# Exploring Multi-messenger Transients with MAGIC

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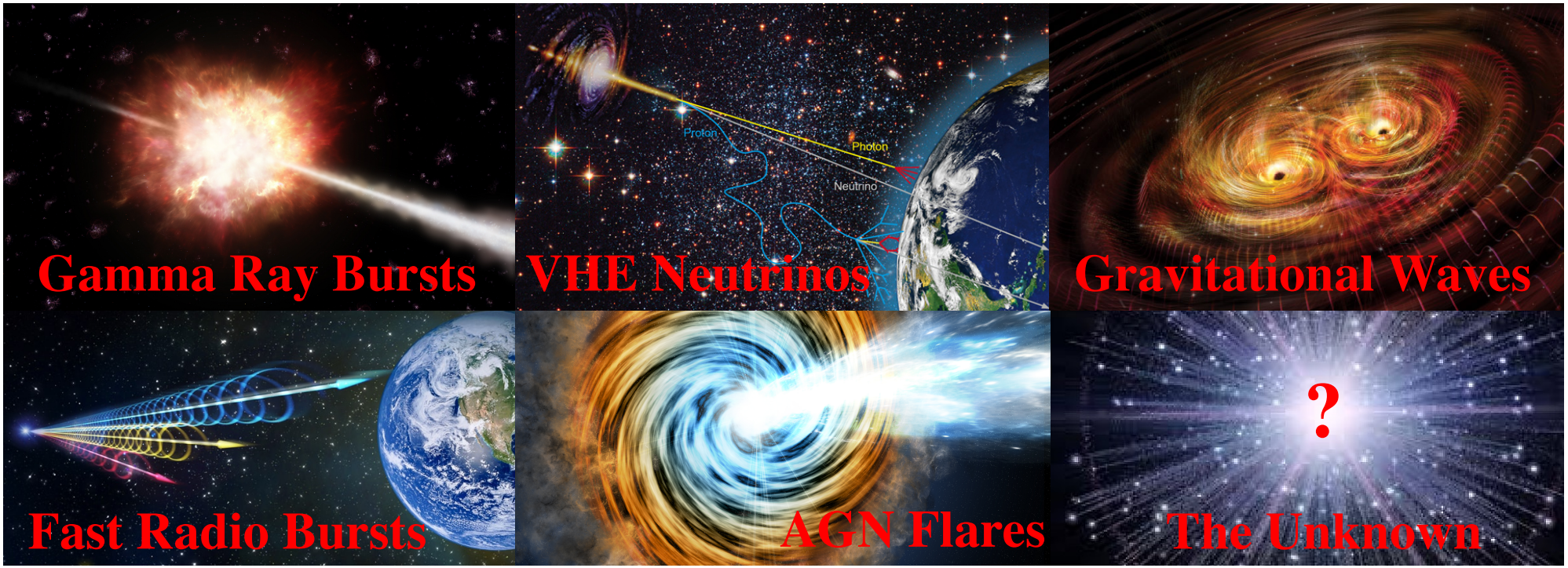
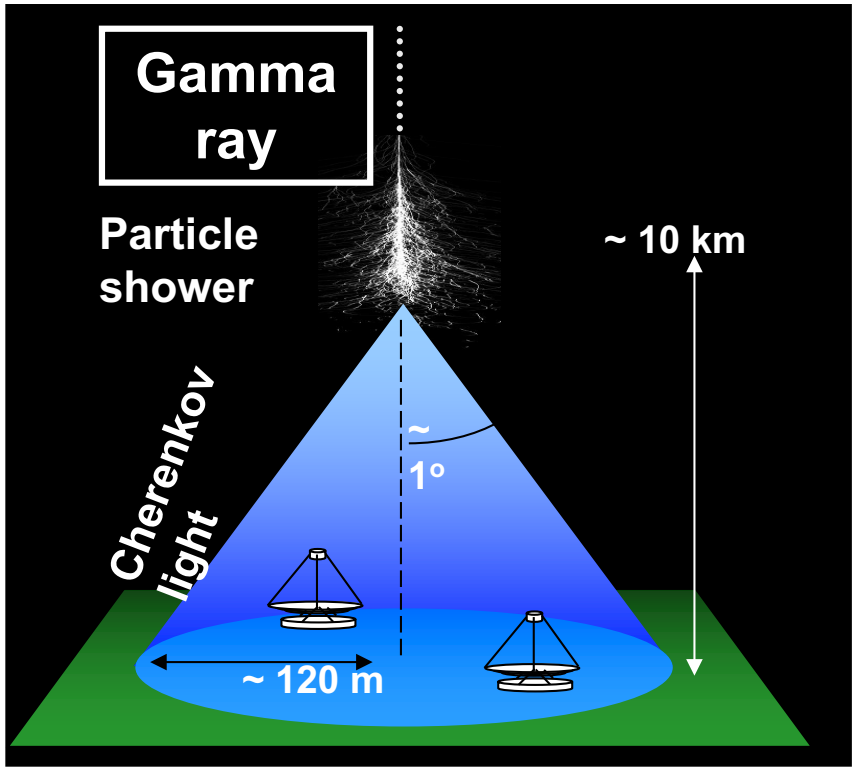
for the Transients
Physics Working Group,
MAGIC Collaboration

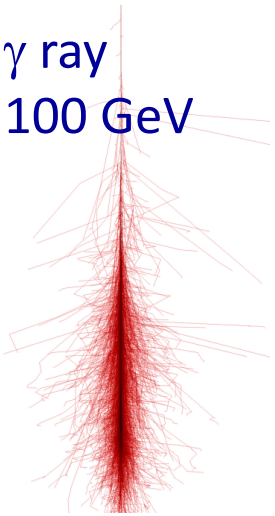


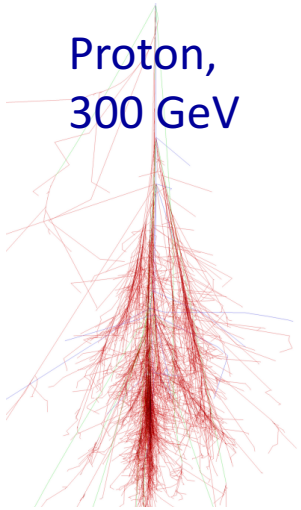
## outline

1. introduction
2. high-energy neutrinos
   - IC-170922A / TXS 0506+056, interpretation
3. gamma-ray bursts
   - short GRB 160821B
4. gravitational waves

# VHE gamma-ray detection by Cherenkov telescopes




**γ showers**

- Narrow images
- Aligned towards source direction

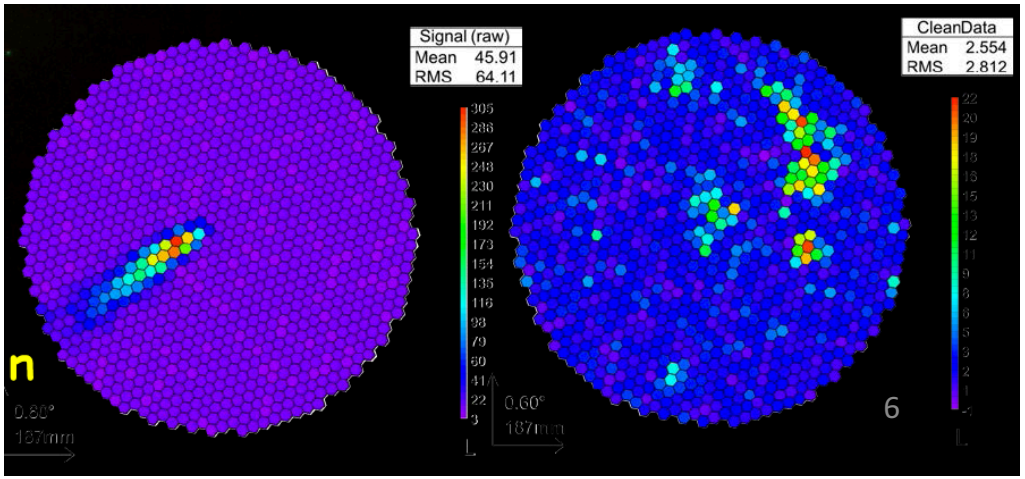
**hadronic showers**

- Spread images
- Isotropic arrival direction

- **Cherenkov light** is emitted by relativistic particles in the shower

- **number of hadron/gamma more than 1000 times**
  **-> need to reject hadron events**

from M. Hayashida



# Transient astronomy with Cherenkov telescopes

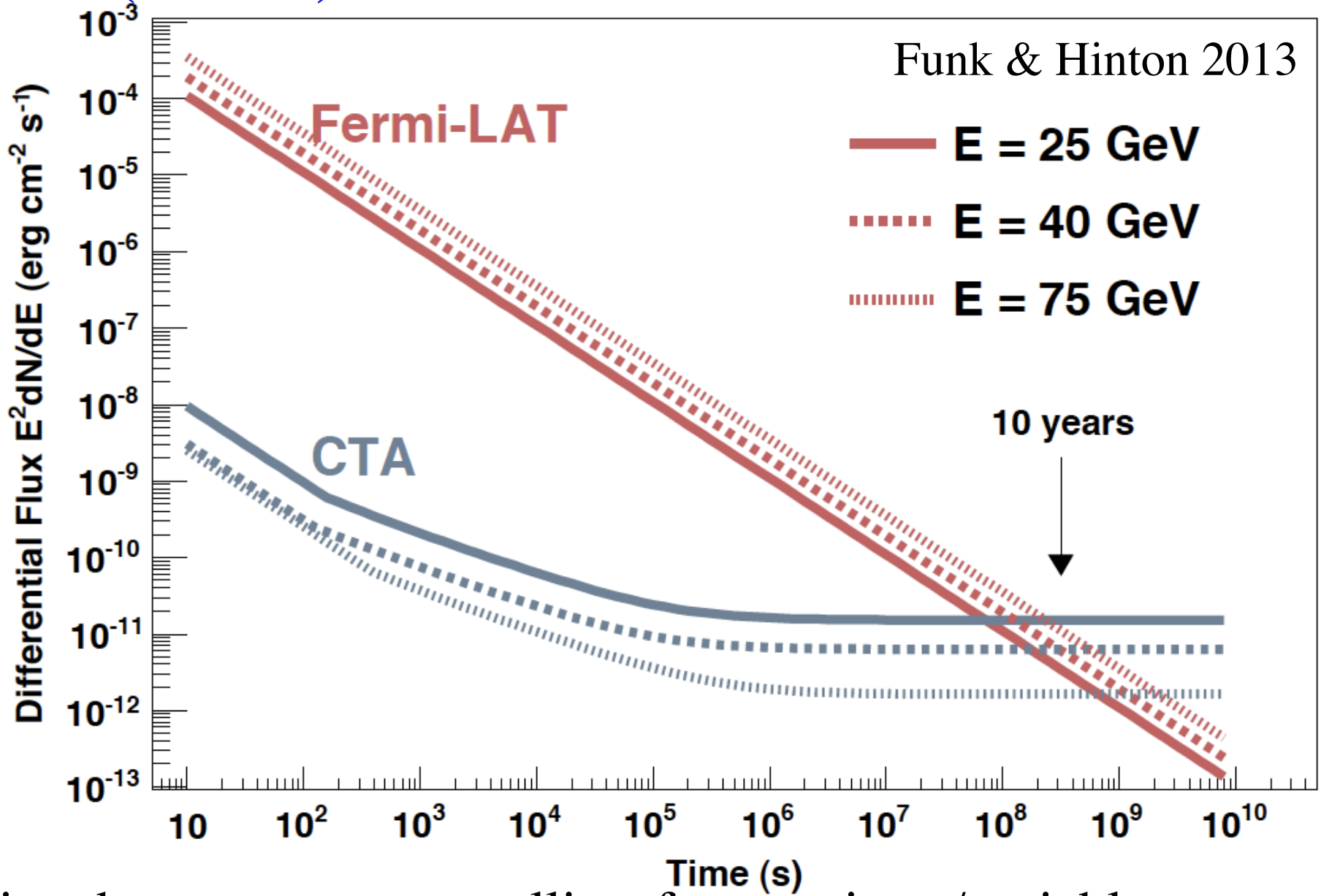
Pros:

- Large effective area (~few $10^4$-$10^5$ $m^2$)
- Relatively large field of view (>~3.5-5 deg)
- Relatively fast repointing (>30 sec)

Cons:

- Limited duty cycle (~15%)
- Limited zenith angle range (~<70 deg)
- EBL attenuation for high-z extragalactic sources

# CTA (IACTs) vs Fermi

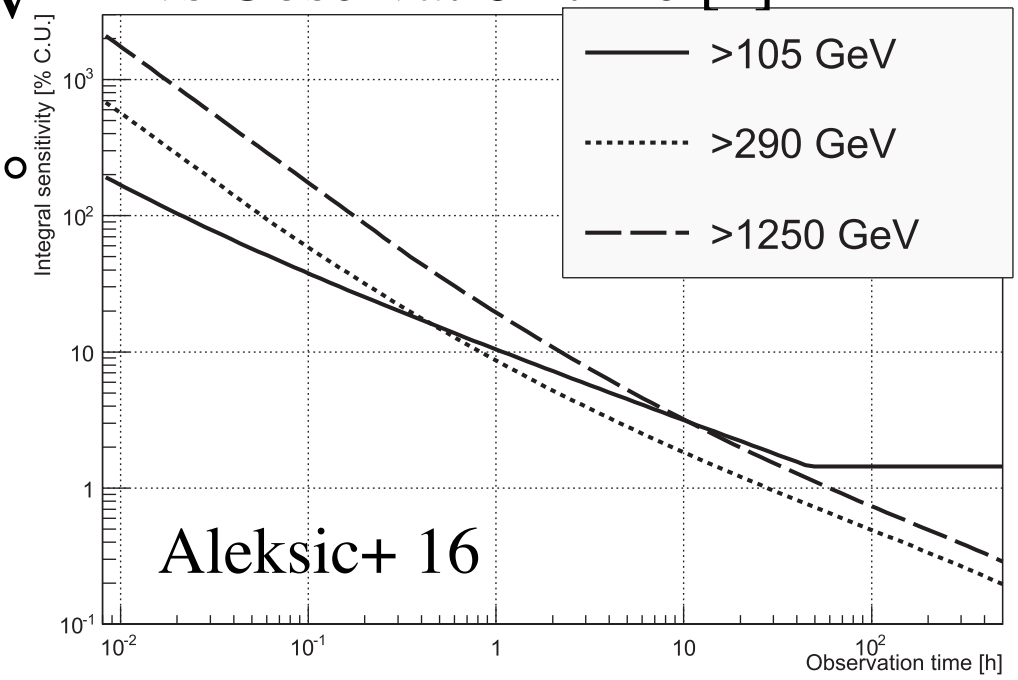



big advantange over satellites for transients/variables:
effec. area ~$10^4$ x LAT@30GeV

# MAGIC telescopes

- 2 × 17m IACTs
  La Palma, Canary Is.
  altitude 2200m
- Field of view: ~3.5°
- Angular resolution: ~0.1°
- Sensitivity:
  ~ 10% Crab in 1 h >100 GeV
- Threshold energy:
  ~50 GeV at zenith angle <20°
- Repointing speed:
  ~30 s for 180°


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



# VHE Neutrinos

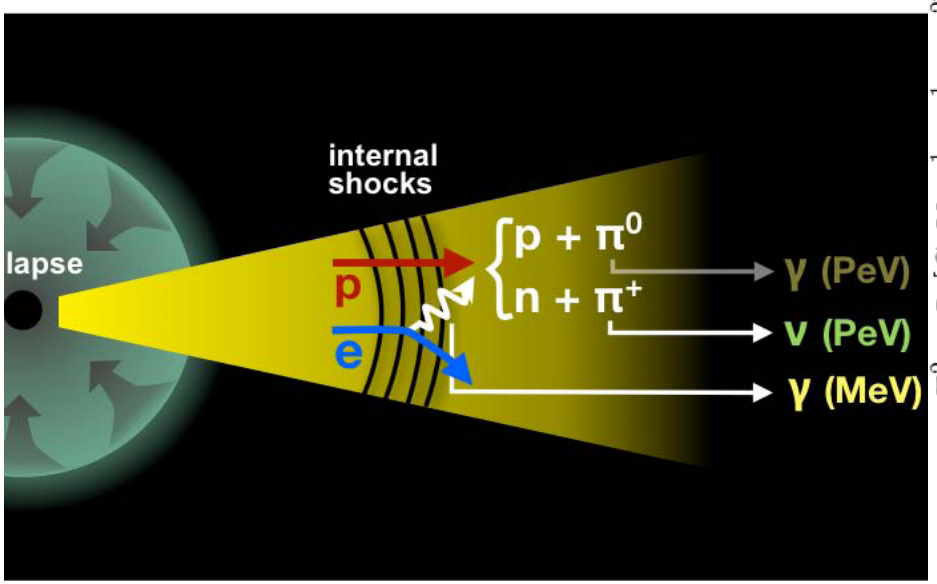
New window onto the Universe (UHECR origin), turned new mystery?

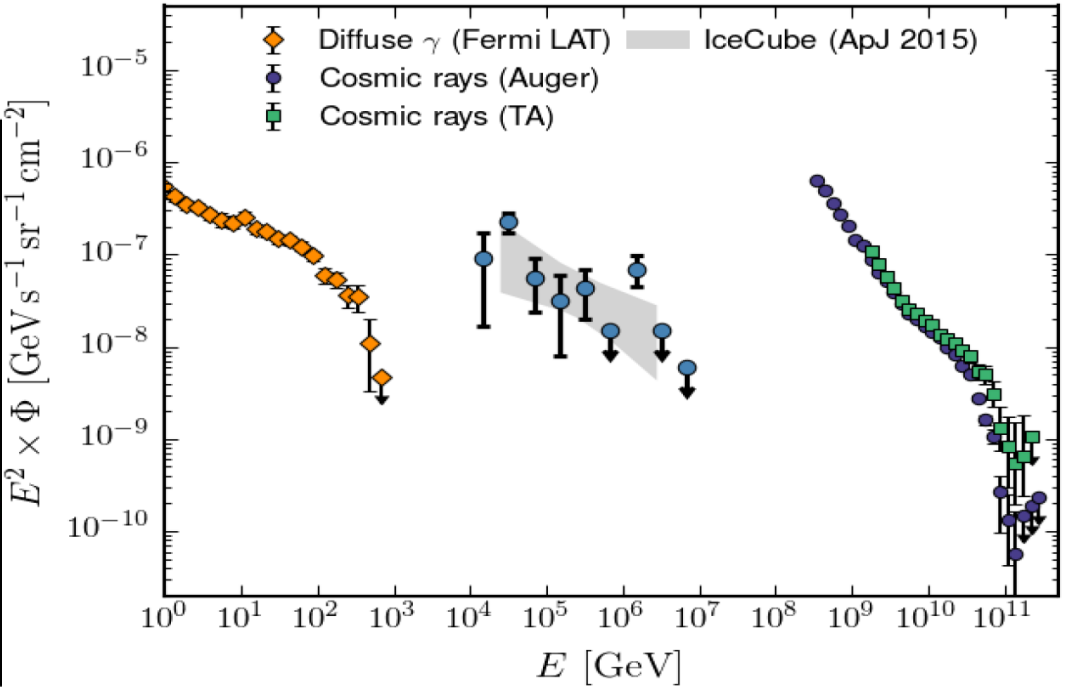
- clear indicators of VHE/UHE cosmic ray production
- being detected by IceCube, but no correlation with promising sources (bright GRBs, bright blazars) until recently

**VHE γ follow-up**

identify via co-produced γ rays (either leptonic or hadronic):

- neutrino sources (if γ-rays escape + propagate)
- VHE/UHECR sources (if γ-rays + CRs escape+propagate)

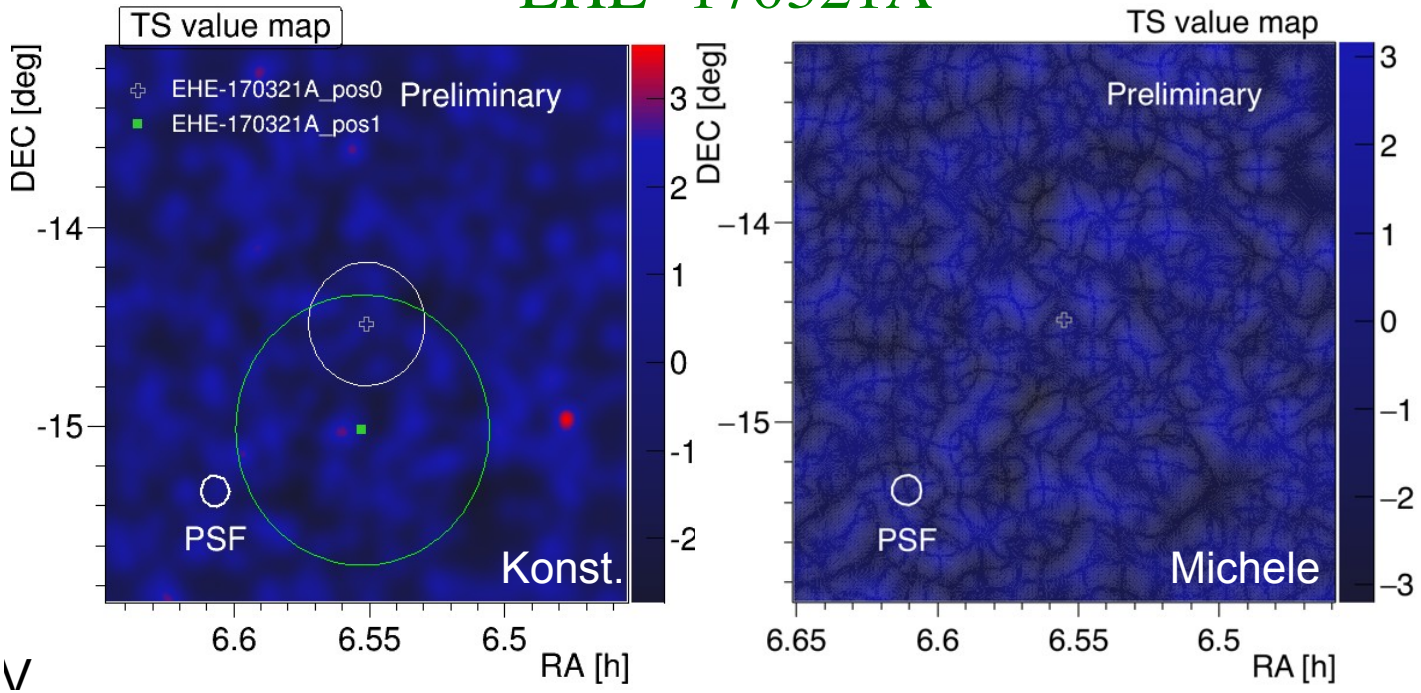


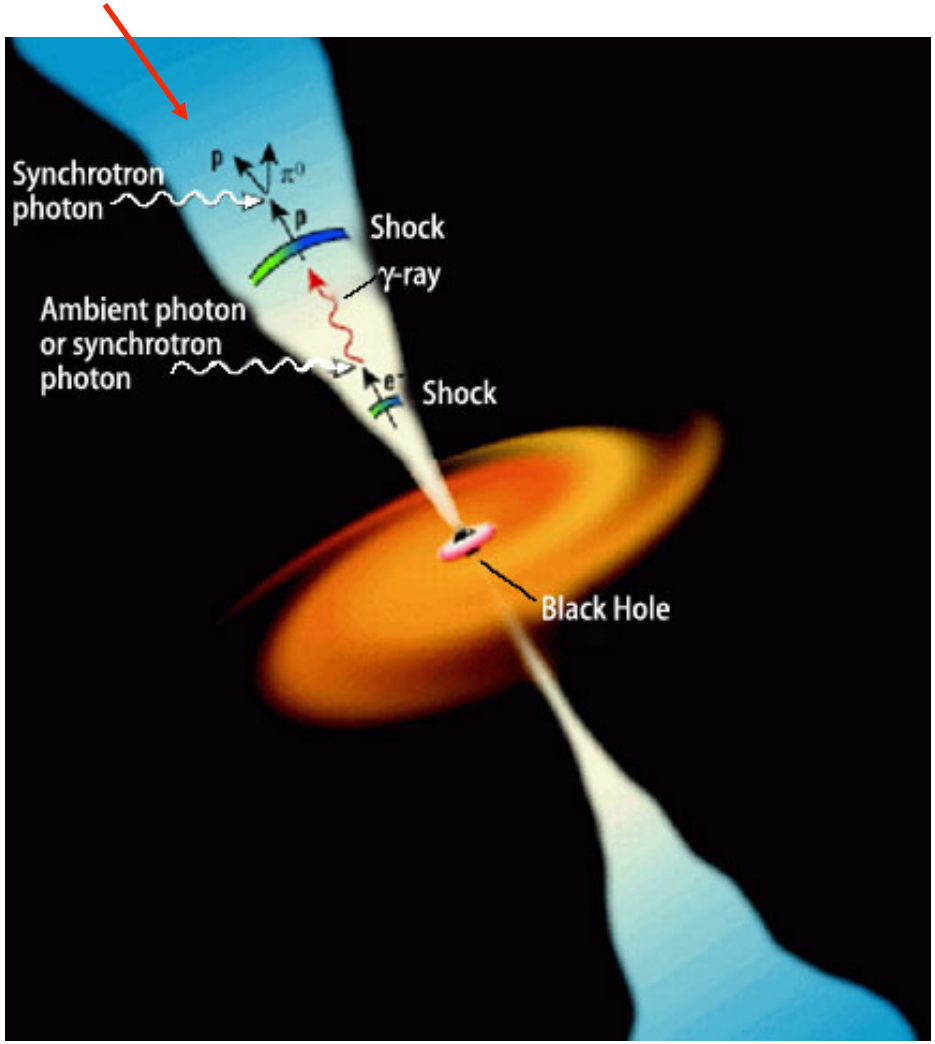
# MAGIC high-energy neutrino follow-up

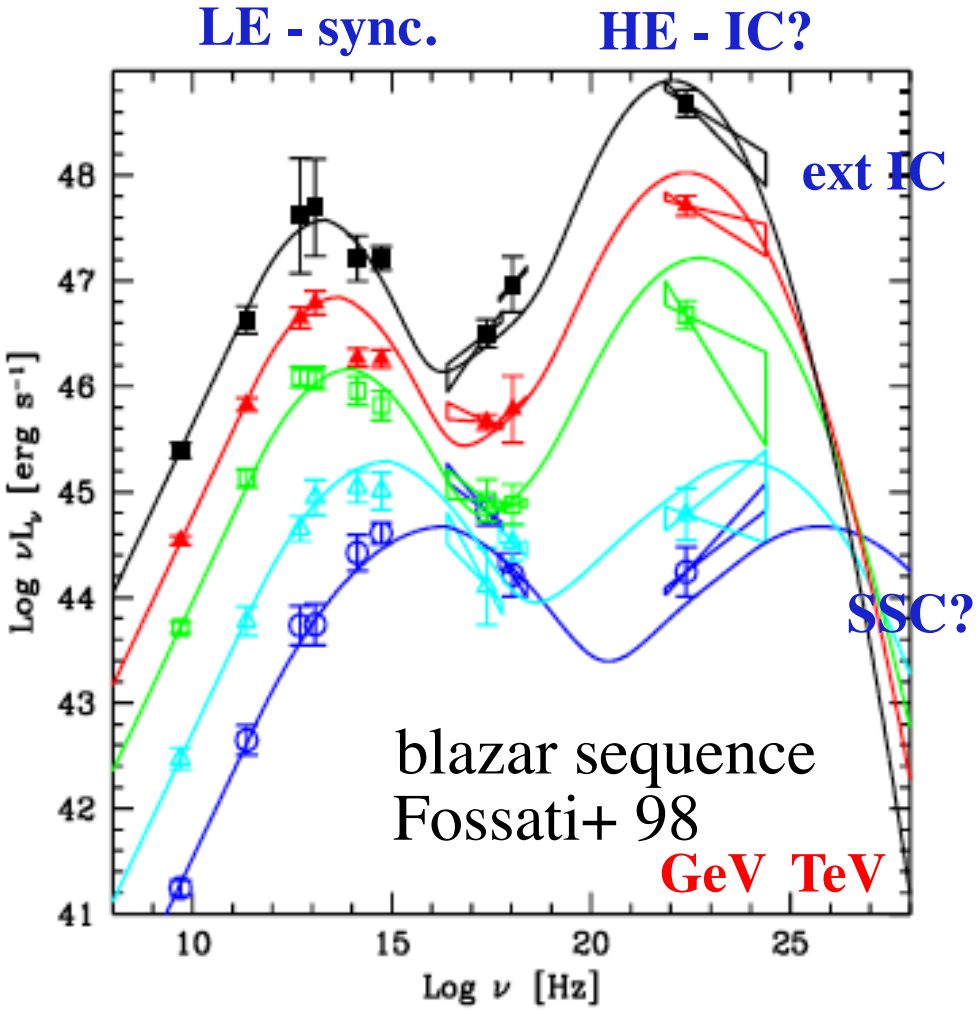
- IC-160427A HESE
- IC-160731A HESE/EHE
- IC-170321A EHE
- IC-170922A EHE -> TXS 0506+056 / 3FGL J0509.4+0541
- IC-171106A EHE (PeV)

EHE -170321A



**blazars** relativistic jet viewed near-axis
electron sync.+IC



# hadronic (proton-induced) emission in blazars

$e^- + B \rightarrow e^- + \gamma_{LE}$

$p + \gamma_{LE} \rightarrow N + \pi^0, \pi^{+-}$ photo-meson

$\pi^0 \rightarrow 2\gamma$ $\pi^{+-} \rightarrow \mu^{+-} + \nu \rightarrow e^{+-} + 3\nu$

$\mu^{+-} + B \rightarrow \mu^{+-} + \gamma$ muon synchrotron

$p + \gamma_{LE} \rightarrow p + e^+e^-$ photo-pair (Bethe-Heitler)

$\gamma + \gamma_{LE} \rightarrow e^+e^-$

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

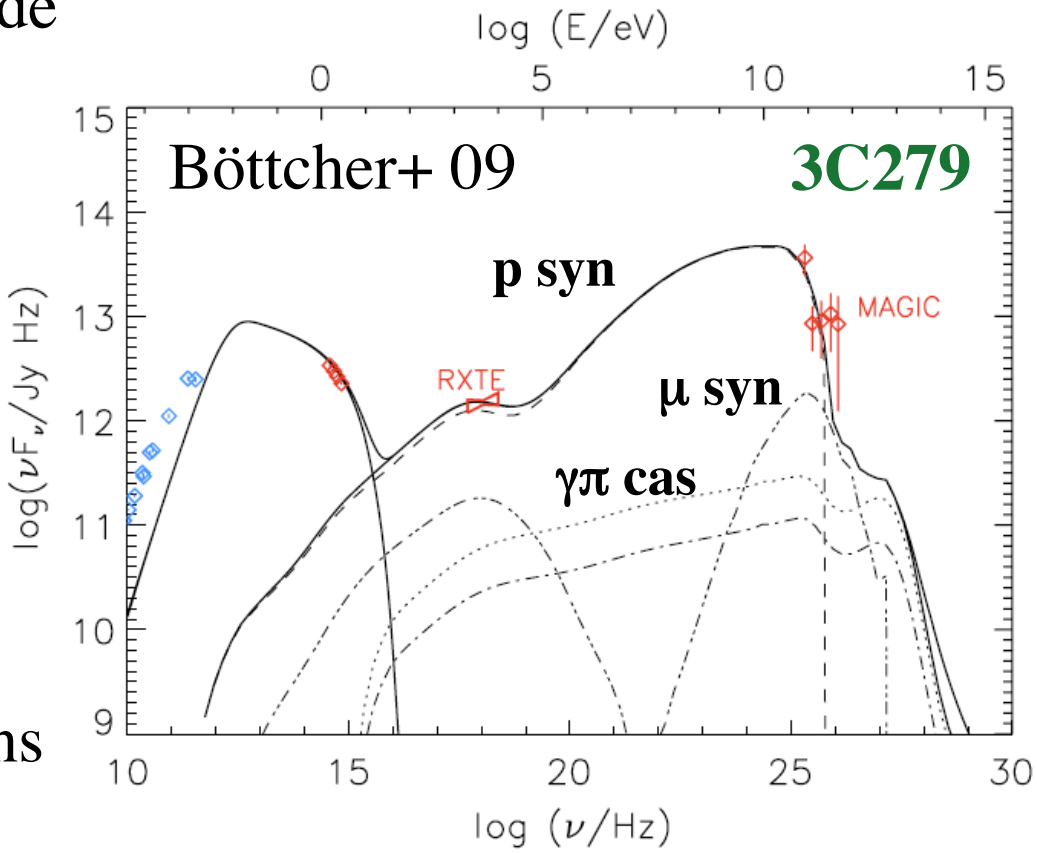
electron-positron sync. cascade

$p + B \rightarrow p + \gamma$ proton synchrotron

Mannheim 93
Aharonian 00
Mücke+ 02,03…

Potential issues as dominant component

1. Low radiative efficiency generally high $L_p$ required
2. Poor fit to broadband spectra?
3. $t_{p\gamma}$, $t_{pB}$ too long to explain <day timescale X-TeV correlations in HBLs



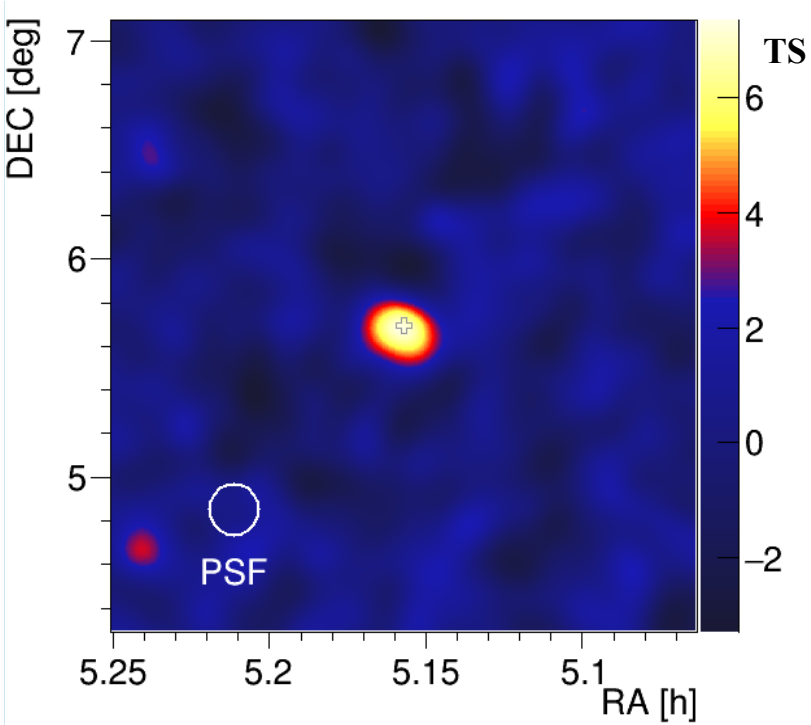
# blazar TXS 0506+056

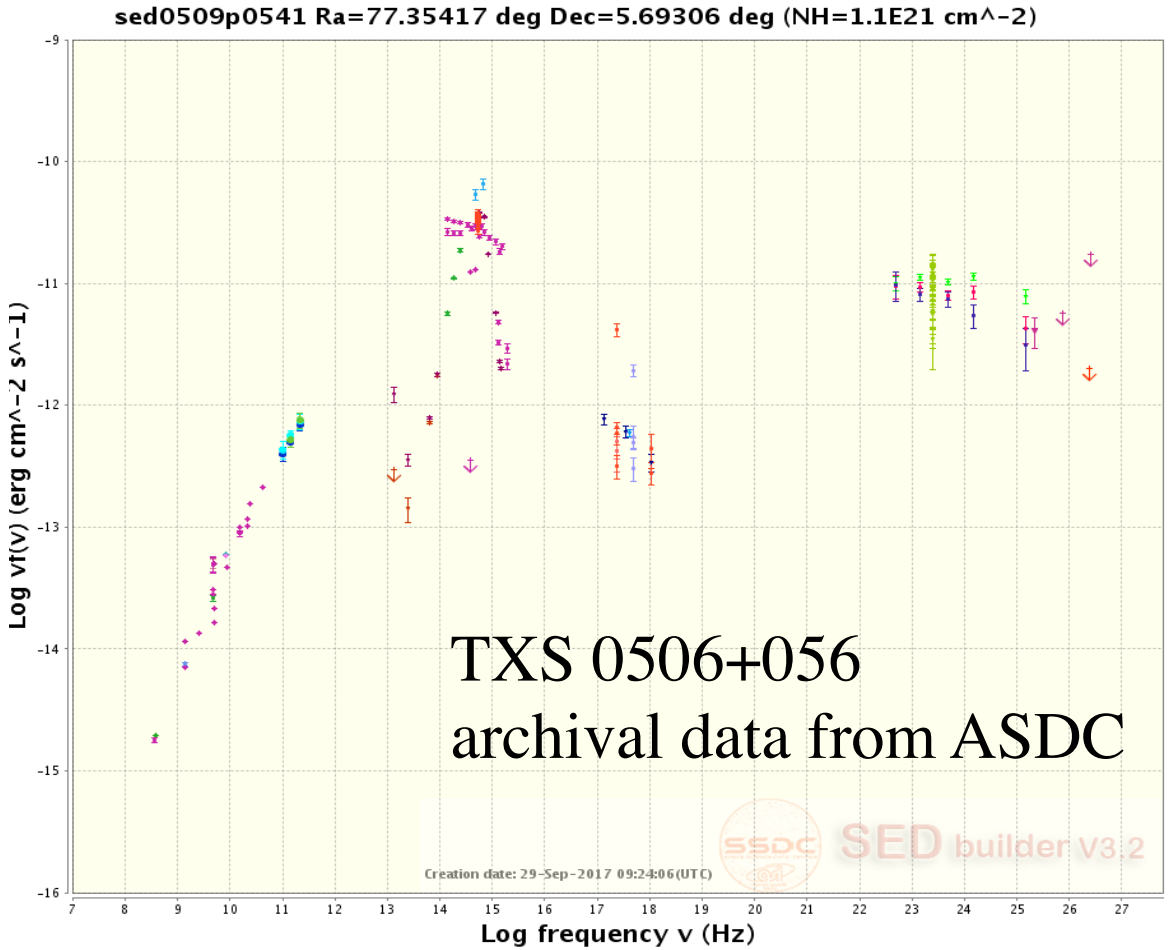
BL Lac (intermediate or low-frequency peaked)

z=0.03365+-0.0010  Paiano+ 18

apparently “typical” SED -> leptonic dominant?

MAGIC: >6σ detection above 100 GeV



# Gamma-Ray Bursts

Most luminous explosions
in the Universe,
largely unexplored at VHE

via VHE observations:

**Clarify physics of GRBs**

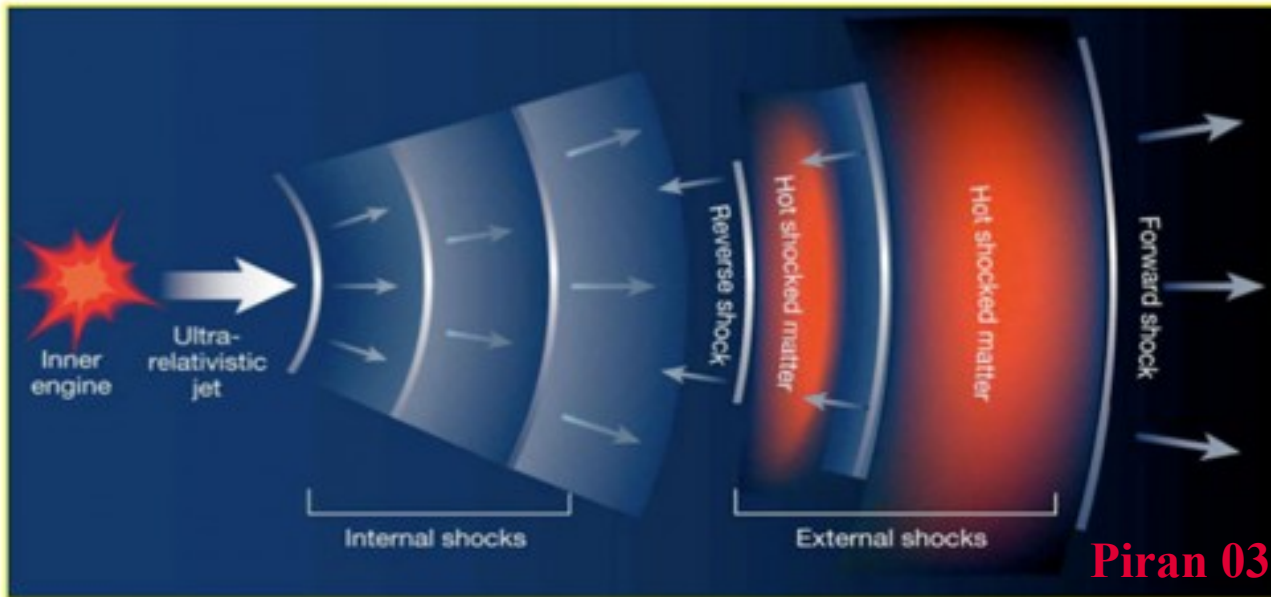
- prompt: mechanism, jet properties (central engine: NS/BH?)
- early afterglow: mechanism (plateau phase),
  particle acceleration, B field generation

**Probe the Universe**

- extragalactic background light (deeper than AGN)
- intergalactic magnetic fields

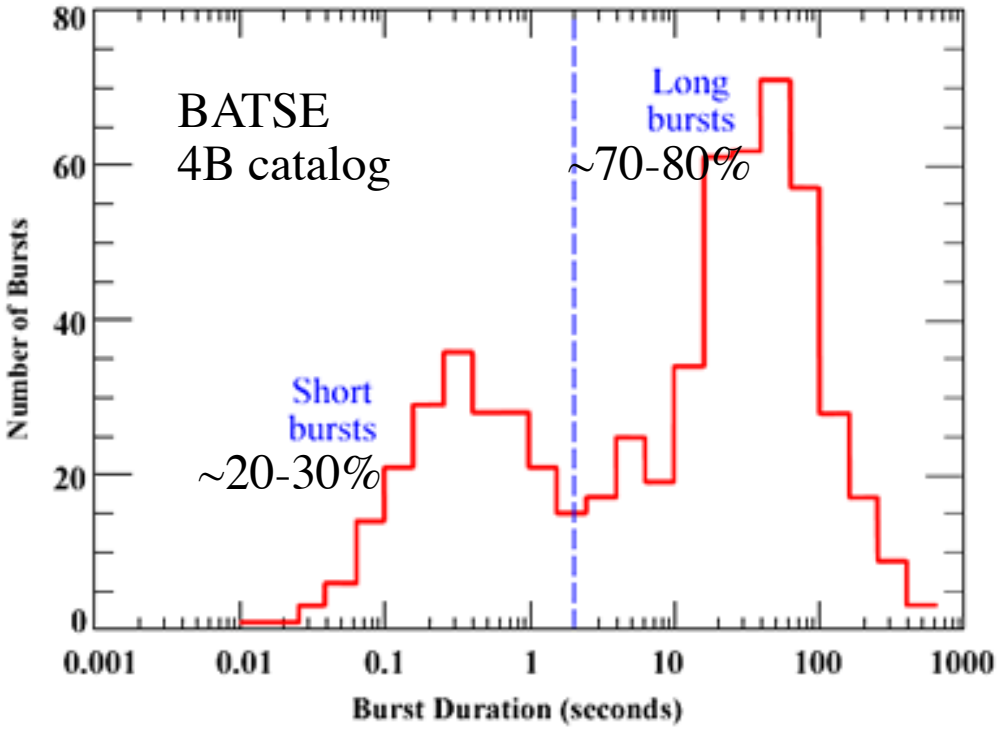
**Test UHECR origin, fundamental physics**
search for
signatures of:

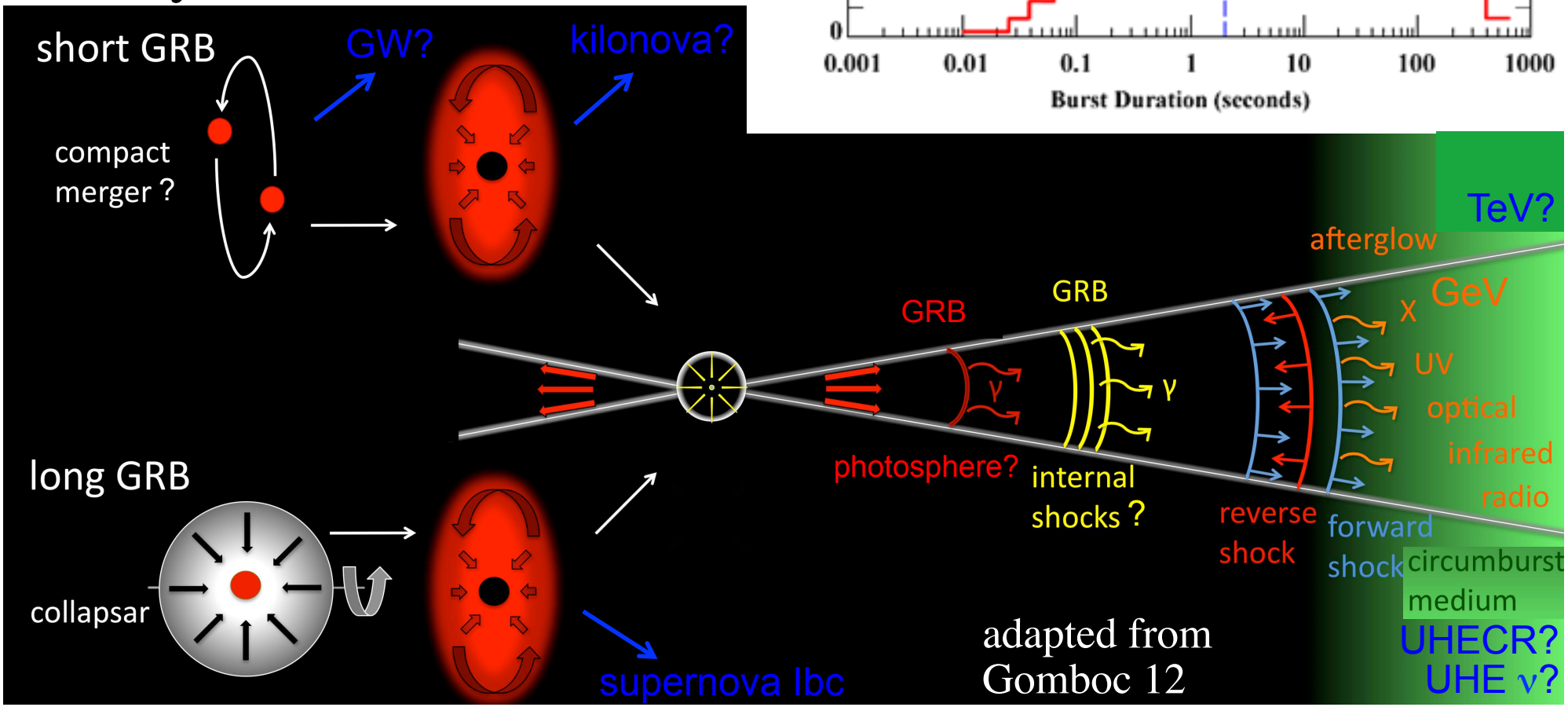
- accelerated hadrons
- Lorentz invariance violation



# GRBs: short vs long

Many systematic differences:
MeV spectra, z distribution,
host galaxy type, environment
-> likely distinct progenitors
-> high-energy properties
may well be different



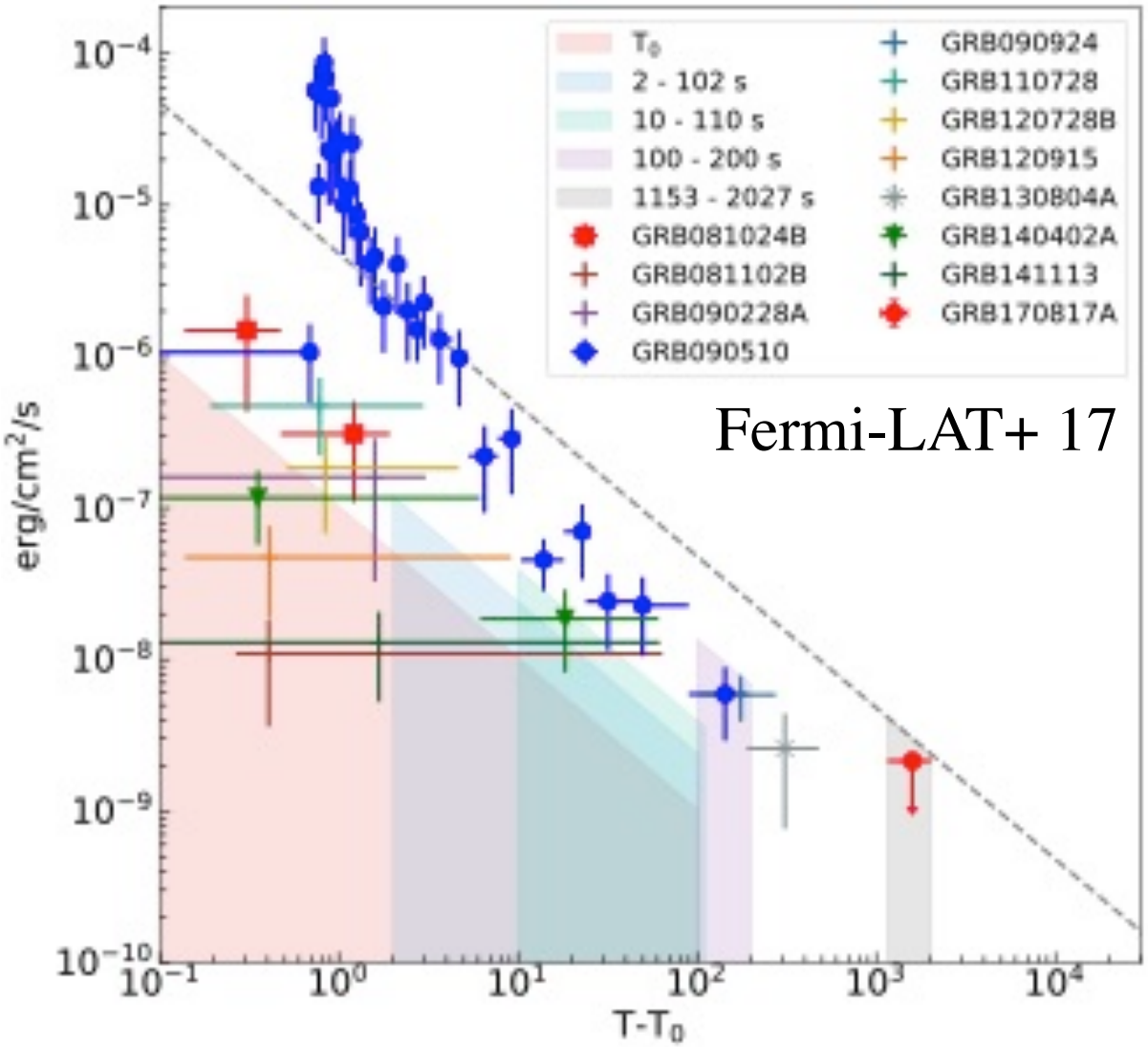
# short GRBs: GeV

LAT detections, as of July 2017

~120 long GRBs vs.

~11 short GRBs,

only 1 with z




GRB 090510

z=0.903 ($D_L$~6 Gpc)

detected by LAT up to

$E_\gamma$~31 GeV, t~178 s

Human knowledge on high-energy properties of short GRBs is sorely lacking

# short GRB 160821B

z=0.16 one of nearest ever

GBM: $T_{90}$~1s, $E_p$~84 keV, S~$1.7\times10^{-6}$ erg cm$^{-2}$ -> $E_{iso}$~$1.2\times10^{50}$ erg

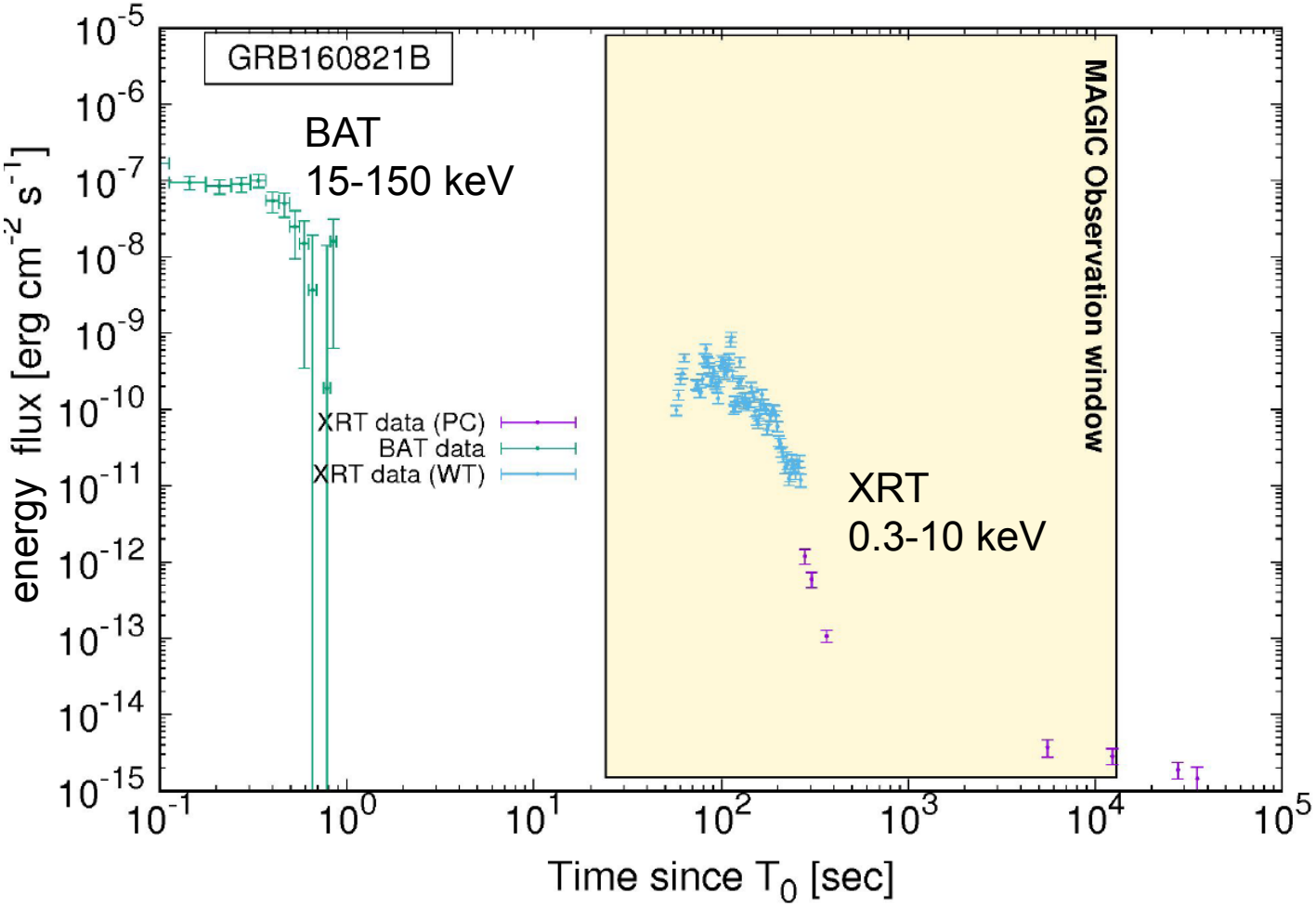
c.f. 090510: $E_{iso}$~$10^{53}$ erg , 130427A (long): >$10^{54}$ erg

XRT: "extended emission"+ steep decay t~<500s, "plateau" t~<30ks

Lü+ 17

optical, IR: afterglow, constraints on kilonova

Kasliwal+ 17, Tanvir+ in prep




**MAGIC:**

automatic follow-up

t~24 s - 1.5 h

$Z_d$~34-40°

poor weather

NSB ~3-5 ×dark

t~1.5 - 4 h

$Z_d$~40-55°

good weather

NSB ~5-9 ×dark

(higher Moon)

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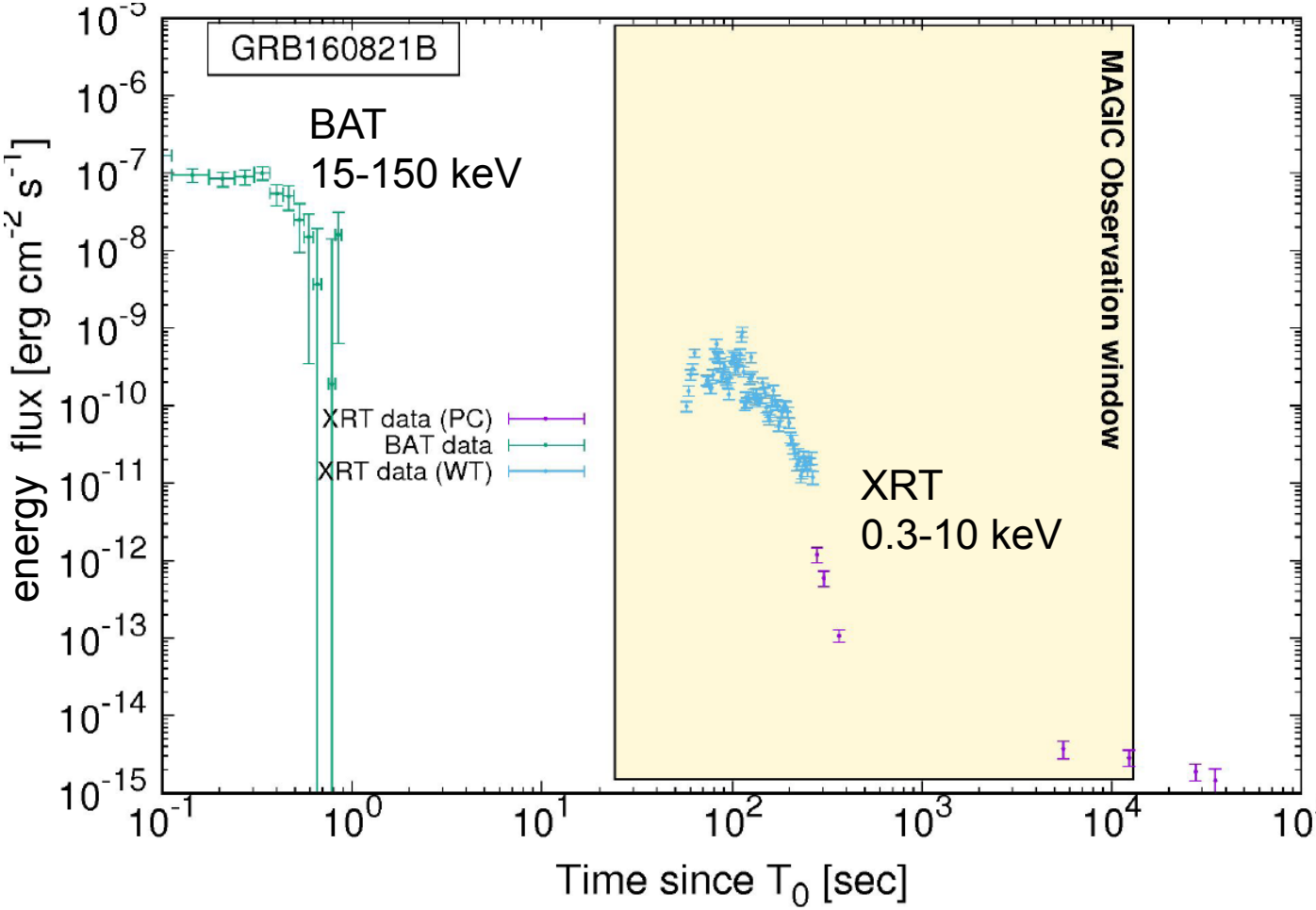
XRT: "extended emission"+ steep decay t~<500s, "plateau" t~<30ks

Lü+ 17

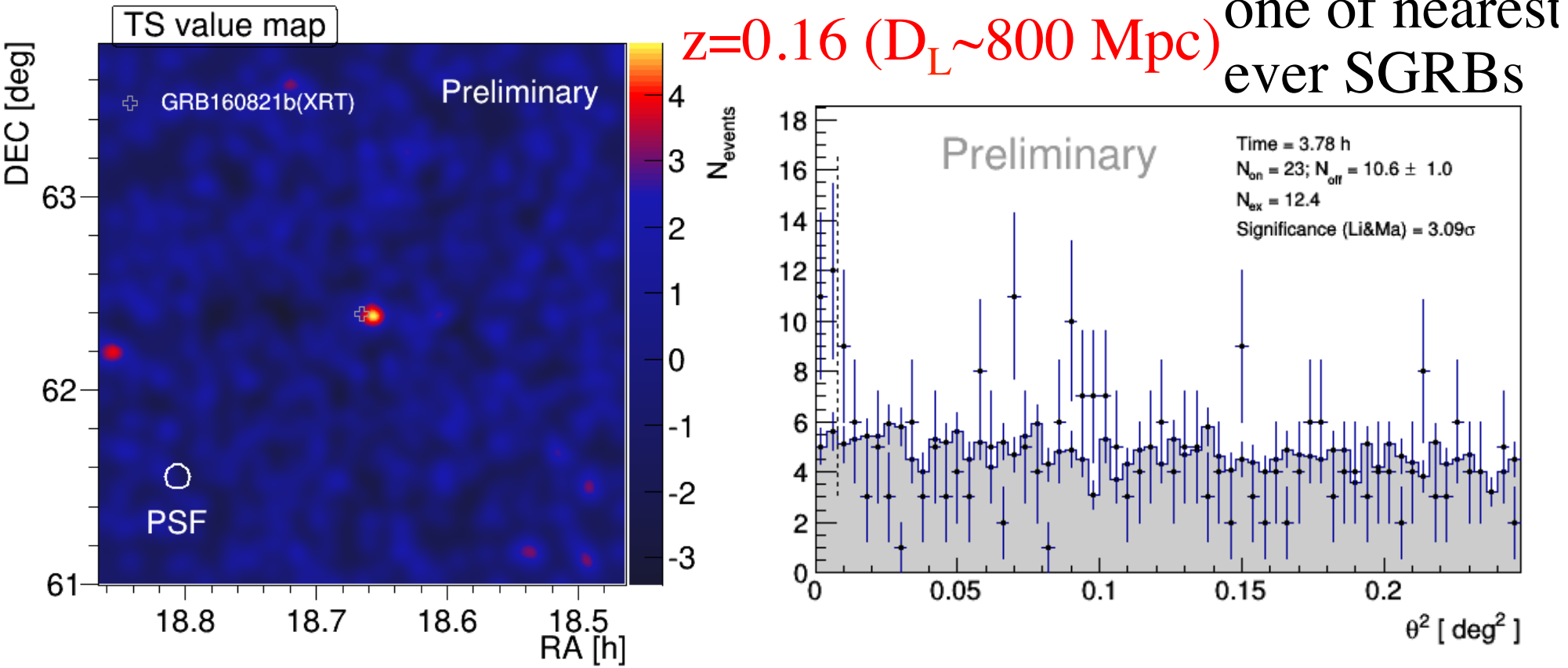
LAT: no detection reported, but likely not strong limit
(outside FoV at t<5 ks, around edge of FoV at t~5-9 ks) Tanvir+ in prep




**MAGIC:**
automatic follow-up
t~24 s - 1.5 h
$Z_d$~34-40°
poor weather
NSB ~3-5 ×dark
t~1.5 - 4 h
$Z_d$~40-55°
good weather
NSB ~5-9 ×dark
(higher Moon)

# MAGIC observations of low-z short GRB 160821B

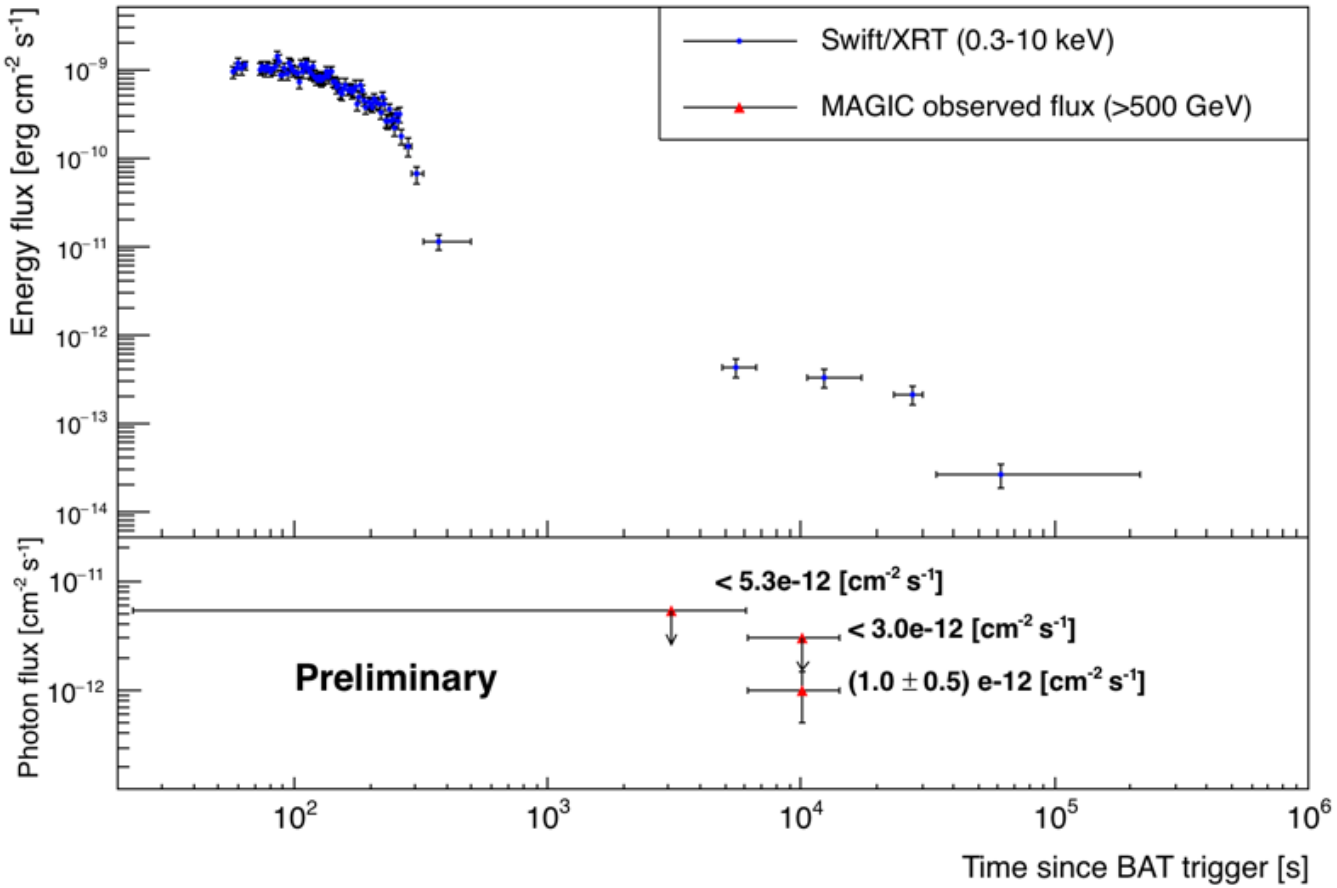
z=0.16 ($D_L$~800 Mpc) one of nearest ever SGRBs




- Followed up from t~24 s to t~4 h. Fastest ever, nearest ever for MAGIC, but under non-ideal weather, high Moon.

- Dedicated analysis yields >4 sigma (pre-trial), ~3.1 sigma (post-trial) at >600-800 GeV at GRB position.
  Possible evidence of gamma-ray signal, but not firm detection.

# MAGIC observations of low-z short GRB 160821B




IF signal is real:

- energy flux >500 GeV ~ 2 × energy flux in X-rays at t~$10^4$ s
- First SGRB seen >500 GeV

  First SGRB seen >GeV to t~$10^4$s

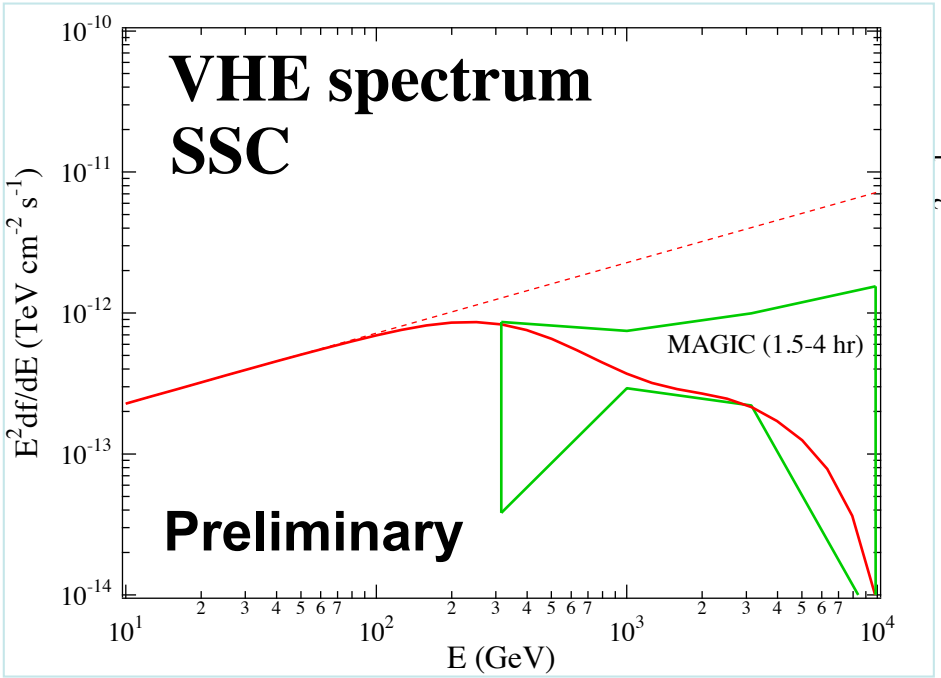
  Only second SGRB with known z seen >GeV

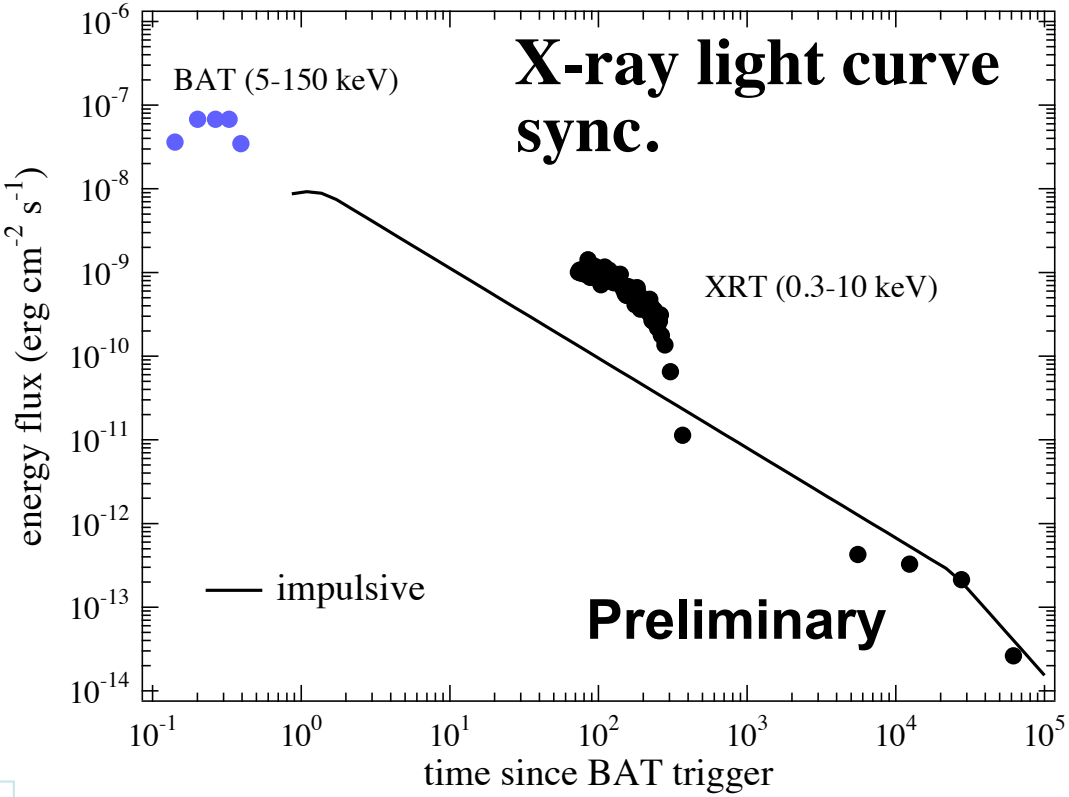
  -> Advances our knowledge of HE properties of sGRBs

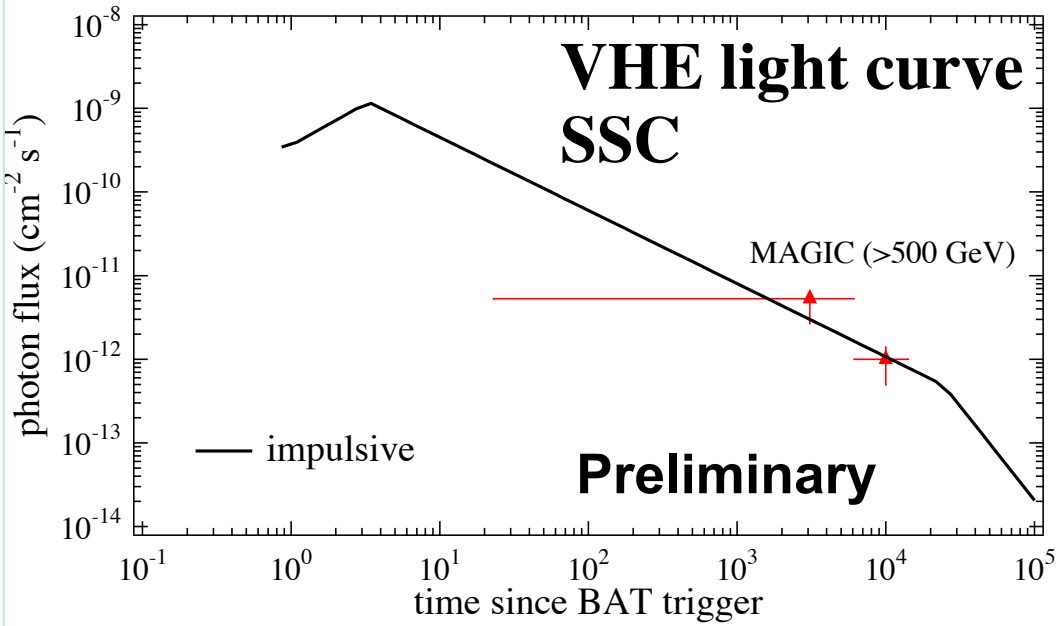
# short GRB 160821B interpretation

simple impulsive blastwave
uniform ISM
$E_{kin}=10^{51}$ erg, n=0.1 cm$^{-3}$
$\varepsilon_e=0.1$, $\varepsilon_B=0.01$, p=2.1, $\theta_{jet}=0.1$
EBL Dominguez+ 11

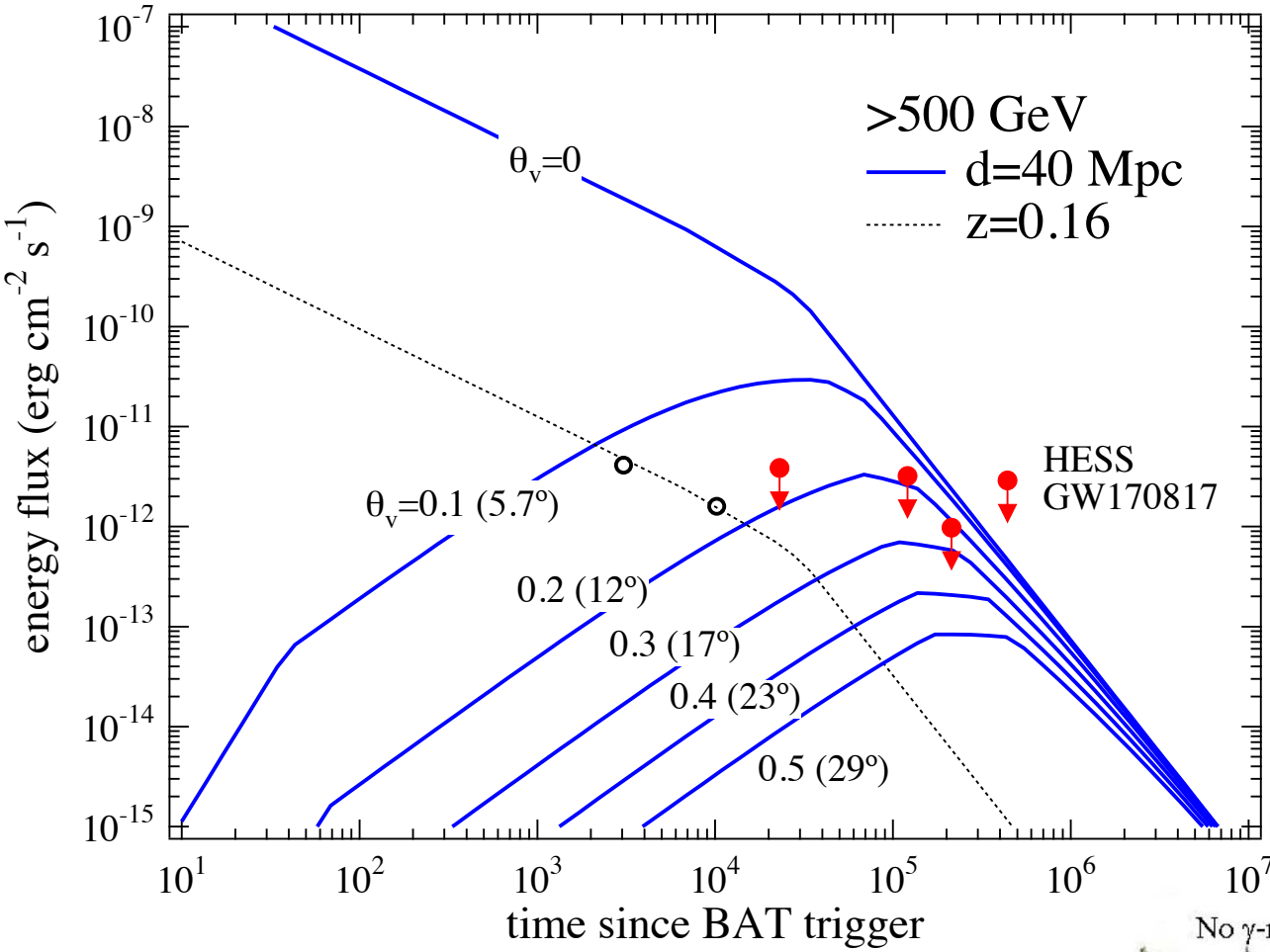
interesting implications
for GW follow-up



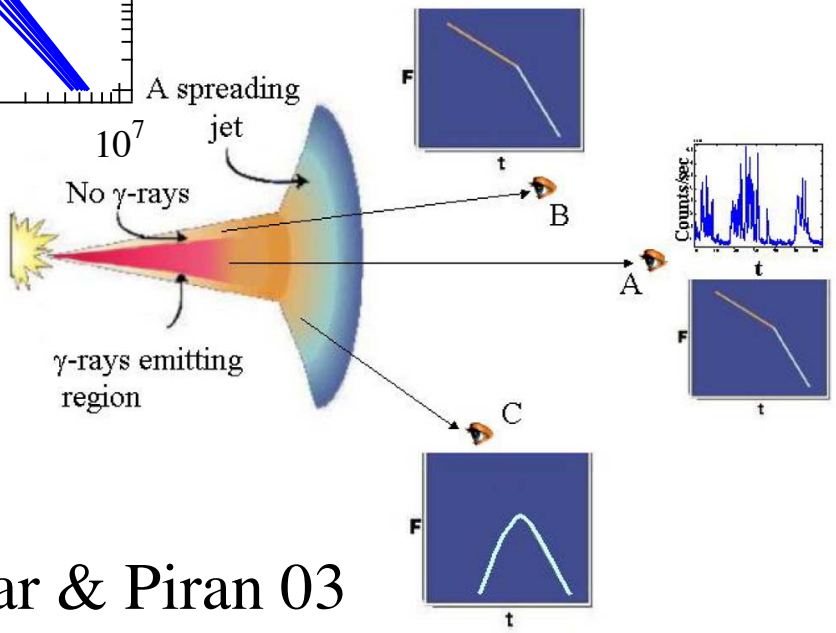



# short GRB off-axis afterglow




c.f. Granot+ 2002




Nakar & Piran 03

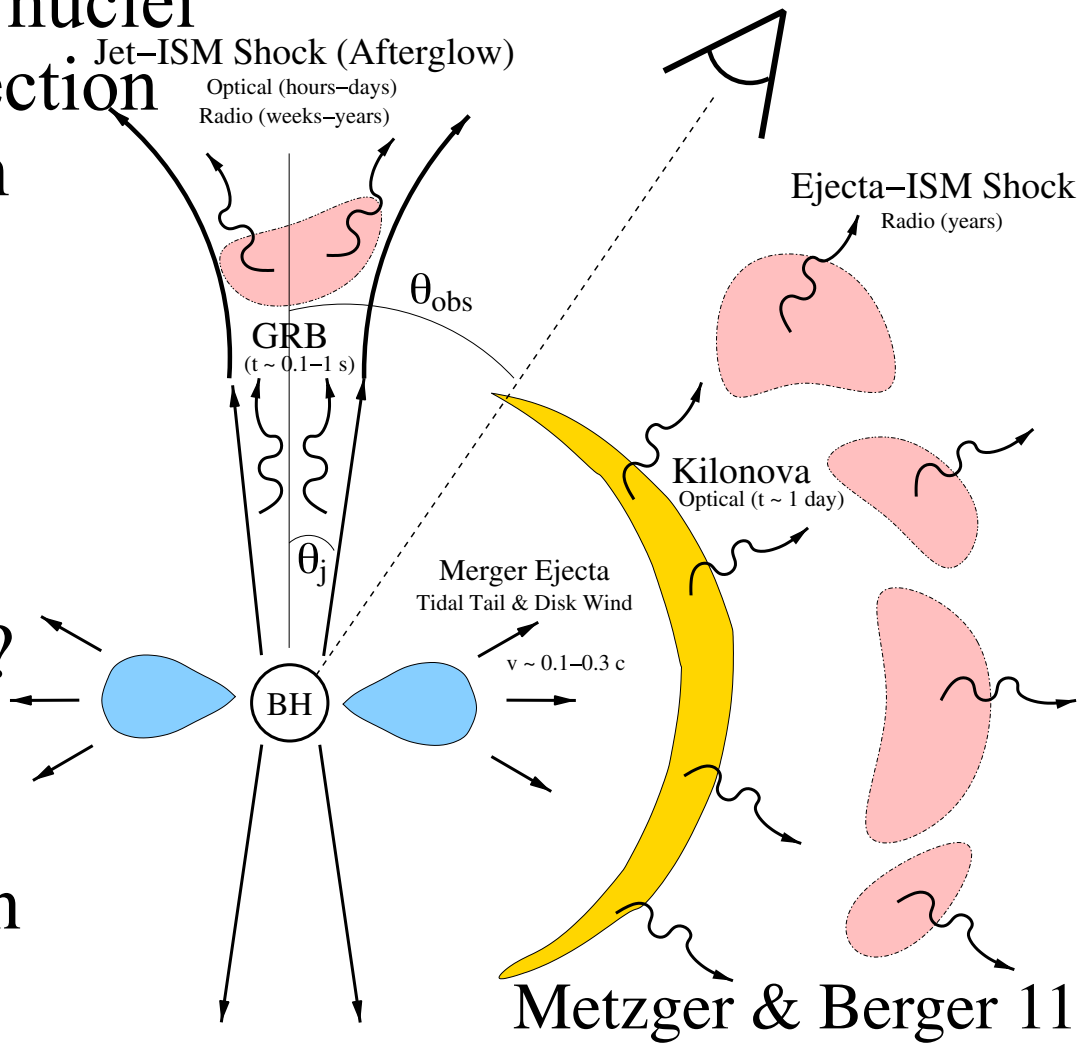
# Gravitational Waves

Newest window onto the Universe, connection with GRBs, etc

- powerful probe of relativistic dynamical phenomena, especially compact binary mergers
- NS-NS/BH mergers potential sources of short GRBs; fast ejecta rich in r-process nuclei
  -> coincident EM-GW detection provides new dimension

## VHE γ follow-up

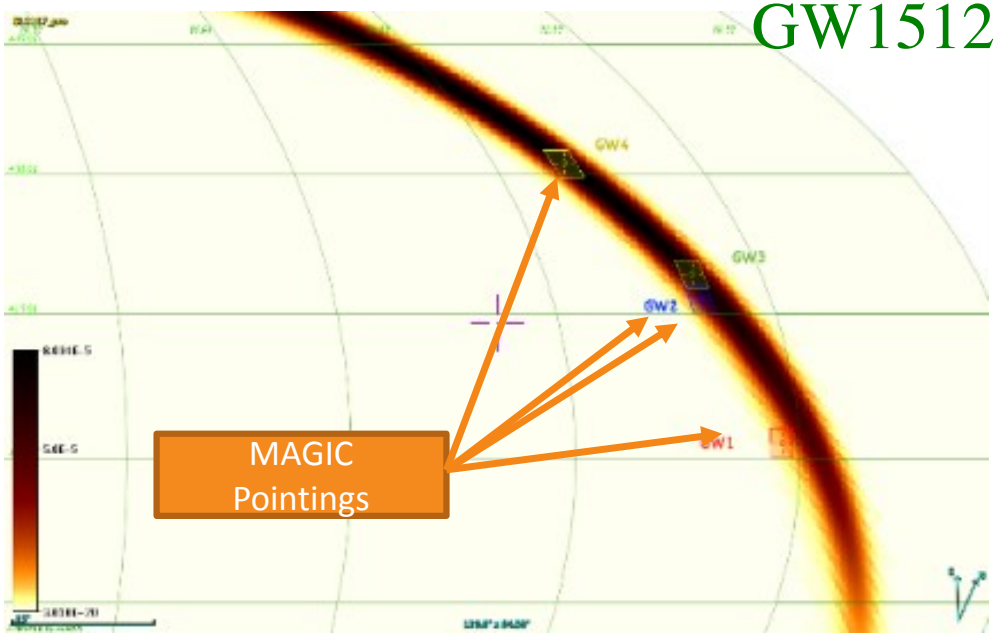
- test short GRB physics via:
  on-beam afterglow
  off-beam orphan afterglow?
- probe merger physics via emission due to ejecta + ambient medium interaction



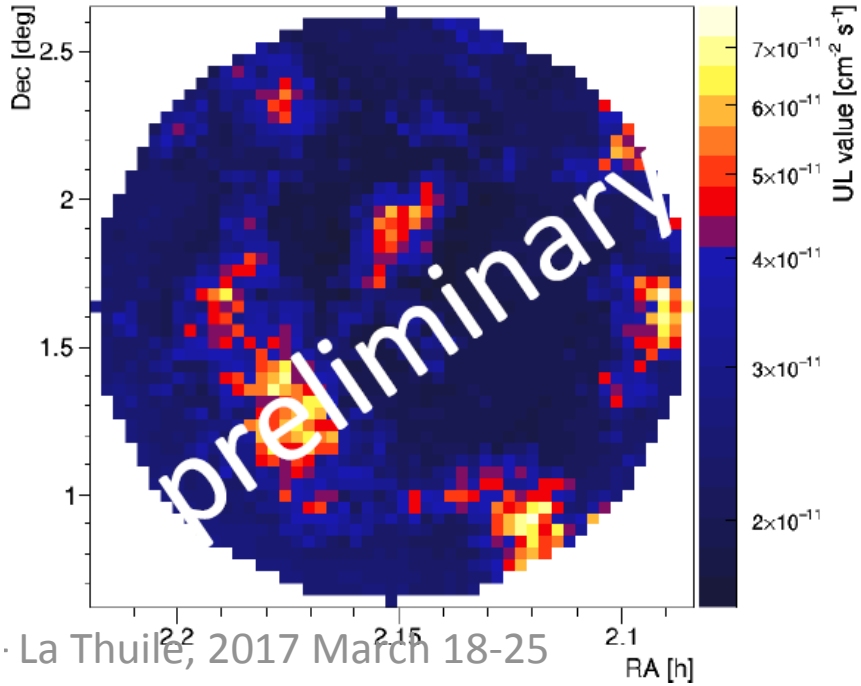
# MAGIC gravitational wave follow-up

- GW151226: BH-BH
  upper limits for small part of error region
- GW1708__: potential binary with NS
  upper limits for optical transients (likely supernovae)

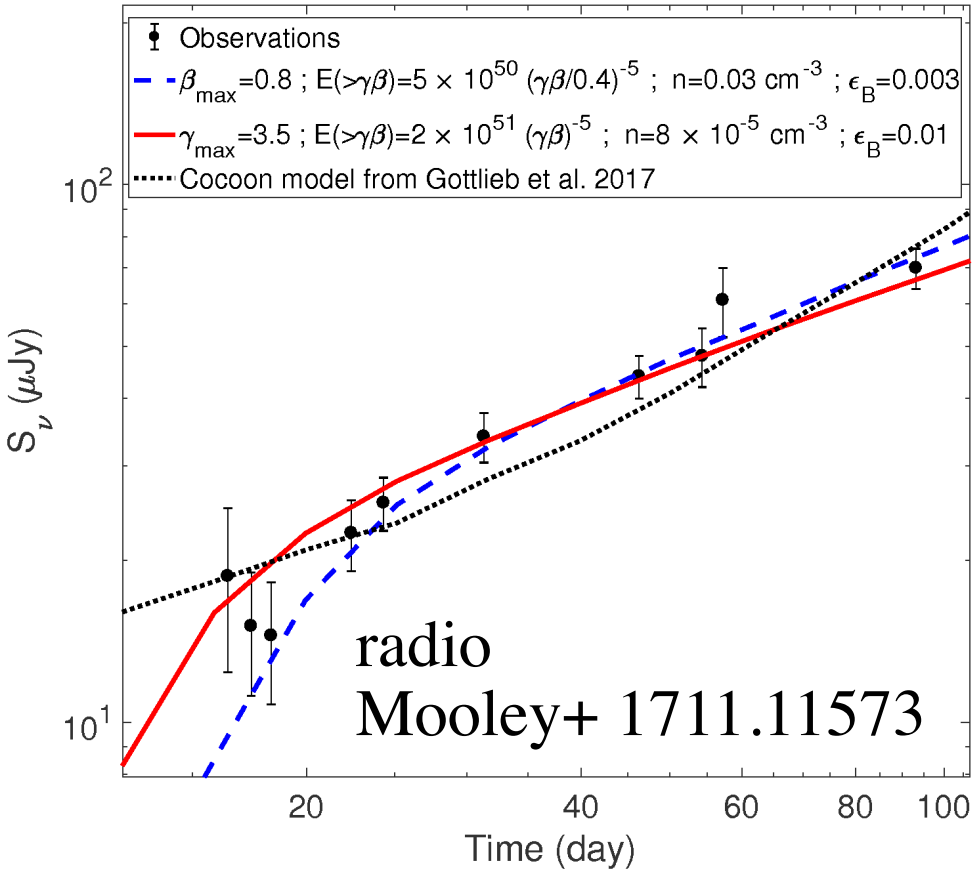
c.f. GW170817: NS-NS
  unobservable due to high ZA(~88 deg)

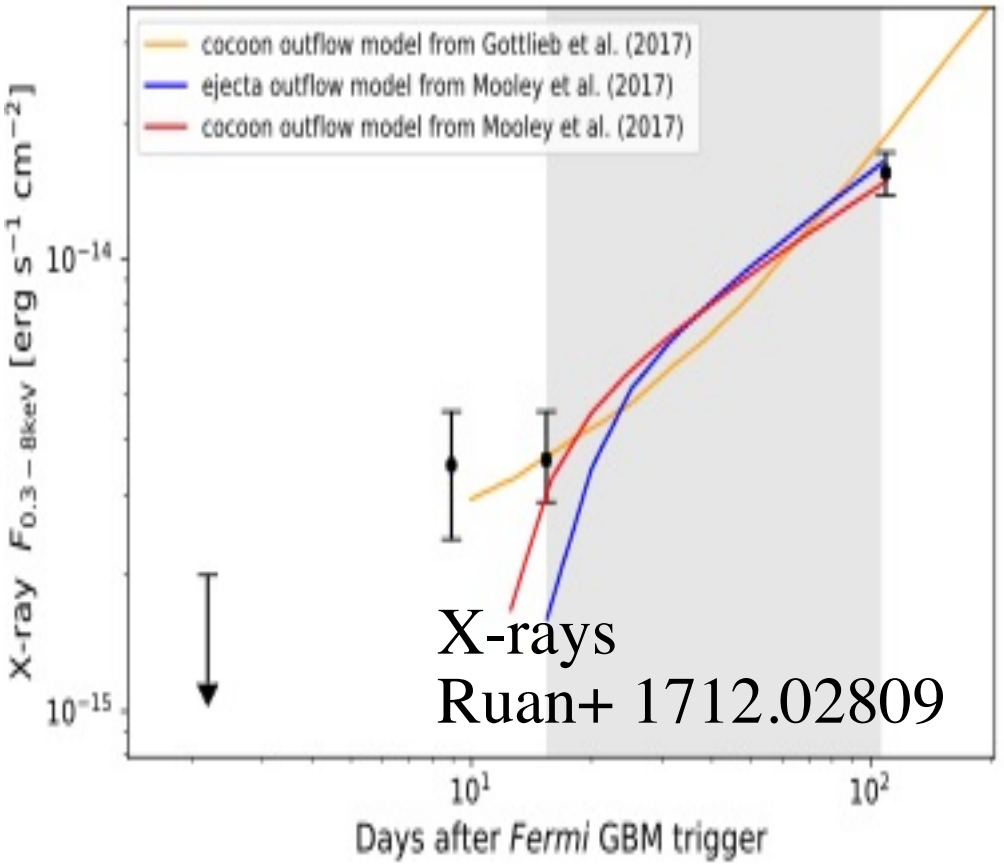



GW151226



# **GW170817 late-time X-ray, radio** rising up to ~100 days




simple off-axis (uniform jet) disfavored
-> off-axis structured jet or cocoon / merger ejecta
(quasi-spherical, mildly relativistic outflow w. energy injection)

cocoon/merger ejecta: $Y_{comp}$~a few, $E_{e,max}$~1-100 TeV Hotokezaka priv. com.
associated HE/VHE emission?

# future: MAGIC+CTA

CTA LST1
Real photo from Feb 2017

## summary

MAGIC observations of multi-messenger transients

neutrinos

- first indications for BL Lac TXS 0506+056!
- more observations toward solving mystery of their origin

GRBs

- intriguing hints for nearby short GRB 160821B
  - interesting implications for GW follow-up
- almost there; clearer detection imminent!

GWs, FRBs

- ongoing with interesting prospects

Future: off-line joint observations with CTA LST1