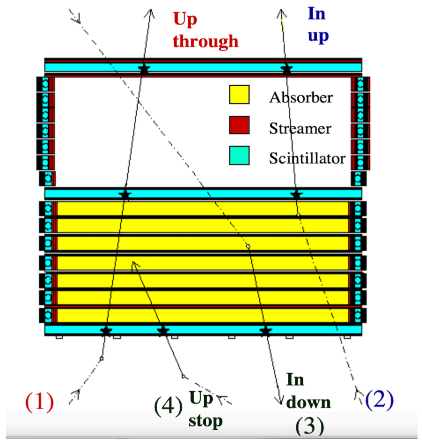
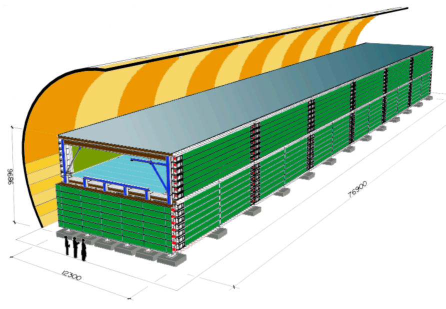
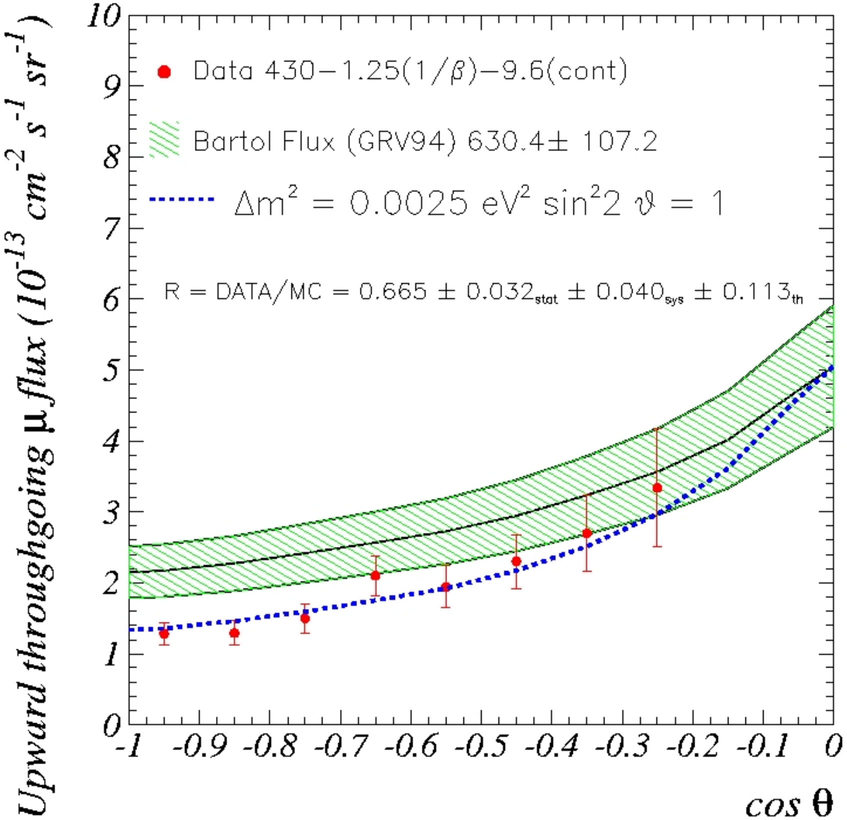
From neutrinos underground to water, ice and space

Teresa Montaruli 28.06.2025





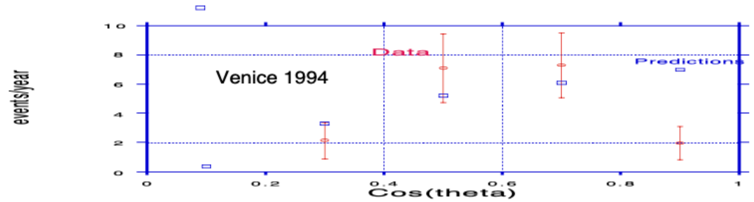


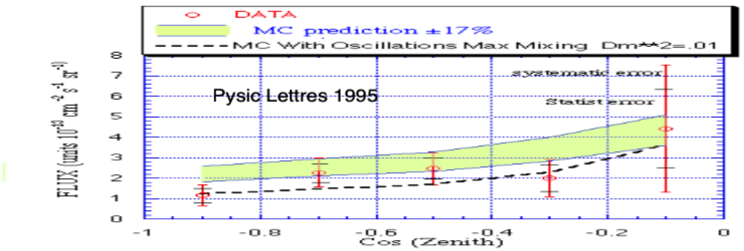


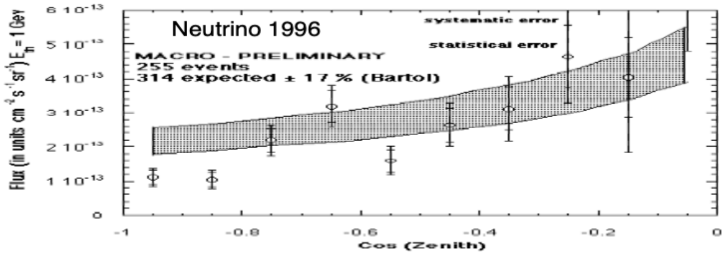
That bump…

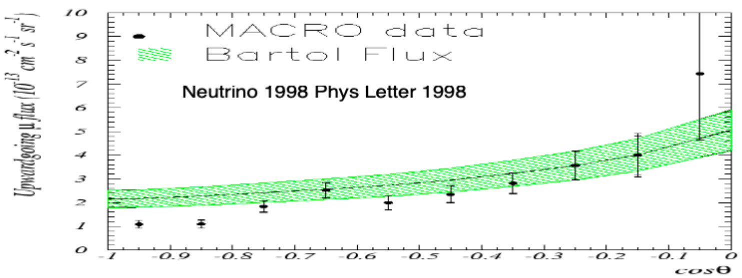
Also in 3 scint. events

The bump history

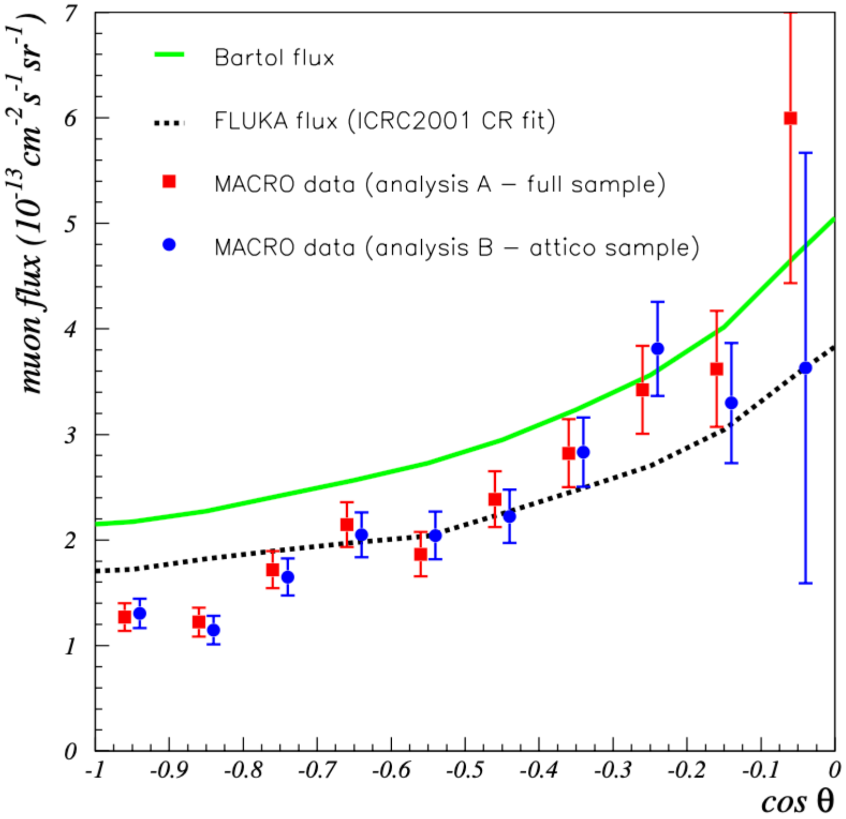








Eur. Phys. J. C 36, 323–339 (2004)



Defining quantities semi-analytically

$$\Phi_\mu(E_\mu^{\rm th}, E_\nu, \delta) = N_{\rm A} \int_{E_\mu^{\rm th}}^{E_\mu^{\rm max}} \frac{d\sigma_\nu}{dE'_\mu}(E'_\mu, E_\nu) \times R_{\rm eff}(E'_\mu, E_\mu^{\rm th}){\rm Area}(E'_\mu, \delta)\Phi_\nu(E_\nu)dE'_\mu \,.$$

Still binned methods

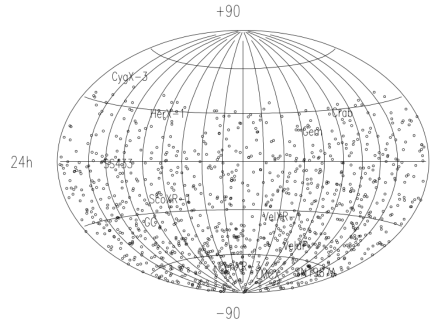


FIG. 9.—Upward-going muon distribution in equatorial coordinates (1100 events).

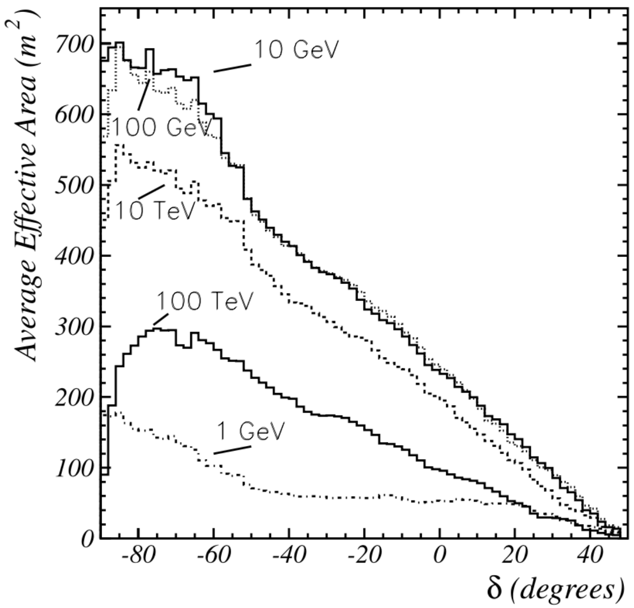
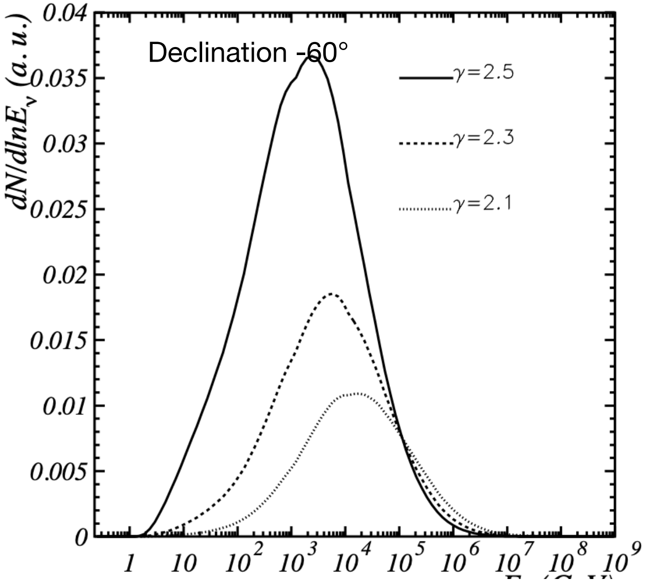
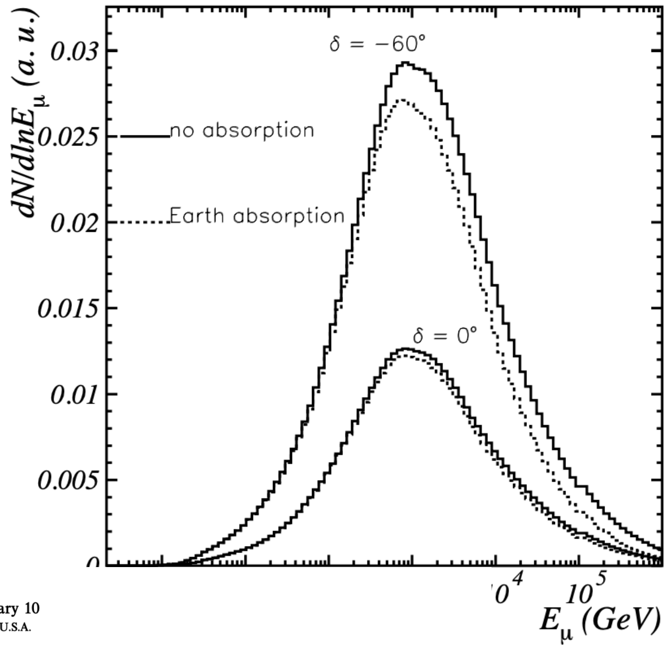


FIG. 5.—MACRO average effective area as a function of declination for various muon energies. From top to bottom lines: 10 GeV (*solid line*), 100 GeV (*dotted line*), 10 TeV (*dashed line*), 100 TeV (*solid line*), and 1 GeV (*dot-dashed line*).



THE ASTROPHYSICAL JOURNAL, 546:1038–1054, 2001 January 10

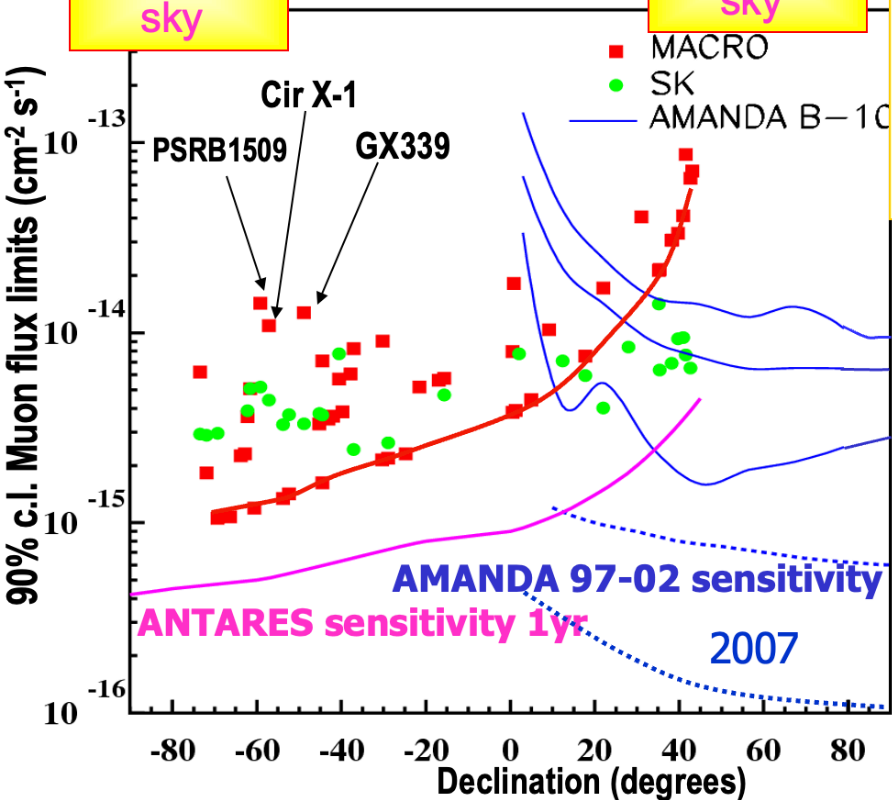


NEUTRINO ASTRONOMY WITH THE MACRO DETECTOR

Neutrino astrophysics

Results: Point-like sources

TAUP 2003



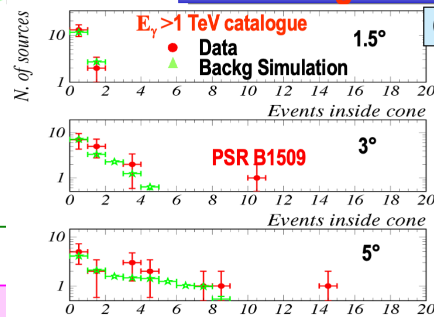
Final MACRO (first results in ApJ 546, 2001): 1388 μ↑
$\langle E_\mu \rangle$ >1.5 GeV ~6 yrs 3° half-width ang res <1°

AMANDA II (ICRC03) 197 d
$\theta_{\mu\nu}$~2.3° 699μ↑ 300 bin grid
Sensitivity ~flat with δ
AMANDA B-10 (ApJ 583, 2003)
130 d ang res ~3.9° 154 bin grid

SK (ICRC03) 2369 μ↑ $\langle E_\mu \rangle$ >3
4.6 yr 4° half-width cone
ang res ~2°
NEW: showering sample
$\langle E_\nu \rangle$ ~ 1 TeV (354)

ANTARES (ICRC03)
ang. res. 0.15° E_ν>10 TeV
const backg grid 1.5° x 1.5°
Larger potential discovery
for LR unbinned method
compared to binned ones

The largest excess (MACRO)



Circinus Constellation an interesting region?!
Not convincing: Point Spread Function

Signal	1.5°	3°	5°	
E^{-2}	66.5%	90.6%	97.7%	
$E^{-2.2}$	55.1%	86.0%	96.5%	
$E^{-2.5}$	42.3%	80.5%	95.1%	
Exp. bckg	0.5	2.0	5.6	events
Data	1	10	14	

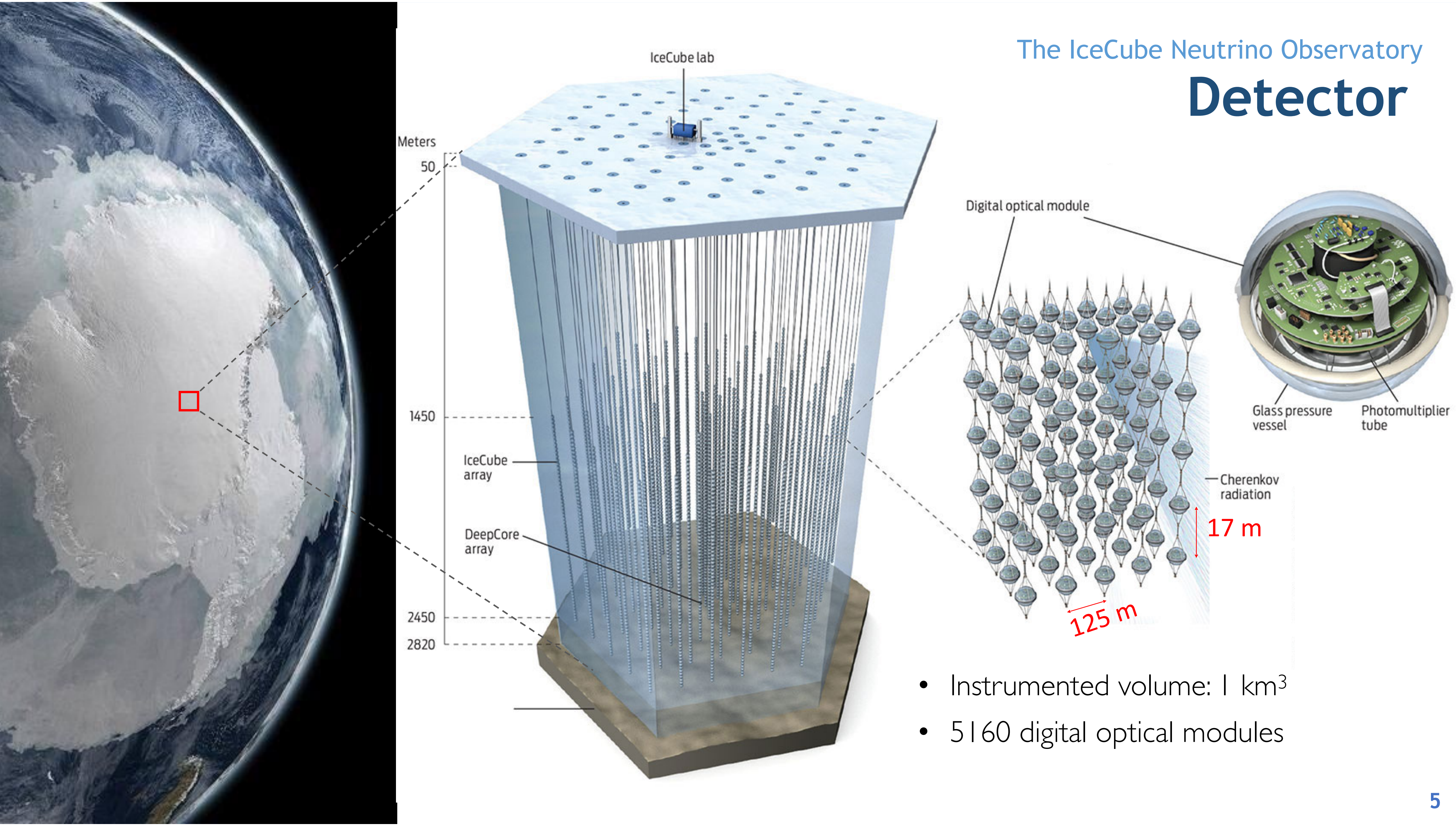
In 1.5° there should be 4-7 events!
Excess disappears when all event directions considered

CANGAROO: 1997 > 1.9 TeV 4.1 σ (astro-ph/000252)

	δ (°)	N_{obs}	Exp Bckg (3°)	Upper lim Feldman&Cousins (90%cl)	Sensitivity
MACRO 1388 events					
PSR B1509	-59.14	10	2.0	14.5	3.9
Cir X-1	-57.17	7	2.0	10.5	3.9
GX339-4	-48.79	7	1.9	10.6	3.9
SK 2369 events (4°)		9	5.4	9.9	5.3
		8	5.7	8.3	5.4
		4	4.4	4.2	5.0

Analysis in coll. with F. Ronga

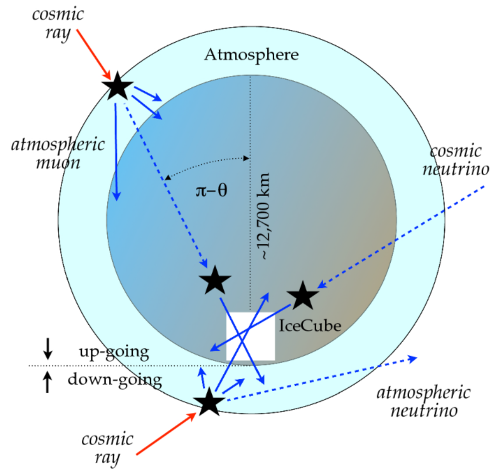
Detector



- Instrumented volume: 1 km^3
- 5160 digital optical modules

Likelihood Statistical Method

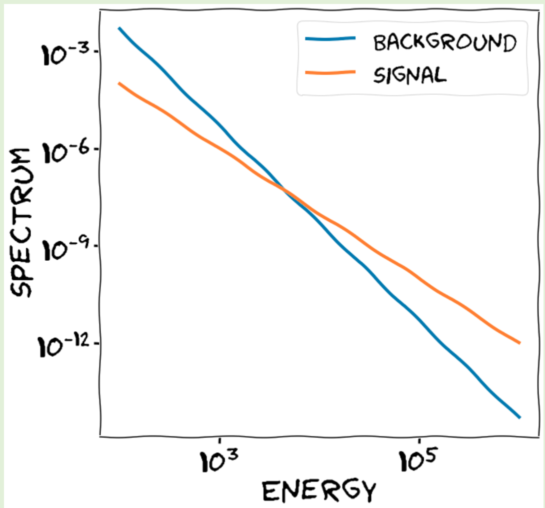
$$\mathcal{L}(n_s,\gamma,t_0,\sigma_T|\boldsymbol{X}) = \prod_{j=1}^{5}\prod_{i=1}^{N_j}\left[\frac{n_{s,j}}{N_j}\mathcal{S}_j(\gamma,t_0,\sigma_T|X_i) + \left(1-\frac{n_{s,j}}{N_j}\mathcal{B}_j\right)\right]$$



- Declination bands in $-80^\circ < \delta < 80^\circ$ where the background is calculated from data
- Sky grid
  Adaptive binning method, with pixel resolution $\sim 0.1^\circ$
- Local hot spot
  Cluster of pixels around a local minimum in p-val map

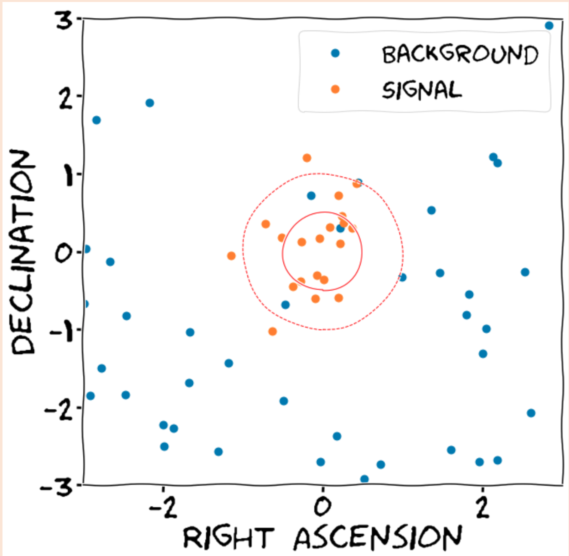
Energy PDF

Signal: power-law $\propto E^{-\gamma}$
Background: data-driven

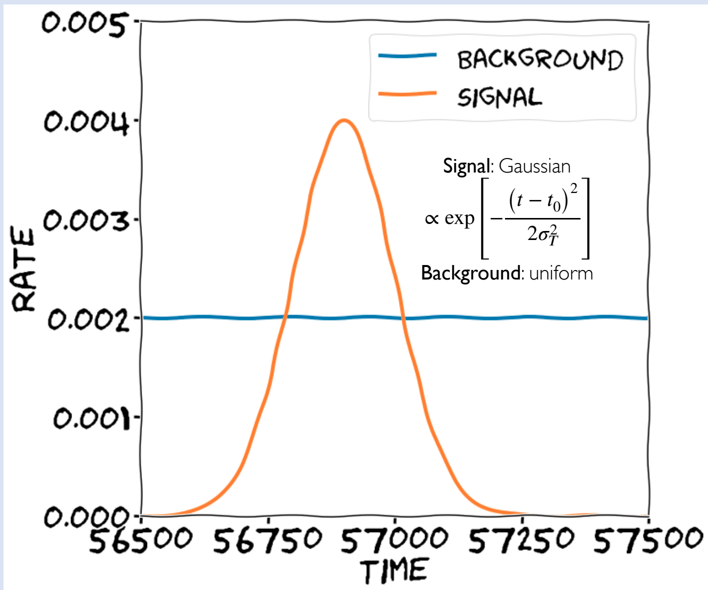


Space PDF

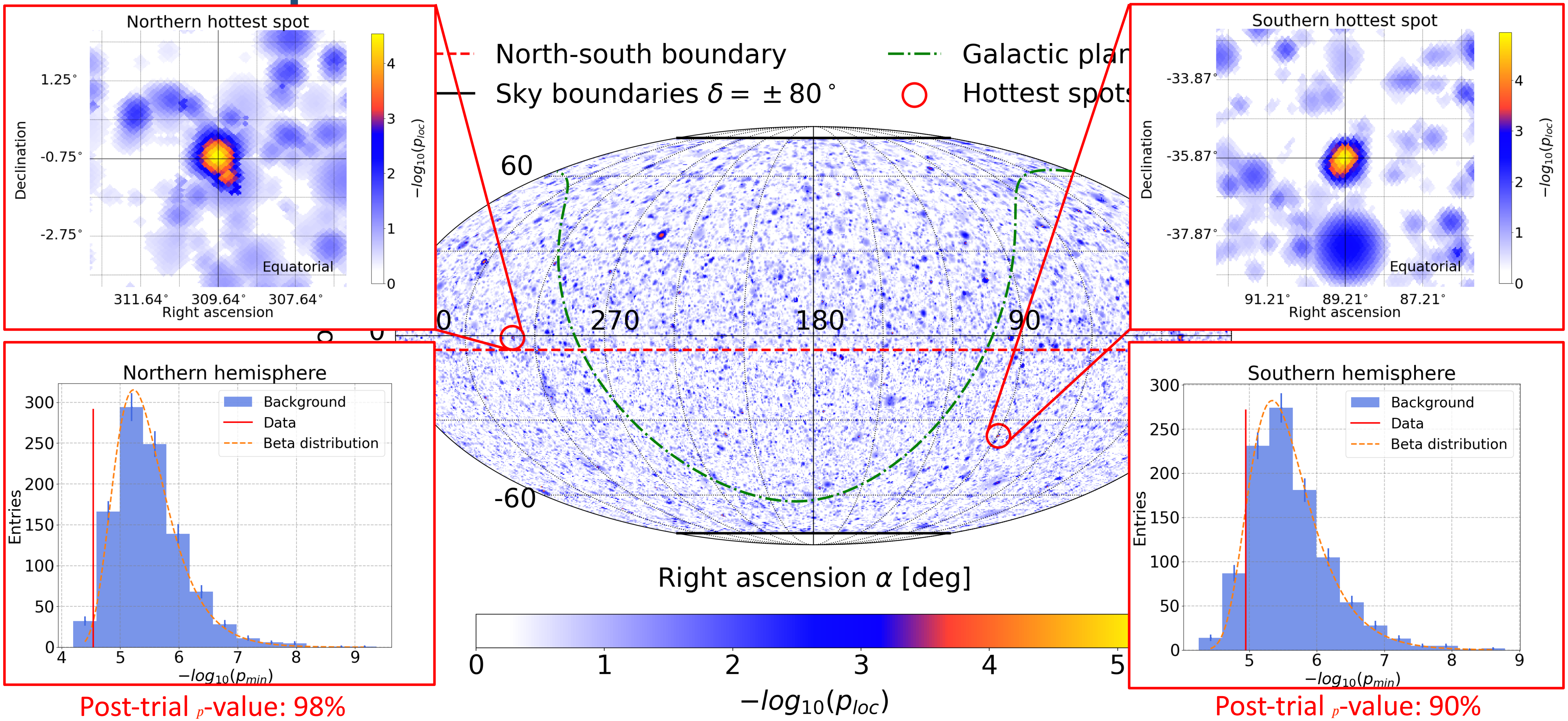
Signal: 2D Gaussian
Background: data-driven



Time PDF



Hottest Spots

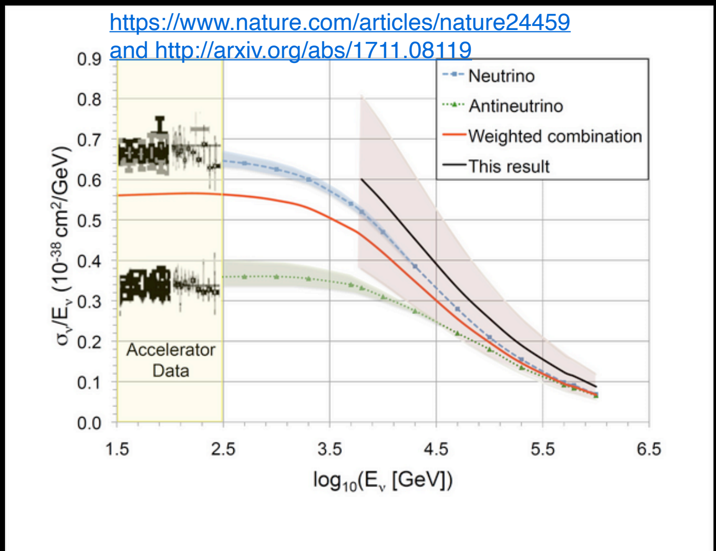


Post-trial p-value: 98%

Post-trial p-value: 90%

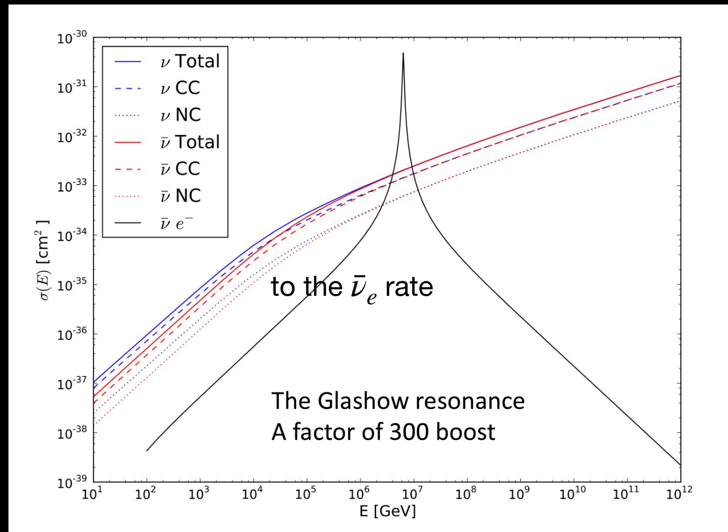
Neutrino cross section

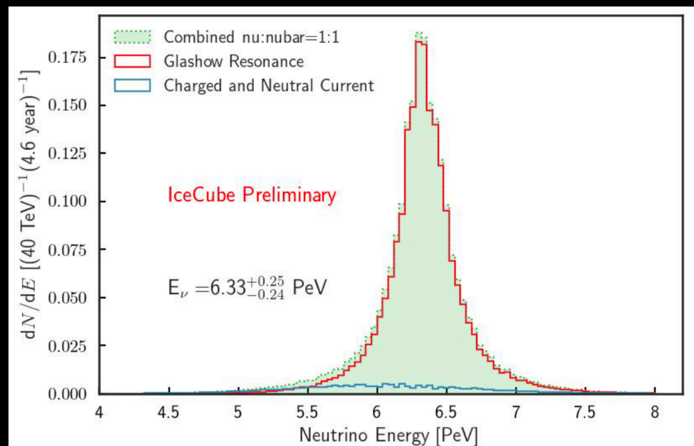
- Neutrino beam crosses 20-12700 km in the Earth where it oscillates and interacts
- $\nu_\mu \rightarrow \nu_\tau$ disappearance probes high energy (TeV scale) neutrino cross section
- Absorption is measured from neutrino spectral changes with zenith
- First cross-section measurement for a a flux-weighted sum of ν_μ and anti-ν_μ in the energy range 10^3 higher than particle accelerators



- The SM predicts a resonance effect in the $\overline{\nu}_e + e^- \rightarrow W^-$ process at center of mass energy: $\sqrt{s} = M_W = 80.38$ GeV
- At the electron rest frame: $E_R = M_W^2/2m_e = 6.32$ PeV
- Observed one event with most likely neutrino energy: 6.35 ± 0.3 PeV

Glashow resonance Nature 2021



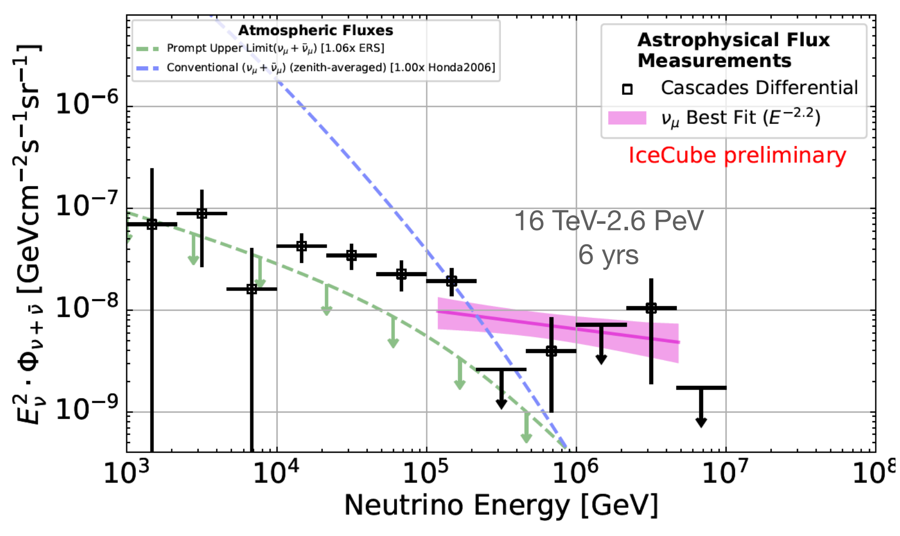


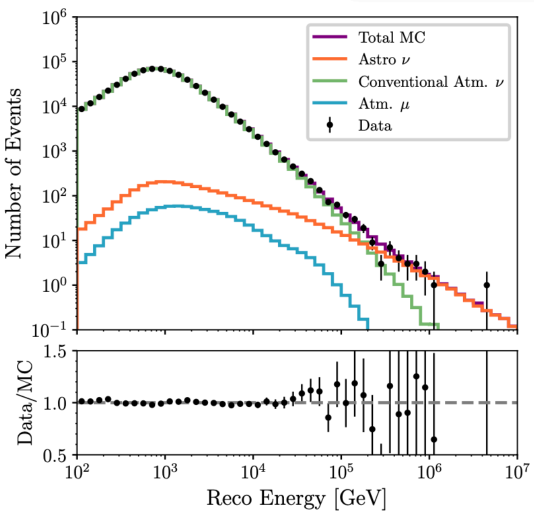
Diffuse flux with cascades and muons

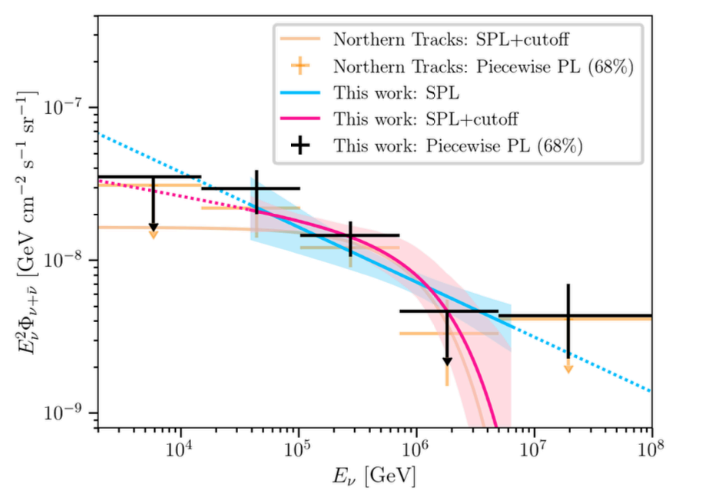
Physical Review Letters 125, 121104 (2020)

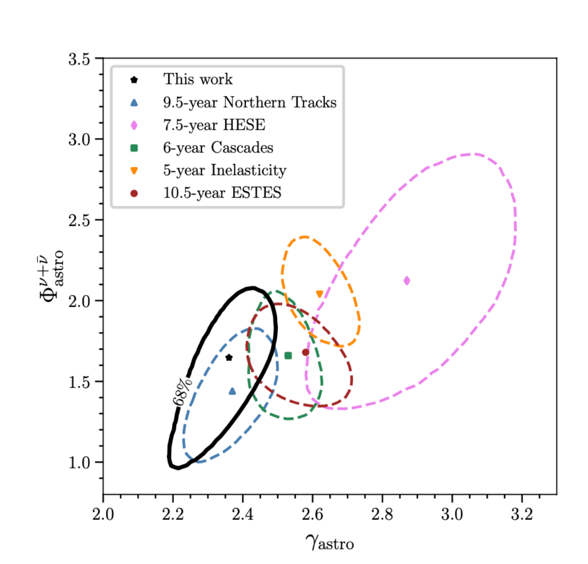
https://arxiv.org/abs/2502.19776

electron and tau neutrinos (showers)









$$\Phi_{\rm astro} = 1.90^{+0.37}_{-0.42}$$
$$\gamma_{\rm astro} = 2.14^{+0.20}_{-0.22}$$
$$E_{\rm cutoff}/{\rm PeV} = 1.83^{+6.92}_{-0.81}.$$

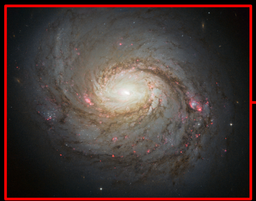
7 tau neutrinos

Blazars:

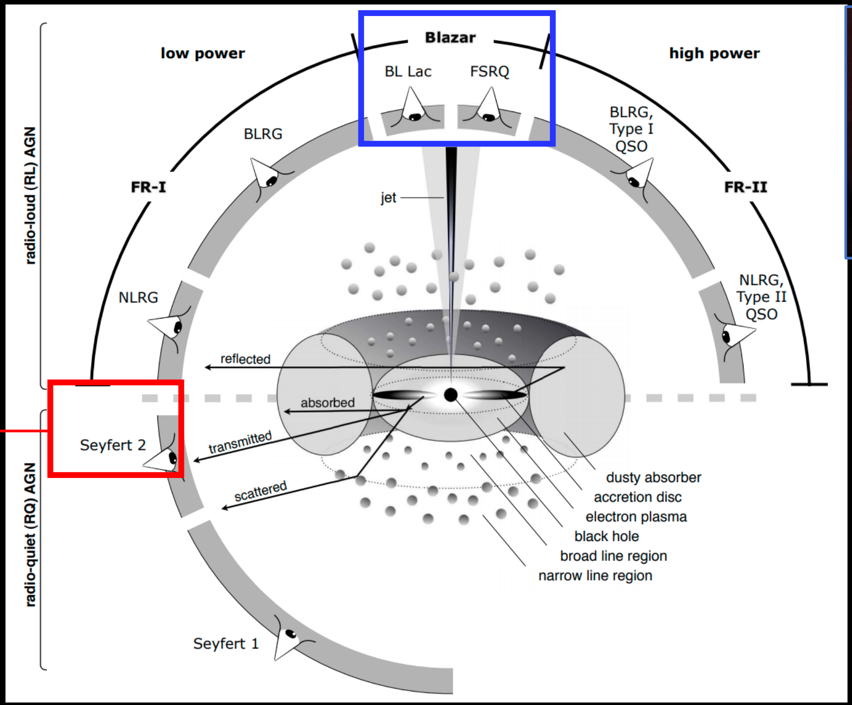
Leptonic scenarios:

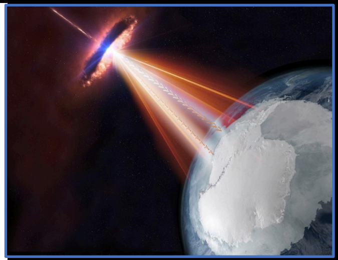
Synchrotron Self-Compton (SSC): seed photons for IC scattering are synchrotron photons produced by nonthermal electron–positron pairs accelerated in the jet.

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.



NGC 1068





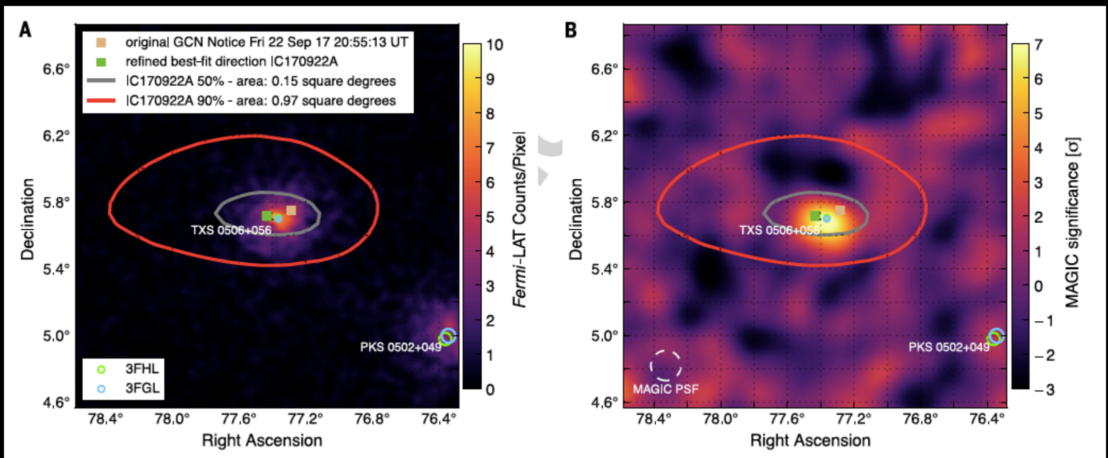
TXS 0506+056

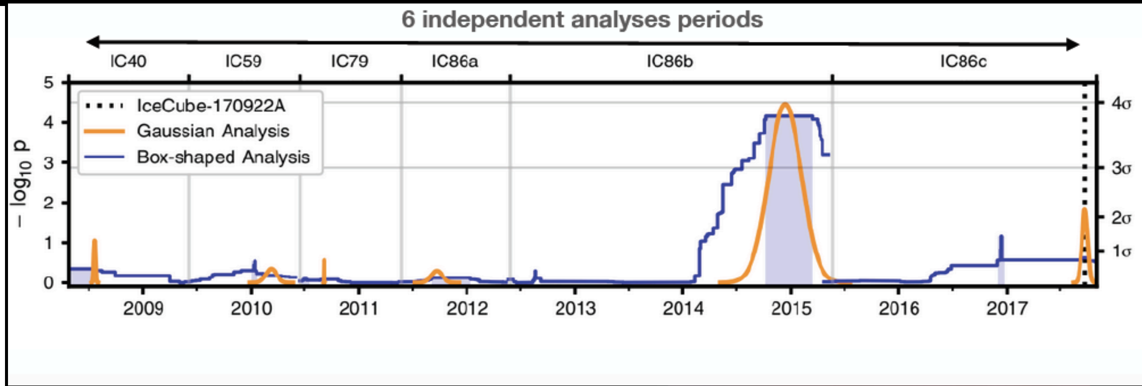
IceCube (ApJ 2016) set an upper limit of about 30% (50%) to the blazar contribution to the diffuse ν flux between 10 TeV- PeV which nonetheless assumes all blazars produce similar power law spectra with spectral index -2.5 (-2.2).
Assuming that all sources in a class are identical ignores the role of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

IC170922A and TXS 0506+056

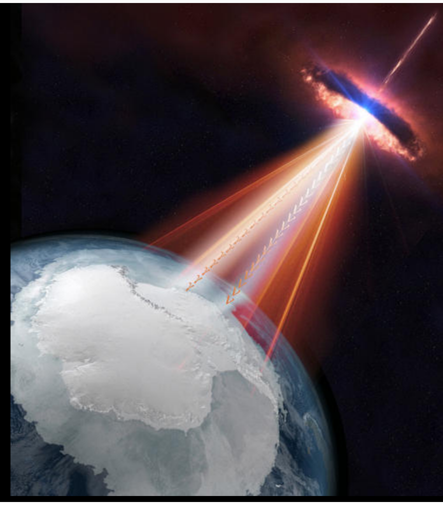
IceCube sent an alert including the direction of a muon neutrino event of ~ 3 x 10^{14} eV in only 43 s. Shortly after, Fermi (20 MeV-300 GeV) discovered a blazar, TXS 0506+056 at 0.06° distance from the IceCube event in a flaring state (ATel#10791). In a follow up from 1.3-40 d, MAGIC detected gamma 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 blazars in Fermi catalogue. z= 0.336.



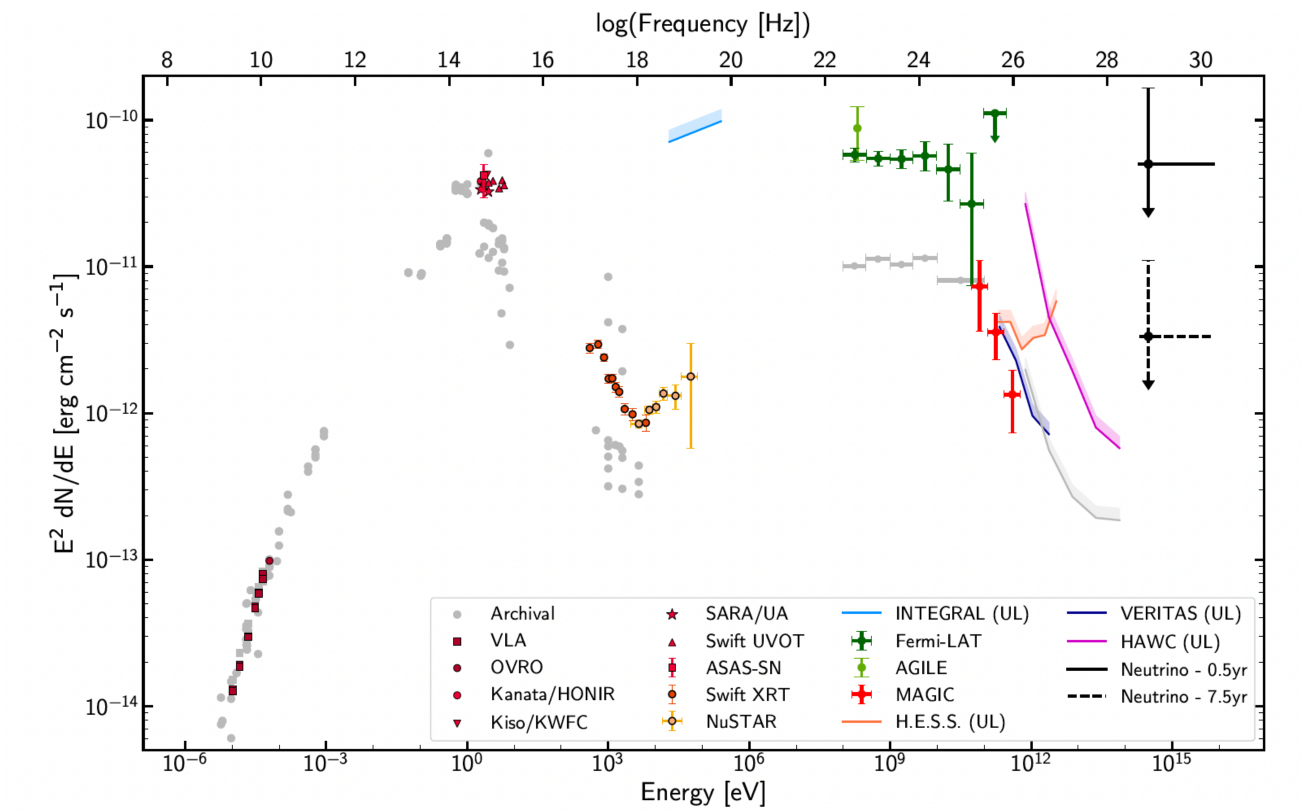


Science 361, 147-151 (2018)
A. Christov thesis UNIGE archive



MAGIC @ Los Roche de los Muchachos, La Palma

The first SED with hadronic guesses: TXS 0506+056

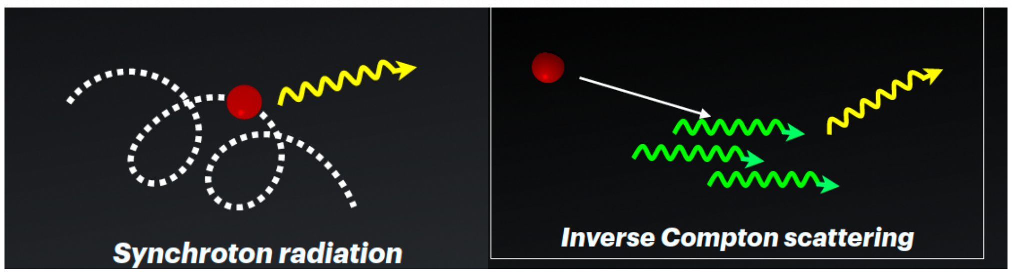


UL producing one detection as IC170922A in 0.5 yr
Assuming E^{-2}

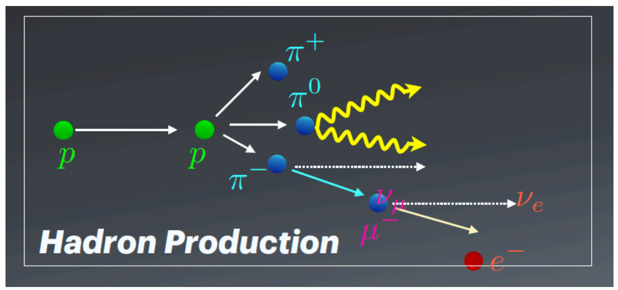
UL producing a detection as IC170922A in 7.5 yr

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

Letonic scenarios:



Hadronic scenarios:

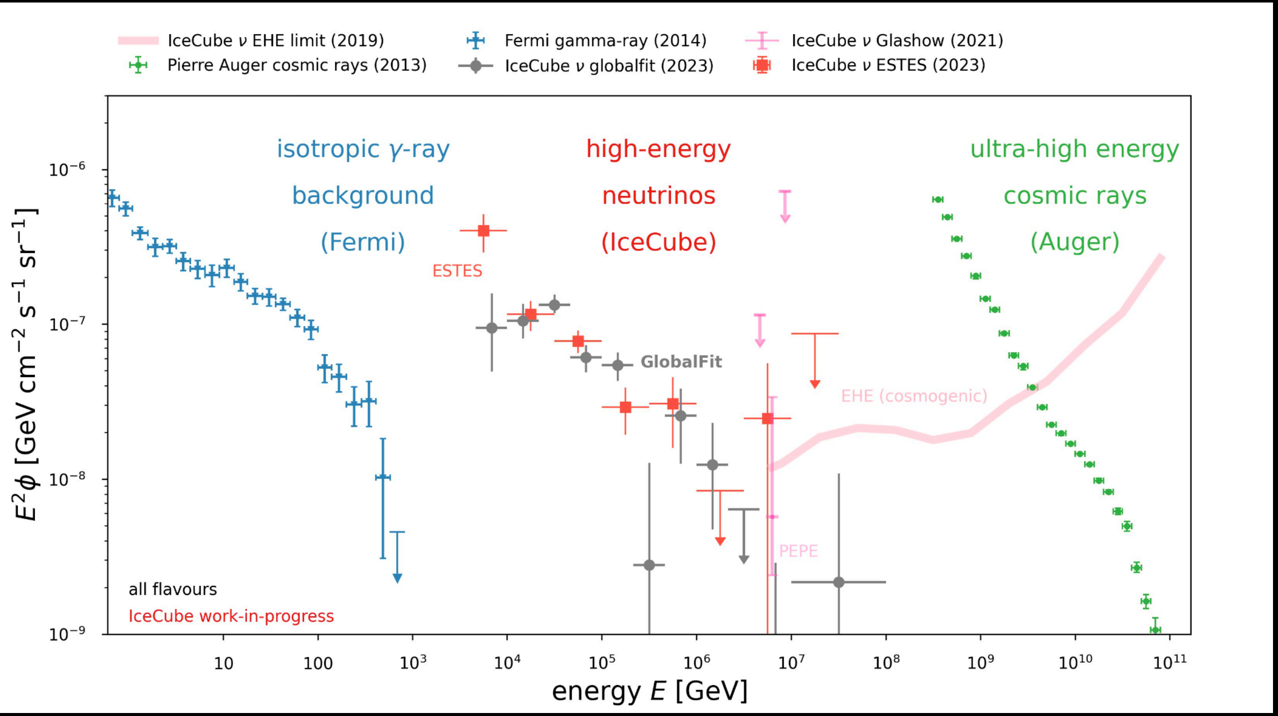


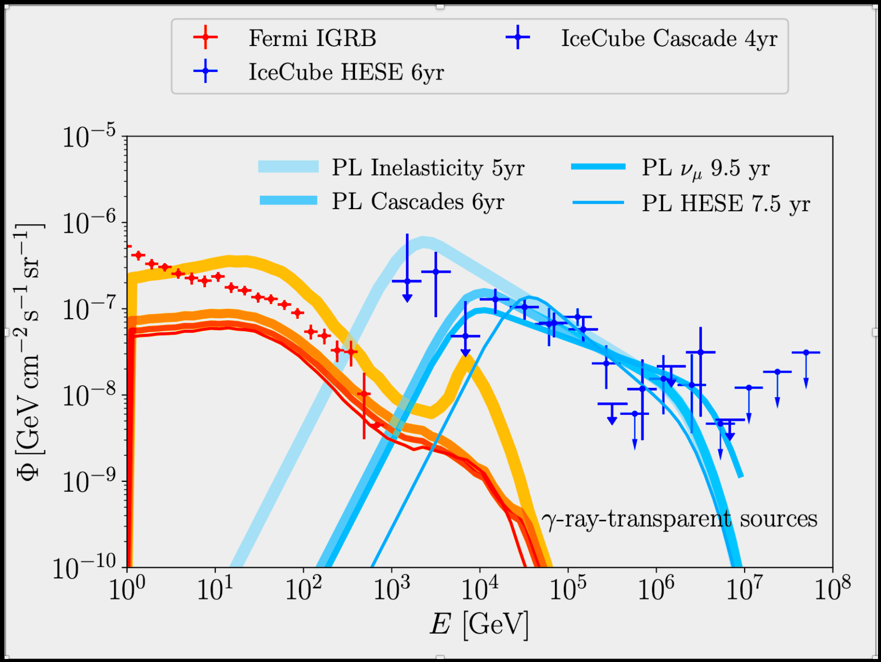
The UHECR- Neutrino - Gamma Diffuse fluxes

HESE: IceCube, PRD 104 (2021)

Tracks: IceCube Coll. ApJ 928 (2022) 50
Glashow resonance Nature 2021

Most probably opaque sources exist

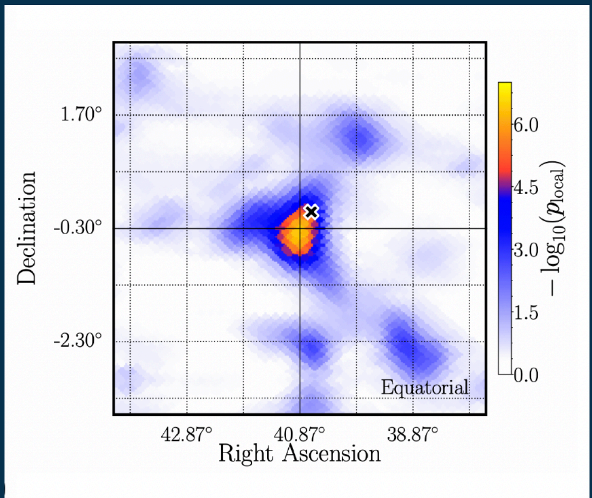




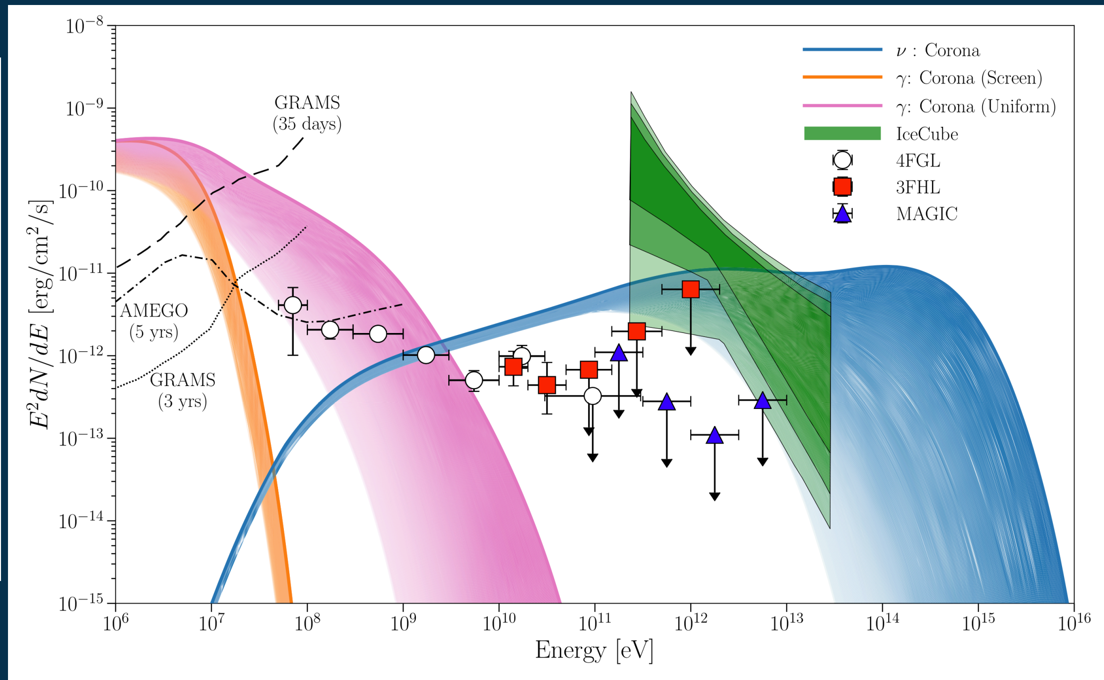
N. Kurahashi et al ICRC 2023

The first standalone neutrino source NGC 1068

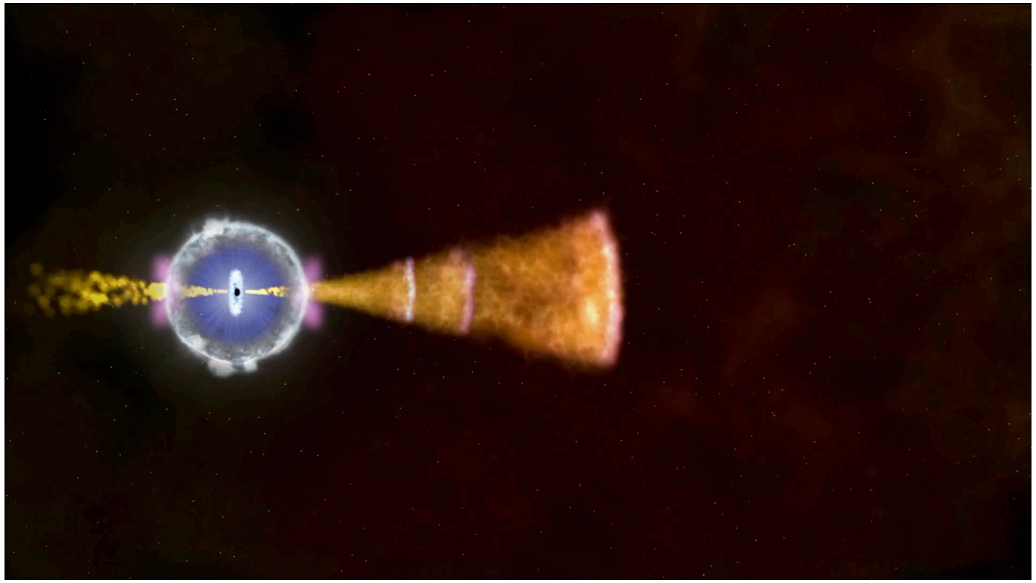
First image of NGC 1068 in neutrinos
(IceCube PRL 124 (2020))

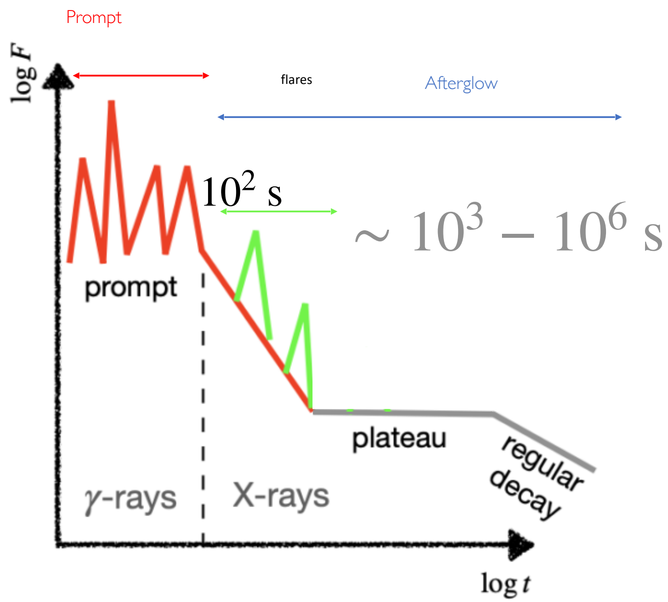


- Only if gammas are produced at the center of the corona and not uniformly.
- Other mechanisms needed to explain Fermi data.
- Large gamma-ray flux at MeV where there is no observations!



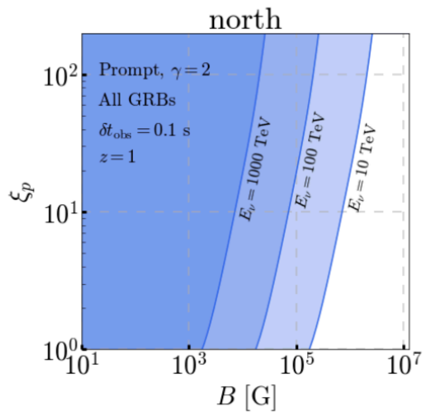
Gamma-Ray Bursts

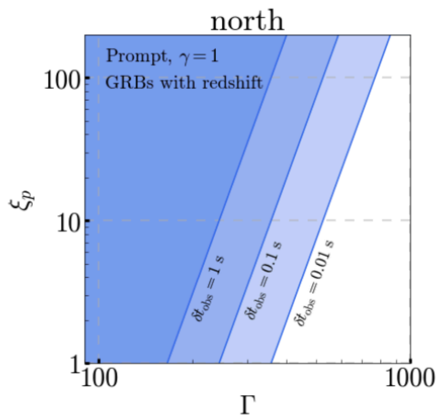




For the afterglow phase, we focus in particular on GRBs with X-ray flares and plateaus.

- Constraints on single-zone fireball model parameters. $\xi_p < 10$: GRBs unlikely sources of UHECRs
- Magnetic-dominated ejecta may produce neutrinos of much lower energy GeV (synchrotron cooling time $t \propto B^{-2}E_i^{-1}$ < muon and pion decay $t_d \propto E_i$)





In a **single-zone model**, different messengers are produced jointly in many similar shocks

- Neutrino emission is correlated to the amount CRs in the fireball
- Amount of CRs is parametrised by the baryon loading factor:

$$\xi_p = \frac{E_p}{E_{\gamma,\,\mathrm{iso}}}$$

- $\xi_p > 10$ required for GRBs to explain the observed ultra-high-energy CR flux

Neutrinos can be used to study the possibility that GRBs are the sources of UHECRs

The multi-messenger galactic plane

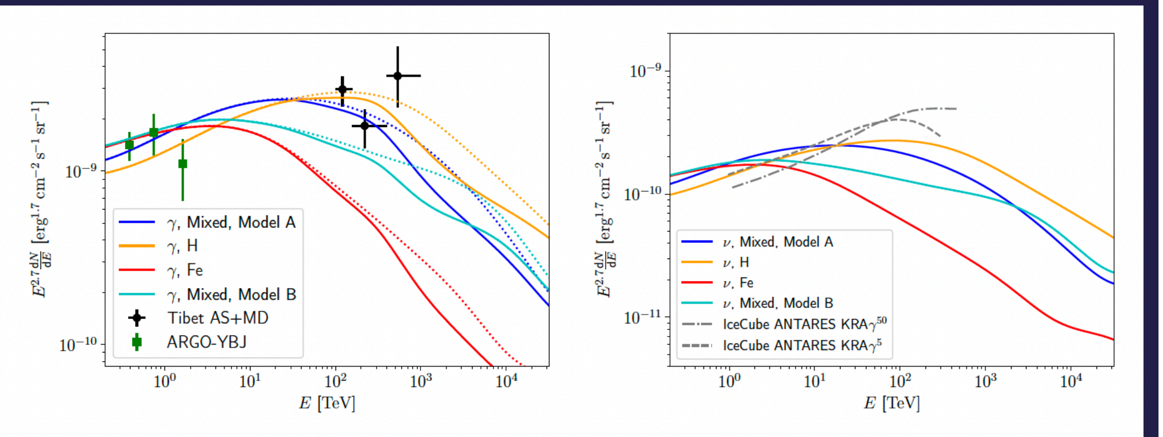
Breuhaus et al , 2022; Ahlers et al, 2016

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

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

Gamma-rays

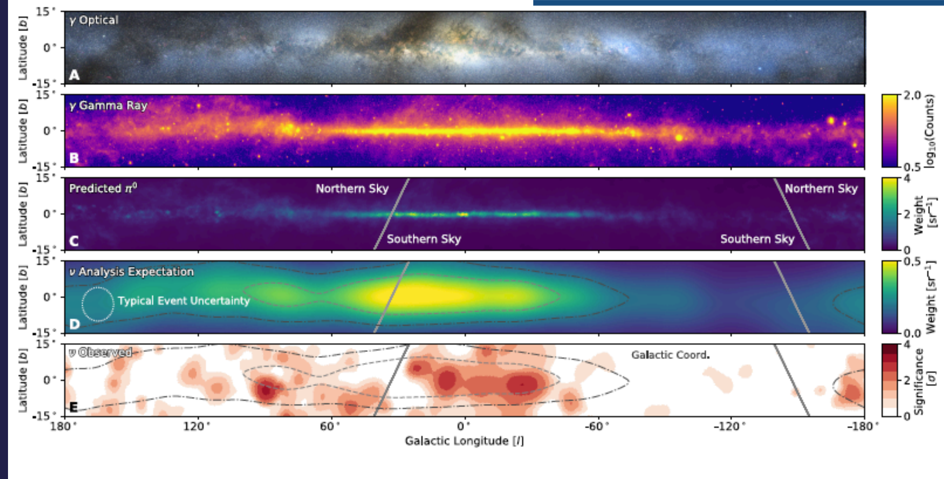
Neutrinos



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

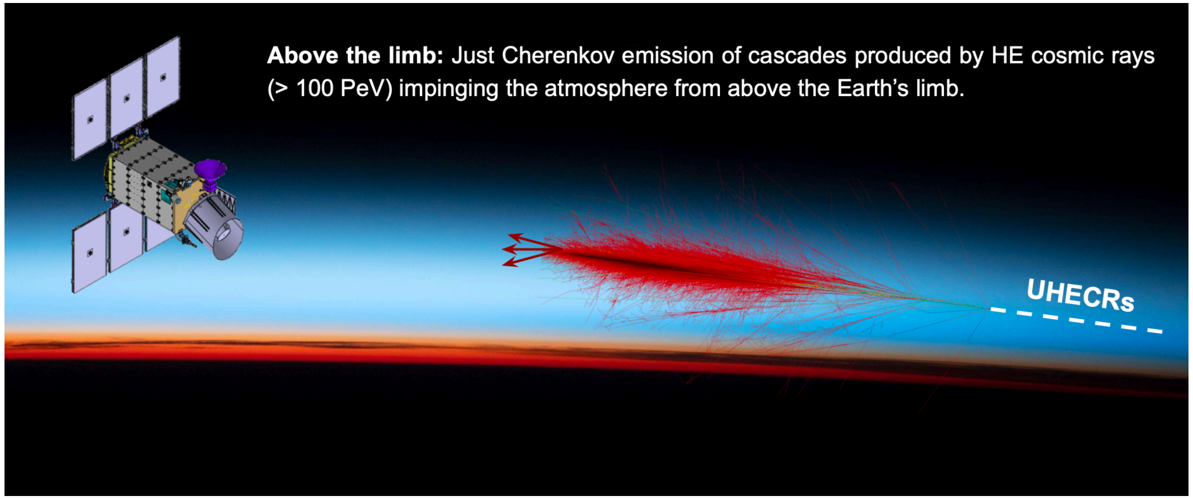
Neutrino limits touch KRA models of diffuse galactic emission from CRs interacting on ISM (Gaggero et al 2015, 2017). IceCube > 20 TeV diffuse muon flux and > 100 TeV diffuse flux contributes < 10% to it. Finding significant contributions from the Galactic Plane requires lowering the threshold in ν energy.

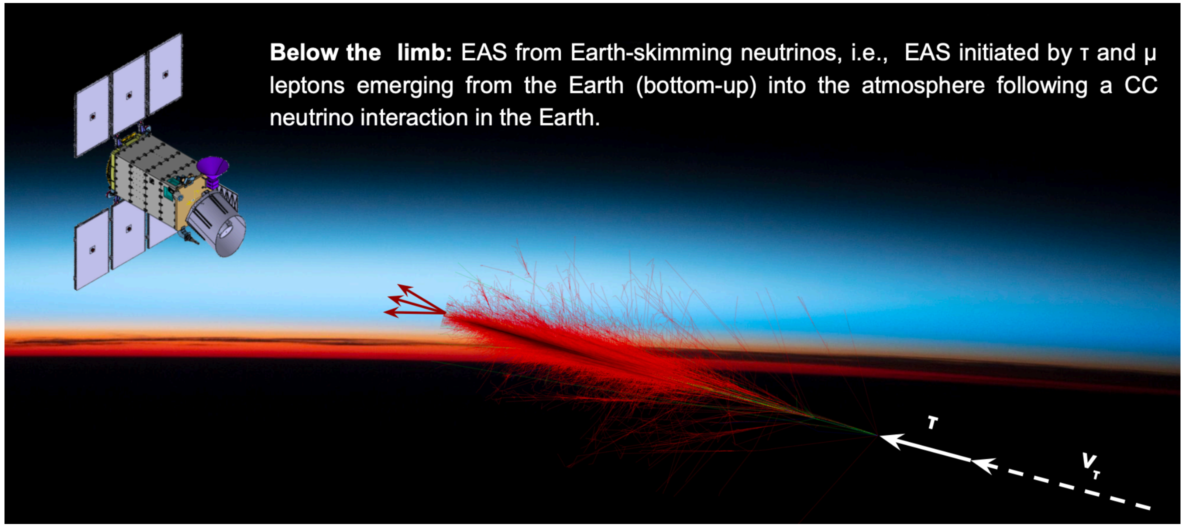
π^0	4.71σ
KRA_γ^5	4.37σ
KRA_γ^{50}	3.96σ



Science 380 (2023) 1338

Terzina onboard NUSES





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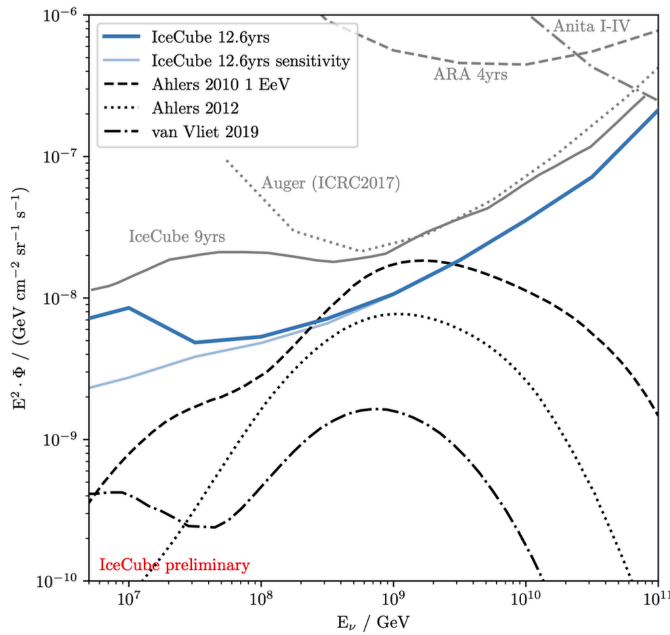
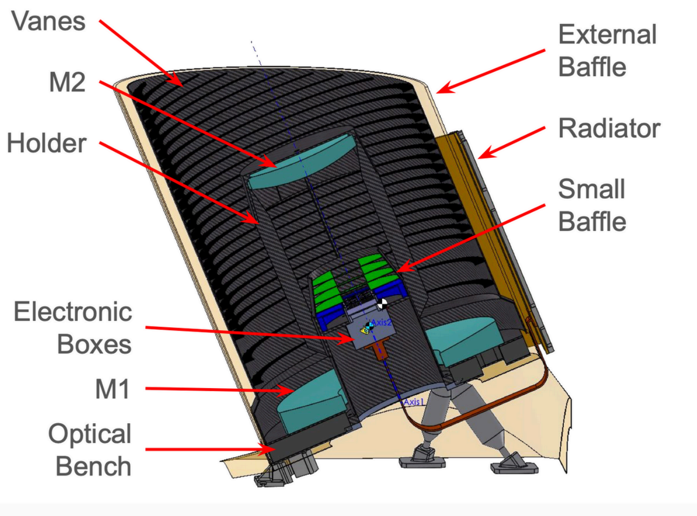


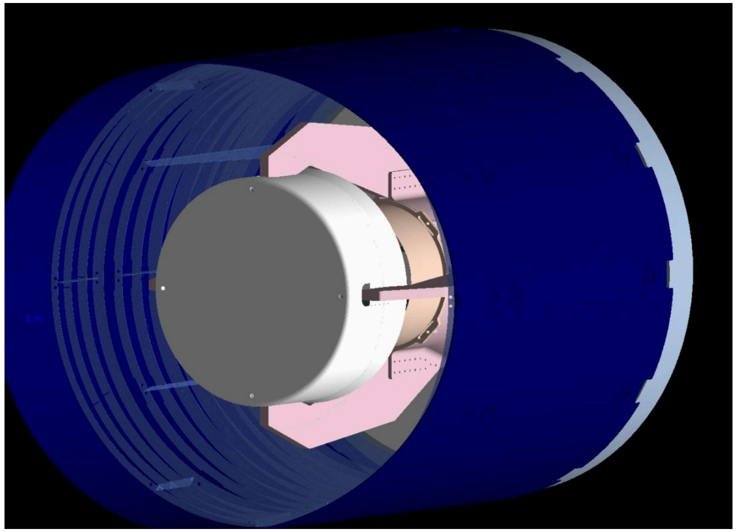
Terzina telescope

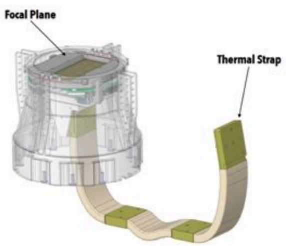
LEO at 550 km (BoL) on the day-night border.

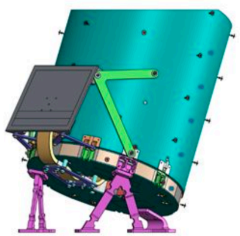
Flight could be as early as fall 2026

Lifetime	3y
Altitude (BoL)	550 km
Altitude (EoL)	535 km
Eccentricity	< 10^{-3}
Inclination	97.8 deg
LTAN	18:00:00
Pointing	< 0.1 deg

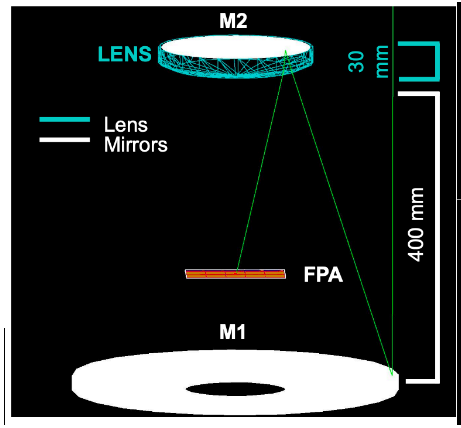


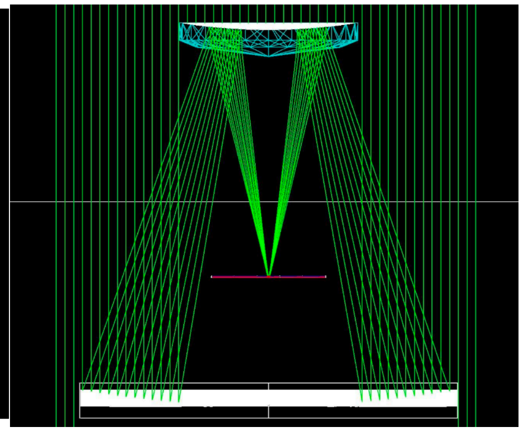




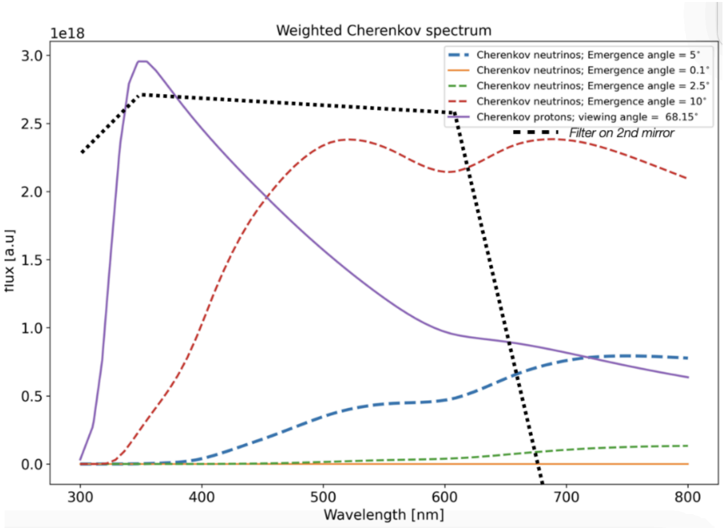


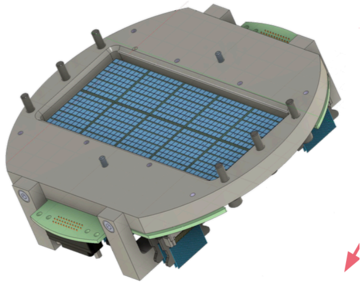
Full simulation based on G4





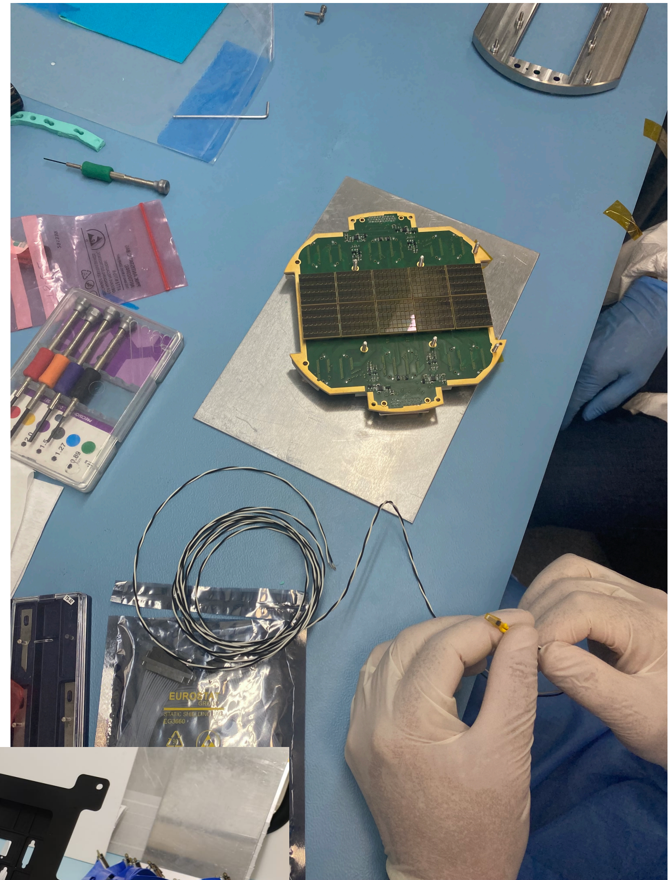
Cherenkov signal



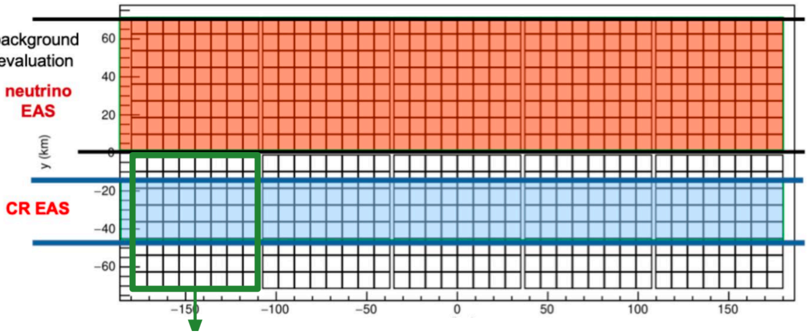


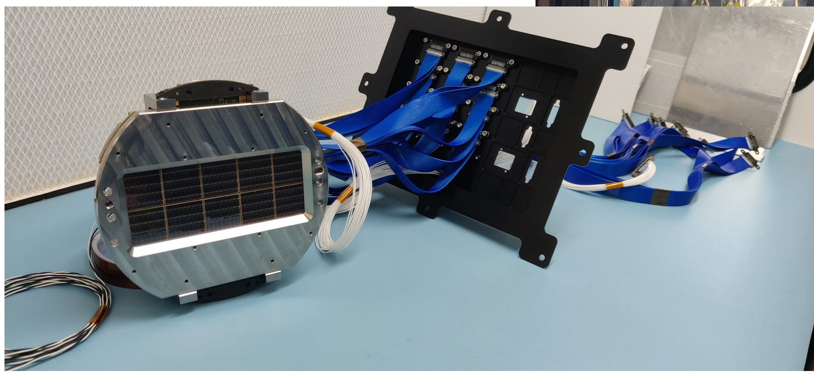
SiPM Information:

- Size: 2.3 mm x 2.7 mm
- FoV = atan(r_{SiPM} / F_L) ~ 0.18°
- DCR ~ 100 kHz / mm^2
- CT ~ 7%
- PDE @ 450 nm ~ 50 %
- V_{BD} = 32.6 V

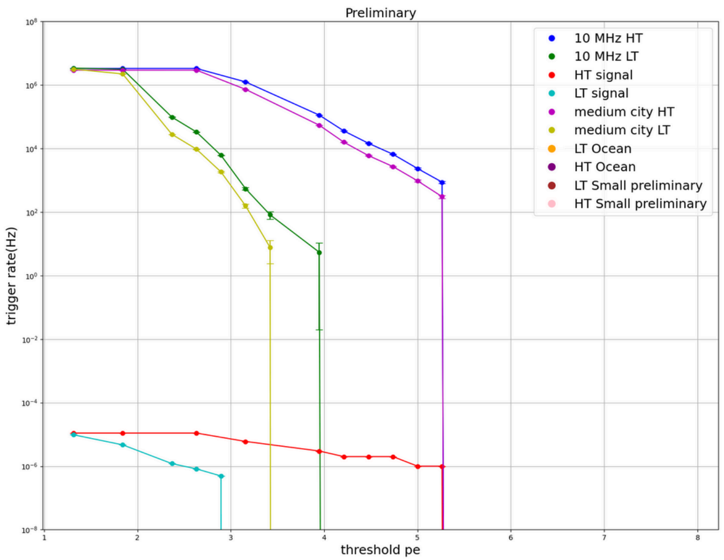


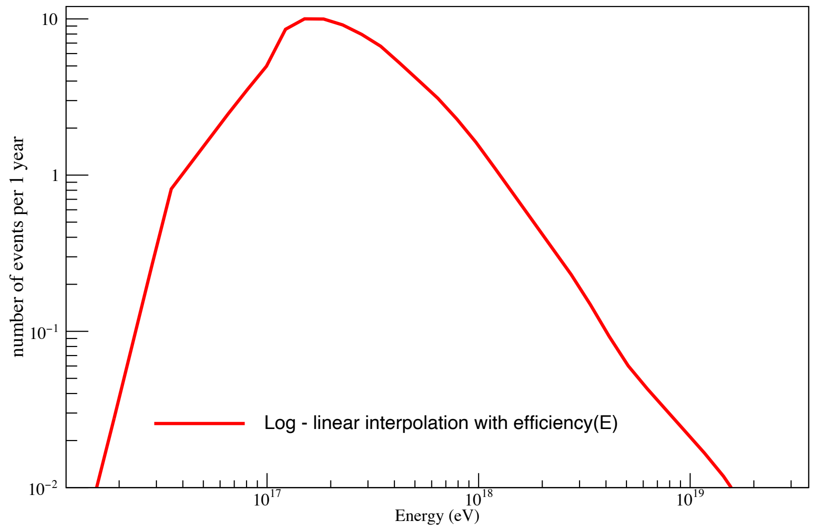
Camera plane with projection on the Earth (total area 360 x 140 km^2)



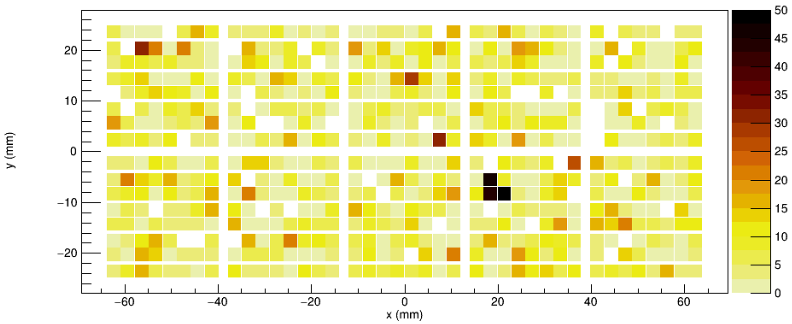


Signal and noise

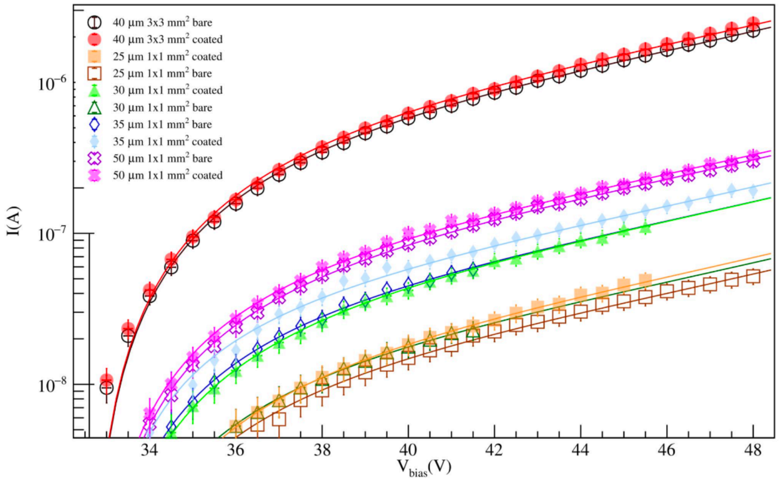




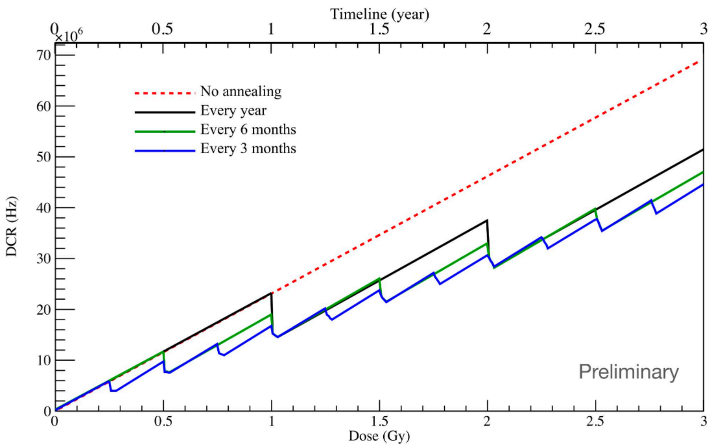
1 ev/year Terzina sees from 5×10^{16} (50 PeV in the most optimistic background of 100 kHz (which means the plot is optimistic as I hardly think HT can be 5 p.e.)



Effect of SiPM radiation damage



Accepted by JCAP https://arxiv.org/html/2503.00532v3



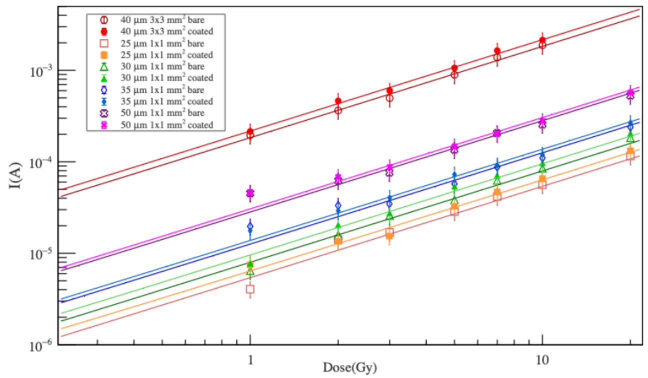
Radiation damage to the SiPM increases:

- DCR,
- power consumption,
- energy threshold.

Annealing as a mitigation strategy:

- heating above 50° C for 84 hours,
- followed by gradual cooling,
- every 3 to 6 months.

Measurements in a climate chamber show that up to 40% of the response recovered.



Come to these venues!