J. BOLMONT

TESTING LORENTZ INVARIANCE WITH AGN : CURRENT STATUS AND PROSPECTS

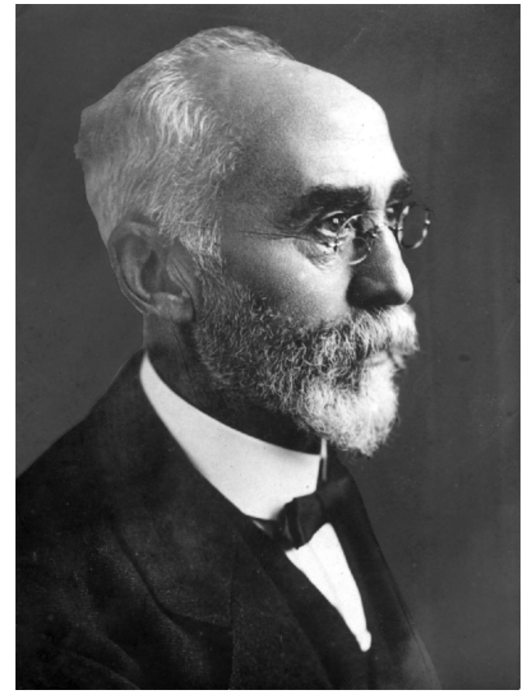
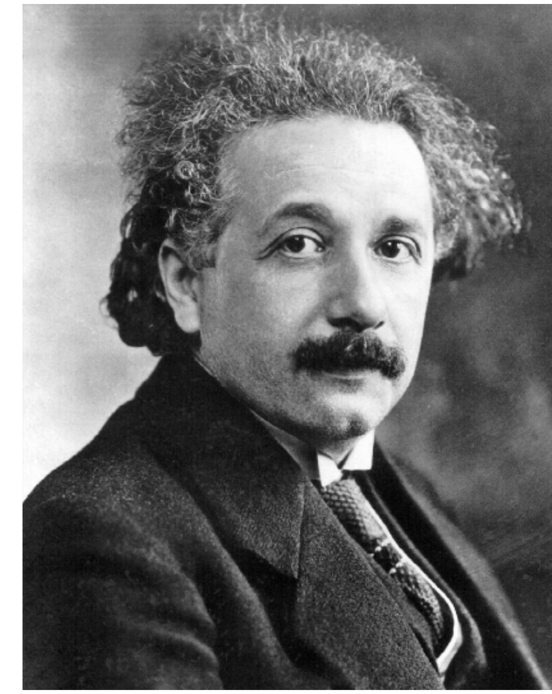
14th Rencontres du Vietnam

August 12-18, 2018

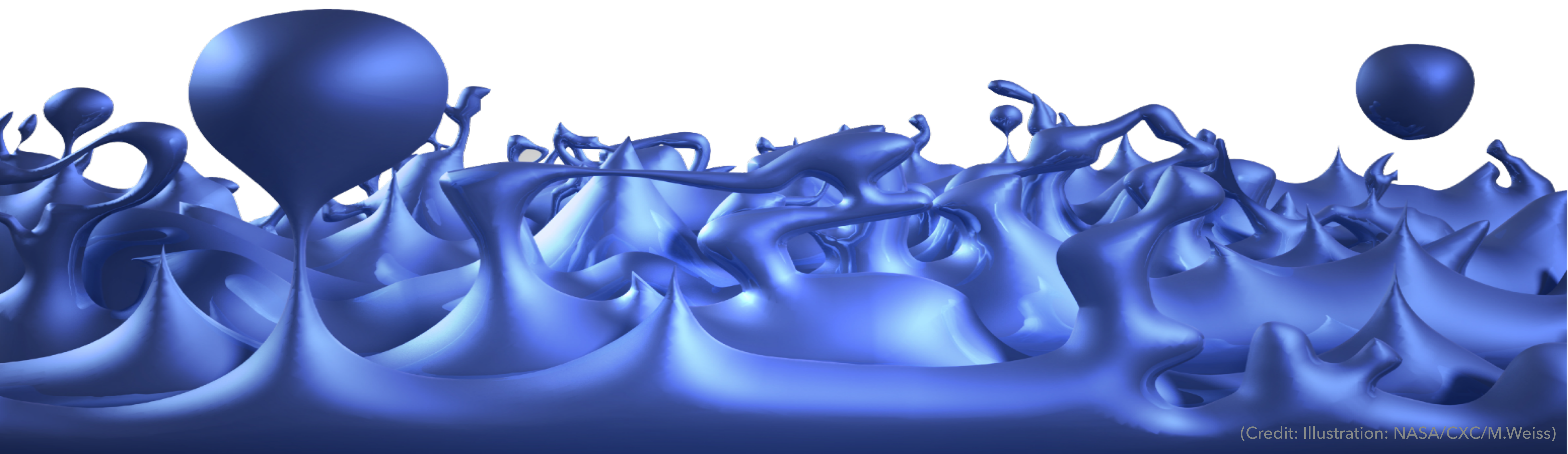
CONTENTS

- Lorentz Invariance and Quantum Gravity
- Testing Modified Dispersion Relations with gamma-ray sources
- Review of some results from AGN observations
- Where do we go next ?
  - Understanding the sources
  - Population studies
- Conclusions

I WILL COVER ONLY :
- AGN IN THE GEV-TEV RANGE
- « TIME-OF-FLIGHT » STUDIES

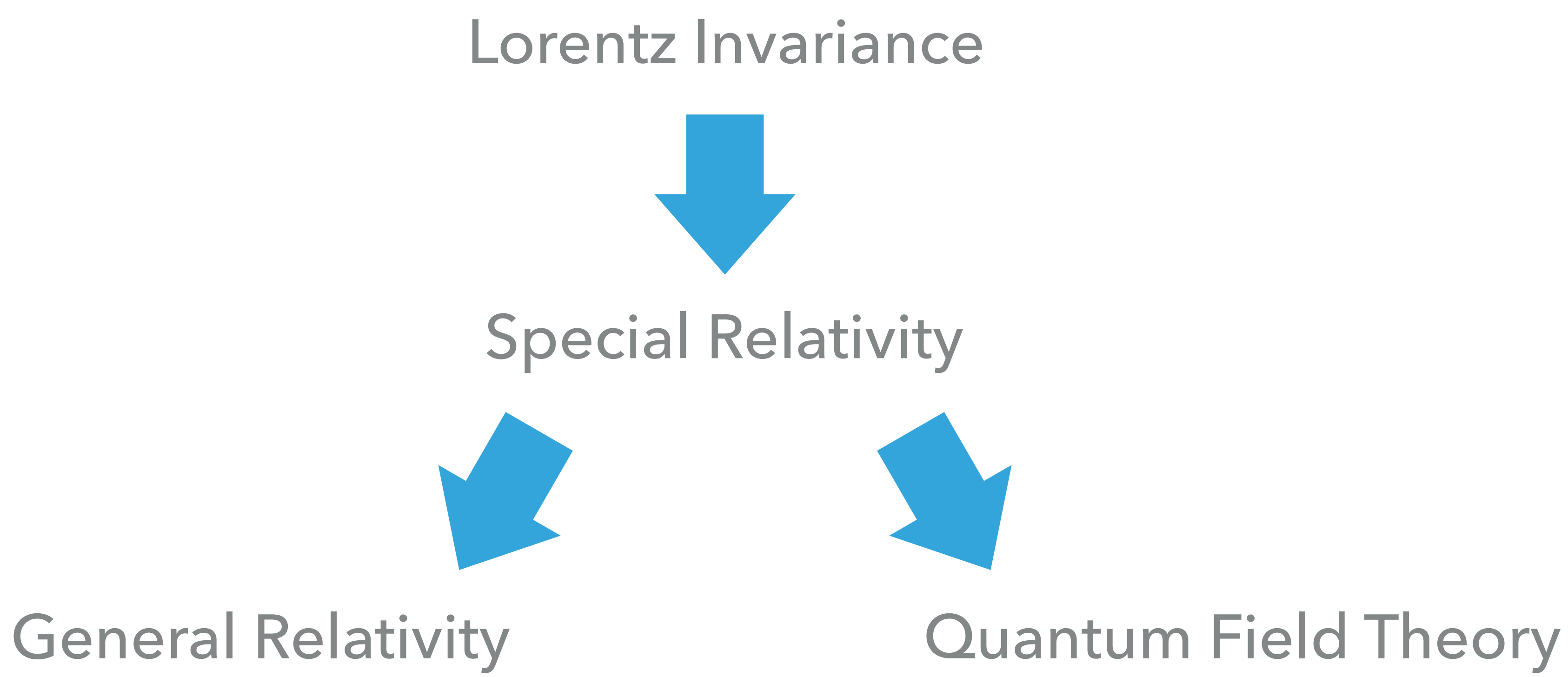
   

LORENTZ INVARIANCE & QUANTUM GRAVITY



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

A CORNERSTONE OF MODERN PHYSICS (1)



TESTING LI: A COMPELLING DUTY !

Liberati (2013)

A CORNERSTONE OF MODERN PHYSICS (2)

Lorentz Invariance

Special Relativity

General Relativity

CURVED SPACETIME
SINGULARITIES

Quantum Field Theory

FLAT SPACETIME
NO GRAVITY

GR AND QFT HAVE LIMITATIONS

A CORNERSTONE OF MODERN PHYSICS (3)

Lorentz Invariance

Special Relativity

General Relativity

CURVED SPACETIME
SINGULARITIES

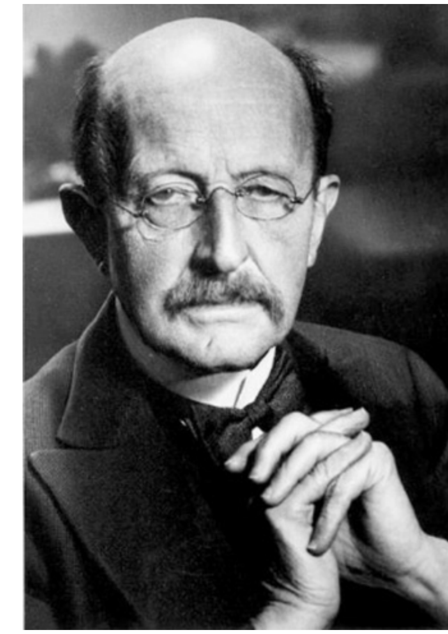
Quantum Field Theory

FLAT SPACETIME
NO GRAVITY

Quantum Gravity

WHAT IS THE FATE OF LORENTZ INVARIANCE AT E_{QG} ?

THE PLANCK SCALE

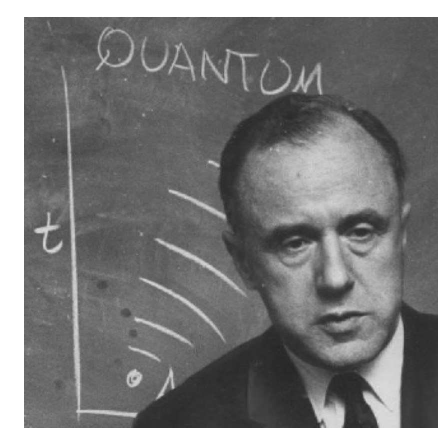


- Planck units (M. Planck, 1899)

$$l_P = \sqrt{\frac{\hbar G}{c^3}} = 1.616\,229(38) \times 10^{-35}\ \mathrm{m},$$

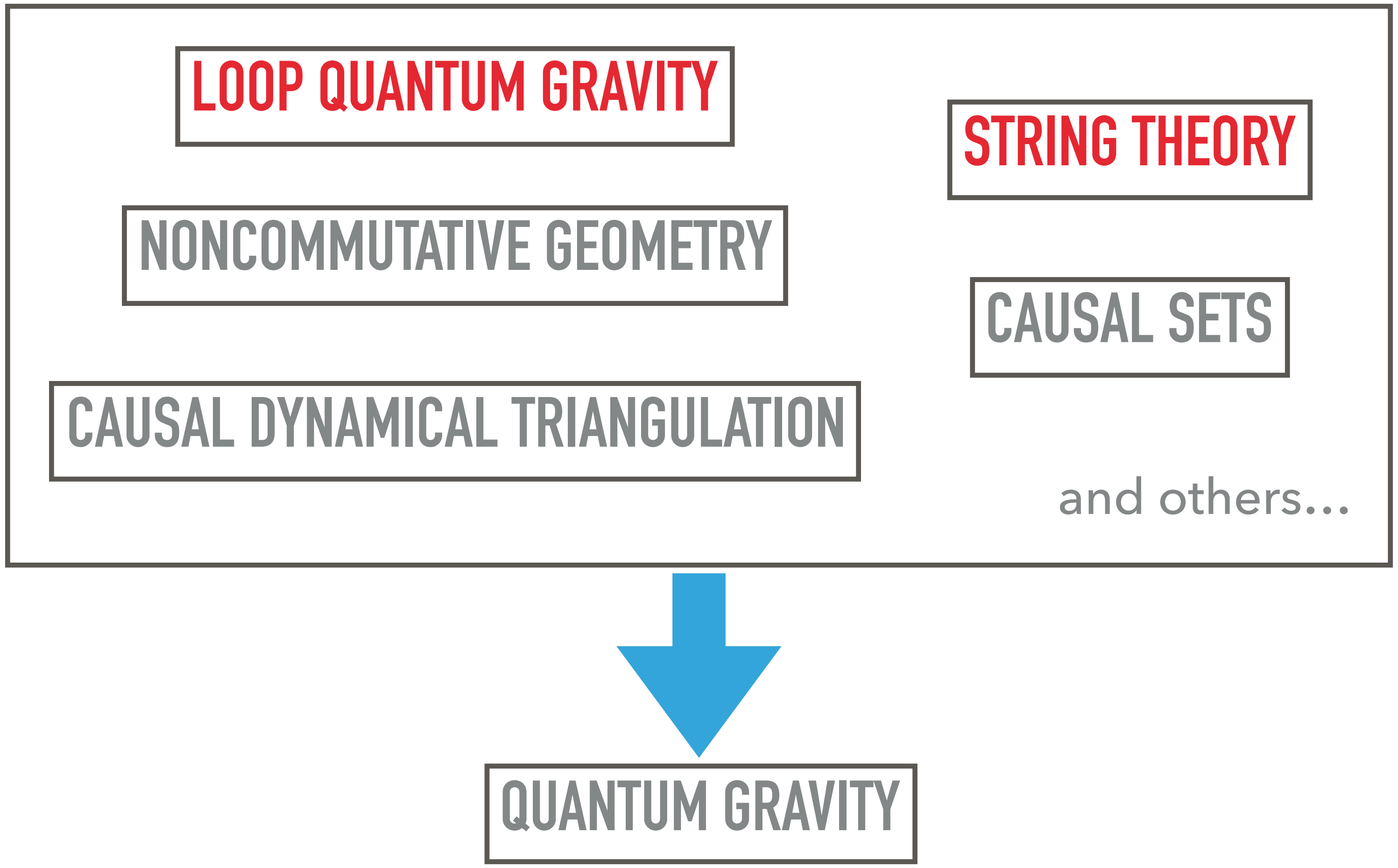
$$E_P = m_P\, c^2 = 1.220\,910(29) \times 10^{19}\ \mathrm{GeV}.$$

- A limit for Quantum relativistic theory (M. P. Bronstein, 1936)
- The quantum limit of General Relativity (J. A. Wheeler, 1955)
  - The energy scale of Quantum Gravity
- But, the Planck scale should be considered only as a rough order of magnitude
  - The speed of light may depend on the energy
  - The Gravitational constant may run



SOME ROADS TO A SINGLE THEORY

- No experimental input
- Several approaches are followed
- All these approaches should help design the « ultimate » theory of QG



THE TWO MAIN ROADS

STRING THEORY

e.g. Mavromatos (2010)

- Unification of the 4 forces
- Starting point: the string
- Gravity is a gauge interaction
- Some models of stringy spacetime foam predict a modified dispersion relation for photons in vacuum

$$\Delta t \sim \alpha' p^0$$

String scale ~10^{-34} m

LOOP QUANTUM GRAVITY

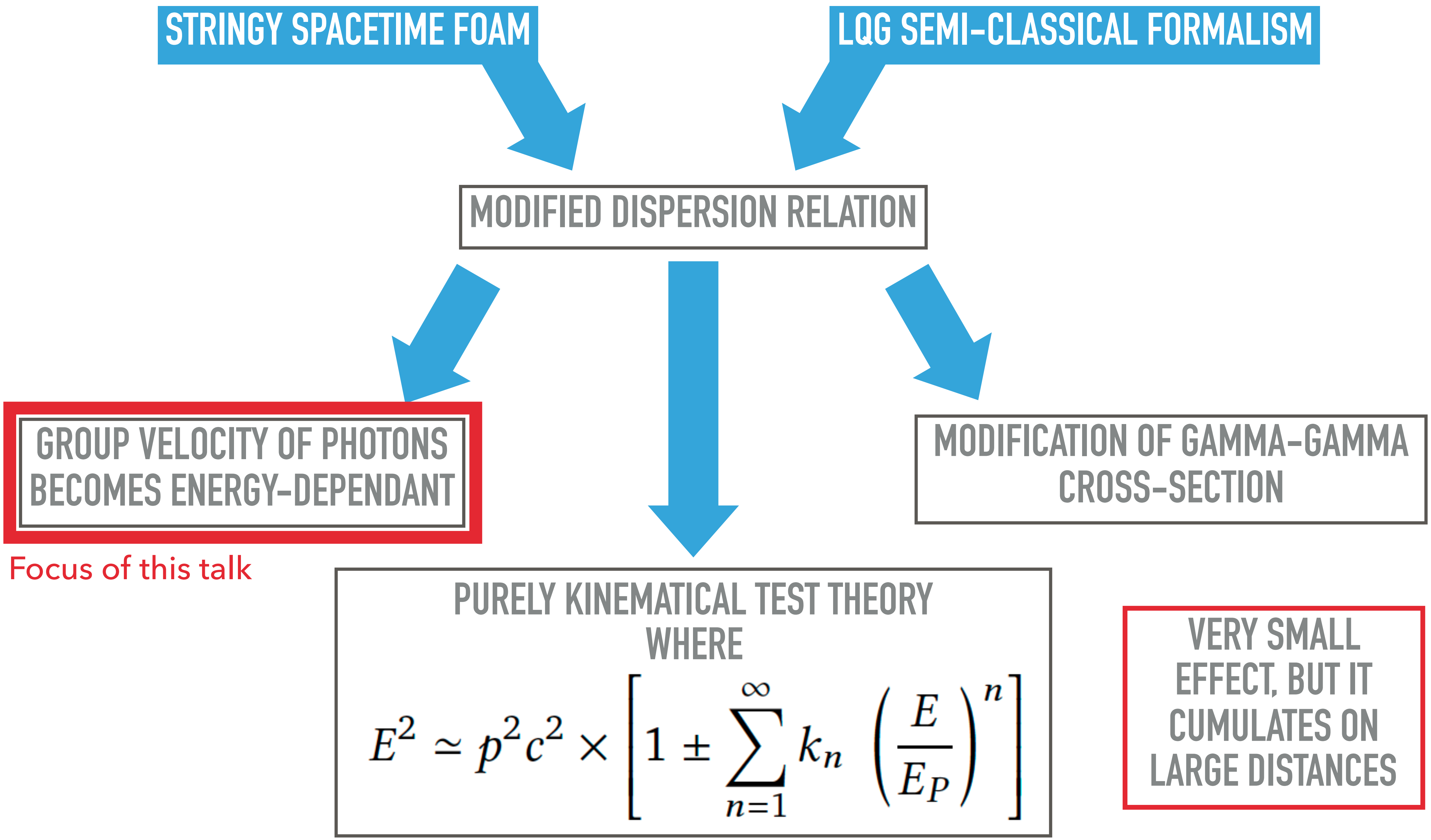
Gambini & Pullin (1999)

- Description of Quantum spacetime
- Starting point: a Hamiltonian formulation of GR
- Spacetime is discrete
- Modified dispersion relation can be obtained in a semiclassical regime

$$\omega_\pm(k) \simeq ck(1 \mp 2\xi l_P k)$$

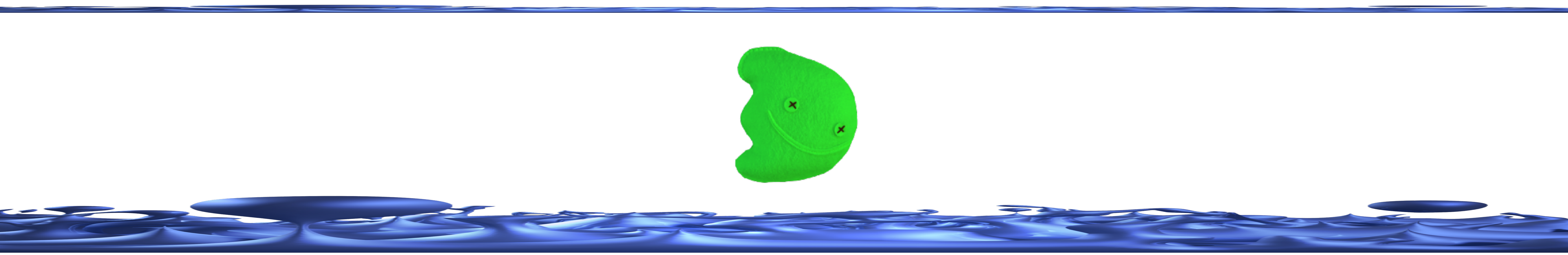
BREAKING OF LORENTZ INVARIANCE

TWO MODELS, A COMMON CONSEQUENCE

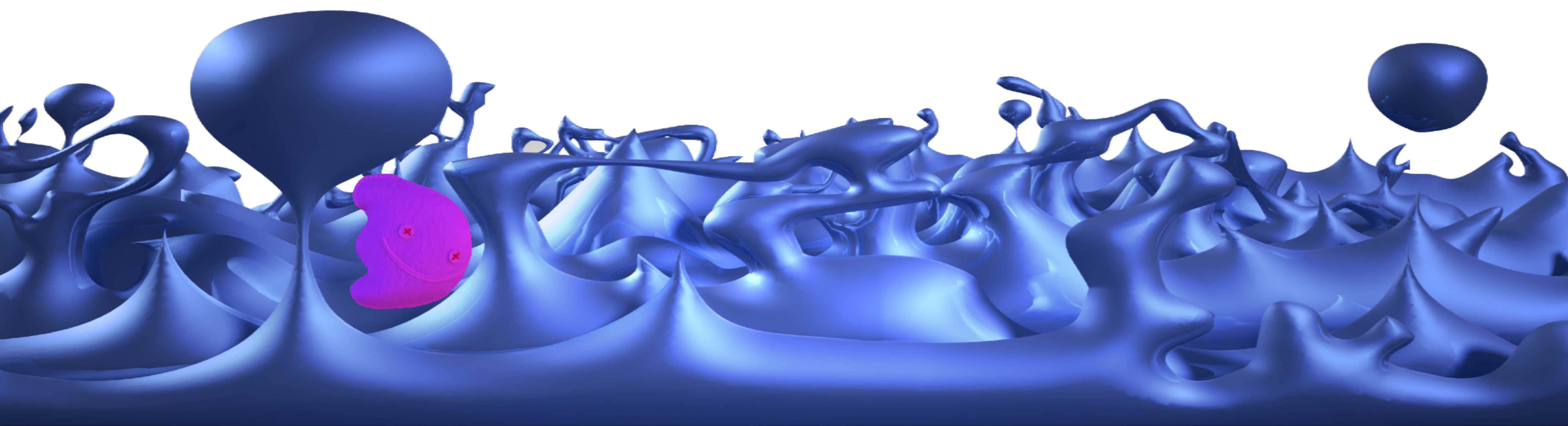


SUMMARY

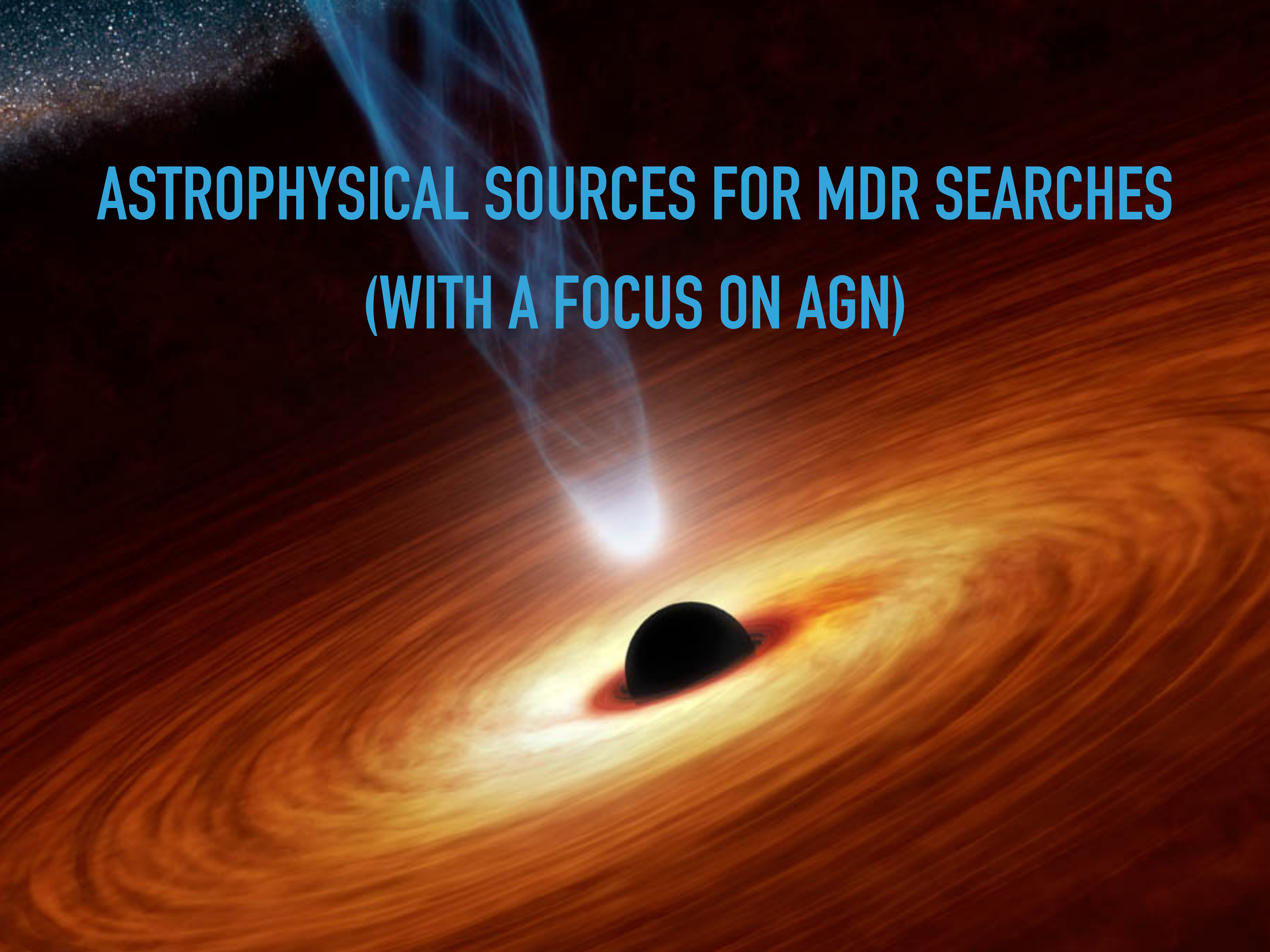
- A low energy photon « feels » spacetime as flat



- A high energy photon « feels » spacetime as foamy



ASTROPHYSICAL SOURCES FOR MDR SEARCHES (WITH A FOCUS ON AGN)



FROM MDR TO TIME-LAG

- As Universe is expanding, the expansion has to be taken into account when calculating the delay (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)

- Usually, another parameter is used:

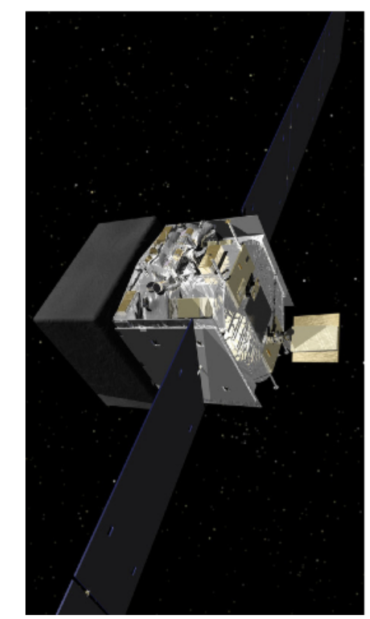
$$\tau_n \equiv \frac{\Delta t_n}{E_h^n - E_l^n} \simeq s_\pm \frac{n+1}{2 H_0} \frac{1}{E_{QG}^n} \int_0^z \frac{(1+z')^n}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}} dz'$$

FROM MDR TO TIME-LAG

Go !

LE photon arrives first !

A source



A detector

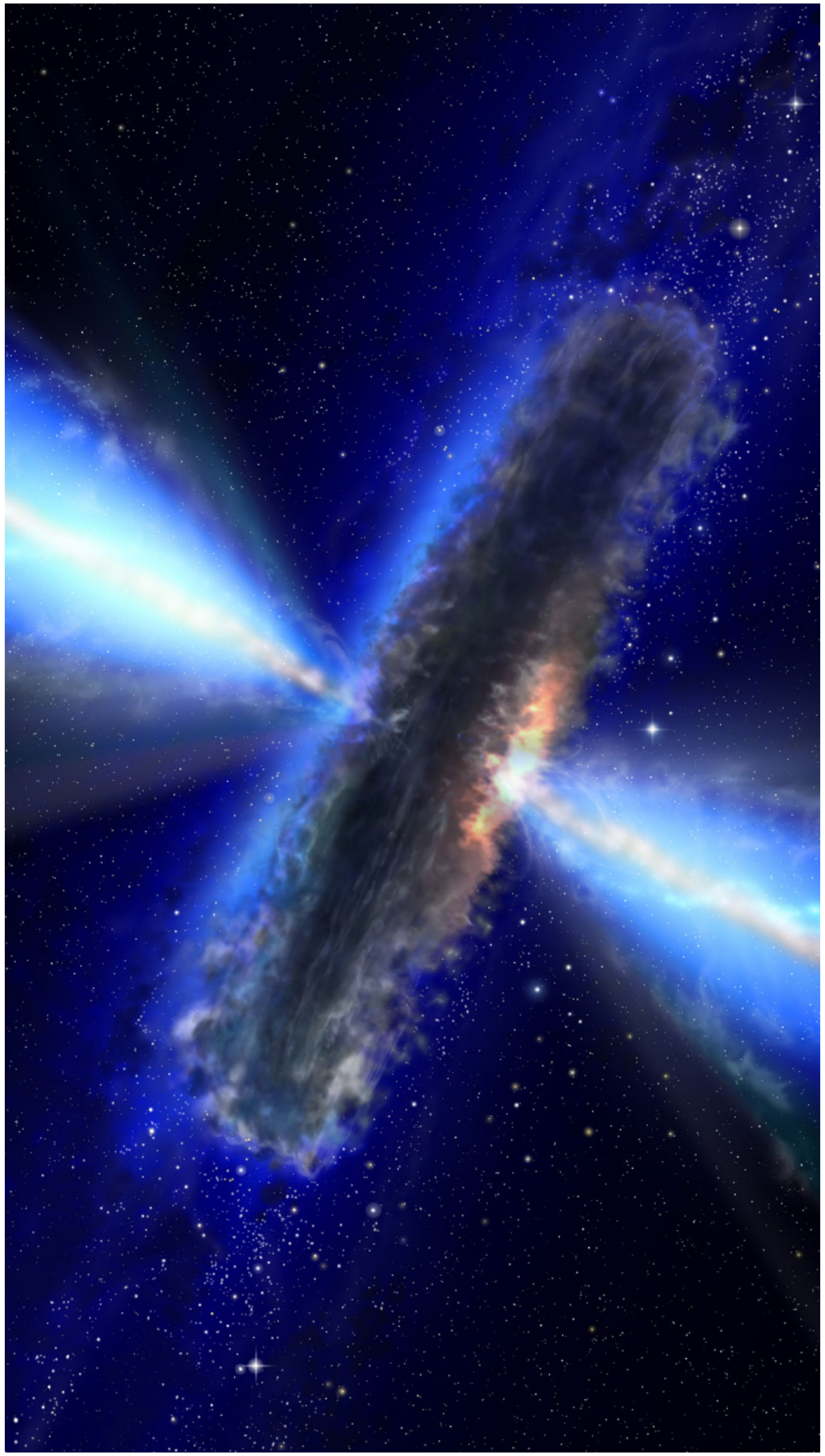
- Subluminal effect
- The two photons are assumed to be emitted at the same time

ASTROPHYSICAL SOURCES FOR MDR SEARCHES

- The time-lag Δt_n is proportional to:
  - The distance parameter
  - The energy difference $\Delta E^n \equiv E_h^n - E_l^n$
- Need for sources that are
  - Distant
  - Variable or transient
  - Energetic
- Candidates:
  - Gamma-Ray Bursts (GRBs)
  - Flaring Active Galactic Nuclei (AGNs)
  - Pulsars (PSRs)
- These sources have advantages and drawbacks

FLARING ACTIVE GALACTIC NUCLEI

- Galaxies with 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
  - 👎 Hints of intrinsic temporal effects
  - 👎 Details of emission mechanisms poorly understood



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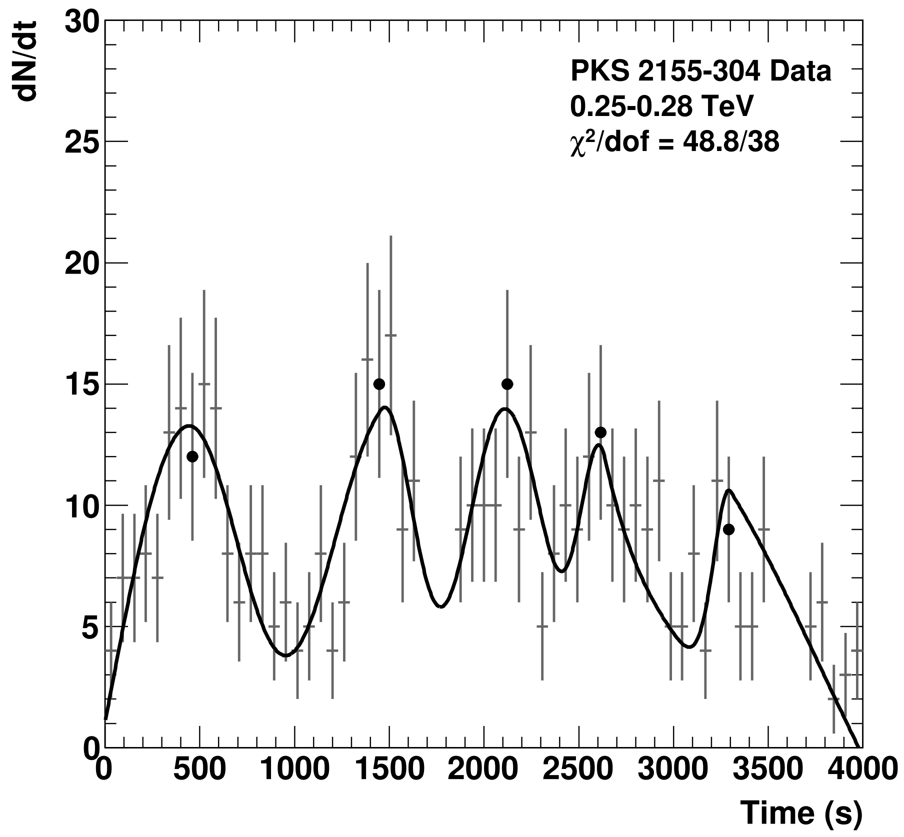
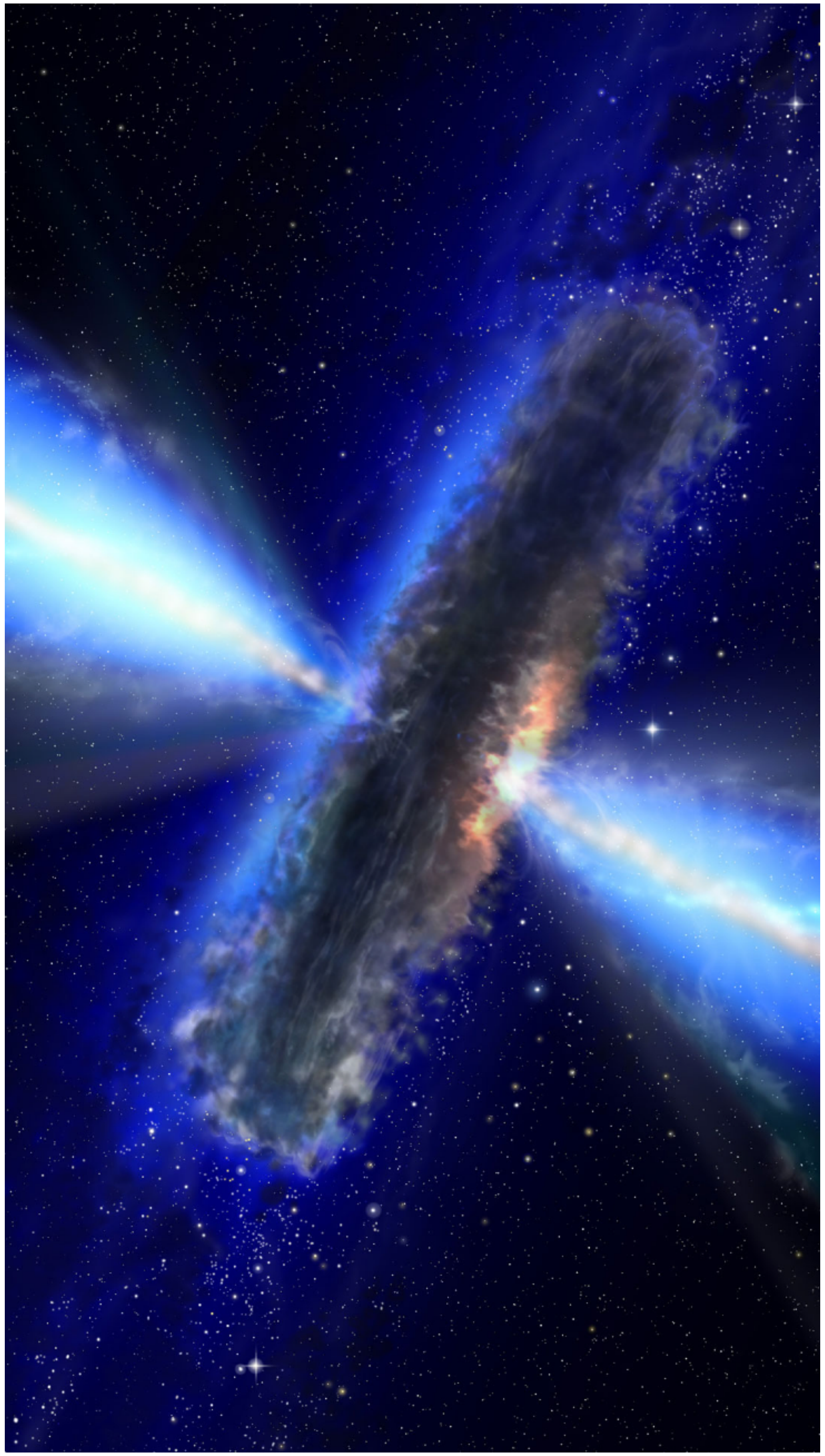


RECENT RESULTS & PROSPECTS



PRELIMINARY COMMENTS

- Results span from the end of 90s to now
- The main result after 25+ years of hard work:

NO SIGNIFICANT TIME-LAG WAS FOUND !

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

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

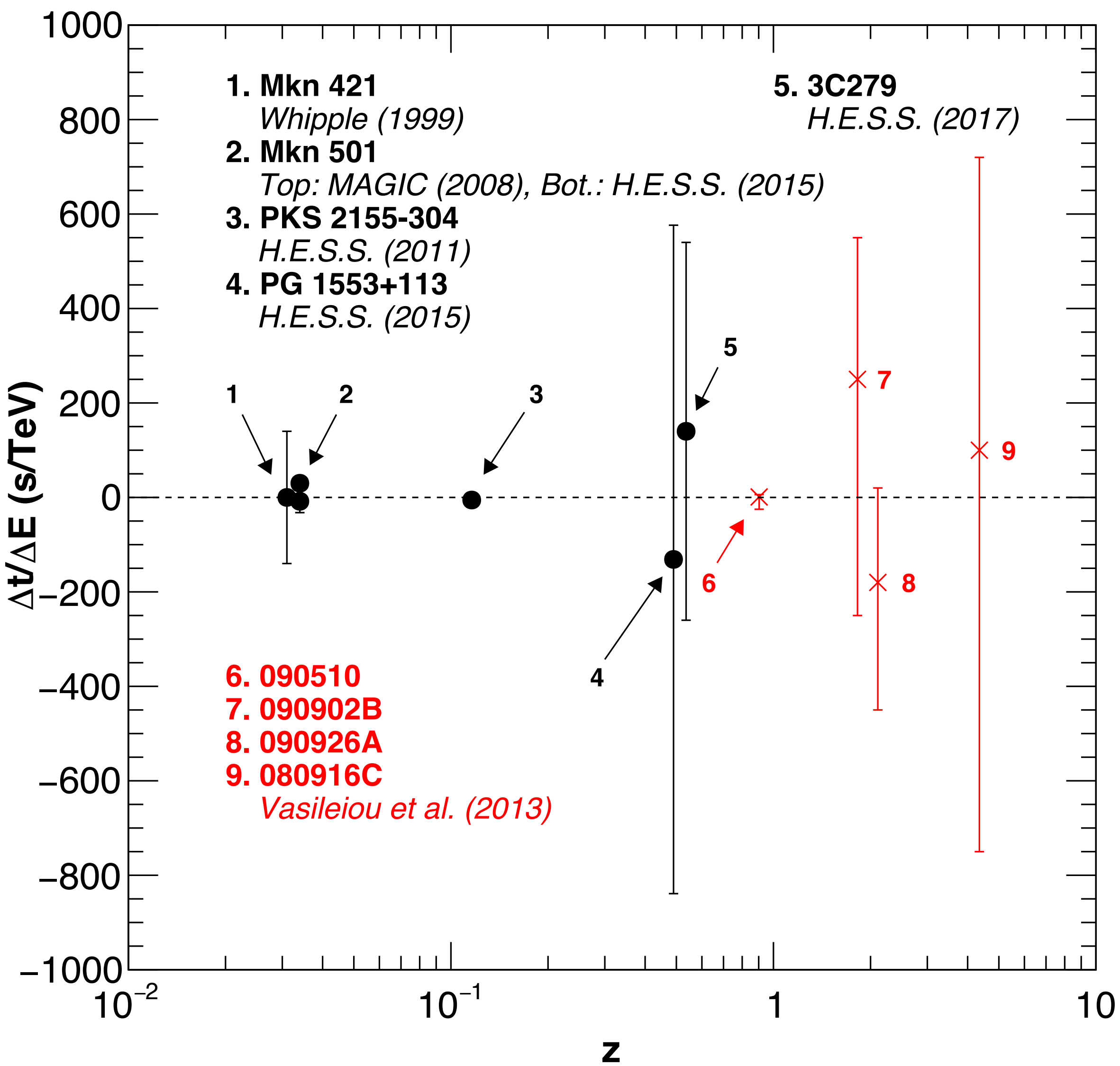
* Preliminary

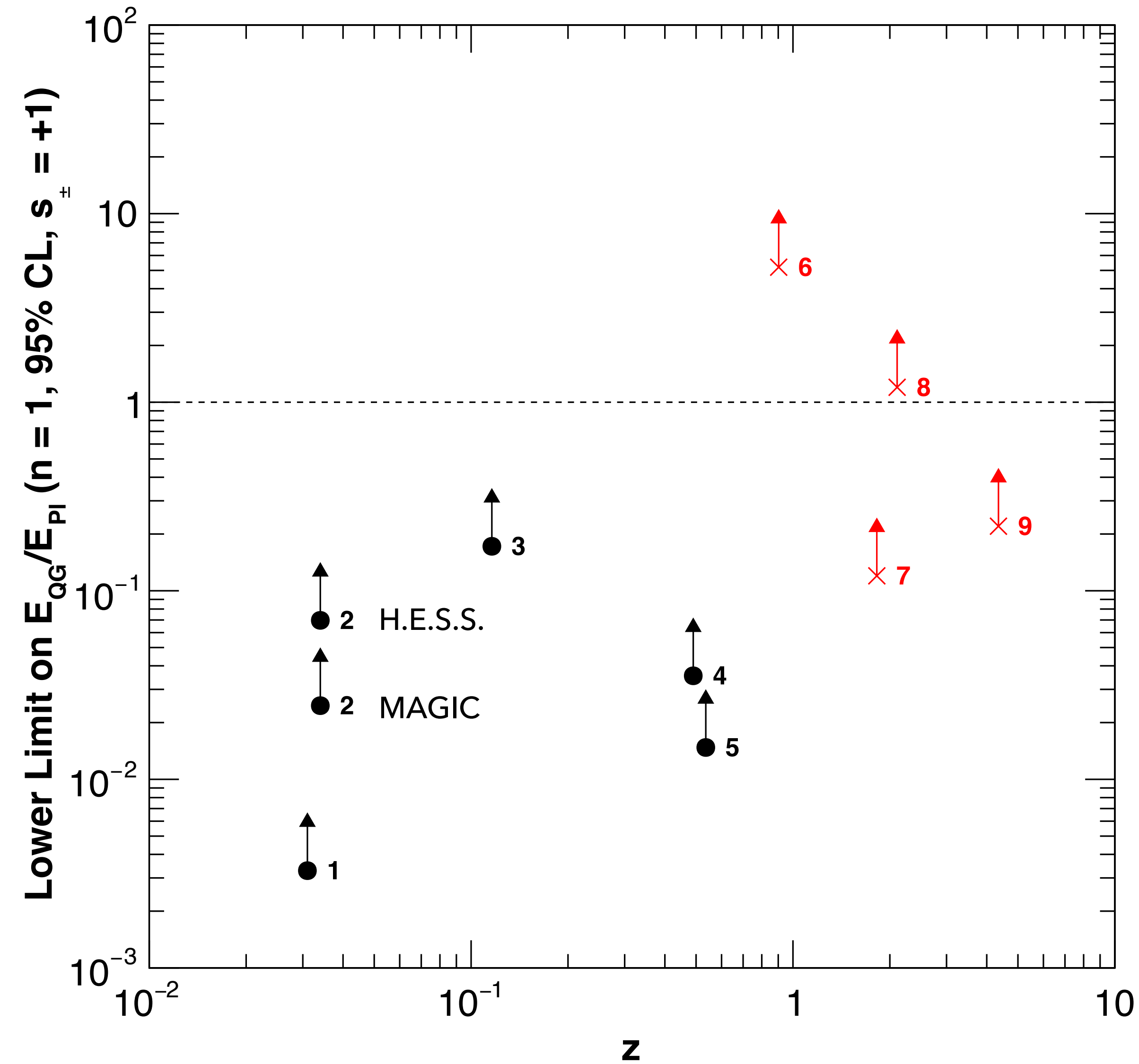
Source(s)	Experiment	Method	Results		
Mrk 421	Whipple	average time of the main pulse in different energy bands	$E_{QG,1} > 0.4 \times 10^{17}$ GeV		
Mrk 501	MAGIC	ECF, likelihood	$E_{QG,1} > 0.2 \times 10^{18}$ GeV	$E_{QG,2} > 2.6{\times}10^{10}$ GeV	
		likelihood	$E_{QG,1} > 0.3 \times 10^{18}$ GeV	$E_{QG,2} > 5.7 \times 10^{10}$ GeV	
	H.E.S.S.	likelihood	$E_{QG,1} > 8.5 \times 10^{17}$ GeV	$E_{QG,2} > 1.1 \times 10^{11}$ 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	$E_{QG,1} > 1.7 \times 10^{17}$ GeV	$E_{QG,2} > 2.0 \times 10^{10}$ GeV	*

- 5 different objects
- Limits at 95% CL
- Redshift ranging from 0.03 (Mrk 421) to 0.54 (3C279)
- Best limit for $E_{QG,1}$: PKS 2155 and for $E_{QG,2}$: Mrk 501
- The sensitivity of analyses depends on several factors

Reference
Biller et al. (1999)
Albert et al. (2008)
Martínez and Errando (2009)
Cologna and the H.E.S.S. Collaboration (2015)
Aharonian et al. (2008)
Abramowski et al. (2011)
Abramowski et al. (2015)
Romoli and the H.E.S.S. Collaboration (2017)

SUMMARY

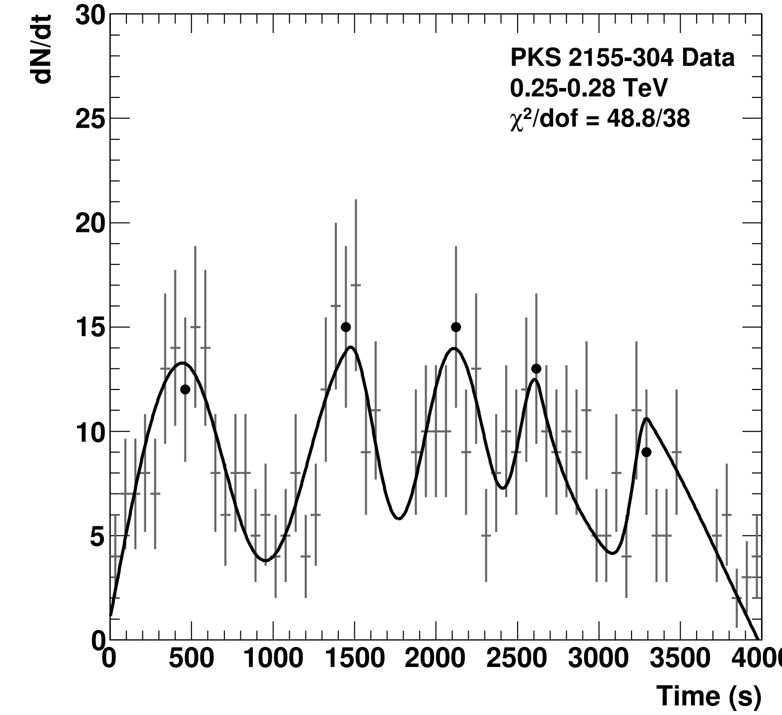


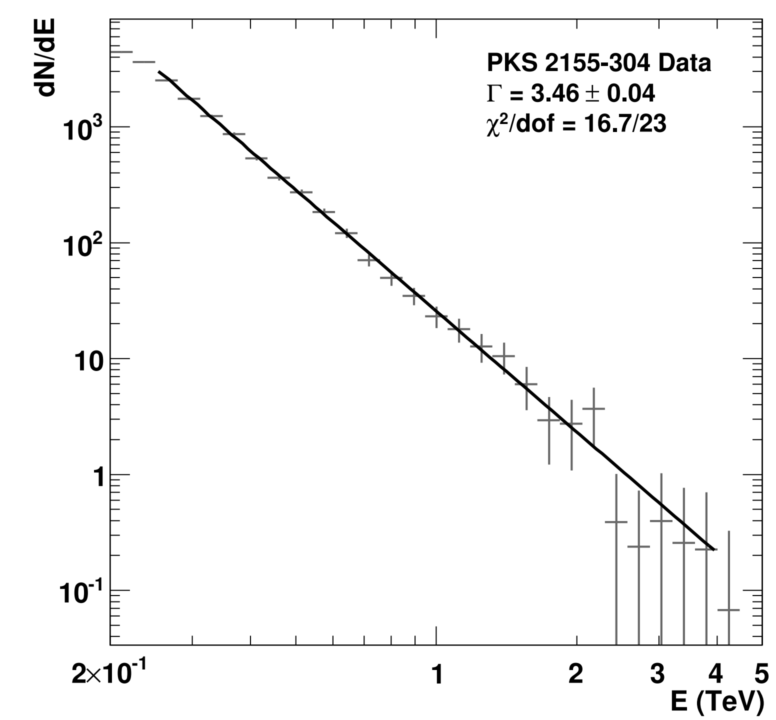


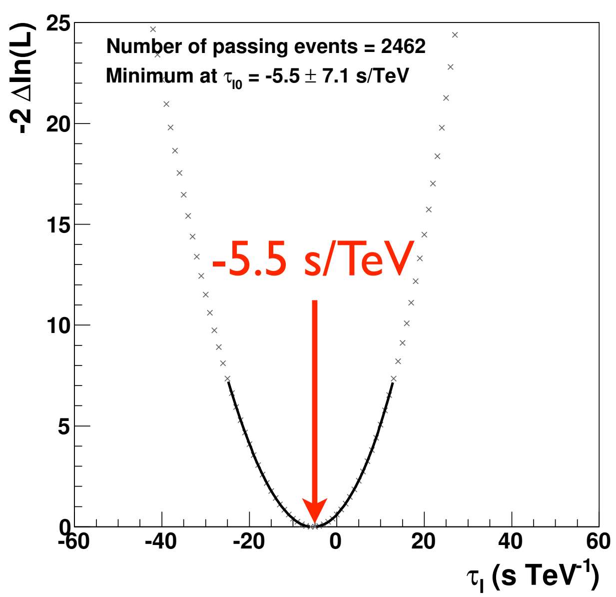
- Results for linear and subluminal effect
- 4 Fermi-LAT GRBs included (Vasileiou et al., 2013)

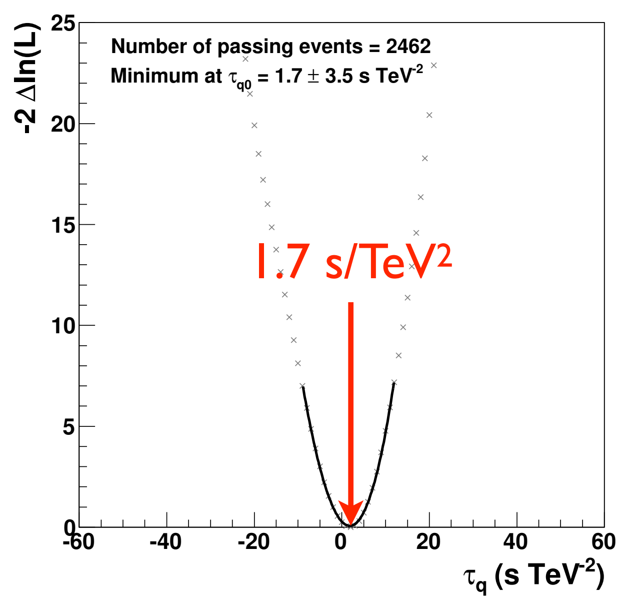
PKS 2155-304 FLARE SEEN BY H.E.S.S. IN 2006

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









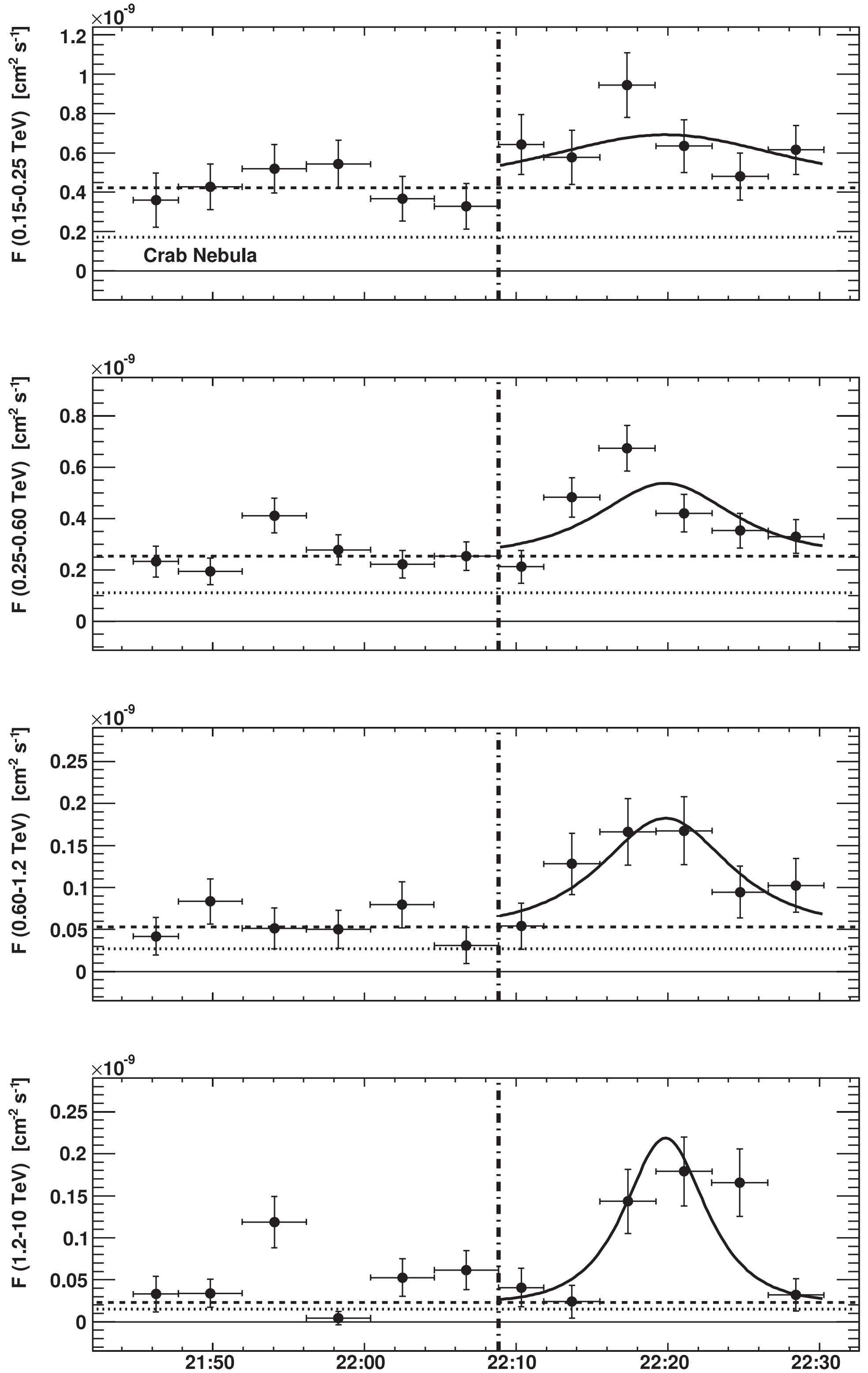
$\tau_l = -5.5 \pm 10.9_{(stat)} \pm 10.3_{(sys)}$ s/TeV

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

MKN 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
    - Albert et al. (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), Albert et al. (2007)



Lag of 4±1 min (< 250 GeV, >1.2 TeV)

HOW TO DEAL WITH INTRINSIC EFFECTS ?

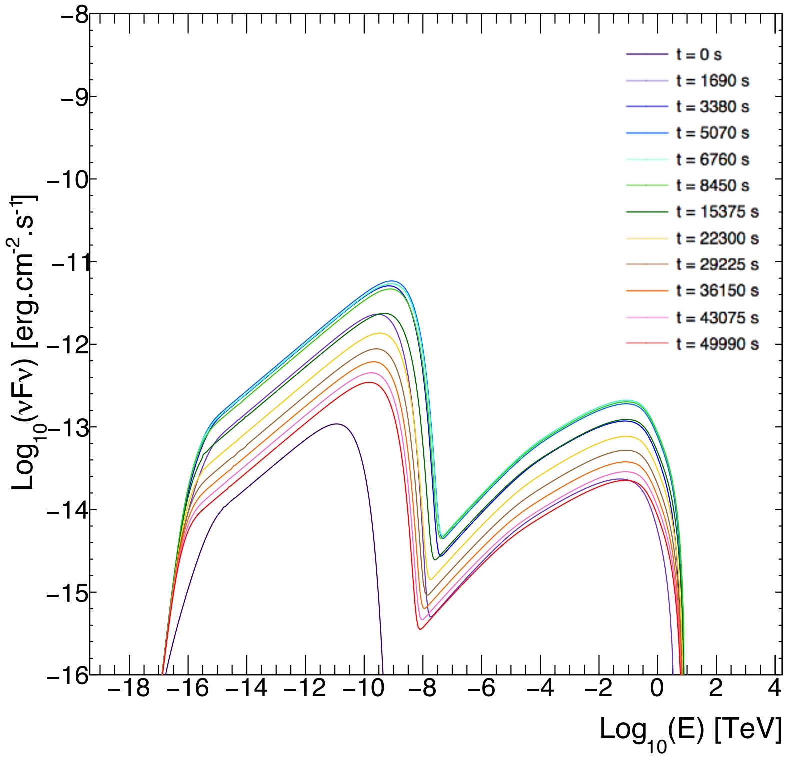
$$\tau_{n\,(\mathrm{total})} = \tau_{n\,(\mathrm{LIV})} + \tau_{(\mathrm{source})}$$

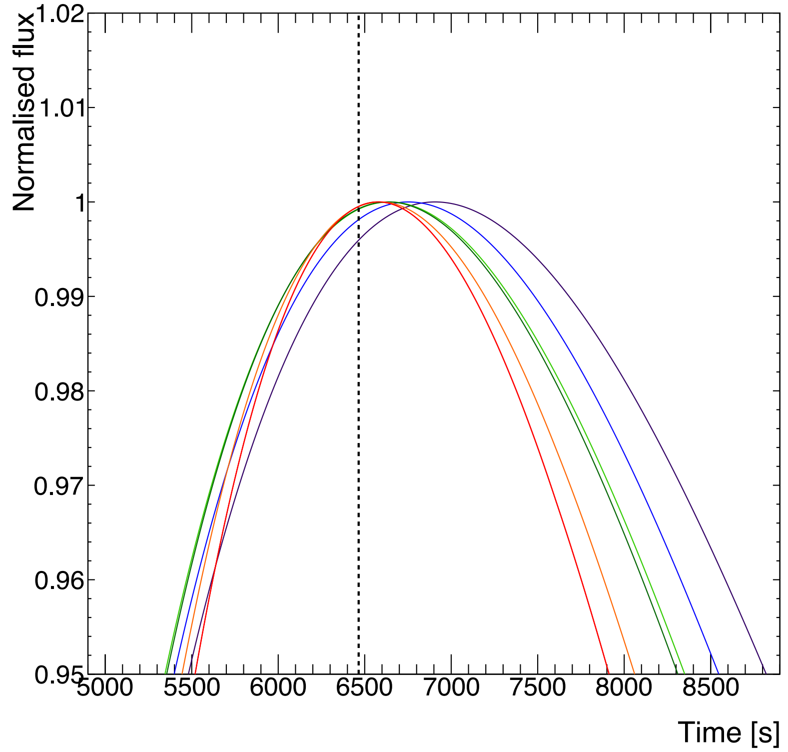
- Neglect intrinsic effects → Restrict the energy range; Restrict the time domain
- Full modeling of the sources → TASKS FOR THE FUTURE
- Use population studies to separate intrinsic and propagation effects → TASKS FOR THE FUTURE

C. Perennes, 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
- 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)

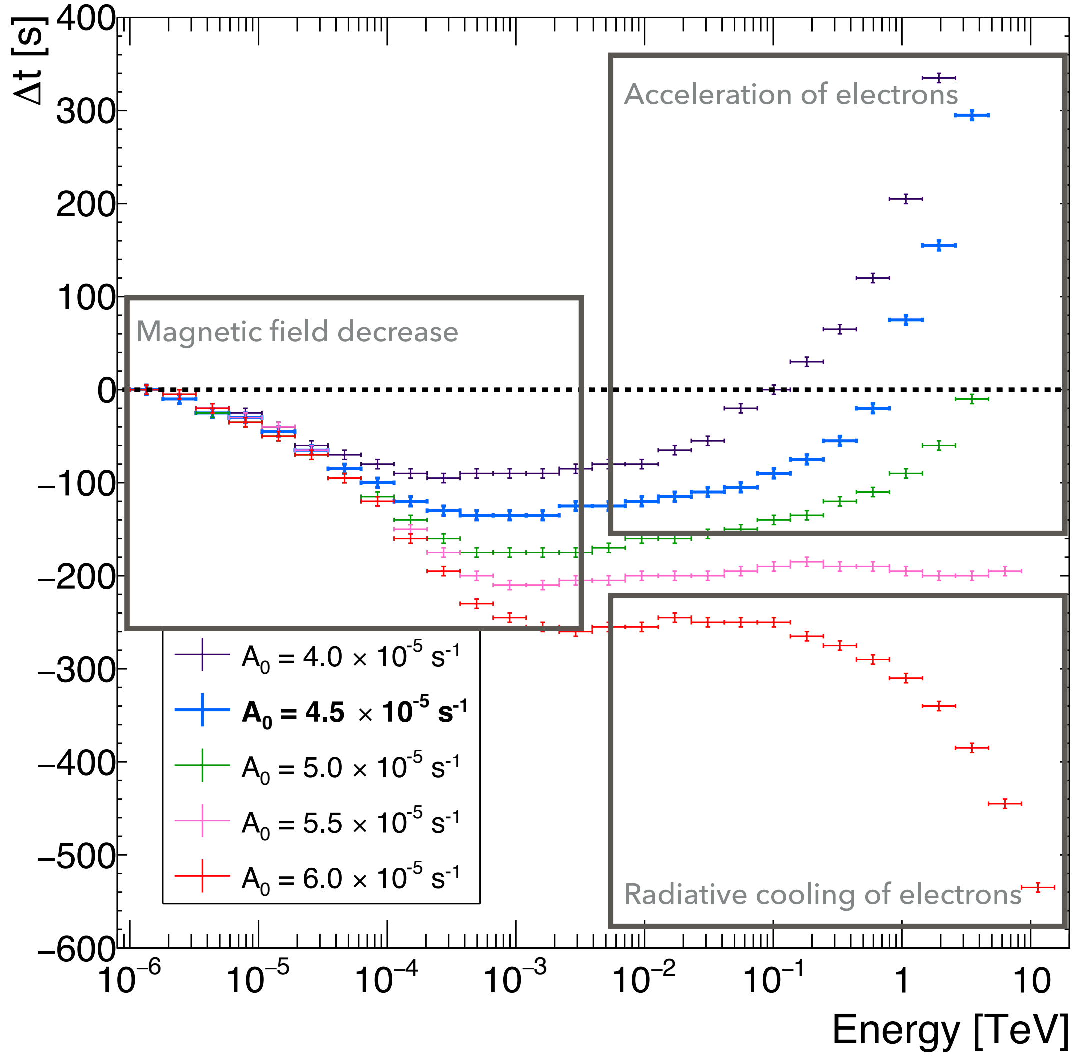




Plots from C. Perennes

UNDERSTANDING INTRINSIC EFFECTS

- Time delays which 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

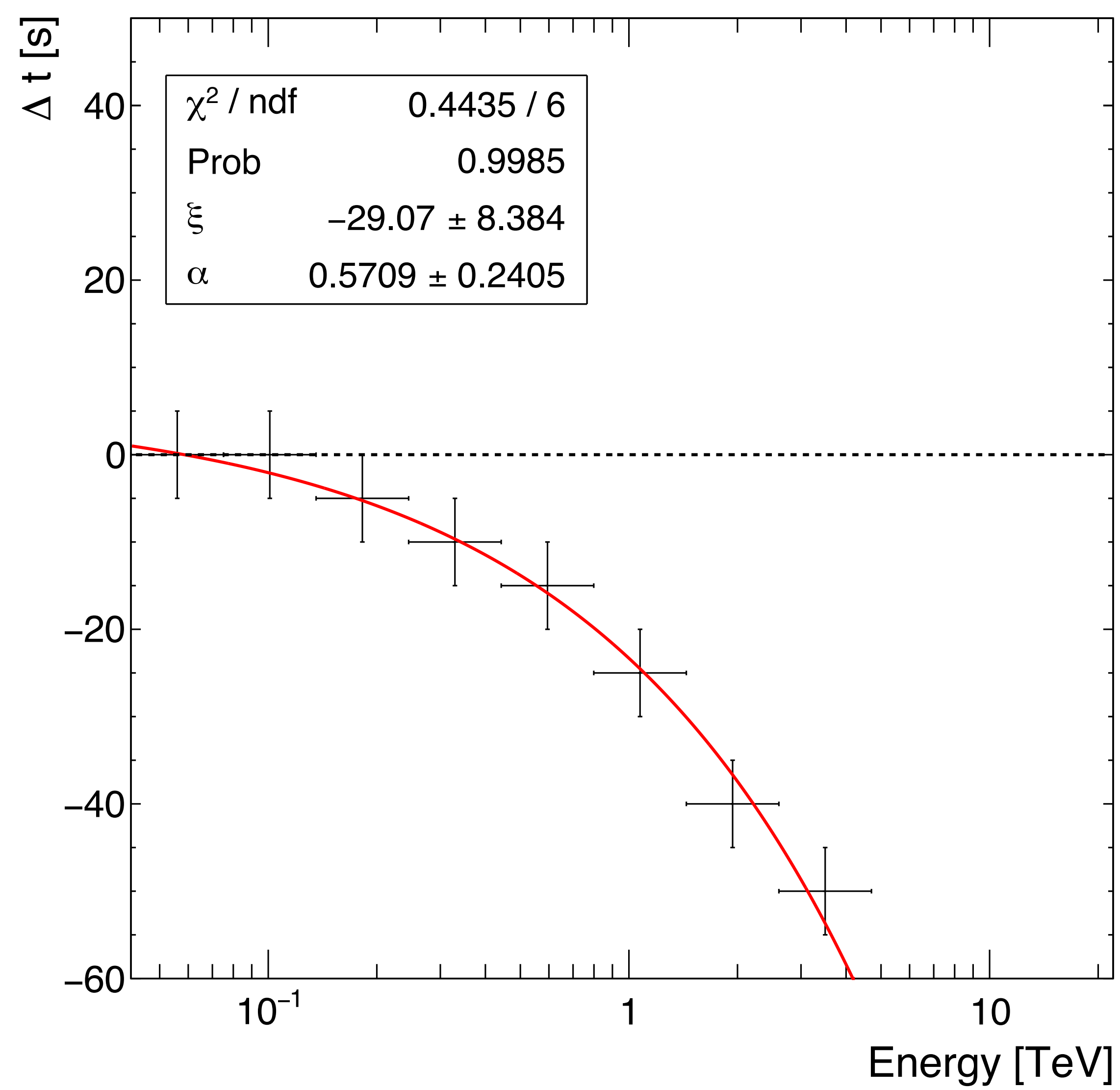
Plots from C. Perennes

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)



- Present knowledge on QG theories (LQG, ST) leads only to α = 1 or 2…
- Hope is to be able to distinguish between LIV and intrinsic effects
  - Progress needed on both the theory side and experimental side…

PAPER IN PREPARATION

PREPARING POPULATION STUDIES

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

- Joint effort initiated in a working group gathering MAGIC, VERITAS and H.E.S.S. members
- Goal :
  - Combining existing data for AGNs and Pulsars 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

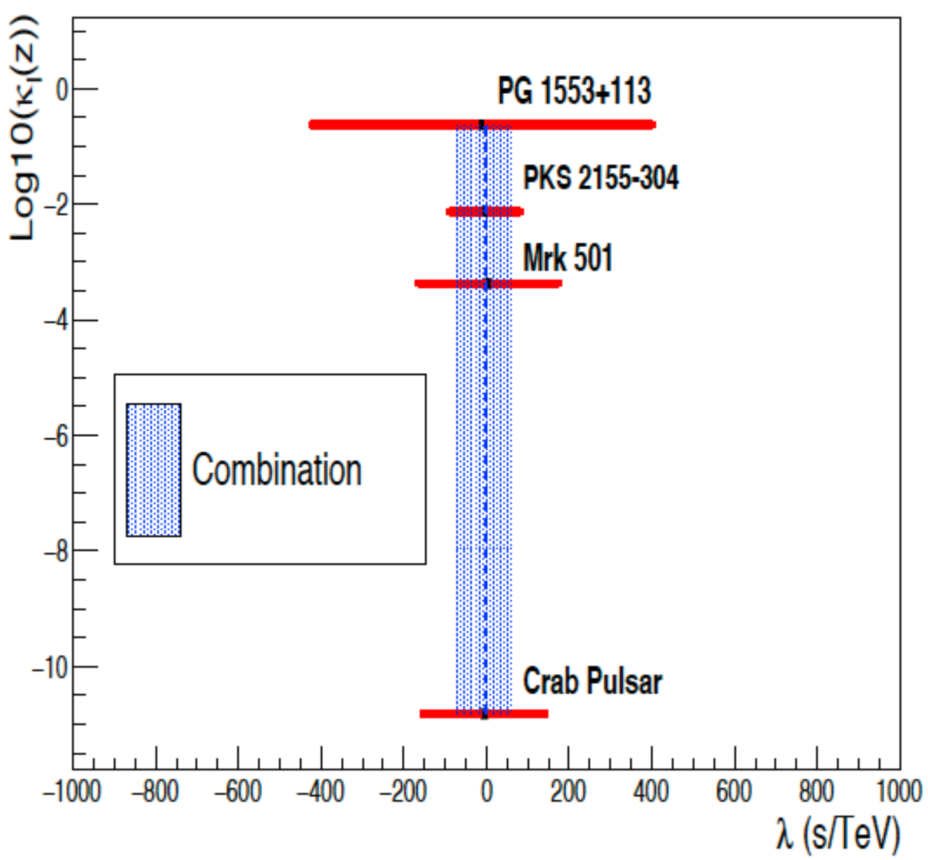
$$L_{Comb}(\lambda) = \prod_{i=1}^{Nsource} L_i(\lambda) \longrightarrow -2log(L_{Comb}(\lambda)) = -2 \sum_{i=1}^{Nsource} log(L_i(\lambda))$$

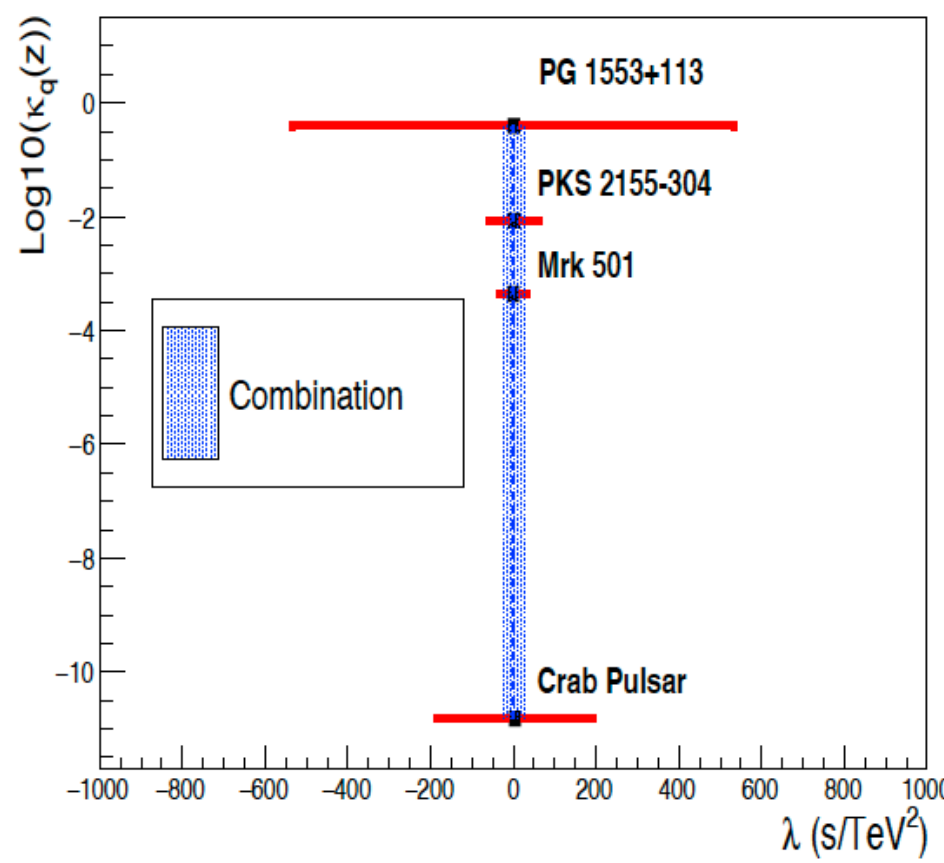
with $\lambda = \dfrac{\Delta t_n}{\Delta E^n \ \kappa(z)}$

Plots from Nogués et al., ICRC 2017

PREPARING POPULATION STUDIES

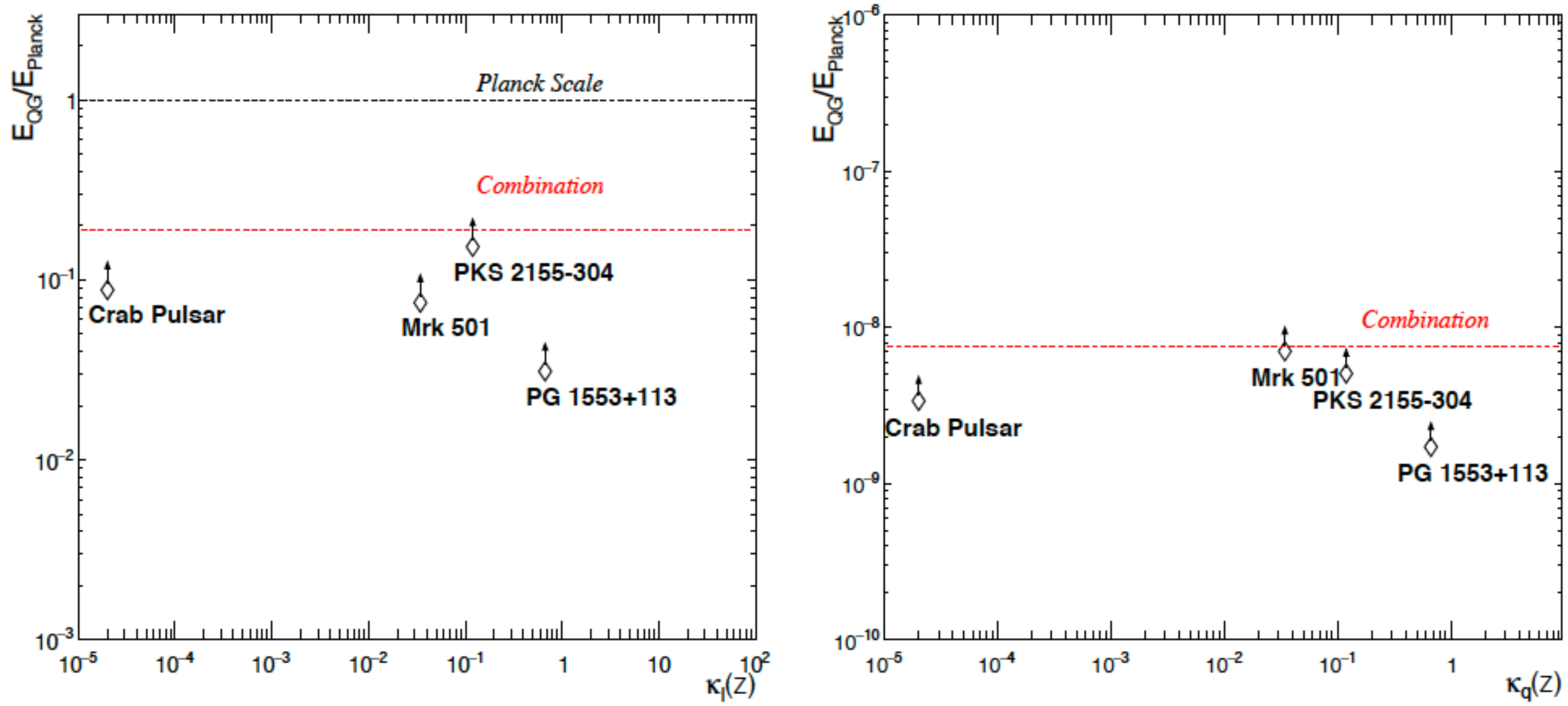
- For now, only simulations
- 990 sets of simulated data from published spectra and light curves
  - Mrk 501 2005 flare detected by MAGIC
  - PG 1553+113 2012 flare detected by H.E.S.S.
  - PKS 2155-304 2006 flare detected by H.E.S.S.
  - VHE Crab Pulsar detected by VERITAS





Plots from Nogués et al., ICRC 2017

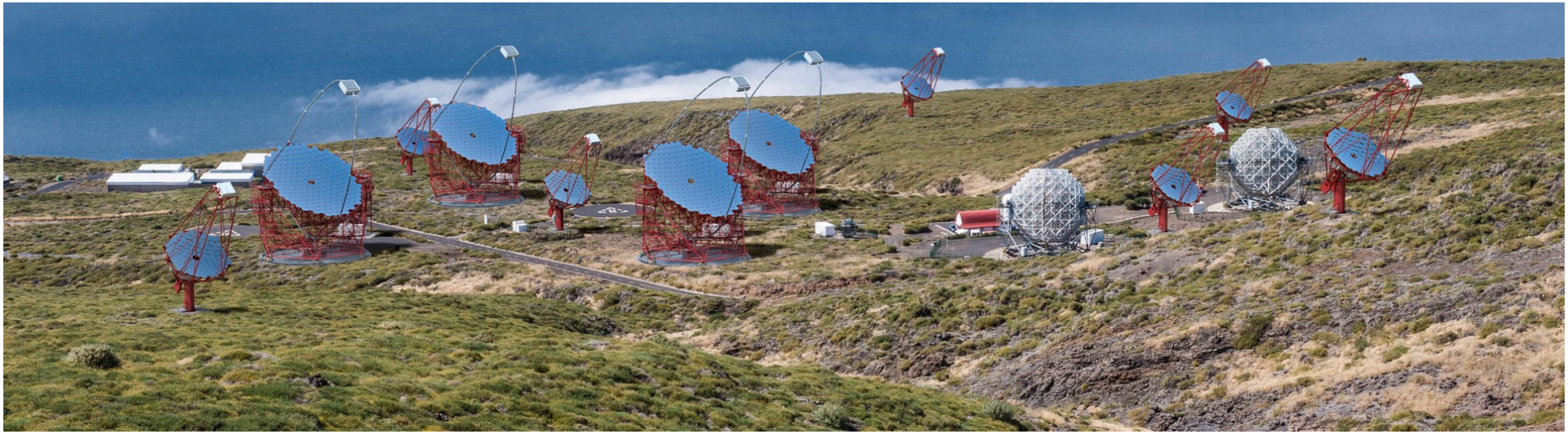
PREPARING POPULATION STUDIES



- 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 2019
- Final paper with all available sources to follow

A CRUCIAL STEP BEFORE CTA !

CONCLUSIONS



For more about CTA, see the talk by S. Funk on Thursday morning !

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 Causal sets, Non-commutative spacetime…

- Astrophysical sources are good tools to probe MDR
- 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
    - It needs to be secured !

- Population studies are needed

SUMMARY

- Population studies should be done with all possible sources
- Sources are complementary :
  - AGN flares with IACTs
    - Moderate z
    - High ΔE
    - Random
  - GRBs with satellites
    - High z
    - Time scale O(1 s)
    - Random
  - PSR with both IACTs and satellites
    - Small distance
    - Time scale O(ms)

WHAT CAN BE IMPROVED ?

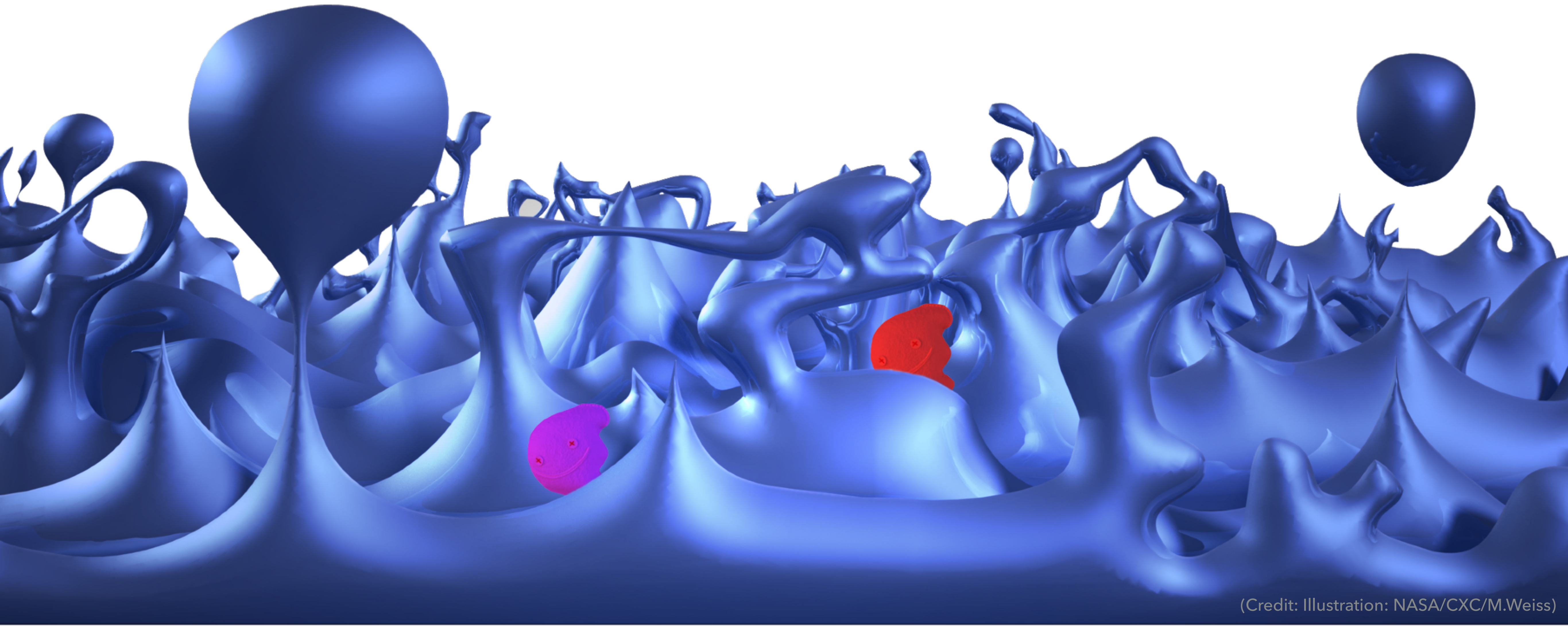
- We need more data for all possible sources
- Progress is needed on the theory side
- Population studies will be essential to
  - Obtain better limits on LIV
    - Effort on-going in MAGIC, H.E.S.S. and VERITAS as a preparation for CTA
  - Gain knowledge on the sources
- Progress on source modeling
  - Allow to interpret non-zero lags
  - (Hopefully) allow to disentangle propagation and intrinsic effects

A LOT REMAINS TO BE DONE !

MERCI !

THANKS !

CẢM ƠN !



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