Insights into Extragalactic Background Light constraints with MAGIC archival data

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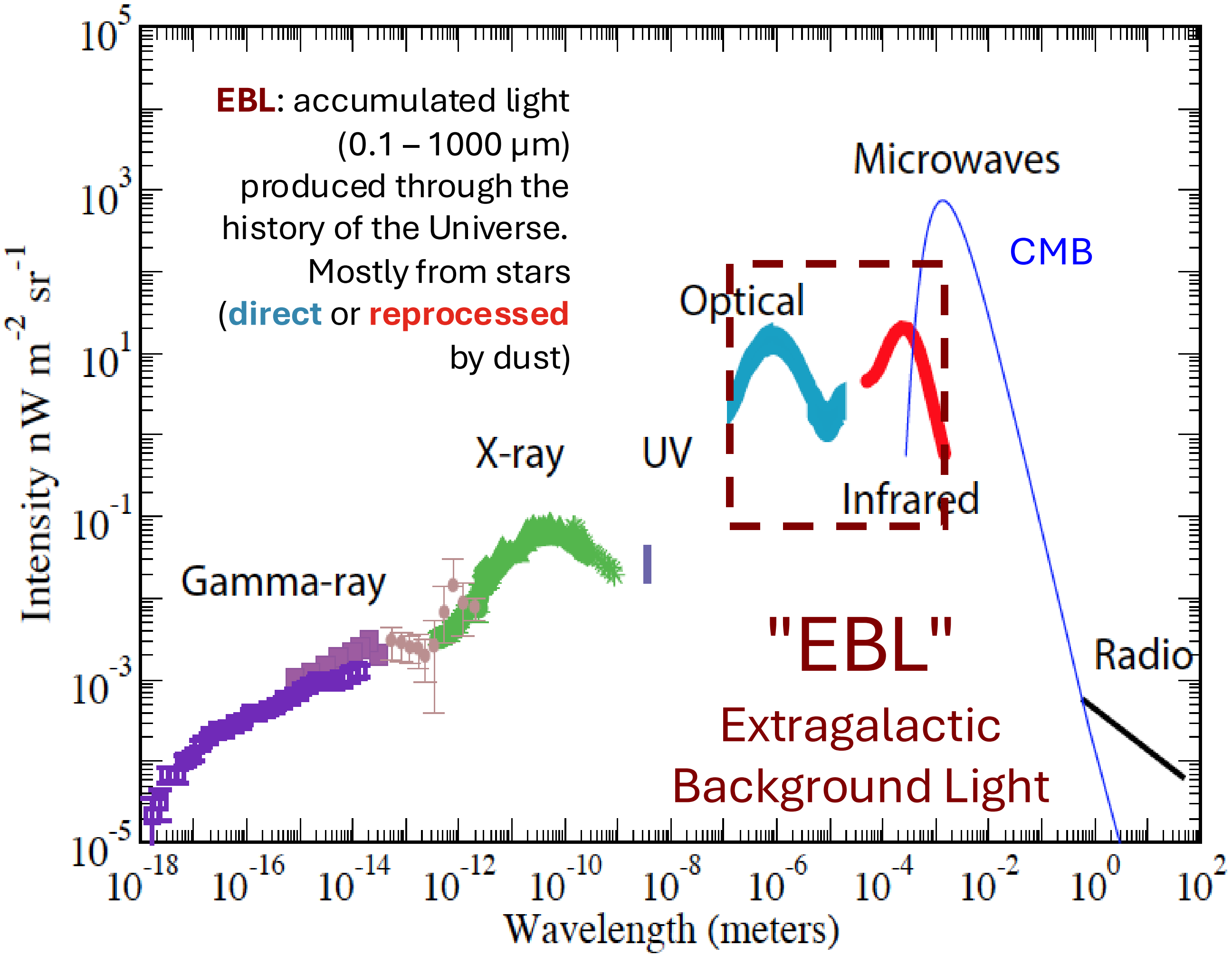
Introduction: Extragalactic Background Light

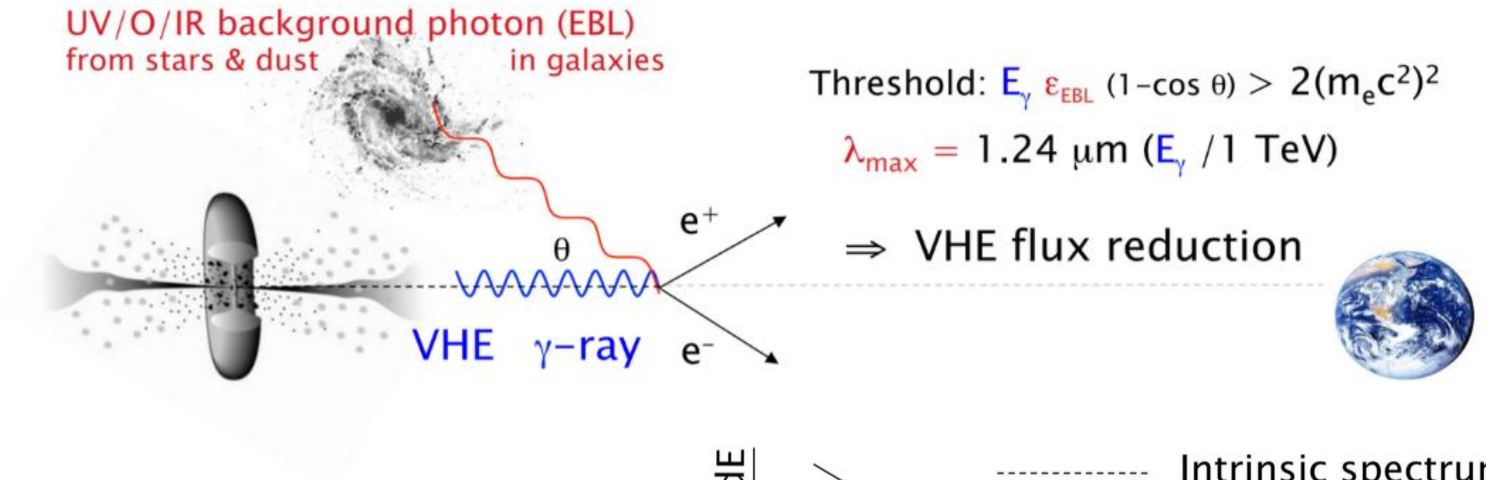
- Second most intense "diffuse" photon field.
- Cosmic Optical Background:
  - (Mostly) Light from stars.
- Infrared background:
  - (Mostly) Light re-radiated after being absorbed by dust



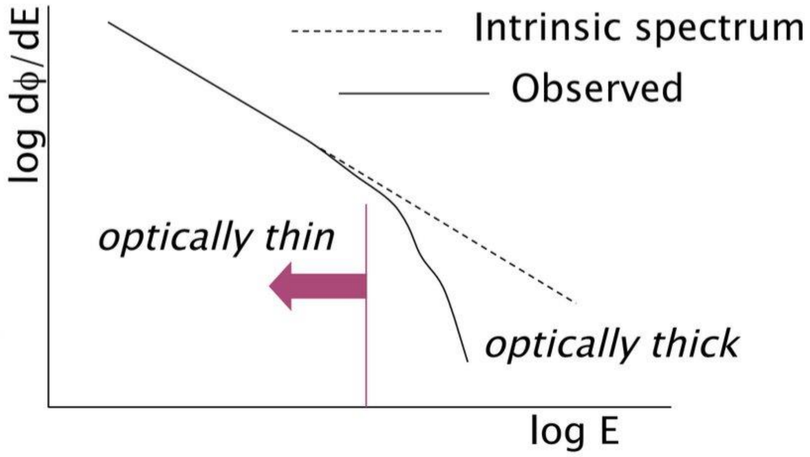
Cooray, Physics Reports, vol. 667, p2016

Introduction: Probing the EBL

- Gamma-ray-based method
  - Gamma rays interact with the EBL photons to produce e+e- pairs. This produces an energy 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
- $\tau = \tau(E, z)$



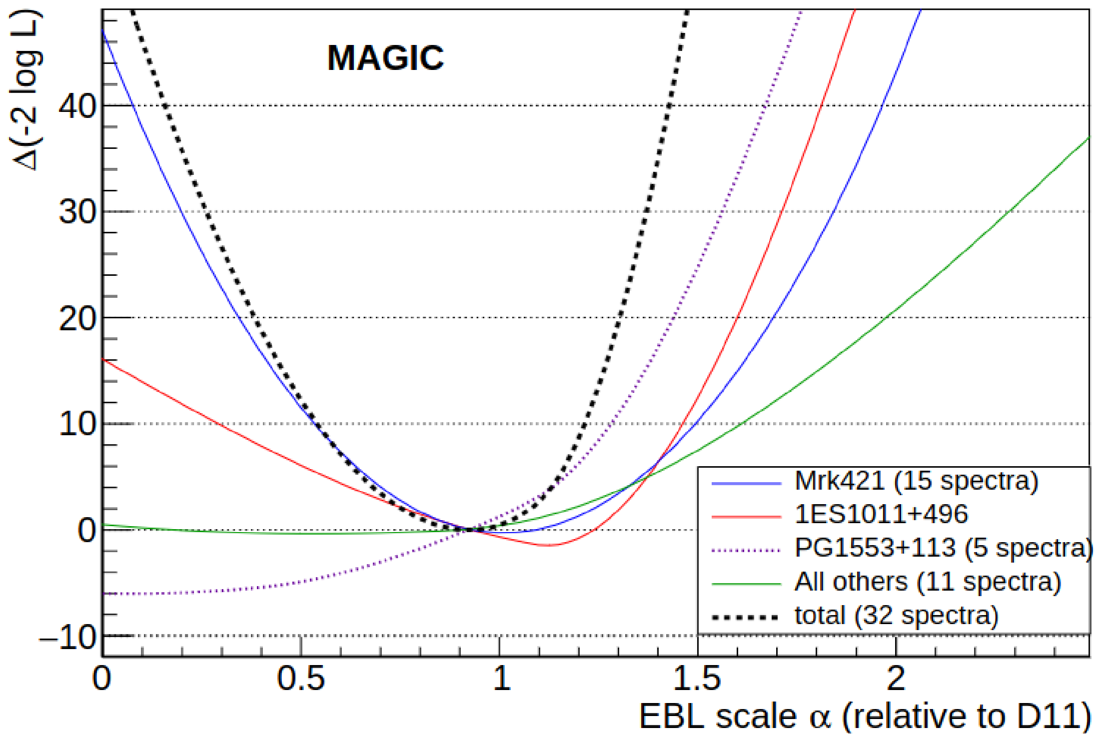
Extracting EBL from direct measurements is difficult as it requires subtracting much larger foregrounds.

Previous MAGIC results

Select a (concave) function to fit the intrinsic spectrum of the source and then do a frequentist likelihood ratio test of the EBL density (α) for a given EBL model.

$$\frac{dF}{dE} = g(E) \cdot e^{-\alpha\tau(E,z)}$$

Where $g(E)$ is the fit function for the intrinsic spectra, α is the EBL scale and $\tau(E, z)$ is the EBL optical depth of the model

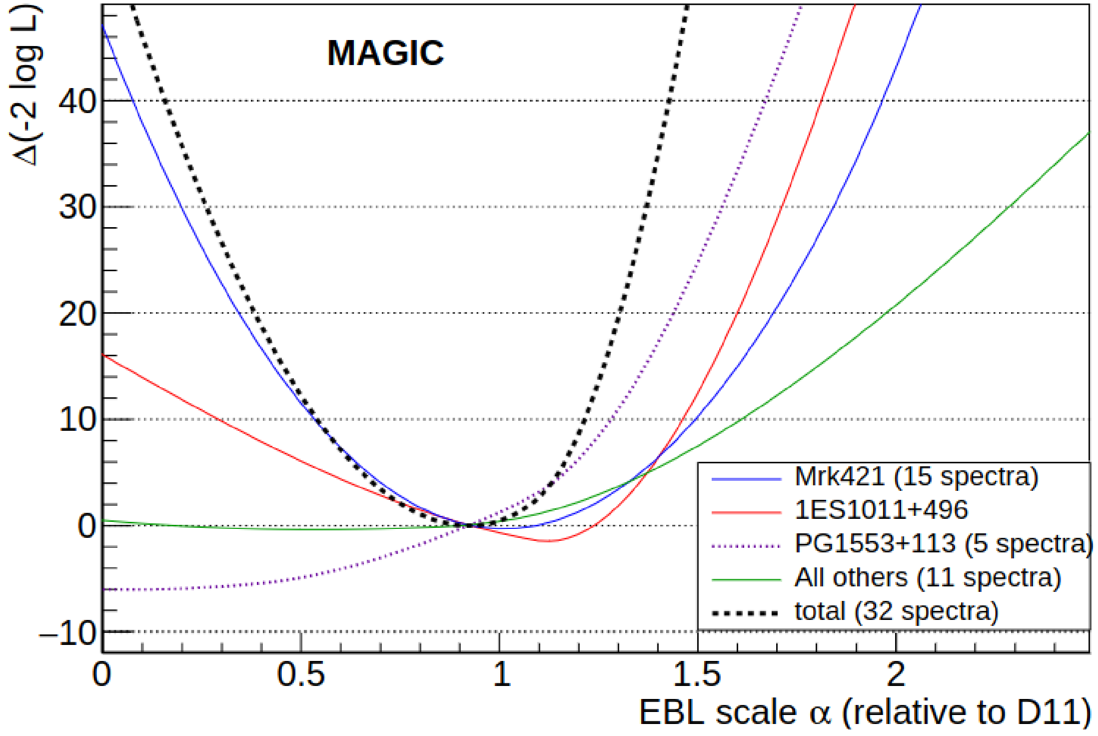


*MAGIC collaboration, arXiv:*1904.00134v1
MNRAS: 486

Previous MAGIC results

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.



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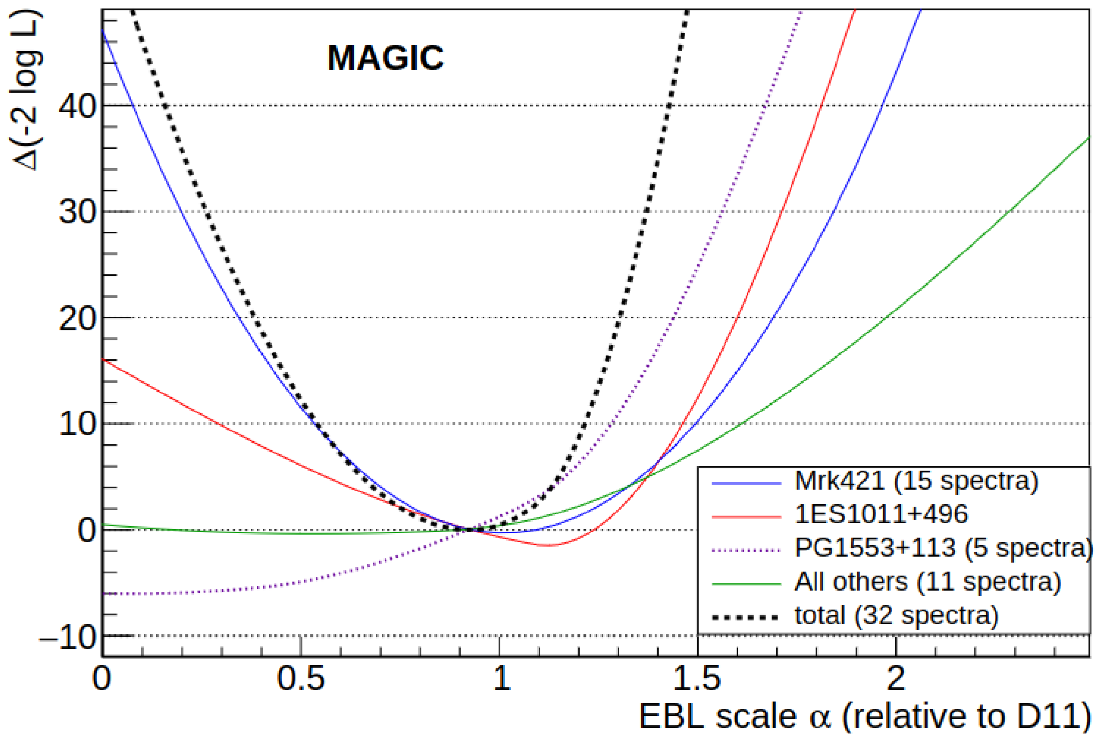
Previous MAGIC results

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,…
    - Using too simple spectral models?
- Parameters reaching limits (like concavity limit)



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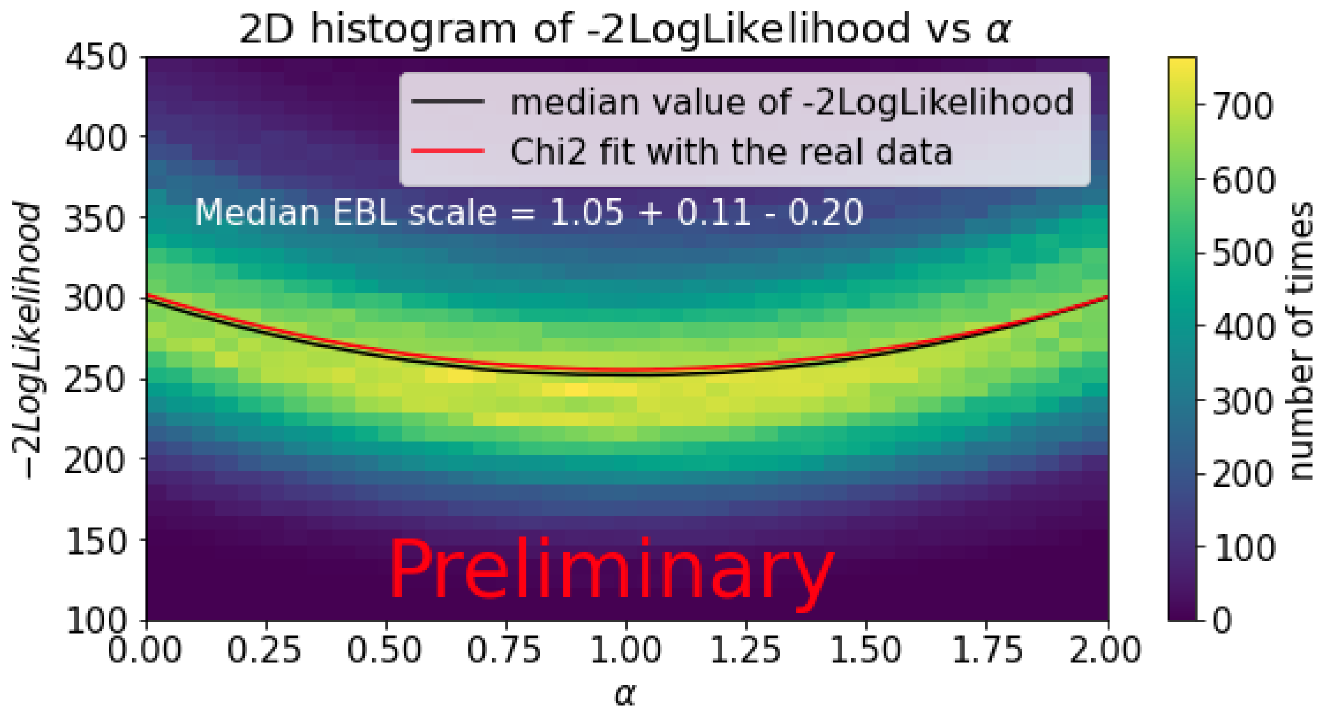
Objectives

- Check the validity of Wilks' theorem using a Monte Carlo simulation:
  - Compute the uncertainties if it is not applicable
- Test 2 new methods to constrain EBL with less assumptions:
  - Multiply Broken Power-Law
  - "Concave EBL" method
  - Both aim to look for the inflection points imprinted by the EBL in the spectra as it is the only feature of the EBL absorption shape which in principle is not expected in the intrinsic spectrum of the source

- The data used in this work are MAGIC data only with energies from 0.06 TeV to 20 TeV.
- The EBL model used for this study is Domínguez et al. (2010) (MNRAS:410)

Monte Carlo simulation

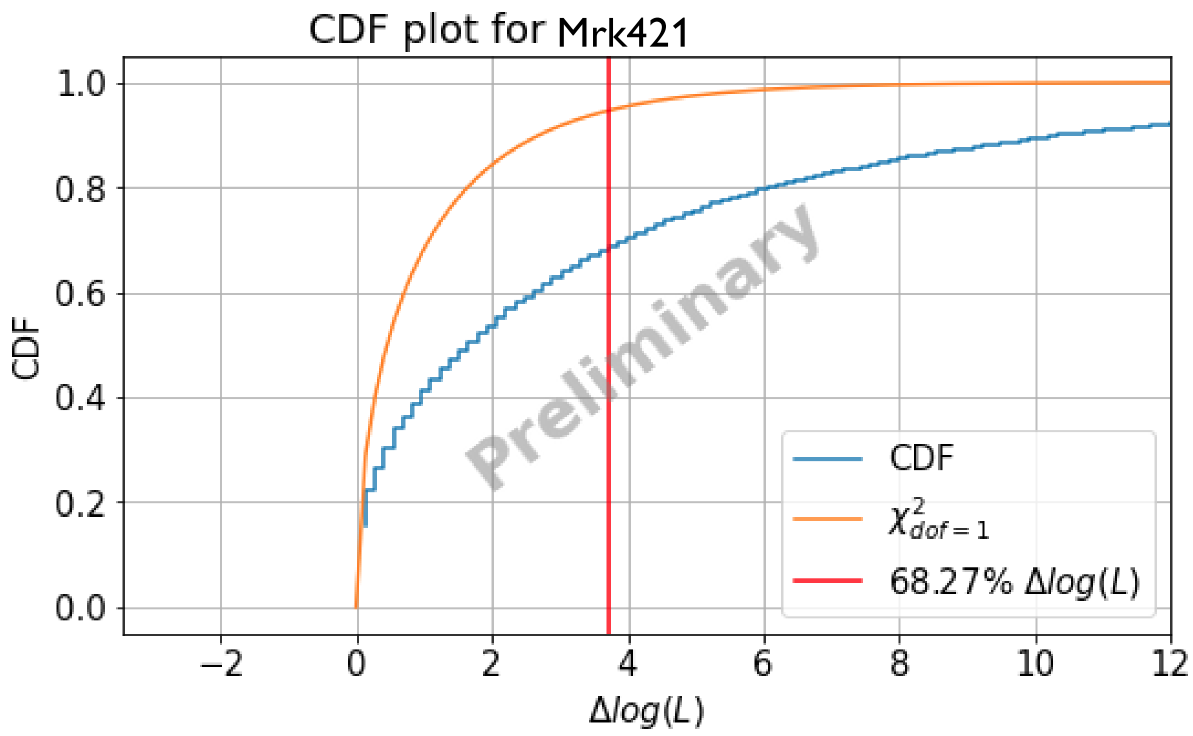
- We run different Poisson realizations of an observation of the same spectra (modeled with a function such as power-law (PWL), log-parabola (LP),…) using MAGIC IRF.
- Then every realization is analyzed with a Poissonian likelihood maximization.
- As the real data P-values were very small and the P-values of the simulation had reasonable values (flat probability density function (PDF) from 0 to 1), we added Gaussian systematics in the effective area, independent in each energy bin.



Result of the combined fit of the Mrk421 simulation (10k realizations). With 2.35% gaussian systematics in the effective area, independent in each energy bin. (ndof = 221)

Monte Carlo simulation

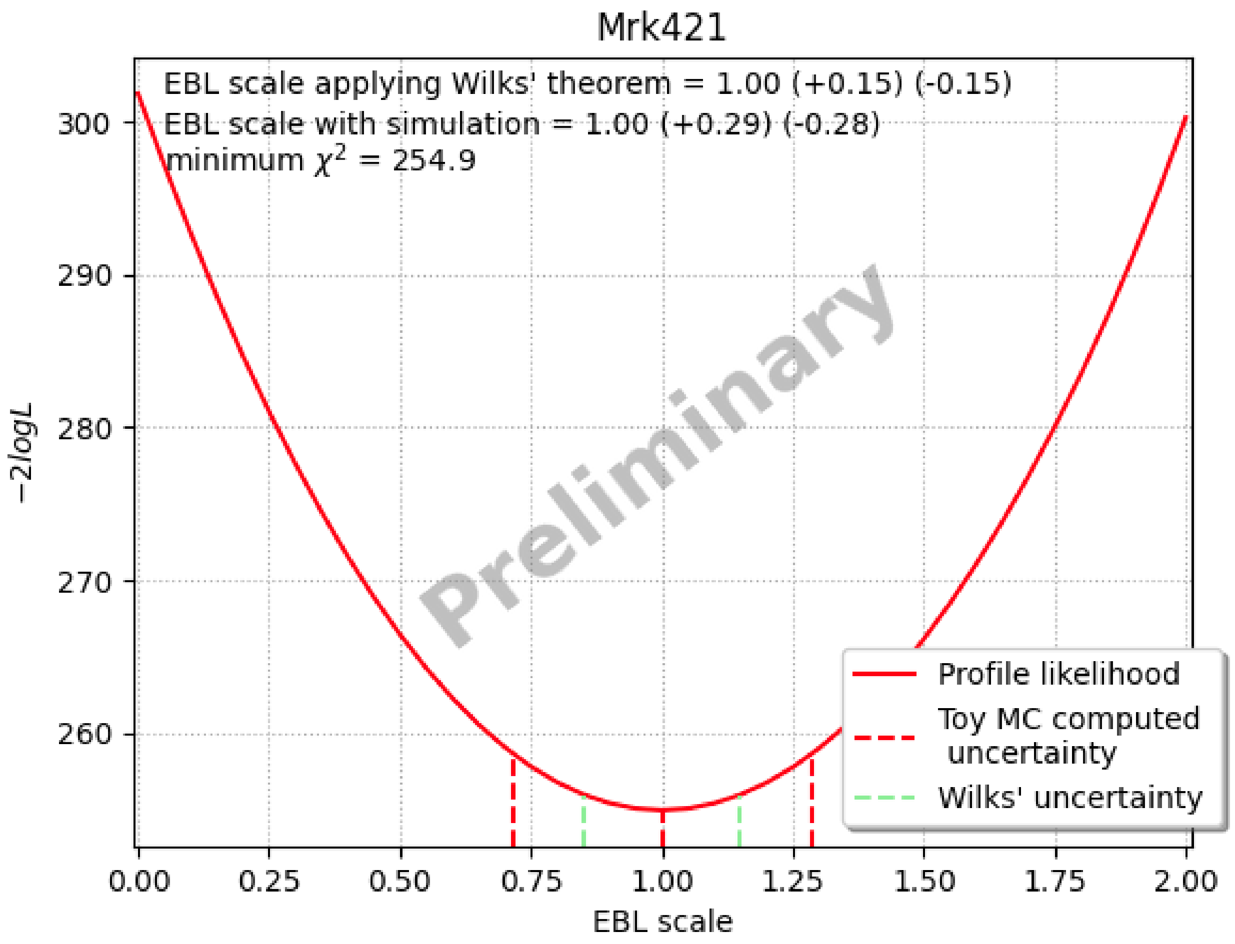
- If Wilks' theorem can be applied, the cumulative distribution function (CDF) of the difference of -2logL between the minimum of each realization and its value at the the true value of α (α=1) should follow a χ2 distribution, but it doesn't.
- Therefore we cannot use the Δ-2logL =1 to compute the uncertainty (68% CL) of the results.
- We will use the Δ-2logL corresponding to 0.68 in the CDF.



Cumulative distribution function of the simulation compared to a χ^2 distribution. The vertical red line shows the point where the CDF equals 68.27%

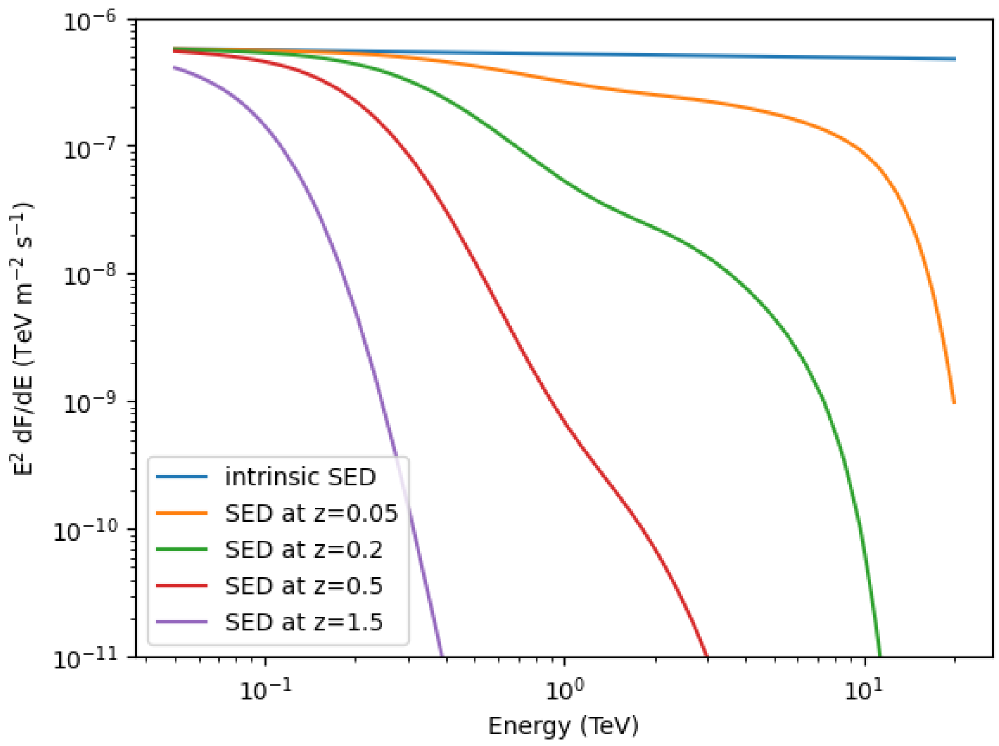
Real data analysis

- Thanks to the simulation and the CDF we can compute the uncertainty of the constraint on EBL density obtained with the real data.
- The Δ-2logL needed in this case is 3.72 instead of 1.
- Now the uncertainty is nearly double than before!



New Methods

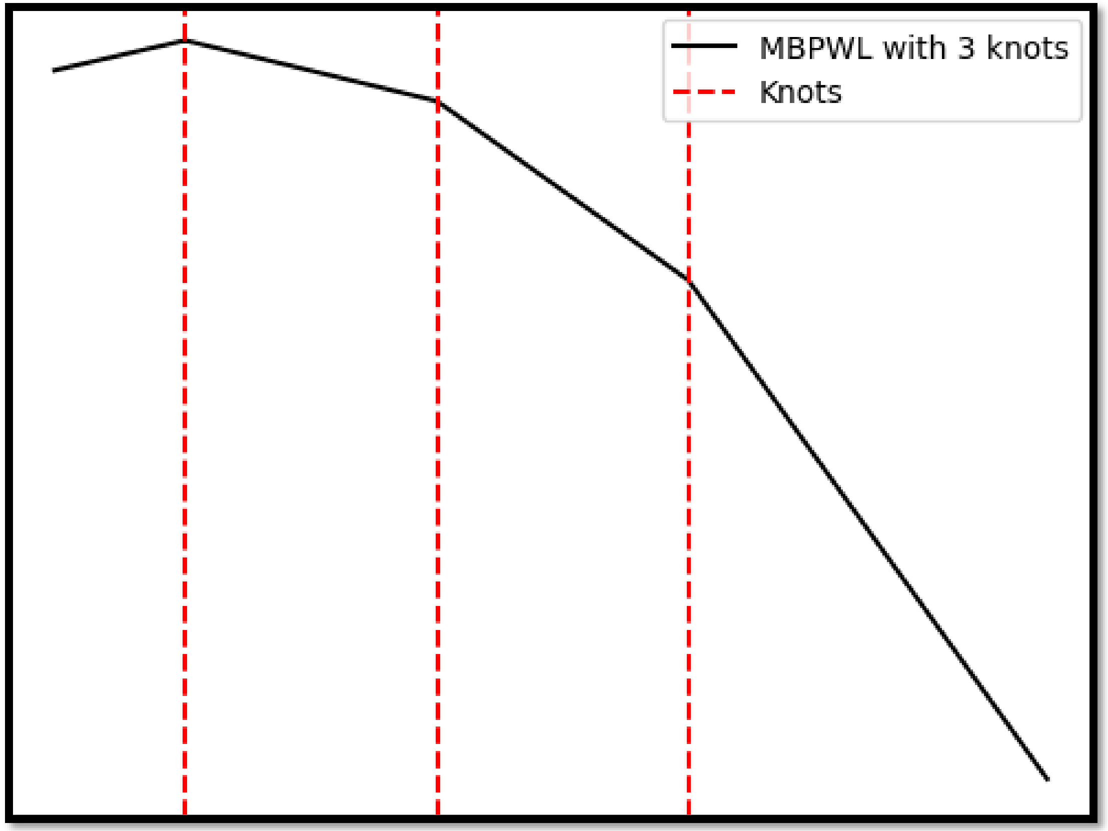
- We do not expect inflection points in the VHE intrinsic spectra of BL Lacs.
- The EBL absorption (log(transmissivity) vs. log(E)) has a wiggle around 1 TeV
- Therefore we are proposing two different ways of constraining EBL using this inflection points.



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

New Methods: Generic concave function

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

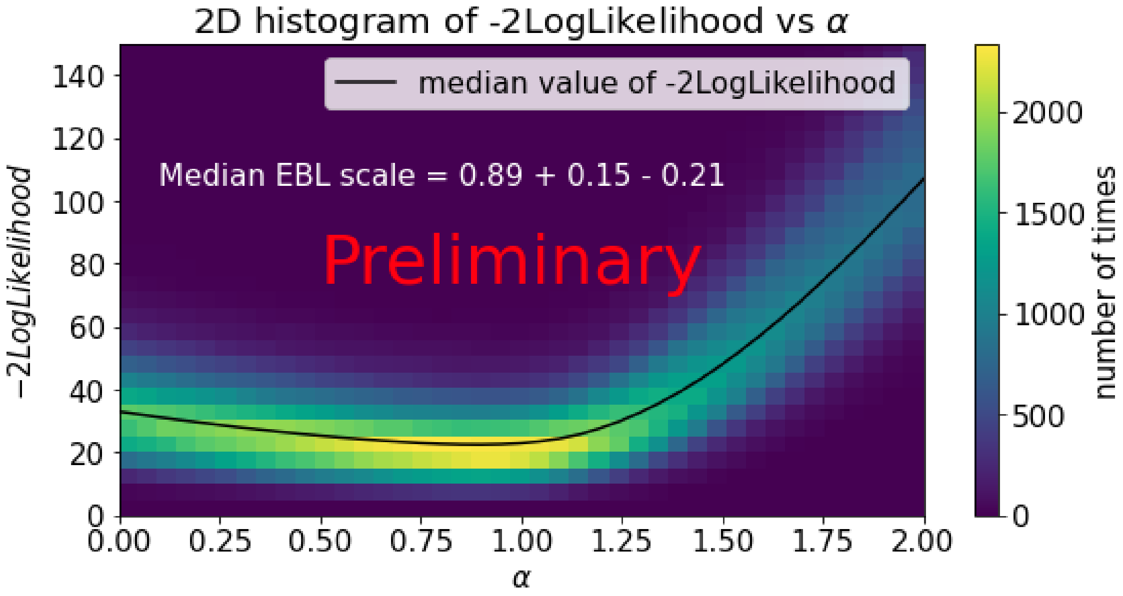


Example of a MBPWL with 3 breaks in log scale (x and y)
X axis would be Energy and Y axis the SED.

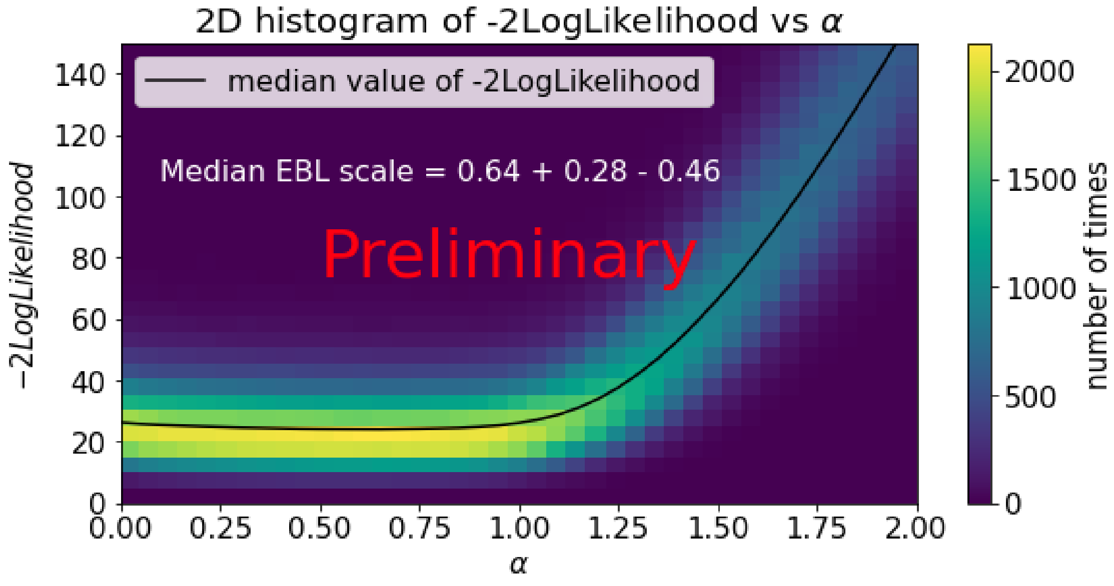
New Methods: Generic concave function

- Analyzing simulated data of 1ES1011+496, with the MBPWL with only 2 knots we have very similar upper constraints to the LP (due to the concavity constraint we have in both functions), but we get more conservative lower constraints.

- 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)



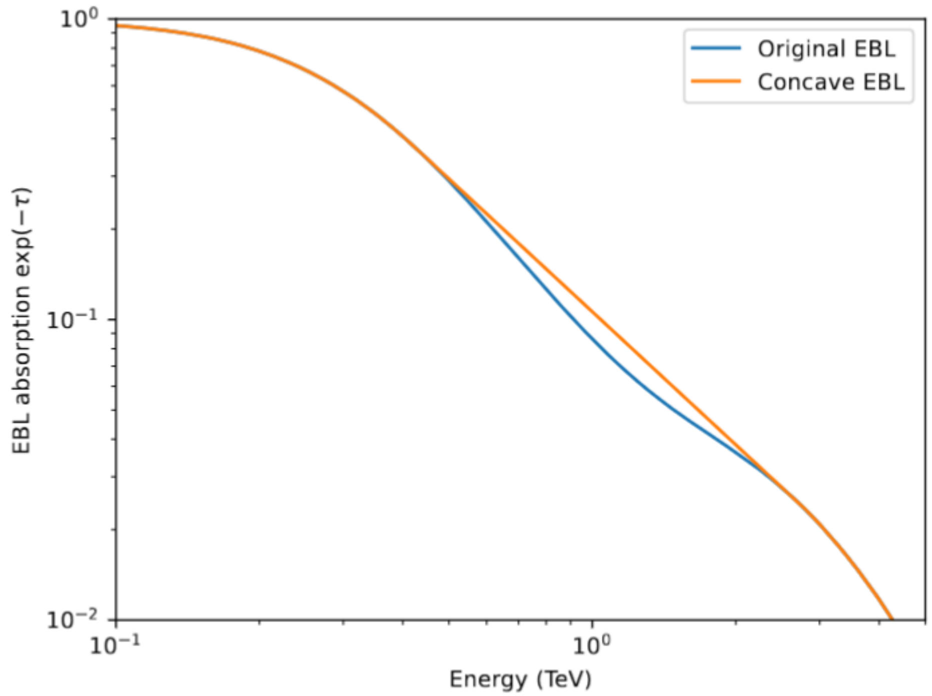
Simulated 1ES1011 2014 flare with a PWL and fitted a MBPWL with 2 nodes (ndof = 16)

New methods: "concave" EBL method

- With the potential issues with the MBPWL we have developed an alternative method for looking for the inflection points of the EBL absorption.
- Instead of scaling the absorption of the EBL model with α, now α scales how deep the wiggle is while maintaining the rest of the EBL model intact.

$$\frac{dF}{dE} = g(E) \cdot e^{-\tau'(E,z)} \cdot e^{-\alpha(\tau(E,z)-\tau'(E,z))}$$

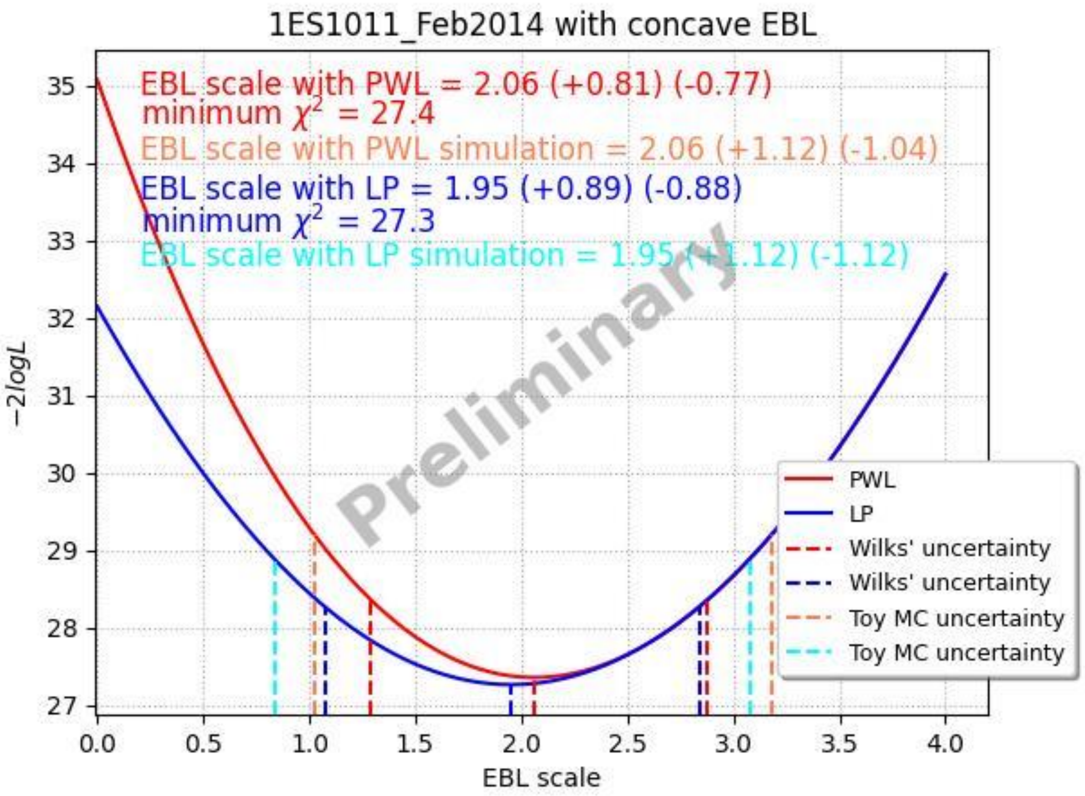
- Where $g(E)$ is the fit function for the intrinsic spectra, α is the EBL scale, $\tau(E)$ is the EBL optical depth of the model and $\tau'(E)$ is the modified EBL optical depth that has no inflection points.



EBL absorption $e^{-\tau}$ compared to the EBL absorption without inflection points $e^{-\tau'}$

New methods: "concave" EBL method

- We have already tested this method with the Monte-Carlo simulation and with real data of 1ES1011+496.
- With the current telescopes, this method does not give very constraining upper and lower bounds to the EBL density.
- But with more energy resultion and statistics, like the ones given by the next generation of telescopes will improve the constraints obtained.



Profile likelihood of the 1ES1011 MAGIC data fitted with a PWL and a LP and using the concave EBL method.

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.
  - This has proven that Wilks' theorem cannot be applied in those cases.
    - Probably due to systematics, using too simple spectral models and/or parameters of the fit function reaching limits.

- Uncertainties in previous studies (not only MAGIC ones) have been underestimated.

Conclusions

- We have developed two different methods to get EBL density constraints with less assumptions in the intrinsic spectral shape.

  - The first one uses a generic concave function (MBPWL) to look for the inflection points. But it has 2 main problems:
    - Selection of number of nodes and their position
    - Problems of convergence with a high number of nodes

  - The second one uses an EBL model where the profile likelihood only changes the depth of the wiggle instead of all the EBL model.
    - The main problem is that we need more statistics and more energy resolution at the wiggle.
    - This will be solved with next generation telescopes.

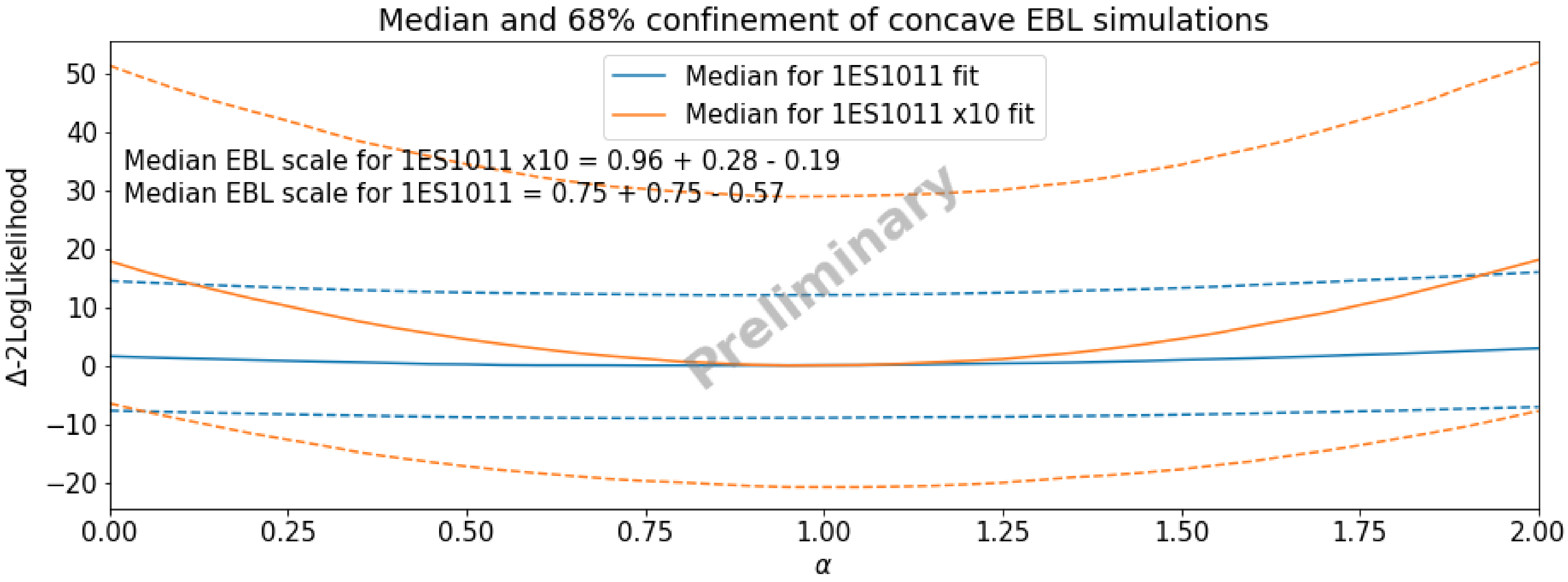
Thank you

Backup slides

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

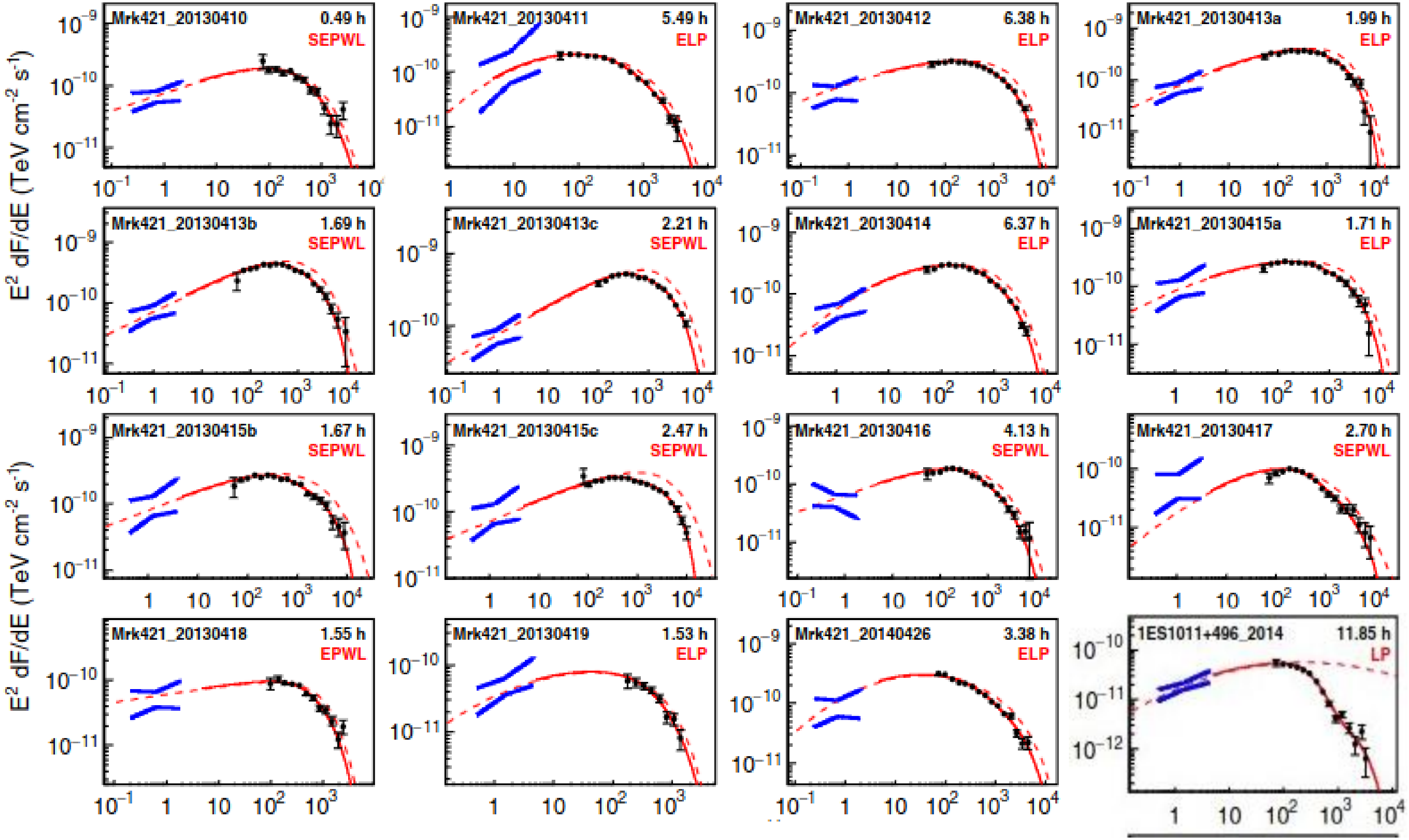
"Concave" EBL

How would the concave EBL work with a flare 10 times brighter than the one of 1ES1011 of Feb 2014?



With higher flux (equivalent to more collection area) the the median minimum gets closer to alpha = 1 and with lower uncertainty values.

Spectra



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