J. BOLMONT

WG3 REVIEW TALK:
LOOKING FOR QG EFFECTS WITH ASTROPHYSICAL GAMMA-RAY SOURCES

SORBONNE UNIVERSITÉ
LPNHE PARIS
CNRS IN2P3 Les deux infinis

QG-MM Workshop
October 2-4, 2019
Barcelona

COST EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

WG3:

CHAIR: D. DOMINIS PRESTER
VICE-CHAIR: J. SITAREK

Milestone for year 1: Set-up a database of all existing results on LIV based on gamma-rays and publish it on web page. Compare the results and methods used.

QG-MM Workshop
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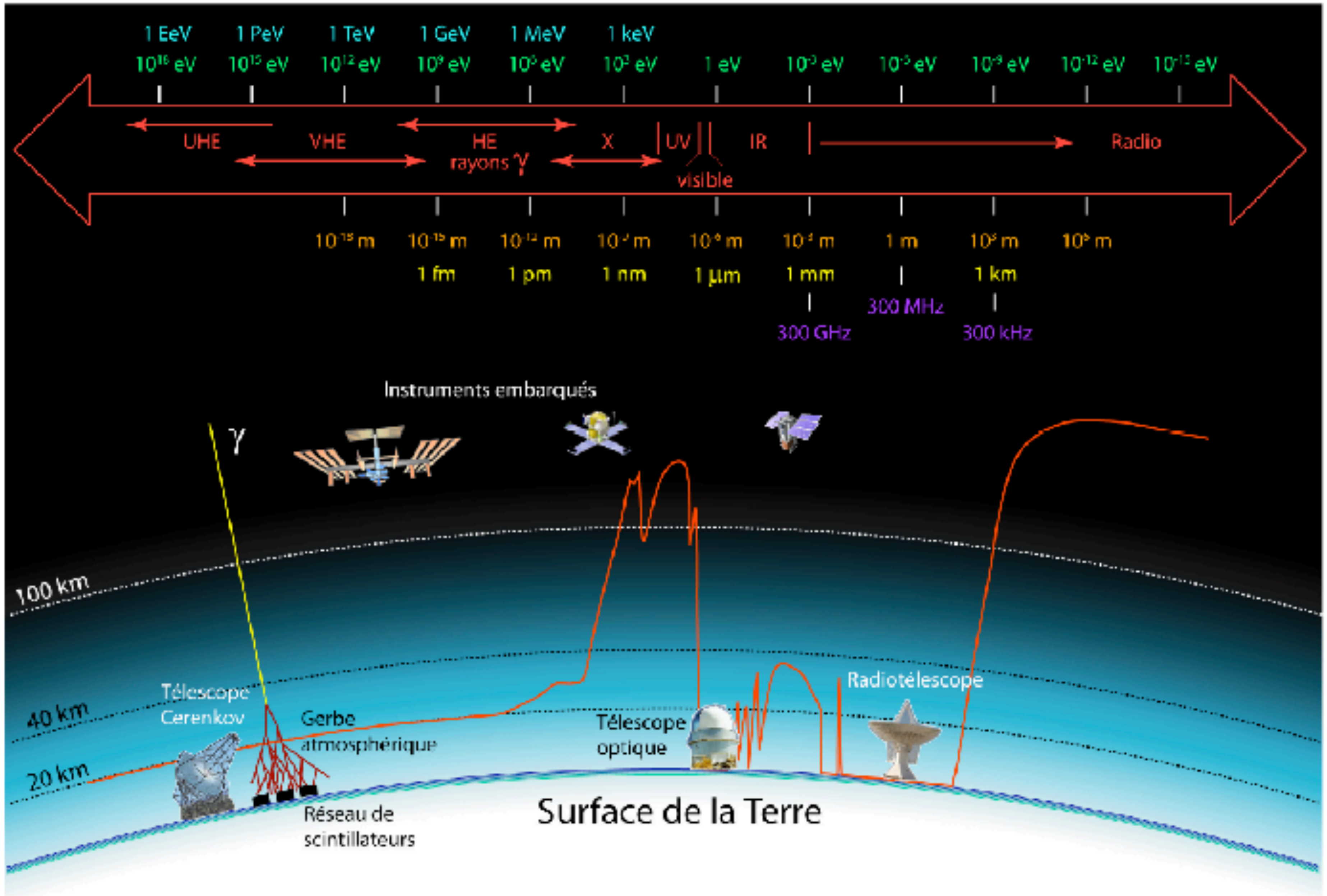
WHAT ARE WE TALKING ABOUT?



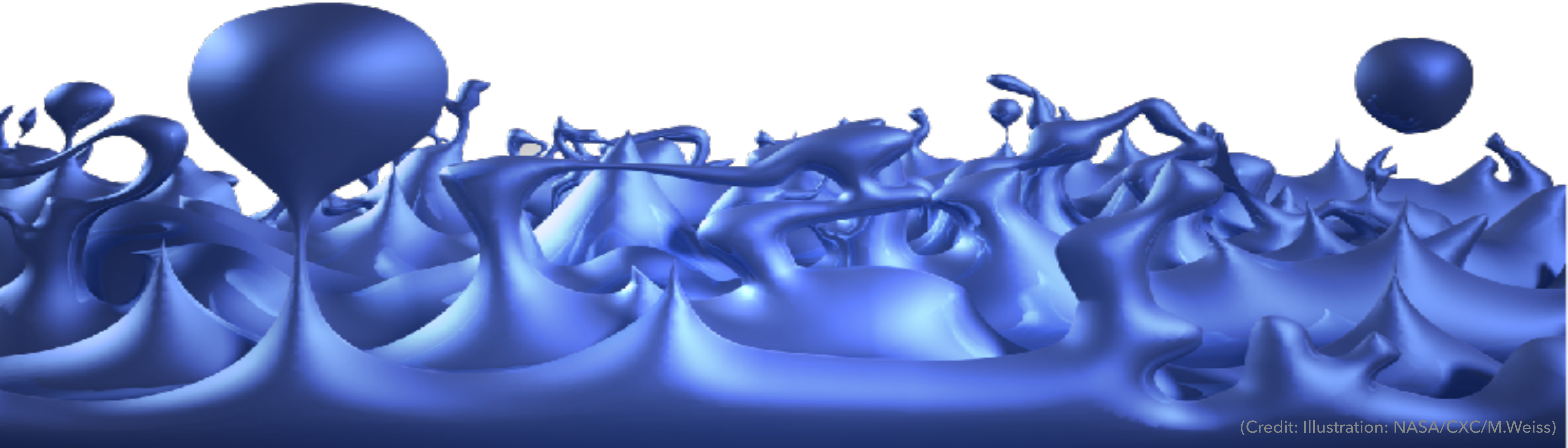
- Focus on GeV - TeV range

THE LANDSCAPE

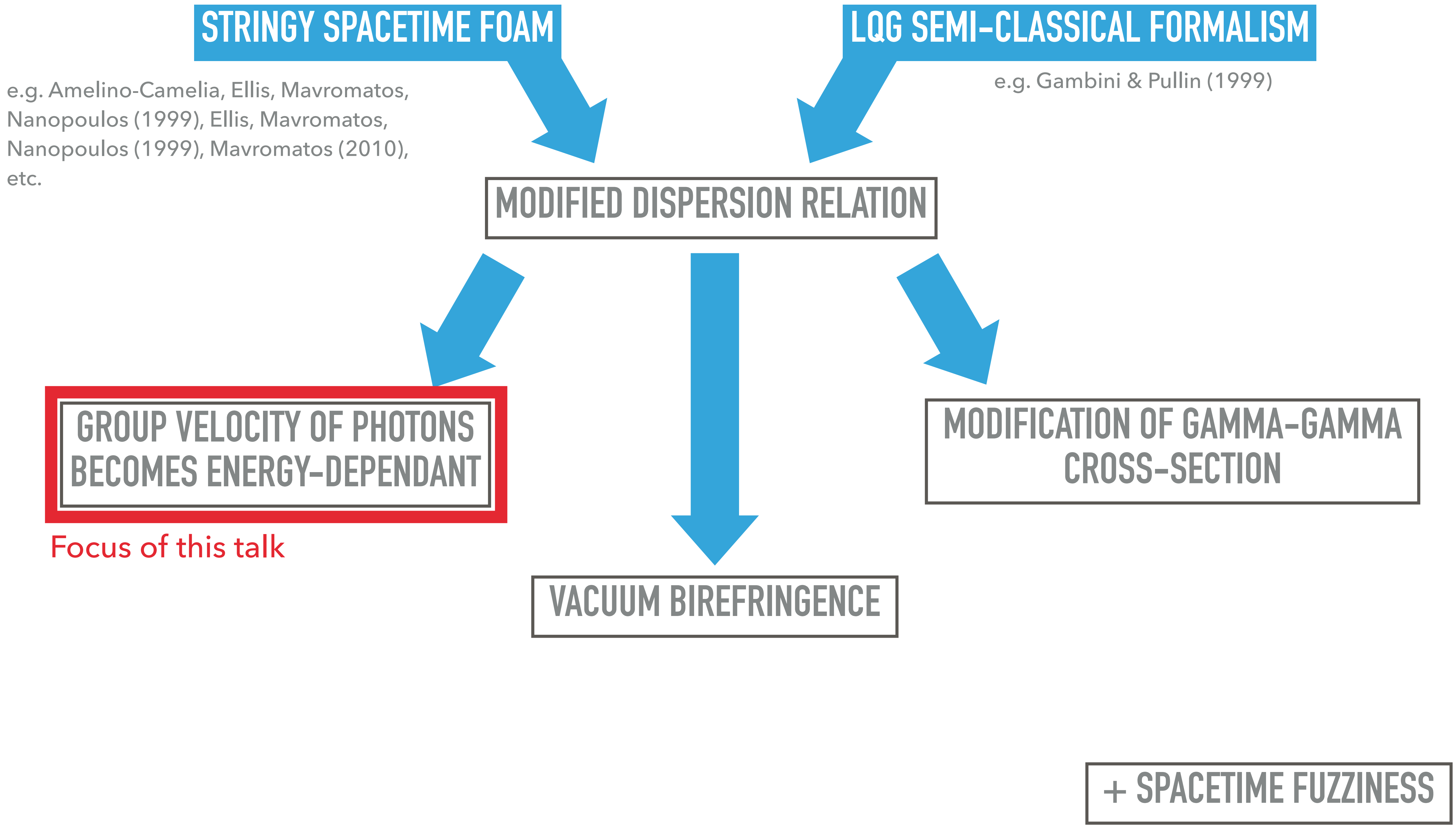
CONTENTS

- Some QG effects to look for
  - Fuzziness, vacuum birefringence, etc.
  - Focus on Time Of Flight (TOF) studies
- Present situation
  - Advantages/Drawbacks of sources for QG searches and complementarity
  - A review of some published results
  - More on source-intrinsic effects
- Future trends
  - Understanding the beam: modeling source intrinsic effects
  - Preparing population studies
- What we would like you to know
- What we'd like to know from you

THE DIFFERENT EFFECTS TO LOOK FOR


(Credit: Illustration: NASA/CXC/M.Weiss)

TWO MODELS, SOME CONSEQUENCES



VACUUM BIREFRINGENCE

- In the LQG approach,

$$\omega_\pm(k) \simeq |k|\left(1 \pm \frac{\xi k}{M_P}\right)$$

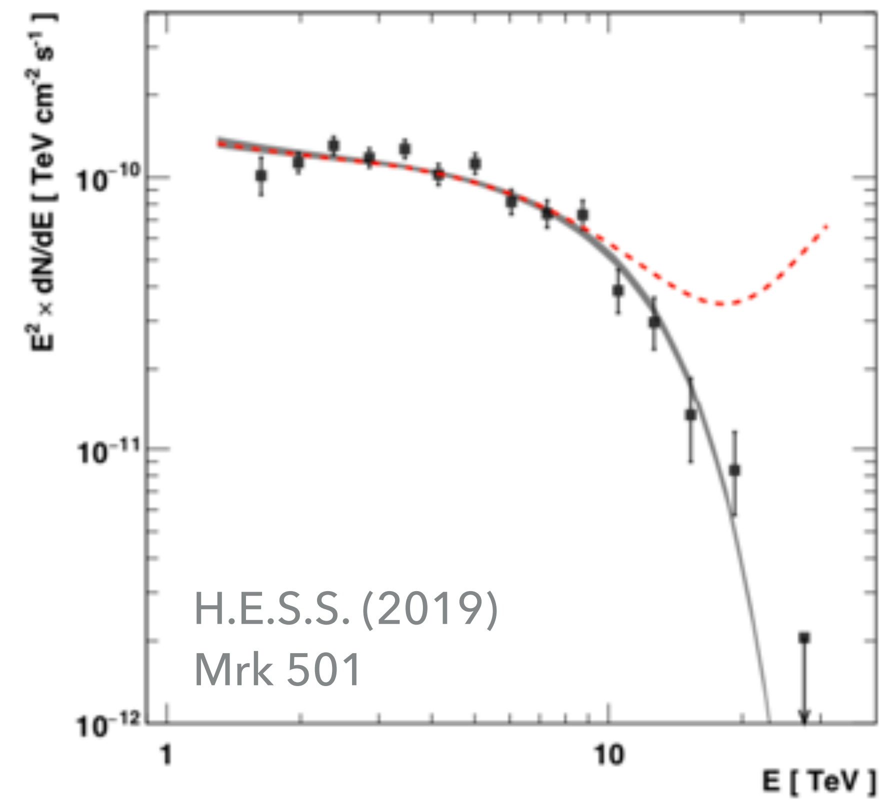
- Rotation of the polarization during propagation

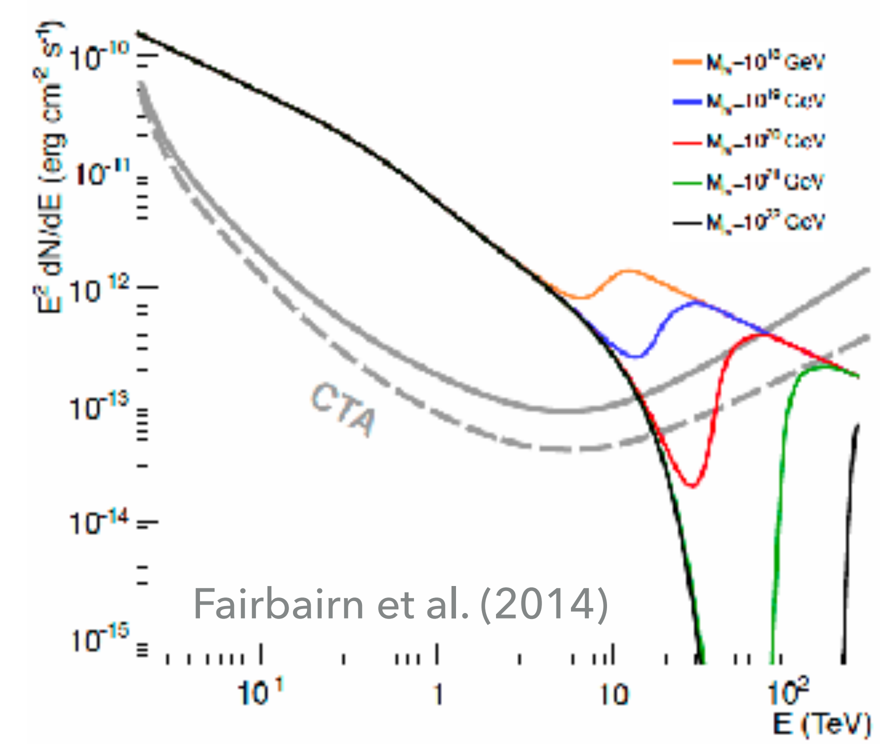
$$\Delta\theta(p) = \frac{\omega_+(k) - \omega_-(k)}{2} d \simeq \xi \frac{k^2 d}{2M_P}$$

- The polarization should cancel-out for a large propagation distance
- Observation of a polarization for GRB 140206A (z = 2.73, 200-400 keV) with INTEGRAL-IBIS: $\xi < 10^{-16}$ (Götz et al. (2014))
- See also Wei (2019): $\xi < 10^{-14}$-10^{-17}

ENERGY THRESHOLD OF GAMMA-GAMMA INTERACTION

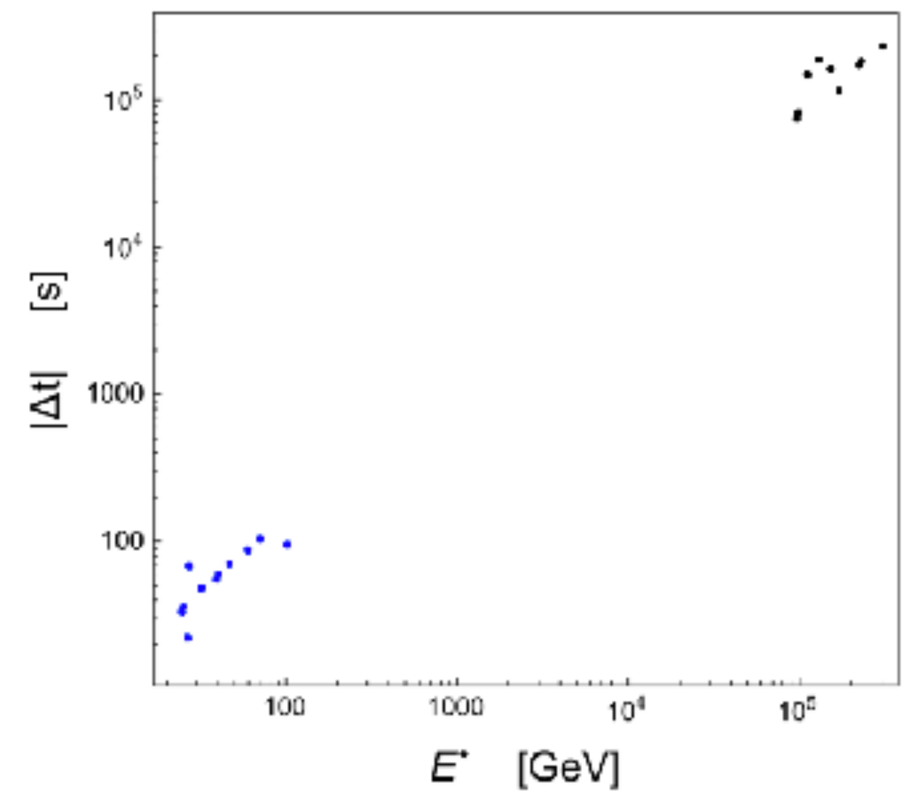
- MDR ➔ non-zero effective mass for the photon
- Modification in dynamics of various mechanisms:
  - Photon decay in vacuum $\gamma \longrightarrow e^+e^-$
  - Vacuum Tcherenkov radiation $e^- \longrightarrow \gamma e^-$
  - …
- Some recent results:
  - Biteau & Williams (2015): 0.6 E_P
  - H.E.S.S. (2019): 2.6×10^{19} GeV
- In reach of CTA
  - Predictions for CTA: Fairbairn et al. (2014)

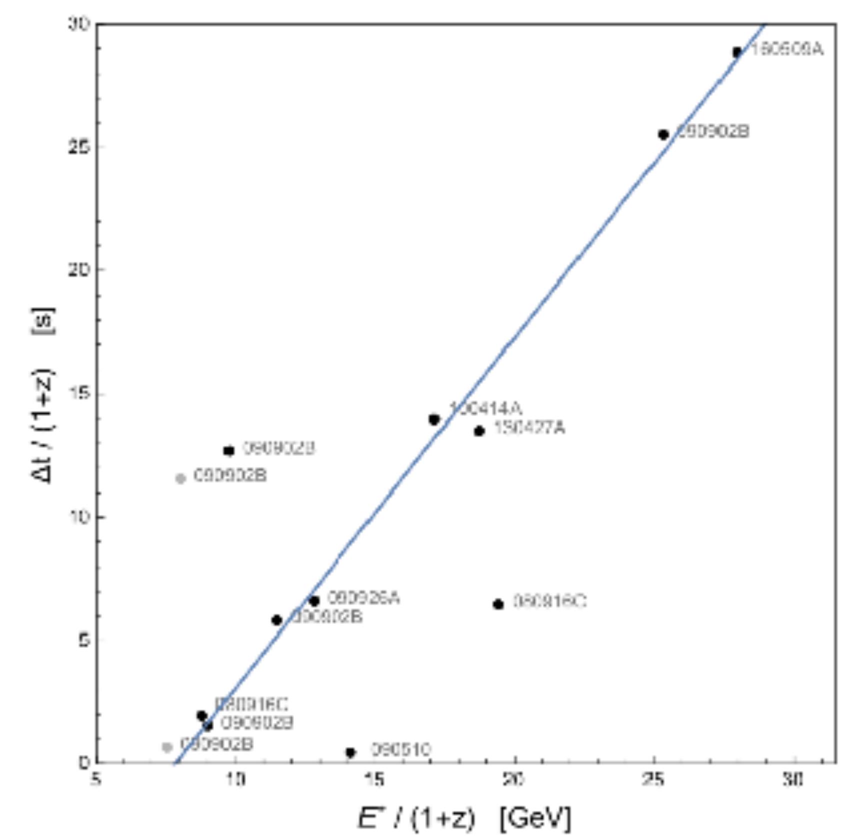




DELAYS

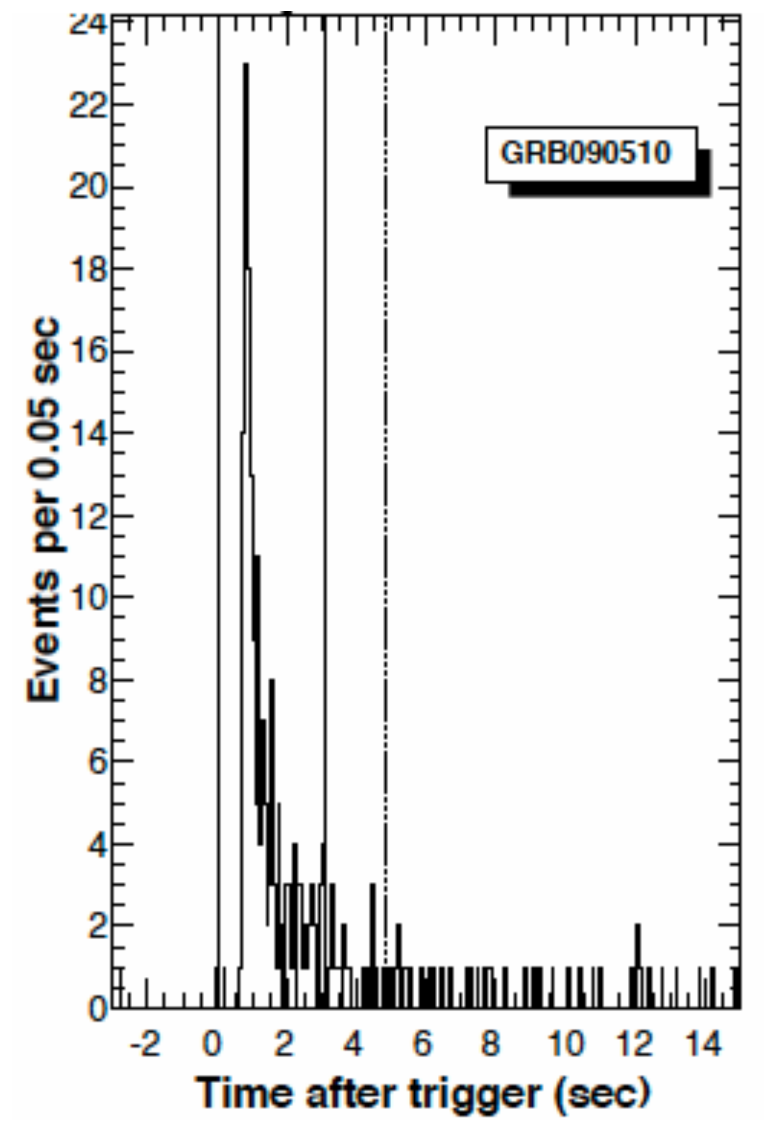
- MDR ➔ energy-dependent time delays
- Photons-photons
  - More details later
- Photons-neutrinos
  - See e.g. Amelino-Camelia et al. (2017)
- etc.





PHOTON/NEUTRINO TIME DELAYS
SEE GIACOMO'S TALK

FUZZINESS



- Stochastic spread of photons of same energy

$$v(E) = c + \delta v(E)$$

- δv(E) follows a Gaussian p.d.f. with zero average and

$$\sigma_n(E) = \frac{1+n}{2}\left(\frac{E}{E_{QG,n}}\right)^n c$$

- Broadening of sharp emission spikes
- Using GRB 090510, $E_{QG,1} > 2.8\ E_P$ (Vasileiou et al. 2015)

ASTROPHYSICAL SOURCES FOR MDR SEARCHES: PRESENT SITUATION

MODIFIED DISPERSION RELATION

STRINGY SPACETIME FOAM

e.g. Amelino-Camelia, Ellis, Mavromatos, Nanopoulos (1999), Ellis, Mavromatos, Nanopoulos (1999), Mavromatos (2010), etc.

LQG SEMI-CLASSICAL FORMALISM

e.g. Gambini & Pullin (1999)

MODIFIED DISPERSION RELATION

GROUP VELOCITY OF PHOTONS BECOMES ENERGY-DEPENDANT

Focus of this talk

PURELY KINEMATICAL TEST THEORY WHERE

$$E^2 \simeq p^2c^2 \times \left[1 \pm \sum_{n=1}^{\infty} k_n \left(\frac{E}{E_P}\right)^n\right]$$

Amelino-Camelia, Ellis, Mavromatos, Nanopoulos, Sarkar (1998)

VERY SMALL EFFECT, BUT IT COULD CUMULATE ON LARGE DISTANCES

FROM MDR TO TIME-LAG

- Photons from astrophysical sources propagate over large distances
- Universe expansion has to be taken into account when calculating the measured delay (expression below from Jacob & Piran, 2008)
- Expression of the time-lag between two photons emitted at the same time at redshift z:

ENERGY LEVER ARM

$$\Delta t_n \simeq s_\pm \frac{n+1}{2} \frac{E_h^n - E_l^n}{E_{QG}^n} \int_0^z \frac{(1+z')^n}{H(z')} dz'$$

DISTANCE PARAMETER

- with

$$H(z) = H_0 \sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}$$

$$\begin{aligned} H_0 &= 67.74 \pm 0.46 \text{ km/s/Mpc} \\ \Omega_m &= 0.3089 \pm 0.0062, \\ \Omega_\Lambda &= 0.6911 \pm 0.0062 \end{aligned}$$

(Planck, 2015)

ASTROPHYSICAL SOURCES FOR MDR SEARCHES

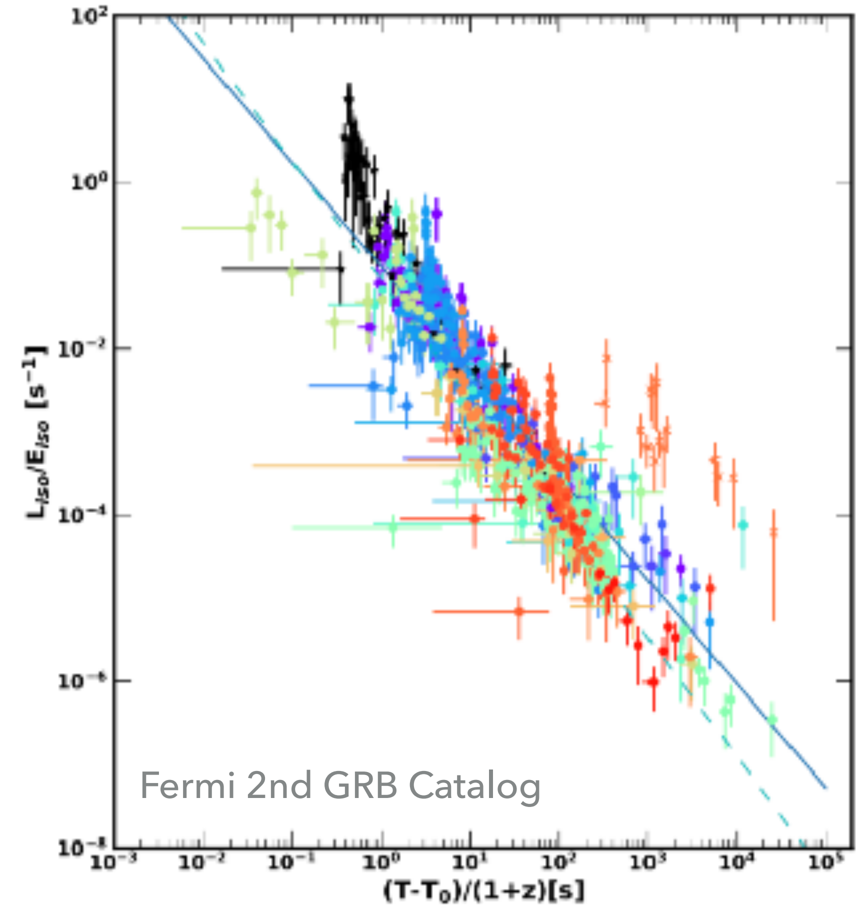
- The time-lag Δt_n is proportional to:
  - The distance parameter
  - The energy « lever-arm » $\Delta E^n \equiv E_h^n - E_l^n$
- Need for sources that are
  - At large distances
  - Variable or transient
  - Energetic (hard spectra)
- Candidates:
  - Gamma-Ray Bursts (GRBs)
  - Flaring Active Galactic Nuclei (AGNs)
  - Pulsars (PSRs)
- The sensitivity of analyses depends on a combination of factors

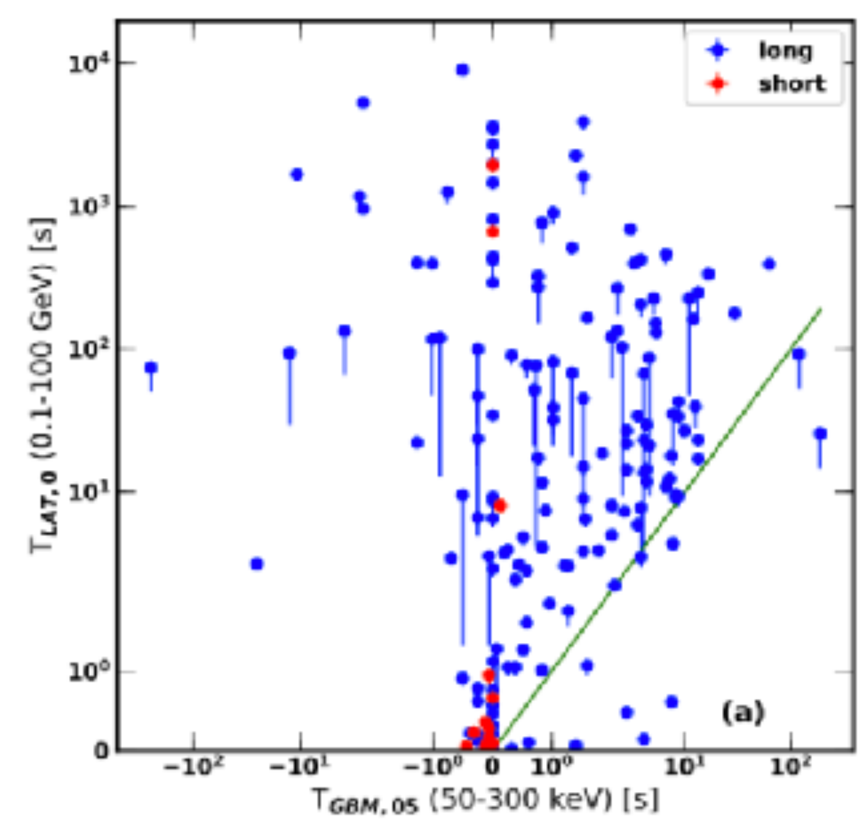
THESE SOURCES HAVE ADVANTAGES AND DRAWBACKS

GAMMA-RAY BURSTS

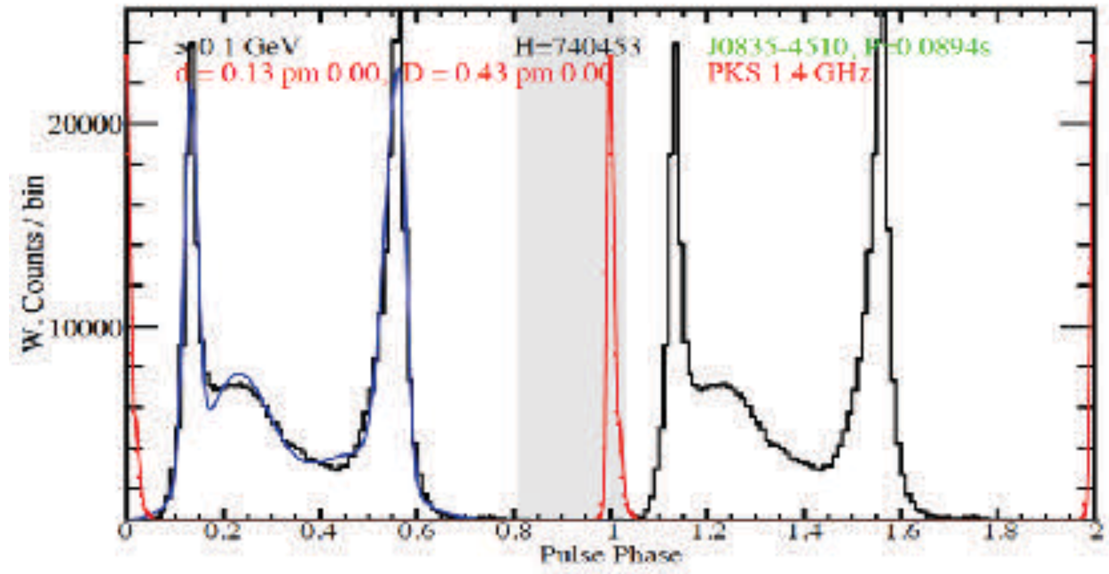
- Random, short and powerful events
- SN or mergers of compact objects
- Prompt emission
  - Detected only with satellites
- Afterglow
  - Detected with satellites and IACTs
- Seen at very high redshifts ($z < 9$)
- Intrinsic effects
  - lag-luminosity correlation
  - onset at high energy delayed with respect to low energies
- From 2nd Fermi GRB Catalog (Ajello et al. 2019): « when high-energy emission is observed in GRBs, this emission is delayed and lasts longer compared to that in the low-energy band »

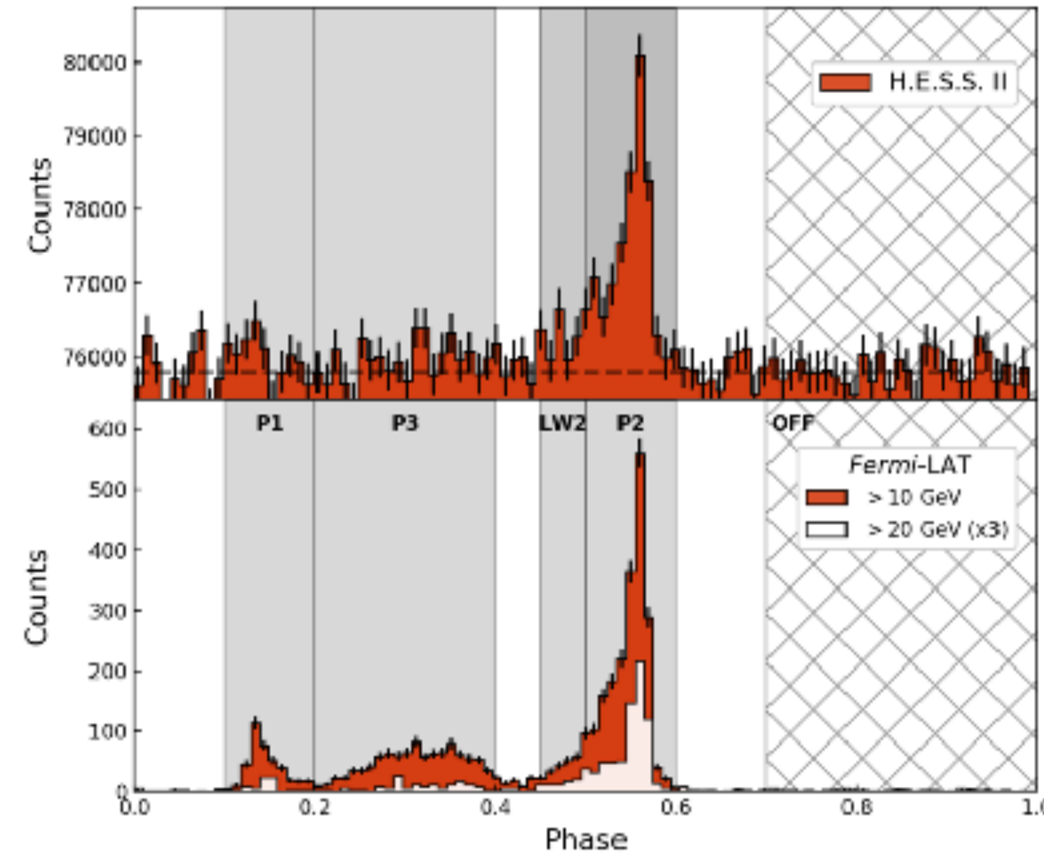
GRB:
👍 VERY LARGE DISTANCES
👍 SHORT
👎 RANDOM





PULSARS



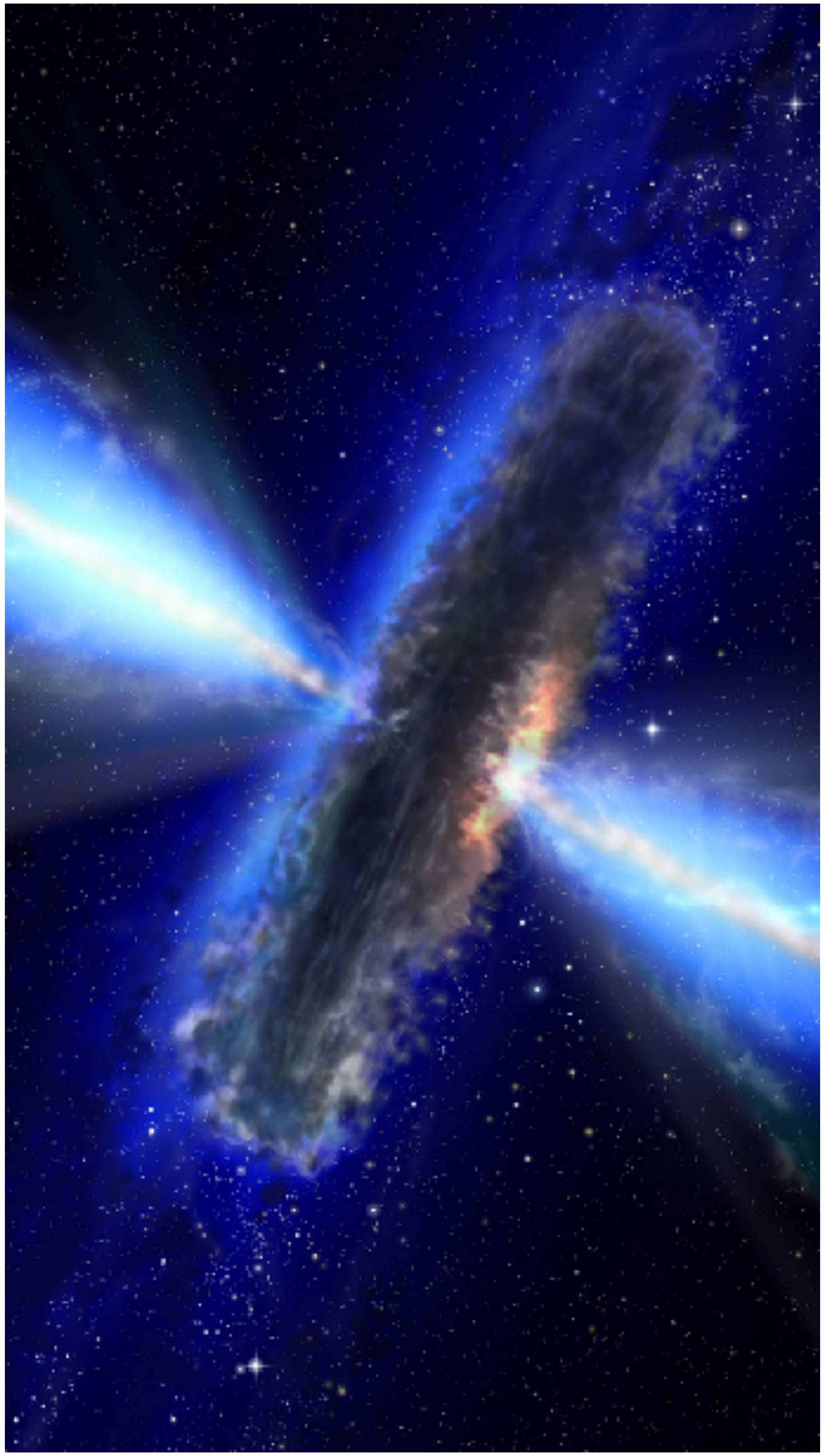


- Highly magnetized rotating neutron star
- Periods as low as a few ms
- Period increase of 10^{-13} - 10^{-20} s/s
- Galactic sources
- Only three PSR detected with IACTs above 100 GeV (Crab, Vela, PSR B1706-44)
- Intrinsic effects:
  - Any intrinsic effect should stay constant when time is expressed as a phase
  - Any propagation effect should slowly evolve when expressed in phase

PSR:
👍 EXTREME VARIABILITY
👍 NOT RANDOM
👎 VERY SMALL DISTANCES

FLARING ACTIVE GALACTIC NUCLEI

- Galaxies with an extremely luminous inner region
- Blazars
  - Jet close to the line-of-sight
  - High variability (flares)
- For MDR searches:
  - 👍 Good statistics with IACTs
  - 👍 High variability (O(min))
  - 👍 Distant sources
  - 👎 Flares happen randomly
  - 👎 EBL absorption of TeV photons
  - 👎 Hints of intrinsic temporal effects
  - 👎 Details of emission mechanisms poorly understood



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SUMMARY OF MAIN CHARACTERISTICS

Source	Observed by	Distance	Variability time scale
AGN flare	IACT 👉	z_{max} ~ 0.6	O(1 min)
GRB	Satellites 👉	z_{max} ~ 9	O(0.1 s)
PSR	Satellites & IACT	d_{max} ~ 50 kpc	O(1 ms)

Source	Random ?	Intrinsic effects	Emission mechanisms
AGN flare	Yes	Hints	poorly understood
GRB	Yes	Yes	poorly understood
PSR	No	Can be separated 👉	poorly understood

DELAYS AT THE SOURCE

$$\Delta t_{n\,\mathrm{total}} = \Delta t_{n\,\mathrm{LIV}} + (1+z)\,\Delta t_{\mathrm{source}}$$

- « Source-intrinsic effects »
  - Due to emission mechanisms
  - Differ from one type of source to another
  - Could differ from one flare/burst to another
- Observed for long GRBs
- Only hints for flaring AGNs in the TeV range
  - Details of emission mechanisms are still unknown…

HOW TO DEAL WITH INTRINSIC EFFECTS ?

$$\Delta t_{n\,\mathrm{total}} = \Delta t_{n\,\mathrm{LIV}} + (1+z)\,\Delta t_{\mathrm{source}}$$

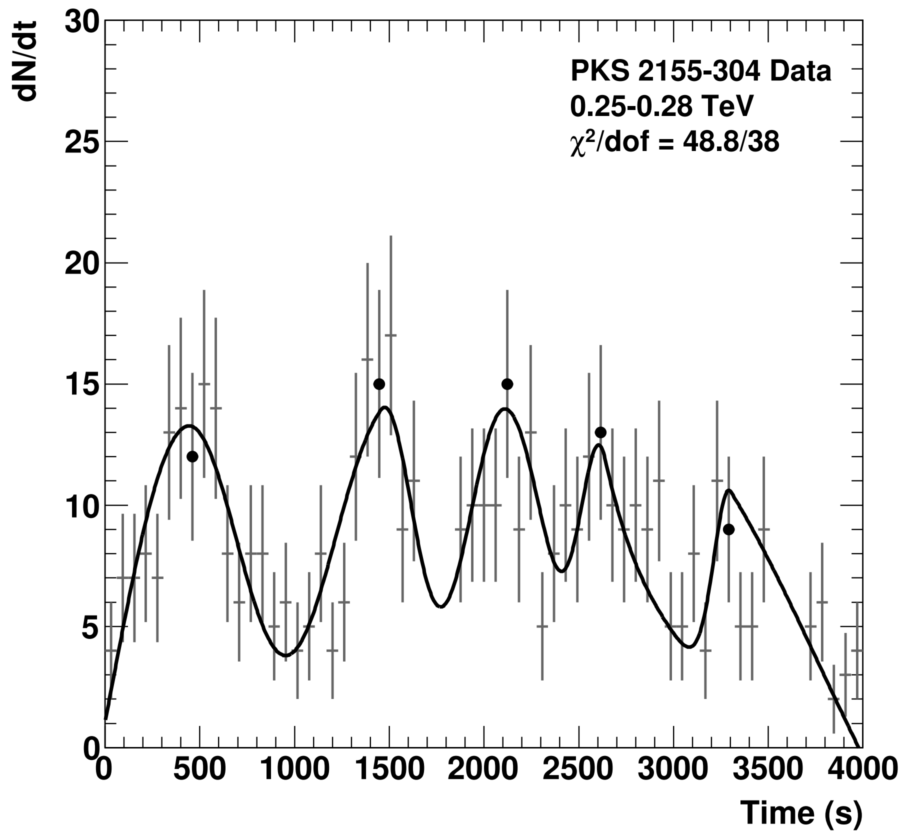
- Neglect intrinsic effects
- Conservative modeling
- Full modeling of the sources
- Use population studies trying to separate intrinsic and propagation effects

ONGOING EFFORT, TO BE DEVELOPED

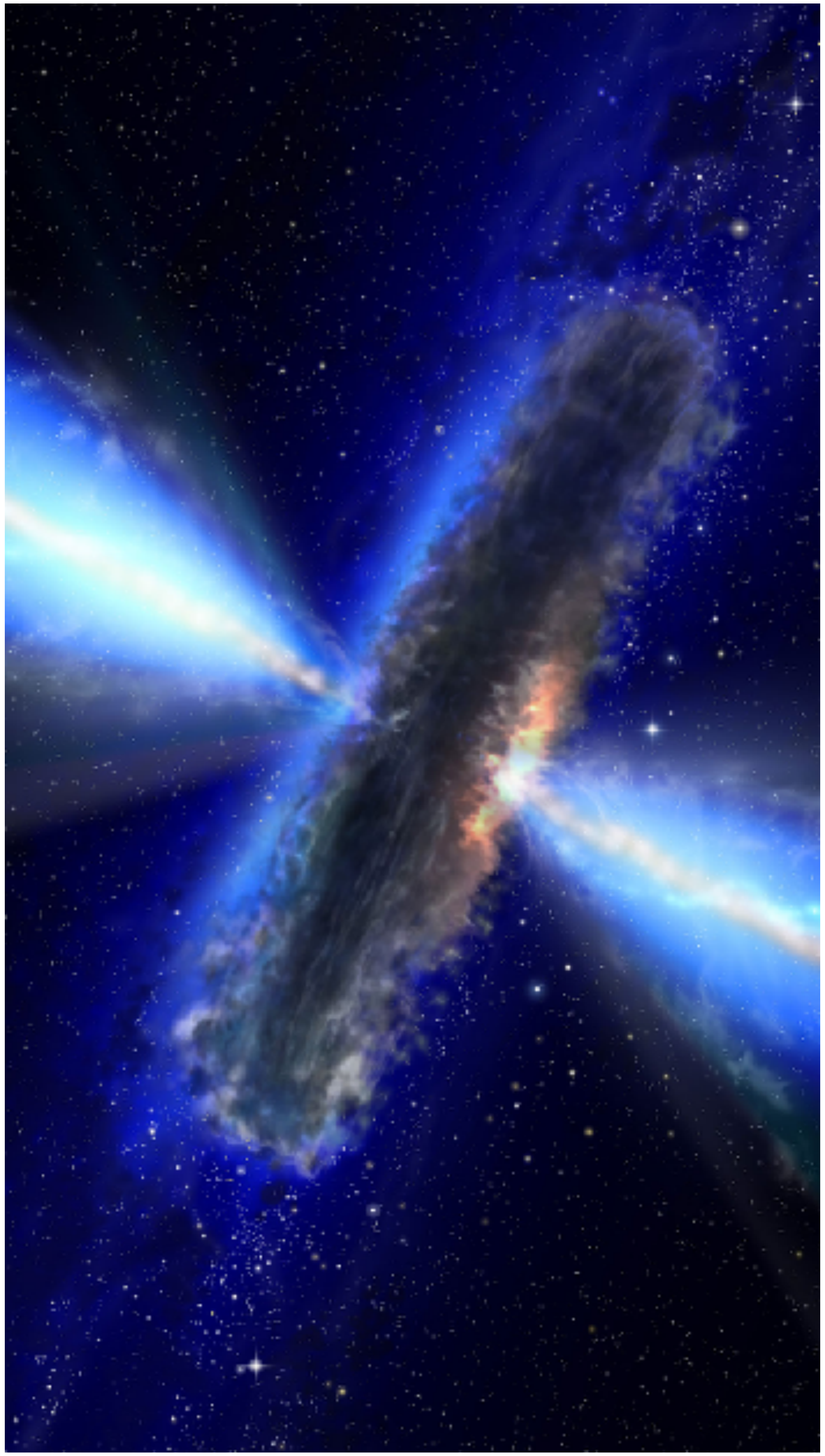
AGN, PSR, GRB COMPLEMENTARITY

- AGN flares
  - Moderate z
  - High ΔE
  - Time scale O(1 min)
  - Random
- GRB
  - High z
  - Time scale O(1 s)
  - Random
- PSR
  - Small distance
  - Time scale O(ms)

ALL THESE SOURCES SHOULD BE USED FOR MDR SEARCHES !



SOME RESULTS



PRELIMINARY COMMENTS

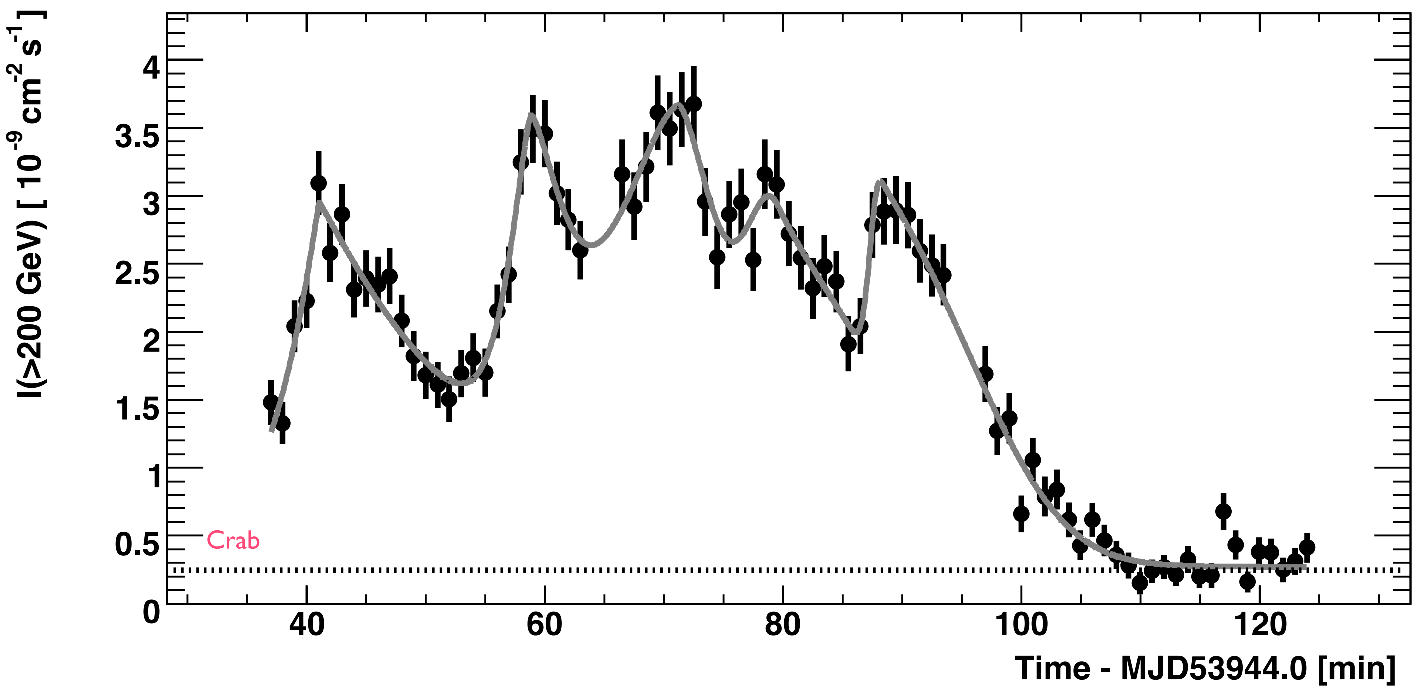
- Results span from the end of 90s to now
- Population studies were done with GRBs (with known z)
- The main result after 25+ years of work:

NO SIGNIFICANT EFFECT WAS FOUND !

- Lower limits on $E_{QG,1}$ and $E_{QG,2}$ are derived
  - Error evaluation is essential
- The only known exception:
  - Flare of Mkn 501 in July 2006, Albert et al. (2008)

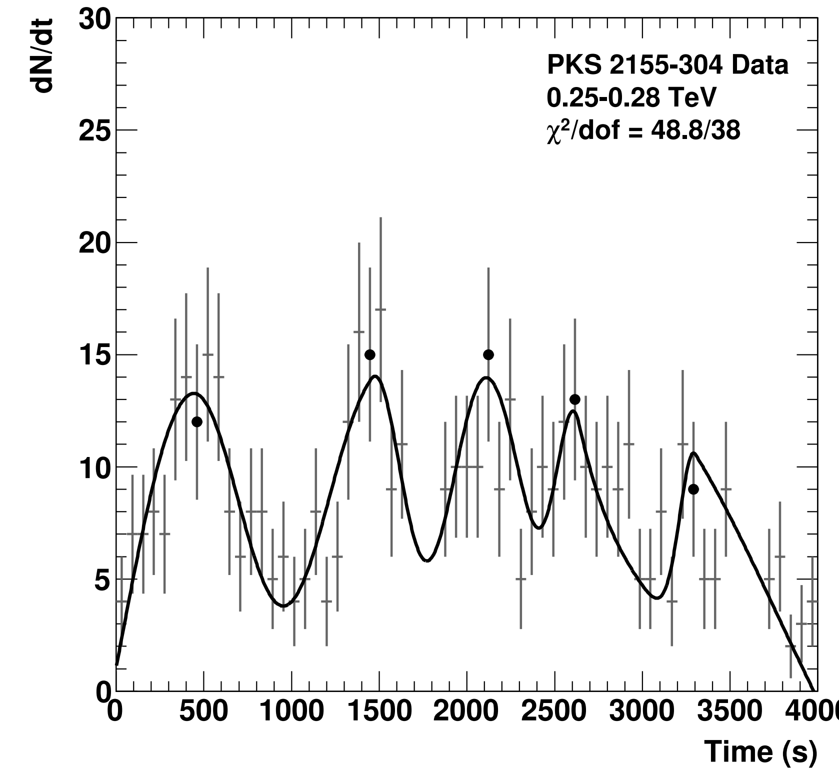
A GIANT FLARE OF PKS 2155–304

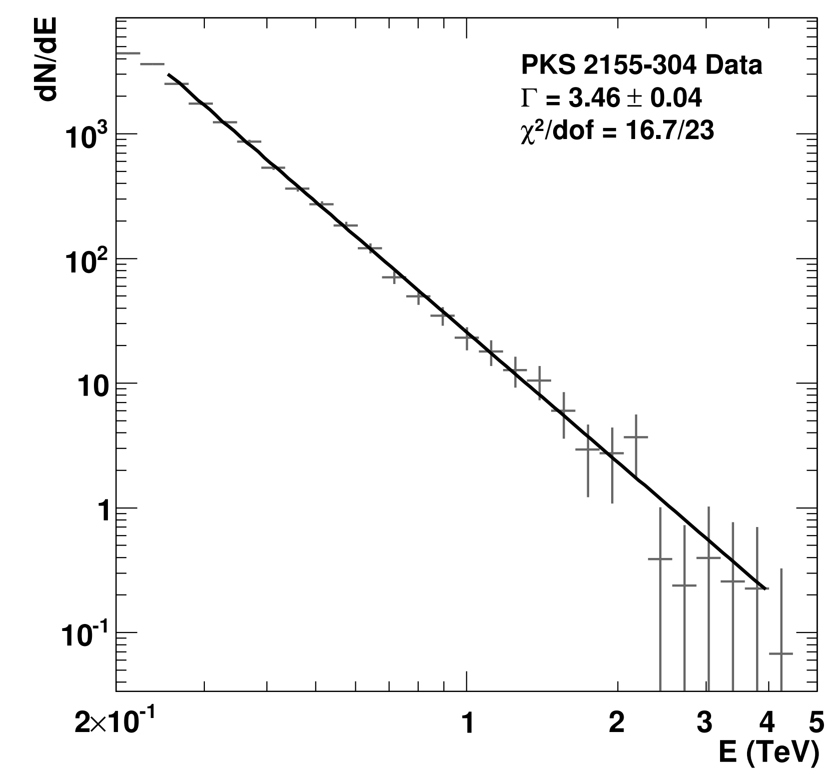
- BL Lac object
- z = 0.116
- Flare in July 2006:
  - ~10000 photons in ~90 min
  - High variability (O(min))
  - Ideal observation conditions
  - Negligible background
- Use of a likelihood procedure (Martinez & Errando, 2009)
- Toy Monte Carlo technique:
  error calibration and systematics studies

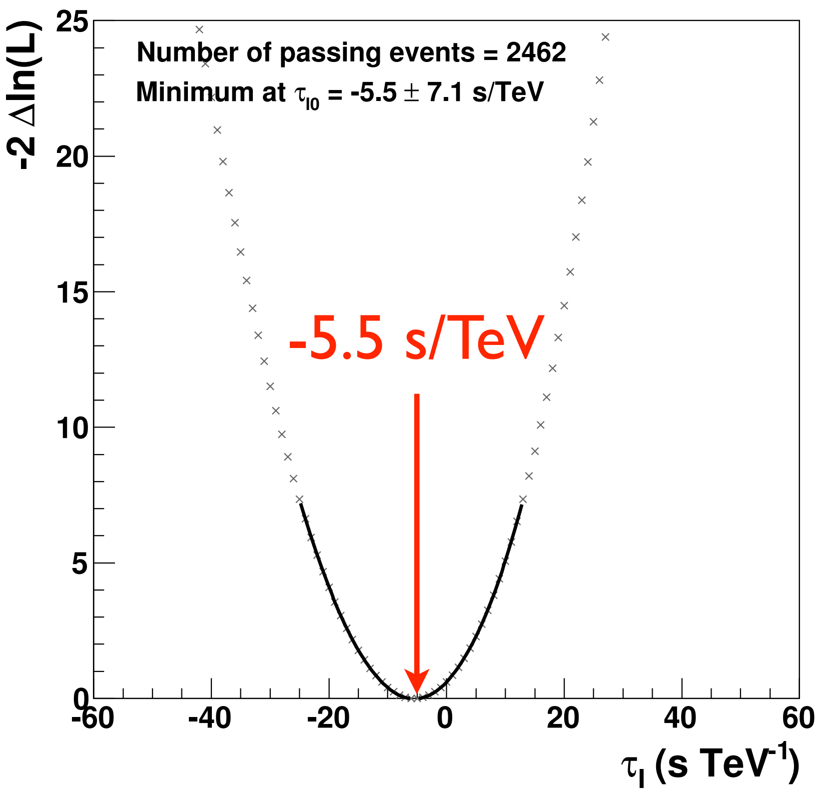


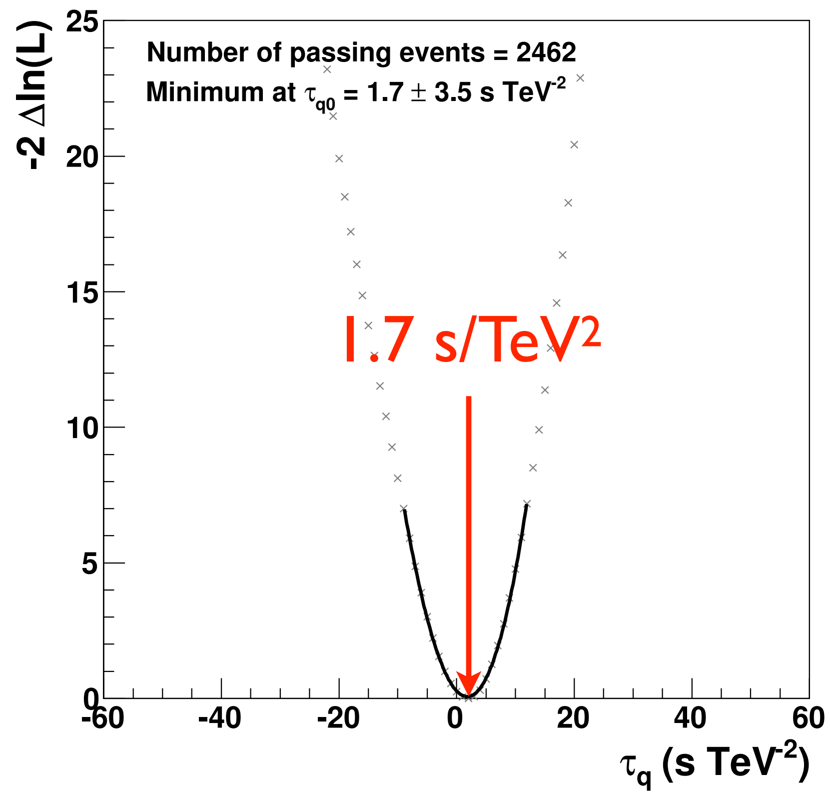
LIKELIHOOD PROCEDURE (IN BRIEF)

- Ingredients
  - Parametrization of low energy light curve
  - Parameterization of spectrum
  - Photon list
- Result: the best estimate of τ_n









TOY MONTE-CARLO

- Good for error calibration and evaluation of systematics
- Summary of systematics:

<table>
<tr><th></th><th>Change in estimated τ_l (s/TeV)</th><th>Change in estimated τ_q (s/TeV^2)</th></tr>
<tr><td>Selection cuts</td><td colspan="2">< 5</td></tr>
<tr><td>Background contribution</td><td colspan="2">< 1</td></tr>
<tr><td>Acceptance factors</td><td colspan="2">< 1</td></tr>
<tr><td>Energy resolution</td><td colspan="2">< 1</td></tr>
<tr><td>Energy calibration</td><td colspan="2">< 2</td></tr>
<tr><td>Spectral index</td><td colspan="2">< 1</td></tr>
<tr><td>Calibration systematics</td><td>< 5</td><td>< 1</td></tr>
<tr><td>$F_S(t)$ parameterization</td><td>≈ 7</td><td>≈3</td></tr>
<tr><td>Total</td><td>< 10.3</td><td>< 6.6</td></tr>
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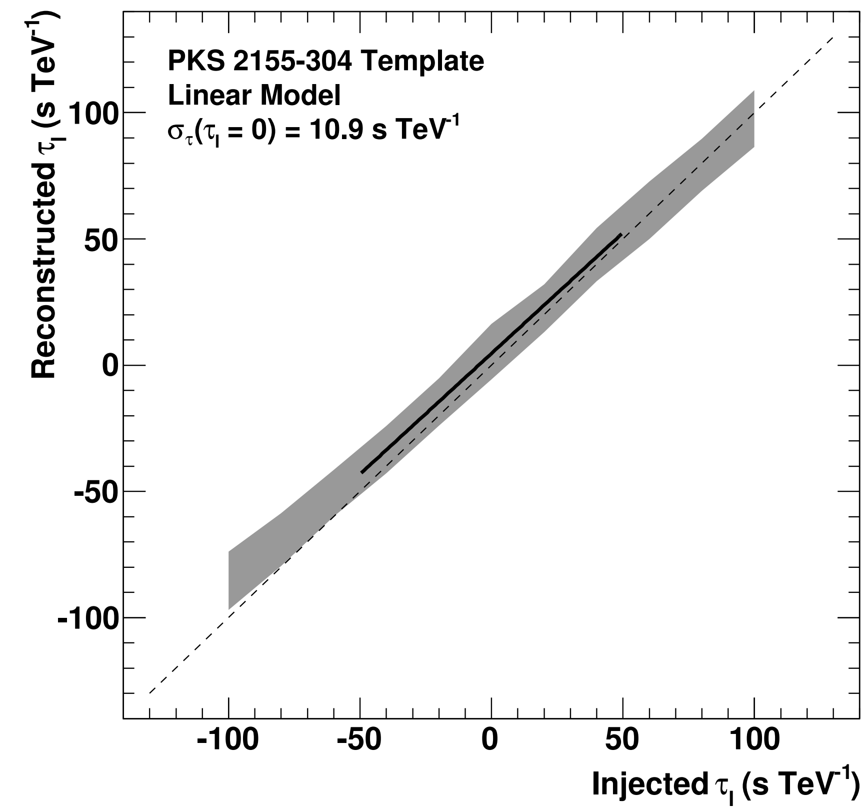
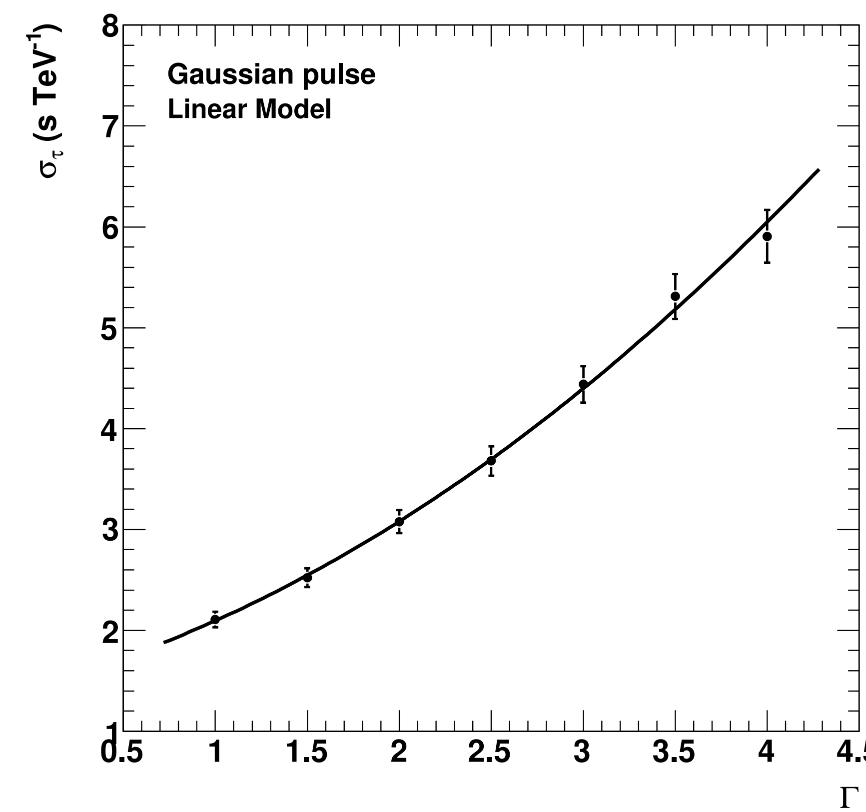
EVALUATION OF SYSTEMATICS IS A CRITICAL STEP
SEE MARKUS' AND SAMI'S TALKS





A GIANT FLARE OF PKS 2155–304

- Time lag parameters:

  $\tau_1 = -5.5 \pm 10.9_{(stat)} \pm 10.3_{(sys)}$ s/TeV

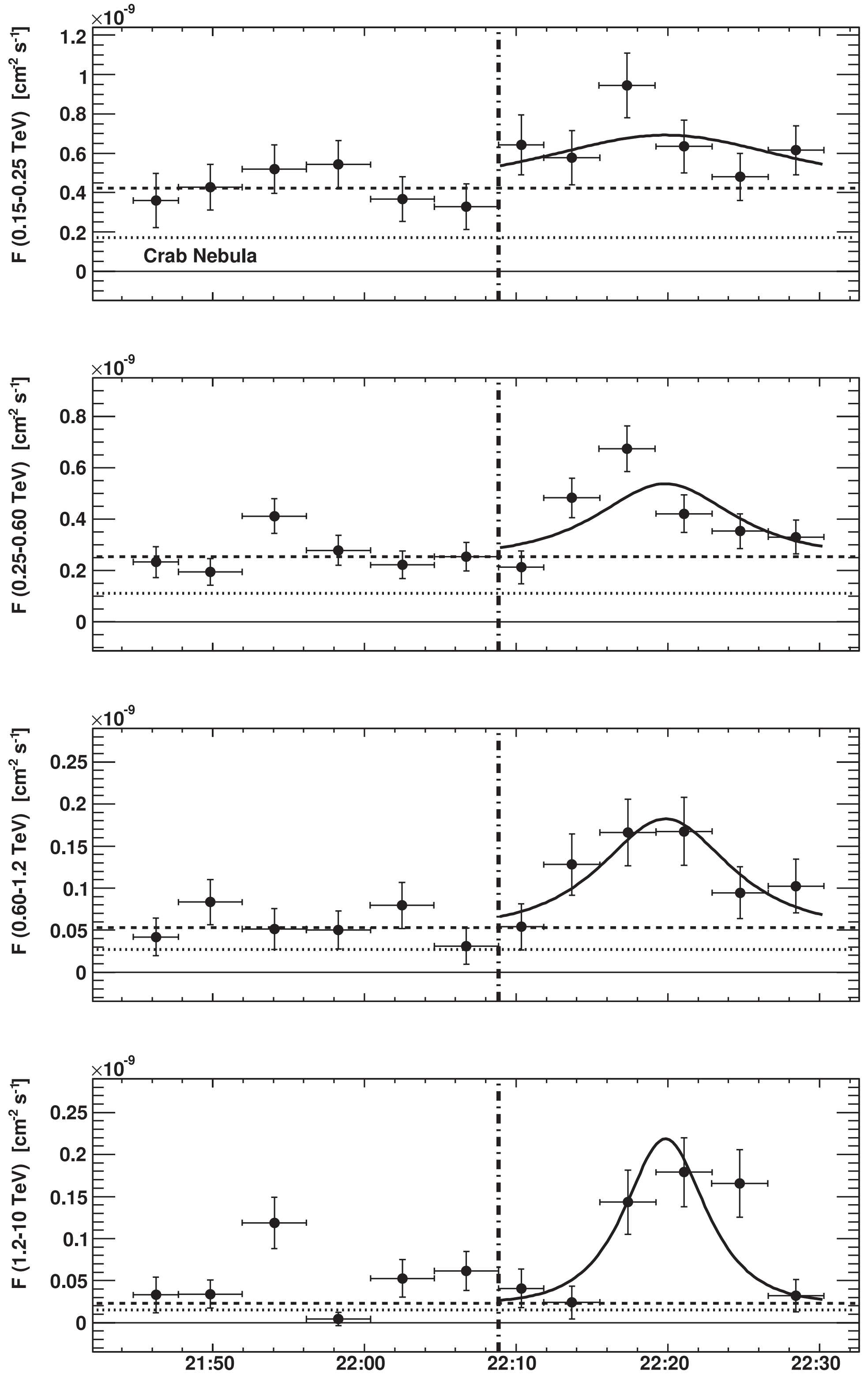
  $\tau_2 = 1.7 \pm 6.3_{(stat)} \pm 6.6_{(sys)}$ s/TeV^2

- Limits:
  - $E_{GQ,1} > 2.1\text{x}10^{18}$ GeV
  - $E_{QG,2} > 0.6\text{x}10^{11}$ GeV

MRK 501 FLARE SEEN BY MAGIC IN 2005

- $z = 0.034$
- ~20 minute long flare on July 9
- ~1500 photons
- Negligible background
- Lag of 4±1 min measured between < 250 GeV and >1.2 TeV
  - Confirmed with 2 methods
    - MAGIC (2008)
    - Martinez & Errando (2009)
- $\tau_1 = (0.030 \pm 0.012)$ s/GeV, and $E_{QG,1} = 0.30^{+0.24}_{-0.10} \times 10^{18}$ GeV
  - Finally interpreted as a source intrinsic effect

Flare of Mkn 501, MAGIC (2007)



Lag of 4±1 min (< 250 GeV, >1.2 TeV)

LIMITS ON $E_{QG,1}$ AND $E_{QG,2}$ FOR THE SUBLIMINAL CASE (95%CL)

	Source(s)	Experiment	Method	Results	
Individual GRB	GRB 021206	RHESSI	Fit + mean arrival time in a spike	$E_{QG,1} > 1.8 \times 10^{17}$ GeV	
	GRB 080916C	Fermi GBM + LAT	associating a 13 GeV photon with the trigger time	$E_{QG,1} > 1.3 \times 10^{18}$ GeV	$E_{QG,2} > 0.8 \times 10^{10}$ GeV
	GRB 090510	Fermi GBM + LAT	associating a 31 GeV photon with the start of any observed emission, DisCan	$E_{QG,1} > 1.5 \times 10^{19}$ GeV	$E_{QG,2} > 3.0 \times 10^{10}$ GeV
		Fermi LAT	PairView, SMM, likelihood	$E_{QG,1} > 9.3 \times 10^{19}$ GeV	$E_{QG,2} > 1.3 \times 10^{11}$ GeV
Several GRB	9 GRBs	BATSE + OSSE	Fit	$E_{QG,1} > 10^{15}$ GeV	
	9 GRBs	BATSE + OSSE	wavelets	$E_{QG,1} > 0.7 \times 10^{16}$ GeV	$E_{QG,2} > 2.9 \times 10^{6}$ GeV
	15 GRBs	HETE-2	wavelets	$E_{QG,1} > 0.4 \times 10^{16}$ GeV	
	17 GRBs	INTEGRAL	likelihood	$E_{QG,1} > 3.2 \times 10^{11}$ GeV	
	35 GRBs	BATSE + HETE-2 + Swift	wavelets	$E_{QG,1} > 1.4 \times 10^{16}$ GeV	
	15 GRBs	SWIFT	CCF (50-100 keV, 150-200 keV)	$E_{QG,1} > 1.48 \times 10^{16}$ GeV	
	8 GRBs	Fermi LAT	irregularity, kurtosis, skewness estimators	$E_{QG,1} > 10^{17}$ GeV	
Individual PSR	Crab pulsar	EGRET	average time of the main pulse in different energy bands, fit of main pulse	$E_{QG,1} > 0.2 \times 10^{16}$ GeV	
		VERITAS	DisCan	$E_{QG,1} > 1.9 \times 10^{17}$ GeV	
		MAGIC	likelihood	$E_{QG,1} > 7 \times 10^{17}$ GeV	$E_{QG,2} > 4.6 \times 10^{10}$ GeV
	Vela pulsar	H.E.S.S.	likelihood	$E_{QG,1} > 3.5 \times 10^{15}$ GeV	$E_{QG,2} > 6.4 \times 10^{8}$ GeV

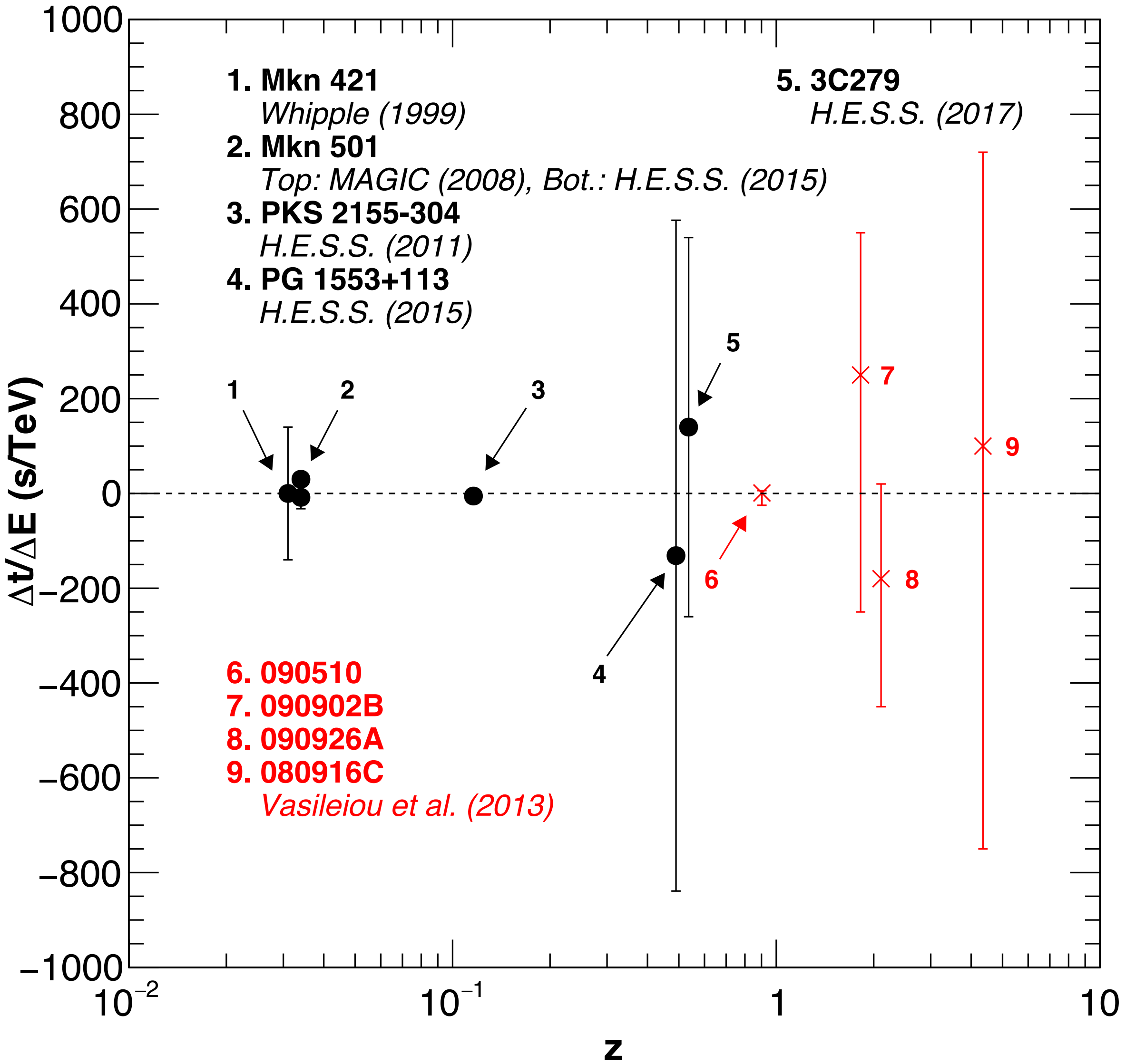
- Best limit so far: $E_{QG,1} > 9.3 \times 10^{19}$ GeV with GRB 090510
- Population studies lead to $E_{QG,1} > 10^{17}$ GeV
- Competitive results possible for pulsars on $E_{QG,2}$

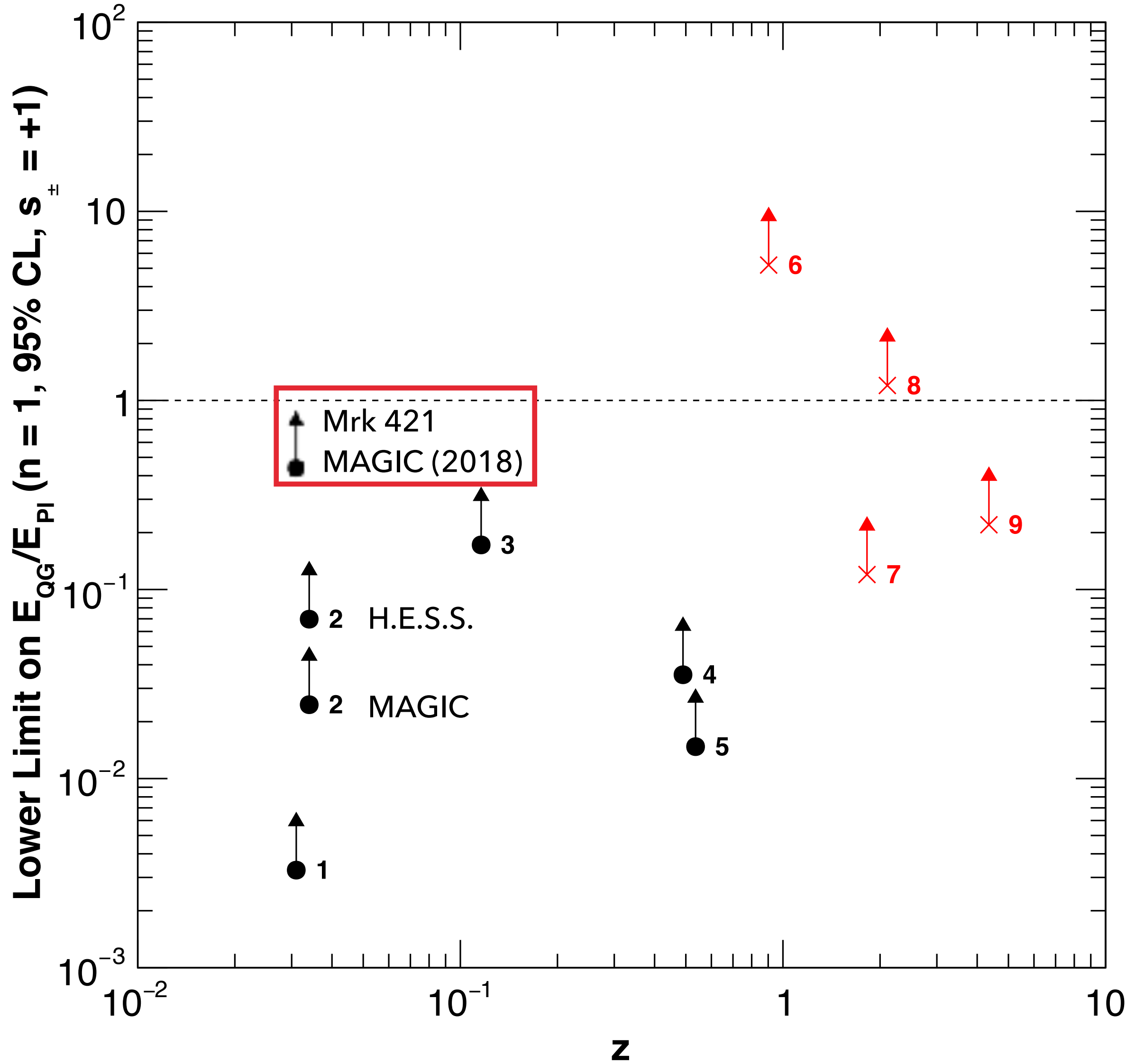
LIMITS ON $E_{QG,1}$ AND $E_{QG,2}$ FOR THE SUBLIMINAL CASE (AGN)

	Source(s)	Experiment	Method	Results	
Individual flaring AGN	Mrk 421	Whipple	average time of the main pulse in different energy bands	$E_{QG,1} > 0.4 \times 10^{17}$ GeV	
	Mrk 421	MAGIC	likelihood	$E_{QG,1} > 5.4 \times 10^{18}$ GeV	$E_{QG,2} > 1.4 \times 10^{11}$ GeV
	Mrk 501	MAGIC	ECF, likelihood	$E_{QG,1} > 0.2 \times 10^{18}$ GeV	$E_{QG,2} > 2.6 \times 10^{10}$ GeV
			likelihood	$E_{QG,1} > 0.3 \times 10^{18}$ GeV	$E_{QG,2} > 5.7 \times 10^{10}$ GeV
	Mrk 501	H.E.S.S.	likelihood	$E_{QG,1} > 3.6 \times 10^{17}$ GeV	$E_{QG,2} > 8.5 \times 10^{10}$ GeV
	PKS 2155-304	H.E.S.S.	MCCF	$E_{QG,1} > 7.2 \times 10^{17}$ GeV	$E_{QG,2} > 0.1 \times 10^{10}$ GeV
			wavelets	$E_{QG,1} > 5.2 \times 10^{17}$ GeV	
			likelihood	$E_{QG,1} > 2.1 \times 10^{18}$ GeV	$E_{QG,2} > 6.4 \times 10^{10}$ GeV
	PG 1553+113	H.E.S.S.	likelihood	$E_{QG,1} > 4.1 \times 10^{17}$ GeV	$E_{QG,2} > 2.1 \times 10^{10}$ GeV
	3C279	H.E.S.S.	likelihood	$E_{QG,1} > 1.6 \times 10^{17}$ GeV	$E_{QG,2} > 1.5 \times 10^{10}$ GeV

- 5 different objects
- Redshift ranging from 0.03 (Mrk 421) to 0.54 (3C279)
- Best limits for $E_{QG,1}$ and $E_{QG,2}$: Mrk 421

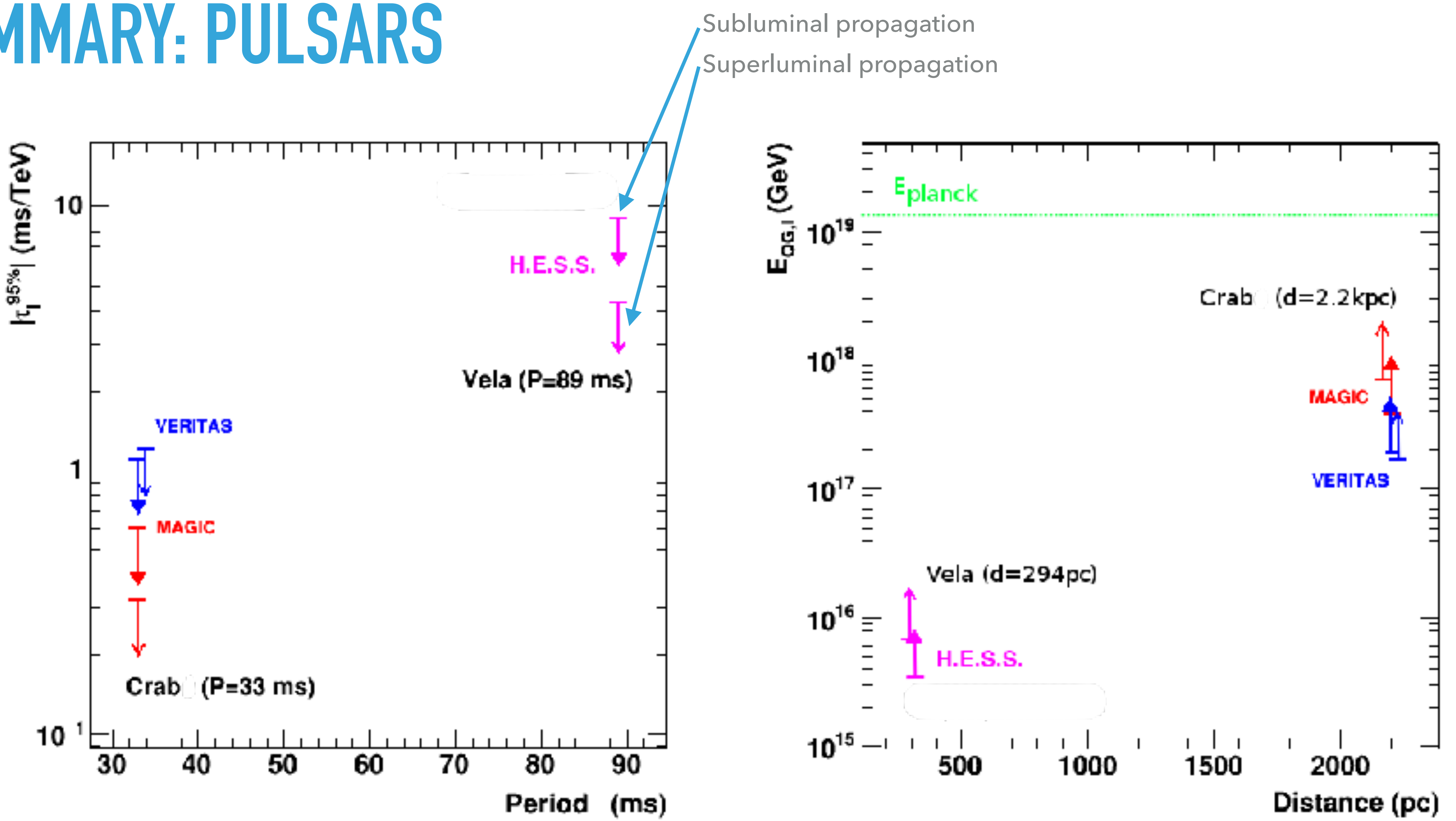
SUMMARY





- Results for linear and subluminal effect, obtained with a likelihood method
- 4 Fermi-LAT GRBs included (Vasileiou et al., 2013)

SUMMARY: PULSARS



- Crab PSR (P = 33 ms, d = 2.2 kpc, 300 h with MAGIC, 107 h with VERITAS)
- Vela PSR (P = 89 ms, d = 294 pc, 24 h with HESS)

ASTROPHYSICAL SOURCES FOR MDR SEARCHES: FUTURE TRENDS

HOW TO DEAL WITH INTRINSIC EFFECTS ?

$$\Delta t_{n\,\mathrm{total}} = \Delta t_{n\,\mathrm{LIV}} + (1+z)\,\Delta t_{\mathrm{source}}$$

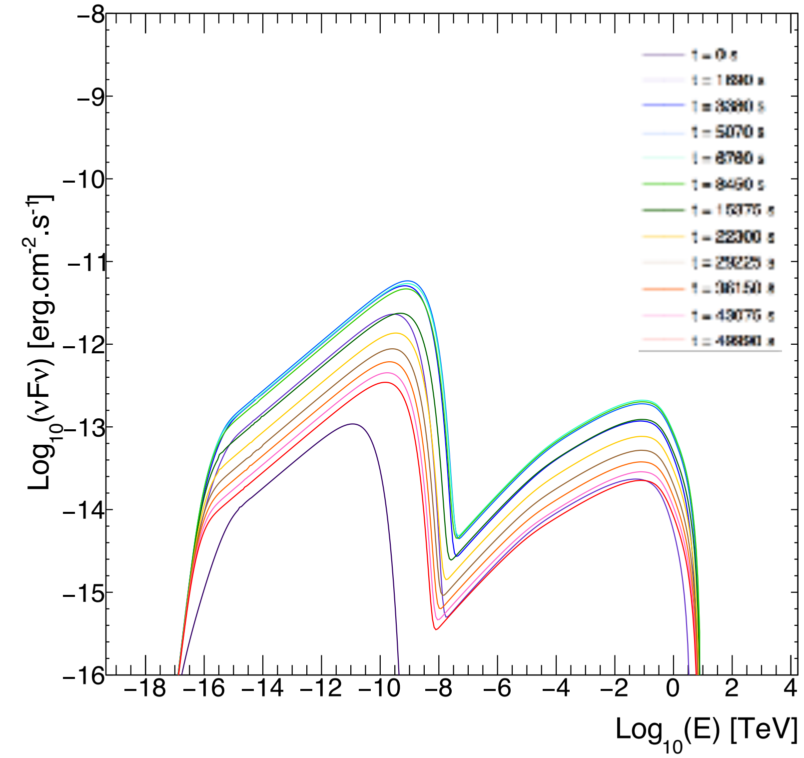
- Neglect intrinsic effects
- Conservative modeling
- Full modeling of the sources
- Use population studies trying to separate intrinsic and propagation effects

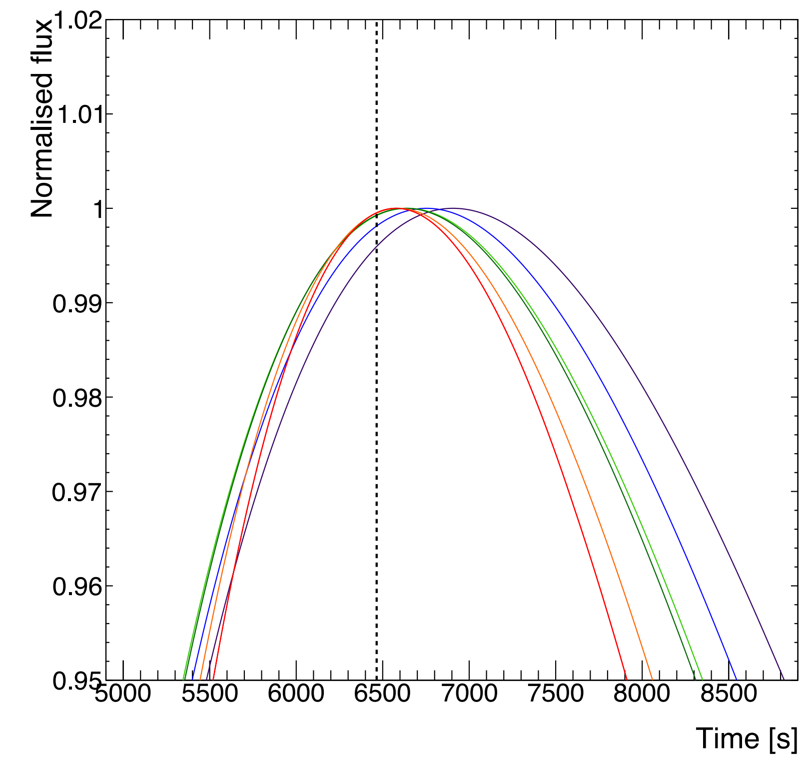
ONGOING EFFORT, TO BE DEVELOPED

C. Perennes, C. Levy, H. Sol, JB
Plots from C. Perennes

UNDERSTANDING INTRINSIC EFFECTS

- Need for a time-dependent model of AGN flare emission
- First attempt to characterize intrinsic effects in AGN flares in connexion to LIV searches
    - PhD thesis by C. Perennes, LPNHE
    - Paper submitted to A&A
- Leptonic model
    - Temporal evolution due to
        - Electron acceleration (flux increase)
        - Electron energy losses and decrease of magnetic field (flux decrease)
    - SED and light curves produced from a simple SSC model (Katarzyński et al. 2001)
- Δt computed from a reference light curve (lowest energy)

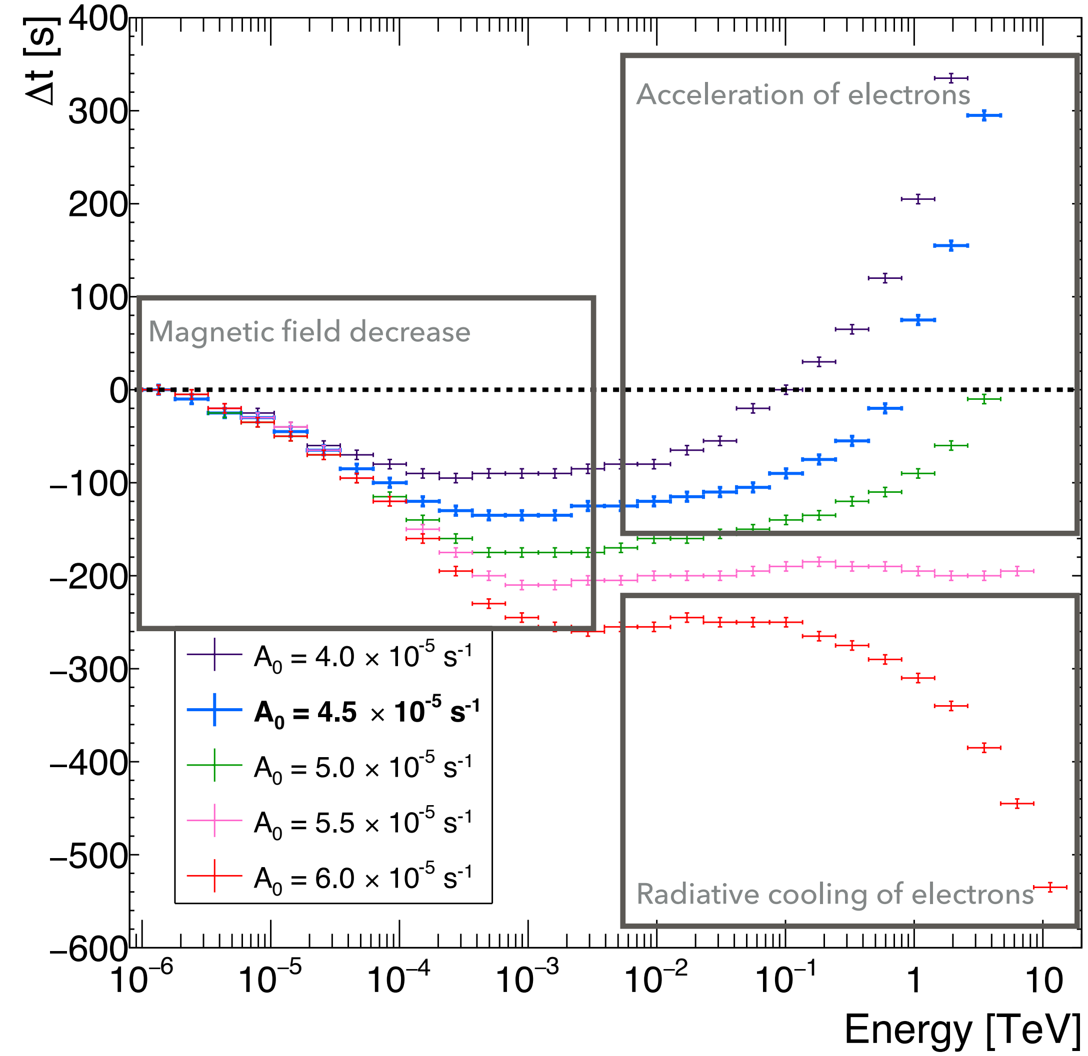




Plots from C. Perennes

UNDERSTANDING INTRINSIC EFFECTS

- Time delays are found to be driven by
  - Acceleration:
    - e- are still accelerating when light curves starts to decay
    - e- need more time to emit the highest energy photons than e- emitting low energy photons
    - LE light curves reach their maximum first
  - Radiative cooling:
    - e- have started to cool down when light curves starts to decay
    - e- emitting the highest energy photons lose their energy faster than e- emitting low energy photons
    - HE light curves reach their maximum first



NB: Adiabatic losses neglected

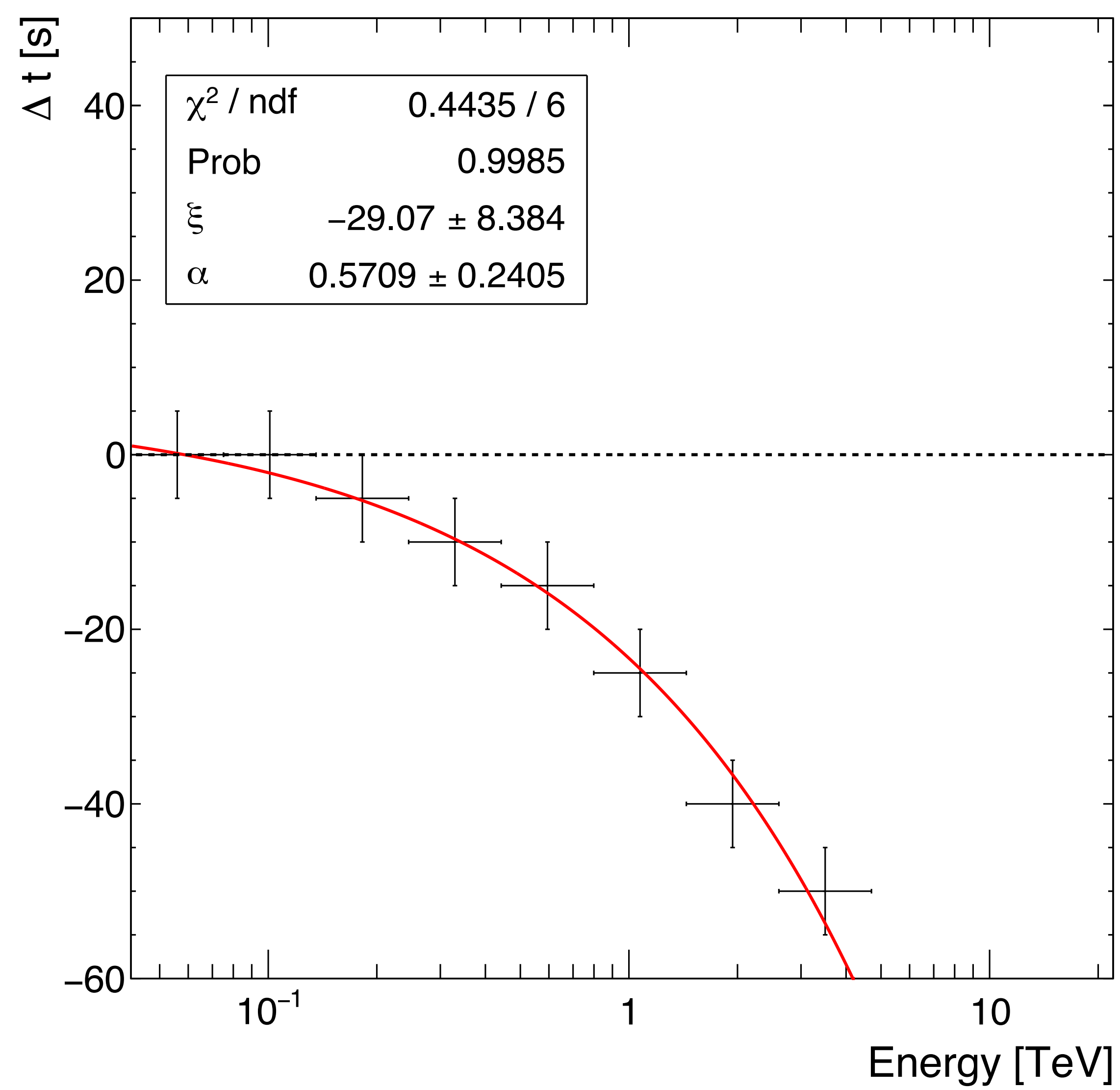
Plots from C. Perennes

UNDERSTANDING INTRINSIC EFFECTS

- Focusing on TeV energies
- Lags can be parameterized by a power law

$$\Delta t = \xi \times (E^\alpha - E_0^\alpha)$$

  - α is found in the range 0.4 - 0.9
  - ξ can be positive (mimicking a subluminal LIV) or negative (superluminal LIV)



- Except for Mkn 501, no lag was measured
  - Constraints on emission, using multi-λ observations
  - From these constraints, get robust constraints on LIV

PAPER SUBMITTED

PREPARING POPULATION STUDIES

L. Nogués, T. Lin, C. Perennes, A. E. Gent, M. Gaug, A. Jacholkowska, M. Martinez, A.N. Otte, J. E. Ward, B. Zitzer, JB

- Joint effort initiated in a working group gathering MAGIC, VERITAS and H.E.S.S. members
- Goal :
  - Combine existing data for AGNs and Pulsars (+GRBs ?) from the three experiments
  - Get combined limits on LIV as a legacy before CTA
  - Redshift dependence study
  - Prepare CTA
- Combine likelihoods to estimate a redshift-independent parameter λ

$$L_{Comb}(\lambda) = \prod_{i=1}^{Nsource} L_i(\lambda) \longrightarrow -2log(L_{Comb}(\lambda)) = -2\sum_{i=1}^{Nsource} log(L_i(\lambda))$$

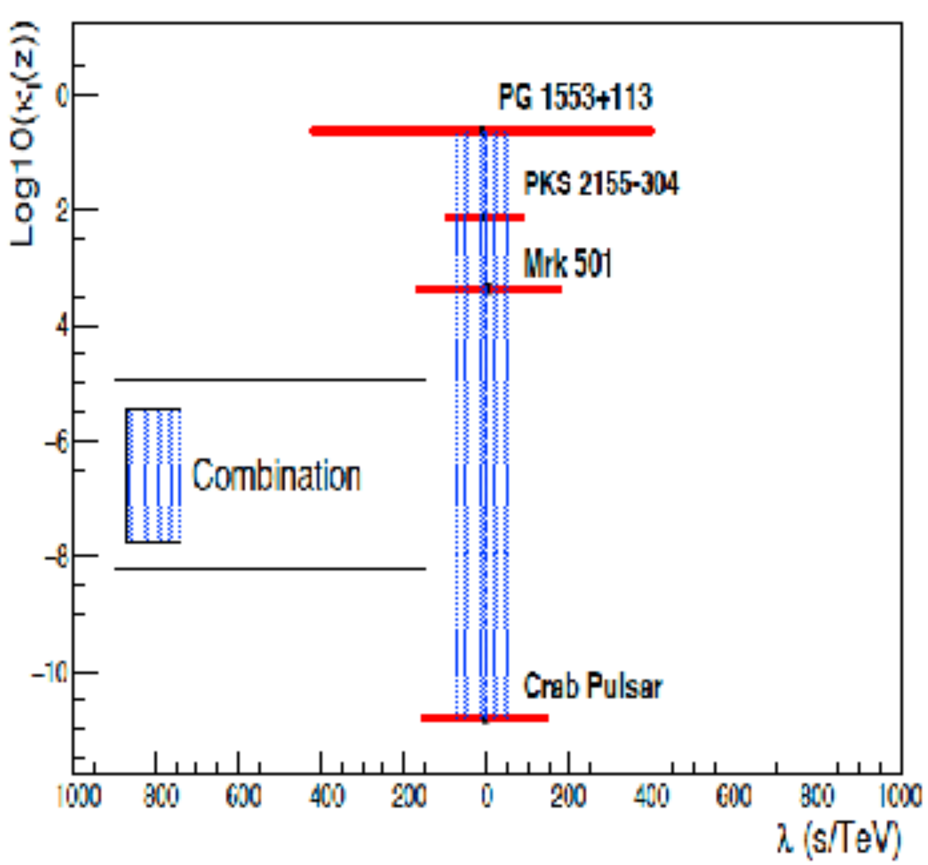
with

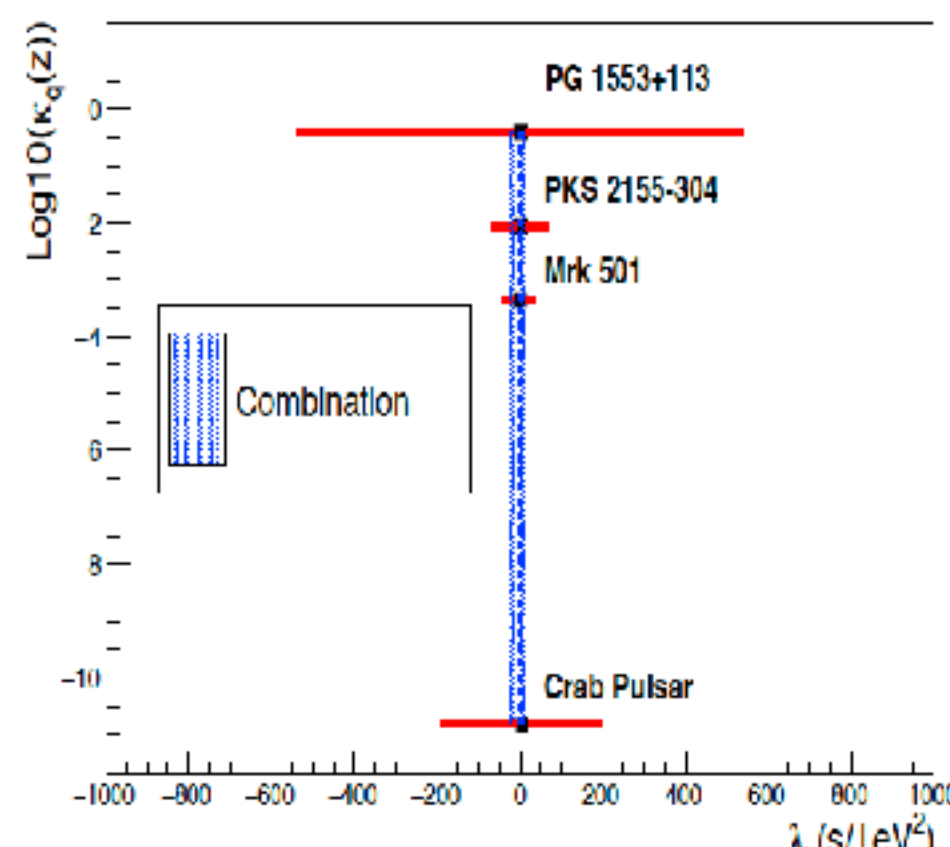
$$\lambda = \frac{\Delta t_n}{\Delta E^n \ \kappa(z)}$$

Plots from Nogués et al., ICRC 2017

PREPARING POPULATION STUDIES

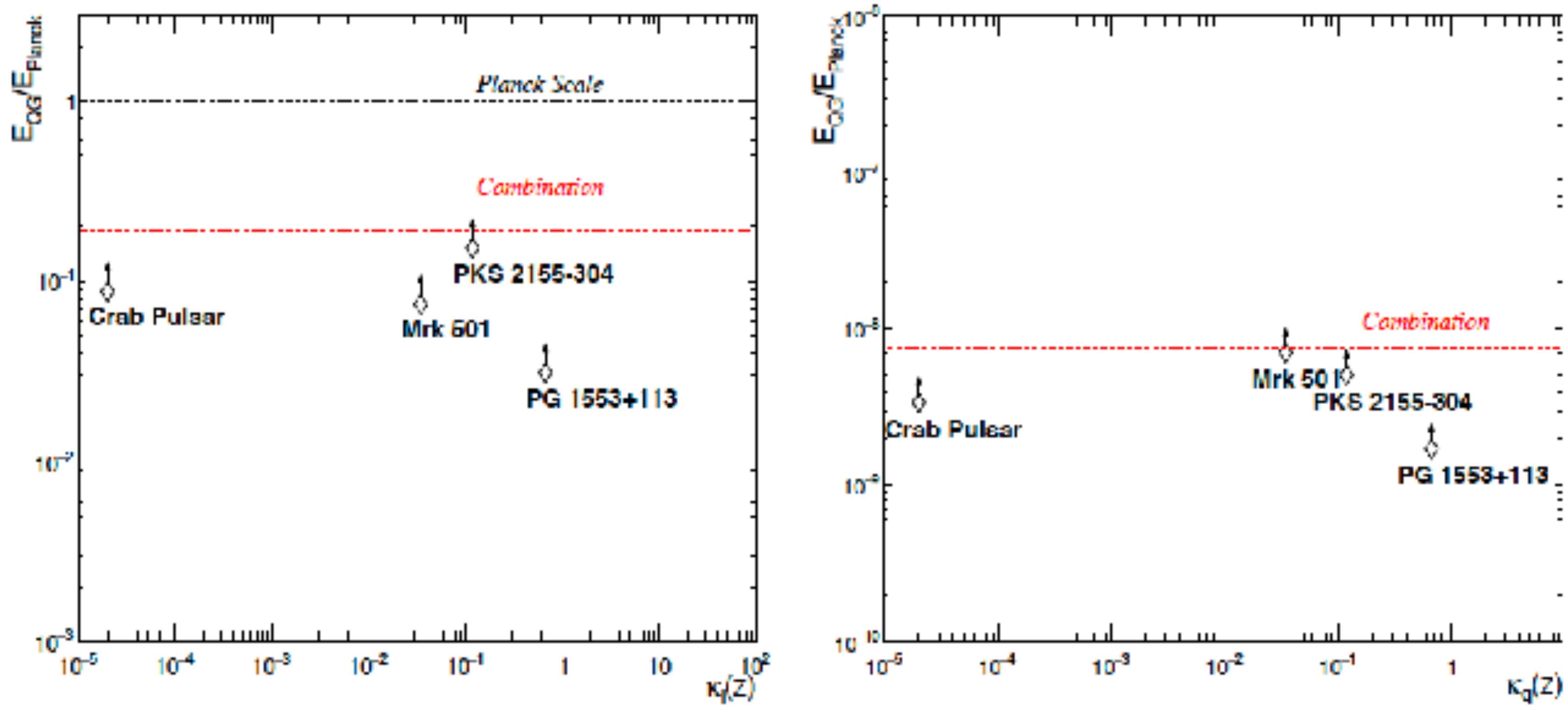
- For now, only simulations
- 990 sets of simulated data from published spectra and light curves
    - Mrk 501 2005 flare detected by MAGIC
    - PG 1553+113 2012 flare detected by H.E.S.S.
    - PKS 2155-304 2006 flare detected by H.E.S.S.
    - VHE Crab Pulsar detected by VERITAS





Plots from Nogués et al., ICRC 2017

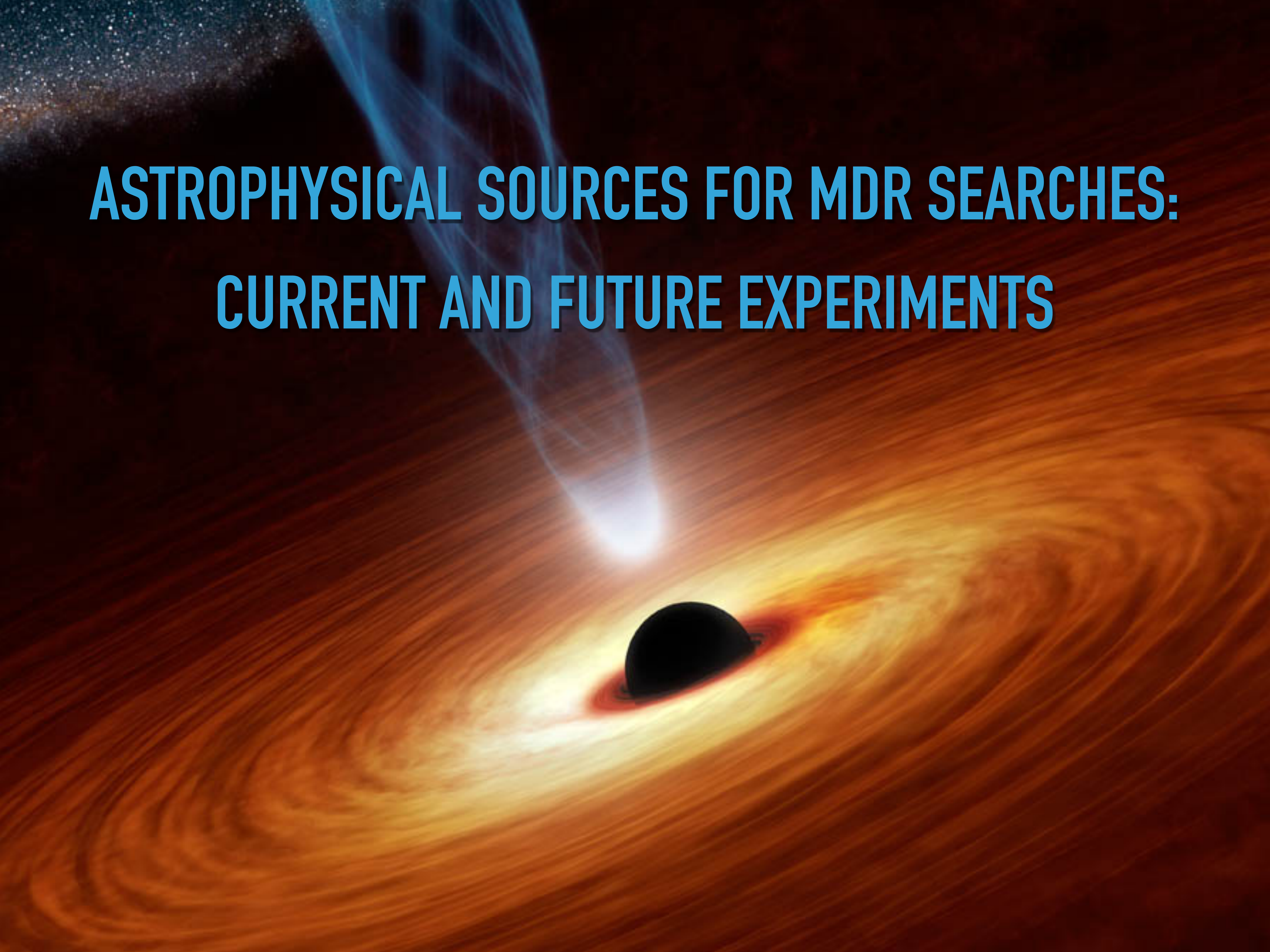
PREPARING POPULATION STUDIES



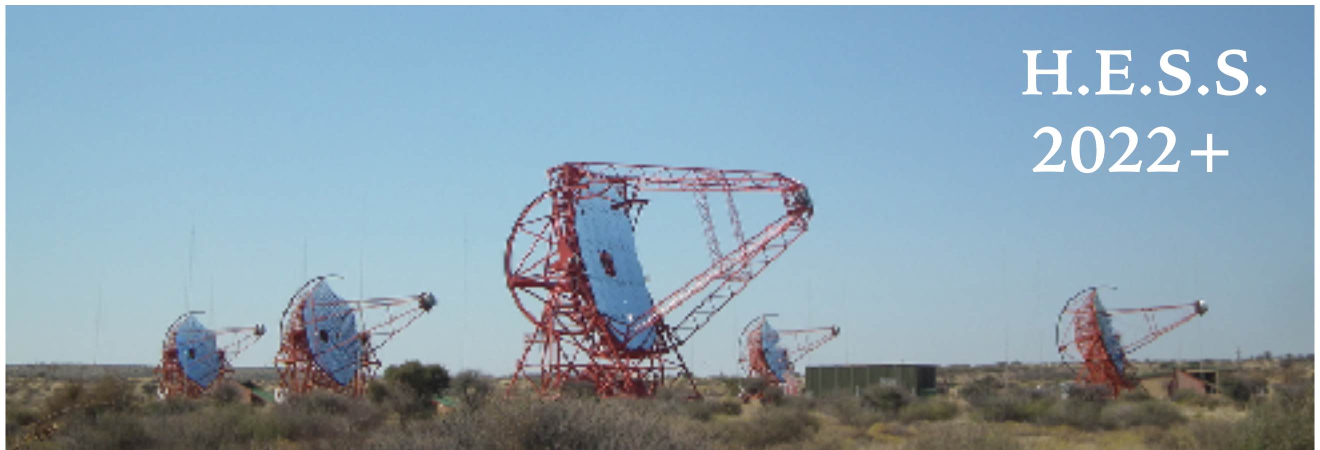
- Combination dominated by
  - PKS 2155 for the linear term
    - 24% improvement w.r.t. the best individual case
  - Mrk 501 for the quadratic term
    - 10% improvement
- Technical paper on the method to appear in early 2020
- Final paper with all available sources to follow

A CRUCIAL STEP BEFORE CTA ! SEE SAMI'S TALK

ASTROPHYSICAL SOURCES FOR MDR SEARCHES: CURRENT AND FUTURE EXPERIMENTS



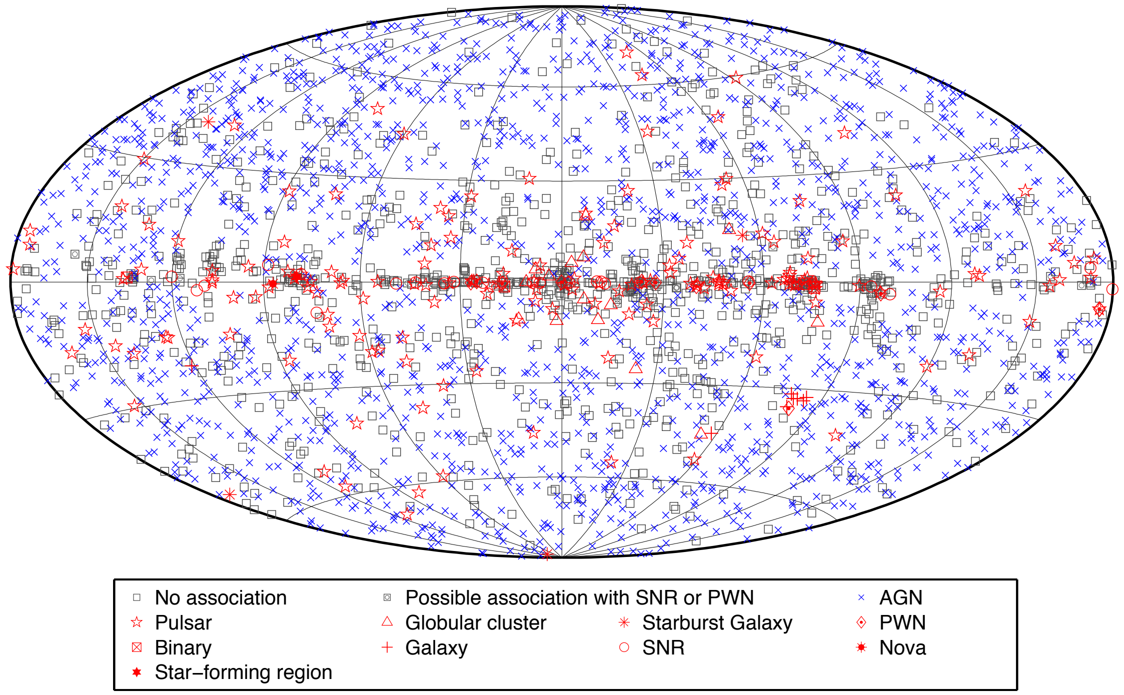
THE LANDSCAPE

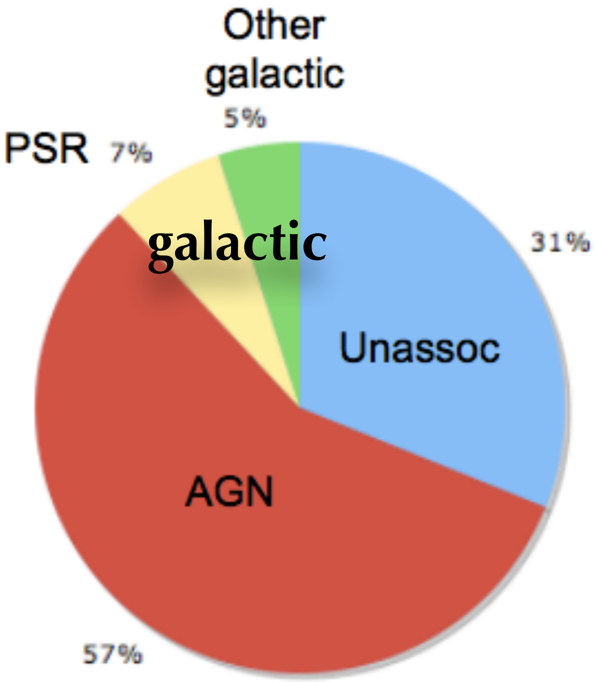


MORE ON FERMI

THANKS TO GABRIJELA ZAHARIAS!

- Mission approved till 2022 (when it will again undergo review)
- Data set publicly available archive at Fermi Science Support Center
- The Fermi mission provides a suite of tools, called the Fermi Science Tools
- ~5000 sources in the Fermi Catalog

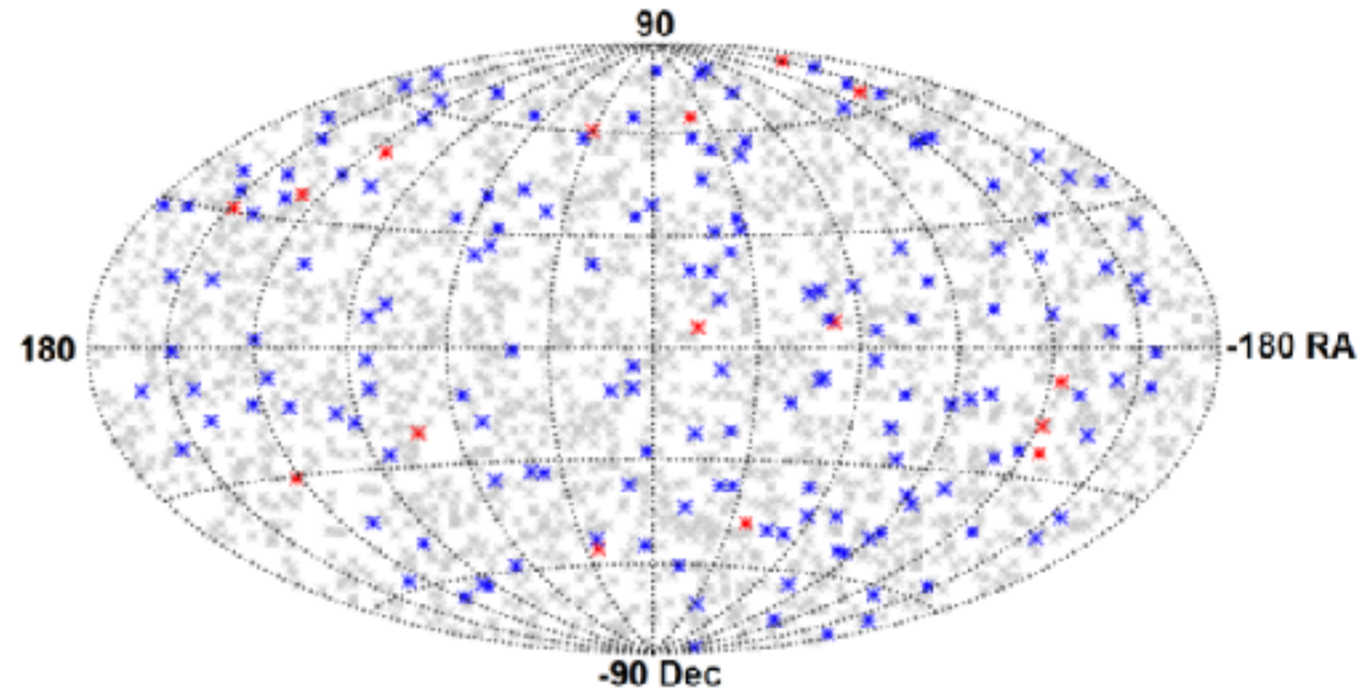


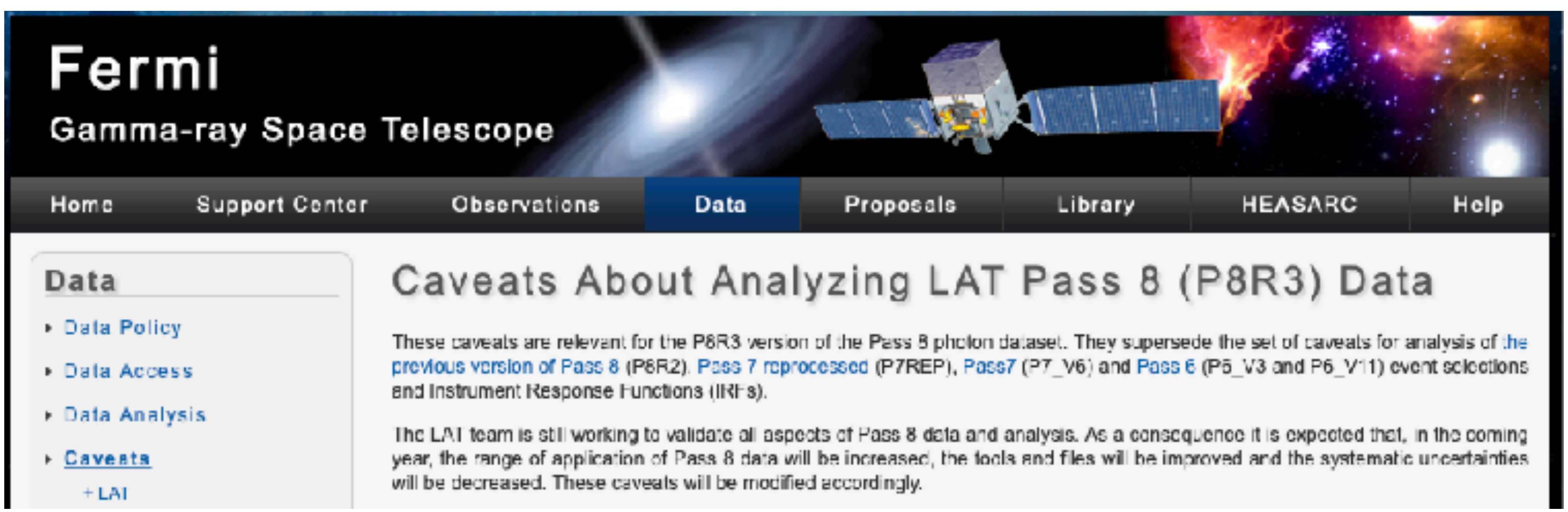


MORE ON FERMI

THANKS TO GABRIJELA ZAHARIAS!

- Second catalog of LAT-detected GRBs: first 10 years of operations
  - Total of 186 GRBs
  - 91 show emission in the range 30 - 100 MeV (17 seen only in this band)
  - 169 are detected above 100 MeV
- The LAT has independently triggered on 4 GRBs
- A must-read !
  - arXiv:1906.11403
- See also: https://fermi.gsfc.nasa.gov/ssc/data/analysis/LAT_caveats.html

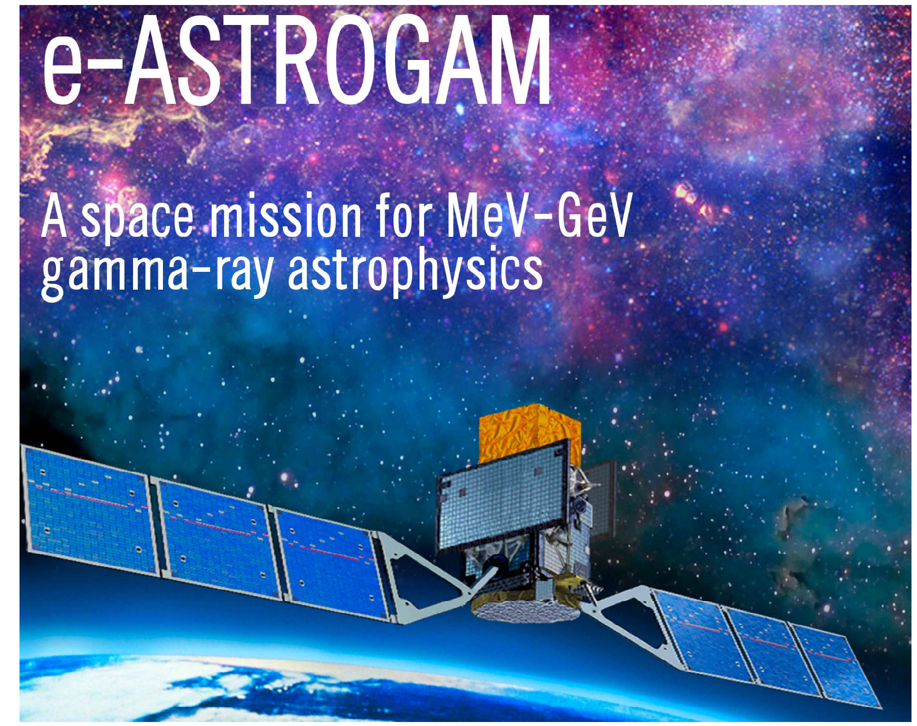


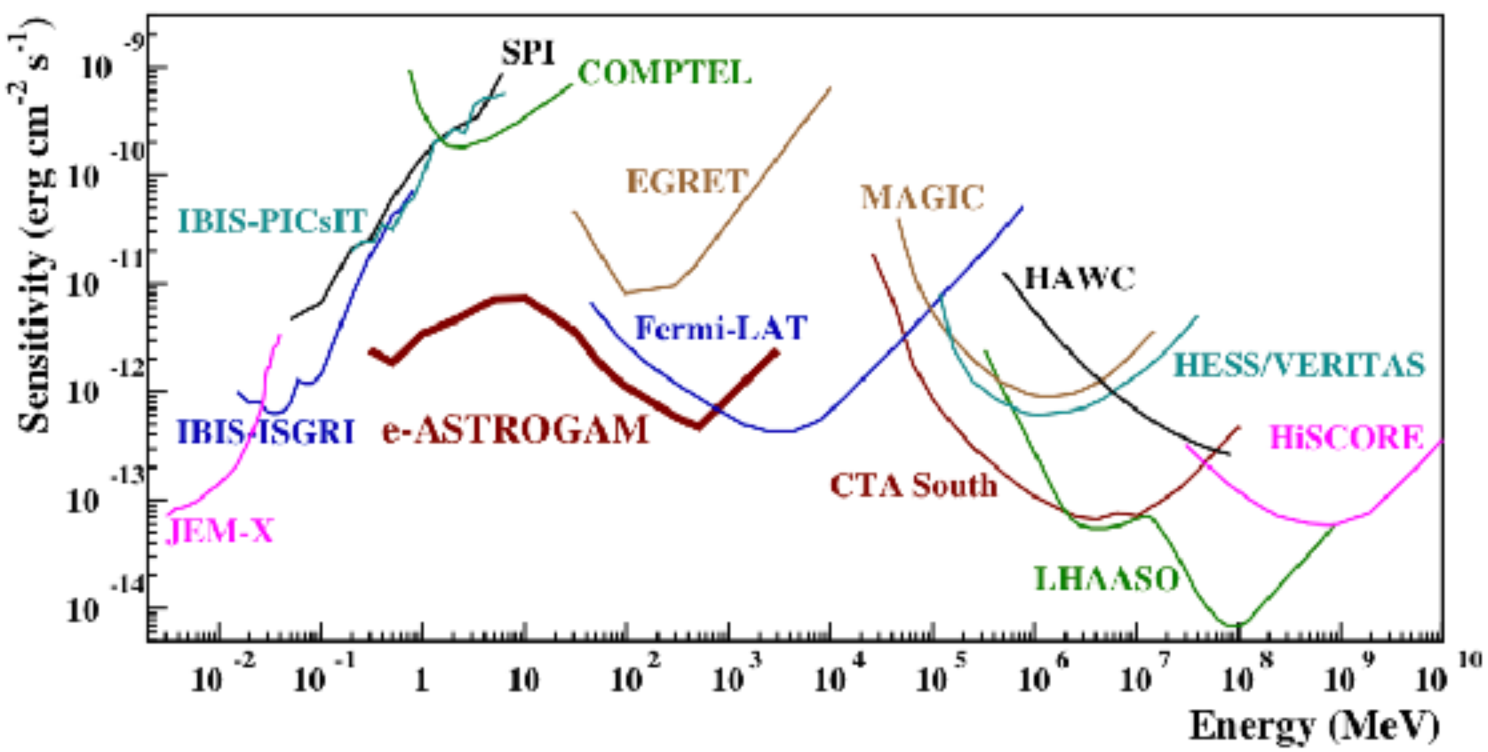


FUTURE: e-ASTROGAM

THANKS TO GABRIJELA ZAHARIAS!

- Broad energy range: 0.3 MeV - 3 GeV
- Large FoV (>2.5 sr)
- Polarization information
  - arXiv:1711.01265





Type	3 yr	New sources
Total	3000 – 4000	~1800 (including GRBs)
Galactic	~ 1000	~400
MeV blazars	~ 350	~ 350
GeV blazars	1000 – 1500	~ 350
Other AGN (<10 MeV)	70 – 100	35 – 50
SNe	10 – 15	10 – 15
Novae	4 – 6	4 – 6
GRBs	~600	~600

CTA IS COMING (202x)

- 20 GeV - 300 TeV
- ~100 telescopes of three different sizes, on two sites
- Sensitivity improved by a factor of ten
- Surveying+Monitoring capability
- Dedicated strategies to maximize transient sources detections
  - Optimized algorithms for quick reactions to alerts
  - Fast analyses to issue alerts
- arXiv:1709.07997

SUMMARY,
ISSUES,
PROSPECTS,
QUESTIONS

Artist's view of CTA Northern site

SUMMARY

- LIV in the form of MDR for photons in vacuum is predicted by different QG approaches
  - Stringy spacetime foam, Semi-classical treatment in Loop QG, but also Non-commutative geometry…
- Astrophysical sources are good tools to probe MDR
  - Complementarity of PSR, GRBs, flaring AGNs
- After 20 years of work on that topic
  - No propagation effect was discovered
  - Limits were set on $E_{QG,1}$ and $E_{QG,2}$
  - Planck scale sensitivity reached for the linear effect
- A number of problems remain

OPEN ISSUES (THEORY/PHENOMENOLOGY SIDE)

- MDR are obtained from « simplified » models
  - Full theory of QG could lead to a neither linear nor quadratic MDR
- The « distance parameter » $\int_0^z \frac{(1+z')^n}{H(z')} dz'$ from Jacob & Piran (2008) is obtained assuming that translations are not affected by Planck scale effects (Rosati et al. 2015)
  - A more thorough study of this question in the DSR approach is on-going and will lead to a re-evaluation of all published limits
- …

OPEN ISSUES (OBSERVATION SIDE)

- MDR « Time of Flight » searches are limited by our limited understanding of astrophysical sources
  - Source-intrinsic effects involve complex processes, difficult to model
- Population studies are still lacking for VHE data
  - Done with GRBs with satellite data, leading to $E_{QG,1} \sim 10^{17}$ GeV
- Methods for lag measurements have all their drawbacks
  - Likelihood procedure is very precise, but requires a fit of the (binned) light curve at low energies
  - Correlation methods give only a lag between two fixed energy bands, etc.
  - New methods could still be proposed
- …

PROSPECTS (FOR THE EXPERIMENTAL SIDE)

- Population studies are a main goal for the future
  - With all possible sources (AGNs, GRBs, PSRs)
  - They will help for
    - Searching for a dependance with redshift
    - Understanding the sources
    - Confirm linear effect exclusion
- Modeling sources with the goal to
  - Constrain (or predict ?) source-intrinsic effects
  - Get more robust constraints on propagation effects
- Multi-λ, multi-messenger and ToO observations will have an important role to play
- A good point: LIV/QG searches come as a bonus with other types of « conventional analyses »

WHAT YOU NEED TO KNOW ABOUT WHAT WE'RE DOING

- IACT data analysis is complex
  - Multiple steps required
    - Calibration, simulations, etc.
  - Complex reconstruction algorithms
    - Hillas, Model, etc.
  - Releasing public data is not easy
- FERMI data analysis may look simple, but
  - Keeping a critical eye is mandatory

THEORY/PHENOMENOLOGY GROUPS WILLING TO ANALYZE DATA SHOULD DO SO IN COLLABORATION WITH EXPERIMENTALISTS!

EXPERIMENTALIST GROUPS SHOULD WORK IN COLLABORATION WITH THEORISTS AND PHENOMENOLOGISTS!

- We spend about the same time to produce results and to evaluate systematics…

WHAT WE WOULD LIKE TO LEARN FROM YOU

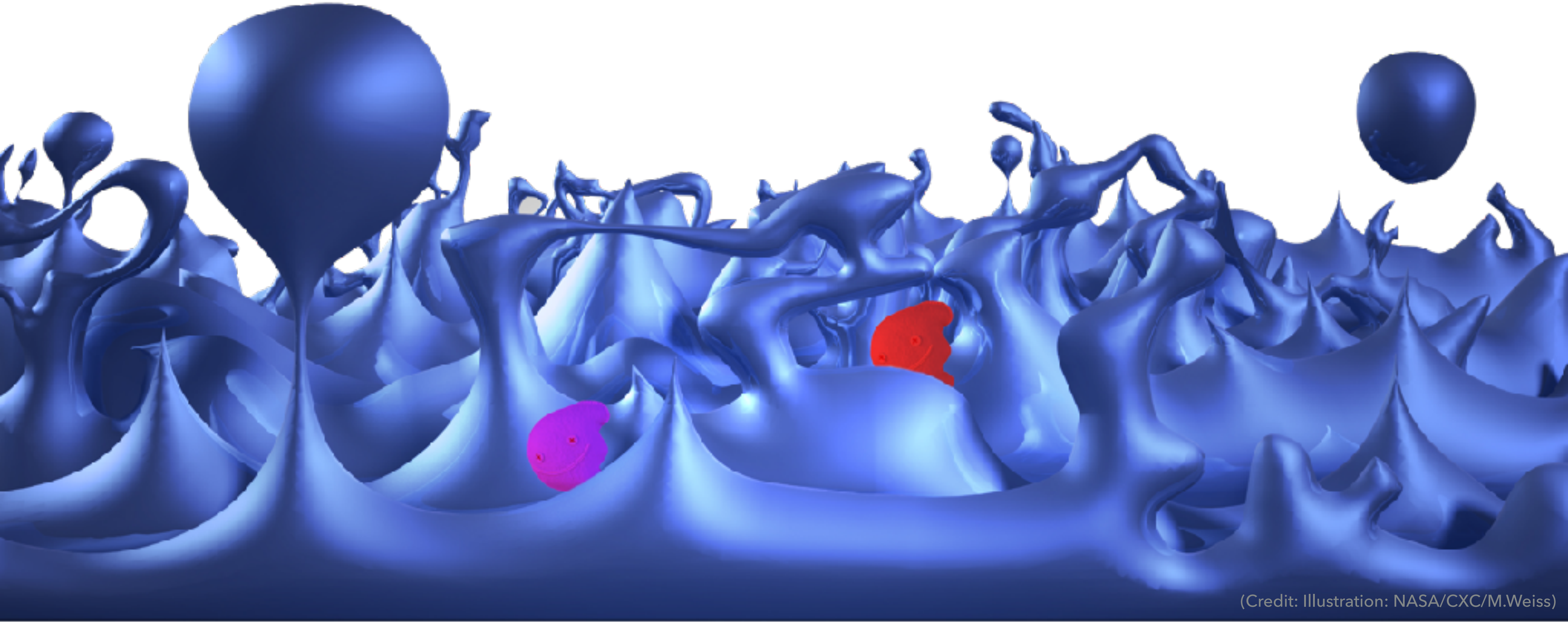
- WG1 & WG2
  - MDR: Could we go further than the simple series expansion we always use?
  - MDR/Fuzziness/…: What is the exact effect of distance?
  - Is there any effect which could be tested now and which is not?
  - If you could design an experiment, what would you do?

- Other working groups:
  - Multi-wavelength/Multi-messenger strategies will be essential
    - Can we do more/better than what we do now?
- For the Action:
  - Experts on source modeling should be invited to join

MERCI !

THANKS !

GRACIAS !



(Credit: Illustration: NASA/CXC/M.Weiss)

LIMITS – REFERENCES

GRBS – PSRS

Reference
Boggs et al. (2004) Abdo et al. (2009b) Abdo et al. (2009a) Vasileiou et al. (2013)
Ellis et al. (2000) Ellis et al. (2003) Bolmont et al. (2008) Lamon et al. (2008) Ellis et al. (2006, 2008) Bernardini et al. (2017) Ellis et al. (2019)
Kaaret (1999) Zitzer and the VERITAS Collaboration (2013) Terrats (2015) Chretien (2015)

AGNS

Reference
Biller et al. (1999) Nogués (2018) Albert et al. (2008) Martínez and Errando (2009) Abdalla et al. (2019b) Aharonian et al. (2008) Abramowski et al. (2011) Abramowski et al. (2015) Abdalla et al. (2019a)

TWO MODELS, A COMMON CONSEQUENCE

$$v_g(E) = \partial E/\partial p \simeq c \times \left[1 - s_{\pm}\frac{n+1}{2}\left(\frac{E}{E_{\mathrm{QG}}}\right)^n\right]$$

QG energy scale

Superluminal (-1) or subluminal (+1)

Only the lowest order dominant terms are considered (n=1,2)

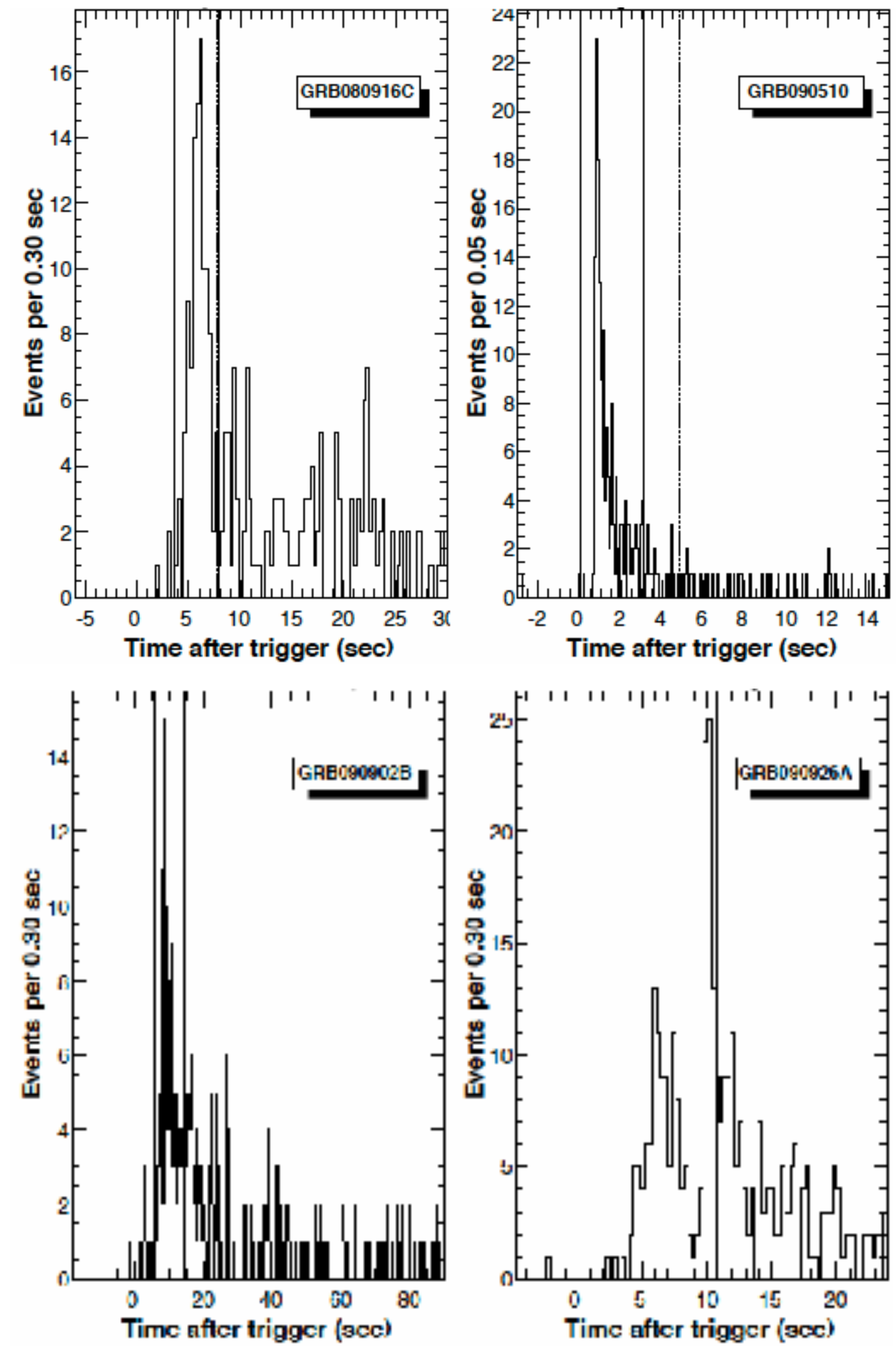
This equality is assumed to be valid at Planck scale

Group velocity

- Photons with different energies have different speeds
- The corresponding time-lag should be greater if they are emitted by a distant source
- Proposition to use Gamma-ray Bursts, Amelino-Camelia et al. (1998)

4 BRIGHT FERMI-LAT BURSTS

- Use of FERMI-LAT data (20 MeV - 300 GeV)
- 4 GRBs analyzed
  - $0.9 < z < 4.3$
  - One short (090510), three long
  - Variability time scale down to tens of ms
  - Maximum energy detected: 31 GeV (090510)
  - ~100 events/GRB above 100 MeV
- 3 different analysis methods
  - PairView, Sharpness Maximization, Likelihood
- Toy Monte Carlo technique:
  error calibration and systematics studies
- Conservative modeling of source effects

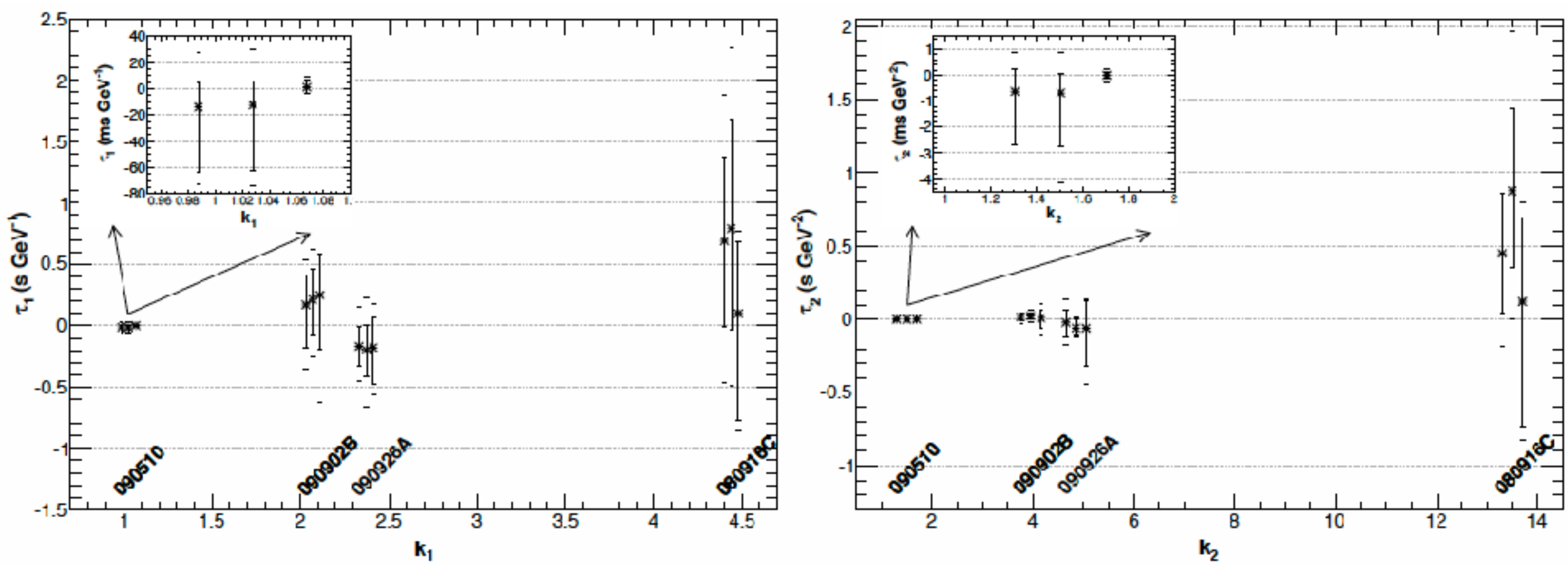


CONSERVATIVE MODELING OF SOURCE EFFECTS

$$\tau_{n\,(\mathrm{total})} = \tau_{n\,(\mathrm{LIV})} + \tau_{(\mathrm{source})}$$

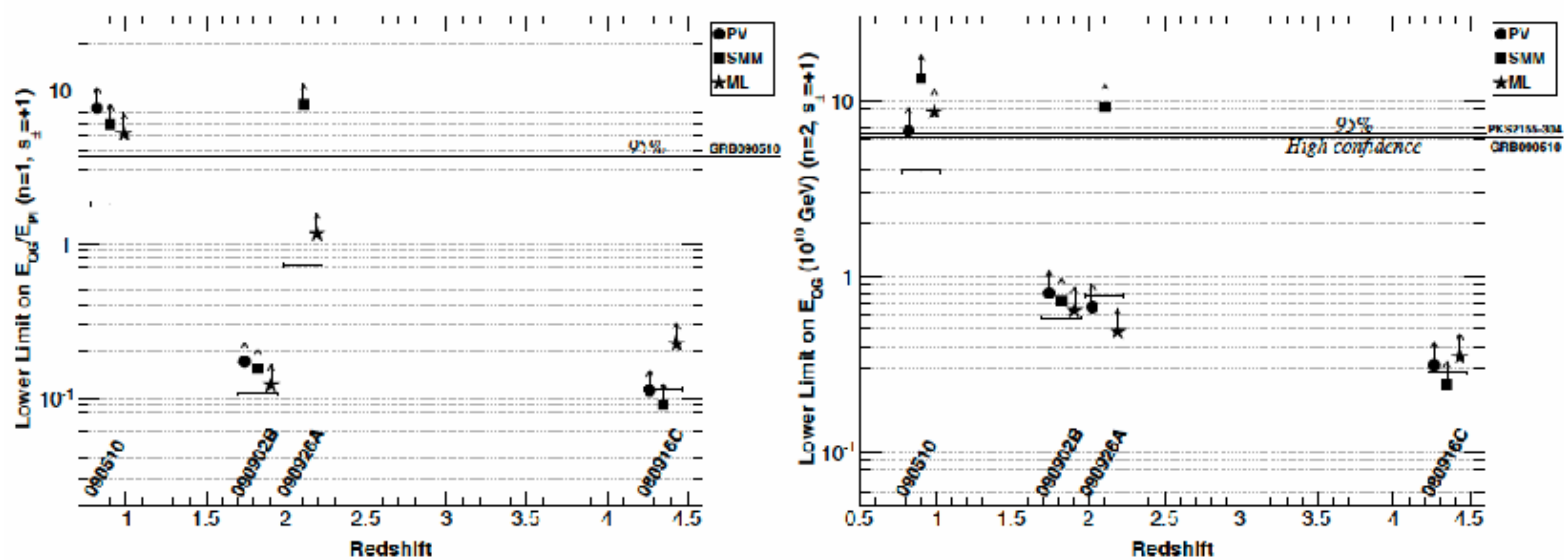
- Measure the Confidence Interval on $\tau_{n(\mathrm{total})}$ from data
- Assume the range of $\tau_{(\mathrm{source})}$
  - is as wide as the CI on $\tau_{n(\mathrm{total})}$
  - is zero on average
- Deduce the allowed range for $\tau_{n(\mathrm{LIV})}$
- Take the value of $\tau_{n(\mathrm{LIV})}$ which gives the least stringent constraint

4 BRIGHT FERMI-LAT BURSTS



- All Confidence Intervals are compatible with 0 dispersion
- Good agreement of the three methods

4 BRIGHT FERMI-LAT BURSTS



- Lower limits on $E_{QG,1}$ and $E_{QG,2}$, subliminal case
  - $E_{QG,1} > 7.6\ E_P$
  - $E_{QG,2} > 1.3\text{x}10^{11}$ GeV
- 090510: Limit still above E_P with intrinsic effect modeling

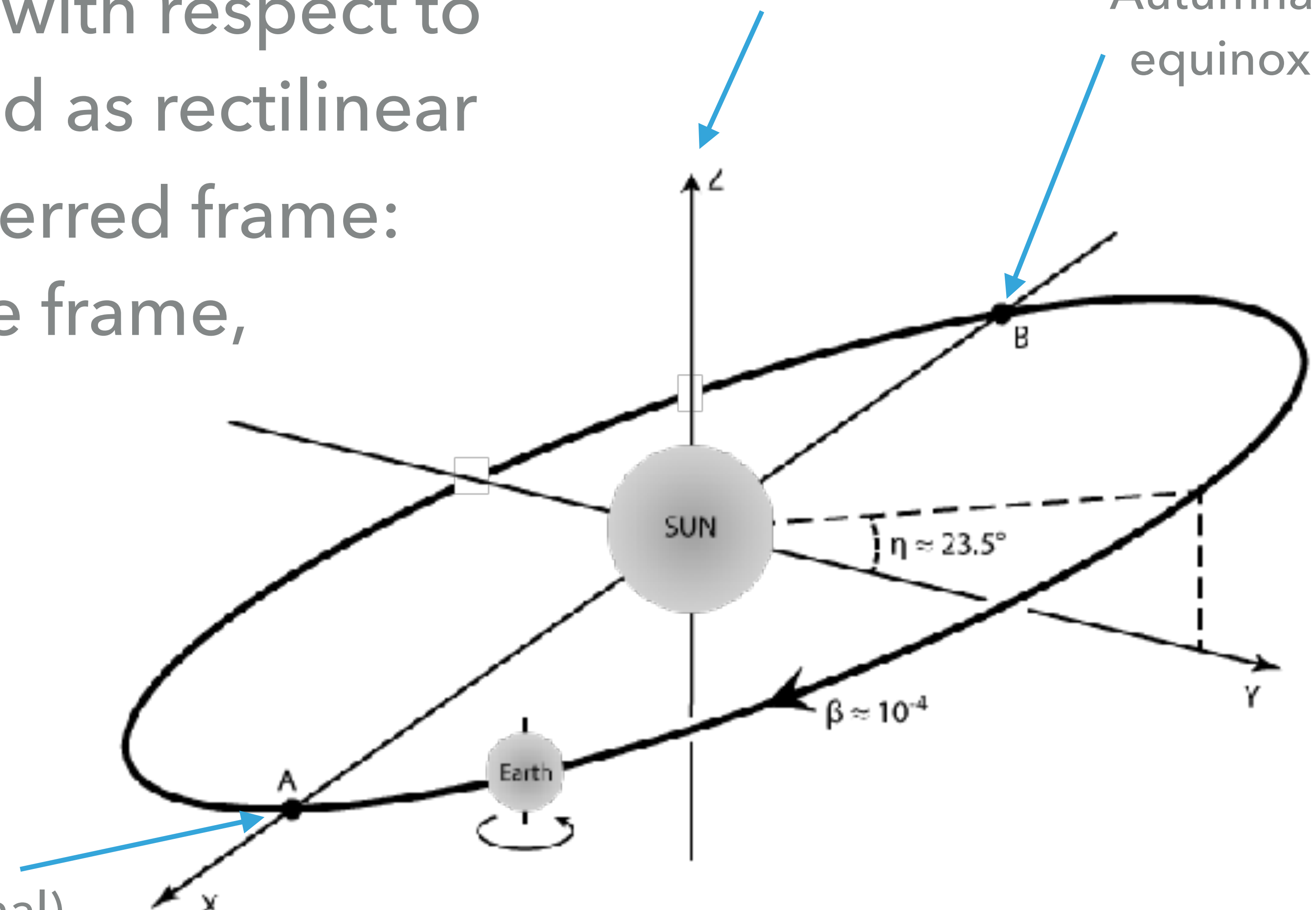
+ BEST LIMITS EVER OBTAINED
- RESULT DOMINATED BY GRB 090510

OTHER DELAYS

- Photons can be delayed by different processes
  - Plasma effects in the source (Latorre et al. (1995))
    - Negligible (~ps for a 1 TeV photon, T~10^{-2} MeV, D~10^{9} km)
  - Interaction with particles candidate for DM (Latimer (2013))
    - Negligible (~10^{-39} s for a source at $z = 8$ and $\Delta E \sim 100$ GeV)
  - Photon-photon interaction + cascade + deflection by Extragalactic Magnetic Fields (Taylor et al. (2011))
    - $\Delta t \sim$ years
  - Gravitational lensing…

PREFERRED FRAME

- Short duration of experiments as compared to the Sun revolution period around the Galaxy
  - The movement of the Sun with respect to the CMB can be considered as rectilinear
  - Natural choice for the preferred frame: the sun-centered reference frame, considered as inertial



THE STANDARD MODEL EXTENSION

- A dynamical test theory
- In the photon sector of the full SME:

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \boxed{+ \frac{1}{2}\epsilon^{\kappa\lambda\mu\nu}A_\lambda(\hat{k}_{AF})_\kappa F_{\mu\nu} - \frac{1}{4}F_{\kappa\lambda}(\hat{k}_F)^{\kappa\lambda\mu\nu}F_{\mu\nu}}$$

LIV terms

- The dispersion relation reads

$$k(\omega) \approx \left[1 + \varsigma^0\right]$$

with

$$\varsigma^0 = \sum_{djm} \omega^{d-4} \, {}_0Y_{jm}(\hat{\mathbf{n}}) c^{(d)}_{(I)jm}$$

- d = 5 (linear LIV) or d = 6 (quadratic LIV)

THE STANDARD MODEL EXTENSION

- Parameters constrained by experiments:
  - General case: $\sum_{jm} {}_0Y_{jm}(\hat{\mathbf{n}}) c^{(d=5,6)}_{(I)jm}$
    Direction of the source in the Sun-centered frame
  - Isotropic case: $c^{(d)}_{(I)00}$

- These parameters can be related to the time-lag parameter measured with astrophysical sources

PARAMETER κ_n

DISTANCE PARAMETER κ_n