LIV effects from anomalous transparency at E >10 TeV:

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Modified dispersion relations

A simple phenomenological approach to LIV

$$E_\gamma^2 = k^2 + \xi^{(n)} \frac{k^n}{E_{\mathrm{PL}}^{n-2}}$$ photons

$$E_{\mathrm{e}}^2 = m_{\mathrm{e}}^2 + p^2 + \eta^{(n)} \frac{p^n}{E_{\mathrm{PL}}^{n-2}}$$ electrons

n>3 (c=1)

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We consider n=3

Energy threshold

Jacob & Piran 2008
Fairbairn et al. 2014

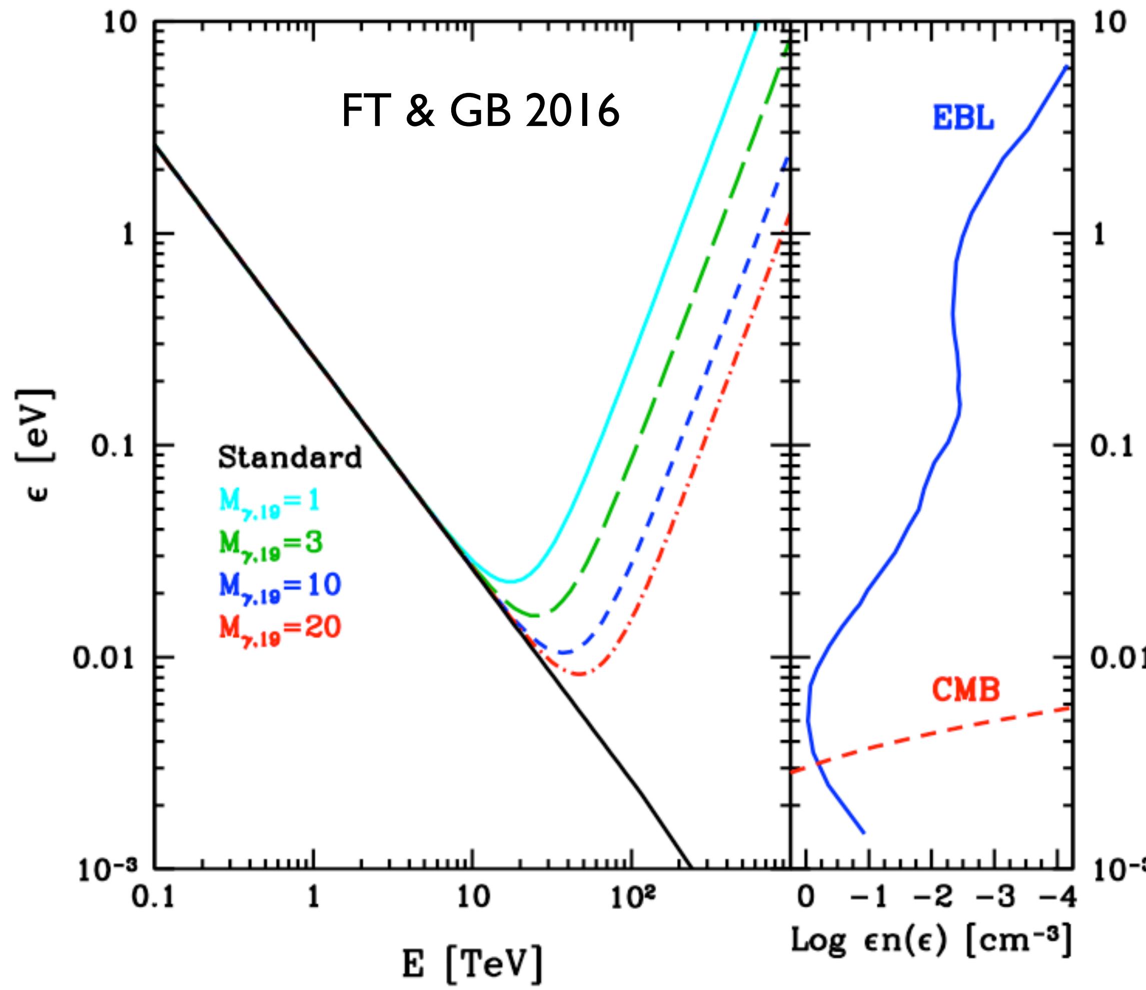
LIV induces an 'effective mass' for the photon

$$E_\gamma^2 = k^2 + \underbrace{\xi^{(n)} \frac{k^n}{E_{\rm PL}^{n-2}}}_{m_\gamma^2}$$

$$\epsilon_{\rm min} = \frac{m_{\rm e}c^2}{E_\gamma} + \xi \frac{E_\gamma^2}{E_{\rm PL}}$$

(Head-on)

Modification of threshold
for pair production at high E



LIV induces suppression of EBL-opacity

The optical depth - I

$$\tau(E) = \int_0^{d_s} \int_{\epsilon_{\min}} n(\epsilon) \int_{-1}^{1} \frac{(1-\mu)}{2} \sigma_{\gamma\gamma}(\beta)\, d\mu\, d\epsilon\, dl,$$

$$\sigma_{\gamma\gamma}(\beta) = \frac{\pi r_e^2}{2}\left(1-\beta^2\right)\left[2\beta\left(\beta^2-2\right)+\left(3-\beta^4\right)\ln\left(\frac{1+\beta}{1-\beta}\right)\right]$$

$$\beta(s) \equiv \left[1 - \frac{4\, m_e^2\, c^4}{s}\right]^{1/2}$$

$$s = 2\epsilon E(1-\mu).$$

Standard:

$$s > 1 \rightarrow \quad \epsilon_{\min} = 2m_e^2c^4/E(1-\mu)$$

$$\beta(\epsilon/\epsilon_{\min}) = \left[1 - \frac{\epsilon_{\min}}{\epsilon}\right]^{1/2}$$

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LIV:

$$\epsilon_{min} = \frac{m_e c^2}{E_\gamma} + \xi \frac{E_\gamma^2}{E_{PL}}$$

↓ J&P

$$\beta(\epsilon/\epsilon_{min}) = \left[1 - \frac{\epsilon_{min}}{\epsilon}\right]^{1/2}$$

The optical depth - 2

$$\tau(E) = \int_0^{d_s} \int_{\epsilon_{\min}} n(\epsilon) \int_{-1}^{1} \frac{(1-\mu)}{2} \sigma_{\gamma\gamma}(\beta) \, d\mu \, d\epsilon \, dl,$$

$$\sigma_{\gamma\gamma}(\beta) = \frac{\pi r_e^2}{2} \left(1-\beta^2\right) \left[2\beta\left(\beta^2 - 2\right) + \left(3 - \beta^4\right) \ln\left(\frac{1+\beta}{1-\beta}\right) \right]$$

$$\beta(s) \equiv \left[1 - \frac{4 m_e^2 c^4}{s}\right]^{1/2}$$

$$s = 2\epsilon E(1-\mu).$$

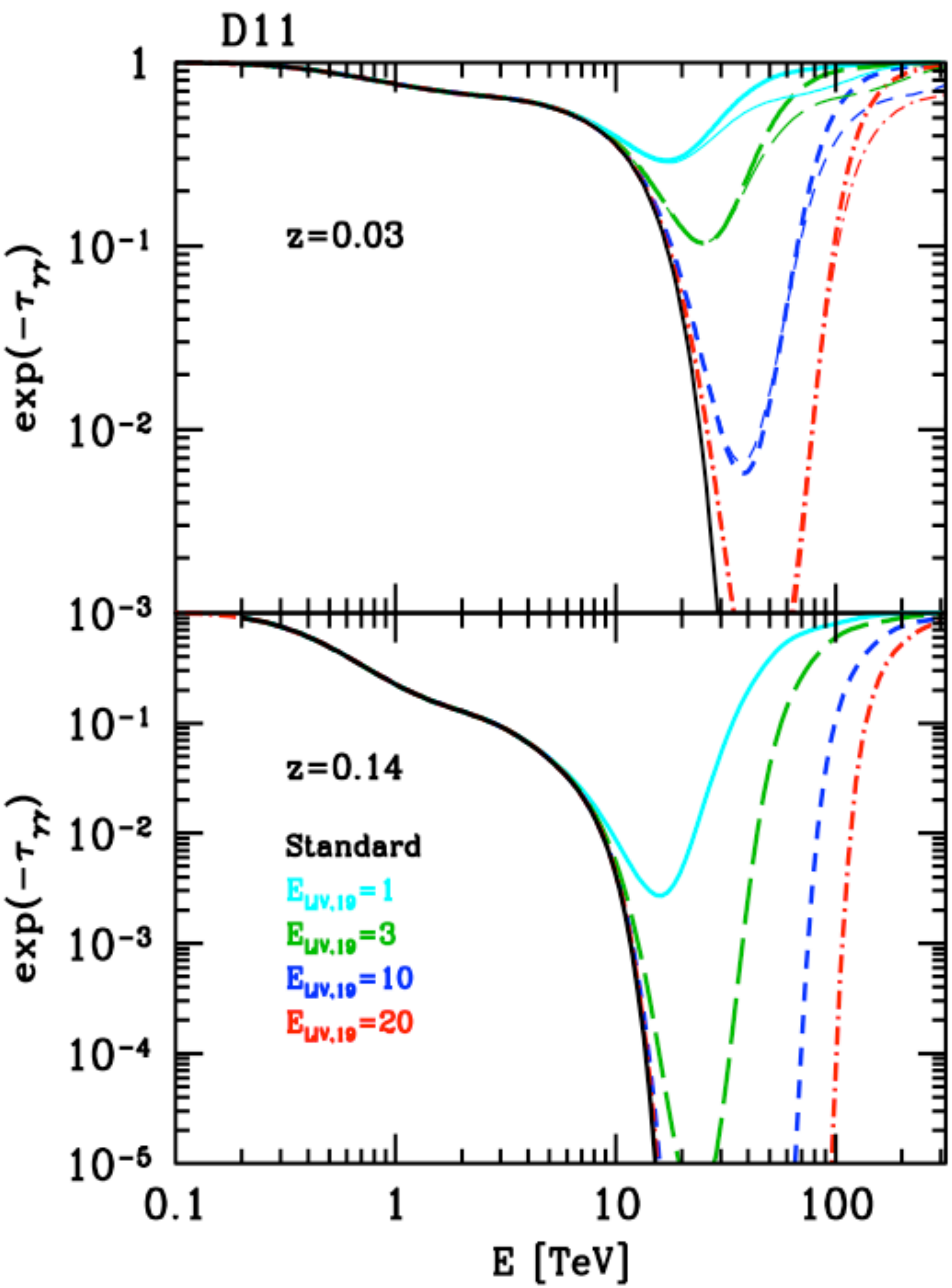
(E-dependent) photon effective mass

LIV:

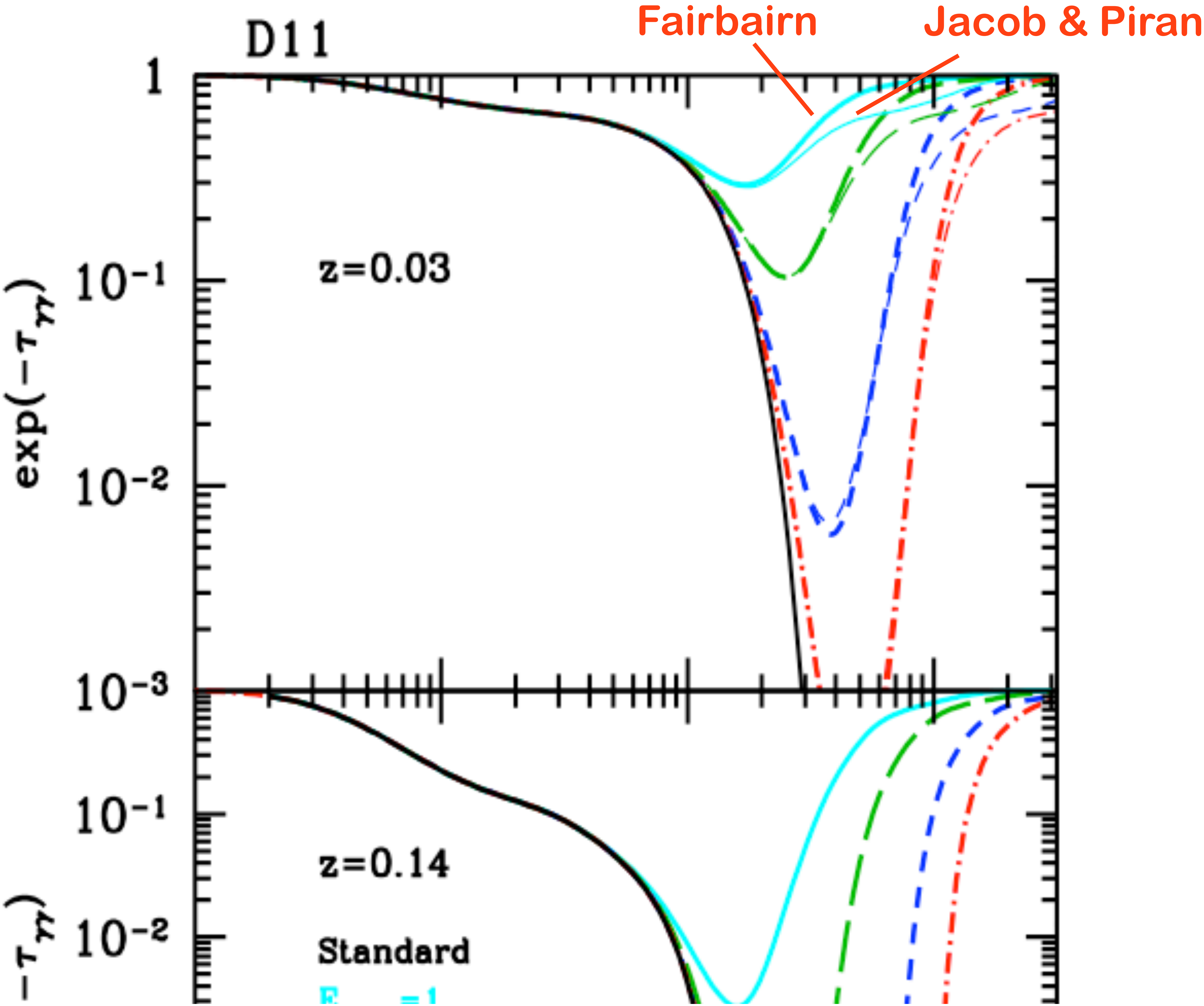
Fairbairn

$$s = m_\gamma^2 + 2\epsilon E(1-\mu)$$

$$\beta(s) \equiv \left[1 - \frac{4 m_e^2 c^4}{s}\right]^{1/2}$$

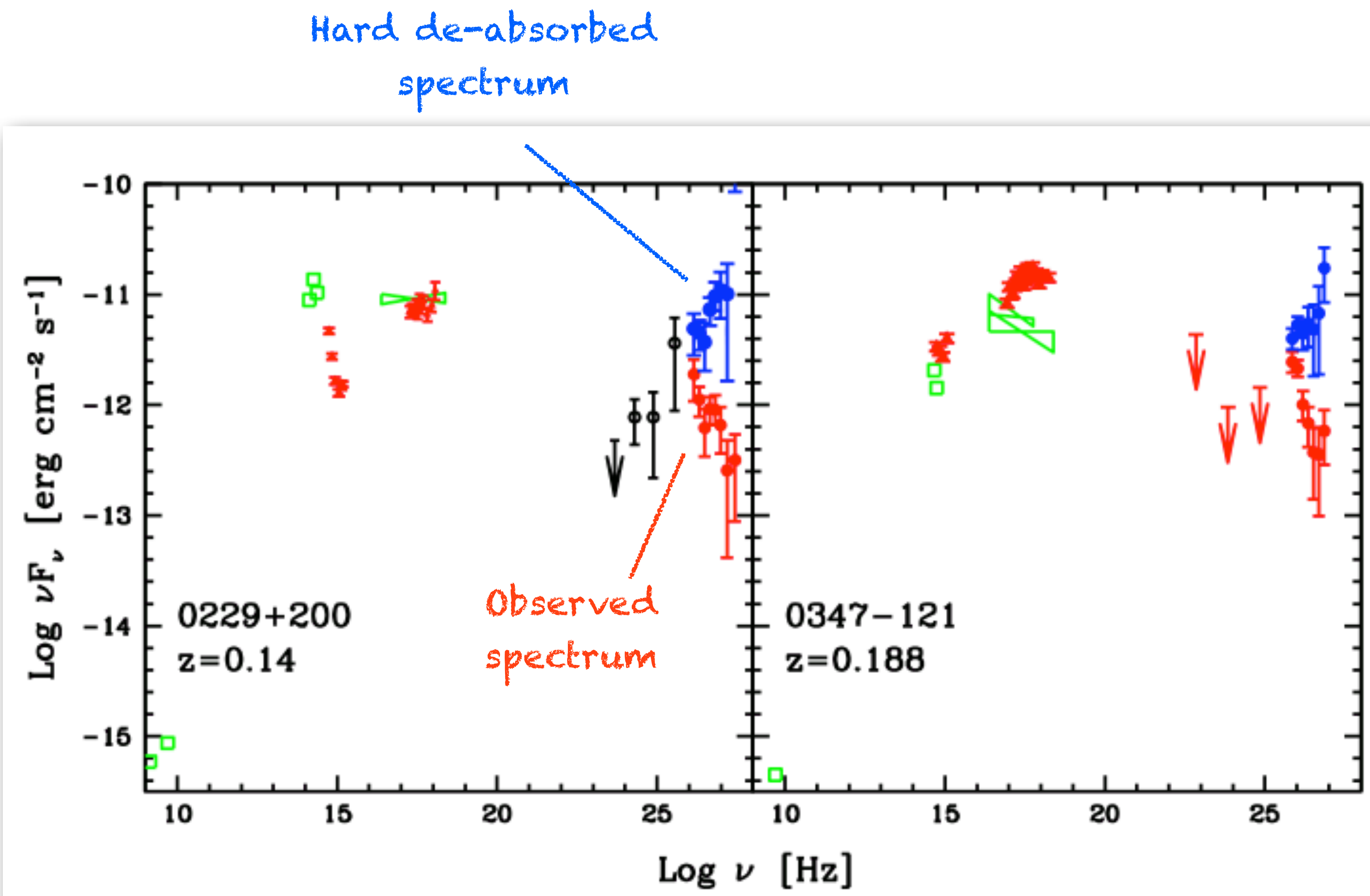


D11
z=0.03
z=0.14
Standard
E_LIV,19=1
E_LIV,19=3
E_LIV,19=10
E_LIV,19=20
exp(−τ_γγ)
E [TeV]
0.1
1
10
100

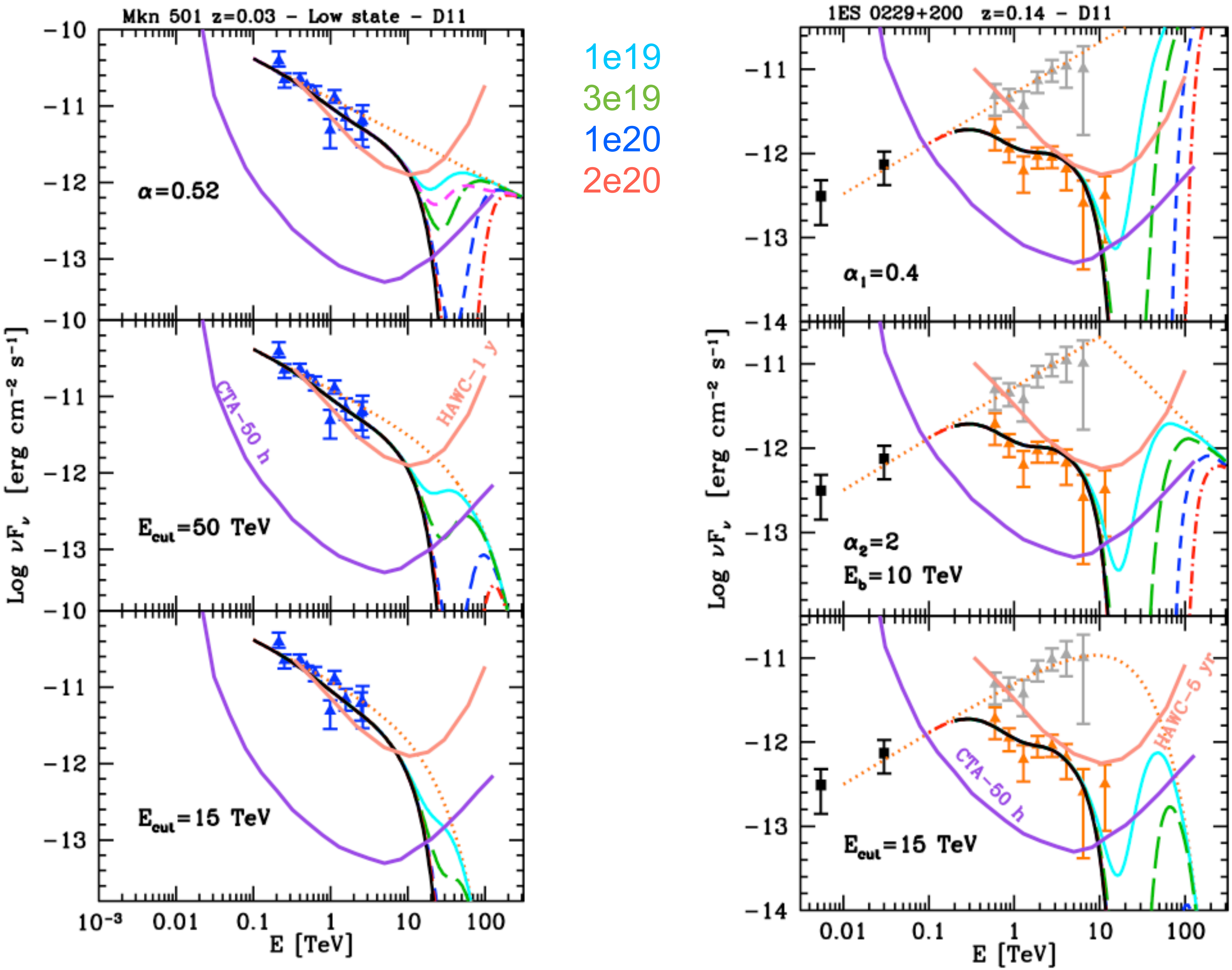


Fairbairn
Jacob & Piran
D11
1
10^{-1}
10^{-2}
10^{-3}
z=0.03
$\exp(-\tau_{\gamma\gamma})$
z=0.14
Standard

Targets: Extreme BL Lacs



Bonnoli et al. 2015


Mkn 501 z=0.03 - Low state - D11
1ES 0229+200 z=0.14 - D11
1e19
3e19
1e20
2e20
α=0.52
E_cut=50 TeV
E_cut=15 TeV
α_1=0.4
α_2=2
E_b=10 TeV
CTA-50 h
HAWC-1 y
HAWC-5 yr
Log νF_ν [erg cm^-2 s^-1]
E [TeV]

FT & GB 2016

Suggestions for Extension

Extensions to $n>3$
and inclusion of $e^{\pm}$