Updates on current UHE hybrid photon activities

- Updates on the hybrid photon analysis toward a Full Phase I paper
- Summary of the Joint IceCube x Auger Photons analysis (ICRC2025 contribution)
- Other activities of the L'Aquila group

Pierpaolo Savina

OVERVIEW

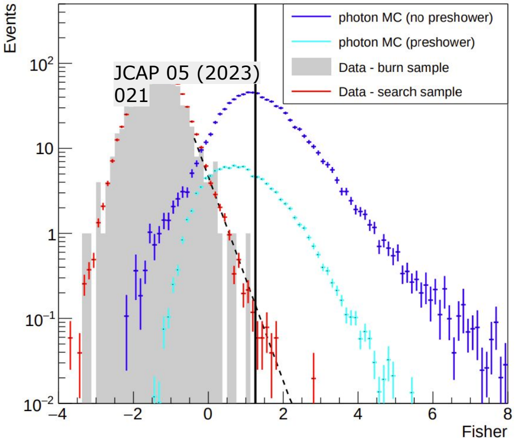
In photon analyses, **background** contributions increasingly **significant**.

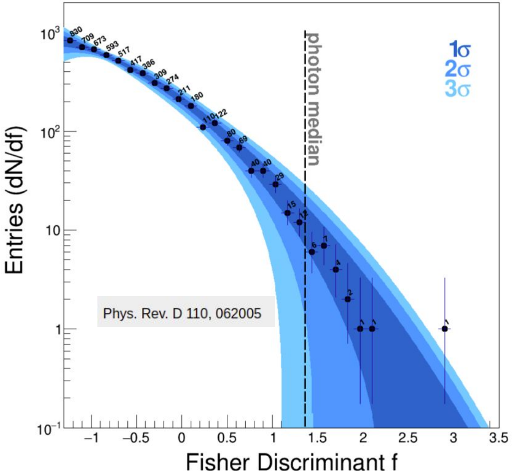
Having a better knowledge of the background can lead us to a better sensitivity -> identify photons

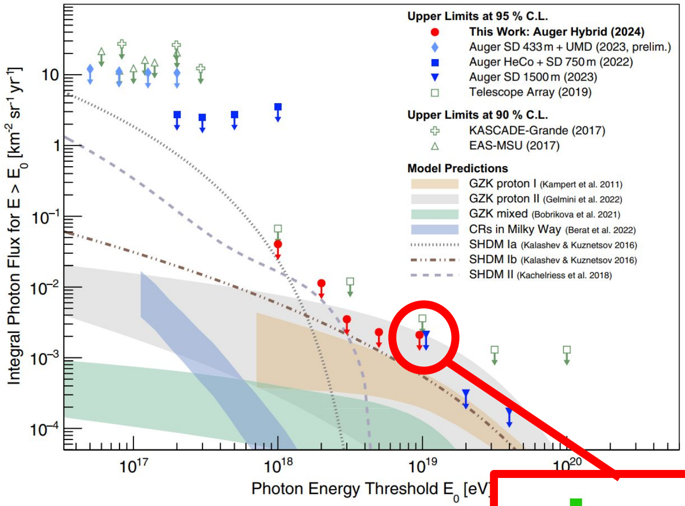
We might need a change of paradigm:

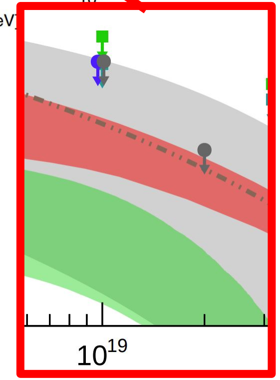
- **New Burn Sample definition**
- **New U.L. Calculation Method**

Focus on the **hybrid** analysis but **valid** for **all** photons analyses



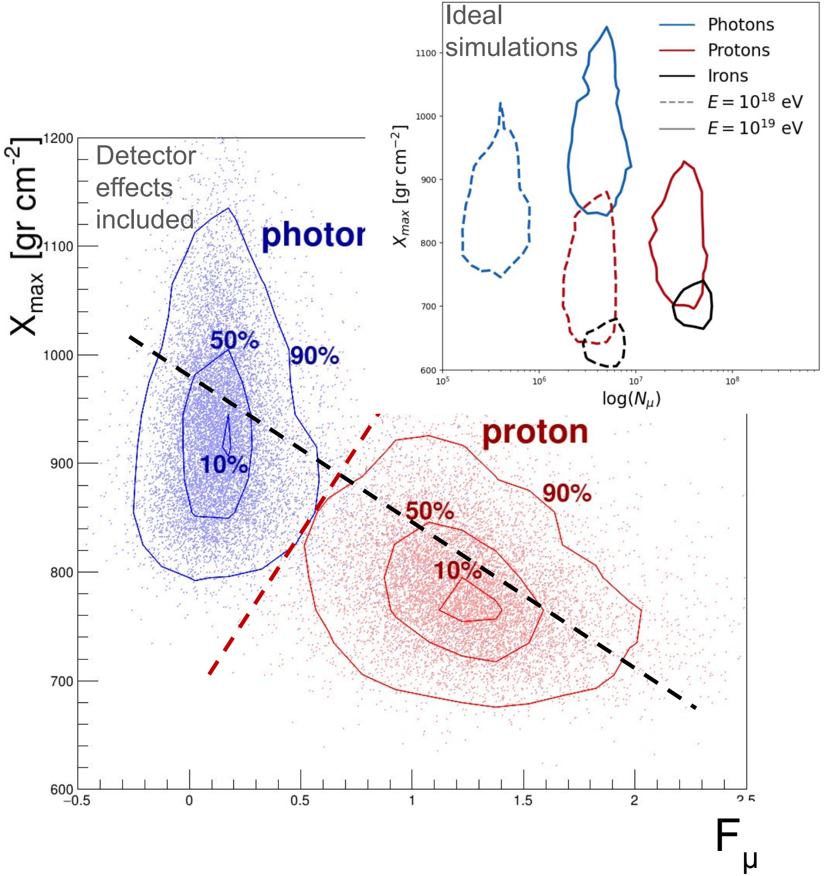


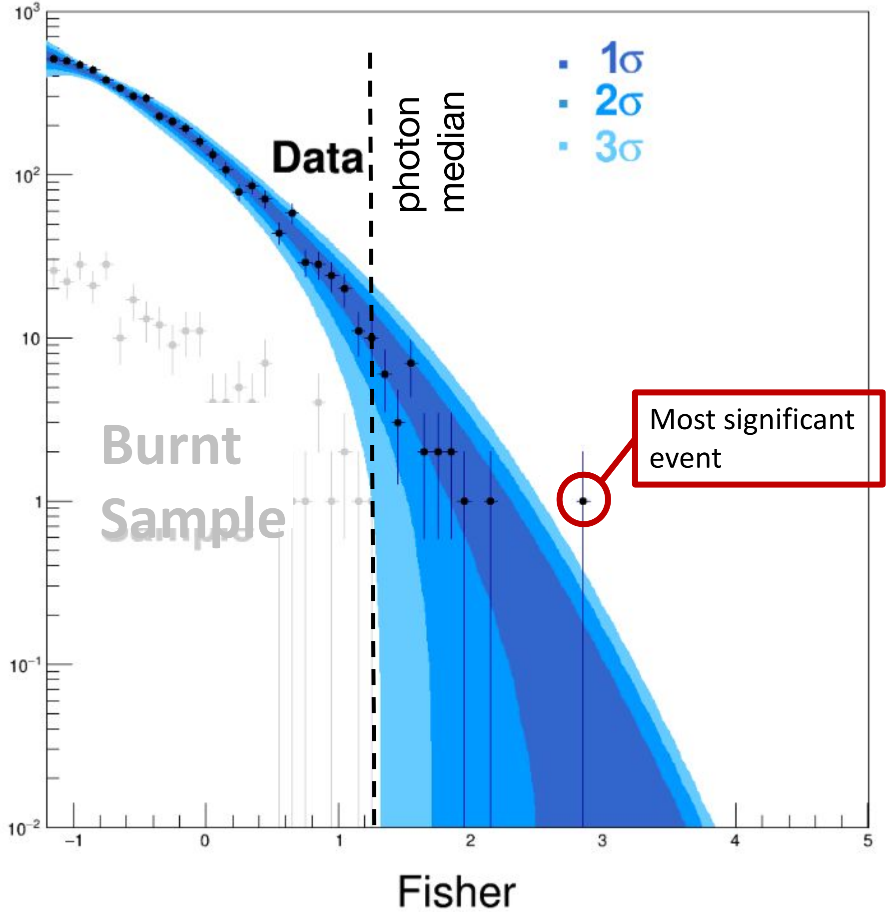




SD sensitivity in the first bins limited by the Background

HYBRID PHOTON ANALYSIS: **ANALYSIS**





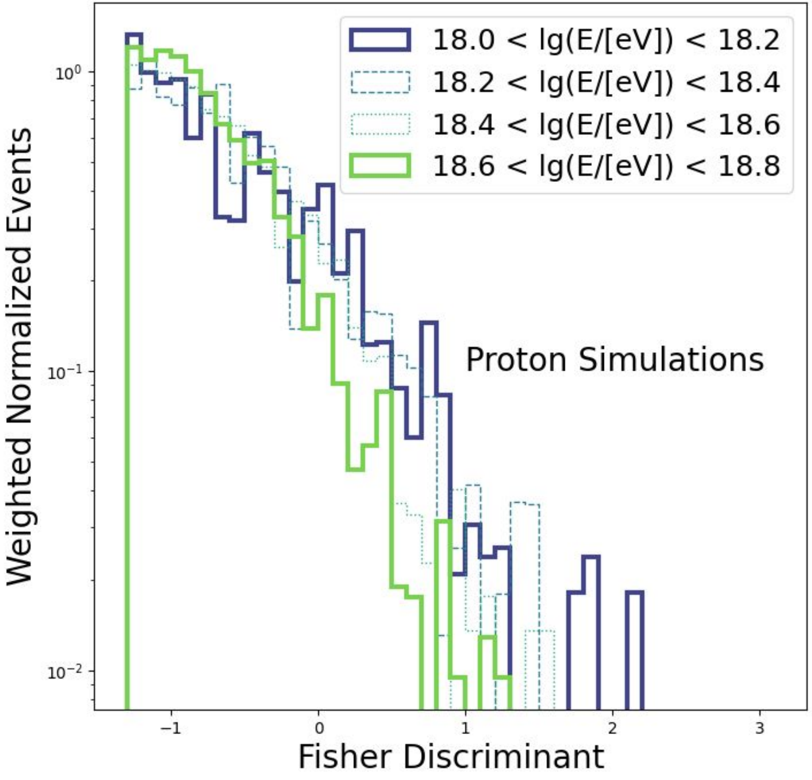
ENERGY DEPENDENT BACKGROUND

Protons simulations suggest that the **background** is **energy dependent**

Additionally, **mass composition** shifts toward **heavier** elements at higher energies, which **enhances separation** even more.

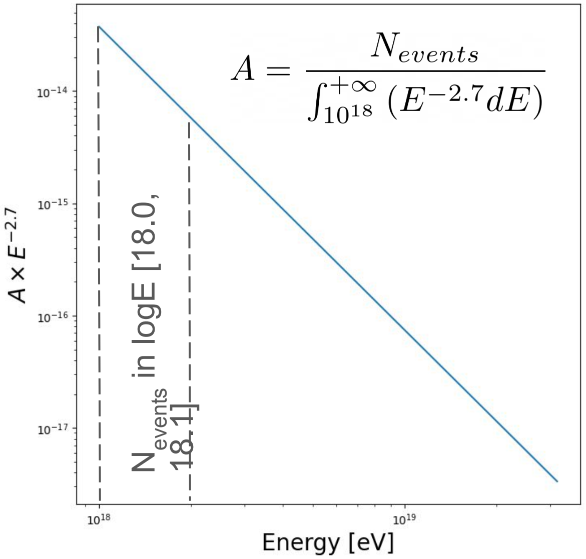
Overall, the **energy-dependent background** acts to **increase the significance** of relevant candidates, potentially leading to a **discovery** rather than just setting an upper limit.

A correct background estimation require a larger Burn Sample.



DERIVING A **NEW BURN SAMPLE** DEFINITION I

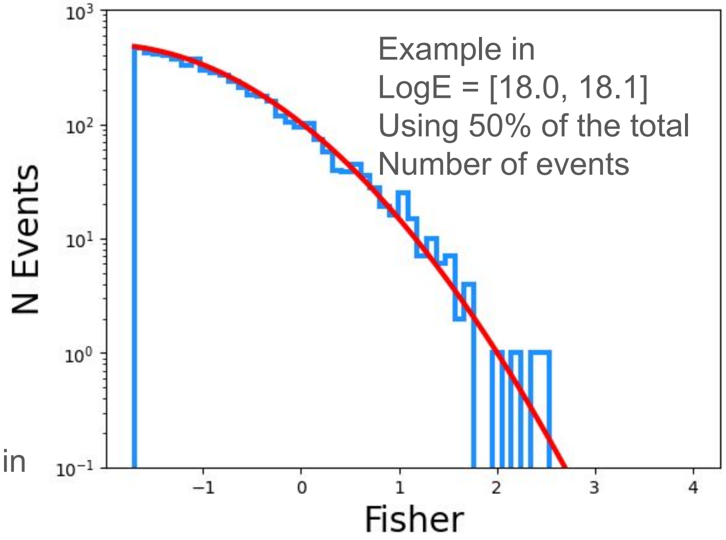
Estimating number of events in different energy bins (according to a $\mathbf{E^{-2.7}}$ and normalizing to data up to **2017**)



Performing **pseudo-experiment** with the number of events extrapolated at a % of the full dataset assuming the parametrized background

Fitting the simulated distributions to identify the **statistical** uncertainties on the background

CAVEAT: Same functional shape in each energy bin

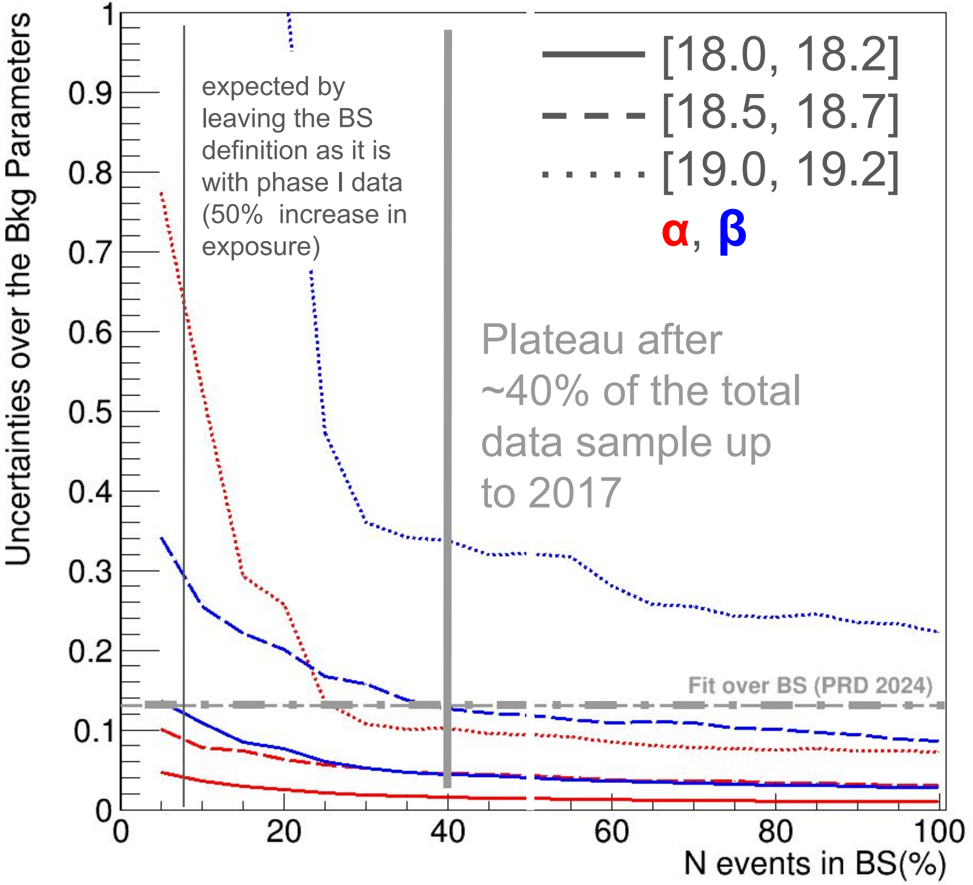


DERIVING A **NEW BURN SAMPLE** DEFINITION II

The statistical uncertainties on **α** and **β** decrease with the % of the BS (as expected)

BS corresponding to **~40%** of the total data optimal

In the logE = [19.0,19.2] we would expect only ~60 events so a larger sample might be required (energy binning still not optimized)



NEW U.L. Calculation method

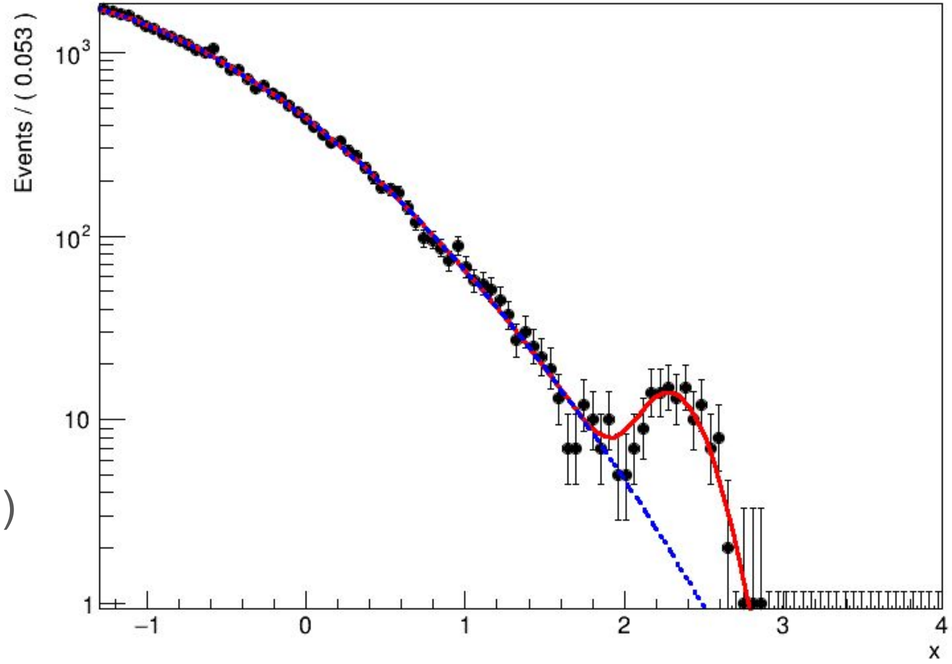
$$\mathcal{L} = \frac{n_s}{N} S + \left(1 - \frac{n_s}{N}\right) B$$

$$B = e^{\alpha x^2 + \beta x}$$ Photon Hybrid PRD

S = Gauss

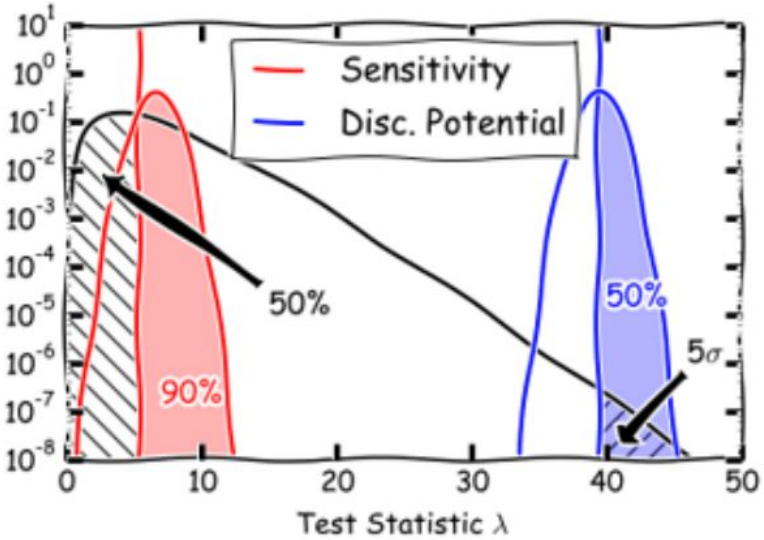
H$_0$: Data described solely by background **B** (n_s = 0)
H$_1$: Data described by background **B** + signal **S**

$$\mathrm{TS} = \frac{\mathcal{L}(n_s = 0)}{\mathcal{L}(\hat{n}_s)}$$



CAVEAT: This is a simple exercise to show the potential of the method. For the sake of simplicity in this exercise I **fixed** the **mean** and the **std** of the signal to what we find in simulations. The **only free parameters** in the fit are **α**, **β** and **n_s**

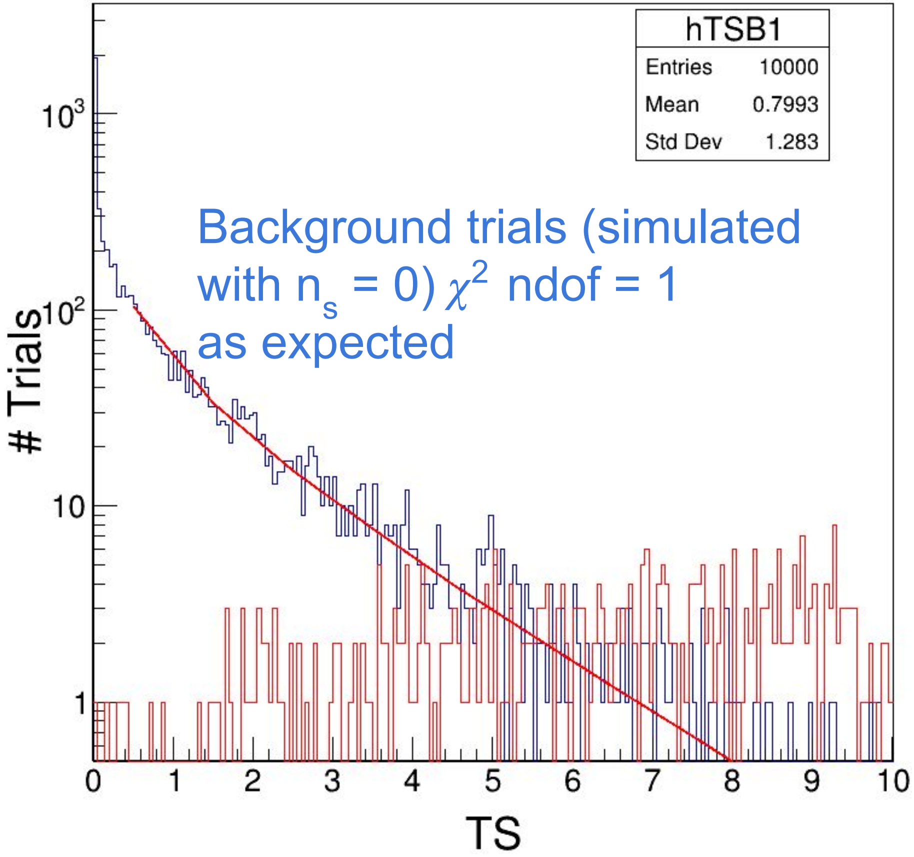
SENSITIVITY THE ICECUBE WAY



Sensitivity: best upper limit in the case of the of a non observation

Discovery potential: flux that yield a 5σ discovery

Sens. and D. Pot. derived from **pseudo-experiments**: "scanning" over n_s to find the <n_s> that gives the trial distribution required



THE PHOTON IDENTIFICATION

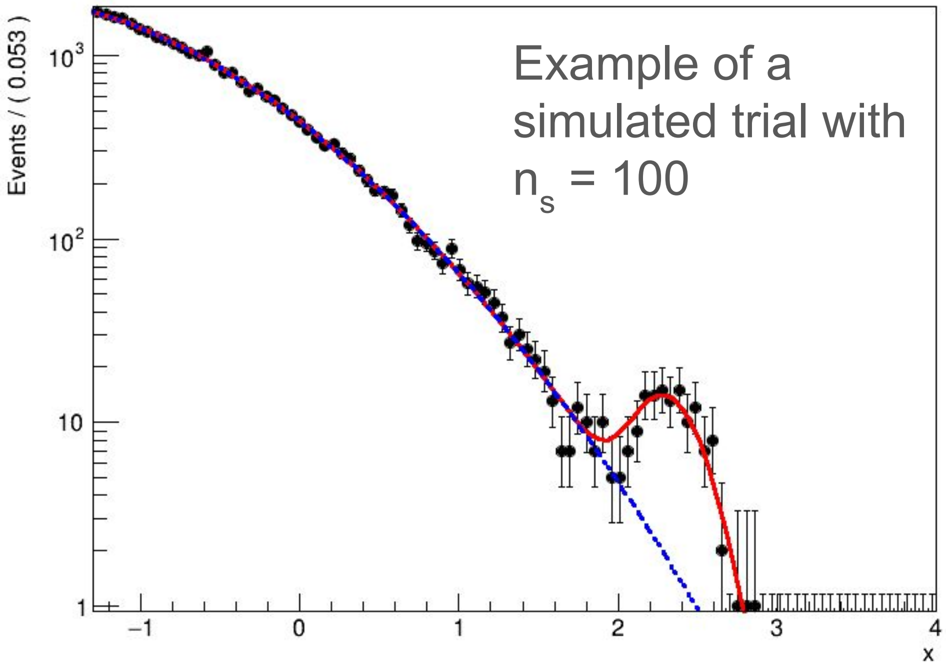
A **new paradigm** in the photon identification:
Photons as an **excess** over the background

Huge benefits:
Larger sensitivity w.r.t. previous methods

No need for the **median** cut anymore!
Search in the **whole phase space** ->
Increase of a factor 2 of the exposure

Costs:
Harder to “identify” candidates
Possible idea: repeat the analysis by removing data events to find candidates pulling the p-value

Systematics related to the background/signal models assumed



Example of a simulated trial with n_s = 100

THE PHOTON IDENTIFICATION

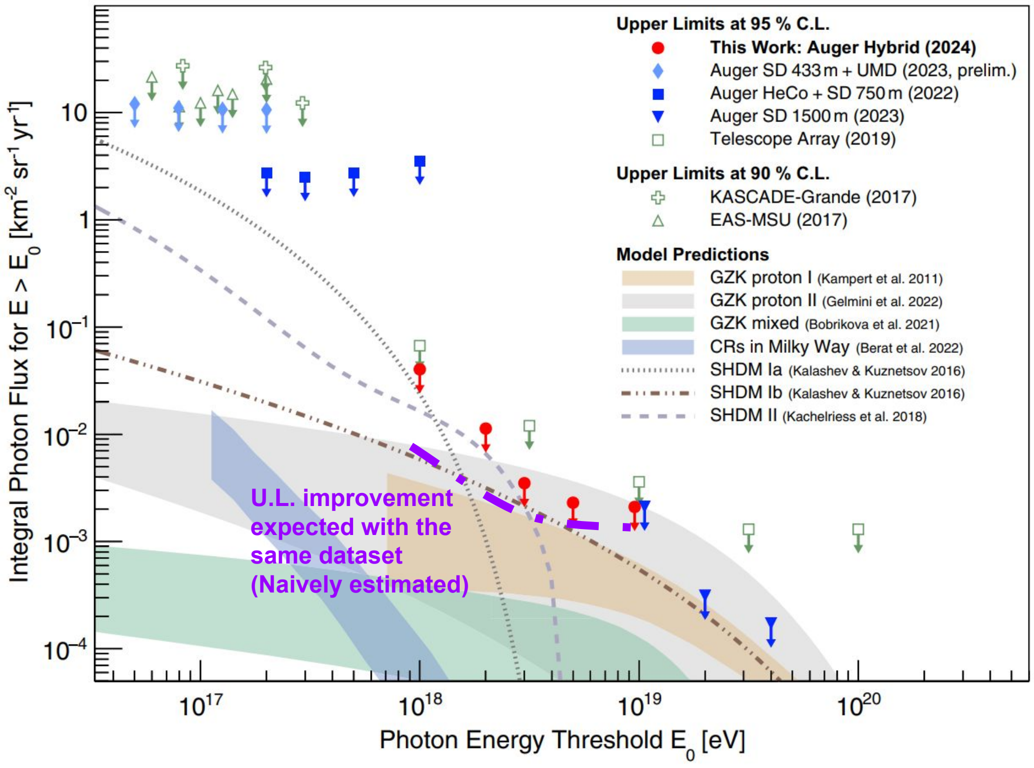
Check considering a similar statistics of the current hybrid photon analysis (no new BS definition or extension to data up to 2021 included)

Sensitivity n_s: **~8** (compared to Rolke $N^{95\%}$ = 23.38)

Overall improvement of **~6x** in the first energy bin expected in the U.L. estimation

The improvement in the last energy bins a.t.m. is mostly due to the “exposure increase”

TAKE HOME MESSAGE:
The results are really promising, but the exercise made is too simple and requires further checks



CONCLUSIONS

Sharing ideas for phase I photon analyses:
Example on the hybrid photon analysis

- Background more significant require a larger Burn Sample:
  BS New definition: **~40% data up to 2017 + 5% data from 2017 to 2021?**
  (**How to define the BS?**)

- New (Photon Identification) U.L. calculation paradigm
  Preliminary results really promising

Transient UHE Source Searches with IceCube and Pierre Auger

M. Nakos, L. Lu, P. Savina

WIPAC

ICECUBE

GSSI

INFN LNGS

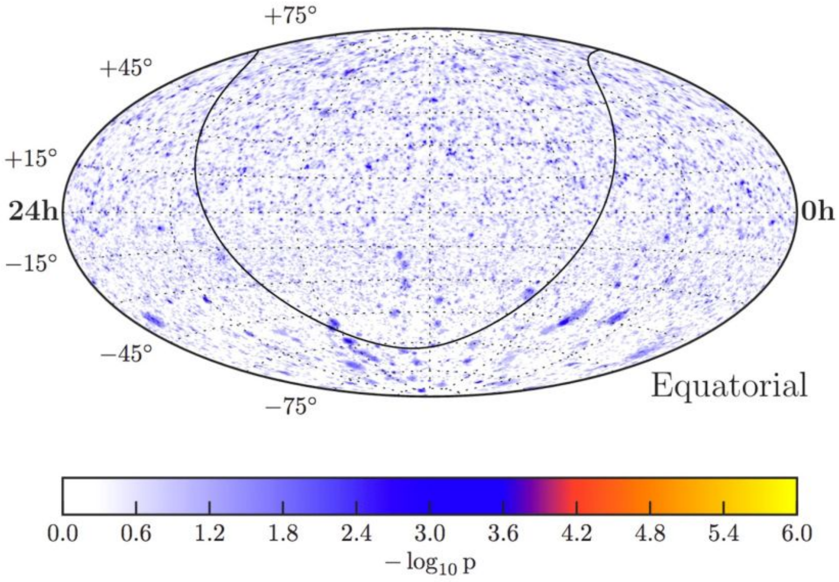
PIERRE AUGER OBSERVATORY

Reminder: Searching for Spatial & Temporal Coincidences Between IceCube Neutrinos and Auger Photon Candidates

- Motivated by LLGRB (Low-Luminosity Gamma-Ray Burst) models, where the spectrum shape depends on detailed source modeling.
- Using a timing window to reduce background, improving signal-to-noise in coincidence searches.
- Null hypothesis (H_0): No spatial or temporal correlation between IceCube neutrino candidates and Auger photon candidates.
- Interpreting a potentially null result:
  - It does not imply IceCube events are not astrophysical neutrinos.
  - It does not imply Auger photon candidates are background/signal.
  - It is only a statement about spatial and temporal correlation constraints.

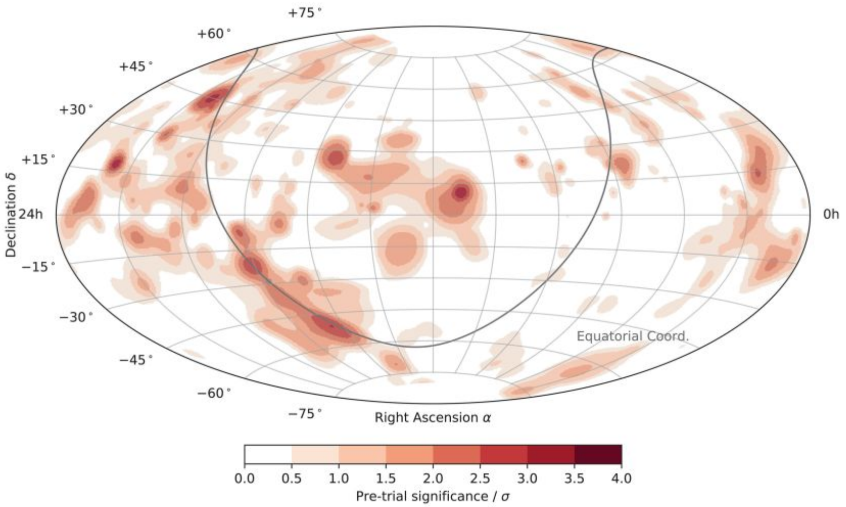
The IceCube dataset

Track sample



Southern sky dominated by atmospheric muons
Excellent pointing, poor energy resolution

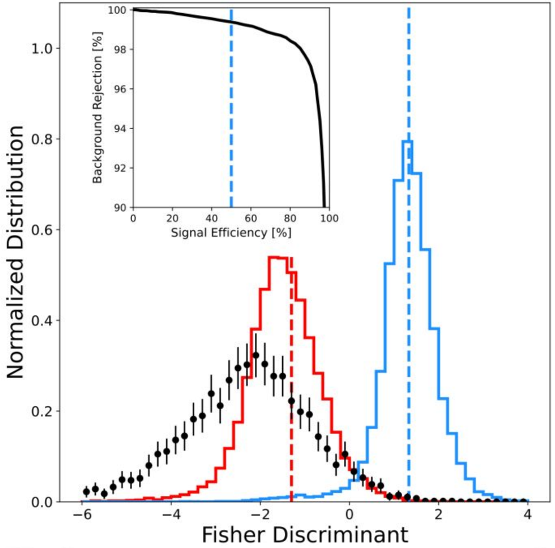
Cascade sample

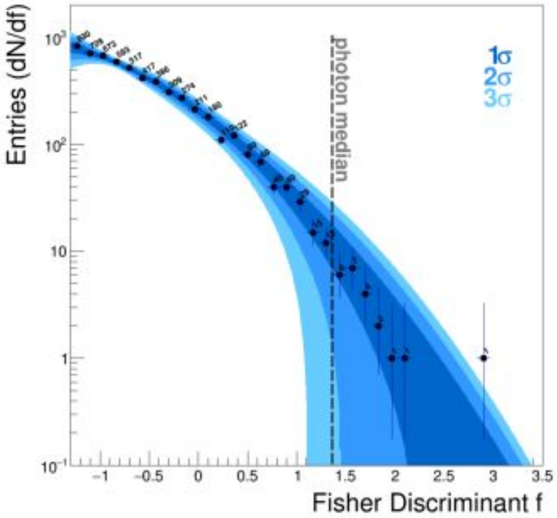


Southern sky signal-pure
Poor pointing, good energy resolution

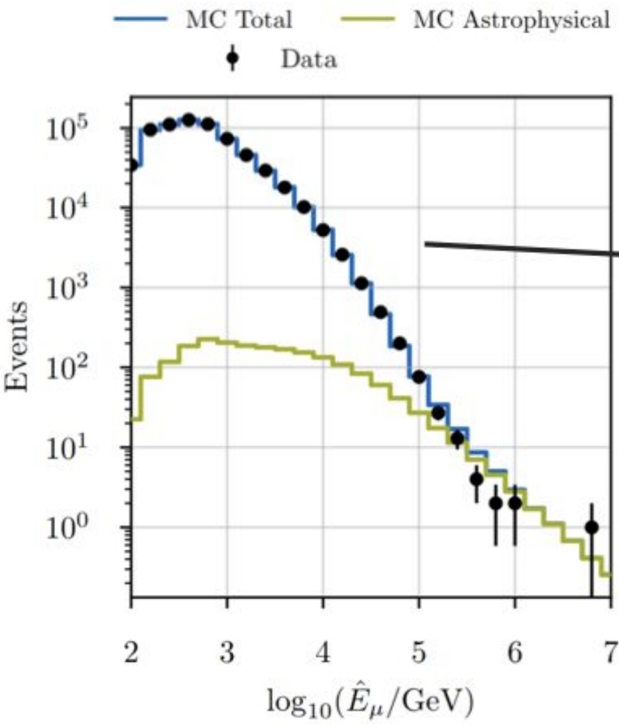
The Auger photon candidates

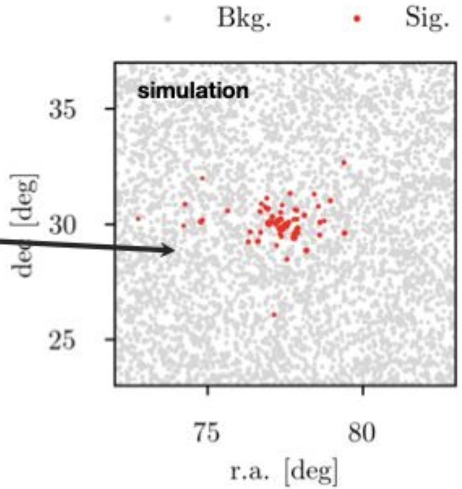
- Photon candidate selection is based on 50% photon efficiency.
- Long tail expected from proton distribution
- Assuming all events are background derived conservative upper limit
- One cannot definitively rule out the possibility that some candidates are photons
  - Background rejection is far from 5σ, meaning that photon classification remains uncertain.
  - A likelihood ratio test incorporating photon probability into the p-value would be a more informative metric, as current rejection methods do not quantify the probability of a photon signal.
  - Since Auger's limits are reported at the 95% confidence level, it is not inconsistent with Auger's publications to consider that some candidates might still be photons.





How does IceCube source search work?

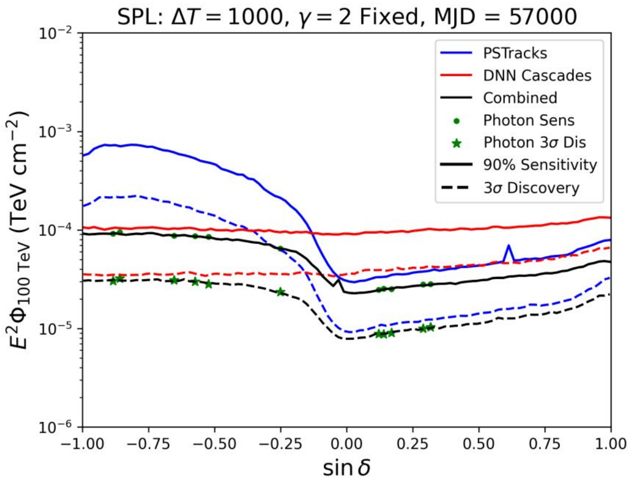


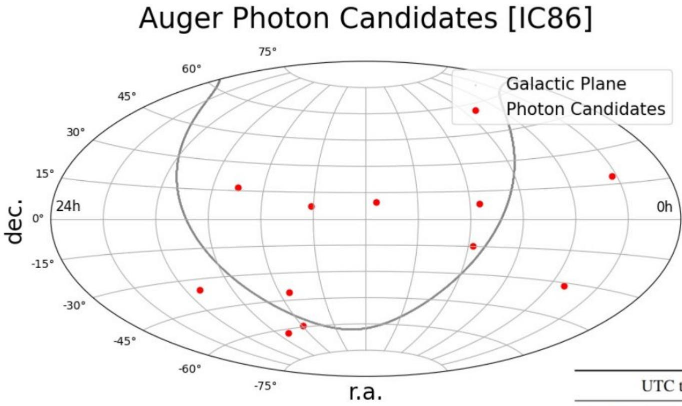


vast majority of the neutrinos are background in s`earches for extragalactic neutrino sources

IceCube sensitivity dependences on declination

Fluence, E^-2





- More locations being checked more likely to see a random coincidence
- Pre-Define the Photon Event List
  - Energy Threshold (prefer high energy due to propagation loss)
  - Quality Cuts (angular resolution, detector in good status)
  - Photon-likelihood Threshold (currently set at 50%)
- After Unblinding
  - Pre-trial p-value
  - Post-trial p-value (Bonferroni Correction)

UTC time	$\lg(E_\gamma/\mathrm{eV})$	$X_{\max}/(\mathrm{g\ cm^{-2}})$	F_μ	$\theta/°$	Fisher
Jun 22, 2006 07:27:16	18.31	987.7	0.42	38.7	1.57
Jun 27, 2006 03:01:26	18.01	1039.9	0.39	47.6	2.12
May 22, 2007 02:58:14	18.24	1245.2	0.75	56.7	2.87
Aug 10, 2007 03:05:06	18.02	907.6	0.22	43.6	1.46
Dec 15, 2007 06:29:00	18.00	913.4	0.29	47.8	1.40
Mar 26, 2009 06:34:56	18.10	938.9	0.11	39.0	1.84
Oct 19, 2009 06:54:20	18.29	1008.7	0.52	47.8	1.57
Oct 21, 2009 03:51:13	18.01	1010.4	0.59	59.3	1.58
Jan 19, 2010 03:55:42	18.21	796.3	-0.23	22.7	1.36
Oct 03, 2010 05:07:00	18.01	1019.9	0.52	49.6	1.75
Oct 16, 2010 07:33:46	18.14	984.7	0.45	47.3	1.57
Jun 26, 2011 05:17:41	18.17	935.6	0.07	30.8	1.86
Jul 05, 2011 06:17:13	18.02	1109.3	1.01	57.2	1.57
Aug 03, 2011 01:59:06	18.20	944.3	0.20	54.6	1.68
Dec 22, 2011 05:31:33	18.08	932.7	0.02	44.2	1.96
Nov 13, 2012 06:51:13	18.04	967.5	0.48	35.0	1.45
Jun 30, 2013 02:01:08	18.04	1061.8	0.86	41.7	1.47
Mar 15, 2015 06:32:28	18.48	1001.9	0.45	51.8	1.55
Mar 08, 2016 01:23:38	18.04	954.3	0.29	54.5	1.67
Jul 05, 2016 06:01:34	18.12	917.0	0.07	48.1	1.74
Aug 11, 2016 07:52:15	18.07	847.4	0.01	58.5	1.38
Jun 19, 2017 01:14:36	18.05	849.9	-0.07	42.4	1.54

IC79

IC86

Table II. Details of the events selected by the photon candidate cut.

Conclusions

- Many interactions with both collaborations largely improved the analysis

- Well received from the collaboration

- Approved contribution at ICRC with the method

- MoU under preparation (by Karl-Heinz)

Other activities

Super Heavy Dark Matter and UHECR Anisotropy at Low Energy

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Abstract

Super Heavy quasi-stable particles are naturally produced in the early universe and could represent a substantial fraction of the Dark Matter: the so-called Super Heavy Dark Matter (SHDM). The decay of SHDM represents also a possible source of Ultra High Energy Cosmic Rays (UHECR), with a reliably calculated spectrum of the particles produced in the decay ($\propto E^{-1.9}$). The SHDM model for the production of UHECR can explain quantitatively only the excess of UHE events observed by AGASA. In the case of an observed spectrum not showing the AGASA excess the SHDM model can provide only a *subdominant* contribution to the UHECR flux. We discuss here the basic features of SHDM for the production of a *subdominant* UHECR flux, we refer our study to the possible signatures of the model at the Auger observatory discussing in particular the expected chemical composition and anisotropy.

Key words: Super Heavy Dark Matter, Ultra High Energy Cosmic Rays, Anisotropy

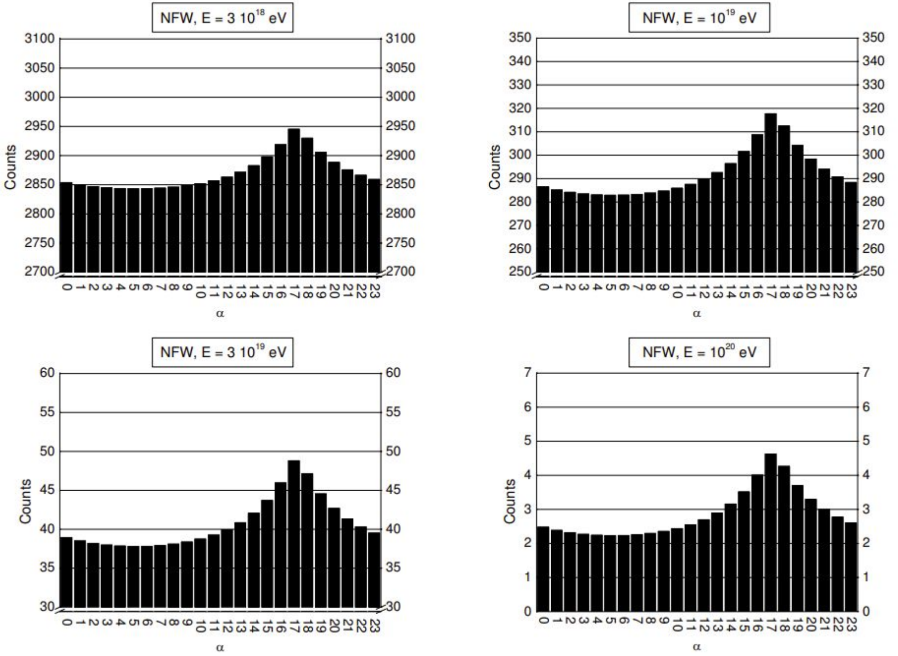


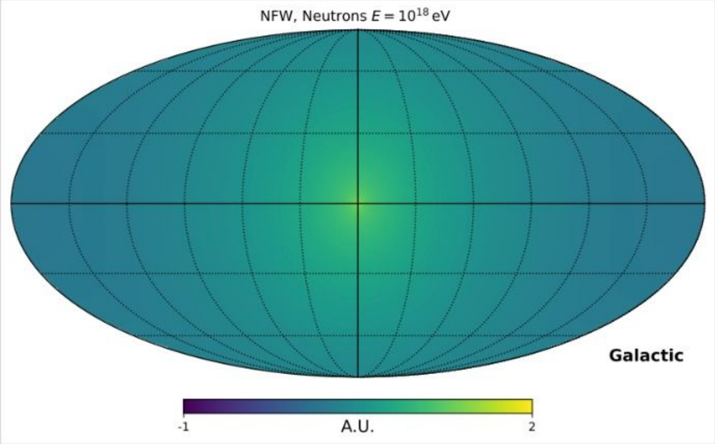
Fig. 4. The expected UHECR events at the Auger observatory in 5 years data taking as function of right ascension. The SHDM contribution is obtained in the case of NFW density profile, assuming a SHDM mass of $M_X = 10^{13}$ eV and averaging, at all energies, the SHDM proton component over the sky.

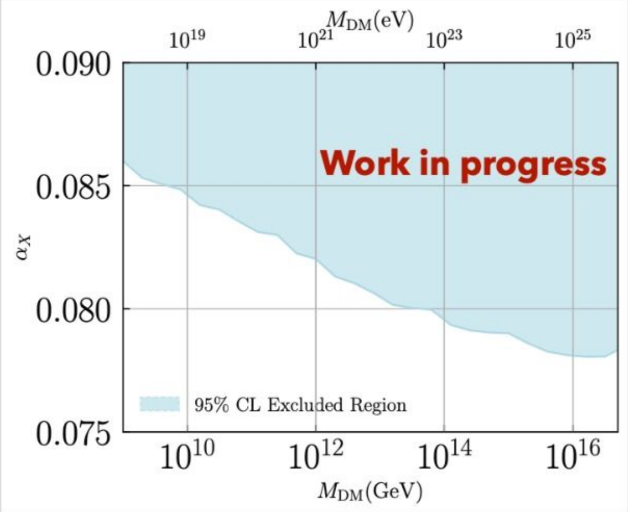
Antonio Ambrosone, Denise Boncioli, Carmelo Evoli, Roberto Aloisio

Probing SHDM with Photon and Neutron Anisotropies

- Photons and Neutrons are not deflected by Magnetic fields

$$\tau_{\rm DM} \simeq \frac{1}{M_{\rm DM}} e^{\frac{4\pi}{\alpha_x}}$$





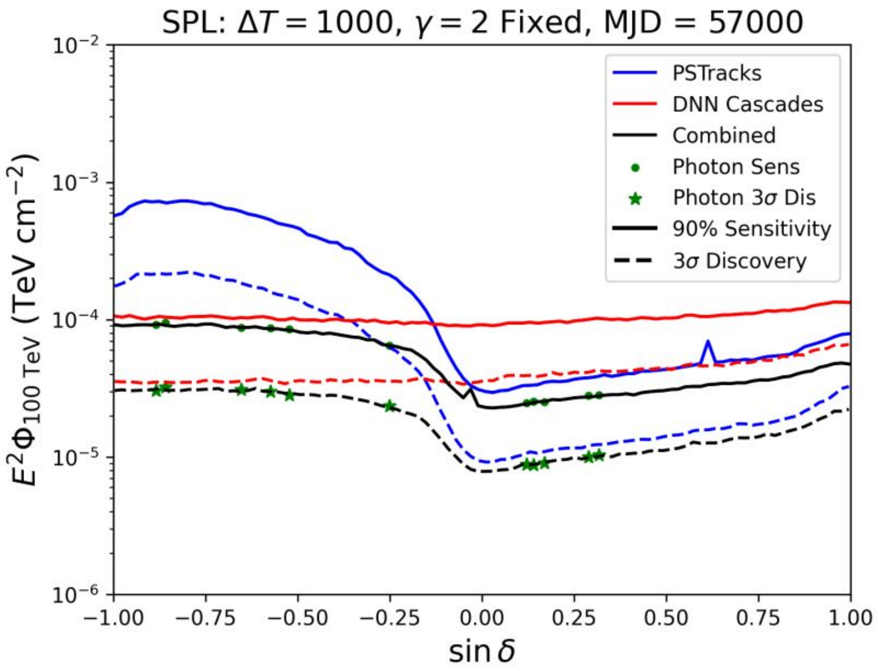
- DM Signal should peak in the Galactic center

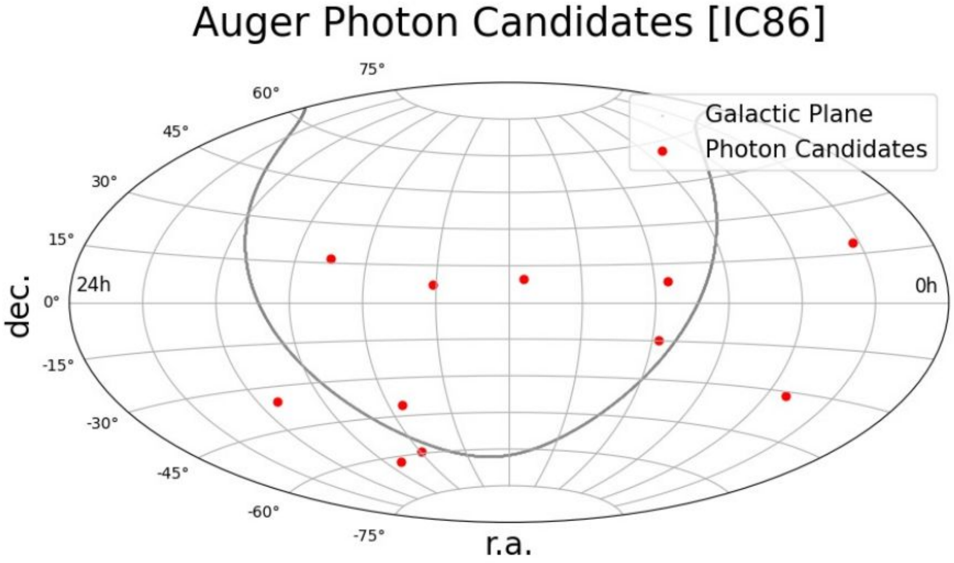
- These upper limits could strongly improve inserting a spatial information in the analysis

Antonio Ambrosone, Denise Boncioli, Carmelo Evoli, Lorenzo Caccianiga

IceCube sensitivity dependences on declination

Fluence, E^-2





How many photon candidates to select?

- More locations being checked more likely to see a random coincidence
- Pre-Define the Photon Event List
  - Energy Threshold (prefer high energy due to propagation loss)
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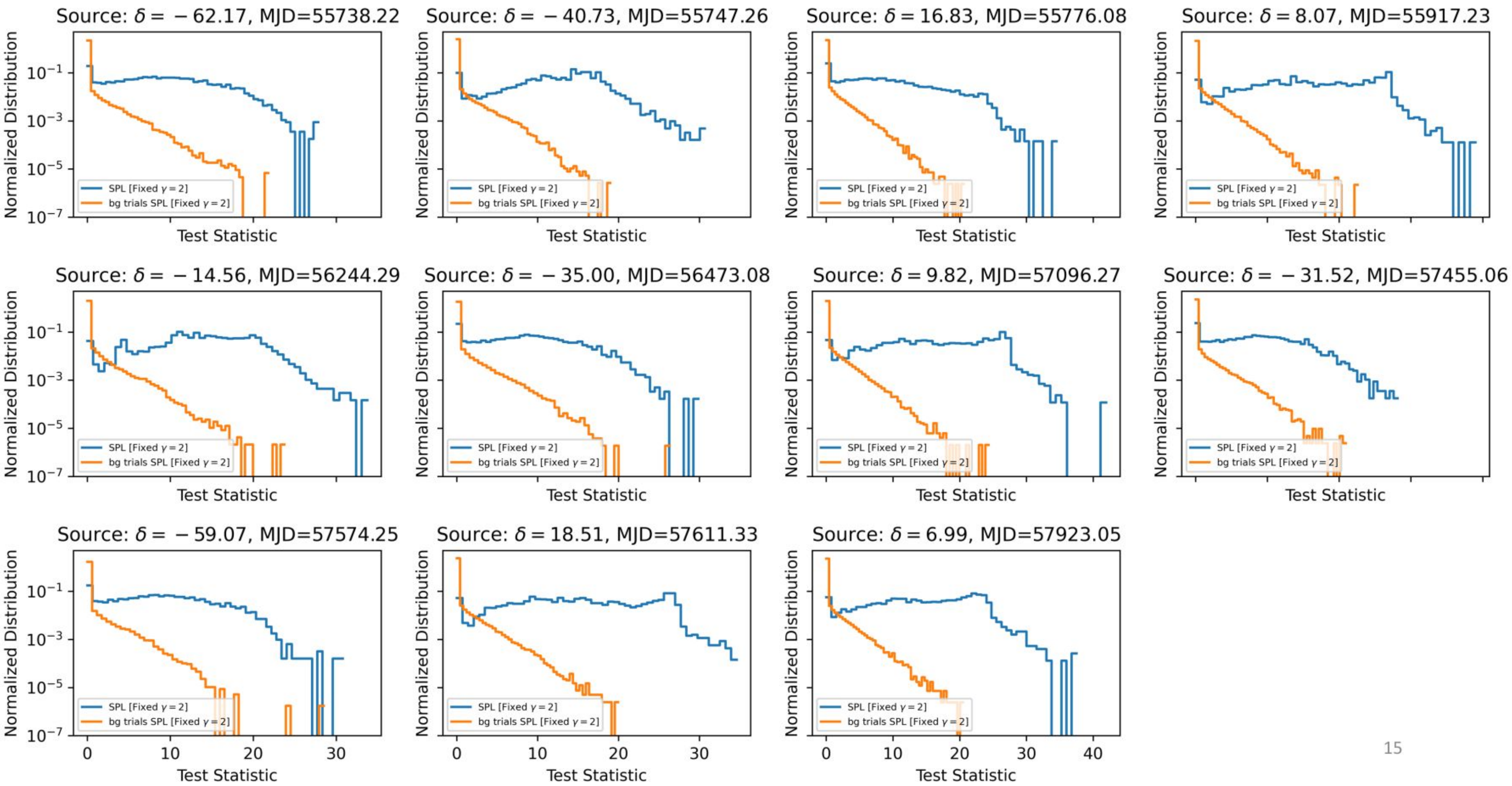
  - Photon-likelihood Threshold (currently set at 50%)
- After Unblinding
  - Pre-trial p-value
  - Post-trial p-value (Bonferroni Correction)

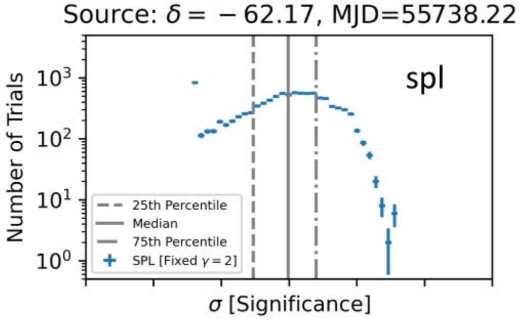
If we detect one neutrino event at the location of an Auger photon candidate, what is the expected statistical significance?

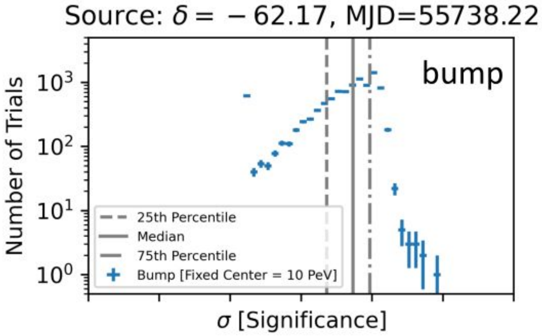
- ->**Inject a simulated neutrino event** following the theoretical neutrino spectrum. Compute Signal TS distribution.
- -> **Scramble background events** to generate background TS distribution.
- -> **Compare the observed TS against the background distribution** to determine the expected **statistical significance** of the detection.

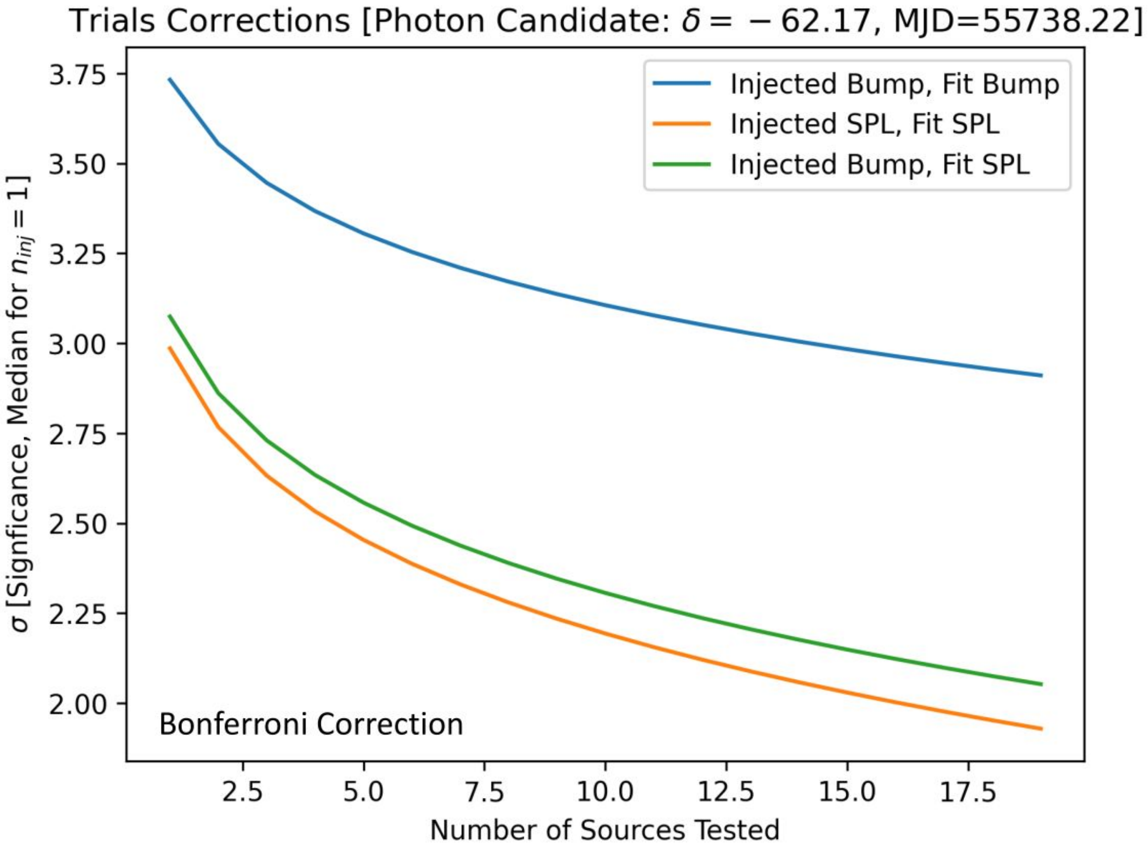
$\Delta T = 20000$ seconds, $n_{inj} = 1$ [SPL $\gamma = 2$ Spectrum]



Look-elsewhere effect



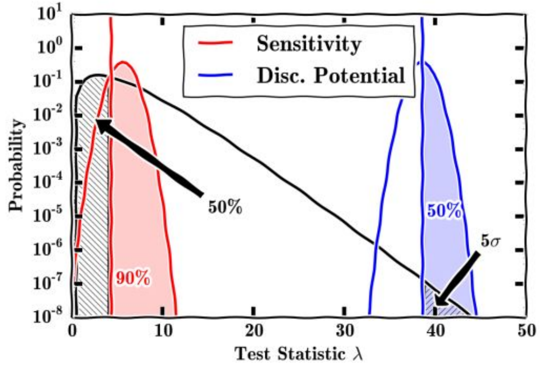


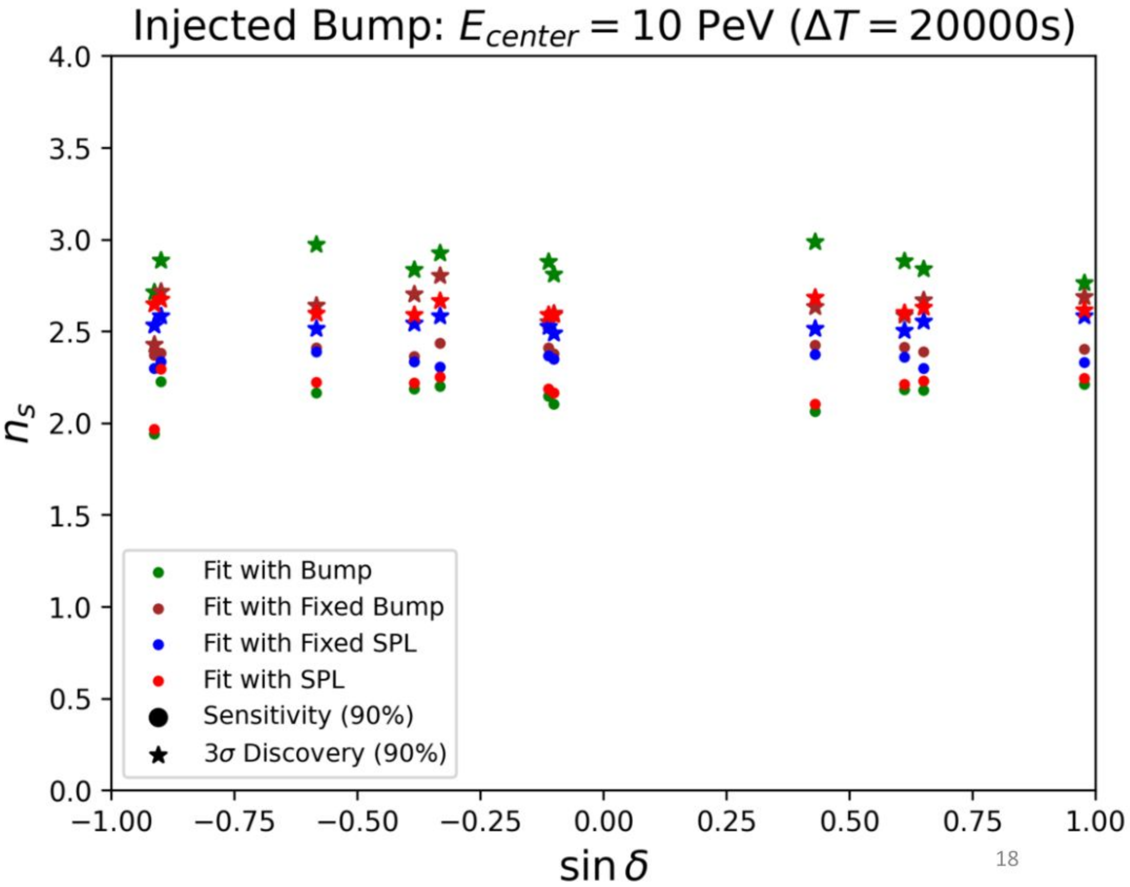


But – this is only true when we know which location is most likely to be a real photon

IceCube sensitivity

- Reminder: timing window, spatial and energy contributes to TS.
- IceCube is sensitive to ~2 neutrinos at an UHE transient source





Interpreting Non-Correlation & Presenting a Null Result

- A null result does not contradict the possibility that photon candidates are real photons.
- It only states that no significant correlation was found at the tested positions/timing windows.
- This means the analysis remains agnostic to the classification of individual events.
- Proposal: Publish Fluence Upper Limits
  - Clearly state all assumptions
  - First time upper limit for transient UHE source searches -> model constraints
  - Standard practice for time-domain null results (gravitational waves, GRBs,…)

e.g.https://iopscience.iop.org/article/10.3847/2041-8213/acc077

Limits on Neutrino Emission from GRB 221009A from MeV to PeV Using the IceCube Neutrino Observatory

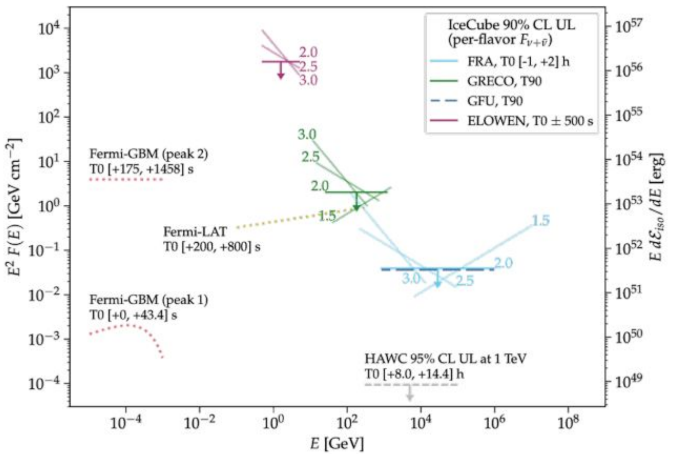


Figure 1. Gamma-ray observations and $F_{\nu+\bar{\nu}}$ upper limits on the time-integrated neutrino flux of GRB 221009A. We show the γ-ray observations from Fermi-GBM (Lesage et al. 2022) and Fermi-LAT (Bissaldi et al. 2022) as well as upper limits from HAWC (Ayala 2022). The Fermi-GBM result covering the prompt phase ("peak 2") had no reported spectral fit, so it is shown here at $\gamma = 2.0$ for visualization purposes. The upper limits on the time-integrated neutrino flux are shown for various spectral indices as indicated by the numbers. The right axis shows the differential isotropic equivalent energy $d\mathcal{E}_{\rm iso}/dE$.

Photon Candidate Classification in Test Statistic Construction:

If photon candidates might not be real photons, should this uncertainty be incorporated into the test statistic (TS) formulation?
Auger classification is based on background expectations—how does this affect the significance of any potential correlation?

- If null result –
  - This does not pose a problem, as it will not affect the upper limit on neutrino flux. The analysis remains model-independent and constraints can still be set.
- If positive result –
  - Since we are not performing a catalogue-based combined likelihood test, incorporating event-specific weights to represent photon likelihood would be necessary in such cases.
  - In other studies, such weights are often based on factors like redshift, luminosity, or gamma-ray flux, hadronic-ness to better reflect astrophysical expectations.
  - The current photon threshold cut saves 50% of photons. One could tune the cut in principle.
  - If Auger intends to conduct specific model tests (i.e., a well-defined photon production model), we could potentially apply a Poisson likelihood ratio test combining both photon and neutrino data in the case of a positive detection. However, our preference is to remain model-independent, presenting experimental results without assuming a specific astrophysical model.
  - Proposal: Clearly state in the paper the photon-ness of each Auger event, ensuring transparency in the interpretation of results.

Backup

From pɣ interaction, can expect a **bump signature** (possible model for these sources).

To test recovery using a **single power law**, we injected a bump model and tested for the number of events needed to reach sensitivity and 3 sigma discovery under different fit models

Bump Model:

$$e^{-w\log^2\left(\frac{E}{E_{\text{center}}}\right)}$$

w : bump width
E_{center} : bump center (peak in spectrum)