Fundamental physics with IACTs
and future prospects in the field

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TeVPA 2026
Tendo
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FIZRI Faculty of Physics University of Rijeka
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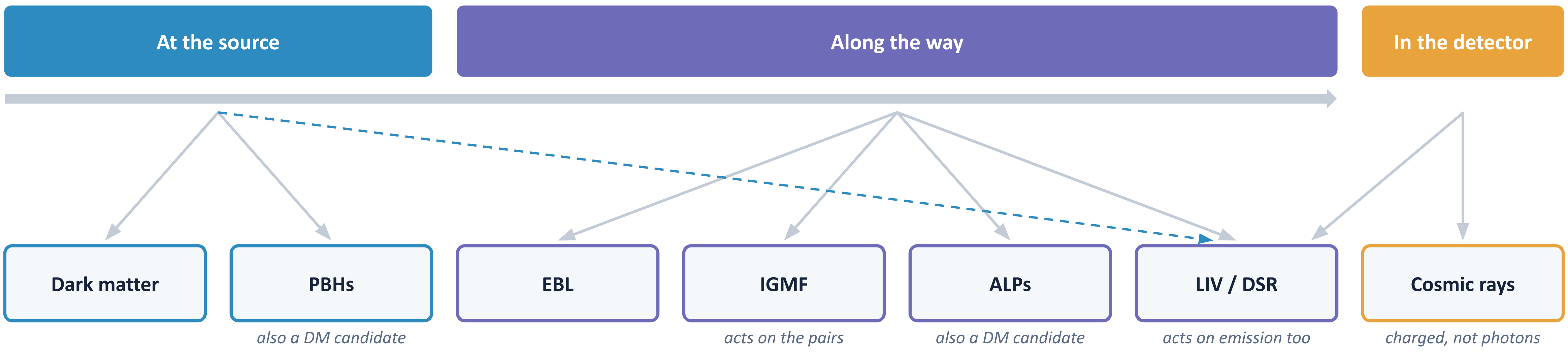
HrZZ Hrvatska zaklada za znanost
IP-2022-10-4595

ROADMAP

Fundamental phenomena, and where they occur



Most of these have a plenary of their own this week

Mon 31 Aug	**Pollmann** #515 direct detection, into the neutrino fog **Kusenko** #382 cosmic-ray cascades, NGC 1068, intergalactic fields
Tue 1 Sep	**Castellina** #456 UHECRs from the Pierre Auger Observatory **Pinetti** #527 hunting new physics in the dark universe
Wed 2 Sep	**Chen** #516 quantum sensors and wave-like dark matter
Thu 3 Sep	**Fujiwara** #466 the WIMP paradigm and beyond **Rawlins** #391 cosmic rays in the region of the knee
Fri 4 Sep	**Bister** #399 UHECR sources with improved magnetic-field modelling **Takahashi** #385 axion and ALP dark matter

1 At the source

Dark matter · primordial black holes

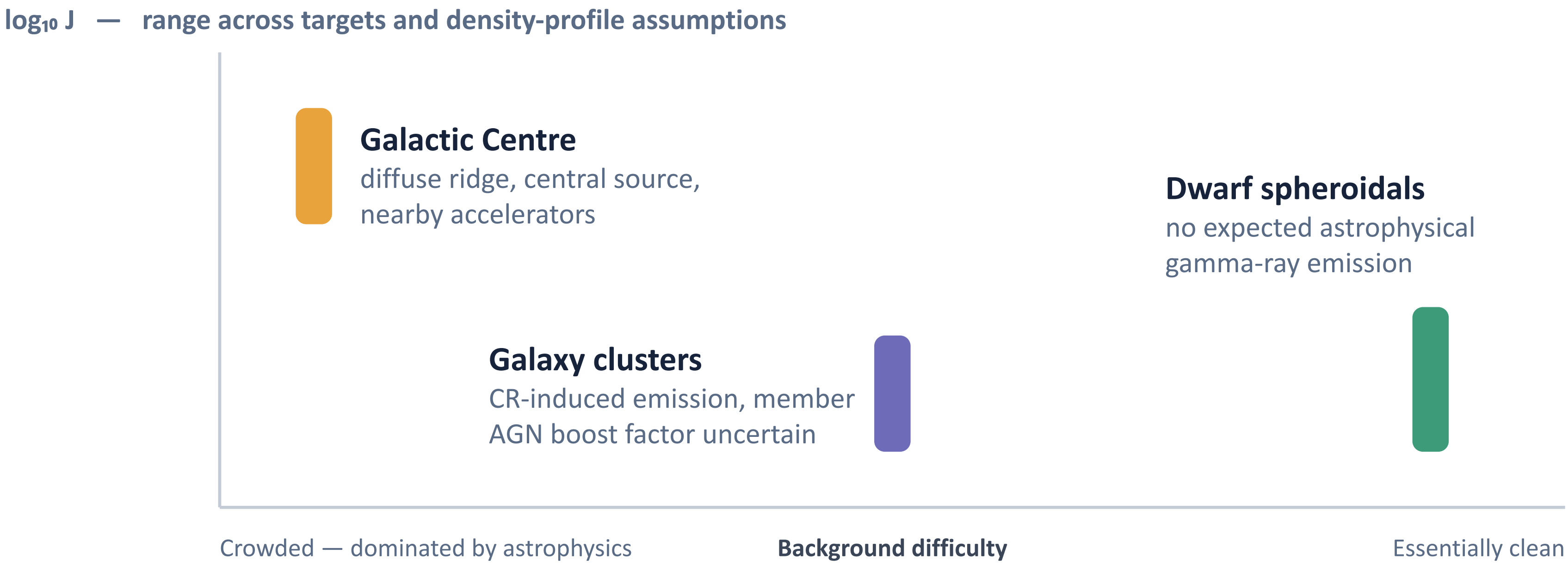
Dark matter: two signatures, and a target trade-off

Continuum

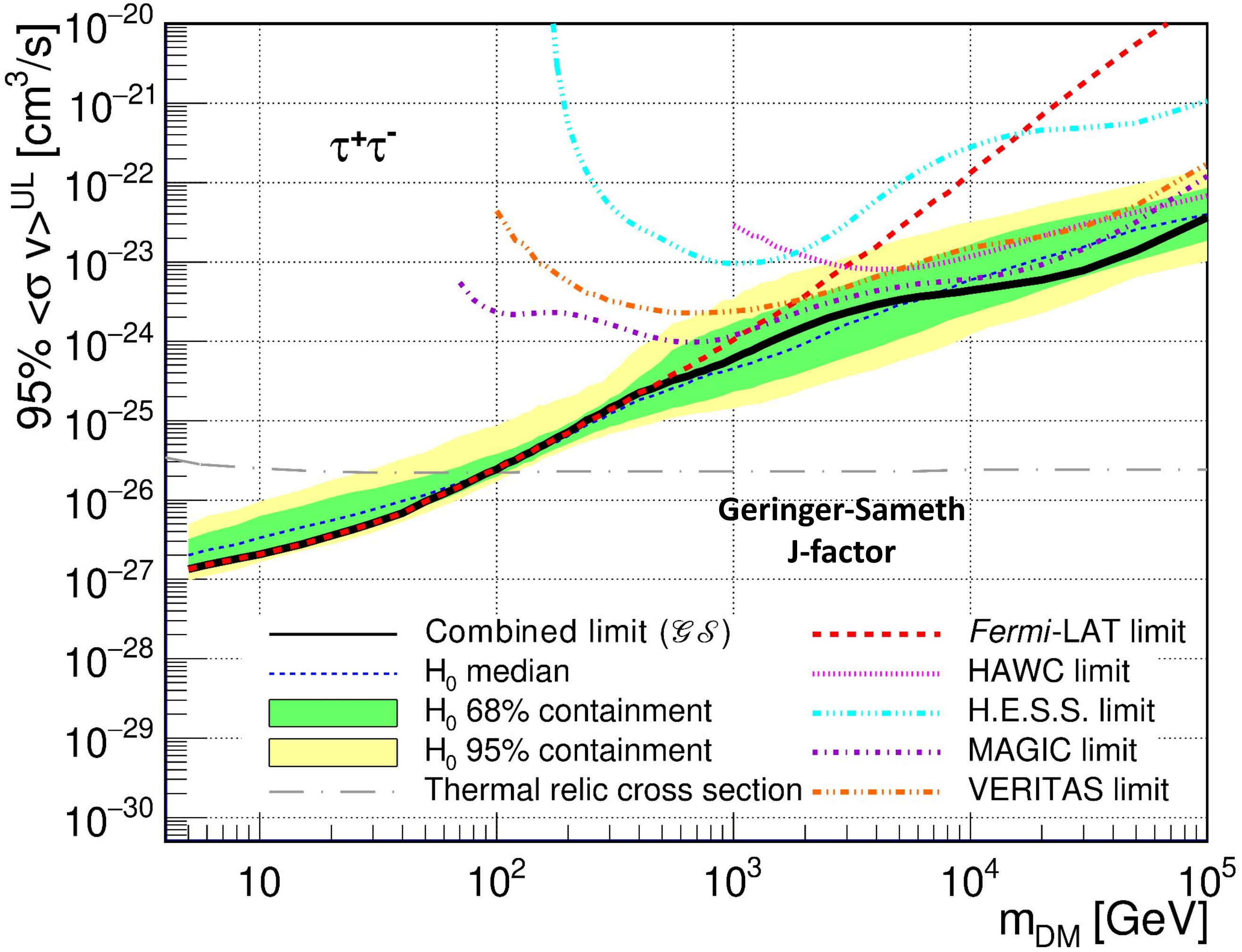
Annihilation / decay to SM states — broad spectrum with a cutoff at the DM mass.
Higher rate, harder to separate from astrophysics.

Lines

$\chi\chi \to \gamma\gamma, \gamma Z$ — monoenergetic, no astrophysical process mimics it.
Low rate, but a smoking gun.



Five instruments, one likelihood



Glory Duck — Fermi-LAT/HAWC/H.E.S.S./MAGIC/VERITAS, JCAP 03 (2026) 035 · arXiv:2508.20229

20 dwarf spheroidals

Fermi-LAT · HAWC · H.E.S.S. · MAGIC · VERITAS.

Individual datasets analysed with a common statistical approach, then combined in a global joint likelihood.

up to

2–3× **more constraining than the individual results over 5 GeV – 100 TeV.**

5 GeV – 100 TeV · $\tau^+\tau^-$ at 2 TeV: 1.5×10^{-24} / 3.2×10^{-25} cm^3 s^{-1}

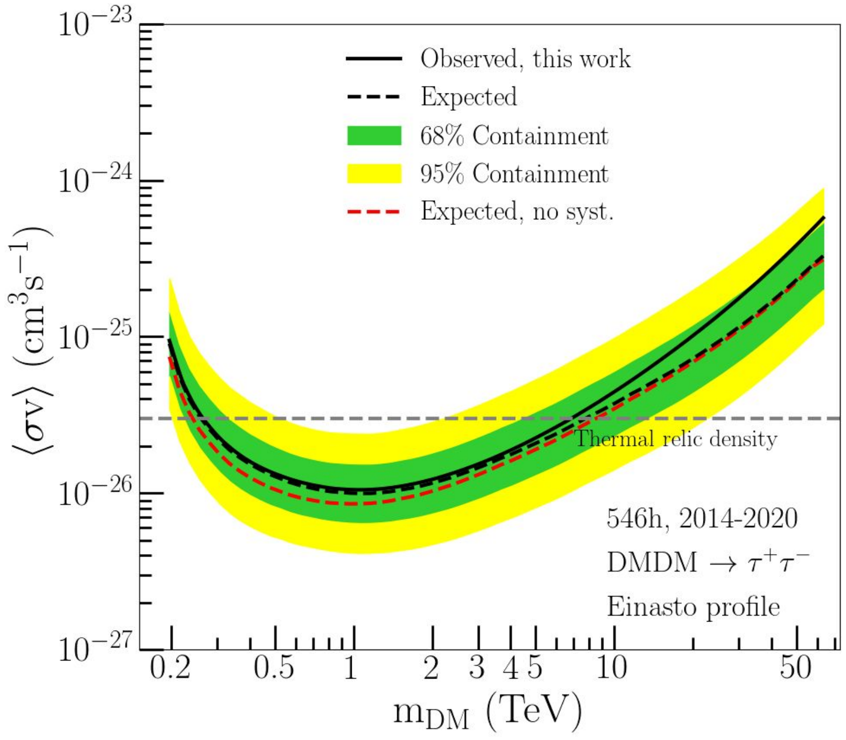
No new observations. No new photons.
The gain came from **five collaborations — common statistical treatment**

The Galactic Centre: one dataset, two searches

546 h of the Inner Galaxy Survey (2014 – 2020) — the same data, analysed twice

Continuum

PRL 129, 111101 (2022) · arXiv:2207.10471



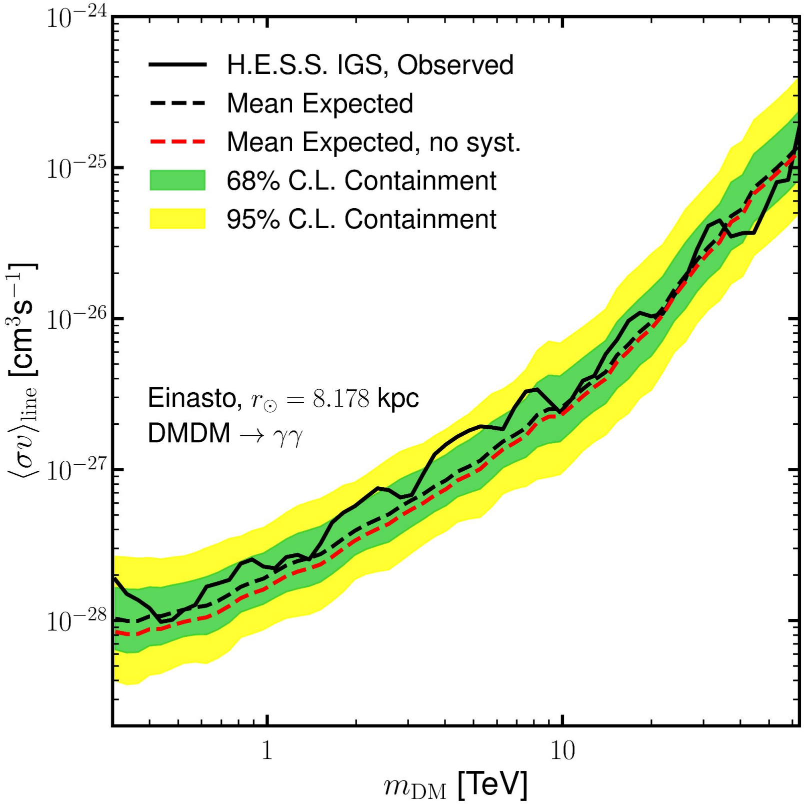
3.7×10^{-26} cm^3 s^{-1} at 1.5 TeV, W^+W^-

1.2×10^{-26} cm^3 s^{-1} at 0.7 TeV, $\tau^+\tau^-$ (Einasto)

Probes $\langle\sigma v\rangle$ values expected from thermal-relic TeV dark matter

Lines

PRL 137, 091002 (2026) · arXiv:2608.07234

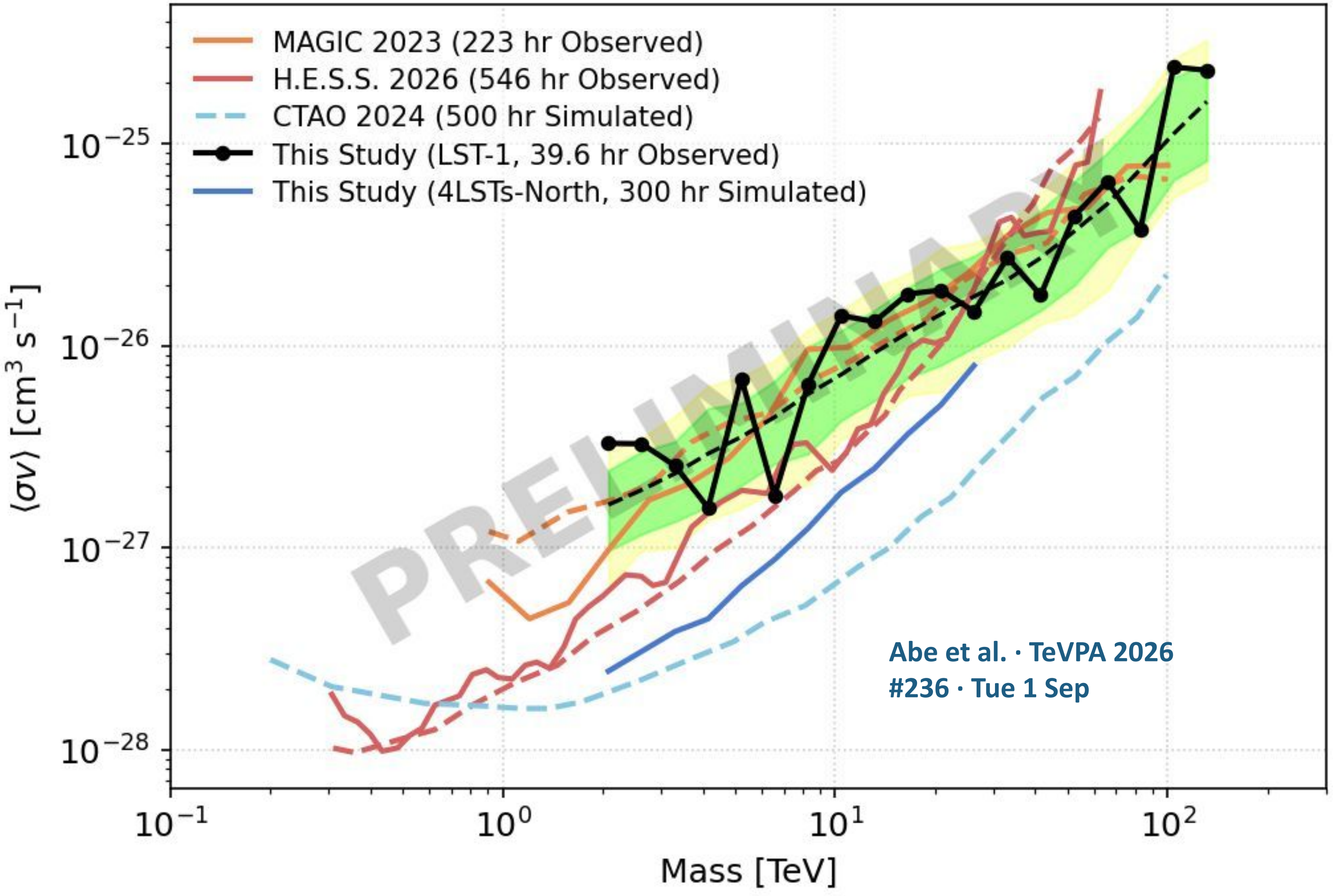


$\langle\sigma v\rangle_{\rm line}$ **$< 2.3 \times 10^{-28}$ cm^3 s^{-1}** at 1 TeV

$\langle\sigma v\rangle_{\rm line}$ **$< 2.4 \times 10^{-27}$ cm^3 s^{-1}** at 10 TeV

First time thermal Higgsino dark matter is probed.

Competitive limits on a sixth of the exposure



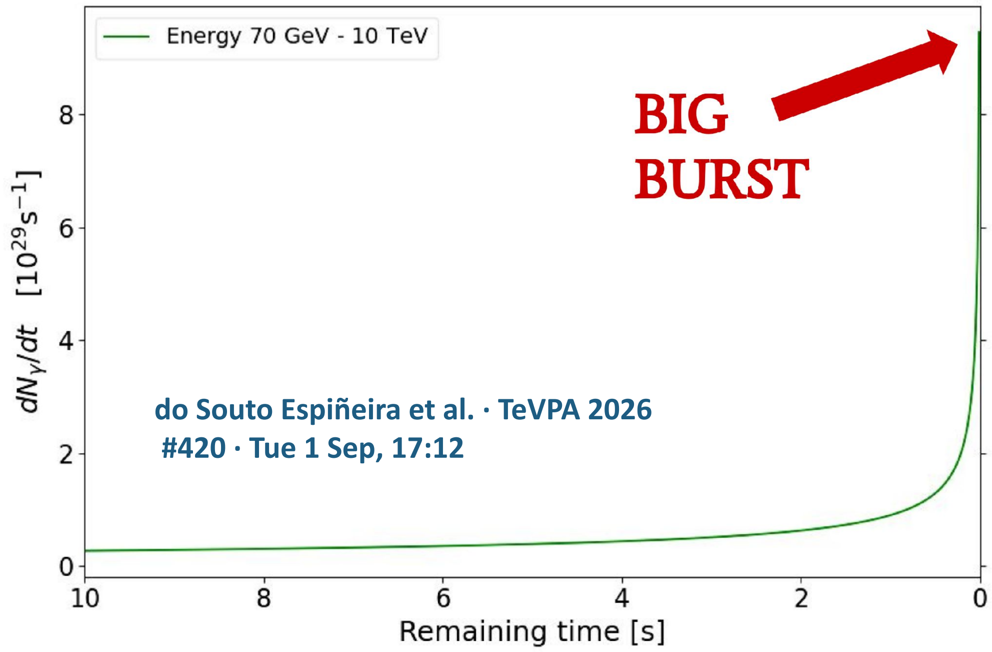
Competitive on a fraction of the exposure.

- Large zenith angle lifts the effective area ~10× to 10^6 m²
- 4.3° field of view suits an extended source
- PWL background spectral model replaces reflected regions

- **The first IACT line search beyond 100 TeV**
- **The leading search above 100 TeV for cored profiles**

Primordial black holes: a burst, and a model assumption

- A PBH of initial mass ~10^{14}–10^{15} g reaches the end of Hawking evaporation now
- $T_{BH} \propto 1/M_{BH}$ so evaporation runs away: the hole heats as it shrinks
- Essentially the whole observable signal arrives in the final fraction of a second
- Unpredictable direction, no host, no repeat



Search timescale is a trade-off, not a free parameter

Burst spectra are computed for τ = 2, 10, 100, 1000 s (Petkov+ 2008). A longer window collects more photons — but from a cooler hole. H.E.S.S. search 10–120 s.

Spin does not matter

Even an initial spin of ~0.99 leaves the final burst unchanged.

Model-dependent burst spectrum

- MacGibbon–Webber: PBH emits the species fundamental at its temperature; TeV temperatures reachable.
- Hagedorn: limiting temperature near 160 MeV; microsecond burst of ~100 MeV photons
- LQG: gives ~10 MeV bursts before total evaporation
- A photosphere would suppress the signal drastically

Waiting for Hawking

Instrument	Exposure	Burst rate (pc^{-3} yr^{-1})	Window, CL	Horizon	Reference
VERITAS	750 h (2009–12), extended to 2017	$< 2.2 \times 10^4$	30 s, 99%	—	arXiv:1709.00307 · 1909.01171
MAGIC	1650.1 h effective, 8122 runs	$< 1.5 \times 10^4$	2–1000 s, 95%	~2 pc	*TeVPA 2026 · preliminary*
HAWC	959 days, wide-field	$< 3.4 \times 10^3$	99%	~0.5 pc	JCAP 04 (2020) 026 · arXiv:1911.04356
H.E.S.S.	4816 h	$< 2.0 \times 10^3$	120 s, 95%	~0.1 pc	JCAP 04 (2023) 040 · arXiv:2303.12855
LHAASO	Mar 2021 – Jul 2024, all-sky	$< 1.8 \times 10^2$	10/20/100 s, 99%	~1 pc	PRL 135, 181005 (2025) · arXiv:2505.24586

Recommendations from MAGIC

- The analysis loses power with more data: trials grow faster than sensitivity
- Burst searches are best suited for detection
- Upper limits on the PBH population are always more constraining when derived from the diffuse gamma-ray background

2 Along the way

EBL · IGMF · ALPs · LIV / DSR

Gamma-ray constraints on the EBL

MAGIC + Fermi 2019 — combined likelihood over blazars, out to z = 1

[MNRAS 486, 4233 (2019) · arXiv:1904.00134]()

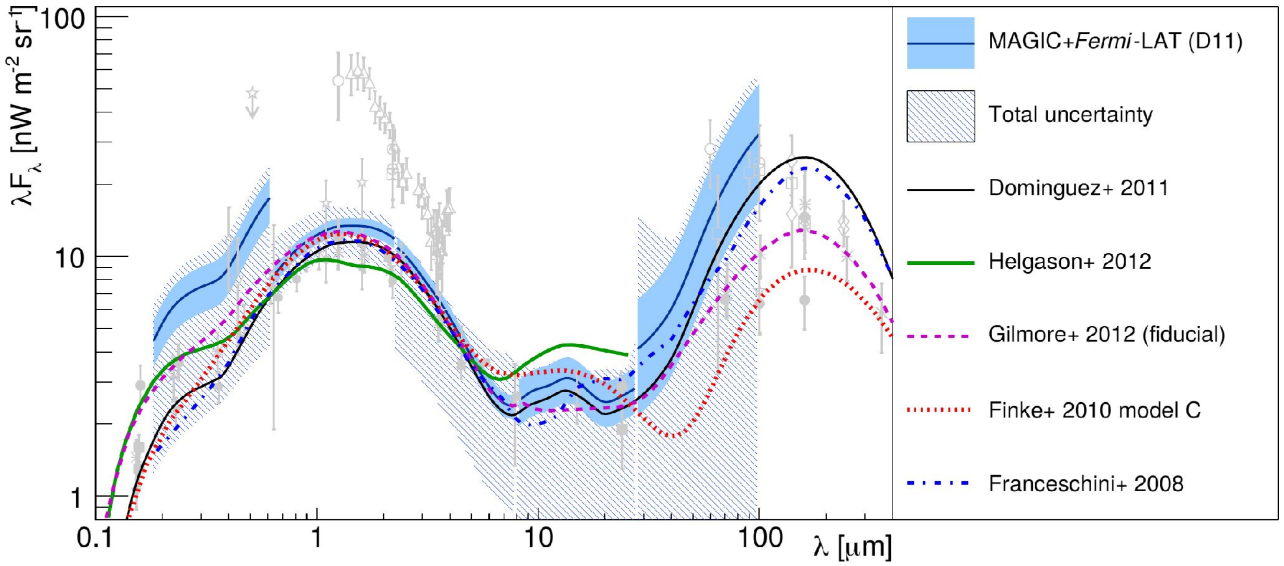
VERITAS 2019 — 14 blazars, 0.56–56 µm, independent of EBL models

[ApJ 885, 150 (2019) · arXiv:1910.00451]()

STeVECat — 403 archival spectra from 73 sources — three instruments

[arXiv:2304.00835 · PoS(Gamma2022)171]()

A new MAGIC EBL result on the way — in the meantime see arXiv:2406.18230 and arXiv:2512.02880



MAGIC + Fermi-LAT against EBL models and direct measurements
MNRAS 486, 4233 (2019), Fig. 12

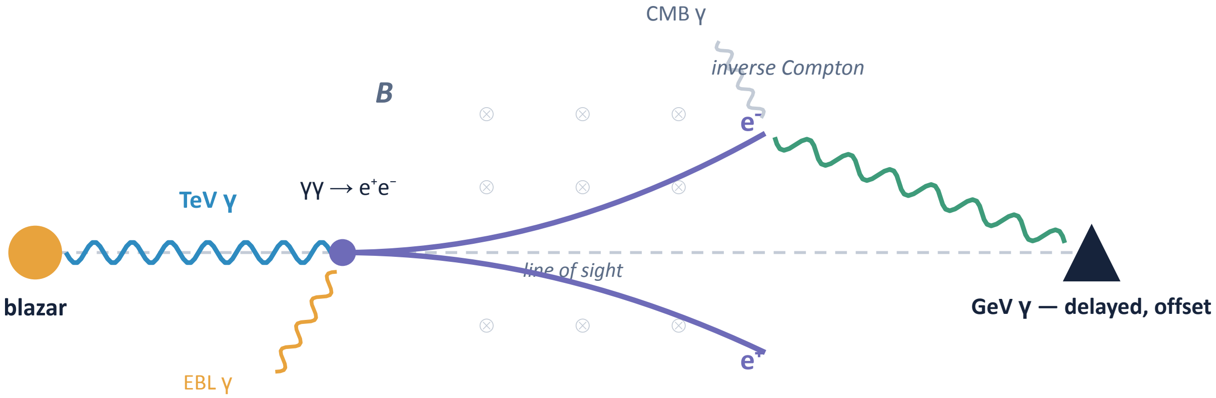
And the farthest yet: LST-1 and MAGIC jointly detected the quasar OP 313 at z = 0.997, giving λI_λ < 8.74 (LST-1) and < 14.7 (MAGIC) nW m^{-2} sr^{-1} at 0.6 µm.
[A&A 712, A91 (2026) · arXiv:2605.26681]()

Baxter · TeVPA 2026 · #283 · Wed 2 Sep, 16:30 **Hashizume · TeVPA 2026 · #424 · Mon 31 Aug, 15:05 — OP 313 emission mechanism**

The missing GeV signal

Origin of the IGMF

Primordial	inflation or phase transitions, then diluted by expansion
Astrophysical	made in objects, then spread through cosmic structure



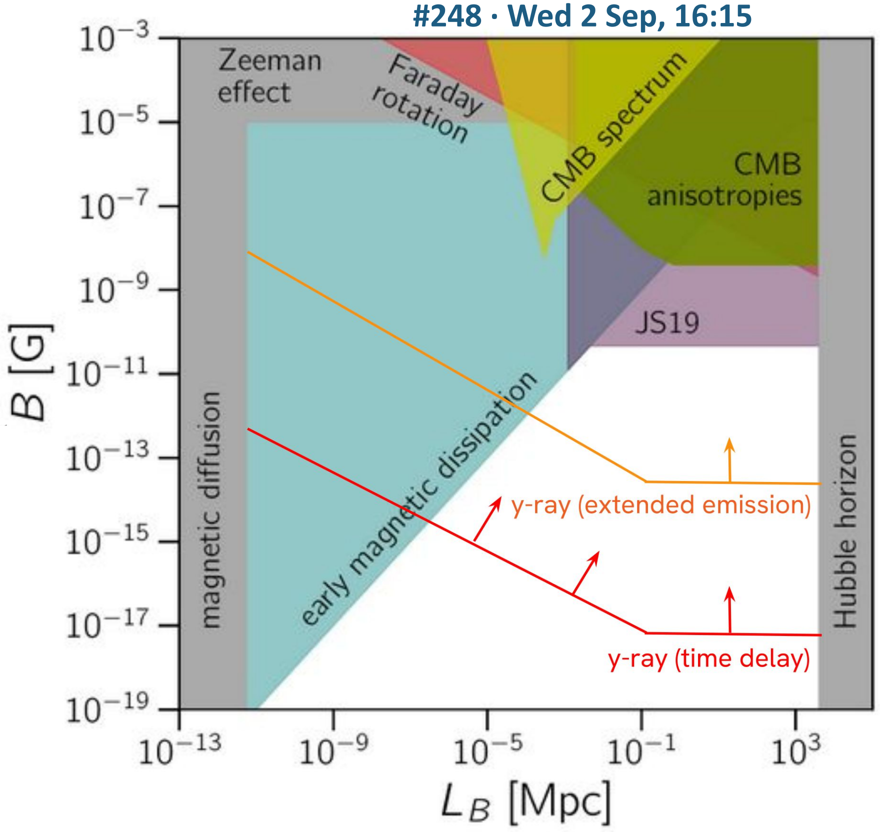
No GeV signal

- **Deflection**
- **Instabilities**

$B > 7.1 \times 10^{-16}$ G H.E.S.S. + Fermi-LAT, λ = 1 Mpc
[ApJL 950, L16 (2023) · arXiv:2306.05132]

$B > 1.8 \times 10^{-17}$ G 1ES 0229+200, four instruments
[A&A 670, A145 (2023) · arXiv:2210.03321]

Croisonnier · TeVPA 2026
#248 · Wed 2 Sep, 16:15



Vovk · TeVPA 2026 · #309 · Wed 2 Sep, 16:00
IGMF with Fermi-LAT only

Photon to ALP in an external magnetic field

Mixing: photon to ALP in an external magnetic field

MAGIC 2024 — NGC 1275 in the Perseus cluster, 41.3 h; cluster field modelled explicitly, full likelihood with statistical coverage

$g_{a\gamma}$ down to 3×10^{-12} GeV^{-1} near $m_a \approx 50$ neV — the strongest IACT limit

Phys. Dark Univ. 44, 101425 (2024) · arXiv:2401.07798

VERITAS 2025 — NGC 1275, second night of the 2017 flare; gammapy analysis using the CLs method

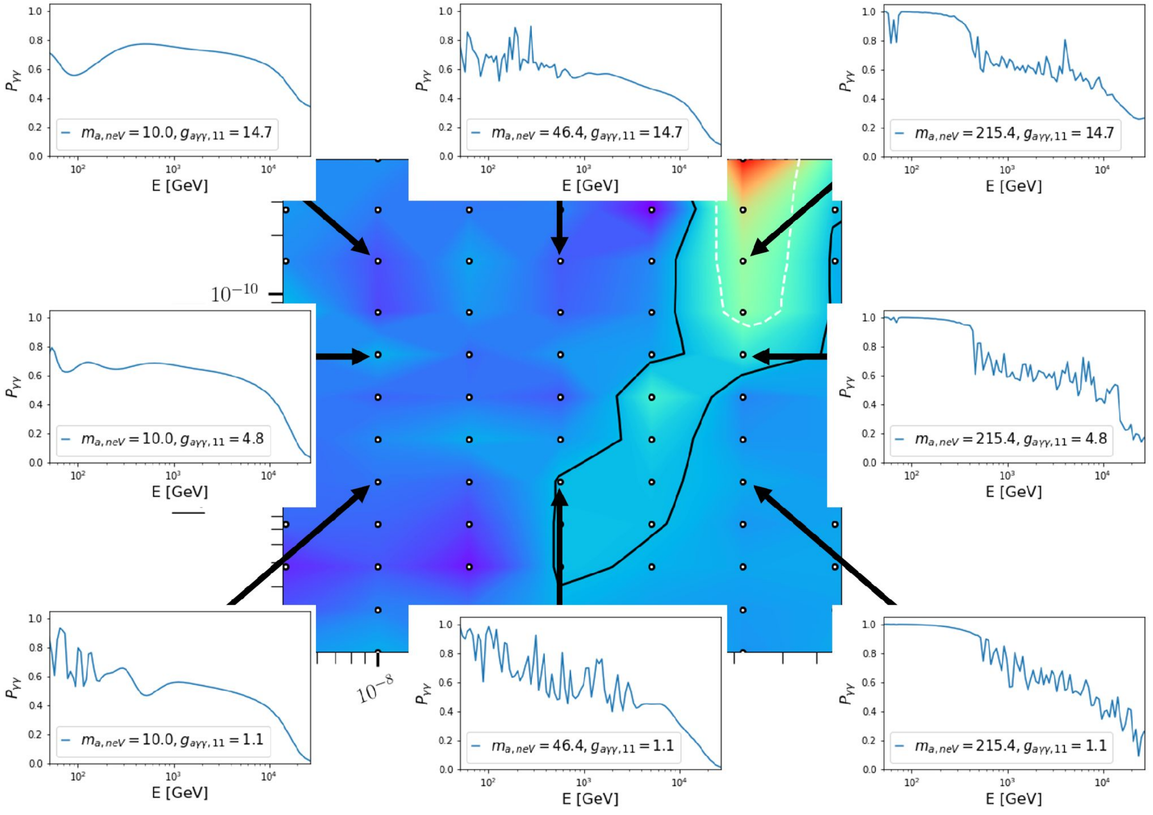
no region excluded at ≥ 95% CL — reports what it cannot exclude

Phys. Rev. D (2025), DOI 10.1103/jydc-npy6 · arXiv:2510.19010

Decay: ALP to two photons, adding to the EBL

H.E.S.S. + Fermi-LAT 2026 — a large sample of blazar spectra; ALPs of $m_a \sim 10$ eV decaying to two photons would enhance the EBL, and so the optical depth

arXiv:2606.11923



Photon survival P(γγ) across the mass–coupling plane — MAGIC, NGC 1275, arXiv:2401.07798, Fig. 3

Bhattacharjee · TeVPA 2026 · #393 · Mon 31 Aug, 15:12 — ALP parameter space via SBI

One modified dispersion relation, many consequences

$$E^2 = p^2c^2 \times \left[1 + \sum_{n=1}^{\infty} S_n \left(\frac{E}{E_{QG,n}}\right)^n\right]$$

$$\mathrm{E_{QG,n}} = \mathcal{O}(E_{\mathrm{Pl}}) \simeq 1.22 \times 10^{19}\,\mathrm{GeV}$$

The usual starting point for quantum-gravity searches with gamma rays.
Not a direct consequence of any particular model.
A simple way of parametrising behaviour out of the ordinary.

Consequences of the MDR

- Energy-dependent photon group velocity
- Modified reaction thresholds and cross sections: Breit–Wheeler, Bethe–Heitler, Compton, synchrotron emission
- Photon decay; vacuum gamma-ray emission
- Vacuum birefringence — needs polarisation measurements

Tiny effects, but cumulative over astronomical distances.

Reviews

Addazi+ 2022 — QG models and tests across cosmic messengers

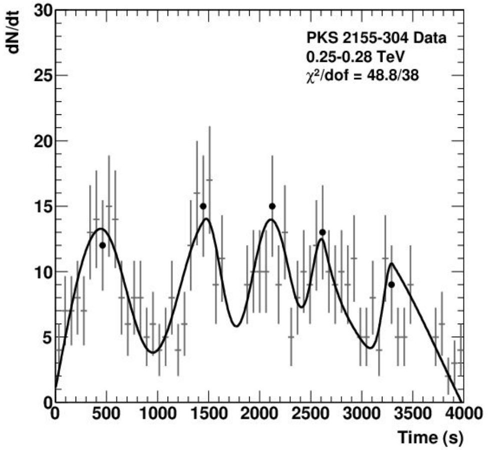
Prog. Part. Nucl. Phys. 125 (2022) 103948 · arXiv:2111.05659

Terzić, Kerszberg & Strišković 2021 — focused on LIV studies with IACTs

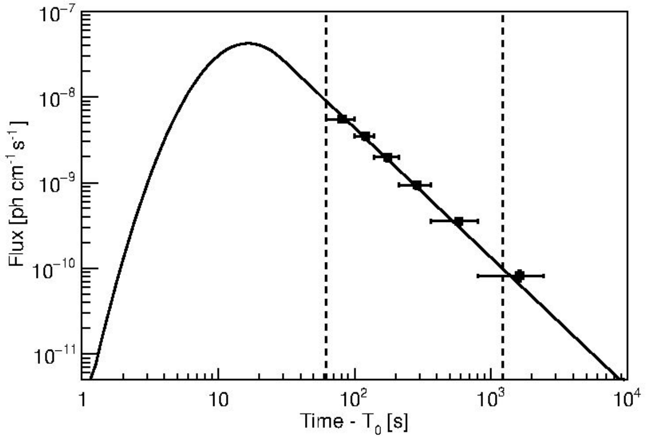
Universe 7 (2021) 9, 345 · arXiv:2109.09072

Time delays / time of flight / energy-dependent group velocity

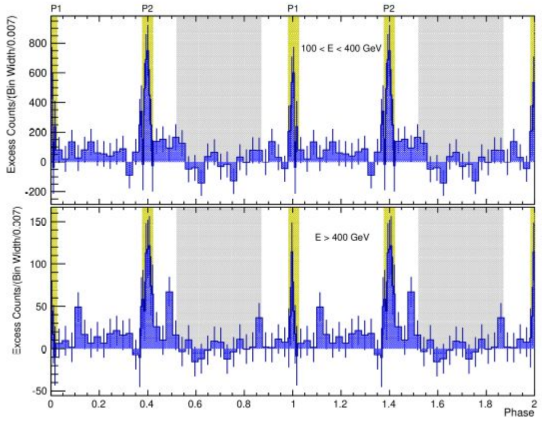
AP 34, 738 (2011) · arXiv:1101.3650



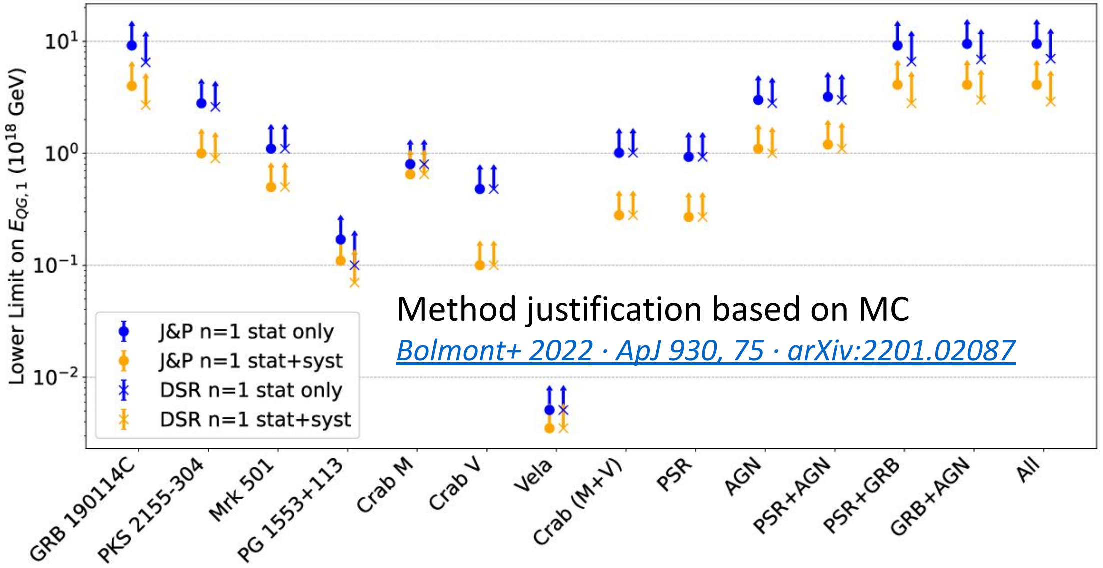
PRL 125, 021301 (2020) · arXiv:2001.09728



ApJS 232, 9 (2017) · arXiv:1709.00346



see also: Campoy Ordaz
TeVPA 2026 · #390 · Thu 3 Sep, 17:12



Method justification based on MC
Bolmont+ 2022 · ApJ 930, 75 · arXiv:2201.02087

γLIV working group

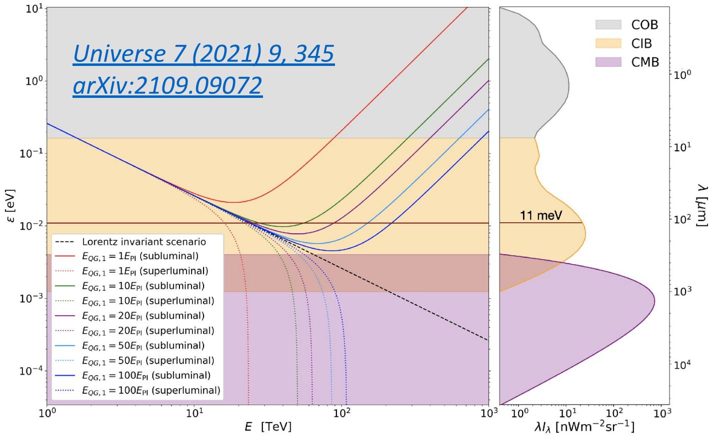
CTAO-LST · H.E.S.S. · MAGIC · VERITAS, ~20 GeV to 100 TeV.
open to expanding the collaboration

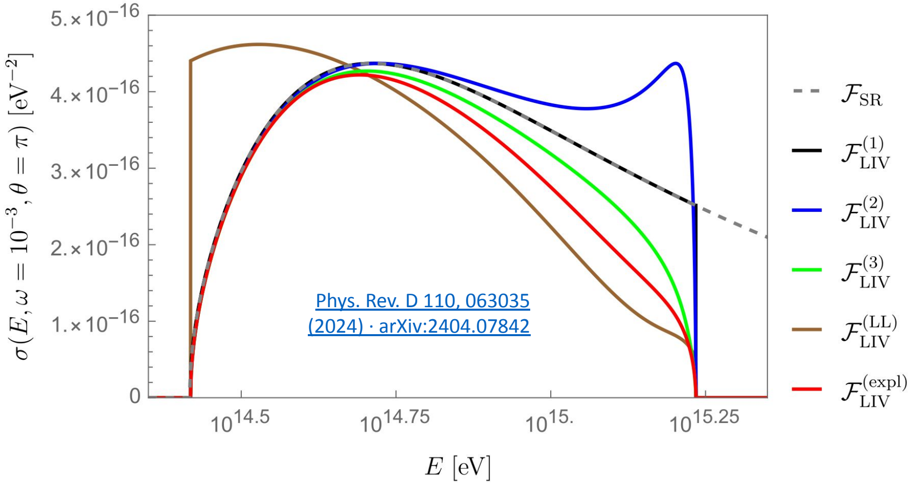
- AGN, GRB, and pulsar data analysed with a common statistical approach, then combined in a global joint likelihood
- Instrument responses handled per source and per instrument
- Different source types dilute the intrinsic effects
- Redshift spread resolves LIV models

Preliminary first results on real data
Plard et al. · PoS(ICRC2025)807 — for the γLIV WG

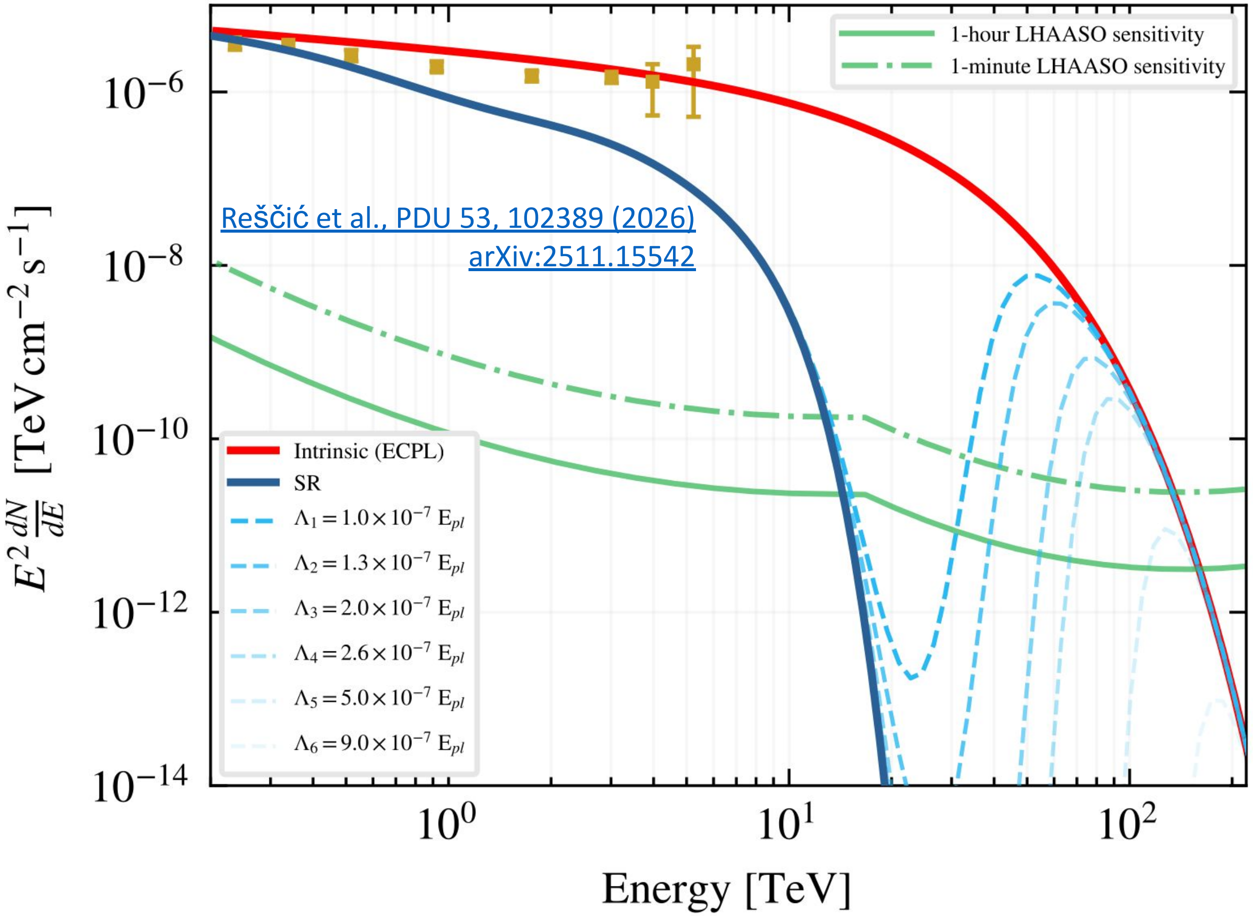
Modified universe transparency

$\gamma + \gamma(\mathrm{EBL}) \to e^{+} + e^{-}$, with the threshold and cross section both modified.





LHAASO: BOAT (GRB 221009A)



3

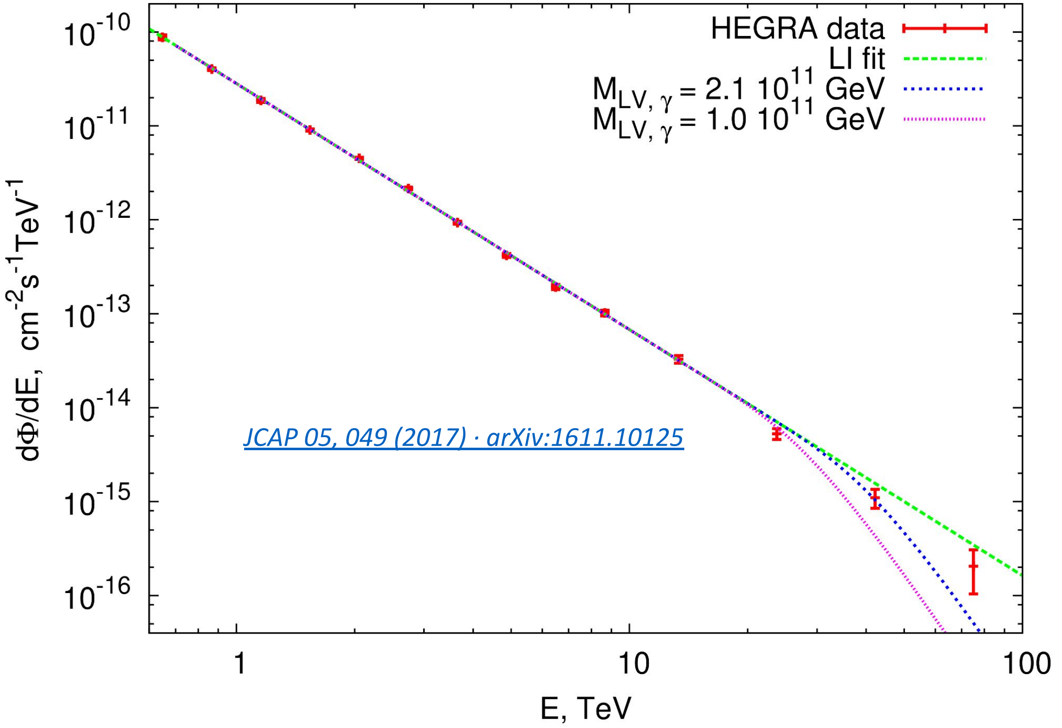
In the detector

Cosmic rays

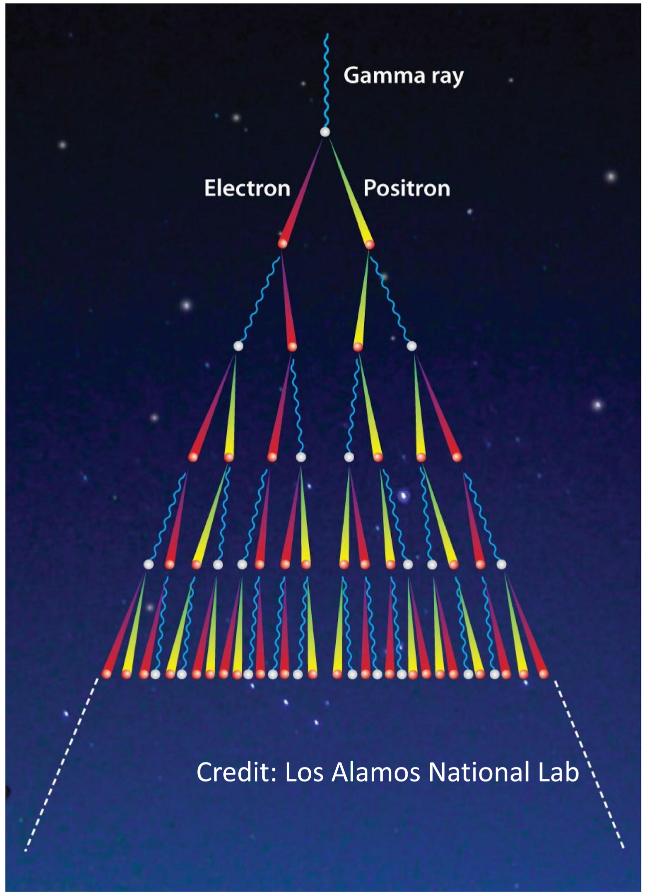
The effect nobody has simulated

The same effect that changes absorption on the background also changes how air showers develop

In the subluminal case the effect runs opposite to EBL absorption.
A signature in the shower could mimic, or mask, one in propagation.



[*JCAP 05, 049 (2017) · arXiv:1611.10125*]



Shower simulations with LIV

BridgeQG

C8

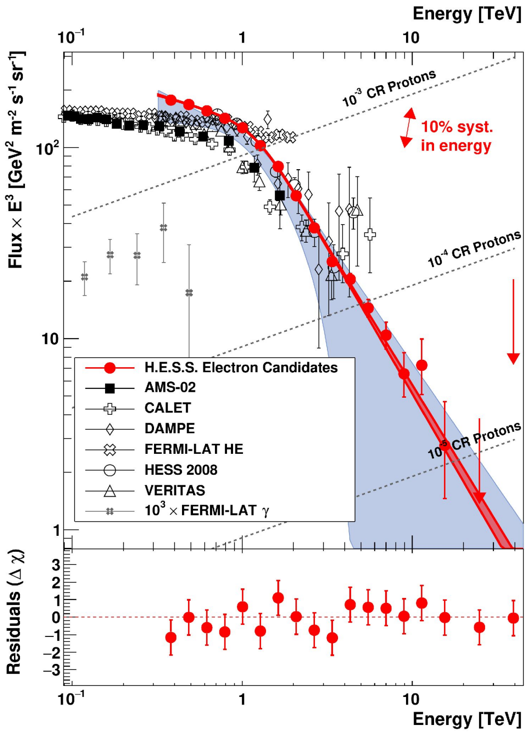
Applicable to cosmic-ray and neutrino-induced showers

Background to the foreground

Filling the gap between satellite detectors and ground-based air-shower detectors

Every gamma-ray analysis is built to reject the hadronic and electronic background. Invert the selection and the same instrument becomes a cosmic-ray detector.

Electrons — H.E.S.S.



Broken power law, break near 1 TeV

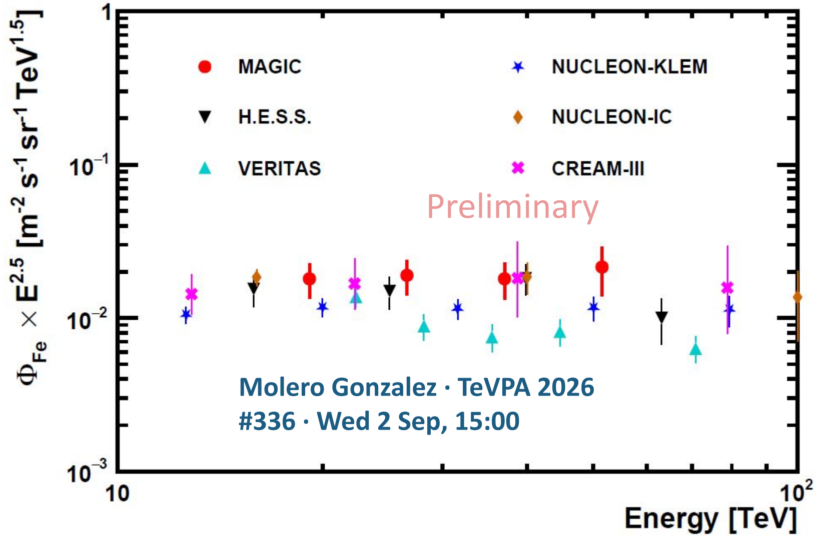
$\Gamma_1 = 3.25$ ± 0.02 stat ± 0.2 sys

$\Gamma_2 = 4.49$ ± 0.04 stat ± 0.2 sys

0.3–40 TeV, proton rejection better than 10^4.

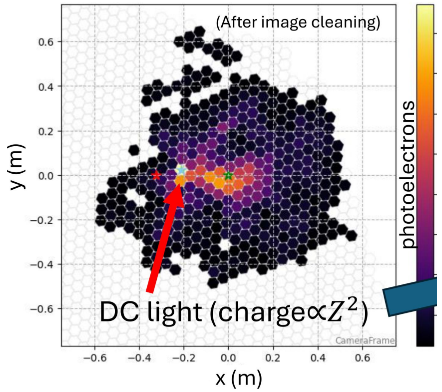
[PRL 133, 221001 (2024)](https://doi.org/)
[arXiv:2411.08189](https://arxiv.org/abs/2411.08189)

Iron — MAGIC



494 h, 293 iron events. Rejection of Z ≤ 14 better than 95%.

Iron — CTAO-LST



Mizuno · TeVPA 2026 · #384 · Wed 2 Sep, 14:30

see also: **Proton — SST-1M**
Jurysek · TeVPA 2026 · #279 · Thu 3 Sep, 17:15

4

Future perspectives

Where do we go now?

What the next few years bring

Dark matter

"...higgsino detection could be possible within this decade with CTAO-North…"

Abe+ 2025 · arXiv:2506.08084

Primordial black holes

- burst searches are for detection; limits on the population from the diffuse background
- CTAO – more telescopes → larger sky coverage

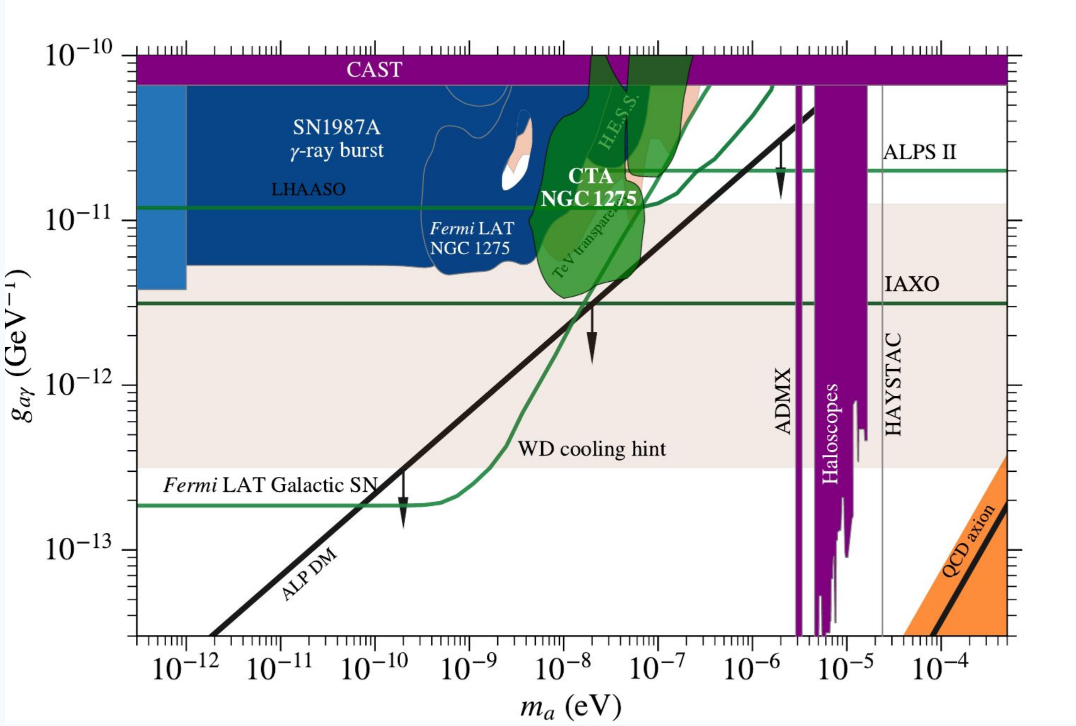
do Souto Espiñeira et al. · TeVPA 2026 · #420 · Tue 1 Sep, 17:12

EBL

γ-ray absorption measured to better than 15% statistical uncertainty, out to z = 2.

JCAP 02 (2021) 048 · arXiv:2010.01349

ALPs



JCAP 02 (2021) 048, Fig. 8 · arXiv:2010.01349

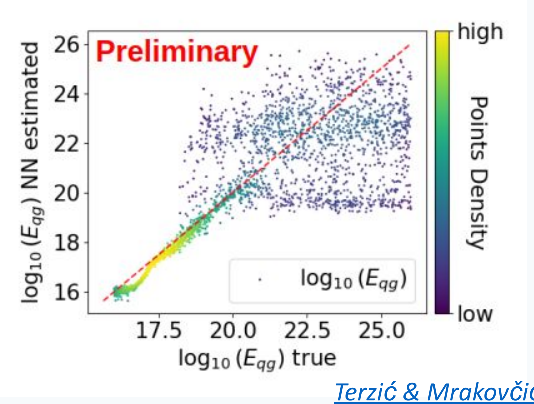
What the next few years bring

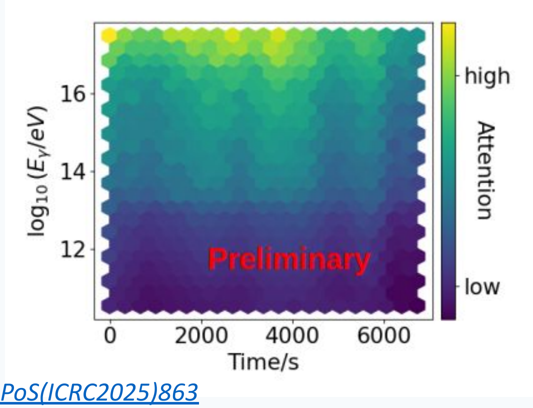
LIV / DSR

CTAO – ~10× better sensitivity → more sources, higher redshifts, **better-sampled light curves**

Where the effort should go (IMHO)

- Combine observations of different (types of) sources in a single analysis
- Put LIV into shower simulations and analyse it — transferable to other experiments and other messengers
- **In collaboration with theorists settle which LIV effects coexist — then fit them in a single analysis**





Terzić & Mrakovčić · PoS(ICRC2025)863

IGMF

Constrain or detect γ-ray halos up to field strengths of at least 0.3 pG.

JCAP 02 (2021) 048 · arXiv:2010.01349

Cosmic rays

· iron with the CTAO-LST array: simultaneous observations improve background rejection and detection efficiency

· the proton spectrum with SST-1M

Mizuno #384 · Wed 2 Sep, 14:30 Jurysek #279 · Thu 3 Sep, 17:15

STATUS

Doing fundamental physics with IACTs in a nutshell

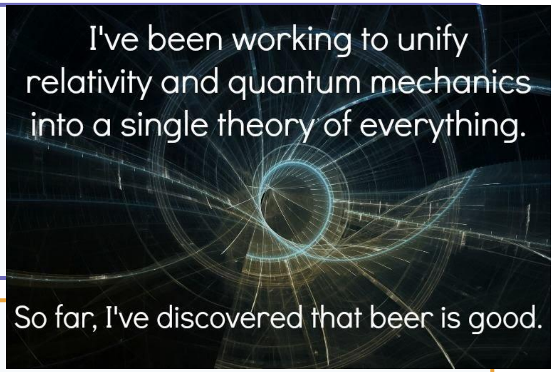
1

Reduce, reuse, recycle

- Not counting DM searches, data for fundamental studies are **as a rule** taken from observations made for other purposes.
- Highly competitive and prominent results.
- **Would dedicated observations yield stronger results?**
- **What about dedicated instruments?**

2

Help wanted



- The IACT core product is astrophysics.
- Fundamental studies **as a rule** require dedicated analysis methods.
- Recruiting from the particle physics community?

3

Synergy — beer tastes better together

- With theorists — complete and clear understanding of investigated phenomena.
- With particle experiments — complementing the parameter space.

The field has been remarkably good at extracting fundamental physics from data mostly collected for other reasons.