The New Era of Multi-Messenger Astroparticle Physics
IFPU Focus week - 19-24 February 2024

Can We Unveil TeV Emission from GW Counterparts?
Do We really Care?
Who's Intrigued and Ready to Dive in?

Antonio Stamerra - INAF (Osservatorio Astronomico di Roma)

INAF
ISTITUTO NAZIONALE
DI ASTROFISICA

MAGIC
Major Atmospheric
Gamma Imaging
Cerenkov Telescopes

cta

What do observations and theory predict for TeV emission?

Can We Unveil TeV Emission from GW Counterparts?
Do We really Care?

What do we learn from TeV emission?

Who's Intrigued and Ready to Dive in?

Which instruments and methodologies will allow us to detect TeV counterparts?

INAF
ISTITUTO NAZIONALE DI ASTROFISICA

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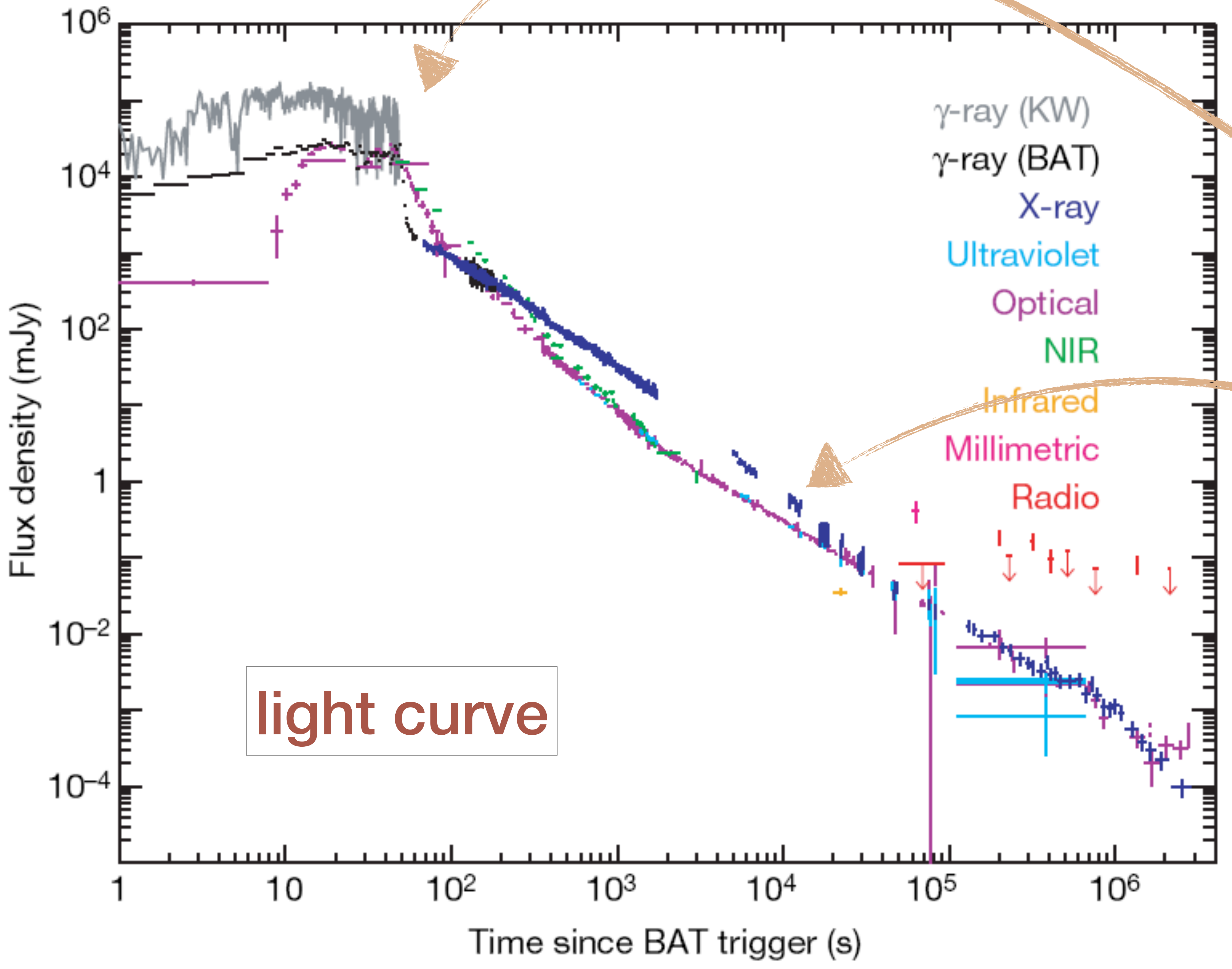
GRB formation and evolution

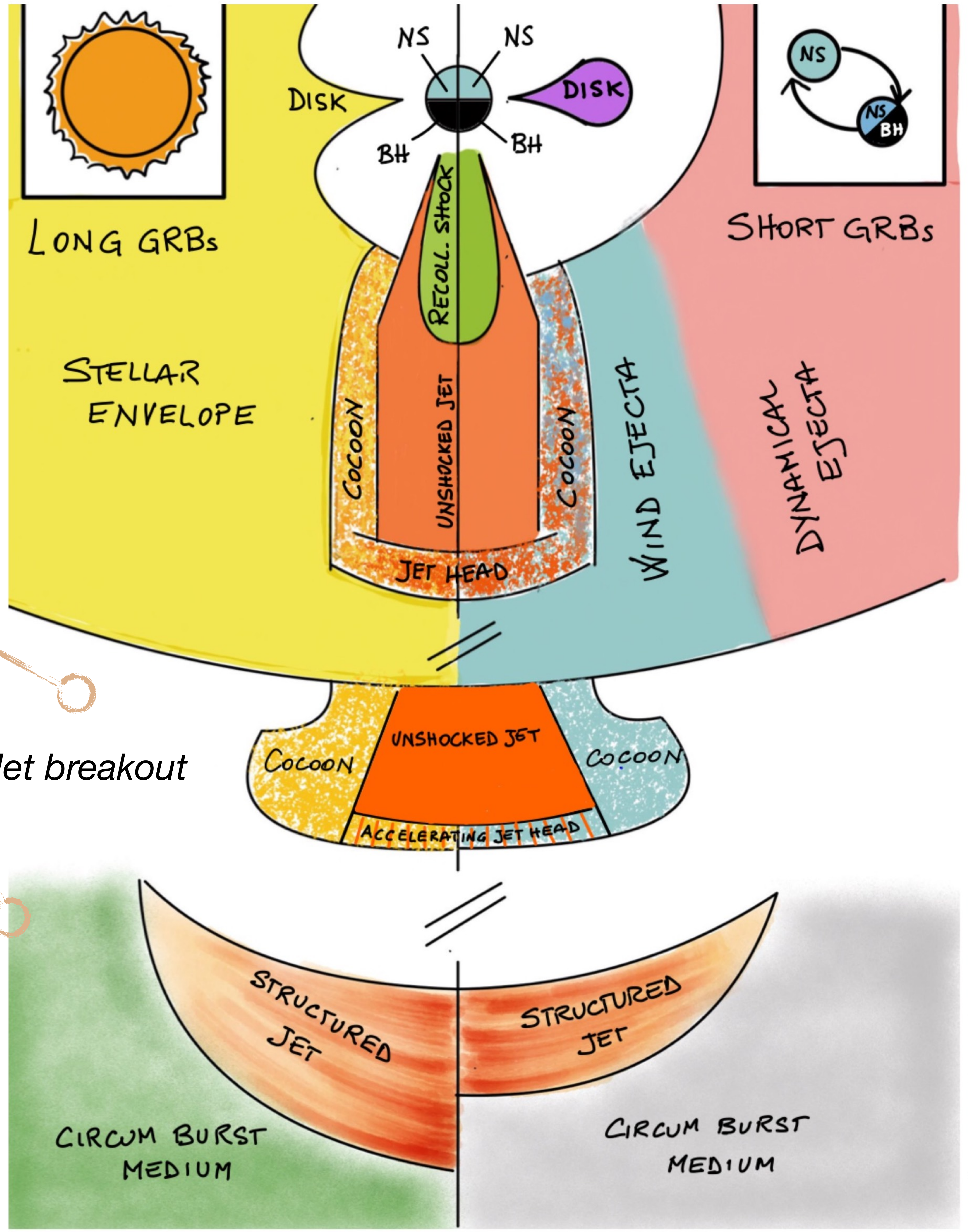
GRB formation and evolution: structured jet

- A structured jet is formed at breakout



Jet formation

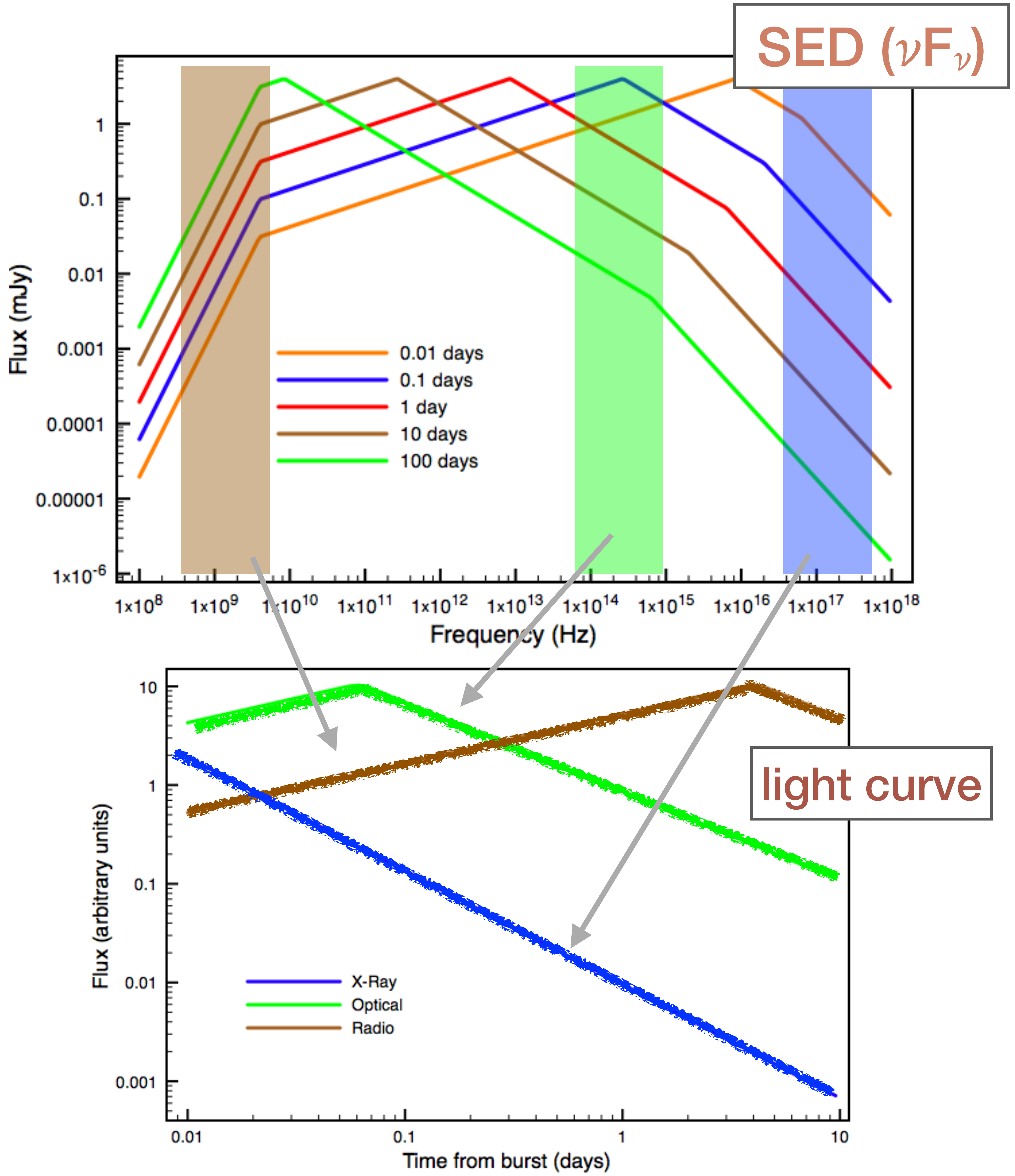
Jet breakout



Salafia&Ghirlanda 2022

Gamma-ray bursts: fireball model

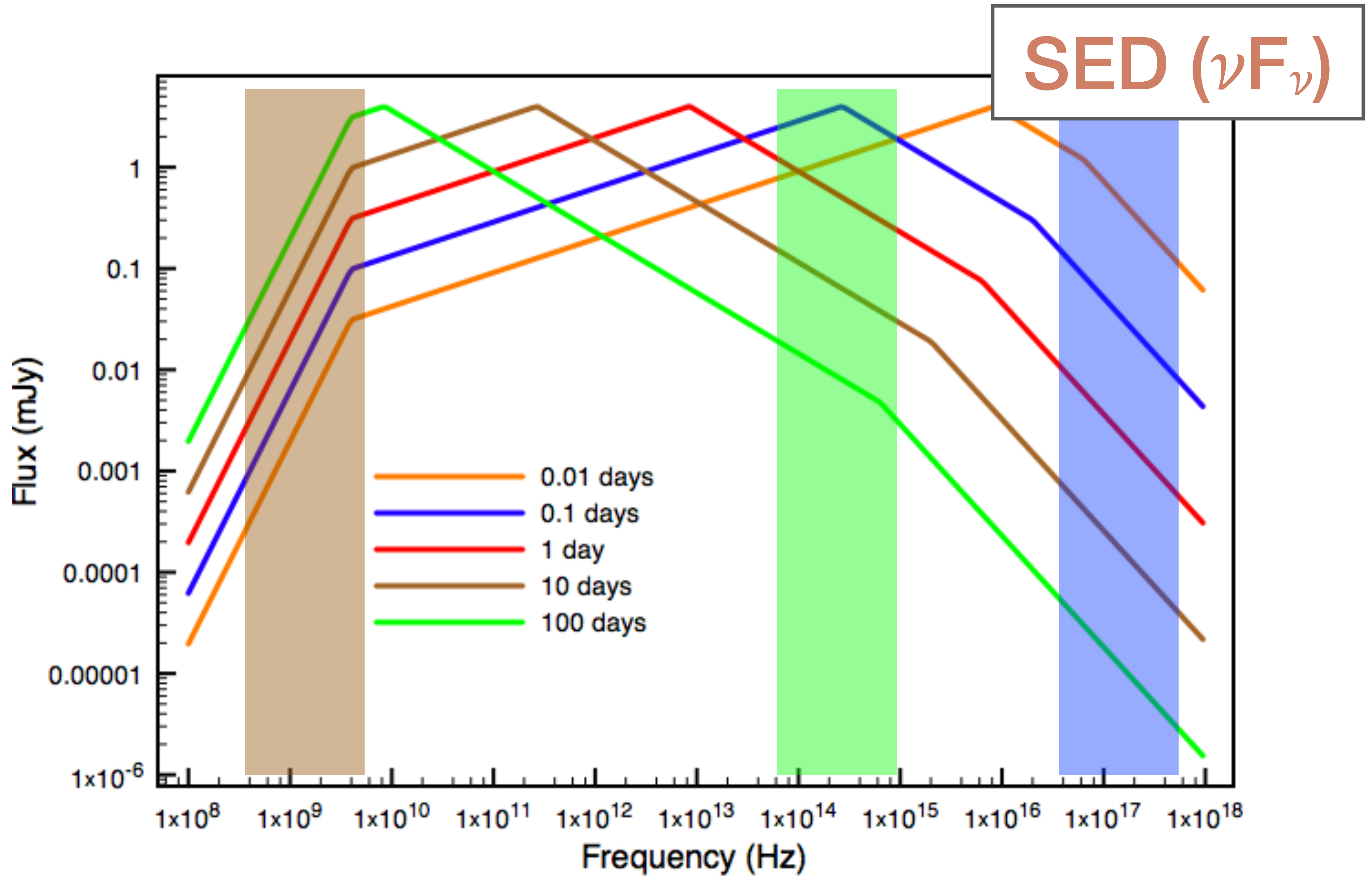
- Synchrotron emission
  - emission of underlying electron population with power law distribution ~E^{-p}
  - Allow to predict the spectral energy distributions (SED) and lightcurves
  - Cooling —> time evolved SED
    - Different Lightcurves in different bands



Sari+1998

Gamma-ray bursts: fireball model

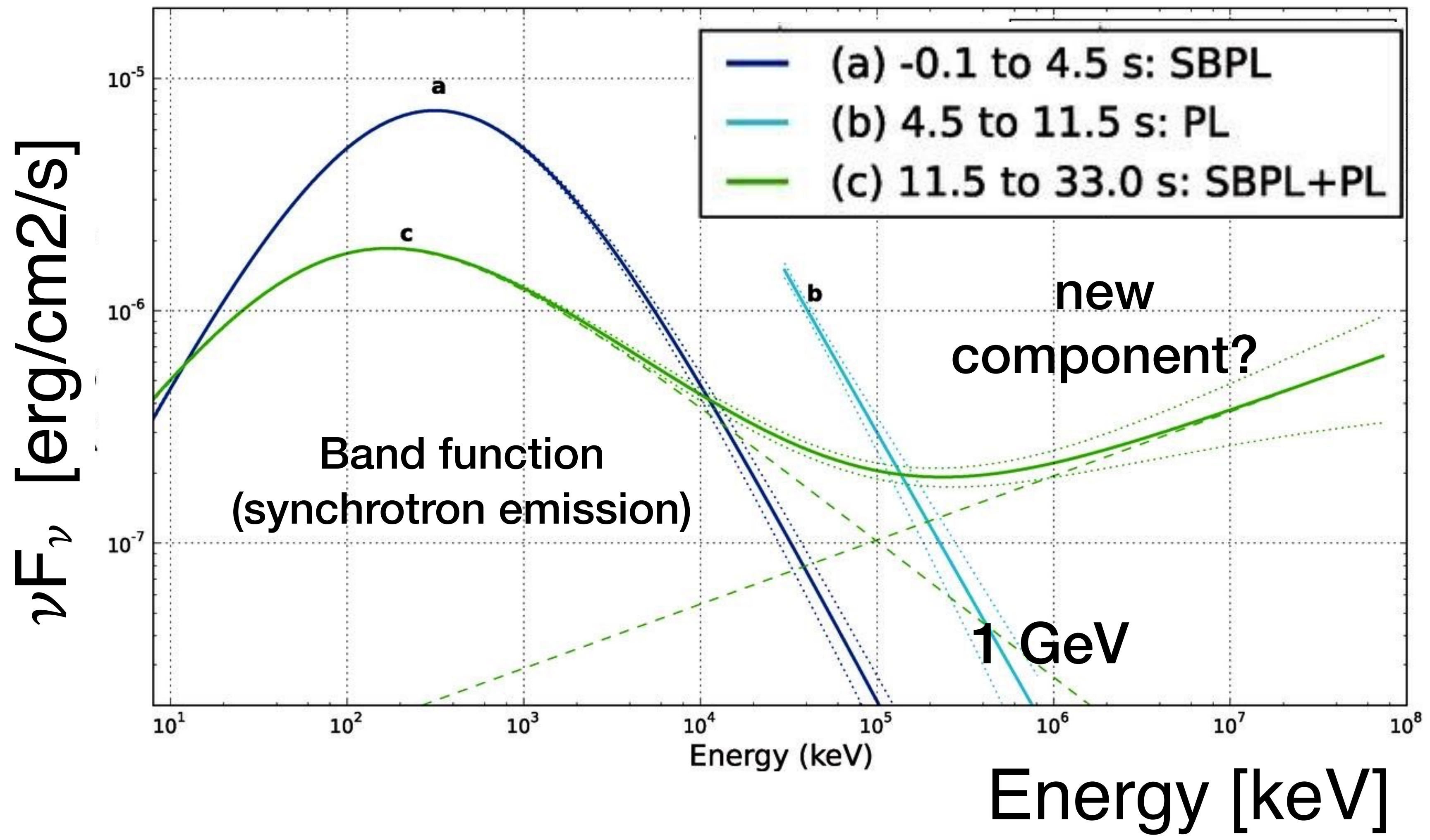
- Synchrotron emission
  - emission of underlying electron population with power law distribution ~E^{-p}
  - Allow to predict the spectral energy distributions (SED) and lightcurves
- Other components other than synchrotron?

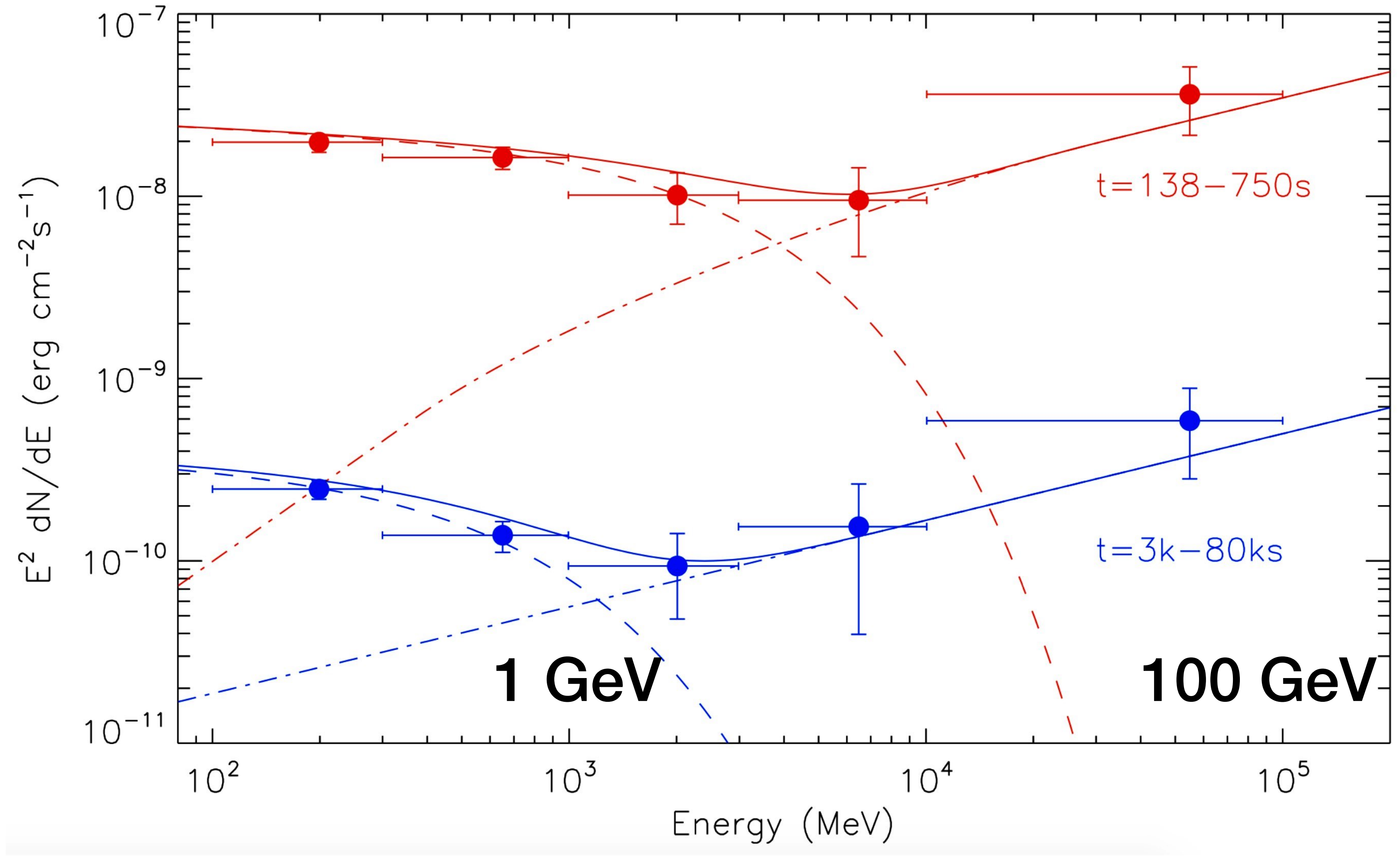


Nava, 2021

The "monster" GRB GRB130427A

In GRB130427A the GeV excess, while higher than the burnoff limit, could be explained with synchrotron emission (see e.g. Gill&Granot 2022).



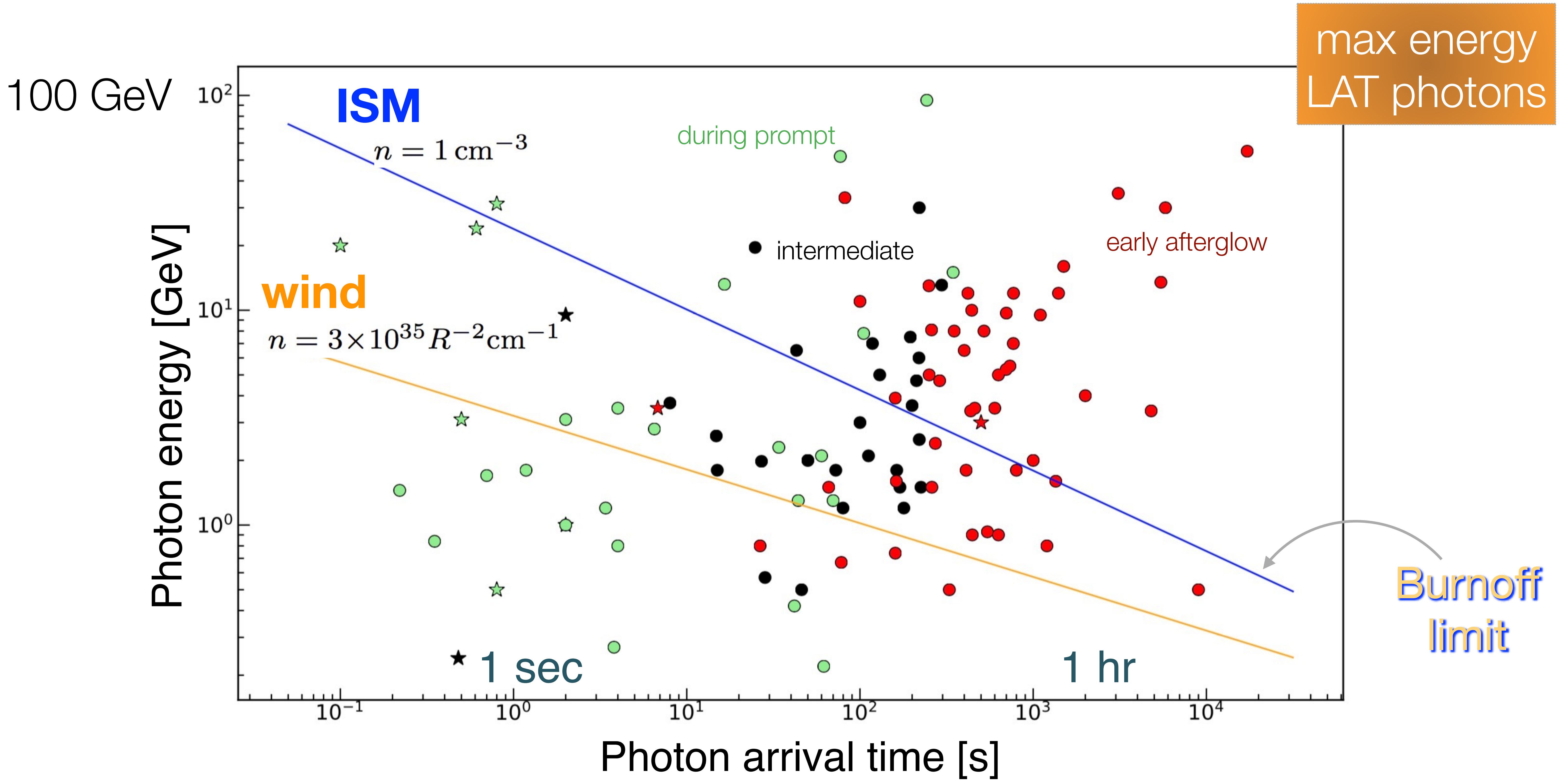


The burnoff limit

- Maximum energy above which the timescale for radiative synchrotron losses becomes shorter than the acceleration timescale

$$E^{\rm obs}_{\rm syn,max} \simeq 50\,{\rm MeV} \times \Gamma/(1+z)$$

deceleration: Γ decreases



L. Nava (2018)
http://adsabs.harvard.edu/abs/2018IJMPD..2742003N

The burnoff limit

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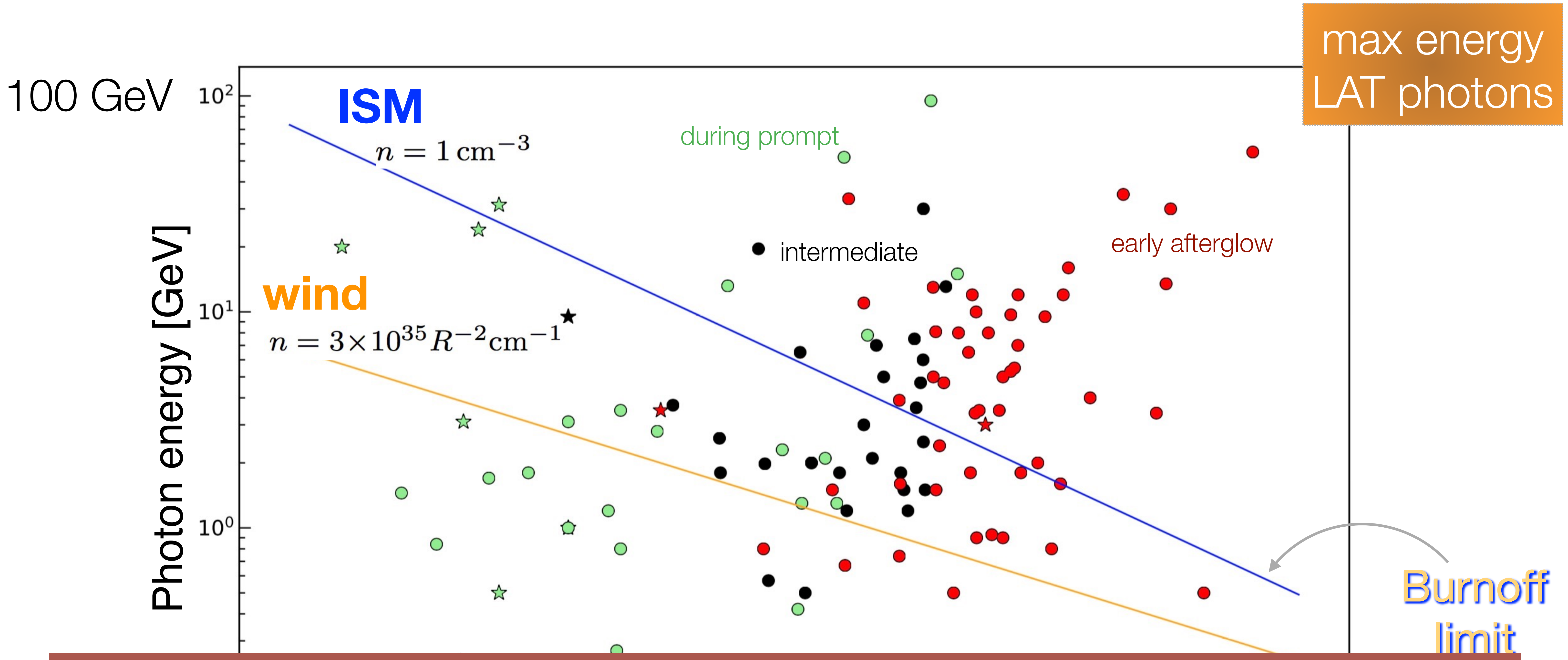
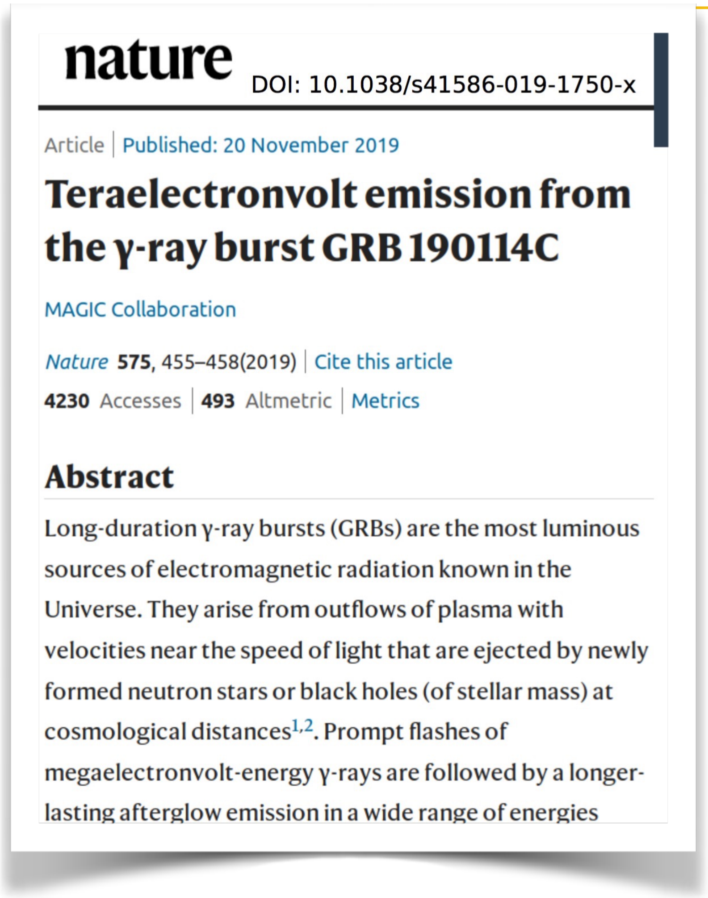


From Fermi-LAT: indications of a high-energy component but not a conclusive proof

L. Nava (2018)
http://adsabs.harvard.edu/abs/2018IJMPD..2742003N

GRB190114C: the high energy SEDs


nature DOI: 10.1038/s41586-019-1750-x

Article | Published: 20 November 2019

Teraelectronvolt emission from the γ-ray burst GRB 190114C

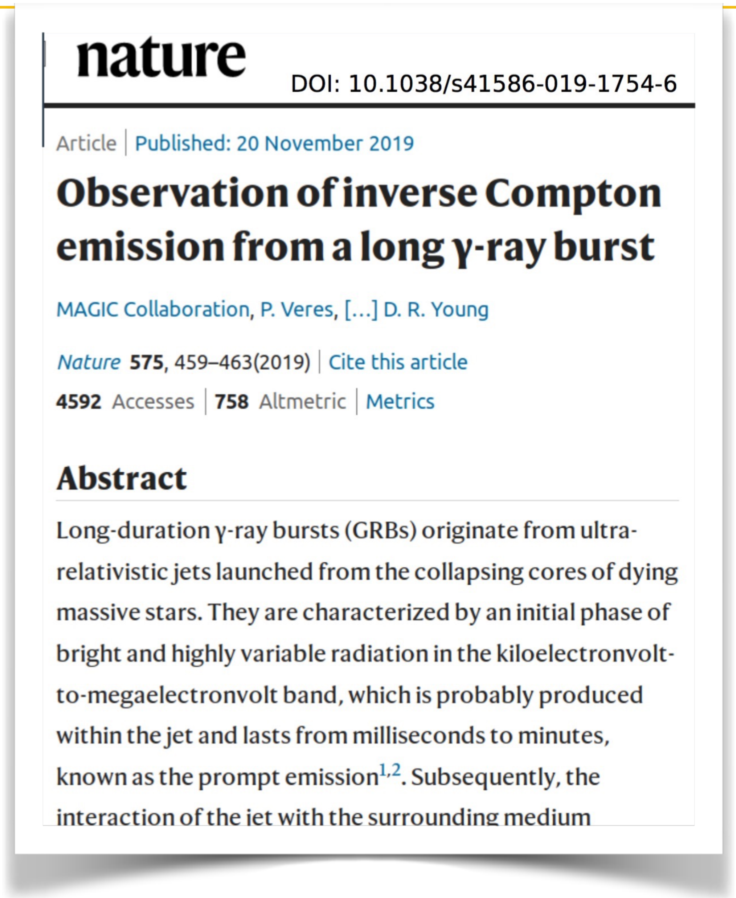
MAGIC Collaboration

Nature **575**, 455–458(2019) | Cite this article

4230 Accesses | **493** Altmetric | Metrics

Abstract

Long-duration γ-ray bursts (GRBs) are the most luminous sources of electromagnetic radiation known in the Universe. They arise from outflows of plasma with velocities near the speed of light that are ejected by newly formed neutron stars or black holes (of stellar mass) at cosmological distances[1,2]. Prompt flashes of megaelectronvolt-energy γ-rays are followed by a longer-lasting afterglow emission in a wide range of energies


nature DOI: 10.1038/s41586-019-1754-6

Article | Published: 20 November 2019

Observation of inverse Compton emission from a long γ-ray burst

MAGIC Collaboration, P. Veres, [...] D. R. Young

Nature **575**, 459–463(2019) | Cite this article

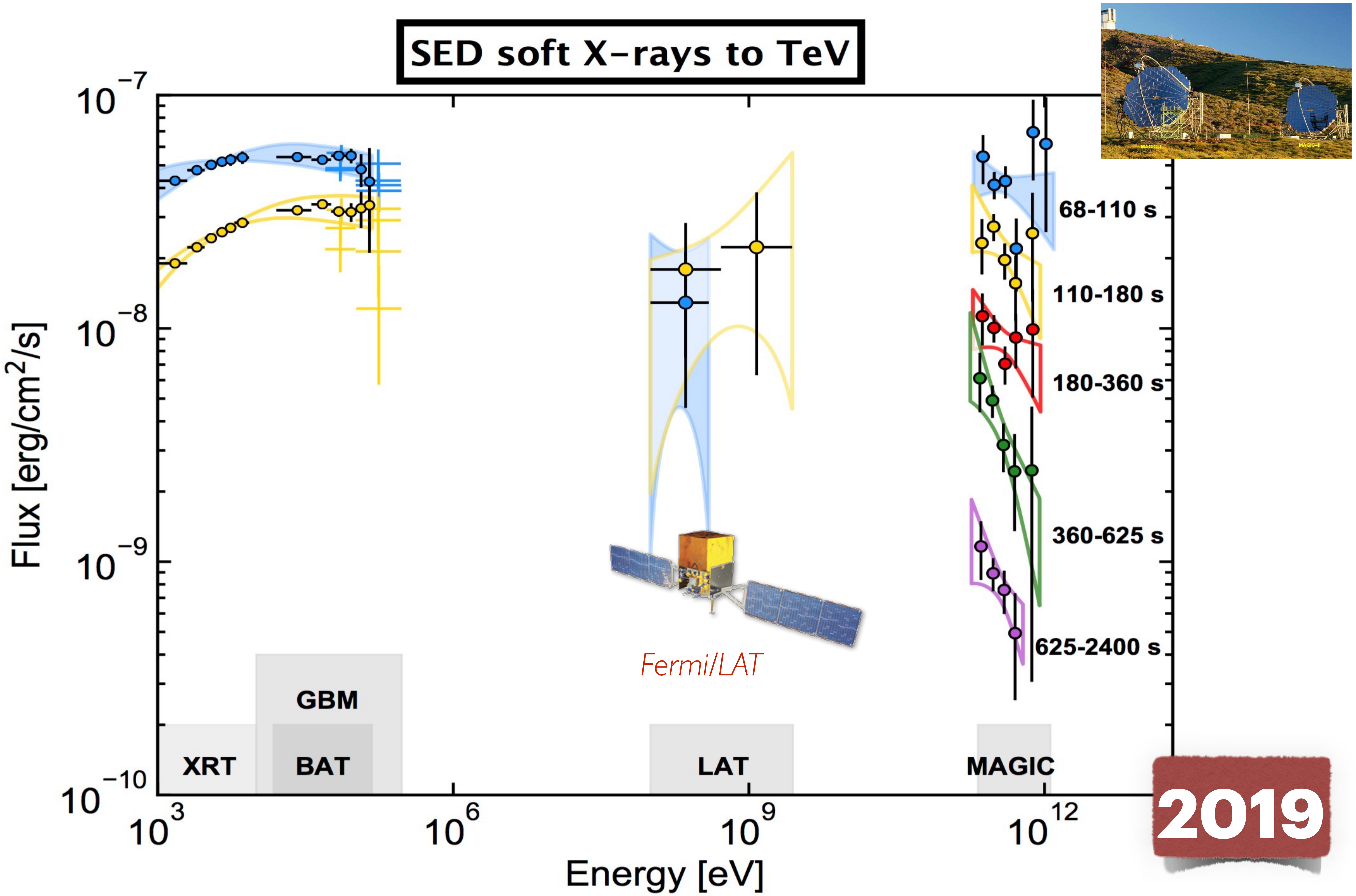
4592 Accesses | **758** Altmetric | Metrics

Abstract

Long-duration γ-ray bursts (GRBs) originate from ultra-relativistic jets launched from the collapsing cores of dying massive stars. They are characterized by an initial phase of bright and highly variable radiation in the kiloelectronvolt-to-megaelectronvolt band, which is probably produced within the jet and lasts from milliseconds to minutes, known as the prompt emission[1,2]. Subsequently, the interaction of the jet with the surrounding medium

- Long GRB at z=0.425
  (GCN #**23695 #23708**)
- E_{iso} = 3x10^{53} erg; bright GRB, but not exceptional
- VHE photons detected by MAGIC, at >100 GeV up to ~1TeV are **well beyond the burnoff limits**

Clear indication of a second energetic component



MAGIC Coll. et al., Nature,575,459-463(2019)

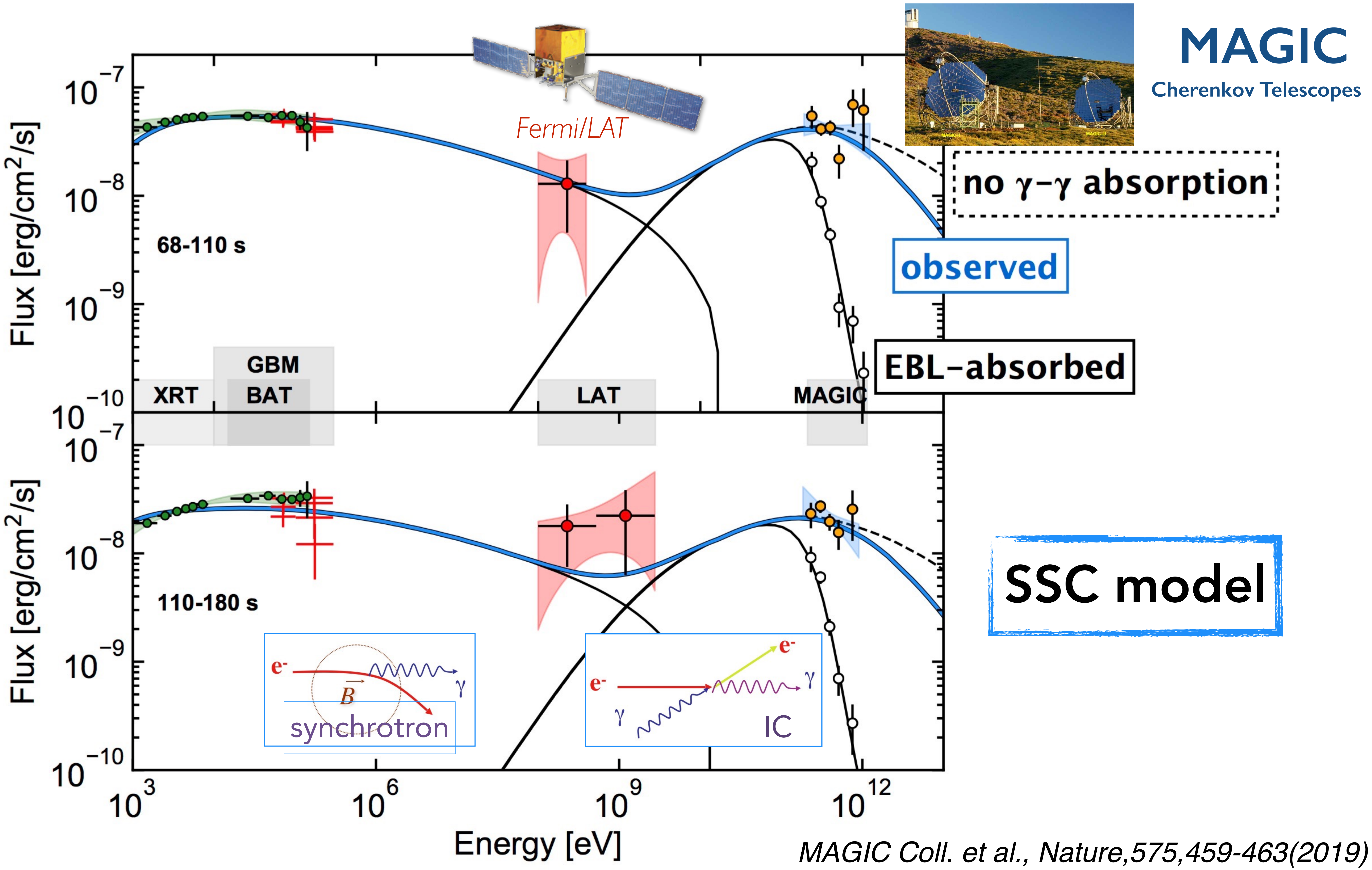
https://www.nature.com/articles/s41586-019-1754-6

GRB190114C: modeling with SSC afterglow radiation

- First modelling of broad-band and TeV emission from a GRB

T: 68-110 s

T: 110-180 s



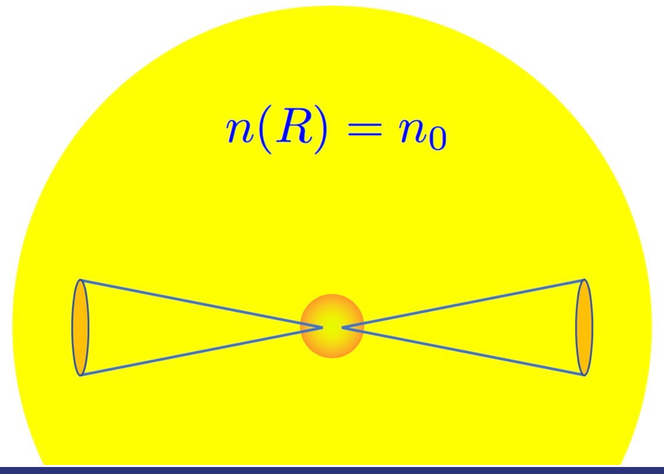
MAGIC Coll. et al., Nature,575,459-463(2019)
https://www.nature.com/articles/s41586-019-1754-6

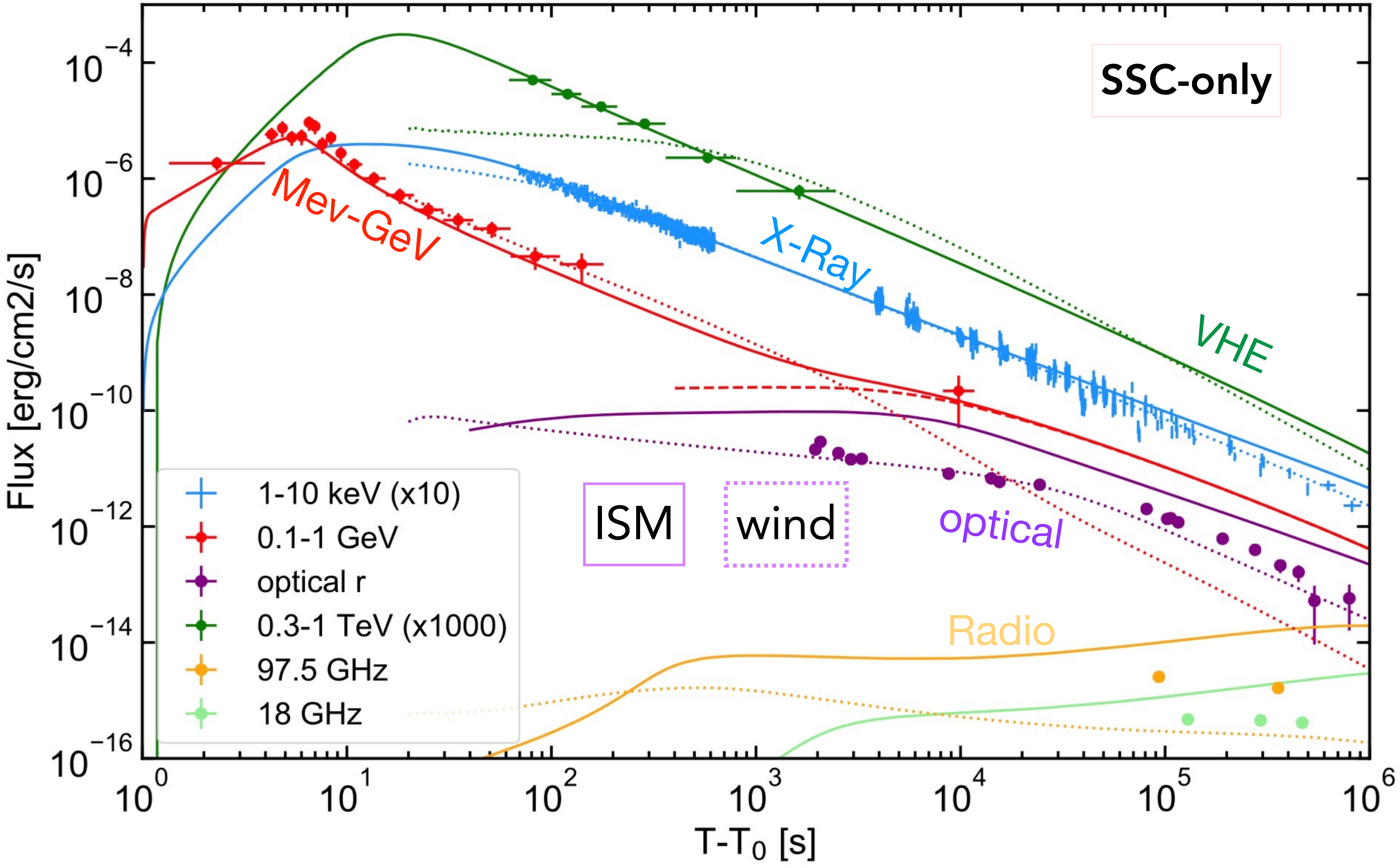
GRB190114C: modelling physical parameters

- SED and light curves probe different external environments
- MWL data are key to constrain the physical parameters (jet, environme

$s = 0$,
$\varepsilon_e = 0.07$,
$\varepsilon_B = 8 \times 10^{-5}$,
$p = 2.6$,
$n_0 = 0.5$
$E_k = 8 \times 10^{53}$ erg

ISM

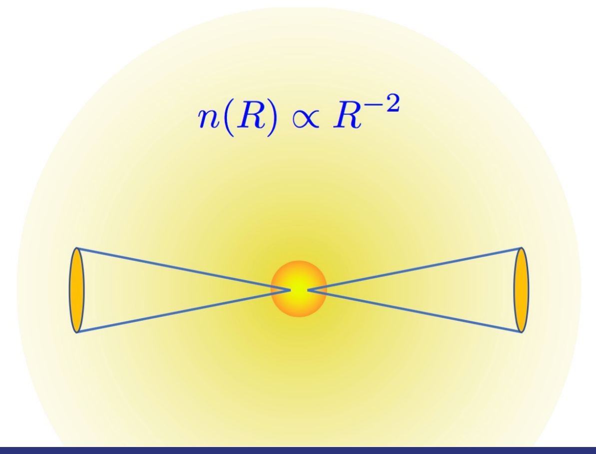




Adapted from MAGIC Coll. et al., Nature,575,459-463(2019)
https://www.nature.com/articles/s41586-019-1754-6

$s = 2$,	ext. medium
$\varepsilon_e = 0.6$,	electron frac.
$\varepsilon_B = 10^{-4}$,	Magn. field fr.
$p = 2.4$,	particle slope
$n_0 = 0.1$	density
$E_k = 4 \times 10^{53}$ erg	Tot.Power

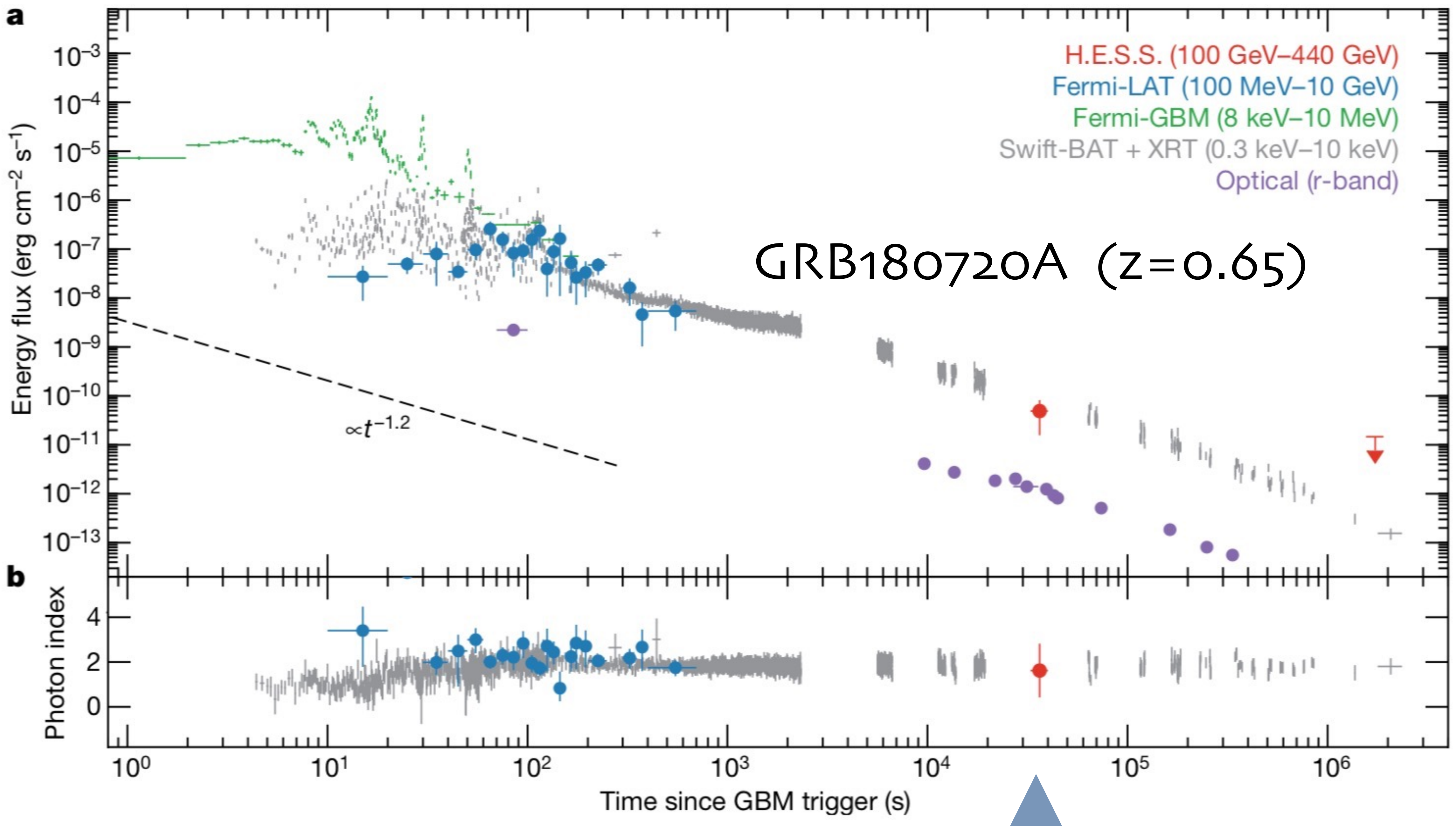
wind



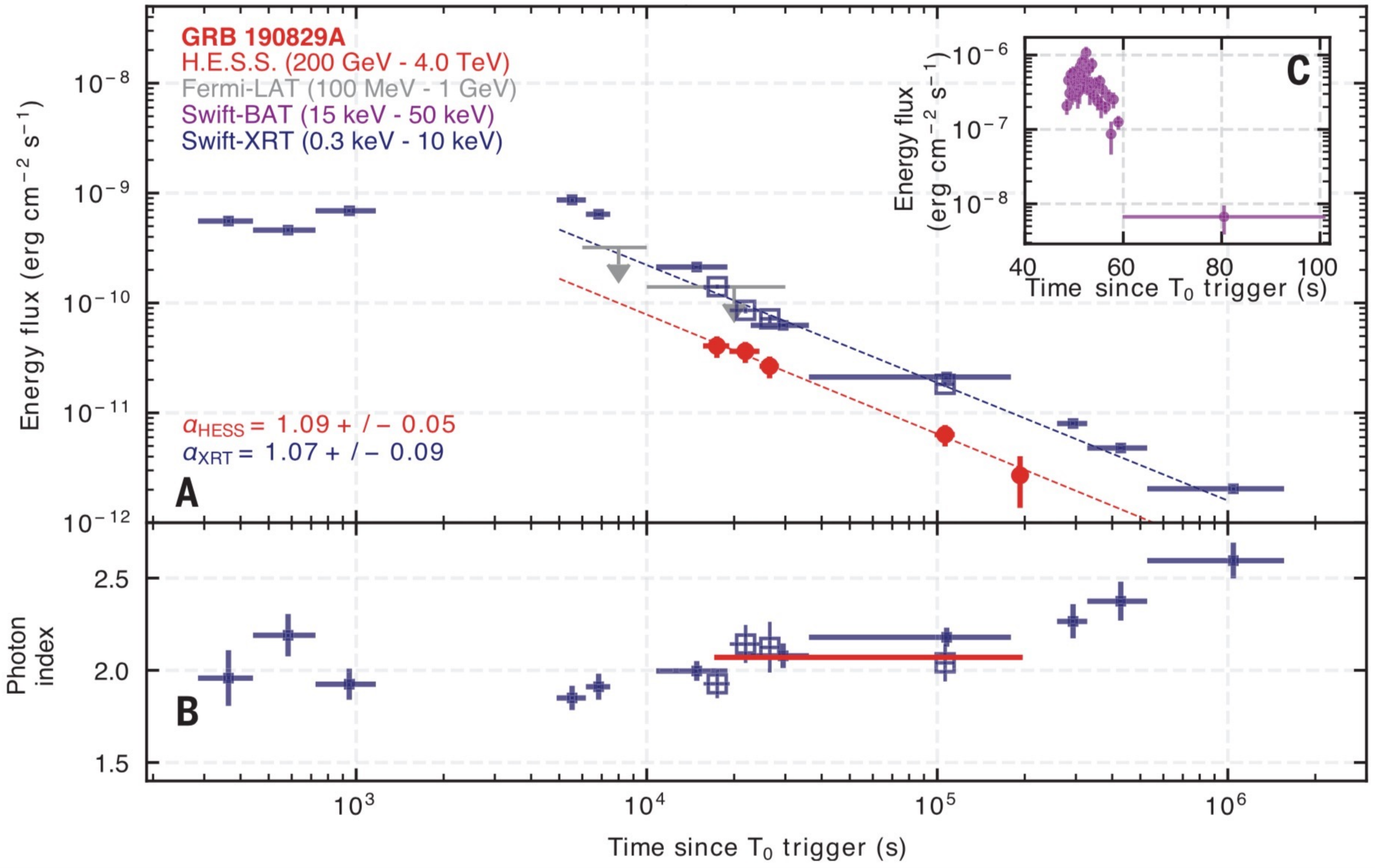
VHE emission deep in the afterglow

- H.E.S.S. observations of GRB180720A and GRB 190829A

(z=0.078)



GRB180720A (z=0.65)



Article | Published: 20 November 2019

A very-high-energy component deep in the γ-ray burst afterglow

H. Abdalla, R. Adam, … O. J. Roberts + Show authors

Nature 575, 464–467 (2019) | Cite this article

6508 Accesses | 83 Citations | 383 Altmetric | Metrics

Abstract

Gamma-ray bursts (GRBs) are brief flashes of γ-rays and are considered to be the most energetic explosive phenomena in the Universe[1]. The emission from GRBs comprises a short (typically tens of seconds) and bright prompt emission, followed by a much longer afterglow phase. During the afterglow phase, the shocked outflow—produced by the interaction between the ejected matter and the circumburst medium—slows down, and a gradual decrease in brightness is observed[2]. GRBs typically emit most of their energy via γ-rays with energies in the kiloelectronvolt-to-megaelectronvolt range, but a few photons with energies of tens of gigaelectronvolts have been detected by space-based instruments[3]. However, the

~6 hrs after the burst

RESEARCH

GAMMA-RAY BURSTS

Revealing x-ray and gamma ray temporal and spectral similarities in the GRB 190829A afterglow

H.E.S.S. Collaboration†*

Gamma-ray bursts (GRBs), which are bright flashes of gamma rays from extragalactic sources followed by fading afterglow emission, are associated with stellar core collapse events. We report the detection of very-high-energy (VHE) gamma rays from the afterglow of GRB 190829A, between 4 and 56 hours after the trigger, using the High Energy Stereoscopic System (H.E.S.S.). The low luminosity and redshift of GRB 190829A reduce both internal and external absorption, allowing determination of its intrinsic energy spectrum. Between energies of 0.18 and 3.3 tera–electron volts, this spectrum is described by a power law with photon index of 2.07 ± 0.09, similar to the x-ray spectrum. The x-ray and VHE gamma-ray light curves also show similar decay profiles. These similar characteristics in the x-ray and gamma-ray bands challenge GRB afterglow emission scenarios.

from ~4 hrs up to ~2 days after the burst!

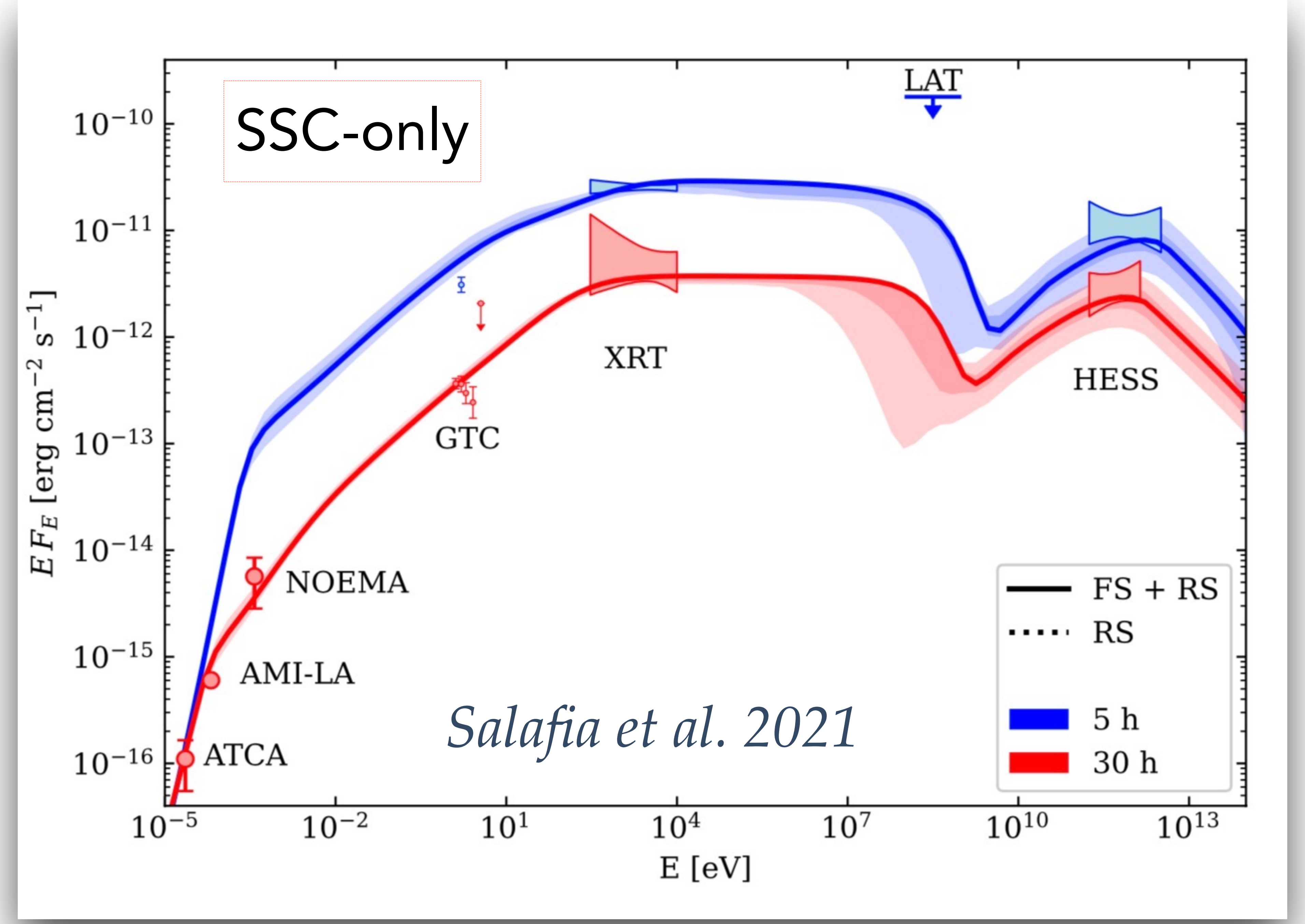
VHE emission deep in the afterglow

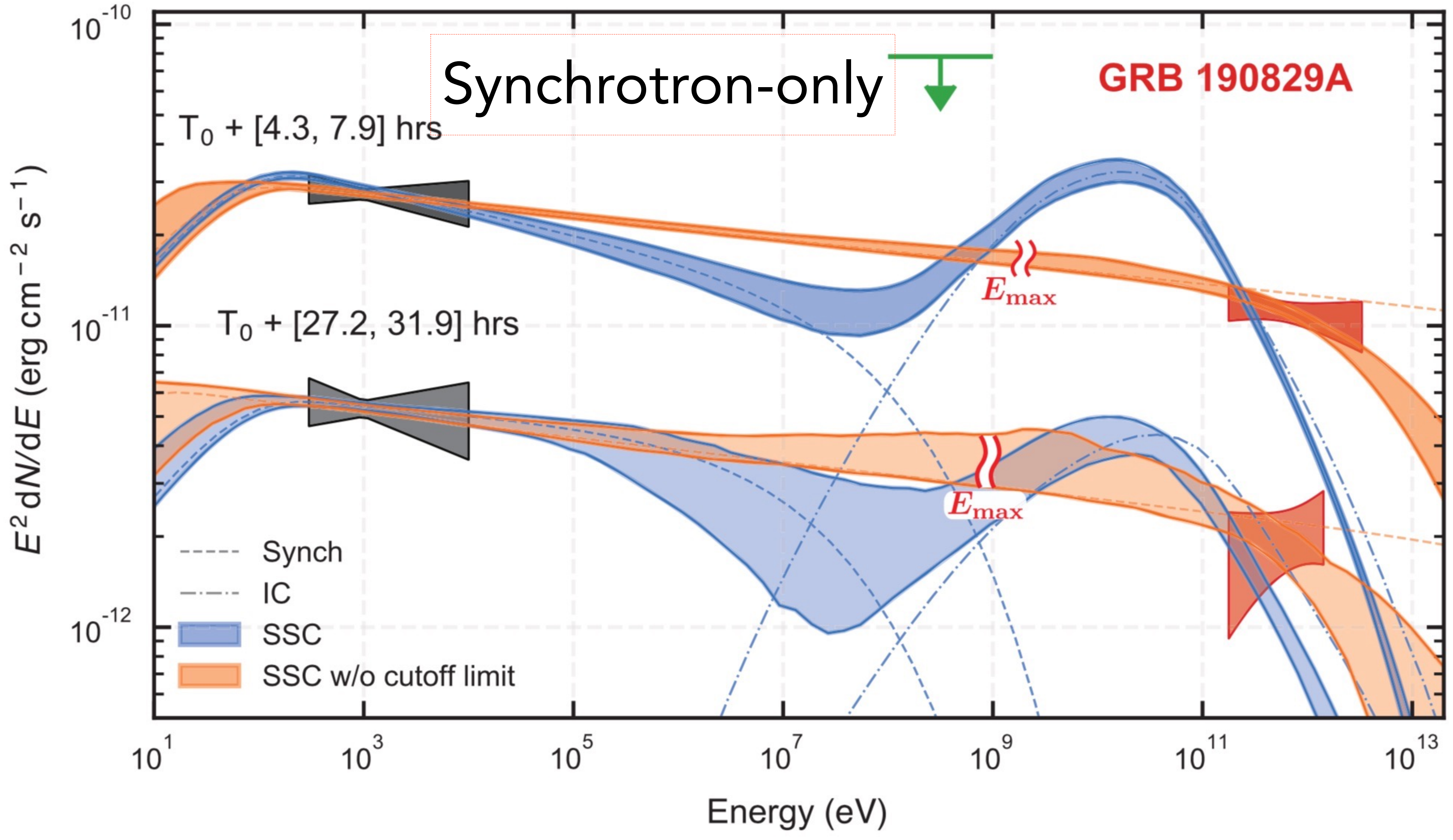
- H.E.S.S. observations of GRB180720A and GRB 190829A

(z=0.078)

➡ TeV emission follows the X-ray emission (decay slope and flux)

- Spectrum extending up to 5 TeV





- No Fermi/LAT data for the SED
- Indication of extended synchrotron emission up to TeV?
- GRB modelling with MWL data allows a **SSC** modeling

TeV emission from external Compton in short GRB

- Simple top-hat jet with **external Compton** from external radiation field (jet, cocoon, stellar emission, …)

THE ASTROPHYSICAL JOURNAL, 854:60 (13pp), 2018 February 10 Murase et al.

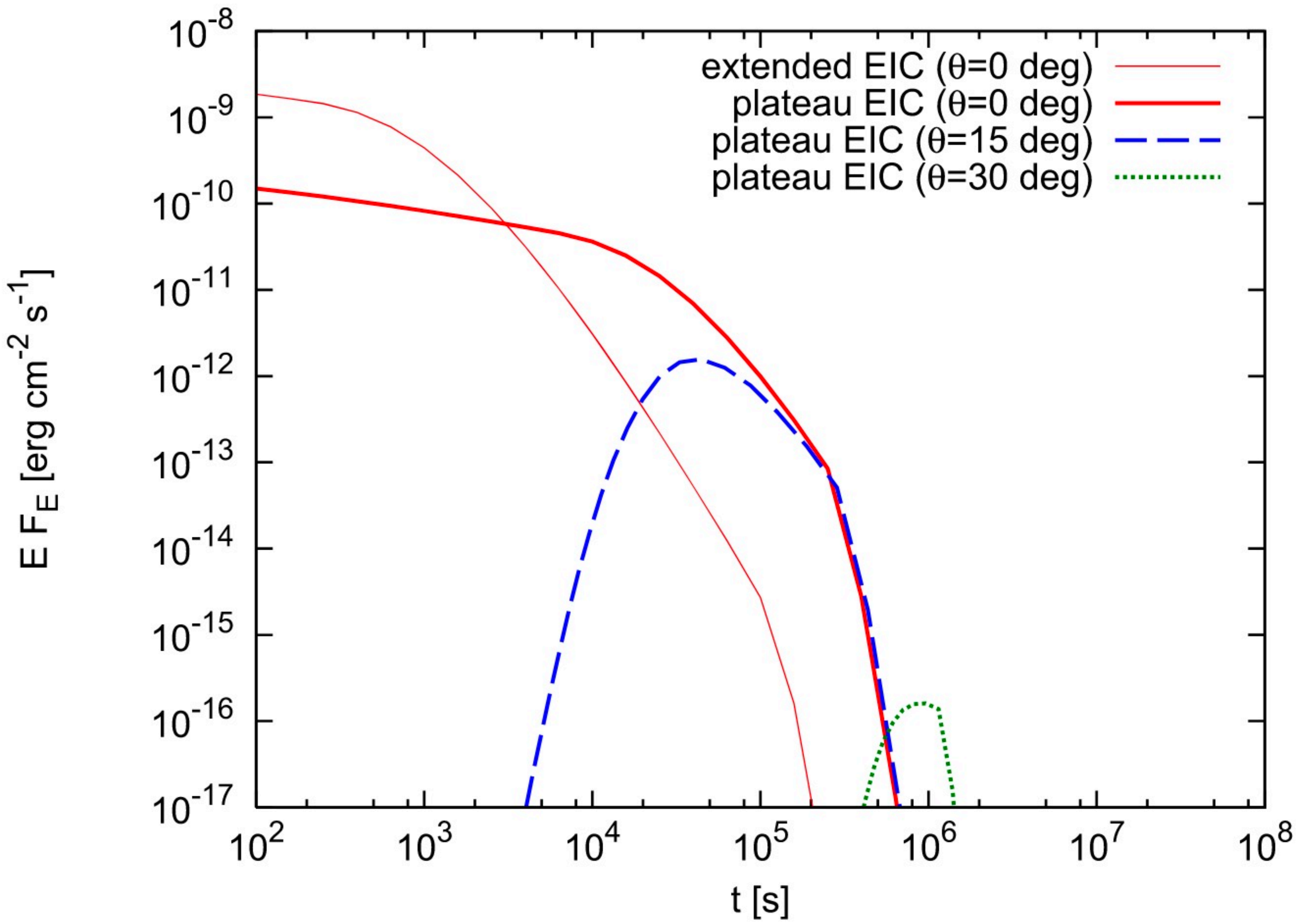


Figure 10. Light curves of high-energy gamma rays generated by external inverse Compton radiation, for $E = 100$ GeV. Three different viewing angles (measured from the jet axis) are considered, and extended emission with $T_a = 10^{2.5}$ s and plateau emission with $T_a = 10^4$ s are assumed as seed photons. The distance is set to $d = 40$ Mpc.

The afterglow parameters are , $n = 10^{-3}$ cm^{-3}, $\epsilon_e = 0.1$, $\epsilon_B = 0.01$, $s = 2.2$, and $\theta_j = 0.2$.

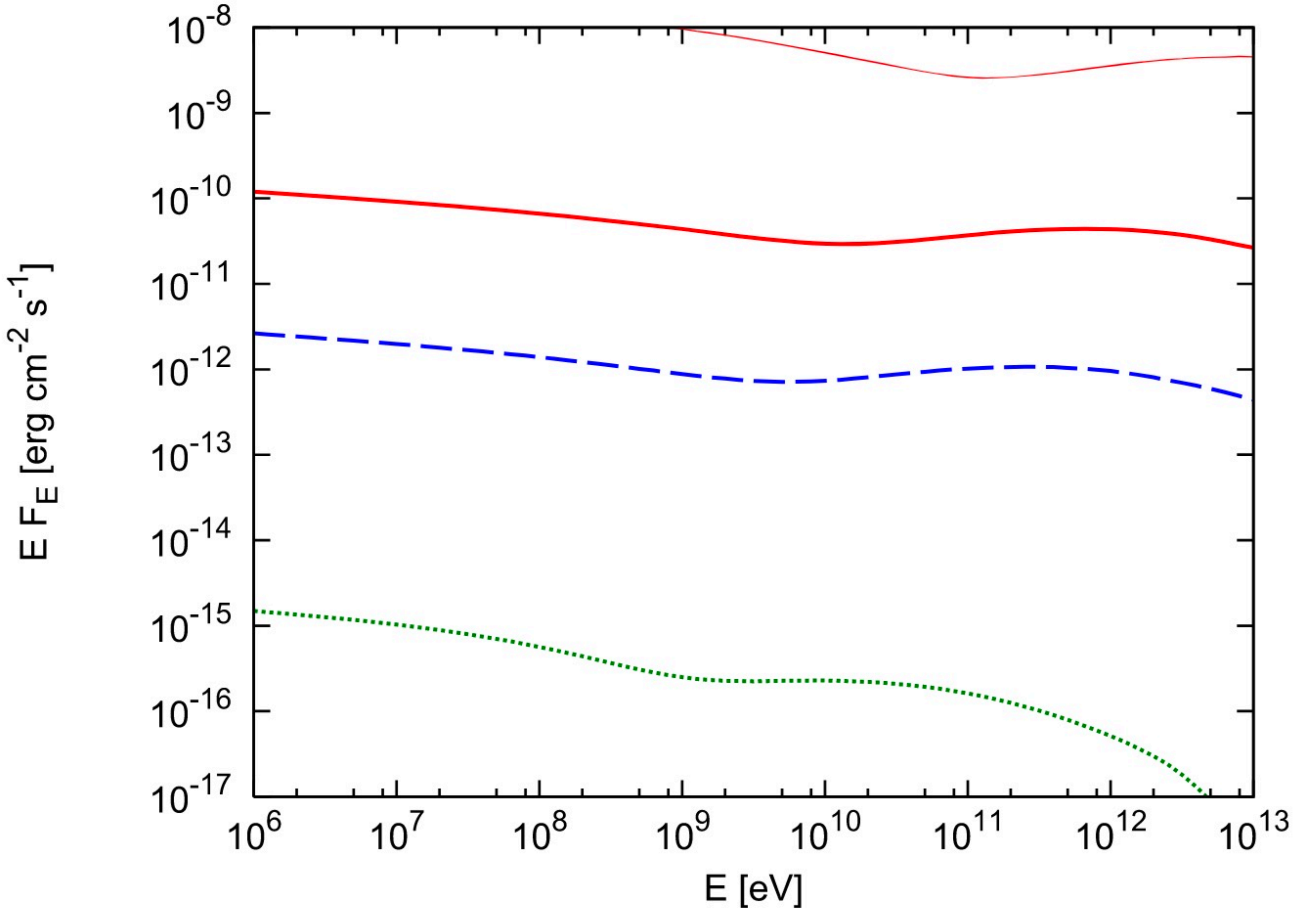
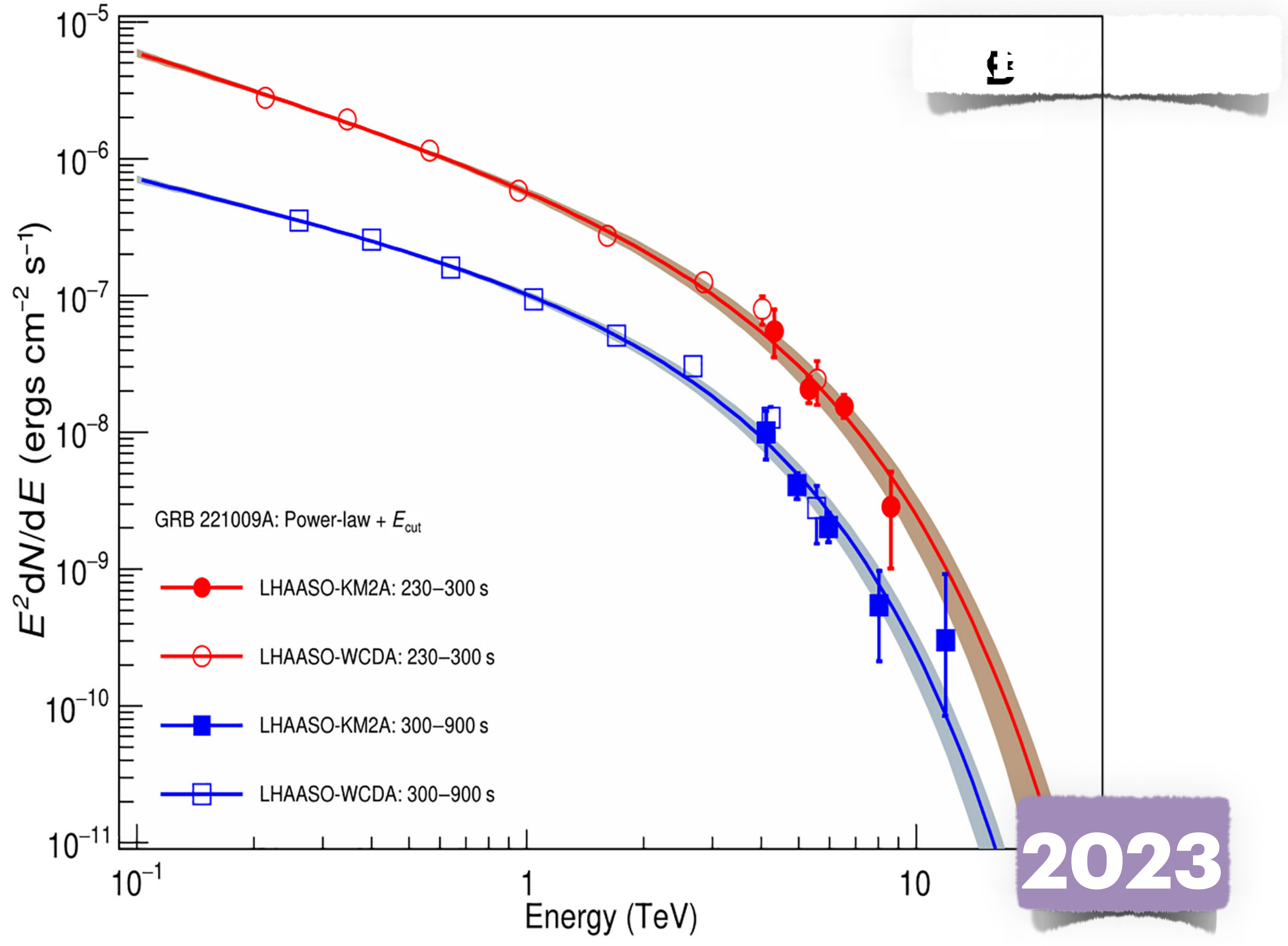


Figure 11. Gamma-ray spectra corresponding to Figure 10. For extended emission with $T_a = 10^{2.5}$ s, the spectrum at $t = 10^2$ s is shown (top curve), and the viewing angle is set to $\theta = 0°$. For plateau emission with $T_a = 10^4$ s, the spectra at $t = 10^4$ s, $t = 2.5 \times 10^4$ s, and $t = 8.2 \times 10^5$ s are shown (from the second top to bottom), and the viewing angles are $\theta = 0°$, $\theta = 15°$, and $\theta = 30°$, respectively.

GRB 221009A with LHAASO

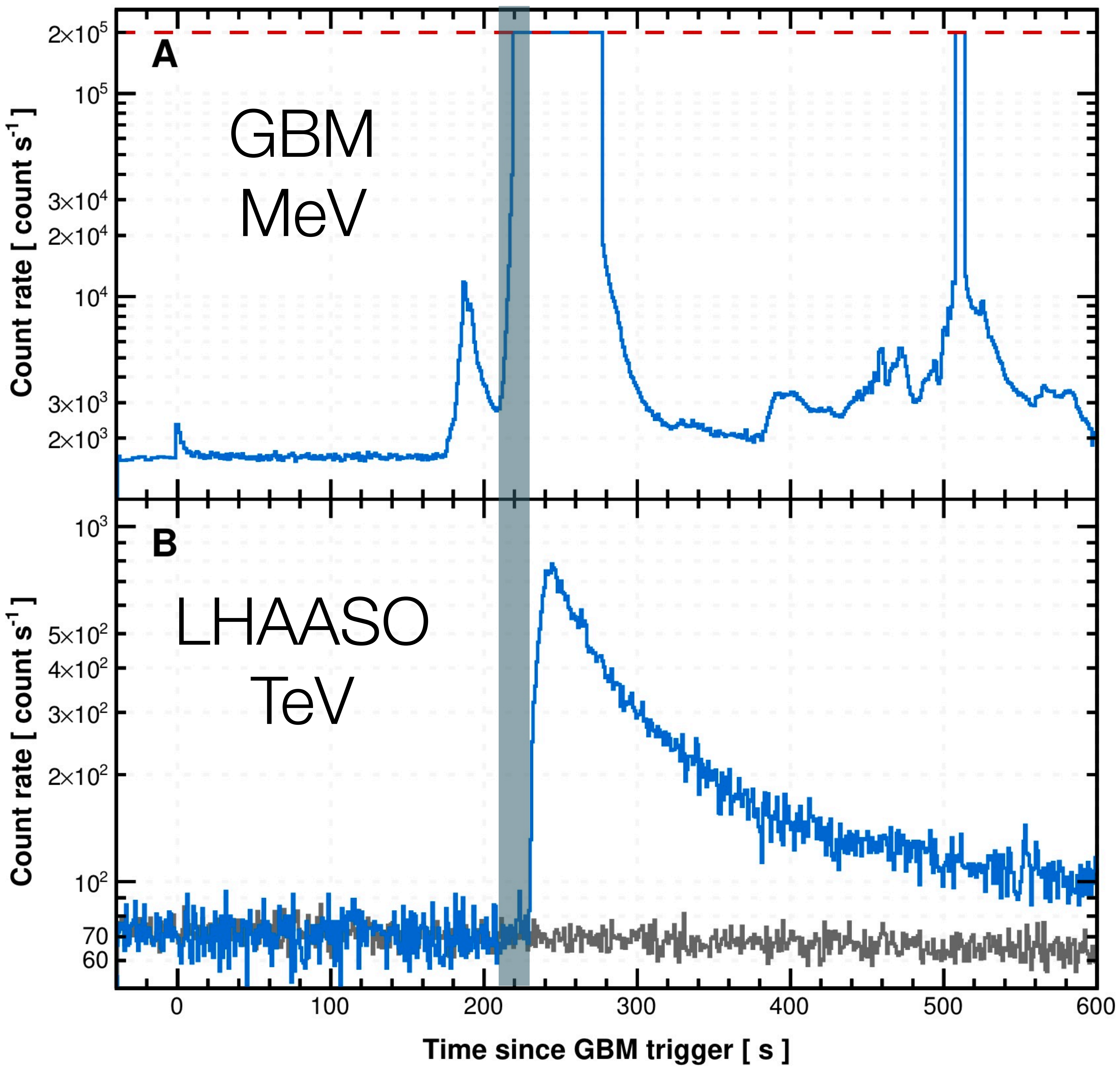
- Highest 13 TeV emission !



LHAASO Coll. et al., Science,9,46 (2023)
https://www.science.org/doi/10.1126/sciadv.adj2778

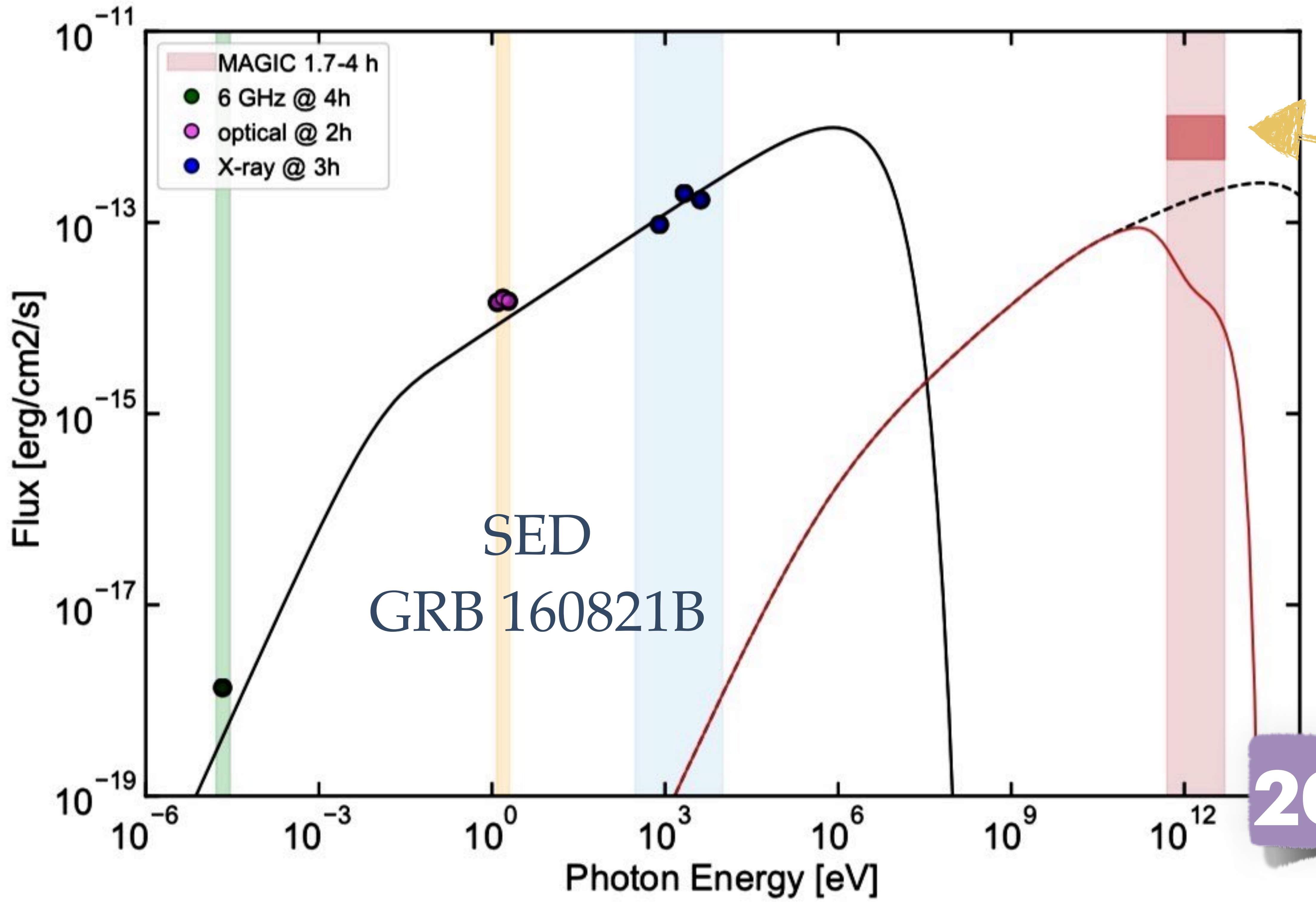
Indication of high-B -> pointing flux dominated jet?

Dai et al.2023ApJ…957L..32D



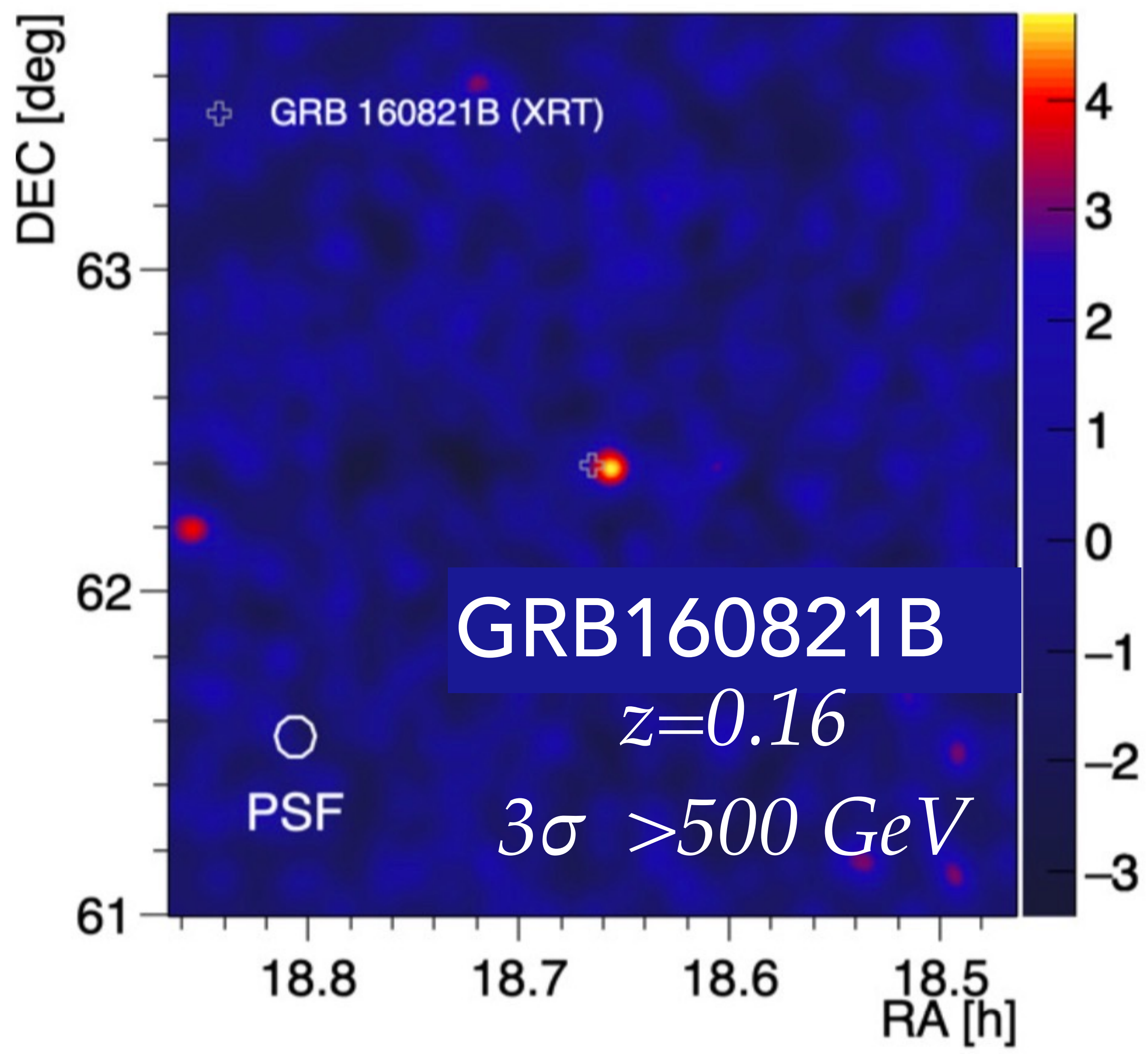
The next frontier: chasing the GW counterparts

- Hint of detection on the **short** GRB160821B by MAGIC
  - associated to a kilonova Lamb et al. 2019, Troja et al. 2019
- **Short GRBs are associated to mergers of compact binaries and GW events** (e.g. GW170817 - GRB170817)



MAGIC

2021

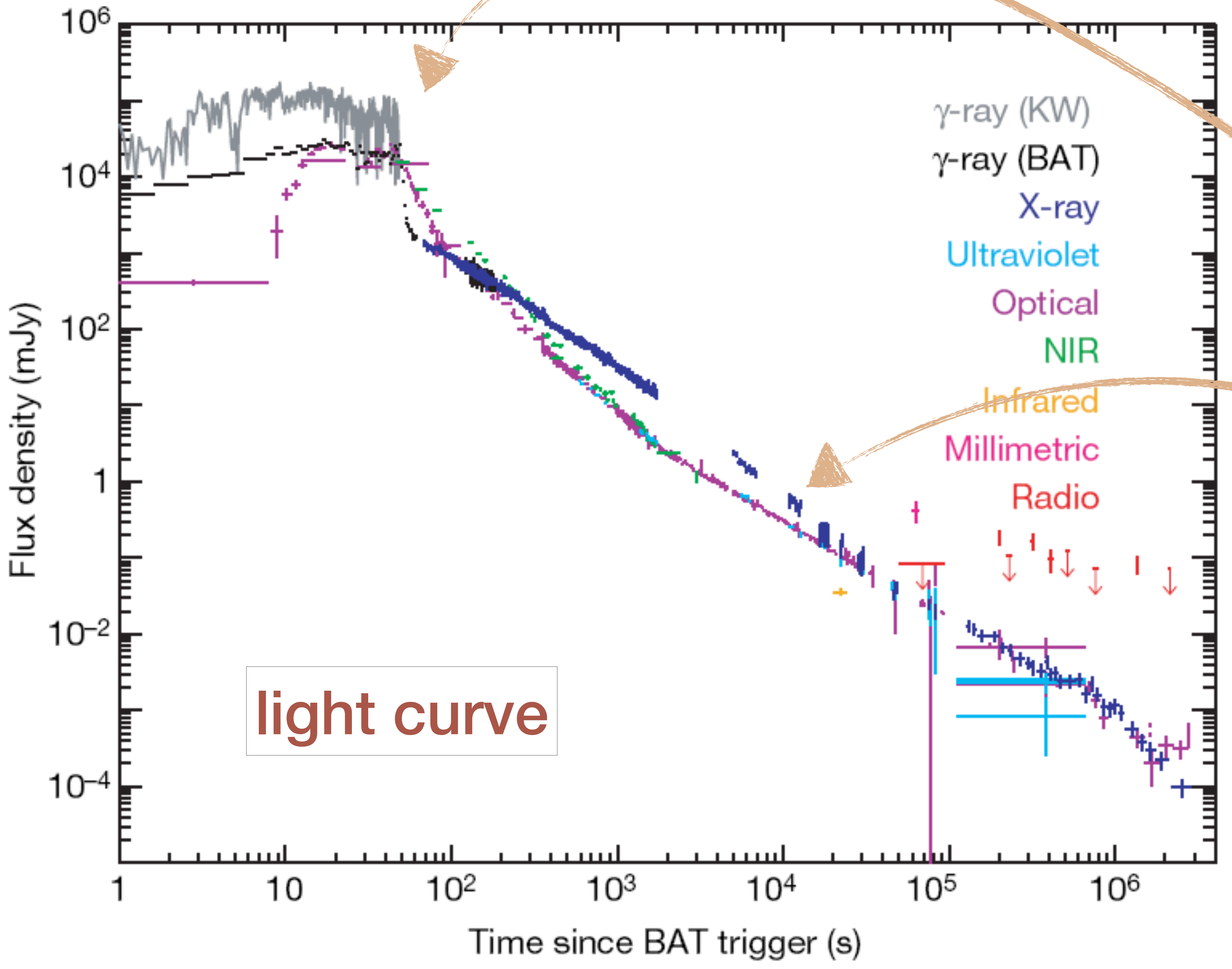


Further suggestive indications that short GRBs might have a second GeV component (e.g. GRB050910)

MAGIC Coll. ApJ, vol. 908 (2021)

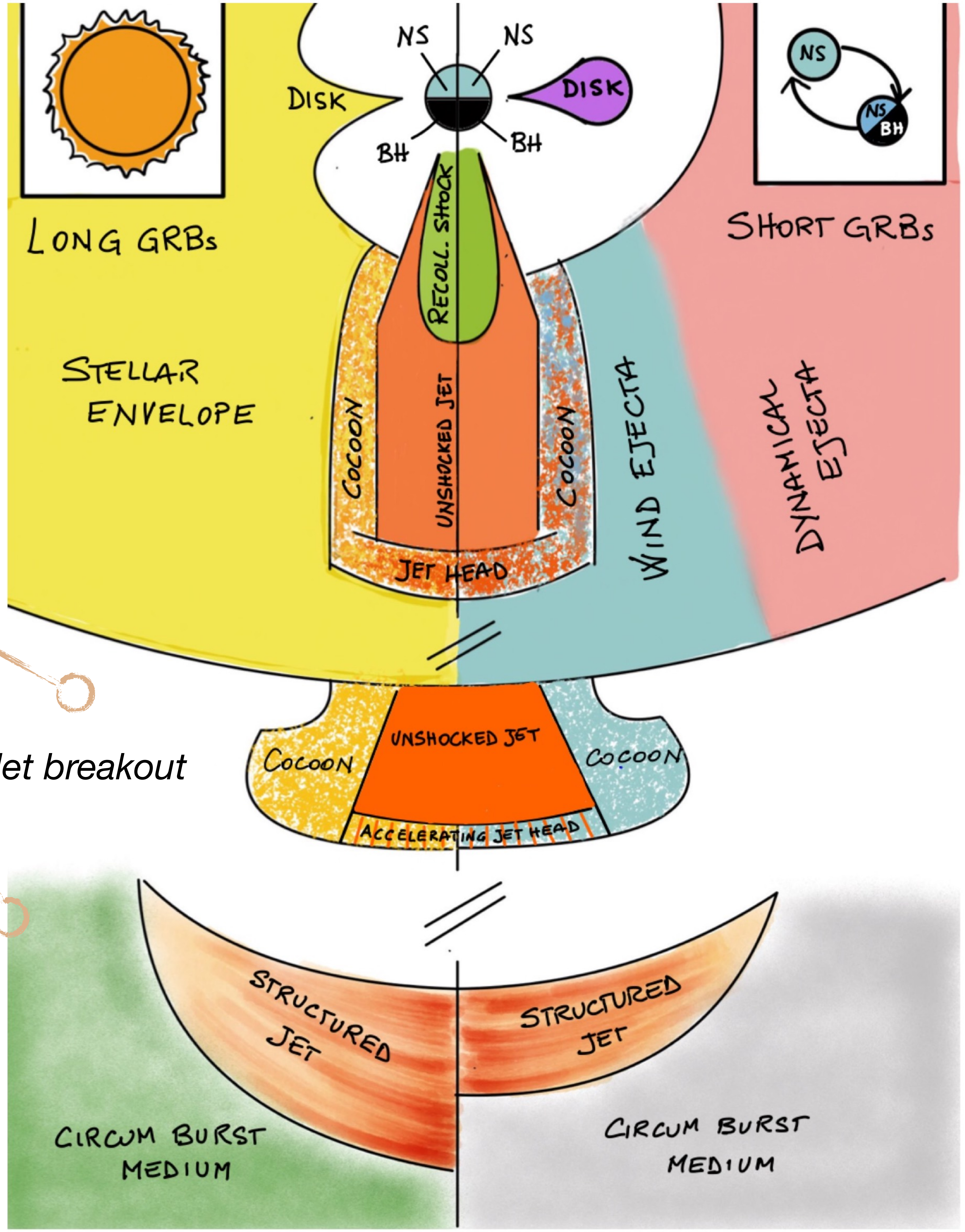
GRB formation and evolution: structured jet

- A structured jet is formed at breakout



Jet formation

Jet breakout

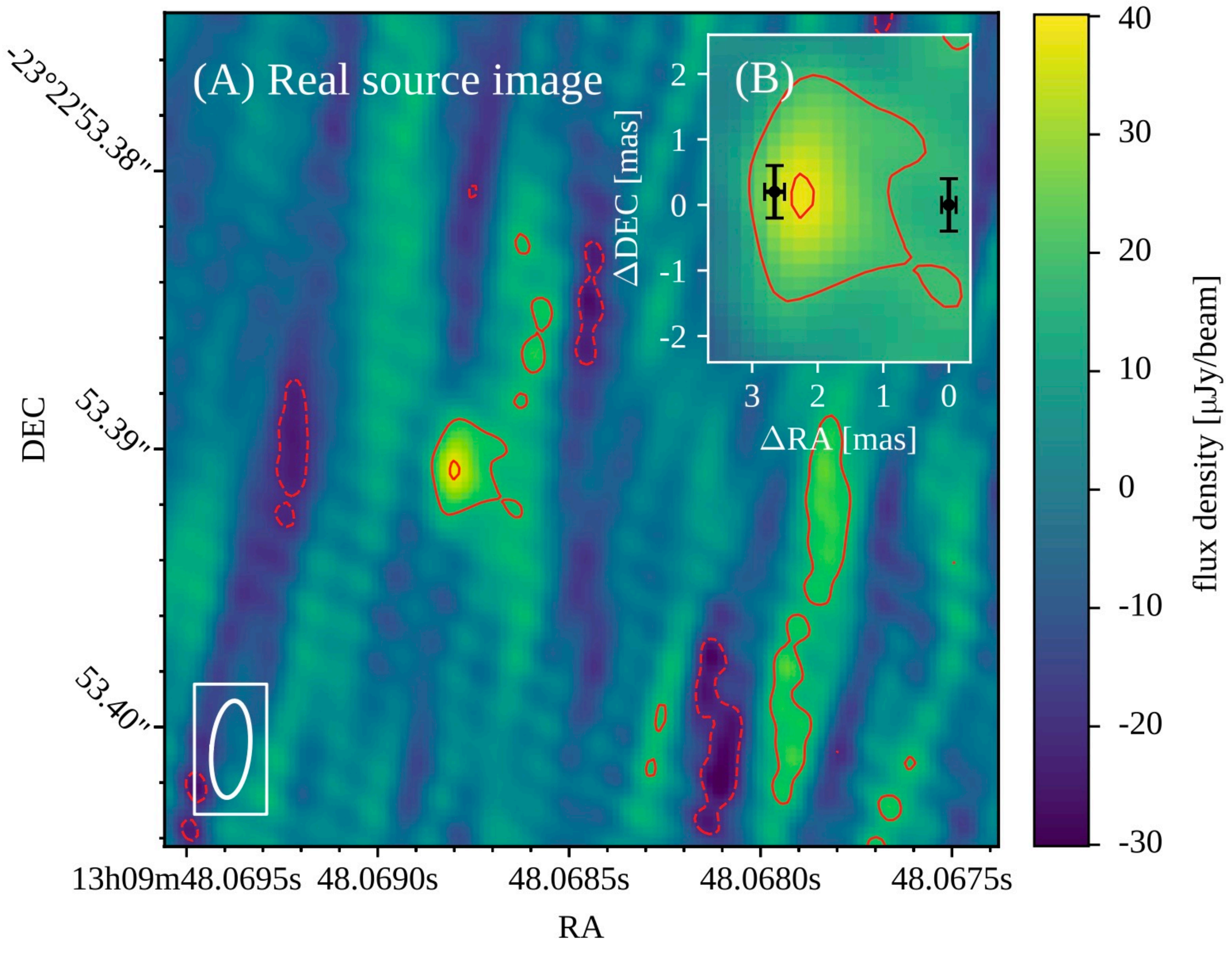


Salafia&Ghirlanda 2022

GRB formation and evolution: structured jet

- A structured jet is formed at breakout
  - Theoretical models (e.g. GRMHD simulations) predict a structured jet; confirmed by observations

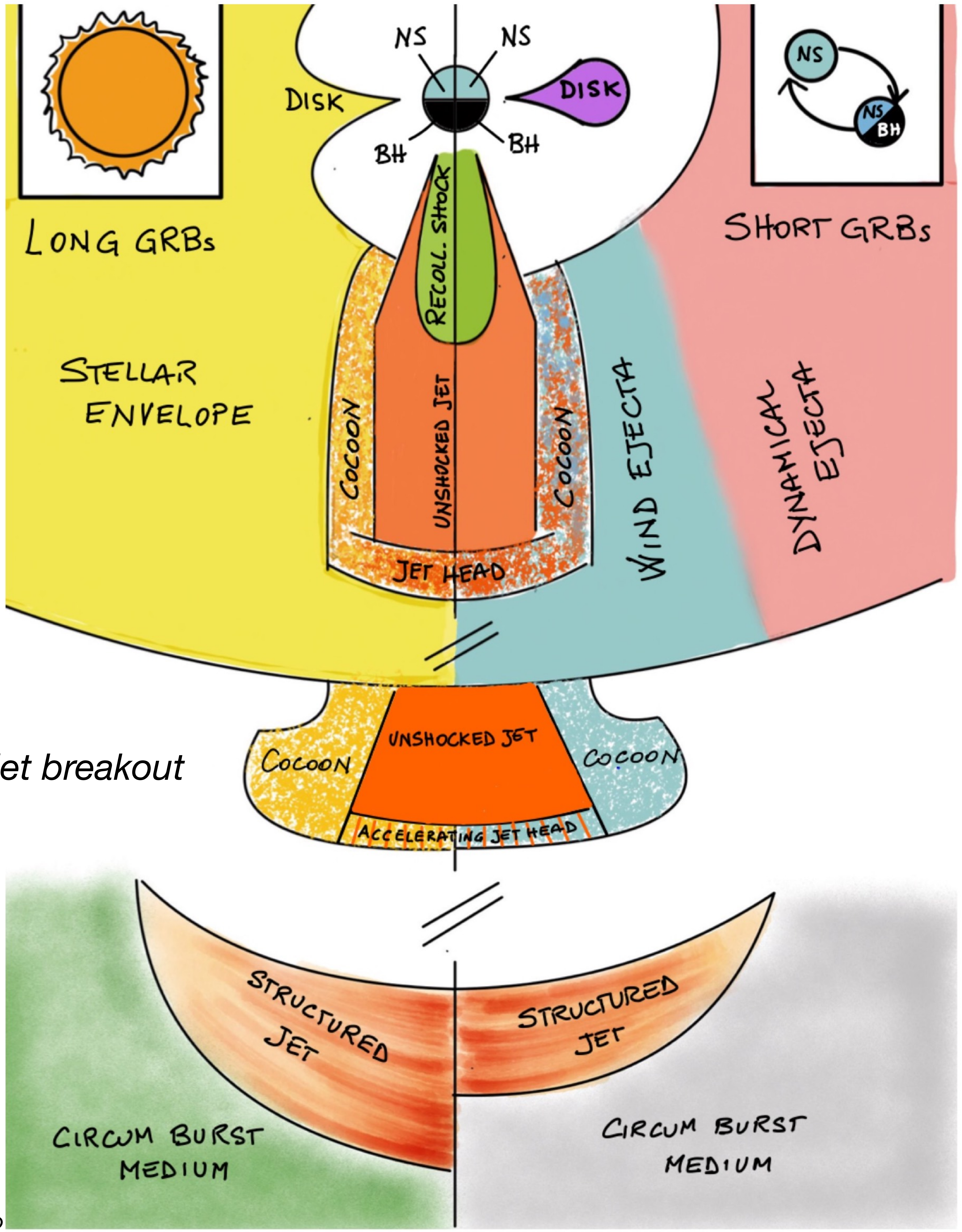
Radio images of GRB/GW 170817 207 d after merger



Ghirlanda+2019

Jet formation

Jet breakout



Salafia&Ghirlanda 2022

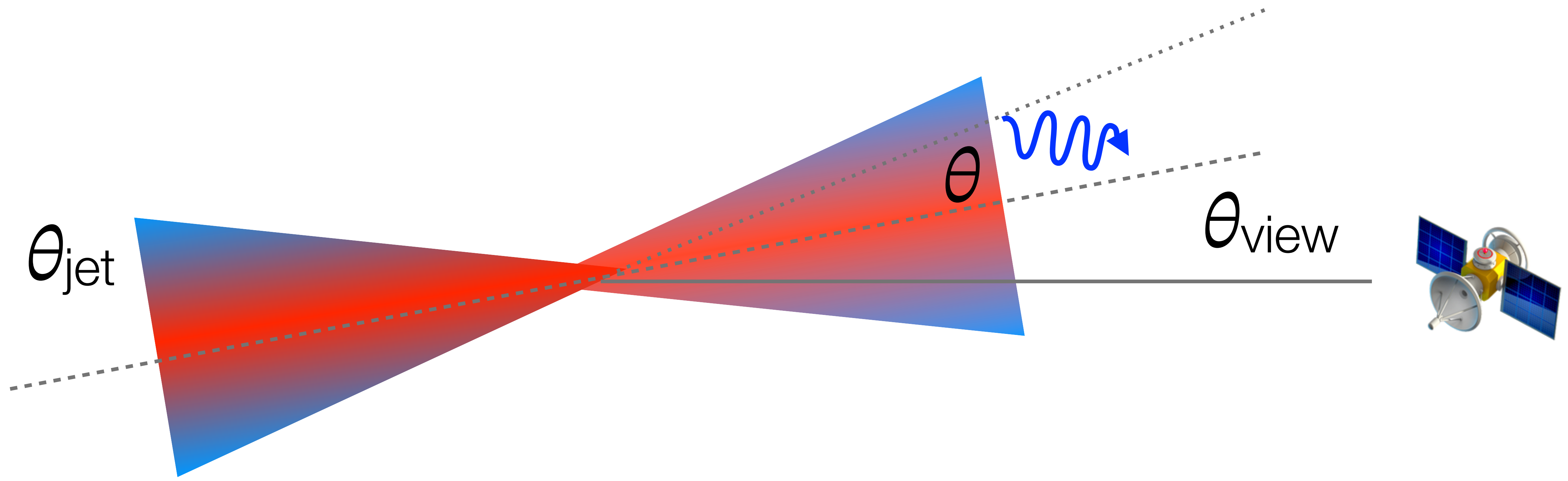
GRB formation and evolution: structured jet

- A structured jet is formed at breakout
  - Observed emission depends on the viewing angle and jet lateral structure.

$$E_{\rm iso}(\theta_{\rm view}) = \int_0^{2\pi} d\phi \int_0^1 d\cos\theta \, \frac{\delta^3(\theta,\phi,\theta_{\rm view})}{\Gamma(\theta)} \eta(\theta) \frac{dE}{d\Omega}(\theta)$$

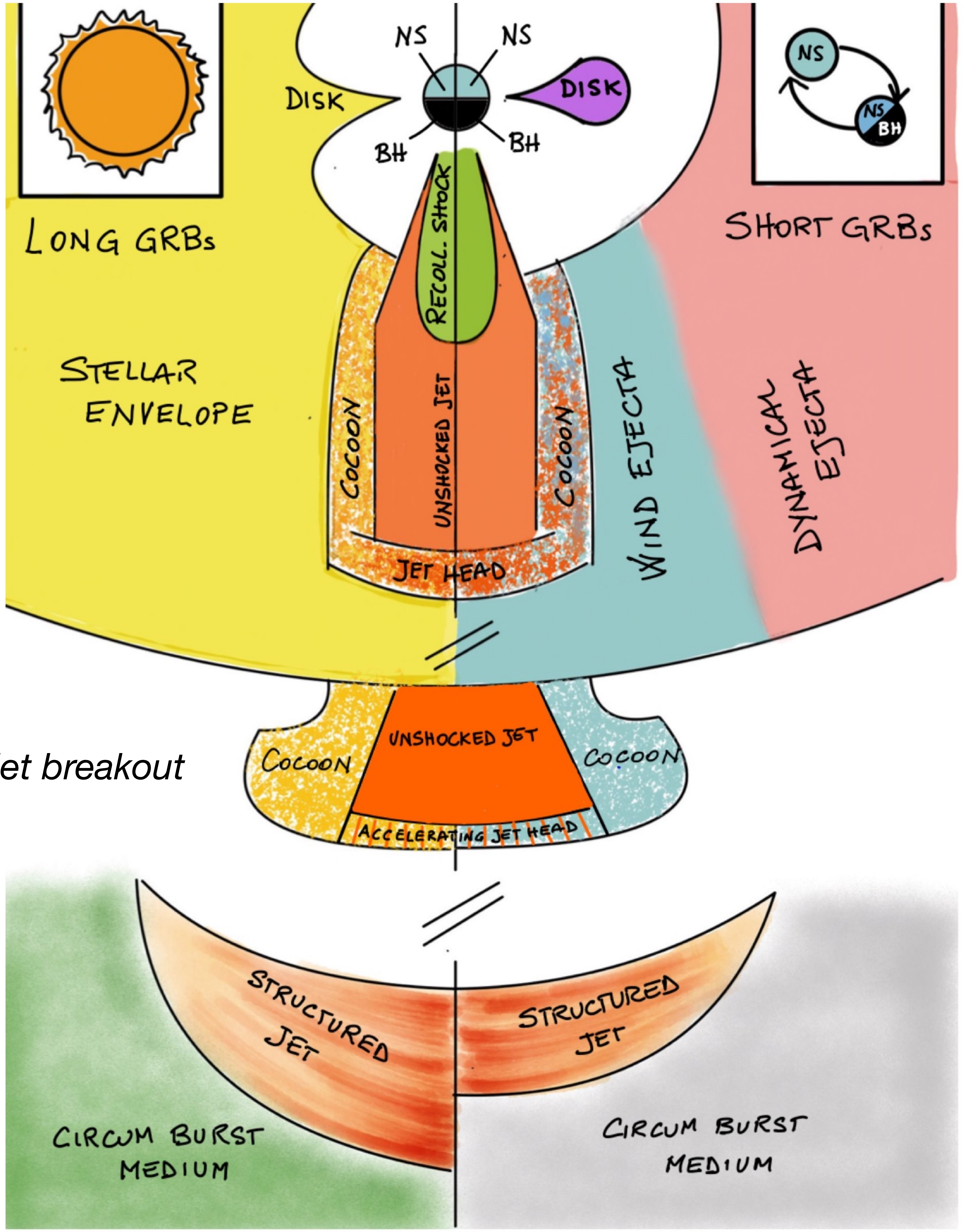
$$\delta = \Gamma(\theta)^{-1}\left[1-\beta(\theta)\cos\alpha(\theta,\phi,\theta_{\rm view})\right]^{-1}$$ Doppler factor (beaming)

$$\beta(\theta) = \left[1-\Gamma(\theta)^{-2}\right]^{1/2} \qquad \cos\alpha = \cos\theta\cos\theta_{\rm v} + \sin\theta\sin\phi\sin\theta_{\rm v}$$



Jet formation

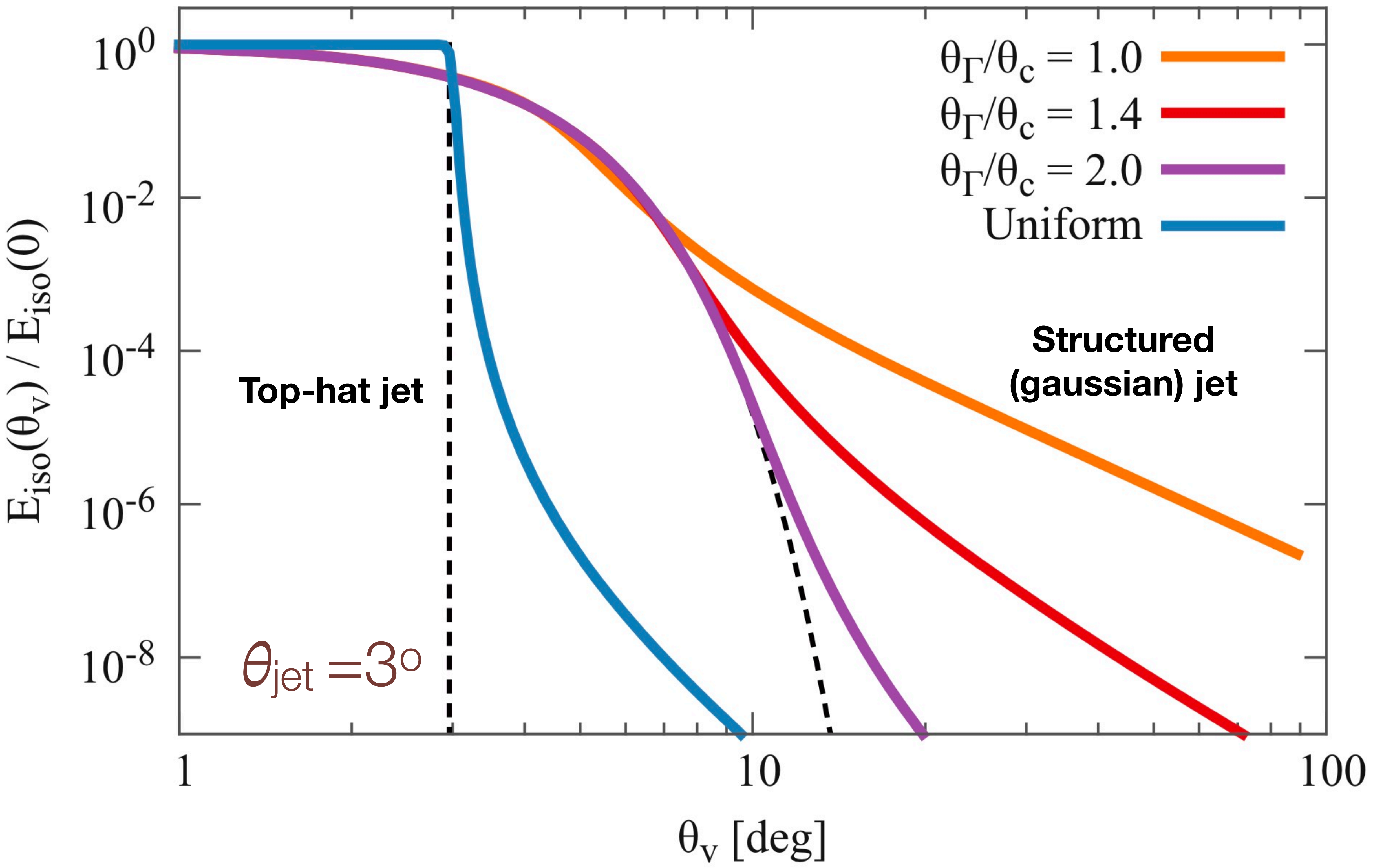
Jet breakout



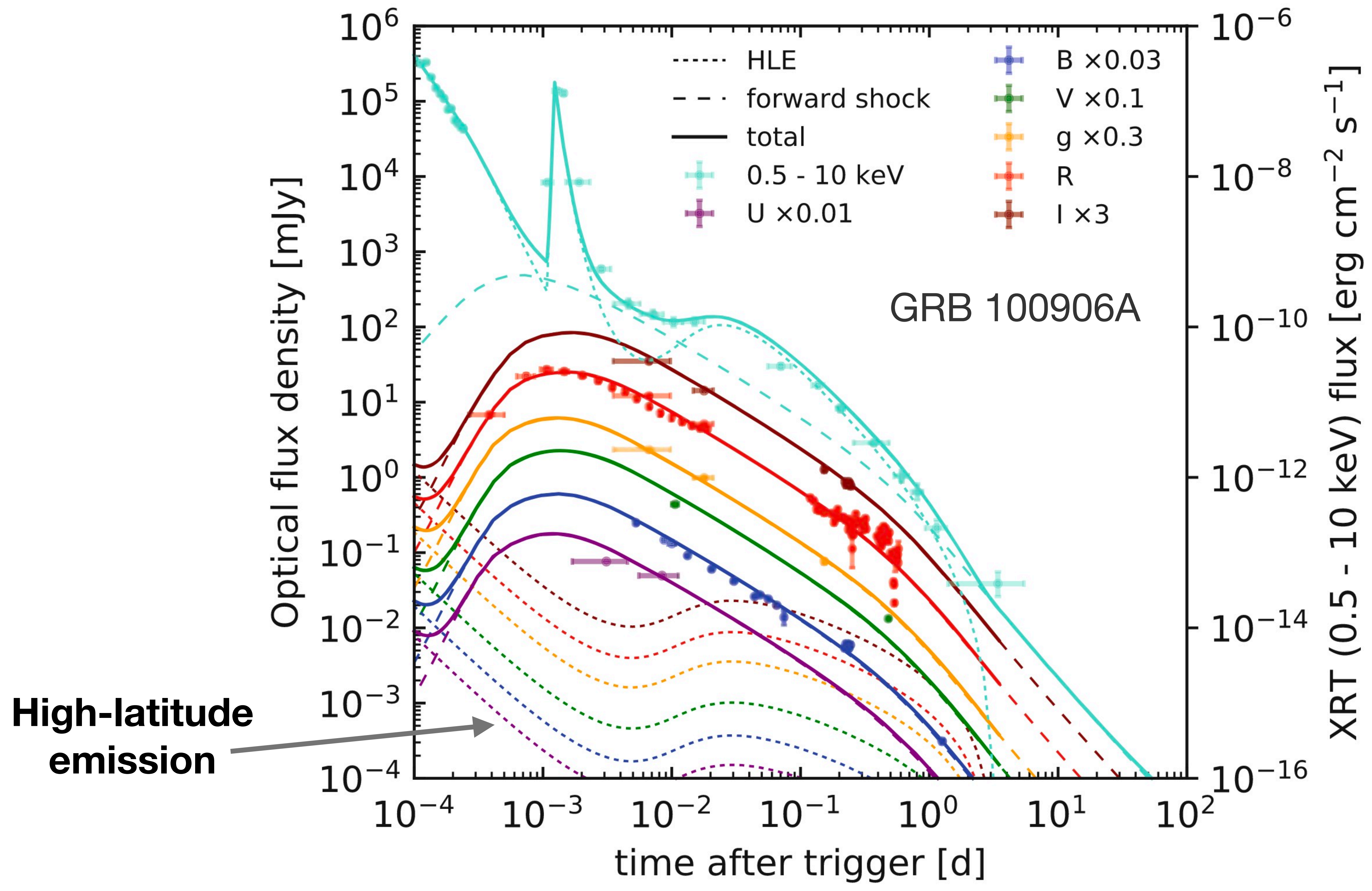
Salafia&Ghirlanda 2022

The role of structured jets

- Energy emission depends on the jet structure
- Emission expected also at larger viewing angles (high-latitude emission)

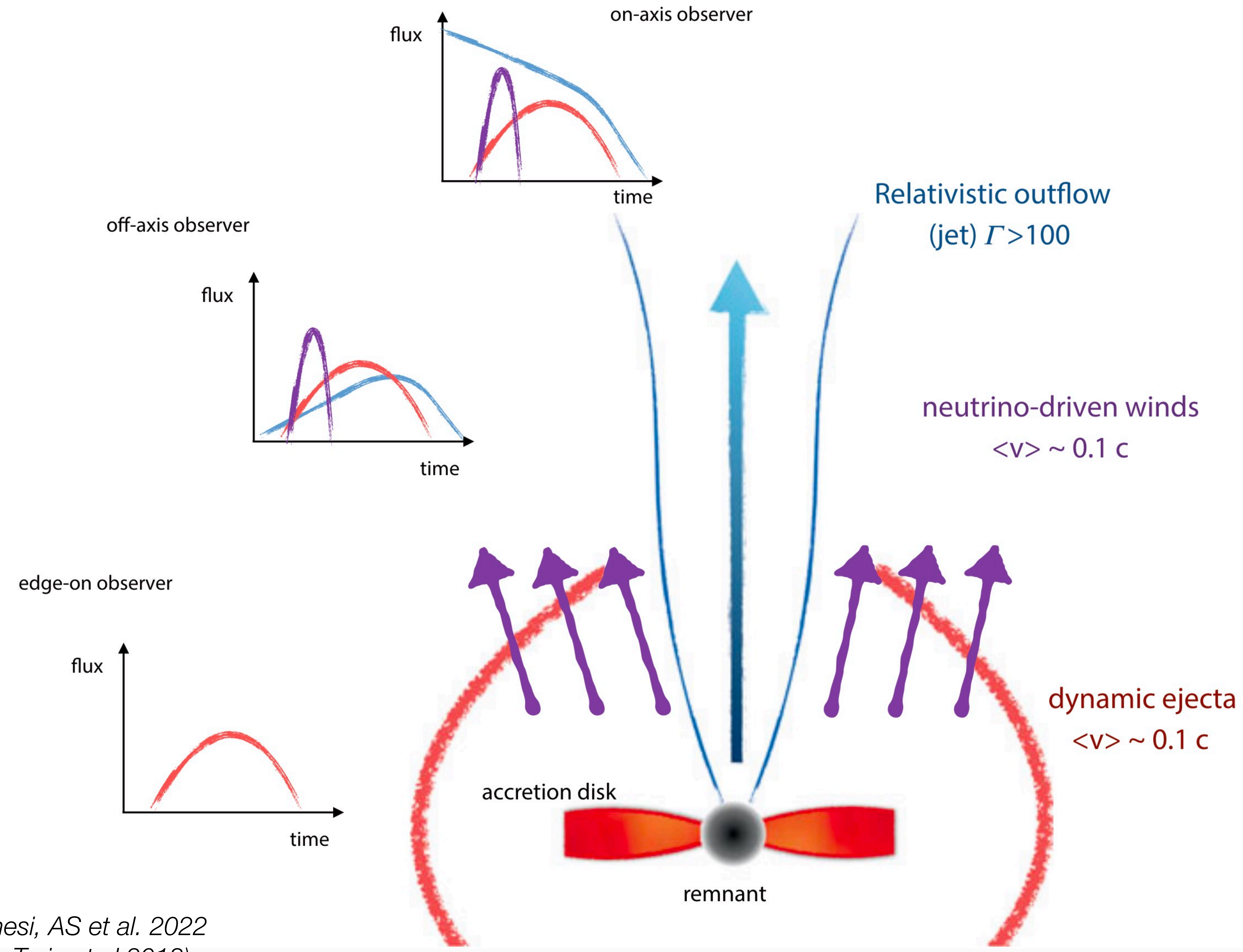


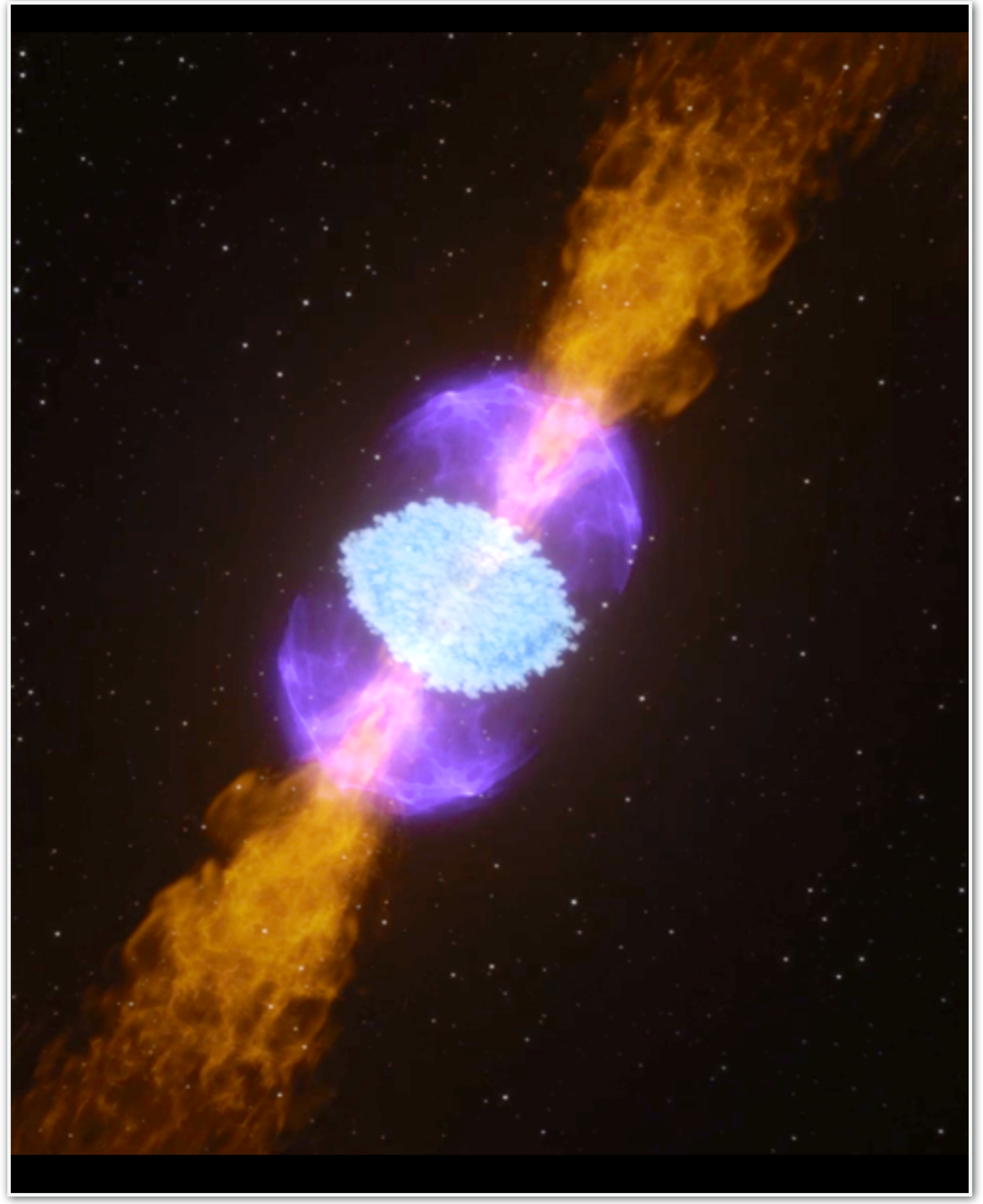
Salafia et al. 2015,
Branchesi et al. 2022



Oganesyan et al. 2020

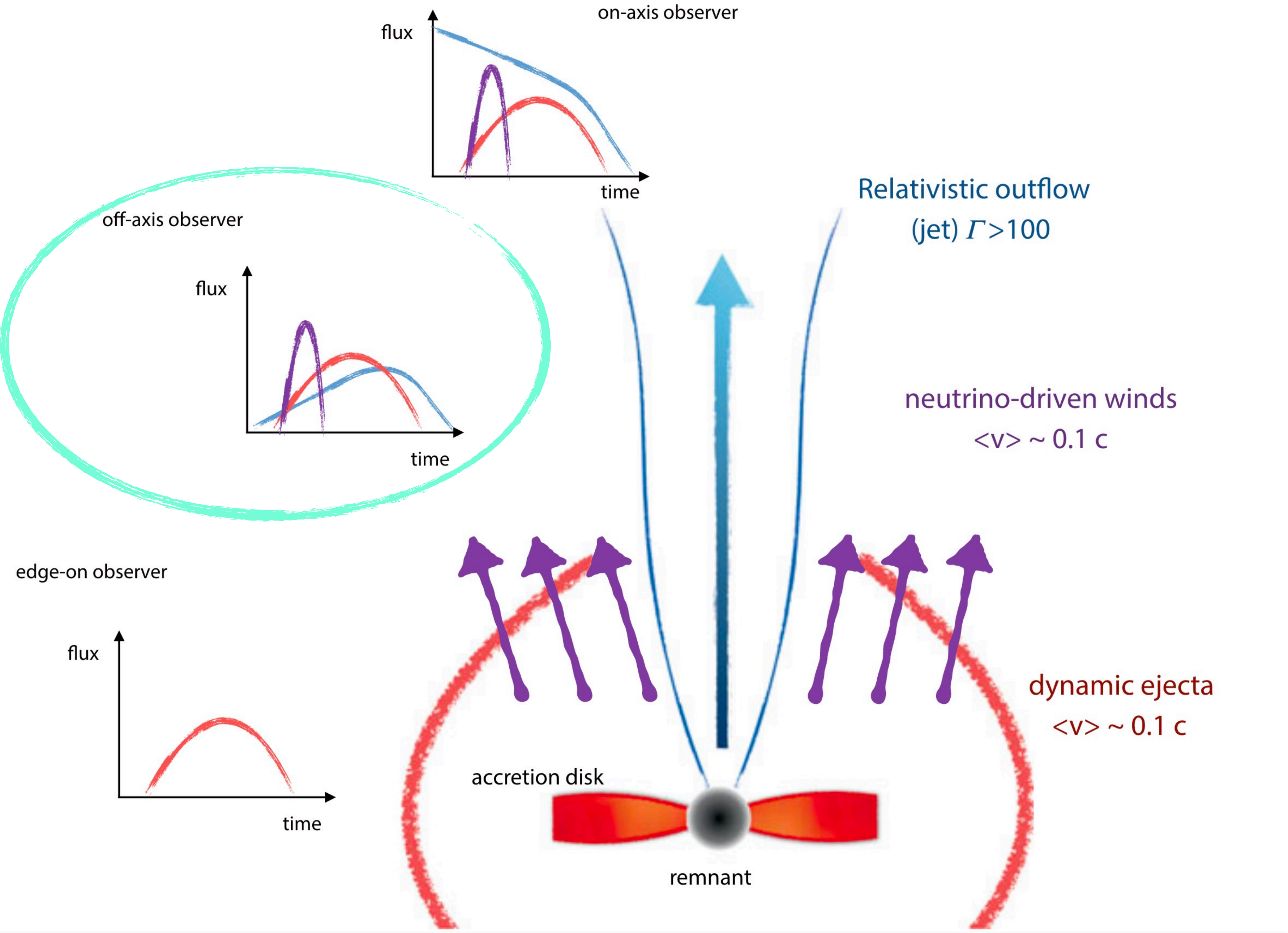
The role of off-axis observations





Branchesi, AS et al. 2022
(From Troja et al 2018)

The role of off-axis observations



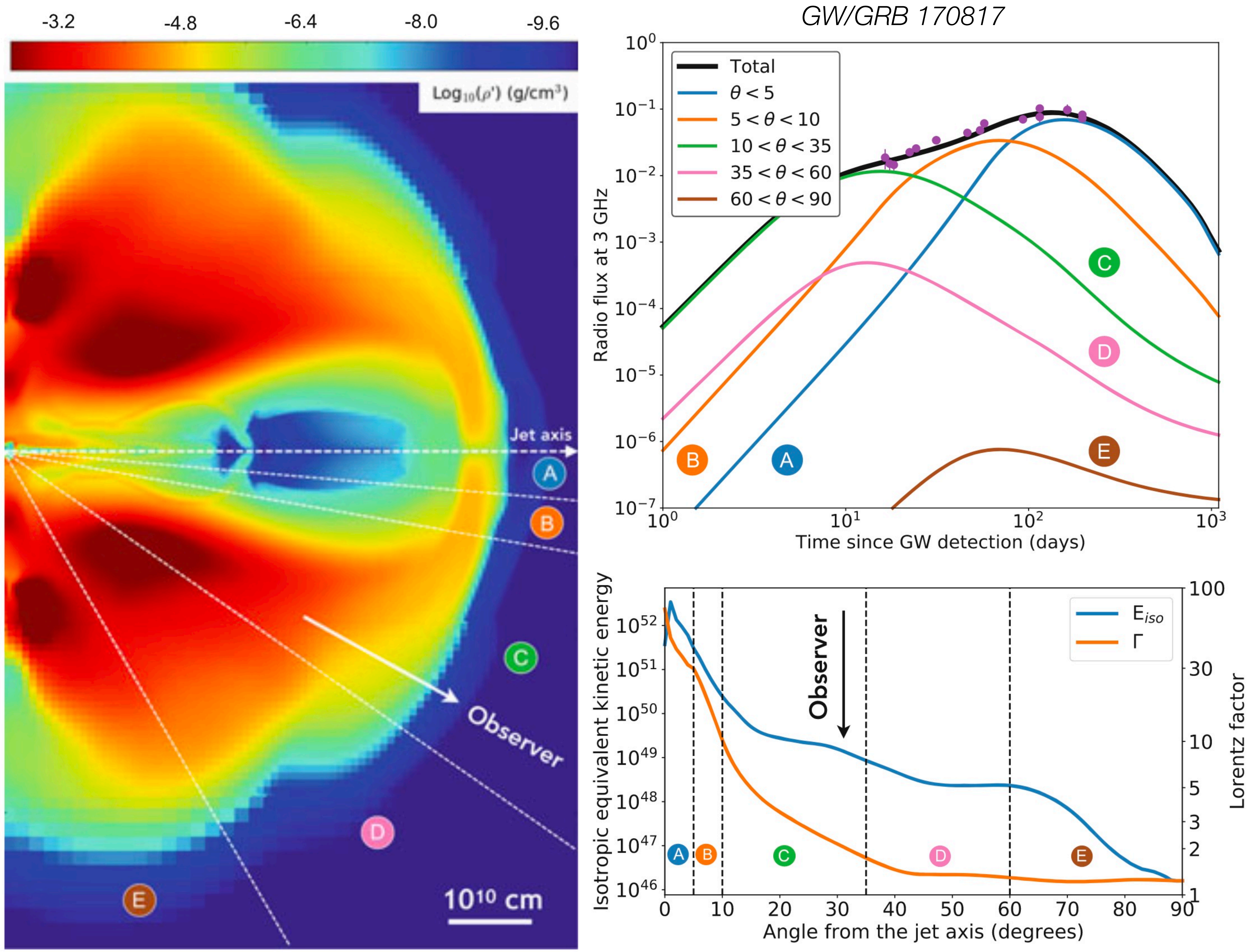


Fig. 3 Jet structure and afterglow emission of a simulated short gamma-ray burst structured jet. The left panel shows the co-moving rest-mass density in a snapshot of a relativistic hydrodynamic simulation of a gamma-ray burst jet that breaks out of kilonova ejecta. The lower right panel shows the angular isotropic equivalent kinetic energy distribution in the jet (blue line) and the bulk Lorentz factor (orange line). The upper right panel shows the 3 GHz light curves from the afterglow of such a jet decelerating in an interstellar medium with number density 4.2×10^{-3} cm^{-3}, seen under a 33° viewing angle, at a 40 Mpc distance. Different curves show the contribution to the emission from the angular portions of the jet indicated in the left panel. The purple points show the light curve of GRB 170817, which is well explained by the model. (Reproduced with permission from

Lazzati+2018

The role of off-axis observations: MeV and TeV emission

- TeV emission scaled (20%) from MeV emission (+internal absorption)

$$\nu_{0,\mathrm{VHE}}(\theta,\phi) = \delta_D \nu'_{0,\mathrm{HE}}(\theta) \approx 0.15\times10^9 \delta_D \left[1+\left(\frac{\theta}{\theta_c}\right)^{3.4}\right] \mathrm{eV},$$

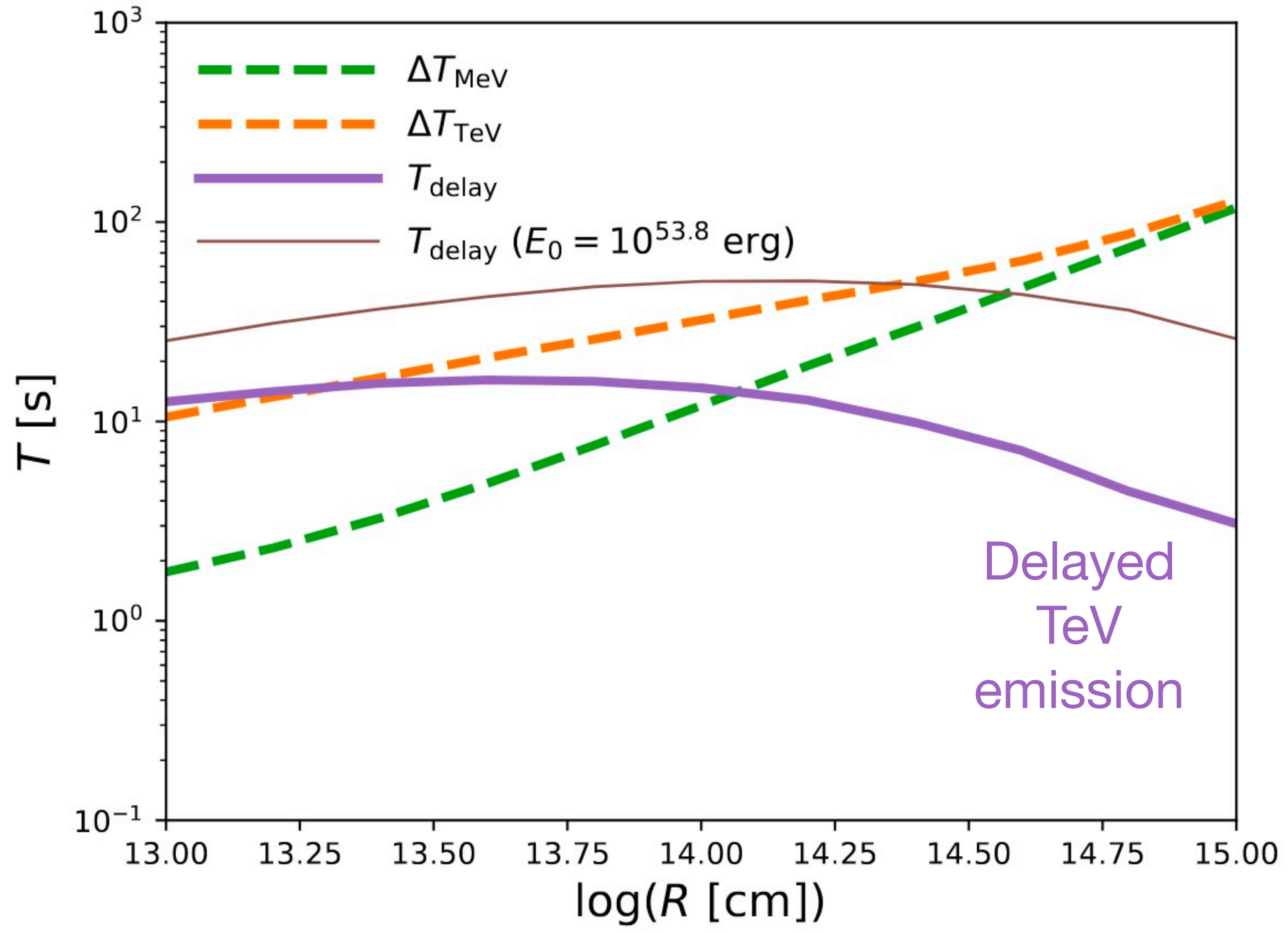
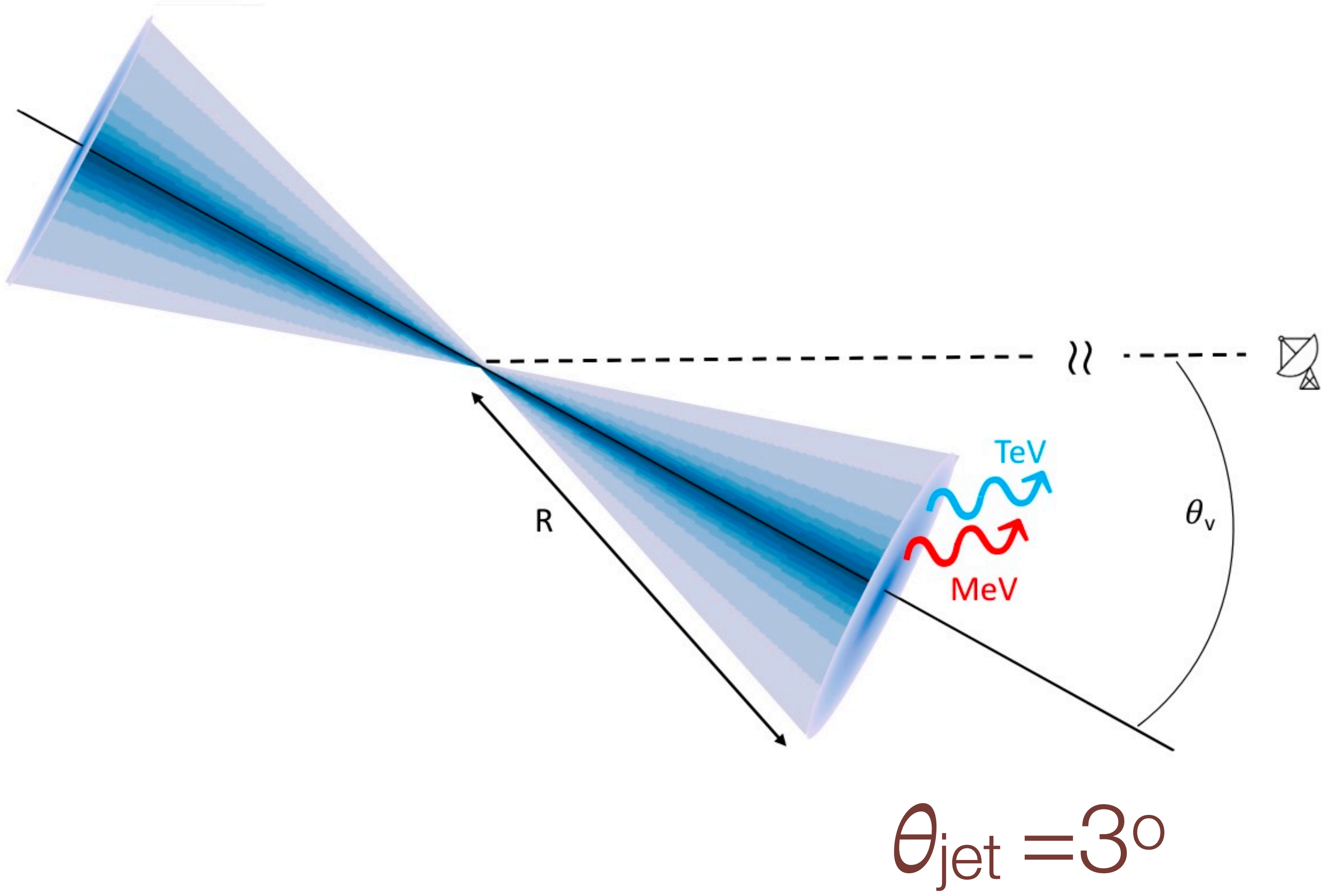
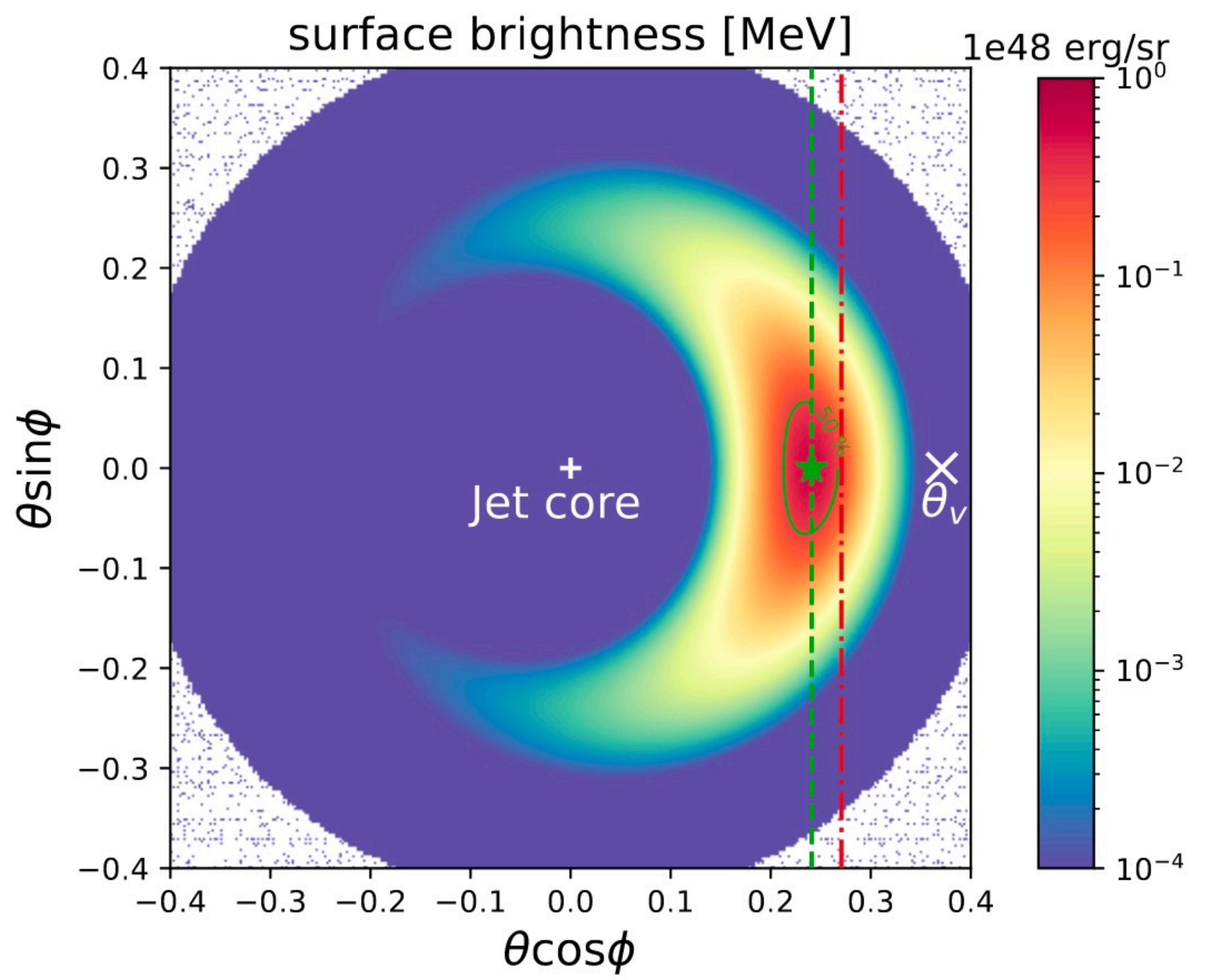
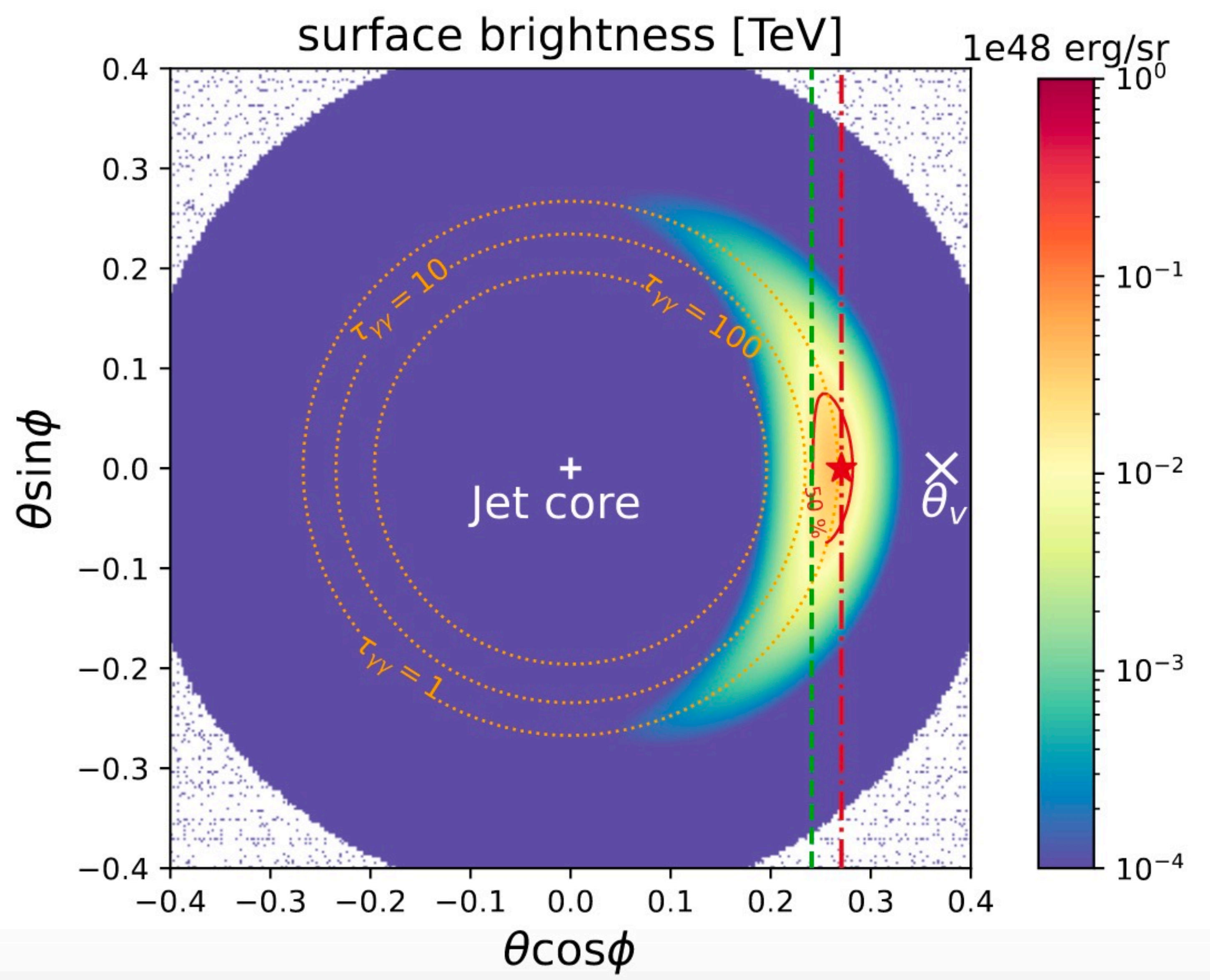


Figure 6. The arrival time delay between TeV and MeV photons and the duration of GRB prompt emission at the MeV energy band as a function of the emission region radius. The spectral and jet parameters are the same as in Fig. 2. Note that the viewing angle is set to $\theta_v = 0.38$.



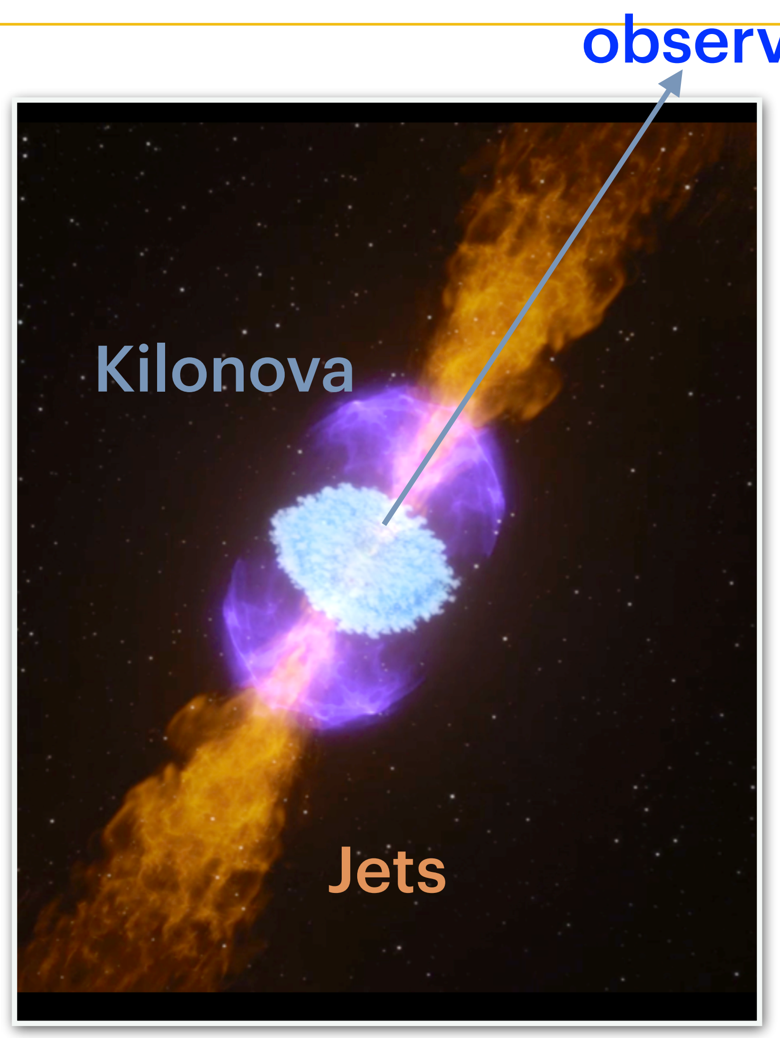


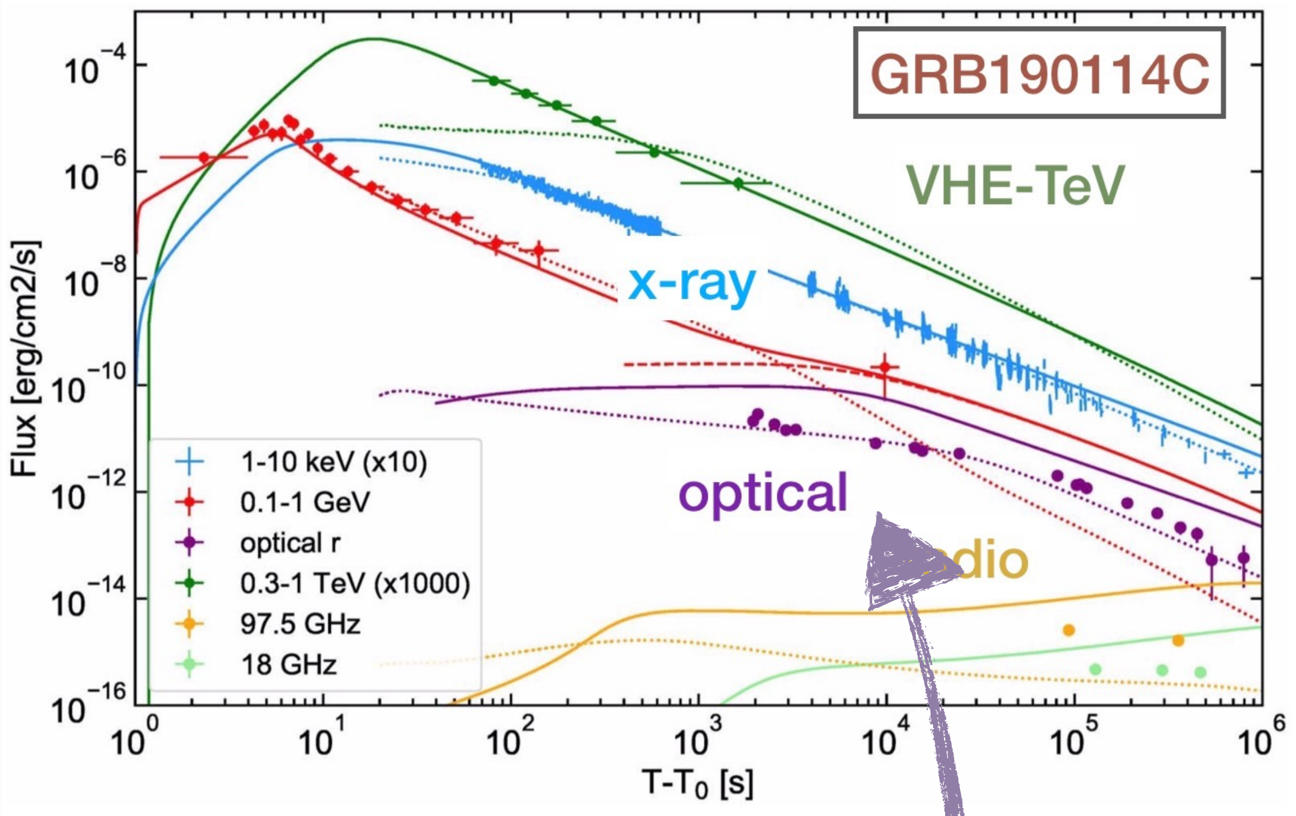


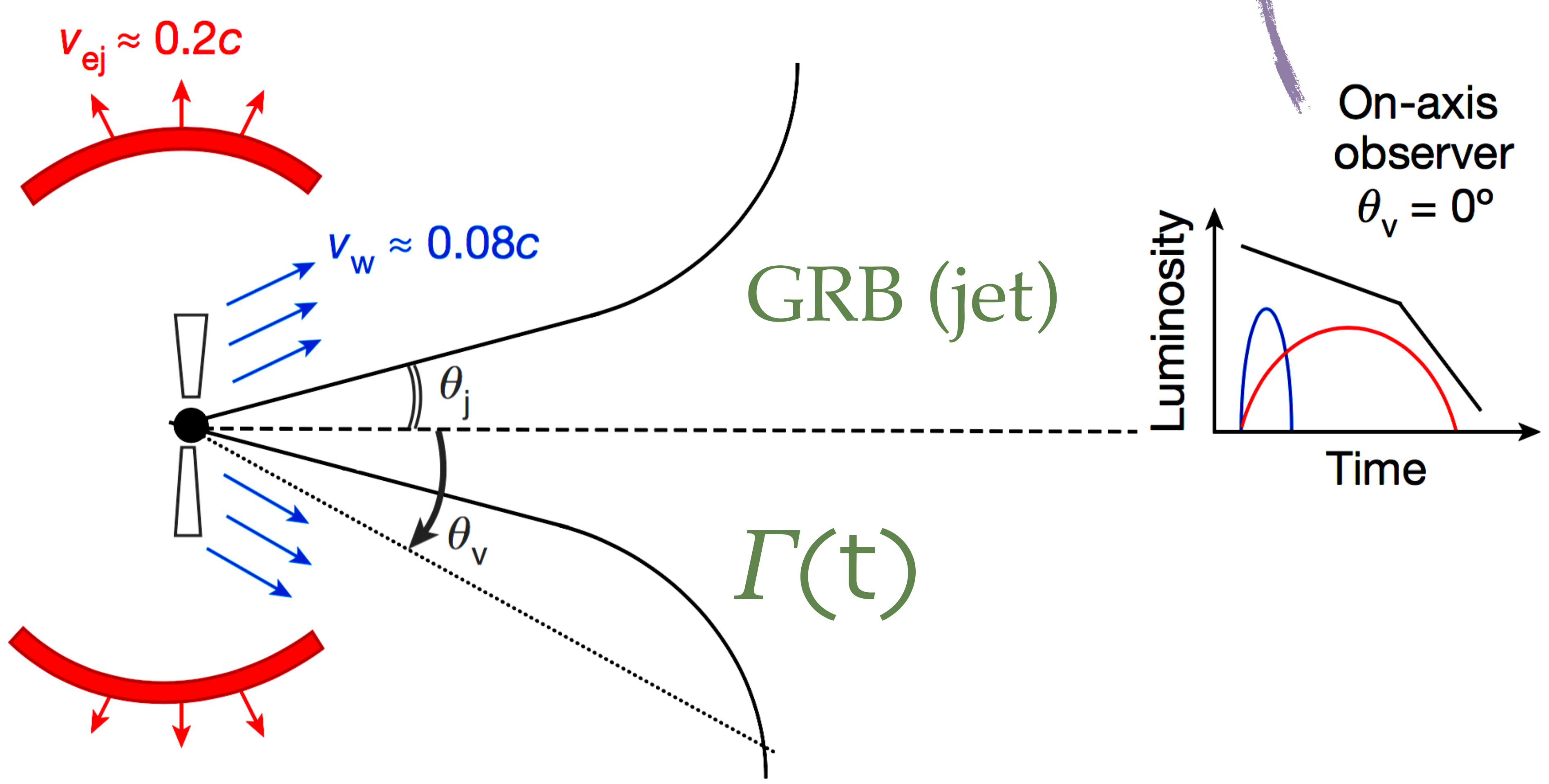
Bošnjak +2024

TeV emission from GW counterparts: an off-axis GRB

- GRB afterglow: beamed emission, Γ>100, time evolution
  - intensity boosted ~Γ^3
  - light curve decreasing ~ $t^{-1.5}$ (depending on frequency)
- High energy emission from GW counterparts is seen **off-axis**, Γ~a few
  - intensity weaker $10^{-4,-6}$
  - light curve Delayed (hours-days-months, depending on θ_{view})





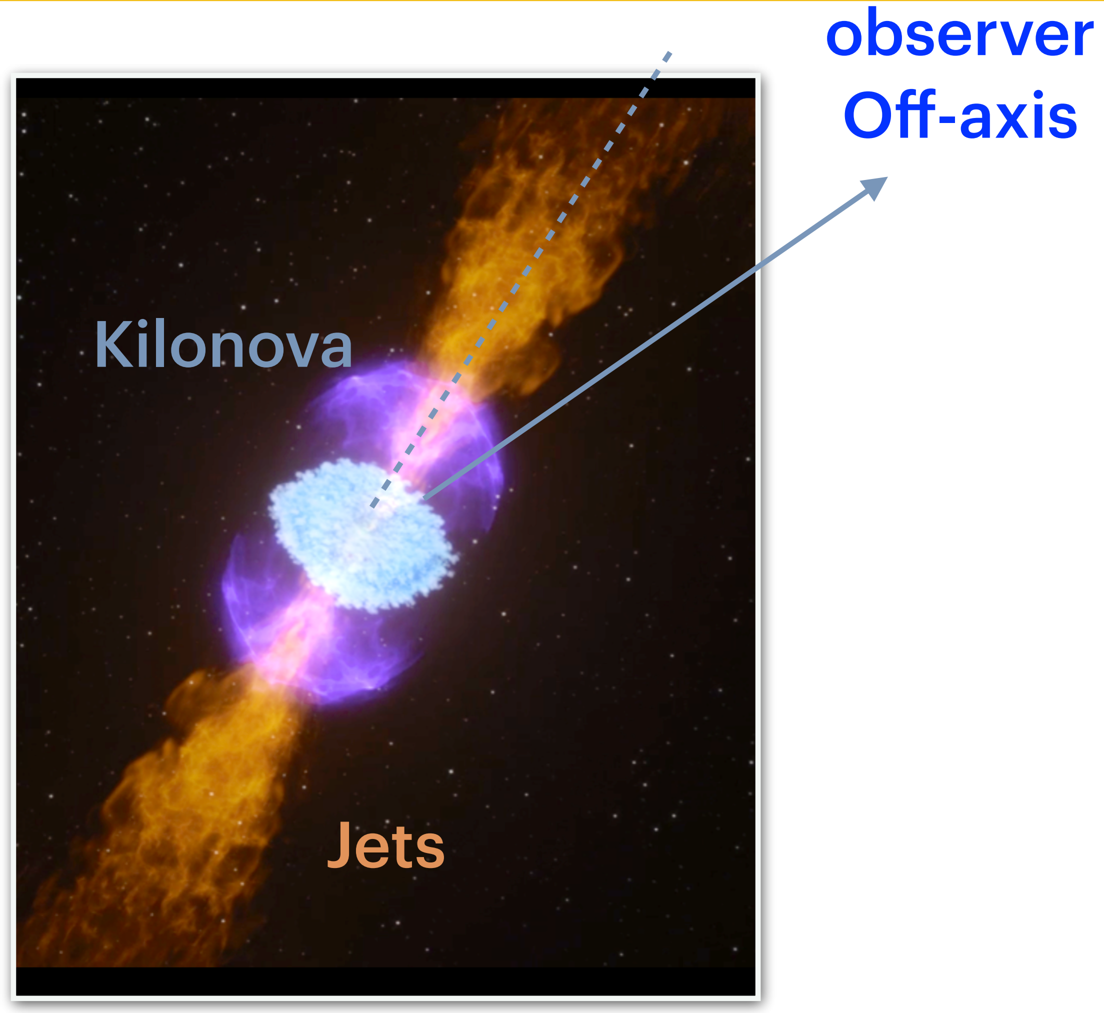


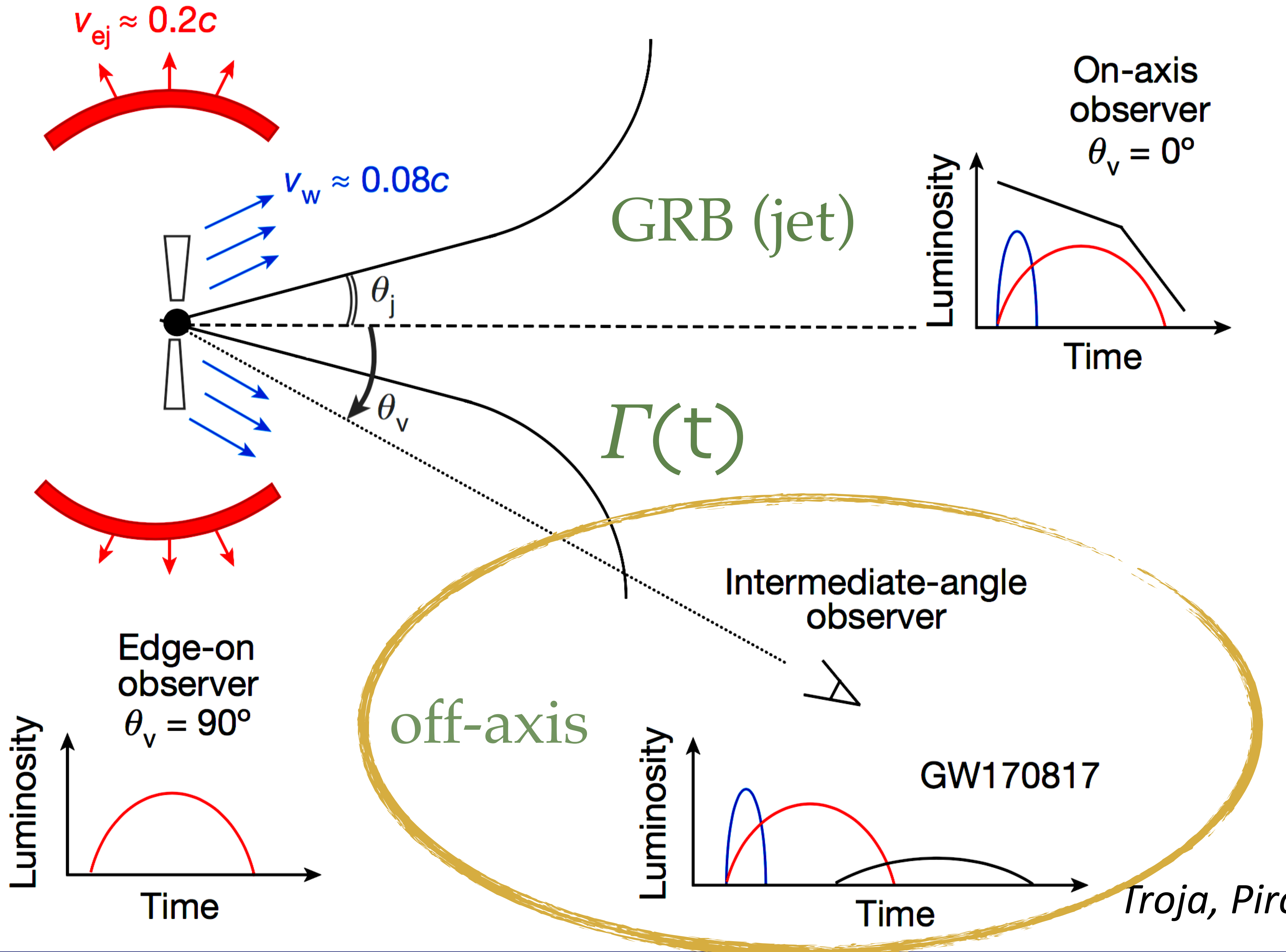
Troja, Piro+2017

TeV emission from GW counterparts: an off-axis GRB

- GRB afterglow: beamed emission, Γ>100, time evolution
  - intensity boosted ~Γ^3
  - light curve decreasing ~ $t^{-1.5}$ (depending on frequency)

- High energy emission from GW counterparts is seen **off-axis**, Γ~a few
  - intensity <u>weaker</u> $10^{-4,-6}$
  - light curve <u>Delayed</u> (hours-days-months, depending on θ_{view})

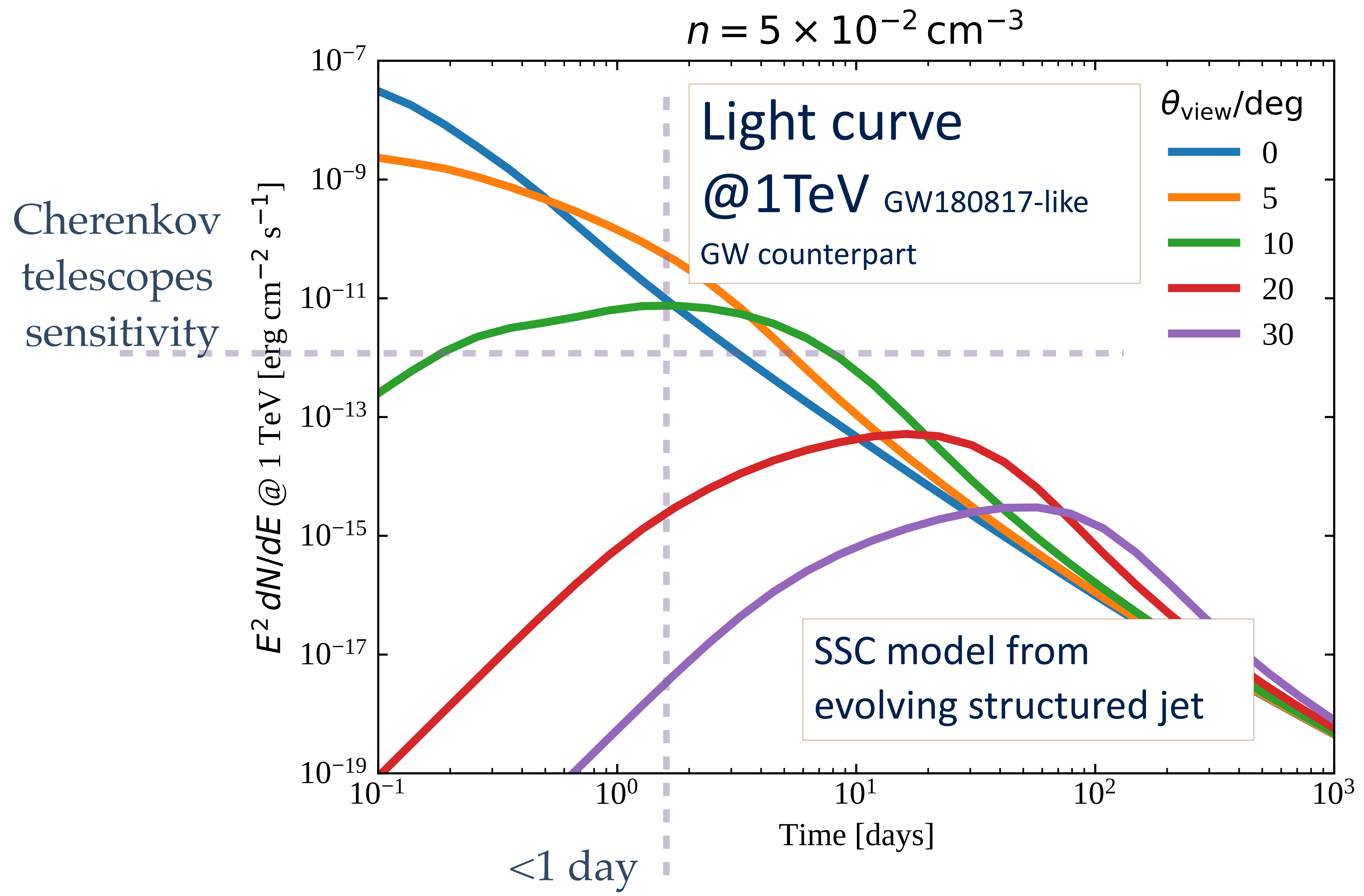




Troja, Piro+2017

TeV emission from GW counterparts: an off-axis GRB

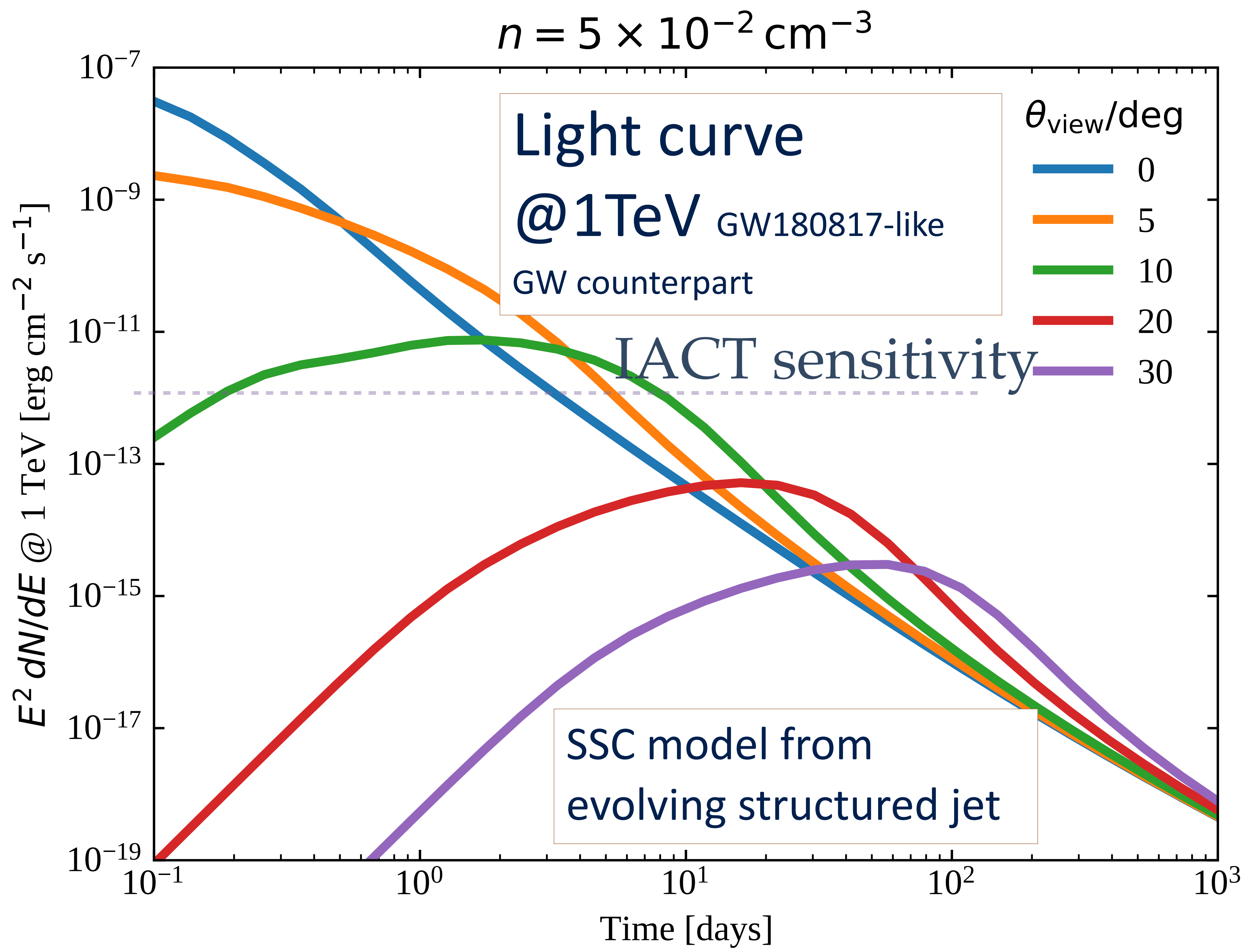
- Small viewing angle: bright, steady fading
  - ➡ **Fast reaction**
- larger viewing angle: weak, delayed emission
  - ➡ Improve sensitivity @TEV

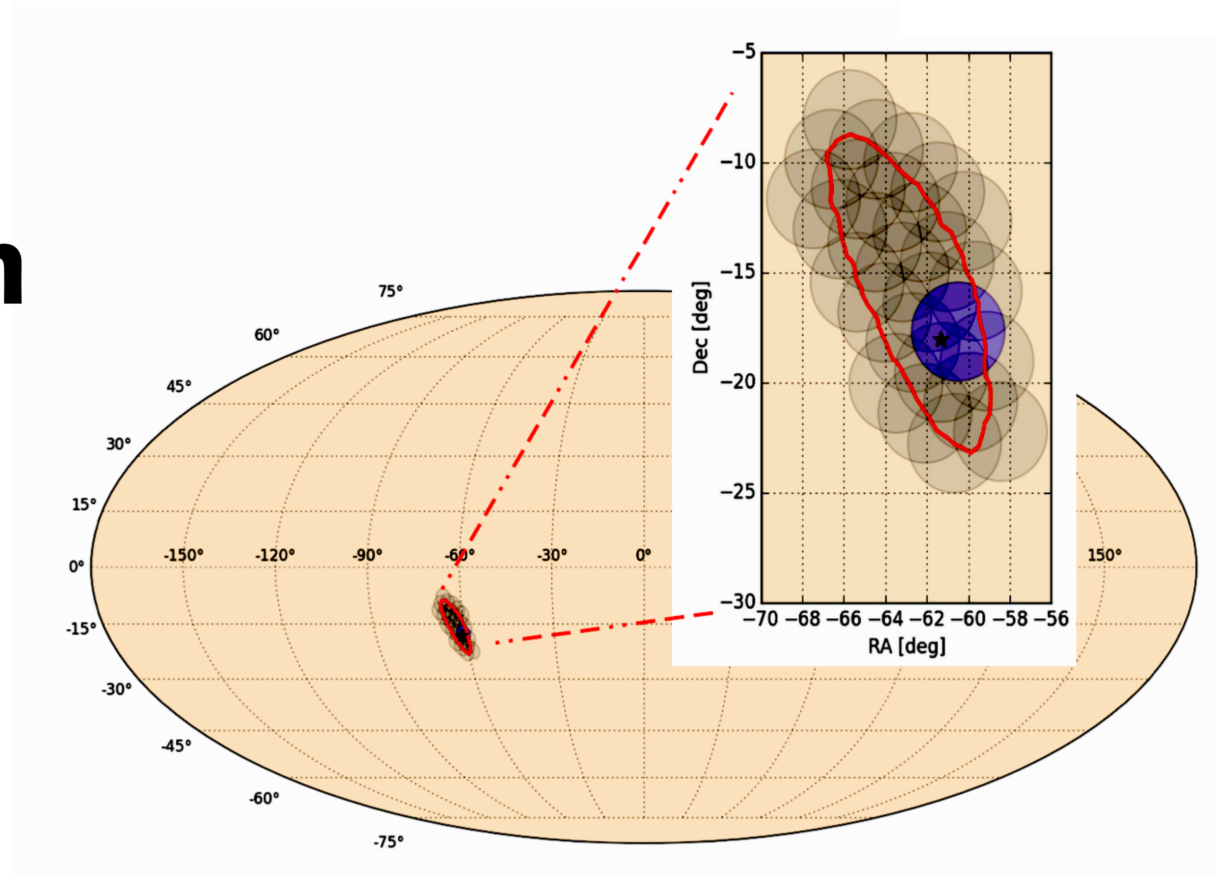


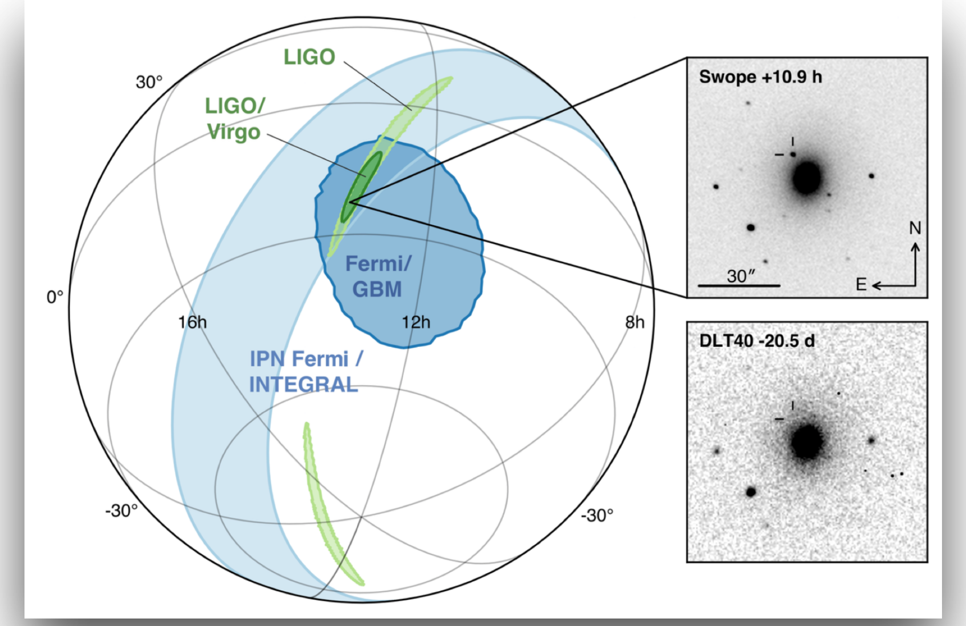
AS&Salafia et al., 2021, ICRC,
https://pos.sissa.it/395/944/

Chasing the VHE counterpart of GW: strategies and optimisation

- Small viewing angle: bright, steady fading
  - ➡ **Fast reaction**
- larger viewing angle: weak, delayed emission
  - ➡ **Improve sensitivity @TEV**
- GW uncertainty location
  - ➡ **optimise observation strategies**







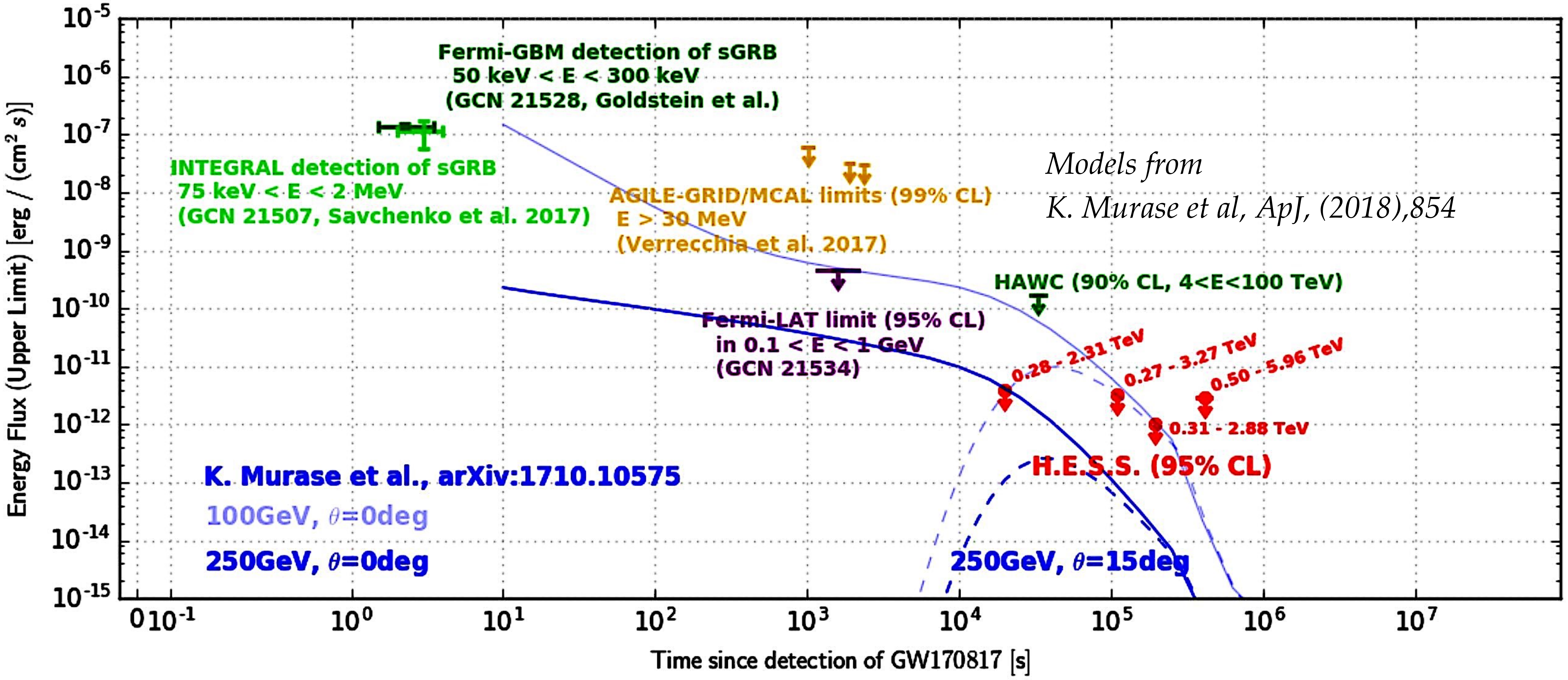
AS&Salafia et al., 2021, ICRC,
https://pos.sissa.it/395/944/

GW and GRB at TeV energies

- No detection of VHE (20 GeV-100 TeV) emission from GW counterpart.

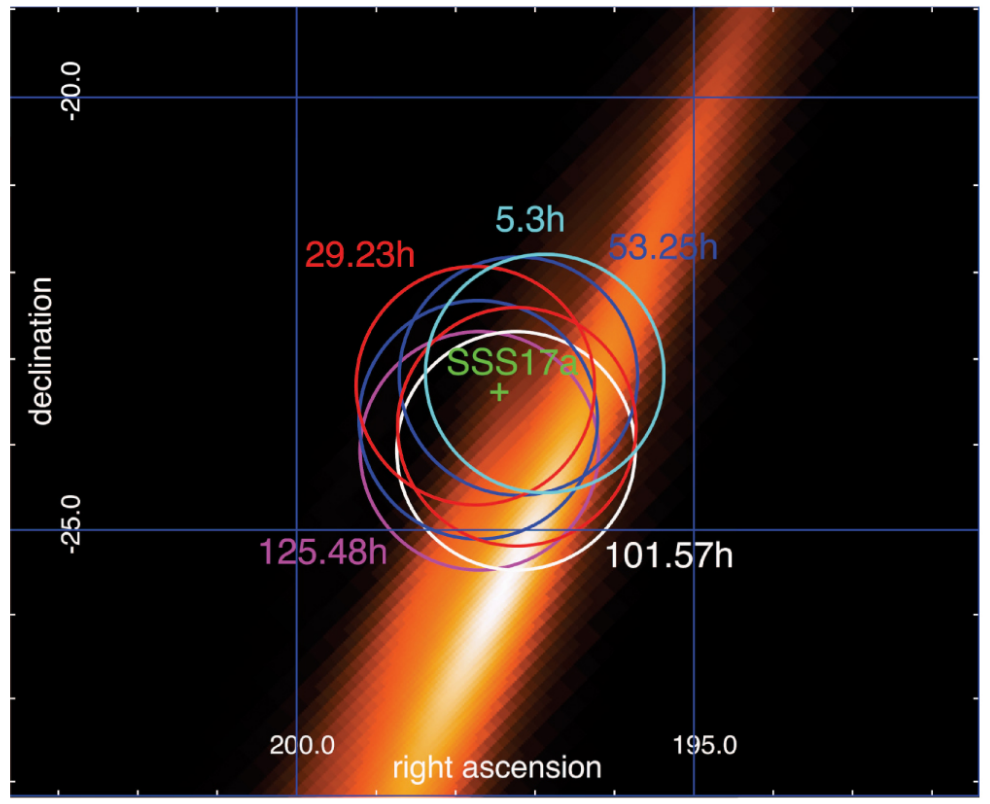
GW170817 - H.E.S.S. (not immediately visible to MAGIC and VERITAS)

- First ground telescope to point to the source location (NGC4993)

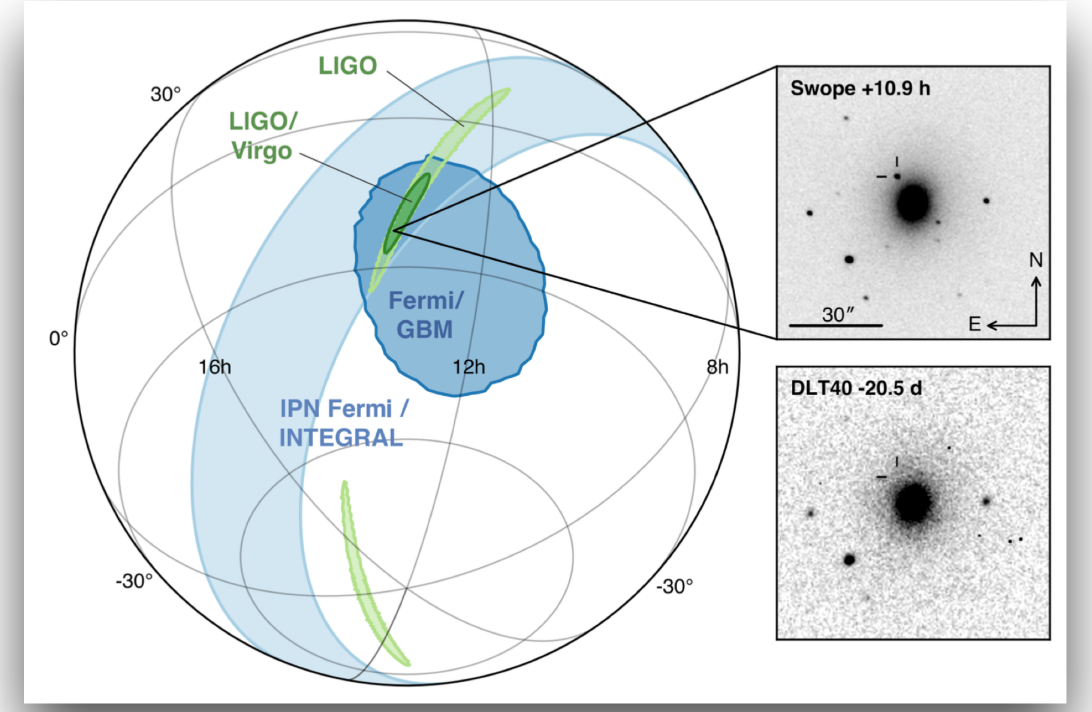


Models from K. Murase et al, ApJ, (2018),854

Abdalla et al. (HESS coll), 2017, ApJL, 850, L22

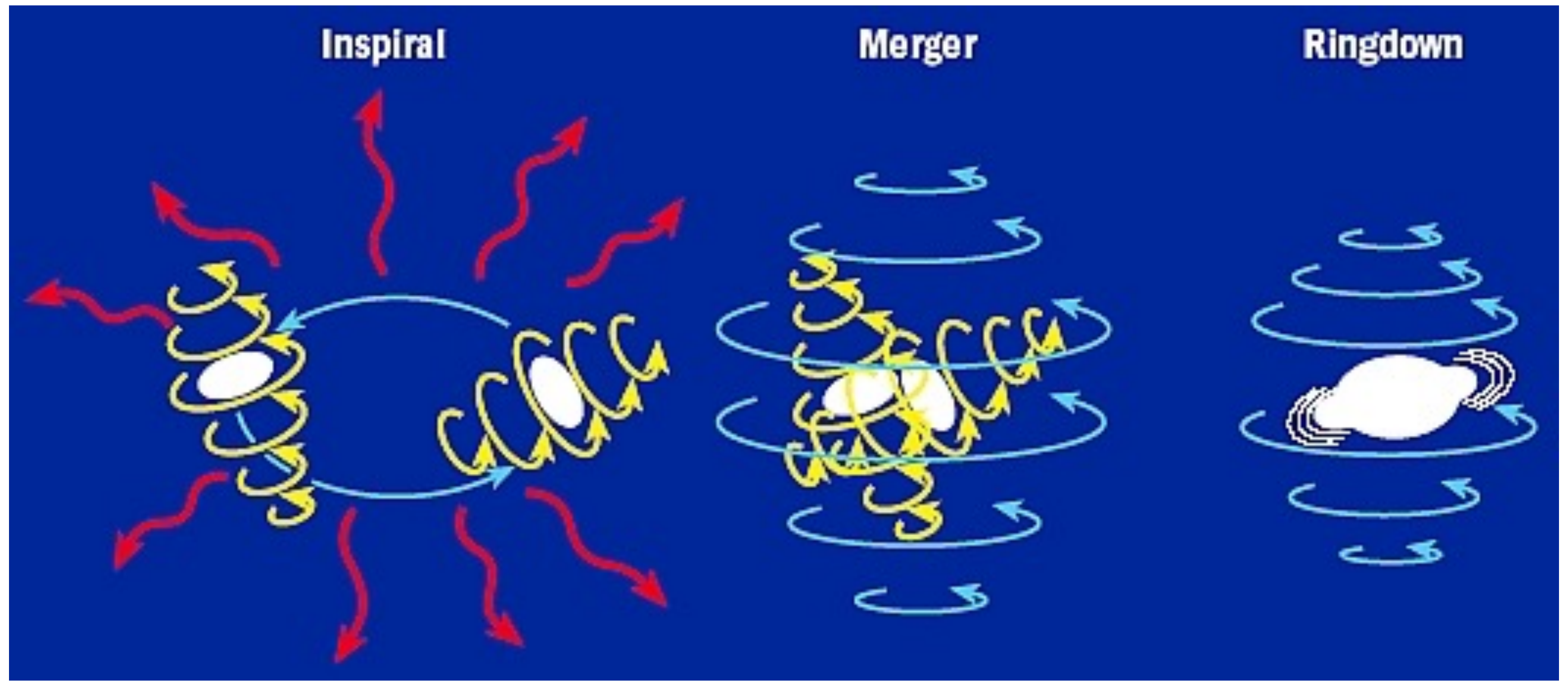


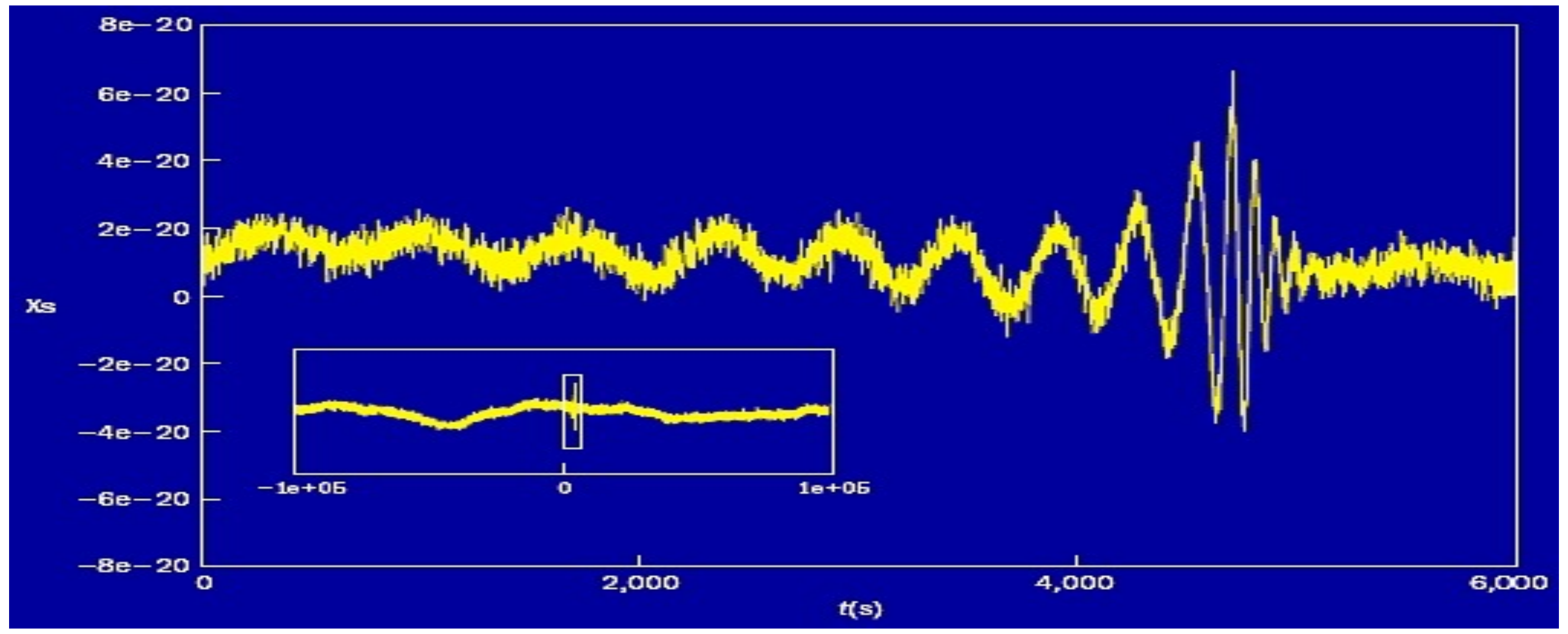
(a) SSS17a: H.E.S.S. pointings

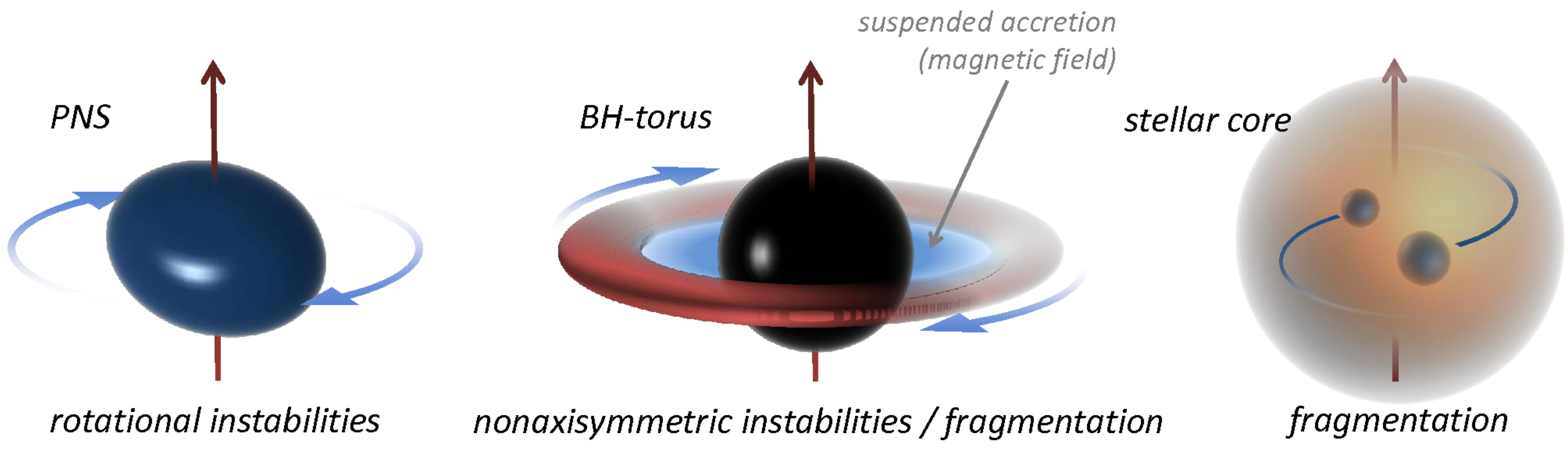


GW e.m. counterparts

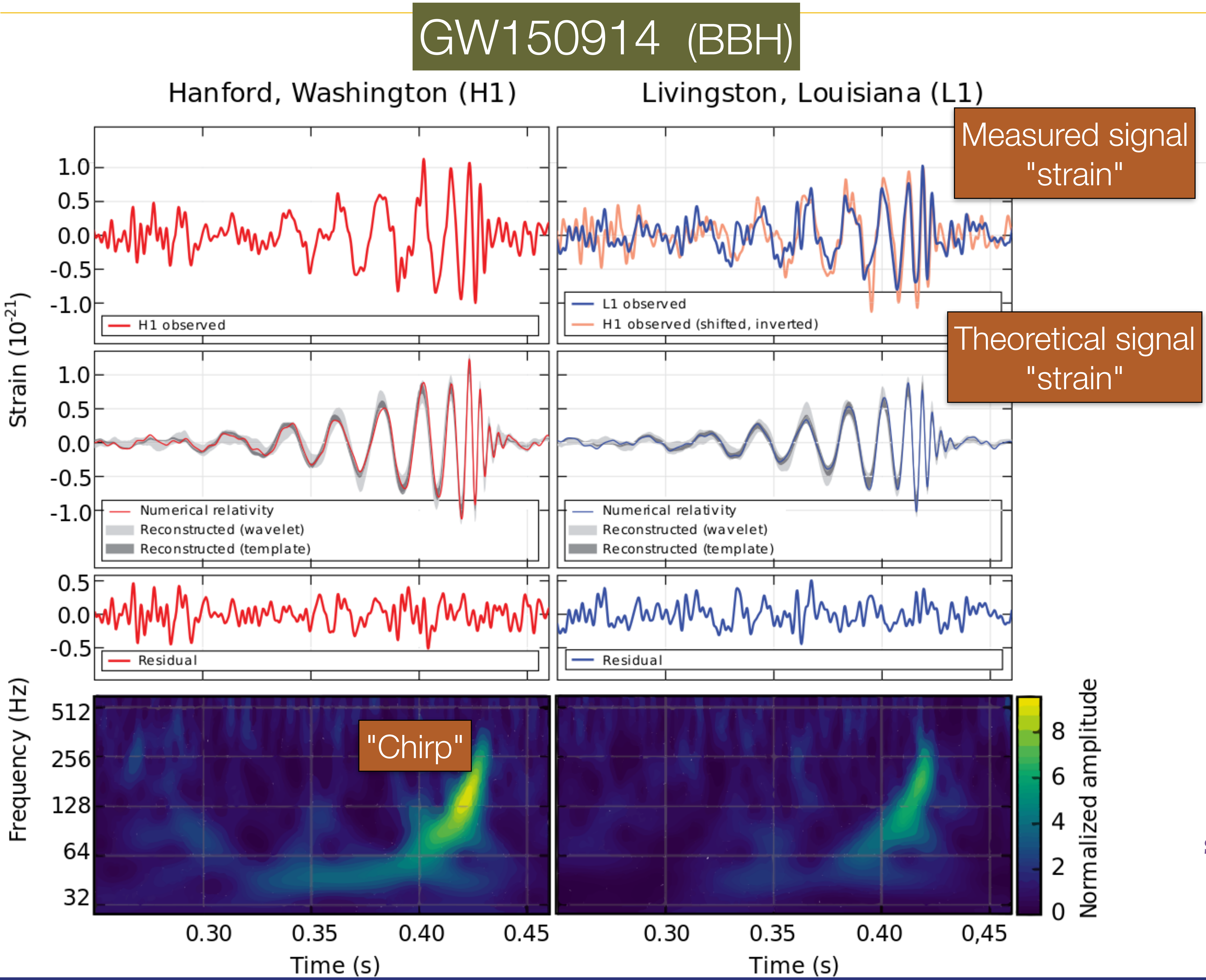
- Binary Neutron star mergers (BNS) ➔ **short GRB**, suggested (since Eichler+1989), expected (GRB050724, Berger+2005) and observed (GW/GRB170817)
- BH-BNS ➔ short GRB? e.g. Berger+2014, Barbieri+2020, Rossi+2019 e.g. GRBs 050509B, 061201.
- BH-BH: ?? no EM emission expected (but Loeb+2016, Perna+2016, Murase+2016,...)
- SN collapse: long-GRB? (LIGO coll. 2014, LVC 2021)







The era of gravitational waves

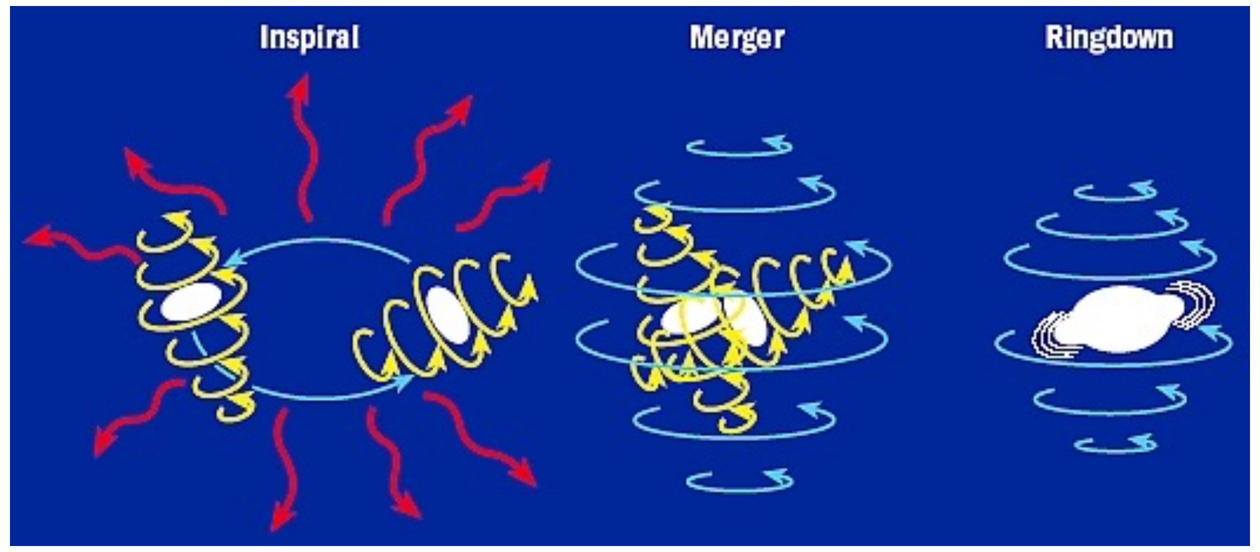


$$R_{\alpha\beta} - \frac{1}{2} g_{\alpha\beta} R = \frac{8\pi G}{c^4} T_{\alpha\beta}$$

strain quadrupole

$$h \sim \frac{2G}{c^4} \ddot{Q} \frac{1}{D_L}$$

distance



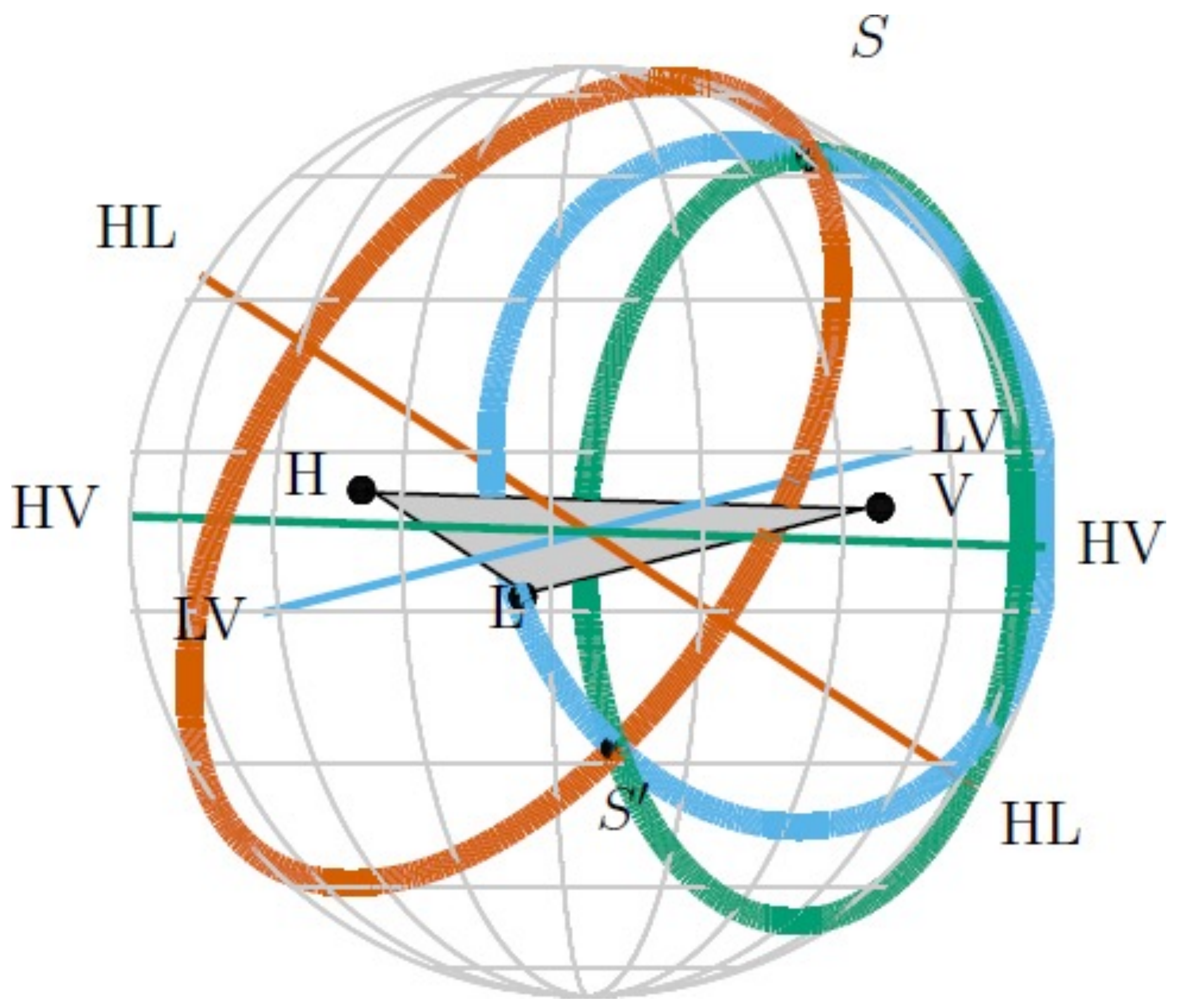
mass

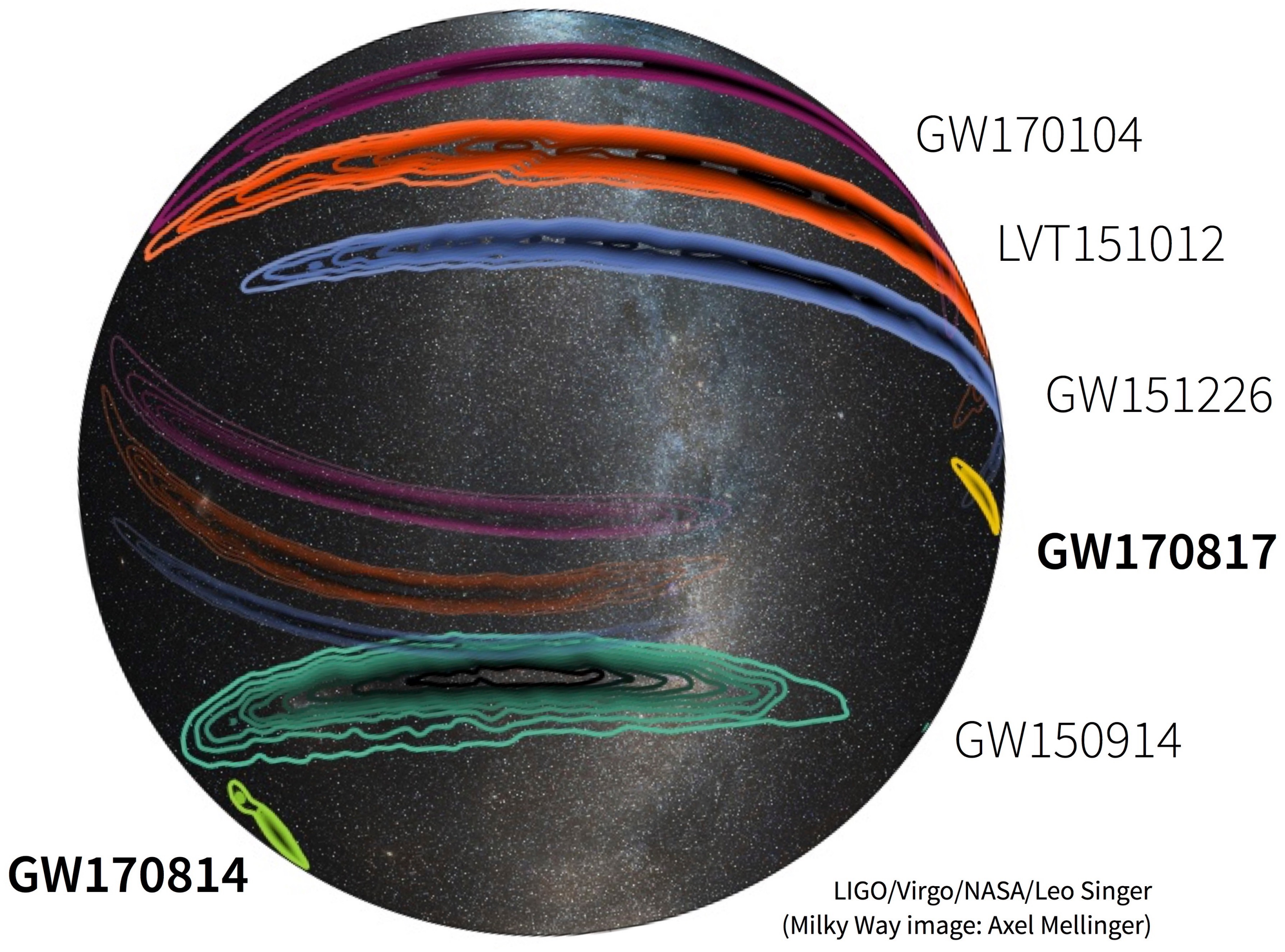
$$h = \frac{G}{c^2} \frac{M_c}{D} \left(\frac{G}{c^3} \pi f M_c \right)^{2/3}$$

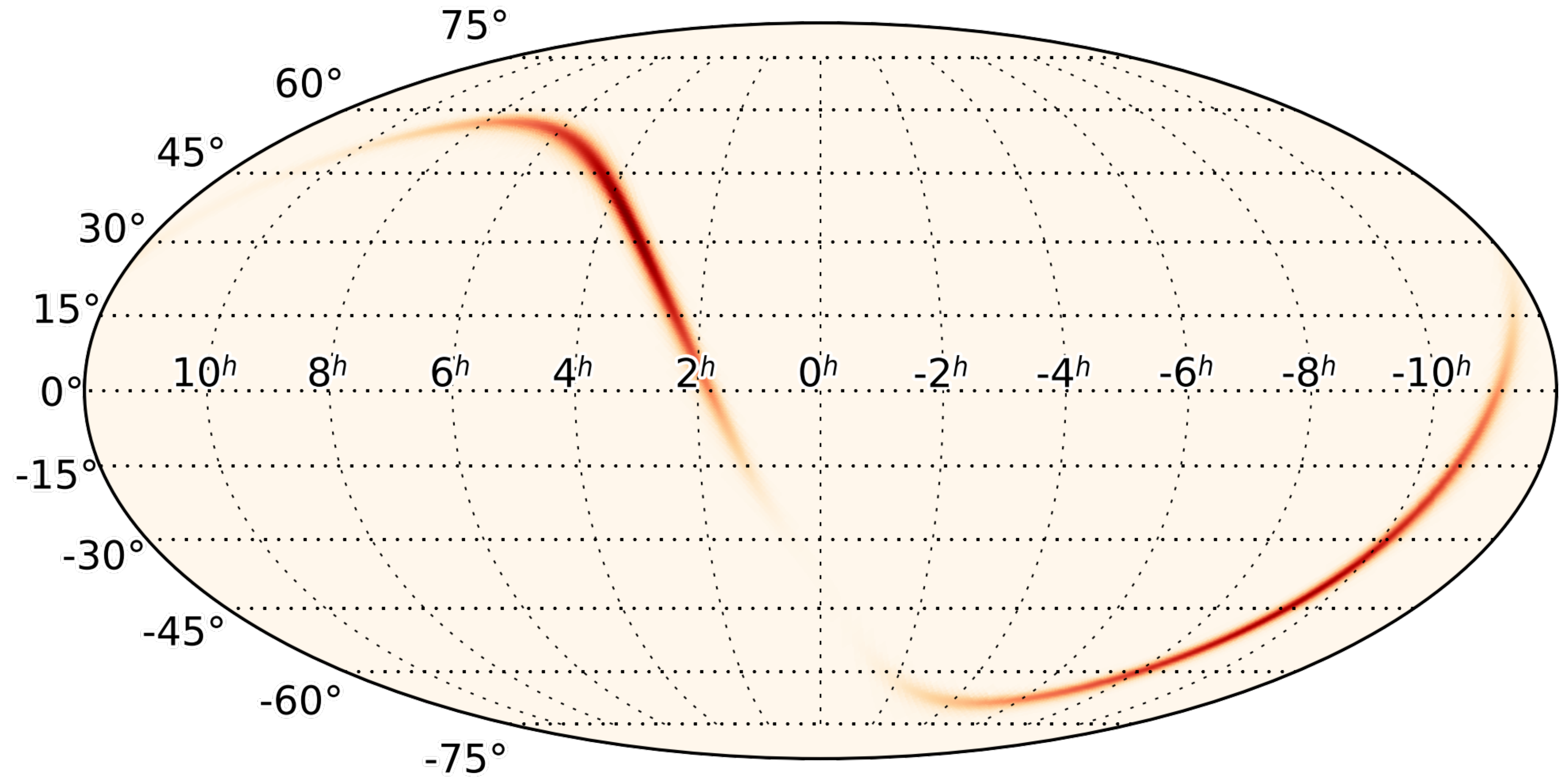
strain distance frequency "chirp"

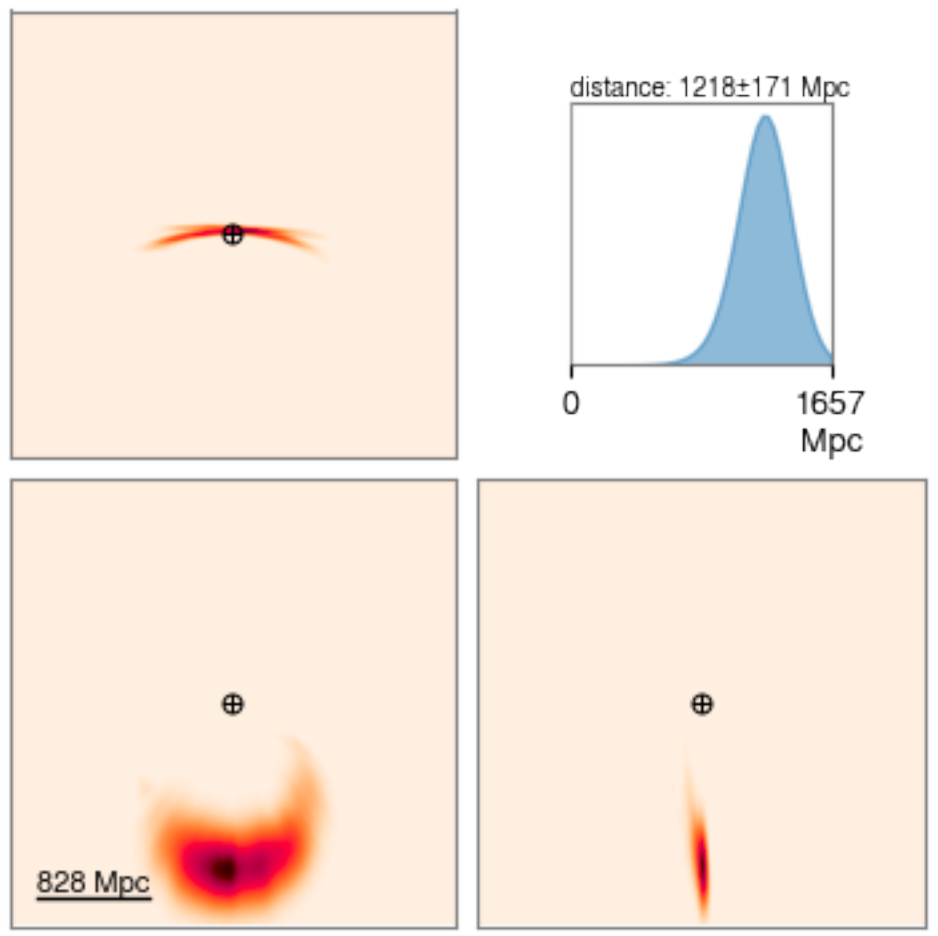
GW sources and detection: properties of the merging binary system

Localization





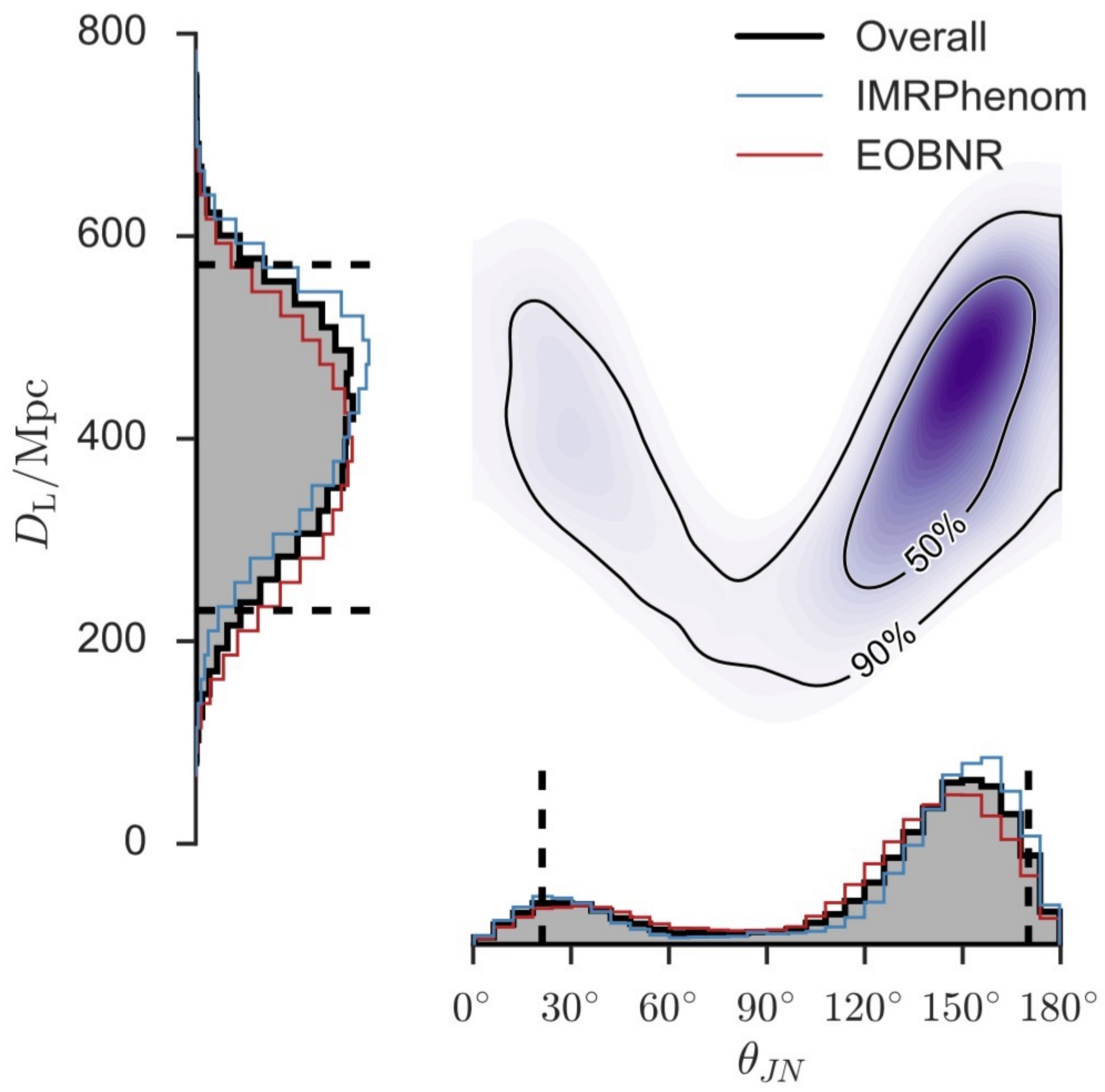




Orientation

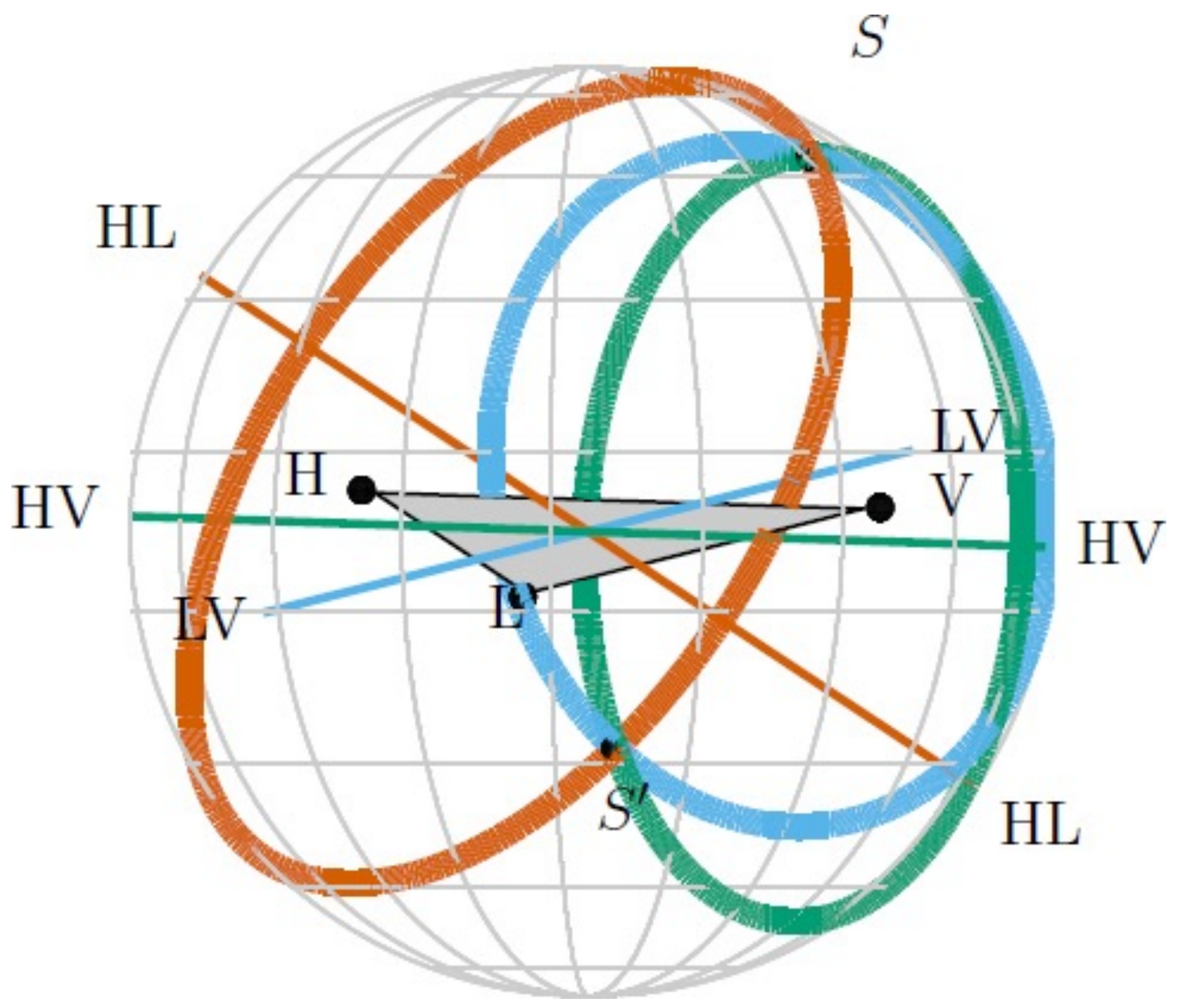
GW150914

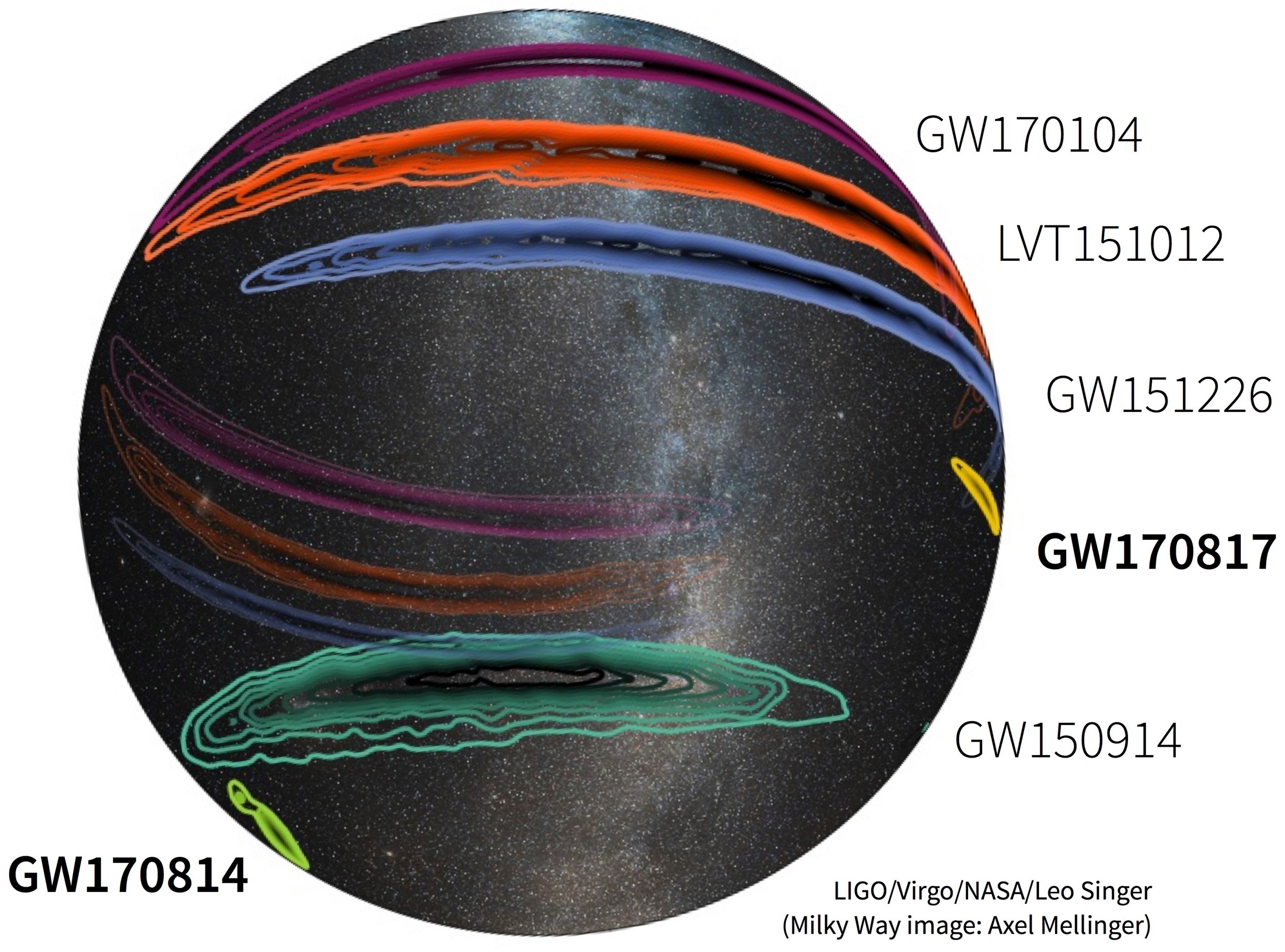
luminosity distance-inclination

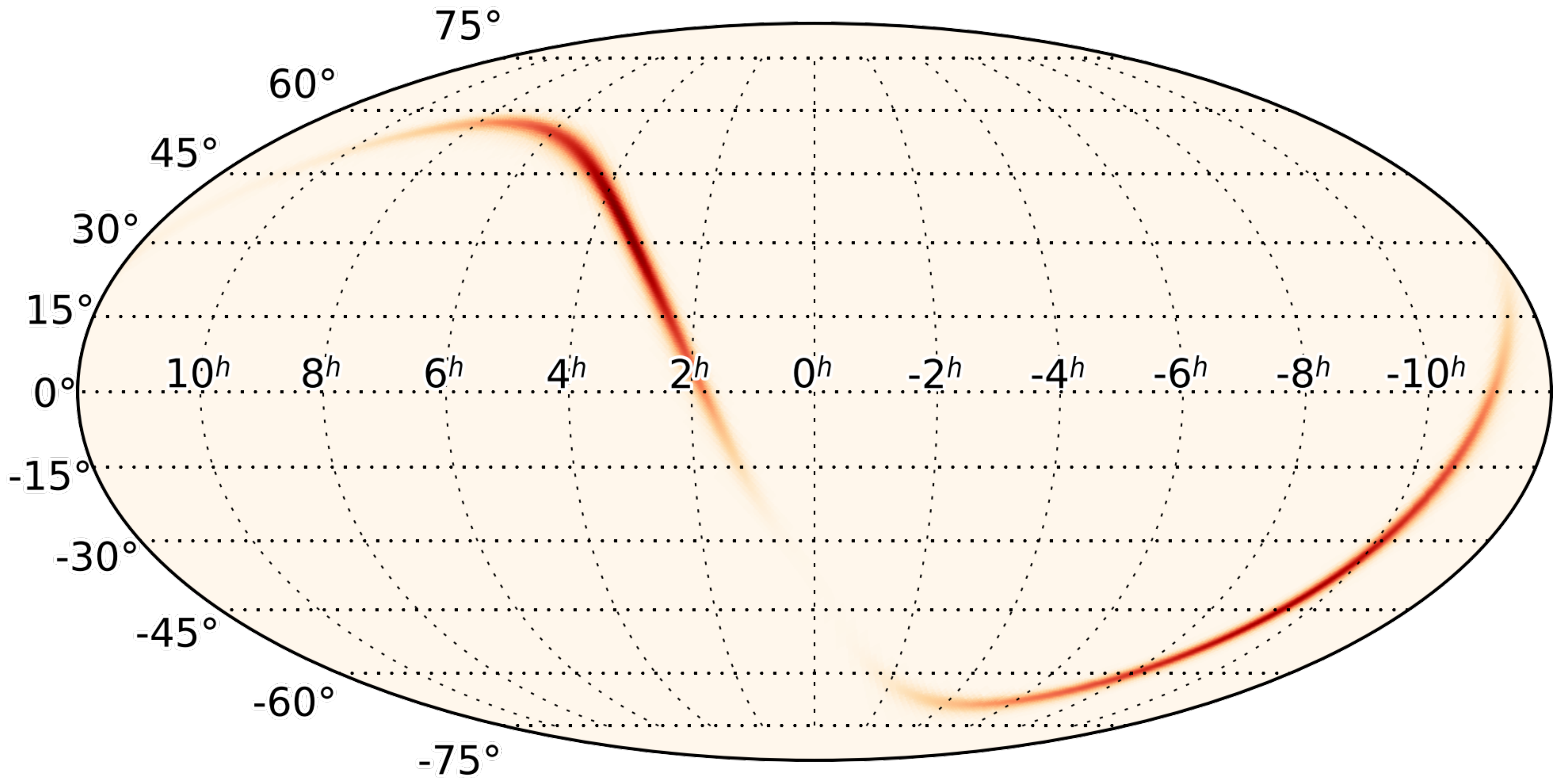


GW sources and detection: properties of the merging binary system

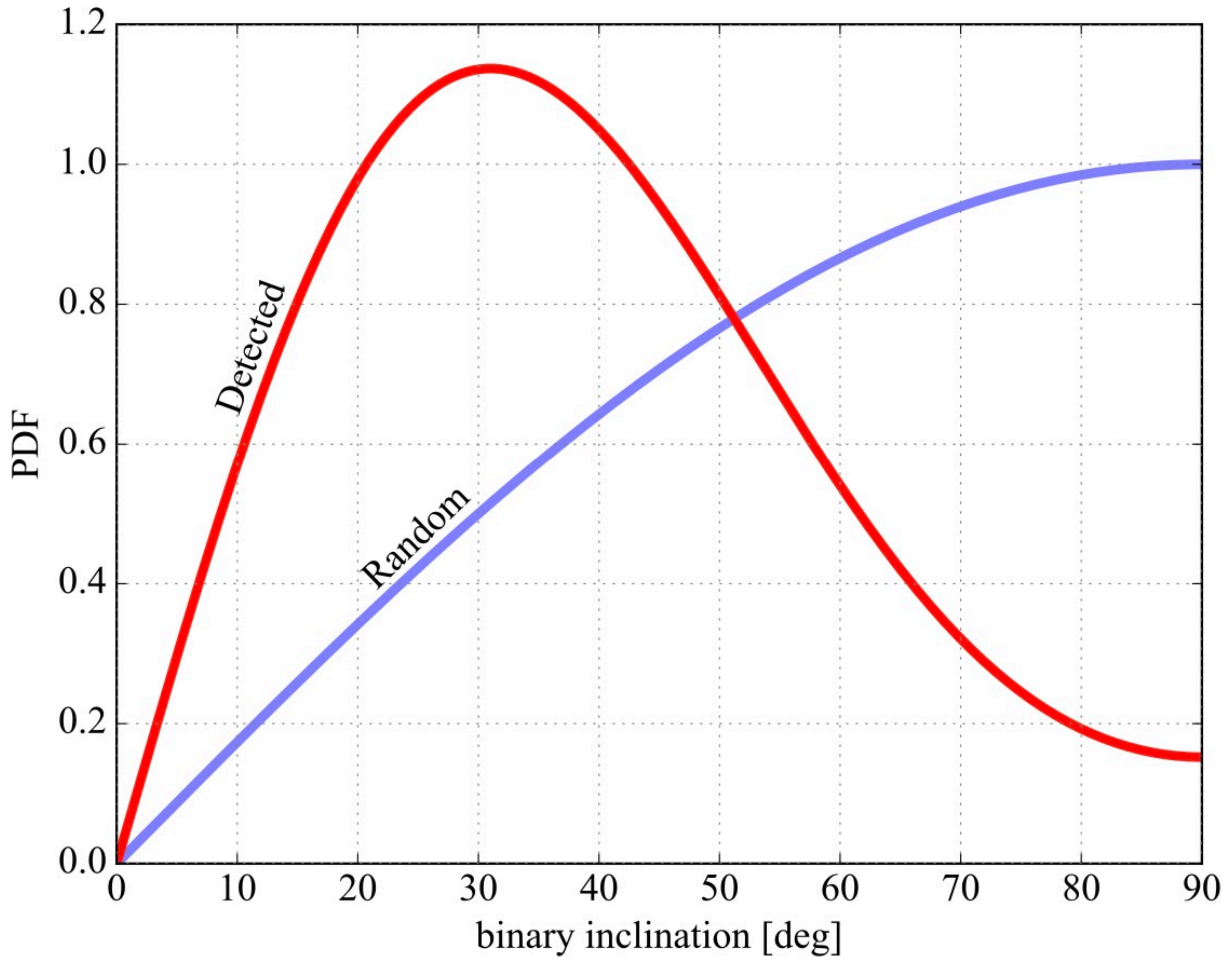
Localization



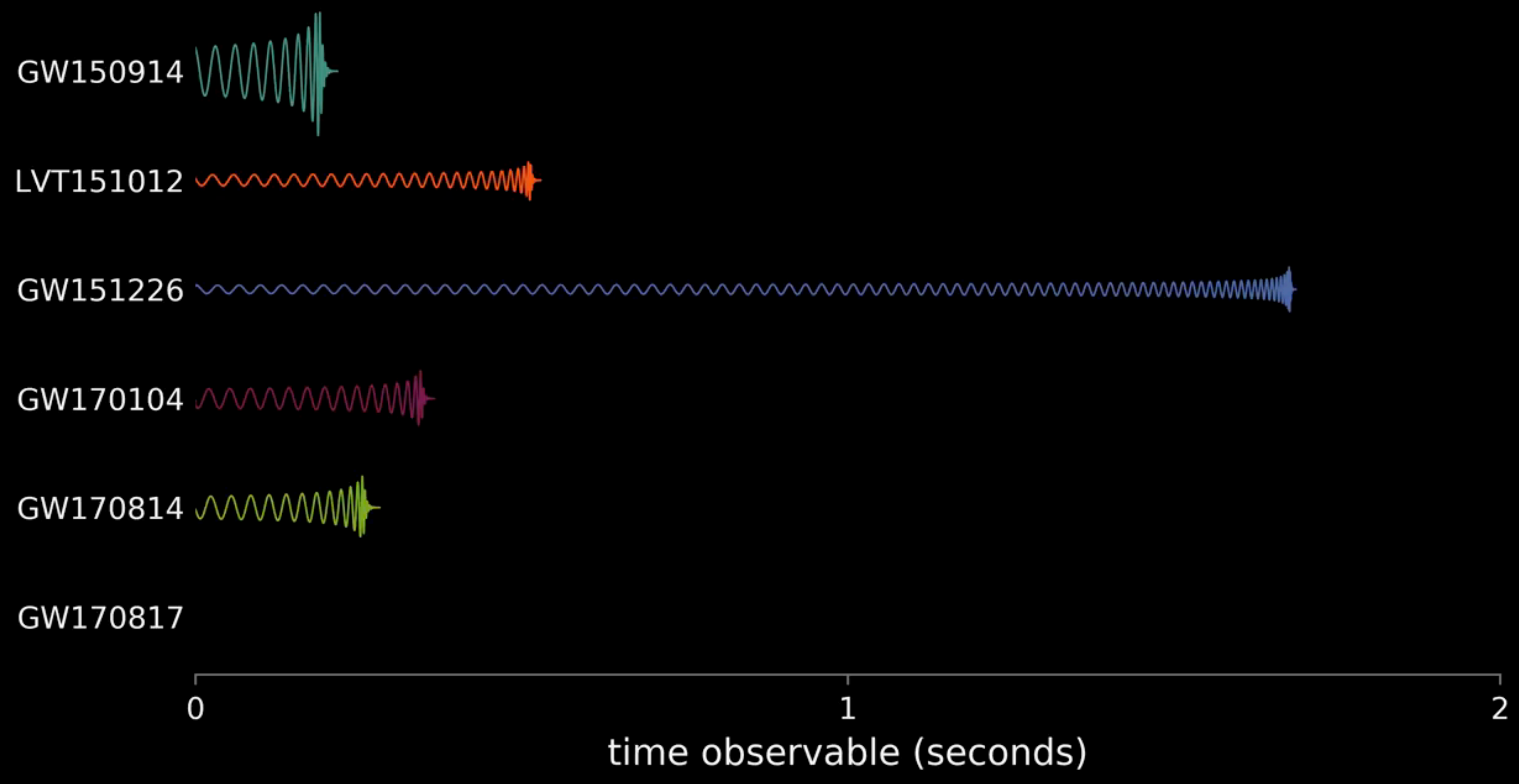




Orientation



Schutz 2011



LIGO/University of Oregon/Ben Farr

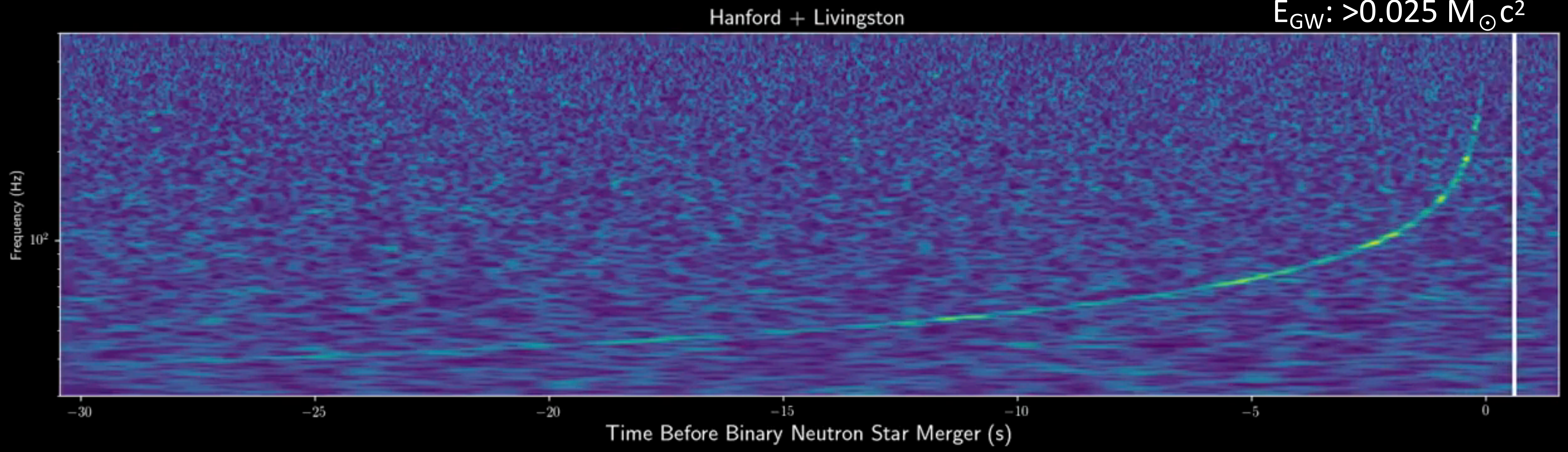
M1: 1.36-2.26 $M_\odot$

M1: 0.86-1.36 $M_\odot$

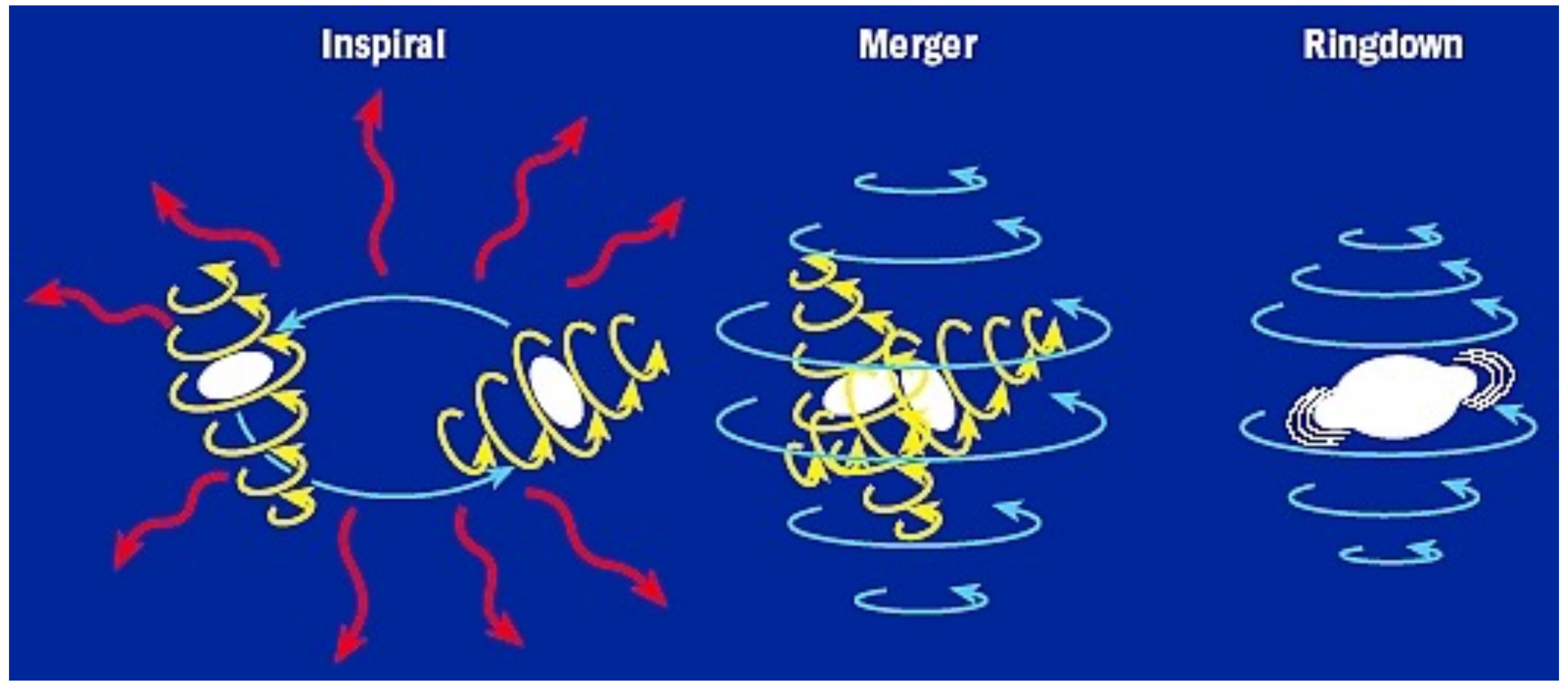
q: 0.4-1

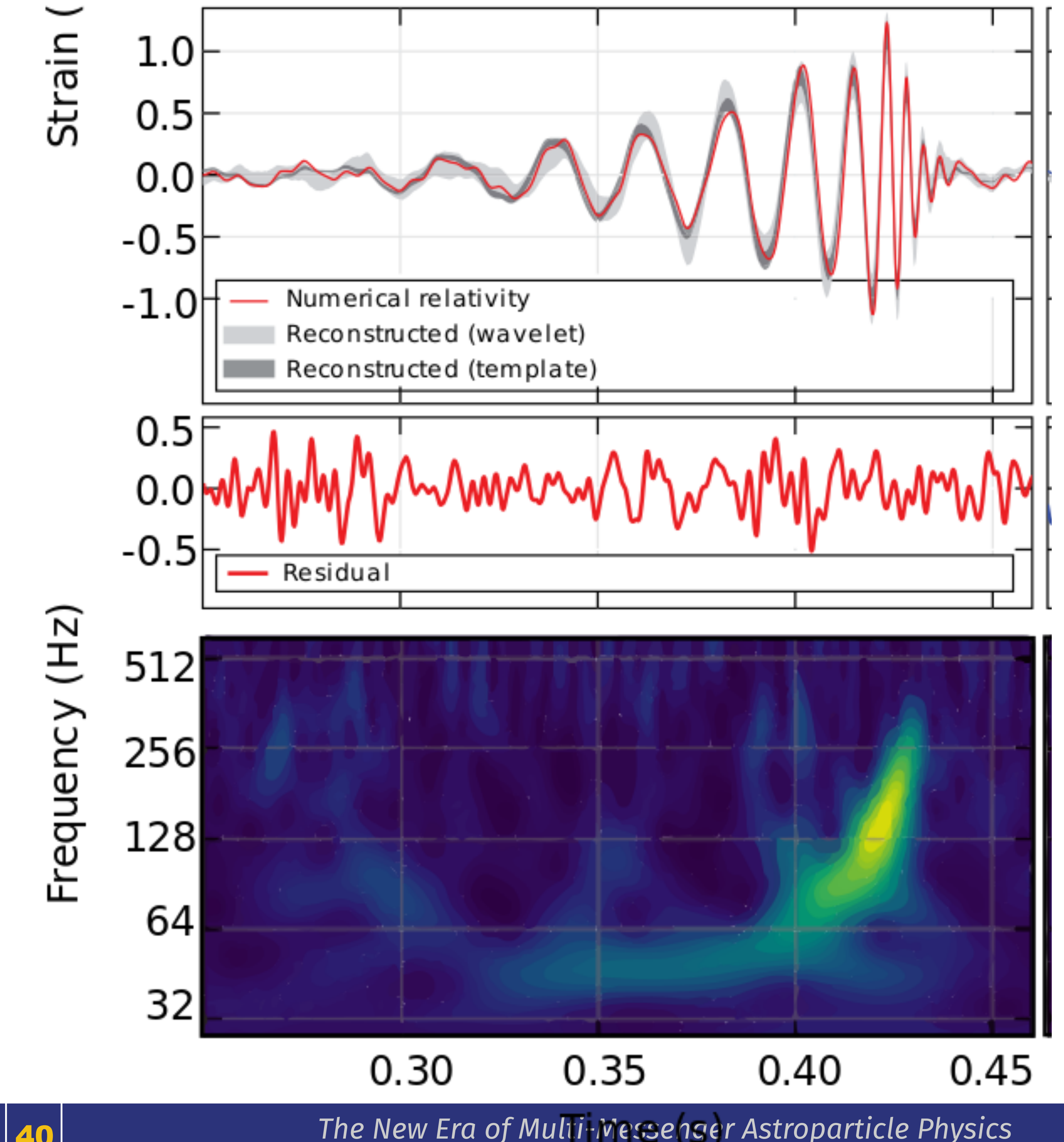
M_{tot}: 2.74–3.29 $M_\odot$

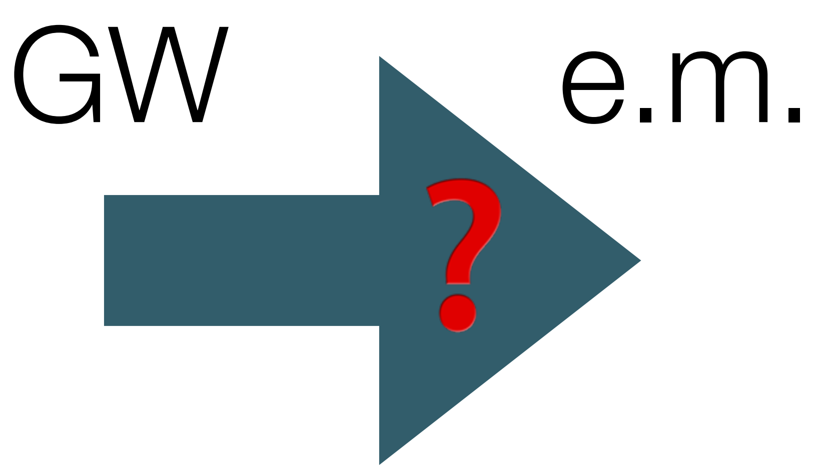
E_{GW}: >0.025 $M_\odot c^2$

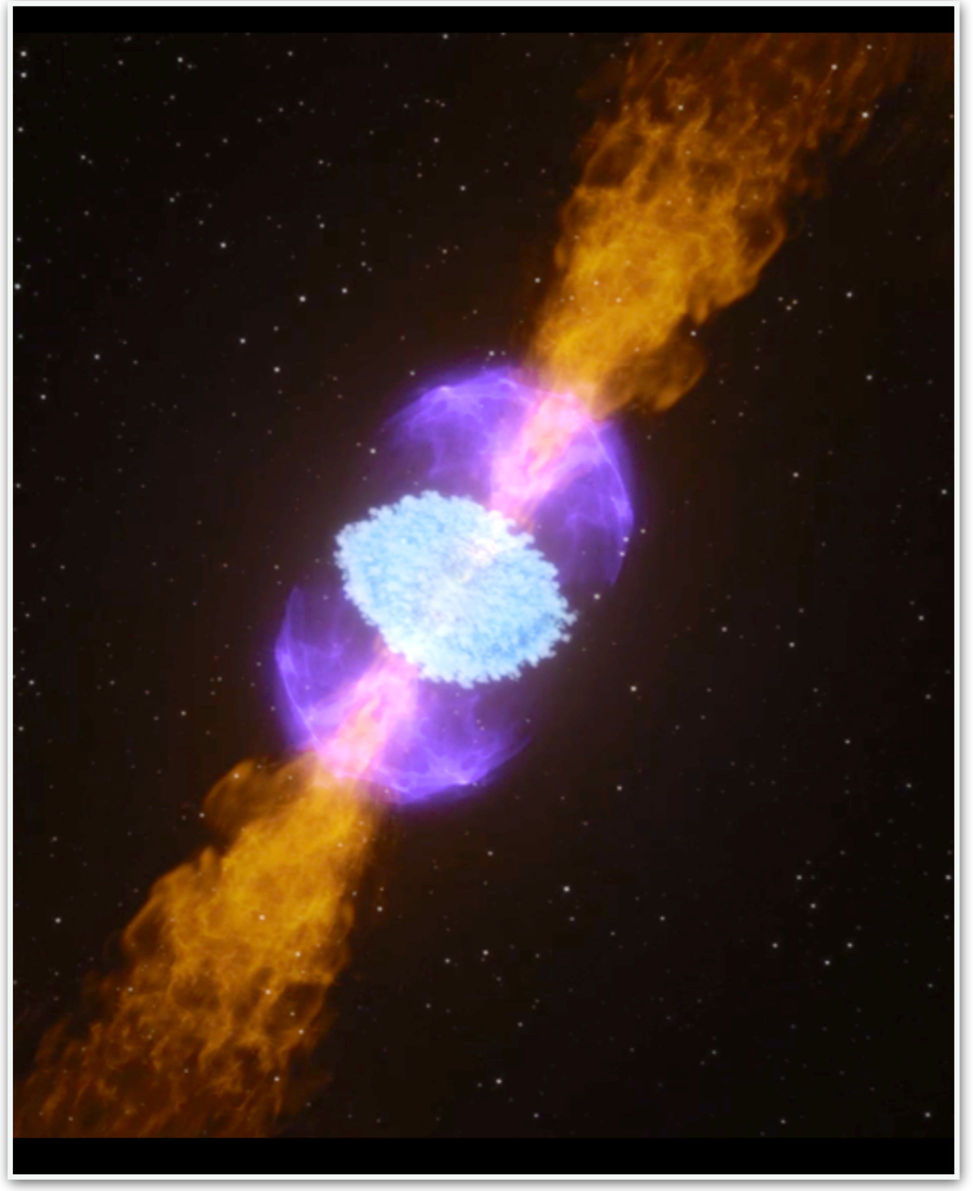


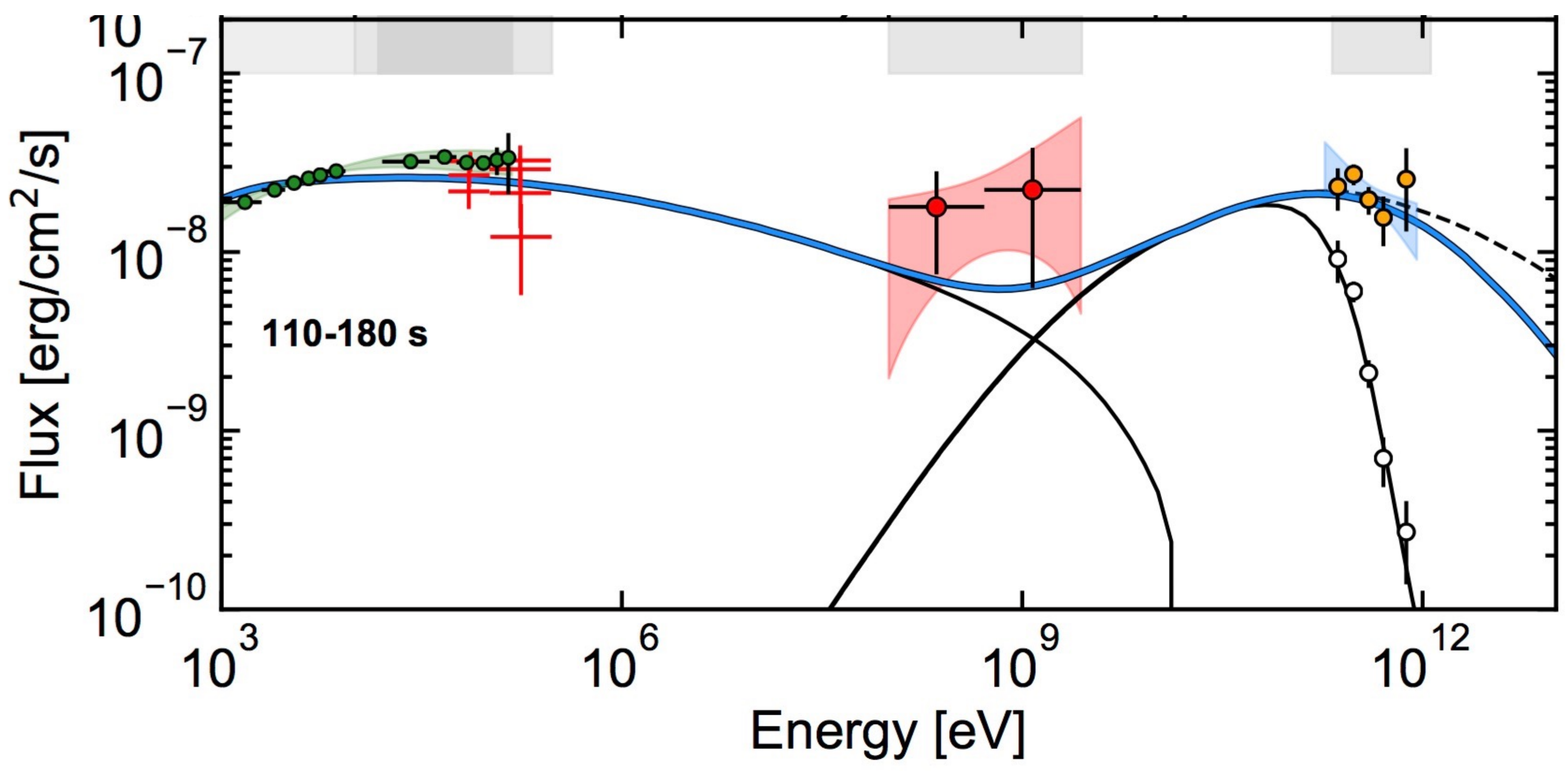
Who's Intrigued and Ready to Dive in?









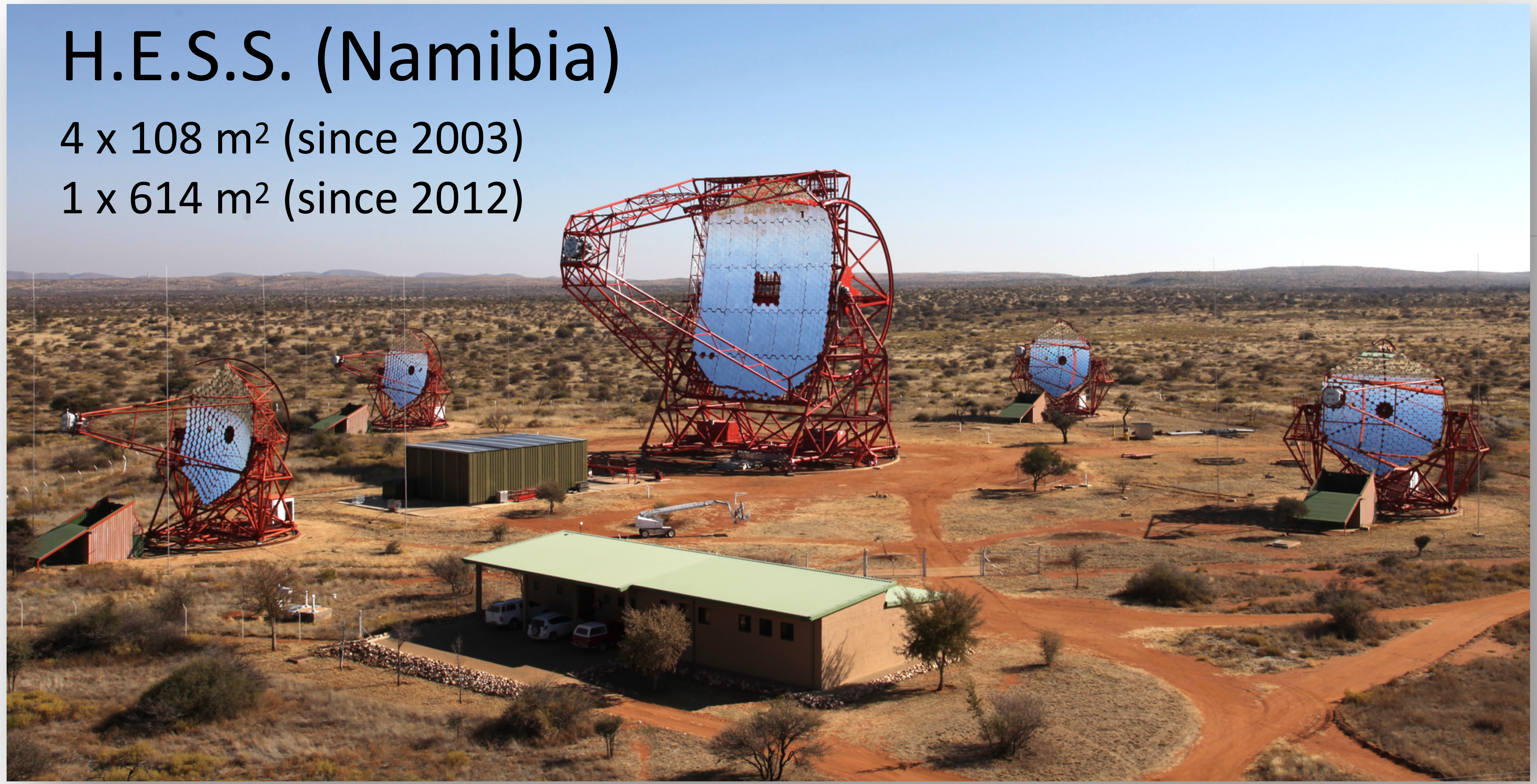


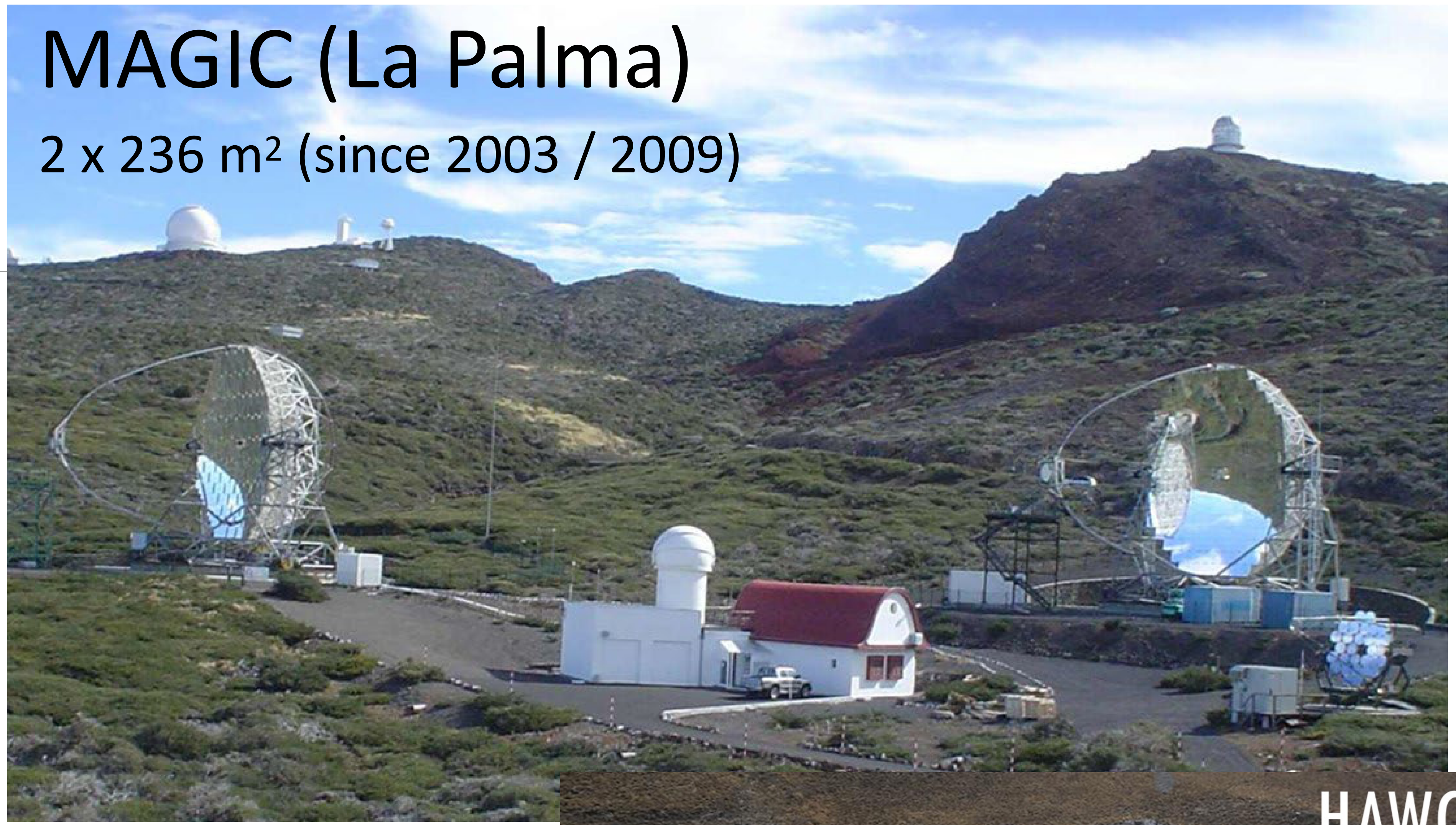
OPEN QUESTION: How do we correlate GW properties (and geometrical properties) into e.m. non-thermal emission (and VHE emission)?

- Phenomenological approach: random connection with population of short-GRB (treated for off-axis emission) —> *next slides*
- Theoretical approach: GW outflow parameters —> e.m. emission parameters
  - *No reference!!! Any help?*

Interlude:
Image Cherenkov telescopes (IACT) as ideal transient detectors

TeV instruments in operation

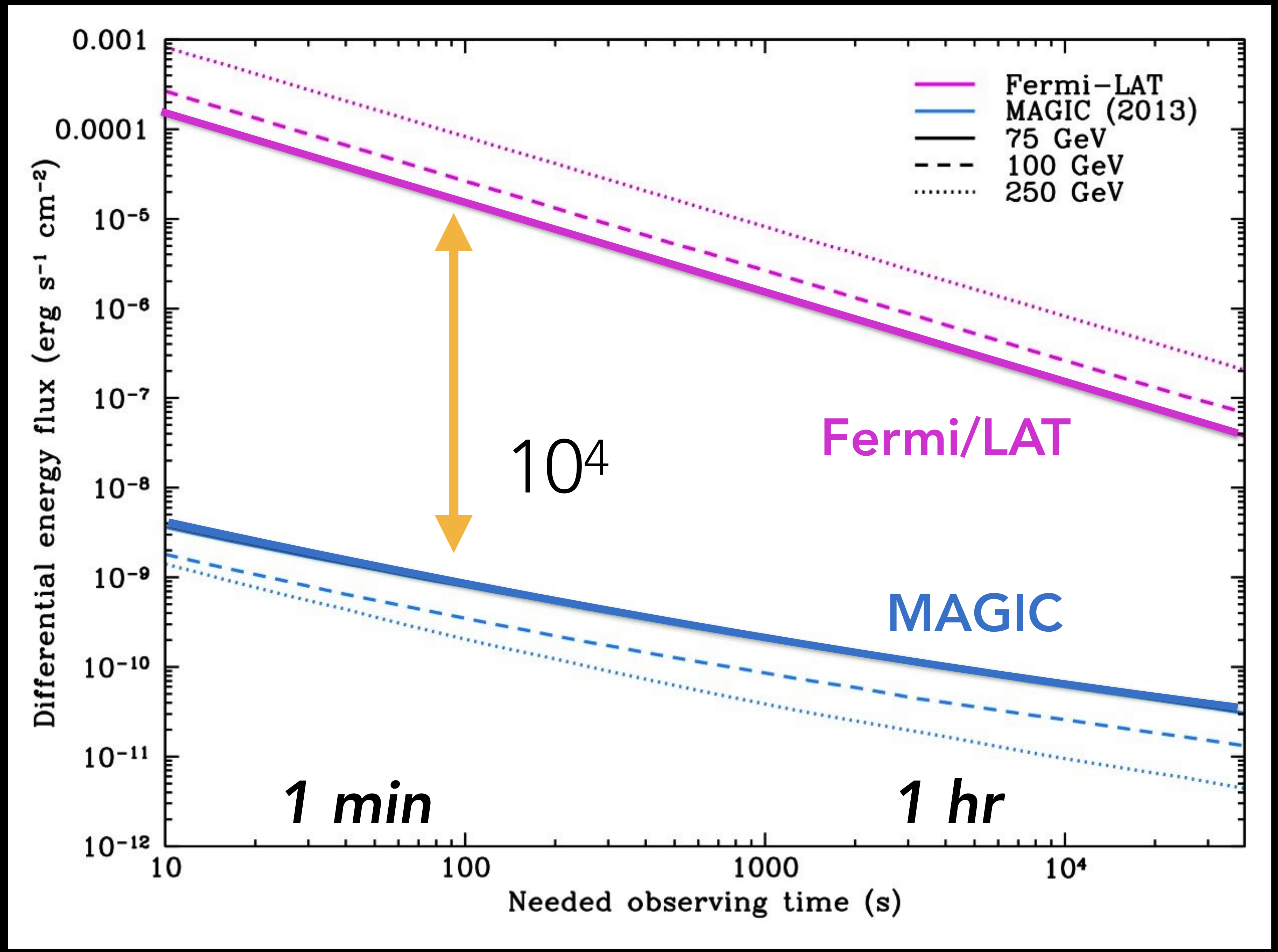


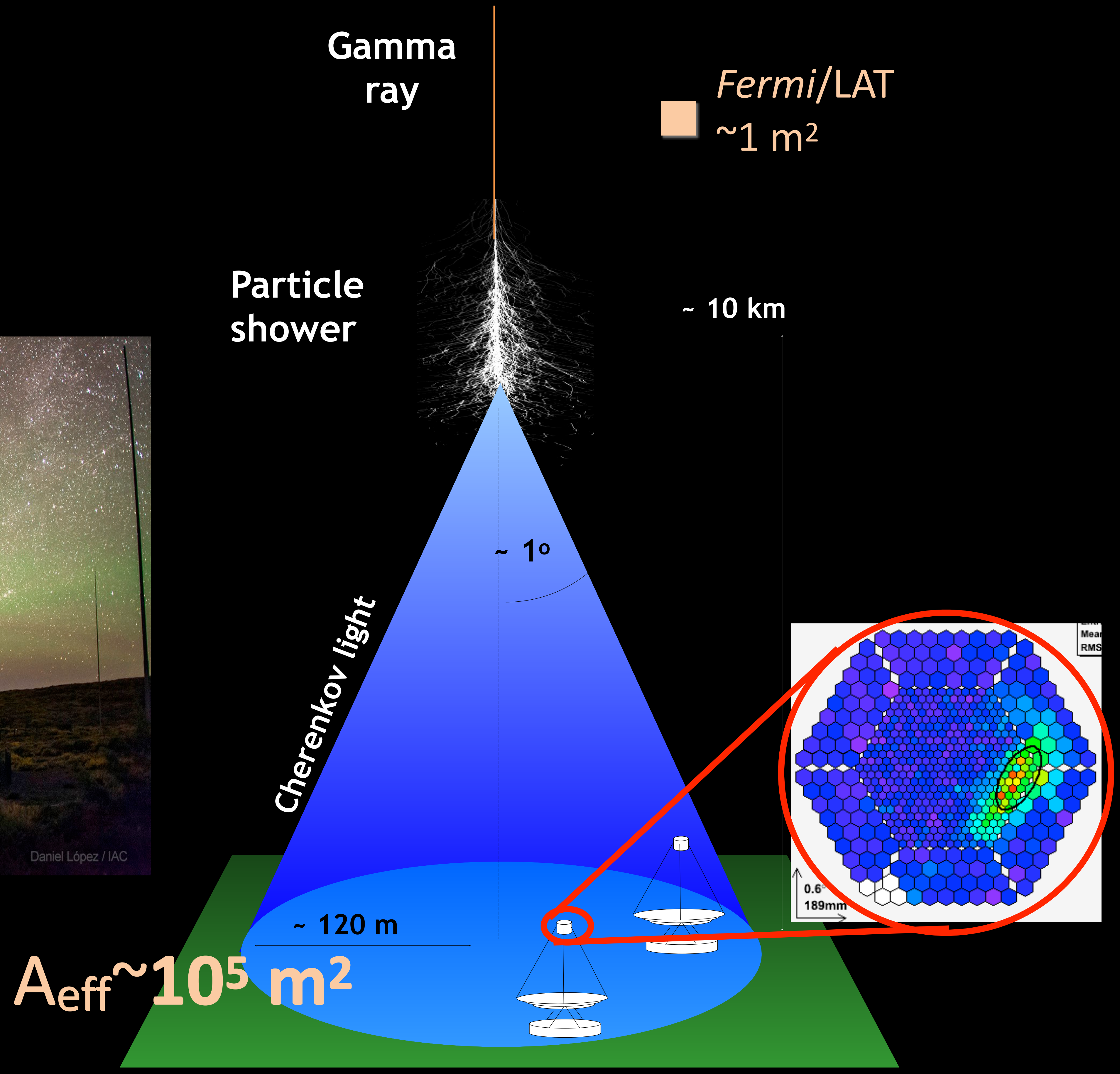


TeV Transients with IACTs

Haunting for transients: IACTs have the required performances

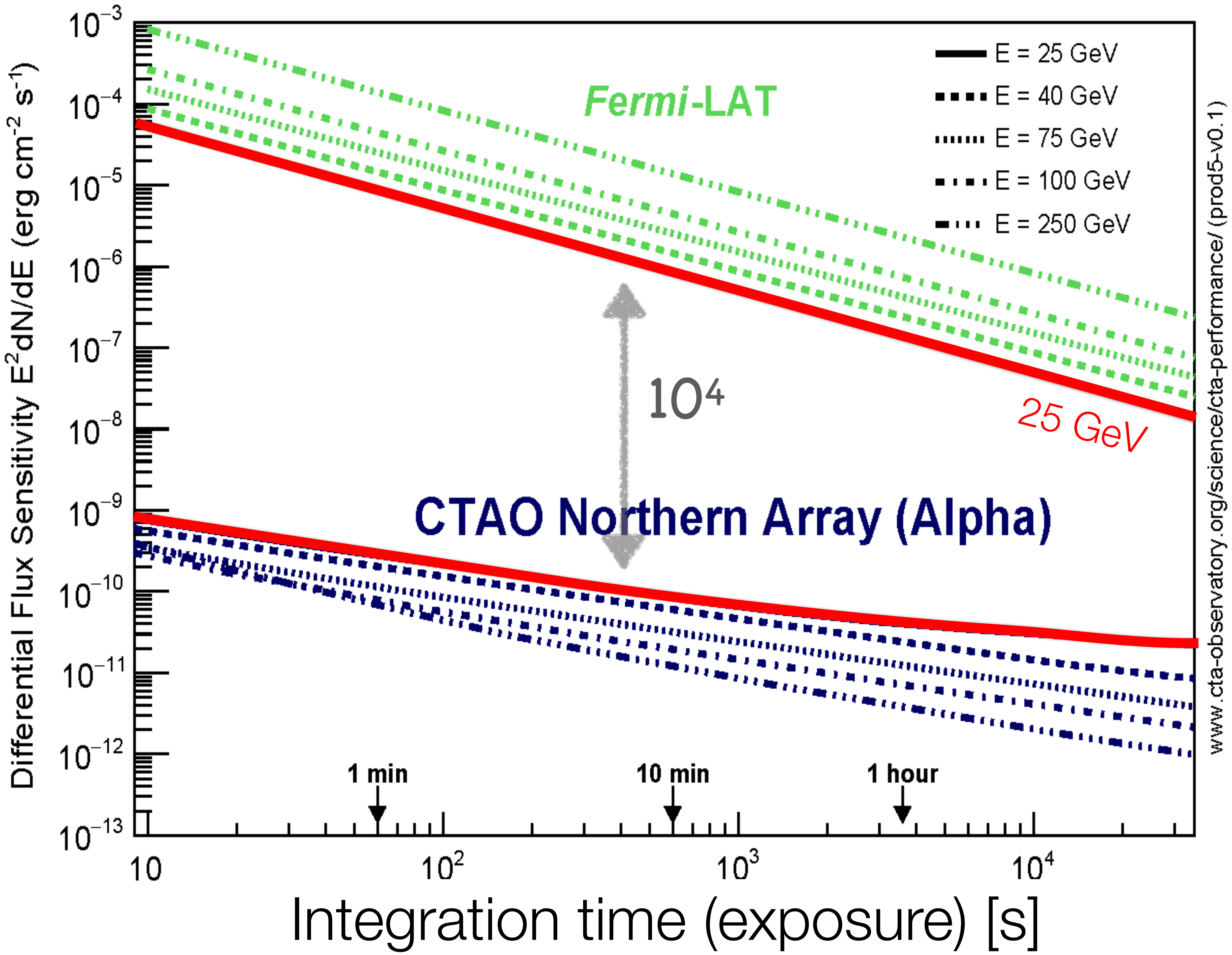
- ✓ **Big effective area** ➠ photon statistics
- ✓ **Low energy** threshold (~50 GeV)
- ✓ **For MAGIC: speed** ~7 deg/s; *automatic* repointing
- ✓ Observations in **moon-time**

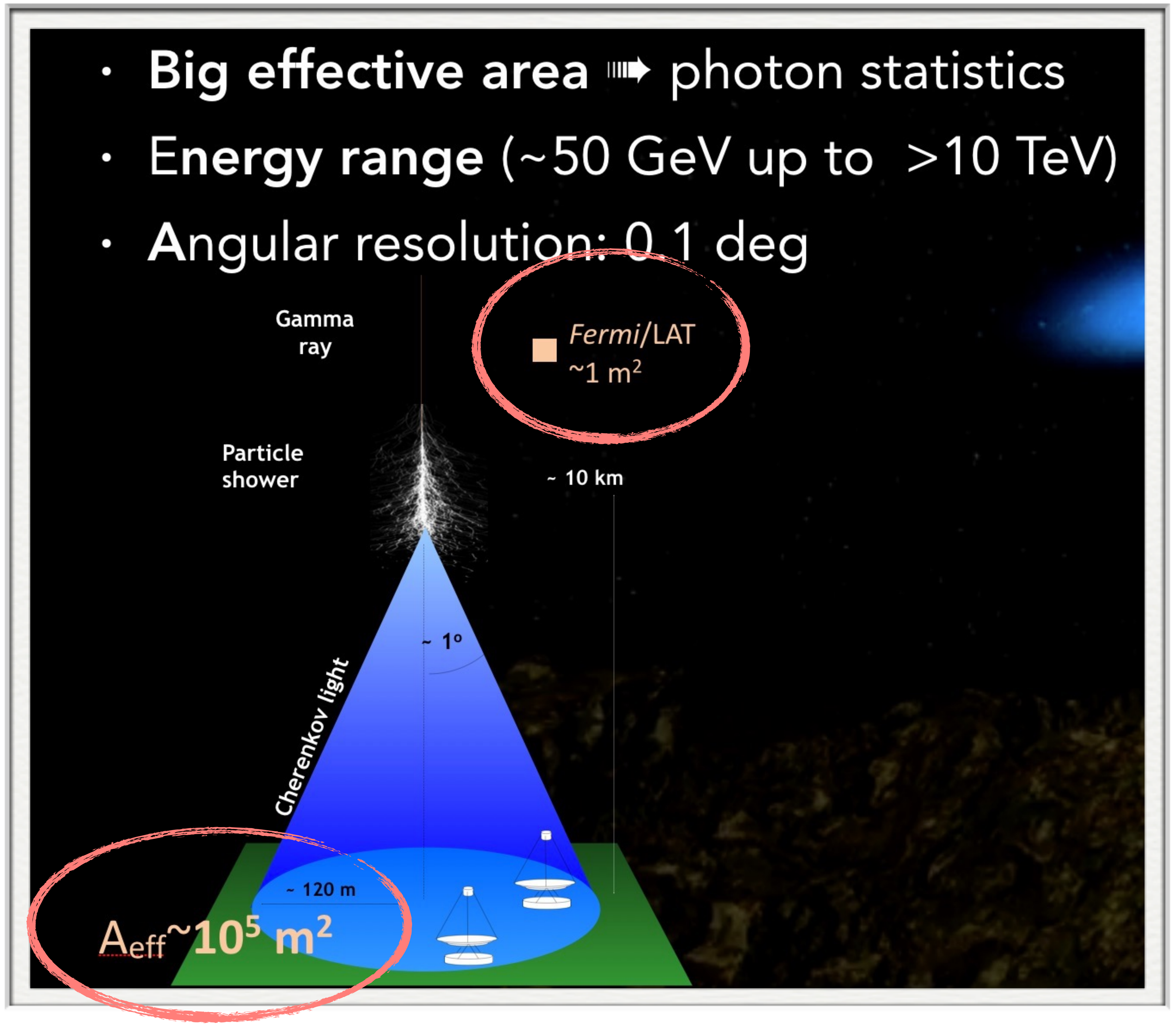




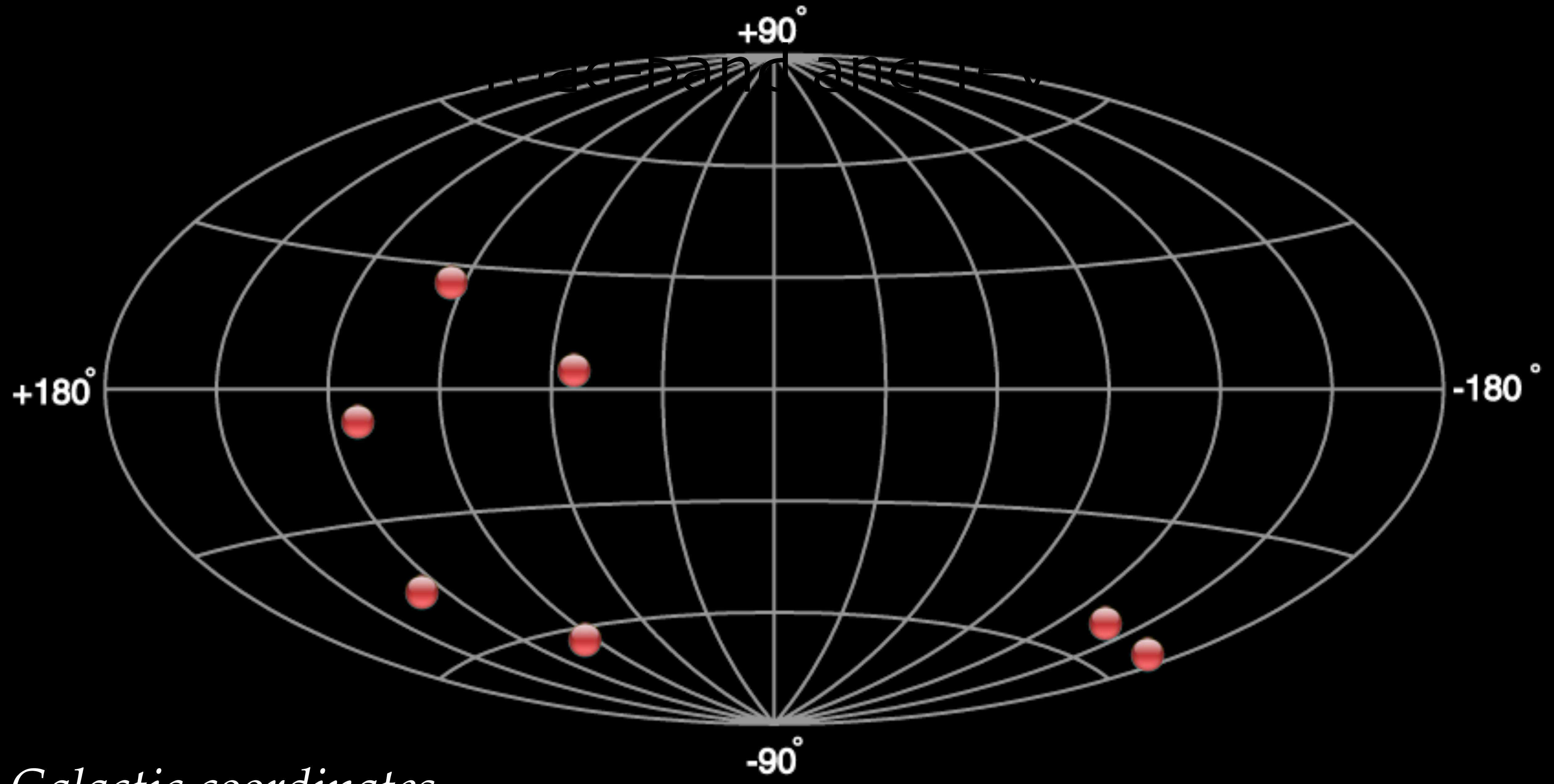
CTA performances: Sensitivity - transient and flaring sources

Extended "spectral arm leverage"
High statistics (=precision) on flares

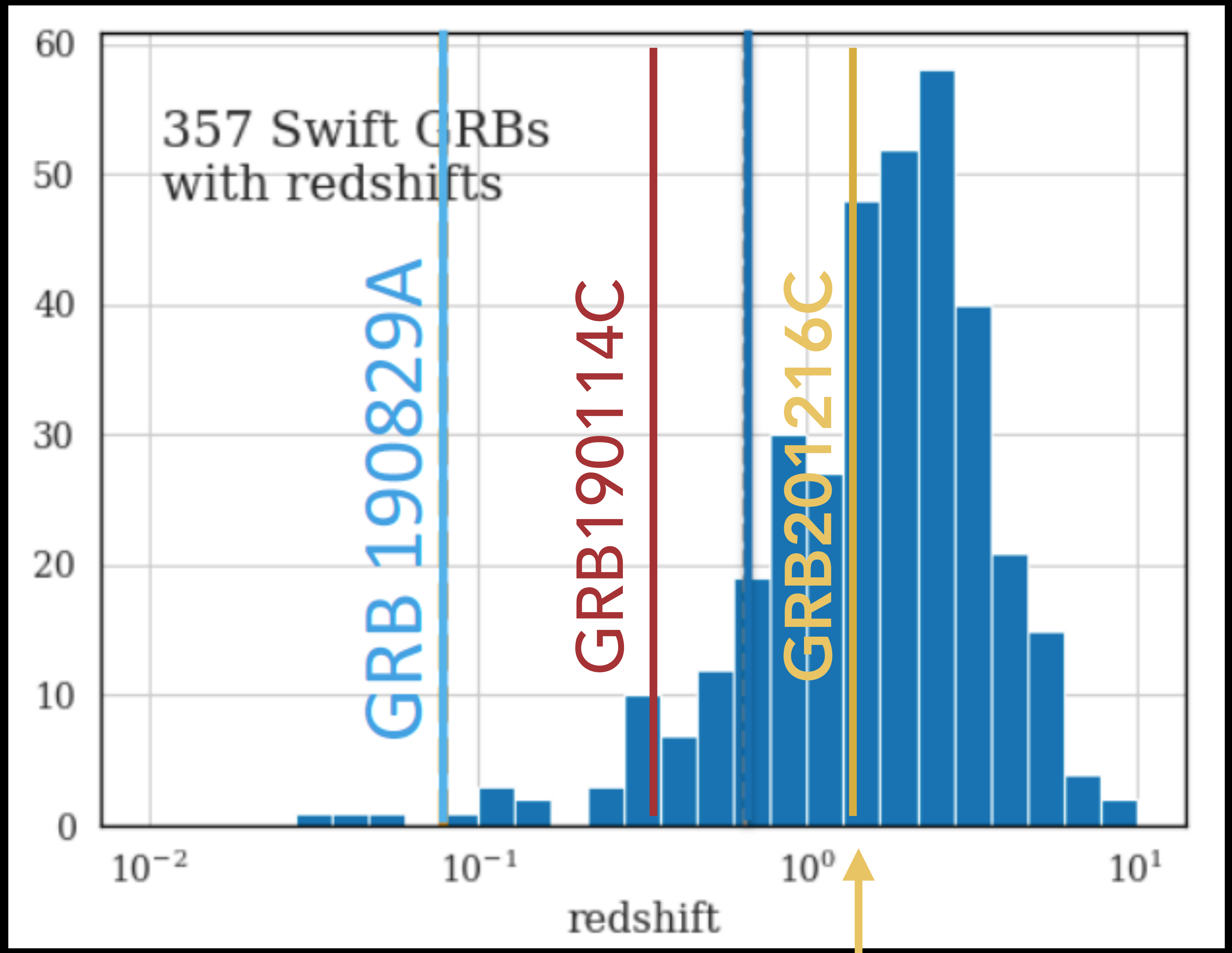




TeV-GRBs: the gamma-ray horizon



Galactic coordinates



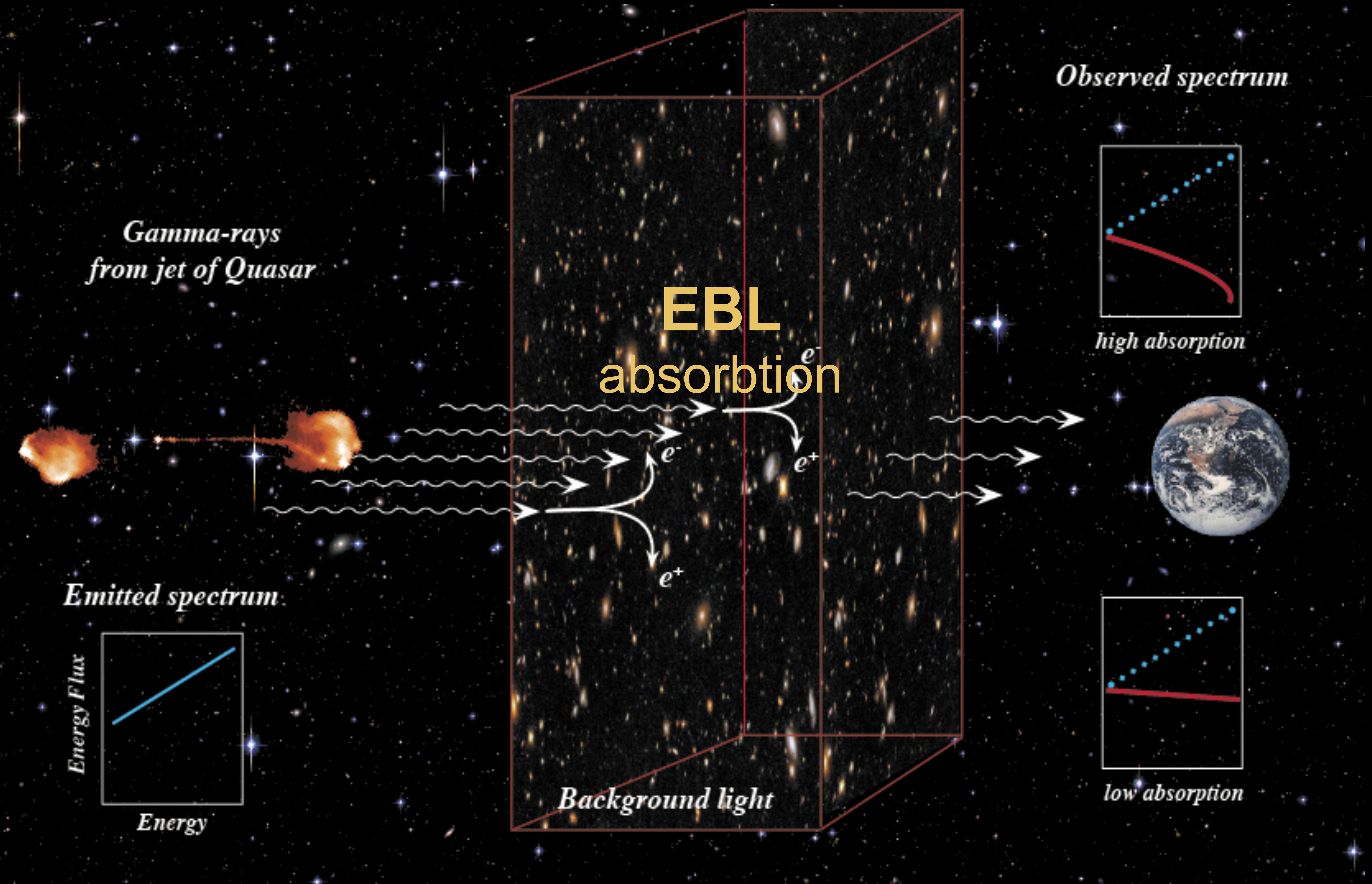
Farthest TeV source

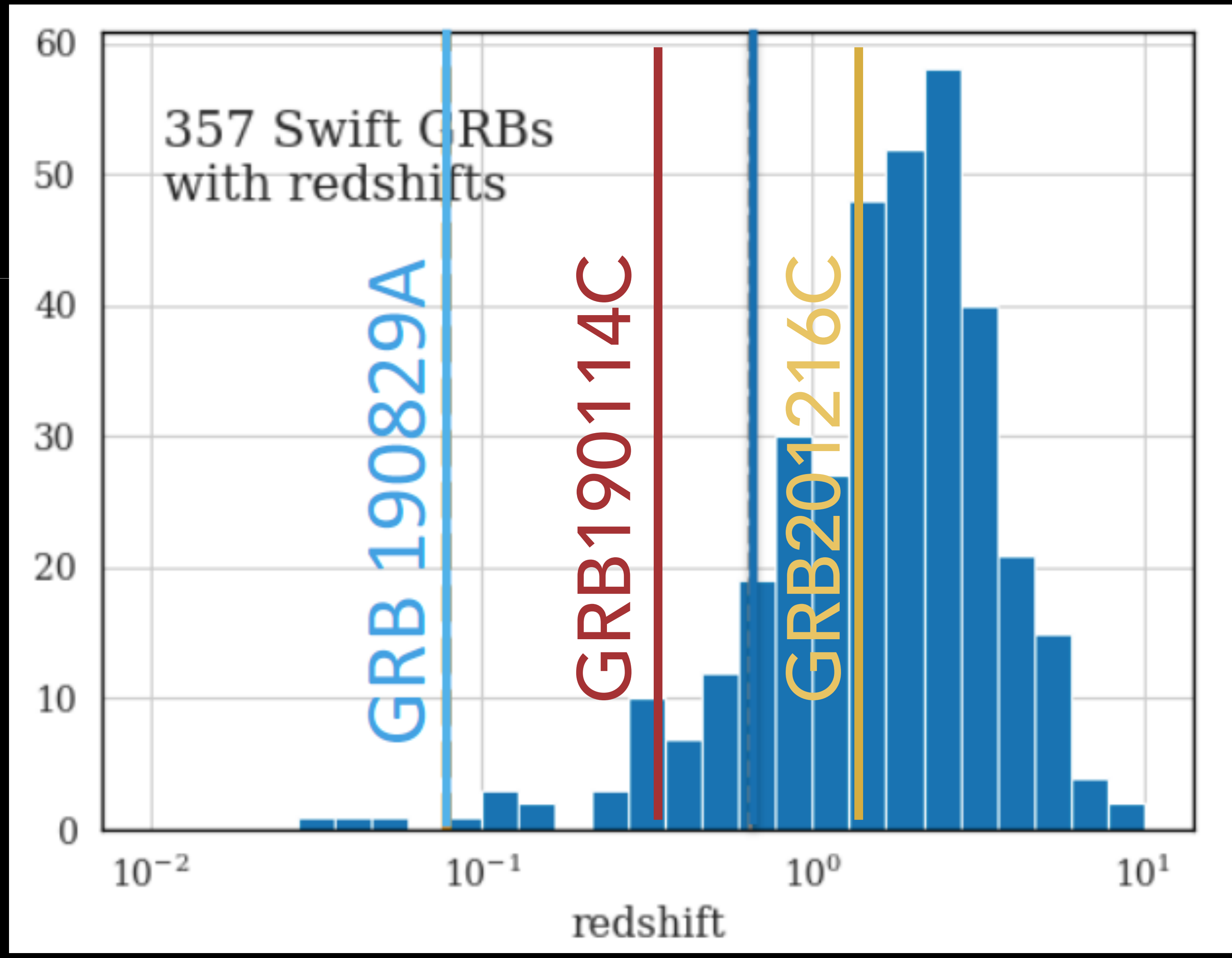
Name	RA	Dec	Type	Discoverer	Date	Dist	Catalog
			...	...			...
GRB 180720B	00 02 07.6	-02 56 06	GRB	H.E.S.S.	2019.05	z = 0.654	Default Catalog
GRB 201216C	01 05 28.88	+16 30 58.0	GRB	MAGIC	2020.12	z = 1.1	Newly Announced
GRB 190829A	02 58 10.51	-08 57 28.1	GRB	H.E.S.S.	2019.08	z = 0.0785	Default Catalog
GRB 190114C	03 38 01.17	-26 56 46.73	GRB	MAGIC	2019.01	z = 0.4245	Default Catalog
GRB 160821B	18 39 54.71	+62 23 34	GRB	null	2016.08	z = 0.16	Source Candidates
GRB 221009A	19 13 03	+19 48 09	GRB	LHAASO	2022.10	z = 0.151	Newly Announced
GRB 201015A	23 37 16.42	+53 24 55.8	GRB	MAGIC	2020.10	z = 0.43	Source Candidates

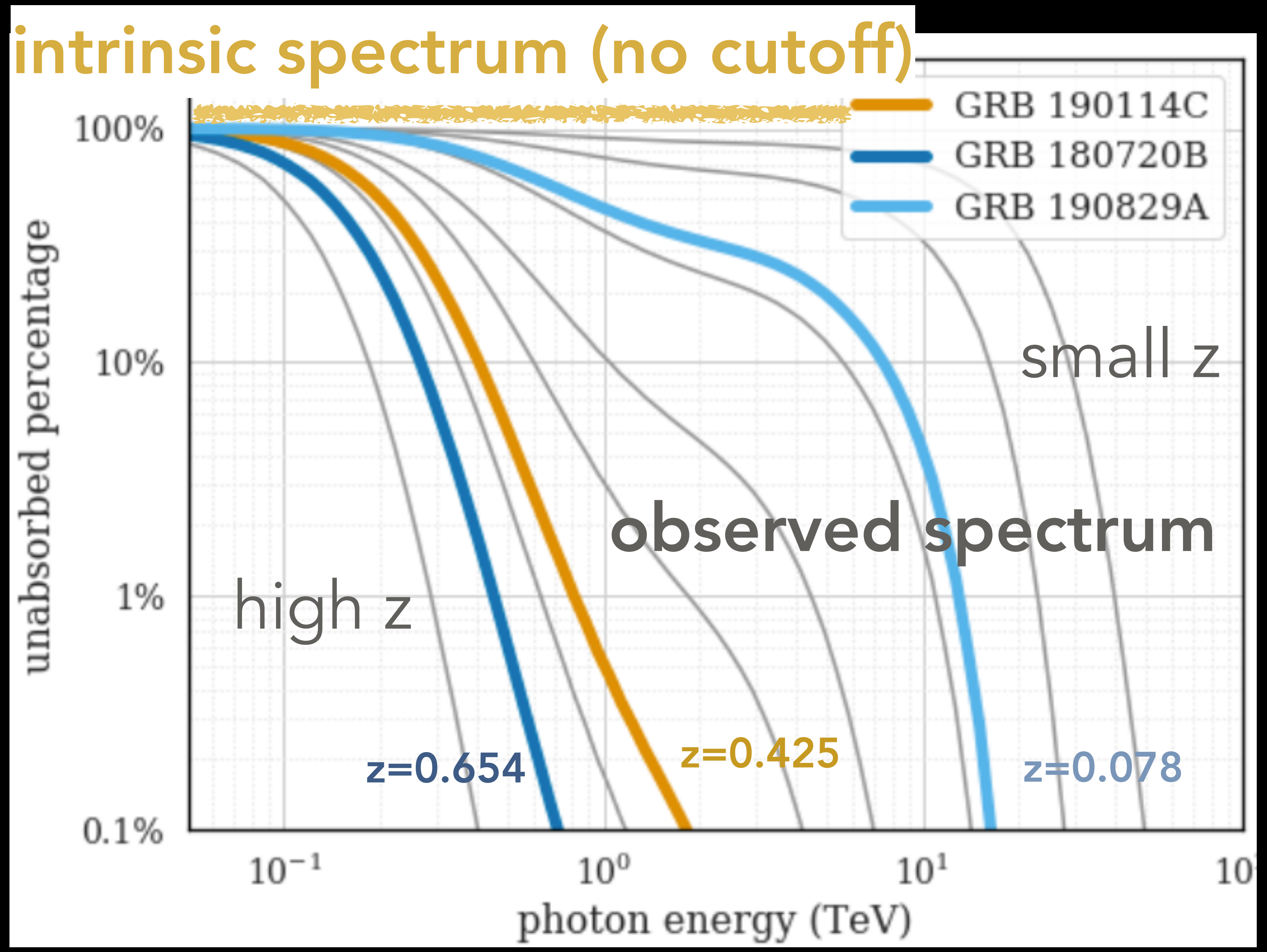
1-7

http://tevcat.uchicago.edu/

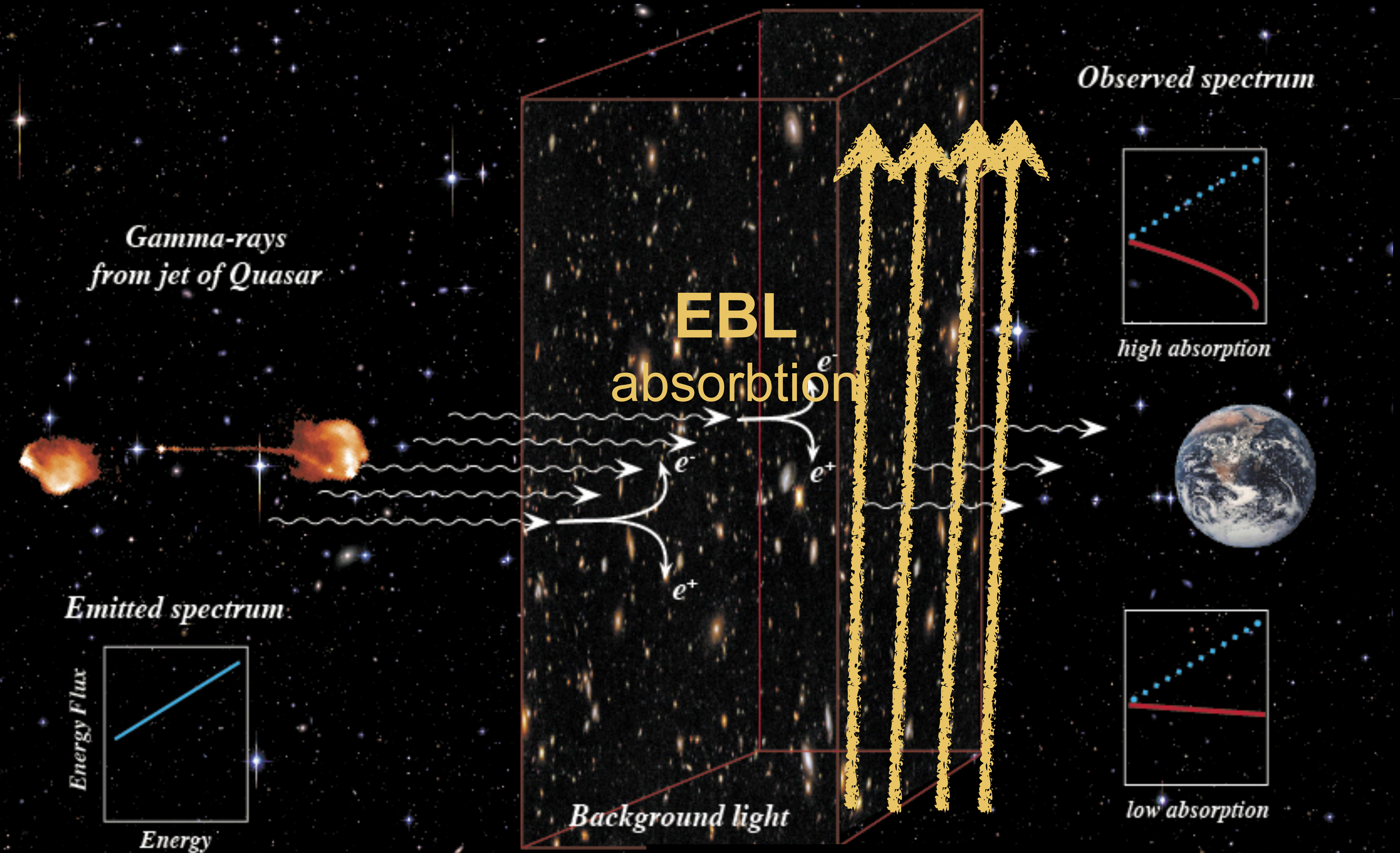
TeV Transients with IACTs



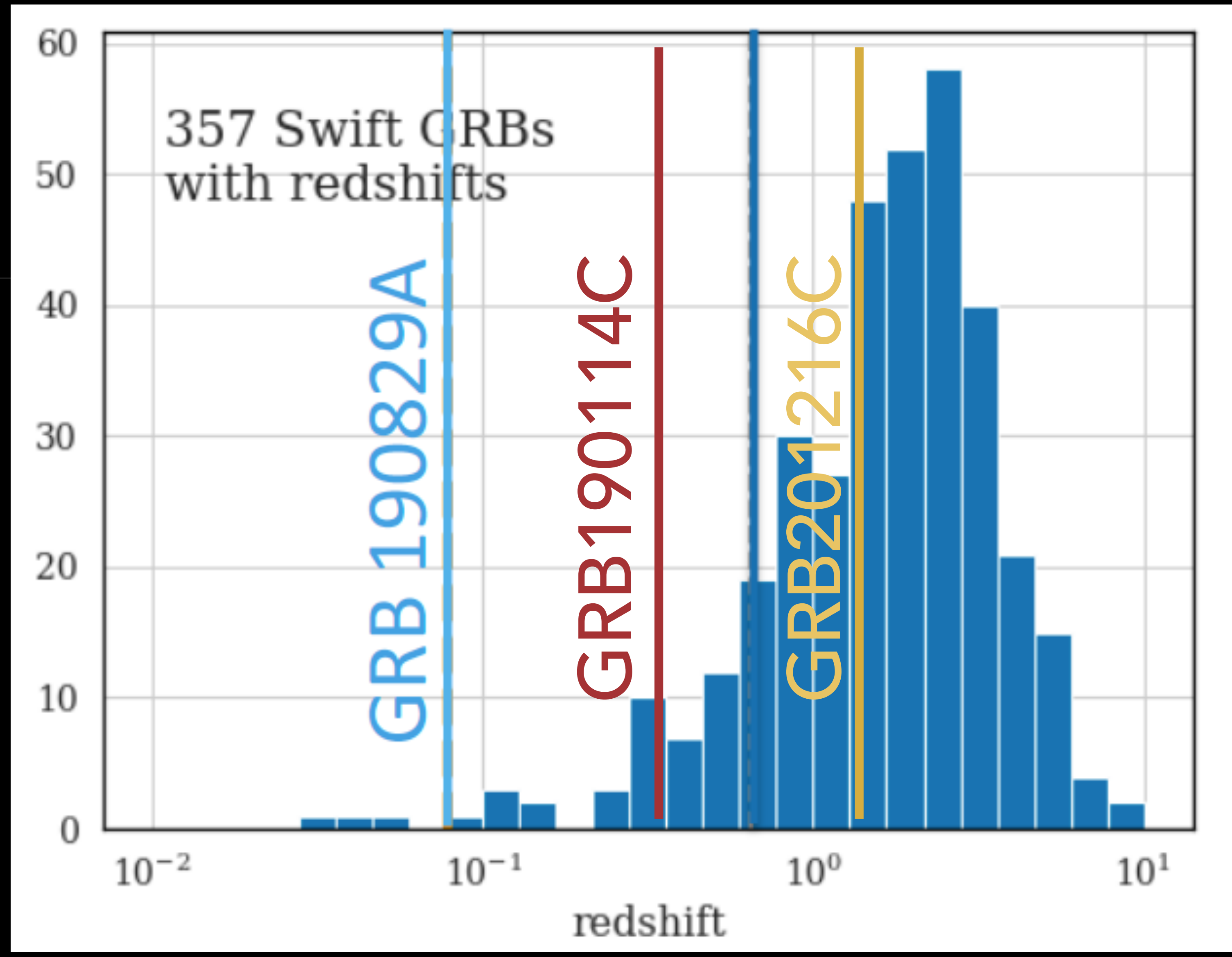


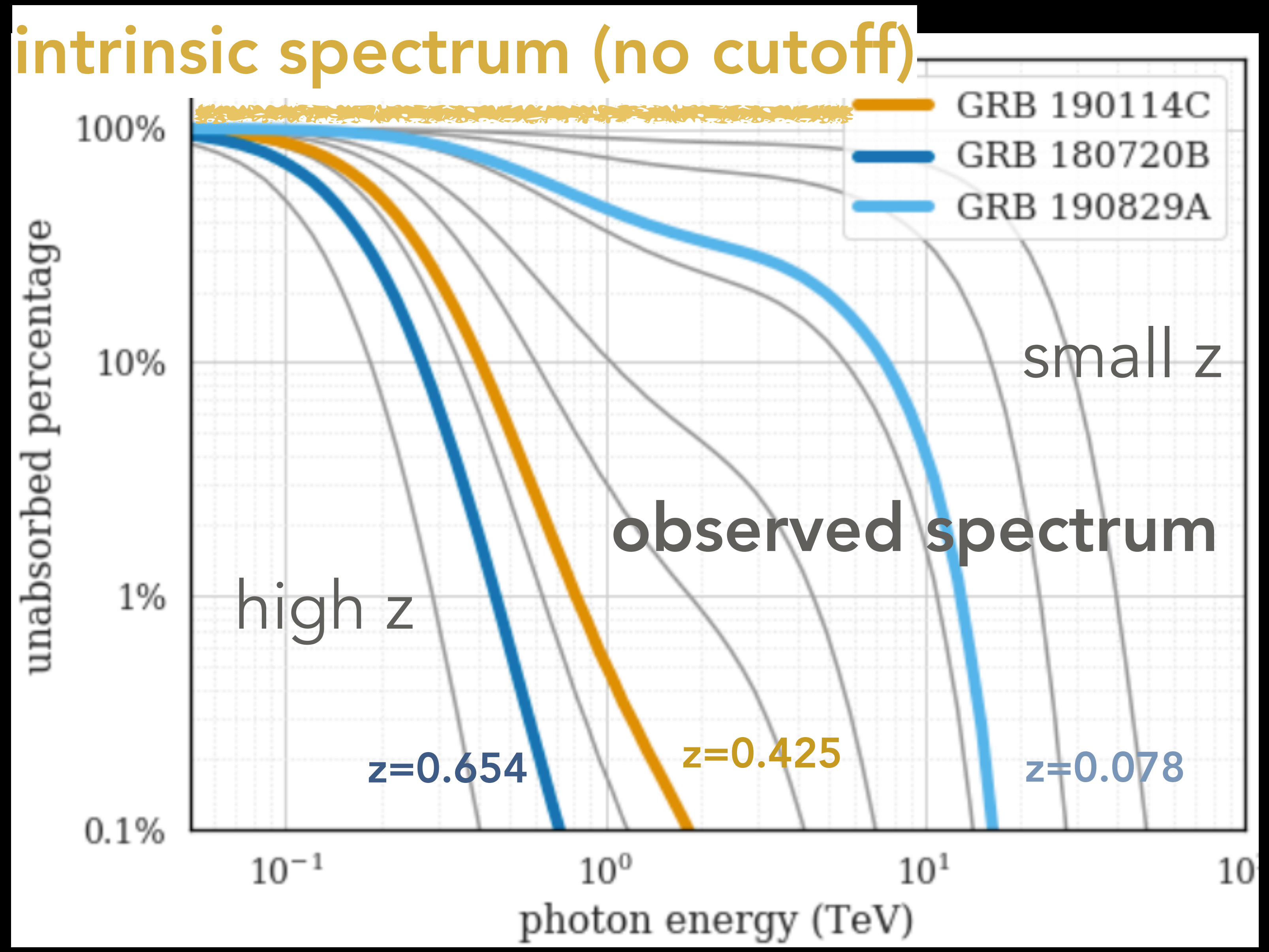


TeV Transients with IACTs



Intergalactic Magnetic Field (IGMF)





The CTA arrays

CTA in a nutshell

Energy range: 30 GeV to 300 TeV

Sensitivity improvement: ×5 to ×20 (mCrab)

Angular resolution: 3 arcmin at 1 TeV

Field of view: ~8 deg (diameter)

Energy resolution: 7% at 1 TeV

Northern site: La Palma
Alpha: 4 Large, 9 Medium
Omega: 4 Large, 15 Medium

Southern Site: Paranal, Chile
Alpha: 14 Medium, 37 Small
Omega: 4 Large, 25 Medium, 70 Small

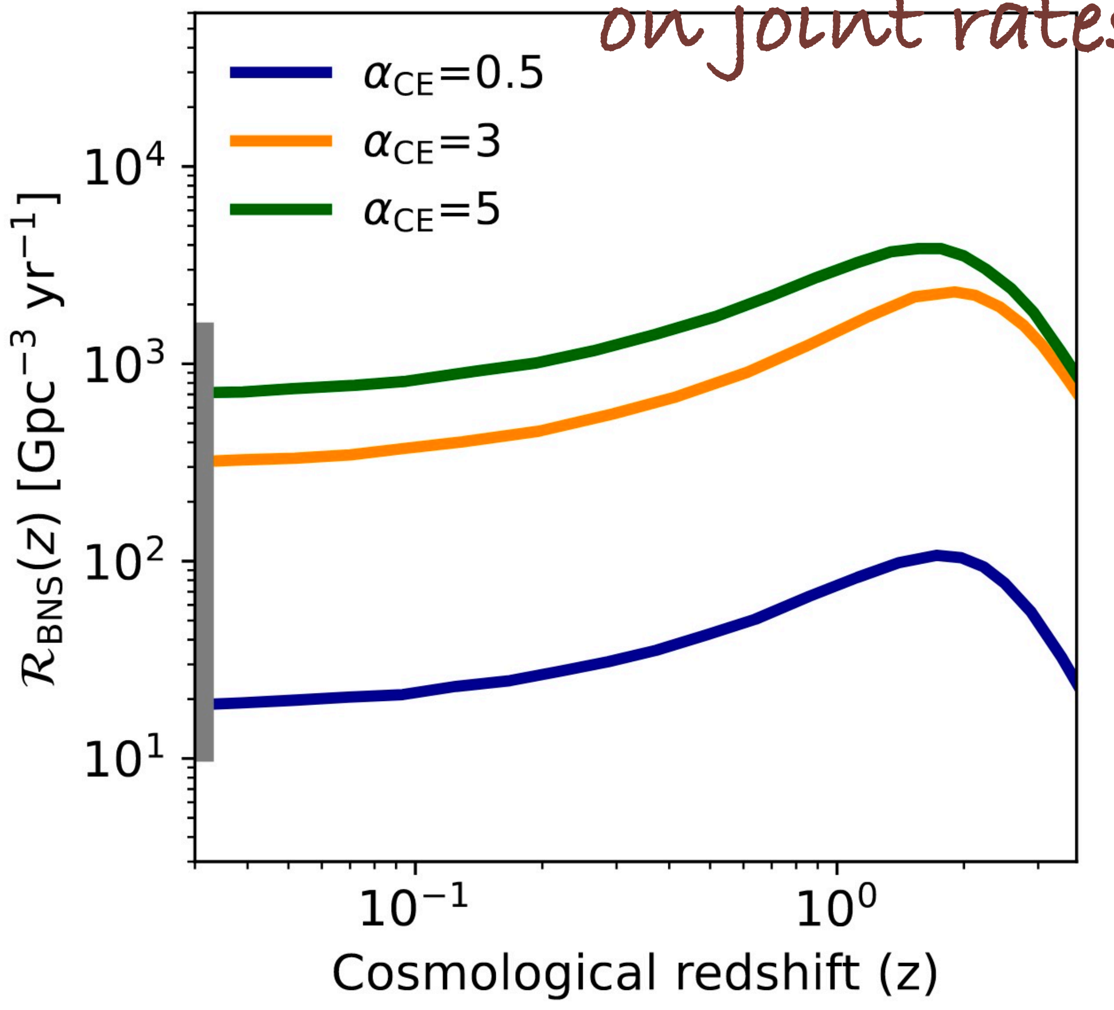
+2 LST with CTA+ PNRR project

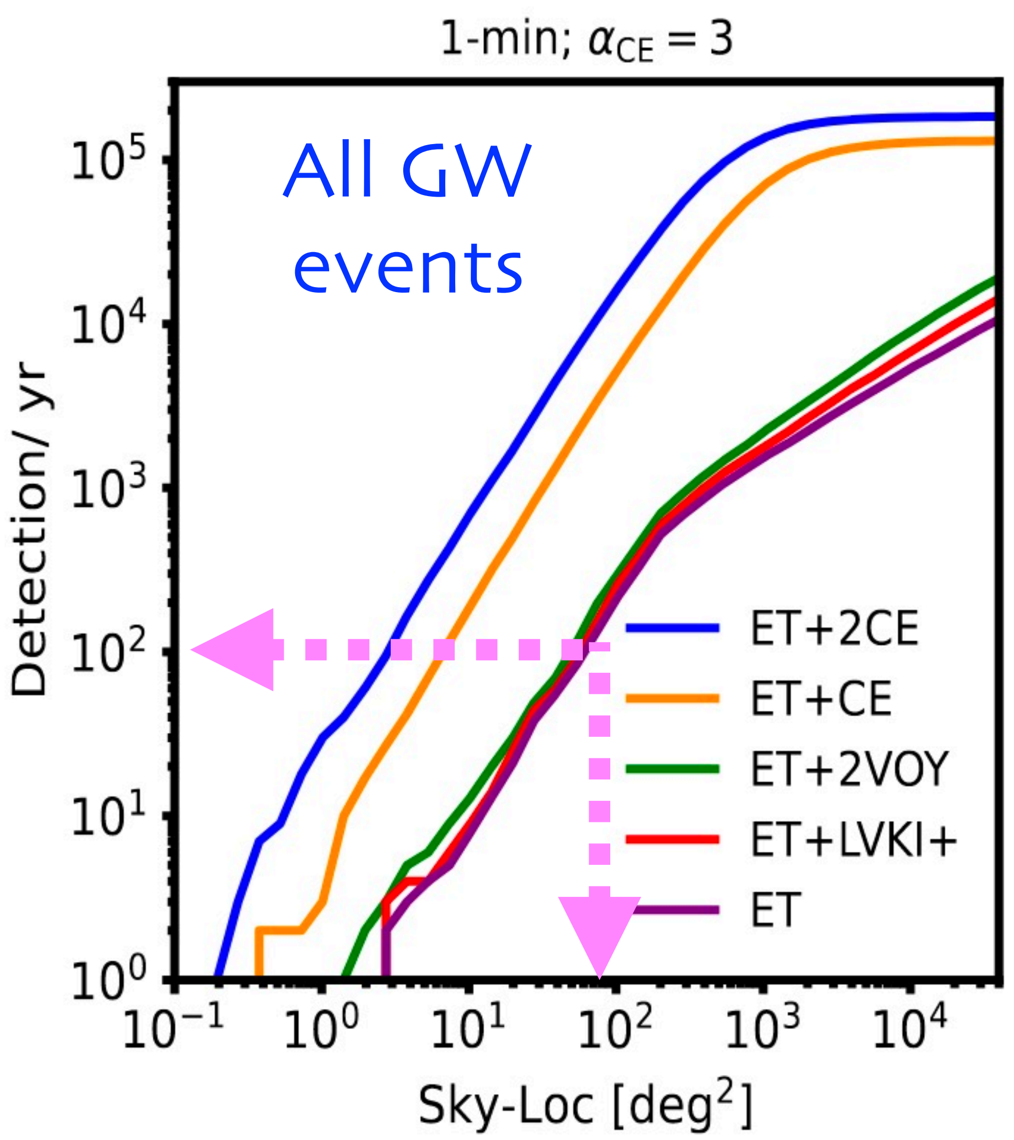
PERSPECTIVES ON GW ALERTS WITH CTA

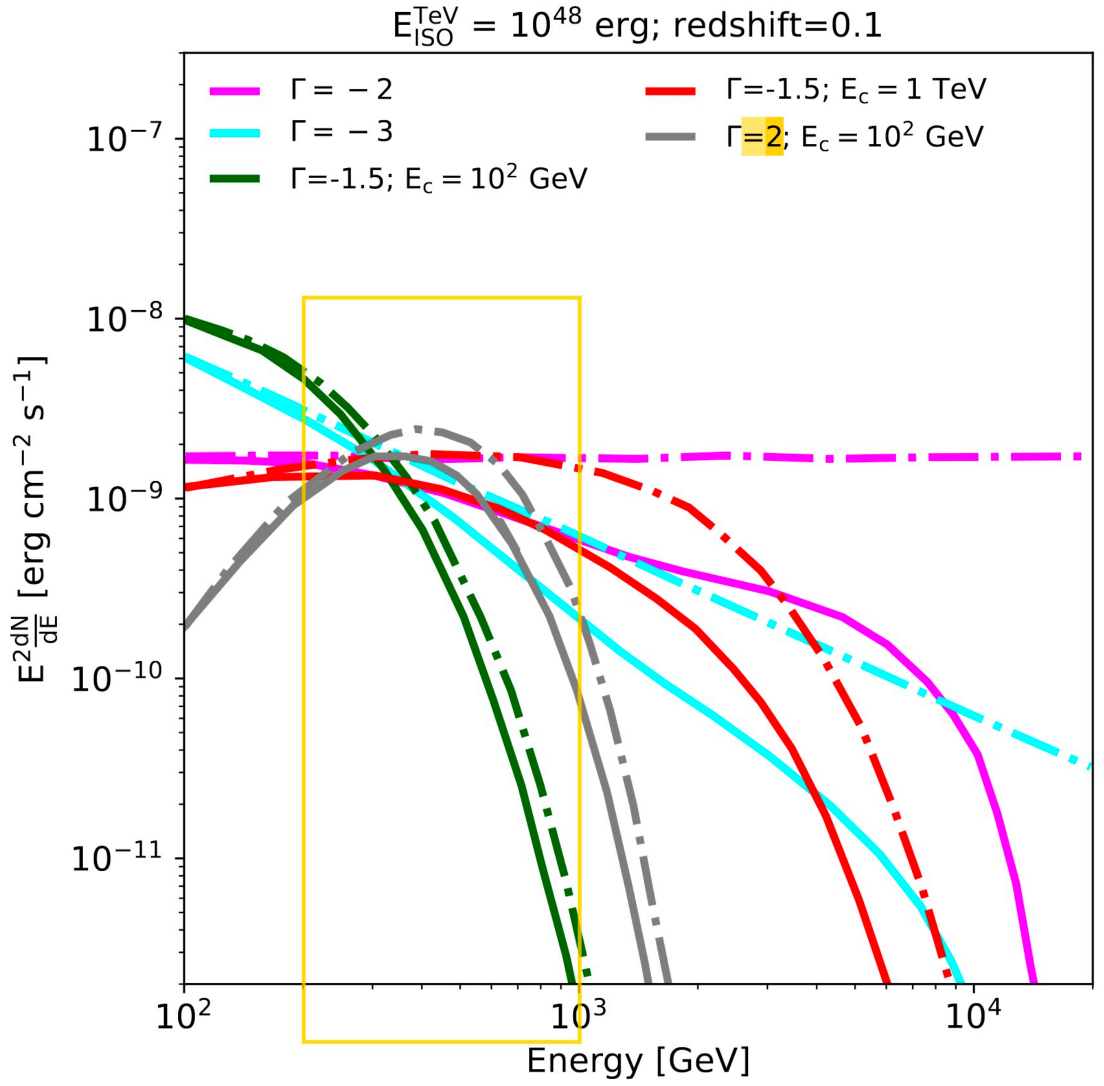
FOLLOW-UP OF GW EVENTS WITH ET AND CTA; JOINT RATES
(BANERJEE ET AL. 2023, A&A 678, A126)

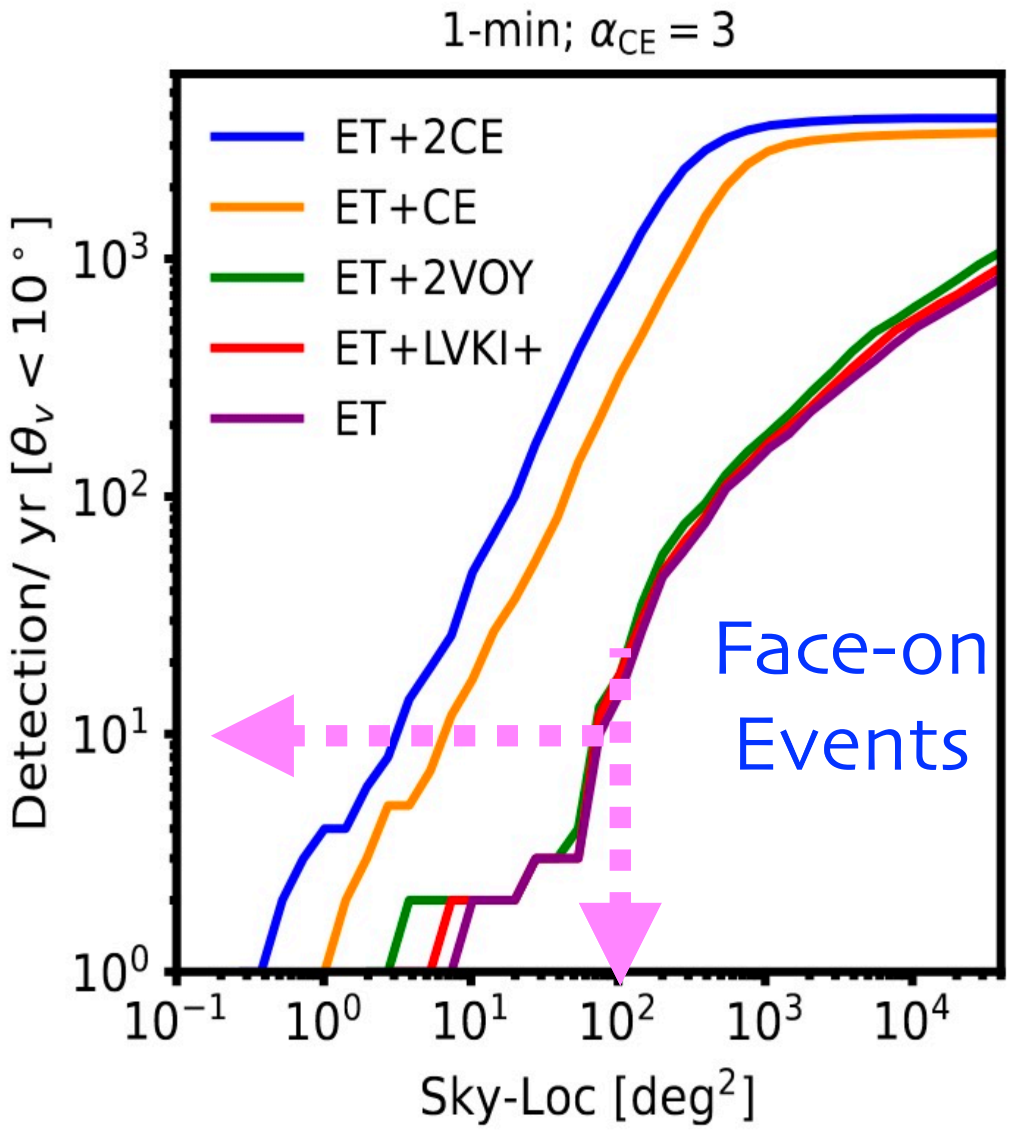
- Simulation of the GW events with a population of BNS
  - Redshift <1.5
  - Face-on events (inclination <10deg)
- Assumptions on the associated TeV emission
  - E_{iso} 10^{42}-10^{53} (0.2-1 TeV)
  - Power-law model with cutoff and with EBL
- Observational constraints on CTA observations
  - Slewing time (20/90s)
  - Duty cycle 15%
  - Visibility Zenith angle <60deg (50%)

Biggest uncertainty on joint rates!









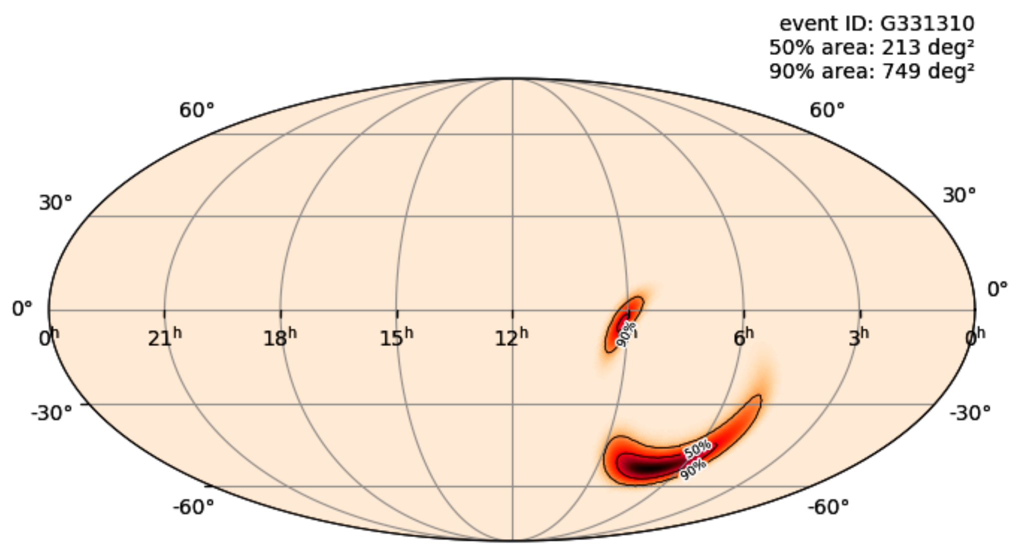
PERSPECTIVES ON GW ALERTS WITH CTA

Simulation of BNS mergers and GW signal in local universe

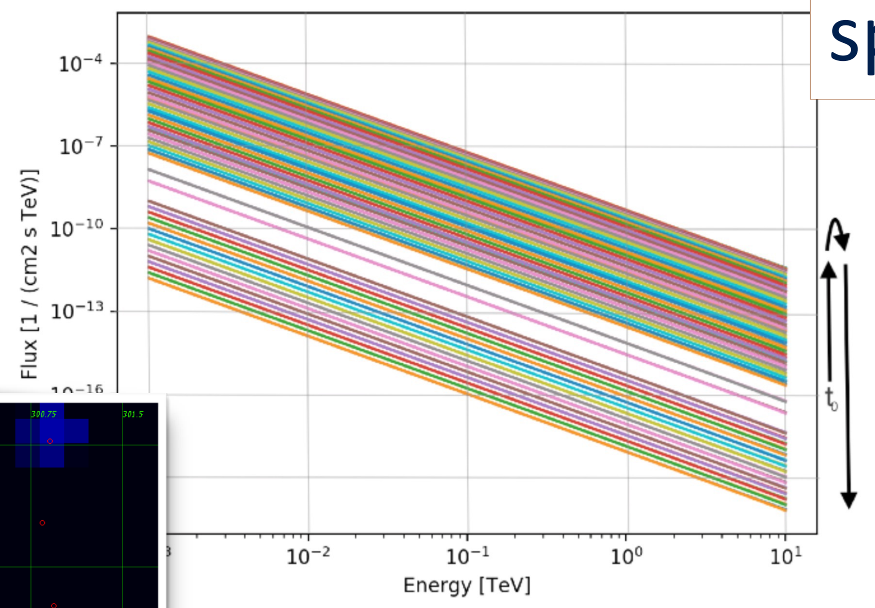
Synthetic GW-GRBs
Phenomenological model of VHE emission of short-GRB

Simulation of CTA response (set of IRFs)
gammapy, ctools

Observation optimisation and scheduler
CTA observing strategy

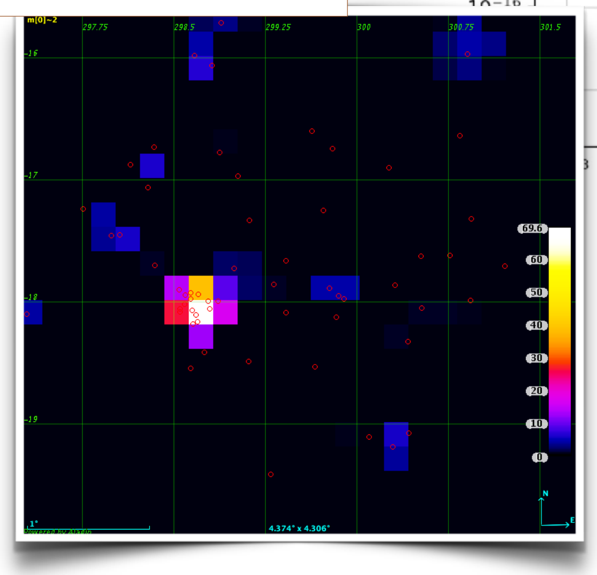


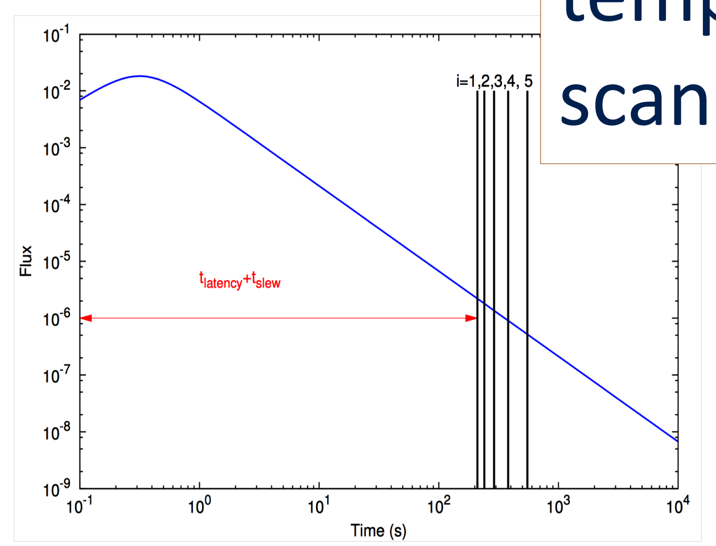
GW skymap



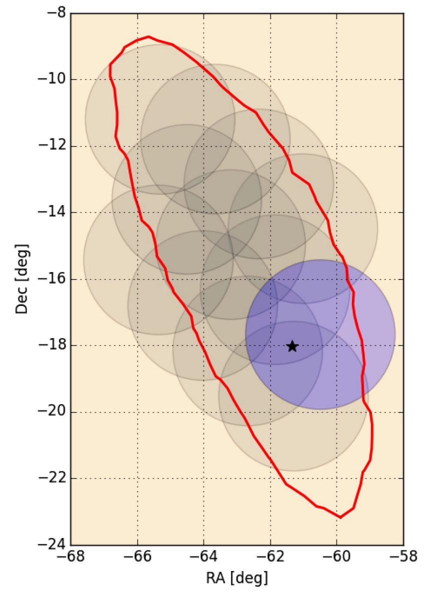
GRB spectra

CTA skymap





temporal scan



CTA tiling

EXPECTED RESULTS

- Joint GW-CTA rates
- Optimization of observing strategy
  - Maximize detection rate
  - **Maximize physical interpretation return**
- Optimal parameter space of GW-GRB
  - physical (luminosity, spectral shapes...)
  - observational (time delays, integration times)

PERSPECTIVES ON GW ALERTS WITH CTA

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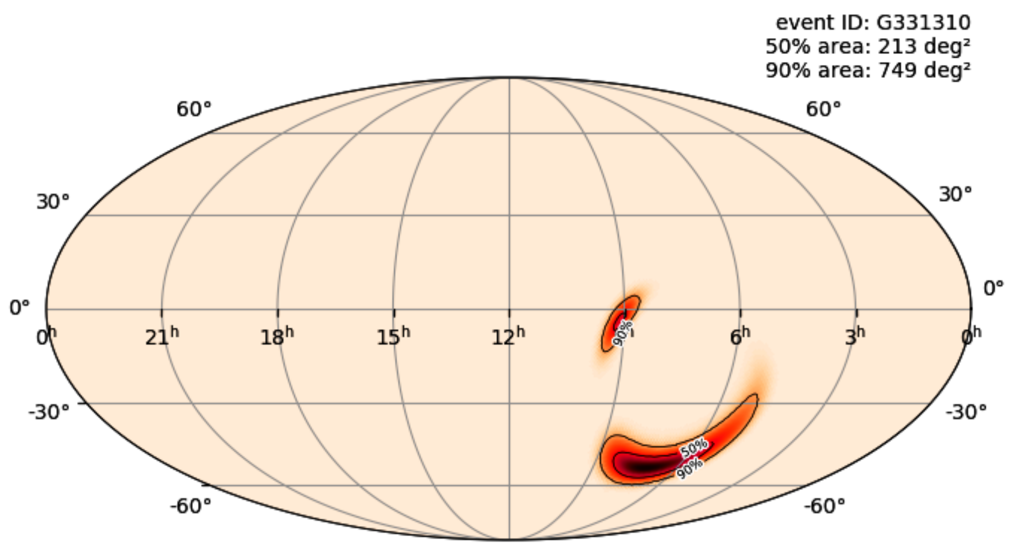
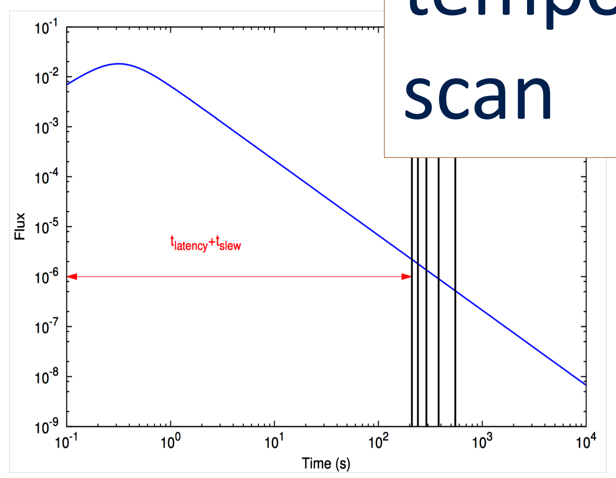
Observation optimisation and scheduler
CTA observing strategy

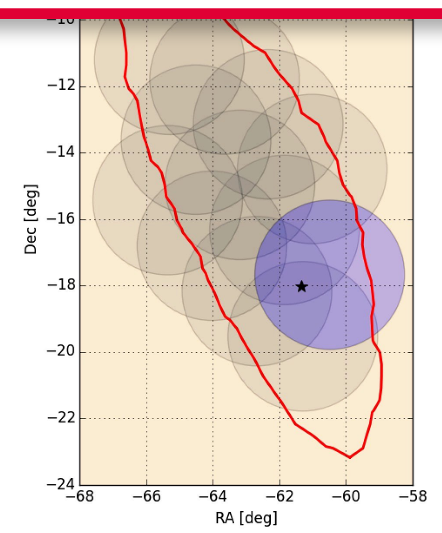


GW skymap

GRB spectra



temporal scan



CTA tiling

✓ CBC catalogs for **O5** and **O6** (Petrov et al. 2022)

- Includes BNS, BH-NS, BBH systems, **isotropically** distributed, with **3D skymaps**
- *Reflects the operating conditions of CTA and GW interferometers.*

Possibility to implement Einstein Telescope (ET) simulations with preliminary studies and then in the context of CTA-O.

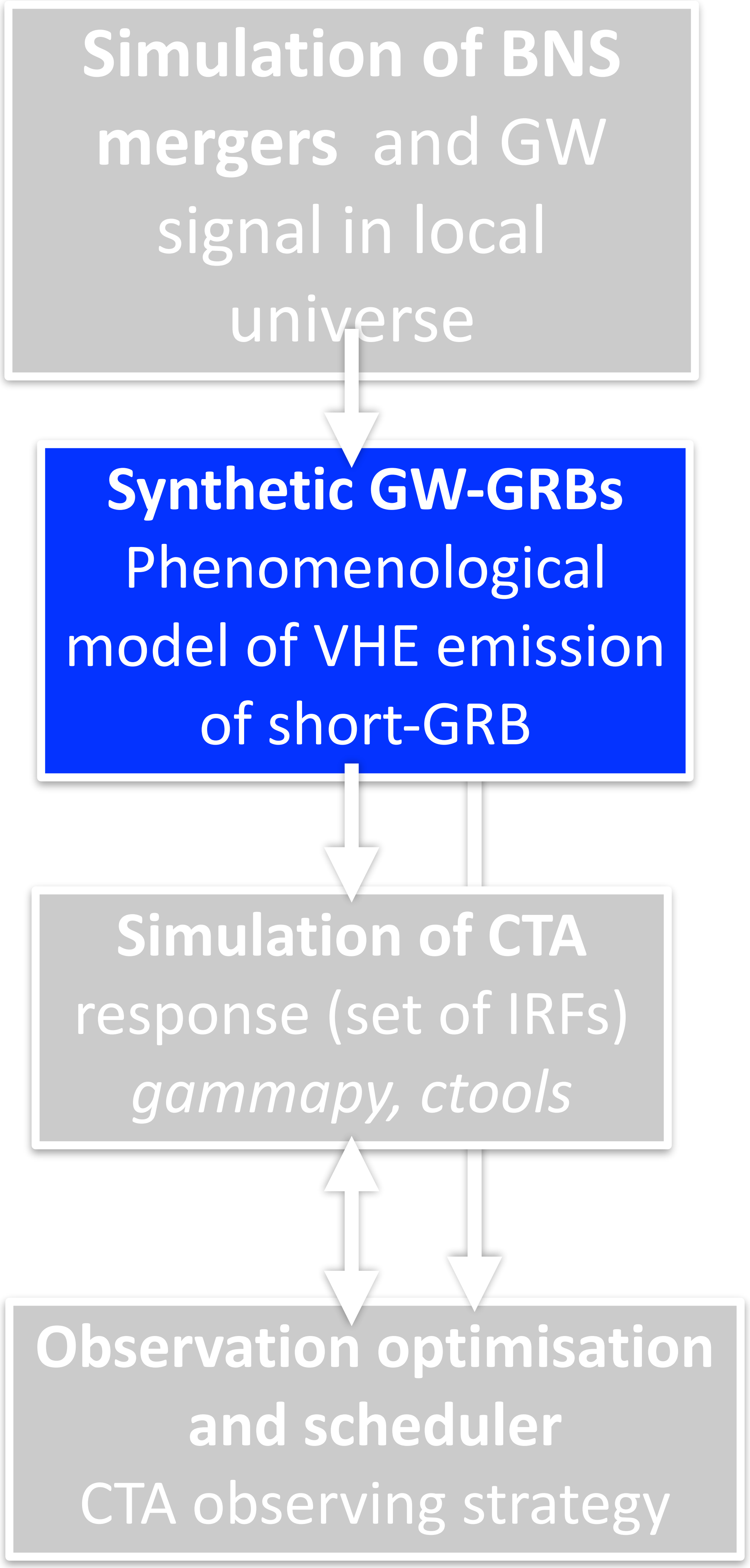
EXPECTED RESULTS

- Joint GW-CTA rates
- Optimization of observing strategy
  - Maximize detection rate
  - **Maximize physical interpretation return**

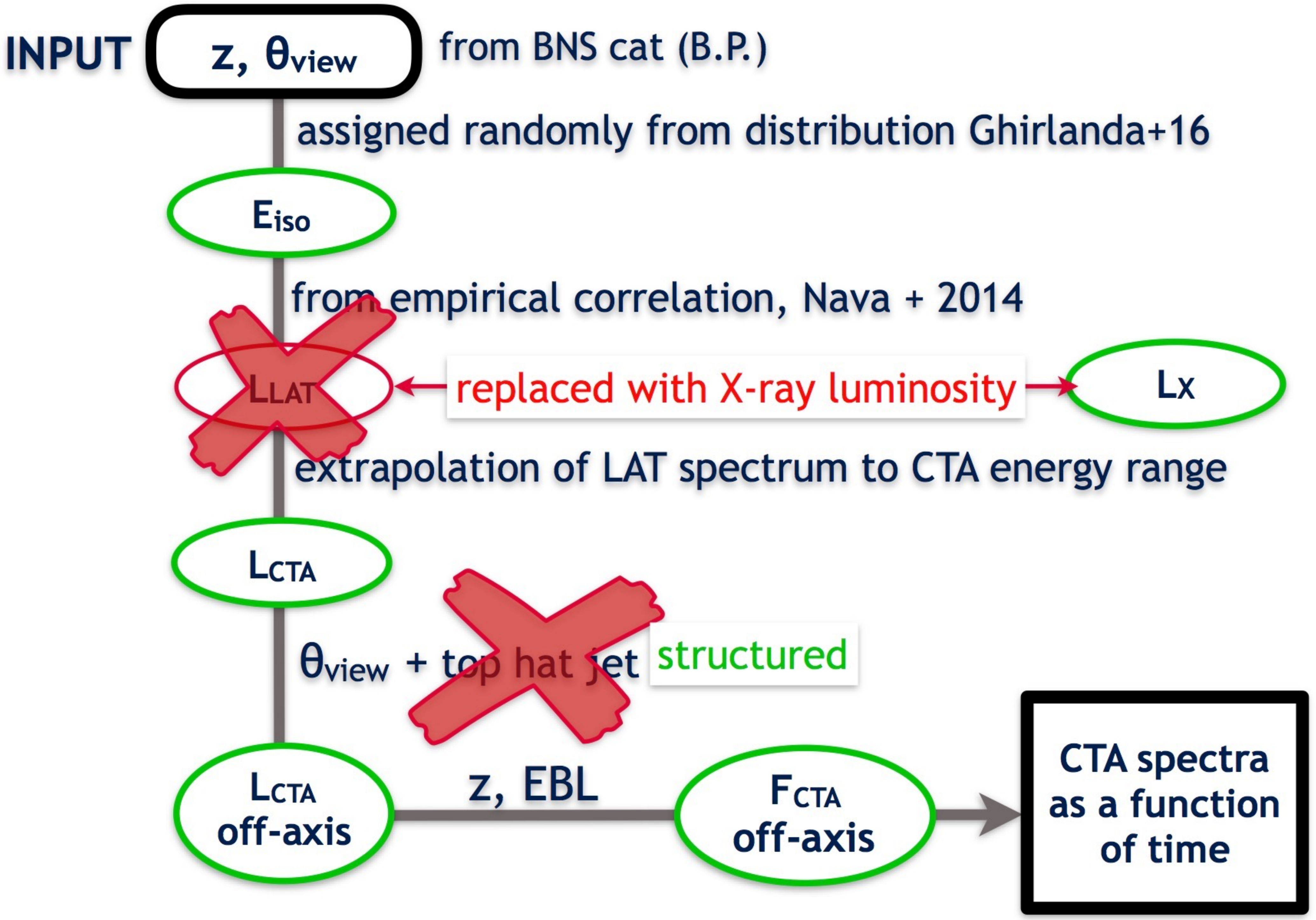
Optimal parameter space of GW-GRB

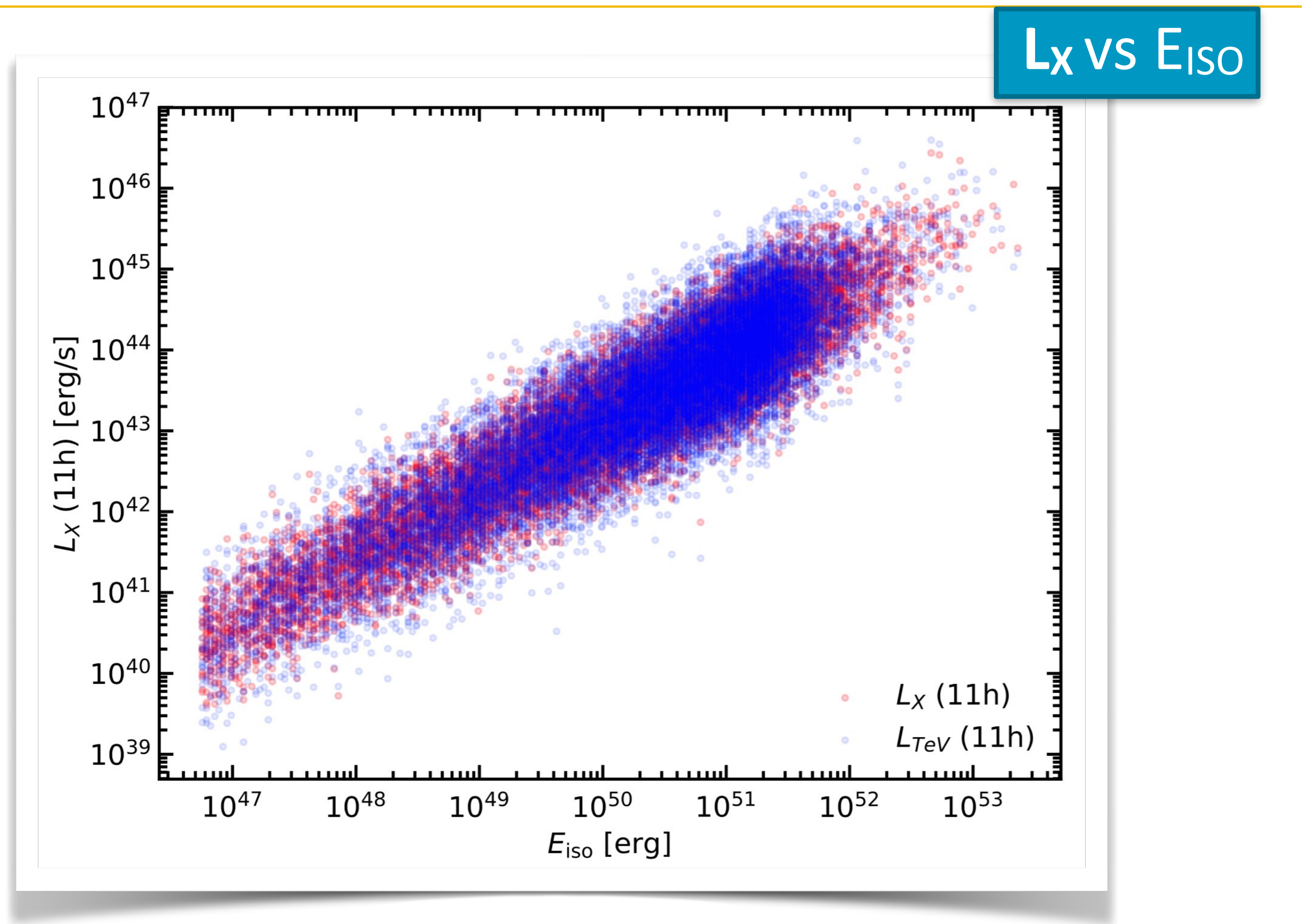
- physical (luminosity, spectral shapes...)
- observational (time delays, integration times)

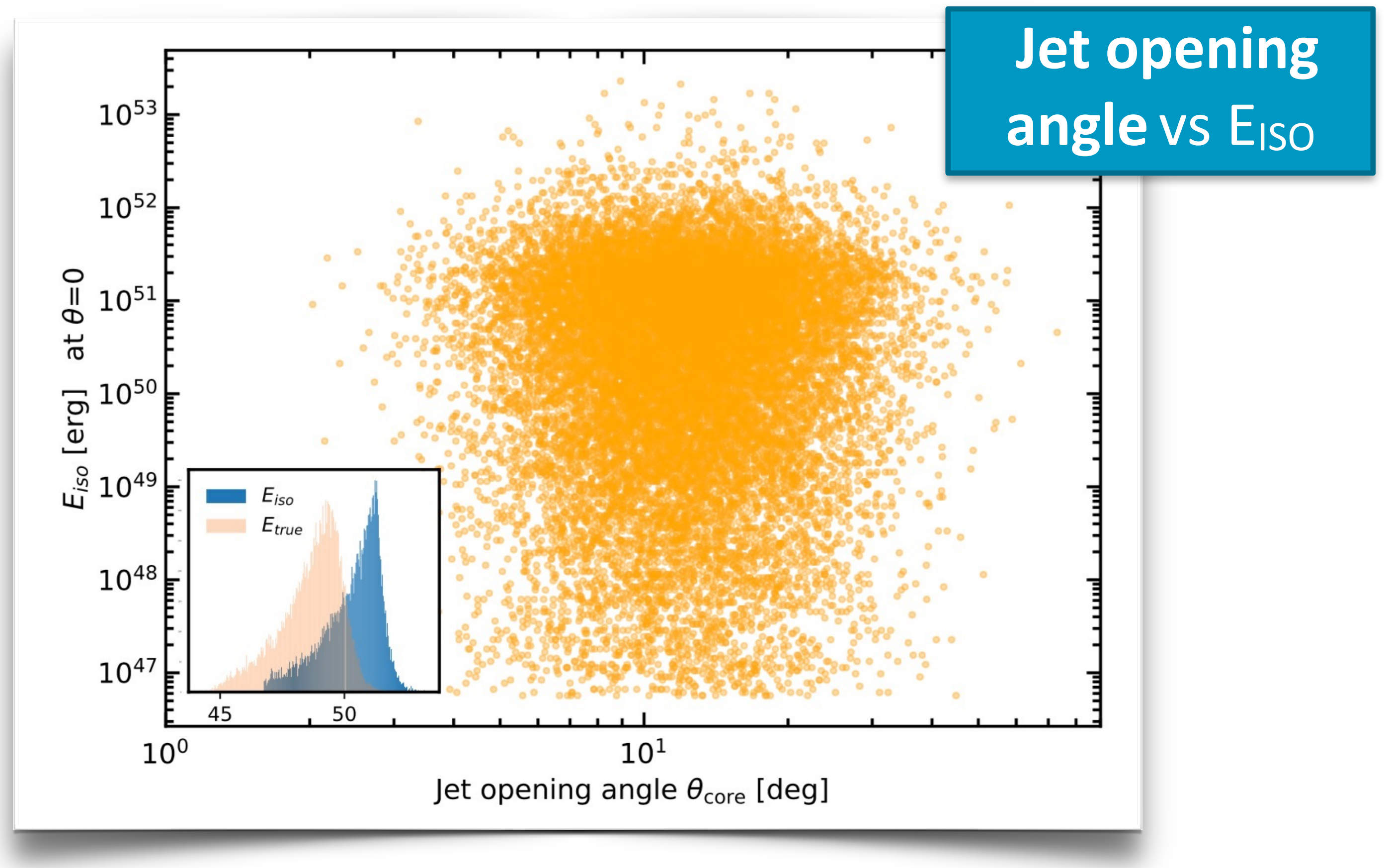
The synthetic-GRB module

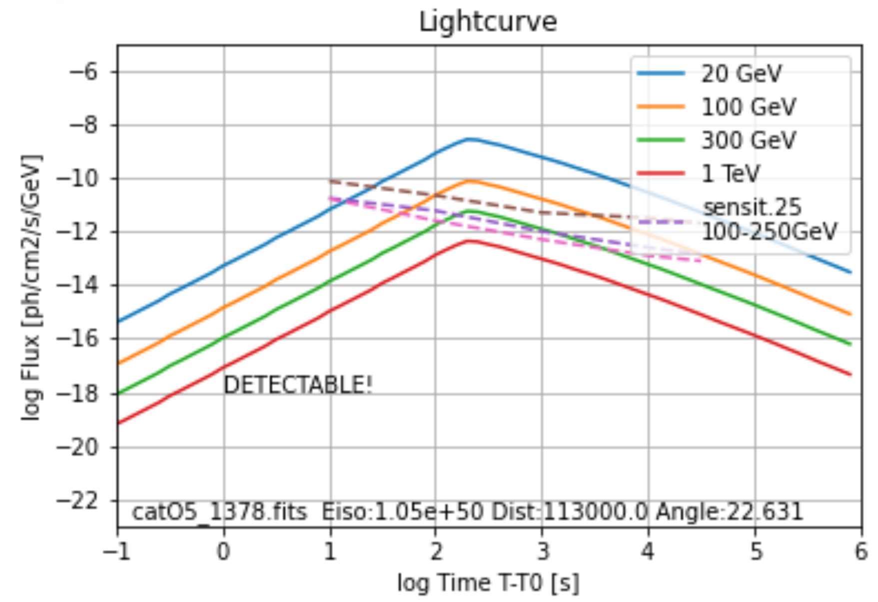


- GRB catalogue containing models for each GW-event with the expected emission in the CTA energy range
  - **empirical** (model-independent) light-curves and spectra

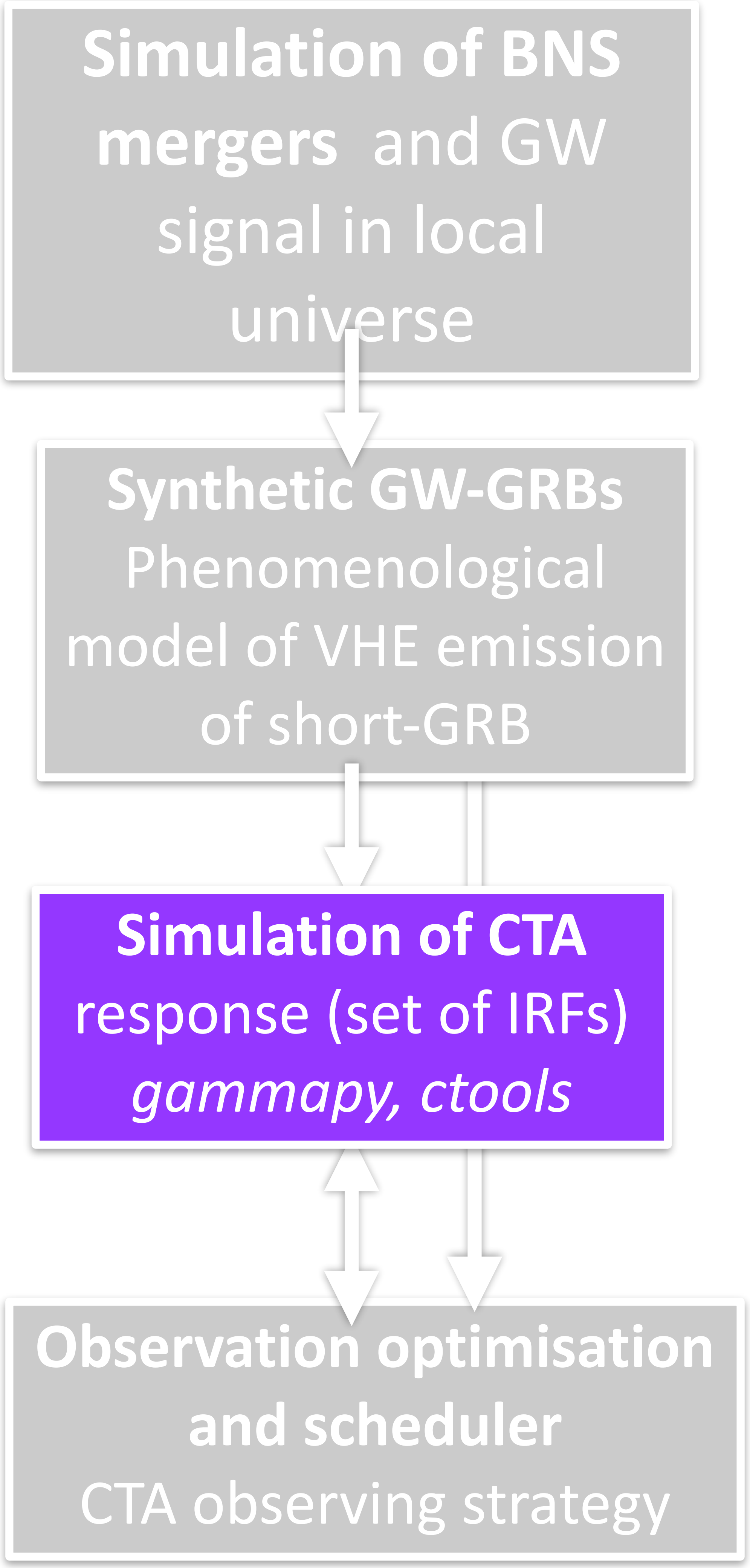




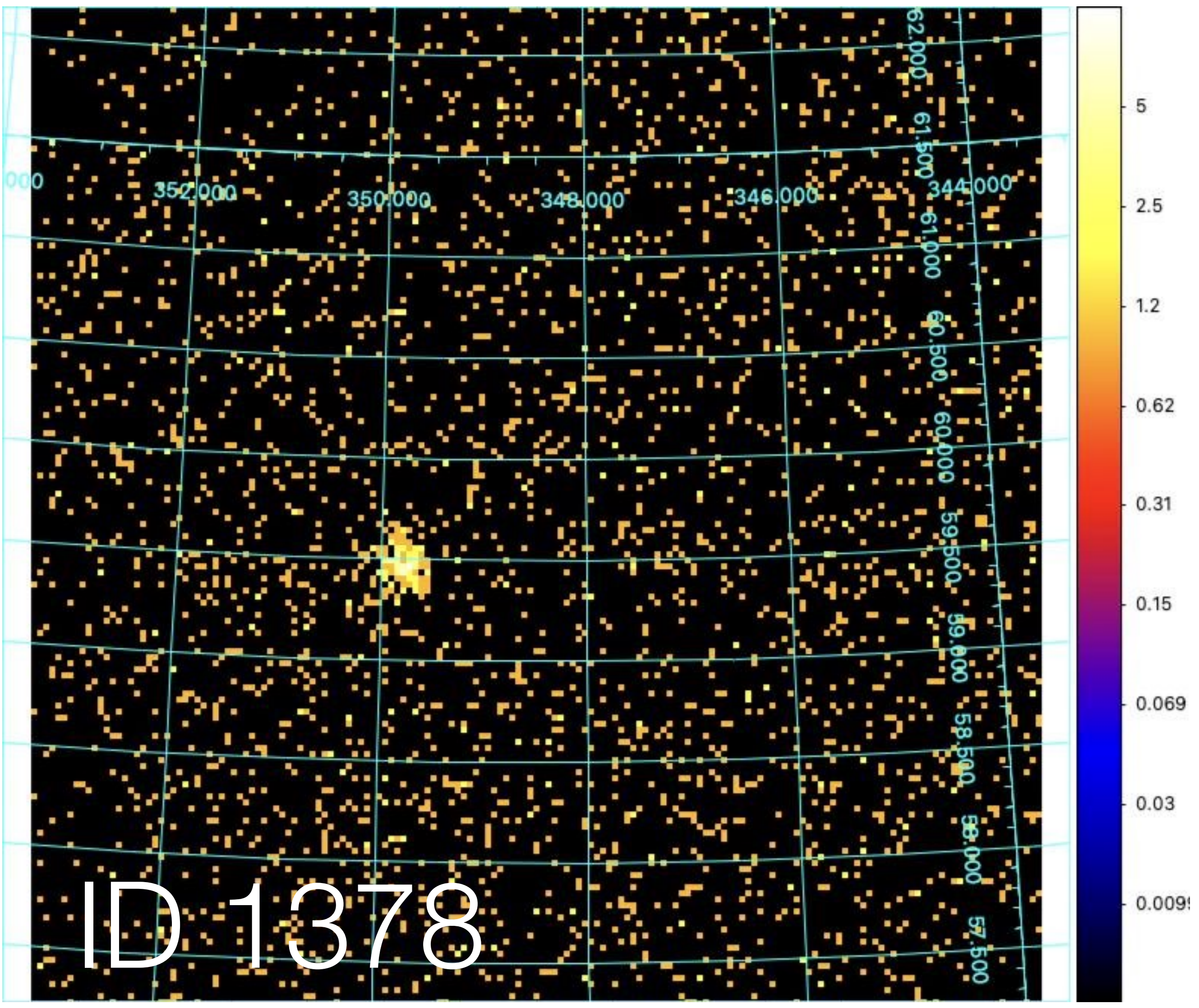




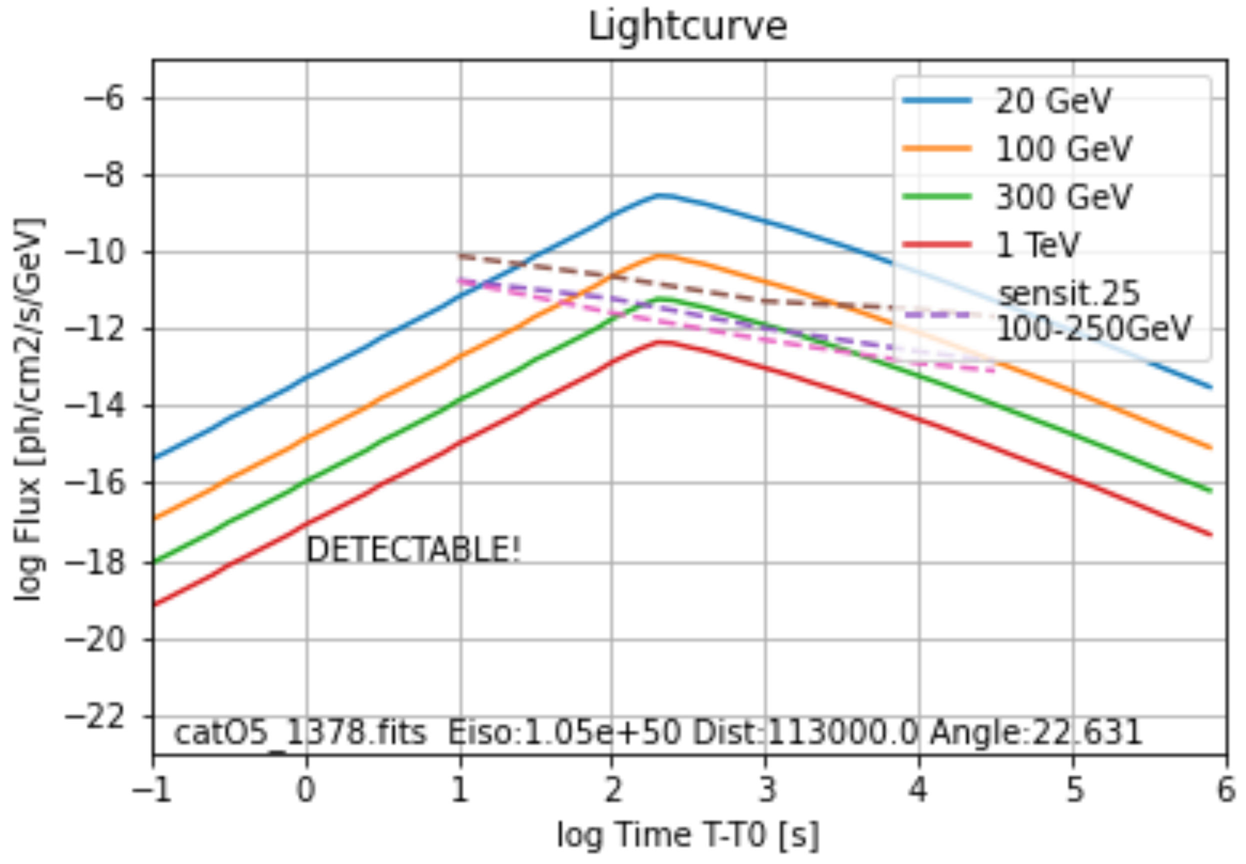
The synthetic-GRB module

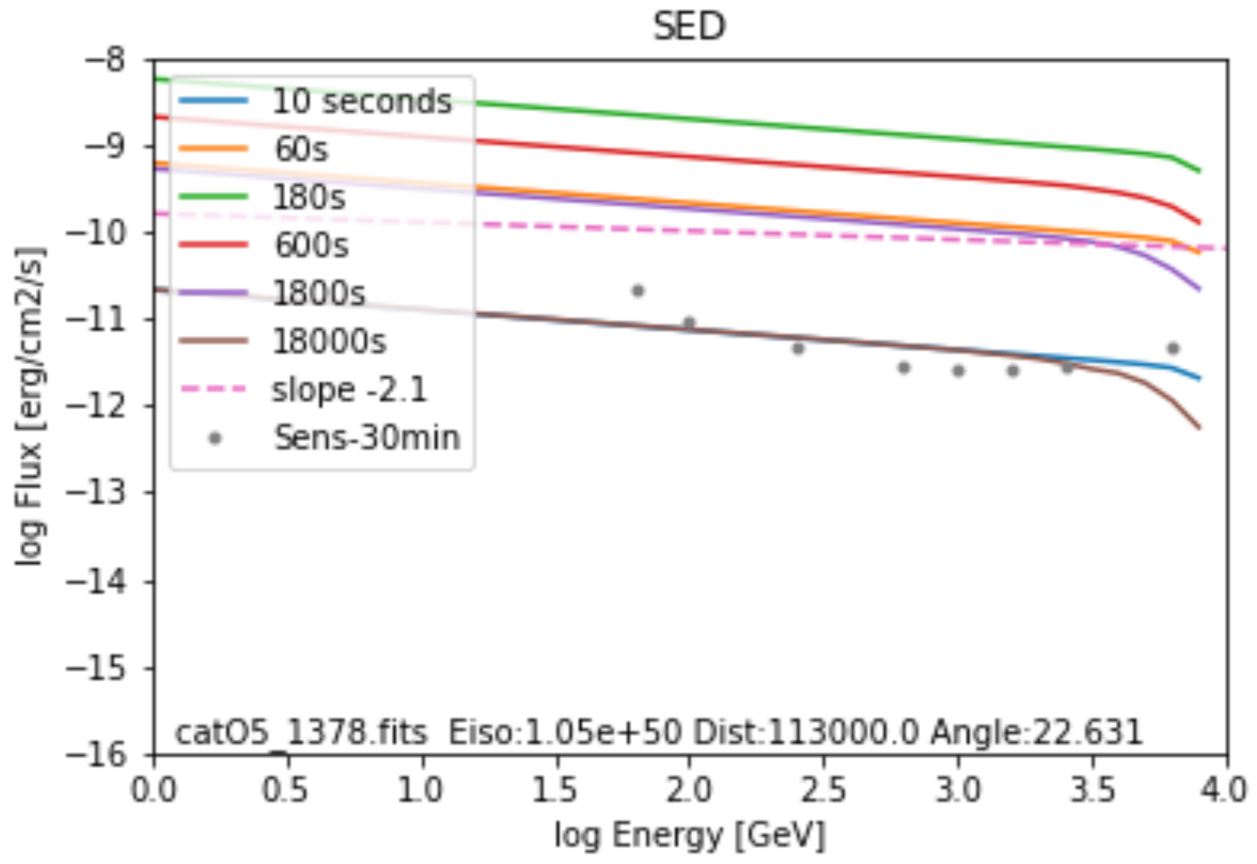


- Table with 2307 events with 1200 observing combinations: 2,768,400 total records
  - Zenith angles: 20-40-60 deg
  - IRF: α and Ω (E>30 GeV)
  - N/S sites
  - Start time/delay To: 10 s -> 7 days
- Detection checked with
  - Integration time (exposure): 10 s —> 1 hr
- Study on the correlation between physical/ phenomenological parameters and detection ongoing

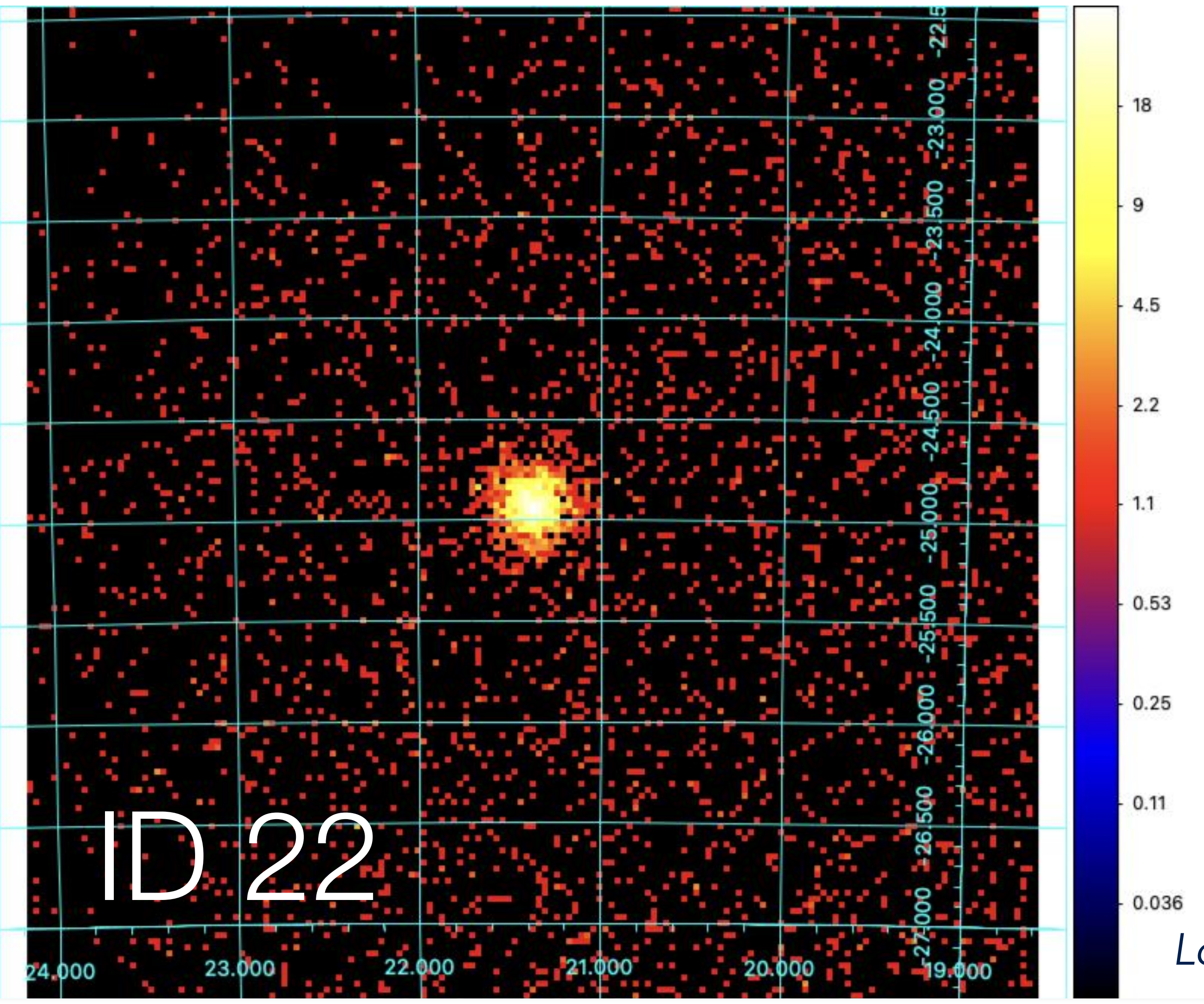


event_id	EISO [erg]	Distance [kpc]	Jet angle [deg]	time_utc	T_start-T0 [s]	Exposure (s)	R
1378	1.050E+50	113000.0	22.631	2012-04-13 23:52:00.045	63	16	34





Simulated GW CTA events

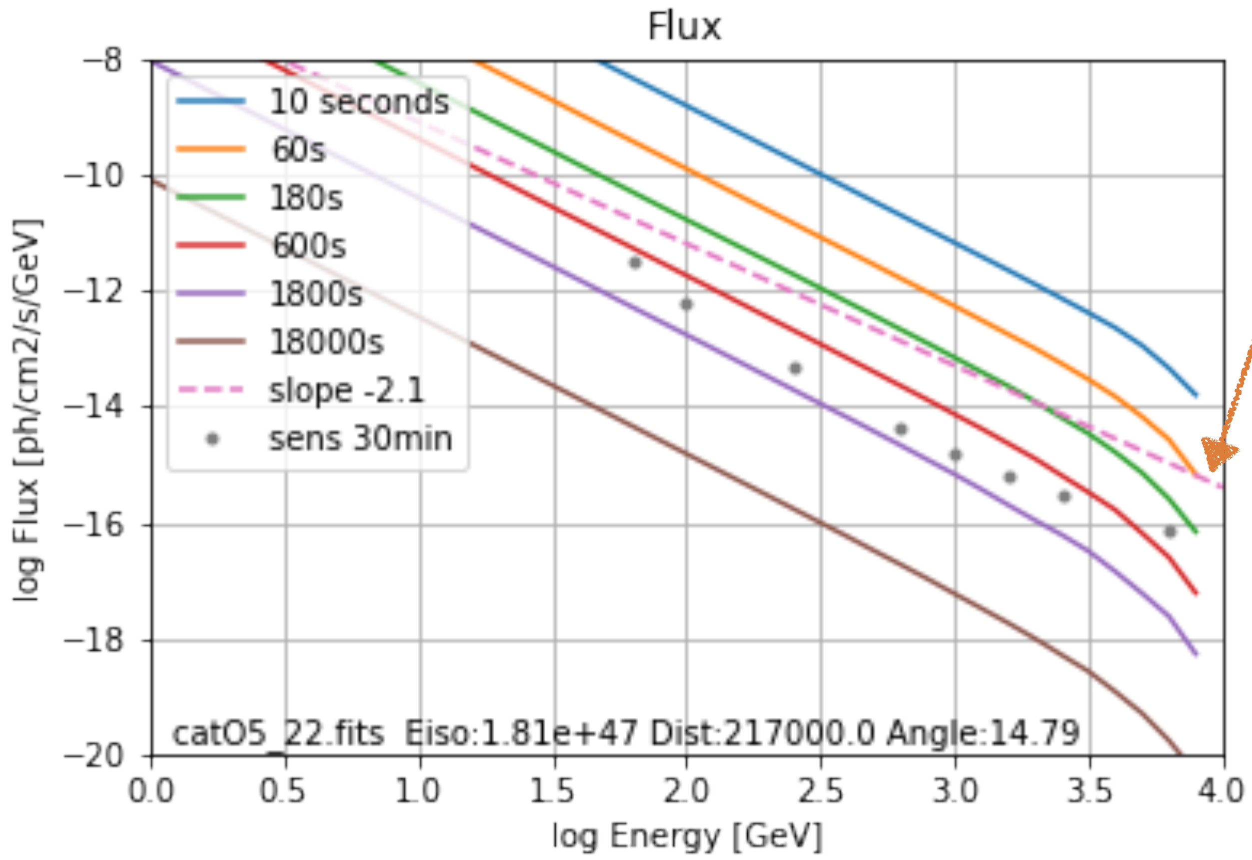


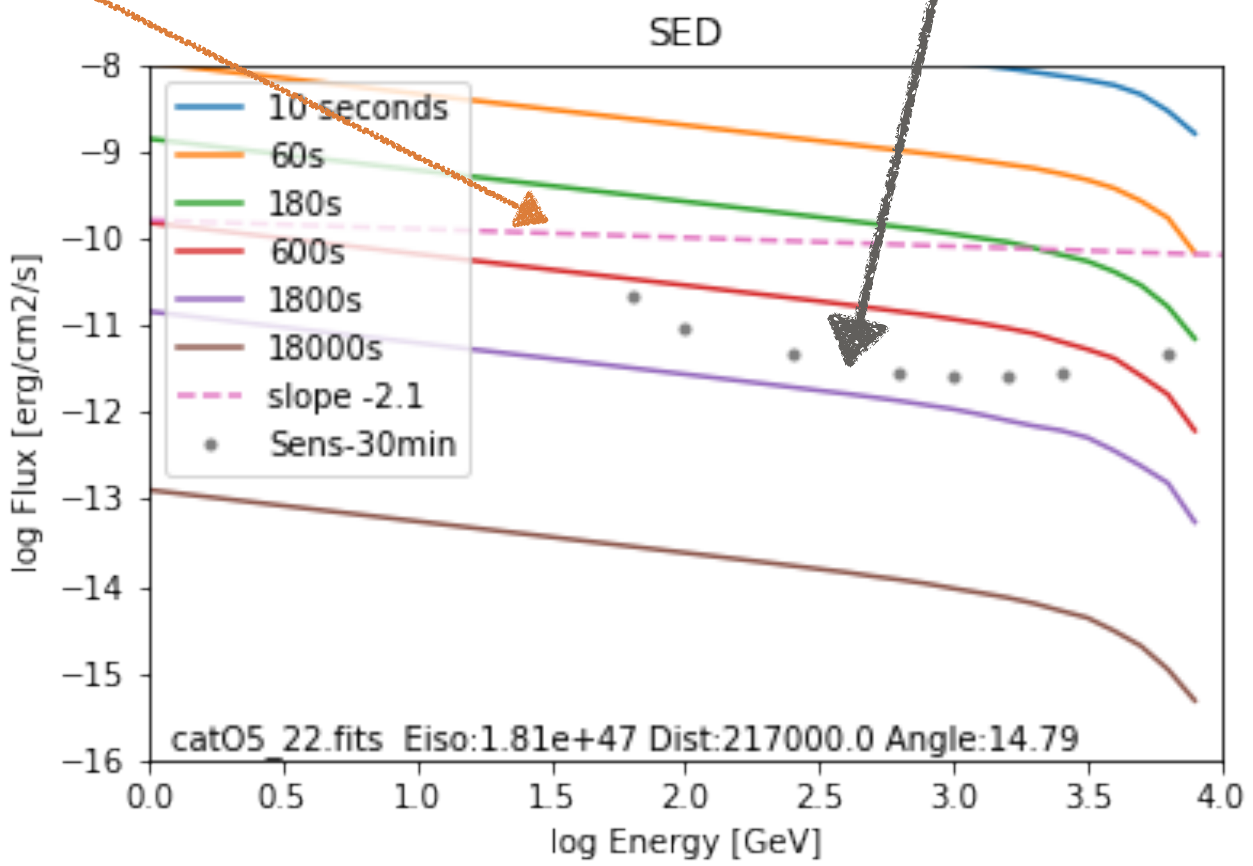
Log scale

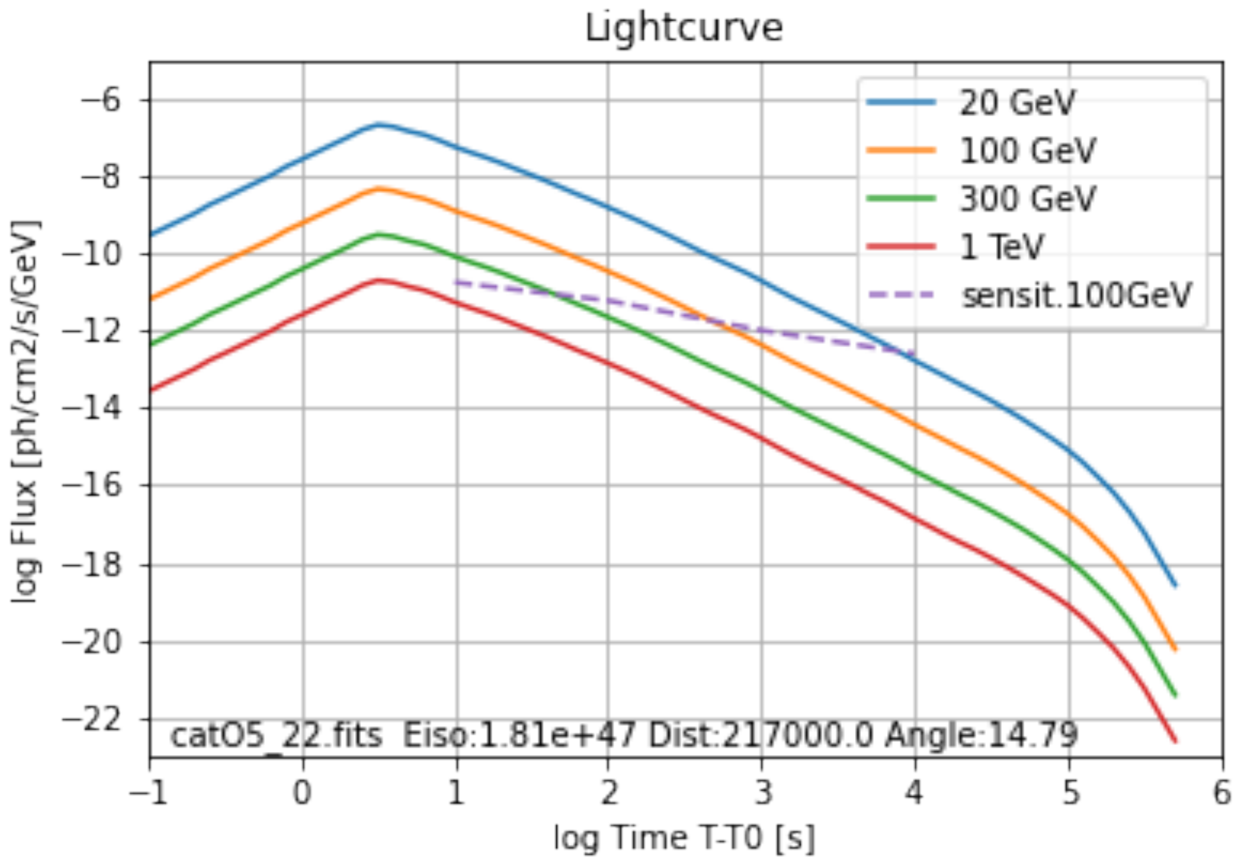
event_id	EISO [erg]	Distance [kpc]	Jet angle [deg]	time_utc	T_start-T0 [s]	Exposure (s)	RA
22	1.810E+47	217000.0	14.79	2012-08-02 18:36:02.537	63	20	20.(

Reference line slope 2.1
(Corresponds ~10 sec-1 min observations)

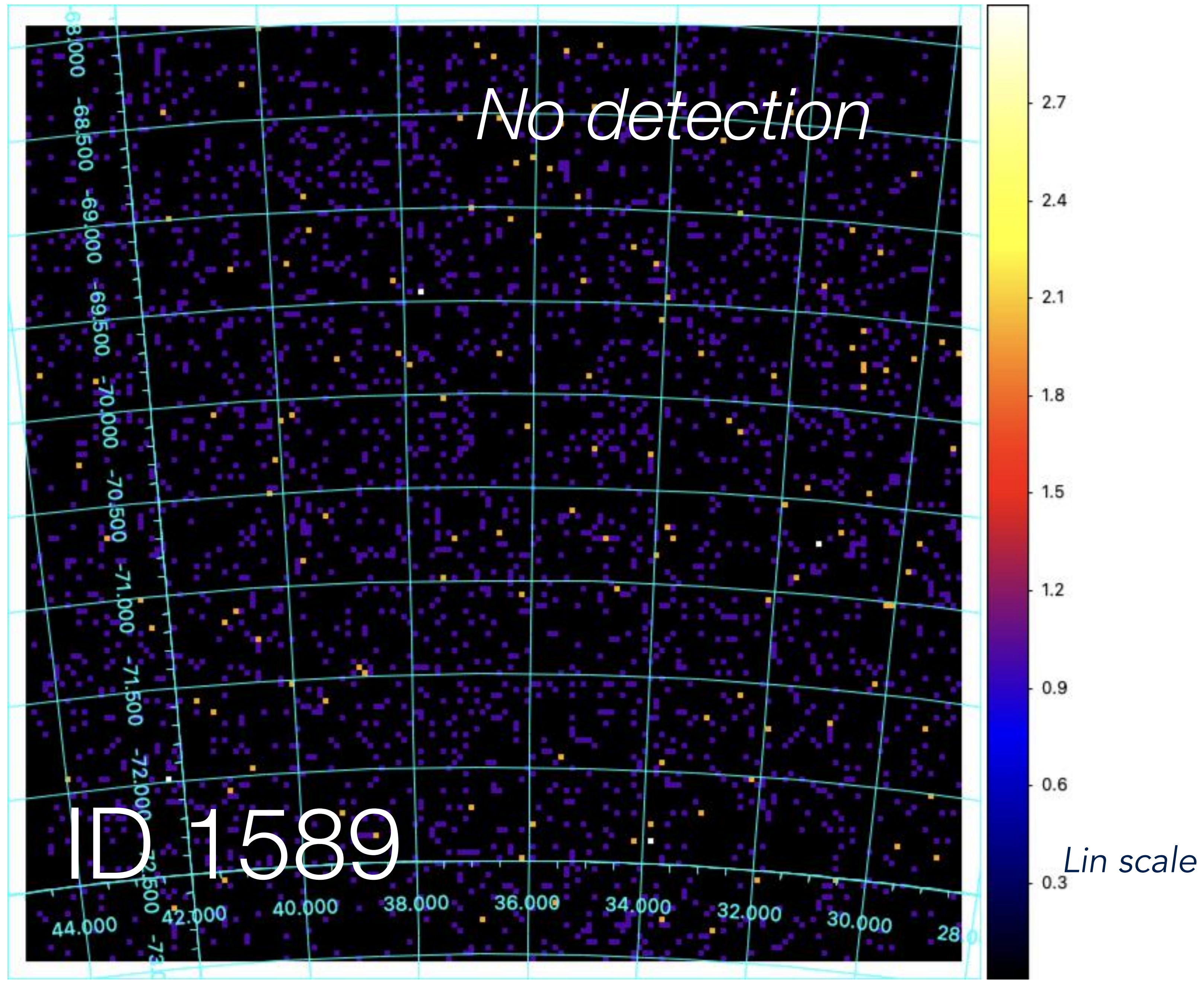
CTA-S sensitivity
30 minutes integration time

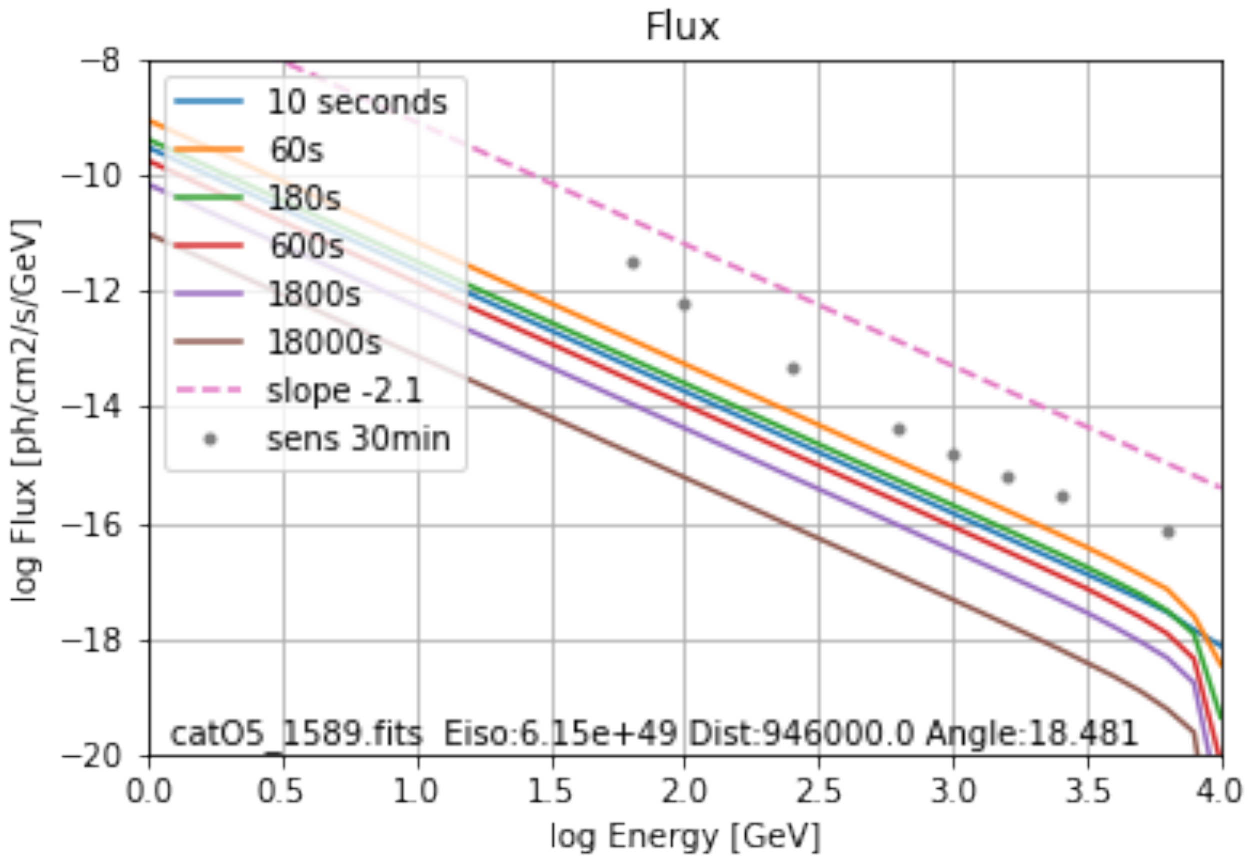


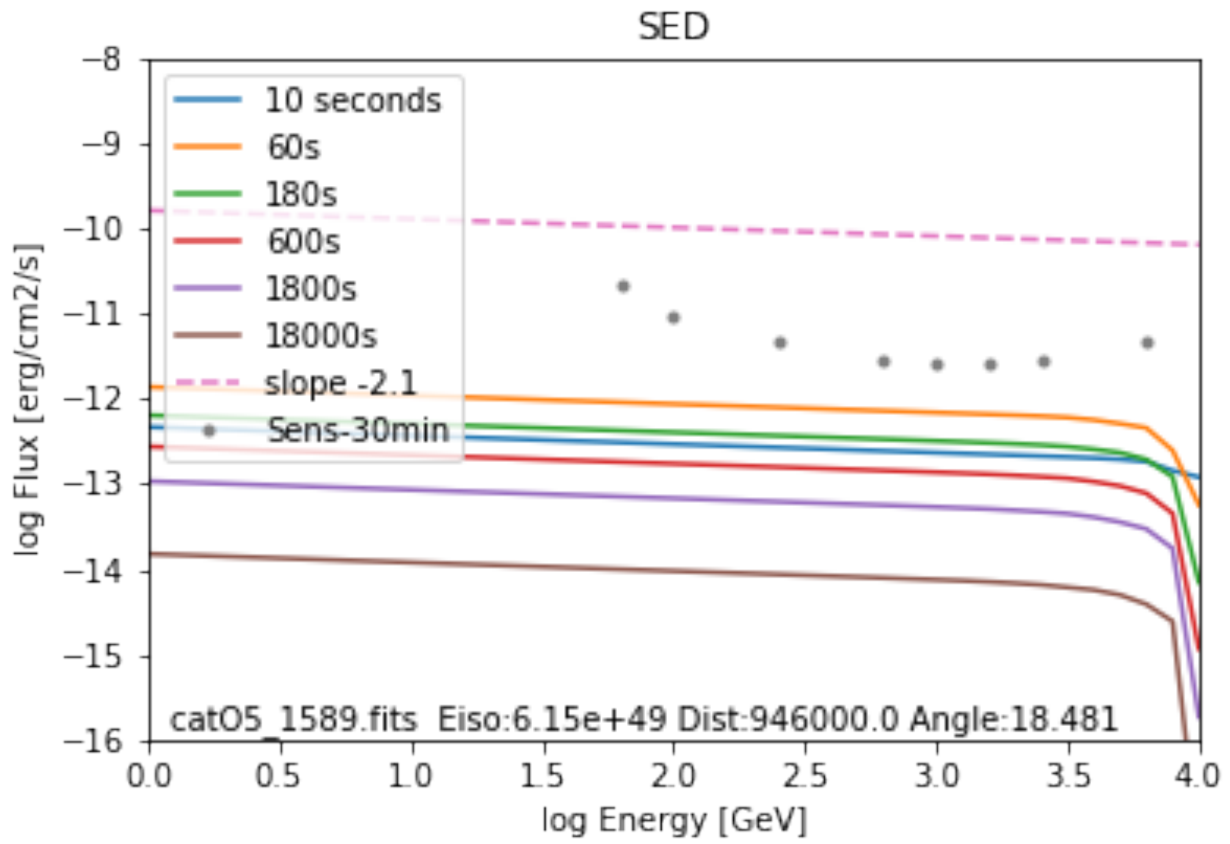


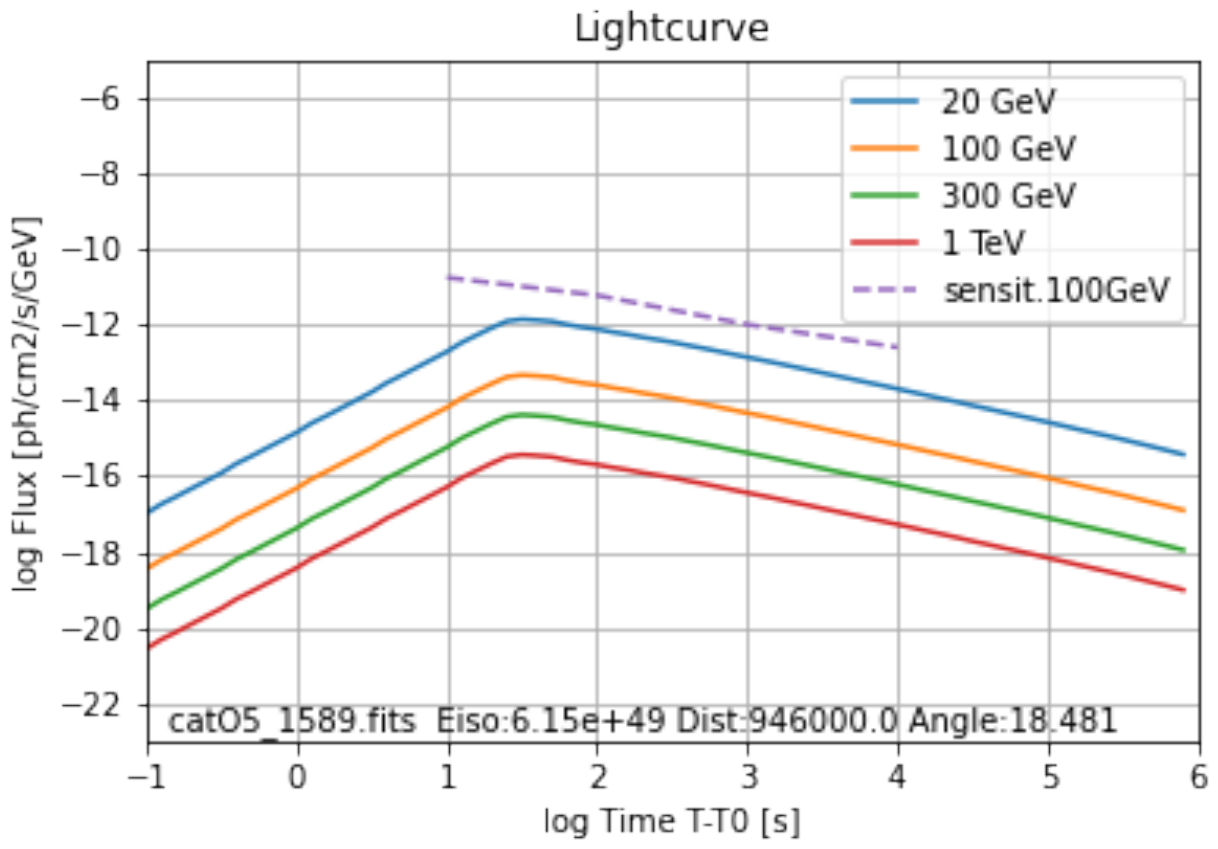


Simulated GW CTA events









E_{ISO}: 6.15e+49
Dist: 946 Mpc
Jet viewing Angle: 18.5 deg

First preliminary results - 1. detectability

- “Real” joint rates need to consider the BNS merger rates
- Not taking into account the observability conditions

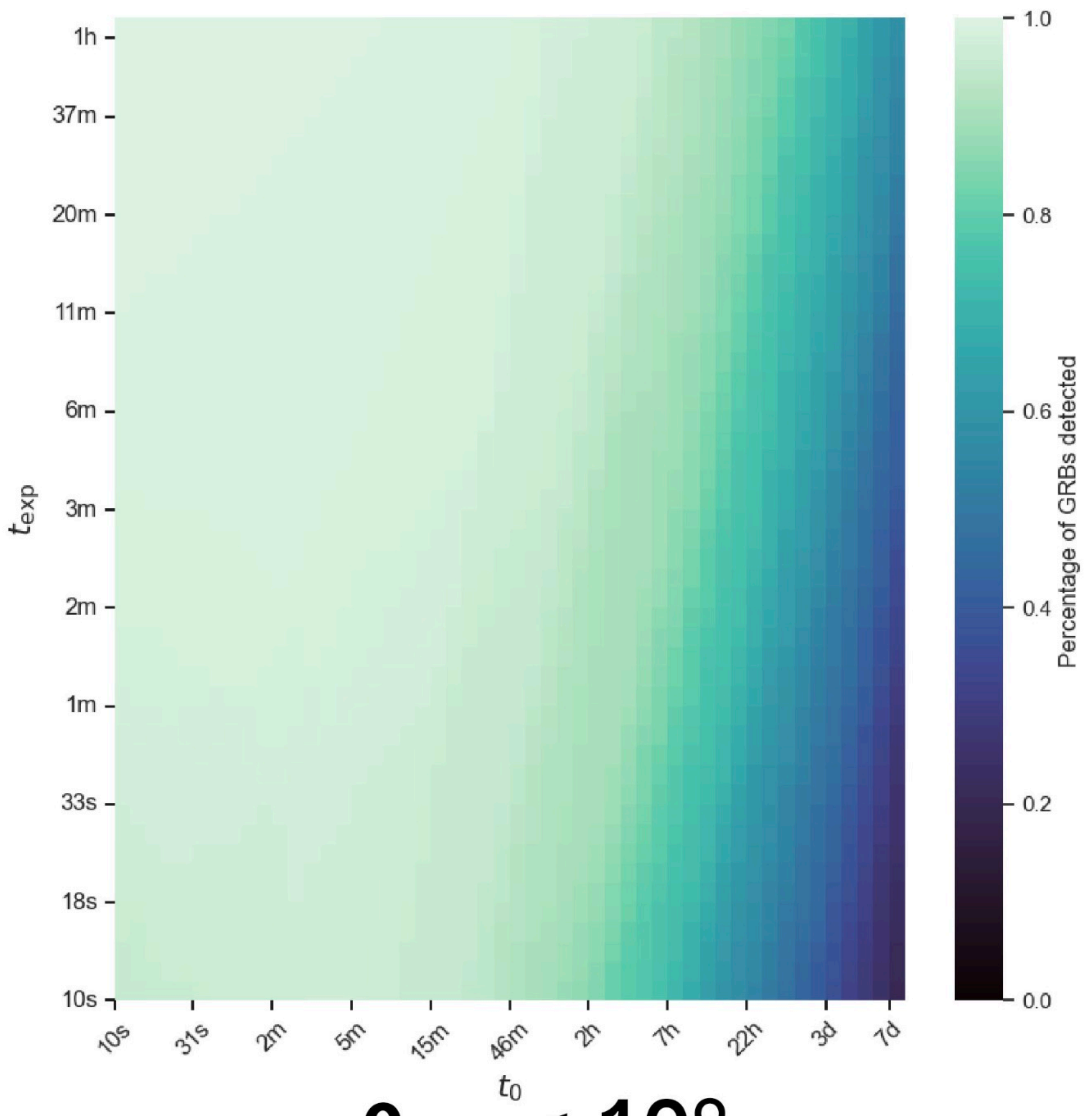
t_0 ~30 sec, ~ 99% detections with $T_{exp} \leq$ 1 min.

t_0 ~10 min ~ 98% detections with T_{exp} ~ 1 min.

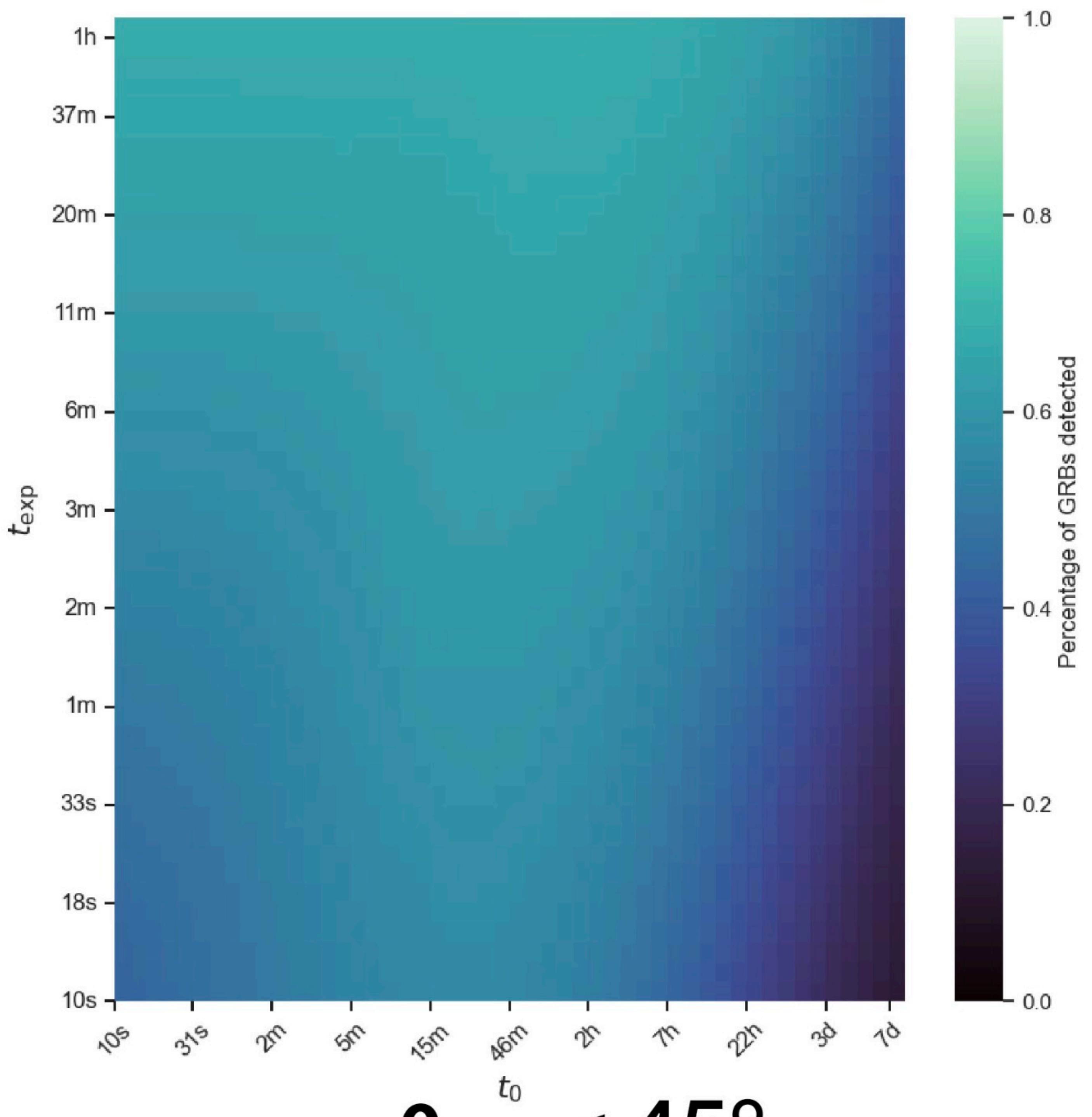
t_0 ~ 30 sec, ~ 60% detections with $T_{exp} \leq$ 1 min.

t_0 ~ 10 min ~ 35% detections with T_{exp} ~ 1 min.

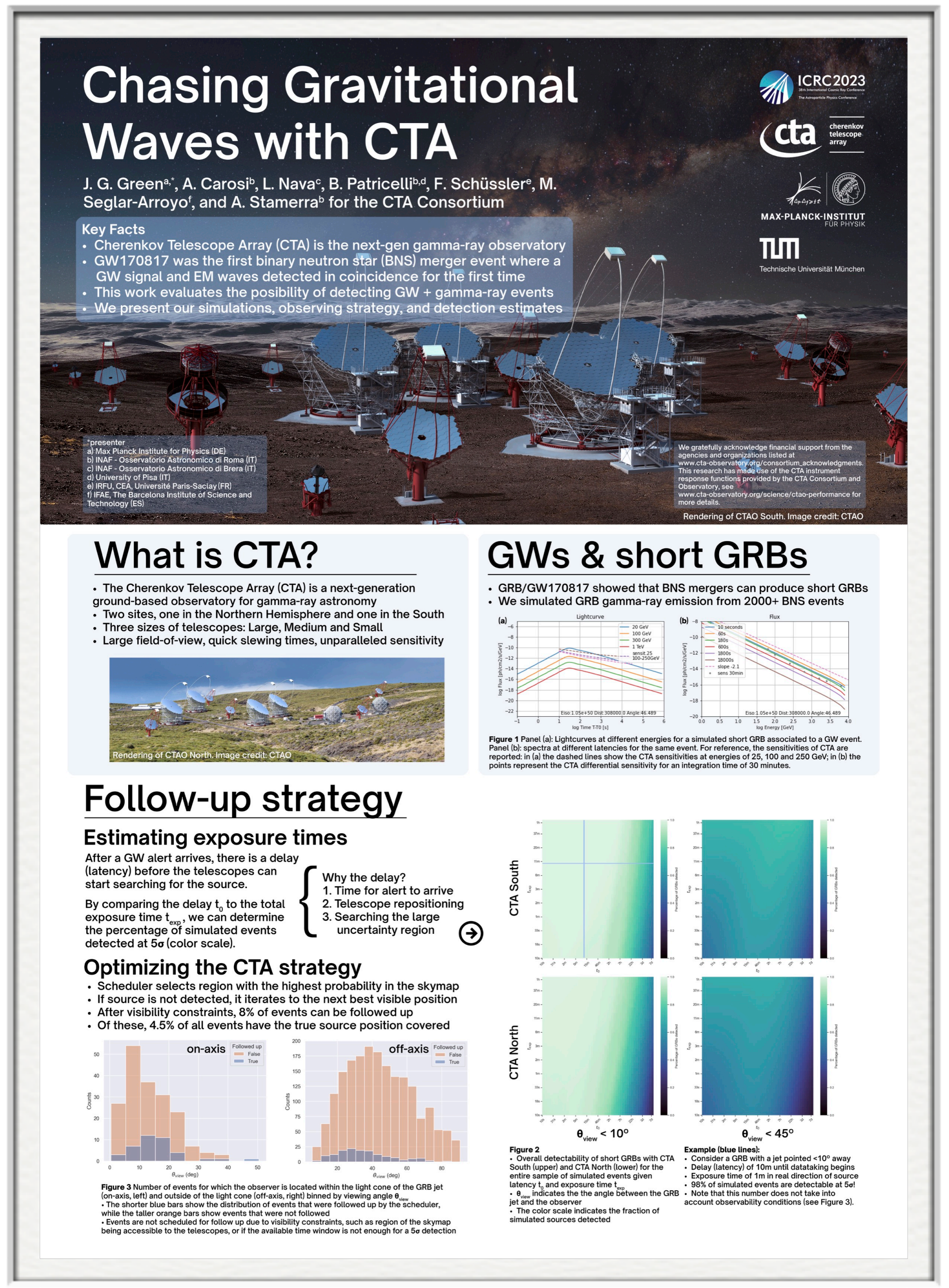
CTA North



θ_{view} < 10°



θ_{view} < 45°



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First preliminary results - 2. Realistic follow-ups and detections

- Followed up GW-GRB events: **8% of the total population**
  - **4.5%** covering the **true location of the source**
- on-axis events: 18% followed up; 10% covered the true location
- off-axis events: 7% followed up; 4% covered the true location

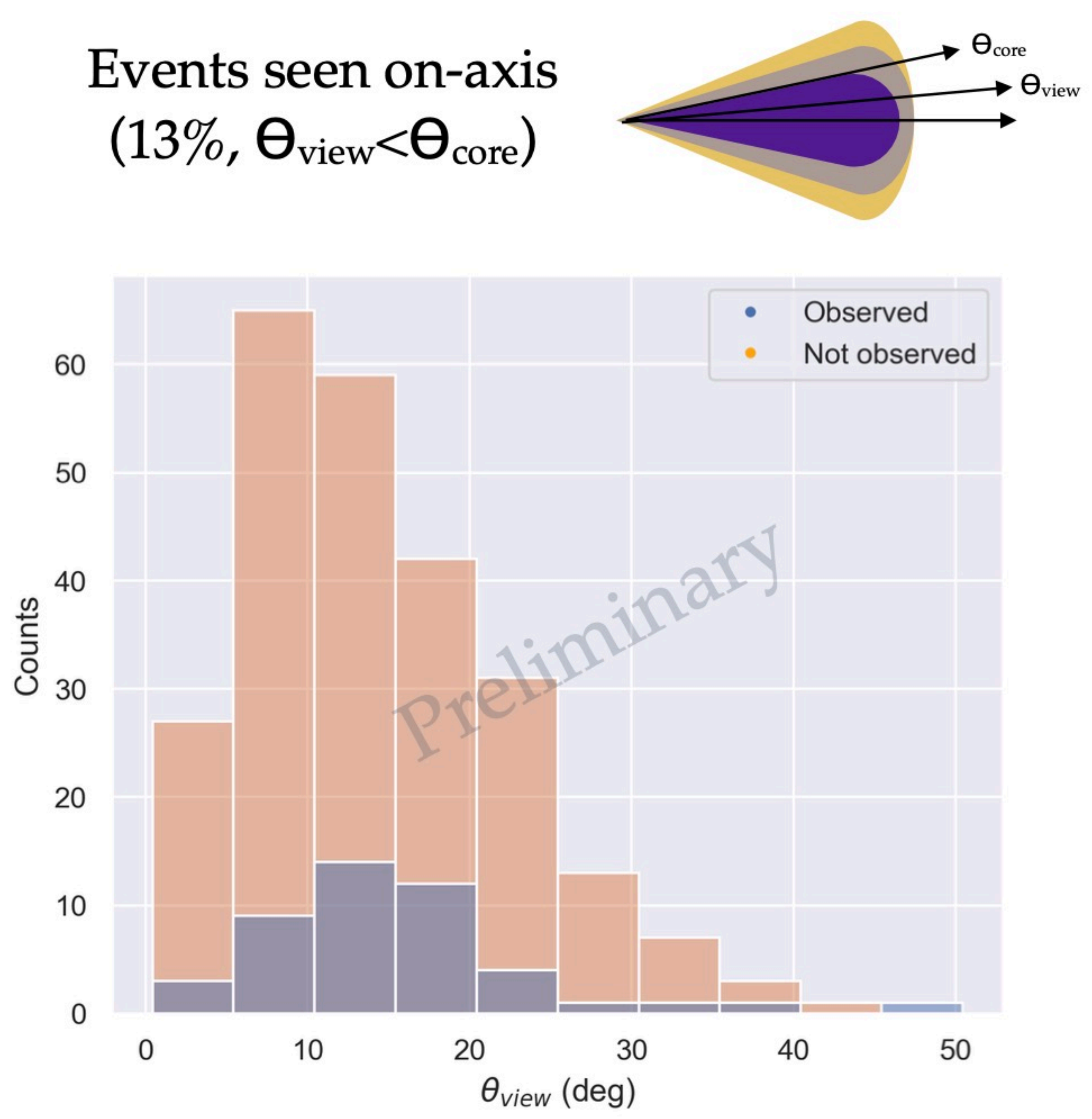
Realistic observations conditions included (visibility, duty cycle telescopes, delays, etc) with an optimised scheduling of the tiling

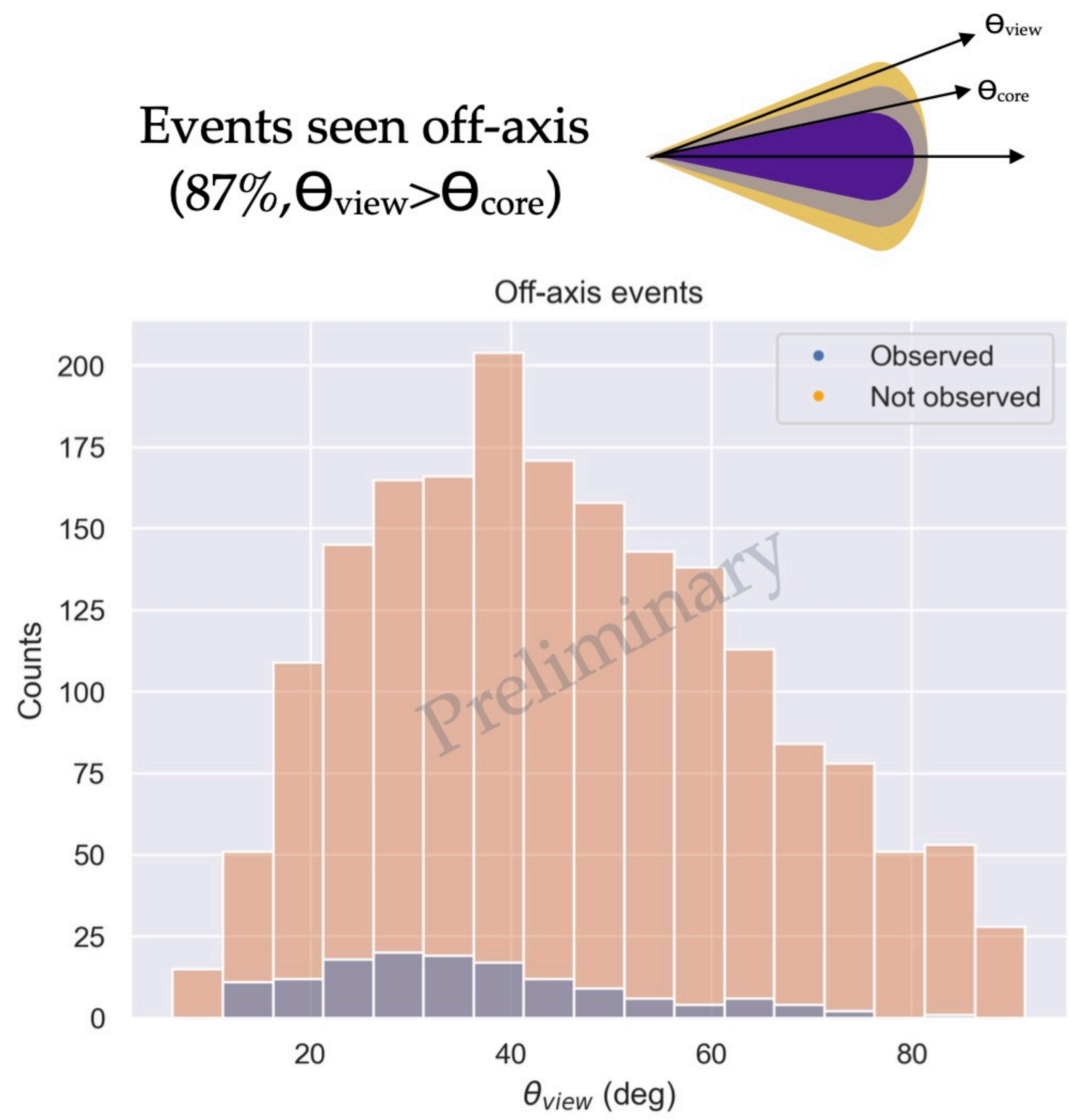
Simulation of BNS mergers and GW signal in local universe

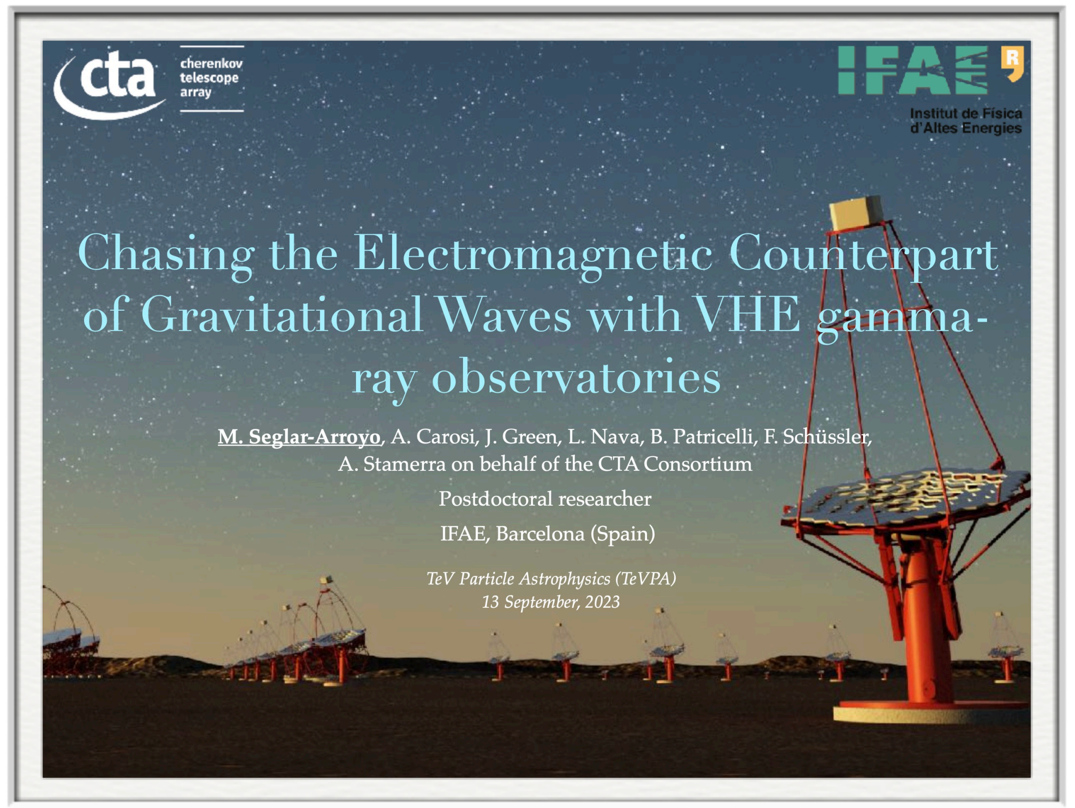
Synthetic GW-GRBs
Phenomenological model of VHE emission of short-GRB

Simulation of CTA response (set of IRFs)
gammapy, ctools

Observation optimisation and scheduler
CTA observing strategy







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The END