What we could learn from Cherenkov Telescope Array observations of Gamma-Ray Bursts

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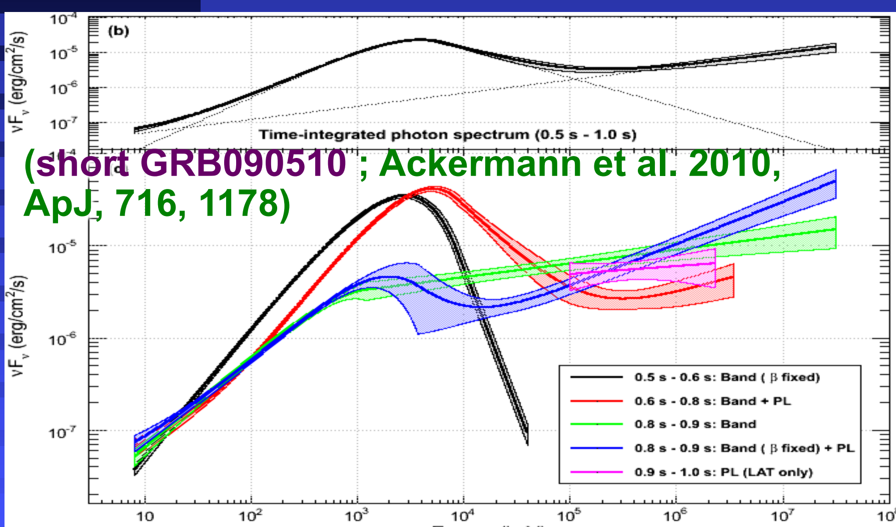
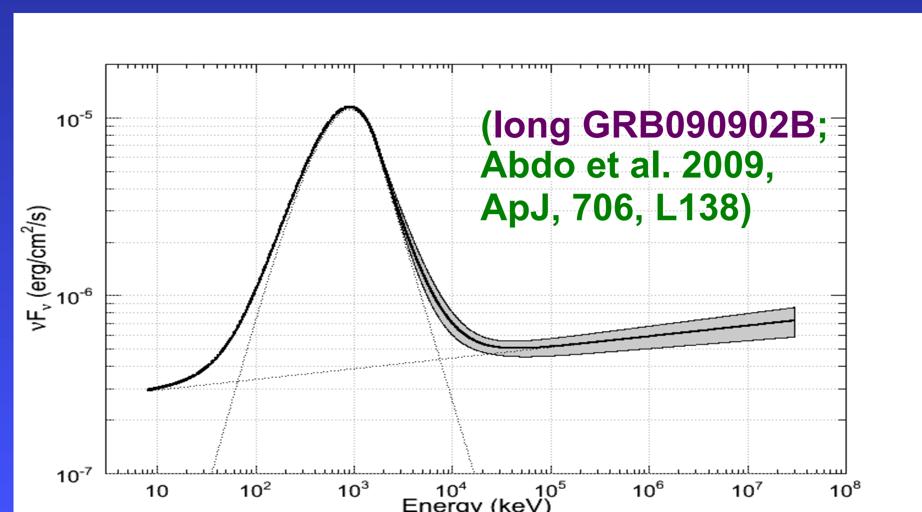
Outline of the Talk:

- GRB high-energy emission: what we know & how CTA could improve their high-energy coverage
- GRB **detection prospects** with CTA
- **GRB physics:** how CTA could help
  - Outflow bulk Lorentz factor Γ & emission radius R
  - Prompt emission: emission mechanism, outflow composition, prospects for high-energy cosmic rays & ν’ s
  - Afterglow: particle acceleration in collisionless shocks
- **Observational cosmology**: EBL, pair echoes
- **Fundamental physics**: testing Lorentz Invariance
- **Conclusions**

GRB High energy emission (Fermi, EGRET):

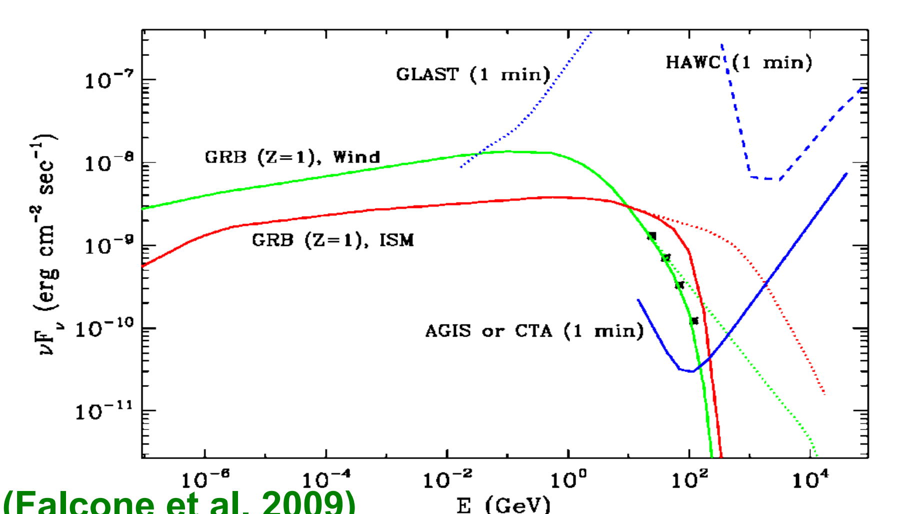
- ~30 GRBs have been detected so far at >100 MeV
- 2 GRBs have been detected at >30 GeV (one photon each from the short GRB 090510 & the long GRB 090902B)
- The >100 MeV emission usually starts later and lasts longer than the ≲1 MeV emission (up to $\sim 10^{2}$-$10^{3.5}$ s)
- A distinct high-energy spectral component – common
- Lower limits on the Lorentz factor $\Gamma_{min} \sim 10^{2.5}$ - 10^{3}





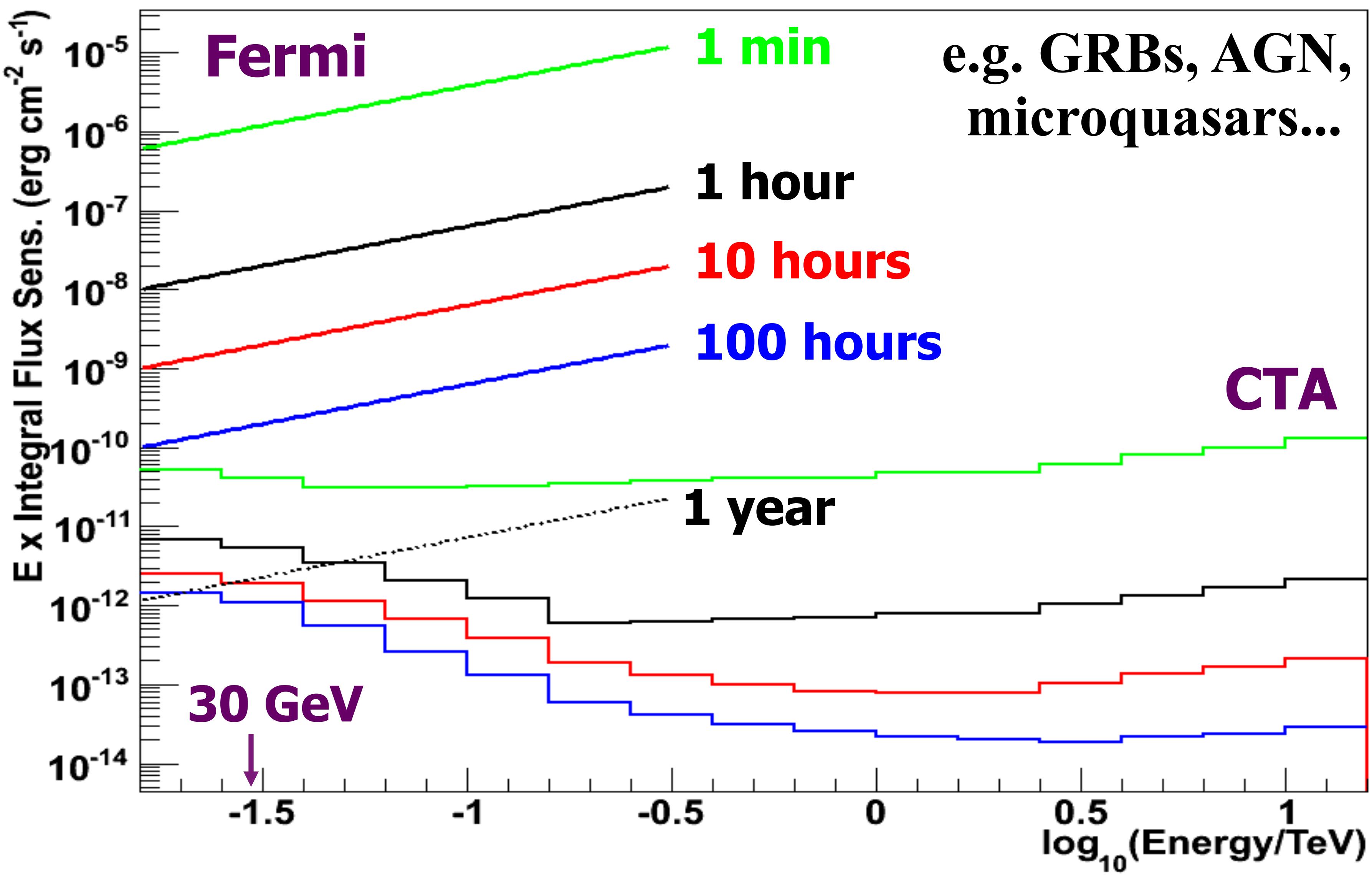
How CTA could improve GRB observations:

- Improved low-energy threshold: $E_{ph,min} < 20$ GeV
  ⇒ less γγ absorption on the EBL – higher z possible
- Fast slewing: 180° in 20 s for LST (similar to MAGIC2)
  ⇒ could catch the prompt emission of long GRBs
- Huge effective area: $>10^4$ m^2 @ 30 GeV ($>10^4$ × Fermi)
  ⇒ $>10^3$ photons above ~10 GeV instead of only 1 ⇒ improve constraints on VHE variability & spectrum
- Could detect up to higher energies than Fermi/LAT



(Falcone et al. 2009)

A bigger difference for transient sources



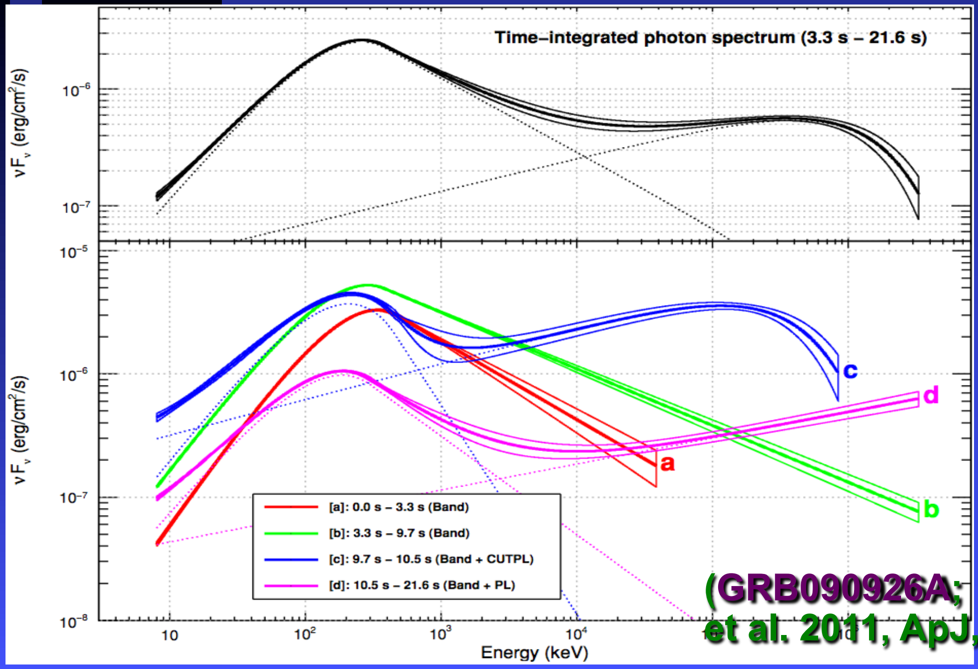
Expected CTA GRB detection rate:

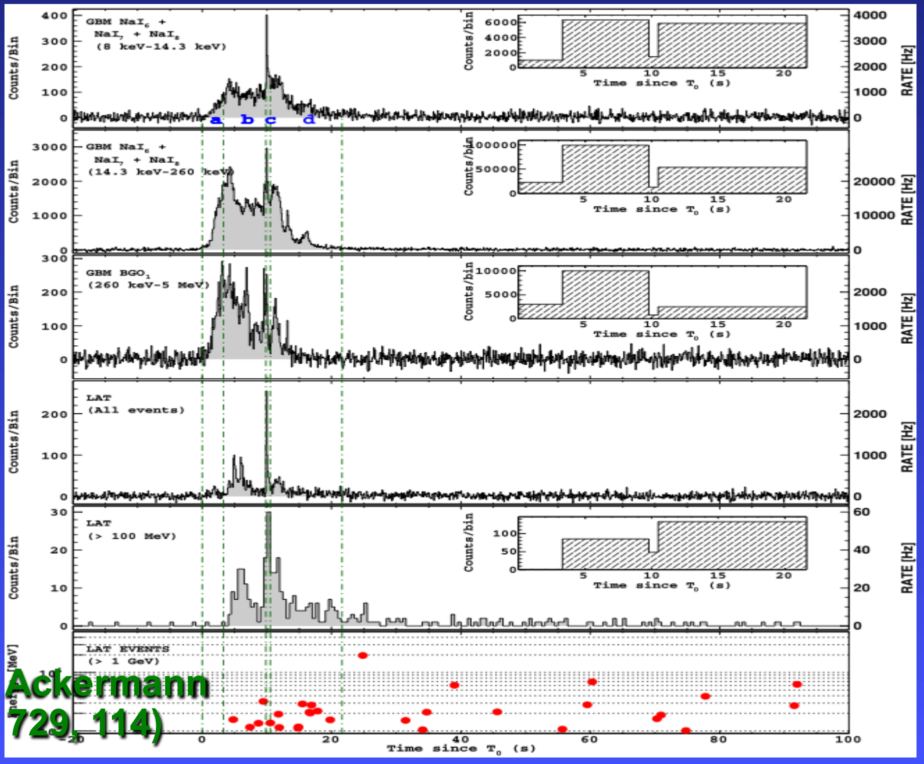
Mission to alert CTA	GRBs /year	Sun anti-correlation factor	Fraction of GRBs in FoV	Duty cycle	Good enough location	Detection efficiency	CTA GRBs / year	CTA GRBs / year
Swift BAT	95	1.4	0.35	0.1 - 0.15	100%	~ 0.25	~ 0.8 - 1.2	0.6 - 0.9 0.1, 1
Fermi GBM	250	1	0.25	0.1 - 0.15	~ 50%	~ 0.5	~ 1.6 - 2.3	0.4 - 0.5 ~ 0.1, 1
SVOM	80	1.6	0.40	0.1 - 0.15	100%	~ 0.25	~ 0.8 - 1.2	~0.6-0.9 ~ 0.1, 1

- × 2 sites / hemispheres: optimistic ~ 8 GRB/yr , more realistic (Bouvier et al.) ~ 4 GRB/yr, pessimistic (Inoue et al.) ~ 0.6 prompt GRB/yr (~ 6 afterglow/yr)
- Bouvier et al. – 10% of ~ MeV fluence + flat νF_ν
- Inoue et al. – t^0 Band extrapolation (AG $F_\nu \propto \nu^{-1} t^{-1.5}$)

Constraints on Γ for Fermi/LAT GRBs: CTA?

- Lack of a high-energy cutoff due to intrinsic pair production
 ⇒ lower limit Γ_{min} on the Lorentz factor of the emitting region
- For bright LAT GRBs (long/short): $\Gamma \gtrsim 10^3$ for simple model (steady-state, uniform, isotropic) but $\Gamma \gtrsim 10^{2.5}$ for more realistic time-dependent self-consistent thin shell model (**JG et al. 2008**)
- **GRB 090926A**: high-energy cutoff – if due to intrinsic pair production then $\Gamma \sim$ **200 - 700**





(GRB090926A; Ackermann et al. 2011, ApJ, 729, 114)

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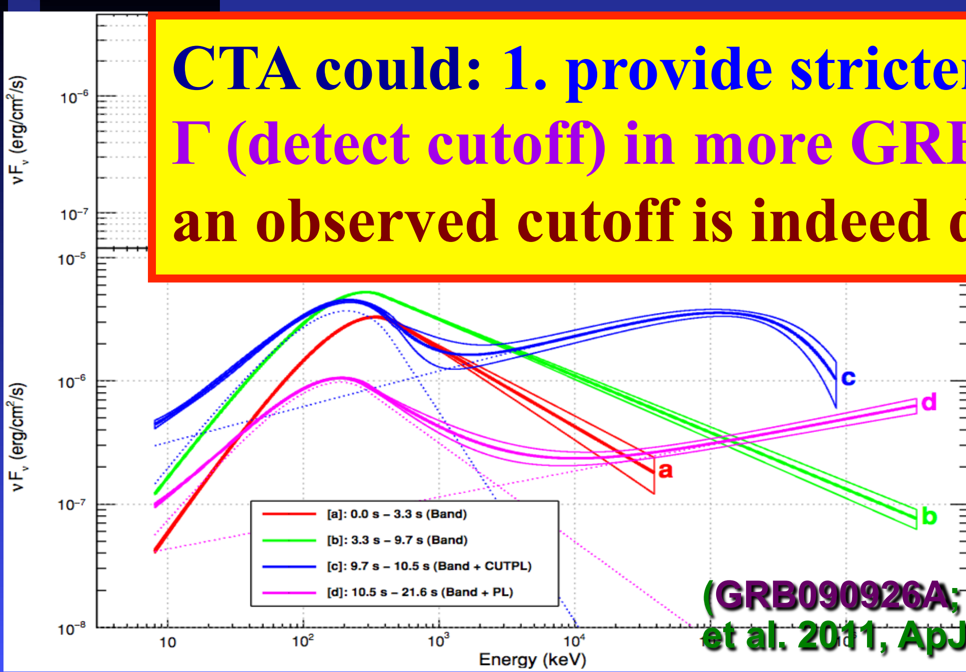
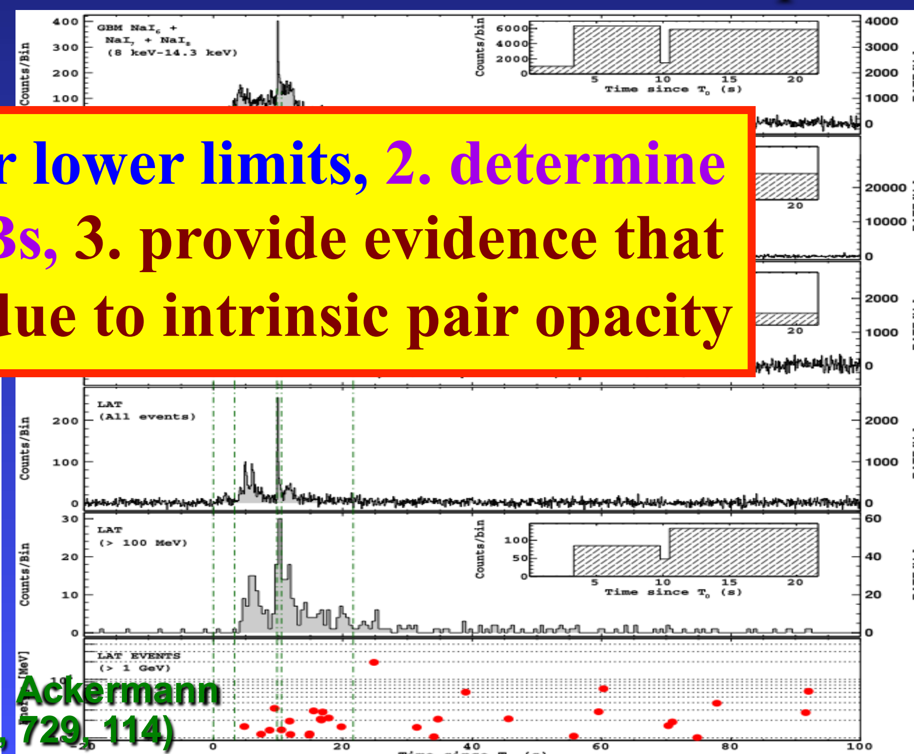
CTA could: 1. provide stricter lower limits, 2. determine Γ (detect cutoff) in more GRBs, 3. provide evidence that an observed cutoff is indeed due to intrinsic pair opacity





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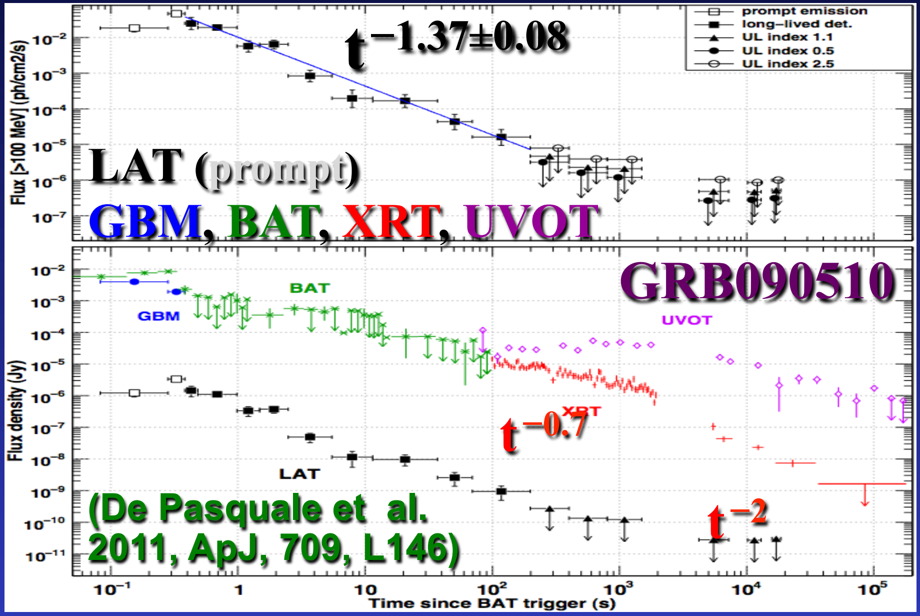
Prompt emission: Possible Origin – Fermi → CTA

- **Leptonic**: inverse-Compton or synchrotron self-Compton ?
- **Hadronic**: e.g. pair cascades, proton synchrotron ?
  - Hard to produce a delayed onset longer than spike widths (the seed photon field builds-up on the dynamical time)
  - Late onset: time to accelerate protons+develop cascades? but hard to also produce spikes coincident with low energies
  - Often requires very large total energies
  - Low-energy power-law: hard; synchrotron of secondary $e^{\pm}$
  - **Both**: gradual increase in HE photon index **β** is not natural
- CTA could help distinguish between leptonic/hadronic origin
- **Physics probed**: particle acceleration in extreme conditions, the role of GRBs as possible sources of UHECRs & HE ν's

Long lived high-energy emission: afterglow?

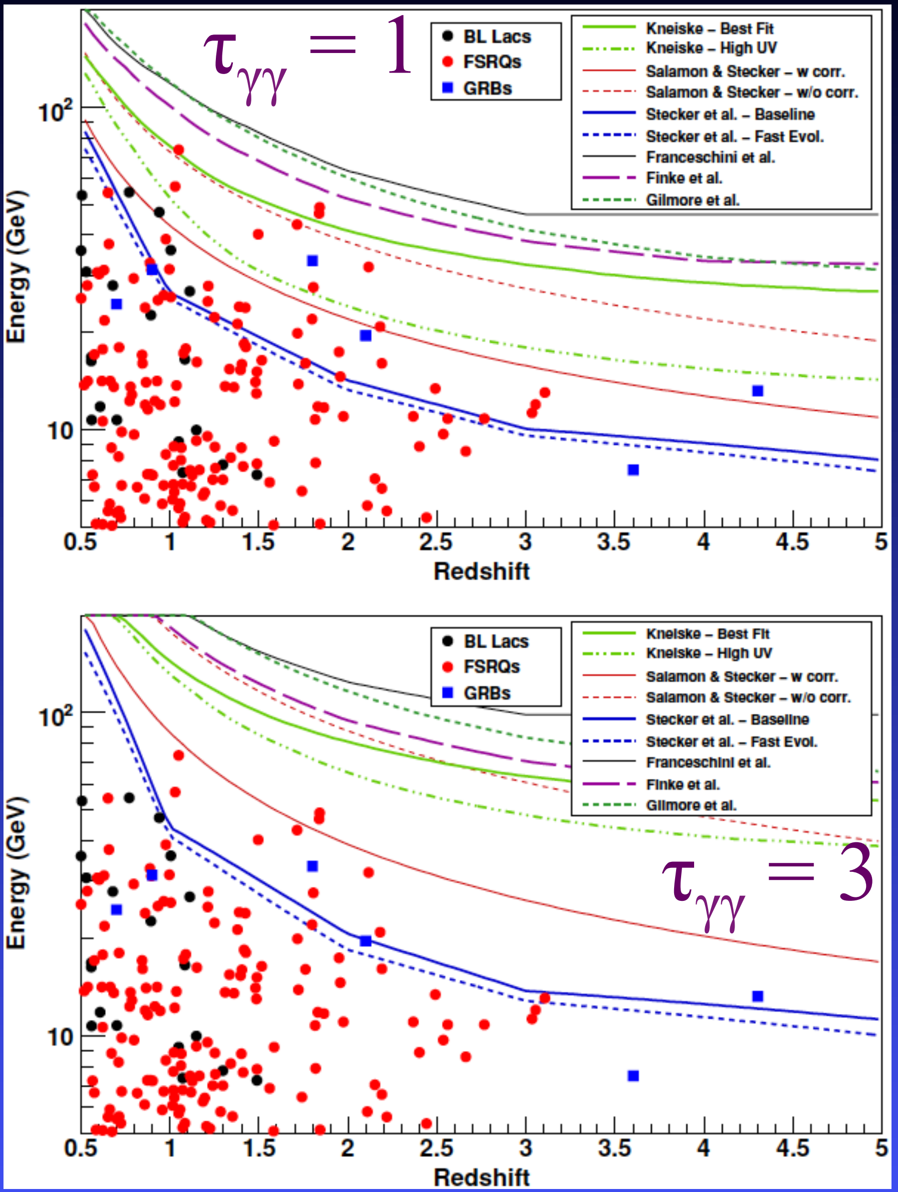
- Long lived HE emission is very common in Fermi/LAT GRBs (originally detected by EGRET; Hurley et al. 94) **Possible origins:**
  - **Afterglow synchrotron**: likely at $t \gg T_{GRB}$; **but:** detection **CTA** detection could exceed $E_{syn,max}$
  - **Afterglow SSC** emission: maybe but no observational support yet – **CTA** might capture the **SSC peak** at high energies



  - **X-ray flare** photons **IC** scattered by afterglow electrons: should be **variable** – **CTA** could test this
  - Long lived cascade induced by ultra-relativistic ions ($t_{ad,cool} \sim t_{var}$)
  - **Pair echo**: TeV + EBL $\gamma\gamma \rightarrow e^+e^-$, & the e^+e^- IC scatter the CMB
- **Physics probed:** particle acceleration in collisionless shocks intra-cluster / intergalactic B-field strengths, GRB physics

Constraining the opacity of the Universe

- γ-rays from distant sources can pair produce ($\gamma\gamma \rightarrow e^+e^-$) with the extragalactic background light (EBL) on the way to us
- This can test the transparency of the Universe and constrain EBL models (or the massive star formation rate at $z \gtrsim 1$)
- GRBs are already competitive with AGN, & probe higher z
- **CTA**'s much larger effective area compared to Fermi would be especially helpful for GRBs



(Abdo et al. 2010, ApJ, 723, 1082)

Limits on Lorentz Invariance Violation

- Some QG models violate Lorentz invariance: $v_{ph}(E_{ph}) \neq c$
- $\Rightarrow$ time delays in the arrival of the high-energy photons
- Fermi/LAT's best & most conservative limit on linear vacuum energy dispersion (GRB090510): $\mathbf{M_{QG,1} > 1.2 M_{Planck}}$
- Method 1: assuming HE γ's are not emitted before < MeV γ's CTA: Fermi's best limit, $|\Delta t/\Delta E| < 30$ ms/GeV, is hard to beat $\Rightarrow$ requires $E_h > 1$ TeV for a 30 s response time, but fewer γ's emitted at > 1 TeV + EBL $\Rightarrow$ need to catch a GRB in the FoV
- Method 2: DisCan (dispersion cancelation; very robust) – lack of smearing of narrow spikes in high-energy light-curve CTA: might work best – sharp bright spikes are observed up to high energies also late within long GRBs: $t_{var} \sim 0.1$ s & $E_h \sim 0.1$ TeV could do ~30 times better than Fermi/LAT limit
- short GRB in FoV (survey mode): 10 ms, 1 TeV: $>10^3 \times$ LAT

Conclusions:

- CTA GRB detection rate is still uncertain (~ 0.6 – 8 yr^{-1})
- Despite a modest detection rate they could teach us a lot:
  - Improve lower limits on GRB outflow Lorentz factor **Γ** + help detect HE cutoff (determine **Γ**) & determine its origin
  - Prompt emission: help determine the emission mechanism & distinguish between leptonic & hadronic models ⇒ constrain outflow composition, particle acceleration & prospects for UHECRs & HE neutrinos
  - Long lived emission ⇒ particle acceleration in relativistic collisionless shocks, inter-galactic magnetic fields
  - EBL: higher z; perhaps finally clearly detect its signatures
  - LIV: good prospects; helps if GRB in FoV (survey mode)