Extreme HBLs as probes for fundamental physics and cosmology

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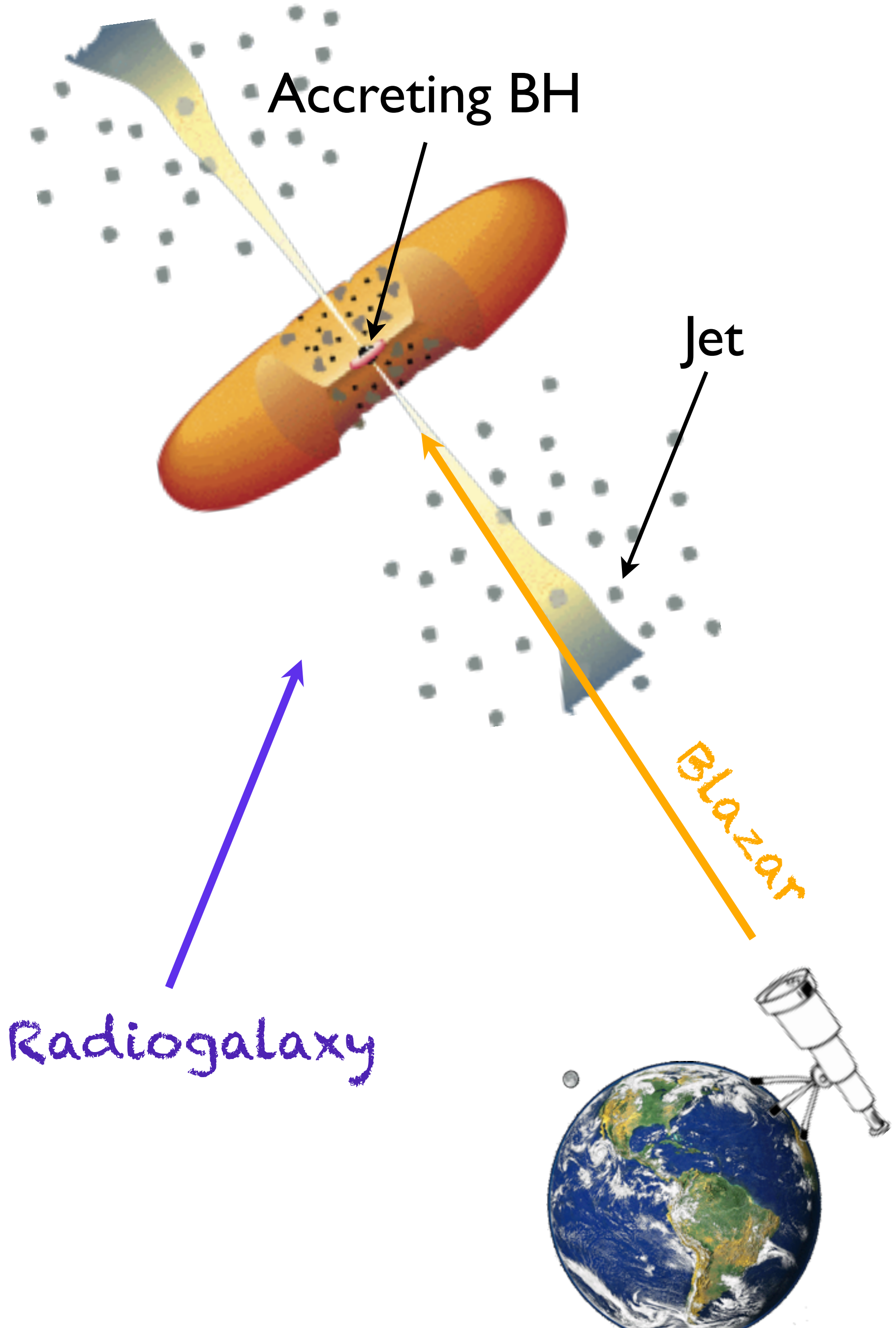
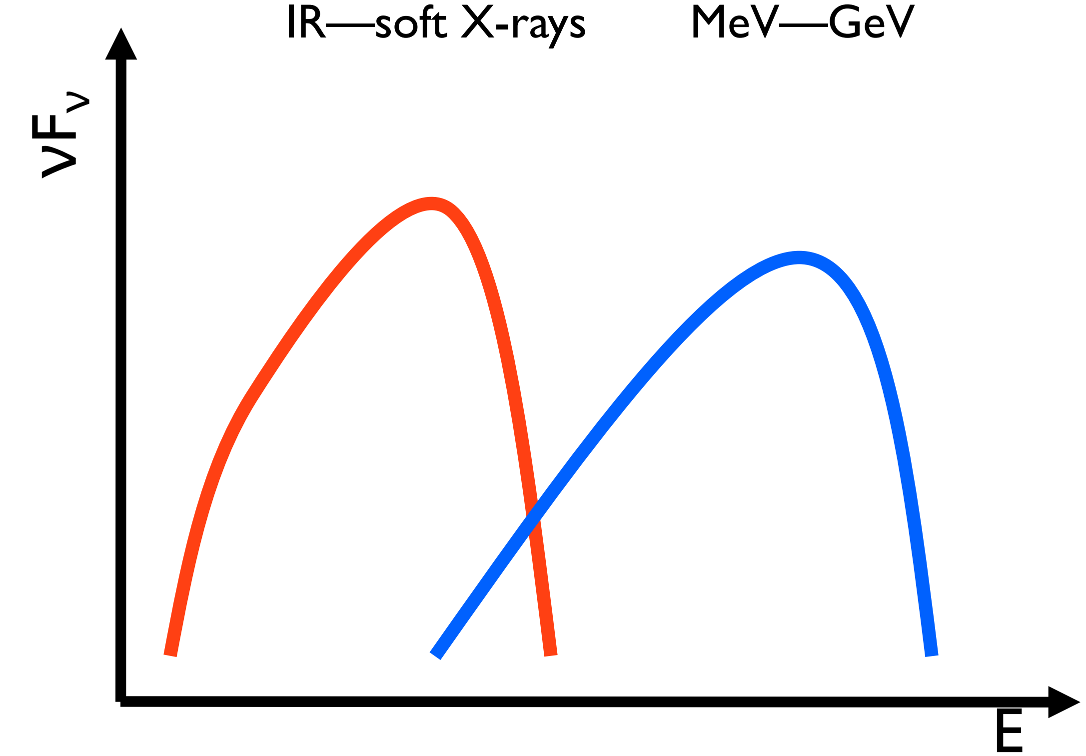
with F. Tavecchio, G. Ghisellini

Jets pointing at us: BLAZARS





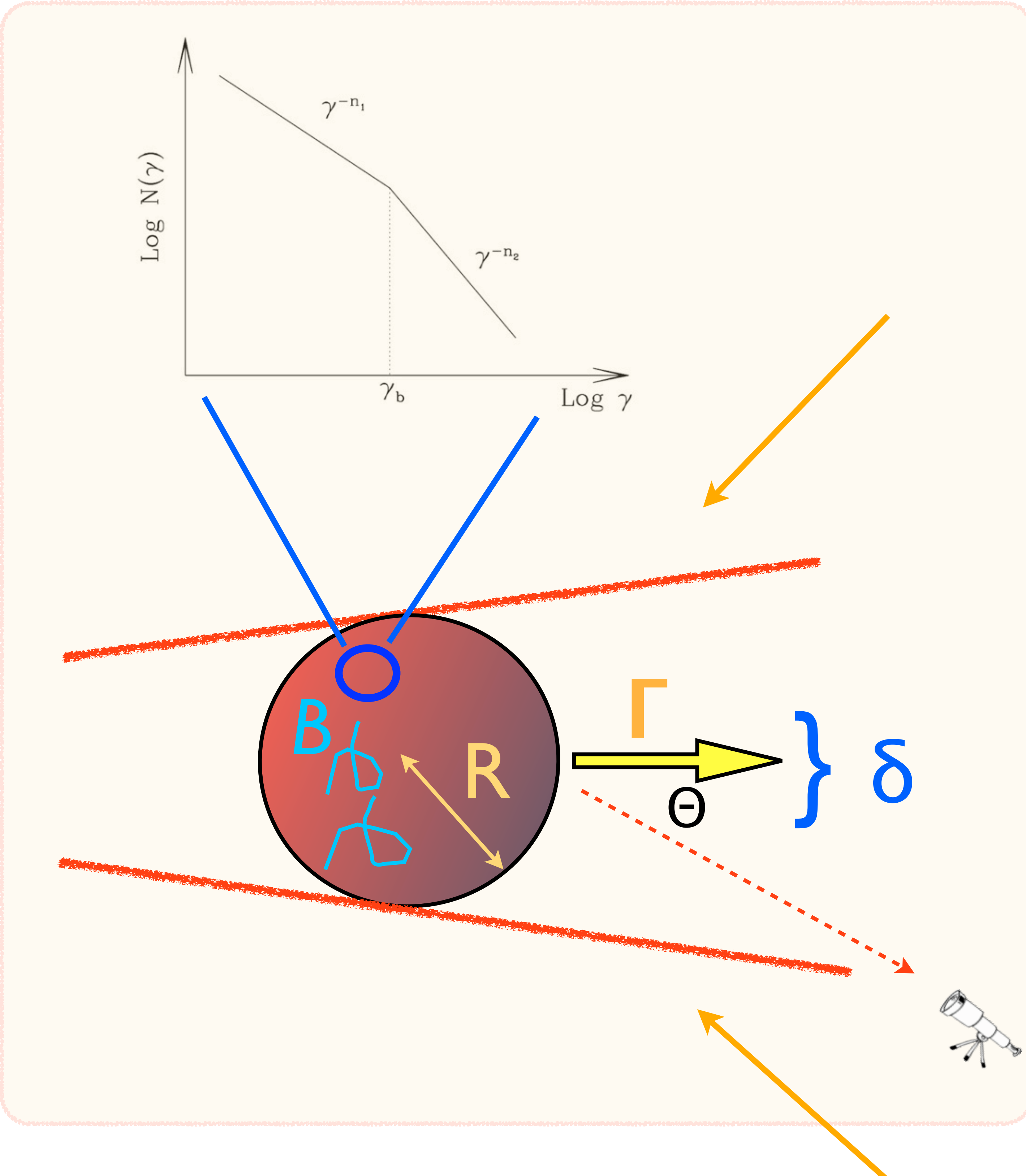
SED dominated by the relativistically boosted non-thermal continuum emission of the jet.

$$L_{\rm obs} = L'\delta^4 \qquad \delta = \frac{1}{\Gamma(1-\beta\cos\theta_{\rm v})}$$

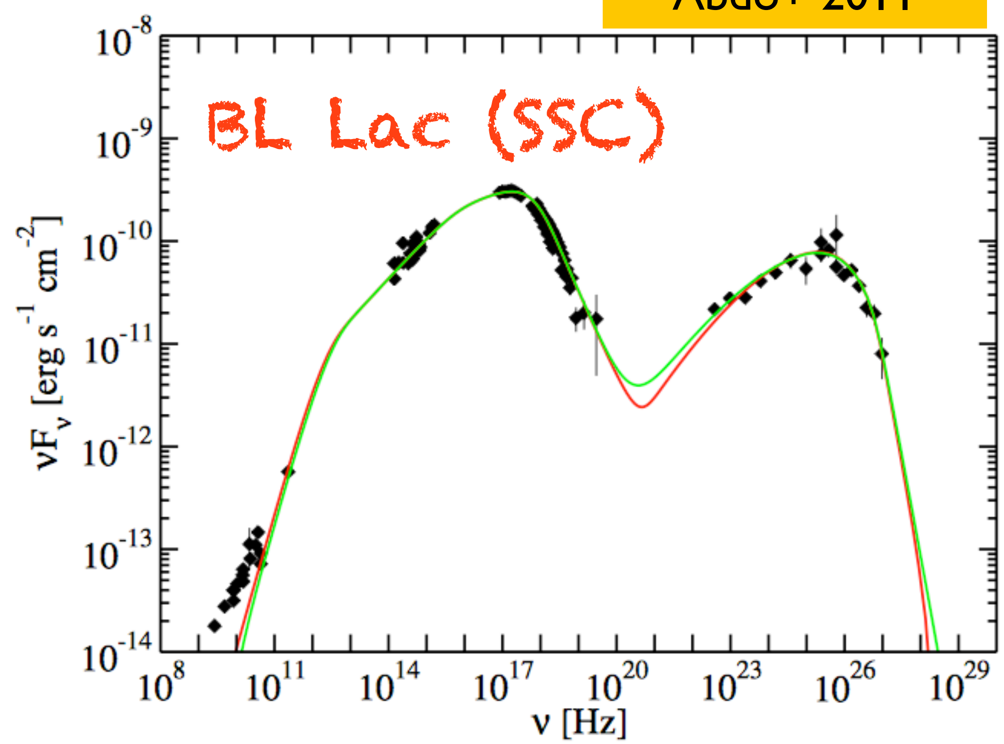
Synchrotron and IC in leptonic models.

Also hadronic scenarios
(synchrotron or photo-meson emission)

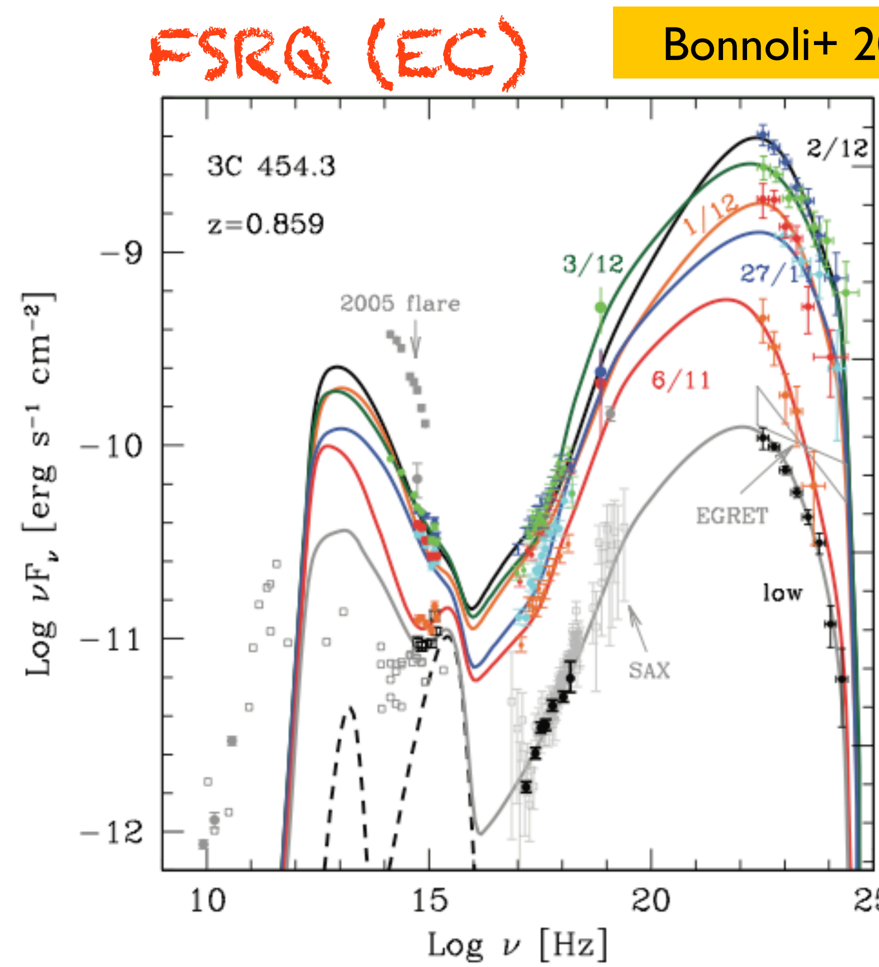
Emission models: one-zone



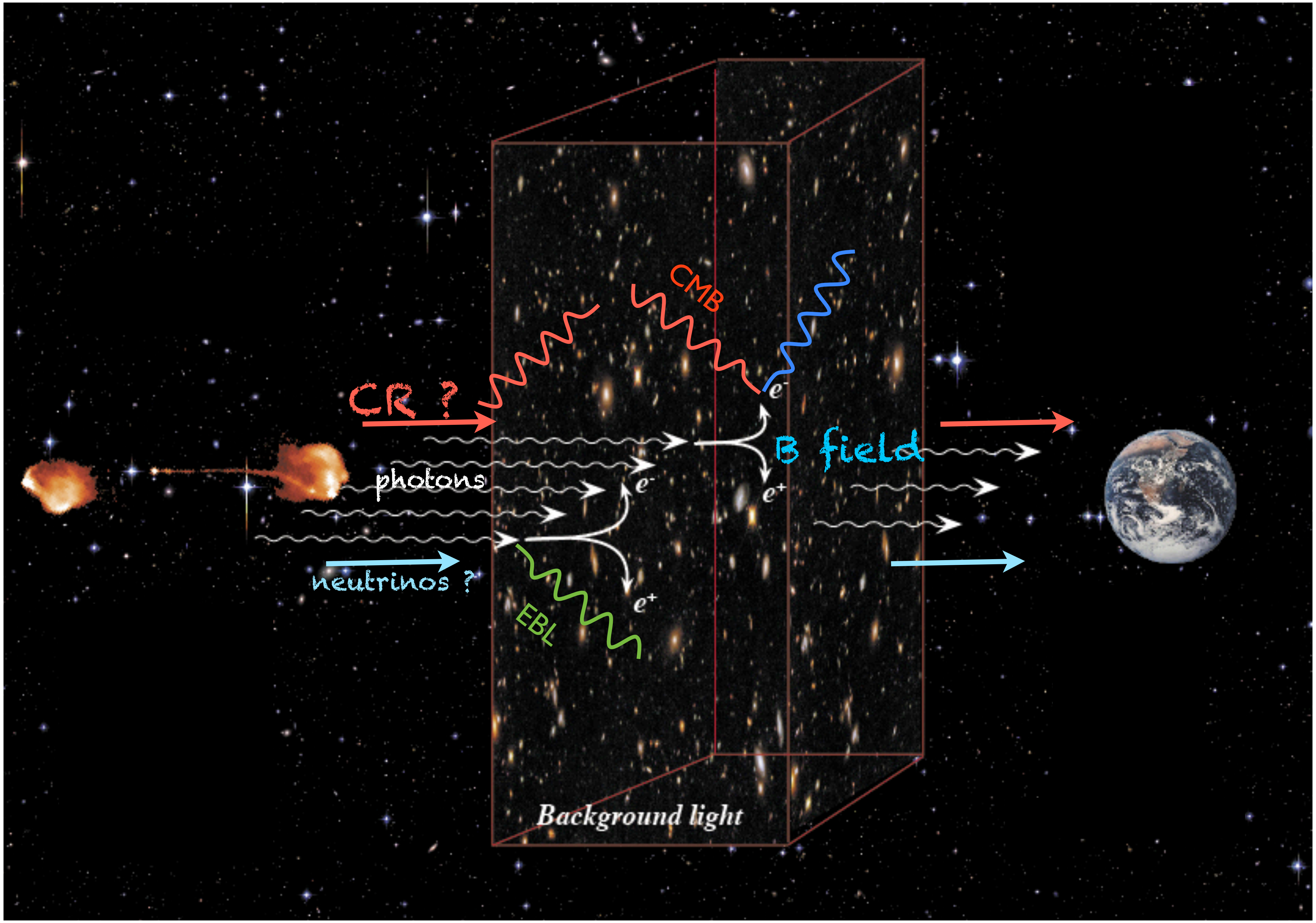
Abdo+ 2011



Bonnoli+ 2011



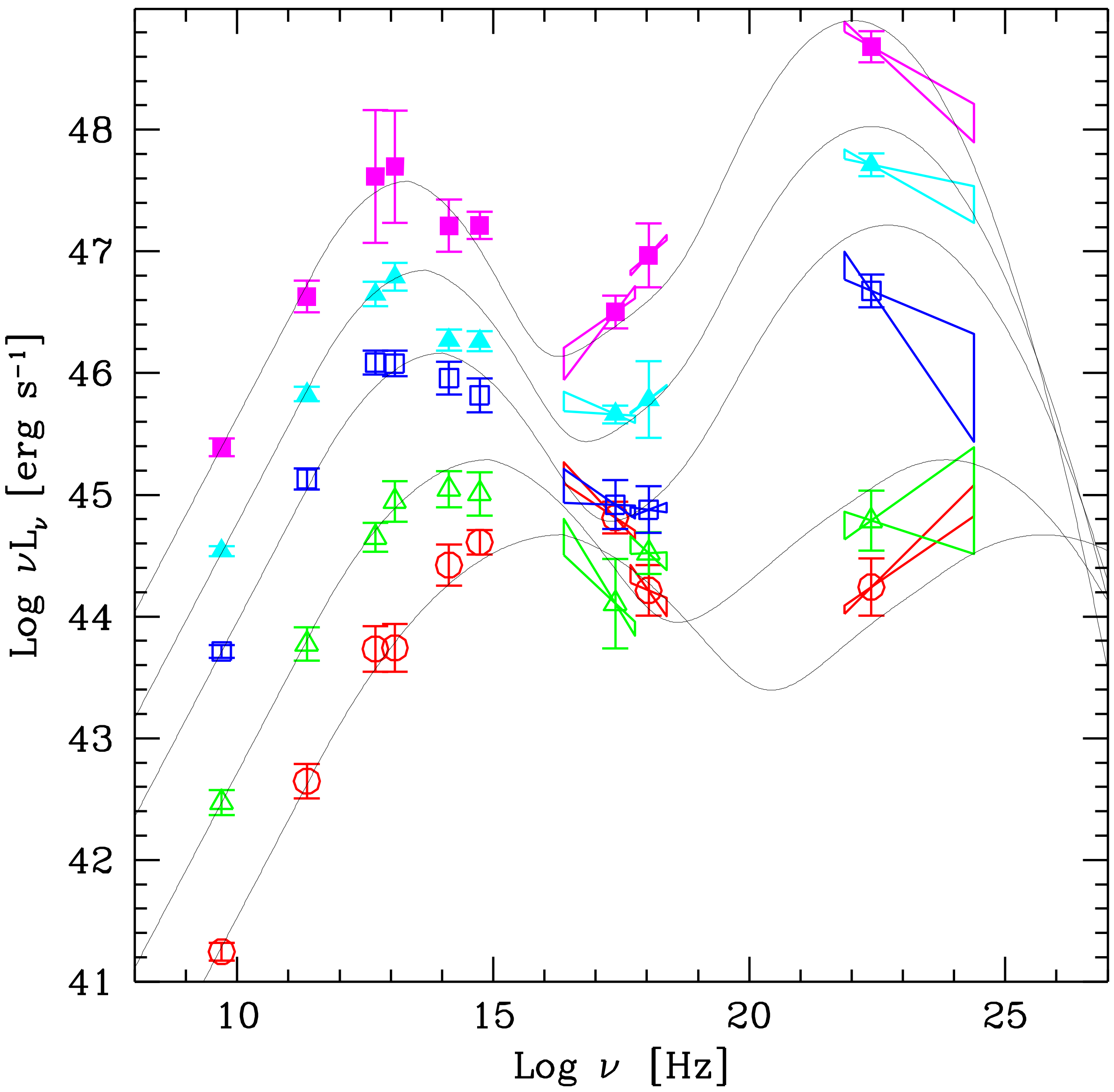
Cosmic particle beams



EHBL: at the edge of the blazar sequence?

- Debated unification model of blazars
- "cooling" paradigm

Fossati+ 1998



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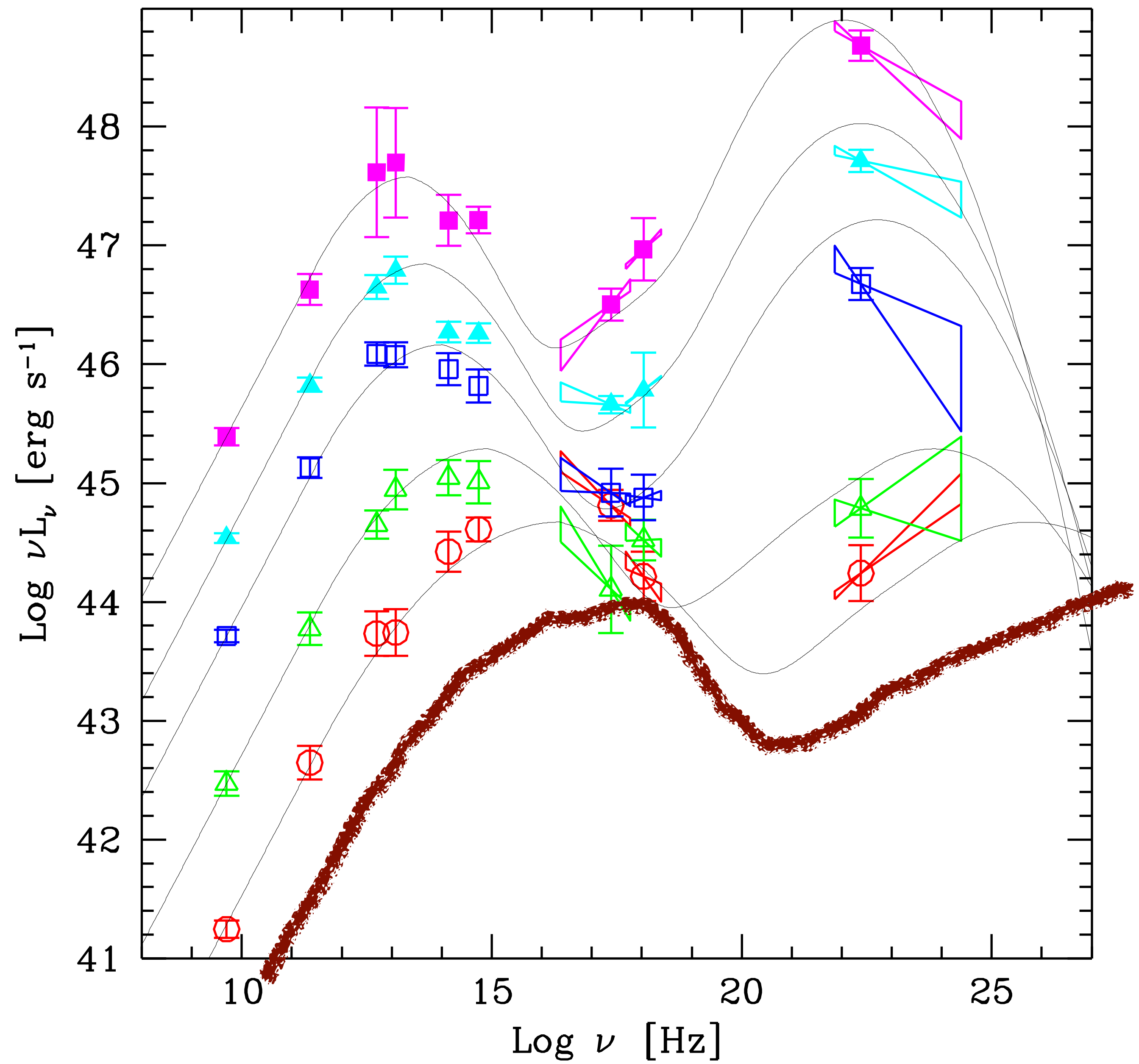

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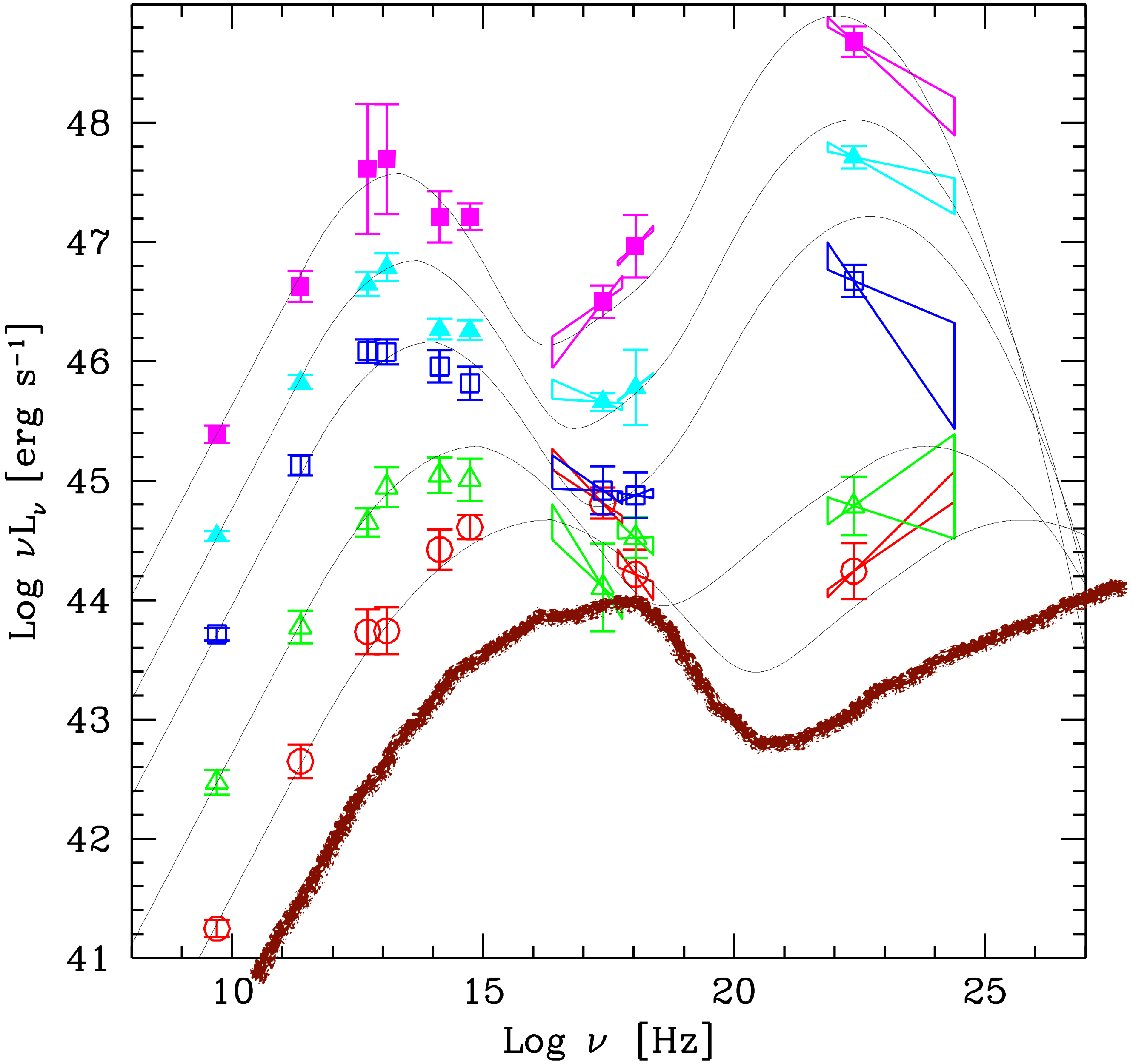

EHBL at the low-L high E_{peak} edge of the sequence

EHBL: at the edge of the blazar sequence?

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Combination of hard VHE spectrum and EBL extinction makes ideal for detection H.E.S.S. or CTA-MST

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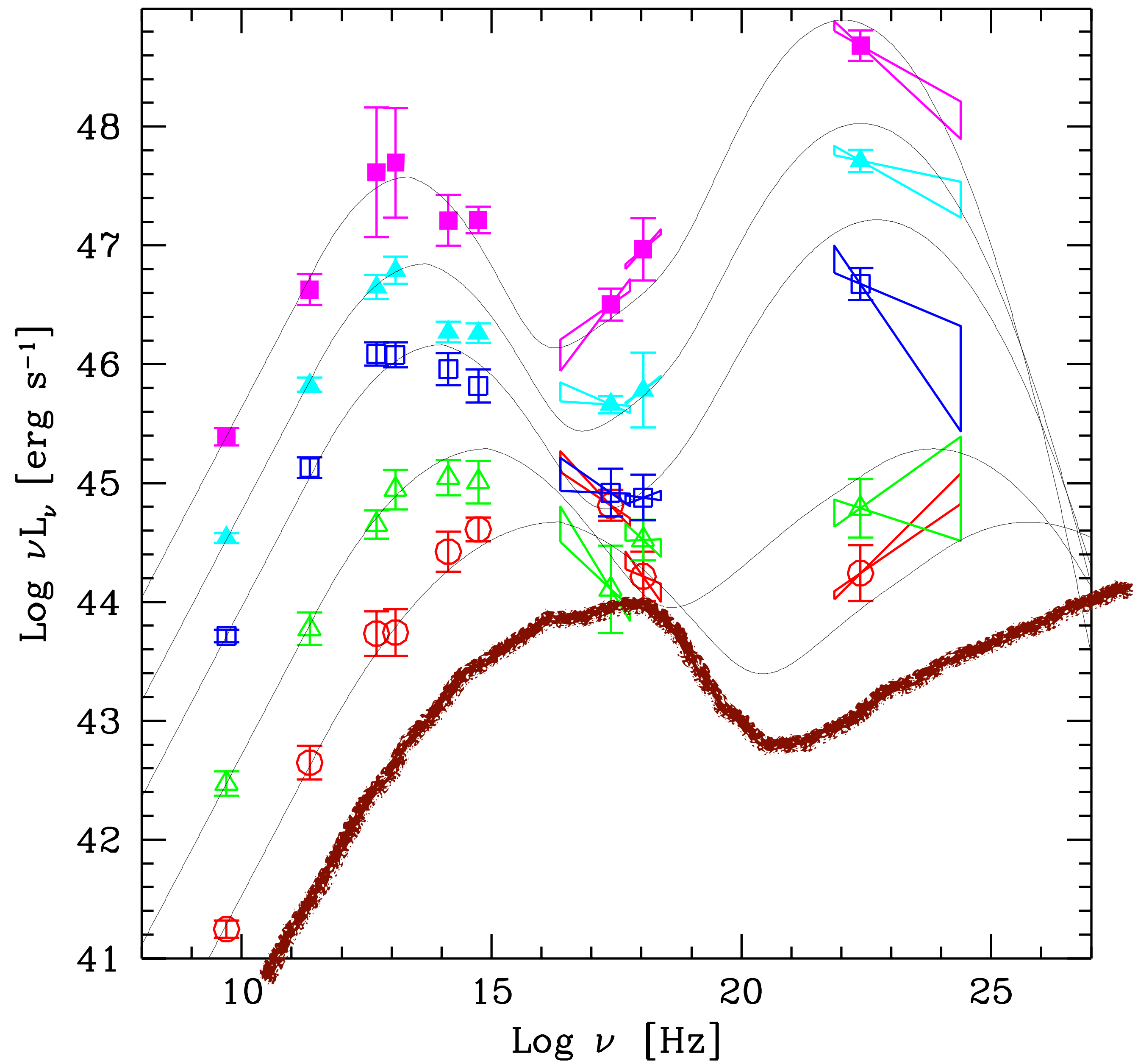

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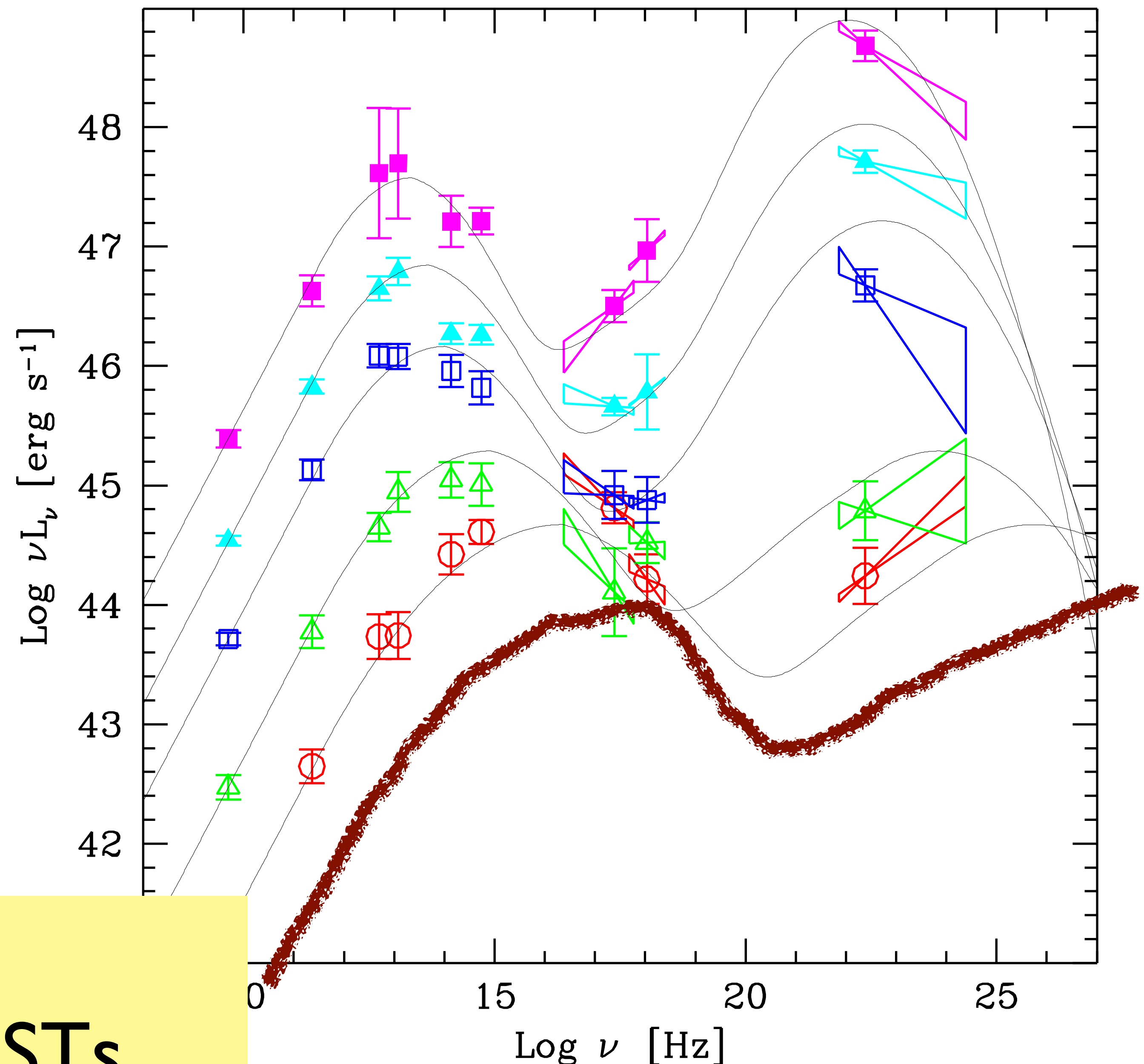


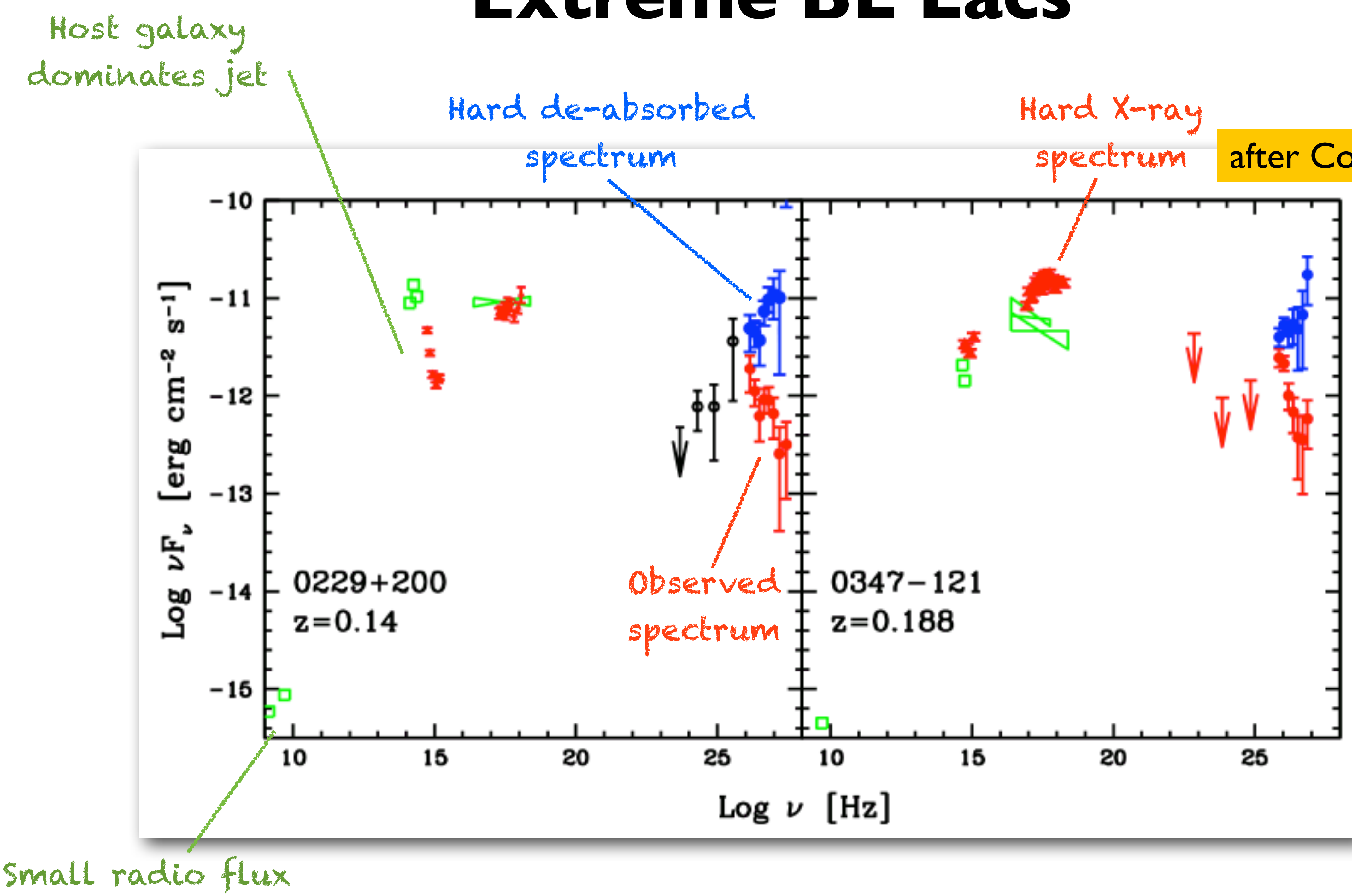
Combination of hard VHE spectrum and EBL extinction makes ideal for detection H.E.S.S. or CTA-MST

As TeV beacons, interesting physics case for SSTs

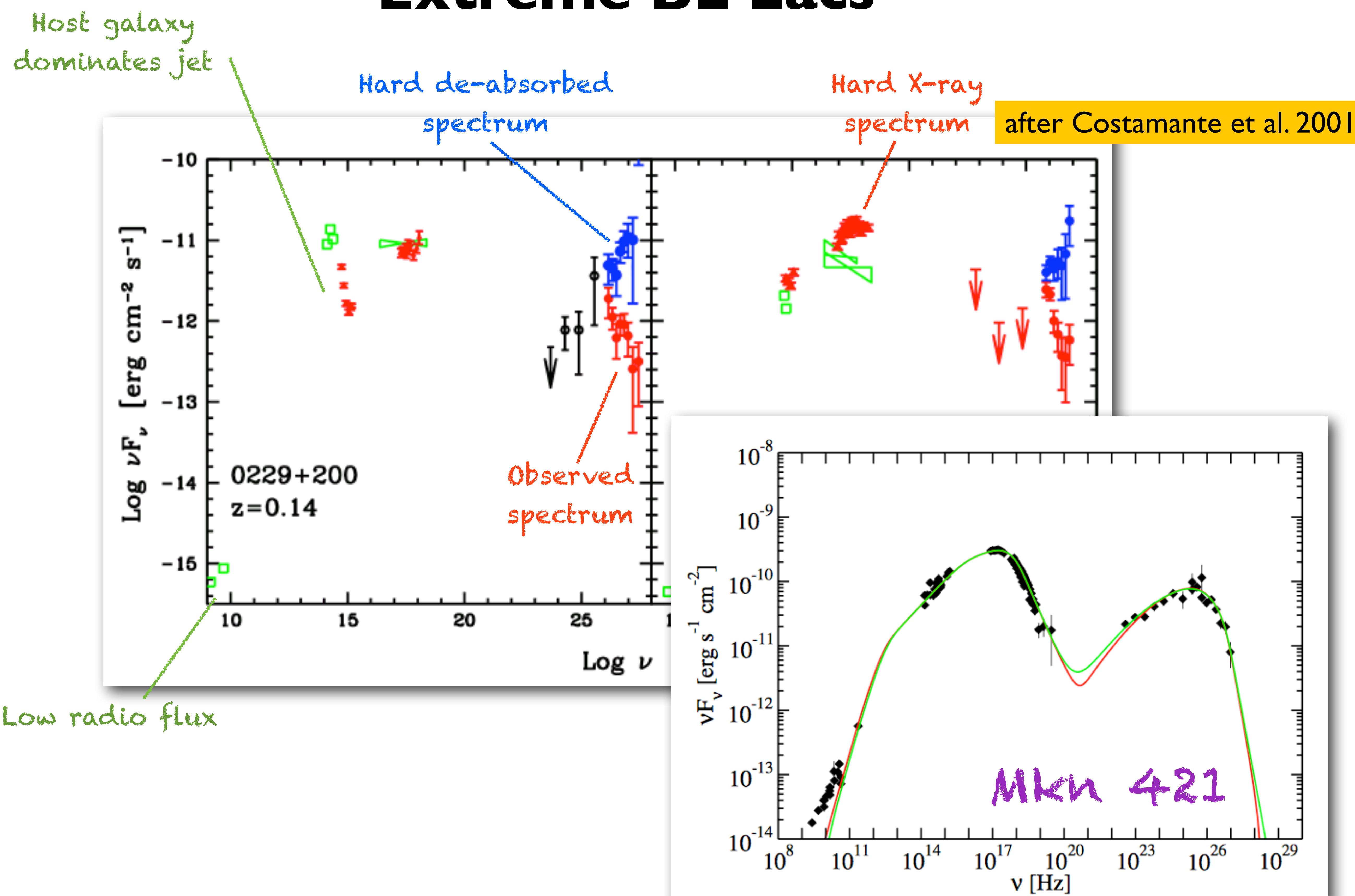
EHBL at the low-L high E_{peak} edge of the sequence

Extreme BL Lacs

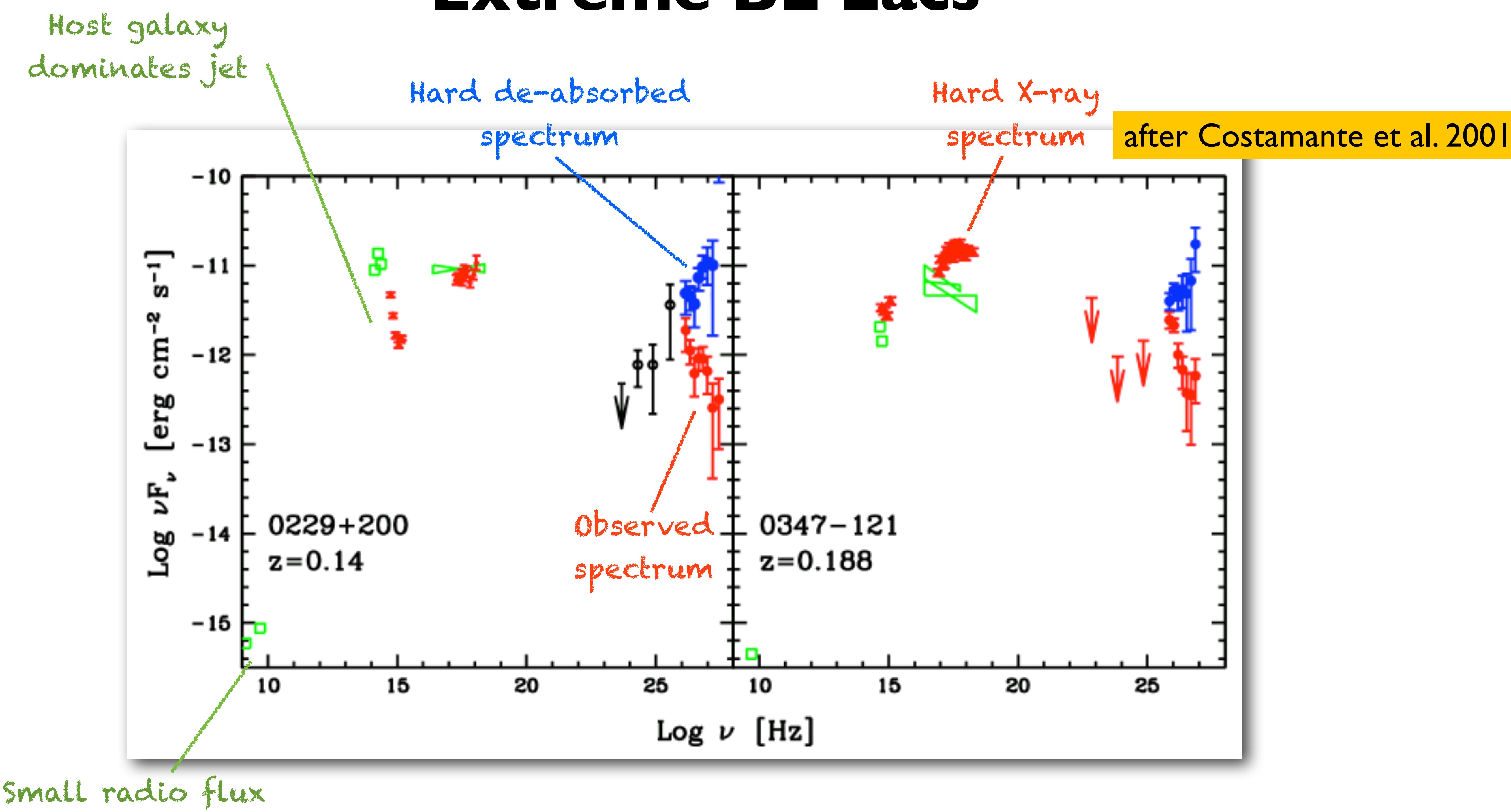
after Costamante et al. 2001



Extreme BL Lacs



Extreme BL Lacs



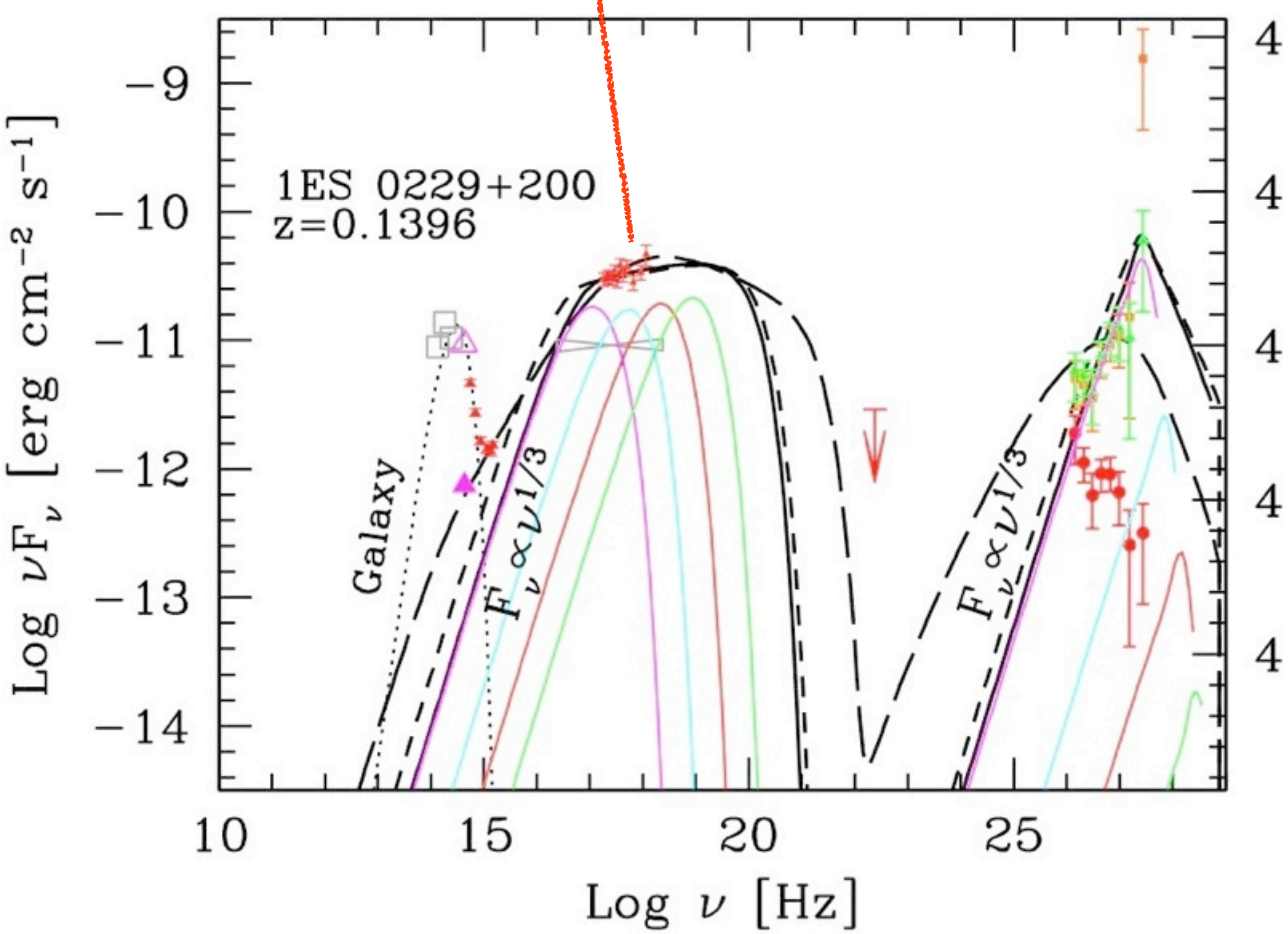
- Very hard X-ray and gamma-ray (deabsorbed) spectra
- Rather modest variability at all frequencies

Related topics

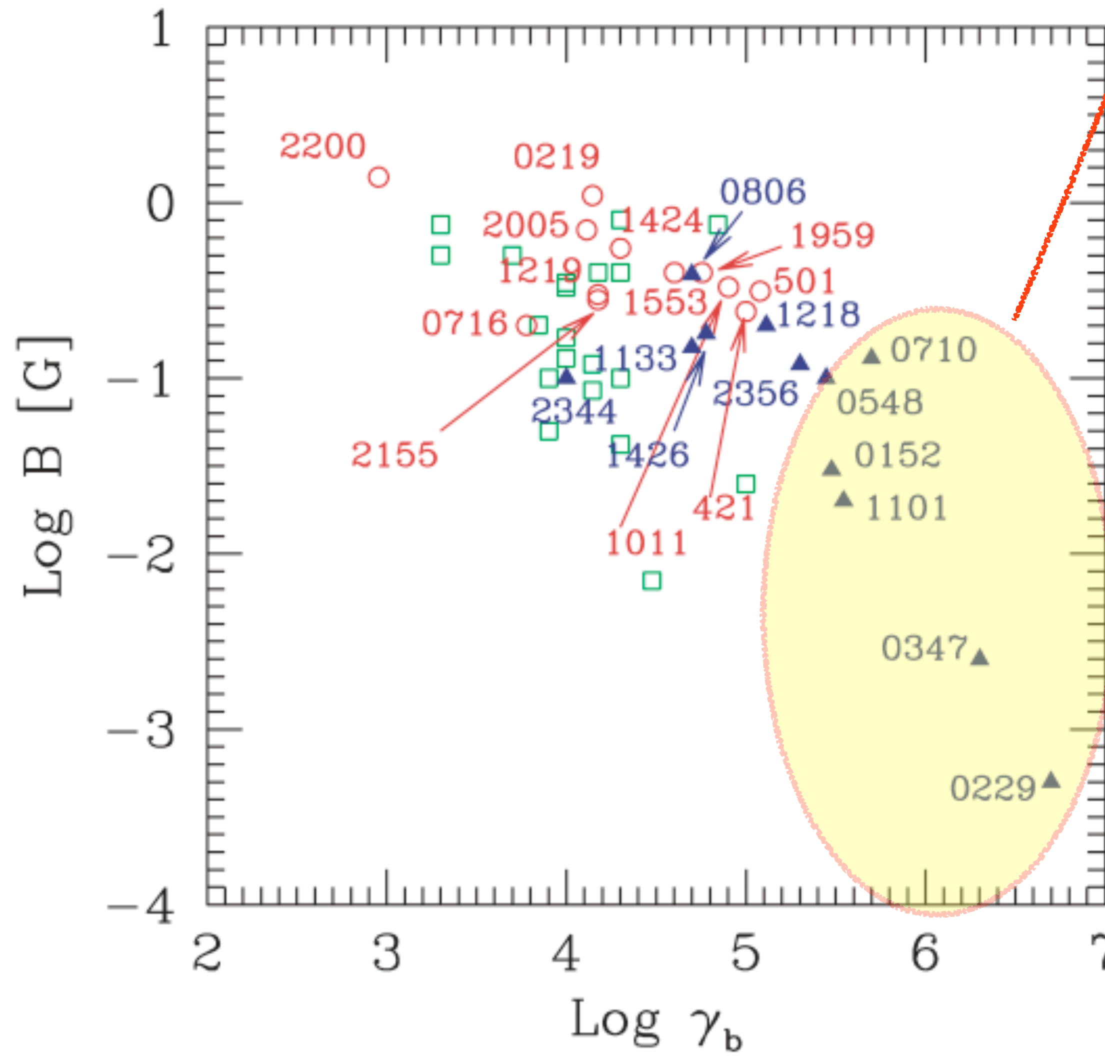
- Acceleration/emission mechanism? — Katarzynski+2006, Tavecchio+ 2009; Lefa et al. 2011, Zacharopoulou et al. 2011
- far-IR EBL-probes — Franceschini+ 2008; Dominguez+ 2011
- Probes for anomalies in EBL opacity:
  - ALPs — De Angelis et al. 2011
  - Hadron beams — Essey & Kusenko 2010; Murase+ 2012
  - LIV — Fairbairn+ 2014, Tavecchio & Bonnoli, A&A 2015
- parent population? "FR0" — Baldi et al. 2009, 2015
- Relevance for HE gamma-ray background — Inoue & Ioka 2012
- IGMF probes — Neronov 2010; Tavecchio+ 2010

Extreme accelerators?

Large minimum electron energy



Very low B
Large e energies

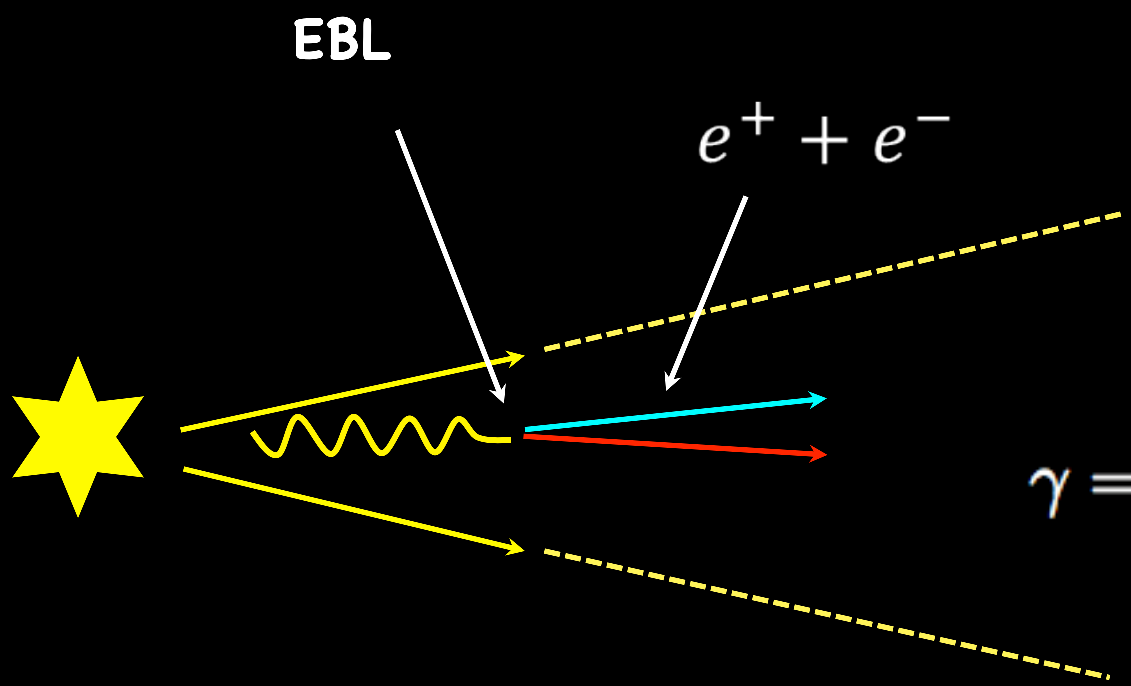


Katarzyński et al. 2005
Tavecchio et al. 2009
Kaufmann et al. 2011

Tavecchio et al. 2010,2011

➤ Acceleration process?
➤ Why cooling so small?
➤ Why weakly/slowly variable?

Probes of IGMF



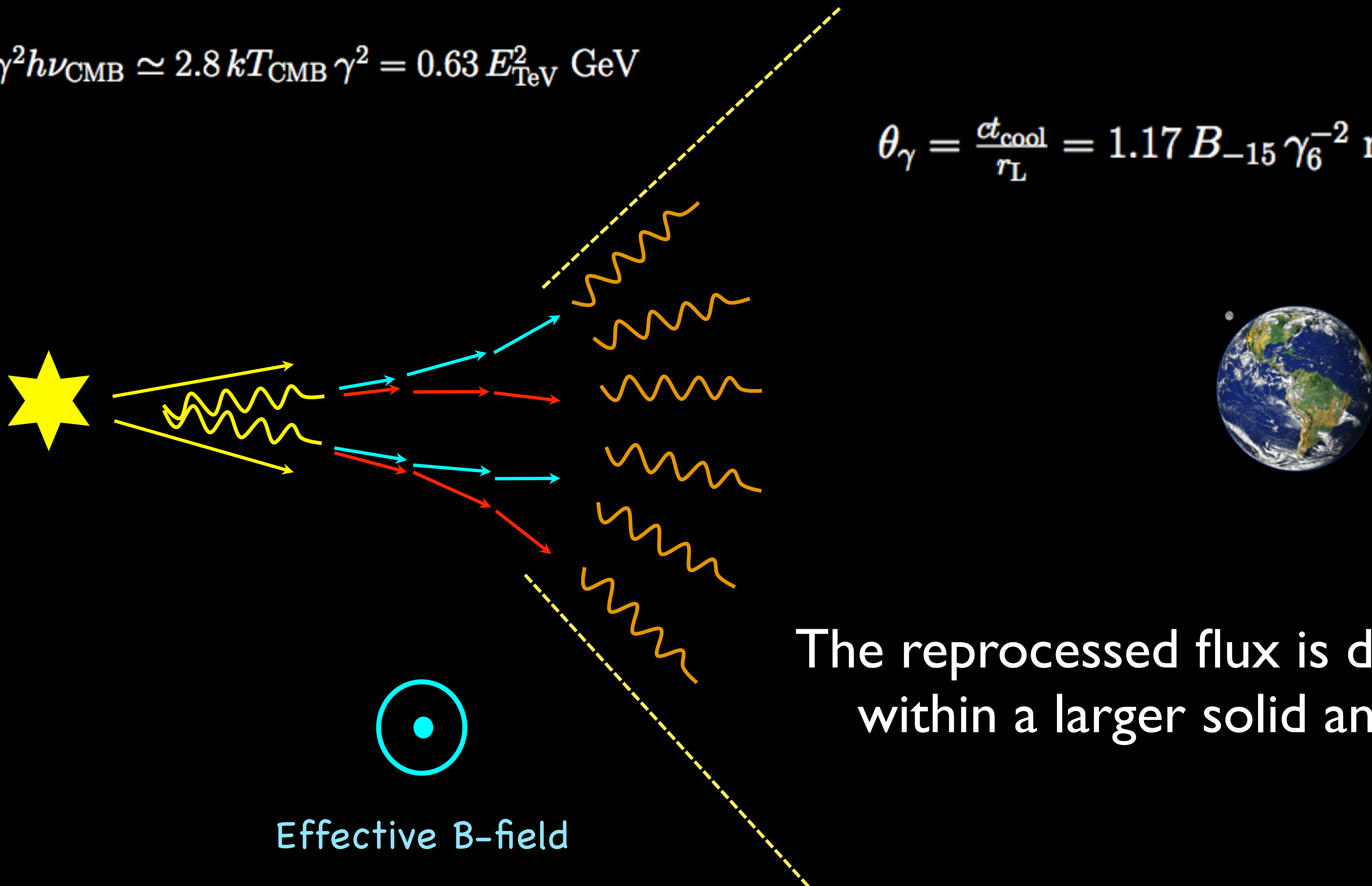
$$\gamma = \frac{E}{2m_e c^2} \simeq 10^6 E_{\rm TeV}$$

$$\gamma_1 + \gamma_2 = e^- + e^+$$

Probes of IGMF

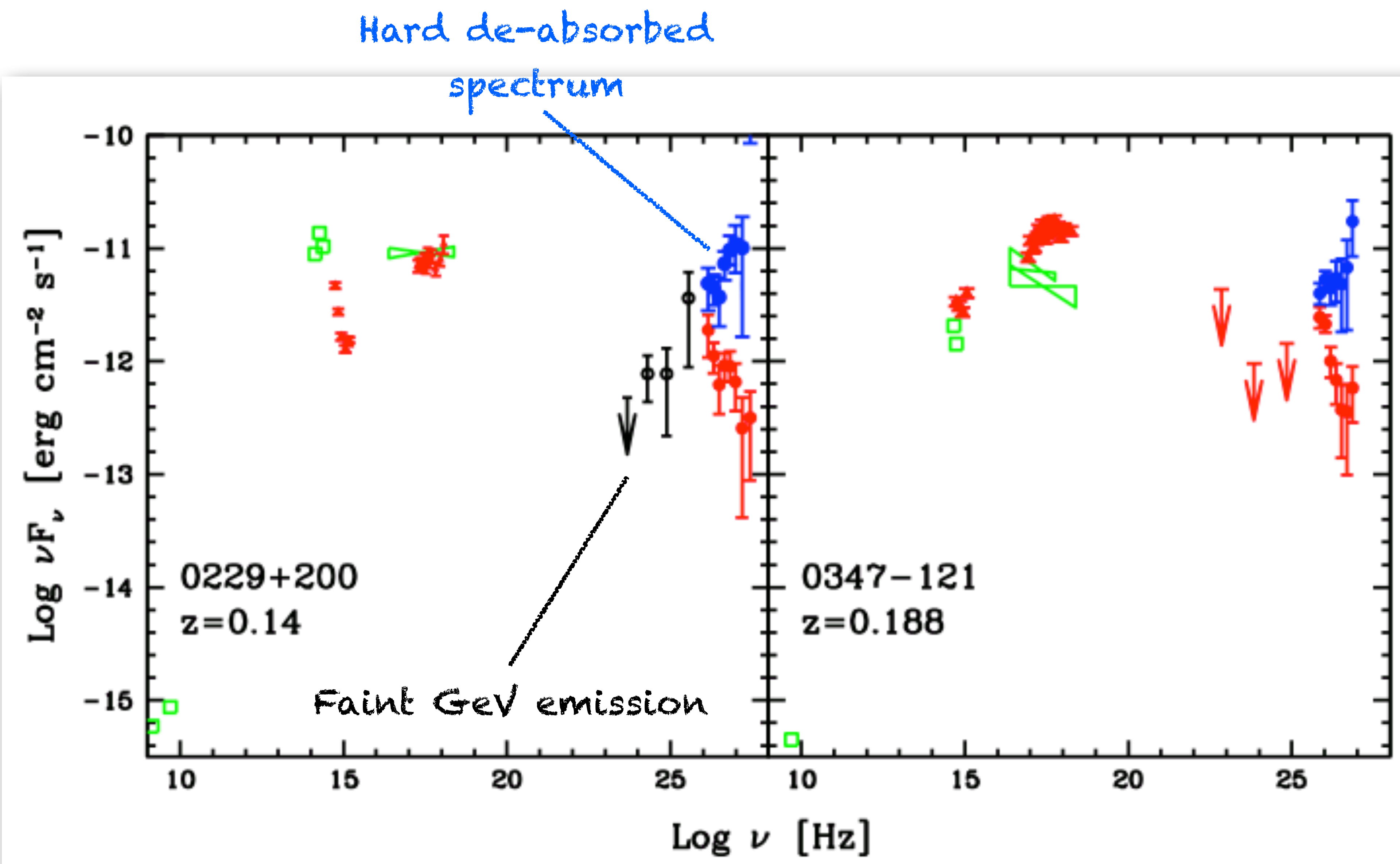
$$\epsilon = \gamma^2 h\nu_{\rm CMB} \simeq 2.8\, kT_{\rm CMB}\, \gamma^2 = 0.63\, E_{\rm TeV}^2 \ {\rm GeV}$$

$$\theta_\gamma = \frac{ct_{\rm cool}}{r_{\rm L}} = 1.17\, B_{-15}\, \gamma_6^{-2} \ {\rm rad}$$



The reprocessed flux is diluted within a larger solid angle

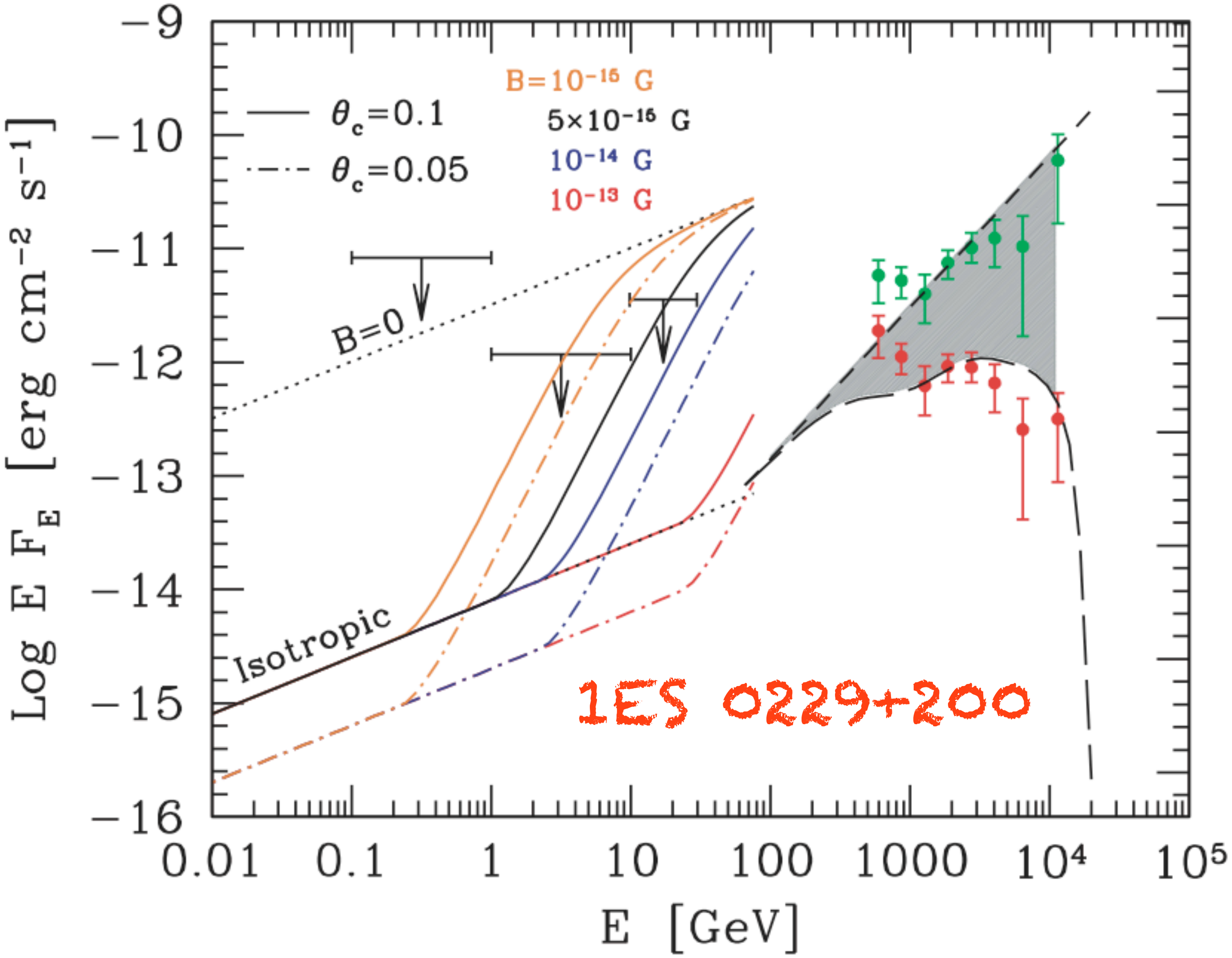
Probes of IGMF



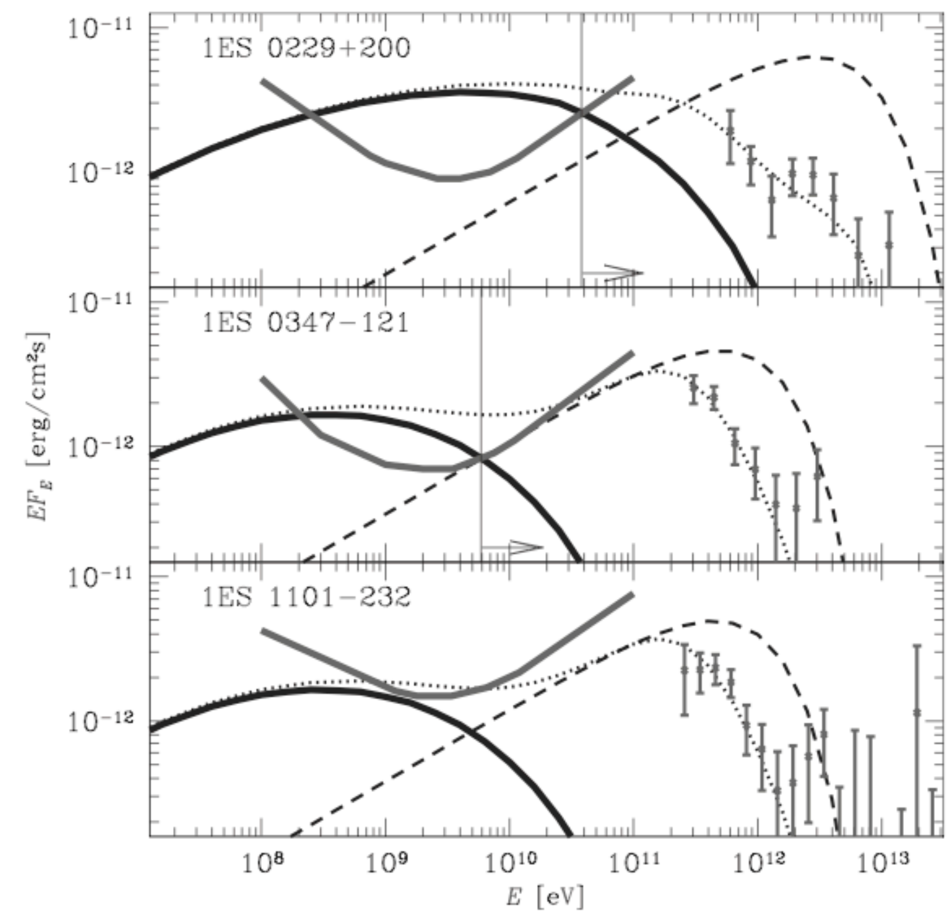
Probes of IGMF

$B > 10^{-18} - 10^{-15}$ G

Tavecchio et al. 2010,2011

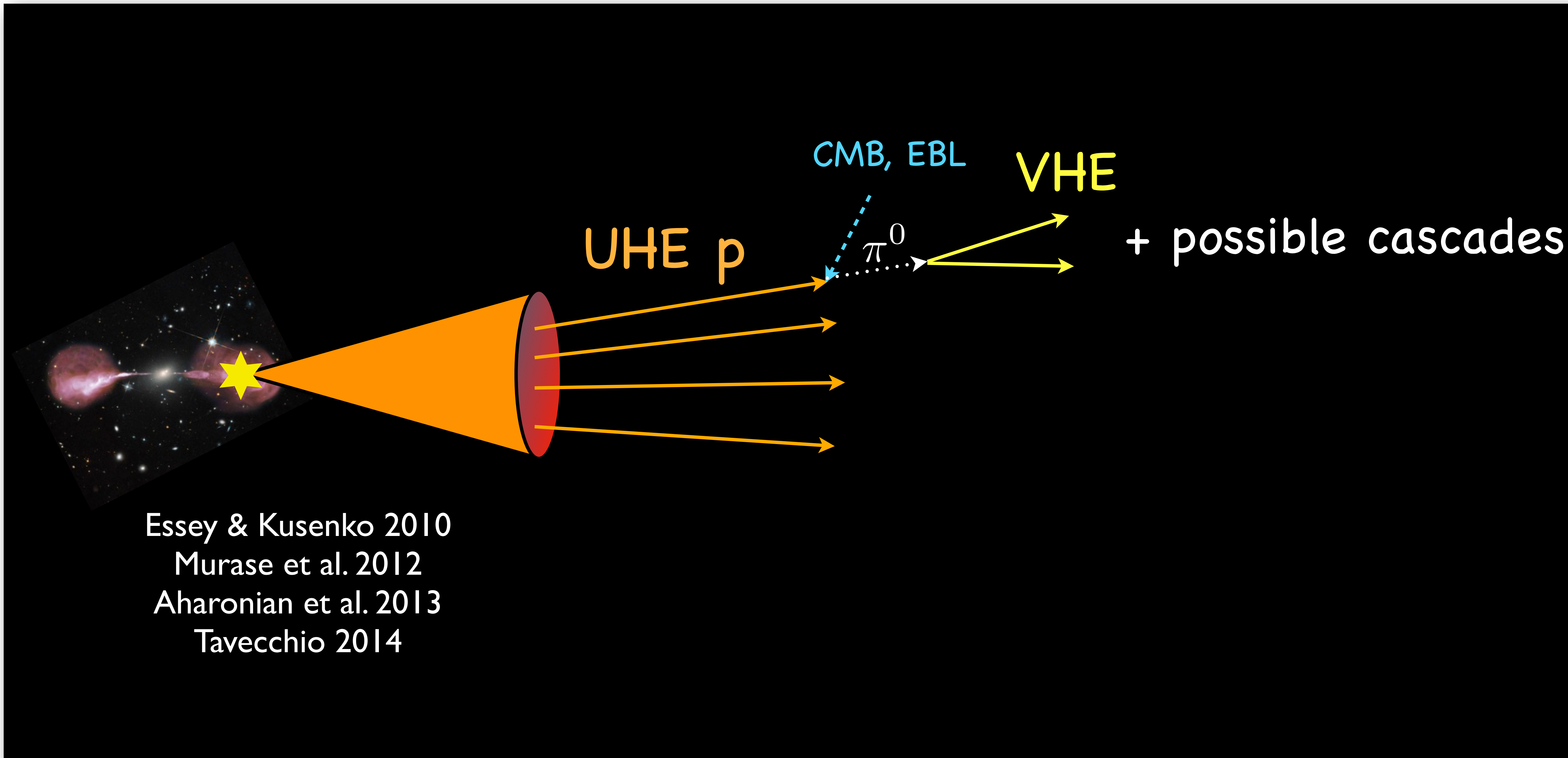


Neronov & Vovk 2010



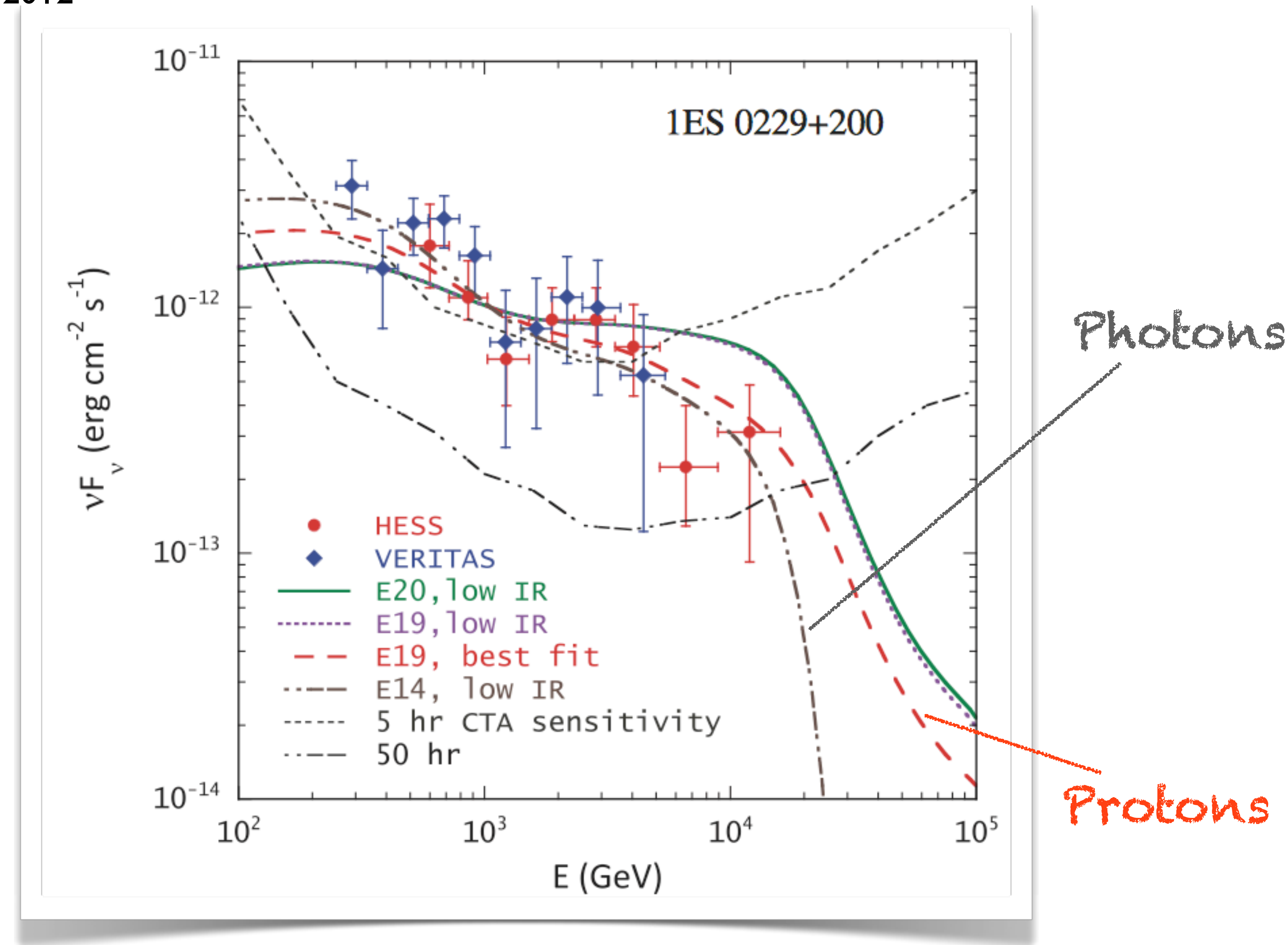
Also Dolag et al. 2011, Dermer et al. 2011, Taylor et al. 2012 ...

Hadron beams?



Hadron beams?

Murase et al. 2012

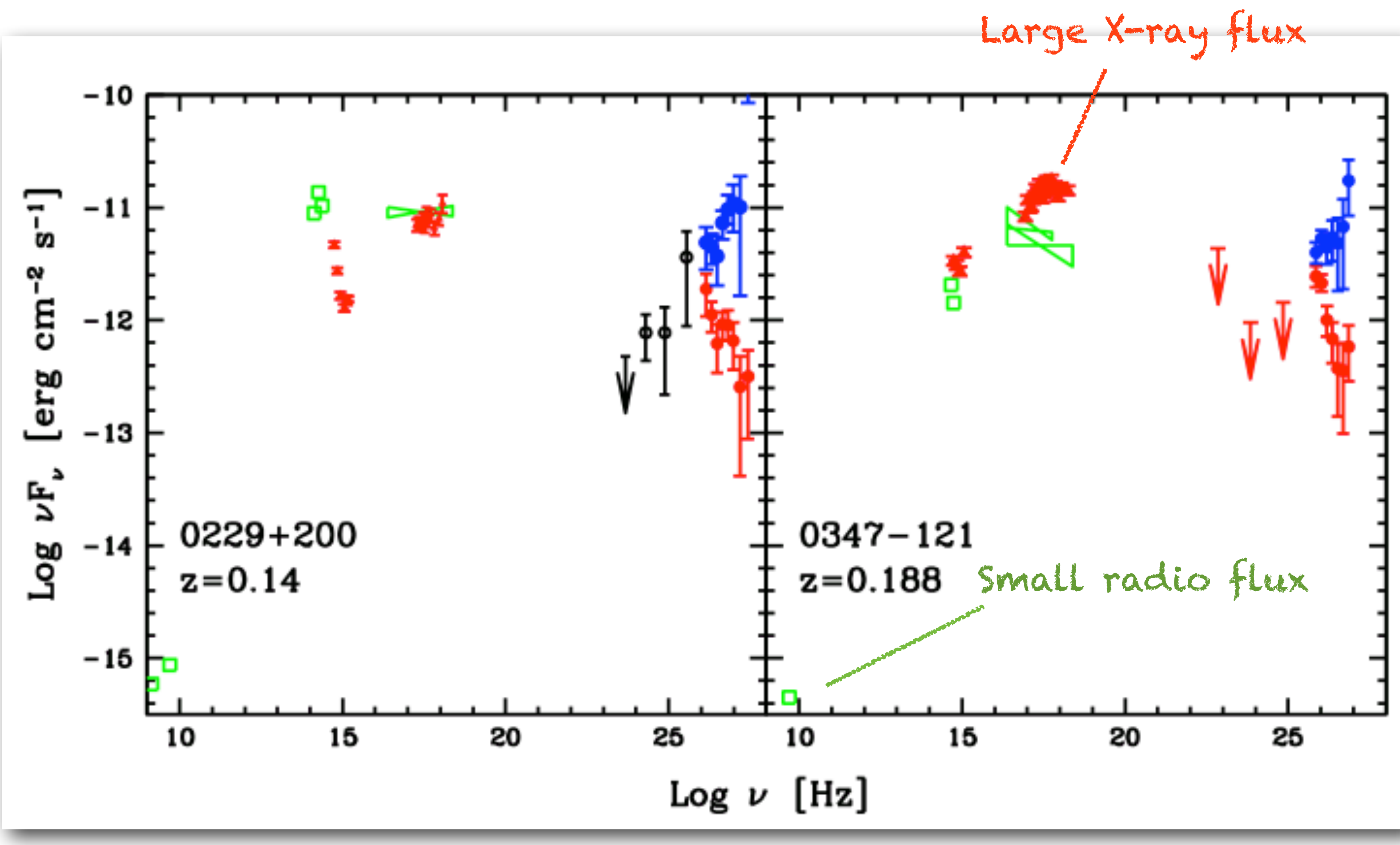


Looking for EHBL

Quite interesting sources, but only a few

Population?
Impact on gamma-ray background?
Evolution?
Parent population?

Looking for EHBL



Look for BL Lacs with large X-ray/radio flux ratio and weak gamma-ray emission

The archetypal EHBL: 1ES 0229+200

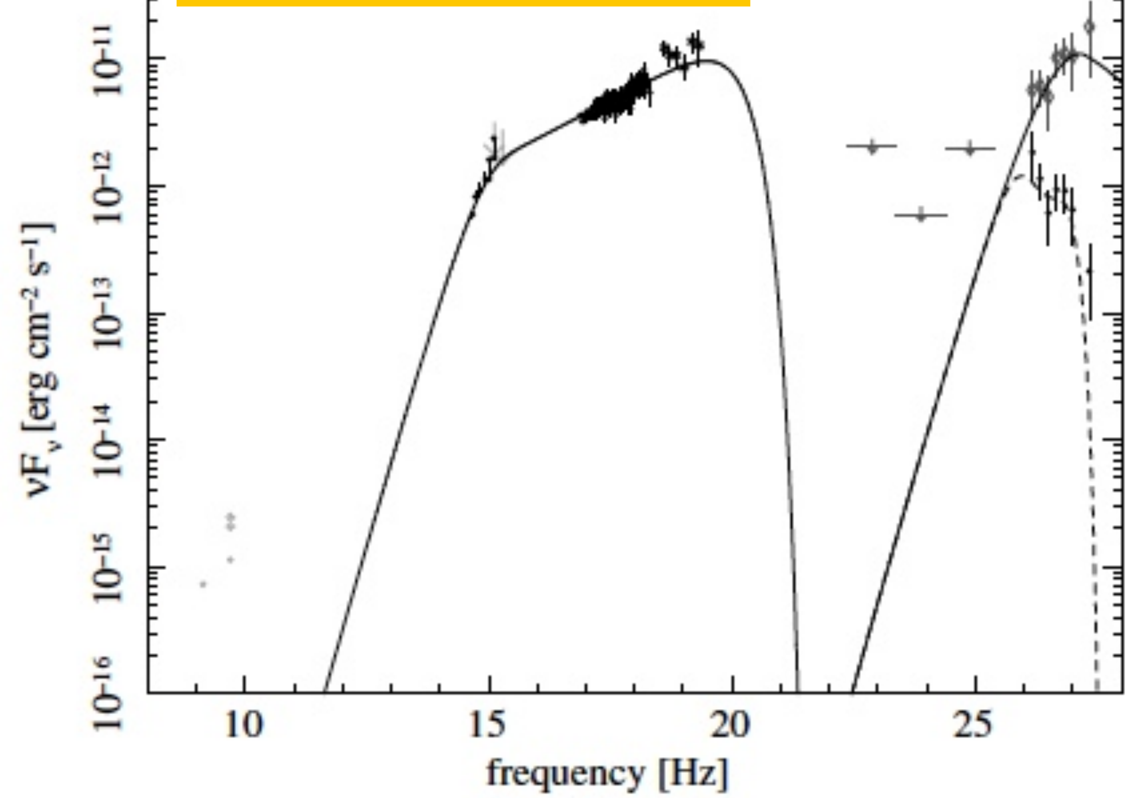
- BL Lac @ z = 0.14
- Hardly detected in HE gamma
- Detected by all current TeV instruments (H.E.S.S. first)
- Synchrotron peak at few keV, low compton dominance,
- in SSC frame, evidence for high lower edge of electron energy distribution

Katarzynski+2006, Tavecchio+ 2009

- Deabsorbed IC peaks at multi TEV
- TeV beacon-probe for EBL and anomalies in opacity, UHECR beams
- TeV beacon-probe for IGMF

Neronov 2010
Tavecchio+ 2010

Kaufmann+ 2011



Looking for EHBL

Bonnoli+ 2015

71 BL Lacs form SDSS+FIRST
(Plotkin et al. 2011)
+
z<0.4 (small EBL absorbtion)
+
X-ray detection

↓

50 BL Lacs

Looking for EHBL

Bonnoli+ 2015

71 BL Lacs form SDSS+FIRST (Plotkin et al. 2011)
+
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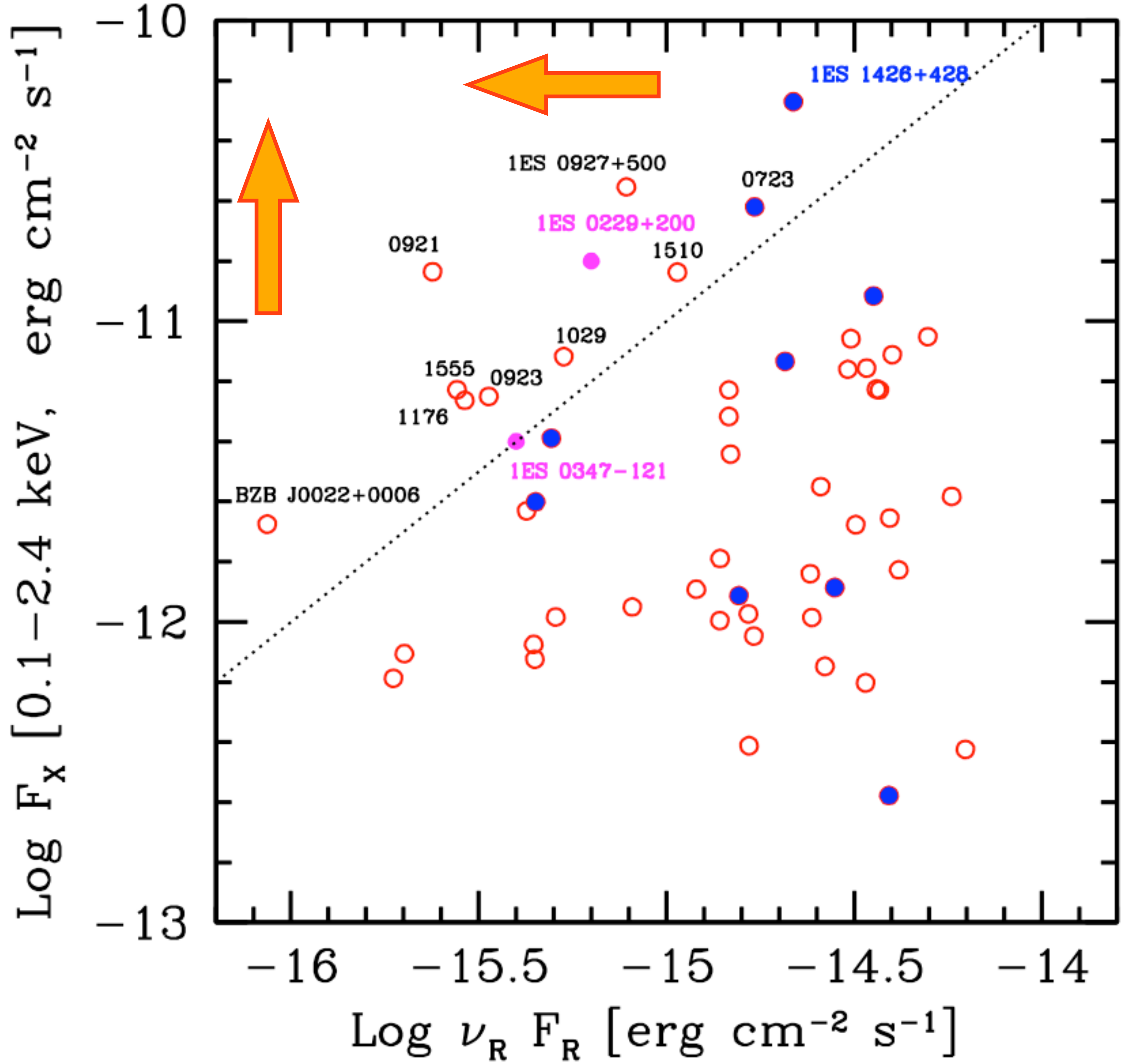
50 BL Lacs



Looking for EHBL

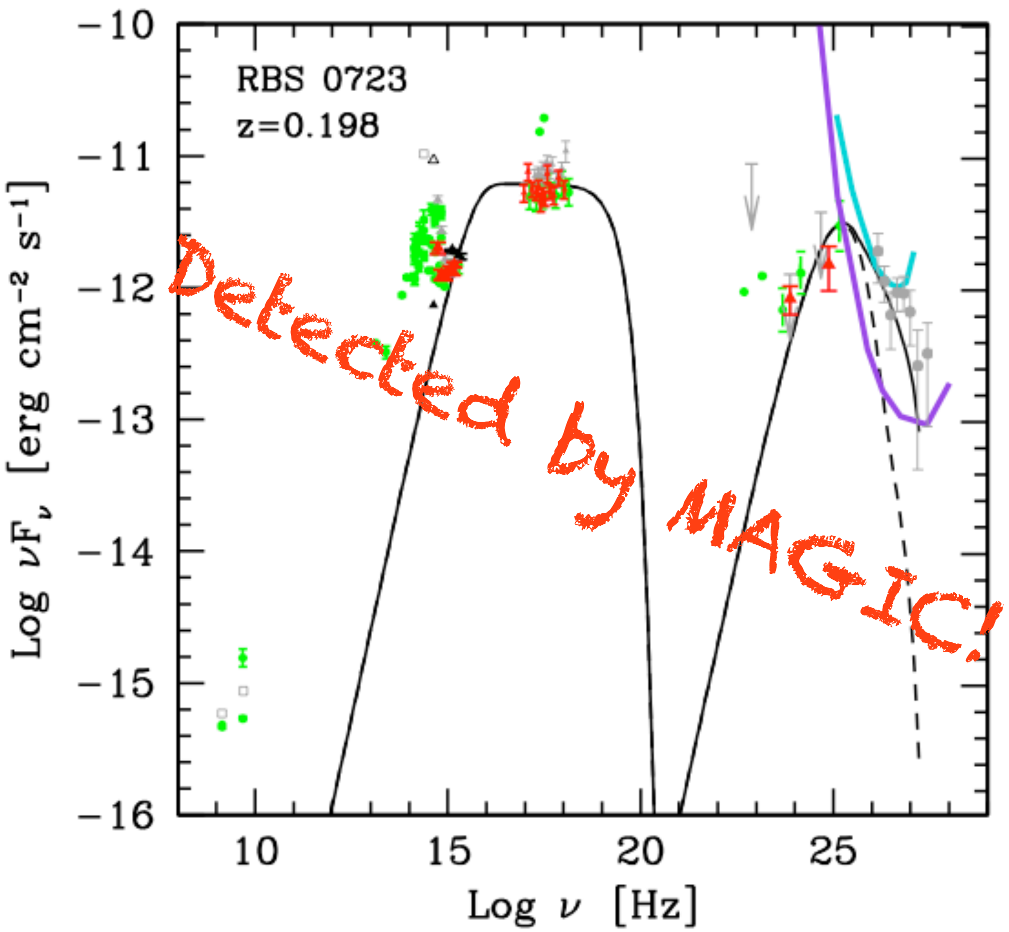
Bonnoli+ 2015

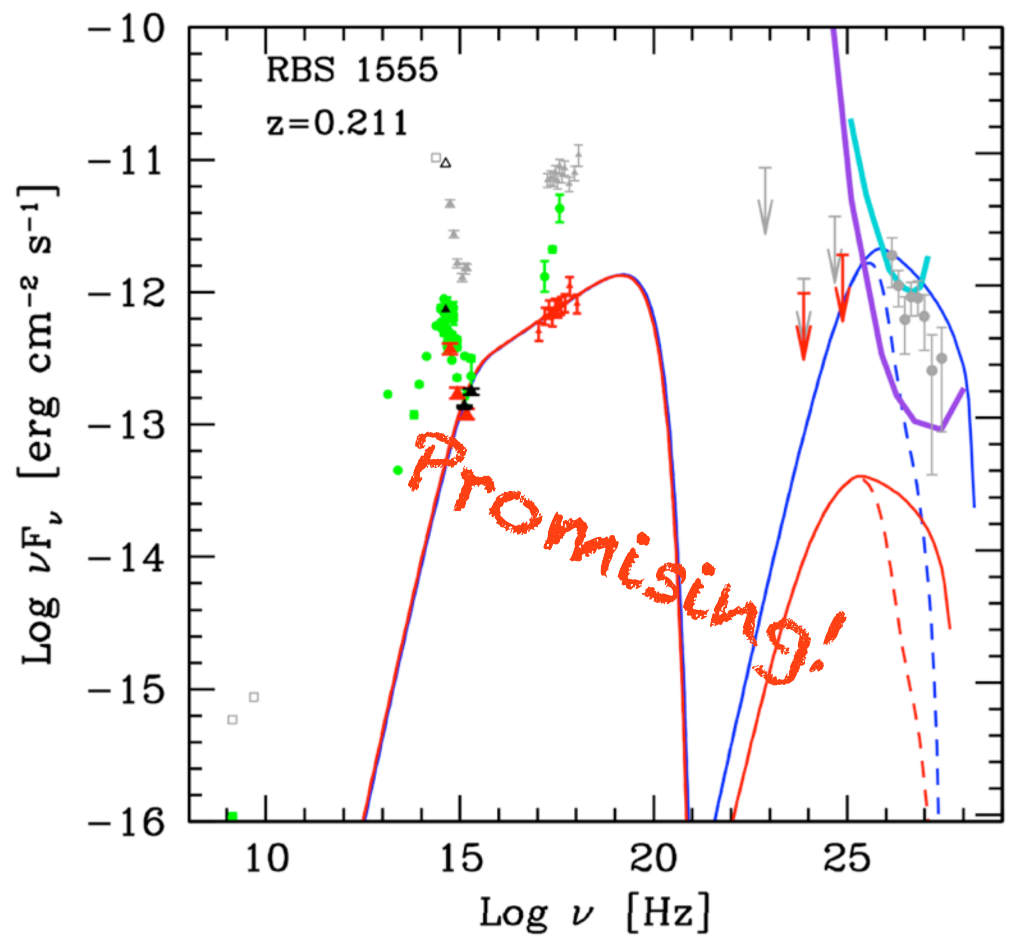
9 candidates

Source Name	R.A.(J2000)	δ(J2000)	l	b	Redshift	A_B
BZB J0022+0006	5.5040	0.1161	107.18	− 61.85	0.306	0.108
RBS 0723	131.8039	11.5640	215.46	30.89	0.198	0.093
1ES 0927+500	142.6566	49.8404	168.19	45.71	0.187	0.073
RBS 0921	164.0275	2.8704	249.28	53.28	0.236	0.178
RBS 0923	164.3462	23.0552	215.96	63.91	0.378	0.088
RBS 1029	176.3963	− 3.6671	273.11	55.34	0.168	0.130
RBS 1176	193.2540	38.4405	121.36	78.68	0.371	0.083
RBS 1510	233.2969	18.9081	29.21	52.05	0.307	0.210
RBS 1555	241.3293	54.3500	84.35	45.60	0.212	0.041

Source name	B (G)	K	γ_{min}	γ_{max}	n
BZB J0022+0006	0.1	1.7×10^{11}	3×10^4	2×10^6	3.5
	0.01	2.75×10^{13}	9×10^4	6×10^6	3.5
RBS 0723	0.15	6×10^8	2.1×10^4	1.5×10^6	3.0
1ES 0927+500[1] 1	0.05	1.7×10^{10}	4.1×10^4	3×10^6	3.3
2+3	0.035	1.3×10^7	2.7×10^4	3×10^6	2.7
RBS 0921	0.1	8×10^7	4.7×10^4	1.8×10^6	2.8
	0.01	6×10^9	1.3×10^5	6×10^6	2.8
RBS 0923	0.1	1.4×10^8	2.2×10^4	2×10^6	3.3
	0.01	5.1×10^{12}	1.2×10^5	5.2×10^6	3.3
RBS 1029	0.1	1.4×10^8	2.2×10^4	2×10^6	3.0
	0.01	1.4×10^{10}	7×10^4	6×10^6	3.0
RBS 1176[2]	0.1	6×10^7	2.3×10^4	10^6	2.8
	0.01	4.6×10^9	7.3×10^4	3×10^6	2.8
	0.01	3×10^{11}	4×10^5	3×10^6	3.1
RBS 1510[3]	0.12	6.2×10^9	2×10^4	2×10^6	3.35
RBS 1555	0.1	1.2×10^6	1.3×10^4	3×10^6	2.6
	0.01	7.5×10^7	4.3×10^4	10^7	2.6

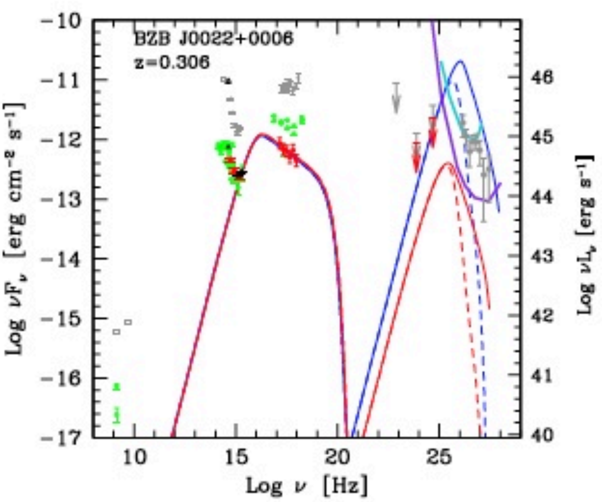
Swift (UV-X-ray) observations Confirmation

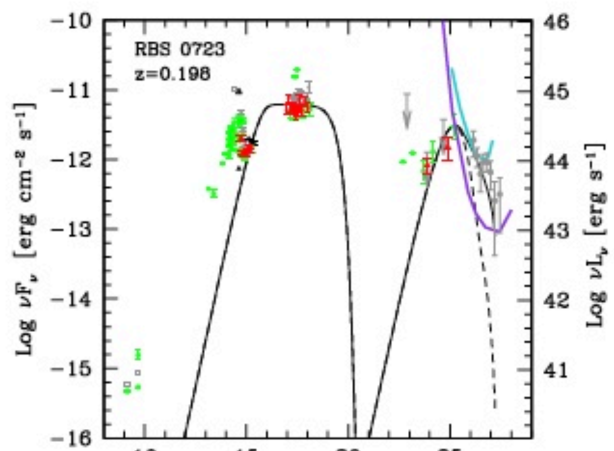




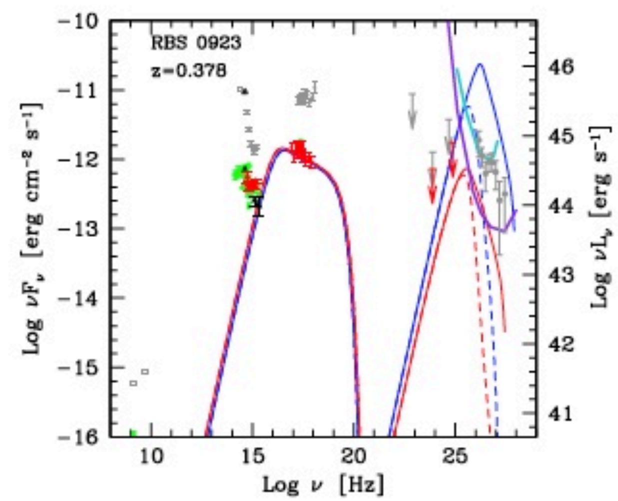
Spectral Energy Distributions

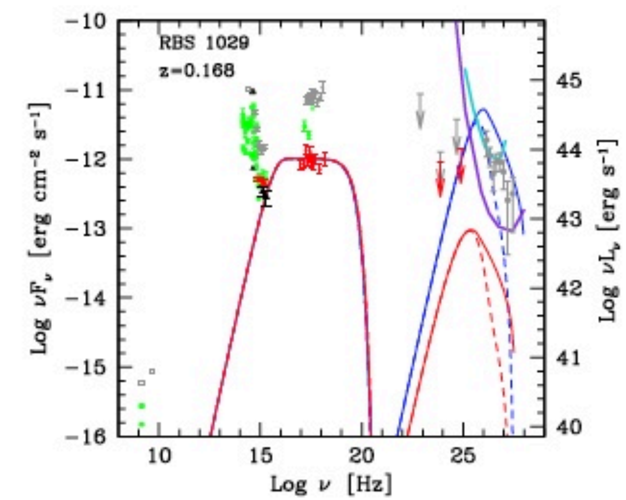
Bonnoli+ 2015

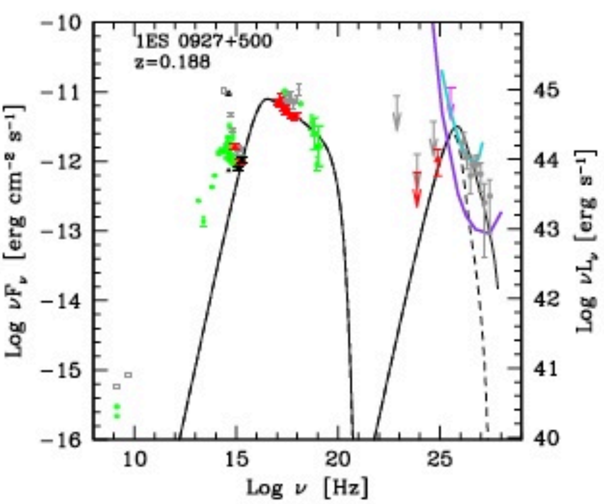


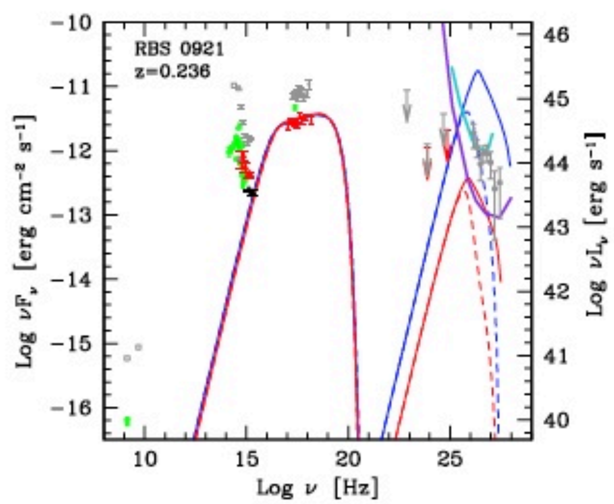


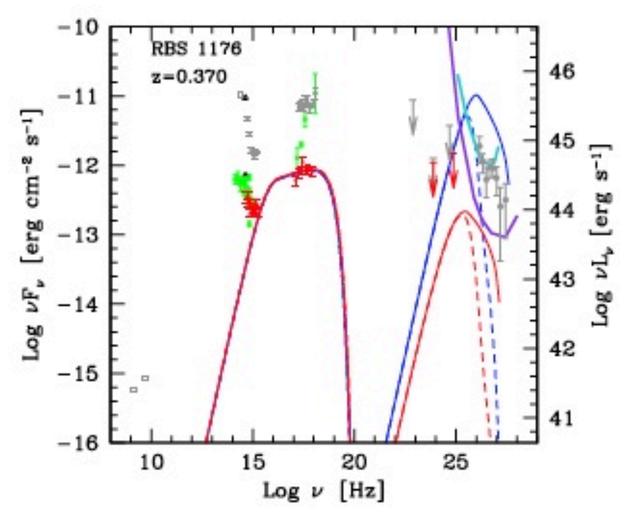
RBS 0723
MAGIC-detected!!

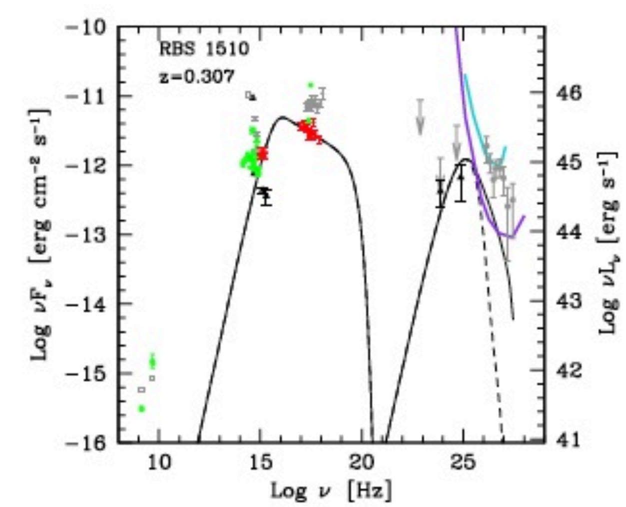


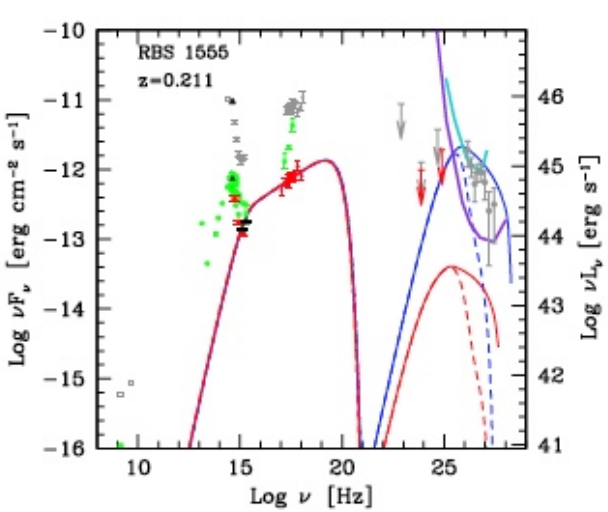








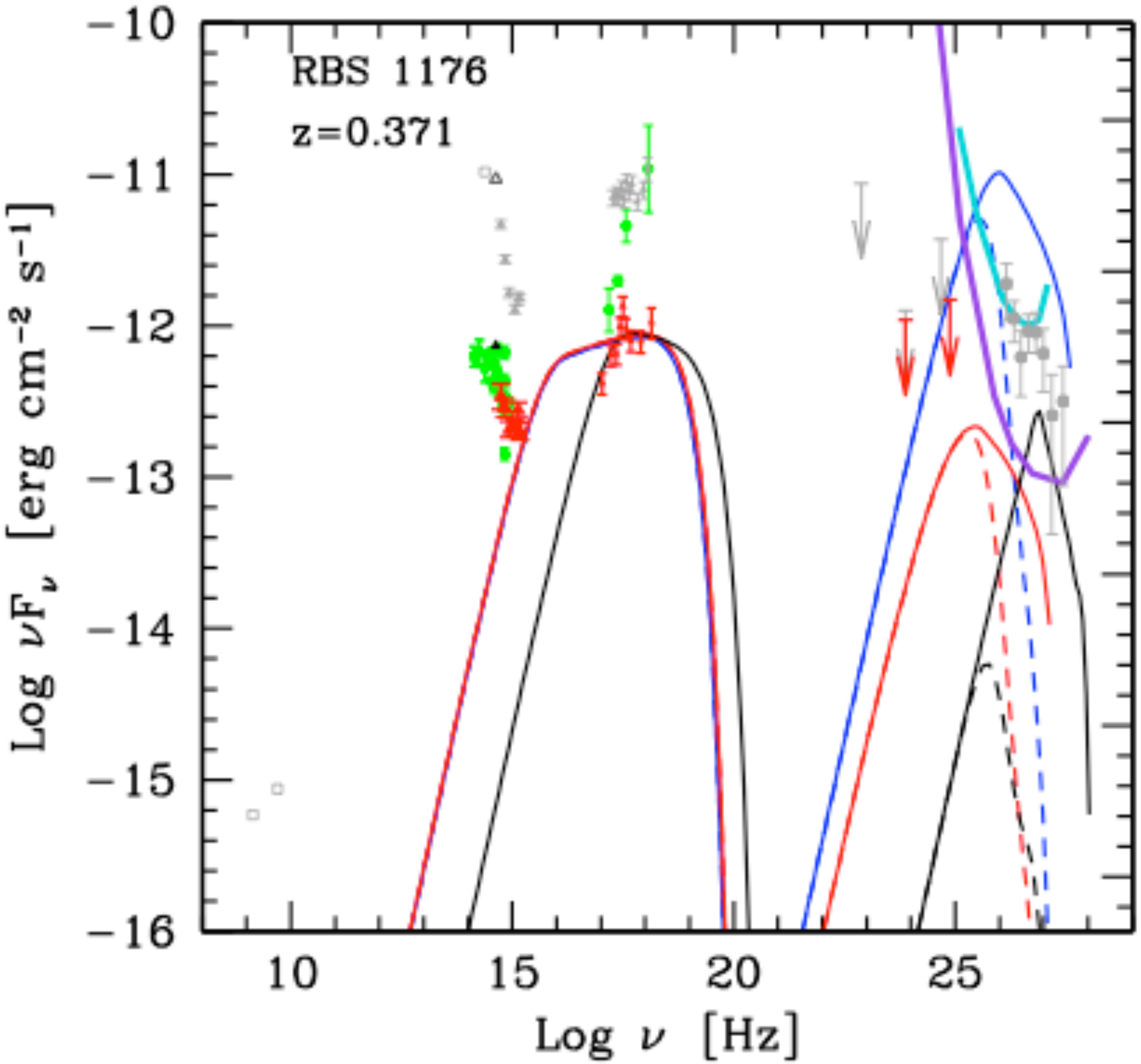




Looking for EHBL

Bonnoli+ 2015

RBS 1176: an ultra-extreme HBL?



Looking for EHBL

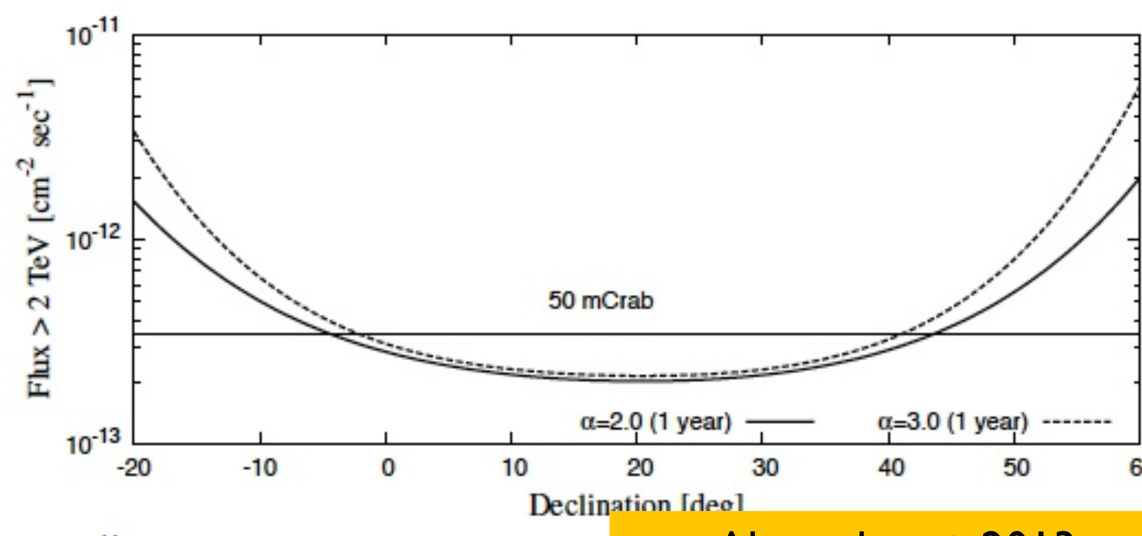
We start to extend the selection

Rosat Bright Survey
+
FIRST (1.4 GHz)
+
No 3FGL

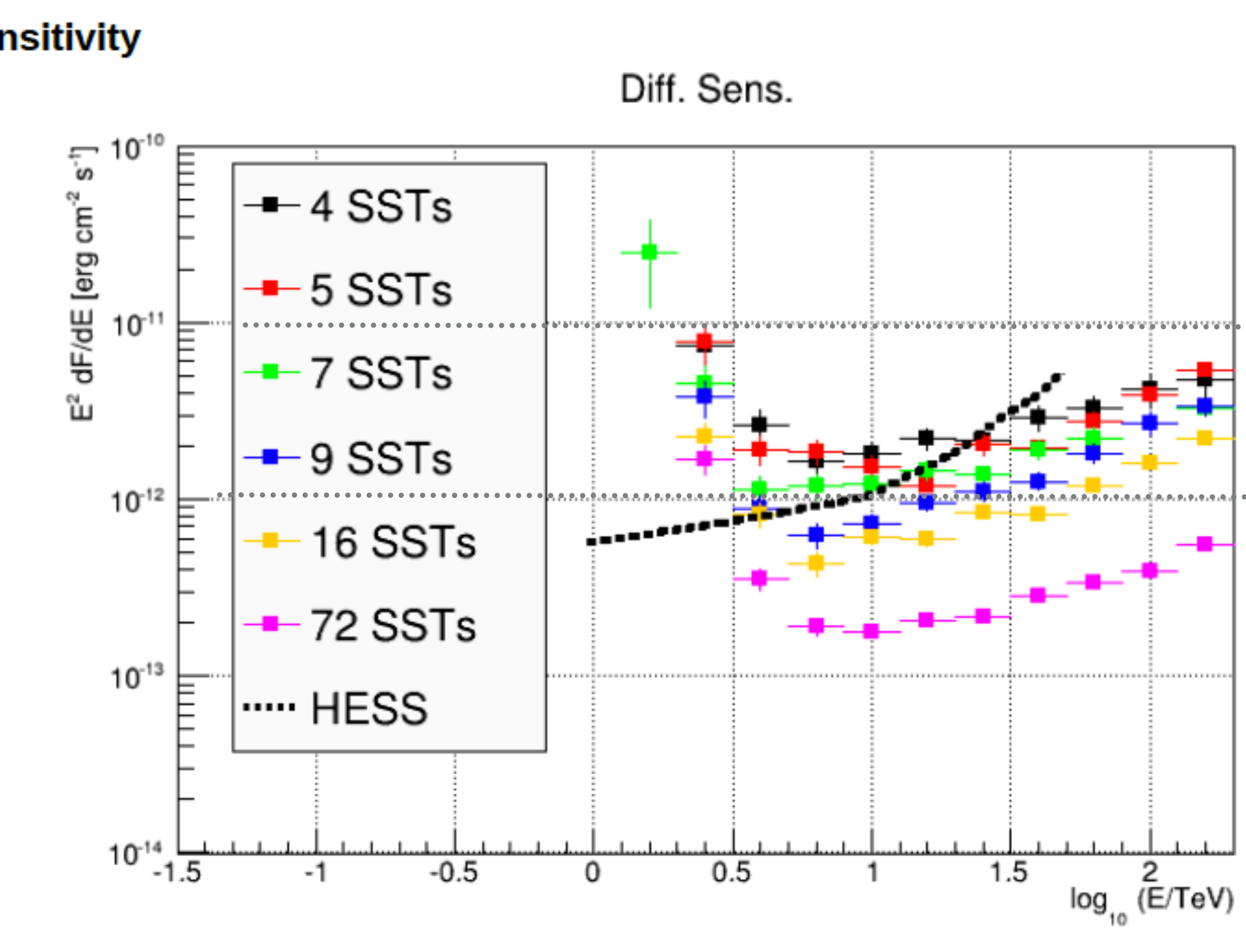
14 new + 4 in Bonnoli 2015

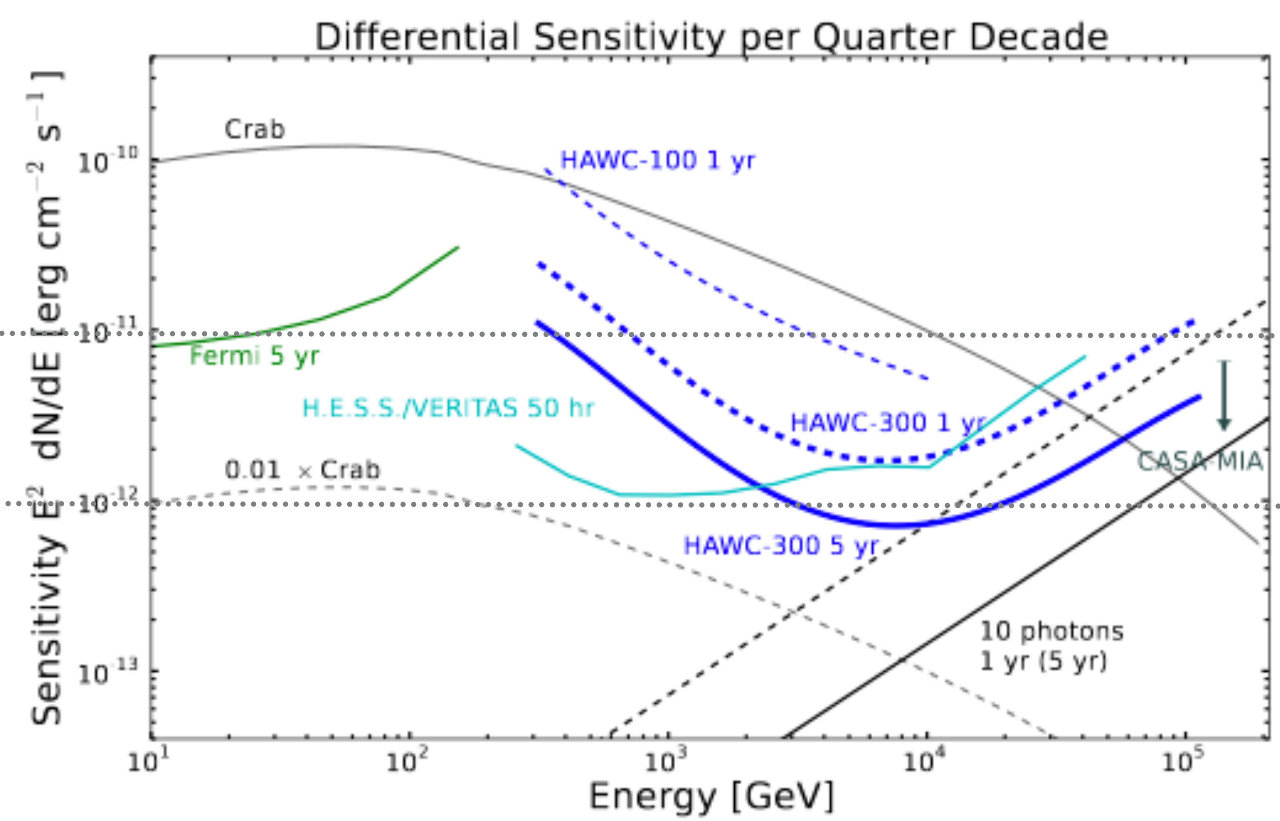
HAWC survey

Partial declination match (+19°) with CTA-S (-25°)
Comparison is good for steady sources (EHBL?)
Arguably HAWC will provide clear indications for targets to go deep observing with IACTs (H.E.S.S., ASTRI mini-array, CTA-SST array)



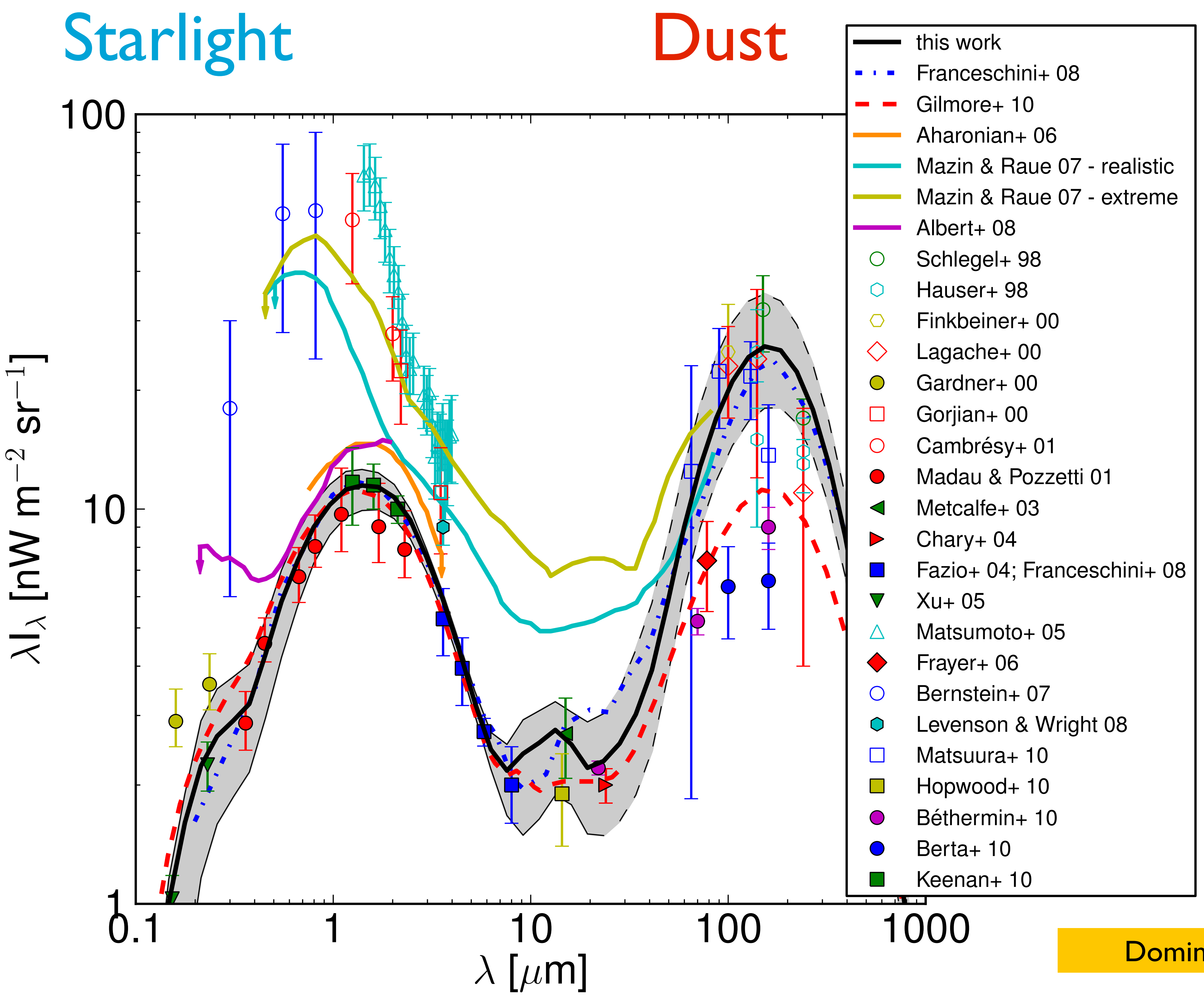
Abeysekara+ 2013





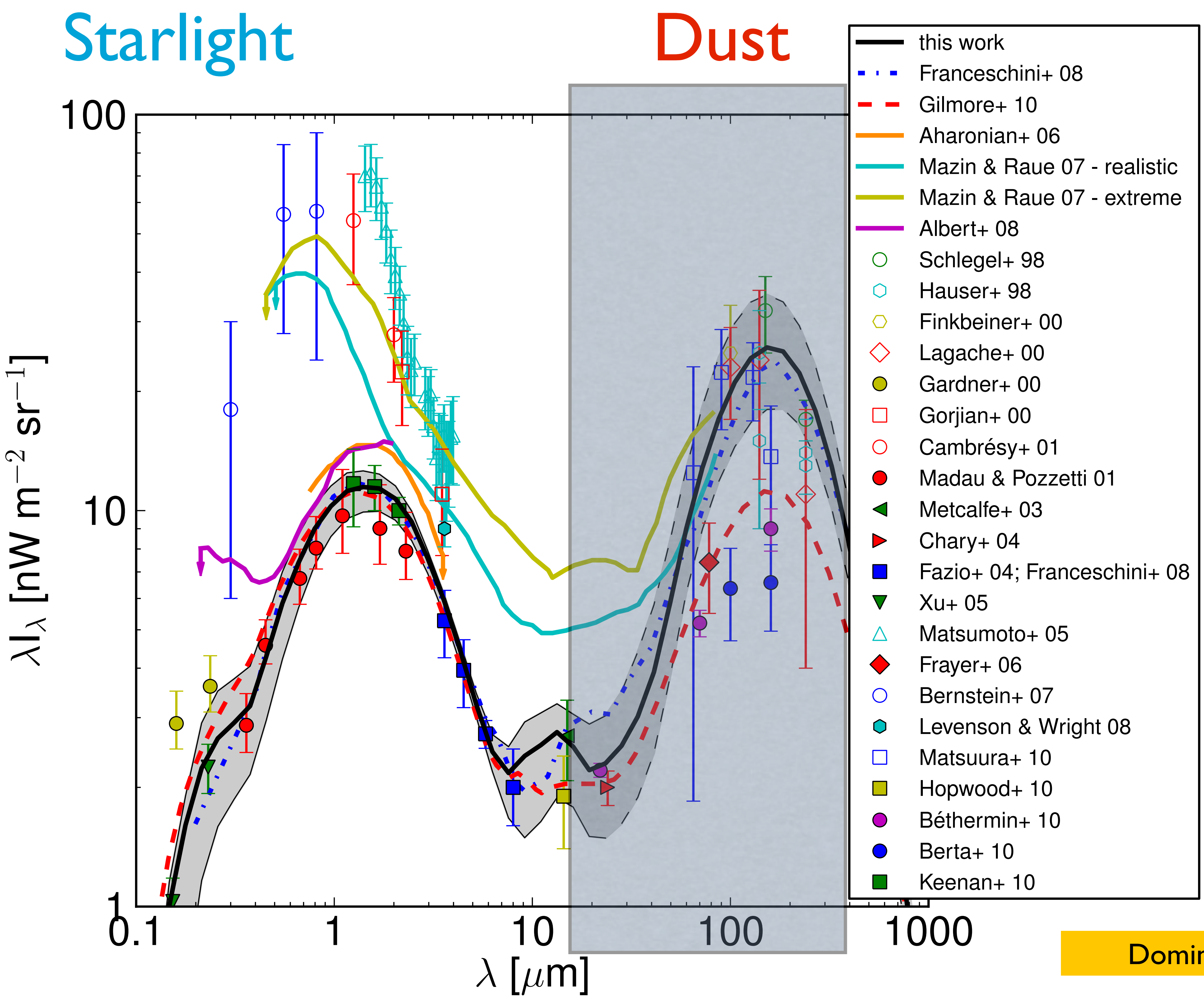
http://arxiv.org/pdf/1306.5800v1.pdf

EHBLs as far-IR EBL beacon probes



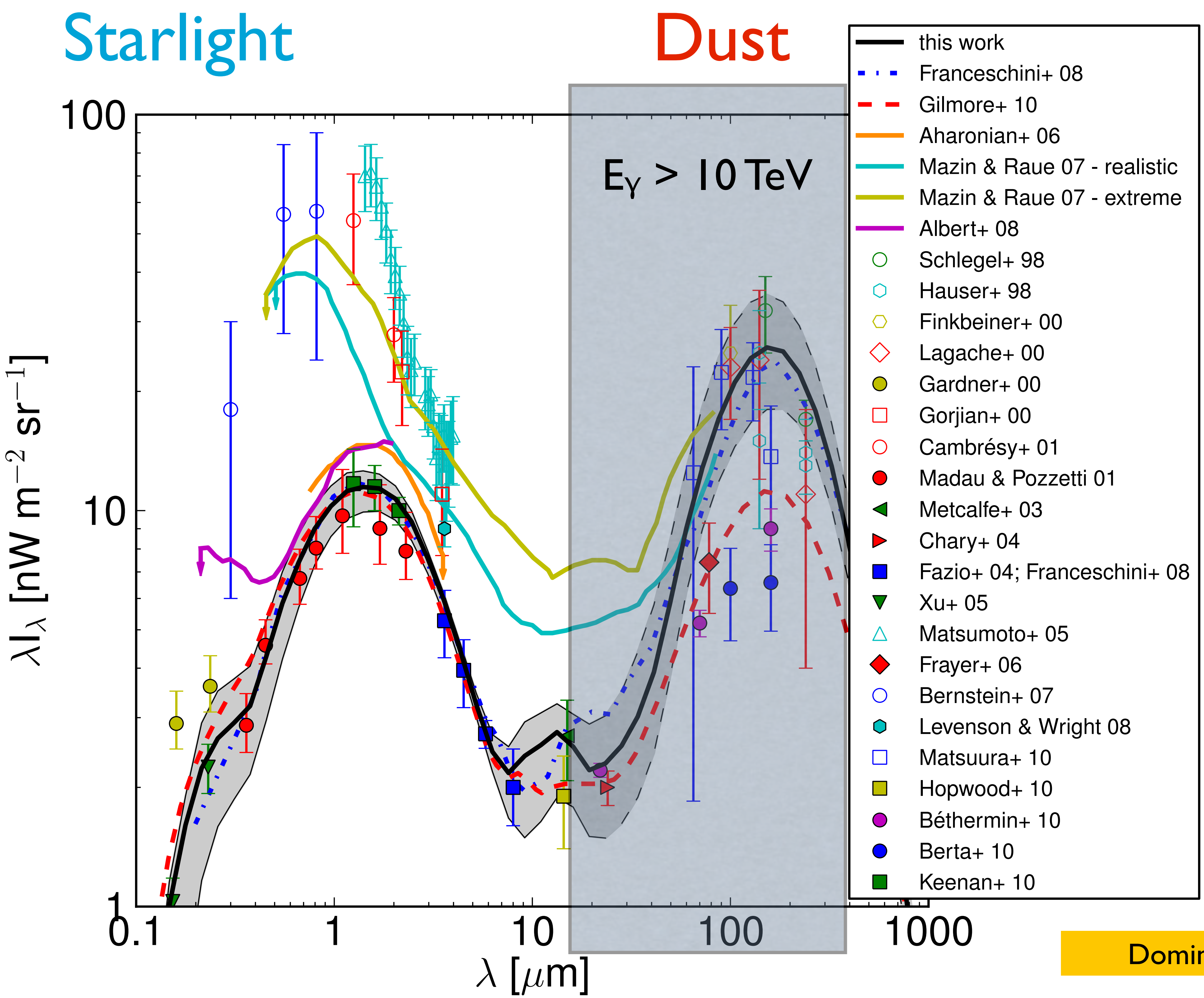
Dominguez+ 2011

EHBLs as far-IR EBL beacon probes



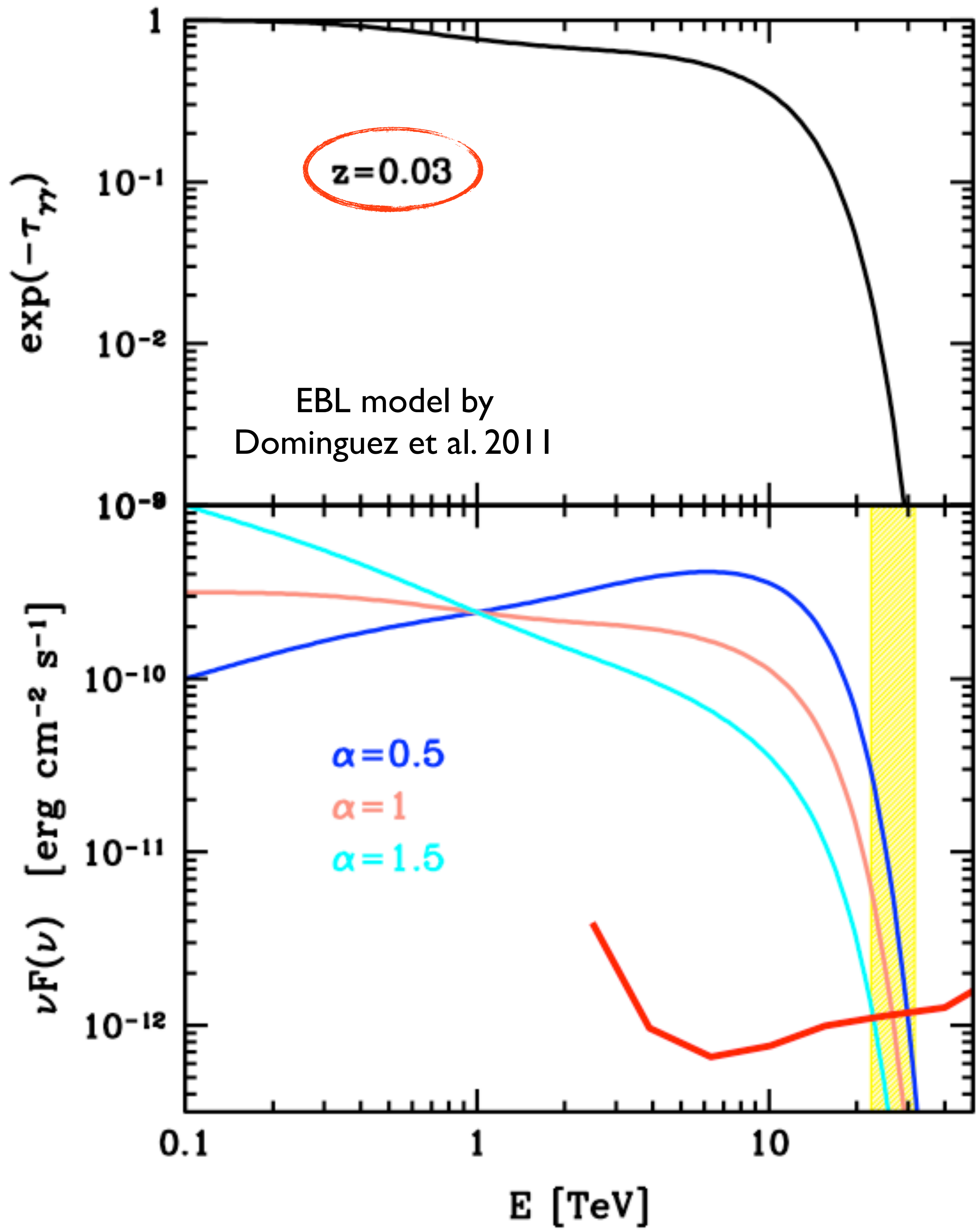
Dominguez+ 2011

EHBLs as far-IR EBL beacon probes



Dominguez+ 2011

The "EBL wall"



E max ~30 TeV

Cosmic opacity anomaly: LIV

LIV induces an effective mass for the photon

$$\beta_\gamma = 1 - \left(\frac{E_\gamma}{M_{LVn}}\right)^n \quad ; \quad m_\gamma^2 = -\frac{E_\gamma^{2+n}}{M_{LVn}^n},$$

Modification of threshold for pair production at high E

LIV induces suppression of EBL-opacity

Fairbairn+ 2014

CTA-SST

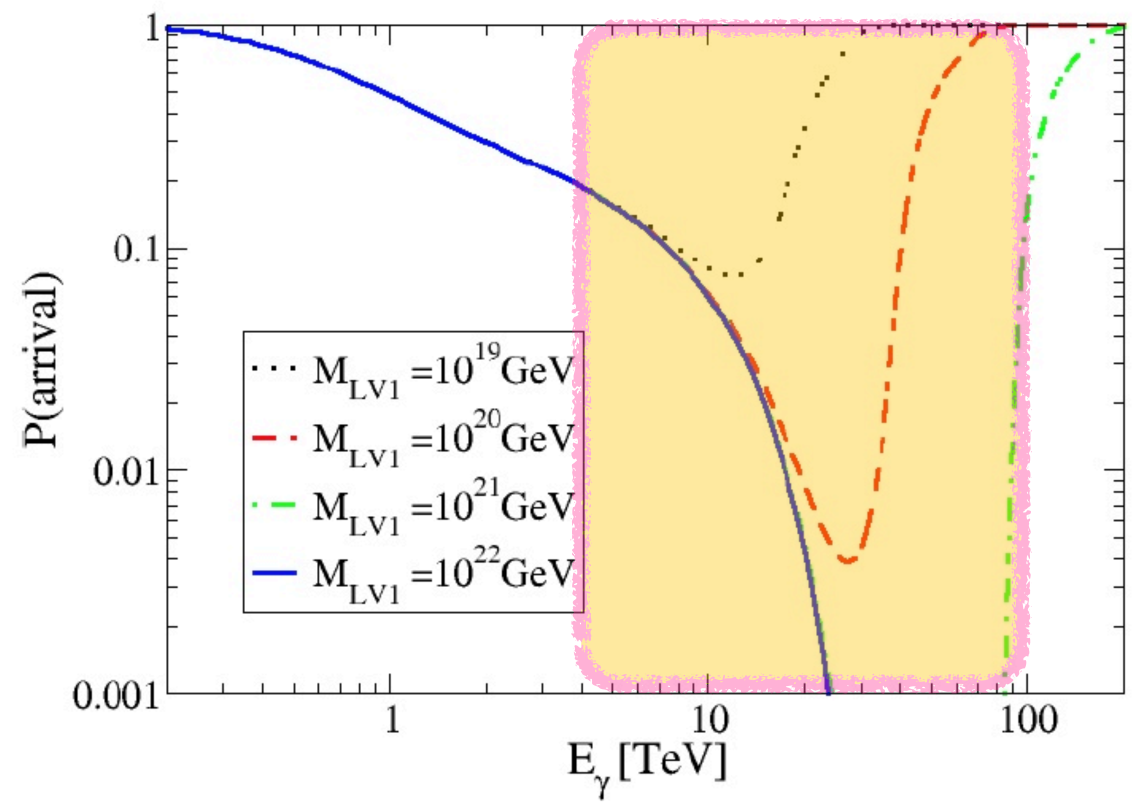
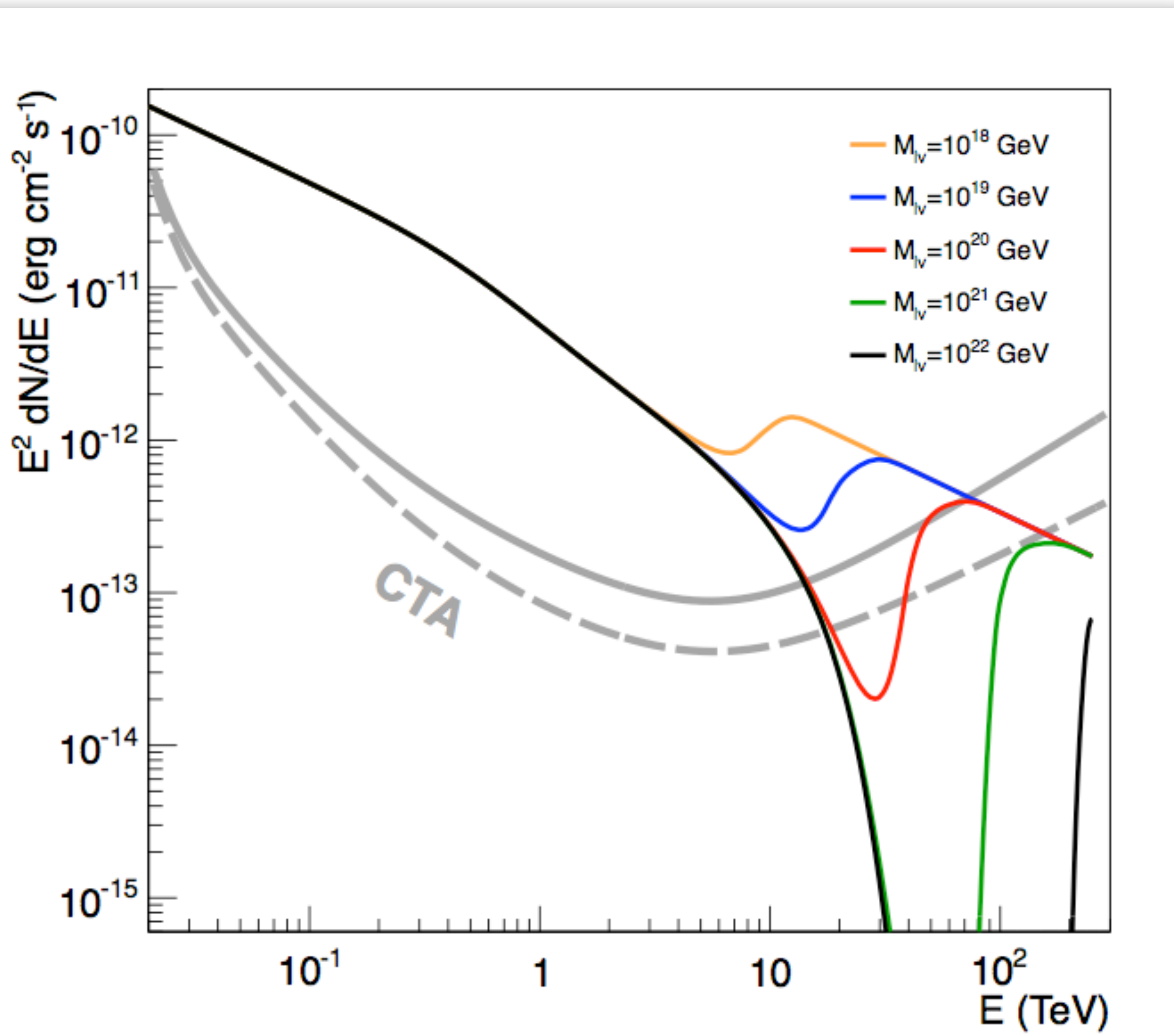
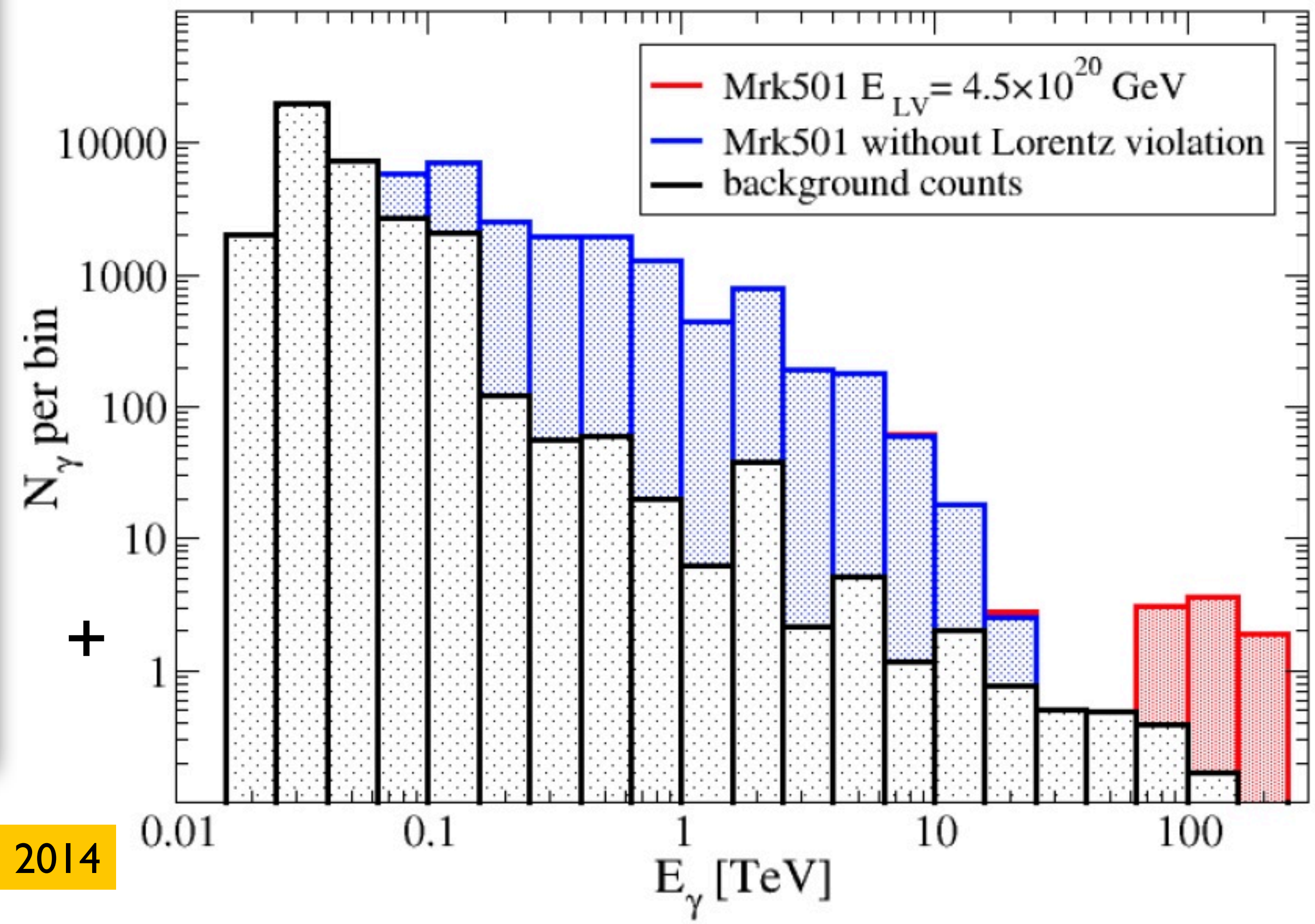


Figure 2. *The arrival probability of a photon emitted from a hypothetical source at redshift $z = 0.05$ as a function of energy. The different curves represent different values of the Lorentz-violating scale M_{LV1}. VHE photons with energies $\gtrsim 100$ TeV can travel through the CMB effectively unimpeded.*

Cosmic opacity anomaly: LIV





Fairbairn+ 2014

Astronomy & Astrophysics manuscript no. paper
October 6, 2015 ©ESO 2015

On the detectability of Lorentz invariance violation through anomalous multi-TeV γ-ray spectra of blazars

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October 6, 2015

ABSTRACT

Context. Cosmic opacity for very high-energy gamma rays ($E > 10$ TeV) due to the interaction with the extragalactic background light can be strongly reduced because of possible Lorentz-violating terms in the particle dispersion relations expected, e.g., in several versions of quantum gravity theories.
Aims. We discuss the possibility to use very high energy observations of blazars to detect anomalies of the cosmic opacity induced by LIV, considering in particular the possibility to use – besides the bright and close-by BL Lac Mkn 501 – *extreme* BL Lac objects.
Methods. We derive the modified expression for the optical depth of γ rays considering also the redshift dependence and we apply it to derive the expected high-energy spectrum above 10 TeV of Mkn 501 in high and low state and the extreme BL Lac 1ES 0229+200.
Results. We find that, besides the nearby and well studied BL Lac Mkn 501 – especially in high state –, suitable targets are *extreme* BL Lac objects, characterized by quite hard TeV intrinsic spectra likely extending at the energies relevant to detect LIV features.

Key words. astroparticle physics – gamma rays: general – BL Lacertae objects: individual: Mkn 501, 1ES 0229+200

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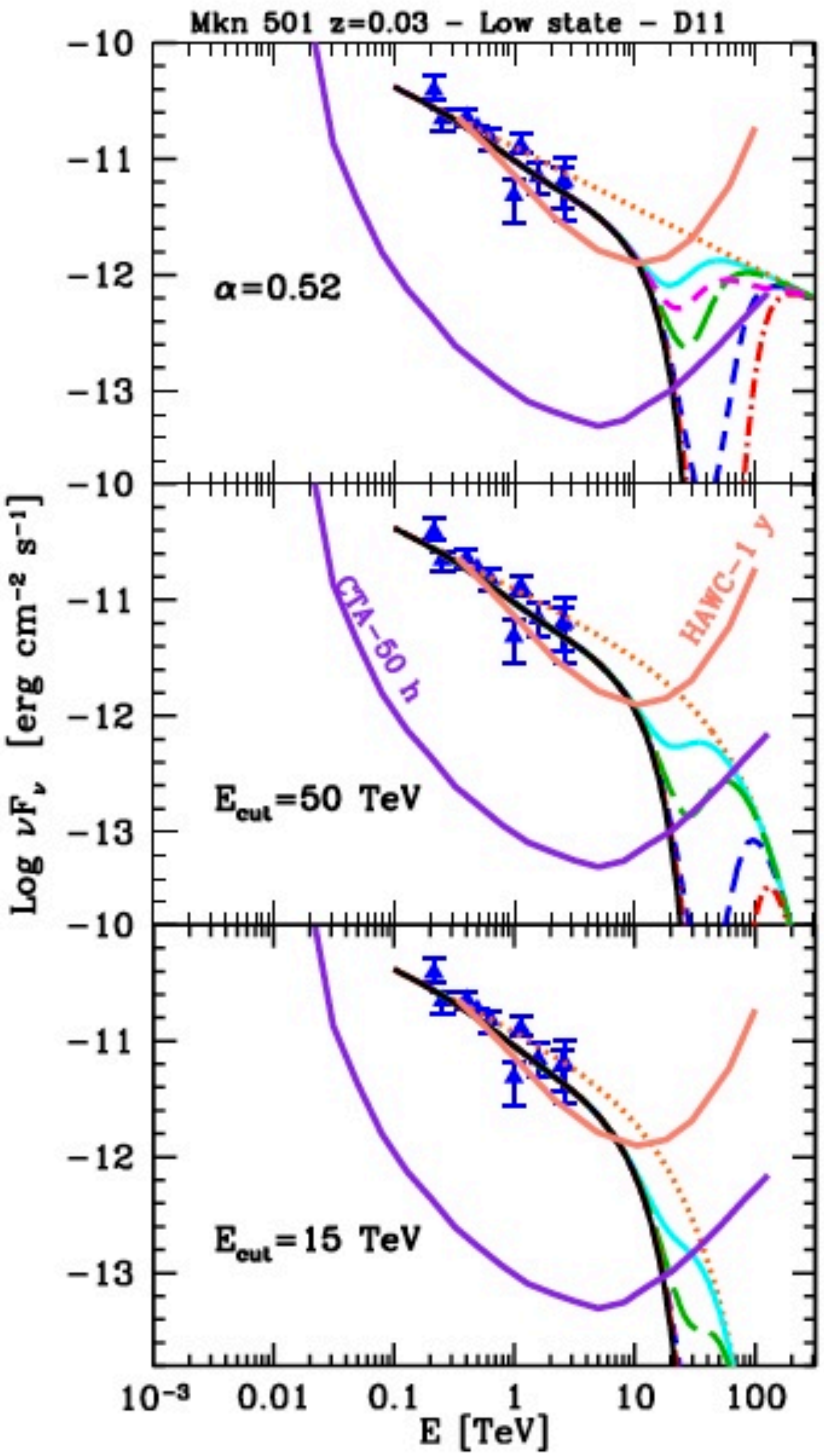

# of Lorentz invariance violation through
ıulti-TeV γ-ray spectra of blazars

F. Tavecchio and G. Bonnoli

ʹia E. Bianchi 46, I–23807 Merate, Italy

ABSTRACT

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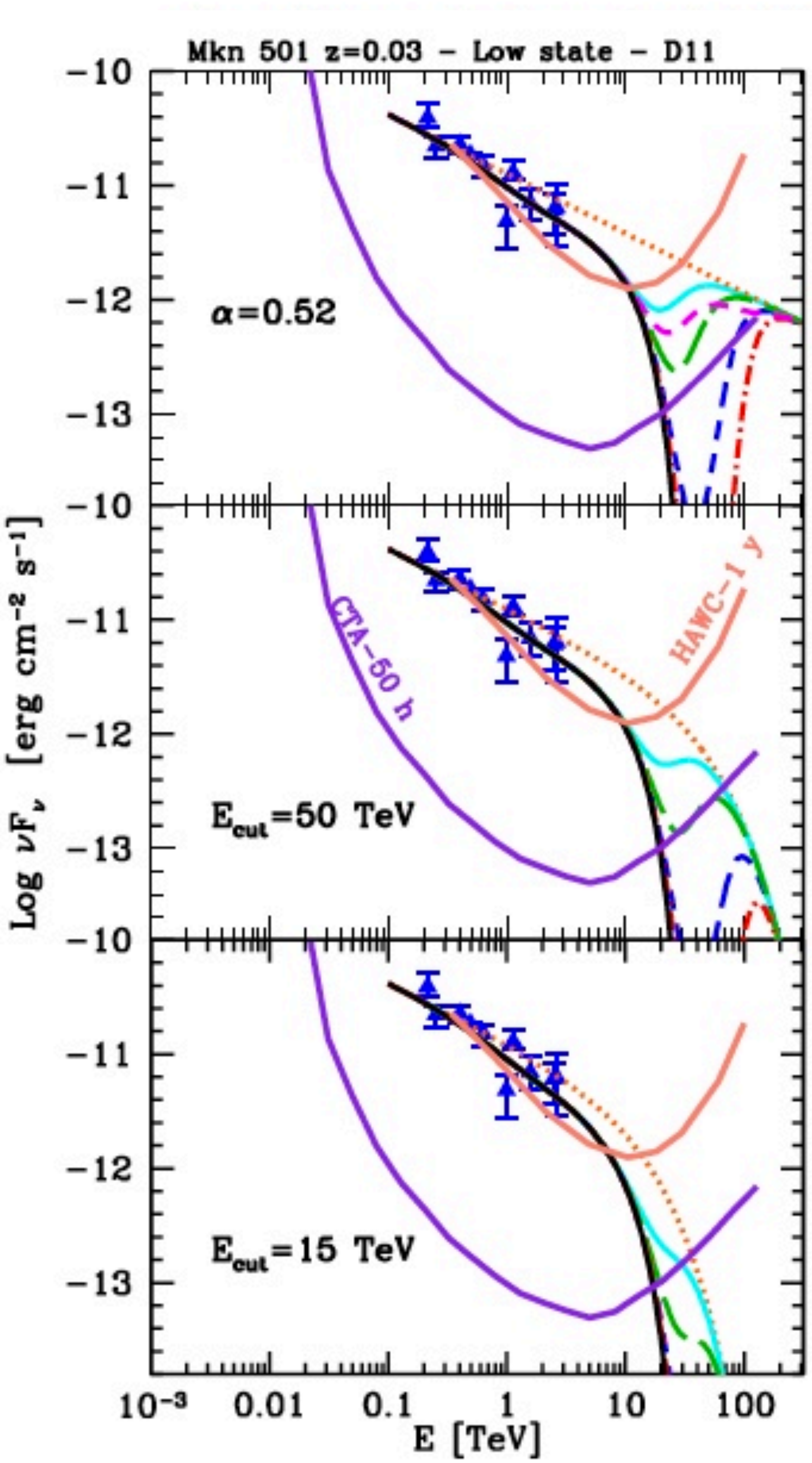

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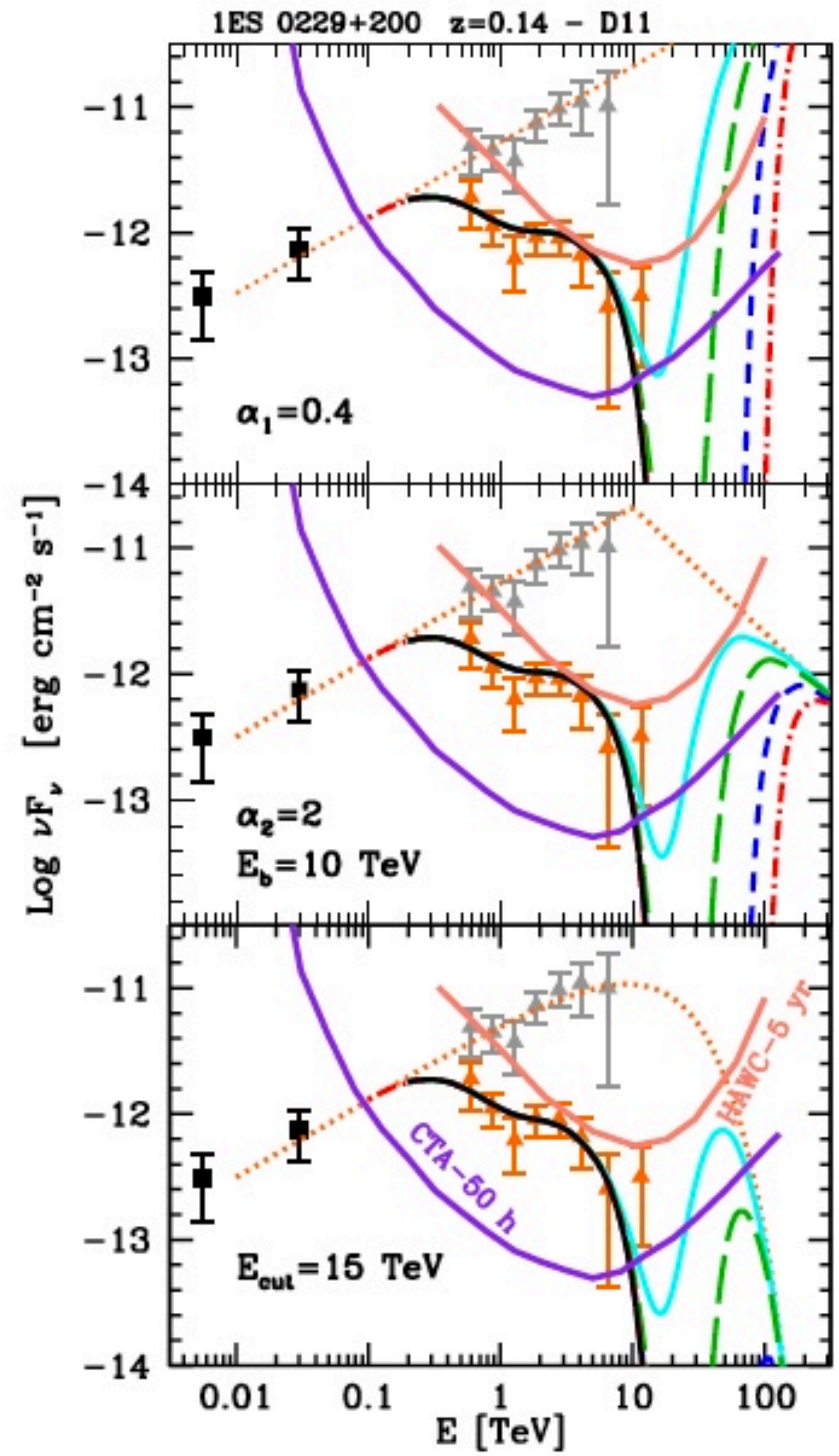

ABSTRACT

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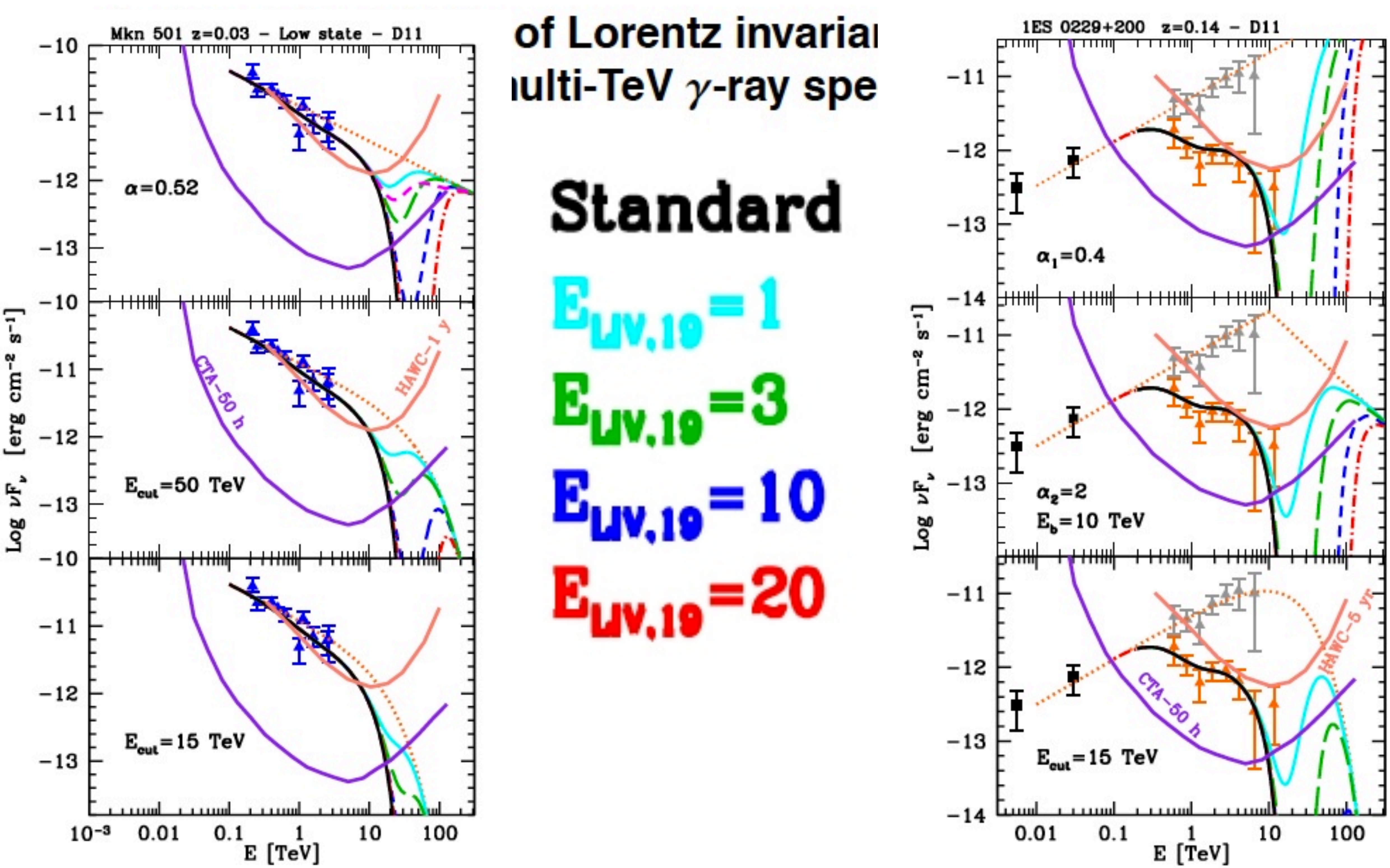

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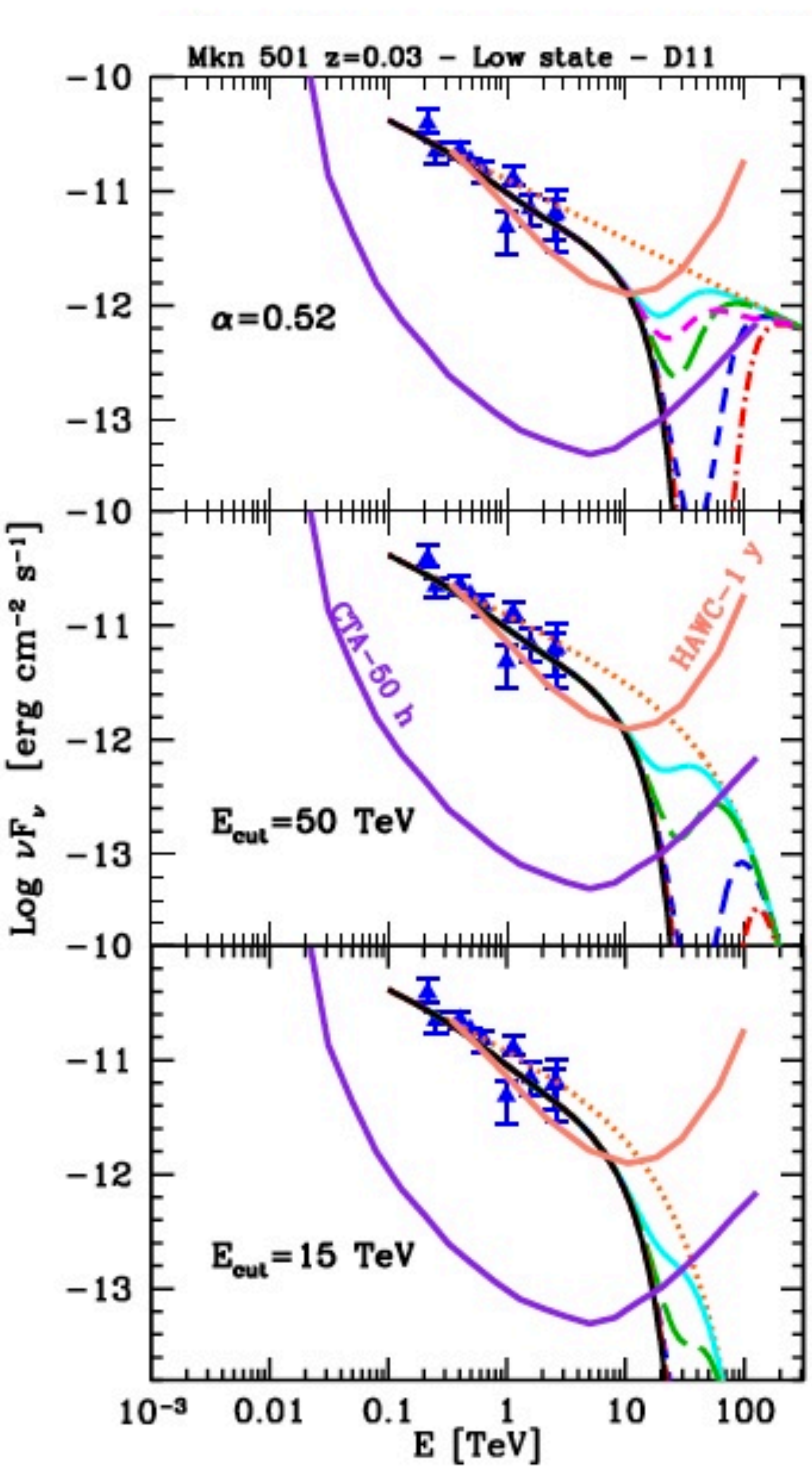

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ulti-TeV γ-ray spe

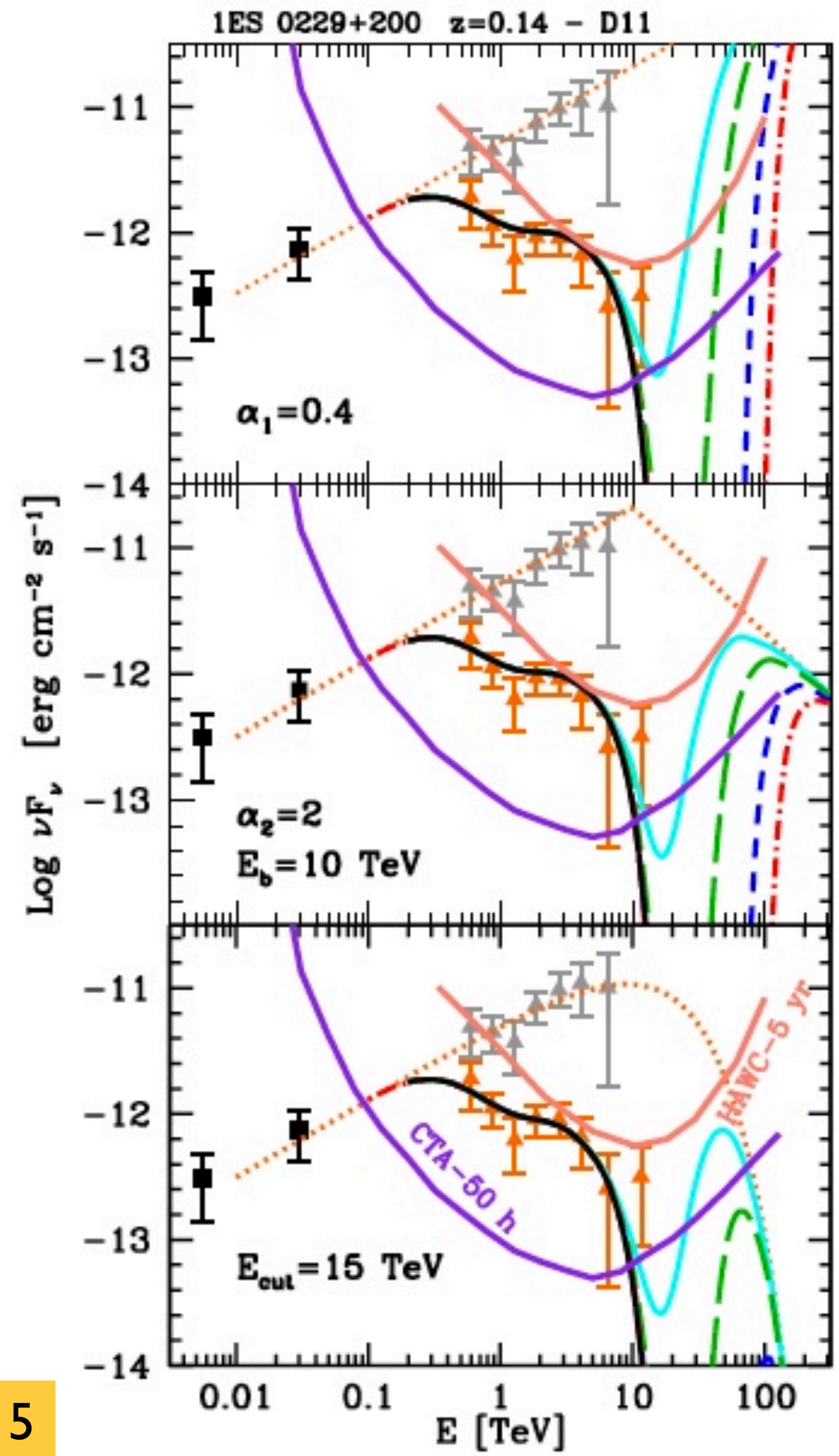
Standard

$E_{LIV,19} = 1$

$E_{LIV,19} = 3$

$E_{LIV,19} = 10$

$E_{LIV,19} = 20$



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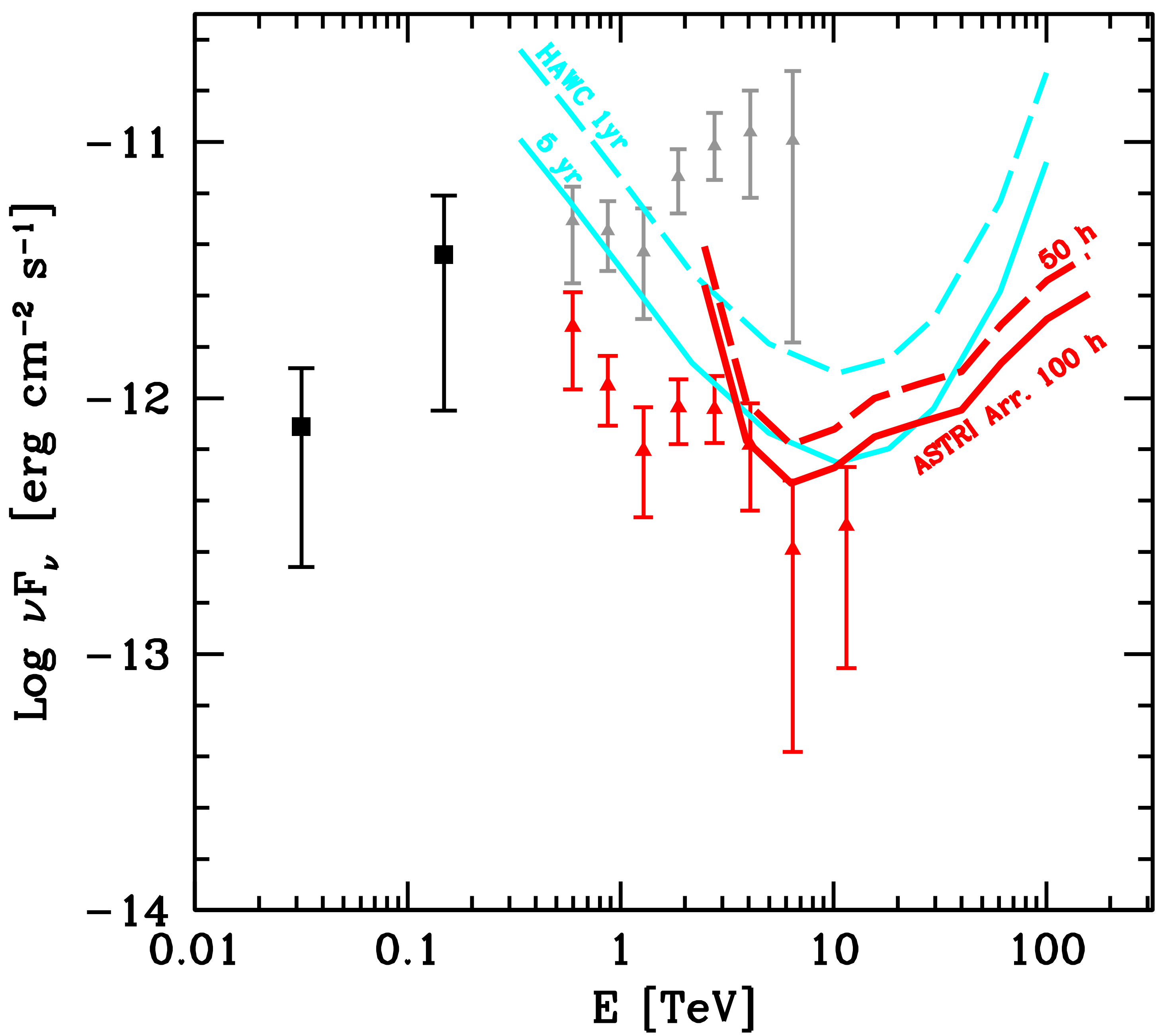
1ES 0229+200 VHE SED

Fermi/LAT
Vovk et al. 2012

HESS
Aharonian et al. 2007

HESS De-absorbed
with Dominguez+ 11

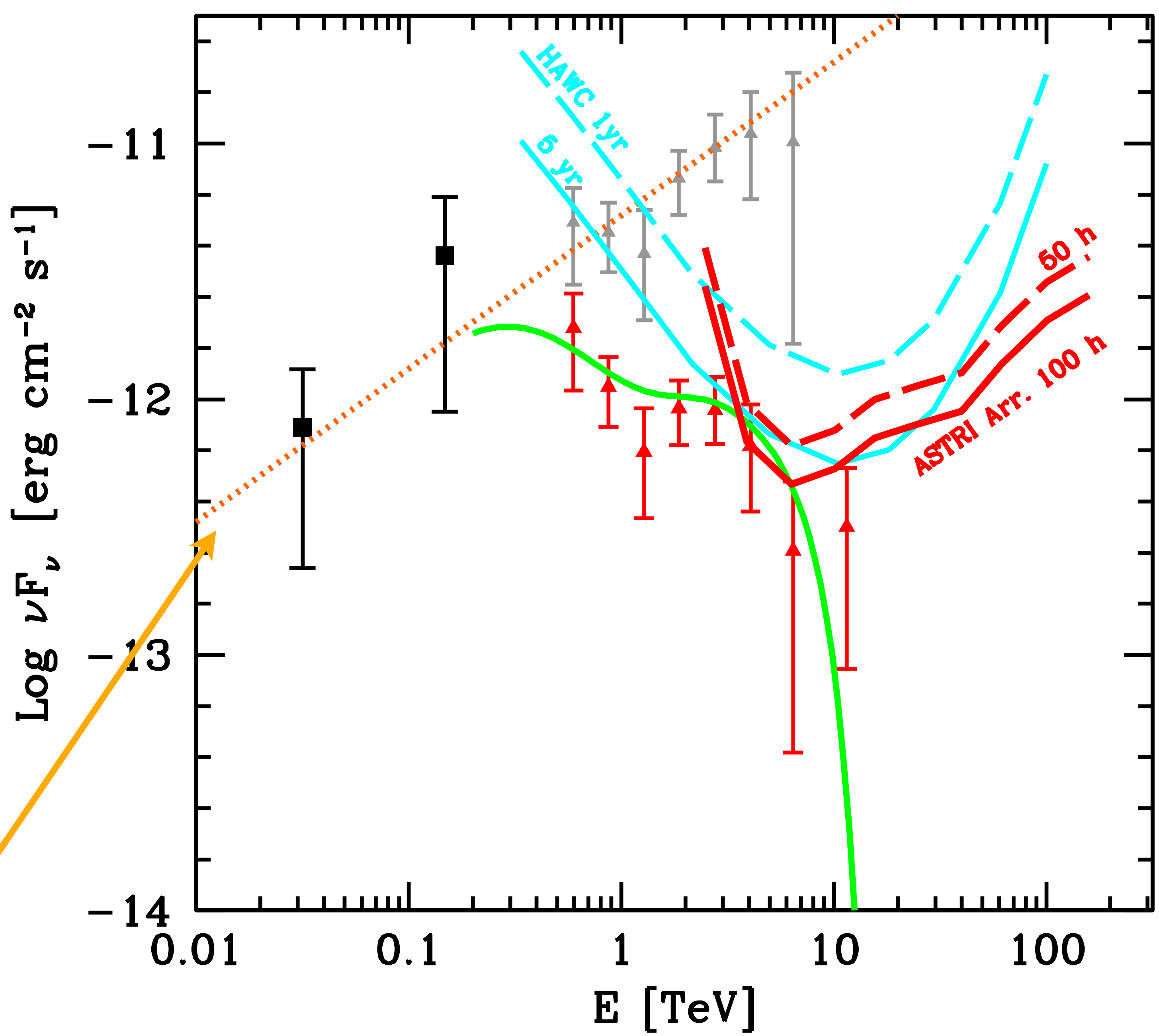


1ES 0229+200, a PL spectrum?

Fermi/LAT
Vovk et al. 2012

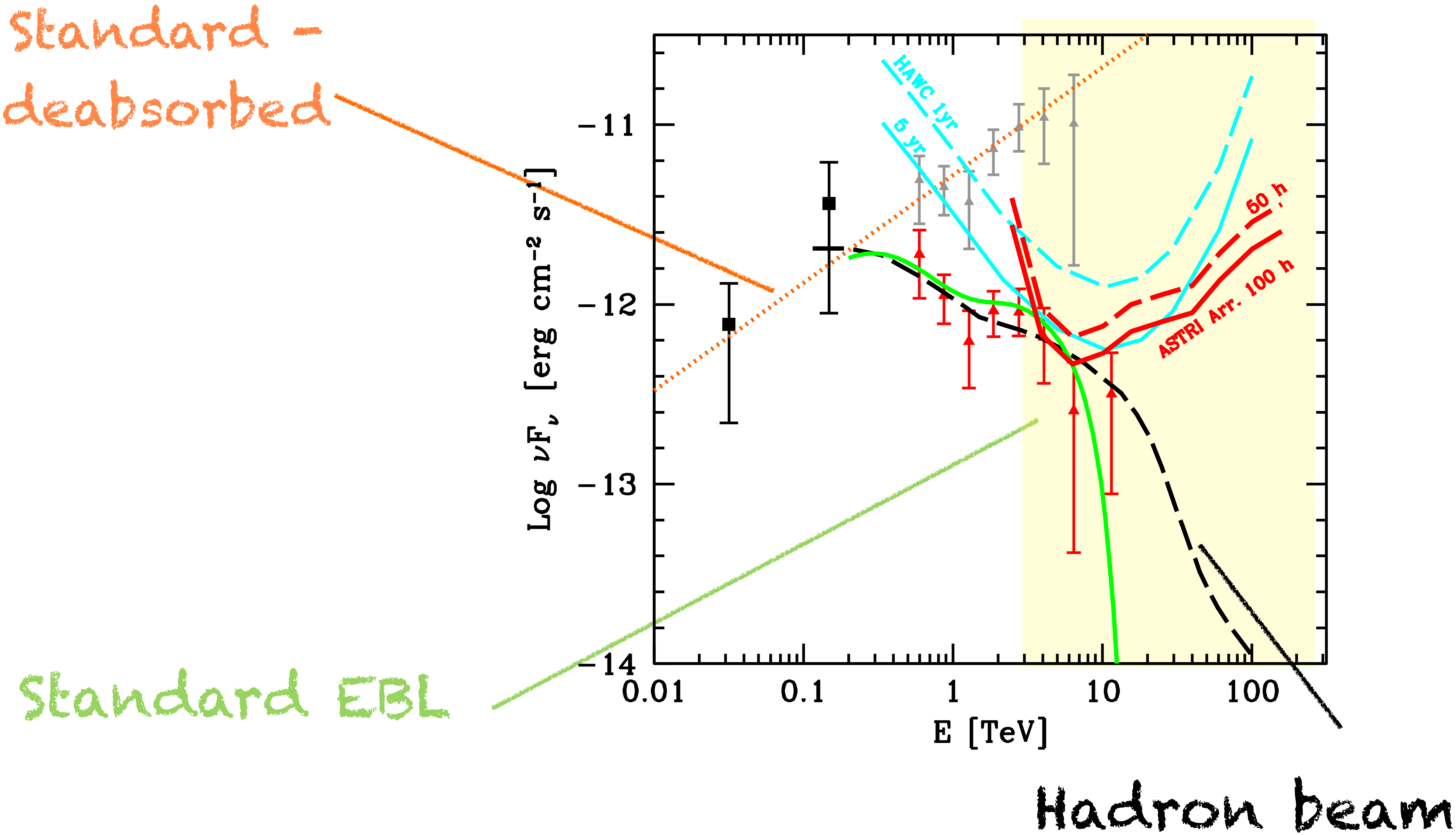
HESS
Aharonian et al. 2007

HESS De-absorbed
with Dominguez+ 11

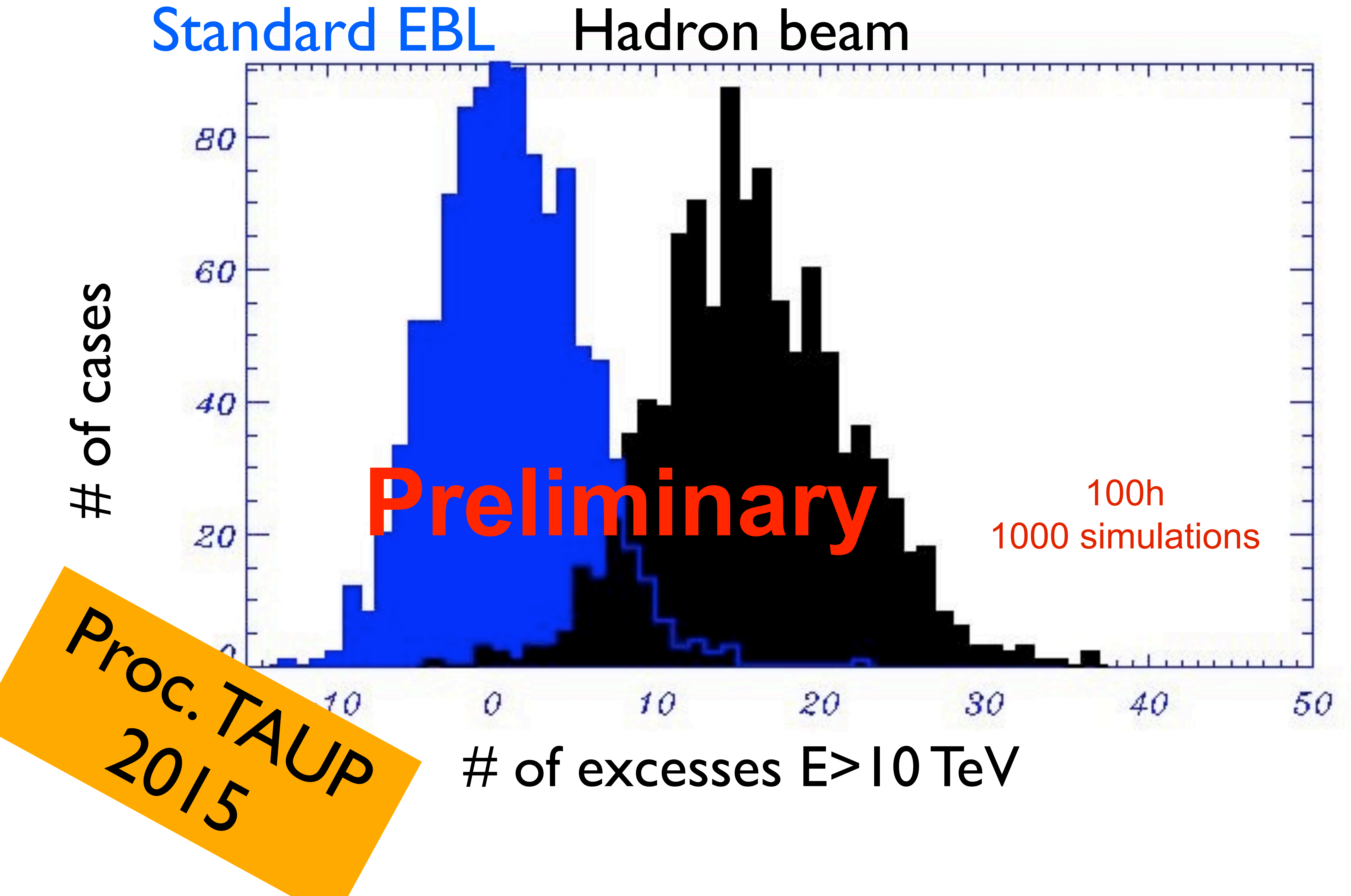


Intrinsic specrum compatible with hard, unbroken power law

Cosmic opacity anomaly: LIV



Leptonic vs hadron beam in 0229 w. ASTRI m.a.

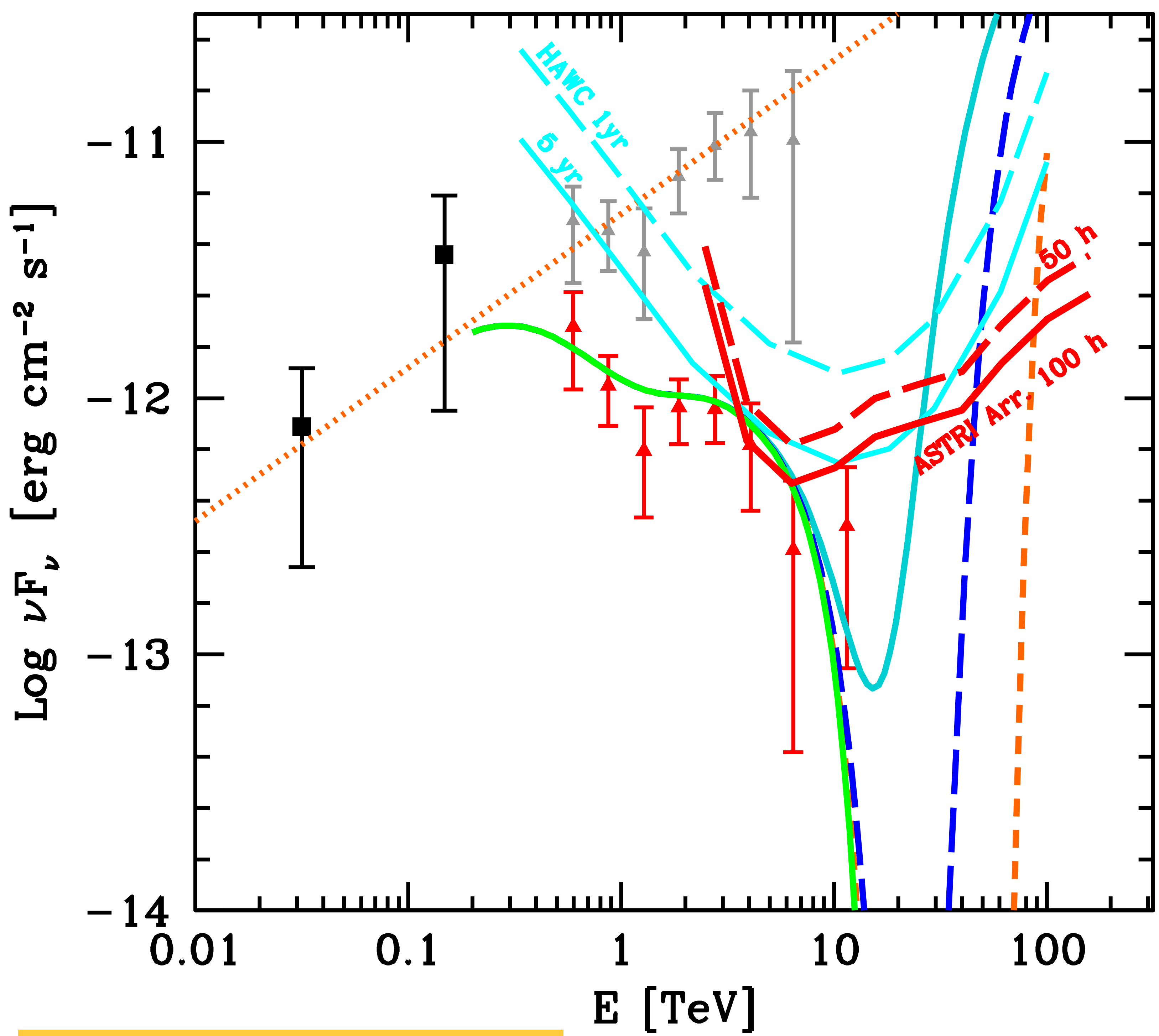


Cosmic opacity anomaly: LIV

$M_{LVI} = 10^{19}$ GeV

$M_{LVI} = 3 \times 10^{19}$ GeV

$M_{LVI} = 10^{20}$ GeV



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Summary

- Extreme HBL are intriguing but elusive sources... how to catch them?

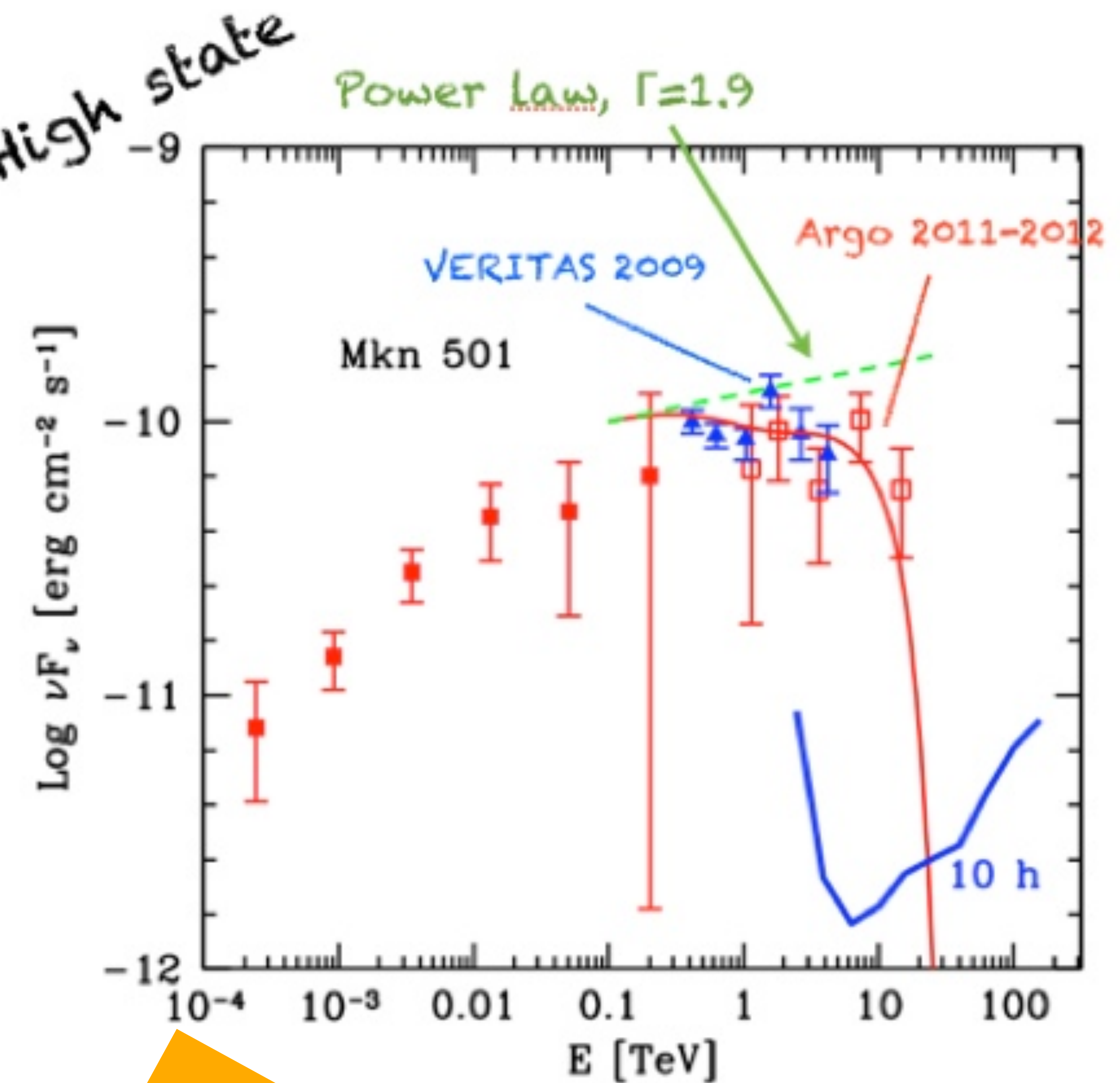
- As preferential TeV emitters, useful probes of the universe (EBL, IGMF, LIV...)

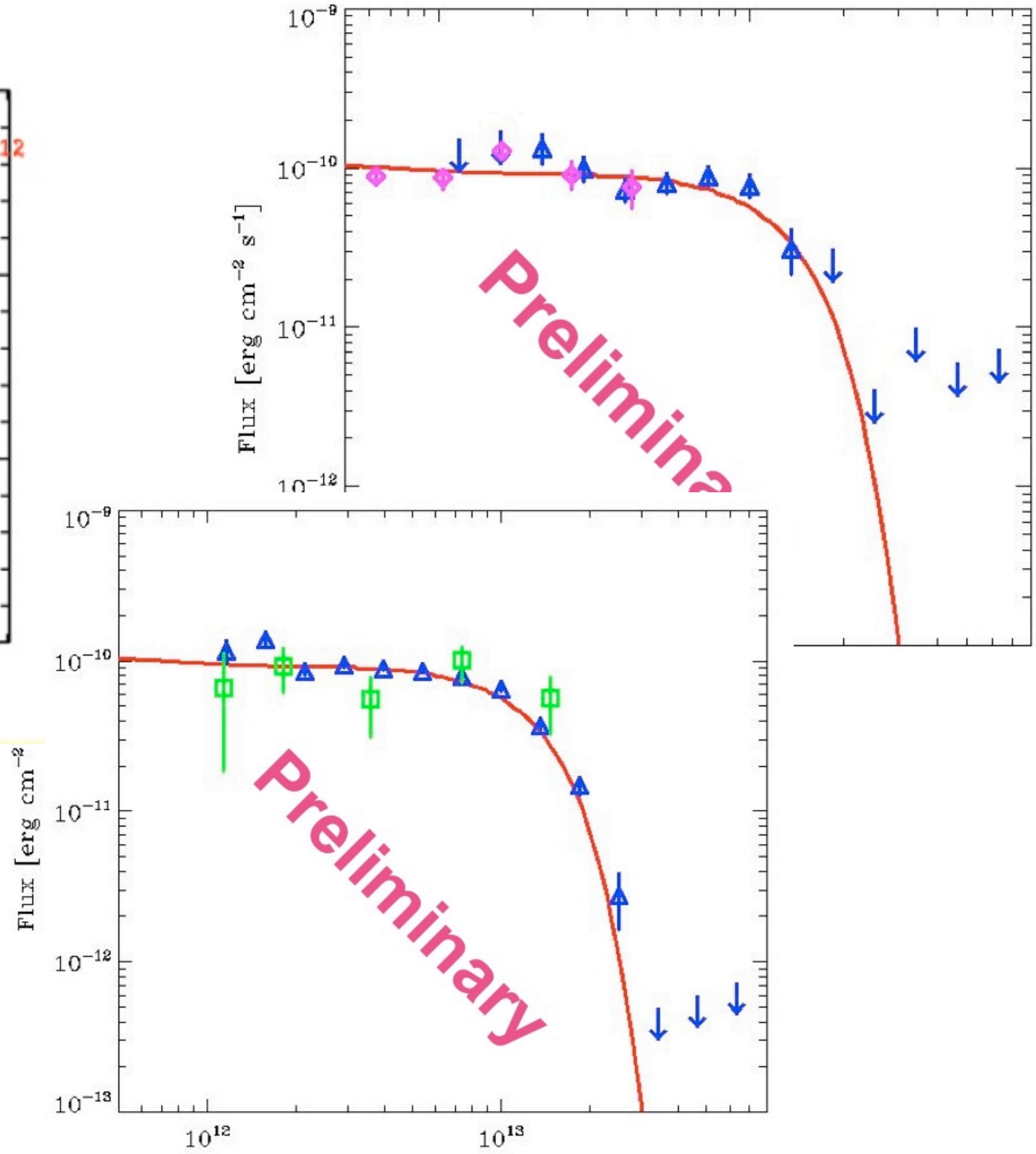
- The E> 10 TeV band may be of great interest for lots of physics

- Large scatter in expectations based on source spectrum (Still we don't know how generous Nature was to us ....)


THANK YOU!

Mrk 501 2009 flare with ASTRI m.a.





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