Measuring the Cosmic Star Formation Rate with Fermi-LAT

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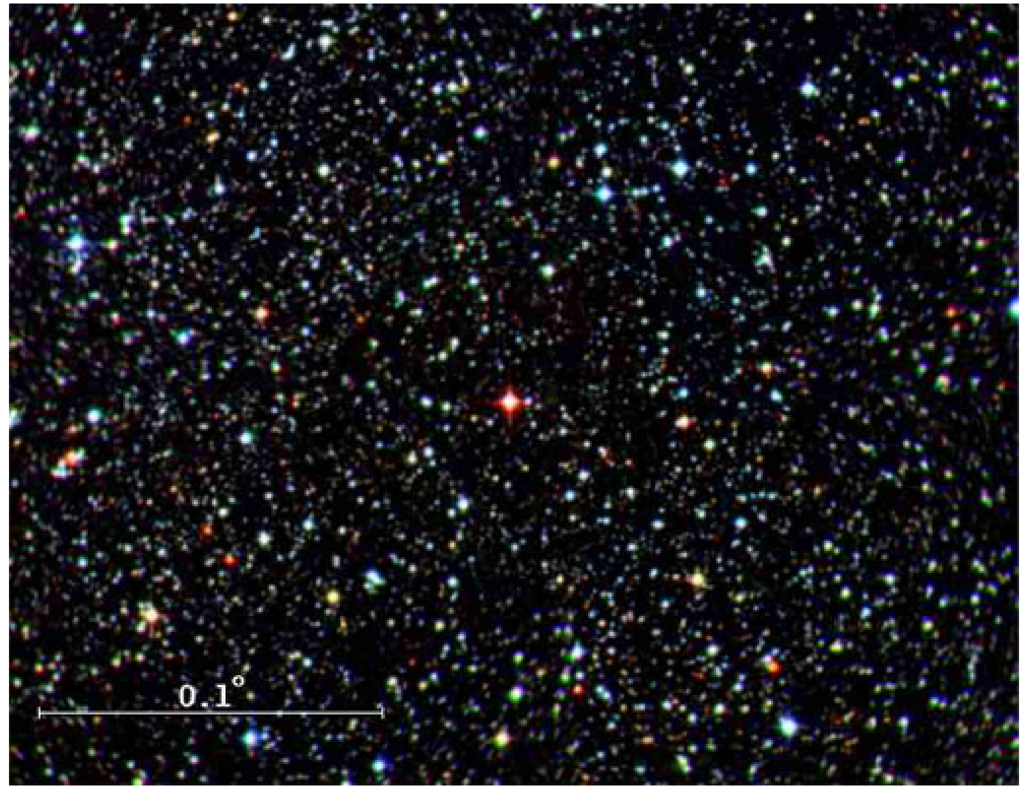
for the Fermi-LAT Collaboration

and

Kari Helgason (Max Planck Institute for Astrophysics)

Extragalactic Background Light

Background light from all the stars that have existed in the observable universe.



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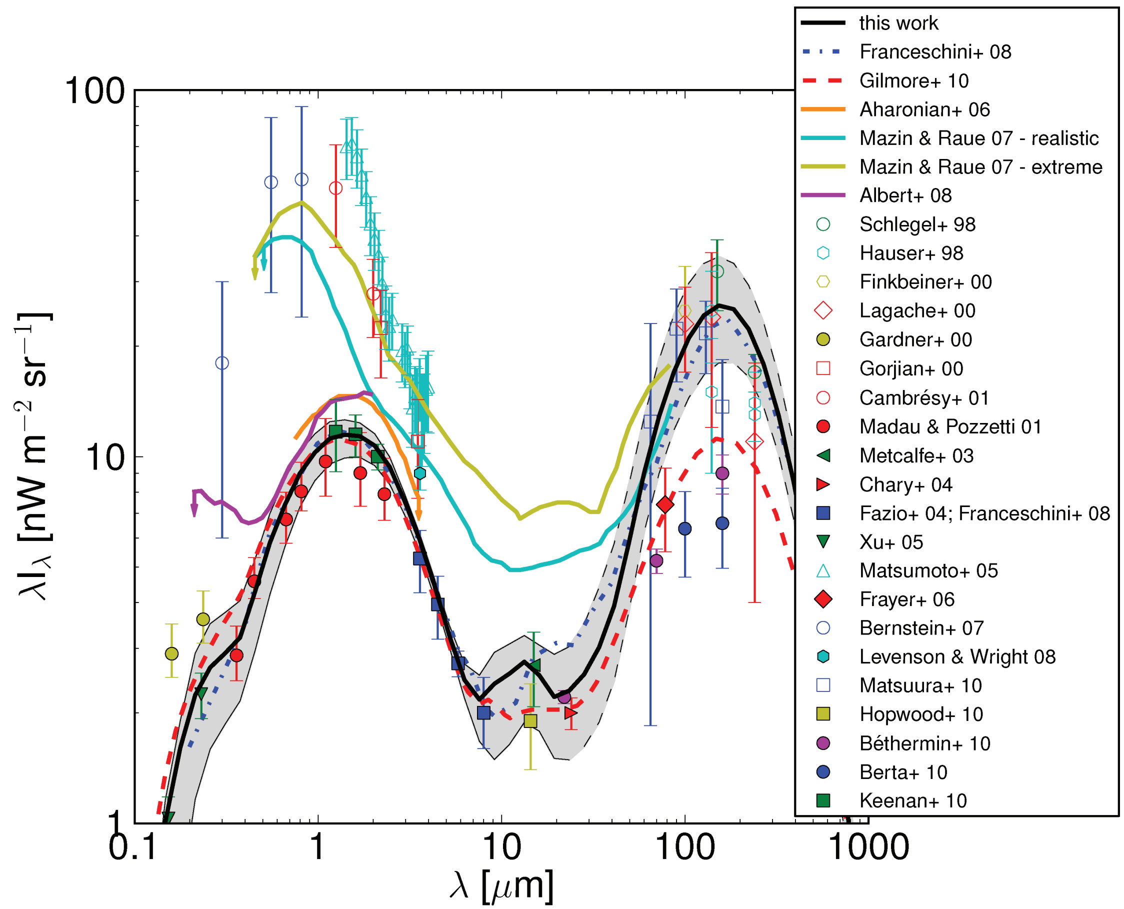
Two broad components: Direct Stellar emission, and stellar emission absorbed by dust and re-radiated in the infrared.



Dominguez et al. (2011)

Gamma-ray absorption by EBL

EBL photons extinguish extragalactic gamma rays.

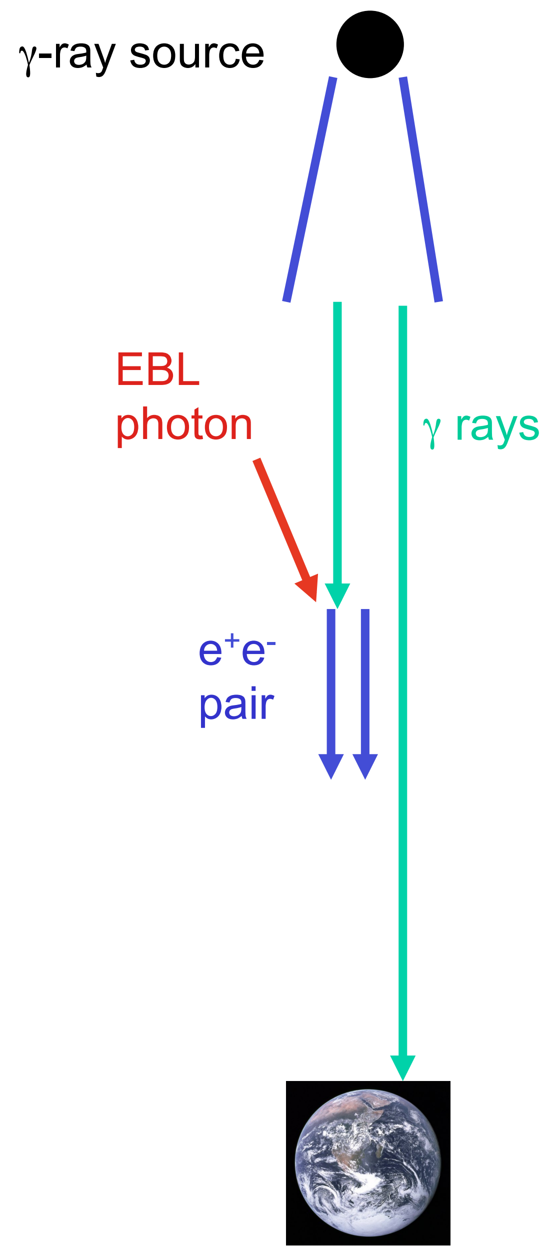
$\gamma_{ebl} + \gamma_{\gamma\text{-ray}} \rightarrow e^- + e^+$

Knowledge of the absorption effects due to EBL is necessary to infer the intrinsic spectra of extragalactic gamma-ray sources.

Gamma rays we see are attenuated by:

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

We want to create a model of the EBL to aid in our understanding of the γ-ray sources.



Extragalactic Background Light

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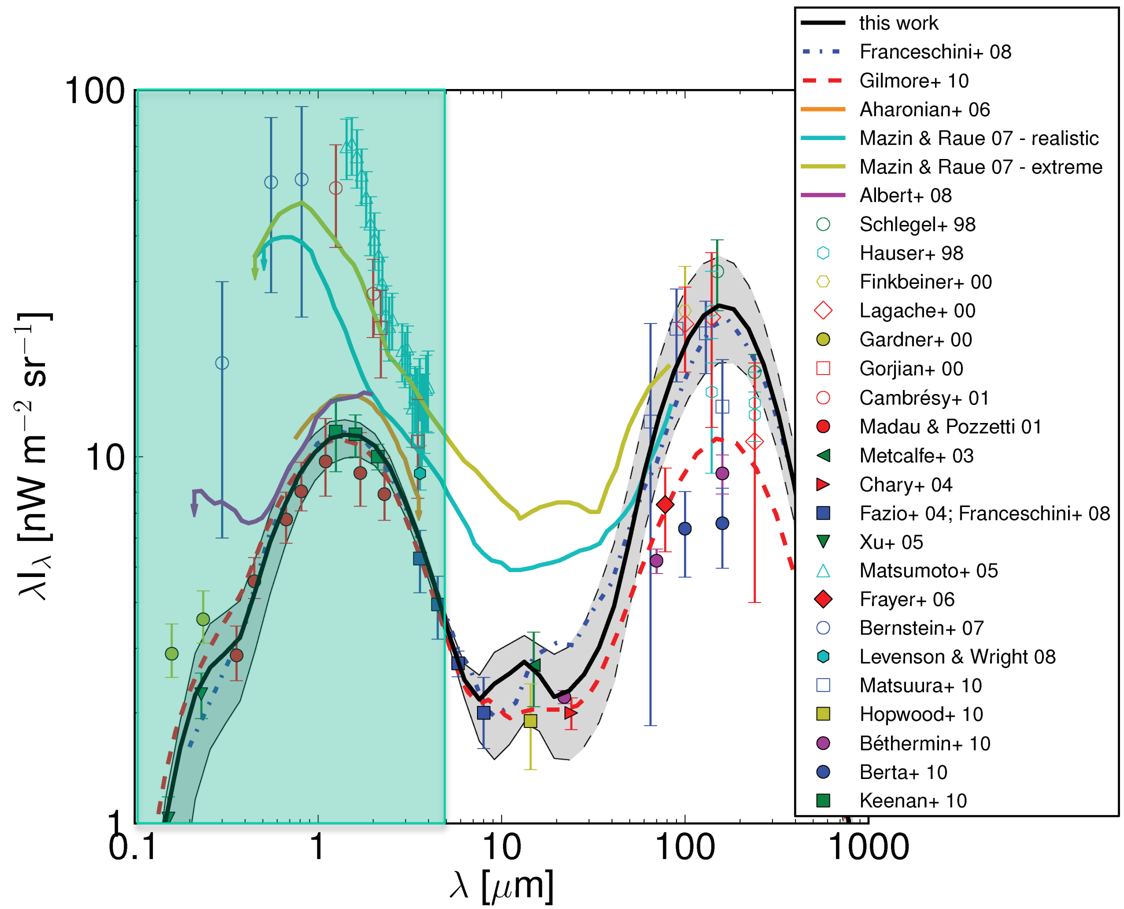
LAT γ-rays absorb mainly direct stellar emission.

UV emission mainly produced by short-lived, high-mass stars

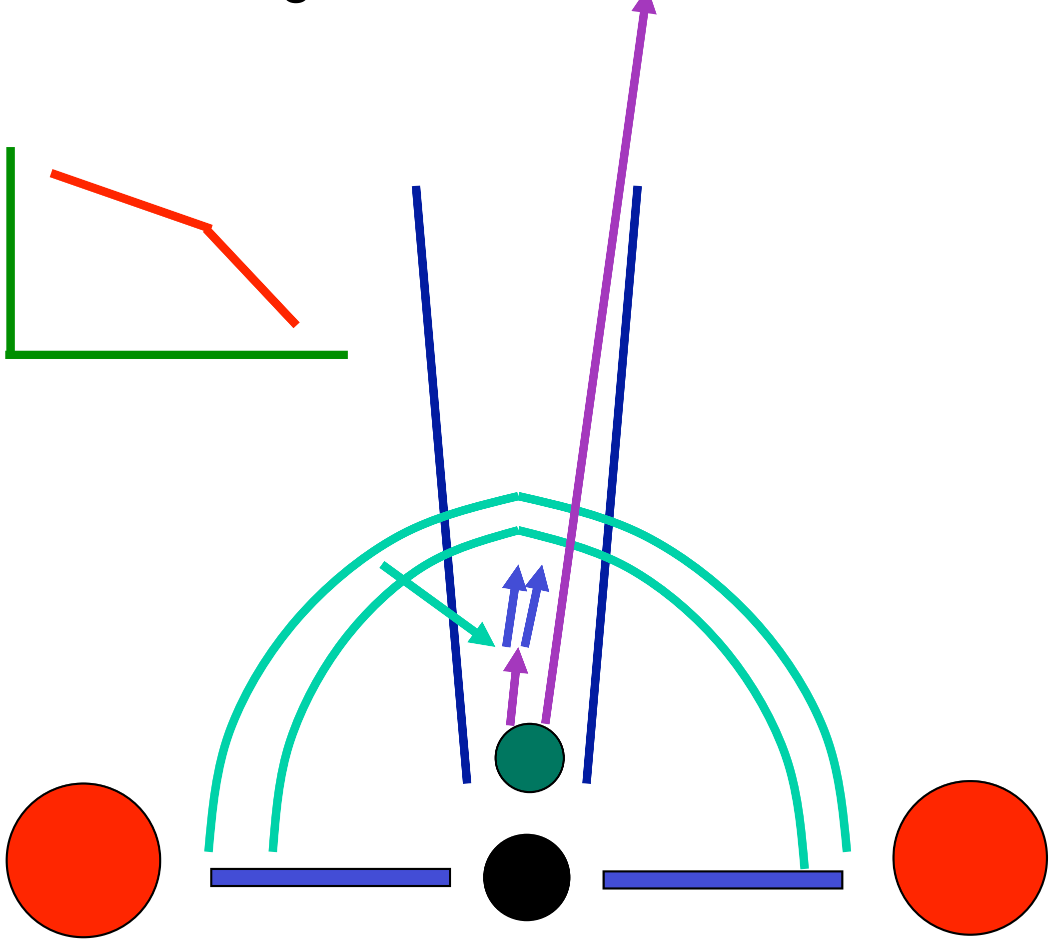


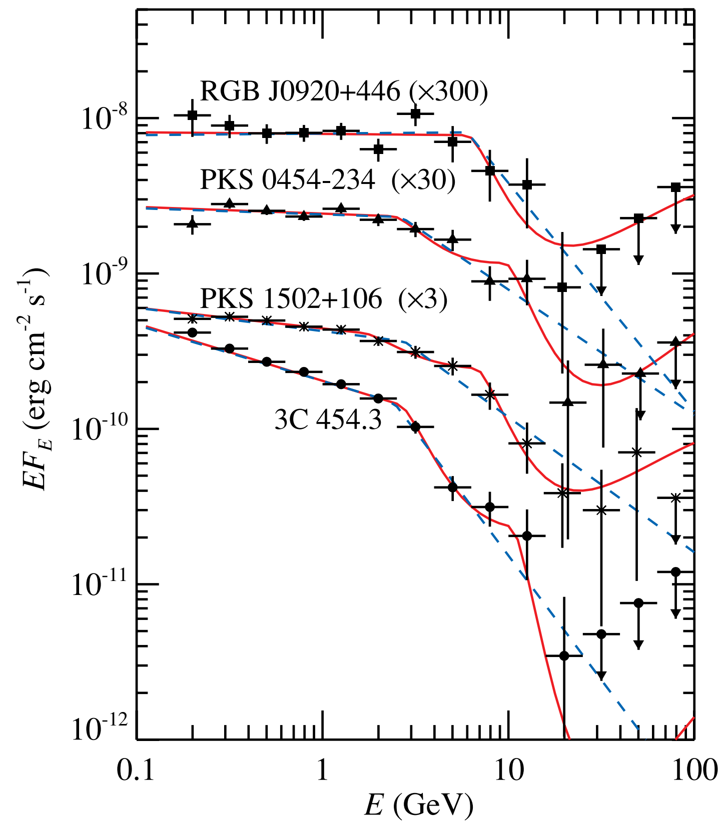
Dominguez et al. (2011)

Internal γγ absorption

FSRQs:

Have strong BLR

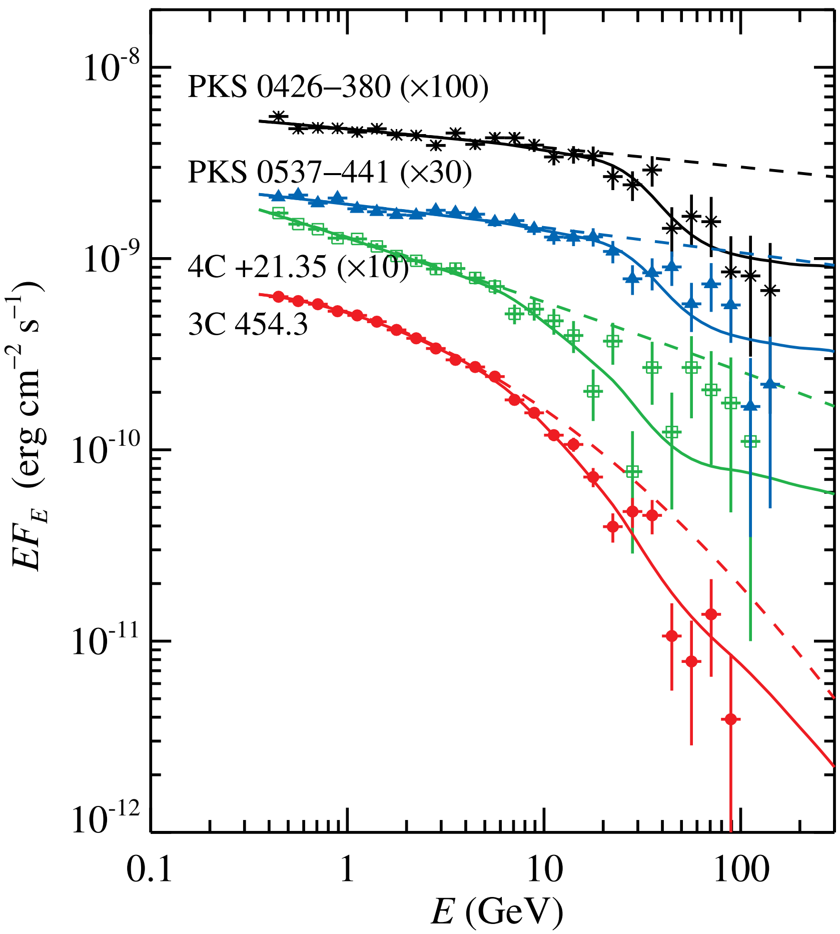




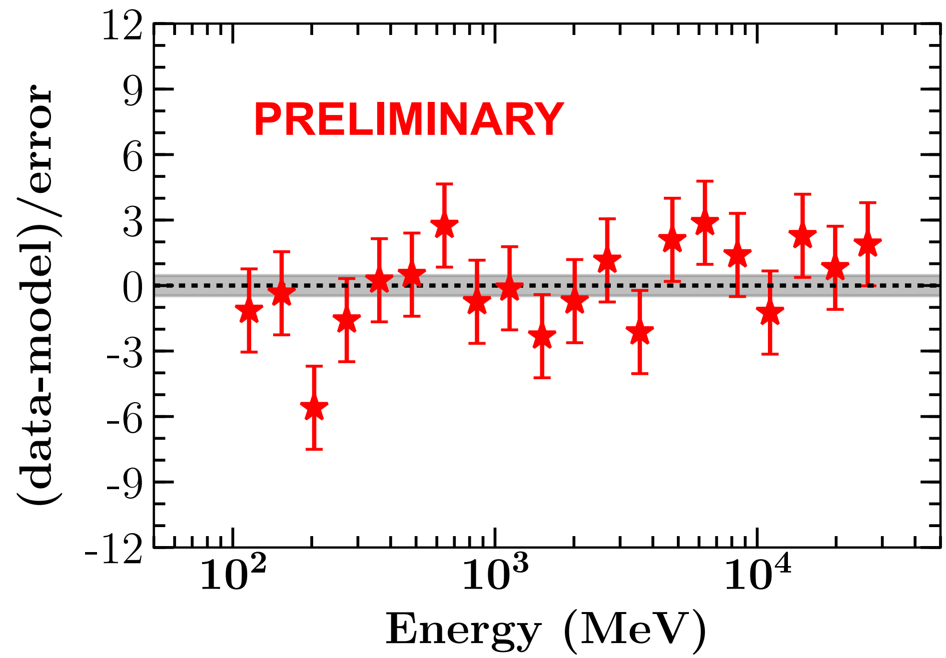
Stern & Poutanen (2010)

See also Reimer (2007)

Internal γγ absorption



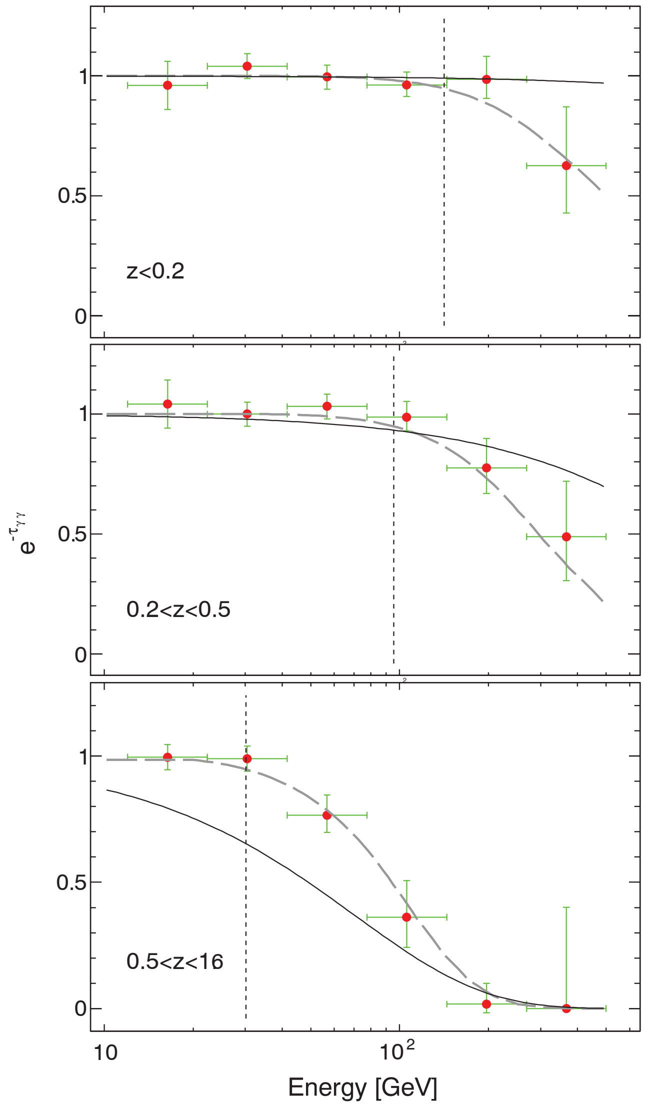
With more data, no evidence for absorption at < 10 GeV. Small ($\tau_{\gamma\gamma}$ ~ 1) absorption at ~ 10 GeV (Stern & Poutanen 2014)



Our analysis: stacked residuals (adjusted for redshift) of best fit model for sources from Poutanen & Stern (2010). No evidence for absorption.

Similar conclusions by Costamante et al. (2017, in preparation).

Measuring EBL Absorption



150 BL Lac Objects

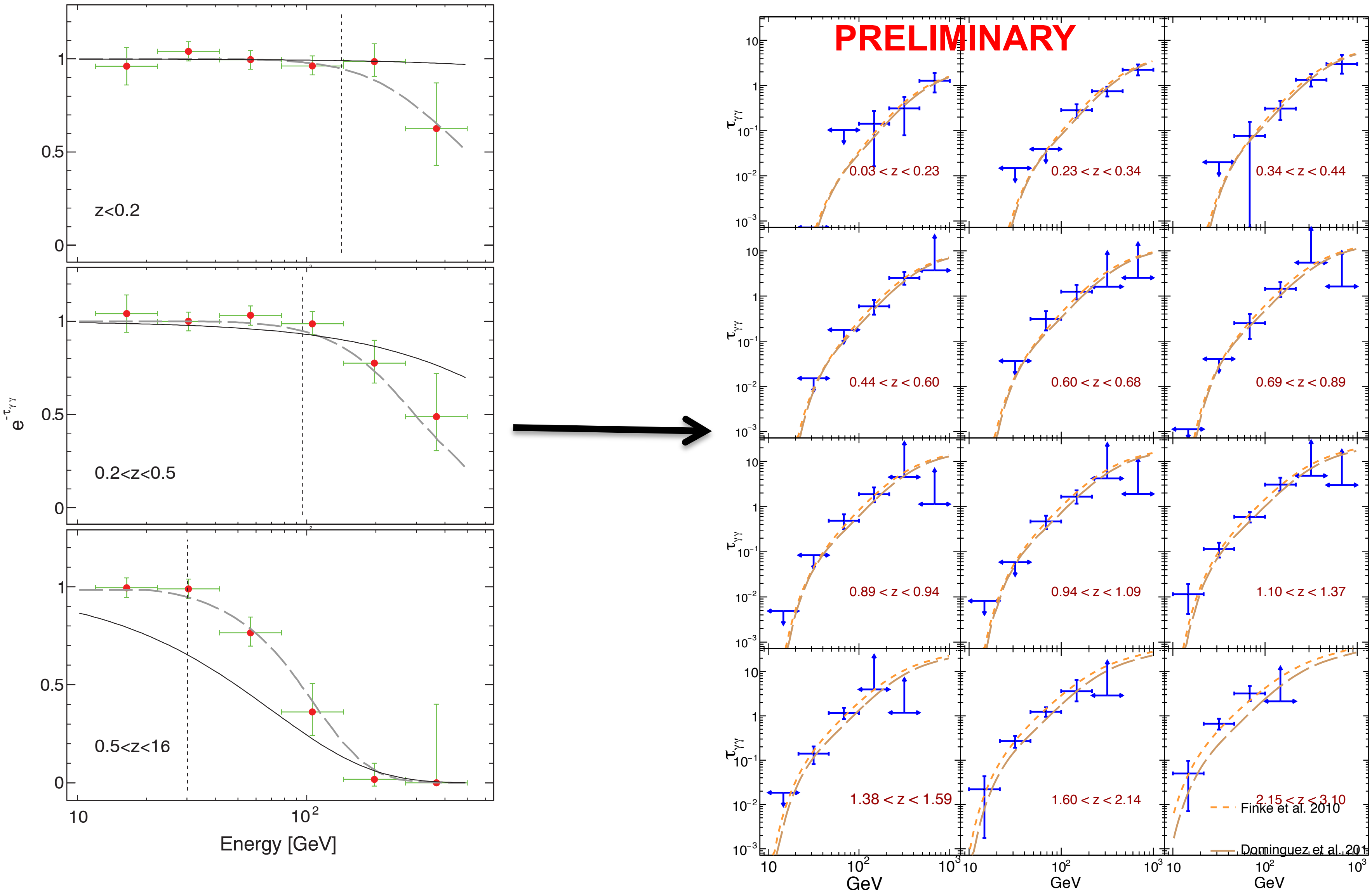
46 months (almost 4 years) of LAT data

Three redshift bins

"Pass 7" instrument response function

Ackermann et al. (2012)

Measuring EBL Absorption



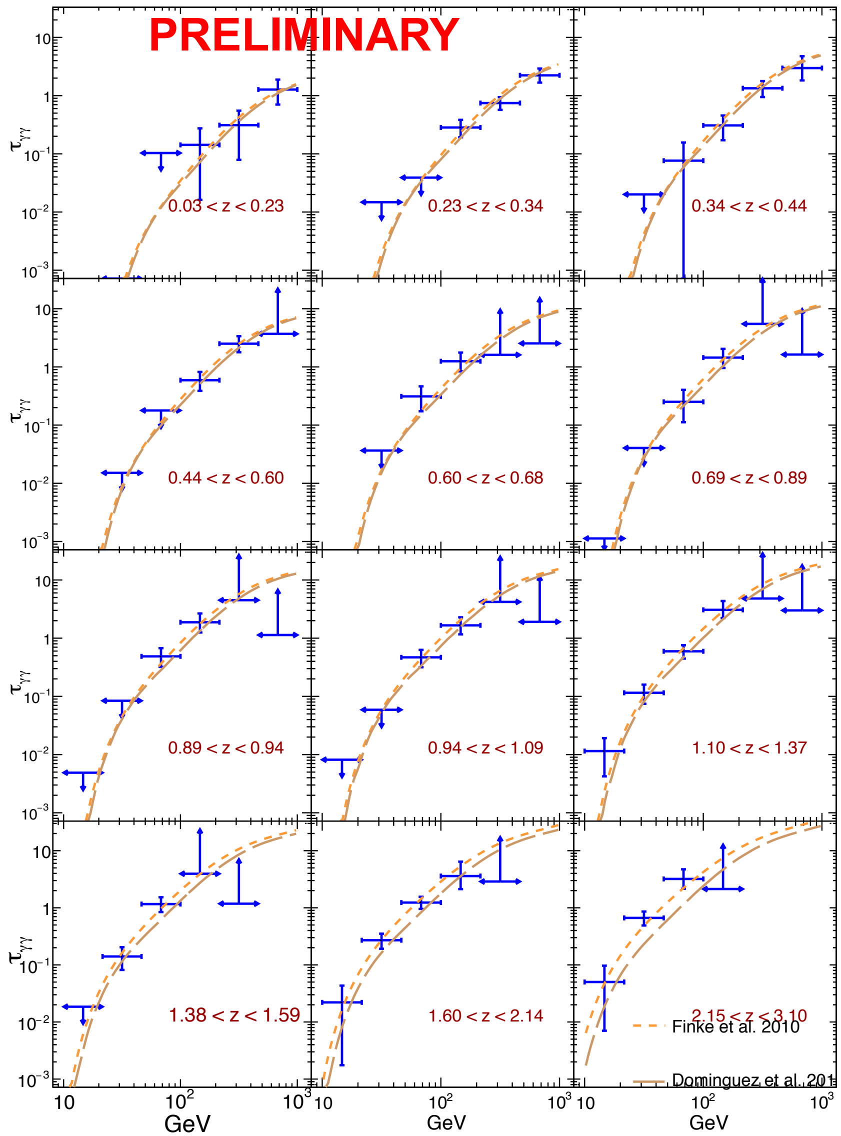
Measuring EBL Absorption

414 FSRQs
327 BL Lac Objects
741 total sources

101 months (~8.5 years) of LAT data

Twelve redshift bins

“Pass 8” instrument response function



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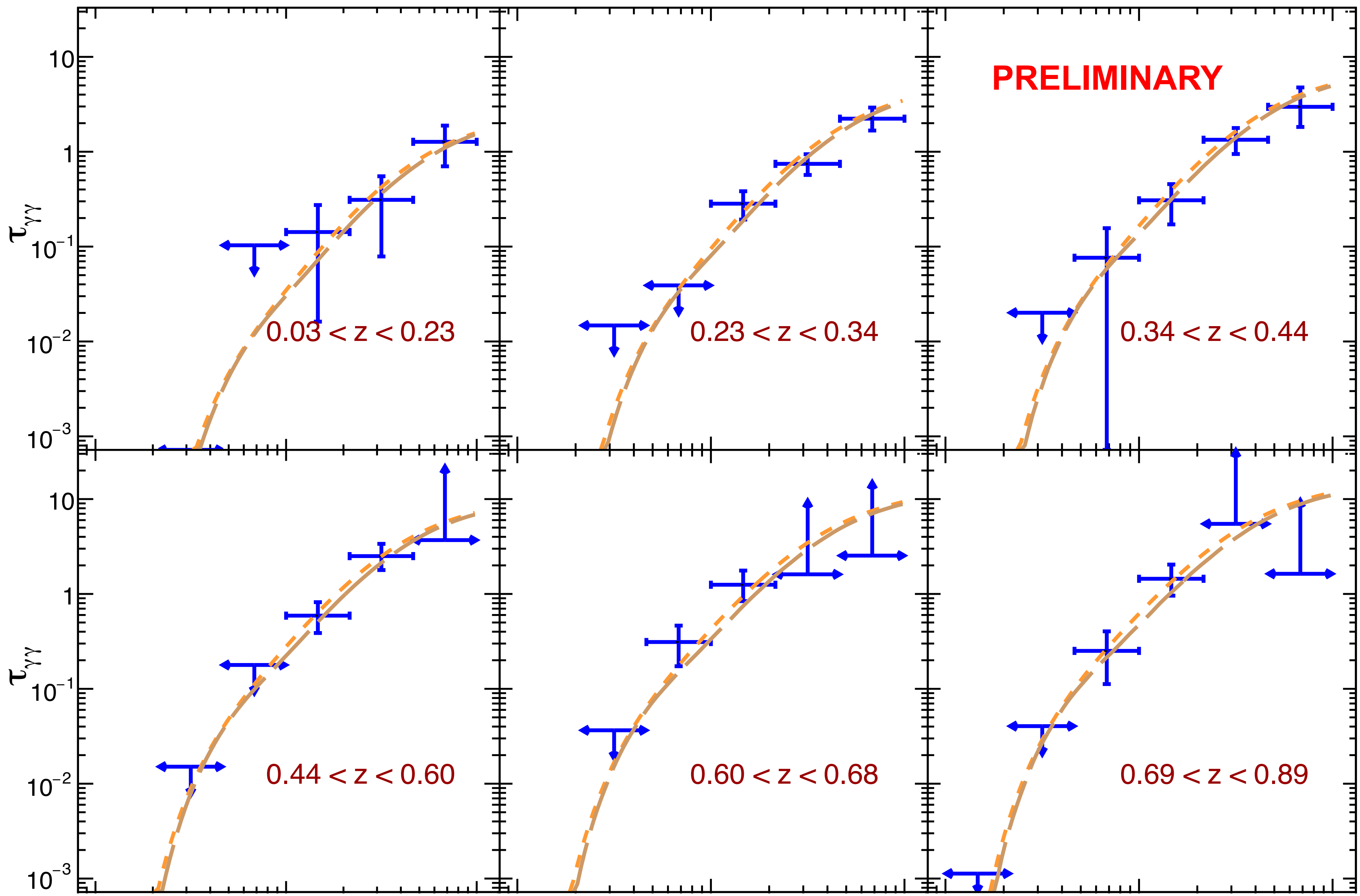

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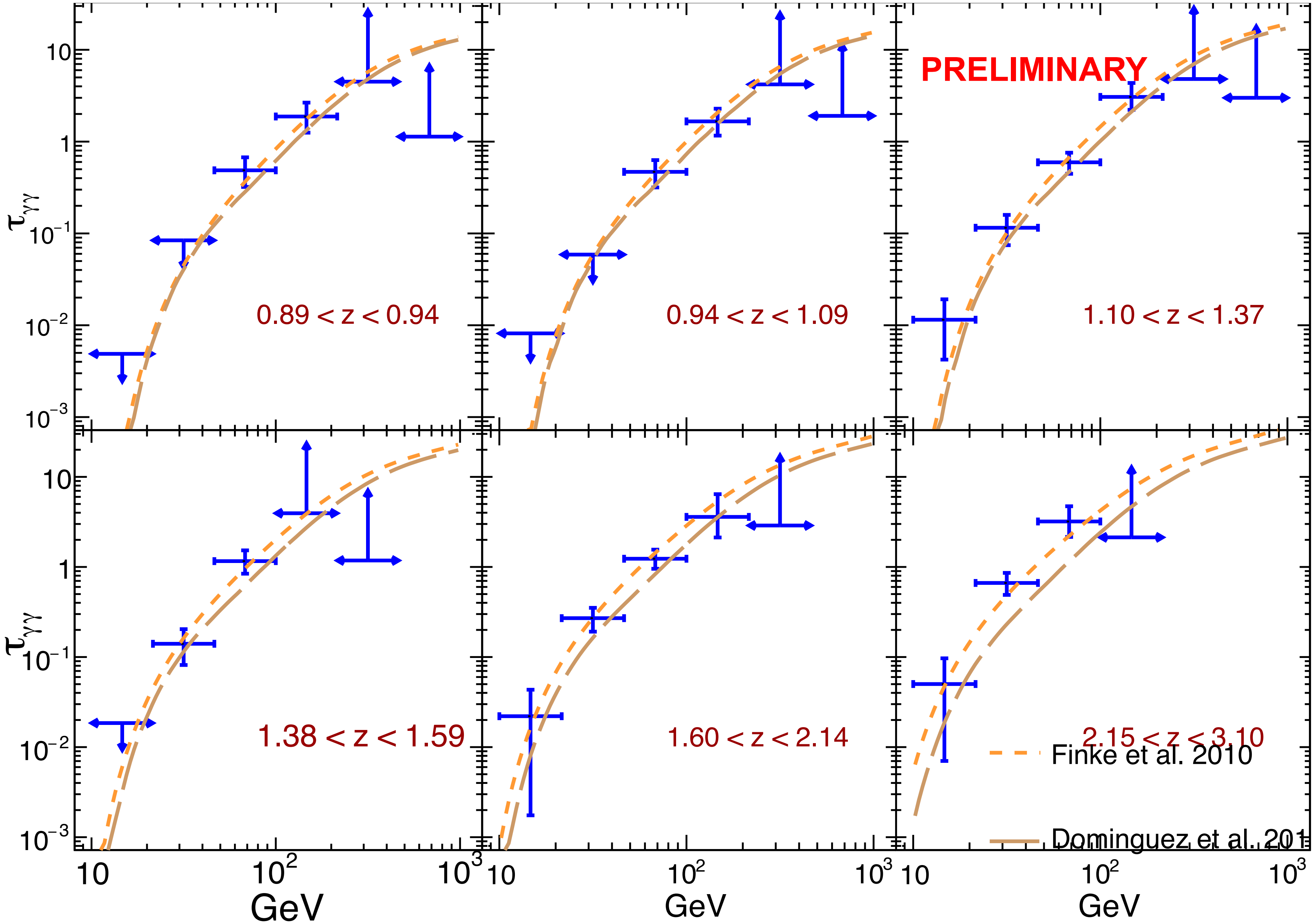


EBL Model

$$\epsilon\, j^{\rm stars}(\epsilon; z) = m_e c^2 \epsilon^2 f_{\rm esc}(\epsilon) \int_{m_{\rm min}}^{m_{\rm max}} dm\, \xi(m) \times \int_{z}^{z_{\rm max}} dz_1 \left|\frac{dt_*}{dz_1}\right| \psi(z_1)\, \dot{N}_\star(\epsilon; m, t_\star(z, z_1)).$$

Initial Mass Function

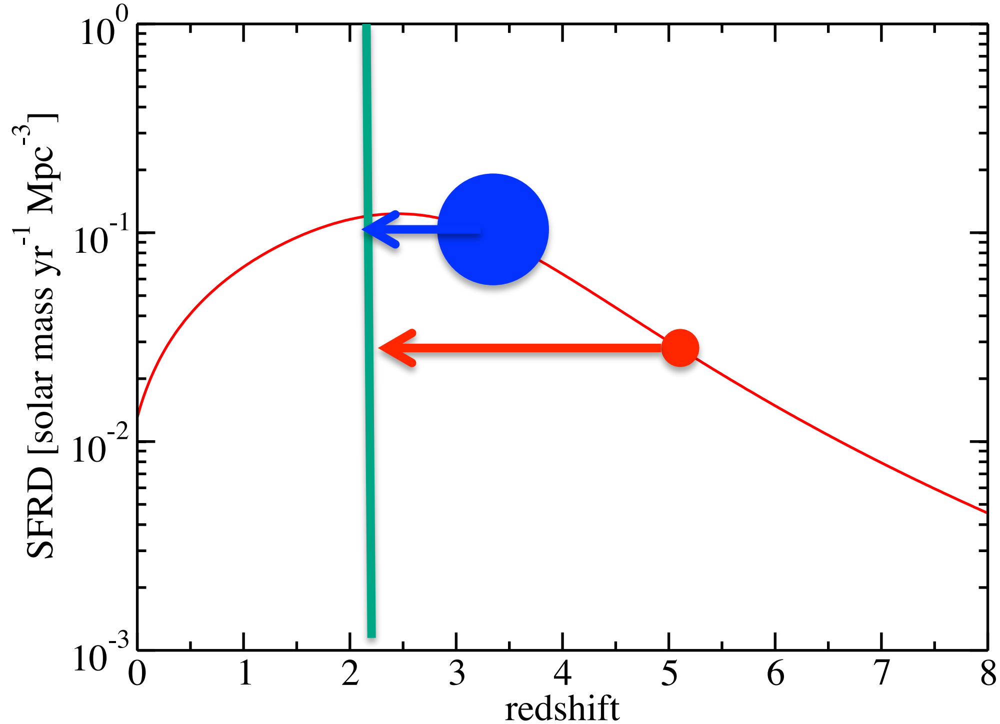
dust extinction

expansion of universe

star formation rate

Stellar evolution

Luminosity Density



JF, Razzaque, & Dermer (2010).
Razzaque, Dermer, & JF (2009).

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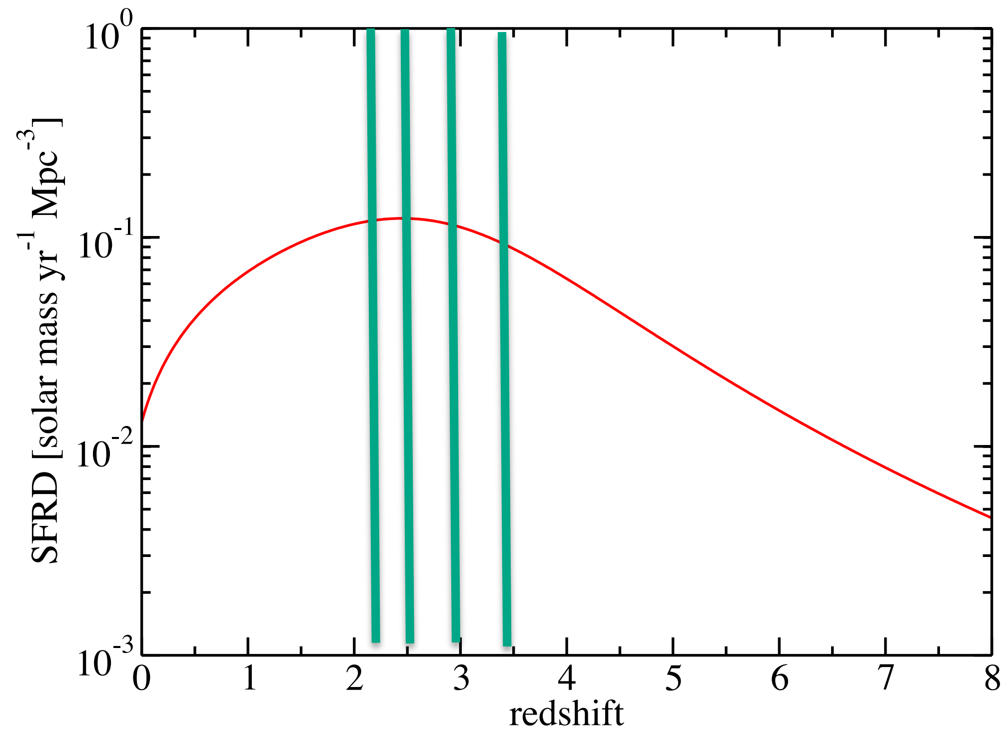

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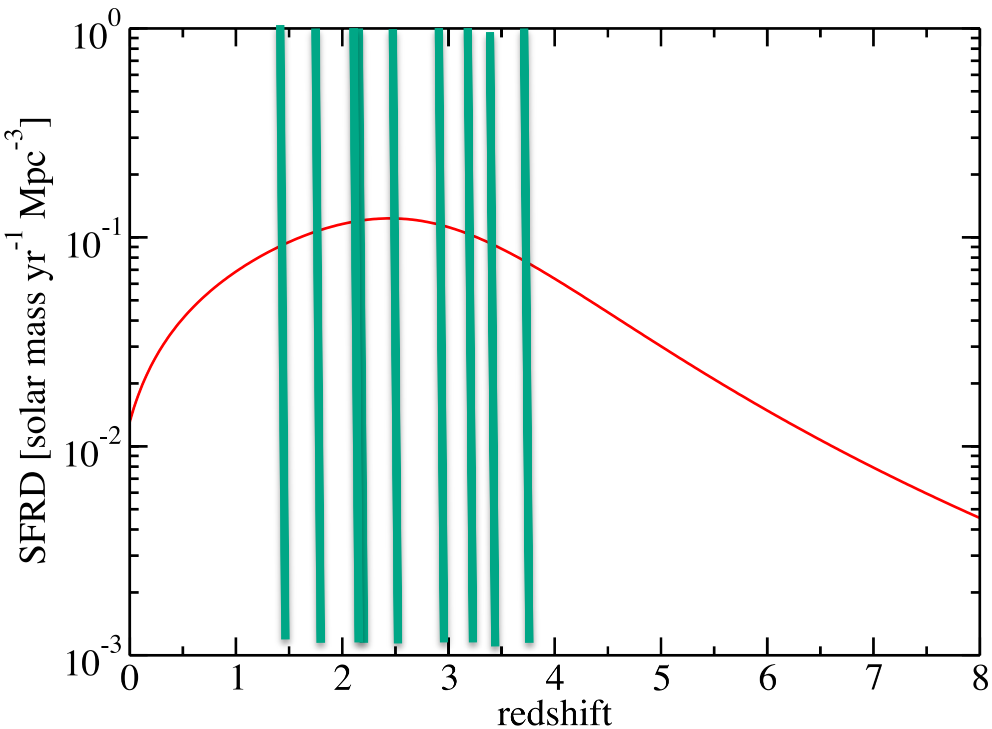

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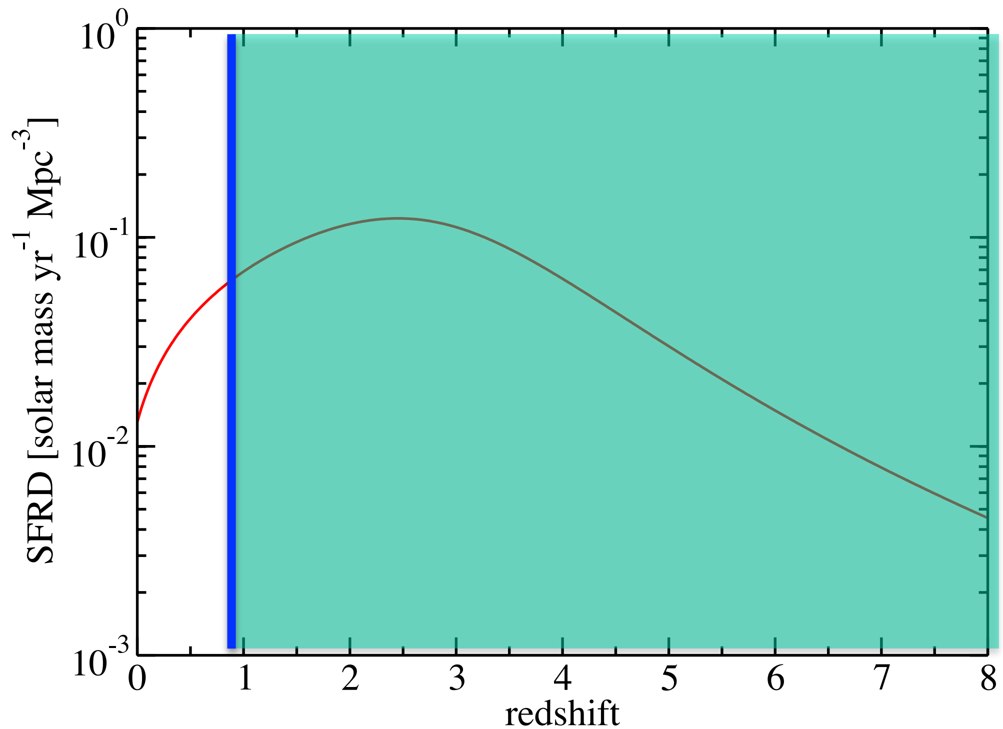
EBL Model

$$u_{\rm EBL}(\epsilon; z) = \int_z^{z_{\rm max}} dz' \; j(\epsilon; z') \; \left| \frac{dt}{dz'} \right|$$

expansion of universe

luminosity density

EBL energy density



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EBL Model

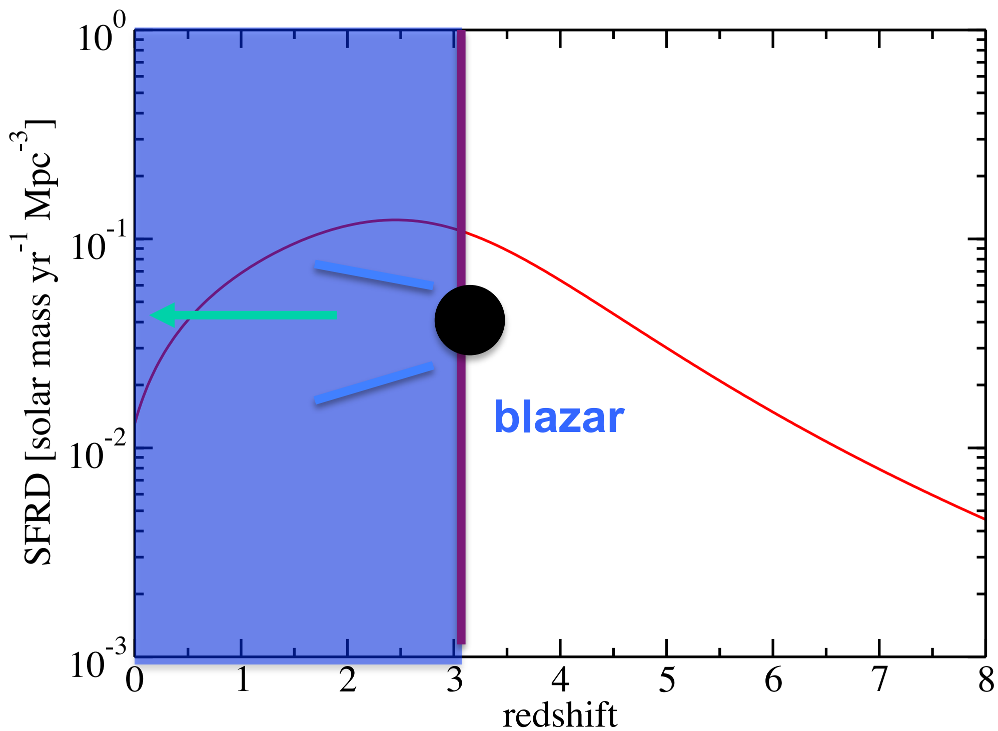
$$\tau_{\gamma\gamma}(E, z_s) = c \int_0^{z_s} dz \left|\frac{dt}{dz}\right| \int_{\epsilon_{\min}}^{\infty} d\epsilon \; n_{\rm EBL}(\epsilon; z) \; \sigma_{\gamma\gamma}(E, \epsilon)$$

absorption cross section

EBL number density

expansion of universe

absorption optical depth



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EBL Model

Do Markov Chain Monte Carlo fit to gamma-ray opacity data.

Use emcee routine (Foreman-Mackey et al. 2013).

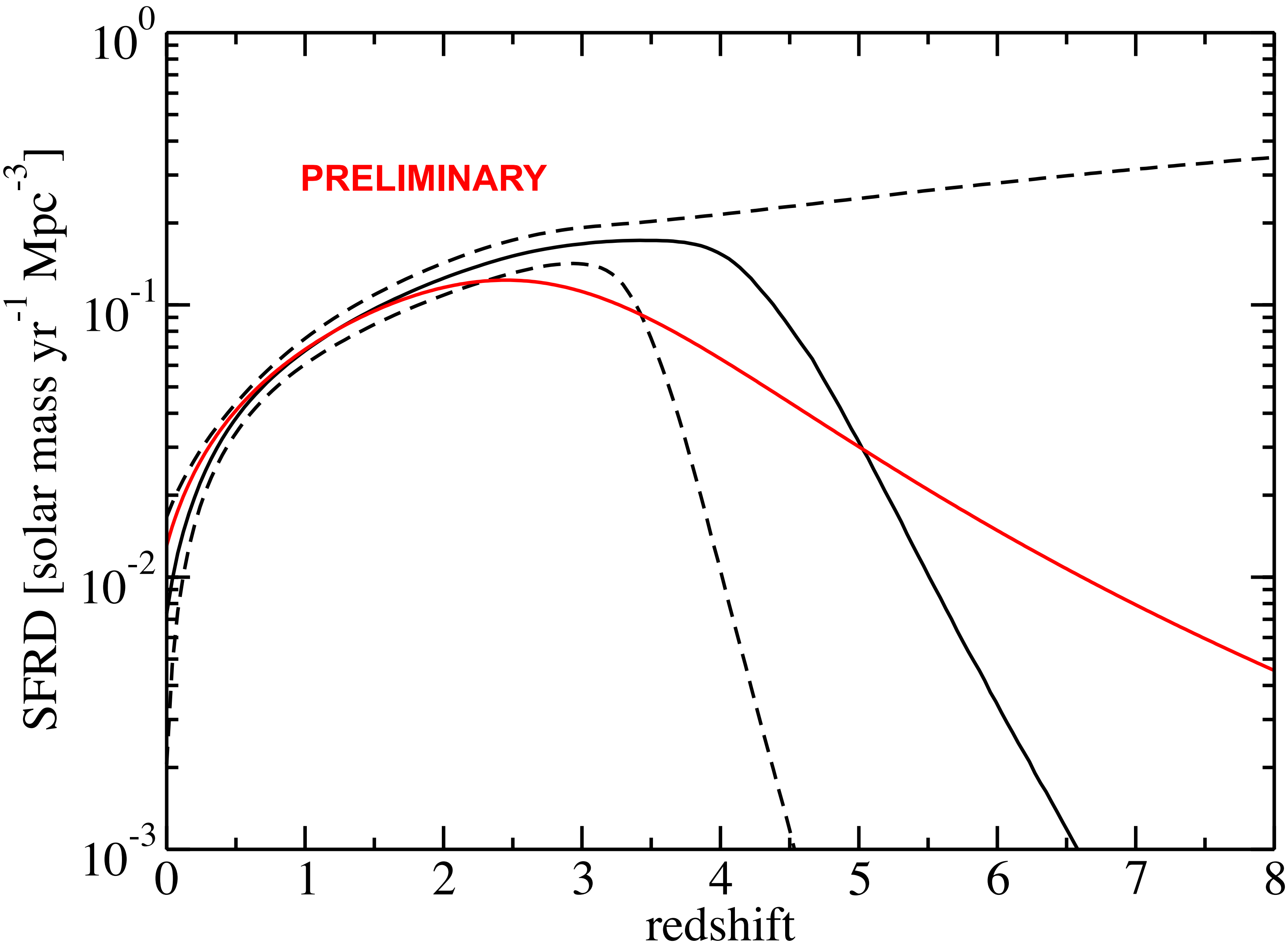
Allow star formation rate density parameters (a, b, c, d) to vary:

$$\psi(z) = h\frac{a + bz}{1 + (z/c)^d}$$

all other parameters kept constant.

Similar method to Gong & Cooray (2013).

Star Formation Rate Result



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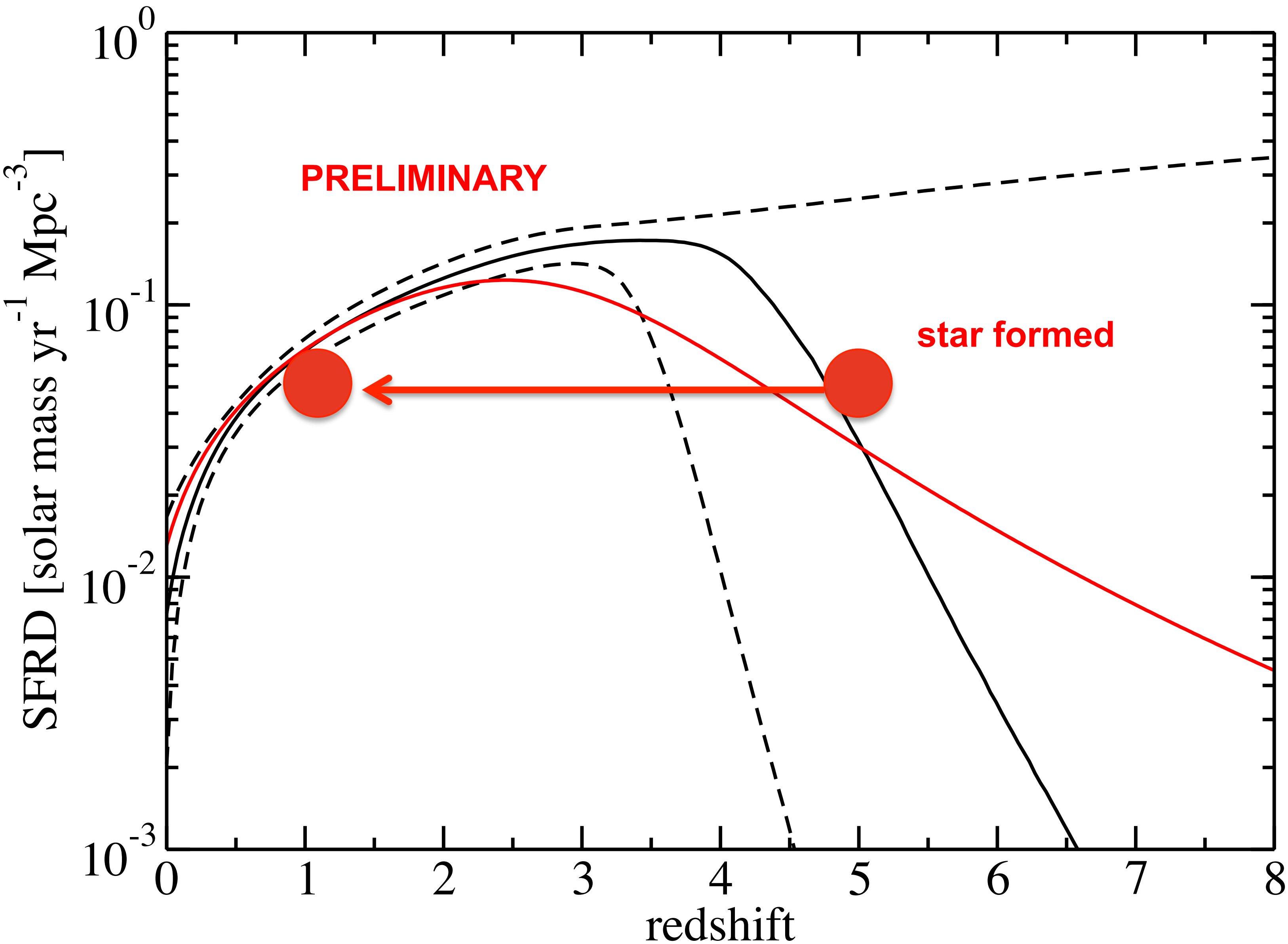

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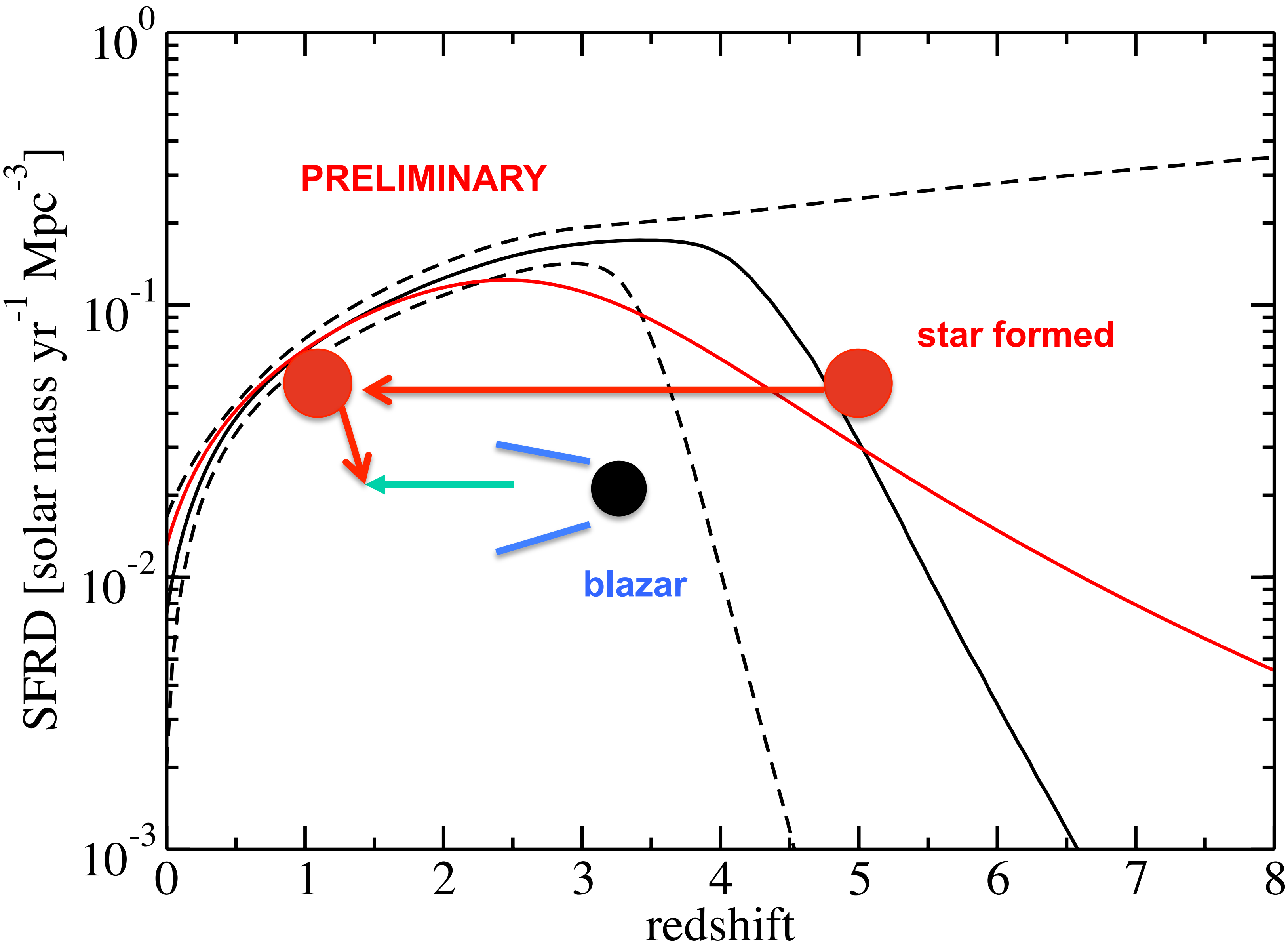

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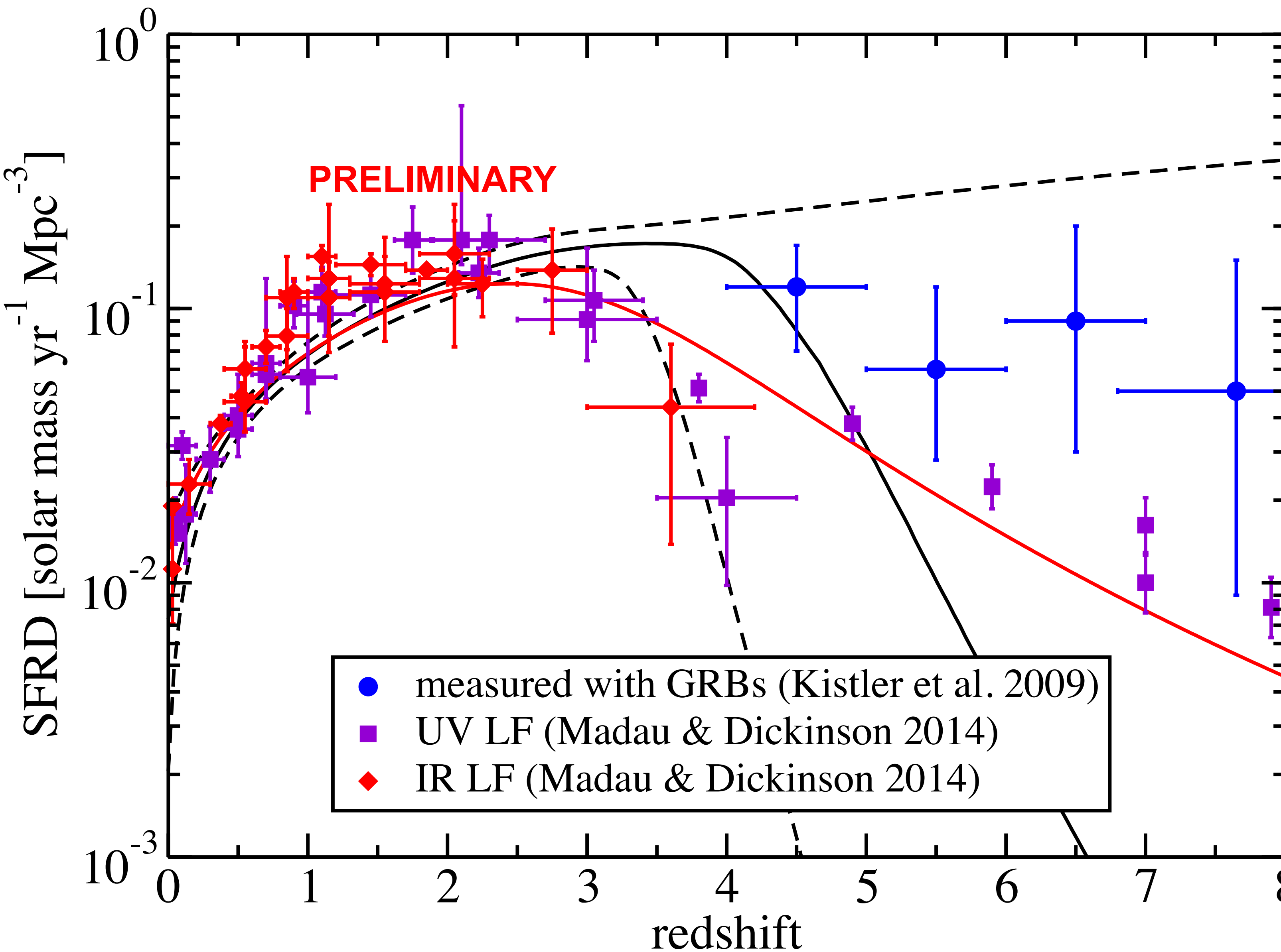

Summary

We've used model fits to these results to make an independent measurement of the cosmic SFRD.

Allows us to constrain high-z SFRD more than previous γ-ray measurements (Gilmore 2012, Inoue et al. 2014).

Our results consistent with stars alone being able to reionize the universe (e.g. Madau et al. 1999, Kistler et al. 2009)

See also: talk by Kari Helgason today at 14:30 on luminosity density measurements

To do:

Different SFR parameterizations (e.g., Madau & Dickenson 2014)

Allow dust model to vary, with different parameterizations
(Driver et al. 2008 dust model used so far)

Extra Slides

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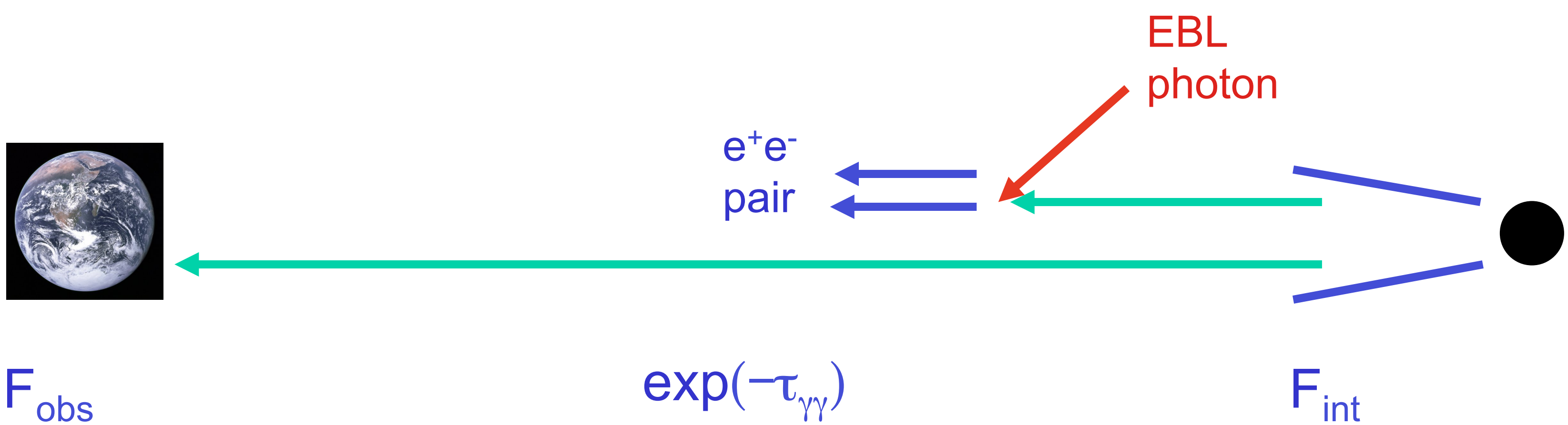
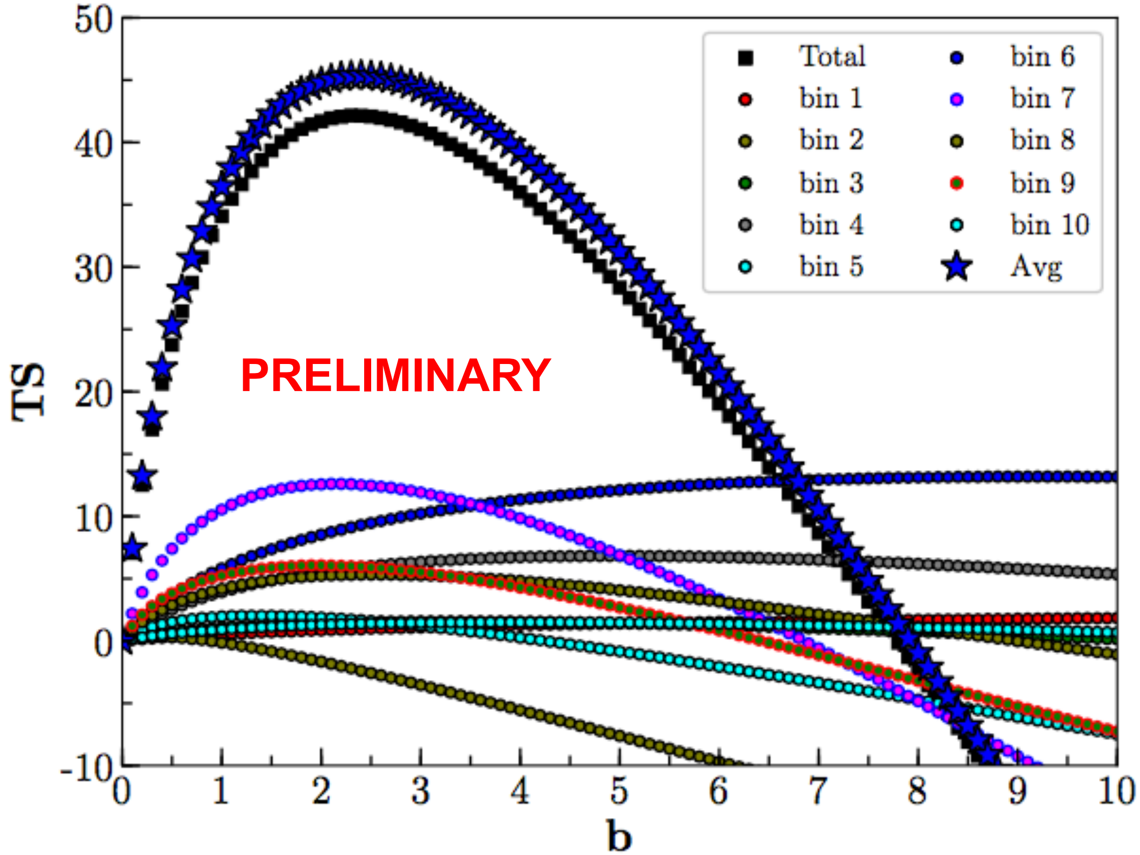
Untangling Intrinsic Brightness and Extinction

To study the EBL with γ-rays ($\tau_{\gamma\gamma}$), we need to know F_{int}. How can we determine the intrinsic γ-ray flux?

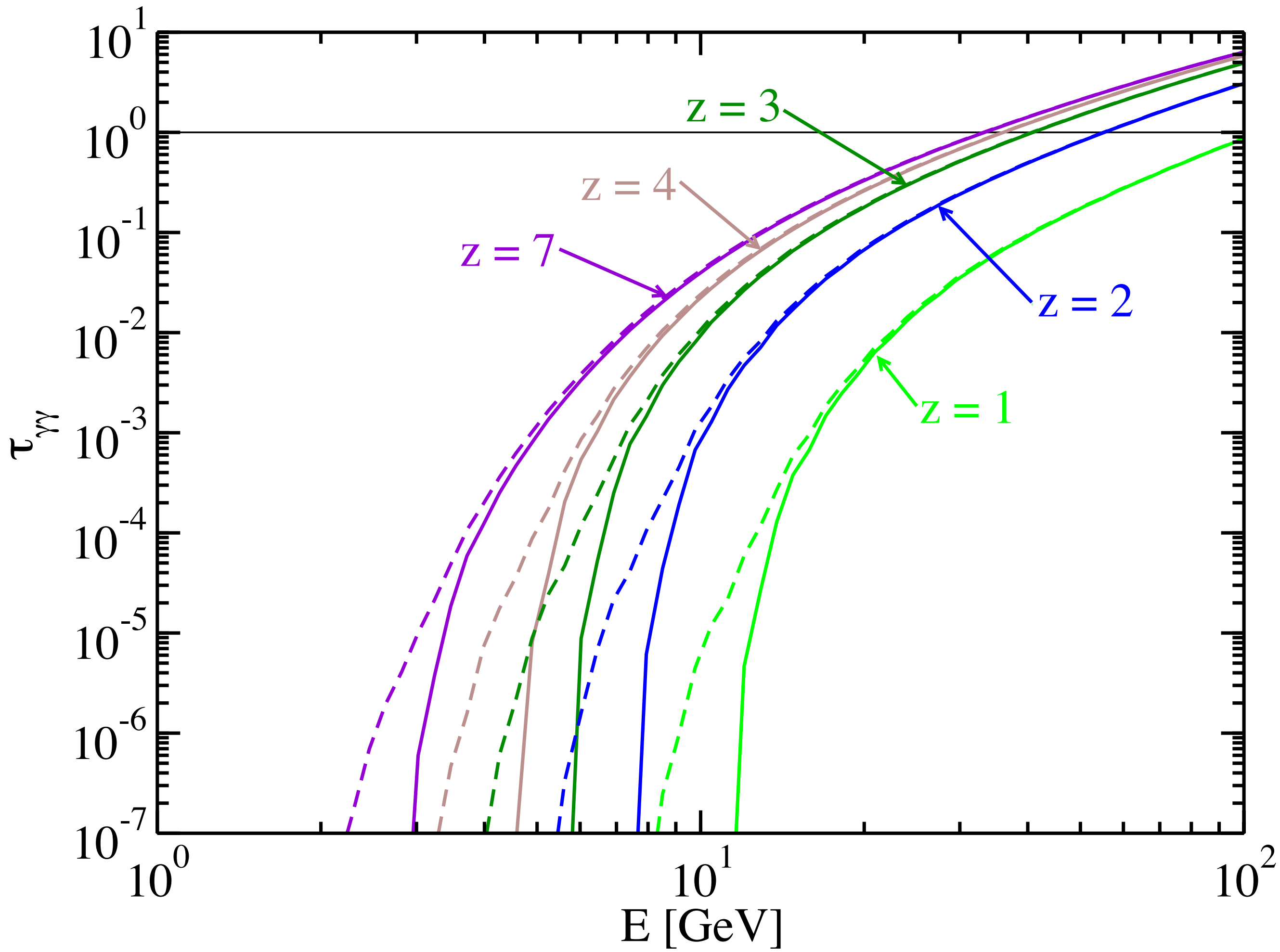


Variability



←Variability
Not a problem !

γ-ray absorption and UV escape fraction



solid: $f_{esc,H} = 0.0$
dashed: $f_{esc,H} = 0.2$

Internal γγ absorption

FSRQs:

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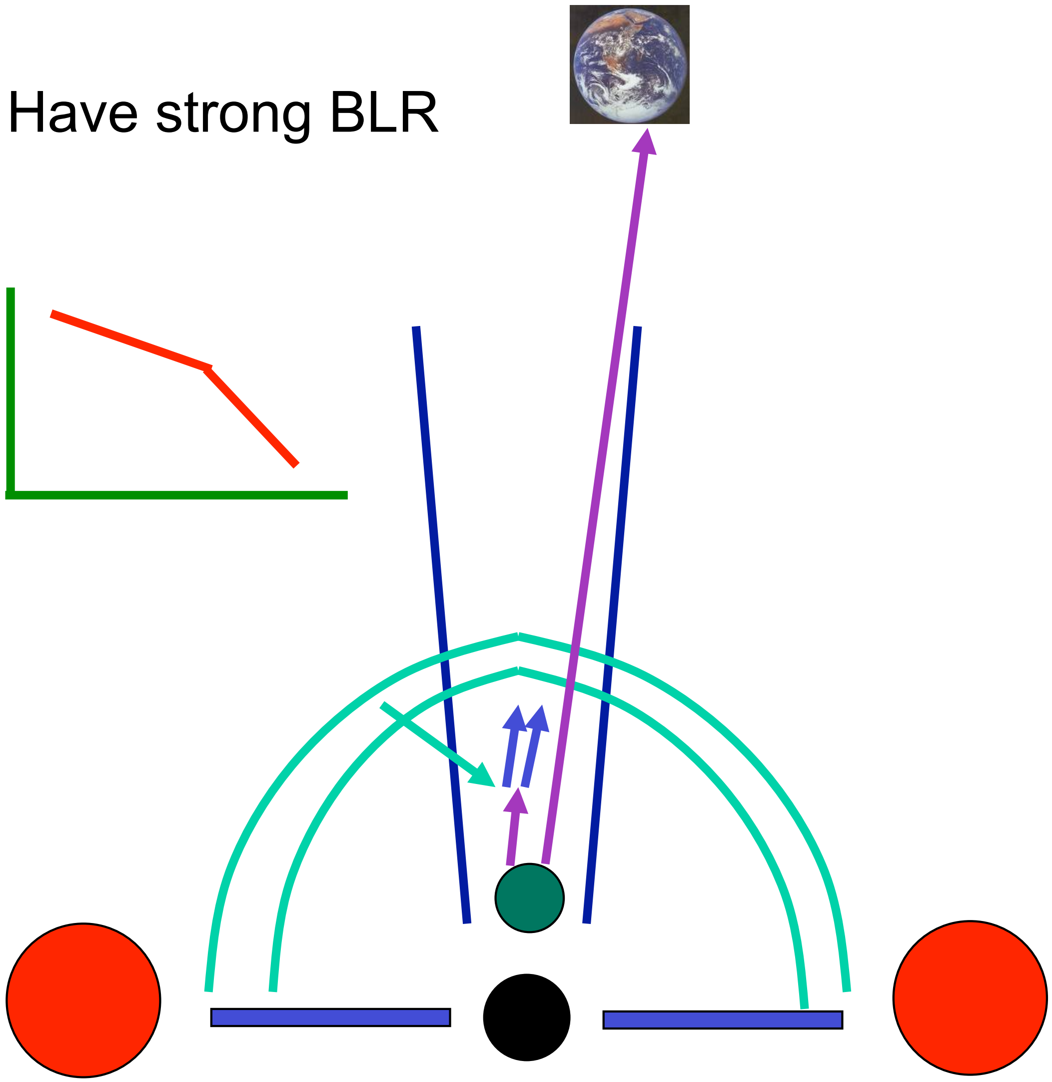

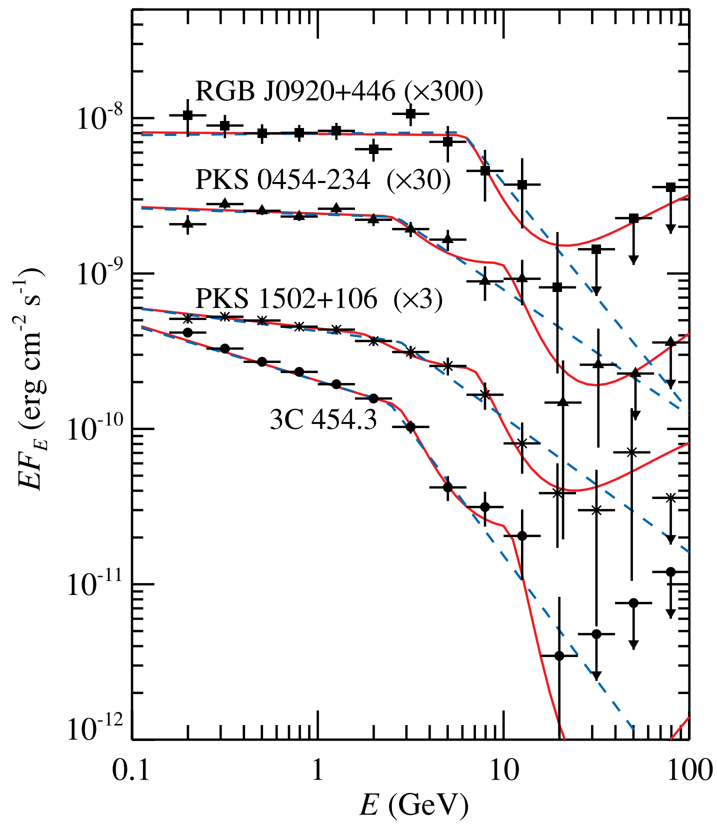

Stern & Poutanen (2010)

See also Reimer (2007)

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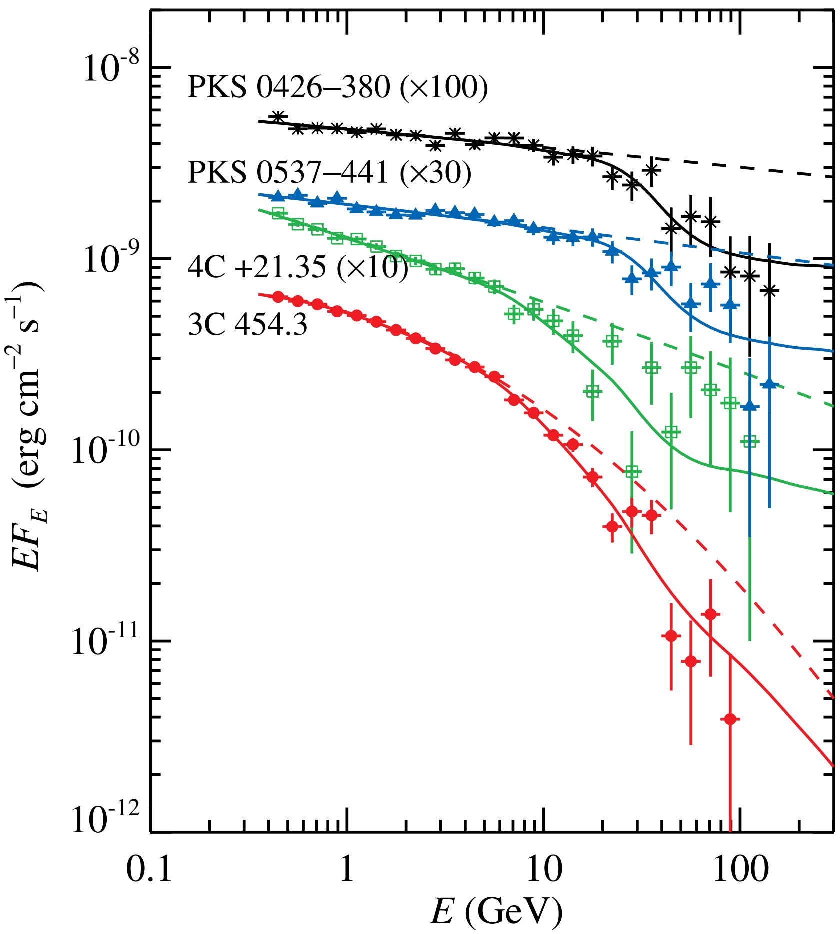

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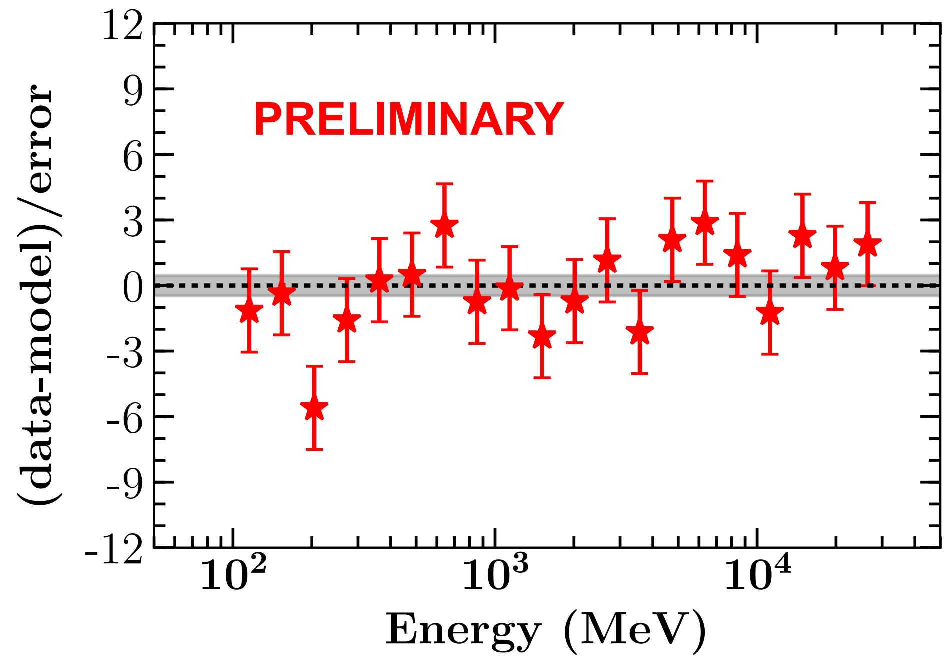

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Cosmic Gamma-ray Horizon