Probing extragalactic magnetic fields (EGMF) with the γ-ray spectrum of PG 1553+113

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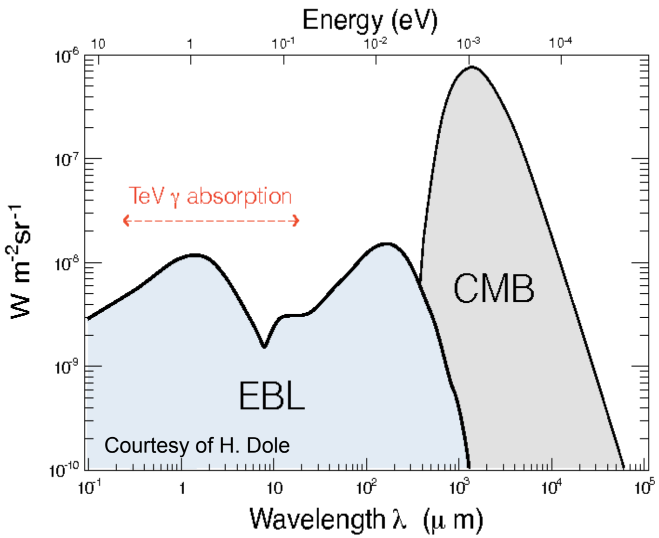
Outline

- Absorption of γ rays on the EBL, subsequent electromagnetic cascades and effects of the EGMF
- PG 1553+113: a γ-ray blazar with excellent properties for EGMF studies
- Simulations of cascades => EGMF constraints for different scenarios concerning the spectrum and temporal activity of PG 1553+113
- Prospects to take advantage periodic flux variations for EGMF measurements

Absorption of VHE γ rays



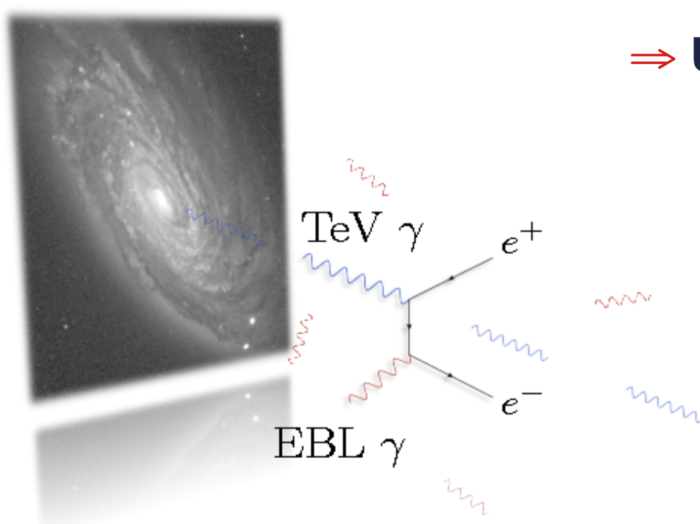
- **Extragalactic Background Light (EBL)**
  Background photon field, from far-IR to UV wavelengths
  Integrated starlight and dust re-emission

- **VHE (E > 100 GeV) photons undergo e^+e^- pair creation on the EBL**

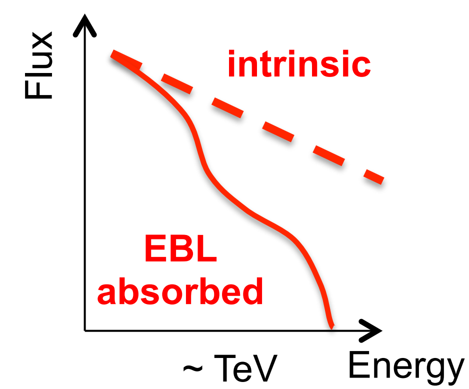
  Reaction threshold: $$\epsilon_{thr}\ (\mathrm{eV}) \simeq \frac{0.26}{E_\gamma(\mathrm{TeV})}$$

⇒ **Universe not fully transparent to VHE γ rays**

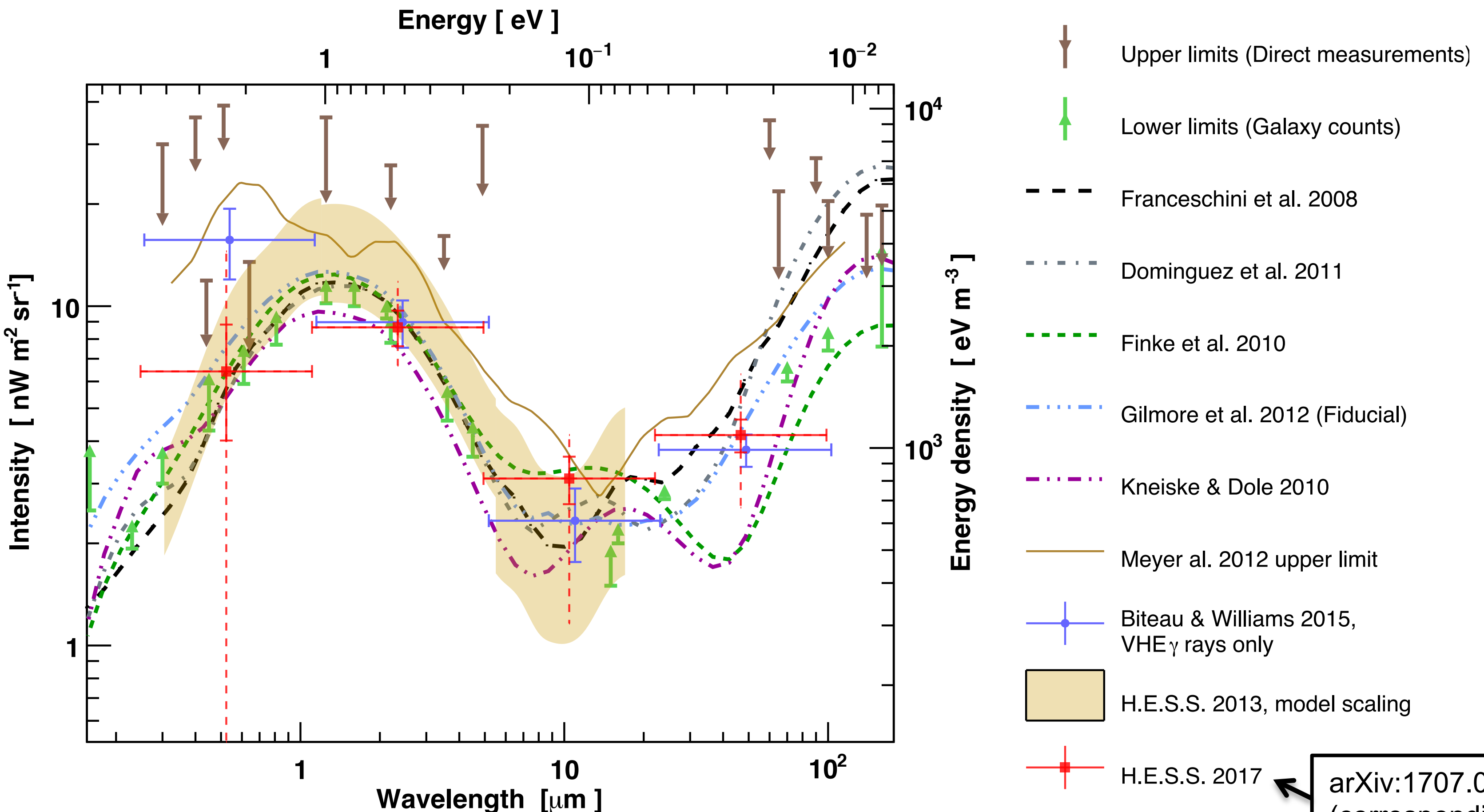
$$\Phi_{obs}(E_\gamma) = \Phi_{int}(E_\gamma) e^{-\tau(E_\gamma, z_s)}$$



Nikishov '62
Gould & Schreder '67
Stecker et al. '92
…



Local EBL energy distribution



arXiv:1707.06090
(corresponding author)

General agreement between models, empirical approaches and γ-ray constraints, in between upper and lower limits

γ-ray induced electromagnetic cascades

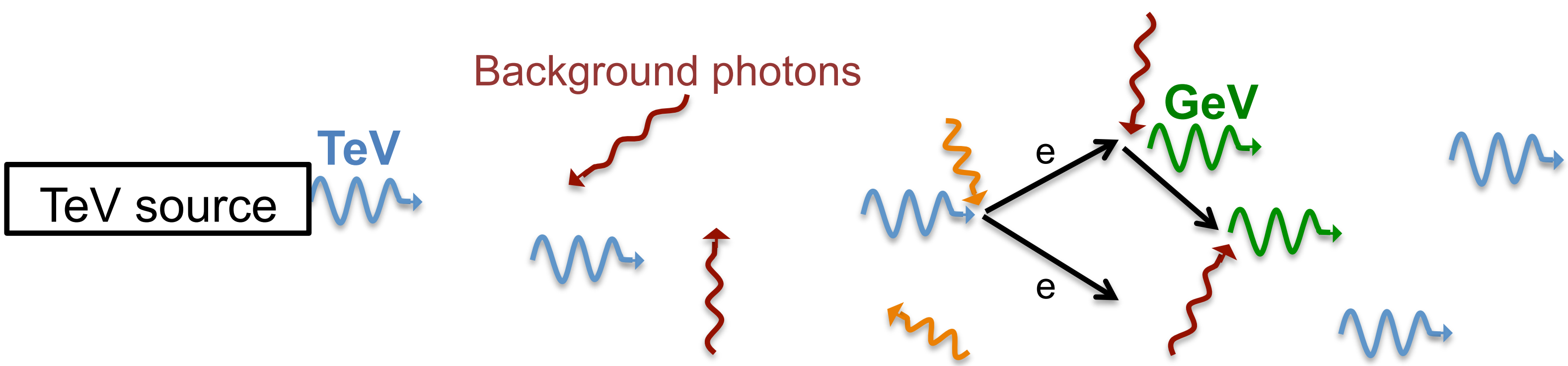
- **Pair creation** on the EBL $\gamma\gamma \rightarrow e^+e^-$ ⇔ injection of electrons and positrons in the extragalactic medium

  Mean free path of TeV photons O(100 Mpc)

- Produced electrons can **inverse Compton (IC) scatter** background photons (CMB + EBL) $e\gamma \rightarrow e\gamma$

  ⇒ Re-emission of γ rays
  $$E_\gamma = \frac{4}{3}\frac{E_e^2}{m_e^2}\epsilon_{\rm CMB} \sim 1 \left[\frac{E_{\gamma_0}}{1\ \rm TeV}\right]^2 \rm GeV$$

  IC losses of electrons in a cascade ~ 0.1 Mpc scale



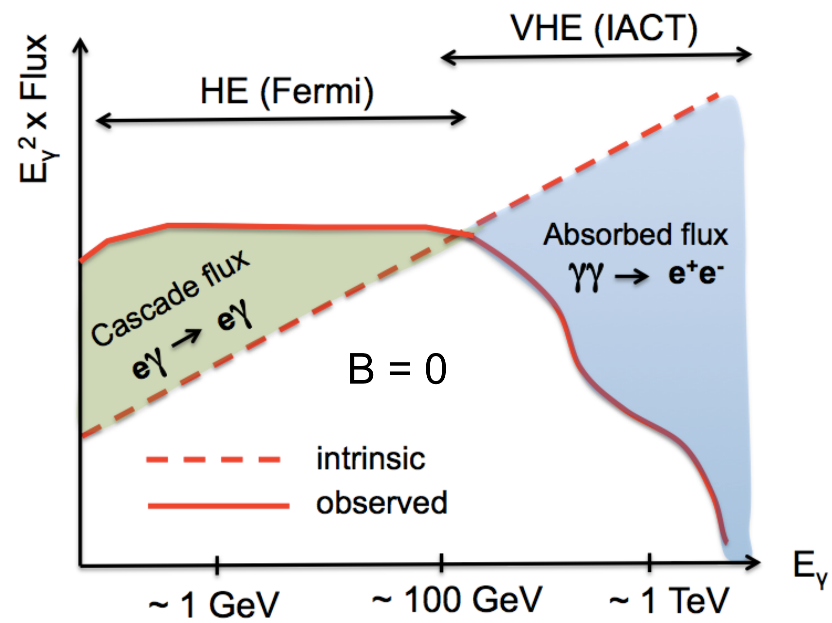
Aharonian, Coppi & Voelk'94
Plaga '95
Neronov & Semikoz '07,'09
Murase et al.'08
…

Scenario valid providing NO dominant energy dissipation via plasma instabilities

Cascade flux and EGMF

- EBL-absorbed VHE flux reprocessed at lower energies

- Non-zero EGMF ⇔ deflection of the electrons and positrons
  - Angular spread
  - Time delays



⇒ **EGMF-induced suppression of the observable cascade flux**

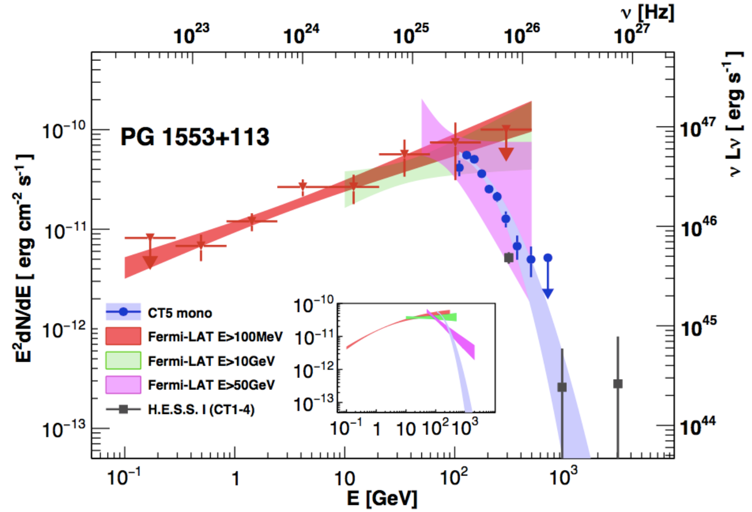
- Non-observation of the cascade flux ⇔ lower limits on the EGMF
  - Ideal source: **hard spectrum blazar, significantly EBL-absorbed**

    1ES 0229+200 (z=0.14) very often considered for EGMF studies

Neronov & Vovk '10
Taylor, Neronov & Vovk '11
…

PG 1553+113

- Bright HBL blazar
  - Hard HE spectrum, index ~ 1.6 - 1.7 (Fermi-LAT, 2009)
  - Soft VHE spectrum, index ~ 4.5 (H.E.S.S., 2008)



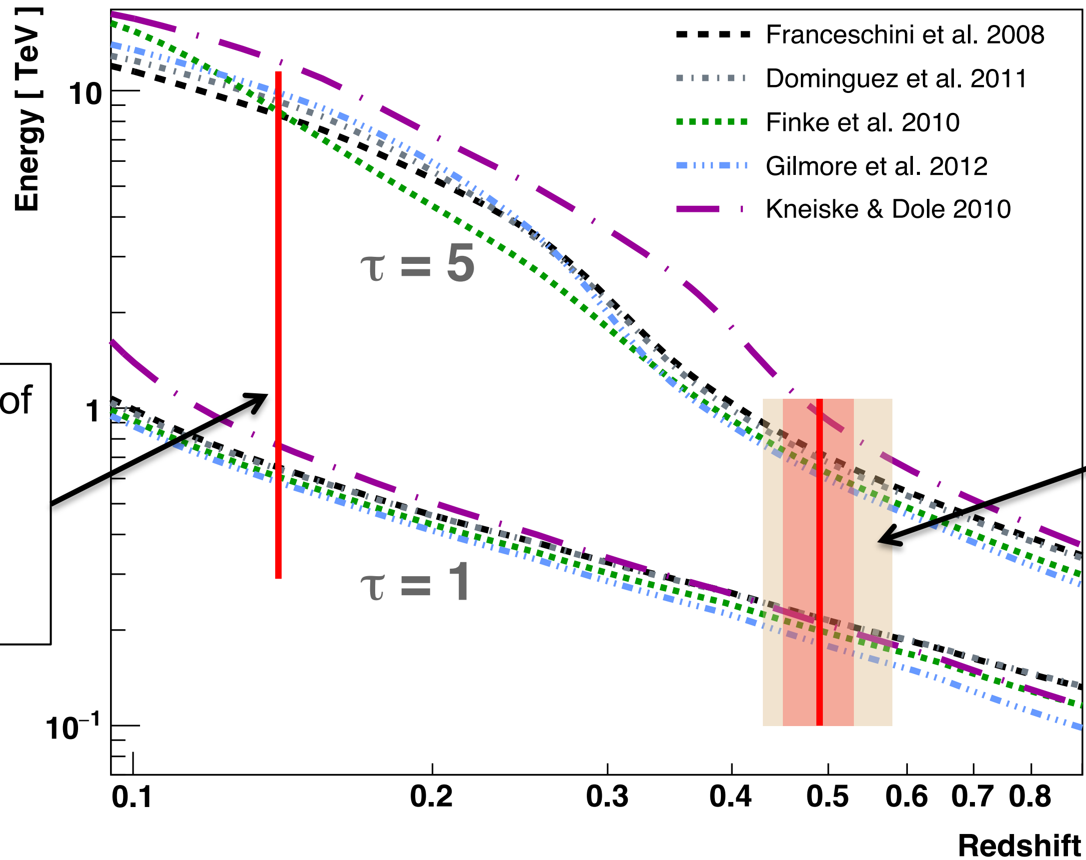
H.E.S.S.-II and Fermi-LAT contemporaneous data
A&A 2017 arXiv:1612.01843

➔ **Strong spectral break due to EBL absorption**

- Redshift uncertainty
  - From spectroscopy **0.43 < z < 0.58** (Danforth et al. 2010)
  - Most probable value based on EBL absorption **z = 0.49 +/- 0.04** (H.E.S.S. 2015)

Value used for this study

PG 1553+113: significant EBL absorption



VHE observations of **1ES 0229+200** by H.E.S.S. and VERITAS
arXiv:0709.4584
arXiv:1312.6592

VHE observations of **PG 1553+133** by H.E.S.S., MAGIC and VERITAS
arXiv:0710.5740
arXiv:1612.01843
arXiv:1101.2764
arXiv:1411.1439

VHE observations of PG 1553+113 extend up to a very significantly EBL-absorbed regime (up to τ ~ 5)

Simulation of cascades

- Public code ELMAG (Kachelriess et al. 2012, elmag.sourceforge.net)
  - EBL model: Dominguez et al. 2011
  - z=0.49
  - Keeping photons within 95% of Fermi-LAT PSF
  - Intrinsic spectrum chosen based on Fermi-LAT data contemporaneous with H.E.S.S.-II observations (intrinsic power-law index 1.59 +/- 0.07)

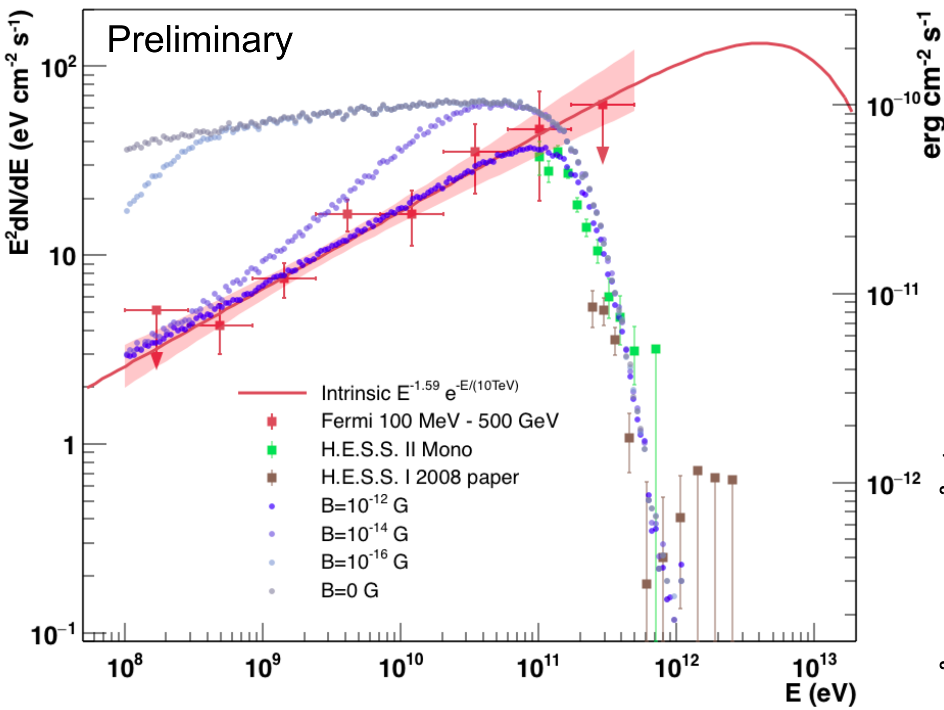
$$\phi_0 \times E^{-1.59} \times \exp\left(-\frac{E}{E_{\mathrm{cut}}}\right)$$

E_{cut}= 1 TeV conservative scenario (limit case w.r.t. VHE observations)

E_{cut}= 10 TeV optimistic scenario

Encompass intermediate cut-offs and log-parabolic intrinsic shapes

Expected spectrum



Optimistic scenario

$B_{EGMF} = 10^{-12}, 10^{-14}, 10^{-16}$ and 0 G

λ_{EGMF} = 1 Mpc

No limit in time integration

$B_{EGMF} > 10^{-14}$ G required

Conservative scenario

$B_{EGMF} = 10^{-12}, 10^{-14}, 10^{-16}$ and 0 G

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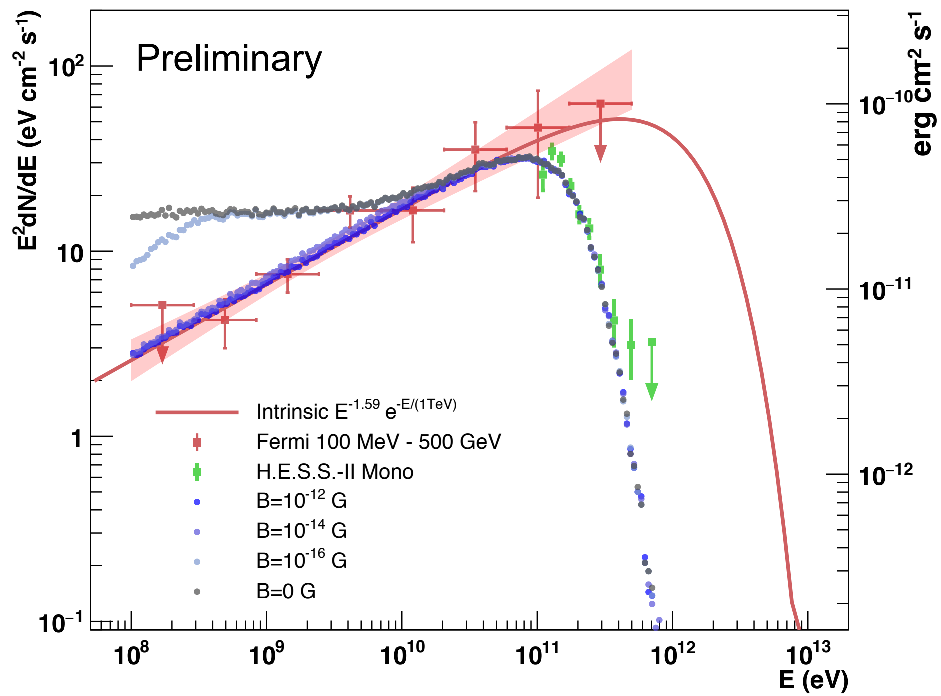
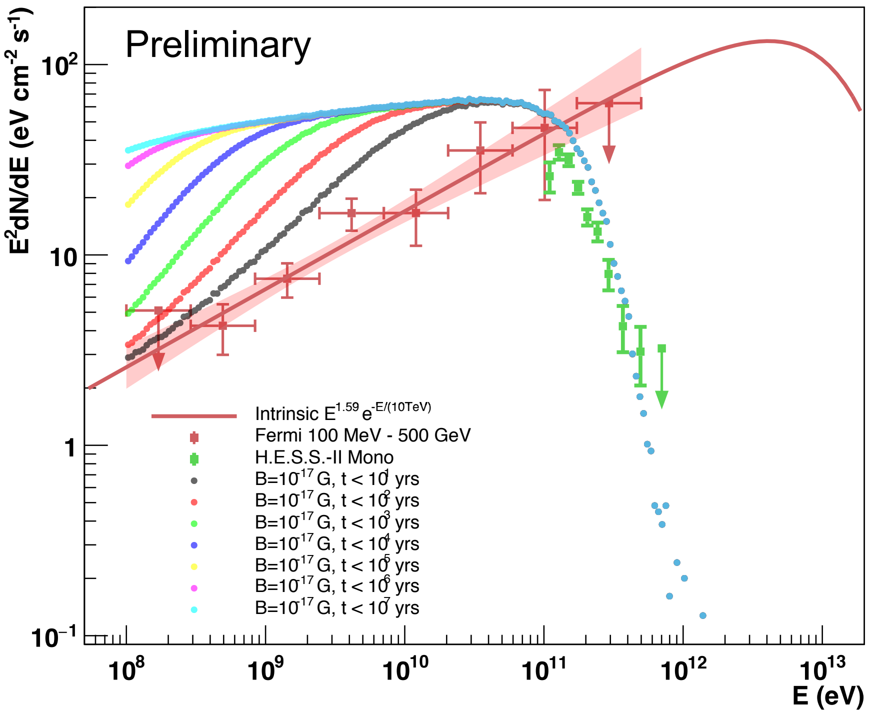


Expected spectrum – limited time integration



Optimistic scenario

B_{EGMF} = 10^{-17} G

λ_{EGMF} = 1 Mpc

Time integration in decade bins

from 10^7 years to 10 years

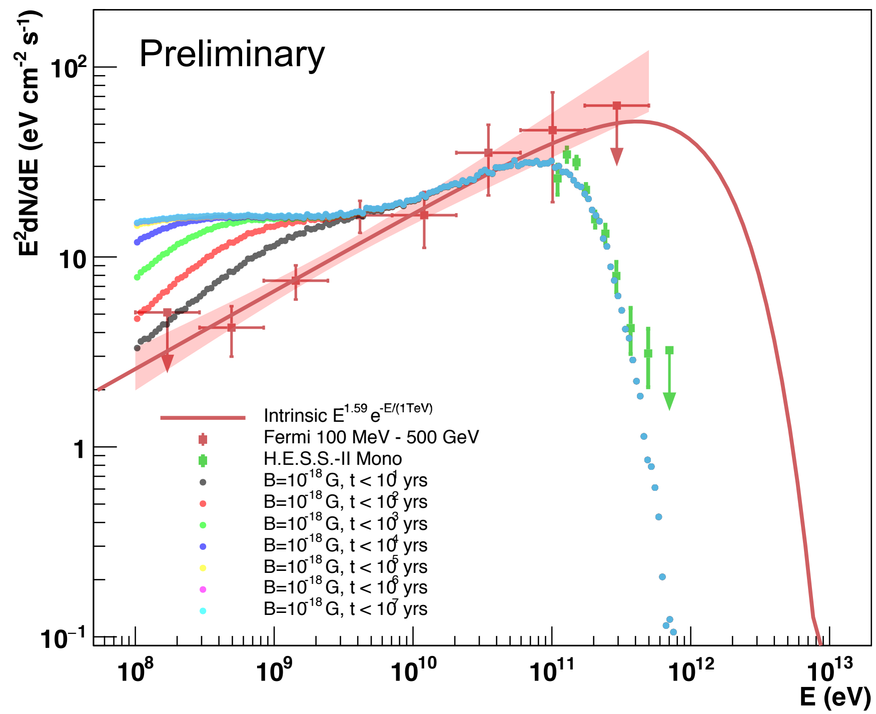
Conservative scenario

B_{EGMF} = 10^{-18} G

λ_{EGMF} = 1 Mpc

Time integration in decade bins

from 10^7 years to 10 years

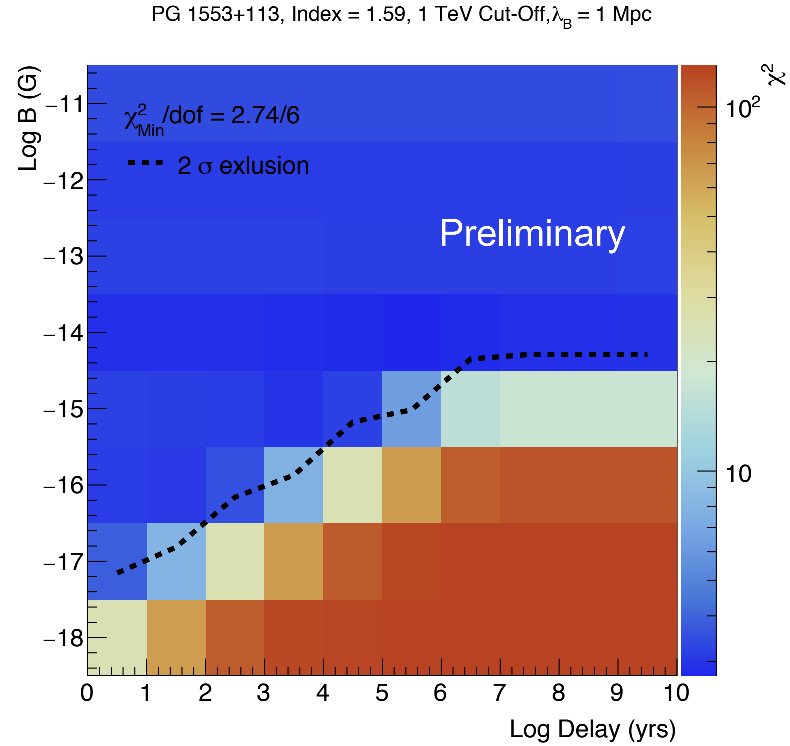


EGMF results

- Non-zero EGMF required **even considering the most conservative scenario:**

  intrinsic cut-off at 1 TeV +
  only 10 years of VHE activity

$$B_{\mathrm{EGMF}} \gtrsim 10^{-17}\mathrm{G},\ 95\%\ \mathrm{CL}$$



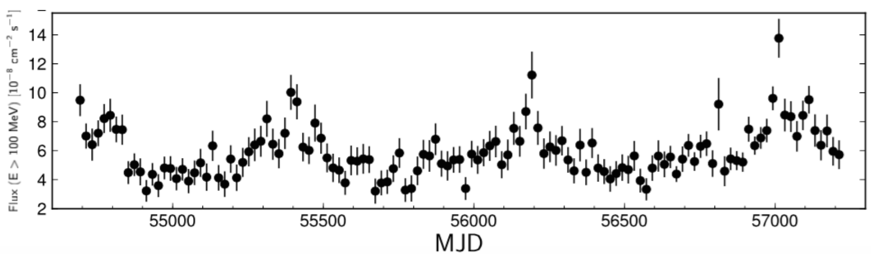
Limit goes up to $B_{EGMF} > 10^{-13}$ G considering a 10^7 yrs activity and a 10 TeV cut-off

χ^2 using Fermi-LAT points

Comparable to existing **spectral** constraints derived from the analysis of 1ES 0229+200 etc.

PG 1553+113 quasi periodic variability

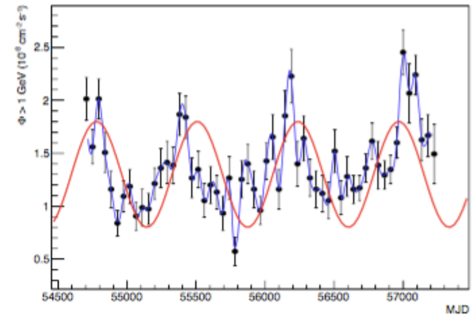
- Previous results assume no flux variation… but PG 1553+113 shows evidence for a quasi-periodic variation from radio to γ-rays, with a ~2.18 year period Fermi-LAT, arXiv:1509.02063



- Periodic behavior: interesting opportunity to measure the EGMF
  - Predictability
  - Specific flux variations at different energies (delayed periodic cascade)
  - Future improved observational coverage with CTA …

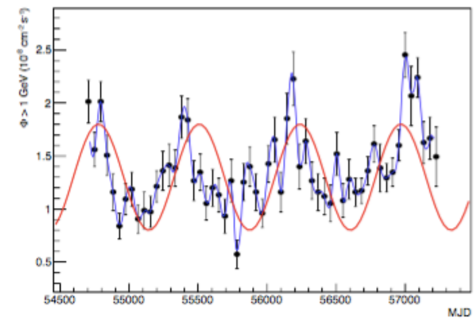
Effect of a periodic modulation

Toy-model flux evolution in time of PG 1553+113 using a cosine with a 2-year period

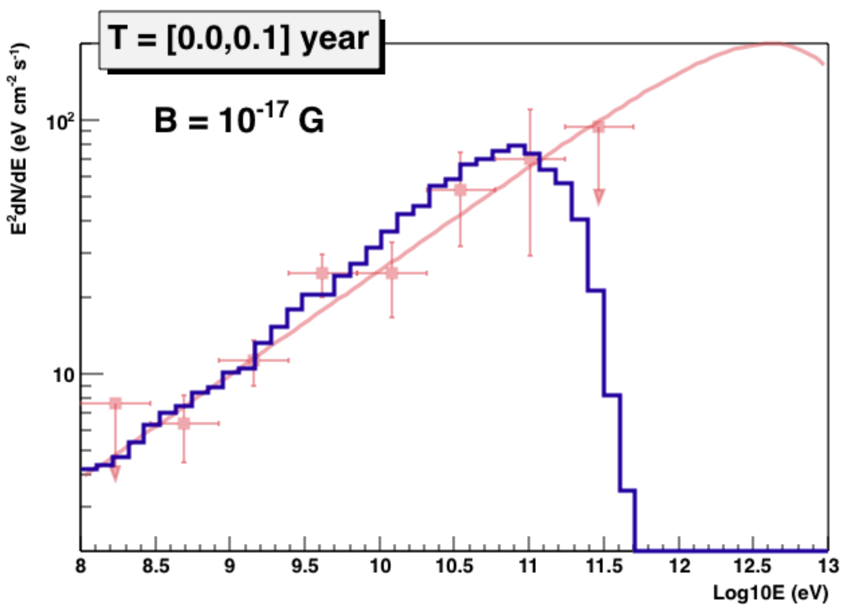


Effect of a periodic modulation

Toy-model flux evolution in time of PG 1553+113 using a cosine with a 2-year period



Example expected spectrum evolution over a 10-year time of activity (optimistic intrinsic scenario):



- Specific energy-dependent flux variations with time
- Observables sensitive to the EGMF
- Motivation for future HE-VHE monitoring

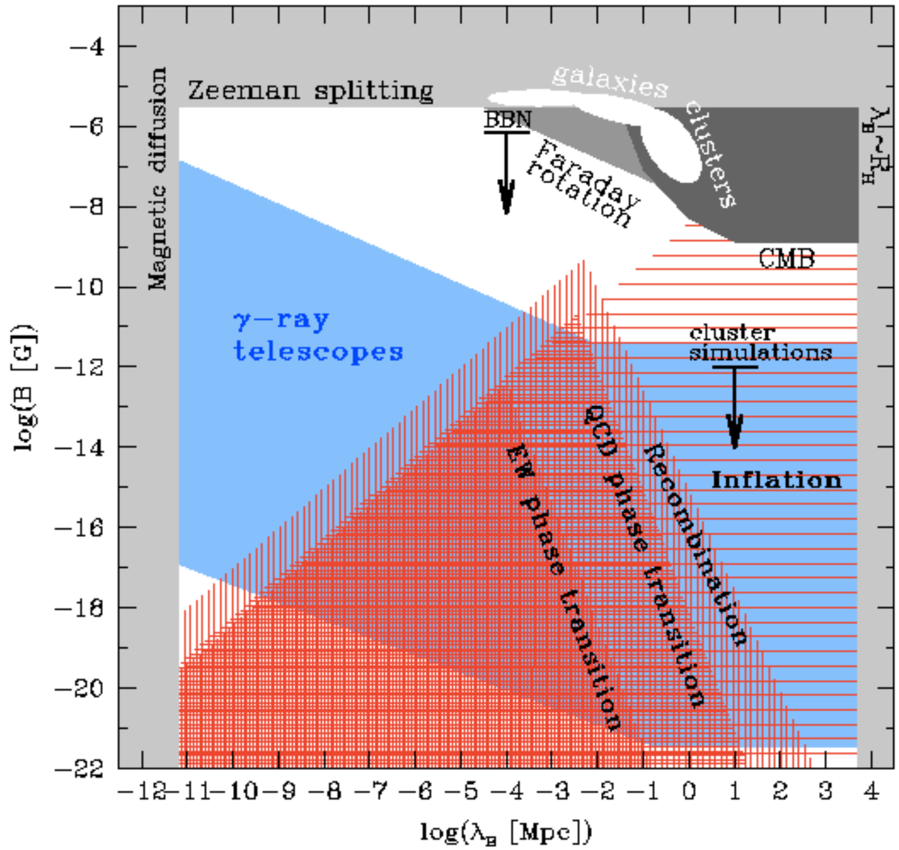
Summary

- PG 1553+113 is an excellent source for EGMF studies despite its z uncertainty
- Non-zero EGMF ($B_{EGMF} \sim > 10^{-17}$ G) required even for conservative scenario
- Interesting prospects to take advantage of its quasi-periodic flux variation

Backup

EGMF – limits and constraints

- Upper limits on EGMF strength from Faraday rotation, CMB anisotropy …
- γ-ray observations: unique opportunity to derive lower limits on EGMF
- Strength and correlation length are important indications concerning EGMF origin (astrophysical / cosmological)



From: www.apc.univ-paris7.fr/~semikoz/EGMF/conference.html

Plasma instabilities

$$\gamma_{\text{TeV}} + \gamma_{\text{eV}} \to e^+ + e^- \to \begin{cases} \text{IC cascade} \to \gamma_{\text{GeV}} \\ \\ \text{plasma instabilities} \end{cases}$$

- **Alternative scenario**: dominant energy losses via instable oscillations with the electron plasma in the extragalactic medium
  - Heating the medium, no secondary gamma-ray emission
  - Affects derived EGMF constraints

- Not clear if this process is dominant or negligible

Chang et al. '12
Broderick et al. '12
Schlickeiser et al. '12
Sironi et al. '13
…