Gamma-ray Bursts at Very High Energies

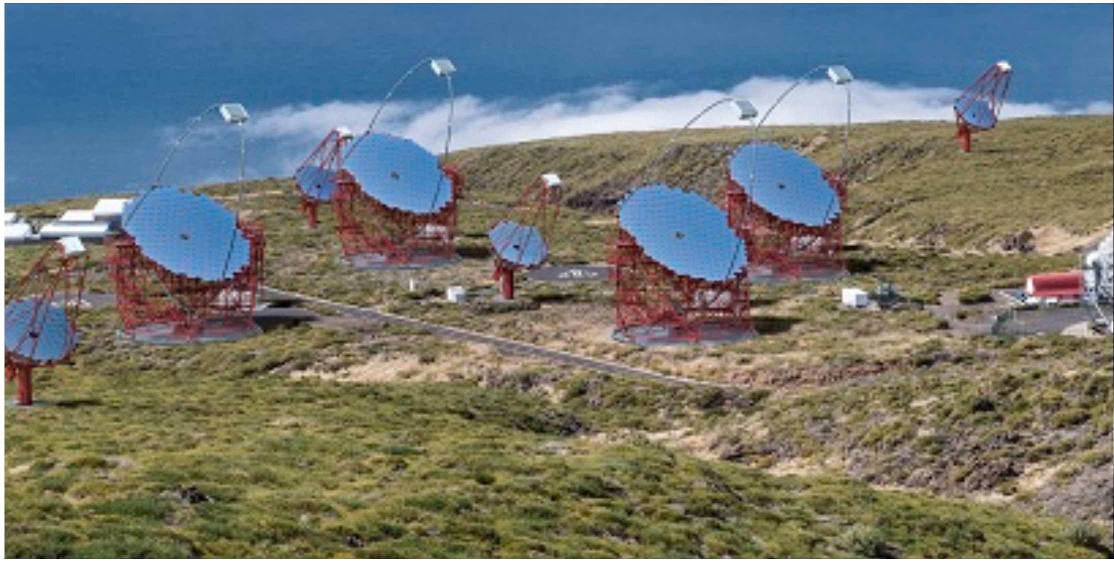
Susumu Inoue (RIKEN)
as a theorist
(not as MAGIC/CTA member)

GRB 190114C (long):
Nature 2019, 575, 455, by MAGIC Collaboration
Nature 2019, 575, 459, by MAGIC, Fermi, Swift, AGILE, optical+radio

GRB 180720B (long):
Nature 2019, 575, 464, by HESS Collaboration

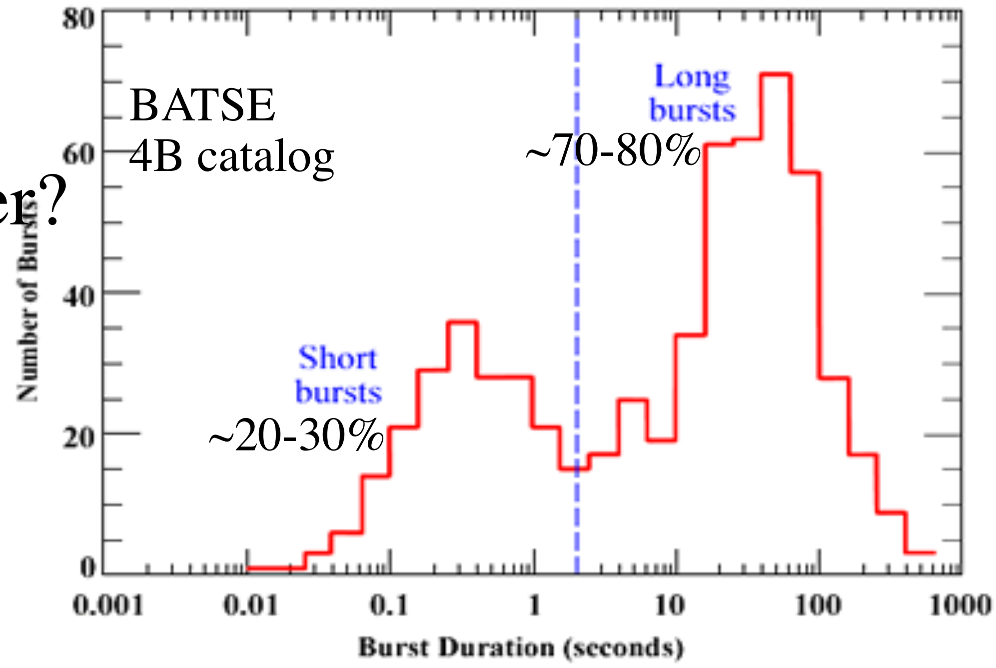
GRB 160821B (short): in preparation by MAGIC Coll.

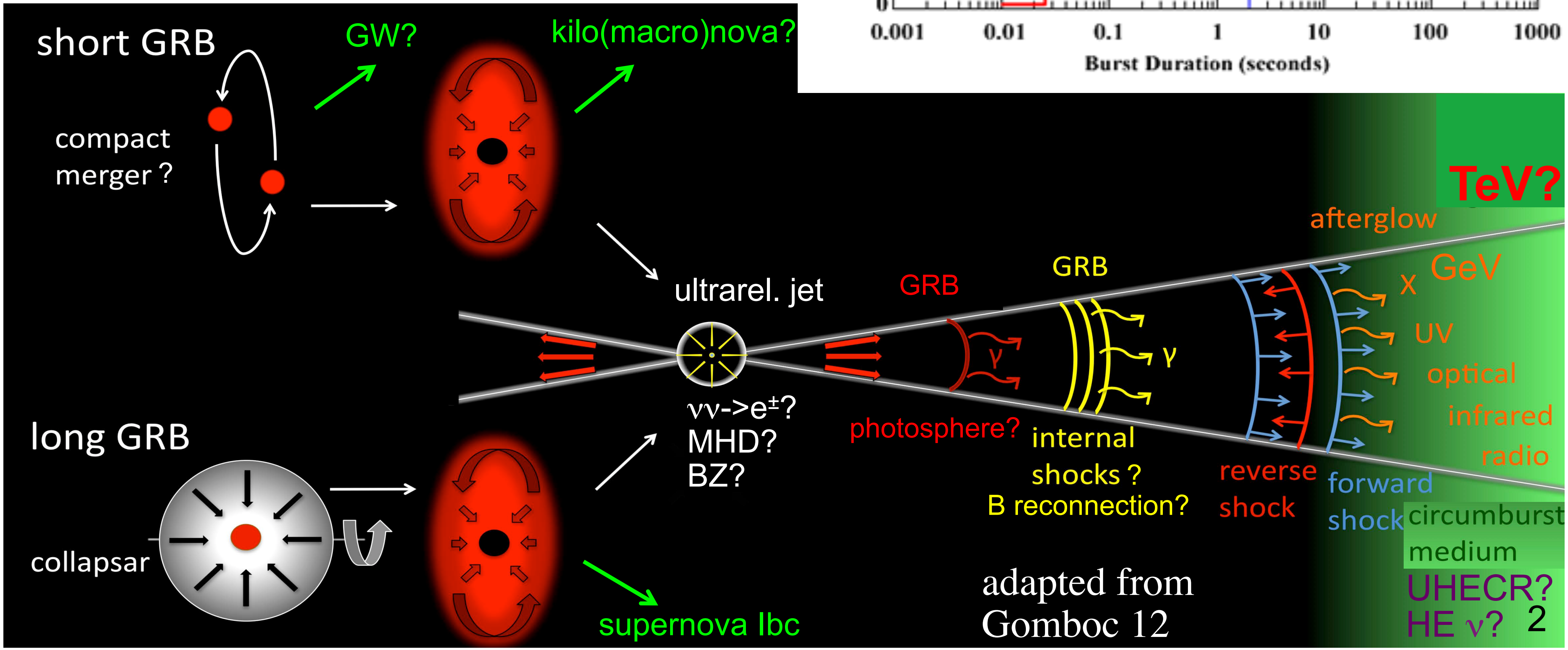
GRB 190829A (low-L): in preparation by HESS Coll.




GRBs: mid 2017

long (>~2s): massive star collapse
short (~<2s): compact binary merger?
-> ultrarelativistic jets
-> prompt: X-MeV
+ afterglow: radio-opt-X-GeV





adapted from Gomboc 12

GRBs: mid 2019

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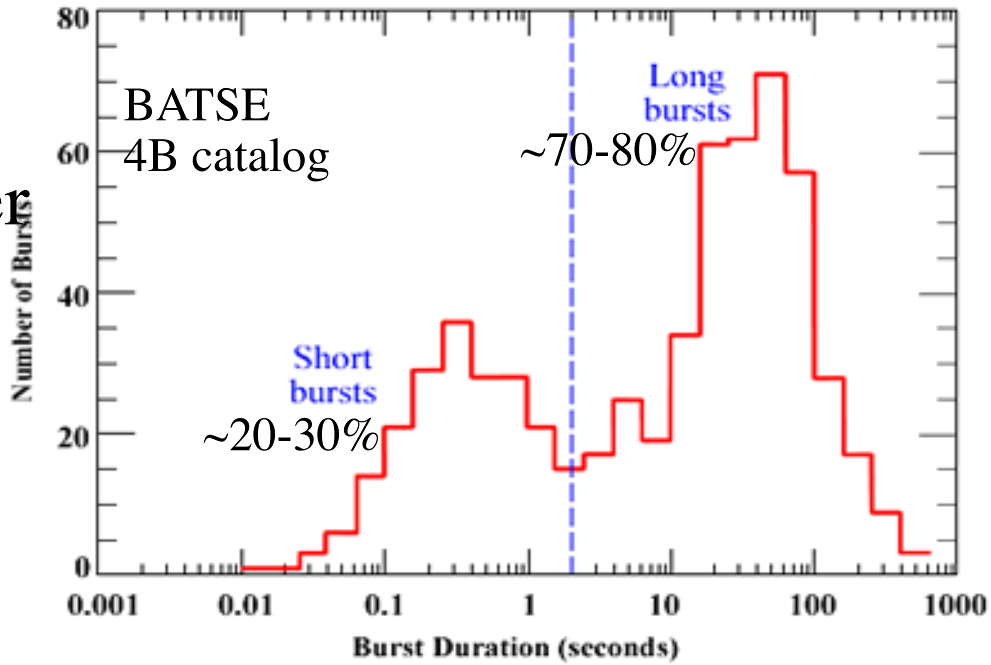
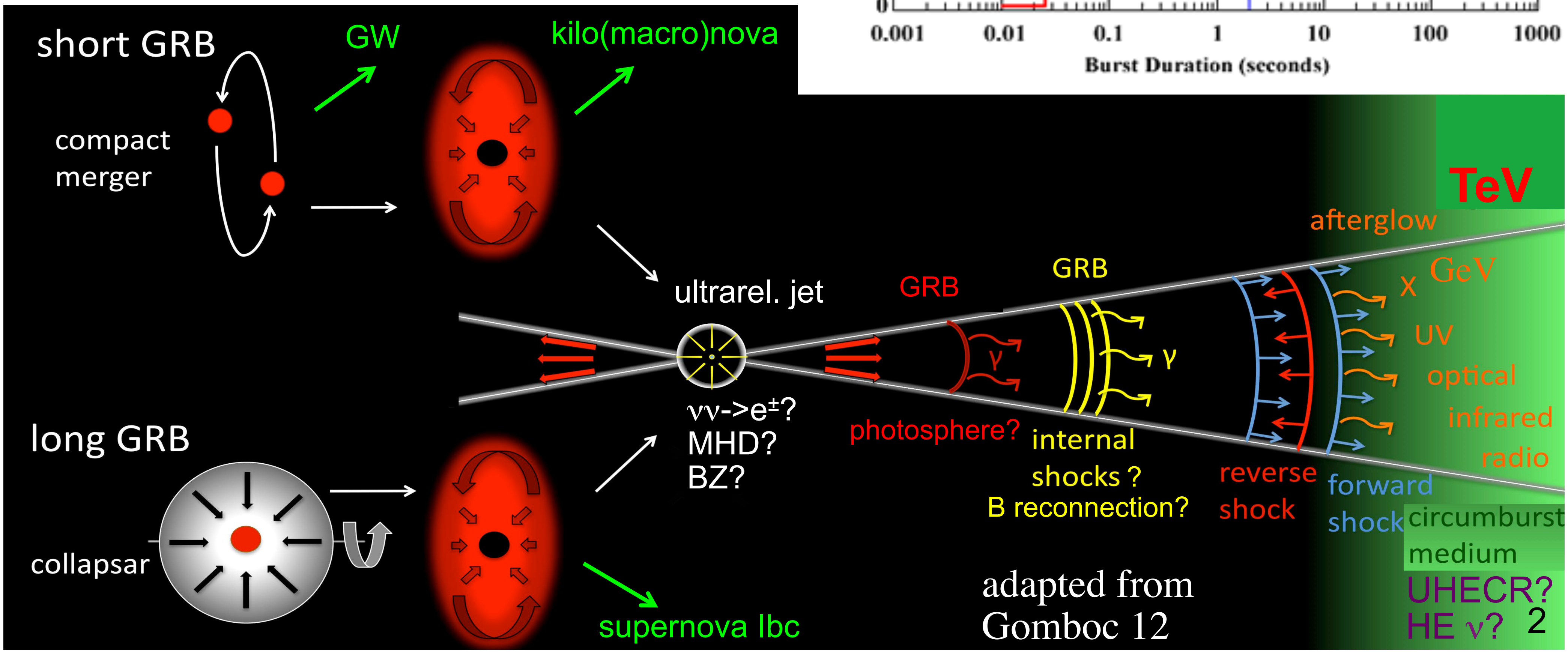
short (~<2s): compact binary merger
-> ultrarelativistic jets
-> prompt: X-MeV
 + afterglow: radio-opt-X-GeV-TeV

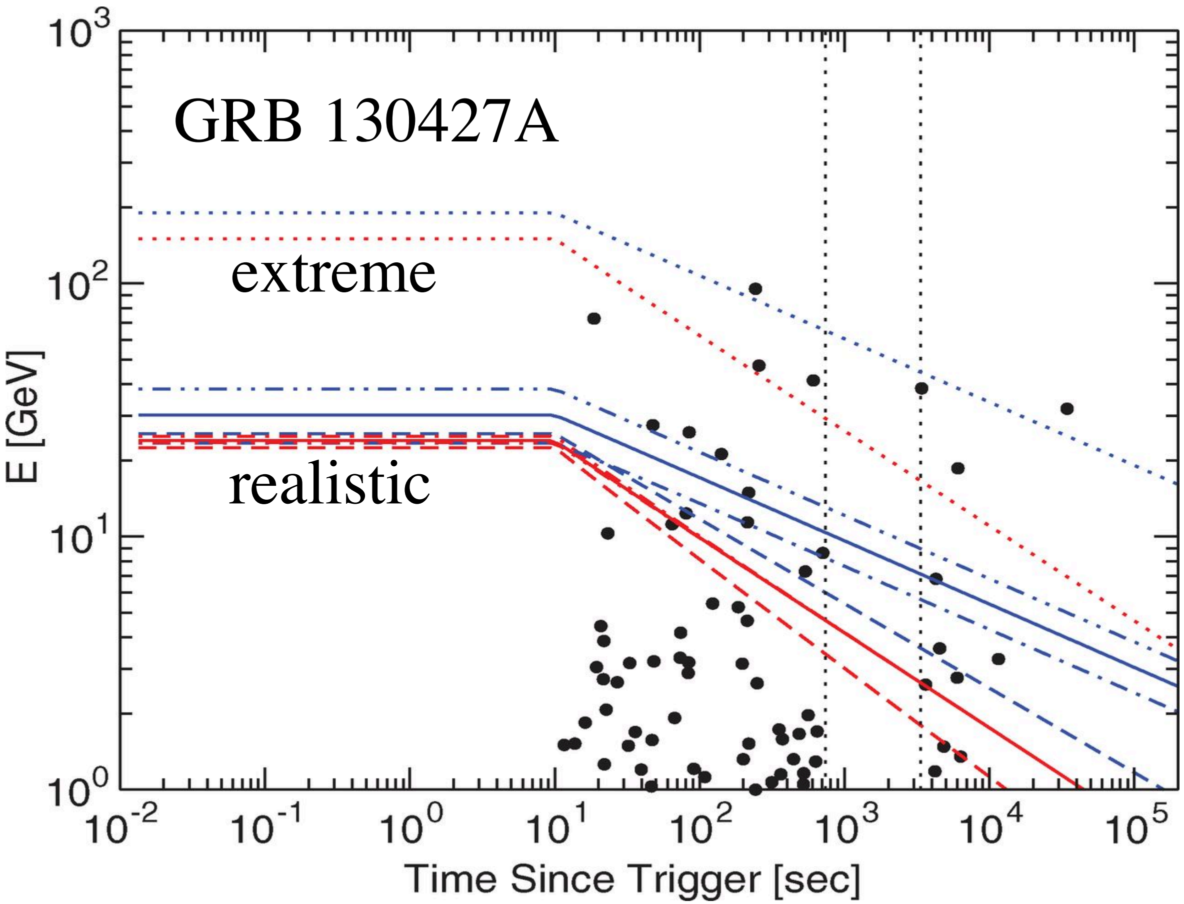




GRB GeV emission

- 186 detections (169 long, 17 short) during Aug 2008 - Aug 2018
- extended emission -> afterglow
- sometimes hard spectrum, separate from Band component
- $E_{\gamma,max}$~<100 GeV

Ajello+ 19, Fermi-LAT 2nd GRB Cat.



Fermi-LAT Coll. 2014, Science 343, 42

maximum synchrotron photon energy for electrons dominated by synchrotron cooling

$\tau_{accel} \propto \gamma_e B^{-1}$, $\tau_{syn} \propto \gamma_e^{-1} B^{-2}$

$\tau_{accel} = \tau_{syn}$ -> $\gamma_{e,max} \propto B^{-1/2}$

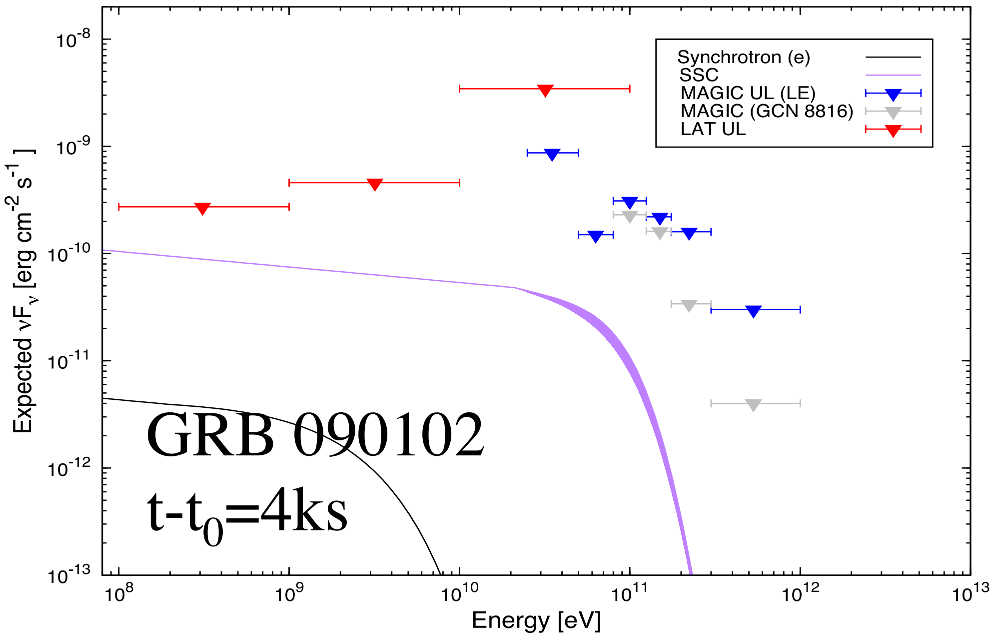
$\nu_{syn,max} \propto B \gamma_{e,max}^2$

$$E_{syn,max} \sim 2^{3/2}[27/(16\pi\alpha_f)] m_e c^2 \times \Gamma(t)(1+z)^{-1}$$

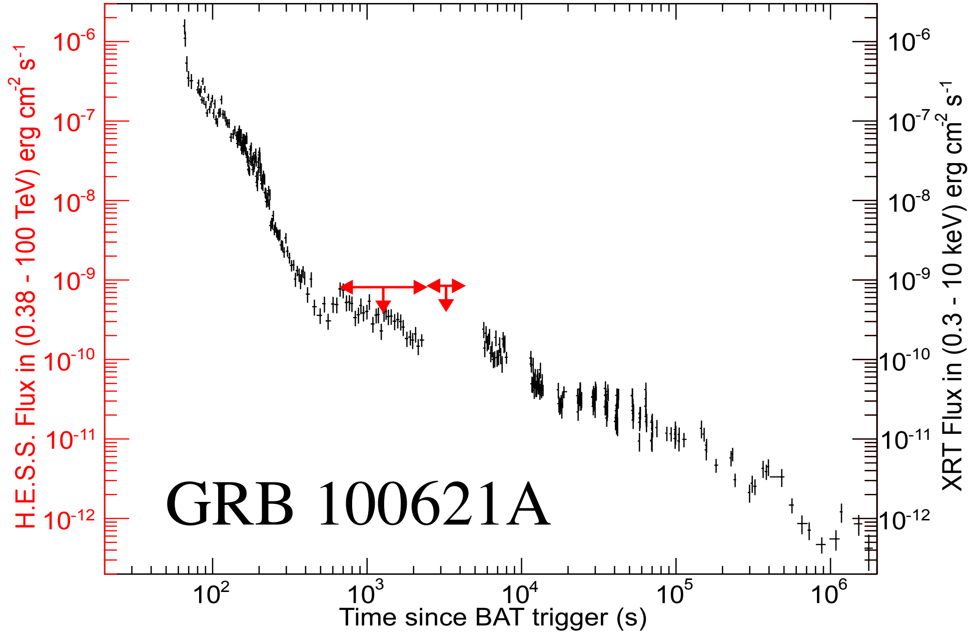
$$\sim 106\ \Gamma(t)(1+z)^{-1}\ \mathrm{MeV}$$

ground-based γ-ray telescopes: some results before 2019

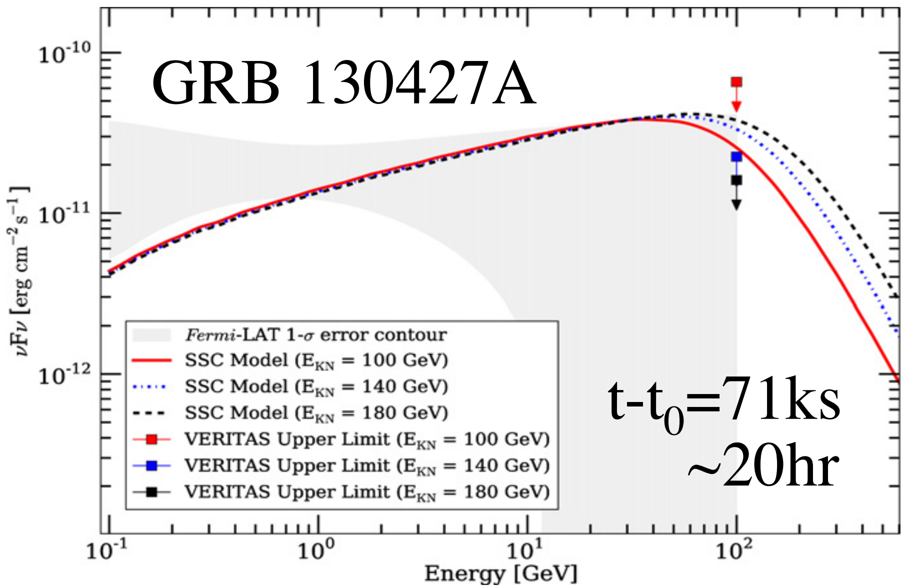
MAGIC+Fermi Aleksic+ 2014



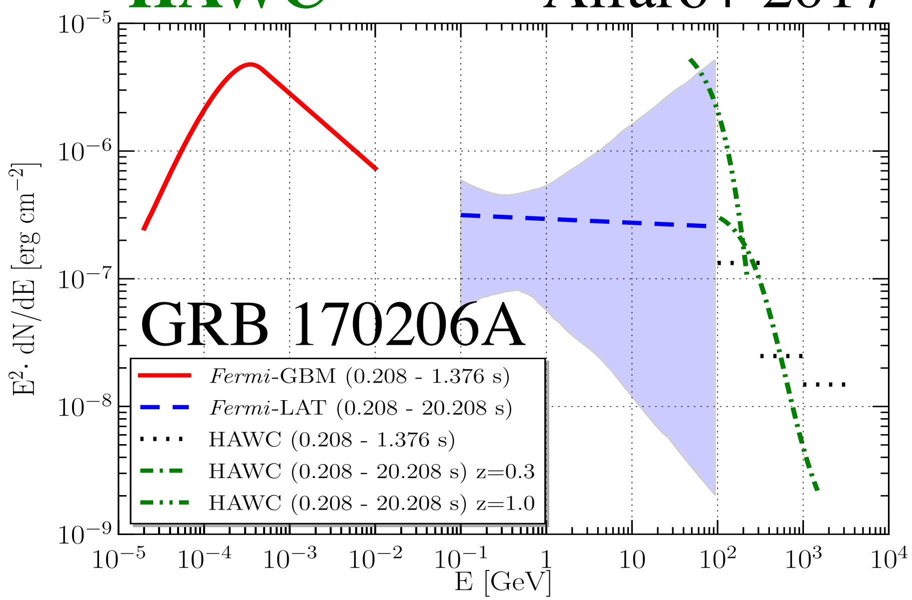
HESS Abramowski+ 2014



VERITAS Aliu+ 2014



HAWC Alfaro+ 2017



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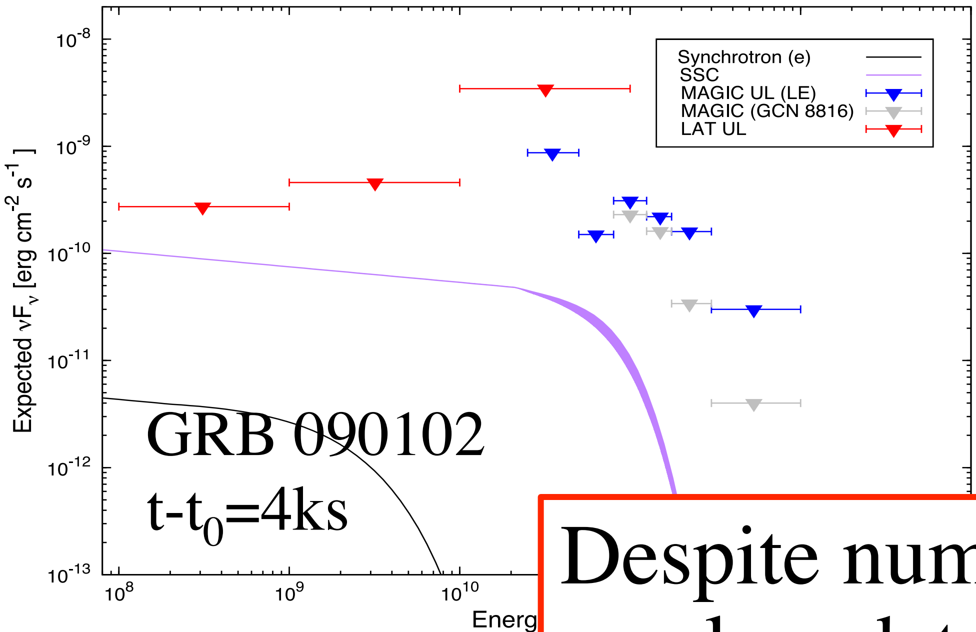
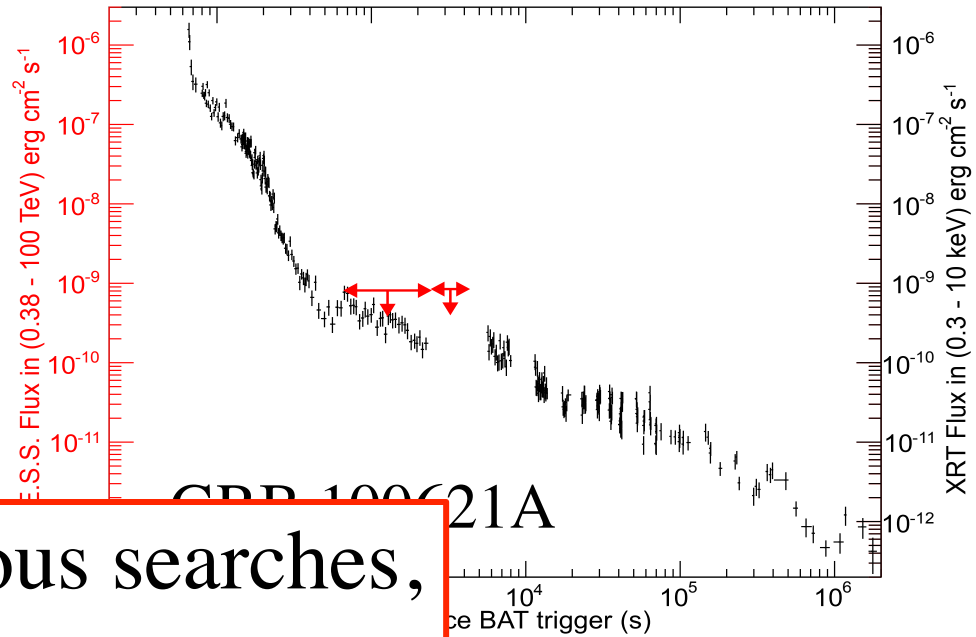
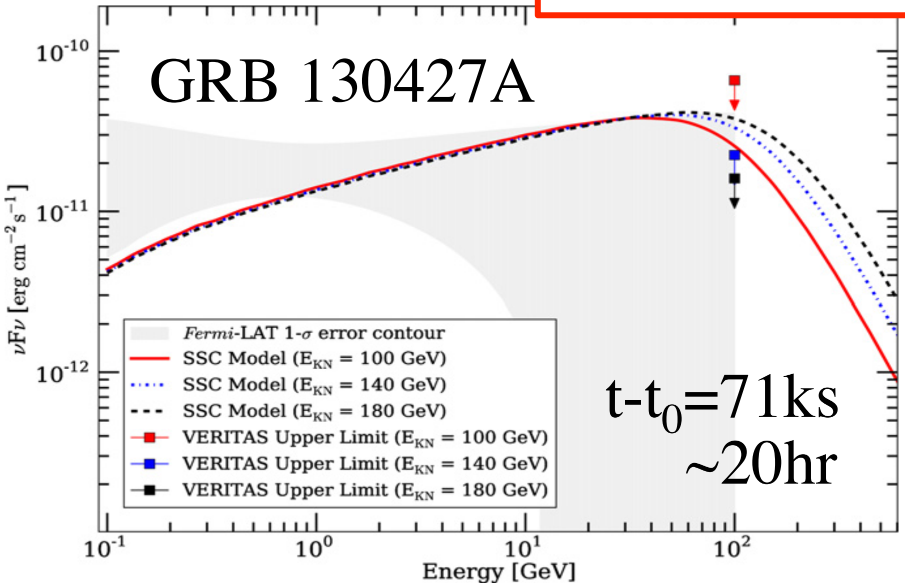


HESS Abramowski+ 2014

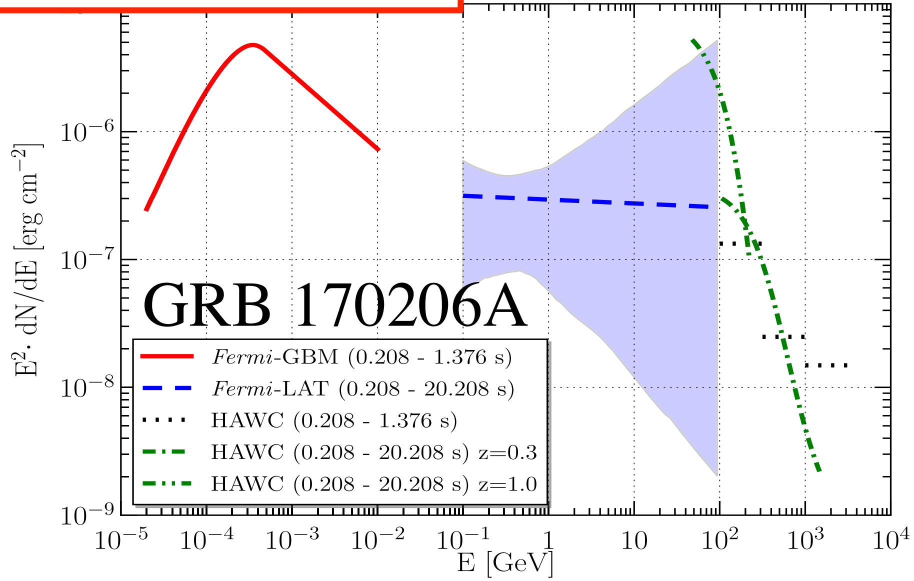


Despite numerous searches, no clear detections…

VERITAS

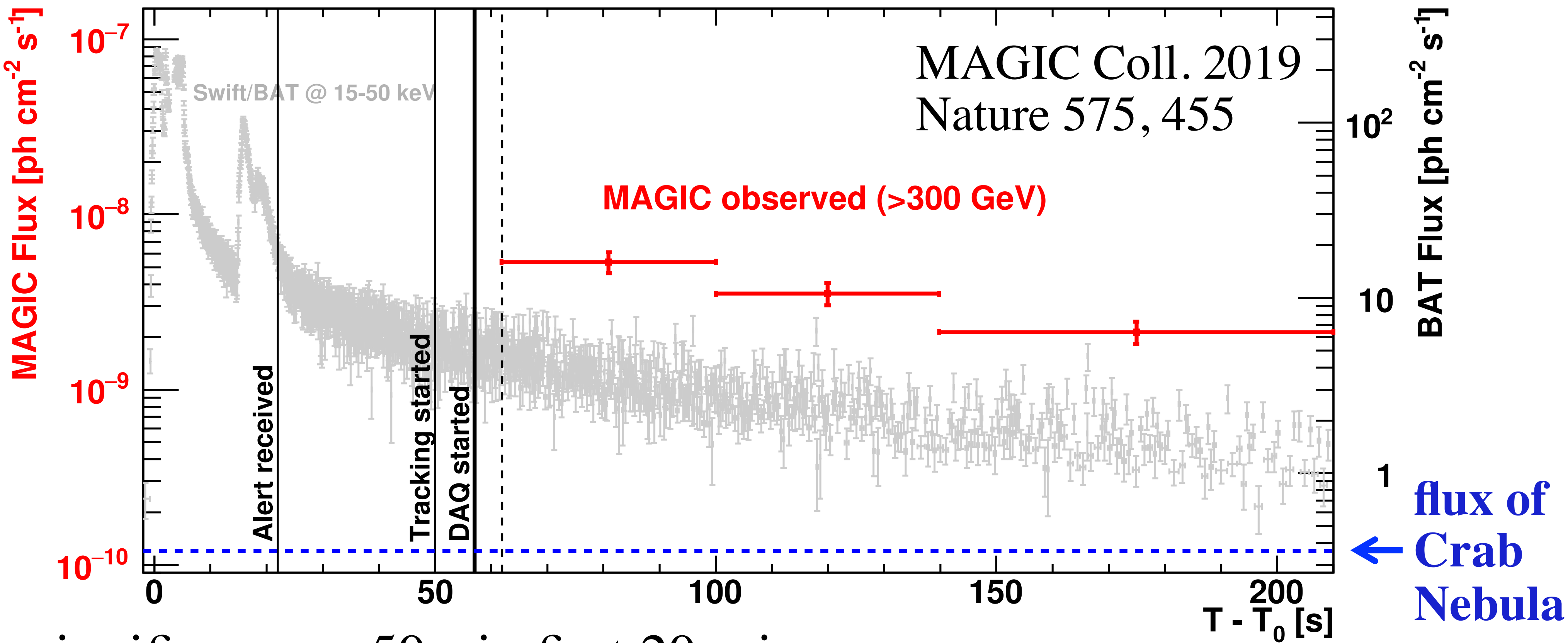


Alfaro+ 2017



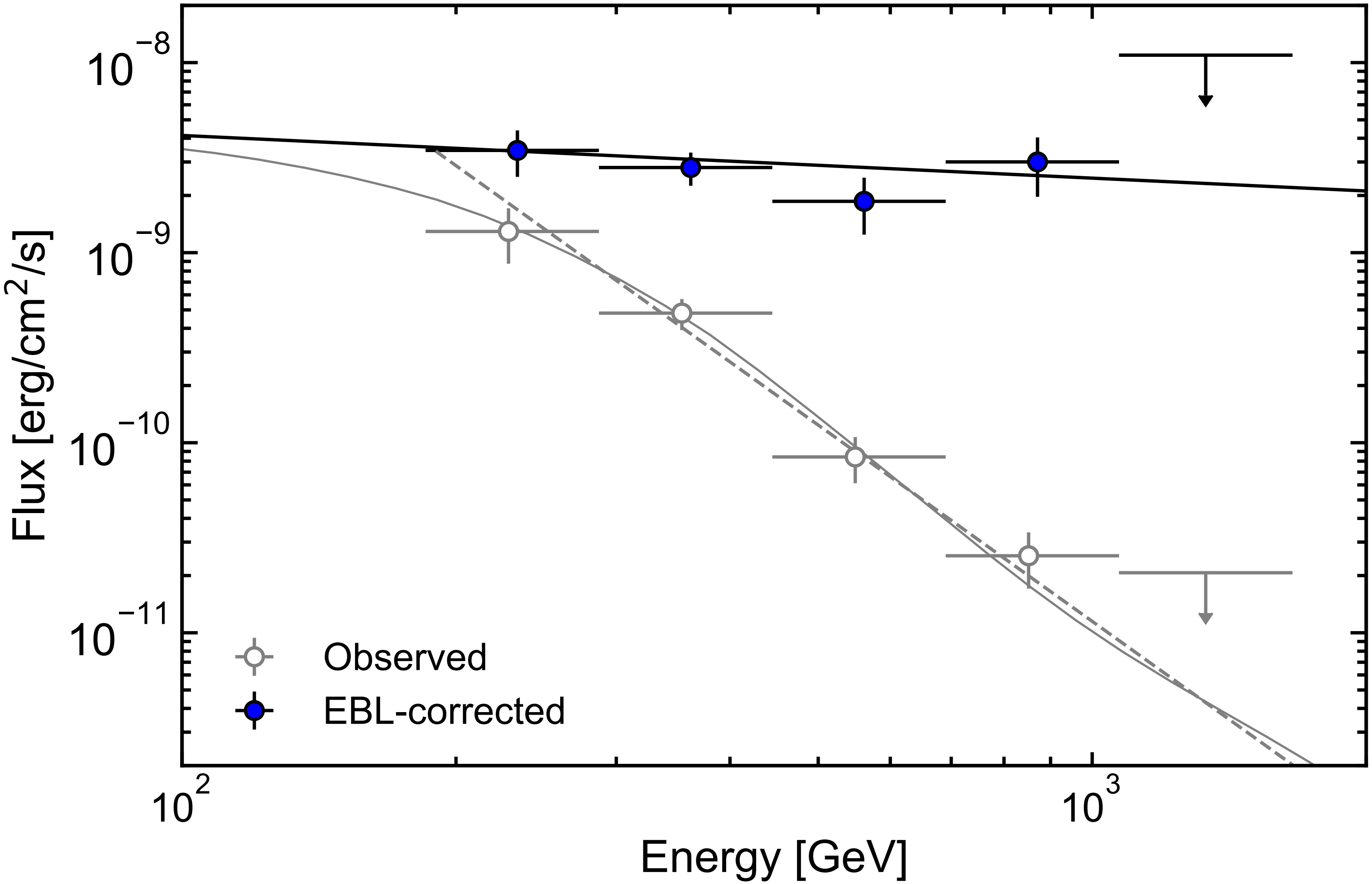
GRB 190114C: keV-MeV vs TeV

- T_{90} ~116 s (GBM), ~362 s (BAT)
- z=0.425 (afterglow abs. + host galaxy emi.)
- E_{iso}~3x10^{53} erg, L_{iso}~1x10^{53} erg/s (1-10^4 keV)



- significance > 50σ in first 20 min
- ~0.1 kiloCrab > 0.3 TeV in first 30 s, brightest TeV source to date
  -> L_{iso} ~3x10^{49} erg/s, most luminous TeV source to date

GRB 190114C: time-integrated TeV spectrum

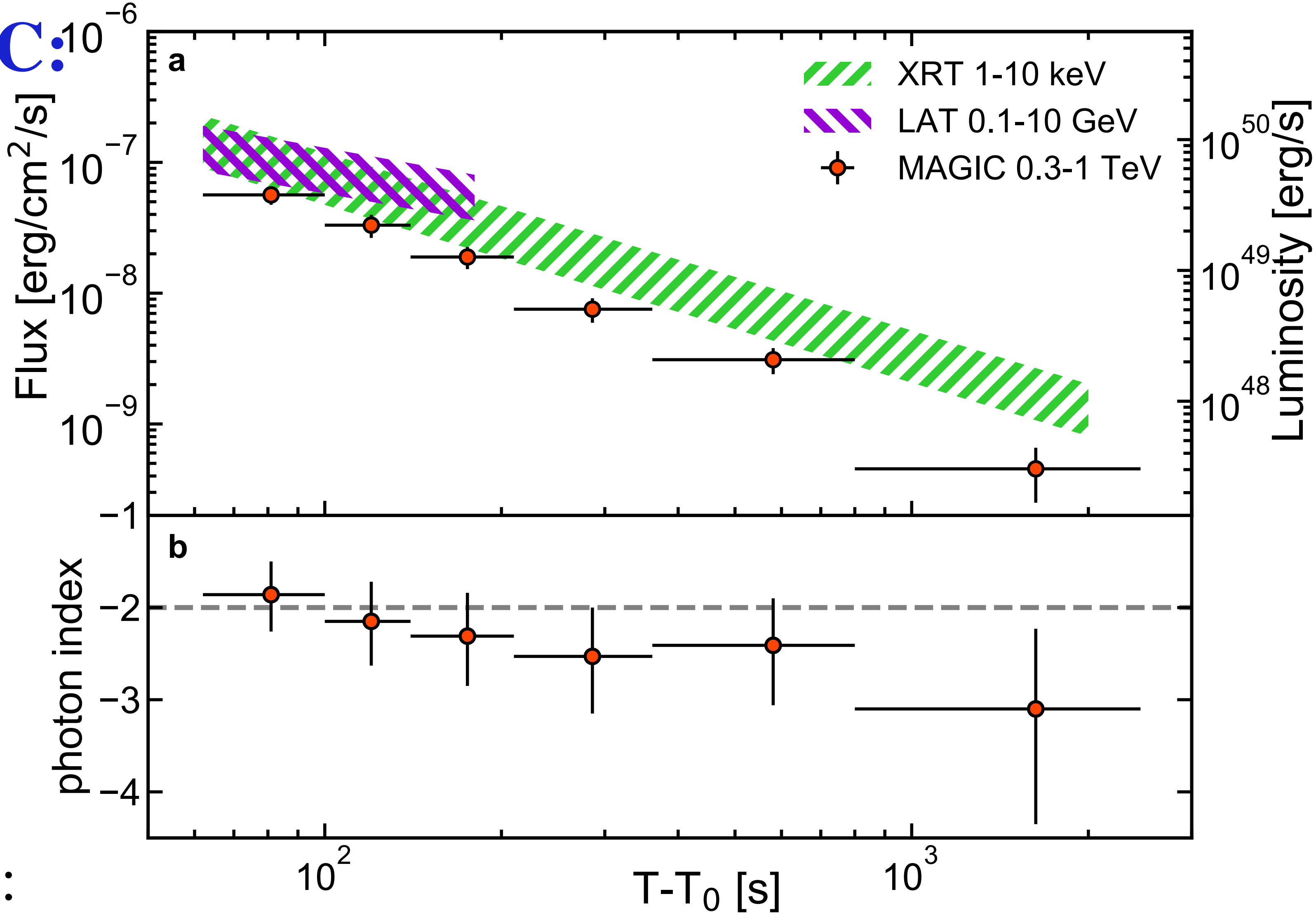


MAGIC Coll.
2019
Nature 575, 455

T_0+62-2454s

- consistent with $E^{-2.22}$ after correcting for attenuation by EBL (factor ~300 at 1 TeV, from $E^{-5.43}$ observed)
- no clear evidence for cutoff above 1 TeV

GRB 190114C: TeV vs keV-GeV light curves, time-dep. TeV spectra

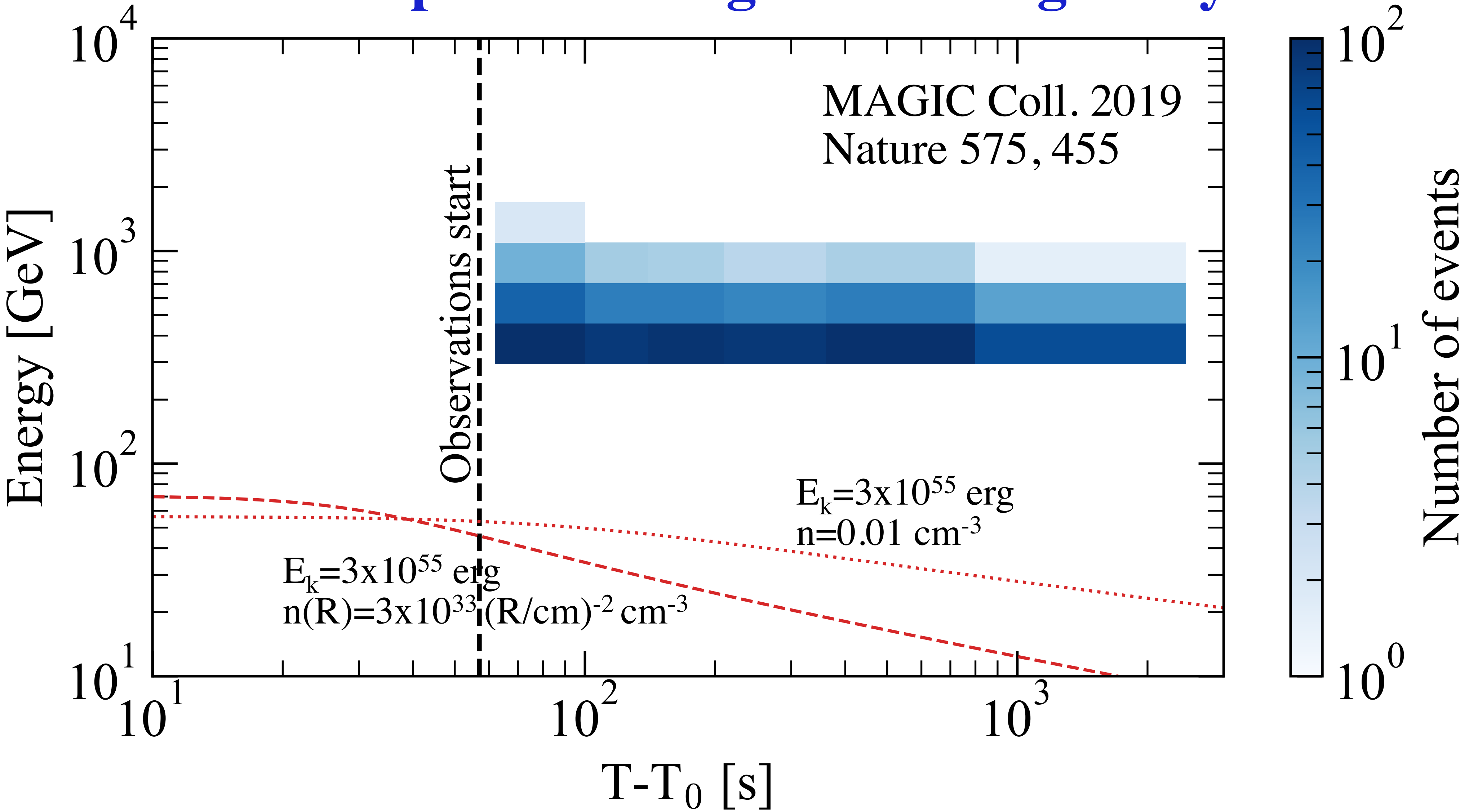


MAGIC Coll. 2019
Nature 575, 455

TeV light curve:
- consistent with $t^{-1.6}$ -> likely predominantly afterglow
- radiated power comparable to X-ray and GeV
- good correlation with X-ray -> close relation with electron sync.

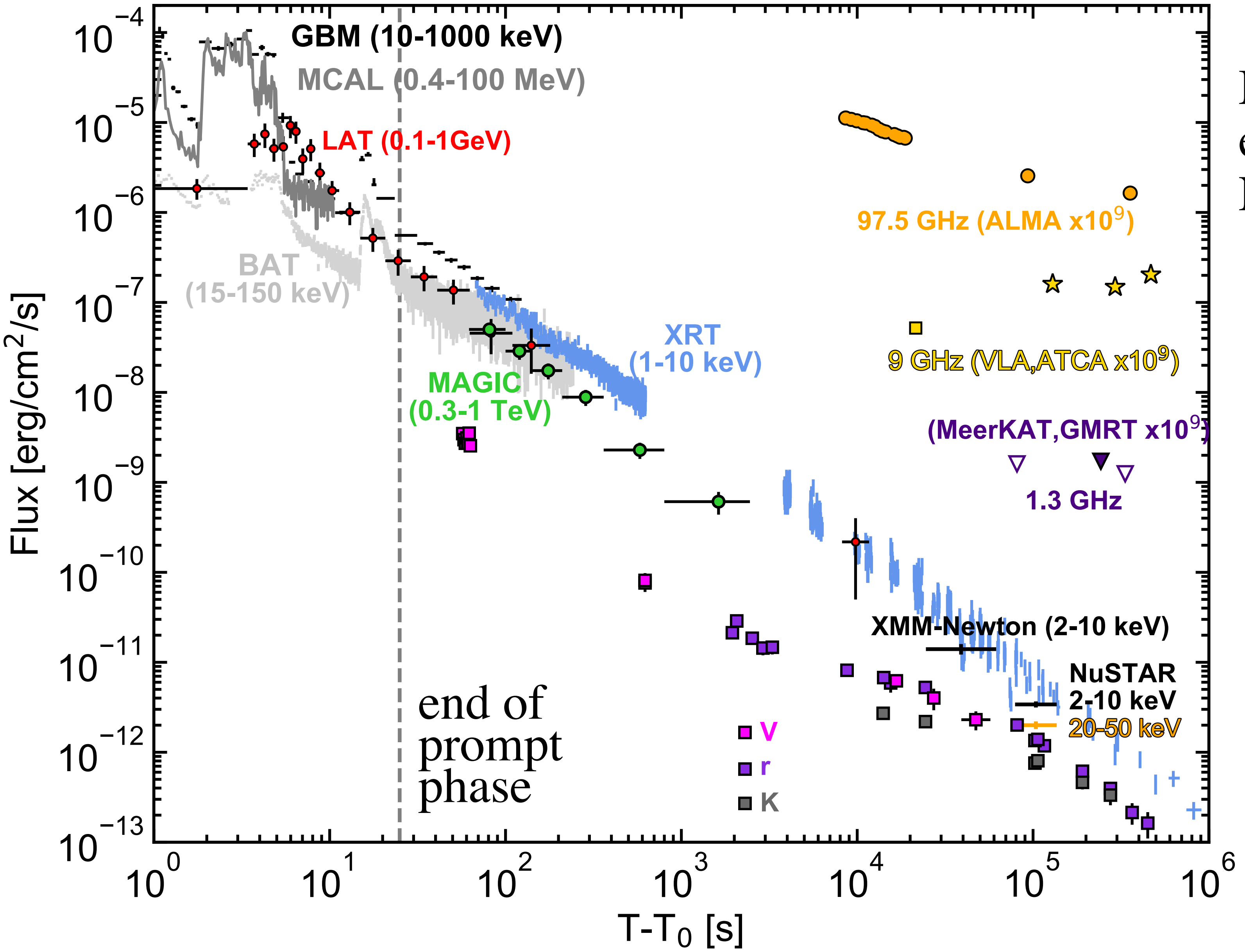
TeV spectra: consistent with ~-2, some evidence for softening

GRB 190114C: photon energies vs afterglow sync. limit



observed energies well above even extreme assumptions for $E_{syn,max}$
-> unambiguous evidence for separate emission component

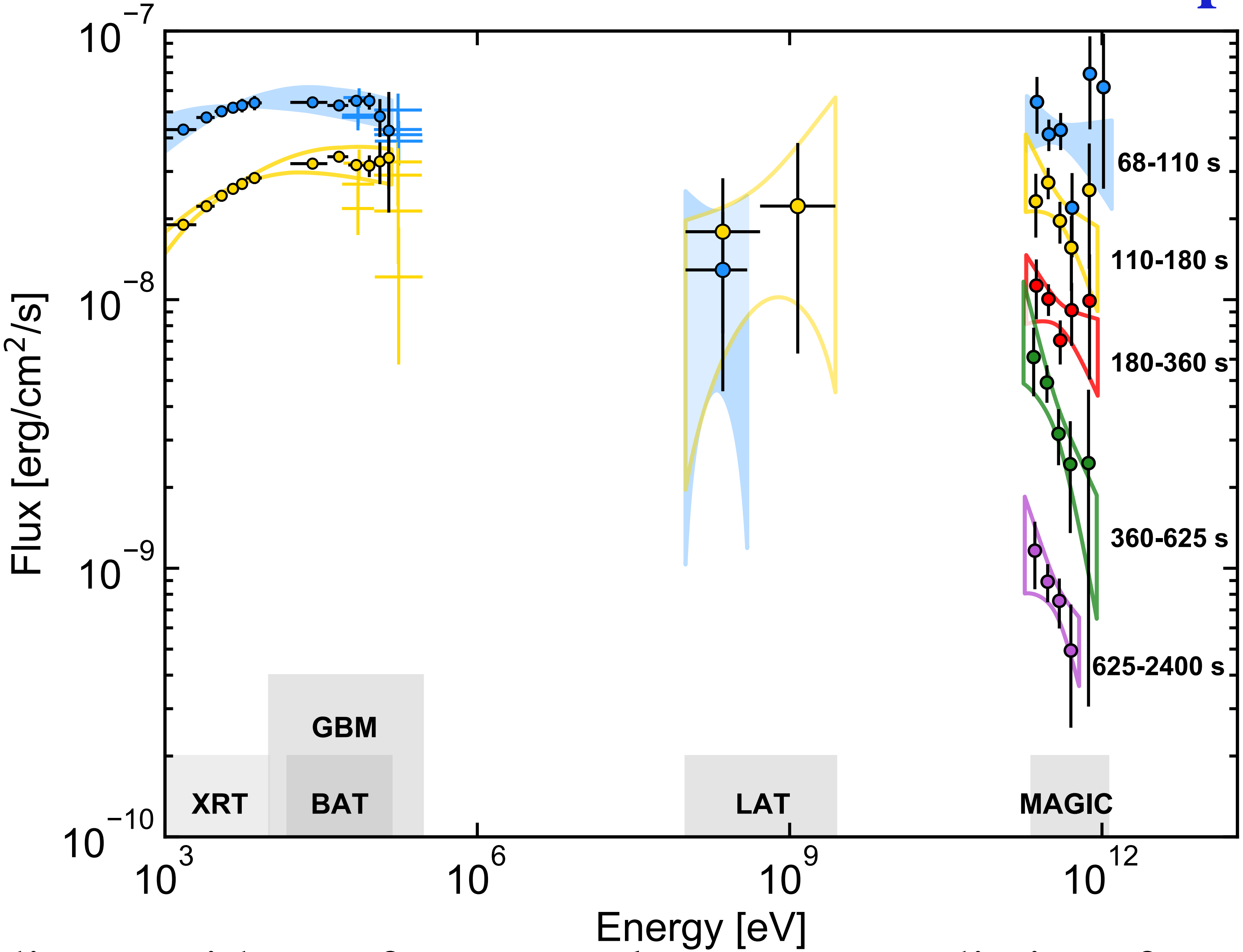
GRB 190114C: multiwavelength light curves



MAGIC Coll. et al 2019 Nature 575, 459

- extensive MWL coverage from GHz to TeV

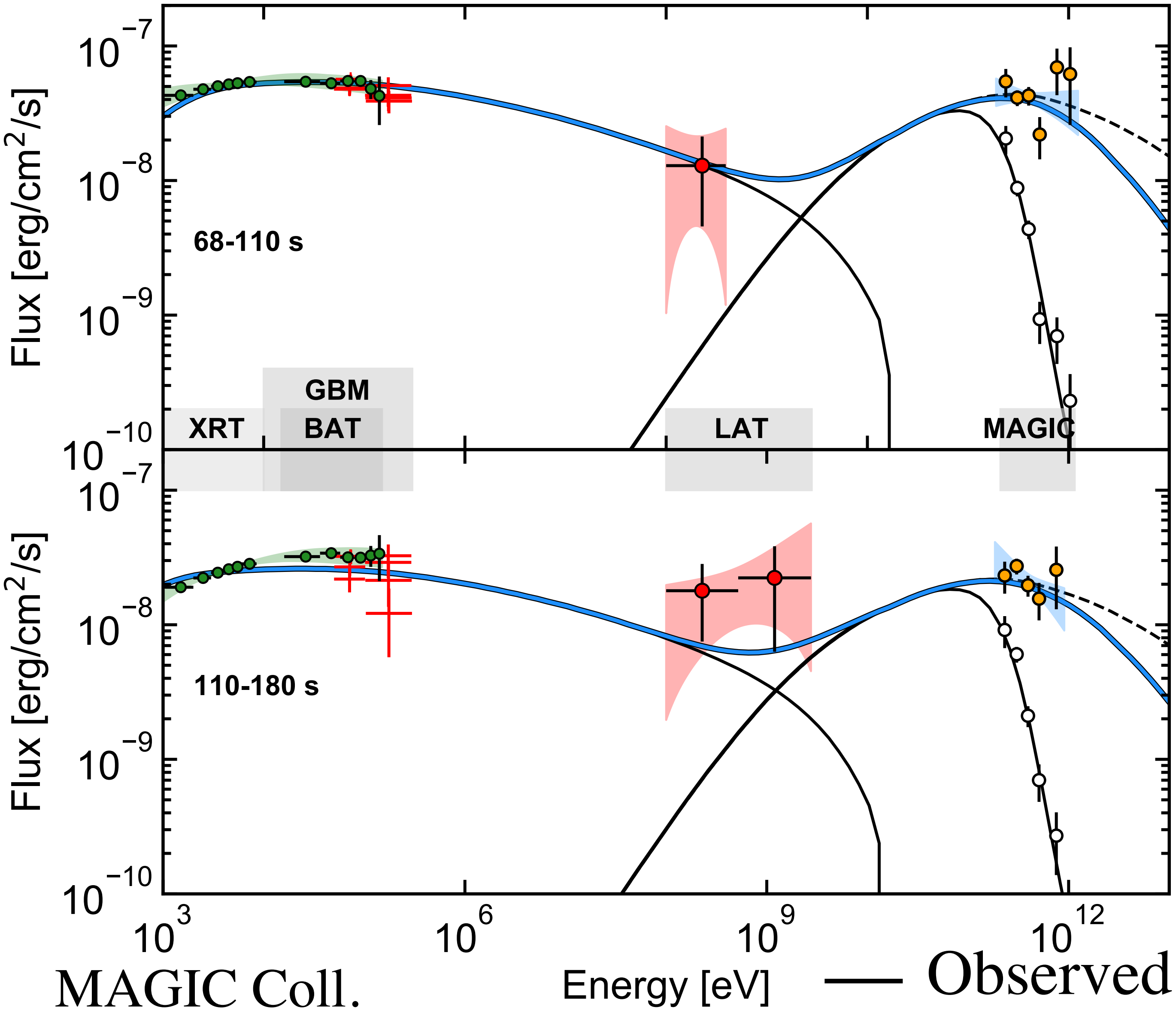
GRB 190114C: time-resolved broadband spectra



MAGIC Coll. et al 2019 Nature 575, 459

- direct evidence for spectral component distinct from synchrotron with comparable power

GRB 190114C: time-resolved spectra vs SSC model



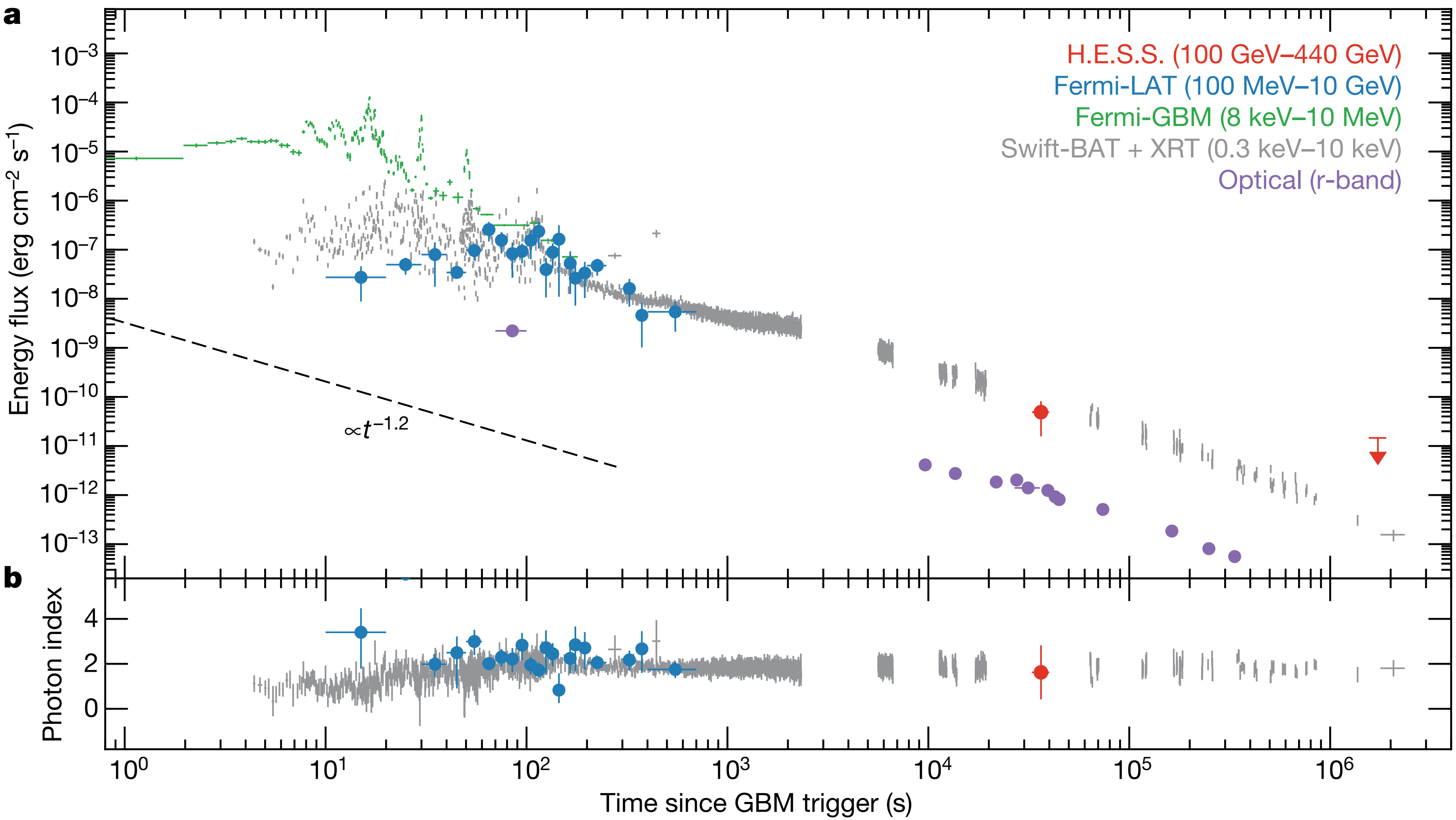
- reasonable SSC interpretation with plausible parameters: $s=0$, $n_0=0.5$ cm^{-3} $\varepsilon_e=0.07$, $\varepsilon_B=8x10^{-5}$ $E_k=8x10^{53}$ erg, $p=2.6$
- supports inference that TeV emission may be common
- steep TeV spectra -> KN+internal γγ abs (otherwise low ε_e, high B required, implying weak SSC)

MAGIC Coll. et al 2019 Nature 575, 459

GRB 180720B: late time TeV observations

HESS Coll. 2019
Nature 575, 464

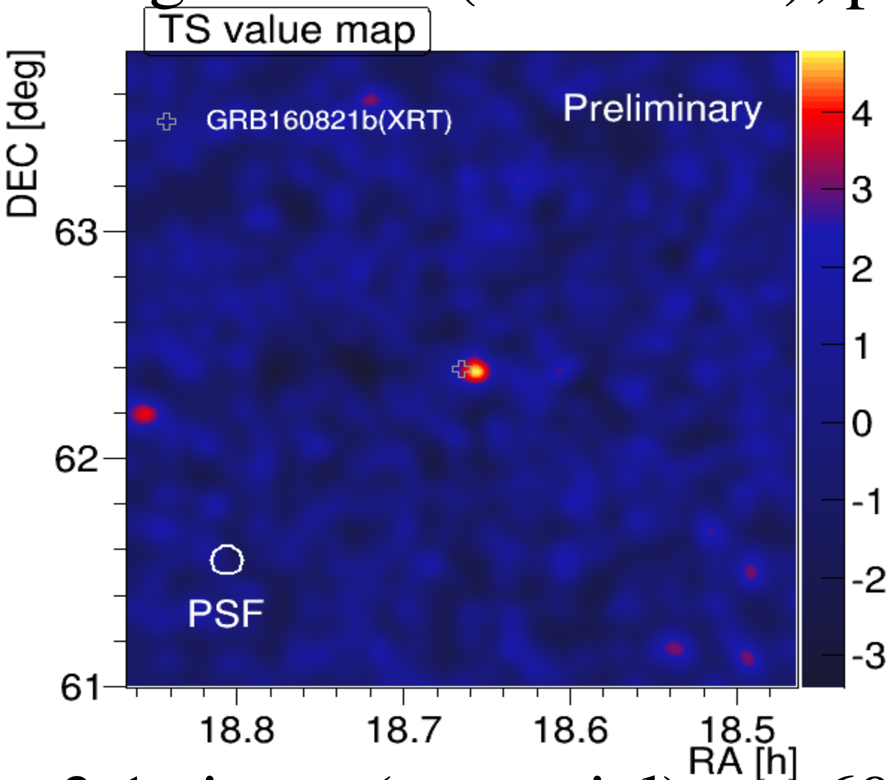
z=0.653, T_{90}~49s, E_{iso}~6x10^{53} erg, L_{iso}~1.8x10^{53} erg/s

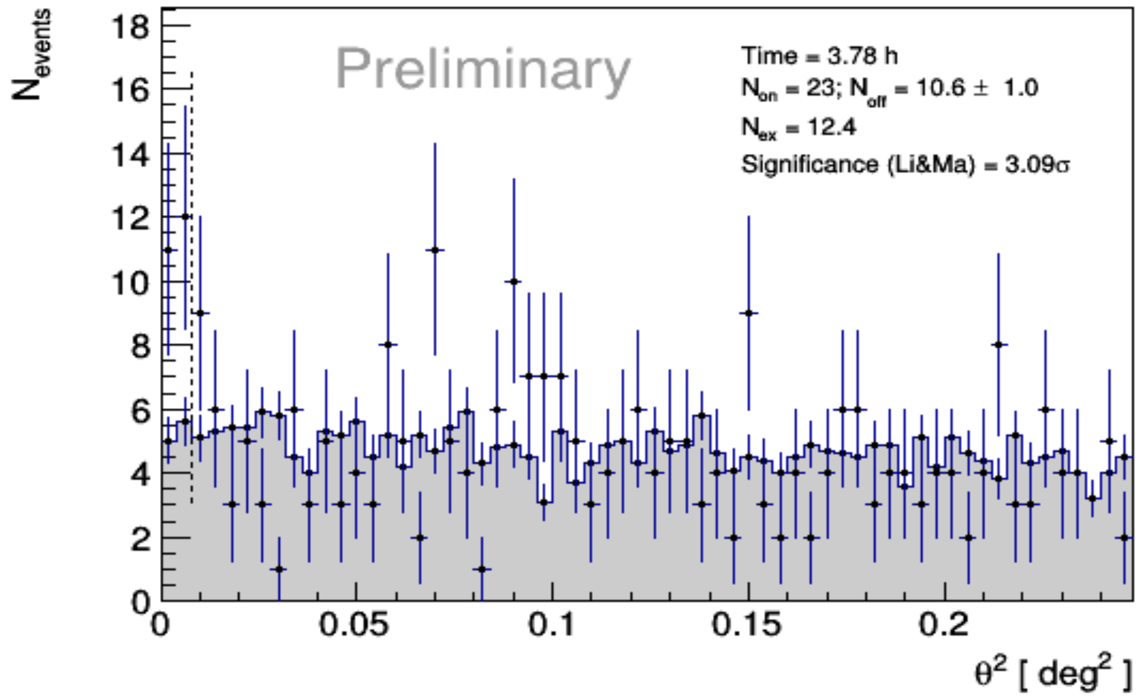


- detected at 5.0σ (post-trial), t~10-12 h, 100-440 GeV
- EBL-corrected photon index Γ_{int}=1.6+-1.2 (stat)+-0.4 (sys)
- SSC most plausible

short GRB 160821B: TeV observations

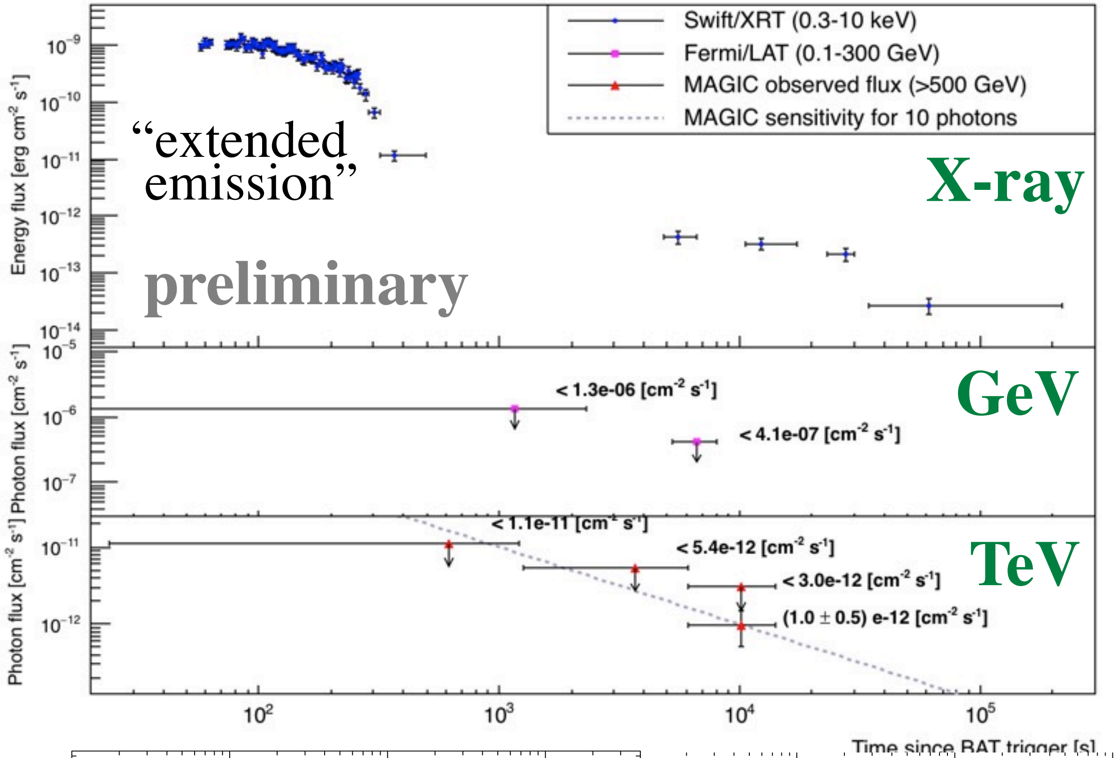
- short GRB (T_{90}~0.5s), nearby (z=0.16) -> E_{iso}~$1.2x10^{50}$ erg/s
- MAGIC follow up t~24 s - 4 hr, zenith angle~34-55°
  bright moon (3-9 x dark), poor weather at t<1.5 hr





- <u>3.1 sigma (post-trial) at >600-800 GeV</u> at GRB position
  -> <u>hint of gamma-ray signal</u>, but not firm detection
- no other VHE source in FoV, steady source excluded by later obs.
- no GeV detection by Fermi-LAT

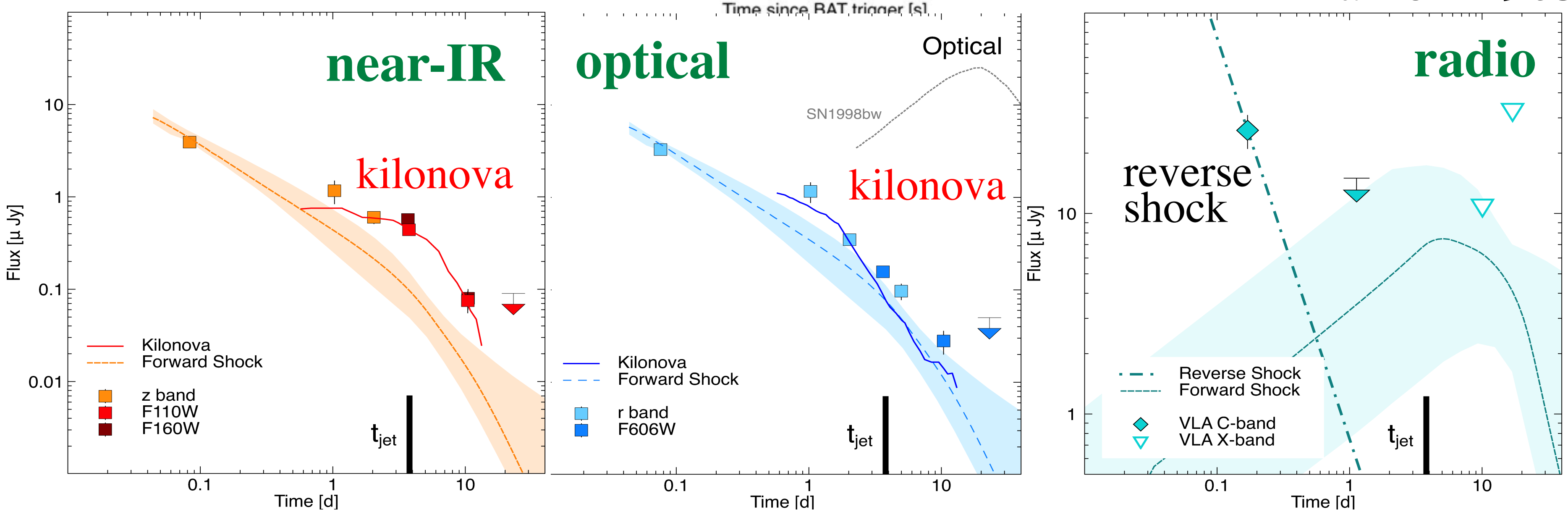
short GRB 160821B: TeV vs MWL observations



TeV: IF real signal
observed energy flux >500 GeV
~2 × that in X-rays at t~10^4 s
(EBL-corrected ~10×)

MWL: broadband forward shock
+ X-ray extended emission
+ optical/IR kilonova
+ radio reverse shock

Troja+ 1905.01290
Lamb+ 1905.02159



low-luminosity GRB 190829A: TeV observations

```
TITLE:   GCN CIRCULAR
NUMBER:  25566
SUBJECT: GRB190829A: Detection of VHE gamma-ray emission with
H.E.S.S.
DATE:    19/08/30 07:08:37 GMT
FROM:    Fabian Schussler at CEA  <fabian.schussler@cea.fr>

M. de Naurois on behalf of the H.E.S.S. collaboration

The H.E.S.S. array of imaging atmospheric Cherenkov telescopes
was used to carry out follow-up observations of the afterglow
of GRB 190829A (Dichiara et al., GCN 25552). At a redshift of
z = 0.0785 +/- 0.005 (A.F. Valeev et al., GCN 25565) this is
one of the nearest GRBs detected to date. H.E.S.S.
Observations started July 30 at 00:16 UTC (i.e. T0 + 4h20),
lasted until 3h50 UTC and were taken under good conditions. A
preliminary onsite analysis of the obtained data shows a
>5sigma gamma-ray excess compatible with the direction of
GRB190829A. Further analyses of the data are on-going and
further H.E.S.S. observations are planned. We strongly
encourage follow-up at all wavelengths.

H.E.S.S. is an array of five imaging atmospheric Cherenkov
telescopes for the detection of very-high-energy gamma-ray
sources and is located in the Khomas Highlands in Namibia. It
was constructed and is operated by researchers from Armenia,
Australia, Austria, France, Germany, Ireland, Japan, the
Netherlands, Poland, South Africa, Sweden, UK, and the host
country, Namibia. For more details see https://www.mpi-
hd.mpg.de/hfm/HESS/
```

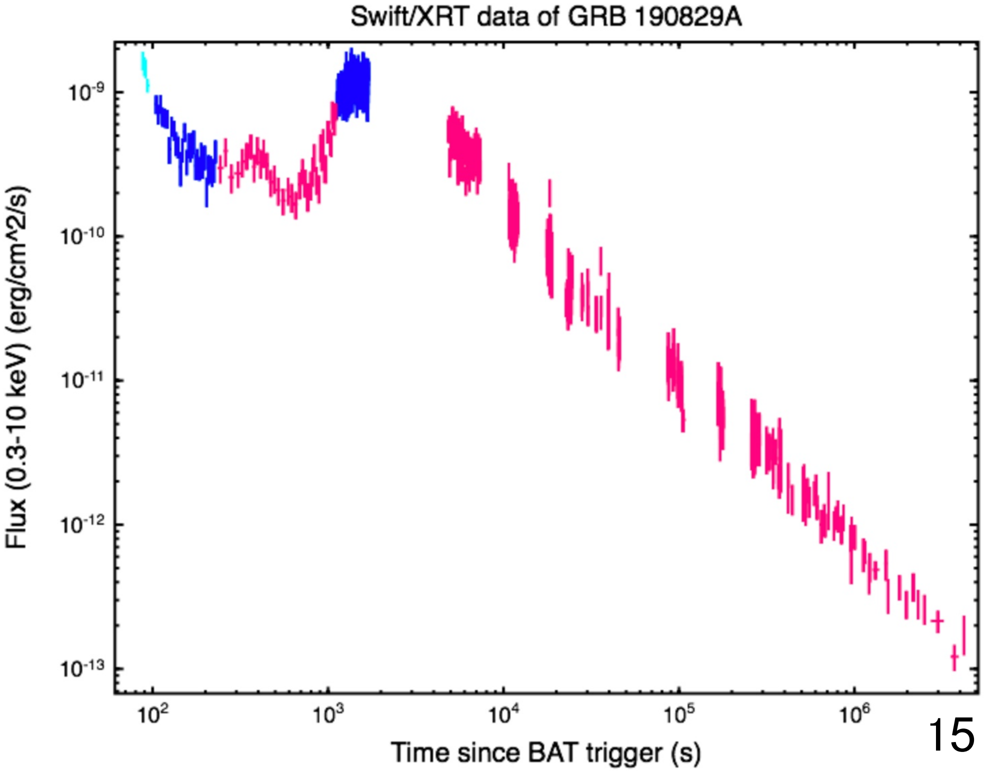
$z=0.0785$

$T_{90}\sim 63s$ (GBM)

$\sim 58.2s$ (BAT)

$E_{iso}\sim 2.0\times 10^{50}$ erg

$L_{iso}\sim 1.9\times 10^{49}$ erg/s



Future prospects for VHE (>20 GeV) GRB observations

1. More VHE afterglows – new window on IC and other components (analogous to 90's discovery of GeV/TeV emission from blazars)
   - Deeper understanding of afterglow dynamics, GRB environment
   - New insight into plasma microphysics of relativistic shocks: particle acceleration, B field amplification...
   - Probe of EBL (IGMF) at high z

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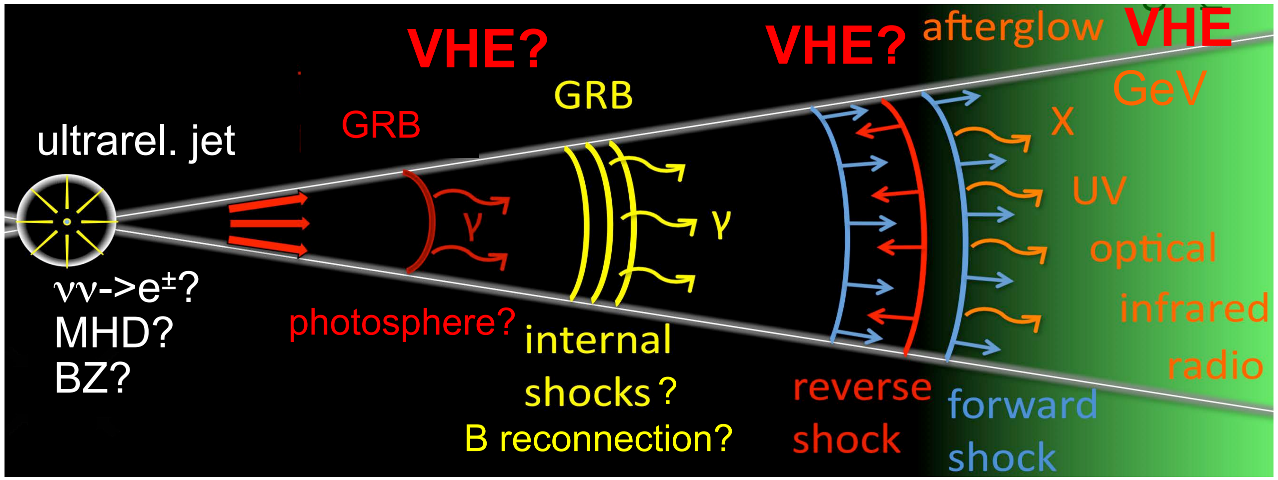
Further, qualitative leaps:

2. Reverse shock VHE emission
   - New insight into GRB jet properties (poorly understood)

3. Prompt VHE emission "Holy Grail"
   - New insight into origin of prompt emission (big mystery)
   - Better tests of Lorentz invariance violation



CTA vs current Cherenkov telescopes for GRBs

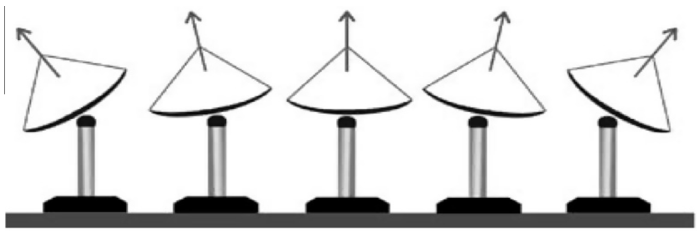
-> D. Hadasch

- lower E_{th}, higher sensitivity, all sky coverage
  -> higher detection rate (~1/yr/site)
  -> better spectra/light curves over broader energy range

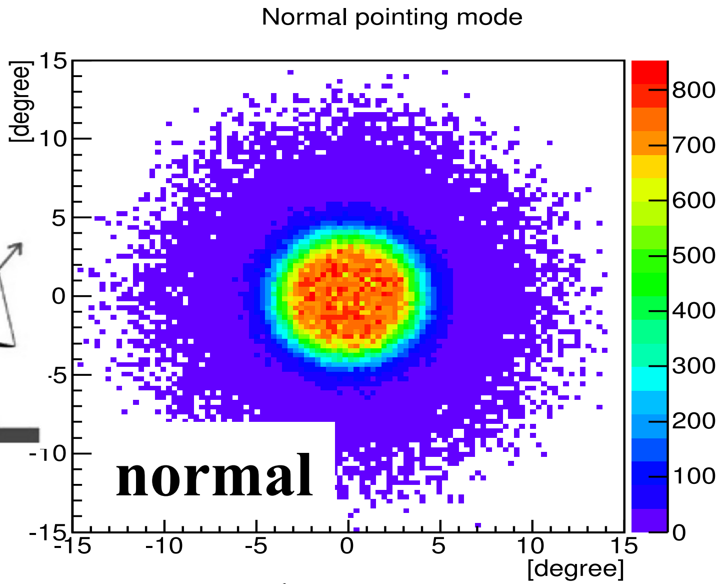
- real-time analysis with automated issuing of alerts (in ~30 sec)

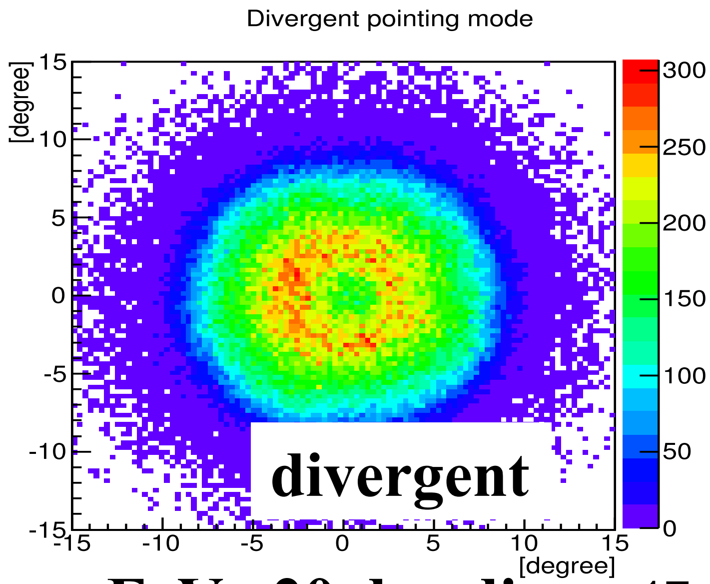
- divergent pointing -> coverage from t=0

divergent pointing
for MSTs/SSTs



Szanecki+ 2015





Gérard+ 2015

FoV ~20 deg dia.

Summary: GRBs at very high energies

- After decades of frustrating non-detections, VHE gamma-ray astronomy of GRBs has suddenly and fully blossomed. Various different types of GRBs are involved.
- Long GRB 190114C:
  Very clear detection, brightest/most luminous TeV source.
  Clear evidence for non-sync. afterglow component, likely SSC.
  First step towards deeper understanding of afterglows, rel. shocks.
- Short GRB 160821B:
  Possible signal. Potential implications for GW follow-up at TeV, potential new insight into NS mergers.
- Long GRB 180720B: Late time detection. SSC favored.
- Low-luminosity GRB 190829A: Clear detection. More details TBC.
- Great prospects for further progress with CTA, etc
  More TeV afterglows, reverse shock/prompt TeV emission...

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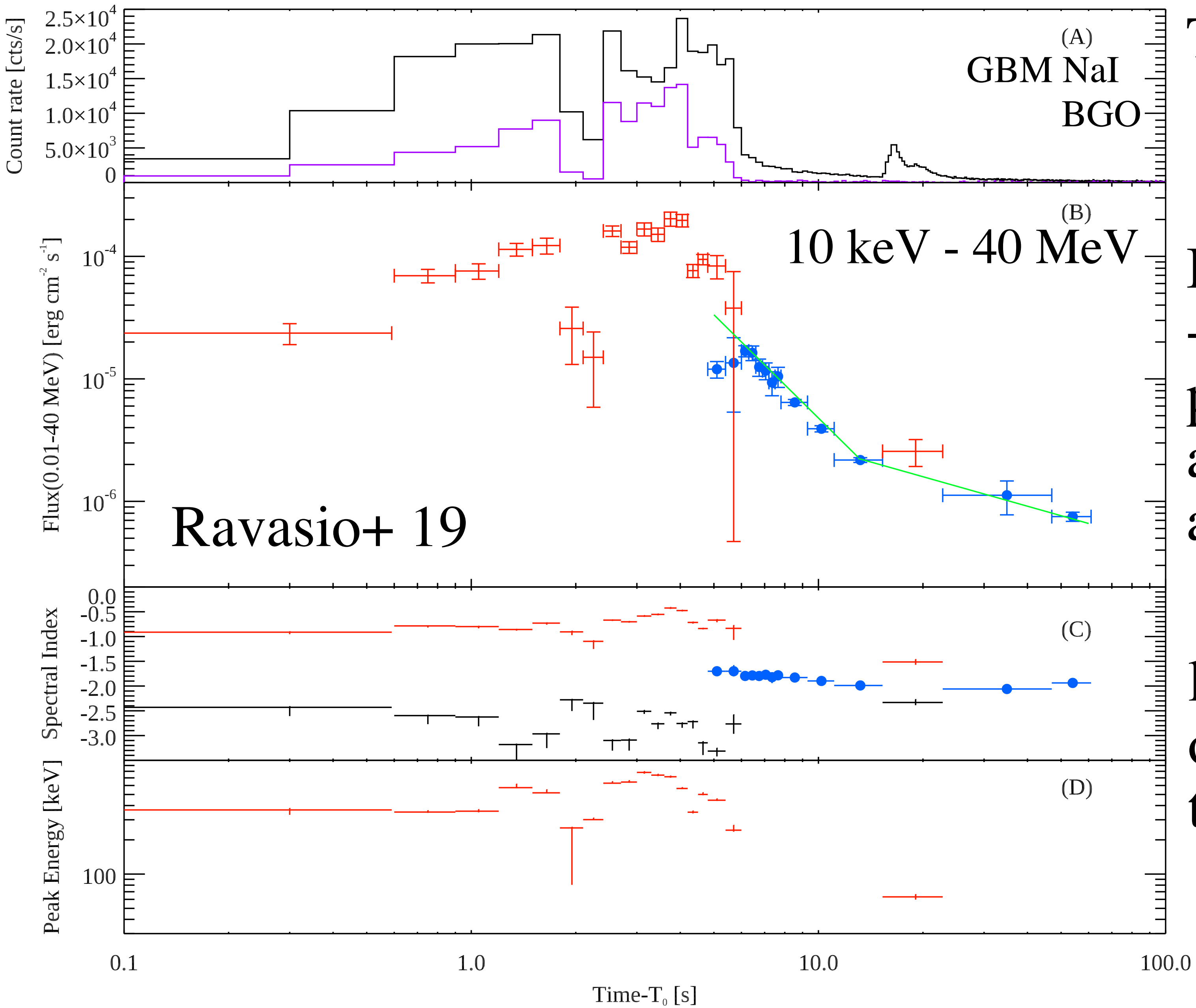
Dawn of a new era in GRB physics!

backup slides

GRB 190114C: prompt vs afterglow



T_{90} ~116 s (GBM)
~362 s (BAT)

BUT light curve +spectra indicate prompt ends <25 s, afterglow starts at t~6 s

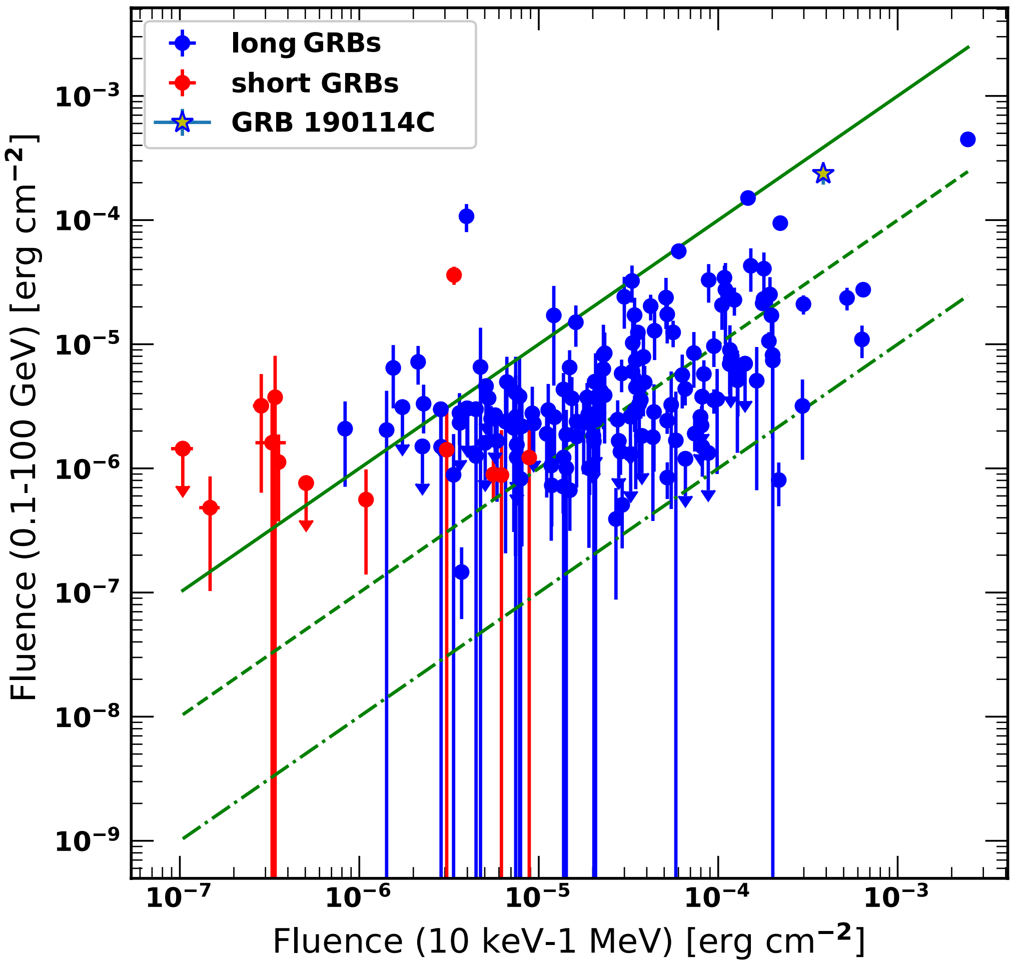
large contribution of afterglow to T_{90}, E_{iso}

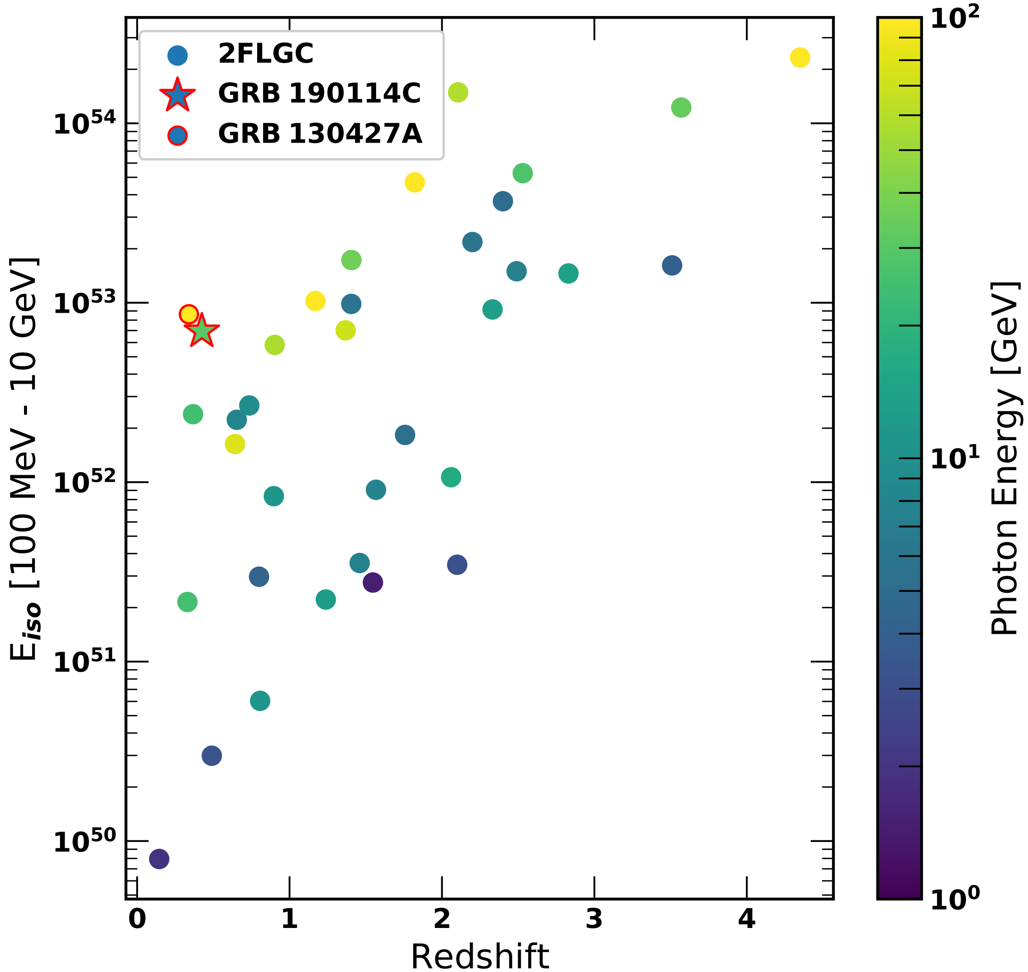
GRB 190114C: comparison with other GRBs

z=0.425, E_{iso}~3x10^{53} erg, L_{iso}~1x10^{53} erg/s (1-10^4 keV)

E_{iso}~7x10^{52} erg (0.1-100 GeV)

-> low z and large E_{iso}, but not peculiar





Fermi+Swift 1909.10605

Comparison with past MAGIC GRB observations

Was 190114C a peculiar GRB? Probably not.

GRBs observed under adequate technical and weather conditions with z<1 and T_{delay}<1 hr:

Event	redshift	T_{delay} (s)	Zenith angle (deg)	class	E_{iso} (erg)
GRB 061217	0.83	786.0	59.9	short	8×10^{49}
GRB 100816A	0.80	1439.0	26.0	short	6×10^{51}
GRB 160821B	0.16	24.0	34.0	short	2×10^{50}
GRB 190114C	0.42	58.0	55.8	long	3×10^{53}

No GRB observed with criteria better than 190114C except 160821B, where a 3σ hint is seen (MAGIC Coll., in prep.)
-> Suggests detection of 190114C is due to low z and fair observing conditions, rather than any intrinsic peculiarity