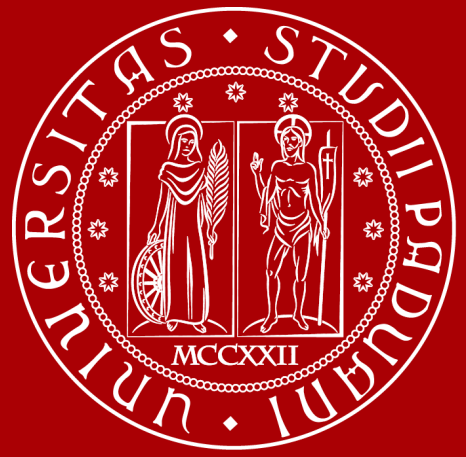

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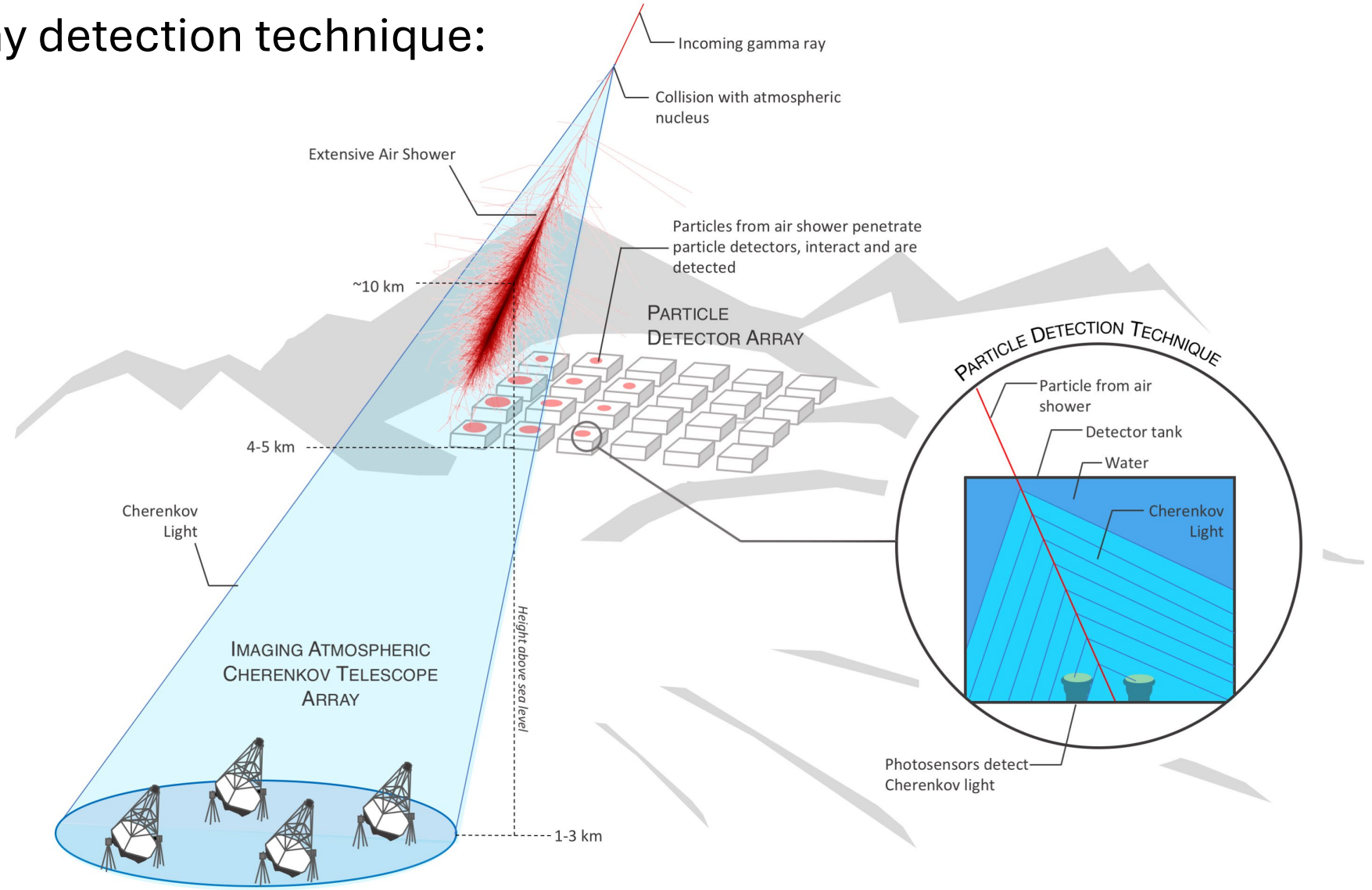
Design and performance optimization of the Southern Wide-field Gamma-ray Observatory at the PeV scale

Luis Recabarren, 39th Cycle
Supervisor: Prof. Michele Doro, Co-supervisor: Dr. Tommaso Dorigo

3rd year admission – 10/09/2025

Introduction: Gamma-ray astrophysics

Ground γ-ray detection technique:



Shower image, 100 GeV γ-ray adapted from: F. Schmidt, J. Knapp, "CORSIKA Shower Images", 2005, https://www-zeuthen.desy.de/~jknapp/fs/showerimages.html

Not to scale

Introduction: Current instruments

Introduction: Current instruments

SWGO: The status

- SWGO is a water Cherenkov particle detector to detect gamma-rays of 100 GeV to tens of PeV. It is under R&D phase. Building phase is expected to start in 2026 (inner array).
- Circular array of ~3800 tanks deployed on~1 km2. It is a wide field of view, 100% duty cycle instrument.
- It will be located at 4770 m.a.s.l, at the Astronomical Park, Atacama desert, Chile.

SWGO members and guests at the site of the project, Pampa La Bola (12th Collaboration Meeting, San Pedro de Atacama, 5-9 May, 2025)

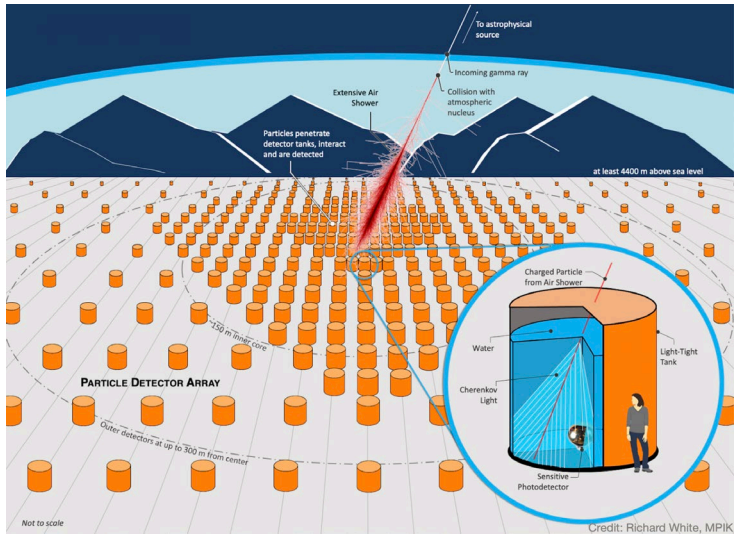
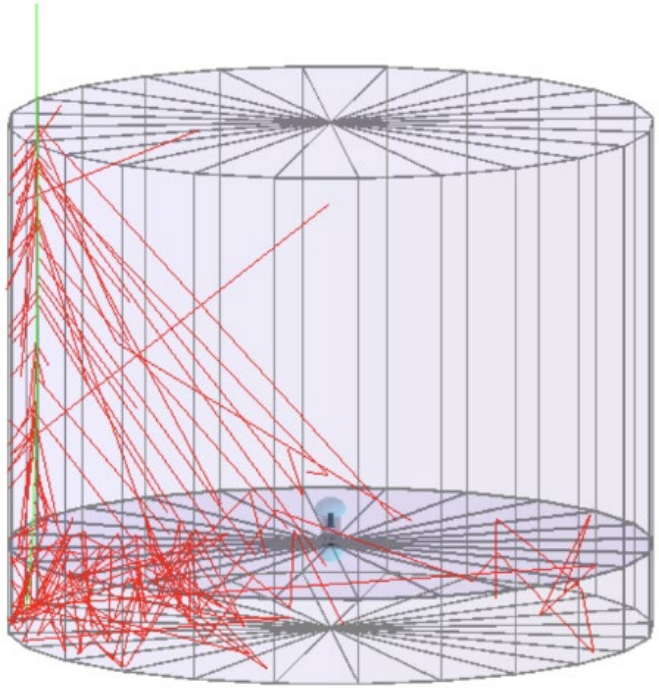


Image credits: SWGO collaboration.

SWGO: The status

- **SWGO-A** refers to a part of the inner array. It is the initial building stage that have already started.
- 70% FF (GeV-TeV sensitivity). Double-layered detector 5.2 m diameter, 4.1 m height.



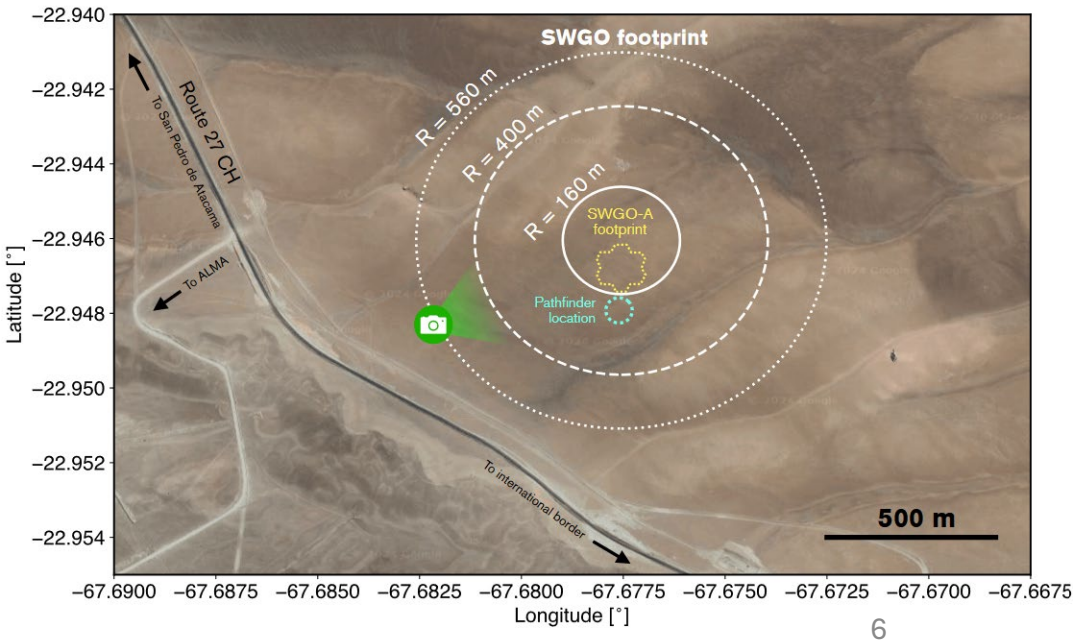
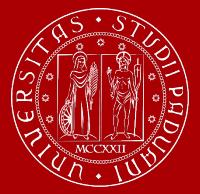


Image credits: SWGO collaboration.



Università degli Studi di Padova

2nd year research

- Focus in three areas
- Array Layout Optimization (SWGO-LO)
- Study on air showers at PeV energy scale.
- SWGO pipeline & Science Case: Lorentz Invariance Violation (LIV) signatures

SWGO-Layout Optimization (SWGO-LO)

- Gradient descent-based algorithm applied on a parametric model of the array layout to optimize the tanks configuration. Work lead by T. Dorigo in collab. with MODE experiment.
- We worked to find a well-defined utility function (essential in our pipeline) & 2 articles submission.

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Nuclear Physics B

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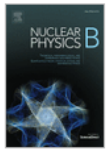
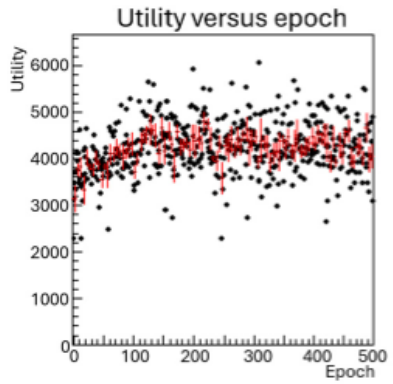
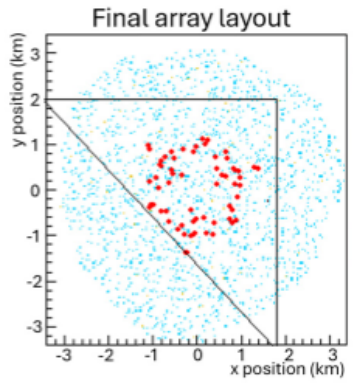


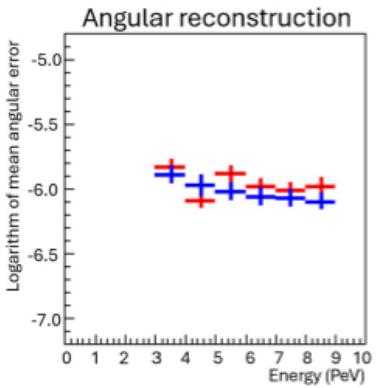
Special Issue on Machine Learning

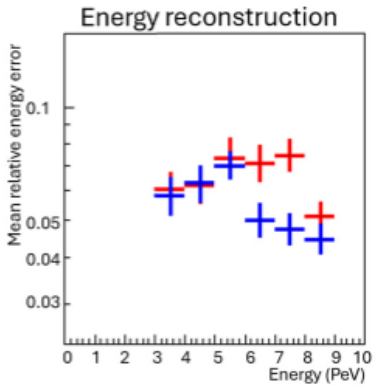
Toward the end-to-end optimization of the SWGO array layout

Tommaso Dorigo [a b c d], Max Aehle [b h], Cornelia Arcaro [c], Muhammad Awais [a c d e], Fabiola Bergamaschi [m], Julien Donini [b d f], Michele Doro [e c], Nicolas R. Gauger [b h], Rafael Izbicki [i], Jan Kieseler [b j], Ann Lee [b g], Luca Masserano [b g], Federico Nardi [b c e f], Raaghav Rajesh [k], Luis Recabarren Vergara [l c e], Alexander Shen [g]



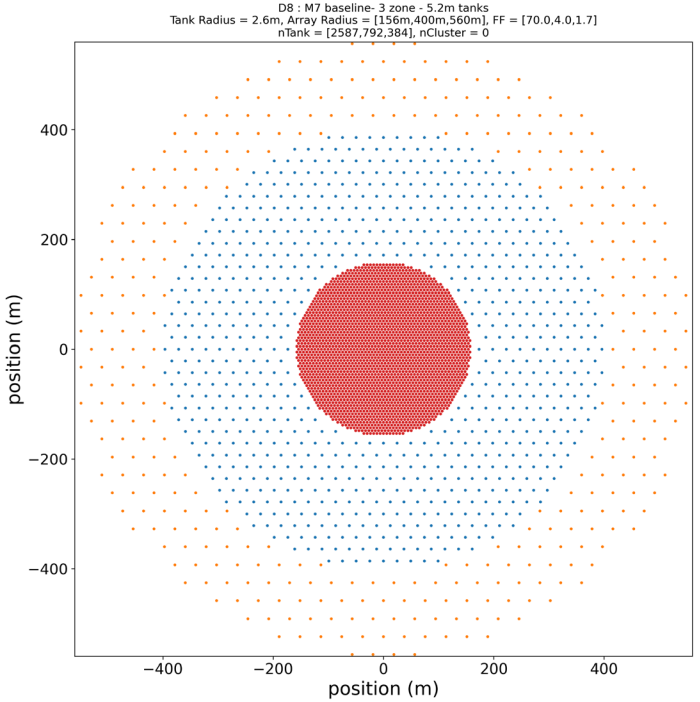






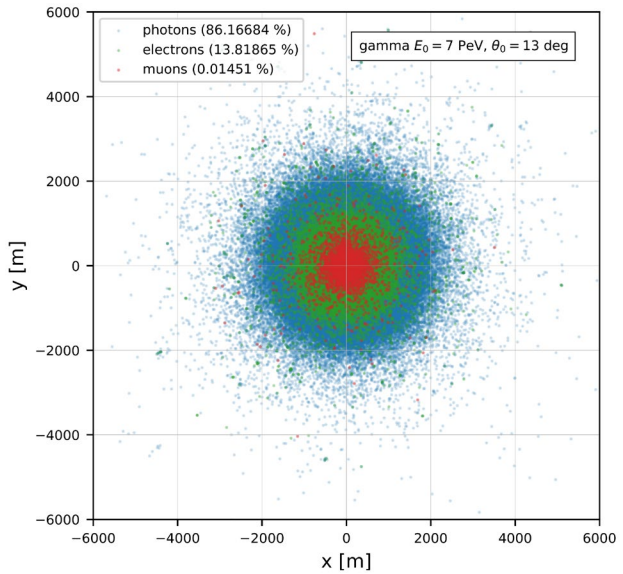
Study on PeV air showers

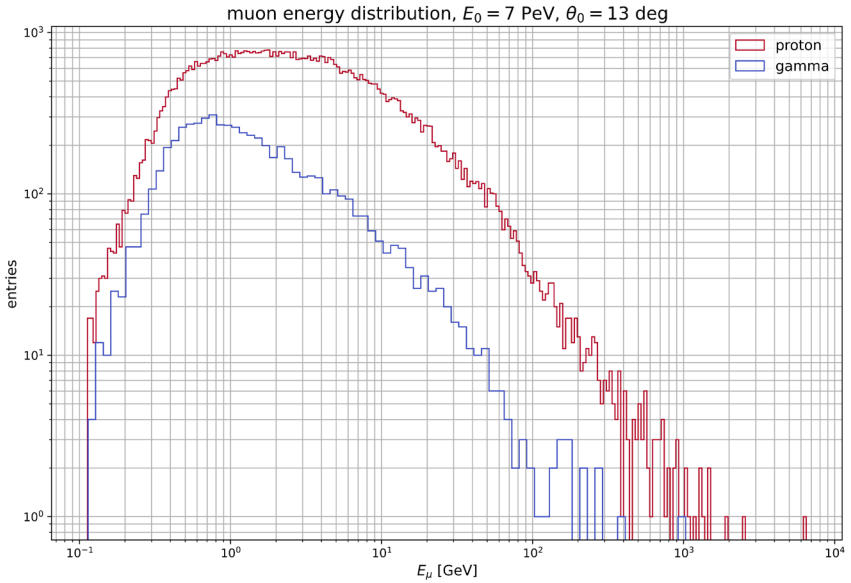
- Study of PeV air showers properties at ground level.
  - γ/h separation feasibility using the N_μ of extensive air showers.
  - Footprint, energy distribution, radial density, μ/EM particle ratio.
  - Test these observables robustness applying fill factors (in particular 1.7% and 4% used in SWGO outer zone layouts)

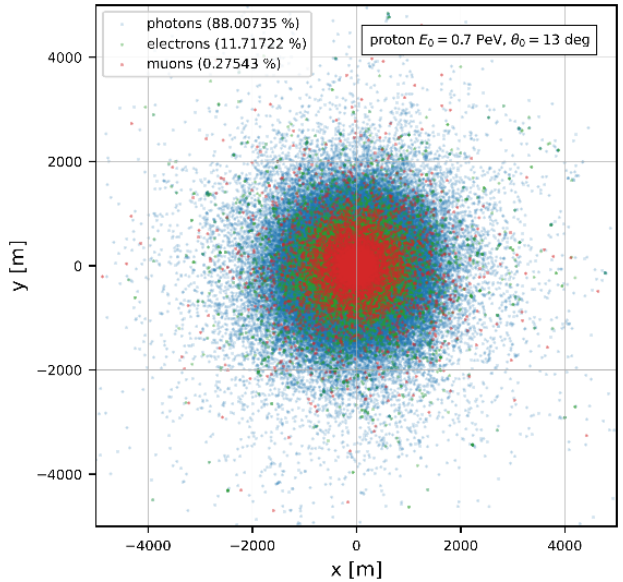


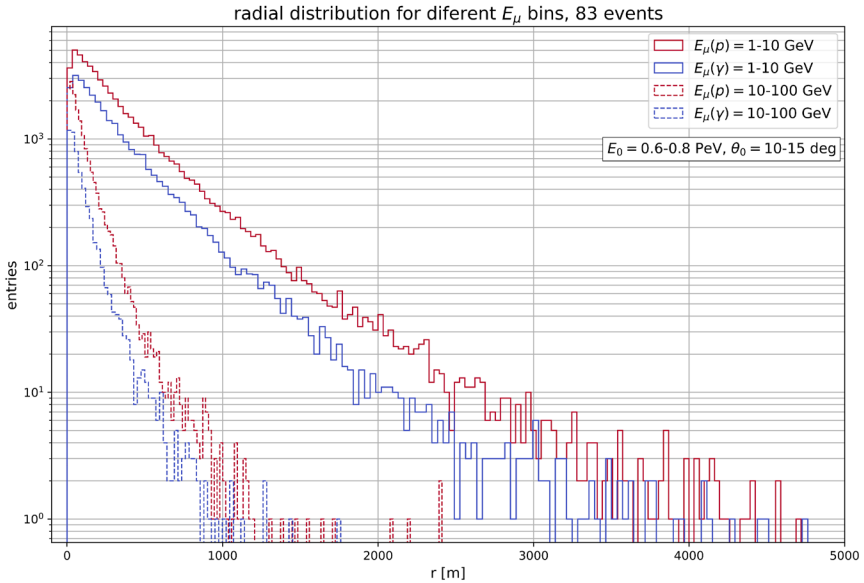
- We use a big production of CORSIKA simulations at CNAF:
  - 30 TeV-10 PeV. Inclination [0,52] deg. Simulated for SWGO site (altitude, magn. Field)
  - 3.8×10^5gammas, 10^6 protons.

Study on PeV air showers



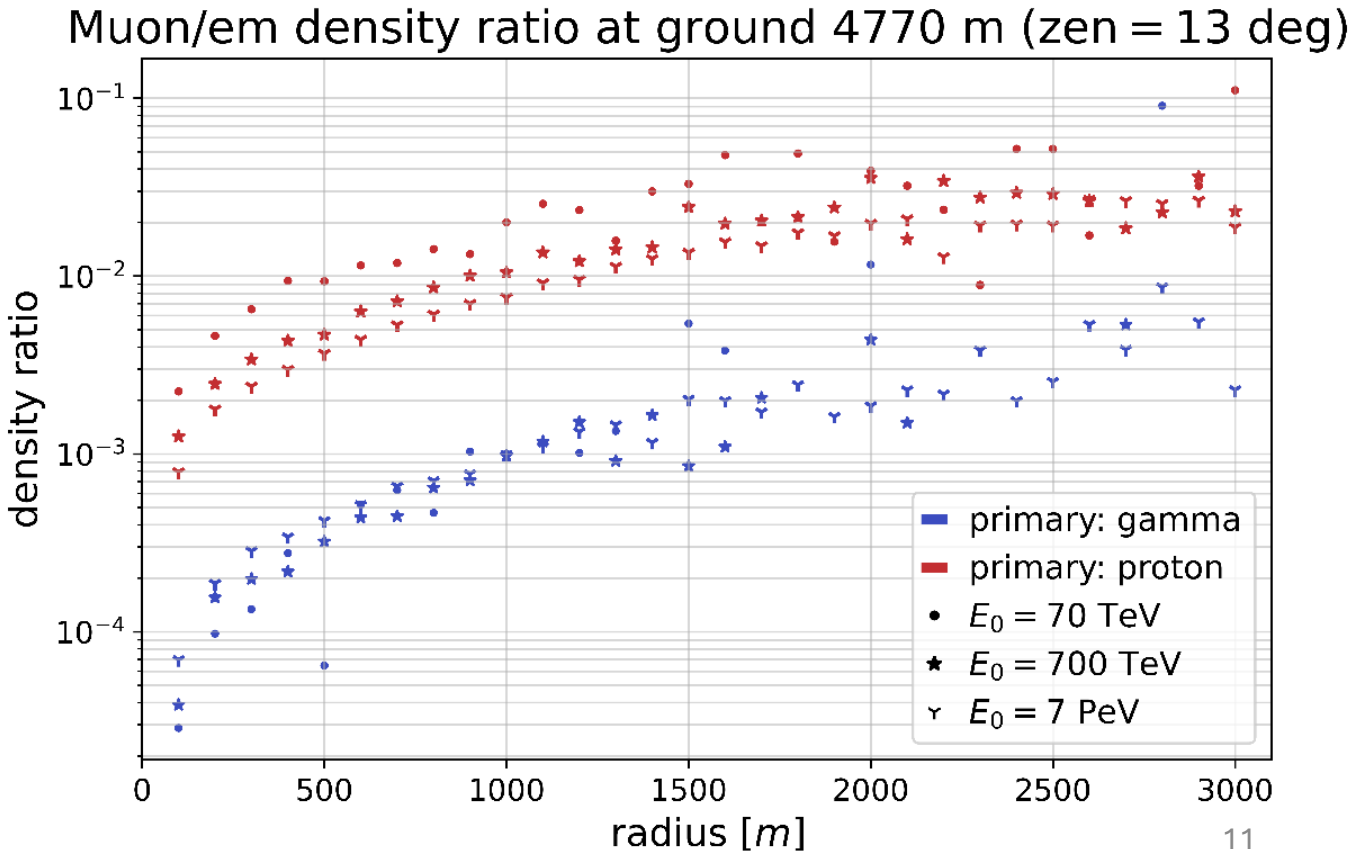






Study on PeV air showers

- From footprints, $N_\mu(p) > N_\mu(\gamma)$.
- Higher energy muons are concentrated close to the core
- Lower energy muons goes to outer radii.
- Observing the muon/EM density ratio, we noticed we could in principle separate gammas and protons.



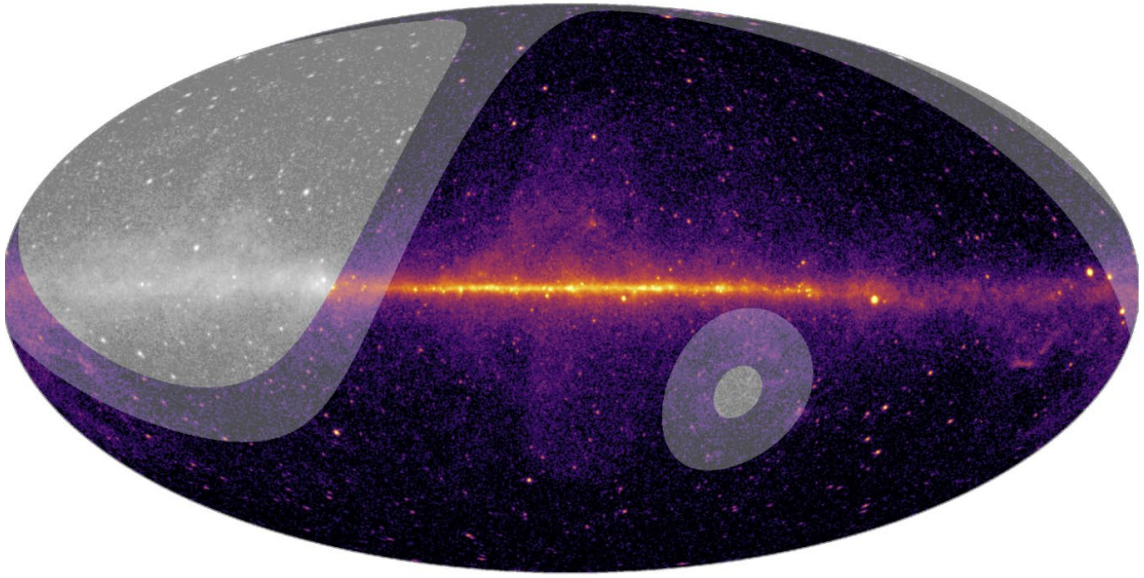
Contribution to SWGO scientific potential paper

- Contributed as author to the section on observational prospects for Primordial Black Hole evaporation.
- The preprint was uploaded to arxiv https://arxiv.org/abs/2506.01786
- A version for a journal is in elaboration.

Science Prospects for the Southern Wide-field Gamma-ray Observatory: SWGO

P. Abreu[1,2], R. Alfaro[3], A. Alfonso[4], M. Andrade[5], E. O. Angüner[6], E. A. Anita-Rangel[7], O. Aquines-Gutiérrez[8], C. Arcaro[9], R. Arceo[10], J. C. Arteaga-Velázquez[11], P. Assis[1,2], H. A. Ayala Solares[12], A. Bakalova[13], E. M. Bandeira[14], P. Bangale[12], U. Barres de Almeida[14,15], P. Batista[16], I. Batković[9,17], J. Bazo[18], E. Belmont[3], J. Bennemann[19], S. Y. BenZvi[20], A. Bernal[7], W. Bian[21], C. Bigongiari[22], E. Bottacini[9,17], R. Branada[23], P. Brogueira[1,2], A. M. Brown[64], T. Bulik[24], K. S. Caballero-Mora[10], P. Camarri[25,26], W. Cao[27], Z. Cao[27], Z. Cao[28], T. Capistrán[29,30], M. Cardillo[22], C. Casentini[22,25], C. Castromonte[31], P. M. Chadwick[64], J. Chanamé[32], J. Chang[28], S. Chen[21], A. Chiavassa[29,30], L. Chytka[13], R. Colalillo[33,34], R. Conceição[1,2], G. Consolati[35,36], R. Cordero[37], P. J. Costa[1,2], R. Covarelli[29,30], X. Cui[38], X. Cui[38], A. De Angelis[9,17], E. de Gouveia Dal Pino[39], R. de Menezes[14], P. Desiati[40], N. Di Lalla[85], F. Di Pierro[29,30], G. Di Sciascio[25], J. C. Díaz Vélez[40], C. Dib[23], B. Dingus[41,48], J. Djuvsland[19], C. Dobrigkeit[43], L. M. Domingues Mendes[1,44], T. Dorigo[9,45,46], M. Doro[9,17], A. C. dos Reis[14], M. Du Vernois[40], D. Elsaesser[47], K. Engel[48], T. Ergin[49,50], M. Errando[51], K. Fang[40], A. Fazzi[36,52], C. Feng[53], M. Feroci[22], C. N. Ferreira[54], N. Fraija[7], S. Fraija[7], A. Franceschini[17,83], G. F. Franco[14], S. Funk[16], R. Galleguillos[55], B. Gao[28], C. Gao[28], A. M. Garcia Reyes[7], S. Garcia[56], F. Garfias[7], G. Giacinti[21], L. Gibilisco[1,2], B. Giovanni[9,17], J. Glombitza[16], H. Goksu[19], G. Gong[57], B. S. González[1,2], M. M. González[7], J. Goodman[48], V. M. Grieco[34,58], M. Gu[28], F. Guarino[33,34], G. P. Guedes[59], J. Gyeong[60], F. Haist[19], G. Han[61], P. Hansen[62], J. P. Harding[41,42], S. Hernandez Cadena[21], I. Herzog[50], J. A. Hinton[19], W. Hofmann[19], C. Hou[28], Hou C.[28], K. Hu[53], D. Huang[48,63], P. Huentemeyer[63], A. Iriarte[7], J. Isakovic[65], A. Jardin-Blicq[66,67], L. I. Junoy[68], J. Juryšek[13], S. Kaci[21], B. Khelifi[69], D. Kieda[70], F. La Monaca[22], G. La Mura[1,71], R. G. Lang[16], J. S. Lapington[72], R. Laspiur[73], L. Lavitola[34], J. Lee[74], F. Leitl[16], M. Lemoine-Goumard[66], L. Lessio[22], T. Lewis[63], C. Li[28], J. Li[27], K. Li[28], T. Li[21], B. Liberti[25], S. Lin[75], R. A. Lineros[68], D. Liu[53], J. Liu[28], R. Liu[76], F. Longo[77,78], Y. Luo[21], J. Lv[79], E. Macerata[36,52], G. Magugliani[36,52], K. Malone[41], A. Mancilla[80], D. Mandat[13], M. Manganaro[65], M. Mariani[36,52], A. Mariazzi[62], M. Mariotti[9,17], T. Marrodan[19], H. Martínez-Huerta[8], I. Martins[1,2], S. Medina[4], D. Melo[80], L. F. Mendes[1,2], E. Meza[81,82],

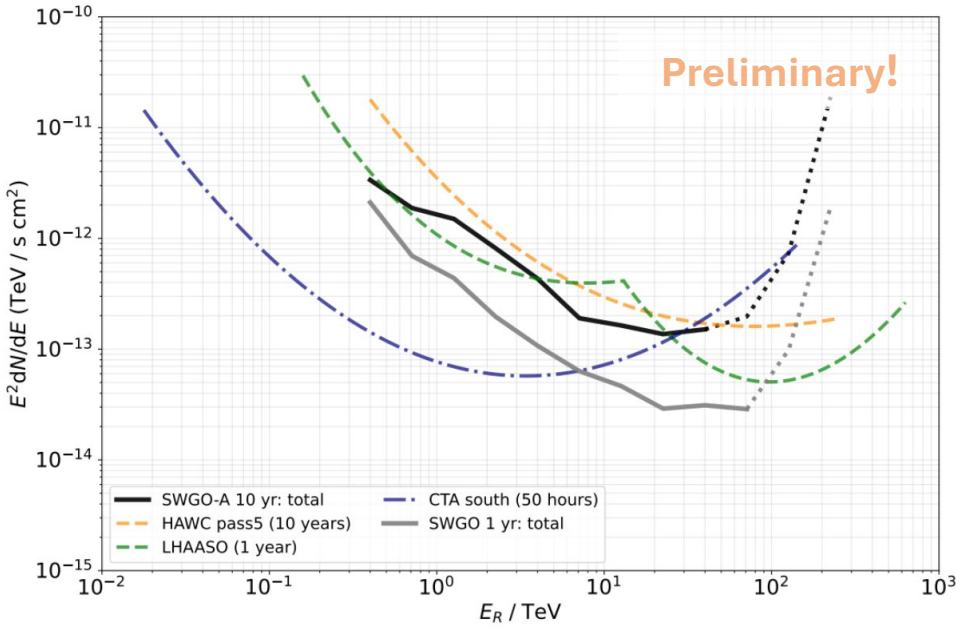
25 Jun 2025

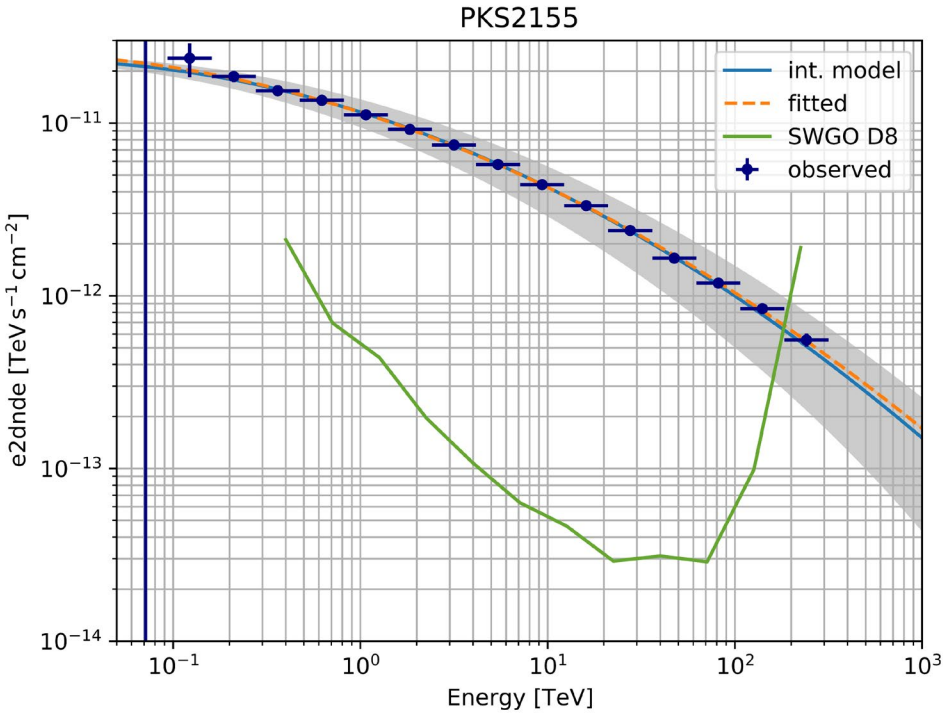


Sky observable to SWGO above 45◦ (full color) and 60◦ (color shaded)

SWGO pipeline & Science Case

- Instrument Response Functions (IRFs) v.2 were released
- SWGO reconstruction pipeline Python-based: ***pyswgo***
- ***pyswgo*** manages the IRFs to use it with Gammapy (state-of-art Python-based package used in gamma-ray astronomy).





SWGO pipeline & Science Case: LIV

- This work is a collaboration with the SWGO-Croatia group (U. of Rijeka)
- Lorentz Invariance Violation is a phenomenon in many quantum theories of gravity [Colladay, Kostelecky; 1998]. Observable is the modified dispersion relation:

$$E^2 - k^2 = \sum_{n=1}^{\infty} S_n \left(\frac{E}{E_{LIV,n}}\right)^n$$

where $S_n = \pm 1$. Superluminal (subluminal) case equal $+(-)$.

- The process $\gamma_{low}\ \gamma_{vhe} \rightarrow e^+\ e^-$ (low can be EBL, CMB…). In SR, from kinematics

$$2E\omega(1 - \cos\theta) \geq 4m_e^2$$

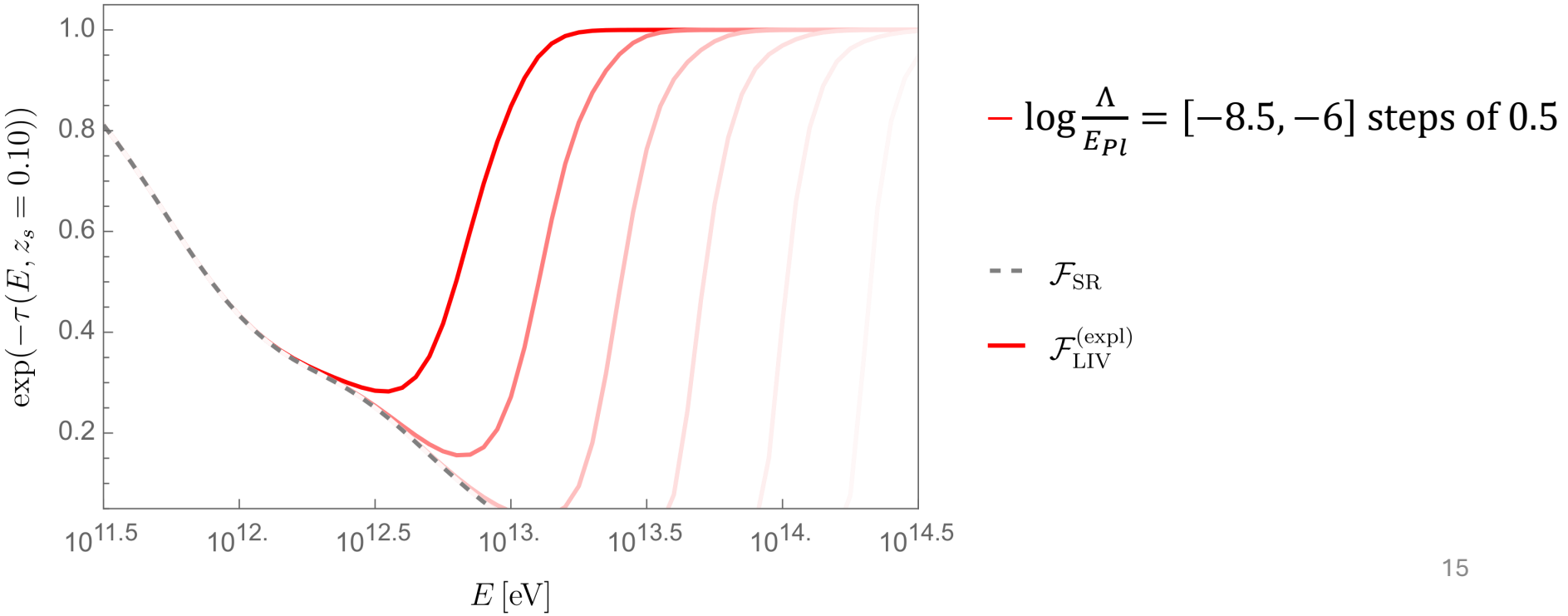
→E, ω the energy of the vhe, low photon
→θ the angle between both photons.
→$\Lambda \equiv E_{LIV,2}$

$+\text{LIV}\ (n = 2, S_2 = -1)$ the energy threshold

$$\omega_{thr}(E, \theta, \Lambda) = \frac{2m_e^2}{E(1 - \cos\theta)} + \frac{E^3}{2\Lambda^2(1 - \cos\theta)}$$

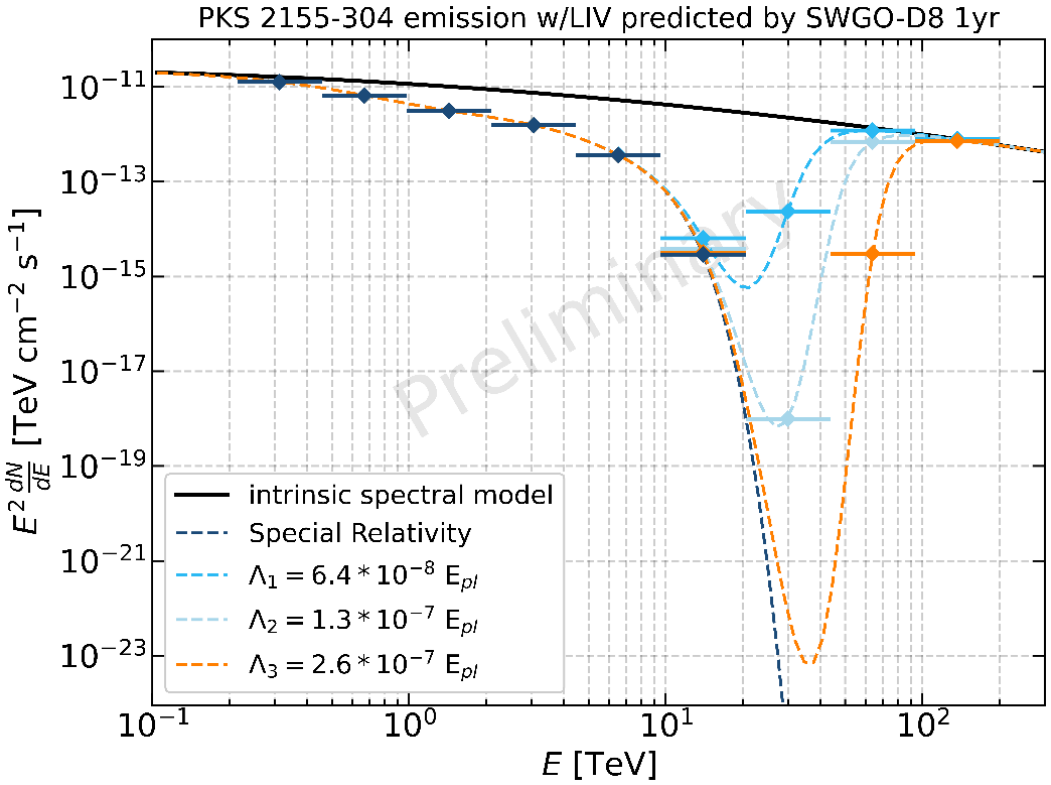
SWGO pipeline & Science Case: LIV

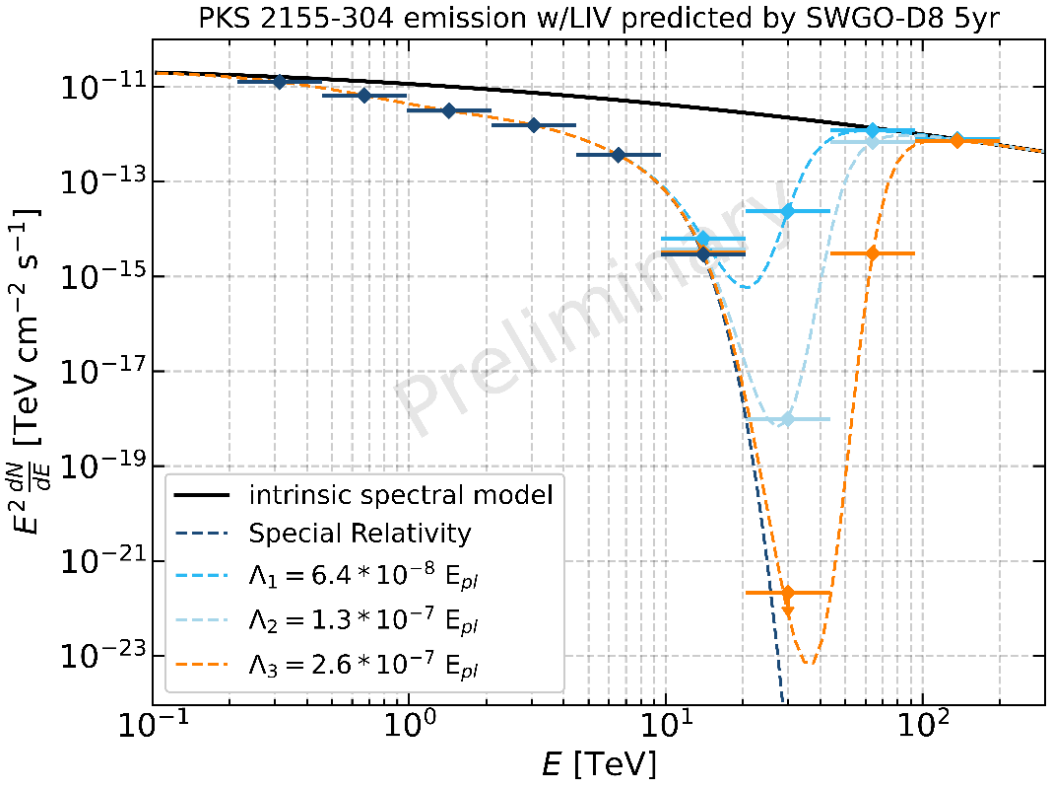
- For $(n = 2, S_2 = -1)$ the cross section is computed and introduced in the opacity τ (survival probability): $P(E, z) = \exp\{-\tau(E, z)\}$ [Carmona et al. (2024)]
- The flux is $\Phi_{obs} = P(E, z) \times \Phi_{int}$



SWGO pipeline & Science Case: LIV

- We try the source PKS 2155-304 ($z = 0.116$) observable by SWGO
- Fermi-Lat catalog 4FGL Extrapolation (LogParabola)





Congresses & progress

- Congresses:
  - 12th SWGO collaboration meeting, San Pedro de Atacama, Chile. SWGO site visit.
  - 21ma edizione degli Incontri di Fisica delle Alte Energie, INFN/University of Cagliari, Italy.
- Dissemination activity:
  - Collaborator for the exhibition “Sperimentando 2025-H2O una molecola per la vita”

Research program: Conclusions

- SWGO is a frontier science experiment that certainly will impact in Gamma-ray astrophysics and in Multimessenger era.
- SWGO design is not trivial. A lot of techniques/methods and technologies must be developed.
- Muon content in PeV air showers is a relevant study to the validation of hadronic models at very high energies.
  - An article with the concluded results is in elaboration.
- The first two versions of SWGO IRFs were released together with the reconstruction pipeline *pyswgo*. It is critical for the experiment to test and validate this software.
- LIV studies demonstrate that SWGO could be sensitive to signatures. The future work holds on upper limits computation and test with another spectral models/sources.
  - An article with the concluded results is in elaboration.
- Prepare PBHs evaporation observational prospects with new IRFs to update previous works.

Thanks for your attention!

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