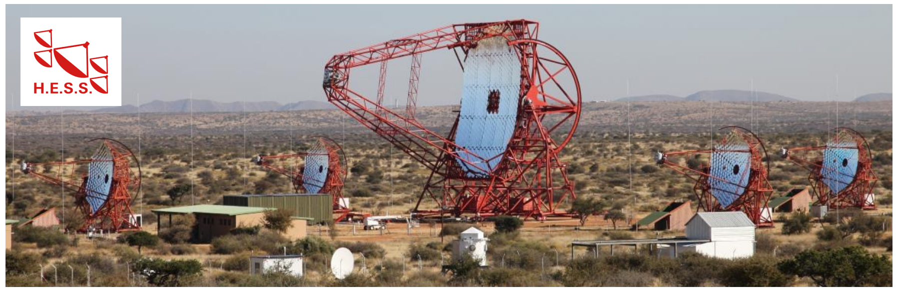
Spectral and Temporal Behaviour of Mrk 501 in Gamma Rays

Nachiketa Chakraborty
for HESS and FACT collaborations

TeVPA, 8th August, 2017
Columbus, Ohio, USA



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Introduction : Gamma-rays

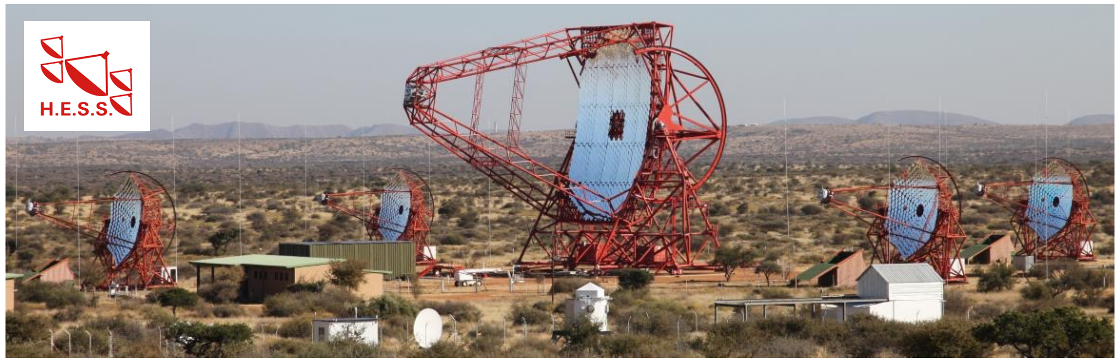
- ***Individual gamma-ray sources are excellent laboratories*** for studying particle acceleration and radiative processes

- They are also, often very useful in ***probing general properties of universe*** as a whole (**E**xtragalactic **B**ackground **L**ight, **L**orentz **I**nvariance **V**iolation)

- Broad energy range from
  GeV : Fermi Gamma-ray Space Telescope (20 MeV to > 300 GeV)
  TeV : FACT (> 750 GeV, even sampling->monitoring long term) ,
  HESS(> 100 GeV, sensitivity->fast flares) [IACT]
  great dynamic range and complementary information on processes in the source and environment

- Gamma-ray data on **Mrk 501** including some of the largest flares help us to exactly this in this study

- Here we specifically use ***spectral*** and ***temporal*** properties from 100 MeV to tens of TeVs



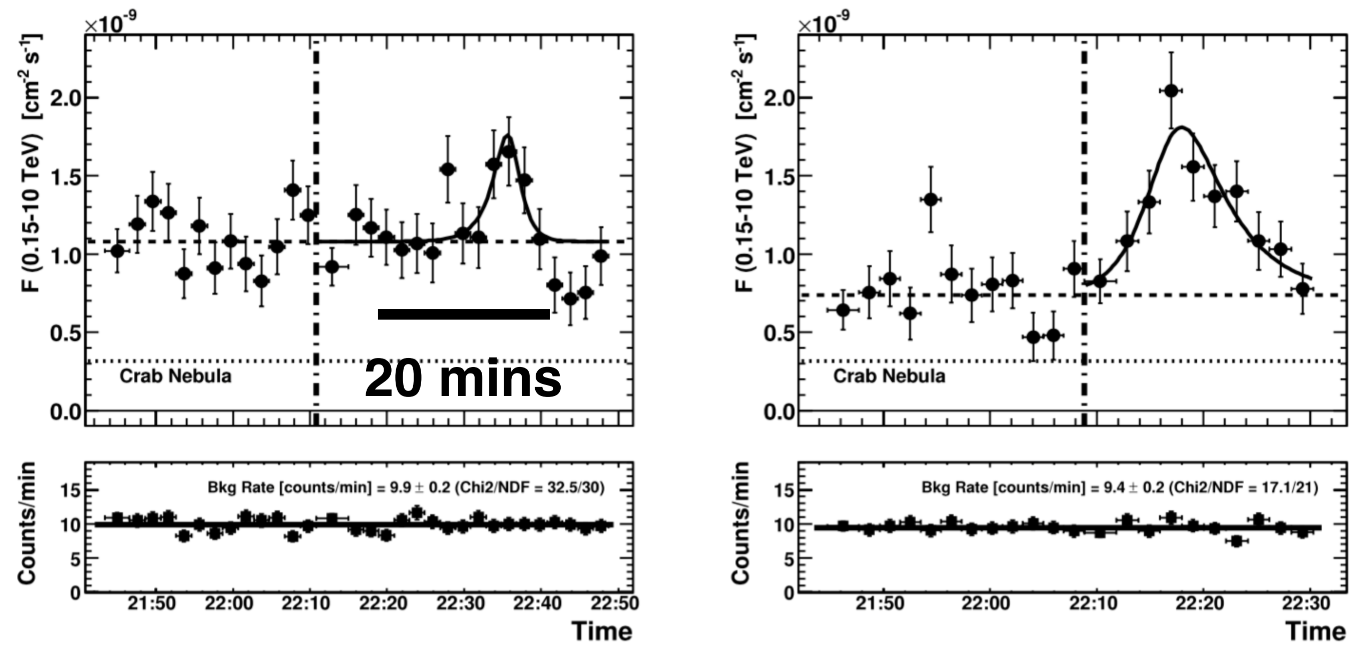
Mrk 501 as a TeV emitter

- Markarian 501
  - BL Lac AGN at z = 0.034
  - 2nd extragalactic object discovered at VHE in 1995 (Quinn, J. et al., ApJ 456 pL83+)
  - Very bright, strongly variable at all energies

- Object of several MWL campaigns
  - Historically highest VHE flux on April 16, 1997
  - ***Rapid flares down to minutes***

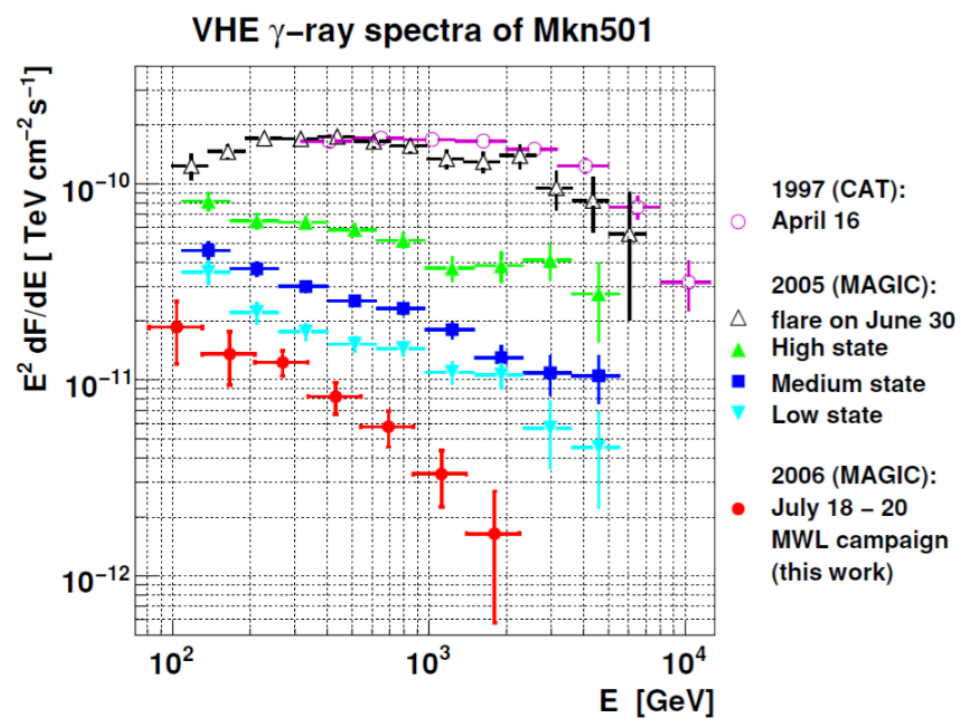
- TeV peaks go to higher energies during flares ; ***harder when brighter*** behavior

Flux



Albert et al.,2007

Time



MAGIC – Anderhub et al. 2009

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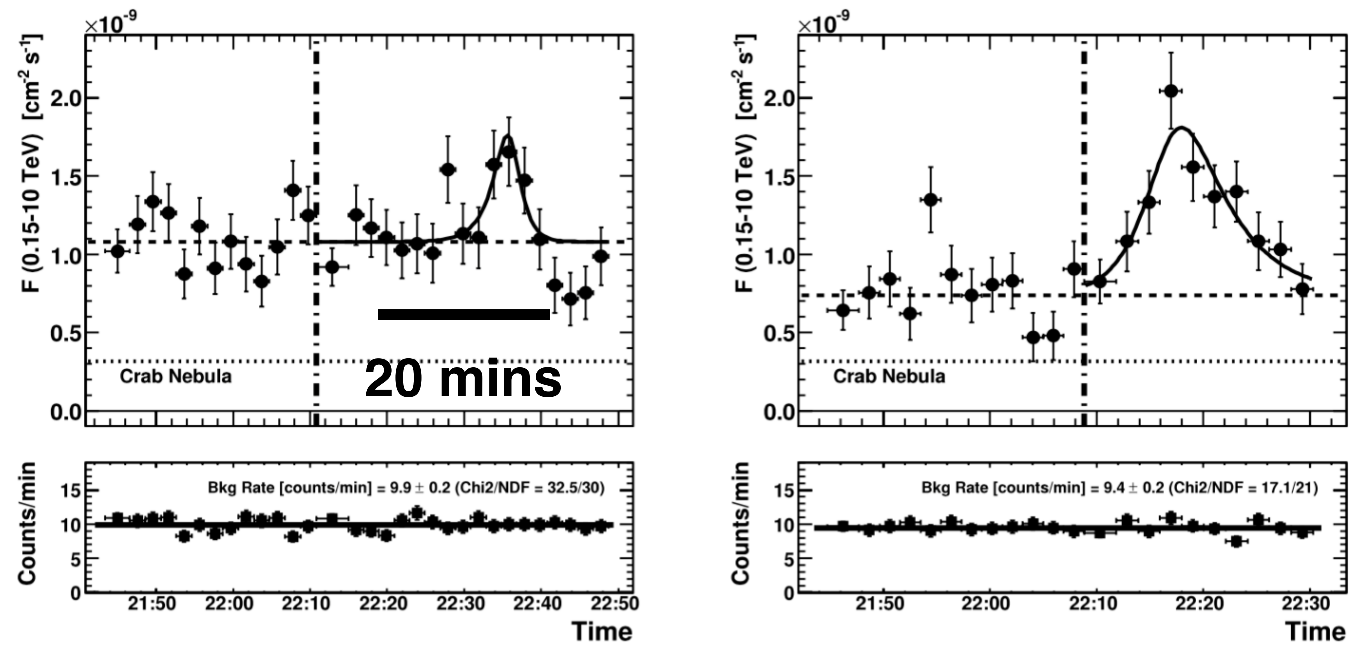

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Time

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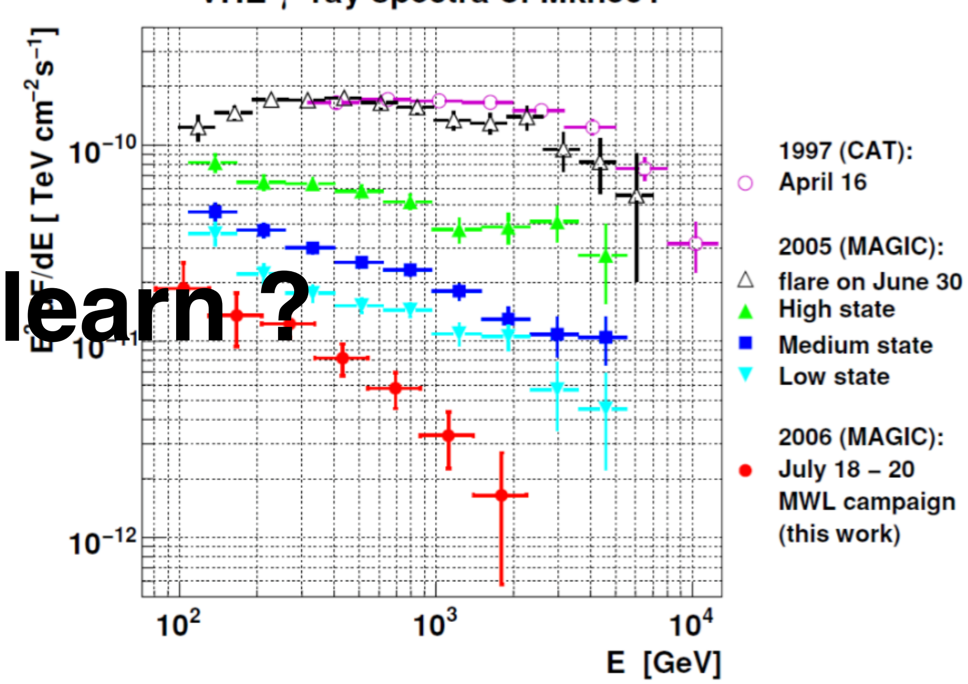
What more can we learn ?

- TeV peaks go to higher energies during flares ; ***harder when brighter*** behavior



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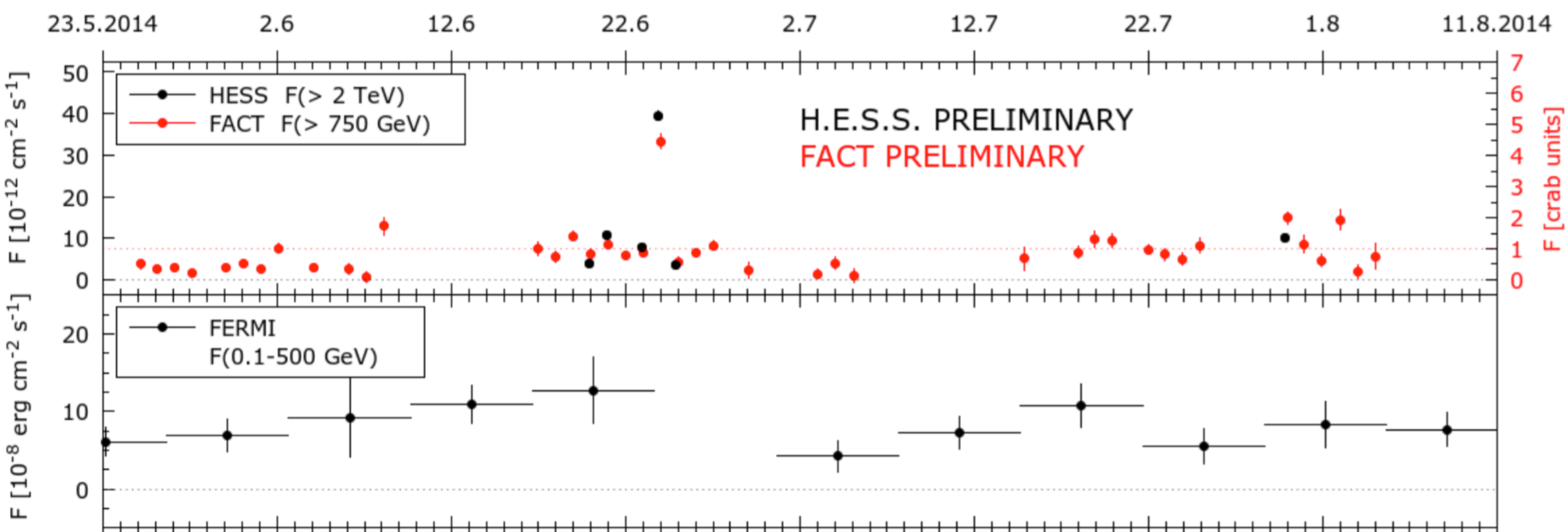
FACT
First G-APD Cherenkov Telescope

Current Gamma-ray Observations of Mrk 501

- FACT monitors TeV blazars - tracking long term behaviour like Fermi at GeV
- HESS high sensitivity => high statistics
- Flux level comparable to the 1997 historical maximum
- Full Array (CT1-5)

- High ZA (~64 deg)=> High energy threshold (> 2 TeV)
  => 2 - 20 TeV (larger range HESS II)
  => Exclusively TeV photons
  Including highest energy photons
- Rapid variability above 2 TeV
  - down to few minutes
  (doubling times < 10 min - Chakraborty et al., ICRC2015)
  => Favours lepton induced VHE γ-ray emission > 2 TeV



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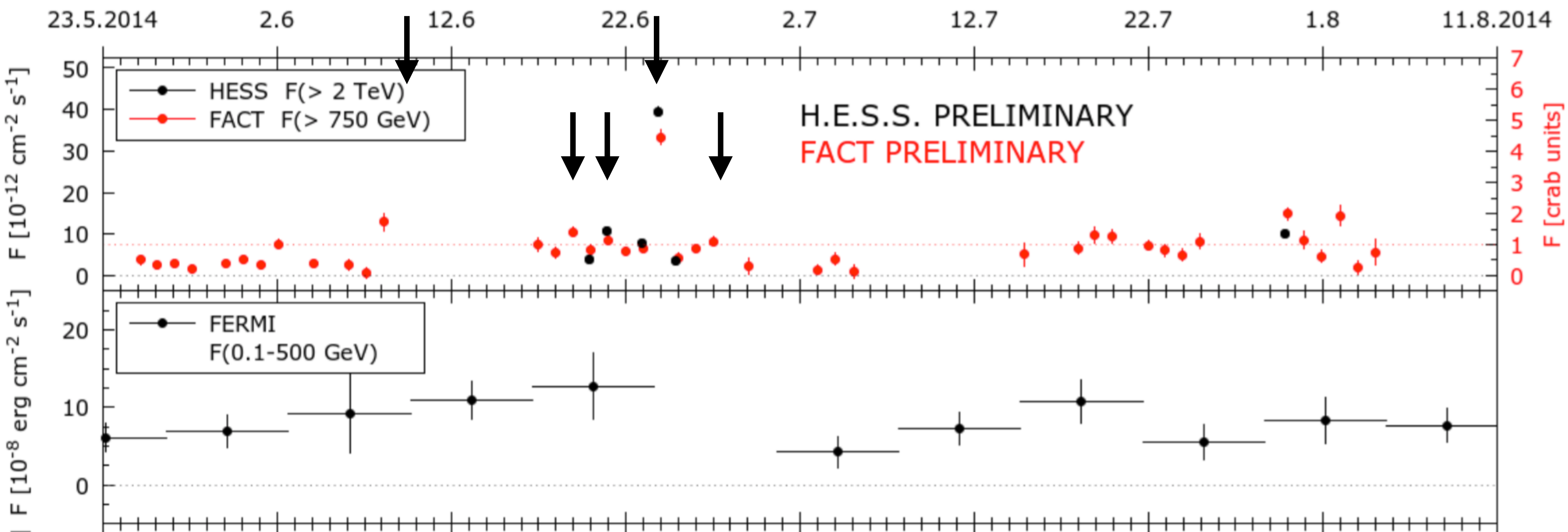
Triggers from FACT



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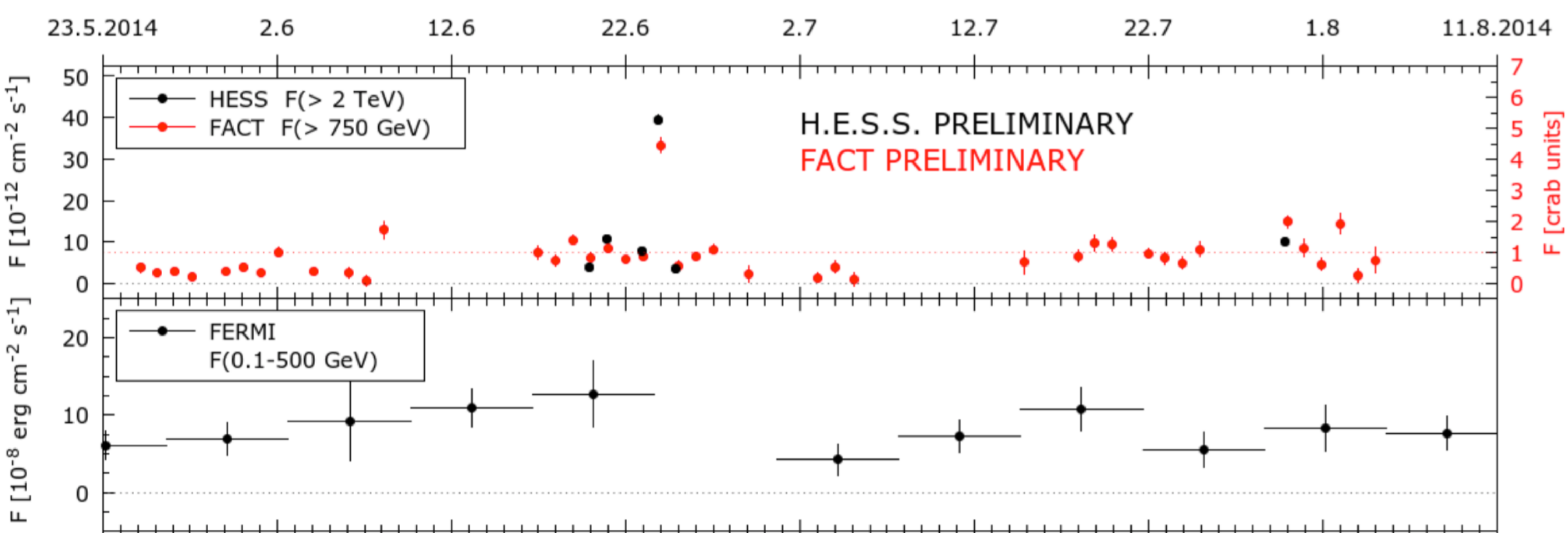

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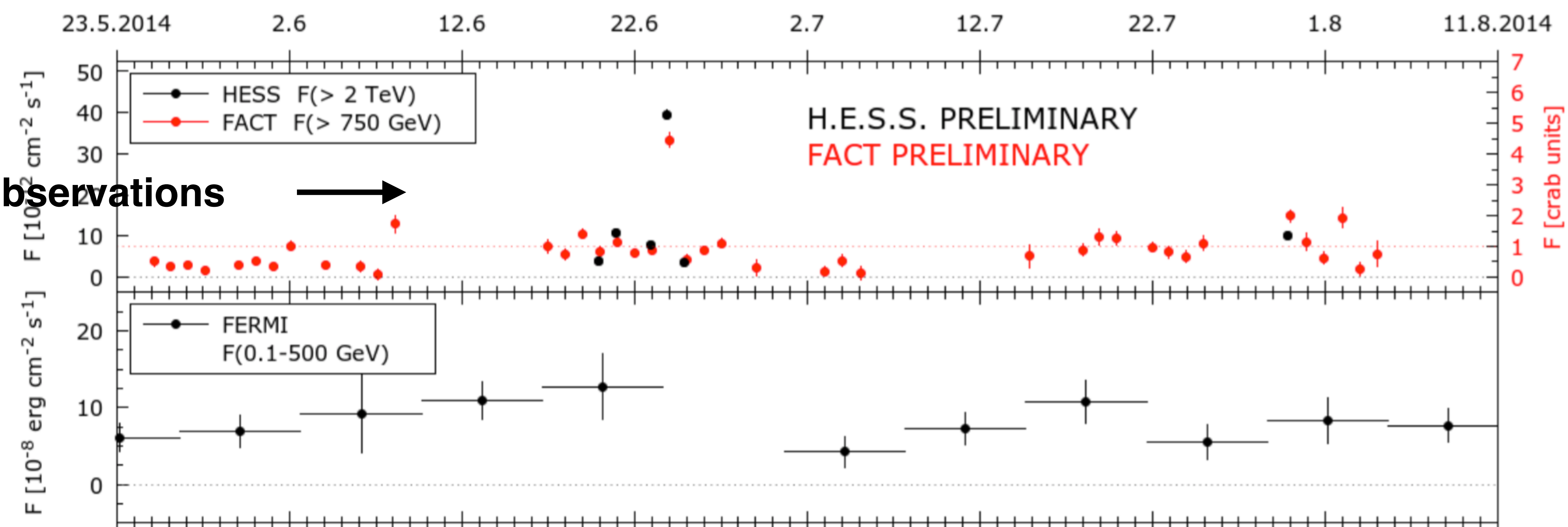
HESS II Observations →



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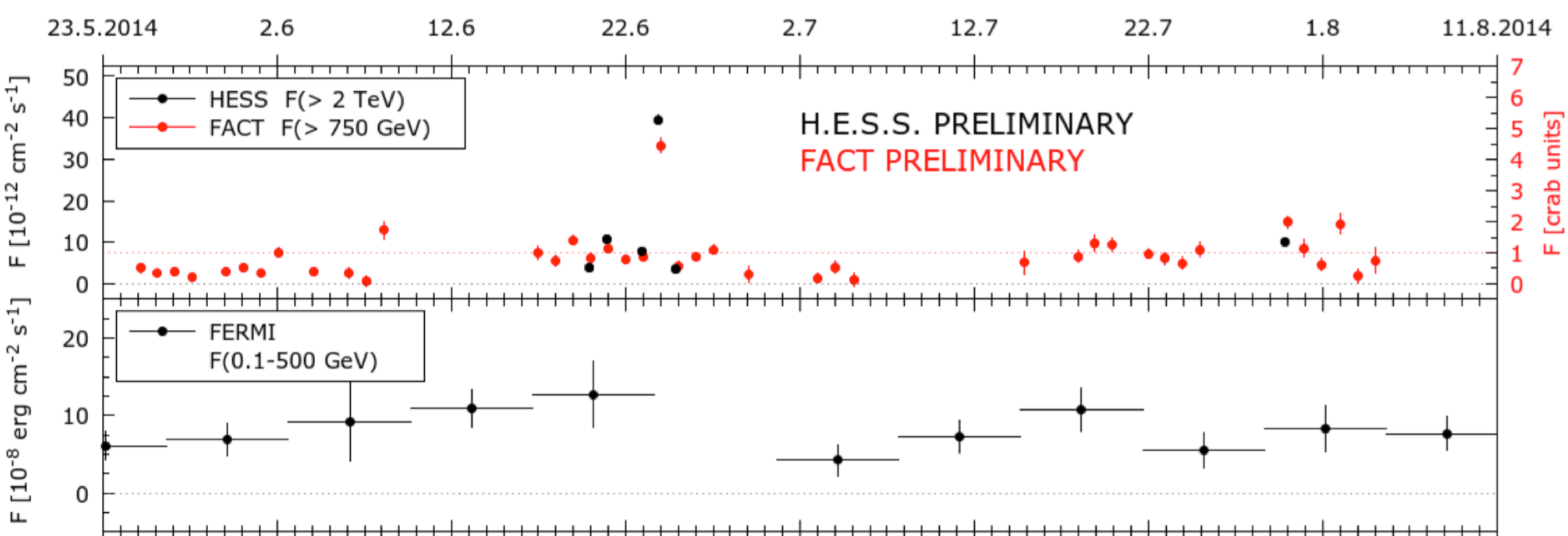

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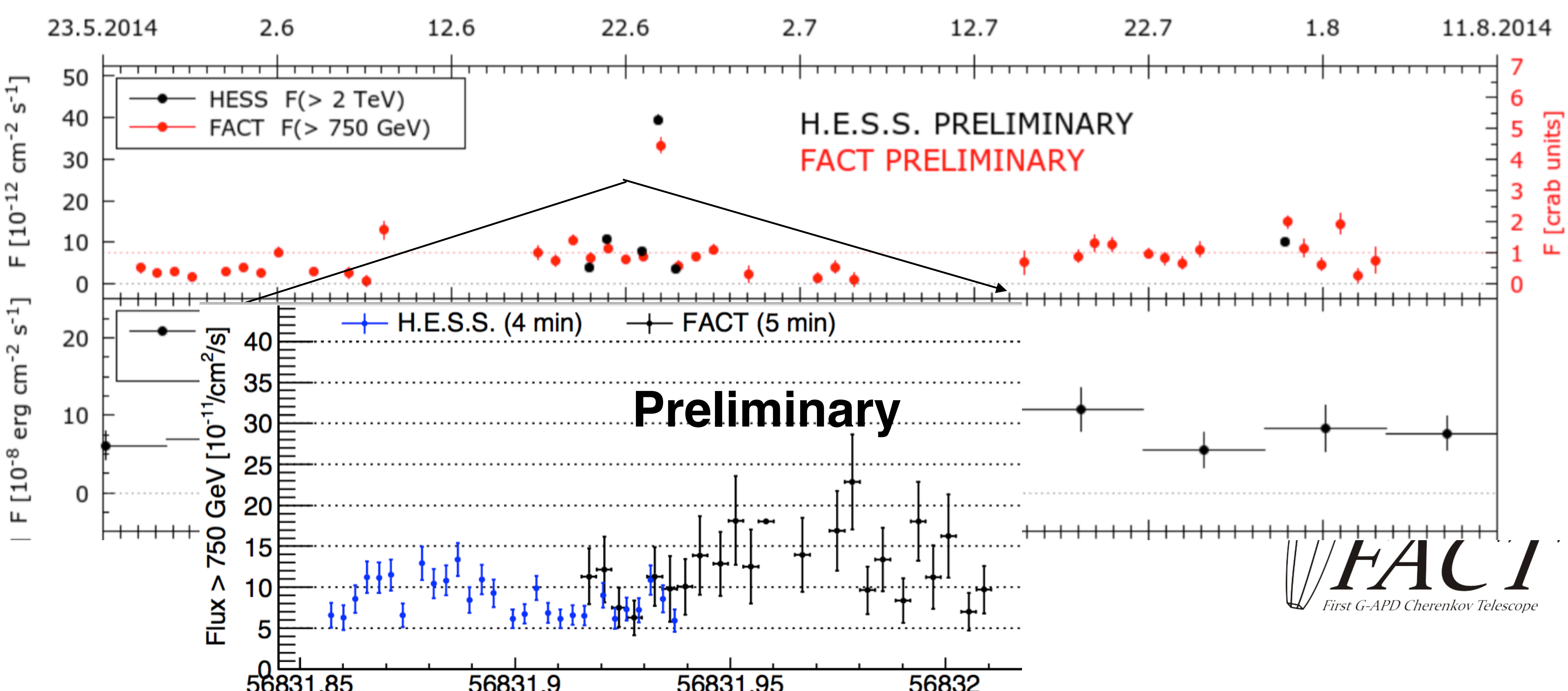

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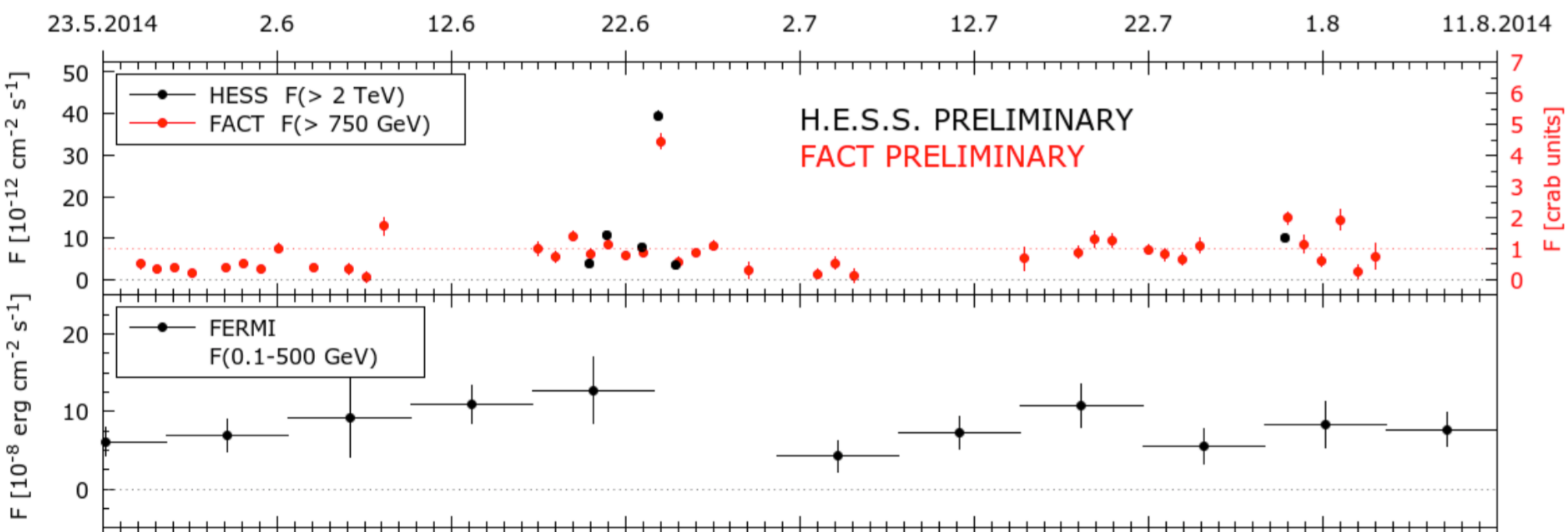

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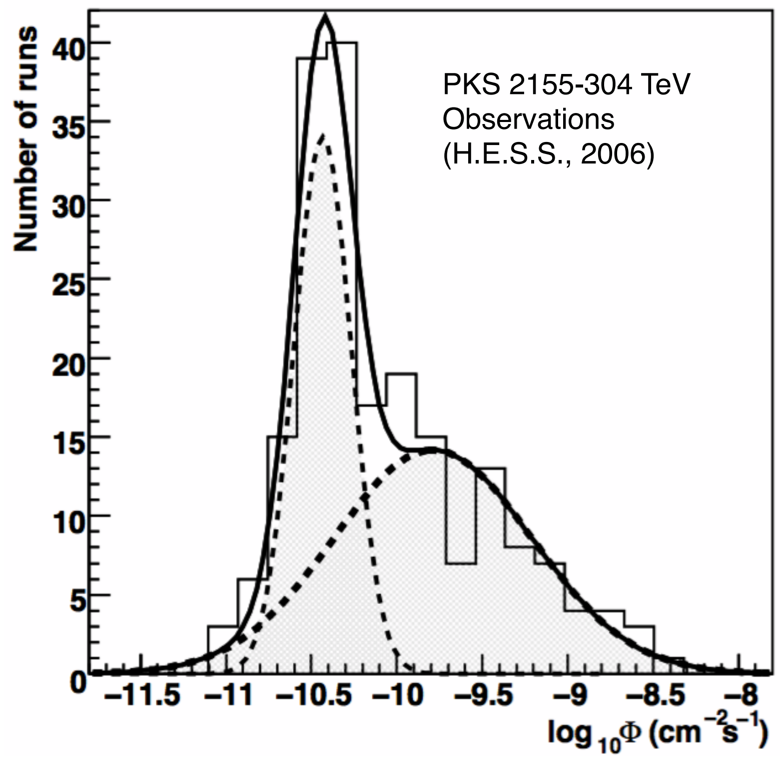
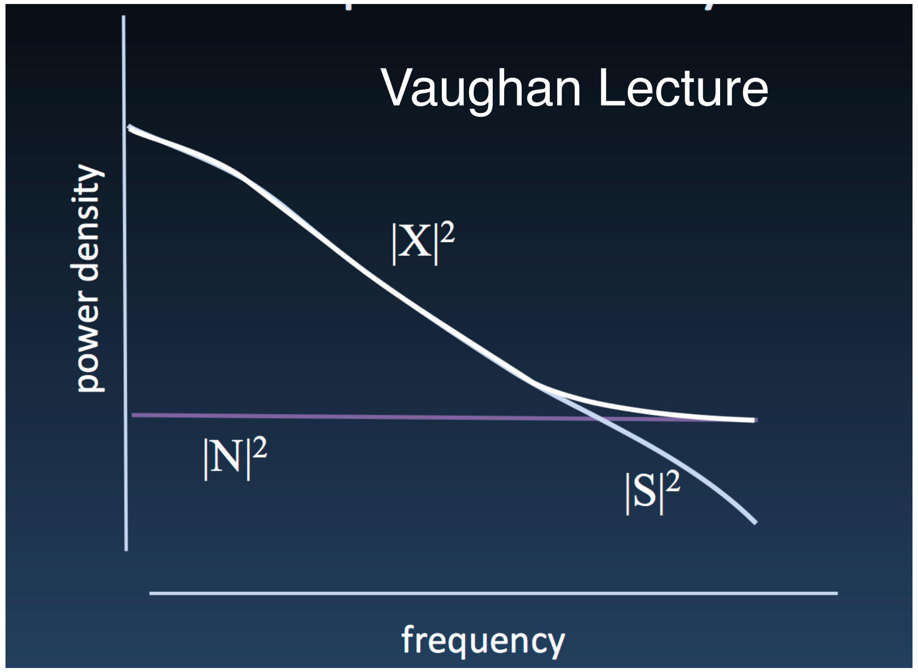
Beyond max fluxes and min timescales





- **Distribution of fluxes (or PDF) probes the fundamental form of the physical processes**

- Default assumption is Gaussian ; evidence for lognormality => Multiplicative **(Lyubarskii 97, Uttley et a., 2005)** or Cascade like processes (exception see Biteau and Giebels, 2012)

- **Distribution of timescales" (or PSD) encodes temporal structure**

- Time : x = s + n (Vaughan Lecture)
  Fourier : X = S + N
  $|X|^2 = |S|^2 + |N|^2$ + Cross
  PSD(f) $= \langle |S|^2 \rangle = \langle |X|^2 \rangle - \langle |N|^2 \rangle$

- Formally (for AGNs and others)
  Time : Lightcurve(t) = Dynamical(t) x Acceleration(t) x Radiation(t) x Observation(t) **[Product]**

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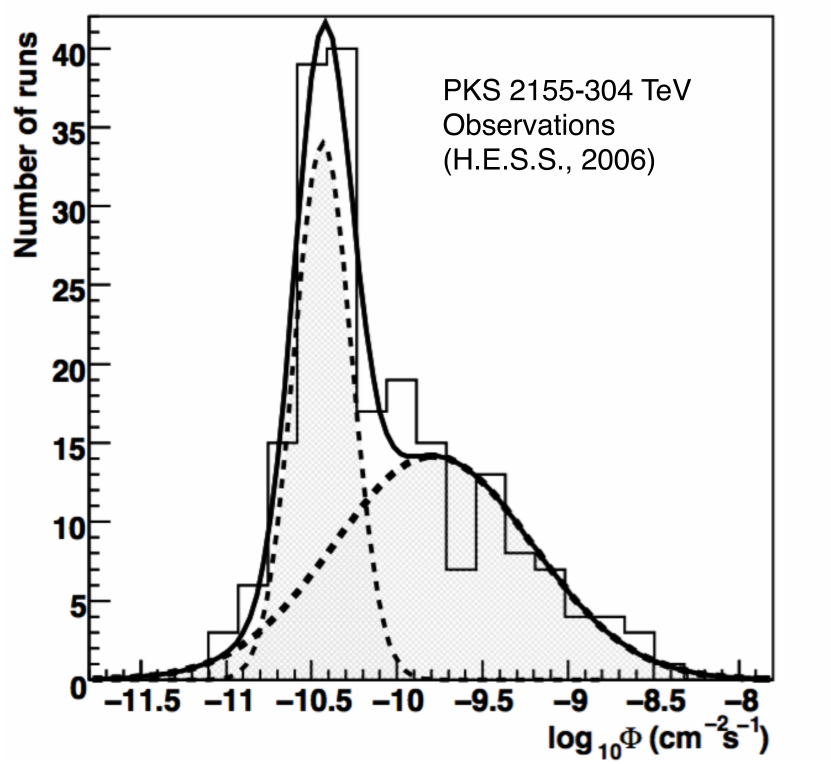
Beyond max fluxes and min timescales

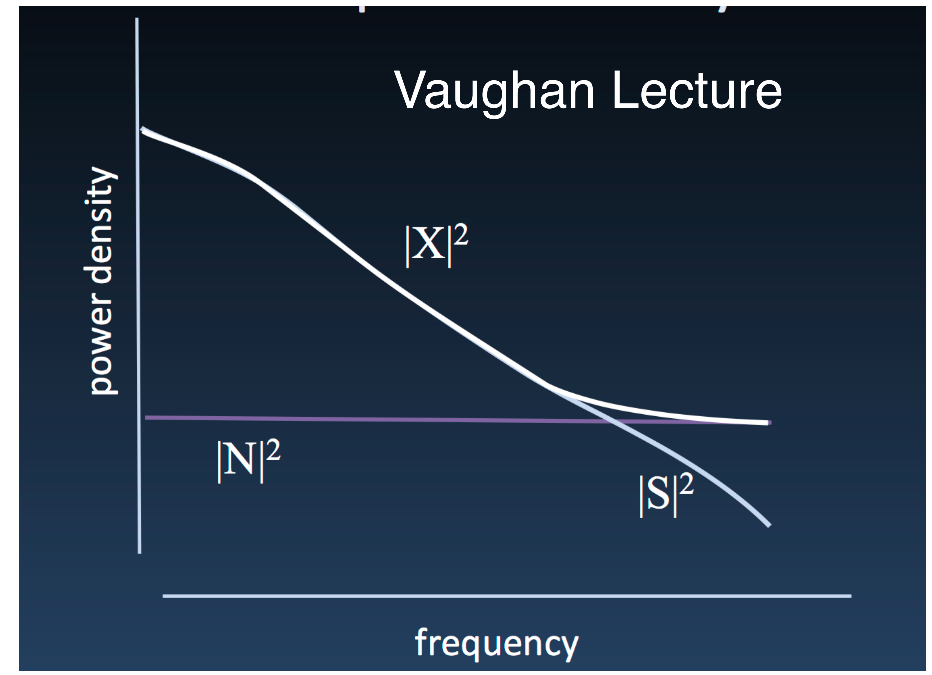


- **Distribution of fluxes (or PDF) probes the fundamental form of the physical processes**

$$\sum f_i(t) = f_1(t) + f_2(t) + ... \xrightarrow{\text{Central Limit Theorem}} \frac{e^{-\left(\frac{f-\mu_f}{\sigma_f}\right)^2}}{2\,\pi\,\sigma_f^2}$$

Multiplicative **(Lyubarskii 97, Uttley et a., 2005)**

$$\prod f_i(t) \xrightarrow{\log} \log\left[f_1(t)\right] + \log\left[f_2(t)\right] + ... \xrightarrow{\text{Central Limit Theorem}} \frac{e^{-\left(\frac{\log f-\mu_{lf}}{\sigma_{lf}}\right)^2}}{2\,\pi\,\sigma_{lf}^2}$$



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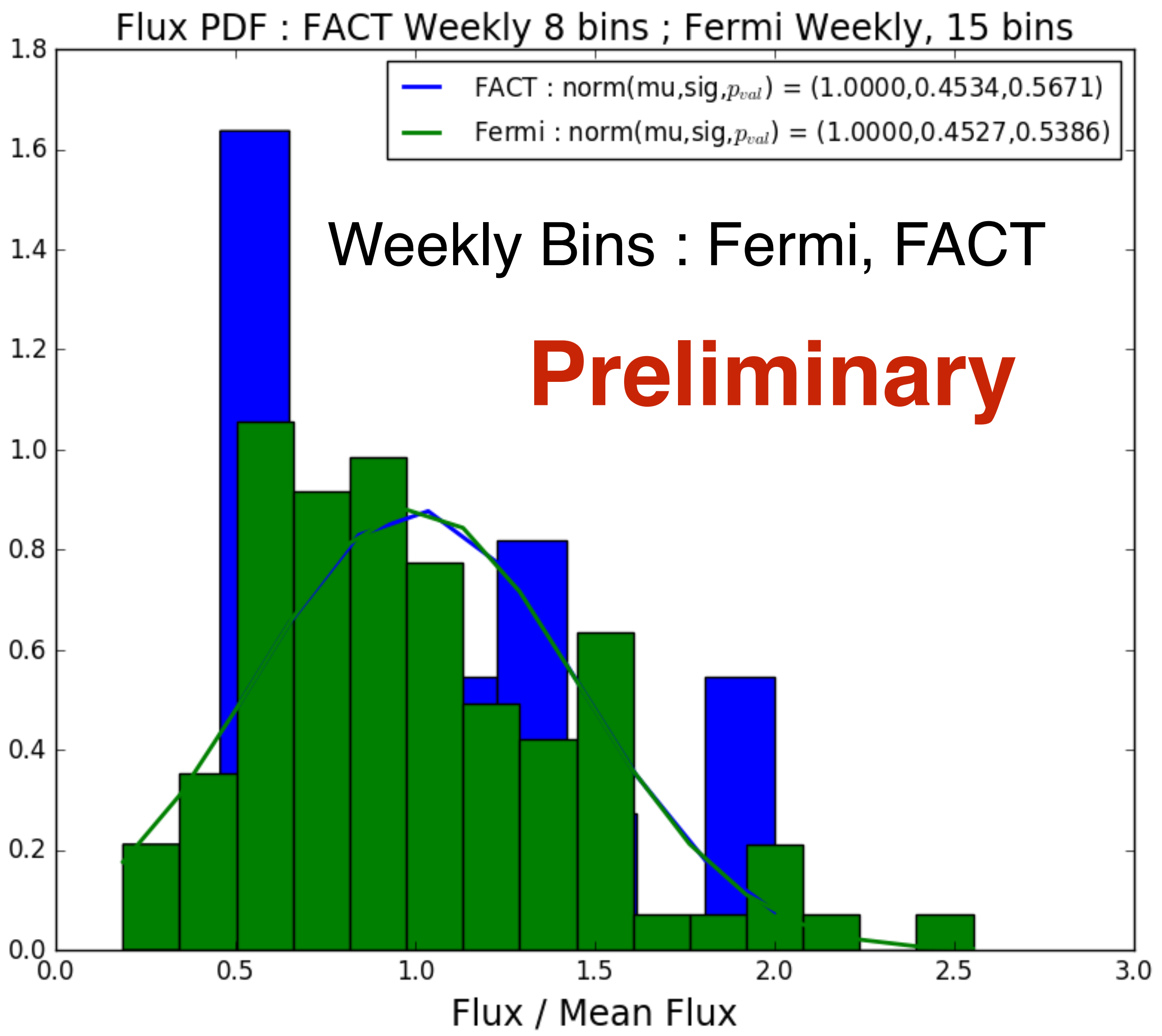
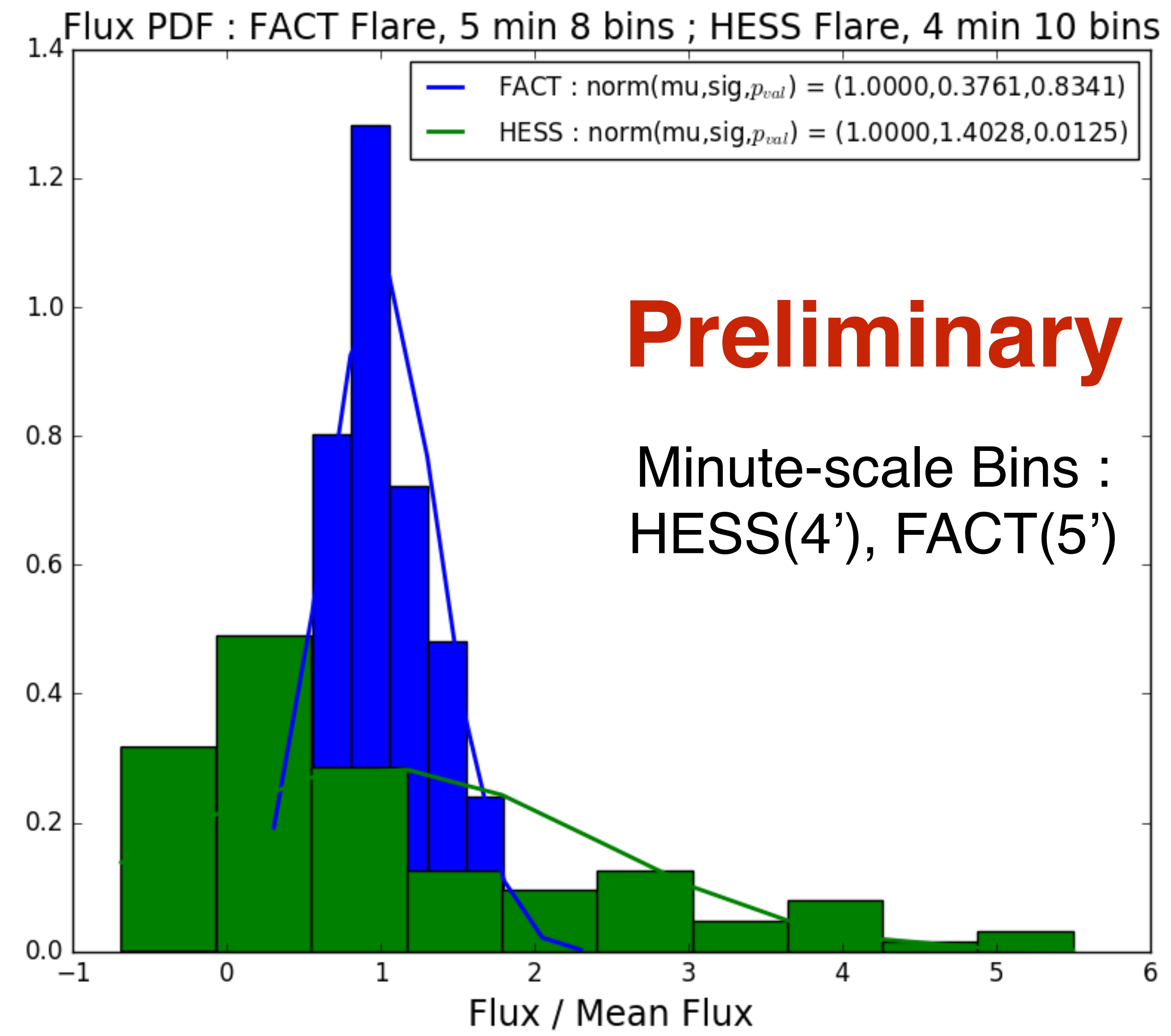
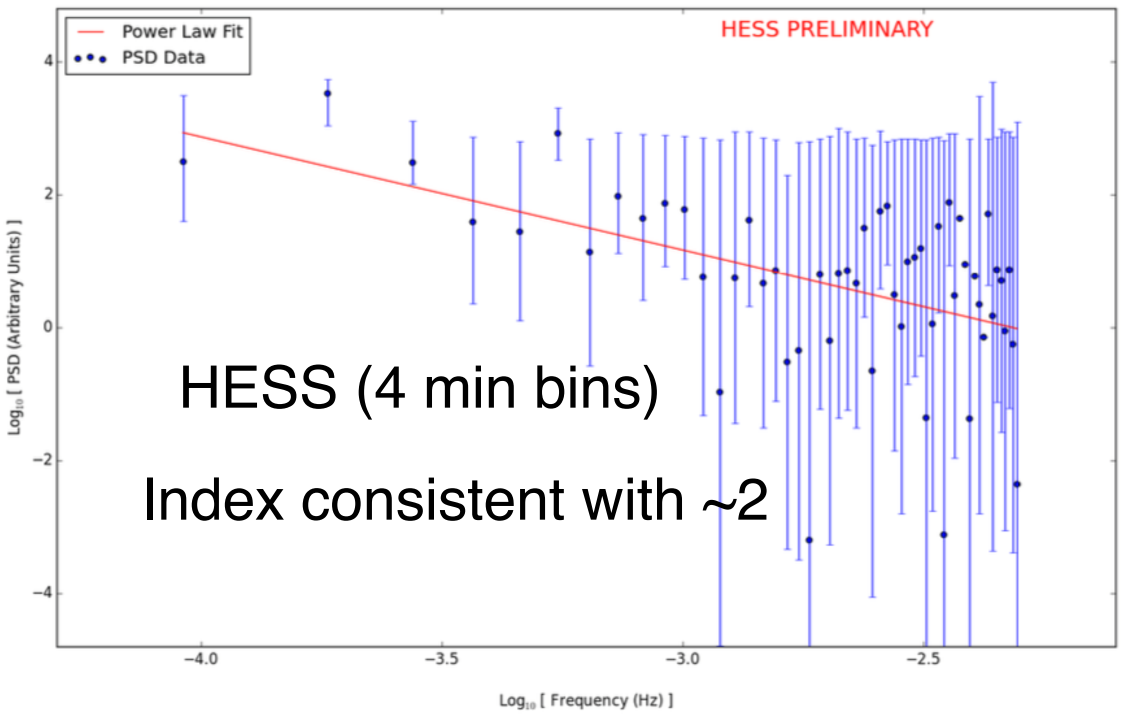
Temporal behavior : Flux PDF

- ***Deviations from normal PDF at GeV - TeV*** energies (not additive for ɣ-rays)
- Skew from normal towards higher fluxes / lognormality seen
- Similarity to PKS 2155-304 flare

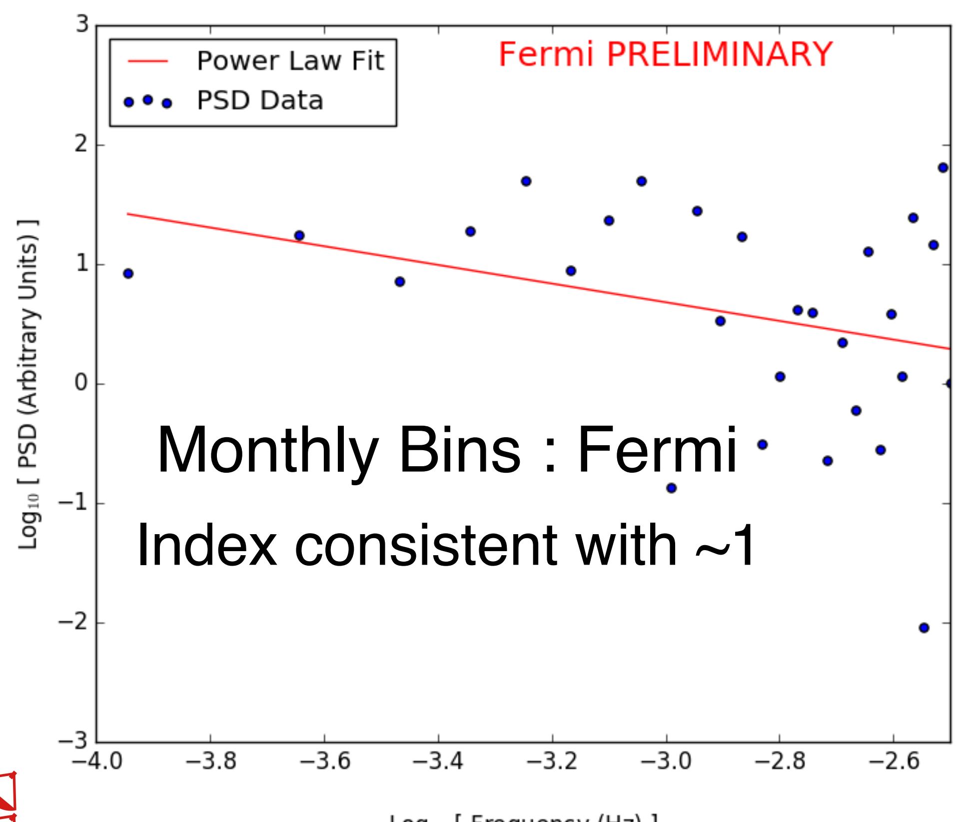




Temporal behavior : Power Spectral Density (PSD)

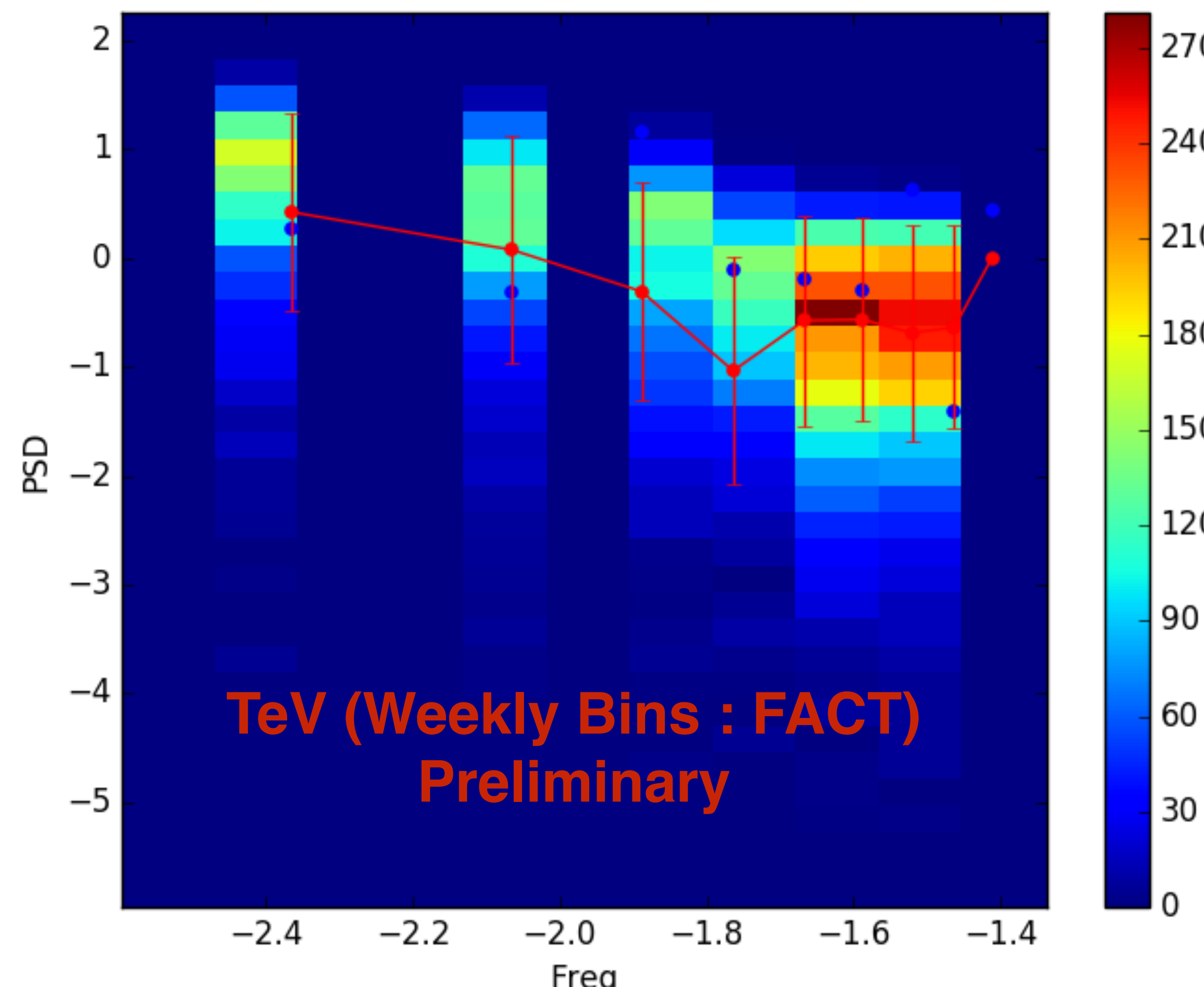


Observational biases and uncertainties => Simulations



- Initial estimates encouraging -> Long term seems to be close to index ~ 1

- Stay tuned….

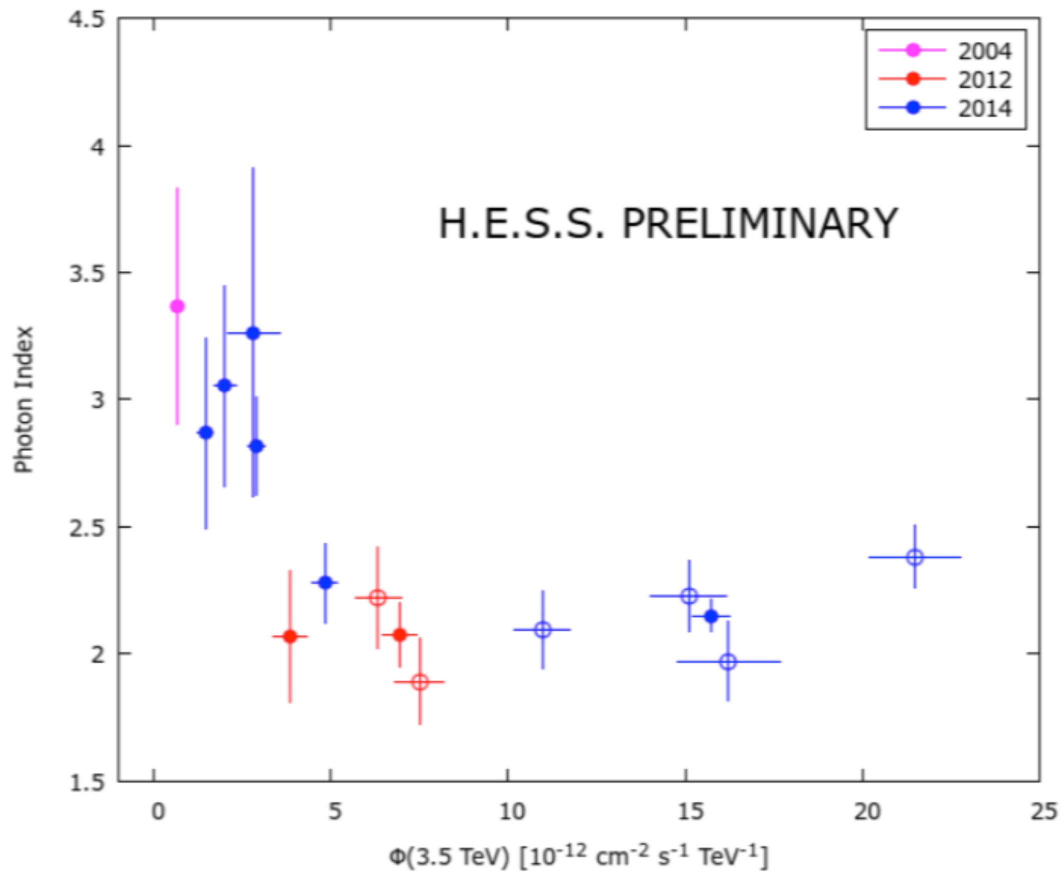


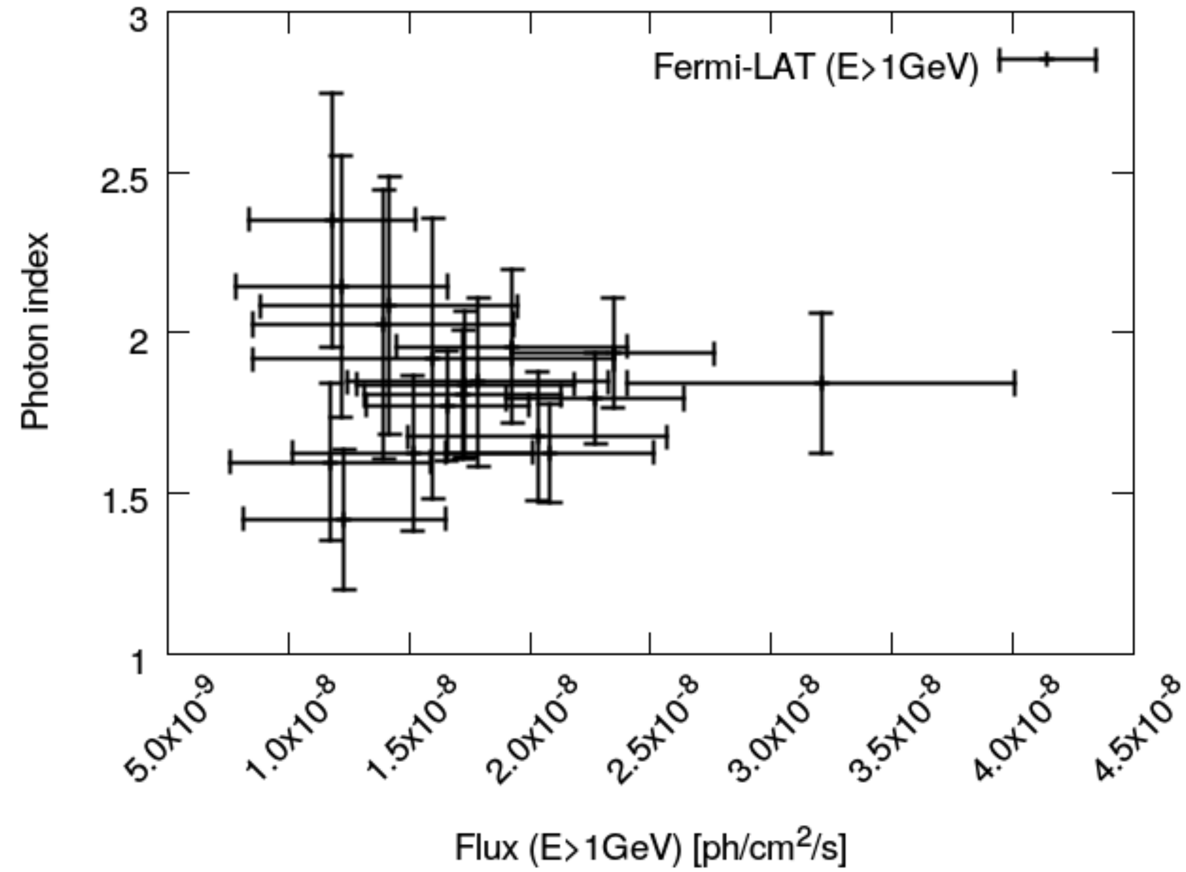
FACT Weekly : PSD index ~ 1

(trends of reduced chi-square and residuals give $\beta = 0.8$)

Spectral Behavior

- Harder when brighter
- Possible Bi-modal behavior
- Could relate to -> Complex superposition of multiple emission zones (Shukla et al.,2015)





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First G-APD Cherenkov Telescope

Lorentz invariance violation and γ-ray absorption

Symmetry breaking around Planck energy in some quantum gravity models

$$E_{\mathrm{LIV}}^{n}/\xi_n = E_{\mathrm{Planck}} = \sqrt{\hbar c^5/G} \simeq 1.22 \times 10^{28} eV$$

⇒ Propagates into EBL optical depth

Jacob, U., & Piran, T. (2008). Phys. Rev D, arxiv 0810.1318

Fairbairn, M., Nilsson, A., Ellis, J., Hinton, J., & White, R. (2014) JCAP

Effective parameterization of LIV with modified dispersion relation

$$E_\gamma^2 = p_\gamma^2 \pm E_\gamma^2 \left(\frac{E_\gamma}{E_{\mathrm{LIV}}} \right)^n$$

courtesy : Matthias Lorentz, RICAP16

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$$\tau(E_\gamma, z_s) = c \int_0^{z_s} dz \frac{dt}{dz} \int_0^2 d\mu \frac{\mu}{2} \int_{\epsilon_{thr}}^{\infty} d\epsilon \frac{dn_{EBL}(\epsilon, z)}{d\epsilon} \sigma_{\gamma\gamma} \left(E_\gamma(1+z), \epsilon, \mu\right)$$

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Cross-section and threshold

Ef $s \rightarrow s \pm \frac{E_\gamma^{n+2}}{E_{\mathrm{LIV}}^{n}}$ $\epsilon_{\mathrm{thr}} \rightarrow \epsilon_{\mathrm{thr}} \mp \frac{1}{4}\frac{E_\gamma^{n+1}}{E_{\mathrm{LIV}}^{n}}$ rsion relation

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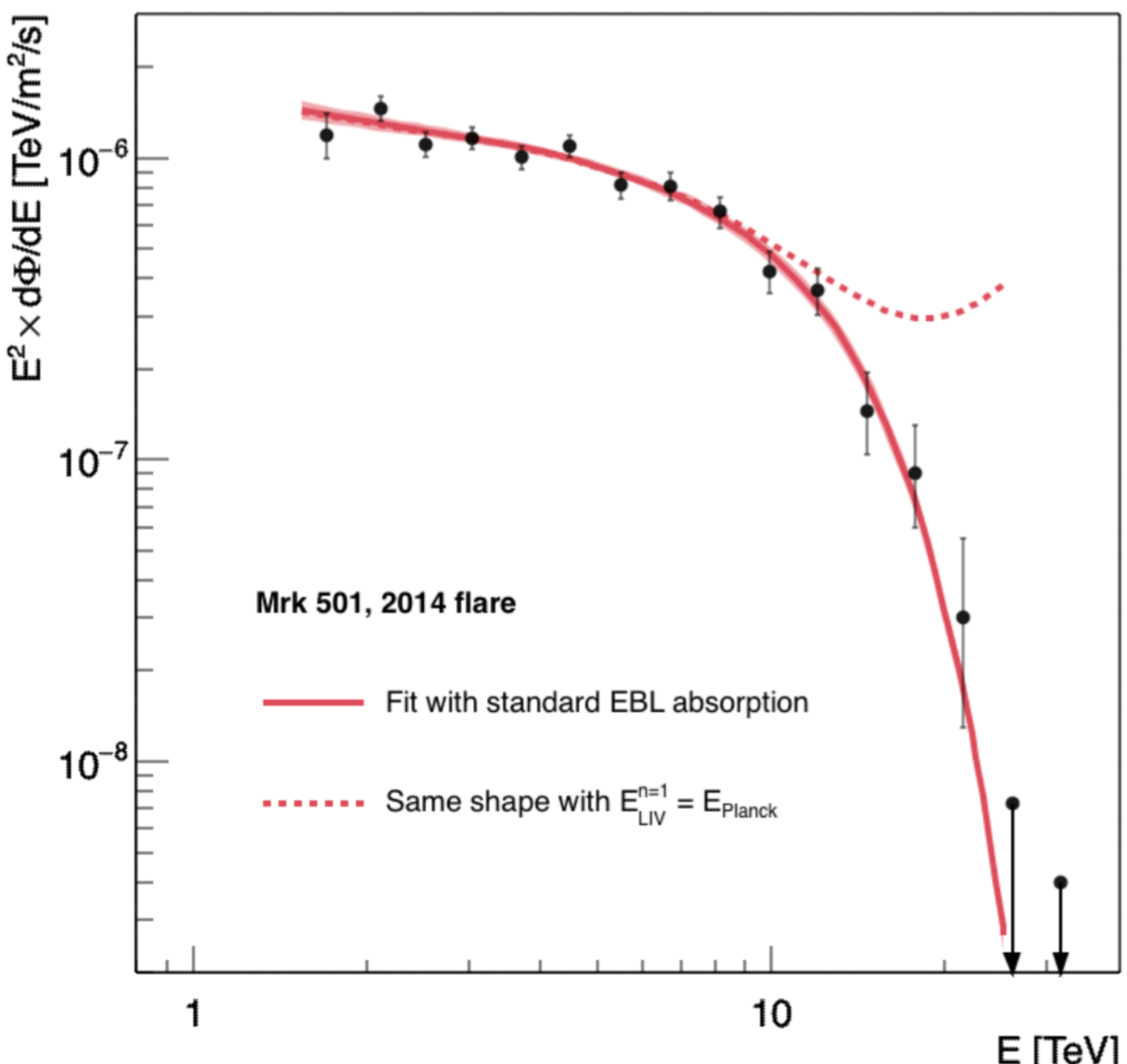
Mrk 501, 2014 flare : VHE spectrum

H.E.S.S. phase I analysis
G. Cologna et al. (ICRC 2015)

Well fitted by an EBL- absorbed power law, up to ~ 20 TeV

No sign of intrinsic curvature

- ➢ Probe ~ 10^{-2} eV EBL region
- ➢ **Ideal to test LIV at E_{Planck}**



$$\frac{d\Phi_{\rm int}}{dE} = (1.68 \pm 0.16) \times 10^{-6} \left(\frac{E}{1\ \rm TeV}\right)^{-2.15\pm0.06} \rm m^{-2}\ s^{-1}\ TeV^{-1}$$

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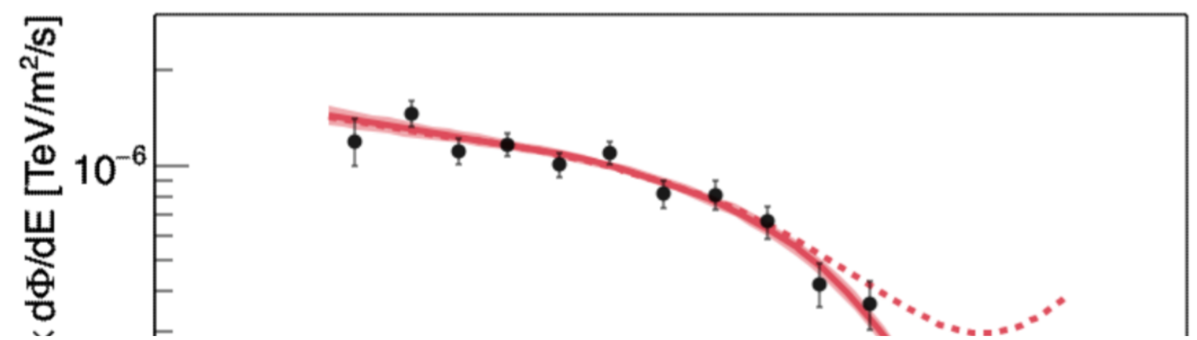

Best limits obtained with AGNs

	$2\,\sigma$	$3\,\sigma$	$5\,\sigma$
n=1	2.8×10^{28} eV ($2.29 \times E_{\text{Planck}}$)	1.9×10^{28} eV ($1.6 \times E_{\text{Planck}}$)	1.04×10^{28} eV ($0.86 \times E_{\text{Planck}}$)
n=2	7.5×10^{20} eV	6.4×10^{20} eV	4.7×10^{20} eV

- **Ideal to test LIV at E_{Planck}**

$$\frac{d\Phi_{\text{int}}}{dE} = (1.68 \pm 0.16) \times 10^{-6} \left(\frac{E}{1\ \text{TeV}}\right)^{-2.15\pm0.06} \text{m}^{-2}\ \text{s}^{-1}\ \text{TeV}^{-1}$$

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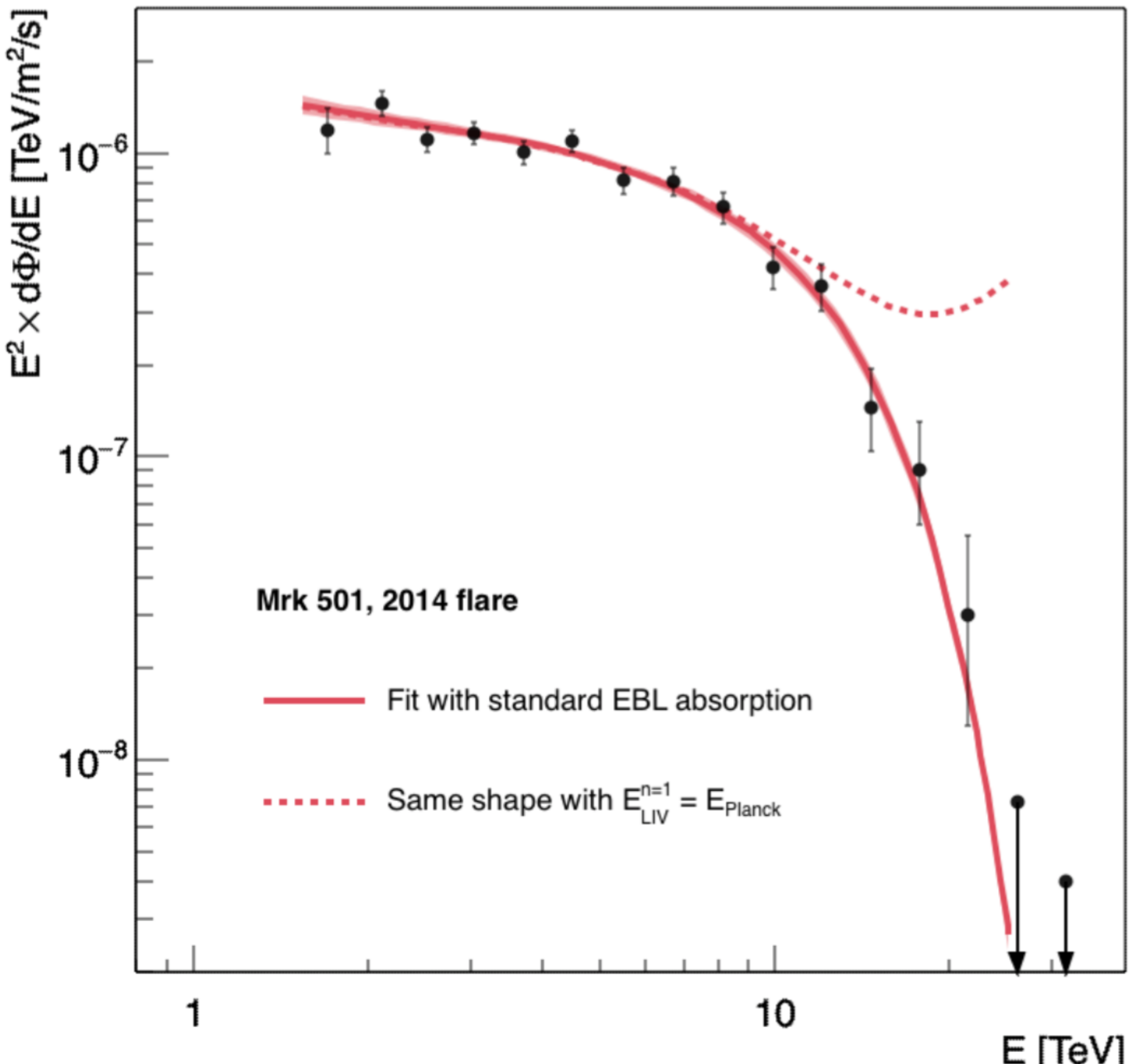

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Conclusions

- *Complementarity* of HESS, FACT and Fermi are exploited in exploring the *complex temporal and spectral behavior* of Mrk 501 in gamma-rays

Individual properties

- Rapid variability down to few minutes in the 2-20 TeV energy range during flares
  - extends preference for lepton induced VHE emission to above 2 TeV
  - sufficient statistics for probing structure of variations
- Deviations from normal PDF -> not simple superposition
- PSD index compatible w
- Hints of bimodal behavior in spectral index - flux relation (clear ones at GeV, complex at TeV)

General properties

- Strong limits on the LIV energy scale
  - strongest limits for the quadratic scenario

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First G-APD Cherenkov Telescope

Thank you for your attention !

- Gabriele Cologna (LSW, Heidelberg Germany)
  Mahmoud Mohamed
  Stefan J. Wagner
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- Daniela Dorner (Univ of Wuerzburg, Germany)
  Michael Blank
  Maximilian Noethe (TU Dortmund)

- Carlo Romoli (DIAS, Dublin, Ireland)
  Andrew Taylor

- Omar Kurtanidze (Abastumani, Georgia)

- Agnieszka Jacholkowska (LPNHE, Paris, France)

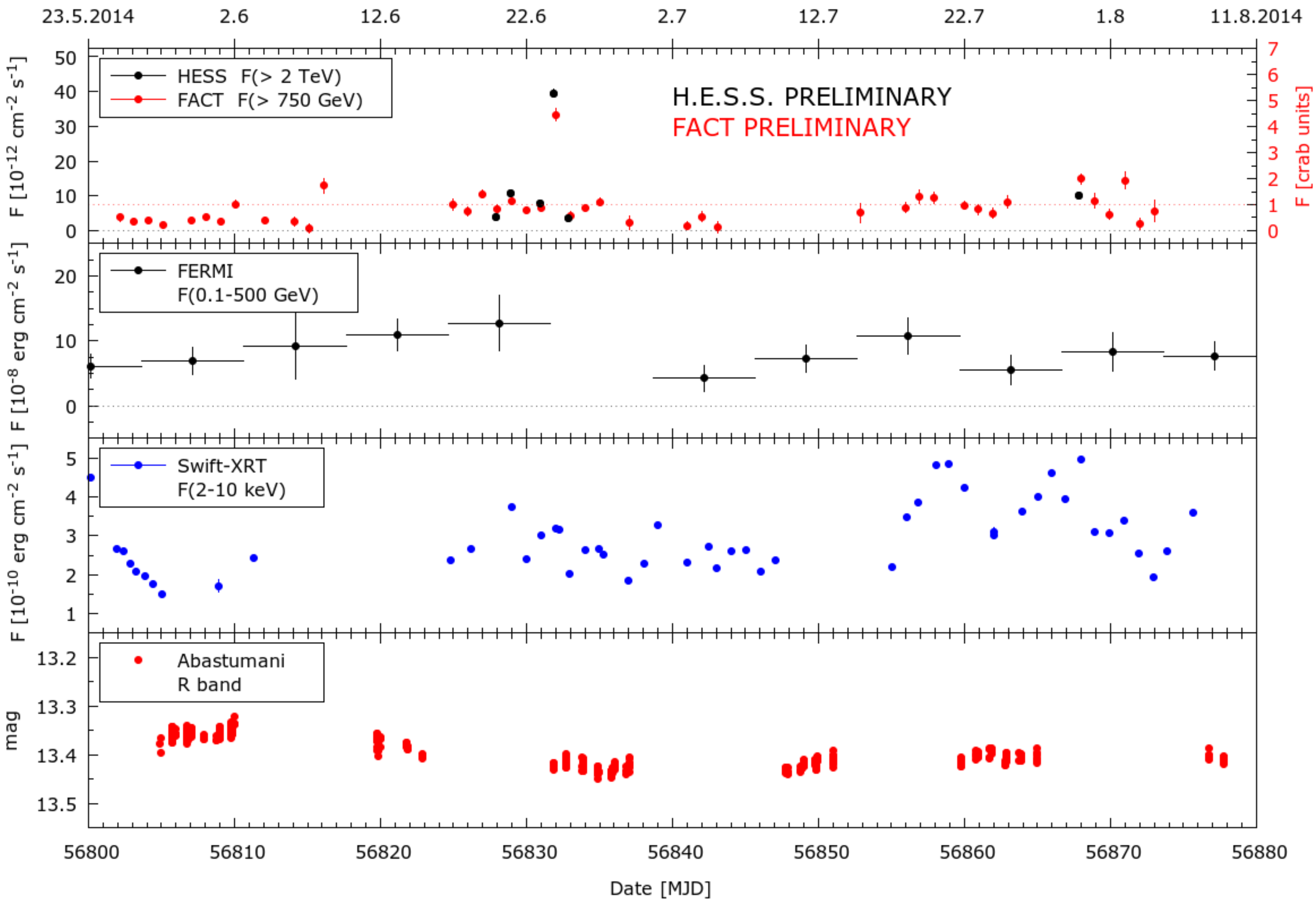
- Matthias Lorentz (CEA, Saclay, France)
  Pierre Brun

- Nachiketa Chakraborty (MPIK, Heidelberg, Germany)
  Frank Rieger

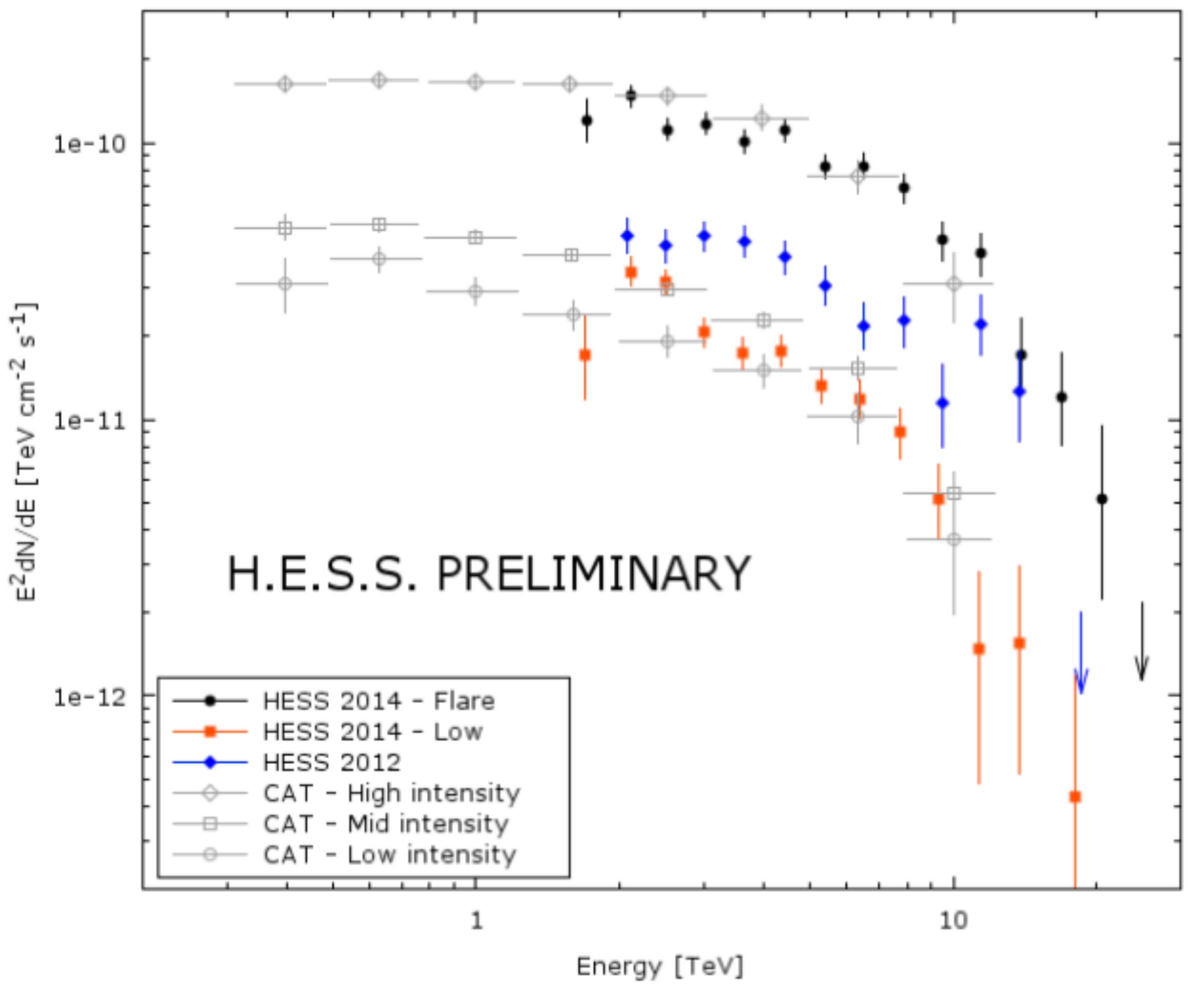
- Markus Böttcher (NWU, South Africa)

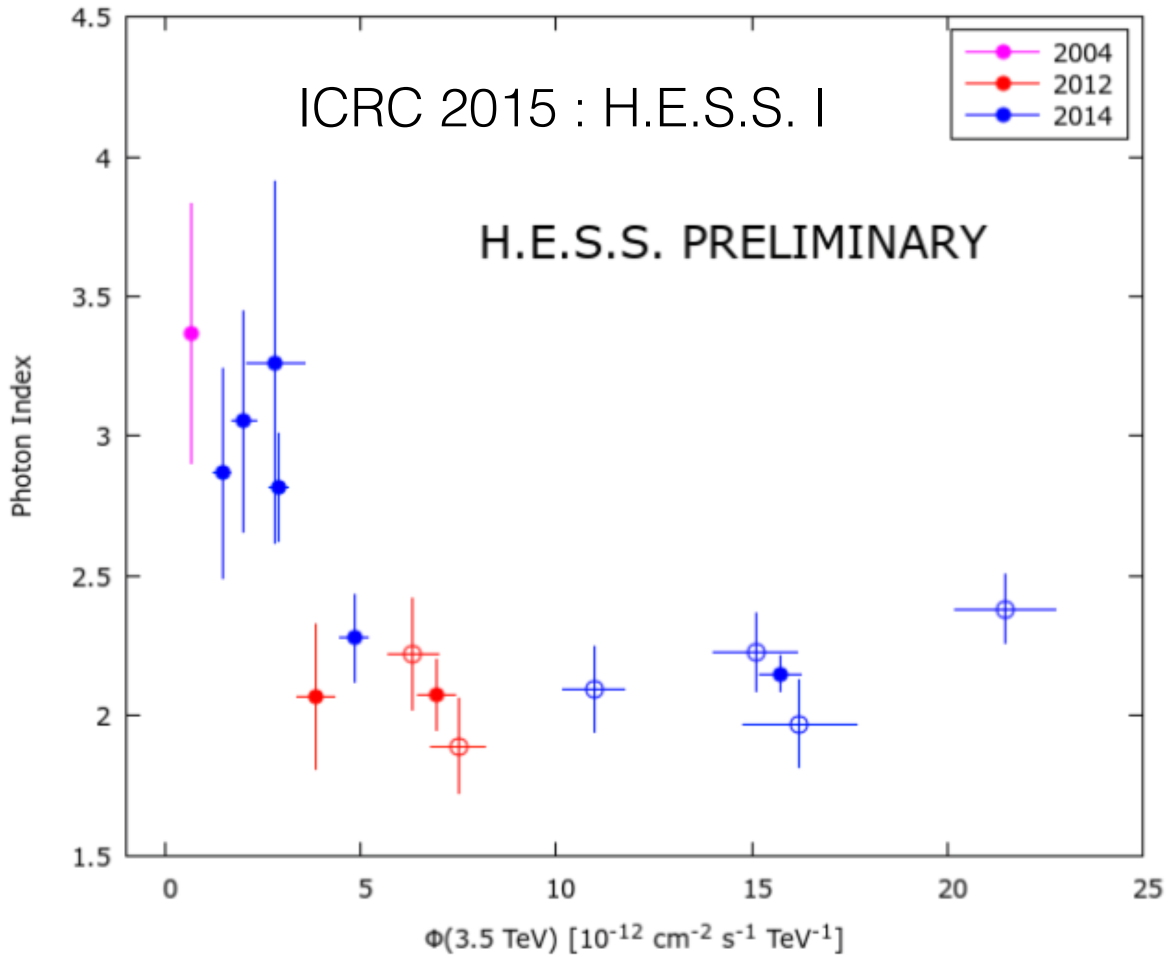
SUPPLEMENTARY

MWL Lightcurves

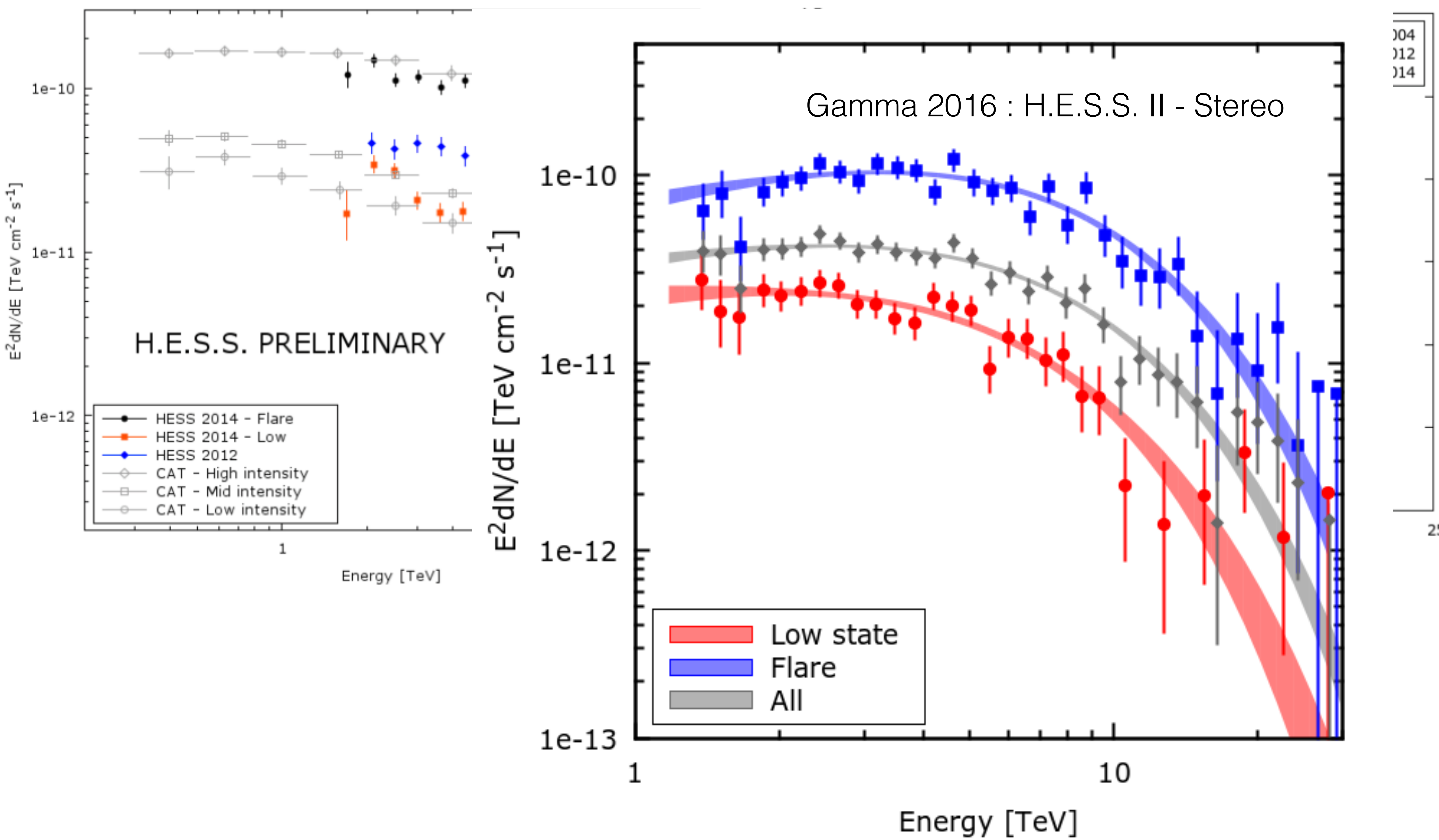


Spectral States

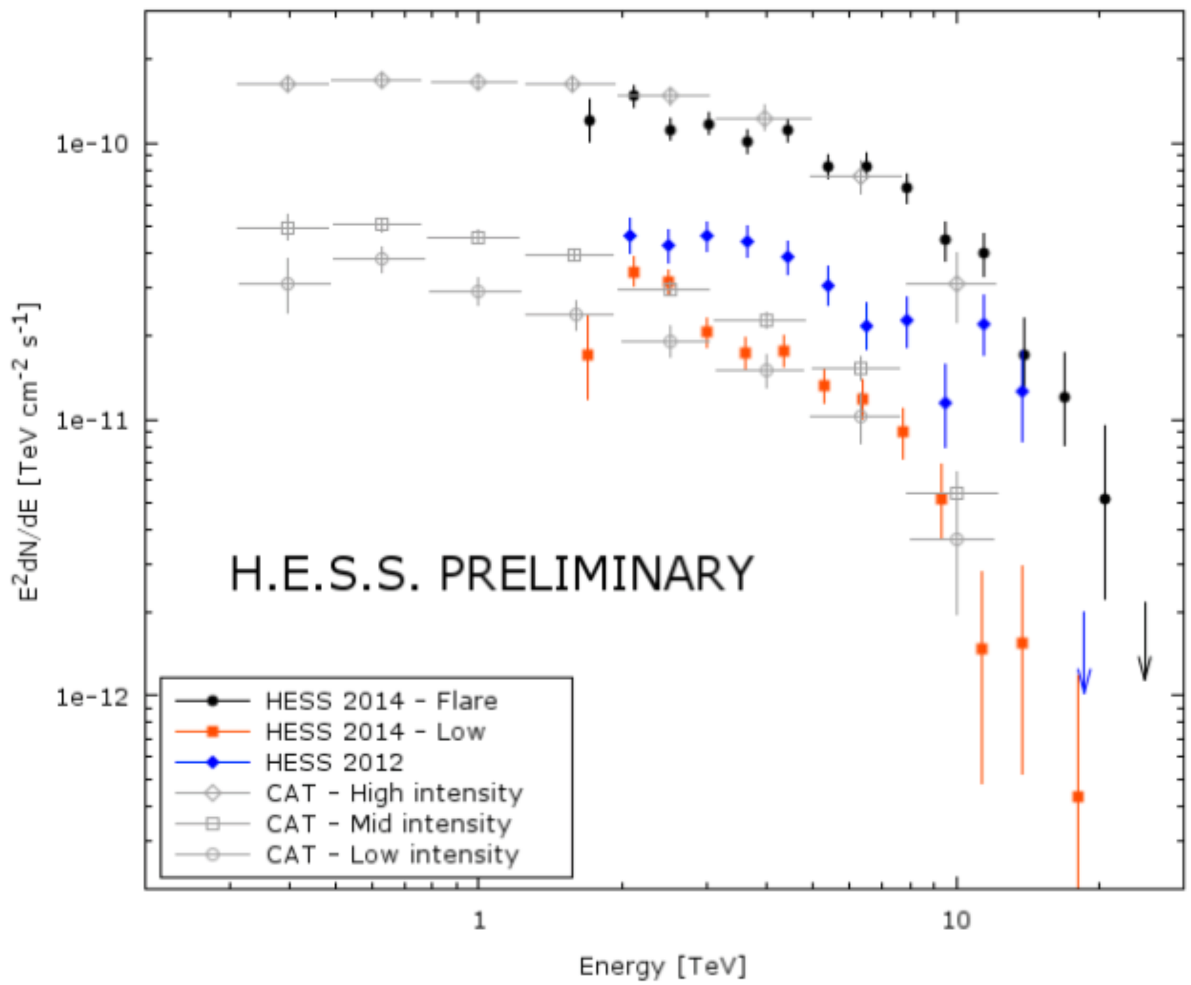


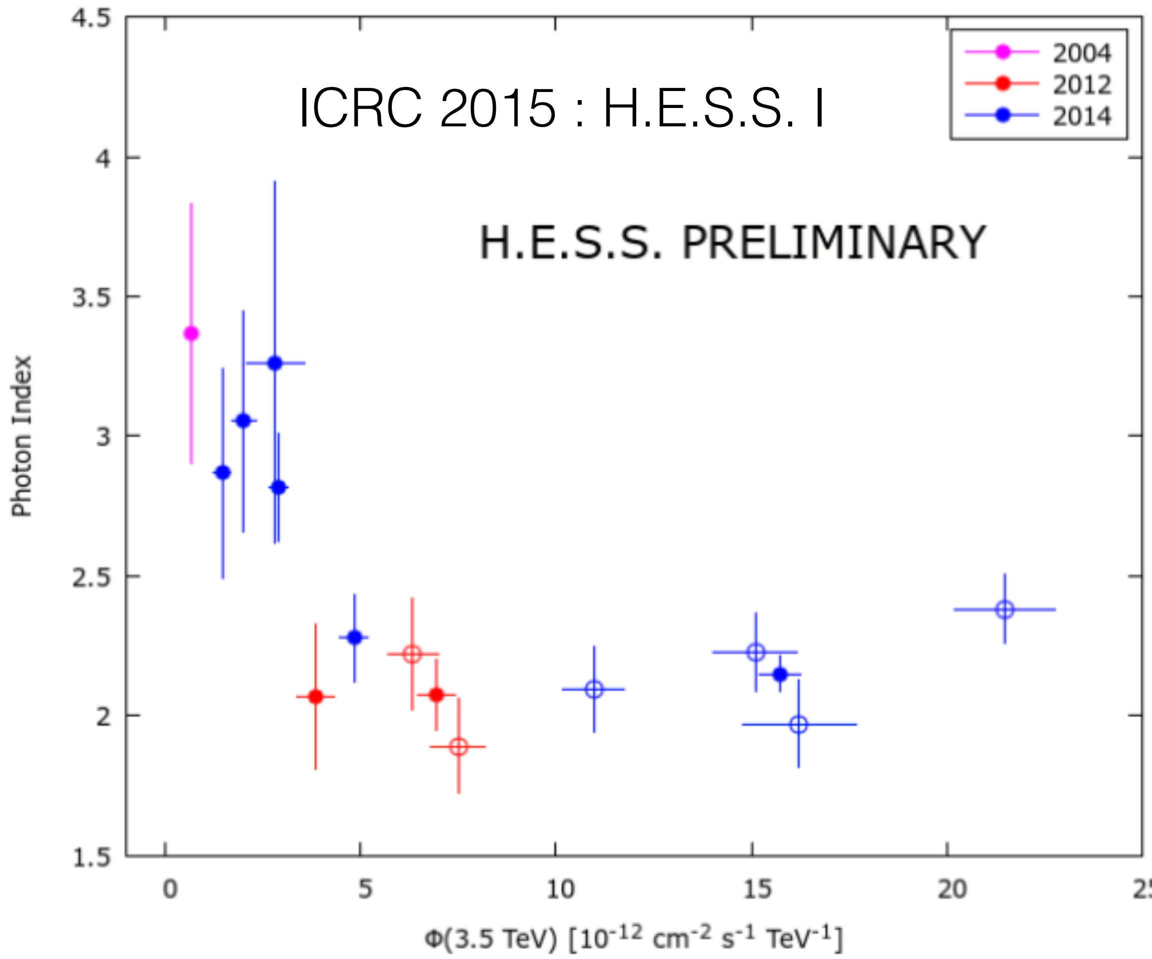


Spectral States



Spectral States





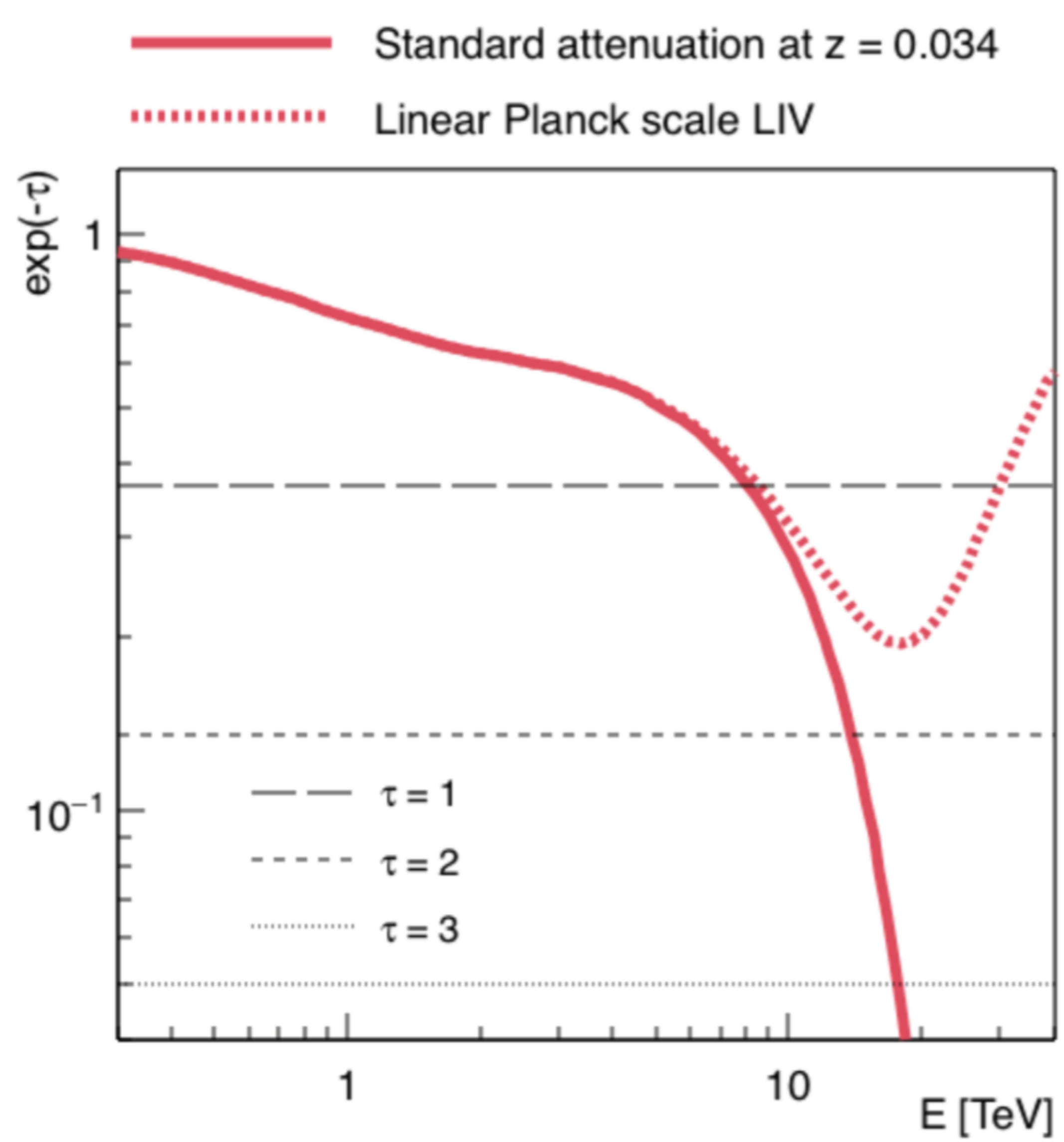
LIV : Optical Depth

LIV-modified dispersion relation affects pair creation threshold
⇒ Propagates into EBL optical depth

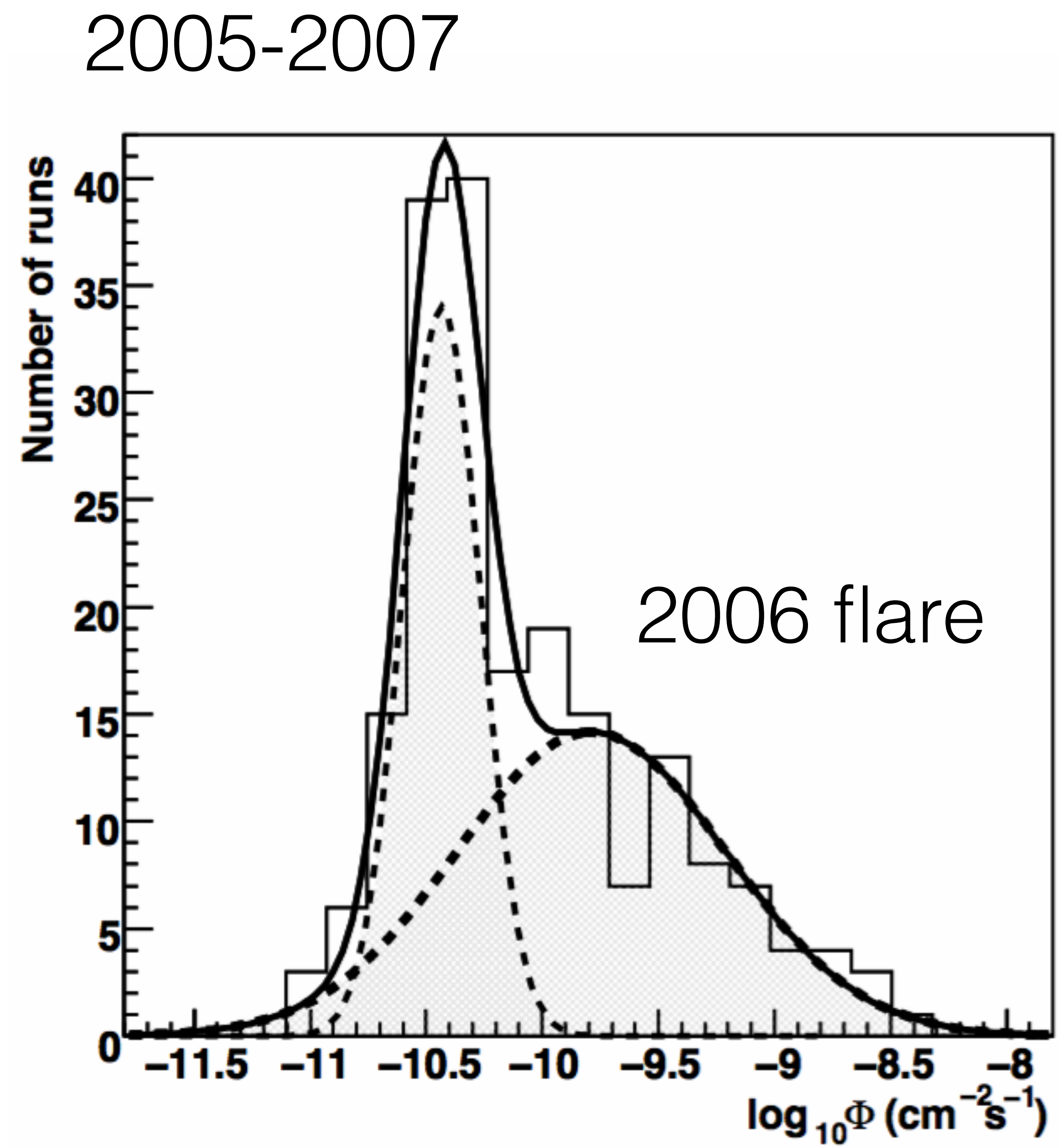
Subluminal scenario : reduced opacity at highest energies

Constraints on LIV scale, assuming NO intrinsic upturn - *Degenerate Effect*

FwdFolding fit with LIV-modified EBL optical depth



PKS 2155-304 : Spectral and Temporal Variability Paper



LIV exclusion limits : linear case

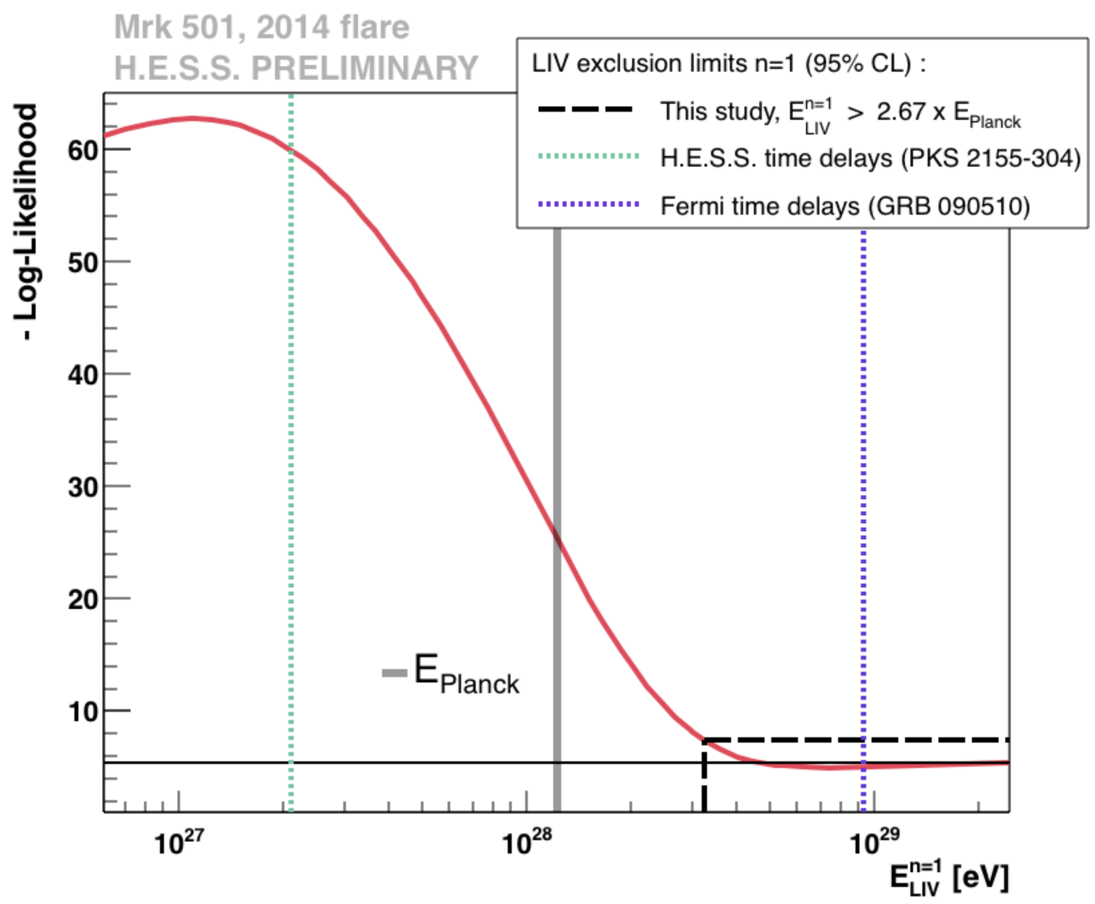
Scanning E_{LIV} values via τ with spectral parameters free in the fit

Fit reaches plateau
-> Standard case

$E^{n=1}_{LIV} > 2.67\ E_{Planck}$ (95% CL)

E_{Planck} excluded at 5.5 σ

Results are obtained with Franceschini EBL and prior of **no intrinsic curvature**



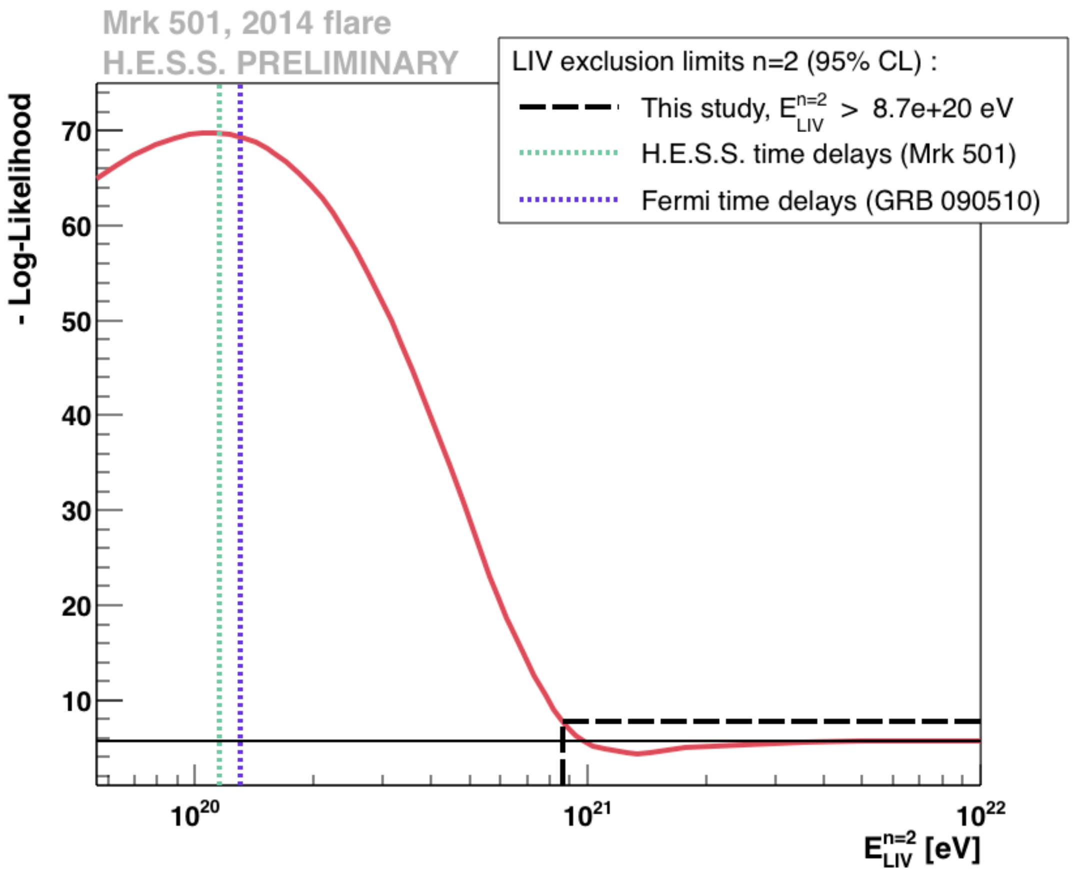
LIV exclusion limits : quadratic case

$E^{n=2}_{LIV} > 8.7 \times 10^{20}$ eV

(95% CL)

Currently the best

limits in the quadratic case



	$2\ \sigma$	$3\ \sigma$	$5\ \sigma$
n=1	3.3×10^{28} eV $(2.67 \times E_{\rm Planck})$	2.6×10^{28} eV $(2.13 \times E_{\rm Planck})$	1.7×10^{28} eV $(1.37 \times E_{\rm Planck})$
n=2	8.7×10^{20} eV	7.8×10^{20} eV	6.3×10^{20} eV

Time of flight measurements - Cologna, et al., ICRC 2015

Sub-luminal	8.5×10^{17} GeV	1.15×10^{11} GeV

H.E.S.S.

FACT First G-APD Cherenkov Telescope