The Opacity of the Universe in Gamma Rays: Recent Results & Future Prospects

Frank Krennrich, Iowa State University

Collaborators

Eli Dwek, Goddard Space Flight Center

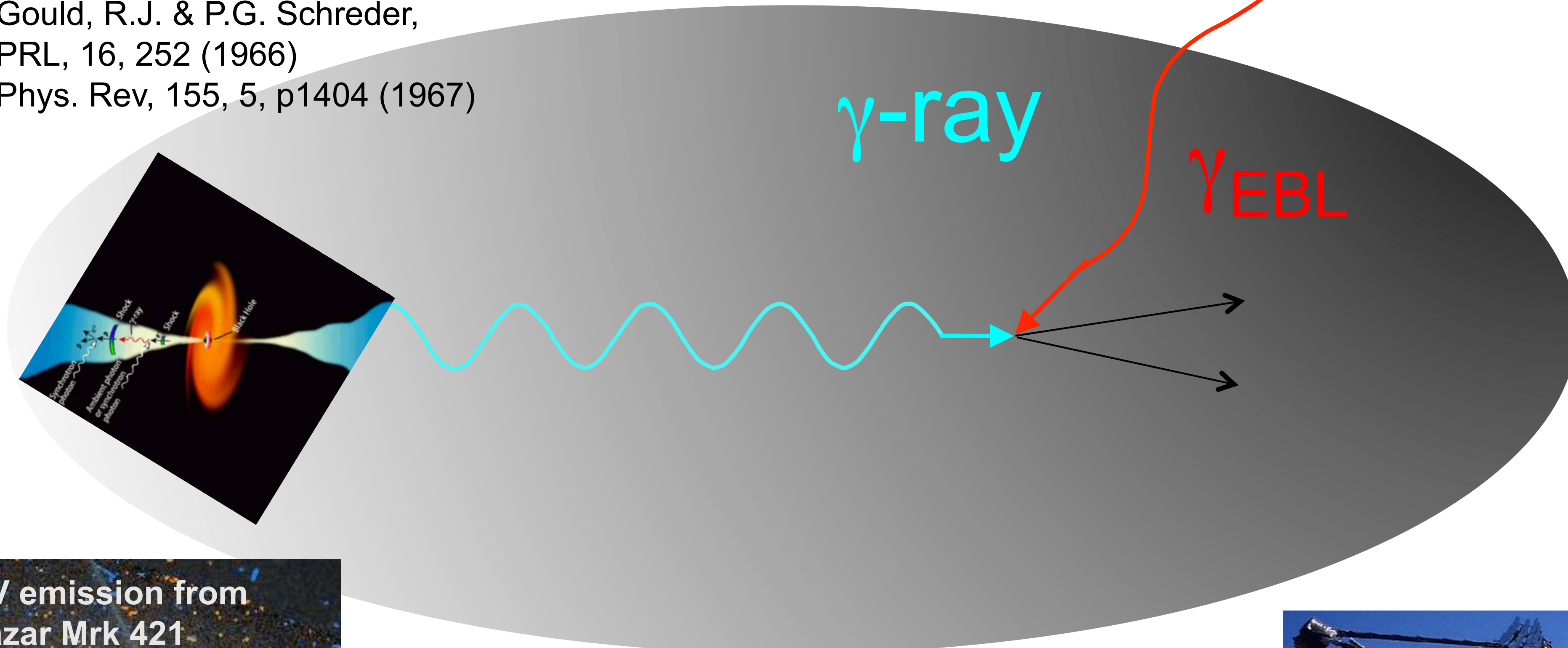
Matt Orr, Iowa State University

Key Questions

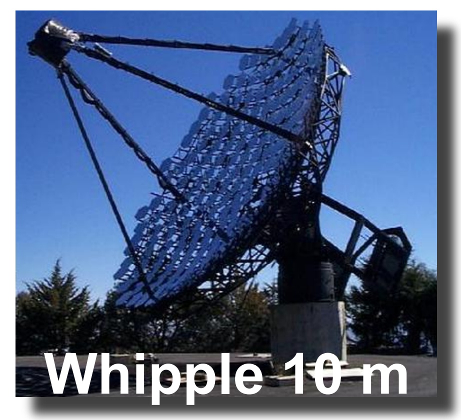
- **Direct measurements/TeV γ-ray limits: what do we make of this?**
- **What has been done so far with TeV instruments?**
- **What are the conclusions from TeV data, how reliable are they?**
- **What do we expect from ongoing observations & future instruments?**

Historical Note

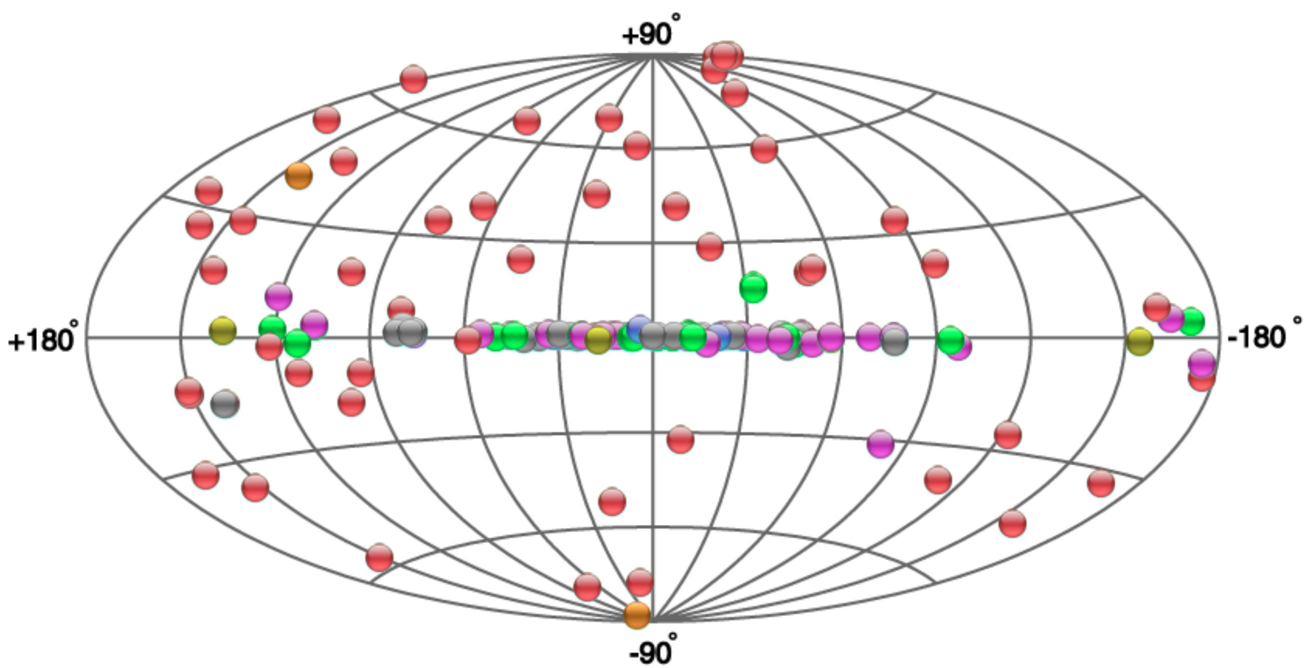
Gould, R.J. & P.G. Schreder,
PRL, 16, 252 (1966)
Phys. Rev, 155, 5, p1404 (1967)



$$\gamma_{TeV} + \gamma_{near\text{-}IR} \rightarrow e^+ + e^-$$



TeV γ-ray Sky 2012



extragalactic sources

Name	Class	redshift
Centaurus A	R. G.	0.0008
M82	S.B.G.	0.00085
NGC253	S.B.G.	0.00093
M87	R. G.	0.0036
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Markarian 421	HBL	0.031
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PKS 2005-489	HBL	0.071
W Comae	IBL	0.103
PKS 2155-304	HBL	0.116
B3 2247+381	HBL	0.119
RGB J0710+591	HBL	0.125
H 1426+428	HBL	0.129
1ES 1215+303	IBL	0.13♡
1ES 0806+524	HBL	0.137
1RXS J101015.9-311909	HBL	0.143
1ES 1440+122	IBL	0.163
H 2356-309	HBL	0.165
VER J0648+152	HBL	0.179
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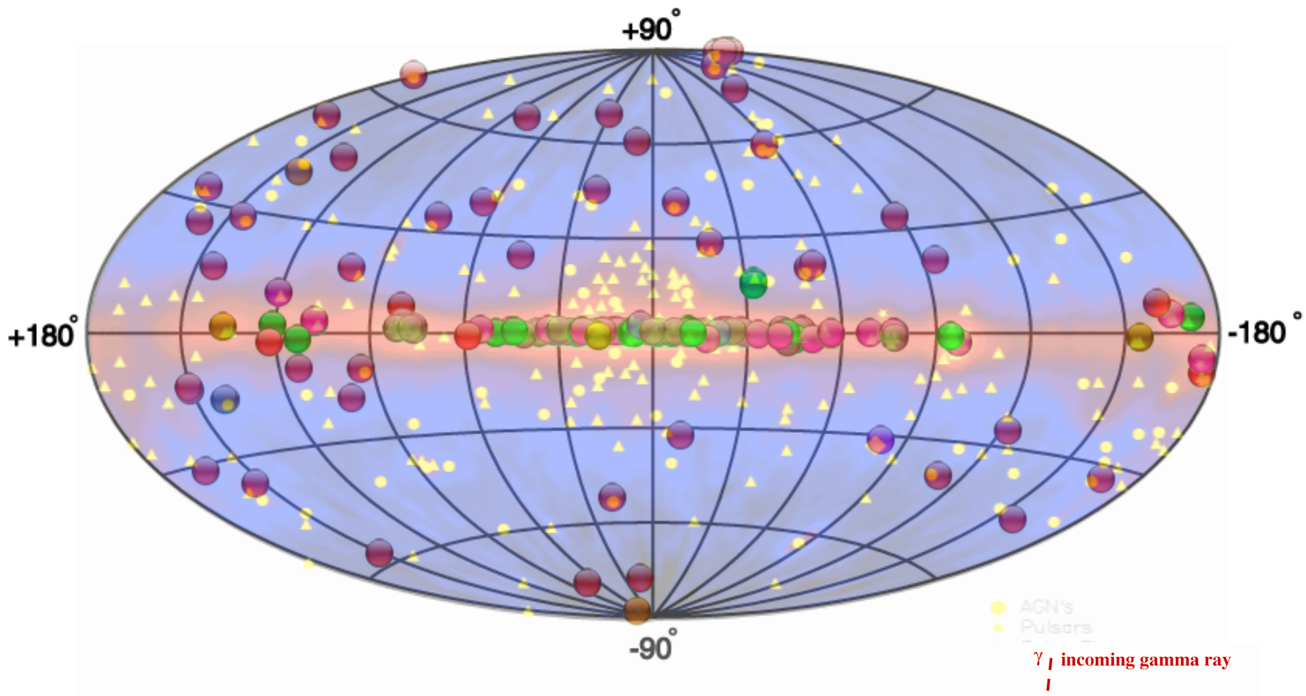
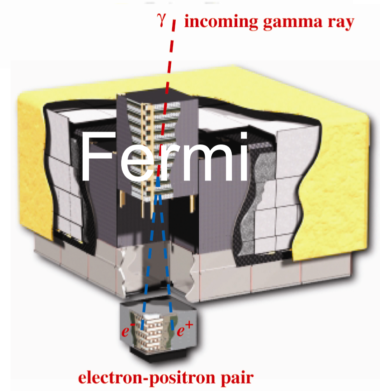
RBS 0413	HBL	0.19
PKS-0447-439	HBL	0.205
1ES 1011+496	HBL	0.212
1ES 0414+009	HBL	0.287
S5 0716+714	LBL	0.31
1ES 0502+675	HBL	0.416♣
4C 21.35	FSRQ	0.43
3C 66A	IBL	0.44♣
3C 279	FSRQ	0.536

unexpected

GeV/TeV γ-ray Sky 2012





extragalactic sources

GeV & TeV spectra

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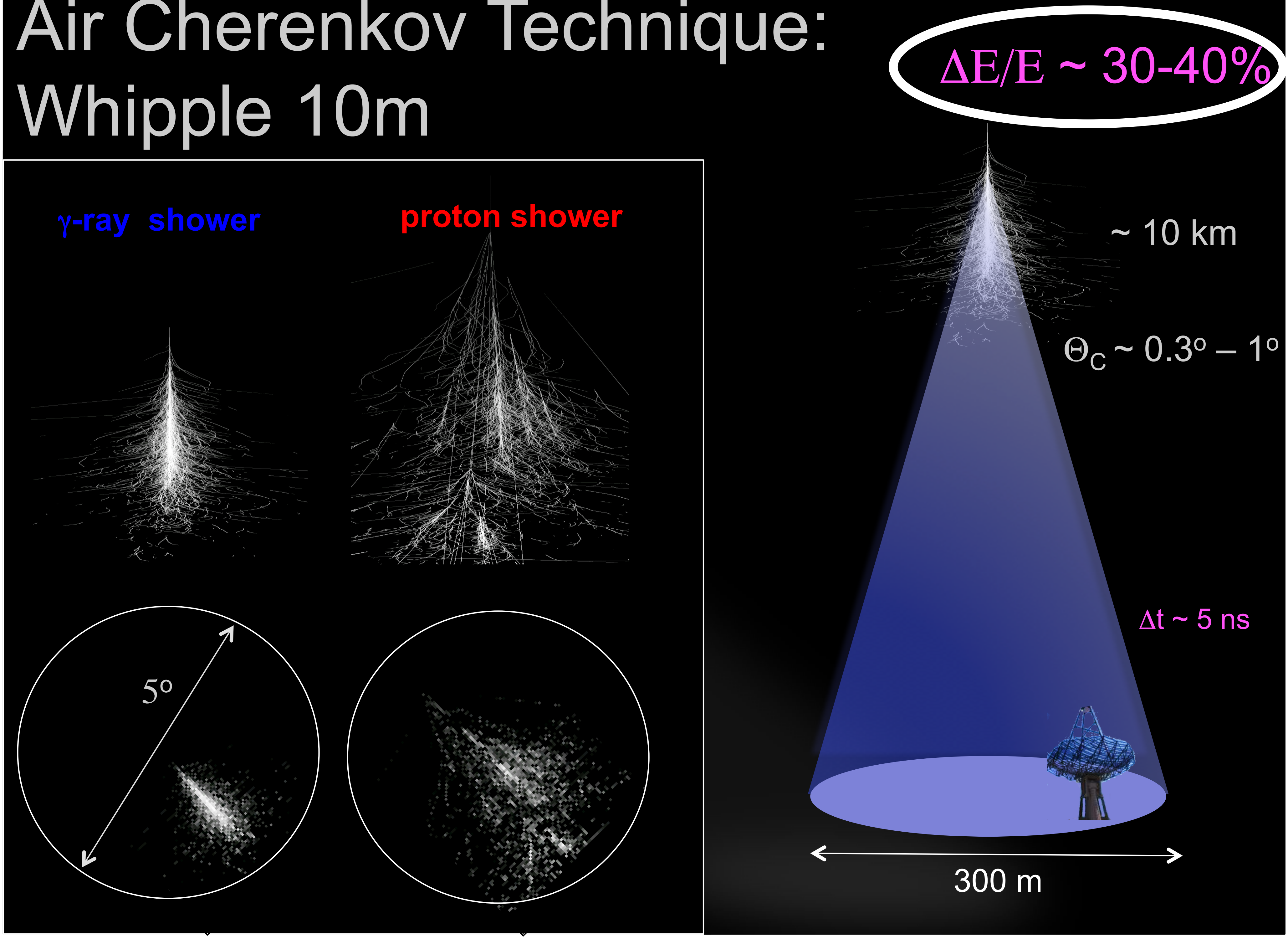
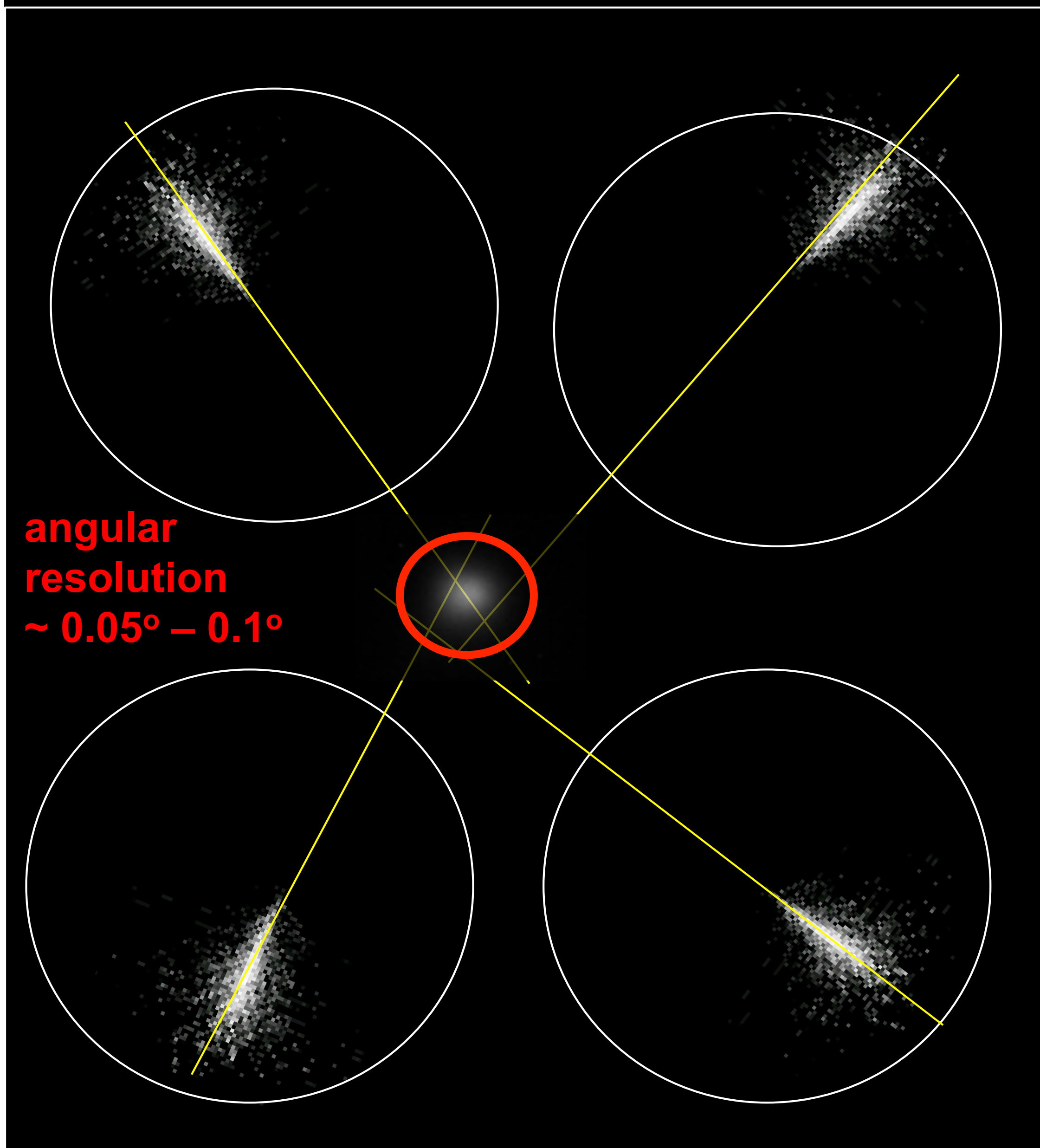
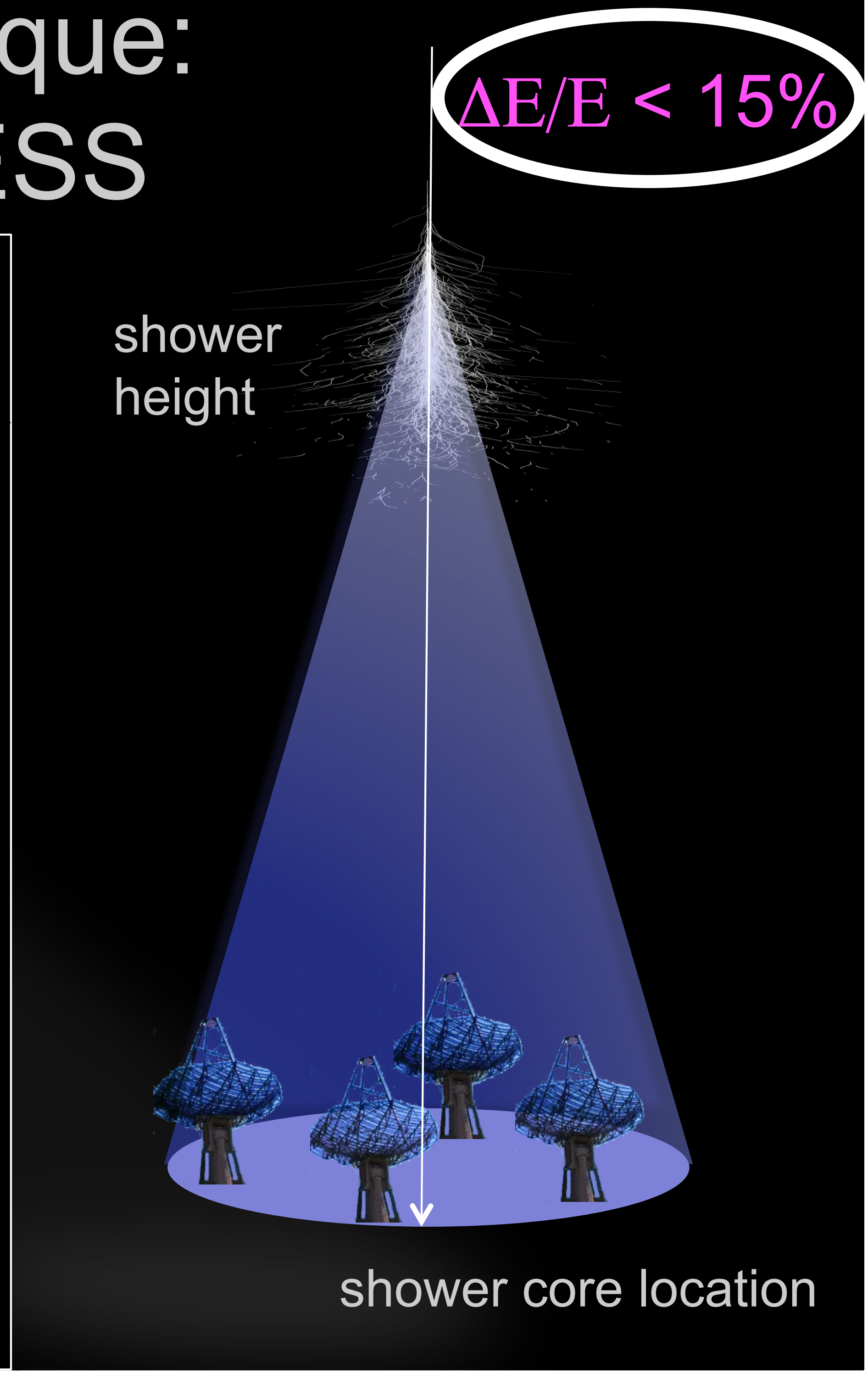
unexpected

Air Cherenkov Technique: Whipple 10m

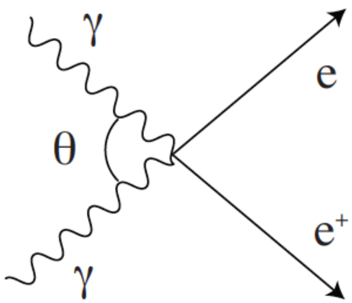


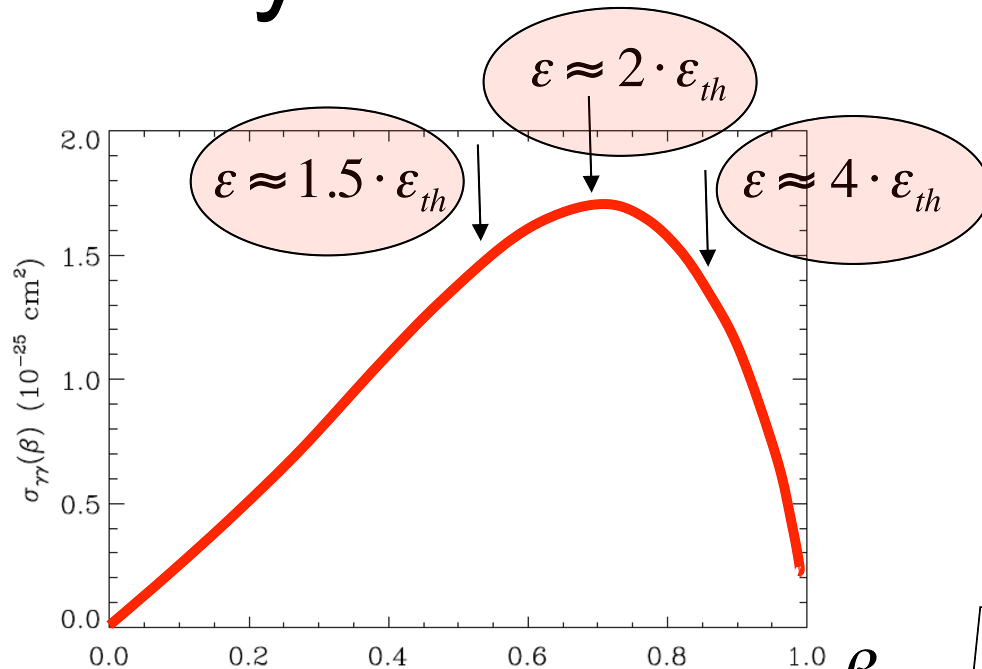
Air Cherenkov Technique:
Stereo: VERITAS, HESS





γ-ray Absorption by the EBL





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

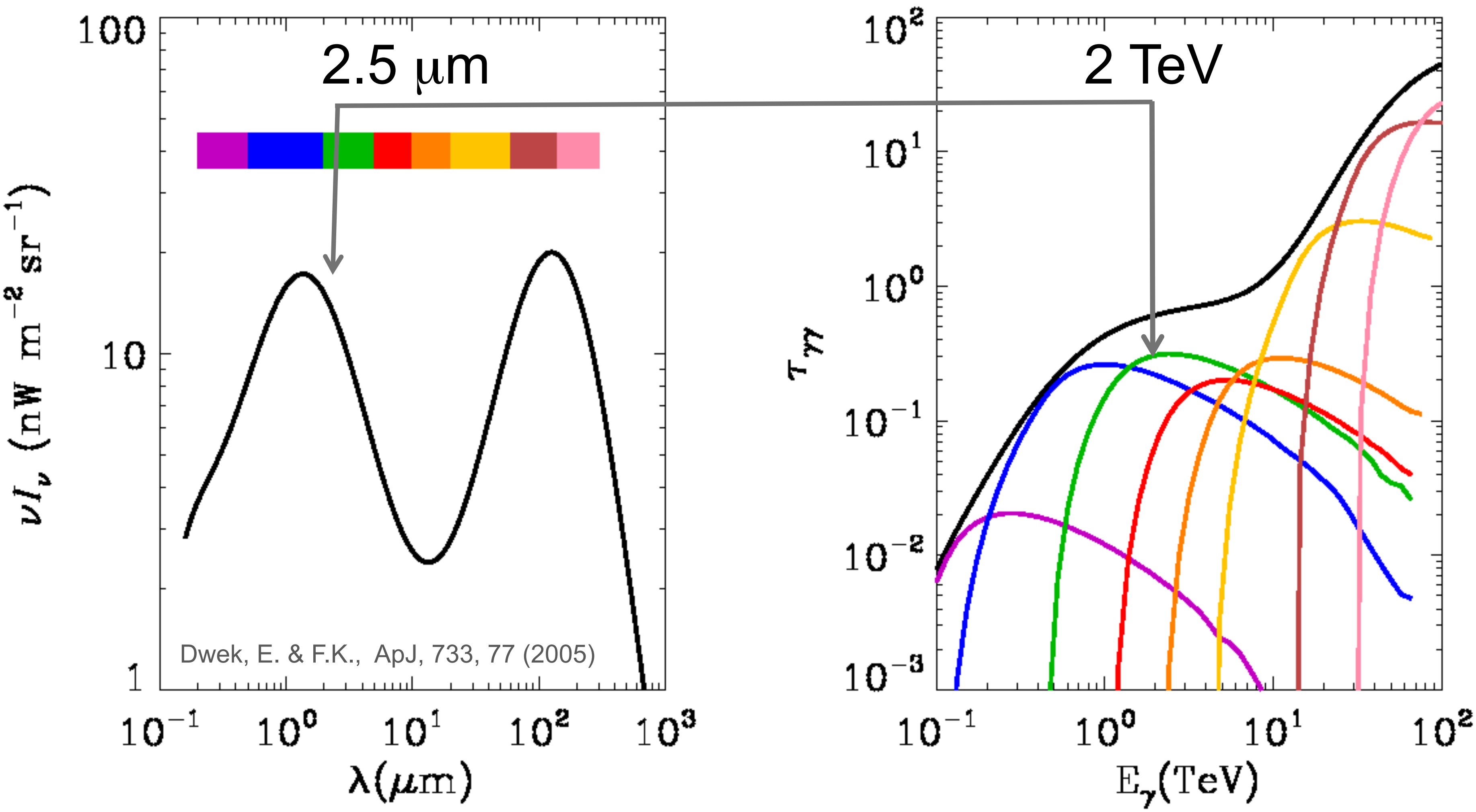
$$\varepsilon_{th}(E_\gamma, \mu, z) = \frac{2(m_e c^2)^2}{E_\gamma (1 - \cos\theta)}$$

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

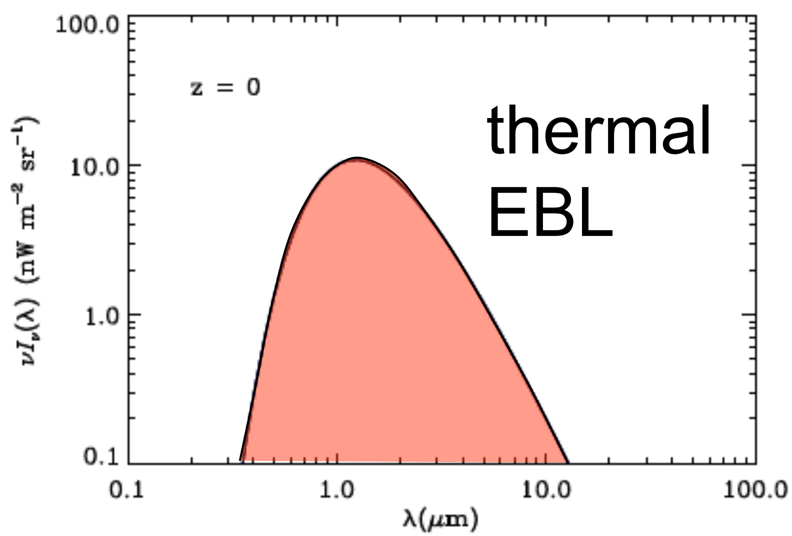
- cross section effective over a broad range of target photon energies (for a given E_γ)
- cross section peaks at $\beta = 0.7$

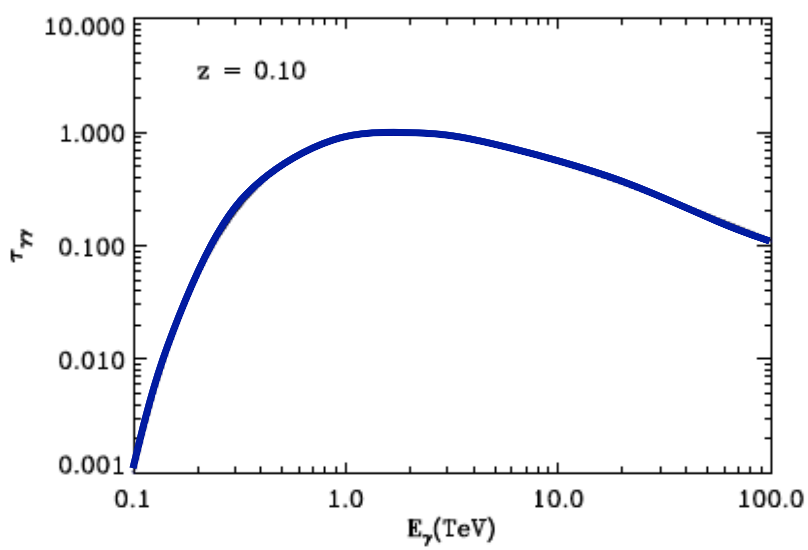
$$E_\gamma[TeV] = \frac{0.86\lambda[\mu m]}{1 - \cos\theta}$$

γ-ray Absorption by the EBL



γ-ray Absorption by the EBL

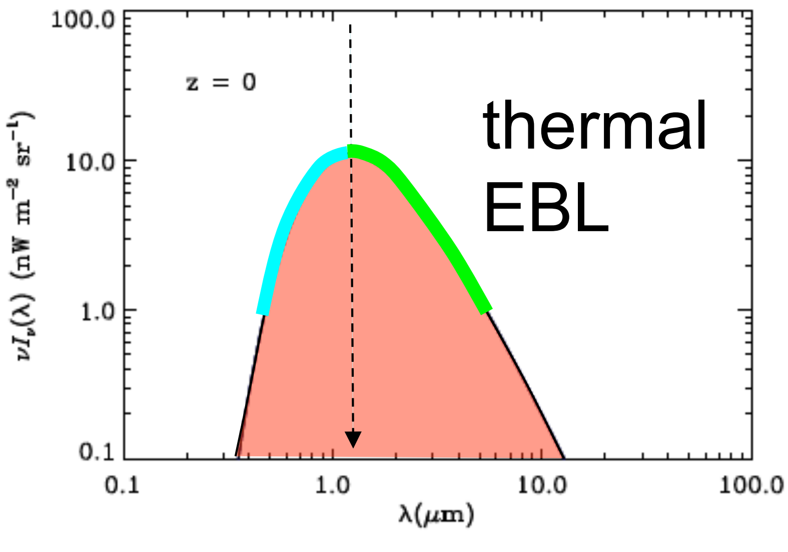


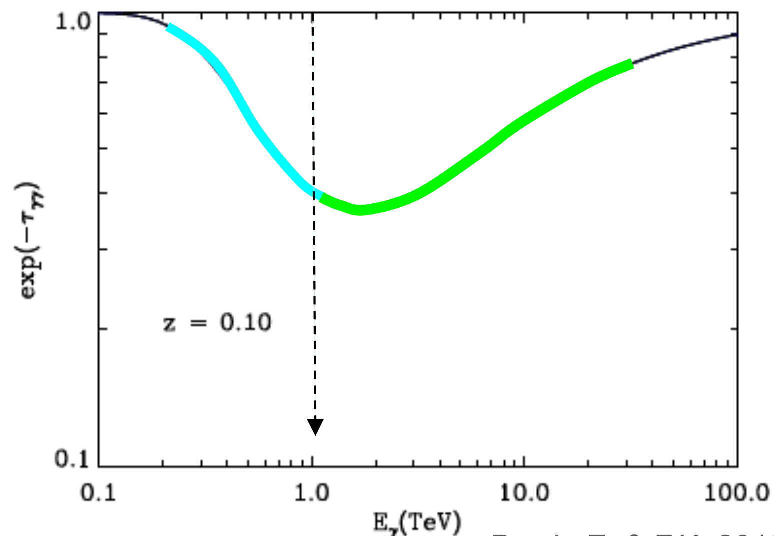


Consider special case:

absorption by a black body photon gas with peak at 1 μm

γ-ray Absorption by the EBL

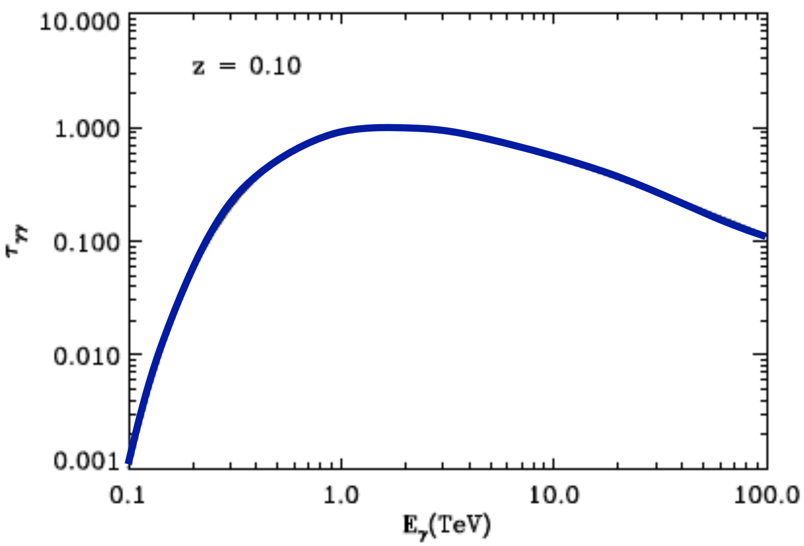




change in slope

at ~ 1 TeV

Dwek, E. & F.K. 2012, in preparation

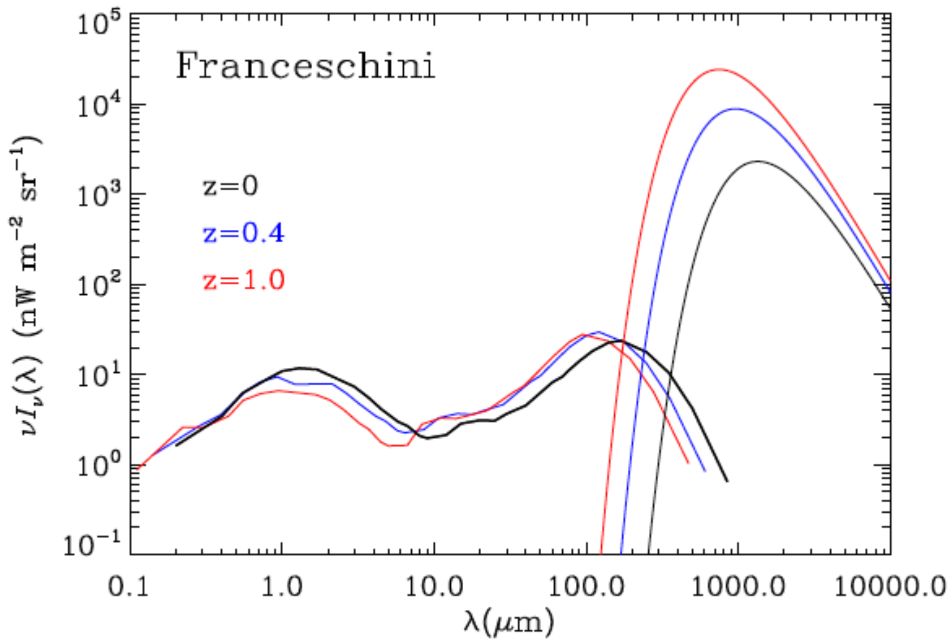


<u>"typical" blazar spectrum:</u>

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

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

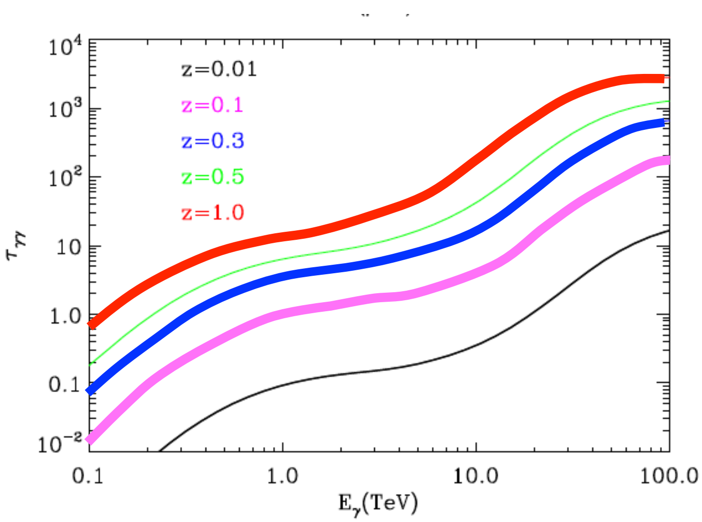
γ-ray Absorption by the EBL



<u>Consider more realistic case:</u>

EBL model (Franceshini)

Franceschini et al., A&A, 487, 837



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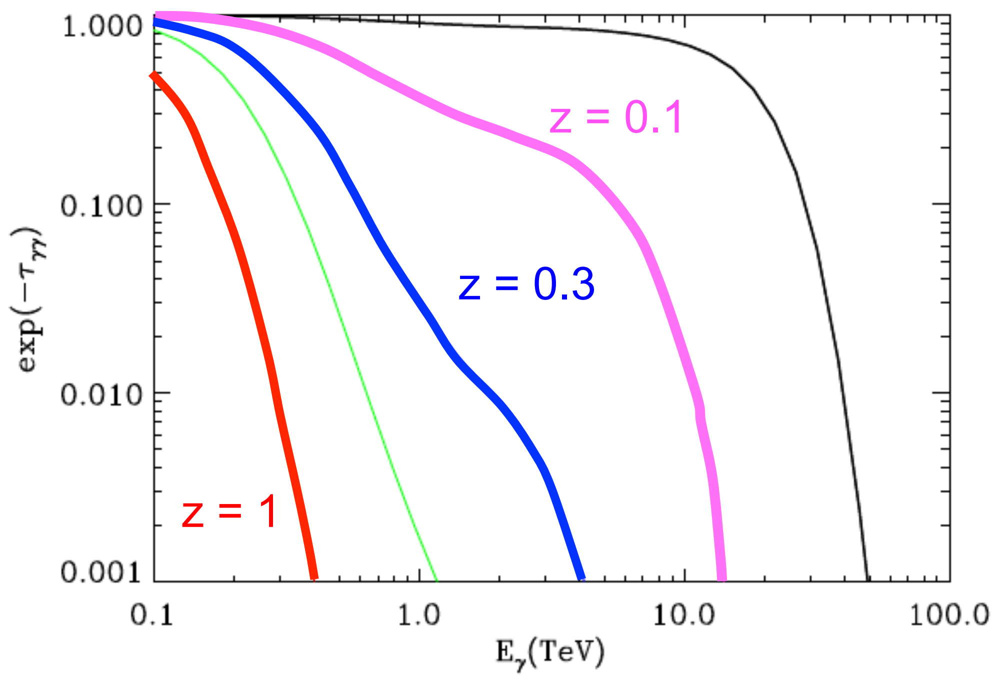

Sources for probing the EBL

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
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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
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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
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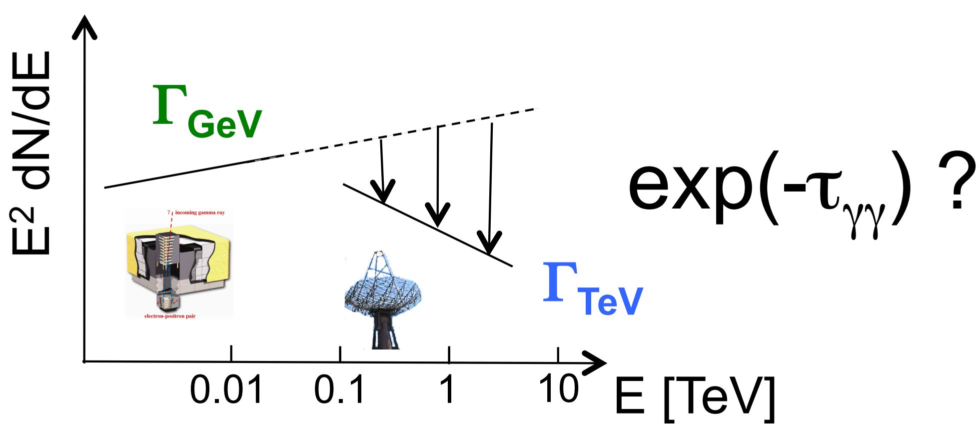
4C 21.35	FSRQ	0.43	2.12±0.02	3.75±0.27	0.07 - 0.4
3C 66A	IBL	0.44♣	1.85±0.02	4.1±0.4	0.22 - 0.45
3C 279	FSRQ	0.536	2.22±0.02	3.03±0.9	0.1 - 0.35

Do we see spectral softening (z)?

- 3 dozen extragalactic sources (blazars, few radio & starburst galaxies
- Spectra ~ 1 GeV – 1 TeV
- redshift (known for 50% of BL Lacs)



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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
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VER J0648+152	HBL	0.179	[illegible]	[illegible]	0.3 - 0.8
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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
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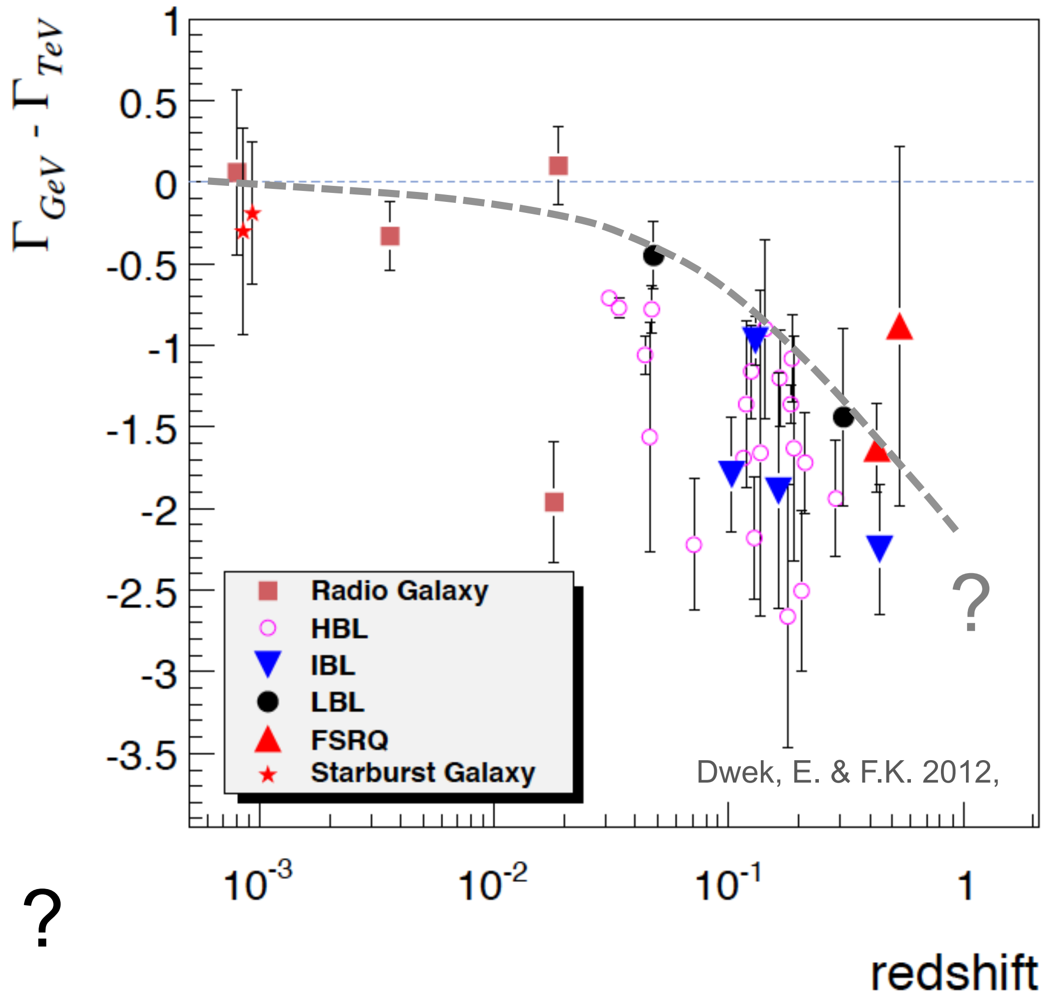
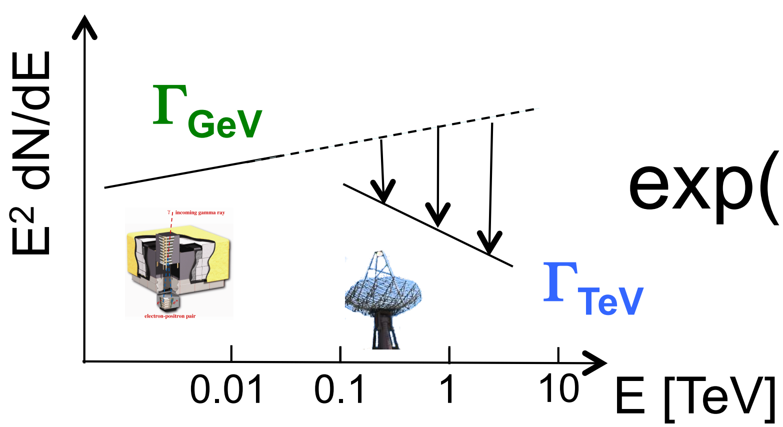


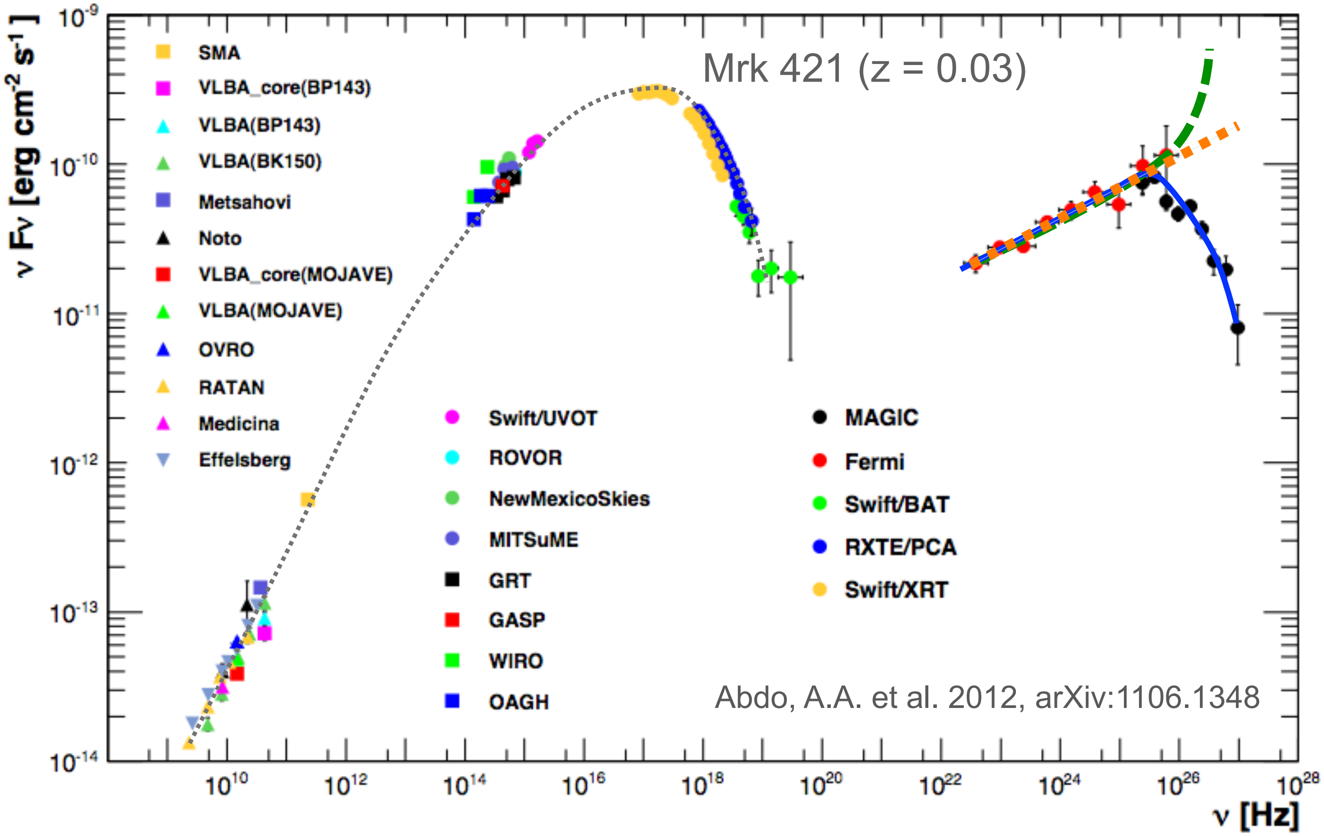


$\exp(-\tau_{\gamma\gamma})$?

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

Sources for probing the EBL

unphysical (no exp. rise!)

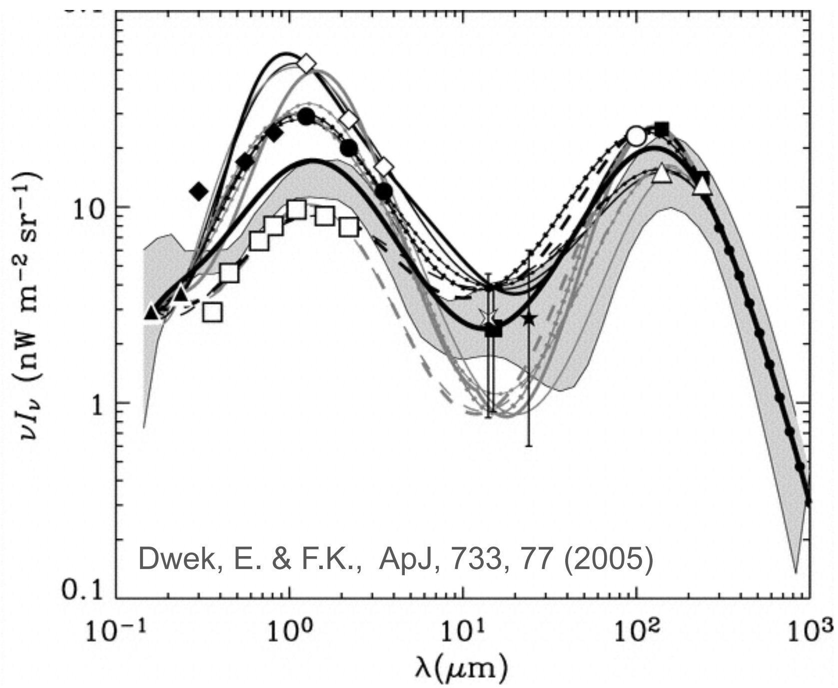


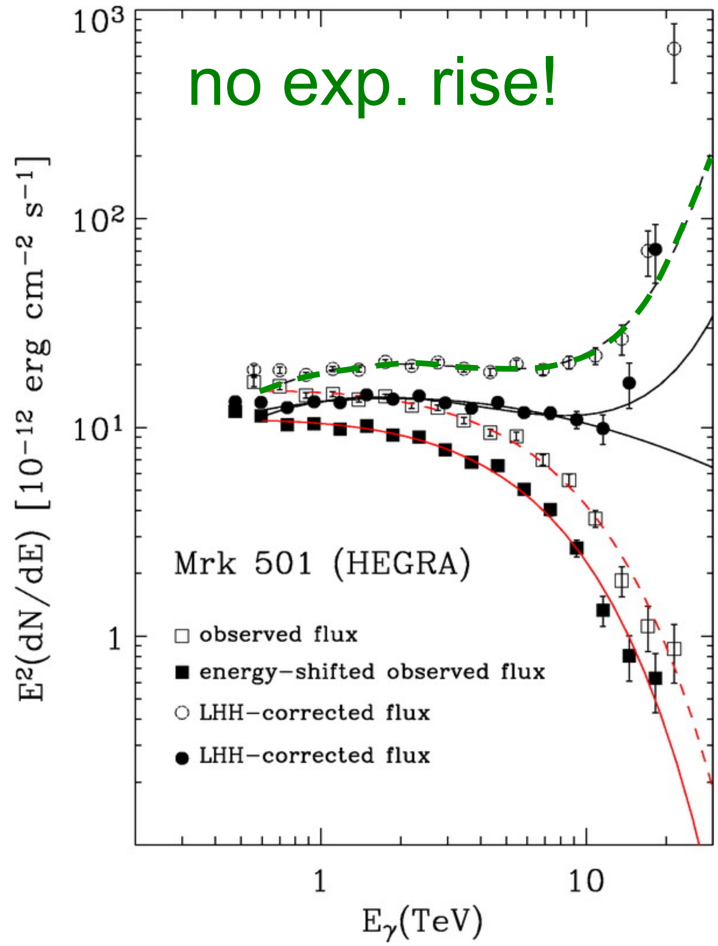
possible (if $\Gamma>1.5$)

measured

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

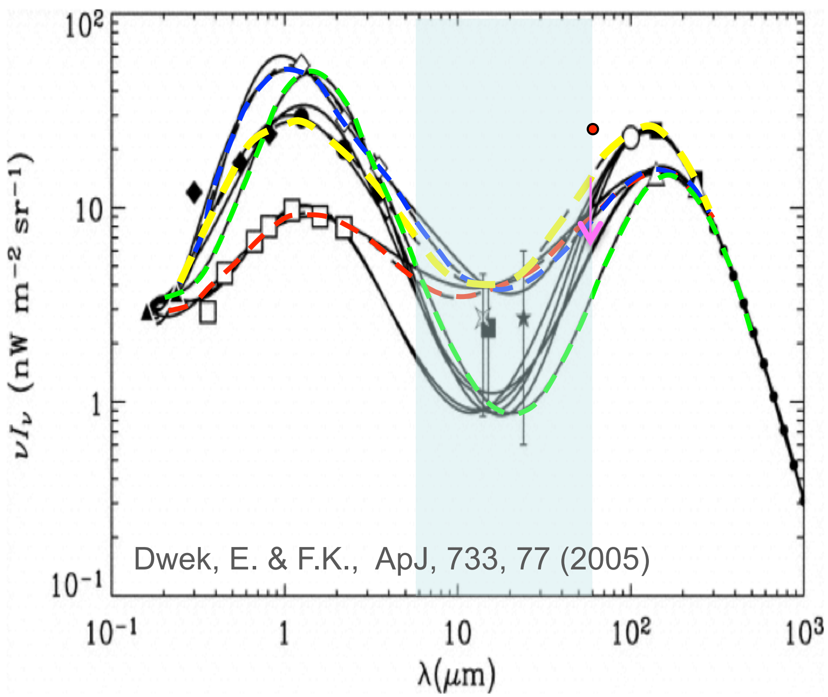
Methods I: no exponential rise!

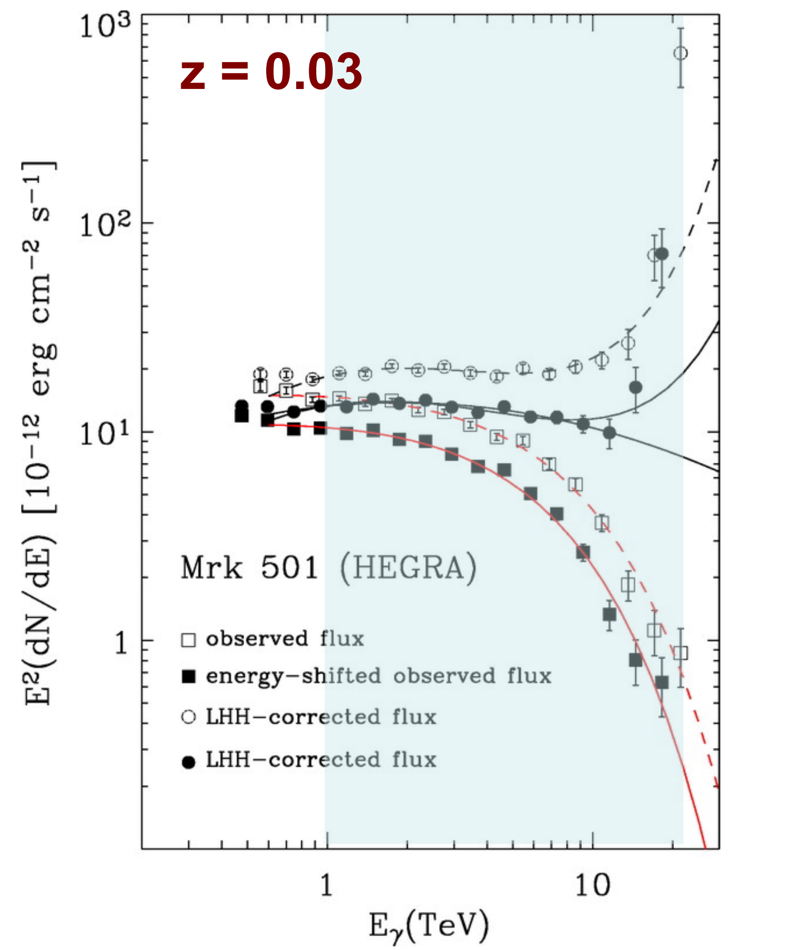




- consider range of EBL scenarios with different near-IR, mid-IR far-IR intensities
- consistent with limits (2005)
- use to unfold absorption-corrected blazar spectra
- **exponential rise**: → EBL intensity is too high ✖

Methods I: no exponential rise!



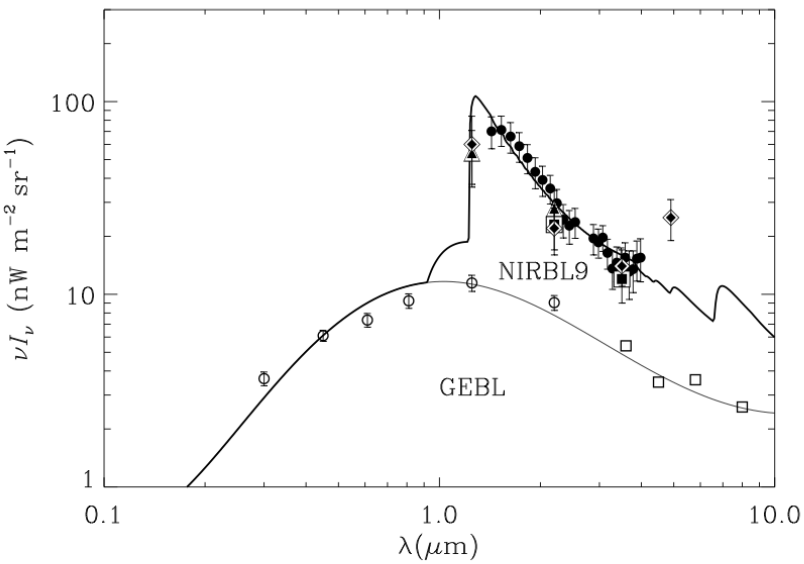


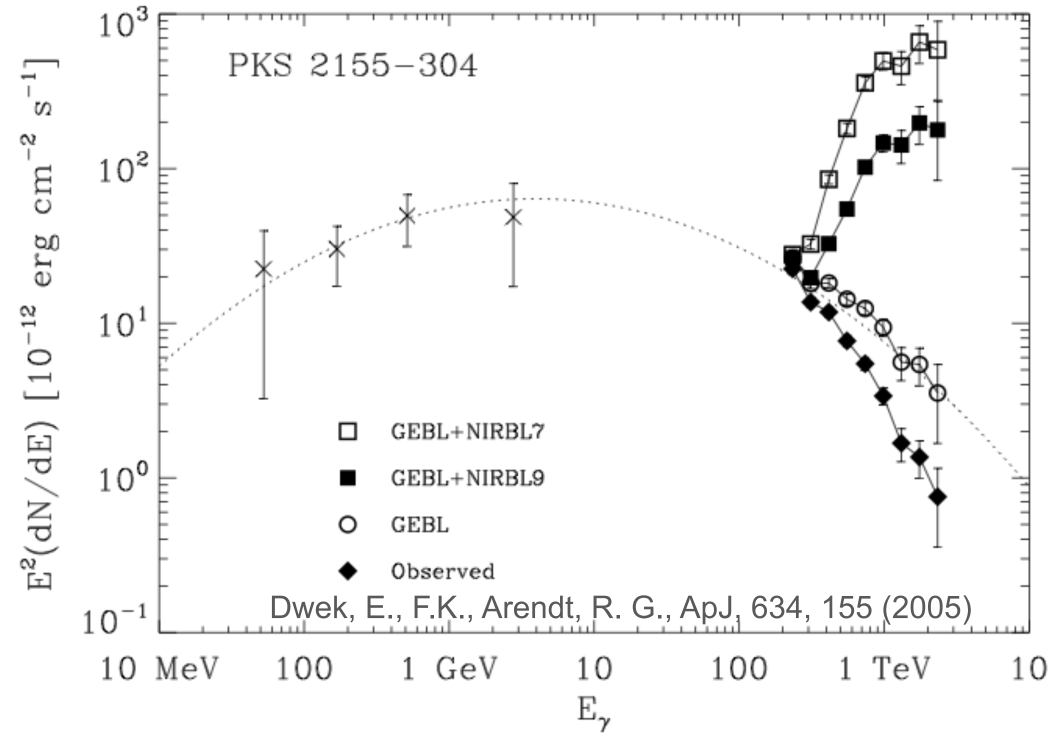
multi-TeV data sensitive to mid-IR

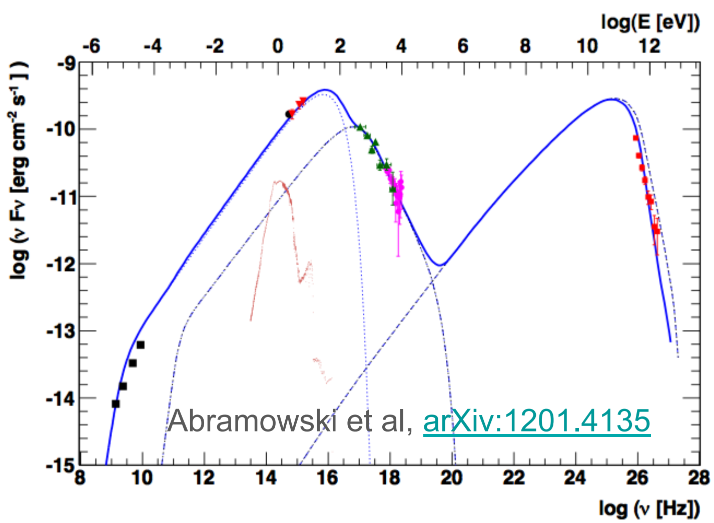
- 3 EBL scenarios with high mid-IR (10 – 60 μm) are rejected using 2 nearby blazars (z ~ 0.03)
- only 1 EBL scenario with moderately high mid-IR but extremely high near-IR remains!
- strong upper limit: **νI_ν (60 μm) < 15 nW/m^2/sr**

Methods I: no exponential rise!

z = 0.116

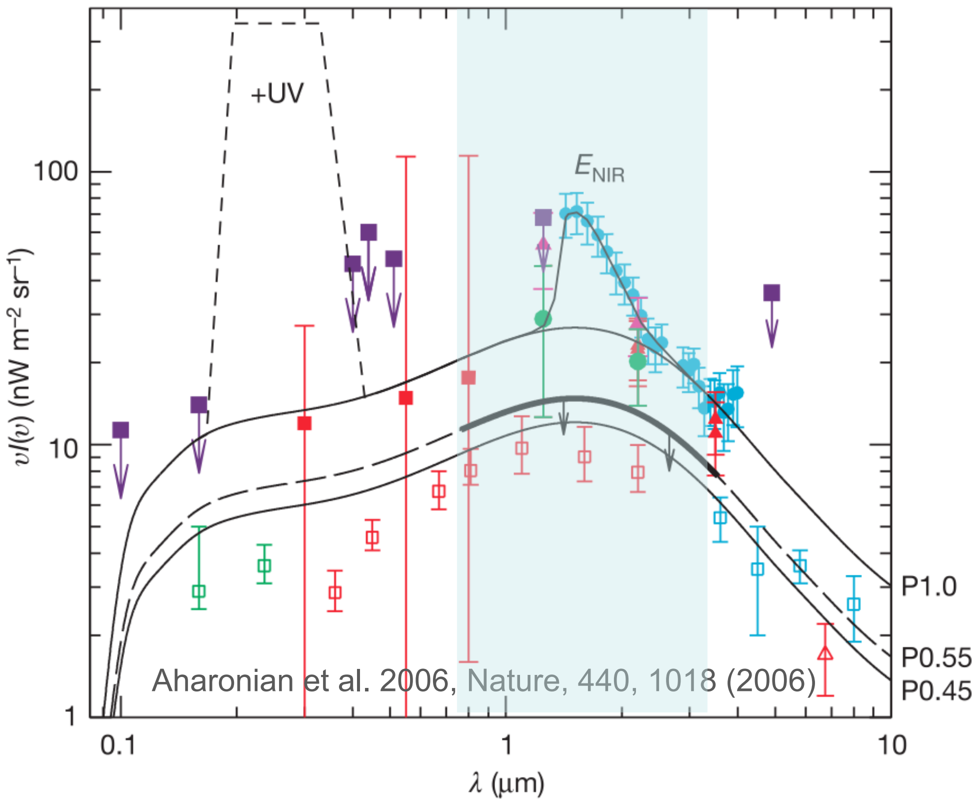


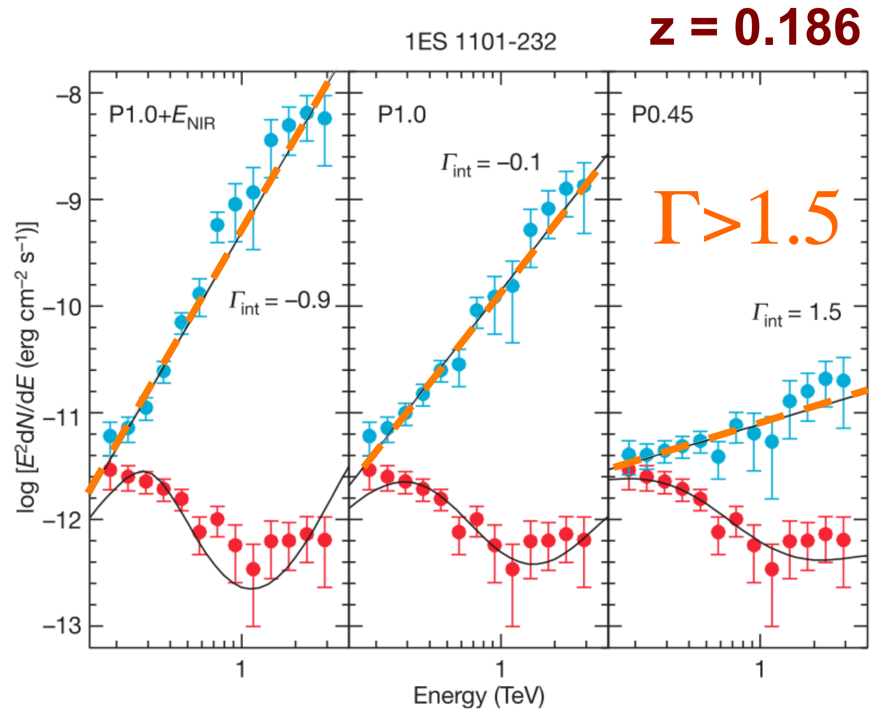




- excess near-IR background light (NIRBL): incompatible with “typical” blazar spectrum!

Method II: hardness limit Γ > 1.5

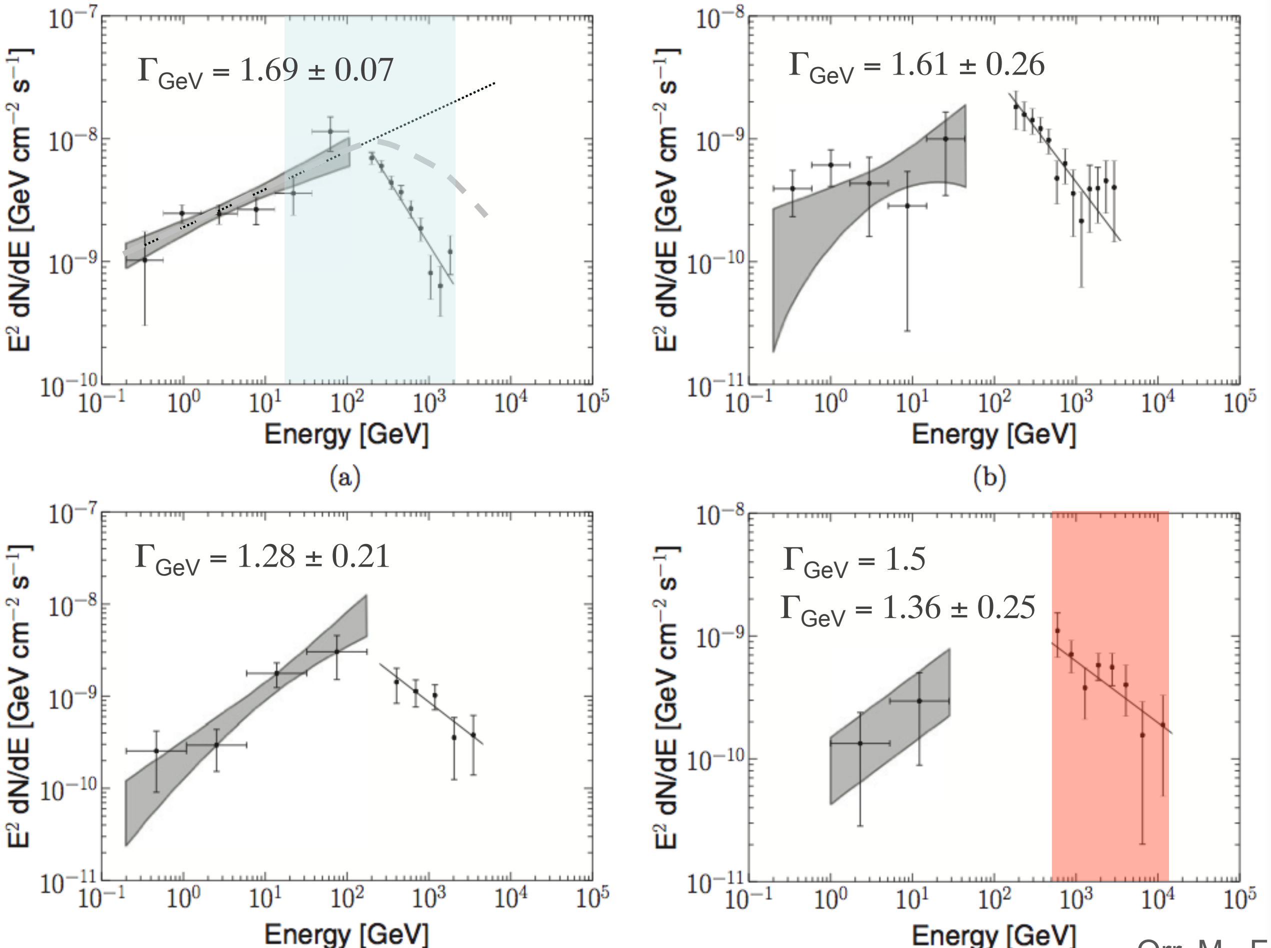




- EBL intensity near-IR (1 – 4 μm) is constrained by allowing absorption-corrected spectra with Γ > 1.5 only!
- strong upper limit in near-IR: **νI_ν (1-2 μm) < 14 ± 0.4 nW/m²/sr**
- dependents on assumed intrinsic source spectrum! (Γ ~ 1.2 Fermi spectra!)

More comprehensive analysis is given in Mazin, D. & Raue M., A&A, 471, 439 (2007)

Method III, part I: $\Gamma_{TeV} > \Gamma_{GeV}$



1ES 1218+304: z = 0.182

1ES 1101-232: z = 0.186

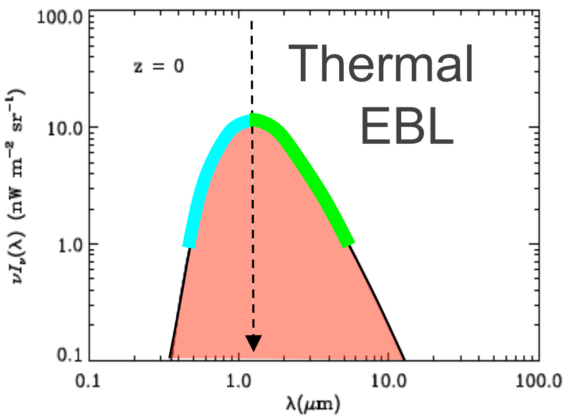
RGB J0710+591: z = 0.125

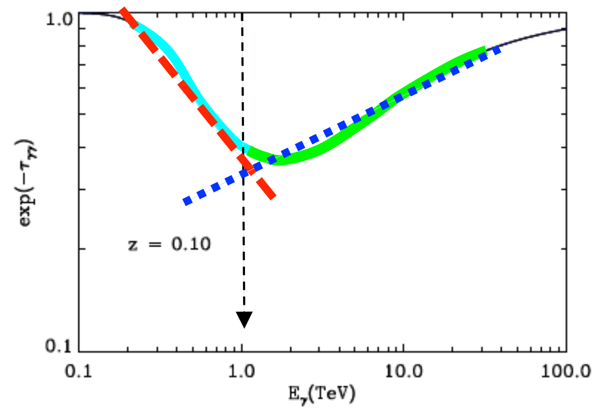
1ES 0229+200: z = 0.13

Orr, M., F.K. & Dwek, E., ApJ, 733, 77 (2011)

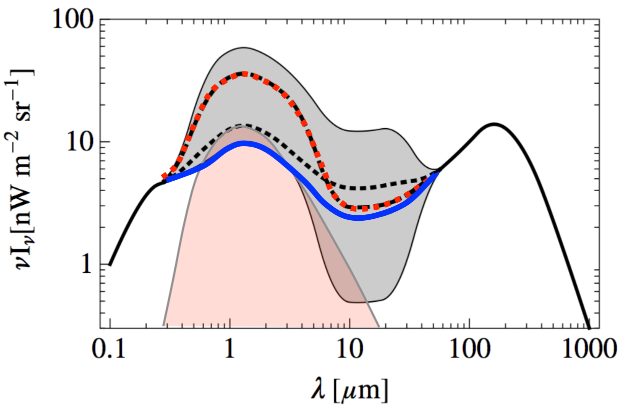
- simultaneous EBL constraints in near-IR & mid-IR
- requires distant sources (z ~ 0.1 – 0.3) with hard spectra
- Fermi spectral index used to set **upper limit in near-IR**
- use Fermi spectra combined with multi-TeV spectra

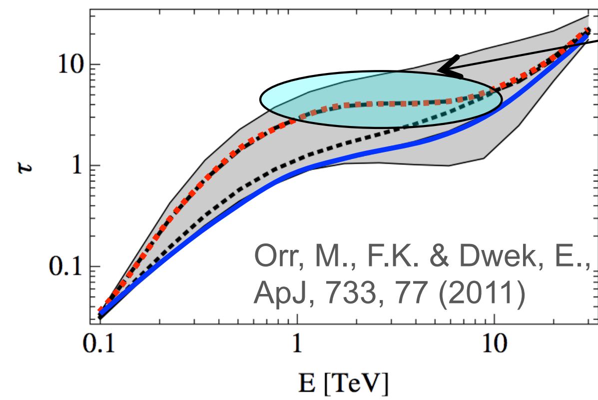
Method III, part II: 1 TeV break





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



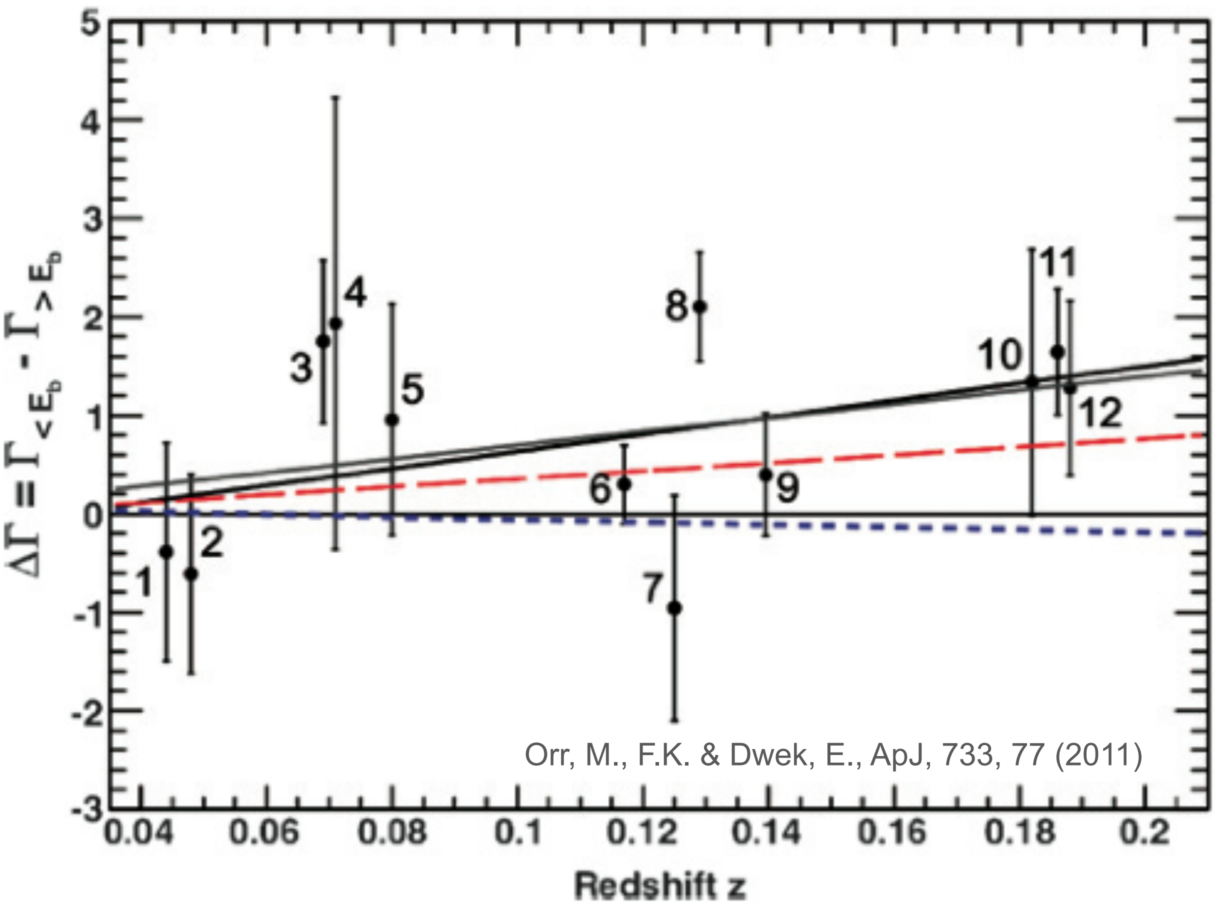


$$\tau_{\gamma\gamma}(E) \approx const.$$

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

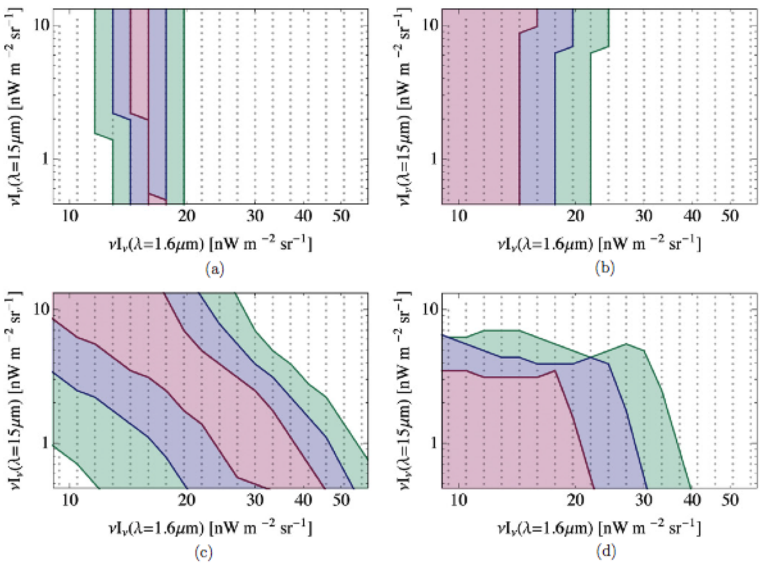
- shape of EBL may produce unique imprint in TeV spectra
- effect would be very strong in purely thermal photon field
- strength depends on **ratio** of **near-IR to mid-IR**
- constant tau (1 – 10 TeV): the observed spectrum ≈ intrinsic source spectrum

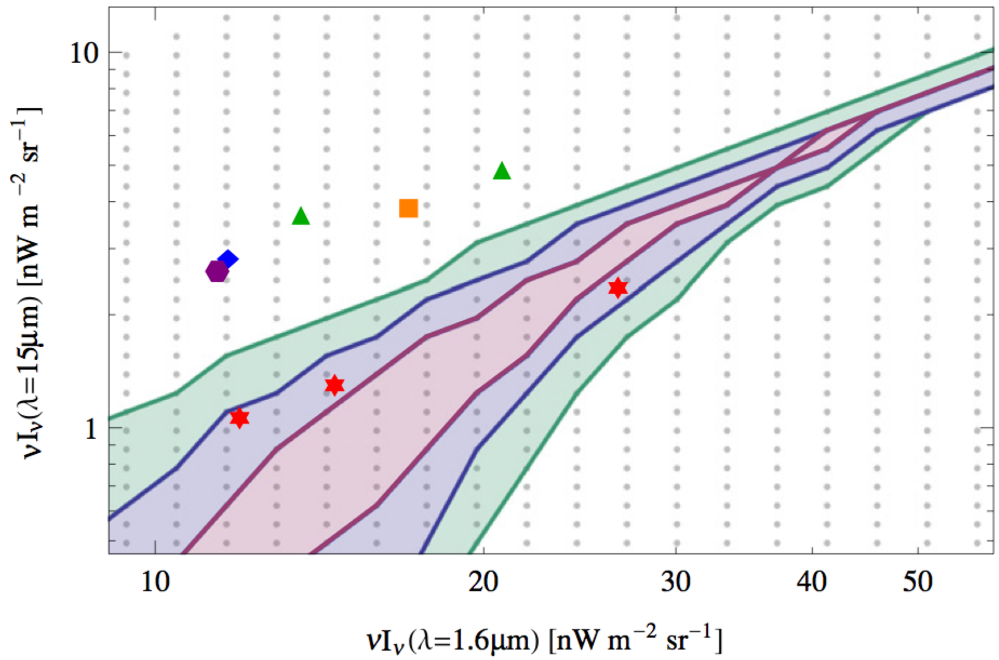
Method III, part II: 1 TeV break

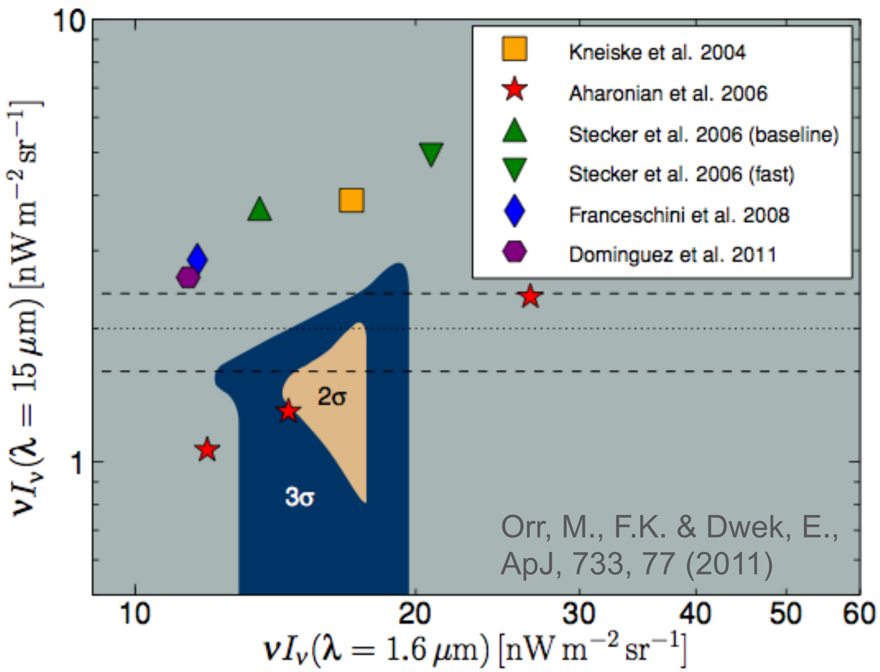


Source Name	Redshift	Γ_{LAT}	Γ_{VTS}	Method(s)	# Spec. Points l.t./g.t. E_{break}
1ES 2344+514	0.044	1.57 ± 0.17	2.95 ± 0.12	TeV Break	4 / 3
1ES 1959+650	0.047	2.10 ± 0.05	2.58 ± 0.18	TeV Break	4 / 2
PKS 0548-322	0.069	-	2.8 ± 0.3	TeV Break	3 / 2
PKS 2005-489	0.071	1.90 ± 0.06	4.0 ± 0.4	TeV Break	6 /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

Method III: part I+II (Data)

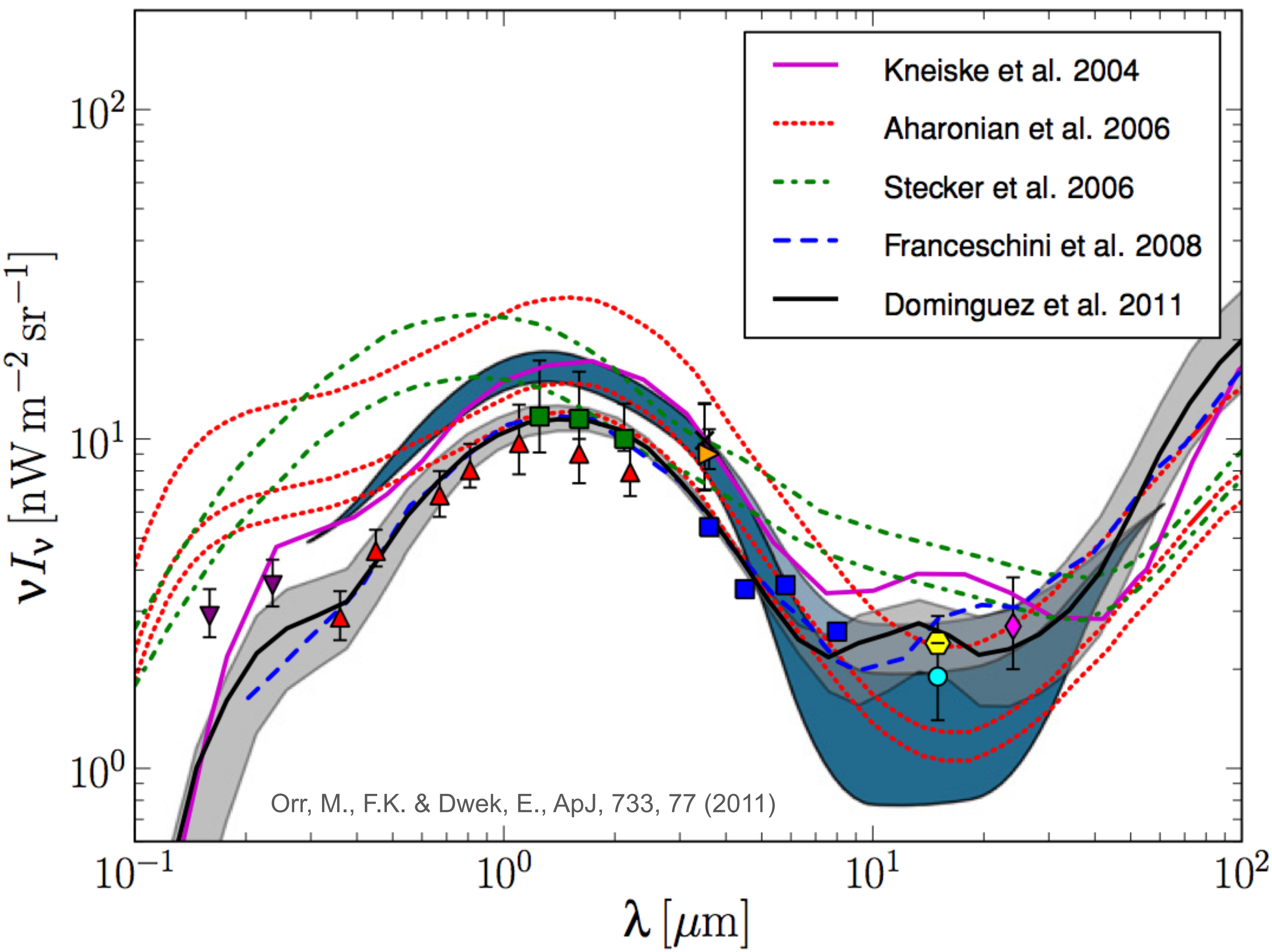






- part I and part II are "orthogonal"
- constrain near-IR to mid-IR ratio!
- considering lower limits (direct), also constrains absolute level!

Method III:



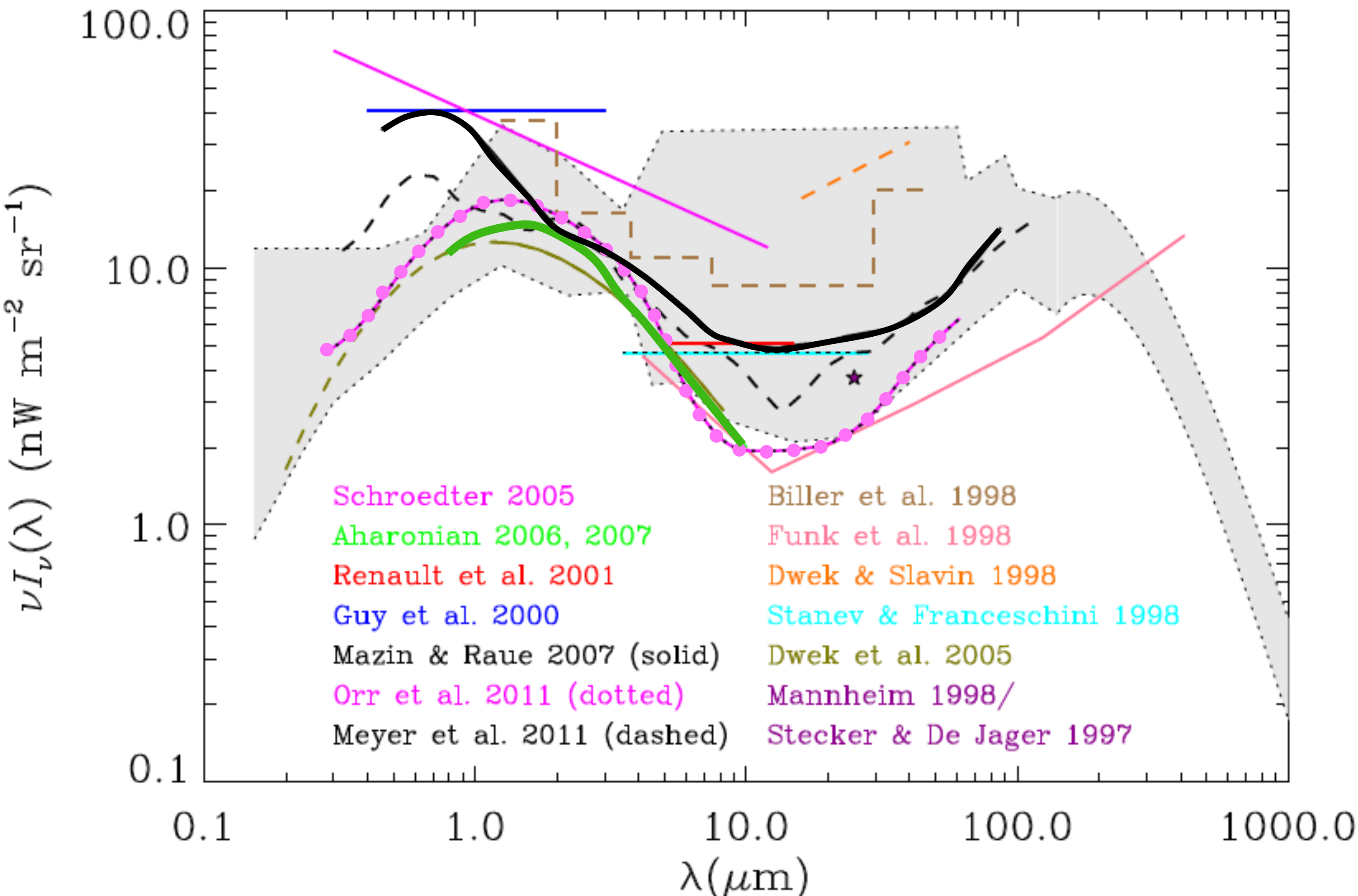
at 1.6 μm:

17 ± 0.3 nW/m²/sr

at 15 μm:

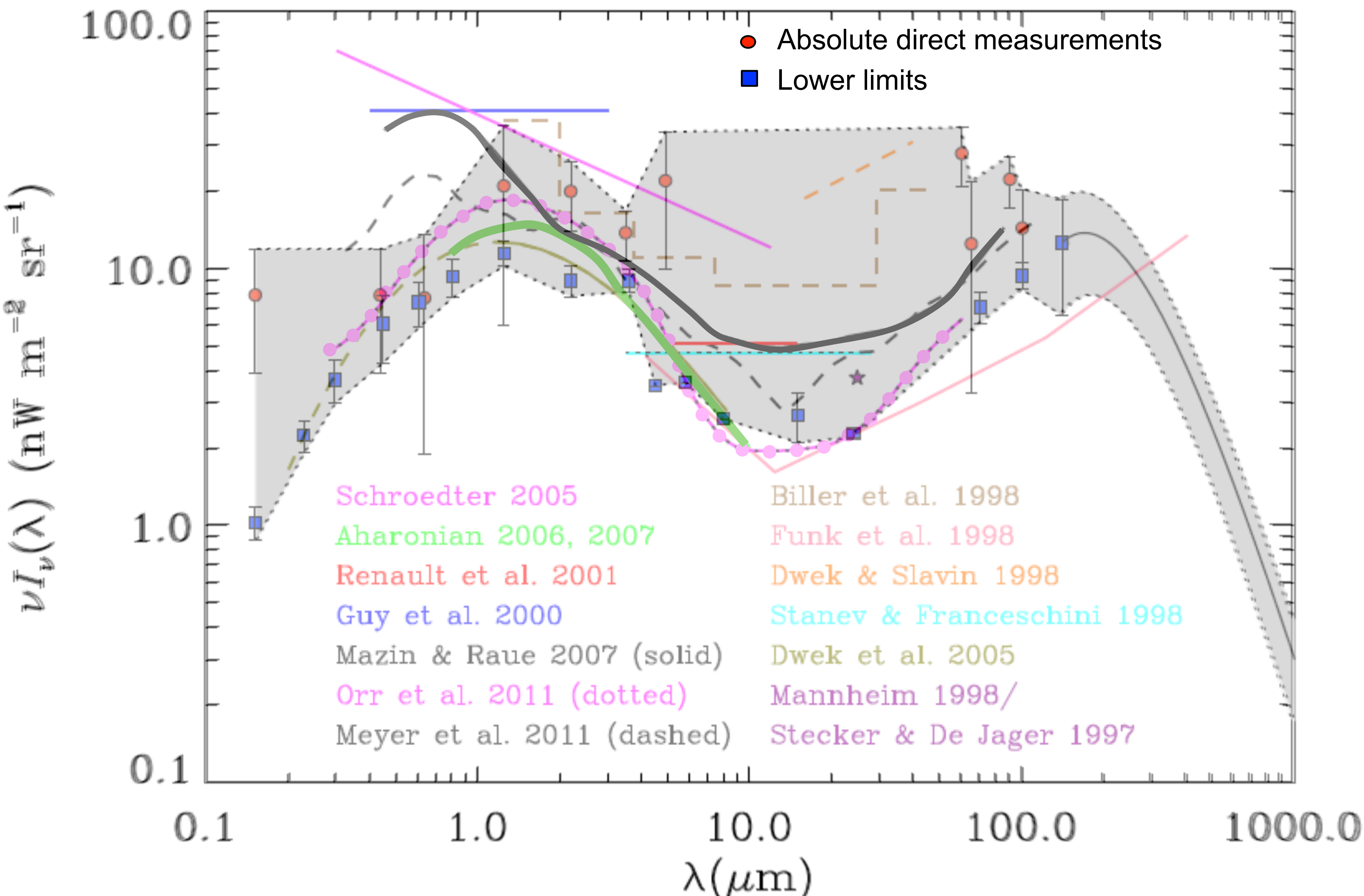
1.36 ± 0.58 nW/m²/sr

Summary of EBL limits from γ-rays



Dwek, E. & F.K. 2012,

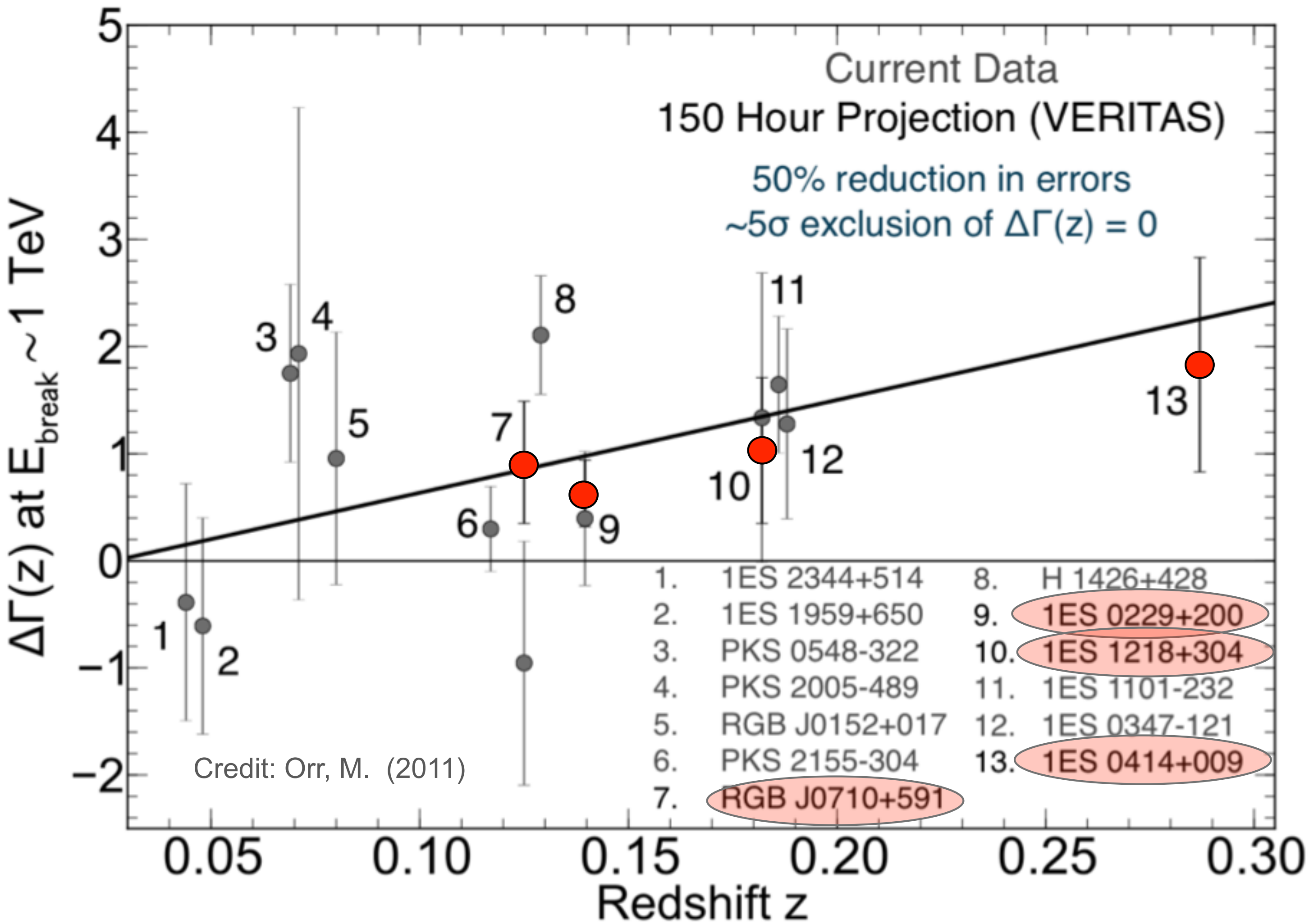
Summary of EBL limits from γ-rays



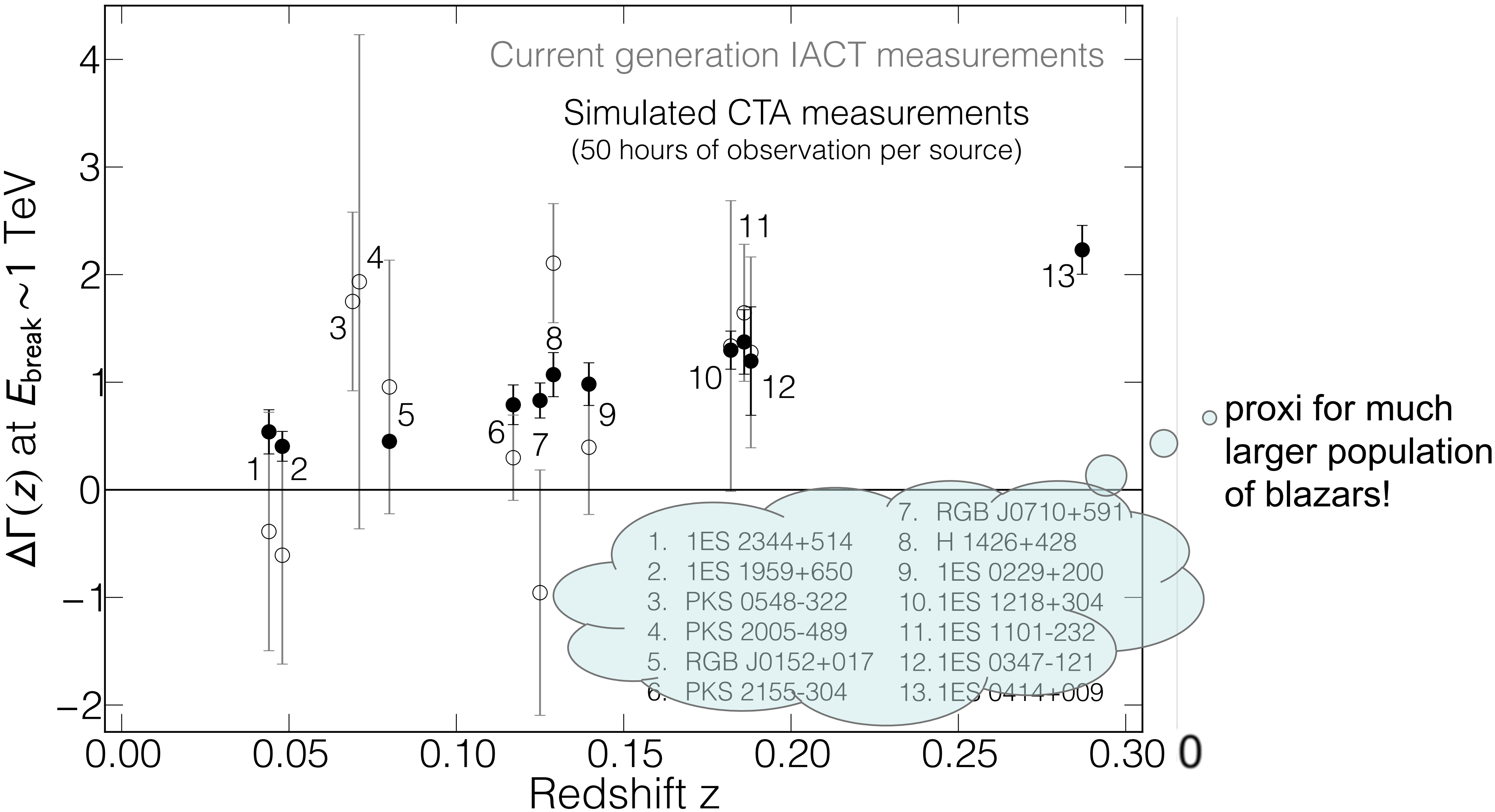
Dwek, E. & F.K. 2012,

Future

Unique Signature? (VERITAS-II)



Unique Signature? (CTA)



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

Summary

- TeV γ-ray data provide <u>strong constraints</u> to the <u>near-IR</u> and <u>mid-IR</u>
- Range of methods (assumptions) yield comparable results
- > 35 sources with GeV - TeV spectra: better constraints!
- Potential for a unique signature from EBL absorption ~ 1 TeV
- Deep exposures (100h VERITAS-II) required to achieve sensitivity
- precision measurements of absorption effects likely with CTA
- potential for using different classes of sources:

  hard spectra BL Lacs: <z> ~ 0.3 → near-IR + mid-IR
  radio galaxies: nearby → mid-IR + far-IR
  SB galaxies: nearby → mid-IR + far-IR
  FSRQs: likely to extent to z ~ 1