Insights into Extragalactic Background Light constraints with MAGIC archival data

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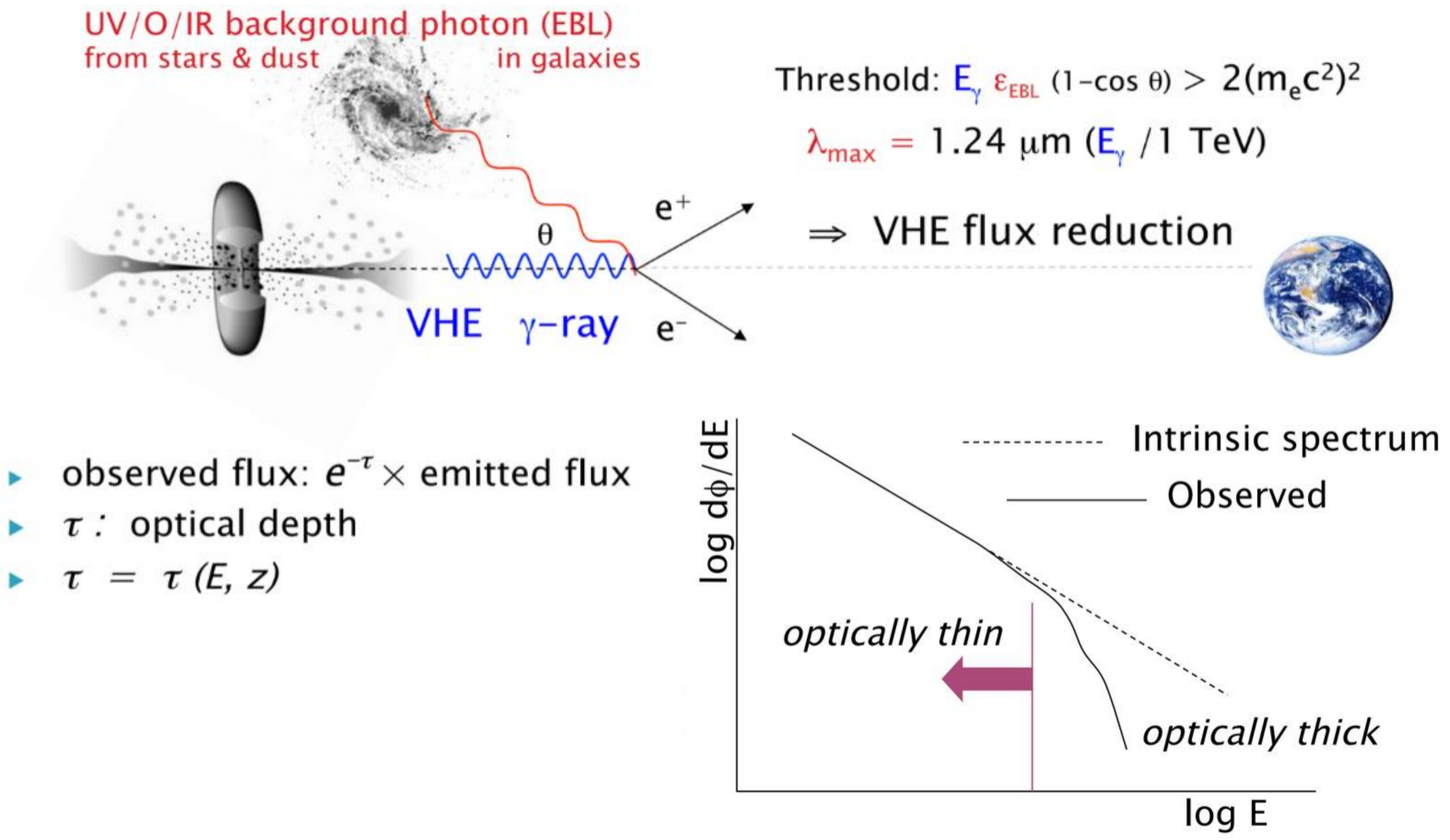
Introduction: Probing the EBL

- 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 gamma-ray source intrinsic spectrum.

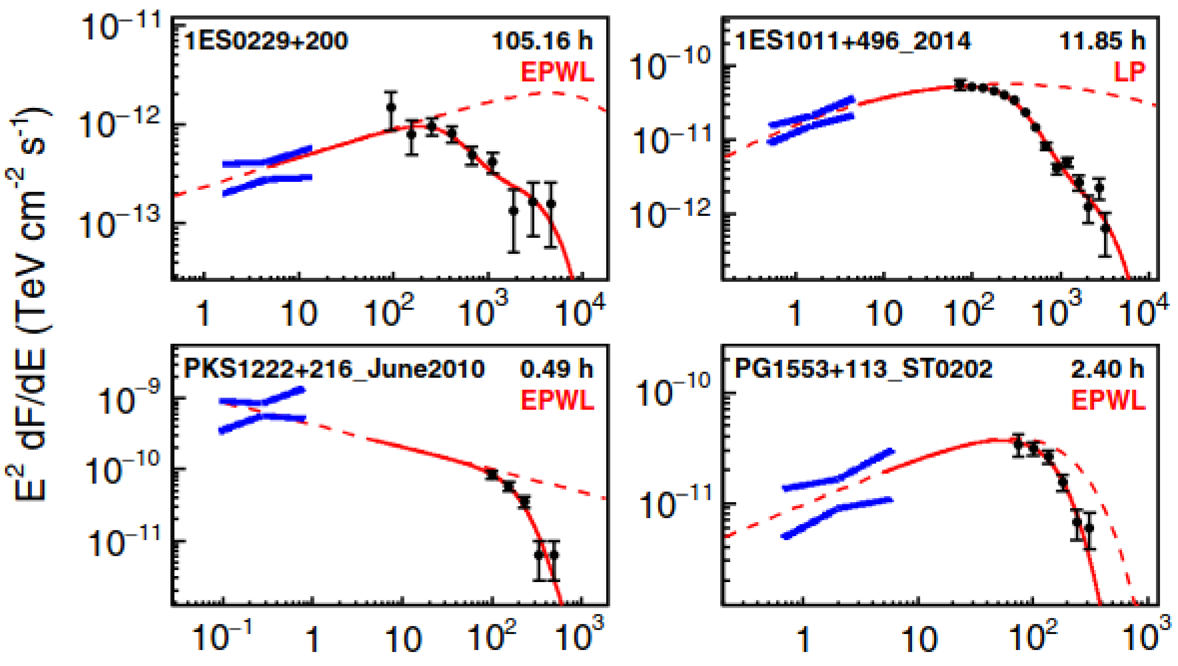


Previous MAGIC results

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) relative to a given EBL model.

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

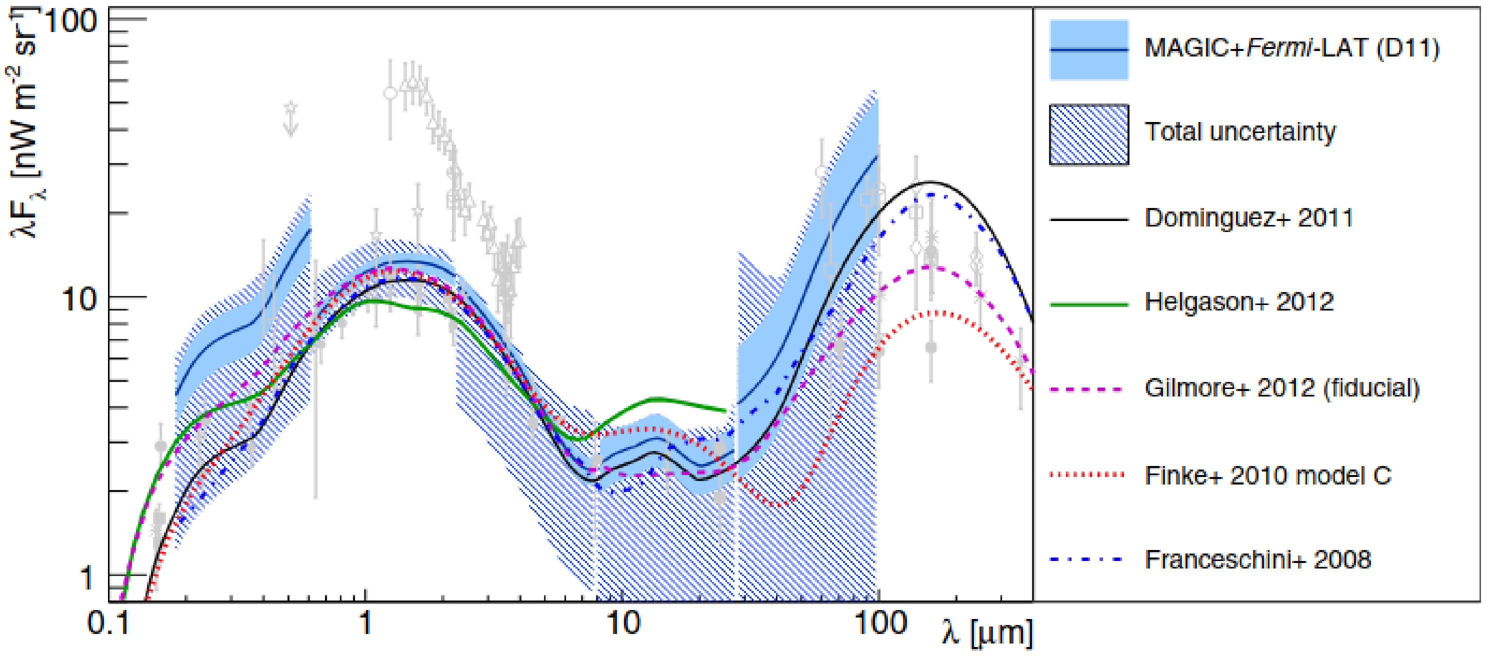
Where $g(E)$ is the fit function for the intrinsic spectrum, α is the EBL scale and $\tau(E, z)$ is the EBL optical depth according to the model



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

Previous MAGIC results

Previous MAGIC results also included wavelength-dependent constraints of the EBL intensity using Fermi-LAT + MAGIC data. Systematic uncertainties are dominant.



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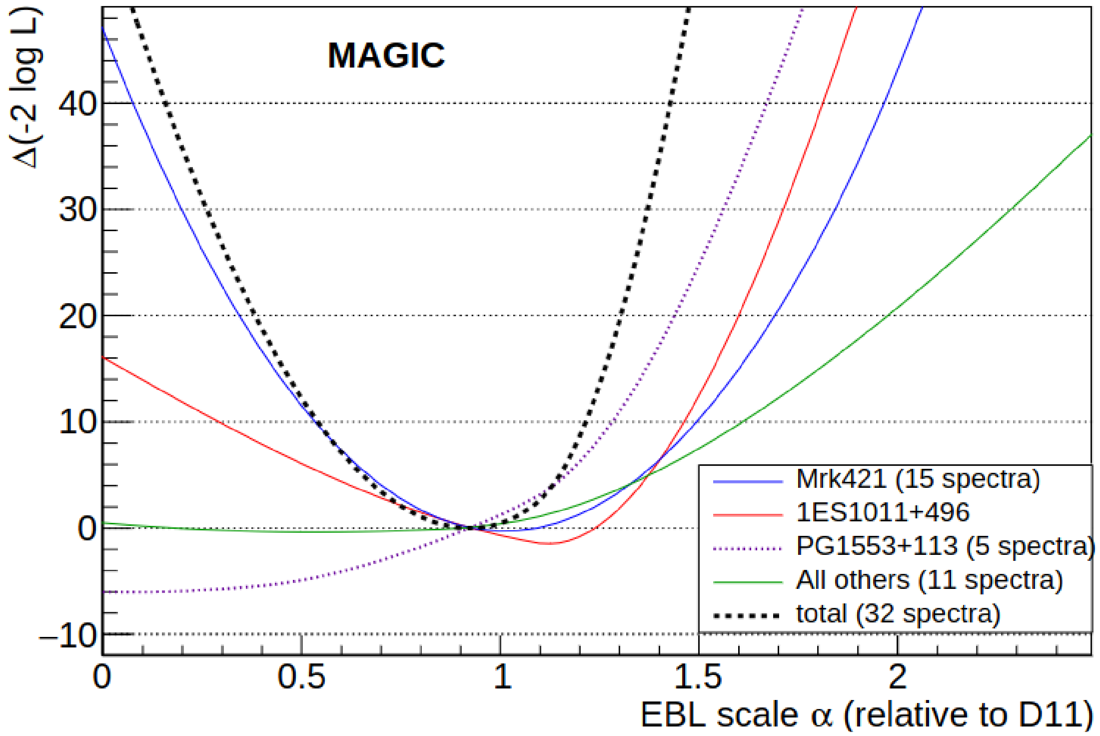
Previous MAGIC results

Robustness of result?

- Results compatible with the EBL density in the model (i.e. with alpha=1) but with very low P-value
- Results depend on the 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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Wilks' theorem:

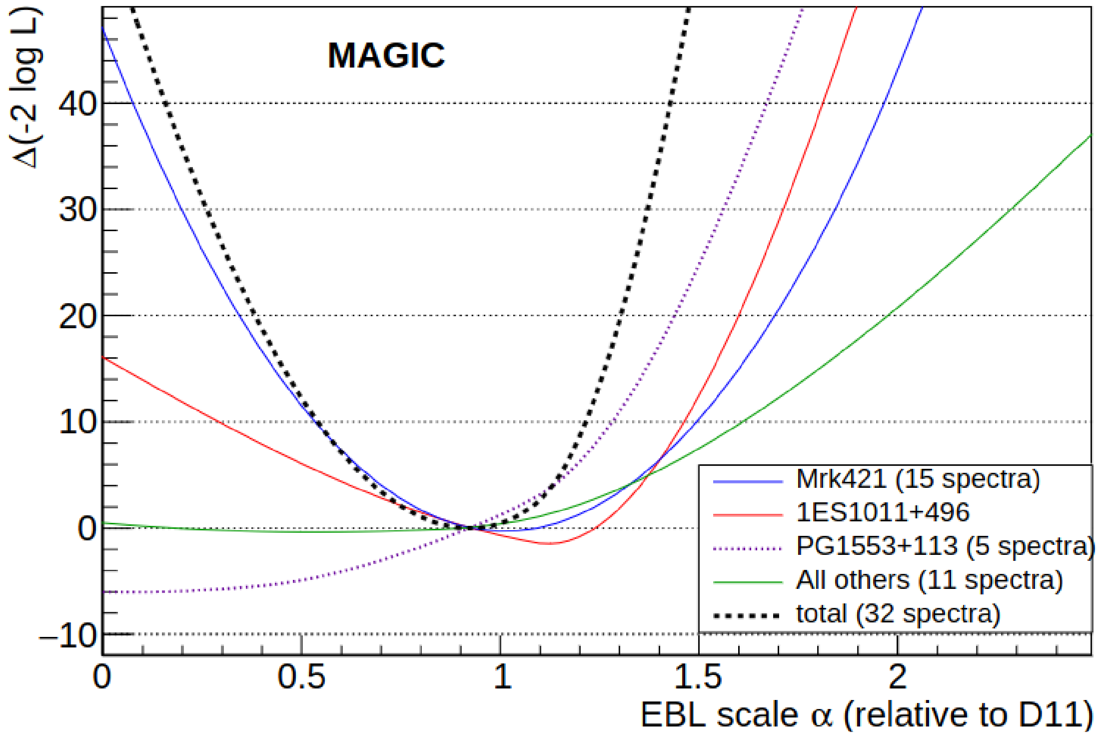
- Under certain regularity conditions, 2 times the difference in the log-likelihoods of two nested models follows a χ^2 distribution.

- Conditions:
  - Nested models
  - Large sample size -> Assumes asymptotic (large-sample) properties.
  - Parameters should be in the interior of the parameter space, with no boundaries that the tested parameters are approaching.

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

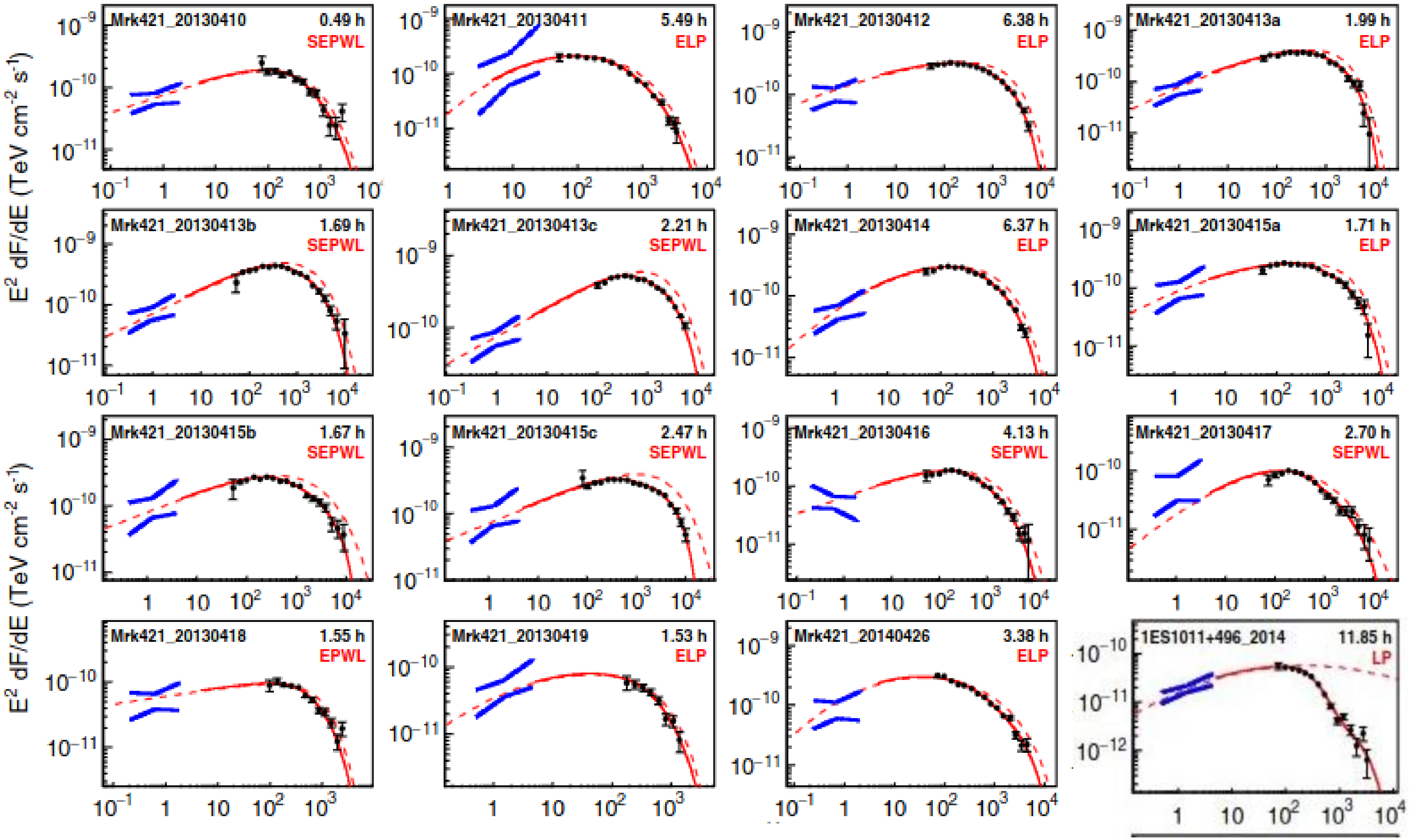
- Check the validity of Wilks' theorem using a Monte Carlo simulation:
  - Compute the uncertainties if it is not applicable
- Test 2 new methods to constrain EBL with less assumptions:
  - Multiply Broken Power-Law
  - "Concave EBL" method
  - Both aim to look for the inflection points imprinted by 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 EBL model used for this study is Domínguez et al. (2011) (MNRAS:410)

Data used

- The data used in this work are MAGIC data only with energies from 0.06 TeV to 20 TeV.

(We will not use FERMI data)

- Assuming that the spectra follows a simple function for more than 3 decades in energy is a stronger assumption than using the same function only in the MAGIC (or future IACTs) range.



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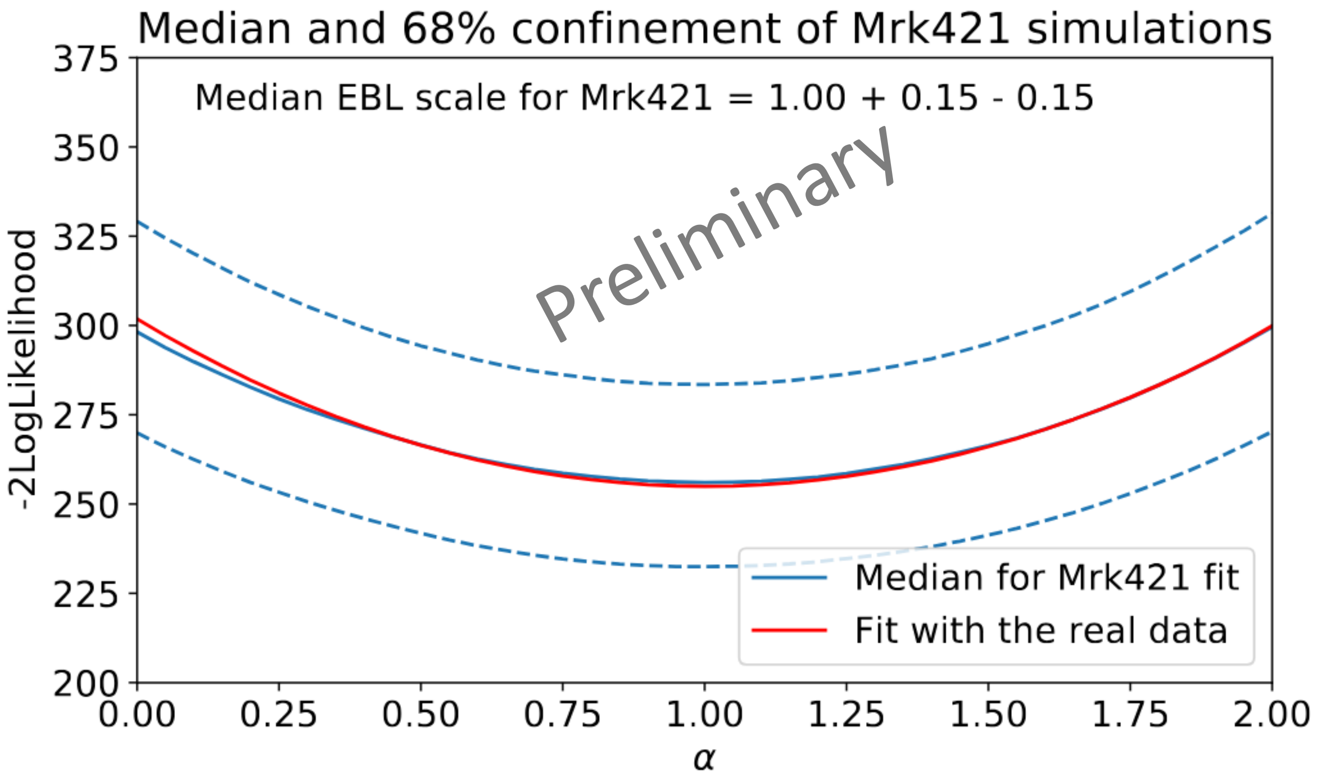
Monte Carlo simulation

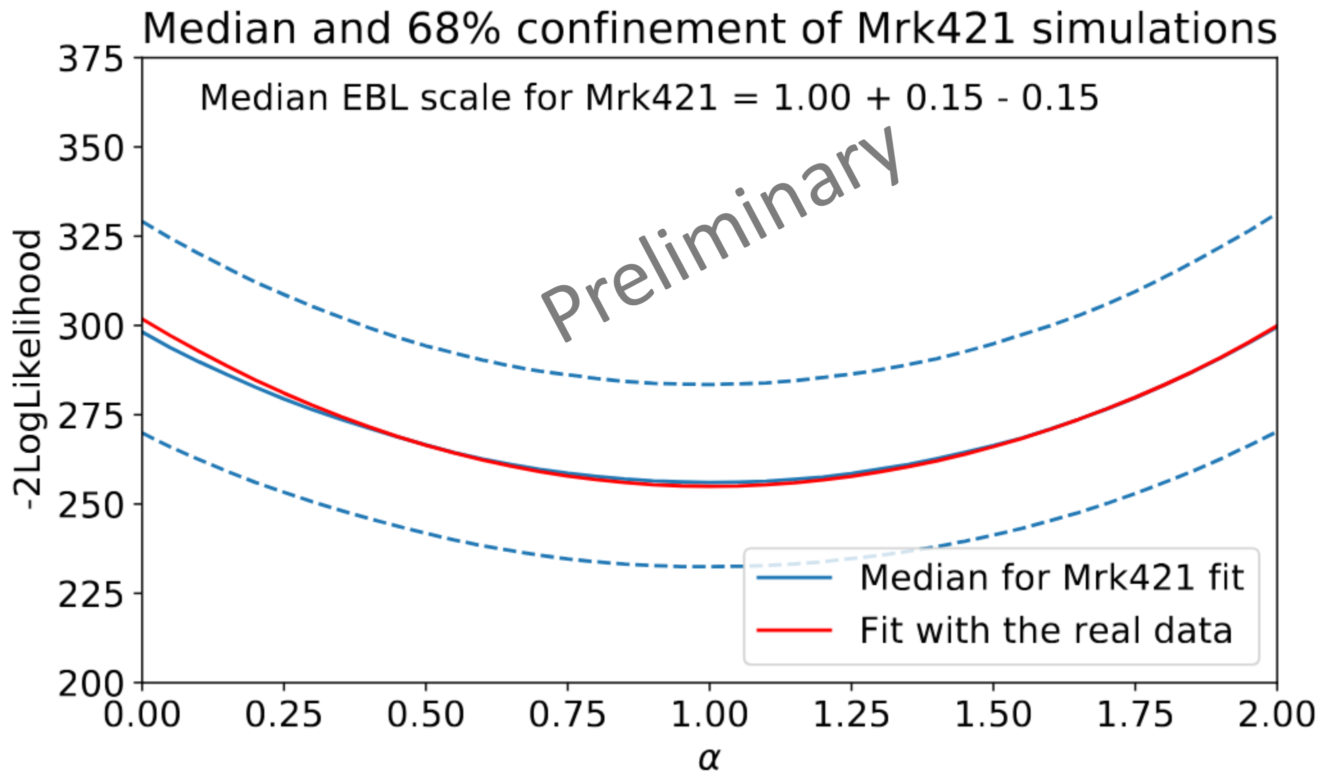
- We run different Poisson realizations of an observation of the same spectra (modeled with a function such as power-law (PWL), log-parabola (LP),…) using MAGIC IRF.
- Then every realization is analyzed with a Poissonian likelihood maximization.



Result of the combined fit of the Mrk421 simulation (10k realizations). With 3.3% gaussian systematics in the effective area, independent in each energy bin. (ndof = 221)

Monte Carlo simulation

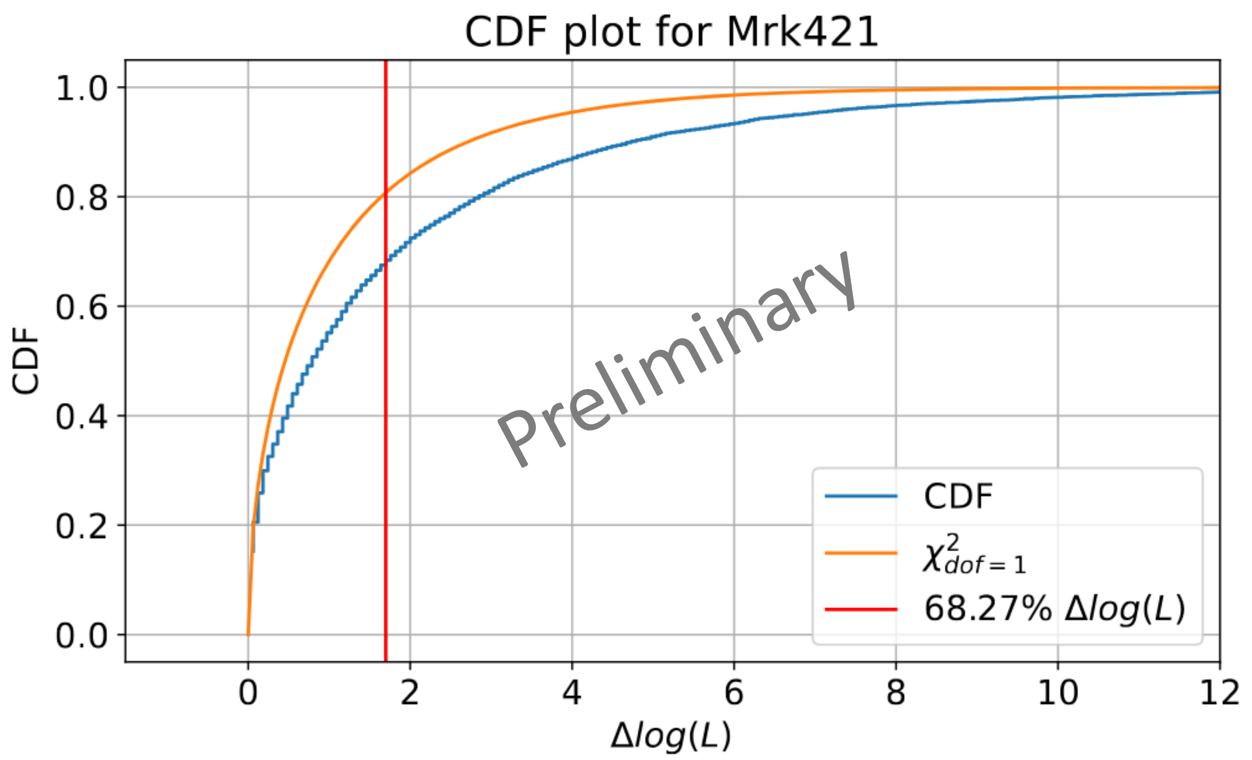
- As the real data P-values were very small and the P-values of the simulation had reasonable values (flat probability density function (PDF) from 0 to 1), we added Gaussian systematics in the effective area, independent in each energy bin.
- We belive there are systematic errors between the real instrument and the IRF used, which could be energy-dependent.



Result of the combined fit of the Mrk421 simulation (10k realizations). With 3.3% 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.



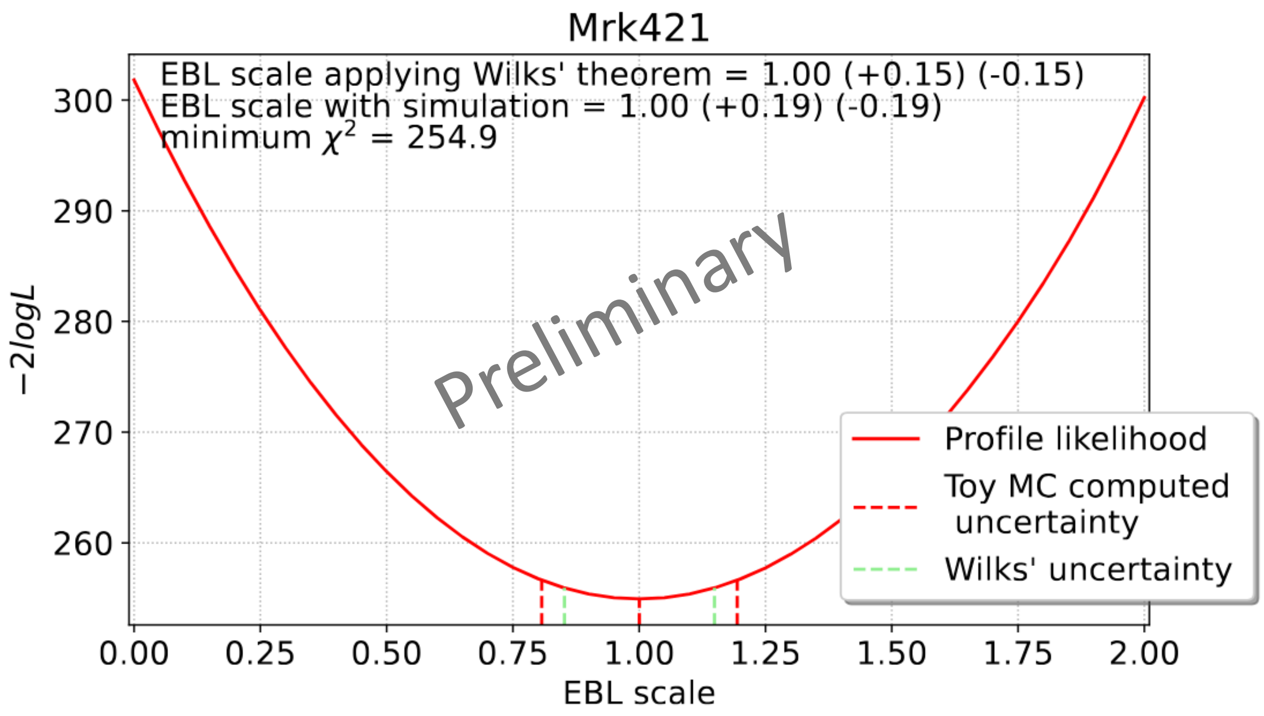
Cumulative distribution function of the simulation compared to a χ^2 distribution. The vertical red line shows the point where the CDF equals 68.27%

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 1.70 instead of 1.

•The uncertainty increased from ±0.15 to ±0.19, a 27%



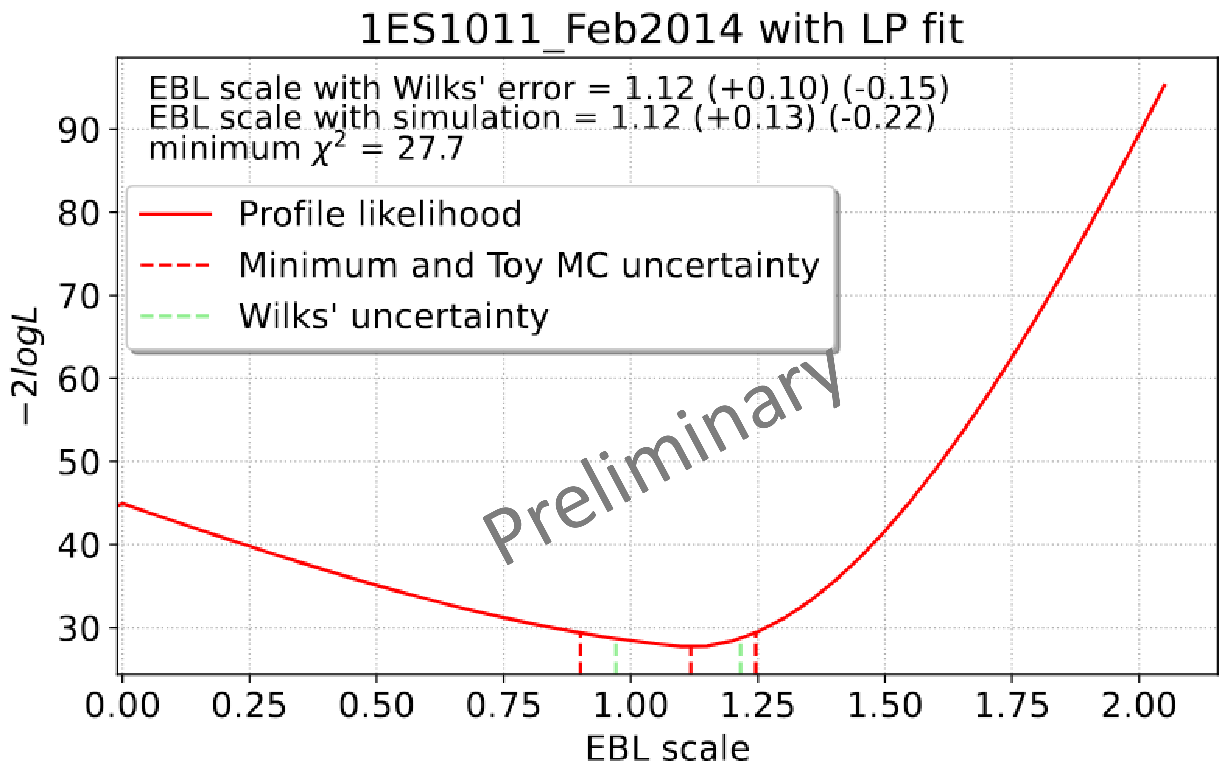
Profile likelihood of the EBL scale for the Mrk421 data

Real data analysis

- We did the same with 1ES1011+496:

- The Δ-2logL needed in this case is 1.69 instead of 1.

- The uncertainty increased from a 30% in the positive side and a 46% in the negative side.



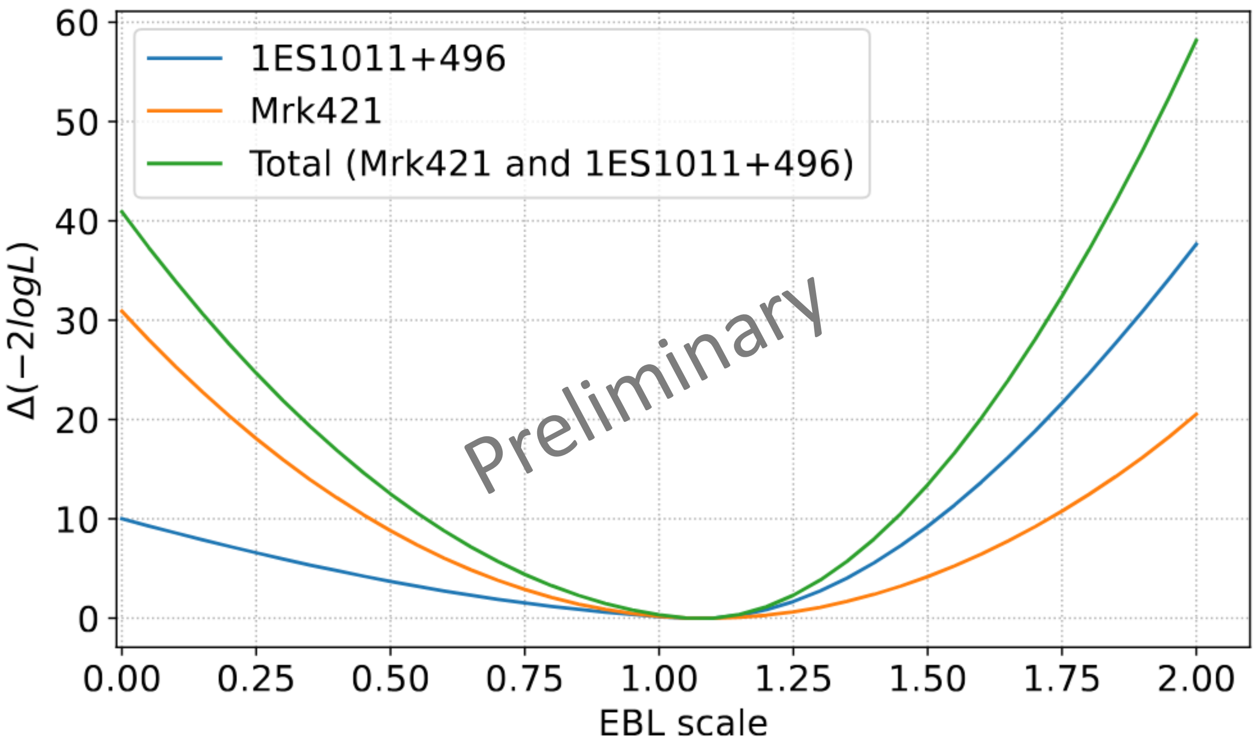
Profile likelihood of the EBL scale for the 1ES1011+496 data

Real data analysis

- Another way of computing the uncertainties is, now that we computed the value of the systematics for our model of each dataset, we can add them in the Gaussian terms of the likelihood of the analysis, which account for the uncertainty in the energy-dependent effective area (treated as nuisance).

- This allows the nuisance parameters to take into account this systematics.

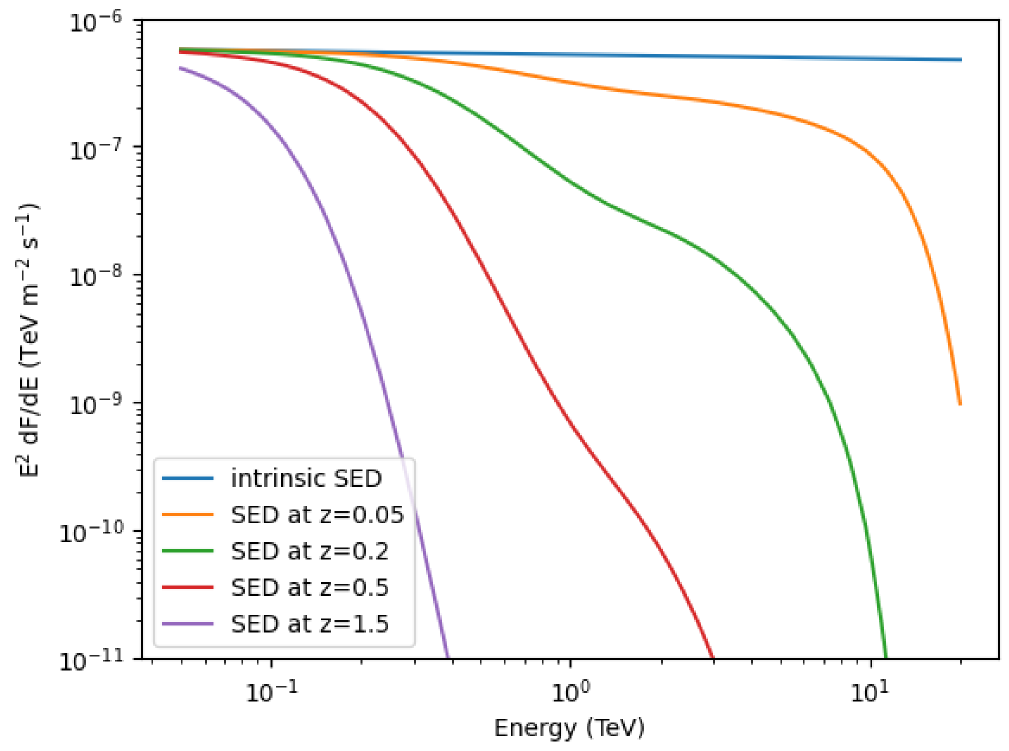
- Uncertainties obtained in this way are consistent with the ones obtained from the original analysis using the MC simulation to compute uncertainties, but the P-values are now reasonable.



Profile likelihood of the EBL scale for the 1ES1011+496 and Mrk421 data. Also the combined one. All taking into account the systematics in the analysis.

New methods

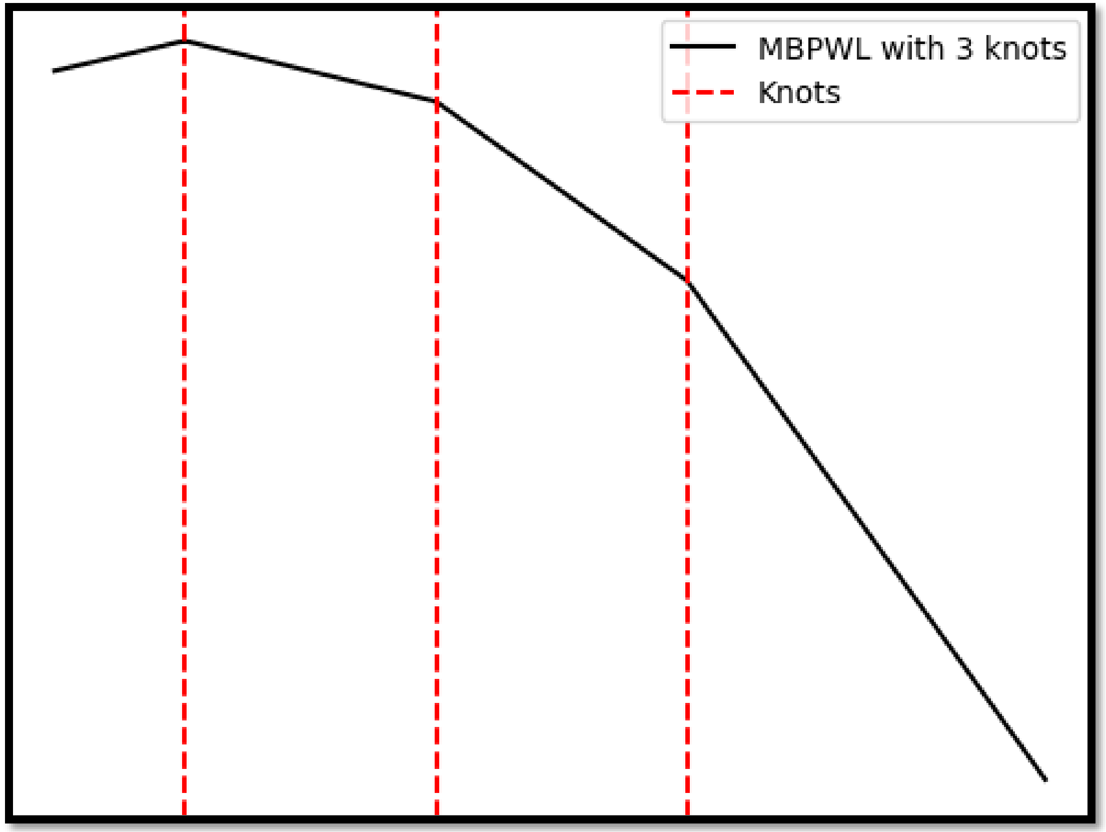
- We do not expect inflection points in the VHE intrinsic spectra of BL Lacs.
- The EBL absorption (log(transmissivity) vs. log(E)) has a wiggle around 1 TeV
- Therefore we are proposing two different ways of constraining EBL using this inflection points.



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

New methods: Generic concave function

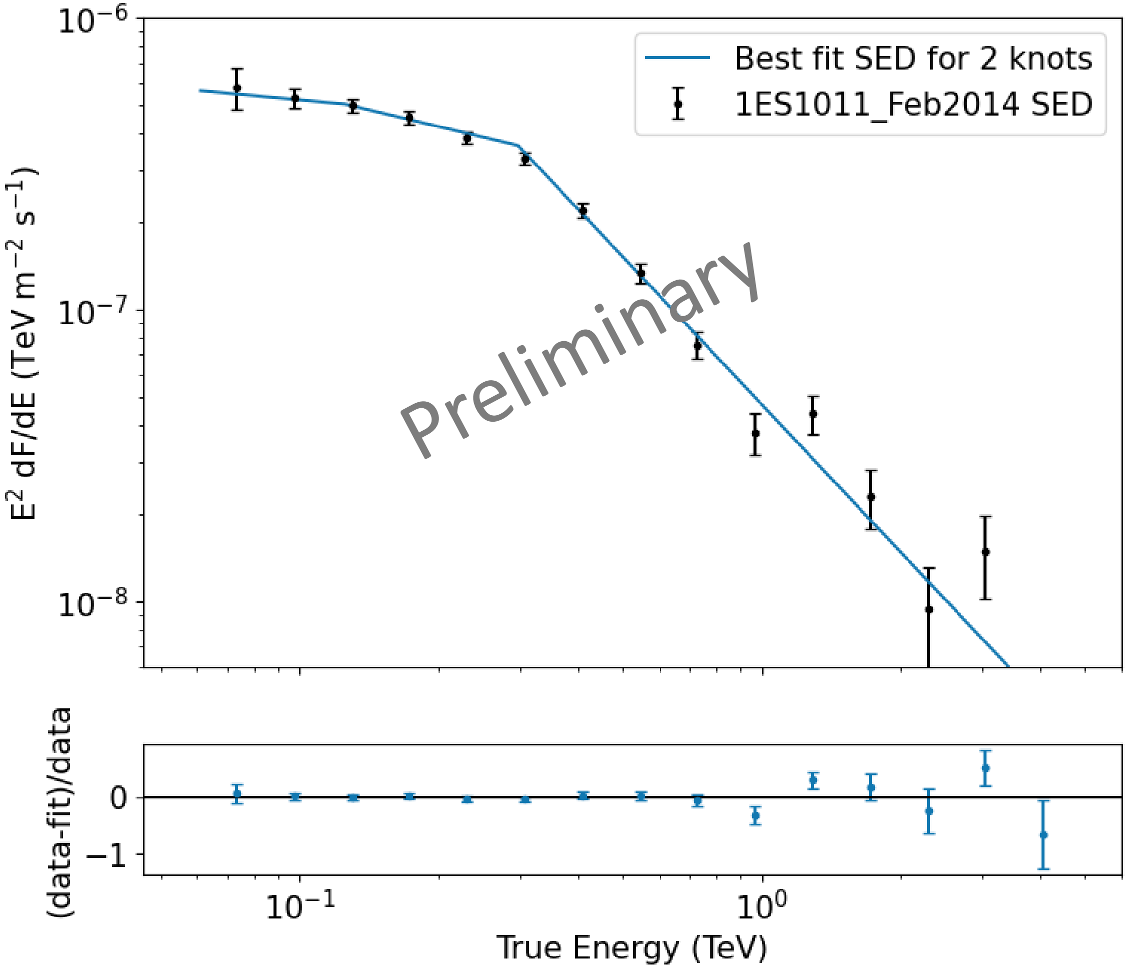
- Multiply-Broken Power-Law (MBPWL)
  - Power law with changes in the photon index in points called breaks.
    - To impose concavity the photon index increases on every break.
    - The breaks are logarithmically spaced between the first and last break.
- Problems:
  - How to choose number of breaks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

- Multiply-Broken Power-Law (MBPWL)
  - Since the MBPWL should fit well the spectrum of a source even under the assumption of no EBL (α = 0), except for the wiggle. In this way, if the fit improves when adding EBL, it should be because it adds the presence of the inflection points
  - Number of breaks selection criteria:
    - We fix α = 0 and we find the best fit for different number of nodes.
    - We check the different values of the variation of photon index (Γ) and pick the greater number of nodes where all of them are larger than 0.01.



Example of a MBPWL with 3 breaks in log scale (x and y)
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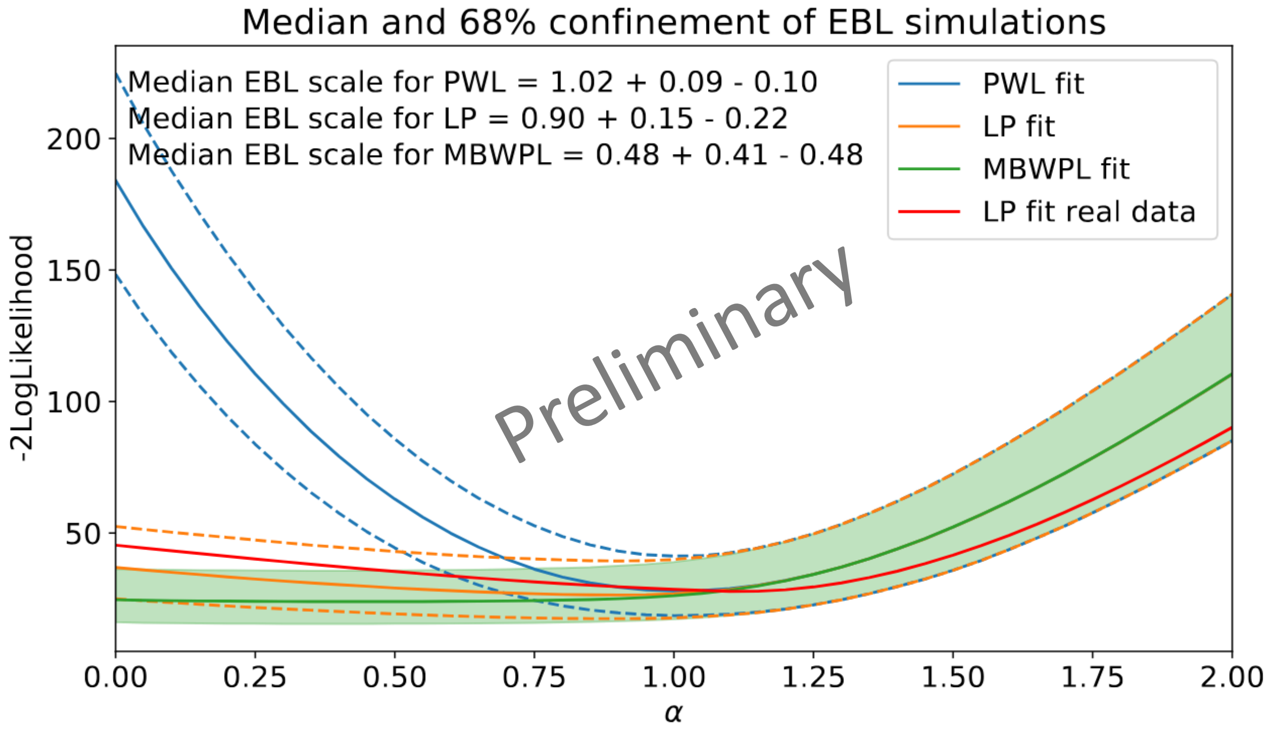
New methods: Generic concave function

- 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.



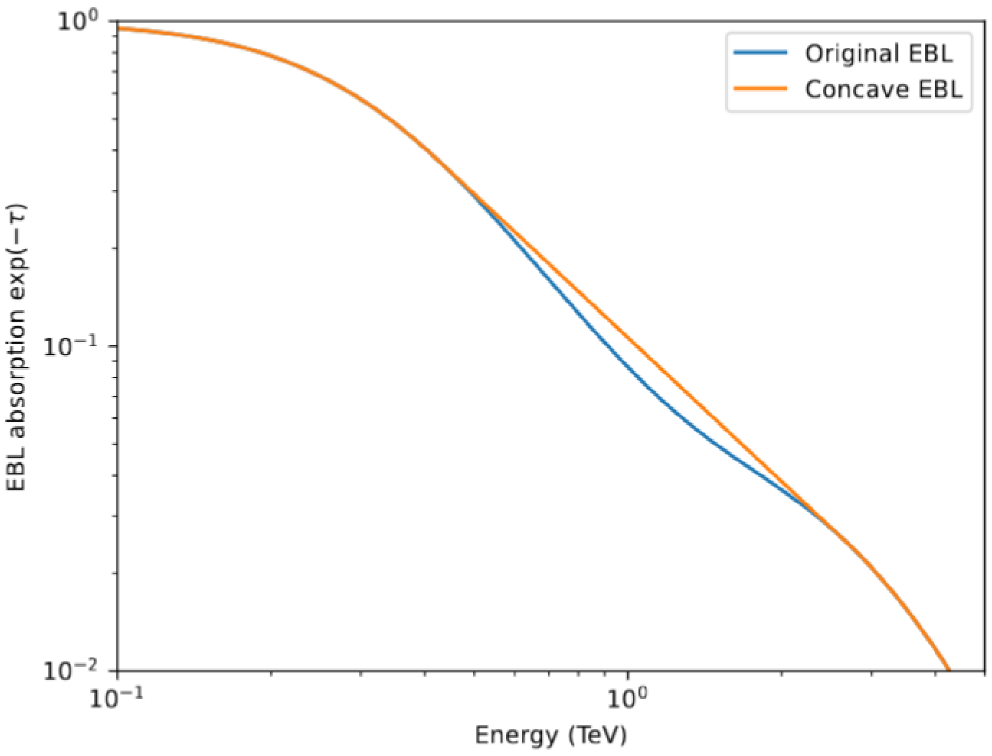
Simulated 1ES1011 2014 flare with a PWL and fitted a PWL (ndof = 18), LP (ndof = 17) and MBPWL with 2 nodes (ndof=16)

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

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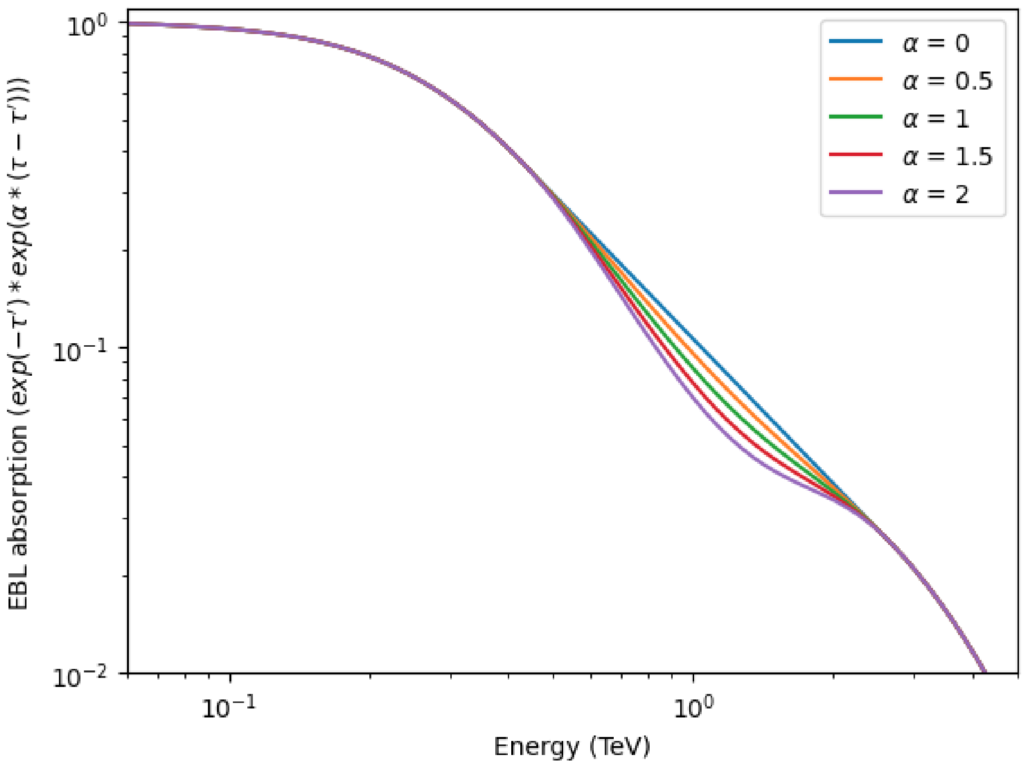
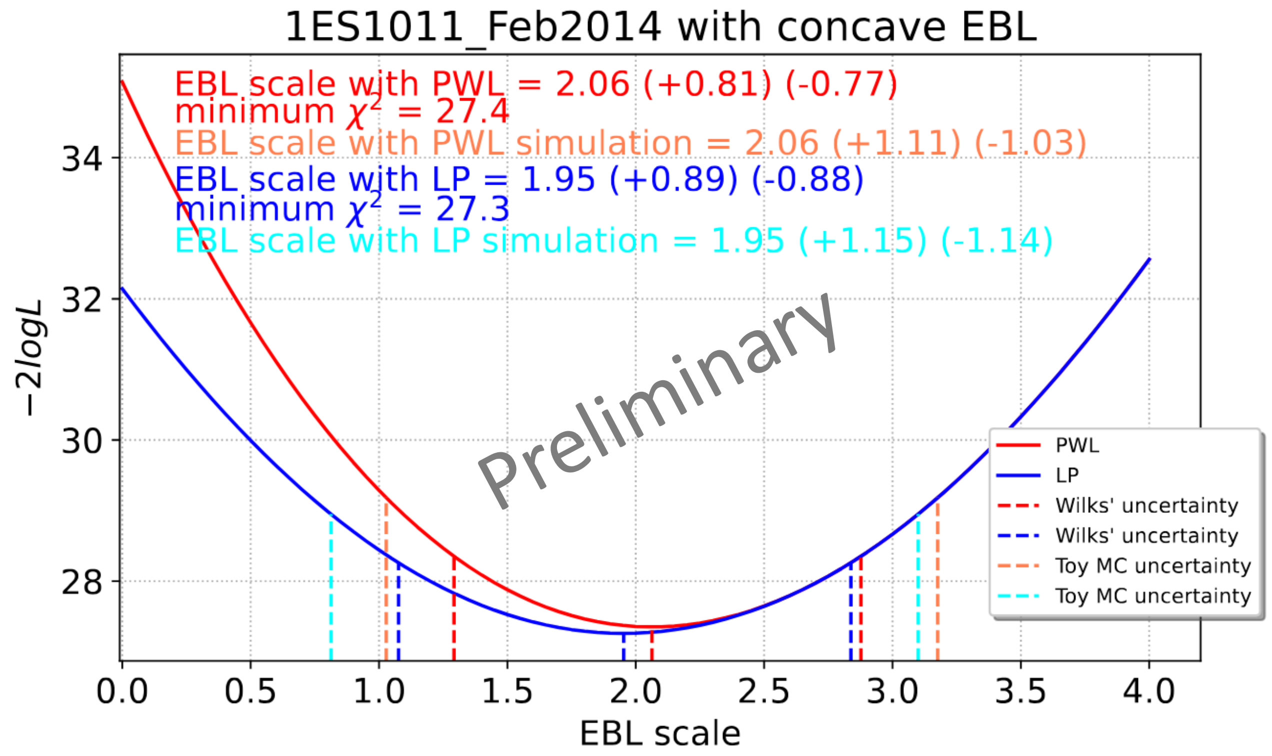


EBL absorption of the concave EBL method for different values of α for a redshift of 0.212

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 resolution and better flux sensitivity, like the ones given by the next generation of telescopes, we may obtain competitive constraints.



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

New methods: "concave" EBL method

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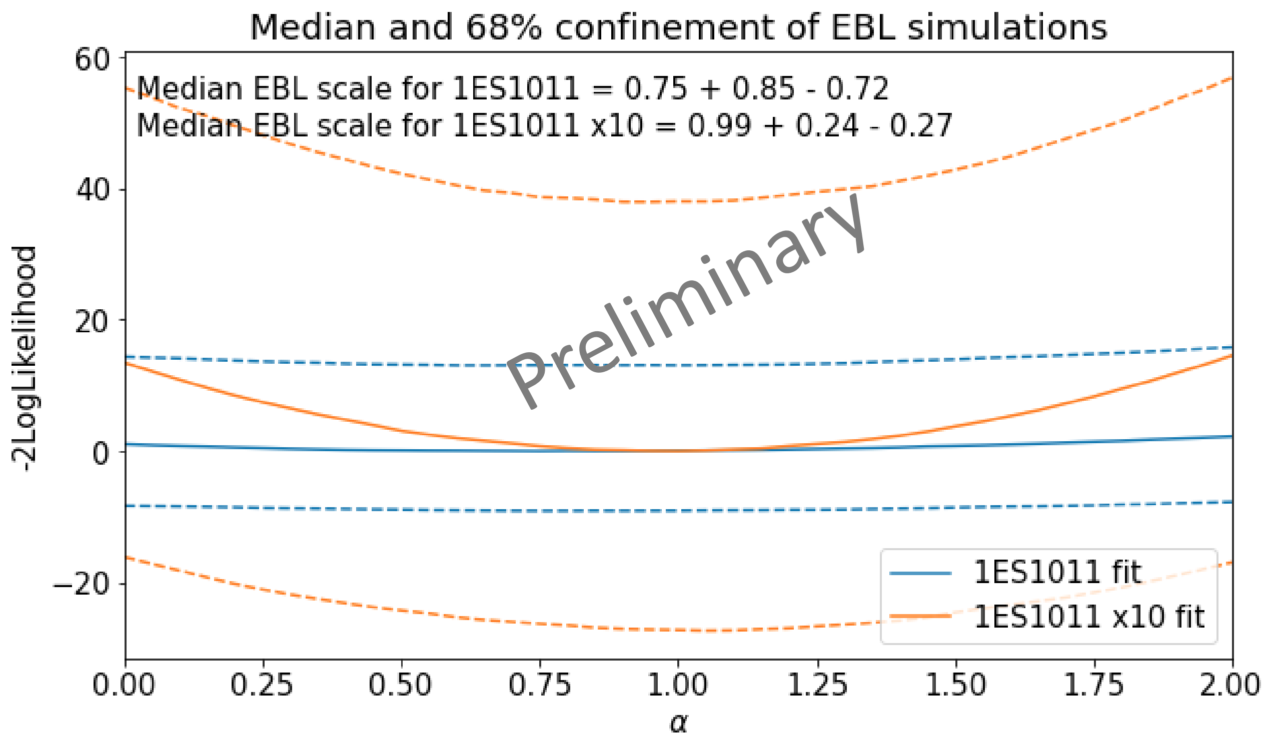


Result of the simulation of 1ES1011+496 and 1ES1011+496 with 10 times its flux using the concave EBL method.

Conclusions: previous results

- 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 test the validity of these methods:
  - 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.

Conclusions: better systematic treatment

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

- We have found two ways of computing the uncertainties with a plausible systematics model:
  - Using the Toy MC to get the value of $\Delta(-2\log(L))$ needed to get the desired 1sigma uncertainty
  - Using the systematics found in the MC to take them into account in the analysis of the real data.
- Both methods give consistent results when applied on MAGIC data

Conclusions: new methods

- 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
    - Probably not practical for CTAO (unless these caveats are solved)
  - 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

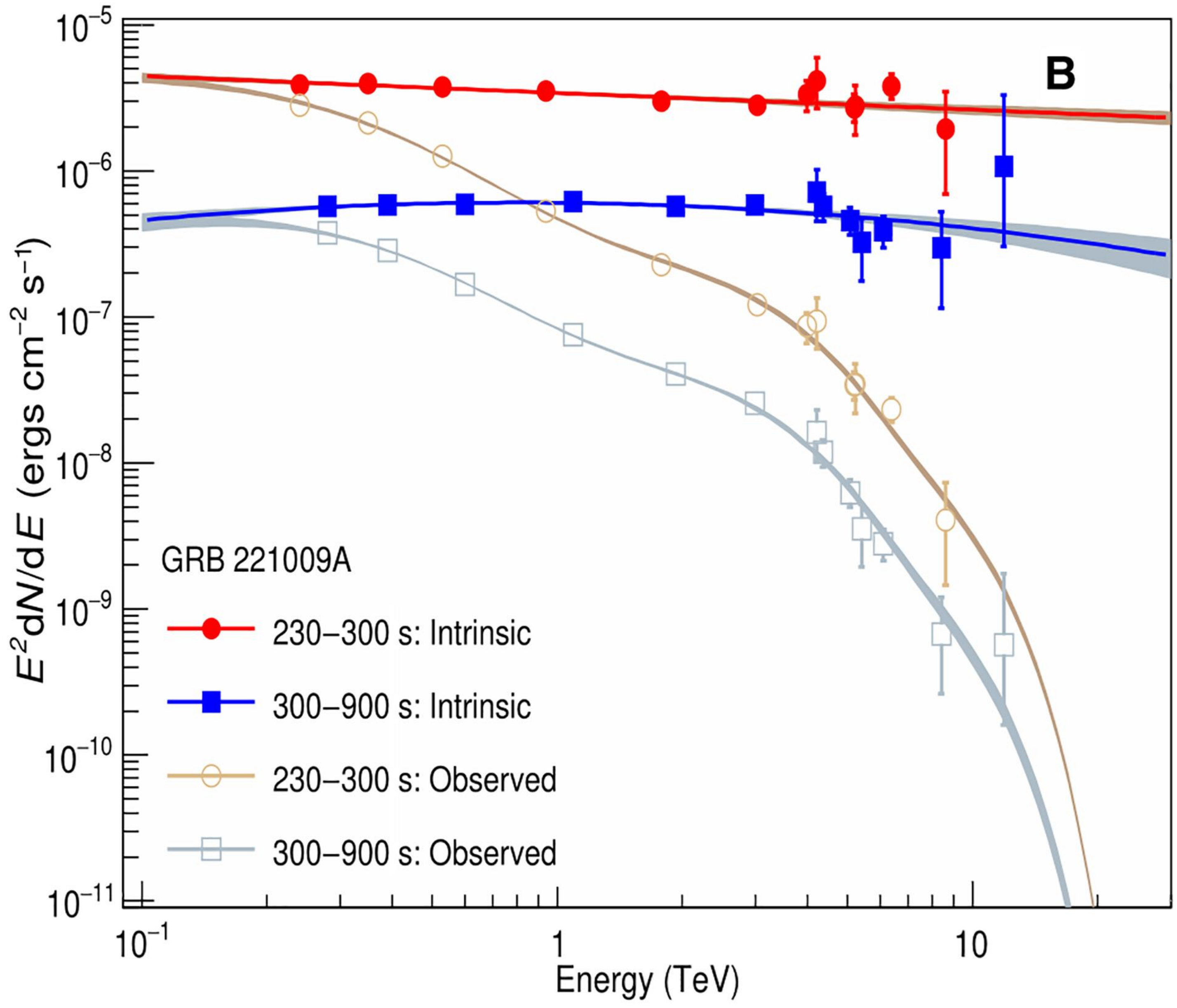
Backup

Likelihood expression:

$$L_i(ebl, \theta) = Poisson(g'_i(ebl, \theta) + b_i, N_{\mathrm{on},i}) \cdot$$
$$Poisson(b_i/\beta, N_{\mathrm{off},i}) \cdot Gauss(g'_i; g_i, \Delta g_i)$$

Backup

GRB 221009A spectra:



LHAASO collaboration
https://doi.org/10.1126/sciadv.adj2778