Very High Energy Photons from Distant Blazars and the Potential for Cosmological Insight

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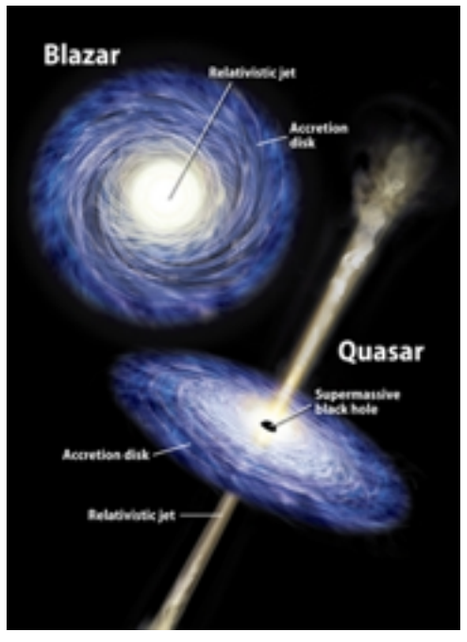
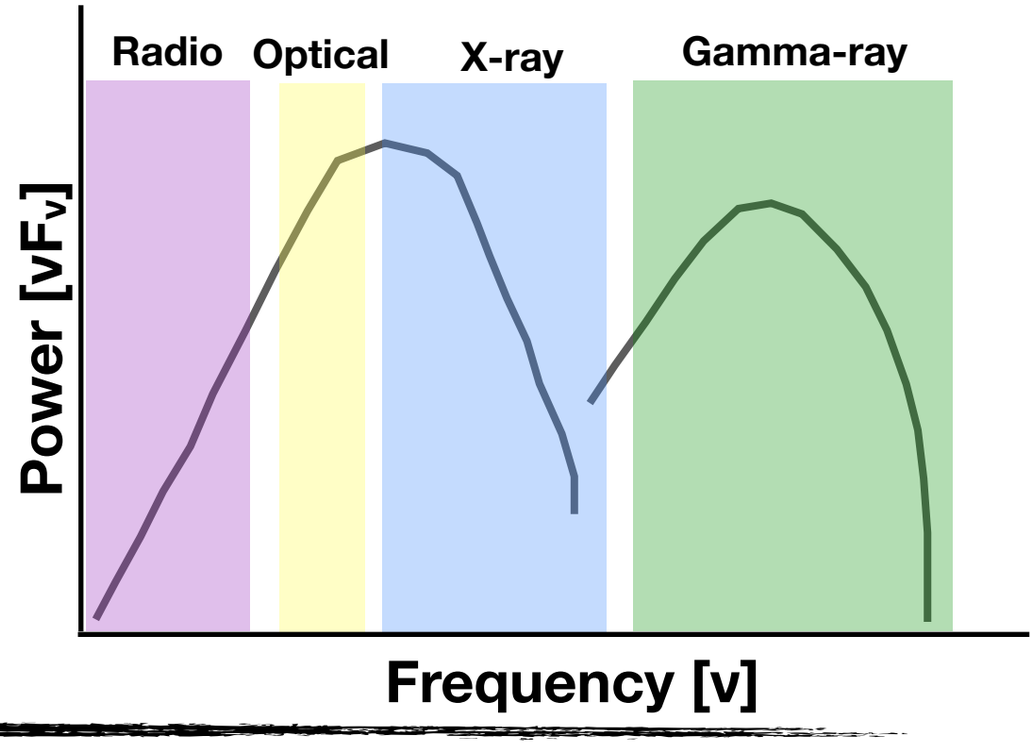
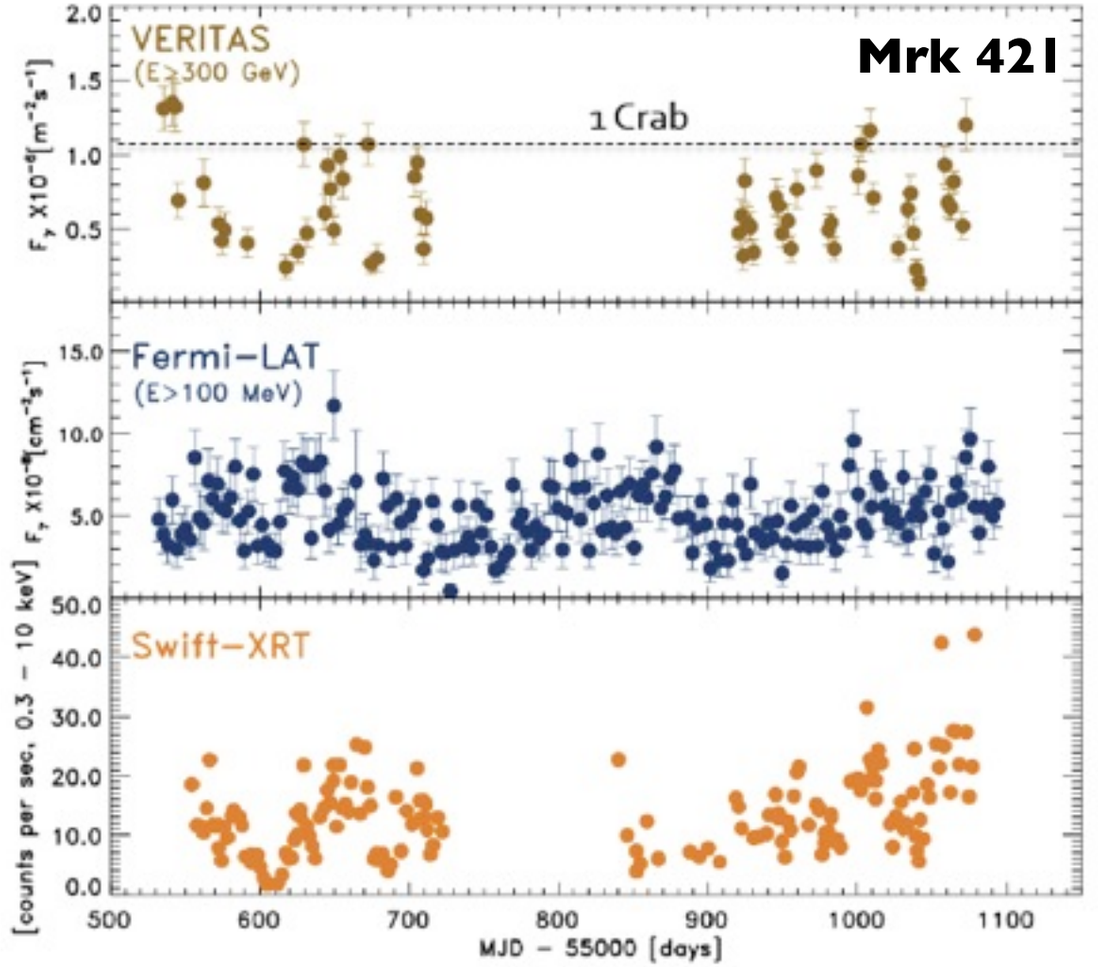
Blazars



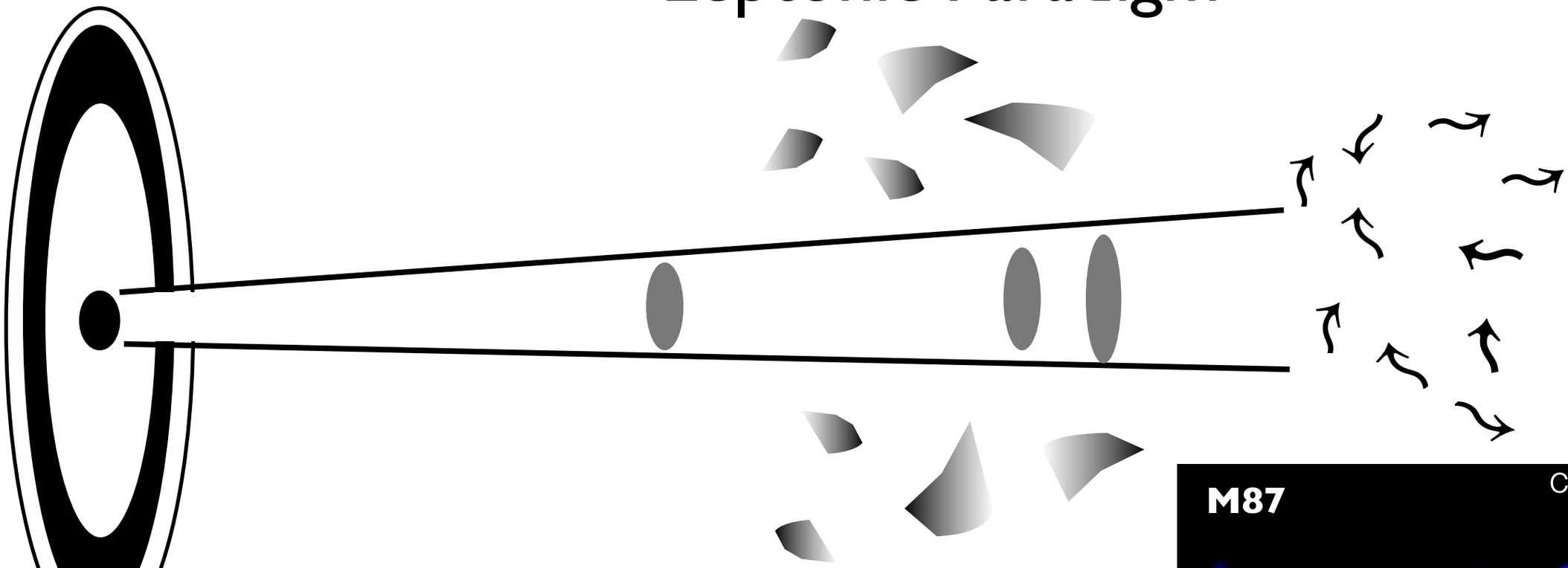


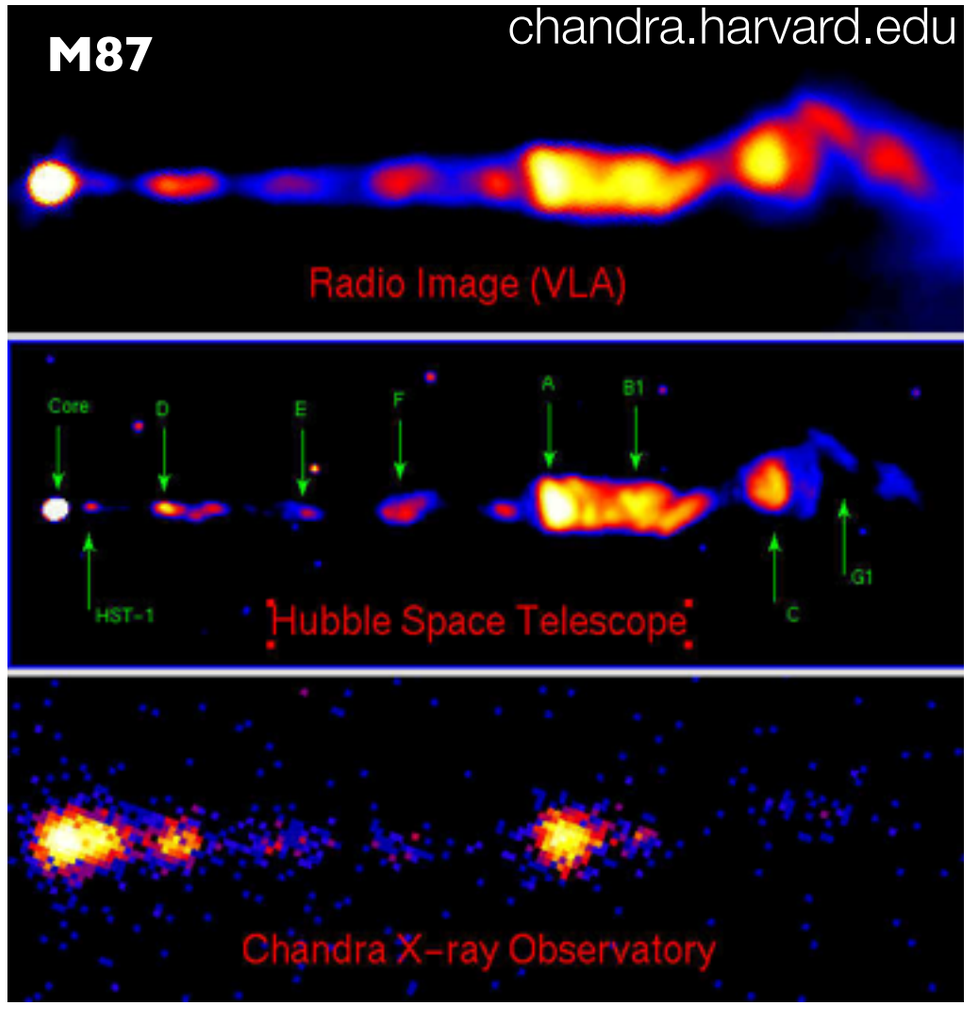
- Geometrically-selected set of jetted active galactic nuclei (AGN)
- Among the most energetic phenomena in the Universe
- Powered by supermassive black holes (~$10^9 M_\odot$)
- Beamed non-thermal emission
- Double-peaked broadband spectral energy distribution (SED)
- Variable in every band
- Variable at every timescale so far probed



The Origin of Non-Thermal Emission

Leptonic Paradigm





- Blob(s) of relativistic charged particles
- Origin of relativistic particles - turbulent magnetohydrodynamic shocks
  - Spectral limitation: $\Gamma > 1.5$ where $dN/dE \propto E^{-\Gamma}$
- Up-scattering of synchrotron and/or external photons
- Correlated synchrotron and gamma-ray peak variability

The Origin of Non-Thermal Emission

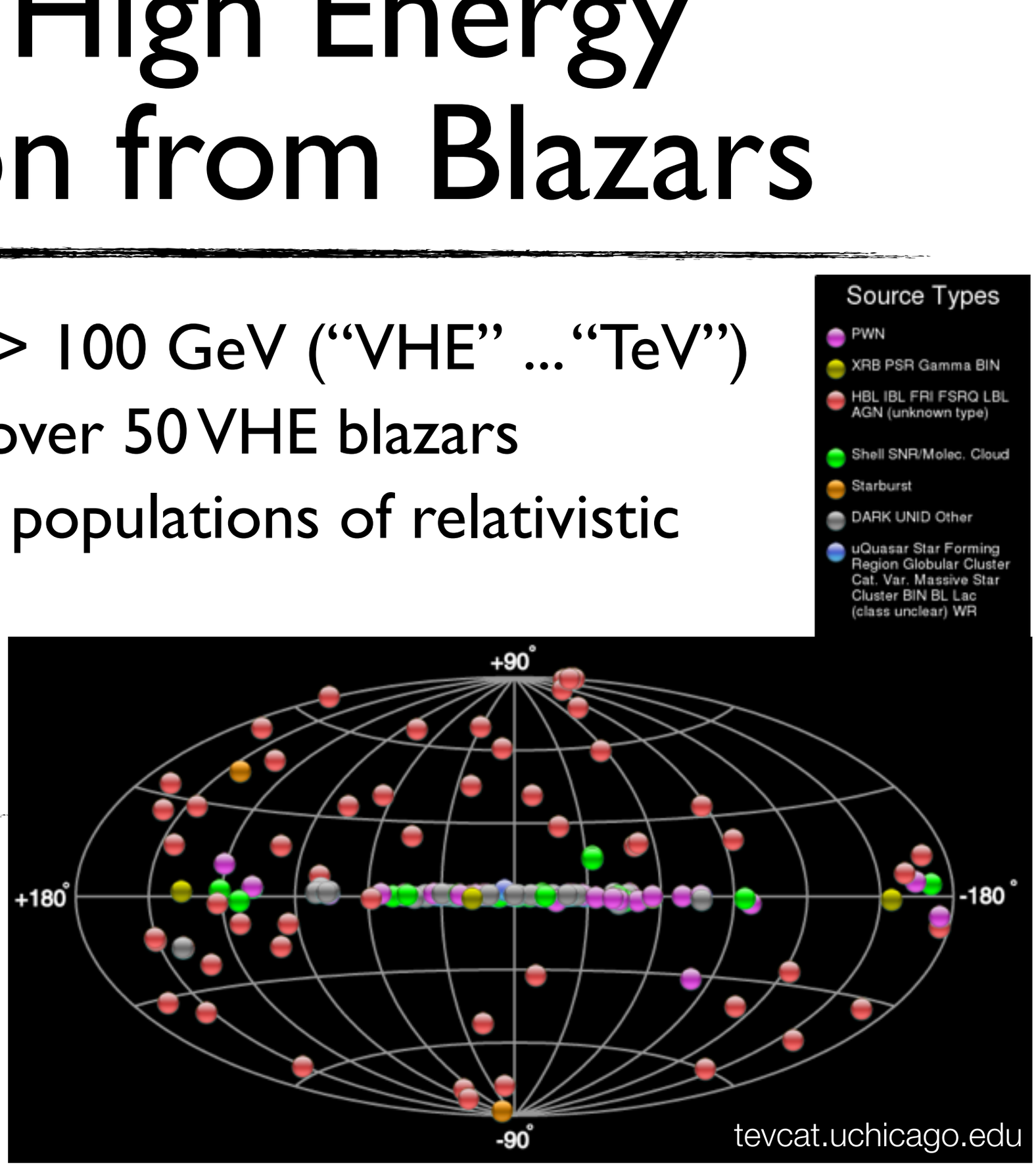
(Lepto-Hadronic Paradigm)

- Gamma-ray peak partial result of hadronic interactions and resulting cascade emission
  - $p+\gamma \rightarrow p' + e^+ + e^-$
  - $p+\gamma \rightarrow n+\pi^+$
  - $p+\gamma \rightarrow \Delta^{++}+\pi^-$
  - $p+\gamma \rightarrow \Delta^0\pi^+$
  - $p+p \rightarrow N+N+n_1(\pi^+ + \pi^-)+n_2(\pi^0)$
  - $\pi^\pm \rightarrow \mu^\pm + \nu_\mu$
  - $\pi^\pm \rightarrow e^\pm + \nu_e$
  - $\gamma+\gamma \rightarrow e^+ + e^- \rightarrow \gamma+\gamma \rightarrow e^+ + e^- \rightarrow \ldots$
- Uncorrelated synchrotron/gamma-ray peak variability
- Possible source of high energy cosmic rays
- Expected neutrino flux signature
- Introduces possibility for observation of non-intrinsic gamma-rays

Very High Energy Emission from Blazars

- Very high energy → > 100 GeV ("VHE" ..."TeV")
- Currently there are over 50 VHE blazars
- VHE emission traces populations of relativistic particles
  - Detections up to 10s of TeV
  - Range of VHE spectra ($1.5 < \Gamma < 5$)
  - Rapid variability (~min) timescales

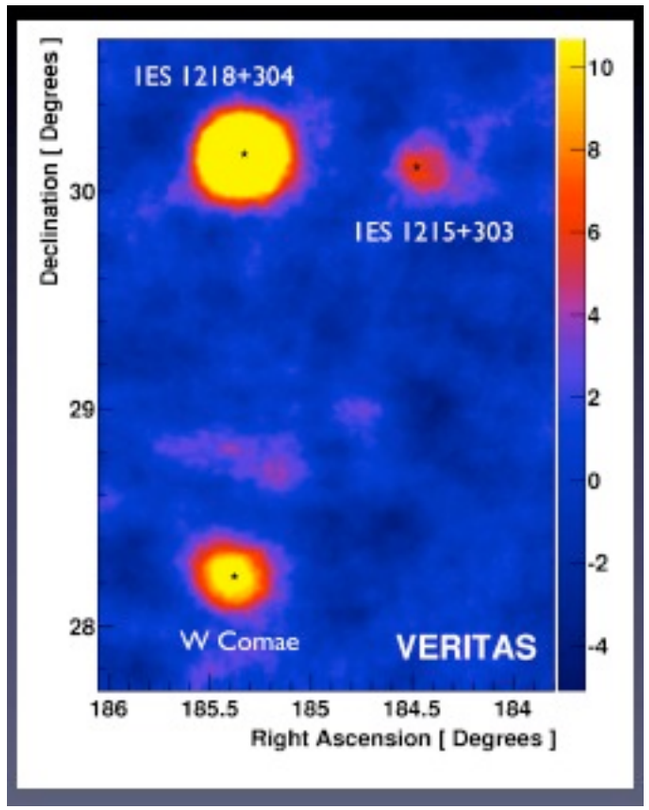
Understanding the origin of VHE emission from blazars enables other high impact research

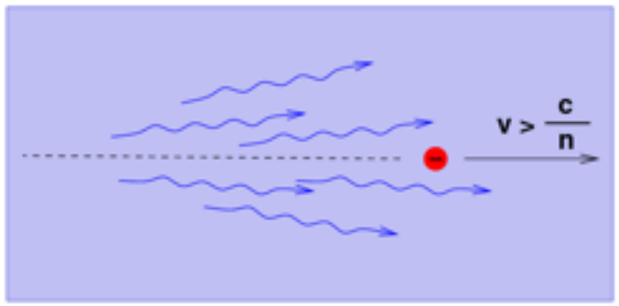


Expanding the VHE Blazar Catalog

Beyond a collection

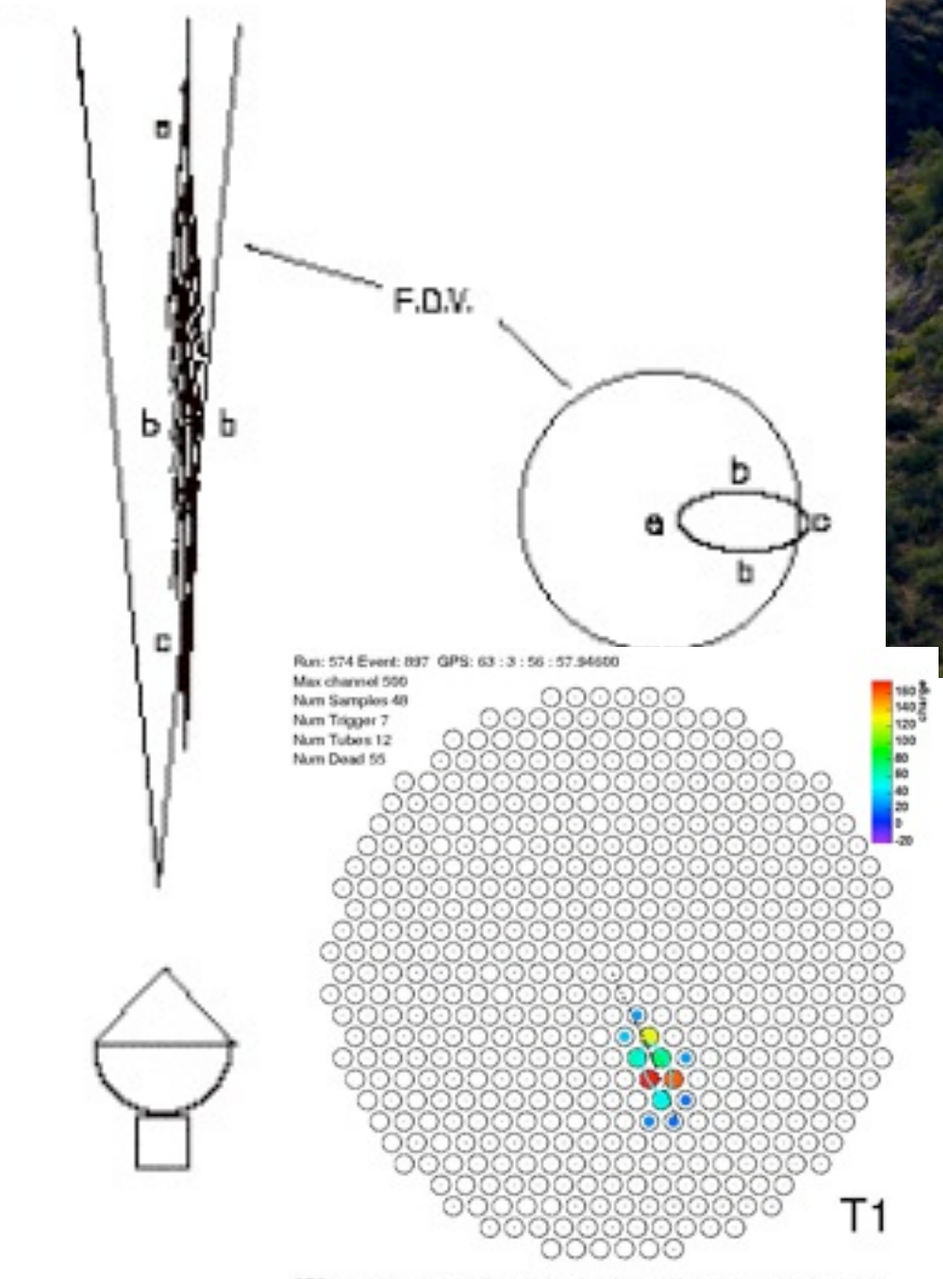
- Particle Physics and Fundamental Laws
  - Particle processes at the highest energies
  - Lorentz invariance
  - Origin of ultra high energy cosmic rays
- Cosmology
  - Extragalactic background light density
  - Magnitude of the intergalactic magnetic field
- Black holes
  - Supermassive black holes
  - Jet physics
  - Evolution
  - Environment





VERITAS

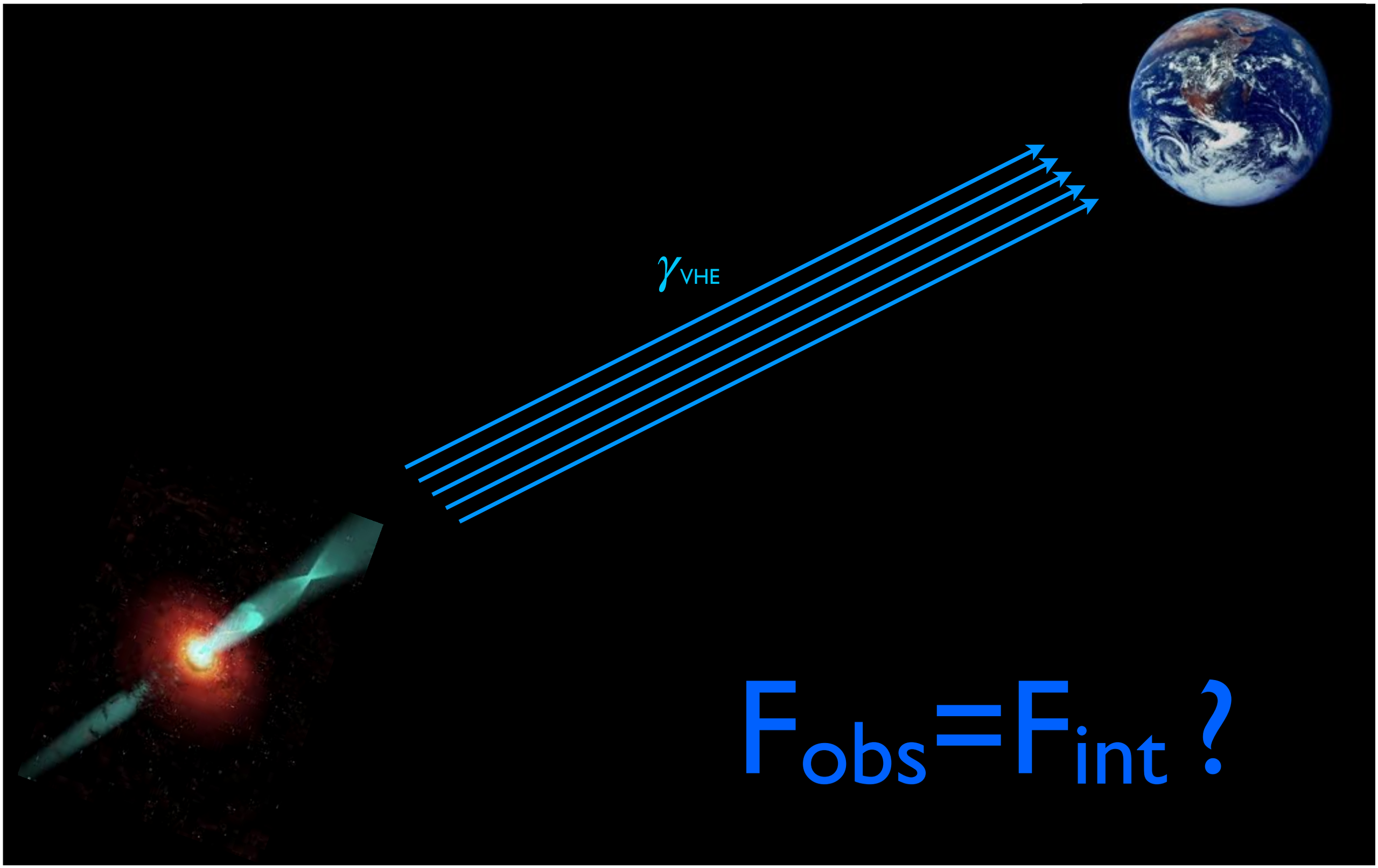
Very High Energy
γ_E>100 GeV



- **~70 GeV - 30 TeV**
- **15–20% energy resolution**
- **0.1° angular resolution**
- **Detect 1% Crab in < 30 hrs**
- **Upgrade complete: trigger (2011) and camera (2012)**

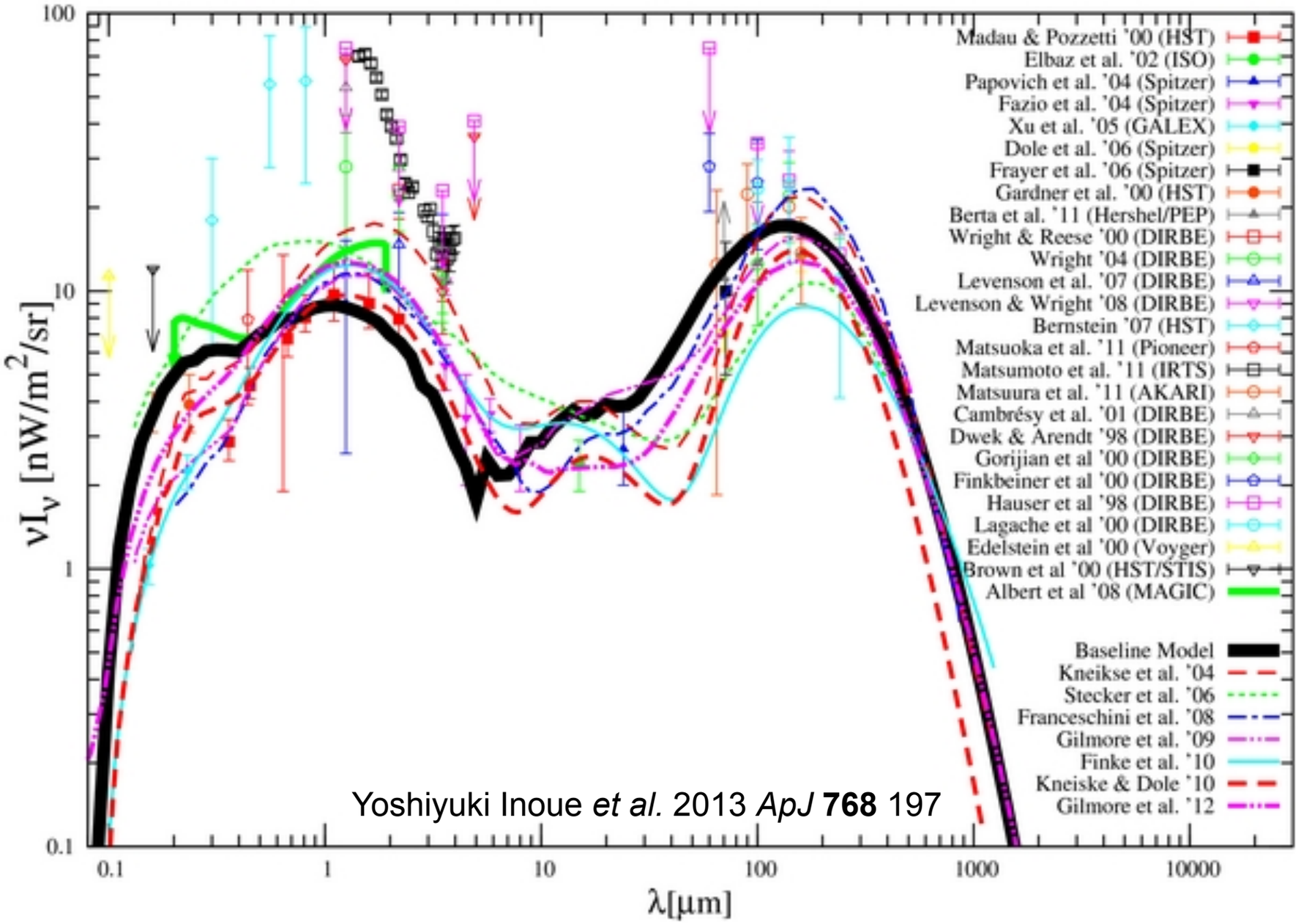
Extragalactic VHE Photons

Going the distance....

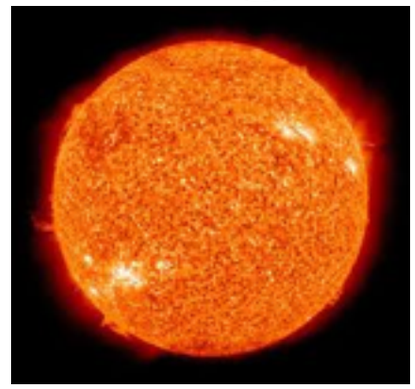


Extragalactic Background Light

The sum of the emitted and reprocessed starlight since the beginning of the Universe

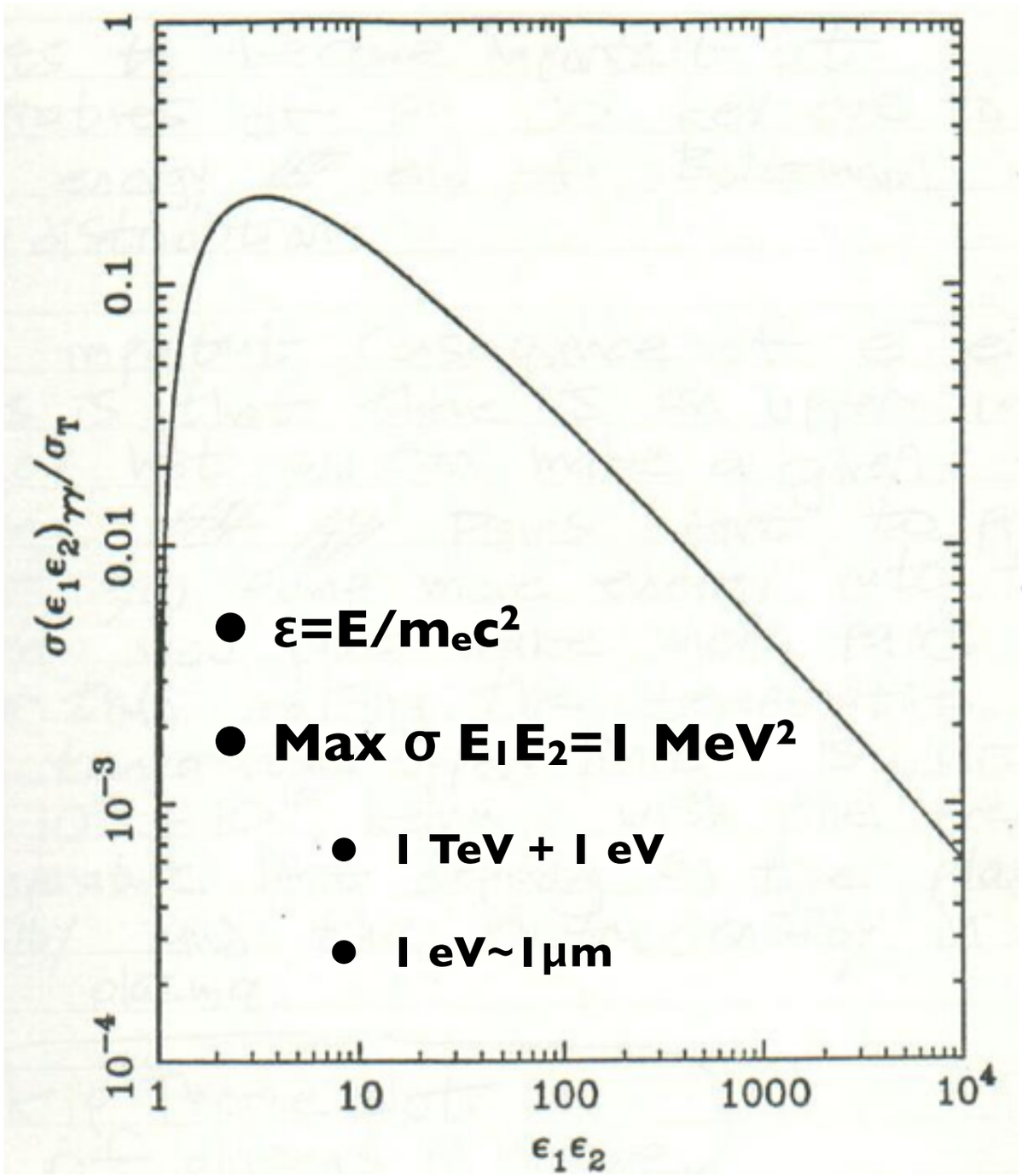


Yoshiyuki Inoue *et al.* 2013 *ApJ* **768** 197

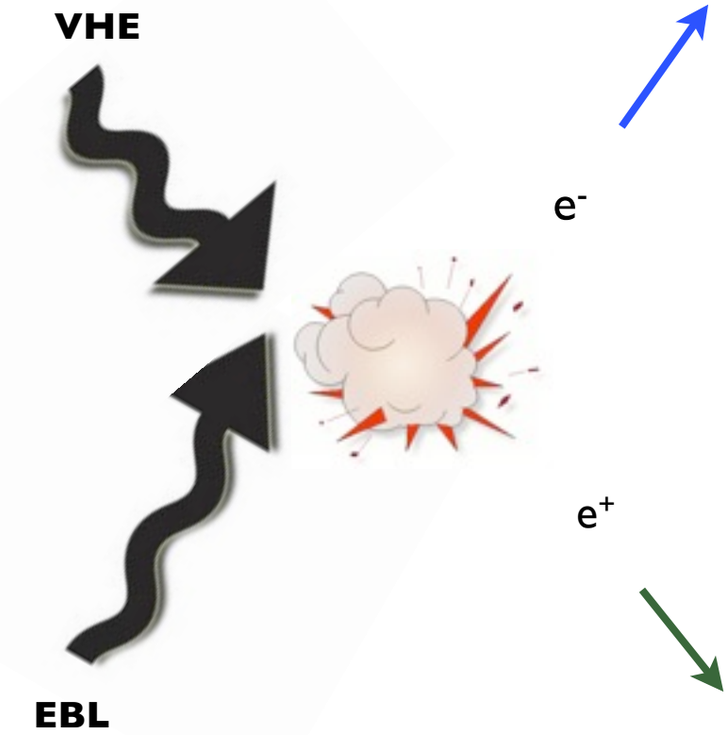


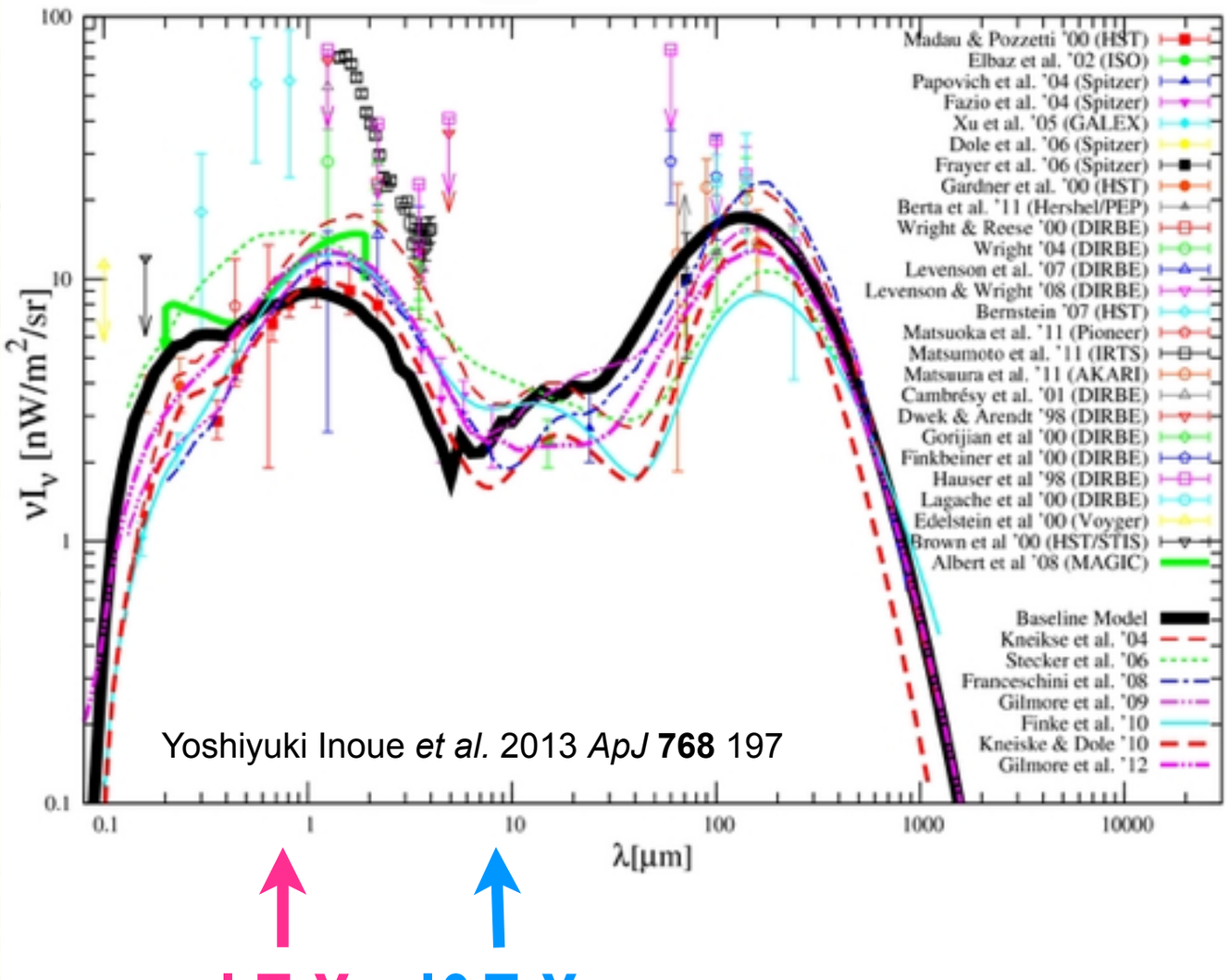
Difficult to observe directly due to strong foreground sources....

Photon-Photon Pair Production



- $\varepsilon = E/m_e c^2$
- Max σ E_1E_2=1 MeV^2
  - 1 TeV + 1 eV
  - 1 eV~1μm





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1 TeV 10 TeV

VHE/EBL PHOTON PAIR-PRODUCTION

$$F_{obs} = F_{int} e^{-\tau(z,E)}$$

The distance is key!

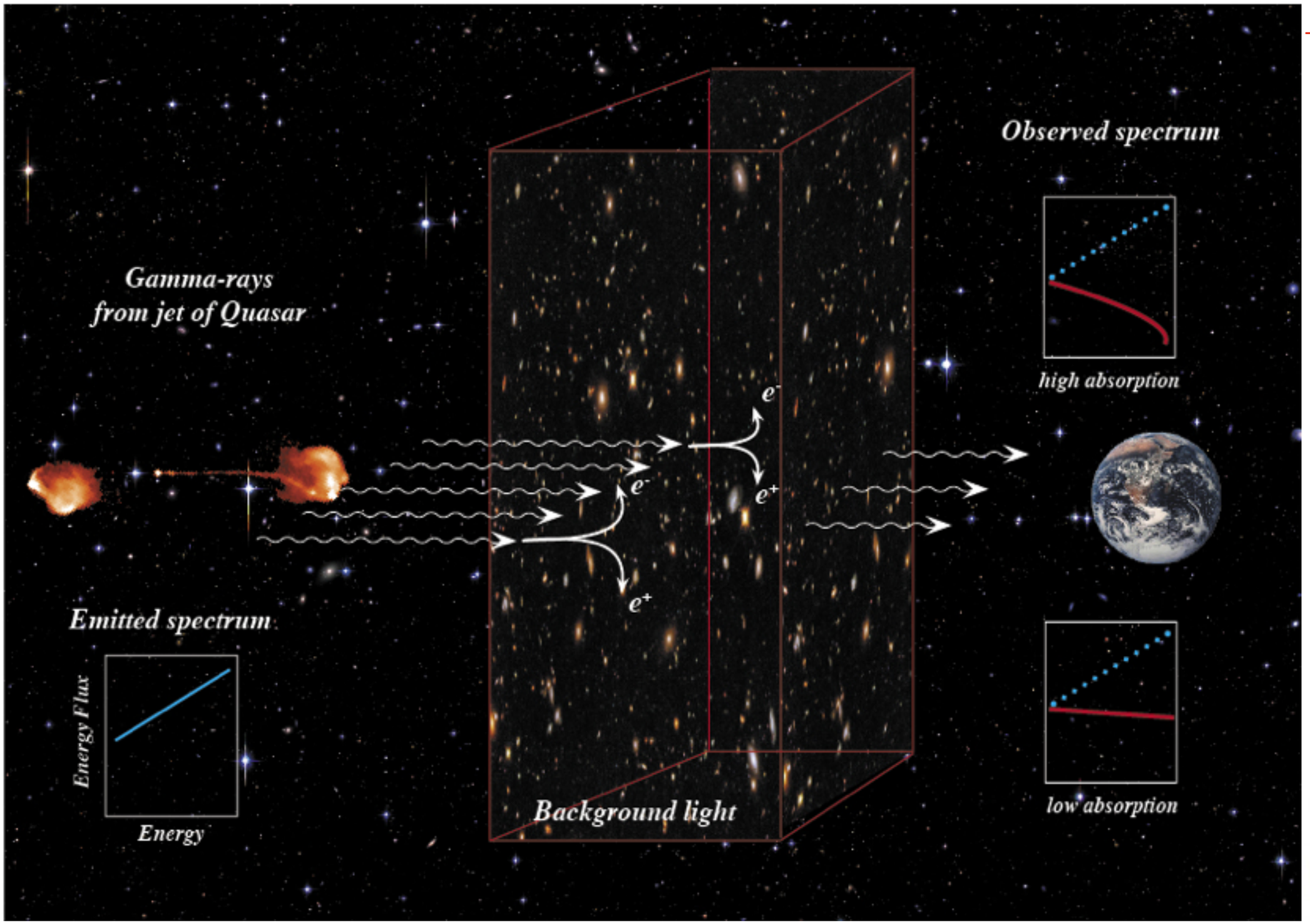


Image courtesy of cta cherenkov telescope array

Effect of the Gamma-ray Horizon

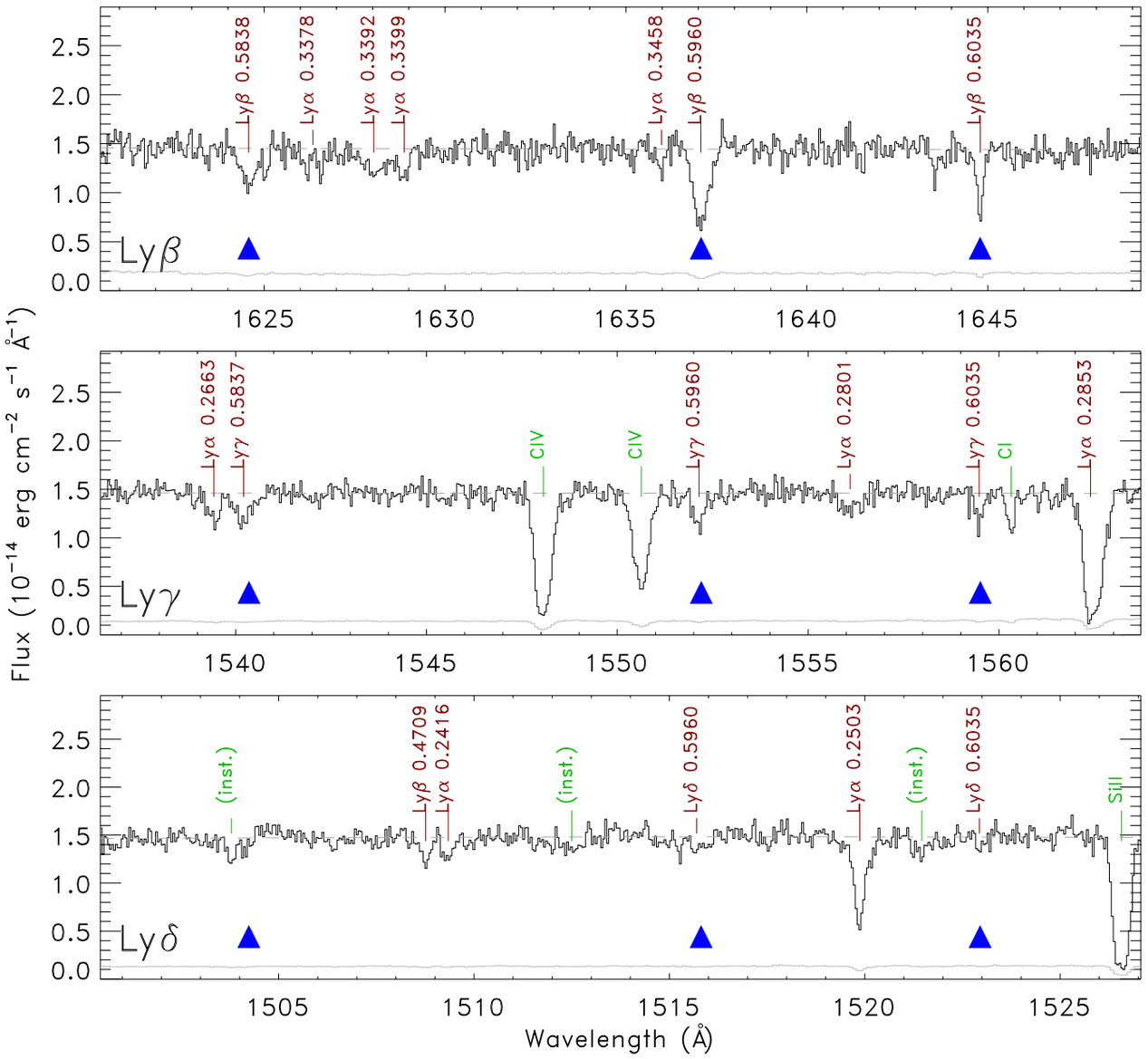
- PKS 1222+216 at z=0.432
- 3C 279 at z=0.536
- KUV 0033-1938 at z>0.51

Gamma-ray interactions with the EBL limit the distance out to which VHE sources should be detectable

(VERITAS-detected sources only...)

AGN	Type	z
M 87	FR I	0.004
NGC 1275	FR I	0.018
Mkn 421	HBL	0.030
Mkn 501	HBL	0.034
1ES 2344+514	HBL	0.044
1ES 1959+650	HBL	0.047
1ES 1727+502	HBL	0.055
BL Lac	LBL	0.069
1ES 1741+196	HBL	0.086
W Comae	IBL	0.102
VER J0521+211	HBL	0.108
RGB J0710+591	HBL	0.125
H 1426+428	HBL	0.129
1ES 0229+200	HBL	0.139
1ES 0806+524	HBL	0.138
1ES 1440+122	HBL	0.163
RX J0648.7+1516	HBL	0.179
1ES 1218+304	HBL	0.182
RBS 0413	HBL	0.190
1ES 1011+496	HBL	0.212
1ES 0414+009	HBL	0.287
1ES 0033+595	HBL	~~0.086~~ ?
B2 1215+30	IBL	~~0.13~~ ?
1ES 0647+250	HBL	~~0.203~~ ?
1ES 0502+675	HBL	0.34 ?
3C 66A	IBL	0.33 < z < 0.41
PG 1553+113	HBL	0.395 < z < 0.58
PKS 1424+240	IBL	>0.604

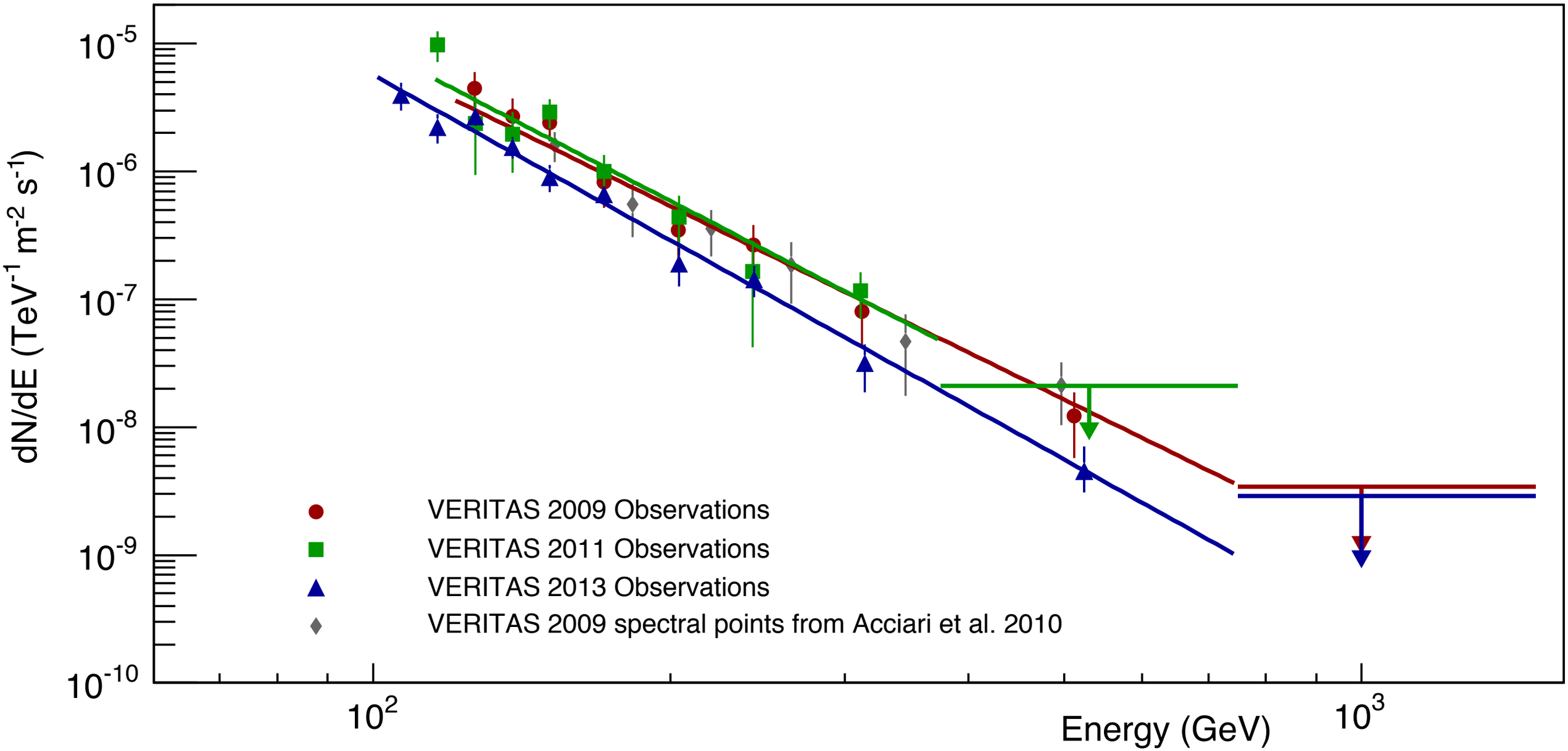
Redshift Lower Limit of PKS 1424+240 from Far UV Observations



PKS 1424+240 at z>0.6!

- Observations of PKS 1424+240 on April 19, 2012 show higher-order Lyman absorption at z=0.6035 (Furniss et al. 2013, ApJ Letters 768, 31)

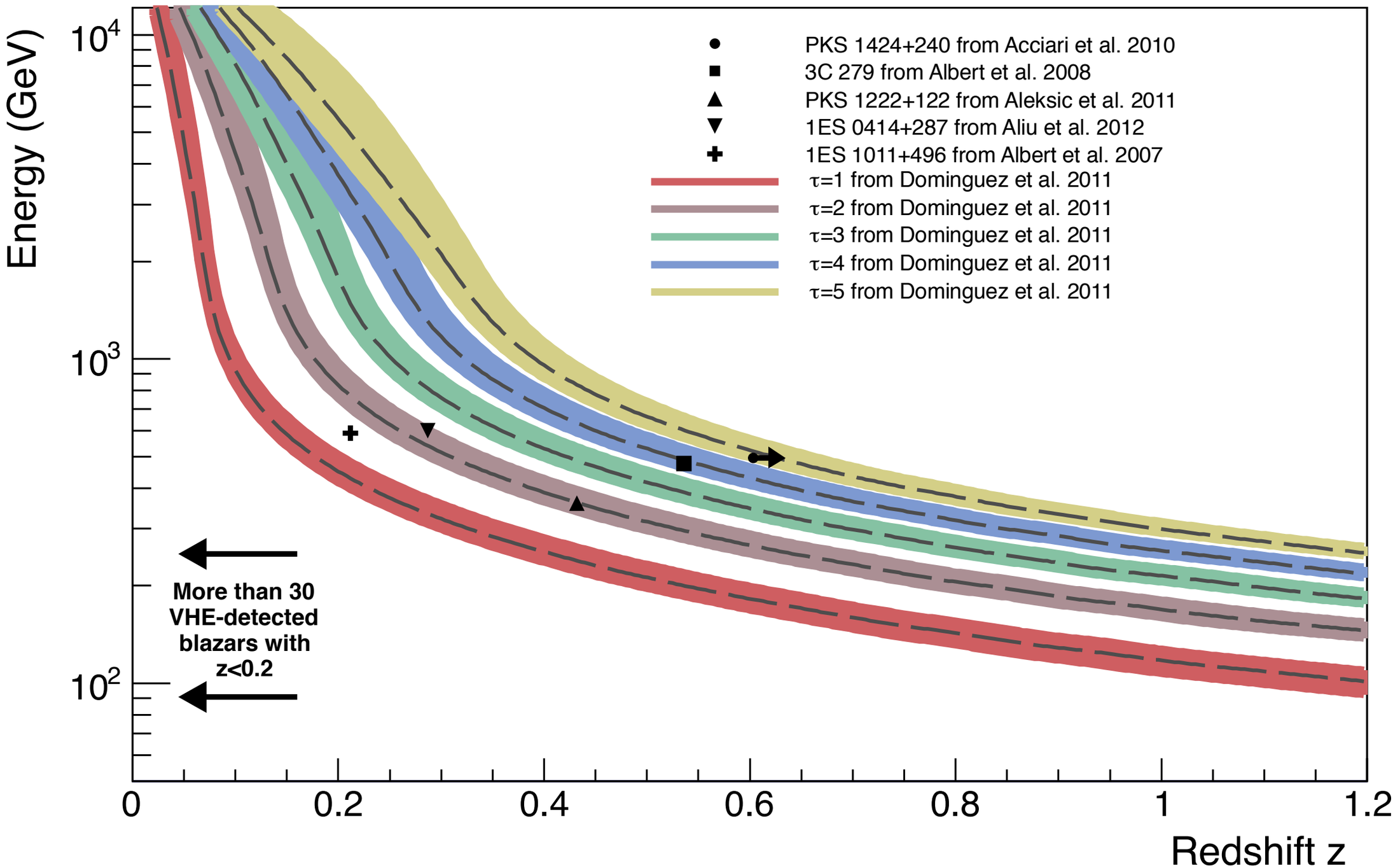
Deep Gamma-ray Observations of PKS 1424+240 by VERITAS Over Multiple Years



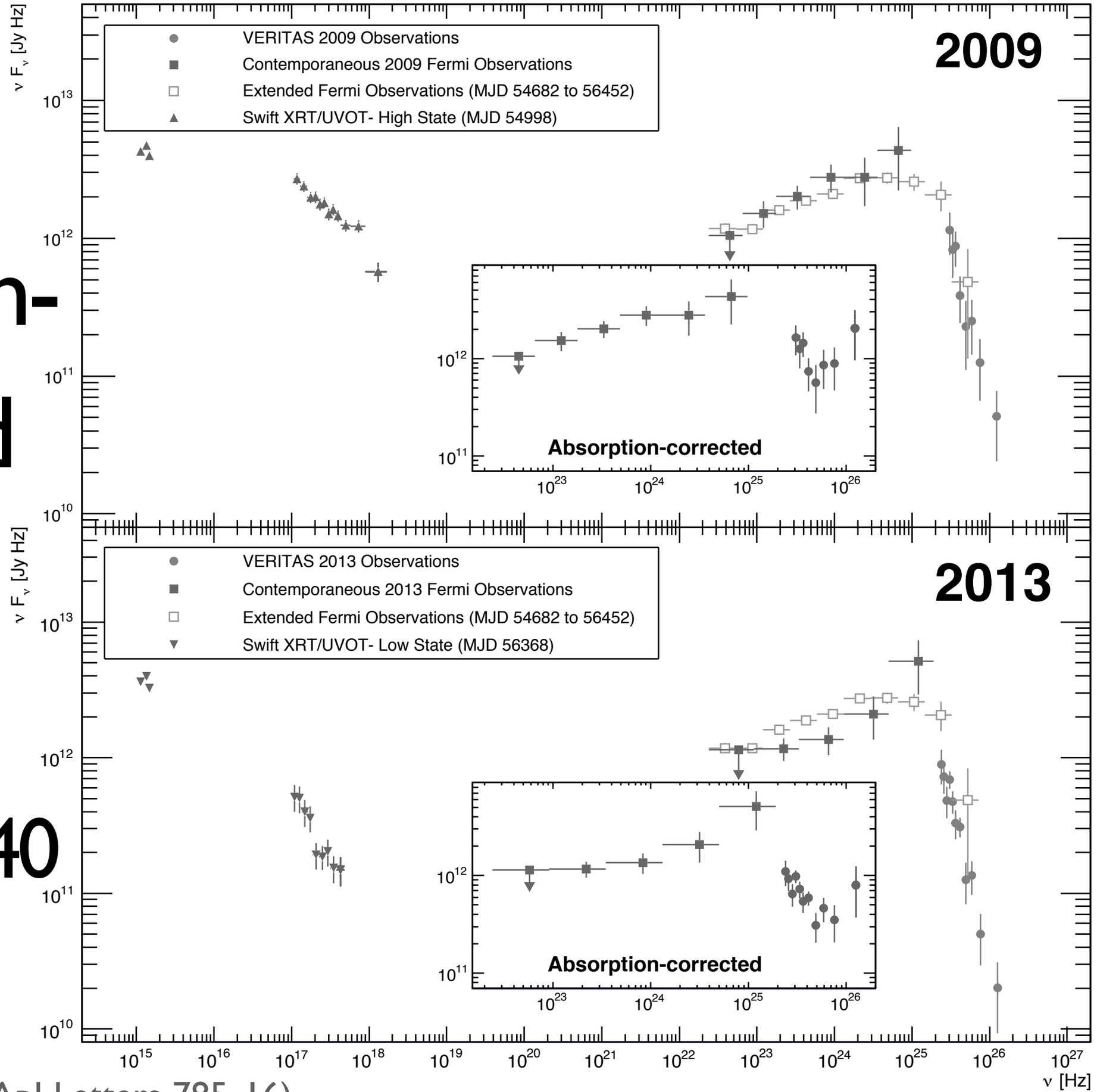
(Archambault et al. 2014, ApJ Letters 785, 16)

PKS 1424+240
and the
Gamma-ray Horizon

$$F_{obs} = F_{int} \times e^{-\tau}$$



Absorption-corrected SED of PKS 1424+240



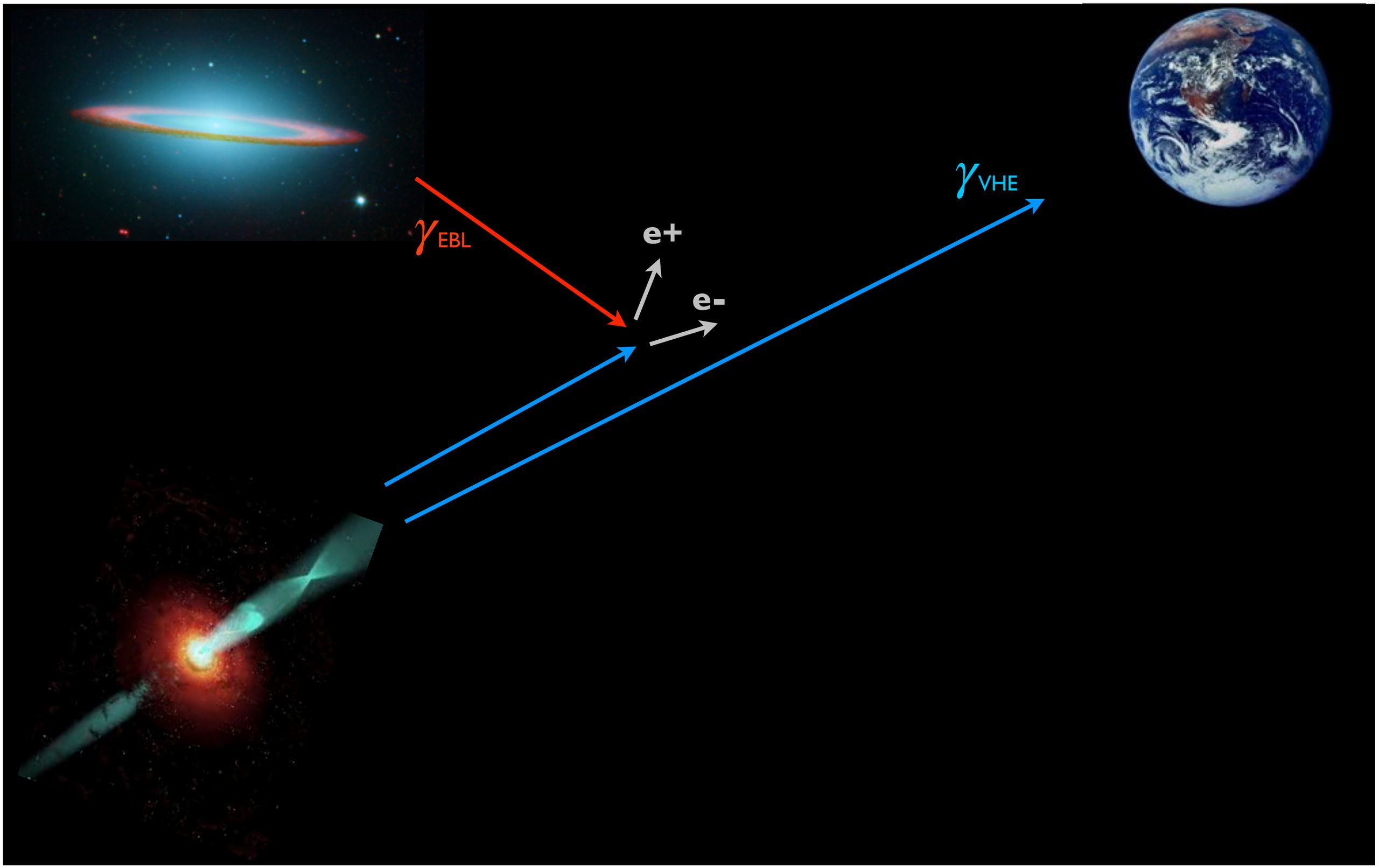
(Archambault et al. 2014, ApJ Letters 785, 16)

Possible explanations for the detection of exceptionally distant VHE blazars

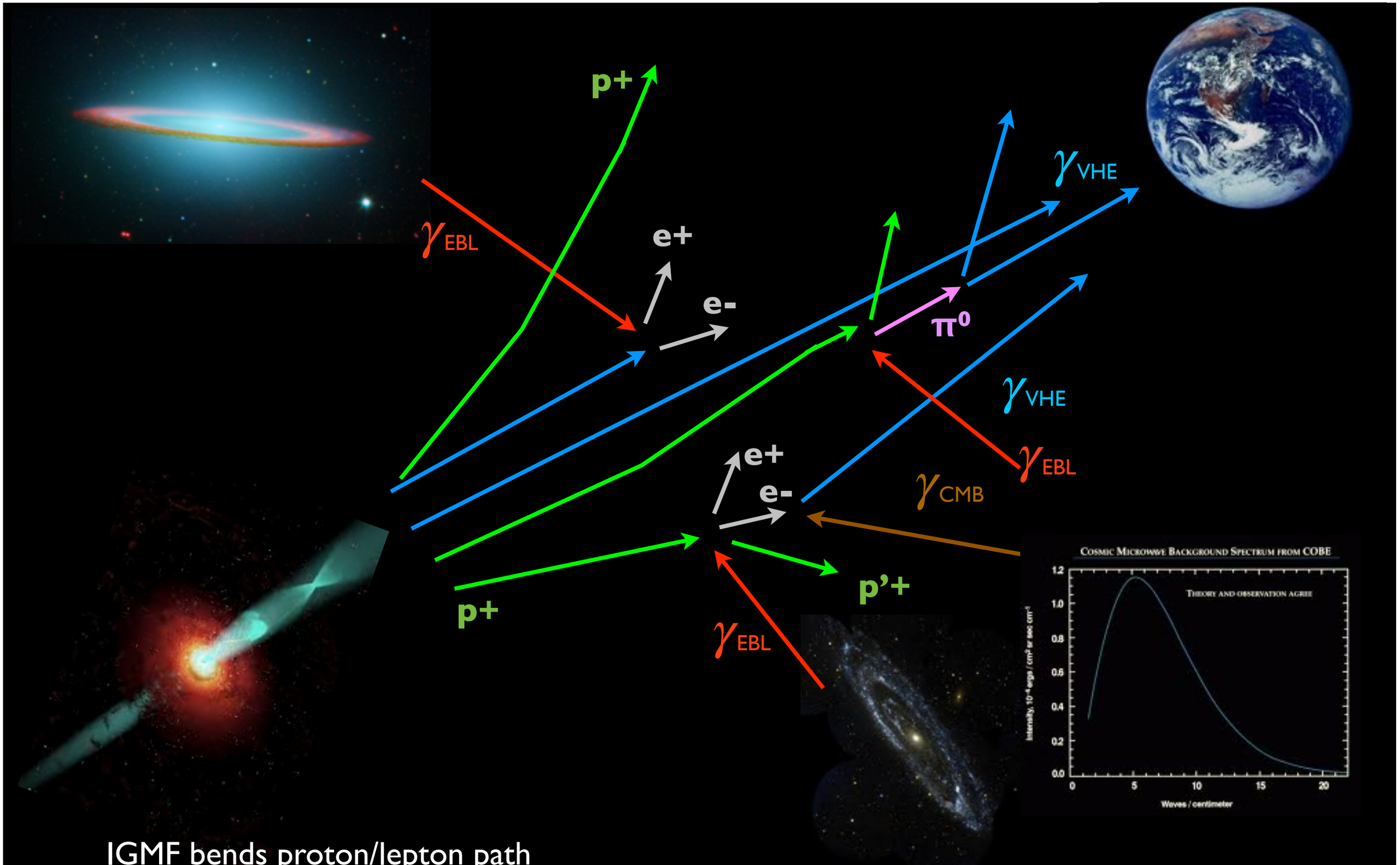
- Assumed EBL-model density, evolution or spectral shape is incorrect
- Observation of secondary emission from extragalactic cosmic ray propagation
- Lorentz invariance violation
- Evidence of axion-like particles
- ?

Commonly Applied Assumption

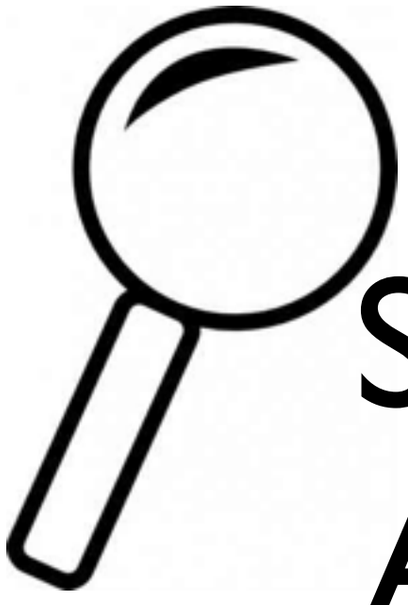
Intrinsic VHE photons+EBL



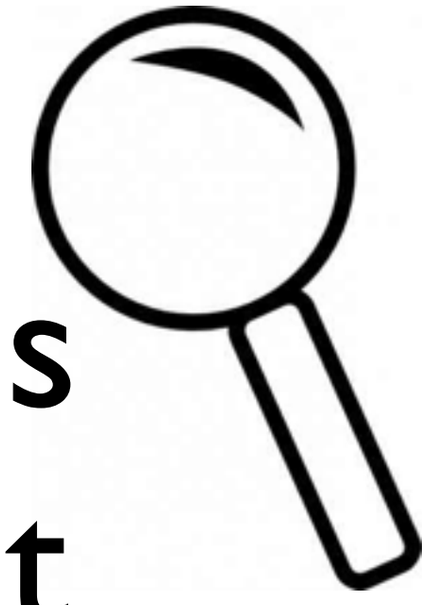
Cosmic-ray Contribution?



IGMF bends proton/lepton path



Evidence of CR Secondary Interactions Along the Line of Sight



- Lack of variability τ>2 on less than year timescale for extragalactic line of sight interactions
- Lack of correlated variability between τ>2 and τ<2
- Evidence of an *opacity-specific* spectral feature in multiple blazars
    - 12 blazars in northern sky alone which probe τ>2 opacity

Implications of CR Secondary Interactions

- Our current understanding of star formation history would remain valid
- Strong evidence for AGN as progenitors of most energetic cosmic rays
- Relativistic jets may not be field dominated
- Intergalactic magnetic field required to be relatively low
- No need for exotic physics...

Conclusion

- The VHE extragalactic sky is not a stamp collection
- Extragalactic VHE sources provide ample opportunity to study fundamental physics and cosmology
- Observations continue to unravel new mysteries such as those displayed by the VHE emission from PKS 1424+240
- Additional VHE observations of blazars will hopefully address long standing questions but will undoubtedly uncover new mysteries