Atmospheric Calibration of Cherenkov Telescopes

(and their relationship with time-of-flight studies to constrain LIV)

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Introduction

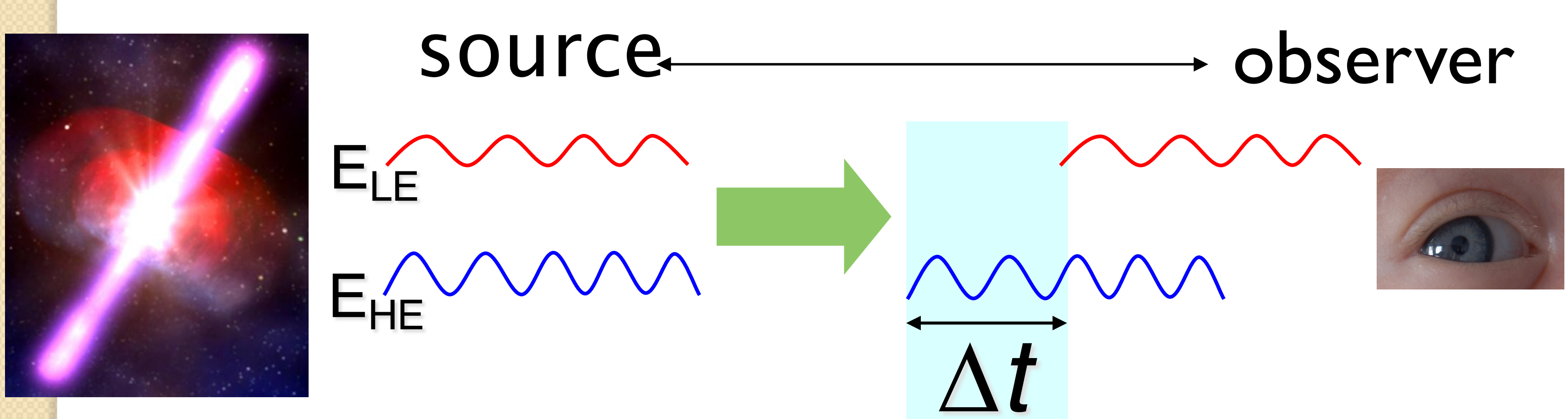
- ToF studies and their current limitations
- Systematic uncertainties of IACTs
- Atmospheric Calibration of IACTs
- Plans for CTA
- Conclusions

Photon time-of-flight

$$u_\gamma(E) = \frac{\partial E}{\partial p} \approx c \cdot \left[1 - \sum_n \xi_n \frac{n+1}{2} \left(\frac{E}{E_{\mathrm{QG}_n}} \right)^n \right]$$

$$\Delta t_1 = \frac{d}{c} \cdot \frac{E_2 - E_1}{E_{QG_1}} \qquad \Delta t_2 = \frac{3}{2}\frac{d}{c} \cdot \frac{E_2^2 - E_1^2}{E_{QG_2}^2}$$

…plus cosmological corrections (Amelino-Camelia et al., Nature 393 (1998) 763)



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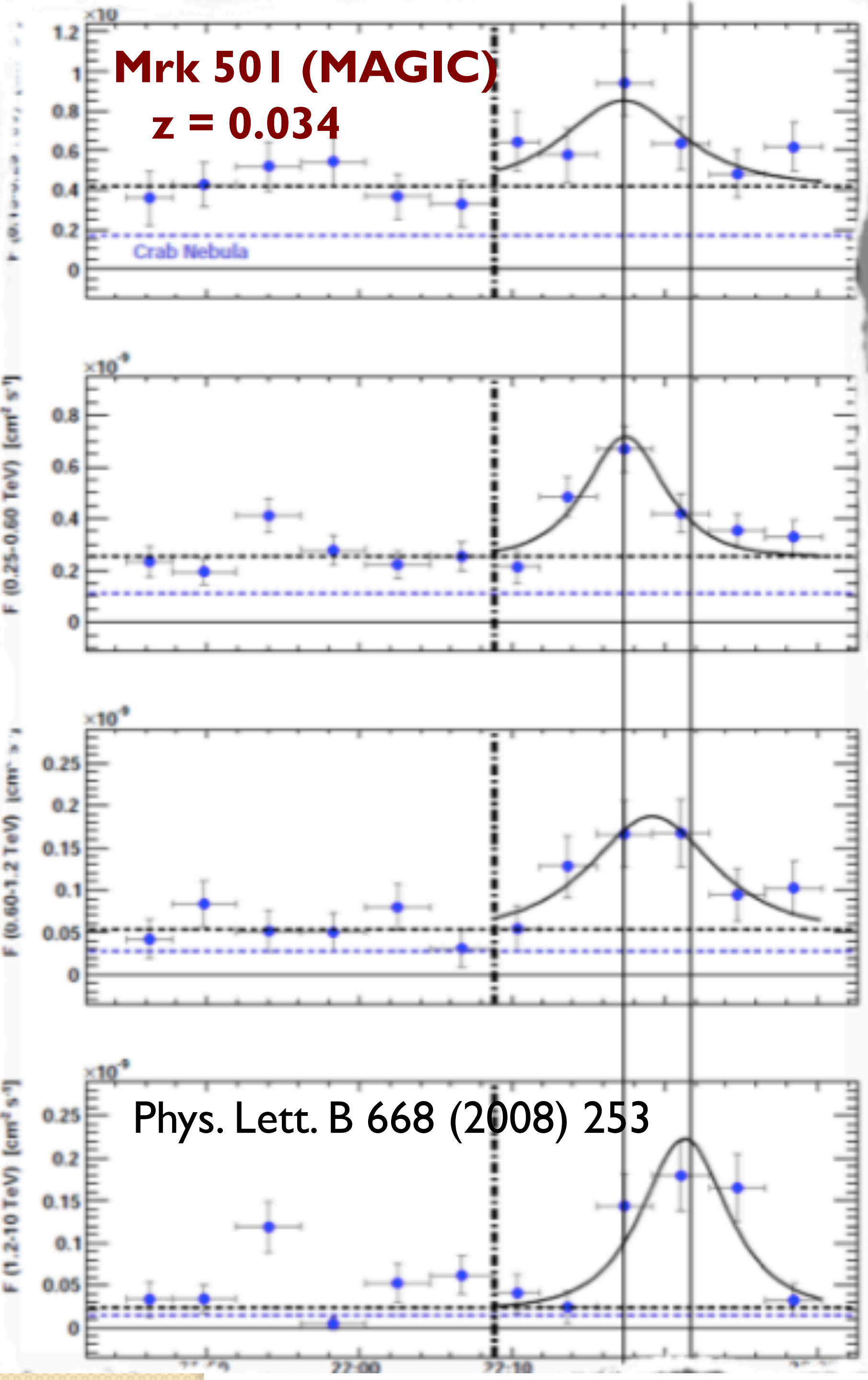
✦ Tests from astrophysical sources:

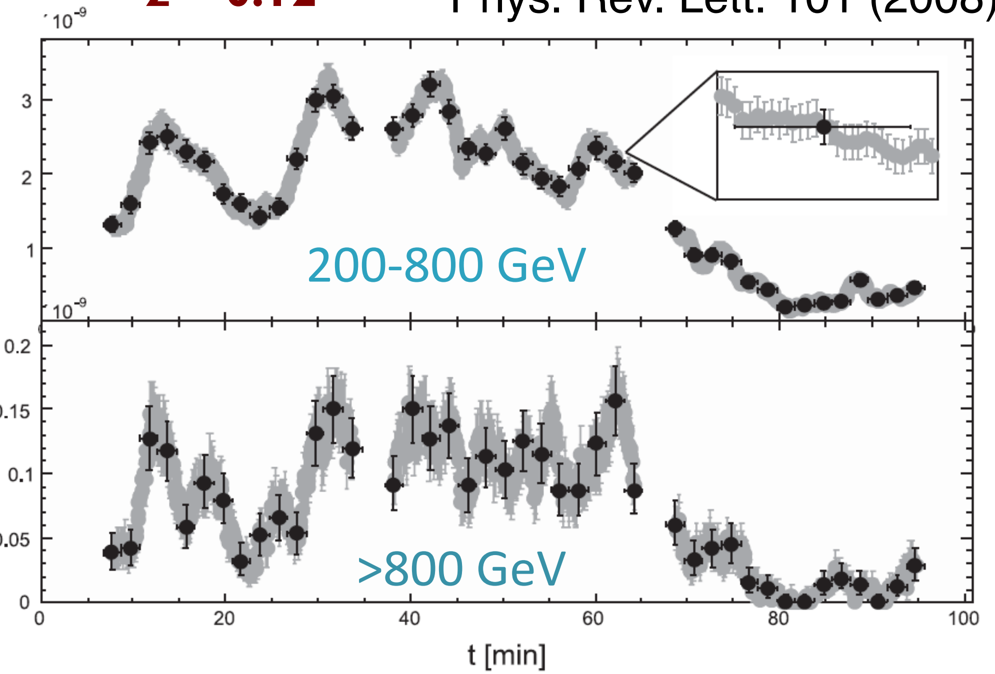
Source family	d [pc]	E [GeV]	δt [s]	Expected limits E_{QG1} [GeV]	Expected limits E_{QG2} [GeV]
GRB	10^{10}	10^1	$10^0 - 10^2$	$10^{17} - 10^{19}$	$10^9 - 10^{10}$
AGN	10^8	10^4	$10^2 - 10^5$	$10^{15} - 10^{18}$	$10^9 - 10^{11}$
Pulsar	10^3	10^2	$10^{-4} - 10^{-2}$	$10^{17} - 10^{19}$	$10^{10} - 10^{11}$



$M_{QG1} > 0.3 \times 10^{18}$ GeV

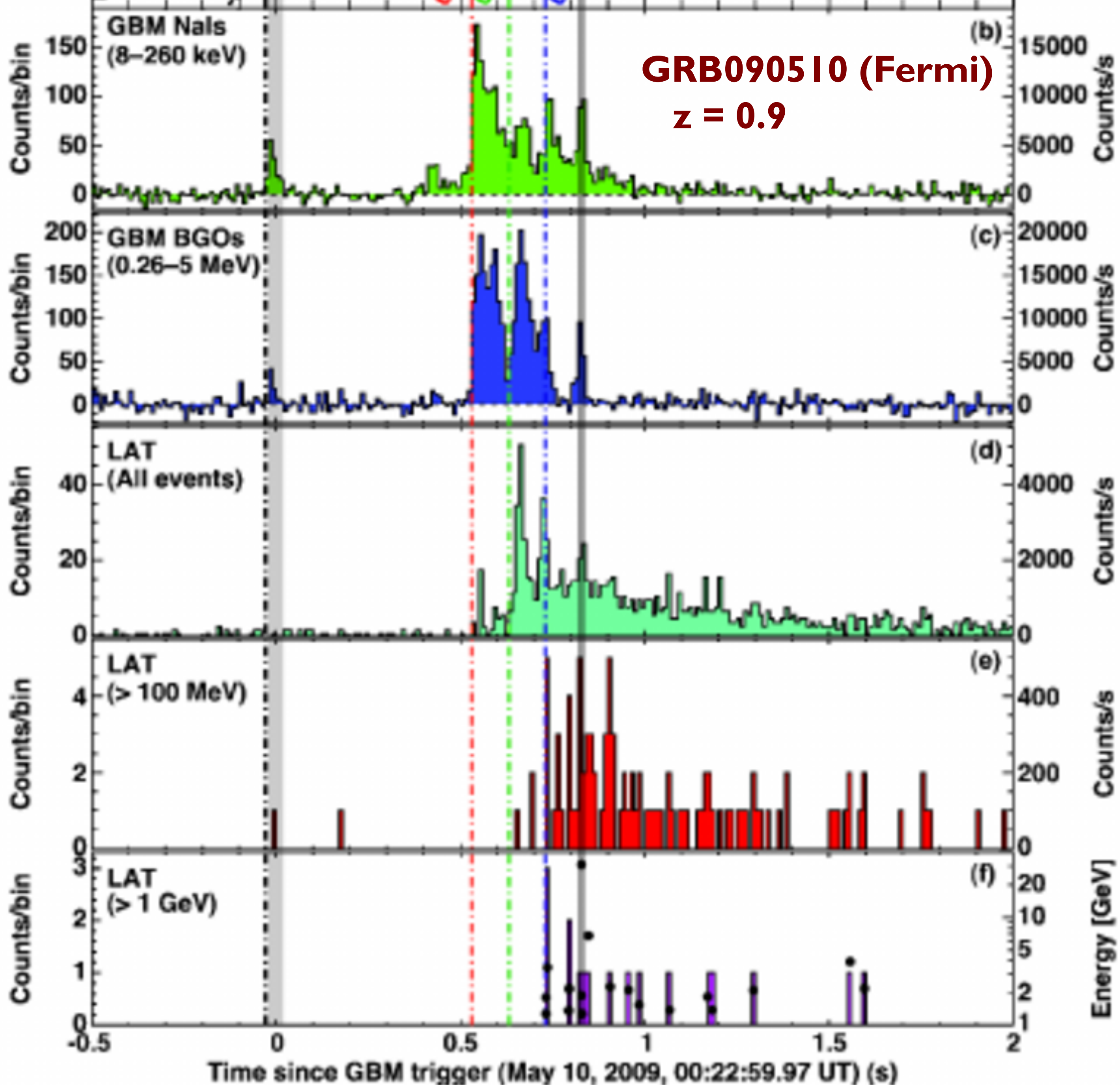
$M_{QG2} > 5.7 \times 10^{10}$ GeV

PKS2155 (H.E.S.S.)
z = 0.12
Phys. Rev. Lett. 101 (2008)



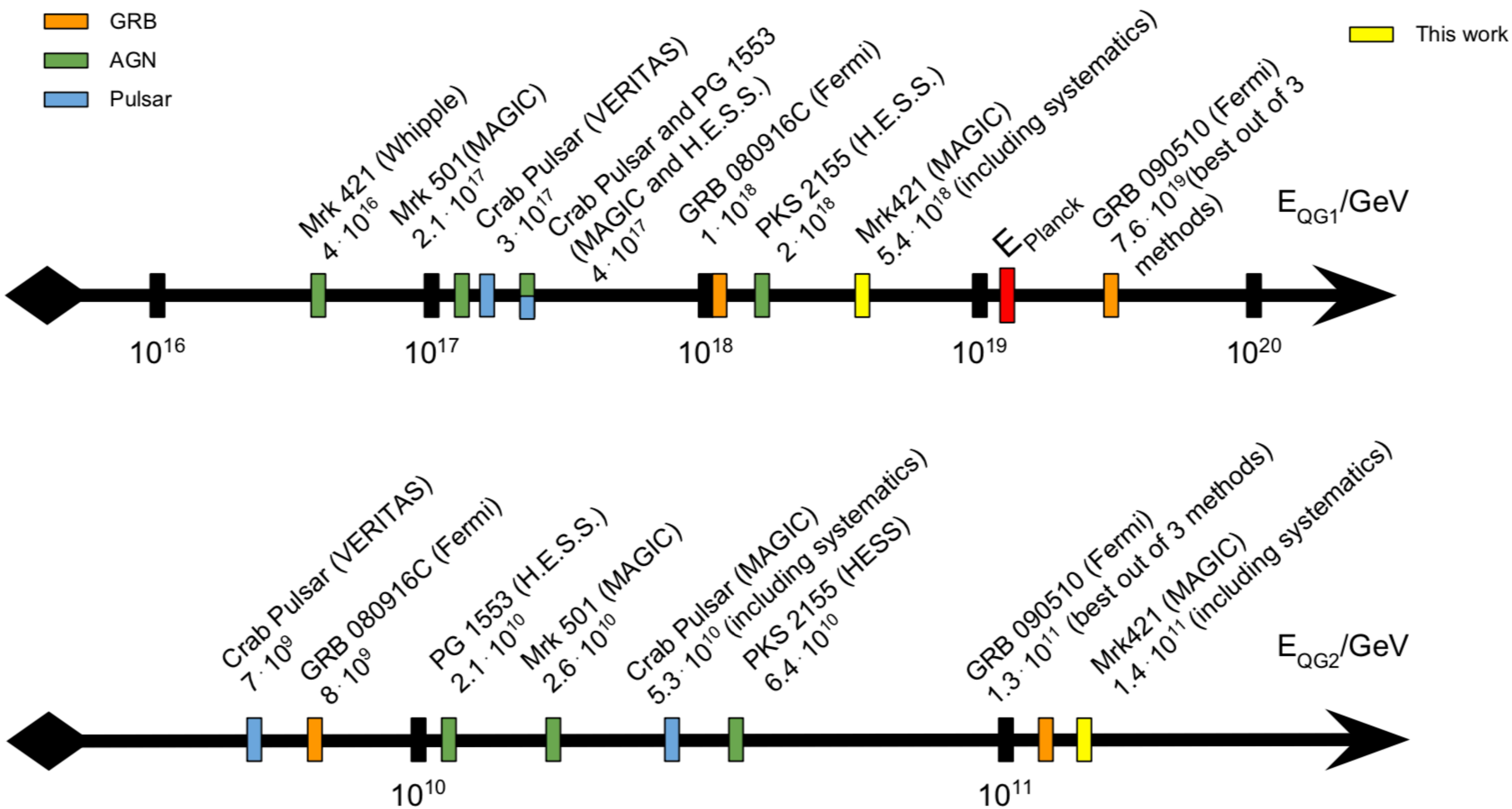
$M_{QG1,\ 95\%CL} > 2.1 \times 10^{18}$ GeV

$M_{QG2,\ 95\%CL} > 6.4 \times 10^{10}$ GeV



Fermi Collaboration Nature 462 (2009) 331-334

Photon time-of-flight limits from astrophysical sources



From L. Nogués Marcén, PhD thesis, Universidad de Zaragoza 2018, https://zaguan.unizar.es/record/76918.

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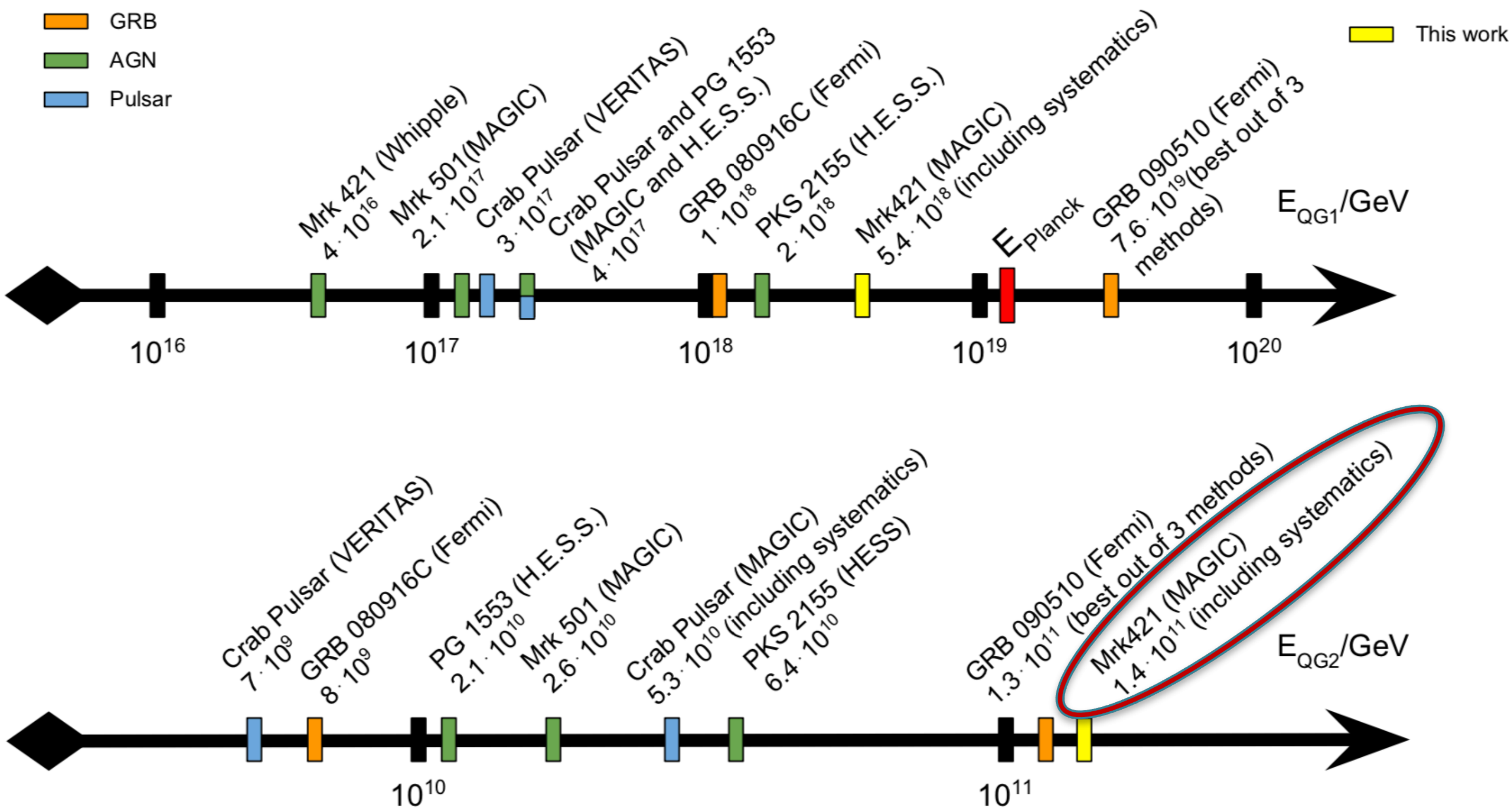

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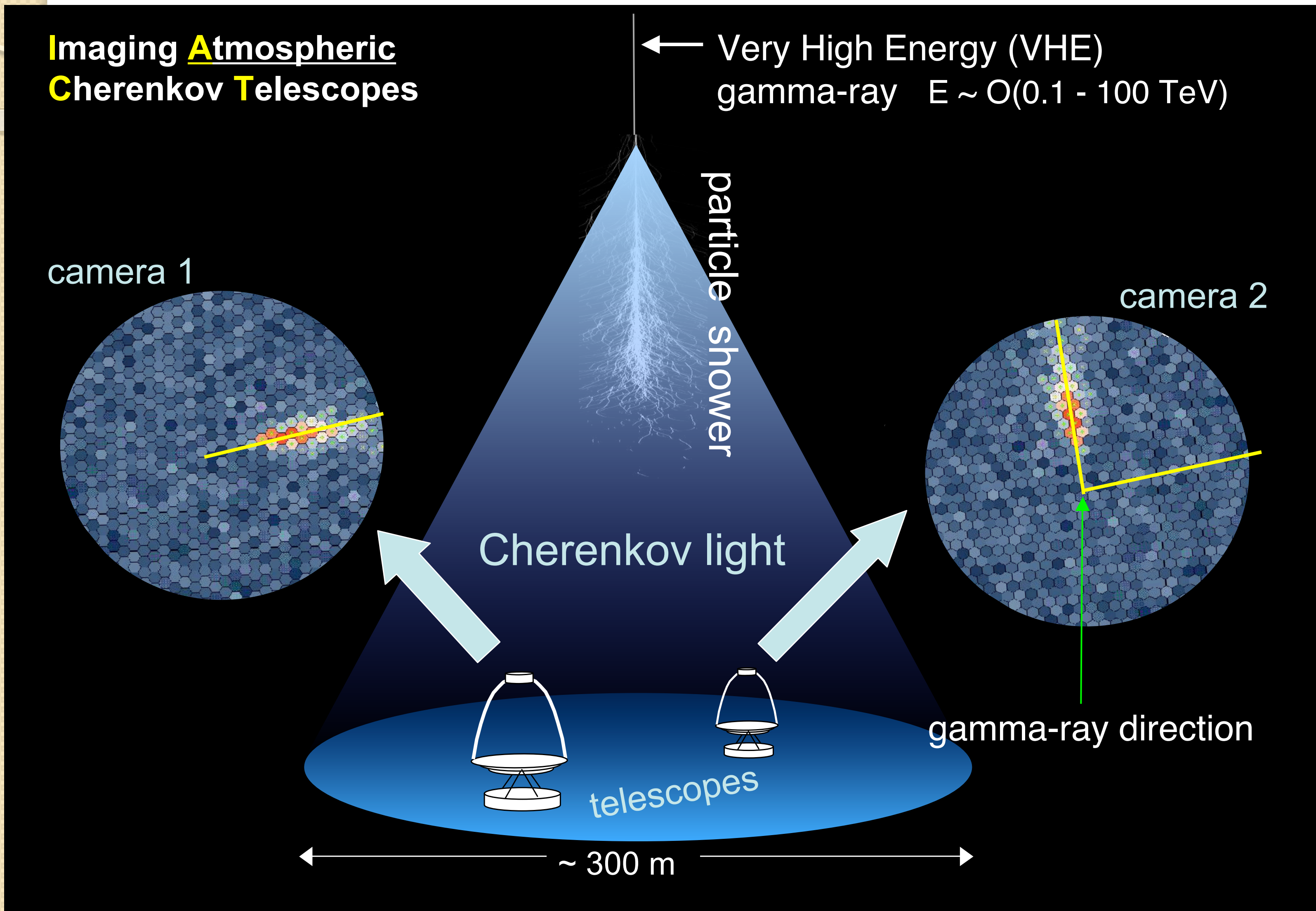
Introduction to IACTs



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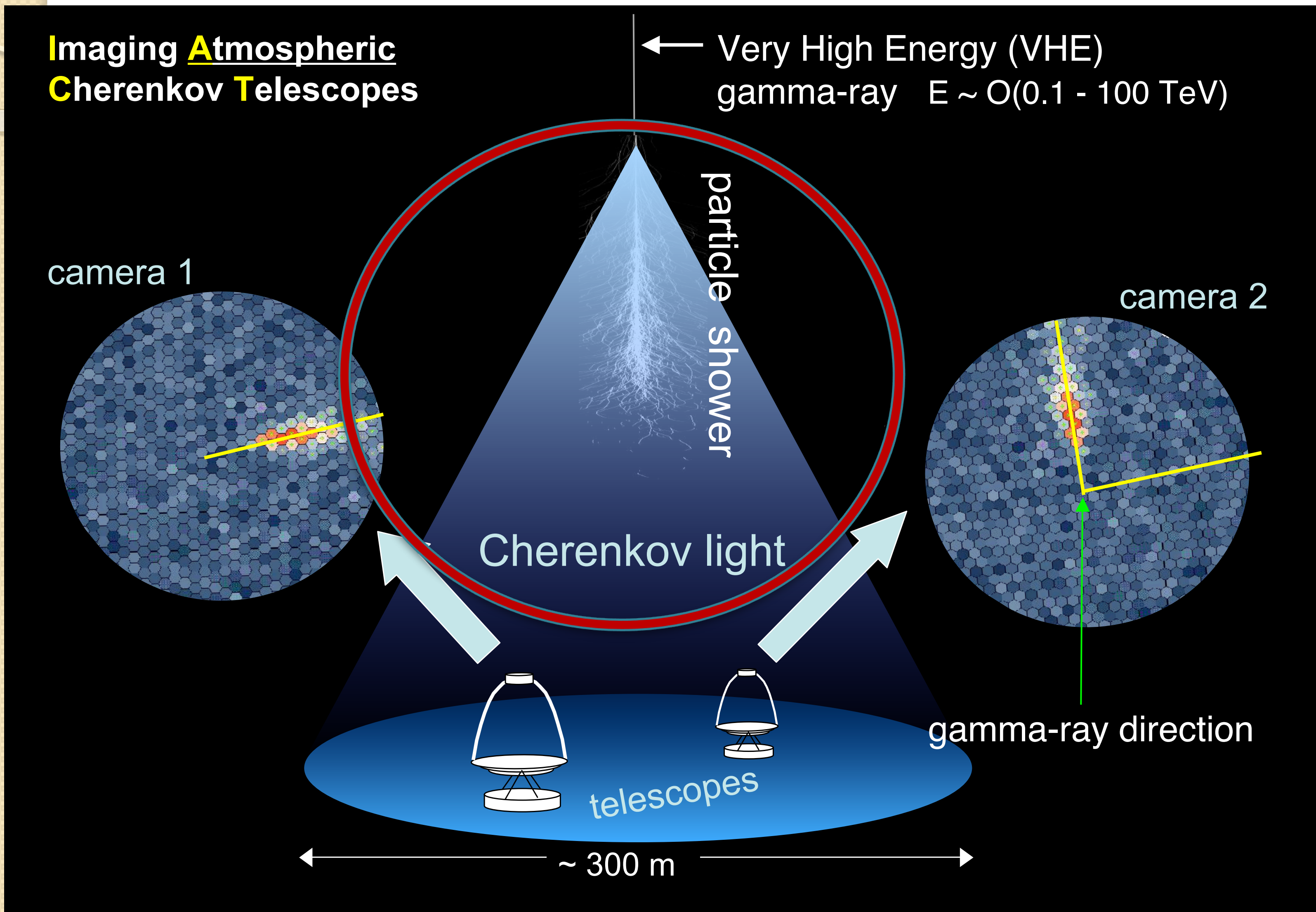

Introduction to IACTs

- Gamma-ray precision astronomy and astrophysics from 50 GeV to 100+ TeV

- Very limited in energy resolution (currently 15%-20%, worsening towards the highest energies!)
- Limited by systematic uncertainties (e.g. 12%-15% for the absolute energy scale)

- For strong sources, limitations of both are equally important.

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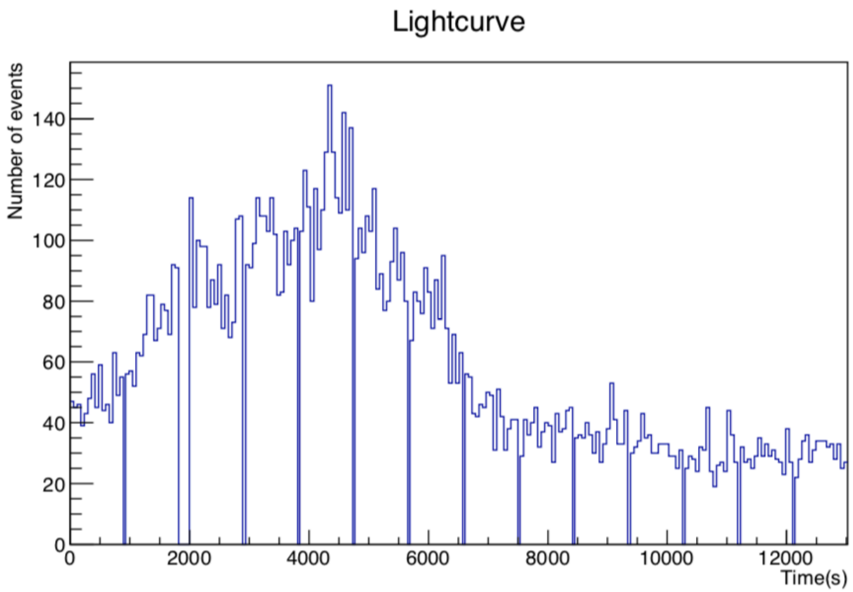
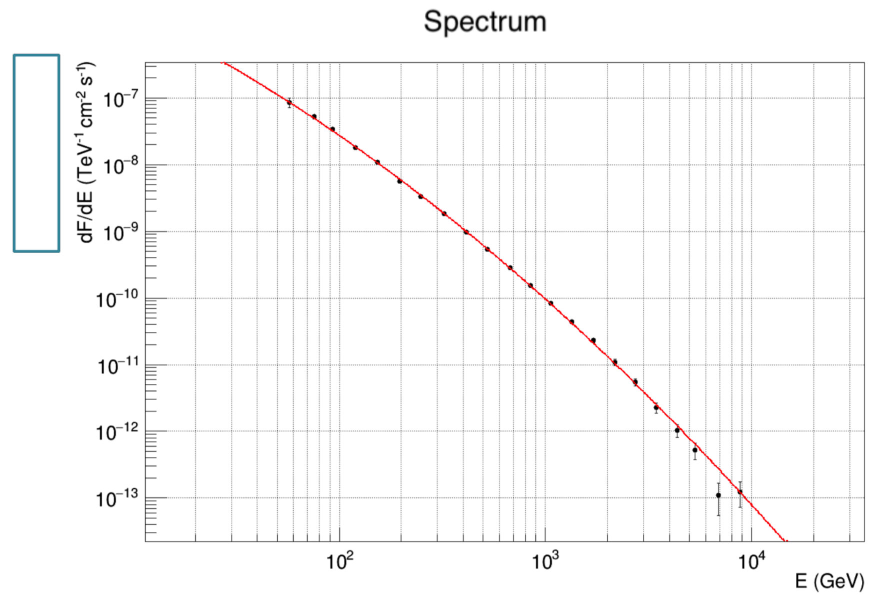
IMPORTANCE WILL BE REVERSED FOR STRONG SOURCES IN CTA !

Current possibilities of IACTs





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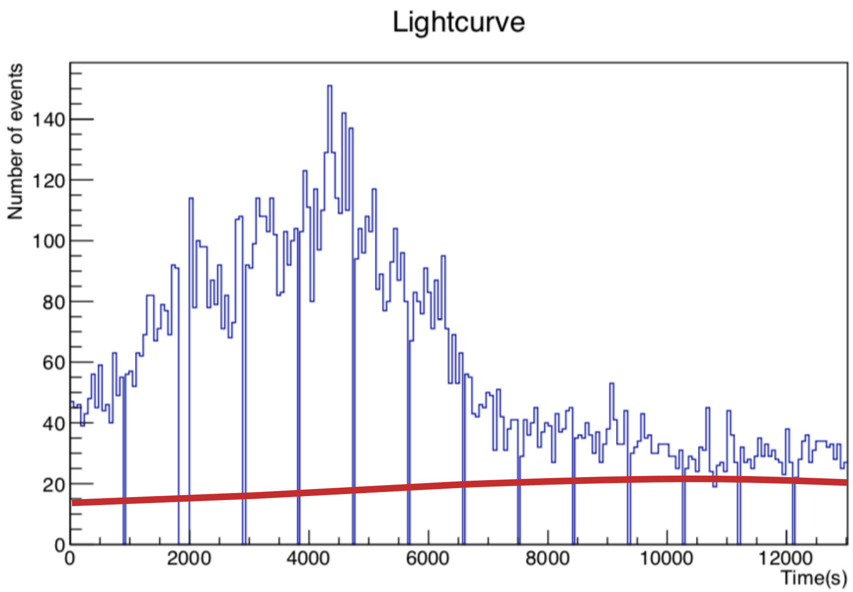

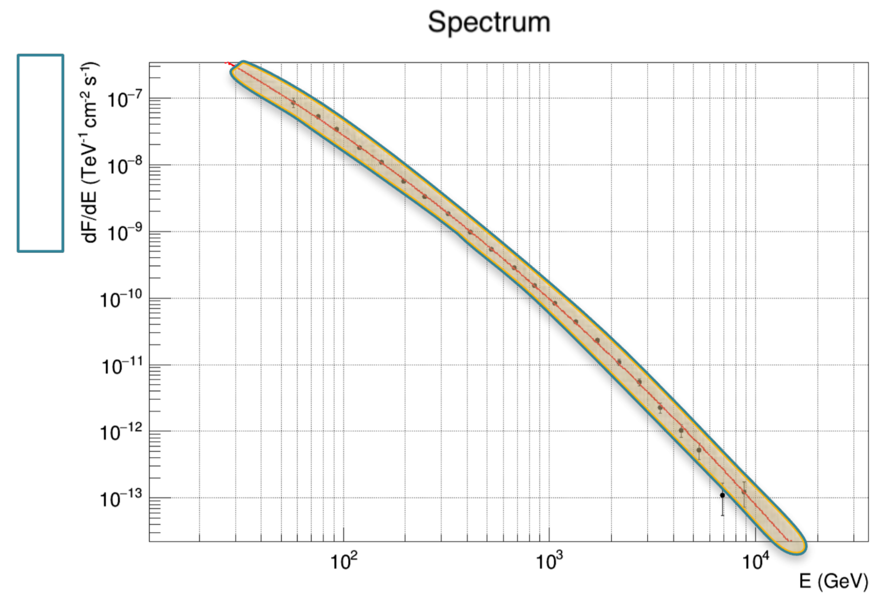

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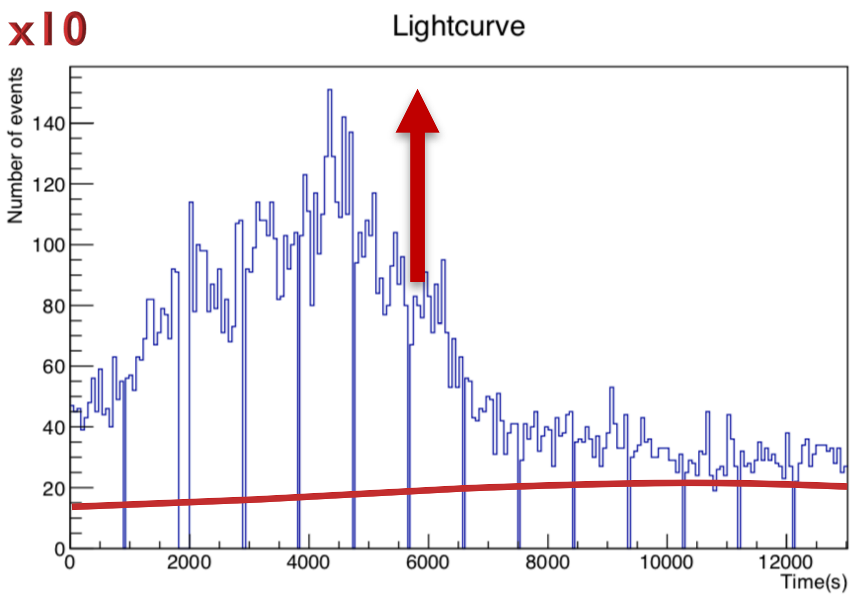
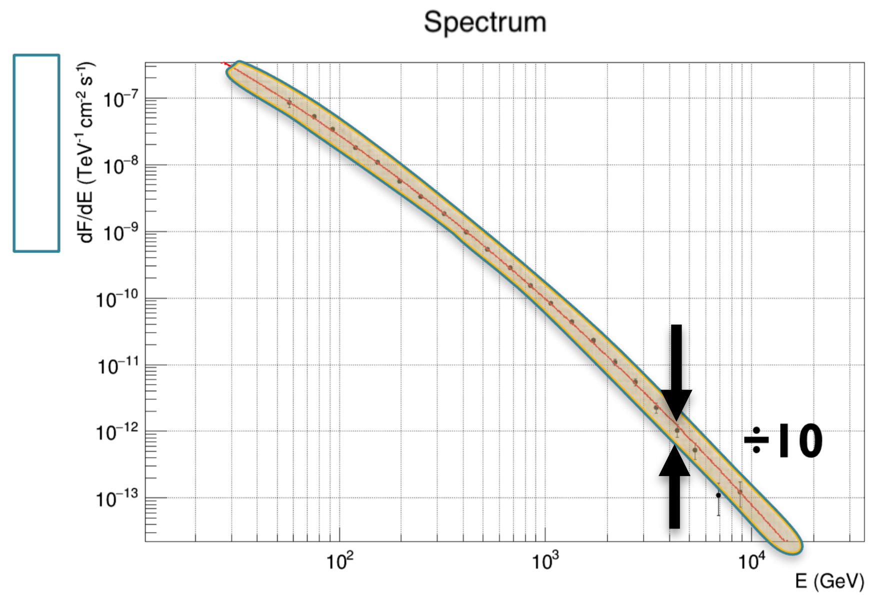
Situation for CTA





Size of statistical error bars will become **factor ~5-10 smaller**

Systematic uncertainties will get reduced only by **a factor of two or less**

Photon time-of-flight limits from astrophysical sources – current situation

Study of systematic uncertainties		
Systematic effect	**Size(E_{QG1})**	**Size(E_{QG2})**
Spectrum uncertainties	$< 6\%$	$< 4\%$
Energy scale	$< 10\%$	$< 20\%$
Extrapolation uncertainty	$< 1\%$	$< 1\%$
Background estimation	$< 5\%$	3%
Total	12.7%	20.6%

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	Linear Scenario	**Quadratic Scenario**
	$E_{QG1} \propto \frac{E_2 - E_1}{\Delta t}$	$E_{QG2} \propto \frac{E_2^2 - E_1^2}{\Delta t}$
Global shift of energy scale $\Delta E = \Delta E_0$	$\frac{\Delta E_{QG1}}{E_{QG1}} \approx 0$	$\frac{\Delta E_{QG2}}{E_{QG2}} \approx \frac{2\,\Delta E_0}{E_2 + E_1}$
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The atmosphere is responsible for the largest part of systematic uncertainties of an IACT

Part	currently achieved	goal for CTA	comments
Simulation codes	5%	1-2%	
Simplifications in MC	2%	2%	
Cherenkov light creation	5%	2%	
Ozone absorption	3%	1%	
Molecular extinction	2%	1%	
Cirrus layers extinction	5-20%	1-2%	Raman LIDARs and FRAM
Boundary layer extinction	5-20%	1-2%	Raman LIDARs and FRAM
Scattered Cherenkov light	<1%	<2%	

Characterization of the atmosphere

Need to continuously characterize:

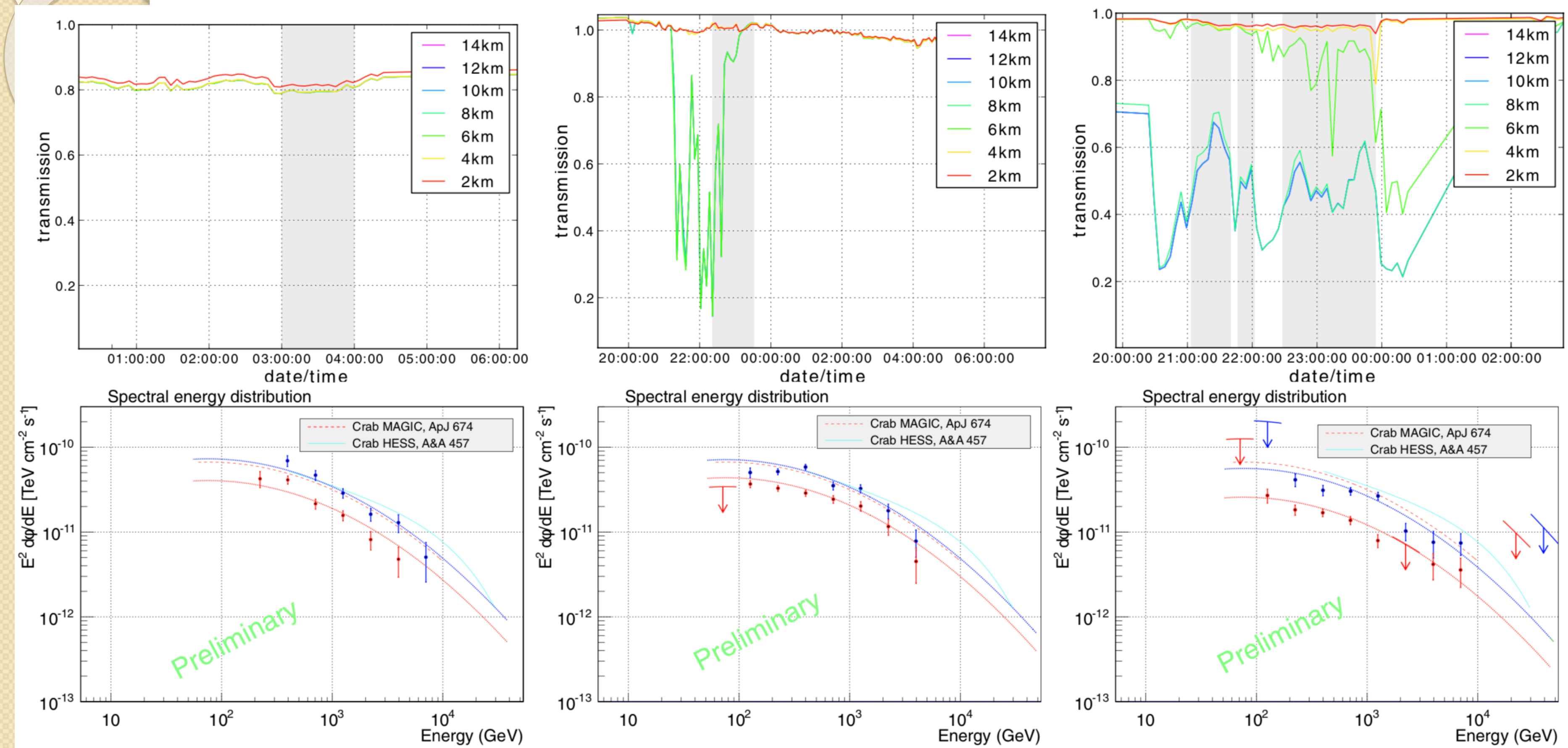
1. The profile from ground to 25 km distance
   - Raman LIDARs
2. The extension of clouds across the FOV of 10°, determination of time slots with equal atm. conditions
   - FRAM
3. For cross-checks:
   - The Cherenkov Transparency Coefficient

IFAE/UAB LIDAR for CTA

FRAM

MAGIC LIDAR

Performance of atmospheric corrections



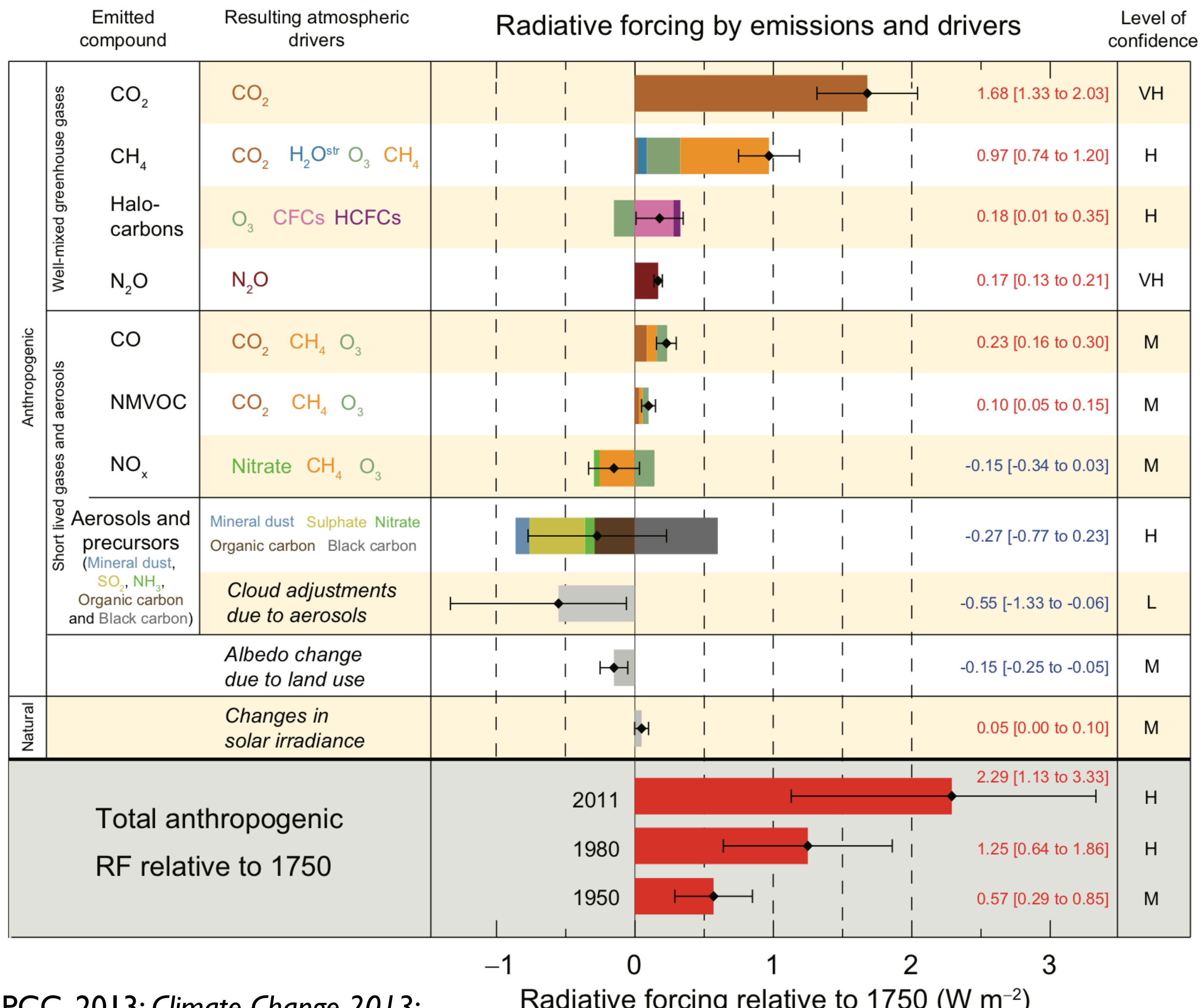
From Ch. Fruck et al., EPJ Web of Conferences **89**, 02003 (2015)
https://doi.org/10.1051/epjconf/20158902003

Additional ”practical” use of LIDARs

*“**Characterization of aerosols** in the atmosphere, important for precise calculations of data measured by Imaging Atmospheric Cherenkov Telescopes (IACTs), and needed for studies proposed in this project (Working Group 3), will **have a long-term impact on the development of environmental research and its application to climate research.** In particular, physical and chemical properties of aerosols will be assessed at the remote sites where IACTs are located”.*

From our **COST proposal**: *Quantum gravity phenomenology in the multi-messenger approach*

Additional "practical" use of LIDARs



From: IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the IPCC*

Conclusions

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A GRB or strong AGN flare tends to occur in IACTs under the most unfavorable atmospheric conditions

(high zenith angles, moon, dust instrusions, cirrus in the field-of-view, etc.)

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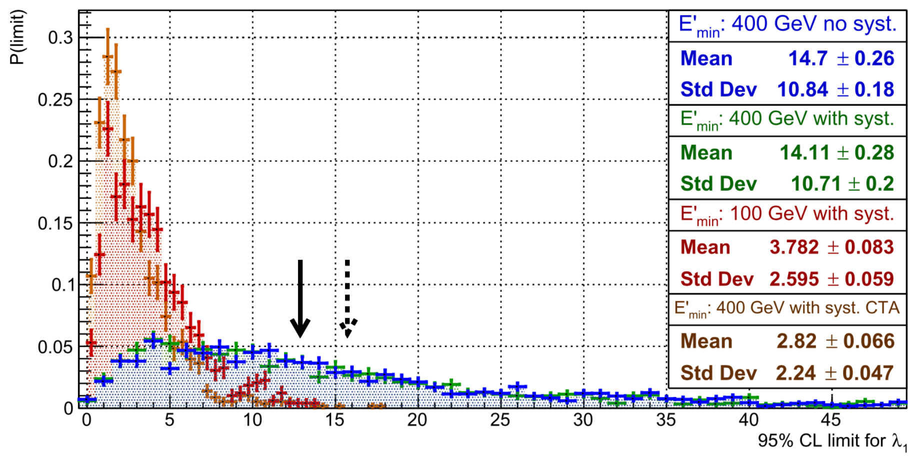
- Nevertheless, for ToF analyses, these conditions will dramatically limit sensitivity to E_{QG}, particularly for the quadratic case.

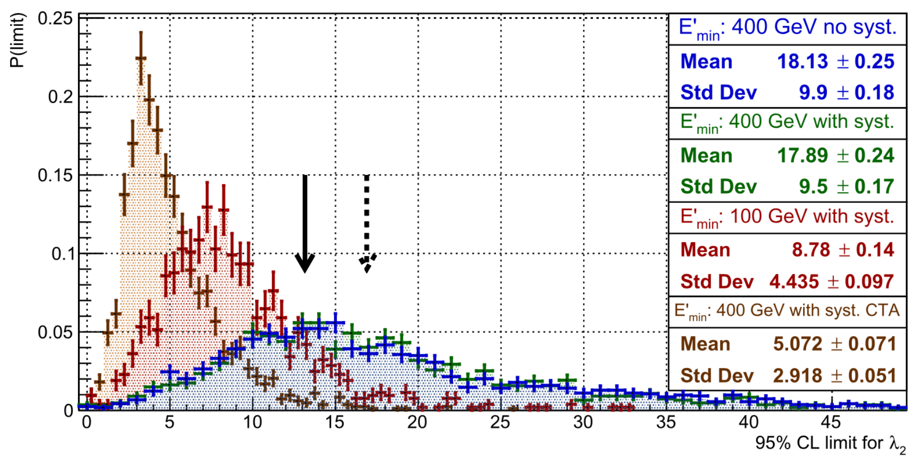
- **Develop a standard** to characterize atmospheric aerosols **based on LIDAR** (Light Detection and Ranging) and **stellar extinction measurements**, and provide the corresponding **corrections to IACT data**, based on tailored Monte Carlo simulations;

From our **COST proposal**: *Quantum gravity phenomenology in the multi-messenger approach*

Backup

Expected limits ($\lambda_1+\lambda_2$)





From Ahnen et al., APJS **232** (2017) 9

https://doi.org/10.3847/1538-4365/aa8404