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GRBs in the very high energy (VHE) domain: status and future perspective

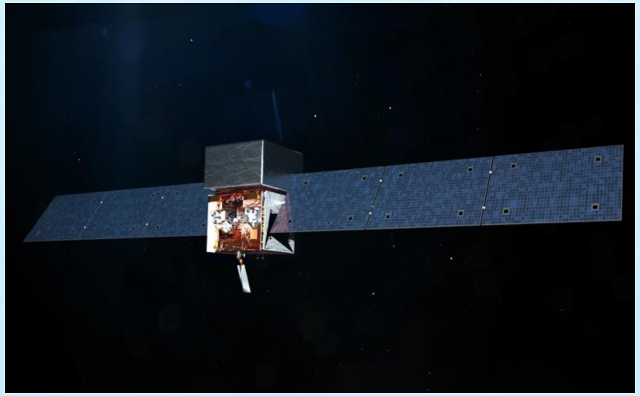
Davide Miceli
INFN Padova

" Advances in Modeling High-Energy Astrophysical Sources: Insights from recent multimessenger discoveries"
Sexten, 30/06/2025

Observations of GRBs from keV to TeV

keV → GeV → TeV

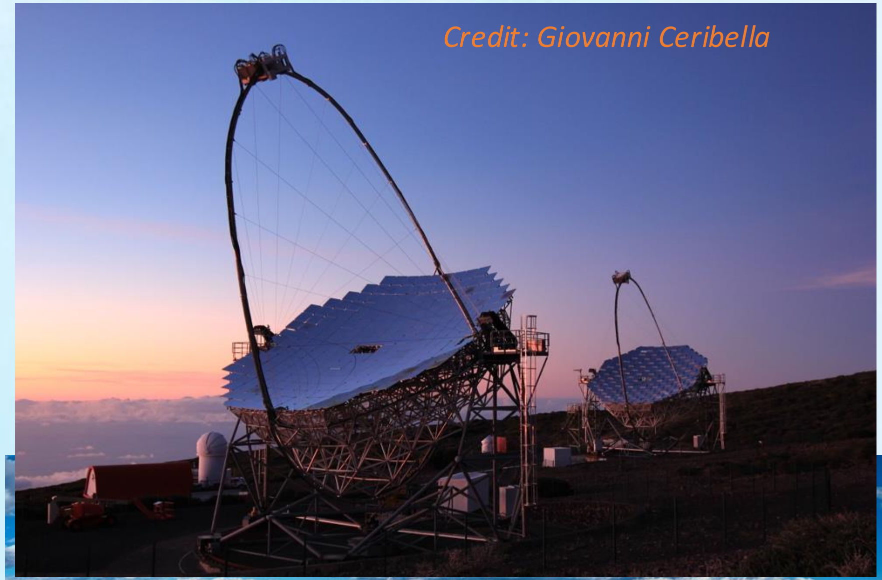
Credit: ESA



Credit: NASA

Credit: NASA

Space telescopes



Credit: Giovanni Ceribella

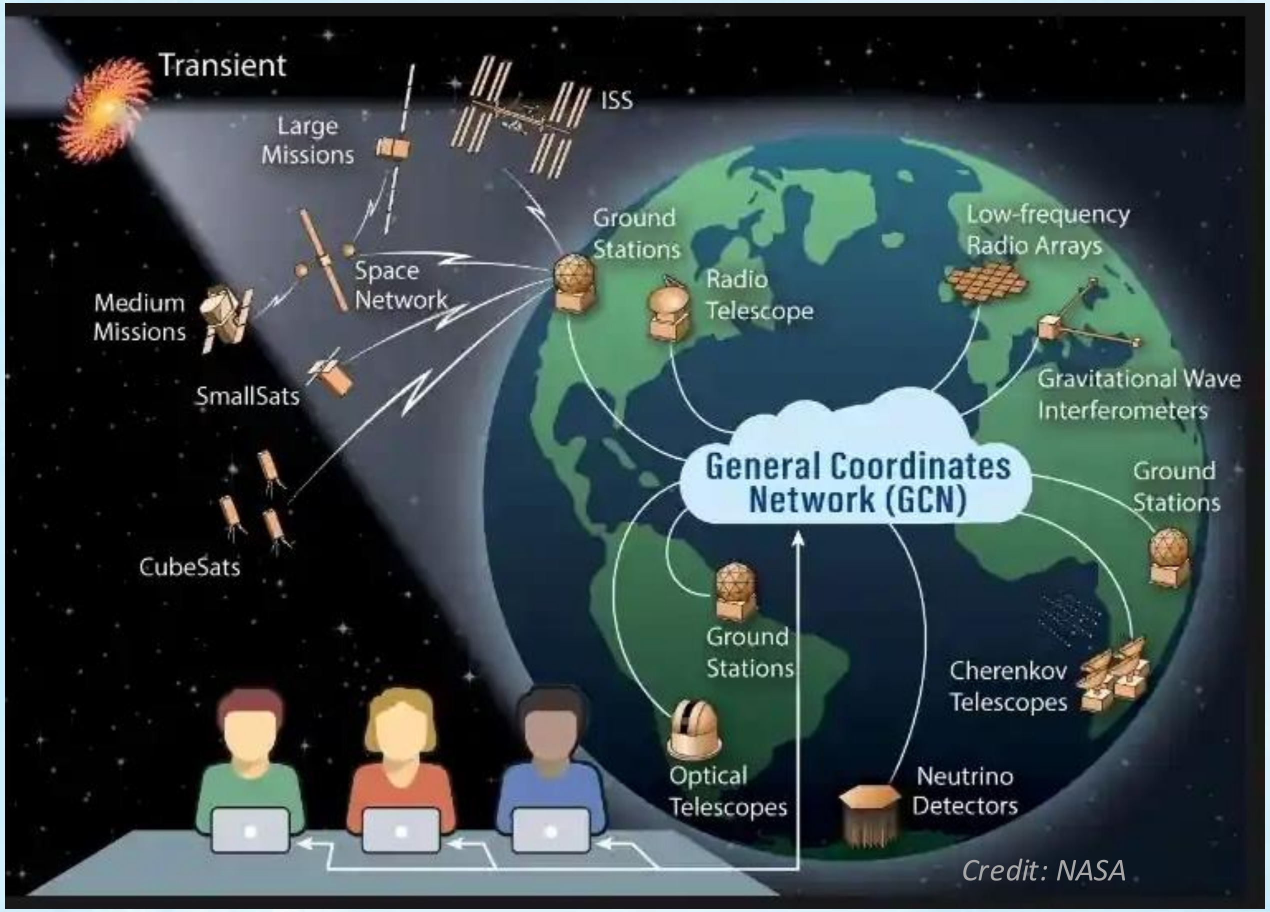
Credit: LHAASO

Ground-based observatories

Observations of GRBs at TeV energies

Long story short:

- We need to know **where** to look (space telescopes trigger and send alert with position uncertainty of arcmins)
- We need to be **fast** (follow-up starting at order of min or even sec)

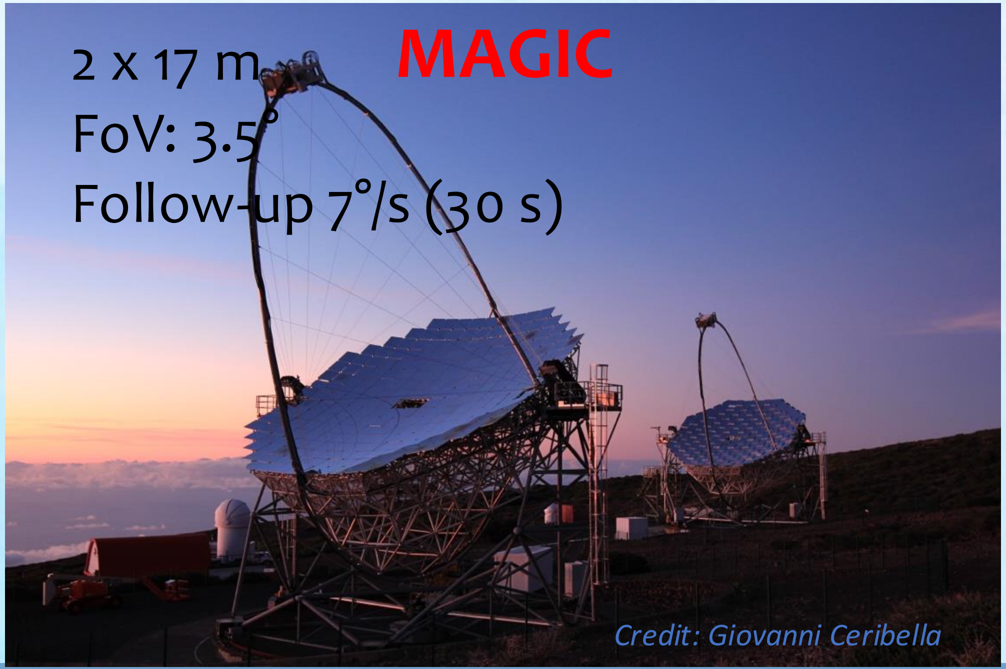


Credit: NASA

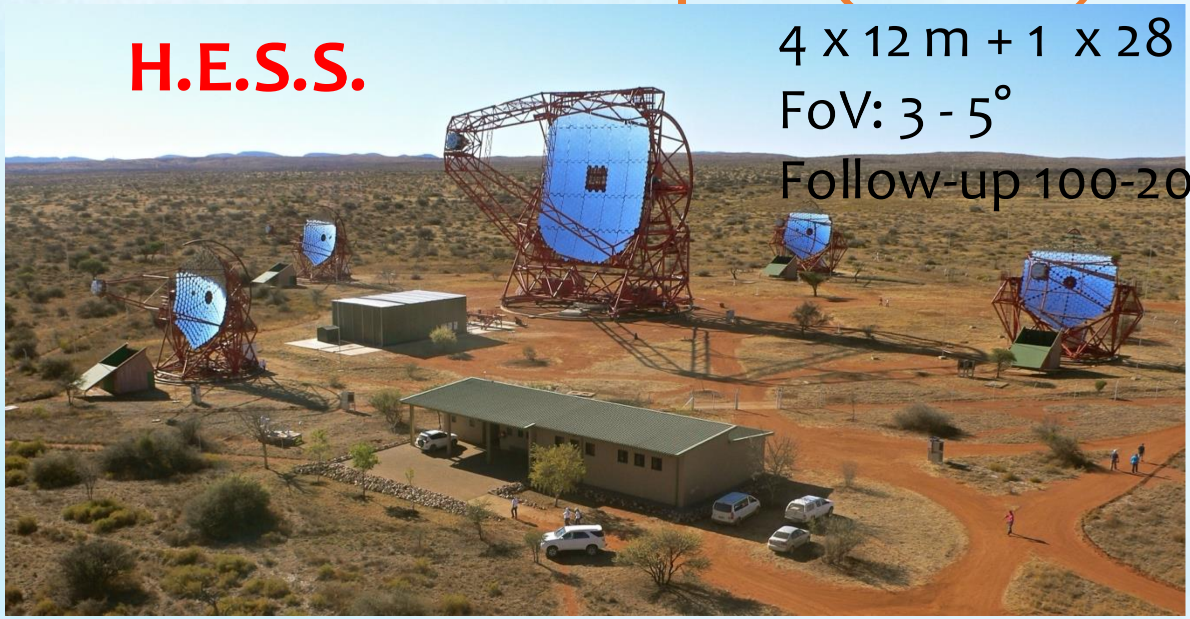
Observations of GRBs at TeV energies

- Imaging Atmospheric Cherenkov Telescopes (IACTs) [30-50 GeV – 10s TeV]
  - Narrow field of view (FoV) (3-5 °) → need external alert + automatic alert system + fast repointing
  - Small duty cycle (10%)
  - Low energy threshold: 30-50 GeV
  - Best sensitivity up to a few TeV
- Shower front arrays [100s GeV – >100s TeV]:
  - Wide field of view → no repointing needed
  - Large duty cycle (100%)
  - High energy threshold: 100s GeV – TeV → extragalactic background light (EBL) absorption
  - Large collection area → can reach 100s TeV and above

Imaging Atmospheric Cherenkov Telescopes (IACTs)

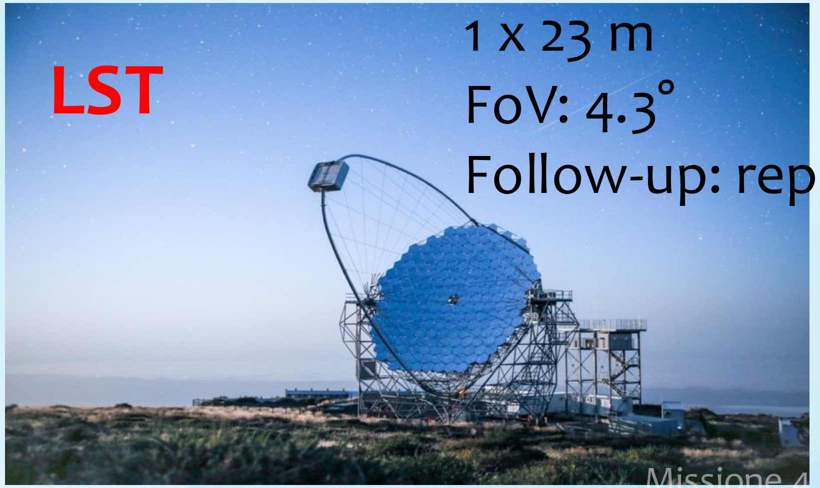


Credit: Giovanni Ceribella



Credit: Klepser, DESY, H.E.S.S. collaboration

Credit: VERITAS



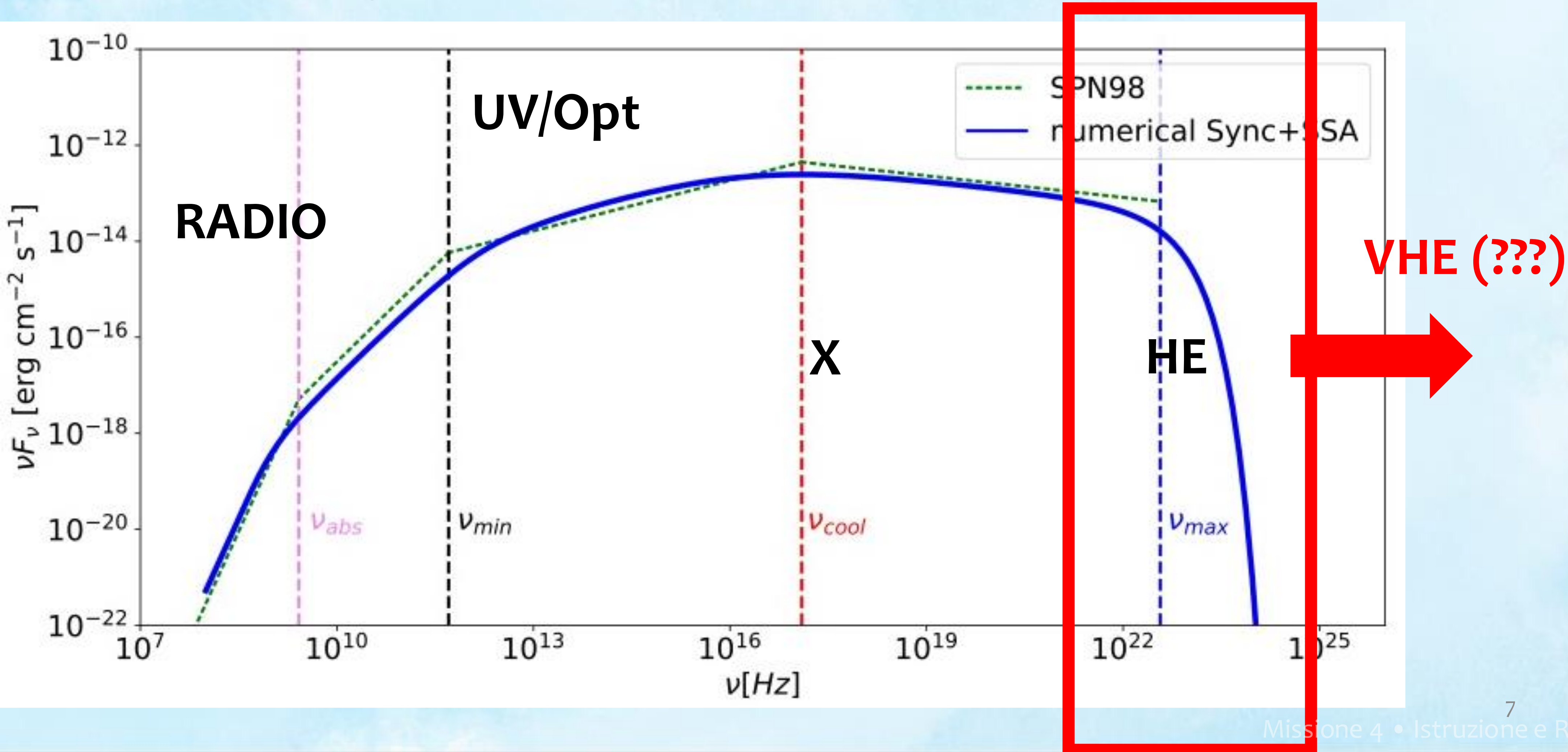
Credit: Tomohiro Inada, CTAO

Imaging Atmospheric Cherenkov Telescopes (IACTs)

Credit: MAGIC Collaboration

Theoretical expectations from GRBs in the VHE domain

Afterglow: the external forward shock scenario



Theoretical expectations from GRBs in the VHE domain

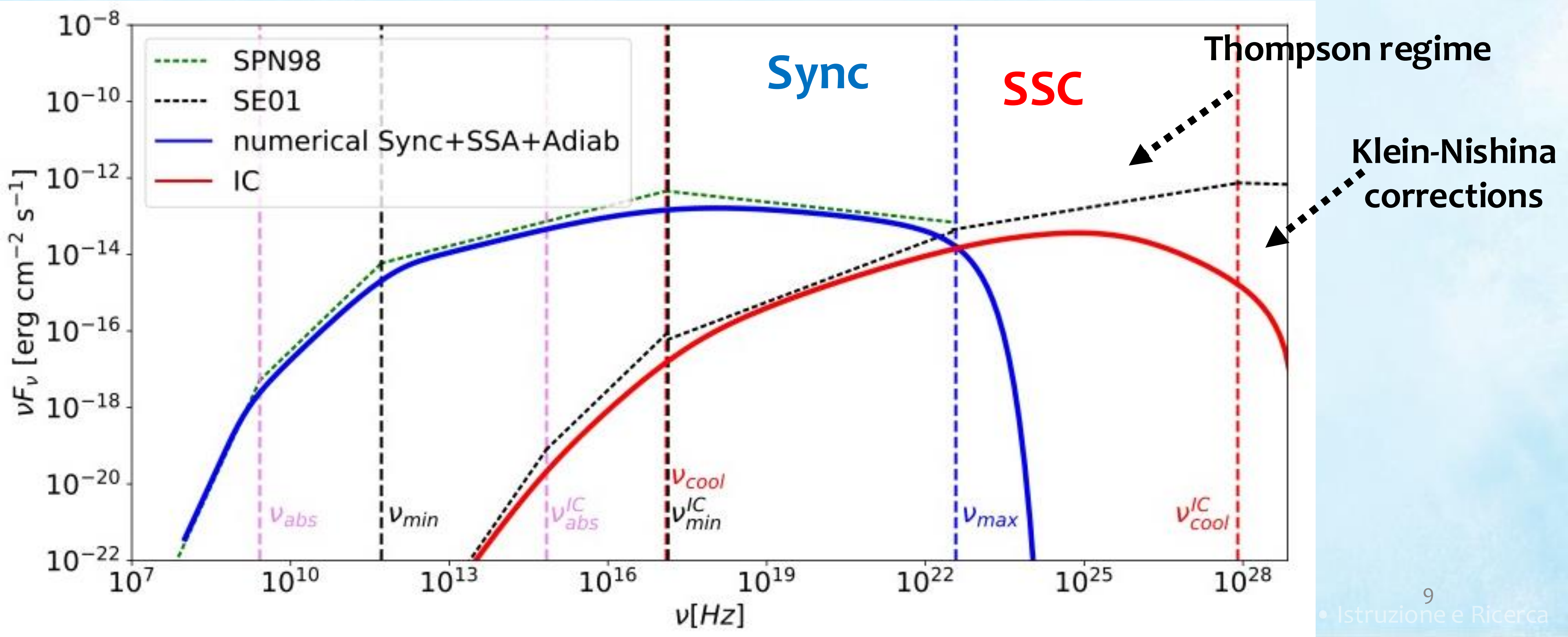
VHE emission

Possible radiation processes

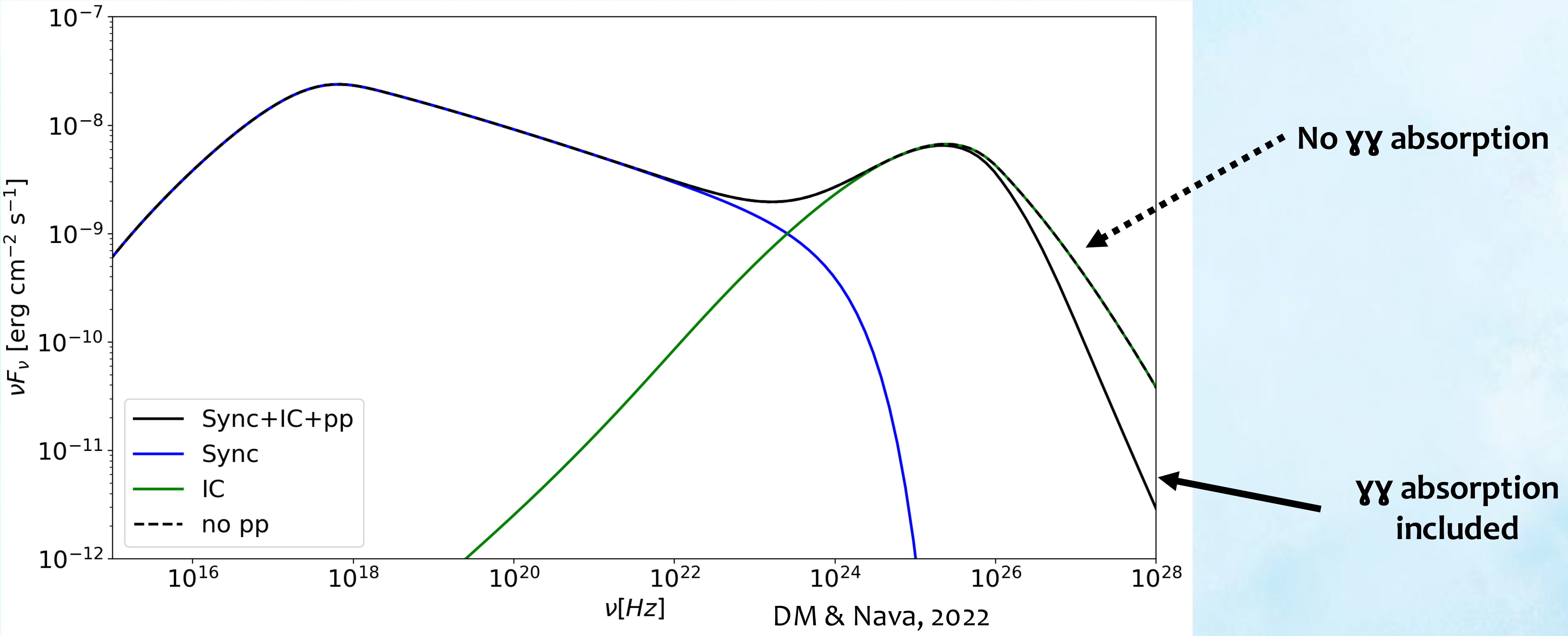
- Synchrotron emission from e^- — Limited by burnoff limit, microphysics conditions, particle acceleration assumptions
- Synchrotron emission from *p* — Requires high radiative efficiency
- Synchrotron Self Compton (SSC) emission — Natural candidate (Sari & Esin, 2001; Nakar et al. 2009)

Theoretical expectations from GRBs in the VHE domain

Synchrotron self-Compton (SSC) emission has been predicted for GRB afterglows: nature candidate for VHE domain (Meszaros et al. 1994; Zhang et al. 2001; Sari et al. 2001; Meszaros et al. 2004; Fan et al. 2008; Galli et al. 2008; Nakar et al. 2009; Xue et al. 2009; Piran et al. 2010)



Theoretical expectations from GRBs in the VHE domain



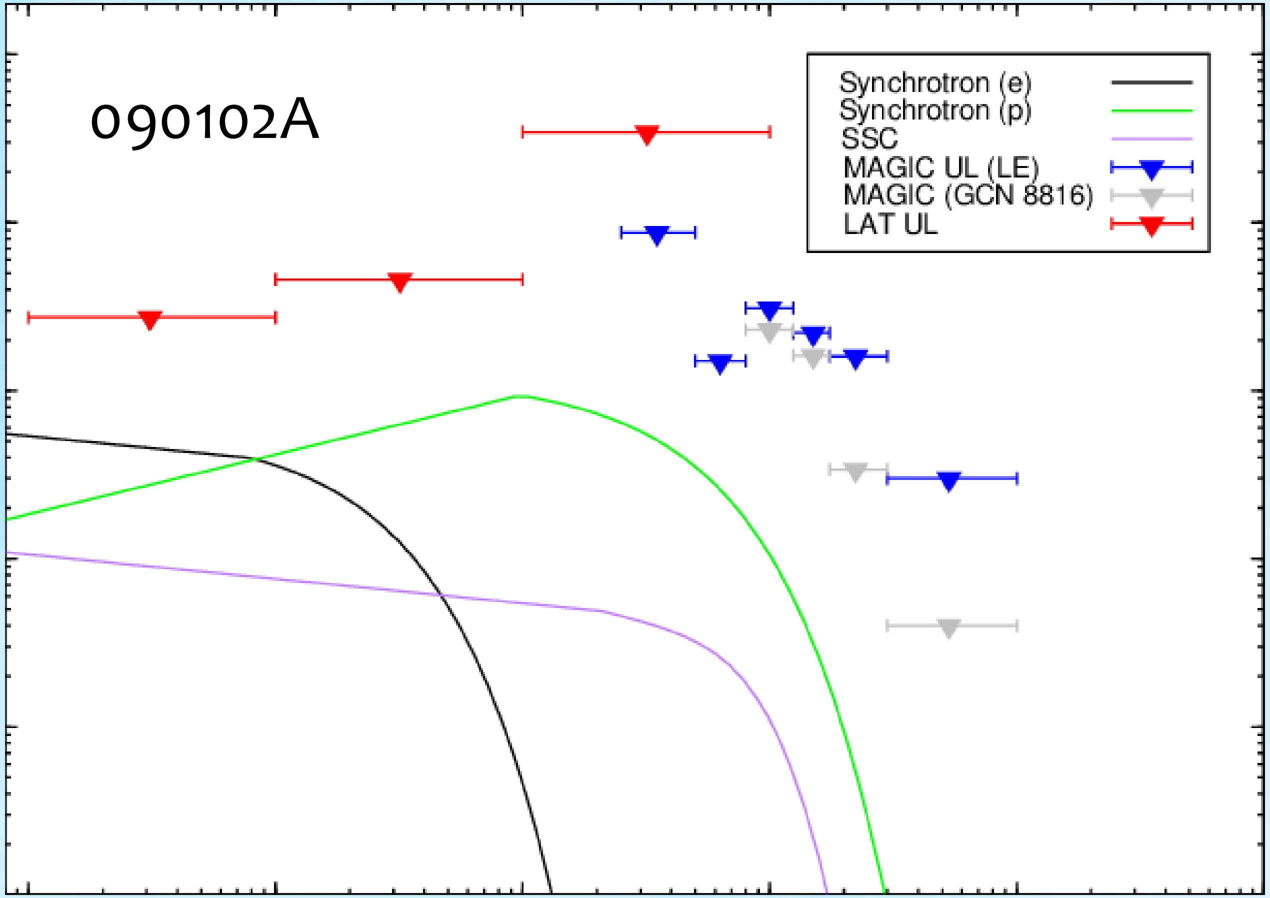
Hunting GRBs in the VHE domain: a non-homogeneous story

From Berti & Carosi 2022

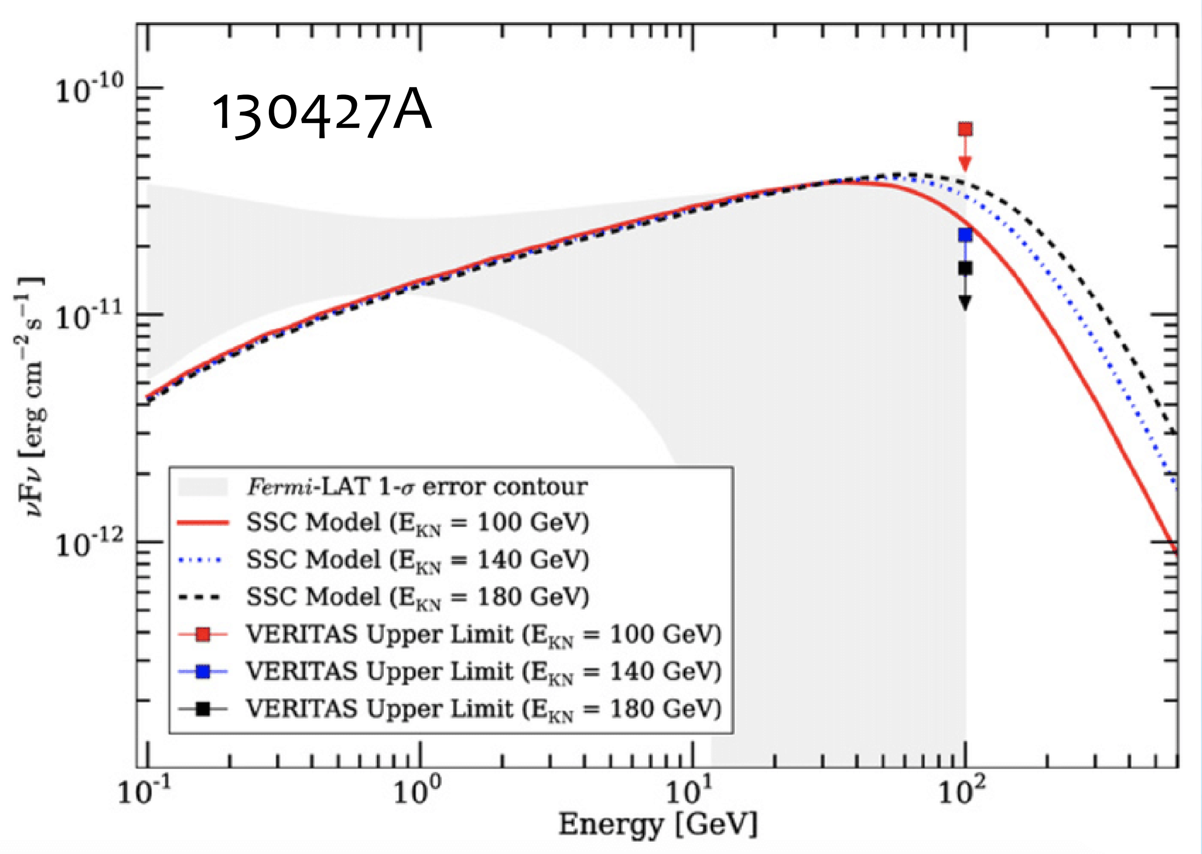
- 1989: first detection of VHE source (Crab Nebula) by IACT (Whipple telescope)
- 1991-2000 BATSE, EGRET operations
- 1994-95: first follow-ups by IACT (Whipple, 9 GRBs) → delays from T_0 ~ 2-56 minutes
- 1996: launch of Beppo-Sax
- 1994-00: several EAS searches for TeV/PeV emission from GRBs (including hint of Milagrito on 970417A)
- 2004 launch of Swift → fundamental for alerts and successfully rapid repointing
- 2004: MAGIC-I, H.E.S.S. phase-I (4x12m) and ARGO-YBJ started operations and GRB follow-up
- 2007: VERITAS started operations and GRB follow-up
- 2007-08 AGILE (07) and Fermi (08) were launched
- 2009: MAGIC-II started operations → big sensitivity improvement
- 2012 HESS phase-II: add 28 m telescope → transient dedicated telescope

Decades of searches for the VHE emission

Cherenkov telescope observations: only upper limits until 2019



Aleksic et al. 2014



Aliu et al., 2014

GRB 190114C: 1° announcement from IACTs

```
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>
```

R. Mirzoyan (MPP Munich), K. Noda (ICRR University of Tokyo),

E. Moretti (IFAE Barcelona), A. Berti (University and INFN Torino),

C. Nigro (DESY Zeuthen), J. Hoang (UCM Madrid), S. Micanovic

(University of Rijeka), M. Takahashi (ICRR University of Tokyo),

Y. Chai (MPP Munich), A. Moralejo (IFAE Barcelona) and the MAGIC

Collaboration report:

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.,

GRBs at VHE: the current status

5 GRBs detected at > 5σ

	T_{90} s	$E_{\gamma,iso}$ erg	z	T_{delay} s	E_{range} TeV	IACT (sign.)
160821B	0.48	1.2×10^{49}	0.162	24	0.5-5	MAGIC (3.1σ)
180720B	48.9	6.0×10^{53}	0.654	3.64×10^4	0.1-0.44	H.E.S.S. (5.3σ)
190114C	362	2.5×10^{53}	0.424	57	0.3-1	MAGIC ($> 50\sigma$)
190829A	58.2	2.0×10^{50}	0.079	1.55×10^4	0.18-3.3	H.E.S.S. (21.7σ)
201015A	9.78	1.1×10^{50}	0.42	33	0.14	MAGIC (3.5σ)
201216C	48	4.7×10^{53}	1.1	56	0.1	MAGIC (6.0σ)
221009A	289	1.0×10^{55}	0.151	0-3000	0.3-13	LHAASO (250σ)

Adapted from DM & Nava, 2022

GRBs at VHE: the current status

2 GRBs detected at ~ 3σ

	T_{90} s	$E_{\gamma,iso}$ erg	z	T_{delay} s	E_{range} TeV	IACT (sign.)
160821B	0.48	1.2×10^{49}	0.162	24	0.5-5	MAGIC (3.1σ)
180720B	48.9	6.0×10^{53}	0.654	3.64×10^{4}	0.1-0.44	H.E.S.S. (5.3σ)
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Adapted from DM & Nava, 2022

Population of GRBs at VHE: what we thought vs what we discovered

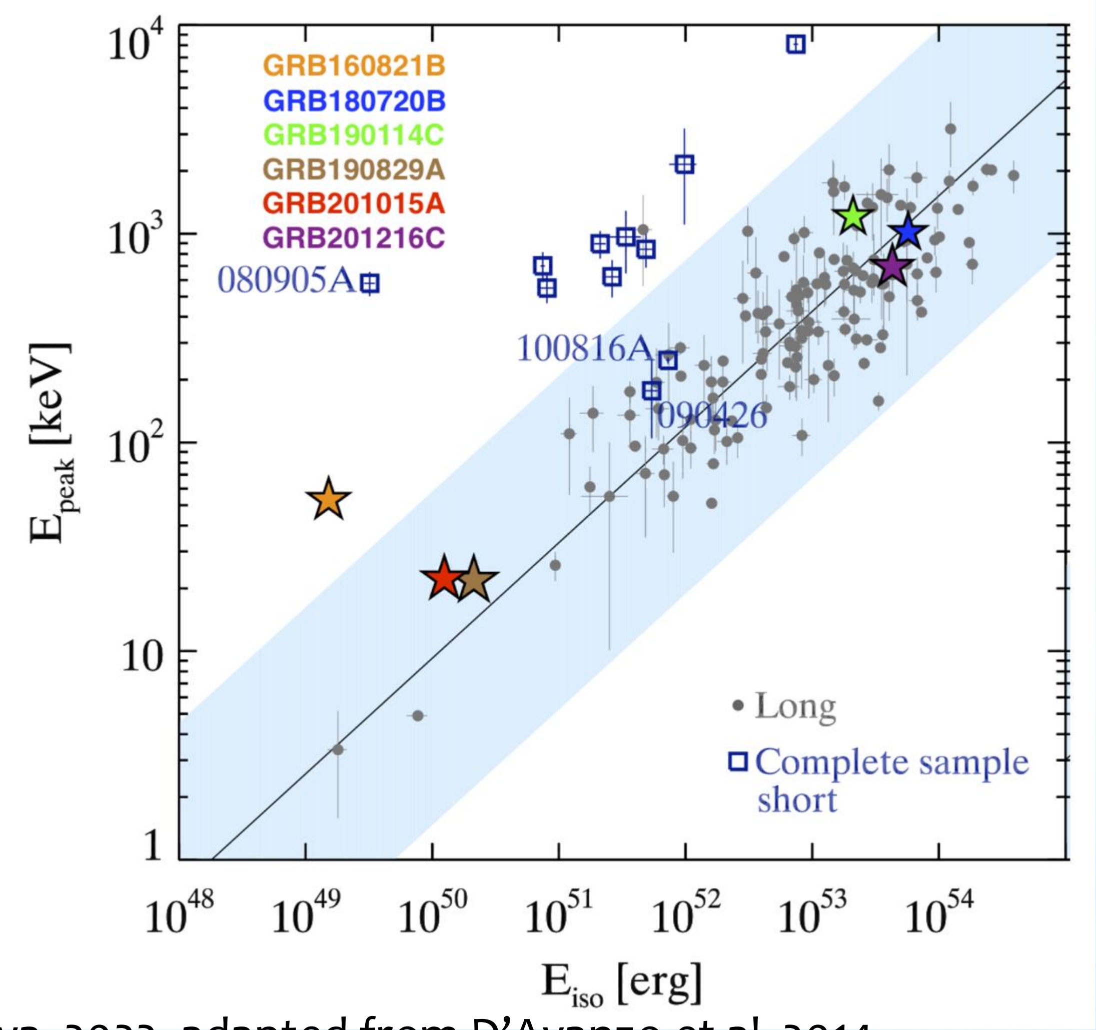
"Mandatory" requirements:

- low zenith angles (energy threshold below ~ 100 GeV)
- dark nights
- small delays from T_0
- low z
- highly energetic events

GRB190114C: zenith >55°, Moon conditions
GRB160821B: Moon conditions
GRB180720B, GRB190829A: T_{delay} ~ hrs/days
GRB201216C: z = 1.1
GRB190829A, GRB201015A, GRB160821B: $E_{\gamma,iso} \sim 10^{49} - 10^{50}$ erg

Population of GRBs in VHE domain

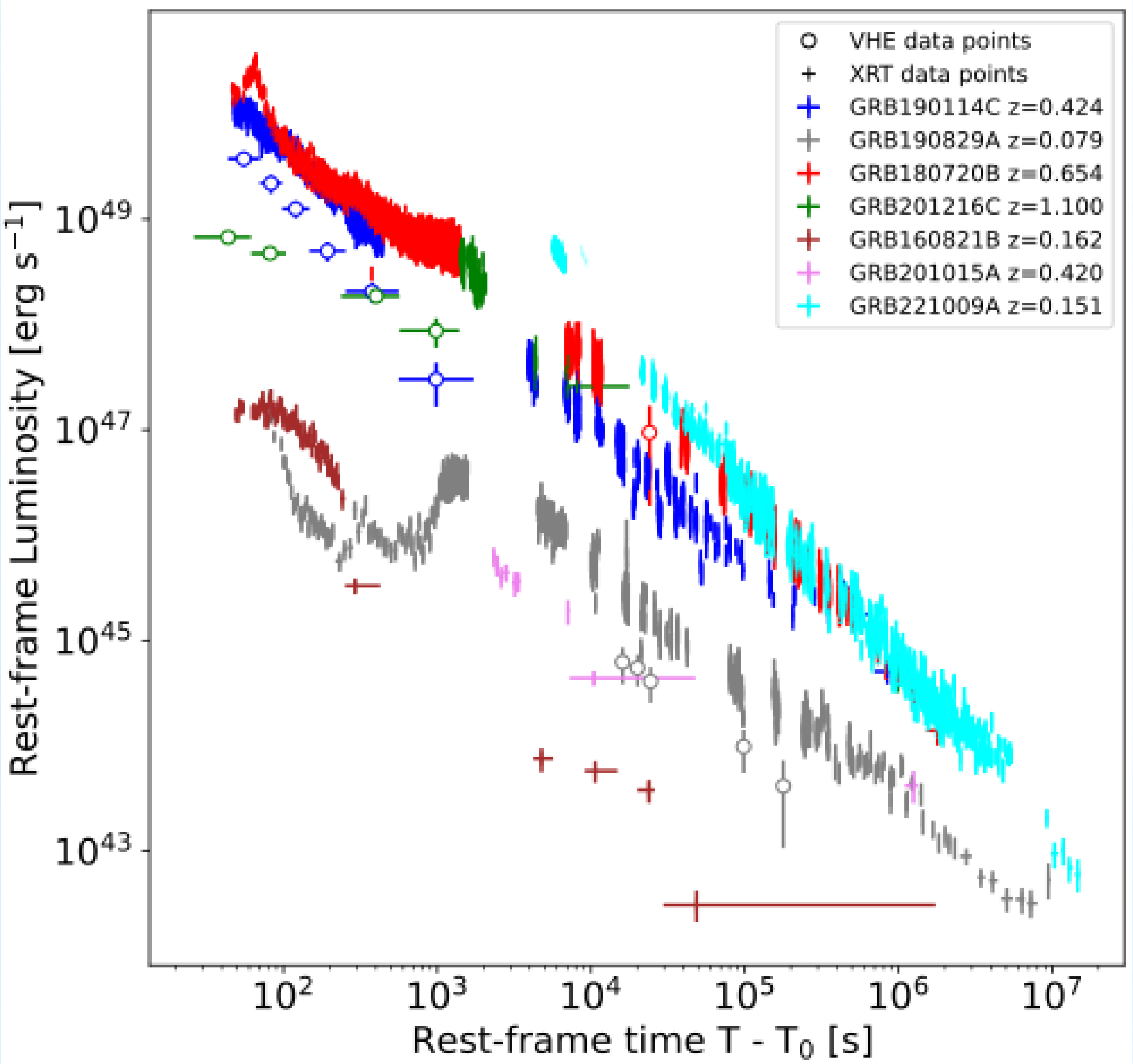
- Broadband intrinsic properties:
  - span more than 3 orders of magnitude in $E_{\gamma,iso}$
  - Span 2 orders of magnitude in terms of L_{VHE}
  - ranging in redshift between 0.079–1.1



DM & Nava, 2022, adapted from D'Avanzo et al. 2014

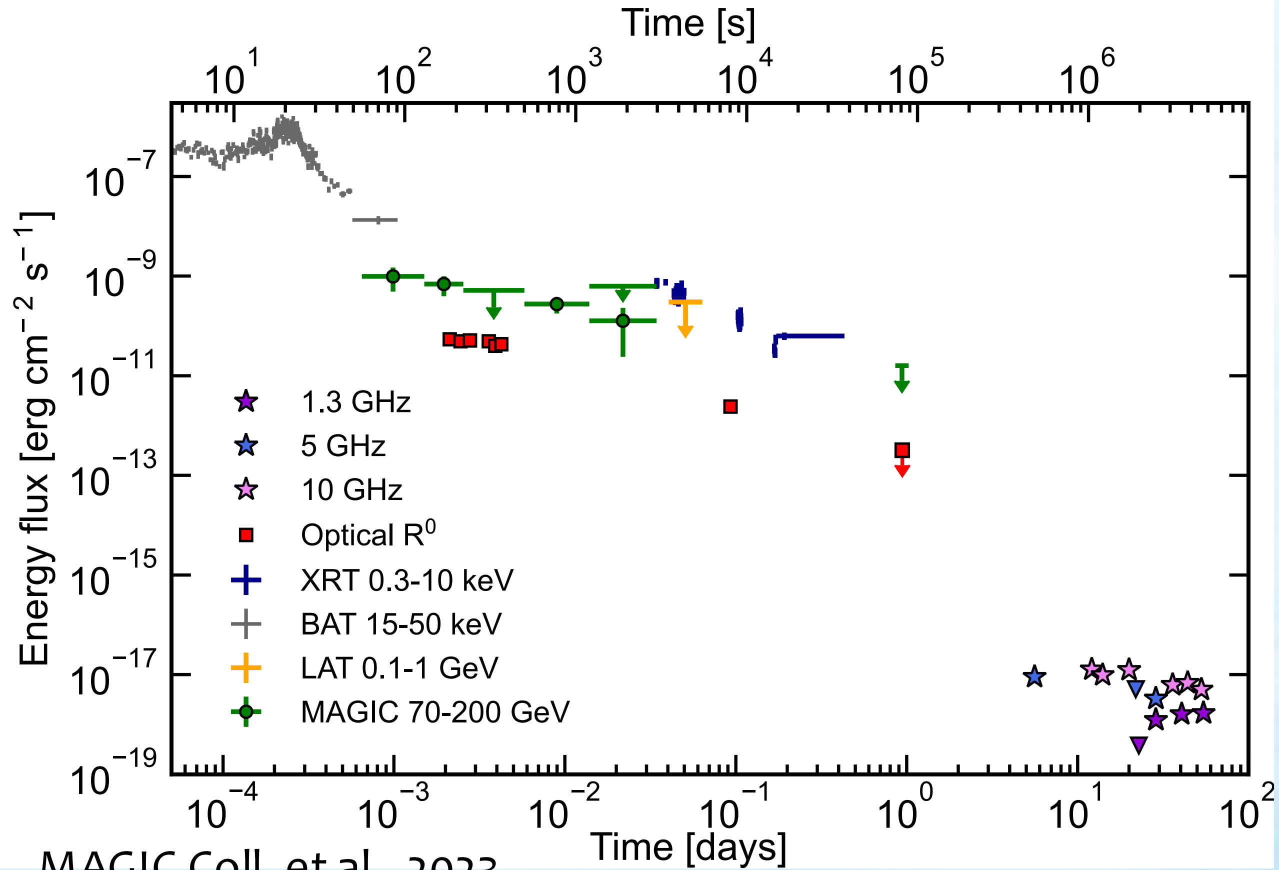
Population of GRBs in VHE domain

- Broadband intrinsic properties:
  - span more than 3 orders of magnitude in $E_{\gamma,iso}$
  - Span 2 orders of magnitude in terms of L_{VHE}
  - ranging in redshift between 0.079–1.1
- X-ray – TeV connection:
  - similar fluxes and decay slopes
  - similar amount of radiated power (L_{VHE} 15-60% $L_{X\text{-ray}}$)



Population of GRBs in VHE domain

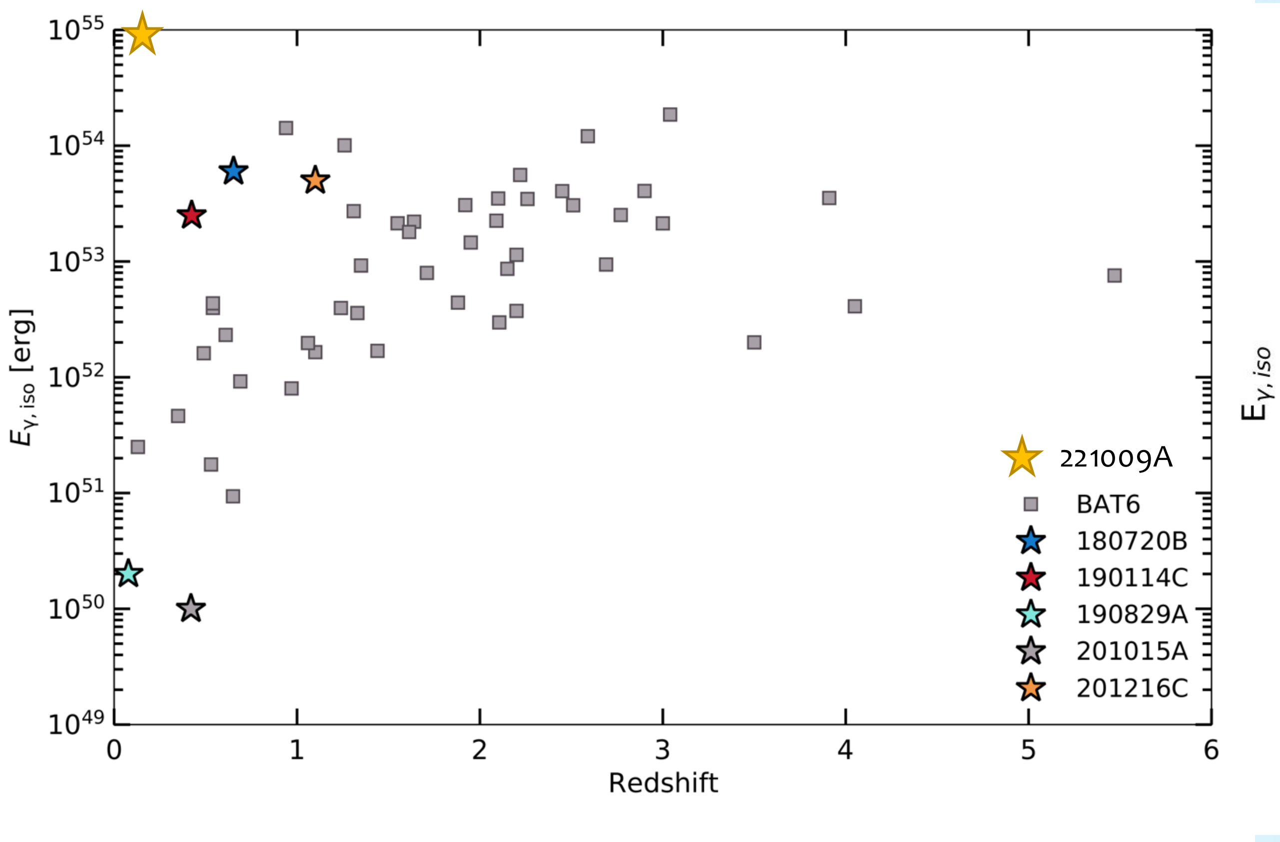
- Broadband intrinsic properties:
  - span more than 3 orders of magnitude in $E_{\gamma,iso}$
  - Span 2 orders of magnitude in terms of L_{VHE}
  - ranging in redshift between 0.079–1.1
- X-ray – TeV connection:
  - similar fluxes and decay slopes
  - similar amount of radiated power
- Data modeling:
  - SSC suggested (not conclusive)
  - no preferences on constant/wind-like medium
  - $\varepsilon_e \sim 0.1$, $\varepsilon_B \sim 10^{-5}$–$10^{-3}$, $\xi<1$



MAGIC Coll. et al., 2023

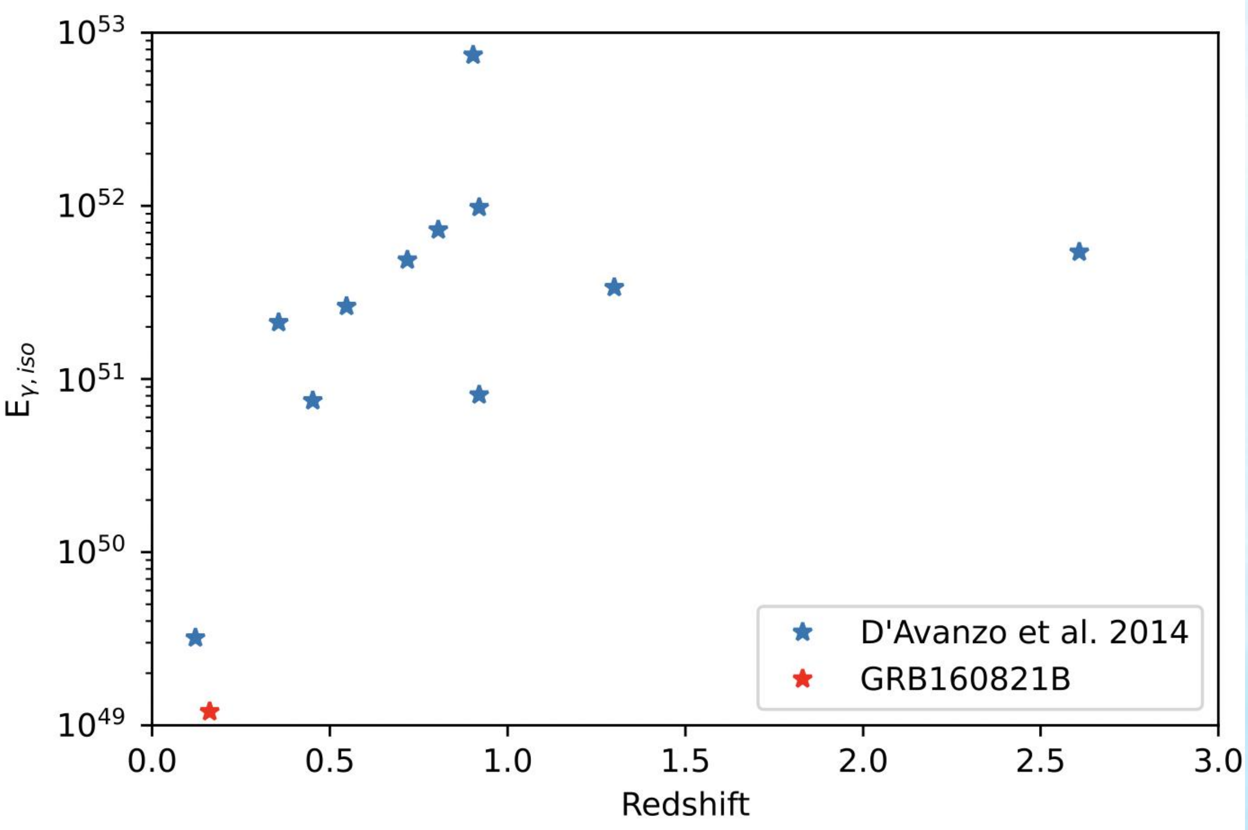
Population of GRBs in VHE domain: the role of redshift

long GRBs

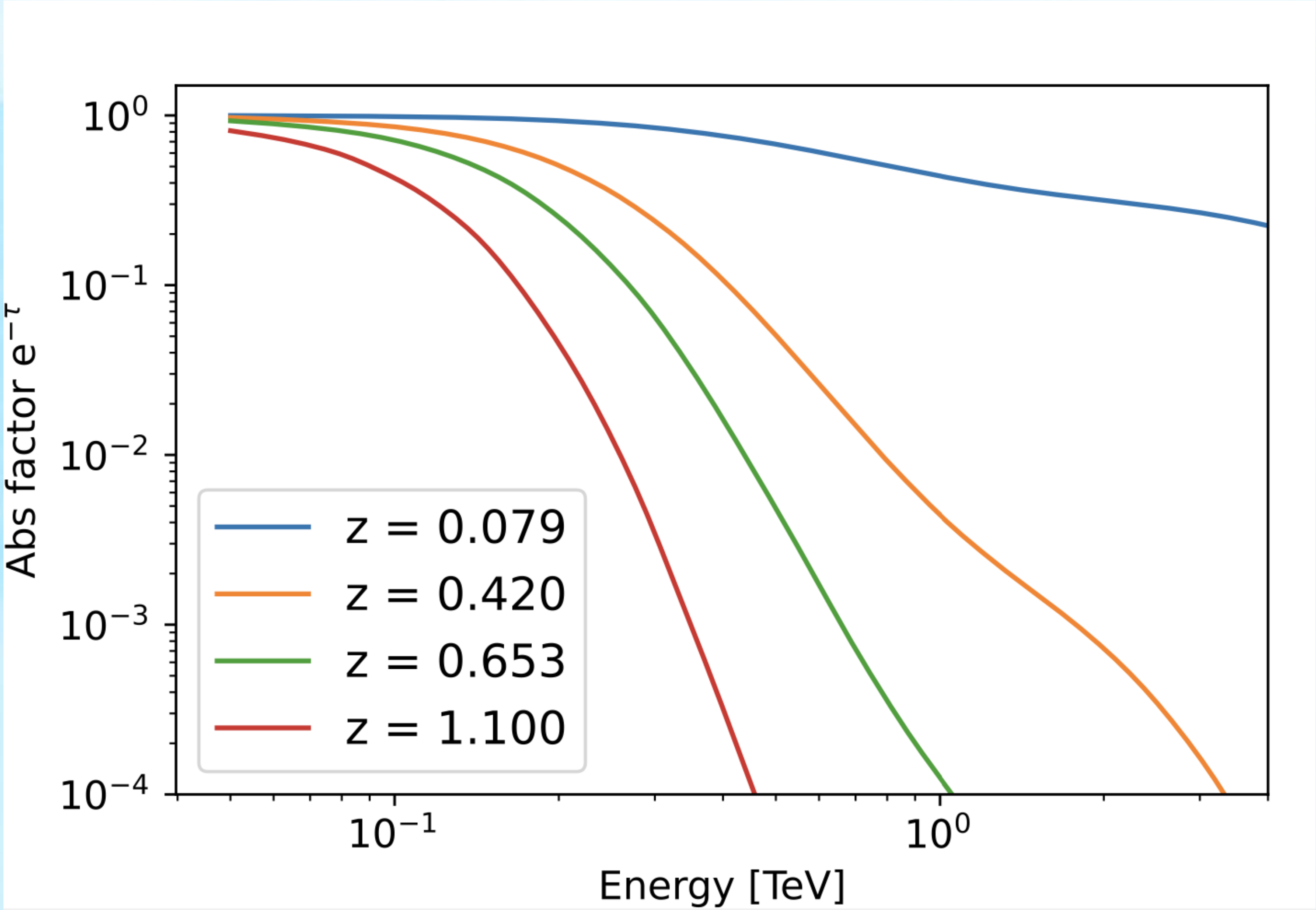


adapted from Nava, 2021

short GRBs



Population of GRBs in VHE domain: the role of redshift



Dominguez et al., 2011
(similar for other EBL models)

$z \lesssim 0.1 - 0.2$

- F_{att} relevant above 300 GeV
- F_{att}~ 90% at 1 TeV

z = 0.4

- F_{att}~ 50% at 0.2 TeV
- F_{att}~ 99.5% at 1 TeV

z = 1.1

- F_{att}~ 95% at 0.2 TeV

Open question: degeneracy of afterglow parameters

	E_k erg	ϵ_e	ϵ_B	n cm^{-3}	p	ξ_e	θ_j rad
Hess Coll. (SSC)	2.0×10^{50}	0.91	$5.9–7.7 \times 10^{-2}$	1.	2.06–2.15	1.	/
Hess Coll. (Sync)	2.0×10^{50}	0.03–0.08	≈ 1	1.	2.1	1.	/
Salafia + 2021	$1.2–4.4 \times 10^{53}$	0.01–0.06	$1.2–6.0 \times 10^{-5}$	0.12–0.58	2.01	$<6.5 \times 10^{-2}$	0.25–0.29
Zhang + 2021	9.8×10^{51}	0.39	8.7×10^{-5}	0.09	2.1	0.34	0.1

	E_k erg	ϵ_e	ϵ_B	n cm^{-3}	p	ξ_e
MAGIC Coll.	$\gtrsim 3 \times 10^{53}$	0.05–0.15	$0.05–1 \times 10^{-3}$	0.5–5	2.4–2.6	1
Wang + 2019	6×10^{53}	0.07	4×10^{-5}	0.3	2.5	1
Asano + 2020	10^{54}	0.06	9×10^{-4}	1	2.3	0.3
Asano + 2020	10^{54}	0.08	1.2×10^{-3}	0.1 (wind)	2.35	0.3
Joshi + 2021	4×10^{54}	0.03	0.012	2×10^{-2} (wind)	2.2	1
Derishev + 2021	3×10^{53}	0.1	$2–6 \times 10^{-3}$	2	2.5	1

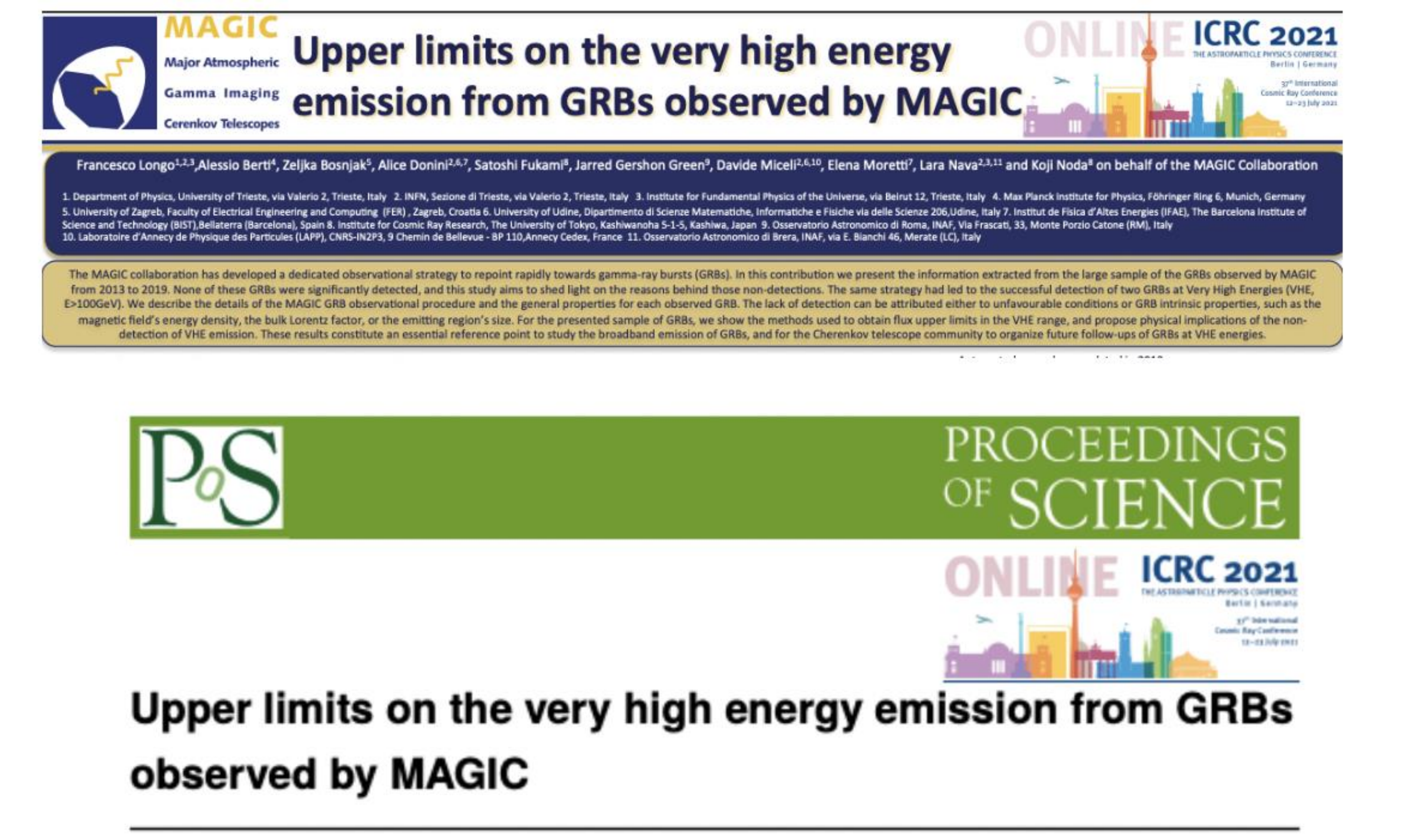
	E_k erg	$\log(\epsilon_e)$	$\log(\epsilon_B)$	log(n) cm^{-3}	p	ξ_e	θ_j rad
MAGIC Coll.	$10^{51}–10^{52}$	[−1; −0.1]	[−5.5; −0.8]	[−4.85; −0.24]	2.2–2.35	1	/
Troja + 2019	$10^{50}–10^{51}$	[−0.39; −0.05]	[−3.1; −1.1]	[−4.2; −1.7]	2.26–2.39	1	0.08–0.50
Zhang + 2021 (SSC)	3×10^{51}	−0.52	−5	−1.3	2.3	0.5	0.15
Zhang + 2021 (EIC)	2×10^{51}	−0.3	−6	−1	2.5	0.1	0.1

Open question: is the VHE component universal in GRBs?

- Broad properties (energetics, luminosity, redshift) of the current GRBs detected at VHE point towards the universality of TeV emission

- Sample of non-detected GRBs can provide further results

- Paper on MAGIC GRB ULs submitted for publication

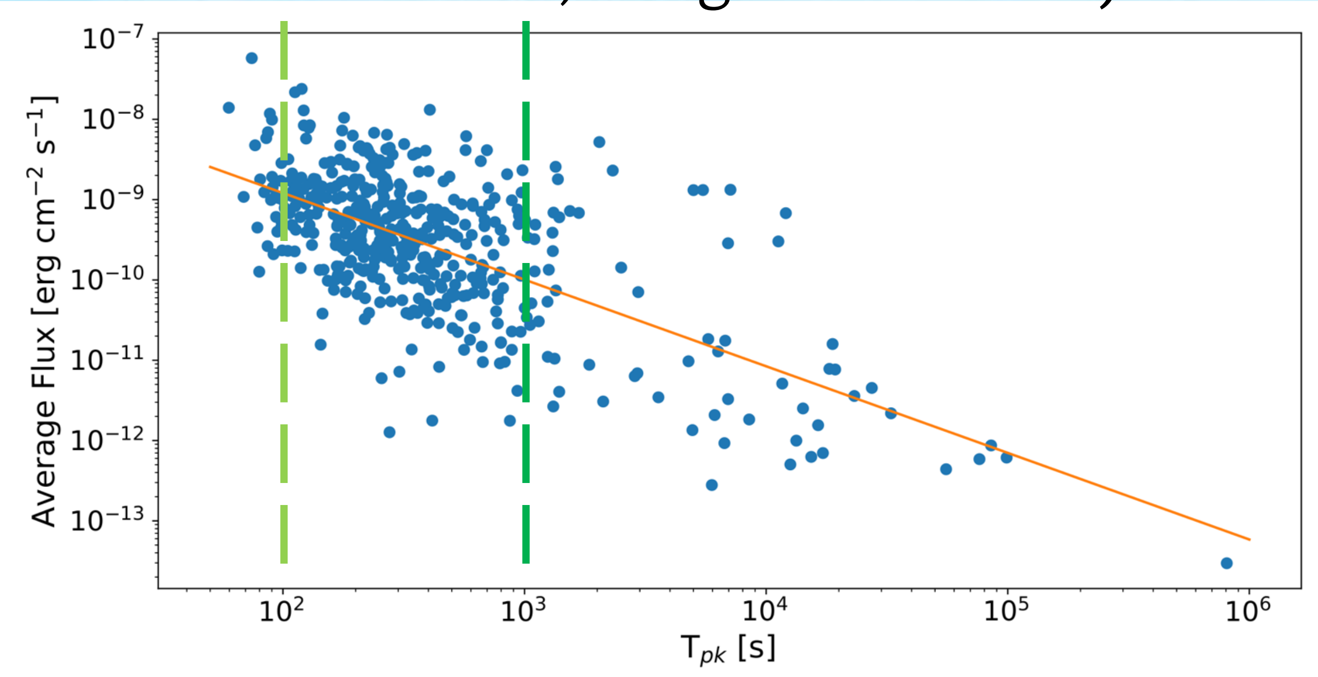


A future challenge for VHE: X-ray Flares

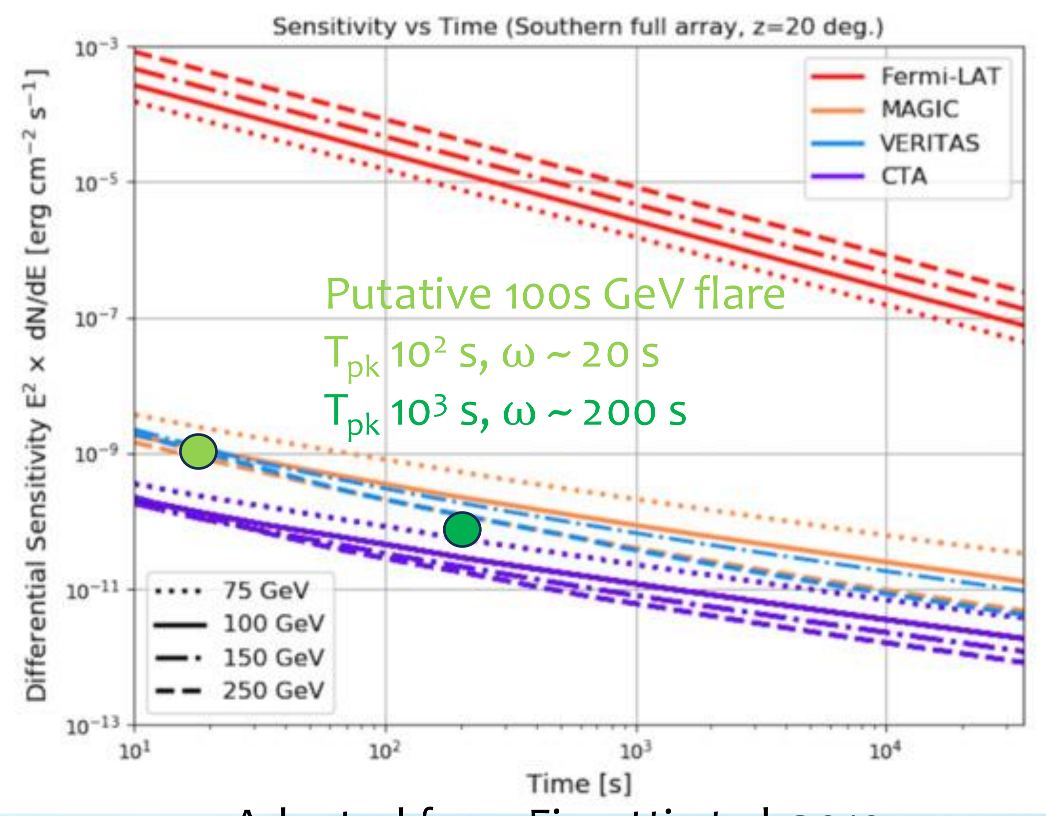
Wang et al. 2006
He et al. 2012
Wang et al. 2013

Signatures of X-ray flares can be found in the GeV-TeV domain?

1/3 of GRBs display X-ray flare episodes (Chincarini et al. 2010, Margutti et al. 2011)



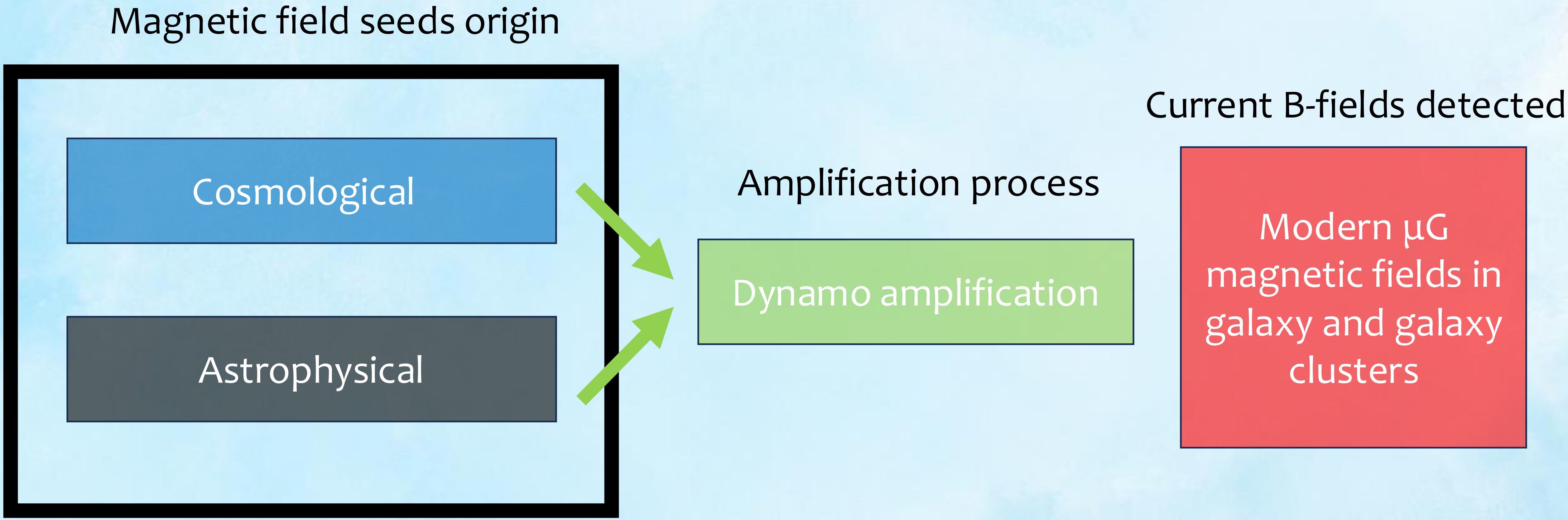
DM, Nava 2022



Adapted from Fioretti et al. 2019

GRBs at VHE: impact on fundamental physics

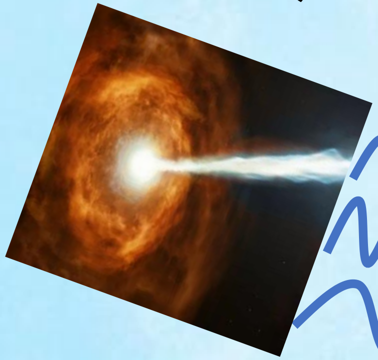
Intergalactic Magnetic Field (IGMF) studies

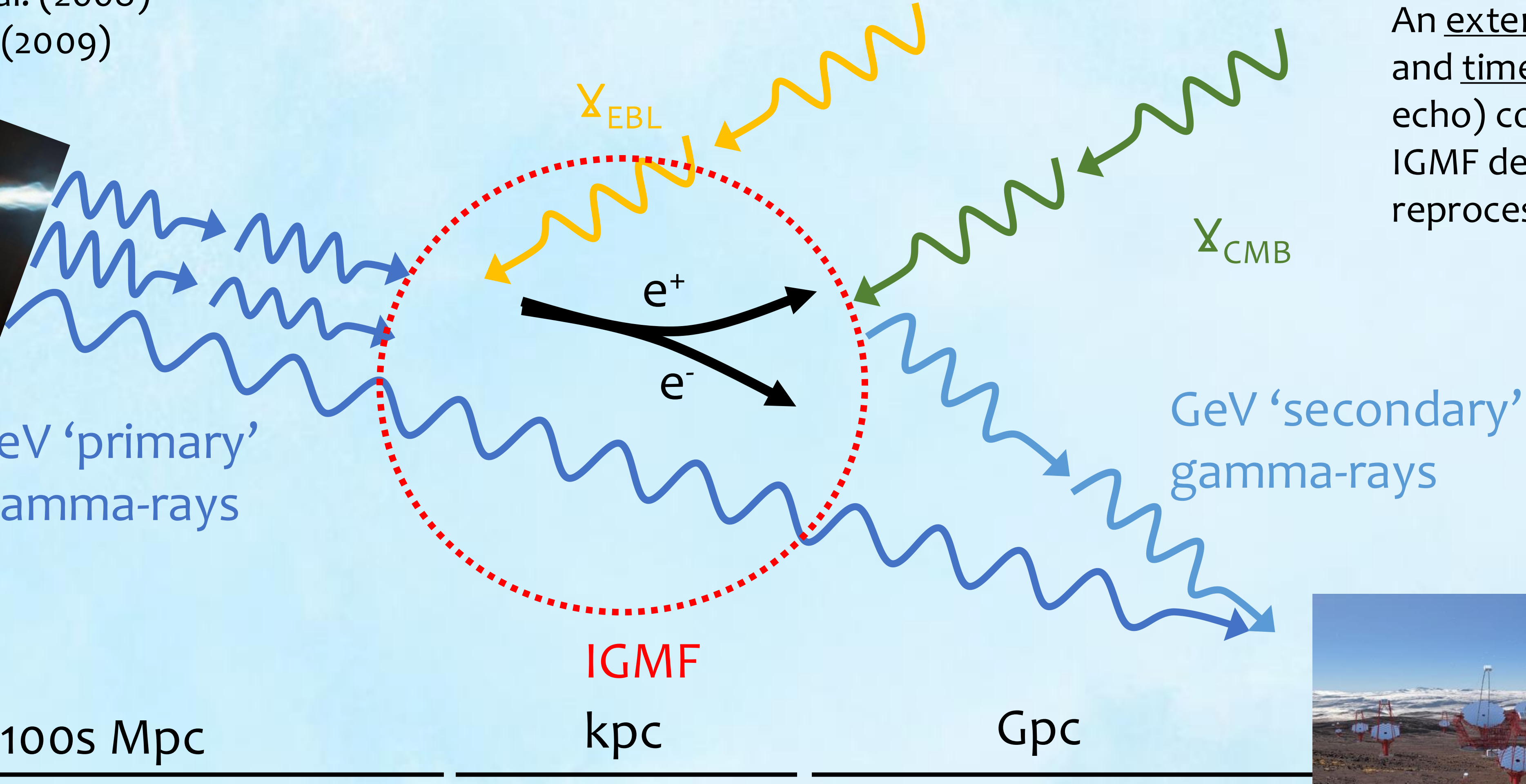


GRBs at VHE: impact on fundamental physics

Intergalactic Magnetic Field (IGMF) studies

Razzaque et al. (2004)
Ichiki et al. (2008)
Takahashi et al. (2008)
Murase et al. (2009)





An extended (pair-halo) and time-delayed (pair-echo) component due to IGMF deflection + CMB reprocessing

How GRBs impact on IGMF studies?

Intrinsic source properties

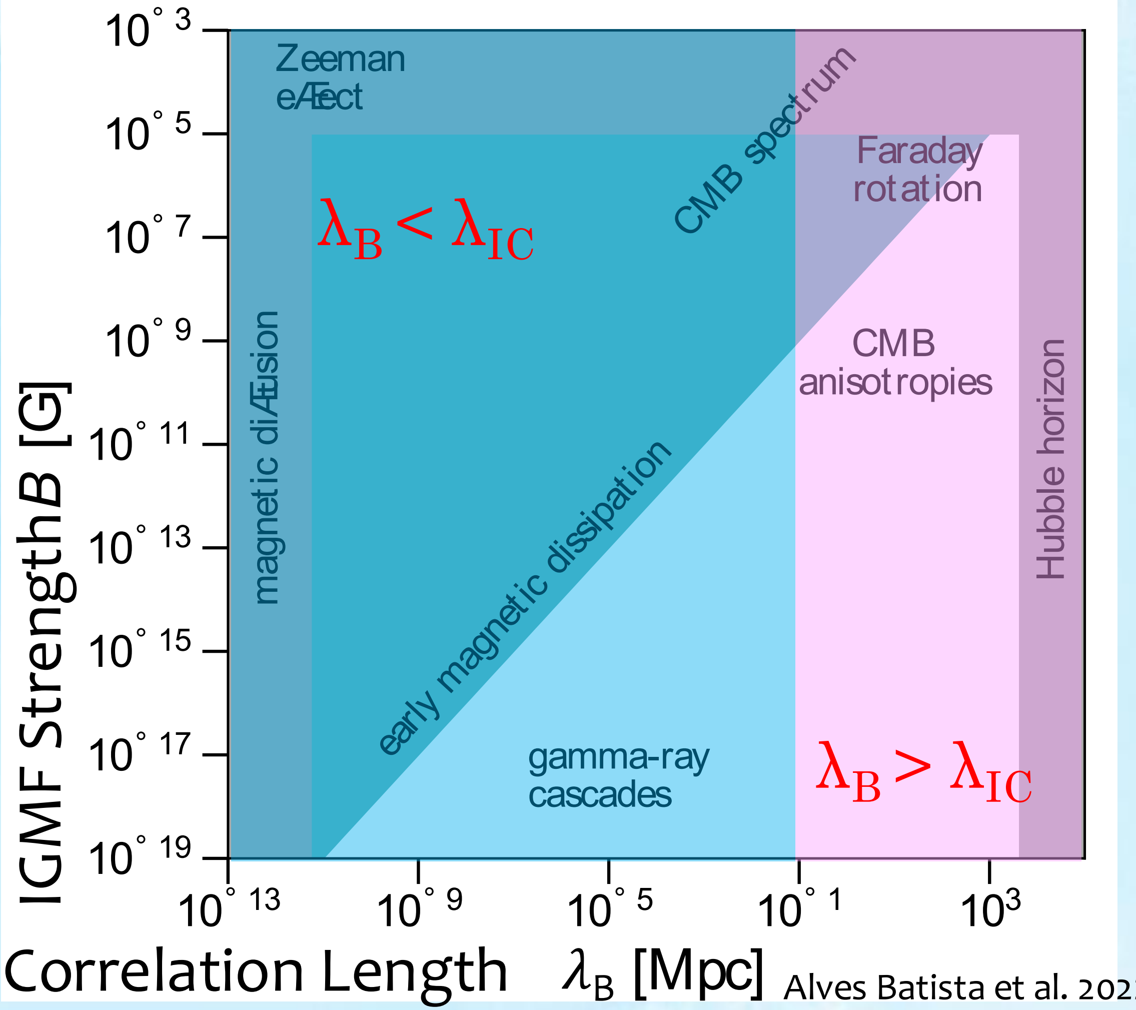
Gamma-ray propagation (EBL, pair scatter, IC) and magnetic field models

Instrument sensitivity

GRB intrinsic source spectrum (spectral and temporal evolution) → input for gamma-ray propagation

Intergalactic Magnetic field (IGMF) studies

IGMF studies investigate a 2D parameter space: Correlation Length (λ_B) – IGMF Strength (B)



Alves Batista et al. 2022

Results on IGMF are typically given considering two regimes:

- Long correlation length ($\lambda_B >> \lambda_{IC}$) (motion in homogeneous B, ballistic $e^{\pm}$)
- Short correlation length ($\lambda_B << \lambda_{IC}$) (diffusion in angle, diffusive $e^{\pm}$)

Search for the time-delayed 'pair-echo' cascade emission

$$E_{rep} \sim 0.32 \left(\frac{E\gamma}{20\ TeV}\right)^2 \text{TeV}$$

$$F_{delay} \sim F_0 \frac{T}{T_{delay}+T}$$

$$T_{delay} \propto B^2 E_\gamma^{-5/2} \qquad \lambda_B >> \lambda_{IC}$$

$$T_{delay} \propto B^2 E_\gamma^{-2} \lambda_B \qquad \lambda_B << \lambda_{IC}$$

Neronov et al. 2009
Batista et al. 2021

- 100s GeV photons experience shorter delays (~ hrs/days) than GeV photons (~ weeks/yrs)
- Weak B field (10^{-17} – 10^{-21} G) are compatible short delays
- Stronger B are compatible with longer delays (and a more diluted cascade)

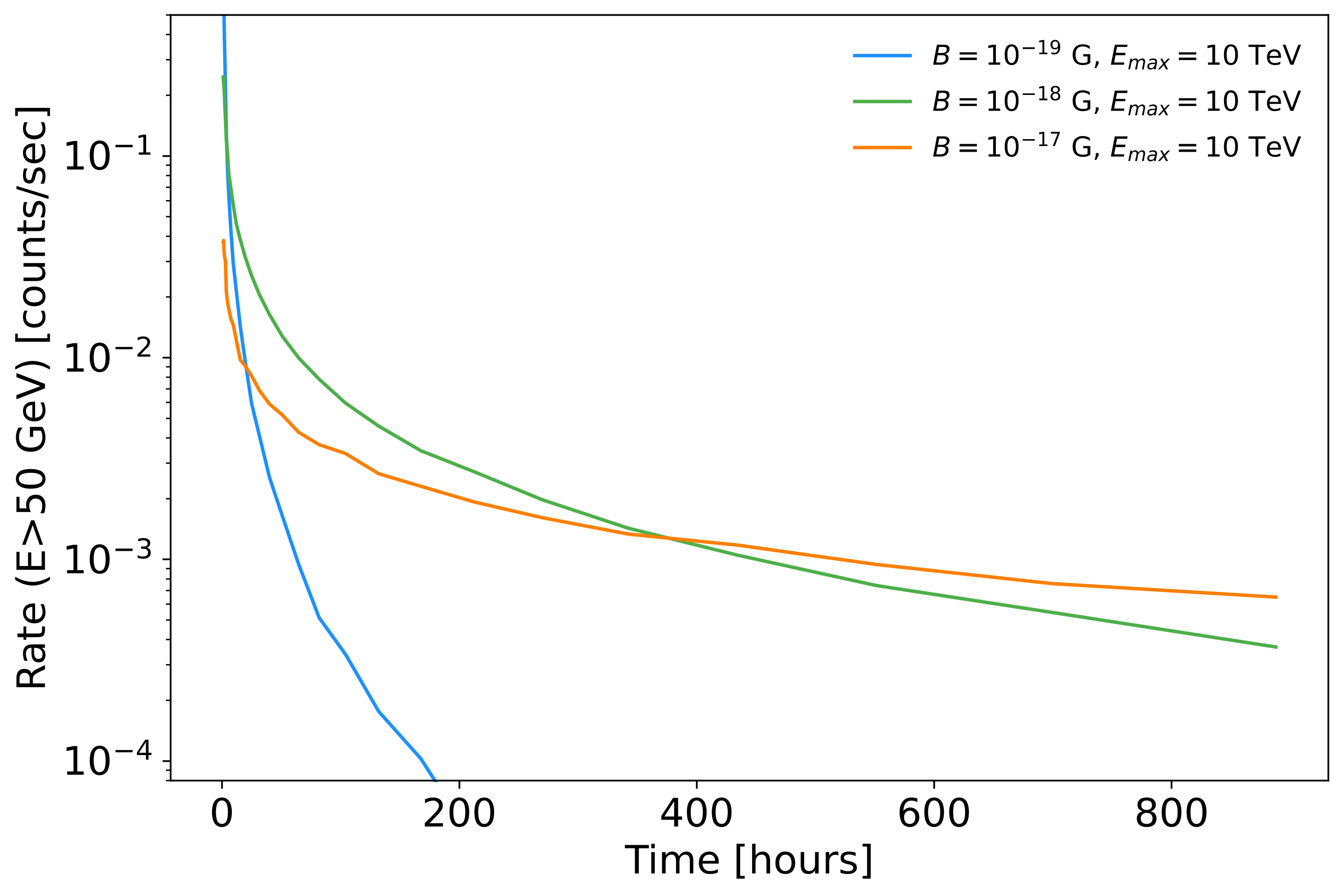
Search for the time-delayed 'pair-echo' cascade emission

$$E_{rep} \sim 0.32 \left(\frac{E\gamma}{20\ TeV}\right)^2 \text{TeV}$$

$$F_{delay} \sim F_0 \frac{T}{T_{delay}+T}$$

$T_{delay} \propto B^2 E_\gamma^{-5/2}$ $\lambda_B >> \lambda_{IC}$

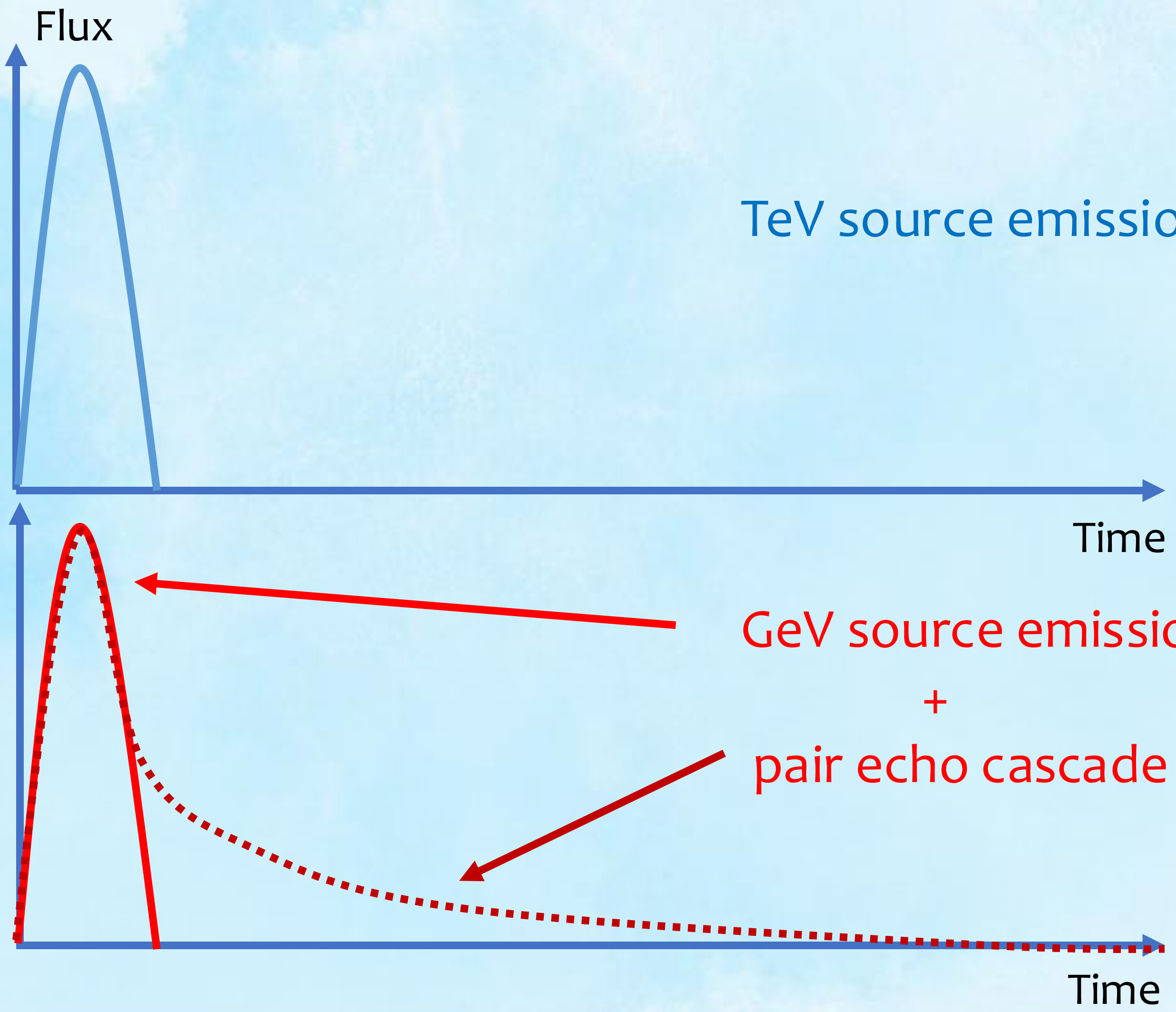
$T_{delay} \propto B^2 E_\gamma^{-2} \lambda_B$ $\lambda_B << \lambda_{IC}$



Neronov et al. 2009
Batista et al. 2021

Pair-echo after end of TeV-detected GRBs

Plaga 1995
Murase et al. 2008



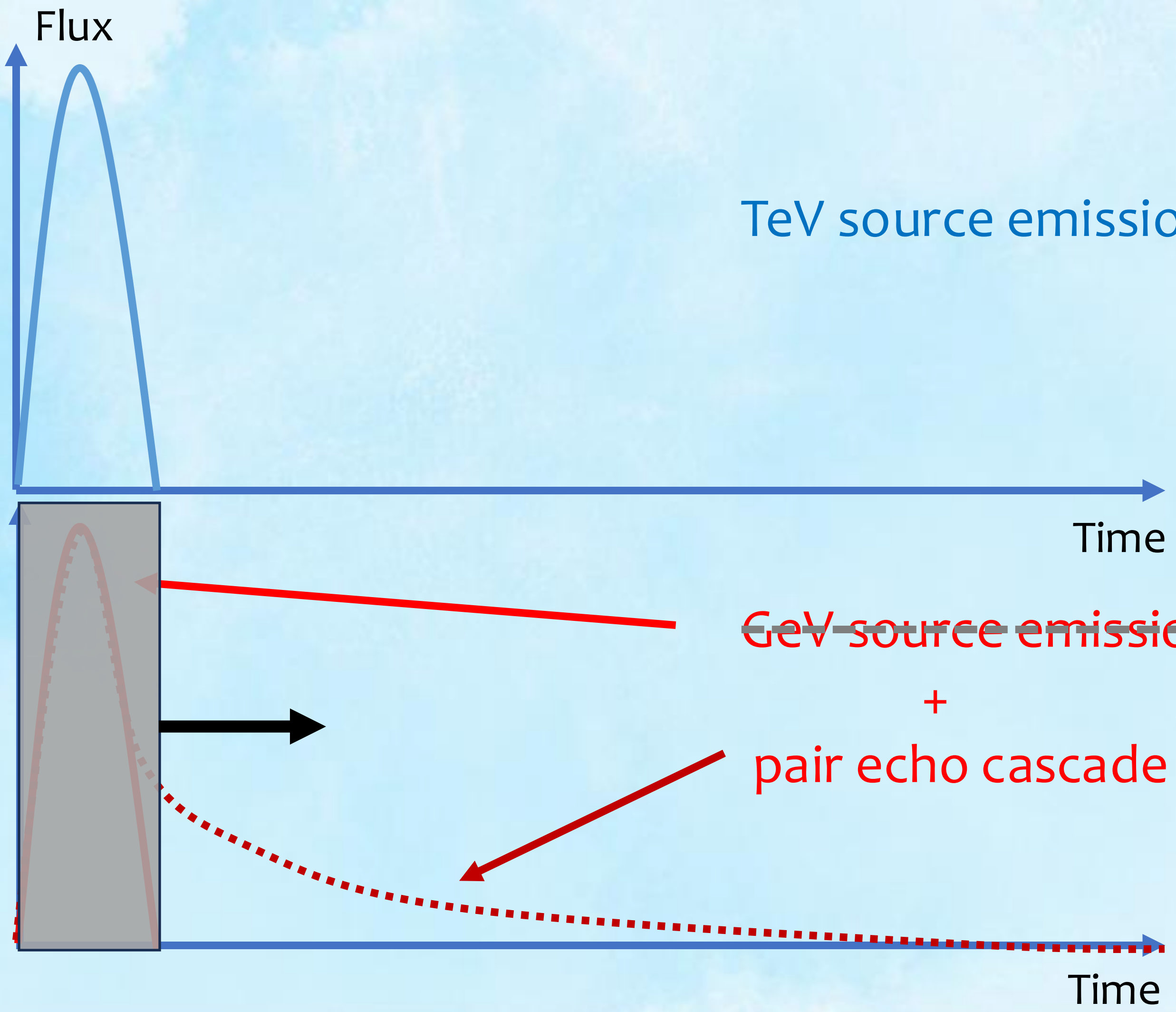
TeV source emission

GeV source emission
+
pair echo cascade emission with non-negligible IGMF

Interesting for AGN flares or transient sources

Pair-echo after end of TeV-detected GRBs

Plaga 1995
Murase et al. 2008



TeV source emission

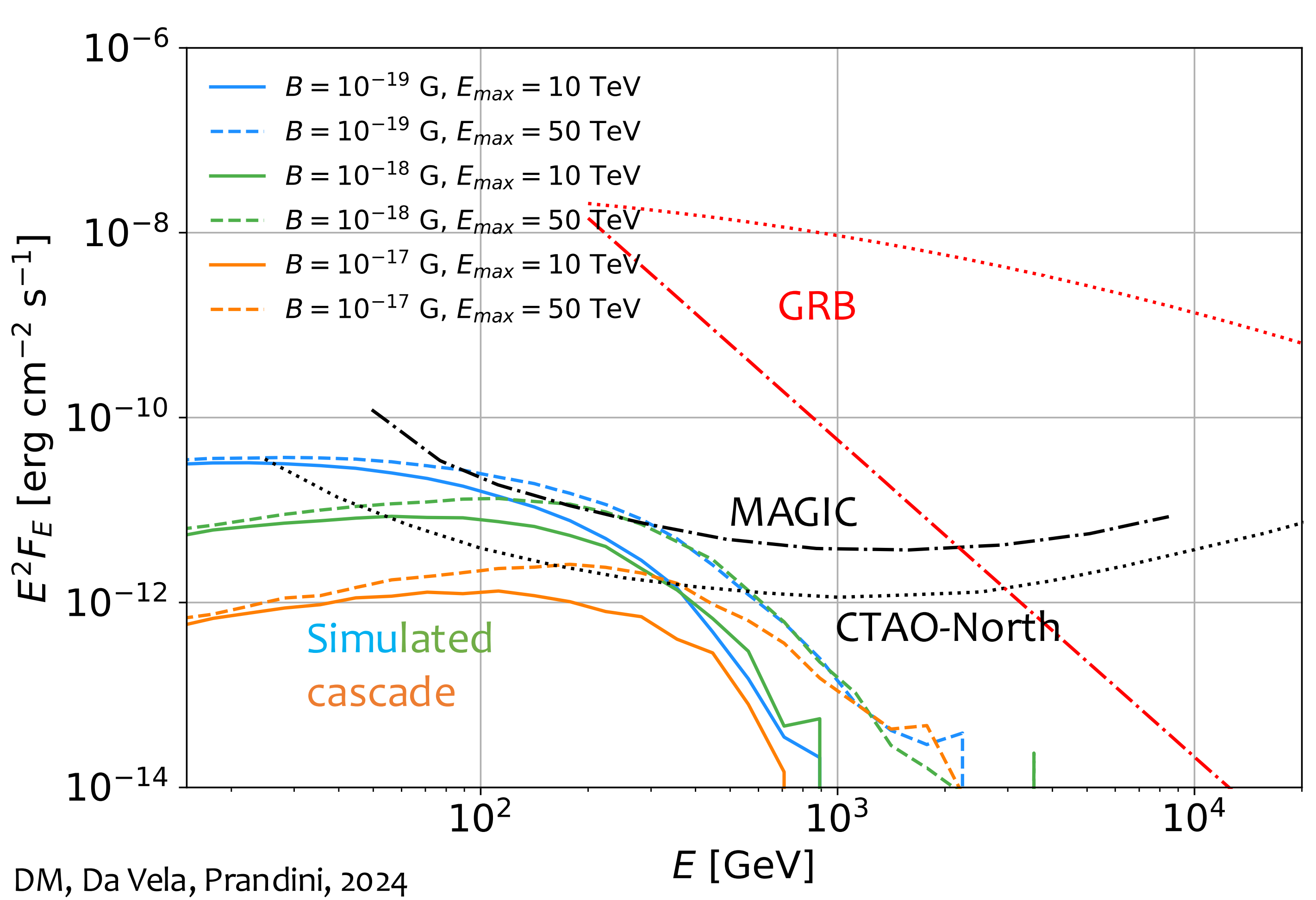
~~GeV source emission~~

+

pair echo cascade emission with non-negligible IGMF

Pair-echo after end of TeV-detected GRBs

GRB190114C (z = 0.42)



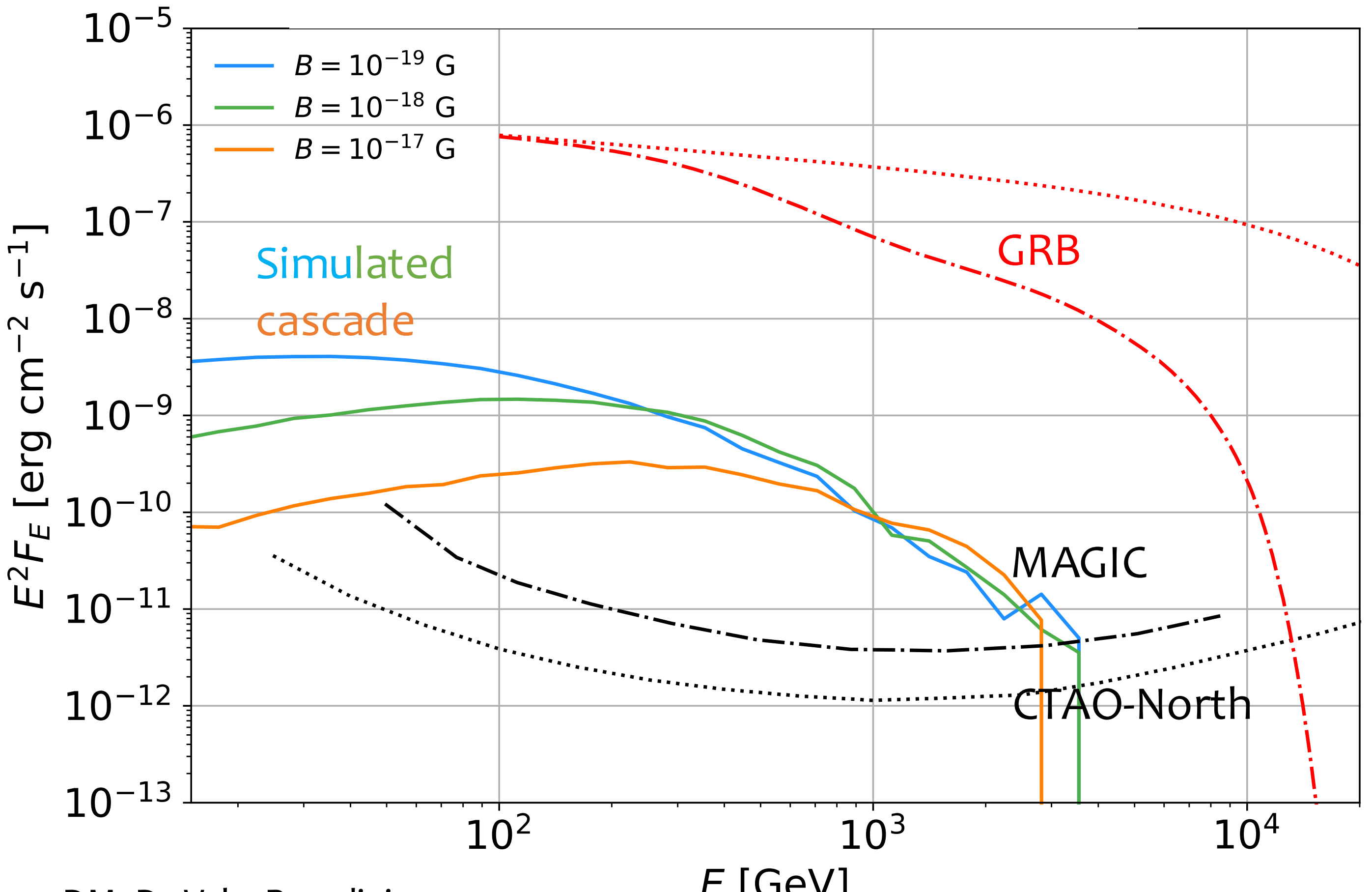
DM, Da Vela, Prandini, 2024

Spectral energy distribution

- Primary GRB emission
- Secondary emission
- Observational time: 3 hours starting from 2400 s after trigger burst
- MAGIC and CTAO sensitivity derived and rescaled in time ($S \propto (1/\sqrt{t})$)

Pair-echo after end of TeV-detected GRBs

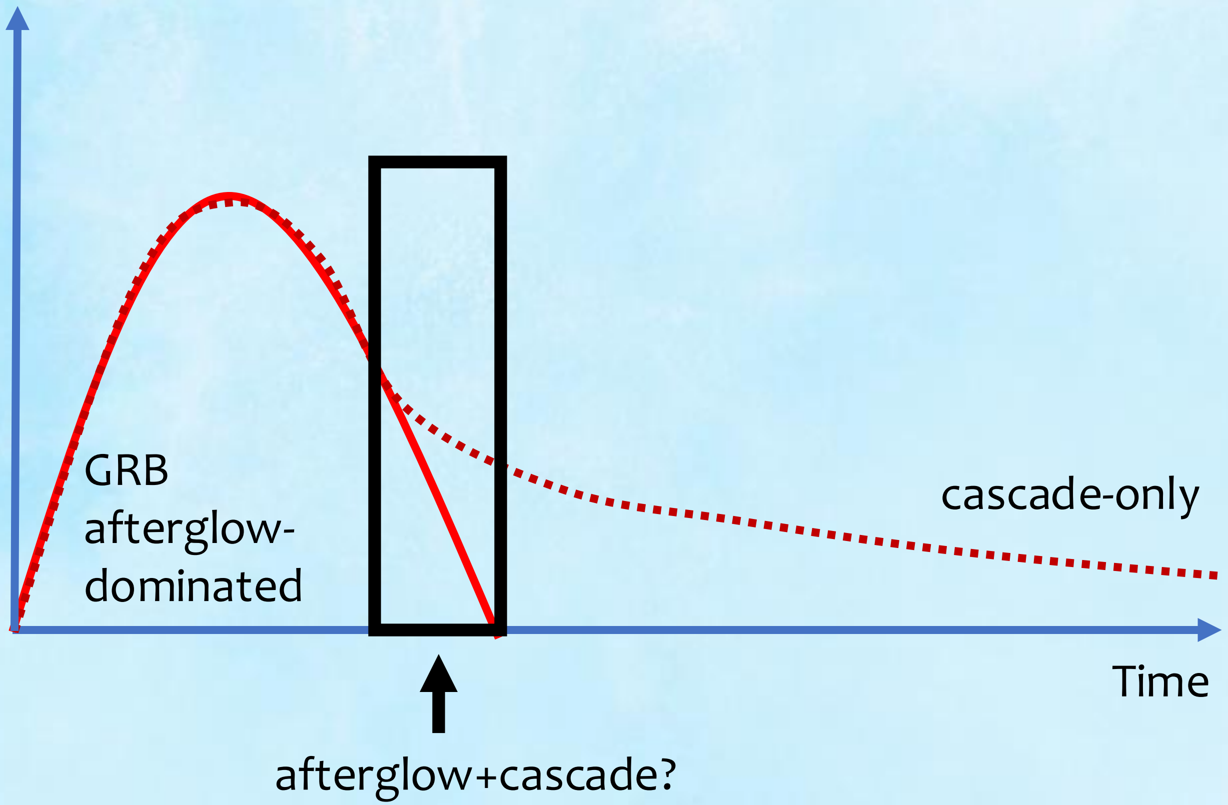
GRB221009A (z = 0.151)



DM, Da Vela, Prandini, 2024

- Extend observations for at least 3 hours after GRB detection
- GRBs observations can probe IGMF strengths in the $10^{-17} – 10^{-19}$ G → competitive with most stringent AGN results

Pair-echo emission + GRB afterglow convolution



- A significant emission can also be present also during *fading phase* of GRB afterglow emission
- Afterglow emission and GRB properties (energetics, distance) can vary of several orders of magnitude
- Model to convolve:
  - simultaneous GRB afterglow
  - pair-echo cascade contribution

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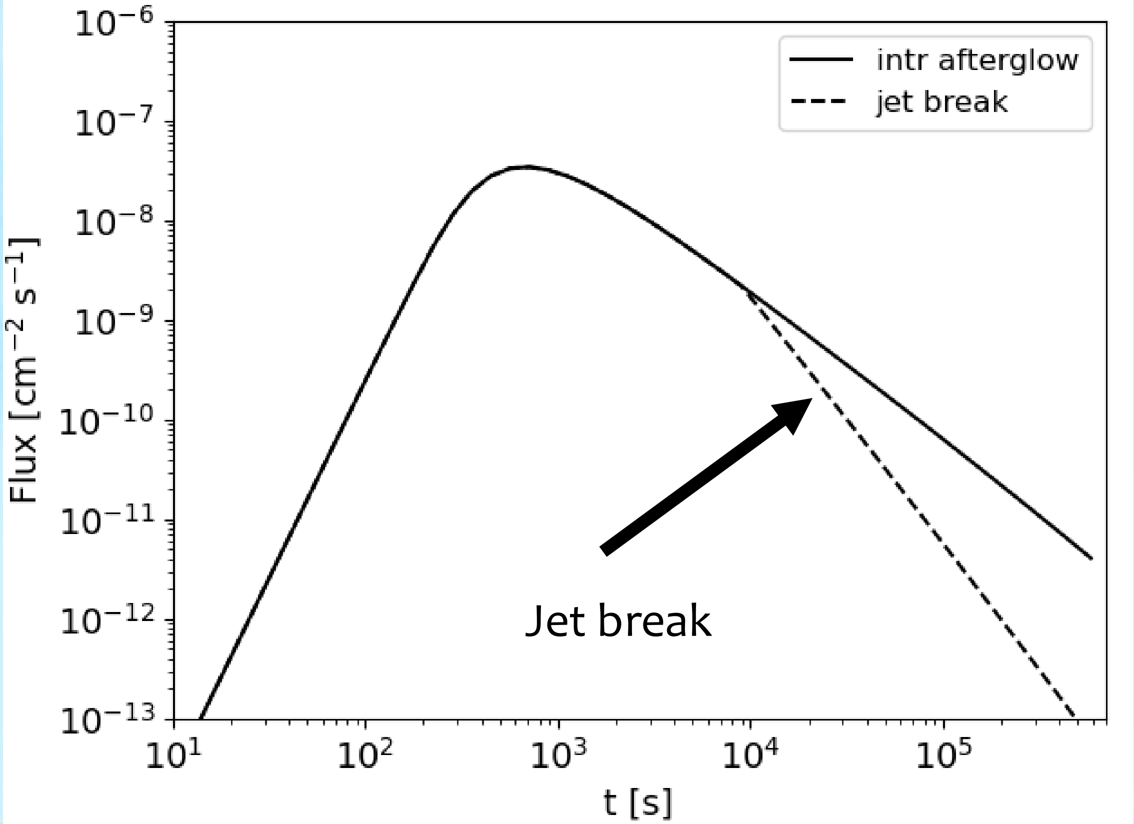
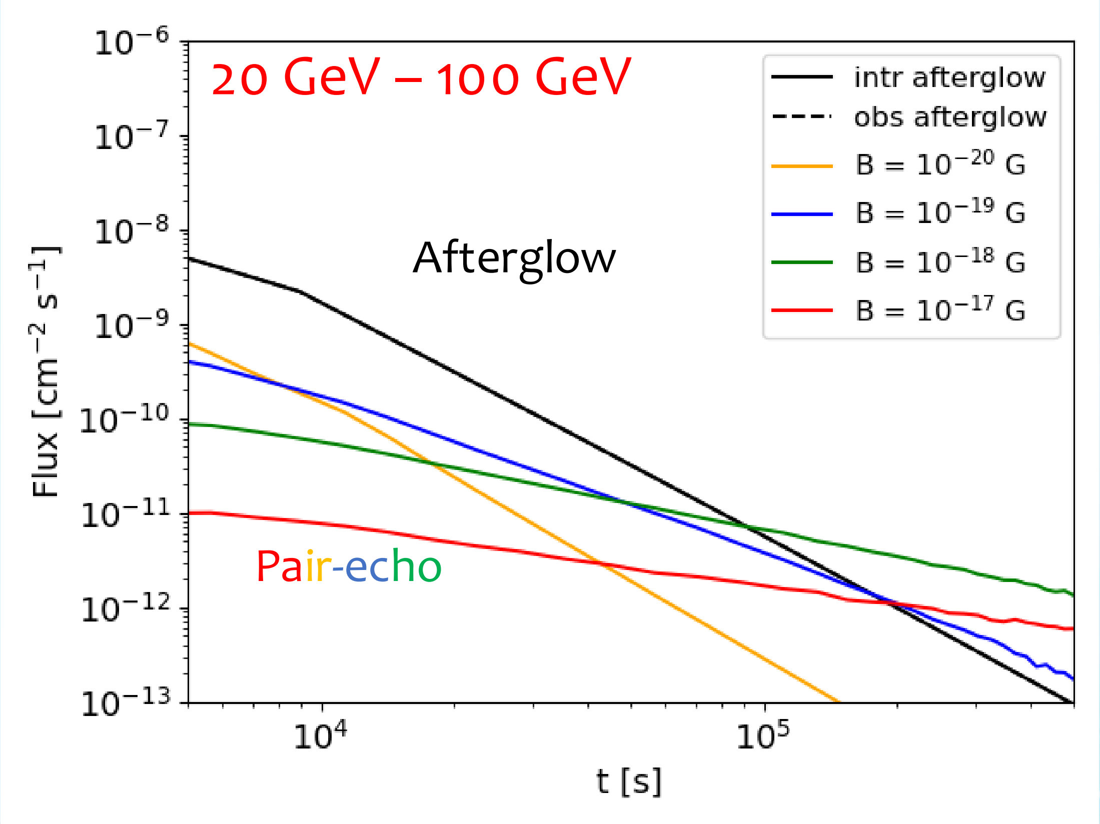
Pair-echo emission + GRB afterglow convolution

On going study with Da Vela, Ghirlanda, Nava

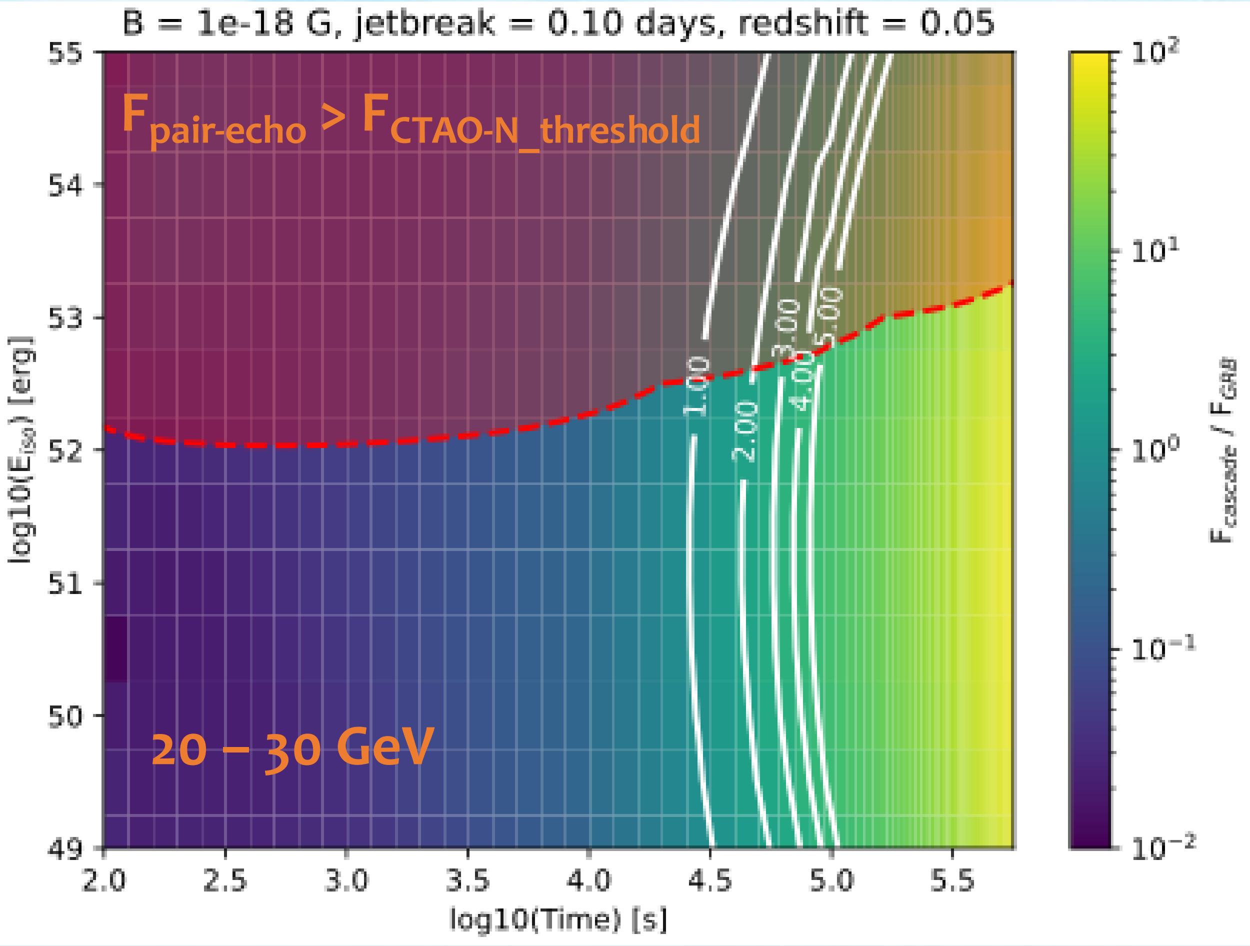
- Simulated GRB afterglows in a grid of redshift z and energetics E_{iso}
- Simulations of expected pair-echo emission in energy ranges and in grid of IGMF strength B
- Convolution of results providing GRB afterglow + cascade lightcurves and estimate of CTAO sensitivity

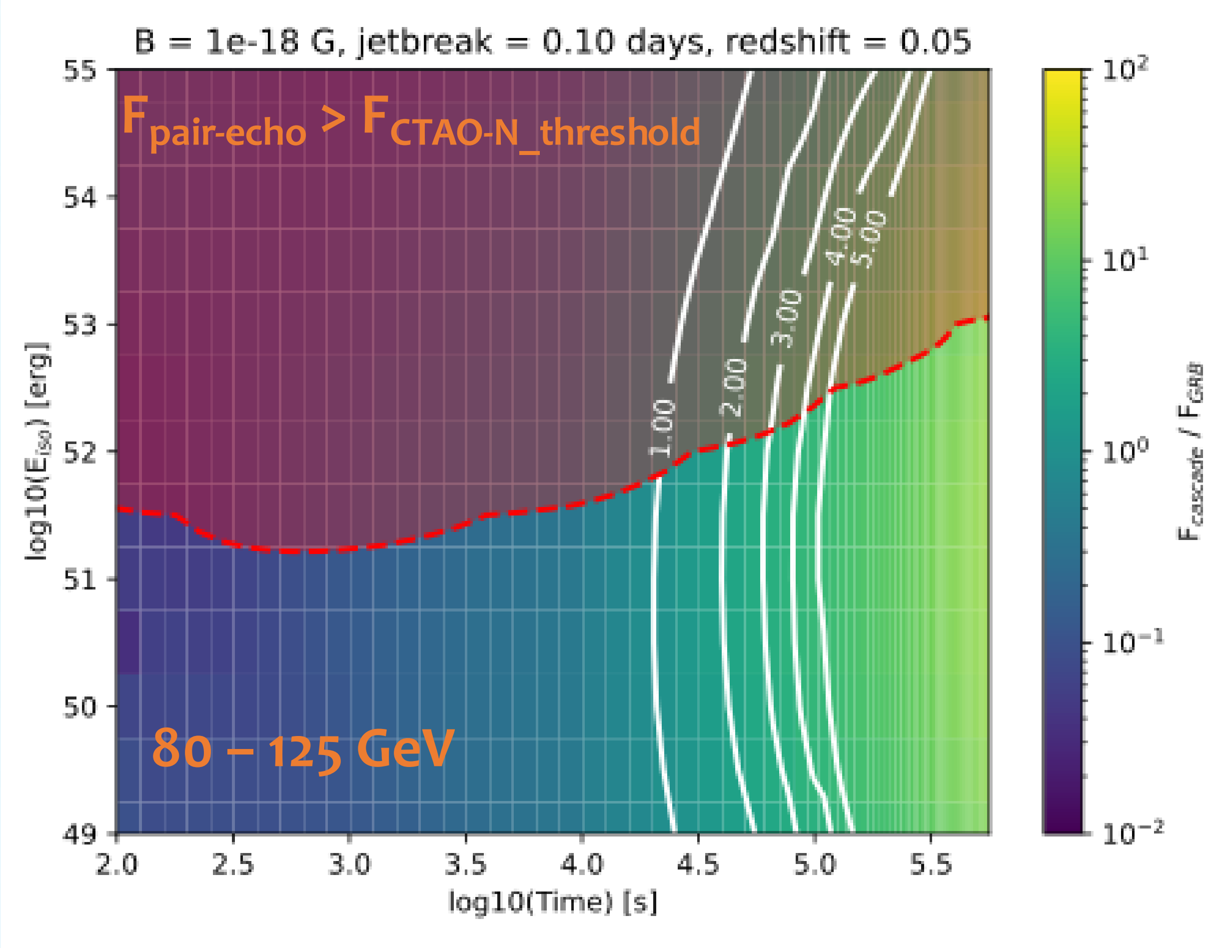




Pair-echo emission + GRB afterglow convolution

On going study with Da Vela, Ghirlanda, Nava



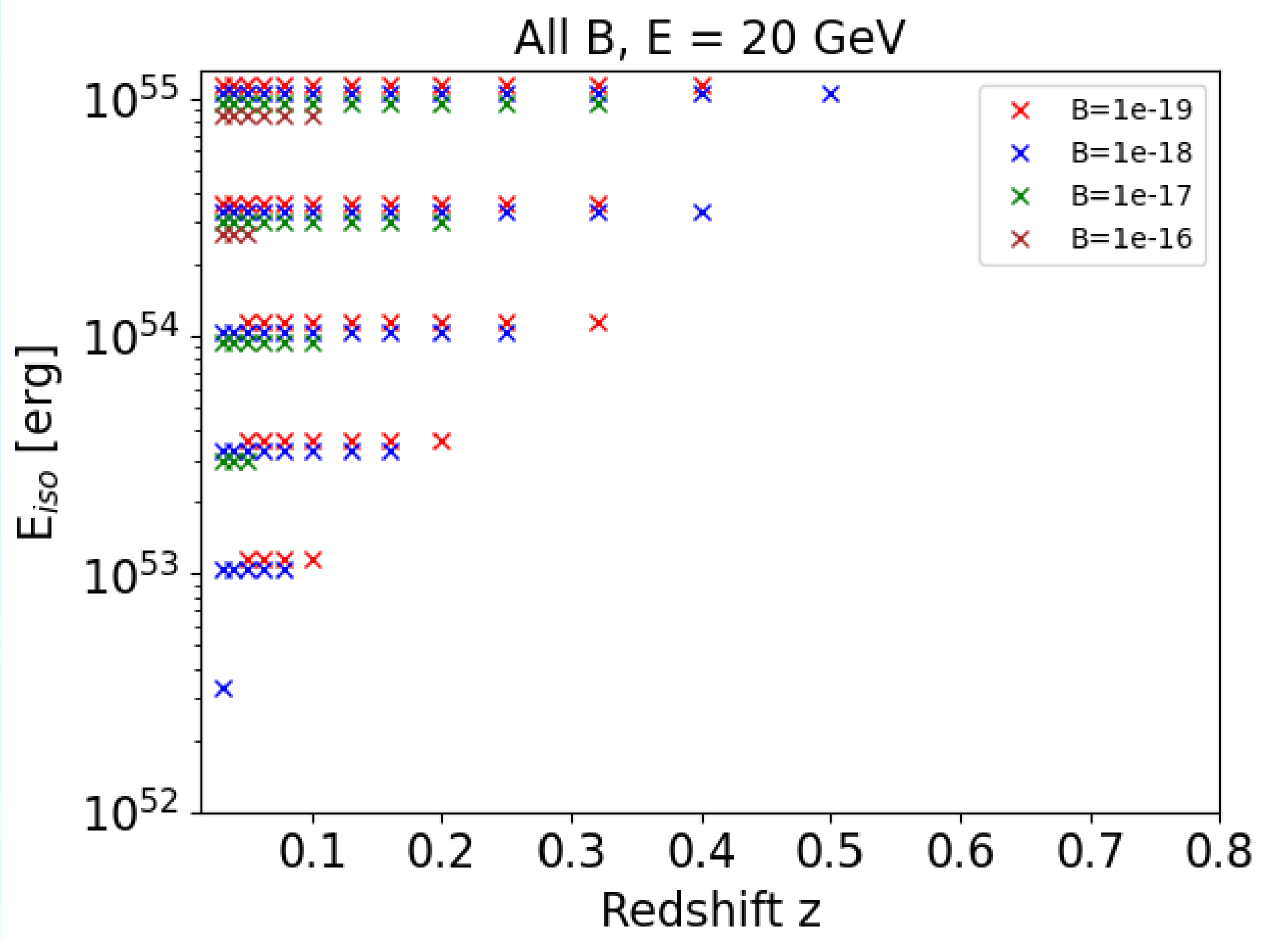


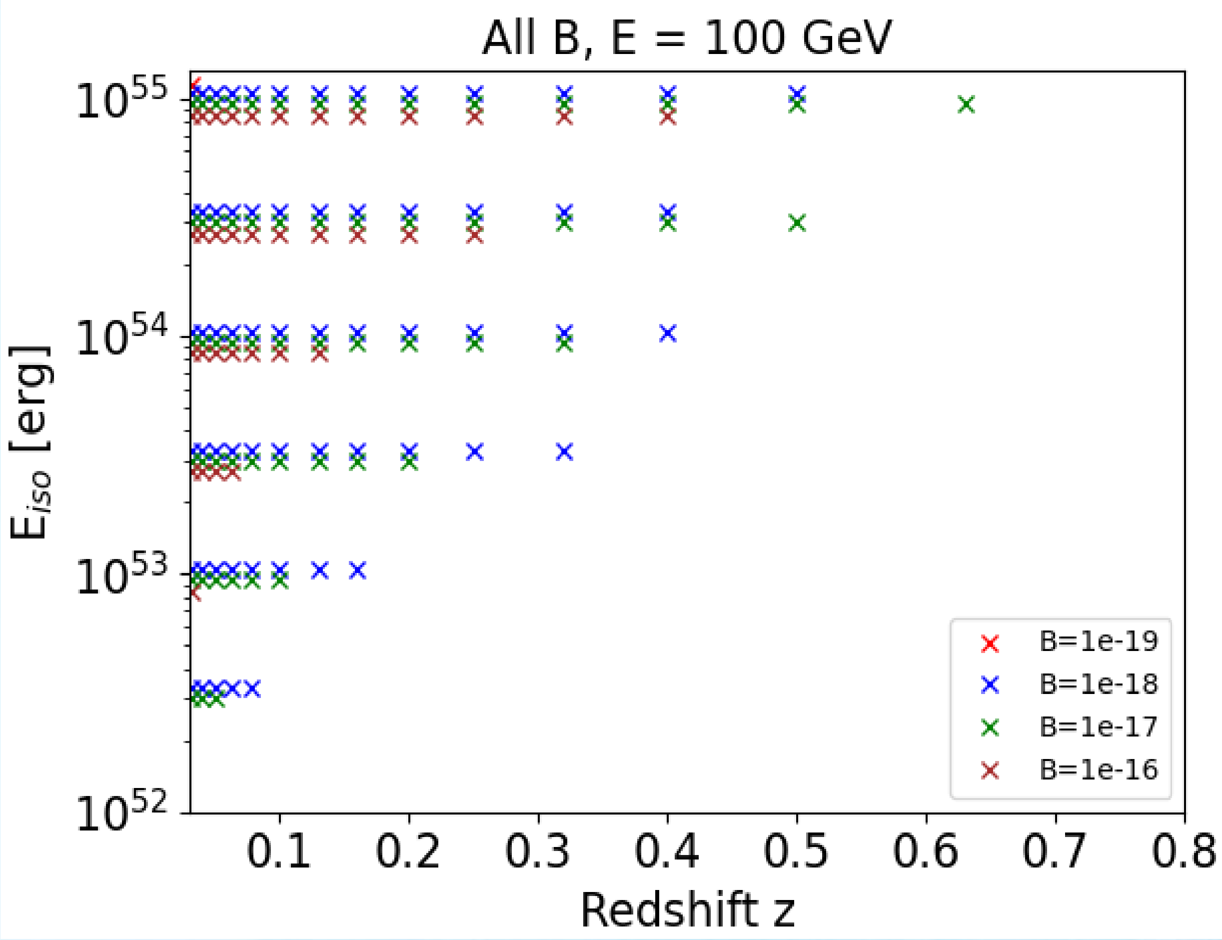
Pair-echo emission + GRB afterglow convolution

On going study with Da Vela, Ghirlanda, Nava

Each cross is a GRB event with corresponding (z,E_{iso}) if $\mathbf{F_{cas} > F_{thr}}$ and if it exist one t_i for which $\mathbf{F_{cas}/F_{aft}\ (\mathit{t_i}) > 2}$

B information is included (legenda)





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Next generation: Cherenkov Telescope Array Observatory (CTAO)

CTAO North (Alpha configuration)

4 LSTs (23 m)
9 MSTs (12 m)

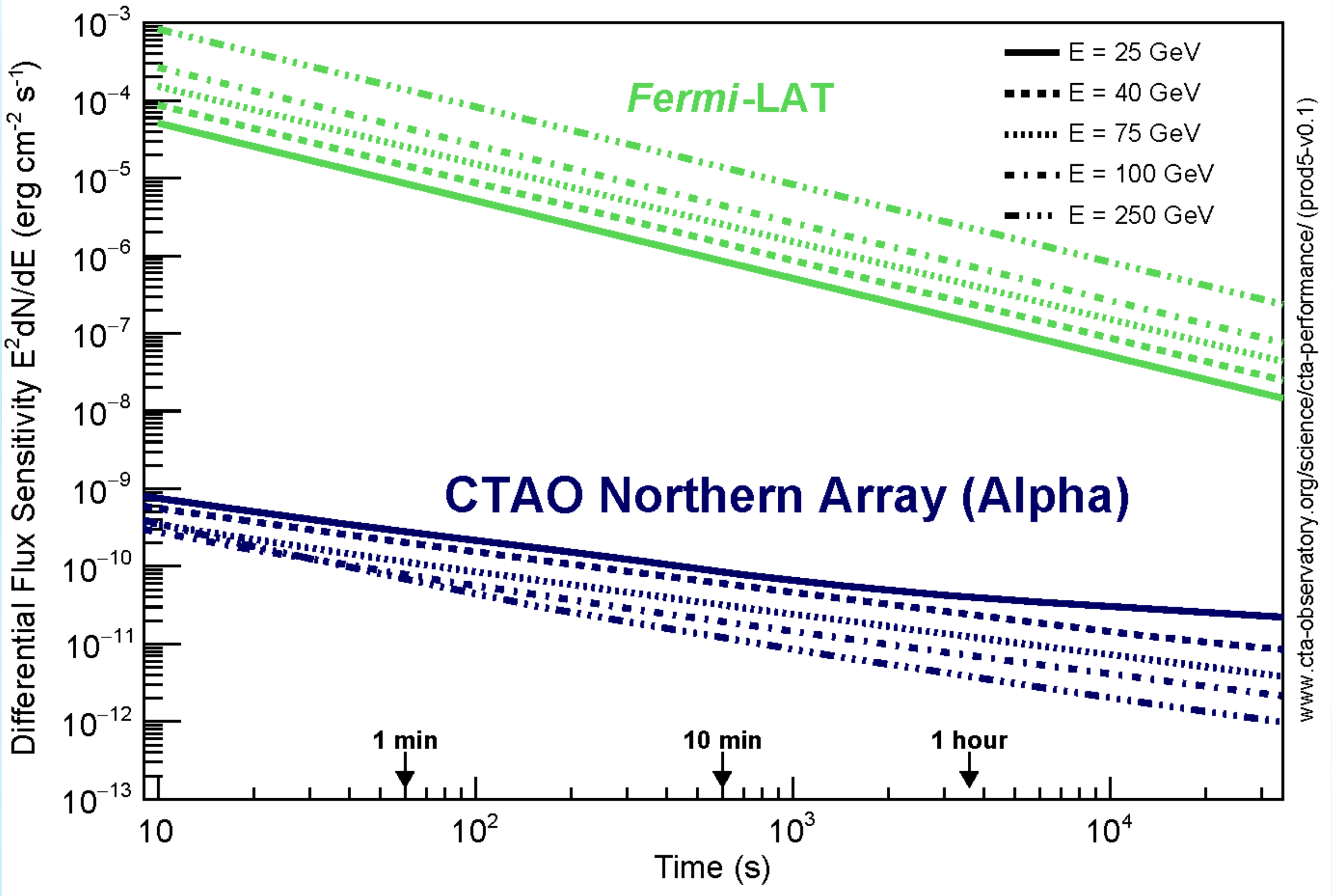
CTAO South (Alpha configuration + CTA+)

2 LSTs
14 MSTs
37+5 SSTs

CTAO for GRBs: an upcoming revolution

CTAO revolution:

- x10 sensitivity to gamma-ray signal
- x10^4 sensitivity to short-term (< 10^4 s) emission below 250 GeV with respect to Fermi-LAT
- Intermediate arrays at both sites operative by 2027; full array by 2031-2032
- GRB detection rates (Inoue et al. 2013): > 1-4 GRBs/year/site (but to be updated with new VHE GRB discovery!)



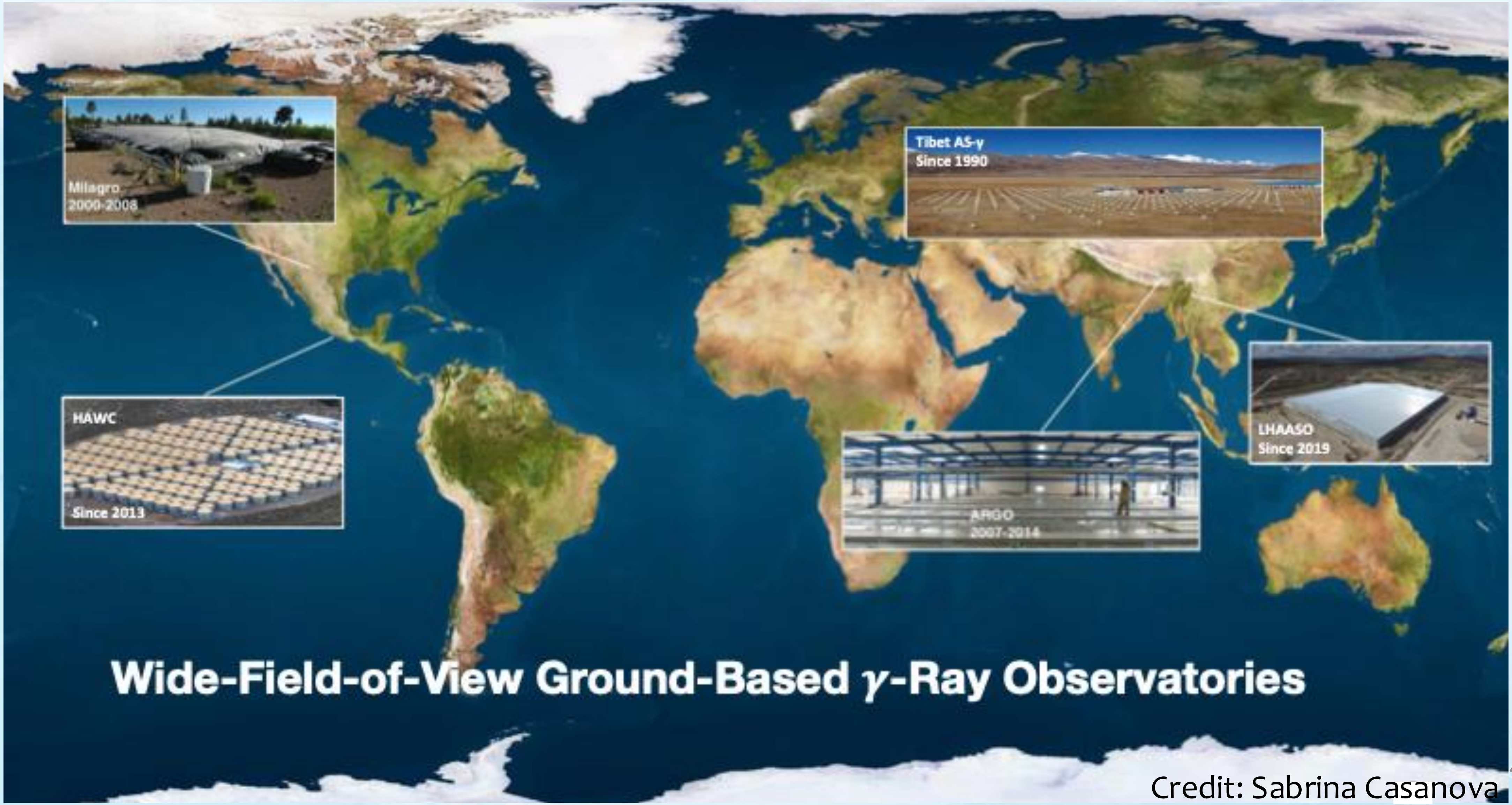
https://www.cta-observatory.org/science/ctao-performance/

Conclusions (+ future prospects)

- Discoveries in the past 5 years have open a new observational window for GRBs: the TeV domain
- Results have shown that (to some extent) VHE emission is compatible with broadband intrinsic properties of GRBs (energetics, luminosity, distance) and broad observational requirements (timing, VHE range) → universality of TeV component?
- So far modeling reproduced the VHE component in the context of the SSC emission from external forward shock scenario, but still not conclusive results (Synchrotron, EIC, p-synchrotron)
- Modeling still not show a clear consensus on the GRB afterglow theory micro-physical parameters and environmental conditions → multi-wavelength coverage can help to disentagle degeneracy
- Open questions and future challenges: flares, VHE prompt emission, GW-GRB observations (tiling strategies developed)
- GRBs for IGMF studies: competitive results, can provide important independent verification of complementary studies and explore IGMF parameter space with relaxed assumptions. Impact of intrinsic source features (distance, brightness, intrinsic spectrum shape and features, time evolution, jet break) under investigation
- Current and future generation instruments (CTAO, SWGO) are ready in the game, improvements are under investigation, 15 years of continuous improvements lead to first GRB VHE detections

BACKUP SLIDES

Shower front arrays

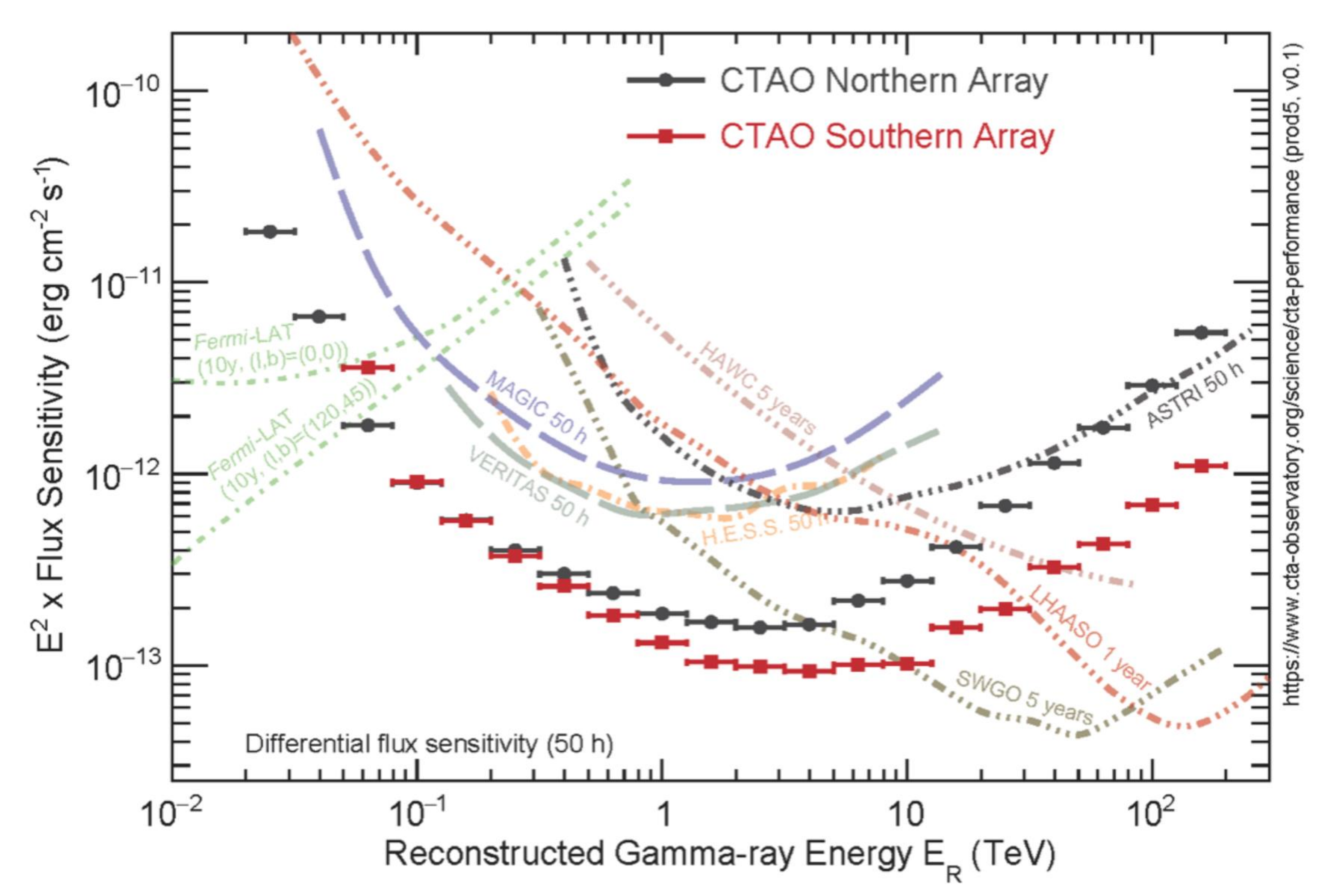


Credit: Sabrina Casanova

Next generation: Cherenkov Telescope Array Observatory (CTAO)

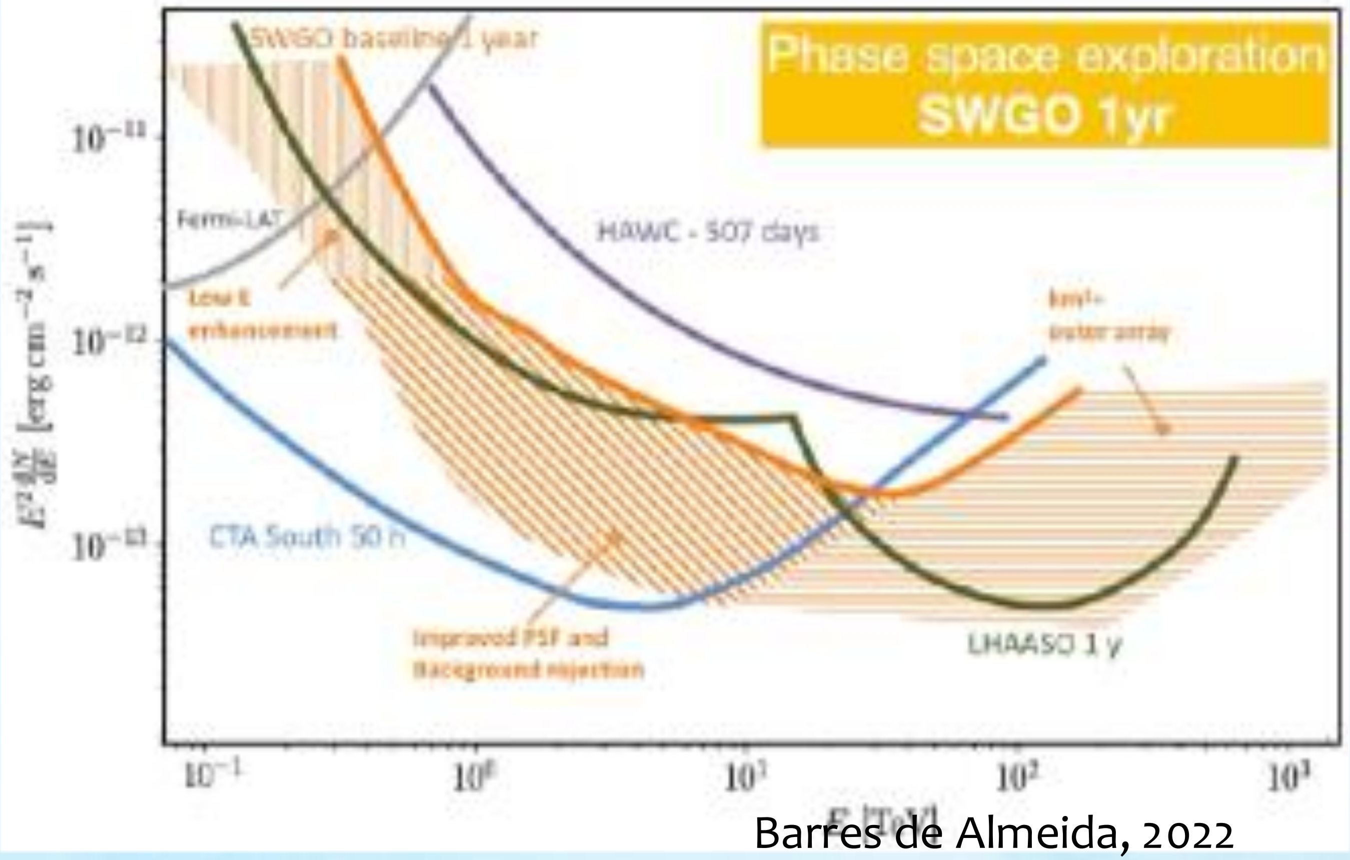
CTAO upgrades:

- a lower energy threshold (<30 GeV)
- a larger effective area at multi-GeV energies (~ 10^4 times larger than Fermi-LAT at 30 GeV)
- a rapid slewing capability (180 degrees azimuthal rotation in 20 s).
- a full sky coverage



https://www.cta-observatory.org/science/ctao-performance/

Next generation: the Southern Wide-field Gamma-ray Observatory (SWGO)



Barres de Almeida, 2022

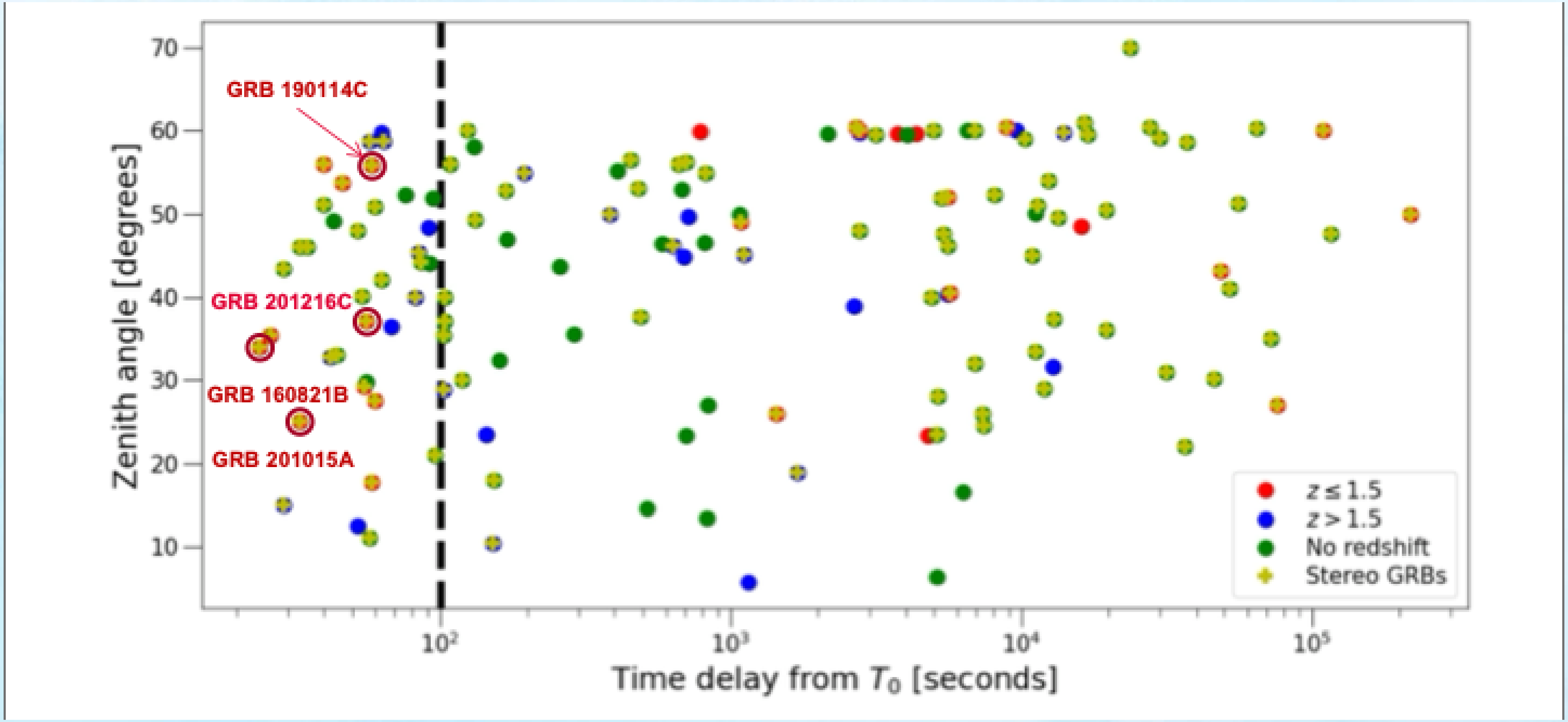
Next generation: Cherenkov Telescope Array Observatory (CTAO)

Next generation: Cherenkov Telescope Array Observatory (CTAO)

CTAO North status May 2024 → commissioning in 2025/2026

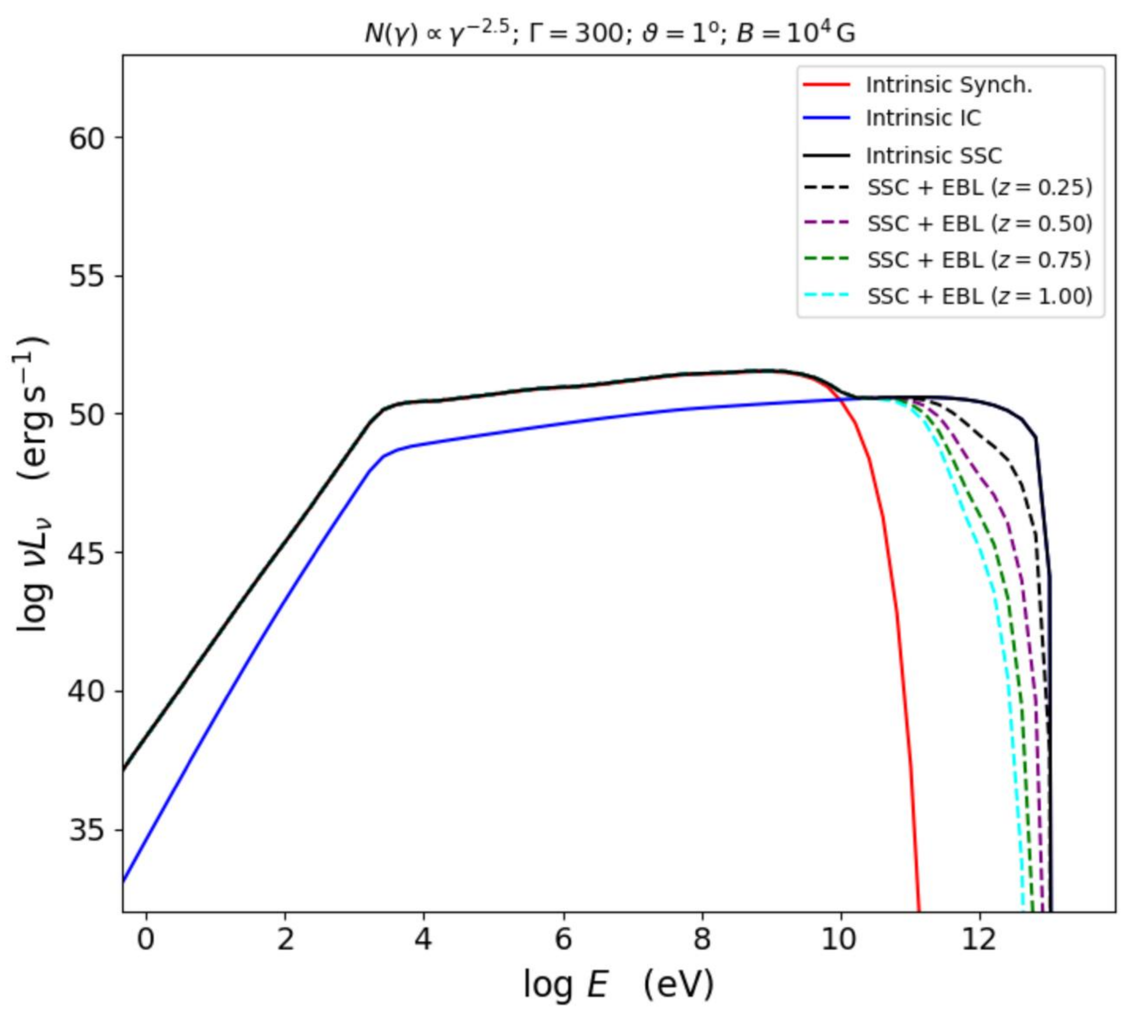
Credit: M.Mariotti

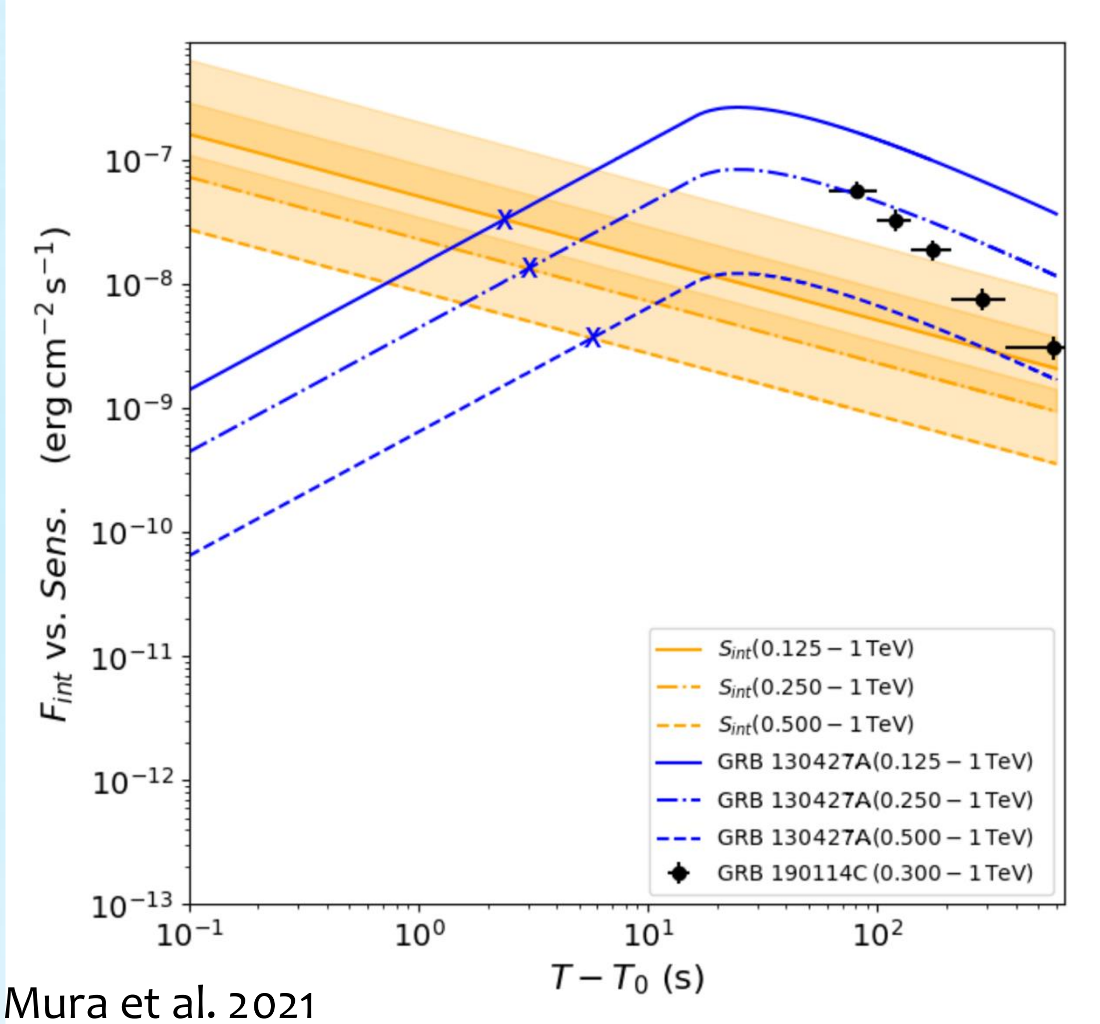
Decades of searches for the VHE emission



Berti et al., ICRC 2021

Gamma-ray bursts with SWGO





La Mura et al. 2021

Search for the time-delayed 'pair-echo' cascade emission

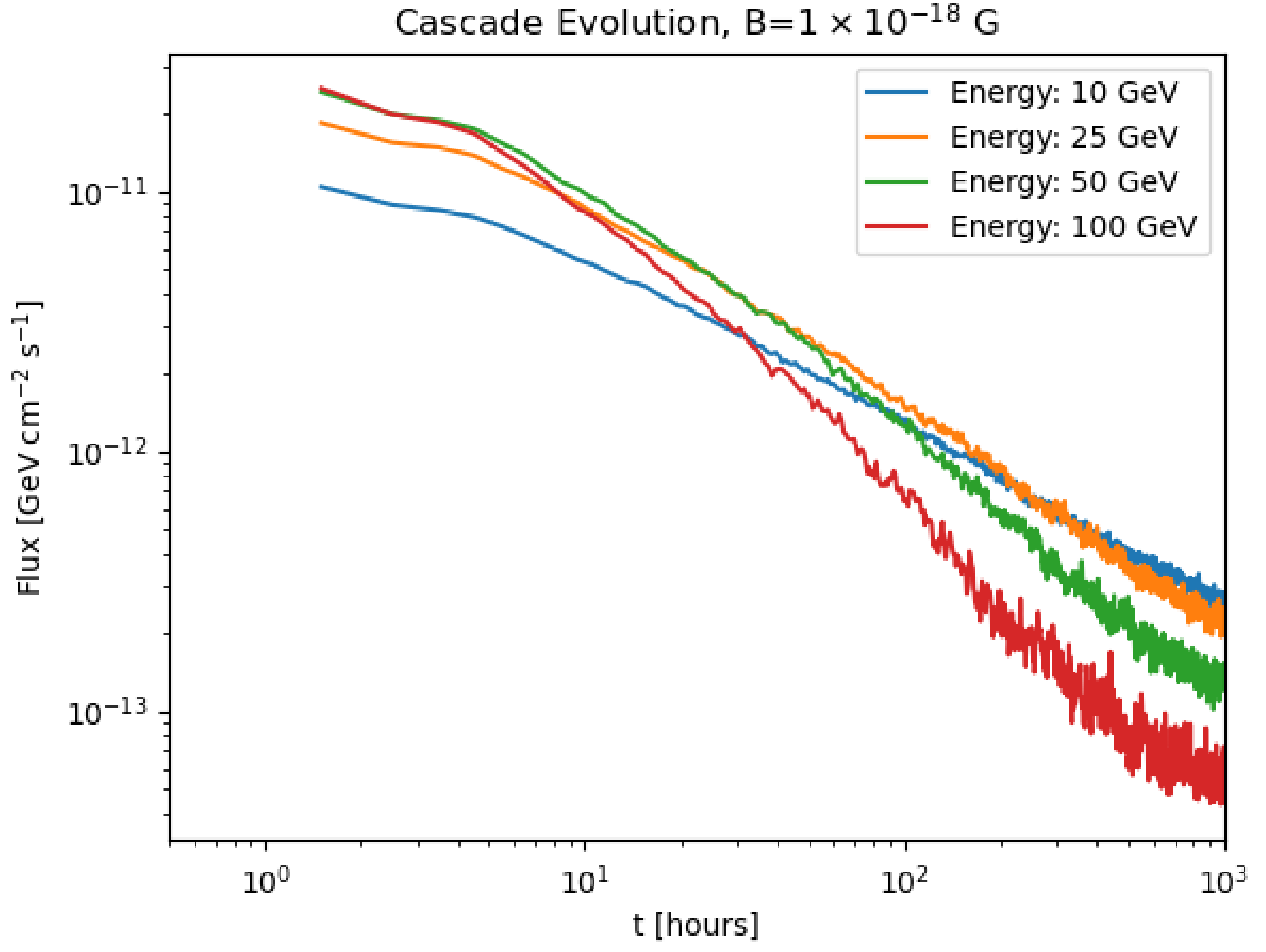
$$E_{rep} \sim 0.32 \left(\frac{E\gamma}{20\ TeV}\right)^2 \text{TeV}$$

$$F_{delay} \sim F_0 \frac{T}{T_{delay}+T}$$

$T_{delay} \propto B^2 E_\gamma^{-5/2}$ $\lambda_B >> \lambda_{IC}$

$T_{delay} \propto B^2 E_\gamma^{-2} \lambda_B$ $\lambda_B << \lambda_{IC}$

Neronov et al. 2009
Batista et al. 2021



Search for the time-delayed 'pair-echo' cascade emission

$$E_{rep} \sim 0.32 \left(\frac{E\gamma}{20\ TeV}\right)^2 \text{TeV}$$

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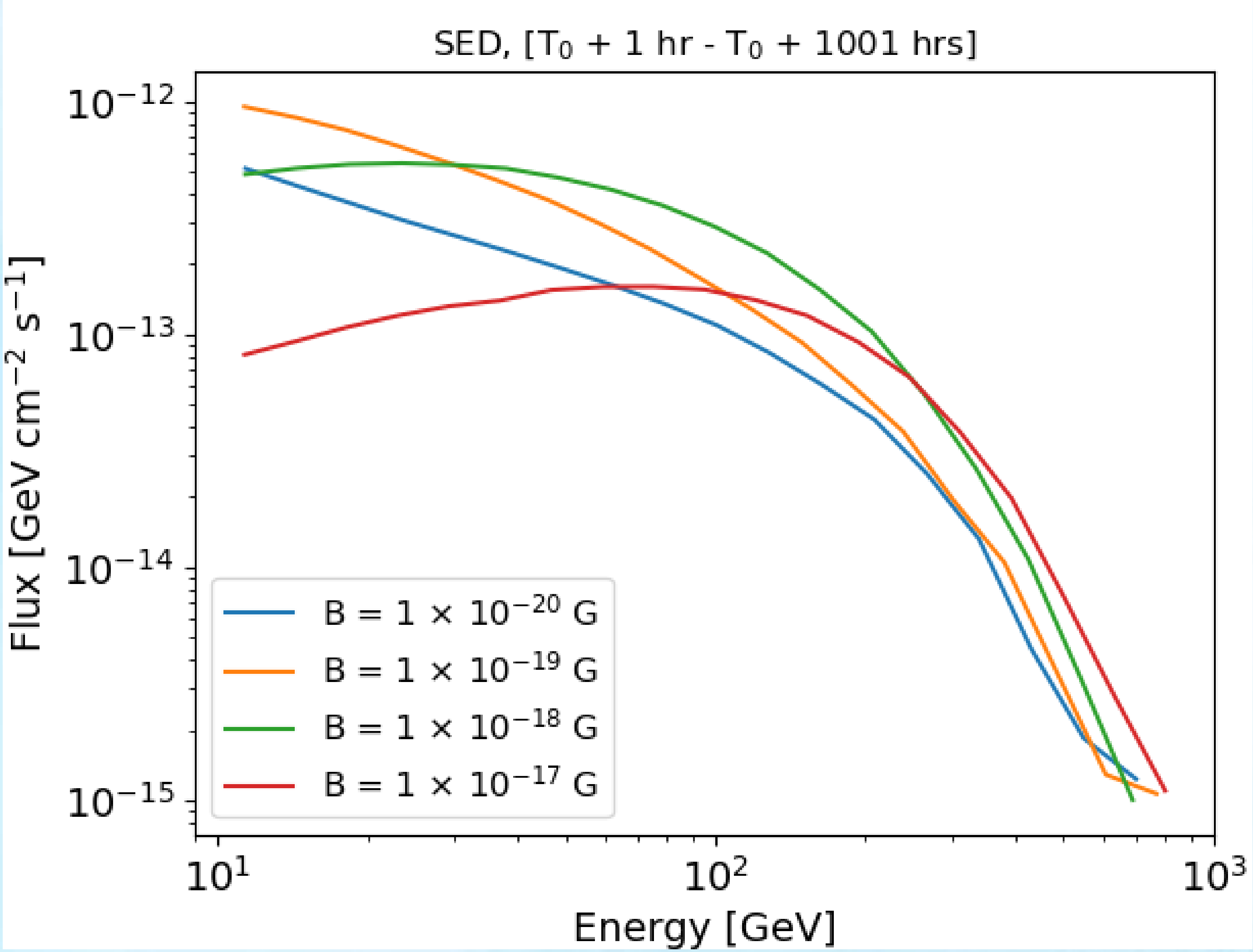
Neronov et al. 2009
Batista et al. 2021

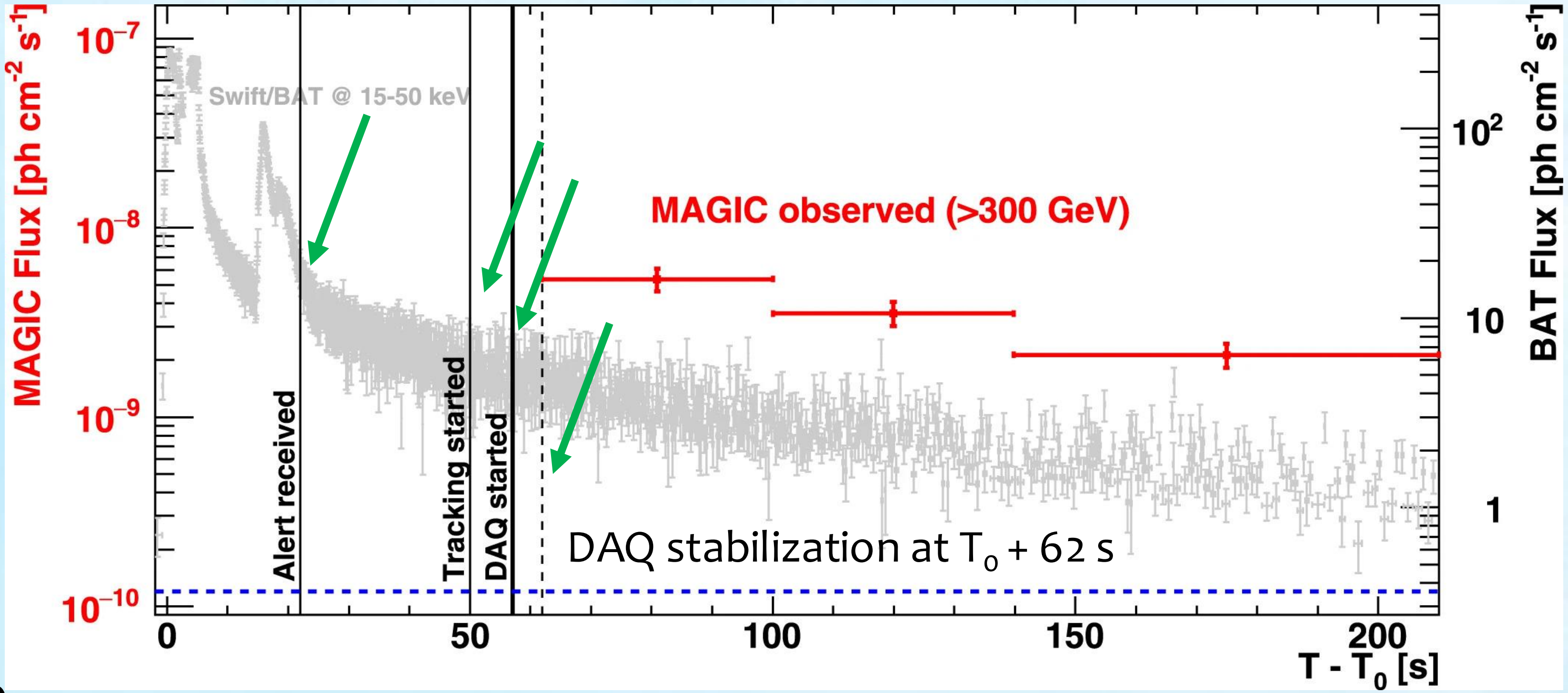


GRB 190114C -- Timeline

- $E_{\gamma,iso} \sim 2.5 \times 10^{53}$ erg
- z = 0.42

MAGIC detection info:

- $T_{delay} \sim 57$ s
- > 50σ in 20 minutes
- detection up to 40 min
- 0.3 - 1 TeV energy range
- moon conditions and Zd>50

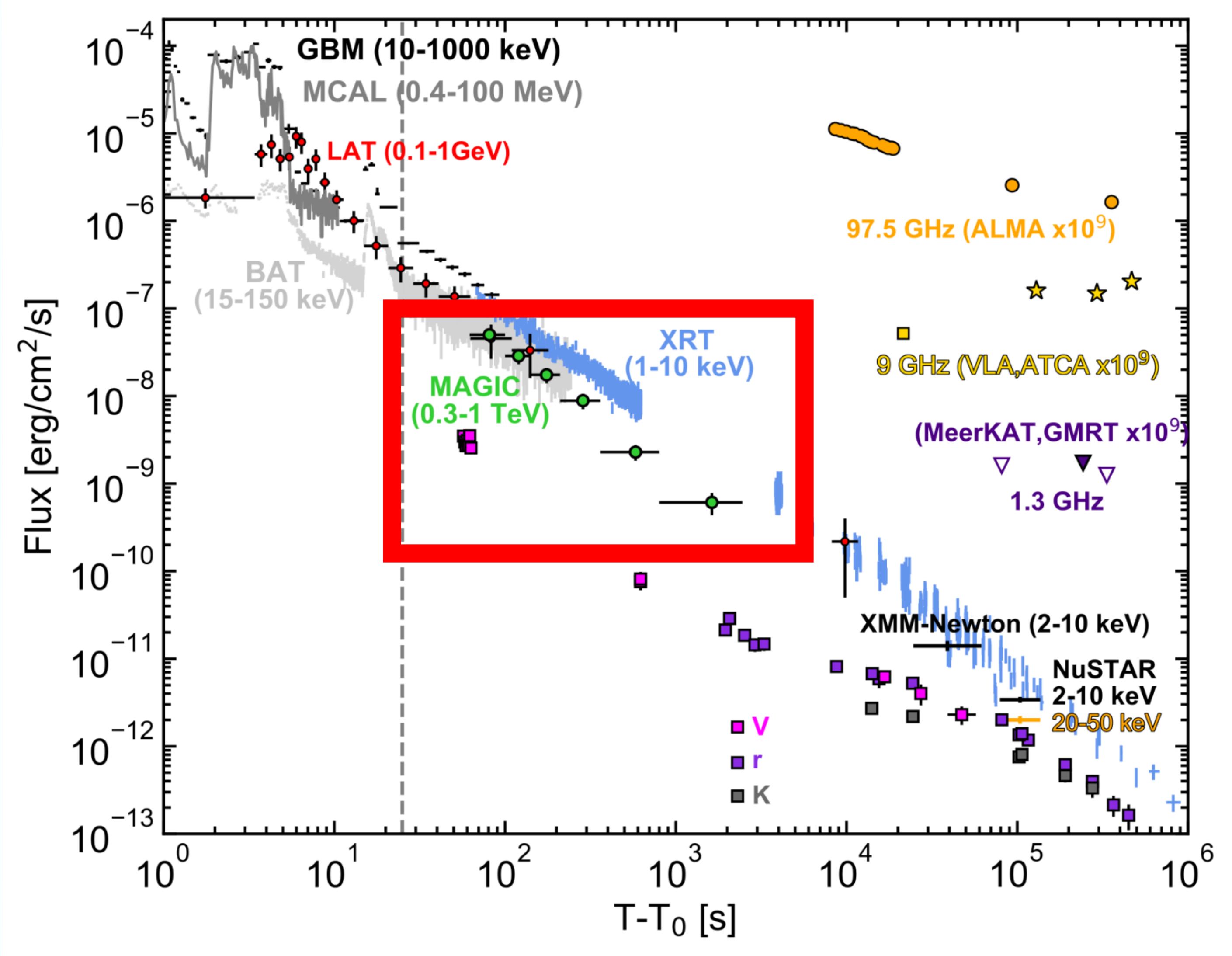


MAGIC Coll. et al., 2019

GRB 190114C – Light curve

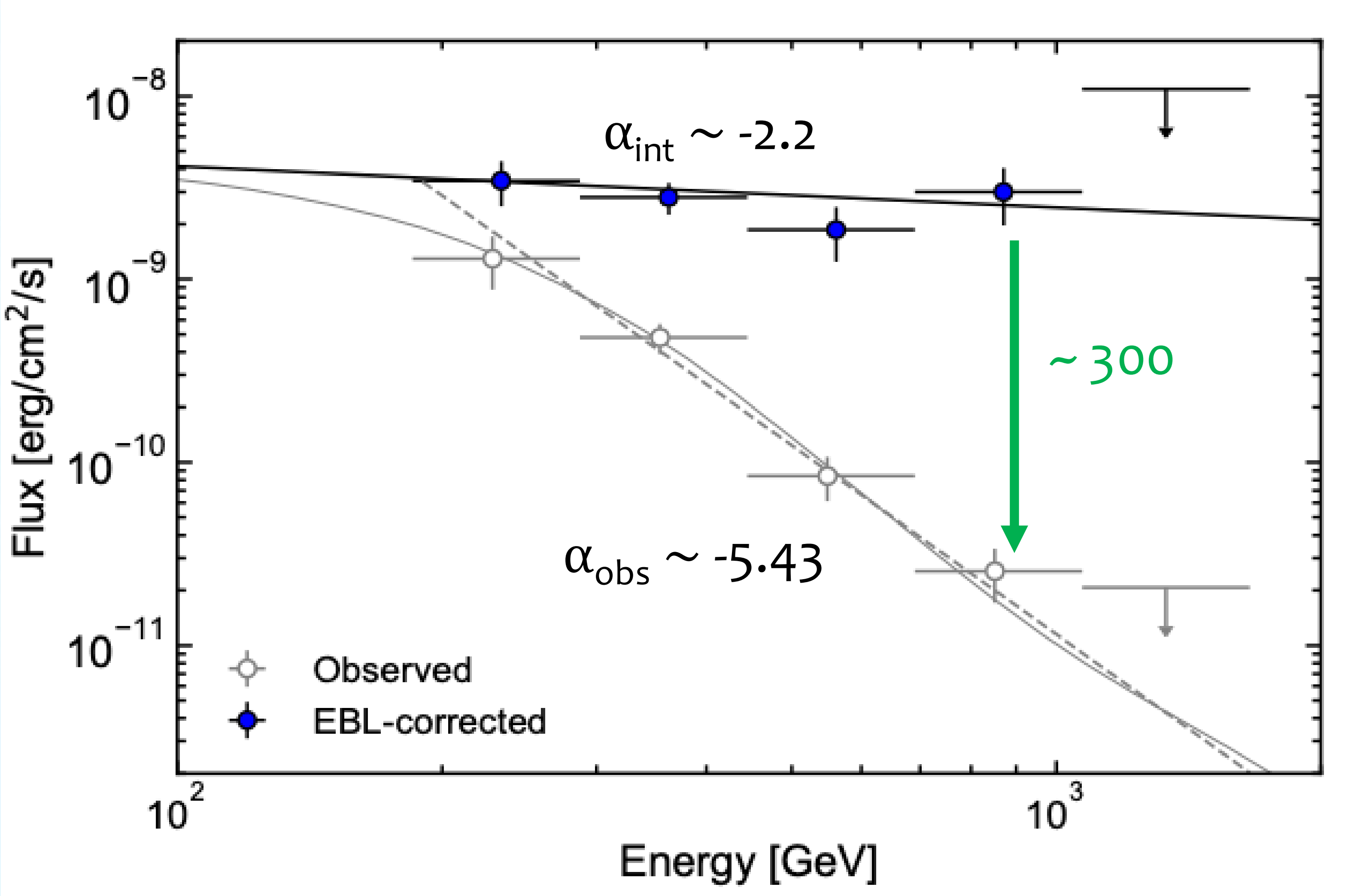
VHE light curve:

- No evidences for breaks, cut-offs or irregular variability → afterglow emission
- Similar decay and radiated power in soft X-ray – GeV and TeV domain



MAGIC Coll. et al., 2019

GRB 190114C – VHE SED



MAGIC Coll. et al., 2019

GRB 190114C -- interpretation

Acceleration timescale (Bohm level)

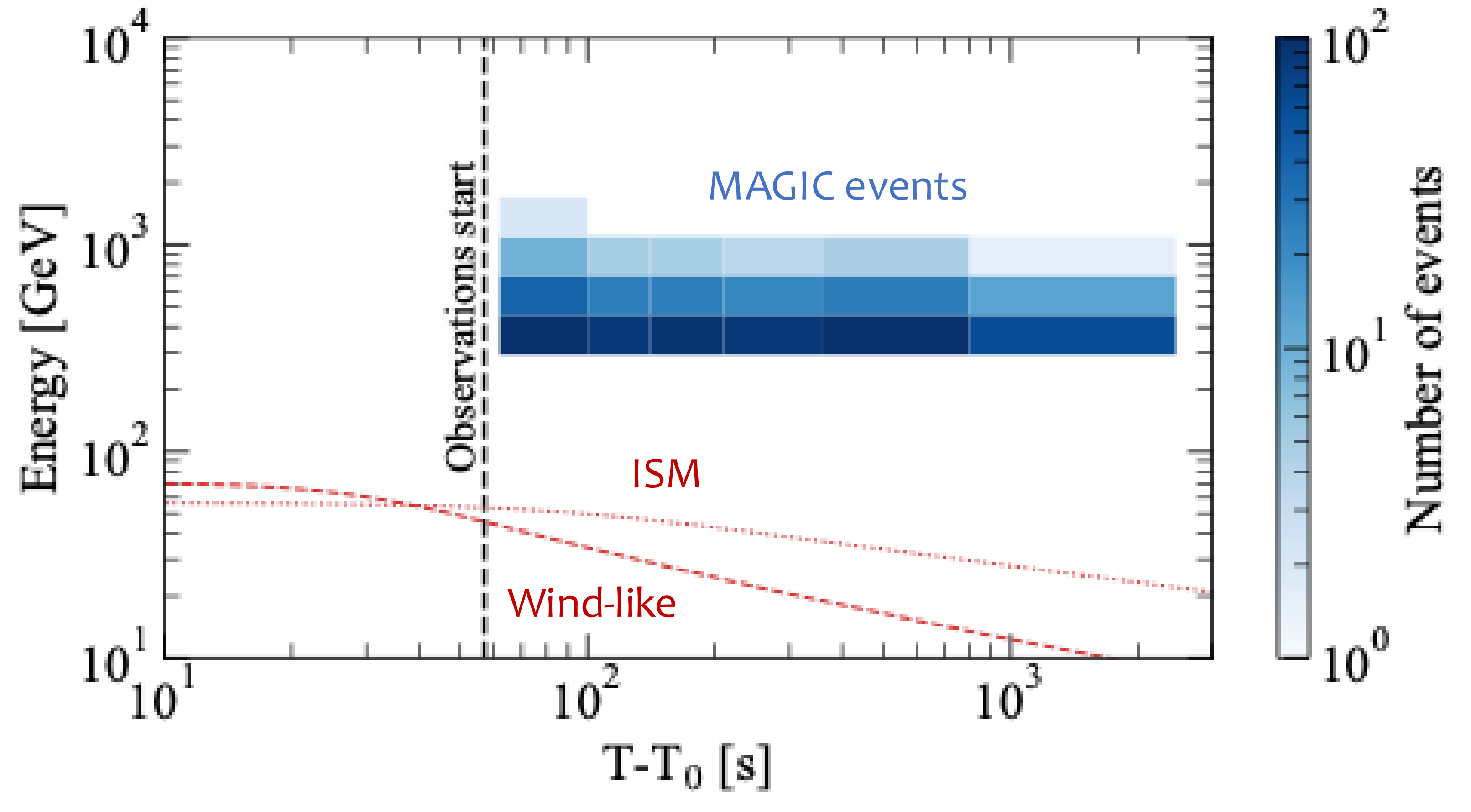
$$t'_L = \frac{r_L}{c} = \frac{\gamma m_e c}{eB'}$$

e-Synchrotron cooling timescale

$$t'_{cool} = \frac{E'}{|dE'/dt'|} = \frac{6\pi m_e c}{\gamma \sigma_T B'^2}$$

Synchrotron burnoff limit

$$\varepsilon_{sync,max} \sim 100 \left(\frac{\Gamma_b}{1000}\right) \text{GeV}$$



MAGIC Coll. et al., 2019

GRB 190114C -- interpretation

X-ray + GeV + TeV

↓

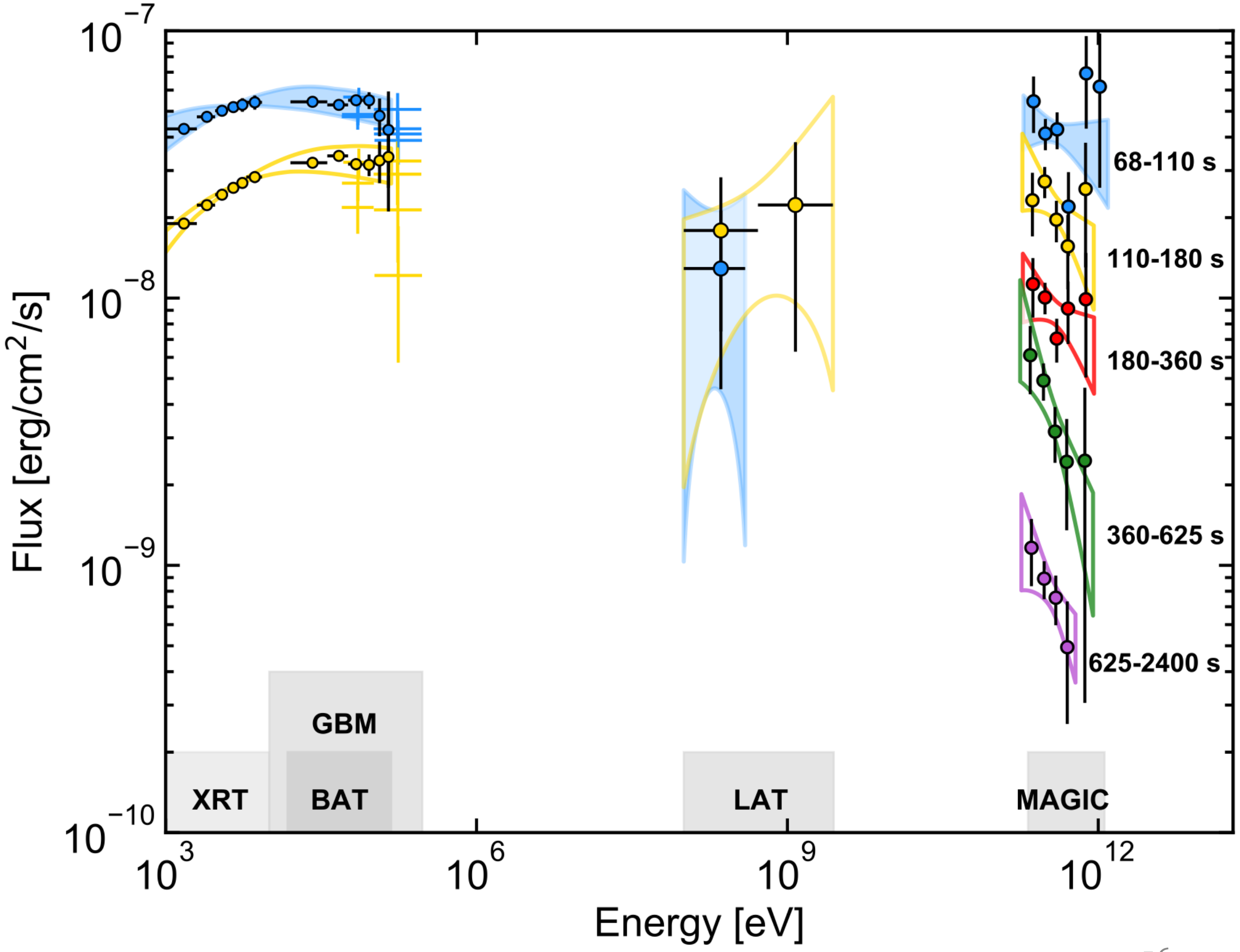
Spectral hardening for E > 0.2 TeV

↓

Can't be extention of Synchrotron component

↓

New emission component at VHE



MAGIC Coll. et al., 2019

GRB 190114C -- modeling

Synchrotron + Synchrotron Self-Compton (SSC) from external forward shock

Observed
No γ-γ opacity
EBL-deabsorbed

MAGIC soft spectrum:

- Klein-Nishina
- γ-γ internal absorption

GRB afterglow parameters:

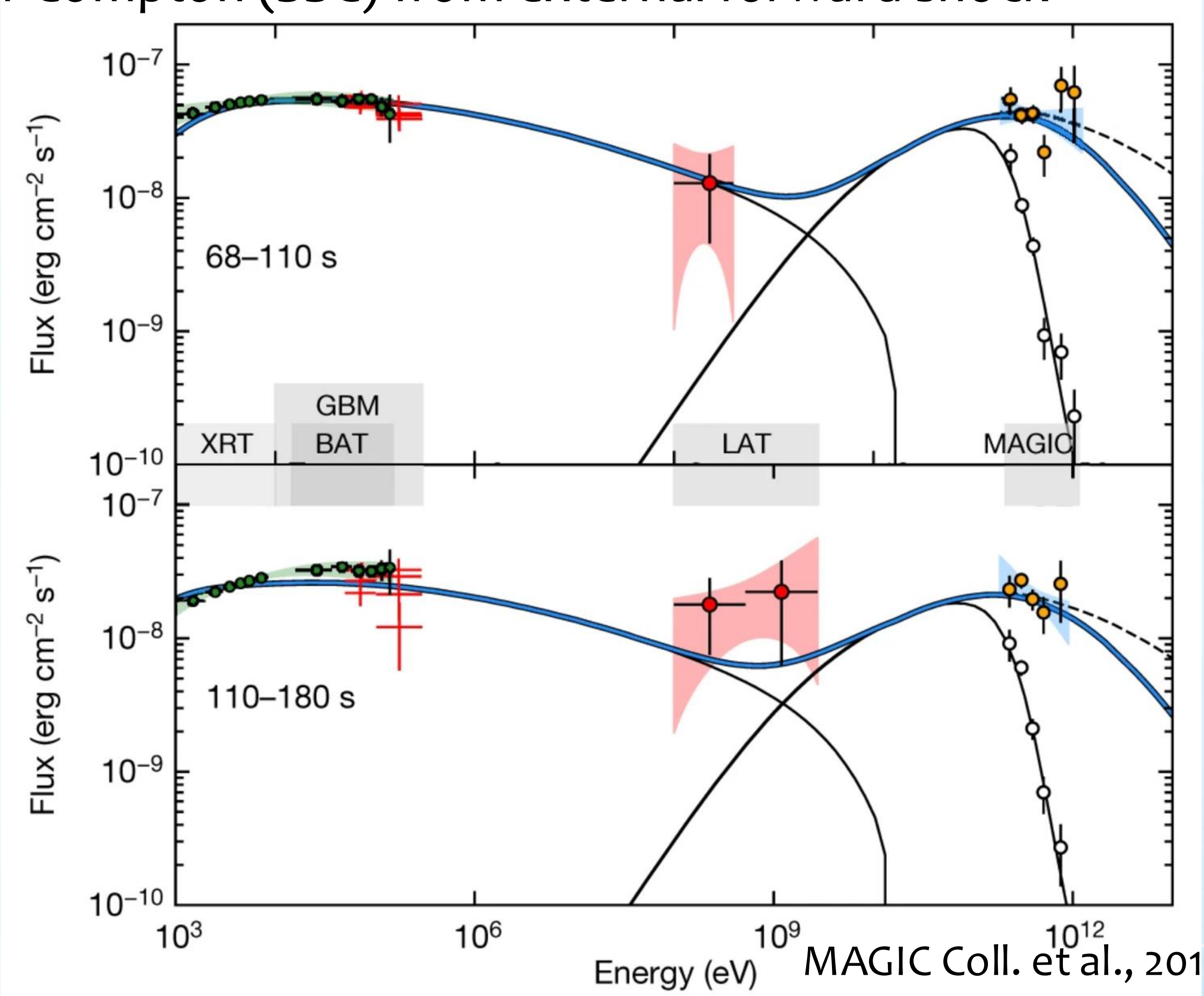
$E_k \gtrsim 3 \times 10^{53}$ erg

$\varepsilon_e \sim 0.05 - 0.15$

$\varepsilon_b \sim 0.05 - 1 \times 10^{-3}$

$n \sim 0.5\text{-}5\ cm^{-3}$

$p \sim 2.4 - 2.6$



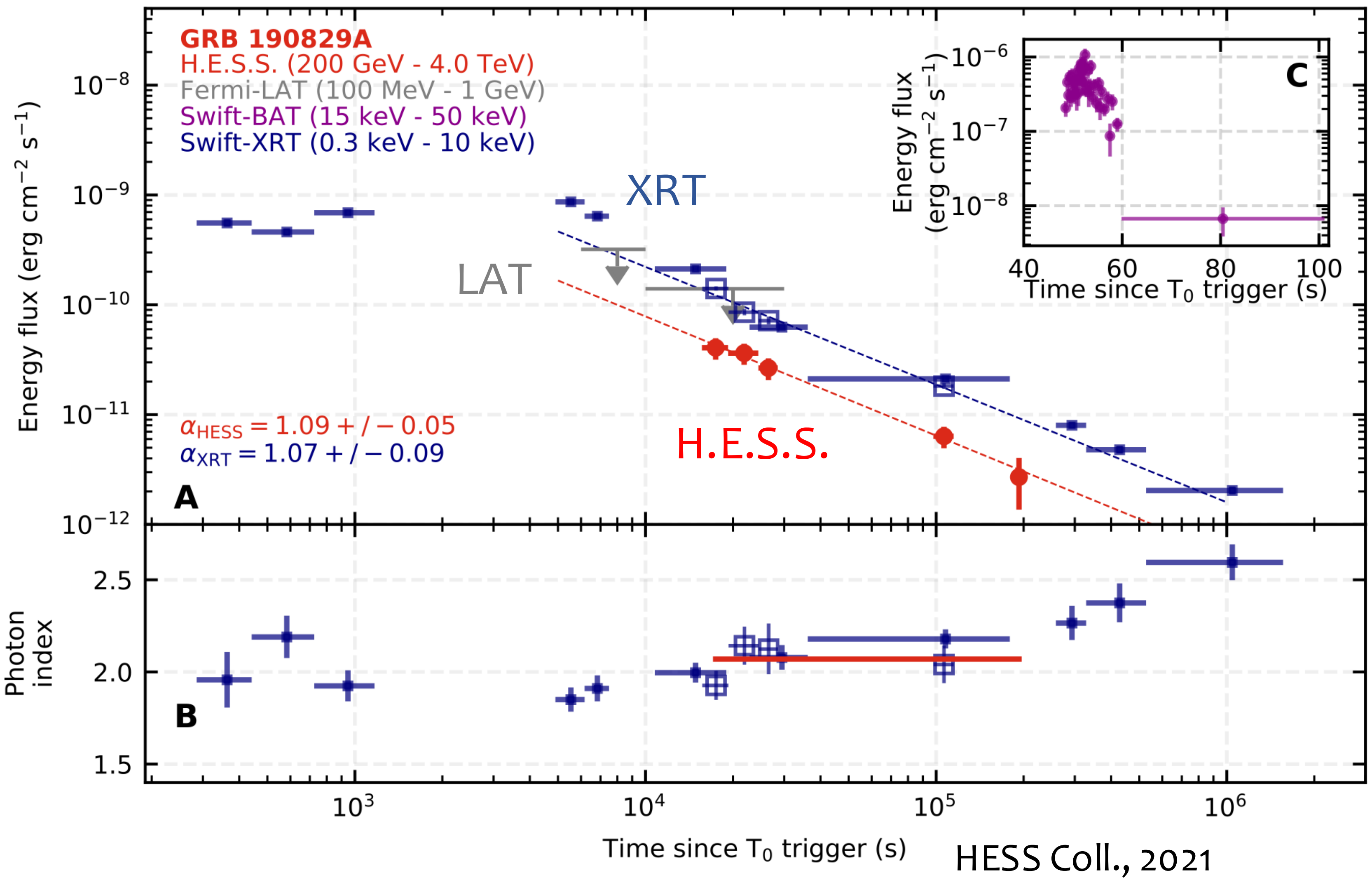
MAGIC Coll. et al., 2019

GRB 190829A

- $E_{\gamma,iso} \sim 2.0 \times 10^{50}$ erg
- z = 0.079

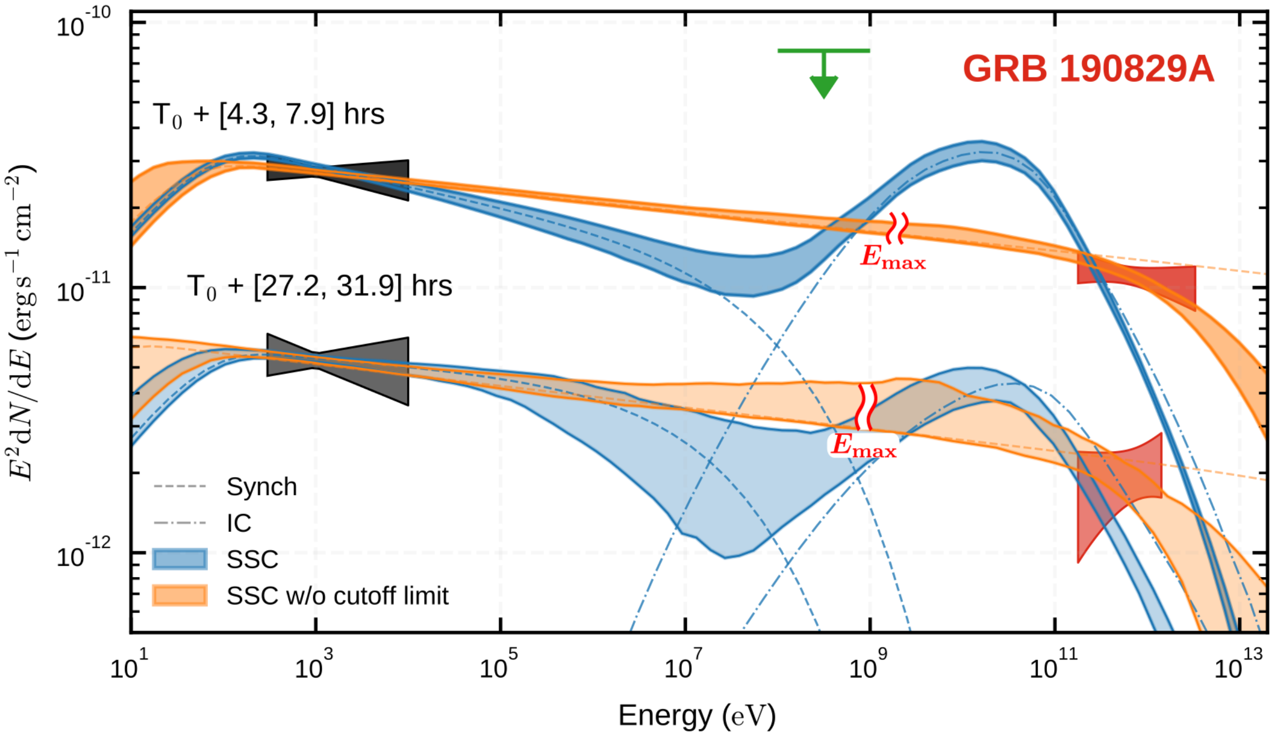
H.E.S.S. detection info:

- $T_{obs} \sim 4.3 - 55.9$ hrs
- 21.7σ, 5.5σ, 2.4σ,
- 0.18 – 3.3 TeV energy range

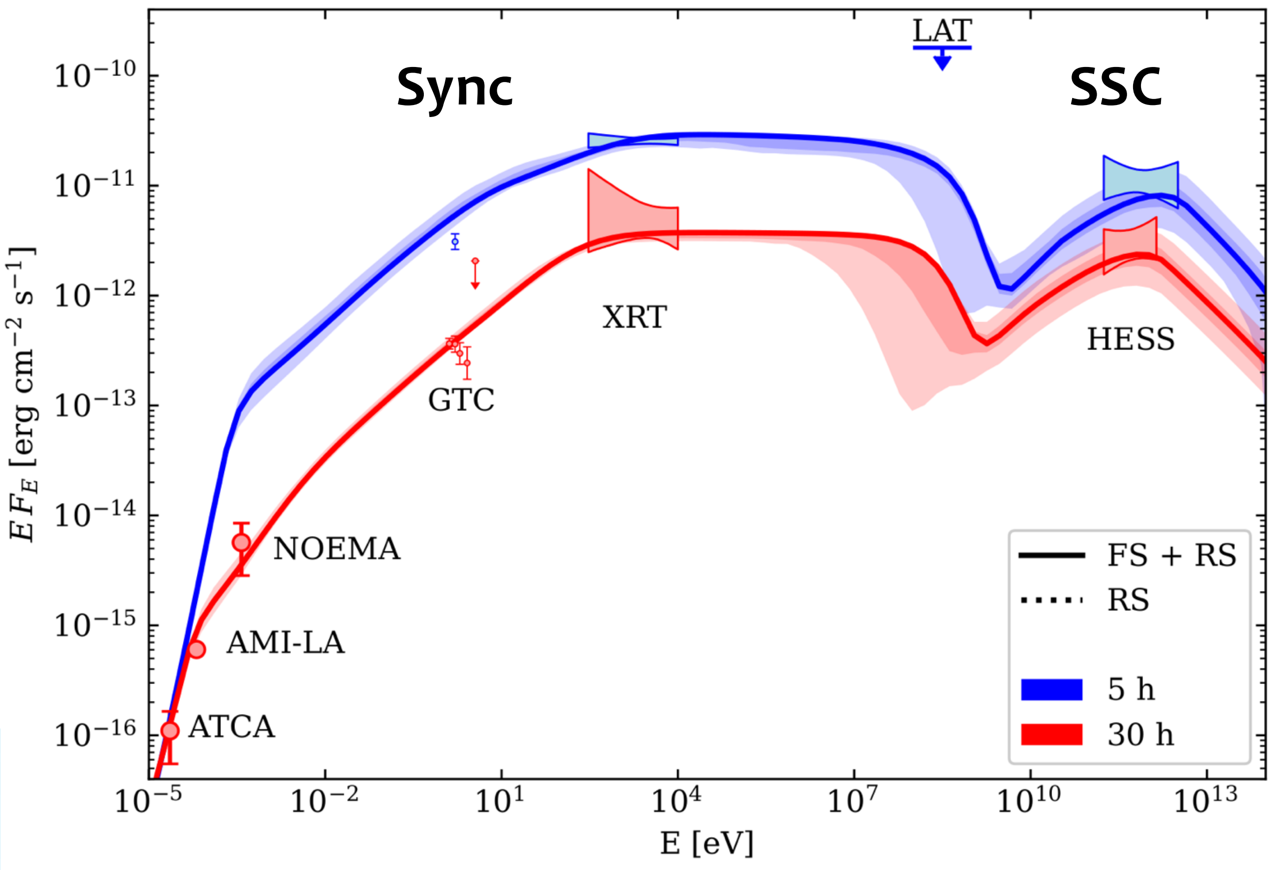


HESS Coll., 2021

GRB 190829A



HESS Coll., 2021



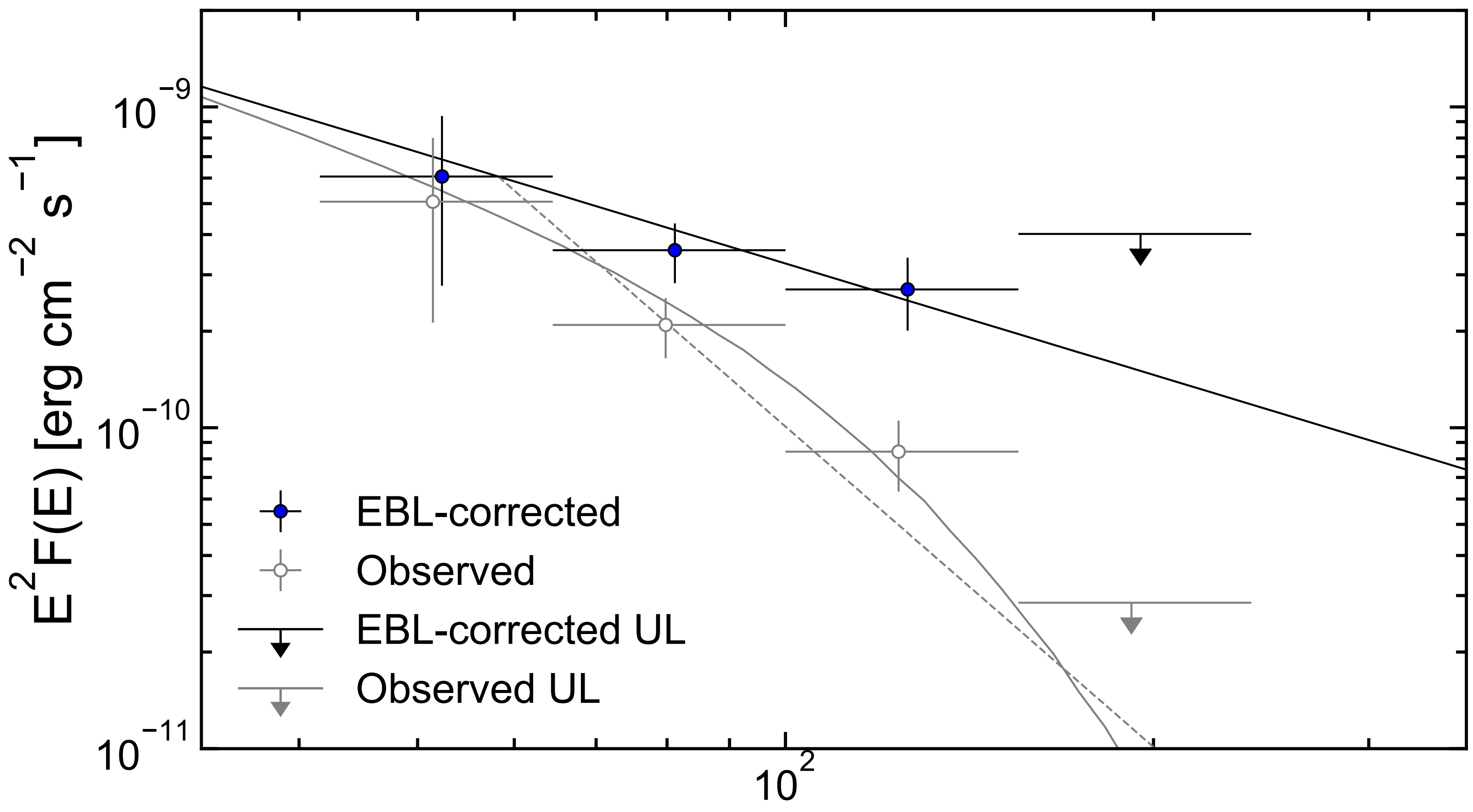
Salafia et al., 2021

GRB 201216C

- $E_{\gamma,iso} \sim 4.7 \times 10^{53}$ erg
- z = 1.1

MAGIC detection info:

- Tdelay ~ 56 s
- 6σ in 20 minutes
- 0.07 – 0.2 TeV energy range

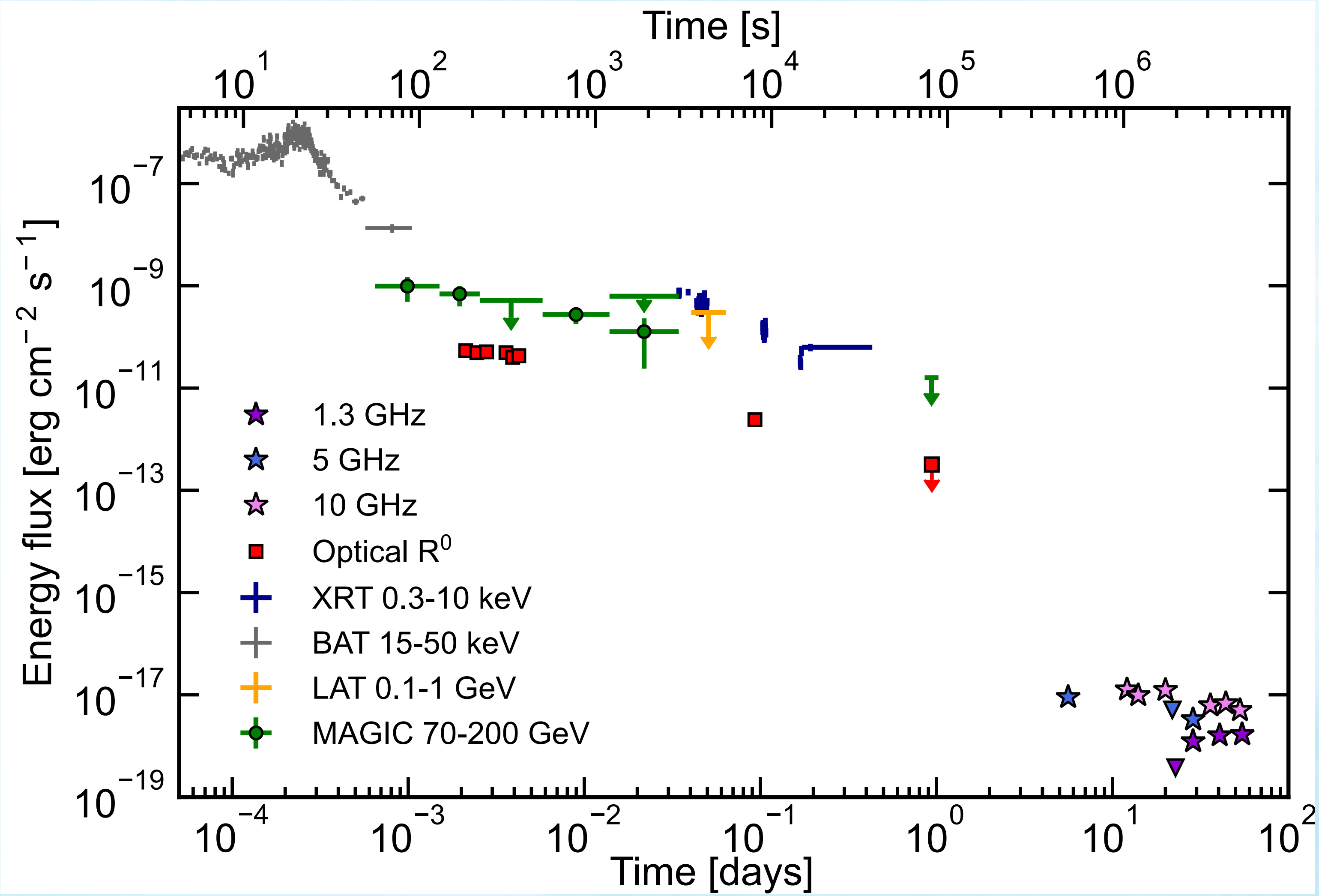


MAGIC Coll. et al., 2023

GRB 201216C

Parameter	Range	Best fit value
E_k [erg]	$10^{50} - 10^{54}$	4×10^{53}
θ_{jet} [degrees]	$0.5 - 3$	1
Γ_0	80-300	180
n_0 [cm^{-3}] $(s = 0)$	$10^{-2} - 10^{2}$	-
$A_\star$ $(s = 2)$	$10^{-2} - 10^{2}$	2.5×10^{-2}
p	2.05 - 2.6	2.1
ϵ_e	0.01-0.9	0.08
ϵ_B	$10^{-7} - 10^{-1}$	2.5×10^{-3}

Strong indication in favour of a wind-like medium



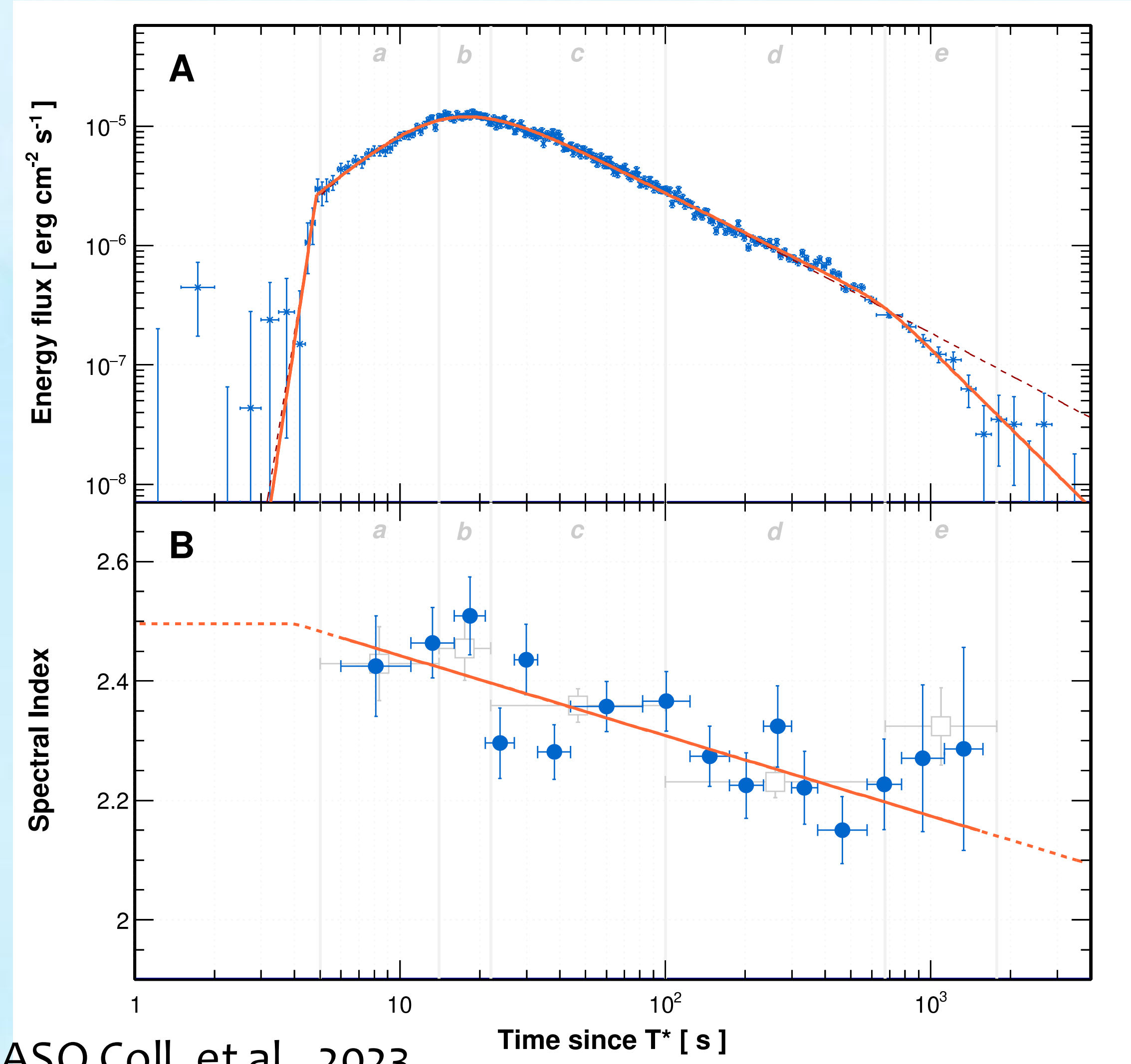
MAGIC Coll. et al., 2023

GRB 221009A

- $E_{\gamma,iso}$ 1 x 10^{55} erg
- z = 0.15

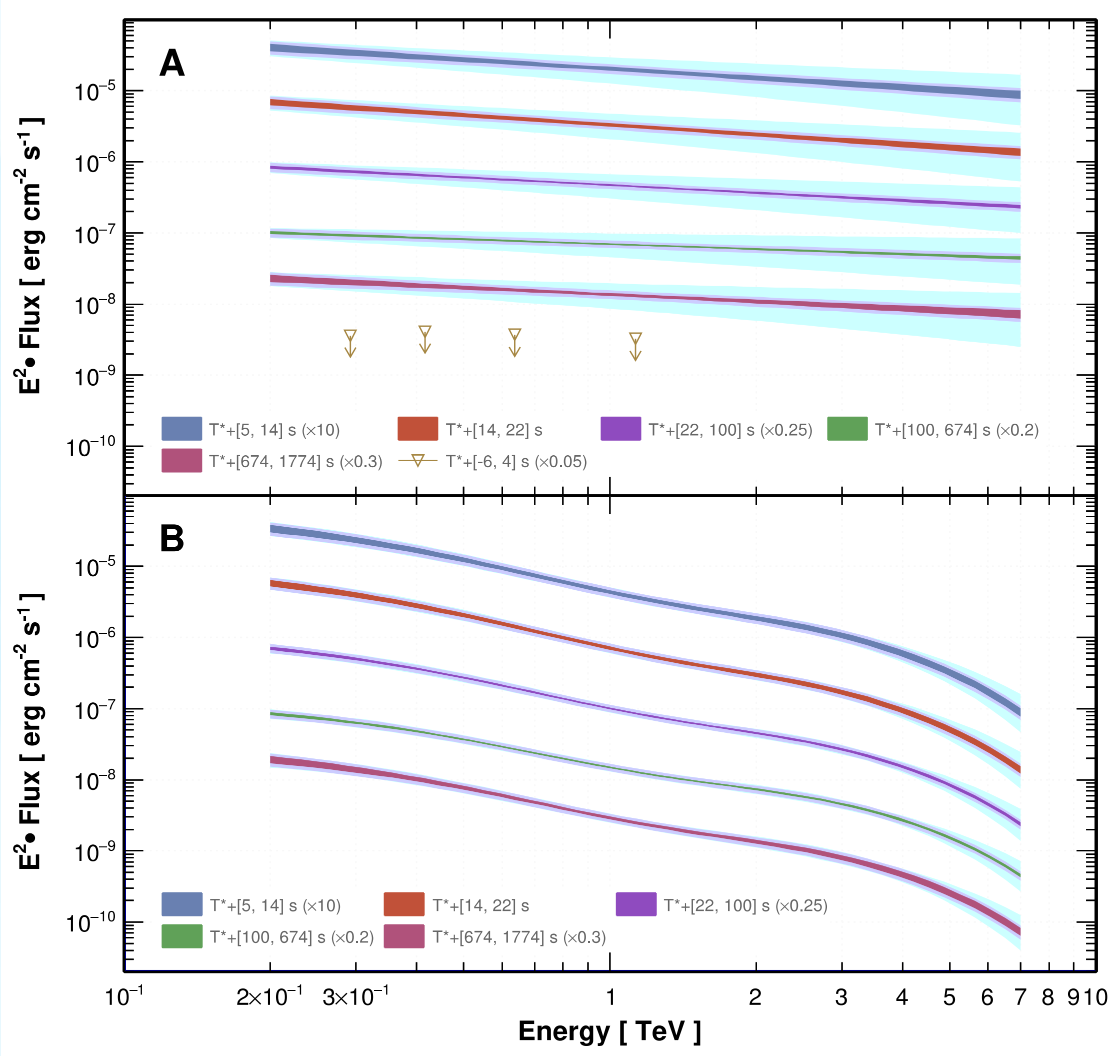
LHAASO detection info:

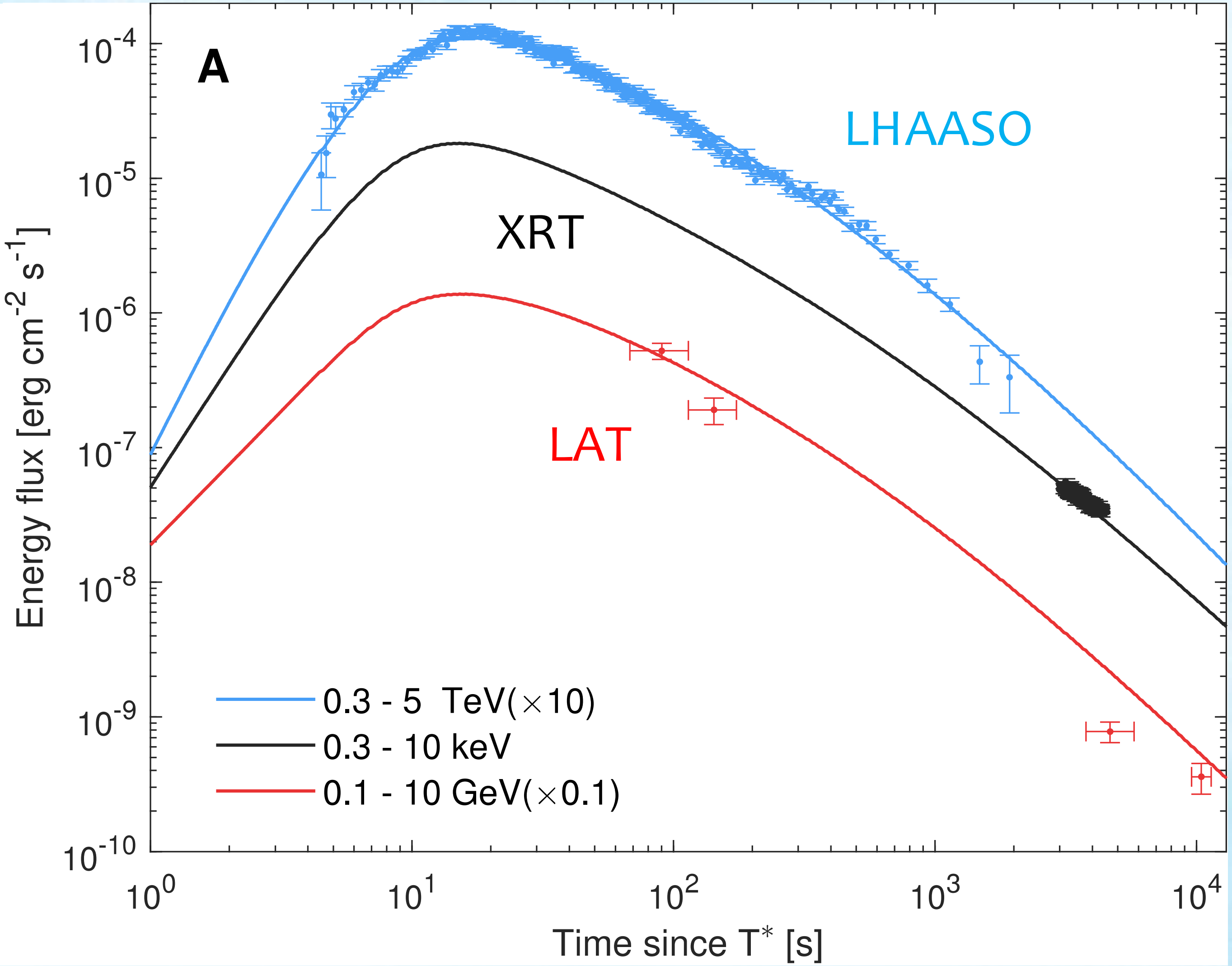
- > 250σ in 230 – 3000 s
- 0.3 – 13 TeV energy range



LHAASO Coll. et al., 2023

GRB 221009A





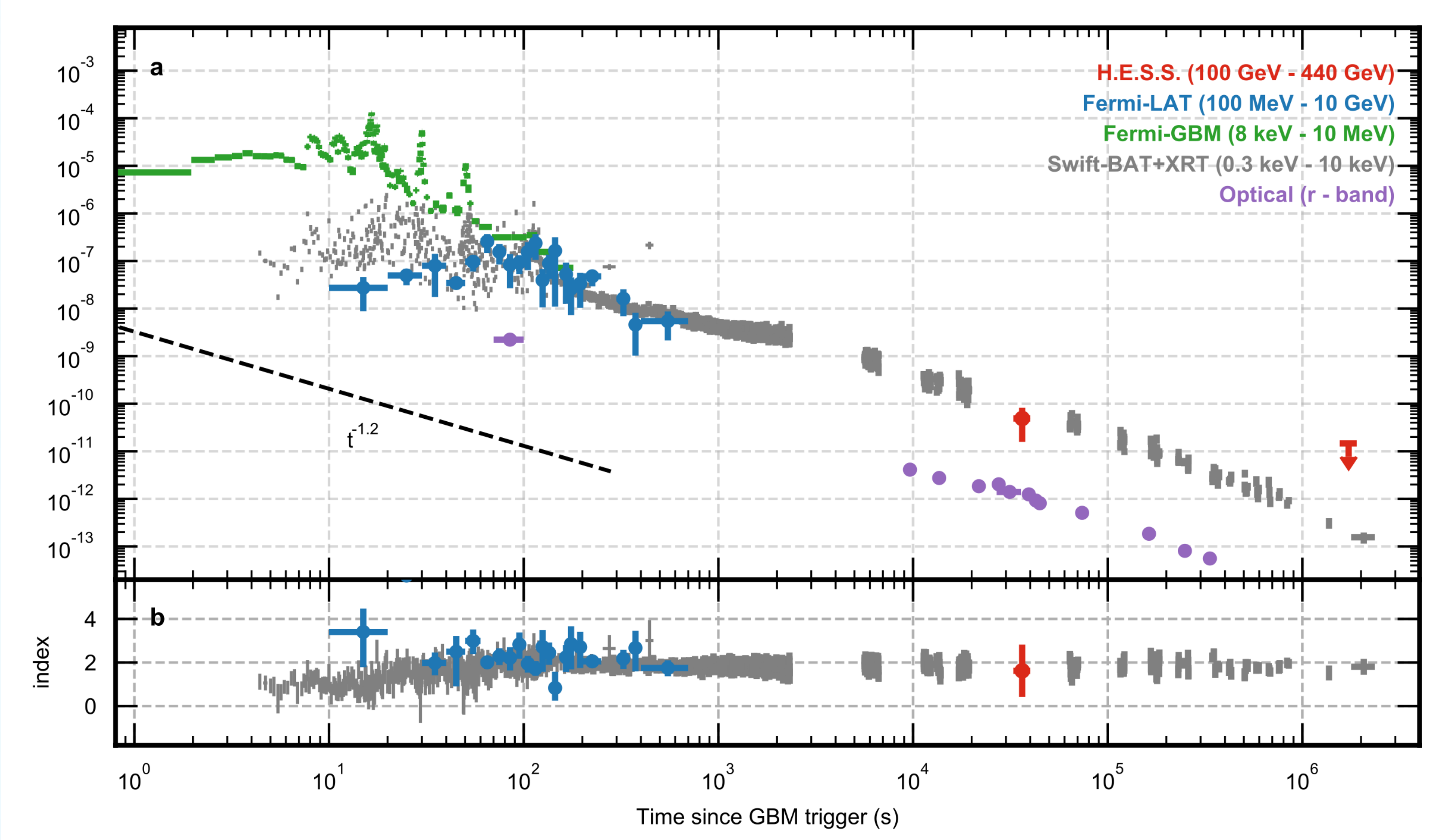
LHAASO Coll. et al., 2023

GRB 180720B

- Long GRB
- $E_{\gamma,iso} \sim 6.0 \times 10^{53}$ erg
- z = 0.654

H.E.S.S. detection info:

- Tdelay ~ 10 hrs
- > 5.3σ in 2 hrs
- 0.1 – 0.44 TeV energy range



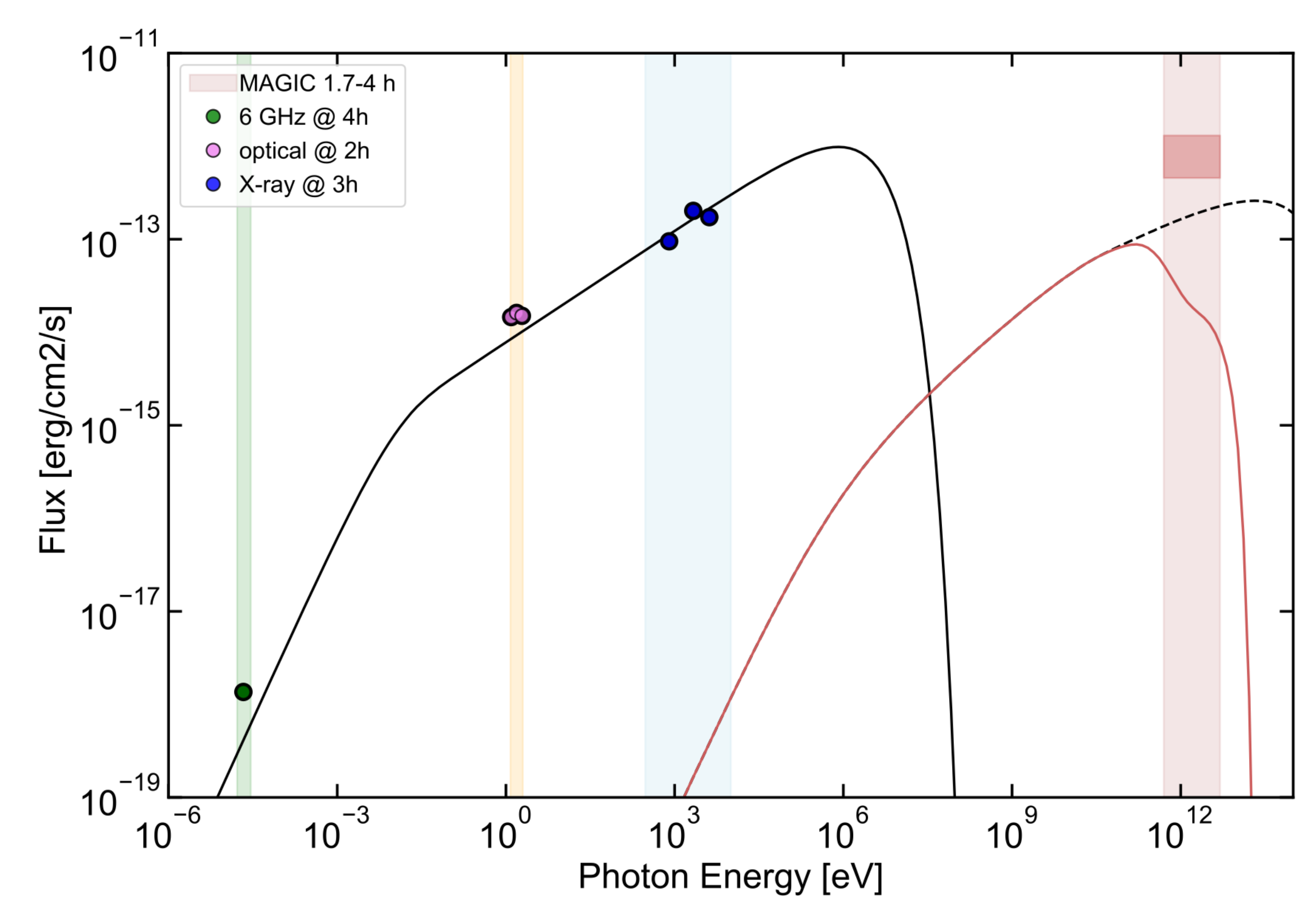
HESS Coll., 2019

GRB 160821B

- short GRB
- $E_{\gamma,iso} \sim 1.2 \times 10^{49}$ erg
- z = 0.162

MAGIC info:

- Tdelay ~ 24 s
- 3σ in 4 hrs
- 0.5 - 5 TeV energy range
- moon conditions, dedicated analysis



MAGIC Coll., 2021

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GRB 190114C

Time bin [seconds after T_0]	Energy flux [$\mathrm{erg\,cm^{-2}\,s^{-1}}$]	Spectral index
62 – 100	$[5.64 \pm 0.90\,(\mathrm{stat})\,^{+3.24}_{-3.22}\,(\mathrm{sys})] \cdot 10^{-8}$	$-1.86\,^{+0.36}_{-0.40}\,(\mathrm{stat})\,^{+0.12}_{-0.21}\,(\mathrm{sys})$
100 – 140	$[3.31 \pm 0.67\,(\mathrm{stat})\,^{+2.71}_{-1.84}\,(\mathrm{sys})] \cdot 10^{-8}$	$-2.15\,^{+0.43}_{-0.48}\,(\mathrm{stat})\,^{+0.25}_{-0.32}\,(\mathrm{sys})$
140 – 210	$[1.89 \pm 0.36\,(\mathrm{stat})\,^{+1.72}_{-0.94}\,(\mathrm{sys})] \cdot 10^{-8}$	$-2.31\,^{+0.47}_{-0.54}\,(\mathrm{stat})\,^{+0.15}_{-0.22}\,(\mathrm{sys})$
210 – 361.5	$[7.54 \pm 1.60\,(\mathrm{stat})\,^{+6.46}_{-4.41}\,(\mathrm{sys})] \cdot 10^{-9}$	$-2.53\,^{+0.53}_{-0.62}\,(\mathrm{stat})\,^{+0.22}_{-0.24}\,(\mathrm{sys})$
361.5 – 800	$[3.10 \pm 0.70\,(\mathrm{stat})\,^{+1.20}_{-2.36}\,(\mathrm{sys})] \cdot 10^{-9}$	$-2.41\,^{+0.51}_{-0.65}\,(\mathrm{stat})\,^{+0.27}_{-0.34}\,(\mathrm{sys})$
800 – 2454	$[4.54 \pm 2.04\,(\mathrm{stat})\,^{+7.66}_{-1.96}\,(\mathrm{sys})] \cdot 10^{-10}$	$-3.10\,^{+0.87}_{-1.25}\,(\mathrm{stat})\,^{+0.75}_{-0.24}\,(\mathrm{sys})$
62 – 2454 (time integrated)	-	$-2.22\,^{+0.23}_{-0.25}\,(\mathrm{stat})\,^{+0.21}_{-0.26}\,(\mathrm{sys})$

GRB 190114C

Time bin [seconds after T_0]	D11	F08	FI10	G12
62 – 100	$-1.86^{+0.36}_{-0.40}$	$-2.04^{+0.36}_{-0.40}$	$-1.81^{+0.36}_{-0.40}$	$-1.95^{+0.36}_{-0.39}$
100 – 140	$-2.15^{+0.43}_{-0.48}$	$-2.32^{+0.43}_{-0.48}$	$-2.09^{+0.43}_{-0.48}$	$-2.23^{+0.42}_{-0.48}$
140 – 210	$-2.31^{+0.47}_{-0.54}$	$-2.48^{+0.47}_{-0.54}$	$-2.25^{+0.47}_{-0.54}$	$-2.39^{+0.47}_{-0.53}$
210 – 361.5	$-2.53^{+0.53}_{-0.62}$	$-2.69^{+0.52}_{-0.61}$	$-2.46^{+0.52}_{-0.61}$	$-2.60^{+0.52}_{-0.61}$
361.5 – 800	$-2.41^{+0.51}_{-0.65}$	$-2.58^{+0.51}_{-0.64}$	$-2.34^{+0.51}_{-0.64}$	$-2.49^{+0.51}_{-0.64}$
800 – 2454	$-3.10^{+0.87}_{-1.25}$	$-3.20^{+0.83}_{-1.20}$	$-2.96^{+0.83}_{-1.20}$	$-3.08^{+0.82}_{-1.19}$
62 – 2454 (time integrated)	$-2.22^{+0.23}_{-0.25}$	$-2.39^{+0.23}_{-0.25}$	$-2.15^{+0.23}_{-0.25}$	$-2.29^{+0.23}_{-0.24}$

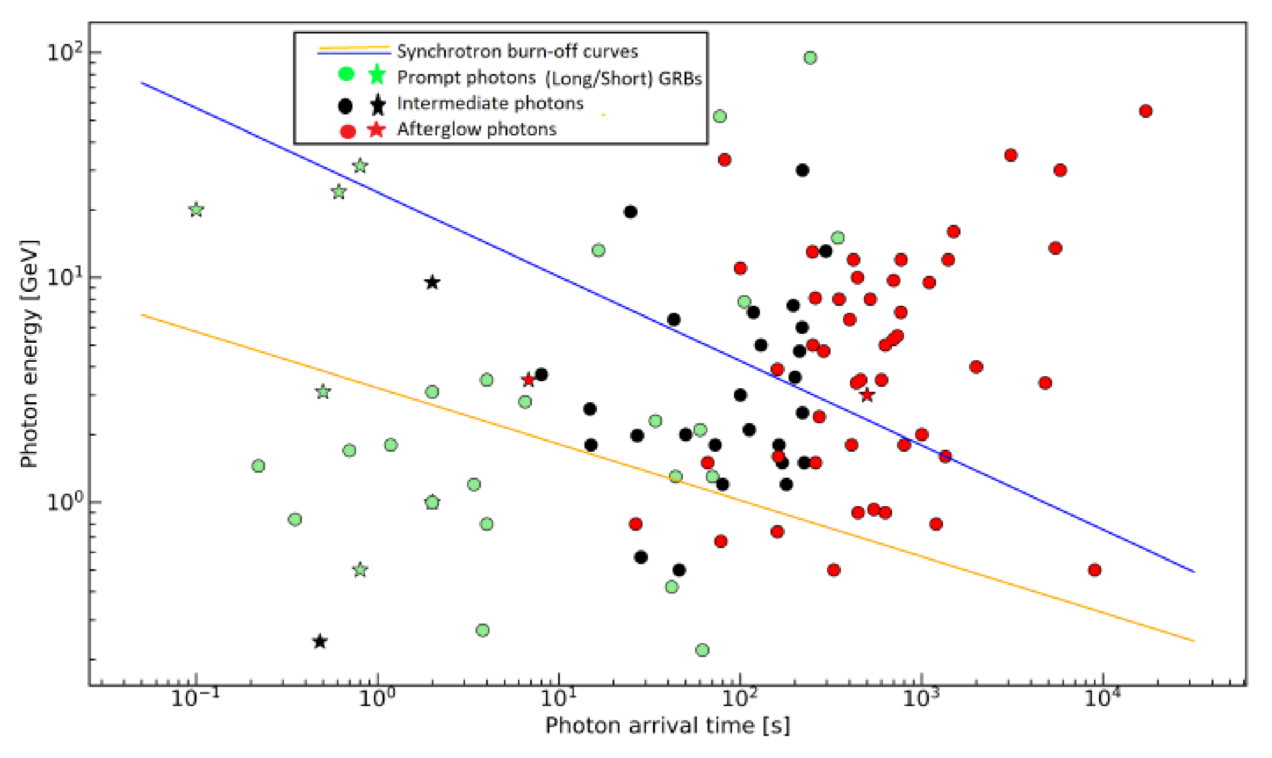
GRB 190114C

Event	redshift	T_{delay} (s)	Zenith angle (deg)
GRB 061217	0.83	786.0	59.9
GRB 100816A	0.80	1439.0	26.0
GRB 160821B	0.16	24.0	34.0
GRB 190114C	0.42	58.0	55.8

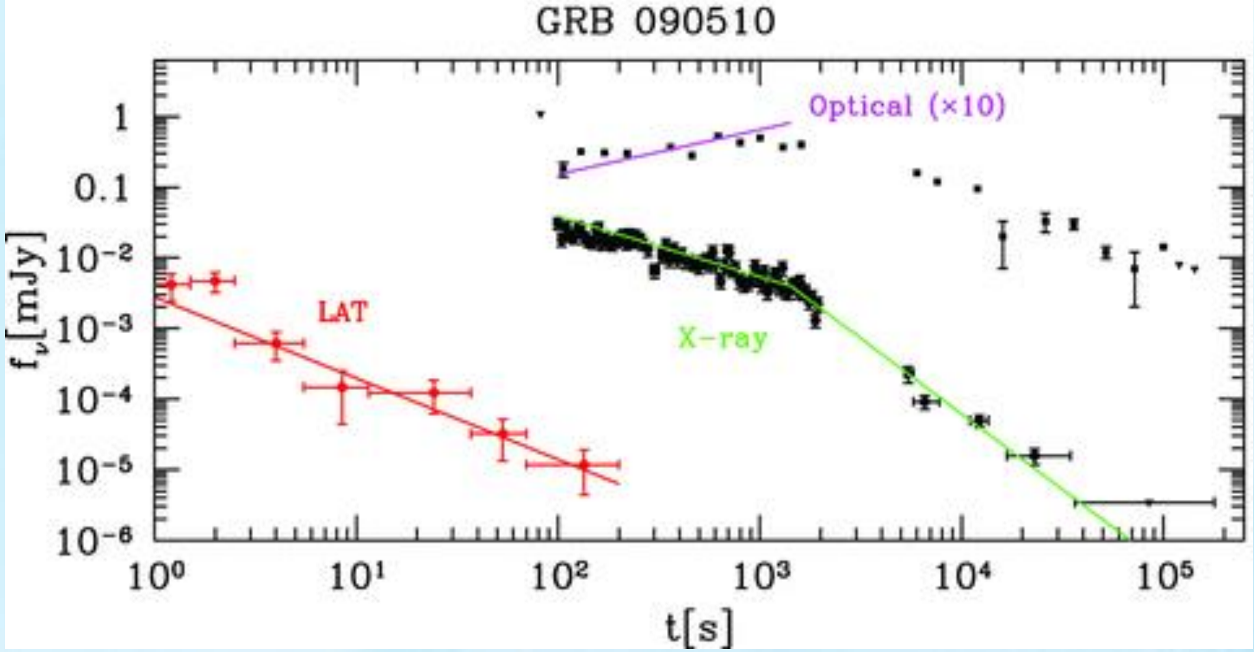
Theoretical expectations from GRBs in the VHE domain

HE emission (< 100 GeV)

- Almost consistent with synchrotron radiation (synchrotron burnoff limit)
- No spectral cut-off identified (shock microphysics uncertainties, non-uniform magnetic fields)



Nava, 2018



Kumar et al., 2010

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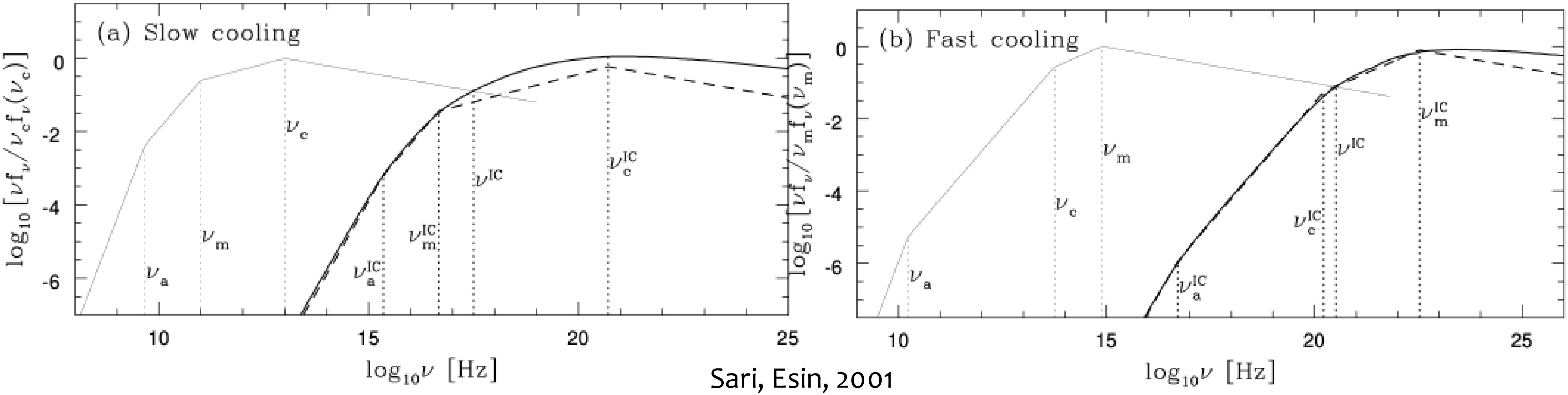
Theoretical expectations from GRBs in the VHE domain

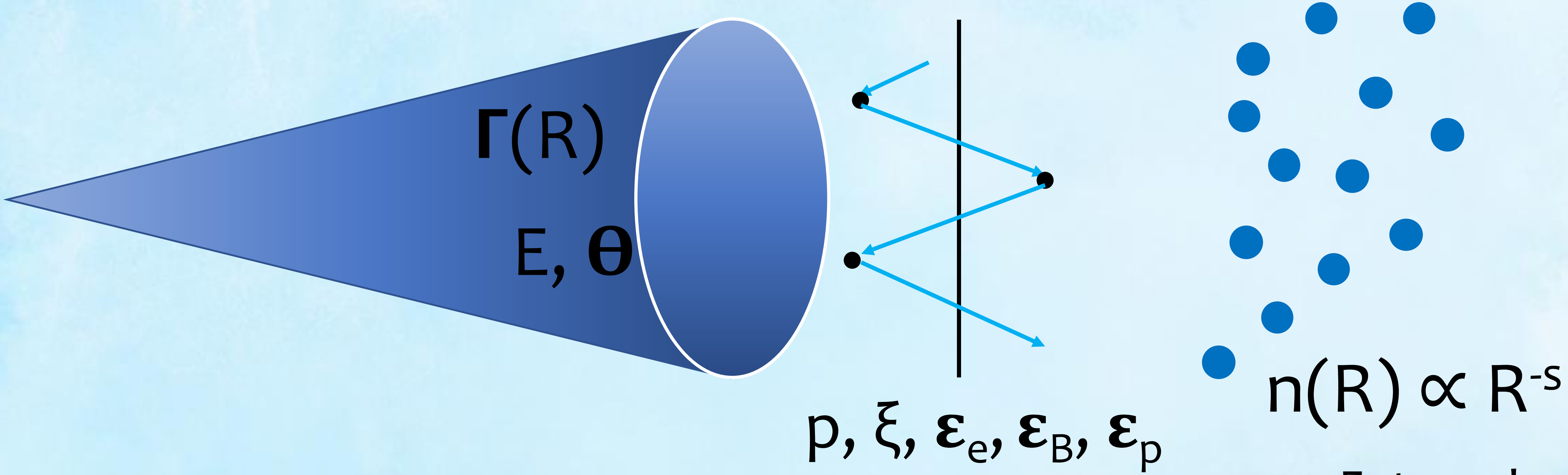
Synchrotron self-Compton (SSC) emission has been predicted for GRB afterglows: nature candidate for VHE domain (Meszaros et al. 1994; Zhang et al. 2001; Sari et al. 2001; Meszaros et al. 2004; Fan et al. 2008; Galli et al. 2008; Nakar et al. 2009; Xue et al. 2009; Piran et al. 2010)



Sari, Esin, 2001

Afterglow modeling: external forward shock scenario

Decelerating blastwave interacting with the circumburst external medium



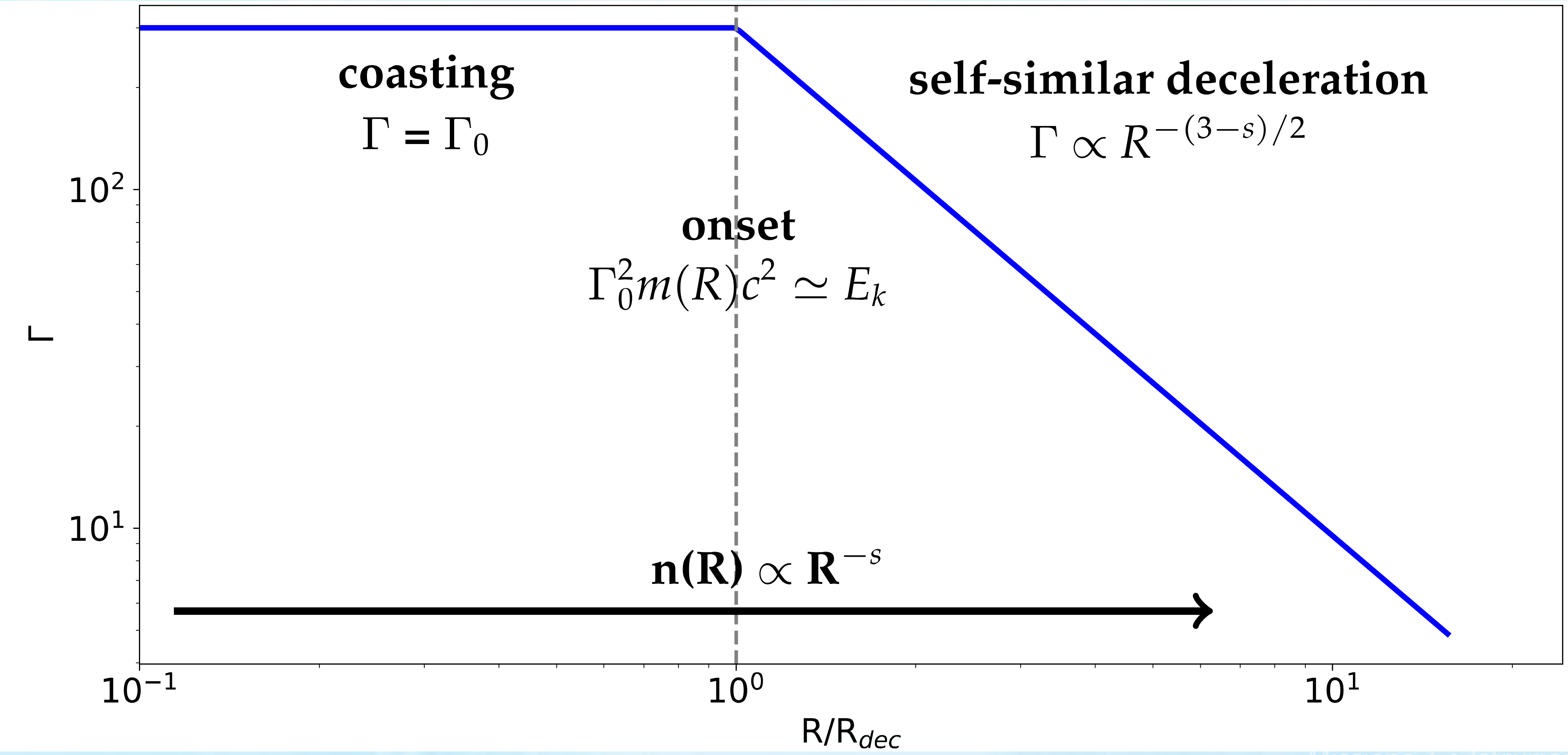
Jet structure and dynamics

Relativistic shock acceleration

External circumburst medium

Afterglow modeling: external forward shock scenario

Jet dynamics

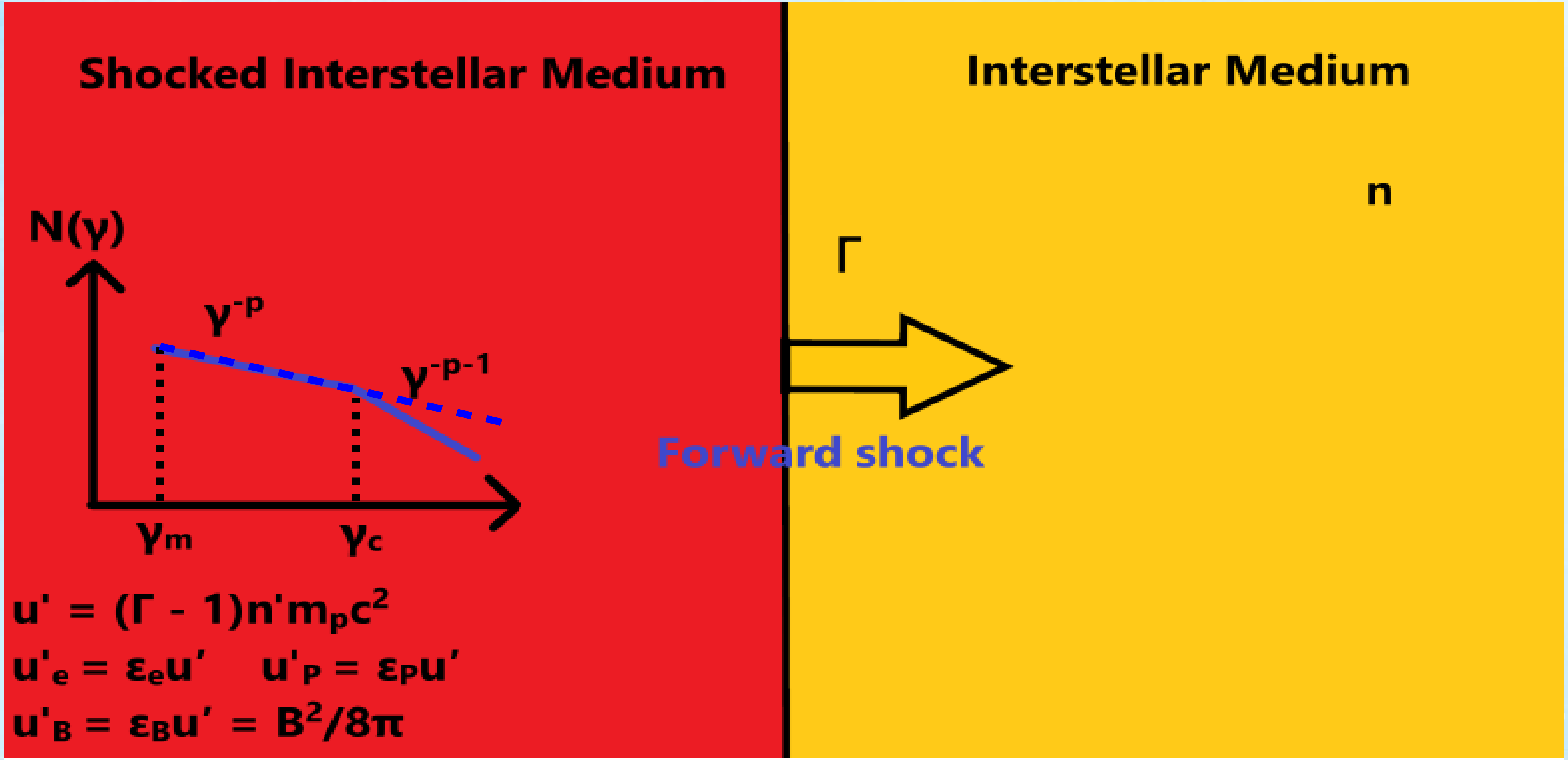


See Blandford & Mckee, 1976; Nava et al., 2014

Afterglow modeling: external forward shock scenario

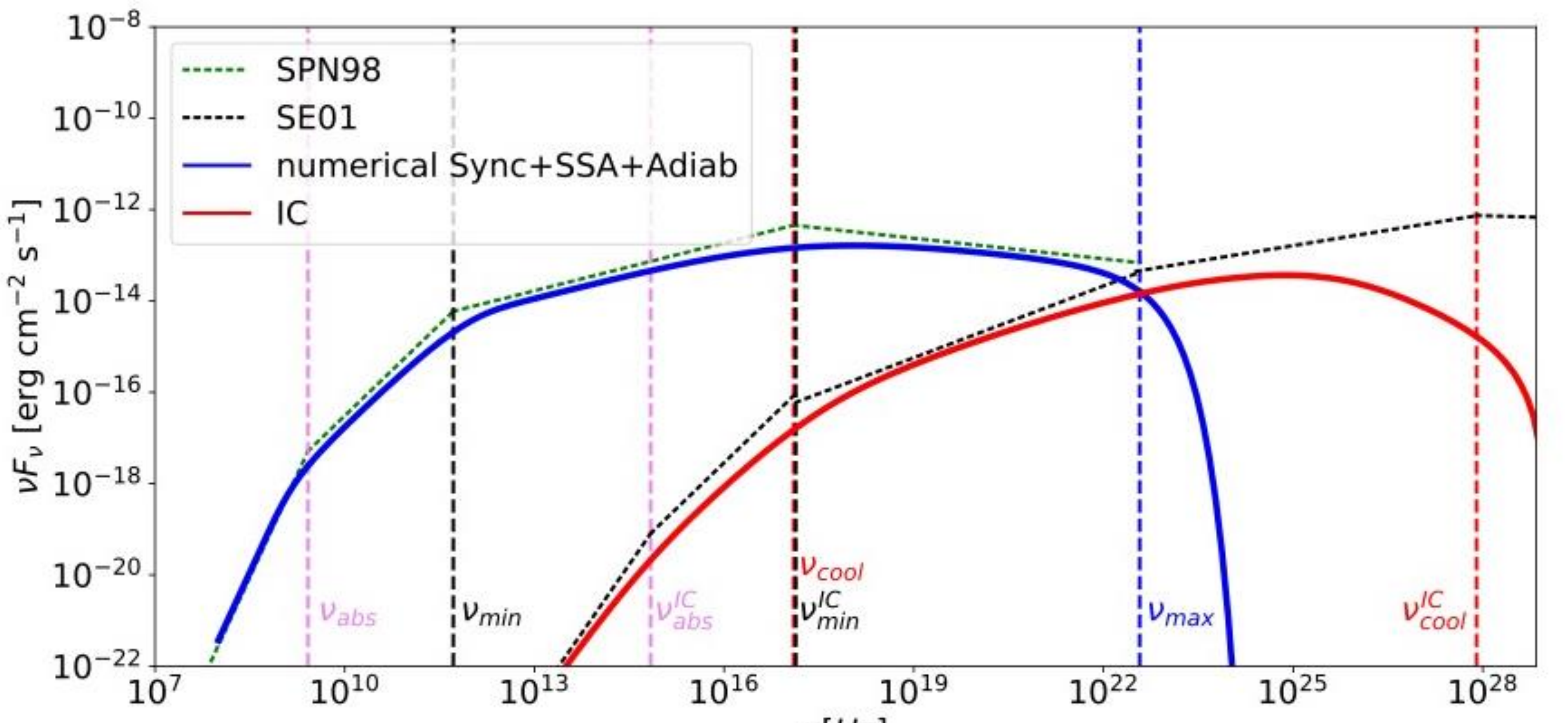
Relativistic shocks in GRB afterglow

See Sari et al. 1998, Panaitescu et al. 2000 Granot et al. 2002



Afterglow modeling: external forward shock scenario

See
Sari et al. 1998,
Panaitescu et al. 2000
Granot et al. 2002



DM, Nava, 2022

GRBs at VHE: impact on fundamental physics

Lorentz Invariance Violation (LIV) studies

$$\Delta t = s_\pm \frac{n+1}{2} D_n(z) \left(\frac{E}{E_{\mathrm{QG,n}}} \right)^n$$

Photon energy at the detector

$$D_n(z) = \frac{1}{H_0} \int_0^z \frac{(1+\zeta)^n}{\sqrt{\Omega_\Lambda + (1+\zeta)^3 \Omega_m}} d\zeta$$

$$\Delta t(E, \eta_1) = \eta_1 \cdot 17\ \mathrm{s/TeV} \cdot E$$
$$\Delta t(E, \eta_2) = \eta_2 \cdot 25\ \mathrm{s/TeV^2} \cdot E^2$$

Assuming **η_n = 1** a **1 TeV** gamma should have a **time delay** of
- **17 seconds** (n=1)
- **25 seconds** (n=2)

Where we have defined **η** as the **ratio** between the **Planck energy** and the **Q.G. energy scale**

$$\eta_1 = s_\pm \cdot E_{\mathrm{Pl}}/E_{\mathrm{QG,1}} \qquad \eta_2 = 10^{-16} \cdot s_\pm \cdot E_{\mathrm{Pl}}^2/E_{\mathrm{QG,2}}^2$$

From the GRB 190114C data we got the following 95% lower limits on the Q.G. energy scale

	superl.	subl.	
$E_{QG,1}$ [10^{19} GeV]	0.55	0.58	← linear scenario
$E_{QG,2}$ [10^{10} GeV]	5.6	6.3	← quadratic scenario

95% lower limit on the Q.G. energy scale for linear scenario / quadratic scenario

$$E_{Pl} \sim 1.2 \cdot 10^{19}\ \mathrm{GeV}$$

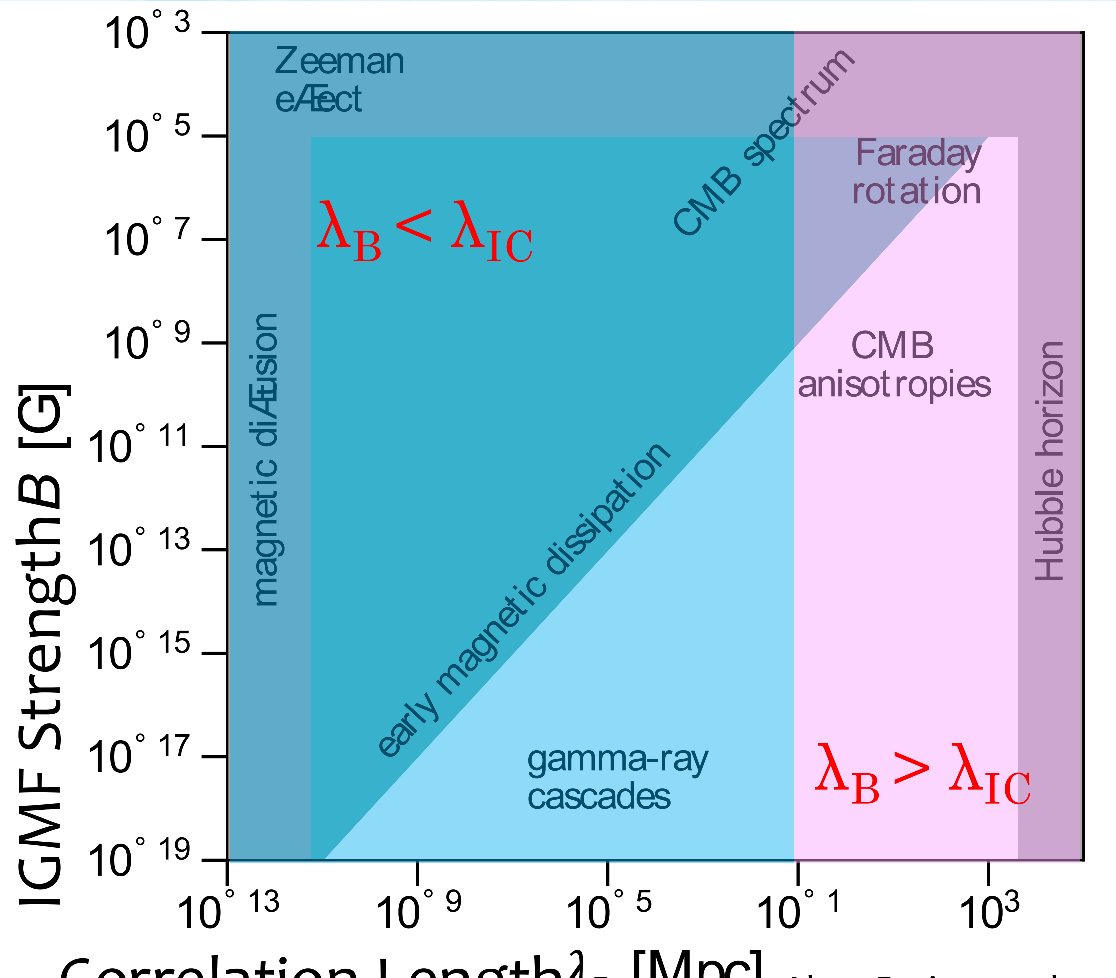
COMPARISON WITH PREVIOUS LIMITS

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)

D'Amico, ICRC2021

Intergalactic Magnetic field (IGMF) studies



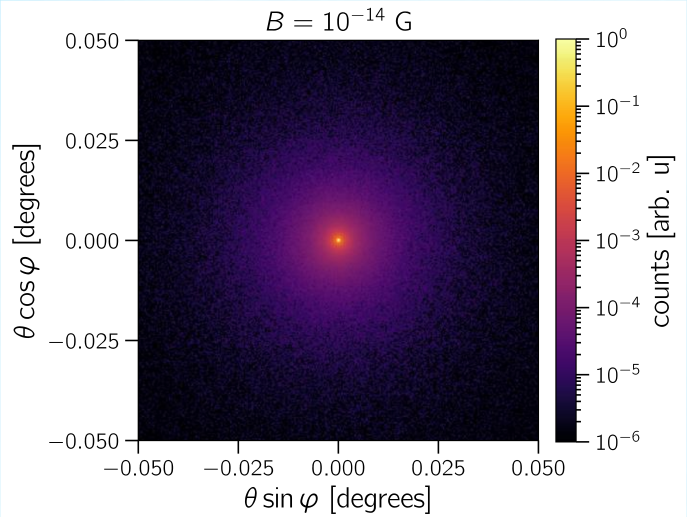
Alves Batista et al. 2022

Results on IGMF are typically given considering two regimes:

- Long correlation length ($\lambda_B >> \lambda_{IC}$)
(motion in homogeneous B, ballistic $e^{\pm}$)
- Short correlation length ($\lambda_B << \lambda_{IC}$)
(diffusion in angle, diffusive $e^{\pm}$)

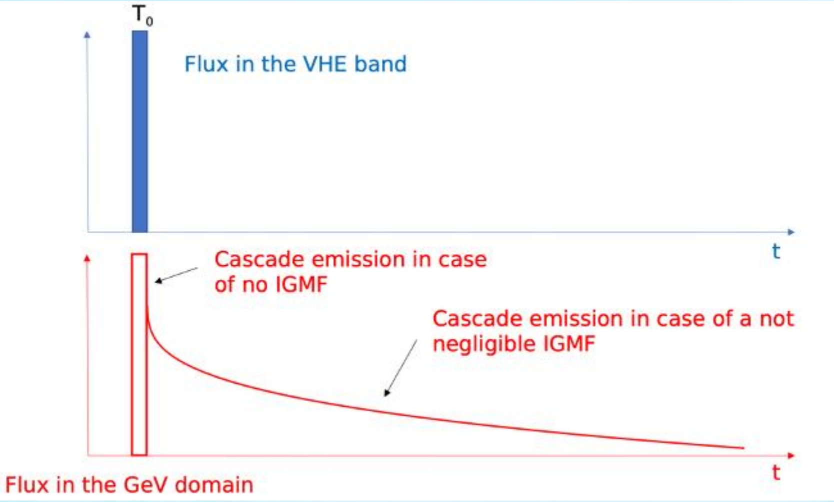
How can gamma-ray probe IGMF properties (B strength and correlation length λ_B)?

Extended emission



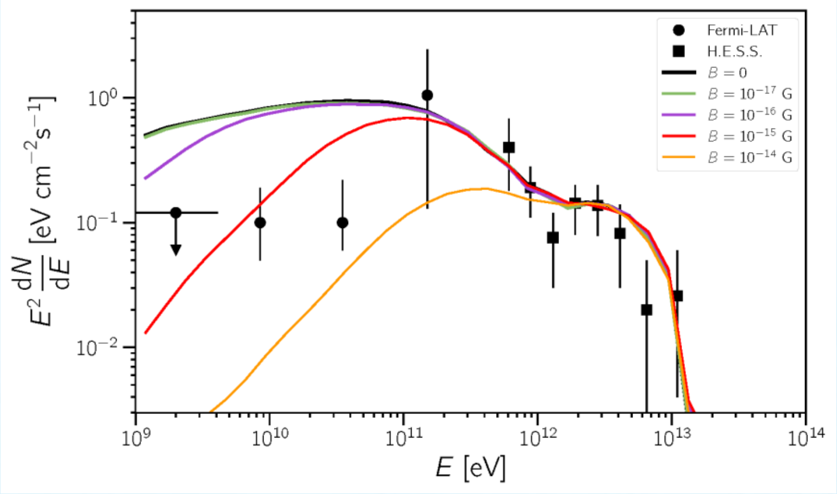
Alves Batista et al. 2022

Time-delayed "pair-echo" emission



Da Vela, TeVPa 2022

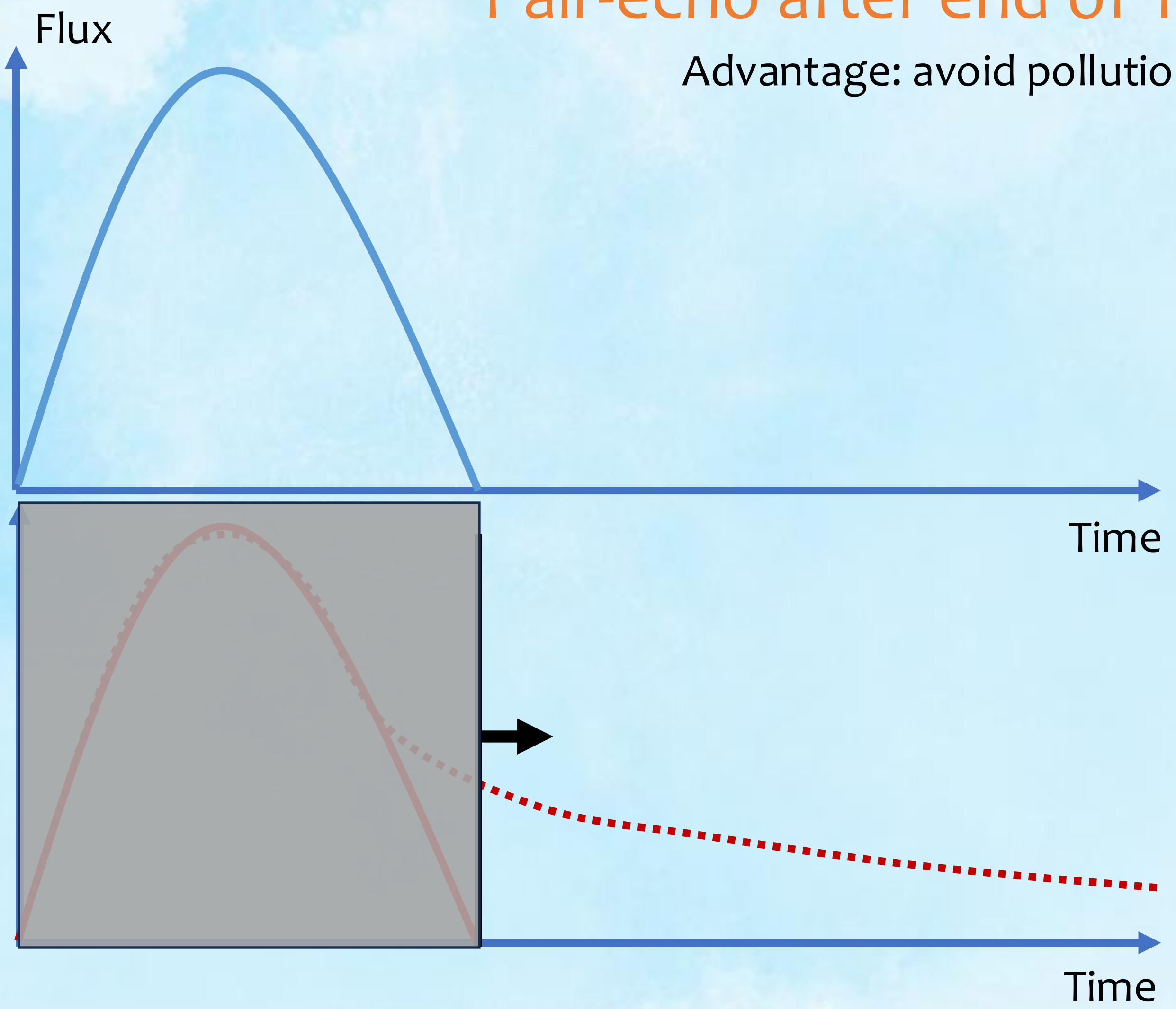
SED signatures



Alves Batista & Saveliev, 2021

Pair-echo after end of TeV afterglow emission

Advantage: avoid pollution by source GeV emission



Source intrinsic properties

~~GeV source emission~~

+

pair echo emission with non-negligible IGMF

Pair-echo emission + GRB afterglow convolution

$$F_c(E,t) = \int_0^\infty \int_E^\infty G(E_0, E, t-\tau, \tau) F_s(E_0, t-\tau) dE_0 d\tau$$

Cascade Flux

Kernel describing the distribution in energy and time of the cascade signal

"Variability pattern" (Source intrinsic properties and time evolution)

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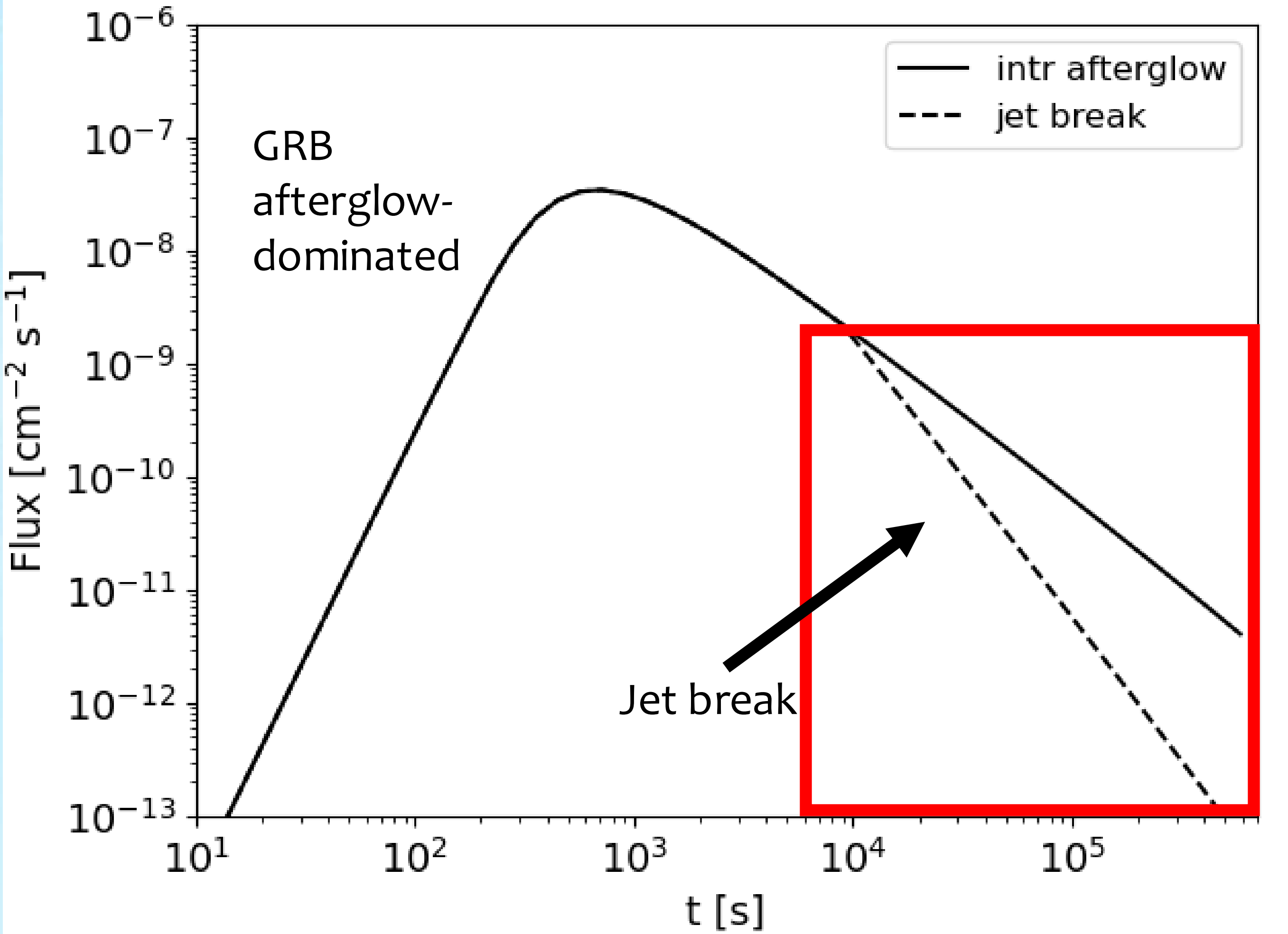
Pair-echo emission + GRB afterglow convolution

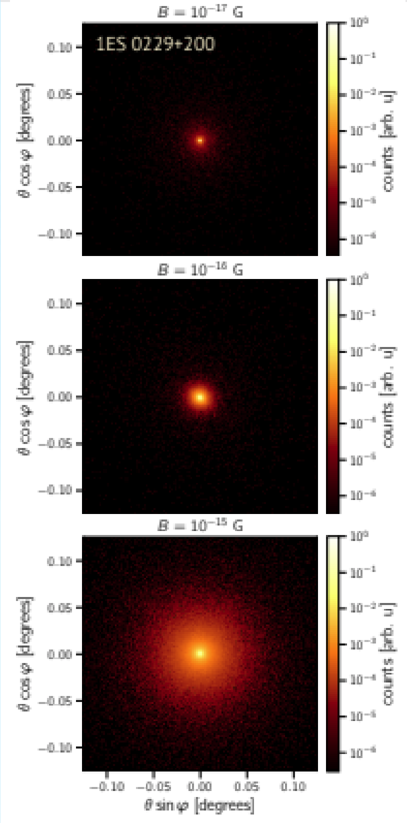


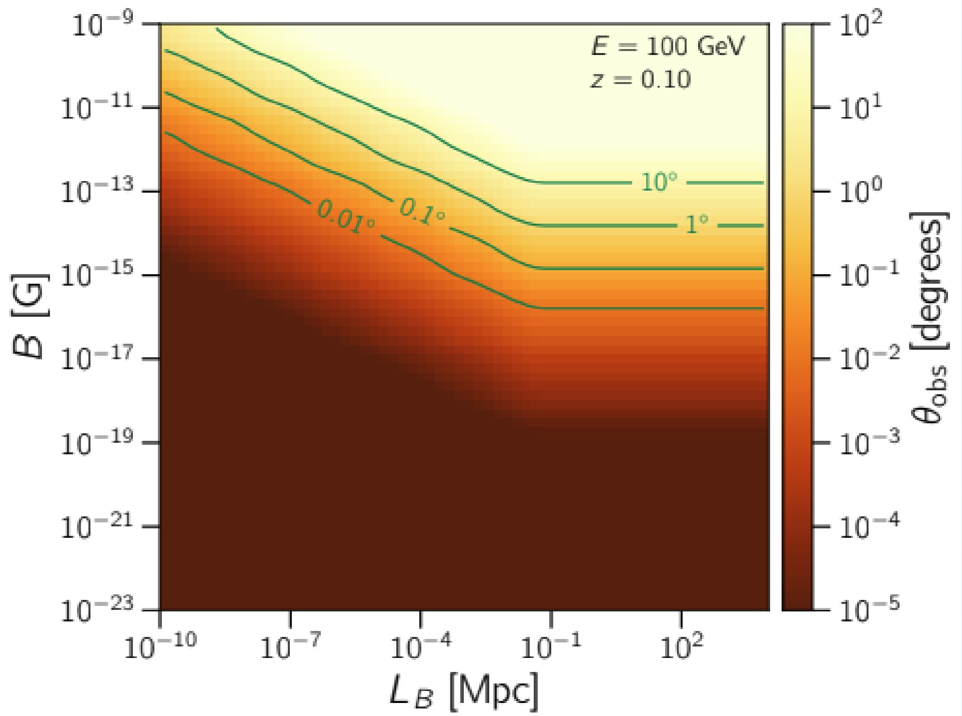
- Assuming a smaller redshift (z=0.15) with same GRB properties
- Add a "jet break" at 10^4 s (light curve steeping of a factor $\propto t^{-1}$)

Gamma-rays for IGMF studies: Methods

How gamma-ray can probe IGMF properties (B strength and correlation length λ_B)?

- Method I : search for extended emission





Alves Batista, 2021

Alves Batista & Saveliev. Universe 7 (2021) 223. arXiv:2105.1202

- A "smoking gun" for IGMF discovery
- Size and shape depend on IGMF strength and source parameters (jet opening and orientation)

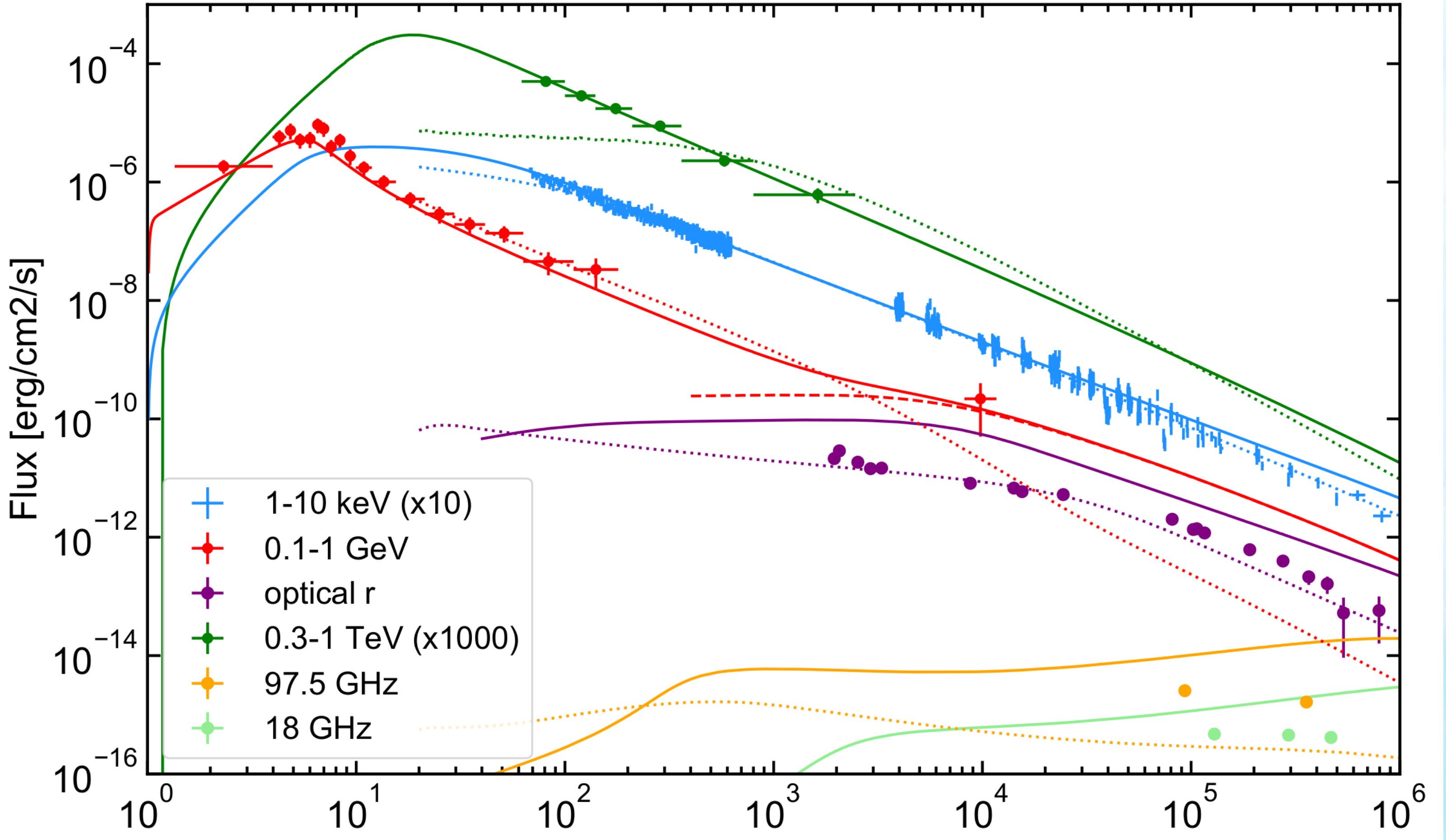
$\theta_{ext} \propto B\, E_\gamma^{-1}$ $\lambda_B >> \lambda_{IC}$

$\theta_{ext} \propto B\, E_\gamma^{-3/4}\, \lambda_B^{1/2}$ $\lambda_B << \lambda_{IC}$

MWL LIGHT CURVES

GRB190114C

- Sync+SSC external forward scenario
- Two modeling displayed:
  - X to TeV (solid lines)
  - Radio-optical (dotted lines)
  - SSC contribution (dashed lines)
- Indication of time-dependent afterglow parameters



MAGIC Coll. et al., 2019