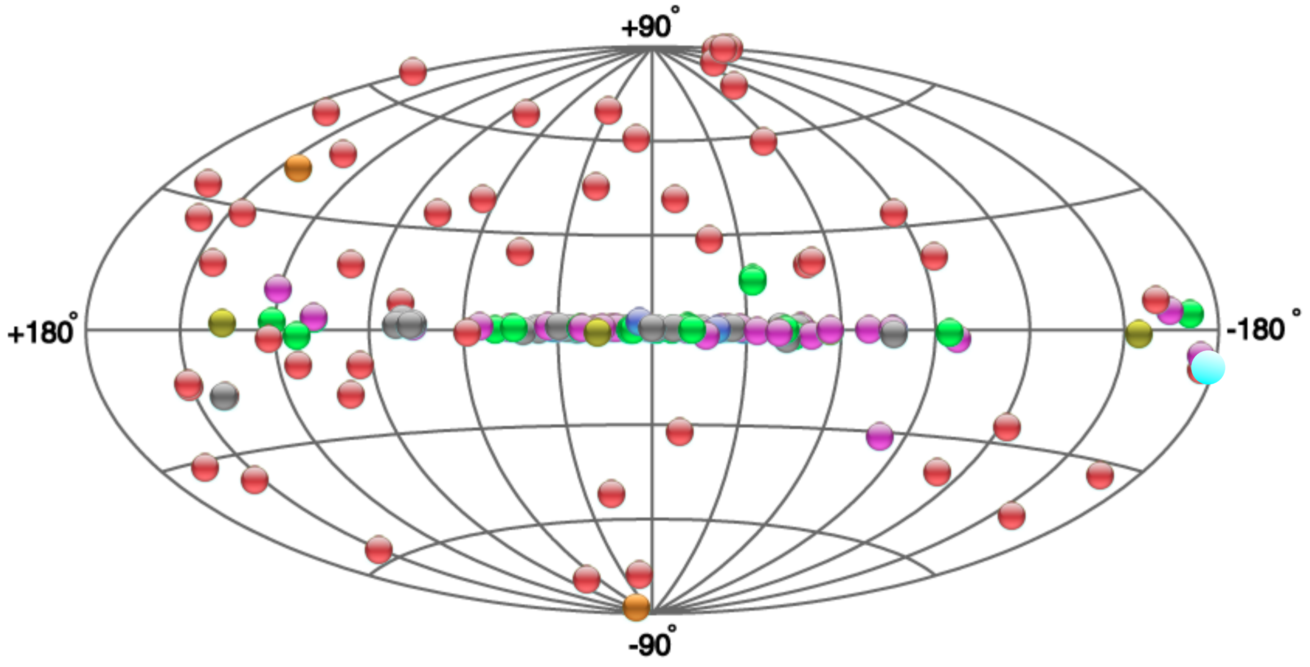
TeV Gamma Rays: Observations versus Expectations (Theory)

Frank Krennrich, Iowa State University

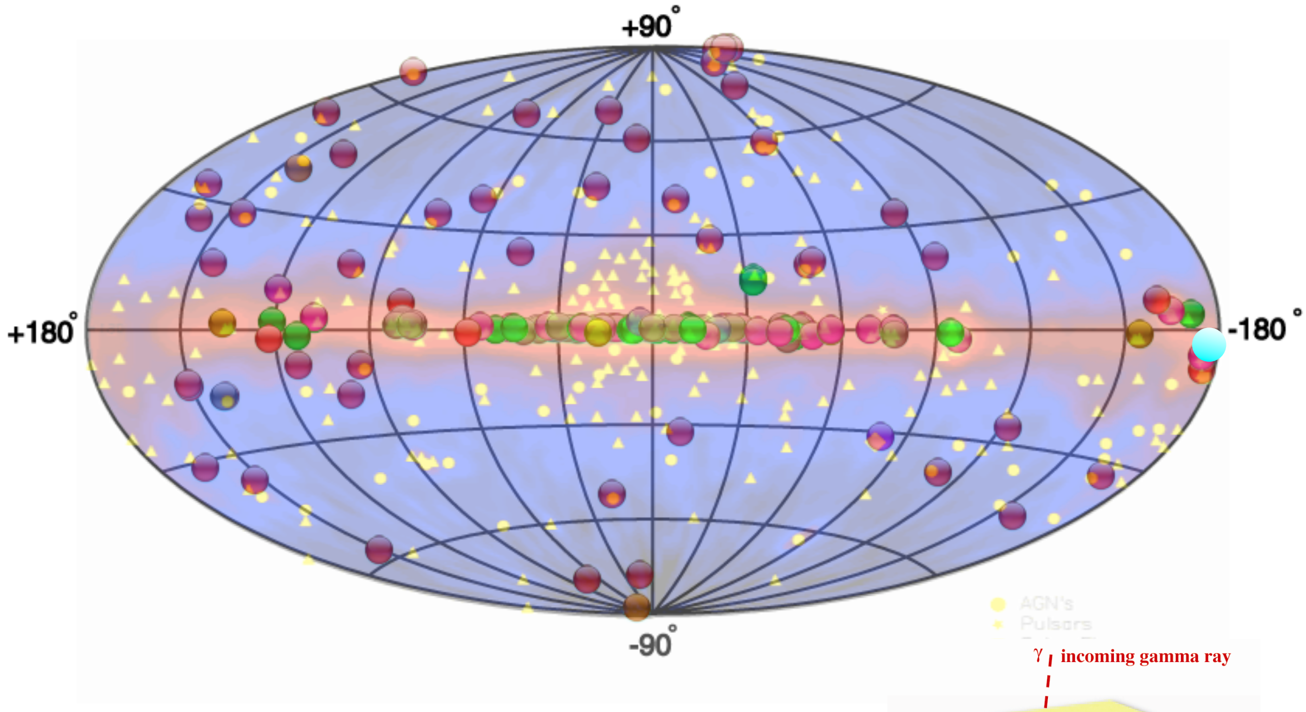
TeV γ-ray Sky 2012

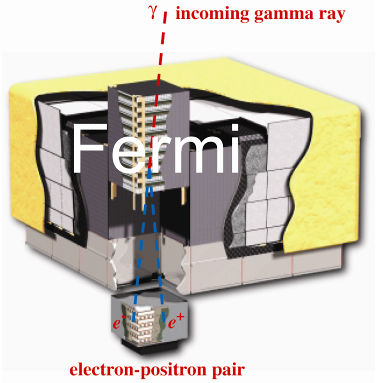


source classes

- ● 50 AGN ☑
- ● 2 starburst galaxies ☑
- LMC ☐
- ● 30 PWN ☐
- ● 10 SNRs ☑
- ● 3(4) compact object Binary systems ☐
- ● 30 unidentified Objects ☐
- ● 1 Pulsar ☐

GeV/TeV γ-ray Sky 2012





source classes

● 50 AGN ☑

● 2 starburst galaxies ☑

LMC ☐

● 30 PWN ☐

● 10 SNRs ☑

● 3(4) compact object Binary systems ☐

● 30 unidentified Objects ☐

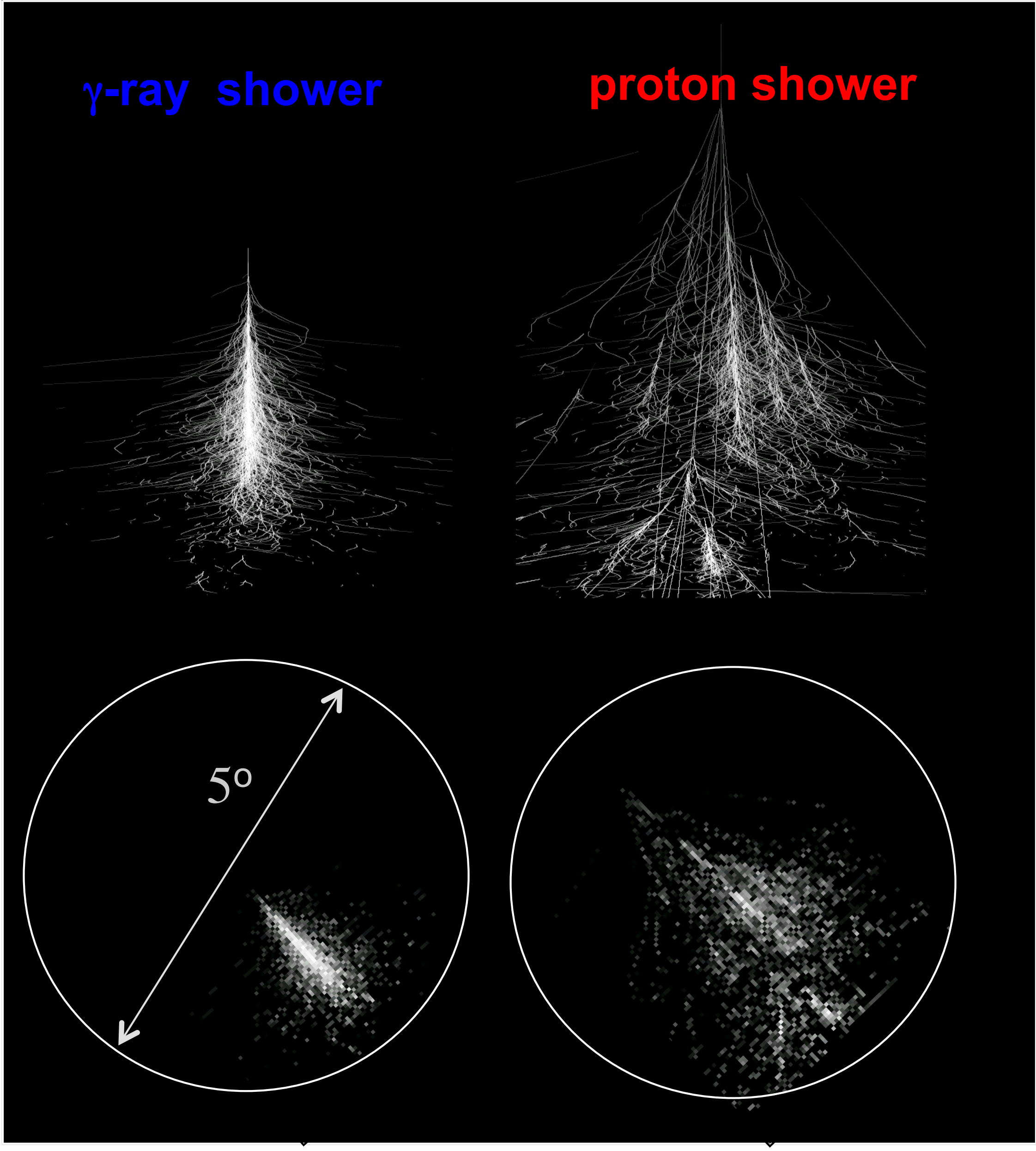
● 1 Pulsar

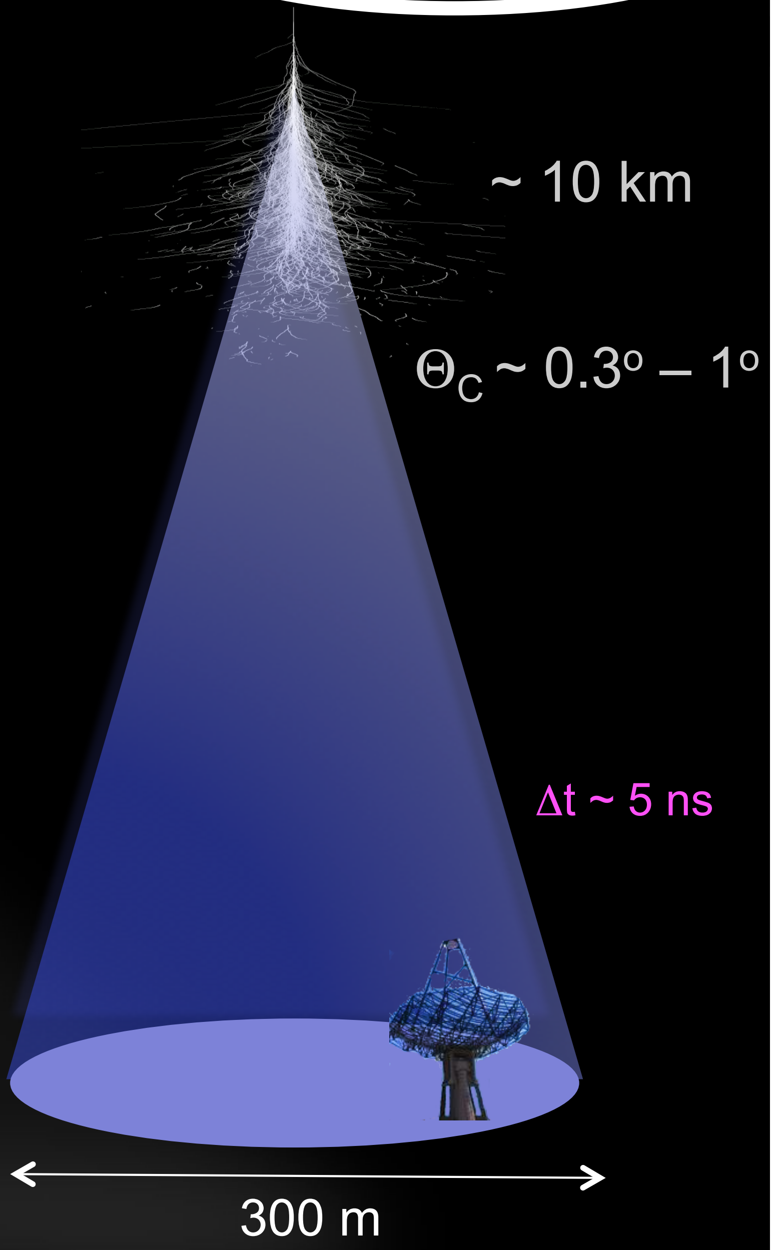
Key Questions

- Origin of cosmic particles and cosmic rays?
- How do cosmic particle accelerators work? How efficient?
- How transparent is the universe?
- What is the spectrum of the Extragalactic Background Light?

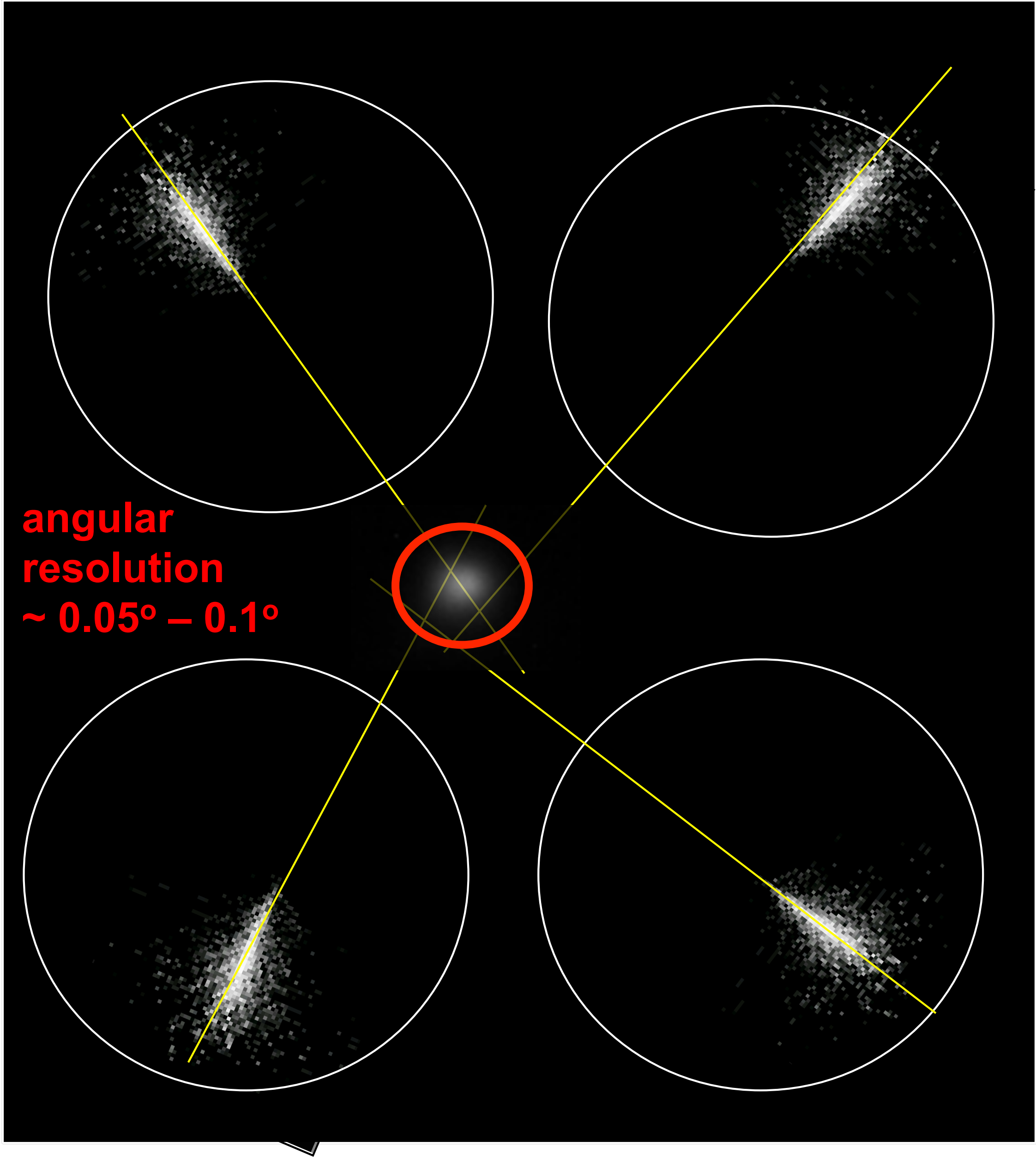
Air Cherenkov Technique: Whipple 10m

ΔE/E ~ 30-40%

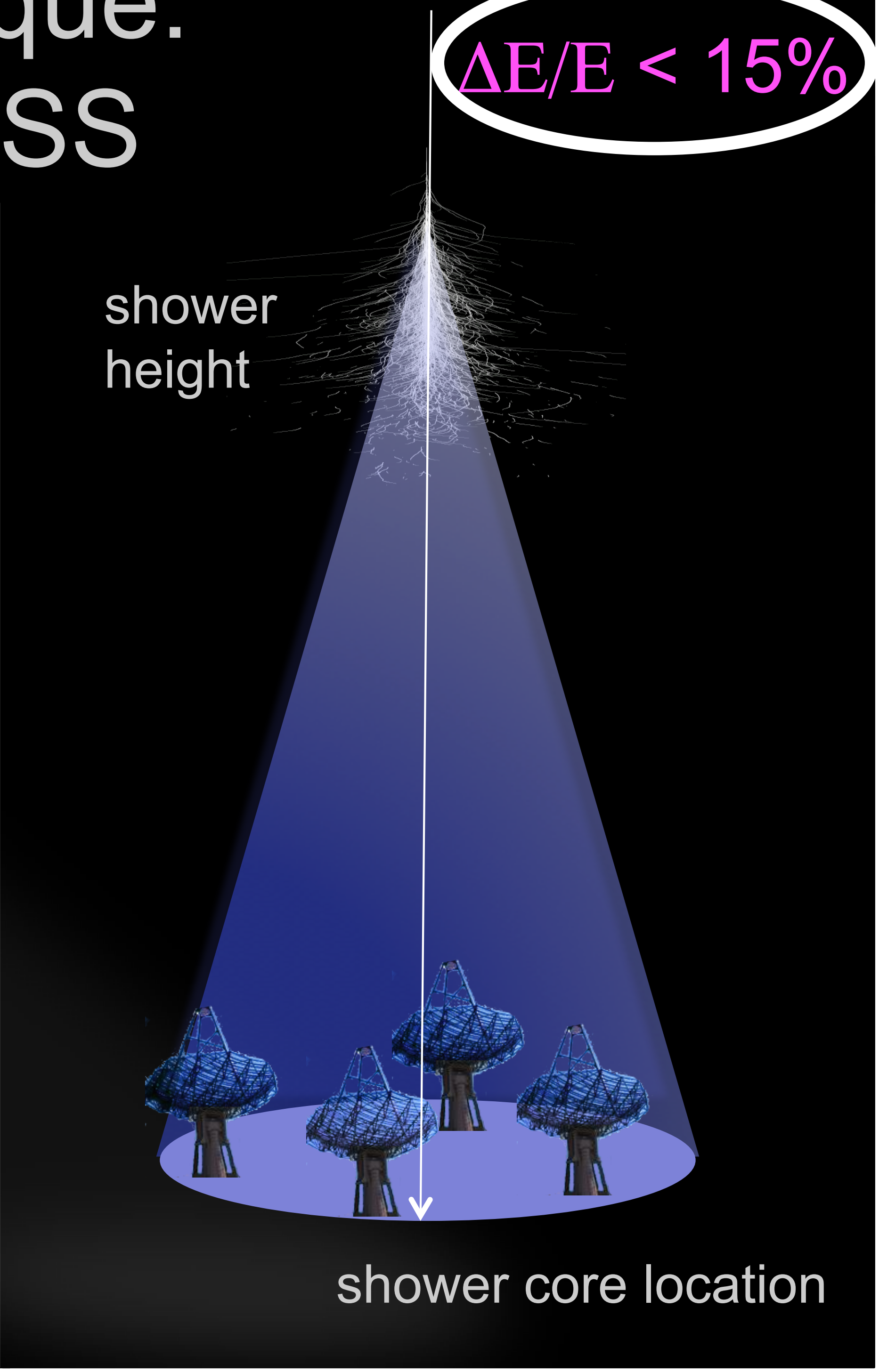




Air Cherenkov Technique:
Stereo: VERITAS, HESS



angular resolution ~ 0.05° – 0.1°



$\Delta E/E < 15\%$

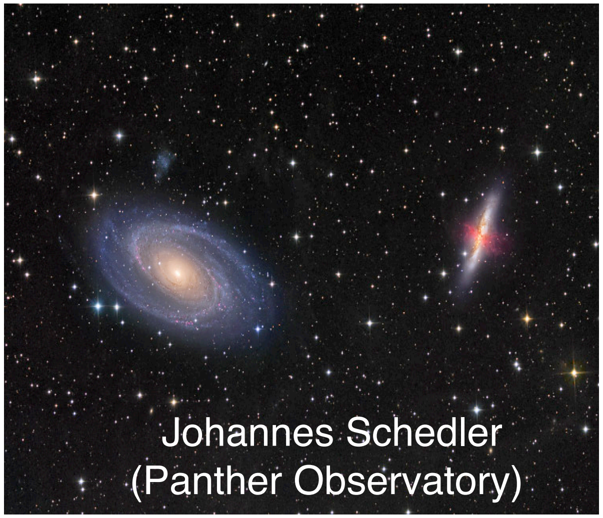
Cosmic Accelerators

Cosmic Ray Accelerators In Bulk

- **M82** is the prototype starburst galaxy
- Distance ~ 3.9 Mpc
- Diameter ~ 1’ (0.016^{o})
- SMBH ~ 3 x 10^{7} M_{solar} (no activity)
- Interacts with group of galaxies (M81)
- Hubble ST: 200 massive star clusters
- High supernova rate ~ 0.1 - 0.3 per year
- Moderate gas density 150 particles/cm^{3}

-> excellent candidate for
cosmic ray interactions &
gamma ray emission.

-> probing paradigm that SNRs
are the origin of C.R.s.

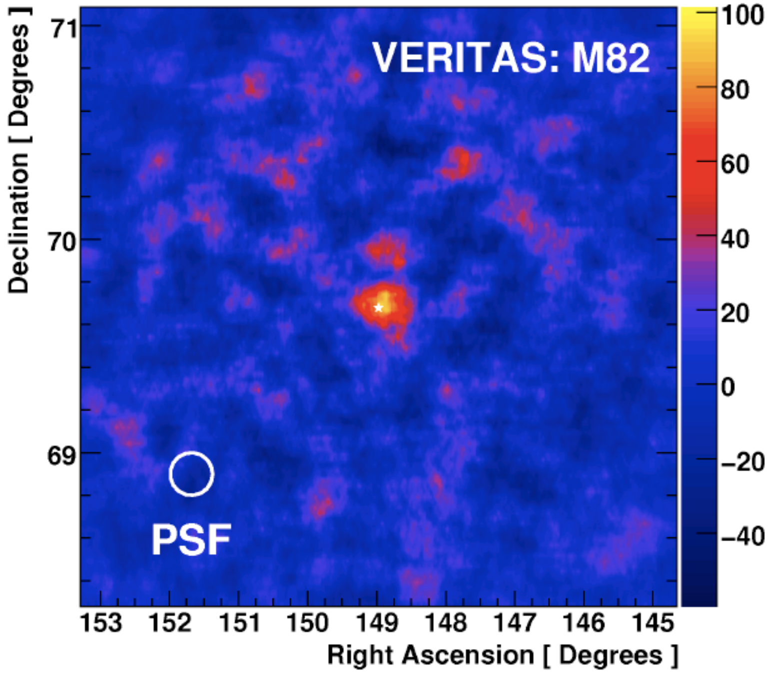


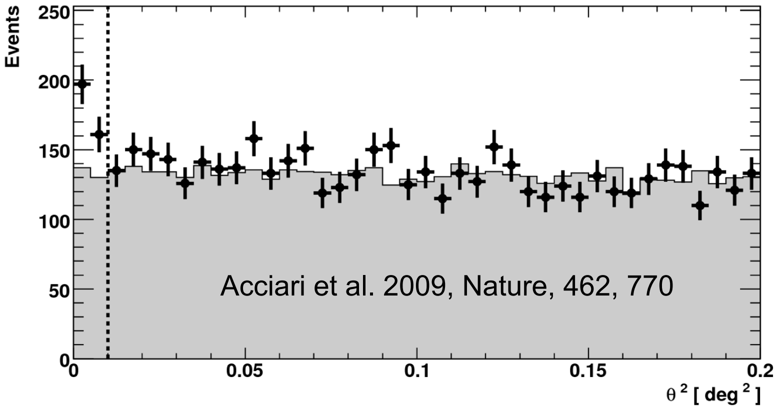
Johannes Schedler
(Panther Observatory)

NASA, ESA, The Hubble
Heritage Team, (STScI / AURA)

Cosmic Ray Accelerators In Bulk

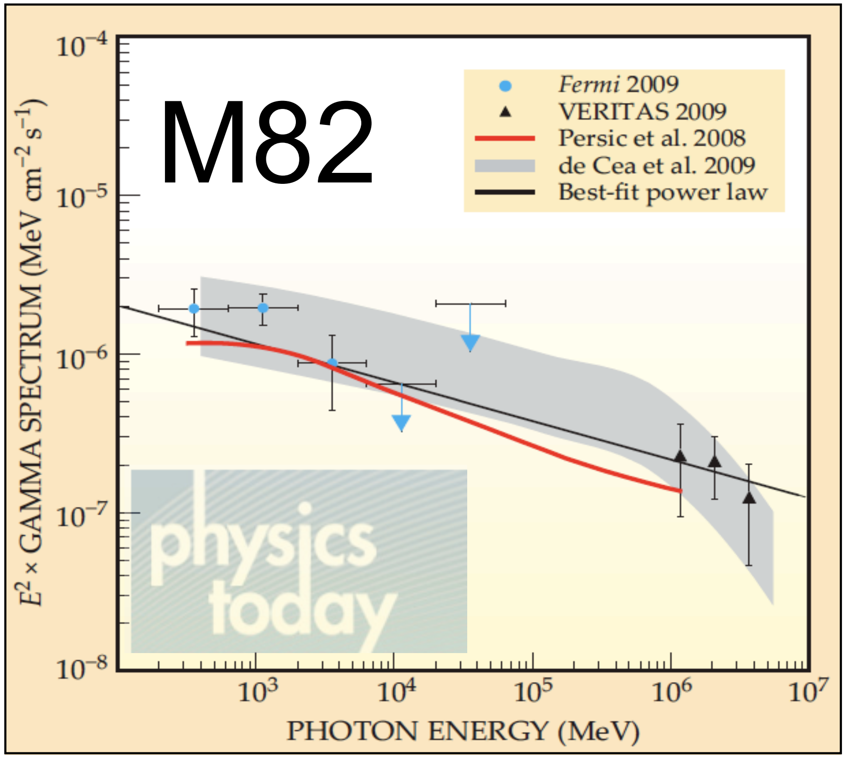
- VERITAS data ~ 137 h livetime
  - only astronomical dark time, large zenith angle ~ 39°
  - increased E_{thres}
  - bad weather removed
- Standard VERITAS analysis (“hard cuts”)
  - Et_{hres} ~ 700 GeV
  - cuts a priori optimized on Crab
  - hard spectrum expected from theory
  - but we count for 3 trials (standard, hard & soft)
- Point-like excess of 91 γ; 5.0 σ (pre-trial)
  - 3 independent analyses
  - many systematic checks performed
- Post-trial: 4.8 σ
  - steady signal
  - excess consistent with instrument PSF
- M82 weakest source ever detected @ VHE
  - 0.9% of Crab
  - Gamma-ray rate: 0.7 γ/hour





Acciari et al. 2009, Nature, 462, 770

Cosmic Ray Accelerators In Bulk



Acciari et al. (VERITAS Collab.), Nature, 462, 770 (2009)
Abdo et al. (Fermi Collab.), arXiv:0911.5327
B. Schwarzschild, Physics Today, vol. 63, p 13 (2010)

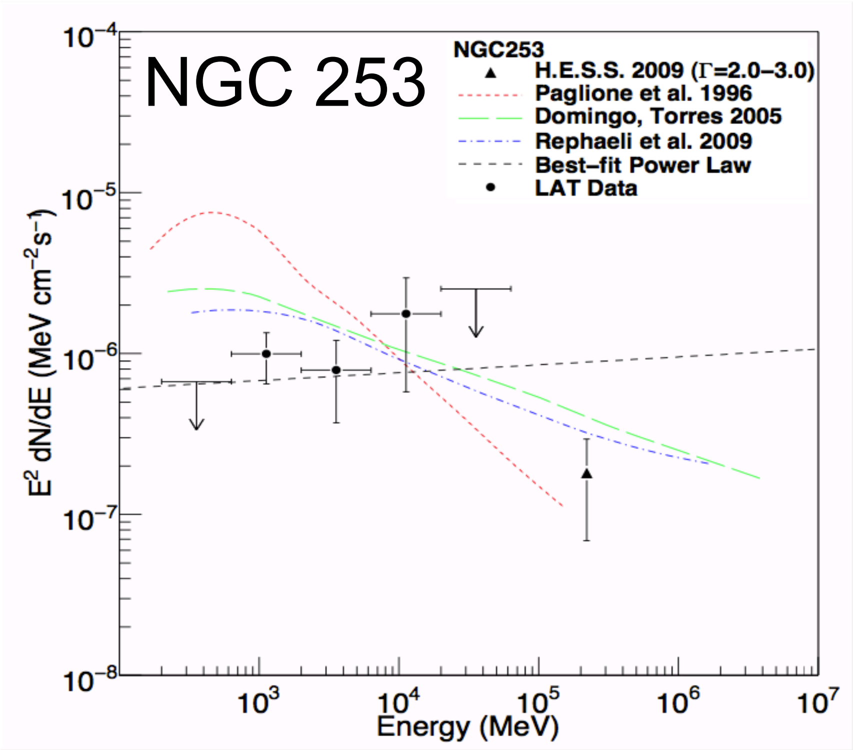
<u>Expectation</u>: $dN/dE \sim E^{-2}$

Fermi (0.1 – 3 GeV):
$dN/dE \sim E^{-2.2 \pm 0.2}$

VERITAS (0.7 – 4 TeV):
$dN/dE \sim E^{-2.5 \pm 0.6}$

$\Bigg\}$ (✓)

Cosmic Ray Accelerators In Bulk



Acero et al. (HESS Collab.), Science, 326, 1080 (2009)
Abdo et al. (Fermi Collab.), arXiv:0911.5327

Expectation: dN/dE ~ E^{-2}

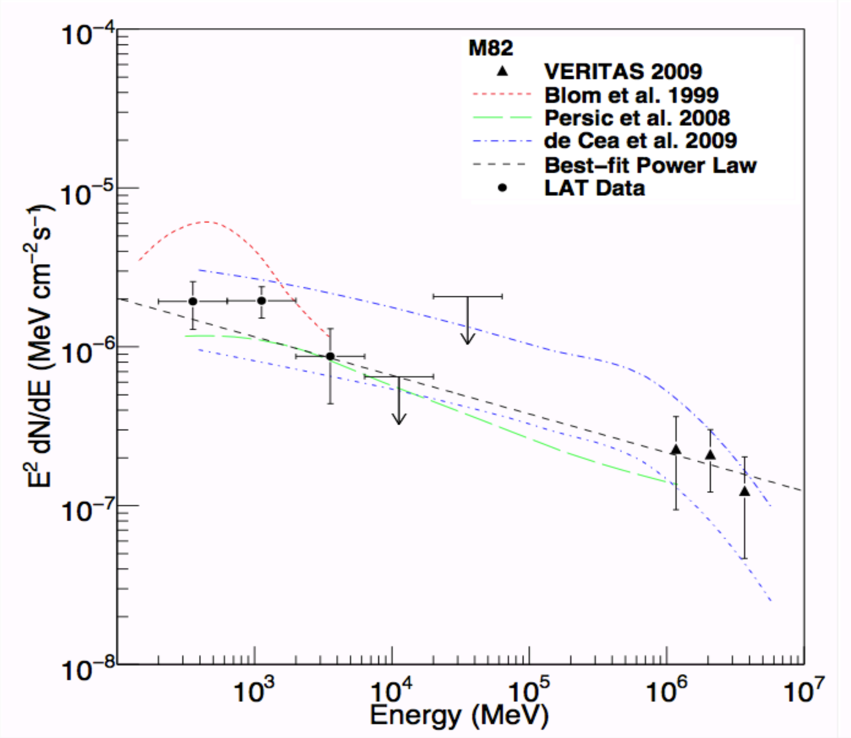
Fermi (1 – 20 GeV):
dN/dE ~ $E^{-1.95 \pm 0.4}$

HESS (0.3 – 5 TeV):
dN/dE ~ $E^{-2.14 \pm 0.18}$

(✓)

Ohm et al. (HESS Collab.), ICRC Beijing (2011)

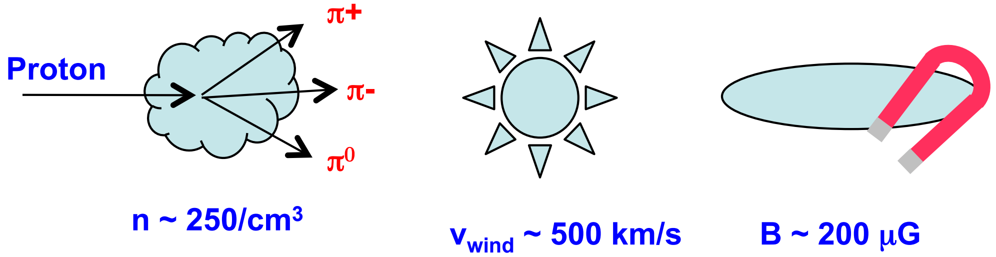
Cosmic Ray Accelerators In Bulk



Abdo et al. (Fermi Collab.), arXiv:0911.5327
Lacki et al., arXiv:1003.3257v3

Expectation: Flux

- uncertainties in SN rate ~ 0.08 – 0.3/yr
- conversion efficiency of p to pions (t_π vs. $t_{p\text{-}esc}$ (advection, diffusion)



- M82 a "proton calorimeter" as $t_\pi \sim t_{adv}$?

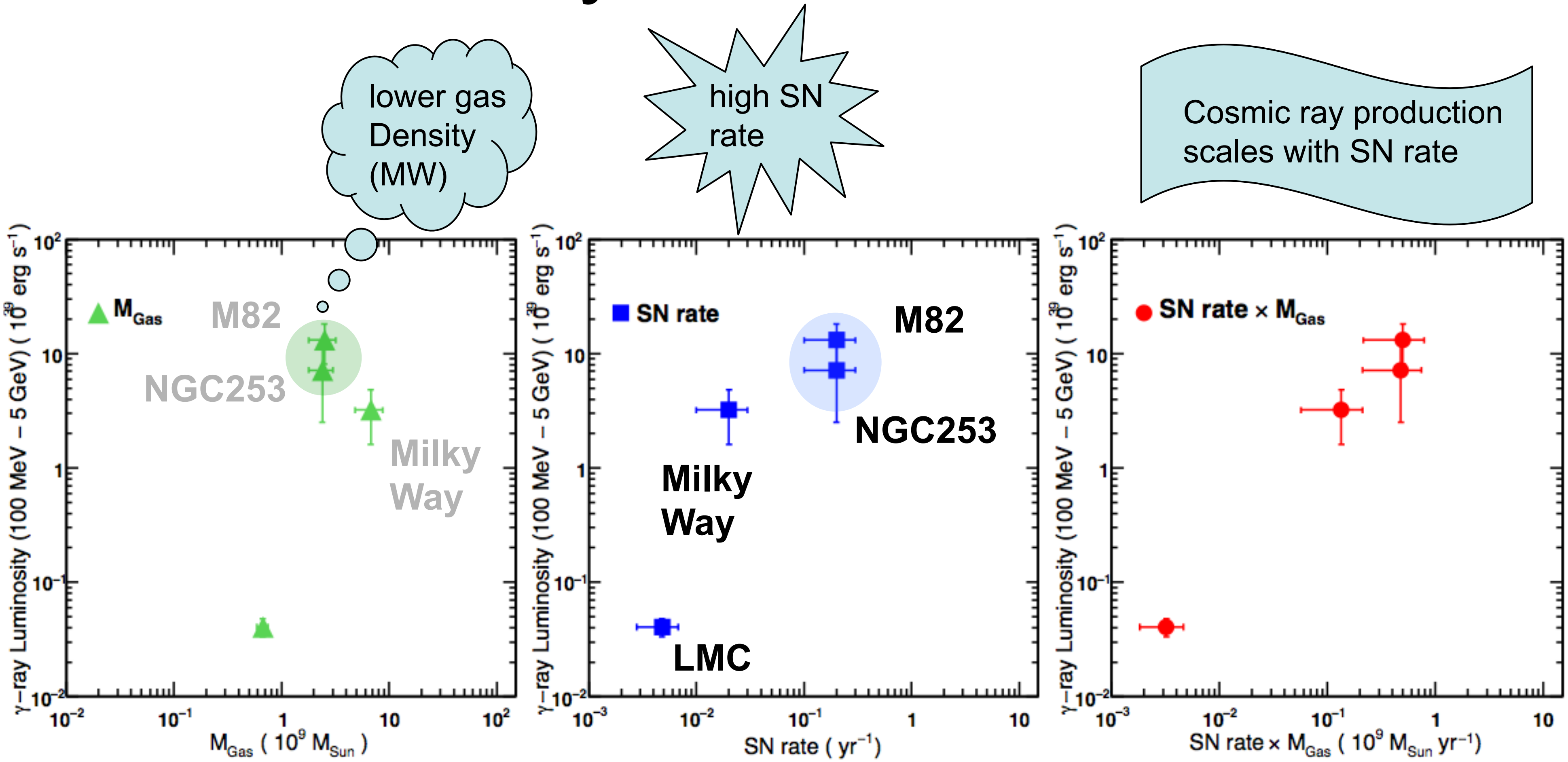
Caveats:

- short t_{adv} due to fast wind
  v ~ 1,000 – 2,000 km/s
- long t_π if CR travel mostly through low density gas

Conclusions:

- GeV/TeV spectra consistent with typical CR injection spectra
- either "proton calorimetry" or advective losses dominate

Cosmic Ray Accelerators In Bulk



lower gas Density (MW)

high SN rate

Cosmic ray production scales with SN rate

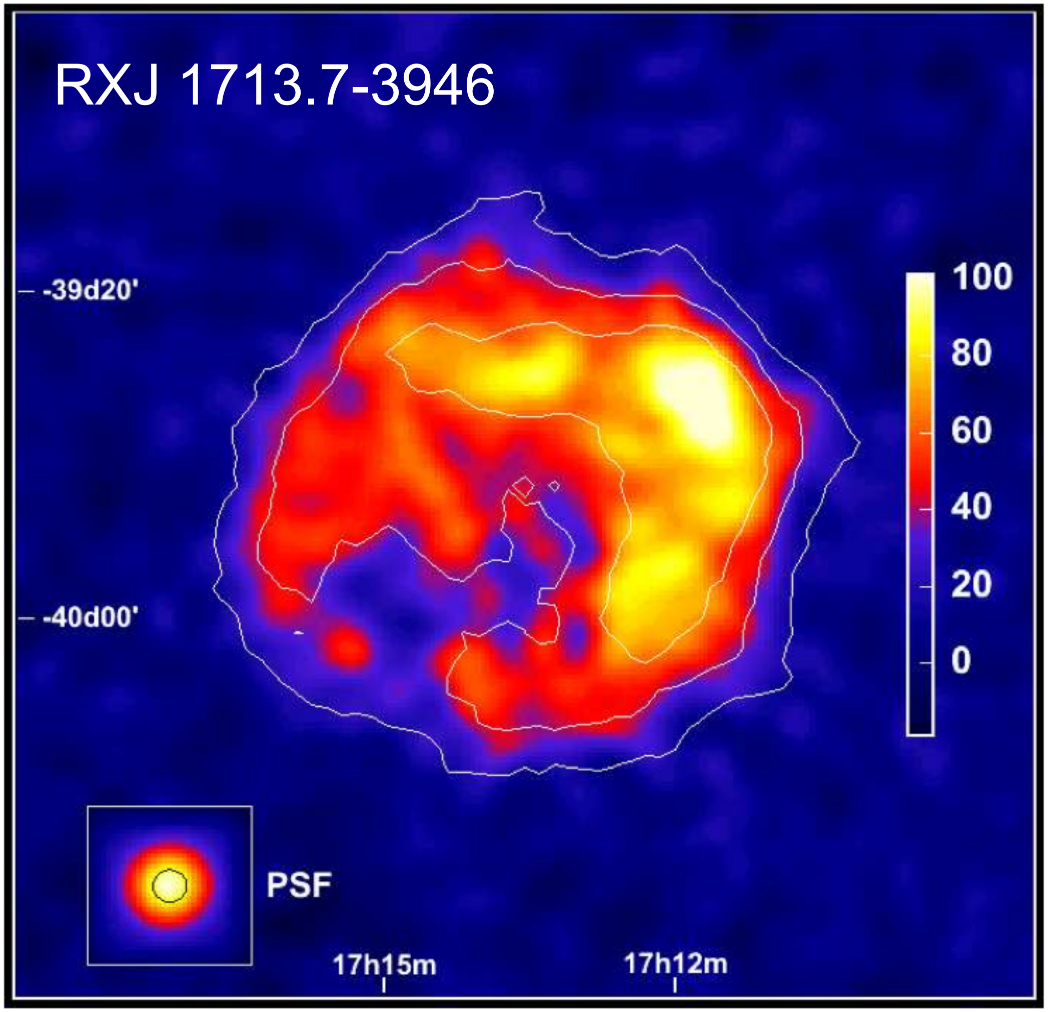
Abdo et al. (Fermi Collab.), arXiv:0911.5327

*Milky Way γ-ray luminosity based on estimates of gas density, pion decay, inverse Compton & bremsstrahlung photons

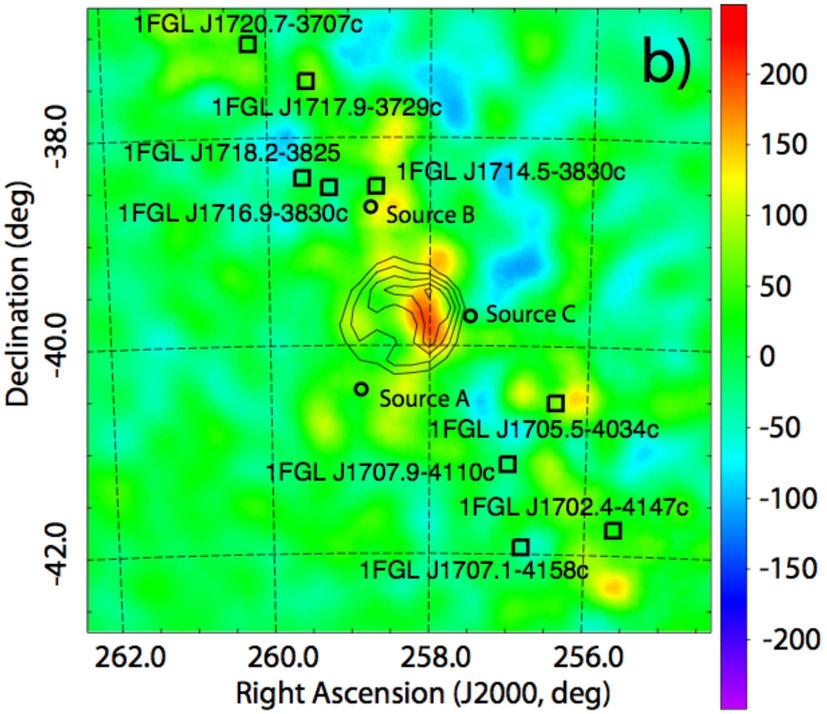
Future steps:

- better GeV/TeV spectra for M82, NGC253
- ULIRGs (Arp 220) to test high gas density …(proton calorimetry)

Cosmic Ray Accelerators: individuals



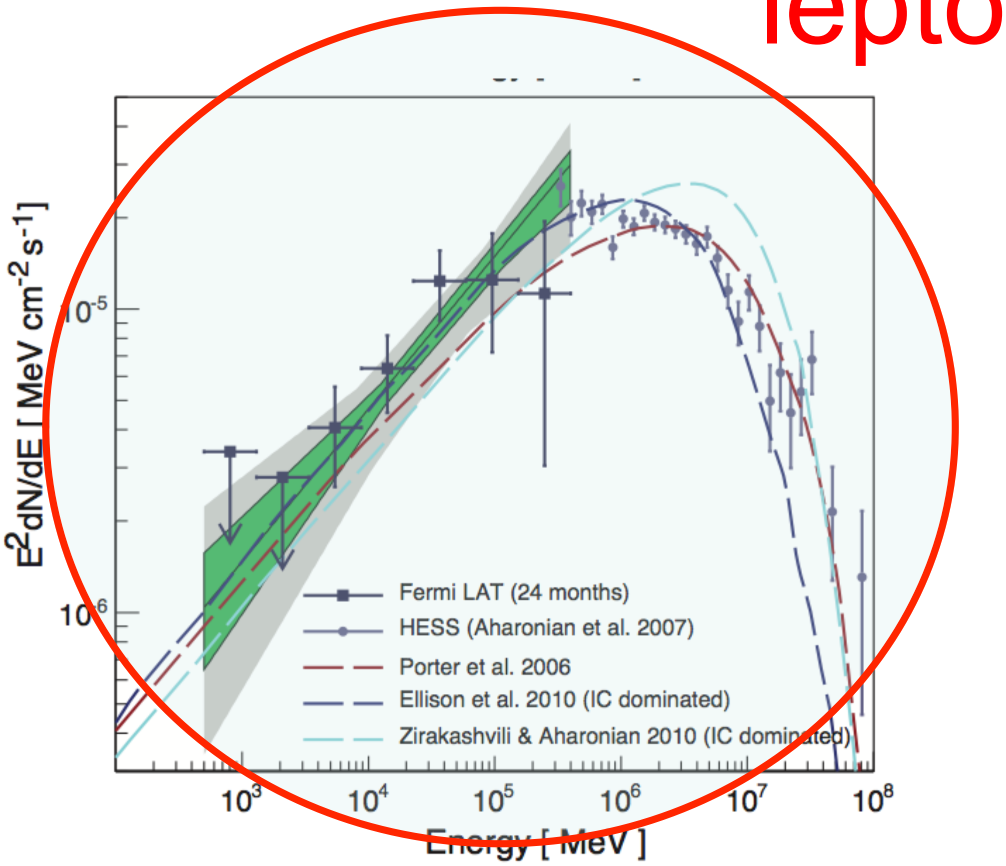
Aharonian et al. (**HESS Collab.**), A&A, 449, 223 (2006)

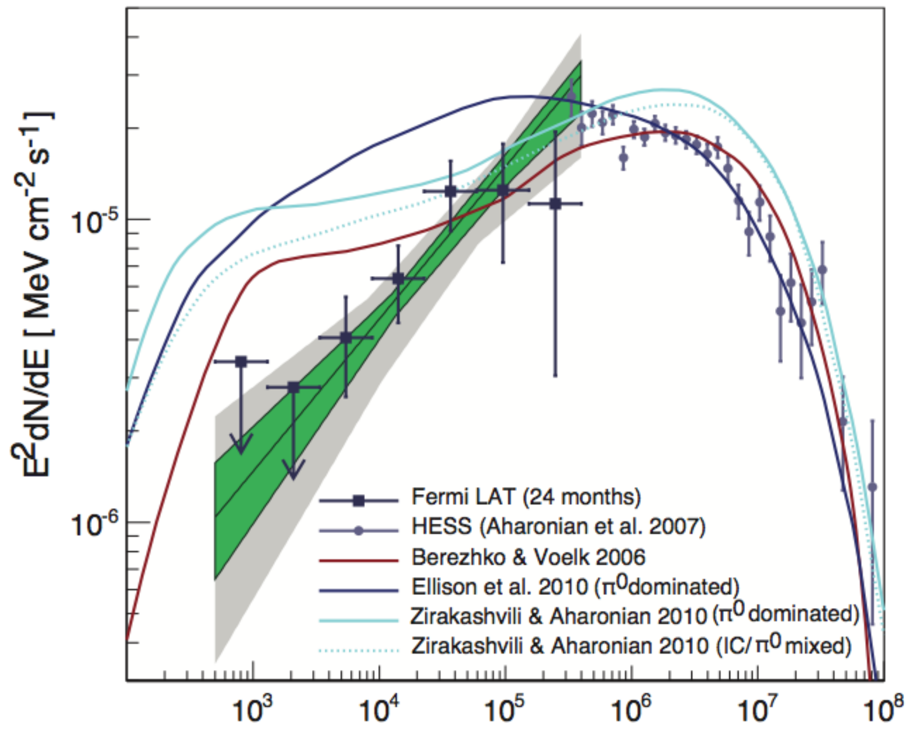


Abdo et al. (Fermi Collab.), ApJ, 734, 28 (2011)

Cosmic Ray Accelerators: individuals

leptonic



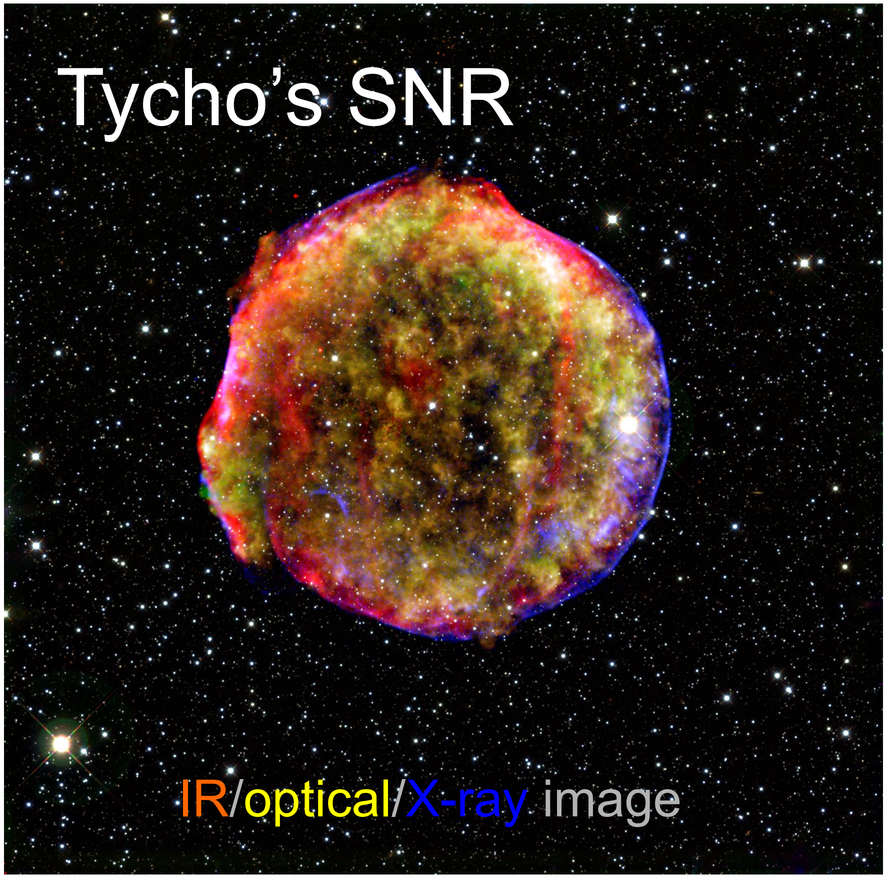


- electron acceleration
- inverse Compton scattering

  $e + \gamma \rightarrow e + \gamma$

- proton acceleration
- $p + p \rightarrow \pi^0 + \pi^+ + \pi^- + \ldots$

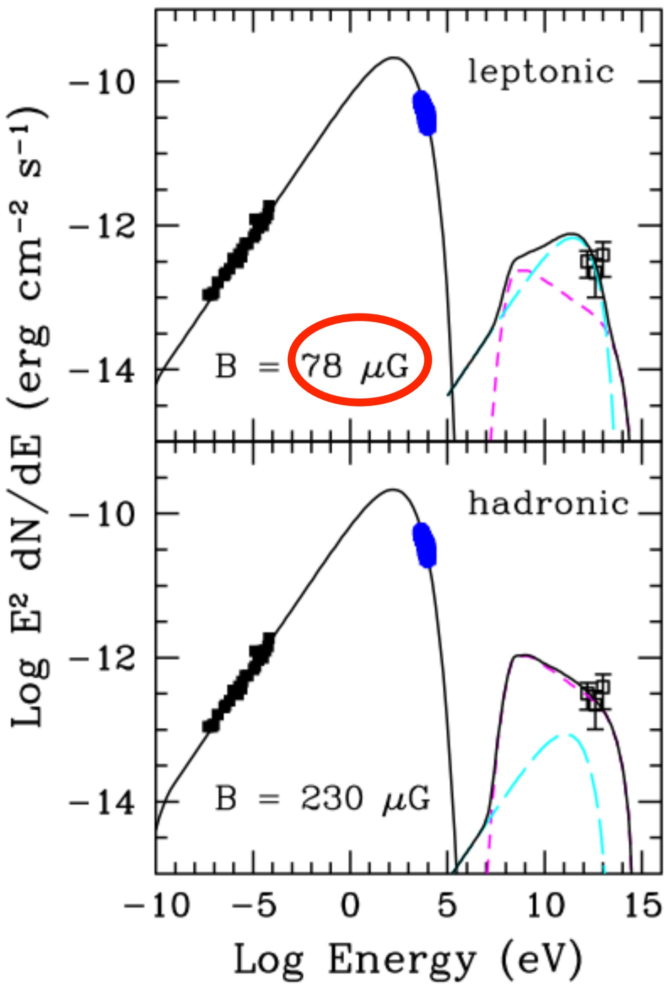
Cosmic Ray Accelerators: individuals



- known Type Ia SN, age = 439 y.
- X-ray filaments of non-thermal
  - → electron acceleration
- shell-like morphology
- northeastern ridge expanding at slower rate
  - → interaction with molecular cloud
- molecular cloud seen in HI and CO.
- one of the best contenders for hadronic accel.
- distance ~ 2.5 – 4.5 kpc

Cosmic Ray Accelerators: individuals

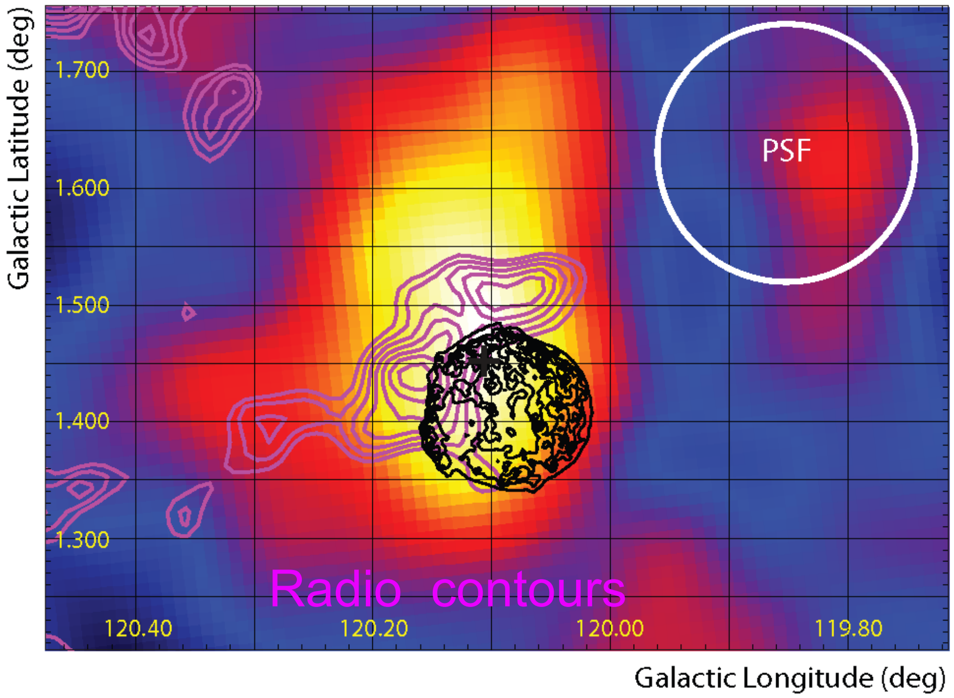
- Unveiling a hadronic accelerator?



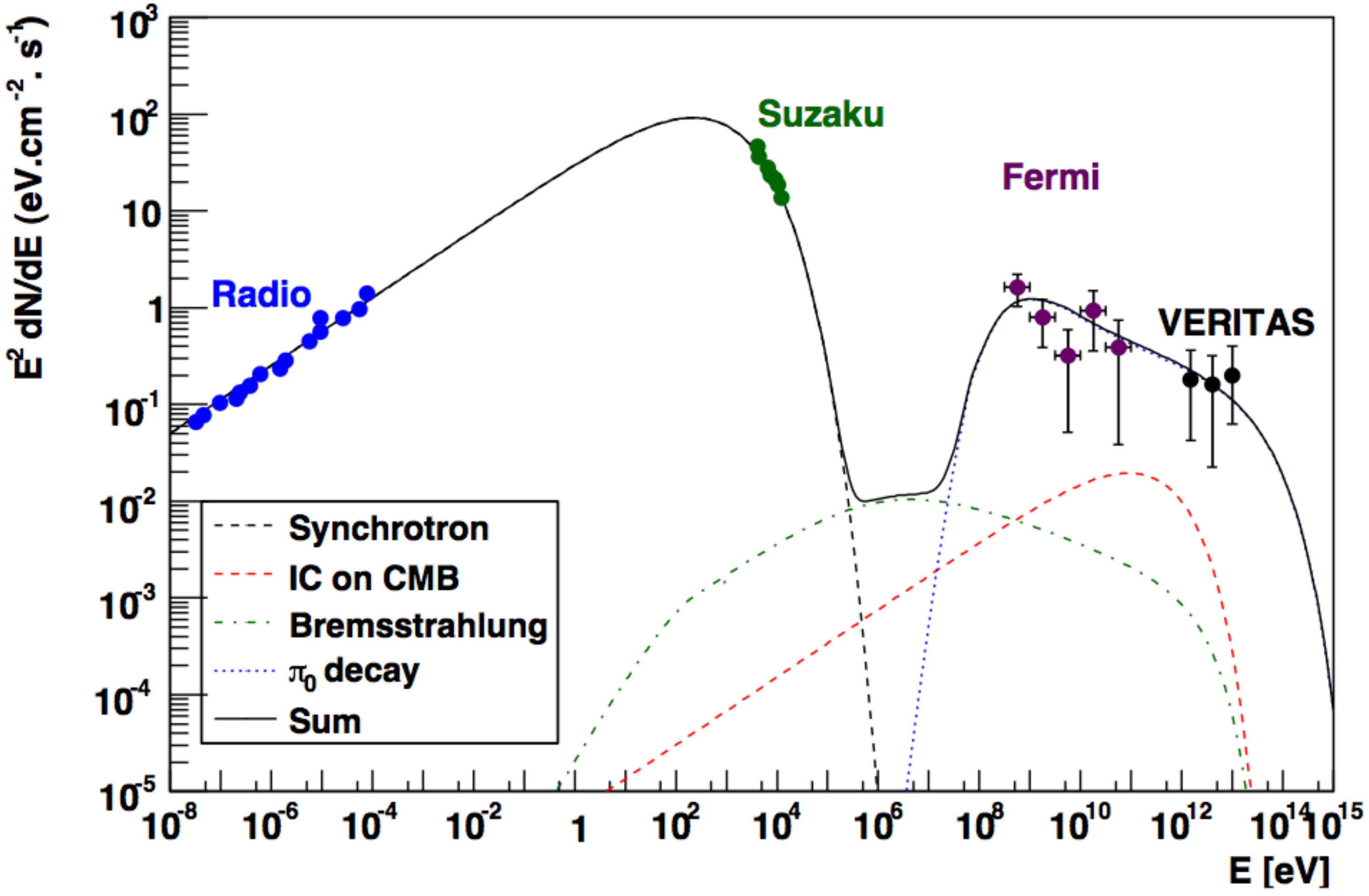
IC emission (CMB+synch.)

π decay

- energy spectrum hard.
- simple leptonic+hadronic model.
- radio/X-ray for normalization.
- IC(CMB) & pion decay.
- leptonic → 78 uG
- hadronic → 230 uG
  → **magnetic field amplification in shocks!**



Cosmic Ray Accelerators: individuals



Morlino & Caprioli, arXiv:1105:6342v1

Giordano et al., ApJL, 744, L2 (2012)

Conclusion:

- power law: 500 MeV – 5 TeV: “looks” hadronic?
- reduce statistical uncertainties with Fermi/VERITAS
- search for pion cutoff (difficult analysis)

Summary: Cosmic Ray Origin

- **Starburst galaxy spectra & fluxes compatible with predictions!**

  → proton calorimetry with objects of higher gas density

  → correlation analysis with a range of objects

  → extend spectra to ~ 100 TeV

- **SNRs as cosmic ray accelerators compatible with observations**

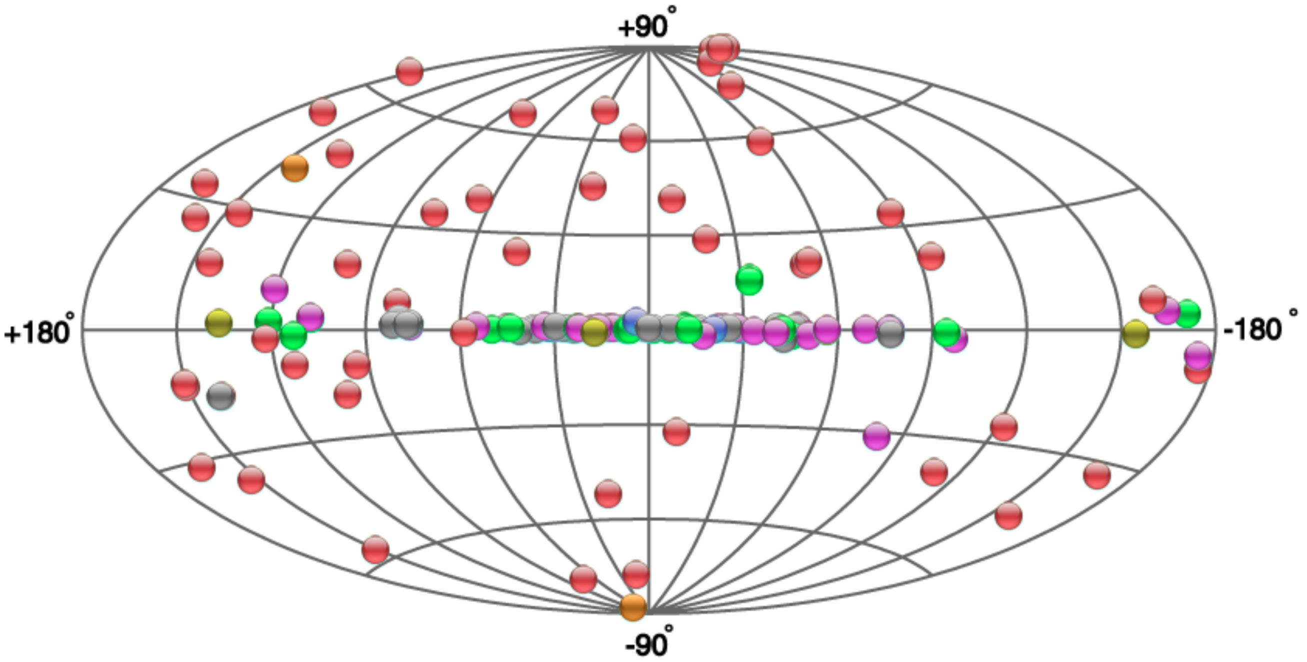
  → population studies of SNRs – efficiency of acceleration process

  → search for SNRs with spectra up to 100 TeV

  → high energy cutoffs related to age of SNR?

Cosmological Sources

TeV γ-ray Sky 2012



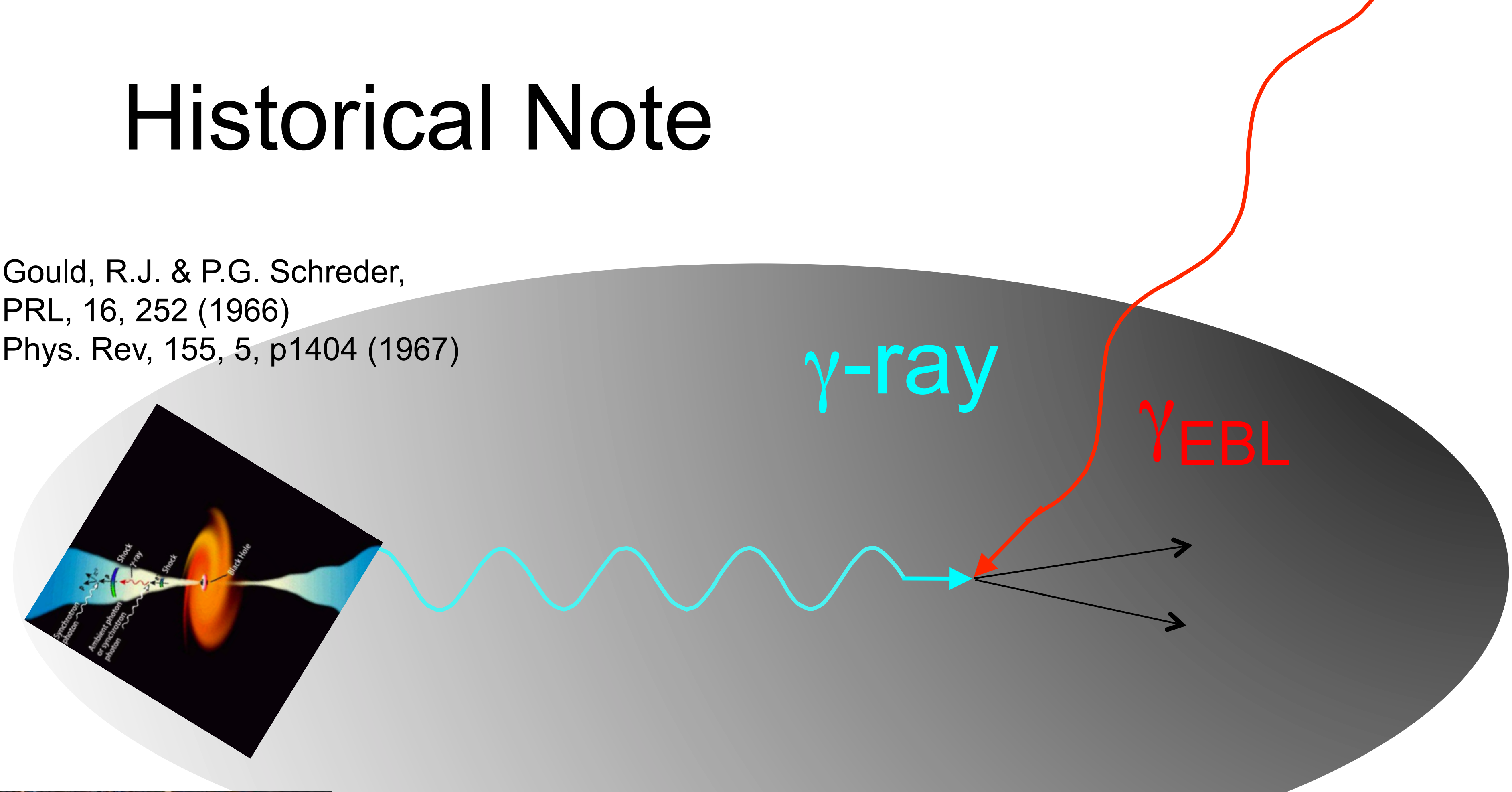
extragalactic sources

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
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

unexpected

Historical Note

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



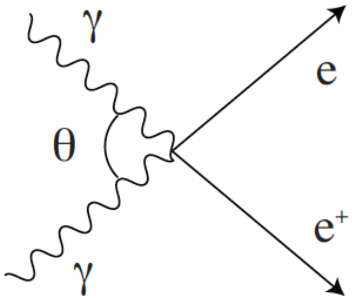
TeV emission from Blazar Mrk 421 Redshift z=0.03

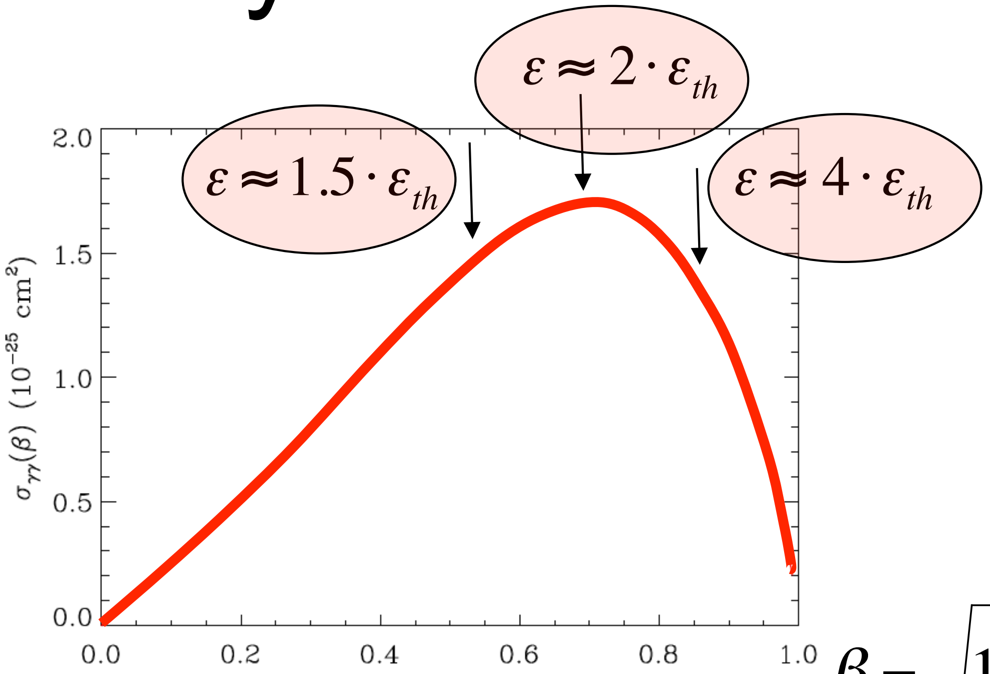
Punch, M. et al. (Whipple collaboration), Nature, 358, 477 (1992)

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

Whipple 10 m

γ-ray Absorption by the EBL





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

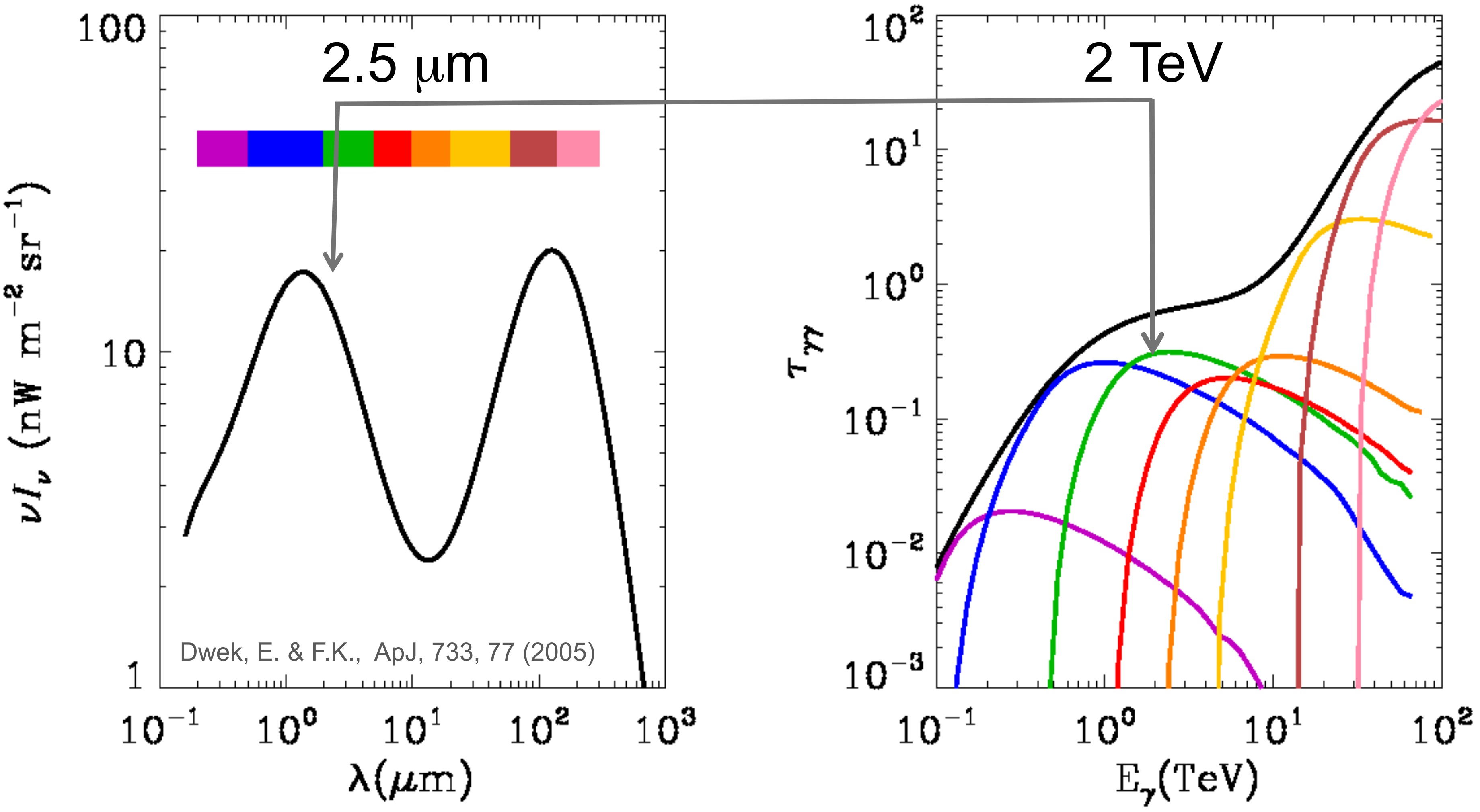
$$\varepsilon_{th}(E_\gamma, \mu, z) = \frac{2(m_e c^2)^2}{E_\gamma (1 - \cos\theta)}$$

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

- 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

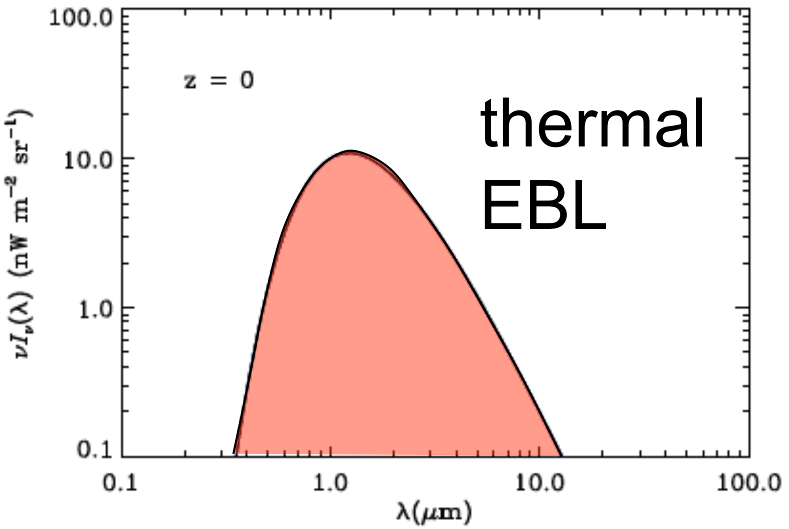


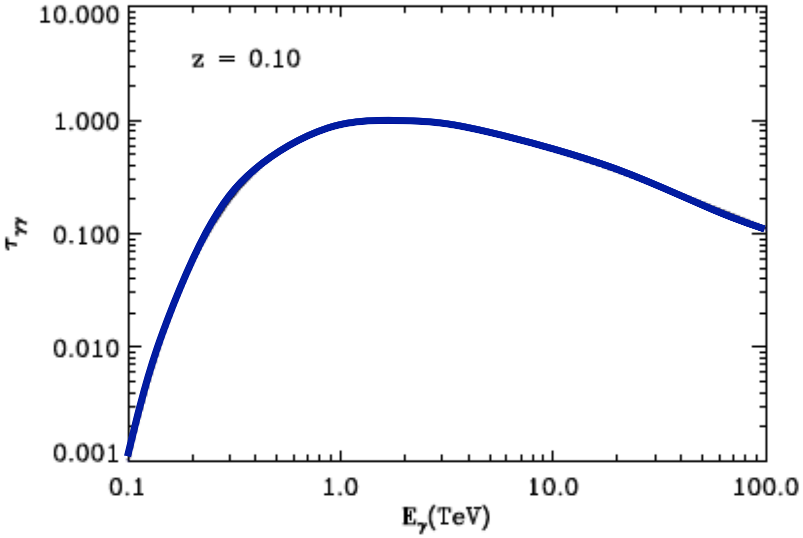
2.5 μm

2 TeV

Dwek, E. & F.K., ApJ, 733, 77 (2005)

γ-ray Absorption by the EBL

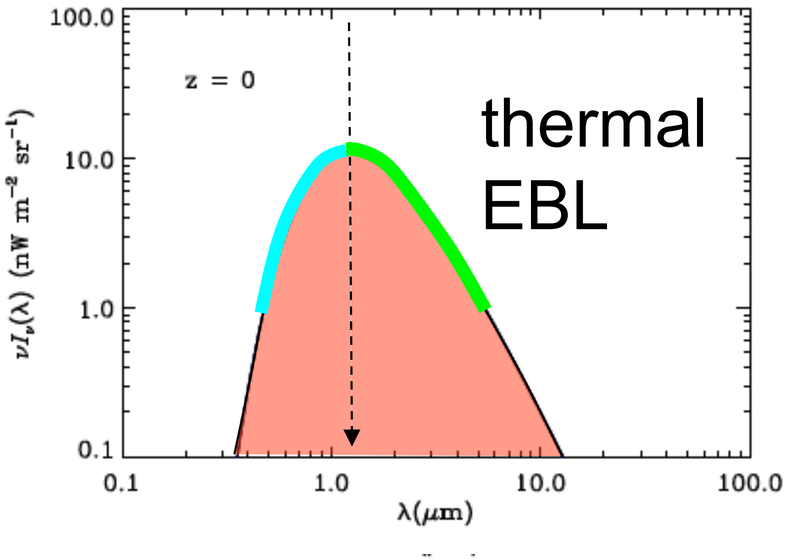




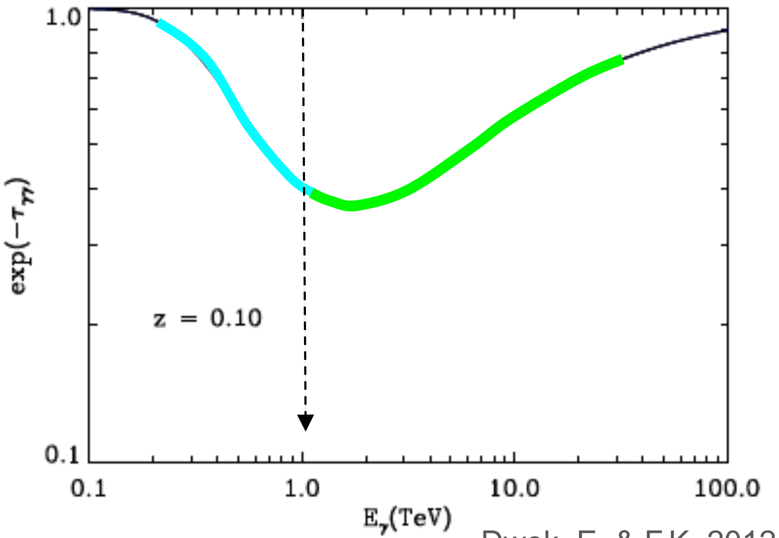
<u>Consider special case:</u>

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

γ-ray Absorption by the EBL

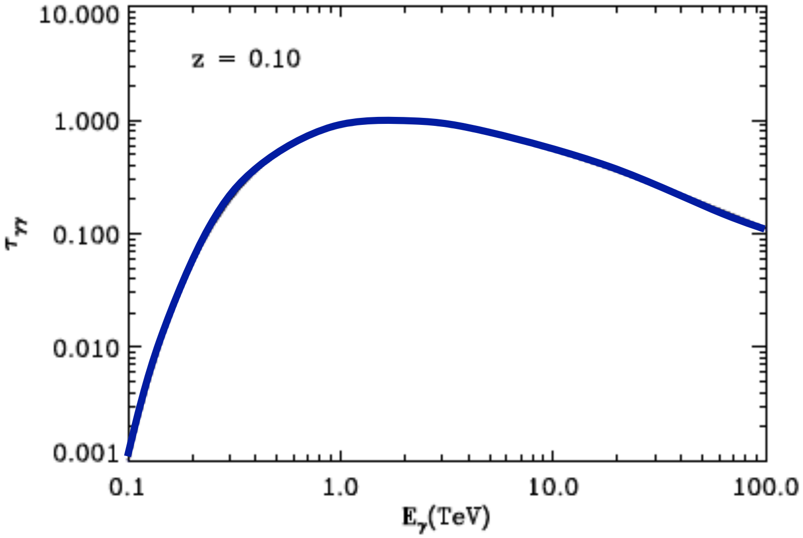


thermal
EBL



change in slope
at ~ 1 TeV

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



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

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

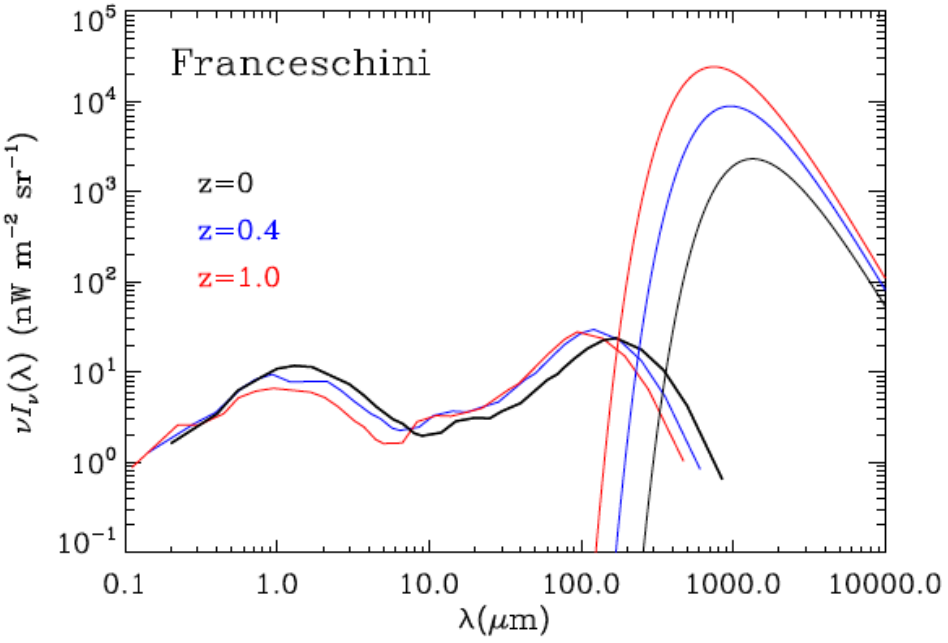
$$\Rightarrow \quad \frac{dN}{dE} \propto E^{-\Gamma} \cdot \exp(-\tau_{\gamma\gamma})$$

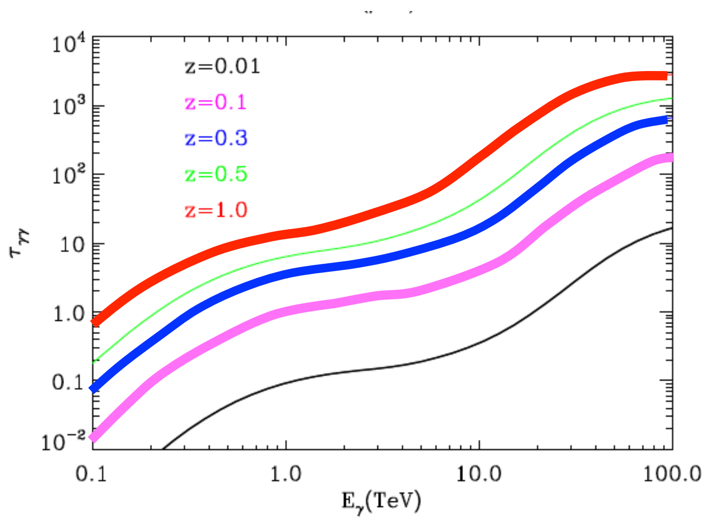
γ-ray Absorption by the EBL

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

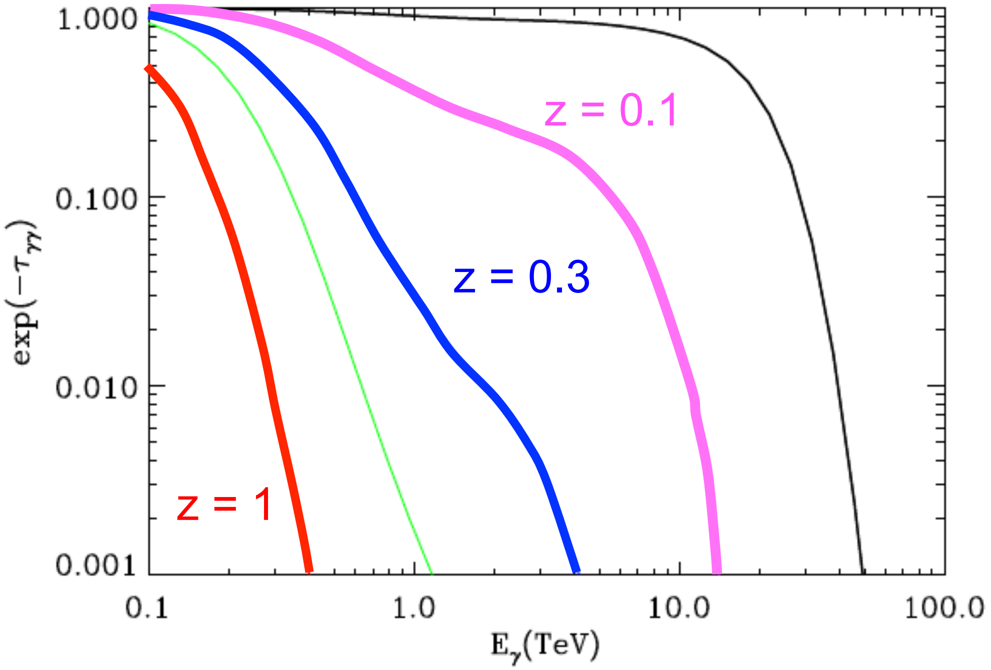
EBL model (Franceshini)

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

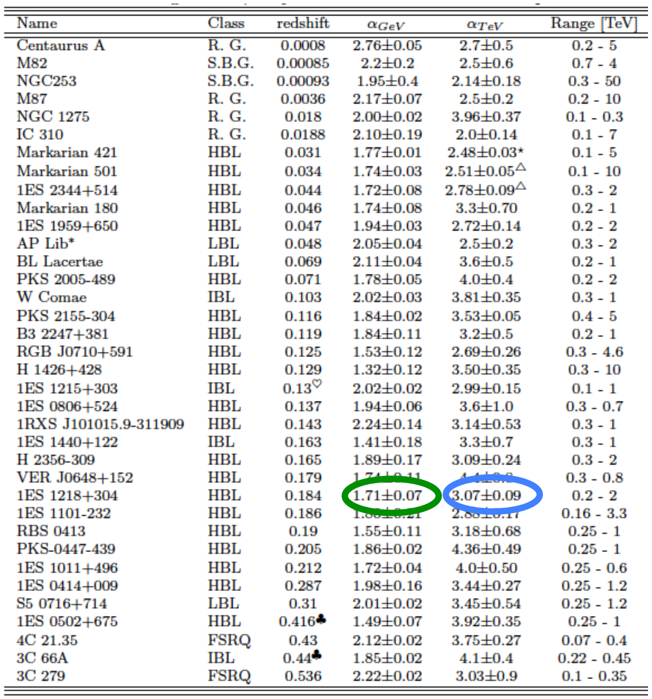




Dwek, E. & F.K. 2012, in preparation



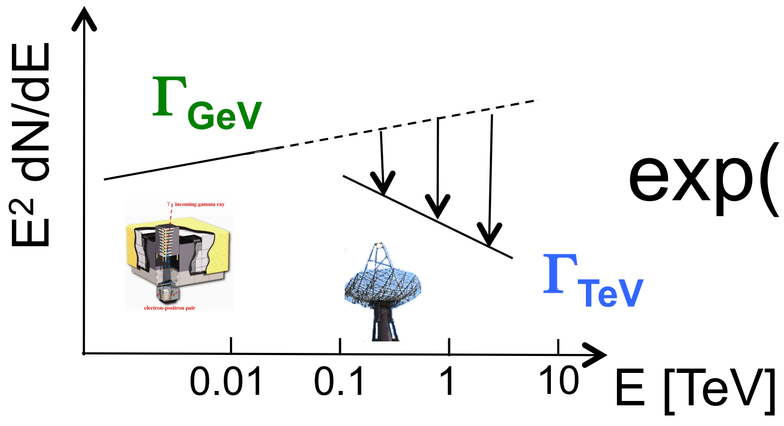
Sources for probing the EBL



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

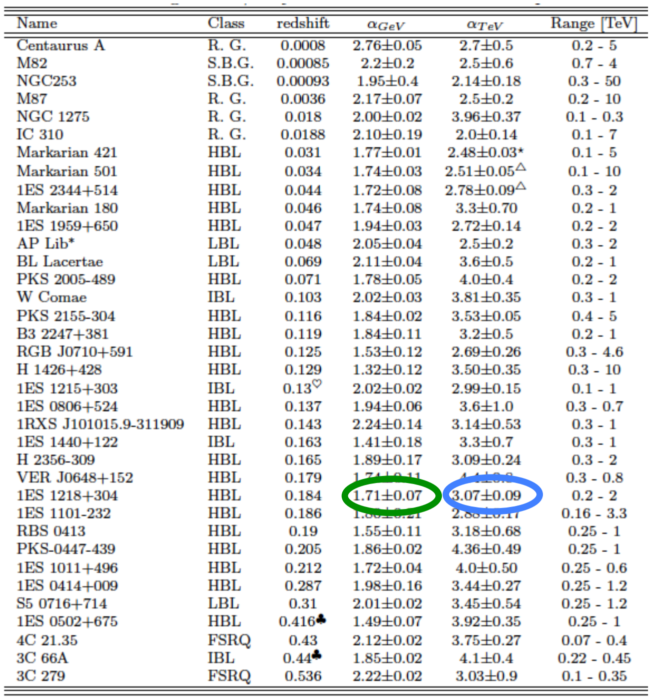
Do we see spectral softening (z)?

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



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$^{\triangle}$	0.1 - 10
1ES 2344+514	HBL	0.044	1.72±0.08	2.78±0.09$^{\triangle}$	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$^{\heartsuit}$	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
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1ES 0502+675	HBL	0.416$^{\clubsuit}$	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
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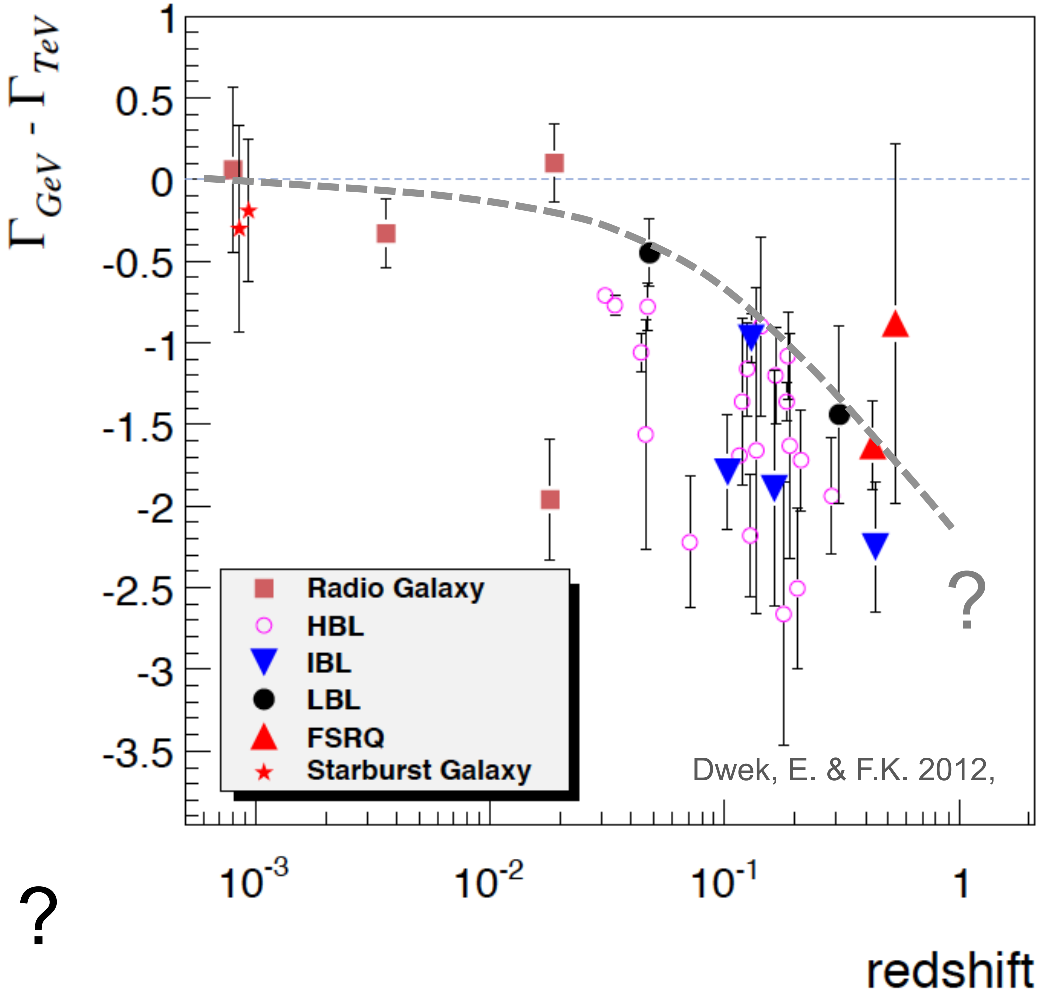
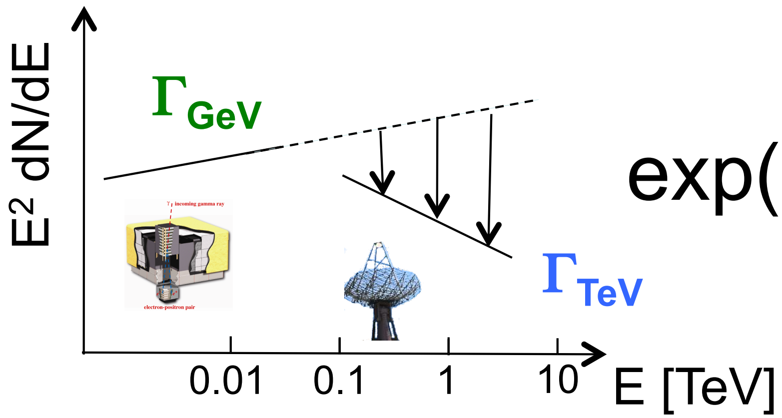
3C 279	FSRQ	0.536	2.22±0.02	3.03±0.9	0.1 - 0.35



Dwek, E. & F.K. 2012,

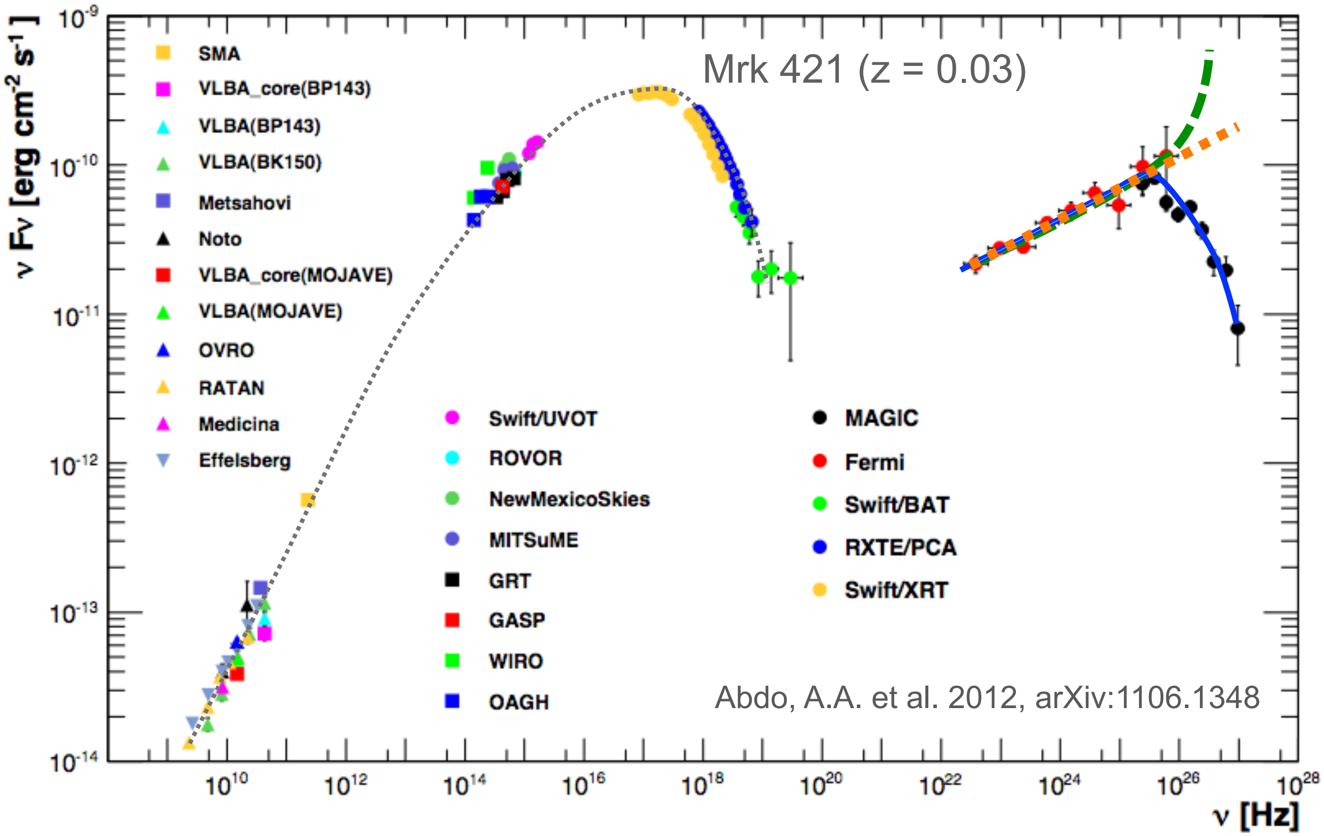


exp($-\tau_{\gamma\gamma}$) ?

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

Sources for probing the EBL

unphysical (no exp. rise!)



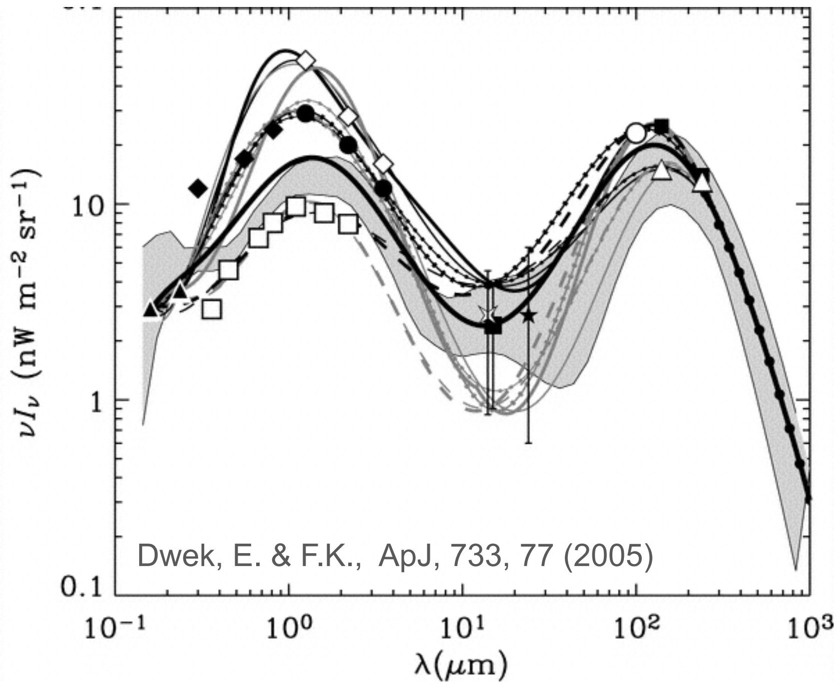
Abdo, A.A. et al. 2012, arXiv:1106.1348

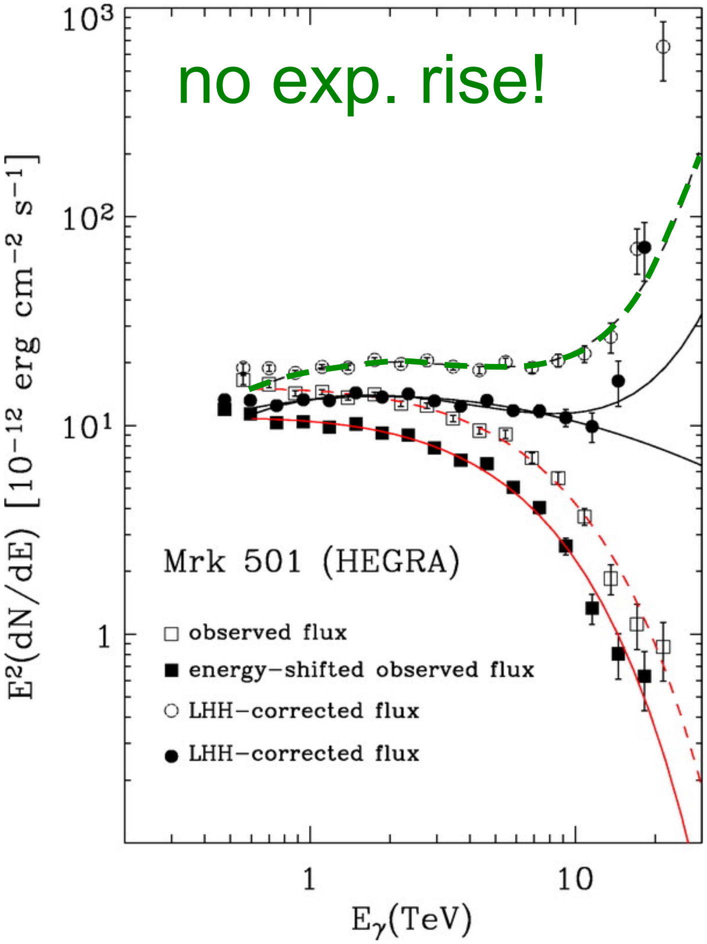
possible (if $\Gamma>1.5$)

measured

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

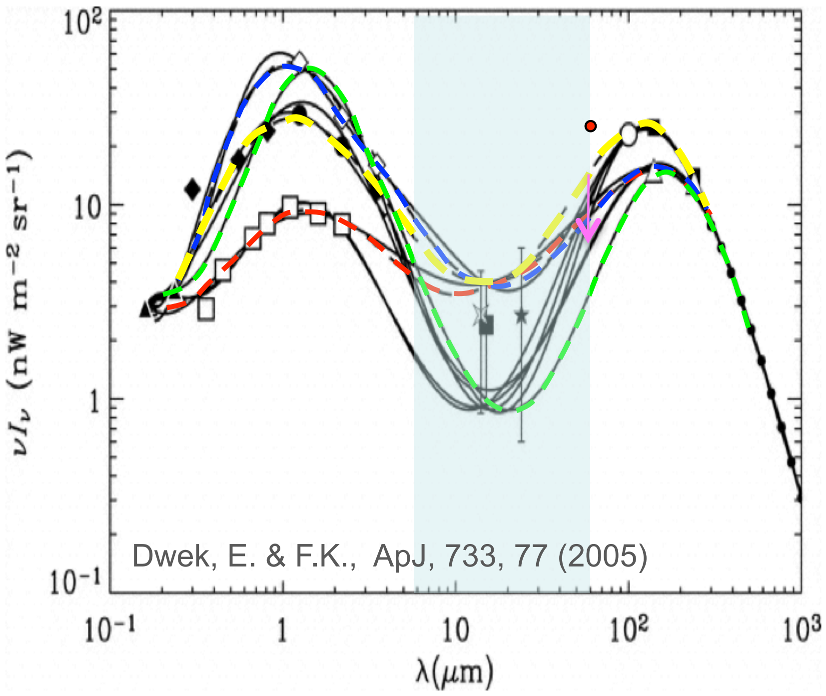
Methods I: no exponential rise!


Dwek, E. & F.K., ApJ, 733, 77 (2005)

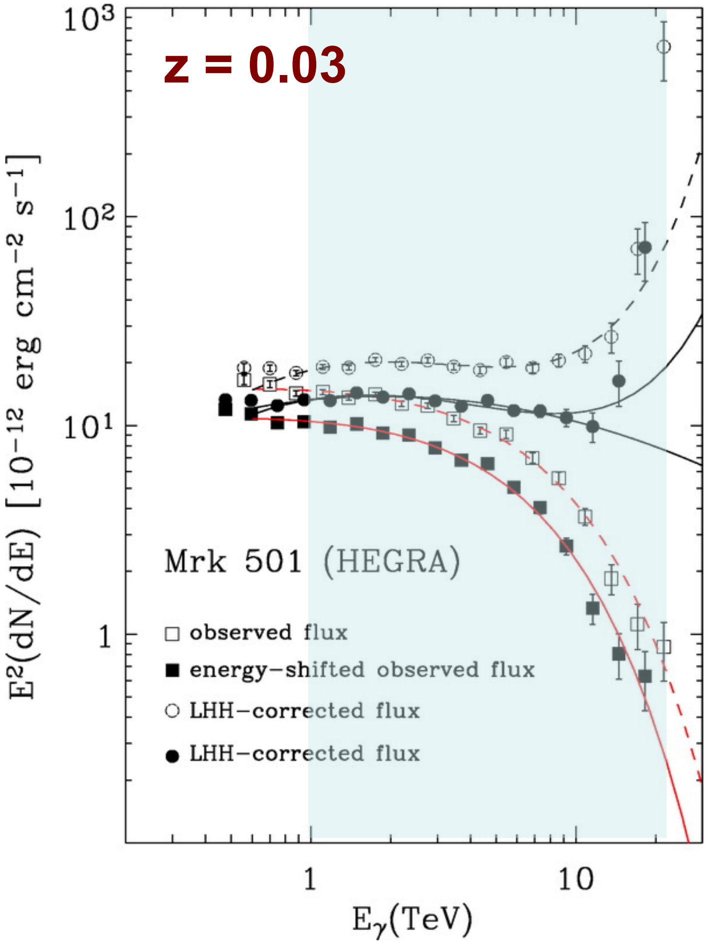

no exp. rise!

- 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!



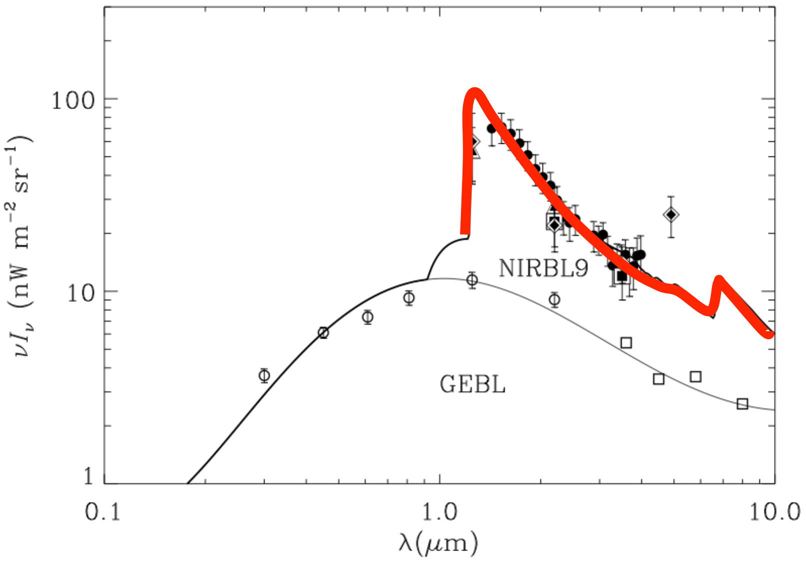
Dwek, E. & F.K., ApJ, 733, 77 (2005)

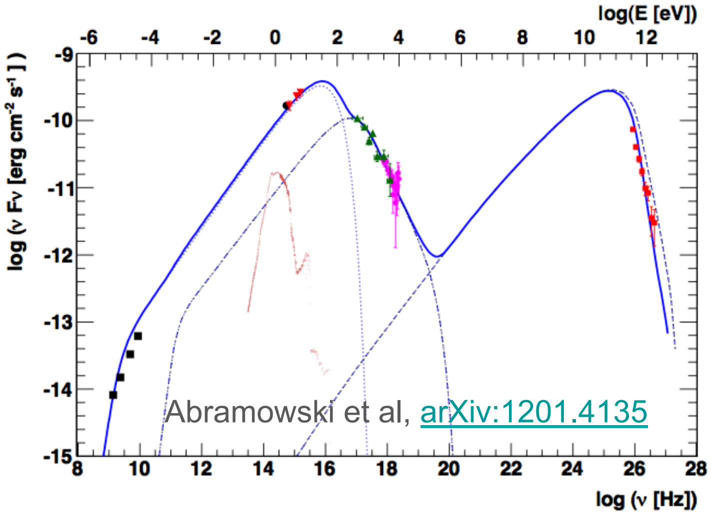


multi-TeV data sensitive to mid-IR

- 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**

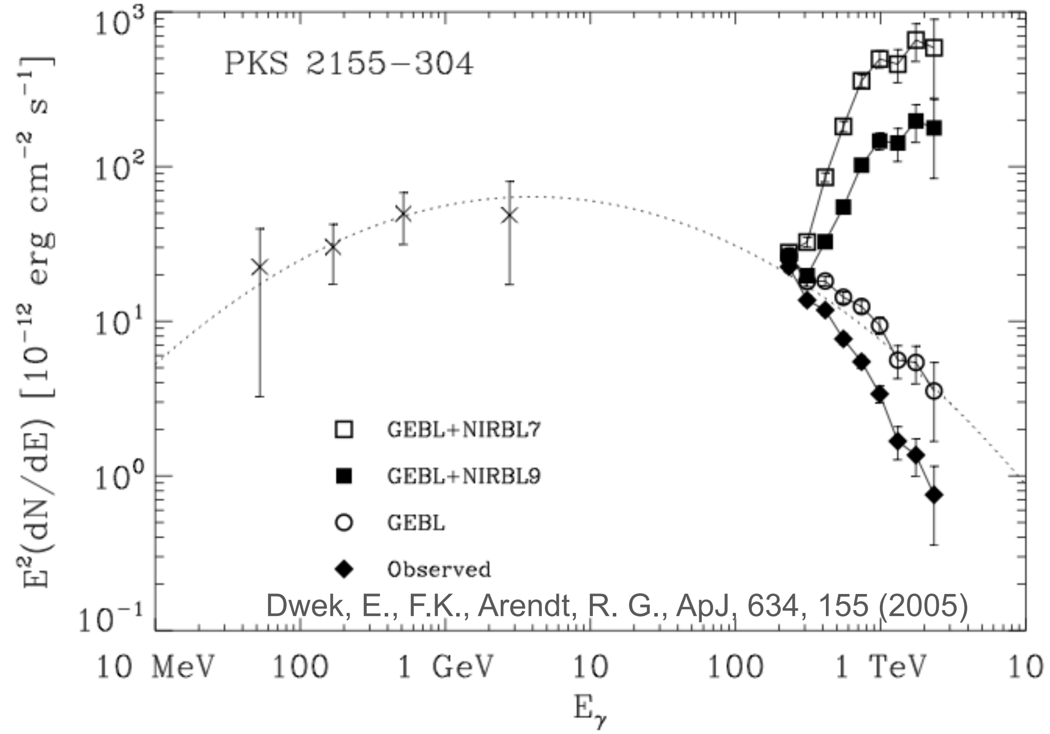
Methods I: no exponential rise!





Abramowski et al, arXiv:1201.4135

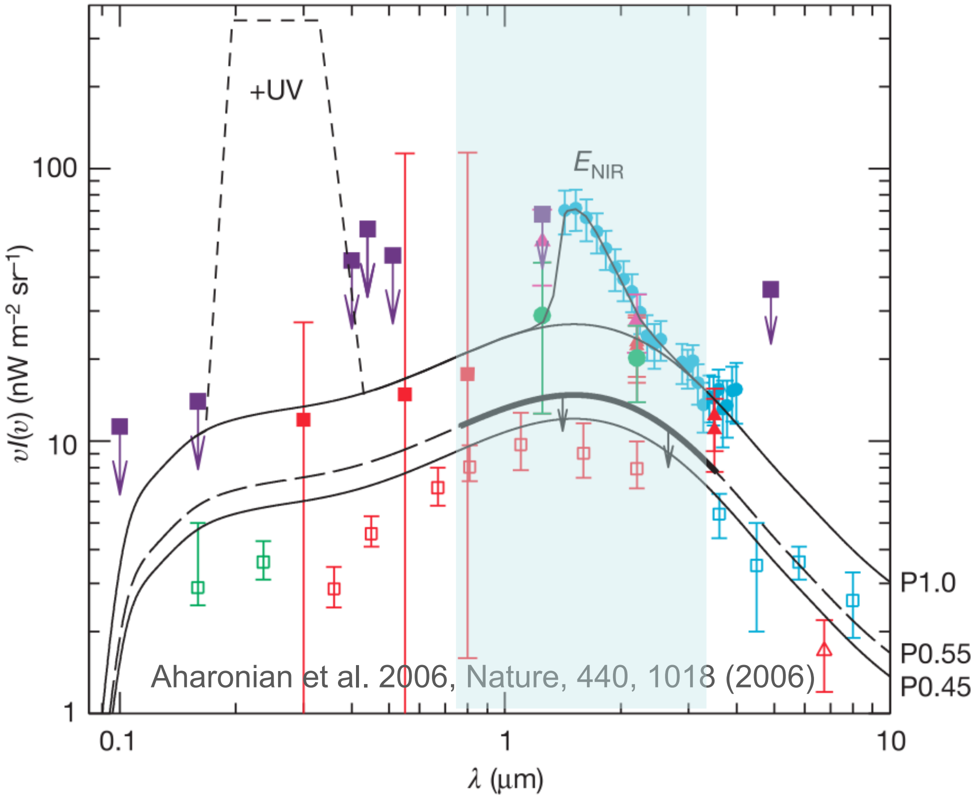
z = 0.116



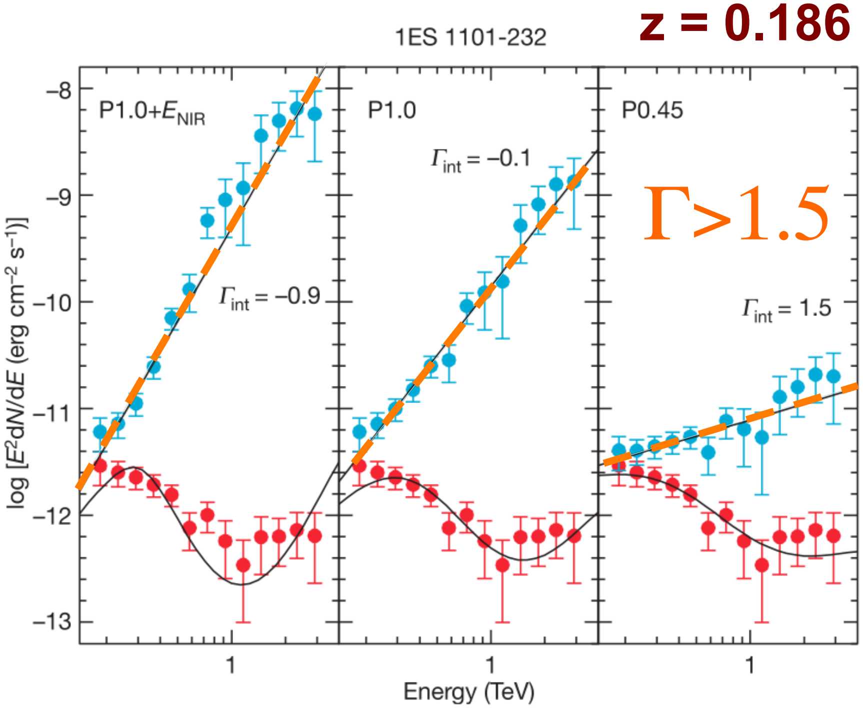
Dwek, E., F.K., Arendt, R. G., ApJ, 634, 155 (2005)

- excess near-IR background light (NIRBL): incompatible with "typical" blazar spectrum!
- constraint on large population III star contribution to EBL!

Method II: hardness limit Γ > 1.5



Aharonian et al. 2006, Nature, 440, 1018 (2006)



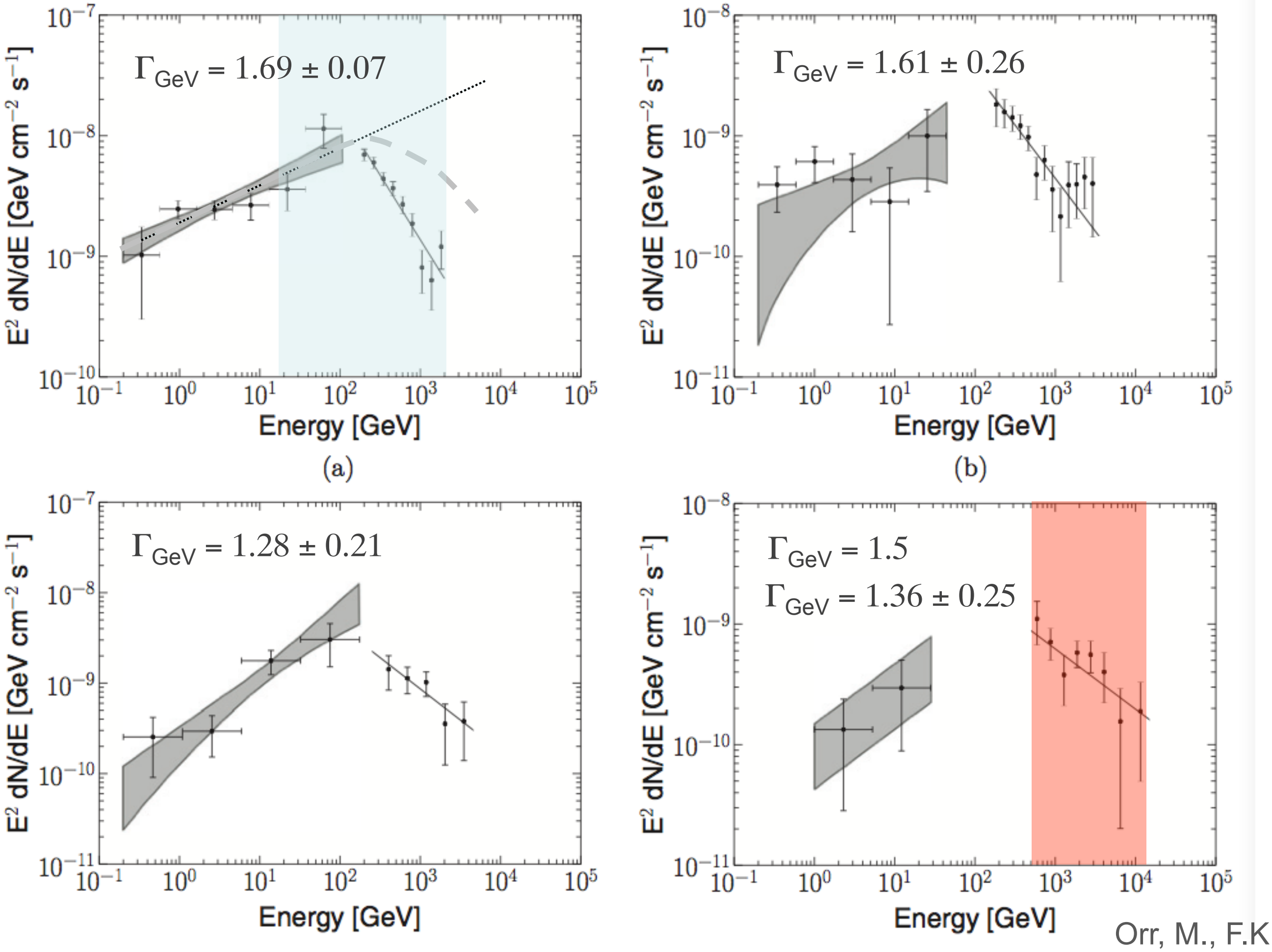
z = 0.186

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

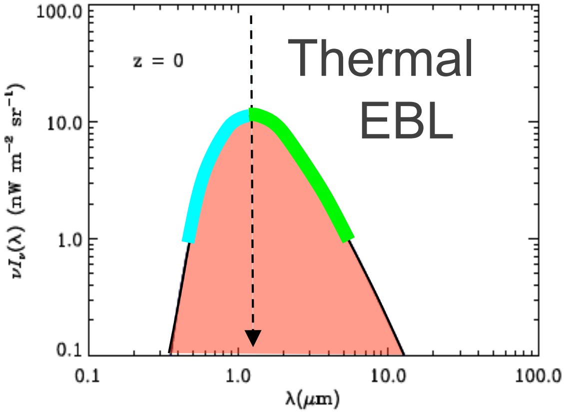
RGB J0710+591: z = 0.125

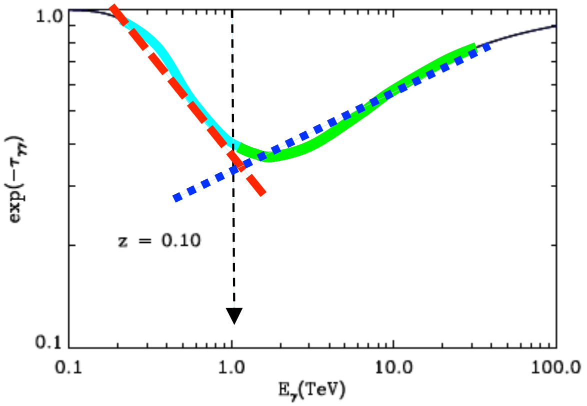
1ES 0229+200: z = 0.13

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

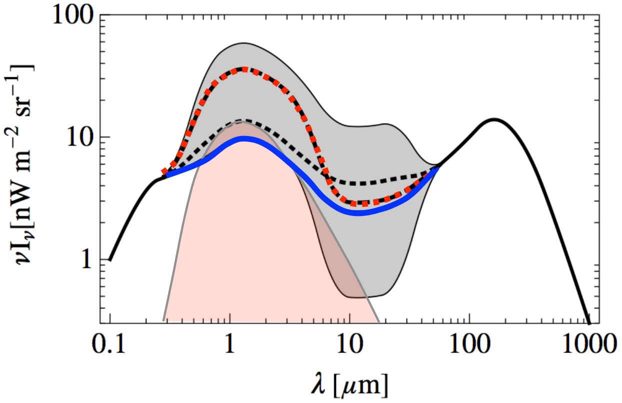
- simultaneous EBL constraints in near-IR & mid-IR
- requires distant sources (z ~ 0.1 – 0.3) with hard spectra
- Fermi spectral index used to set **upper limit in near-IR**
- use Fermi spectra combined with multi-TeV spectra

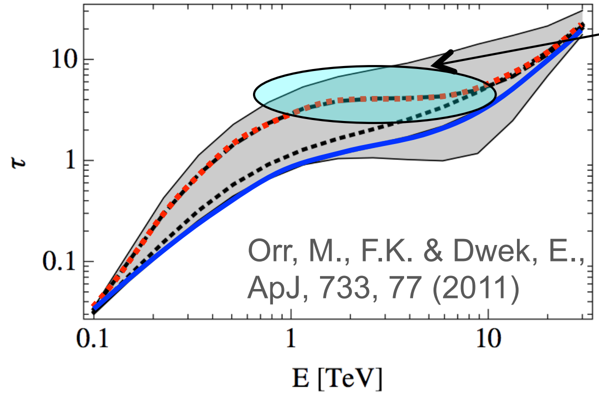
Method III, part II: 1 TeV break





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





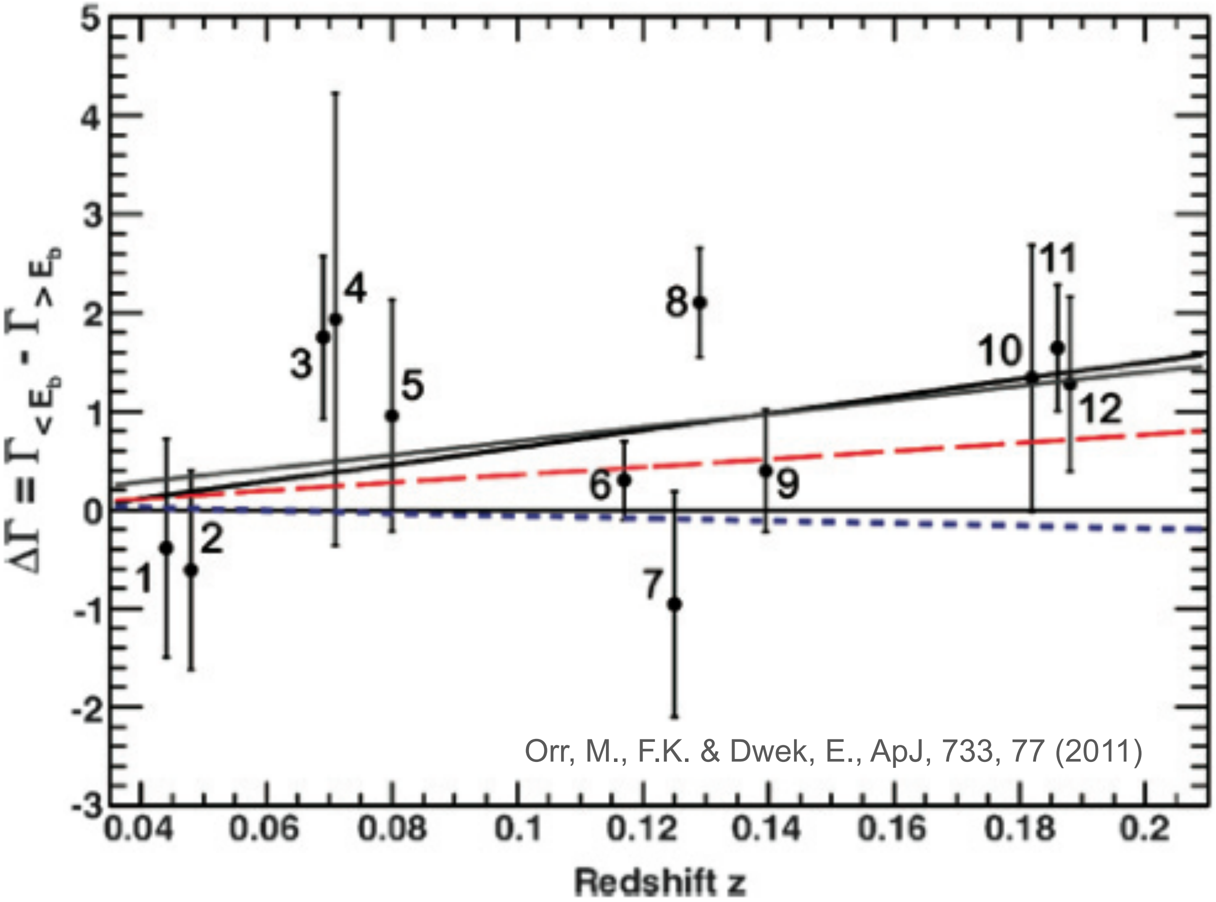
Orr, M., F.K. & Dwek, E., ApJ, 733, 77 (2011)

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

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

- 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

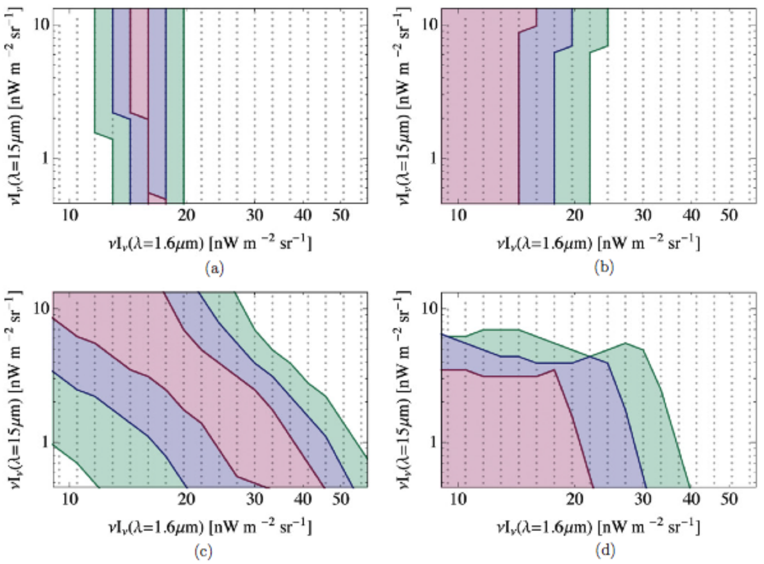
Method III, part II: 1 TeV break



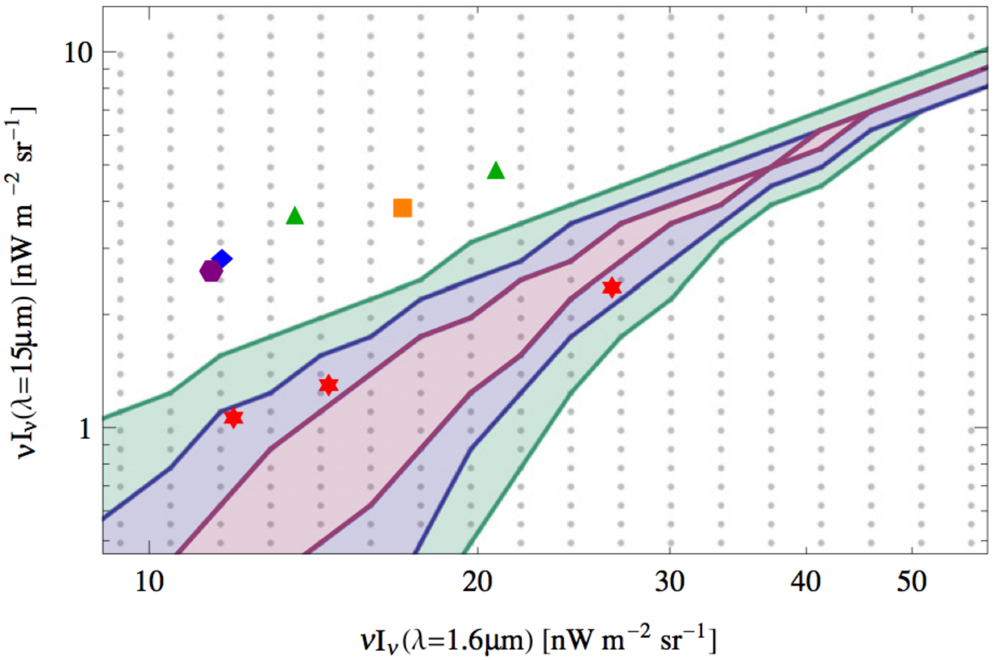
Orr, M., F.K. & Dwek, E., ApJ, 733, 77 (2011)

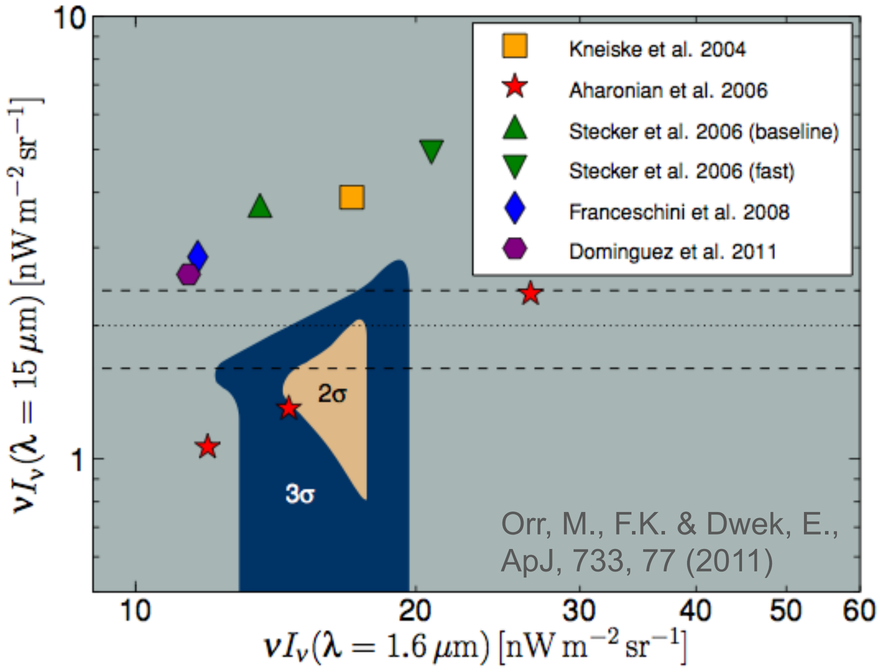
Source Name	Redshift	Γ_{LAT}	Γ_{VTS}	Method(s)	# Spec. Points l.t./g.t. E_{break}
1ES 2344+514	0.044	1.57 ± 0.17	2.95 ± 0.12	TeV Break	4 / 3
1ES 1959+650	0.047	2.10 ± 0.05	2.58 ± 0.18	TeV Break	4 / 2
PKS 0548-322	0.069	-	2.8 ± 0.3	TeV Break	3 / 2
PKS 2005-489	0.071	1.90 ± 0.06	4.0 ± 0.4	TeV Break	6 /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



(a) (b) (c) (d)

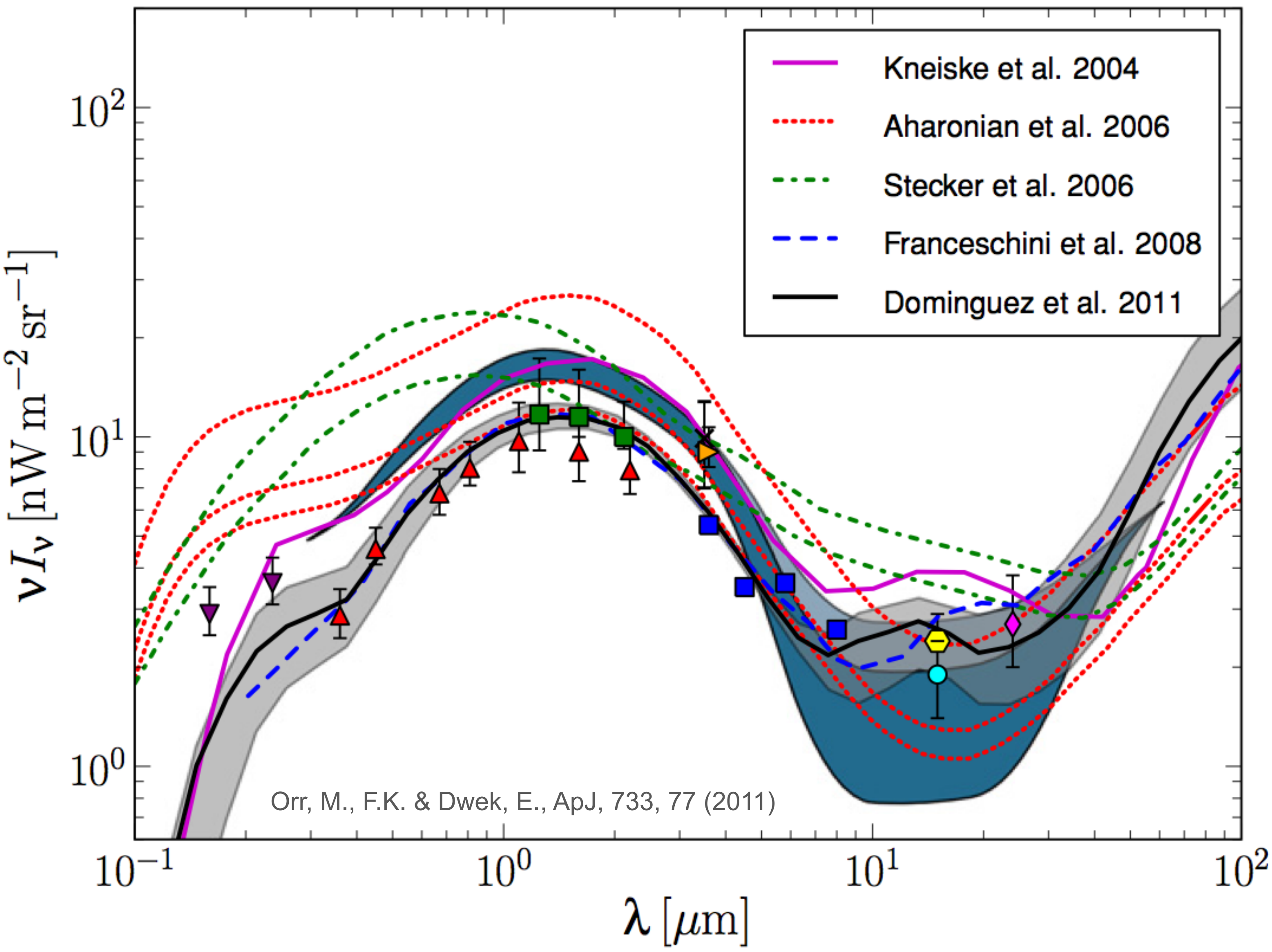




Orr, M., F.K. & Dwek, E.,
ApJ, 733, 77 (2011)

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

Method III:



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

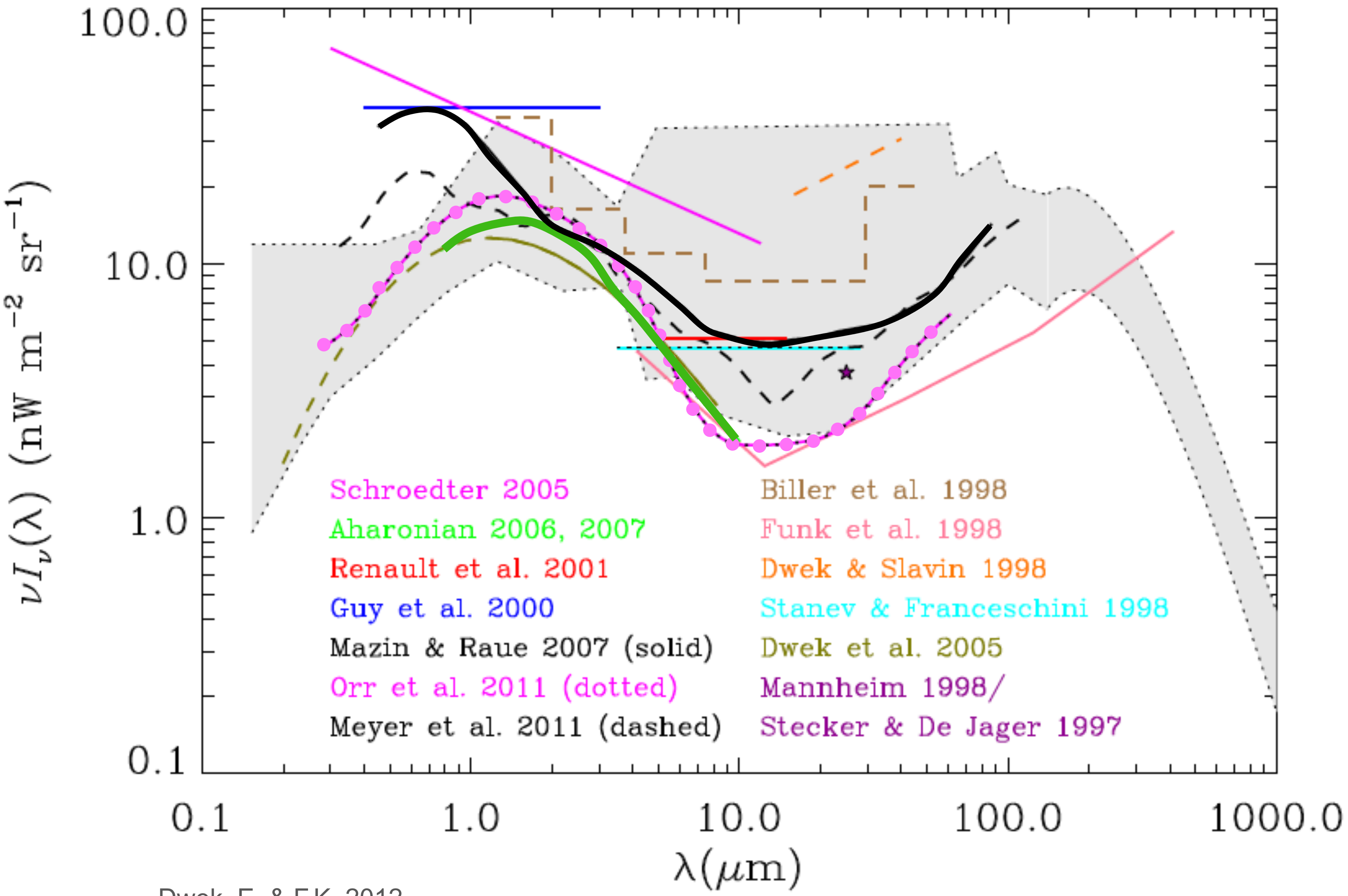
at 1.6 μm:

17 ± 0.3 nW/m^2/sr

at 15 μm:

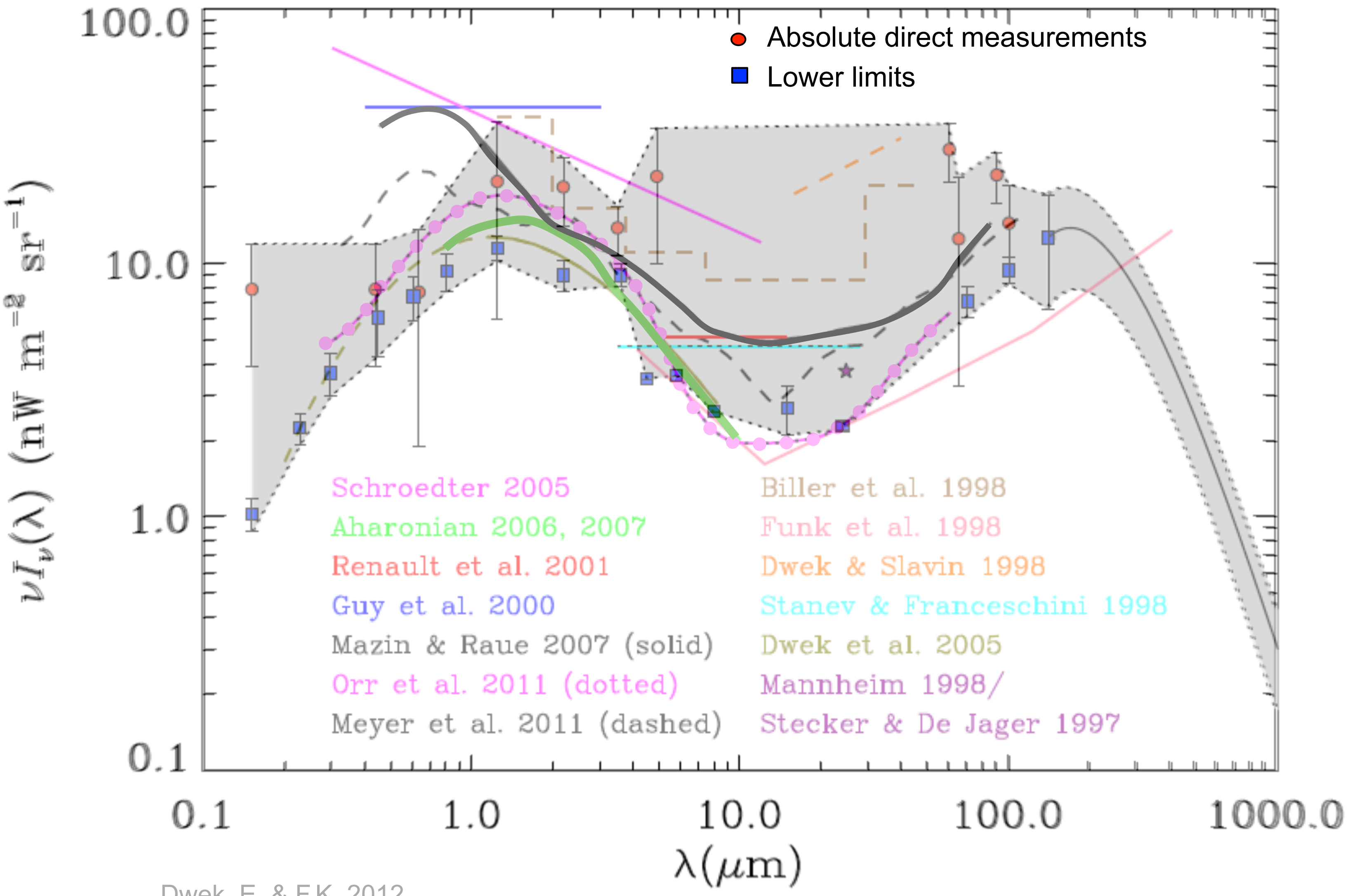
1.36 ± 0.58 nW/m^2/sr

Summary of EBL limits from γ-rays



Dwek, E. & F.K. 2012,

Summary of EBL limits from γ-rays



Dwek, E. & F.K. 2012,

EBL: Summary

- TeV γ-ray data provide strong constraints to the near-IR and mid-IR
- 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