

Gamma-Ray Bursts at Very High Energies (VHE): entering a new era

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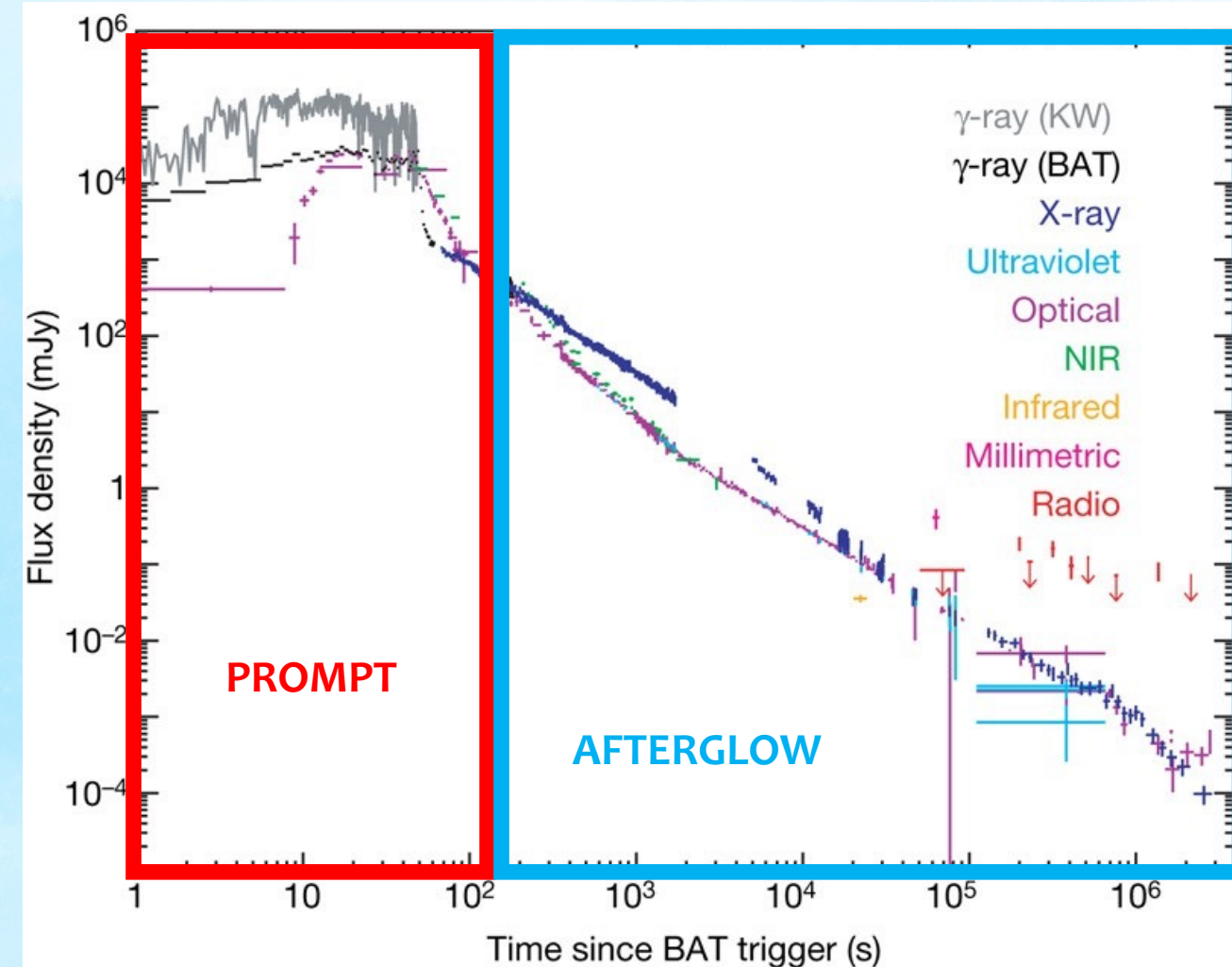


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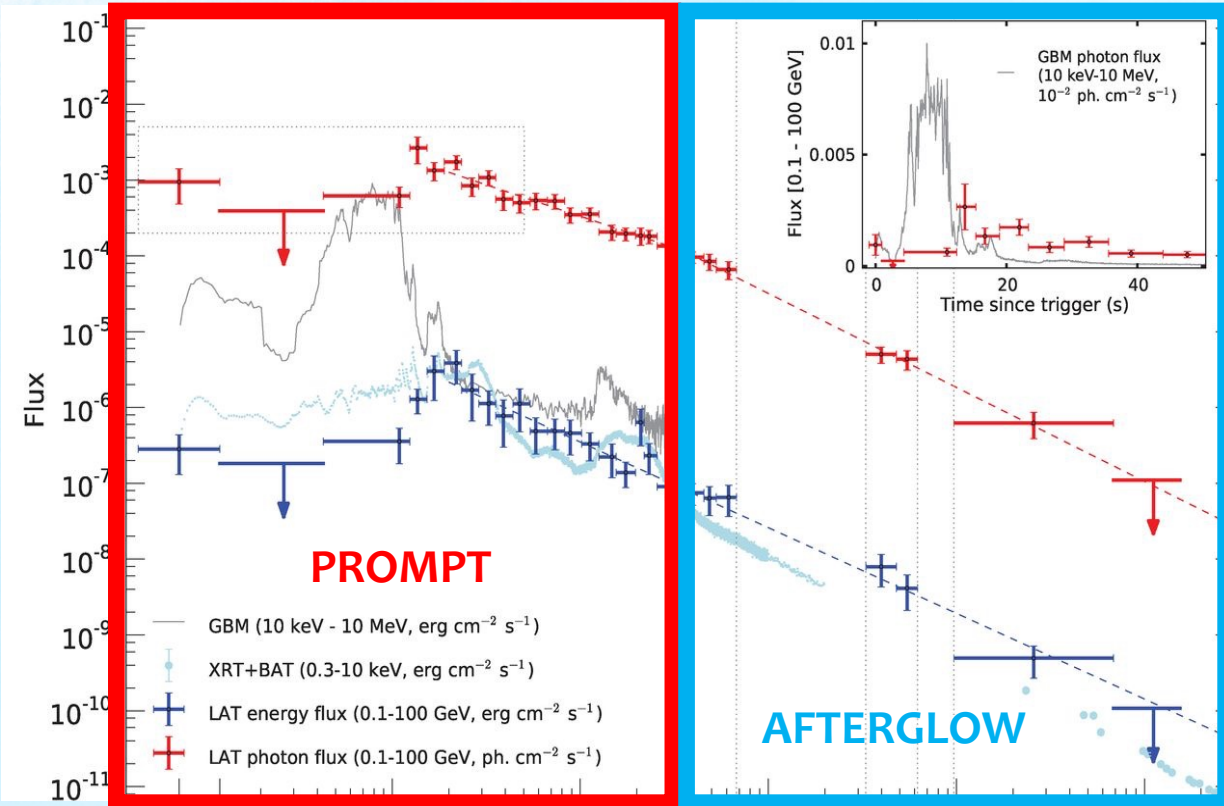
“From 9 to 40: the SST Telescopes and Gamma-Ray Science with ASTRI and CTAO”

Sexten, 23/07/2026

Gamma-ray Bursts (GRBs) emission phases

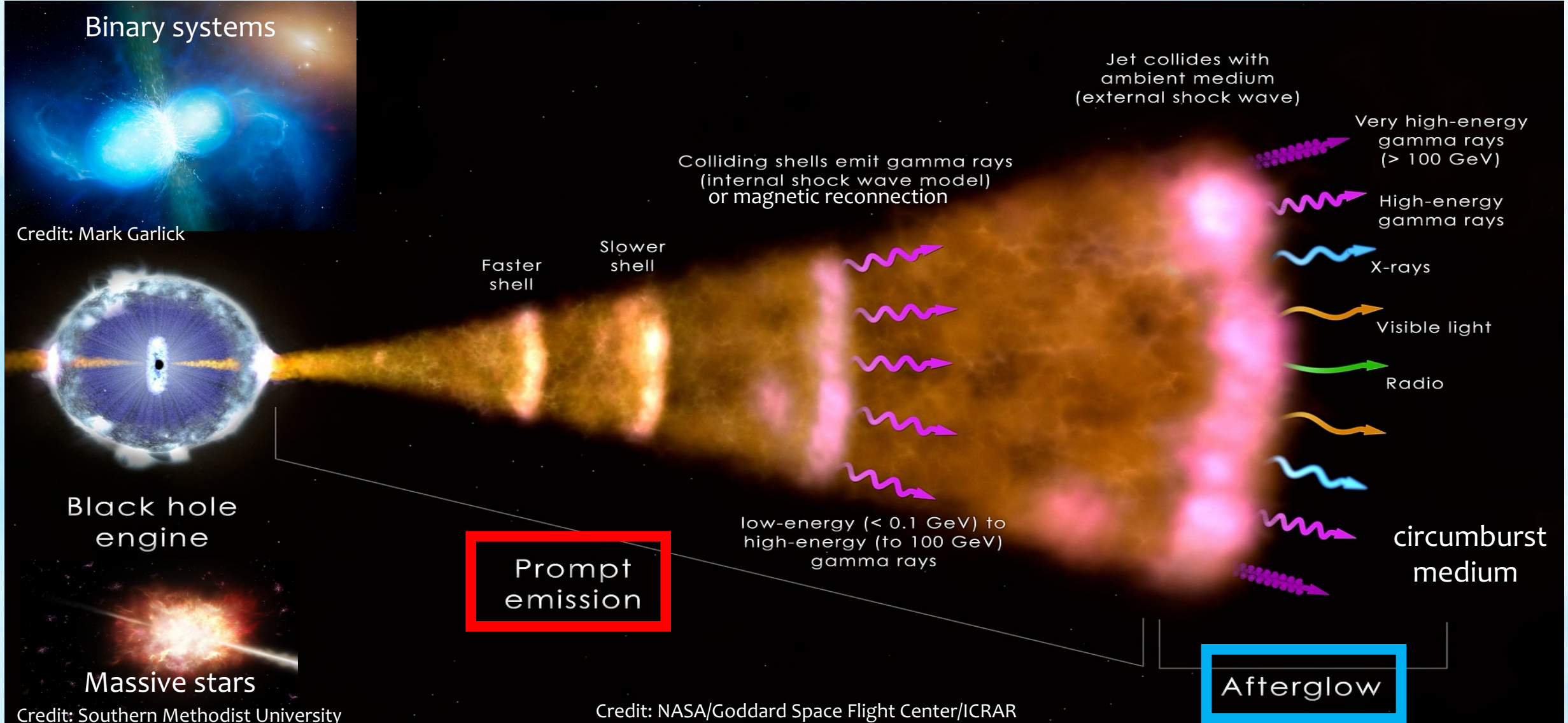


GRB080319B (Racusin et al., 2008)



GRB130427A (Ackermann et al., 2013)

Gamma-ray Bursts (GRBs)

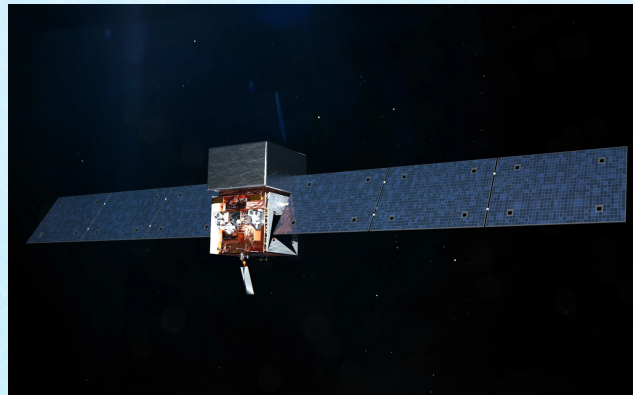


Observations of GRBs from keV to TeV

keV $\longrightarrow$ GeV $\longrightarrow$ TeV



Credit: ESA



Credit: NASA



Credit: NASA

Space telescopes



Credit: Giovanni Ceribella



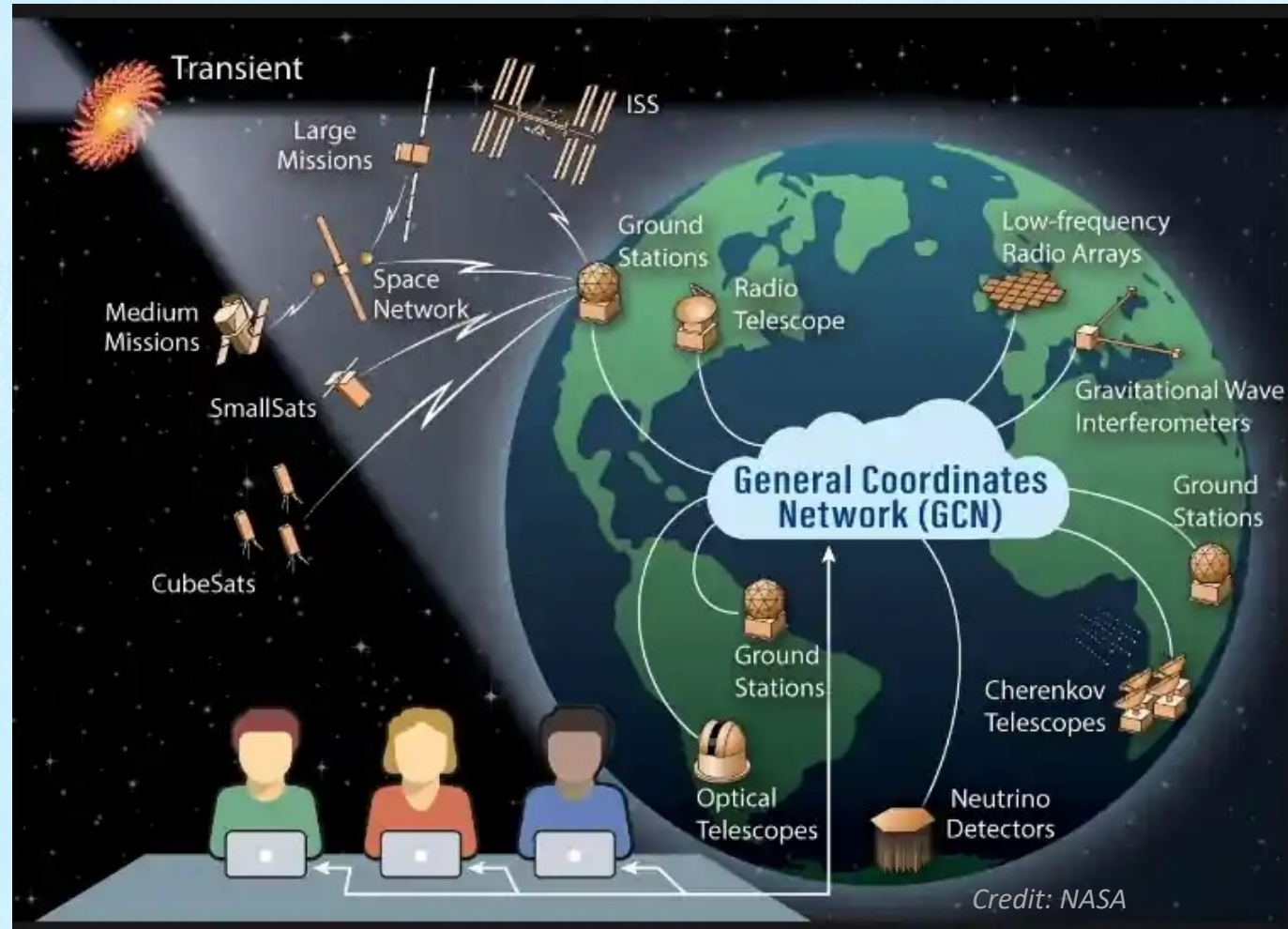
Credit: LHAASO

Ground-based observatories

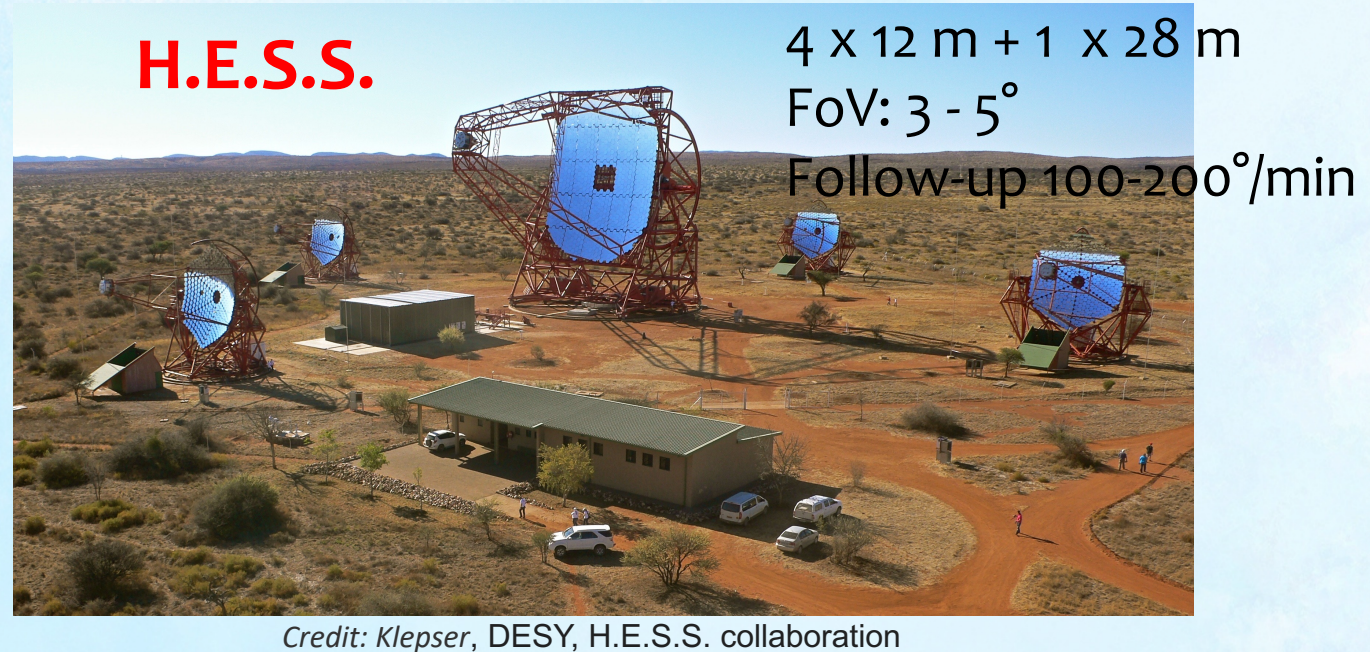
Observations of GRBs at TeV energies

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)



Imaging Atmospheric Cherenkov Telescopes (IACTs)



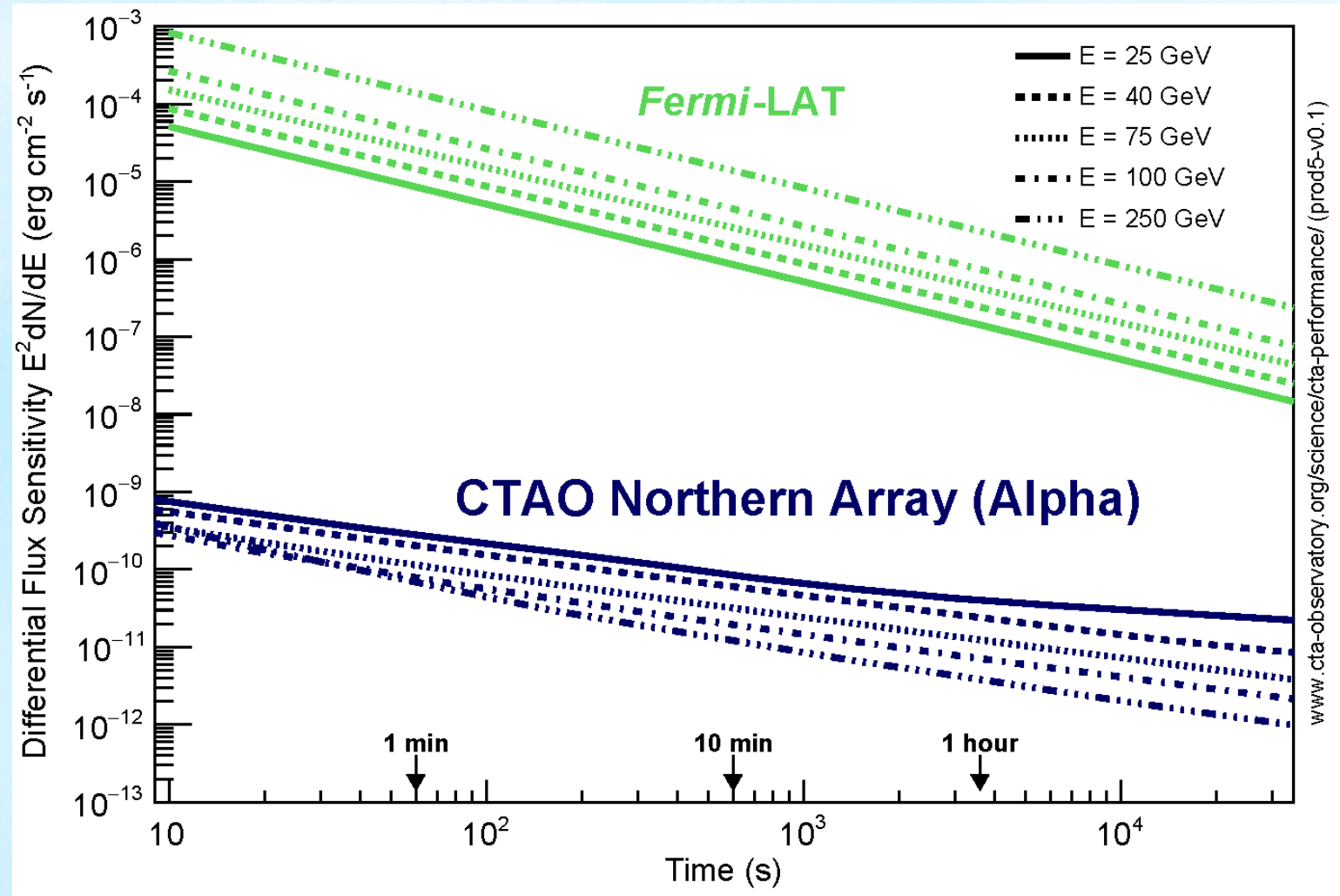


Credit: MAGIC Collaboration

CTAO for GRBs: an upcoming revolution

CTAO revolution:

- $\times 10$ sensitivity to gamma-ray signal
- $\times 10^4$ sensitivity to short-term ($< 10^4$ s) emission below 250 GeV with respect to Fermi-LAT
- GRB detection rates (Inoue et al. 2013): $> 1\text{-}4$ GRBs/year/site (but to be updated with new VHE GRB discovery!)
- A strong MWL (SVOM) and MM (LVK, ET) synergy



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

GRBs at VHE: the current status

5 GRBs detected at $> 5\sigma$

	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 $\sim 3\sigma$

	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

GRBs at VHE: the current status

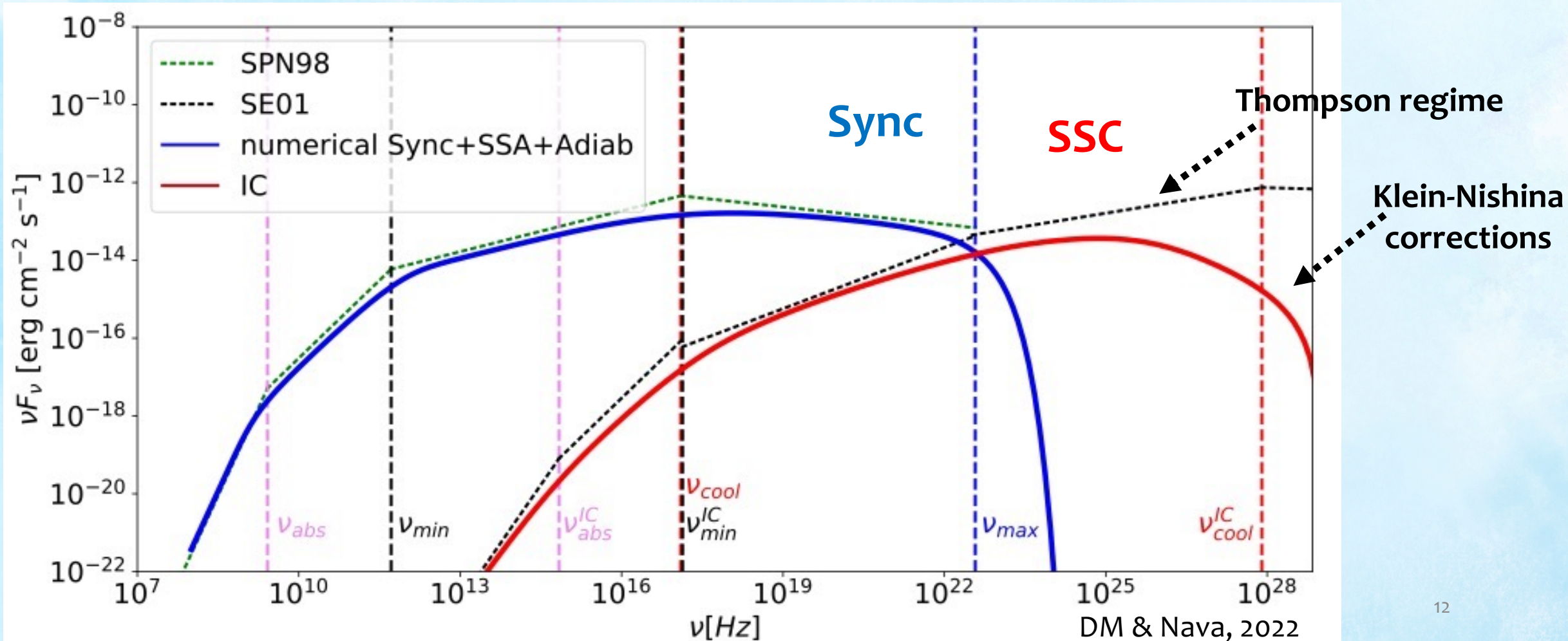
Detections of GRBs also above 1 TeV and at late-time ($t > 10^4$ s)

	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)
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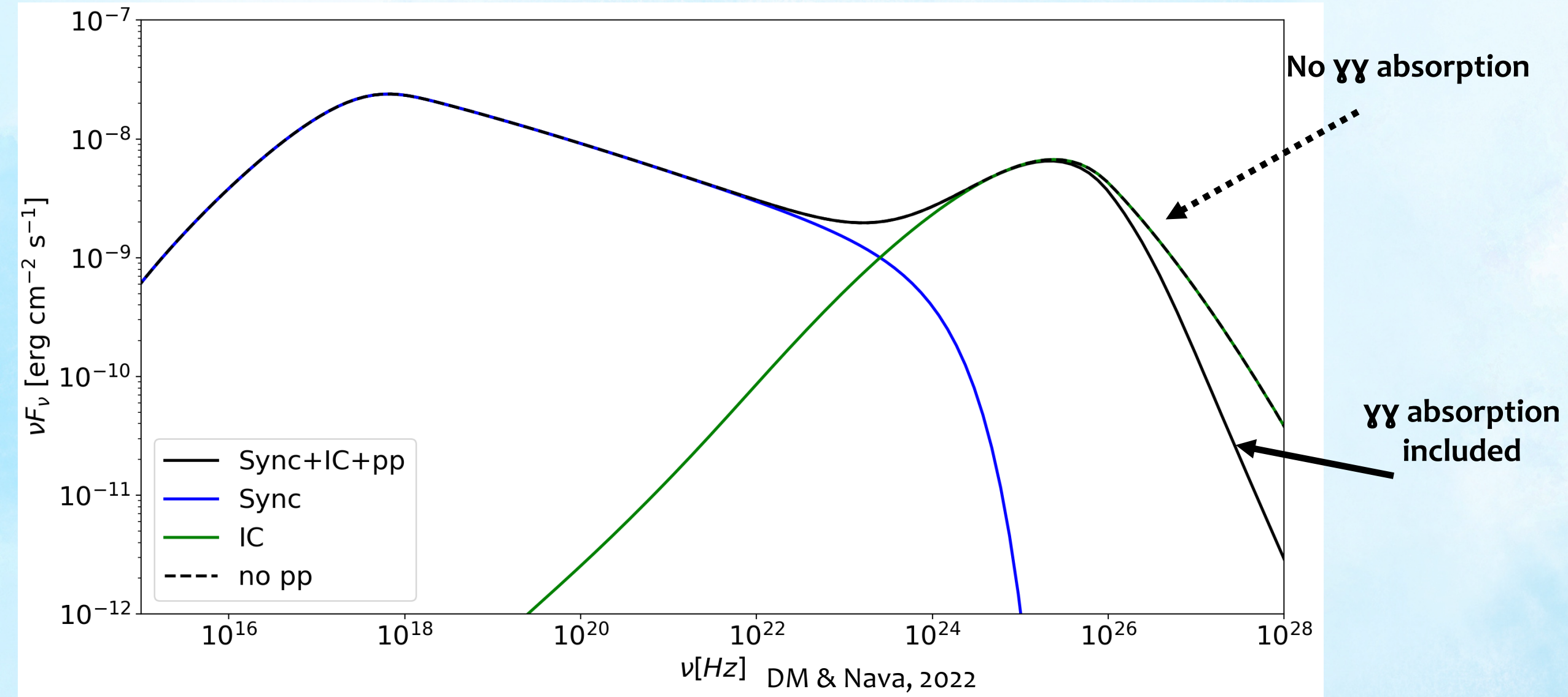
Adapted from DM & Nava, 2022

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)

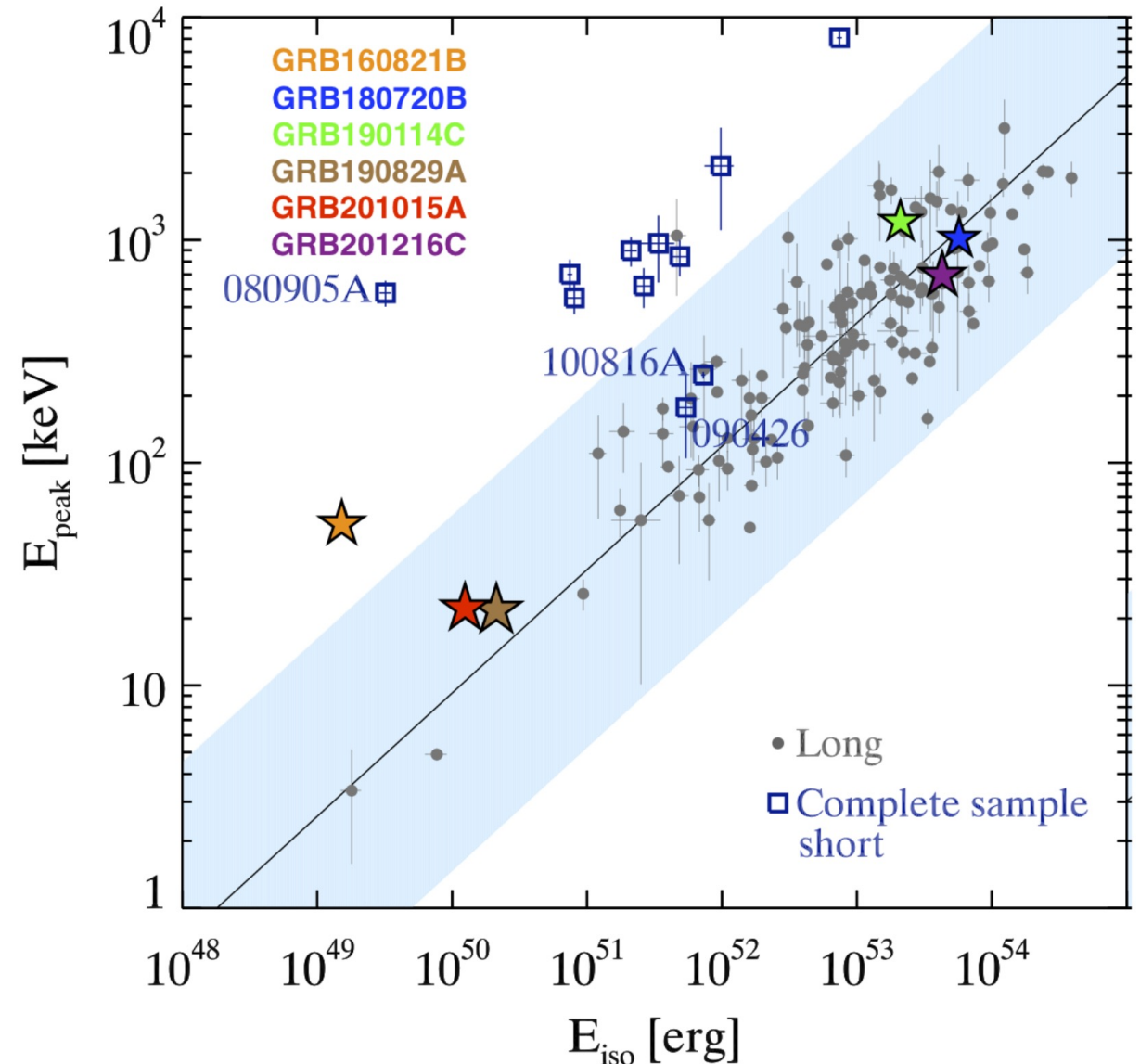


Theoretical expectations from GRBs in the VHE domain



Population of GRBs in VHE domain

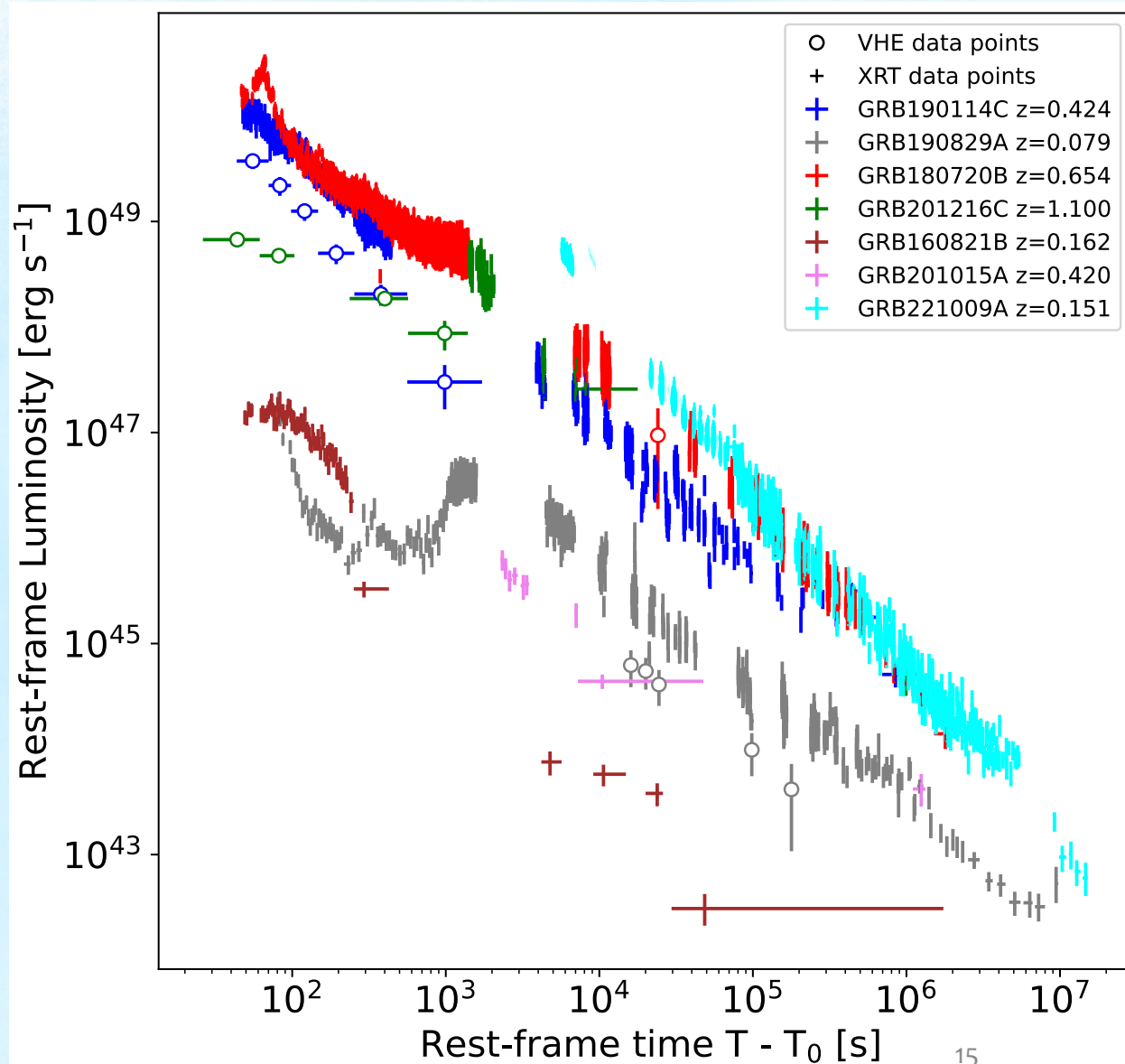
- Broadband intrinsic properties:
 - span more than 3 orders of magnitude in $E_{\gamma, \text{iso}}$
 - Span 2 orders of magnitude in terms of L_{VHE}
 - ranging in redshift between 0.079–1.1



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 $E_{\gamma, \text{iso}}$
 - 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% $L_{\text{X-ray}}$)



Is the VHE component universal in GRBs?

The MAGIC GRBs catalog (2013 – 2019)

GRB name	Redshift	Instrument (position)	T ₉₀ [s]	T ₀ [UTC]	T _{start} [UTC]	T _{delay} [s]	Zenith angle [deg]
130502A		Swift-BAT	3	17:50:30	20:57:03	11193	33.9-40.1
130504A		Swift-BAT	50	02:05:34	02:13:09	455	44.7-56.5
130606A	5.913	Swift-BAT	277	21:04:39	21:15:28	649	1.7-46.1
130612A	2.006	Swift-BAT	5.6	03:22:22	03:23:08	46	38.0-53.0
130701A	1.155	Swift-BAT	4.4	04:17:43	04:18:32	49	15.9-22.6
130903A		INTEGRAL	69	00:47:20	03:57:32	11412	51.9-62.8
131030A	1.295	Swift-BAT	41	20:56:19	20:56:45	26	33.7-39.7
140430A	1.60	Swift-BAT	174	20:33:36	20:52:06	1110	45.6-73.3
140709A		Swift-BAT	98.6	01:13:41	03:22:13	7712	24.6-37.0
140930B		Swift-BAT	0.84	19:41:42	21:10:05	5303	18.8-51.4
141026A	3.35	Swift-BAT	146	02:36:51	02:38:27	96	16.3-54.1
141220A	1.32	Swift-BAT	7.21	06:02:52	06:03:47	55	18.9-24.0
150213A		Fermi-GBM	4.1	00:01:48	00:03:08	80	48.2-60.6
150428A		Swift-BAT	53.2	01:30:40	01:32:11	91	27.0-57.7
150428B		Swift-BAT	131	03:12:03	03:13:03	60	27.0-57.7
150819A		Swift-BAT	52.1	00:50:08	02:11:51	4903	37.4-54.4
151118A		Swift-BAT	23.4	03:06:30	03:07:14	44	42.8-57.4
151215A	2.59	Swift-BAT	17.8	03:01:28	03:01:58	30	15.8-58.0
160119A		Swift-BAT	116	03:06:07	03:17:09	662	13.2-58.7
160310A		Fermi-LAT	18.2	00:22:57	20:30:16	72439	35.5-40.9
160313A		Swift-BAT	42.6	02:37:14	02:39:01	107	30.3-53.3
160504A		Swift-BAT	53.9	19:30:36	20:56:29	5153	26.9-33.7
160509A	1.17	Fermi-LAT	370	08:59:04	21:21:07 (+2d)	217323	49.2-72.2
160623A	0.367	Fermi-LAT	50	05:00:34	02:05:31	75897	27.0-54.7
160625B	1.406	Fermi-LAT	460	22:43:24	23:29:38	2774	21.8-54.9
160821B	0.16	Swift-BAT	0.48	22:29:13	22:29:37	24	33.4-43.6
160910A		Fermi-GBM	24.3	17:19:38	20:21:54	10936	45.4-72.9
160927A		Swift-BAT	0.48	18:04:49	20:03:00	7091	32.0-58.8
161229A		Fermi-GBM	33.5	21:03:48	23:05:54	7326	22.0-26.1
170728B		Swift-BAT	47.7	23:03:19	23:03:58	39	41.8-52.7
170921B		Fermi-GBM	39.4	04:02:11	04:48:04	2753	48.4-60.6
171020A	1.87	Swift-BAT	41.9	23:07:09	23:08:37	88	13.5-34.9
171210A		Fermi-LAT	12	11:49:15	20:33:11	31436	30.9-61.9
180512A		Swift-BAT	24.0	22:01:46	22:03:11	85	7.6-38.4
180715A		Swift-BAT	0.68	18:07:05	21:27:24	12019	27.9-34.5
180720C		Swift-BAT	124.2	22:23:57	22:25:44	107	55.3-55.4
180904A		Swift-BAT	5.39	21:28:32	21:30:07	95	23.7-60.2
181225A		Fermi-LAT	41.5	11:44:10	19:56:06 (+1d)	115916	46.7-62.6
190106B		Fermi-GBM	11.8	20:47:10	20:49:13	123	60.0-60.4
190114C	0.425	Swift-BAT	25 ⁺	20:57:03	20:58:01	58	55.6-80.0
190829A	0.078	Swift-BAT	62.9	19:55:53	02:23:48 (+2d)	109624	37.7-59.6
191004A		Swift-BAT	2.44	18:07:02	00:42:30	23728	65.4-69.9

Goal:

- Deliver a catalog of the non-detected GRBs with MAGIC
- Discuss the implications of non-detections

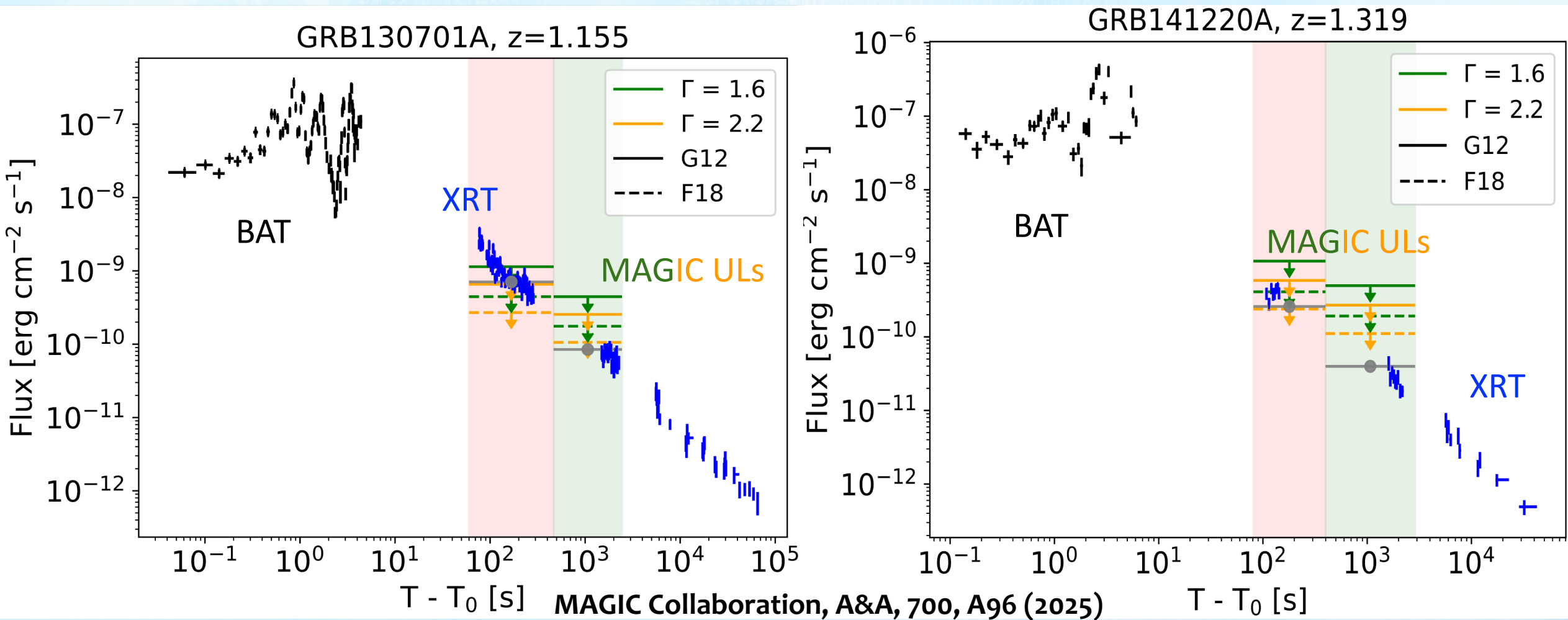
Criteria:

- Non-detected GRBs followed up by MAGIC from **2013** (post automatic procedure update catalog) to **2019** (change of follow-up strategy)
- GRBs observed in good conditions (stereo, good weather, no strong moonlight)

Analysis workflow:

- MAGIC: MAGIC std data analysis + Upper Limit (UL) calculation ([Zanin et al. 2013](#), [Aleksic et al. 2016](#), [Rolke et al. 2005](#))
- MWL: Swift-XRT and Fermi-LAT simultaneous observations

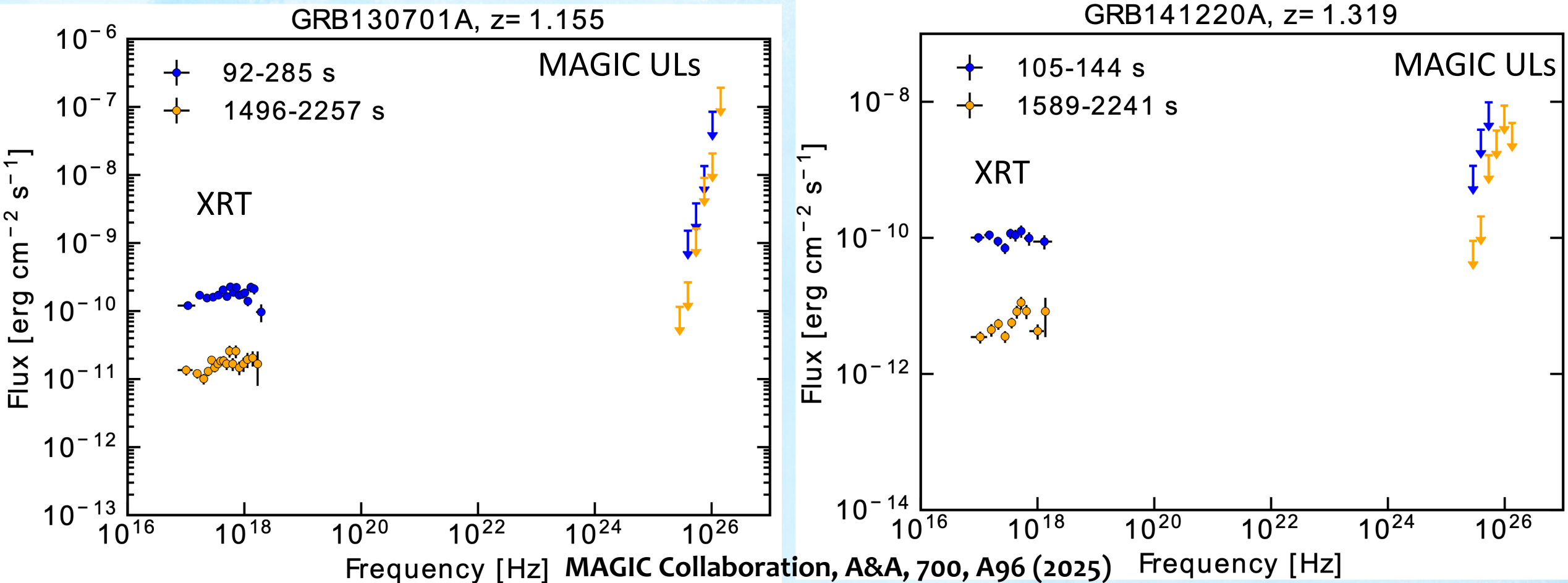
The MAGIC GRBs catalog (2013 – 2019)



MAGIC ULs lies very close (or below) the average XRT flux: **can VHE be constrained?**

The MAGIC GRBs catalog (2013 – 2019)

Spectral MAGIC and XRT analysis in simultaneous time intervals



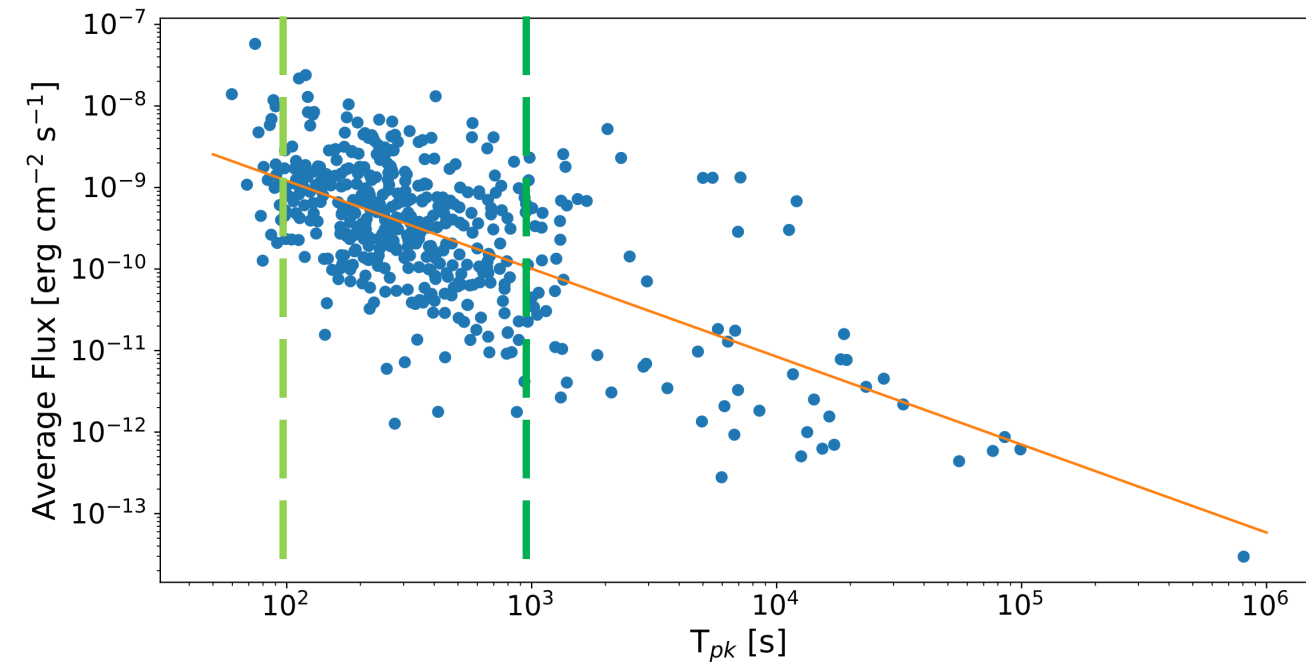
MAGIC differential ULs well above XRT flux

Future challenges for VHE: catching X-ray flares

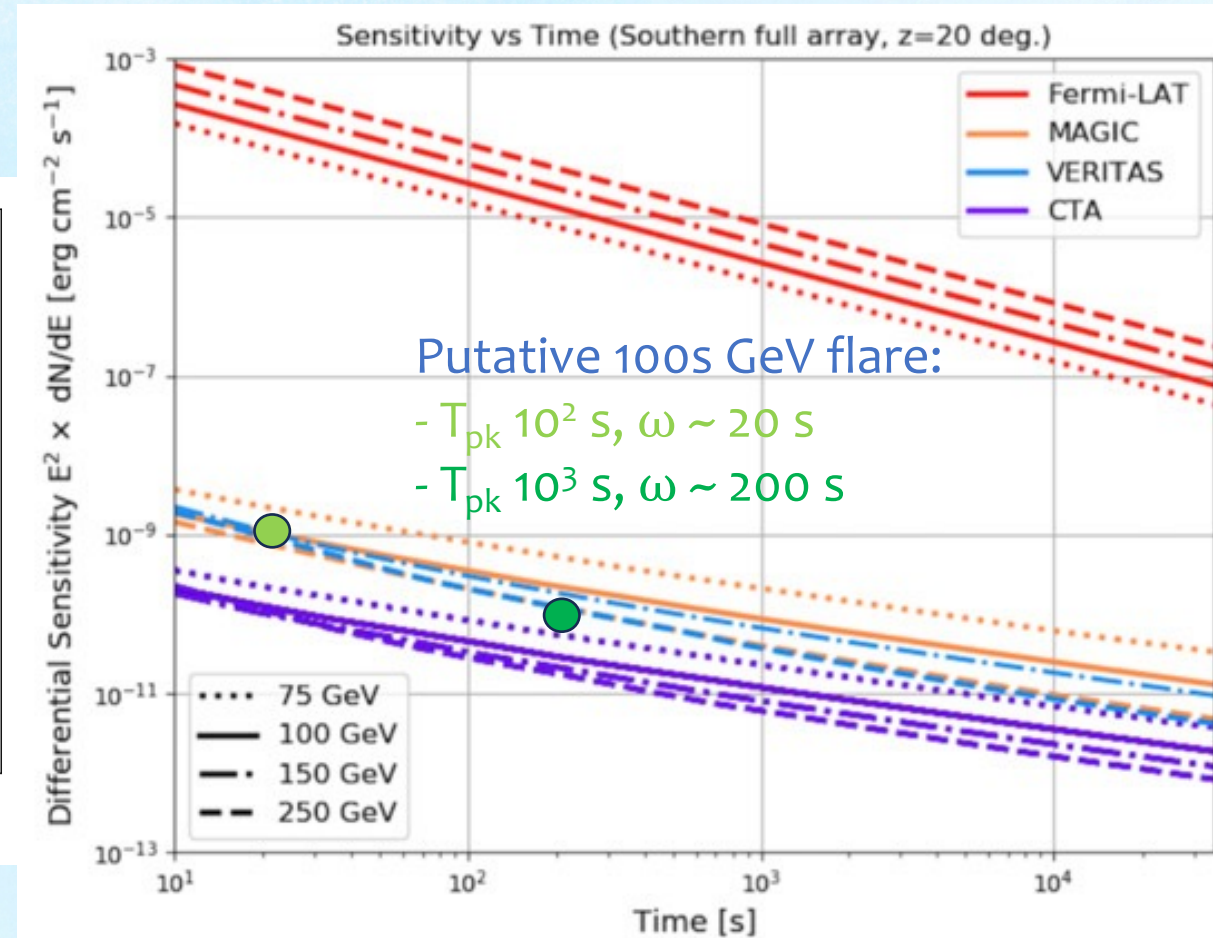
Signatures of X-ray flares can be found in the GeV-TeV domain? Wang et al. 2006
He et al. 2012

Wang et al. 2013

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



DM, Nava 2022

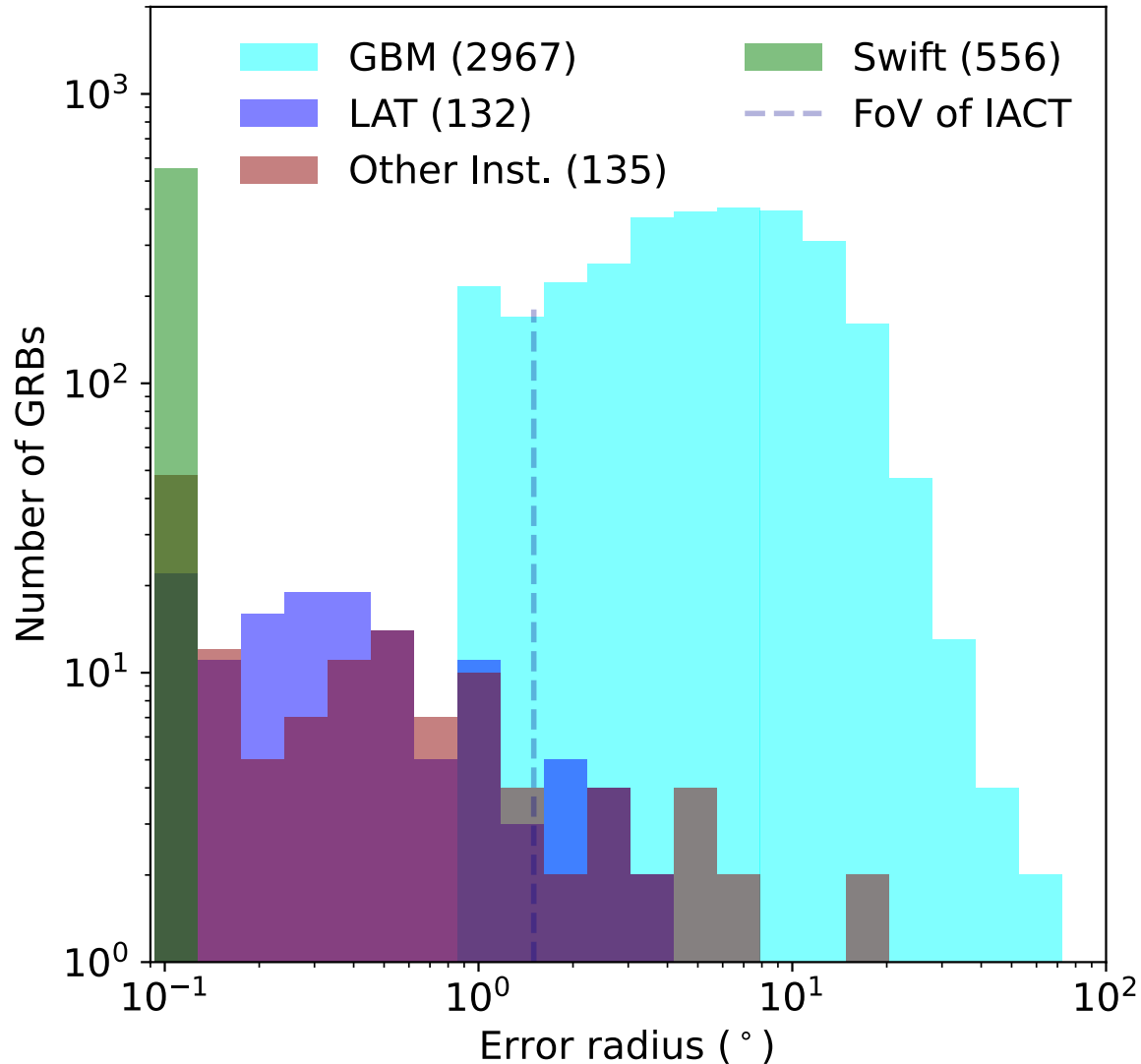


Adapted from Fioretti et al. 2019

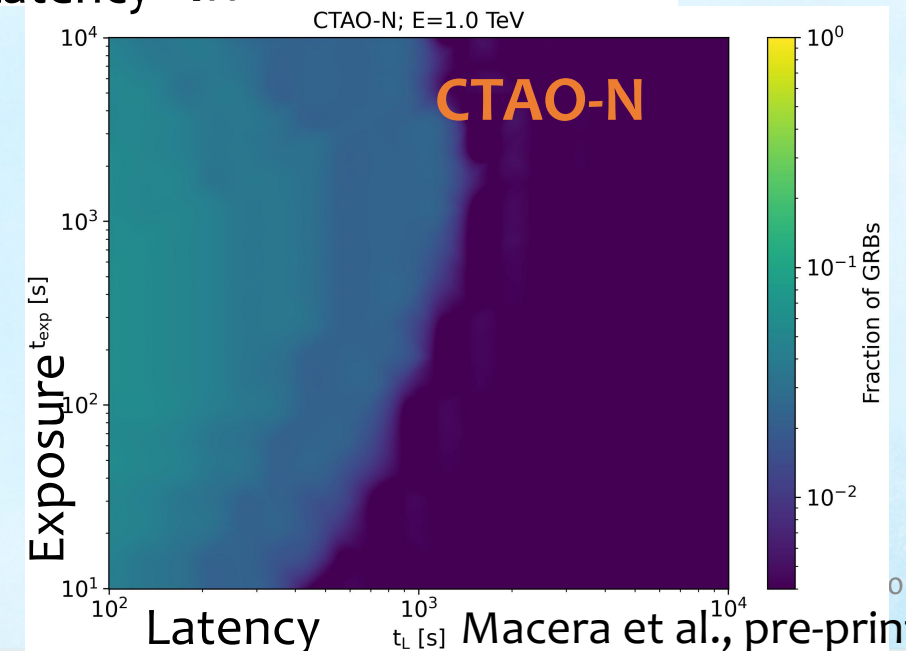
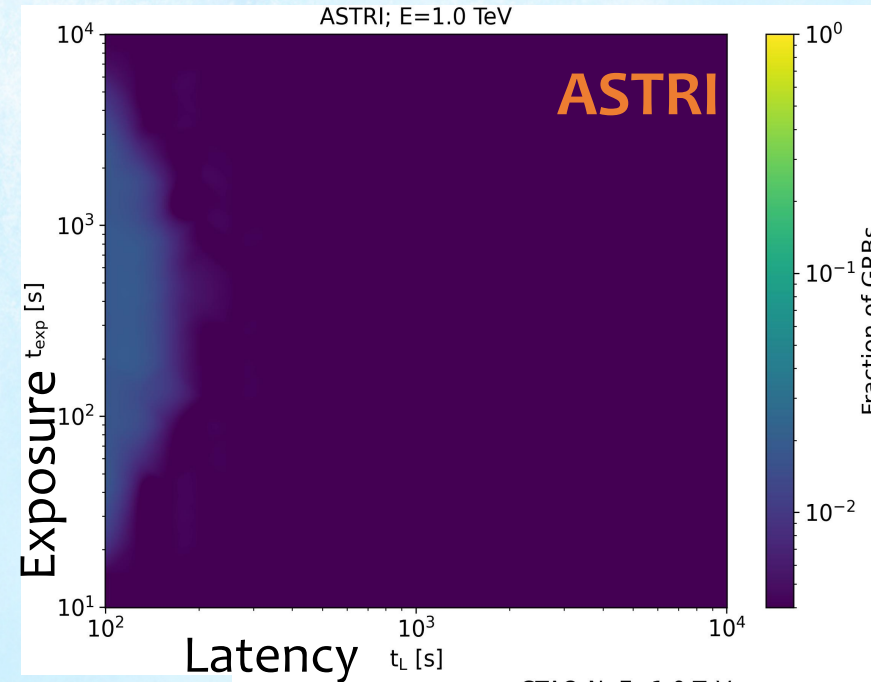
Future challenges for VHE: poorly-localized GRBs

Localization error of GBM detected GRBs

August 2008–July 2024 ($N_{\text{GRB}}^{\text{tot}}=3807$)



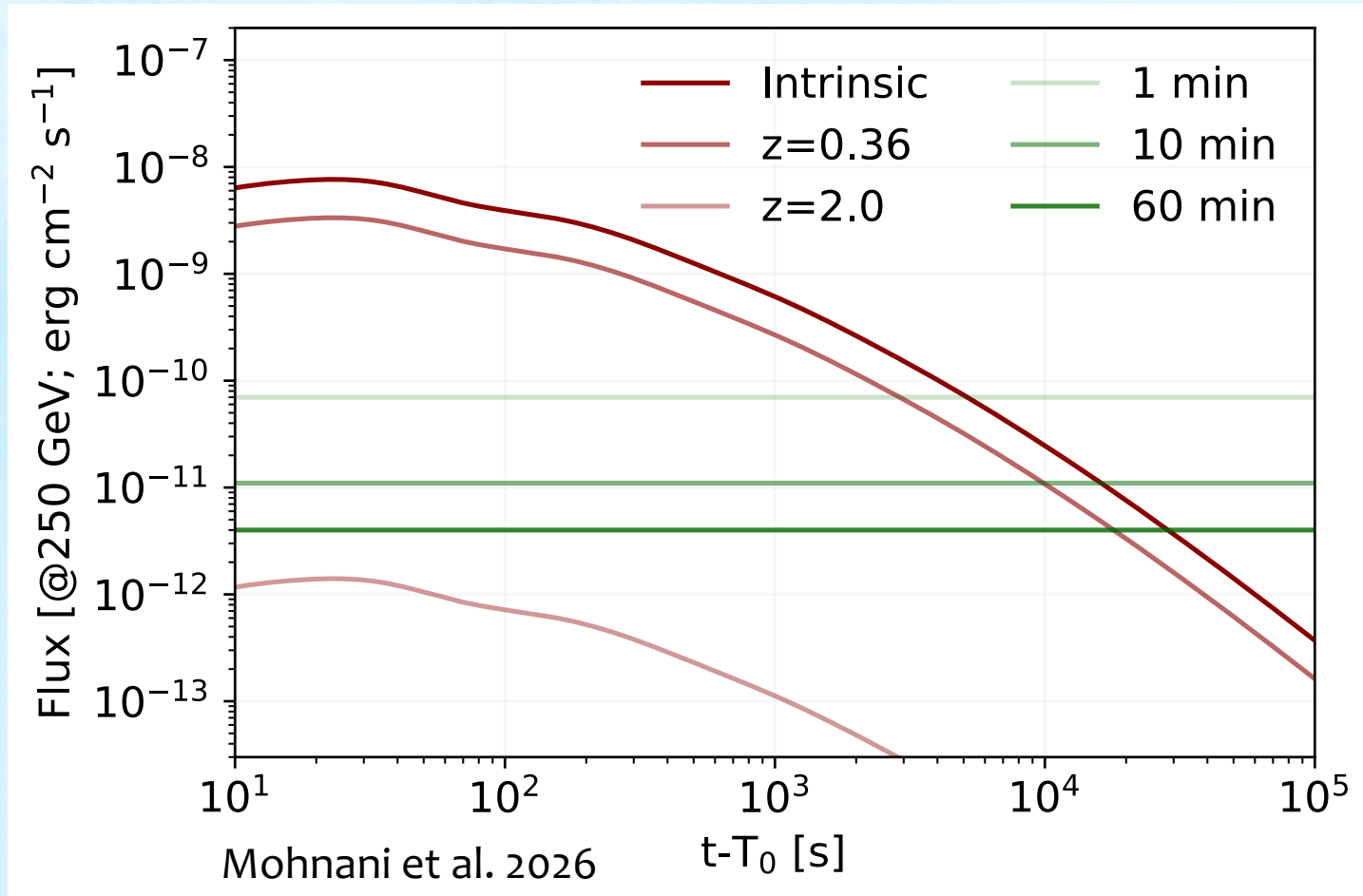
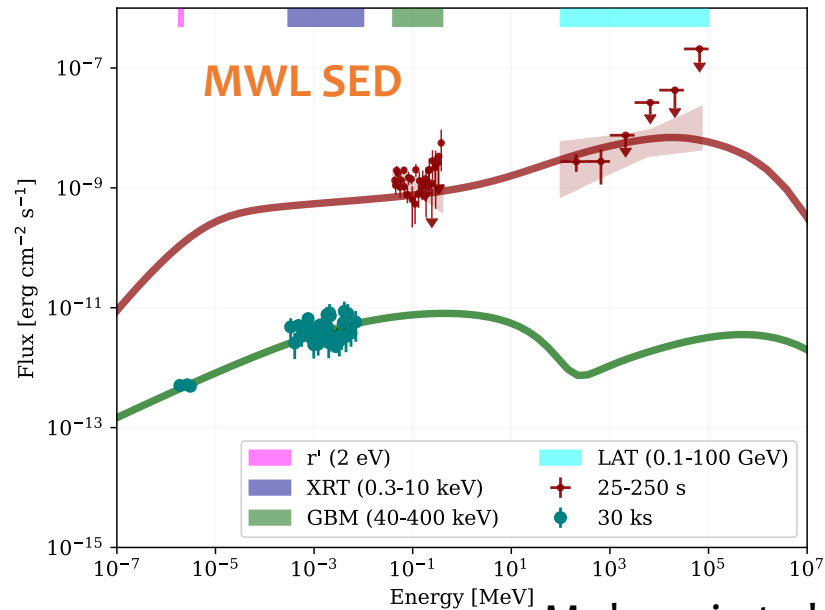
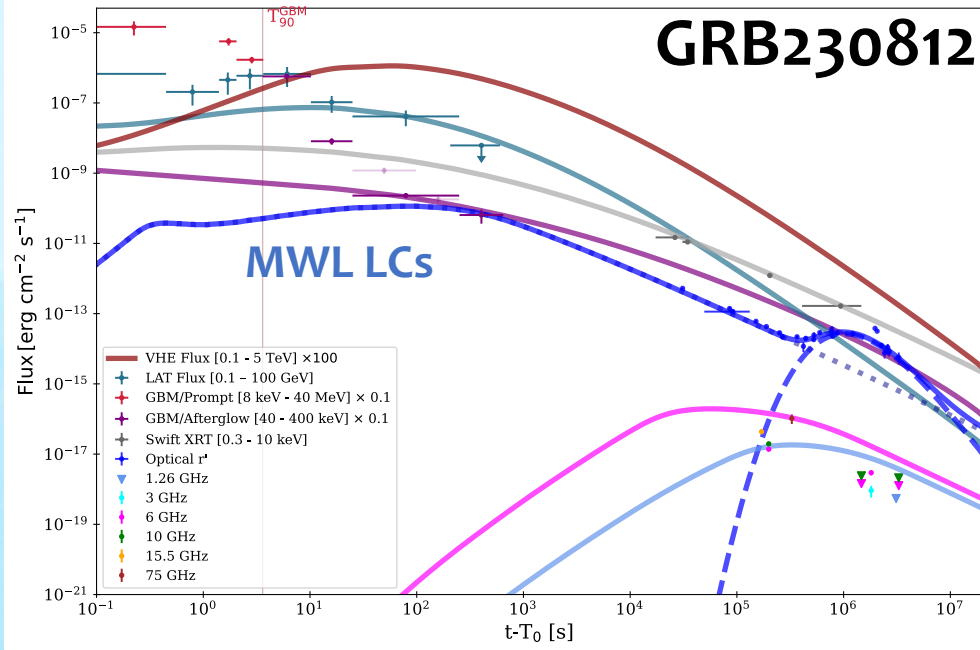
Macera et al., pre-print, 2025



Macera et al., pre-print, 2025

Future challenges for VHE: poorly localized GRBs

GRB230812B: a bright poorly localized GRB



Mohnani et al. 2026

GRBs at VHE: impact on fundamental physics

Intergalactic Magnetic Field (IGMF) studies

Magnetic field seeds origin

Cosmological

Astrophysical

Amplification process

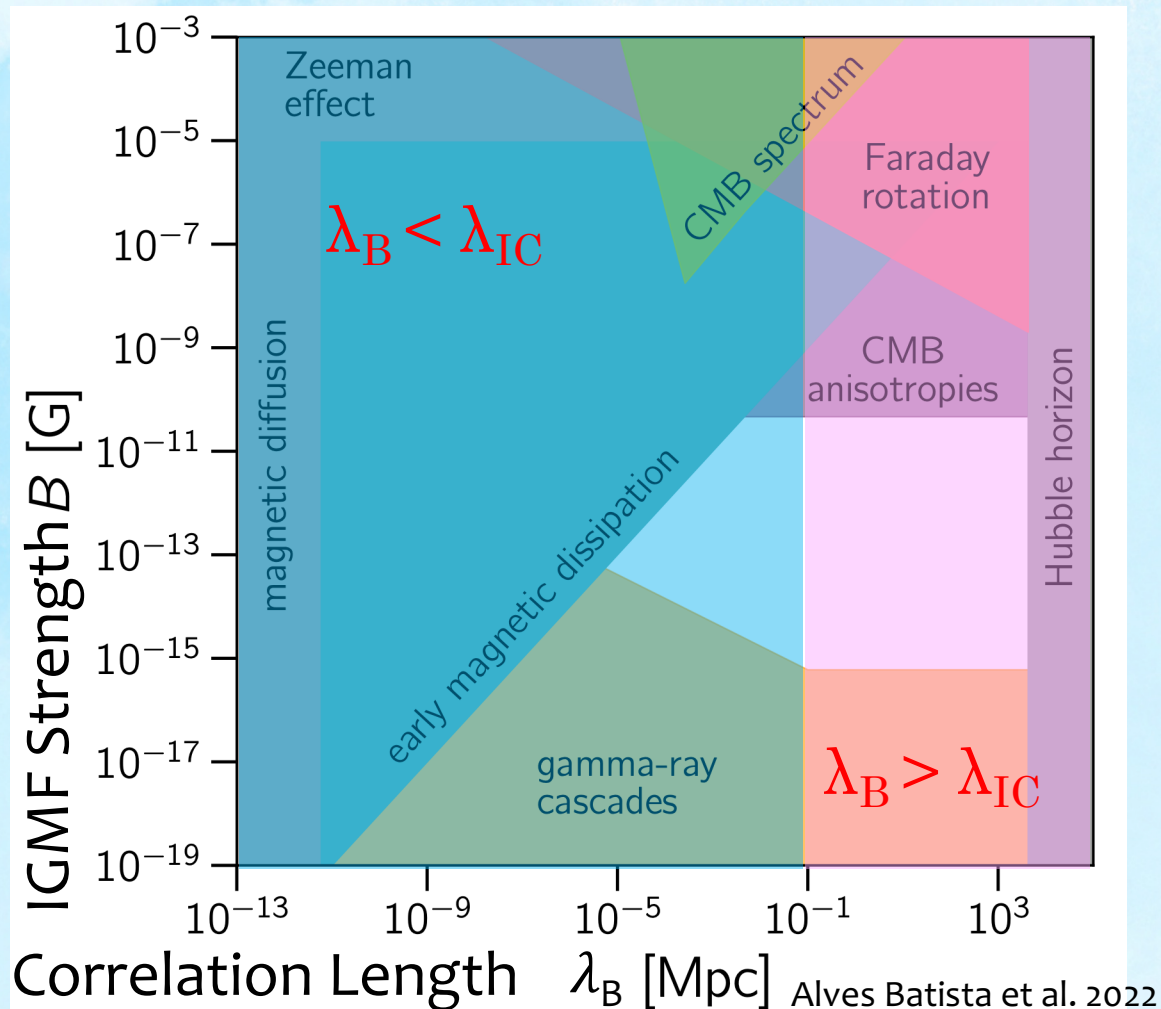
Dynamo amplification

Current B-fields
detected

Modern μG
magnetic fields in
galaxy and galaxy
clusters

Intergalactic Magnetic field (IGMF) studies

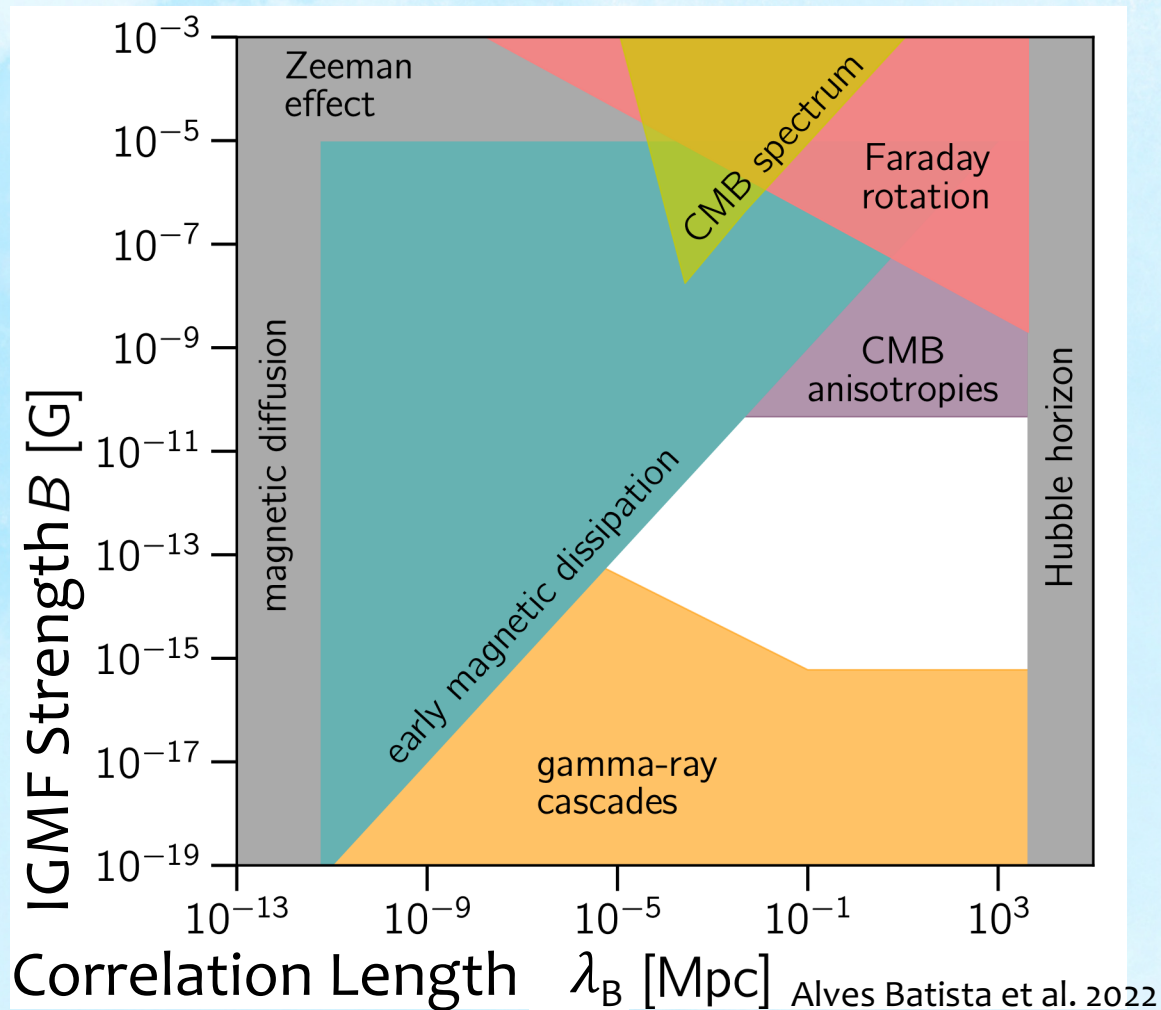
IGMF studies investigate a 2D parameter space: Correlation Length (λ_B) – IGMF Strength (B)



Results on IGMF studies with γ -rays are typically given considering two regimes:

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

Intergalactic Magnetic field (IGMF) studies



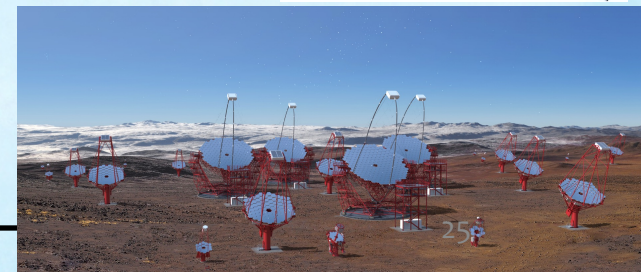
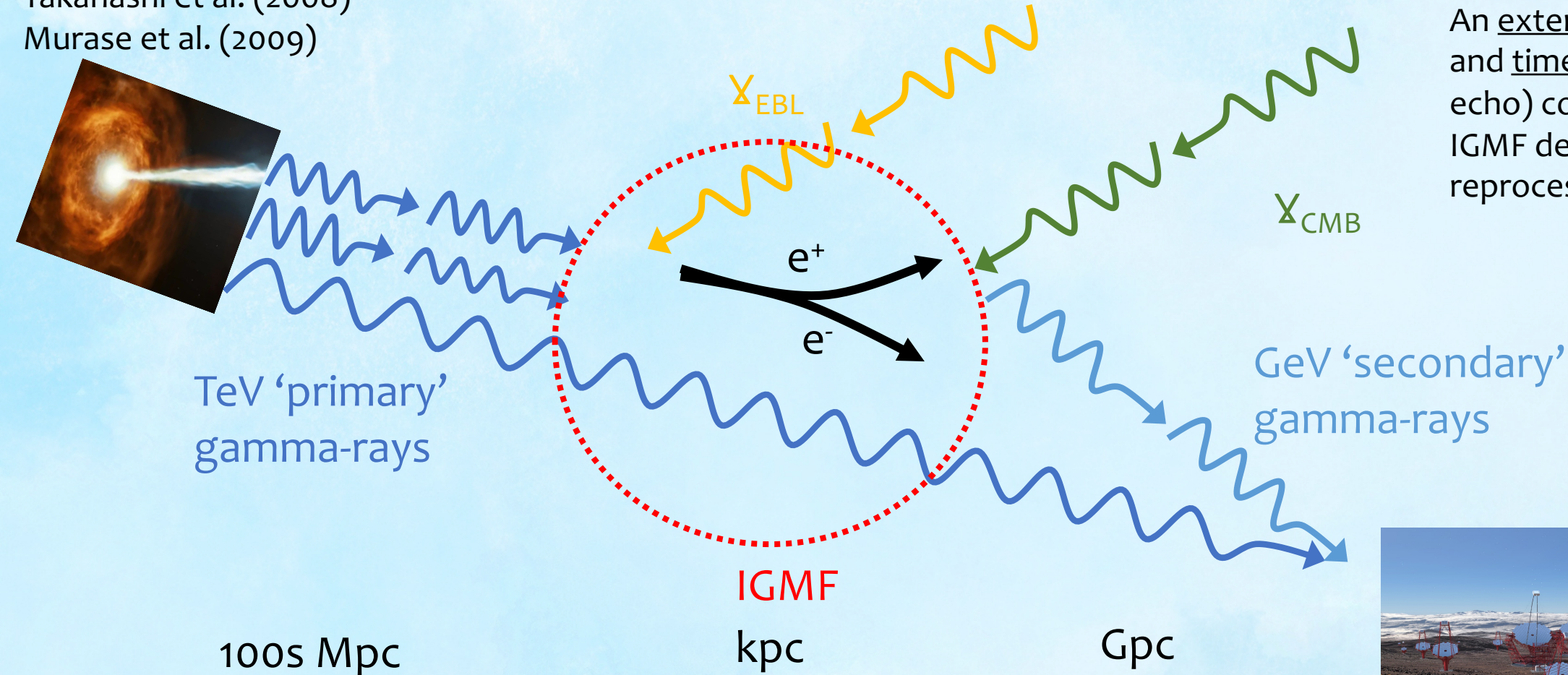
- No IGMF detection so far
- Upper limits (ULs) on strength B (cosmology, CMB, primordial GW)
→ $B < 10^{-10} - 10^{-11}$ G for $\lambda_B > \text{Mpc}$
- Lower limits (LLs) on strength B (γ -ray exclusive!)
→ $B > 10^{-15} - 10^{-19}$ G for $\lambda_B > \text{Mpc}$

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 can γ -rays probe IGMF properties (strength B and correlation length λ_B)?

$$E_{rep} \sim 0.32 \left(\frac{E_\gamma}{20 \text{ TeV}} \right)^2 \text{ TeV} \quad (10 \text{ TeV} \rightarrow 80 \text{ GeV})$$

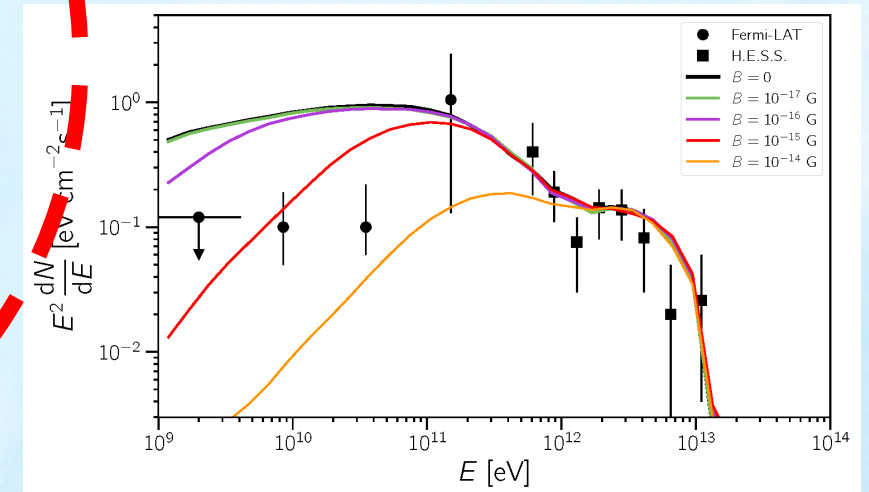
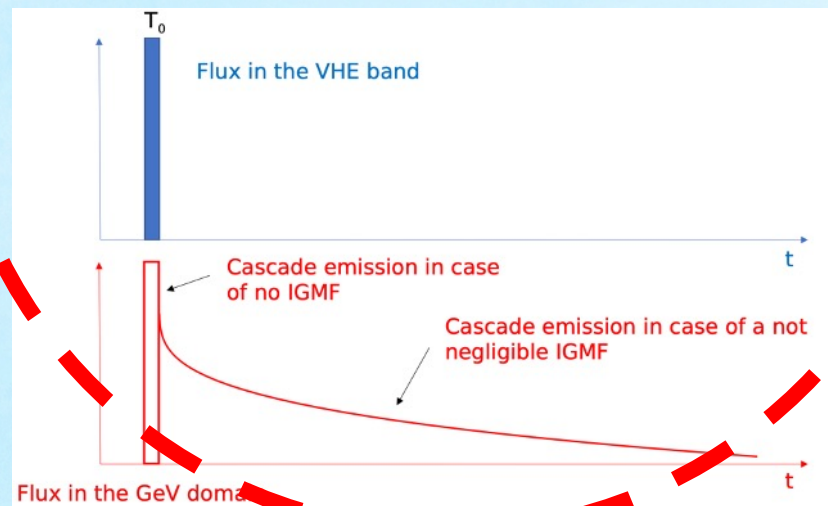
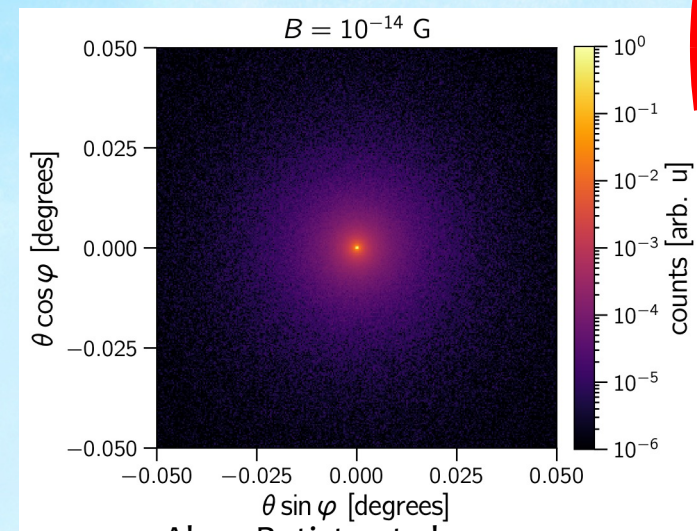
Extended emission

$$\begin{aligned} \theta_{ext} &\propto B E_\gamma^{-1} & \lambda_B \gg \lambda_{IC} \\ \theta_{ext} &\propto B E_\gamma^{-3/4} \lambda_B^{1/2} & \lambda_B \ll \lambda_{IC} \end{aligned}$$

Time-delayed "pair-echo" emission

$$\begin{aligned} T_{delay} &\propto B^2 E_\gamma^{-5/2} & \lambda_B \gg \lambda_{IC} \\ T_{delay} &\propto B^2 E_\gamma^{-2} \lambda_B & \lambda_B \ll \lambda_{IC} \end{aligned}$$

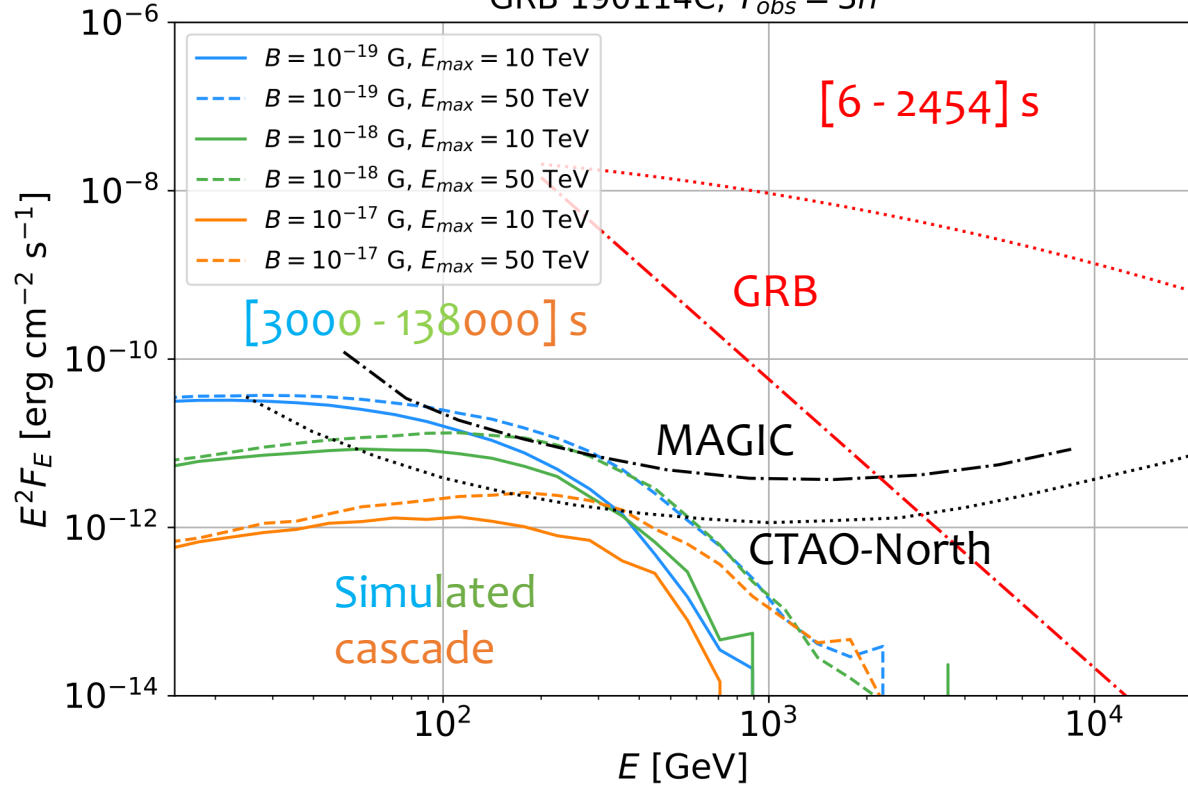
SED signatures



Pair-echo with TeV-detected GRBs

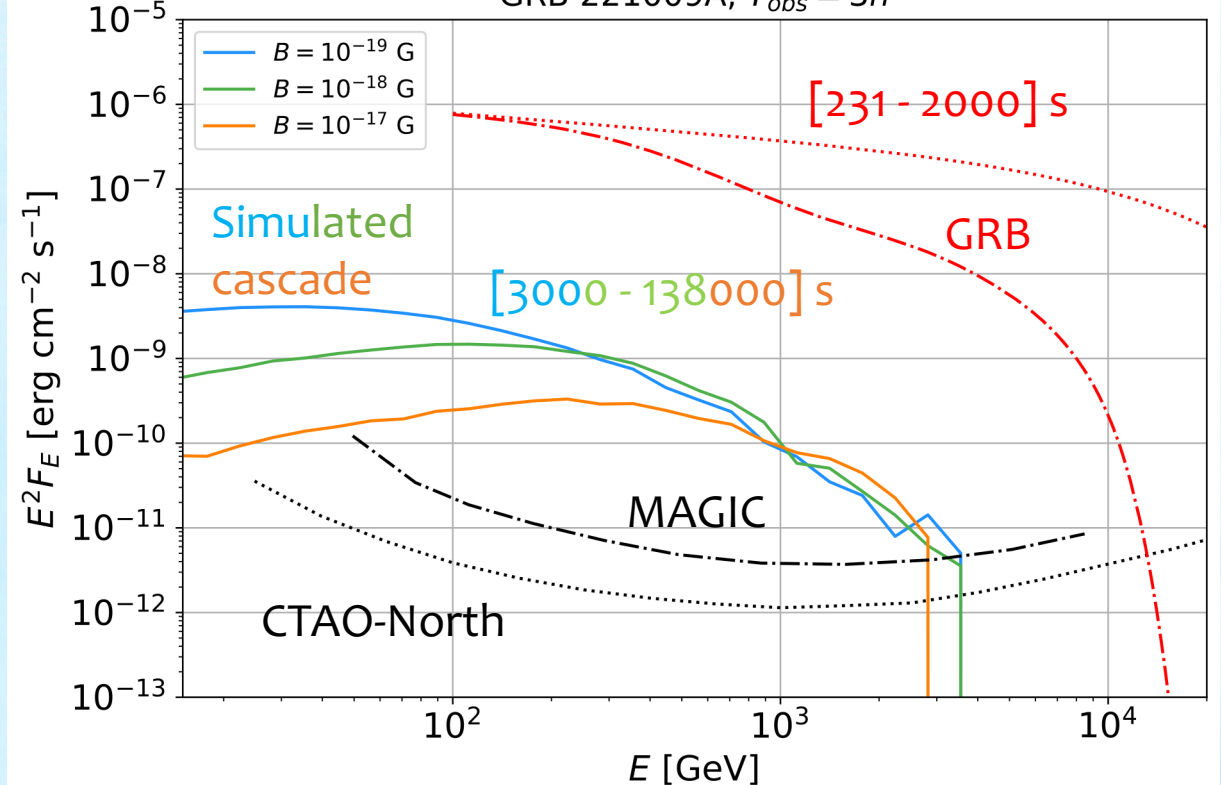
GRB190114C ($z = 0.42$)

GRB 190114C, $T_{obs} = 3h$



GRB221009A ($z = 0.151$)

GRB 221009A, $T_{obs} = 3h$



DM, Da Vela, Prandini (2025), E. A&A, 688, A57, 8.

GRBs observations can probe IGMF strengths in the $10^{-17} - 10^{-19}$ G $\rightarrow$ competitive with most stringent AGN results

Conclusions

- **GRBs detected > 1 TeV $\rightarrow$ GRB science does not stop at 100s GeV:**
 - **intrinsic properties:** KN cut-off, pp
 - **GRB as probes of fundamental physics** (IGMF, EBL, LIV)
- Results have shown that VHE emission is compatible with: (i) **broadband intrinsic properties** of GRBs (E_{iso} , L , z); (ii) **broad observational requirements** (time, E_{range}) $\rightarrow$ **universality of TeV component?**
- The presence of a universal VHE component in GRBs followed-up by MAGIC (2013 – 2019) with $L_{\text{VHE}} \sim L_{\text{X-ray}}$ is **still open** and **cannot be excluded**
- Observations of GRBs in the VHE domain may include **unexpected challenges**: **X-ray flares** in the VHE domain? Enlarge GRB follow-up population to **poorly-localized GRBs**? (IACT FoV will become larger; tiling follow-up strategies)
- GRB emission in the VHE domain can produce non-negligible **IGMF signatures** (*pair-echo emission*) detectable by current and future gamma-ray telescopes
- **GRBs for IGMF studies $\rightarrow$ See [Paolo Da Vela talk](#)**

BACKUP SLIDES

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)

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 $T_0 \sim 2-56$ minutes
- 1996: launch of Beppo-Sax
- 1994-00: several EAS searches for TeV/PeV emission from GRBs (including hint of Milagro 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

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 $>55^\circ$, Moon conditions

GRB160821B: Moon conditions

GRB180720B, GRB190829A: $T_{\text{delay}} \sim \text{hrs/days}$

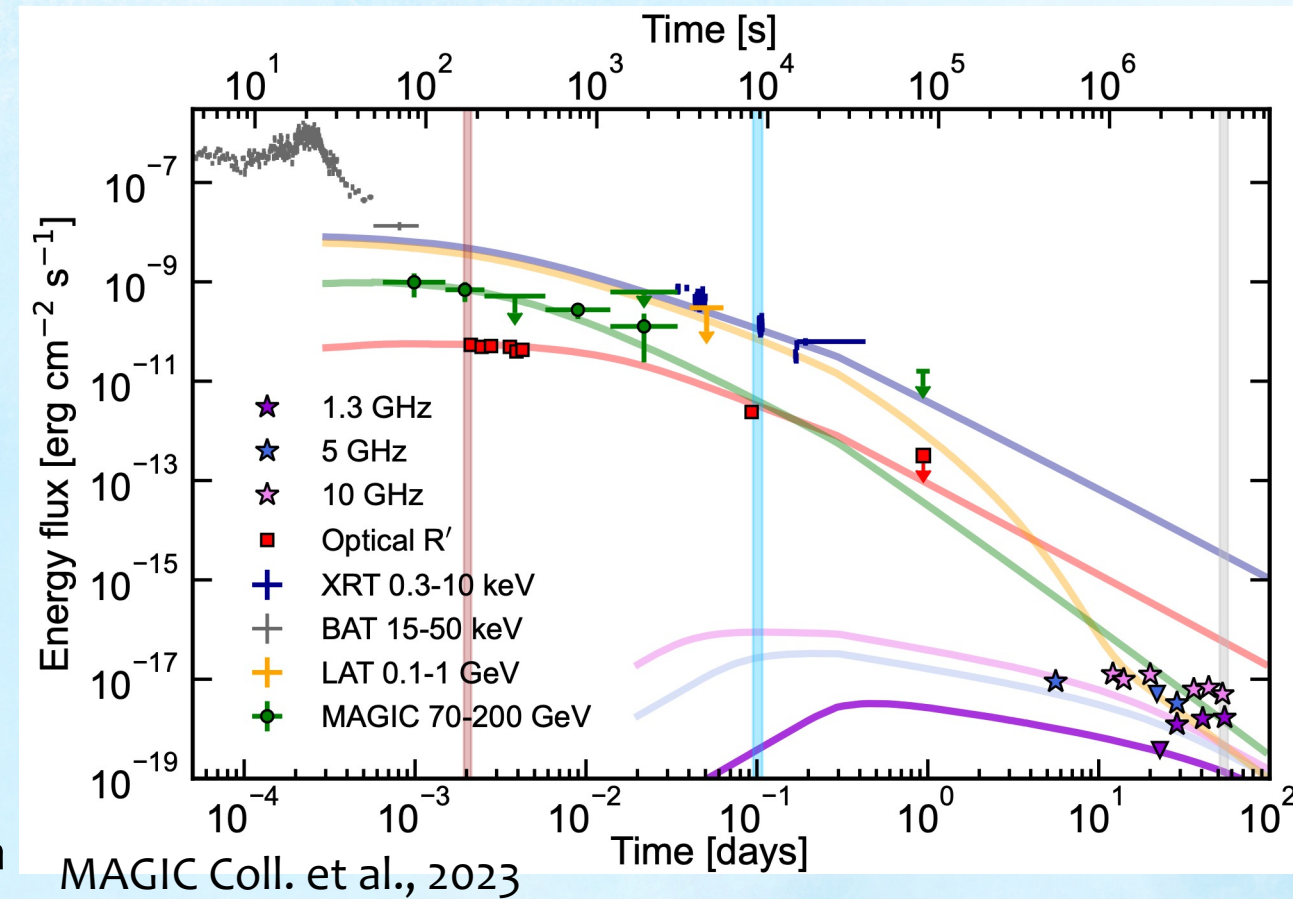
GRB201216C: $z = 1.1$

GRB190829A, GRB201015A, GRB160821B: $E_{\gamma, \text{iso}} \sim 10^{49} - 10^{50}$ erg

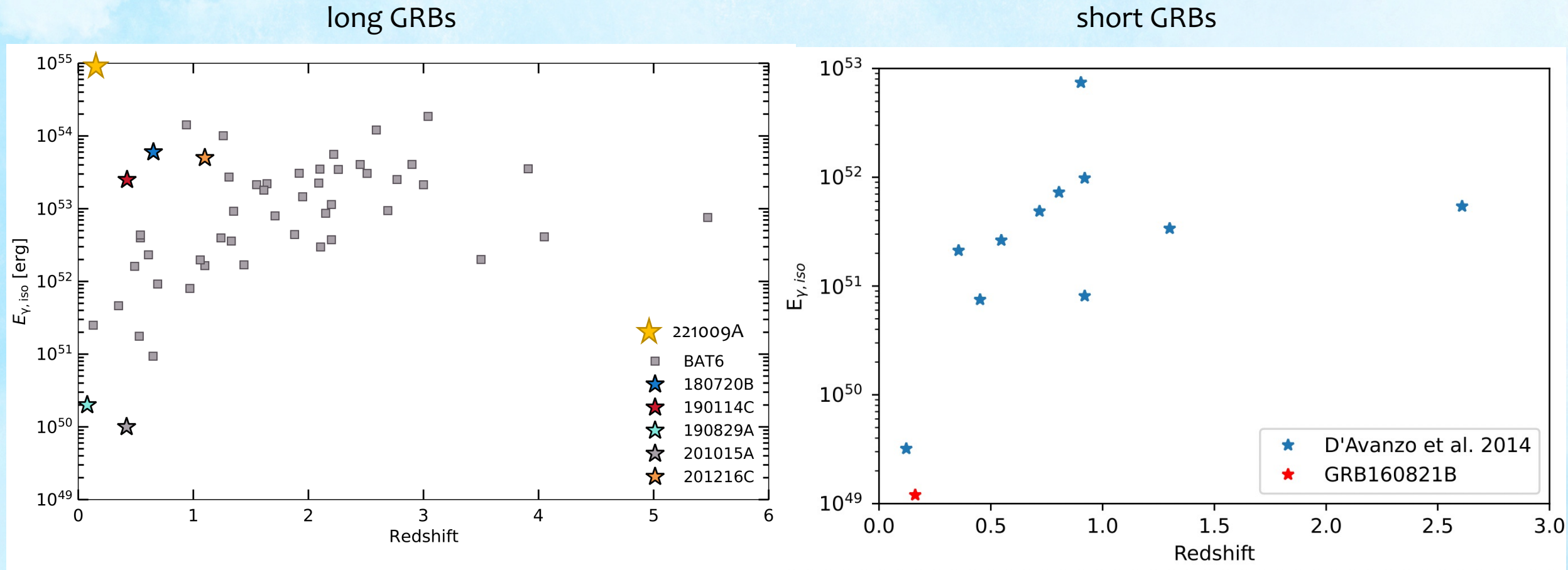
GRB190829A, GRB221009A: detected above 1 TeV

Population of GRBs in VHE domain

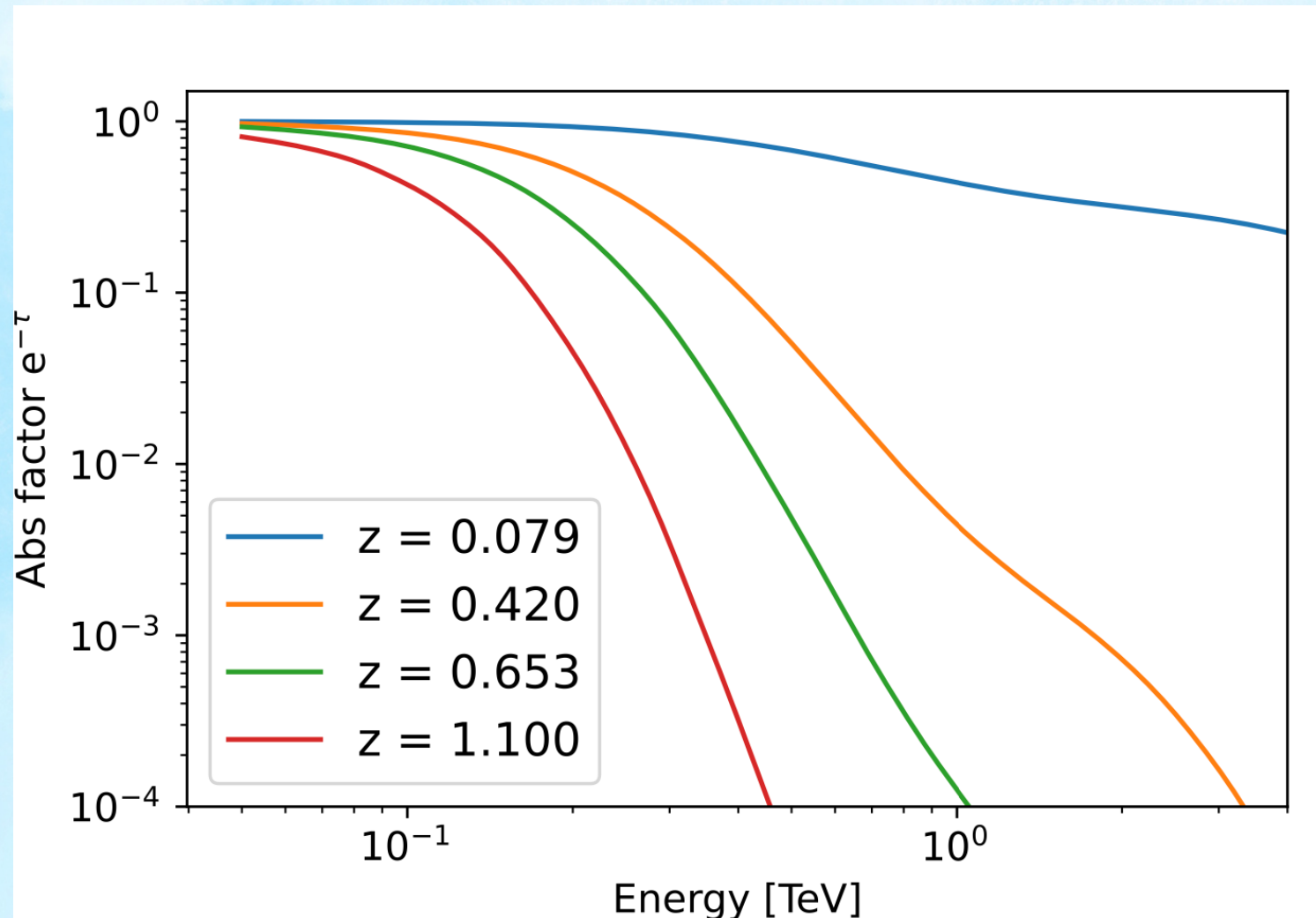
- Broadband intrinsic properties:
 - span more than 3 orders of magnitude in $E_{\gamma, \text{iso}}$
 - Span 2 orders of magnitude in terms of L_{VHE}
 - ranging in redshift between 0.079–1.1
- X-ray – TeV connection:
 - similar fluxes and decay slopes
 - similar amount of radiated power
- Data modeling: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



Population of GRBs in VHE domain: the role of redshift



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
- $F_{\text{att}} \sim 90\%$ at 1 TeV

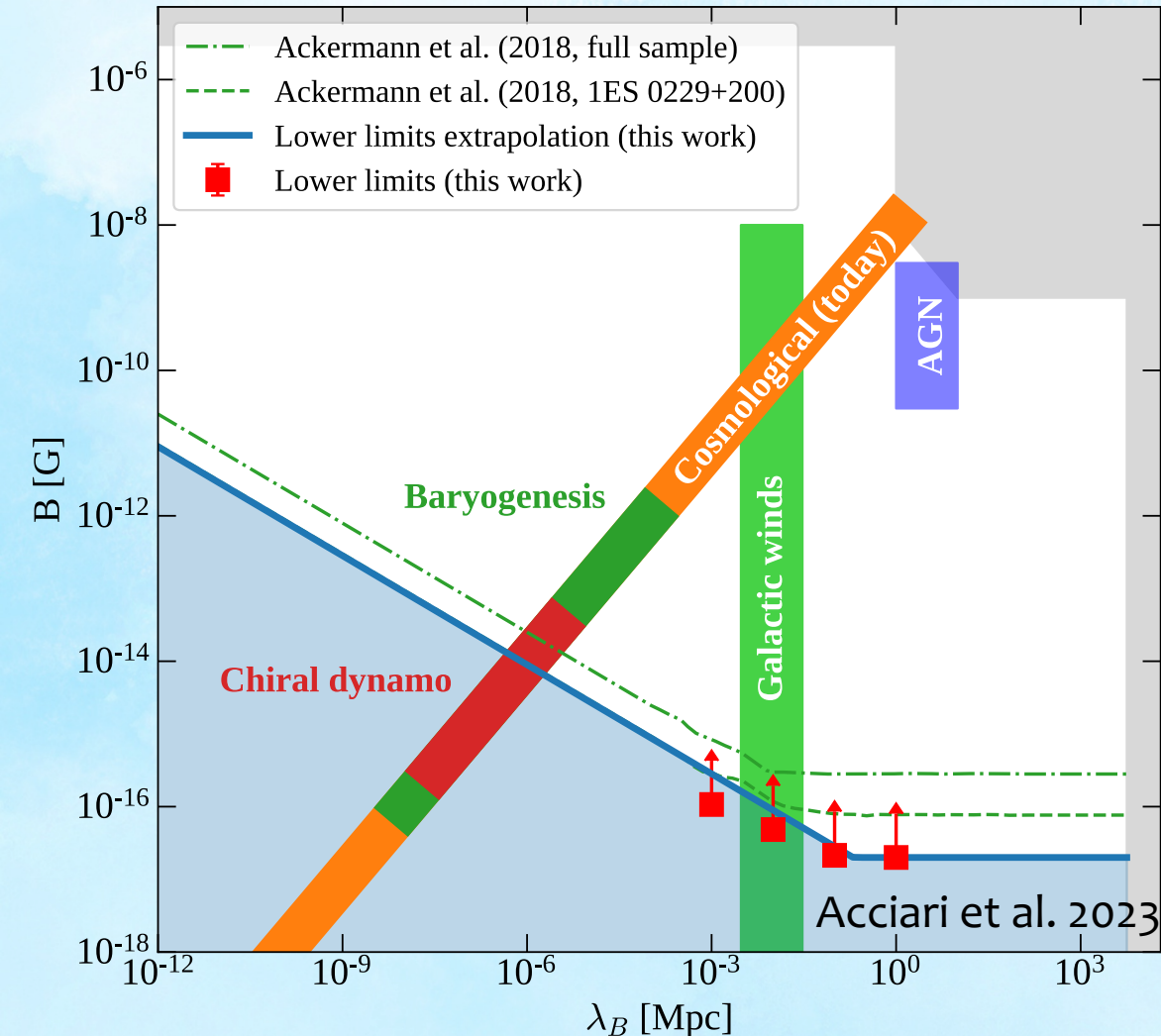
$z = 0.4$

- $F_{\text{att}} \sim 50\%$ at 0.2 TeV
- $F_{\text{att}} \sim 99.5\%$ at 1 TeV

$z = 1.1$

- $F_{\text{att}} \sim 95\%$ at 0.2 TeV

IGMF constraints with AGNs



Features:

- Sources of persistent TeV emission
- Blazars have hard ($\Gamma \lesssim 2$) photon spectrum extending to TeV domain
- Population of ~ 90 sources known as VHE emitters

Limitations for IGMF studies:

- Affected by largely unknown temporal (min-yrs) and/or spectral variability
- Unknown duty cycle ($10 - 10^8$ yrs)
- Pollution by primary source GeV emission → disentangle source+IGMF-induced emission

AGNs open IGMF studies with γ -rays but limitations highlight the need to search for alternative sources

IGMF constraints with GRBs

Recently TeV-detected bright GRBs exploited for first IGMF studies

Advantages:

- Cosmological (long GRBs average $z \sim 3$) and bright ($L \sim 10^{49} - 10^{53} \text{ erg s}^{-1}$) sources $\rightarrow$ increase redshift horizon
- GRBs timescales of emission (hours, days in gamma-ray domain) $\rightarrow$ reduced pollution from primary source
- GRB duty cycle $\rightarrow$ relaxed assumption

Drawbacks:

- Transient nature $\rightarrow$ smaller amount of pair-echo emission $\rightarrow$ less stringent bounds than AGNs in similar conditions
- Limited number of TeV-detected events (5 detections)
- Spectral and temporal variability

So far only episodic studies with Fermi-LAT data on TeV-detected GRBs
(General population of GRBs? IACTs and VHE?)

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

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

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

$$T_{\text{delay}} \propto B^2 E_\gamma^{-5/2}$$

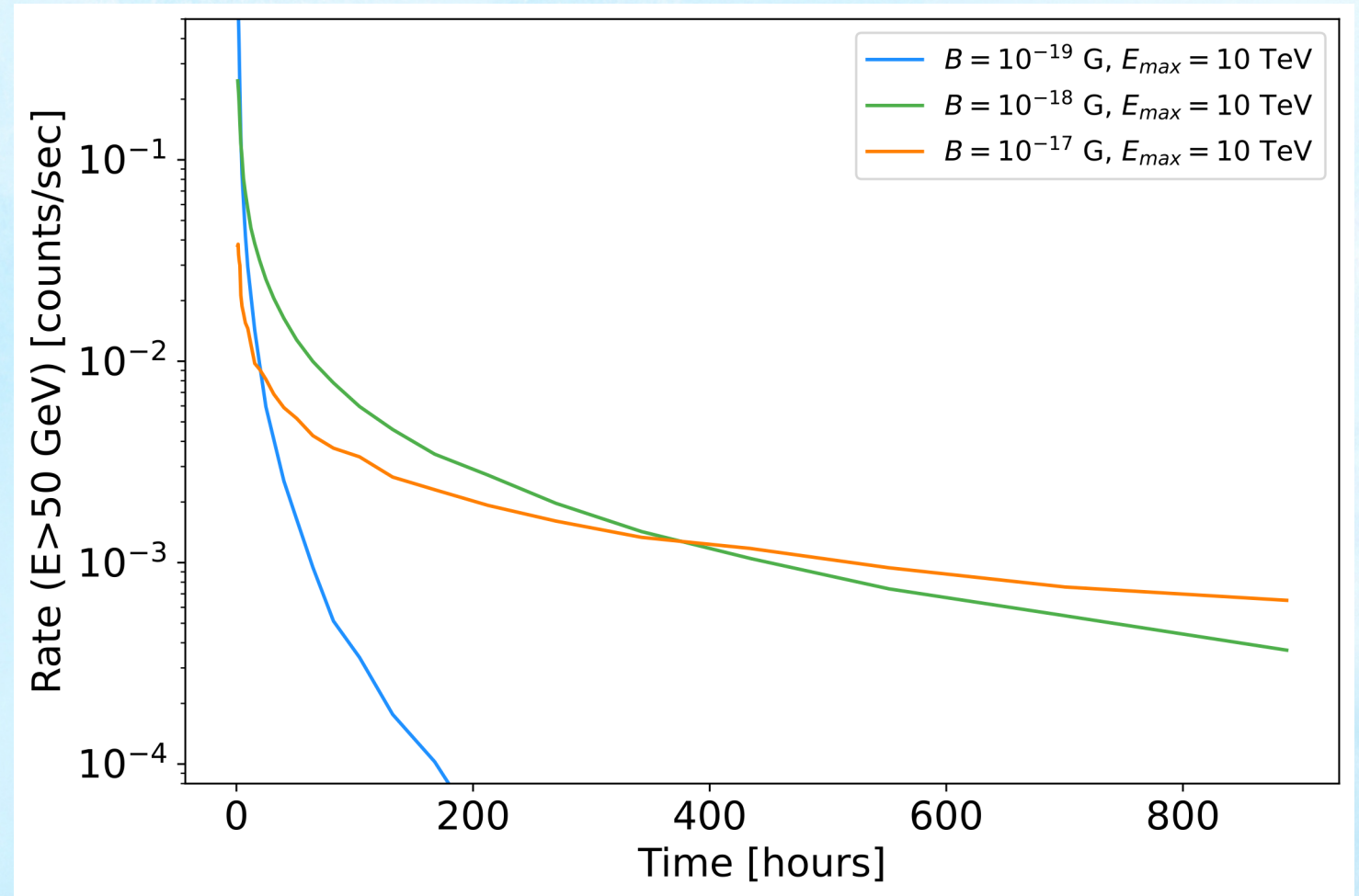
$$T_{\text{delay}} \propto B^2 E_\gamma^{-2} \lambda_B$$

$$\lambda_B \gg \lambda_{IC}$$

$$\lambda_B \ll \lambda_{IC}$$

Neronov et al. 2009

Batista et al. 2021



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

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$$\begin{aligned} T_{\text{delay}} &\propto B^2 E_\gamma^{-5/2} & \lambda_B &\gg \lambda_{\text{IC}} \\ T_{\text{delay}} &\propto B^2 E_\gamma^{-2} \lambda_B & \lambda_B &\ll \lambda_{\text{IC}} \end{aligned}$$

- 100s GeV photons experience shorter delays ($\sim$ hrs/days) than GeV photons ($\sim$ 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)

What impact IGMF studies with γ -rays?

**Intrinsic source
properties**

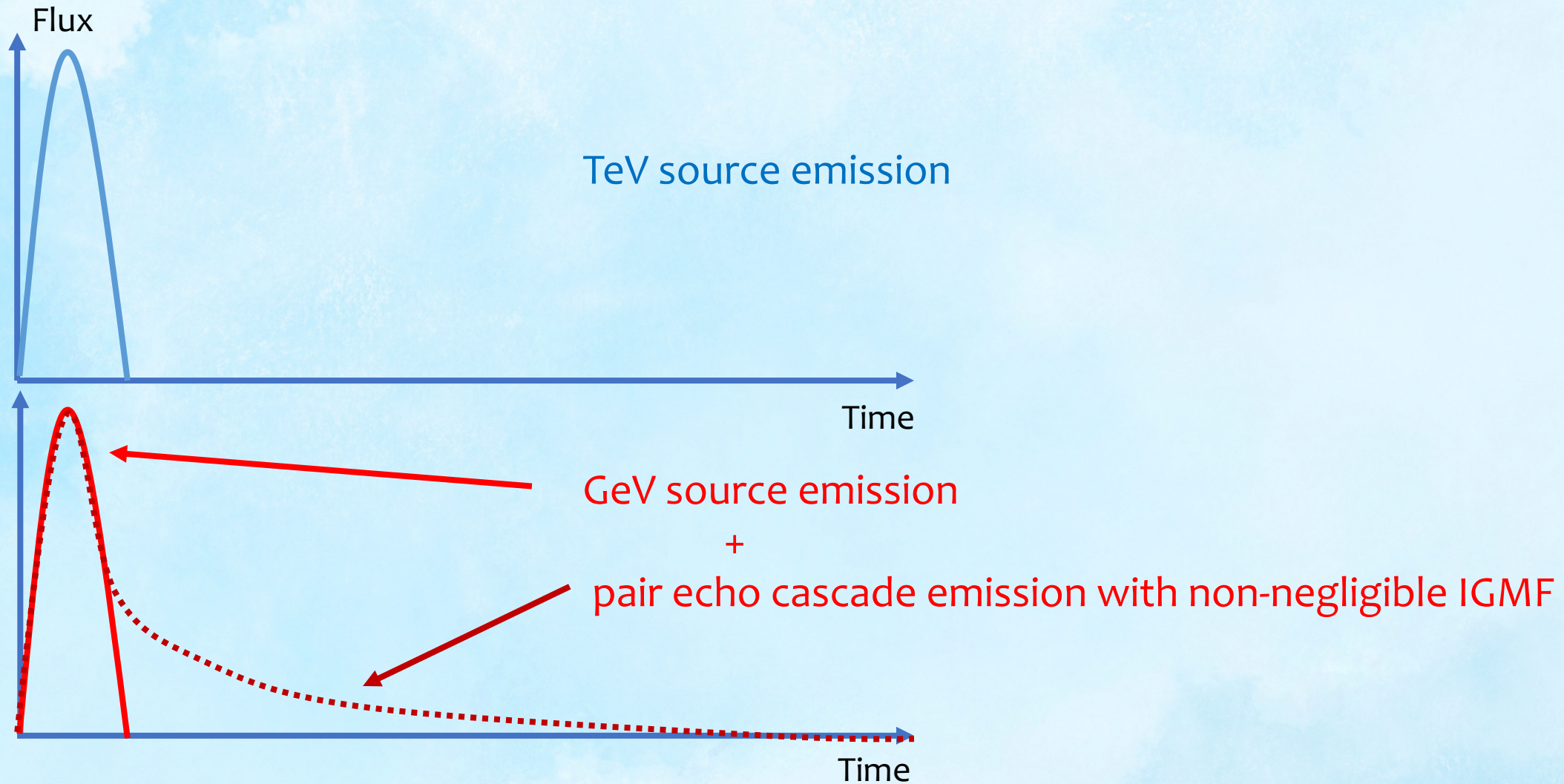
**Gamma-ray propagation
(EBL, pair scatter, IC) and
magnetic field models**

**Instrument
sensitivity**

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

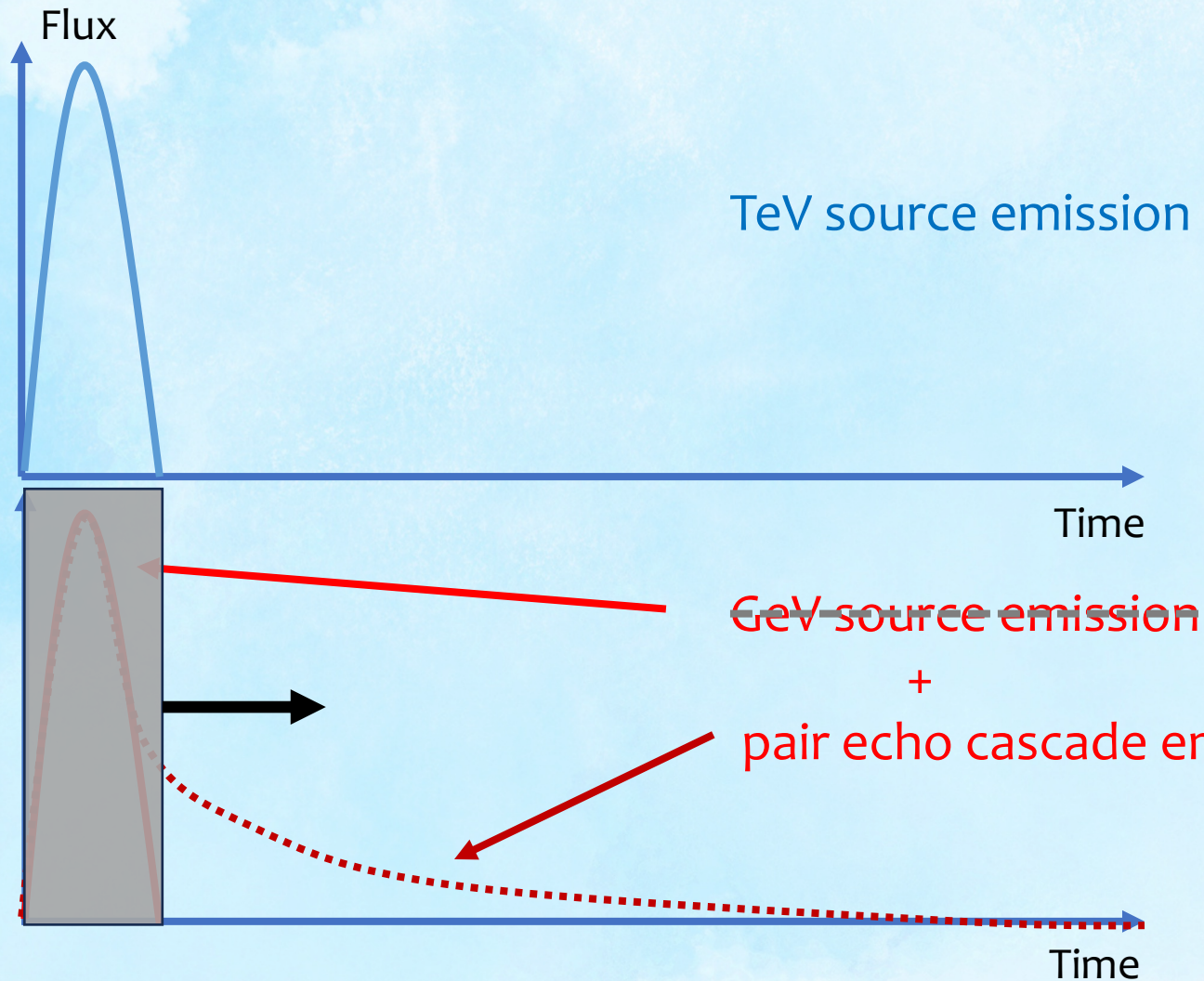
Pair-echo with TeV-detected GRBs

Plaga 1995
Murase et al. 2008



Pair-echo with TeV-detected GRBs

Plaga 1995
Murase et al. 2008

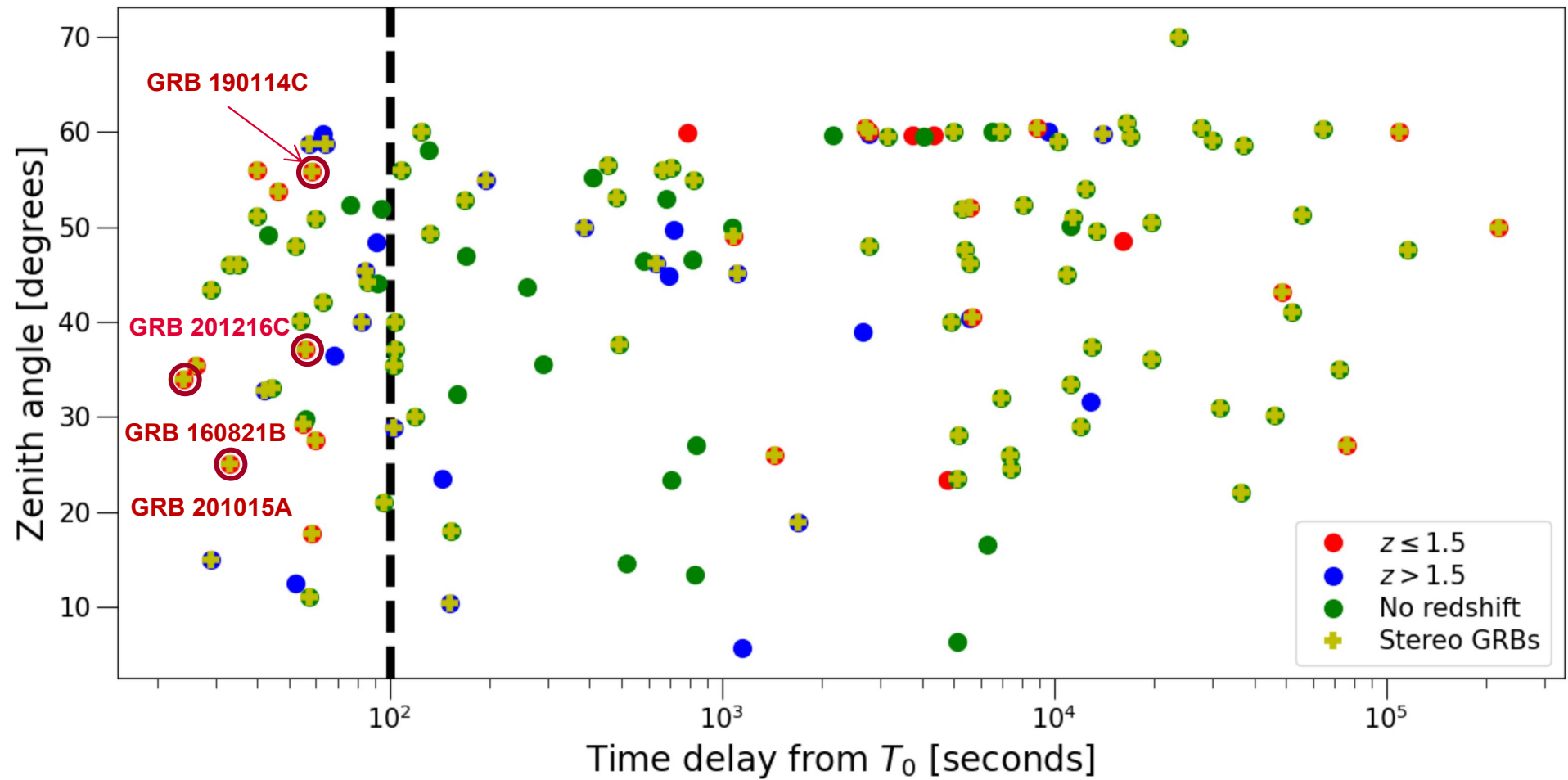


- Select observational time intervals
- Compute pair-echo SEDs
- Compare with instrument sensitivities

Observations of GRBs at TeV energies

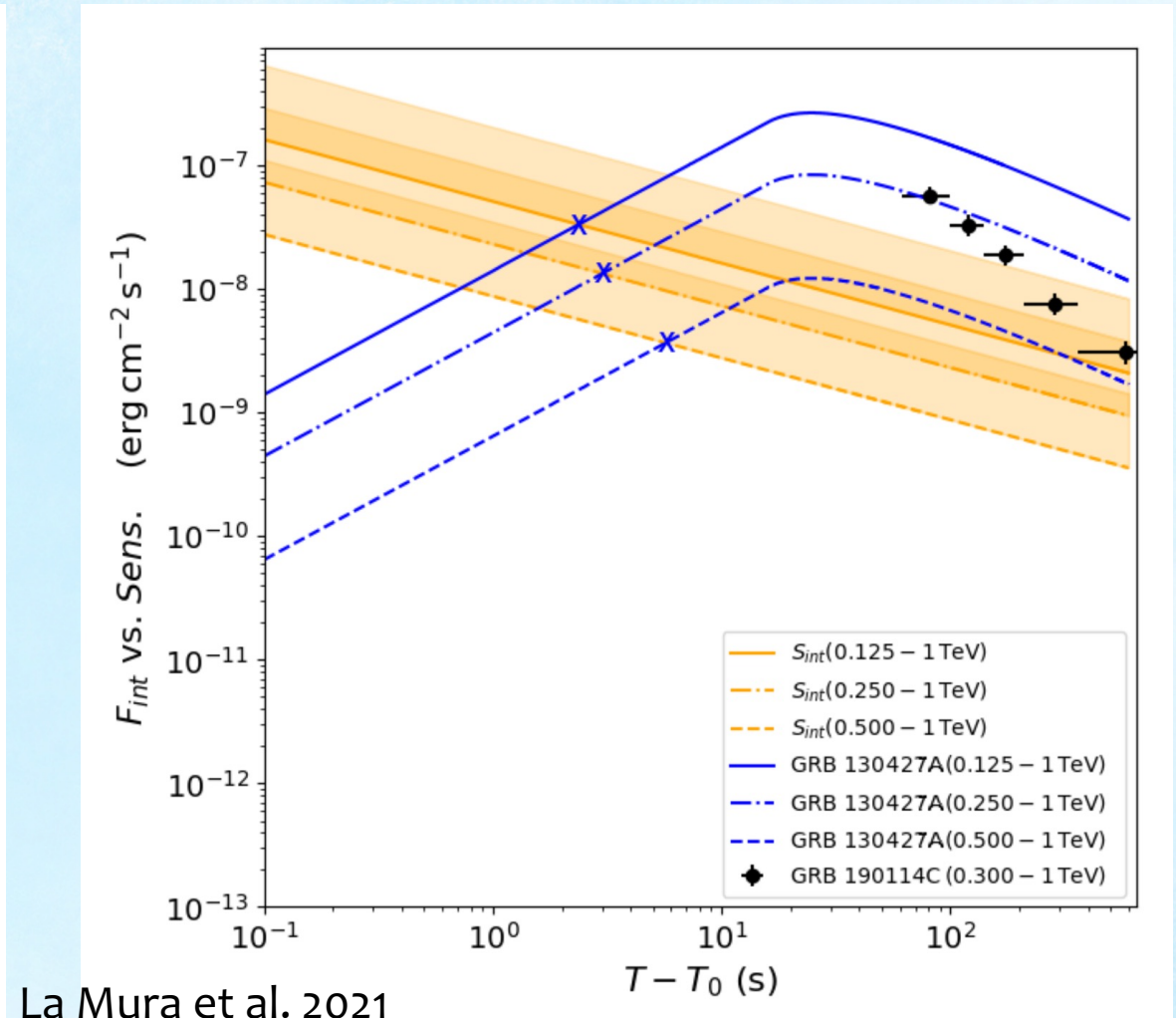
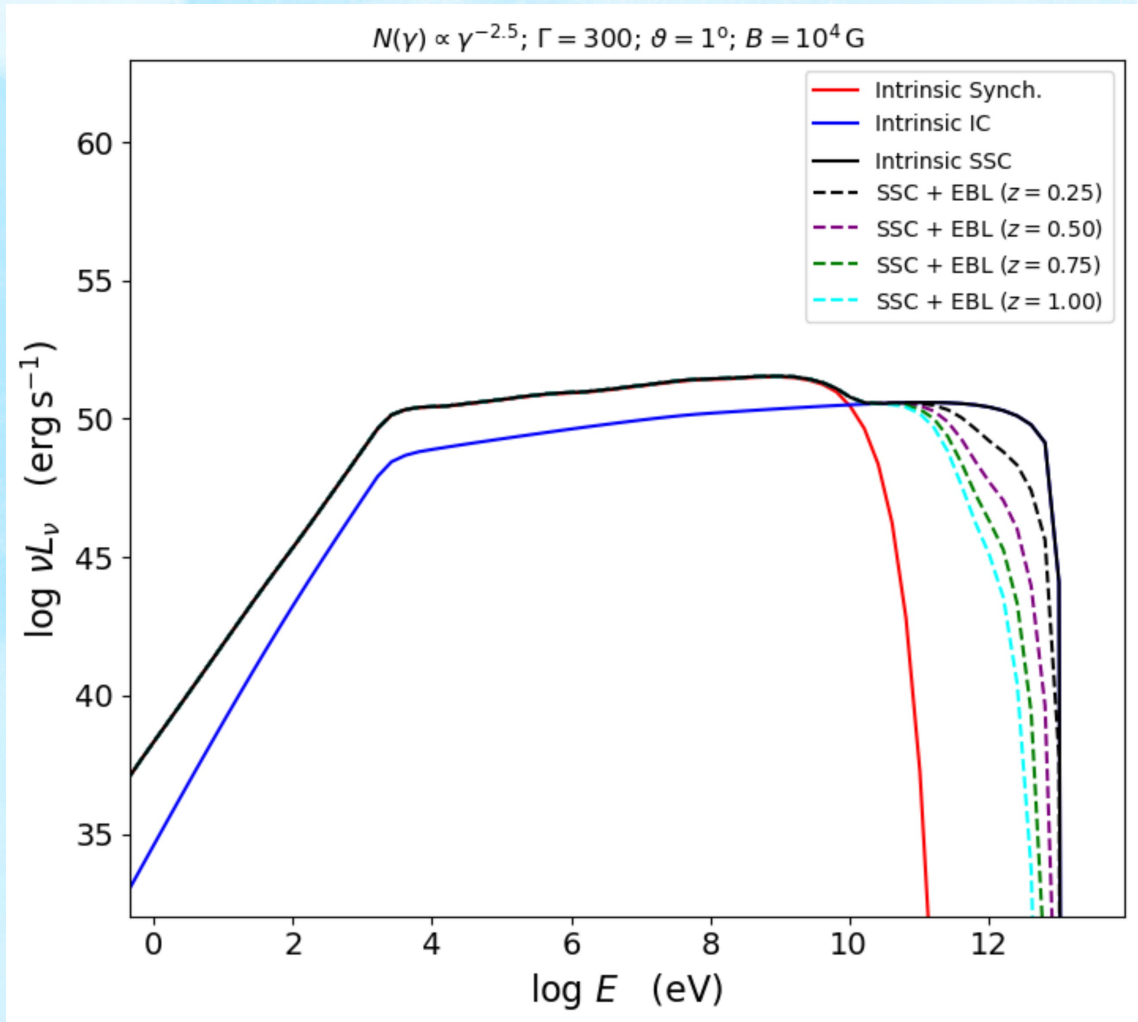
- Imaging Atmospheric Cherenkov Telescopes (IACTs) [30-50 GeV – 10s TeV]
 - Narrow field of view (FoV) ($3-5^\circ$) → need external alert + automatic alert system + fast repointing
 - Small duty cycle (10%)
 - Low energy threshold: 30-50 GeV
 - Best sensitivity up to a few TeV
- Shower front arrays [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

Decades of searches for the VHE emission



Berti et al., ICRC 2021

Gamma-ray bursts with SWGO



La Mura et al. 2021

Ricerca

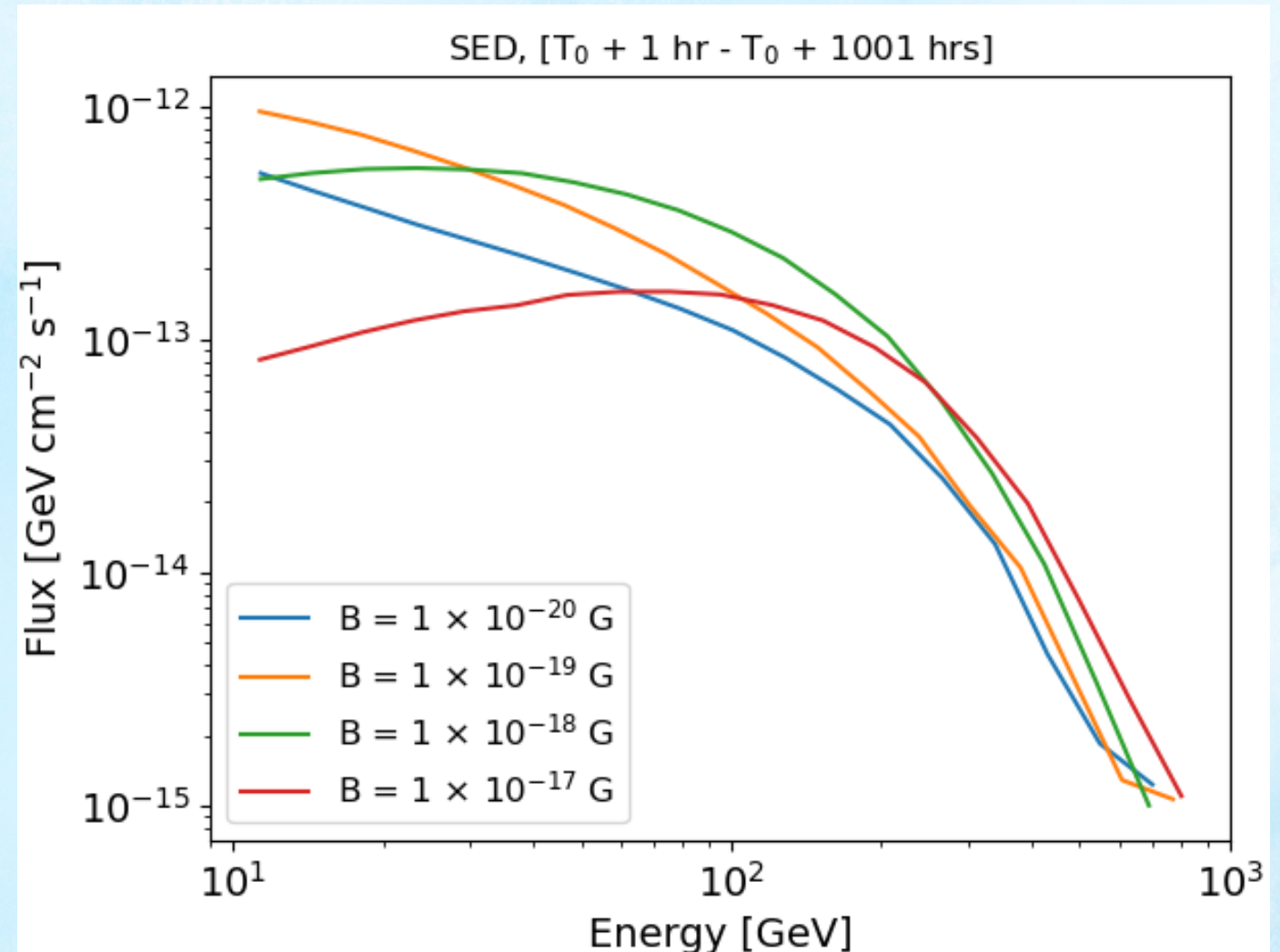
Search for the time-delayed 'pair-echo' cascade emission

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

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

$$\begin{aligned} T_{\text{delay}} &\propto B^2 E_\gamma^{-5/2} & \lambda_B \gg \lambda_{\text{IC}} \\ T_{\text{delay}} &\propto B^2 E_\gamma^{-2} \lambda_B & \lambda_B \ll \lambda_{\text{IC}} \end{aligned}$$

Neronov et al. 2009
Batista et al. 2021

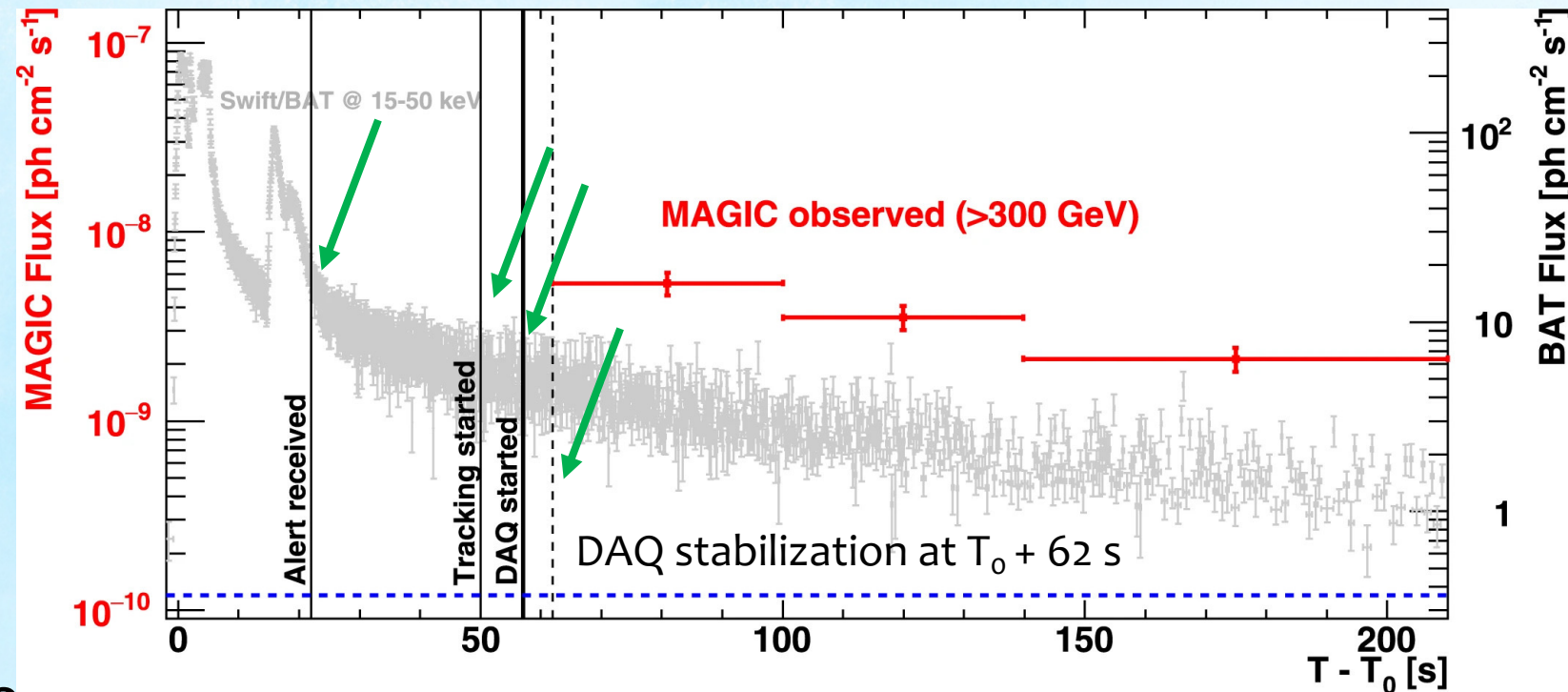


GRB 190114C -- Timeline

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

MAGIC detection info:

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

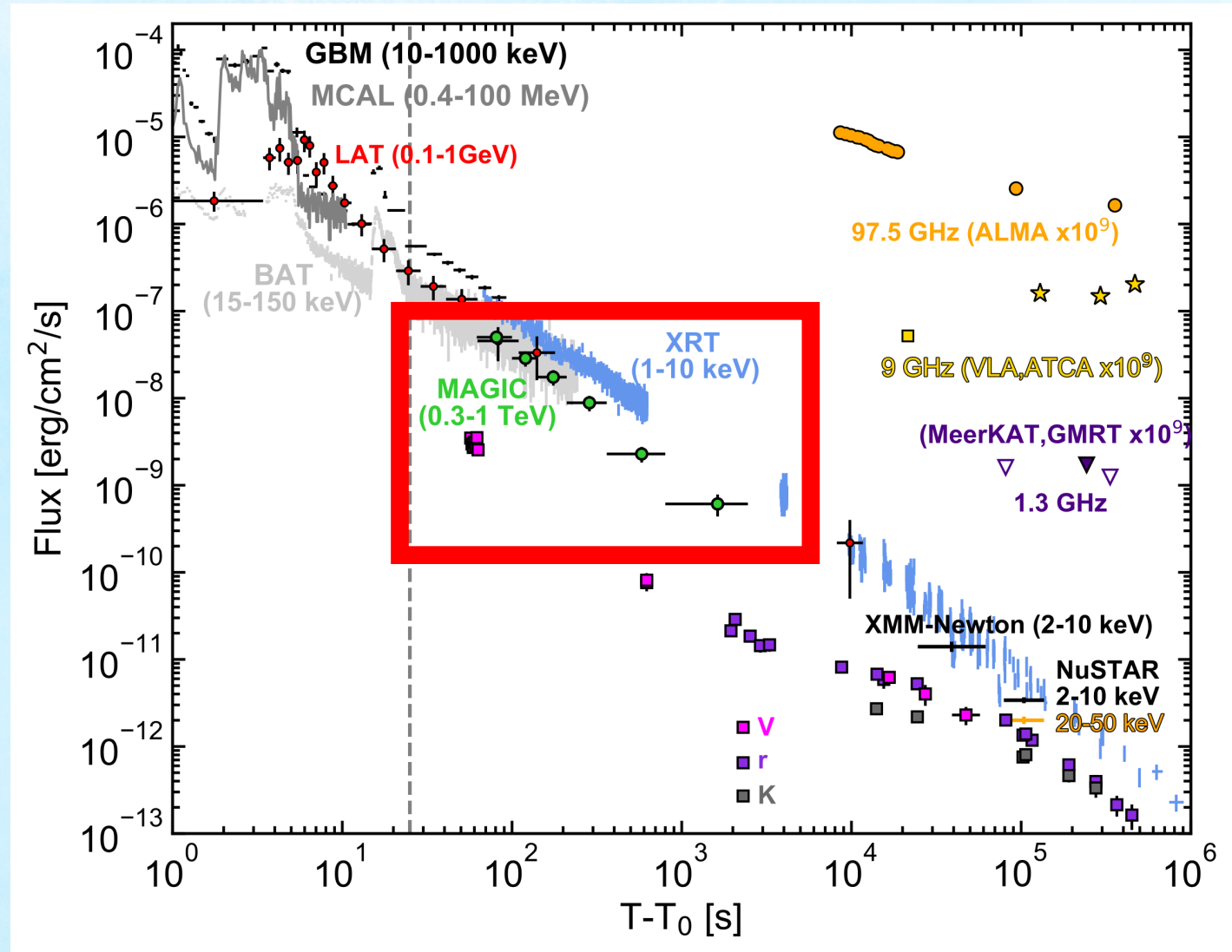


MAGIC Coll. et al., 2019

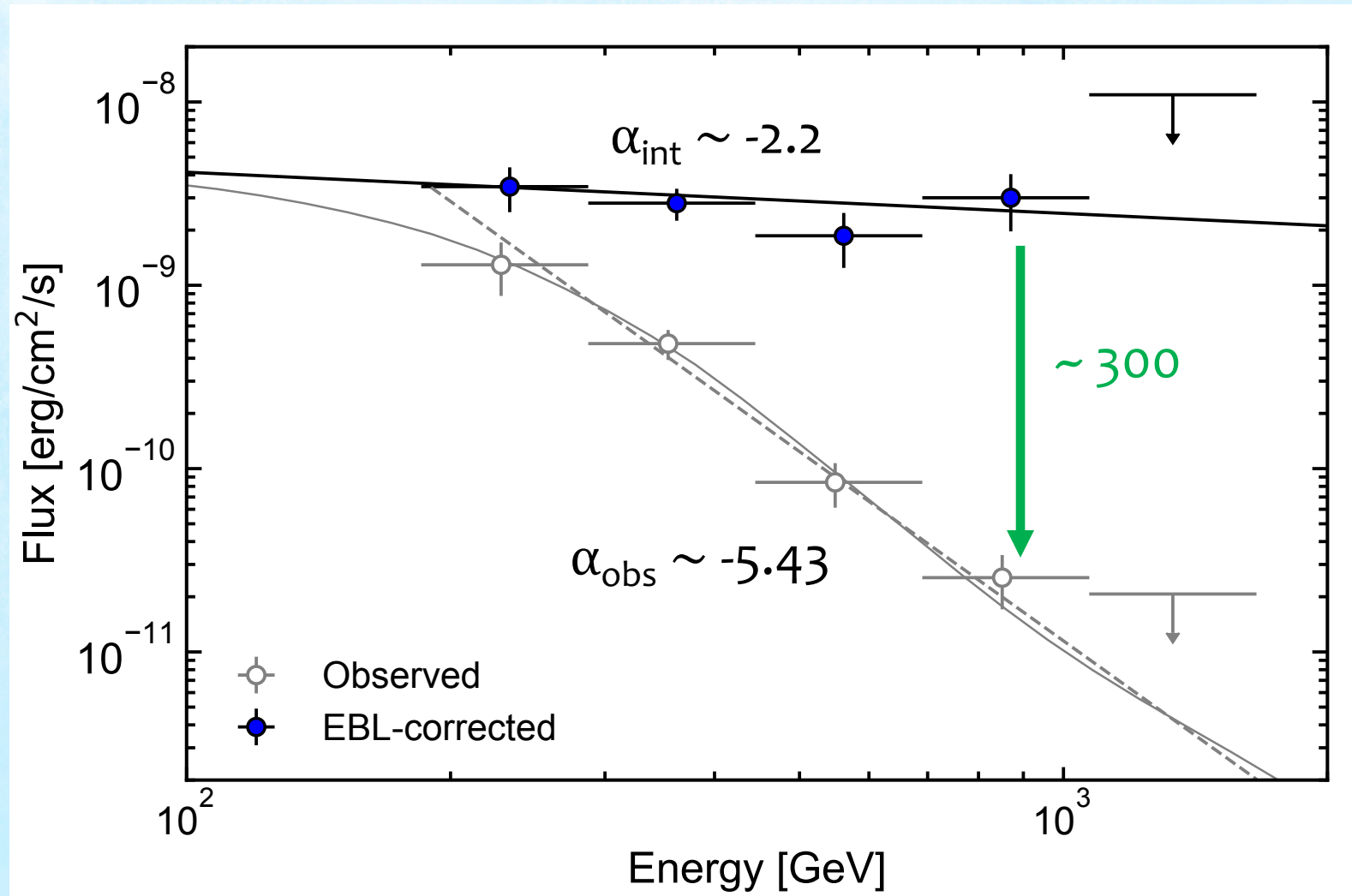
GRB 190114C – Light curve

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



GRB 190114C – VHE SED



GRB 190114C -- interpretation

Acceleration timescale (Bohm level)

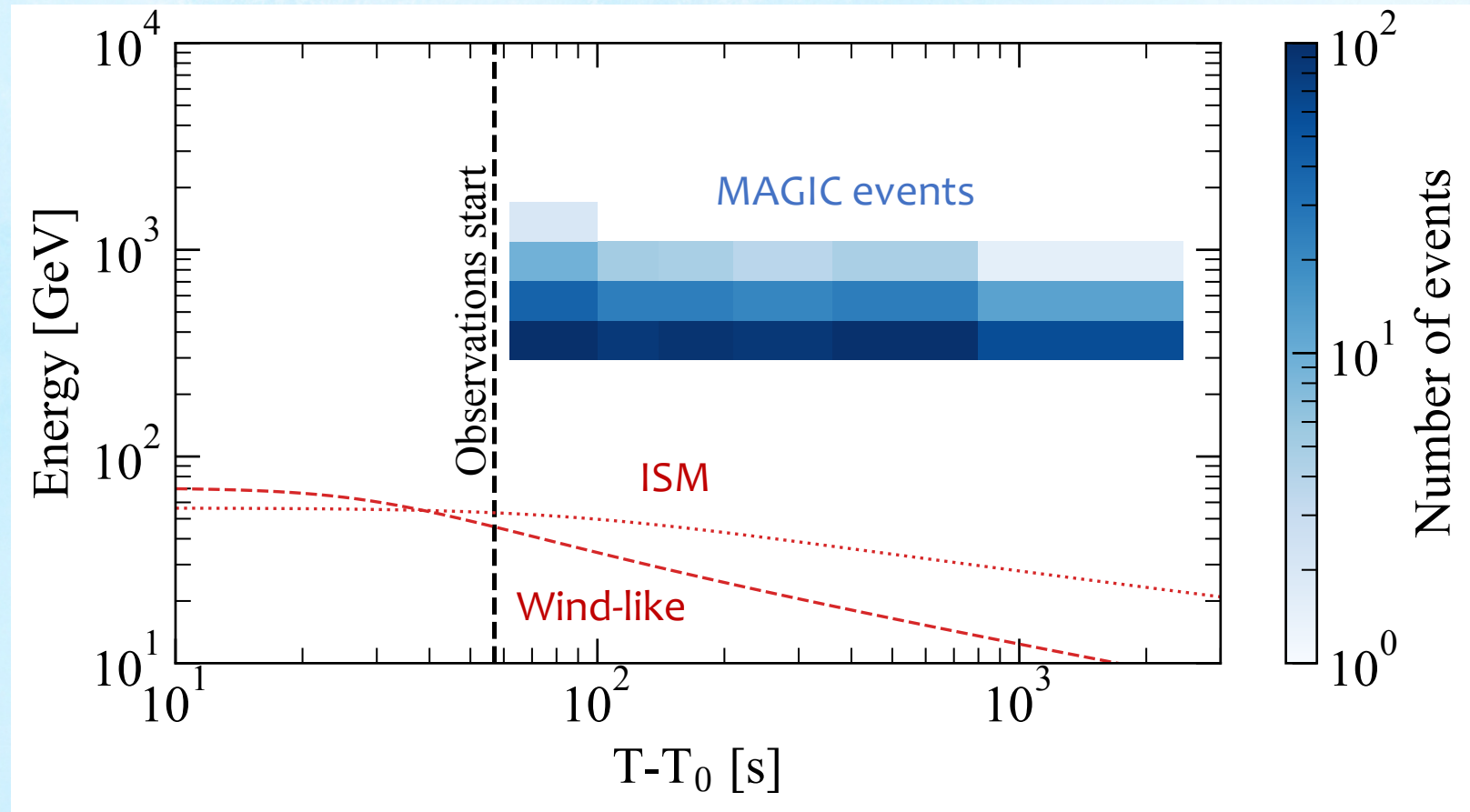
$$t'_L = \frac{r_L}{c} = \frac{\gamma m_e c}{e B'}$$

e-Synchrotron cooling timescale

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

Synchrotron burnoff limit

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



MAGIC Coll. et al., 2019

GRB 190114C -- interpretation

X-ray + GeV + TeV

↓

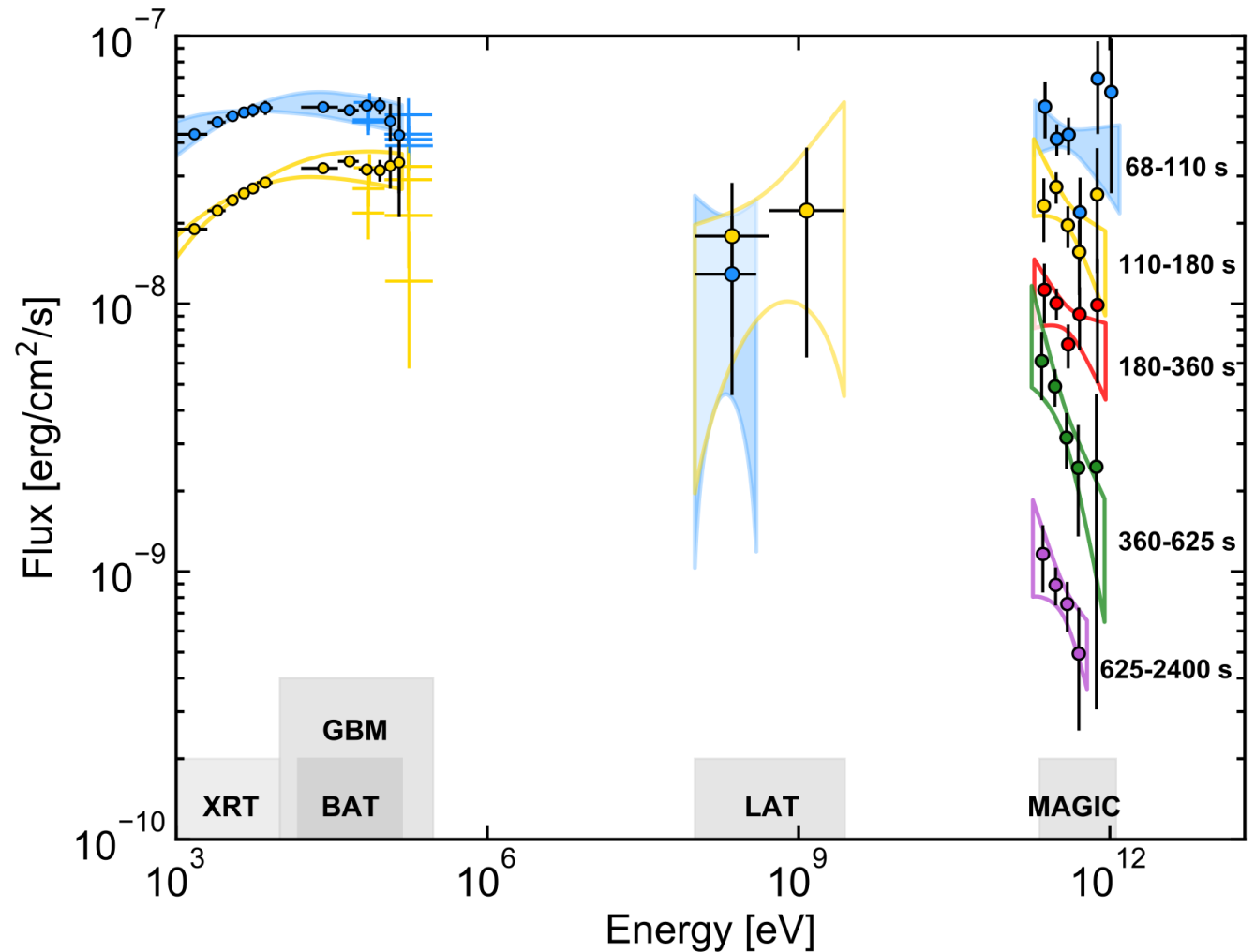
Spectral hardening for $E > 0.2$ TeV

↓

Can't be extension of Synchrotron component

↓

New emission component at VHE



GRB 190114C -- modeling

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

— Observed
- - - No $\gamma\text{-}\gamma$ opacity
— EBL-deabsorbed

MAGIC soft spectrum:

- Klein-Nishina
- $\gamma\text{-}\gamma$ internal absorption

GRB afterglow parameters:

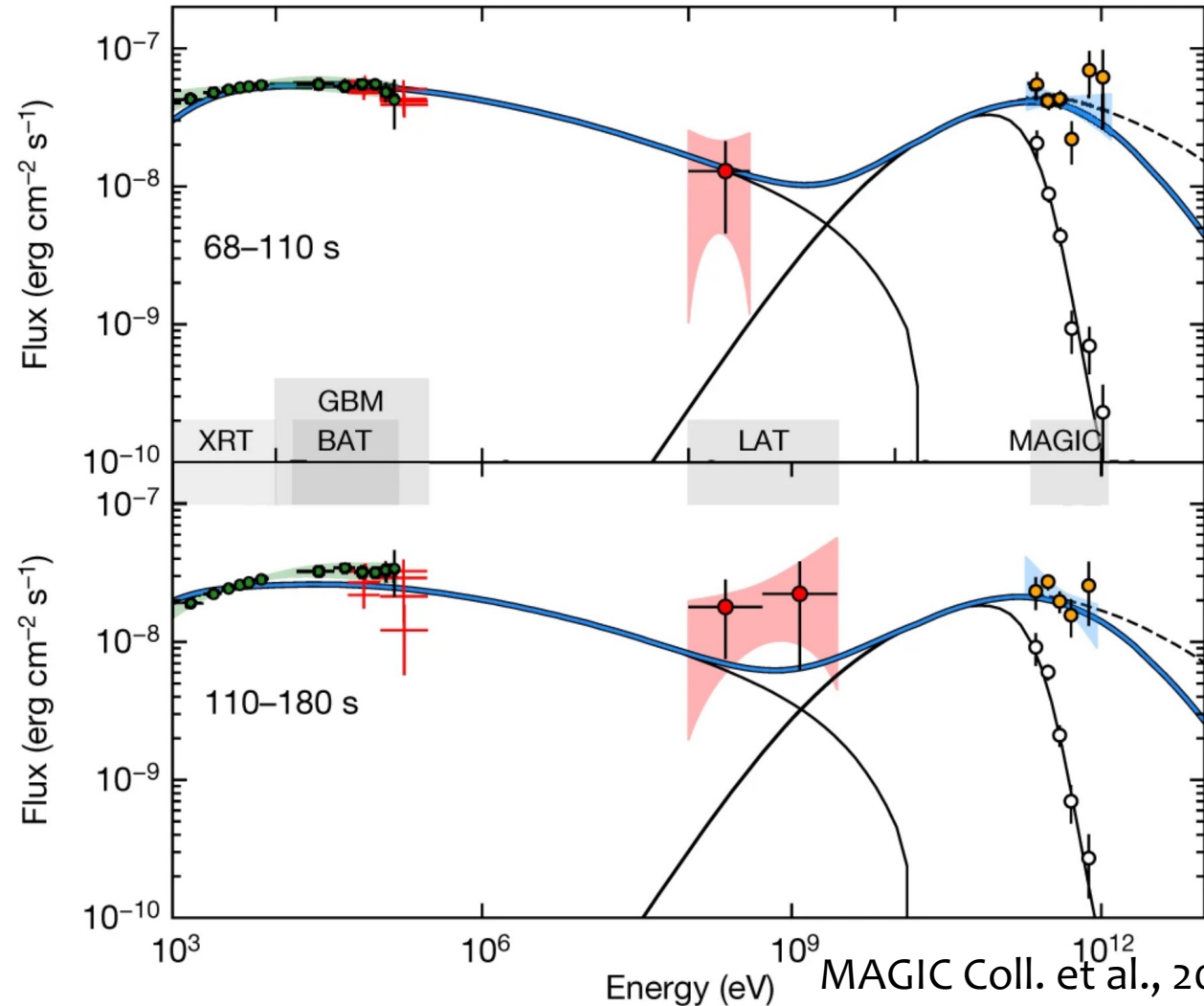
$$E_k \gtrsim 3 \times 10^{53} \text{ erg}$$

$$\epsilon_e \sim 0.05 - 0.15$$

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

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

$$p \sim 2.4 - 2.6$$

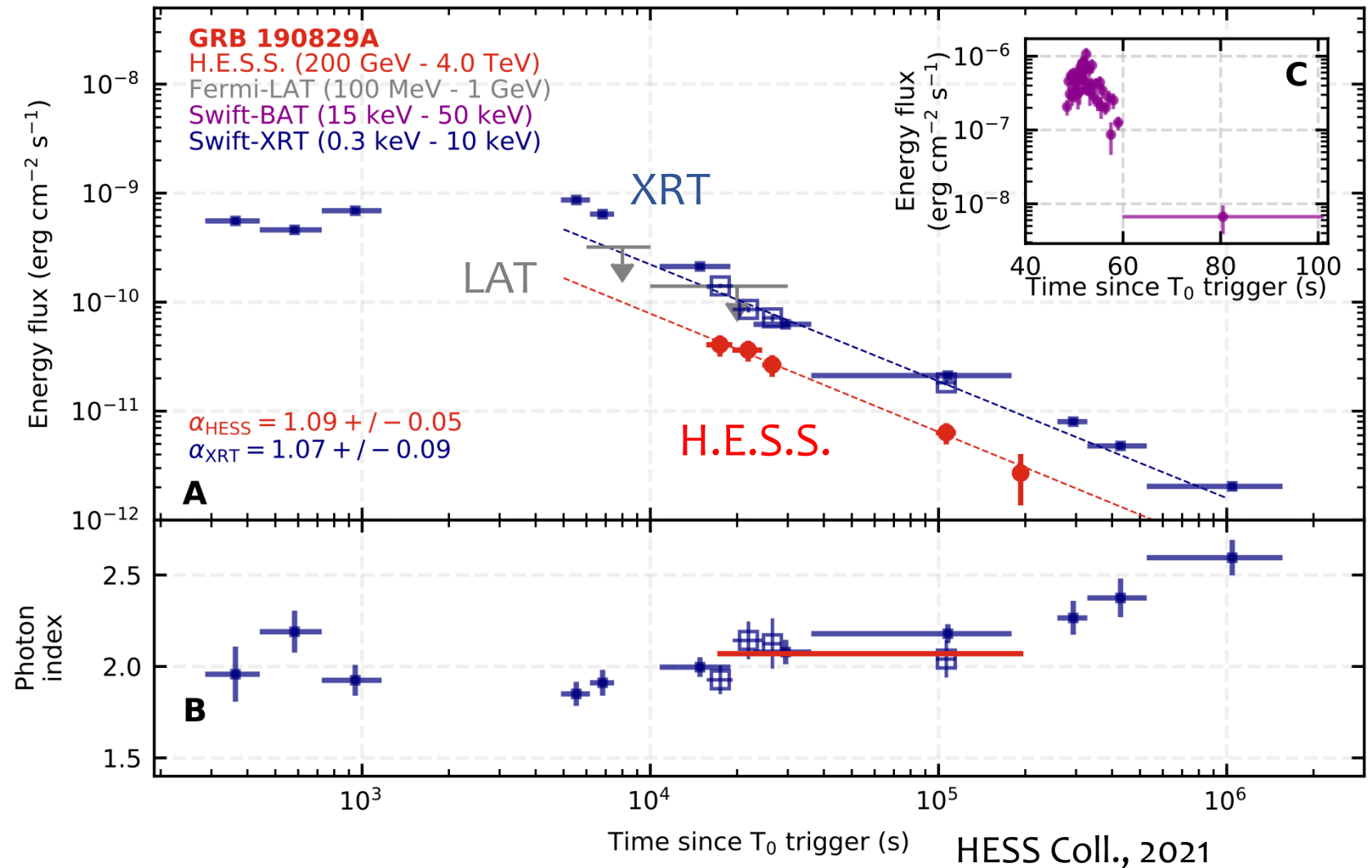


GRB 190829A

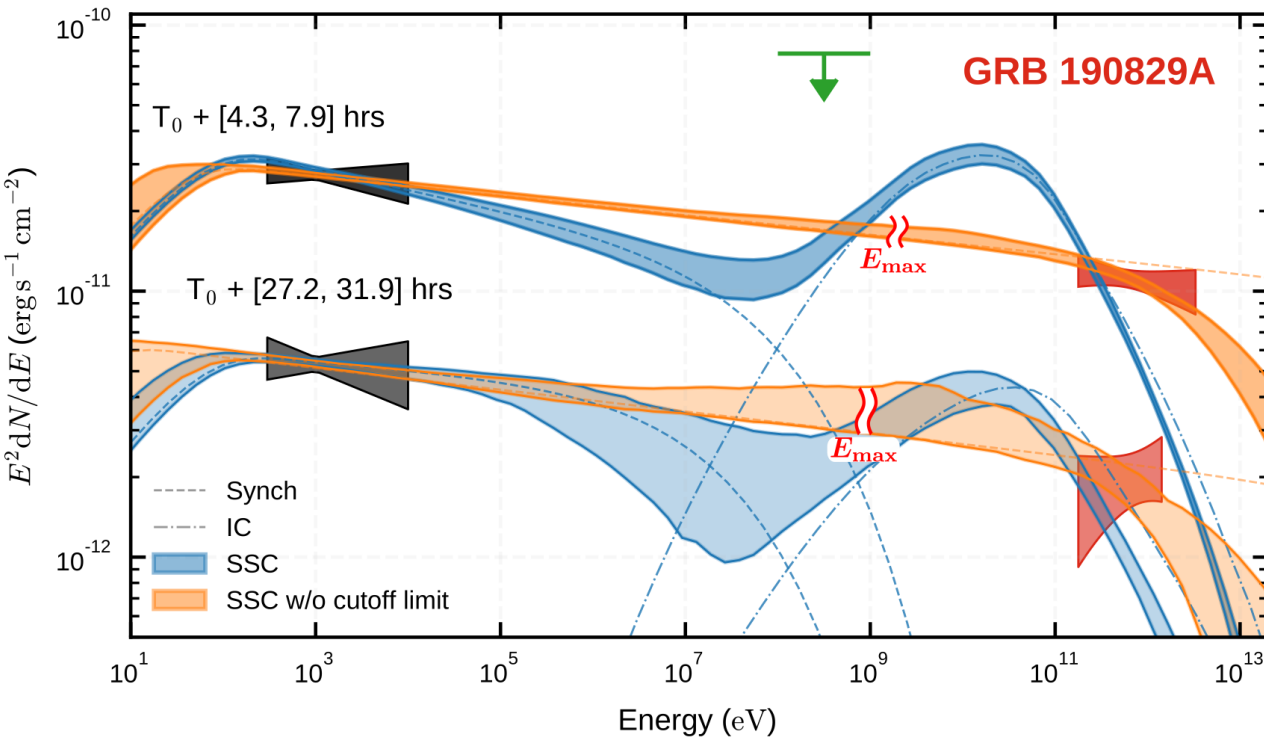
- $E_{\gamma, \text{iso}} \sim 2.0 \times 10^{50} \text{ erg}$
- $z = 0.079$

H.E.S.S. detection info:

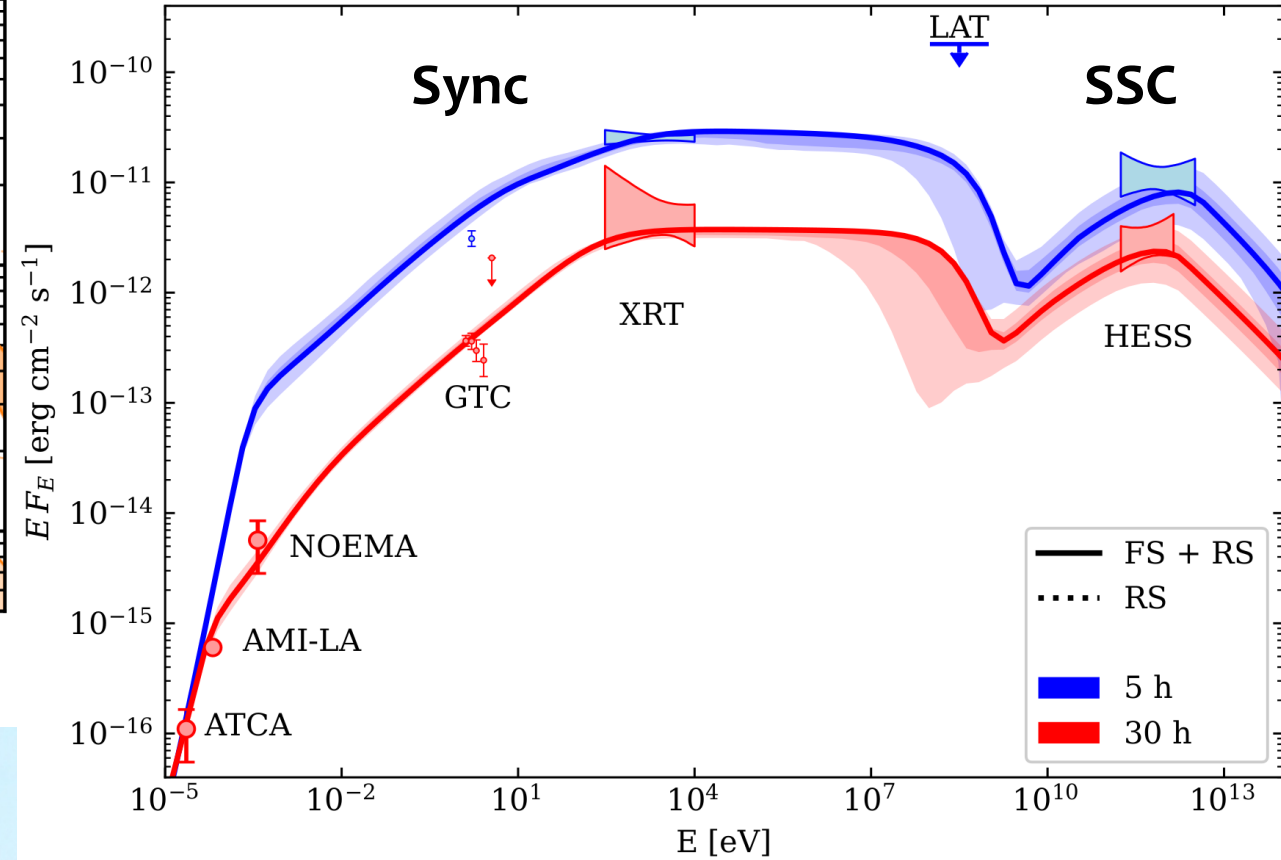
- $T_{\text{obs}} \sim 4.3 - 55.9 \text{ hrs}$
- $21.7\sigma, 5.5\sigma, 2.4\sigma,$
- $0.18 - 3.3 \text{ TeV energy range}$



GRB 190829A



HESS Coll., 2021



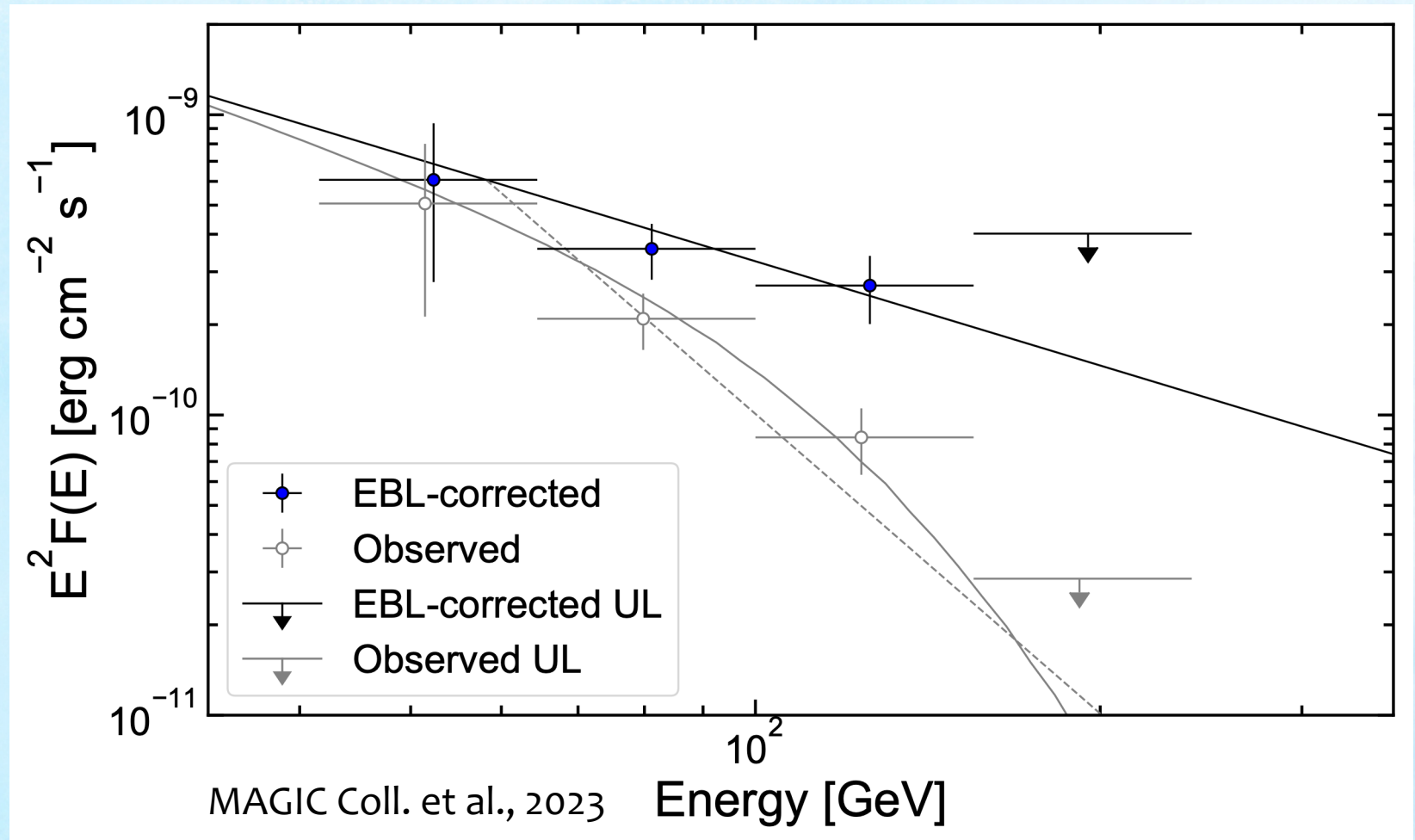
Salafia et al., 2021

GRB 201216C

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

MAGIC detection info:

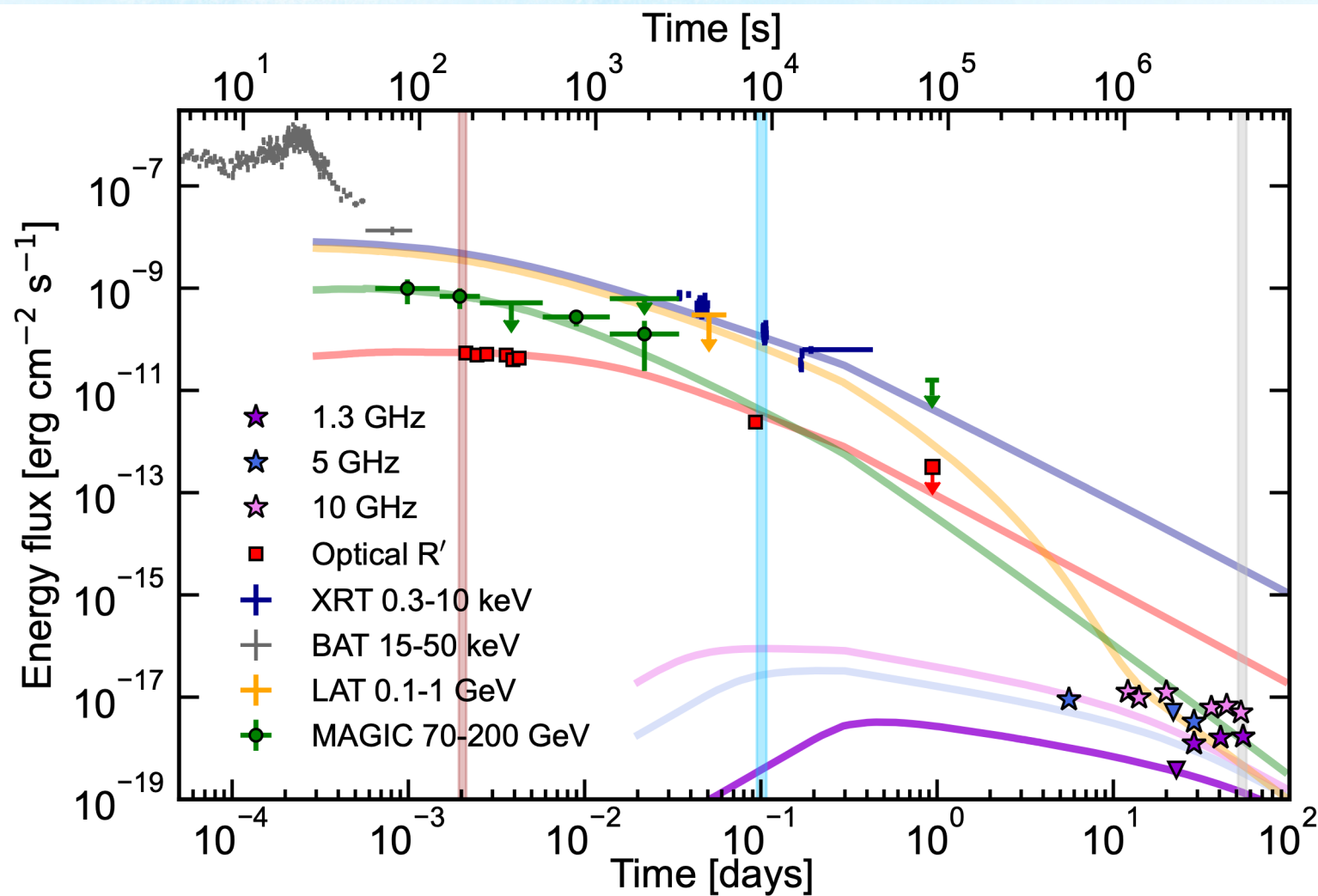
- Tdelay $\sim 56 \text{ s}$
- 6σ in 20 minutes
- 0.07 – 0.2 TeV energy range



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

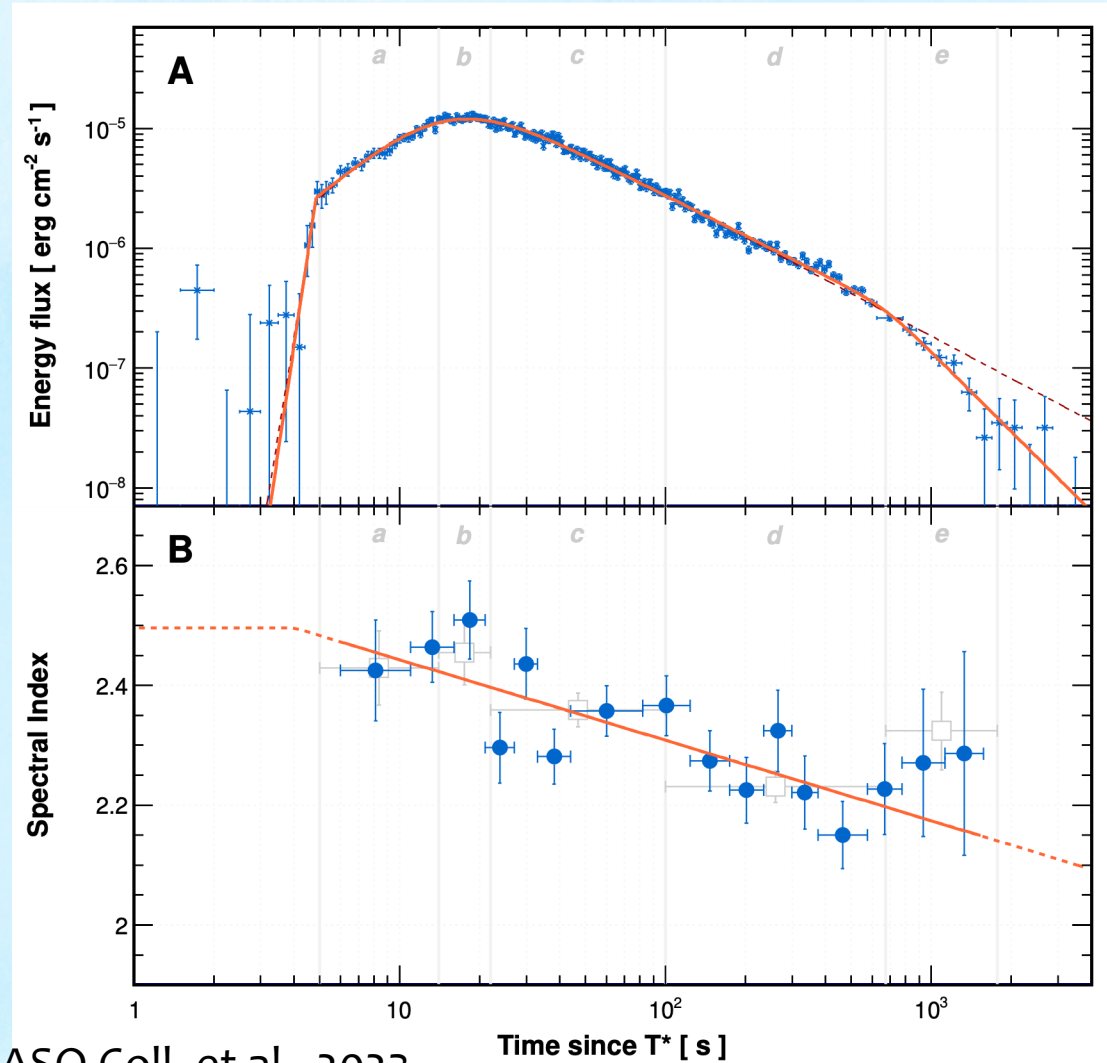


GRB 221009A

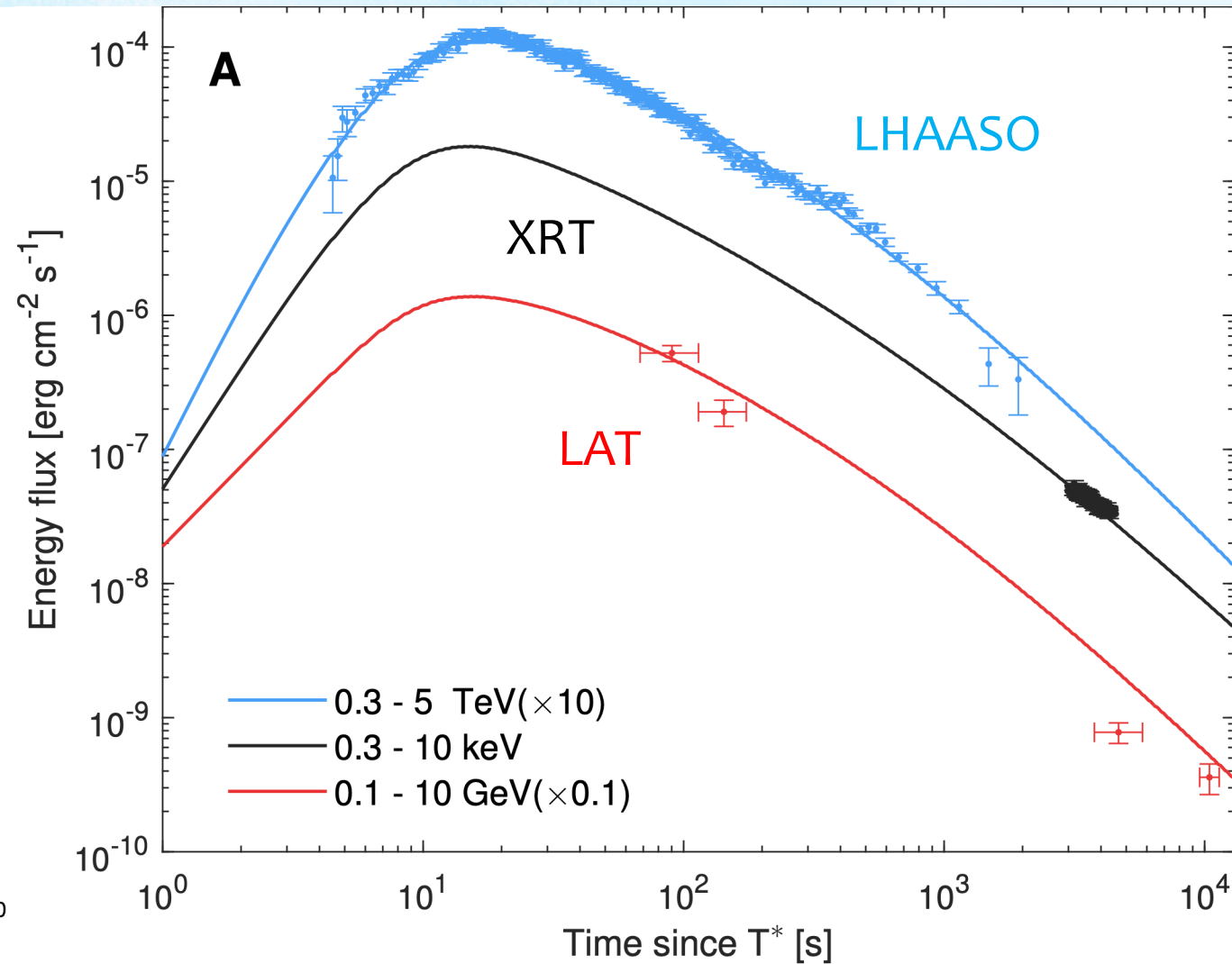
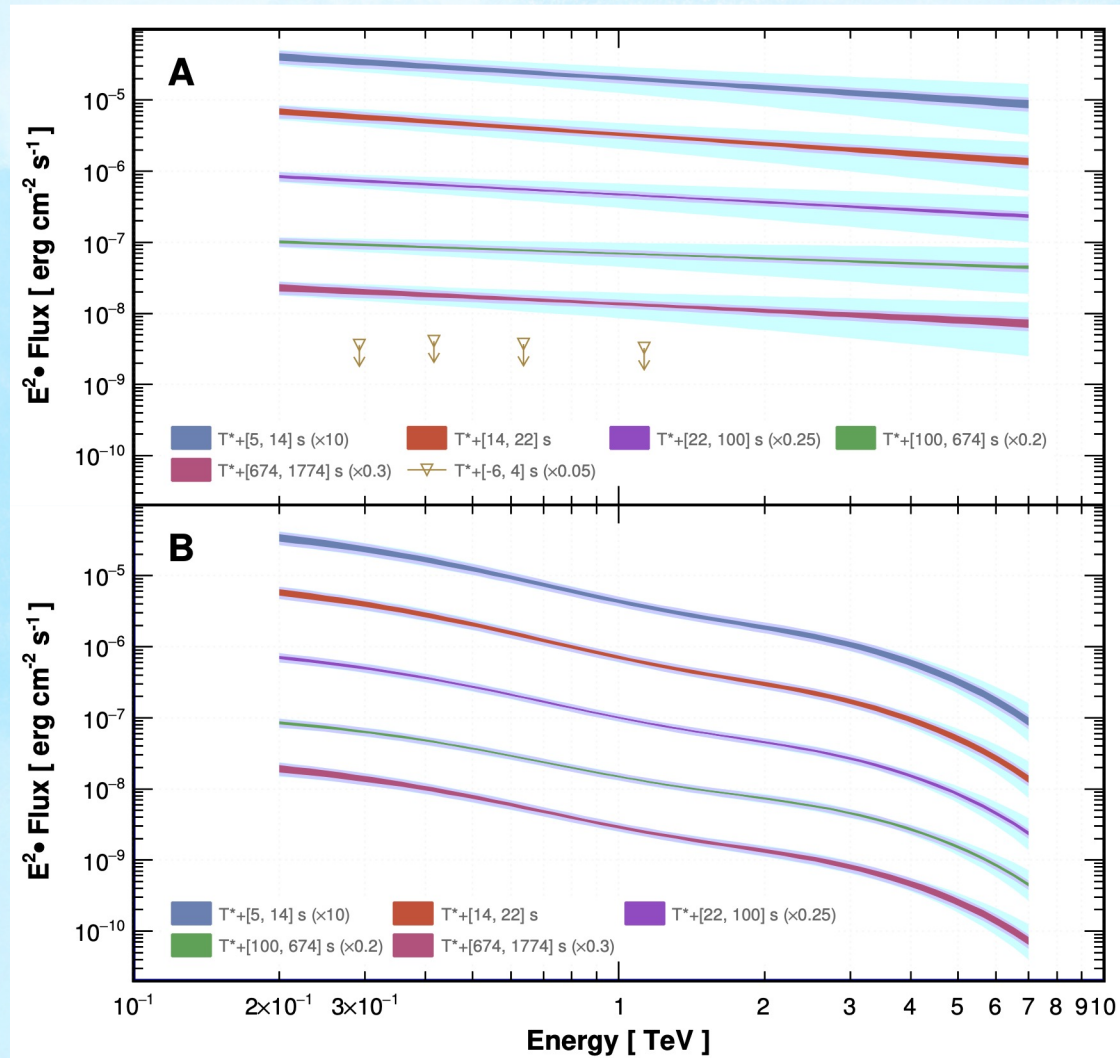
- $E_{\gamma, \text{iso}} \ 1 \times 10^{55} \text{ erg}$
- $z = 0.15$

LHAASO detection info:

- $> 250\sigma$ in 230 – 3000 s
- 0.3 – 13 TeV energy range



GRB 221009A

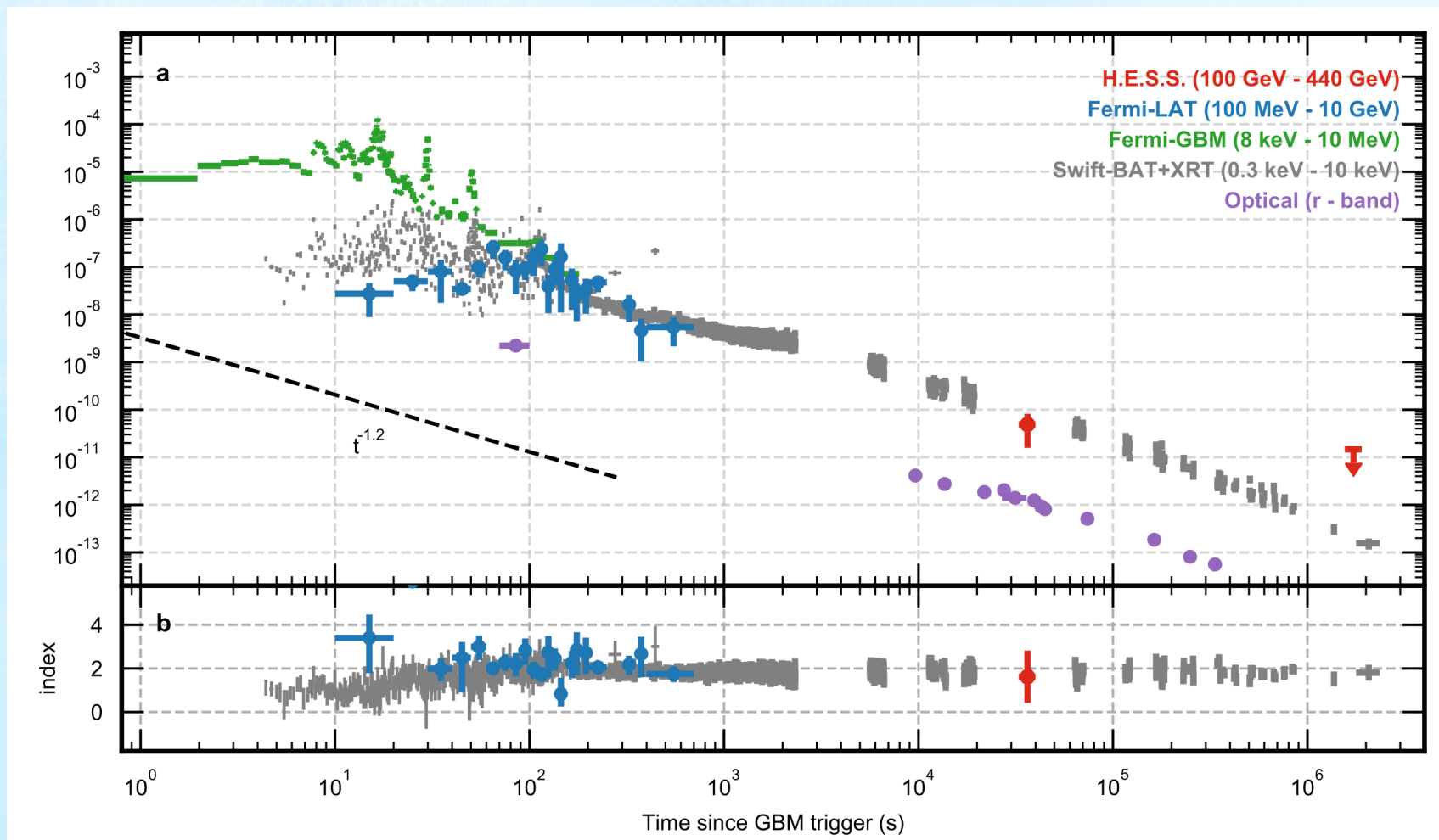


GRB 180720B

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

H.E.S.S. detection info:

- Tdelay ~ 10 hrs
- $> 5.3\sigma$ in 2 hrs
- 0.1 – 0.44 TeV energy range

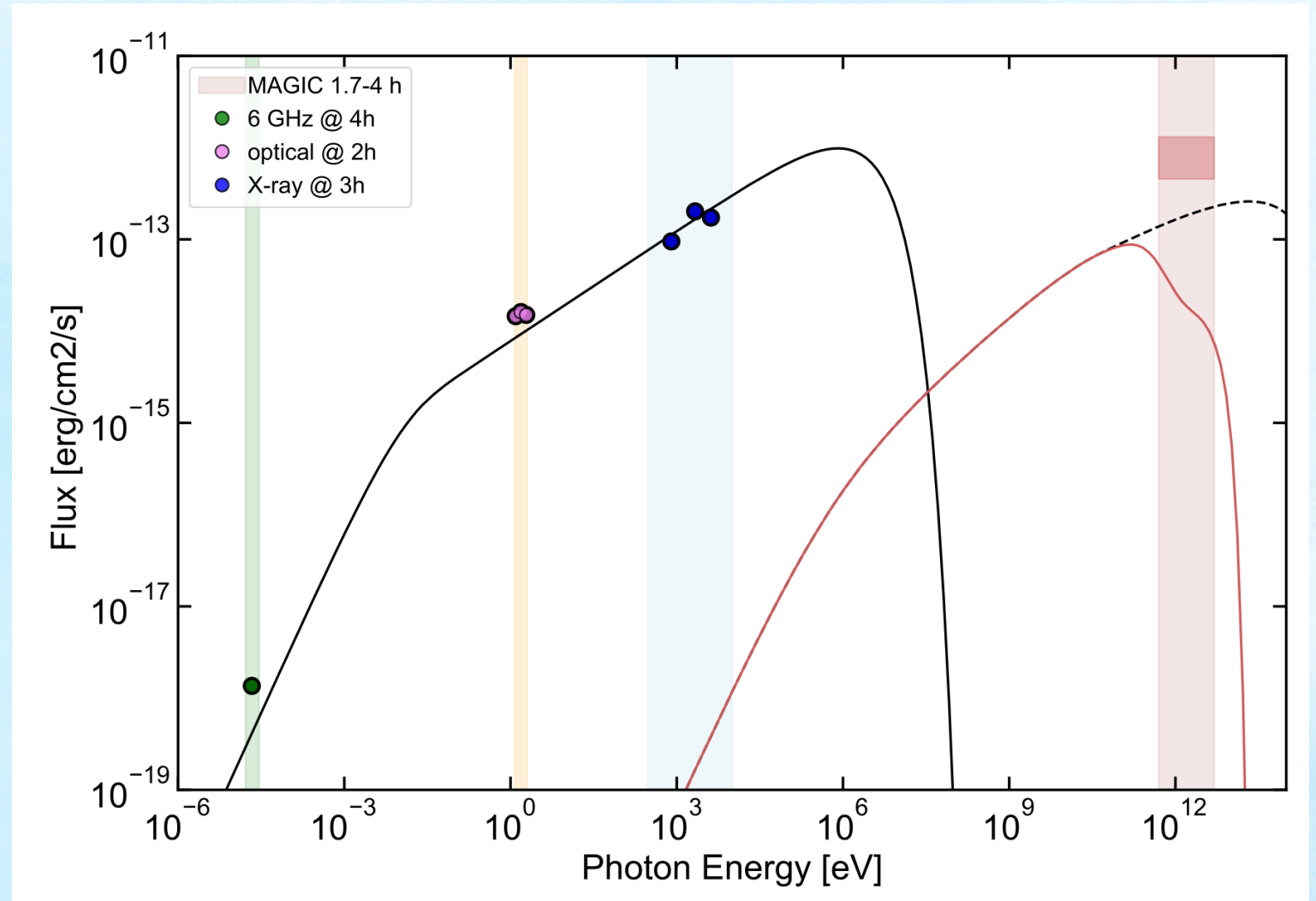


GRB 160821B

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

MAGIC info:

- Tdelay $\sim 24 \text{ s}$
- 3σ in 4 hrs
- 0.5 - 5 TeV energy range
- moon conditions,
dedicated analysis



GRB 190114C

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

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)	$-2.22^{+0.23}_{-0.25}$	$-2.39^{+0.23}_{-0.25}$	$-2.15^{+0.23}_{-0.25}$	$-2.29^{+0.23}_{-0.24}$

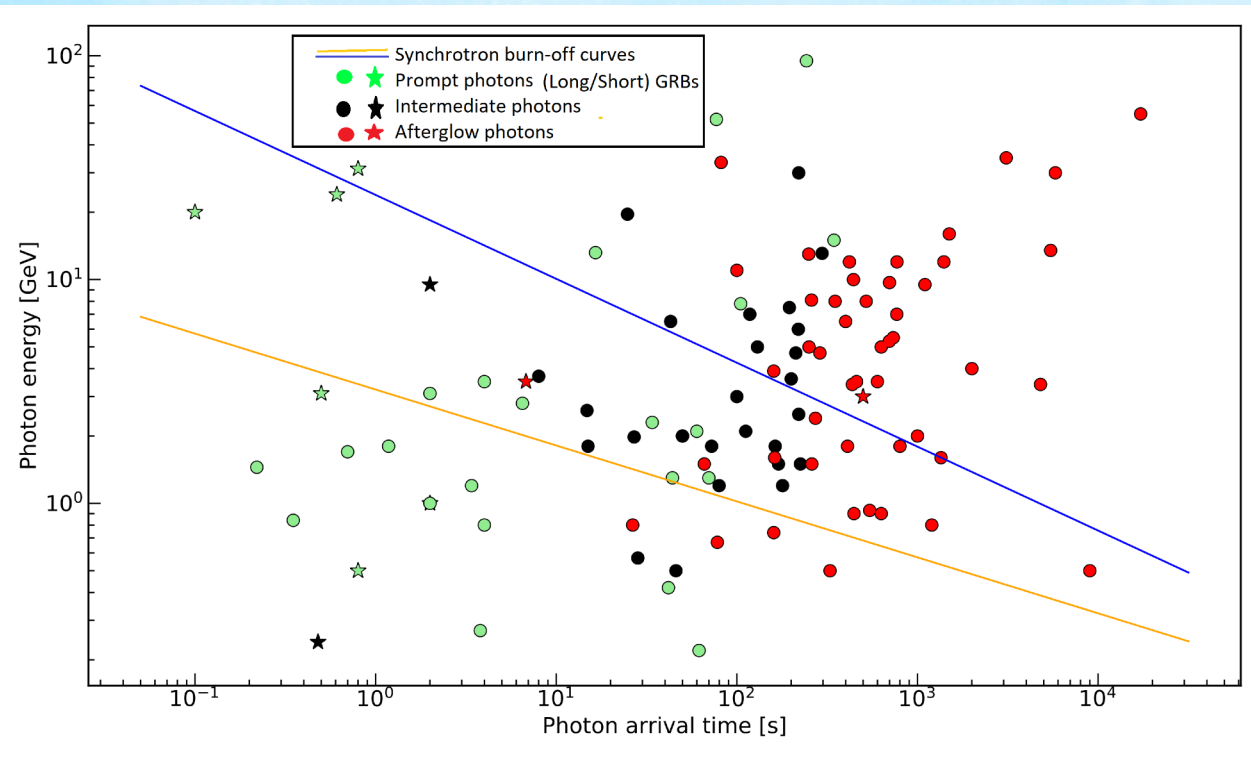
GRB 190114C

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

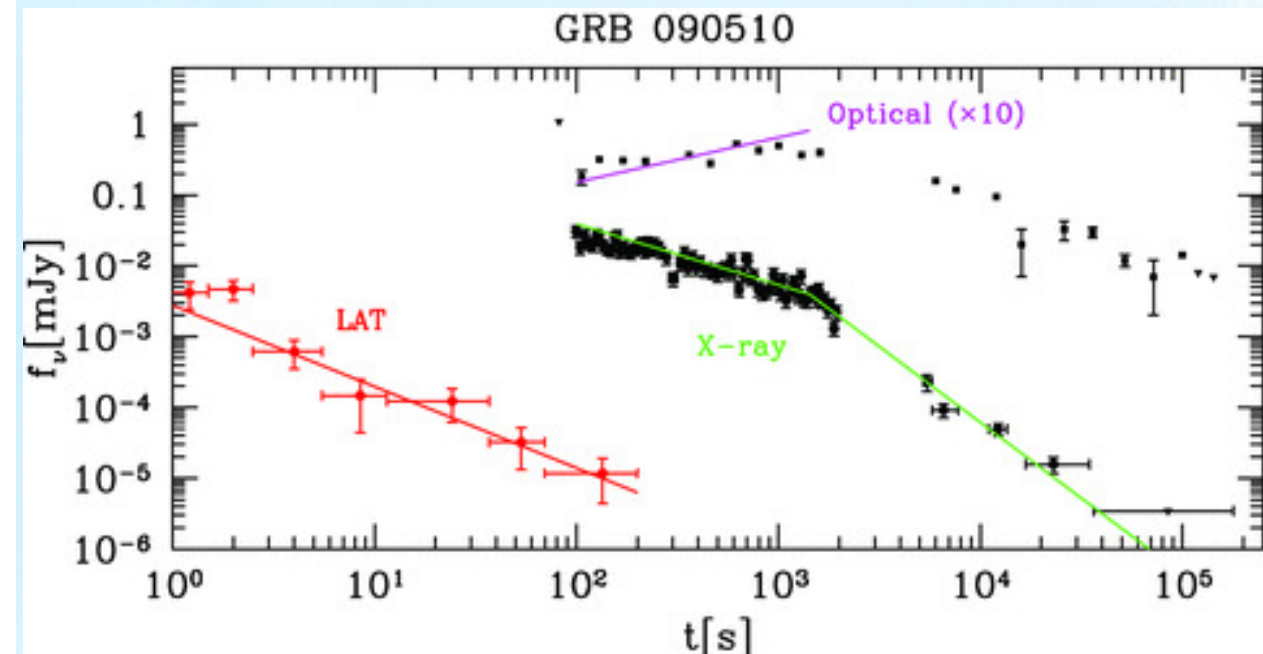
Theoretical expectations from GRBs in the VHE domain

HE emission (< 100 GeV)

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



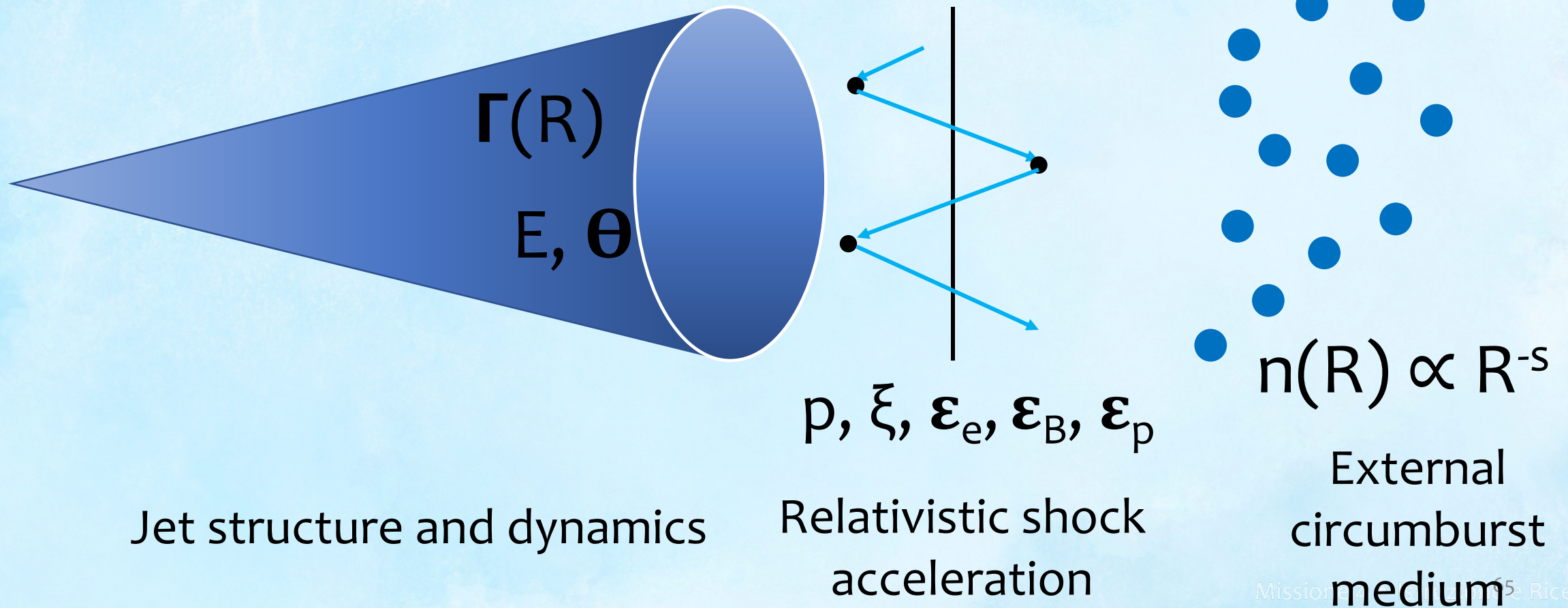
Nava, 2018



Kumar et al., 2010

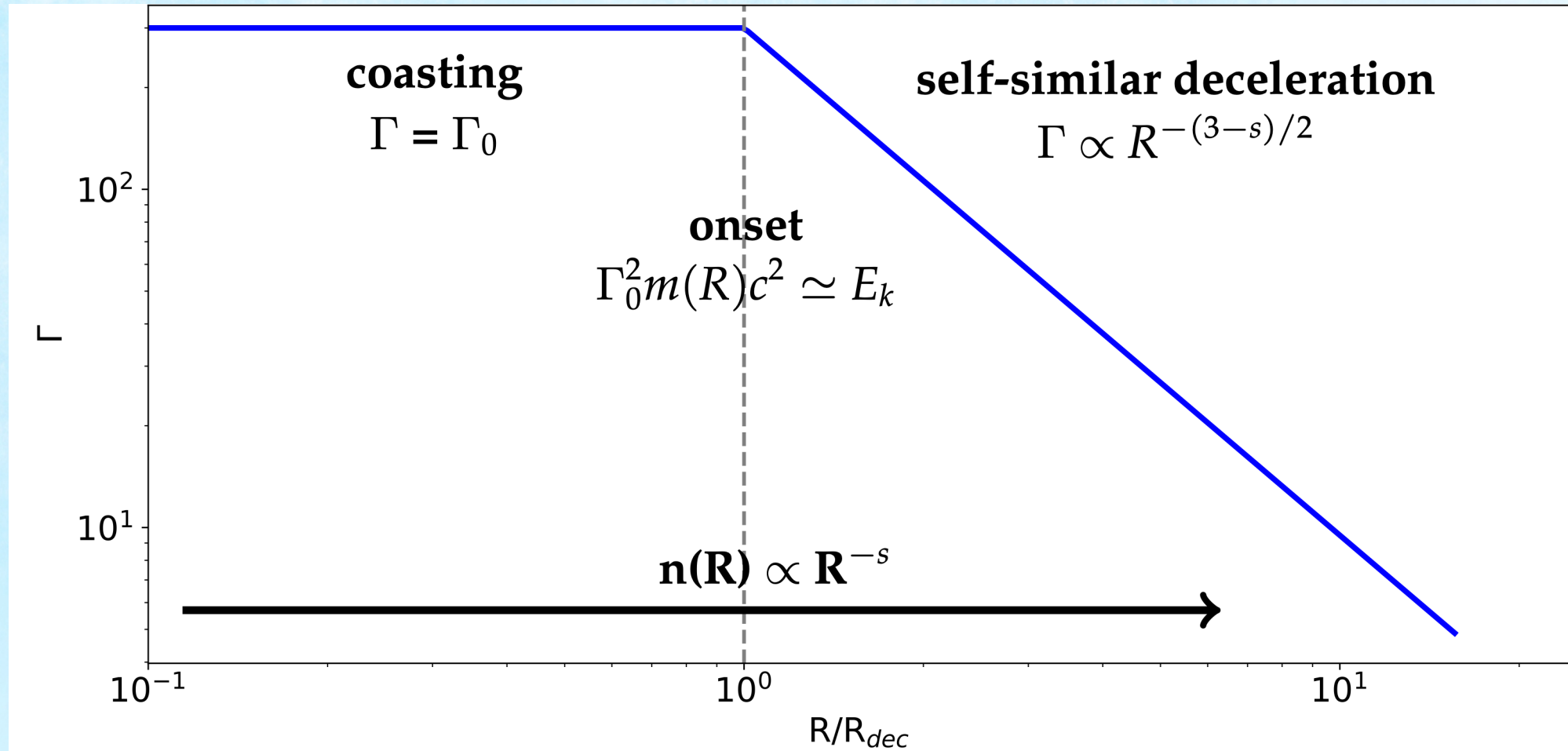
Afterglow modeling: external forward shock scenario

Decelerating blastwave interacting with the circumburst external medium



Afterglow modeling: external forward shock scenario

Jet dynamics

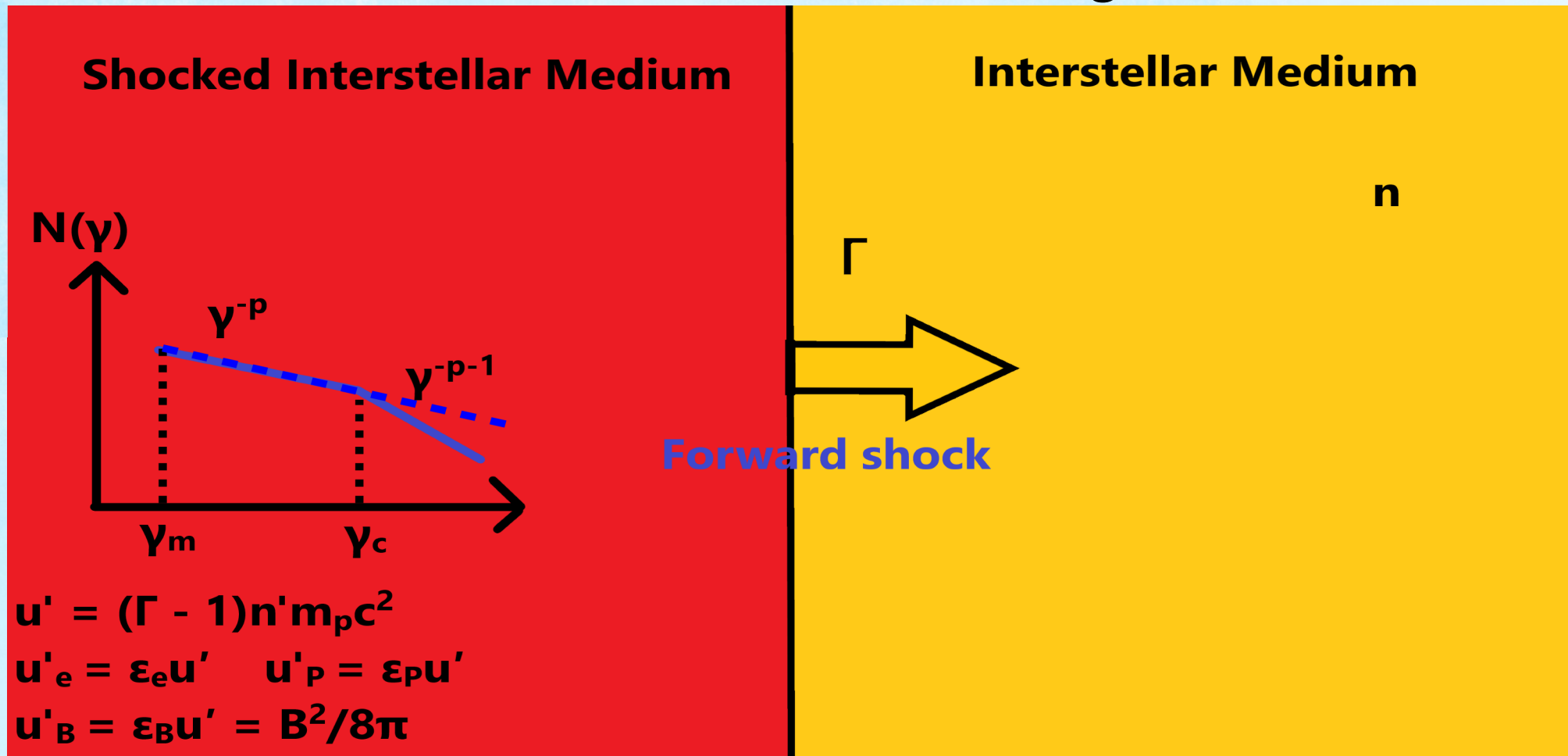


See Blandford & McKee, 1976; Nava et al., 2014

Afterglow modeling: external forward shock scenario

Relativistic shocks in GRB afterglow

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



GRBs at VHE: impact on fundamental physics

Lorentz Invariance Violation (LIV) studies

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

Photon energy at the detector

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

$$\begin{aligned} \Delta t(E, \eta_1) &= \eta_1 \cdot 17 \text{ s/TeV} \cdot E \\ \Delta t(E, \eta_2) &= \eta_2 \cdot 25 \text{ s/TeV}^2 \cdot E^2 \end{aligned}$$

Assuming $\eta_n = 1$ 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

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

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

	superl.	subl.
$E_{QG,1} [10^{19} \text{ GeV}]$	0.55	0.58
$E_{QG,2} [10^{10} \text{ GeV}]$	5.6	6.3

95% lower limit on the Q.G. energy scale for

- ← linear scenario
- ← quadratic scenario

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

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)