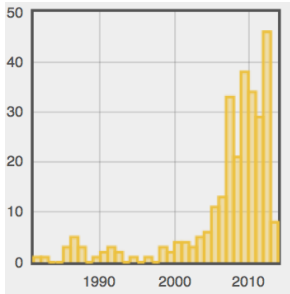
Signatures of Axion-Like Particles in TeV γ-ray Spectra and the Extragalactic Background Light

Frank Krennrich, Iowa State University

Motivations for ALP searches

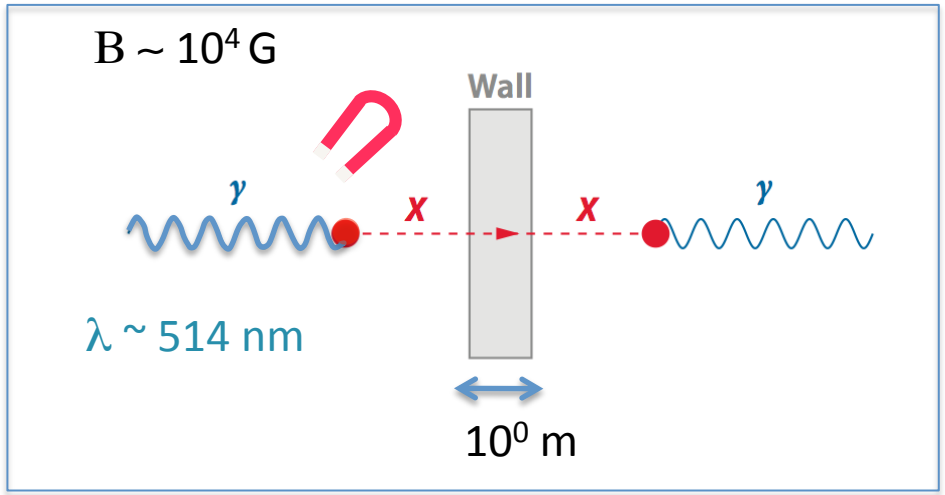


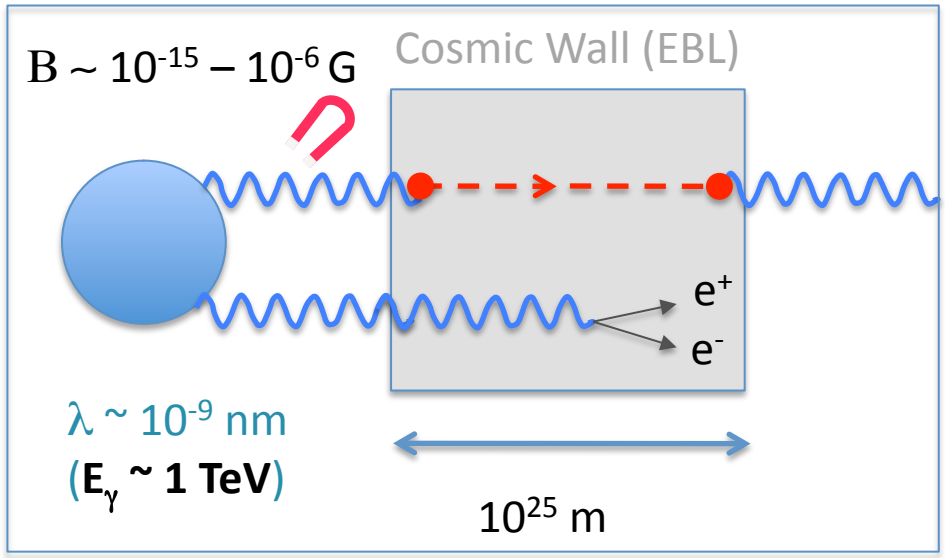
- Weakly Interacting Sub-eV Particles (WISPs) motivated by strong CP-problem (axions), string compactifications (ALPs), …
- Axion-like particles (ALPs) arise naturally in string theory
- astrophysical: Cold Dark matter candidate, couple to photons
- ALP's coupling constant $\mathbf{g_{a\gamma}}$ and mass $\mathbf{m_a}$ are not related

  → searches must cover entire parameter space in $\mathbf{g_{a\gamma}}$ and $\mathbf{m_a}$

  → wide range of experiments and astrophysical observations
- <u>ALP search</u> technique **with γ-rays** (Fermi, VERITAS, HAWC, CTA)

Light Shining Through Walls





- ALPs interact with electromagnetic fields via two photon coupling

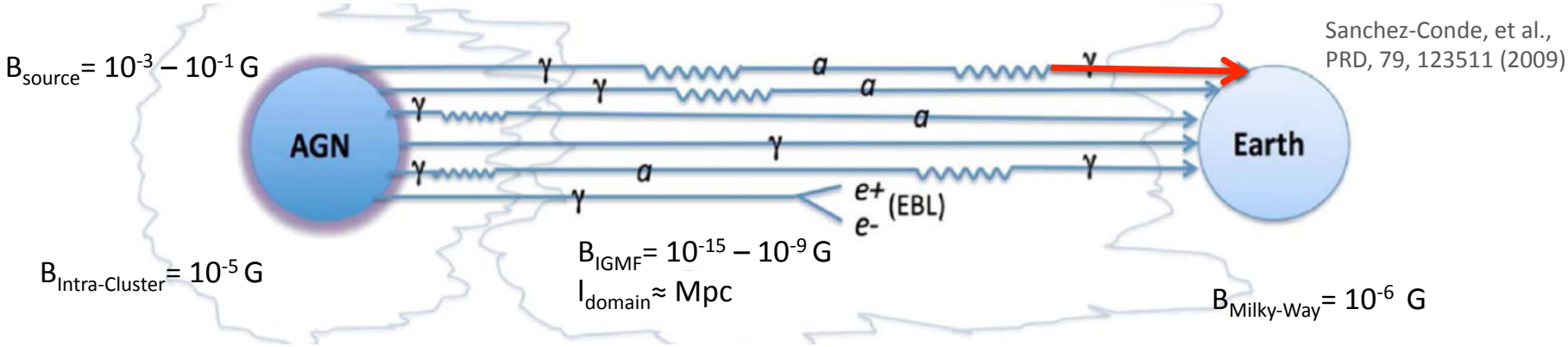
$$L \propto \frac{g_{a\gamma}}{4} \; \varphi \; F_{\mu\nu}\overline{F}^{\mu\nu}$$

- mass mixing term leads to photon-ALP oscillations

- photon-ALP oscillations occur <u>coherently</u> over macroscopic distances

- photon-ALP maximal in strong-mixing regime for photon energies larger than E_{crit}

Light Shining Through a Cosmic Wall



$$P_{osc} = \frac{1}{1+\left(\varepsilon_{crit}/E_{\gamma}\right)^2} \sin^2\left[\frac{g_{a\gamma} B\, l_{domain}}{2}\sqrt{1+\left(\varepsilon_{crit}/E_{\gamma}\right)^2}\right]$$

$$\varepsilon_{crit}[GeV] = \frac{\left(\frac{m_a}{10^{-6}eV}\right)^2\left(\frac{10^{-11}GeV^{-1}}{g_{a\gamma}}\right)}{0.4\left(\frac{B}{G}\right)}$$

Strong mixing if $E_{\gamma} > \varepsilon_{crit}$

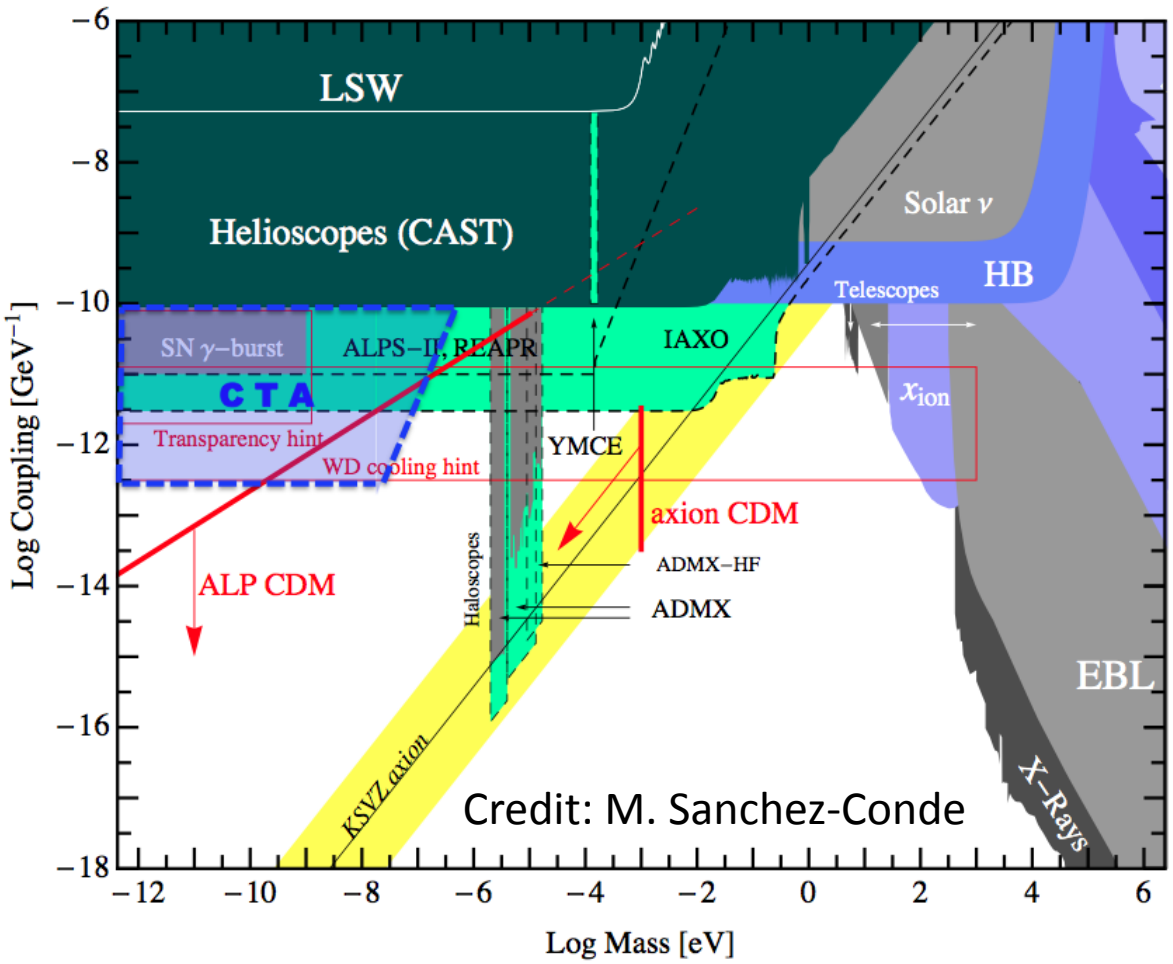
B = 0.1 nG (IGMF)

$m_a = 10^{-10}$ eV

$g_{a\gamma} = 10^{-10}$ GeV^{-1}

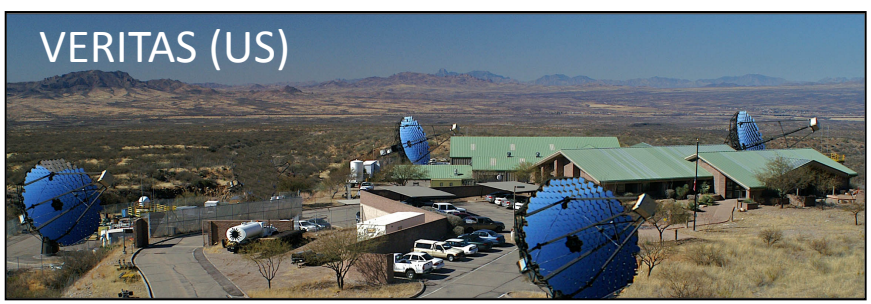
ε_{crit} = 1 TeV

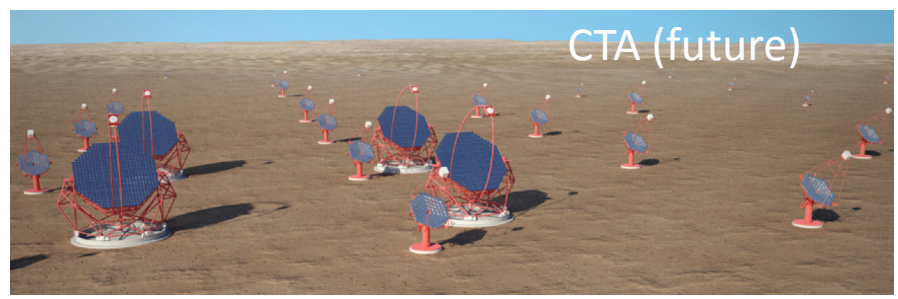
Sensitivity to ALPs



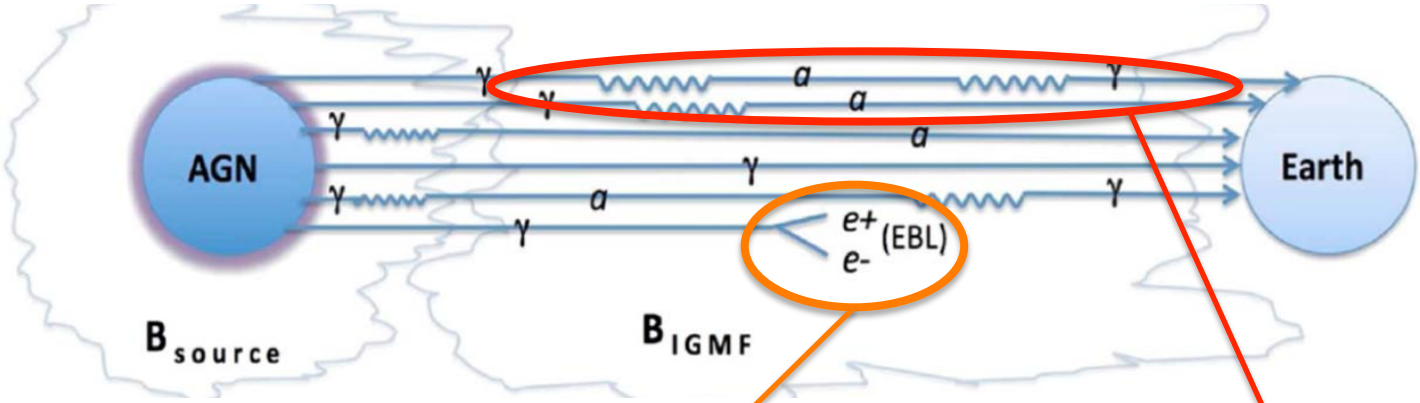
γ-ray constraints require:

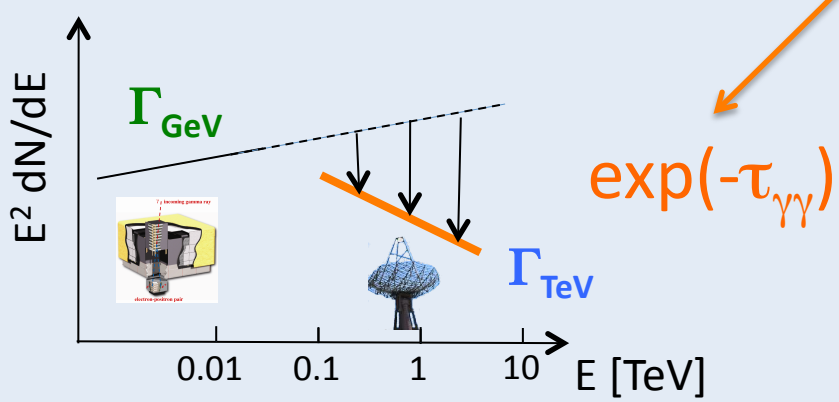
- ALP signature
- EBL intensity
- B_{IGMF}



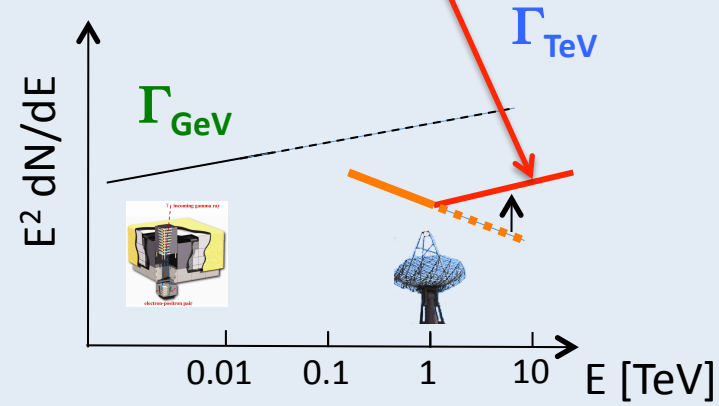


Signatures from the EBL & ALPs





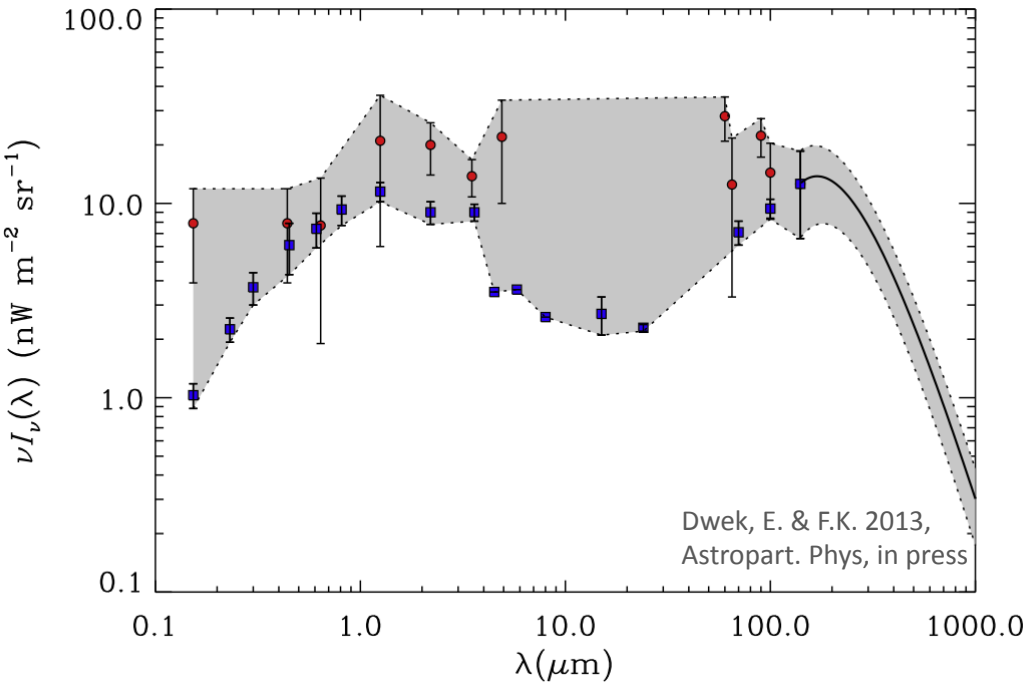
- Absorption of primary γ-rays by diffuse EBL
- spectra soften
- effect increases with distance (redshift z)



- component arises from **secondary γ-rays** generated by ALP-photon mixing
- spectra harden – characteristic energy
- **but spectral rise** may **not** be unique!

What is the intensity of the EBL?

What is the intensity of the EBL?

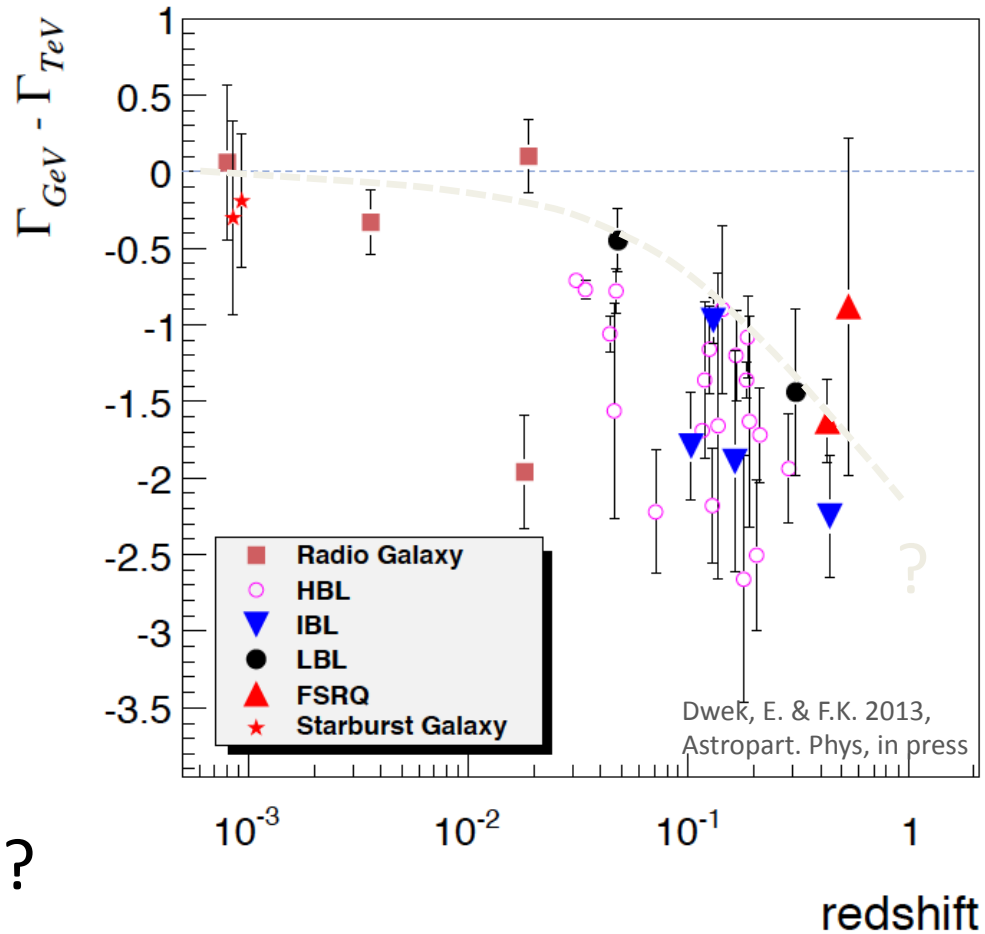


Constraints from fluctuation measurements

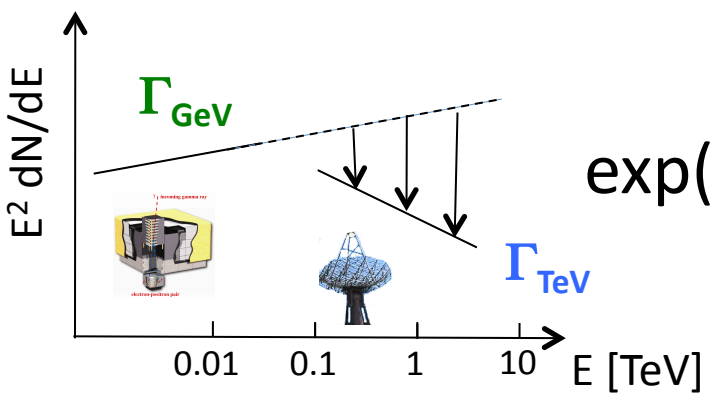
Lower limits from galaxy counts

GeV – TeV Sources: Blazars

Name	Class	redshift	α_{GeV}	α_{TeV}	Range [TeV]
Centaurus A	R. G.	0.0008	2.76±0.05	2.7±0.5	0.2 - 5
M82	S.B.G.	0.00085	2.2±0.2	2.5±0.6	0.7 - 4
NGC253	S.B.G.	0.00093	1.95±0.4	2.14±0.18	0.3 - 50
M87	R. G.	0.0036	2.17±0.07	2.5±0.2	0.2 - 10
NGC 1275	R. G.	0.018	2.00±0.02	3.96±0.37	0.1 - 0.3
IC 310	R. G.	0.0188	2.10±0.19	2.0±0.14	0.1 - 7
Markarian 421	HBL	0.031	1.77±0.01	2.48±0.03*	0.1 - 5
Markarian 501	HBL	0.034	1.74±0.03	2.51±0.05△	0.1 - 10
1ES 2344+514	HBL	0.044	1.72±0.08	2.78±0.09△	0.3 - 2
Markarian 180	HBL	0.046	1.74±0.08	3.3±0.70	0.2 - 1
1ES 1959+650	HBL	0.047	1.94±0.03	2.72±0.14	0.2 - 2
AP Lib*	LBL	0.048	2.05±0.04	2.5±0.2	0.3 - 2
BL Lacertae	LBL	0.069	2.11±0.04	3.6±0.5	0.2 - 1
PKS 2005-489	HBL	0.071	1.78±0.05	4.0±0.4	0.2 - 2
W Comae	IBL	0.103	2.02±0.03	3.81±0.35	0.3 - 1
PKS 2155-304	HBL	0.116	1.84±0.02	3.53±0.05	0.4 - 5
B3 2247+381	HBL	0.119	1.84±0.11	3.2±0.5	0.2 - 1
RGB J0710+591	HBL	0.125	1.53±0.12	2.69±0.26	0.3 - 4.6
H 1426+428	HBL	0.129	1.32±0.12	3.50±0.35	0.3 - 10
1ES 1215+303	IBL	0.13♡	2.02±0.02	2.99±0.15	0.1 - 1
1ES 0806+524	HBL	0.137	1.94±0.06	3.6±1.0	0.3 - 0.7
1RXS J101015.9-311909	HBL	0.143	2.24±0.14	3.14±0.53	0.3 - 1
1ES 1440+122	IBL	0.163	1.41±0.18	3.3±0.7	0.3 - 1
H 2356-309	HBL	0.165	1.89±0.17	3.09±0.24	0.3 - 2
VER J0648+152	HBL	0.179	[illegible]	[illegible]	0.3 - 0.8
1ES 1218+304	HBL	0.184	1.71±0.07	3.07±0.09	0.2 - 2
1ES 1101-232	HBL	0.186	[illegible]	[illegible]	0.16 - 3.3
RBS 0413	HBL	0.19	1.55±0.11	3.18±0.68	0.25 - 1
PKS-0447-439	HBL	0.205	1.86±0.02	4.36±0.49	0.25 - 1
1ES 1011+496	HBL	0.212	1.72±0.04	4.0±0.50	0.25 - 0.6
1ES 0414+009	HBL	0.287	1.98±0.16	3.44±0.27	0.25 - 1.2
S5 0716+714	LBL	0.31	2.01±0.02	3.45±0.54	0.25 - 1.2
1ES 0502+675	HBL	0.416♣	1.49±0.07	3.92±0.35	0.25 - 1
4C 21.35	FSRQ	0.43	2.12±0.02	3.75±0.27	0.07 - 0.4
3C 66A	IBL	0.44♣	1.85±0.02	4.1±0.4	0.22 - 0.45
3C 279	FSRQ	0.536	2.22±0.02	3.03±0.9	0.1 - 0.35



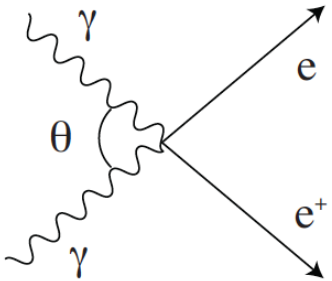
Dwek, E. & F.K. 2013, Astropart. Phys, in press

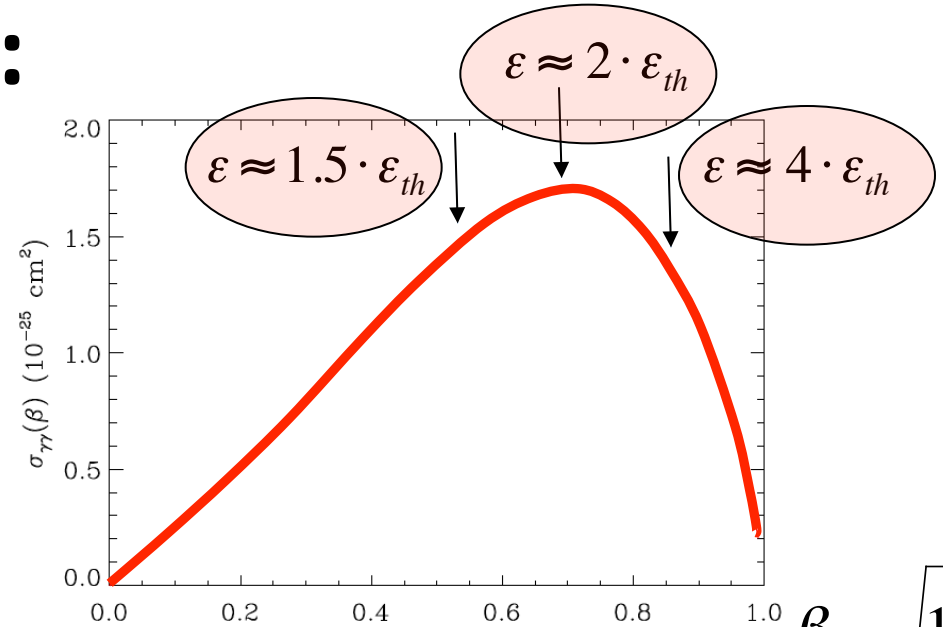


$\exp(-\tau_{\gamma\gamma})$?

- scatter due to deviation from power law in source spectrum?

γ-ray Absorption: cross section





$$\beta = \sqrt{1 - \frac{\varepsilon_{th}}{\varepsilon}}$$

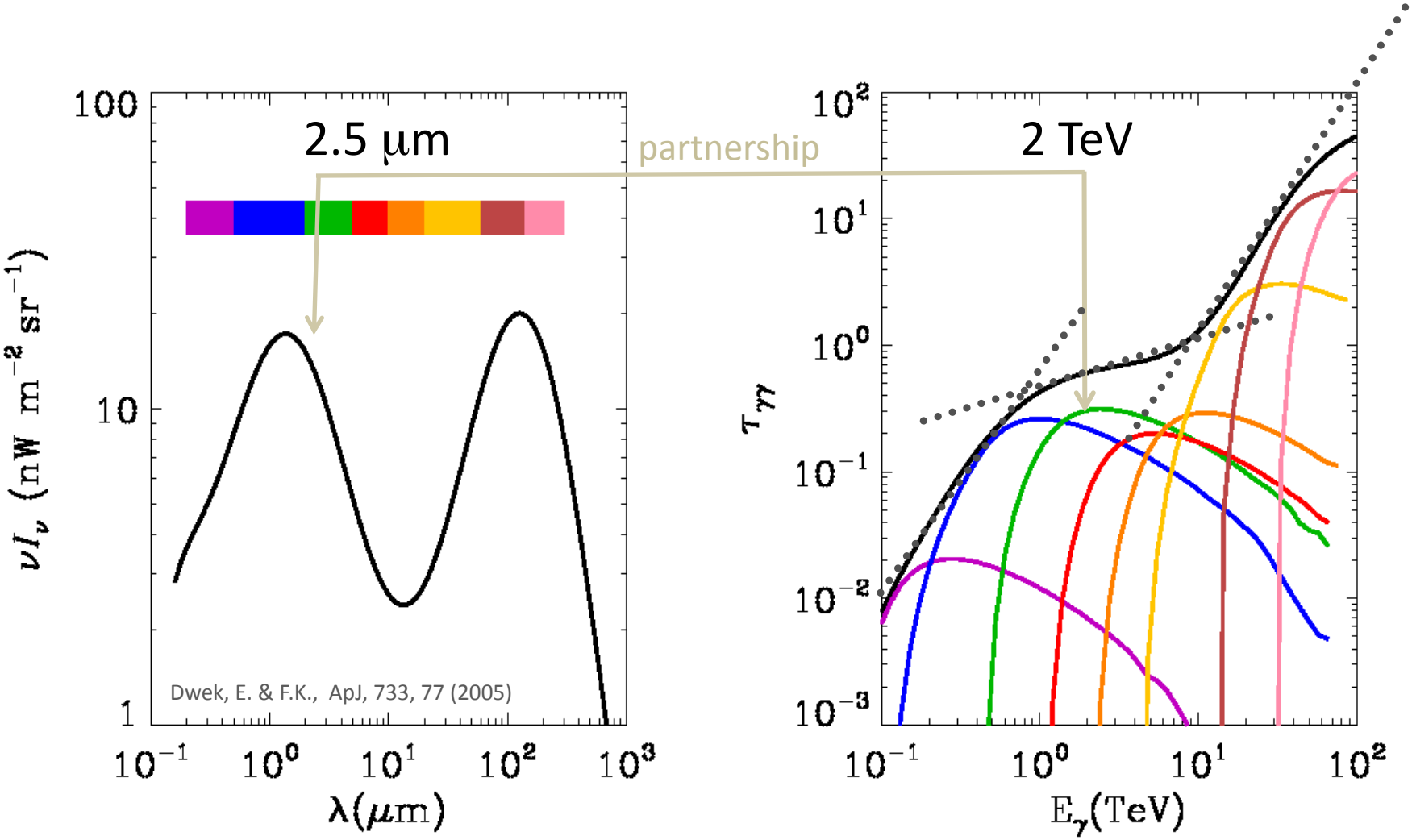
$$\varepsilon_{th}(E_\gamma, \mu, z) = \frac{2(m_e c^2)^2}{E_\gamma (1 - \cos\theta)}$$

$$\sigma_{\gamma\gamma}(E_\gamma, \varepsilon, \mu, z) = \frac{3\sigma_T}{16}(1 - \beta^2) f(\beta)$$

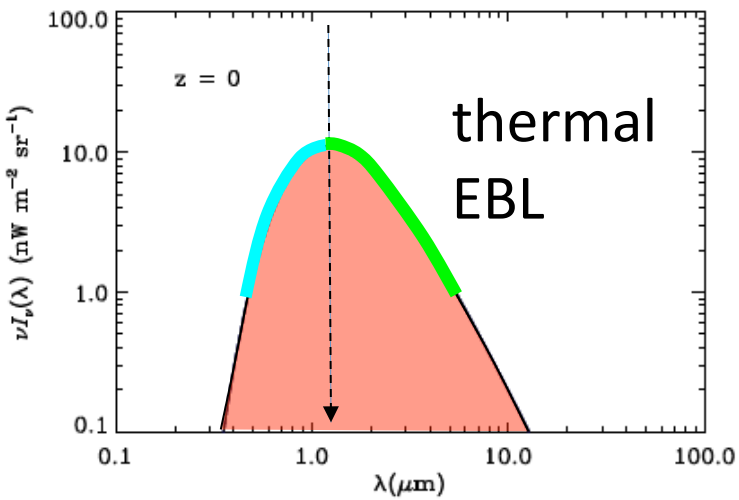
- cross section effective over a broad range of target photon energies (for a given E_γ)
- cross section peaks at β = 0.7

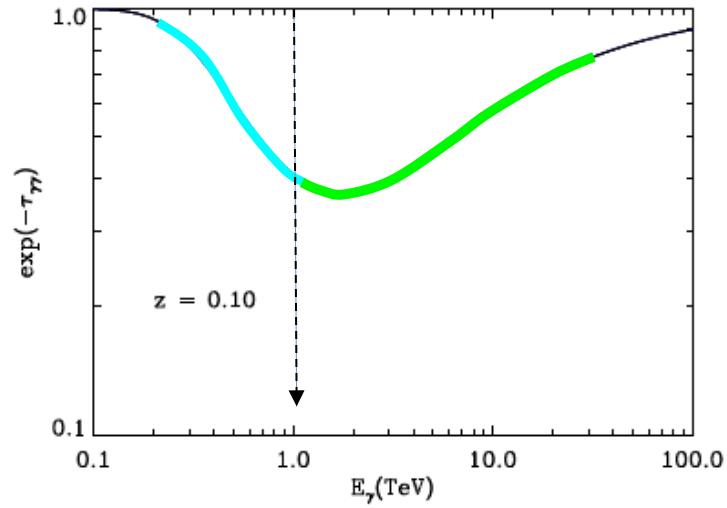
$$E_\gamma[TeV] = \frac{0.86\lambda[\mu m]}{1 - \cos\theta}$$

γ-ray Absorption by the EBL



γ-ray Absorption Signatures from EBL





change in slope

at ~ 1 TeV

Dwek, E. & F.K. 2013, Astrop. Phys., in press

EBL's rapid rise (< 1 μm), drop (> 2 μm)

→ 2 spectral **signatures** in blazar spectra

→ **magnitude** of signatures

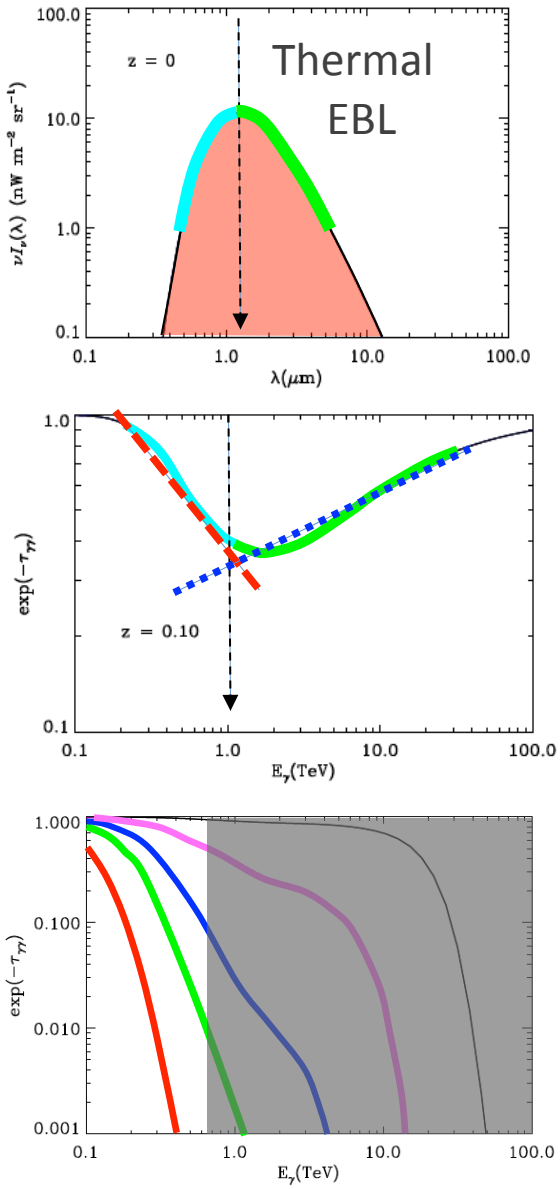
≈ **scales** with redshift **z**

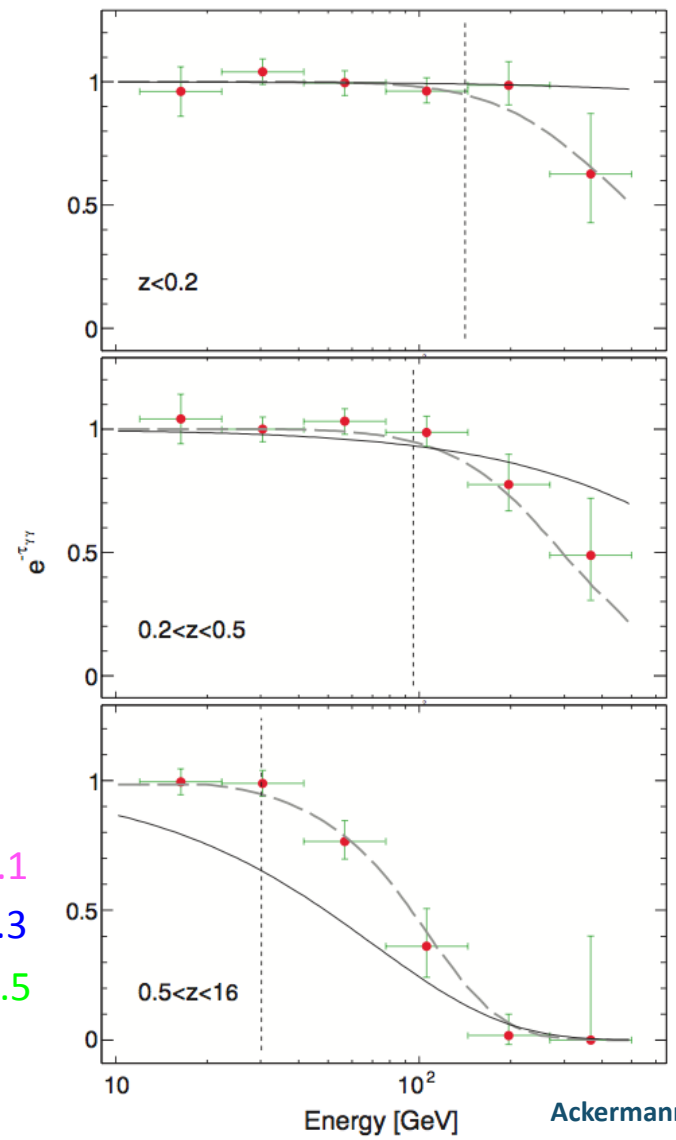
"typical" blazar spectrum:

$$\frac{dN}{dE} \propto E^{-\Gamma} \quad \text{with } \Gamma \sim 1.5 - 2.5$$

$$\frac{dN}{dE} \propto E^{-\Gamma} \cdot \exp(-\tau_{\gamma\gamma})$$

Detection of EBL Imprint by Fermi





150 blazars (BL Lac)
z = 0.03 – 1.6

Fit spectra with:

$dN/dE \sim E^{-\alpha}\, e^{(-\,\mathbf{b} \times \tau(E,\, \varepsilon,\, z))}$

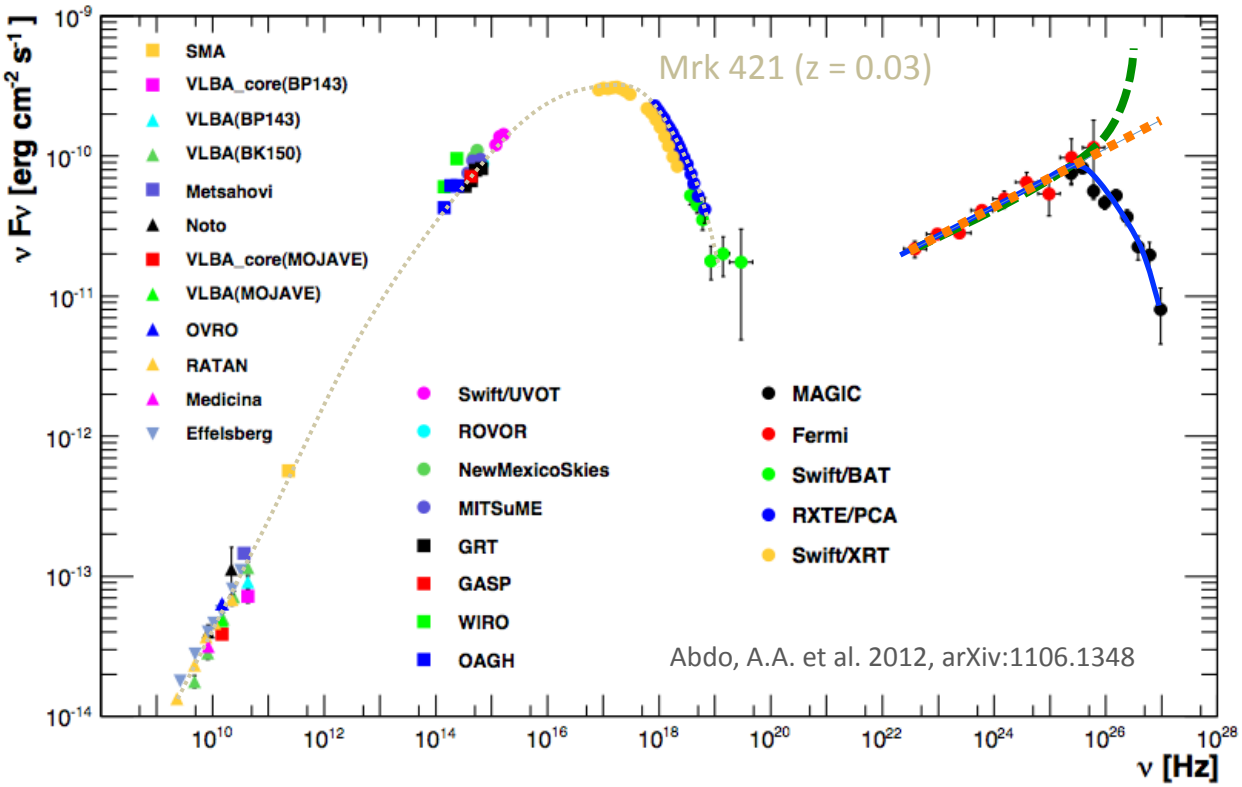
EBL intensity at ≈ 0.3 μm:

3 ± 1 nW/m²/sr

Ackermann et al., Science, 338, 1190 (2012)

EBL constraints from IACTs

unphysical (no exp. rise!)

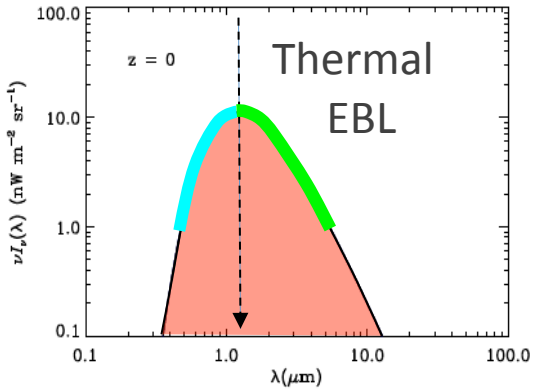


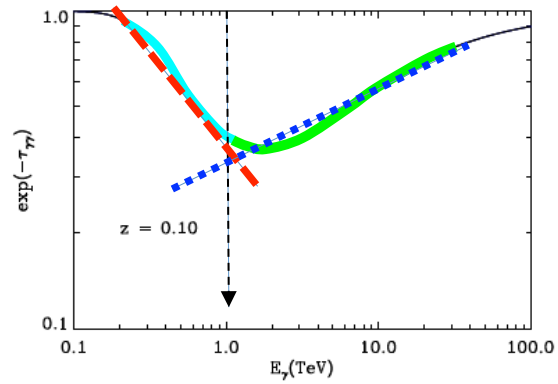
possible (if Γ>1.5)

measured

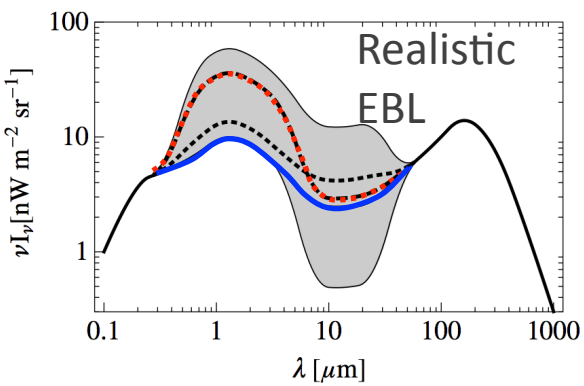
- ‘‘typical’’ blazar SED: synchrotron peak – inverse Compton peak
- SSC model: generally does not allow precise prediction of IC peak!

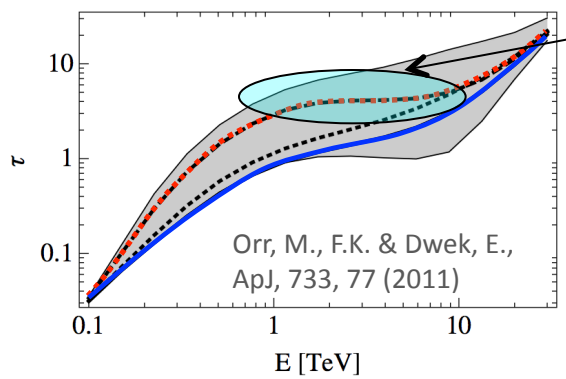
Spectral Signature – break at 1 TeV





$$\Gamma_{\text{break}} = \Gamma_{(E<1\ \text{TeV})} - \Gamma_{(E>1\ \text{TeV})}$$



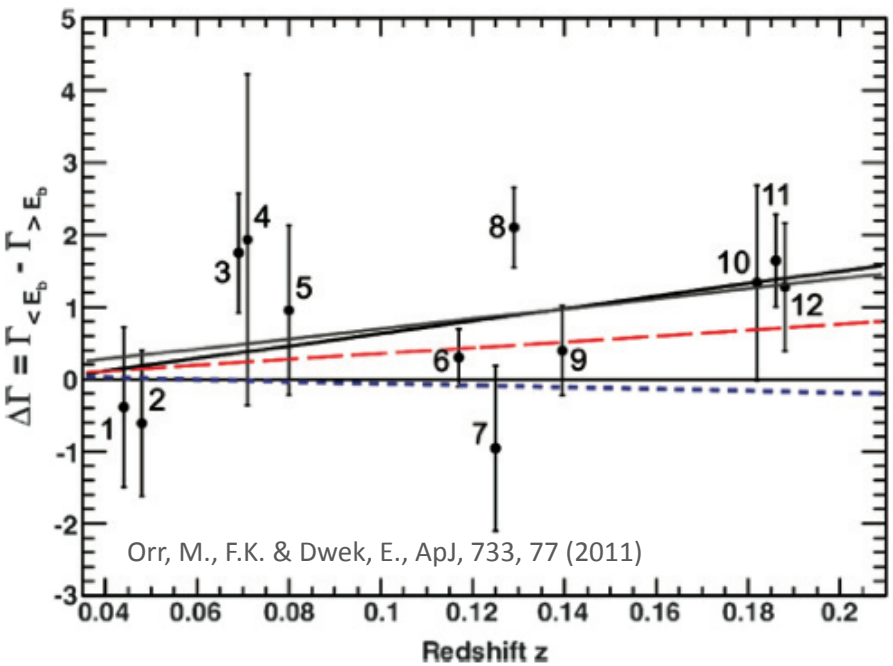


$$\tau_{\gamma\gamma}(E) \approx const.$$

$$\frac{dN}{dE} \propto E^{-\Gamma} \cdot \exp(-\tau_{\gamma\gamma})$$

- shape of EBL may produce unique imprint in TeV spectra at ≈ 1 TeV
- strength depends on **ratio** of **near-IR to mid-IR**
- constant τ (1 – 10 TeV): the observed spectrum ≈ intrinsic source spectrum
- similar to ALP signature if E_{crit} were at 1 TeV

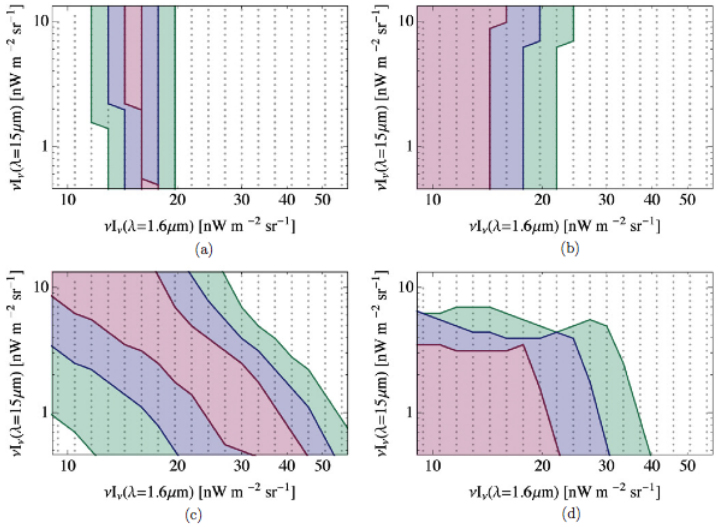
Search for Signature – break at 1 TeV

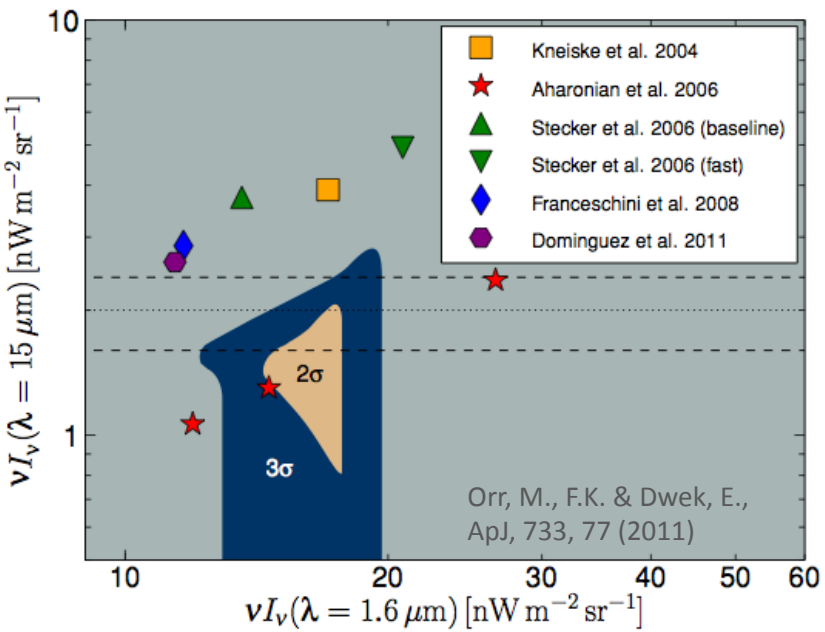


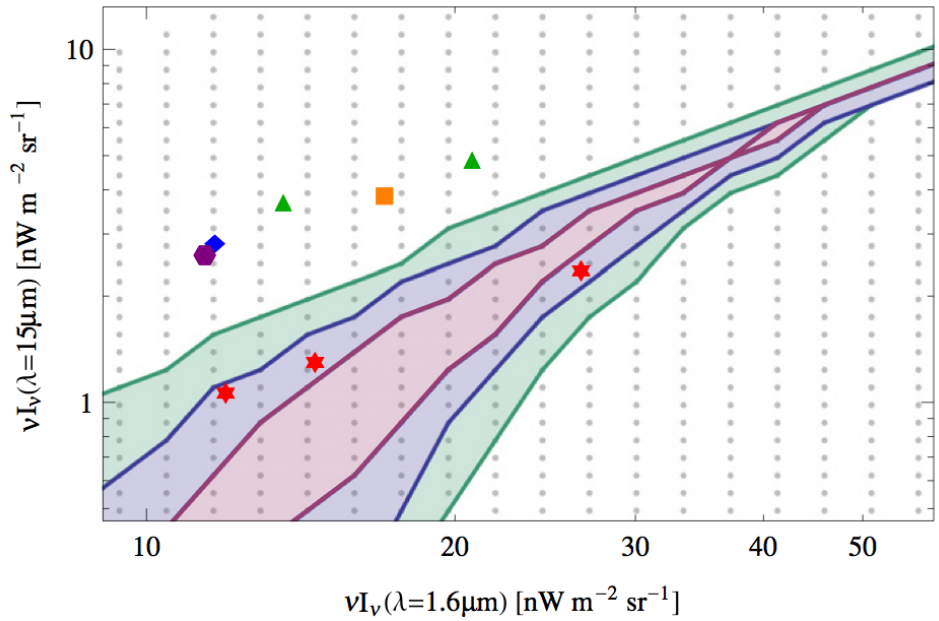
Source Name	Redshift	Γ_{LAT}	Γ_{VTS}	Method(s)	# Spec. Points l.t./g.t. E_{break}	$\Delta\Gamma$
1ES 2344+514	0.044	1.57 ± 0.17	2.95 ± 0.12	TeV Break	4 / 3	-0.39 ± 1.11
1ES 1959+650	0.047	2.10 ± 0.05	2.58 ± 0.18	TeV Break	4 / 2	-0.61 ± 1.01
PKS 0548-322	0.069	-	2.8 ± 0.3	TeV Break	3 / 2	1.75 ± 0.83
PKS 2005-489	0.071	1.90 ± 0.06	4.0 ± 0.4	TeV Break	6 / 3	1.93 ± 2.30
RGB J0152+017	0.080	-	2.95 ± 0.36	TeV Break	4 / 2	0.96 ± 1.18
PKS 2155-304	0.117	1.91 ± 0.02	3.32 ± 0.06	TeV Break	7 / 3	0.30 ± 0.40
RGB J0710+591	0.125	1.28 ± 0.21	2.69 ± 0.26	GeV-TeV / TeV Break	3 /2	-0.96 ± 1.14
H 1426+428	0.129	1.49 ± 0.18	3.50 ± 0.35	TeV Break	3 / 4	2.11 ± 0.55
1ES 0229+200	0.140	-	2.50 ± 0.19	GeV-TeV / TeV Break	3 / 5	0.39 ± 0.62
1ES 1218+304	0.182	1.69 ± 0.07	3.07 ± 0.09	GeV-TeV / TeV Break	7 / 2	1.33 ± 1.35
1ES 1101-232	0.186	1.61 ± 0.26	2.88 ± 0.17	GeV-TeV / TeV Break	9 / 4	1.64 ± 0.64
1ES 0347-121	0.188	-	3.10 ± 0.23	TeV Break	4 / 3	1.28 ± 0.89

- Hint for spectral break but only at 3.5 σ significance
- $\Delta\Gamma(z)$ relation can be used to constrain the mid-IR to near-IR ratio

Near-IR and Mid-IR constraints





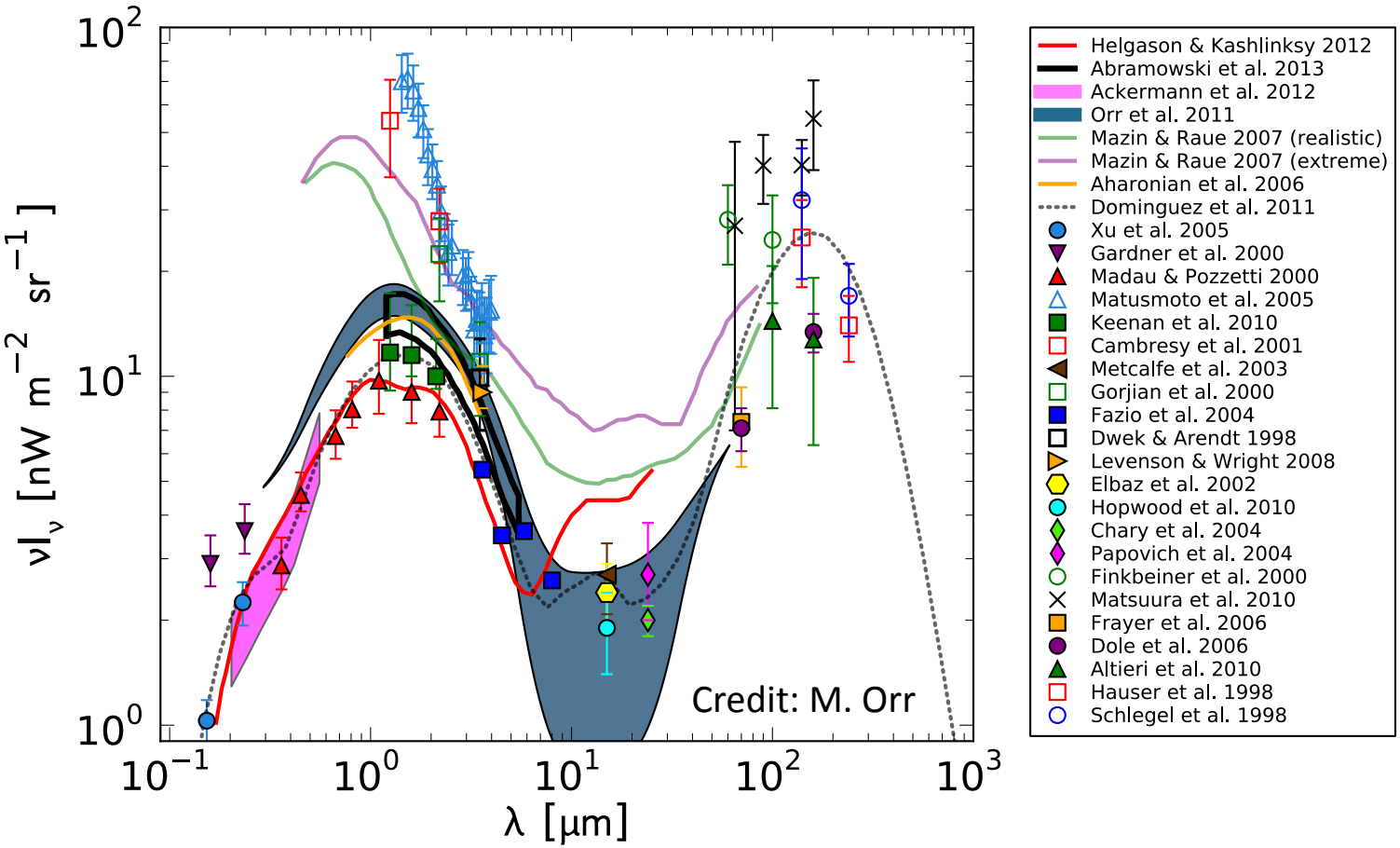


- part I and part II are ‘‘orthogonal’’
- constrain near-IR to mid-IR ratio!
- considering lower limits (direct), also constrains absolute level!

Status of EBL measurements (2013)

Orr et al. 2011, spectral break analysis (GeV-TeV Data)

Ackermann et al. 2012, Spectral softening with z, E (GeV Data)



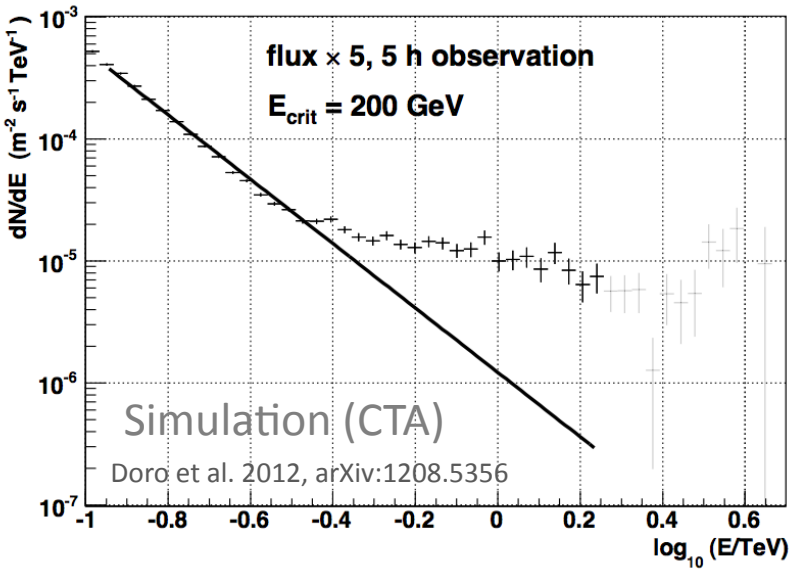
Abramowski et al. 2013, Spectral softening with z, E

Helgason & Kashlinsky 2013, Galaxy luminosity function surveys

Tension?

- perhaps, in mid-IR: galaxy luminosity function surveys ($z < 4$) vs. number counts & TeV constraints

Universal ALP Signature (mixing in IGMF)

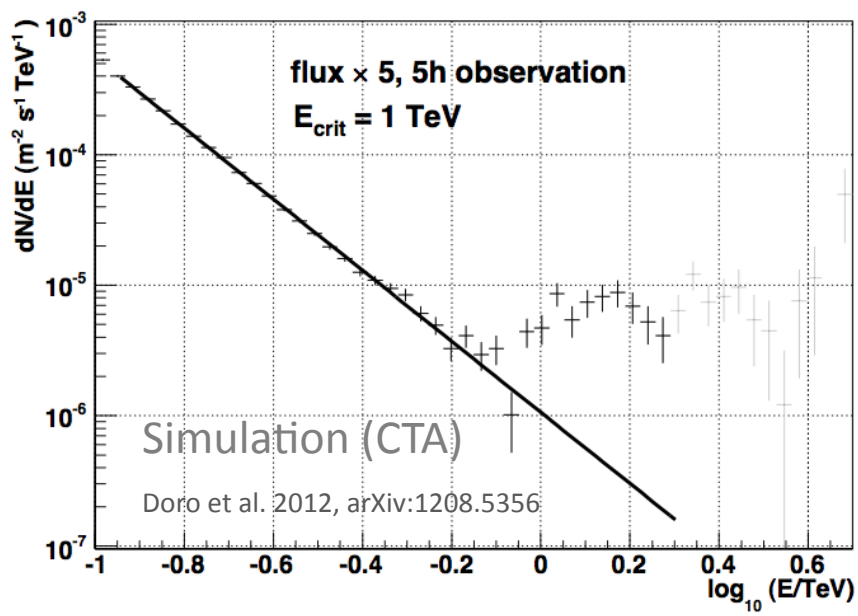


Test source: PKS 1222+21 (z=0.4)

- assumed flux level observed by MAGIC during flaring activity
- EBL model (Dominguez et al. 2011)
- Photon-ALP conversions in IGMF (B = 0.1 nG)

Spectra:

- hardening of the spectra present in moderately absorbed (EBL) regime
- inflection point does **not** provide $\mathbf{E_{crit}}$
- appearance of peak, if $\mathbf{E_{crit}}$ falls into **strongly absorbed** energy regime
- sensitivity to $\mathbf{E_{crit}}$ (0.2 – 1 TeV)



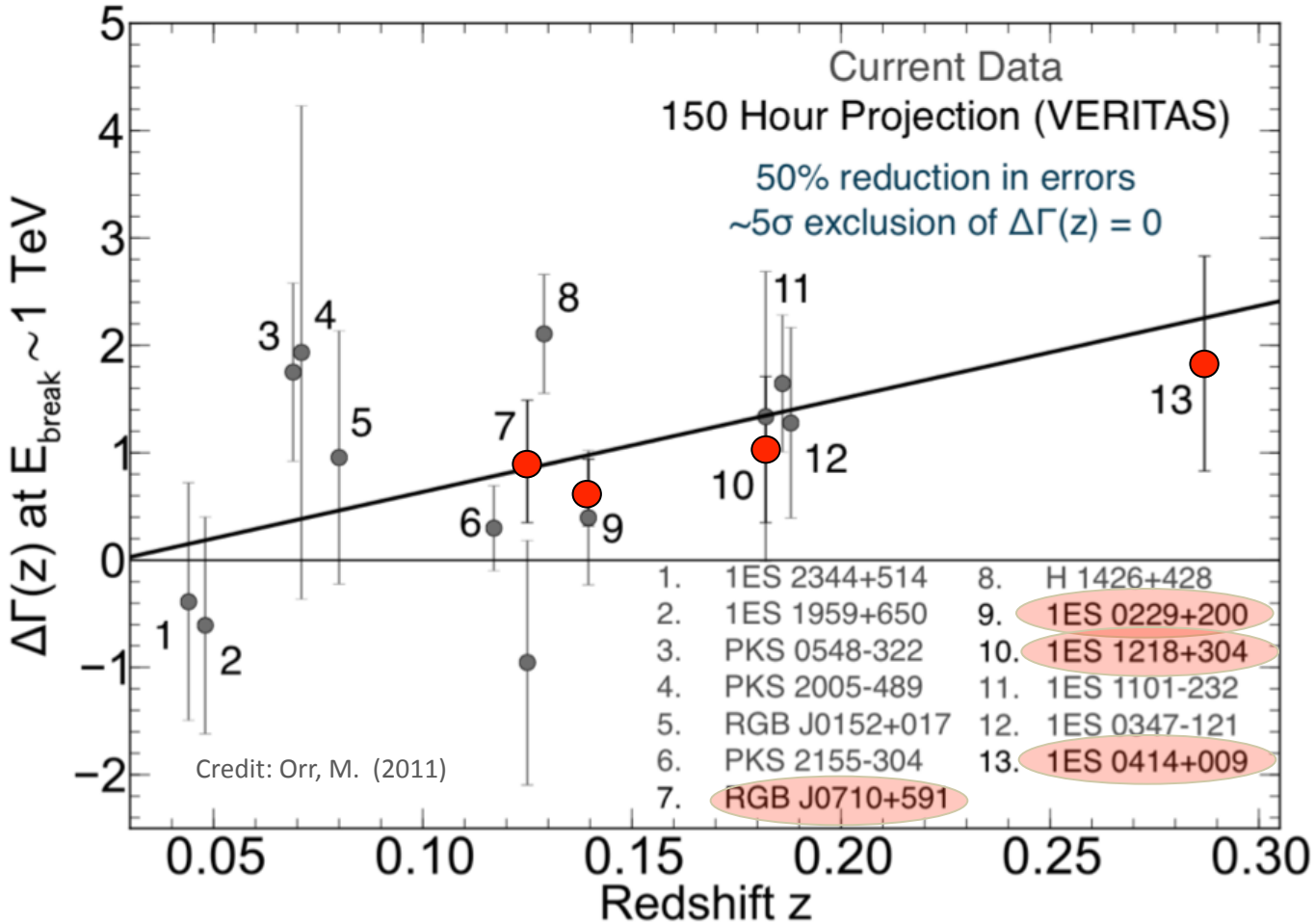
Future ALP searches

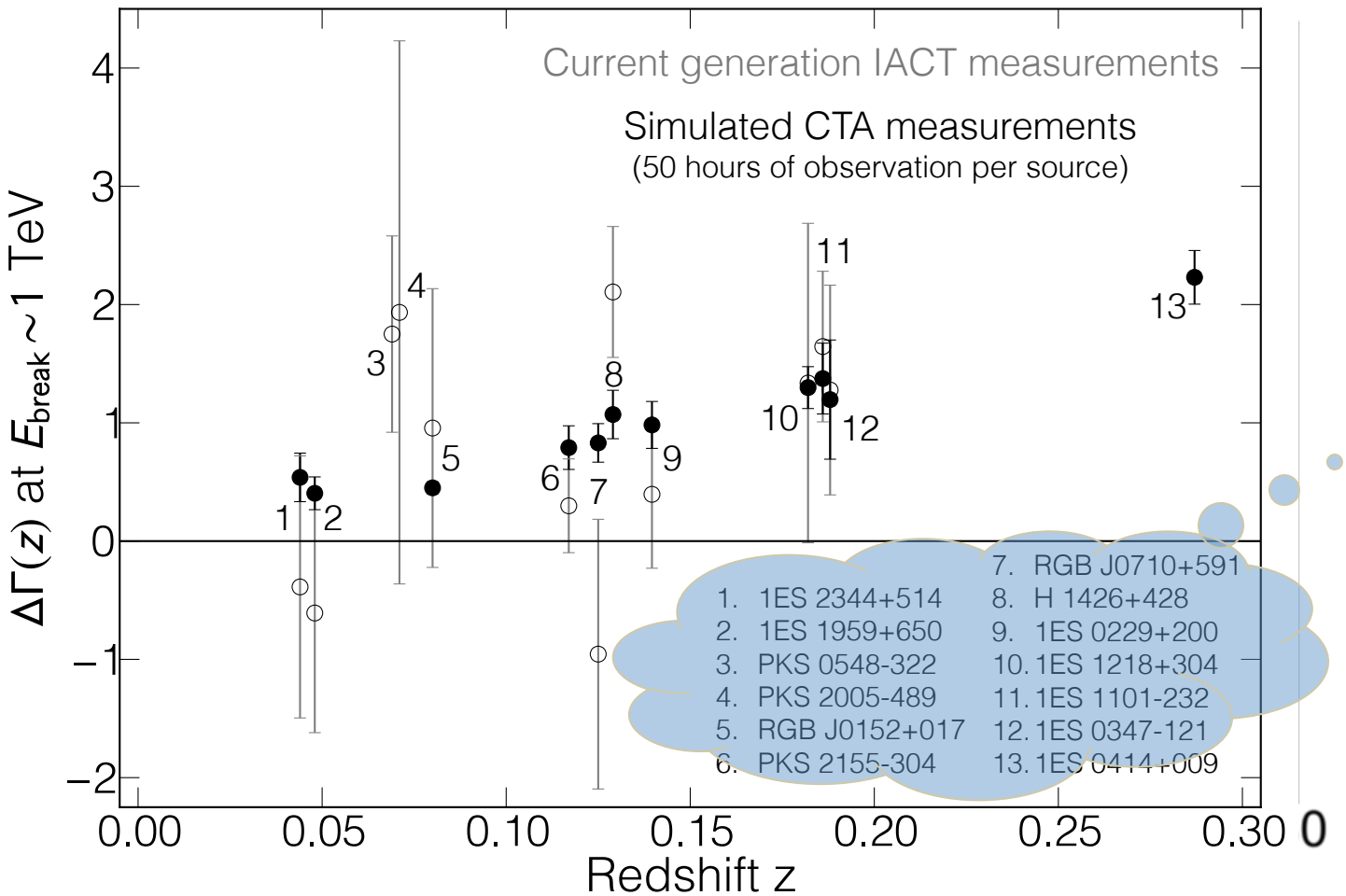
- **Measure EBL (0.2 – 100 μm)**
  - γ-ray absorption signatures: 10s GeV – 10s TeV
  - resolve near-IR EBL with JWST
  - convergence? diffuse component? transparency problem?

- **Search for Axion-like particles signatures**
  - γ-rays passing through EBL wall (sources at redshift $z \geq 0.3$)
  - search for spectral break at E_{crit} of 100s GeV – few TeV
  - universal for all sources above a given redshift

- **Strategy**
  - **current generation IACTs** (VERITAS) to identify **high-z** (> 0.3) flaring **blazars**
  - **next generation IACT** (CTA): precision energy spectra at $E \approx 0.03 – 10$ TeV
  - CTA will deliver > 500 extragalactic sources
  - HAWC as a monitor of the TeV sky to alert CTA
  - CTA-US contribution (36 MSTs) will provide factor of 3 better sensitivity

STOP


Current Data
150 Hour Projection (VERITAS)
50% reduction in errors
~5σ exclusion of ΔΓ(z) = 0
ΔΓ(z) at E_break ~1 TeV
Redshift z
1. 1ES 2344+514
2. 1ES 1959+650
3. PKS 0548-322
4. PKS 2005-489
5. RGB J0152+017
6. PKS 2155-304
7. RGB J0710+591
8. H 1426+428
9. 1ES 0229+200
10. 1ES 1218+304
11. 1ES 1101-232
12. 1ES 0347-121
13. 1ES 0414+009
Credit: Orr, M. (2011)



proxi for much larger population of blazars!

Orr, M., Krennrich, F., Proc. of the 32nd International Cosmic Ray Conference, Beijing, Vol. 8, p161 (2011)