Very-high-energy emission from GRBs: status and perspectives

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Where do we stand with this talk

Commonly, GRBs history can be divided in eras:

1. “dark” era (1973-1991): not much information
2. BATSE era (1992-1996): first spatial distribution
3. BeppoSAX era (1997-2000): afterglow discovery and first host galaxies identifications
4. HETE-2 era (2001-2004): long GRBs and association with supernovae
5. Swift era (2004-present): early afterglow, short GRB study
6. Fermi/AGILE era (2008-present): high-energy emission from GRBs
7. IACTs/EAS era (2019 - ?): TeV emission from GRBs

TeV instruments (at least some of them :))

Why observations of GRBs at VHE?

- Why is the follow-up of GRBs at very high energies (VHE, E>100 GeV) so important? There were/are many key questions:
  - do GRBs emit at VHE?
  - is VHE emission from GRBs energetically relevant?
  - what is the emission process or processes?
  - can this emission process contribute also at lower energies?
  - is there VHE emission in both the prompt and the afterglow?
  - do both short and long GRBs have VHE emission? If they do, are the properties of the emission similar?
  - ...
  - additionally, hints from some Fermi-LAT detected GRBs of an additional emission component at higher energies

Challenges of observations of GRBs at VHE

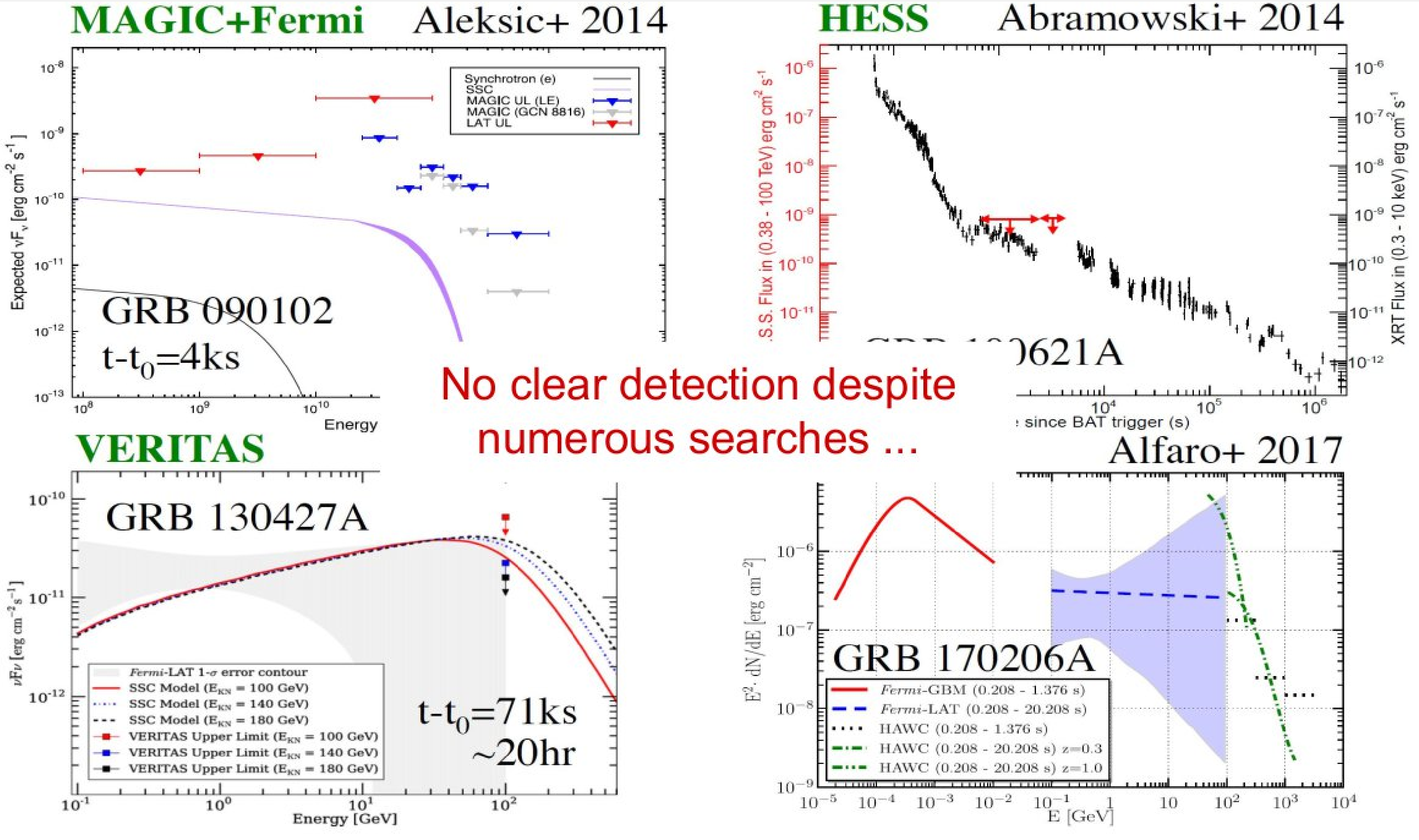
However, there are some challenges (instrument/observation wise)...

- for both IACTs and EAS
  - strong EBL absorption (GRBs at typical moderate-high redshift, stronger absorption in VHE range)

- for IACTs
  - small FoV
  - need to repoint the telescopes --> delay wrt GRB onset
  - reduced duty cycle

- for EAS
  - relatively high threshold (hundreds of GeV)
  - reduced sensitivity for short timescale events

Status of GRBs at TeV energies before 2019



GRBs detected at TeV energies

- A hunt going on since ~2 decades (at least for IACTs), finally getting the reward after several trials

- Now we have 5 detected GRBs:
  - GRB 180720B (H.E.S.S.)
  - GRB 190114C (MAGIC)
  - GRB 190829A (H.E.S.S.)
  - GRB 201216C (MAGIC)
  - GRB 221009A (LHAASO)

- All detected GRBs are of the long class
  - for the short class, we have a strong hint from the short GRB 160821B by MAGIC
    - kilonova associated --> interesting prospects for joined GW/GRB detection in next LIGO-Virgo-KAGRA observation run

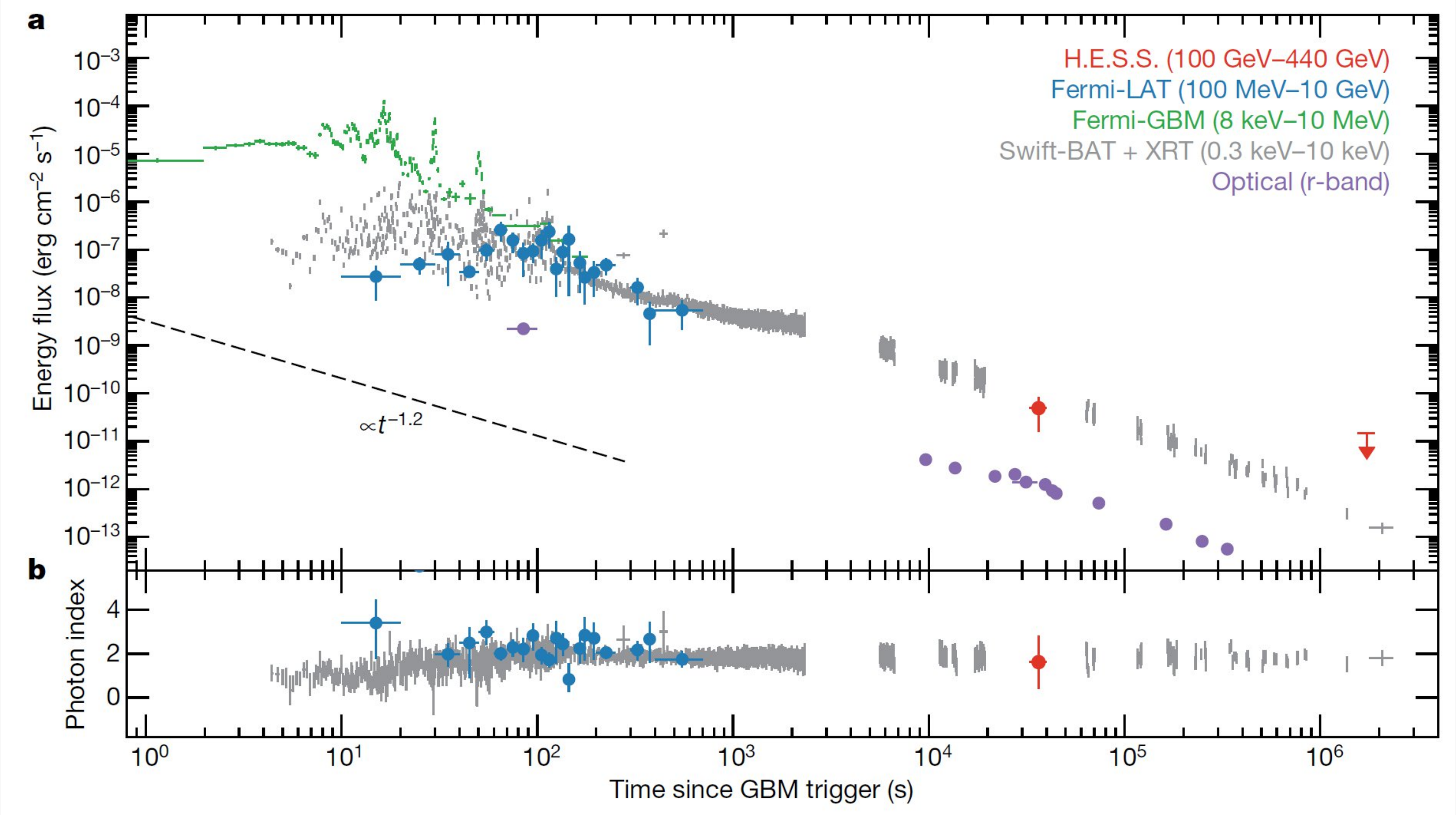
GRB 180720B

- Bright long GRB
  - T_{90}~48.9 s
  - E_{iso}~6x10^{53} (50-300 keV)
  - z=0.653

- Follow-up by H.E.S.S. at T_0+10.1h for 2 hours, detection at 5σ level

- Flux level for 100 GeV < E < 440 GeV similar to that in X-ray band

- Synchrotron self-Compton (SSC) as possible emission scenario



Nature 575, 464-467 (2019)

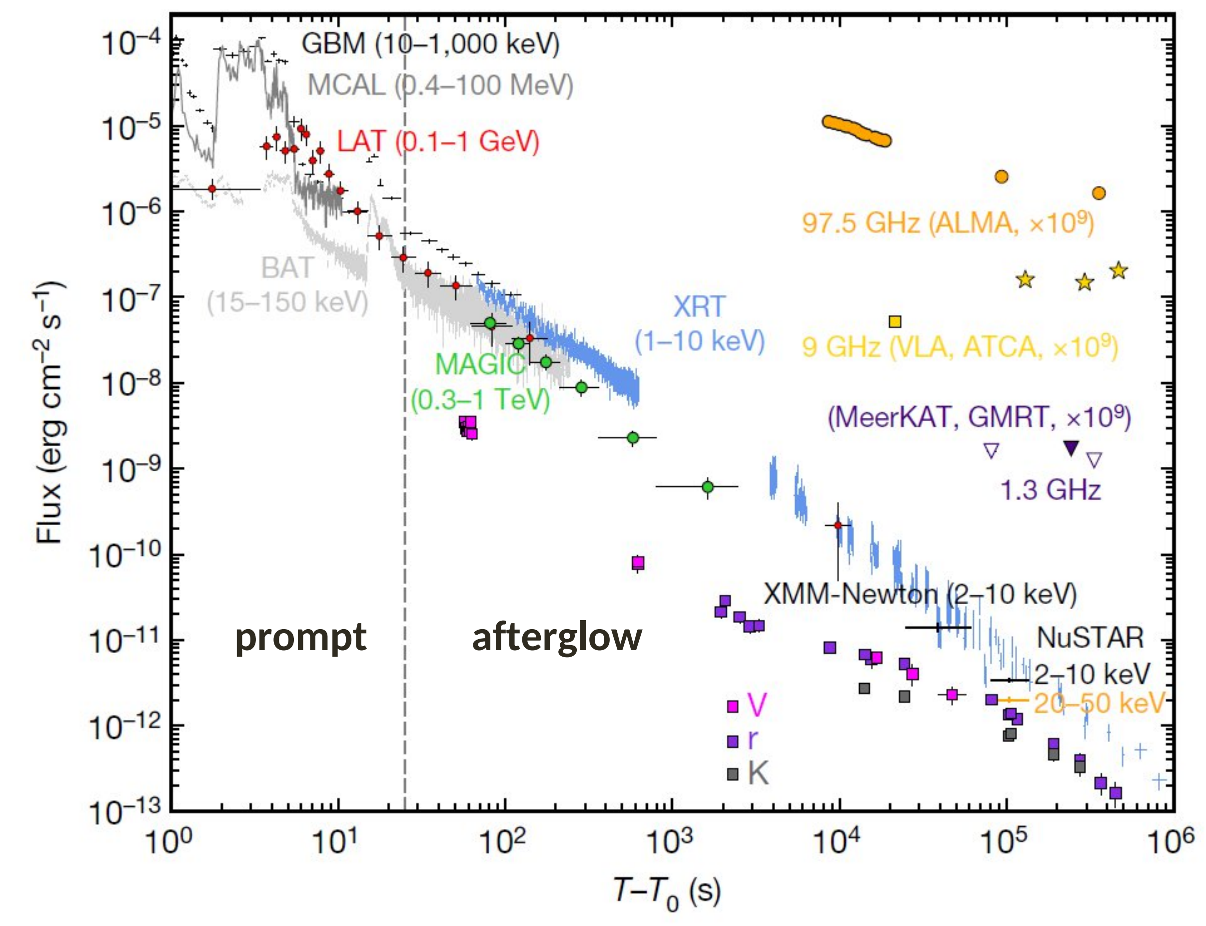
GRB 190114C

- Bright long GRB
  - T_{90}~360 s
  - E_{iso}~3x10^{53} (1-10000 keV)
  - z=0.4245

- Follow-up by MAGIC from T_0+57s for 4.4h hours, detection at 50σ level in the first 20 minutes above 300 GeV up to 1 TeV

- Flux level between 200 GeV and 1 TeV similar to that in X-ray band

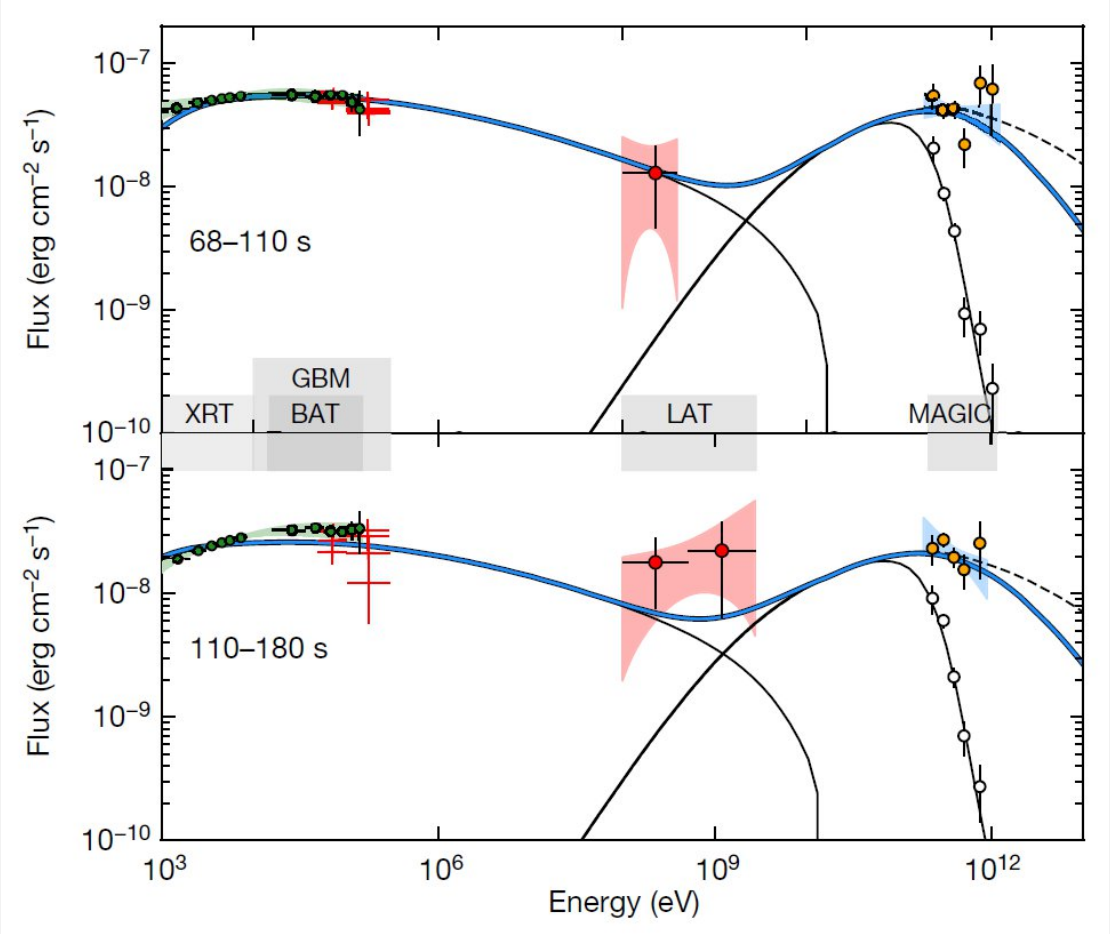
- Flux decay in TeV and X-rays is similar, link between the two processes



Nature 575, 455-458 (2019) & Nature 575, 459-463 (2019)

GRB 190114C

- Energies of photons detected by MAGIC well above the synchrotron burnoff limit for a one zone model (<~ 100 GeV for all the MAGIC observation duration)
  - emission process cannot be synchrotron!
- MAGIC TeV data well described by SSC process, with Klein-Nishina and internal g-g absorption considered
  - possibility of fitting only one synchrotron component? see GRB 190829A in the next slides
- Discovery of a new emission component in the afterglow of a GRB!
- Modeling parameters in agreement with previous GRB aferglow studies, and GRB 190114C does not seem exceptional
  - VHE emission might be common



Nature 575, 455-458 (2019) & Nature 575, 459-463 (2019)

LIV with GRB 190114C

- One can use the observed LC and spectrum to build the likelihood of detecting a LIV effect at a given order n (n=1, 2) and use the maximum likelihood method to constrain the LIV parameters
- First study of this kind using GRB data at VHE, but not so sensitive (at least for n=1):
  - GRB 190114C is at moderate distance
  - it was detected during the afterglow, where LC is a decaying monotonically, so no time variability
  - comparable to past results for n=2 (here Mrk 501 is better given that E_{max} ~ 10 TeV)

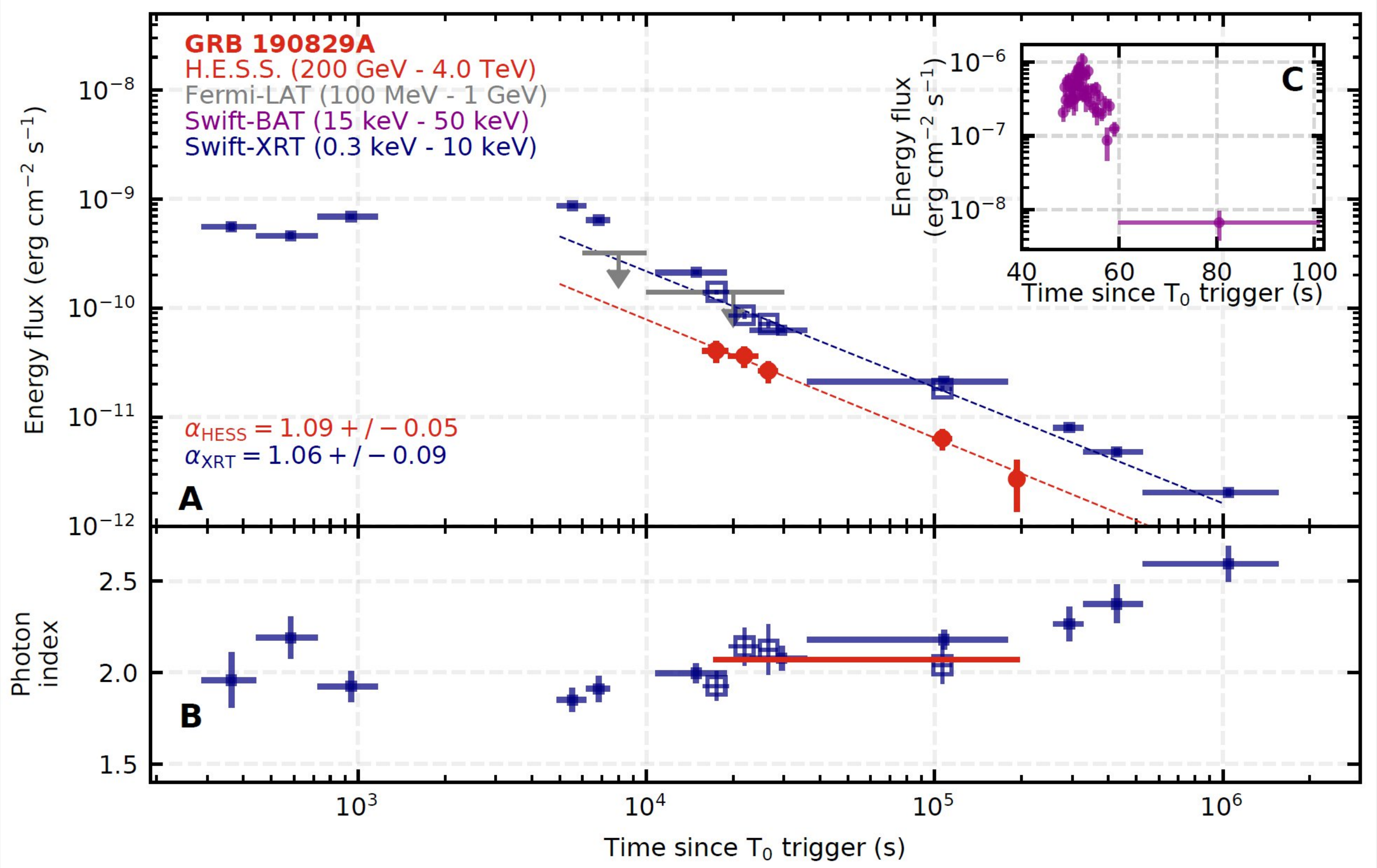
PRL 125, 021301 (2020)

Source	Source type	Redshift	$E_{QG,1}$ [10^{19} GeV]	$E_{QG,2}$ [10^{10} GeV]	Instrument
GRB 090510	GRB	0.9	9.3	13	*Fermi*-LAT[1]
GRB 190114C	GRB	0.42	**0.58**	**6.3**	MAGIC ← **this work**
PKS 2155-304	AGN	0.116	0.21	6.4	H.E.S.S.[2]
Mrk 501	AGN	0.034	0.036	8.5	H.E.S.S.[3]
Mrk 501	AGN	0.034	0.021	2.6	MAGIC[4]
Mrk 421	AGN	0.031	pending	pending	MAGIC
Crab Pulsar	Pulsar	2.0 kpc	0.055	5.9	MAGIC[5]

1 Vasileiou+ (2013)
2 Abramowski+ (2011)
3 Abdalla+ (2019)
4 Albert+ (2008)
5 Ahnen+ (2017)

GRB 190829A

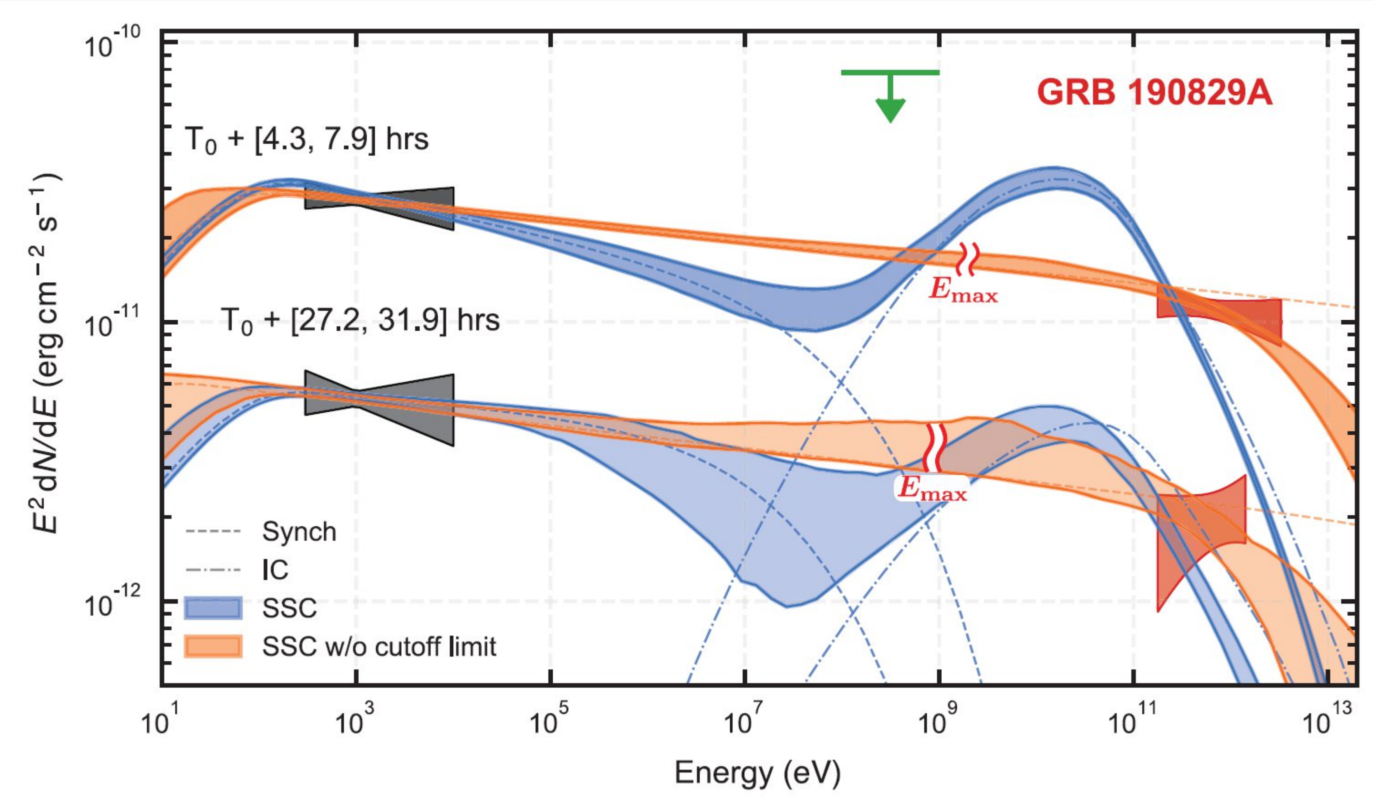
- Low-luminosity long GRB
  - T_{90}~58 s
  - E_{iso}~2x10^{50} (10-1000 keV)
  - z=0.0785
- Follow-up by H.E.S.S. for 3 consecutive nights
  - T_0+4.3h for 3.6h (21.7σ)
  - T_0+27.2h for 4.7h (5.5σ)
  - T_0+51.2h for 4.7h (2.4σ)
- Also in this case, decay of VHE and X-ray light curves is similar



Science 372, 6546, 1081-1085 (2021)

GRB 190829A

- Synchrotron proposed as the possible process responsible for VHE emission
- No maximum energy for the synchrotron process is favored at 5σ level over SSC, given the low Lorentz factor expected (and decreasing over time)
- But see e.g. Salafia et al. to see a possible modeling of VHE emission from GRB 190829A with SSC



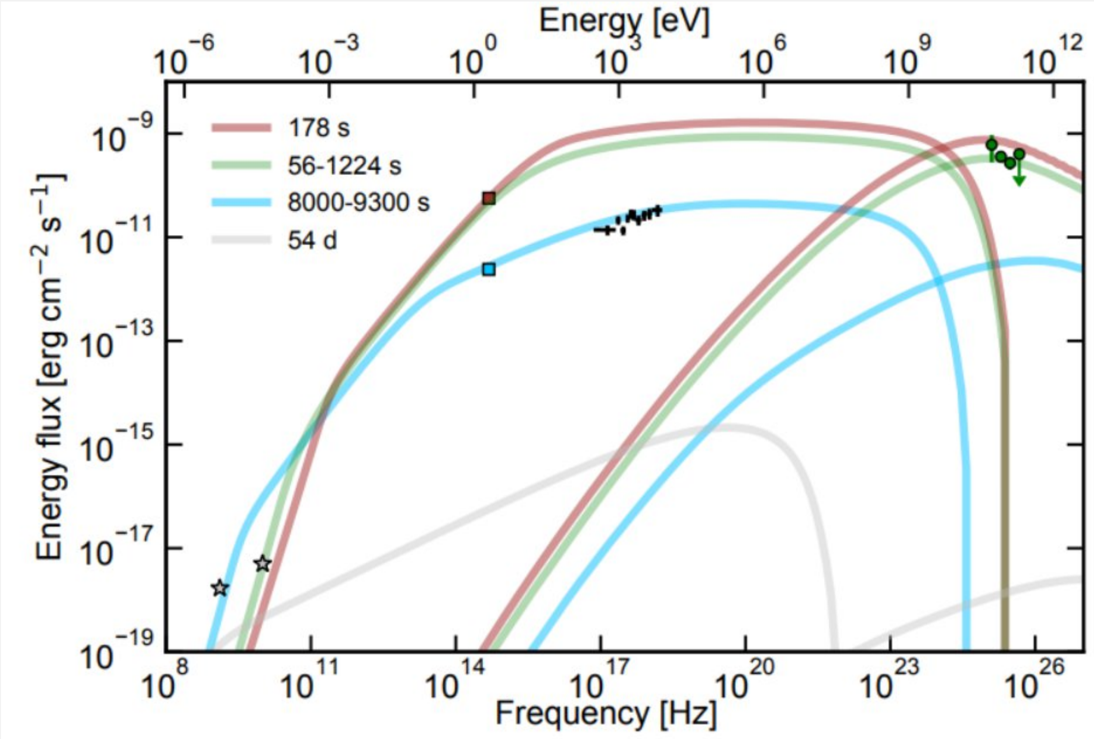
Science 372, 6546, 1081-1085 (2021)

GRB 201216C

- Bright long GRB
  - T_{90}~48 s
  - E_{iso}~5x10^{53} (1-10000 keV)
  - **z=1.1!!!**

- Follow-up by MAGIC from ~1min after T_0, detection above 5σ
  - farthest source detected at VHE

- MWL fluxes are consistent with the synchrotron+SSC model (Miceli&Nava 2022)
  - Sub-TeV emission is well above the maximum synchrotron energy (~10 GeV at T0+~177 s)
  - No solution found with a homogeneous density medium



MNRAS (https://doi.org/10.1093/mnras/stad2958)

GRB 221009A: the BOAT

- Initially classified as bright galactic transient by Swift (Swift J1913.1+1946)
  - Fermi-GBM later reported a detection from a very bright and long GRB positionally consistent with the Swift alert --> renamed to GRB 221009A

- Detection by Fermi-LAT

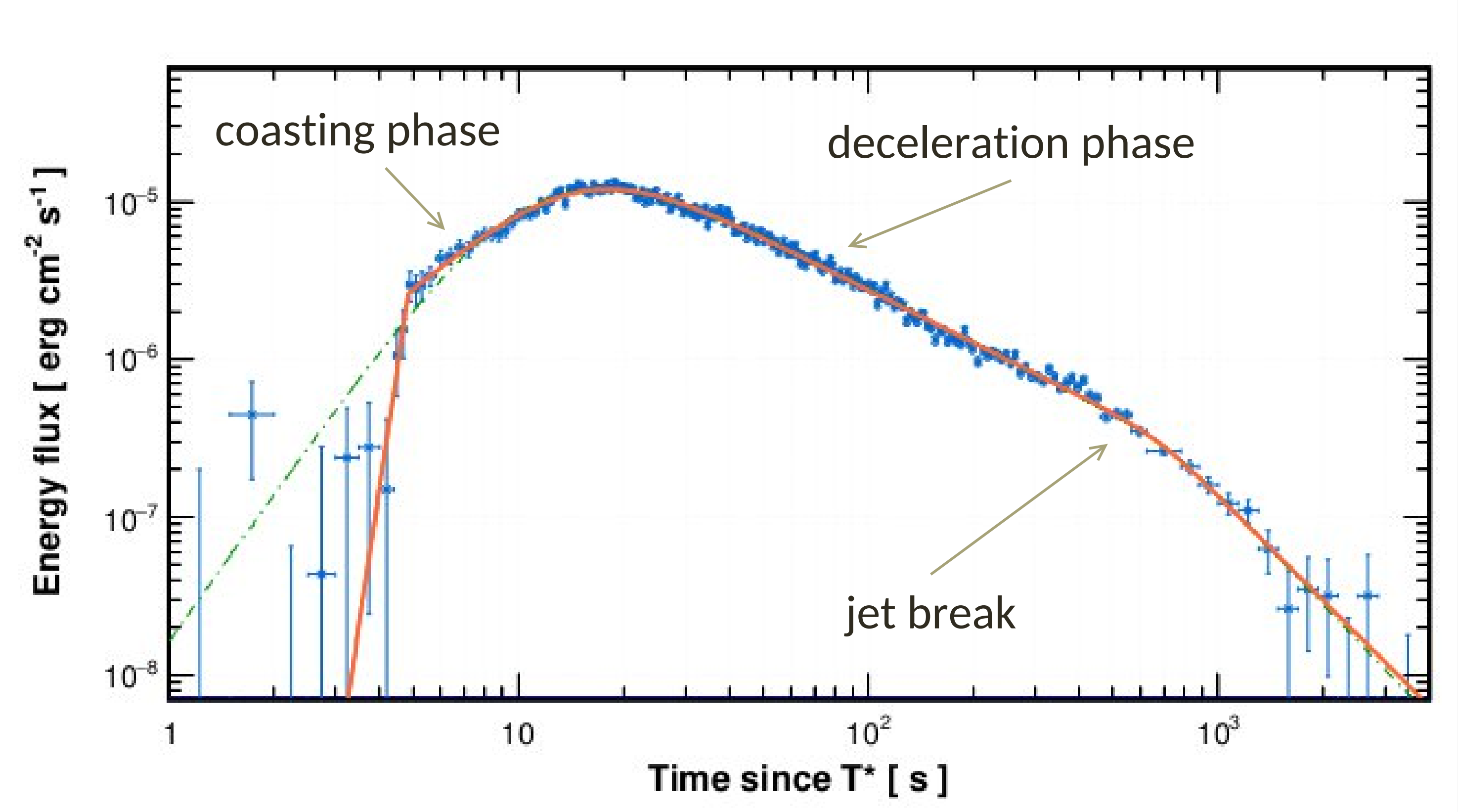
- Very close (z=0.15) and bright (Eiso ~ 2×10^{54} erg) --> the brightest of all time (BOAT)

- First detection of a GRB by an extensive air shower array by LHAASO
  - no detection by HAWC (observation after ~8h from trigger)

- Would have been a perfect GRB candidate for IACTs as well, however it happened during full moon time, when usually IACTs do not operate

GRB 221009A: LHAASO

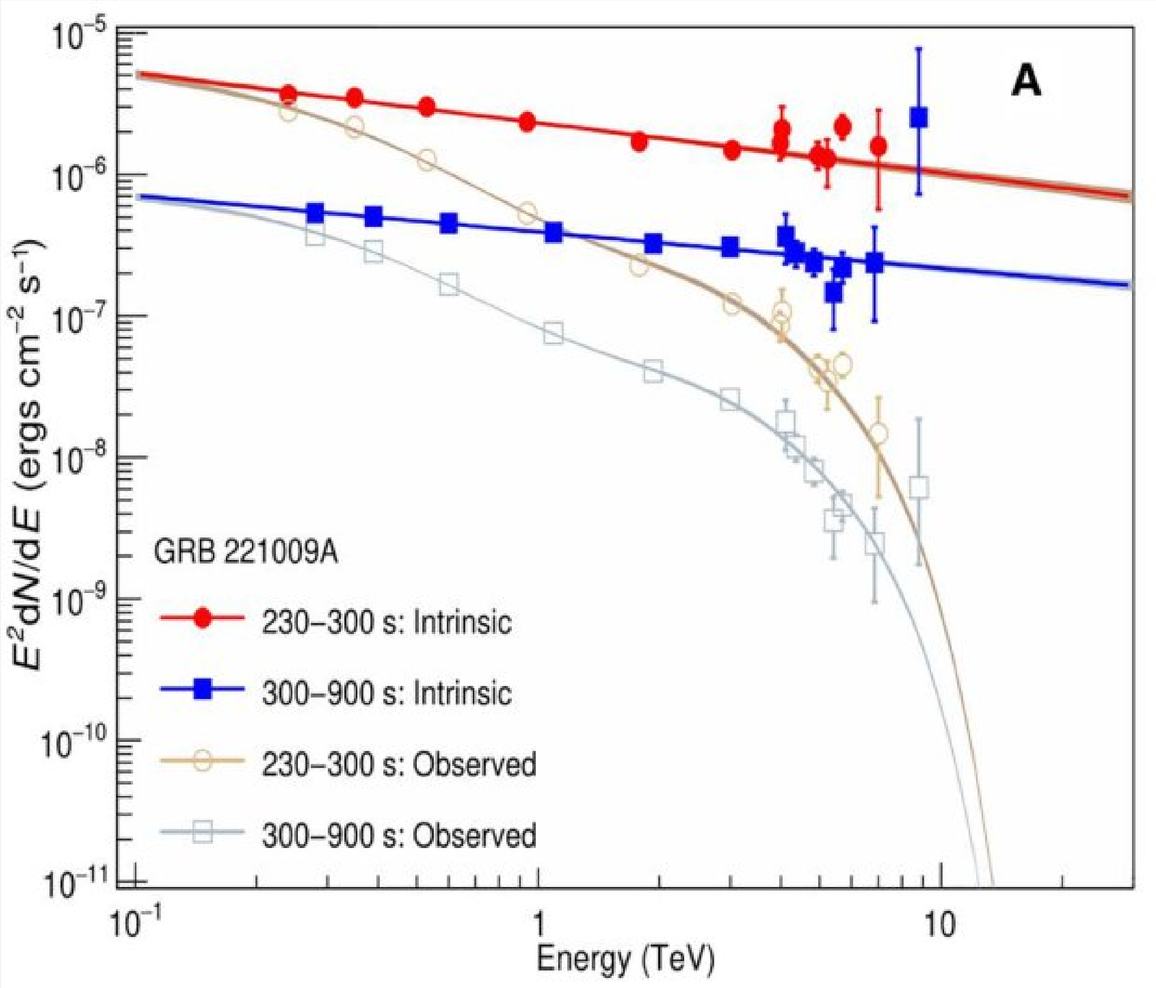
Science 380, 1390–1396 (2023)



Note: T*= T0+225s

- Light curve [0.3-5] TeV is "smooth", no variability as in the simultaneous GBM data --> rise of the afterglow
- Steepening at ~T*+500s: jet break --> small opening angle 0.8deg
- Peak of the afterglow can be used to estimate the Lorentz factor of the GRB (~600 in this case)
- LHAASO does not detect prompt emission, pointing to high optical depth for (sub)TeV gamma rays

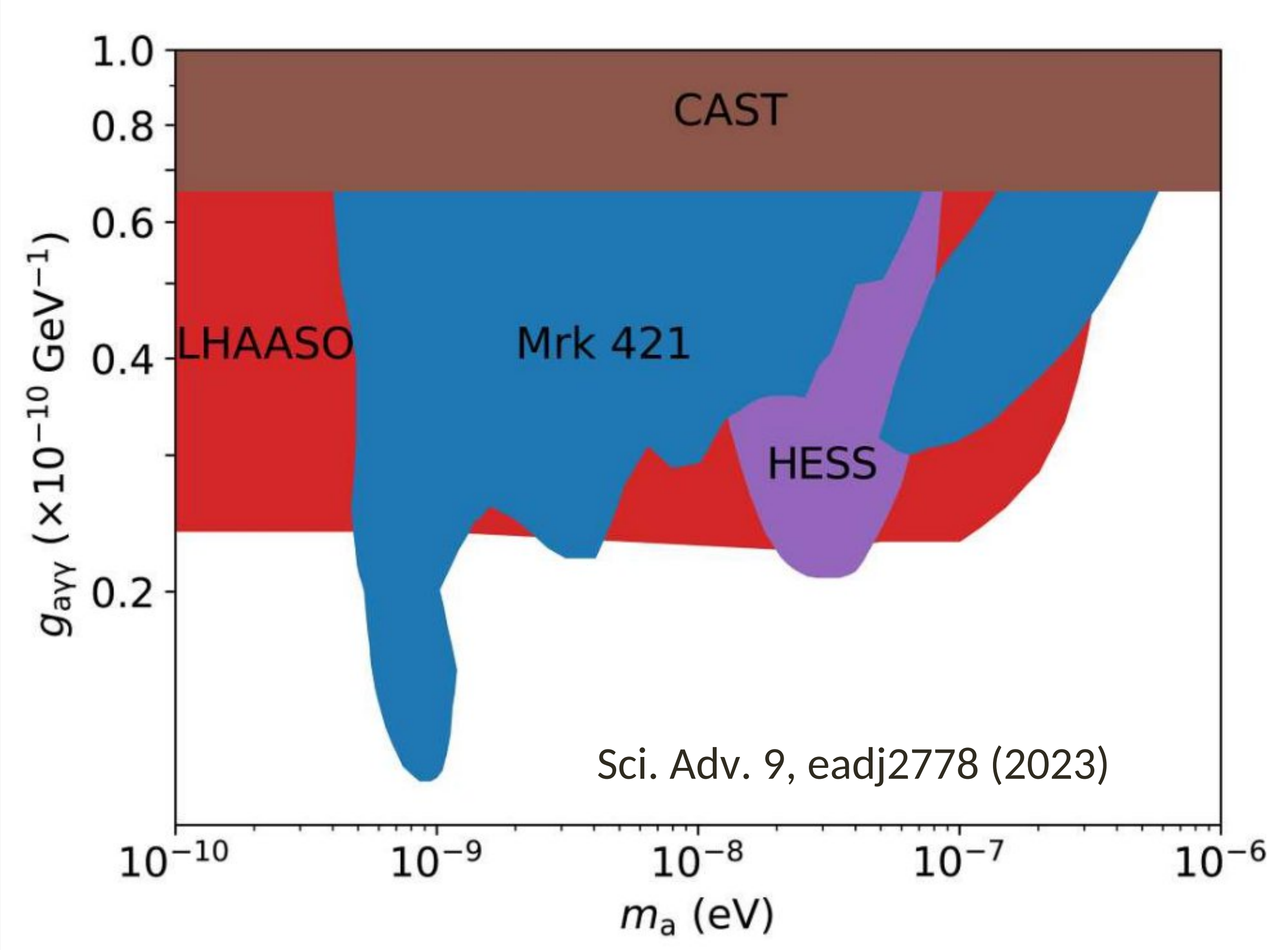
GRB 221009A: LHAASO



Sci. Adv. 9, eadj2778 (2023)

- Data from WCDA modelled within an SSC scenario
- However, also including KM2A data (up to ~10 TeV), intrinsic spectrum does not show any softening due to Klein Nishina effect
  - reverse shock contribution?
  - possible additional leptonic component in a two zone model?

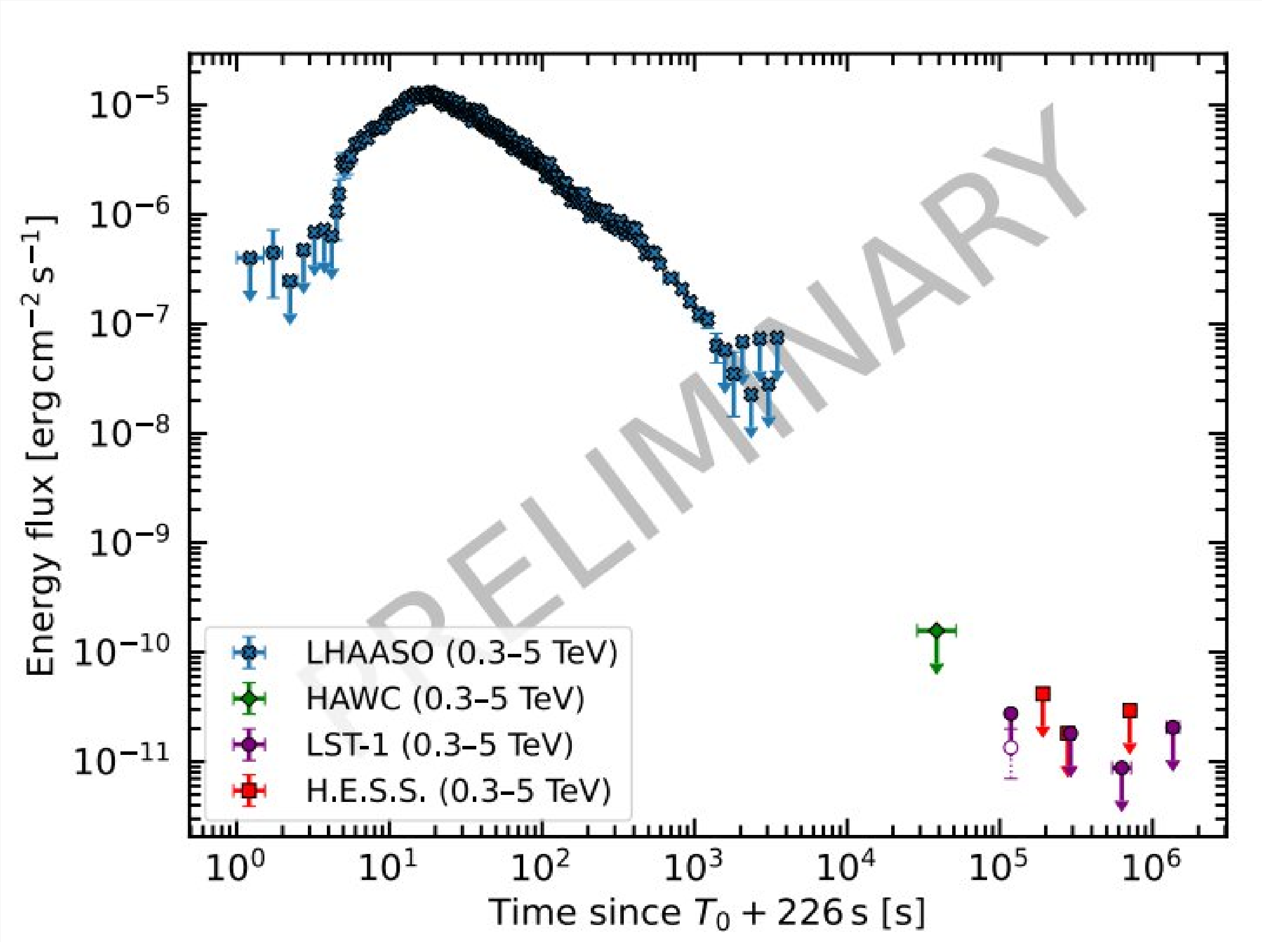
GRB 221009A: LHAASO



- Gamma rays at >10 TeV from z=0.15 should be heavily suppressed
- Possible "natural" explanations
  - lower EBL intensity in infrared range
  - misidentification of a cosmic ray background event as gamma ray
  - misreconstruction (or migration) of events
- Possible exotic explanations
  - Lorentz Invariance Violation
  - Axion-like particles

GRB 221009A: LST-1

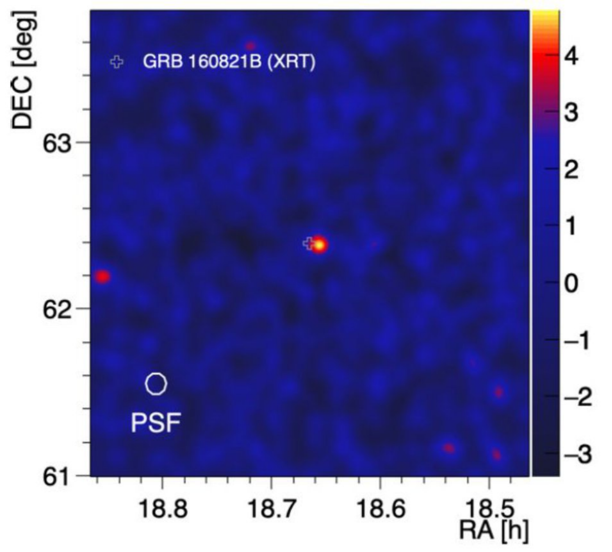
- Light curve with LHAASO, HAWC, LST-1 and H.E.S.S.
- LST-1 performed the first follow-up among IACTs, under very strong moonlight
  - hint at ~4 sigma the first day of follow-up (T0+1.33 days)
- LST-1 ULs are ~1 order of magnitude lower than HAWC, and at a similar level as H.E.S.S.
- For the H.E.S.S. data and interpretation, see https://iopscience.iop.org/article/10.3847/2041-8213/acc405



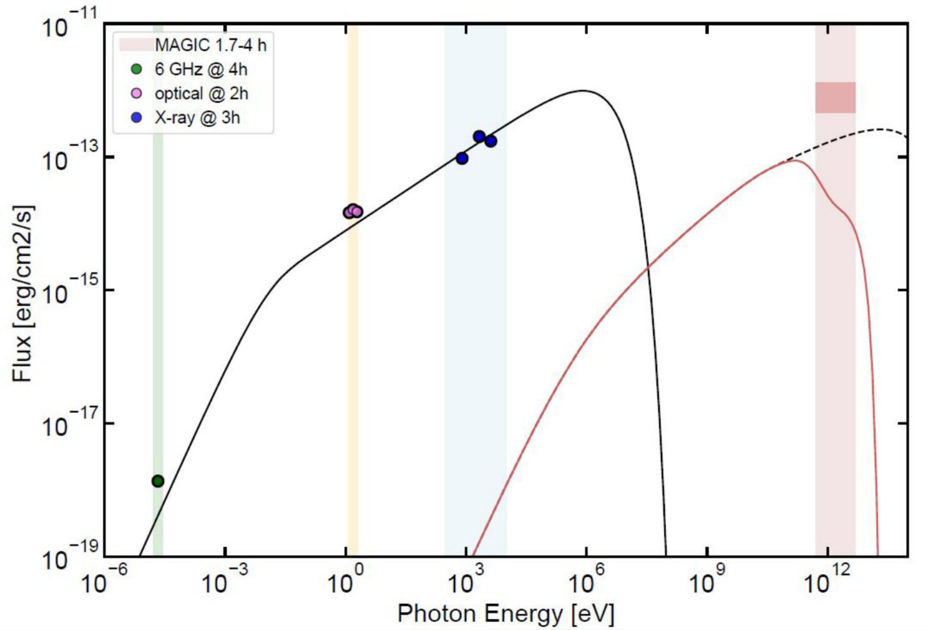
Presented at Gamma 2024 (https://indico.ict.inaf.it/event/2661/contributions/19210/)

GRB 160821B

- Short GRB at low redshift (z=0.16), fast follow-up by MAGIC (24s)
- Data affected by moon and partially by bad weather
- Evidence of gamma-ray signal at 3.1 sigma pre-trial, 2.9 post-trial
- Kilonova emission confirmed
- Simplest emission model (synchrotron +SSC at external forward shock) is in tension with the TeV predicted flux



ApJ, 908 (2021), 90



GRBs at TeV energies: what did we learn?

1. Continued effort pays off at the end! No GRB firmly detected in ~15 years, now 5 in ~4 years
   - certainly technical developments played a role (alert systems, improvement in the sensitivity, lowered energy threshold, ability to observe in diverse weather conditions)
   - changes in strategies e.g. observe not only close to the onset, but also much later, especially for bright events

2. VHE emission is there, it can be detected if GRB is relatively close
   - for the moment 4 out 5 were bright GRBs, but GRB 190829A case tells us that even dim events can be detected if z is low

3. VHE emission is present both in the early and late afterglow

4. Similarities between flux level in X-ray and VHE bands, also similar time decay

5. MWL data crucial for proper modeling of the emission

6. SSC as possible universal process to explain TeV emission or revisitation of synchrotron?
   - SSC seems to be applicable in most cases, but there can be large scatter between different modelers, who apply different assumptions

GRBs at TeV energies: next challenges

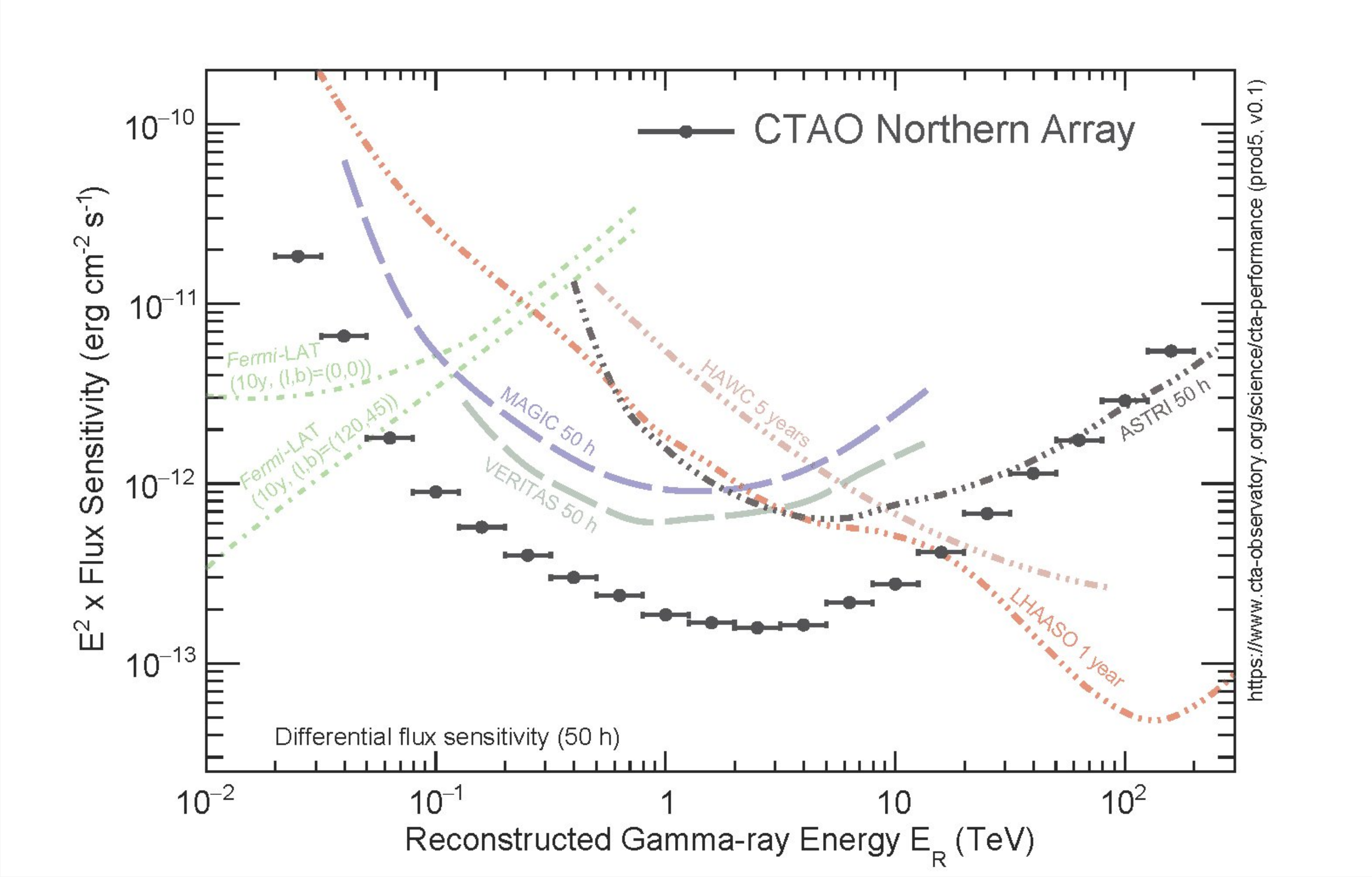
1. Our understanding of the afterglow emission is still uncertain despite the recent detected events
   - we need more GRBs detected at VHE! Looking forward to new facilities like the Cherenkov Telescope Array (CTA)
   - an interesting topic: X-ray flares in the afteglow

2. Another major breakthrough would be the detection of VHE emission during the prompt phase
   - crucial info on the emission process, still heavily debated
   - current and new ground-based wide field of view instruments (HAWC, LHAASO, SWGO) may be better suited for this task, if VHE emission is not totally suppressed
   - optical searches with MAGIC

3. VHE emission from short GRBs? Strong hint from GRB 160821B by MAGIC

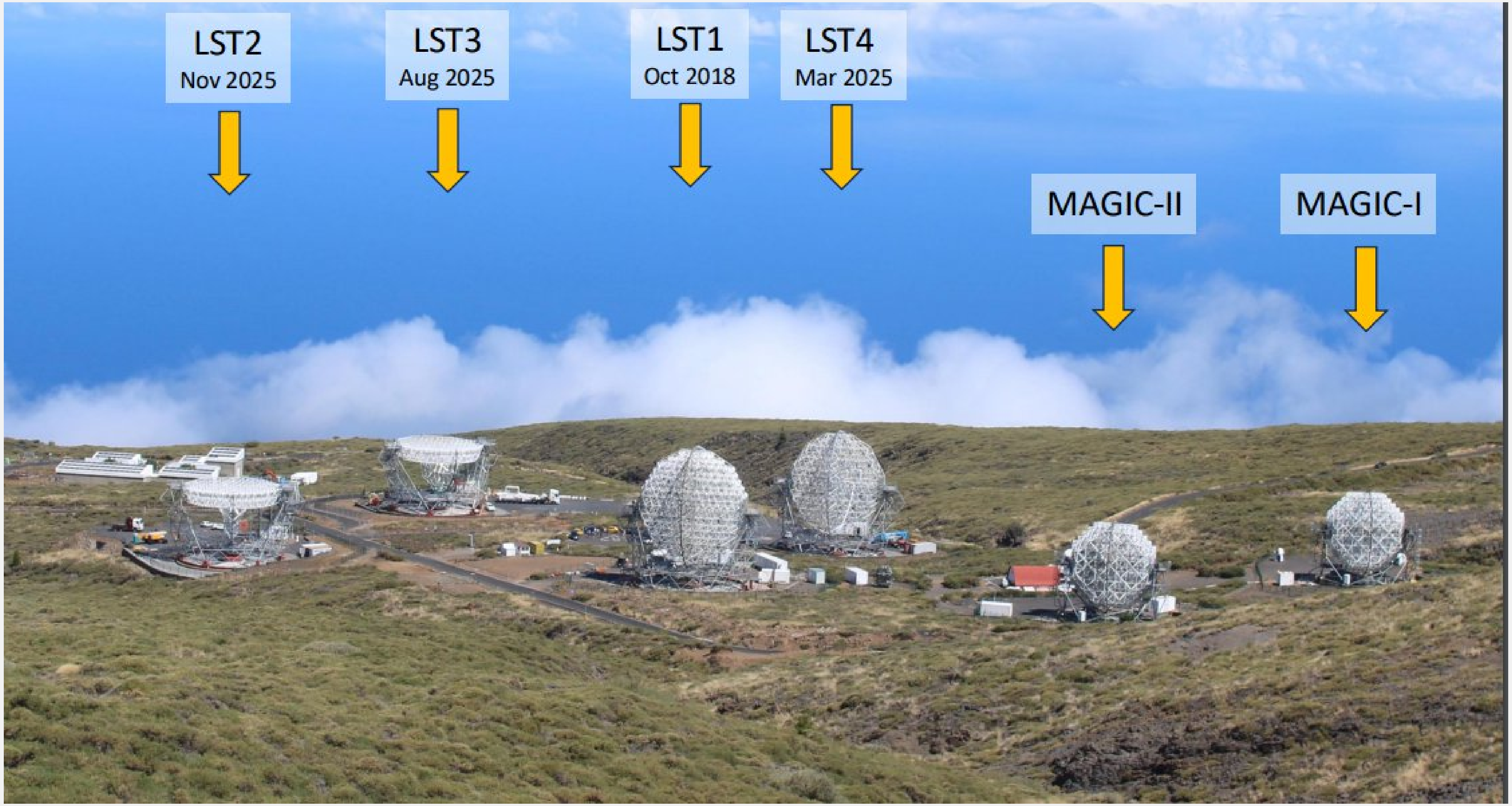
4. New physics
   - Lorentz Invariance Violation (we would need a distant GRB detected in the prompt)
   - Axion-like particles (search for signatures in the spectra; GRBs detected at high redshift)
   - new constraints on EBL?

The (hopefully close, finally) future: CTA

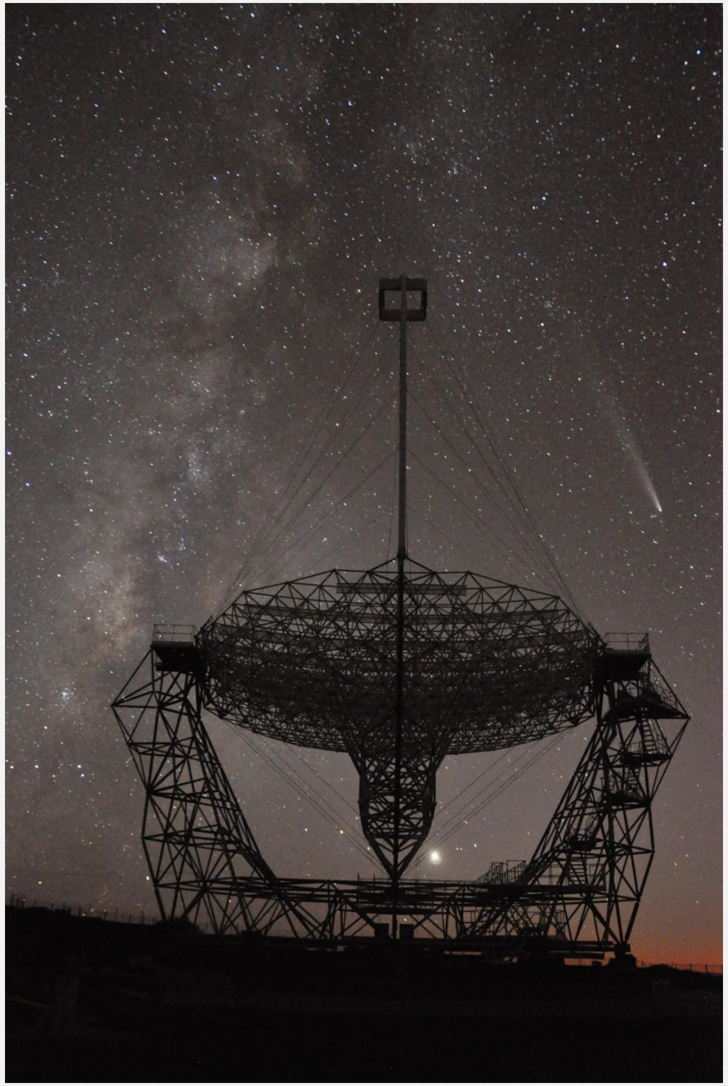


- CTA will provide enhanced sensitivity in all energy ranges
- The most interesting range is the low energy one, where the Large-Sized Telescopes (LSTs) dominate
- 4 LSTs planned in the Northern Array, at least 2 in the Southern
- In the North: 1 LST already operative, 3 under construction
  - energy threshold can be as low as 10-20 GeV

LSTs are growing, fast



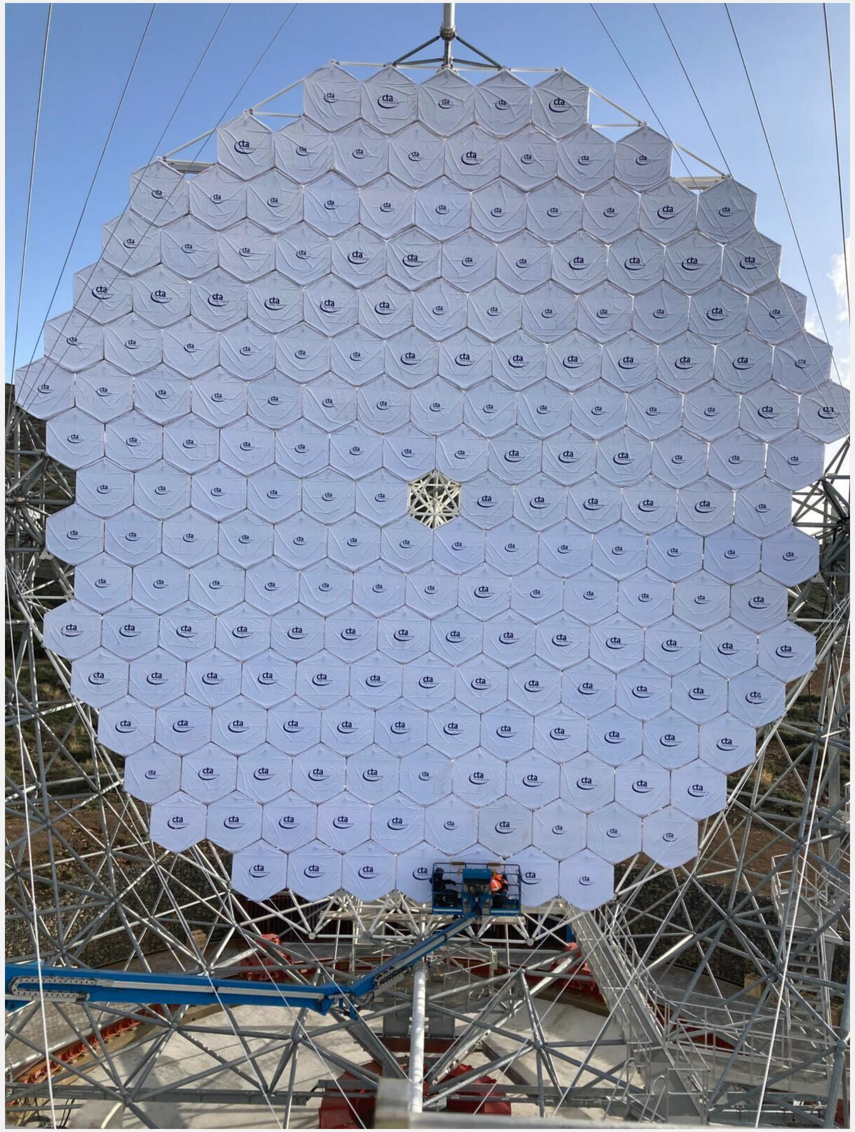
Recent milestones



<-- LST-3 arch installation
(last October)

Construction is progressing well, mostly on schedule! In ~1.5y we will have 4 LSTs ready to hunt GRBs with unprecedented sensitivity!

--> LST-4 mirrors installation complete (yesterday!)



Summary

- After many years of follow-ups, the TeV window on GRBs finally opened

- Quite heterogeneuos GRBs
  - difficult to draw general conclusions, but an important playground for next detections

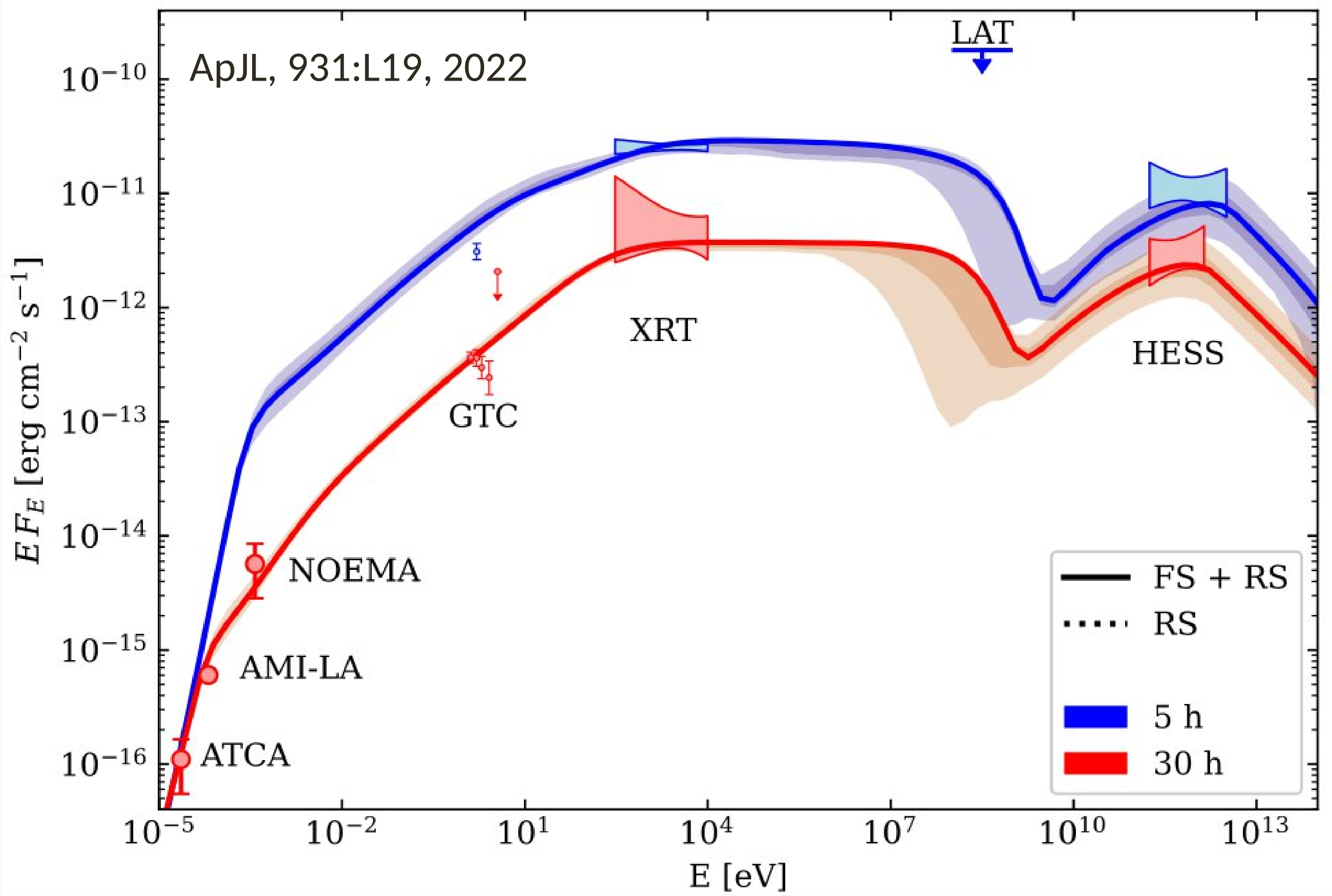
- Modeling/interpretation can be challenging for some of these GRBs
  - still low number of events is one of the limiting factors
  - also, MWL coverage is not always guaranteed

- Current and planned facilities at TeV energies plan to continue the extensive follow-up of GRBs: the TeV era of GRBs has just started!

BACKUP

GRB 190829A

- Possible SSC scenario suggested by Salafia et al.
- Discussed also together with VLBI data



Modeling of GRBs at TeV

Model parameters	E_k (erg)	Γ_0	n_0 (s=0)	A_* (s=2)	ε_e	ε_B	p
180720B							
Joshi et al. 2023	4.5×10^{54}	400	0.035	—	0.05	1.2×10^{-5}	2.4
Wang et al. 2019	10^{54}	300	0.1	—	0.1	10^{-4}	2.4
190114C							
MAGIC et al. 2019	8×10^{53}	700	0.5	—	0.07	8×10^{-5}	2.6
Wang et al. 2019	6×10^{53}	300	0.3	—	0.07	4×10^{-5}	2.5
Zhang H. et al. 2020	5×10^{54}		0.1	—	0.05	5×10^{-6}	2.6
Asano et al. 2020	10^{54}	600	1.0	—	0.06	9×10^{-4}	2.3
Asano et al. 2020	10^{54}	300	—	0.1	0.08	1.2×10^{-3}	2.35
Joshi & Razzaque 2021	4×10^{54}	300		0.02	0.03	1.2×10^{-2}	2.18
Derishev & Piran 2021	3×10^{53}	—	2		0.11	$(3\text{-}6)\times10^{-3}$	2.5
Derishev & Piran 2021	3×10^{53}	—			0.11	$(3\text{-}6)\times10^{-3}$	2.5
190829A							
Salafia et al., 2022	2.5×10^{53}	57	0.21	—	0.03	2.5×10^{-5}	2.01
Zhang L.-L. et al., 2021	10^{51}	35	2.2	—	0.32	6×10^{-4}	2.12
201216C							
MAGIC et al. 2023	4×10^{53}	180	—	2.5×10^{-2}—	0.08	2.5×10^{-3}	2.1
221009A							
LHAASO 2023	1.5×10^{55}	560	0.4	—	0.025	6×10^{-4}	2.2