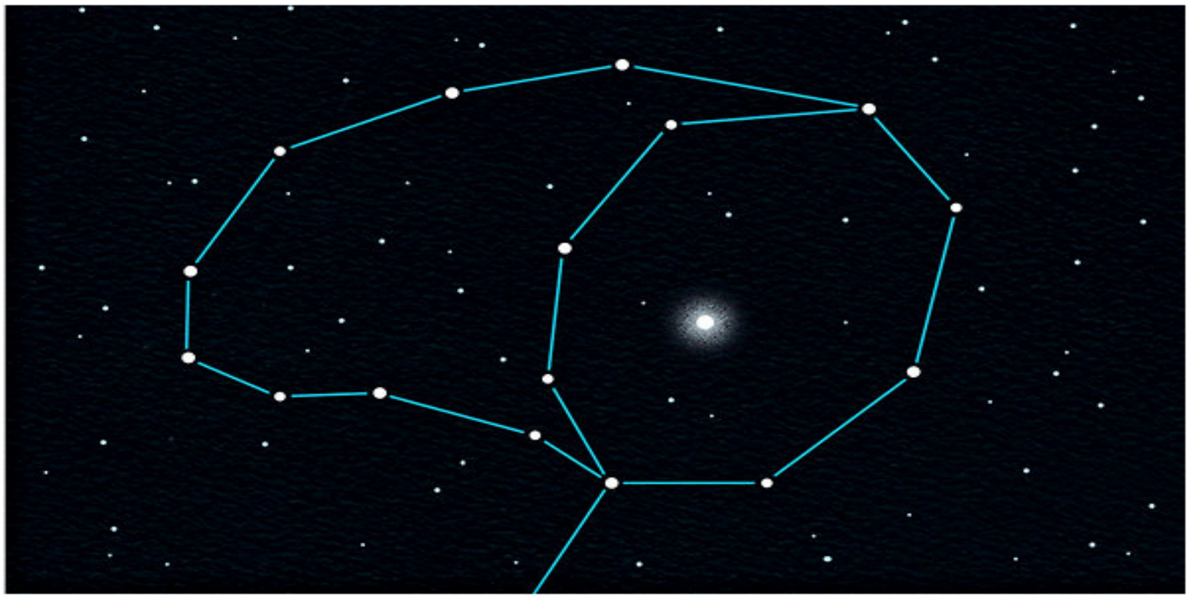
The Imprint of the EBL in the gamma-ray Spectra of Blazars

OBSERVATORY

The New York Times

Telescope Detects Light From the Earliest Stars



Chris Gash

By SINDYA N. BHANOO
Published: November 2, 2012

Based on "Ackermann+12,Science, 338, 1190"

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Anita Reimer[2], Rolf Buehler[3]
on behalf of the Fermi-LAT collaboration

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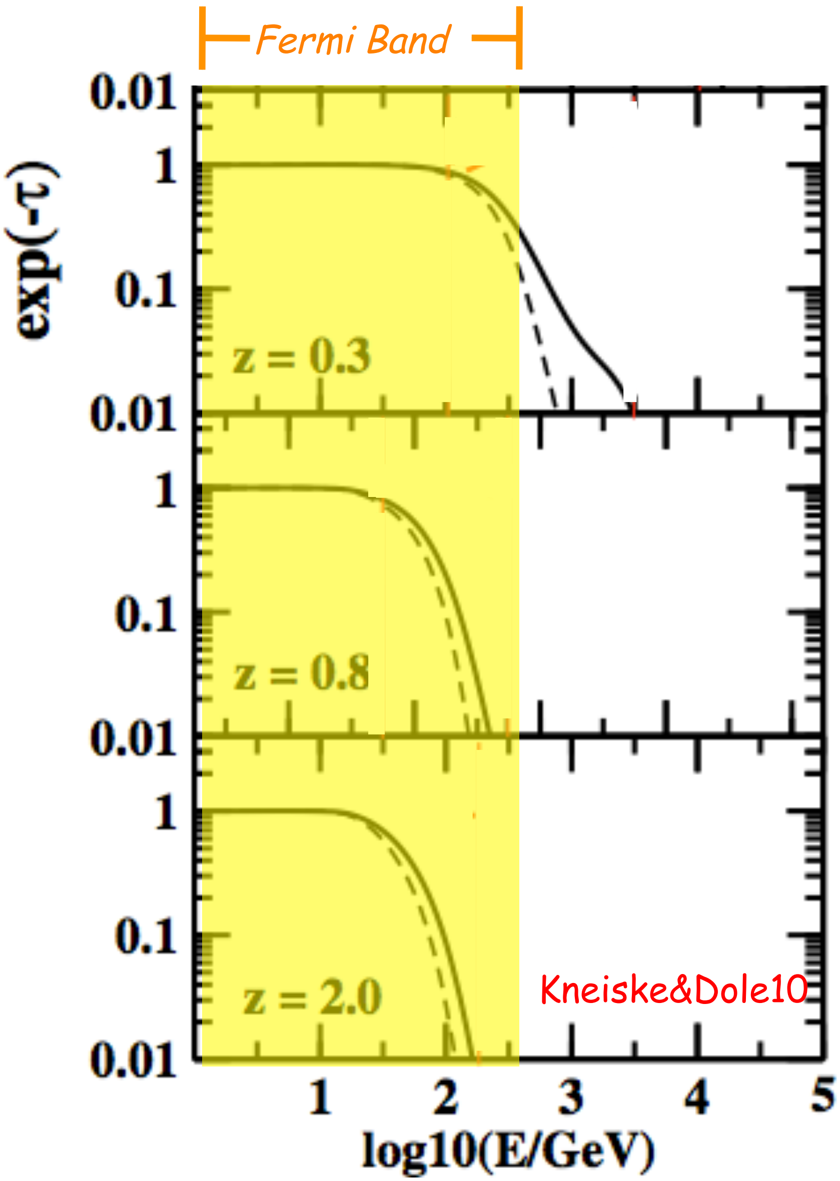
Attenuation due to the EBL

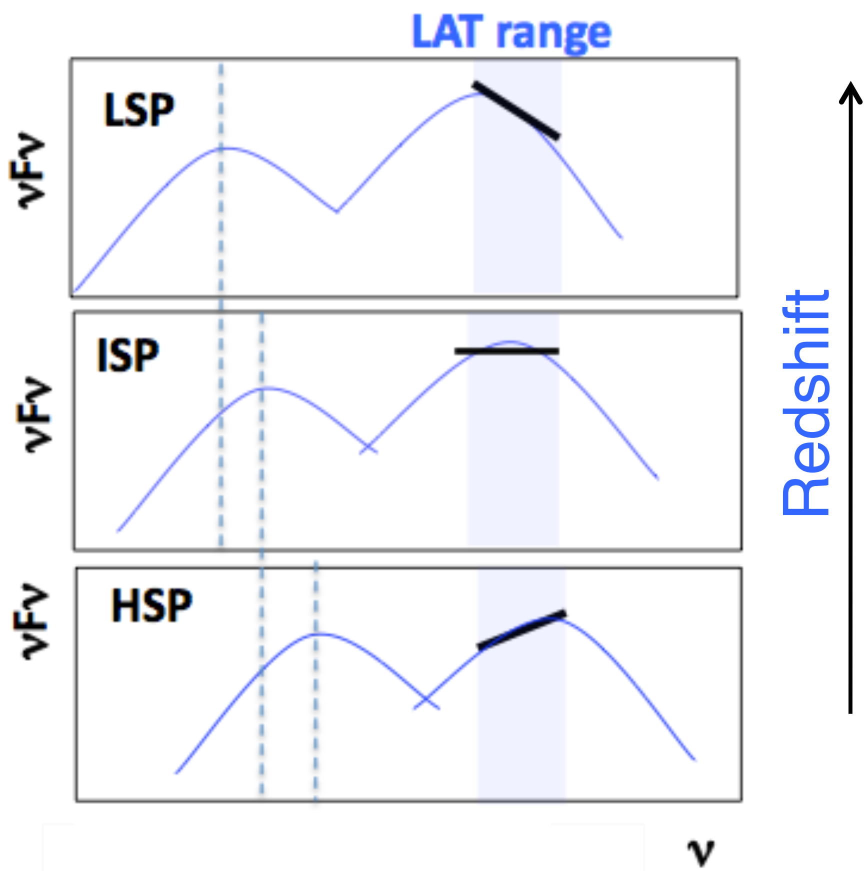


Most models predict an attenuation of >99% at z~1

The EBL leaves a unique redshift/energy dependent attenuation in the spectra of blazars

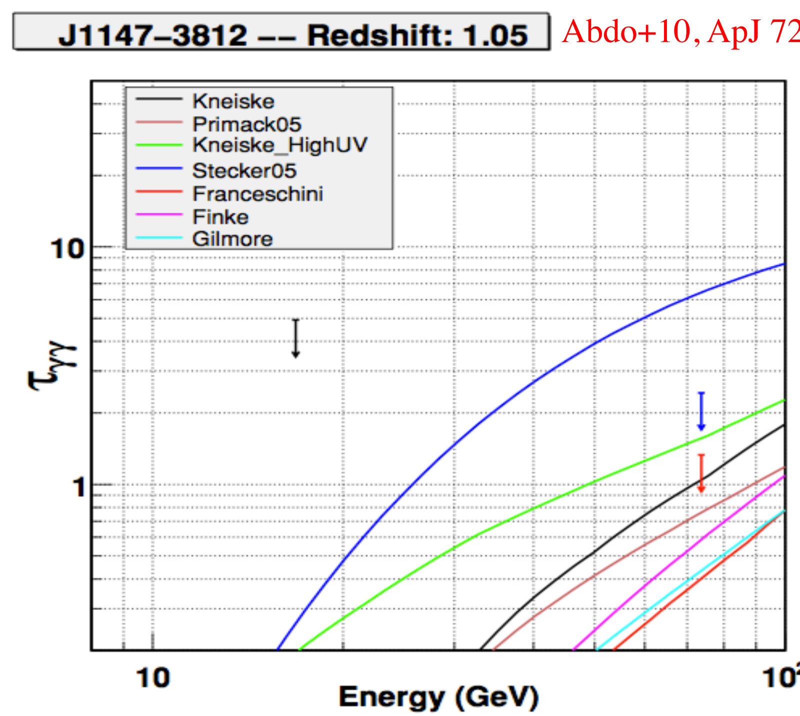
Predictions and Reality

Reality is far more complex due to the non-standard nature of blazars



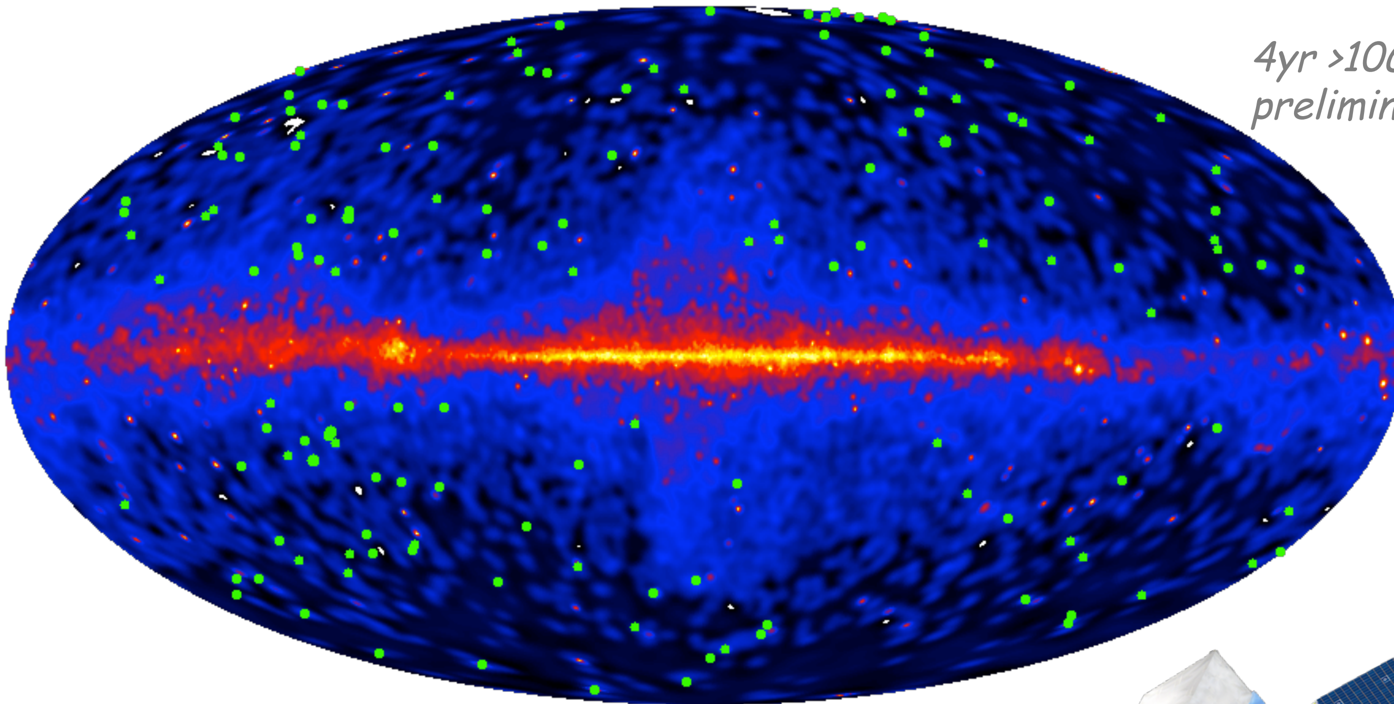
Blazars' spectra are type-dependent and the composition of the blazar sample evolves with redshift

So far only upper limits on the opacity were derived (Abdo+10, ApJ 723, 1082, Raue10, etc.)

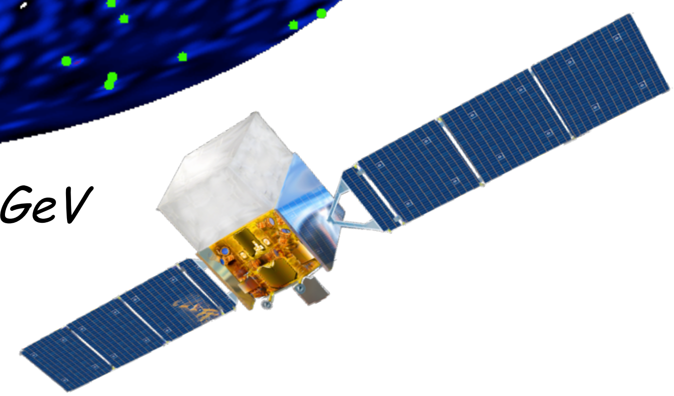


Abdo+10, ApJ 723

Fermi observations



4yr >10GeV Map, preliminary



- *First instrument to detect >500 sources above 10 GeV*

- *Advantages of Fermi:*
  - *Detects blazars up to high redshift*
  - *Fermi's bandpass gives unique handling on the `intrinsic' spectrum*
  - *Continue all-sky observations allow us to assess variability issues (none)*

- *We used the best 150 BL Lacs to measure the EBL*

Analysis Procedure

We look for the collective deviation of the spectra of blazars from their intrinsic spectra

- We use 46months of P7V6 1-500 GeV data
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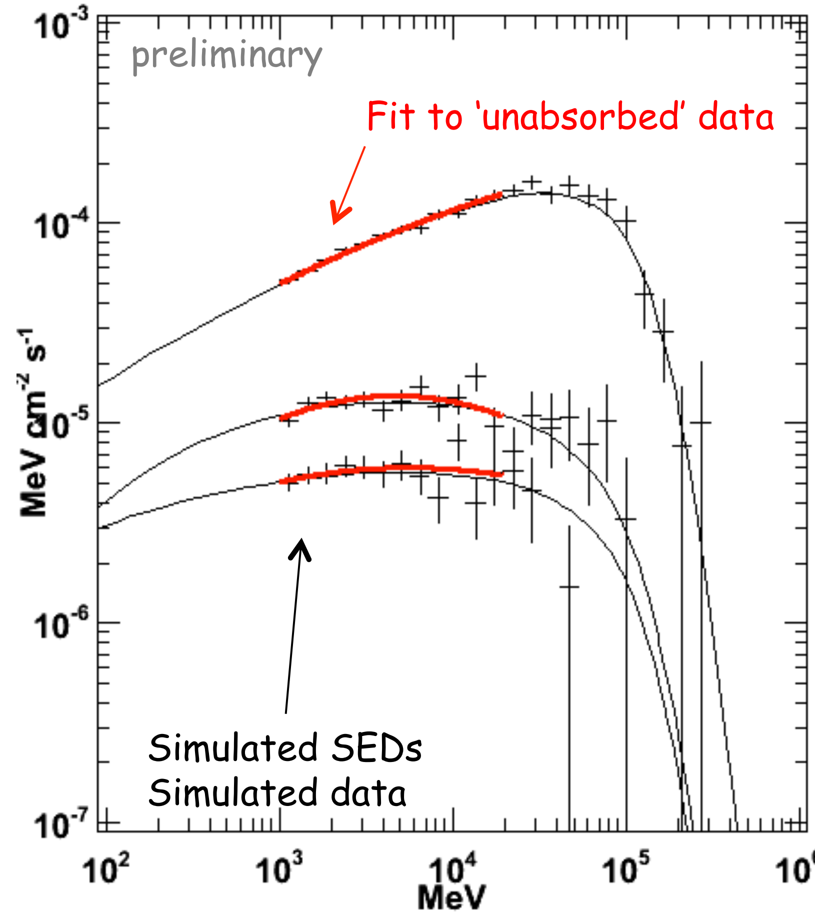
  - z= 0-0.2, 0.2-0.5, 0.5 -1.6
- All BL Lacs are modeled with a *LogParabola* spectrum



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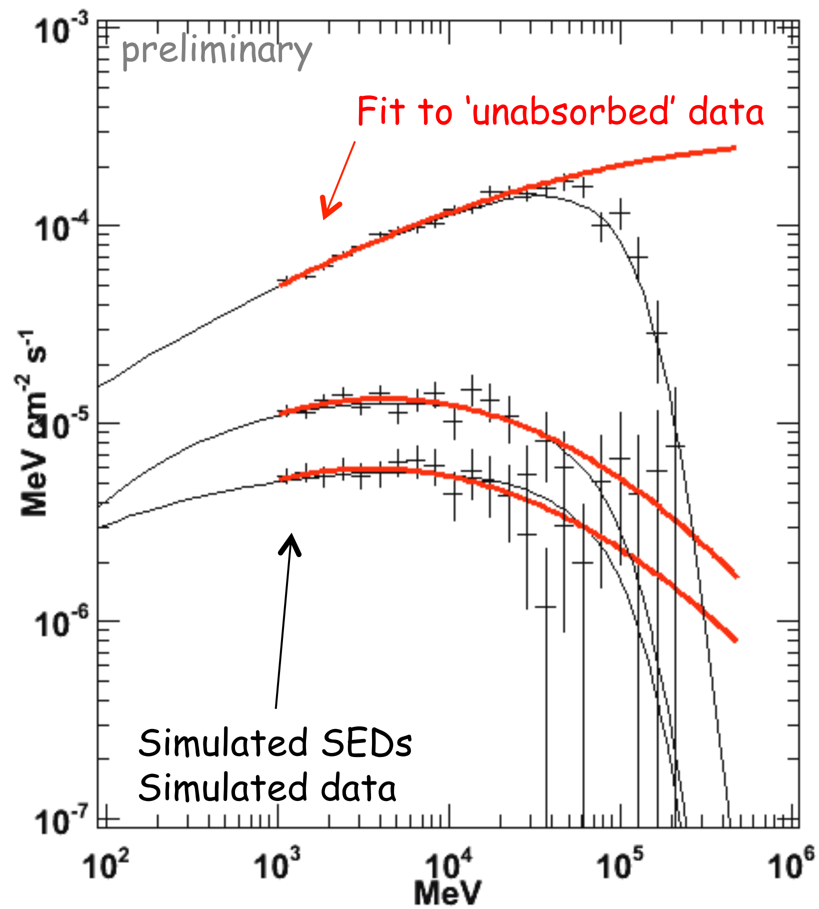
- We perform a combined fit where:
  - The spectra of all sources are fit independently
  - The spectra of all sources are modified by a common $e^{-b\,\tau(E,z)}$ term



$$F(E)_{absorbed} = F(E)_{intrinsic} \cdot e^{-b \cdot \tau_{model}}$$

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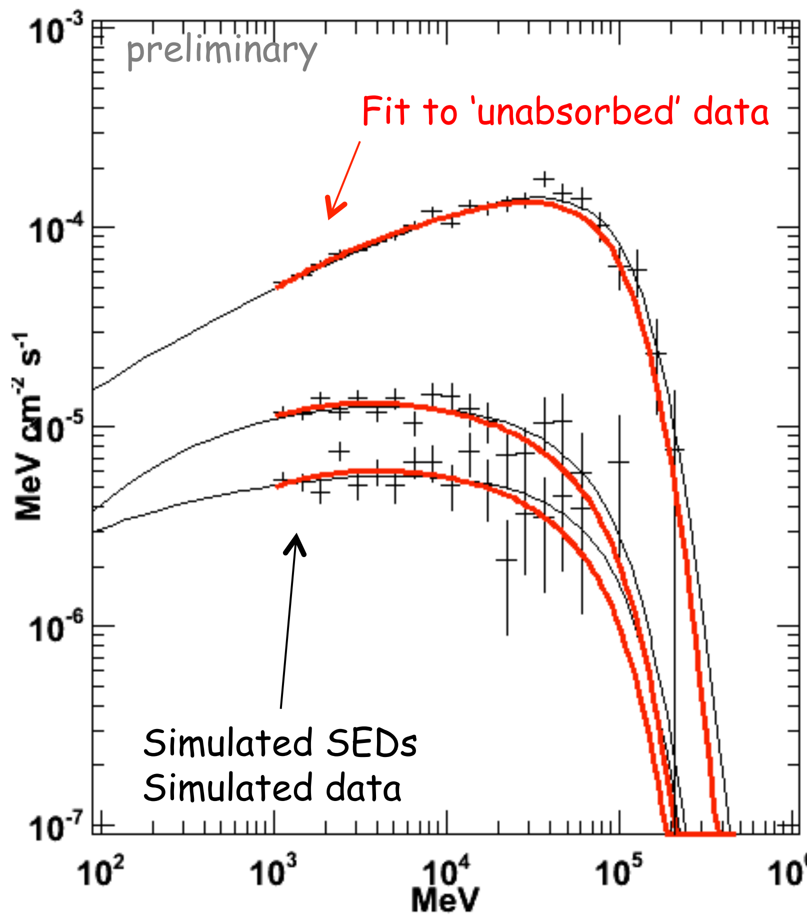
- We evaluate 2 cases:
  1. Null hypothesis b=0 : there is no EBL
  2. Null hypothesis b=1 : the model predictions are correct



$$F(E)_{absorbed} = F(E)_{intrinsic} \cdot e^{-b \cdot \tau_{model}}$$

Composite Likelihood Results: 1

- Significance of the Detection: $$F(E)_{absorbed} = F(E)_{\text{int}\,rinsic} \cdot e^{-b\cdot\tau_{\text{mod}\,el}}$$
  - Best-fit versus null hypothesis b=0: i.e. there is no EBL

- Significance of `Rejection' of a given EBL model:
  - Best-fit versus null hypothesis b=1: i.e. the EBL model predictions are correct

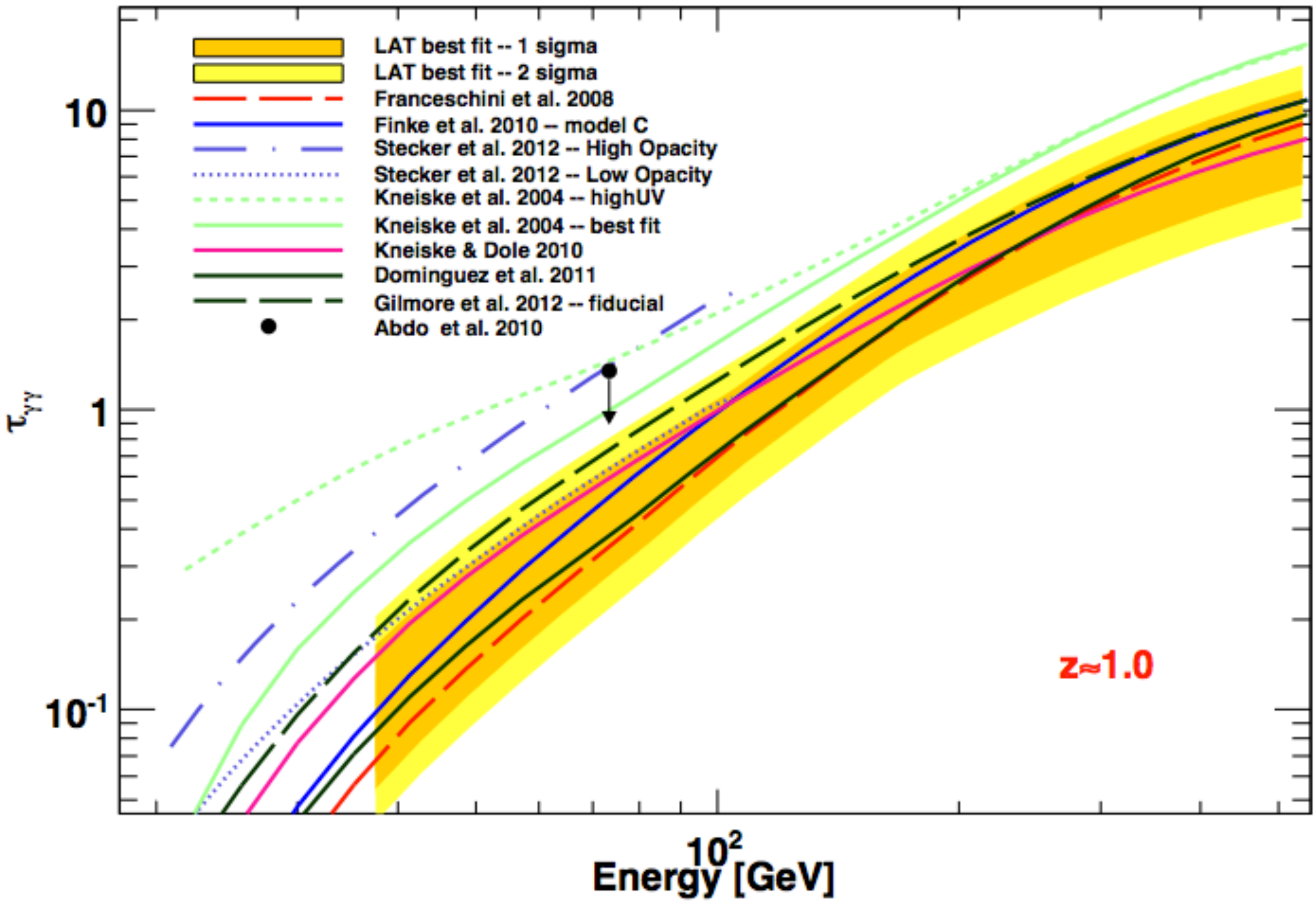
- We tested most of the EBL models: Franceschini08, Kneiske04, Kneiske&Dole10, Gilmore09-12, Dominguez11, Stecker+ etc

- Results (wrt to Franceschini+08 model):

Redshift	Significance	Scaling factor b
z<0.2	~2	1.18(±0.94)
0.2<z<0.5	~2.7	0.82(±0.41)
0.5<z<1.6	~5	1.29(±0.42)
0<z<1.6	*~6*	*1.02(±0.23)*

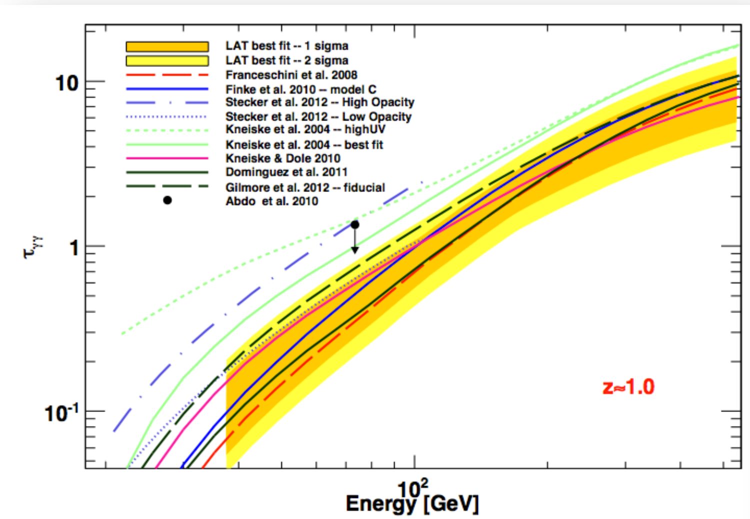
1. *~6σ detection of the EBL absorption feature*
2. *Data compatible with low-opacity models*

Composite Likelihood Results: 2



Composite Likelihood Results: 2

- A significant steepening in the blazars' spectra is detected
- This is consistent with that expected by a 'minimal' EBL:
  - i.e. EBL at the level of galaxy counts
  - 4 models rejected above 3sigma
- All the non-rejected models yield a significance of detection of 5.6-5.9 σ
- The level of EBL is 3-4 times lower than our previous UL (Abdo+10, ApJ 723, 1082)



EBL Detection Significance

Model Rejection Significance

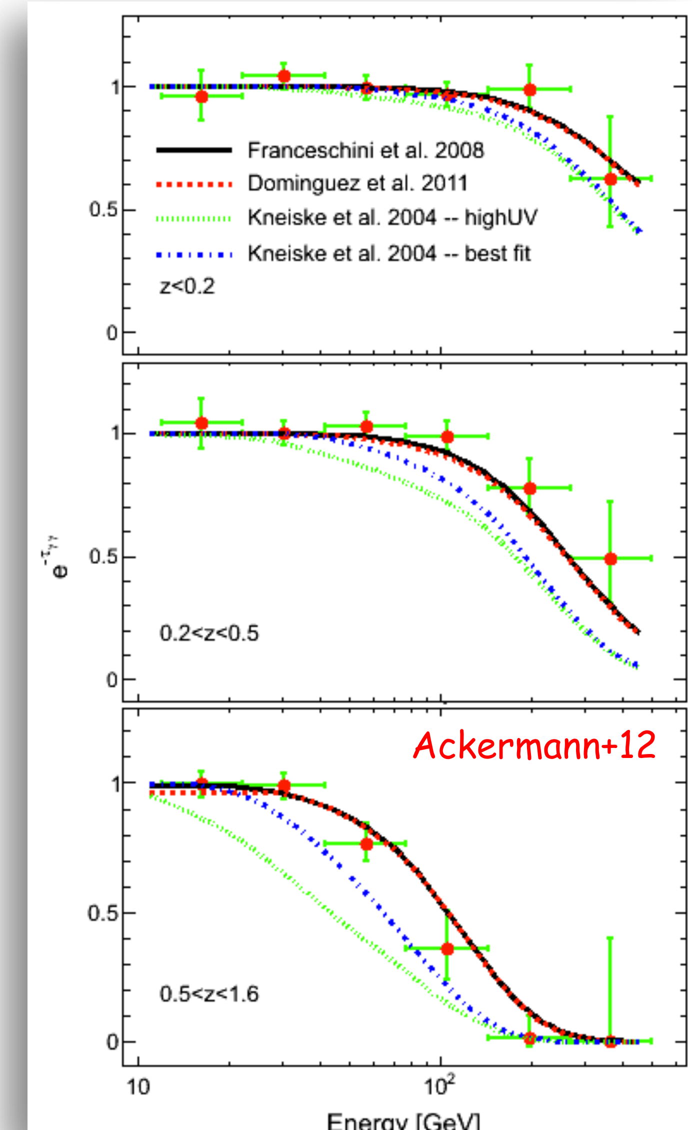
Ackermann+12

Model[a]	Ref.[b]	Significance of b=0 Rejection[c]	b[d]	Significance of b=1 Rejection[e]
Stecker et al. (2006) – fast evolution	(23)	4.6	0.10±0.02	17.1
Stecker et al. (2006) – baseline	(23)	4.6	0.12±0.03	15.1
Kneiske et al. (2004) – high UV	(22)	5.1	0.37±0.08	5.9
Kneiske et al. (2004) – best fit	(22)	5.8	0.53±0.12	3.2
Gilmore et al. (2012) – fiducial	(27)	5.6	0.67±0.14	1.9
Primack et al. (2005)	(56)	5.5	0.77±0.15	1.2
Dominguez et al. (2011)	(25)	5.9	1.02±0.23	1.1
Finke et al. (2010) – model C	(24)	5.8	0.86±0.23	1.0
Franceschini et al. (2008)	(7)	5.9	1.02±0.23	0.9
Gilmore et al. (2012) – fixed	(27)	5.8	1.02±0.22	0.7
Kneiske & Dole (2010)	(26)	5.7	0.90±0.19	0.6
Gilmore et al. (2009) – fiducial	(2)	5.8	0.99±0.22	0.6

Measurement of Tau with Energy and Redshift

- We use the composite likelihood in small energy bins to measure the collective deviation of the observed spectra from the intrinsic ones

- The cut-off moves in z and Energy exactly as expected for EBL absorption (for low opacity models)



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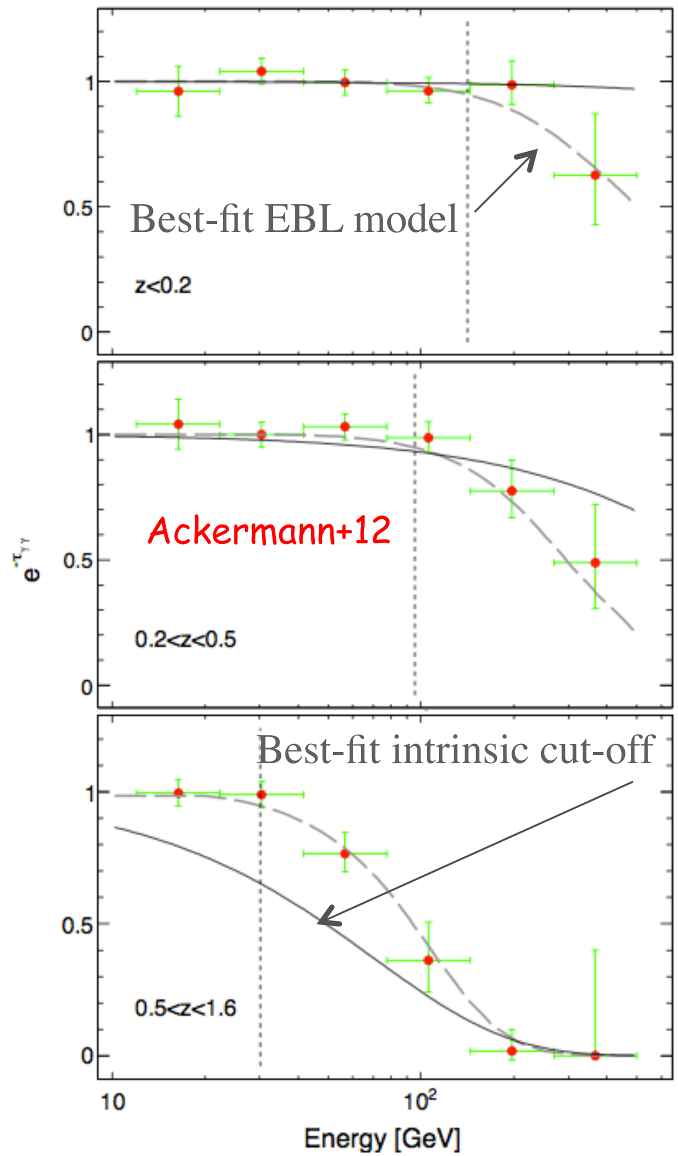
- The cut-off moves in z and energy as expected for EBL absorption (for low opacity models)

- It is difficult to explain this attenuation with an intrinsic property of BL Lacs
  1. BL Lacs required to evolve across the z=0.2 barrier
  2. Attenuation change with energy and redshift cannot be explained by an intrinsic cut-off that changes from source to source because of redshift and blazar sequence effects

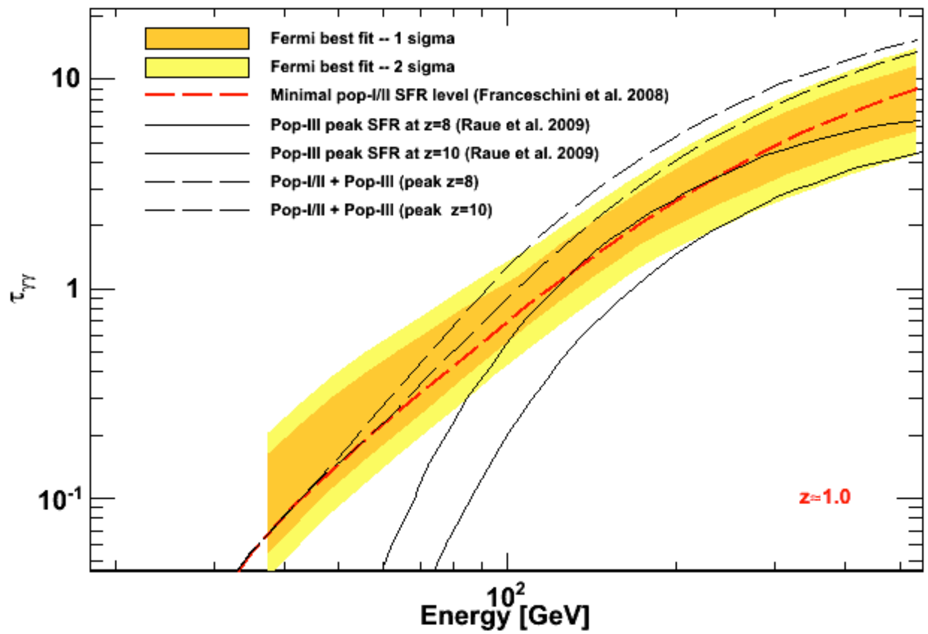


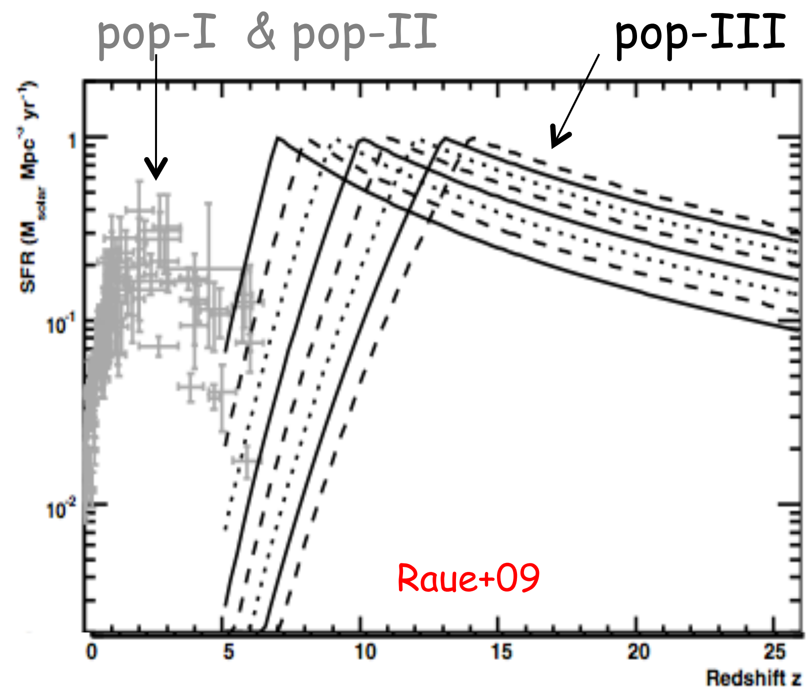
Our Tests

- Analysis is fully validated with simulations
- Results are robust against change of IRF/dataset
  - Systematic of ~10% on $\tau_{\gamma\gamma}$ from IRF
- Results are confirmed when treating the classes independently:
  - HSPs dominate the signal (TS~25)
  - ISPs contribute a little (TS~10)
  - LSPs too soft
- Results do not depend on highest-z sources
- Results are robust against inclusion/exclusion of most variable sources
- Results are only weakly dependent on the accuracy of redshifts (i.e. if some redshifts are lower limits)
- The residual ~30 BL Lacs contribute a TS~3.5
- Results confirmed when decreasing dramatically E_{crit}

Stellar Archeology

- Light of Pop-III stars increase the opacity w.r.t the one of pop-I and II





- Extremely large contr. of pop-III stars ruled out by Aharonian+06

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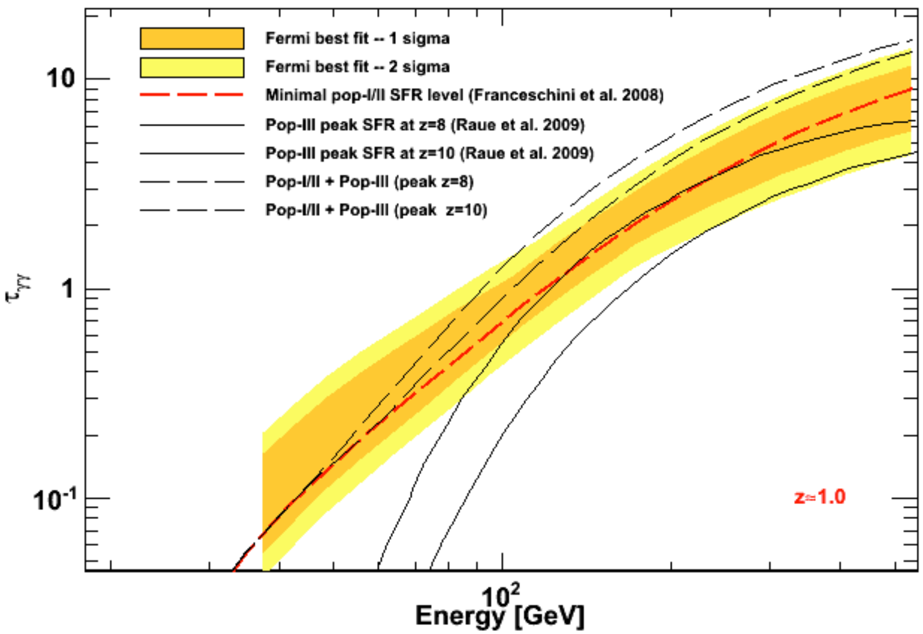

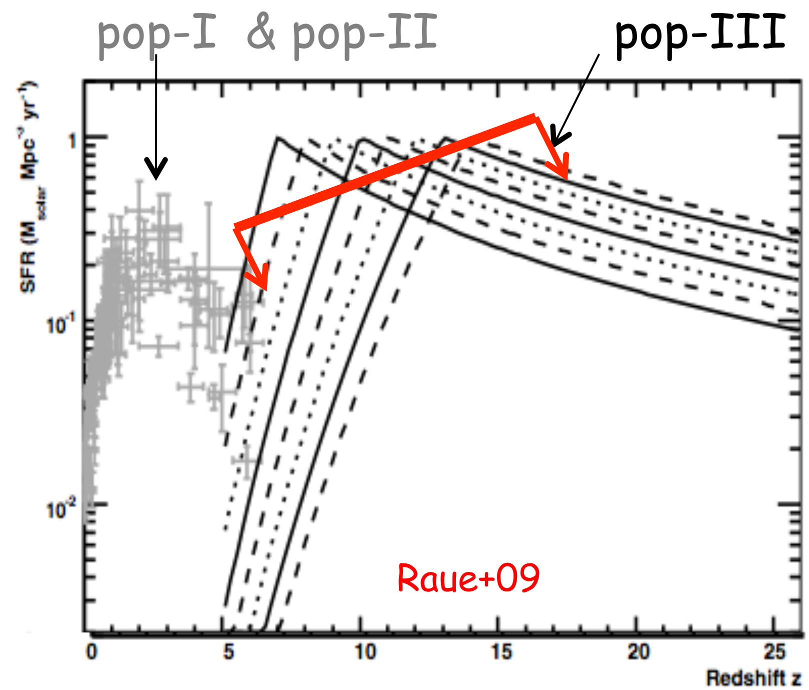

- Extremely large contr. of pop-III stars ruled out by Aharonian+06
- Our measurement constrains the peak SFR of massive stars to be z>10 and have <0.5M_{sun} yr^{-1} Mpc^{-3}

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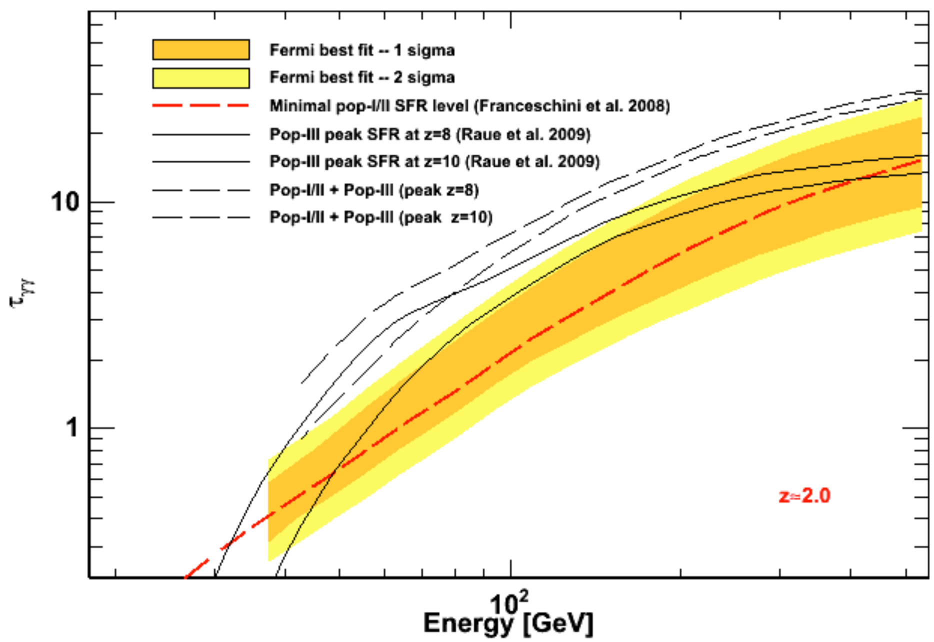
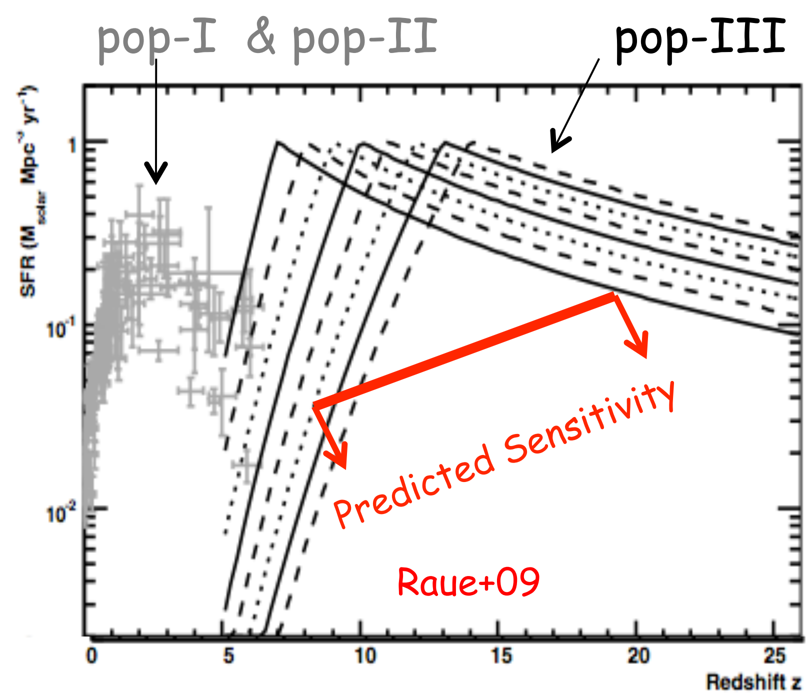




- Large improvement going to higher redshift: current sample has >600 sources up to z~3 -> Use GRBs to get to z~4 !!
- Sample directly the EBL at the peak of the star formation activity

Conclusions

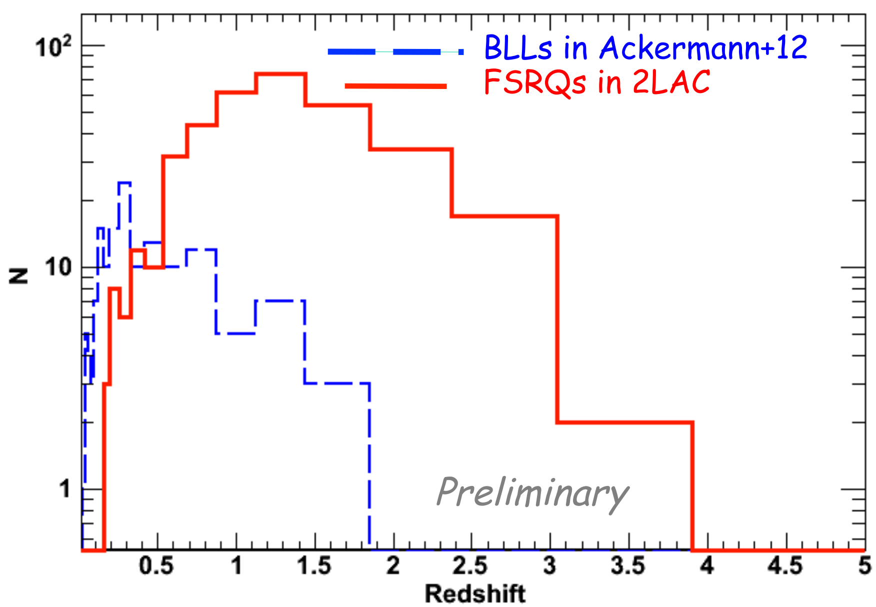
- *Fermi* performed a measurement of the γ-ray opacity
- The measurement is in good agreement with recent EBL models that predict a minimal EBL based on resolved galaxy counts
- The opacity is a factor >3 smaller than the previous LAT upper limit
- A LOT more to come, stay tuned
  - EBL measurement at z~0 using GeV-TeV data (Dominguez+12)
  - EBL measurement at z~0 using H.E.S.S data (see poster 3.5 by B. Giebels)

Cosmic Conspiracy Disclaimer: Our result relies on the assumption that there is no 'conspiracy' in the nature of BL Lacs (or HSPs) that brings them to evolve in a way that mimics EBL absorption from z~0 to z~1.6

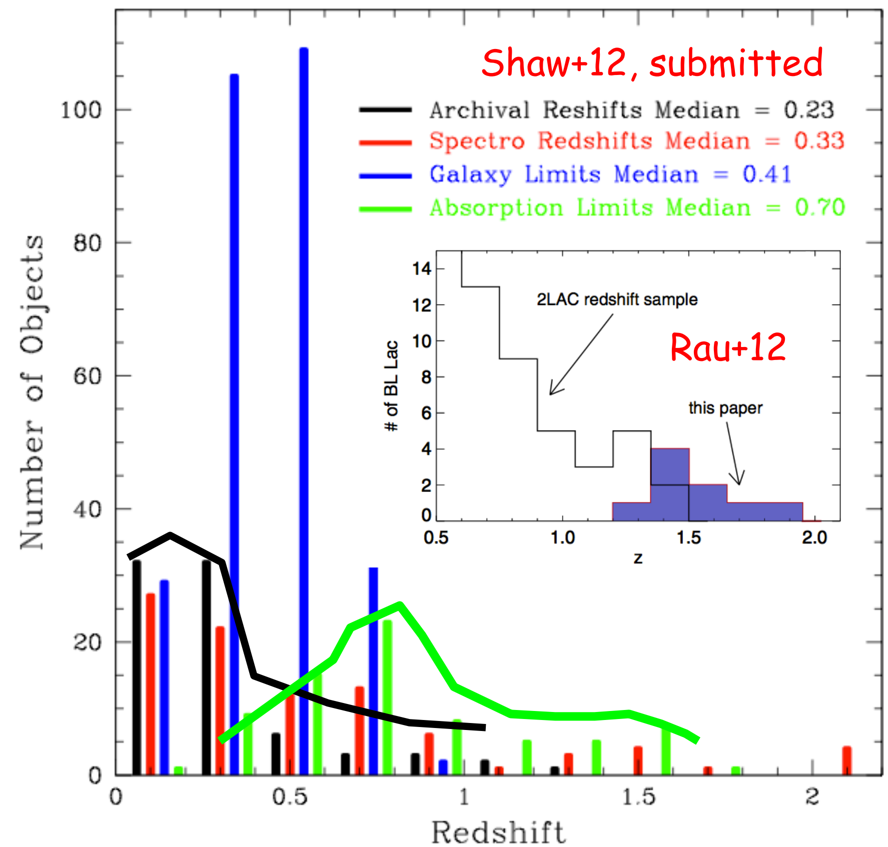
The End

Bright Future

- Use FSRQs to derive (*at least*) *an upper limit to* $\tau_{\gamma\gamma}$ *up to z~3*



- Use the ~200 BL Lacs that now have redshift !



Linear Increase of the TS

- The signal is distributed over all the sources, with each source contributing ~0.5 to the TS

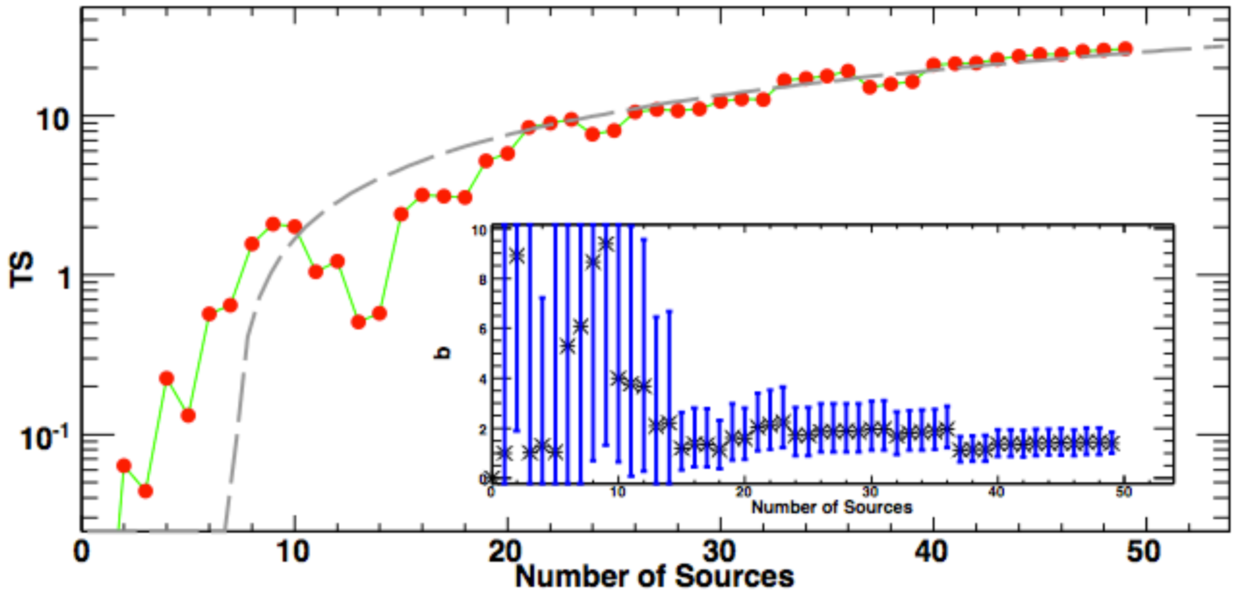
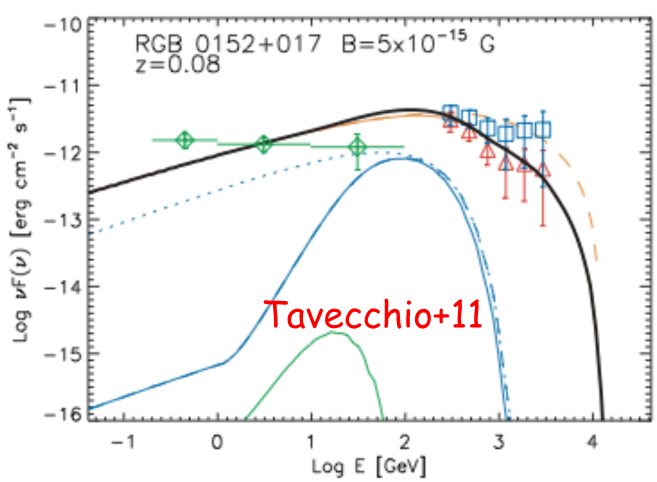


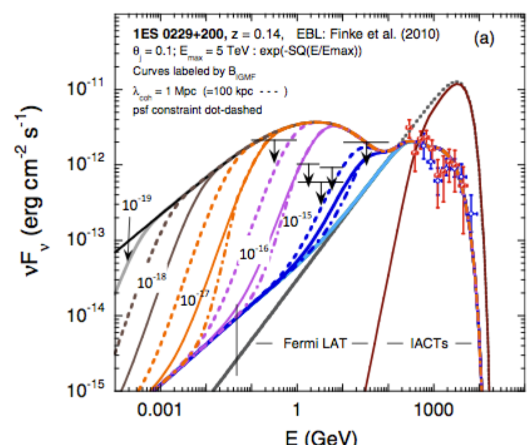
Figure S3 Increase in the TS value of the (renormalized) EBL model of (7) produced in the joint-likelihood fit (to the $0.5 \leq z < 1.6$ interval) while adding one source at a time. The sources have been sorted in redshift (from lowest to highest). The dashed line shows the best-fit linear increase of the TS with the number of sources. The inset shows the best-fit value of the renormalization parameter b applied to the opacity predicted by (7) (see text for details).

Cascades and IGMF

- Cascade emission of TeV γ rays is reprocessed in the GeV energy range
- It may represent a substantial fraction of the GeV spectrum, depending on:
  - Intensity of the EBL
  - Intensity of the IGMF and its coherent length
  - Position of the high-energy SED peak

- For IGMF of ≥10^{-15} G (Neronov&Vovk10, Tavecchio11) the cascade component is greatly suppressed
- For IC peaks <10TeV (i.e. all but extreme HSPs) the cascade component is not expected to be large

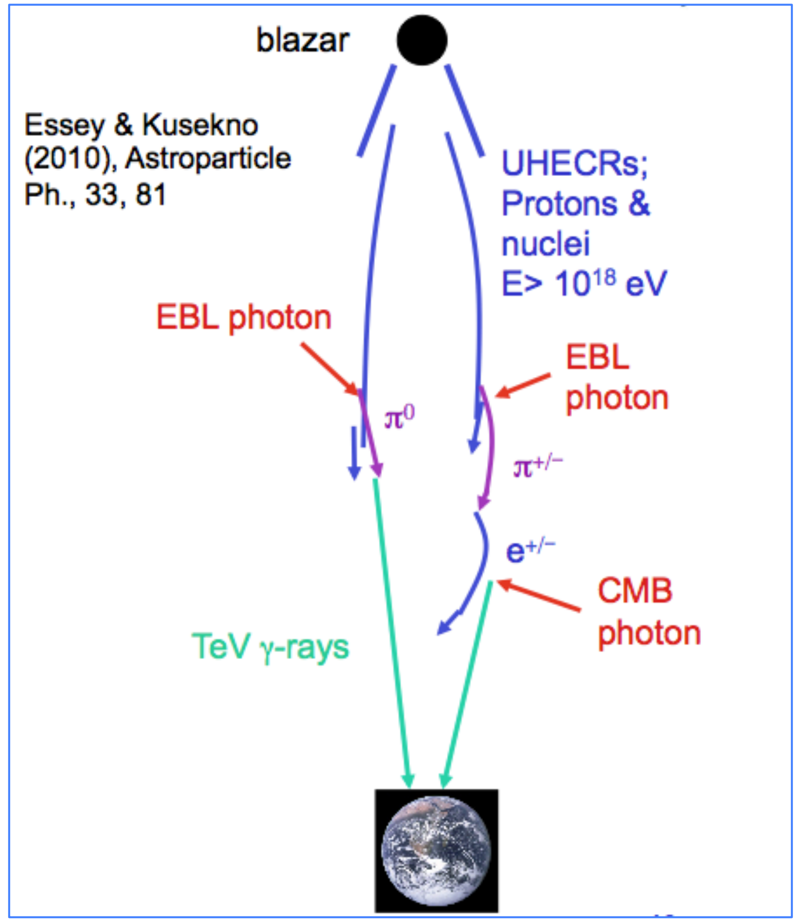




Dermer+11

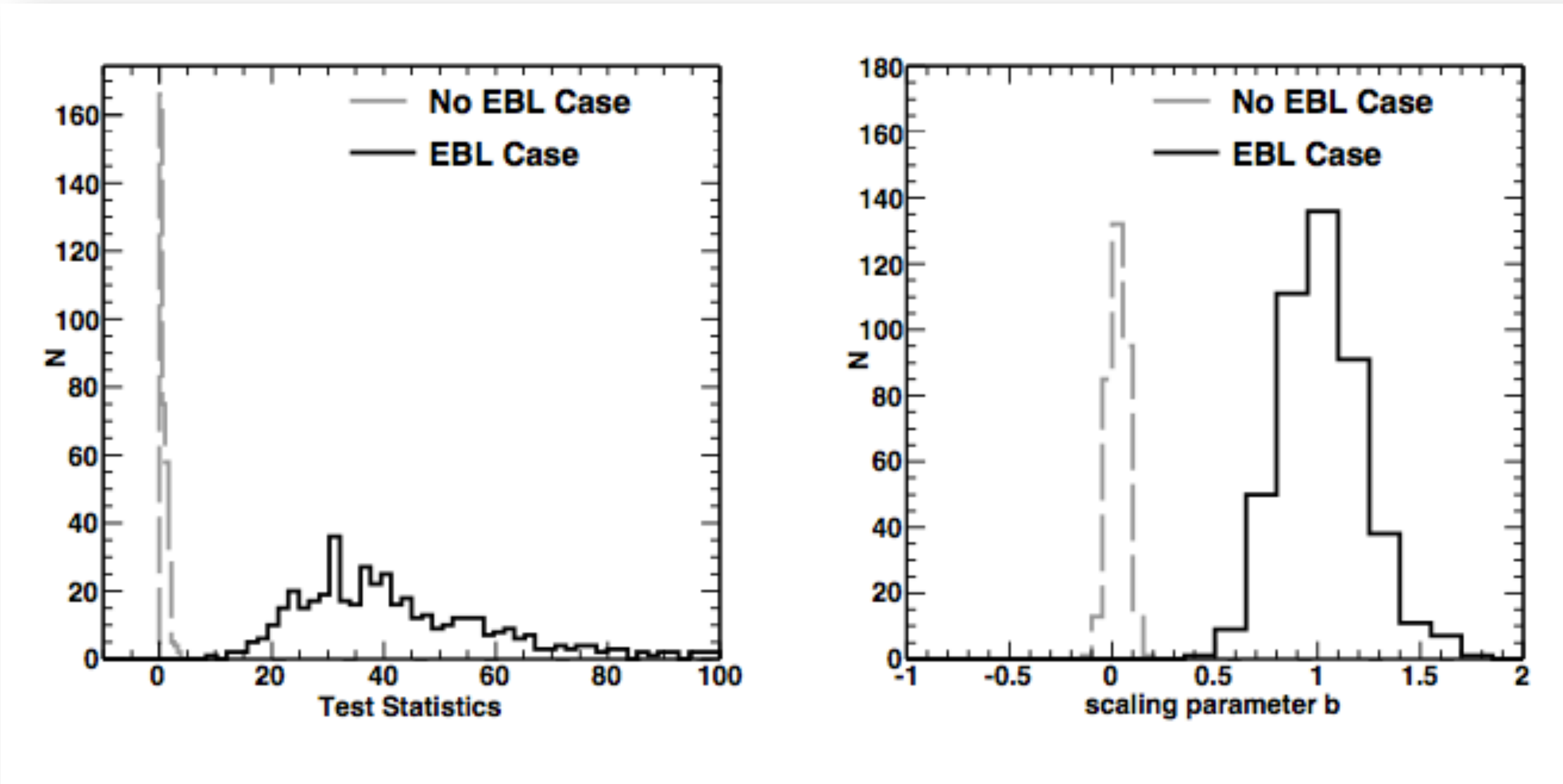
Ultra High Energy Cosmic Rays

- Blazars might be accelerating CRs as well
- CRs would travel further and interact with the EBL/CMB to generate γ rays
- γ-rays would then suffer EBL absorption
- Intense IGMF would deflect cascades out of line-of-sight



Simulations Results

- Analysis validated using Monte Carlo simulations of physical SEDs of blazars based on Fermi observations



Our Approach -- Analysis

- We look for the collective deviation of the spectra of blazars from their *intrinsic* spectra

Source selection

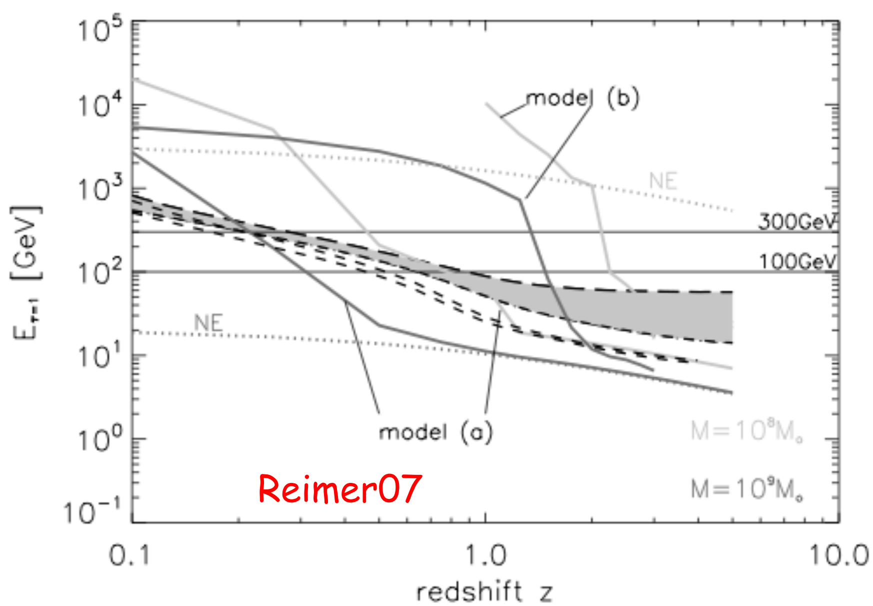
- We select 'non-variable' BL Lacs from 2LAC solely on the 3-10 GeV detection significance
- Advantages:
  - Hard spectrum sources
  - Weak, if any, external photon fields
- Disadvantages:
  - Only ~50% of *Fermi* BL Lacs have redshift in 2LAC
    - But see the talk of M. Shaw for the rest !

Analysis details

- 46months of data (till June 1st)
- P7SOURCE_V6 or P7CLEAN_V6
- zenith angle < 100deg
- ROI radius = 15deg
- Standard P7 diffuse models
- Energy range 1 – 500 GeV

Intrinsic Absorption

- Absorption of gamma rays on the photons of the BLR/disk might show a redshift dependence due to the accretion history of the Universe (Reimer07)
- Most of the signal is in HSPs
- However:
  - If the emission region is far from the core, then no absorption is expected



Source selection

- Delicate problem:
  - Ideally we would like to select a population:
    - Whose properties do not change with redshift
    - Is not affected by intrinsic absorption of photons on the BLR/disk
    - Have hard spectra to probe the EBL
- Such selection is impossible:
  - Blazar types change with redshift
    - HSP -> ISP -> LSP
- FSRQs are soft, have intense photon fields, are very variable:
  - No ideal candidates

- We select BL Lacs:
  - Advantages:
    - Have hard spectrum
    - We think they might not have strong photon fields

  - Disadvantages:
    - Type evolves with z
    - 50% in 2LAC do not have z

EBL and Gamma Rays

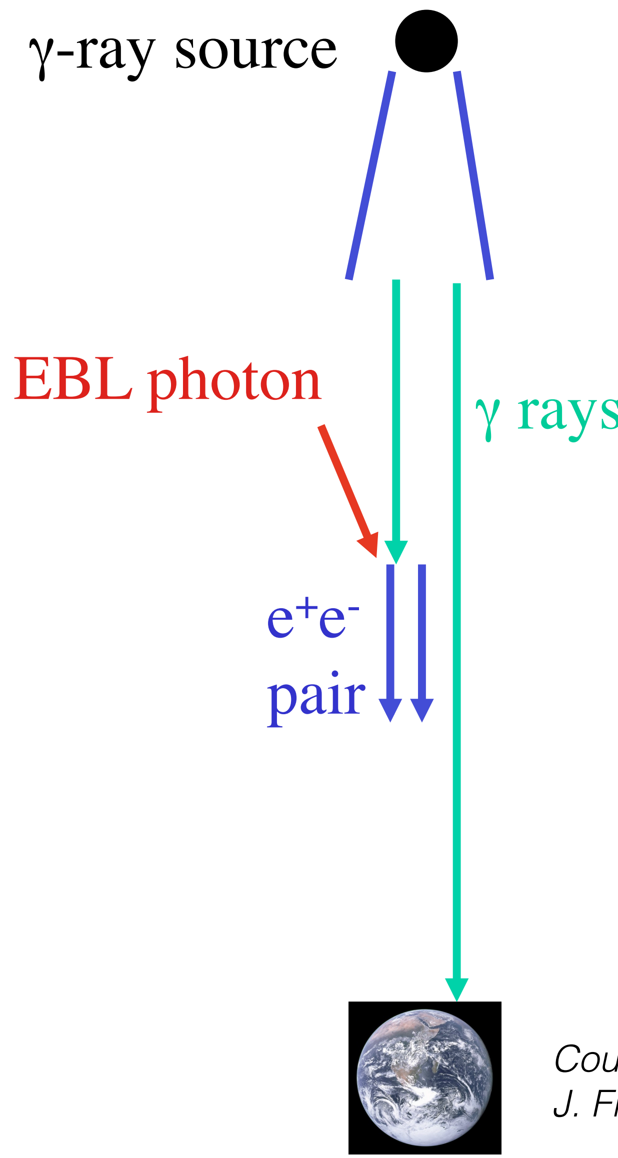
EBL photons extinguish extragalactic gamma rays.

$\gamma_{ebl} + \gamma_{\gamma\text{-ray}} \rightarrow e^- + e^+$

Gamma rays we see are attenuated by:

$$F_{obs} = F_{int} \exp[-\tau_{\gamma\gamma}(E, z)].$$

We want to constrain the EBL models [$\tau_{\gamma\gamma}$ (E,z)] based on γ-ray observations of blazars.

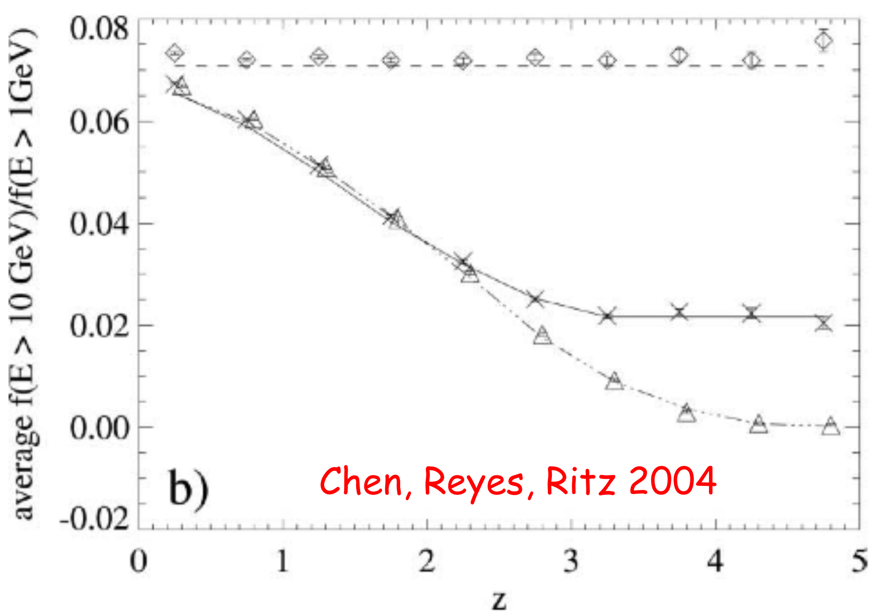


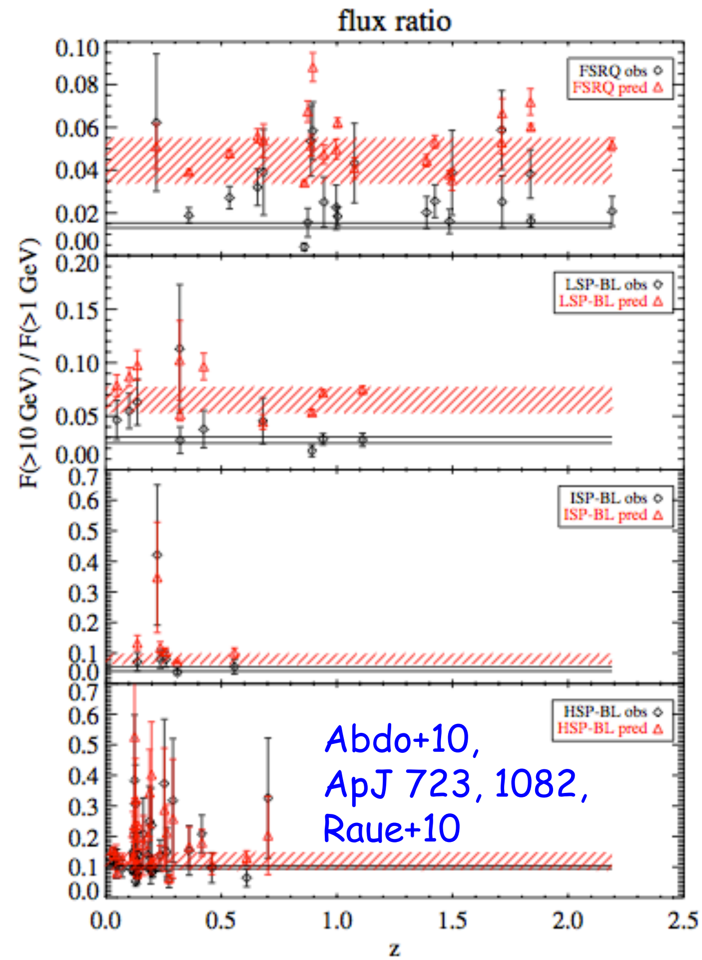
Courtesy J. Finke

Predictions and Reality

- EBL should cause an energy-dependent suppression of the HE flux which increases for larger redshifts

Reality is far more complex due to the non-standard nature of blazars



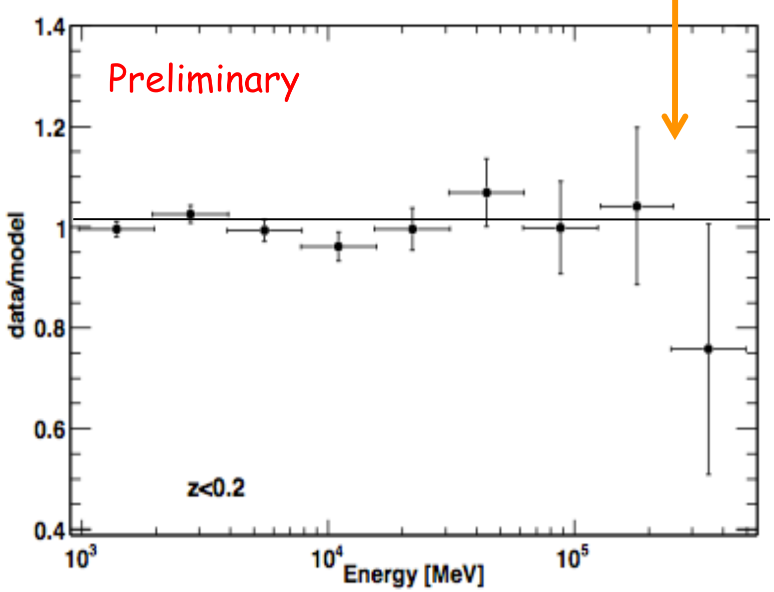


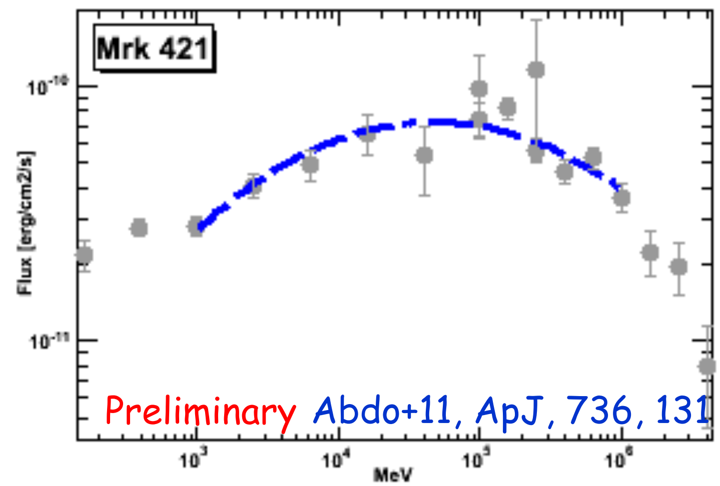
Is the LogParabola good for the intrinsic spec. ?

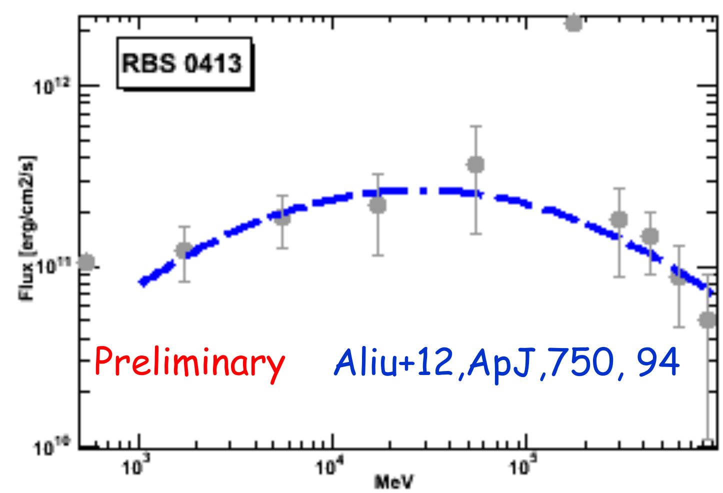
- Answer: *We believe it is good over the chosen energy range*
  1. For z<0.2, EBL absorption becomes important only for E>150GeV

Evidences

- Fit to GeV – TeV: OK
- Residuals to z<0.2 fit: flat







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- 3 Steps Procedure:
  1. fit each ROI (1-500 GeV) to optimize all components
  2. re-fit only up to the energy for which EBL absorption is negligible (we call this E_{crit})
     1. This step is needed to determine the properties of the intrinsic spectrum
  3. Combine the likelihoods of each ROI (for a z-bin) and fit "b"

- We evaluate 2 cases:

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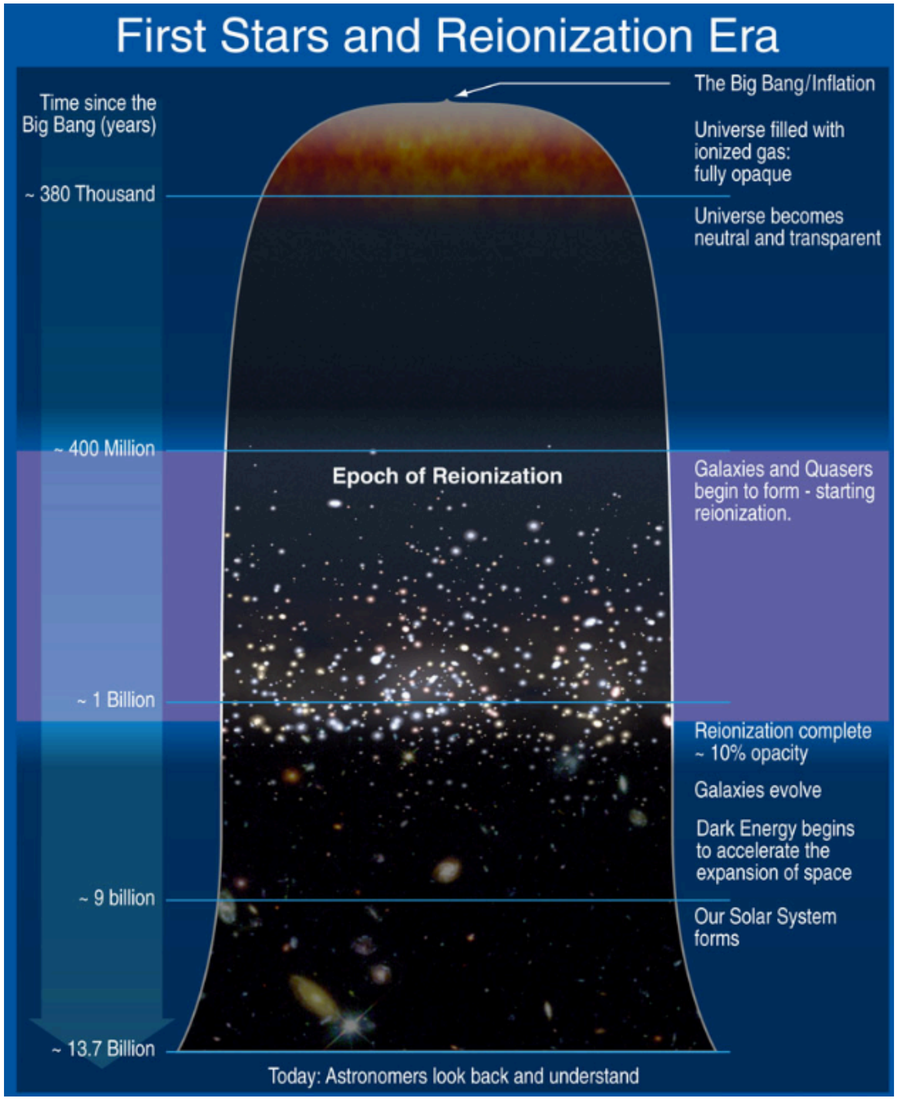
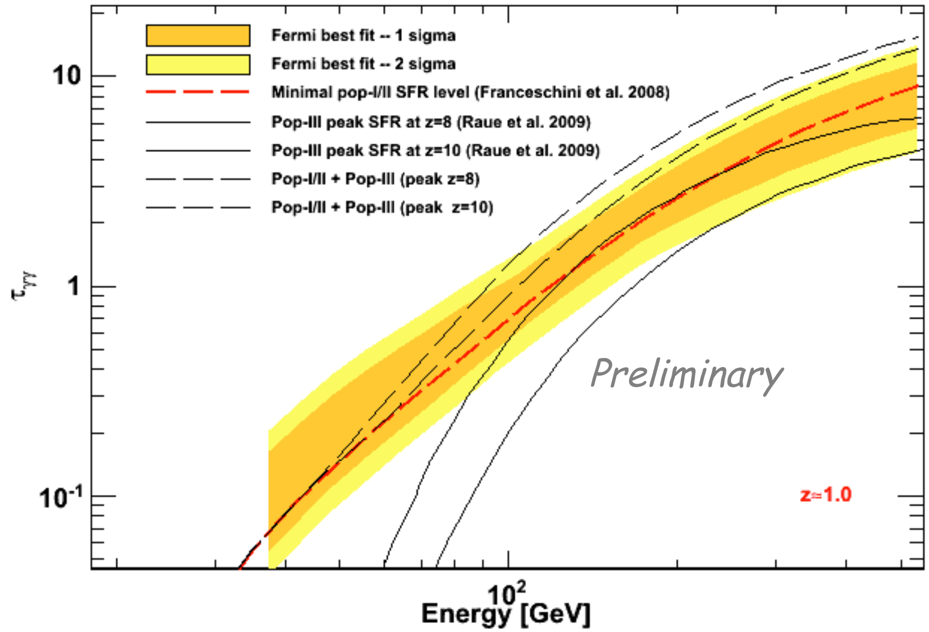
Sensitivity to the light of the First Stars





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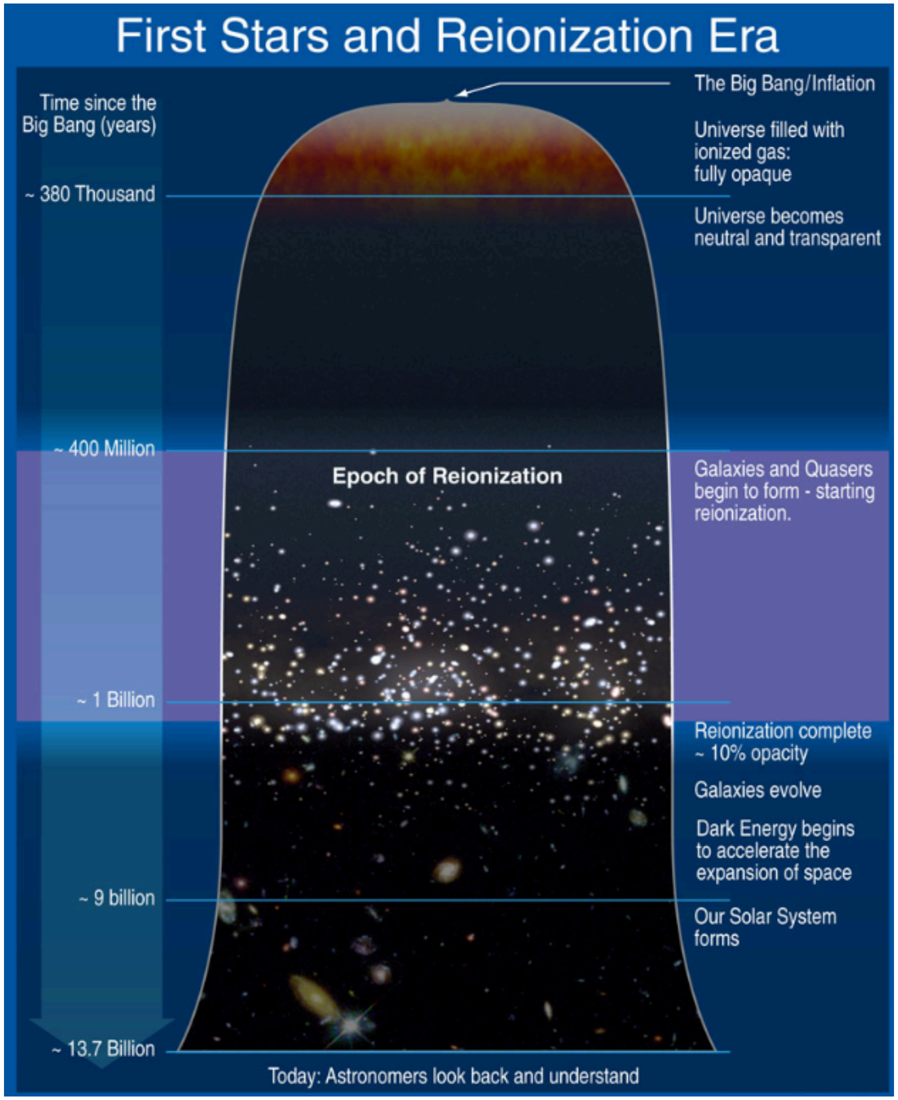

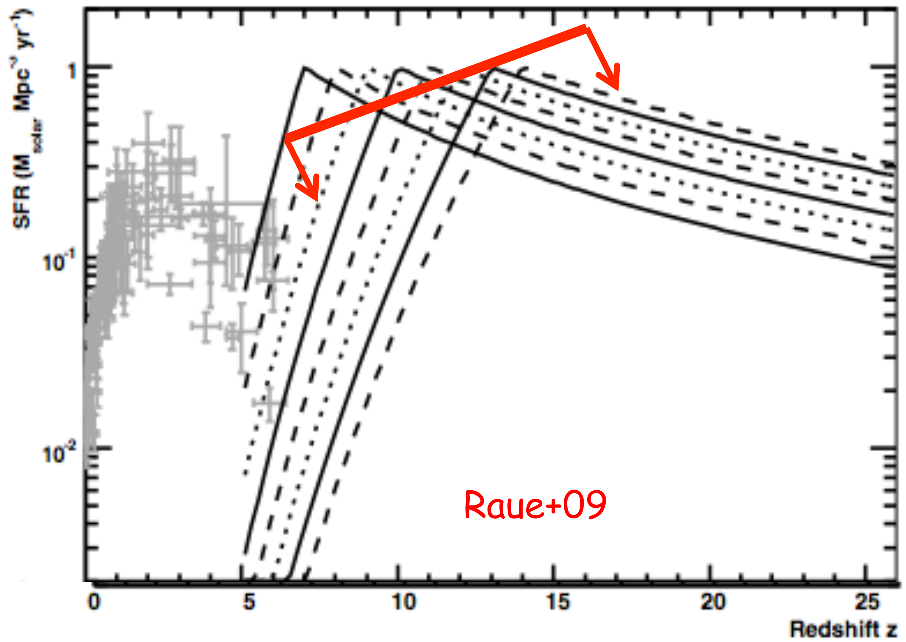

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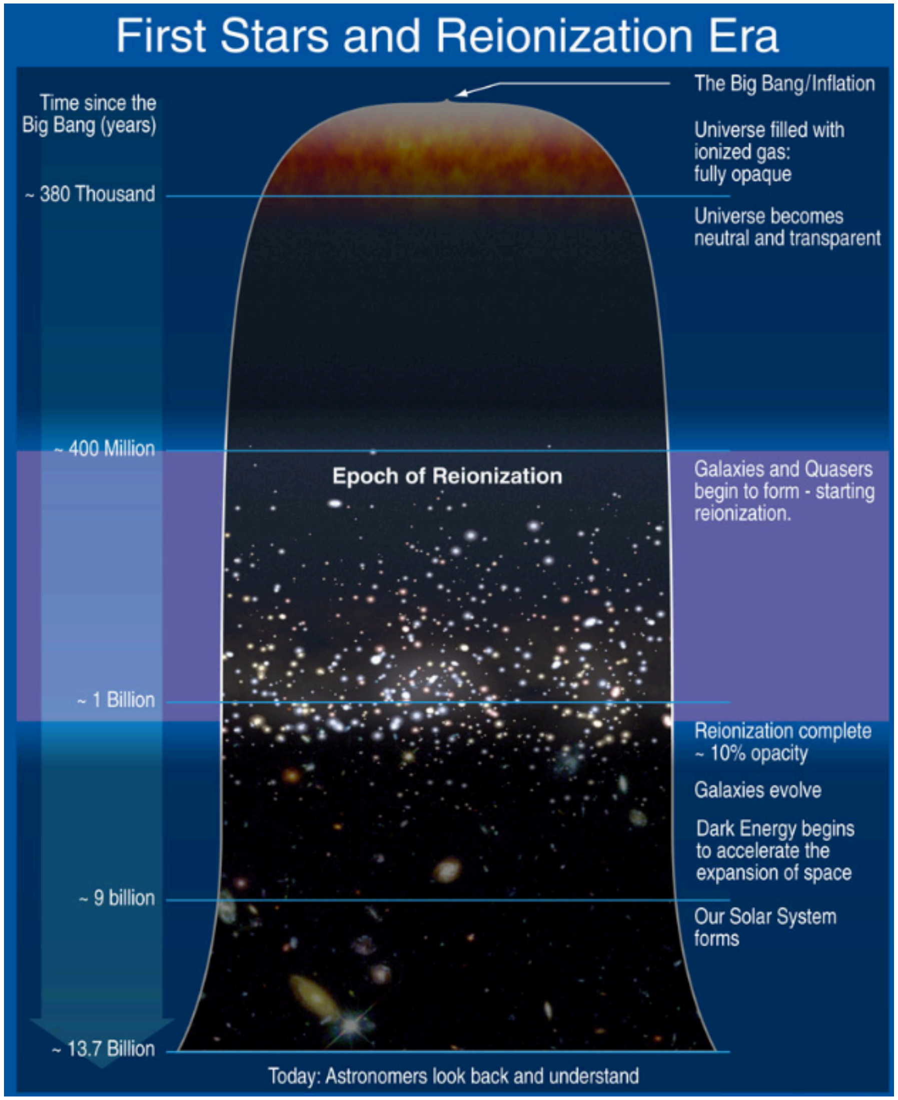
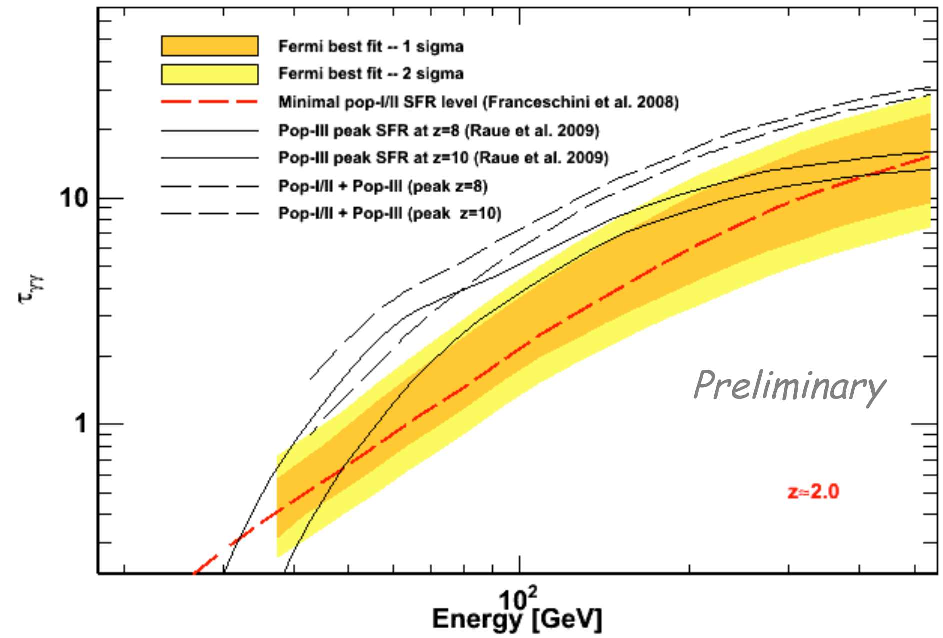
- Our measurement constrains the peak SFR of massive stars to be z>10 and have <$0.5M_{sun}$ yr^{-1} Mpc^{-3}

Sensitivity to the light of the First Stars





- Large contr. of pop-III stars ruled out by Aharonian+06
- Our measurement constrains the peak SFR of massive stars to be z>10 and have <0.5M_{sun} yr^{-1} Mpc^{-3}
- If we only had z≥2 objects !!!