Gamma-Ray Bursts at Very High Energies
Towards LHAASO

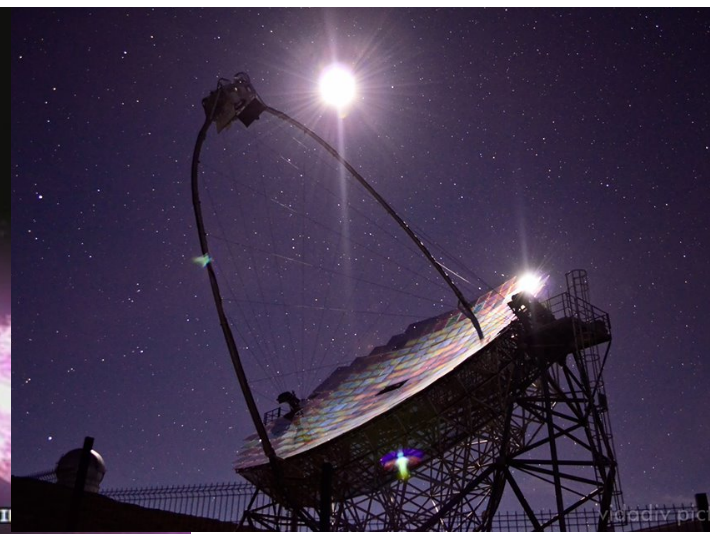
Susumu Inoue (RIKEN) on behalf of the MAGIC Collaboration

GRB 190114C (long):

"Teraelectronvolt emission from the γ-ray burst GRB 190114C"
Nature 2019, 575, 455, by MAGIC Collaboration

"Observation of inverse Compton emission from a γ-ray burst"
Nature 2019, 575, 459, by MAGIC, Fermi, Swift, AGILE, optical+radio

GRB 160821B (short): in preparation by MAGIC Collaboration



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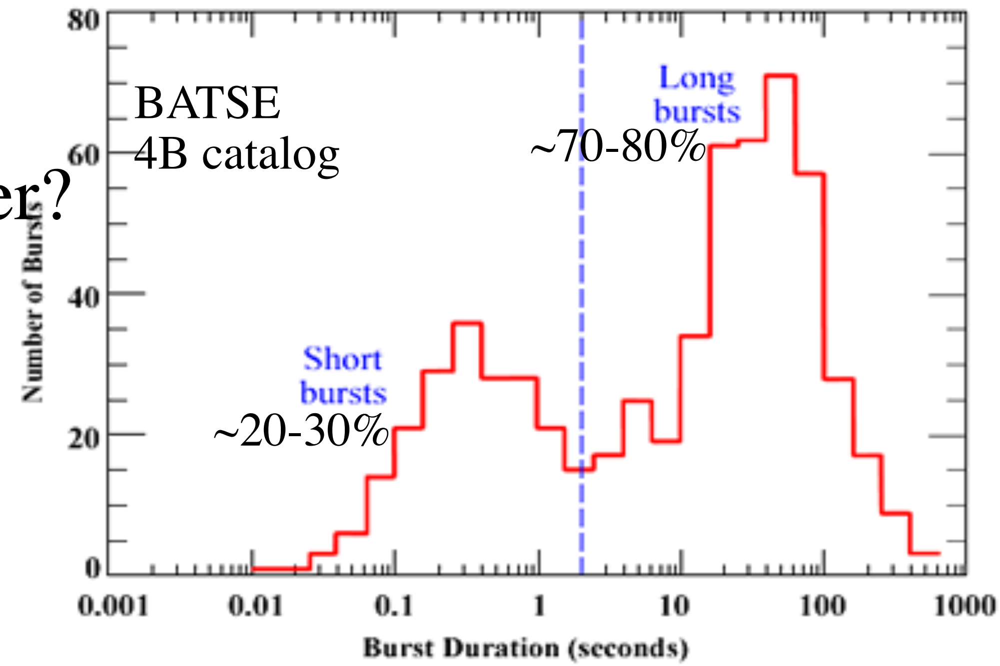
outline

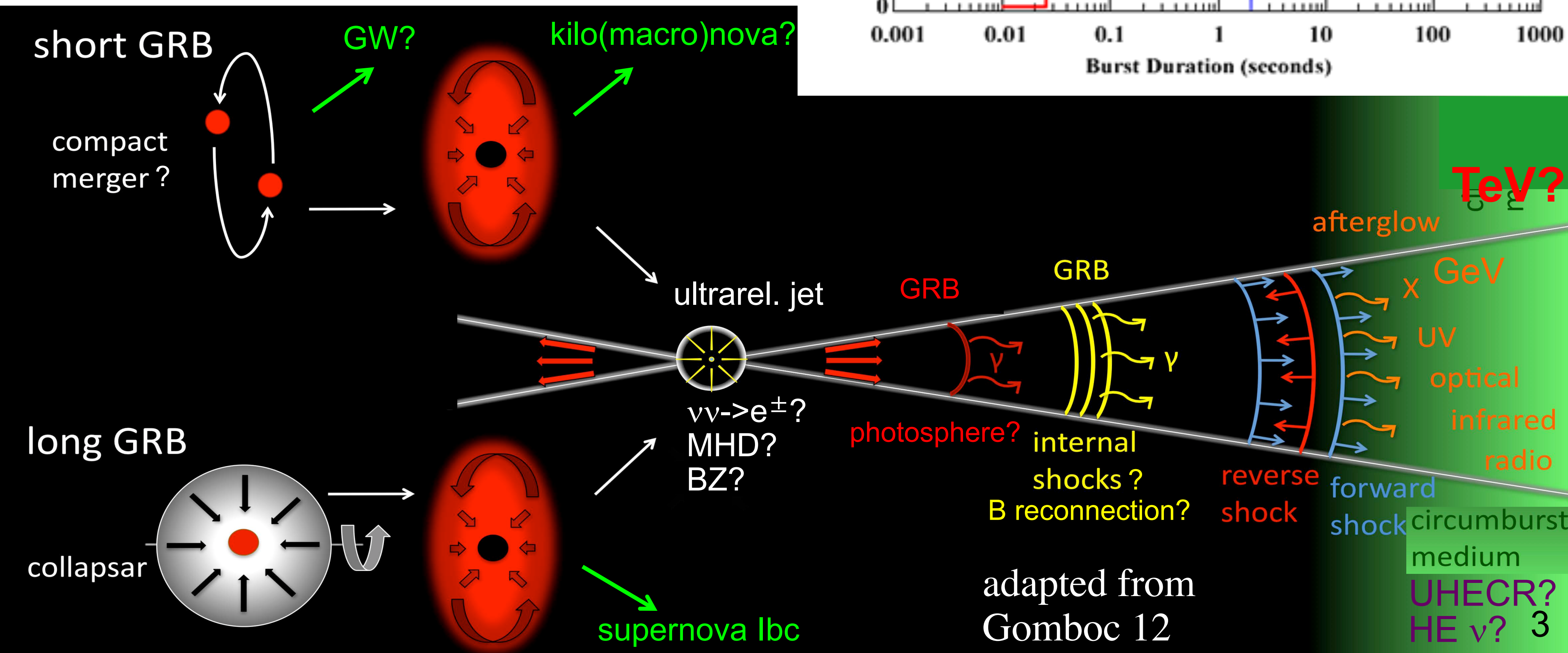
1. Introduction
2. GRB 190114C:
   - MAGIC+MWL observations
   - general physical inferences
   - afterglow modeling
3. GRB 160821B
   - MAGIC+MWL observations (brief)
4. Future prospects: Towards LHAASO
5. Summary and outlook

1. Introduction

GRBs: mid 2017

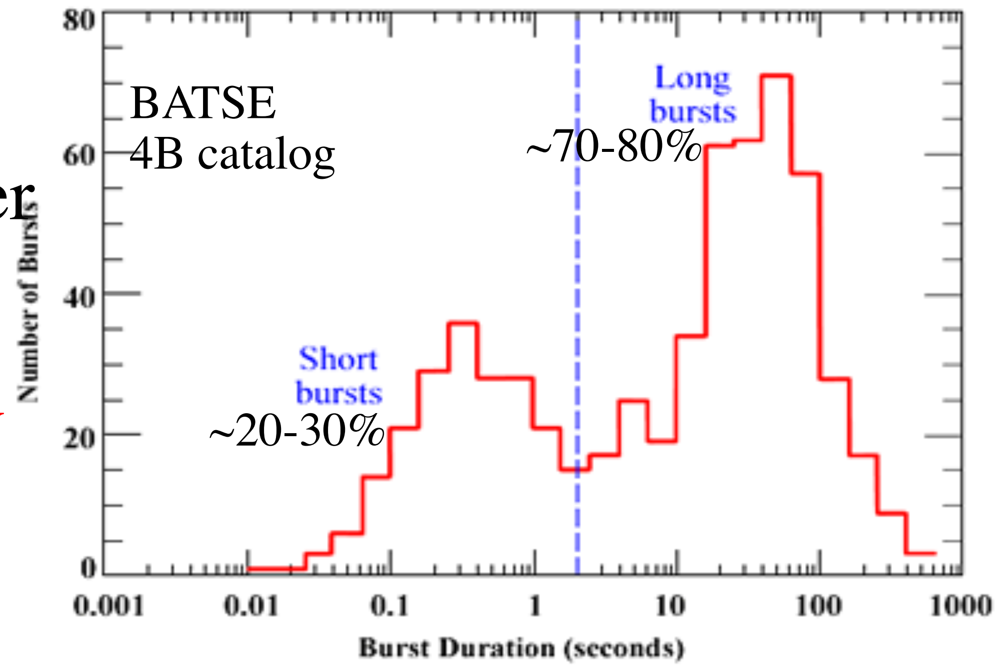
long (>~2s): massive star collapse
short (~<2s): compact binary merger?
-> ultrarelativistic jets
-> prompt: X-MeV
+ afterglow: radio-opt-X-GeV

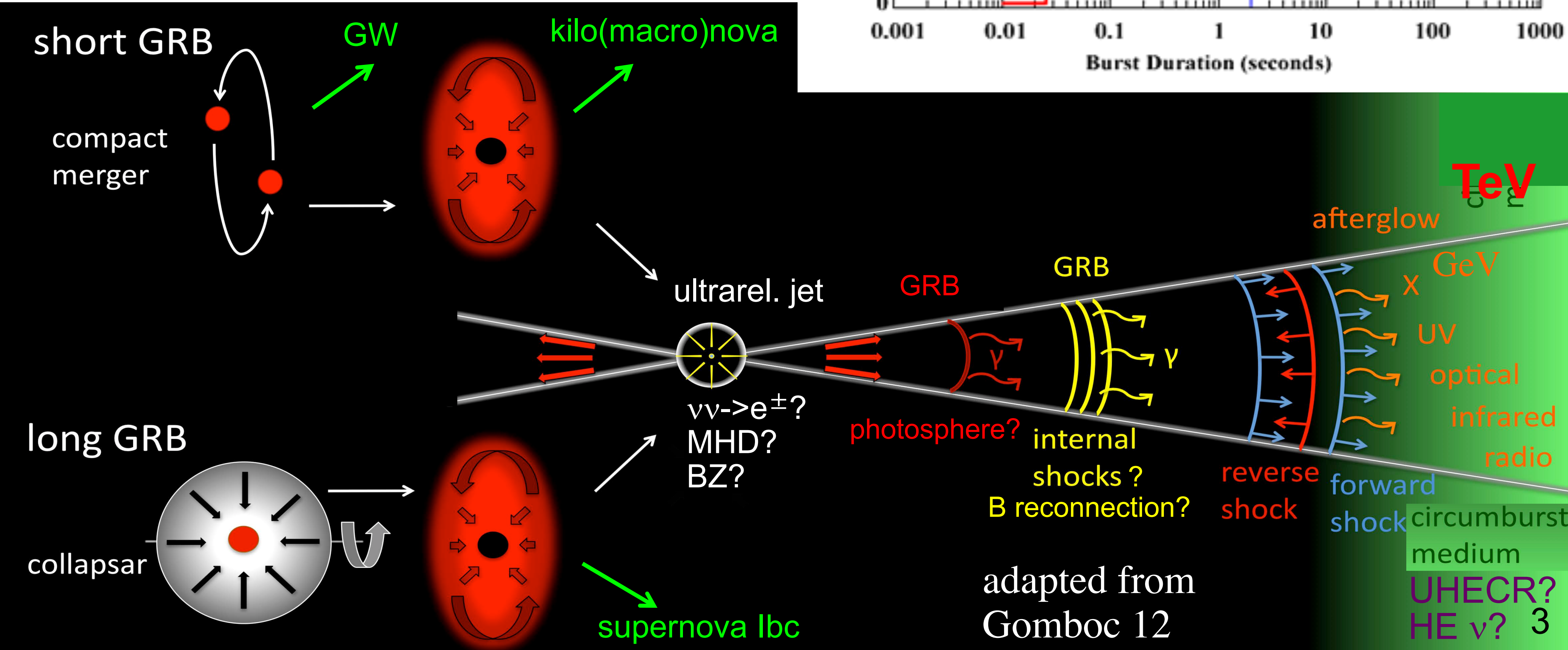




GRBs: mid 2019

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

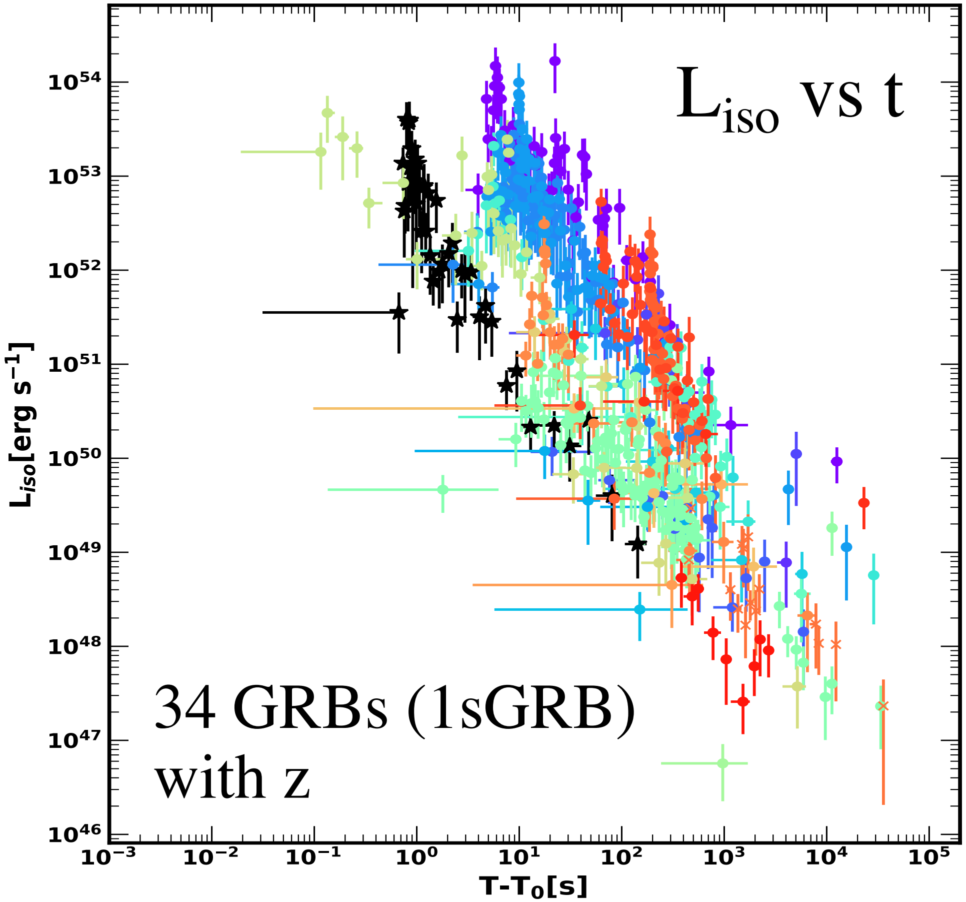


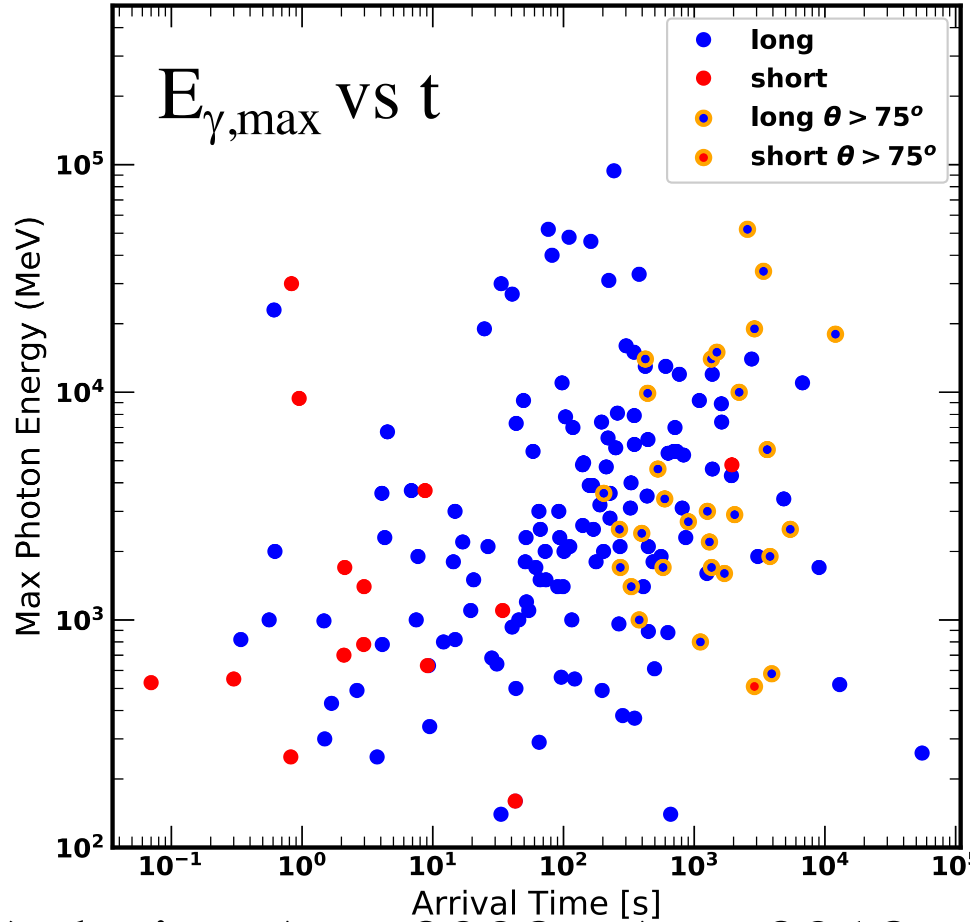


adapted from
Gomboc 12

GRB GeV emission

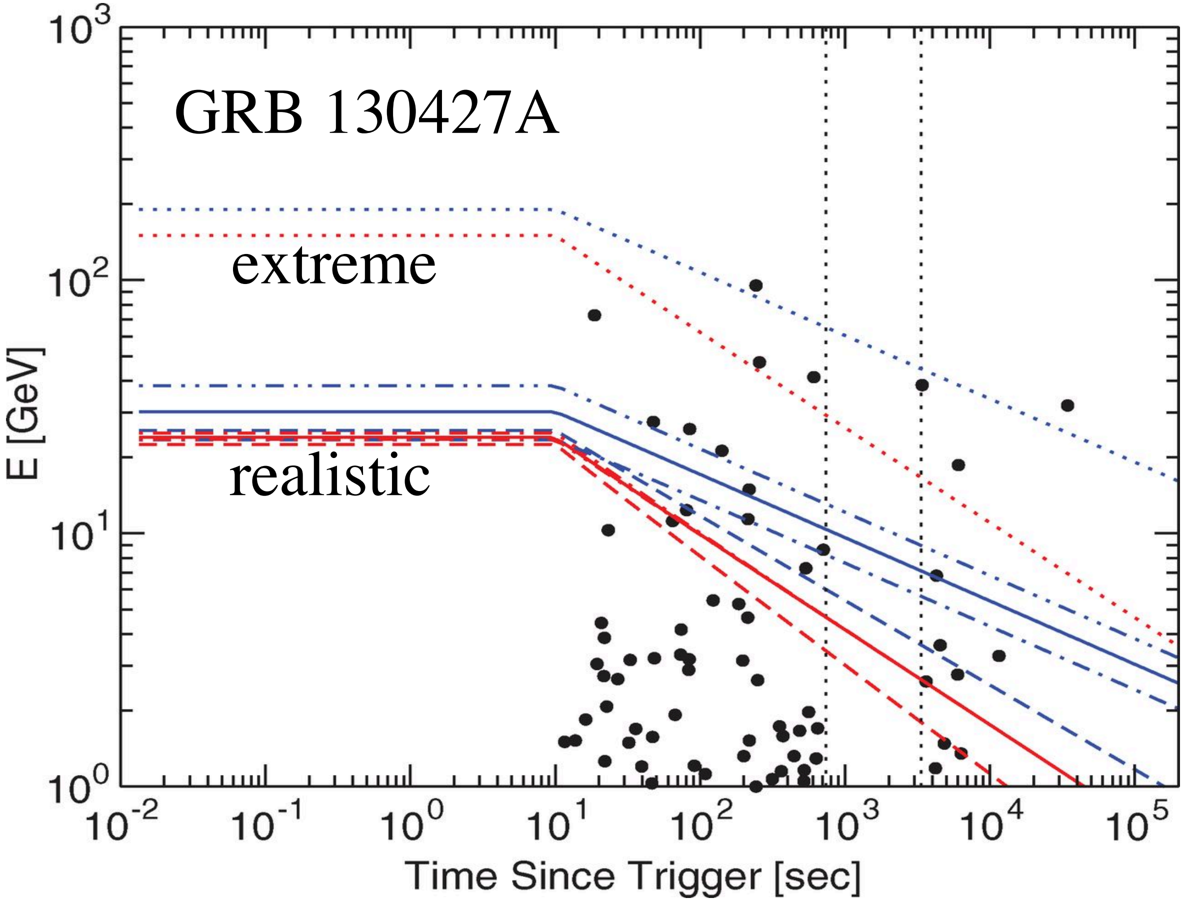
Ajello+ 19, Fermi-LAT 2nd GRB Cat.





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

burnoff limit in afterglow synchrotron emission: Fermi-LAT results



Fermi-LAT Coll. 2014, Science 343, 42

maximum synchrotron photon energy for electrons dominated by synchrotron cooling

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

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

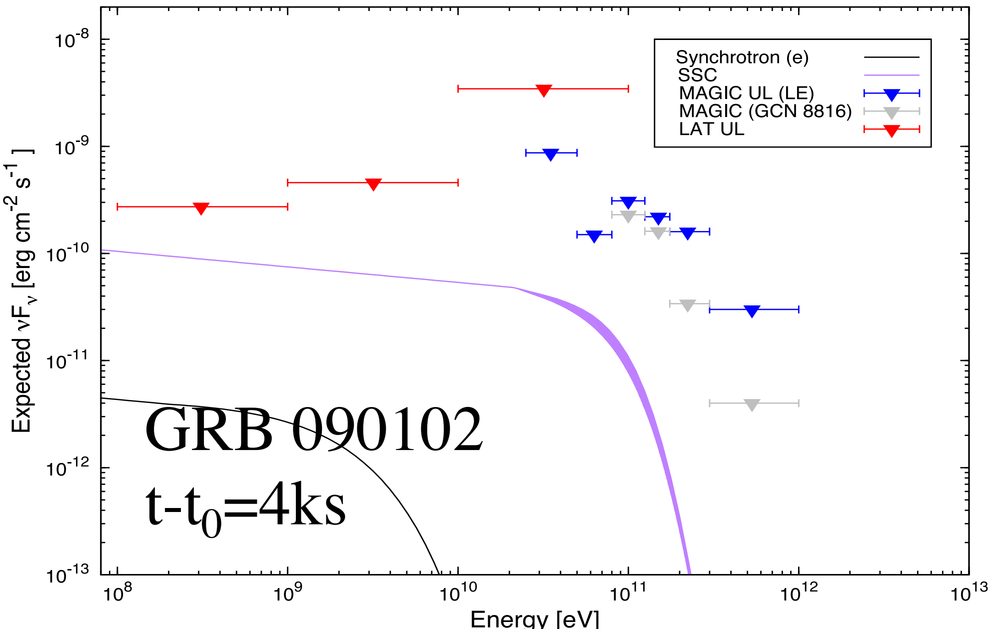
$\nu_{syn,max} \propto B \gamma_{e,max}^2$

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

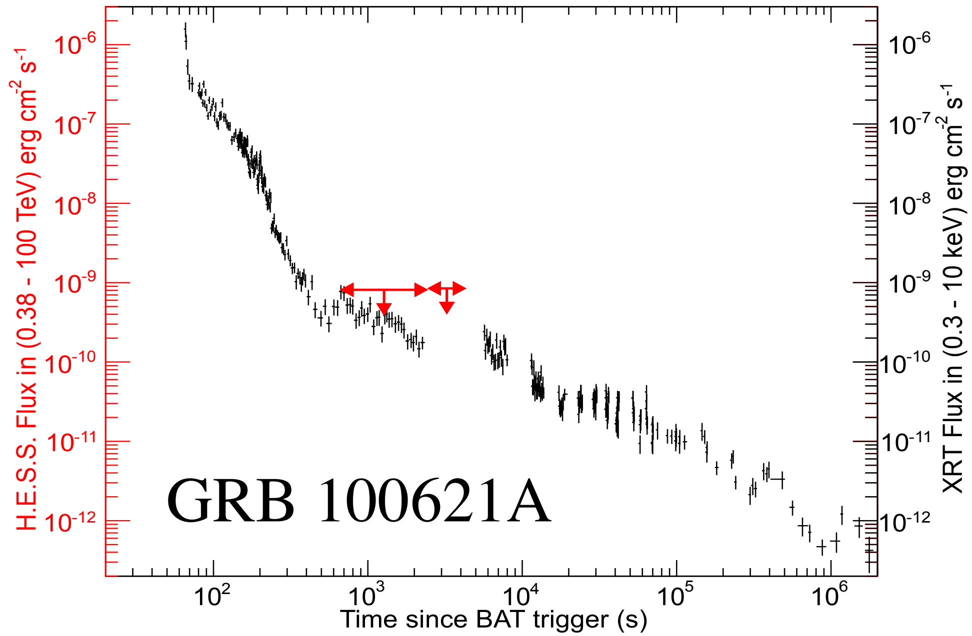
$\sim 106\ \Gamma(t)(1+z)^{-1}$ MeV

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

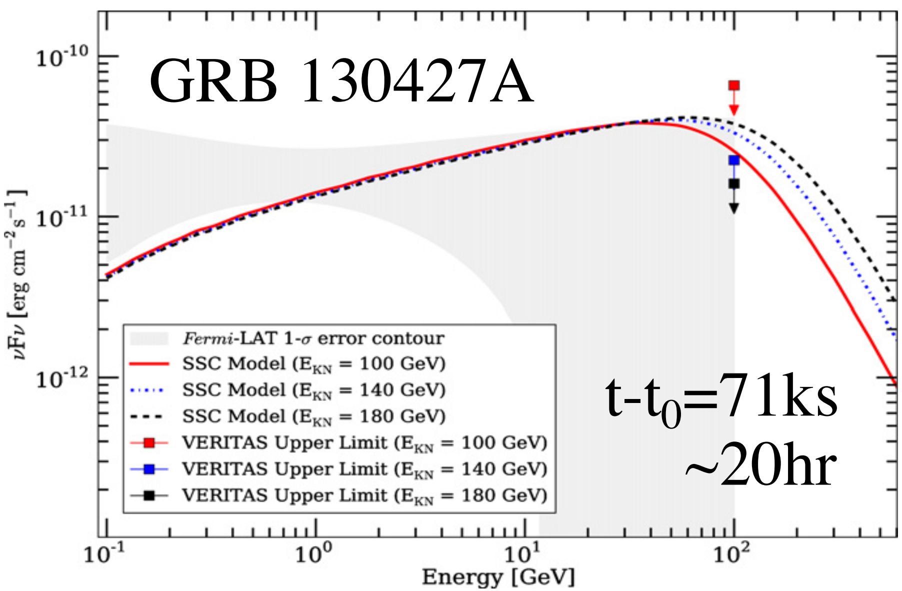
MAGIC+Fermi Aleksic+ 2014



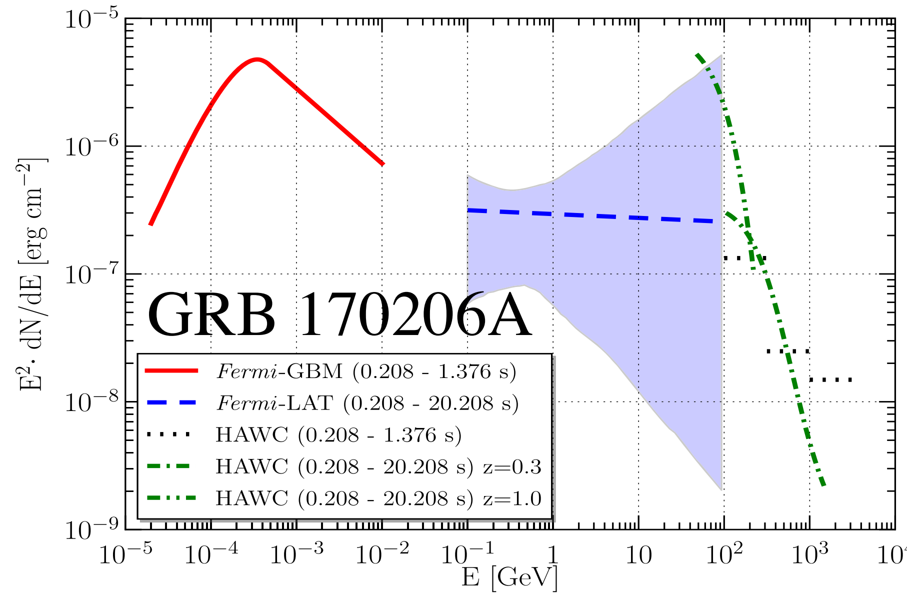
HESS Abramowski+ 2014



VERITAS Aliu+ 2014

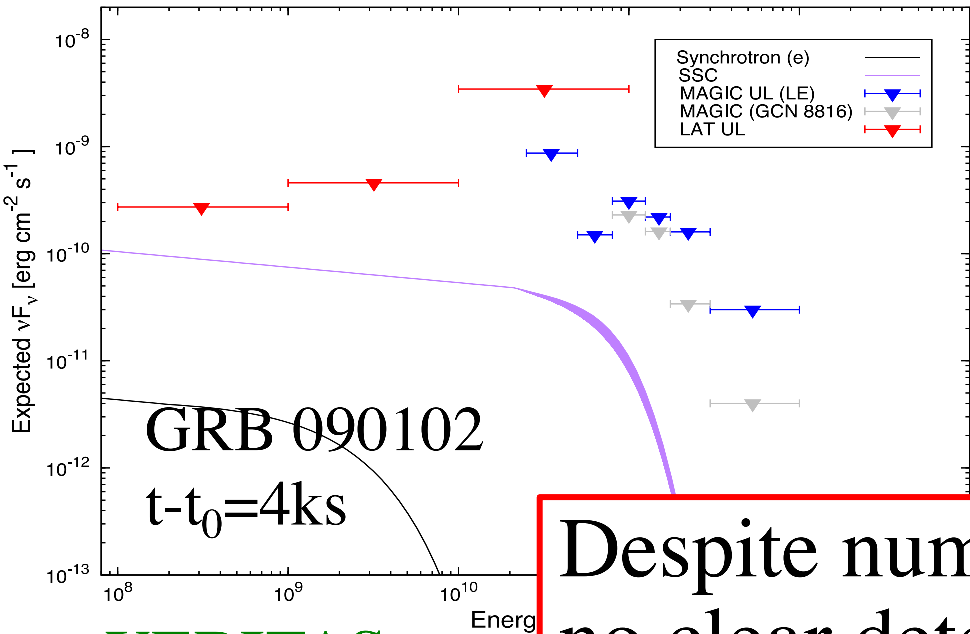


HAWC Alfaro+ 2017

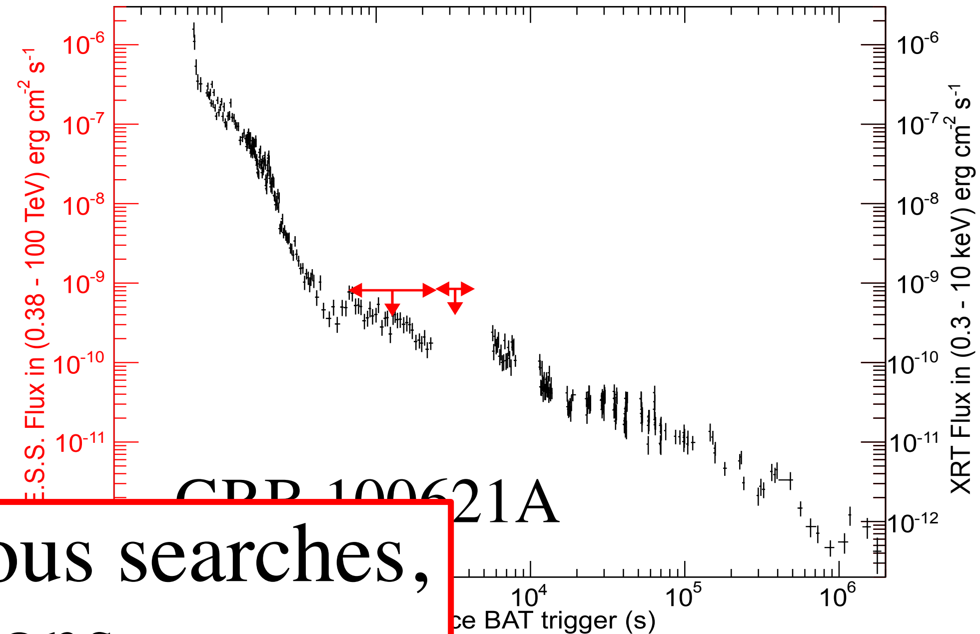


ground-based γ-ray telescopes: some results before 2019

MAGIC+Fermi Aleksic+ 2014

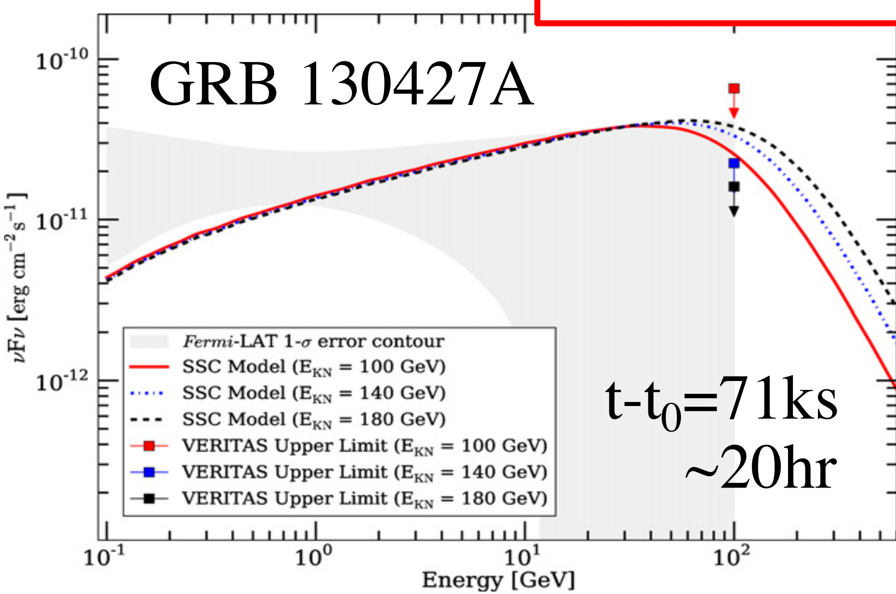


HESS Abramowski+ 2014

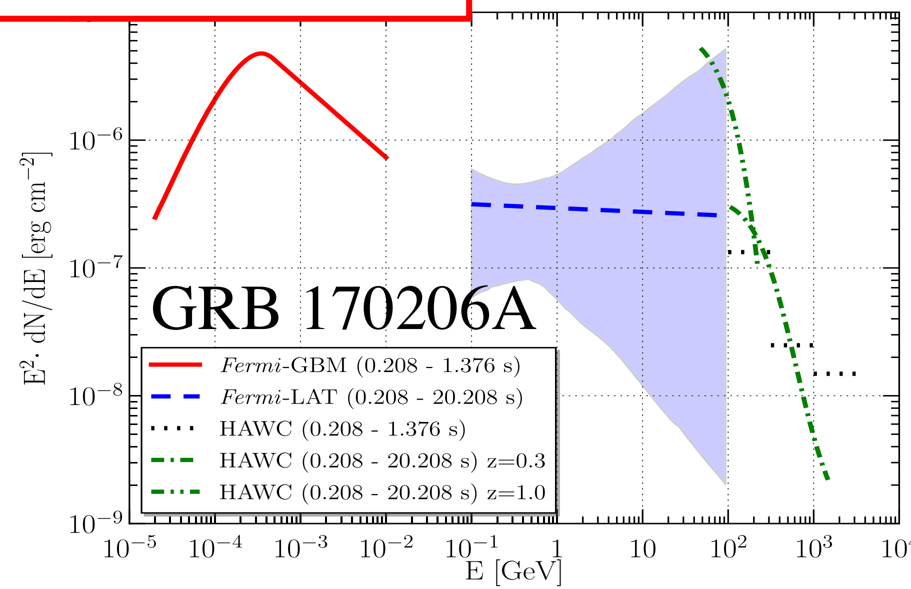


Despite numerous searches, no clear detections...

VERITAS



Alfaro+ 2017

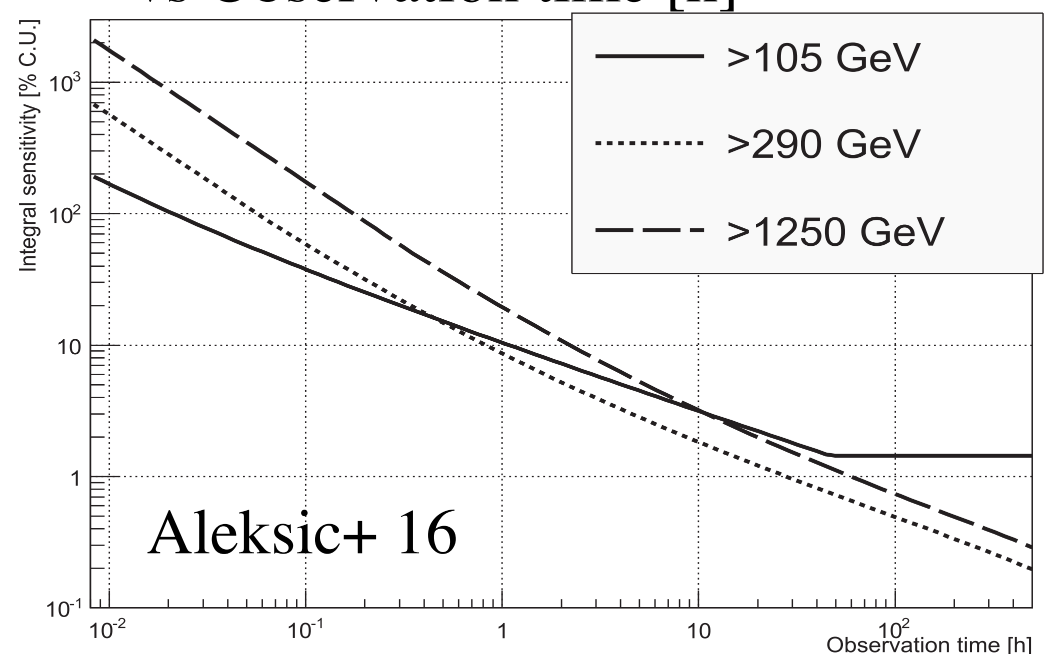


2. GRB 190114C

MAGIC telescopes

- 2 × 17m IACTs
 La Palma, Canary Is.
 altitude 2200m
- Field of view: ~3.5°
- Angular resolution: ~0.1°
- Sensitivity:
 ~ 10% Crab in 1 h >100 GeV
- Threshold energy:
 ~50 GeV at zenith angle <20°
- Repointing speed:
 ~30 s for 180°
- Key observing program
 dedicated to GRB follow-up
 mono from Apr. 2005
 stereo from July 2009

Integral sensitivity [% Crab units]
vs Observation time [h]



GRB 190114C

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)

moderate moon
(~6 x dark)
zenith angle >56 deg

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TITLE:   GCN CIRCULAR
NUMBER:  23701
SUBJECT: MAGIC detects the GRB 190114C in the TeV energy domain
DATE:    19/01/15 01:56:36 GMT
FROM:    Razmik Mirzoyan at MPI/MAGIC  <Razmik.Mirzoyan@mpp.mpg.de>

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Collaboration report:
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GCN Circular on TeV detection

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On January 14, 2019, the MAGIC telescopes located at the Observatorio

Roque de los Muchachos on the Canary island of La Palma, detected

very-high-energy gamma-ray emission from GRB 190114C (Gropp et al.,

GCN 23688; Tyurina et al., GCN 23690, de Ugarte Postigo et al., GCN

23692, Lipunov et al. GCN 23693, J. Selsing et al. GCN 23695).
The observation was triggered by the Swift-BAT alert and it started about

50s after the Swift T0: 20:57:03.19.

The GRB data of MAGIC shows a clear excess of gamma-ray events with the

significance >20 sigma in the first 20 min (starting at T0+50s) for energies

>300GeV. The relatively high detection threshold is due to the large zenith

angle of observations (~60 deg.) and the presence of partial moon. After

the first bright flash the source is quickly fading.

The MAGIC point of contact for this burst is R. Mirzoyan
(Razmik.Mirzoyan@mpp.mpg.de).

Burst Advocate for this burst is K. Noda ( <mailto:nodak@icrr.u-tokyo.ac.jp>
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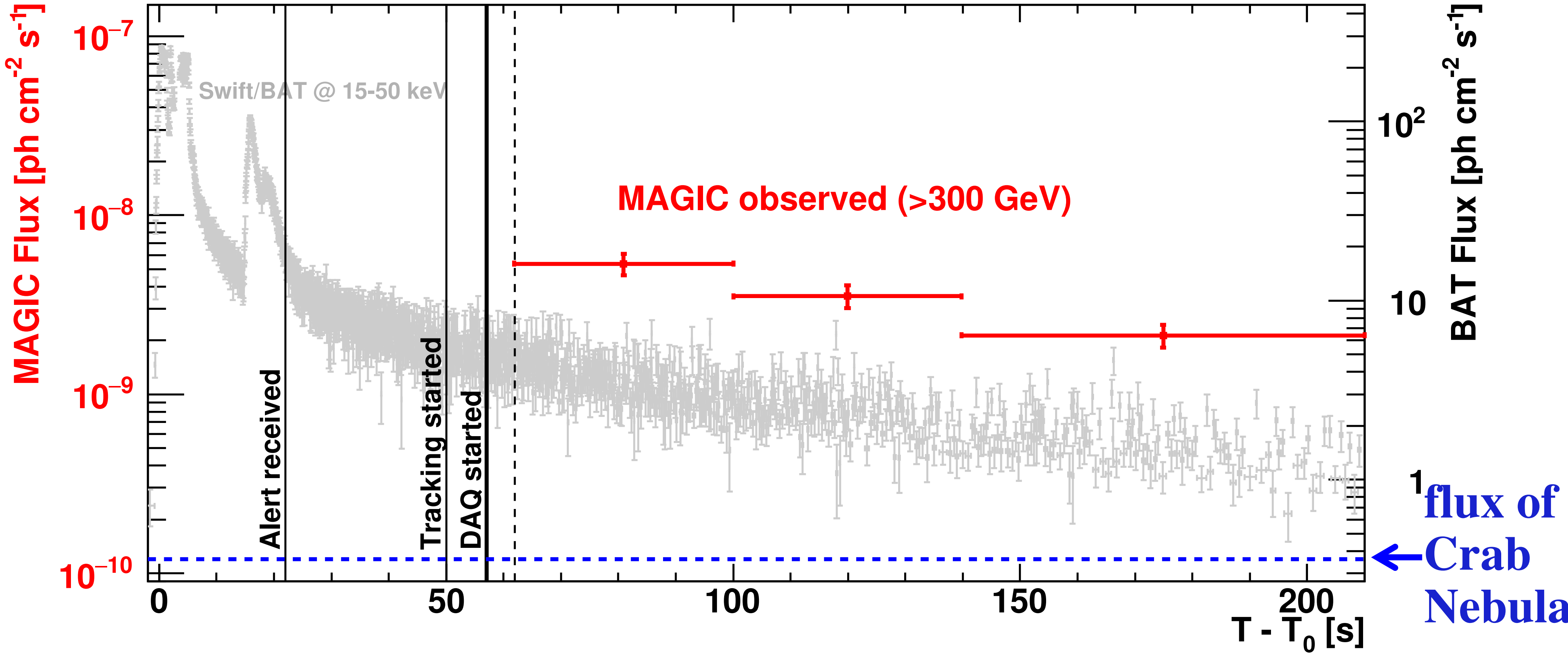
GRB 190114C: early TeV vs keV-MeV light curve

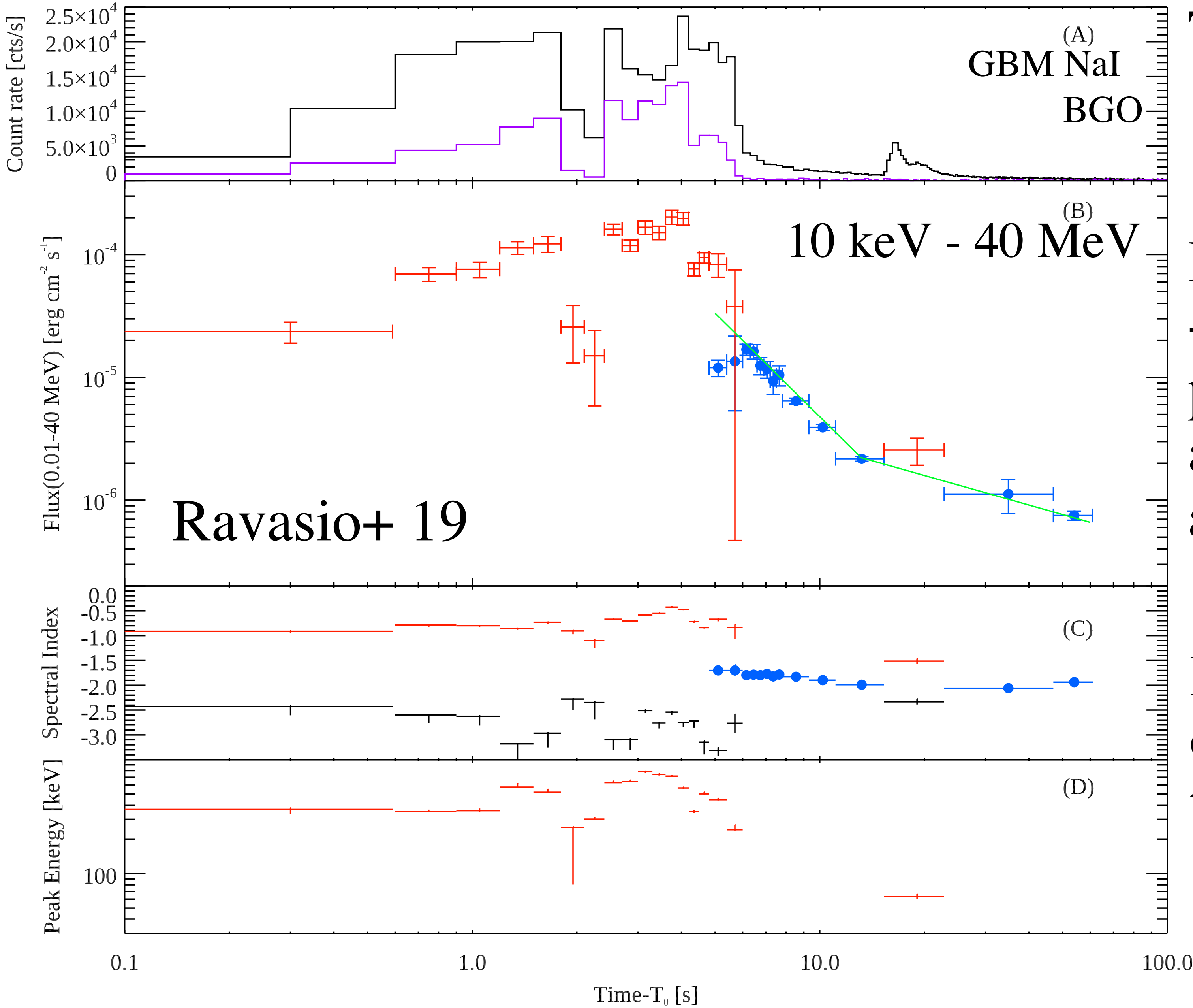


- significance > 50σ in first 20 min

- ~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: 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

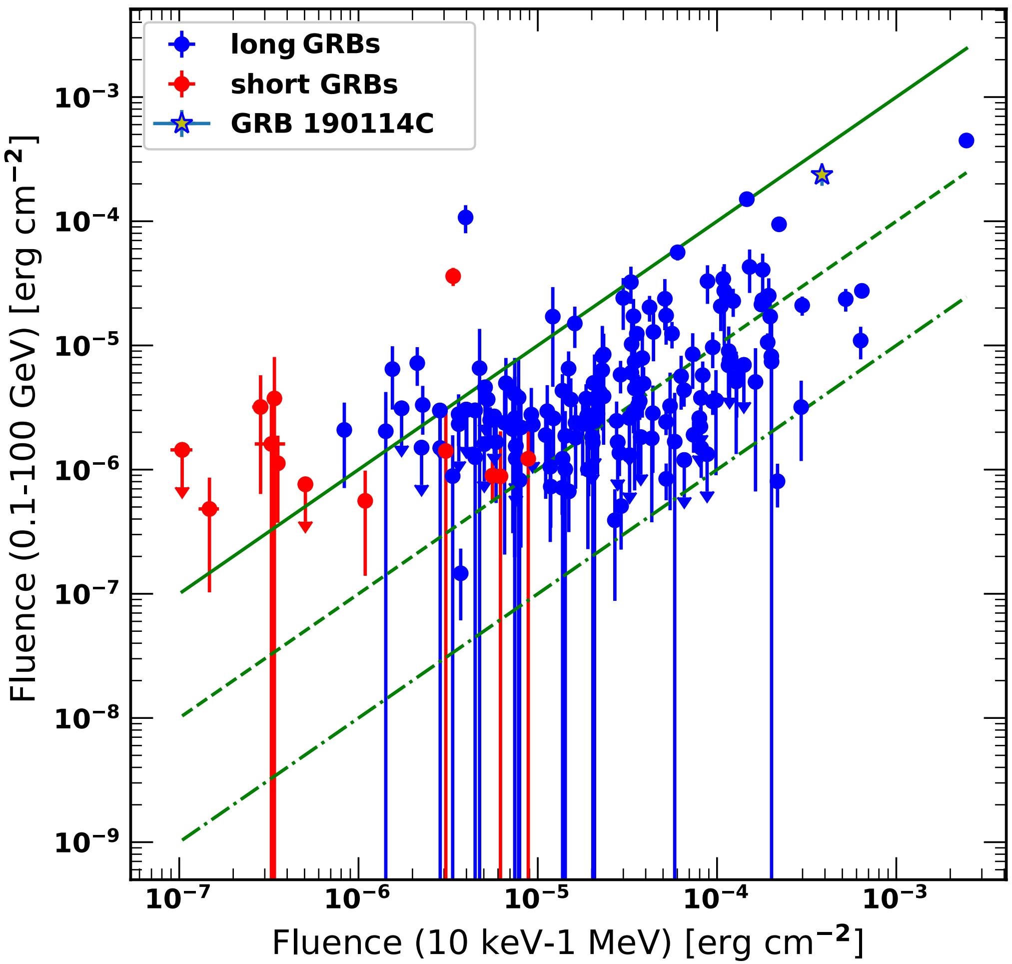
large contribution of afterglow to T_{90}, E_{iso}

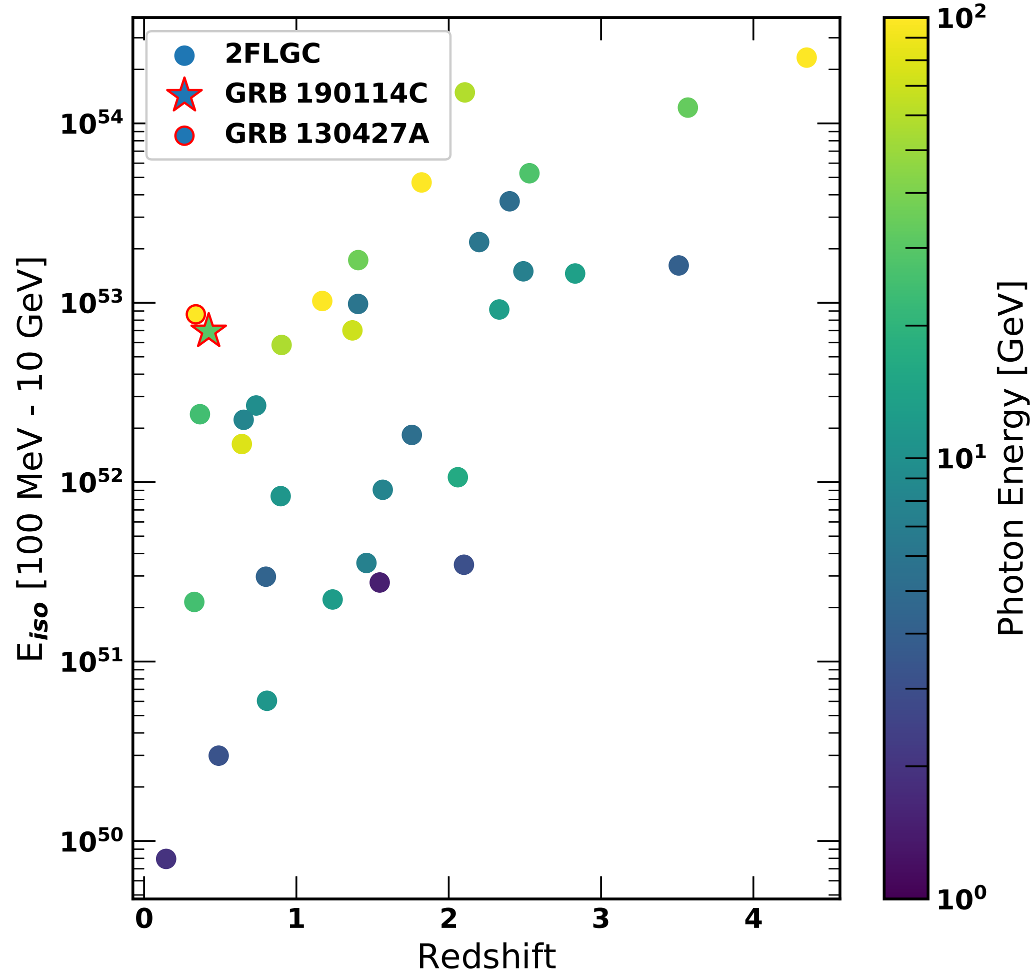
GRB 190114C: comparison with other GRBs

$z=0.425$, $E_{iso}\sim 3\times10^{53}$ erg, $L_{iso}\sim 1\times10^{53}$ erg/s ($1\text{-}10^4$ keV)

$E_{iso}\sim 7\times10^{52}$ erg (0.1-100 GeV)

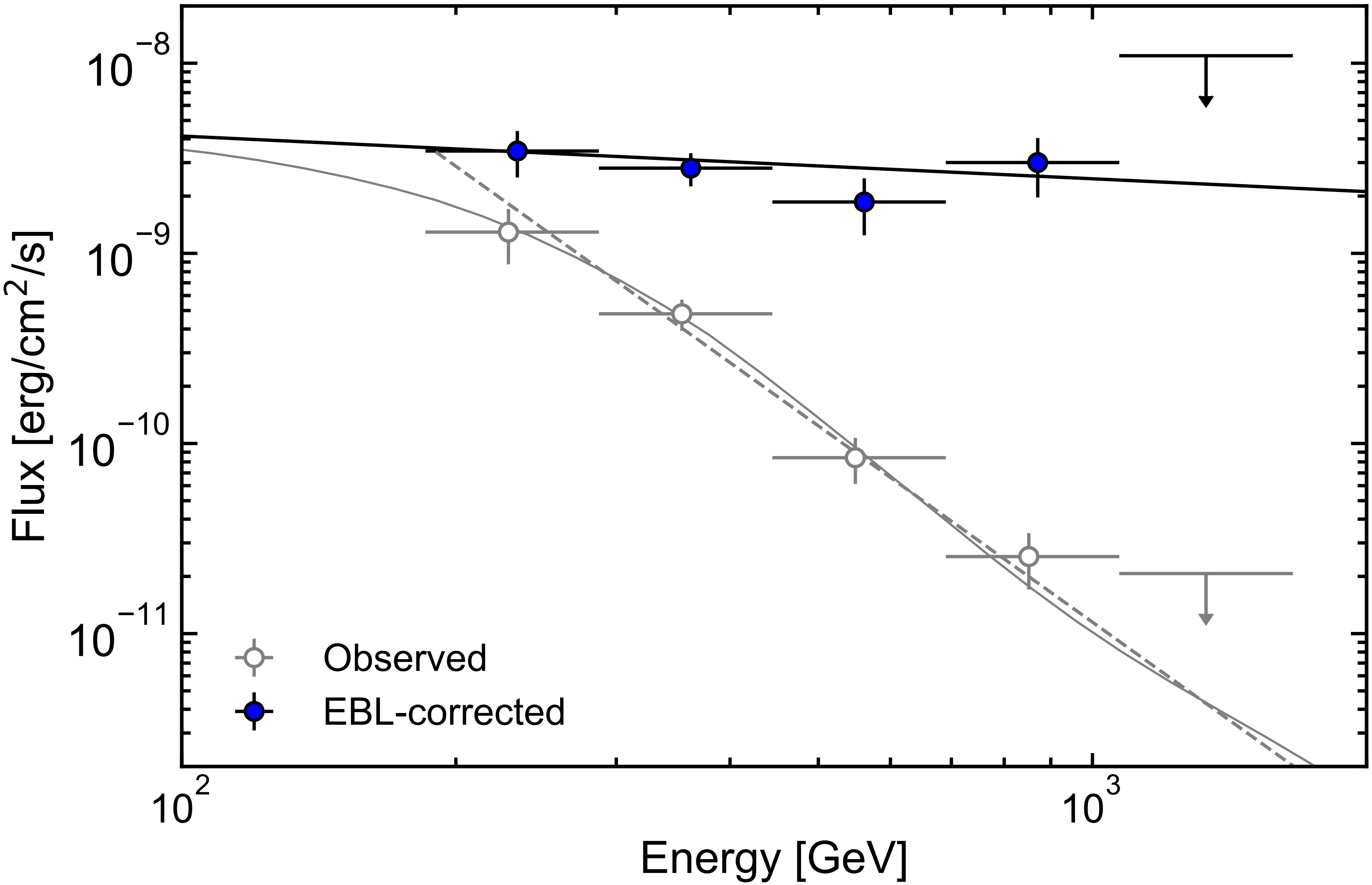
-> low z and large E_{iso}, but not peculiar





Fermi+Swift 1909.10605

GRB 190114C: time-integrated TeV spectrum

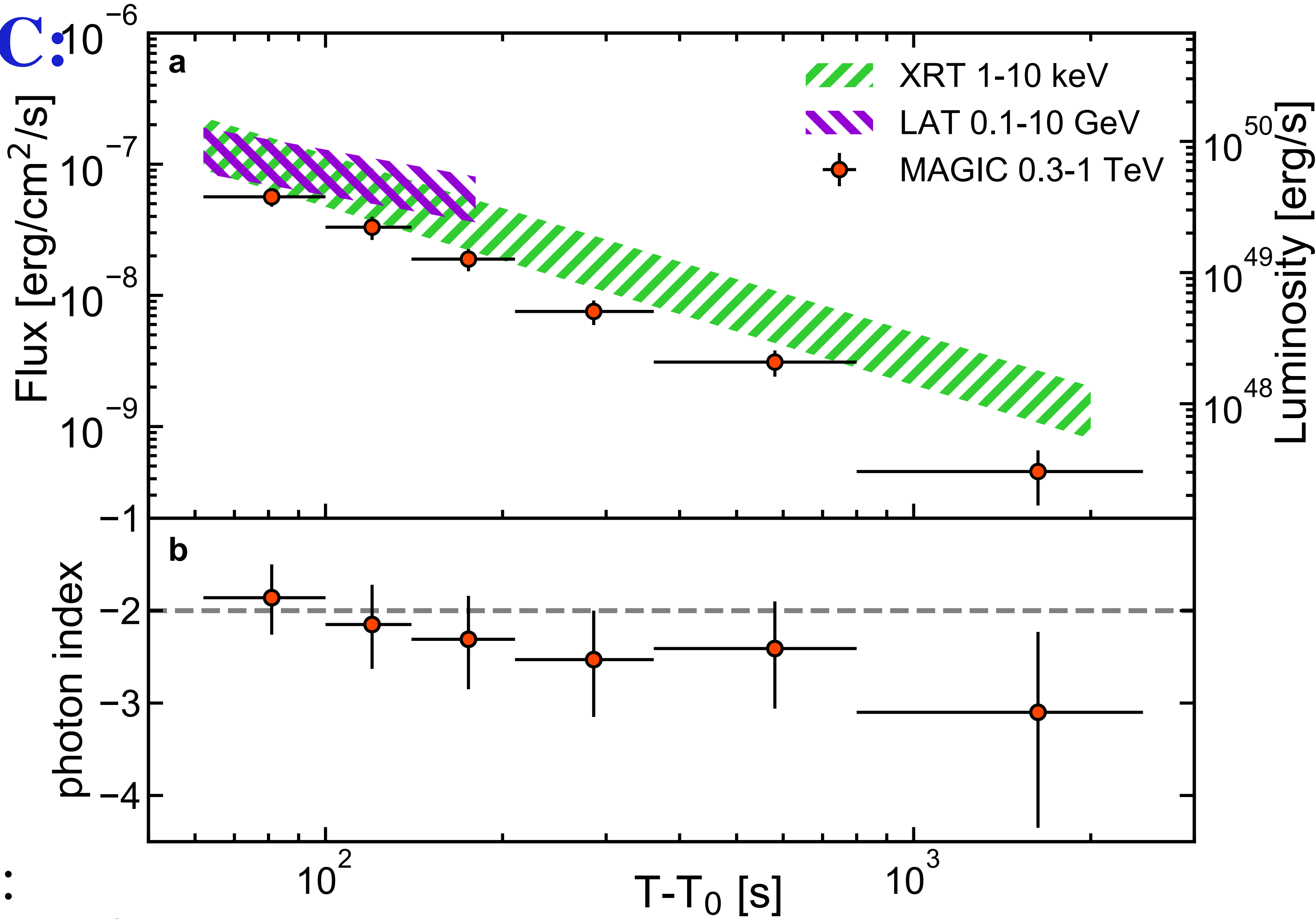


MAGIC Coll. 2019 Nature 575, 455

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



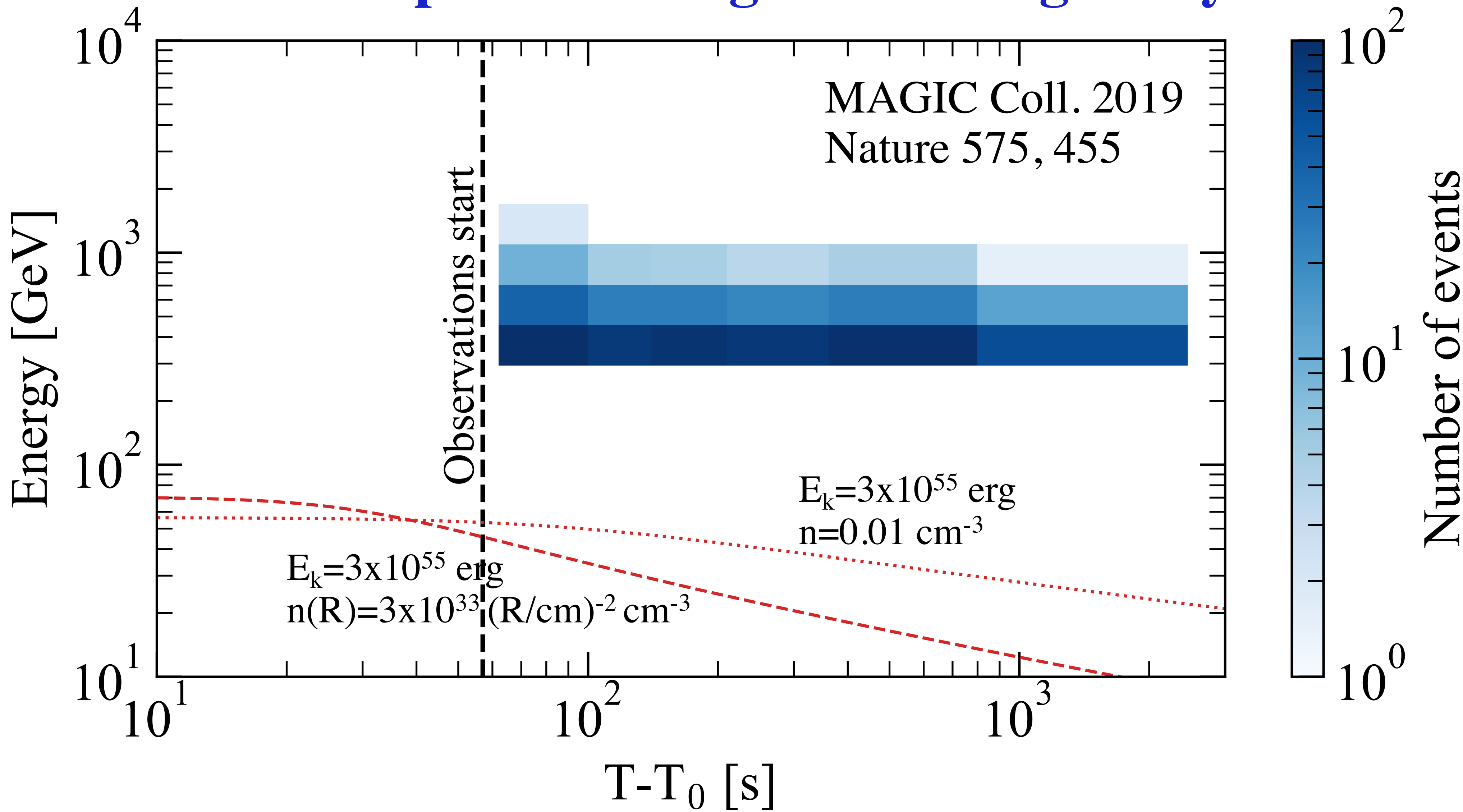
MAGIC Coll.
2019
Nature 575, 455

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

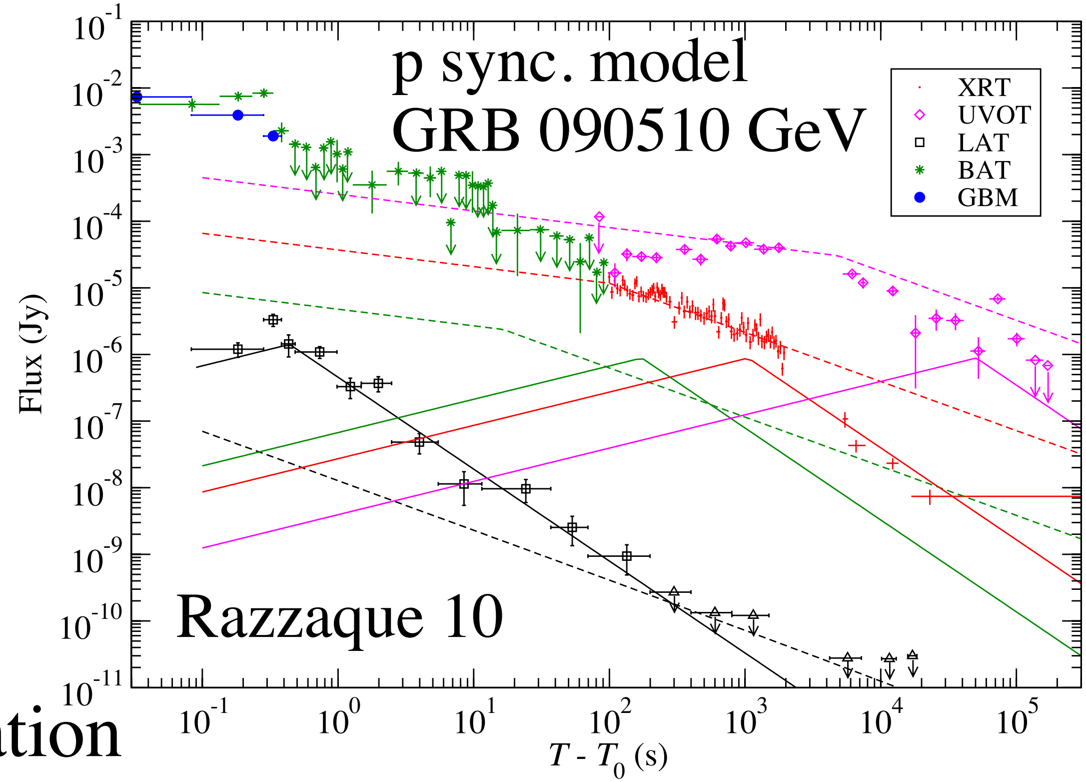


observed energies well above even extreme assumptions for $E_{syn,max}$

-> unambiguous evidence for separate emission component

GRB 190114C: origin of new component beyond sync.

- hadronic processes:
  proton synchrotron
  photohadronic cascade
  proton-proton π^0 decay
  -> highly unlikely due to
  low radiative efficiency



- leptonic processes:
  inverse Compton
  -> supported by TeV-X correlation
  synchrotron-self Compton (SSC)
  -> most natural, discussed in next slides

FYI: several papers on SSC interpretation already published/posted, even without any MAGIC data

Derishev & Piran 1905.08285, Wang+ 1905.11312,
Fraija+ 1904.06976, 1907.06675...

Comparison with past MAGIC GRB observations

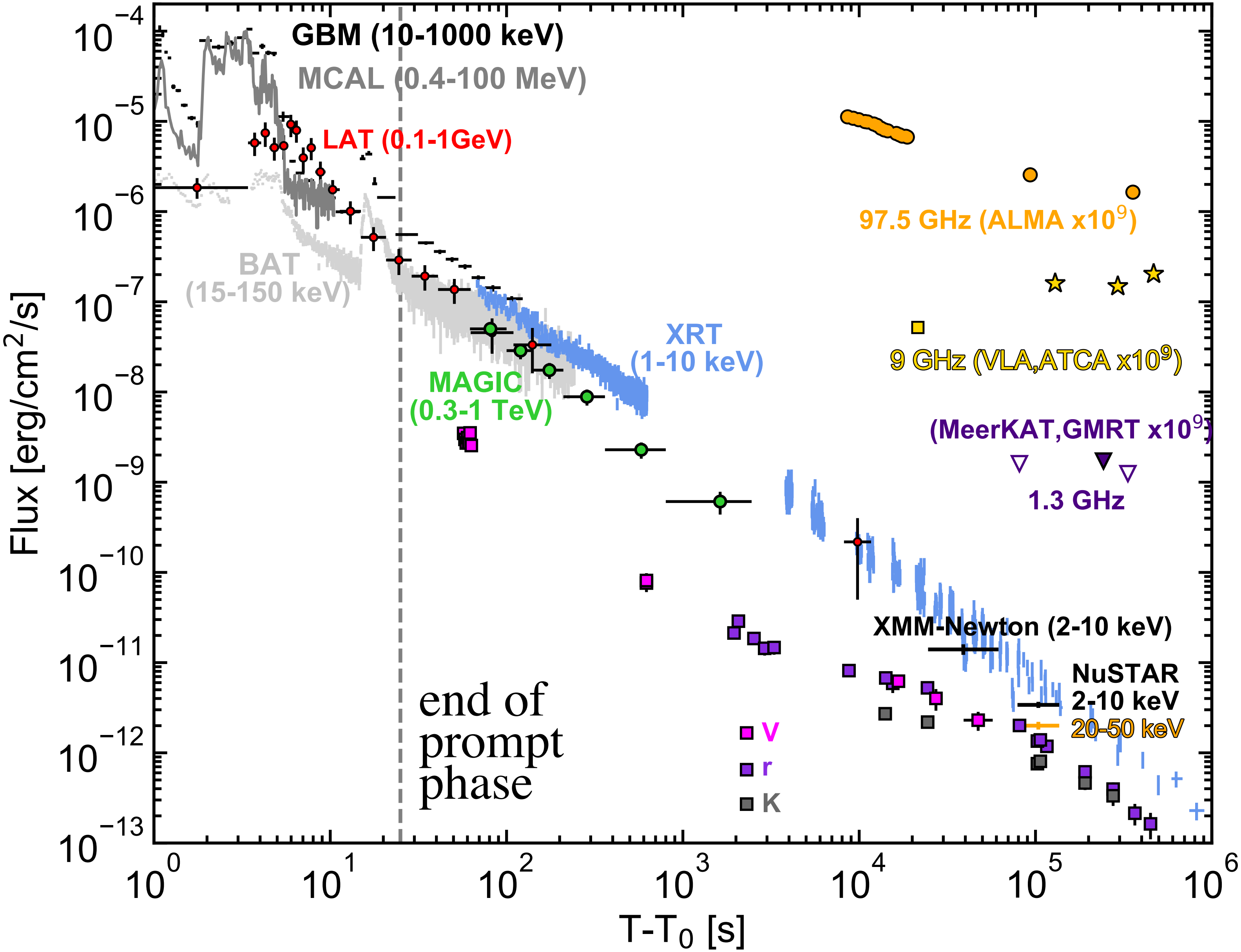
Was 190114C a peculiar GRB? Probably not.

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

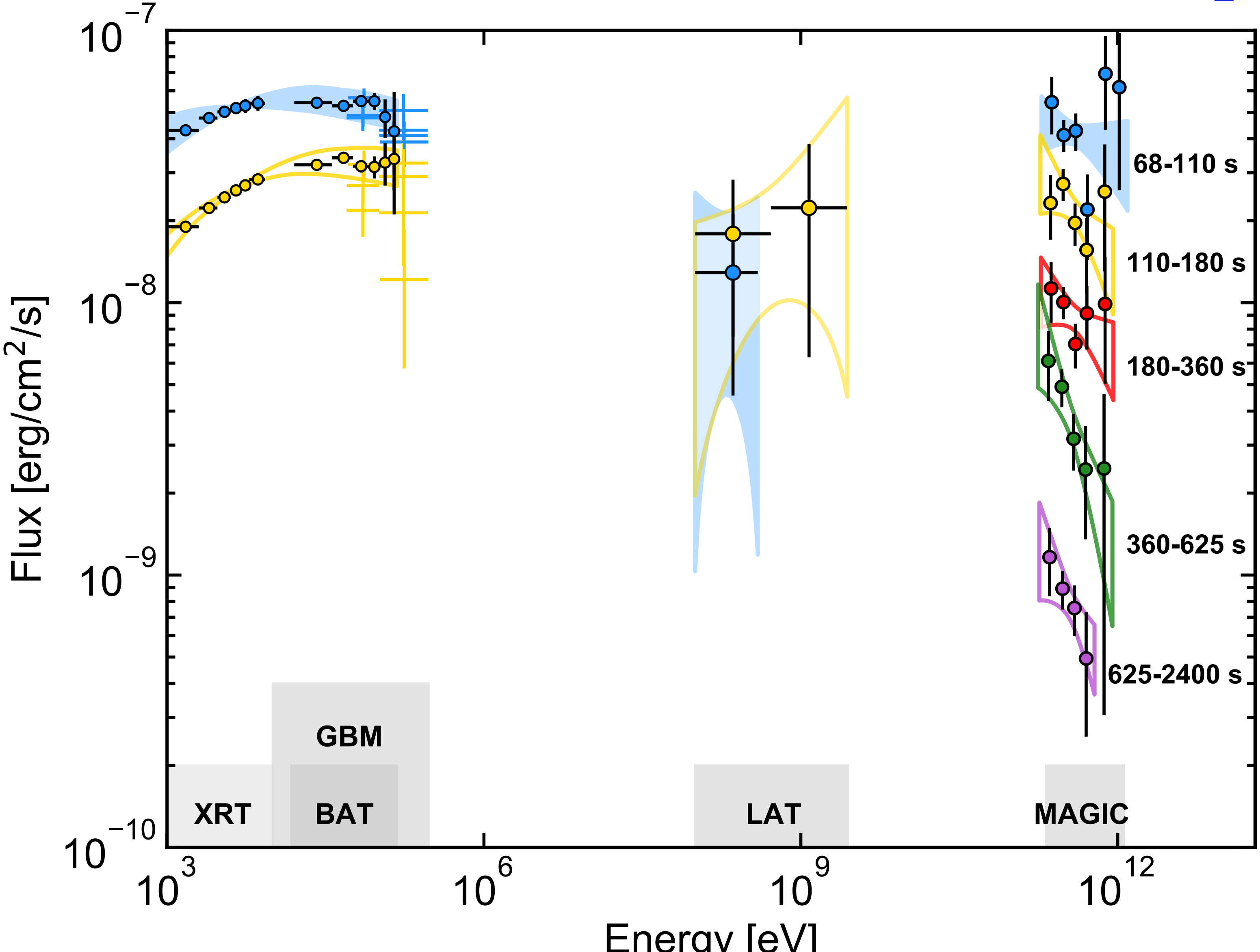
GRB 190114C: multiwavelength light curves



MAGIC Coll. et al 2019 Nature 575, 459

- extensive MWL coverage from GHz to TeV

GRB 190114C: time-resolved broadband spectra



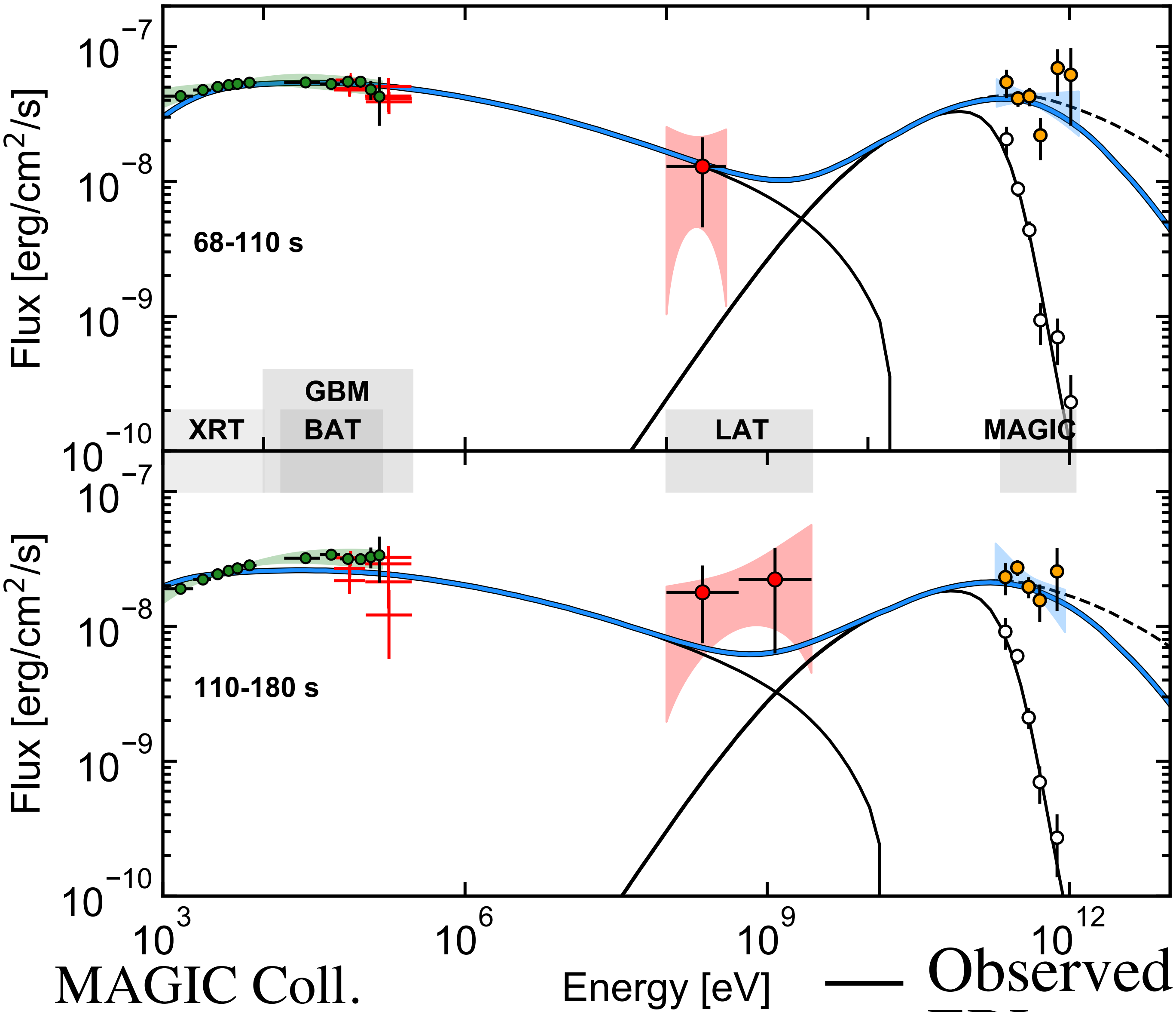
MAGIC Coll. et al 2019 Nature 575, 459

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

multi-wavelength afterglow modeling by Lara Nava

- basic description of external shock hydrodynamical evolution including onset (coasting) phase
- synchrotron+SSC emission with self-consistent evolution of electron distribution including KN regime
- internal $\gamma\gamma$ absorption, emission from secondary pairs
  e.g. Granot & Sari 2002, Sari & Esin 2001, Nakar+ 2009
- main parameters:
  initial kinetic energy E_k
  external medium density $n=n_0R^{-s}$ $\begin{cases} n_0=\text{const.} & (s=0\text{: ISM}) \\ n_0=3\times10^{35}A_* \text{ cm}^{-1} & (s=2\text{: wind}) \end{cases}$
  fraction of shock-dissipated energy channeled into electrons ε_e
  into magnetic field ε_B
  electron injection spectral index p
  (other parameters: f_e, η...)
- fast, systematic search of parameter space

GRB 190114C: time-resolved spectra vs SSC model

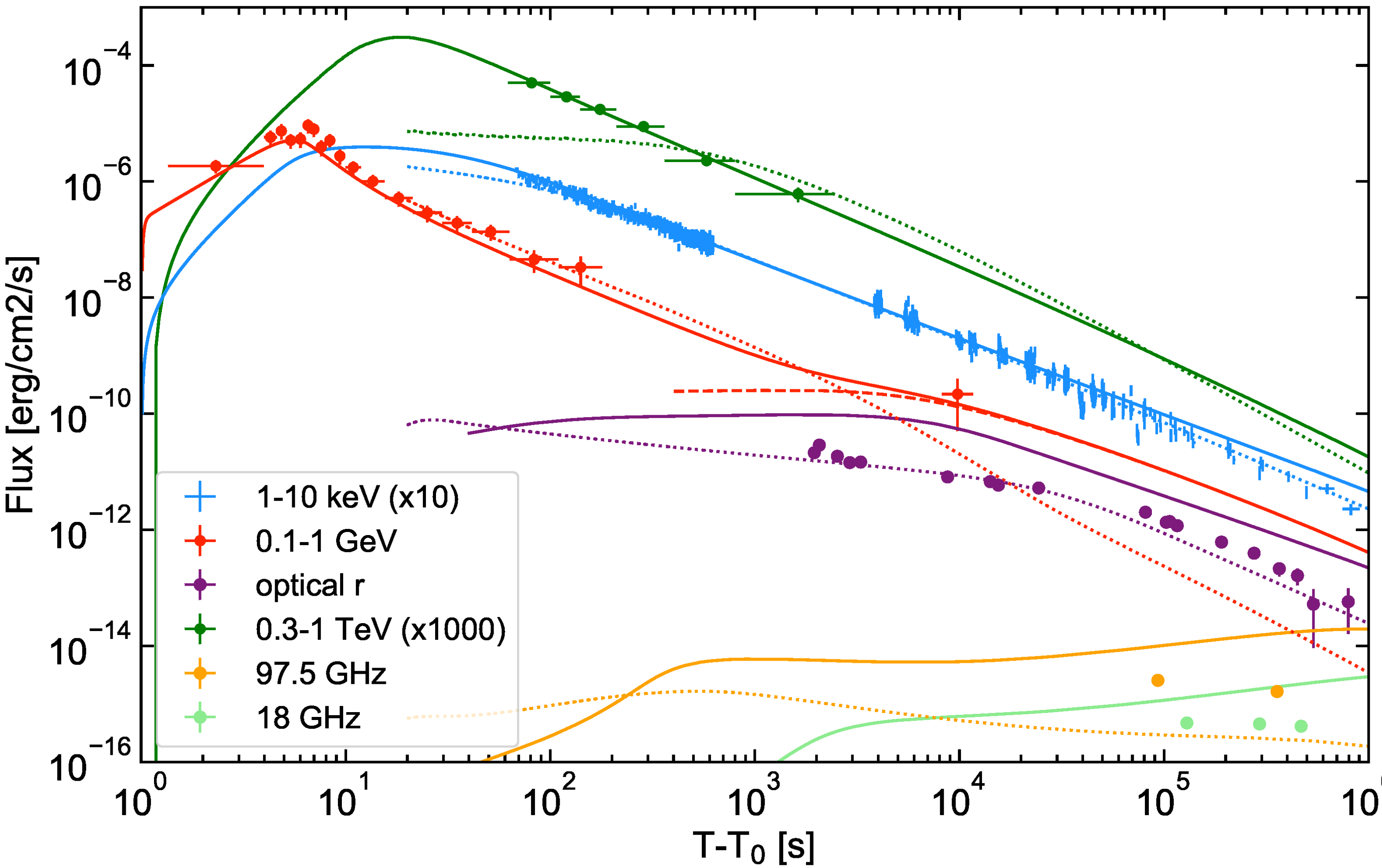


- reasonable SSC interpretation with plausible parameters:
  $s=0$, $n_0=0.5\ cm^{-3}$
  $\varepsilon_e=0.07$, $\varepsilon_B=8x10^{-5}$
  $E_k=8x10^{53}$ erg, $p=2.6$
- supports inference that TeV emission may be common
- steep TeV spectra -> KN+internal $\gamma\gamma$ abs (otherwise low ε_e, high B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

MAGIC Coll. et al 2019 Nature 575,

Observed
EBL-cor., no int. $\gamma\gamma$
EBL-cor., inc. int. $\gamma\gamma$

GRB 190114C: MWL light curves vs SSC models



solid - ISM
(dashed SSC only)
s=0, n_0=0.5 cm^{-3}
ε_e=0.07, ε_B=8x10^{-5}
E_k=8x10^{53} erg
p=2.6

dotted - wind
s=2, A_*=0.1
ε_e=0.6, ε_B=10^{-4}
E_k=4x10^{53} erg
p=2.4

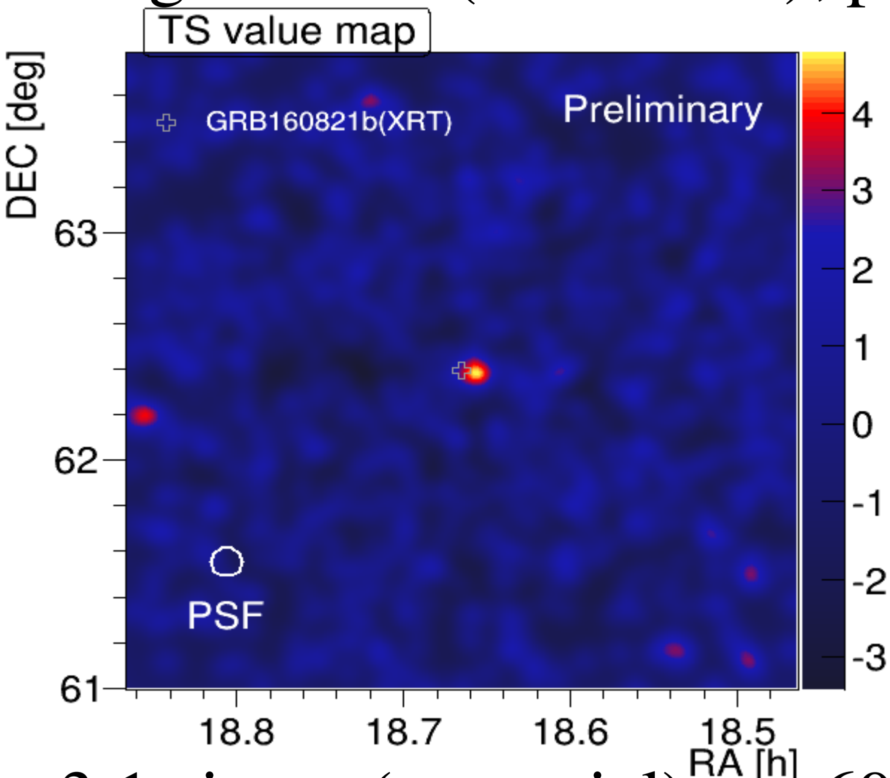
- TeV (smooth decay to t~10^3 s): s=0 slightly better, but s=2 also OK
- late X-ray (break at t~4x10^4 s): s=2 better, as ν_c crossing
- note: optical at t<10^3 s, radio at t<10^5 s likely from reverse shock

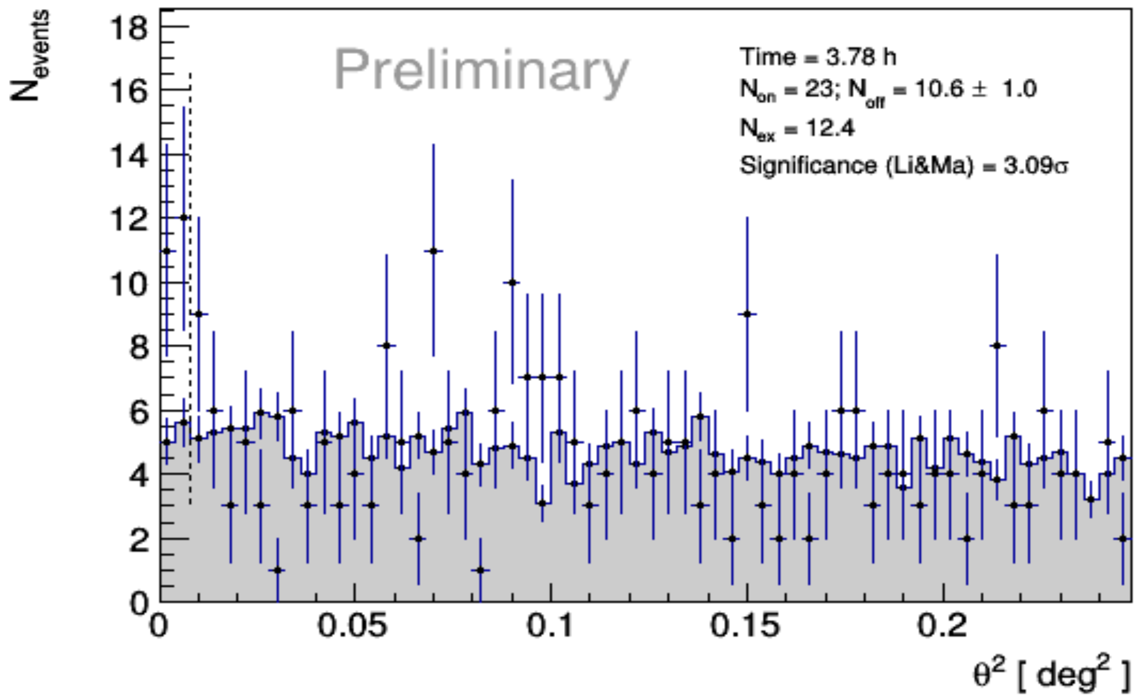
Laskar+ 19

3. GRB 160821B

short GRB 160821B: TeV observations

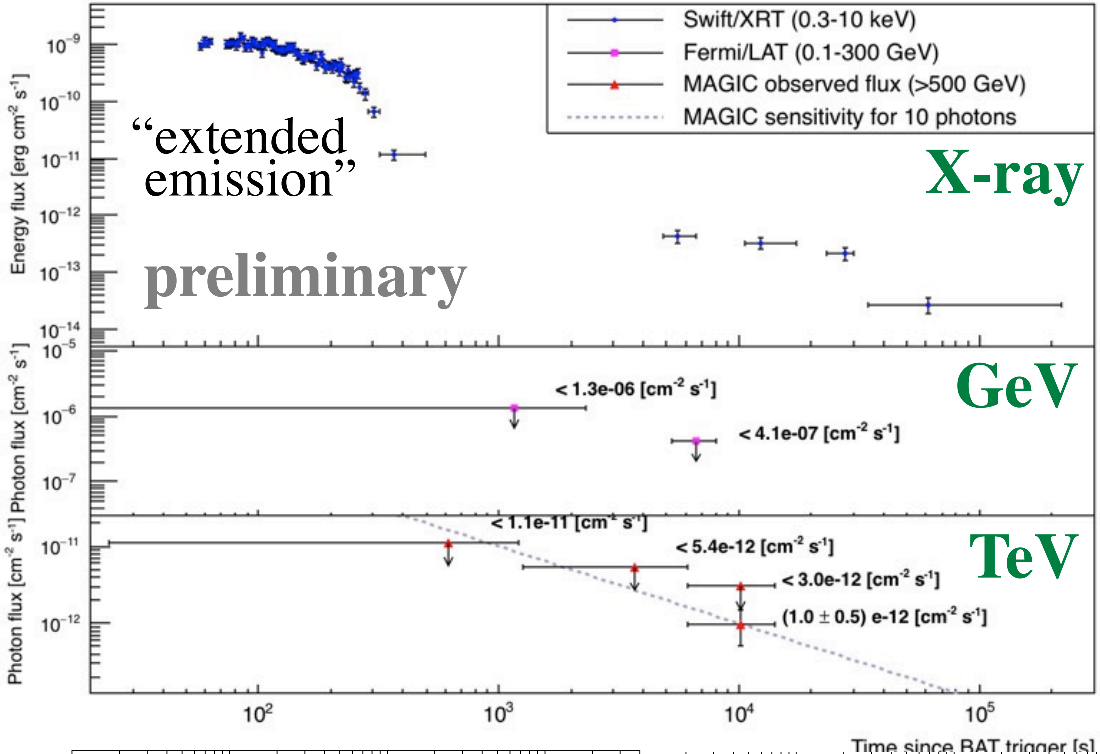
- short GRB (T_{90}~0.5s), nearby (z=0.16) -> E_{iso}~1.2×10^{50} erg/s
- MAGIC follow up t~24 s - 4 hr, zenith angle~34-55°
  bright moon (3-9 x dark), poor weather at t<1.5 hr





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

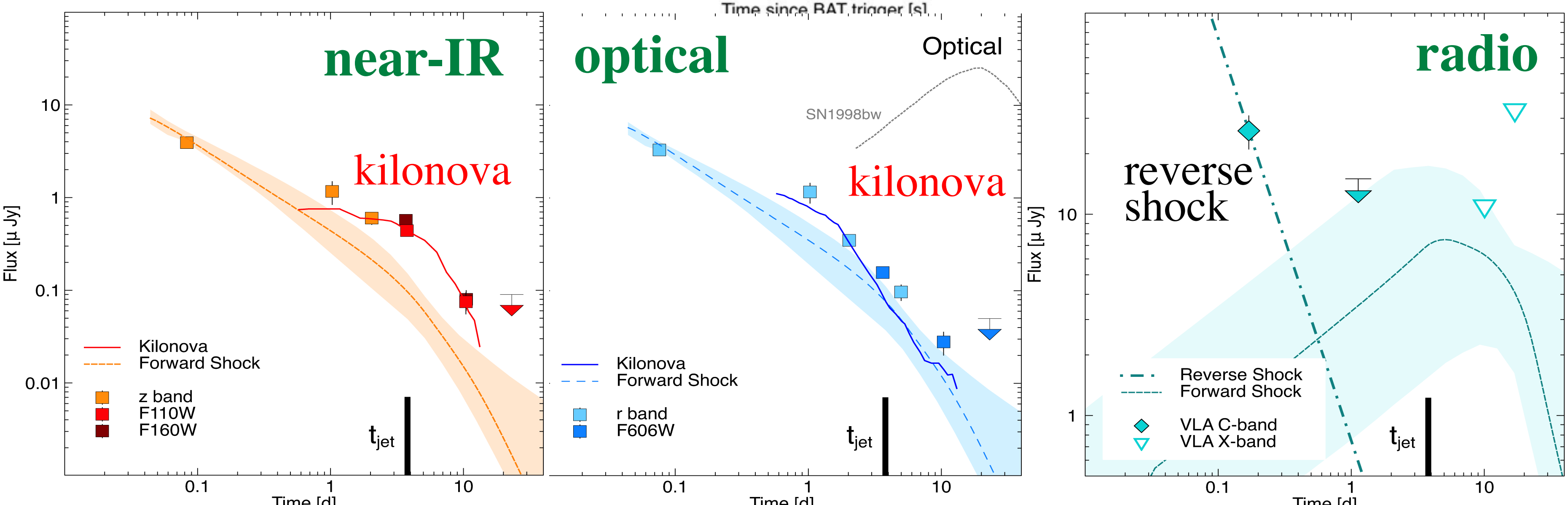
short GRB 160821B: TeV vs MWL observations



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



GRB observations by MAGIC

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}

160821B:
only GRB observed with criteria better than 190114C

4. Future prospects: Towards LHAASO

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- wide field of view
- high duty cycle
- high energy threshold

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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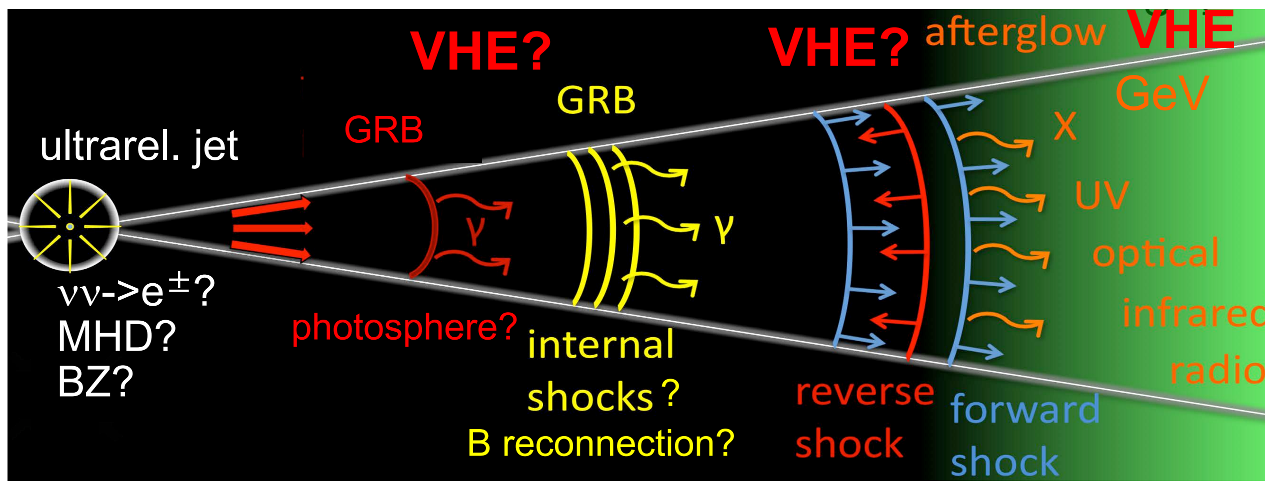
Further, qualitative leaps:

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



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More frequent detections

Observations at earlier times

(more challenging for IACTs)

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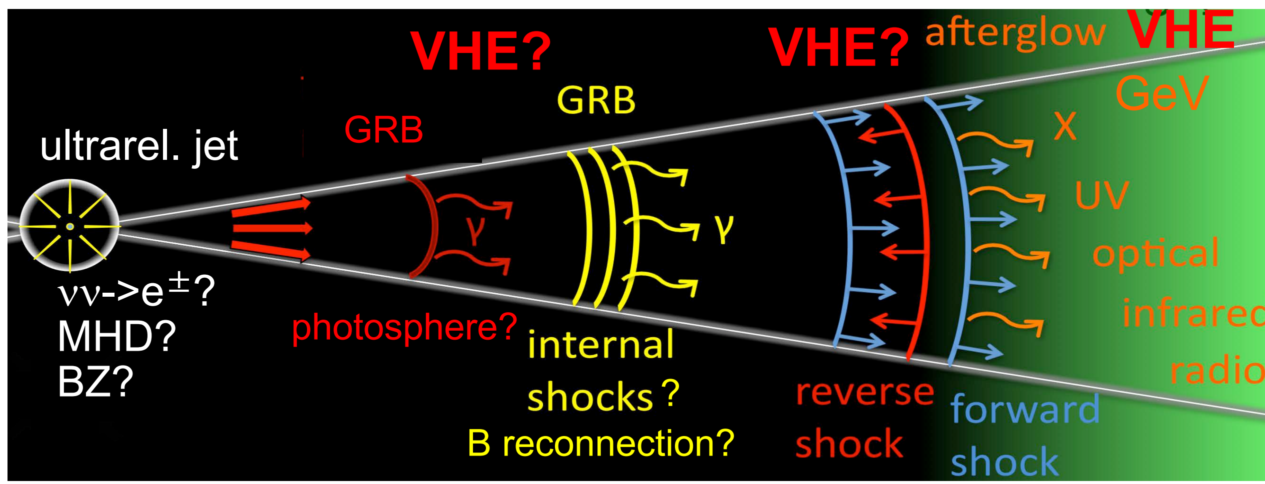
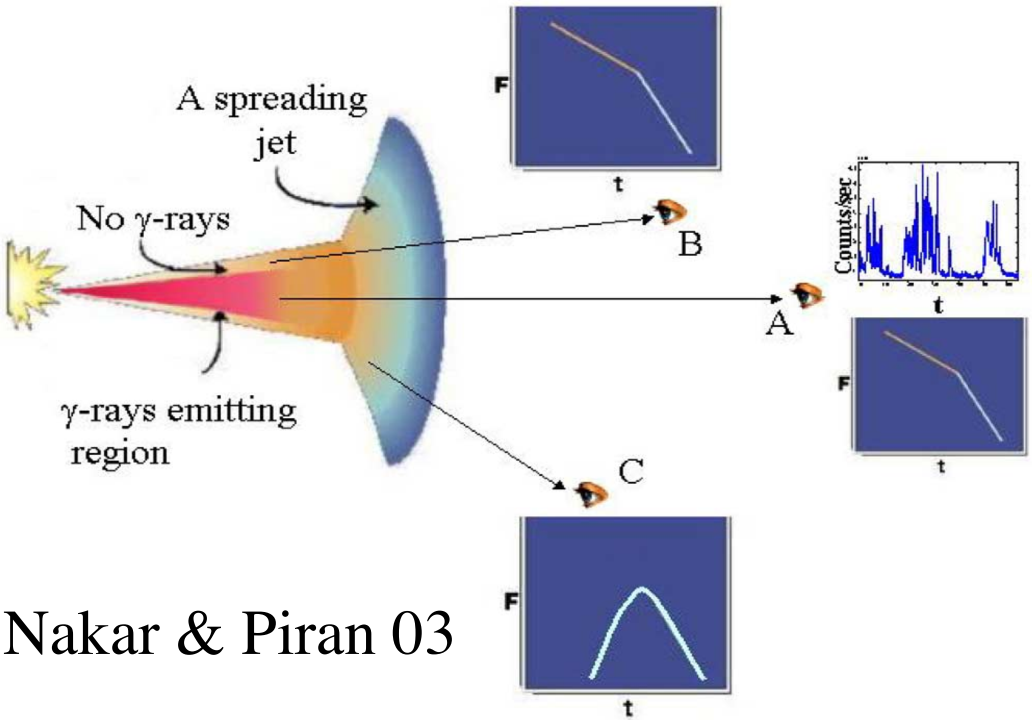
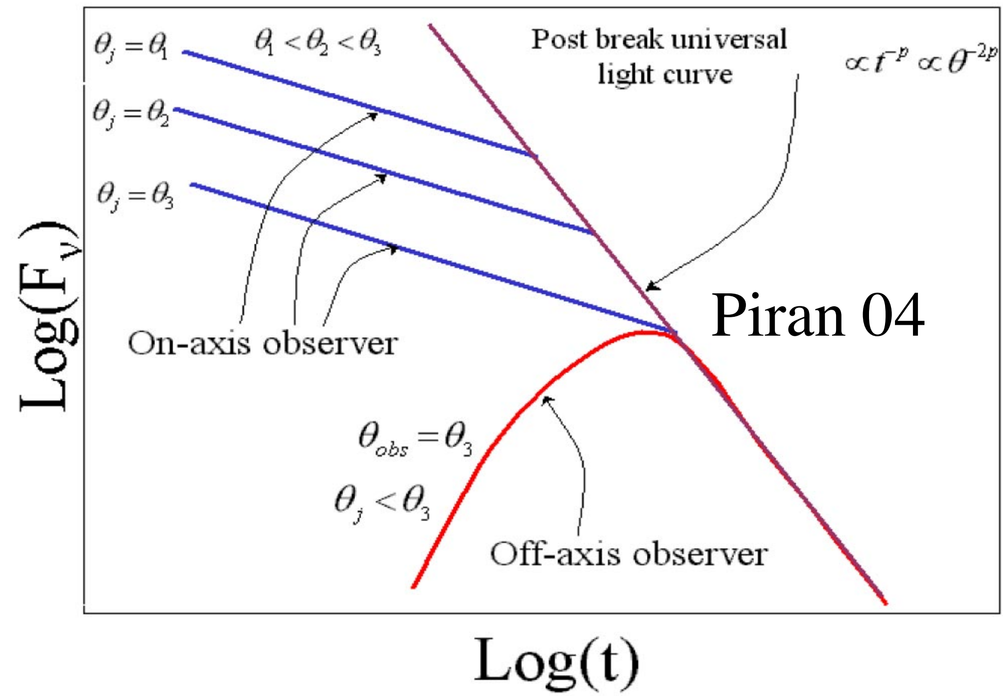


GRBs off-beam: orphan afterglows or GW counterparts



Nakar & Piran 03



Piran 04

SGRB: GW170817 radio-X-ray afterglow, implies structured jet
-> search for TeV counterparts of NS mergers

LGRB: no clear candidates so far in radio, optical, X-ray
-> SKA, LSST, Lobster...
-> searches in GeV-TeV?

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, LHAASO
  More TeV afterglows, reverse shock/prompt TeV emission...
  Orphan TeV afterglows, GW TeV counterparts...

Summary: GRBs at very high energies

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  potential
- Long GR
- Low-lum ... tails TBC.

Dawn of a new era in GRB physics!

- Great prospects for further progress with CTA, LHAASO
  More TeV afterglows, reverse shock/prompt TeV emission...
  Orphan TeV afterglows, GW TeV counterparts...

backup slides

gamma-ray absorption due to extragalactic background light (EBL)

$\gamma + \gamma \rightarrow e^+ + e^-$

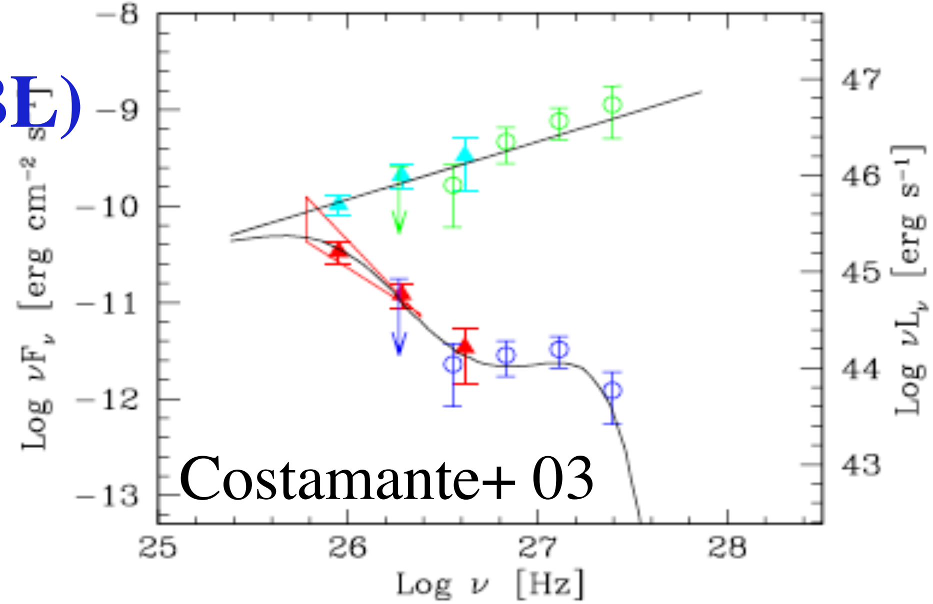
E ε

threshold condition: $E\,\varepsilon\,(1-\cos\theta) > 2\,m_e^2c^4$

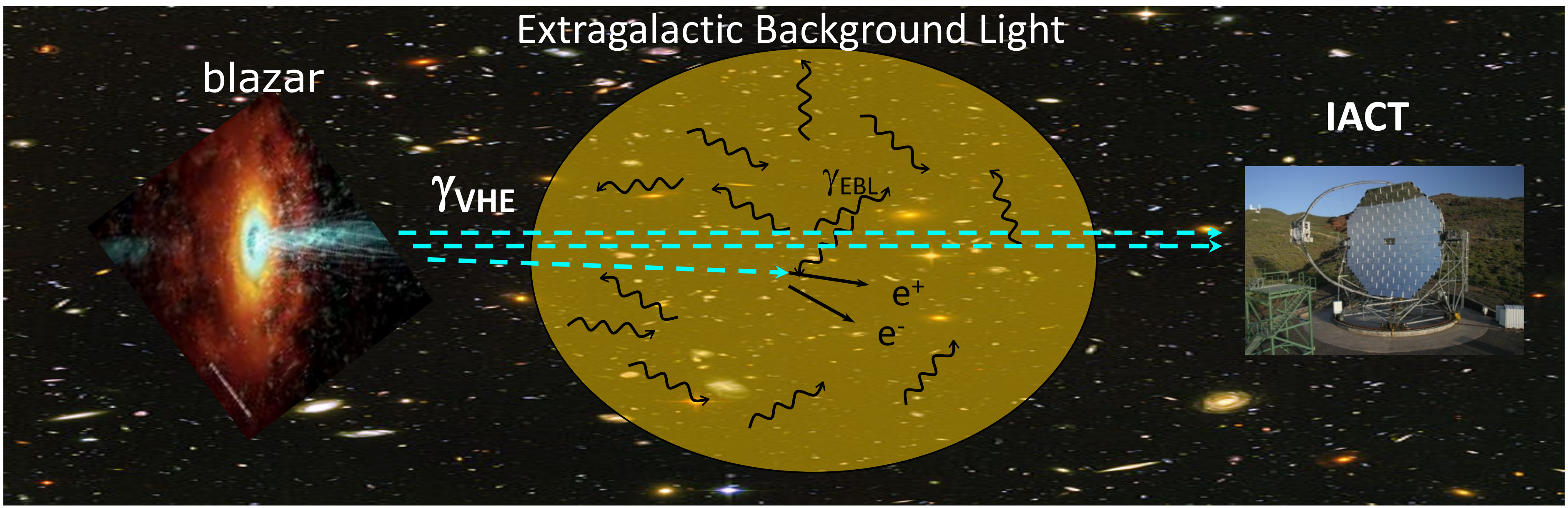
σ peak ,, $= 4\,m_e^2c^4$

e.g. TeV + 1eV (IR)

100 GeV + 10 eV (UV)

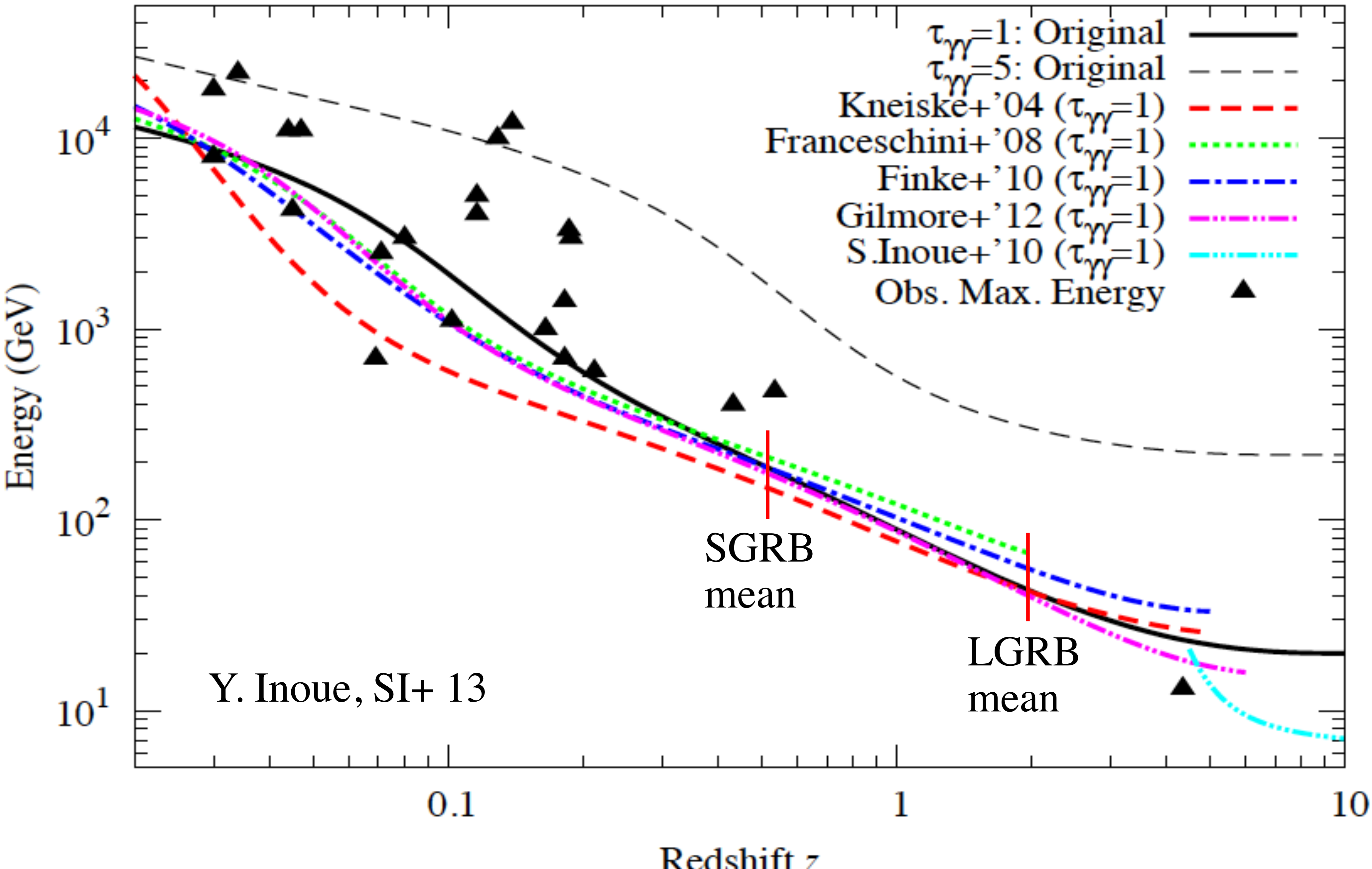


EBL attenuation effect in TeV blazar spectra

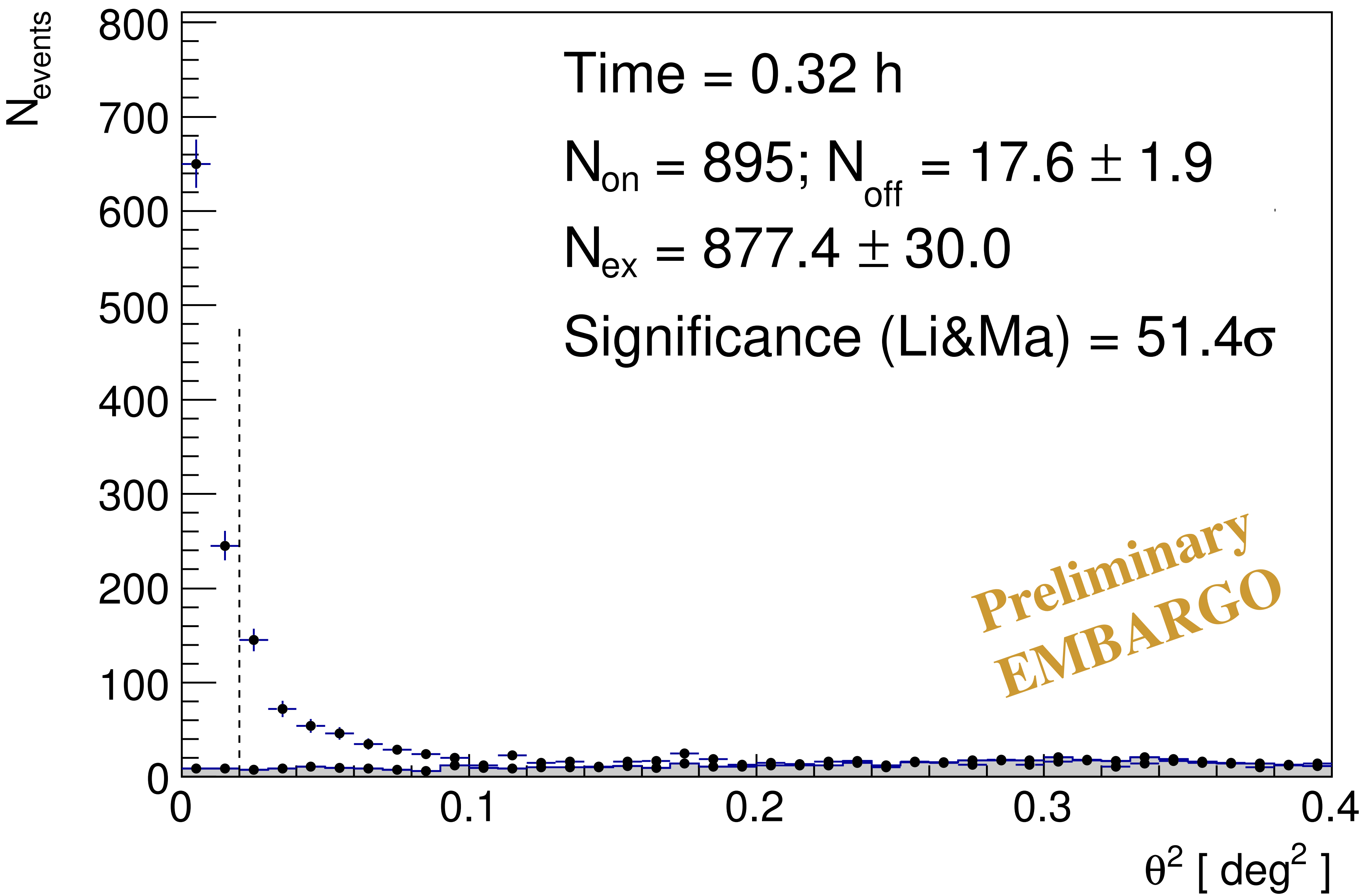


from D. Mazin

gamma-ray horizon $E(\tau_{\gamma\gamma}=1)$ vs z due to EBL

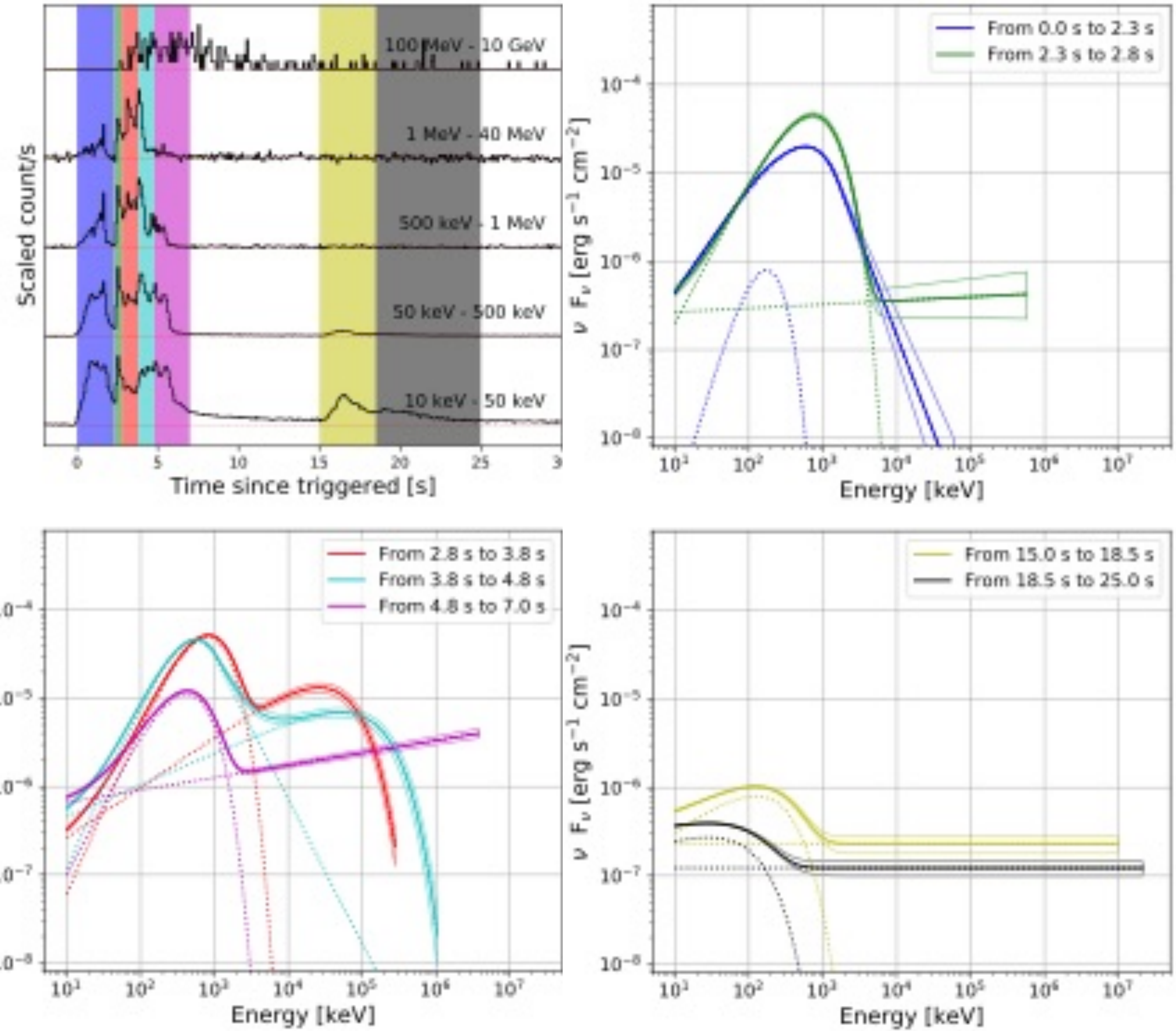


GRB 190114C: theta-squared plot



GRB 190114C: prompt vs afterglow

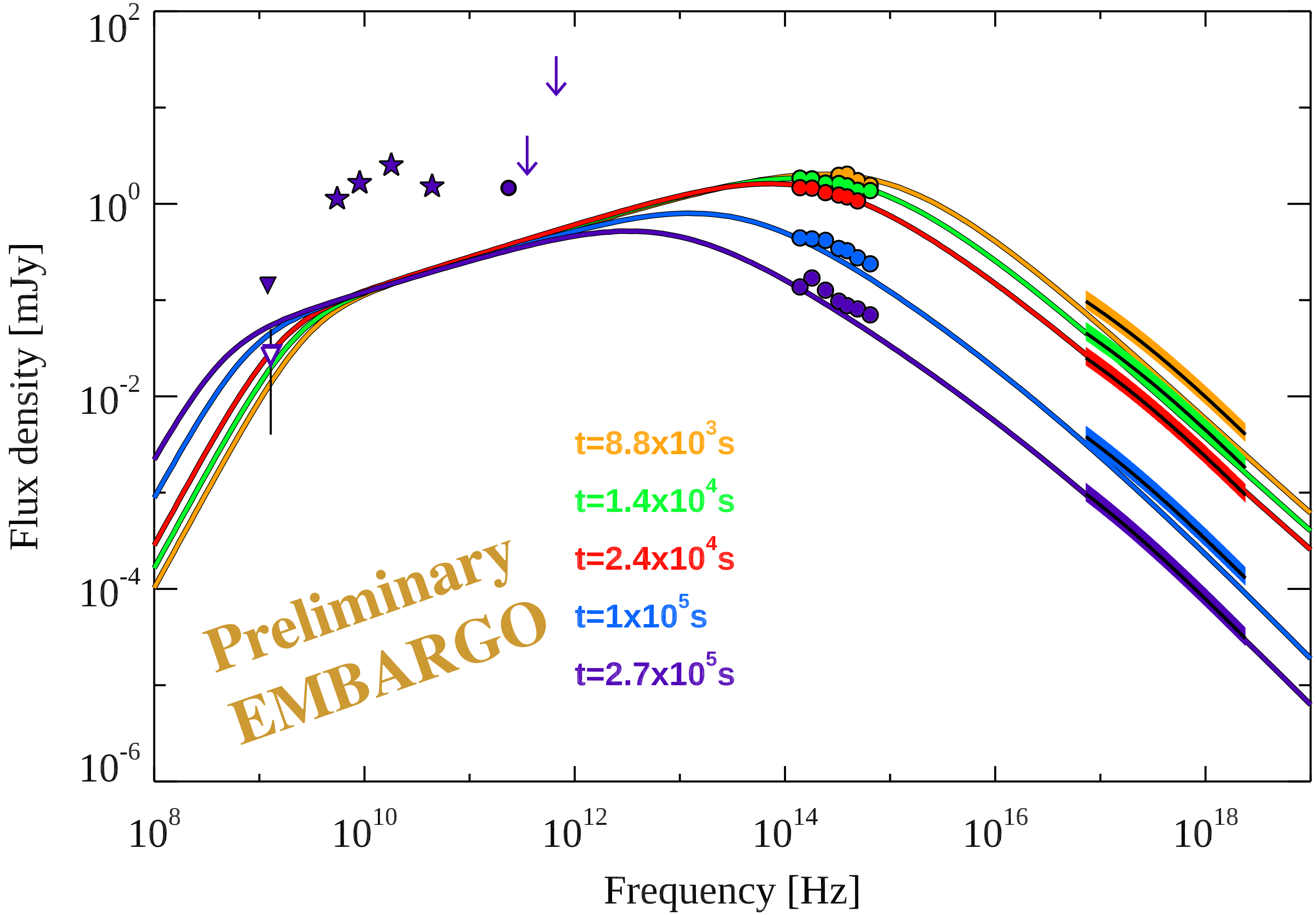
Fermi+Swift
1909.10605



evidence for spectral cutoff @40 MeV t~few sec, evolves to higher E with t -> internal γγ?

also Chand+
1905.11844

GRB 190114C: time-resolved spectra vs SSC model



solid – ISM

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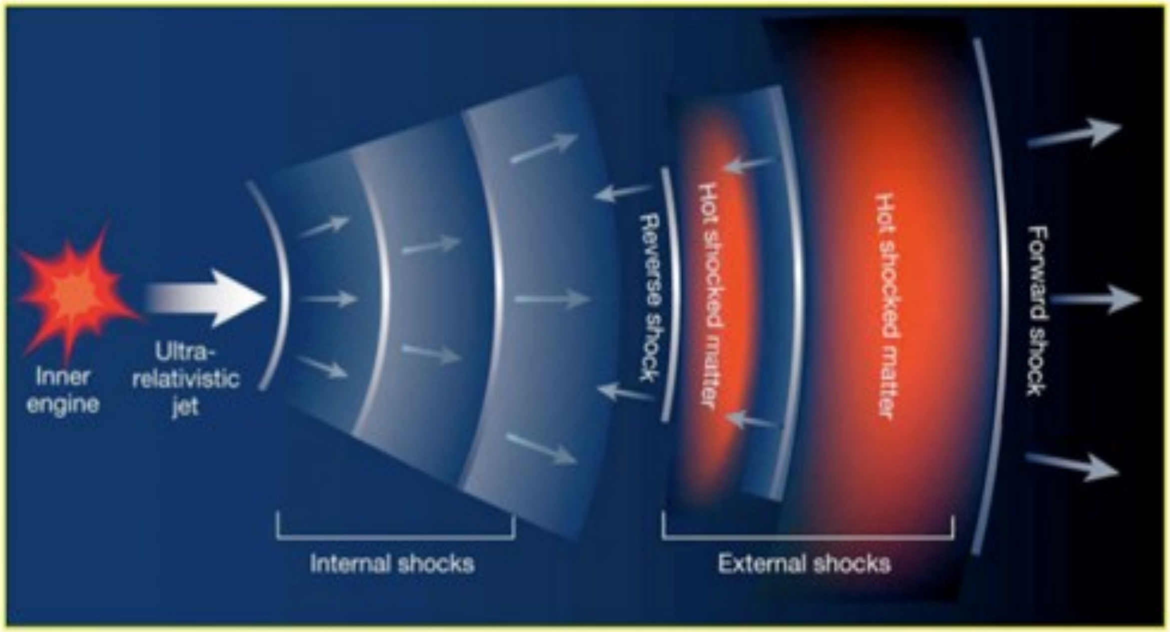
$\varepsilon_e=0.07$, $\varepsilon_B=8\times10^{-5}$

$E_k=8\times10^{53}$ erg

$p=2.6$

afterglow theory: basics

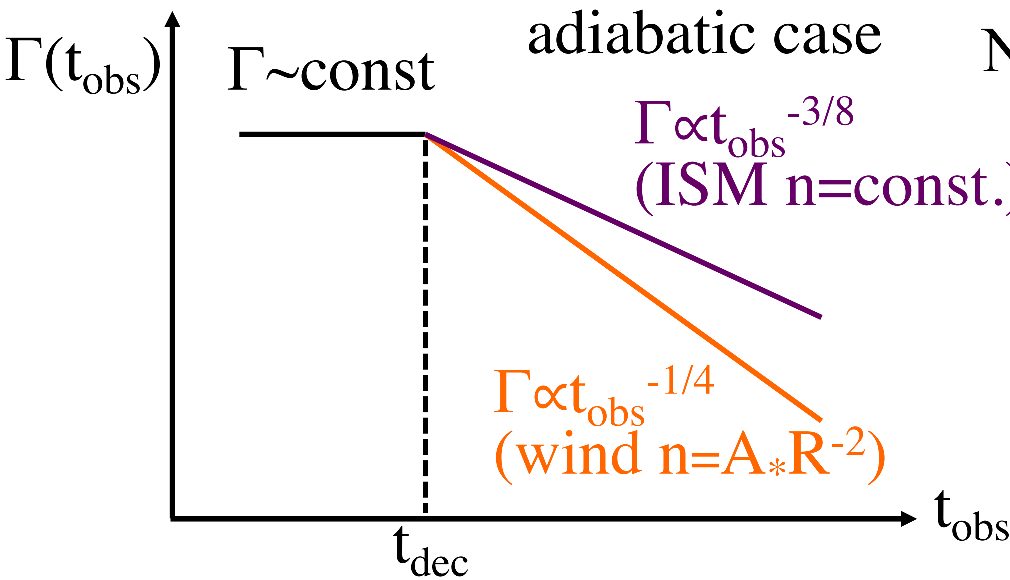
reviews: Meszaros 02, Piran 05, Kumar+ 15

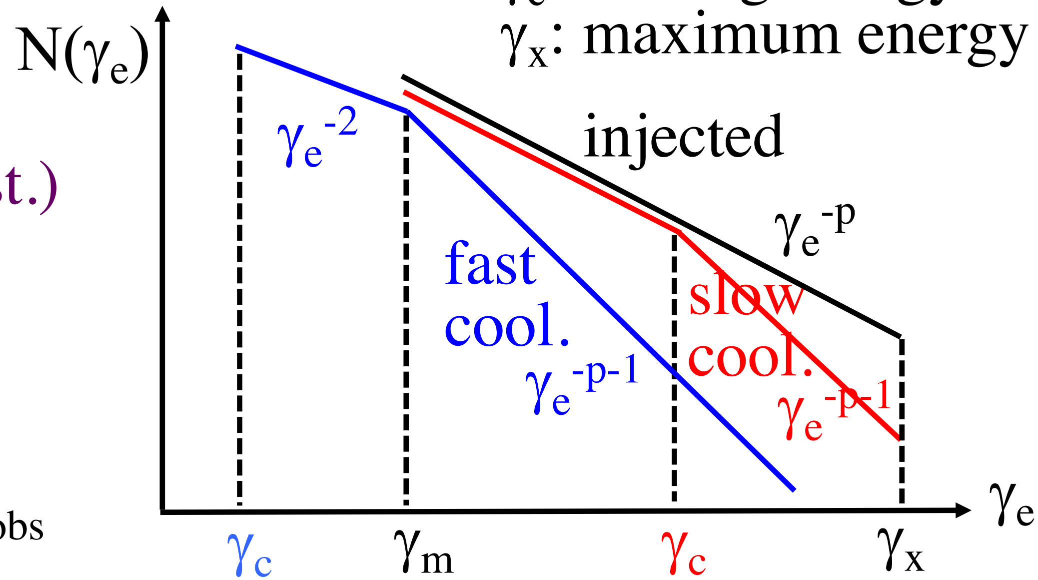


main parameters

- E_k: initial kinetic energy
- n or A_*: external medium density
- θ_j: jet opening angle
- ϵ_B: fraction of shock-dissipated energy in magnetic fields
- ϵ_e: ibid. in accelerated electrons
- p: electron injection spec. index
- ξ_e: no. fraction of accel. electrons

- γ_m: minimum/injection characteristic energy
- γ_c: cooling energy
- γ_x: maximum energy

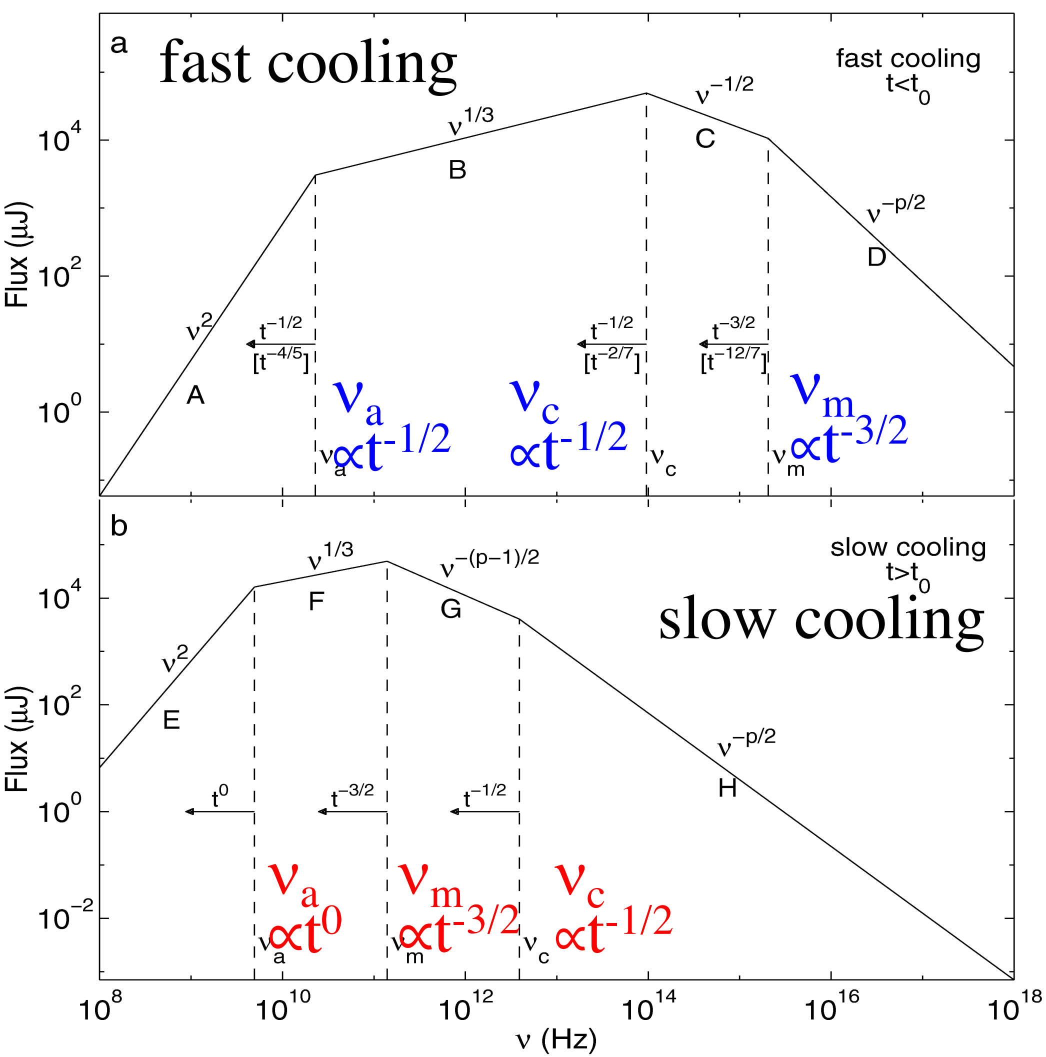




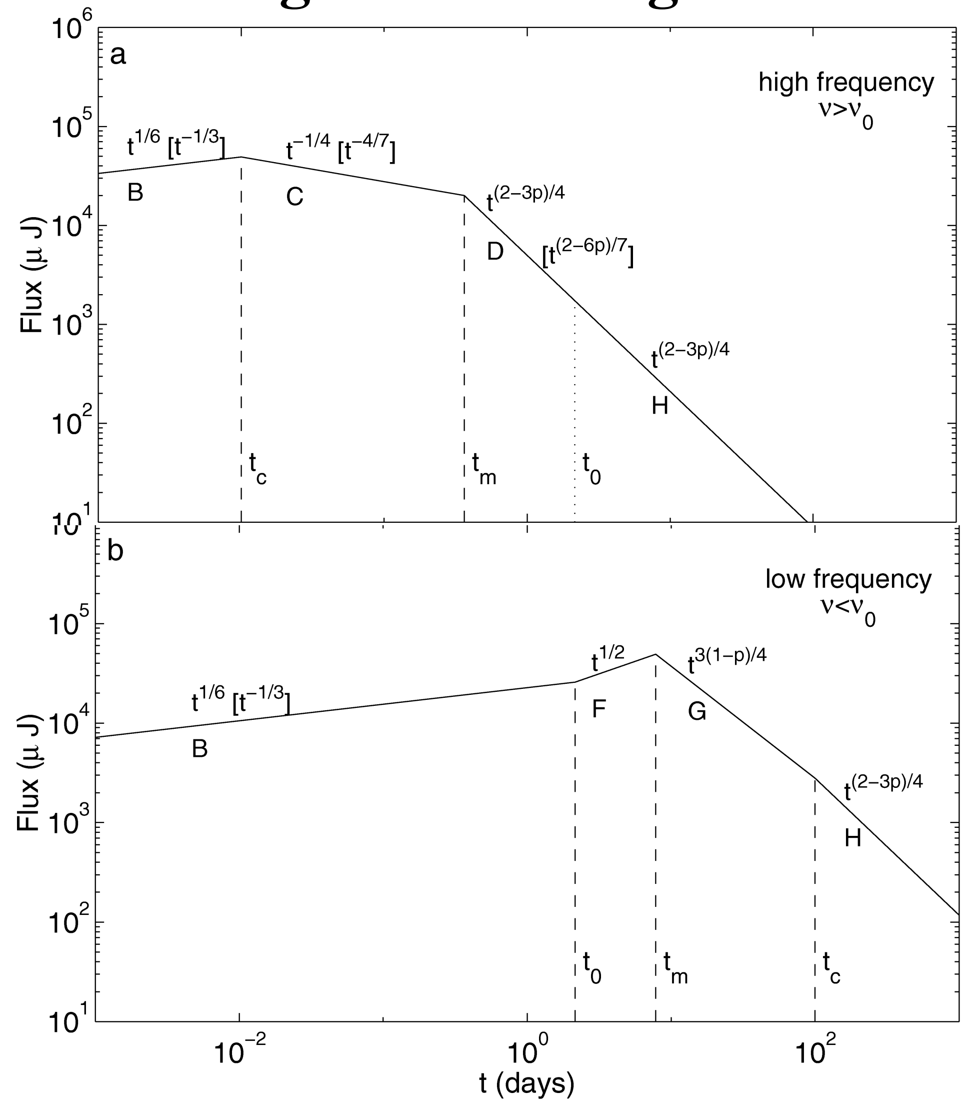
afterglow theory: basics

Sari, Piran & Narayan 98

spectra at given t



light curves at given ν

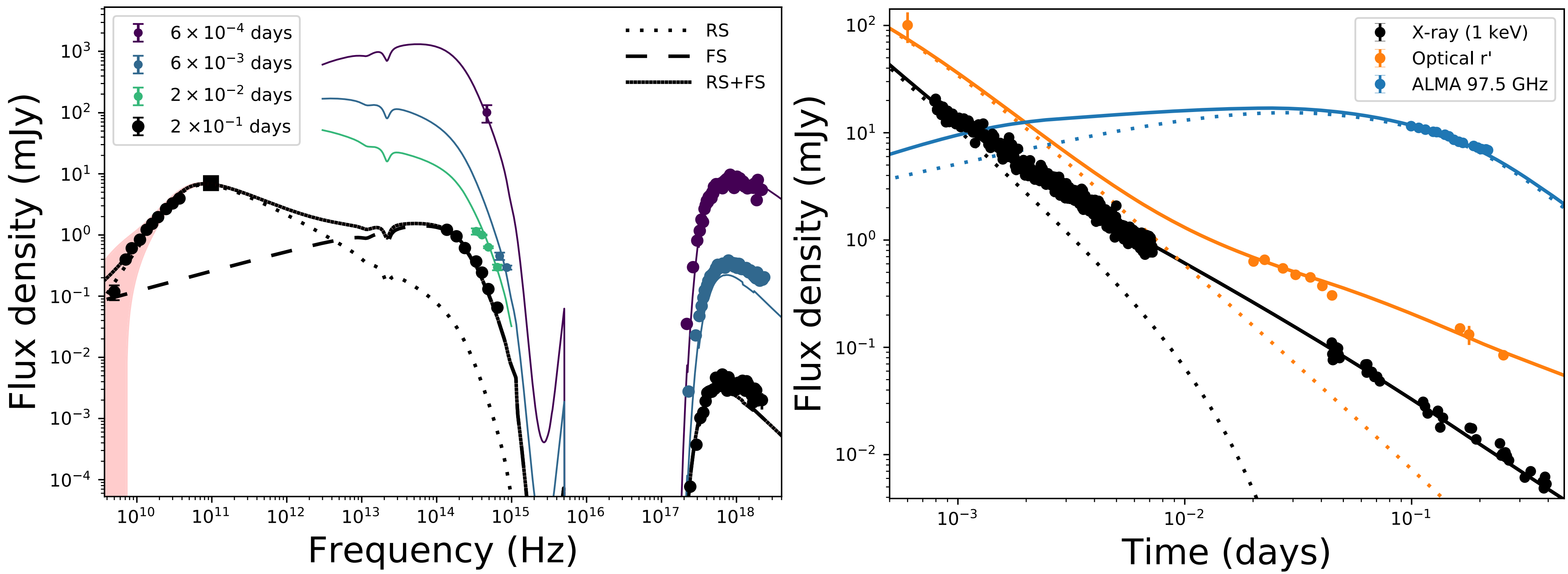


ν_m: minimum/injection/characteristic frequency

ν_c: cooling frequency

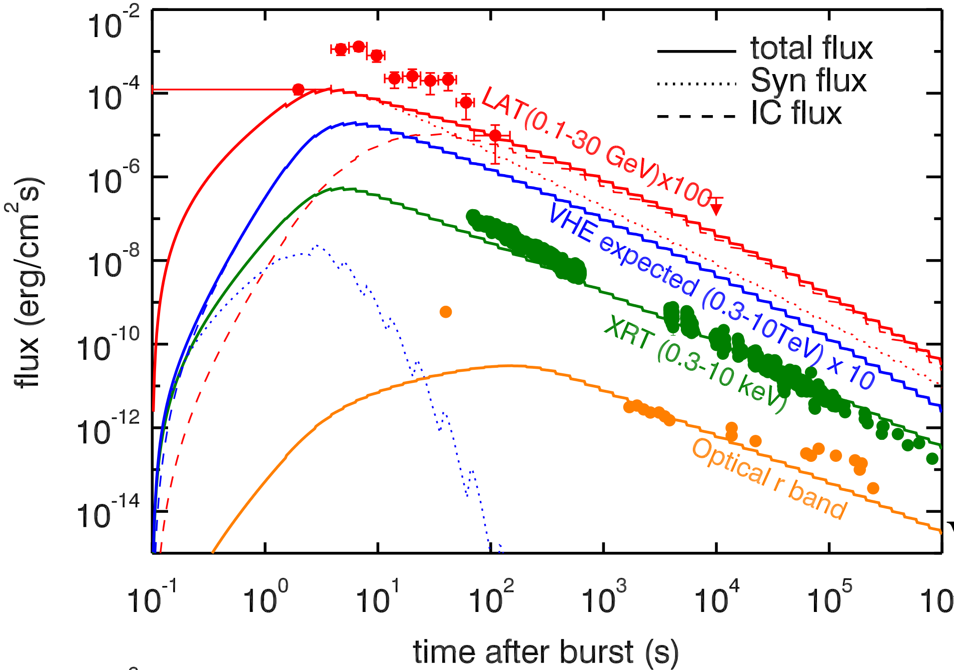
ν_a: self-absorption frequency

GRB 190114C: reverse shock component in radio-optical

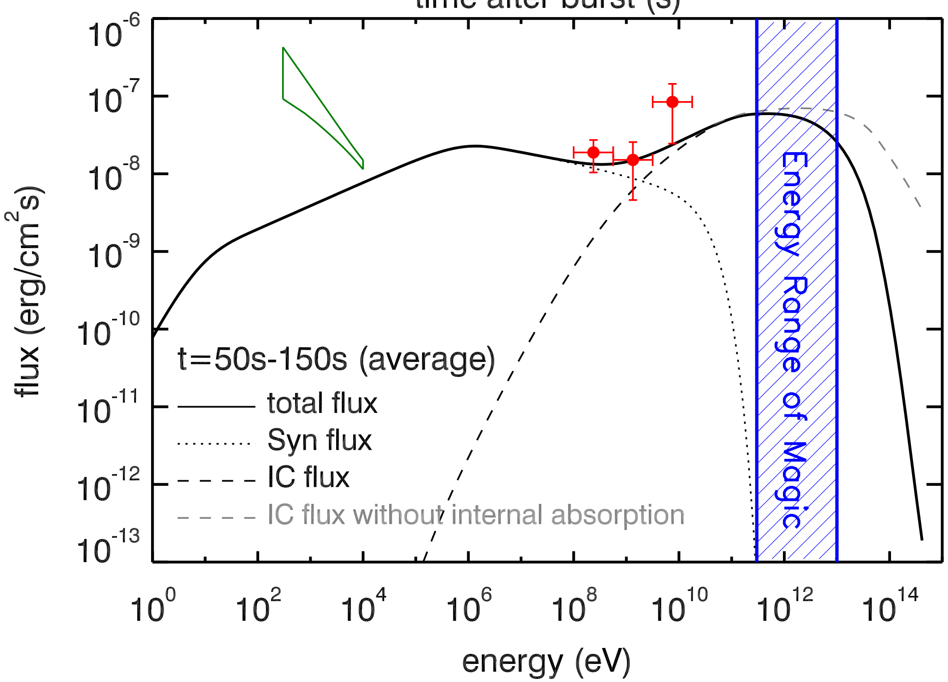


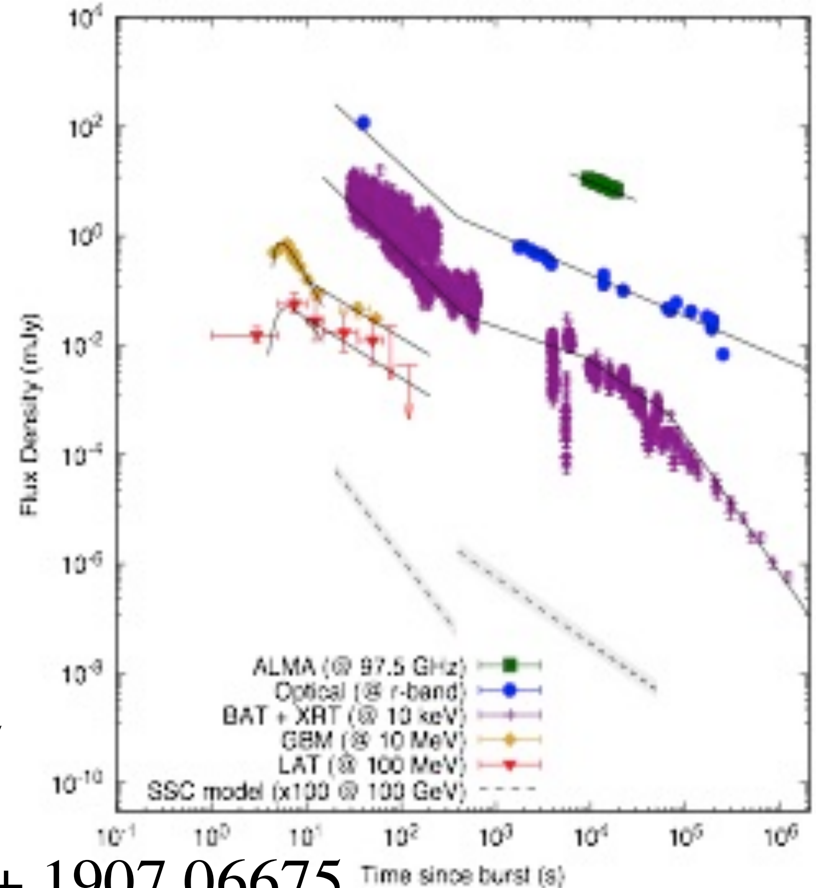
Laskar+ 1904.06721

GRB 190114C: SSC modeling

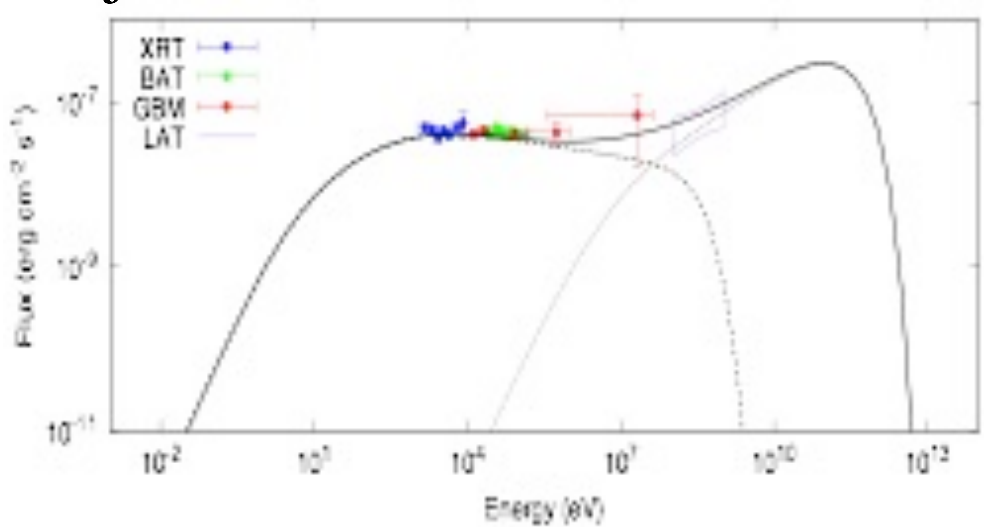


Wang+ 1905.11312





Fraija+ 1907.06675



X-ray afterglows of GeV-TeV GRBs

Yamasaki+ 1910.04097