Testing Lorentz Invariance in the Multi-messanger (TeV) Era.

Tsvi Piran
The Hebrew University of Jerusalem

Cost CA18108 Forth Annual Conference - Rijeka (Croatia)

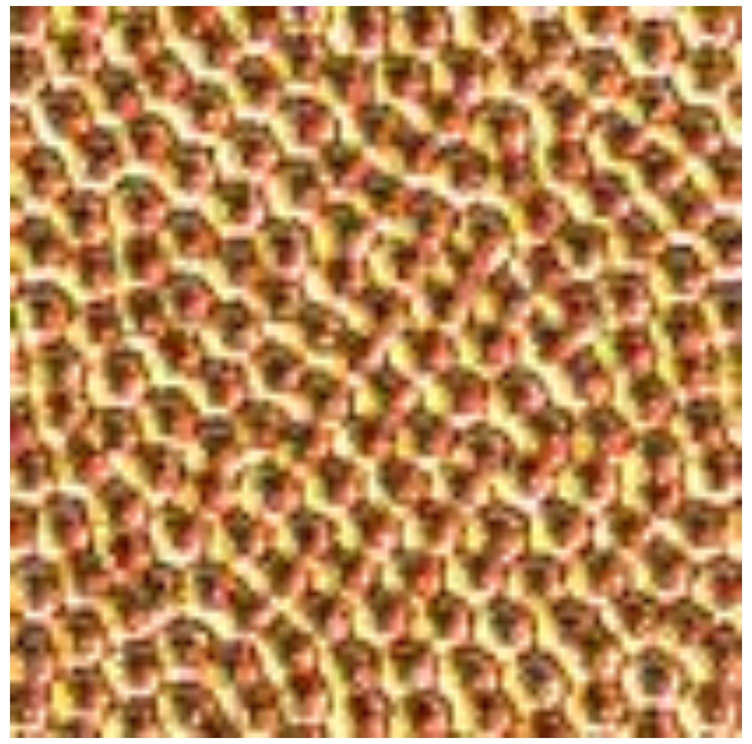
erc
MultiJets

Quantum Gravity Effects at low energies

(Amelino-Camelia et al., 98)

Lorentz Violation (or deformation) appears in various Quantum Gravity Theories.

Energy dependent dispersion and speed of light.



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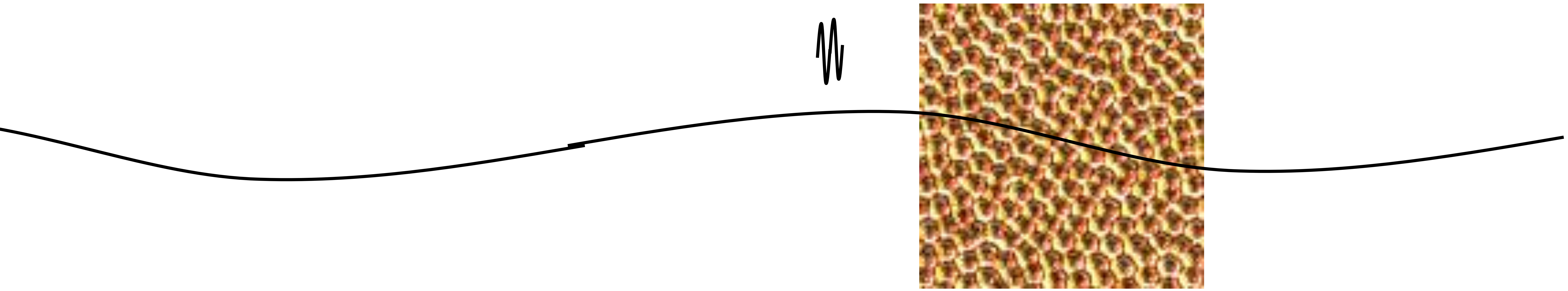

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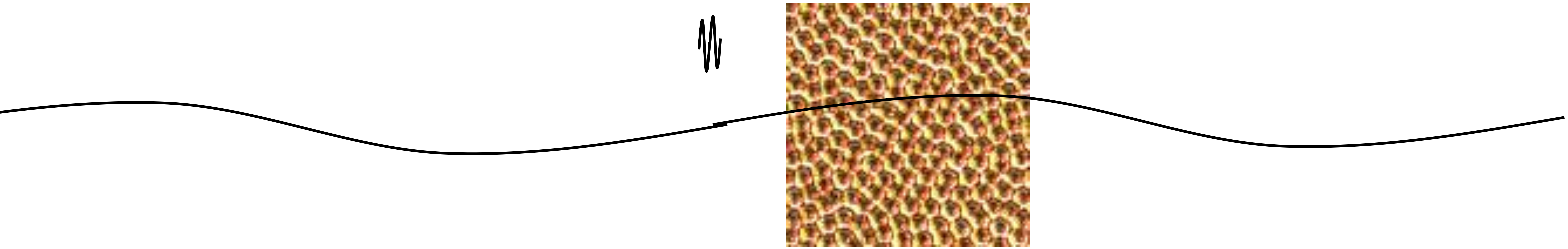

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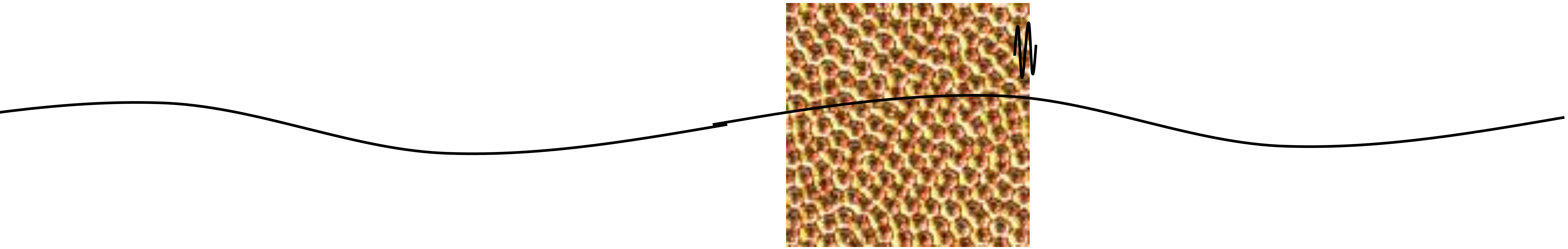


A phenomenological Approach

The simplest leading order low-energy approximation of any theory that breaks Lorentz Invariance at a very high energy scale: ξm_{pl}, for the deformed dispersion relation:

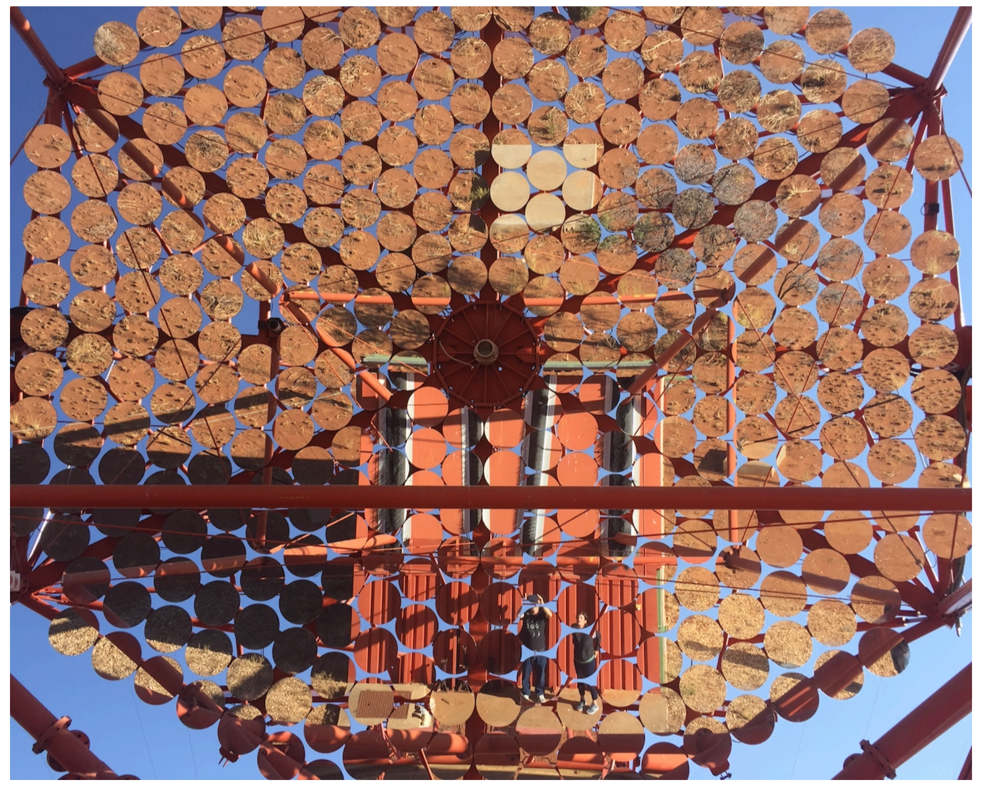
$$E^2 - p^2 - m^2 \approx \pm \left(\frac{E}{\xi_n m_{pl}} \right)^n$$

$$v \approx c \left[1 \pm \frac{(1+n)}{2} \left(\frac{E}{\xi_n m_{pl}} \right)^n \right]$$

Higher energy photons will arrive later (or earlier) than low energy ones emitted **simultaneously**.

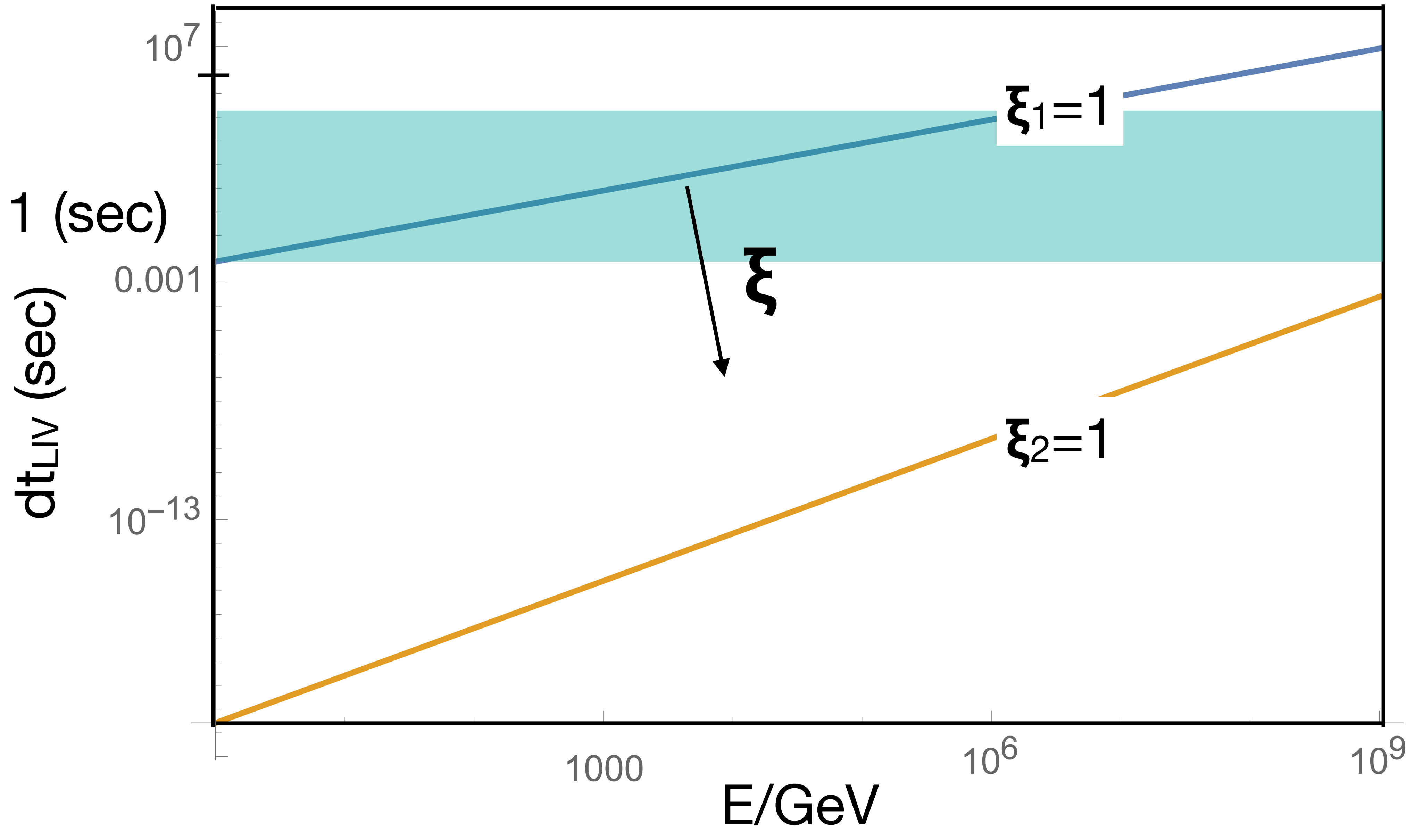
$$dt_{LIV} \approx \pm \frac{d}{c}\left(\frac{E}{\xi_n m_{pl}}\right)^n \approx 0.01\mathrm{sec}\ 10^{-19(n-1)}\left(\frac{E}{\xi_n GeV}\right)^n$$

Fermi

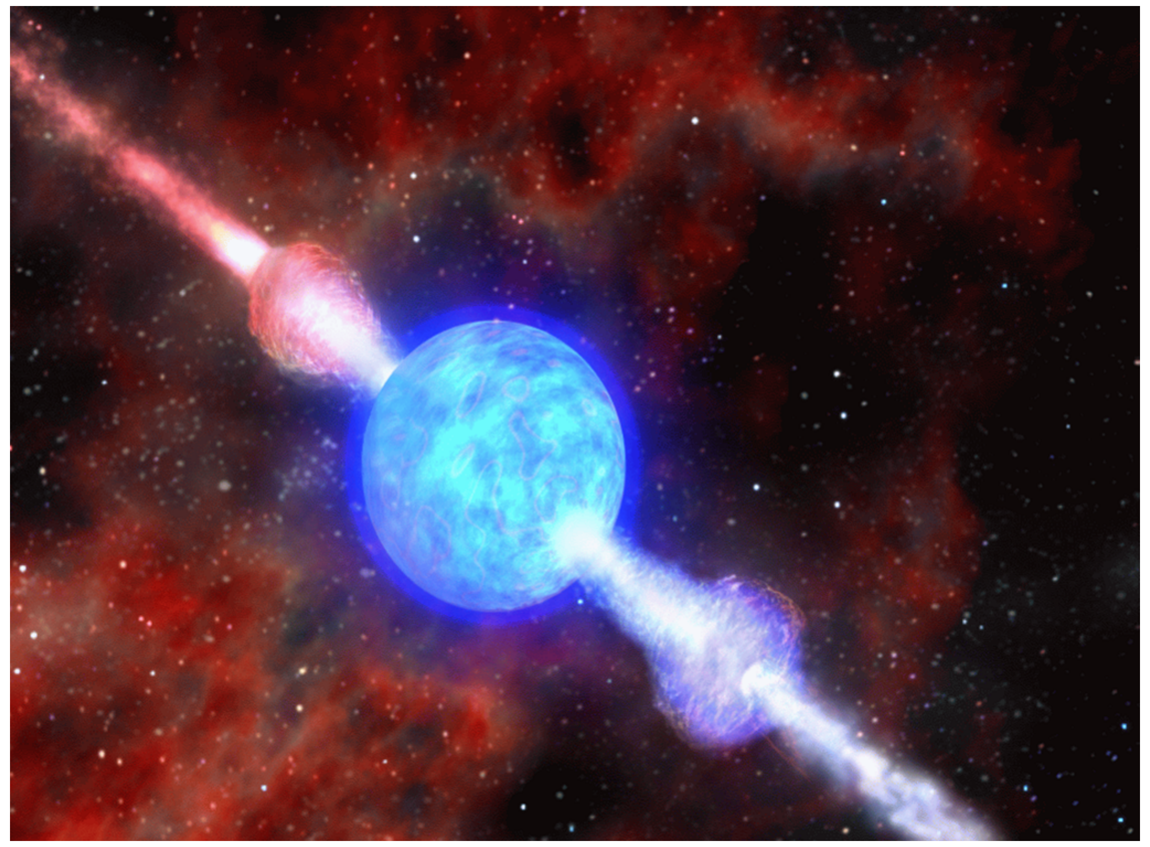


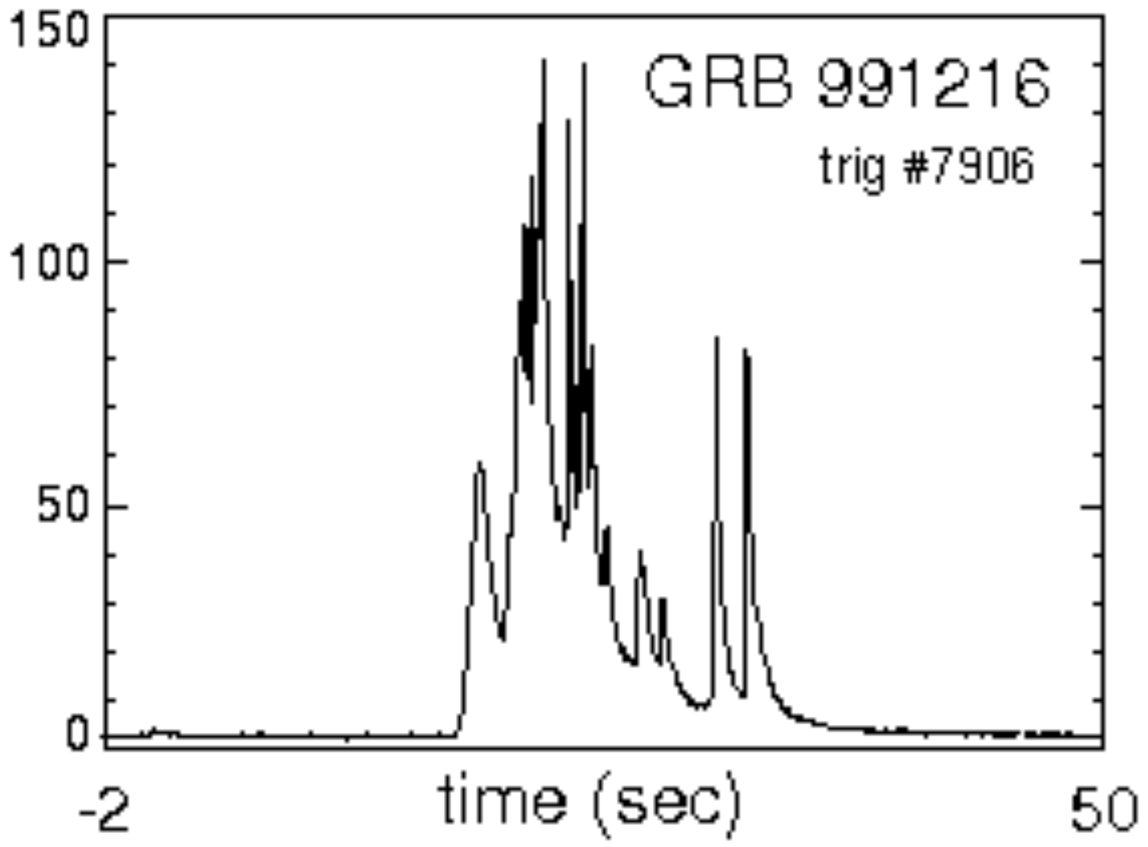
H.E.S.S. ; Magic

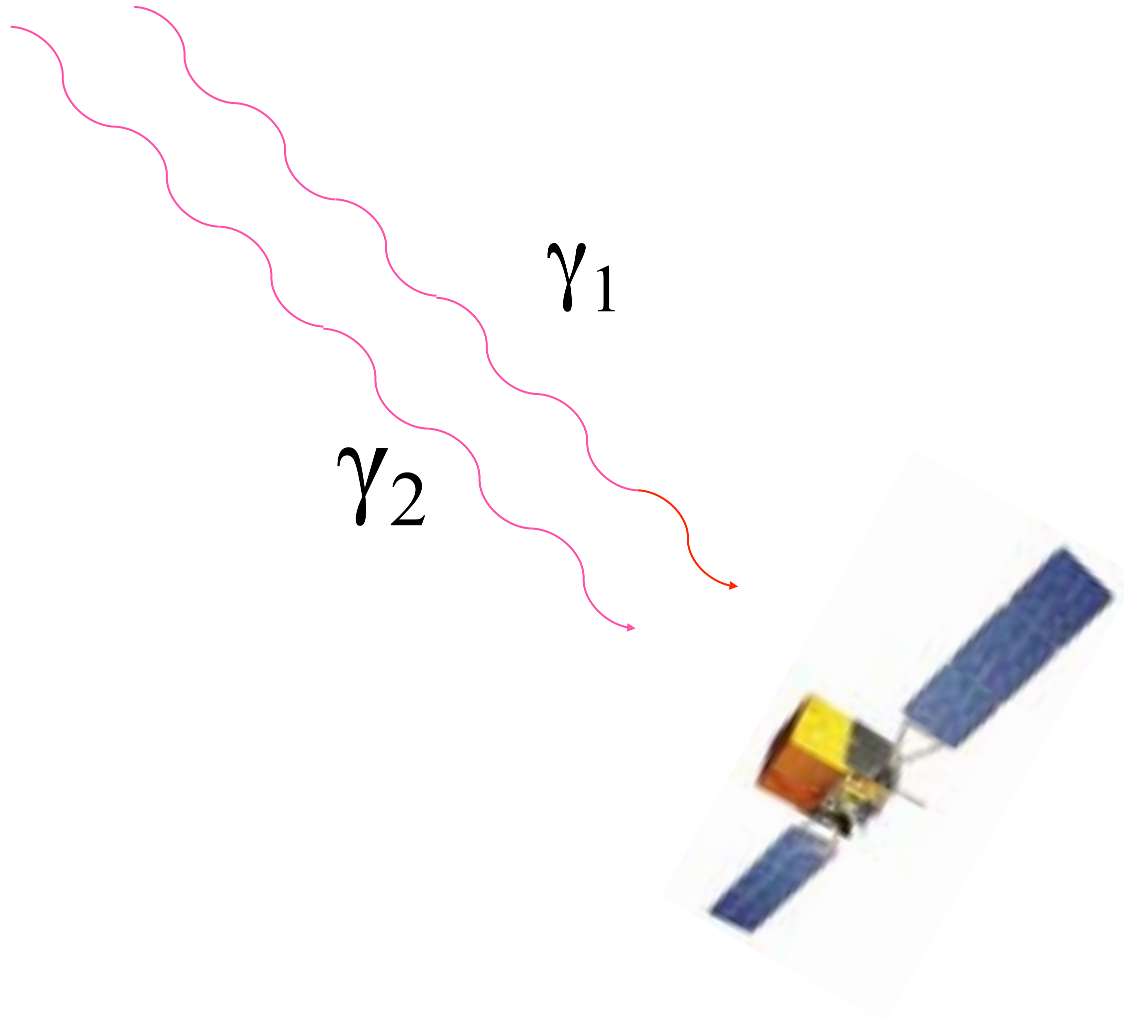
dt for a cosmological source at z=1 for n=1,2 (ξ=1)



Gamma-Ray Bursts

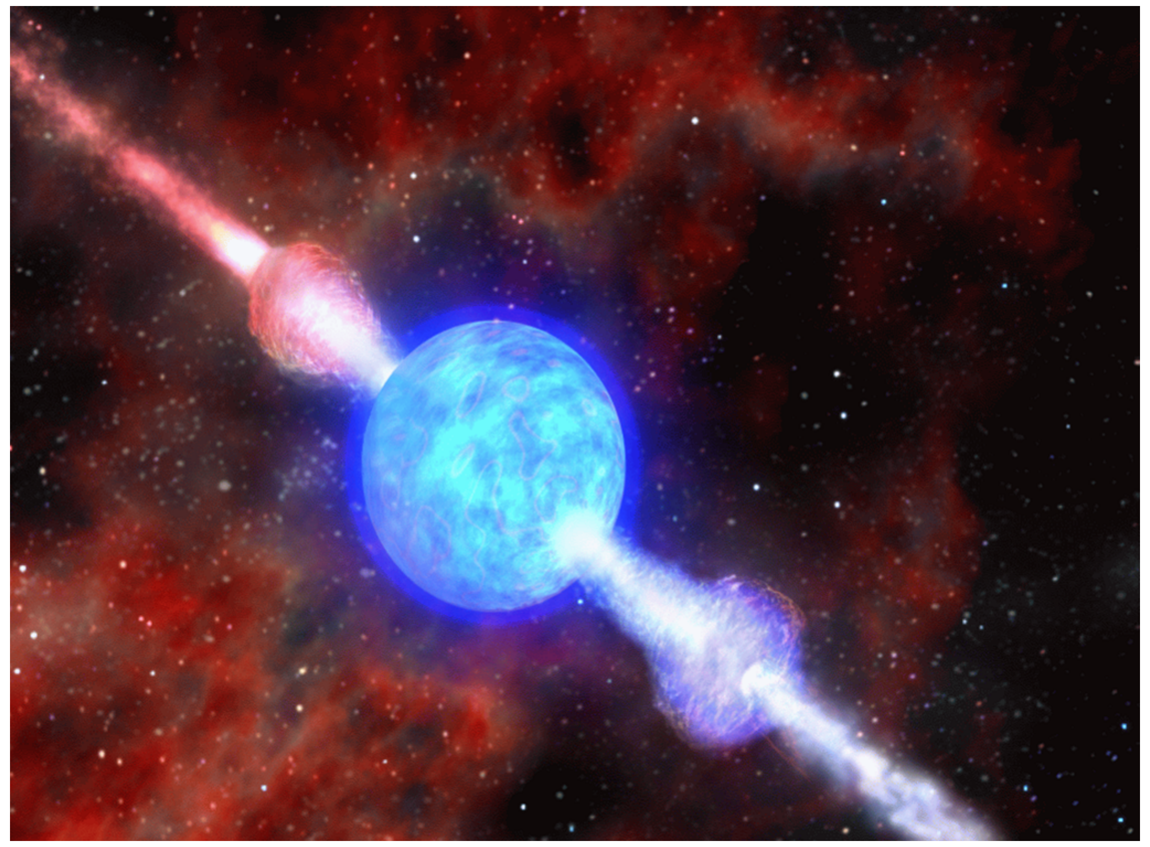


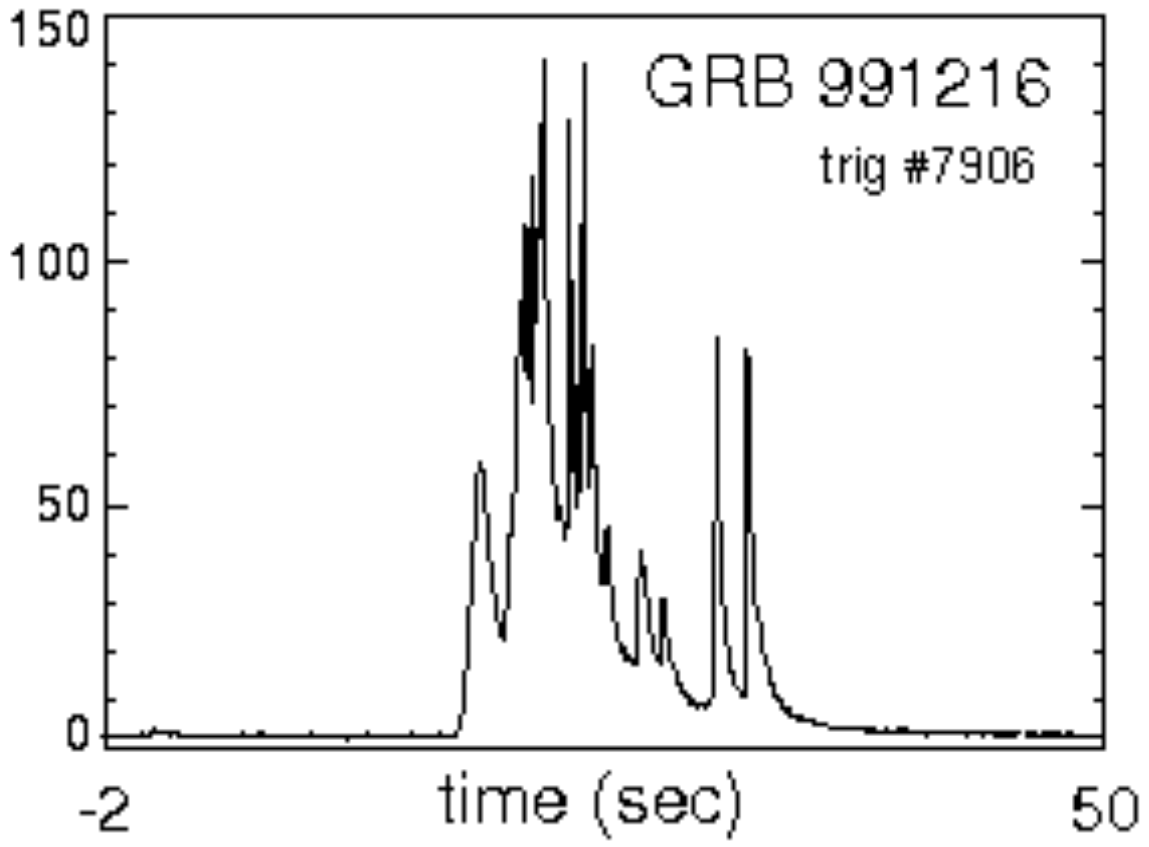


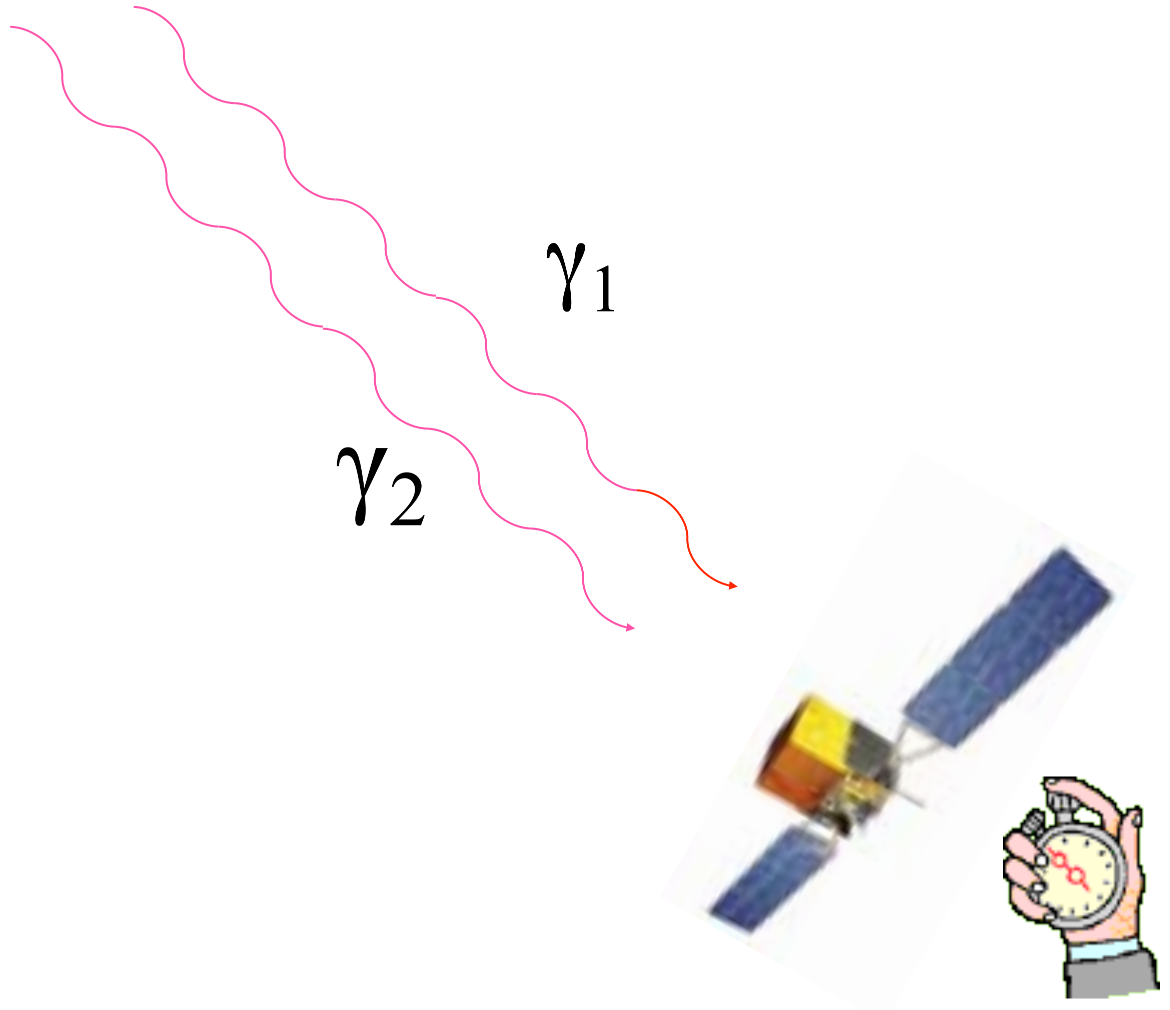


- Gamma-ray bursts (GRBs) are short (1-100 sec) bursts of (mostly) soft gamma-rays (~300 keV) arriving from random directions in the sky and from cosmological distances.
- Long GRBs - collapsing stars: “Collapsars”
- Short GRBs - merging neutron stars: “Mergers”.
- The prompt emission is highly variable up to a scale of milliseconds.
- GRBs are followed by long-lasting afterglow in radio, optical, x-rays *and VHE (TeV)*.

Gamma-Ray Bursts







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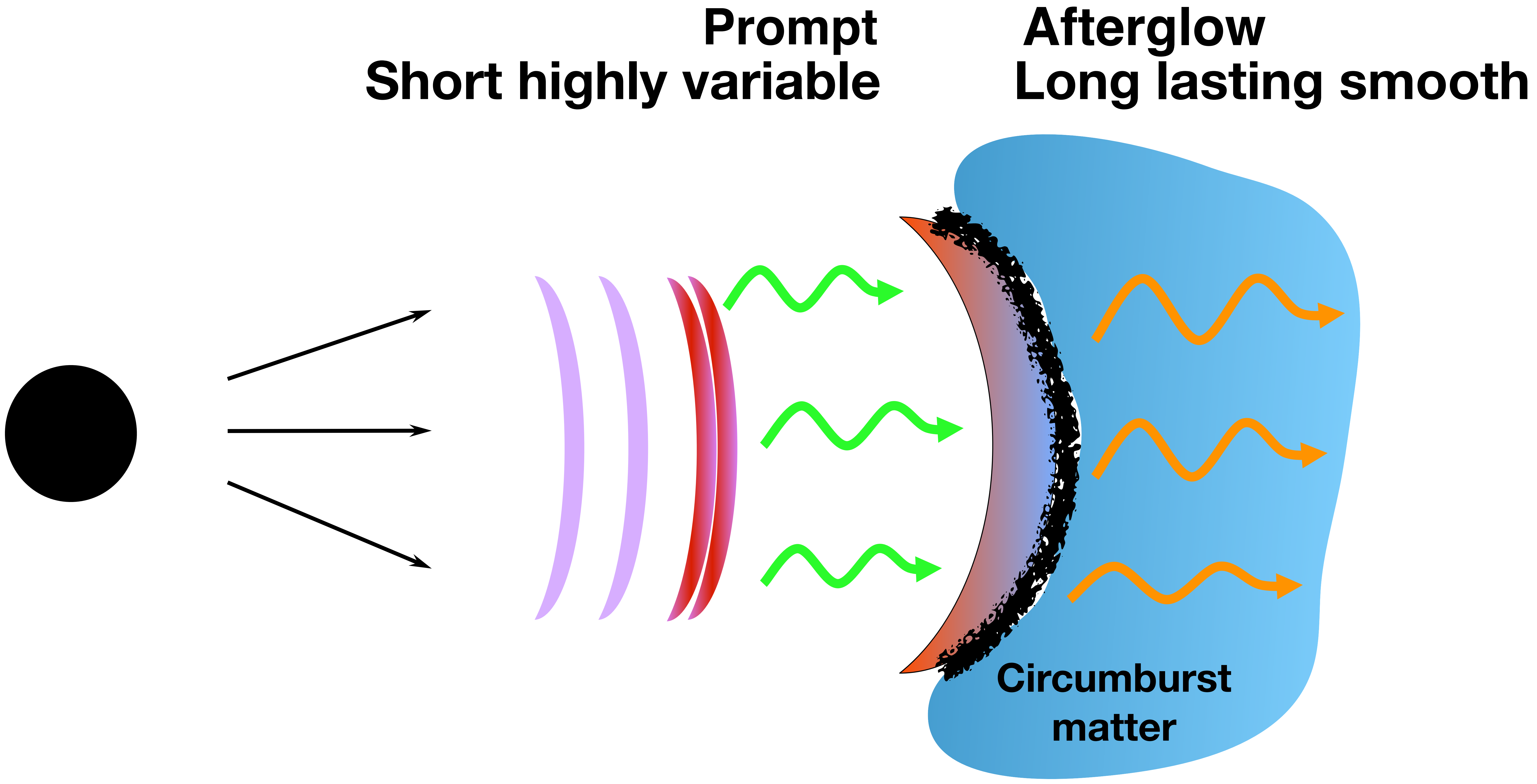
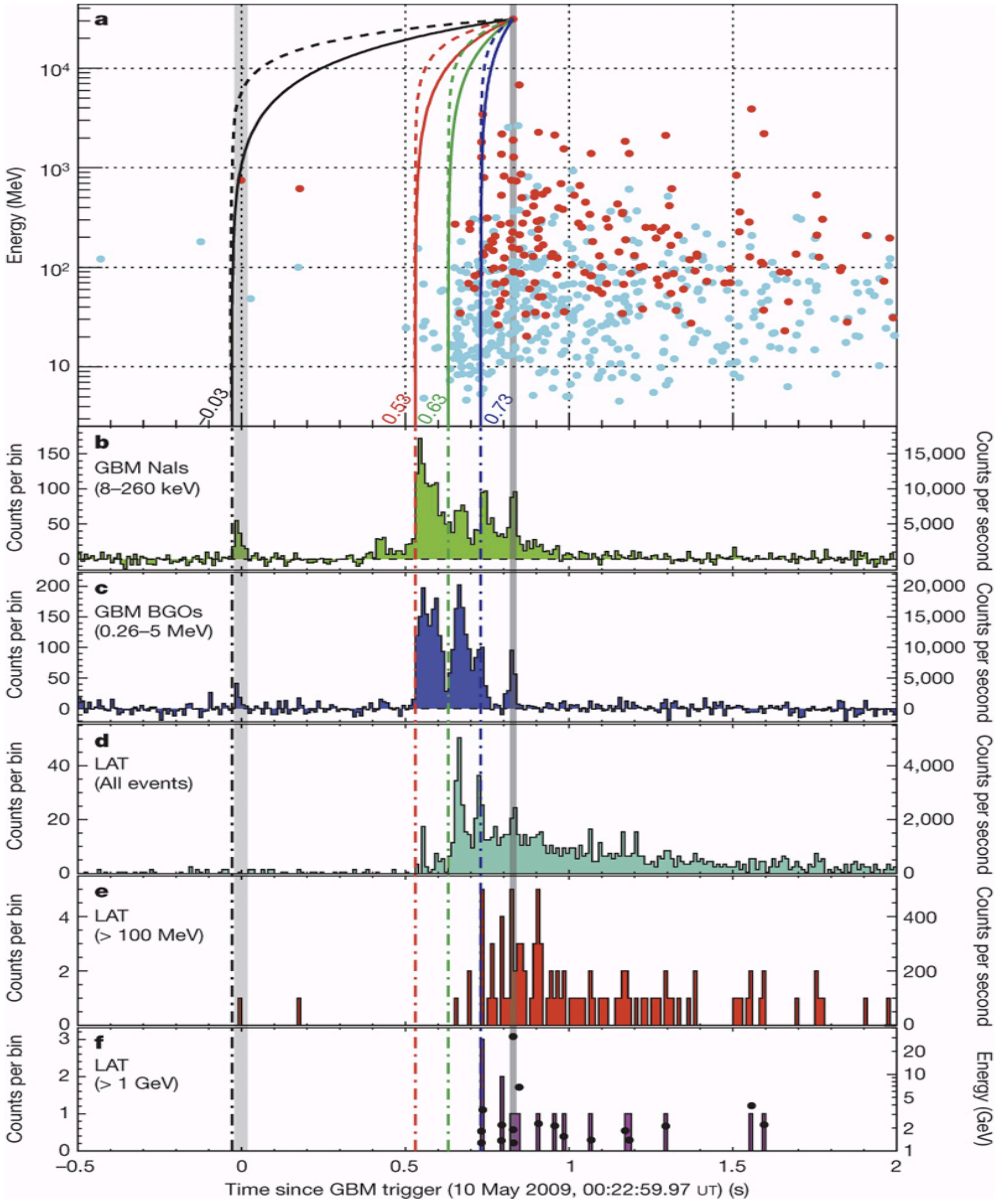
A rough sketch of a GRB



Fermi Observations of GRB 090510

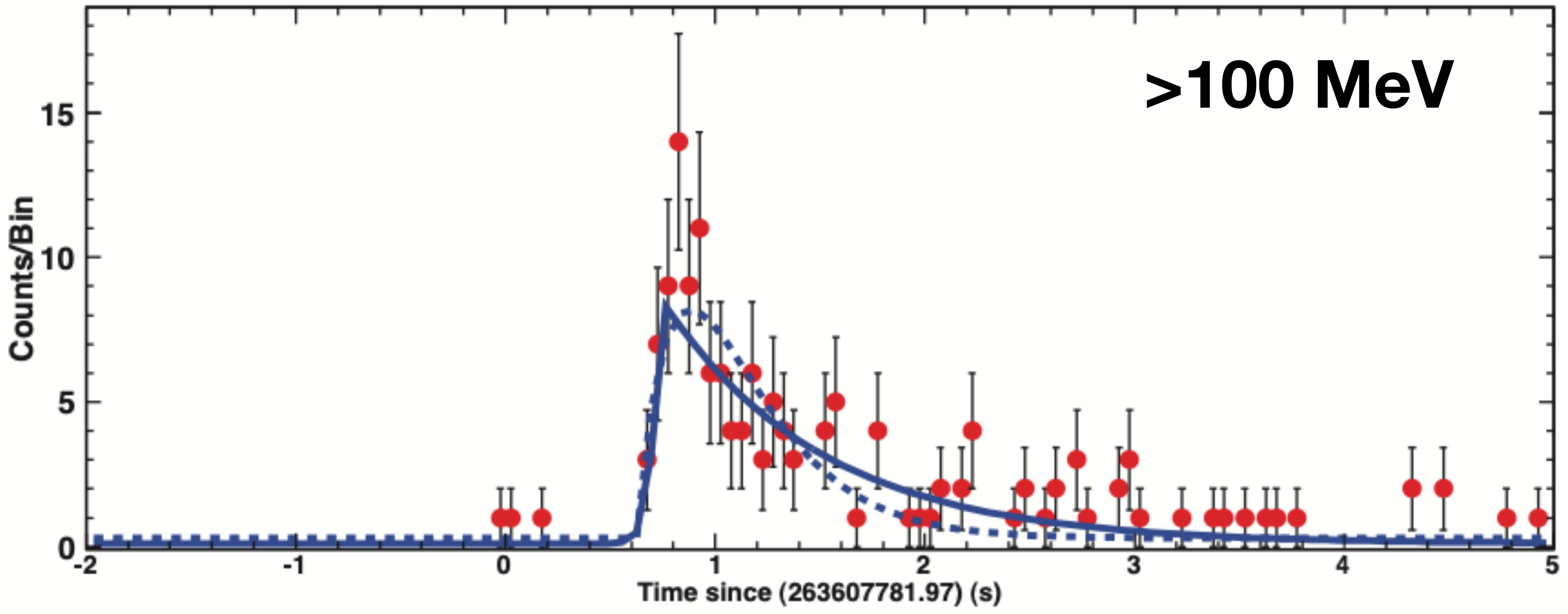


Credit: Fermi Collaboration

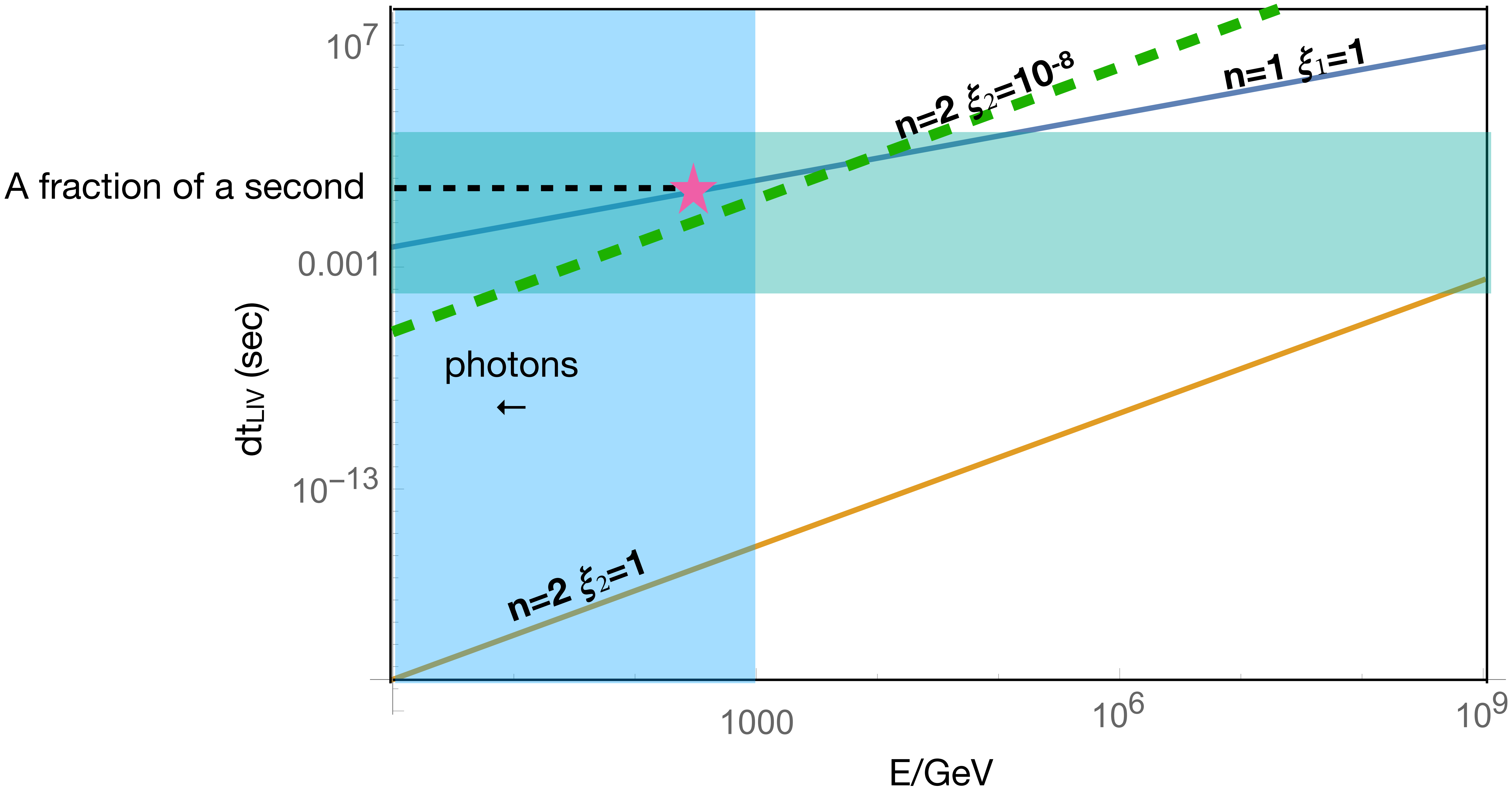
Z=0.903

Δt(0.1MeV-30GeV) < 0.9sec

⇒ $E(1)_{QG} > 1.2 \cdot 10^{19}$ GeV = 1.2 m_{pl}



$t_{\rm start}$ (ms)	limit on $\lvert\Delta t\rvert$ (ms)	Reason for choice of $t_{\rm start}$ or limit on Δt	E_l (MeV)	valid for s_n	lower limit on $M_{\rm QG,1}/M_{\rm Planck}$	limit on $M_{\rm QG,2}$ in 10^{10} GeV/c^2
−30	< 859	start of any observed emission	0.1	1	**> 1.19**	> 2.99
530	< 299	start of main < 1 MeV emission	0.1	1	**> 3.42**	> 5.06
630	< 199	start of > 100 MeV emission	100	1	**> 5.12**	> 6.20
730	< 99	start of > 1 GeV emission	1000	1	**> 10.0**	> 8.79
—	< 10	association with < 1 MeV spike	0.1	±1	**> 102**	> 27.7
—	< 19	if 0.75 GeV γ is from 1st spike	0.1	−1	**> 1.33**	> 0.54
$\lvert\Delta t/\Delta E\rvert$ < 30 ms/GeV		lag analysis of all LAT events	—	±1	**> 1.22**	—



A fraction of a second
photons
←
n=2 ξ2=10-8
n=1 ξ1=1
n=2 ξ2=1
10^7
0.001
10^−13
dtLIV (sec)
1000
10^6
10^9
E/GeV

The Teraelectronvolt Era

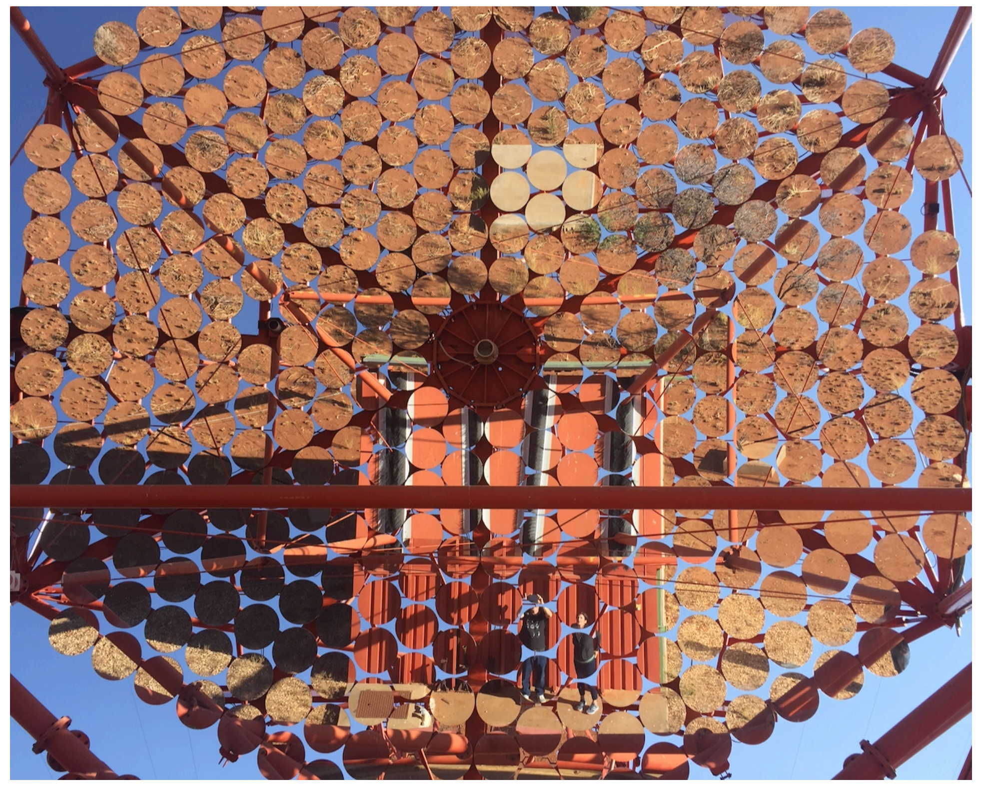
Teraelectronvolt emission from the γ-ray burst GRB 190114C

MAGIC Collaboration

Nature **575**, 455–458(2019)

$$dt_{LIV} \approx \pm \frac{d}{c}\left(\frac{E}{\xi_n m_{pl}}\right)^n \approx 10\ \text{sec}\ 10^{-16(n-1)}\left(\frac{E}{\xi_n TeV}\right)^n$$

Fermi



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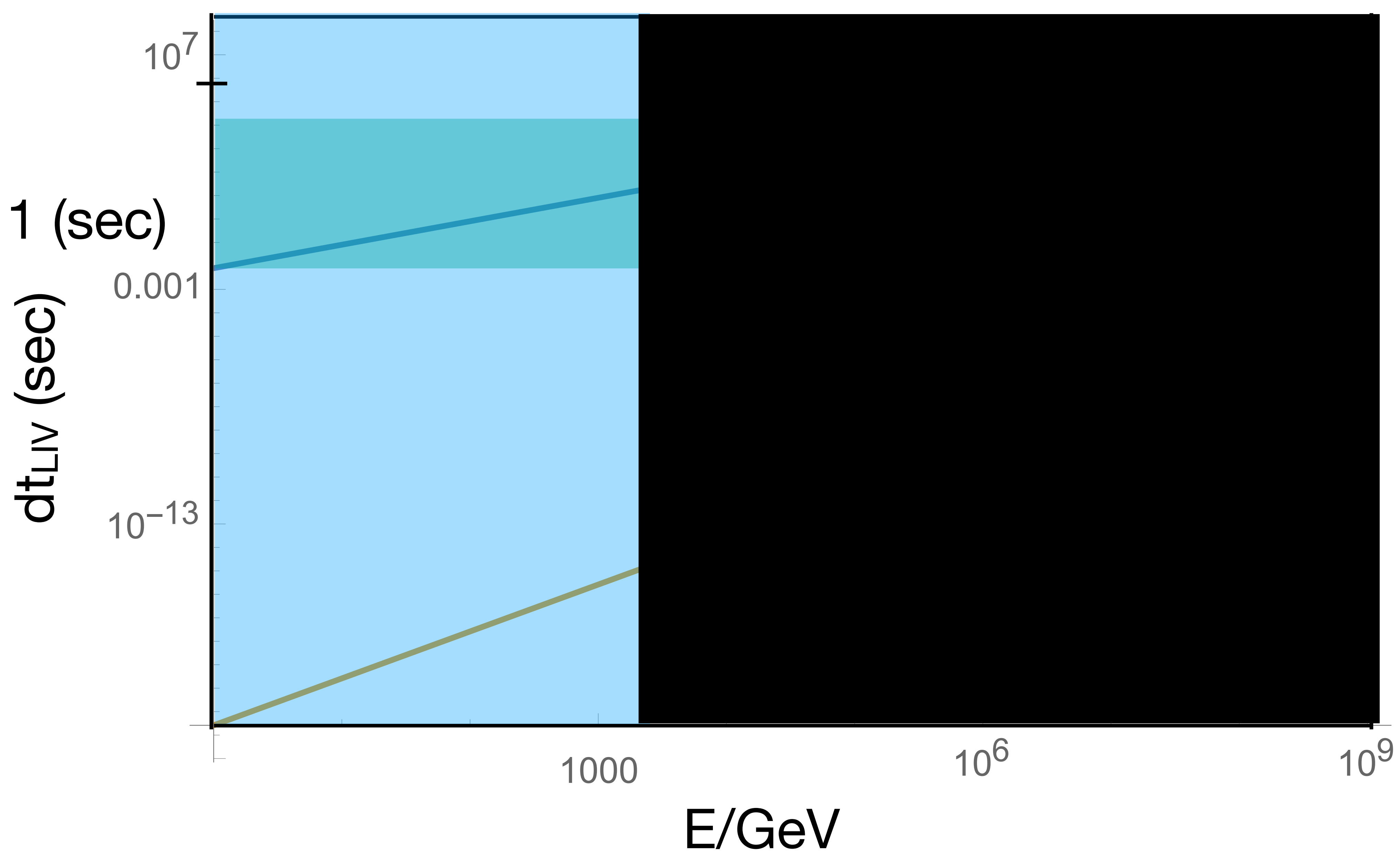
dt for a cosmological source at z=1 for n=1,2 (**ξ**=1)



LHAASO

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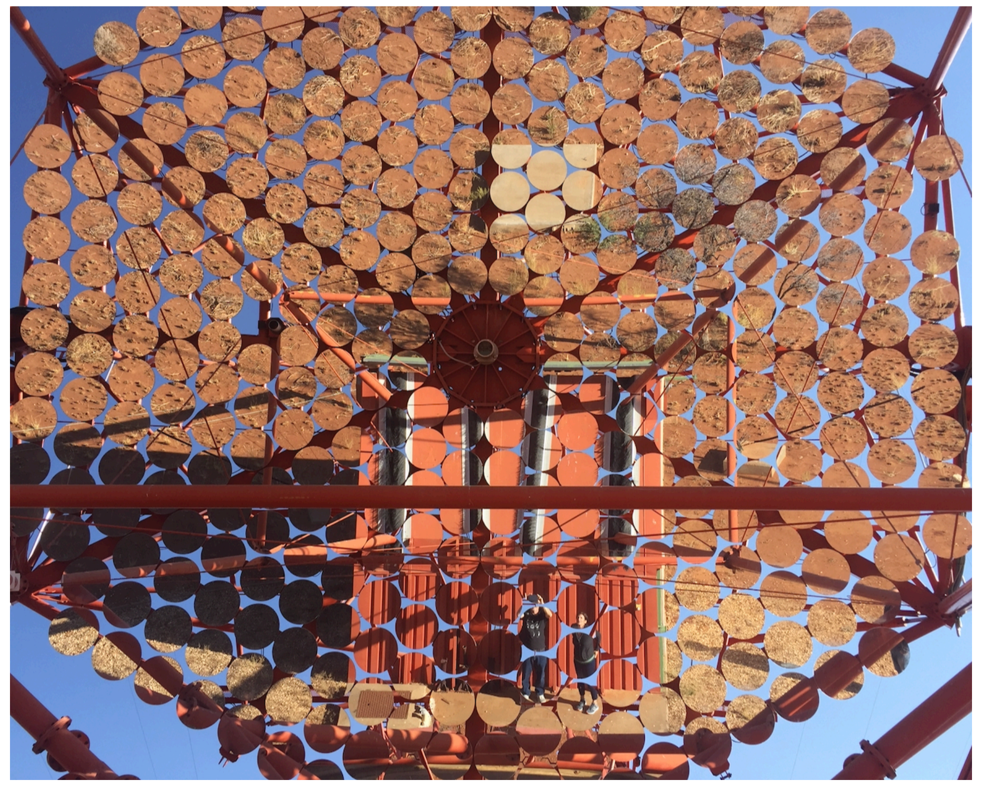

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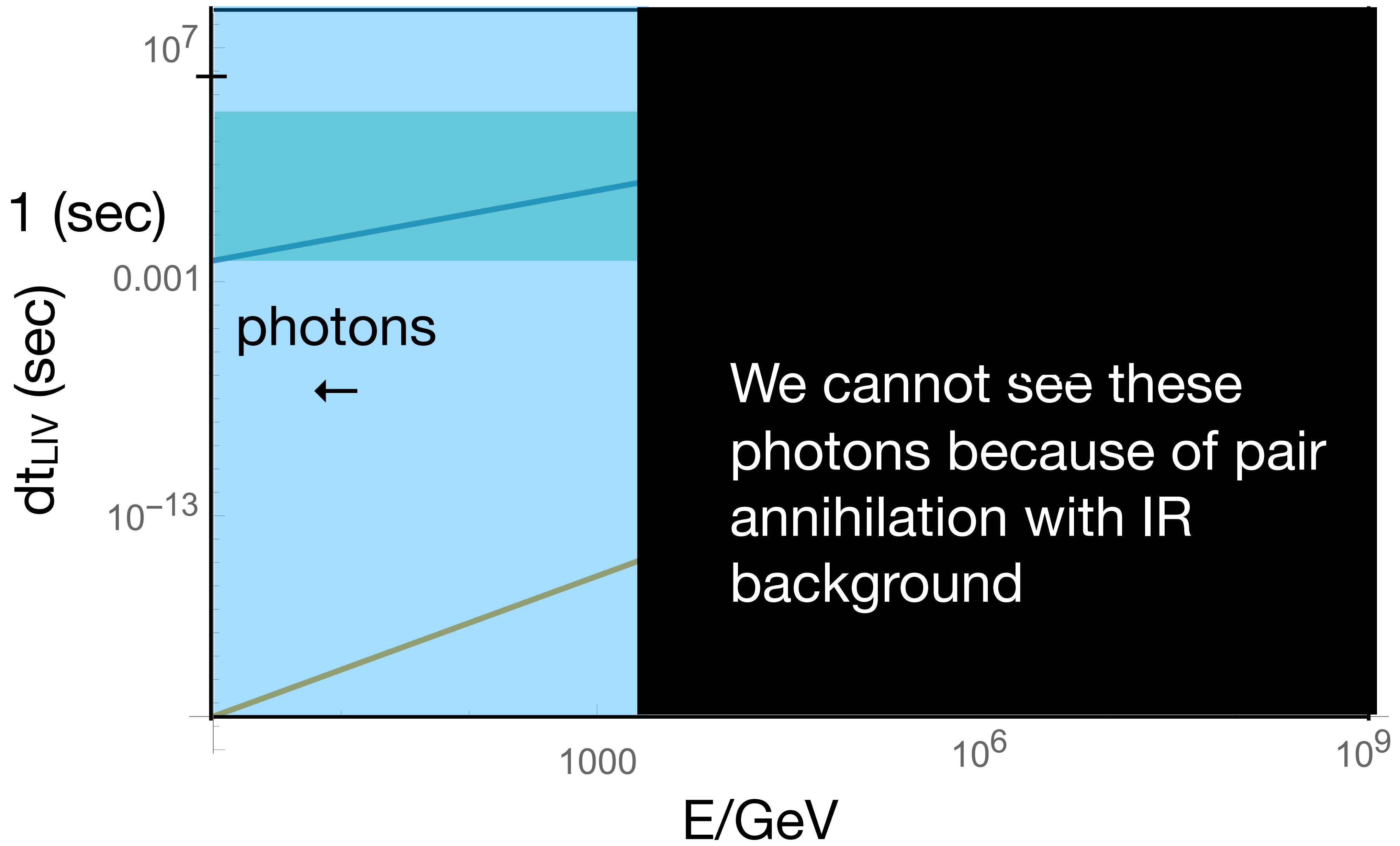
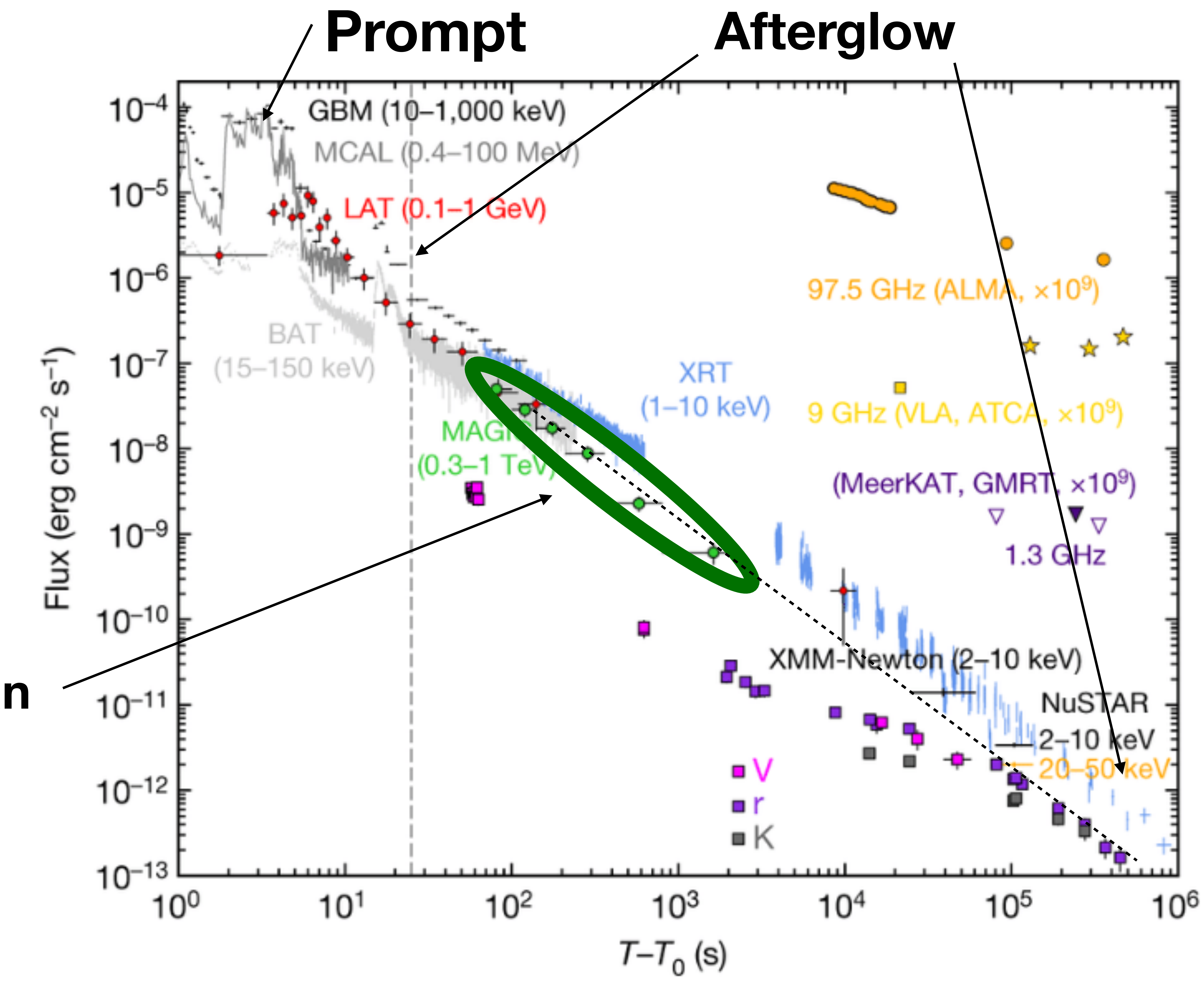


LHAASO

TeV photons from z=0.45



SSC afterglow emission (Derishev & Piran 2019)

Many early predictions including:
Fan, TP, Narayan 2008 Petropoulou, Mastichiadis, TP 2015

The time delay ≲ a few dozen seconds

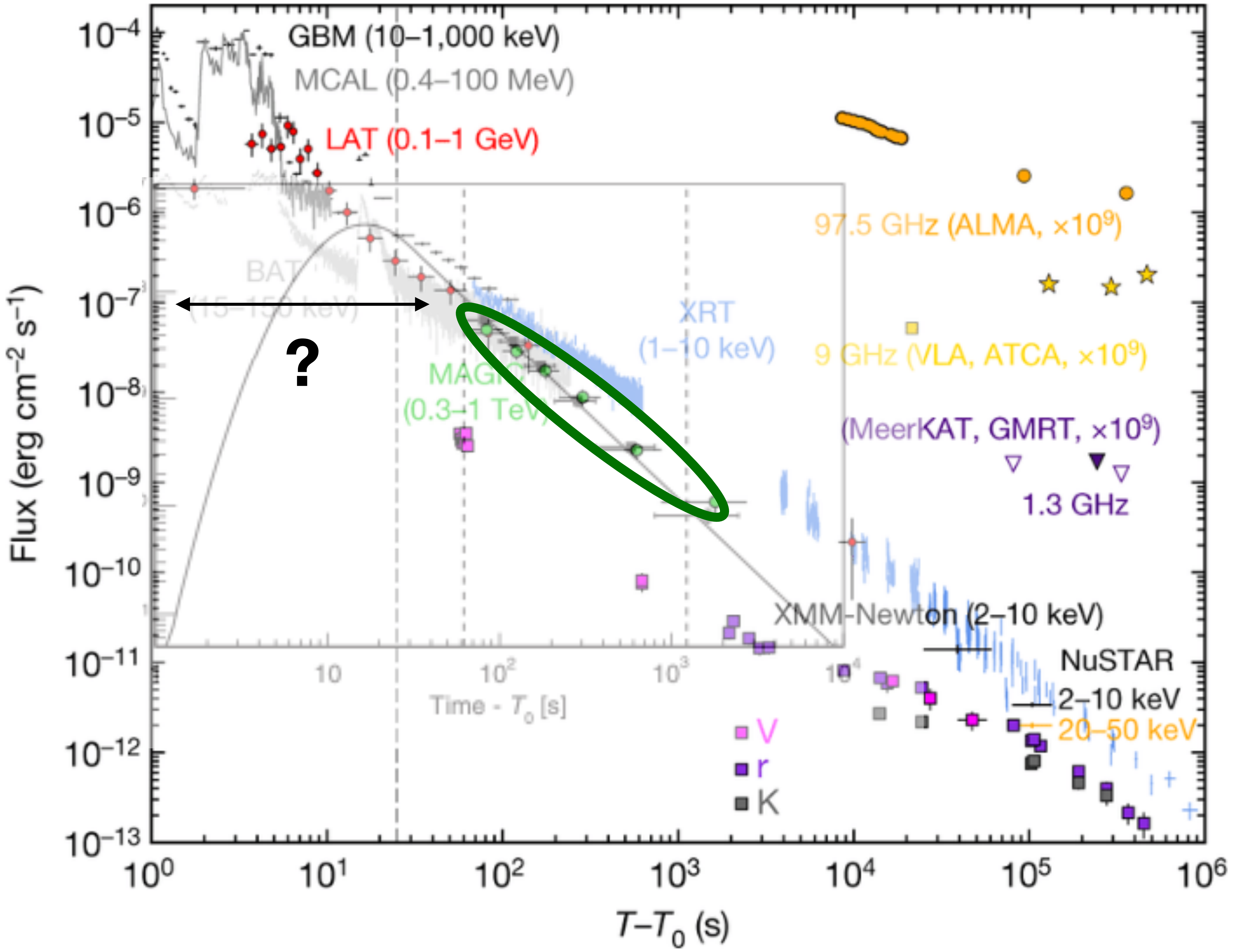
$$dt_{LIV} \approx \pm \frac{d}{c}\left(\frac{E}{\xi_n m_{pl}}\right)^n \approx 10 \text{ sec } 10^{-16(n-1)}\left(\frac{E}{\xi_n TeV}\right)^n$$ **(For z=1)**

z=0.45 + dt ~30-60 sec

LC model	Minimal (step function)	Theoretical ([19])		
	η^{UL}	η^{LL}	η^{BF}	η^{UL}
η_1	4.4	−2.2	0.3	2.1
η_2	2.8	−4.8	1.3	3.7
	subluminal	superluminal		subluminal
$E_{QG,1}$ [10^{19} GeV]	0.28	0.55		0.58
$E_{QG,2}$ [10^{10} GeV]	7.3	5.6		6.3

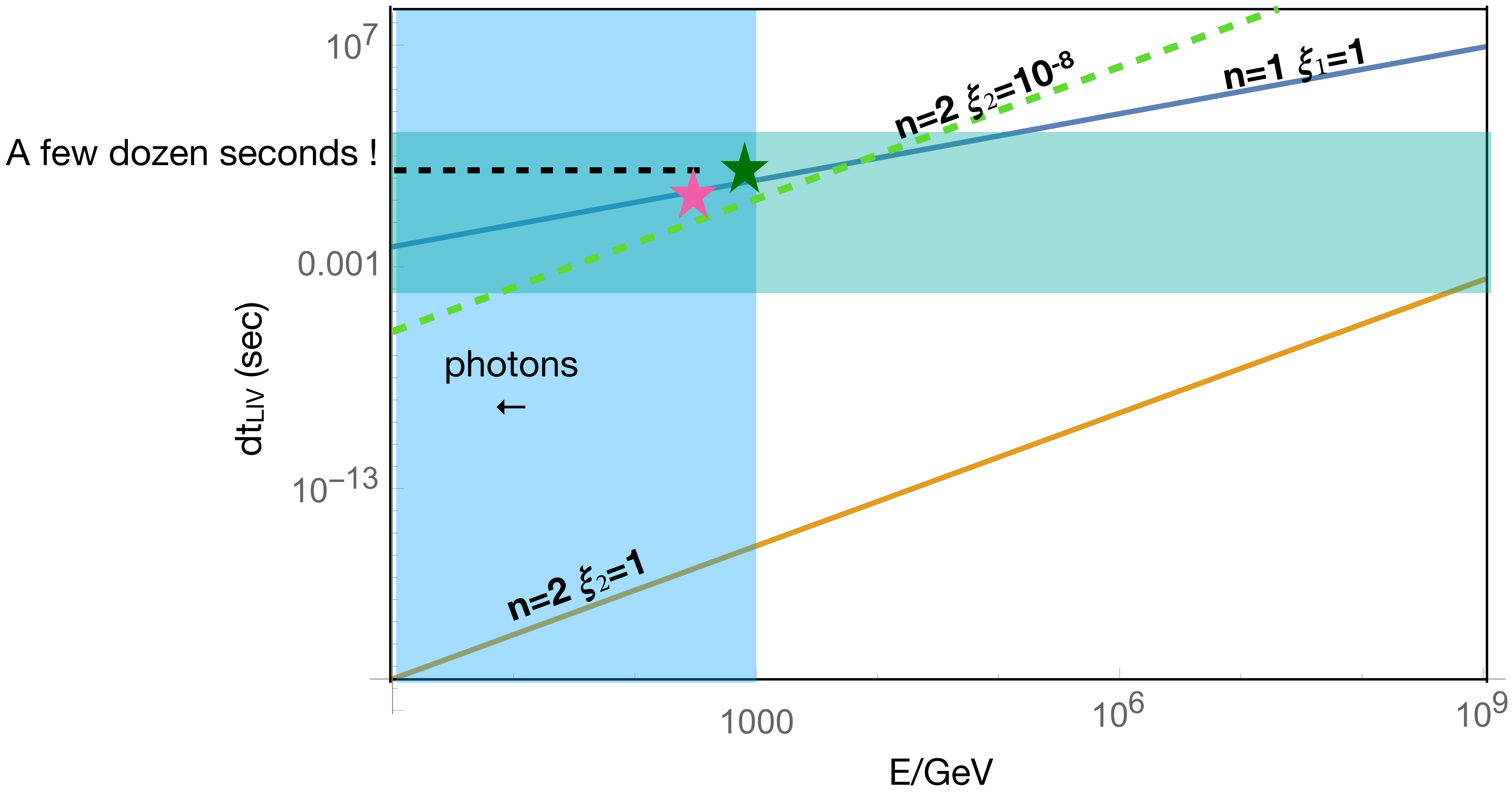
A factor of 4 (7) below the GRB 090510 limits

Comparable to AGN flare limits (Abdalla et al., 2019)



Acciari et al., (Magic Collaboration) + L. Nava 2020

Supported by COST18108!

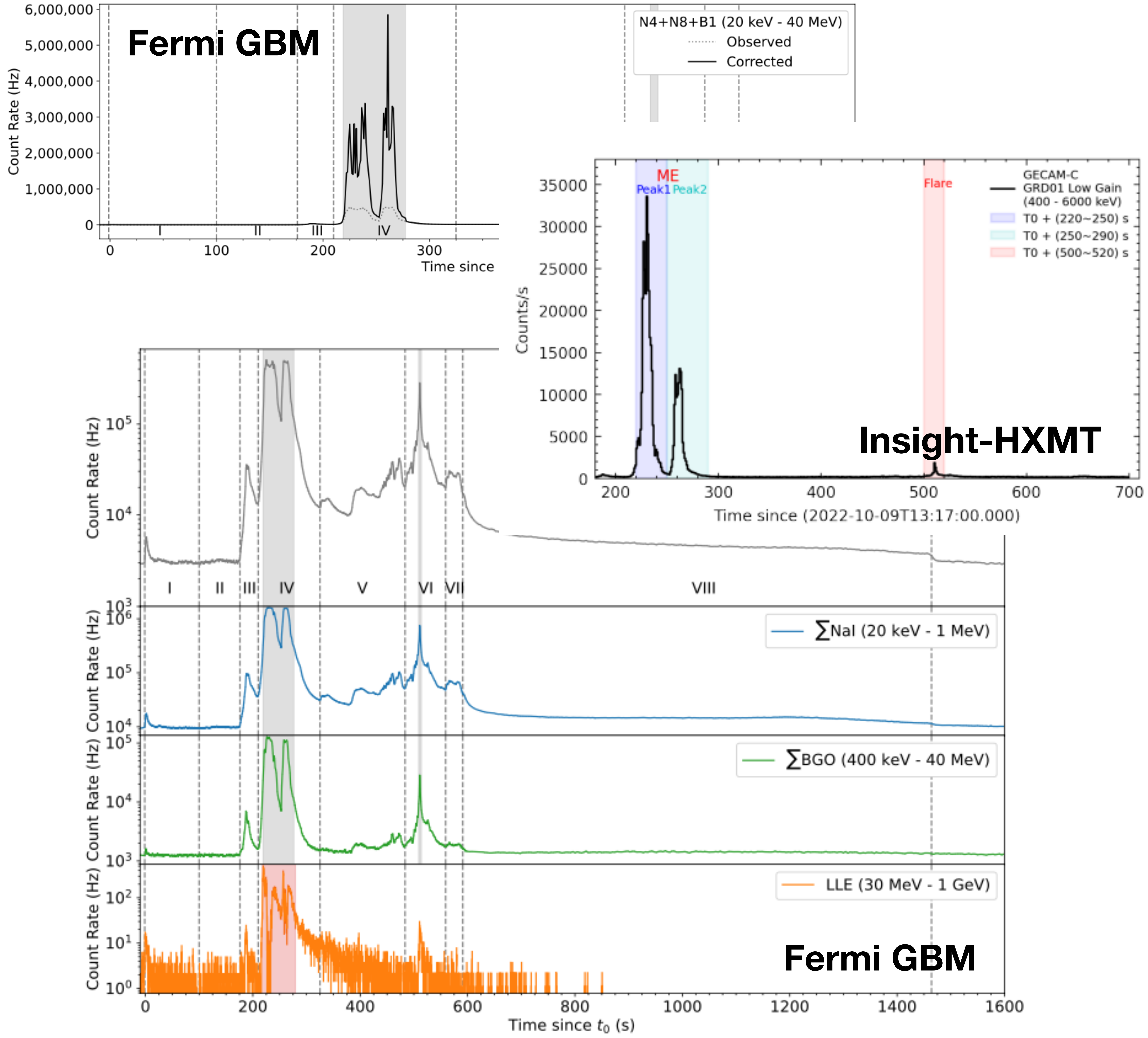


A few dozen seconds !
10^7
0.001
10^{-13}
dt_{LIV} (sec)
photons
←
n=2 ξ_2=10^{-8}
n=1 ξ_1=1
n=2 ξ_2=1
1000
10^6
10^9
E/GeV

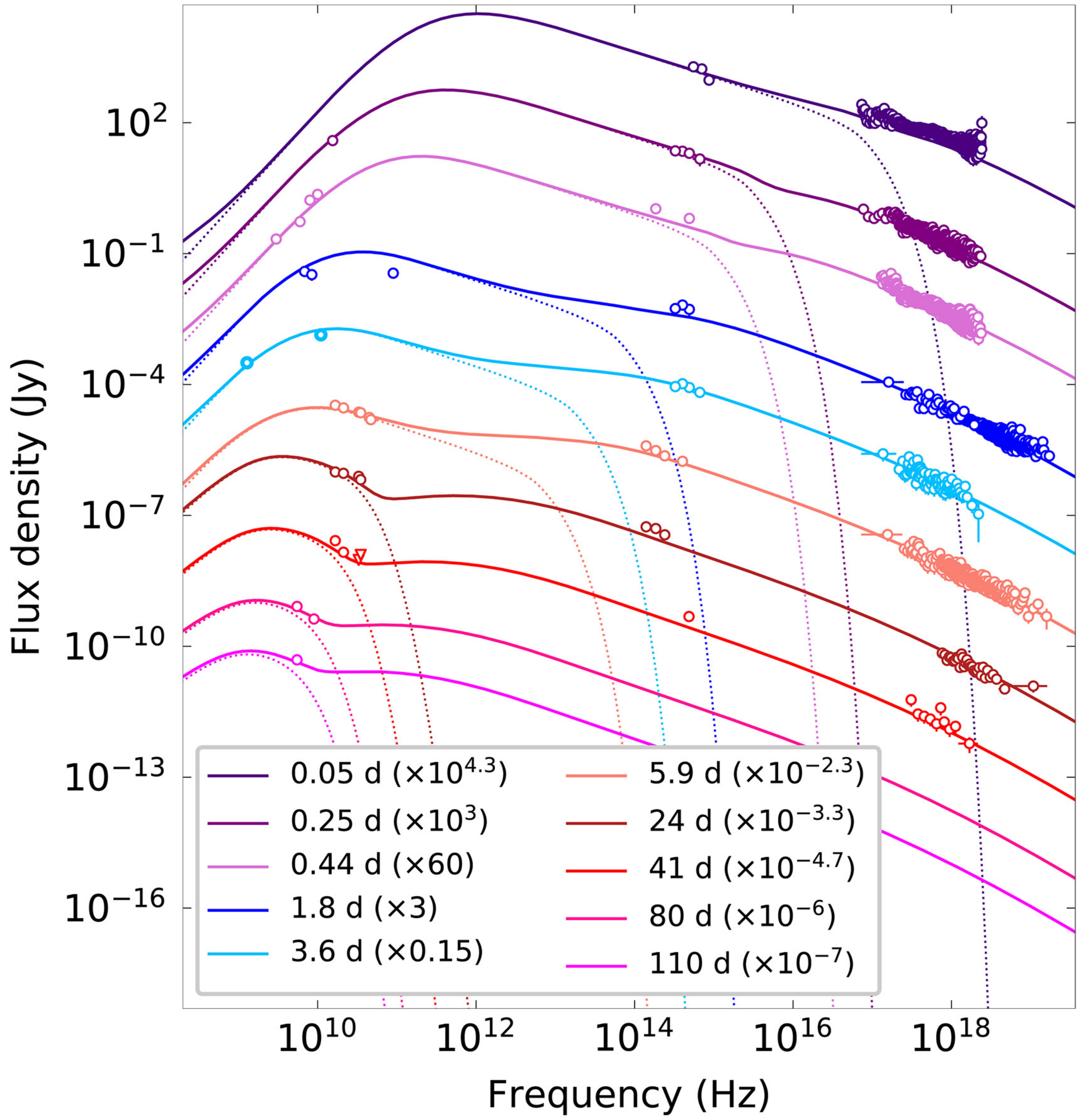

221009A

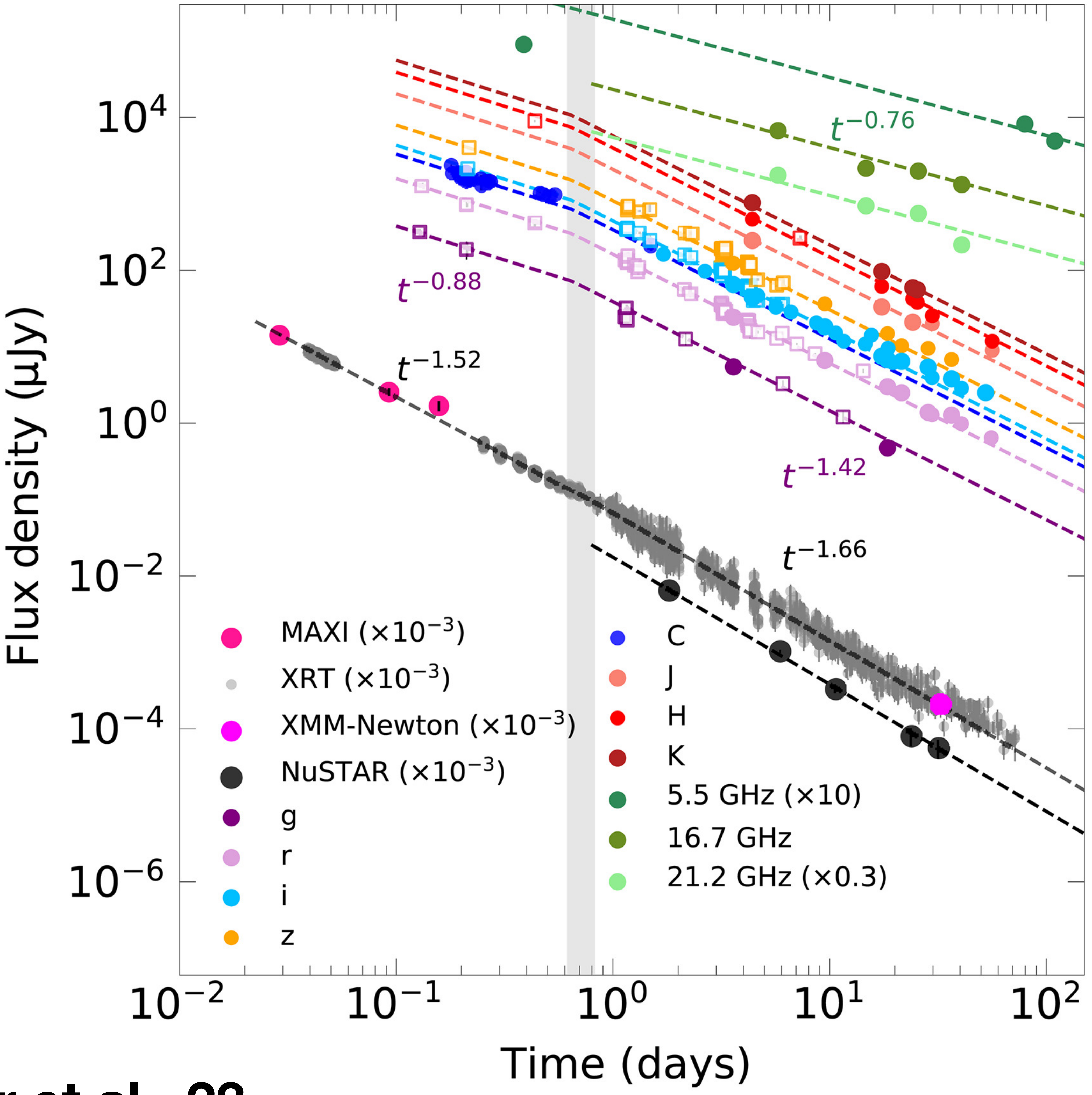
221009A

- $Z=0.151$ (745 Mpc)
- $E_{iso=}1.5 \times 10^{55}$ erg
- If $\vartheta_j=0.7^o$ then $E=1.15\ 10^{51}$ erg
- T_{90}=330 sec
- LHAASO 5000 photons > 500 GeV up to 18 TeV
- The afterglow emission is much less energetic, and it is comparable to other TeV GRBs e.g. 990114c.



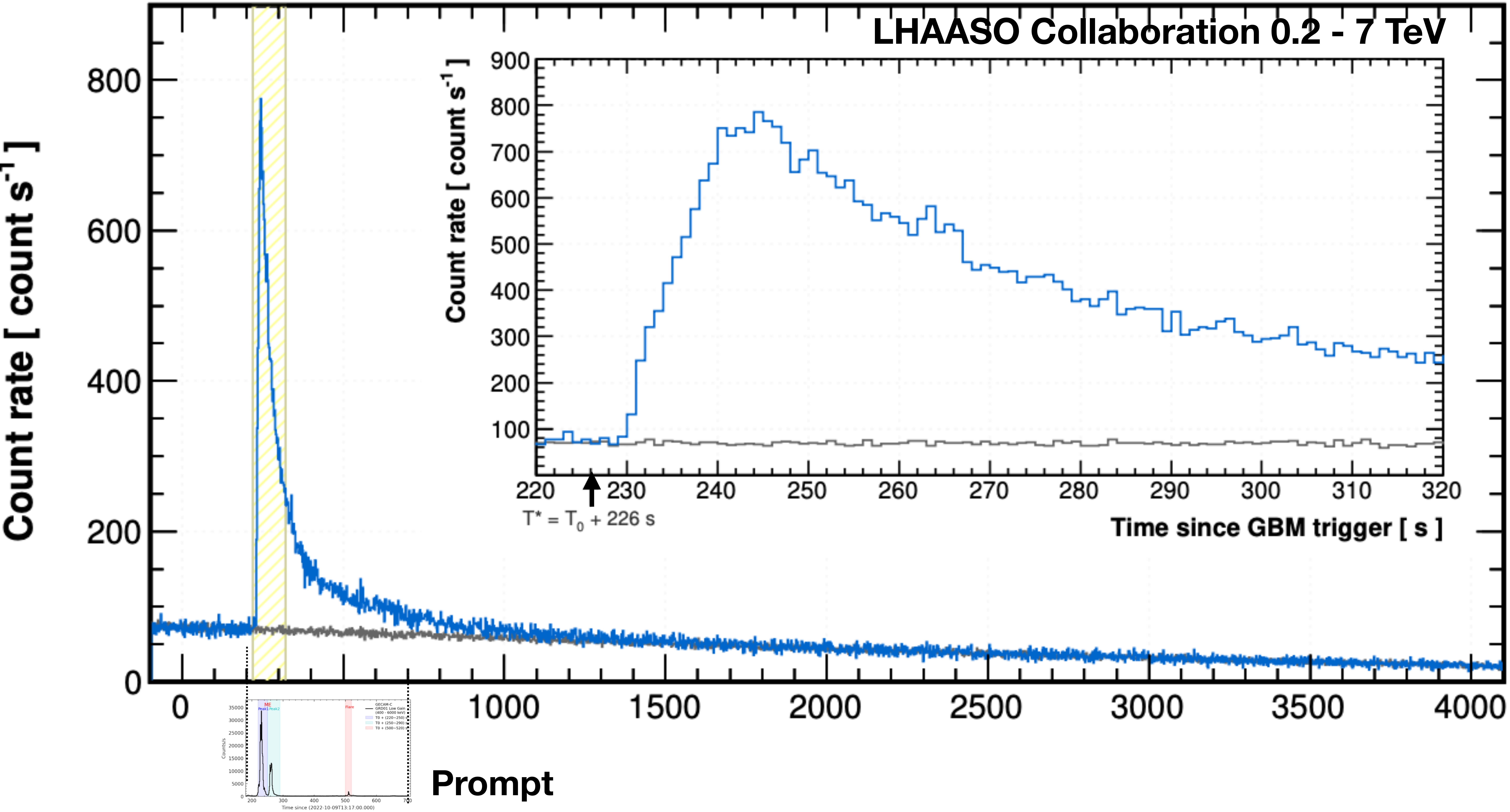
The Low-Energy Afterglow





O'Connor et al., 23

221009A TeV Afterglow



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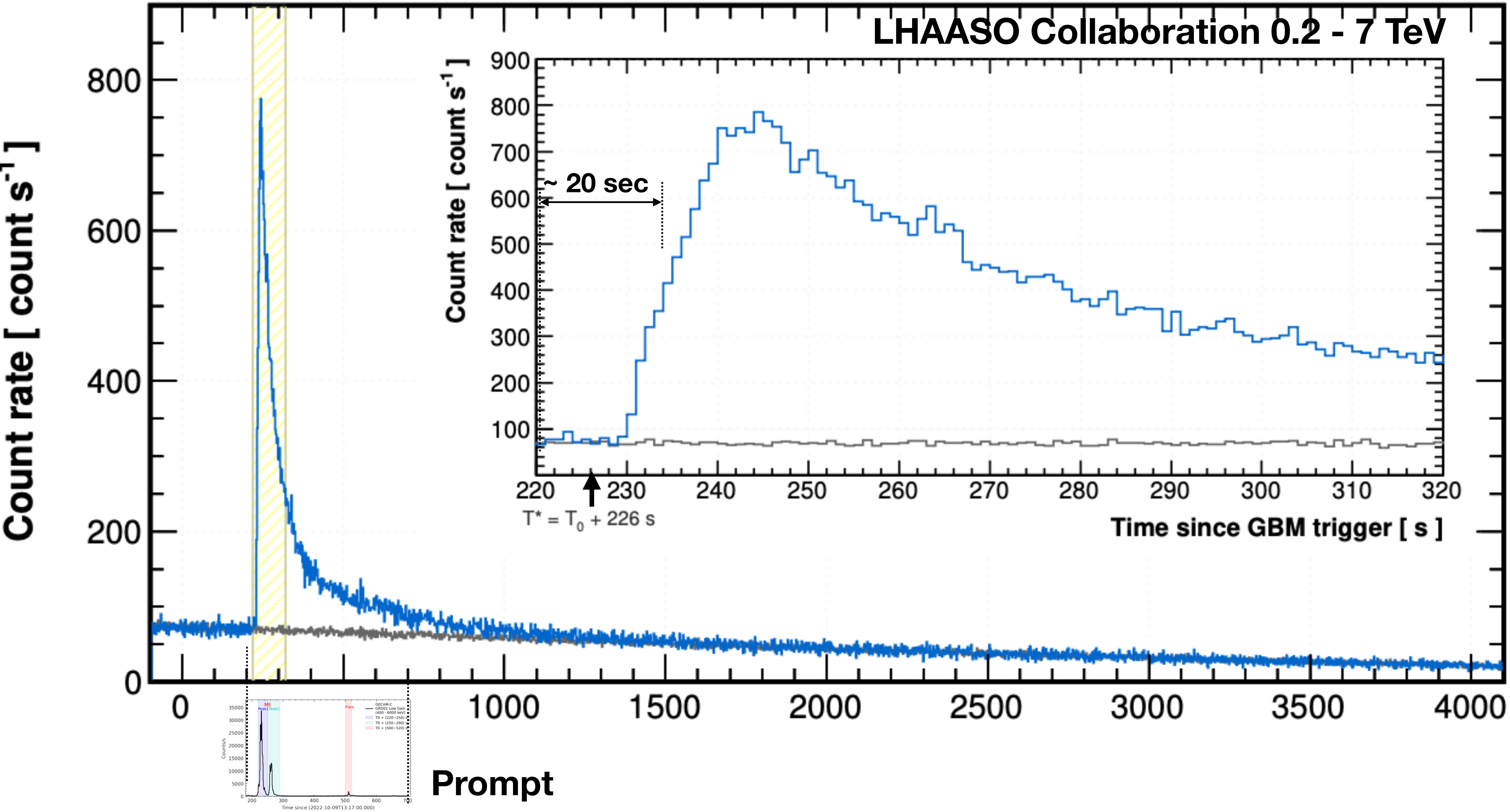
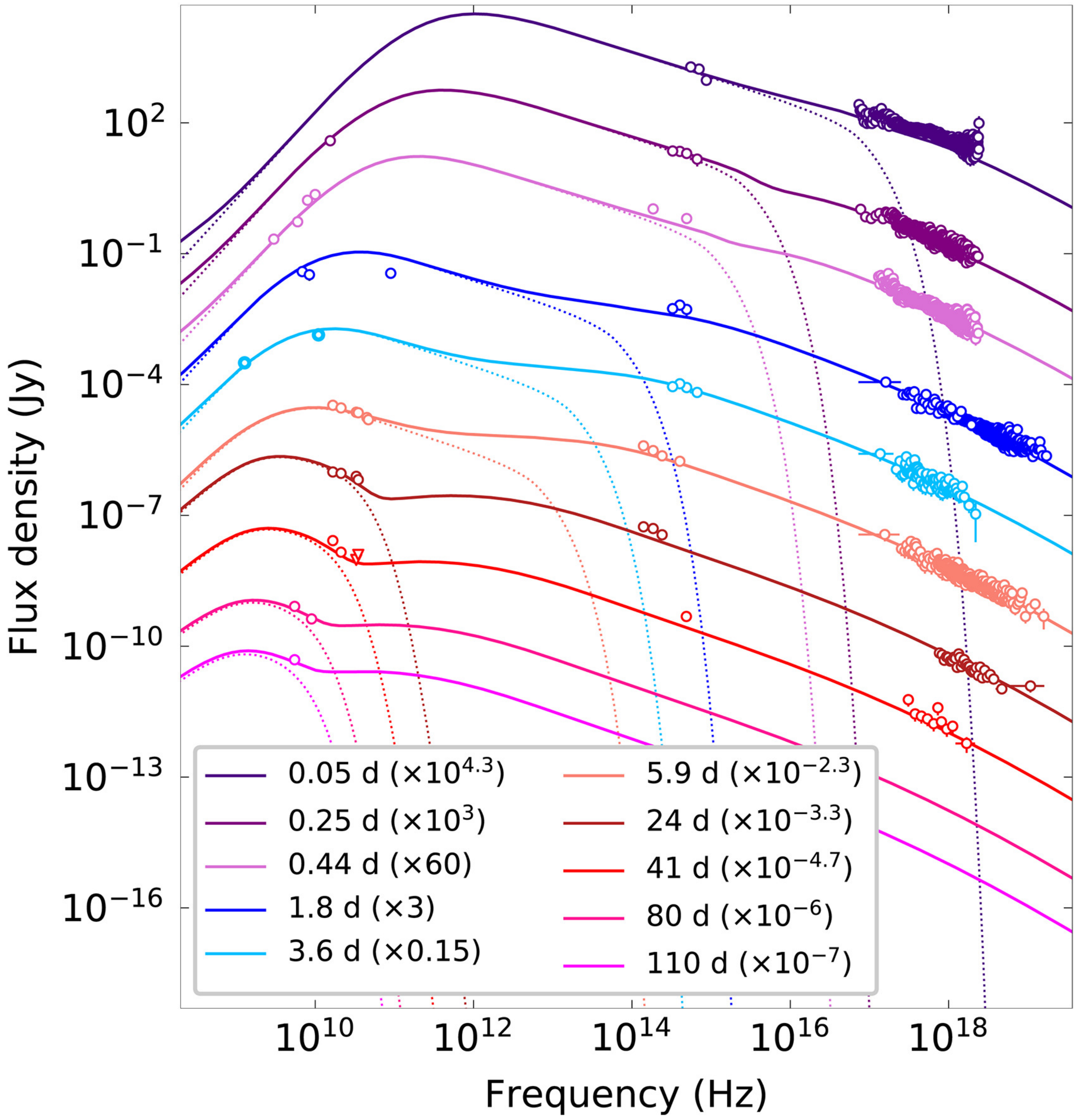


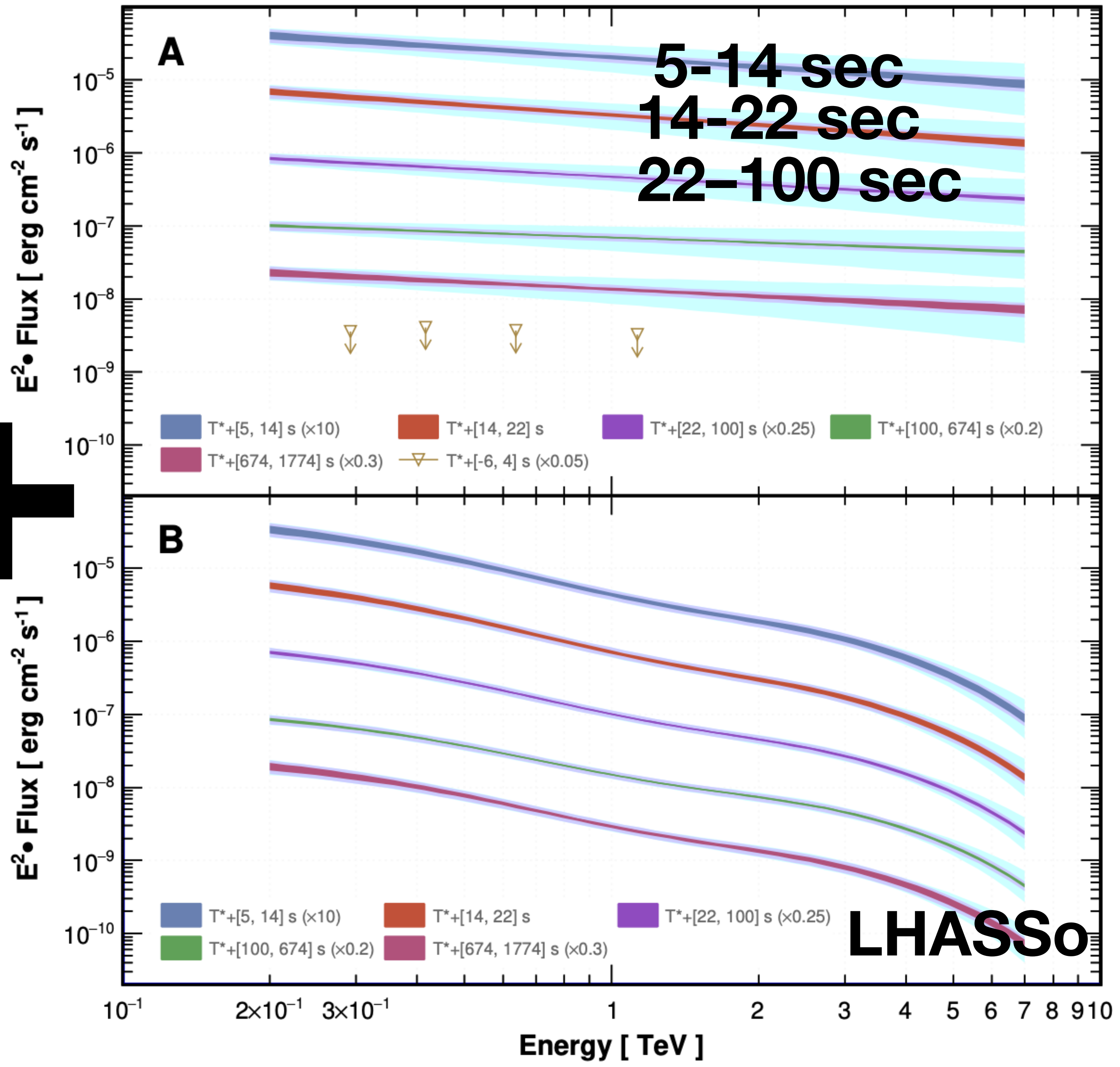
221009A TeV Afterglow - SSC (Within the “pair balance” model)

Derishev and Piran in prep.

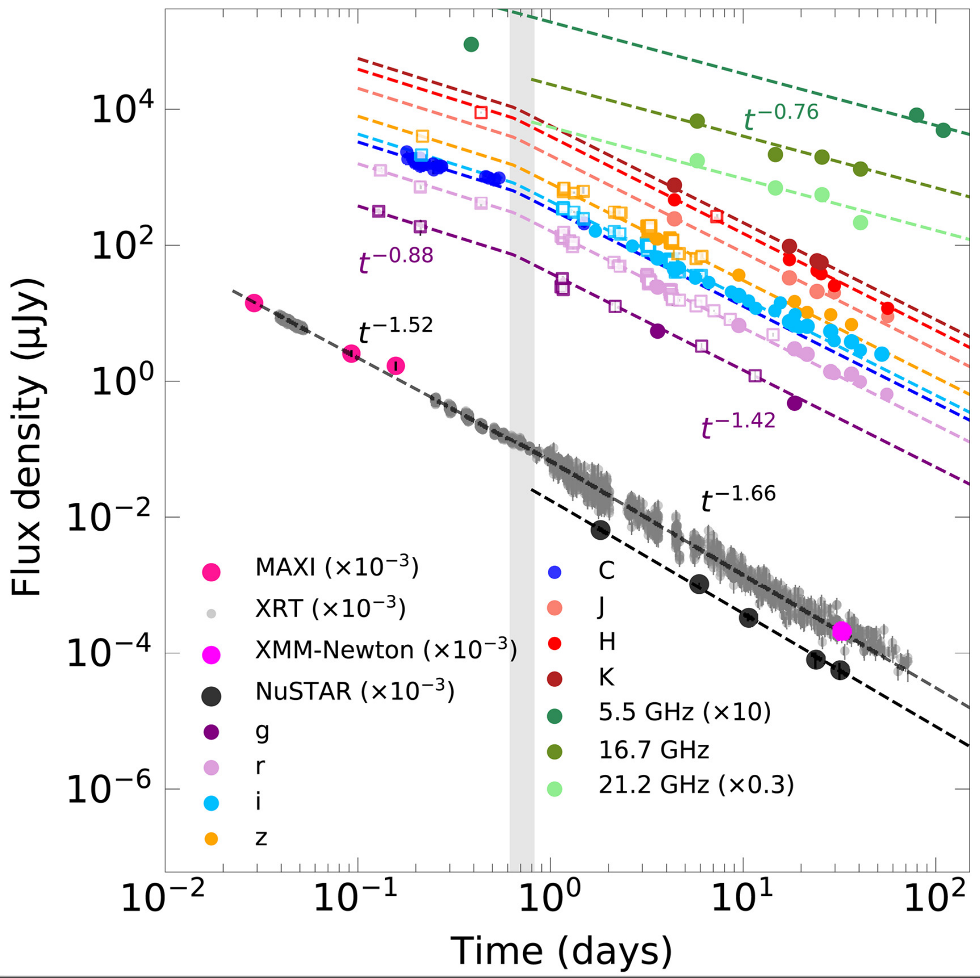


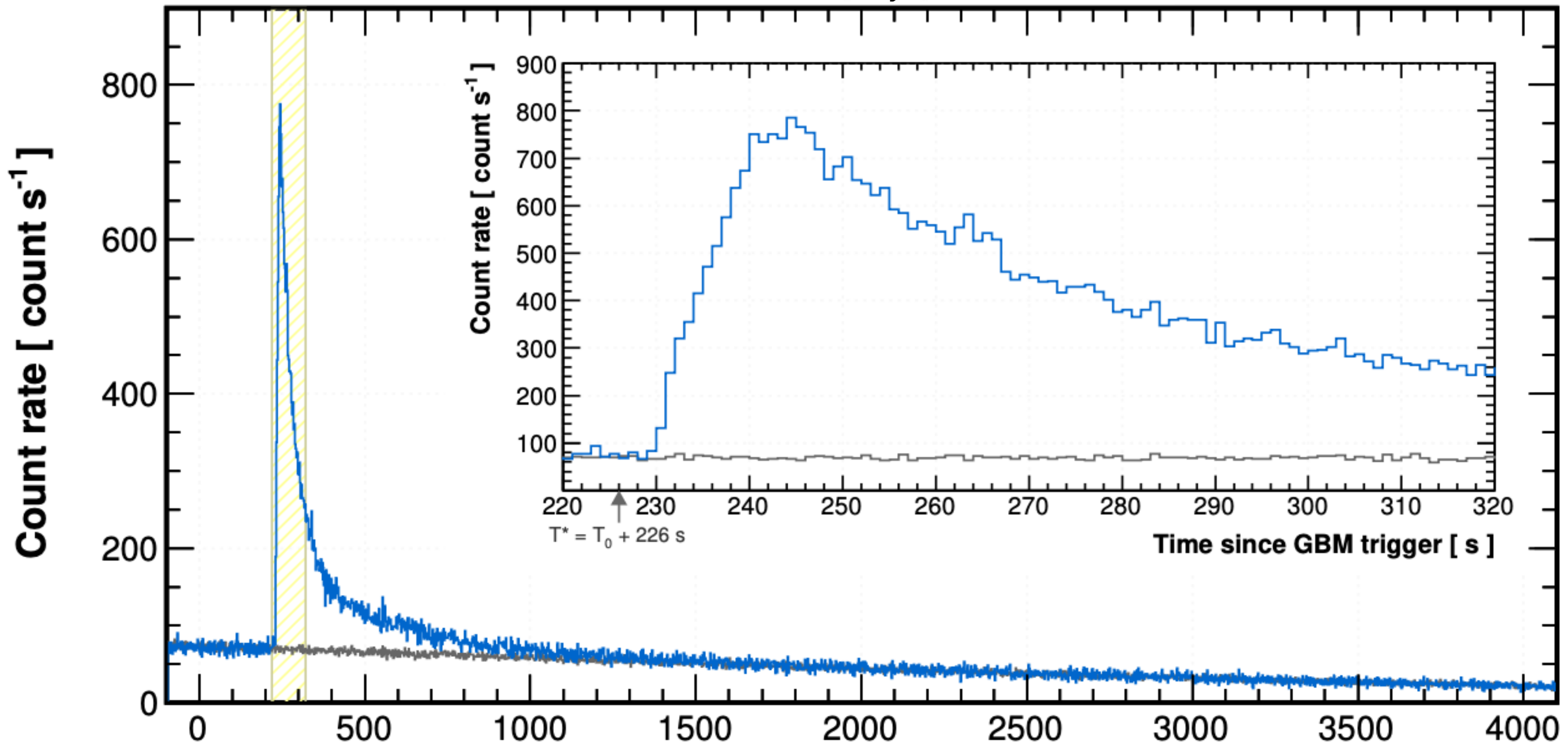
Radio- Optical - X-rays

+



TeV

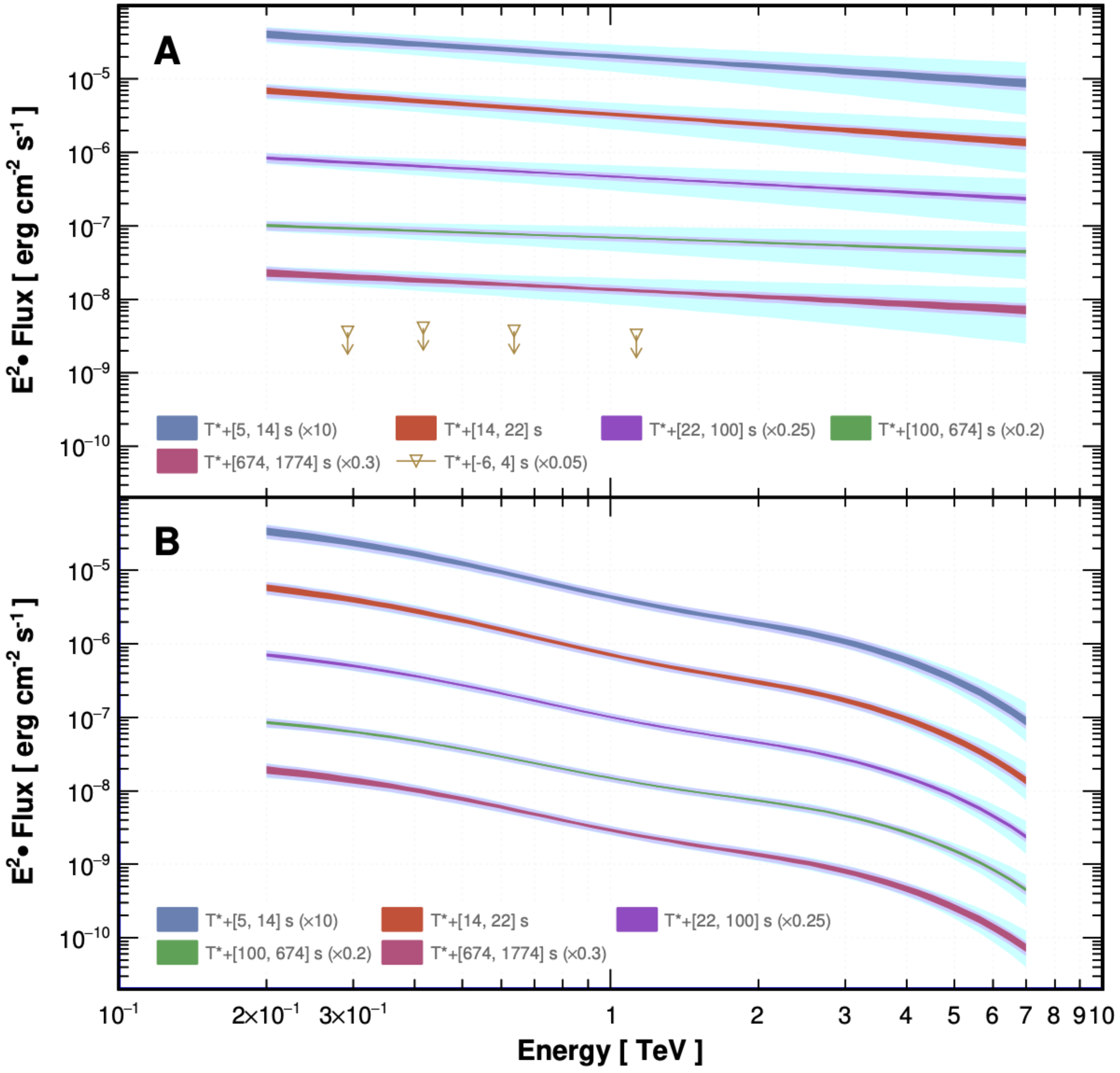


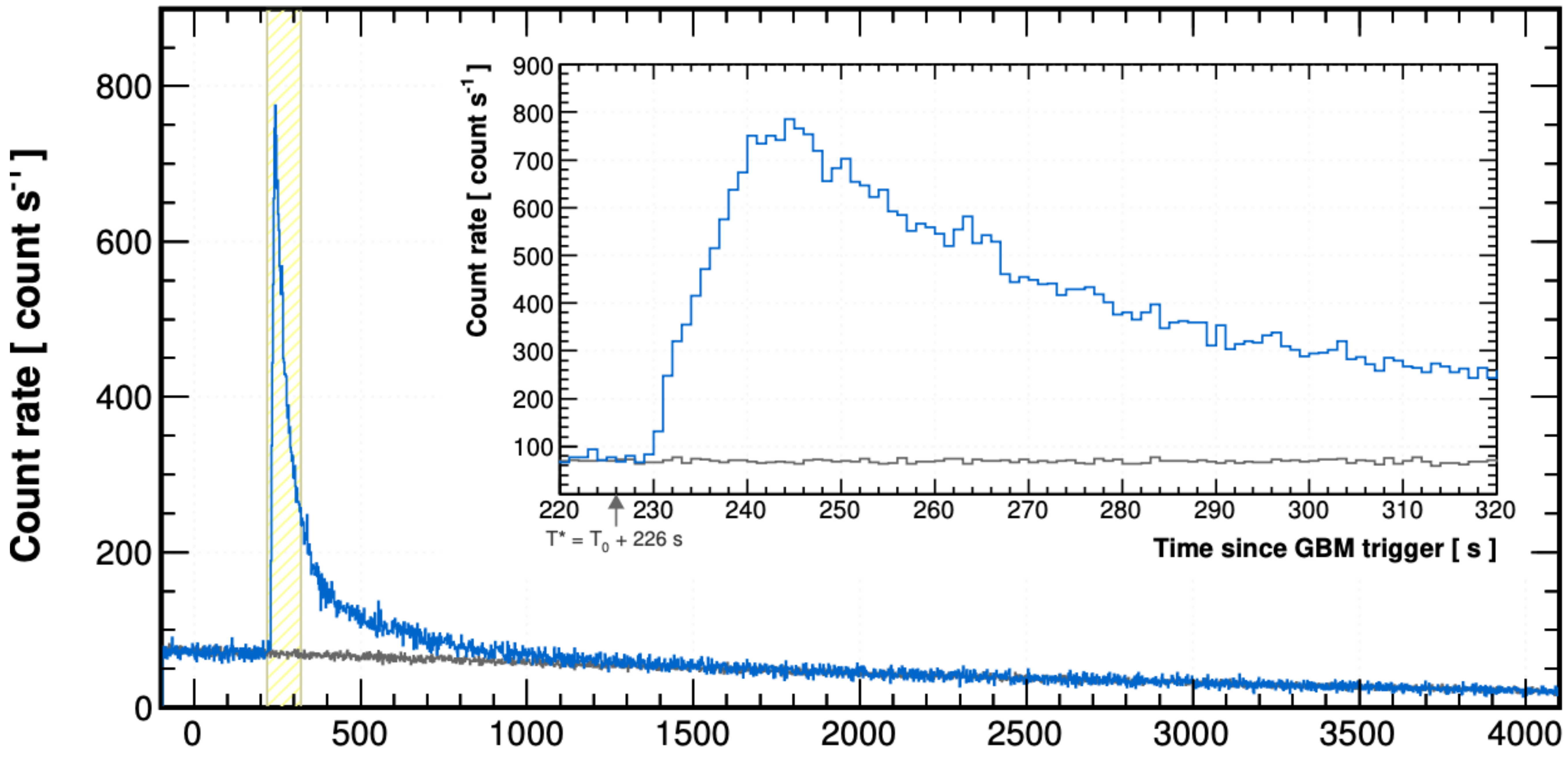


Ssc including Klein-Nishina and self absorption

Regular parameters but $E_{k,iso}$ ~ 10^{53} erg and not 10^{55} erg

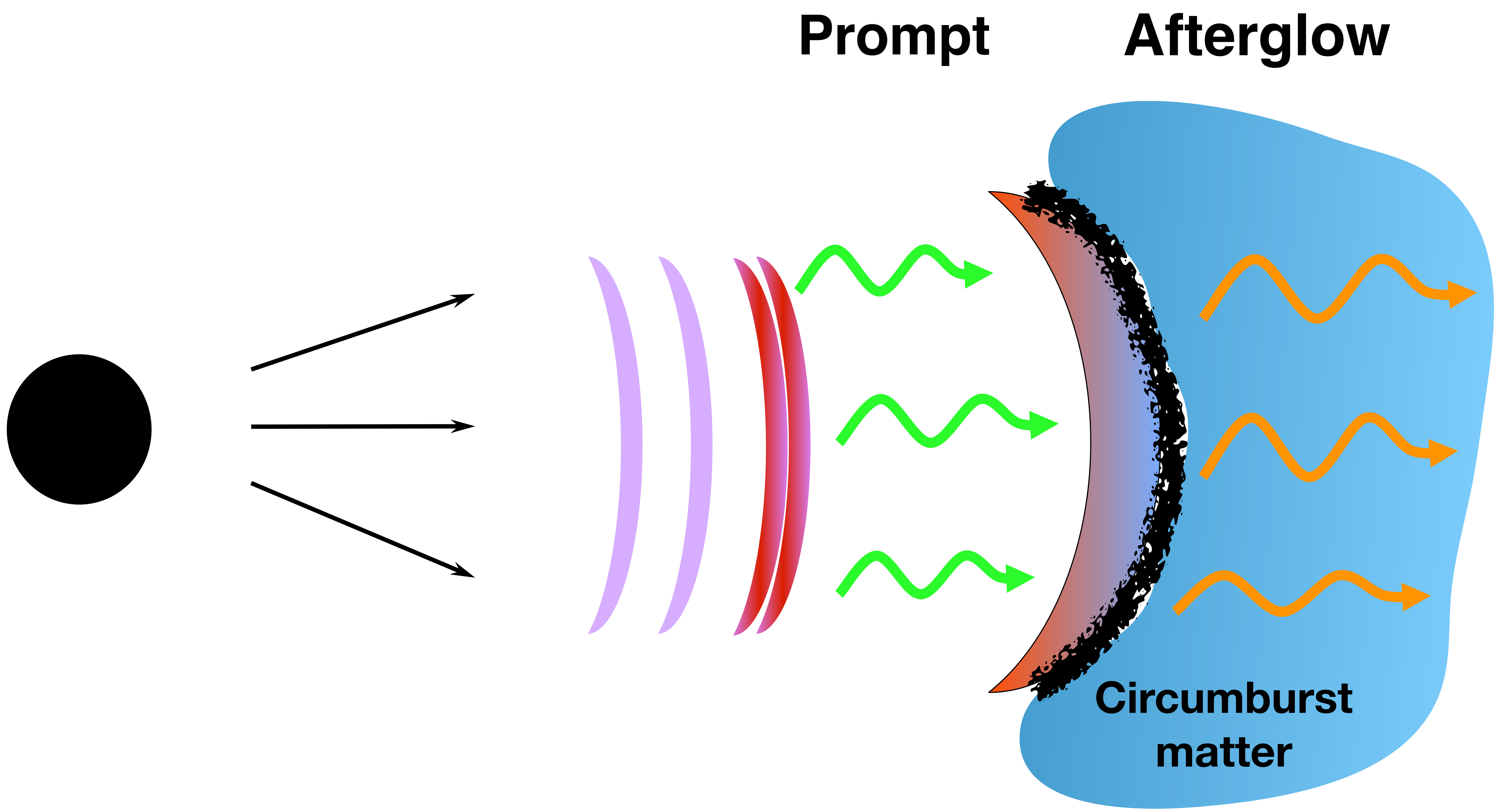
221009A TeV Afterglow - SSC (Within the “pair balance” model)



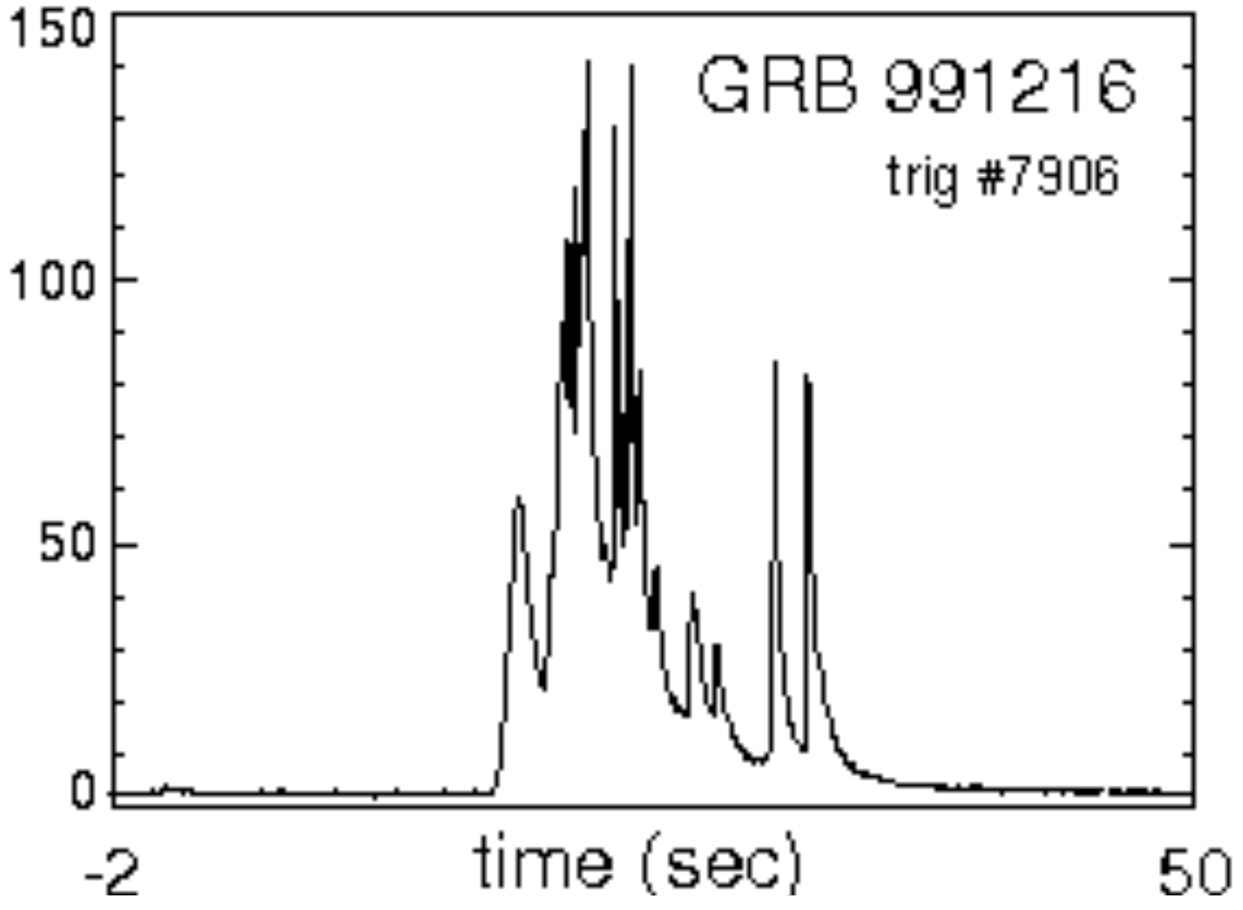


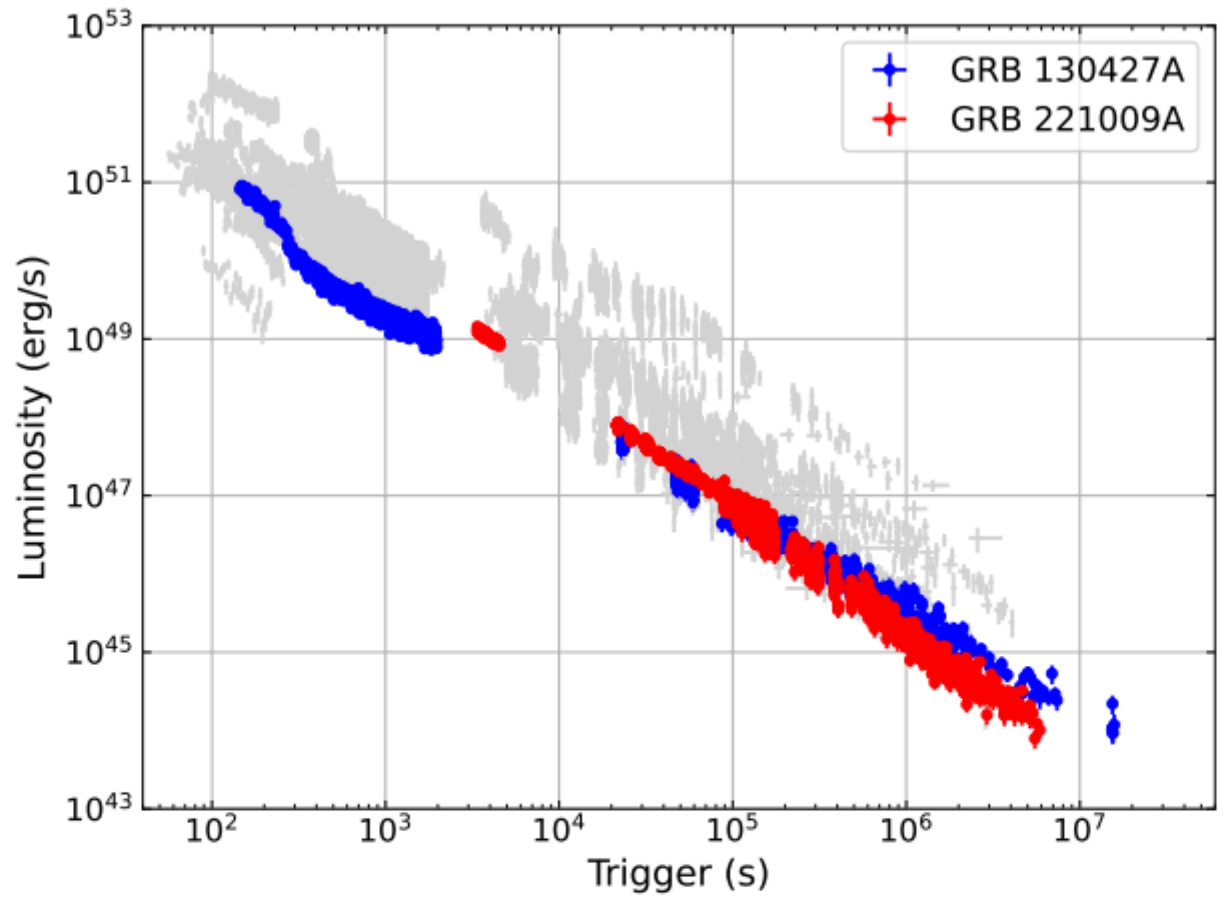
LHAASO Collaboration 0.2 - 7 TeV

The afterglow is smooth :(



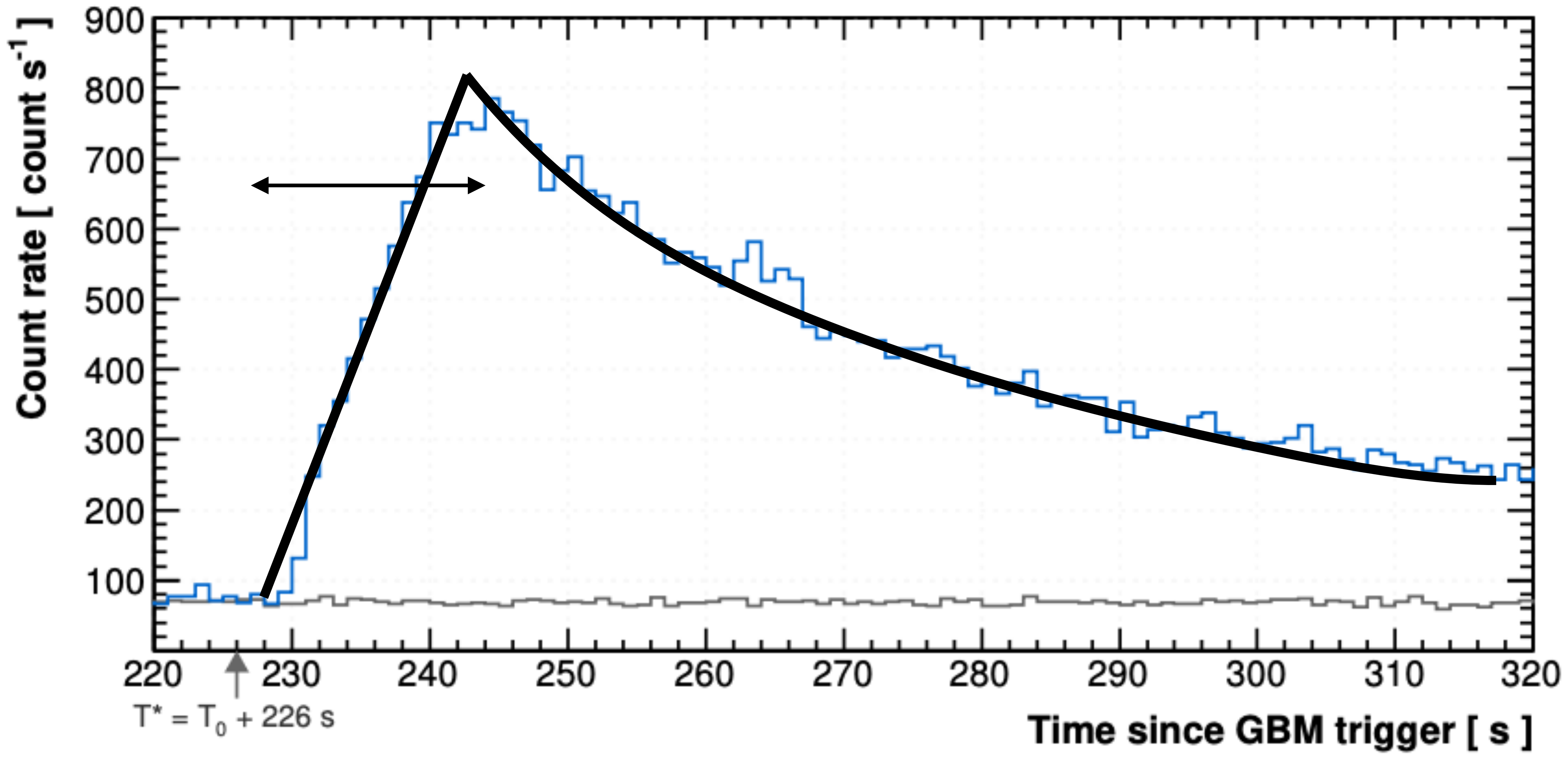
Prompt





Afterglow (from Lan et al., 23)

LIV limits from 221009A TeV Afterglow



The typical time from onset to the peak of the afterglow

$$t_{dec} \approx 6\ \text{sec}\ (1+z)\left(\frac{E_k/10^{53}\ \text{erg}}{n}\right)^{1/3}(\Gamma/300)^{-8/3}$$

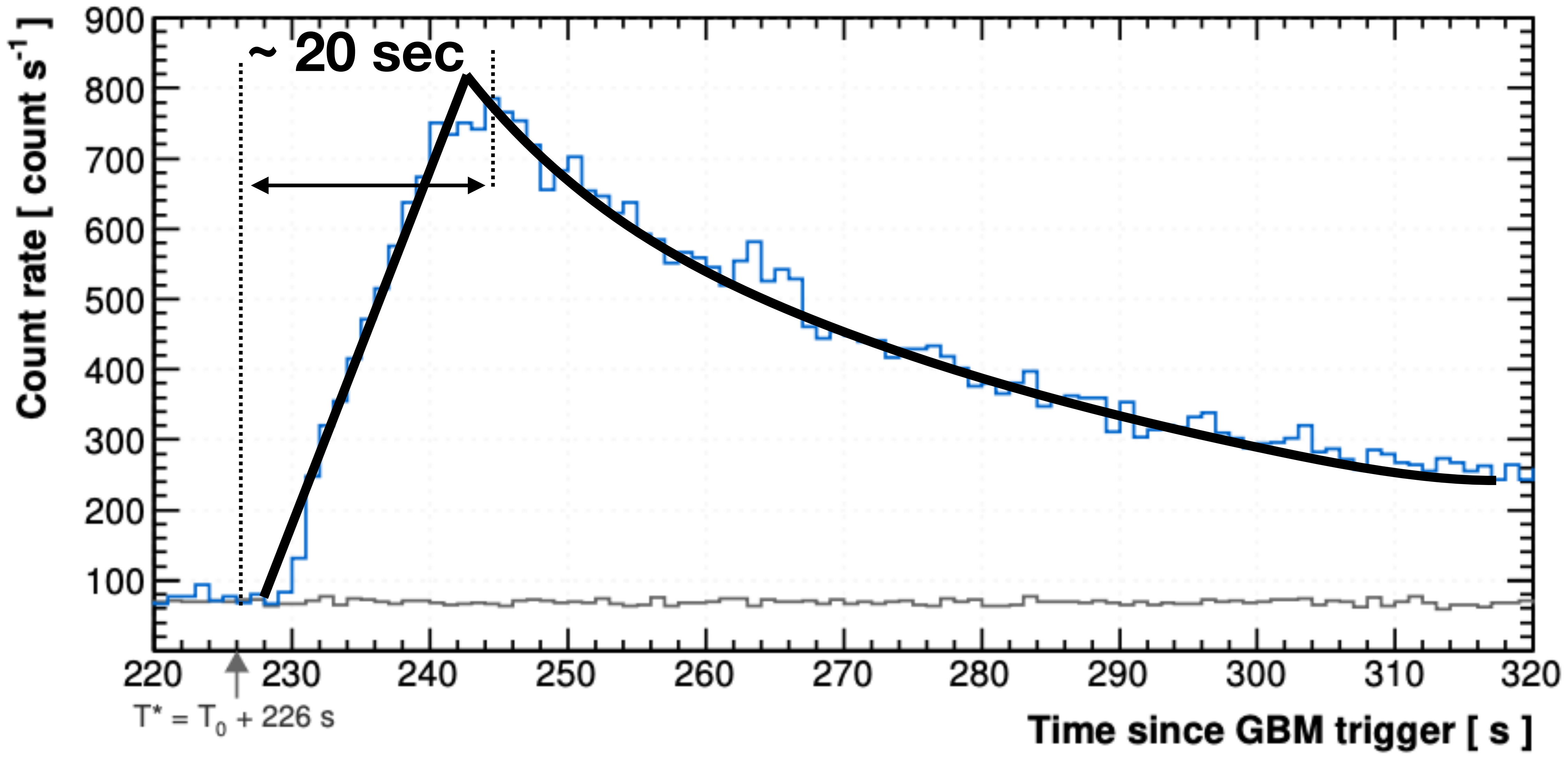
Kinetic Energy (E_k)

Lorentz factor (Γ)

Red shift (z)

Surrounding density (n)

LIV limits from 221009A TeV Afterglow



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Kinetic Energy

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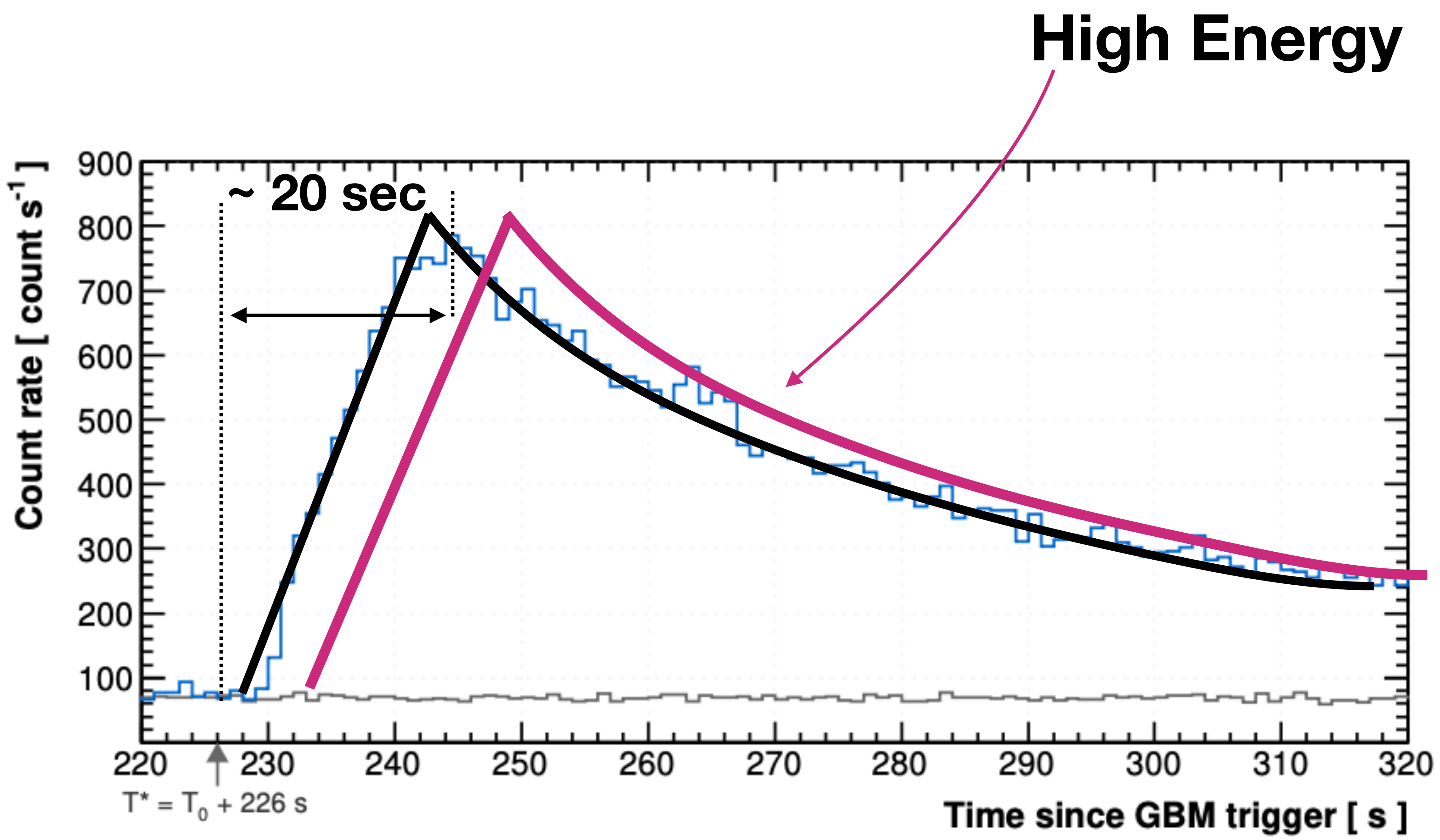

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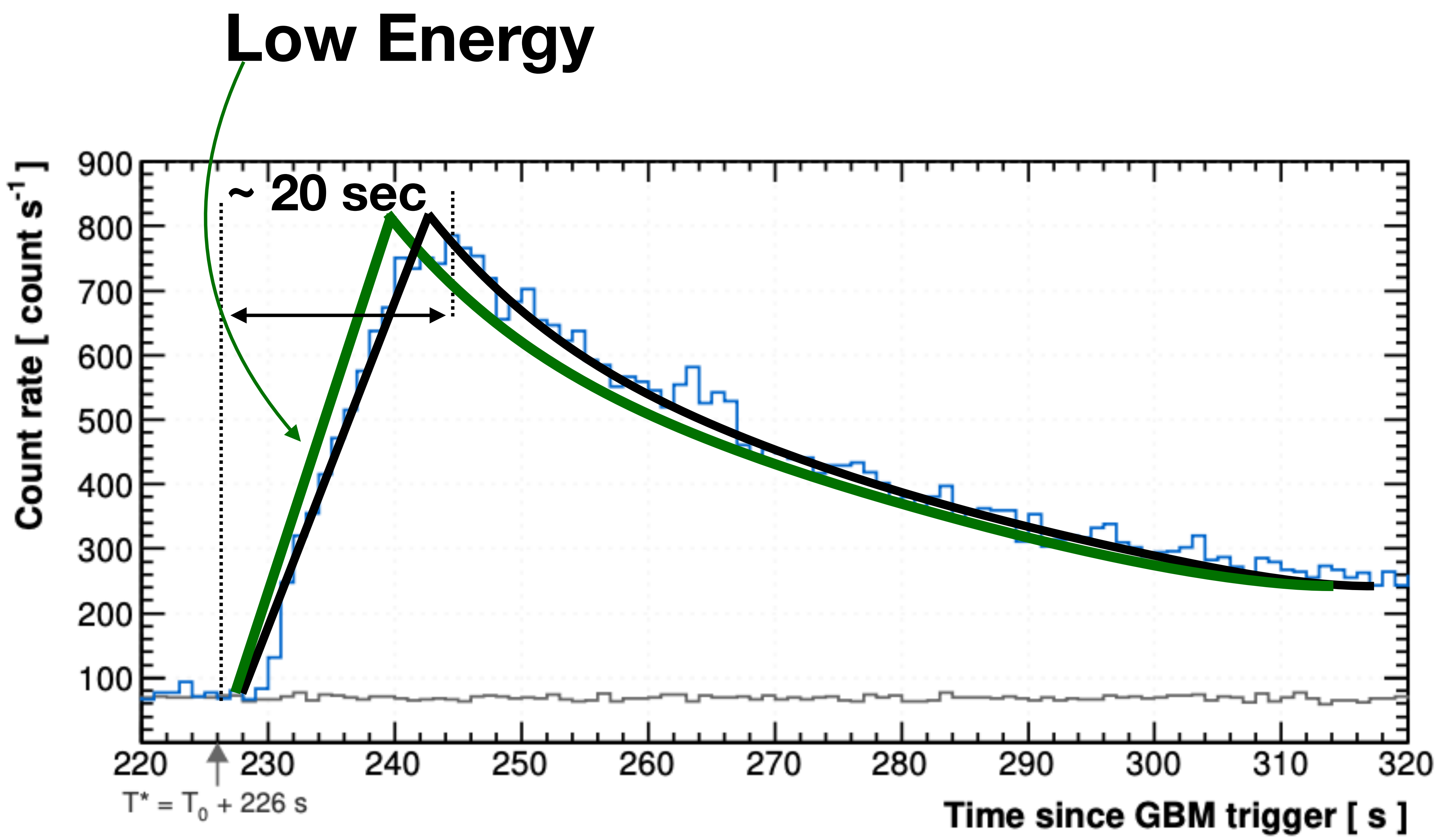

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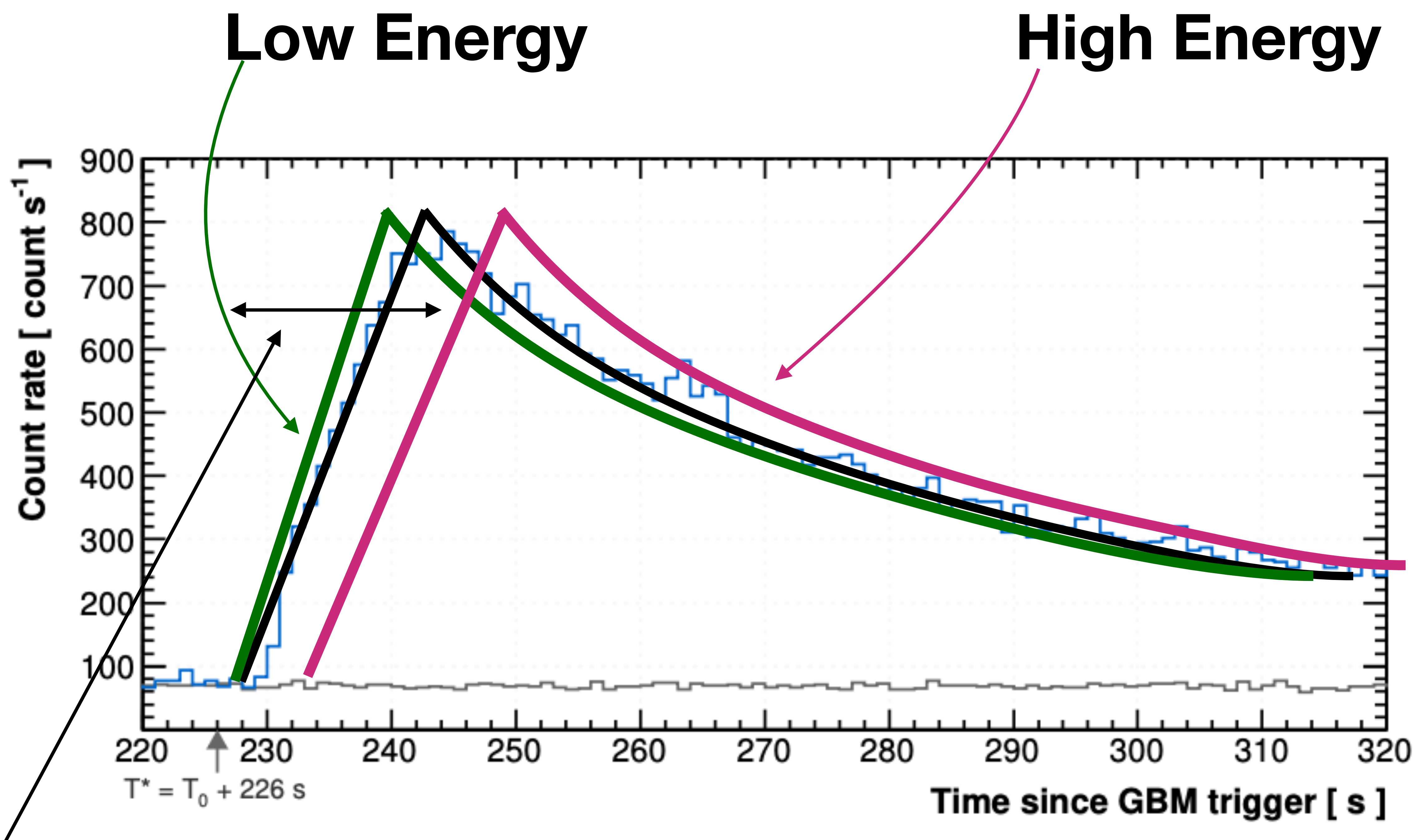


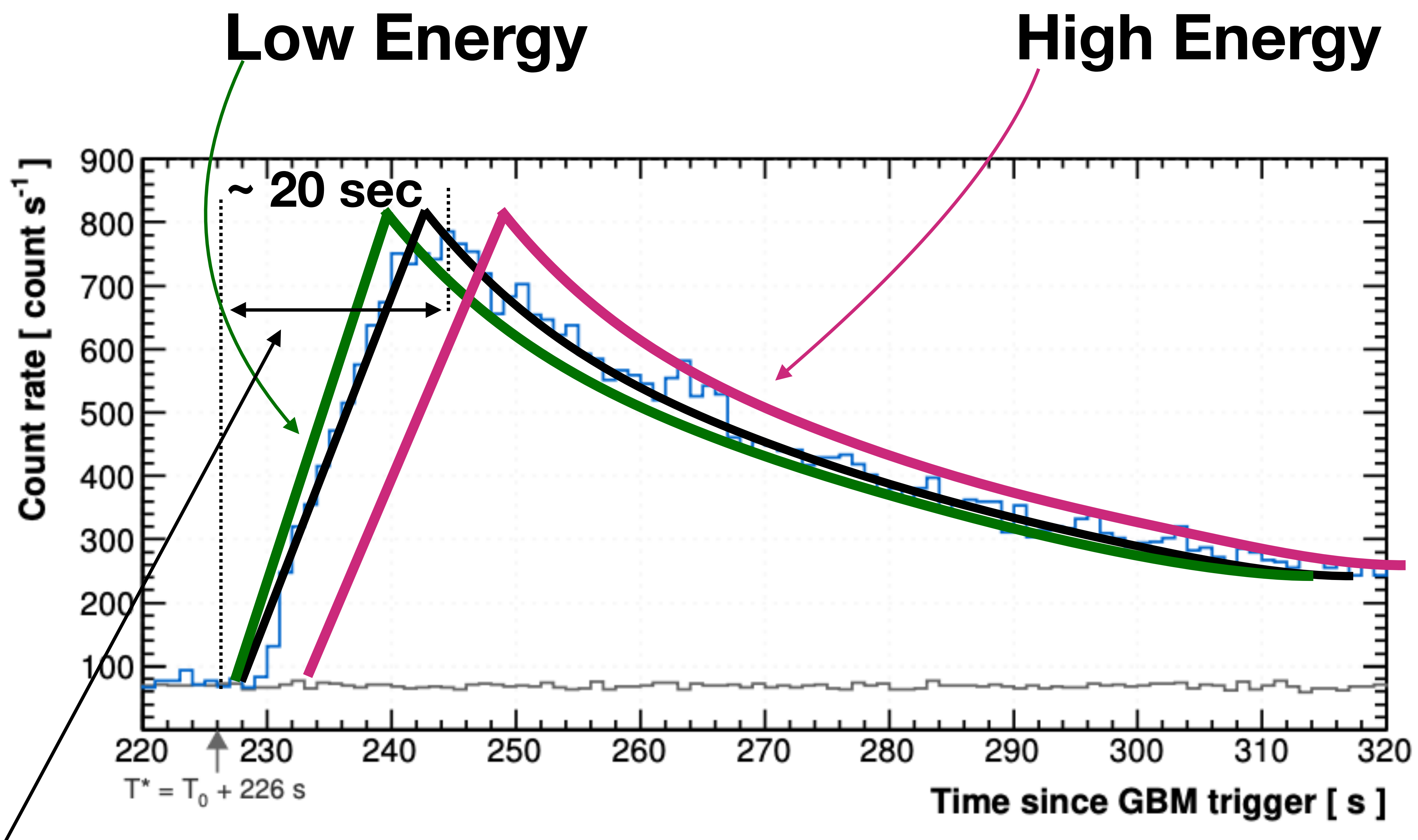
A constant spectral shape during the first 20-40 seconds
=> Strong LIV limits

$$20\ \mathrm{sec} \approx \pm \frac{d}{c}\left(\frac{E}{\xi_n m_{pl}}\right)^n \approx 2\ \mathrm{sec}\ 10^{-16(n-1)}\left(\frac{7\ \mathrm{TeV}}{\xi_n TeV}\right)^n \qquad \begin{cases} \xi_1 > 0.5 \\ \xi_2 > 10^{-8} \end{cases}$$

For a source at z=0.15

Inconsistent with LIV "solution" for an 18 TeV photon from z=0.151 (EBL)

LIV limits from 221009A TeV Afterglow



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$$\begin{cases} \xi_1 > 0.5 \\ \xi_2 > 10^{-8} \end{cases}$$

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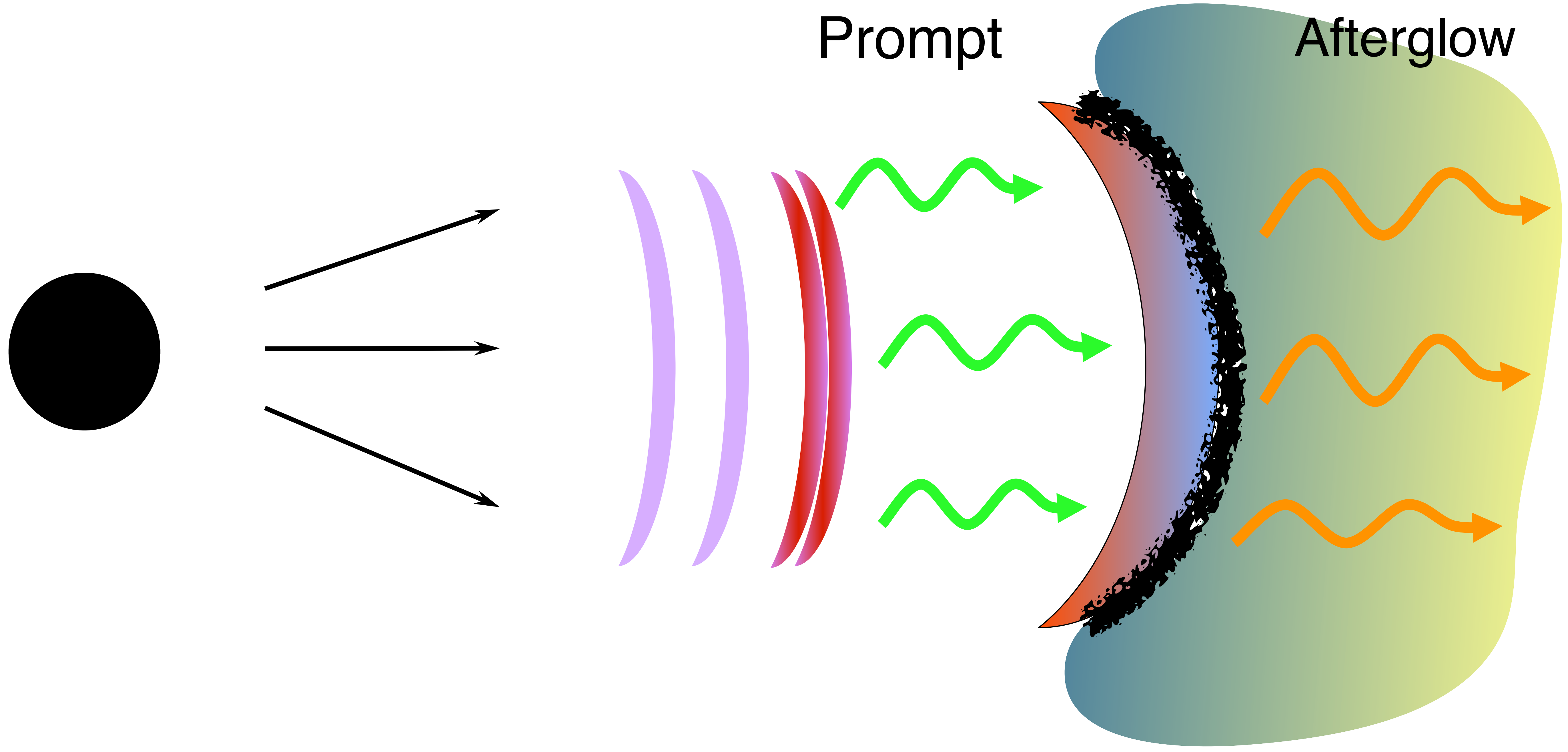
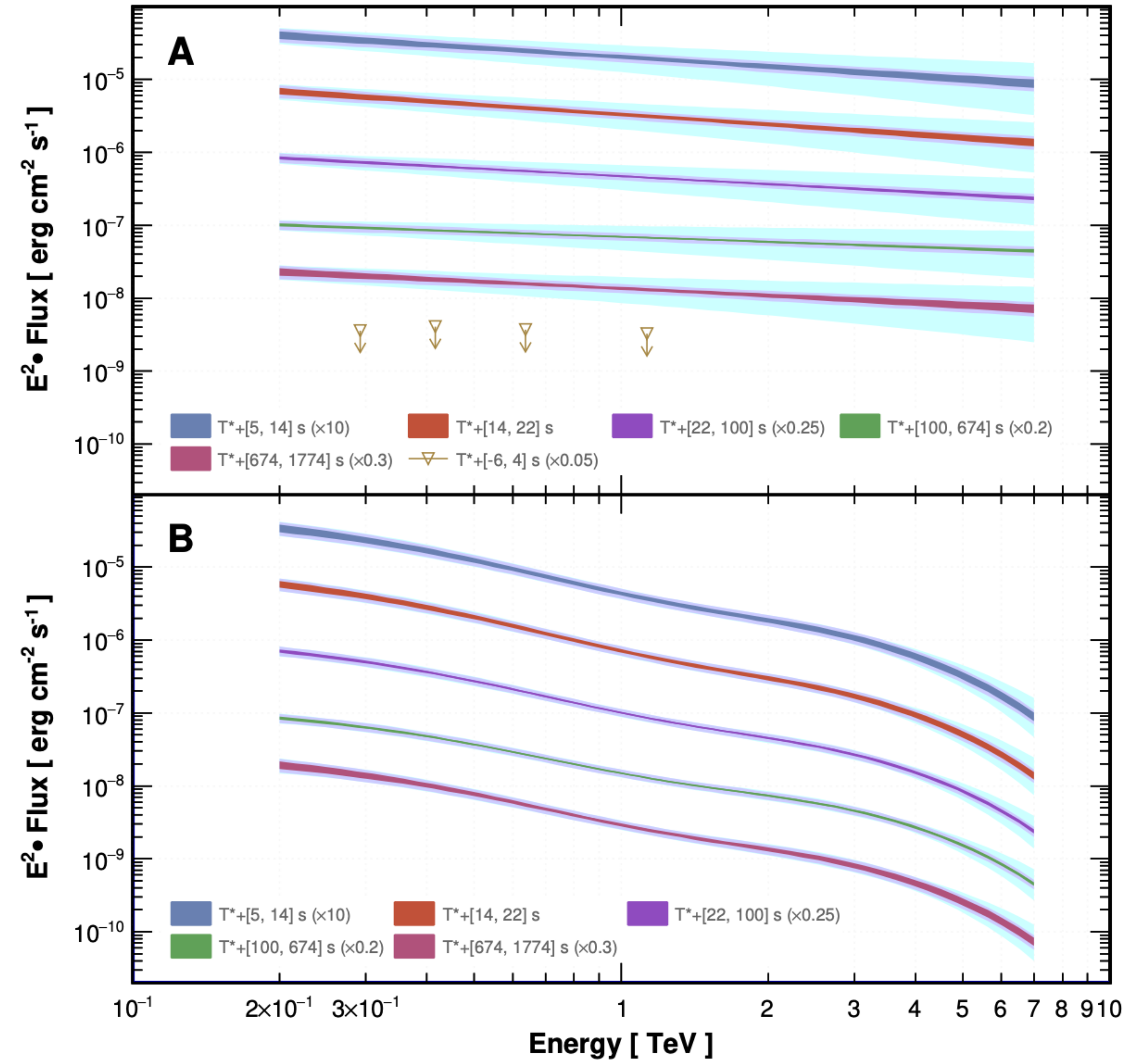
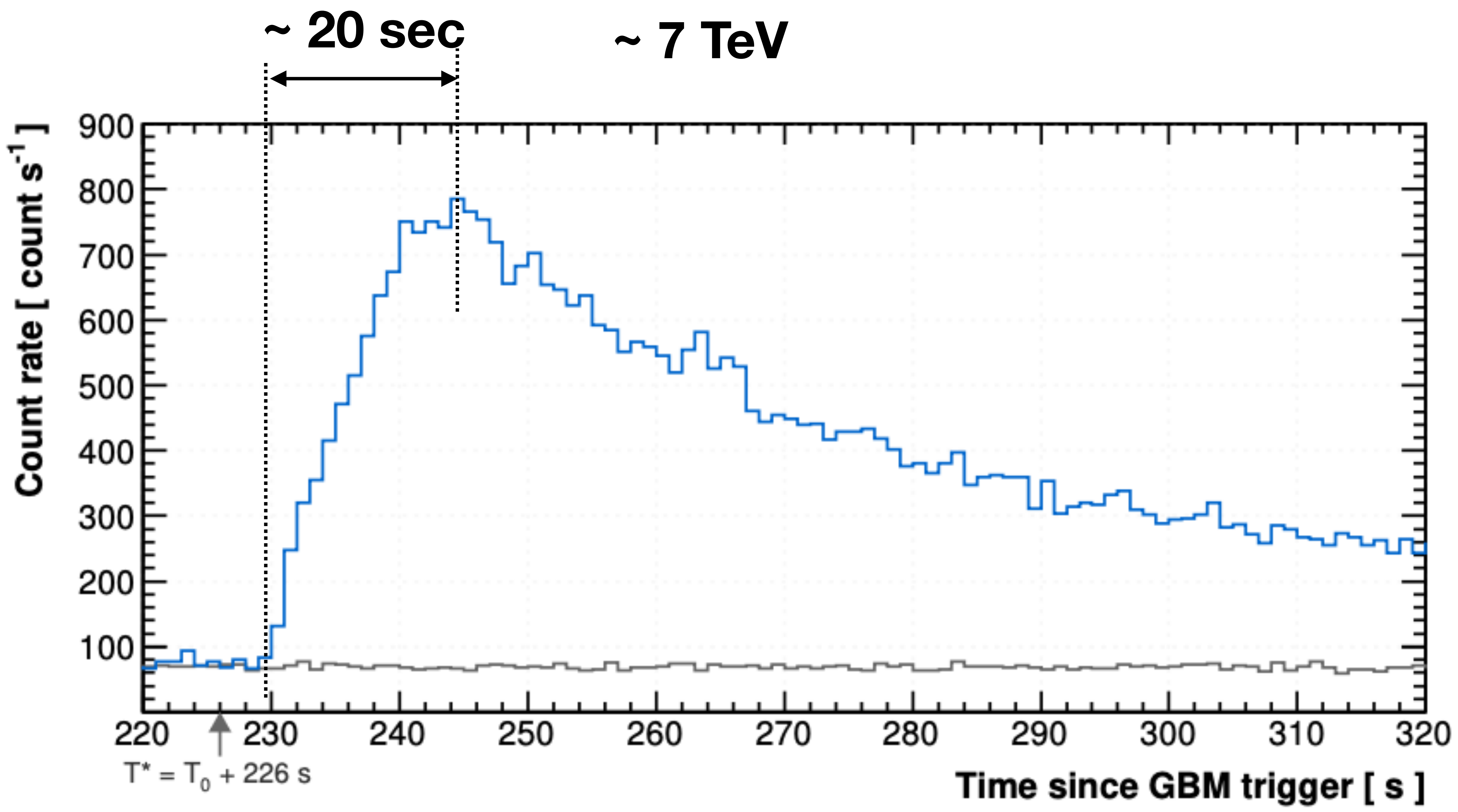
Intrinsic Spectral Evolution?

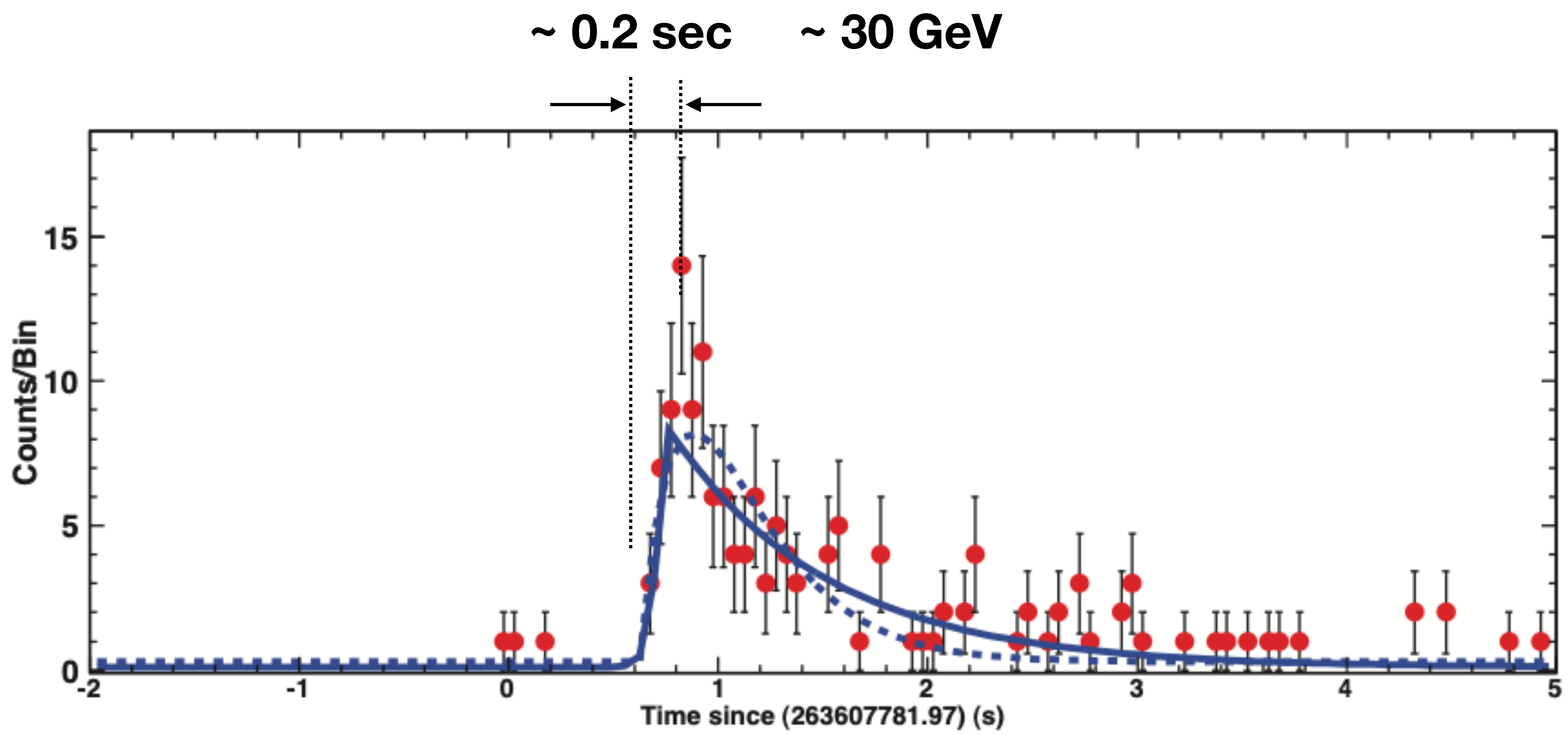


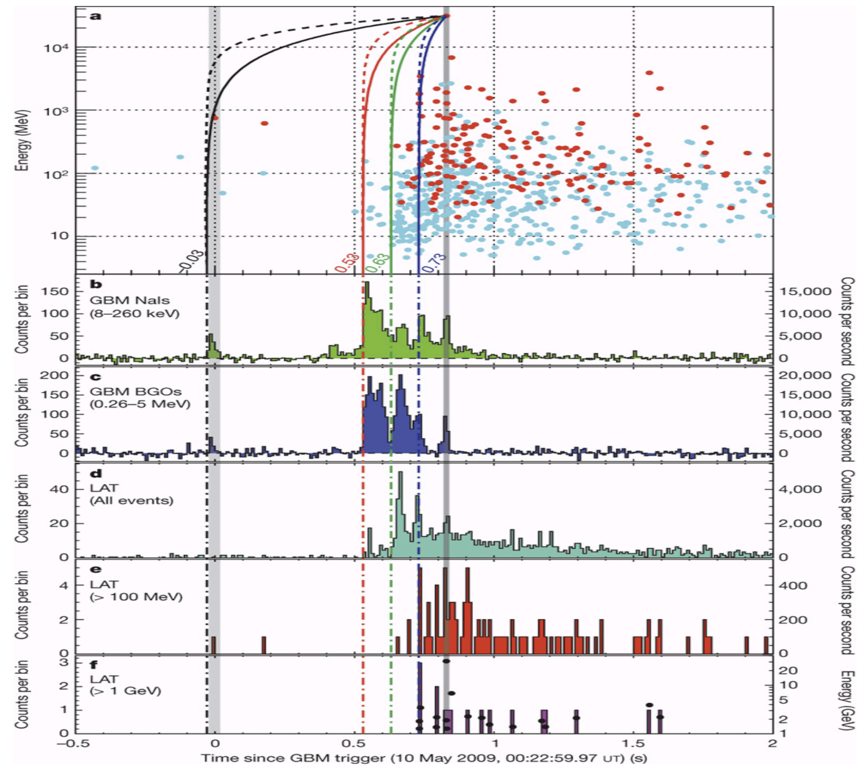


- Intrinsic spectral variations are mostly a problem for a positive signal of spectral evolution
- It is unlikely that intrinsic spectral evolution and LIV will combine to give a constant spectrum

221009A vs 090510







This was also an afterglow (Ghirlanda et al., 2010)

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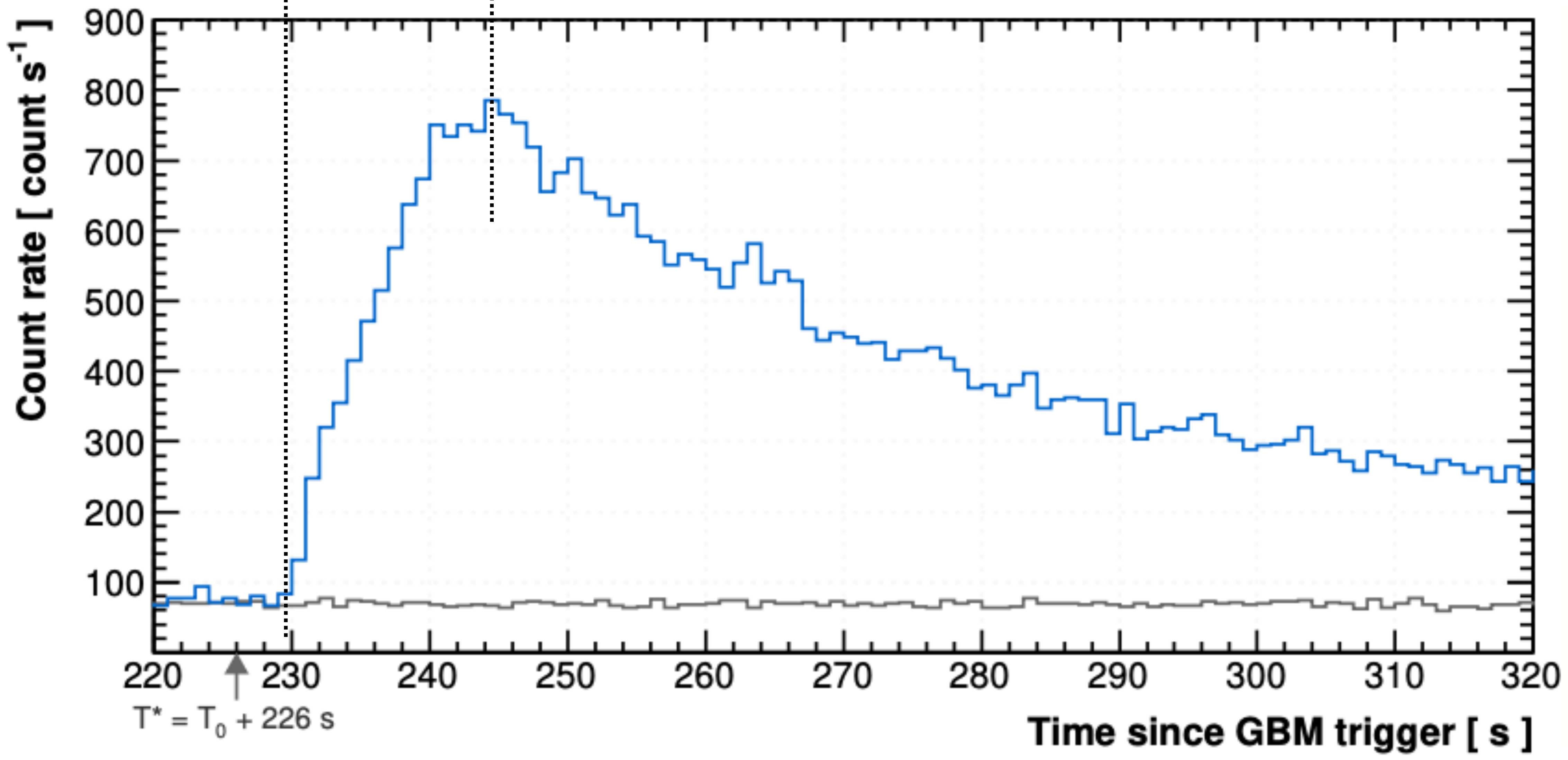
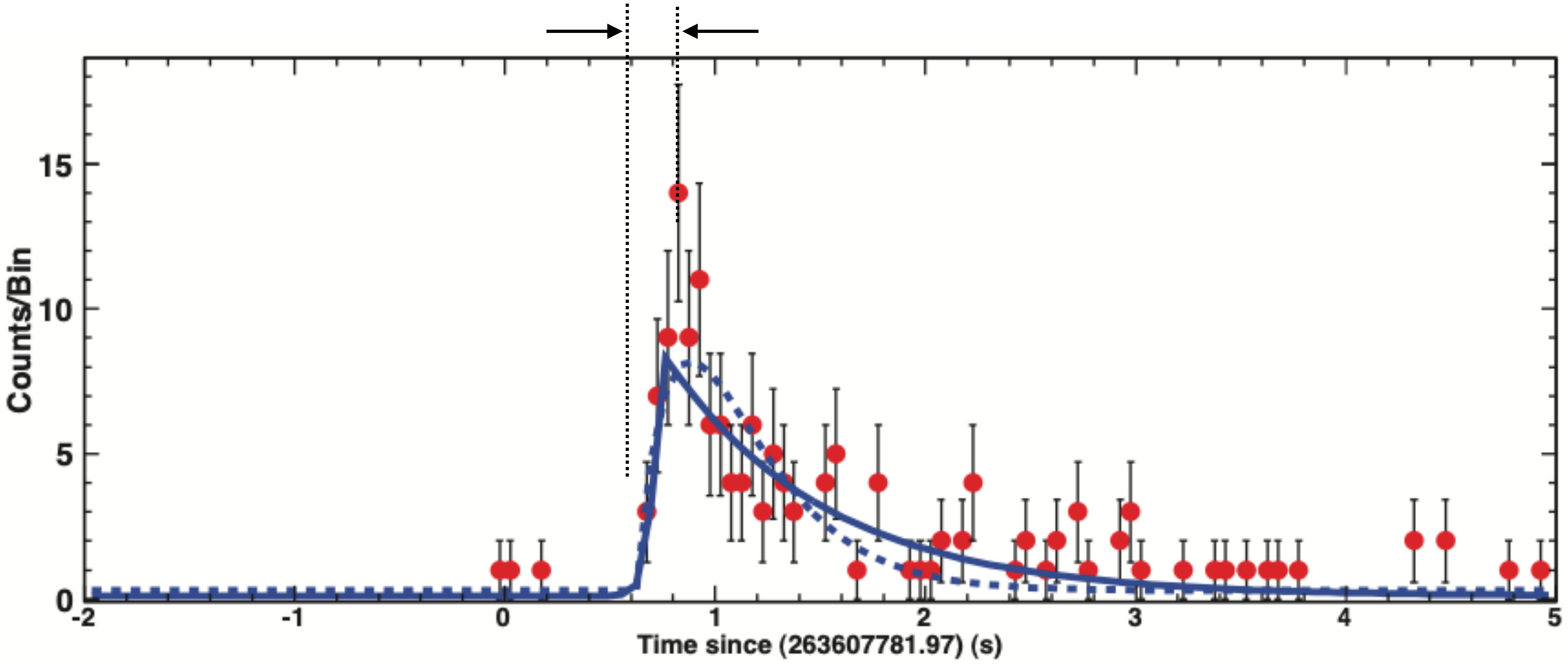
530	< 299	start of main < 1 MeV emission	0.1	1	> **3.42**	> 5.06
630	< 199	start of > 100 MeV emission	100	1	> **5.12**	> 6.20
730	< 99	start of > 1 GeV emission	1000	1	> **10.0**	> 8.79
—	< 10	association with < 1 MeV spike	0.1	±1	> **102**	> 27.7
—	< 19	if 0.75 GeV γ is from 1st spike	0.1	−1	> **1.33**	> 0.54
$\|\Delta t/\Delta E\|$ < 30 ms/GeV		lag analysis of all LAT events	—	±1	> **1.22**	—

221009A vs 090510

~ 20 sec ~ 7 TeV



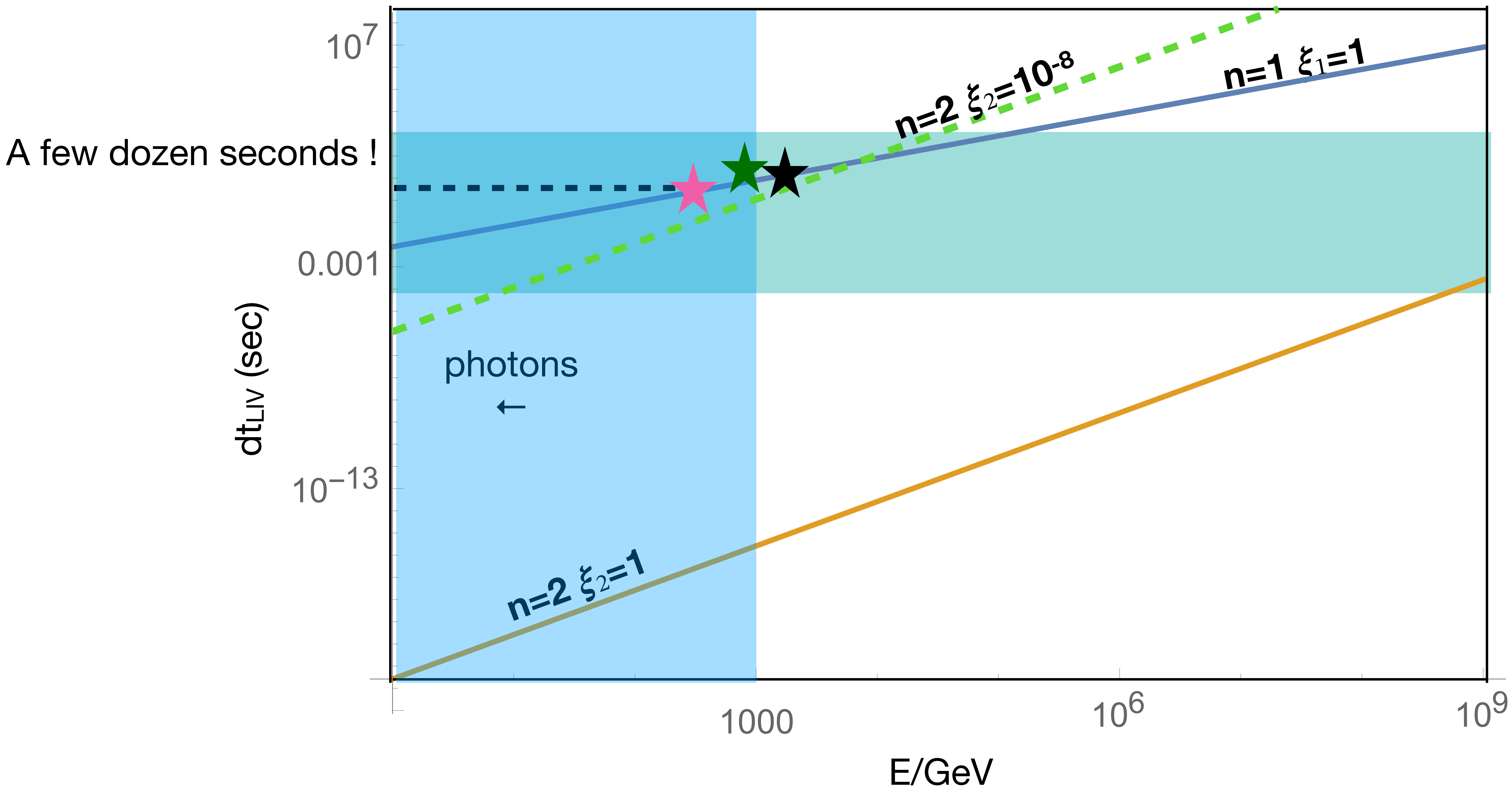
~ 0.2 sec ~ 30 GeV



$$\frac{20}{0.2} \approx \frac{7}{0.03}$$

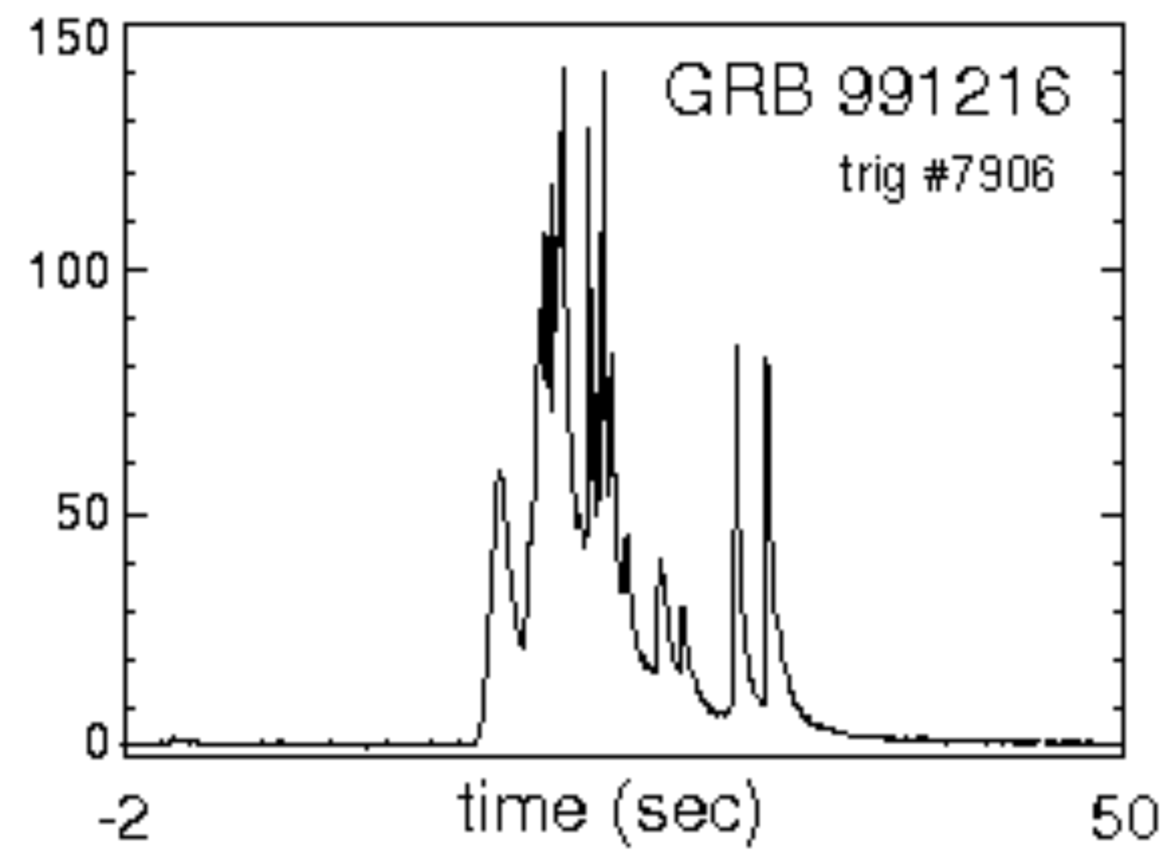
Comparable LIV limits for n=1.
Much better limits for n=2

We should also take into account that 221009A was about 6 times nearer



A few dozen seconds !
10^7
0.001
10^{-13}
dt_{LIV} (sec)
photons
←
n=2 ξ_2=10^{-8}
n=1 ξ_1=1
n=2 ξ_2=1
1000
10^6
10^9
E/GeV

LIV limits from the prompt Phase



- $\delta t = \max\{\delta t_{instrument}, \delta t_{flux}, \delta_{tintrinsic}\} \gtrsim$ a few msec
- $E_{max} \overset{?}{\lesssim}$ 100 MeV

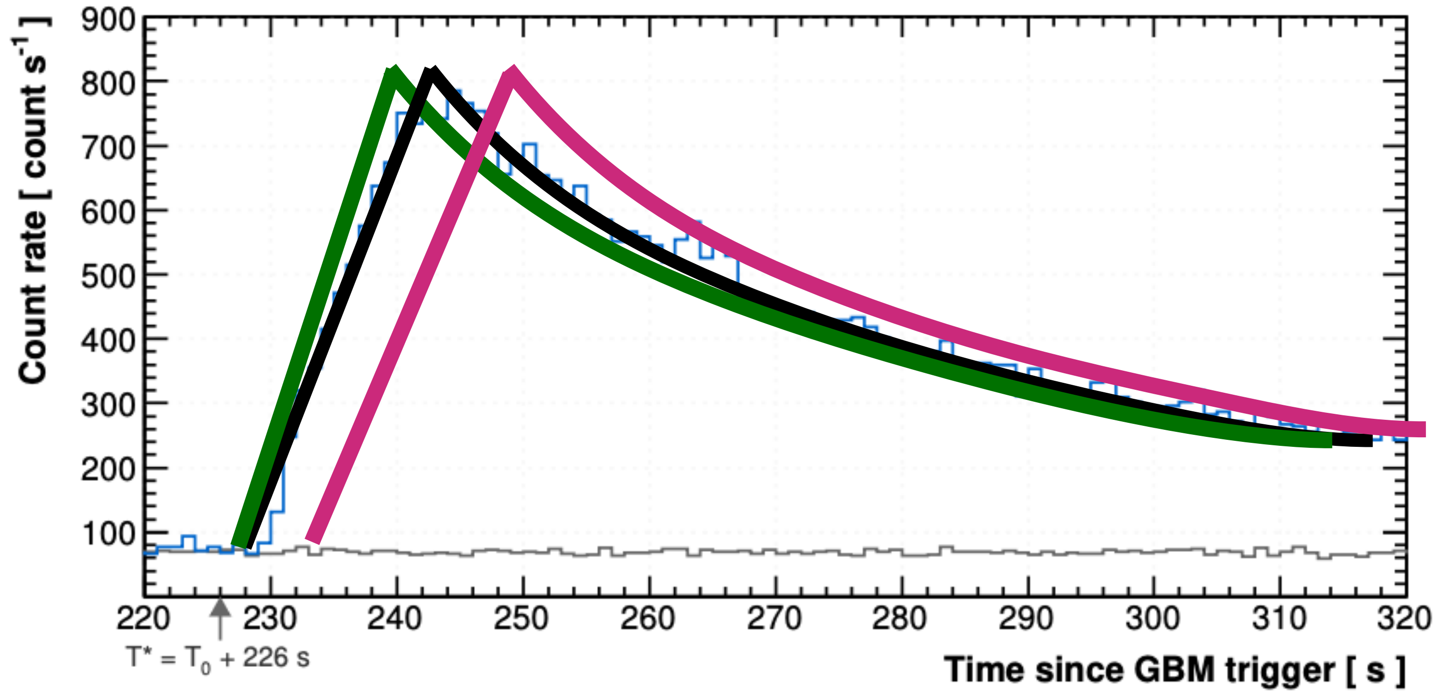
$$dt_{LIV} \approx \pm \frac{d}{c}\left(\frac{E}{\xi_n m_{pl}}\right)^n \approx 0.01\text{sec}\ 10^{-19(n-1)}\left(\frac{E}{\xi_n GeV}\right)^n$$

- Prompt emission time of flight limits will be typically below $0.1M_{pl}$ or lower.

LIV and TeV

- <u>GRB TeV emission is Afterglow</u> (Derishev & Piran 2019) (KumAr & Barniyol Duran 2010; Ghisellini et al., 2010 for GeV emission).

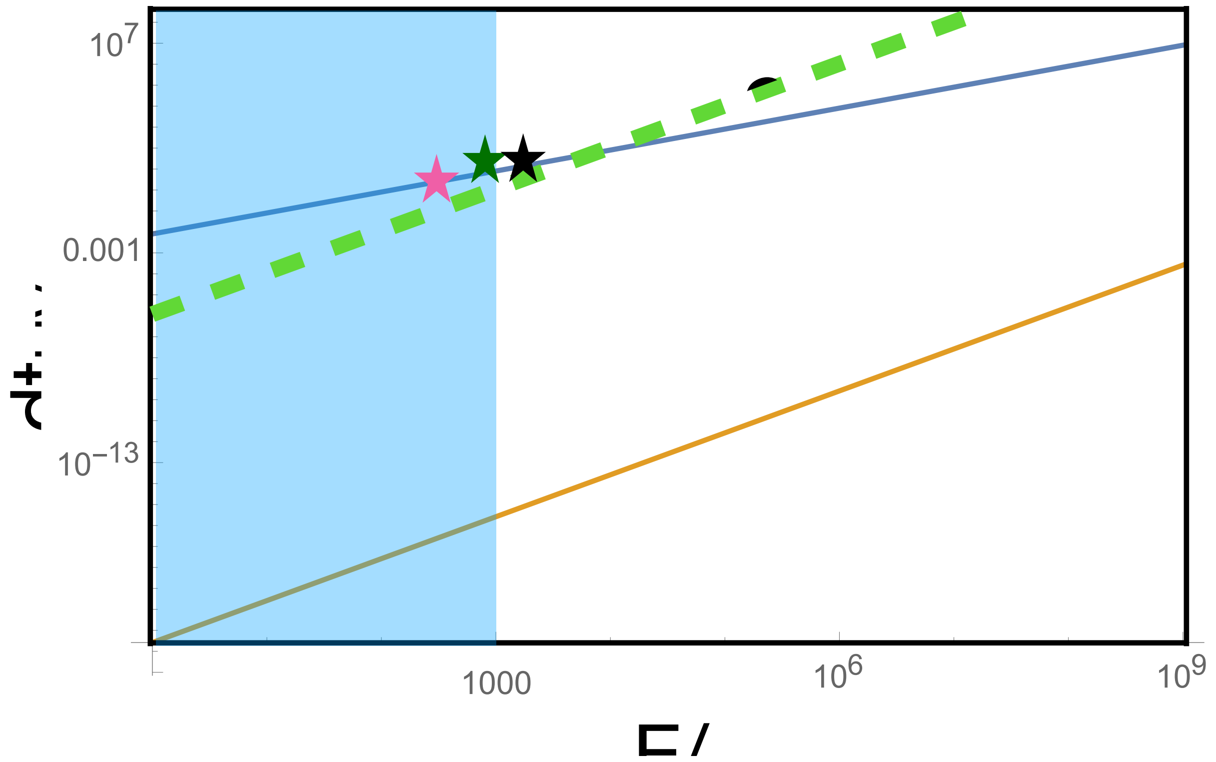
- TeV afterglows are nicely explained as SSC within the “pair balance” model (Derishev Piran 2016,2019,2021)



- The Afterglow is smooth :(

- But, the rising afterglow phase can reveal or set limits on L

- LIV n=1 time of flight limits from **090510A** (GeV) **190114c** (TeV) and **221009A** (TeV) are: <u>**$E_{LIV(1)}$ > a few m_{pl}**</u>



- ~~LIV explanations of the 18 TeV photons~~

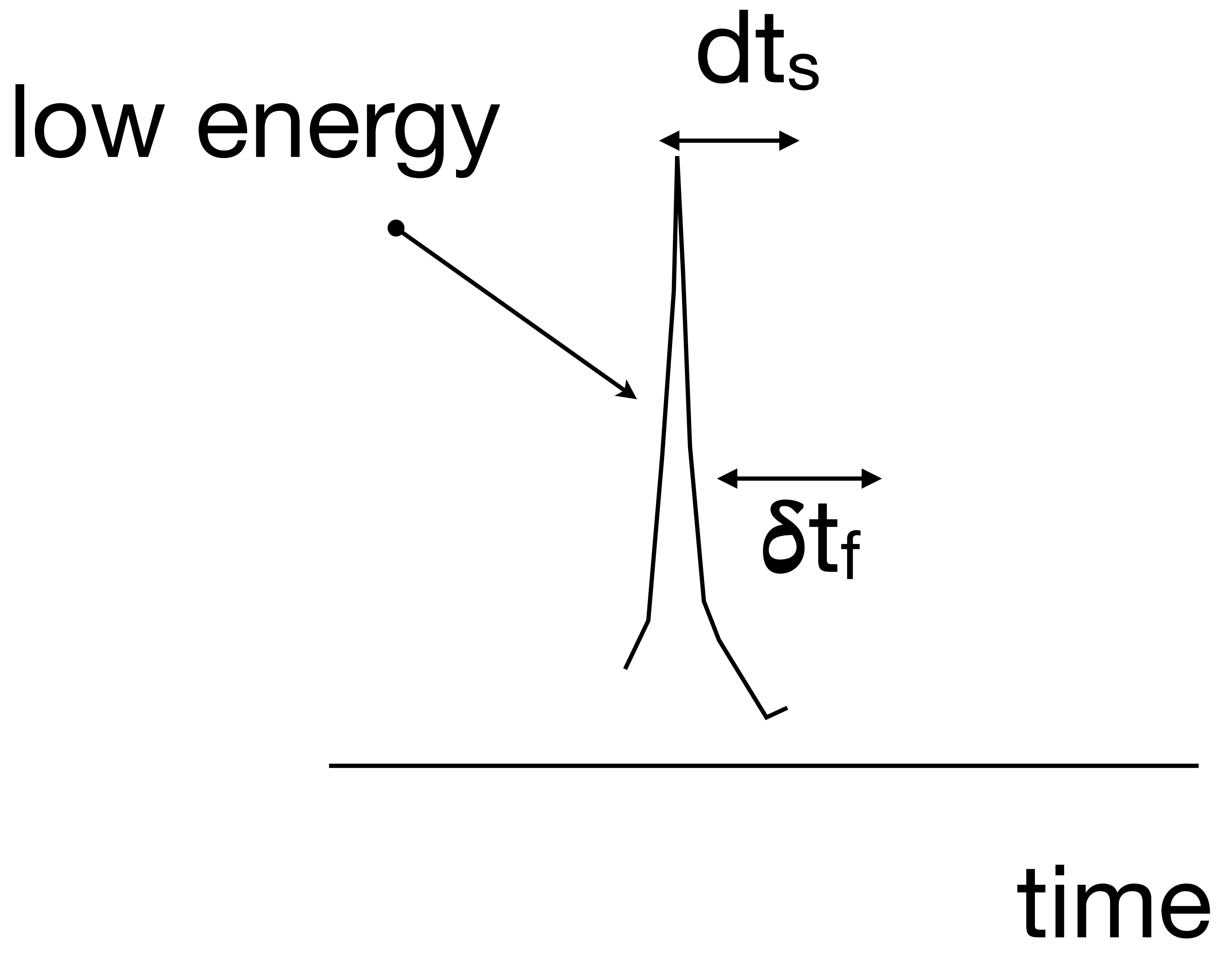
- Prompt emission ($\delta t > 0.01$ sec & $E \overset{?}{<} 100$ MeV) time of flight limits will necessarily be below $0.1 m_{pl}$:(

Fuzzy (stochastic) propagation

(Vasileiou, Granot, TP & Amelino-Camelia, 2015)

$$\delta v(E) = \left(\frac{E}{\xi_f M_{pl}}\right)^n$$

$$\delta T(E) = \delta v(E) T$$



$$dt_{LIV} = dt_s(E) + \delta t_f(E)$$

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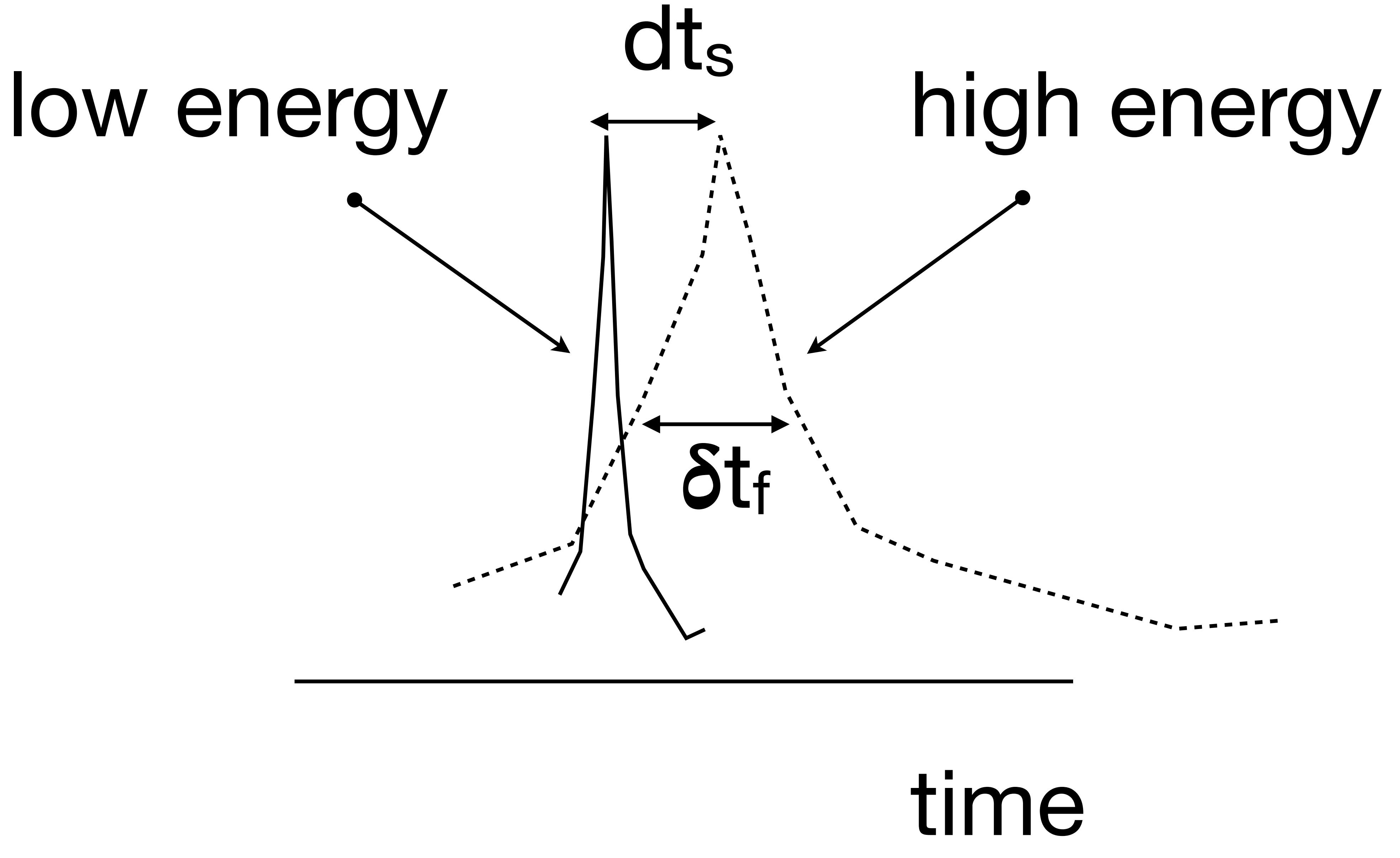
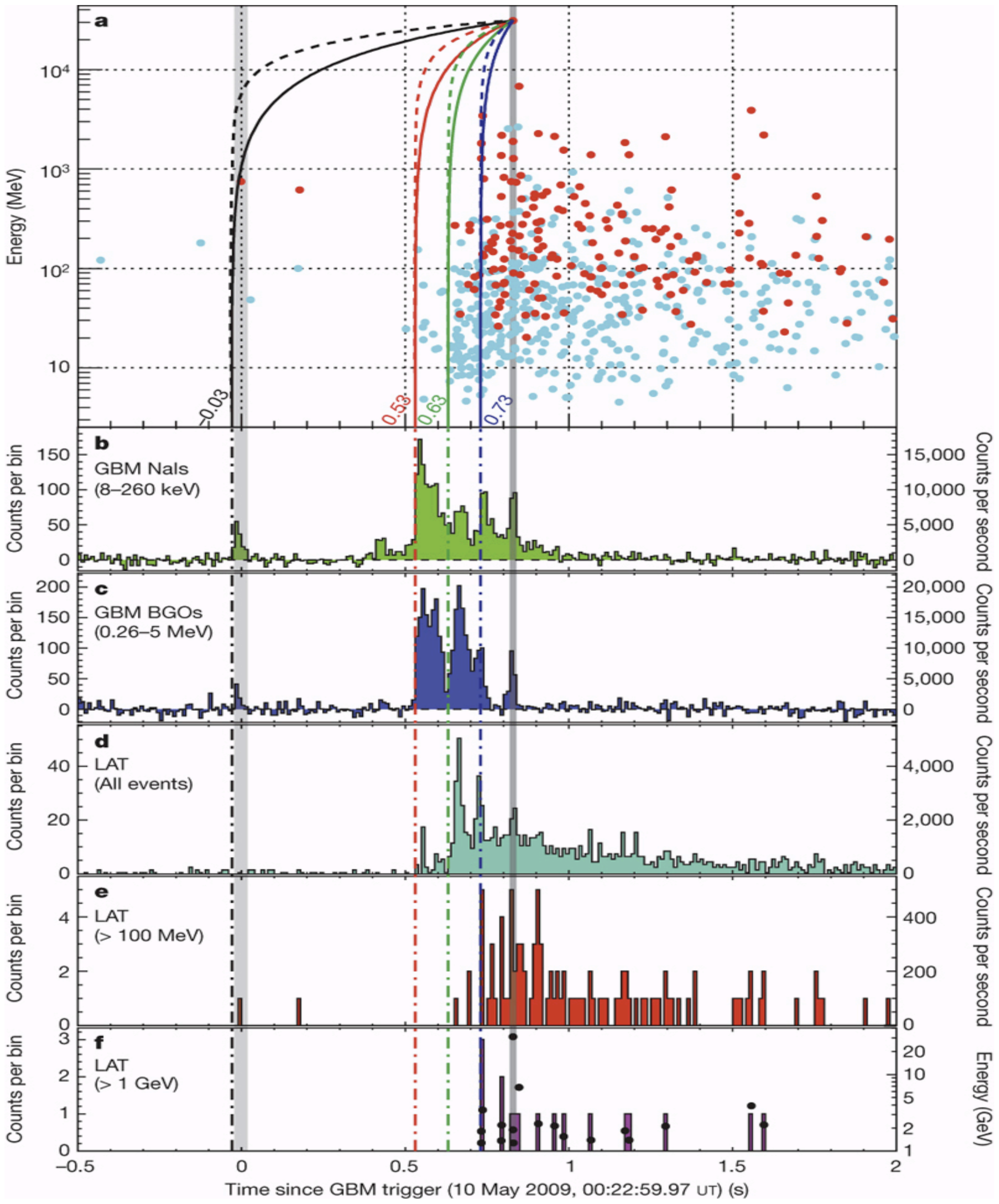
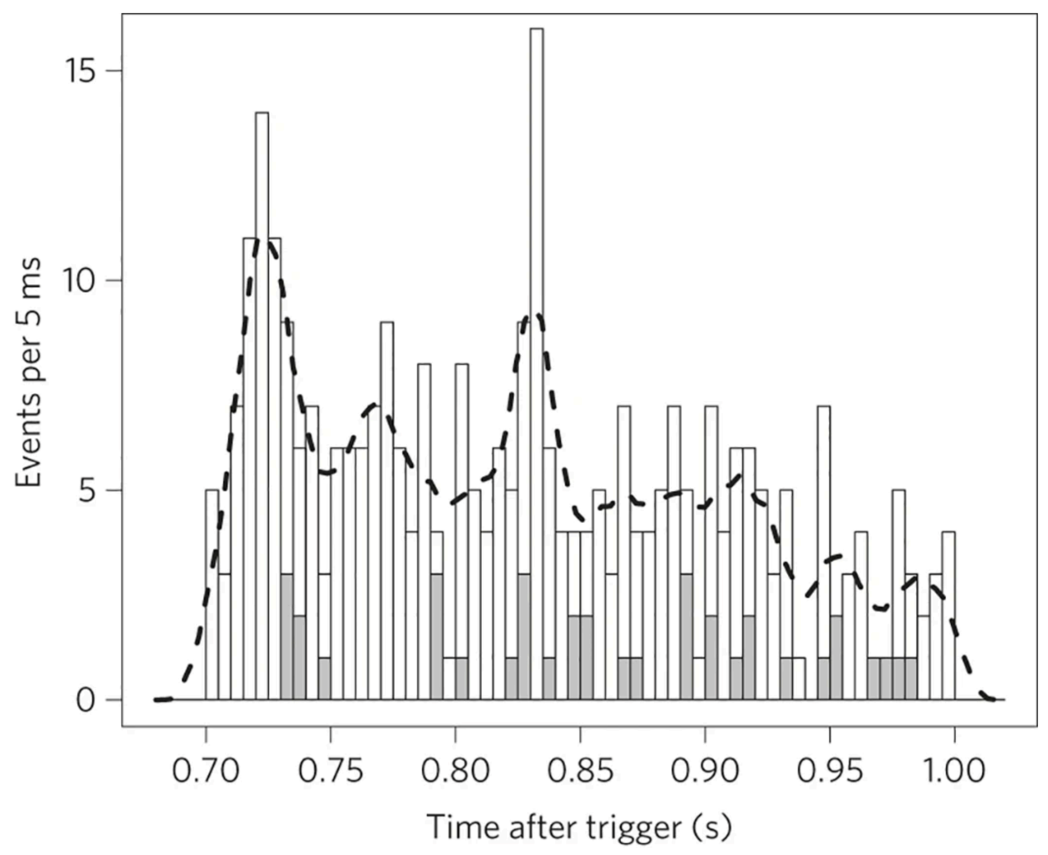


$$dt_{LIV} = dt_s(E) + \delta t_f(E)$$

Fuzzy limits from GRB 090510

(Vasileiou, Granot, Piran & Amelino-Camelia 2015)



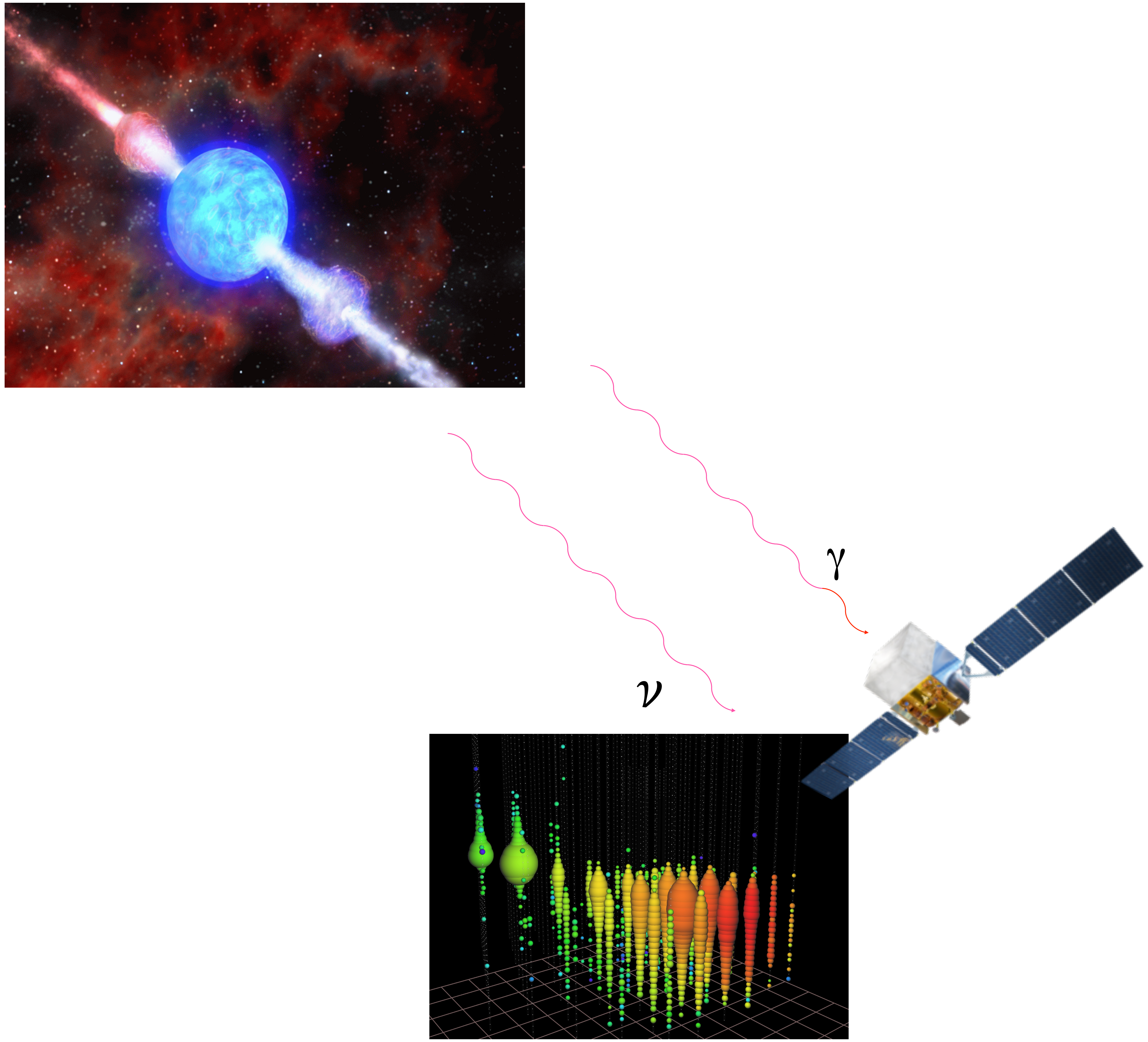


$t = t_{em} + (\Delta t/dE)_s E + f(\delta T/dE)_f E$

f is a random Gaussian variable

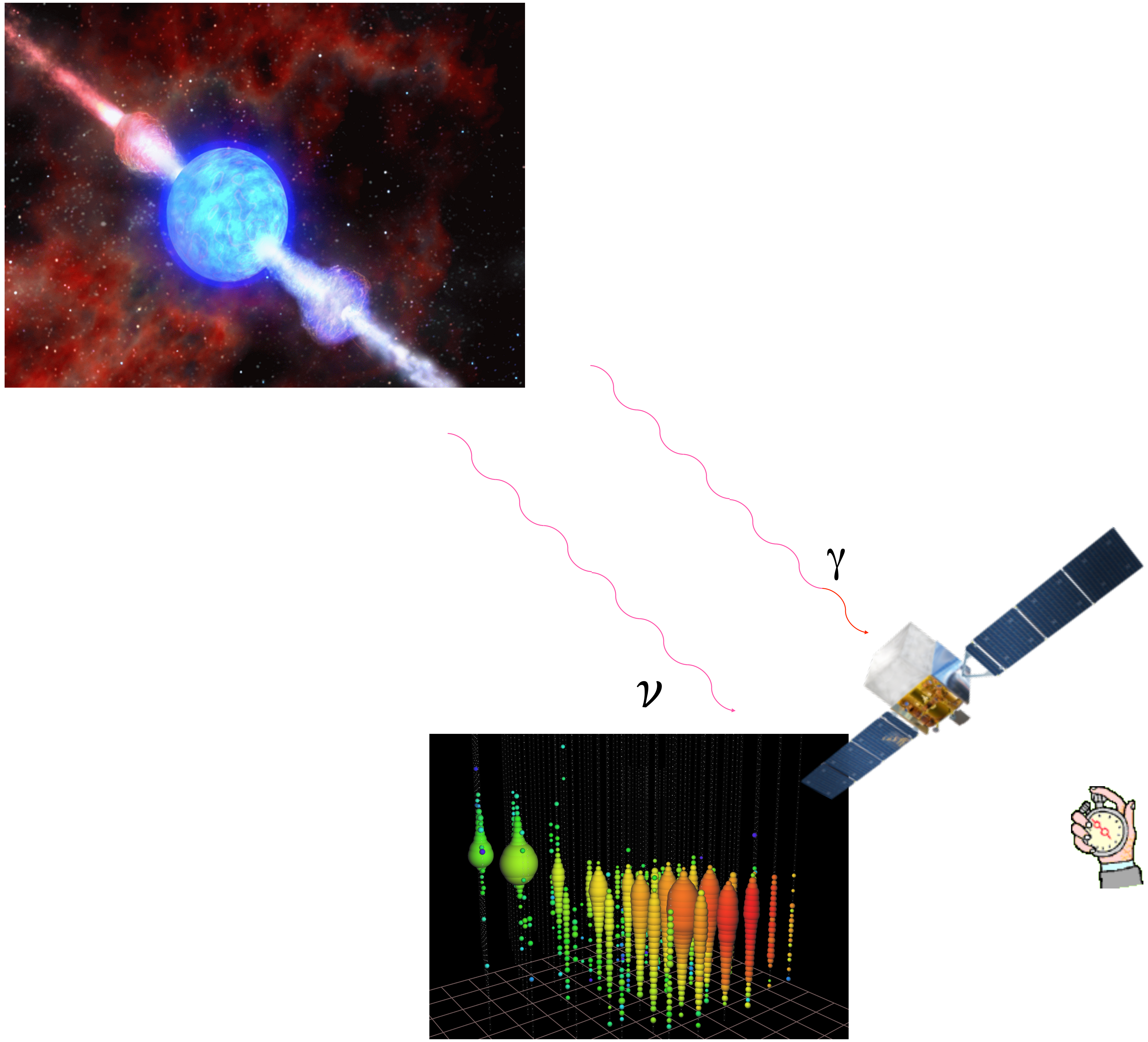
We find
$(\delta T/dE)_f < 0.04$ sec/GeV for the fuzzy shift and
$(\Delta t/dE)_s < 0.01$sec/GeV for the systematic shift.
The limit on "fuzzy" LIV energy scale is> 2 m_{pl}.

High-Energy Neutrinos



If GRBs are also sources of high energy neutrinos we can compare the neutrinos' arrival time with the photons' arrival time.

High-Energy Neutrinos



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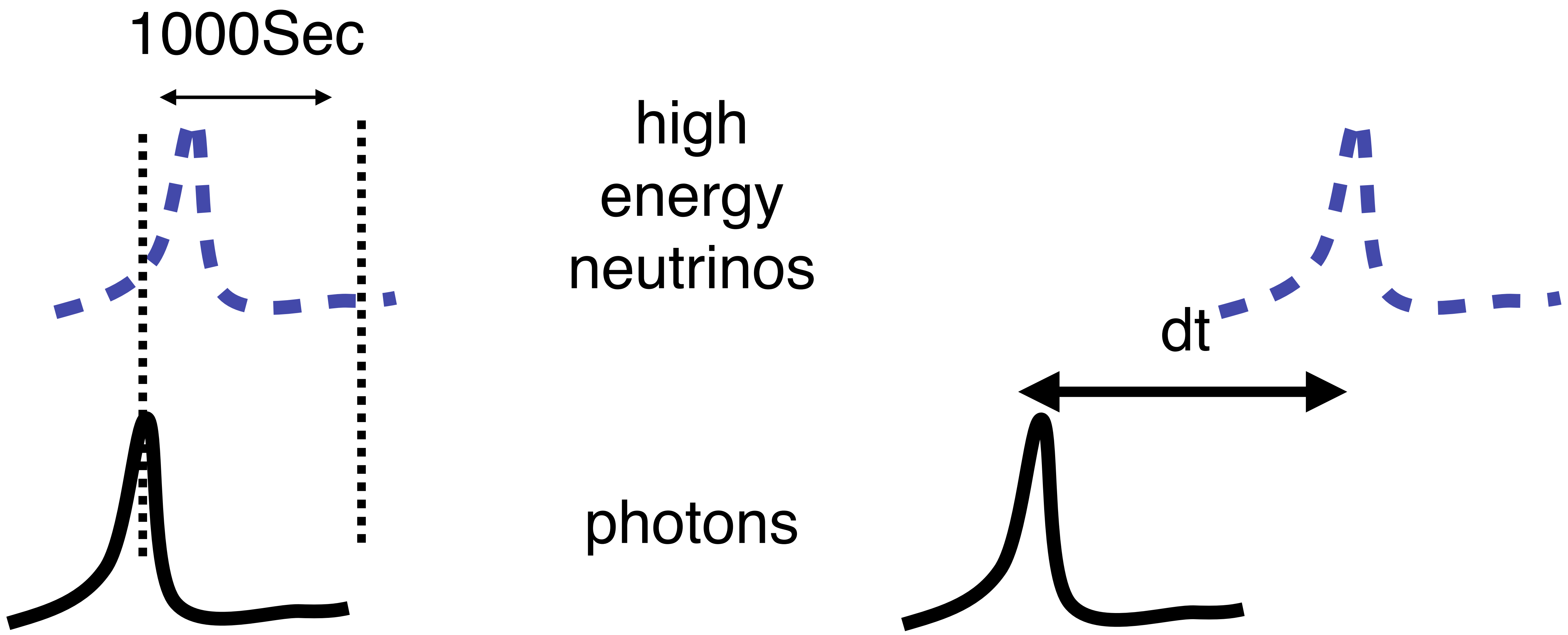
GRB photons and HE neutrinos

(Jacob and TP, 2007)

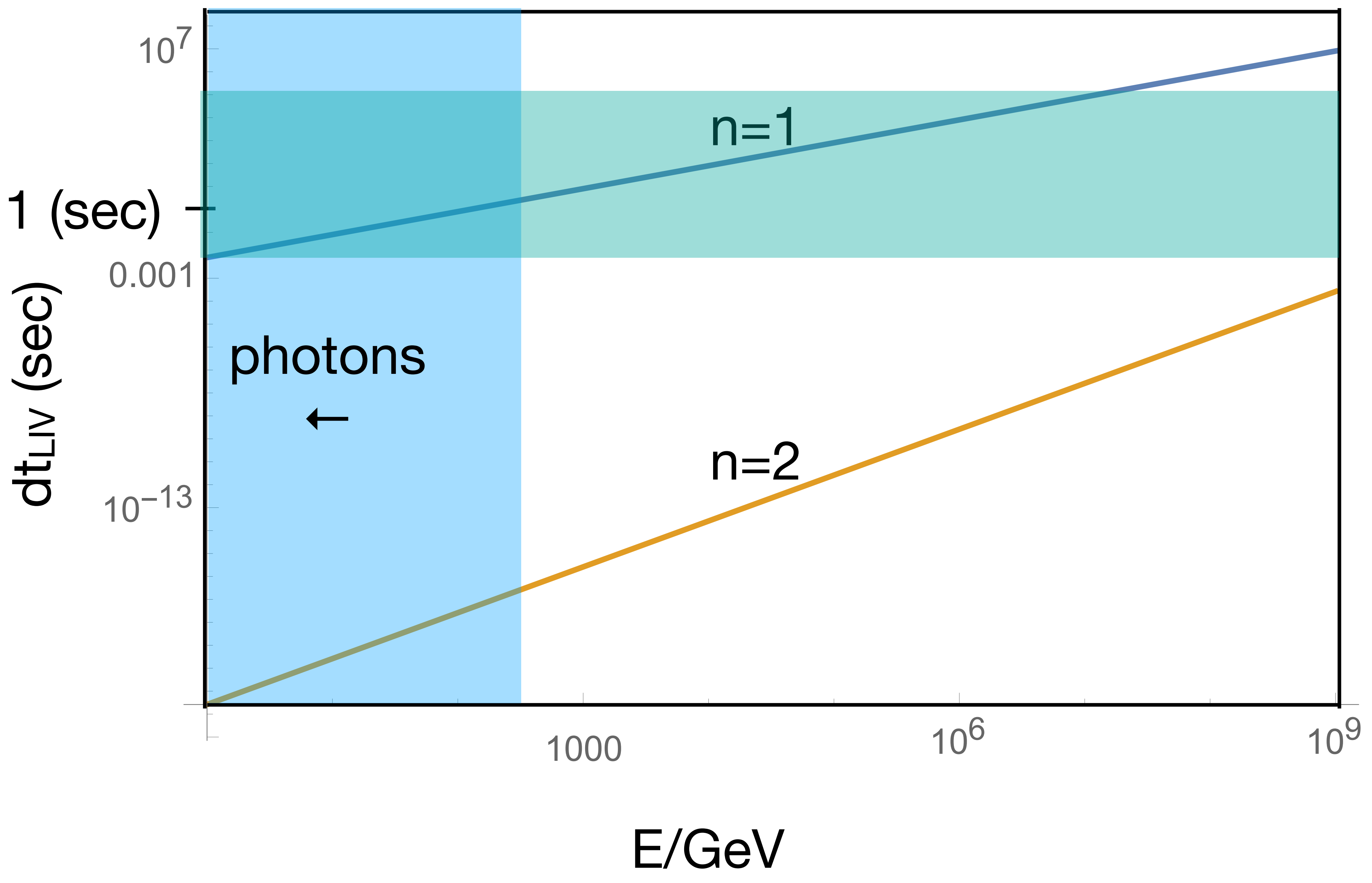
Possible
intrinsic **delay**

With Lorentz
violation

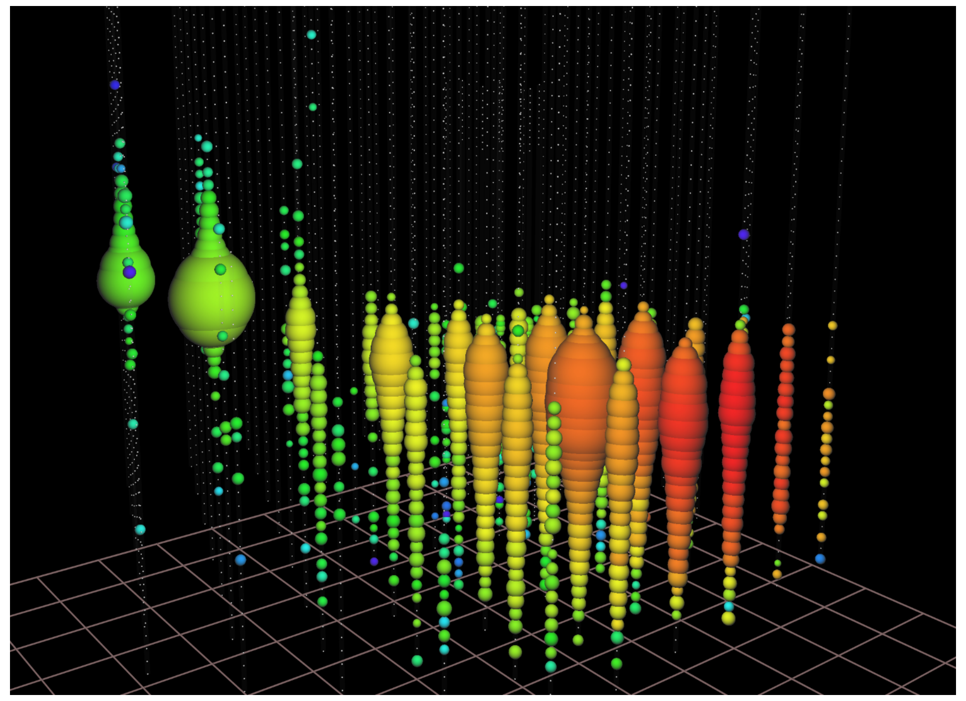


$$dt_{LIV} \approx \pm \frac{d}{c}\left(\frac{E}{\xi_n E_{pl}}\right)^n \approx 10^{-2-19(n-1)}\left(\frac{E}{\xi_n GeV}\right)^n sec$$

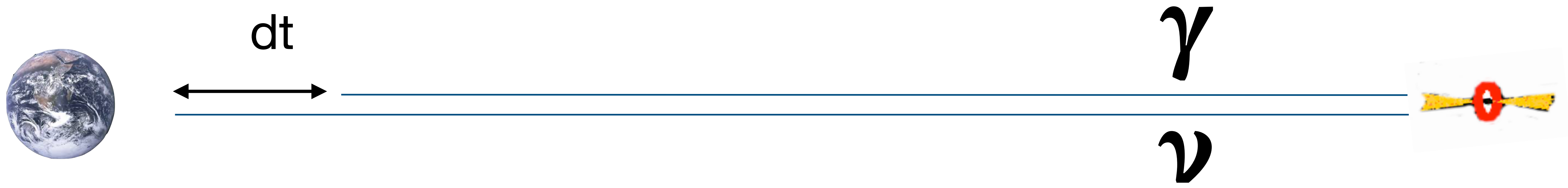
dt for a cosmological source at z=1 for n=1,2 (**ξ**=1)



IceCube



Antares



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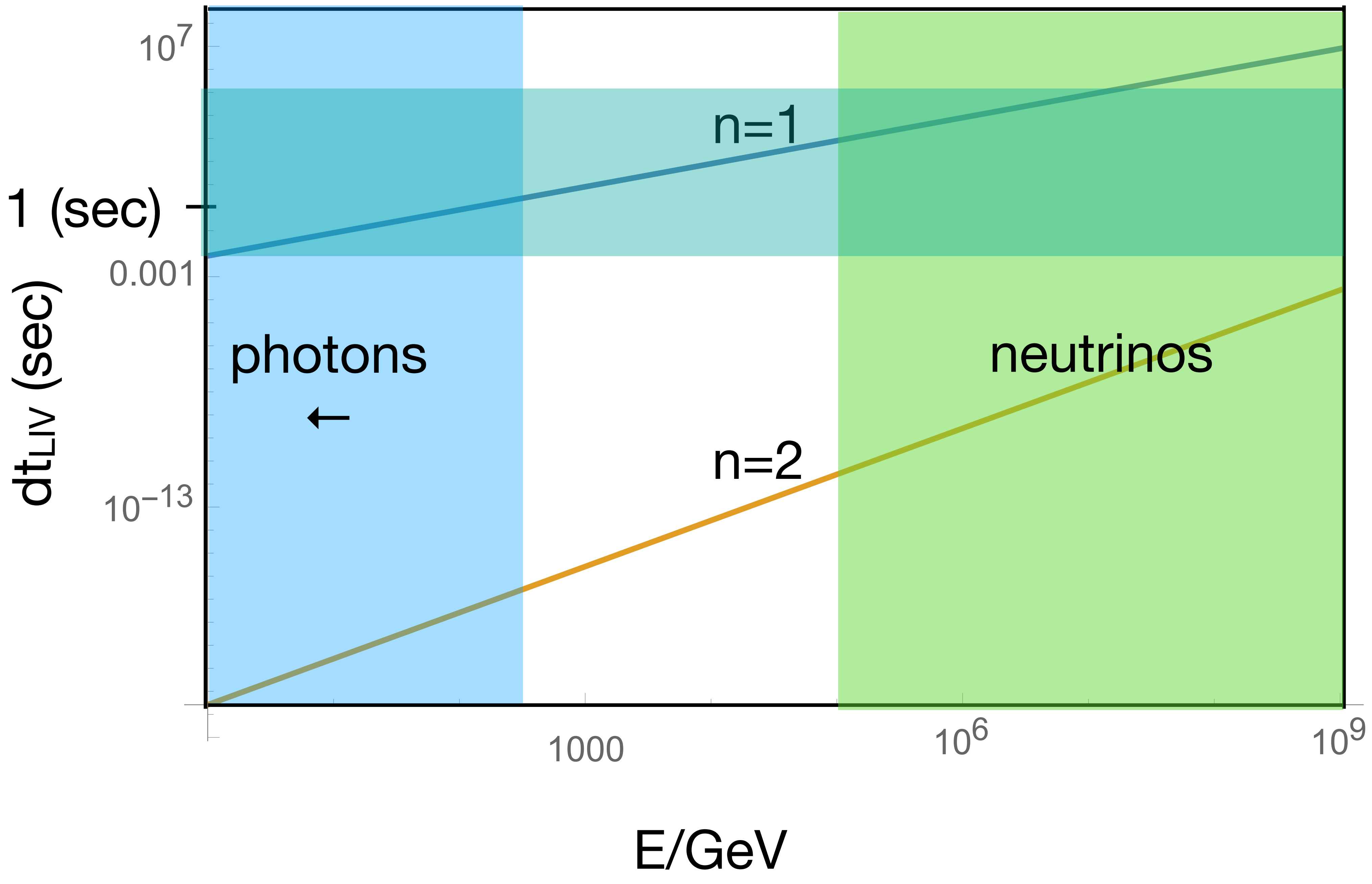

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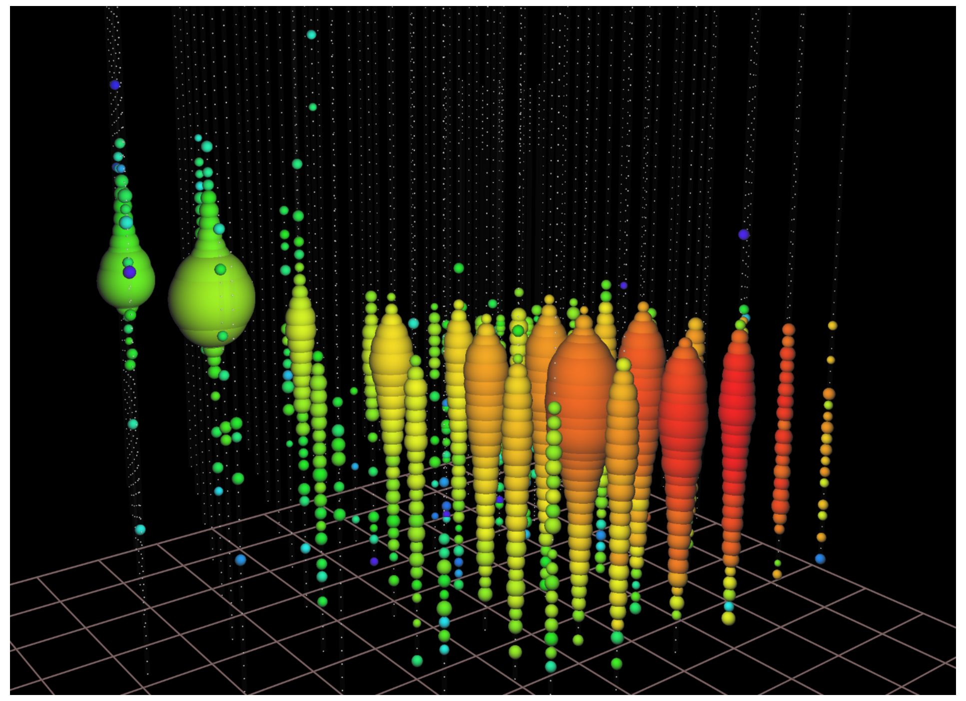
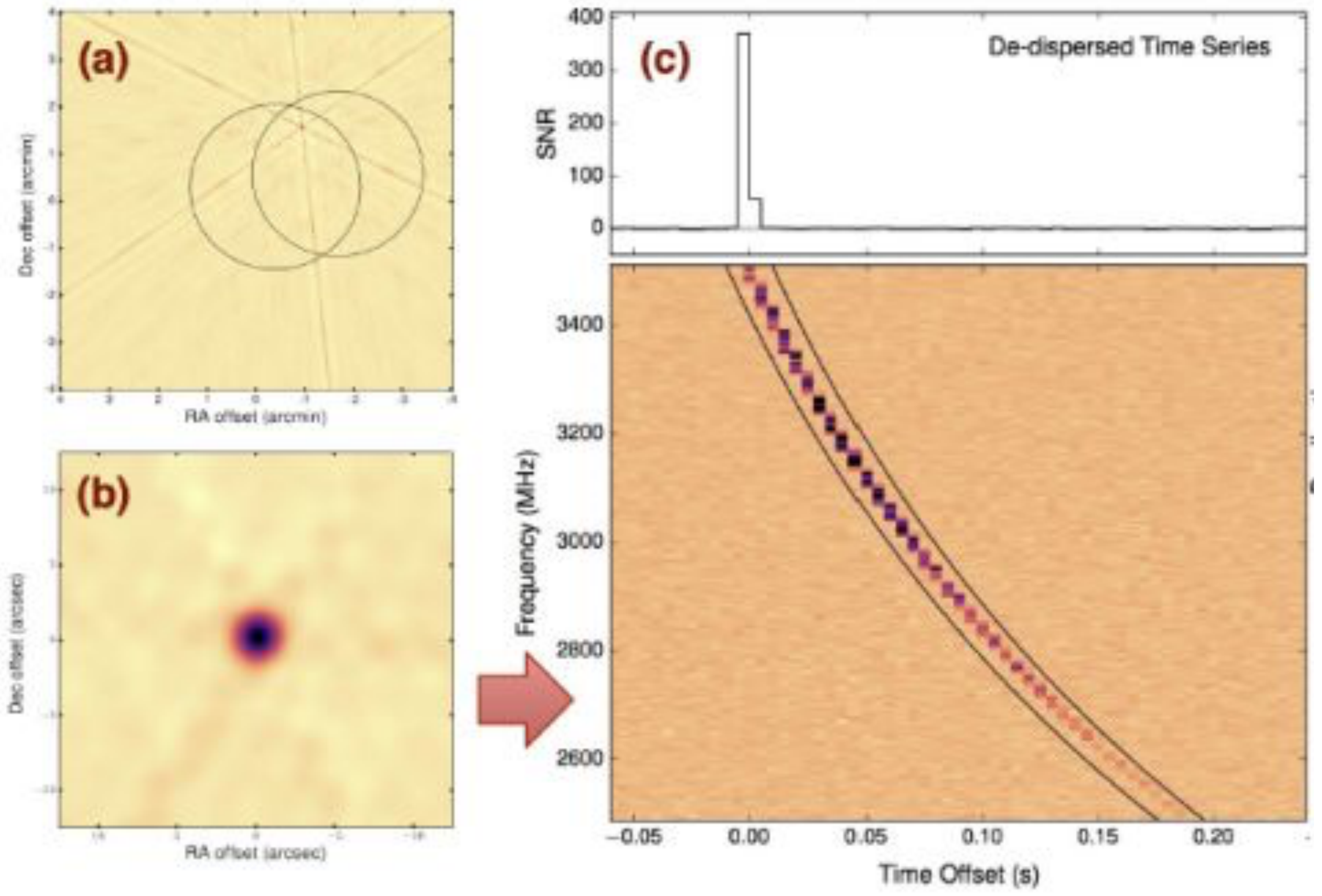


Antares

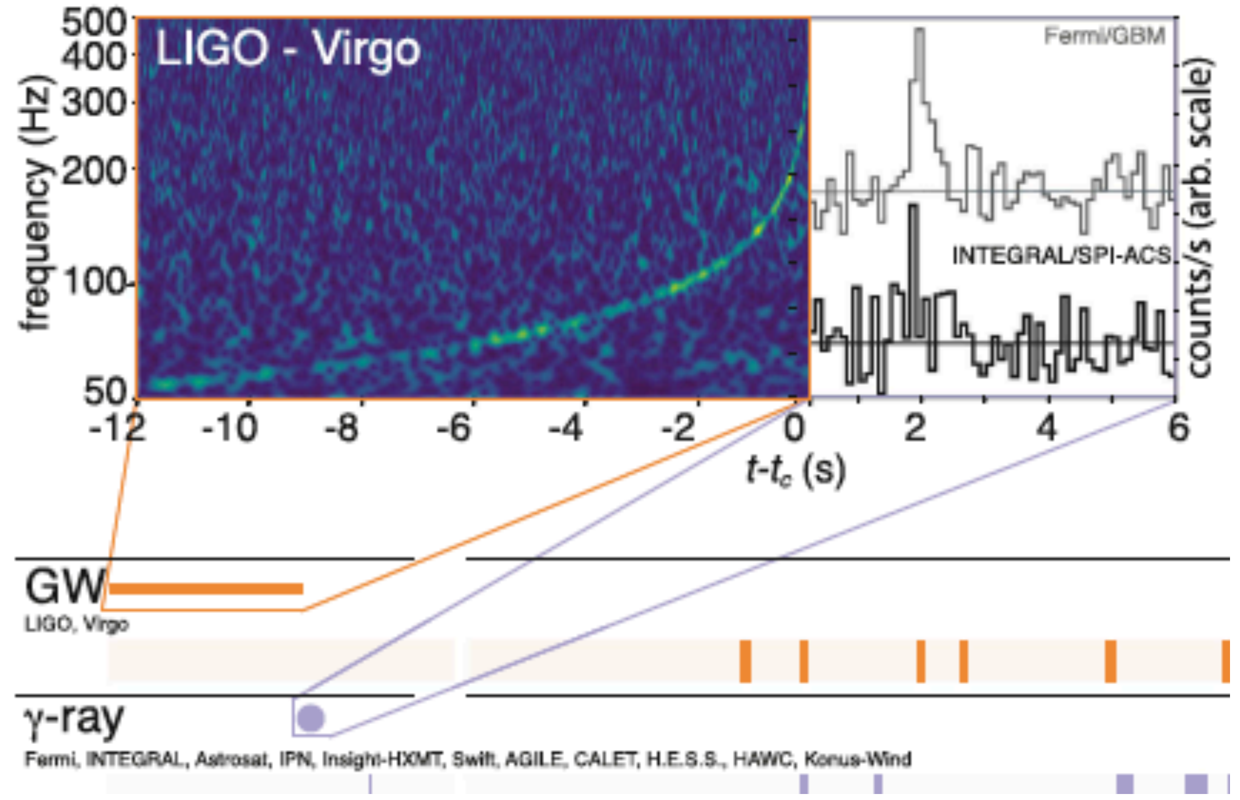
Fast Radio Bursts (the new player in town)



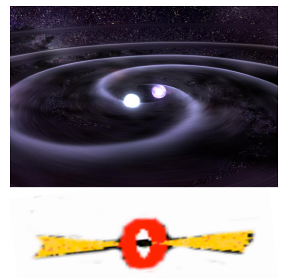
(a) VLA localization of FRB 121102

- msec duration pulses at a ~ GHz
- Limit on photon mass of < 10^{-10} eV (Chibisov 2016)
- Modest cosmological distances
- Ideal for time of flight LIV if accompanied by a high energy counterpart
- So far non was detected ☹️
- Emission mechanism still unknown
- If high energy counterpart is detected - we will have to be sure that there is no intrinsic time delay ☹️

Gravitational waves?



GW



1.7 sec γ-Rays ?

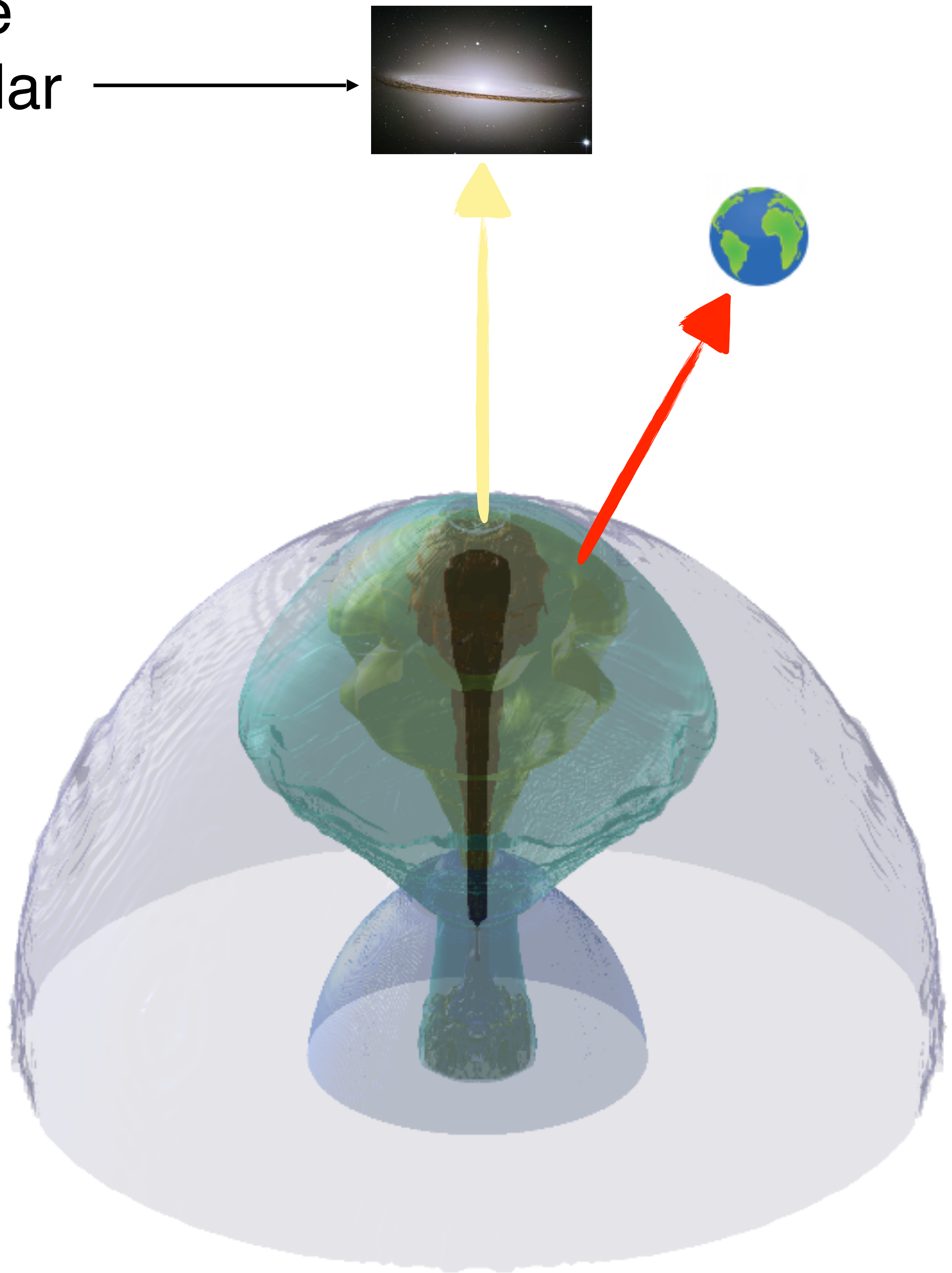
~10^{16} sec ; including ~10^{10} sec of Shapiro time delay

Implications from GW 170817 (e.g. Abbot + 17)

- $(c_{GW} - c_{photons})/c \leq o(10^{-15})$
- Weak equivalence principle $\gamma < 10^{-7}$-10^{-10}

(By the way) GRB 170817A was not a regular short GRB

Aliens living here observed a regular sGRB



GW Lorentz Invariance time of flight ?

For known astronomical objects

$$\omega \approx \sqrt{G\rho} < 10^4\ Hz \quad \rightarrow \quad \hbar\omega < 10^{-20}\ GeV$$

$$\rho < 10^{15} gm/cm^3$$

Even with some unexpected physics

$$10^{-44} sec$$

$$h_{GW} < \frac{GM}{c^2 D} \approx \frac{c}{\omega D} \approx \frac{1}{\omega T}$$

LIV $$dt = \left(\frac{\hbar\omega}{E_{pl}}\right) T \quad \rightarrow \quad \omega T = \frac{dt E_{pl}}{\hbar} = \frac{dt}{t_{pl}}$$

$$\Bigg\} \quad h_{GW} < \frac{t_{pl}}{dt}$$

What can we learn from GW on LIV?

- No direct LIV time of flight effects
- Need an EM or neutrinos high energy counterpart
- GW can set the time identifying a critical moment (e.g. coalescence time in a merger)
- However, like in GW 170817 and GRB 170817A we cannot use this information without a **robust physical model** or an **additional observation (?)** that could tell us what is the intrinsic time delay. ☹️

A remark on the quantum nature of macroscopic GW sources

A Gravitational wave generator

The generator doesn't produce enough power per cycle to emit a single graviton

Energy per cycle

$$\frac{L_{GW}\, t}{\hbar\omega} \approx \left(\frac{M}{m_{pl}}\right)^2 \left(\frac{v}{c}\right)^4 \approx \left(\frac{E_k}{E_{pl}}\right)^2$$

Energy of a single graviton

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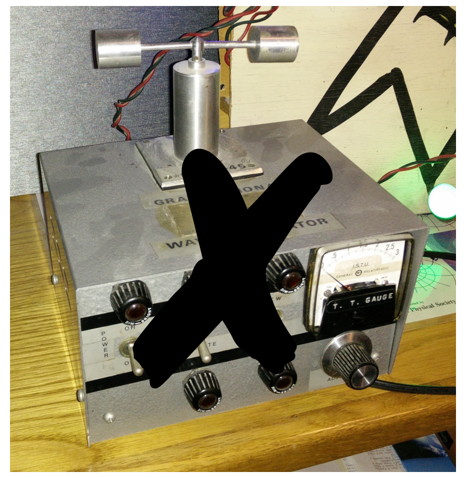

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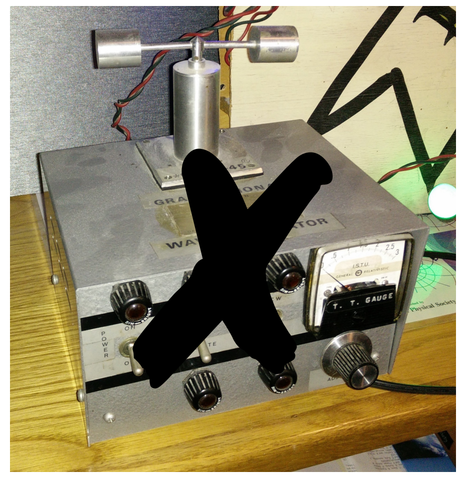

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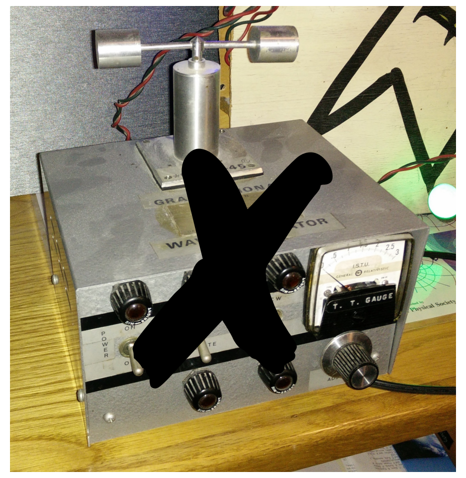

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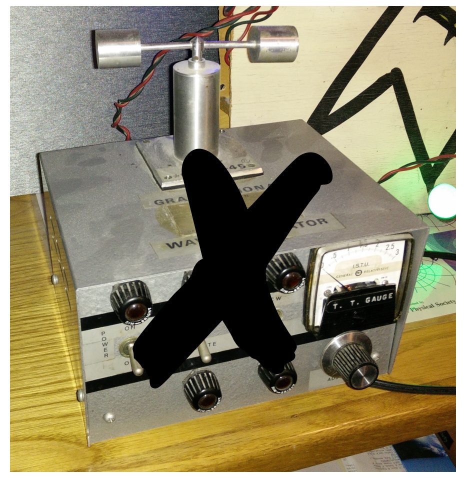
Energy of a single graviton

10^{16} erg



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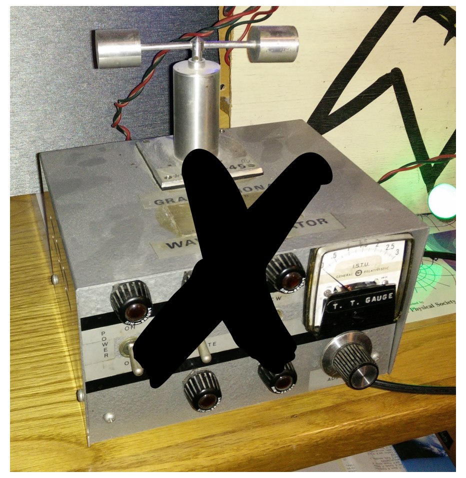

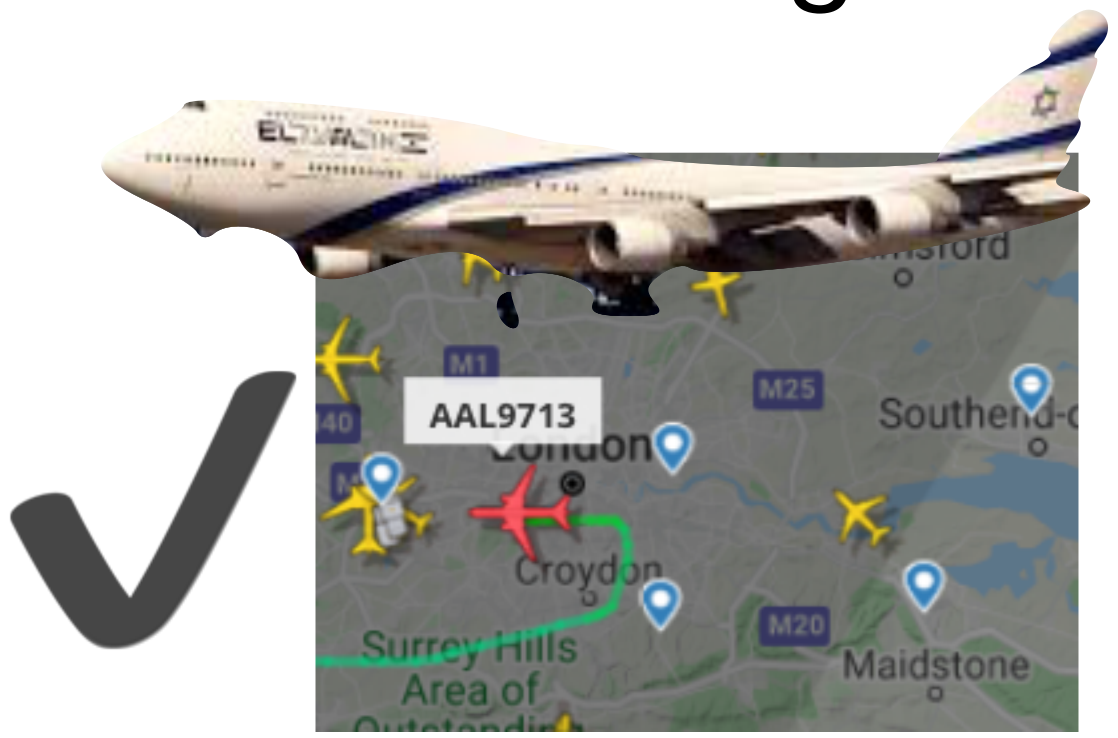

Summary

- We cannot observe energetic (> TeV) photons from distant GBs => dt_{LIV} < a second (for n=1)
- The observed TeV emission is afterglow, that is smooth but rise time can provide some limit.
- GRB 090510 190114c & 221009: the best limits on LIV - $\xi_1 \approx 1$, $\xi_1 \approx 10^{-8}$
- A comparable limit for stochastic LIV for GRB 090510 (but some concern?)
- Prompt emission is highly variable but doesn't have high energy photons $\xi_1 \lesssim 0.1$. Intrinsic time delay is a major obstacle. Can be resolved only using statistics on MANY sources and requires reasonable astrophysics.
- HE (PeV) GRB neutrinos can provide much stronger limits (scratching Planck for n=2)
- FRBs are new interesting candidates to explore time of flight LIV (but no high energy component so far)
- GW 170817+GRB 170817A amazing limits o(10^{-15}) on c_{GW} vs $c_{photons}$
- Impossible to observe LIV time of flight with GWs alone.
- GWs can serve as an onset baseline - but the intrinsic time delay issue remains.
- Because of quantum mechanics waving your hands don't lead to GWs. A jet airplane produces a single graviton per turn around an airport (Planck energy is a macroscopic large quantity).