Fundamental physics with extreme BL Lacs
(a critical appraisal)

Fabrizio Tavecchio
(INAF-OABrera)

extreme19

Basic idea

TeV extreme BL Lacs provide an intense beam of γ-rays with appreciable flux, extending at least up to ~10 TeV.

⇒ Ideal sources to probe cosmic opacity (EBL)

A. Franceschini talk

⇒ Ideal sources to probe intergalactic magnetic fields

E. Pueschel talk

Basic idea

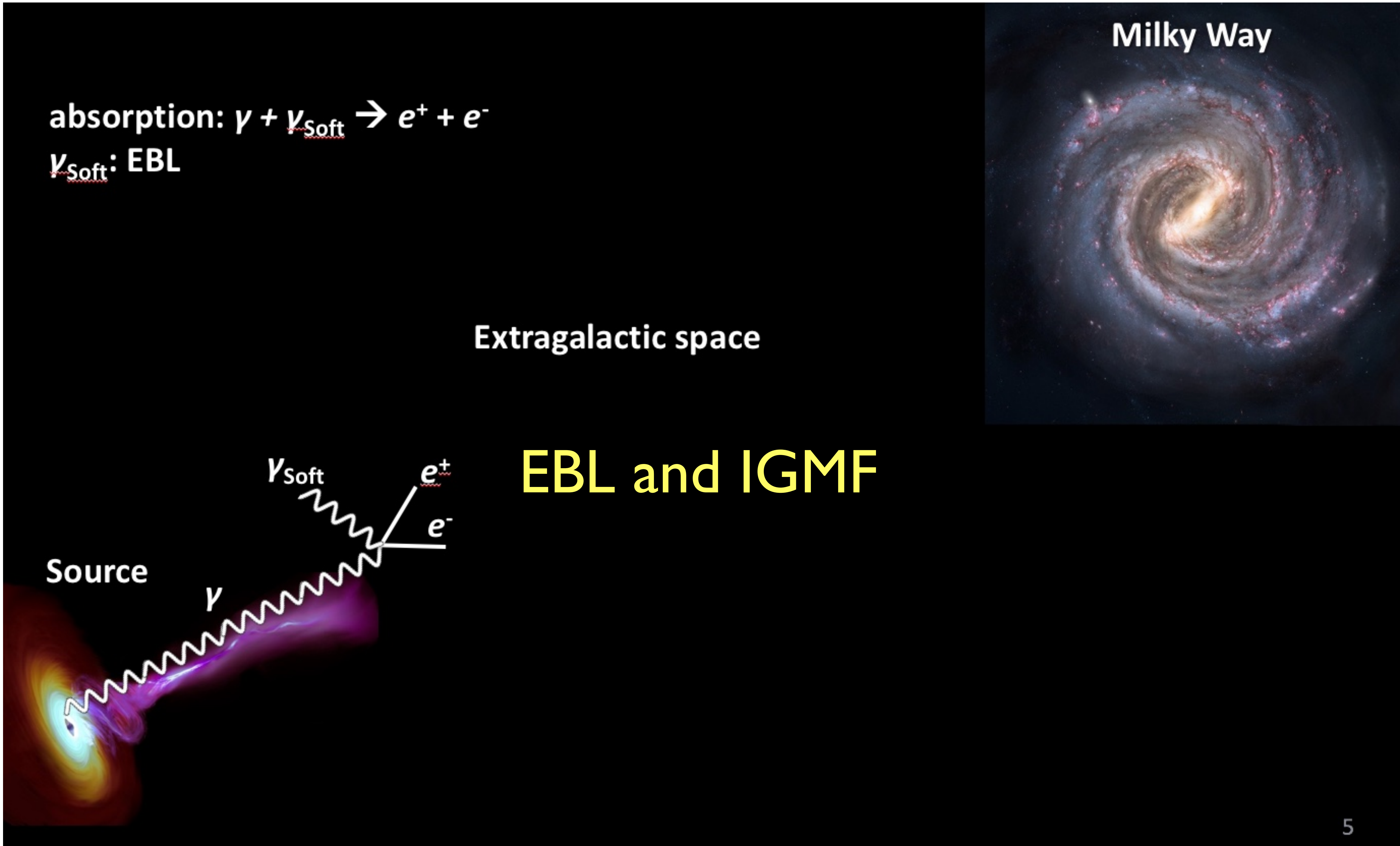
TeV extreme BL Lacs provide an intense beam of γ-rays with appreciable flux, extending at least up to ~10 TeV.

Ideal sources to probe *anomalies* (i.e. reduction) of the cosmic opacity caused by e.g.:

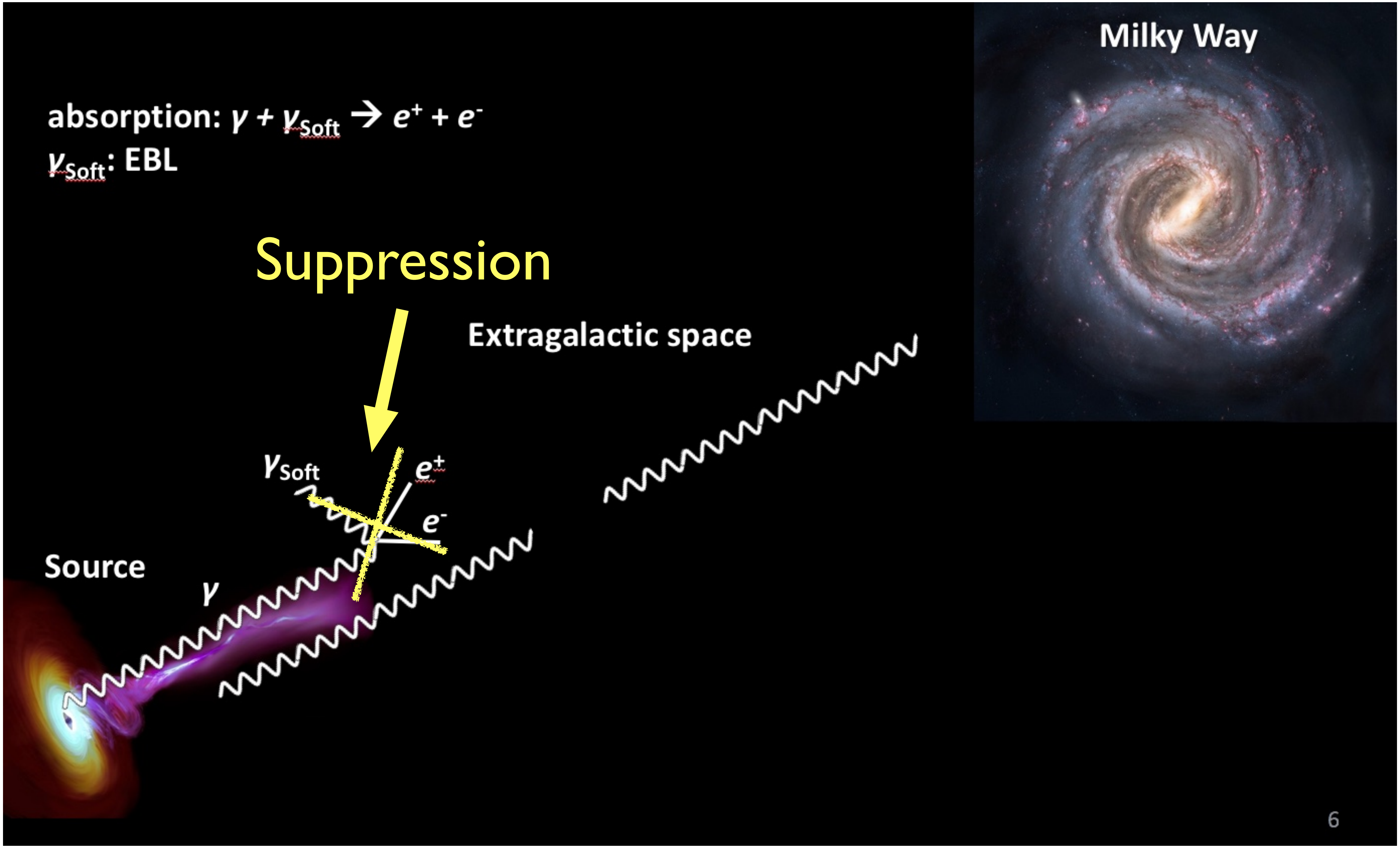
the existence of Axion-like particles (ALP)
the breaking of the Lorentz invariance (LIV)

This talk
G. Galanti talk

Basic idea


Milky Way
absorption: γ + γSoft → e+ + e-
γSoft: EBL
Extragalactic space
EBL and IGMF
γSoft
e+
e-
Source
γ
5

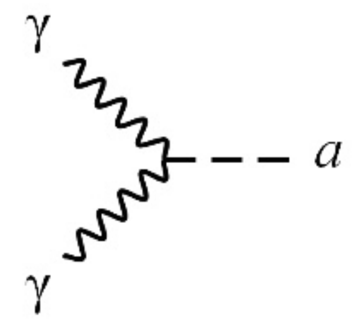
Basic idea


absorption: $\gamma + \gamma_{Soft} \rightarrow e^{+} + e^{-}$
γ_{Soft}: EBL
Suppression
Extragalactic space
Milky Way
γ_{Soft}
e^{+}
e^{-}
Source
γ
6

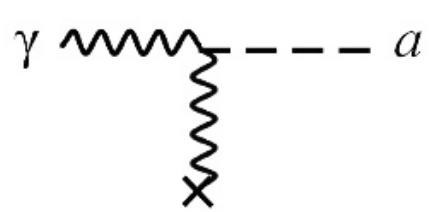
Axion-Like particles

- Predicted by String Theory
- Very light particles ($m_a < 10^{-8}$ eV)
- Spin 0
- Interaction with two photons (coupling $g_{a\gamma\gamma}$)
- Interactions with other particles discarded

Two photons

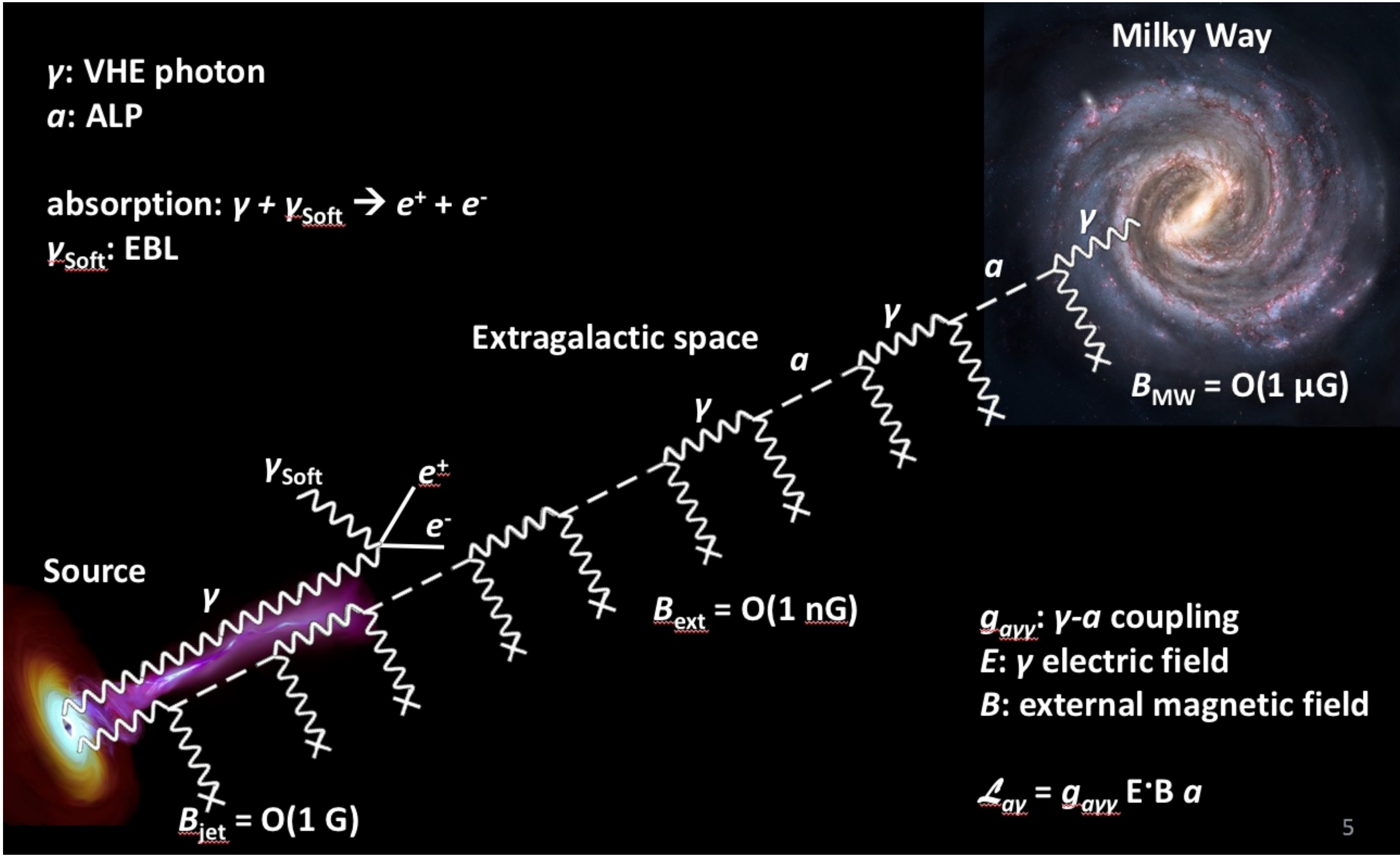


In an external B field



Photon-ALP oscillations

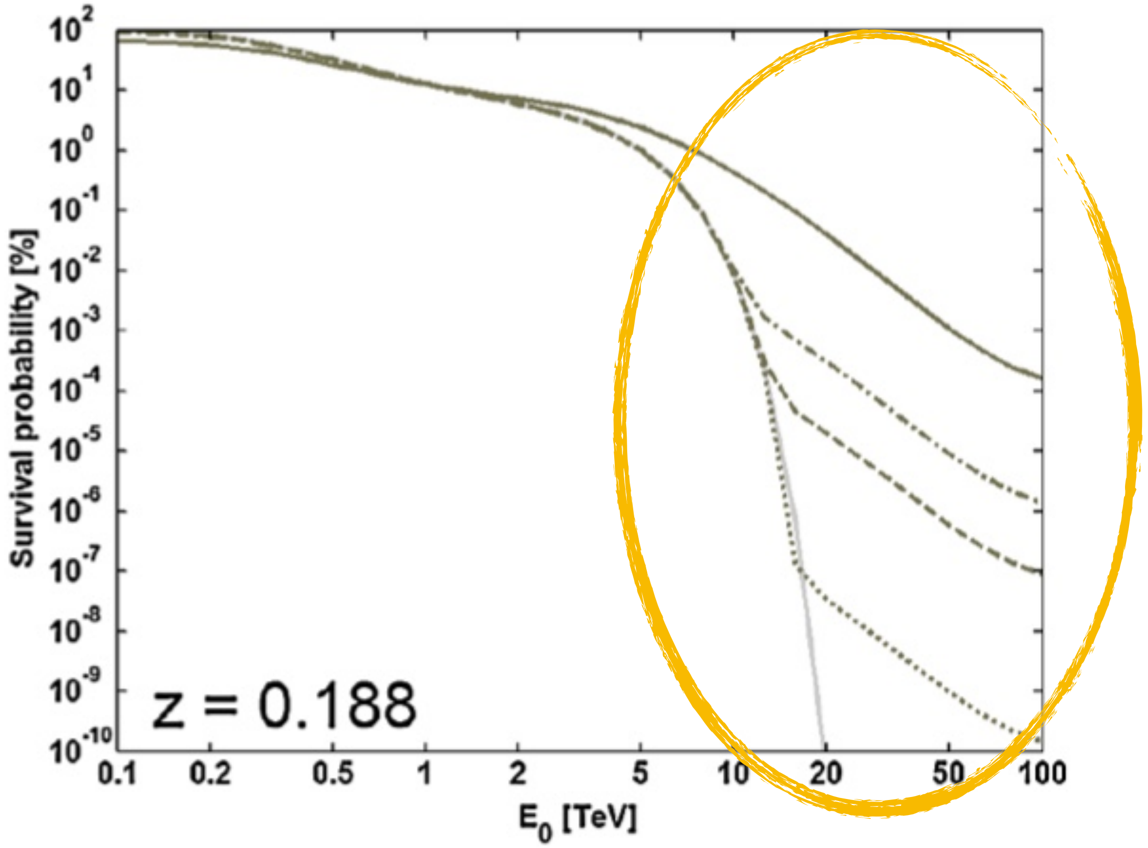
Axion-Like particles



Credits: G. Galanti

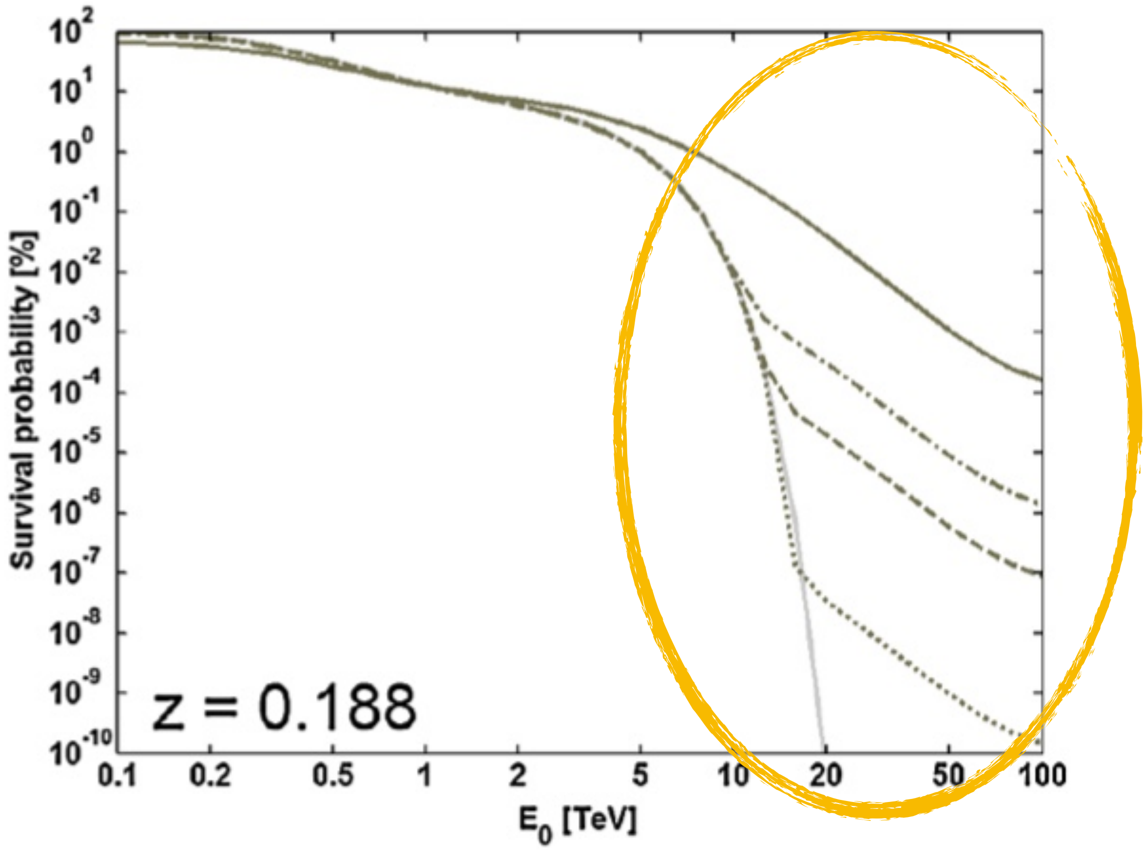
Axion-Like particles

De Angelis et al. 2011



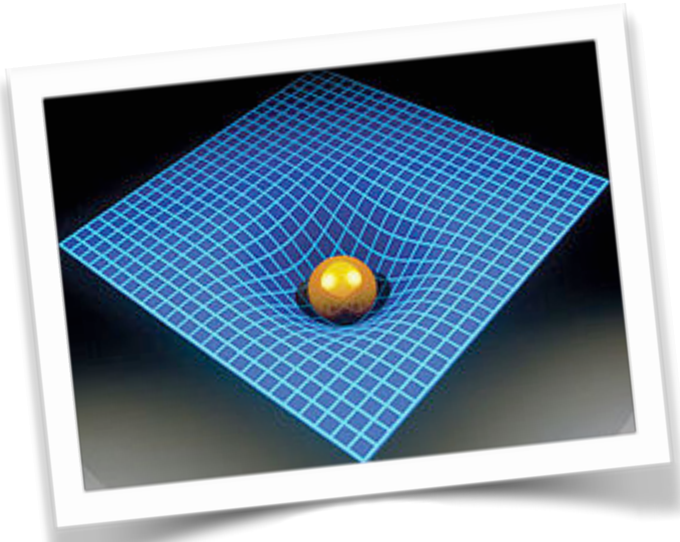
Axion-Like particles

De Angelis et al. 2011



G. Galanti talk

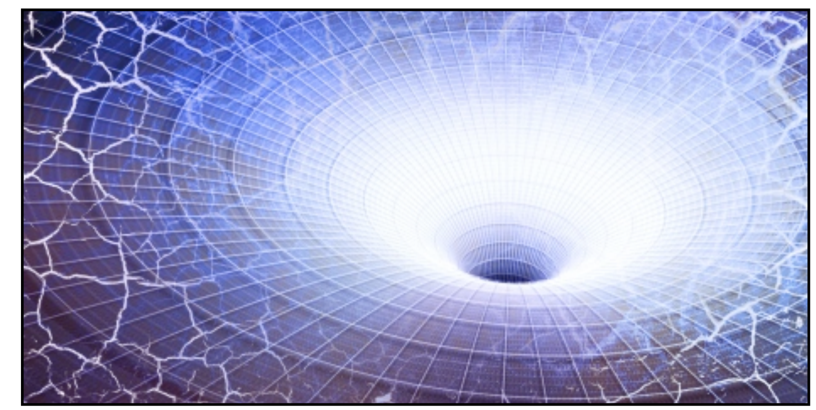
The 'Holy Grail' of physics



General relativity

Quantum mechanics

Quantum gravity



$$E_{\mathrm{Pl}} = \sqrt{\frac{\hbar c^5}{G}} \simeq 1.2 \times 10^{19}\ \mathrm{GeV}$$

$$\ell_{\mathrm{P}} = \sqrt{\frac{\hbar G}{c^3}} \approx 1.616\,199(97) \times 10^{-35}\ \mathrm{m}$$

Lorentz invariance violation

The existence of an invariant length in QG naturally leads to the violation of the Lorentz invariance (LIV)

⇒ Physical effects depend on particle energy (i.e. boost)

Enormous energy! But effects are expected also at lower energies

(see reviews in Mattingly 2005, Liberati 2013, Amelino-Camelia 2013)

(Some) LIV effects

Vacuum birifrangence (depolarization, rotation)

Photon decay, vacuum Cherenkov (max. E for CR)

Energy-dependent photon time of flight

Modification of reaction thresholds (photons, CR)

(Some) LIV effects

Vacuum birifrangence (depolarization, rotation)

Photon decay, vacuum Cherenkov (max. E for CR)

Energy-dependent photon time of flight

Modification of reaction thresholds (photons, CR)

Modified dispersion relations

A first, simple <u>phenomenological</u> approach

$$E_\gamma^2 = k^2 \pm \frac{E_\gamma^n}{E_{LIV}^{n-2}}$$

photons

We consider n>3

Similar expressions for particles
(but stringent constraints for electrons, Jacobson et al. 2003)

E-dependent time of flight

Photon speed is energy dependent!
Vacuum is dispersive.

$$v_g = \frac{\partial E}{\partial k} \neq c$$

Photons with different E emitted simultaneously will arrive at different times.

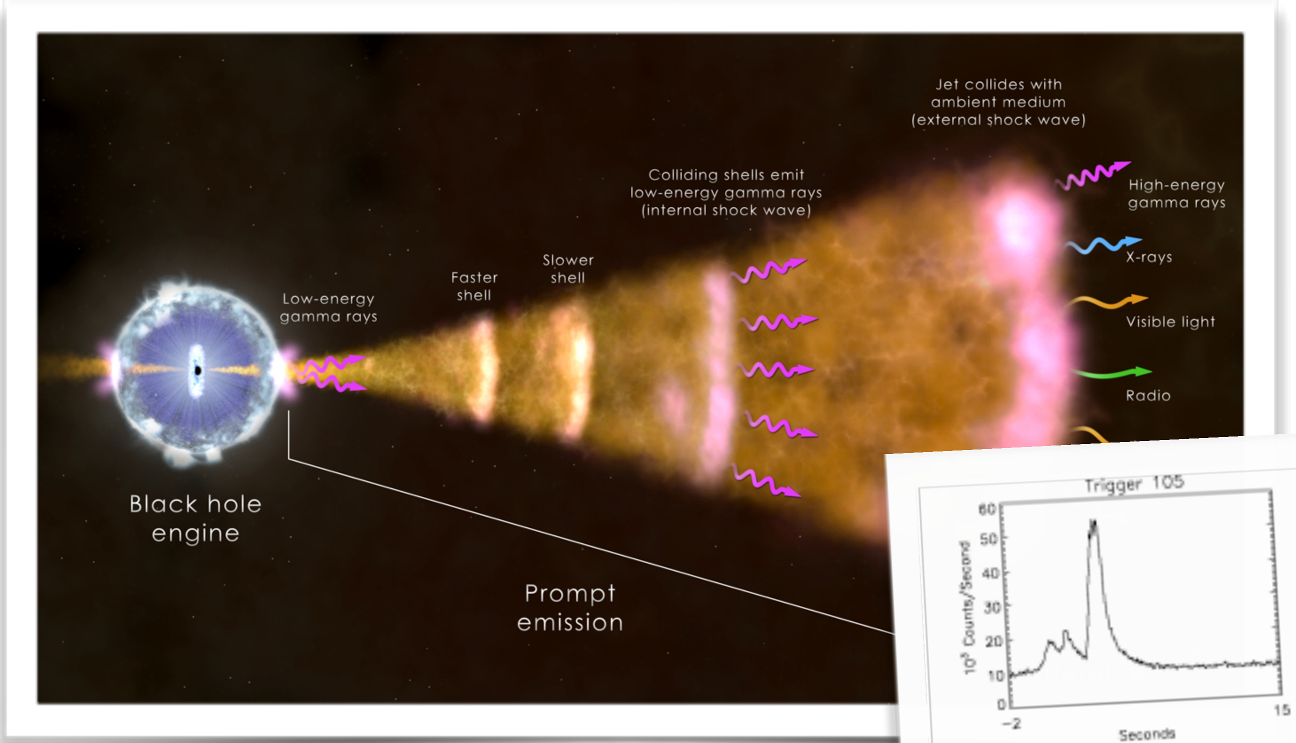
$$\Delta t = \frac{1}{2} \frac{E_2 - E_1}{E_{LIV}} d$$

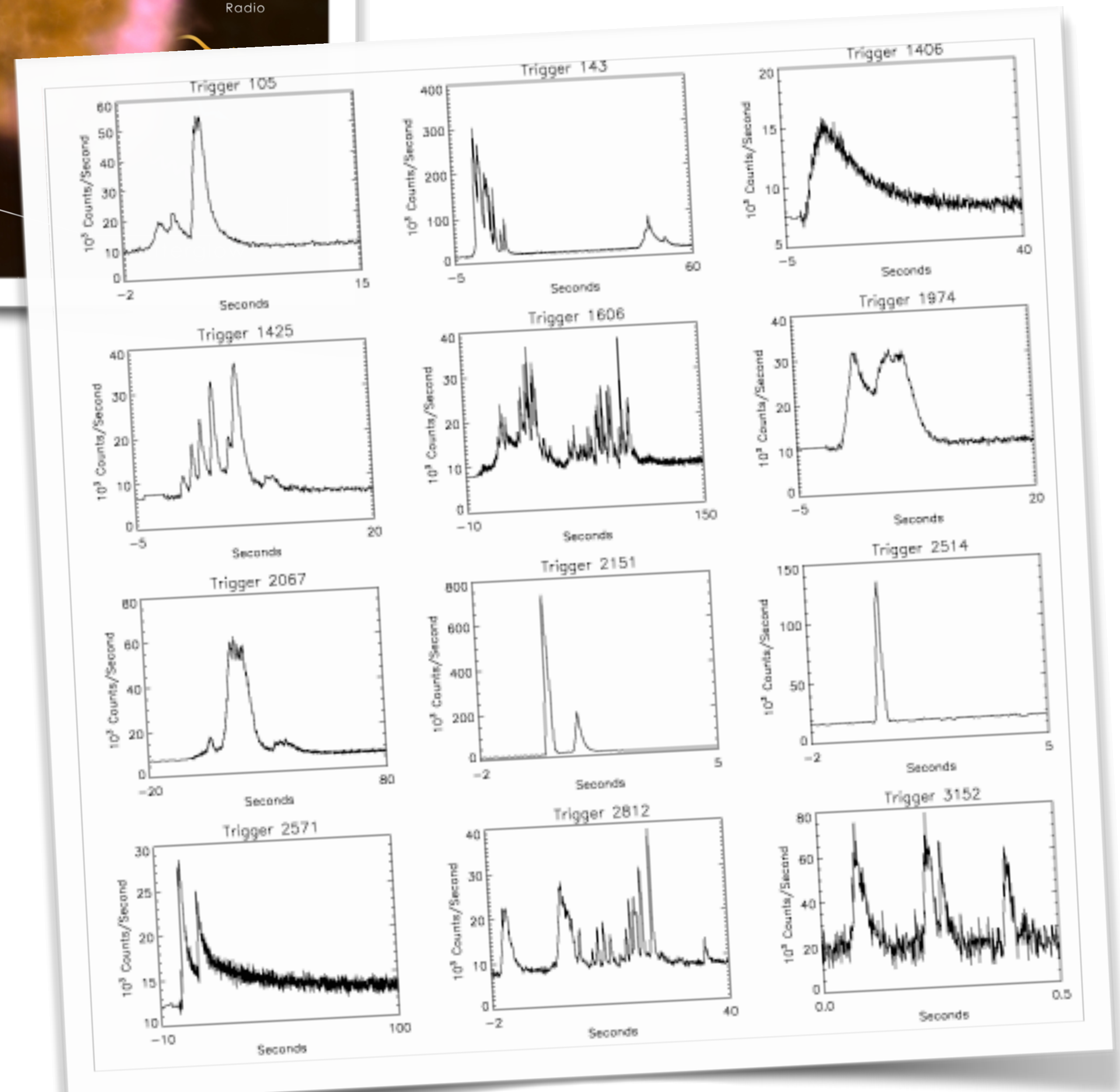
n=3

Caveat: delays can be intrinsic to the source

Amelino-Camelia et al. 1998
But see Chen et al. 2015

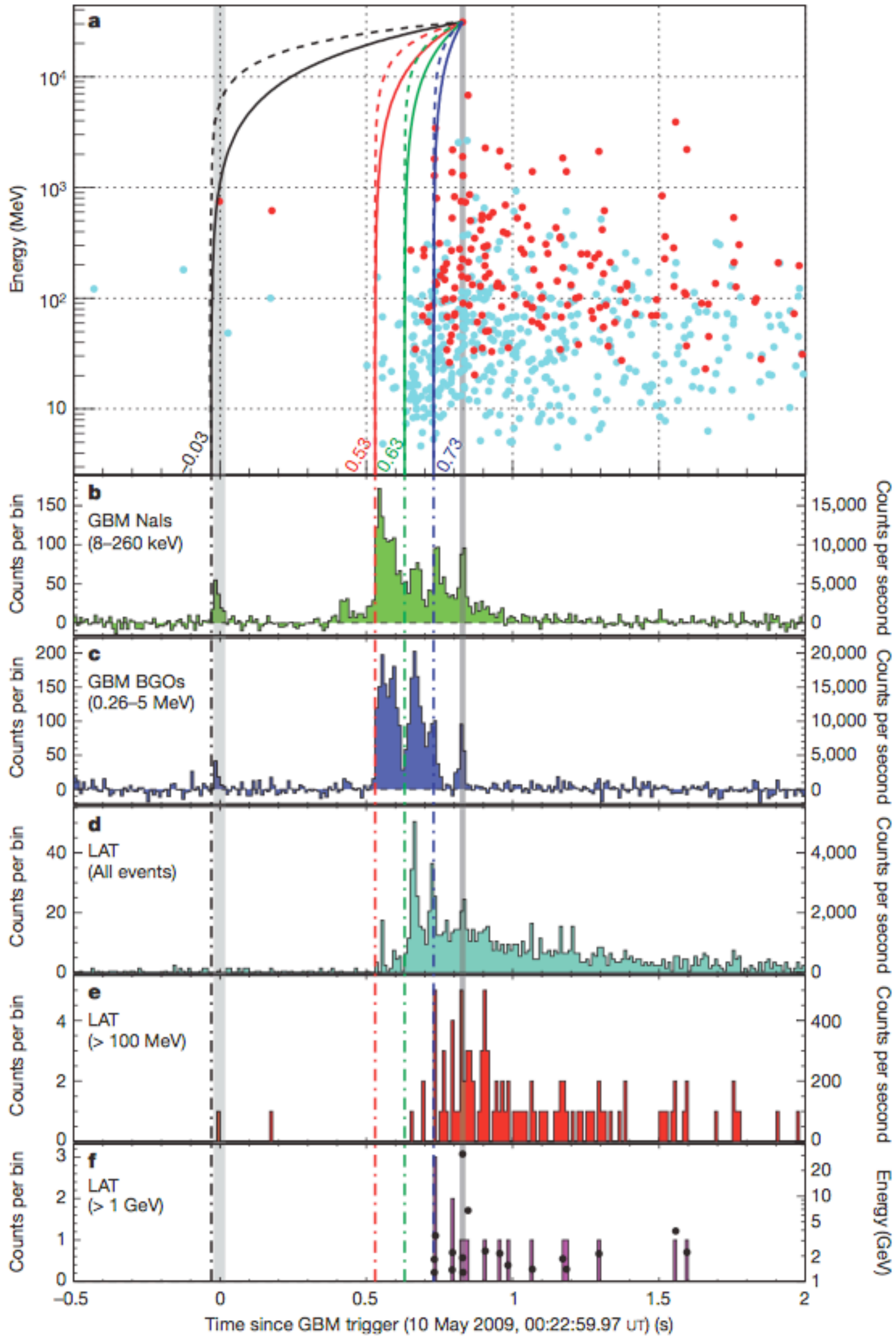
Cosmic clocks: GRBs





GRB 090510

Abdo et al. 2009



z=0.9

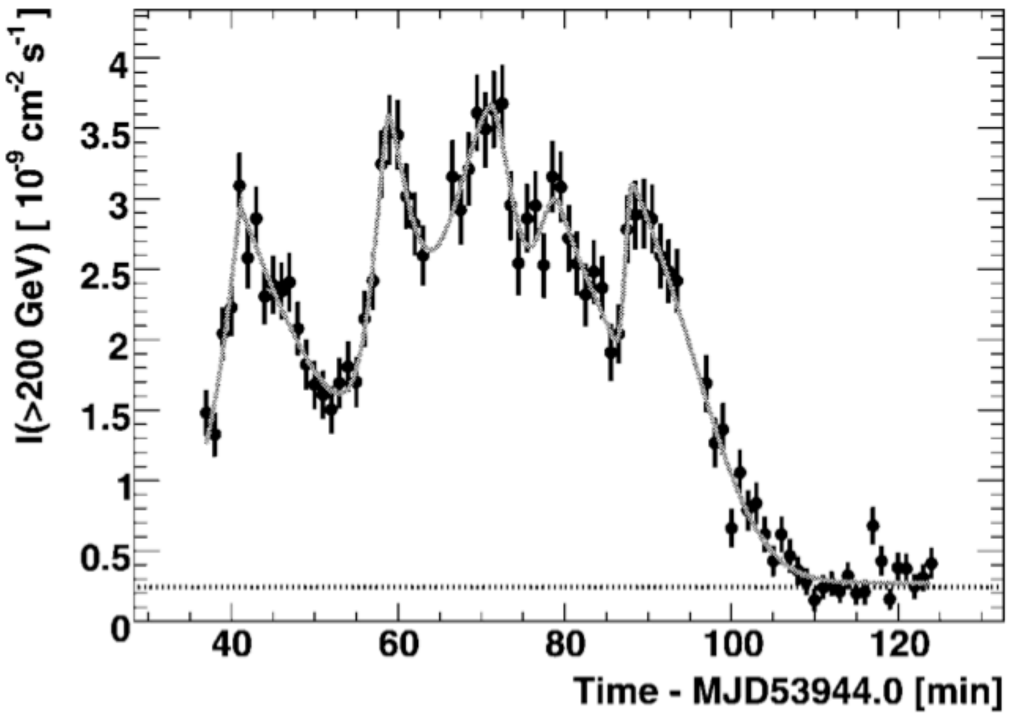
A photon with E=31 GeV after 0.829 s

$$E_{LIV} = 7.6 \times E_{\rm Pl}$$ n=3

Vasileiou et al. 2013

E-dependent time of flight

PKS 2155-304



Aharonian et al. 2007

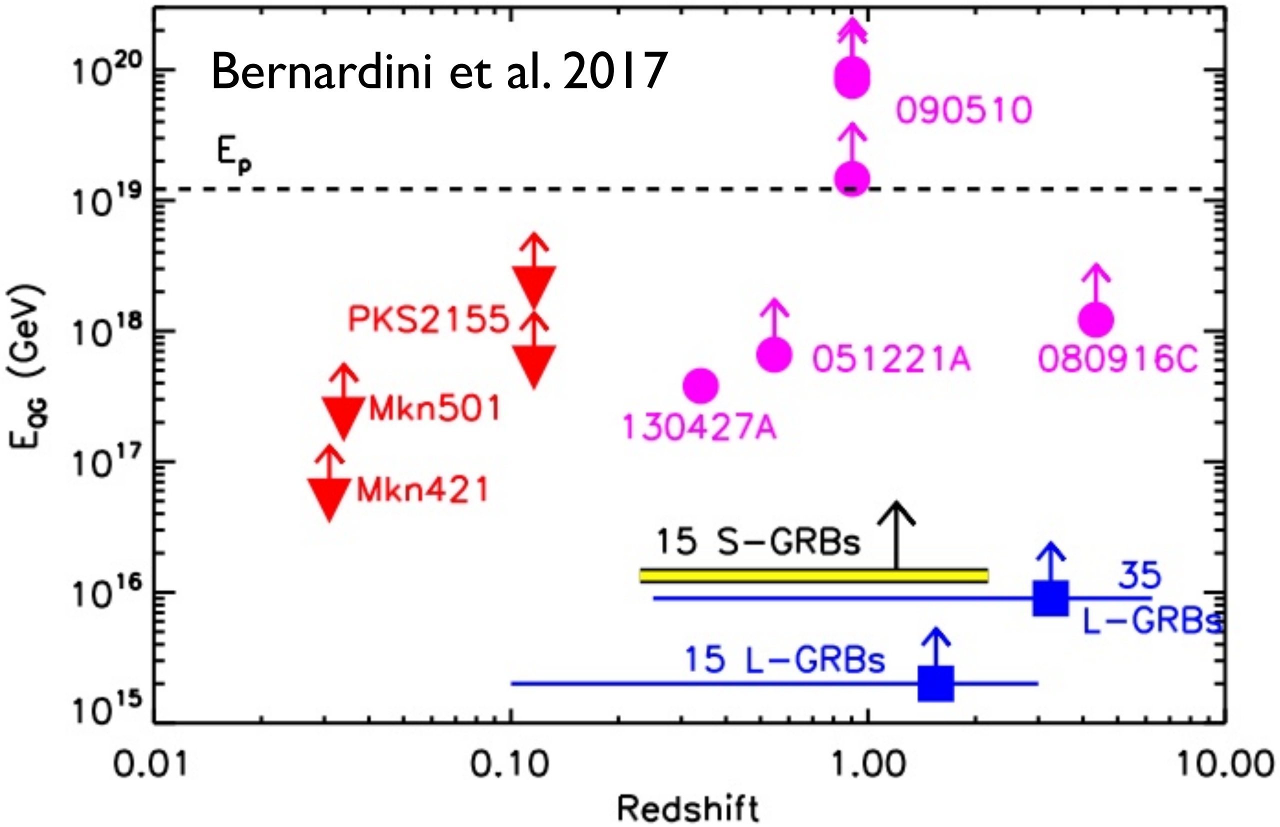
$$E_{LIV} = 0.17 \times E_{\rm Pl}$$ n=3

Abramowski et al. 2011

Long flare timescale (~300 s)!

E-dependent time of flight

Current status



Limitations:

-intrinsic delays (lower limits only)

-not predicted by some LIV schemes

(Some) LIV effects

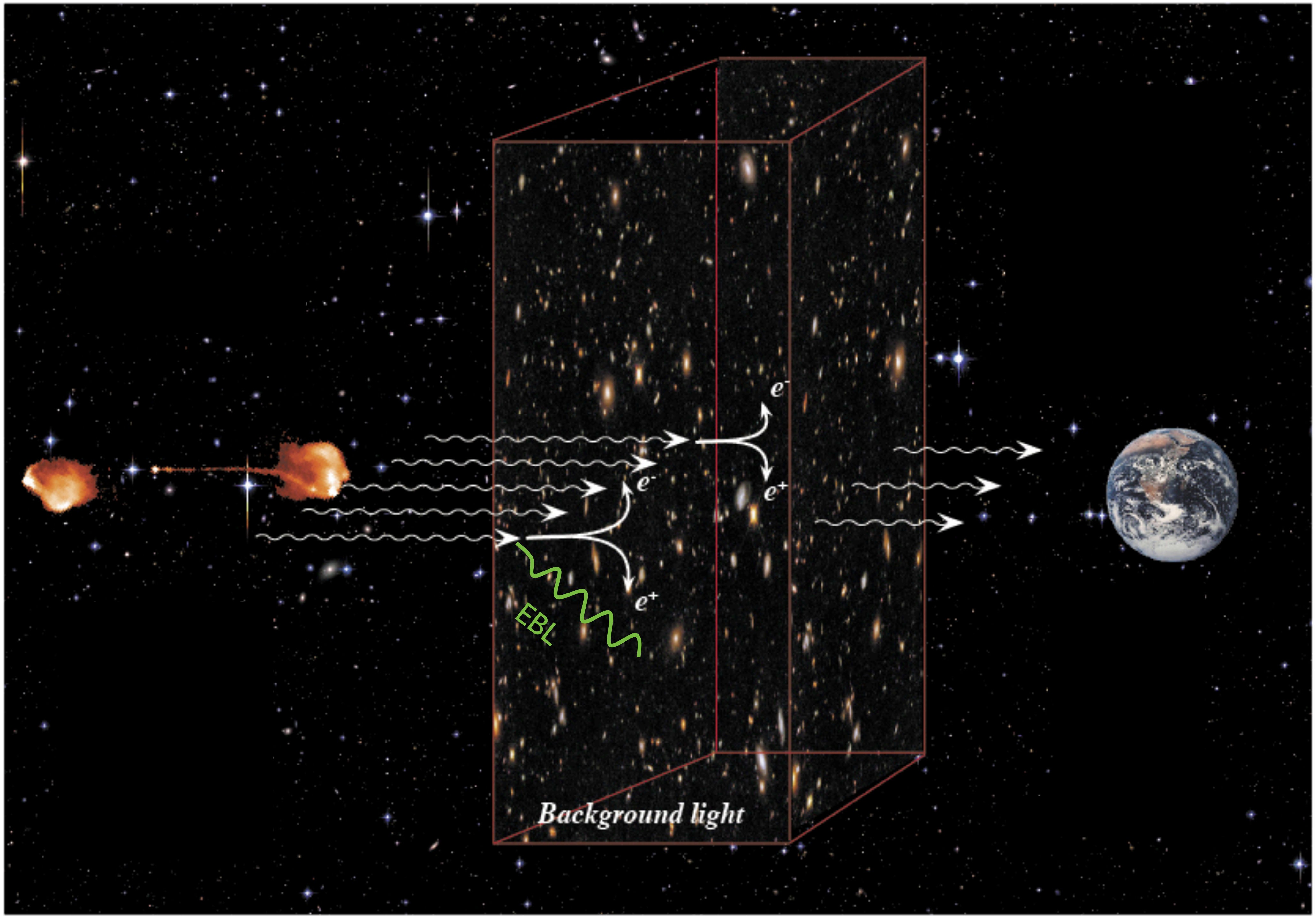
Vacuum birifrangence (depolarization, rotation)

Photon decay, vacuum Cherenkov (max. E for CR)

Energy-dependent photon time of flight

Modification of reaction thresholds (photons, CR)

Gamma-ray absorption



Anomalous transparency

LIV induces an 'effective mass' for the photon

$$E_\gamma^2 = k^2 \pm \underbrace{\frac{E_\gamma^n}{E_{LIV}^{n-2}}}_{m_\gamma^2}$$

Modification of threshold for pair production at high E

n=3
- sign

$$\epsilon_{\min} = \frac{m_e^2 c^4}{E_\gamma} + \frac{E_\gamma^2}{4E_{LIV}}$$

Kifune 1999
Protheroe & Meyer 2000
Jacob & Piran 2008
Fairbairn et al. 2014
Biteau & Williams 2015
Tavecchio & Bonnoli 2016
Abdalla & Boettcher 2018

Anomalous transparency

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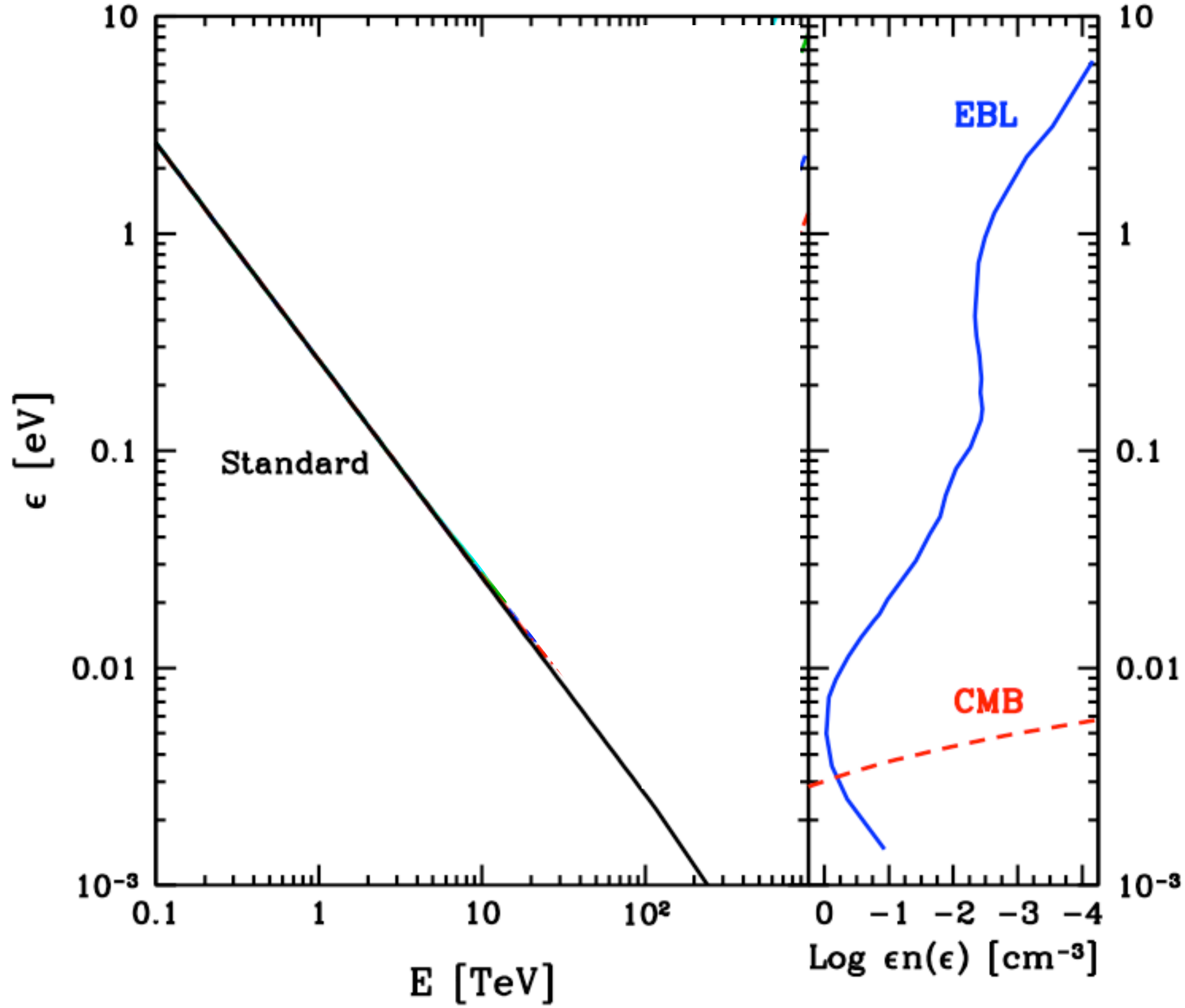

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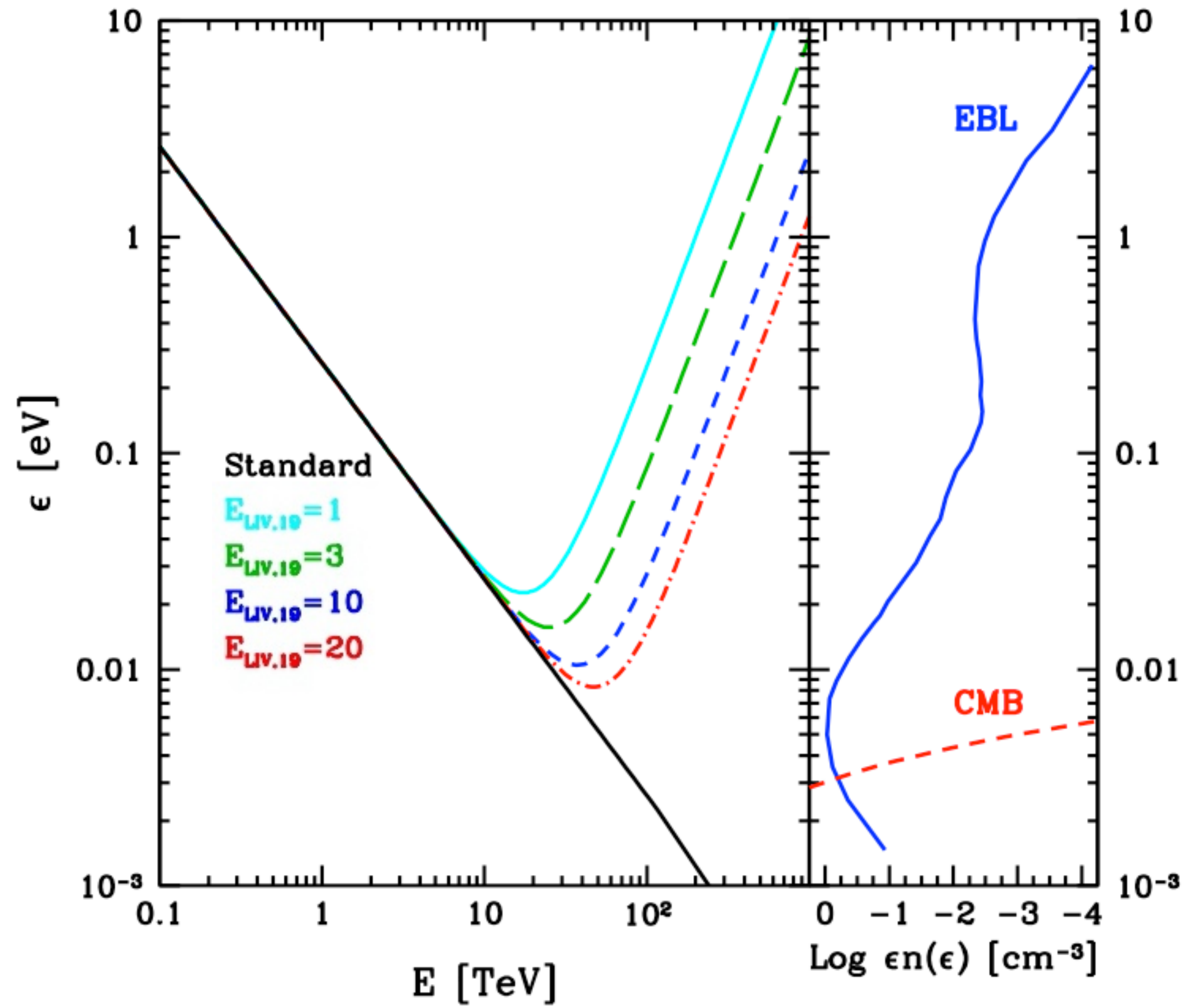
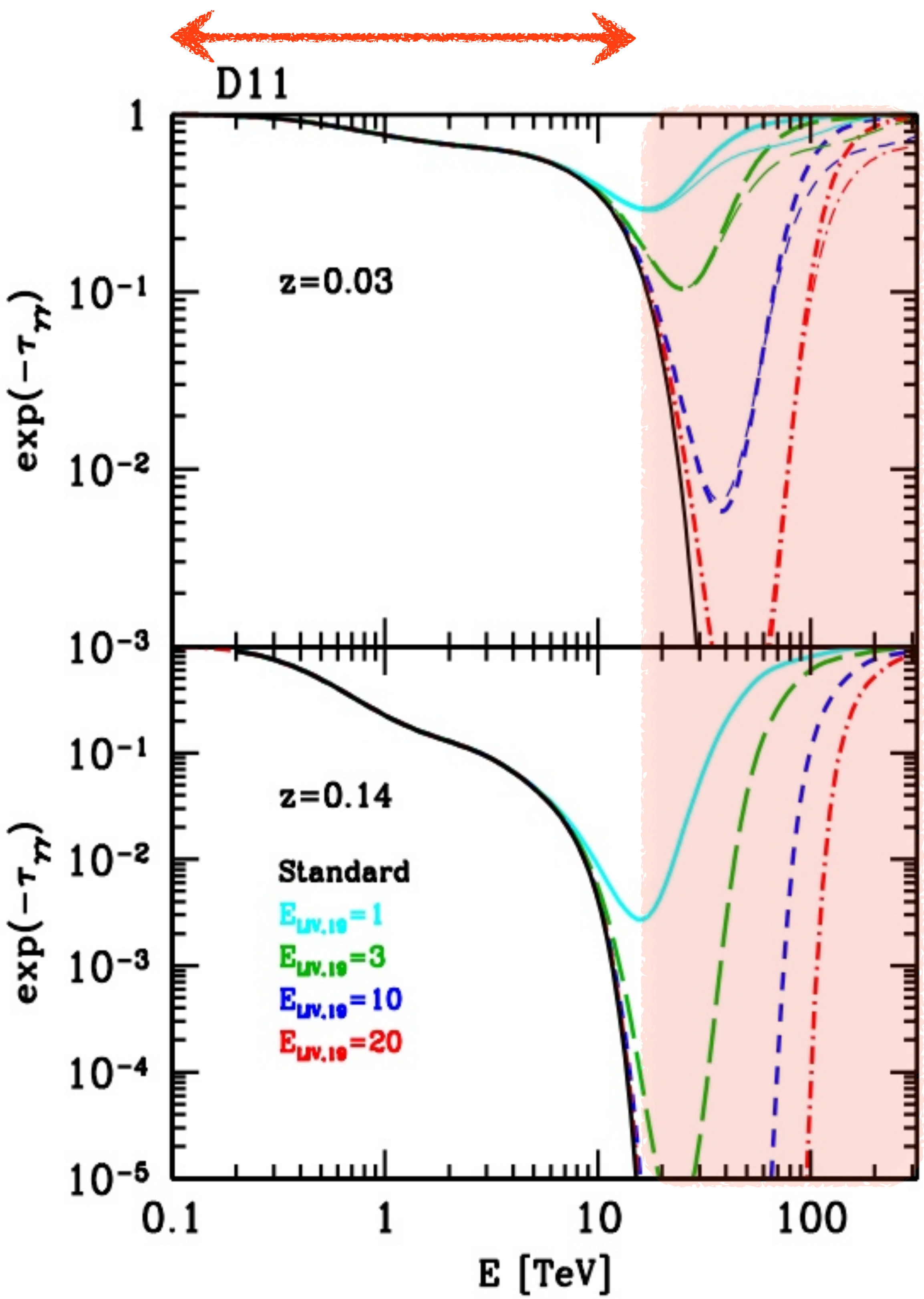


Kifune 1999
Protheroe & Meyer 2000
Jacob & Piran 2008
Fairbairn et al. 2014
Biteau & Williams 2015
Tavecchio & Bonnoli 2016
Abdalla & Boettcher 2018

LIV induces suppression of EBL-opacity

Anomalous transparency

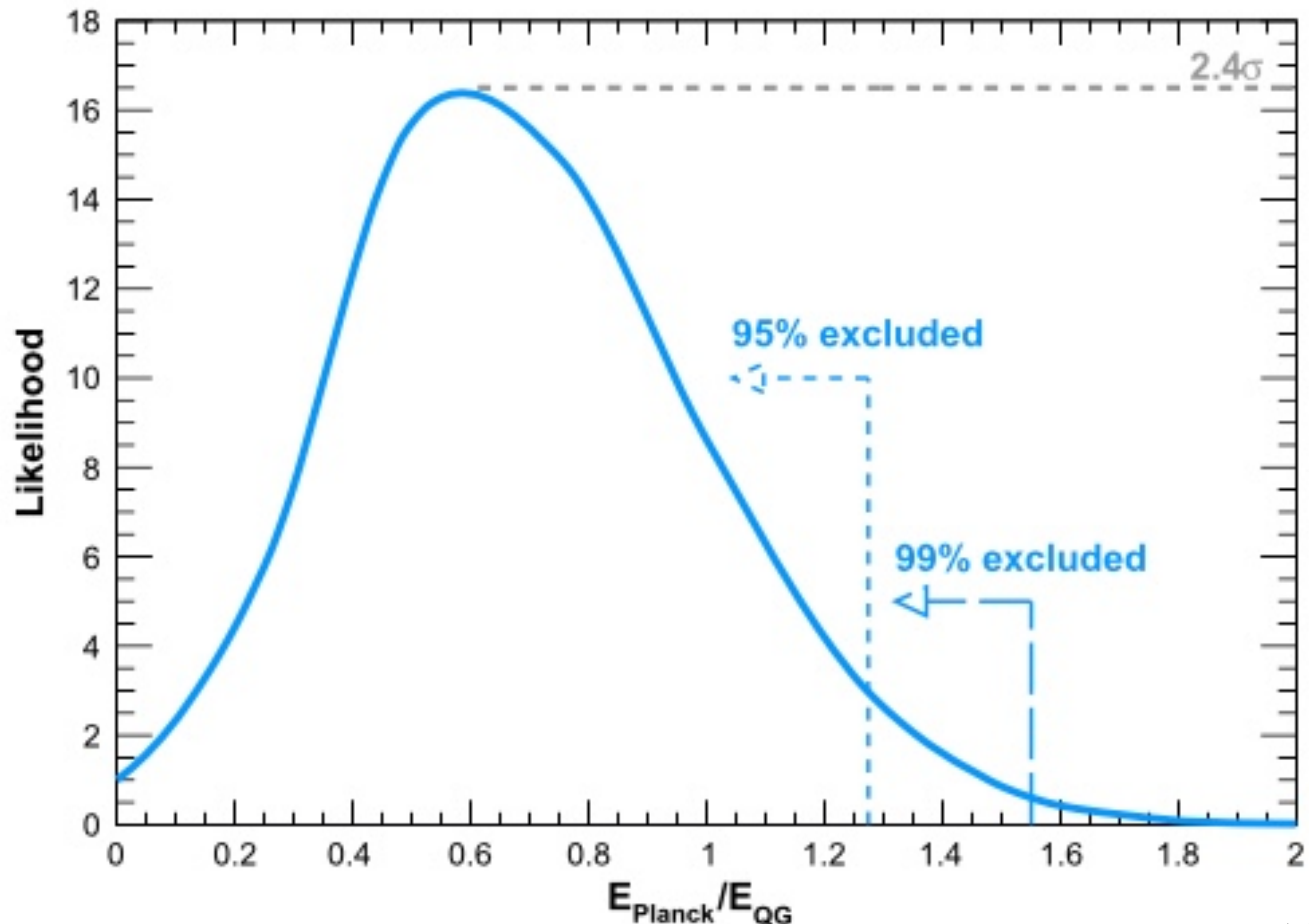


Tavecchio & Bonnoli 2016

Anomalous transparency

Biteau & Williams 2015

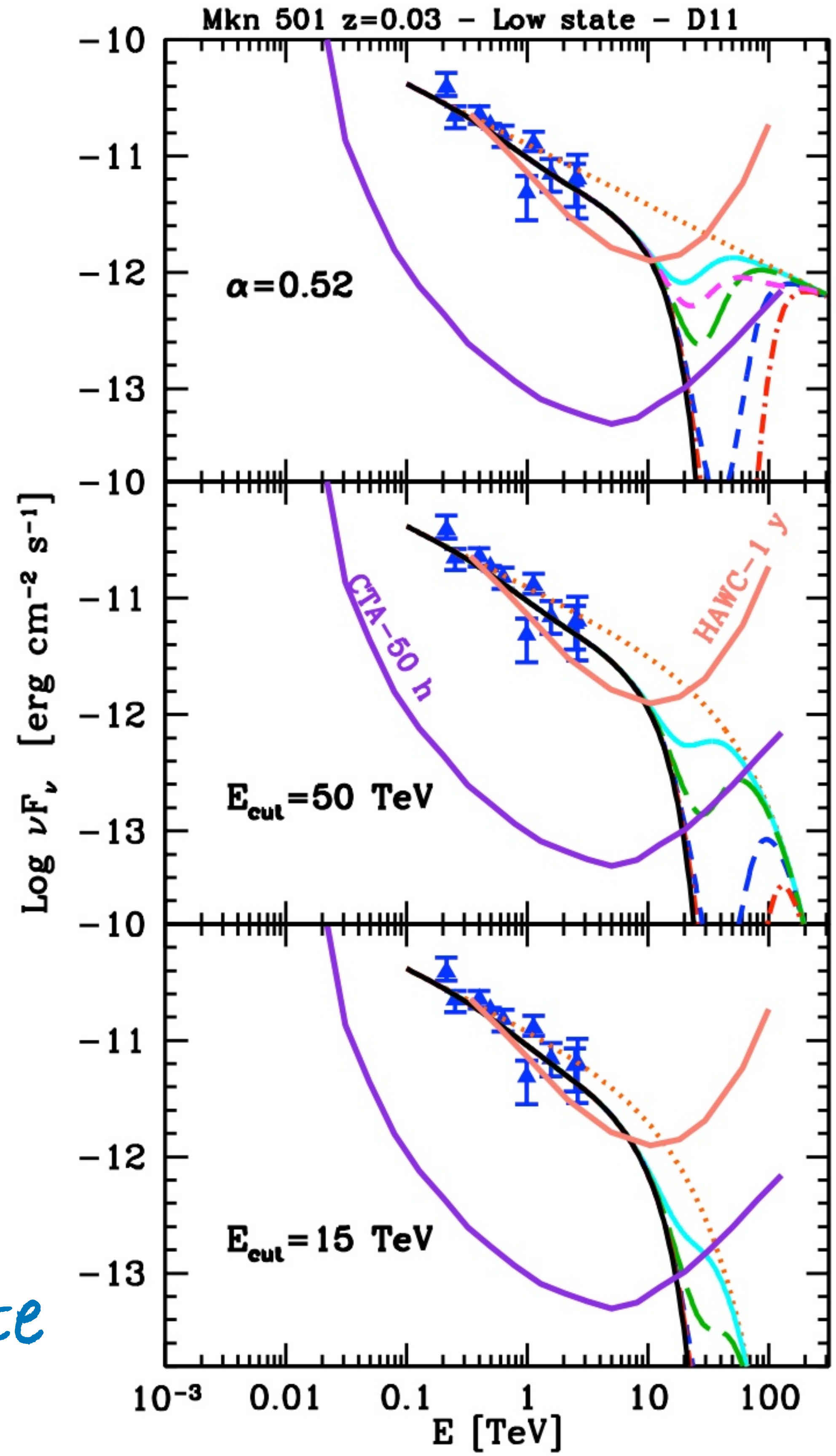
Current limits



Combined, multi-source analysis

$$E_{LIV} \approx 2 \times 10^{19} \text{ GeV}$$

Anomalous transparency



Current limits

E_{LIV}=1e19 GeV
3e19
1e20
2e20

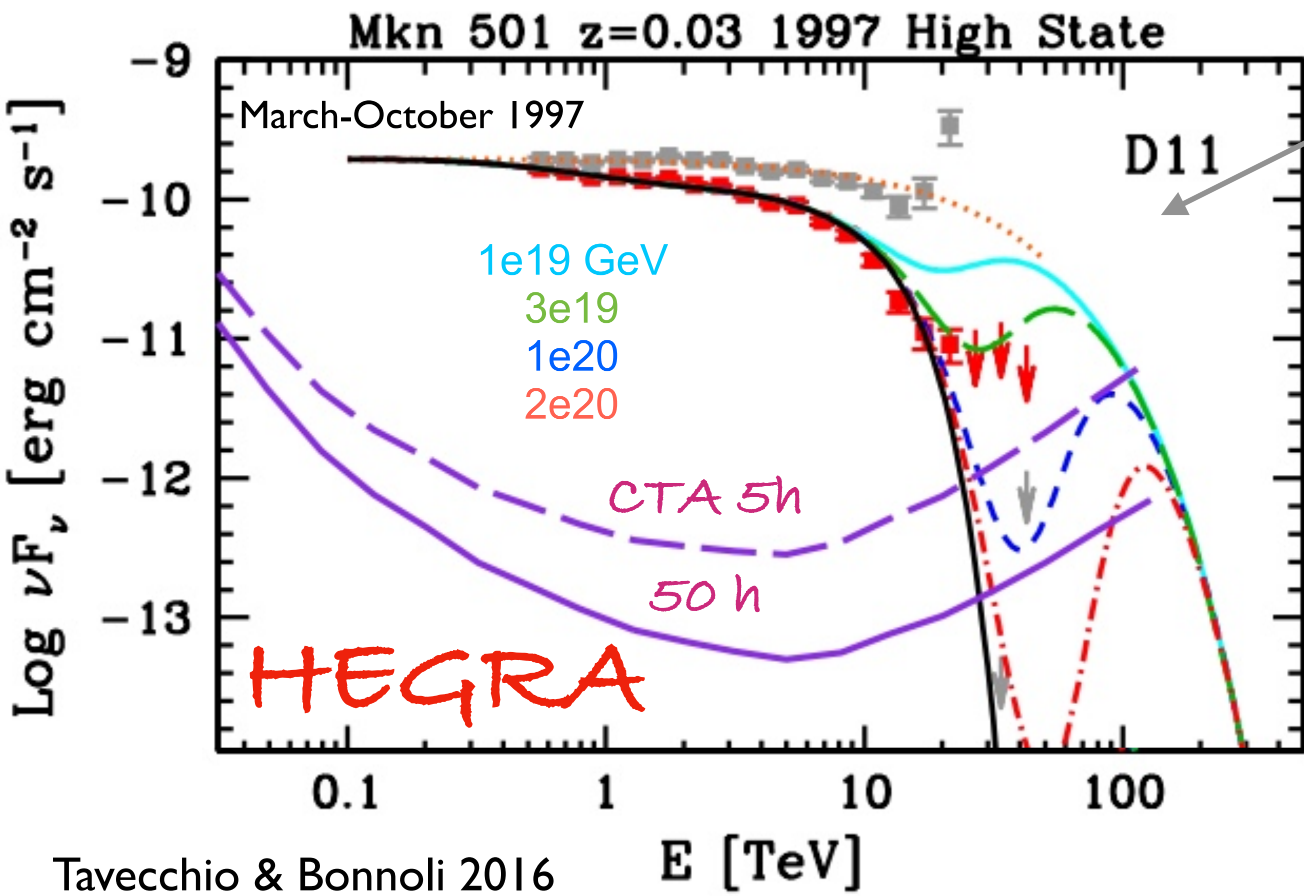
Difficult even for CTA!

Mkn 501
Quiescent state

Tavecchio & Bonnoli 2016

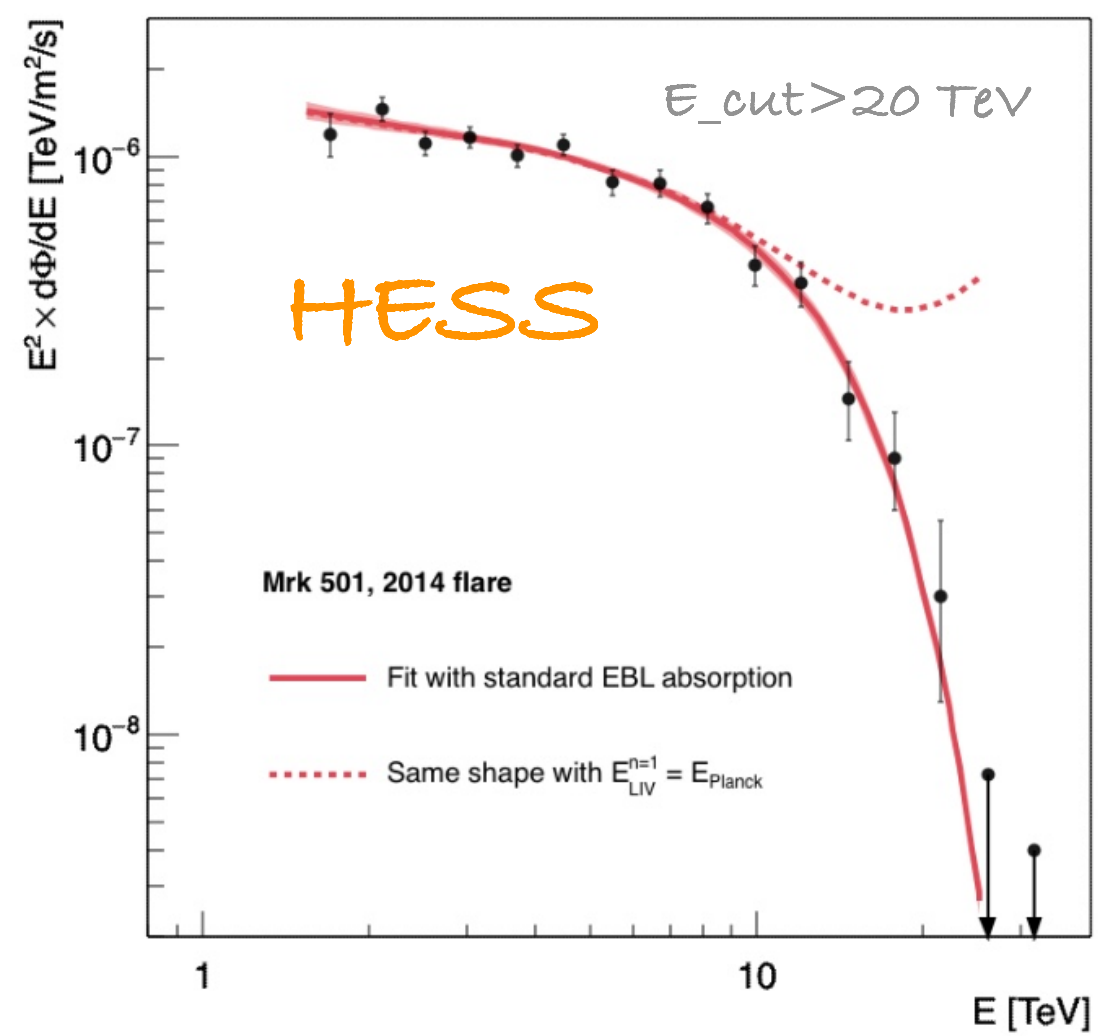
Anomalous transparency

Inferred intrinsic spectrum assuming smooth exponential cut-off, E_cut~20 TeV



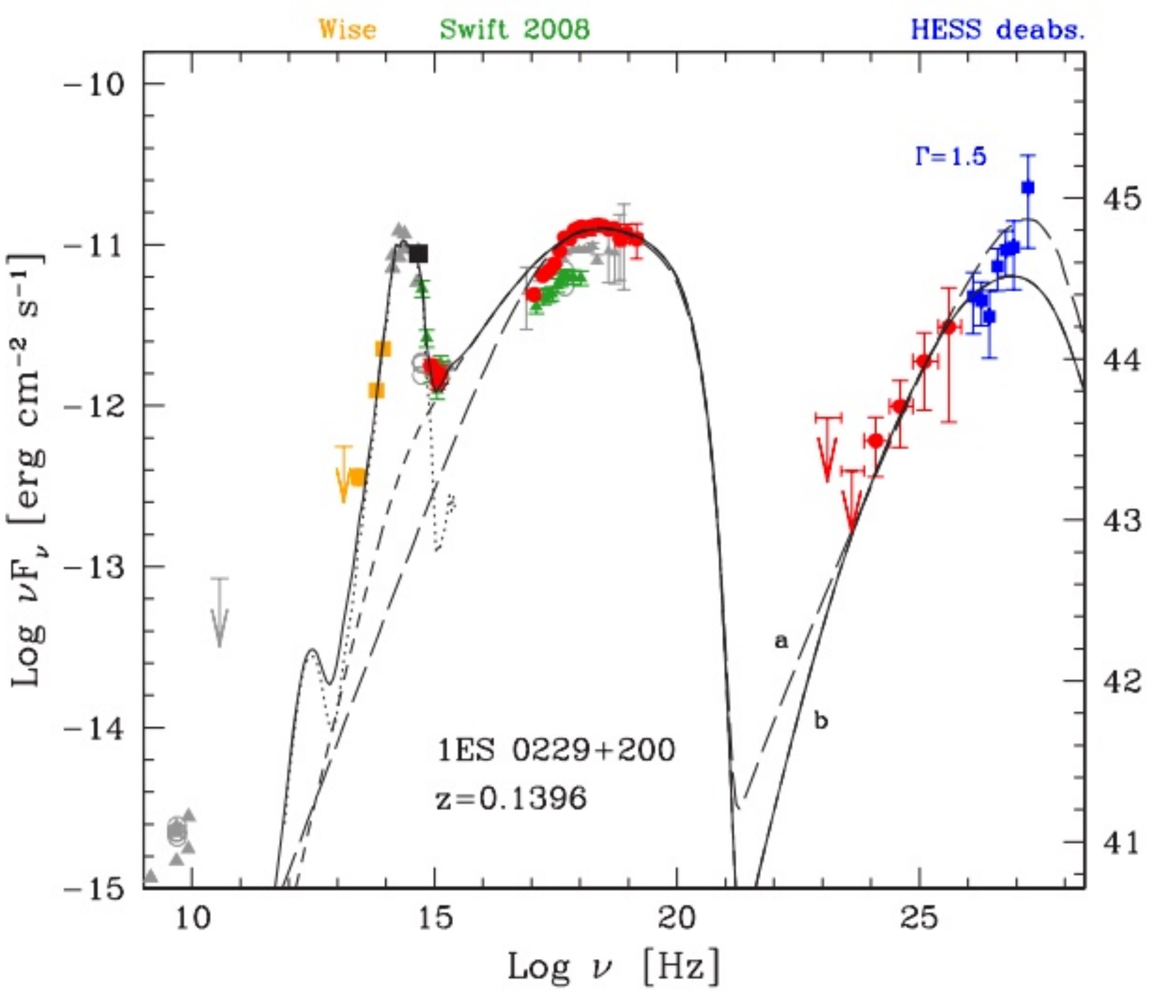
Tavecchio & Bonnoli 2016

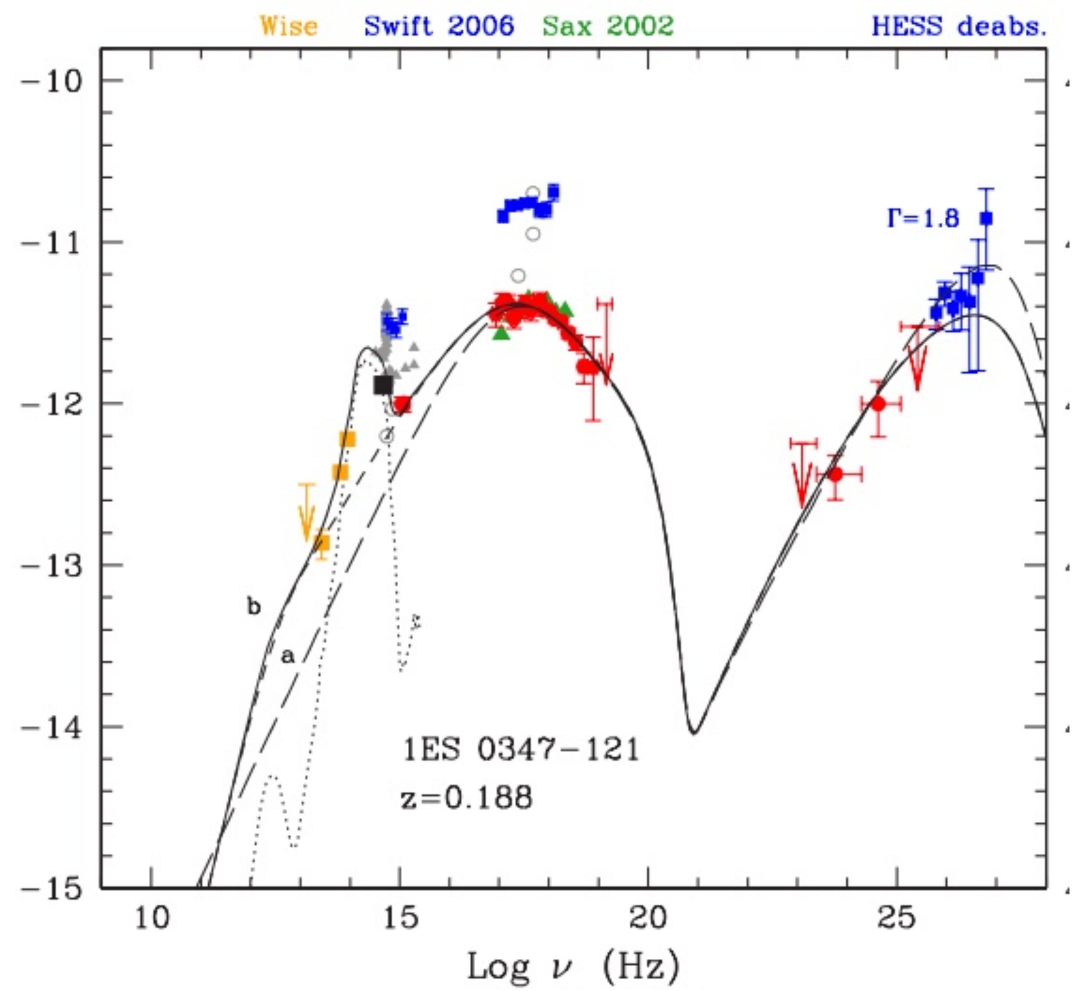
Lorentz & Brun 2017
Abdalla et al. 2019



Rare (?) extreme flaring states

Persistent extreme BL Lacs

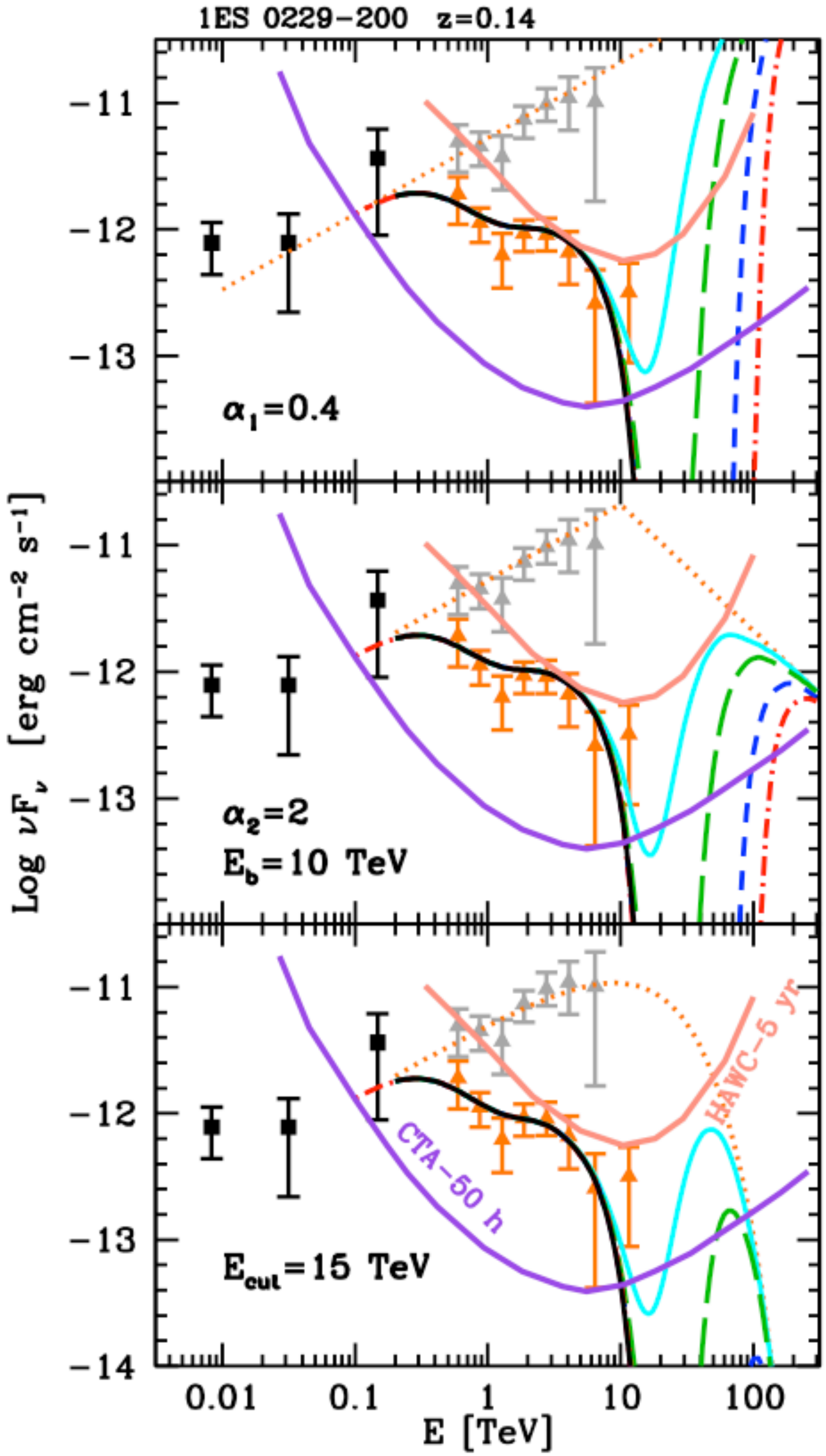




Costamante et al. 2018

$$E_{\text{peak}} \lesssim 10 \text{ TeV}$$

Similar to hadronic models
(e.g. Cerruti et al. 2015)



ELIV=1e19 GeV
3e19
1e20
2e20

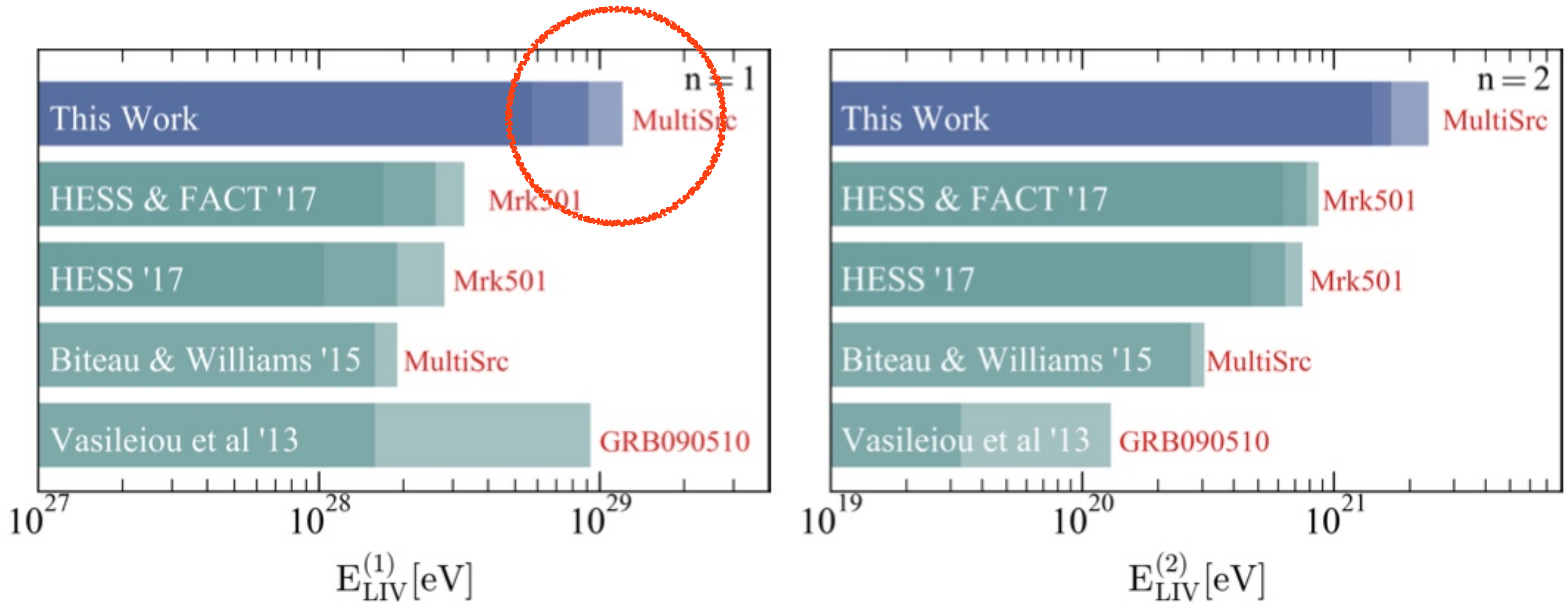
Feasible with CTA!

Tavecchio & Bonnoli 2016

Anomalous transparency

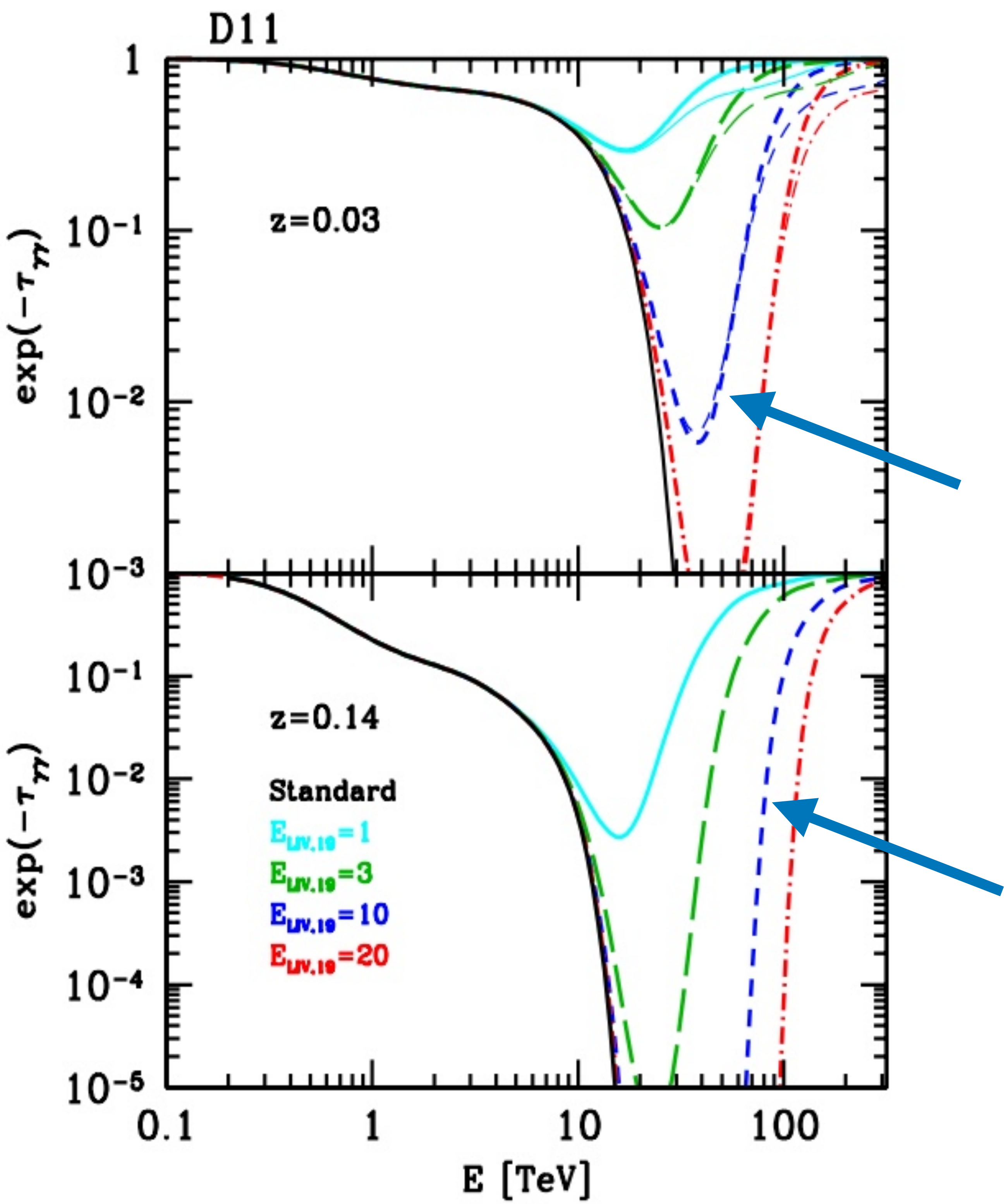
A new, strong limit

Guedes Lang et al. 2018



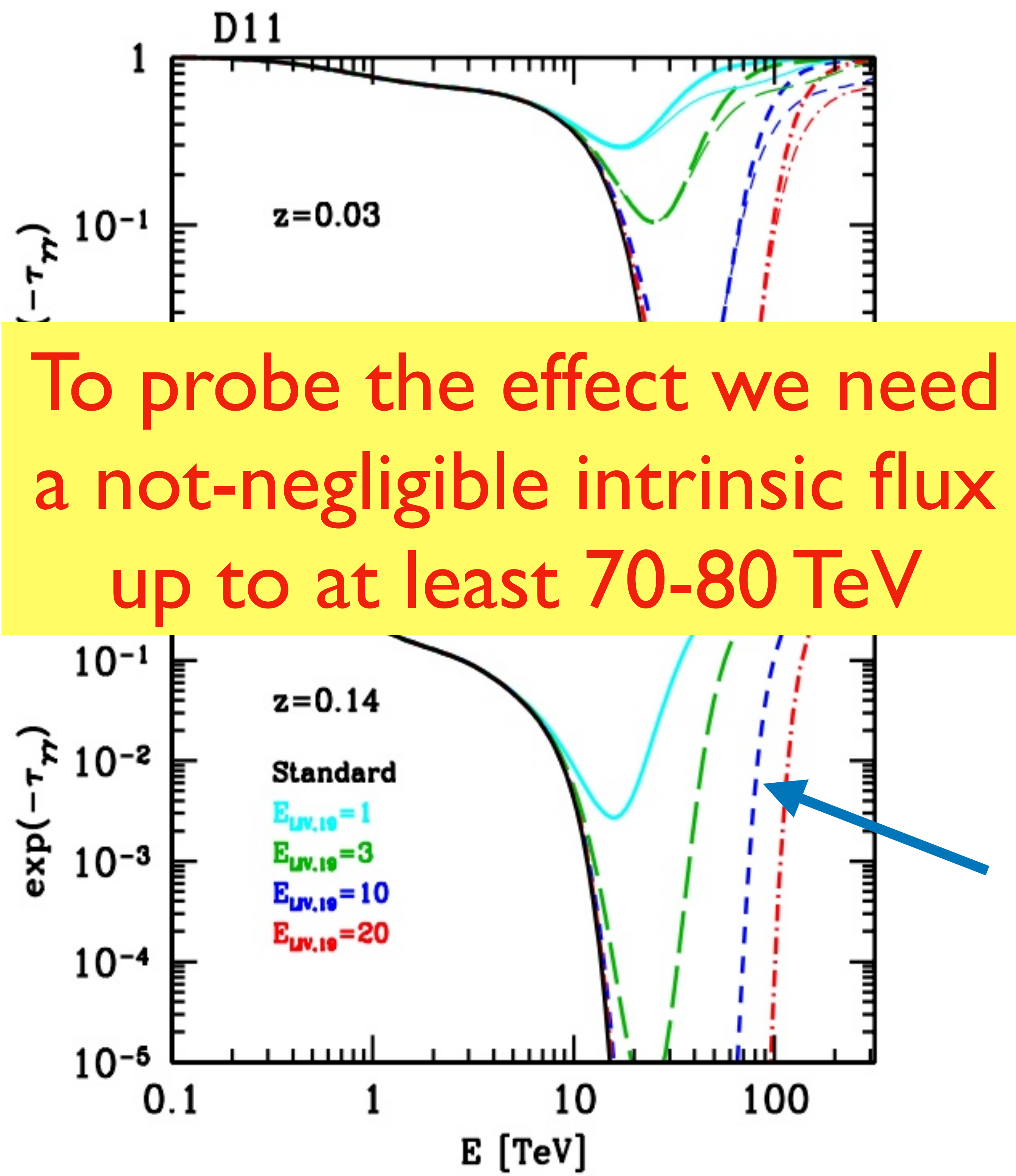
Combined, multi-source analysis

Anomalous transparency

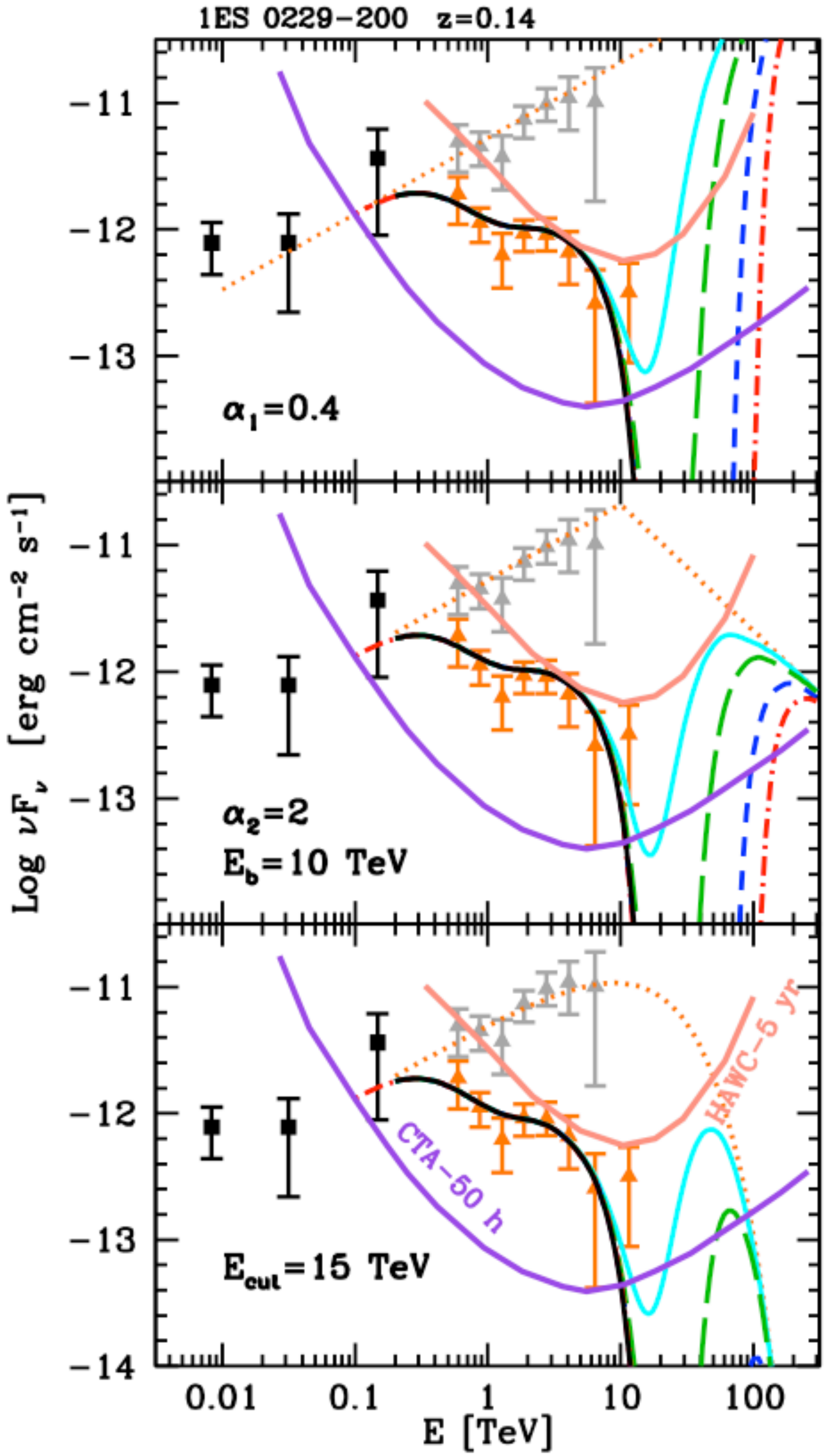


Tavecchio & Bonnoli 2016

Anomalous transparency



Tavecchio & Bonnoli 2016

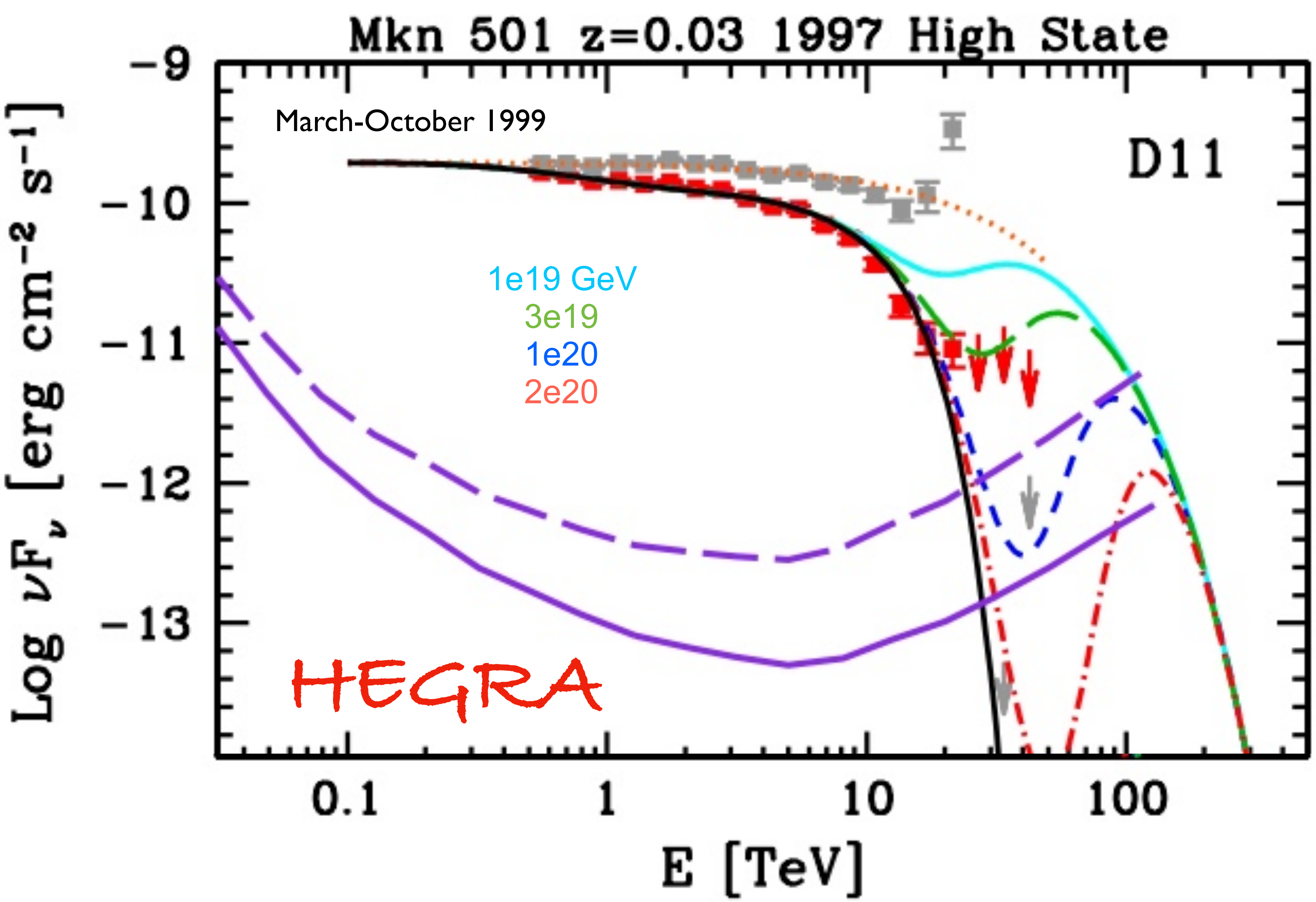


ELIV=1e19 GeV
3e19
1e20
2e20

Difficult!!

Tavecchio & Bonnoli 2016

Mkn 501: a better source?



Tavecchio & Bonnoli 2016
Tavecchio et al. in preparation

Some (a bit pessimistic) conclusions

Test of LIV challenging for persistent extreme HBL

Extreme (rare?) states of Mkn 501 much more promising

Exciting topic for CTA


THANK YOU!

Table 1
A selection of limits obtained with various instruments and methods for GRBs AGNs, and the Crab pulsar. Limits obtained for linear $\left(E^{l}_{\mathrm{QG}}\right)$ and quadratic $\left(E^{q}_{\mathrm{QG}}\right)$ corrections are given.

Source(s)	Experiment	Method	Results[a]	Reference	Note
GRB 021206	RHESSI	Fit + mean arrival time in a spike	$E^{l}_{\mathrm{QG}} > 1.8 \times 10^{17}$ GeV	Boggs et al. (2004)	b,c
GRB 080916C	Fermi GBM + LAT	Associating a 13 GeV photon with the trigger time	$E^{l}_{\mathrm{QG}} > 1.3 \times 10^{18}$ GeV $E^{q}_{\mathrm{QG}} > 0.8 \times 10^{10}$ GeV	Abdo et al. (2009a)	
GRB 090510	Fermi GBM + LAT	Associating a 31 GeV photon with the start of any observed emission	$E^{l}_{\mathrm{QG}} > 1.5 \times 10^{19}$ GeV $E^{q}_{\mathrm{QG}} > 3.0 \times 10^{10}$ GeV	Abdo et al. (2009b)	d
9 GRBs	BATSE + OSSE	Wavelets	$E^{l}_{\mathrm{QG}} > 0.7 \times 10^{16}$ GeV $E^{q}_{\mathrm{QG}} > 2.9 \times 10^{6}$ GeV	Ellis et al. (2003)	b
15 GRBs	HETE-2	Wavelets	$E^{l}_{\mathrm{QG}} > 0.4 \times 10^{16}$ GeV	Bolmont et al. (2008)	e
17 GRBs	INTEGRAL	Likelihood	$E^{l}_{\mathrm{QG}} > 3.2 \times 10^{11}$ GeV	Lamon et al. (2008)	f
35 GRBs	BATSE + HETE-2 + Swift	Wavelets	$E^{l}_{\mathrm{QG}} > 1.4 \times 10^{16}$ GeV	Ellis et al. (2006), Ellis et al. (2008)	g,h
Mrk 421	Whipple	Likelihood	$E^{l}_{\mathrm{QG}} > 0.4 \times 10^{17}$ GeV	Biller et al. (1999)	b,i
Mrk 501	MAGIC	ECF	$E^{l}_{\mathrm{QG}} > 0.2 \times 10^{18}$ GeV $E^{q}_{\mathrm{QG}} > 2.6 \times 10^{10}$ GeV	Albert et al. (2008)	
		Likelihood	$E^{l}_{\mathrm{QG}} > 0.3 \times 10^{18}$ GeV $E^{q}_{\mathrm{QG}} > 5.7 \times 10^{10}$ GeV	Martinez and Errando (2009)	
PKS 2155-304	H.E.S.S.	MCCF	$E^{l}_{\mathrm{QG}} > 7.2 \times 10^{17}$ GeV $E^{q}_{\mathrm{QG}} > 0.1 \times 10^{10}$ GeV	Aharonian et al. (2008)	
		Wavelets	$E^{l}_{\mathrm{QG}} > 5.2 \times 10^{17}$ GeV		
		Likelihood	$E^{l}_{\mathrm{QG}} > 2.1 \times 10^{18}$ GeV $E^{q}_{\mathrm{QG}} > 6.4 \times 10^{10}$ GeV	Abramowski et al. (submitted for publication)	
Crab pulsar	EGRET	Shift of pulsation maxima in different energy bands	$E^{l}_{\mathrm{QG}} > 0.2 \times 10^{16}$ GeV	Kaaret (1999)	

Bolmont & Jacholkowska 2010