Indications for a transparent universe at very high energies

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27th June, 2011
7th Patras Workshop, Mykonos, Greece

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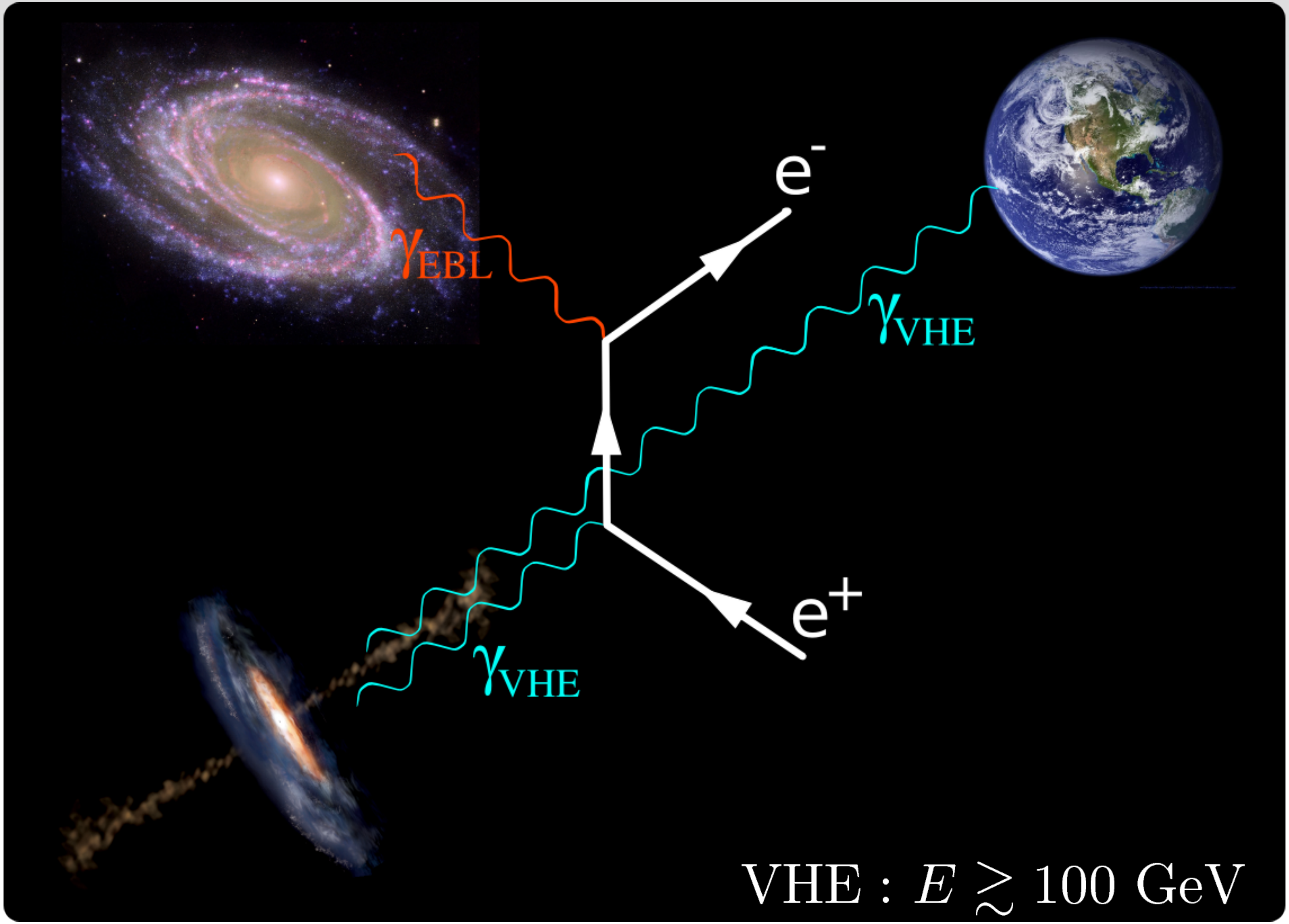
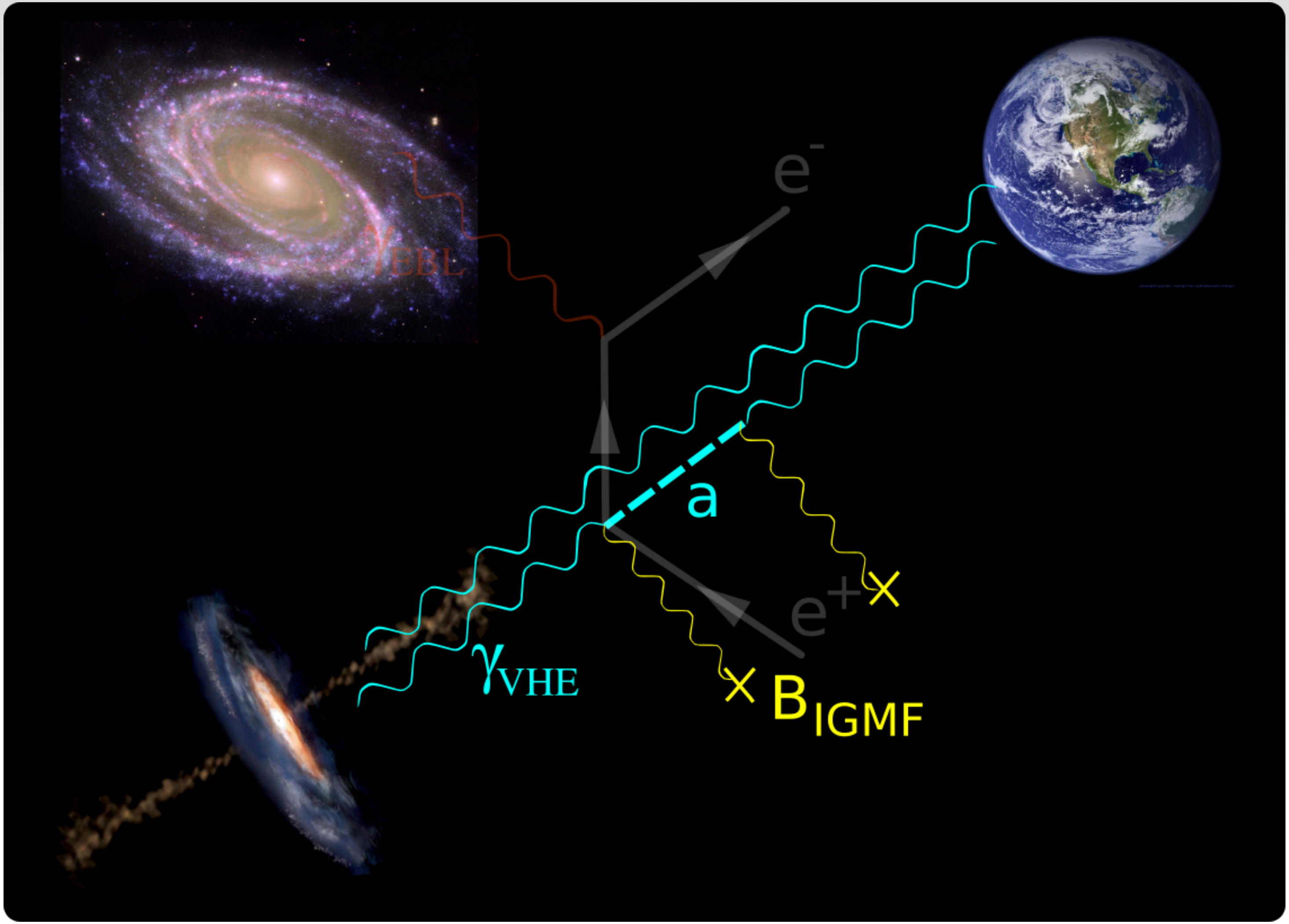
Opacity for extragalactic very-high energy (VHE) photons

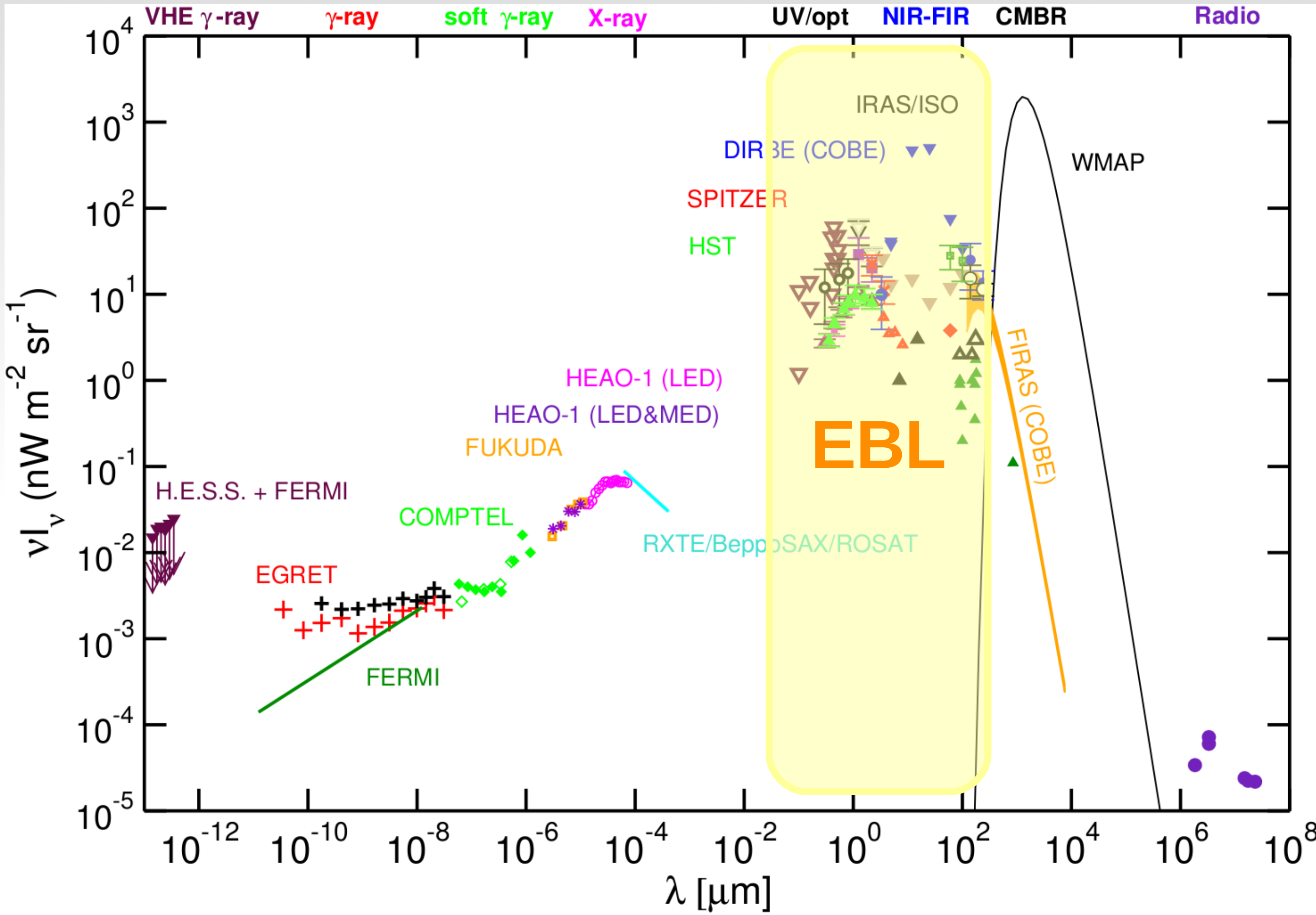


Opacity in the presence of axion like particles (ALPs)



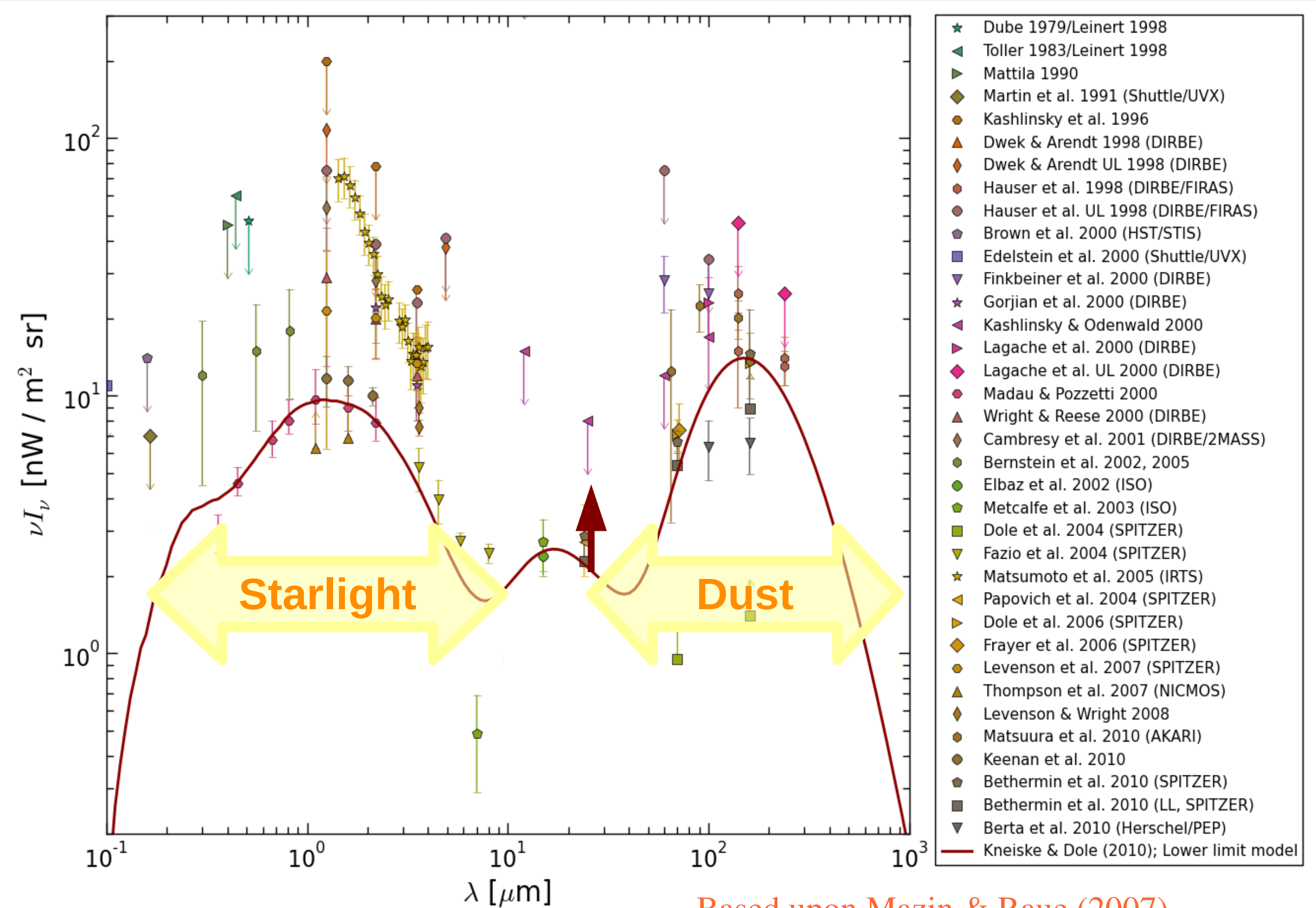
The extragalactic background light (EBL)

- Diffuse background radiation



The extragalactic background light (EBL)

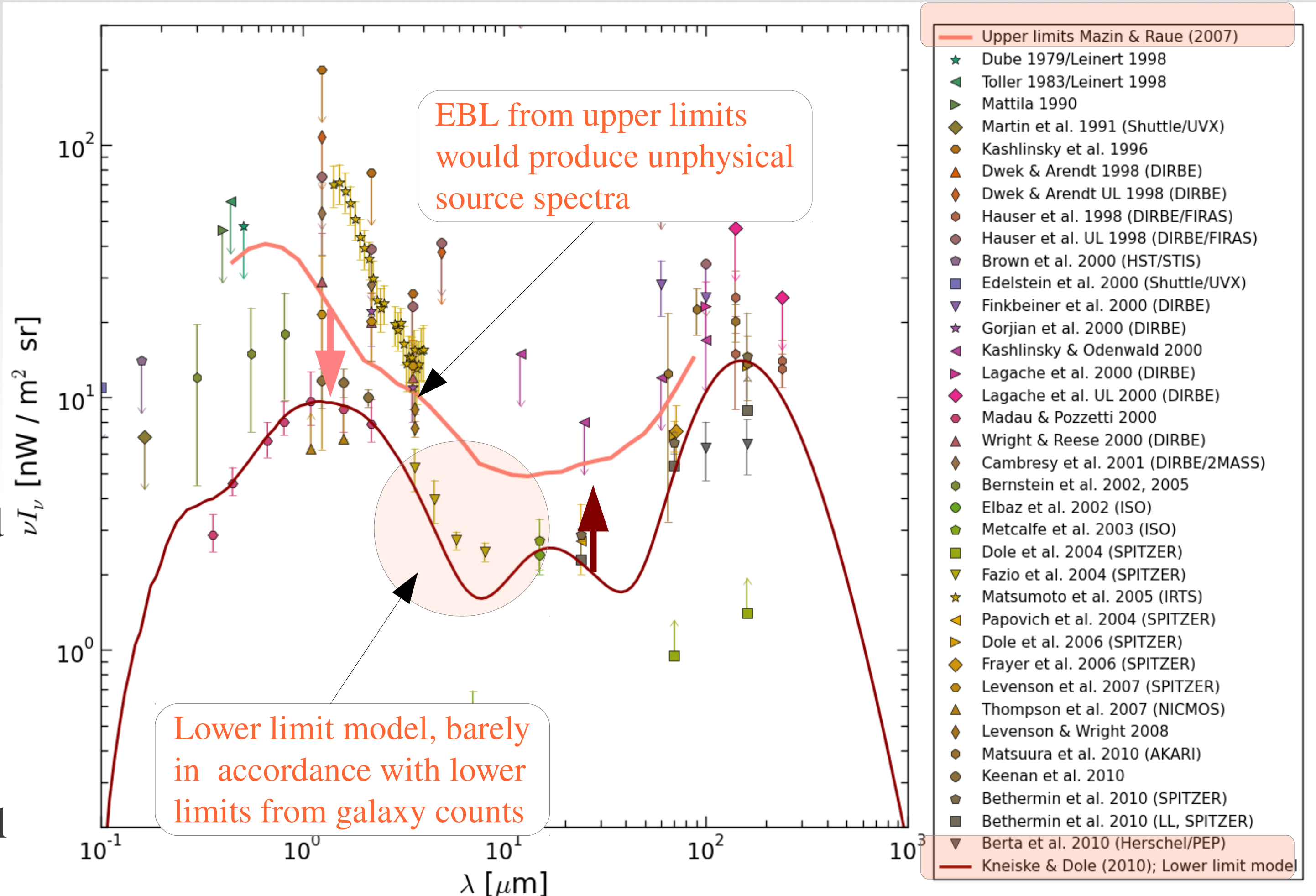
- Diffuse background radiation
- Origin:
  1. integrated starlight
  2. Starlight absorbed by dust and re-emitted in the (far-) infra-red
- Direct measurements difficult due to foreground emission



Based upon Mazin & Raue (2007)

The extragalactic background light (EBL)

- Diffuse background radiation
- Origin:
  1. integrated starlight
  2. Starlight absorbed by dust and re-emitted in the (far-) infra-red
- Direct measurements difficult due to foreground emission
- Use lower limit EBL model to be conservative: Universe as transparent as possible with conventional physics



Based upon Mazin & Raue (2007)

Propagation of extragalactic VHE photons

- Attenuation of initial photon flux described by the **optical depth $\tau_{\gamma\gamma}$**

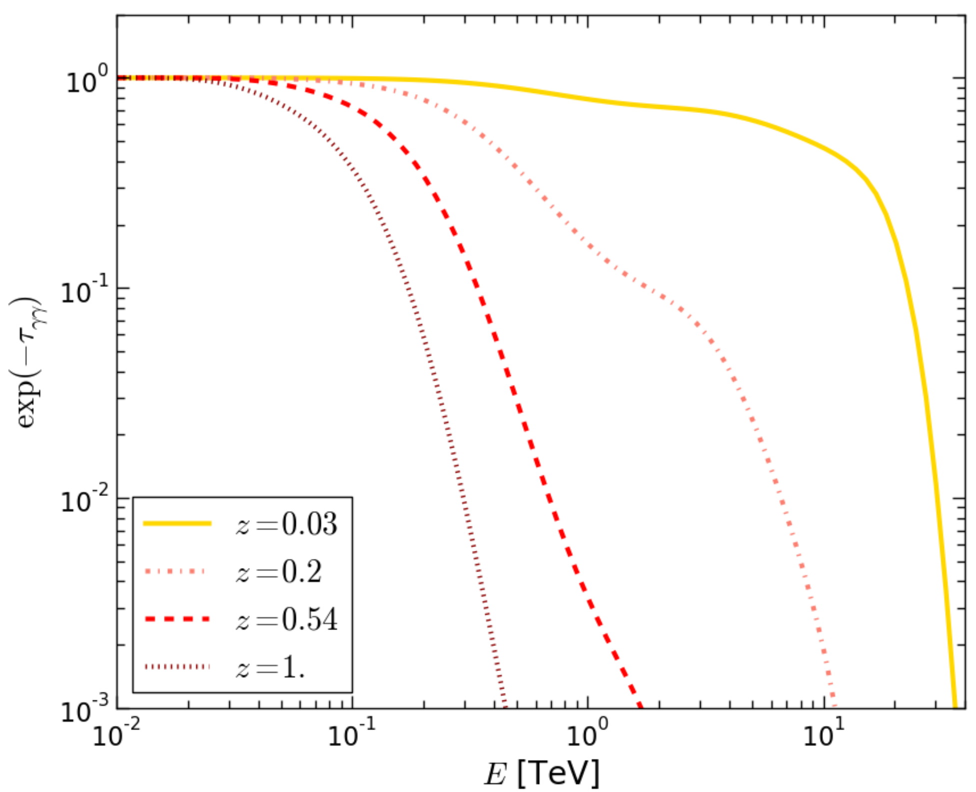
$$\frac{\mathrm{d}N_{\mathrm{obs}}}{\mathrm{d}E} = \frac{\mathrm{d}N_{\mathrm{int}}}{\mathrm{d}E} \times \exp\left[-\tau_{\gamma\gamma}(E, z)\right]$$

Observed spectrum

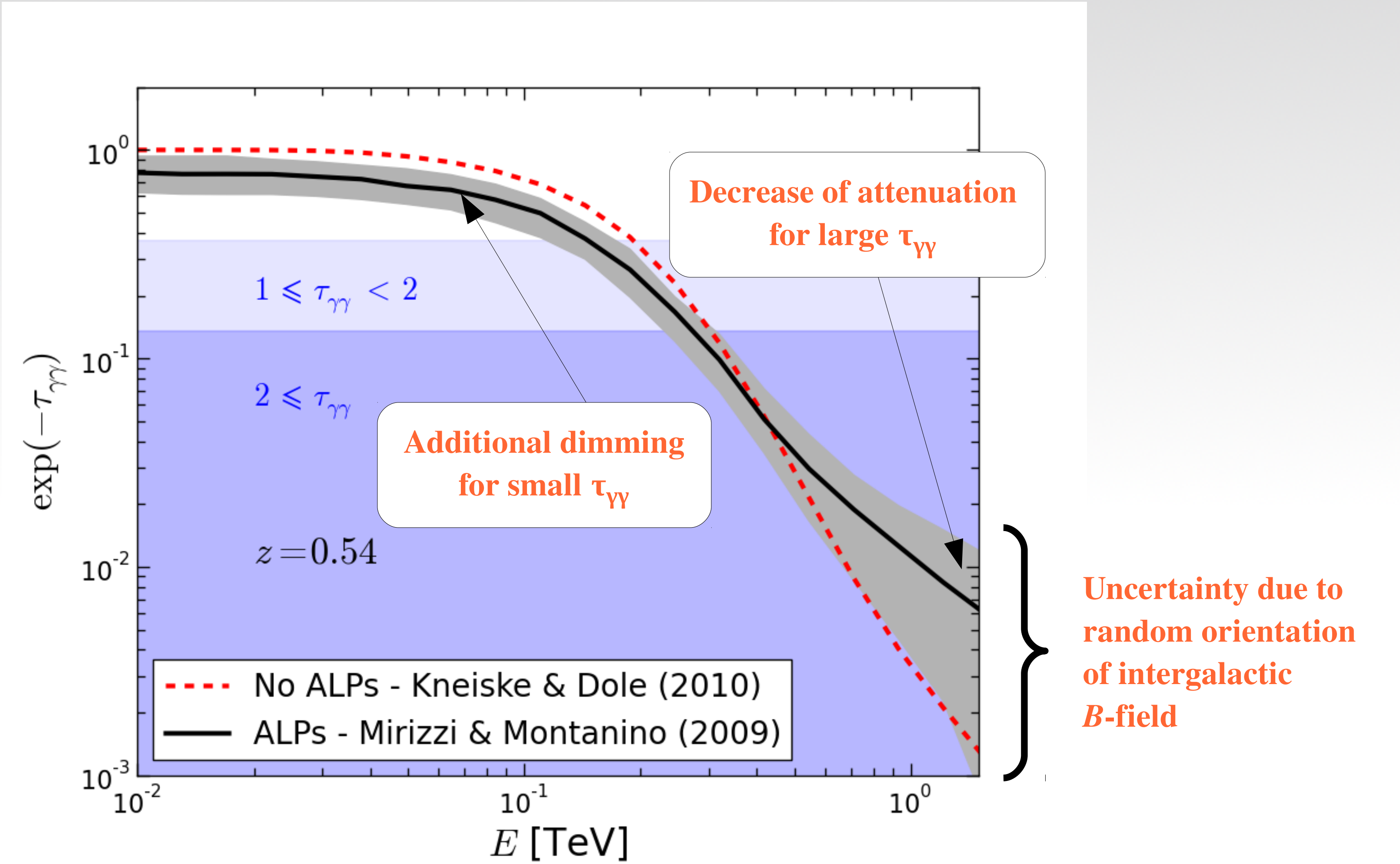
Intrinsic spectrum

Attenuation due to interaction with EBL photons

$$\tau_{\gamma\gamma} = \int_0^z \mathrm{d}\ell(z) \int_{-1}^{+1} \mathrm{d}\mu \frac{1-\mu}{2} \times \int_{\epsilon_{\mathrm{thr}}}^{\infty} \mathrm{d}\epsilon' n_{\mathrm{EBL}}(\epsilon') \sigma_{\gamma\gamma}(E', \epsilon', \mu)$$

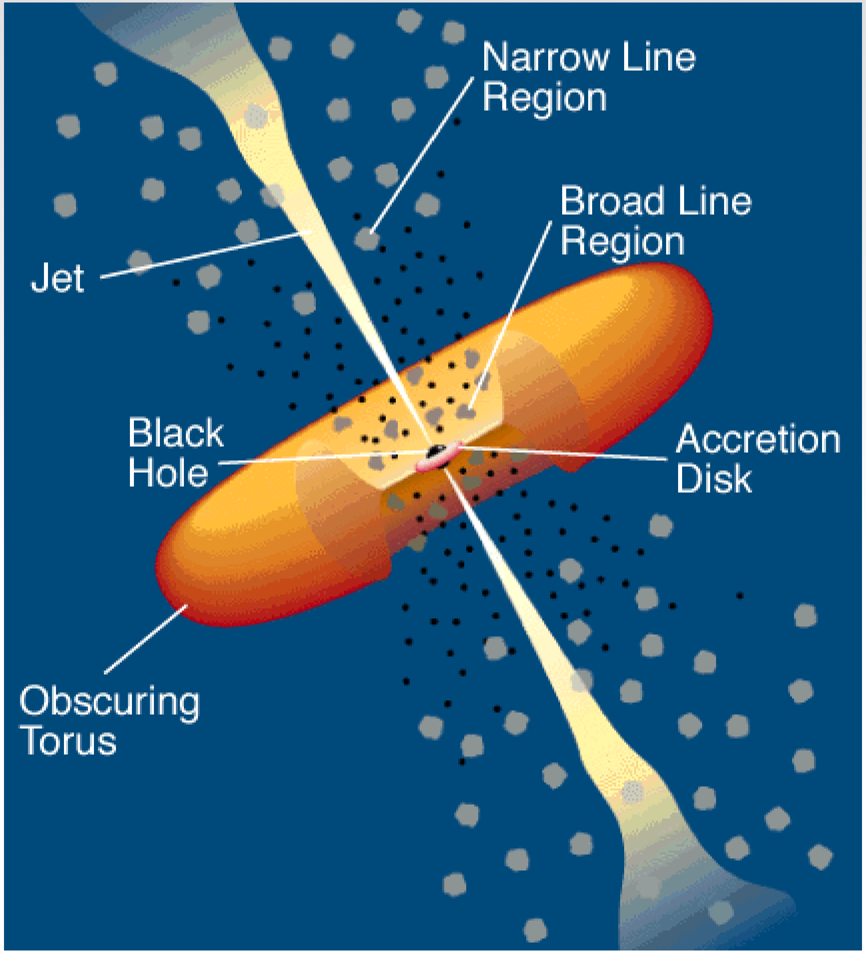


Optical depth in the presence of ALPs



Active galactic nuclei (AGN) as VHE γ-ray sources

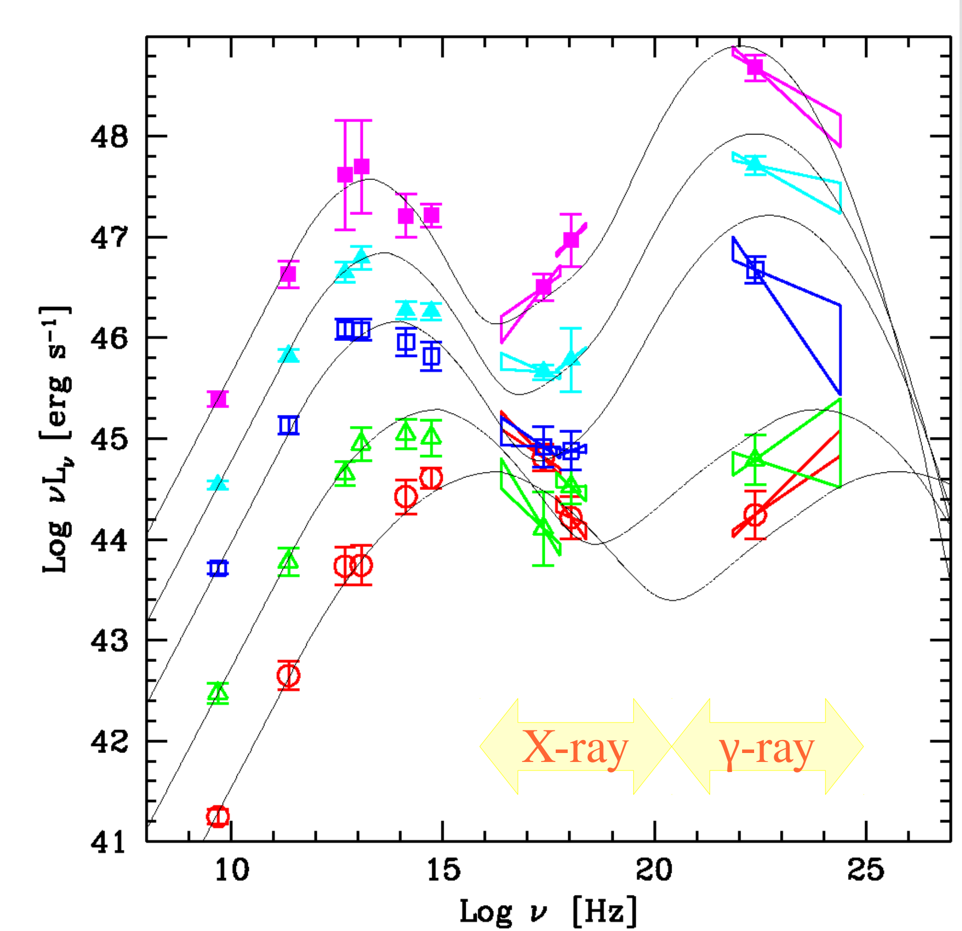
- Center of AGN: super massive black hole with accretion disk
- VHE emission originates in the jets
- If observer looks into the jet → blazar



Urry & Padovani (1995)

Spectral energy distribution (SED) of blazars

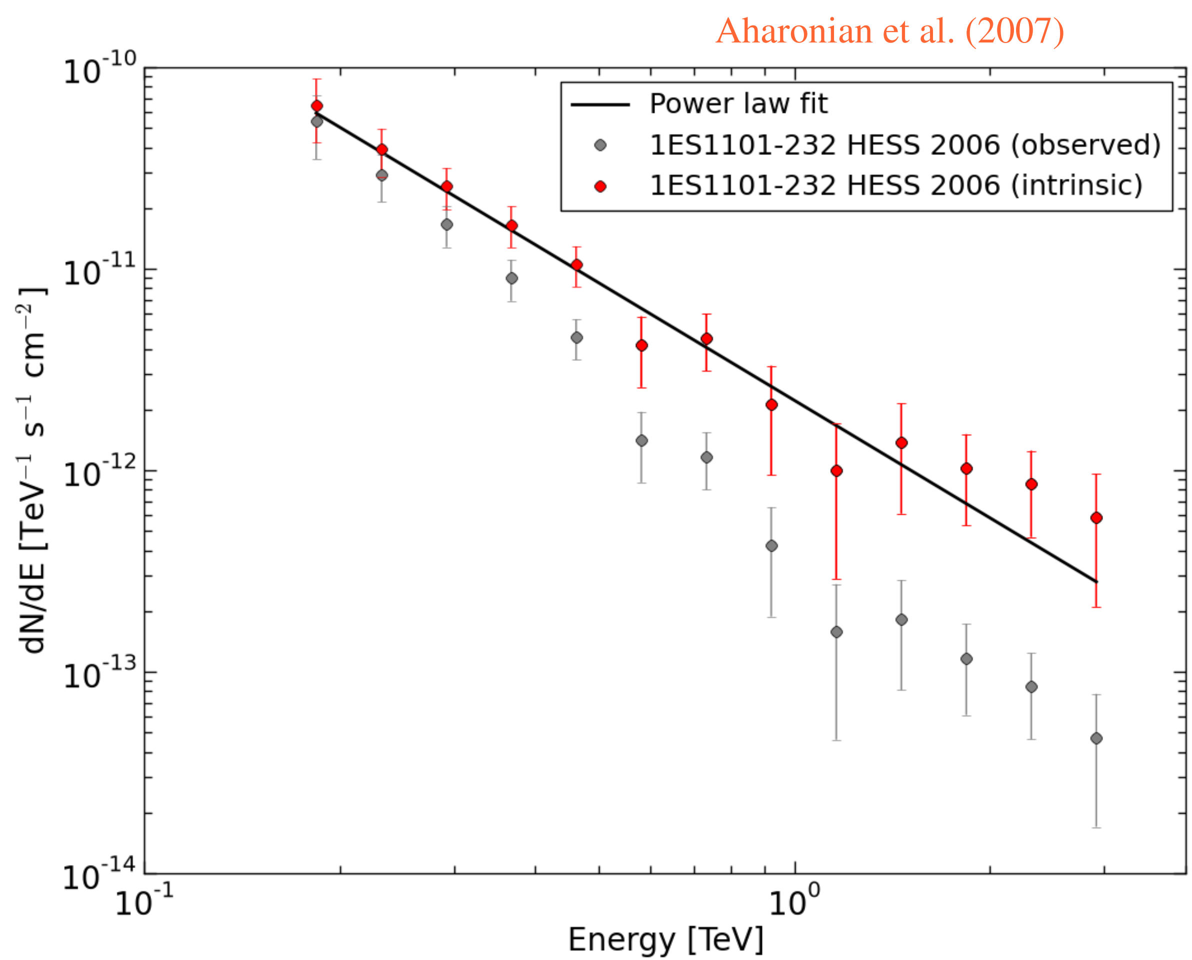
- Blazar SED: two peaks
- *Blazar sequence*: correlation between peak frequency and luminosity → observational bias
- Large scatter of measured photon indices
- At VHE energies: impossible to measure intrinsic spectrum directly



Blazar sequence (Fossati 1998; Donato et al. 2001)

Intrinsic VHE spectrum – corrected with EBL model

- Observed spectrum: reduced flux and softer
- With ALPs: additional spectral hardening expected at high energies
- Feature not significant for one single spectrum



Use large sample of VHE spectra

Source	Instrument	Redshift	E_{max} [TeV]	$\Gamma_{obs} \pm \sigma$
1ES0229+200	HESS	0.14	11.45	2.5 ± 0.19
1ES0347-121	HESS	0.188	3.03	3.1 ± 0.23
1ES0414+009	HESS	0.287	1.13	3.44 ± 0.27
1ES0806+524	MAGIC	0.138	0.63	3.6 ± 0.1
1ES1011+496	MAGIC	0.212	0.59	4.0 ± 0.5
1ES1101-232	HESS	0.186	2.92	2.88 ± 0.17
1ES1218+304	VERITAS	0.182	1.48	3.08 ± 0.34
1ES1218+304	MAGIC	0.182	0.63	3.0 ± 0.4
1ES1959+650	MAGIC	0.048	1.53	2.97 ± 0.14
1ES1959+650	HEGRA	0.048	10.98	2.83 ± 0.14
1ES1959+650	HEGRA	0.048	10	1.83 ± 0.15
1ES1959+650	MAGIC	0.048	2.4	2.58 ± 0.18
1ES2344+514	MAGIC	0.044	4.0	2.95 ± 0.12
3C279	MAGIC	0.536	0.48	4.1 ± 0.7
3C66B	MAGIC	0.021	1.85	3.1 ± 0.2
BL Lacertae	MAGIC	0.069	0.7	3.6 ± 0.5
Centaurus A	HESS	0.009	4.75	2.7 ± 0.5
PKS1222+21	MAGIC	0.432	0.35	3.75 ± 0.27
H1426+428	HEGRA,CAT,WHIPPLE	0.129	10.12	-
H2356-309	HESS	0.165	0.91	3.09 ± 0.24
H2356-309	HESS	0.165	1.71	3.06 ± 0.15
H2356-309	HESS	0.165	0.92	3.06 ± 0.21
M87	HESS	0.004	6.18	2.62 ± 0.35
M87	MAGIC	0.004	5.35	2.3 ± 0.11
M87	HEGRA	0.004	3.38	-
M87	VERITAS	0.004	7.87	2.31 ± 0.17
M87	VERITAS	0.004	4.21	-

Source	Instrument	Redshift	E_{max} [TeV]	$\Gamma_{obs} \pm \sigma$
M87	HESS	0.004	21.13	2.22 ± 0.15
Markarian 180	MAGIC	0.045	1.31	3.25 ± 0.66
Markarian 421	HEGRA	0.031	6.86	2.5 ± 0.4
Markarian 421	HEGRA	0.031	13.59	2.5 ± 0.1
Markarian 421	HEGRA	0.031	13.59	2.19 ± 0.02
Markarian 421	MAGIC	0.031	4.24	1.44 ± 0.24
Markarian 421	WHIPPLE	0.031	8.23	2.31 ± 0.04
Markarian 421	MAGIC	0.031	1.84	2.2 ± 0.08
Markarian 501	CAT	0.034	10	-
Markarian 501	VERITAS	0.034	3.8	2.58 ± 0.08
Markarian 501	VERITAS	0.034	1.9	2.61 ± 0.15
Markarian 501	VERITAS	0.034	3.86	2.31 ± 0.08
Markarian 501	HEGRA	0.034	21.45	1.92 ± 0.03
Markarian 501	MAGIC	0.034	1.76	2.79 ± 0.12
Markarian 501	VERITAS	0.034	3.89	2.48 ± 0.07
Markarian 501	VERITAS	0.034	3.81	2.26 ± 0.06
Markarian 501	MAGIC	0.034	4.43	2.79 ± 0.12
PKS0548-322	HESS	0.069	3.52	2.86 ± 0.34
PKS2005-489	HESS	0.071	2.27	4.0 ± 0.4
PKS2005-489	HESS	0.071	4.57	3.2 ± 0.16
PKS2155-304	HESS	0.116	2.28	3.32 ± 0.06
PKS2155-304	HESS	0.116	3.11	3.37 ± 0.07
PKS2155-304	HESS	0.116	4.72	2.71 ± 0.06
PKS2155-304	HESS	0.116	3.2	3.34 ± 0.05
RGBJ0152+017	HESS	0.08	2.95	2.95 ± 0.36
RGBJ0710+591	VERITAS	0.125	3.65	2.69 ± 0.26
W Comae	VERITAS	0.102	1.15	3.81 ± 0.35
W Comae	VERITAS	0.102	1.49	3.68 ± 0.22

Search for a spectral hardening

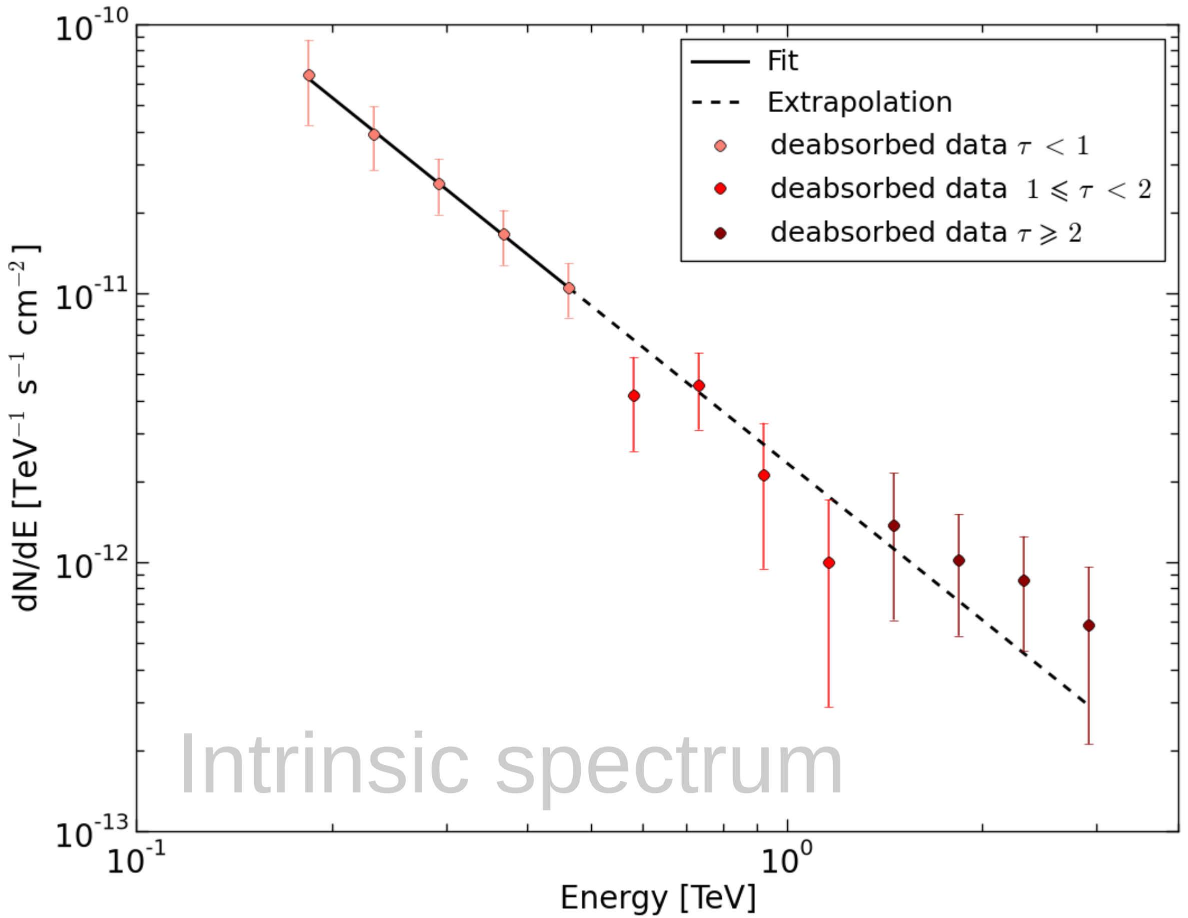
Method:

- Correct spectrum with lower limit EBL model
- Fit power law (with cut-off) to points with $\tau_{\gamma\gamma} < 1$
- Extrapolate fit to points with $\tau_{\gamma\gamma} \geq 1$
- Calculate difference between measurement and extrapolation

$$R_i^{\rm int} = \frac{\ln f_i^{\rm ext} - \ln f_i^{\rm int}}{\ln f_i^{\rm ext} + \ln f_i^{\rm int}}$$

$f_i^{\rm int}$: intrinsic flux

$f_i^{\rm ext}$: extrapolated flux



Statistical test of entire sample of VHE spectra

- Repeat procedure for all spectra and define two distributions:

$$\begin{aligned} \mathcal{S}_{\mathrm{thin}} &= \left\{ R_i^{\mathrm{int}} \middle| 1 \leq \tau_\gamma(E_i, z) < 2 \right\} \\ \mathcal{S}_{\mathrm{thick}} &= \left\{ R_j^{\mathrm{int}} \middle| 2 \leq \tau_\gamma(E_j, z) \right\} \end{aligned}$$

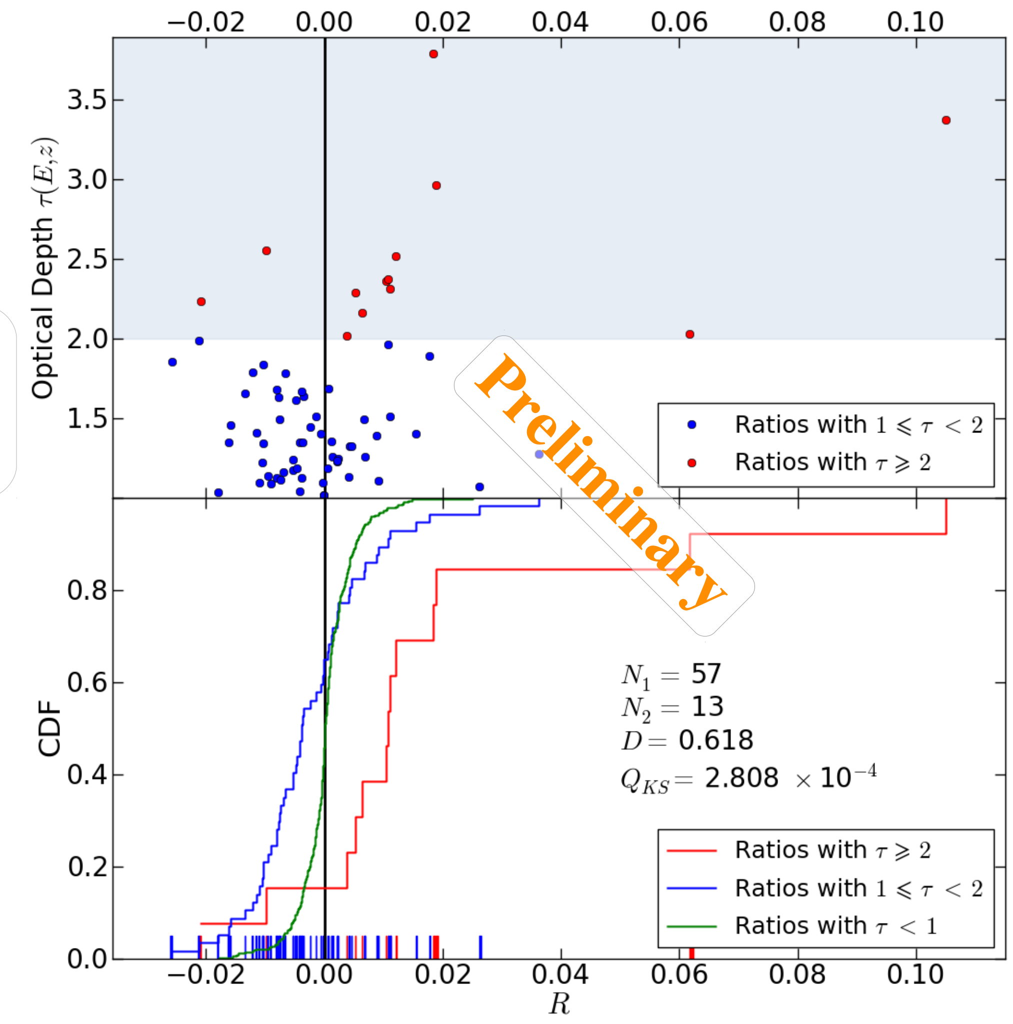
- Compare these distributions with the *Kolmogorov-Smirnov* test
- **Null hypothesis:** N_{thin} and N_{thick} describe the same underlying probability distribution
- Test is independent of statistical uncertainties
- Exact shape of source spectrum *irrelevant*, test searches for a systematic effect at the transition from optical thin to optical thick, independent from distance and energy

Results

- Points in $\mathcal{S}_{\mathrm{thin}}$ scatter around $R = 0$
- Points of $\mathcal{S}_{\mathrm{thick}}$ are shifted to $R > 0$
- Probability that distributions are equal:

$$Q_{\mathrm{KS}} = 2.81 \times 10^{-4} \mathrel{\widehat{=}} 3.45\sigma$$

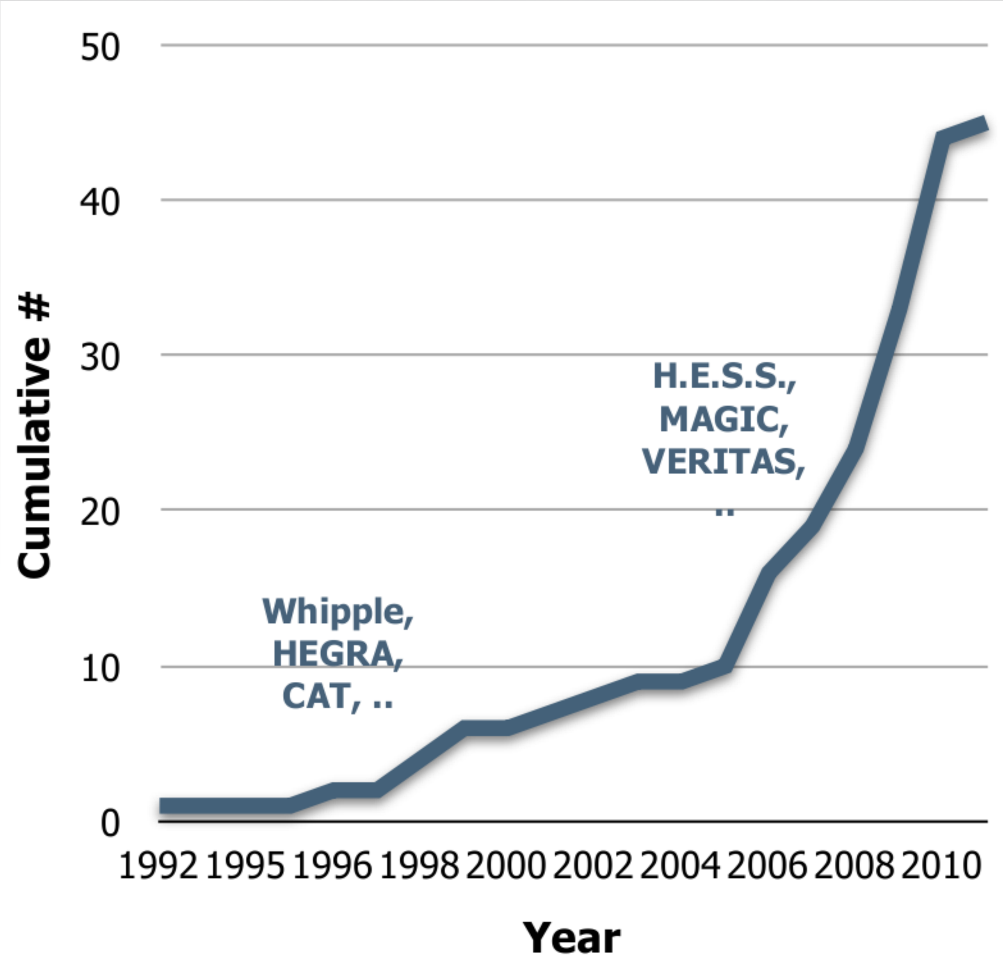
- Indication that correction is too strong at high values of $\tau_{\gamma\gamma}$
- No obvious systematic effect is found that mimics this result



Summary

- ALPs can lead to a decrease of the pair-production opacity of the universe
- For current data: effect is expected to be minute → large data sample required: 55 spectra of 25 sources considered here
- Test is independent of statistical errors of the measurements
- **Result independent of shape of source spectra**
- **New statistical test based on the Kolmogorov-Smirnov test shows an indication of 3.45σ that correction of spectra with lower limit EBL model is too strong**

Outlook


50
40
30
20
10
0
Cumulative #
Whipple,
HEGRA,
CAT, ..
H.E.S.S.,
MAGIC,
VERITAS,
..
1992 1995 1996 1998 2000 2002 2004 2006 2008 2010
Year

Cross check with galactic sources

- Check if highest energy bins tend to show a systematically higher flux than low energy bins
- Assign redshift values of AGN to galactic sources with similar spectral index
- Repeat test, treat the observed spectra as intrinsic spectra
- Result: **high energy bins do not show a higher flux than expected from the extrapolation**
- No obvious systematic effect that mimics the result is found