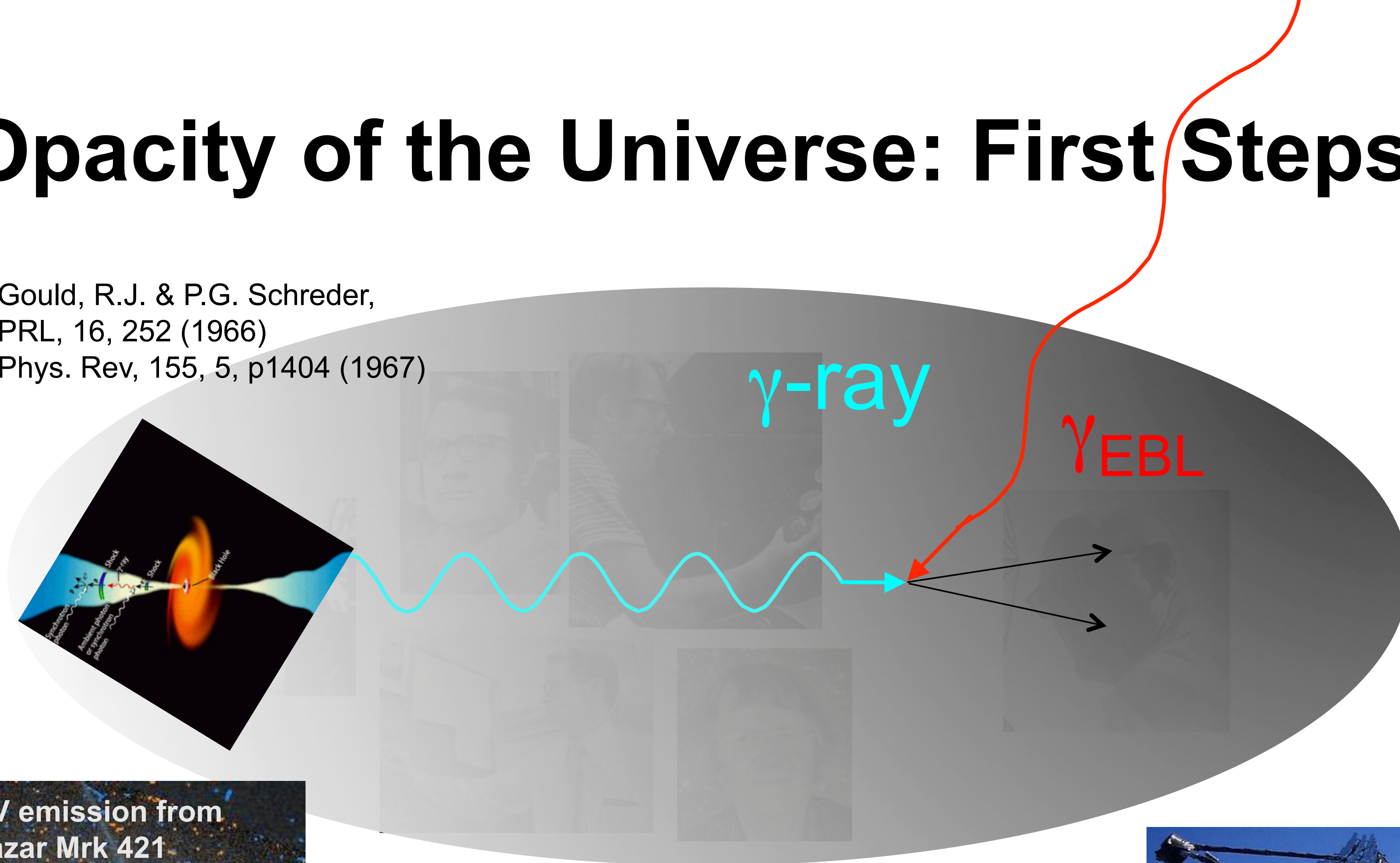
Progress in Understanding the Extragalactic Background Light from Gamma Ray observations

Frank Krennrich, Iowa State University

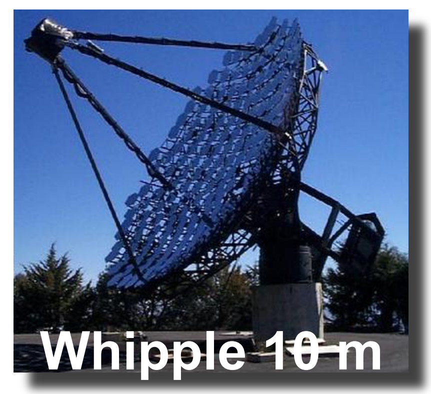
Opacity of the Universe: First Steps

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

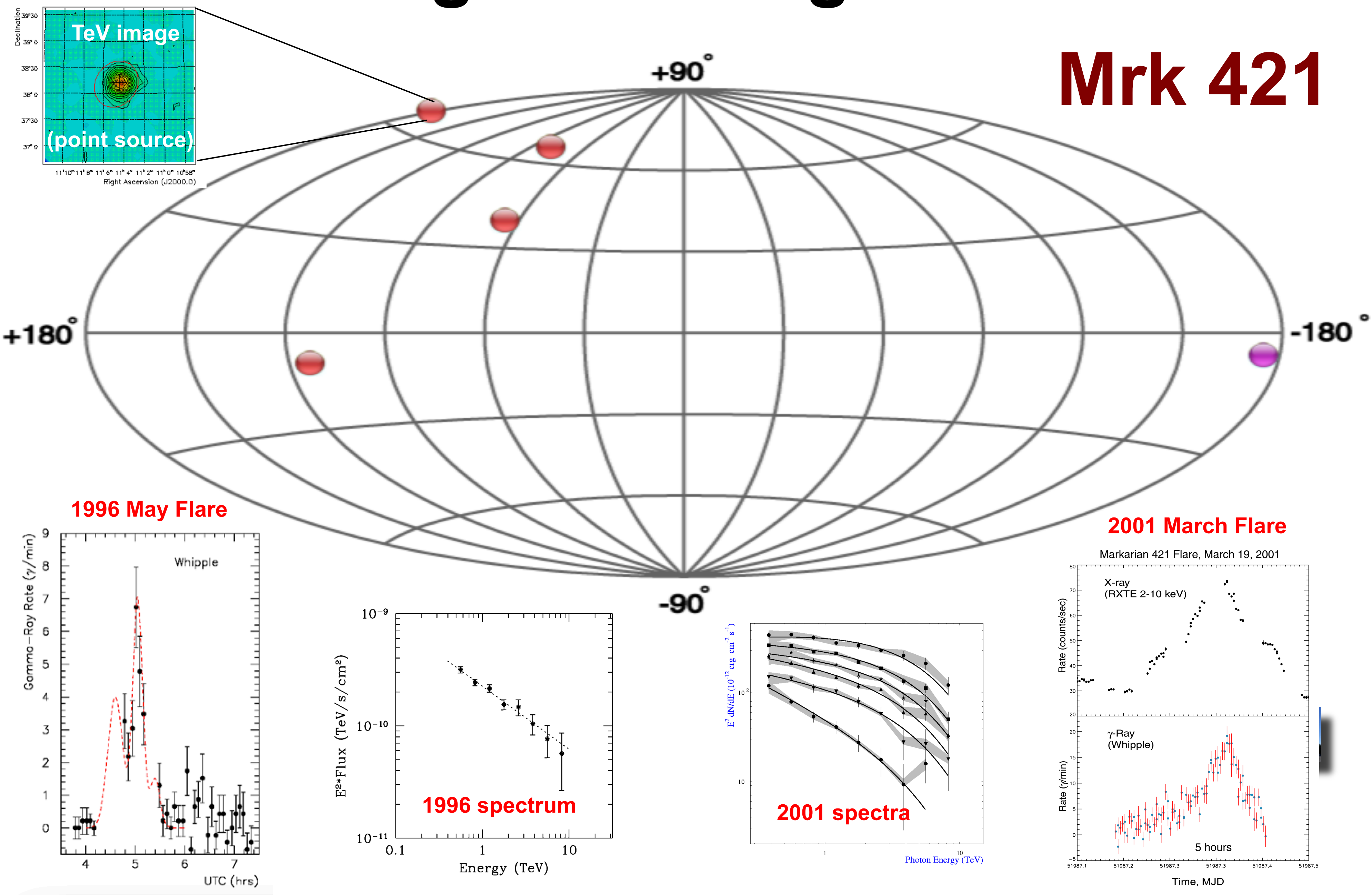


$$\gamma_{TeV} + \gamma_{near\text{-}IR} \rightarrow e^{+} + e^{-}$$

many contributions in 1990s:
F. Stecker, S. Biller, V. Vassiliev, F. Aharonian, E. Dwek, . …

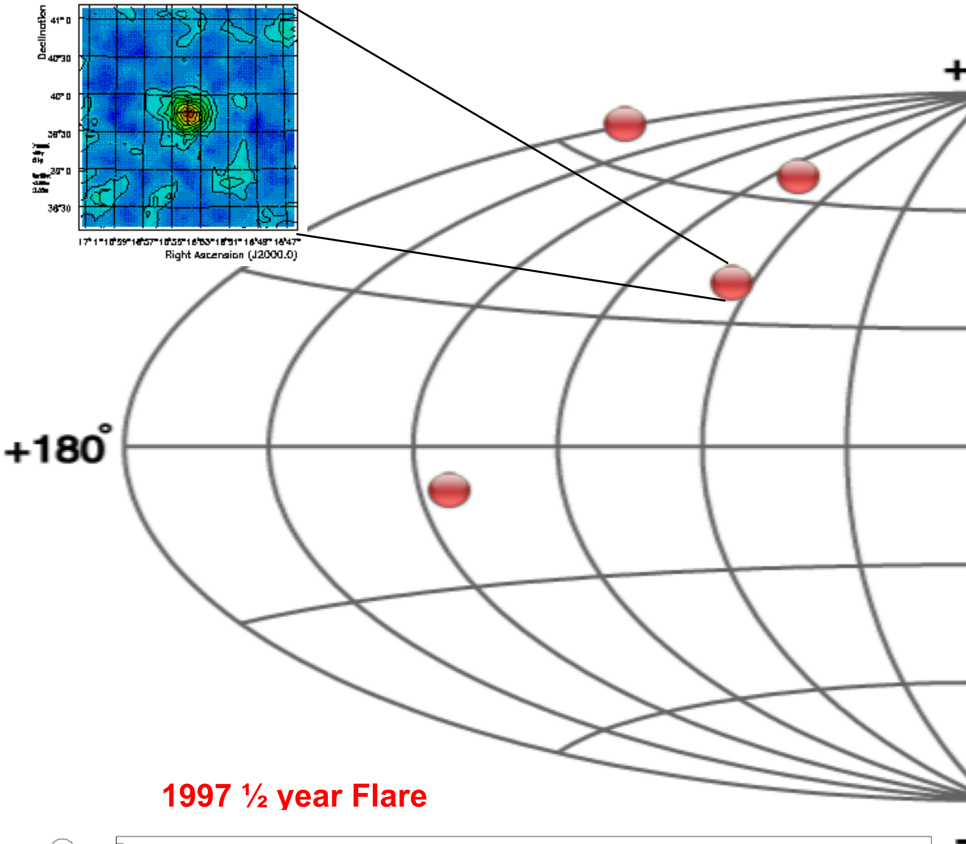


Storm & Urge: Chasing Blazars …

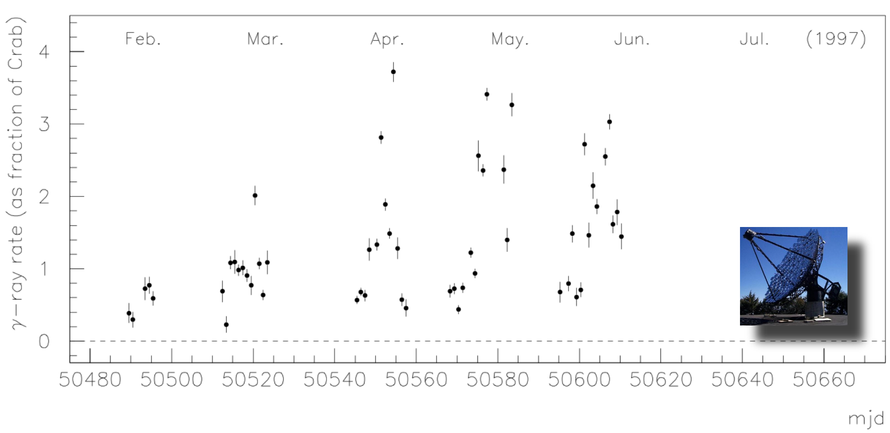


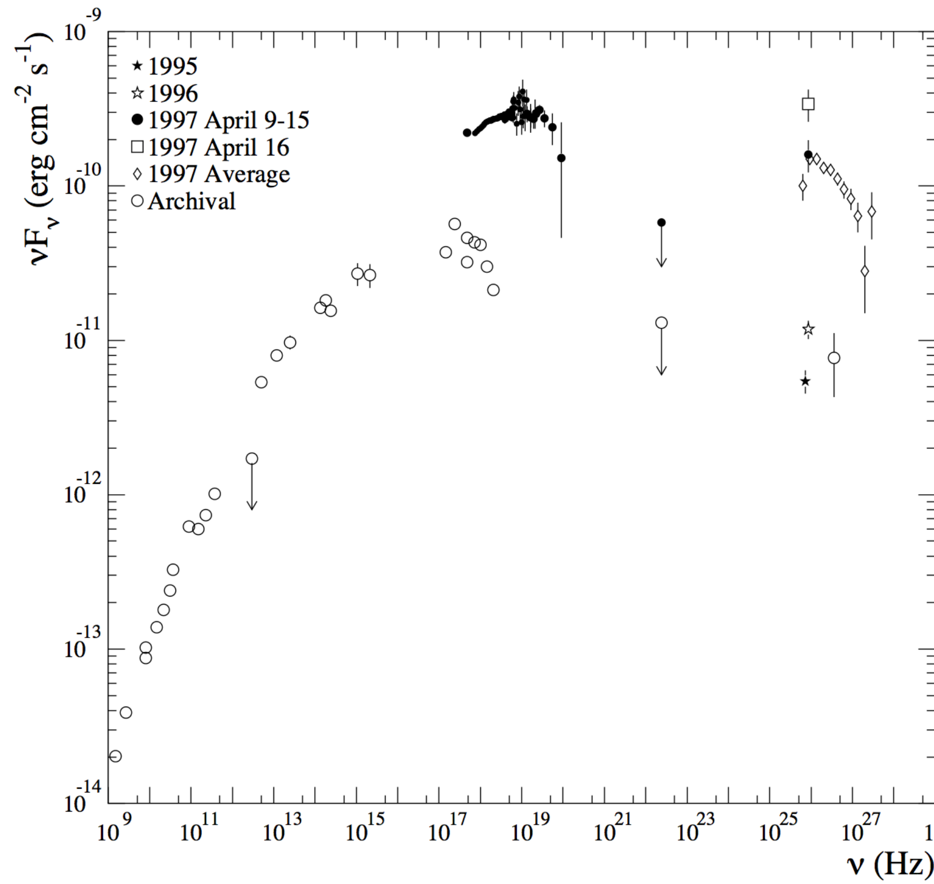
Storm & Urge: Chasing Blazars …

Mrk 501



1997 ½ year Flare





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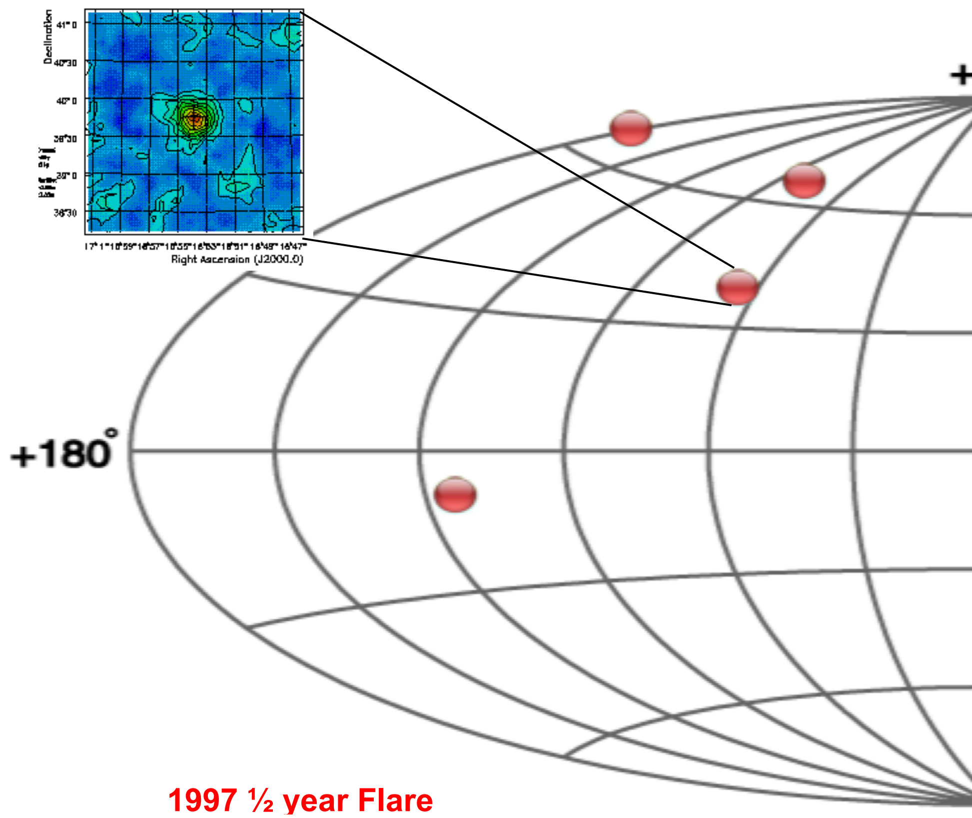

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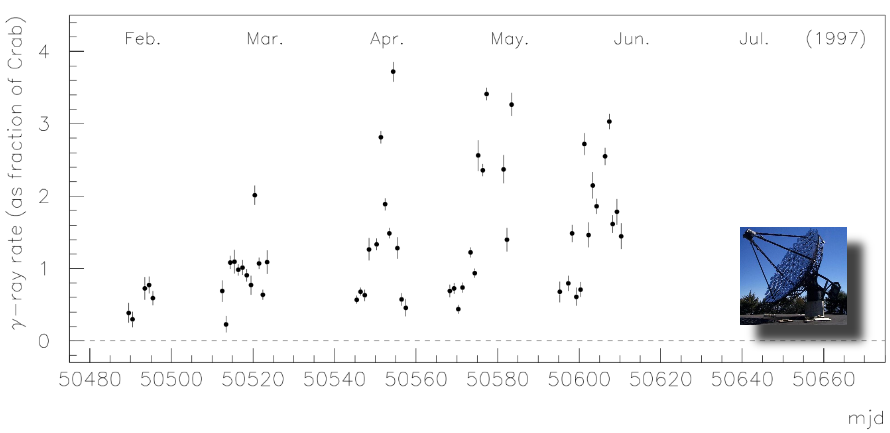

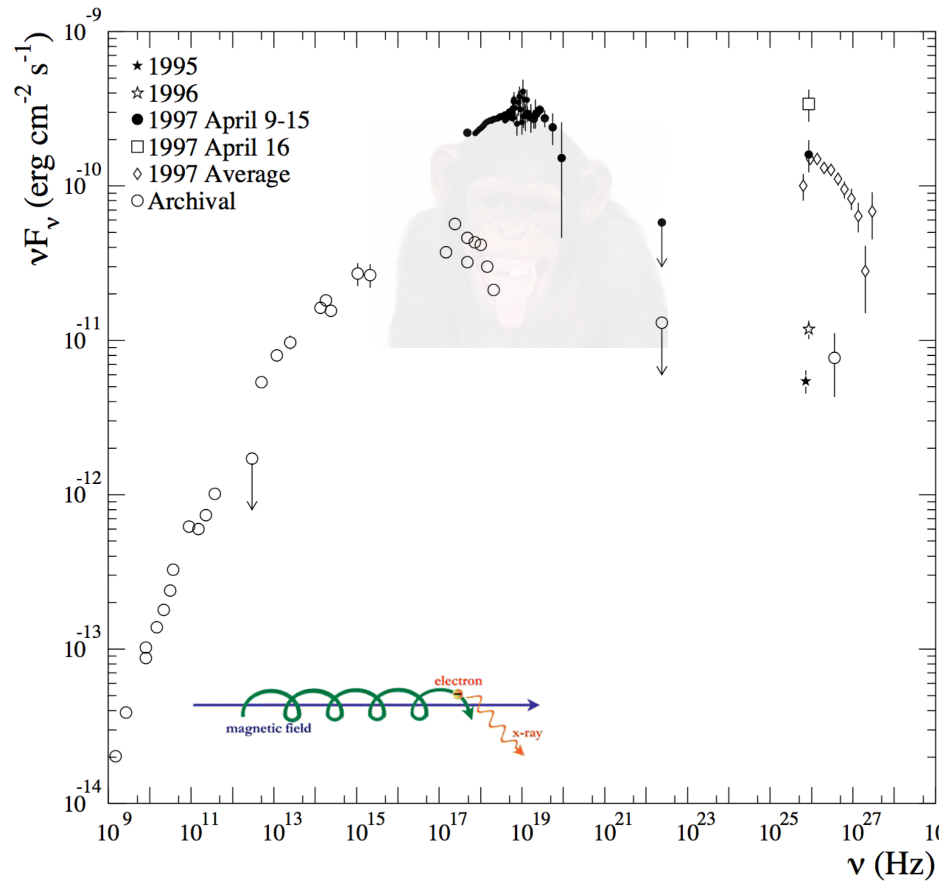

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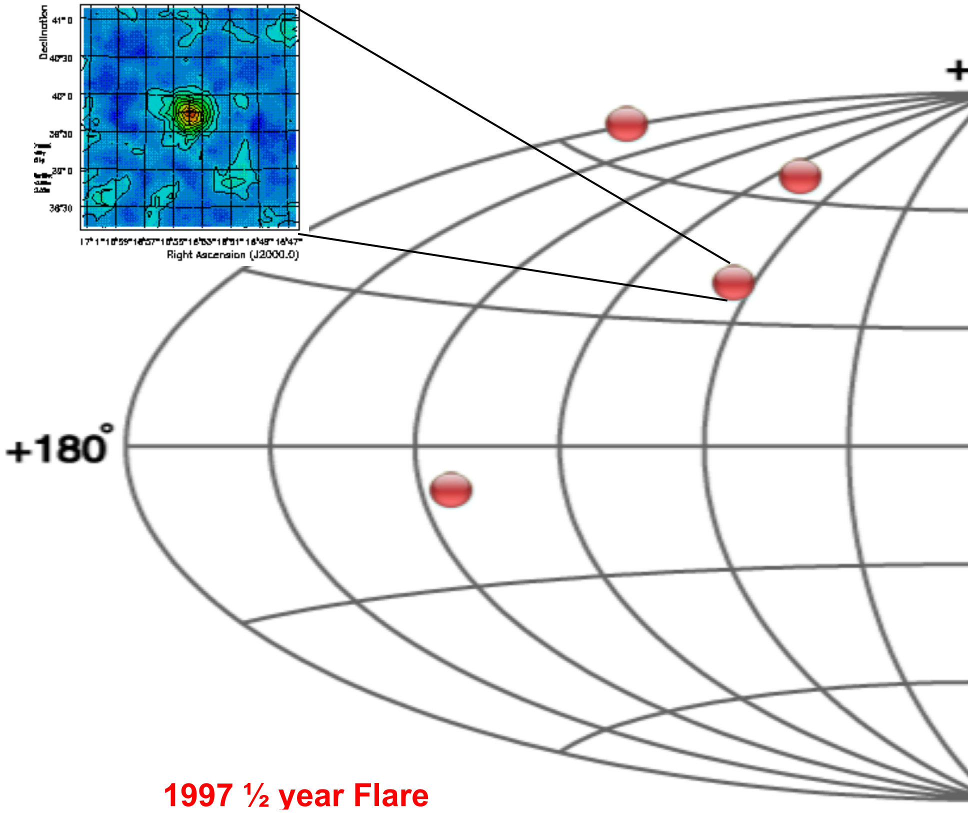

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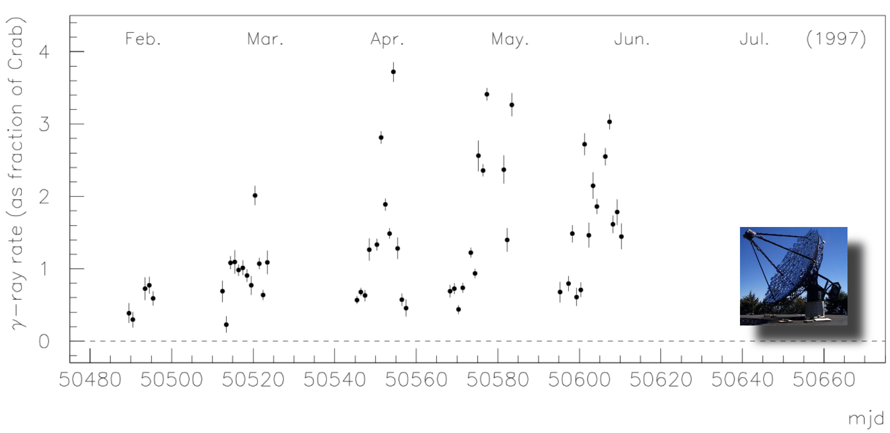

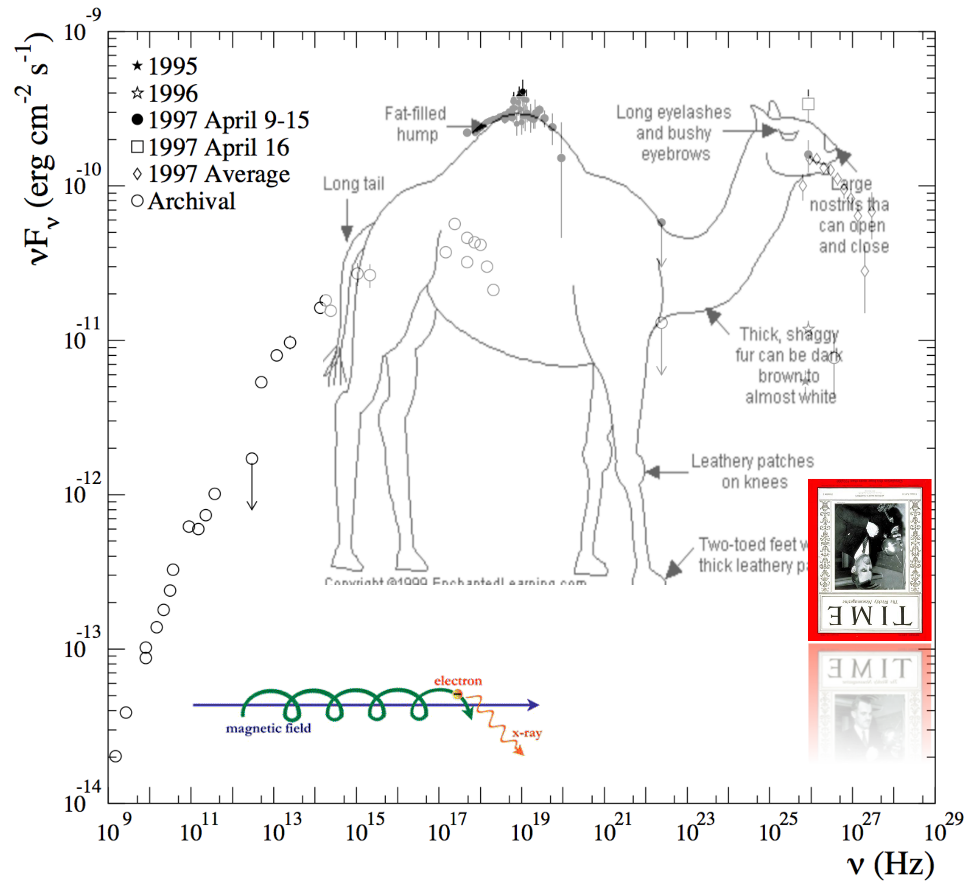

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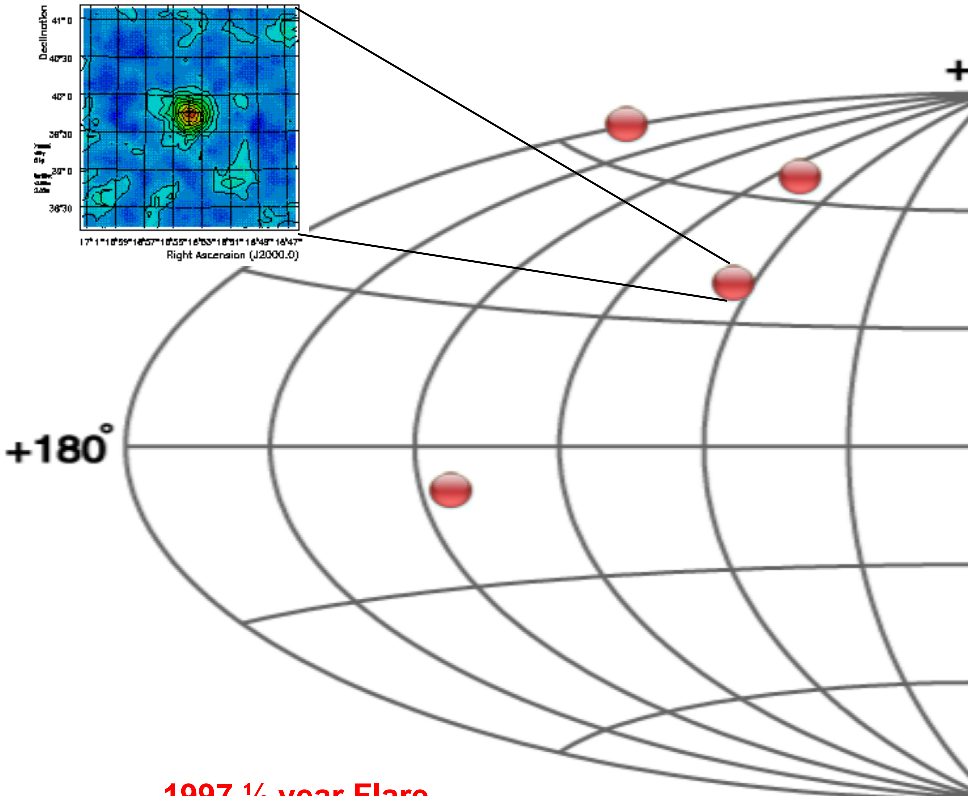

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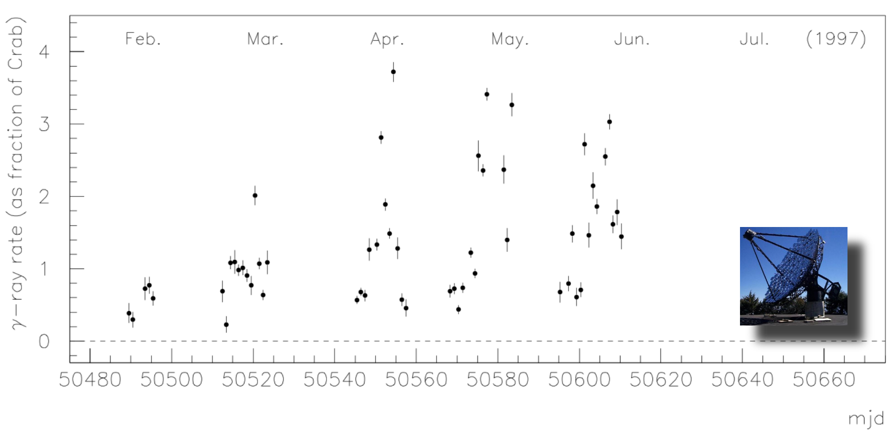

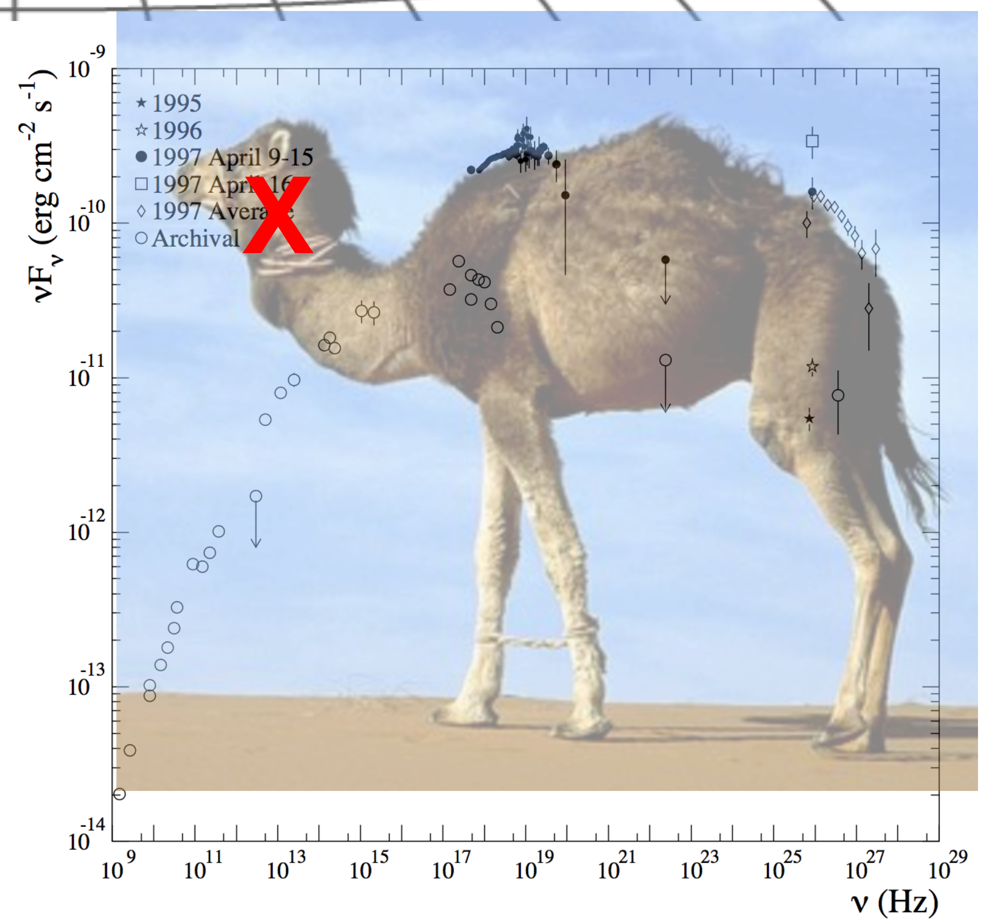

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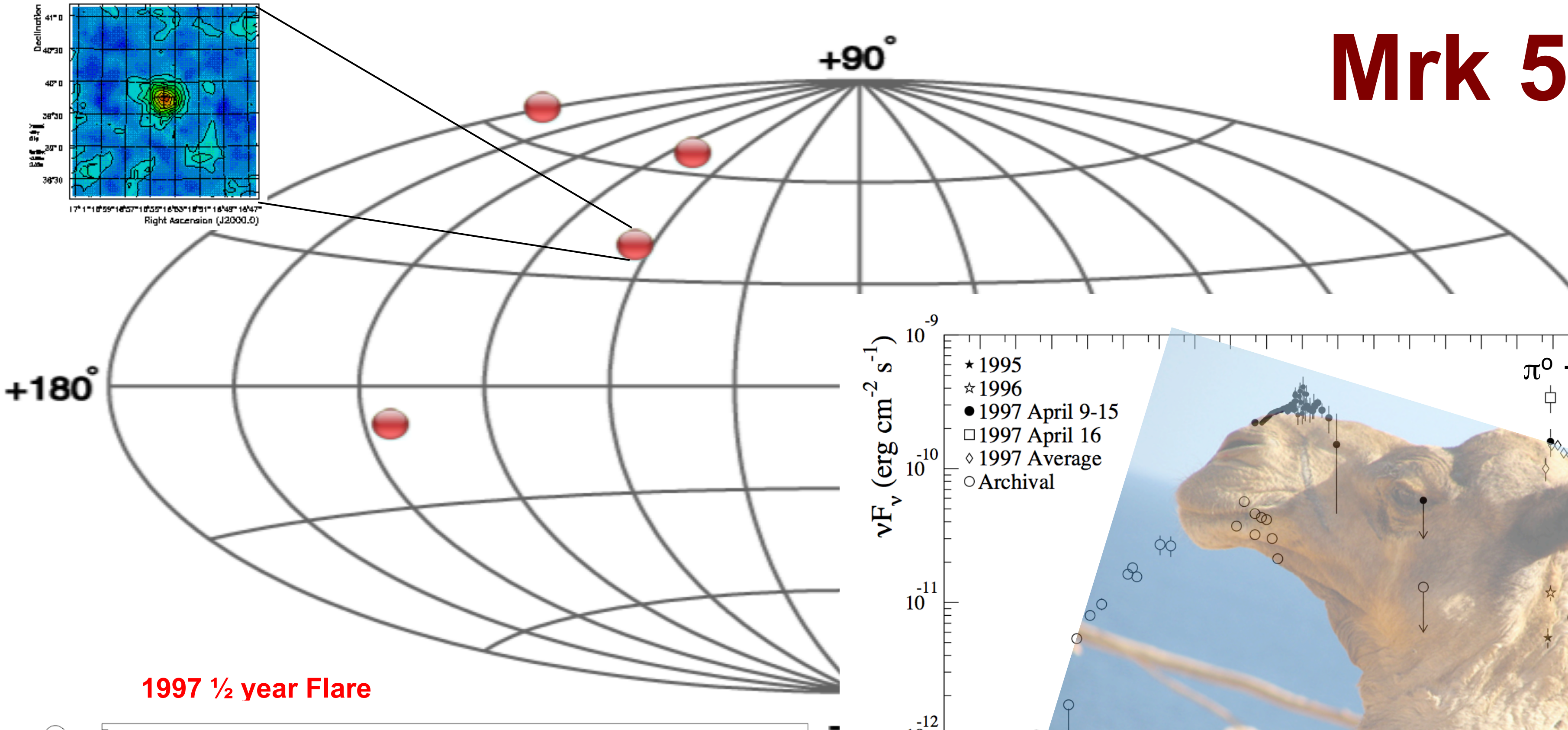

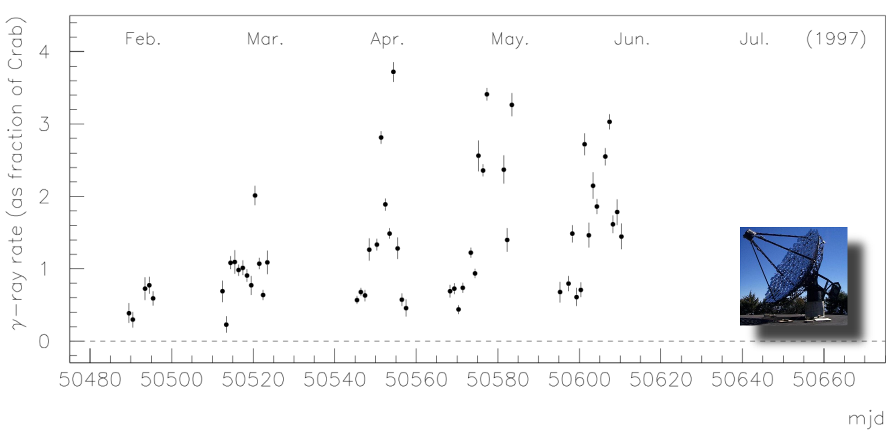

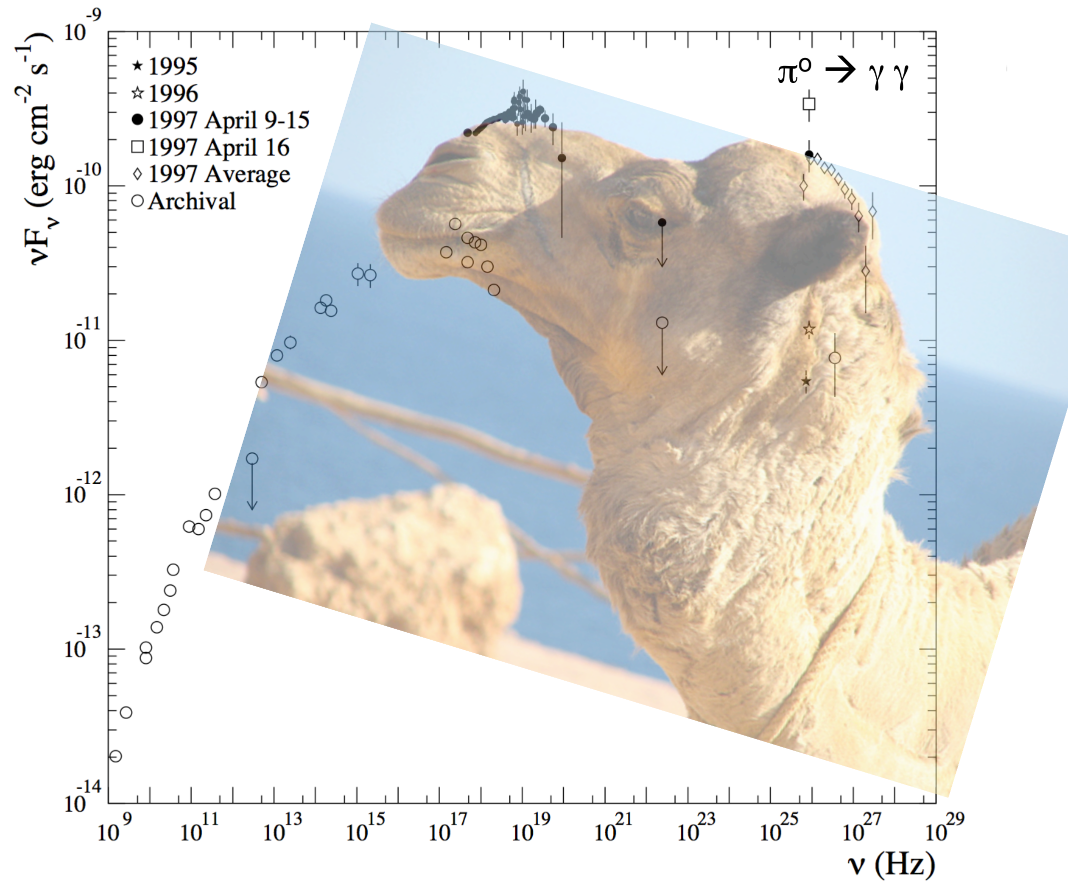

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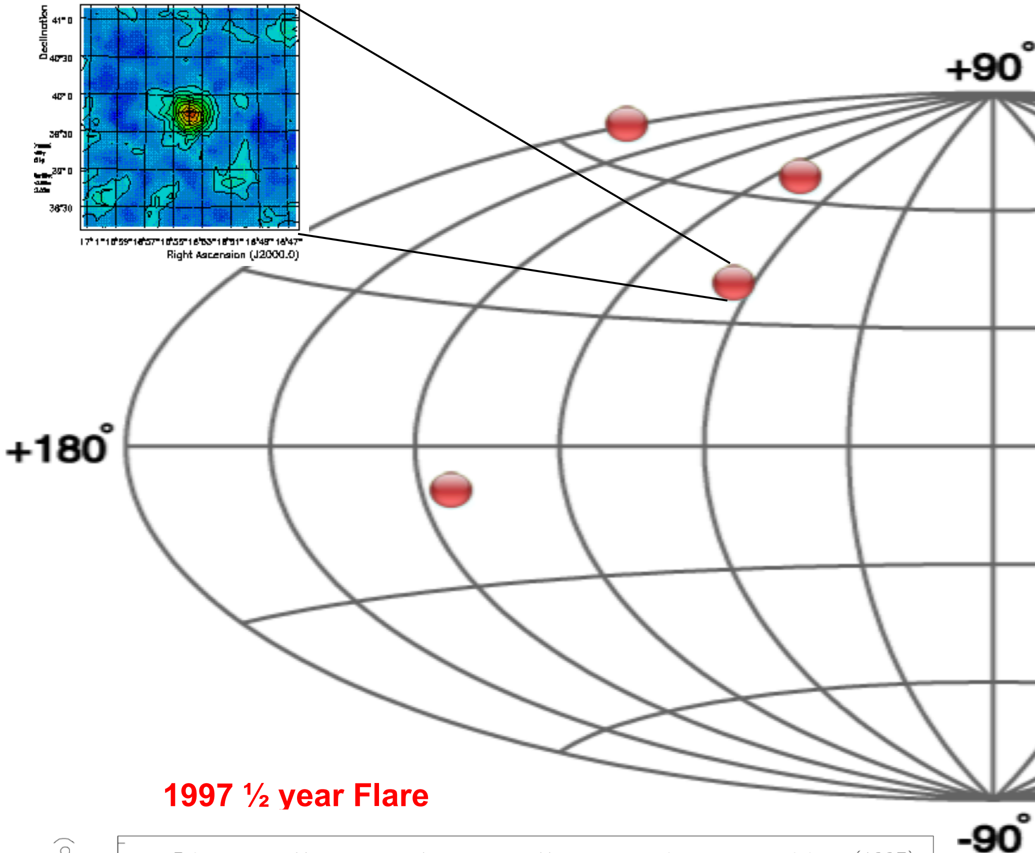

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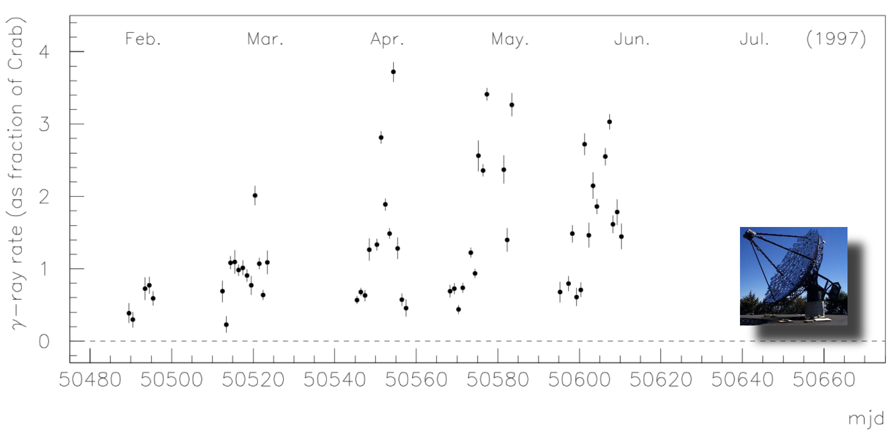

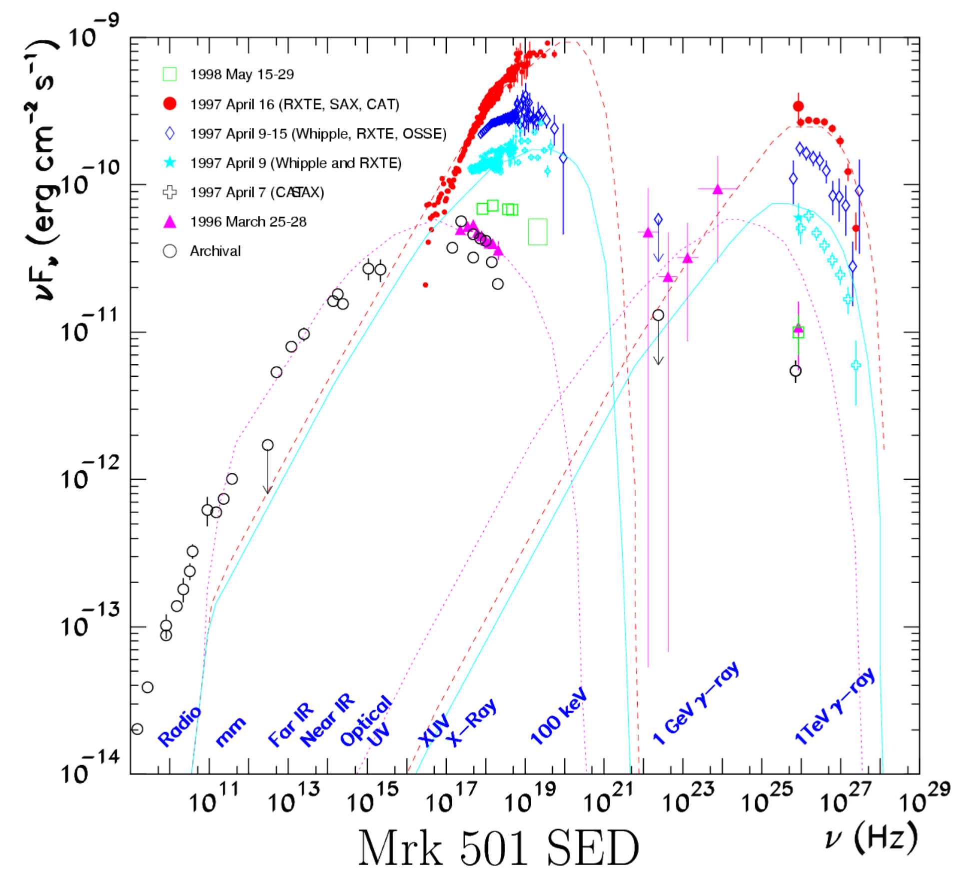

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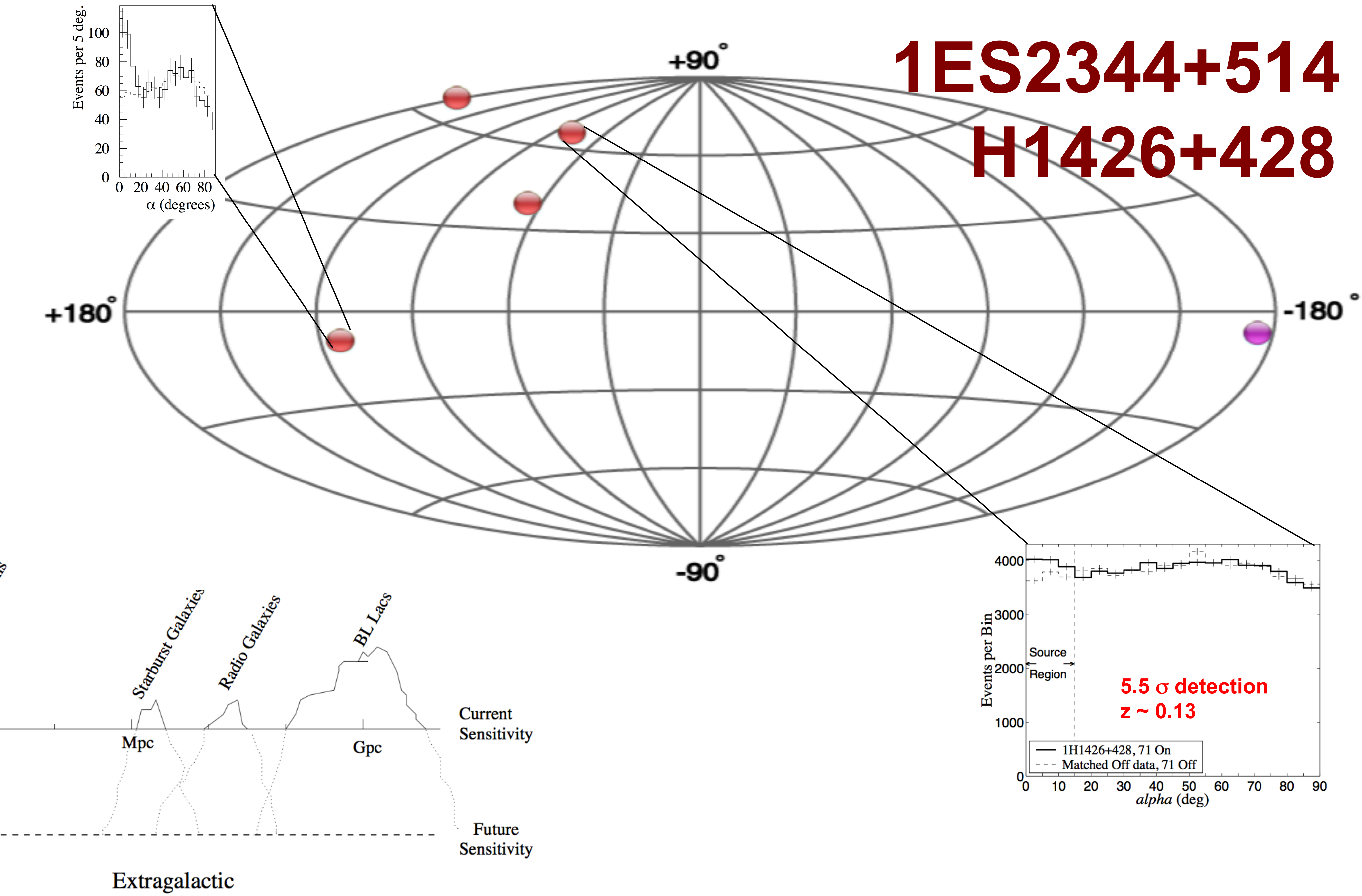

What is the intensity of the EBL?

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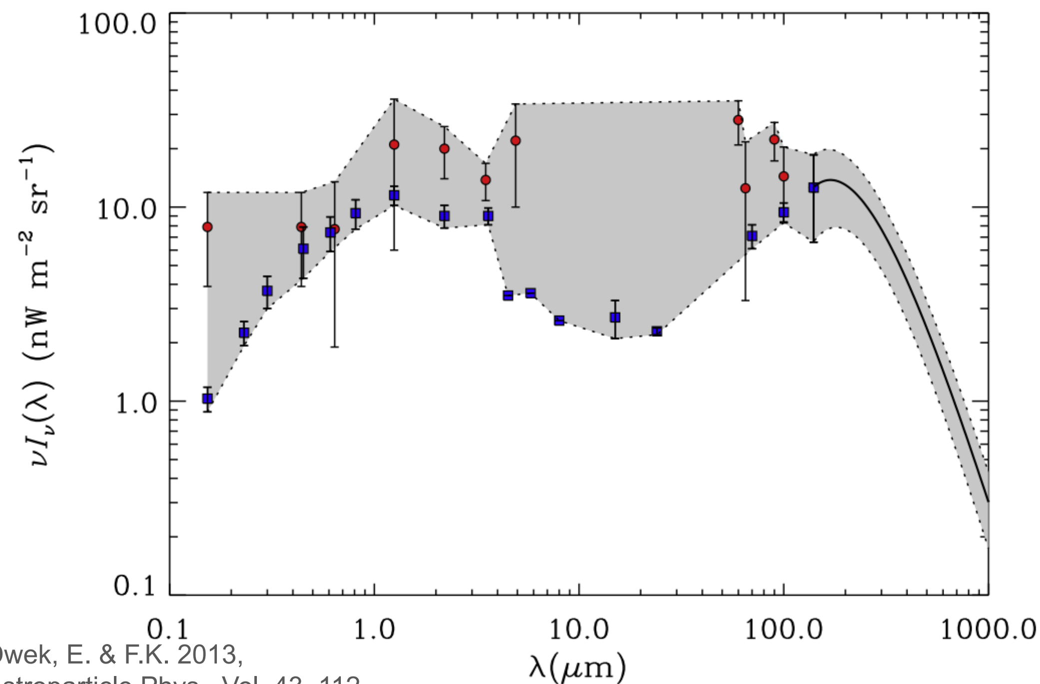
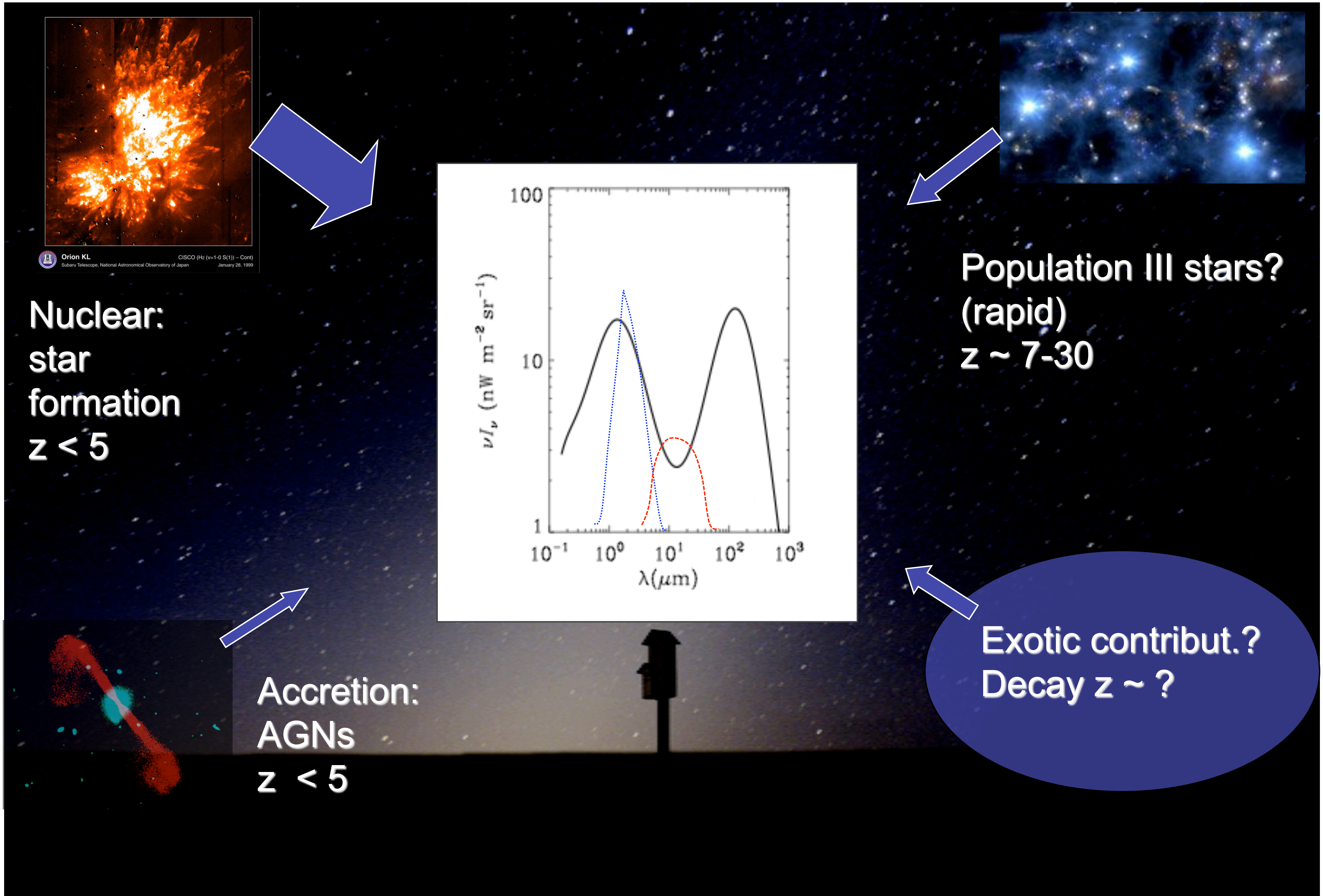


Dwek, E. & F.K. 2013,
Astroparticle Phys., Vol. 43, 112

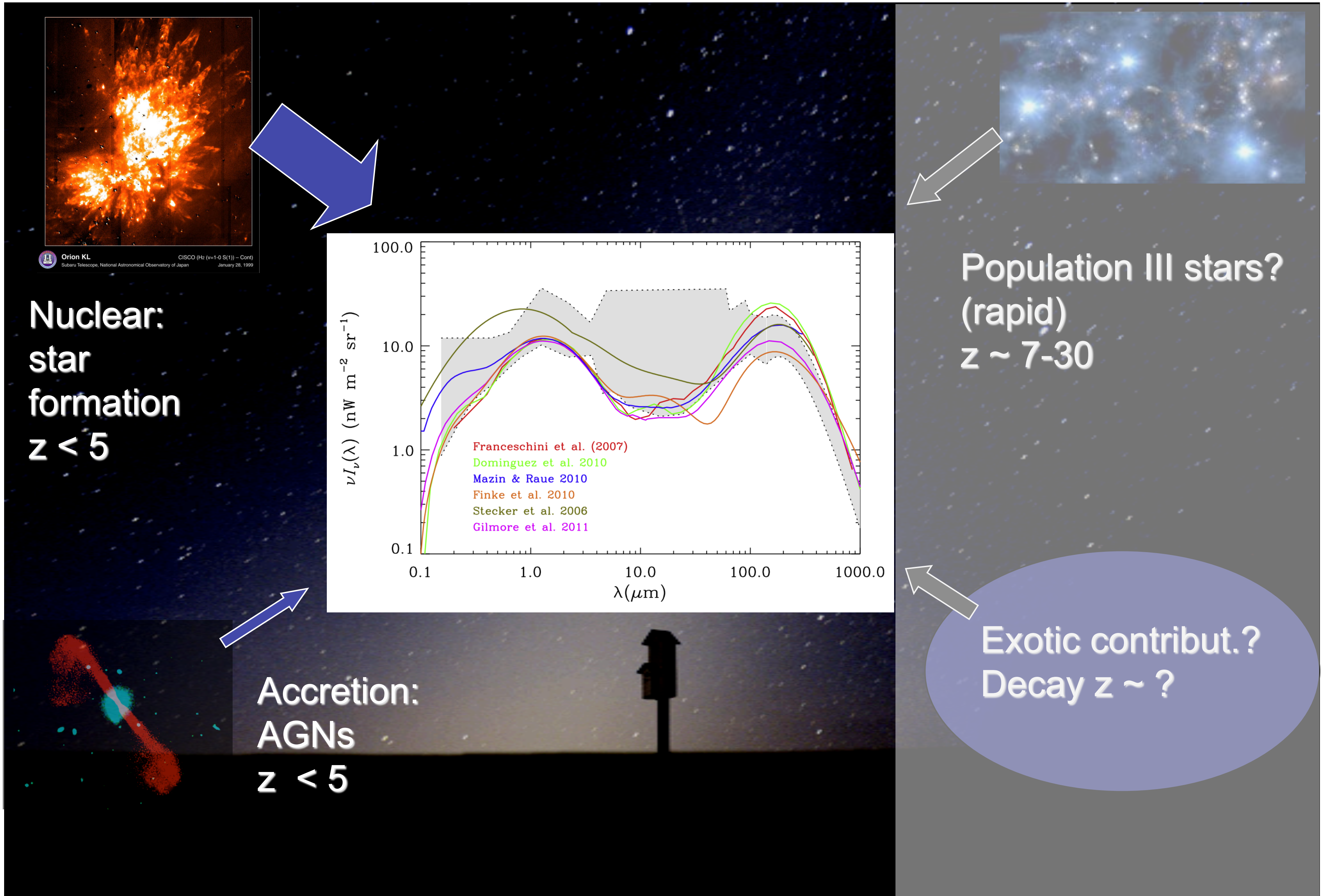
Constraints from fluctuation measurements

Lower limits from galaxy counts

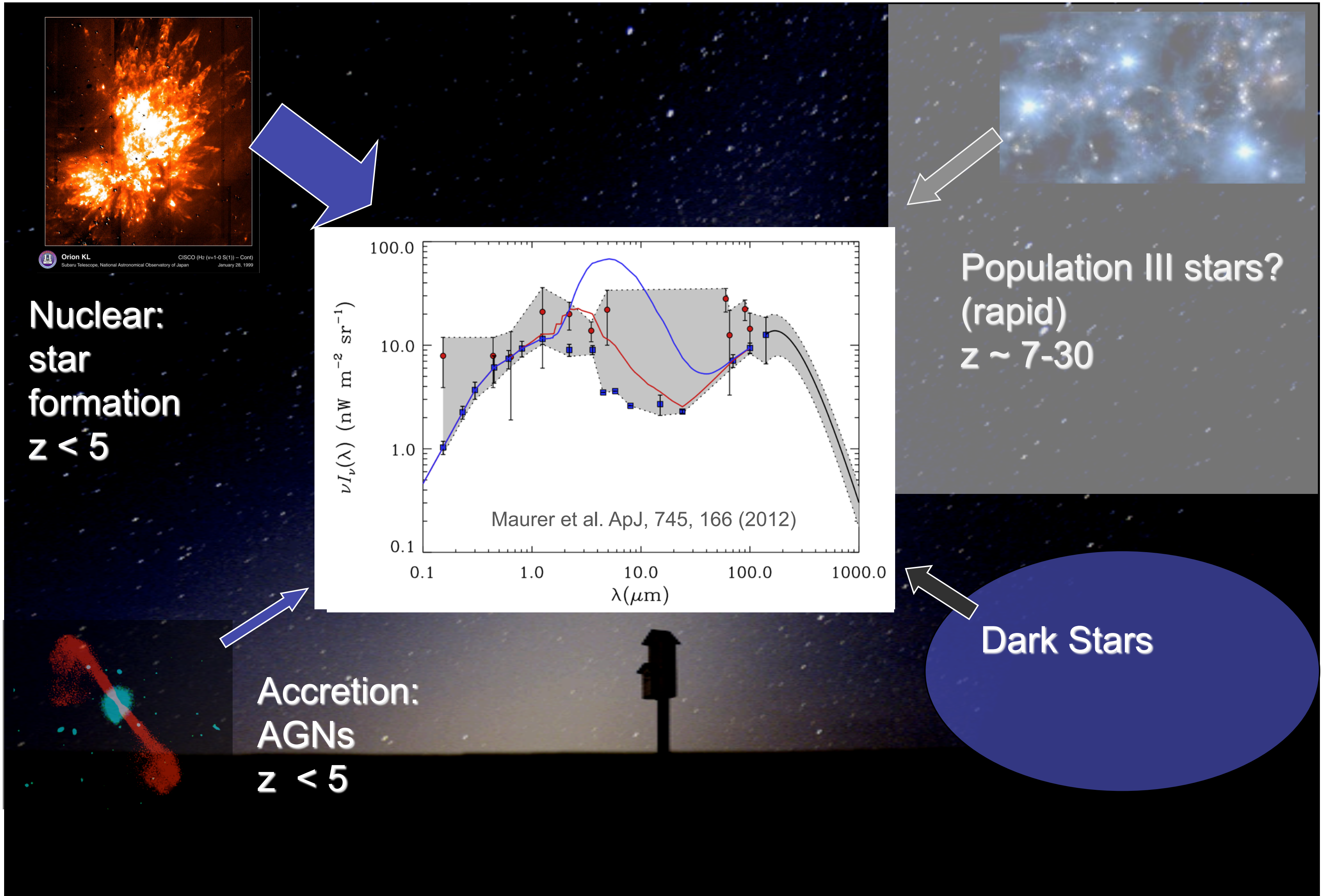
Accounting of the EBL sources



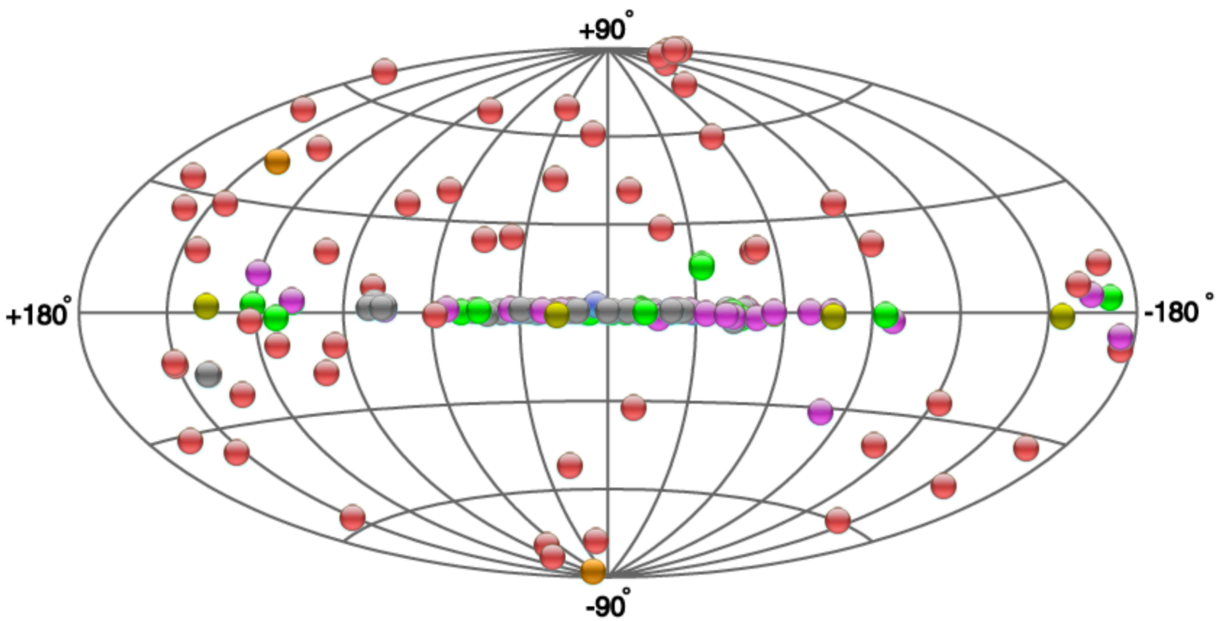
Accounting – Models



Accounting of the EBL sources



TeV γ-ray Sky 2013

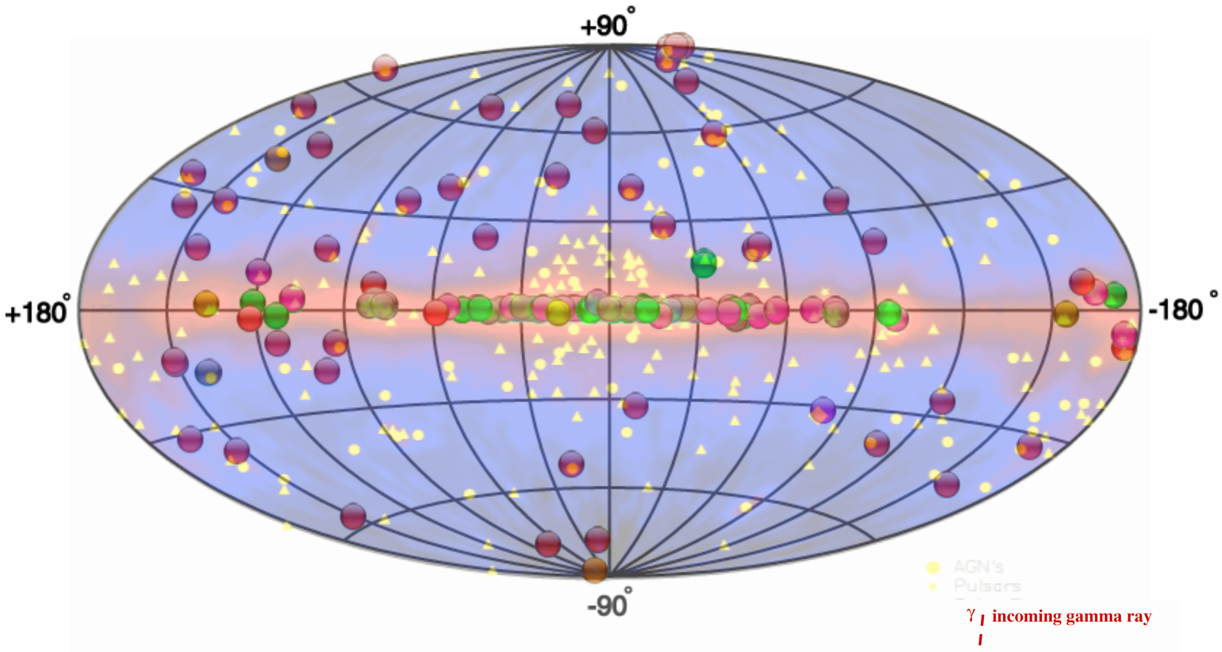


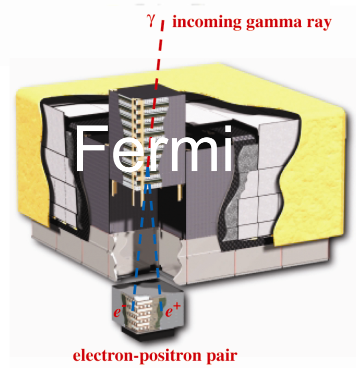
extragalactic sources

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
NGC 1275	R. G.	0.018
IC 310	R. G.	0.0188
Markarian 421	HBL	0.031
Markarian 501	HBL	0.034
1ES 2344+514	HBL	0.044
Markarian 180	HBL	0.046
1ES 1959+650	HBL	0.047
AP Lib*	LBL	0.048
BL Lacertae	LBL	0.069
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
1ES 1218+304	HBL	0.184
1ES 1101-232	HBL	0.186
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
PKS 1424+240	**IBL**	**> 0.6**

unexpected

GeV/TeV γ-ray Sky 2013





extragalactic sources

GeV & TeV spectra

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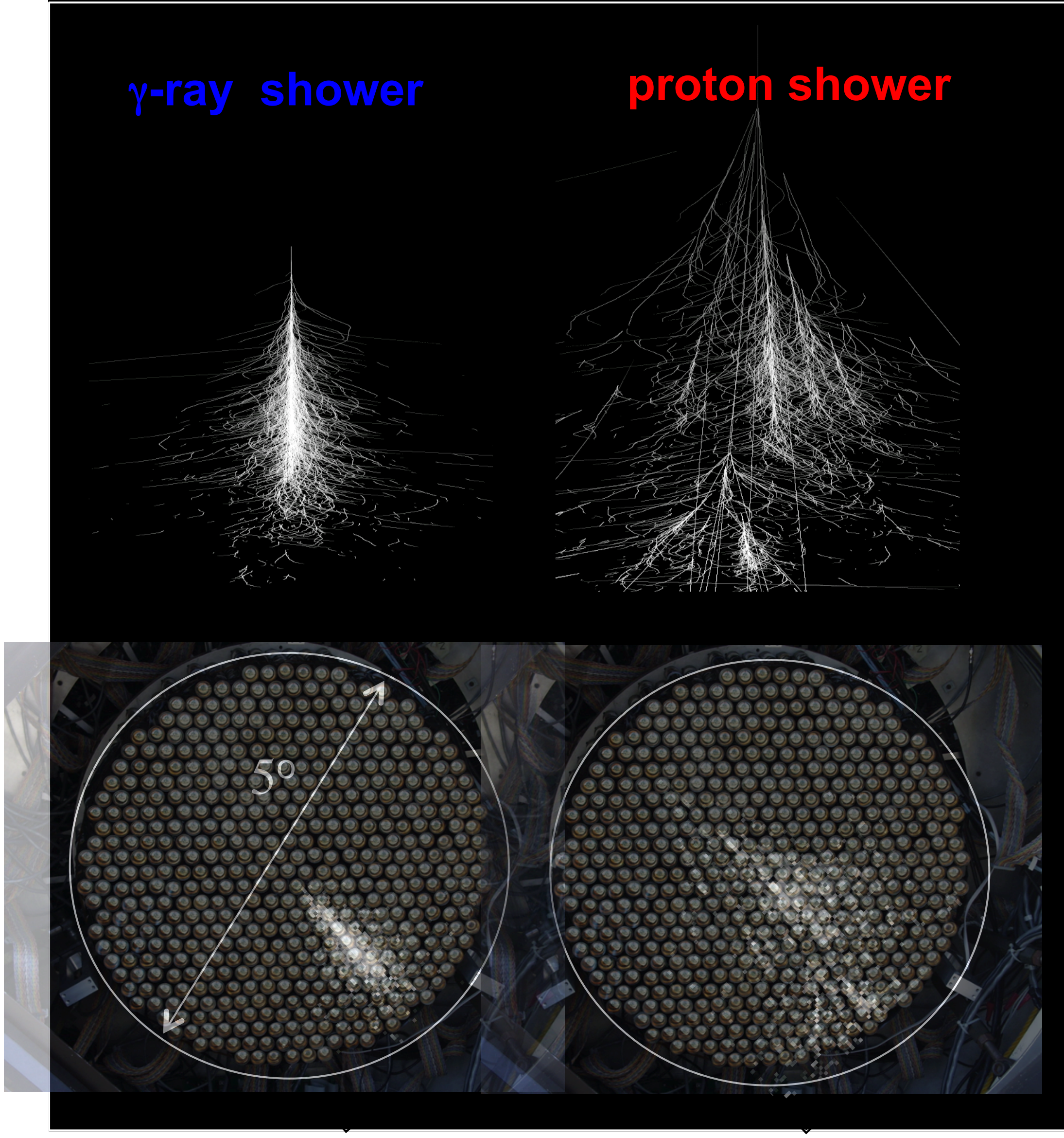
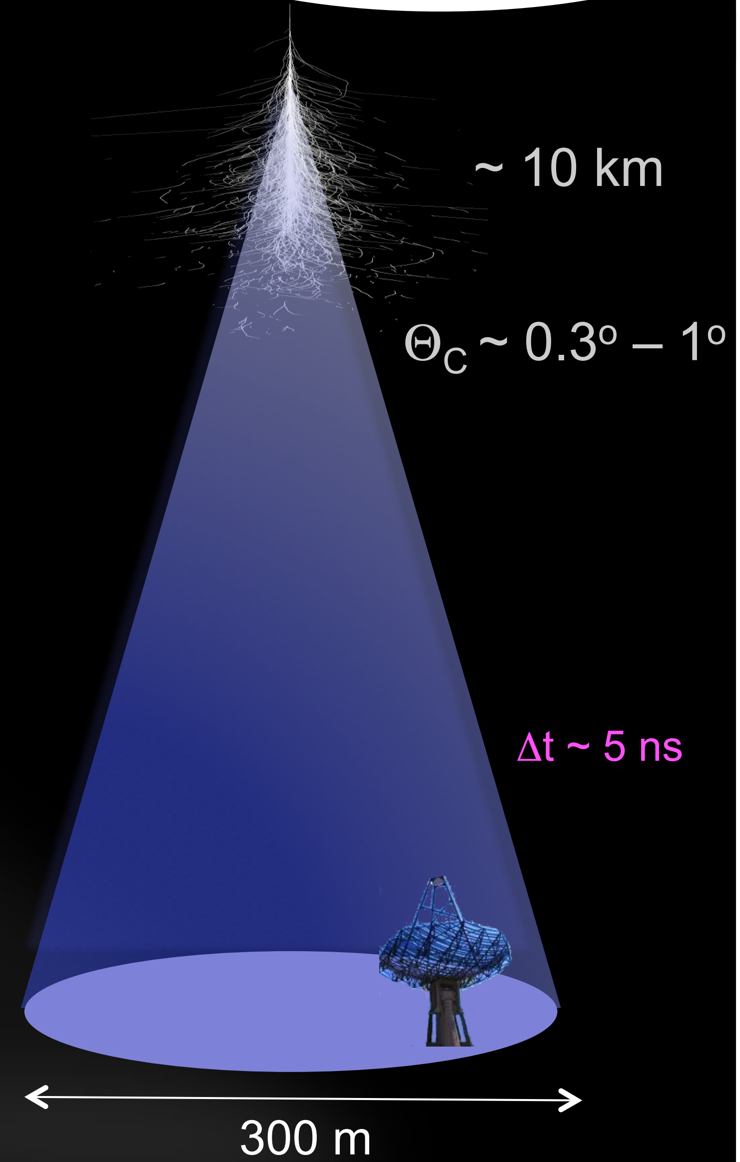
unexpected

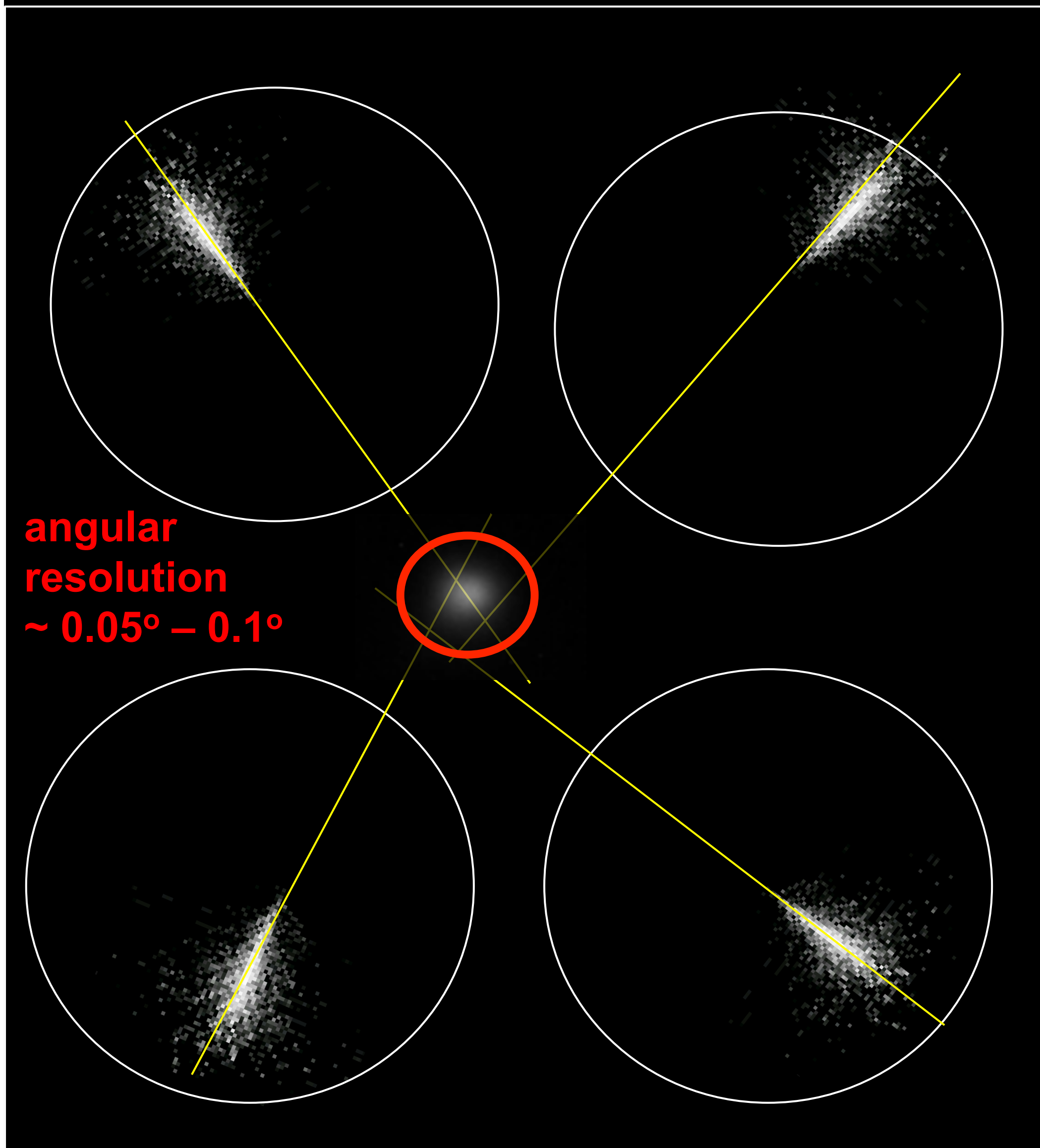
Air Cherenkov Technique: Whipple 10m

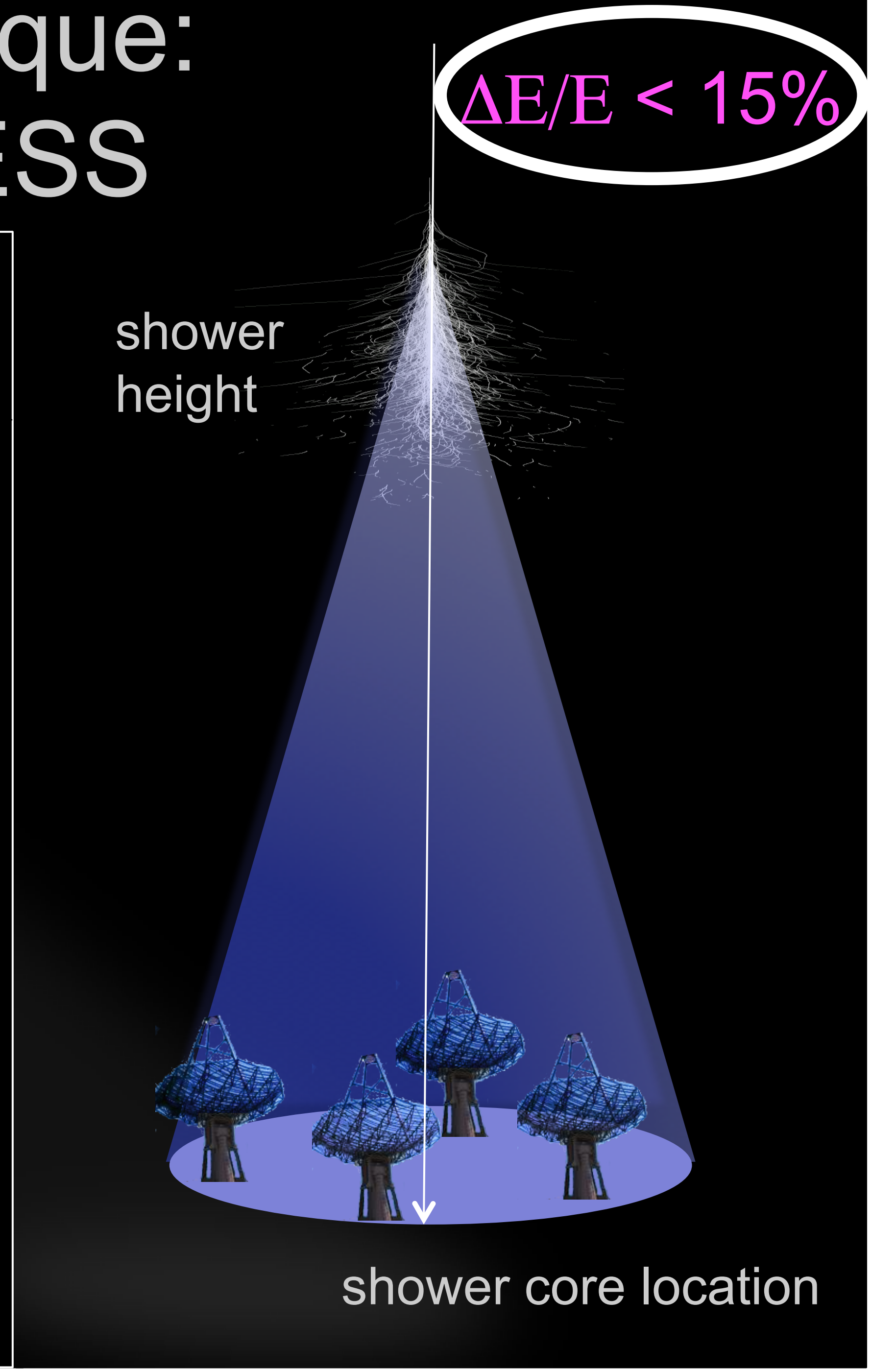
$\Delta E/E \sim 30\text{-}40\%$



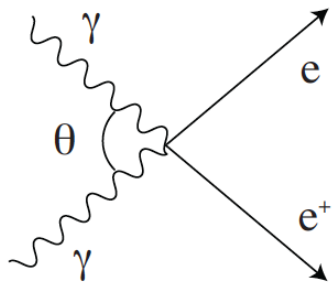


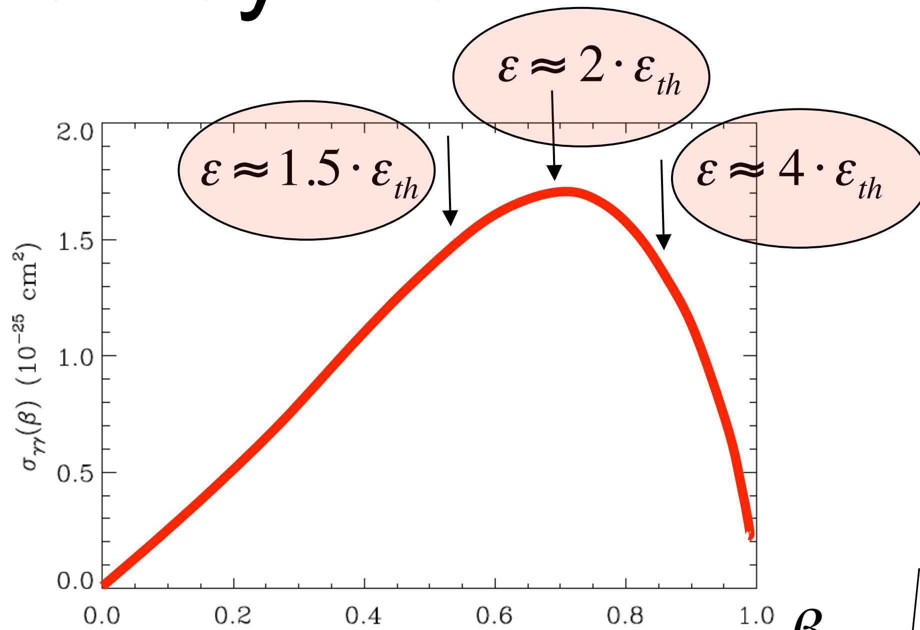
Air Cherenkov Technique:
Stereo: VERITAS, HESS





γ-ray Absorption by the EBL





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

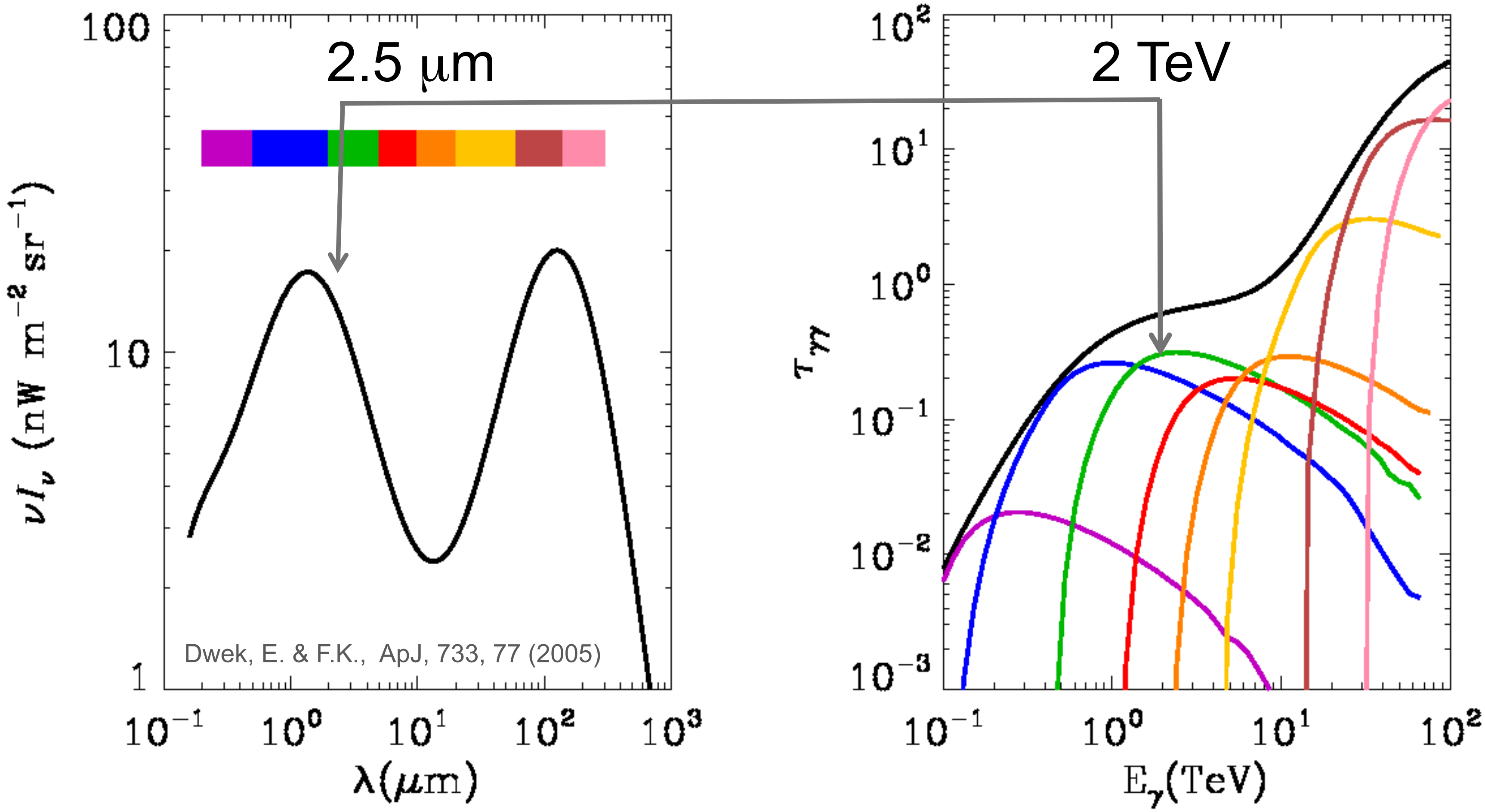
$$\varepsilon_{th}\left(E_\gamma, \mu, z\right) = \frac{2\left(m_e c^2\right)^2}{E_\gamma(1-\cos\theta)}$$

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

- 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



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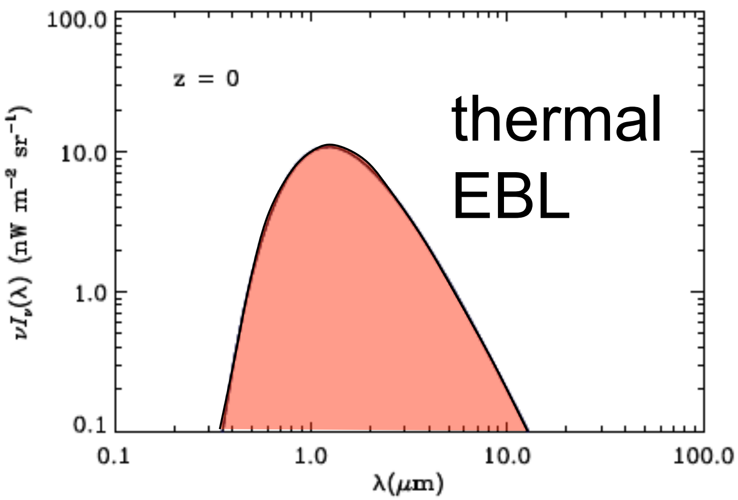
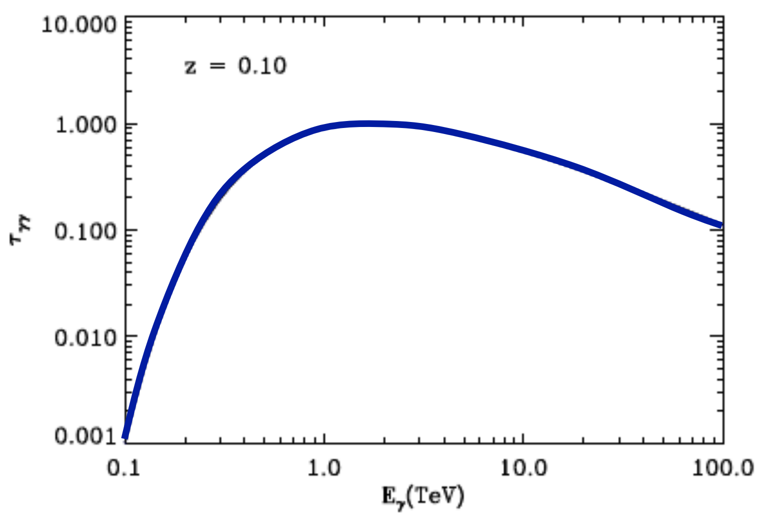
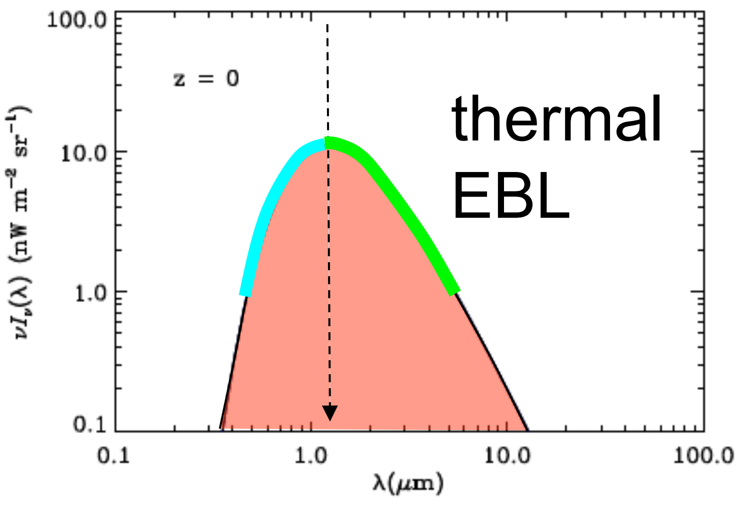
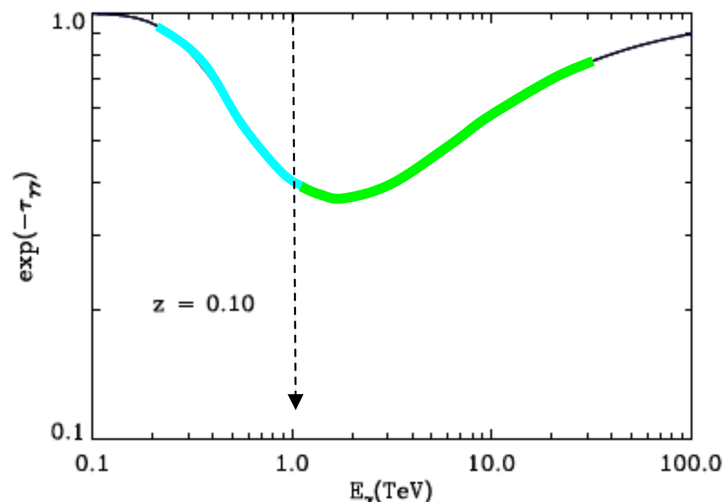




<u>Consider special case:</u>
absorption by a black body photon gas with peak at 1 μm

γ-ray Absorption by the EBL

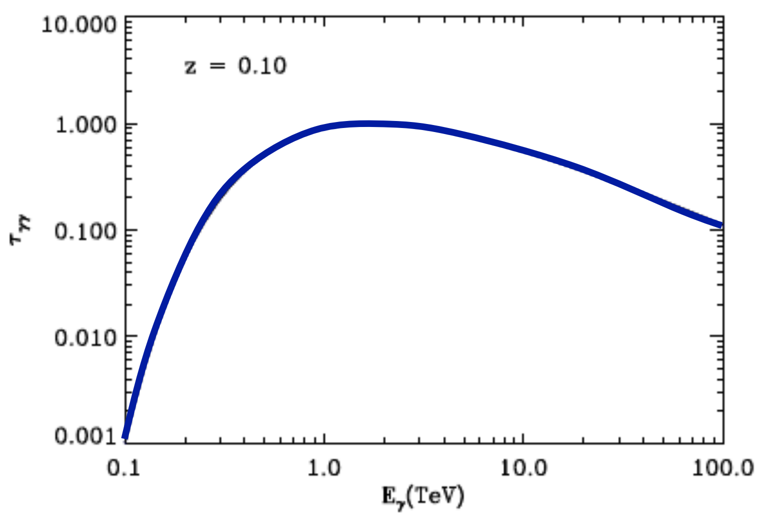




Dwek, E. & F.K. 2012

change in slope

at ~ 1 TeV

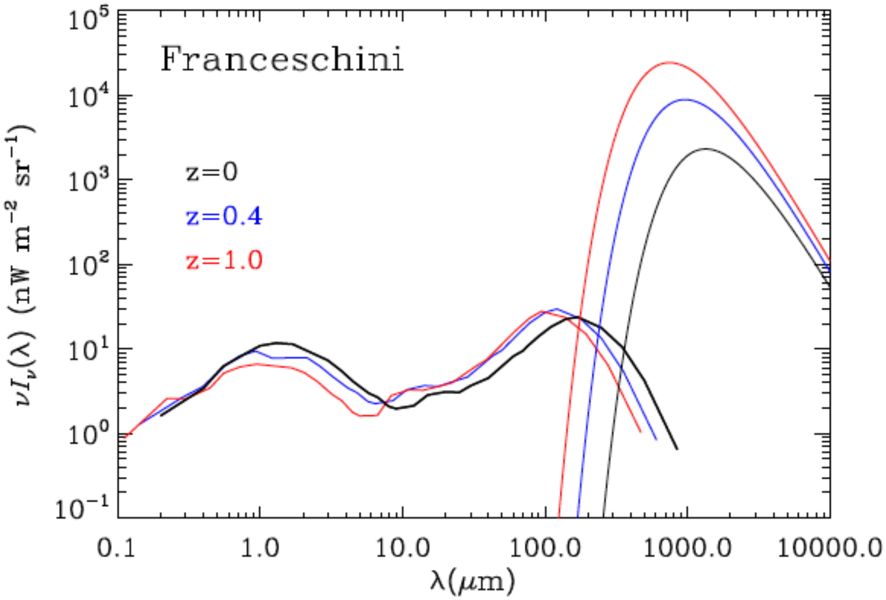


<u>"typical" blazar spectrum:</u>

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

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

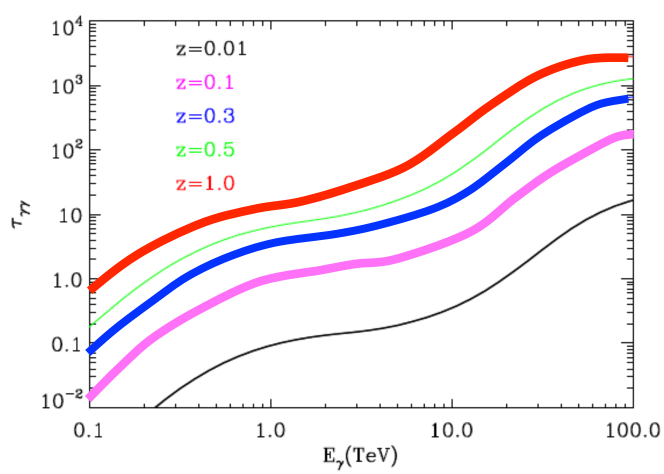
γ-ray Absorption by the EBL



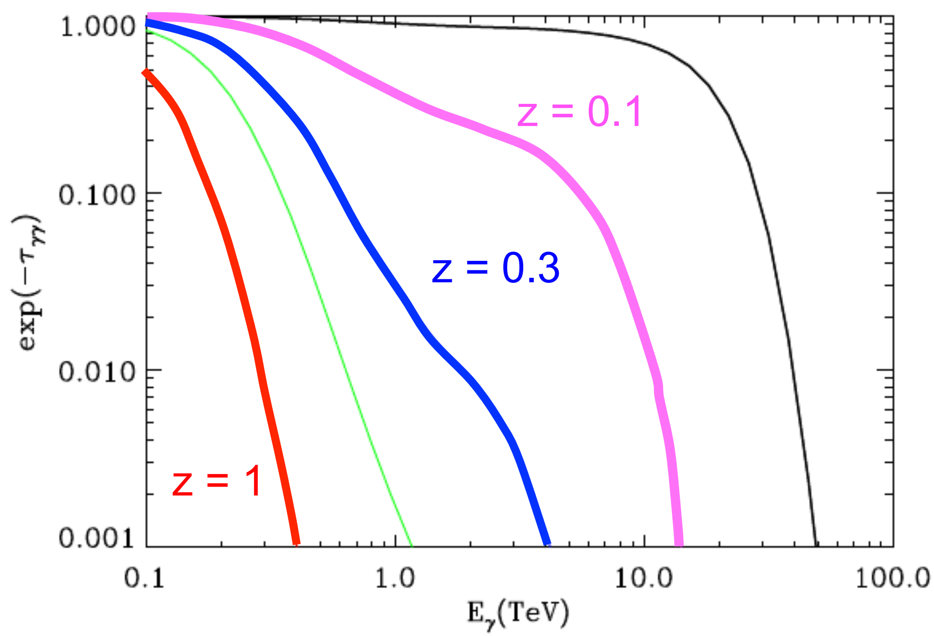
<u>Consider more realistic case:</u>

EBL model (Franceshini)

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



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

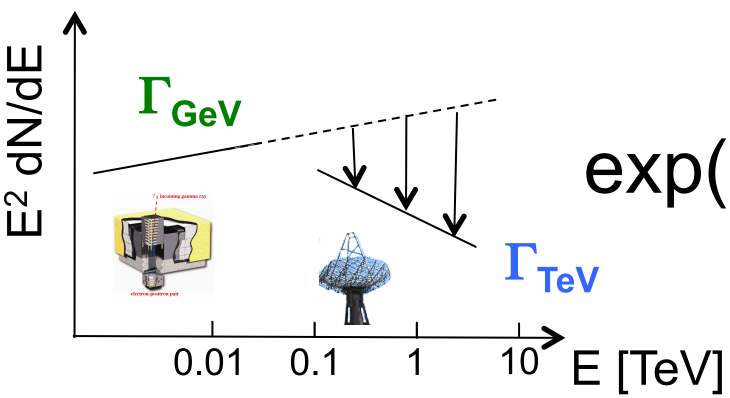


Sources for probing the EBL

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
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	1.74±0.11	4.4±0.8	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	1.80±0.21	2.88±0.17	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

<u>Do we see spectral softening (z)?</u>

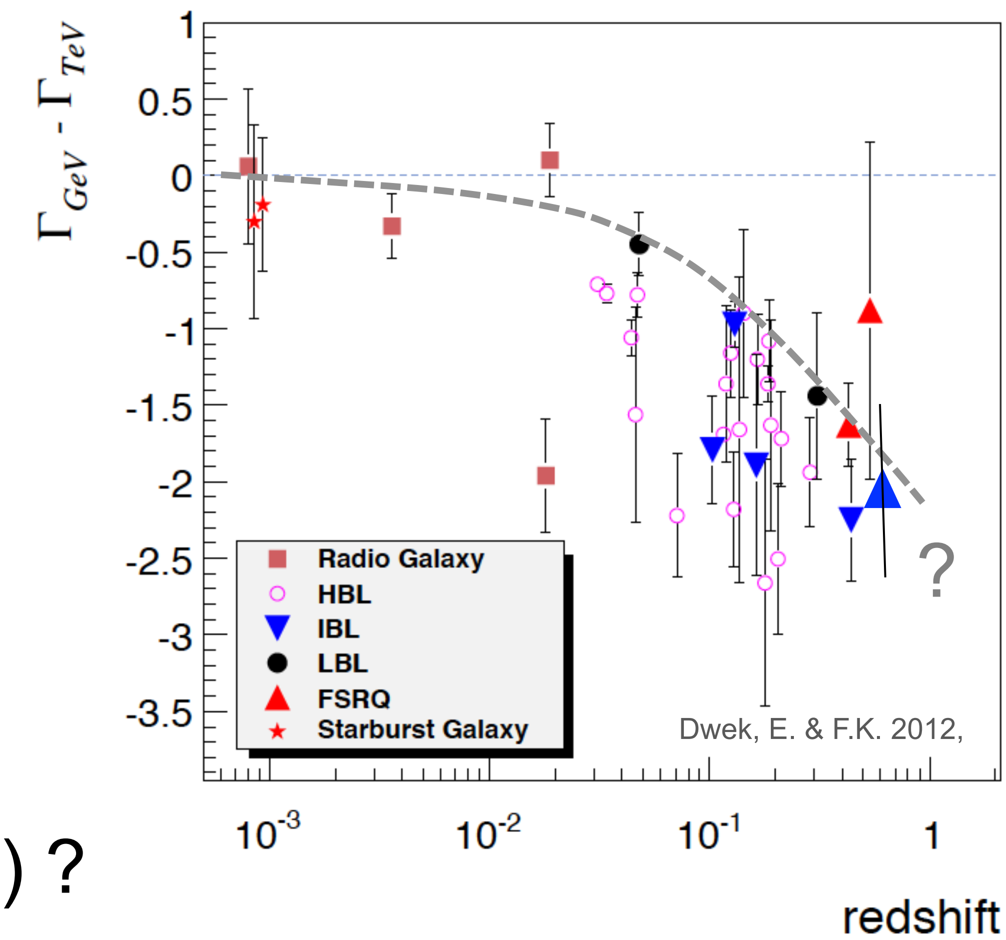
- > 3 dozen extragalactic sources (blazars, few radio & starburst galaxies
- Spectra ~ 1 GeV – 1 TeV
- redshift (known for 50% of BL Lacs)

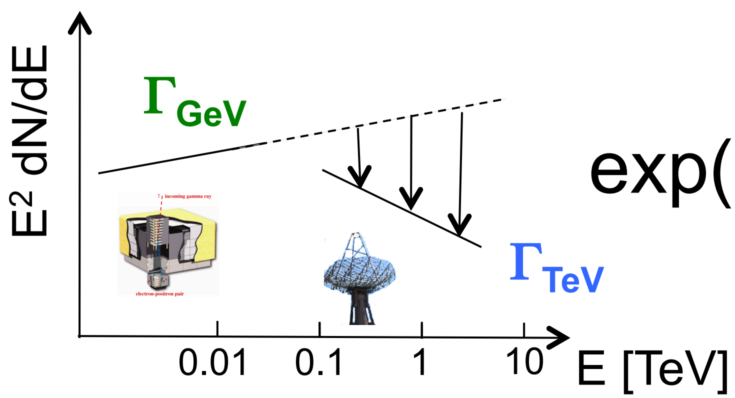


$\exp(-\tau_{\gamma\gamma})$?

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
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



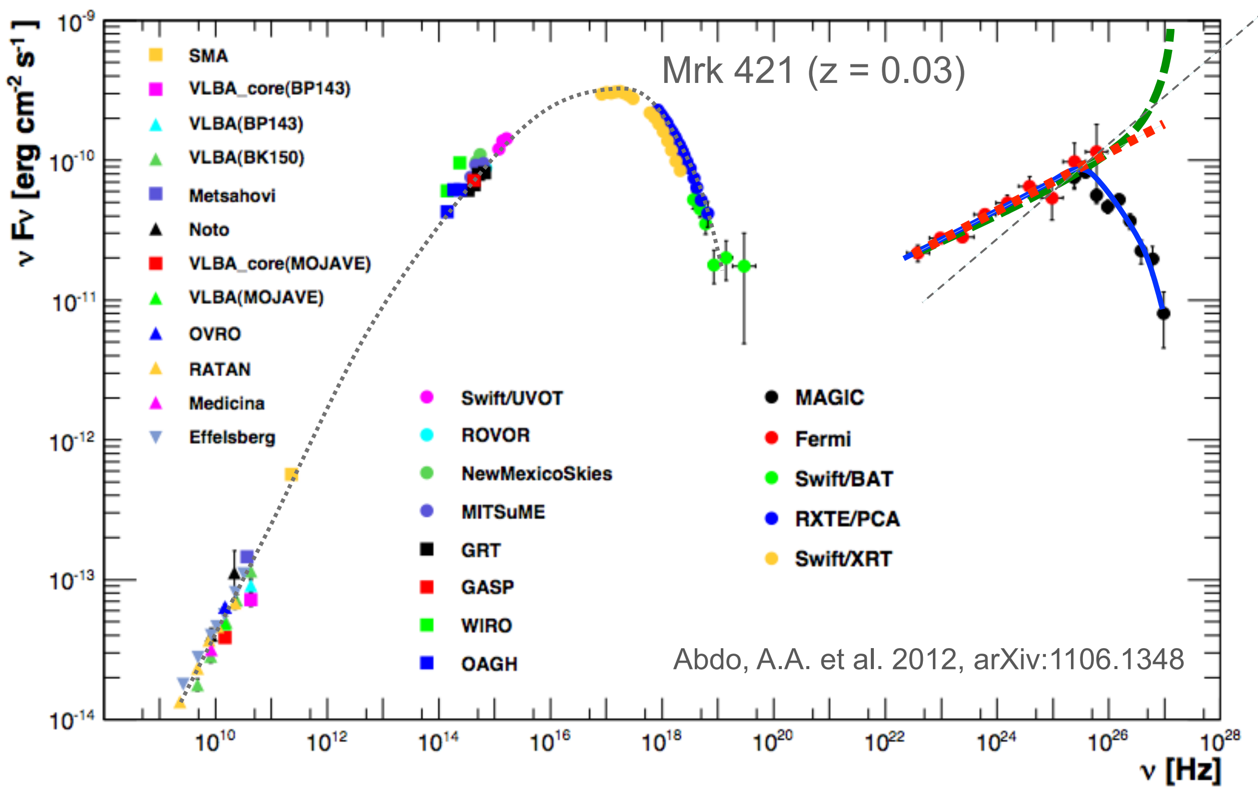


$\exp(-\tau_{\gamma\gamma})$?

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

Sources for probing the EBL

unphysical (no exp. rise!)



empirical:

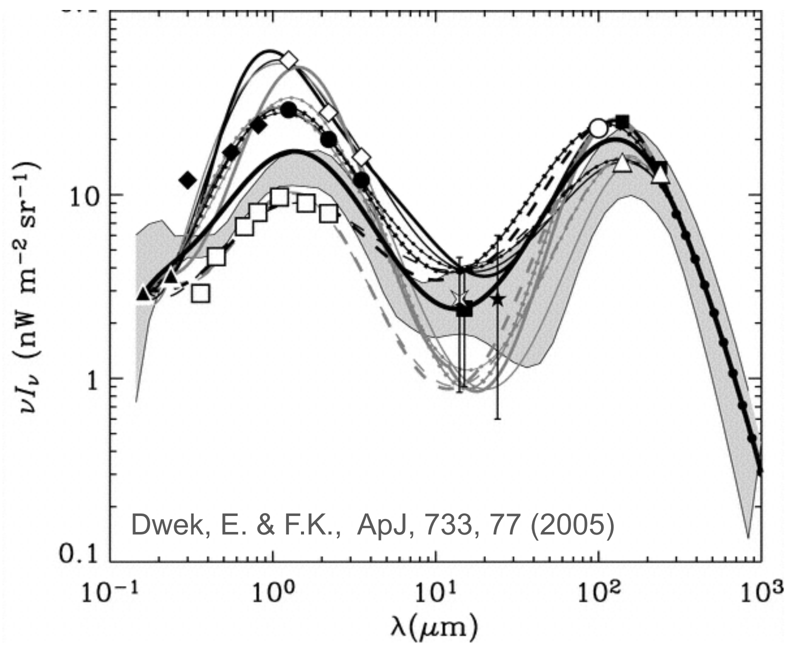
$\Gamma_{TeV} > \Gamma_{GeV}$

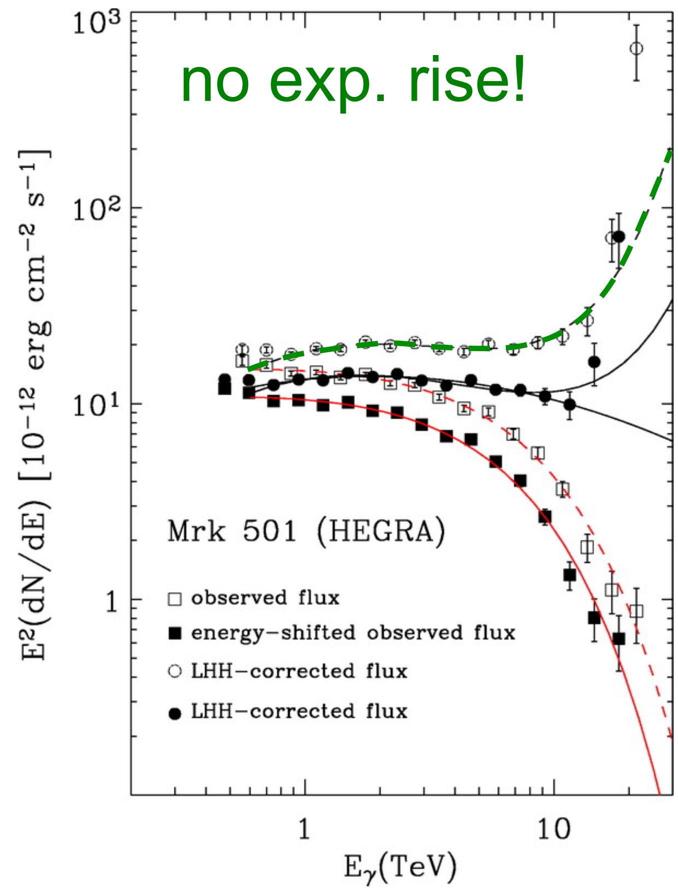
in theory: $\Gamma > 1.5$

measured

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

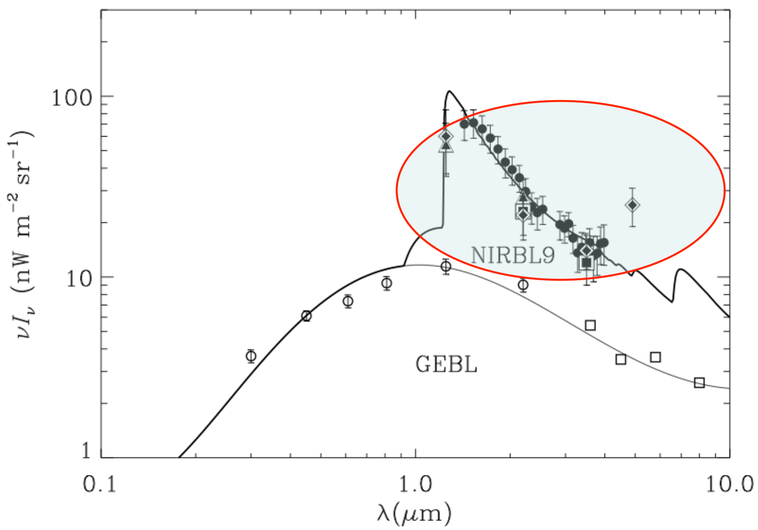
Methods I: no exponential rise!

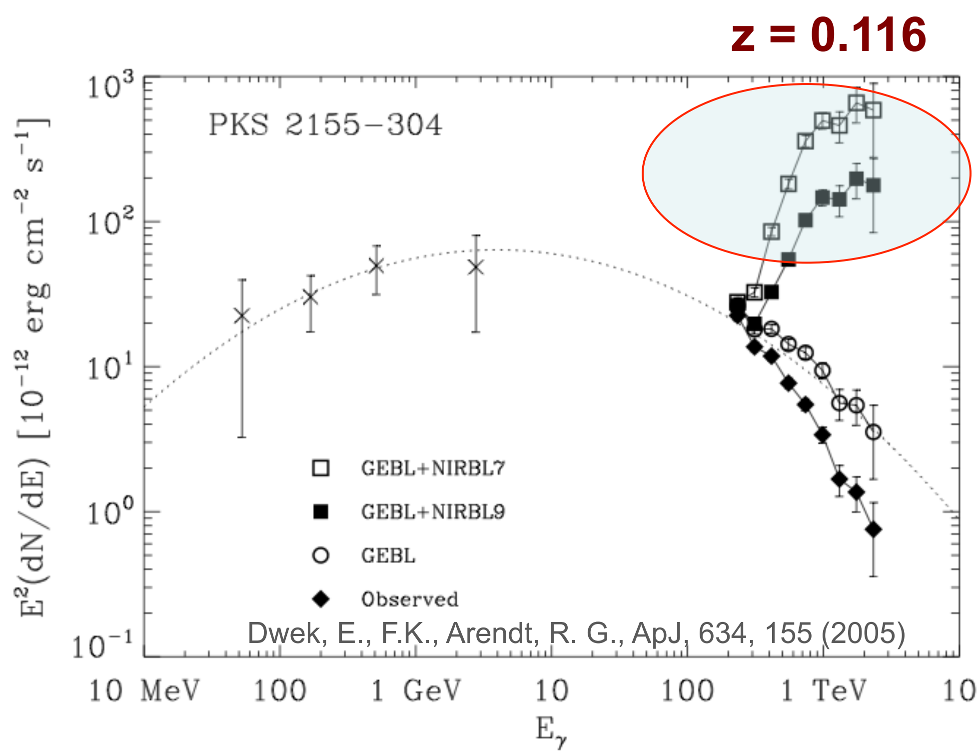


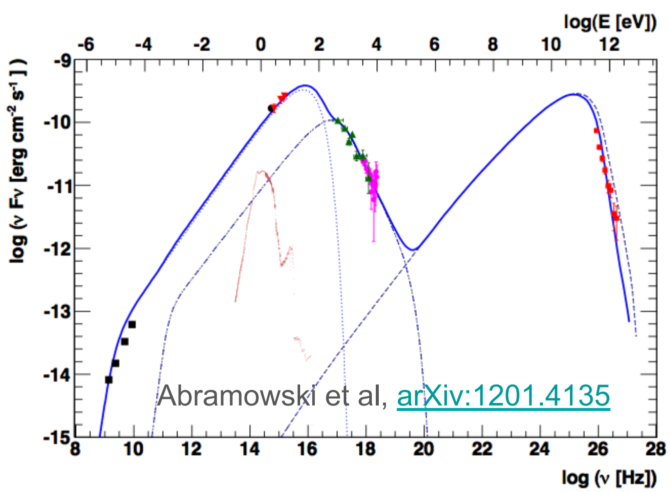


- consider range of EBL scenarios with different near-IR, mid-IR far-IR intensities
- consistent with limits (2005)
- use to unfold absorption-corrected blazar spectra
- **exponential rise**: → EBL intensity is too high ✖

Methods I: no exponential rise!

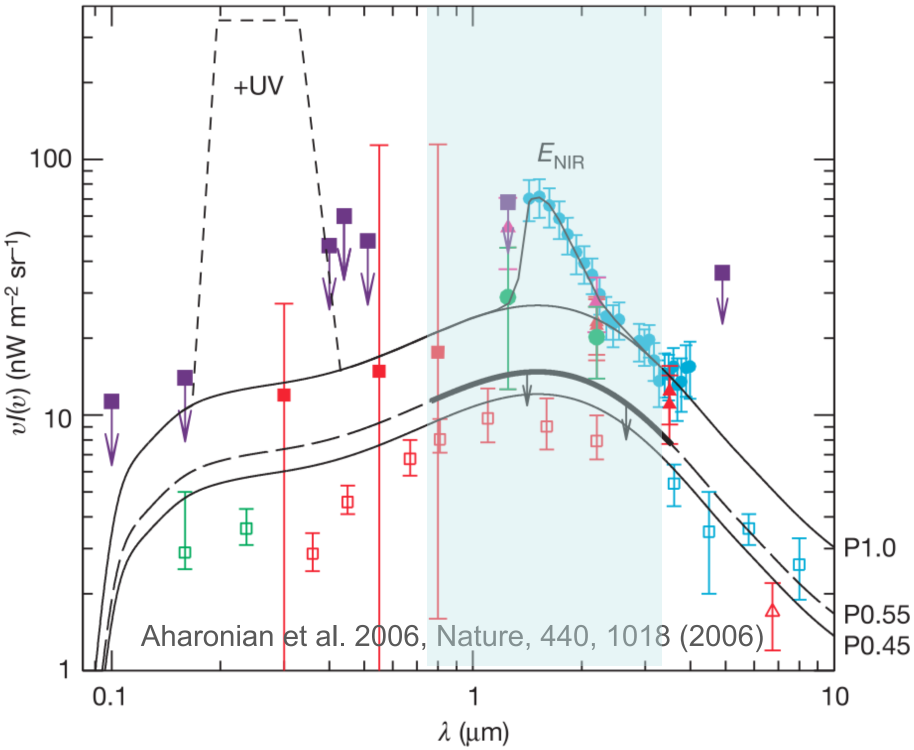


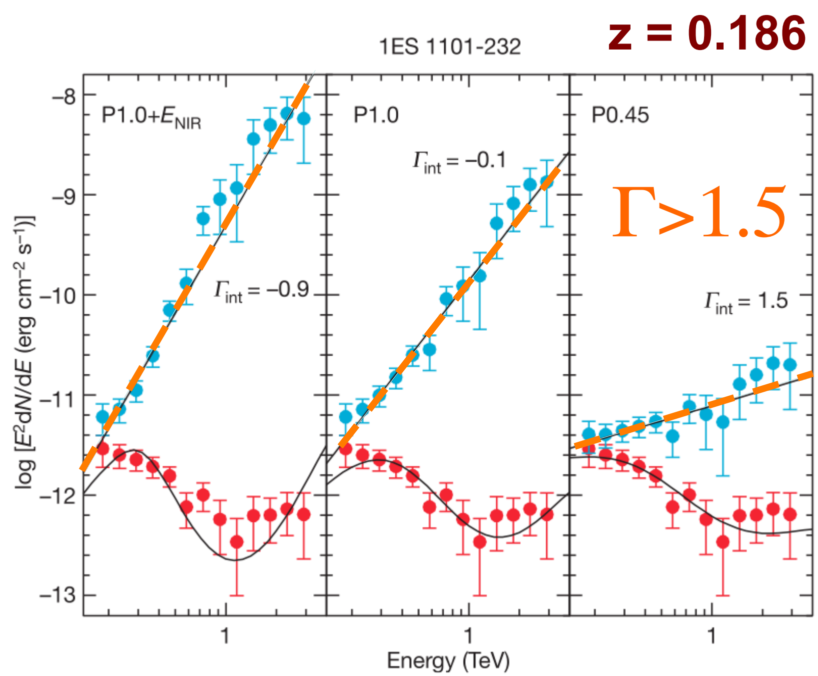




- excess near-IR background light (NIRBL): incompatible with "typical" blazar spectrum!

Method II: hardness limit Γ > 1.5

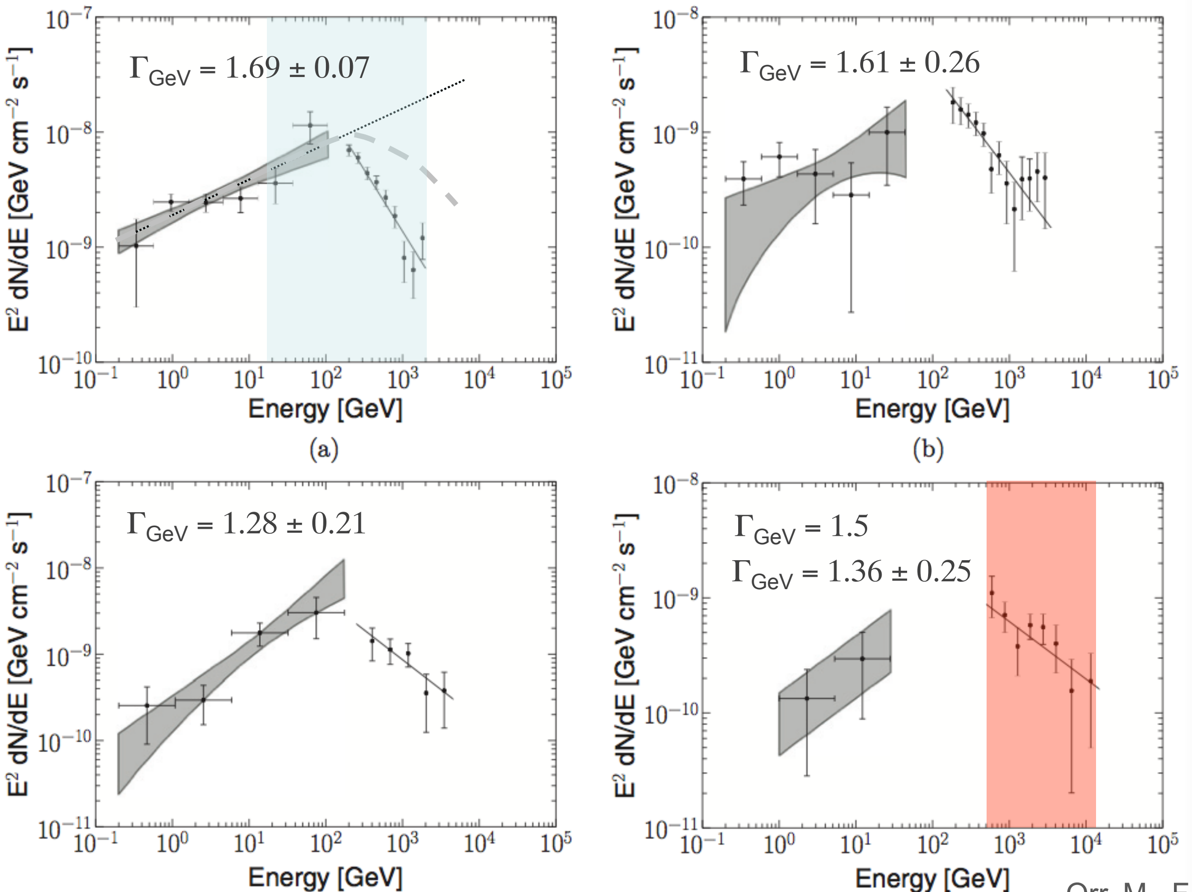




- EBL intensity near-IR (1 – 4 μm) is constrained by allowing absorption-corrected spectra with Γ > 1.5 only!
- strong upper limit in near-IR: **νI_ν (1-2 μm) < 14 ± 0.4 nW/m²/sr**
- dependents on assumed intrinsic source spectrum! (Γ ~ 1.2 Fermi spectra!)

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

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



a) 1ES 1218+304: z = 0.182

b) 1ES 1101-232: z = 0.186

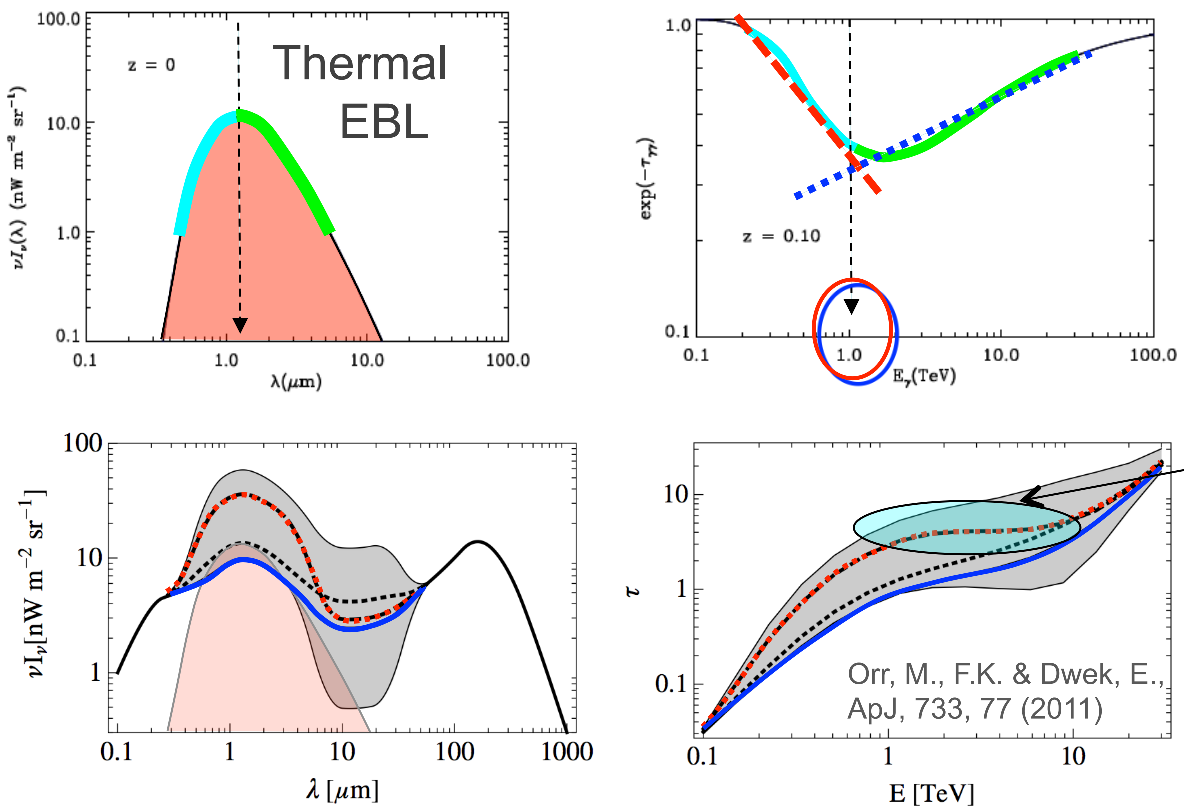
c) RGB J0710+591: z = 0.125

d) 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



Spectral break:

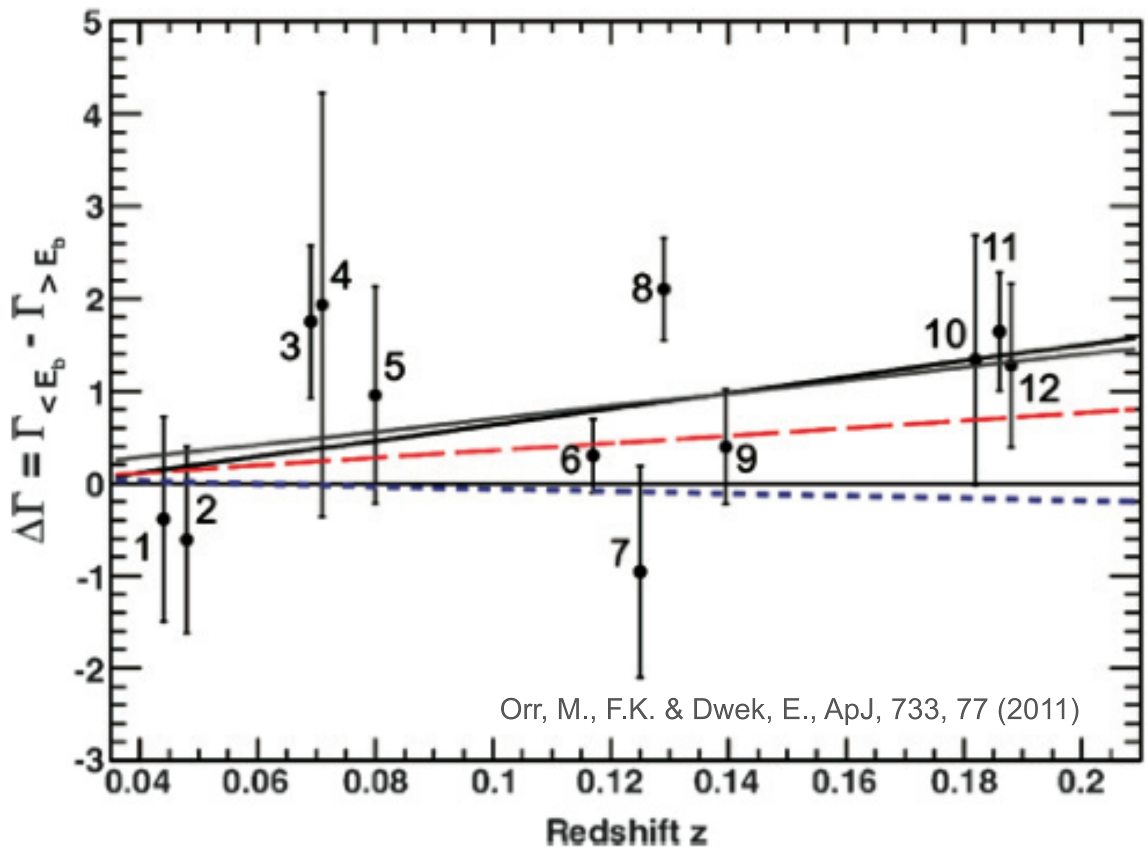
$$\Delta\Gamma = \Gamma_{(E<1\ \mathrm{TeV})} - \Gamma_{(E>1\ \mathrm{TeV})}$$

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

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

- 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

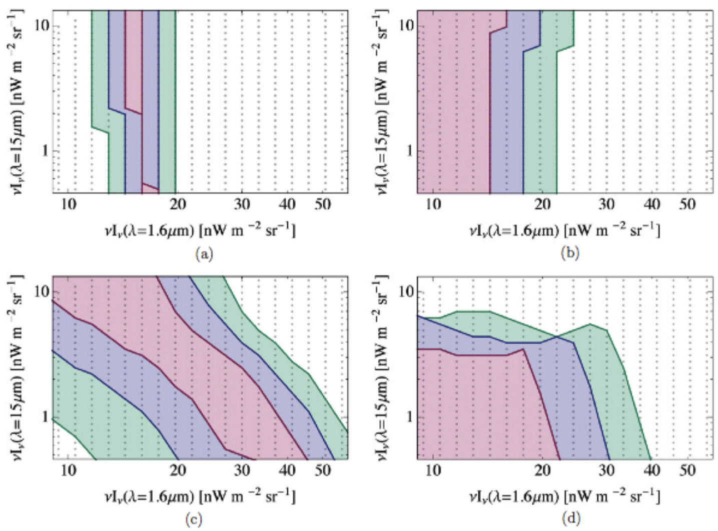
Method III, part II: 1 TeV break

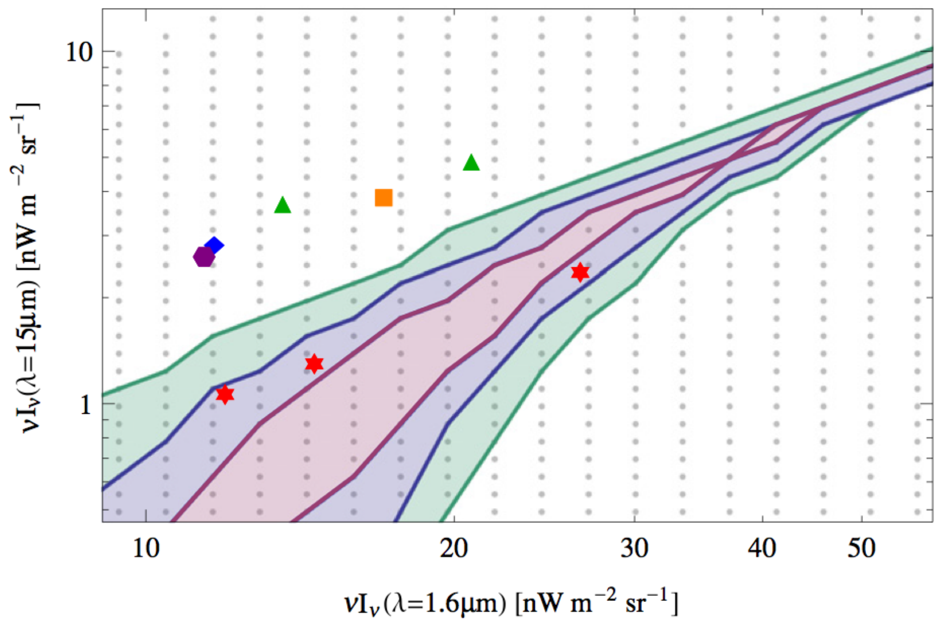


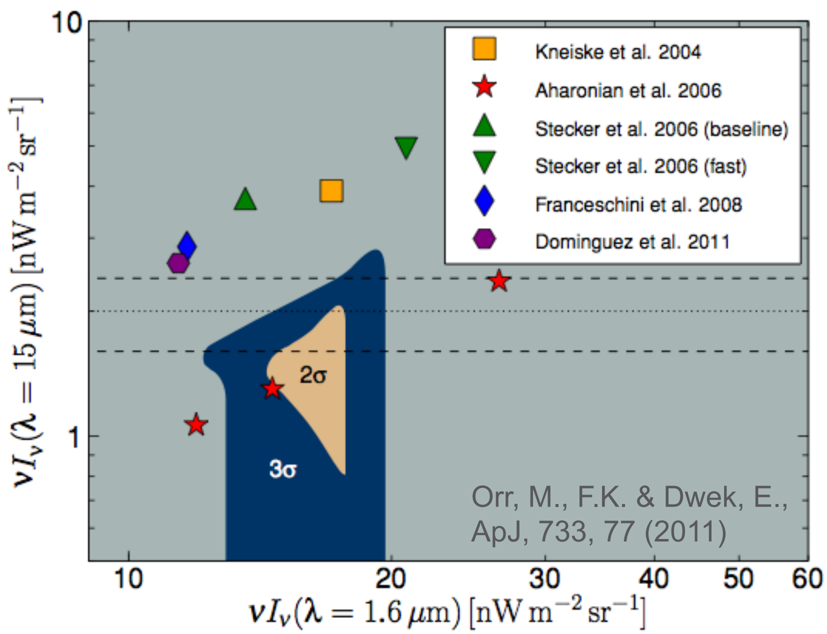
Source Name	Redshift	Γ_{LAT}	Γ_{VTS}	Method(s)	# Spec. Points l.t./g.t. E_{break}
1ES 2344+514	0.044	1.57 ± 0.17	2.95 ± 0.12	TeV Break	4 / 3
1ES 1959+650	0.047	2.10 ± 0.05	2.58 ± 0.18	TeV Break	4 / 2
PKS 0548-322	0.069	-	2.8 ± 0.3	TeV Break	3 / 2
PKS 2005-489	0.071	1.90 ± 0.06	4.0 ± 0.4	TeV Break	6 / 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

12 blazars: z ~ 0.04 – 0.186

Method III: part I+II (Data)

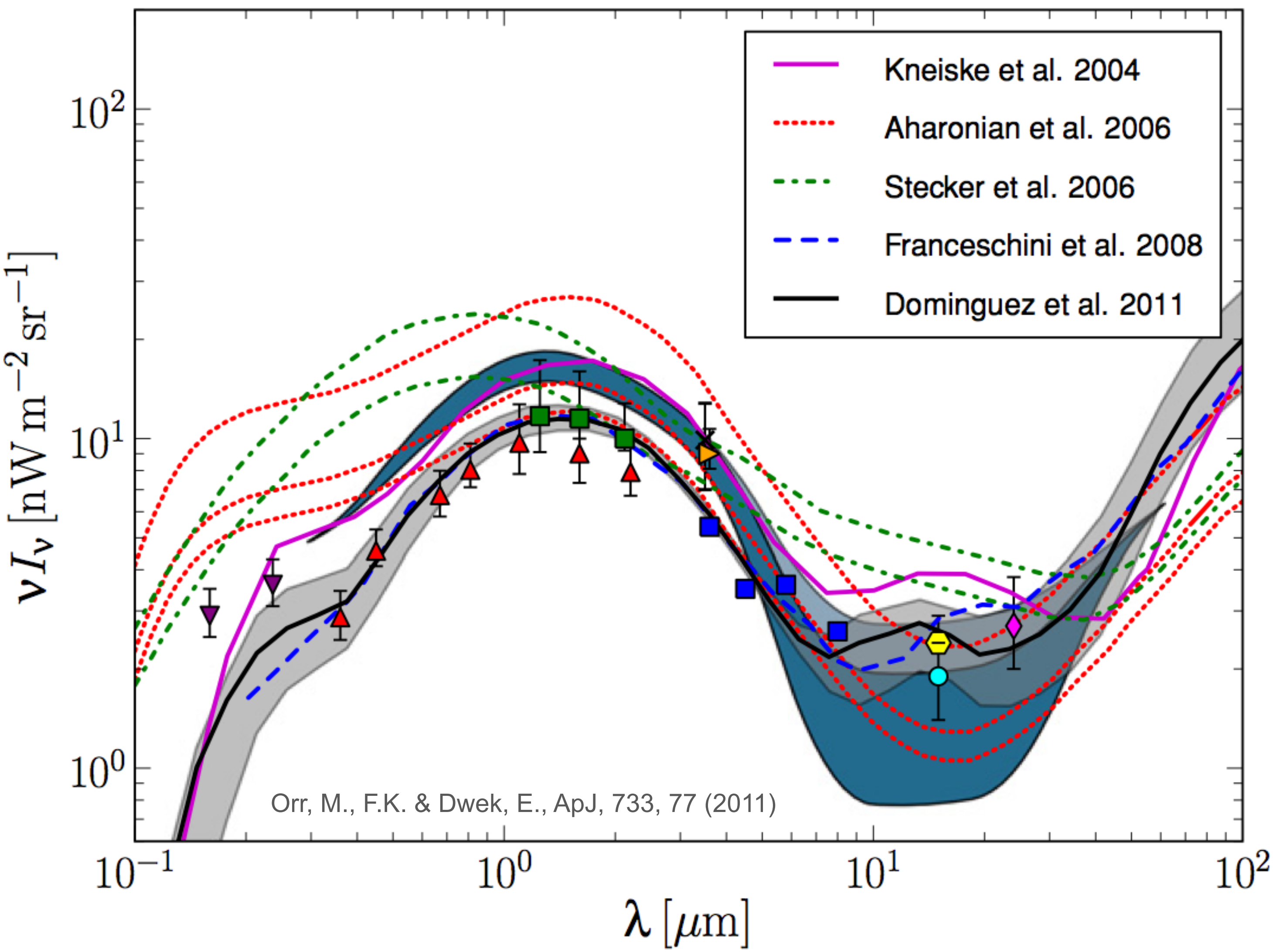






- part I and part II are "orthogonal"
- constrain near-IR to mid-IR ratio!
- considering lower limits (direct) in mid-IR, also constrains absolute level!

Method III:



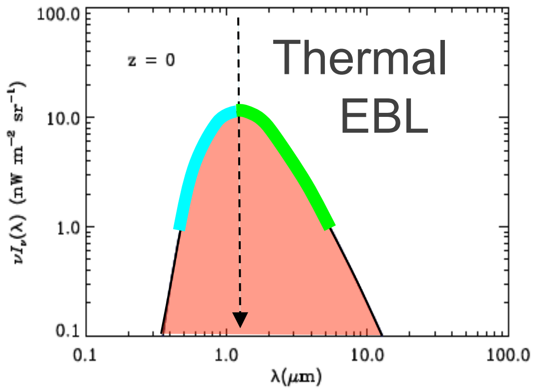
at 1.6 μm:

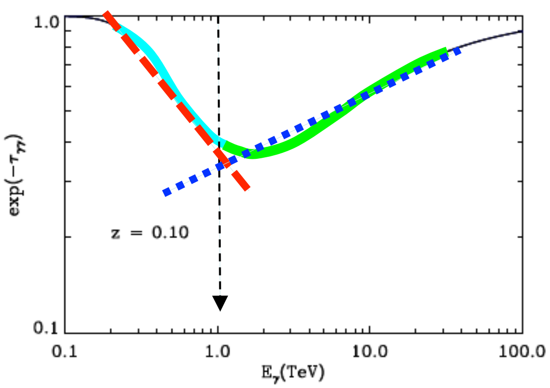
17 ± 0.3 nW/m²/sr

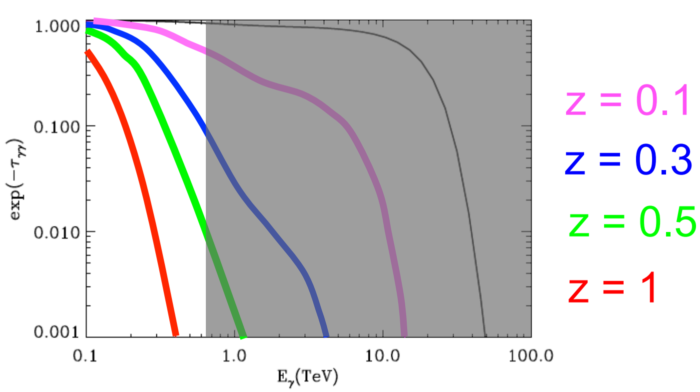
at 15 μm:

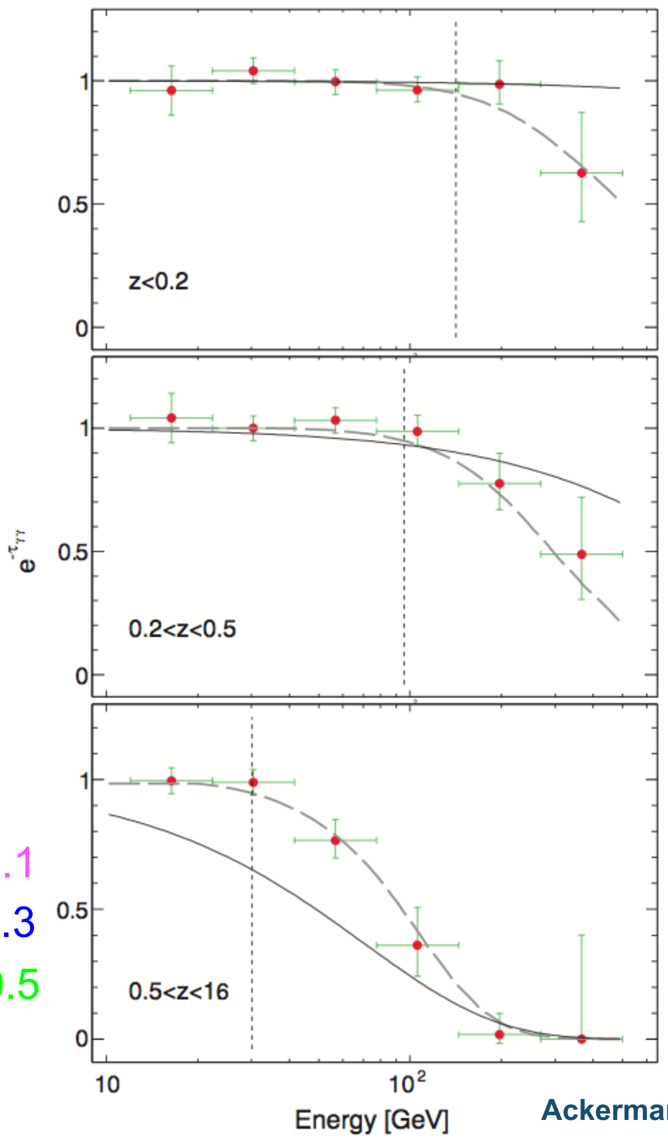
1.36 ± 0.58 nW/m²/sr

Detection of EBL Imprint by Fermi









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

At ≈ 0.3 μm:
3 ± 1 nW/m²/sr

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

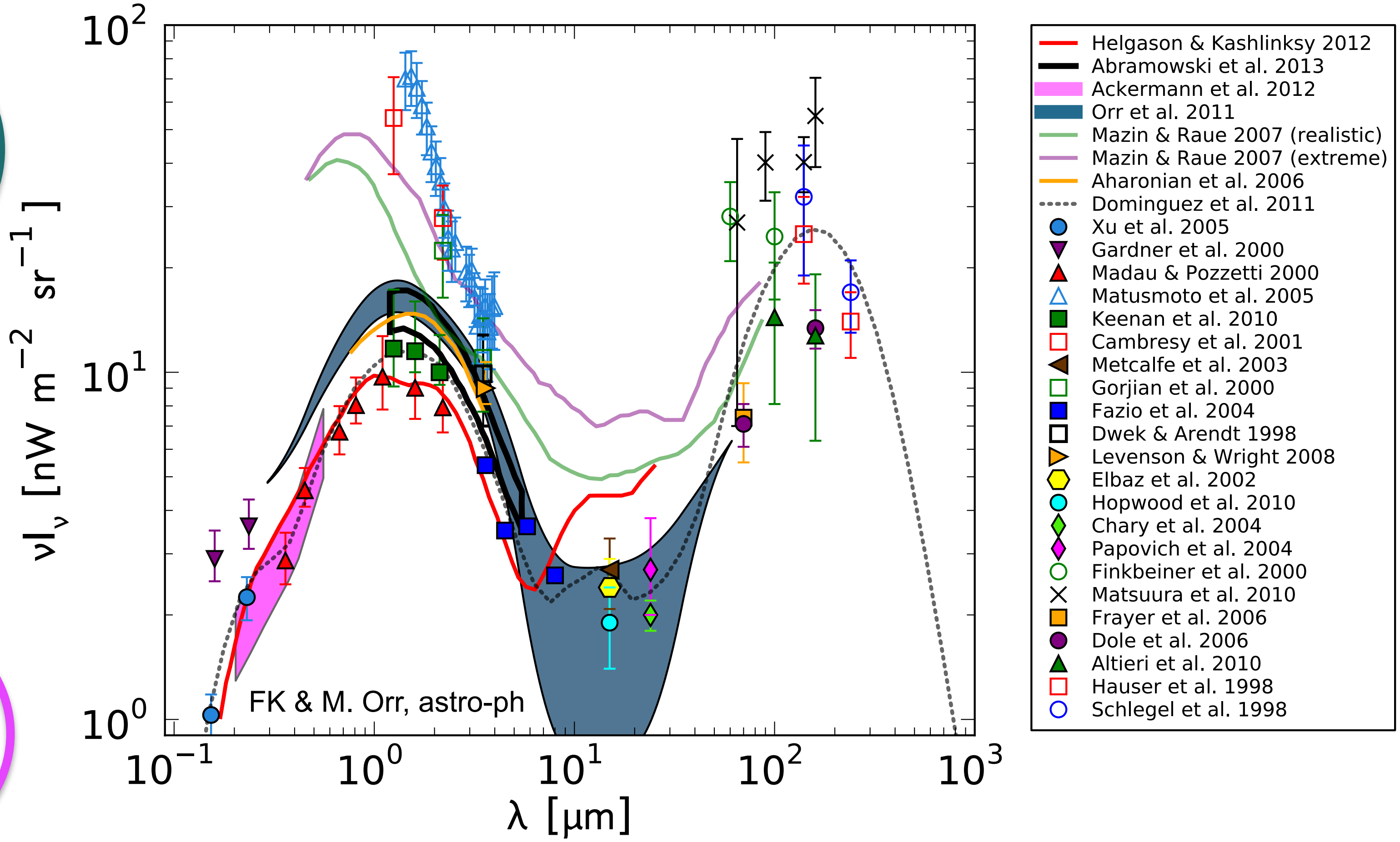
Status of EBL measurements (2013)

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

Future

What else might we uncover?

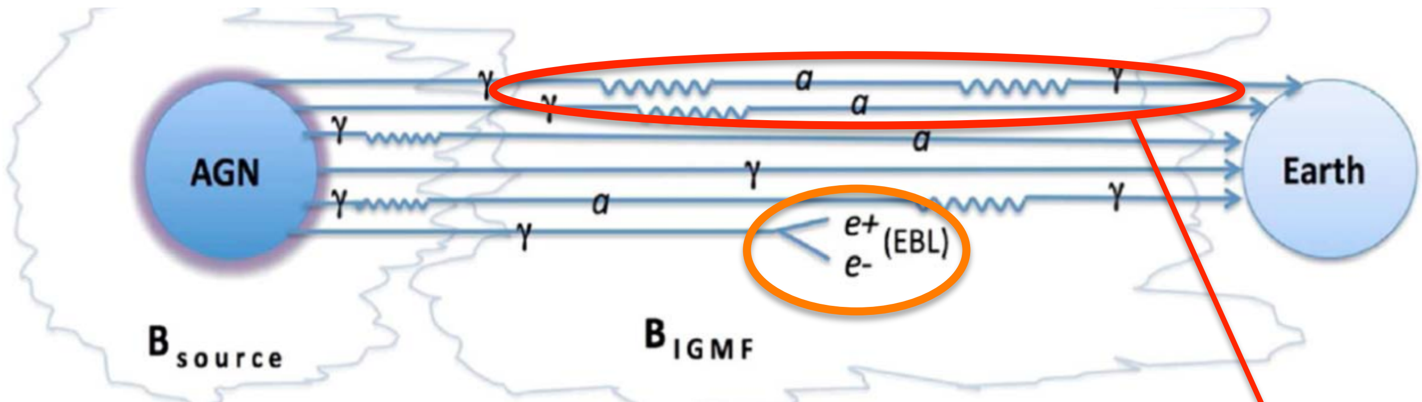
If γ-ray measurements, galaxy counts & direct detections converge we are done!

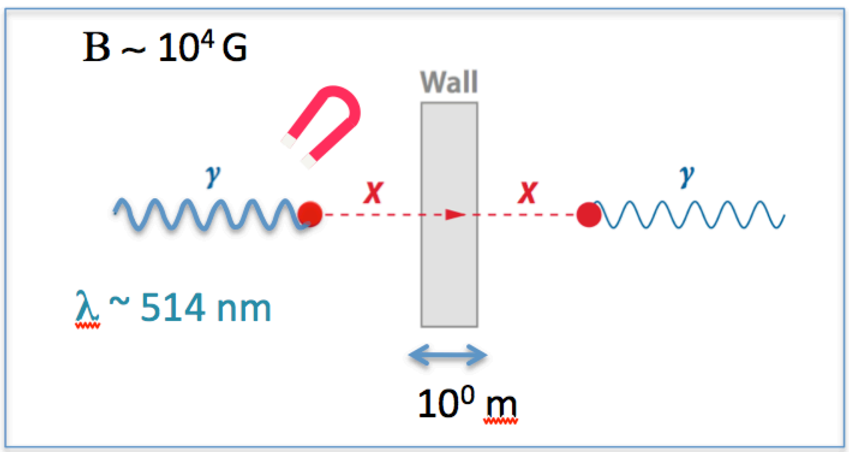
Non-convergence

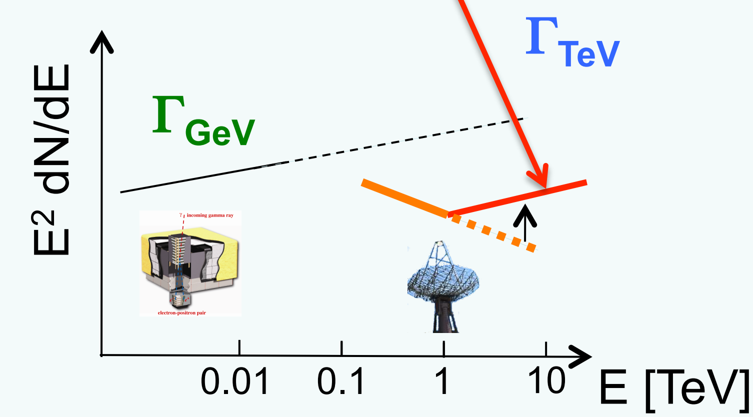
a) EBL from γ-rays >> EBL from resolved galaxy counts
   → diffuse component

b) EBL from γ-rays violates EBL from direct observations
   → secondary γ-rays play an important role

Signatures from the EBL & ALPs

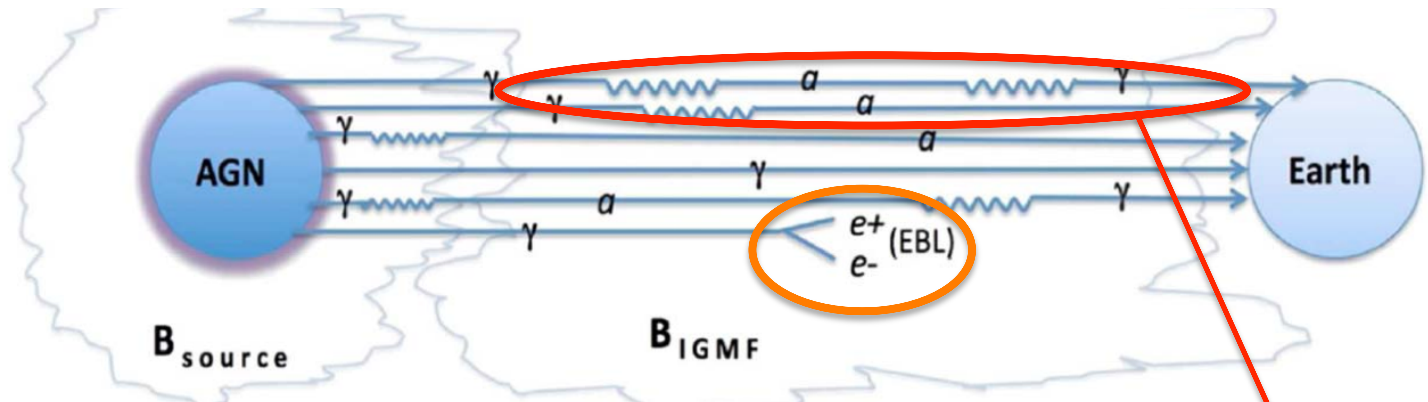


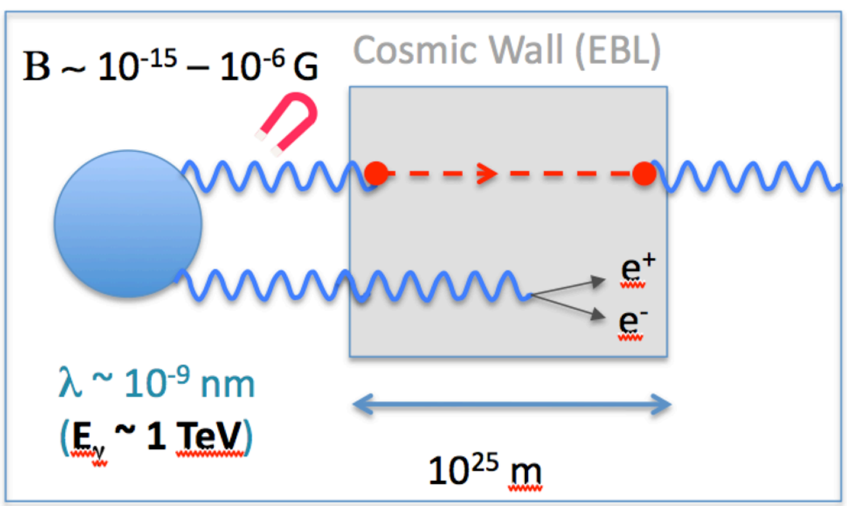


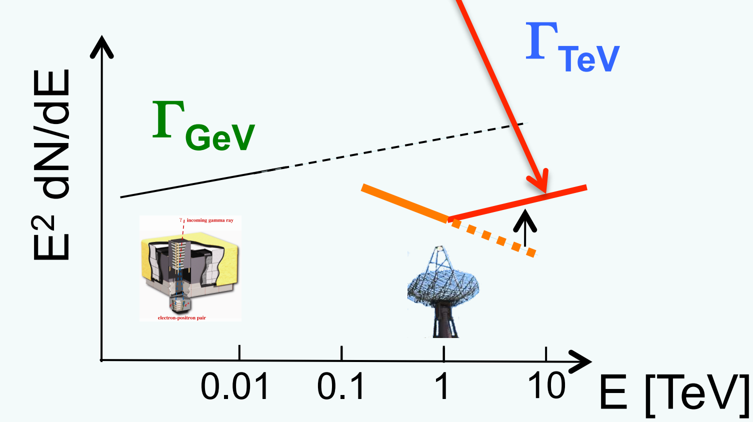


- component arises from **secondary γ-rays** generated by ALP-photon mixing
- spectra harden – characteristic energy
- **but spectral rise** may **not** be unique!

Signatures from the EBL & ALPs

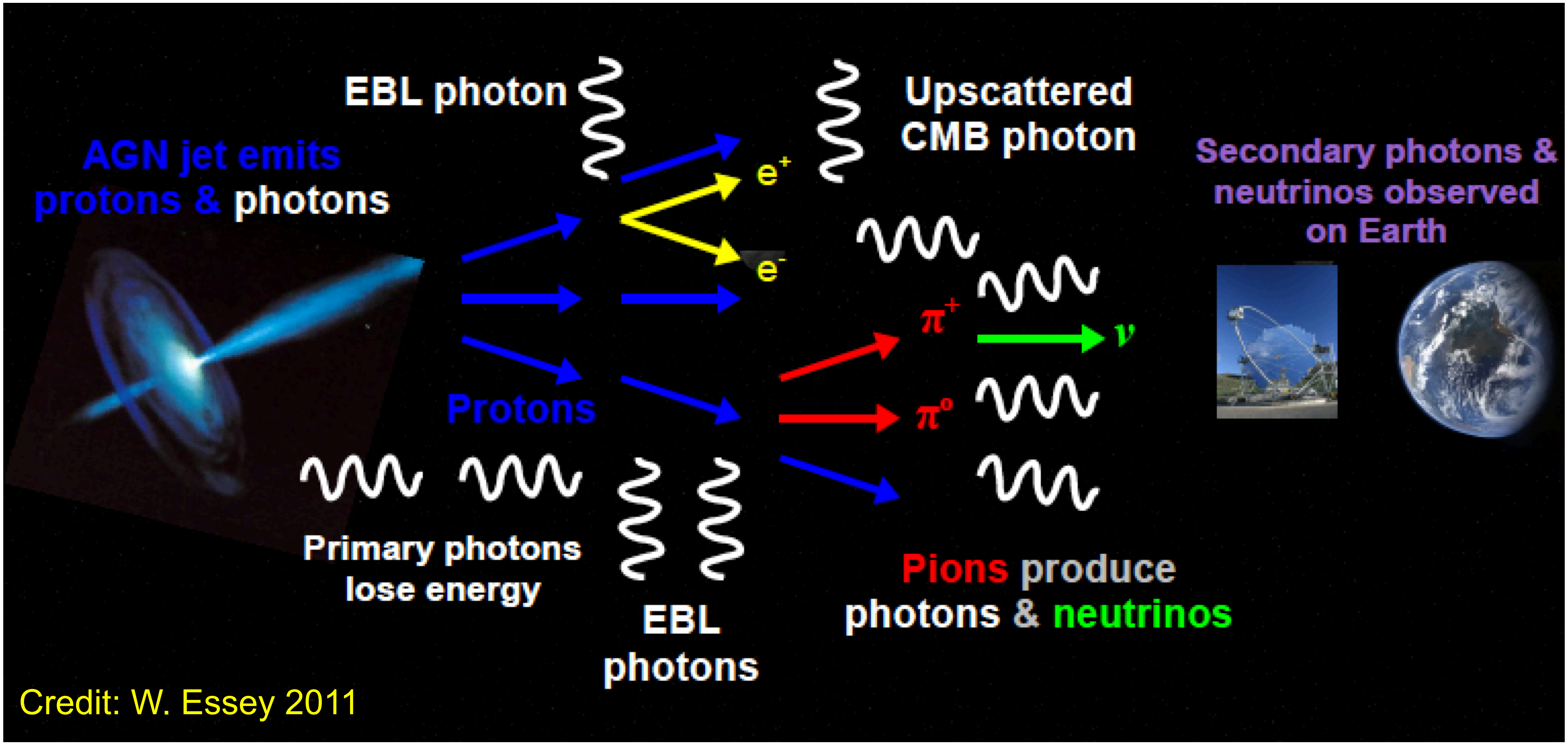






- component arises from **secondary γ-rays** generated by ALP-photon mixing
- spectra harden – characteristic energy
- **but spectral rise** may **not** be unique!

Signatures from Cosmic Cascades



- requires B < 10^{-16} G
- secondary γ-ray fluxes from cosmic ray cascade can only vary slowly (testable)

<u>alternatively</u>

- $e^{\pm}$ could cool rapidly due to plasma-beam instability in IGM
  (Broderick et al., ApJ, 22, 152 (2012))

Summary

- Detection of UV/optical EBL signature by Fermi with ~ 150 BL Lacs
- TeV γ-ray data provide strong constraints to the near-IR and mid-IR
- Range of methods (assumptions) yield comparable results
- Tension in mid-IR: between EBL from γ-ray data and galaxy LF estimate
- Convergence of direct EBL and γ-ray opacity measurements required to

  rule out non-standard EBL contributors and/or secondary γ-ray scenarios

Thank You!