Probing the Extragalactic Background Light with the MAGIC telescopes

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MAGIC
Major Atmospheric Gamma Imaging Cerenkov Telescopes

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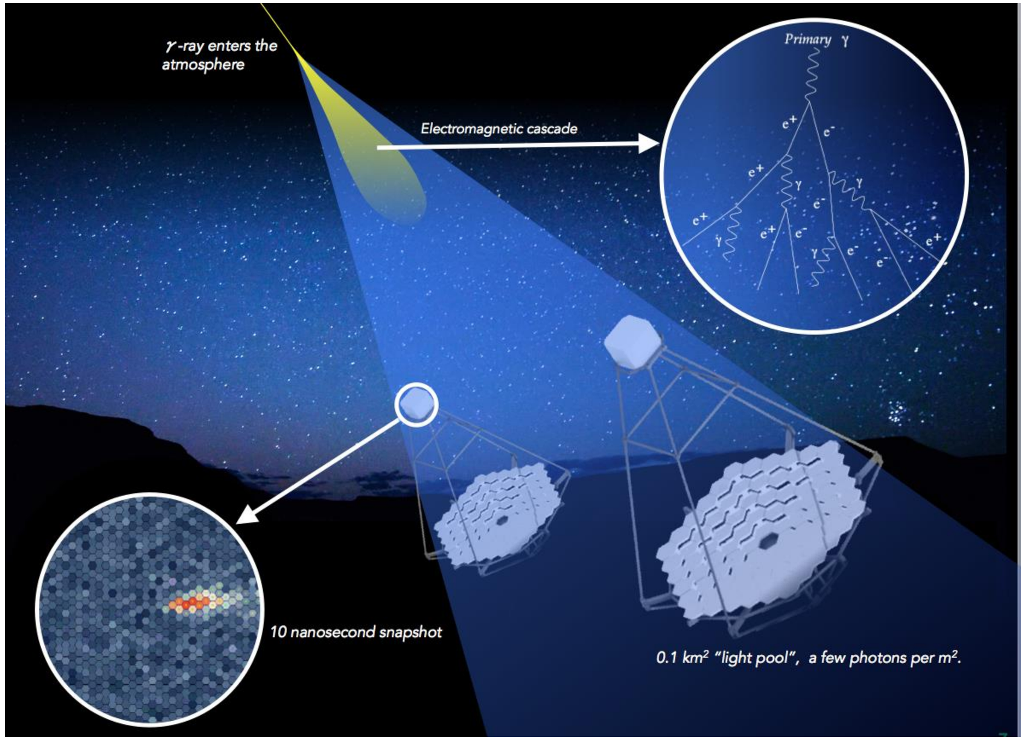
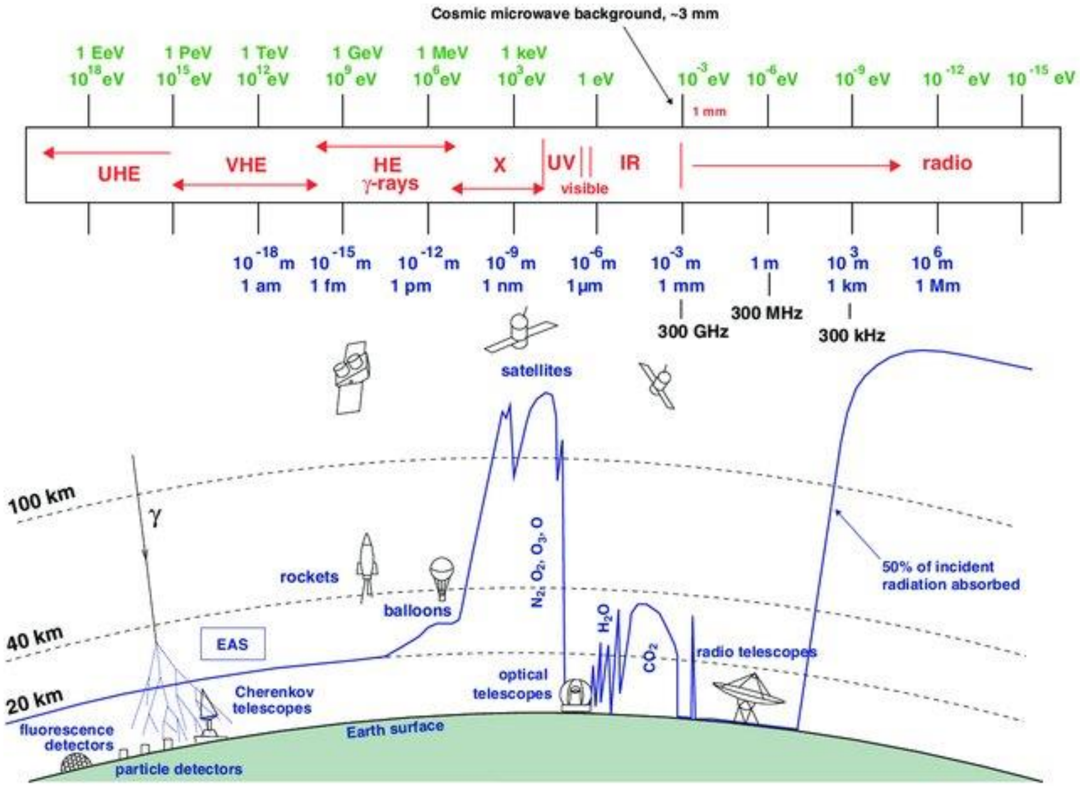
TAUP VIENNA 2023

Introduction: Cherenkov telescopes

- Our atmosphere is not transparent to Gamma rays, but for E>~10GeV we can detect them indirectly through the showers of particles they induce in the atmosphere.
- Imaging Atmospheric Cherenkov Telescopes such as MAGIC, CTA, H.E.S.S., FACT and VERITAS detect the Cherenkov light emission produced by the ultra-relativistic shower particles.



Credit: https://www.cta-observatory.org/astri-detects-crab-at-tev-energies/cherenkov-effect/



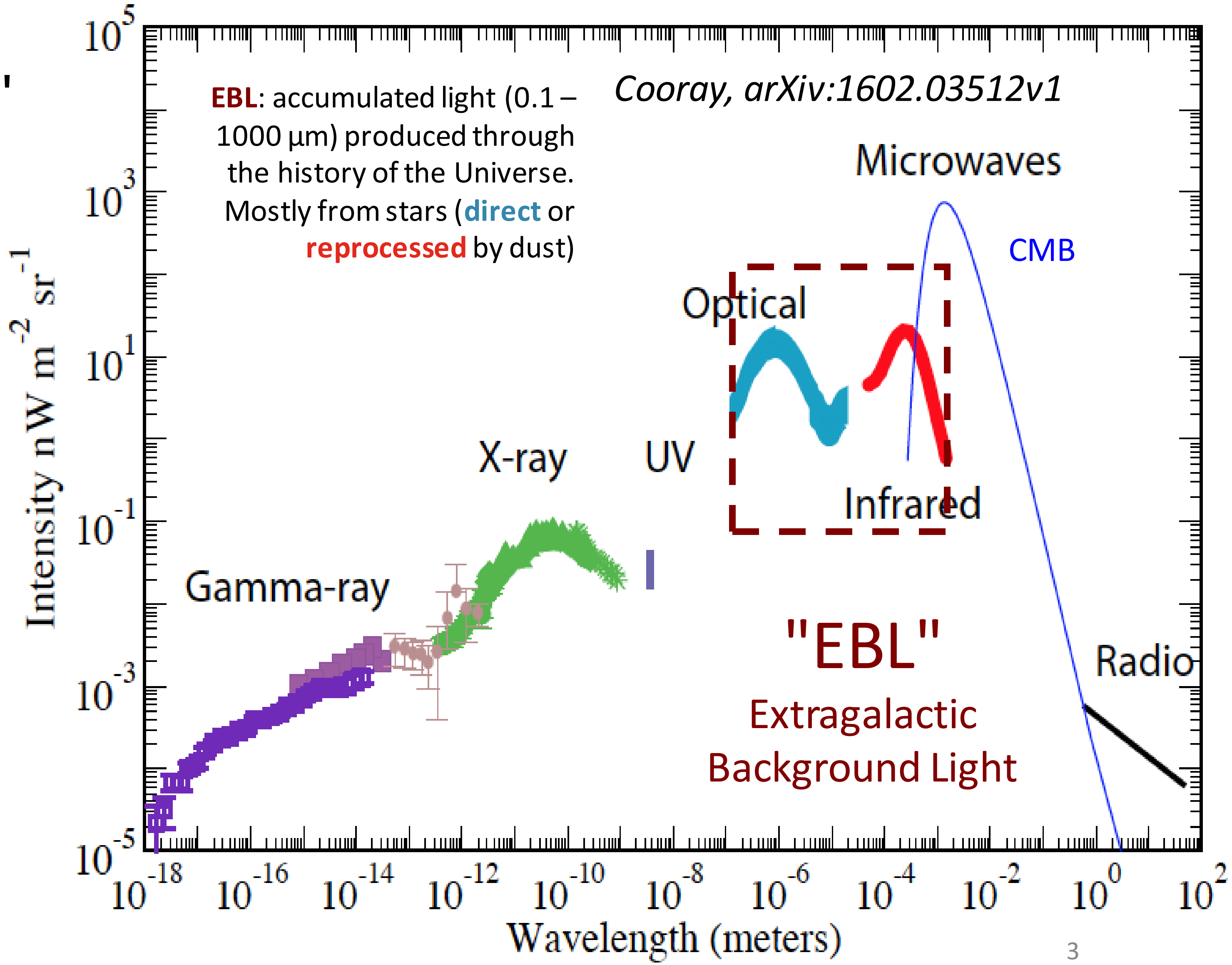
Adapted from Longair "High energy astrophysics" ,1992.

Introduction: Extragalactic Background Light

- Second most intense "diffuse" photon field.

- Cosmic Optical Background:
  - (Mostly) Light from stars.

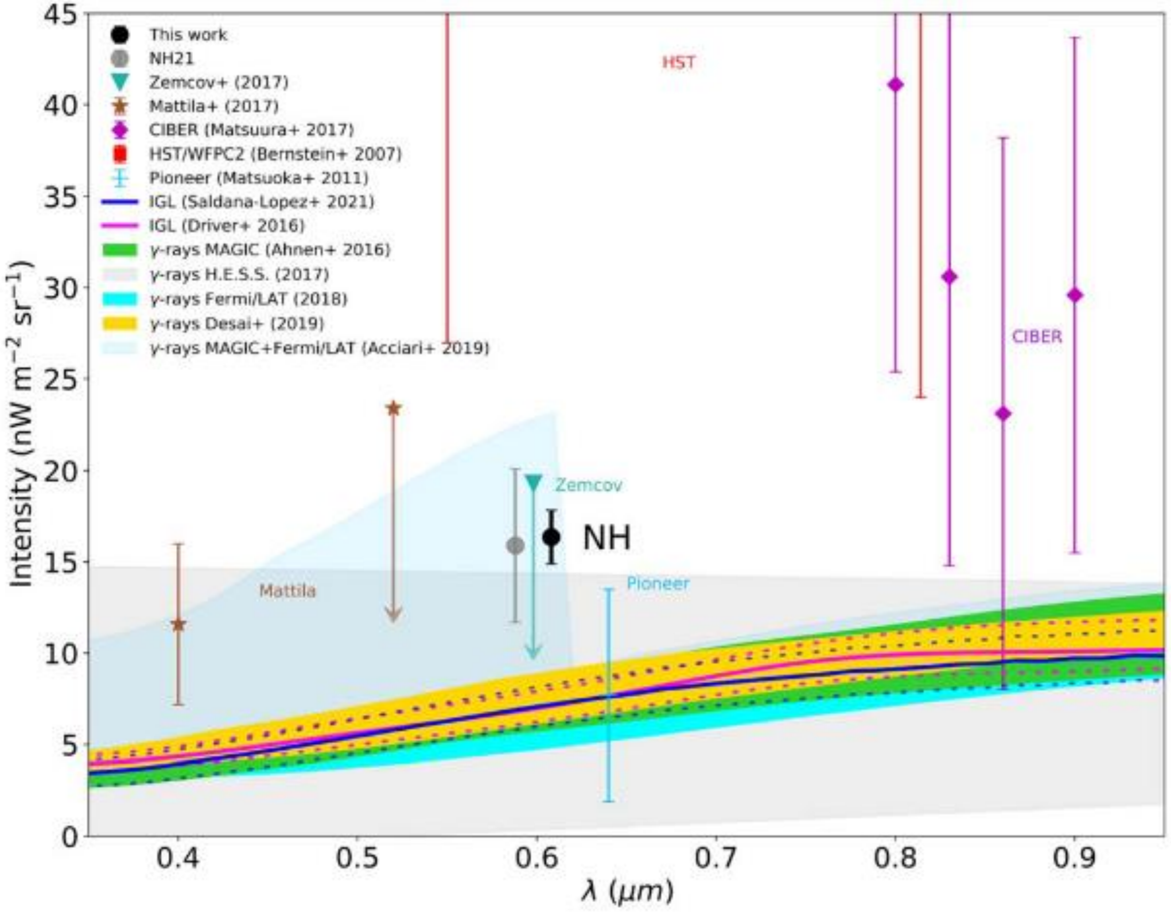
- Infrared background:
  - (Mostly) Light re-radiated after being absorbed by dust



Introduction: Probing the EBL

- Methods:
  - Direct measurements:

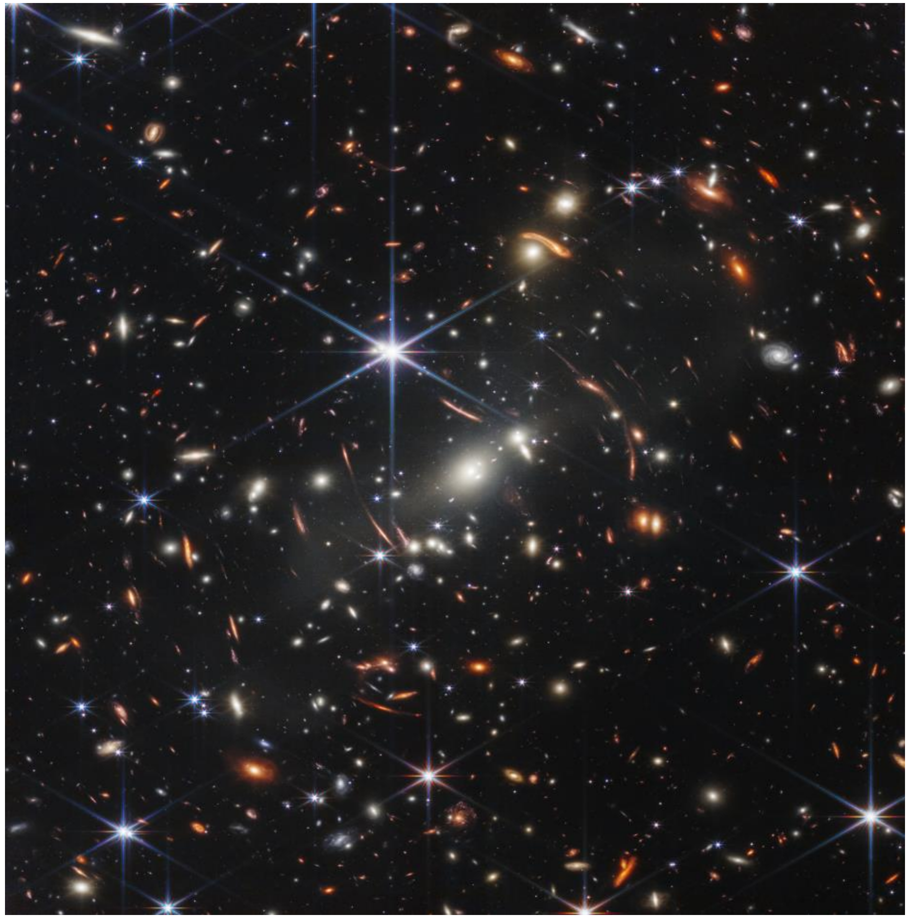
- Extracting EBL from direct measurements is difficult as it requires subtracting much larger foregrounds.
- Lauer et. al. 2022: direct measurement using New Horizons data (~50 a.u. from the Sun => much smaller foregrounds).



Credit: Lauer et al 2022

Introduction: Probing the EBL

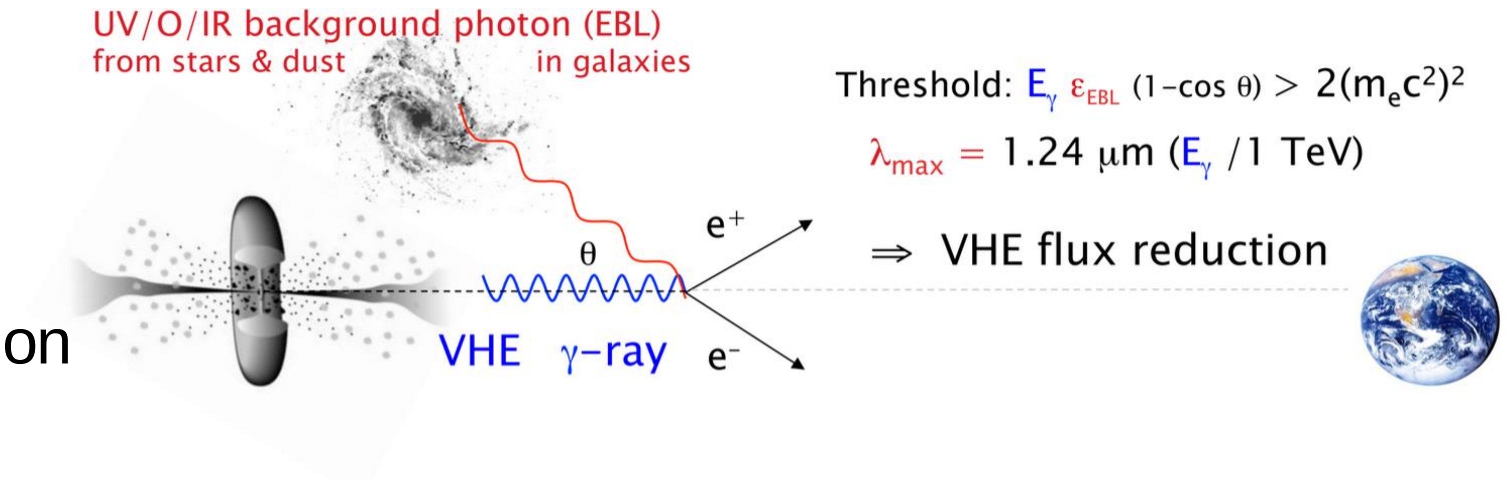
- Methods:
  - Galaxy counts
    - Integration of flux in magnitude bands.
    - Combination of wide deep surveys.
    - Not sensitive to diffuse and unknown components.
    - Can be interpreted as lower limit (contribution from unresolved galaxies is missing).



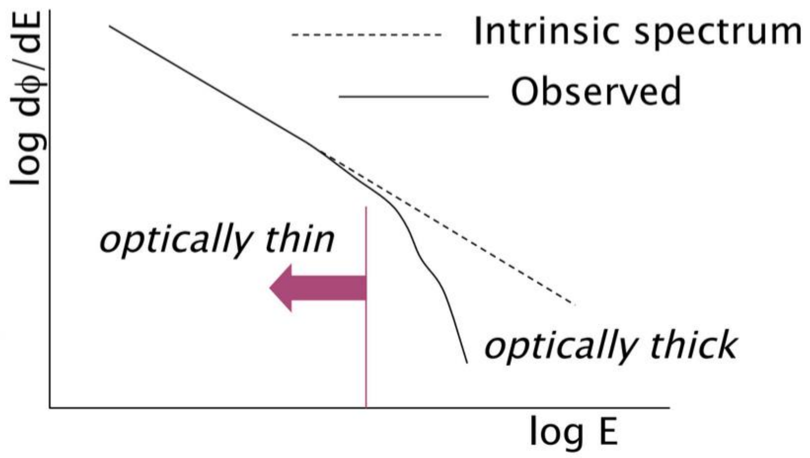
James Webb Space Telescope deep field.
Credit: NASA

Introduction: Probing the EBL

- Gamma-rays-based method
  - Gamma-rays interact with the EBL photons to produce e+e- pairs. This produces an E-dependent imprint of the EBL on the gamma-ray spectra of sources at cosmological distances.
  - Pros: Sensitive to all EBL regardless of the source.
  - Cons: Requires assumptions on the source intrinsic spectra.

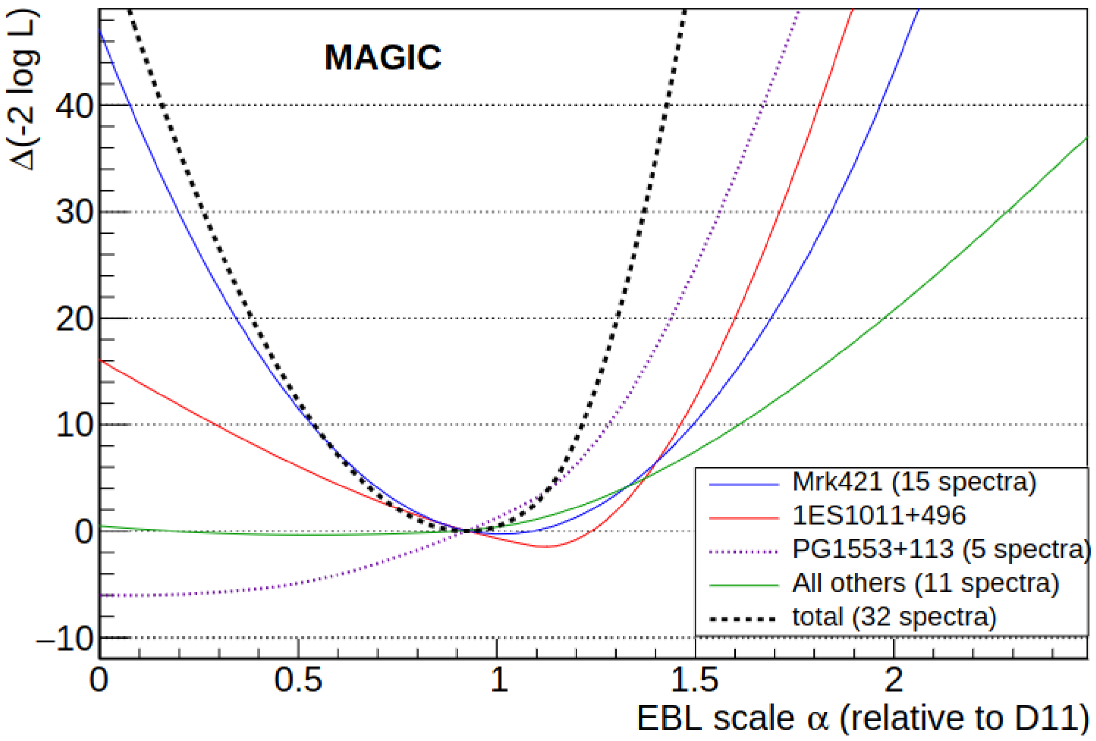


- observed flux: $e^{-\tau} \times$ emitted flux
- τ : optical depth
- $\tau = \tau(E, z)$



Previous MAGIC results

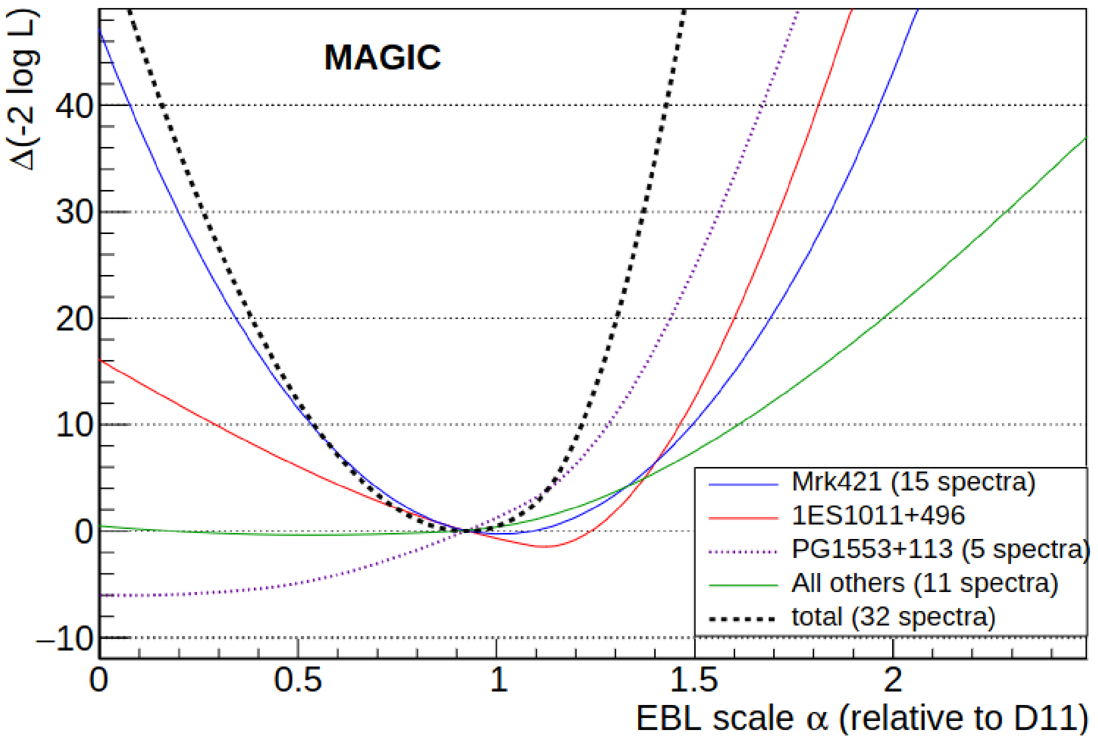
- Select a (concave) function to fit the intrinsic spectrum of the source and then do a profile likelihood of the EBL density (α) for a given EBL model.
- Robustness of result?
  - Results compatible with the EBL density in the model (i.e. with alpha=1) but with very low P-value
  - Selection of the fit function?
  - To get alpha constraints from the profile likelihoods Wilks' theorem is typically used but it may not be applicable.



*MAGIC collaboration, arXiv:*1904.00134v1

Previous MAGIC results

- Doubts with Wilks' theorem:
  - P-values obtained in previous studies are very small (~10^-2)
  - Possible systematics due to EBL model, fit function, telescope effective area,…
  - Parameters reaching limits (like concavity limit)
- Using too simple models



*MAGIC collaboration, arXiv:*1904.00134v1

Objectives

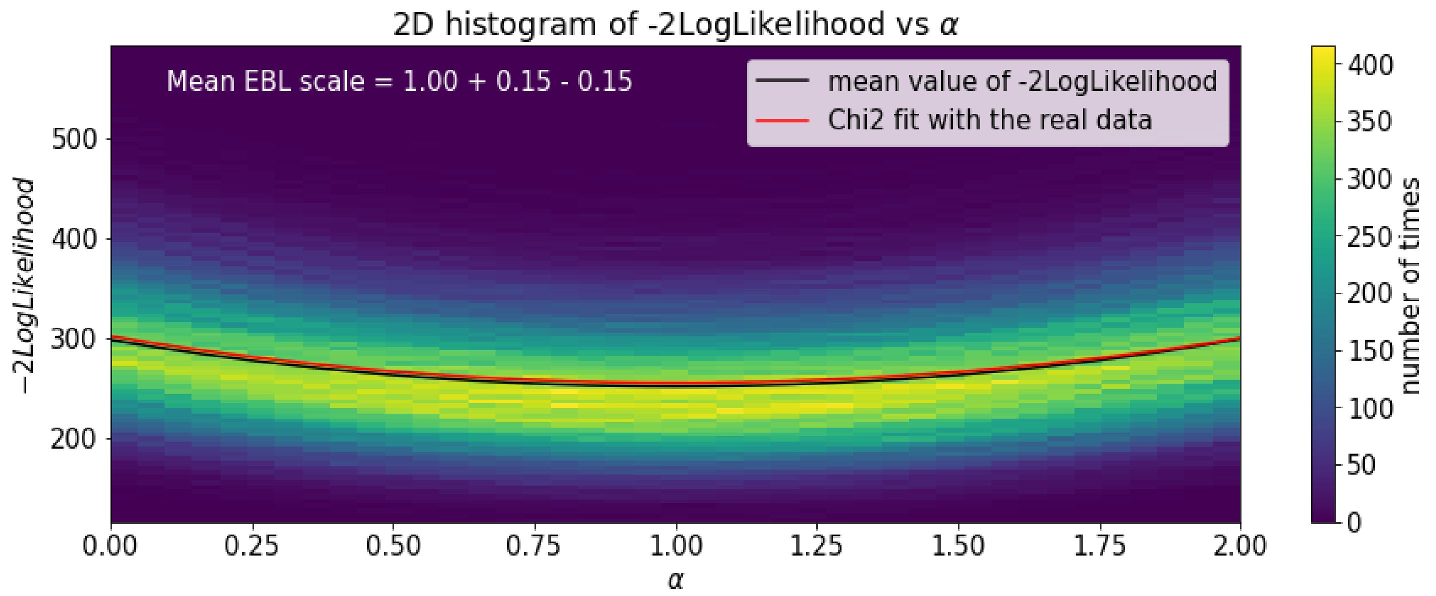
- Check the coverages with a Toy Monte-Carlo simulation
  - Verify validity of Wilks' theorem.

- Try to use less strong assumptions on the intrinsic spectral shape

  ➥ Use a "generic concave function" instead of a log-parabola or other simple parametrizations

Toy Monte-Carlo Simulation

- We run different Poisson realizations of the observation of the same spectra (modeled with a function such as PWL, LP,…) using MAGIC IRF.
- Then every realization is analyzed with a Poissonian likelihood maximization.
- Due to the fact that our P-Values are higher than the real data ones, we added Gaussian systematics in the effective area, independent in each energy bin.

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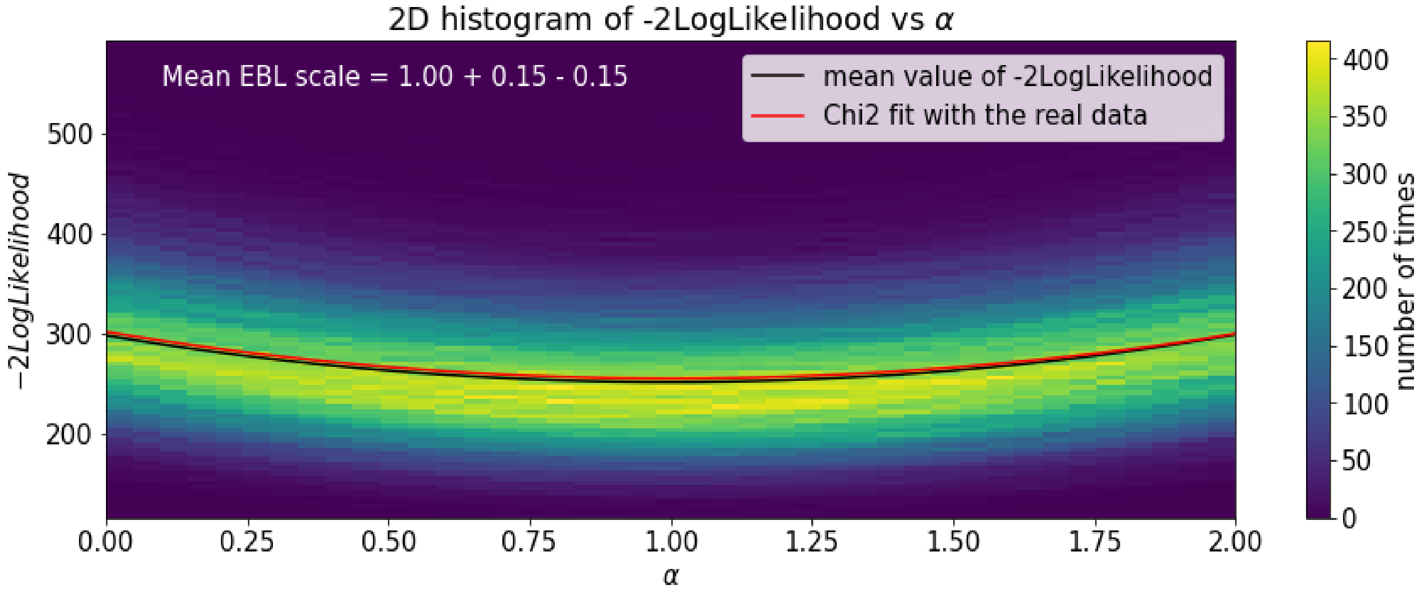
A 40.25 % of the simulations have the true value alpha=1 inside the 1 sigma interval around the minimum
A 71.12 % of the simulations have the true value alpha=1 inside the 2 sigma interval around the minimum
A 88.39 % of the simulations have the true value alpha=1 inside the 3 sigma interval around the minimum
Δχ^2 min-0 = 46.76
Δχ^2 min-2 = 47.60
```

Result of the combined fit of the Mrk421 simulation (10k realizations). With 2.25% gaussian systematics in the effective area, independent in each energy bin. (ndof = 221)

Toy Monte-Carlo Simulation

- We define 1sigma coverage as the % of simulations that have the true value of α (α = 1) inside the region defined by the minimum and Δ–2logL of the minimum + 1.
- If Wilks' theorem can be applied should be ~68% for 1 sigma, ~95% for 2 sigma,…
- We can see that for the simulation they are lower than the expected ones.

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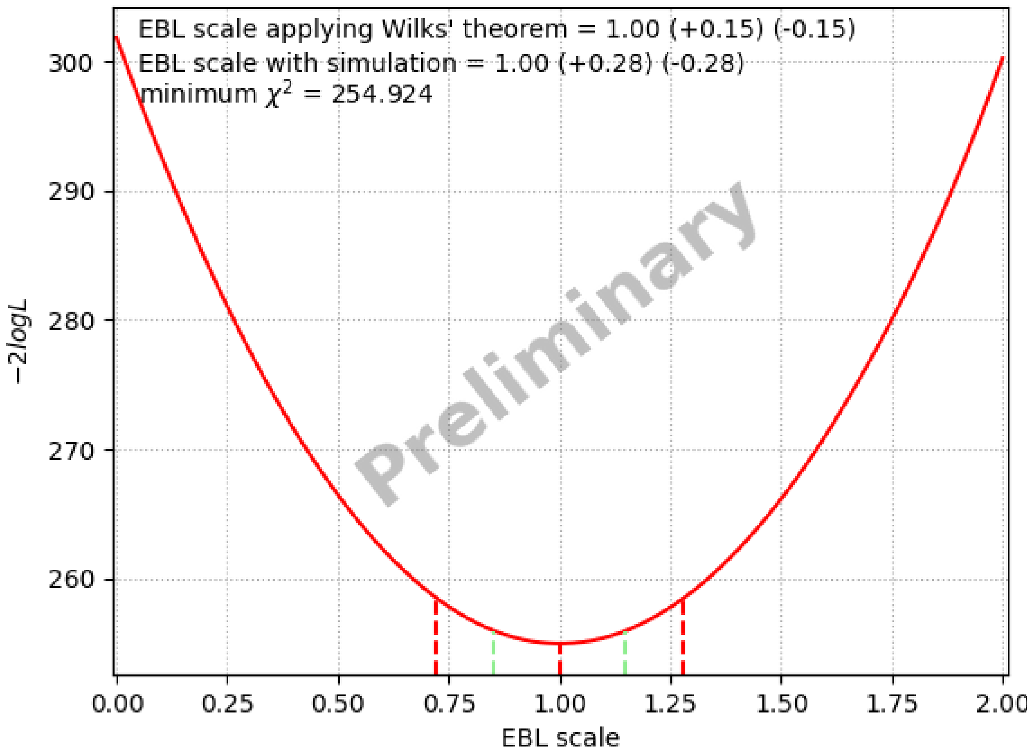
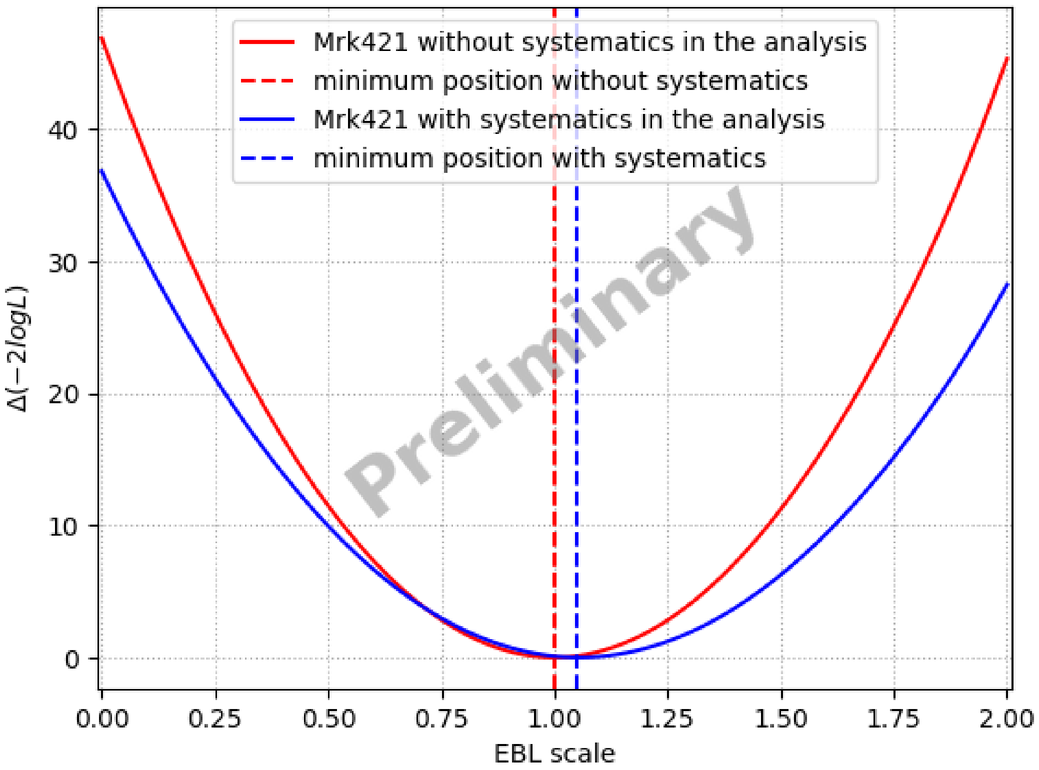
Application to real data

- We also added systematics to the effective area in the analysis to get higher P-Values
  - There can be other systematics



EBL scan of 15 Mrk421 spectra with our code (ndof = 221)

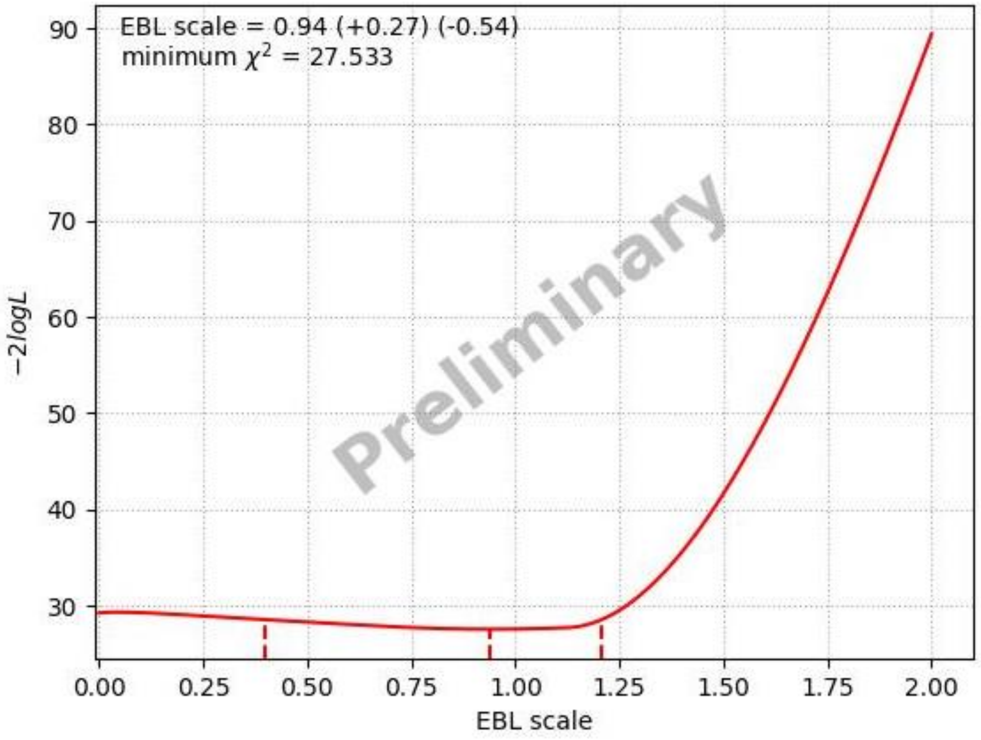


Δ-2logL of the EBL scan of Mrk421 with and without systematics in the analysis. (ndof = 221)

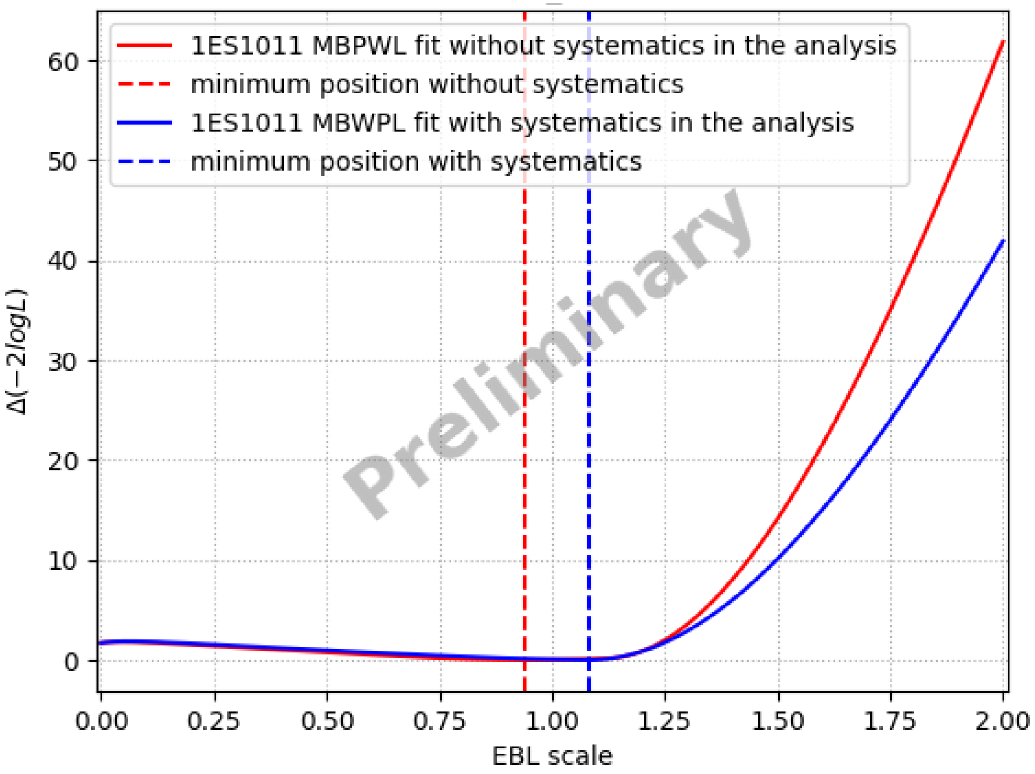
P-value of the min:
0.053 (ndof = 220)
0.467 with systematics (ndof = 220)

Application to real data

- We also added systematics to the effective area in the analysis to get better P-Values
  - There can be other systematics



EBL scan of 1ES1011 with MBPWL (ndof = 16)

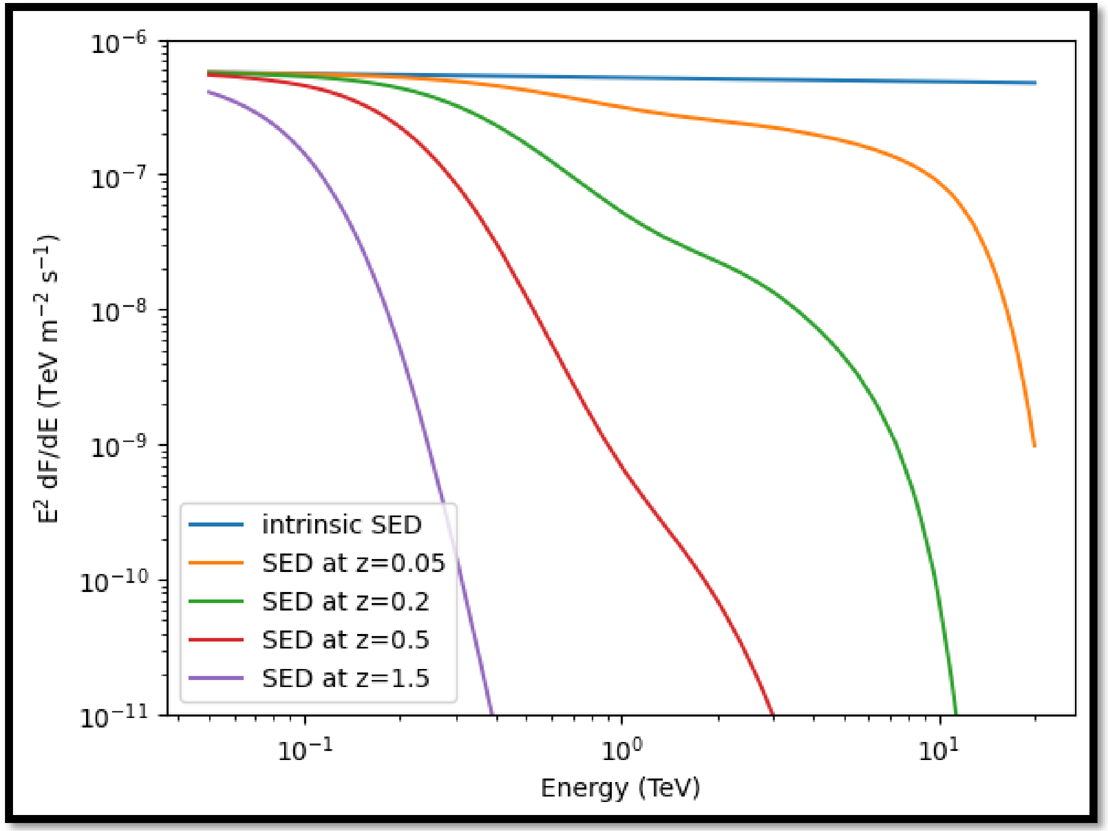


Δ-2logL of the EBL scan of 1ES1011 with and without systematics in the analysis. (ndof = 16)

P-value of the min:
0.025 (ndof = 15)
0.049 with systematics (ndof = 15)

Generic Concave Function

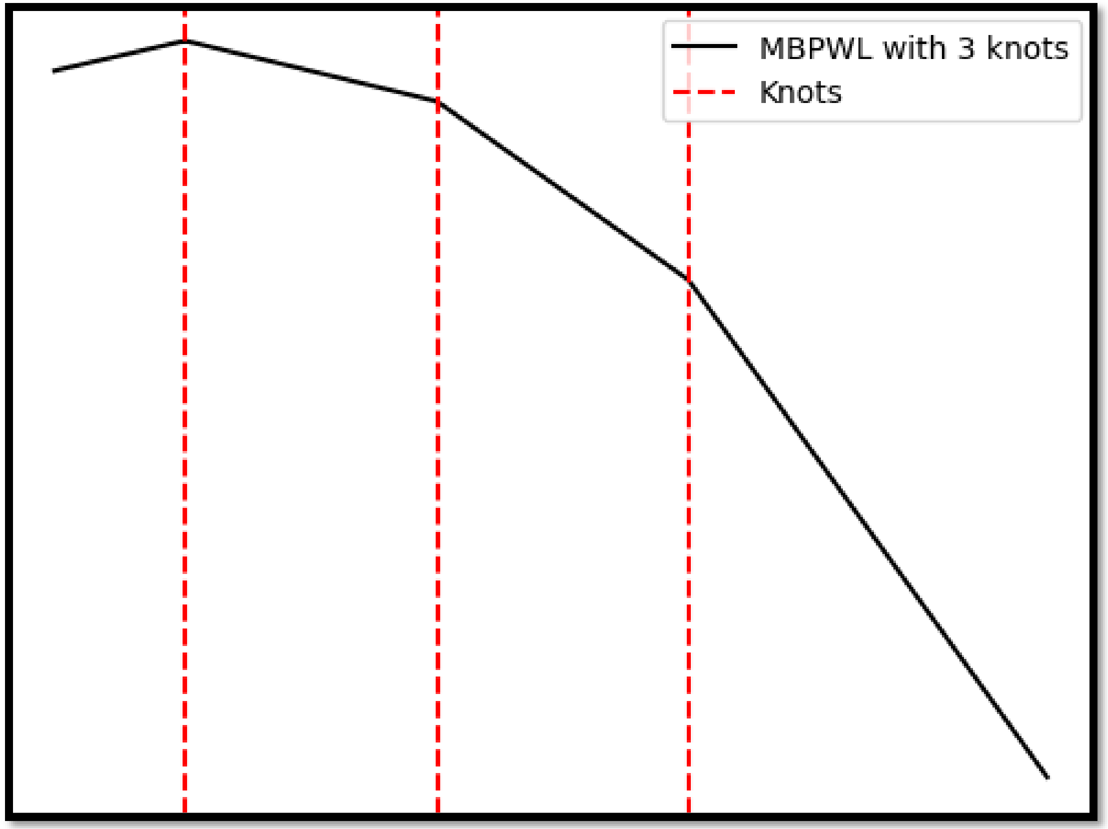
- Using a generic concave function (instead of LP, EPWL,…):
  - We do not expect inflection points in the VHE intrinsic spectra of BL Lacs.
  - The EBL absorption (log(transmissivity) vs. log(E)) has an inflection point around 1 TeV



Example of the effects of EBL to an SED of a source at different redshift

Generic Concave Function

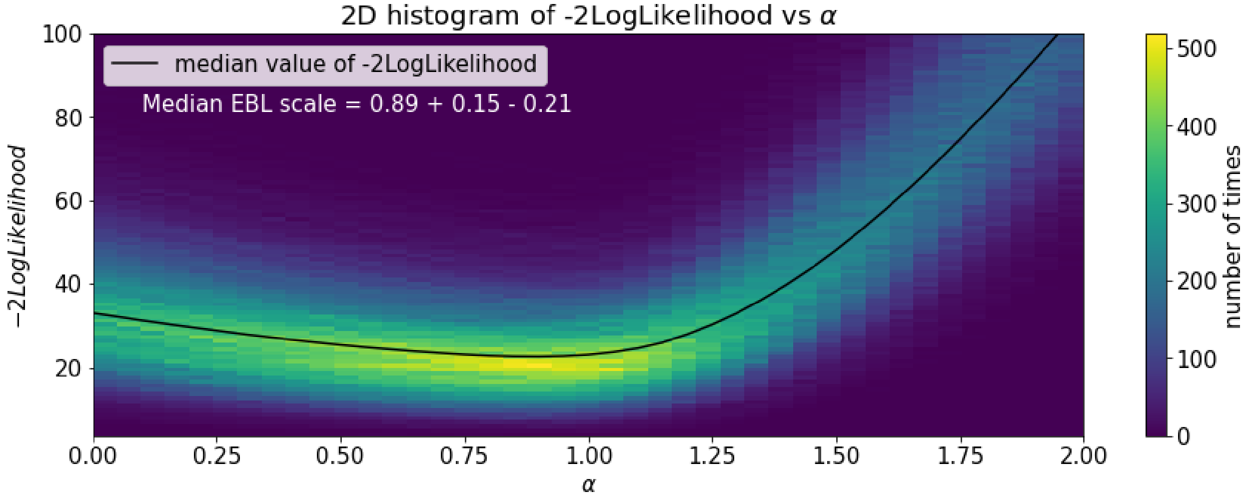
- Multiply-Broken Power-Law (MBPWL)
  - Power law with changes in the photon index in points called nodes or knots.
    - To impose concavity the photon index increases on every knot.
    - The knots are logarithmically spaced between the first and last knot.
  - Problems:
    - How to choose number of nodes and their position.
    - Convergence issues with high number of nodes



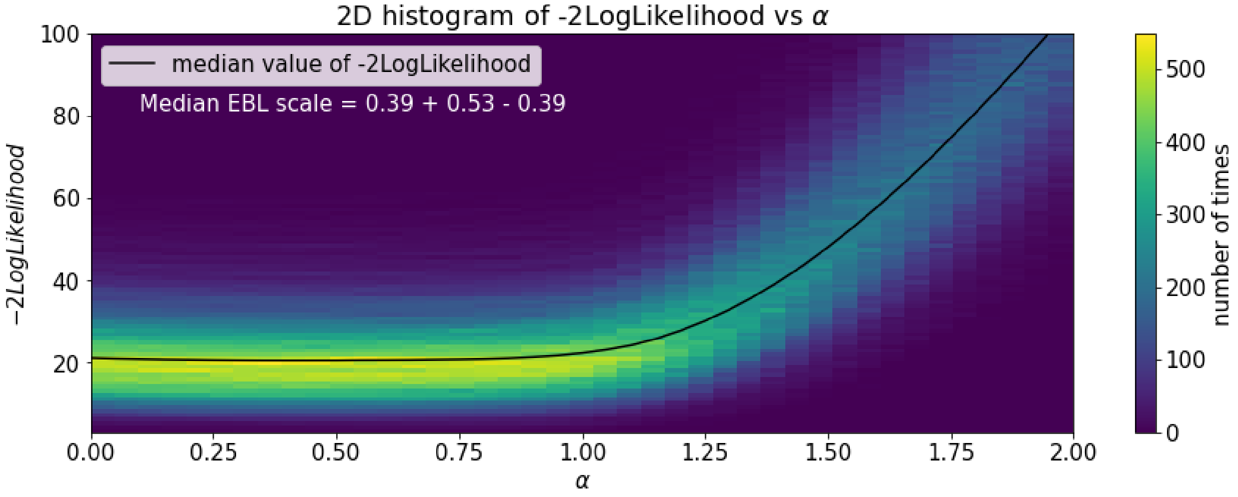
Example of a MBPWL with 3 knots in log scale (x and y)

Generic Concave Function

- Analyzing data of 1ES1011, with the MBPWL with only 2 knots we have very similar upper limits to the LP (due to the concavity constraint we have in both functions), but we get more conservative lower limits.
- Lower constraint essentially disappears because the EBL absorption shape can be better fitted with the MBWPL than with the LP.



Simulated 1ES1011 2014 flare with a PWL and fitted a LP (ndof = 17)



Simulated 1ES1011 2014 flare with a PWL and fitted a MBPWL with 2 nodes (ndof = 16)

Conclusions

- We revised the assumptions and methods used in constraining the EBL density using gamma-ray observations.
- We have made an open source Toy MC simulation to check the coverages of the results obtained for the real data.
  - This has proven that Wilks' theorem cannot be applied in those cases.
    - For example when reaching the concavity limit at high values of the EBL scale.
  - Uncertainties in previous studies (not only MAGIC ones) have been underestimated.
- We are exploring the use of more generic functions for modelling the intrinsic VHE spectra, in order to make the EBL constraints more robust.

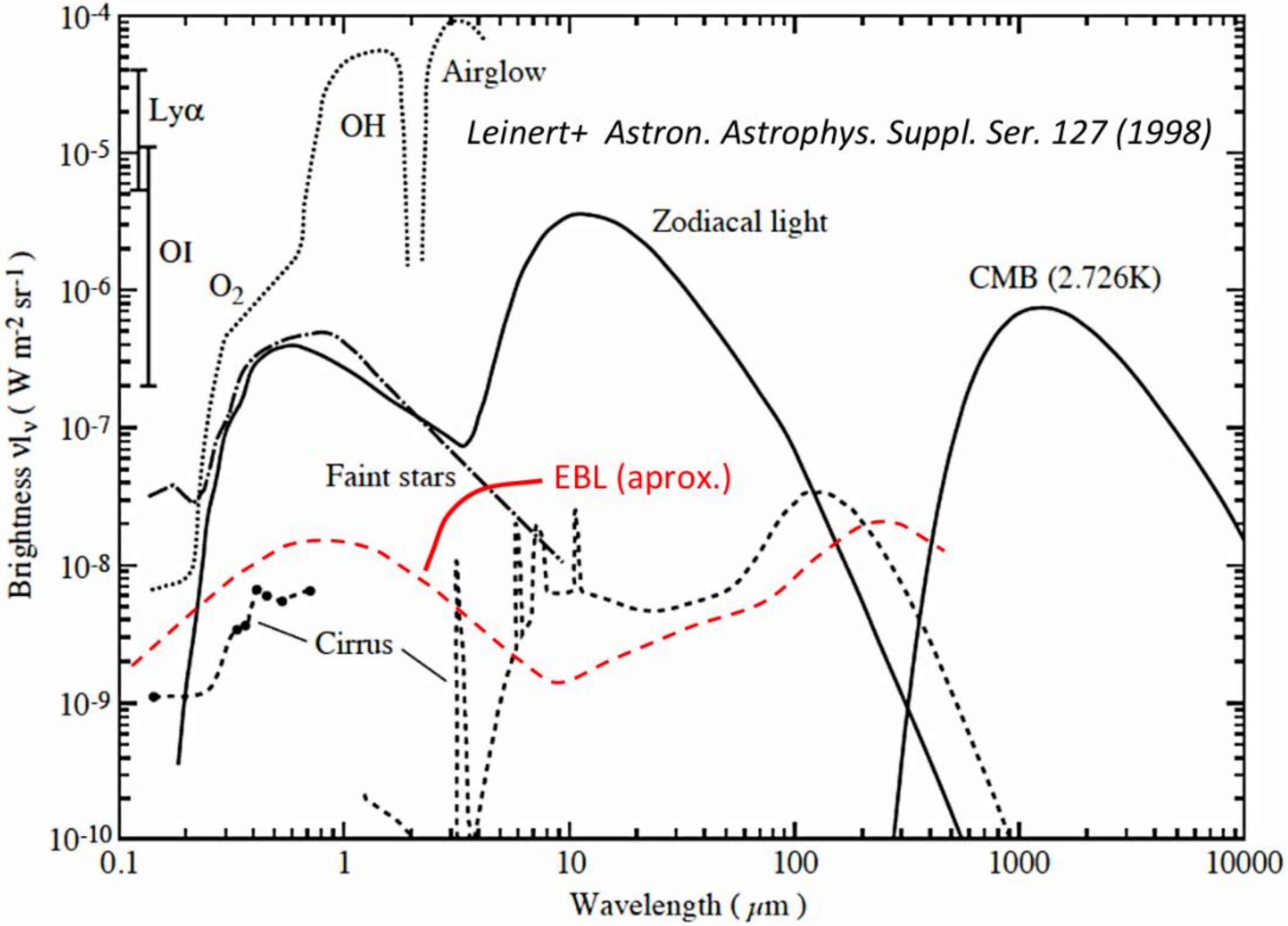
Open-source code

- All the code used in this analysis is public and can be found in:
- https://github.com/R-Grau/EBL_fit_MC

Thank You

Backup slides

• Diffuse night sky brightness (at high galactic & ecliptic latitudes)



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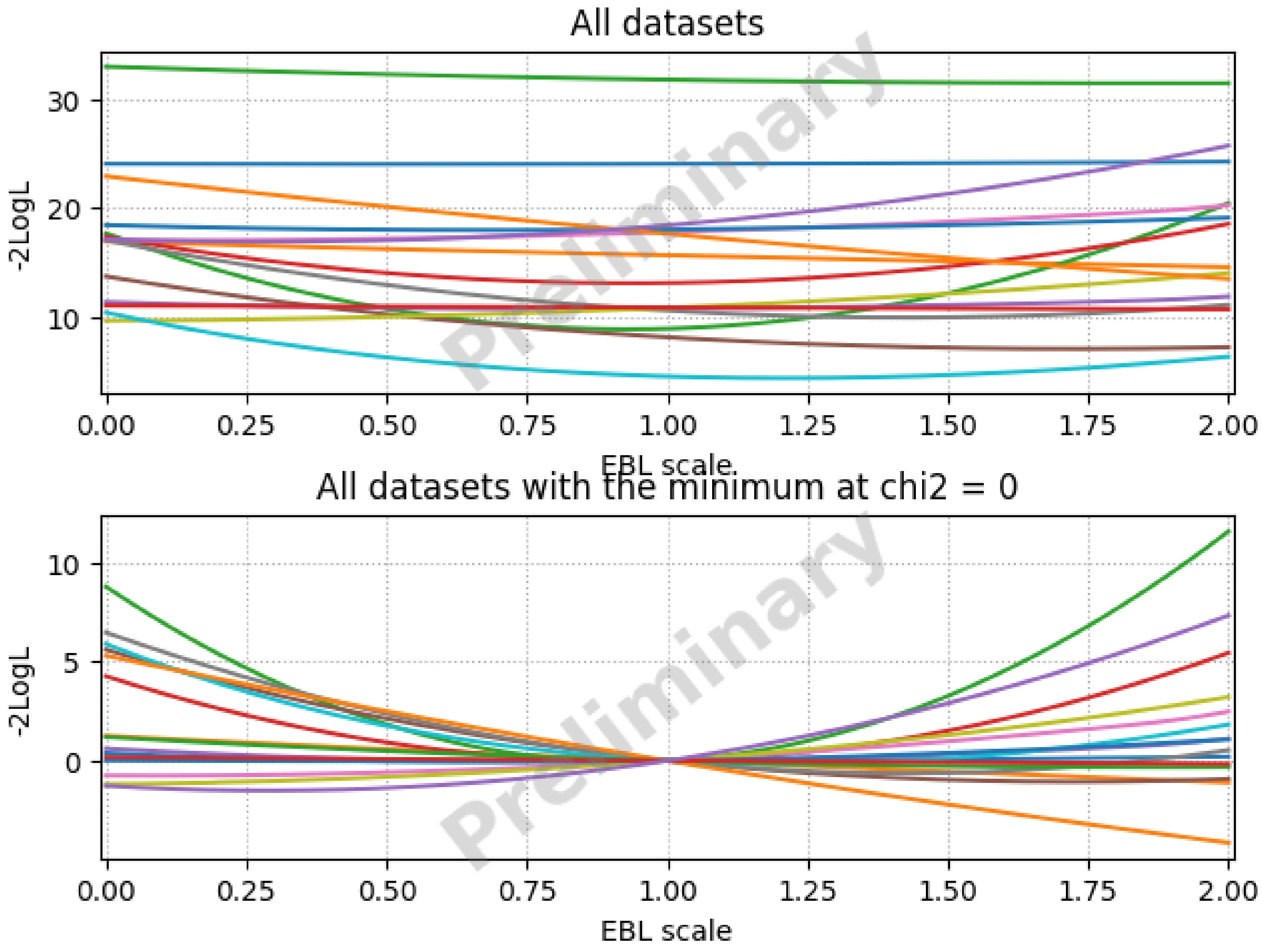
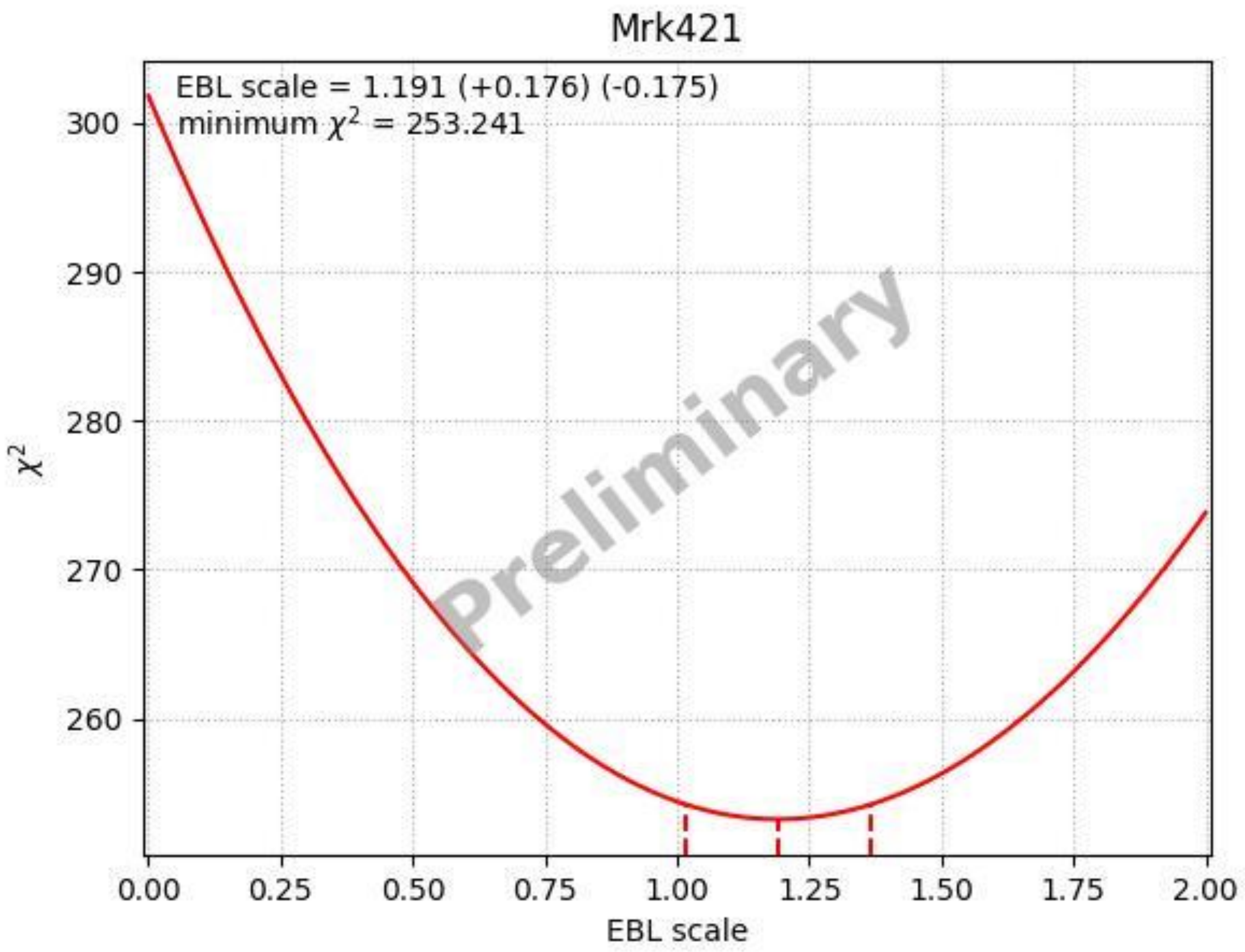
- Mrk421 with Dominguez 2011 EBL model



EBL scan of the individual 15 Mrk421 spectra with our code with Dominguez 2011 EBL model

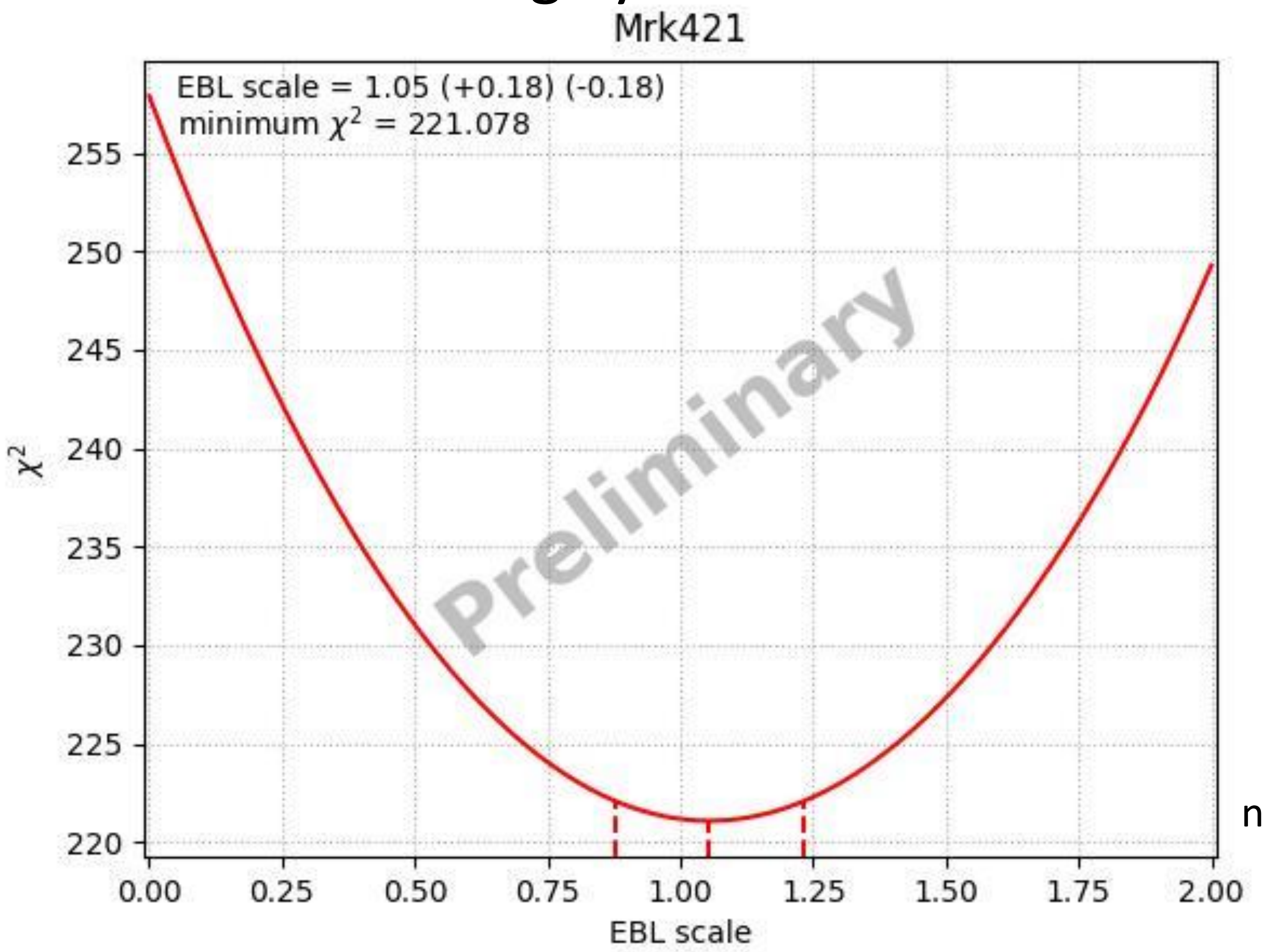
- Mrk421 with Saldaña 2021 EBL model



EBL scan of 15 Mrk421 spectra with our code with Saldaña 2021 EBL model

ndof = 221

- Mrk421 including systematics



EBL scan of 15 Mrk421 spectra with our code with Dominguez 11 EBL model and adding 2.25% gaussian systematics to the analysis

ndof = 221