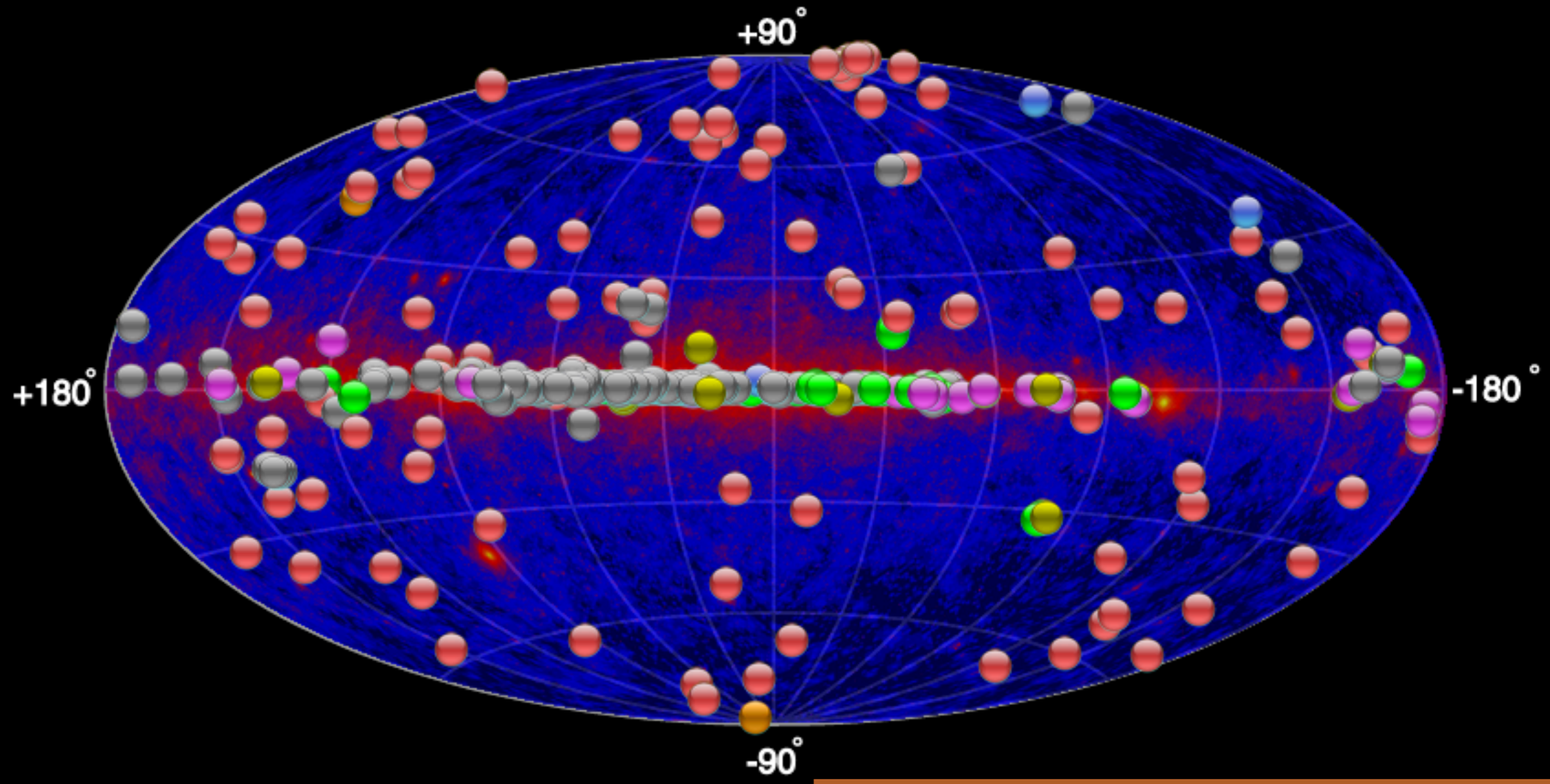
Surveys in TeV Astronomy with Cherenkov telescopes in a multi messenger and multifrequency context

Antonio Stamerra (INAF-OAR and ICSC)

With the contributions by several others from the CTAO-Consortium and MAGIC Collaboration

The TeV gamma-ray sky (E>~20 GeV-100 TeV)



Source Types

- TeV Halo PWN/TeV Halo PWN
- Binary XRB,PSR,Gamma BIN
- HBL,IBL,GRB,FRI,FSRQ Blazar,LBL,AGN, (unknown type)
- Shell SNR/Molec. Cloud, Composite SNR, Superbubble
- Starburst
- DARK UNID,Other
- uQuasar,Star Forming Region,Globular Cluster, Cat. Var. Massive Star Cluster, (class unclear),WR

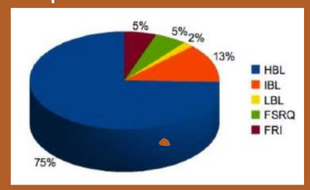
Most of these TeV sources are variable (minutes-to-months)

308 sources in total

93 are AGN-blazars/radiogalaxies

Blazar subclasses: HBL (high-peaked BL-Lac), IBL, LBL (low-peaked), FSRQ (flat spectrum radio quasars)

FRI: Fanarov-Riley type 1



http://tevcat.uchicago.edu

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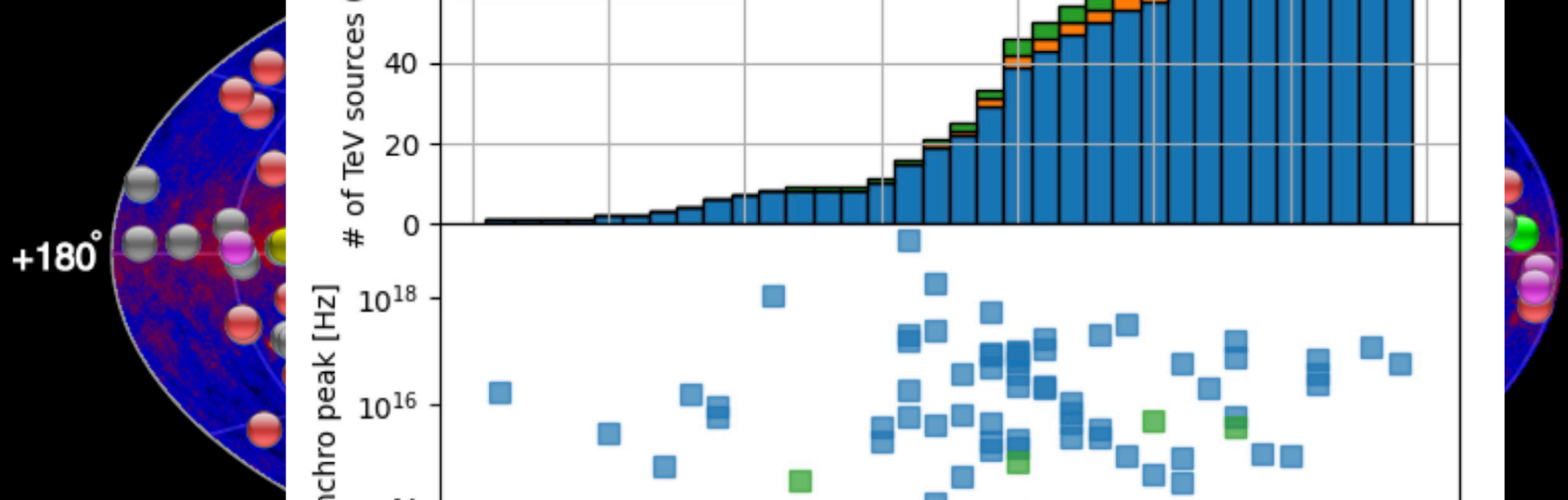

Righi, Prandini, Viale, Bovolon in prep.

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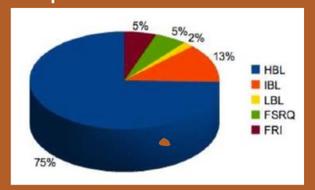

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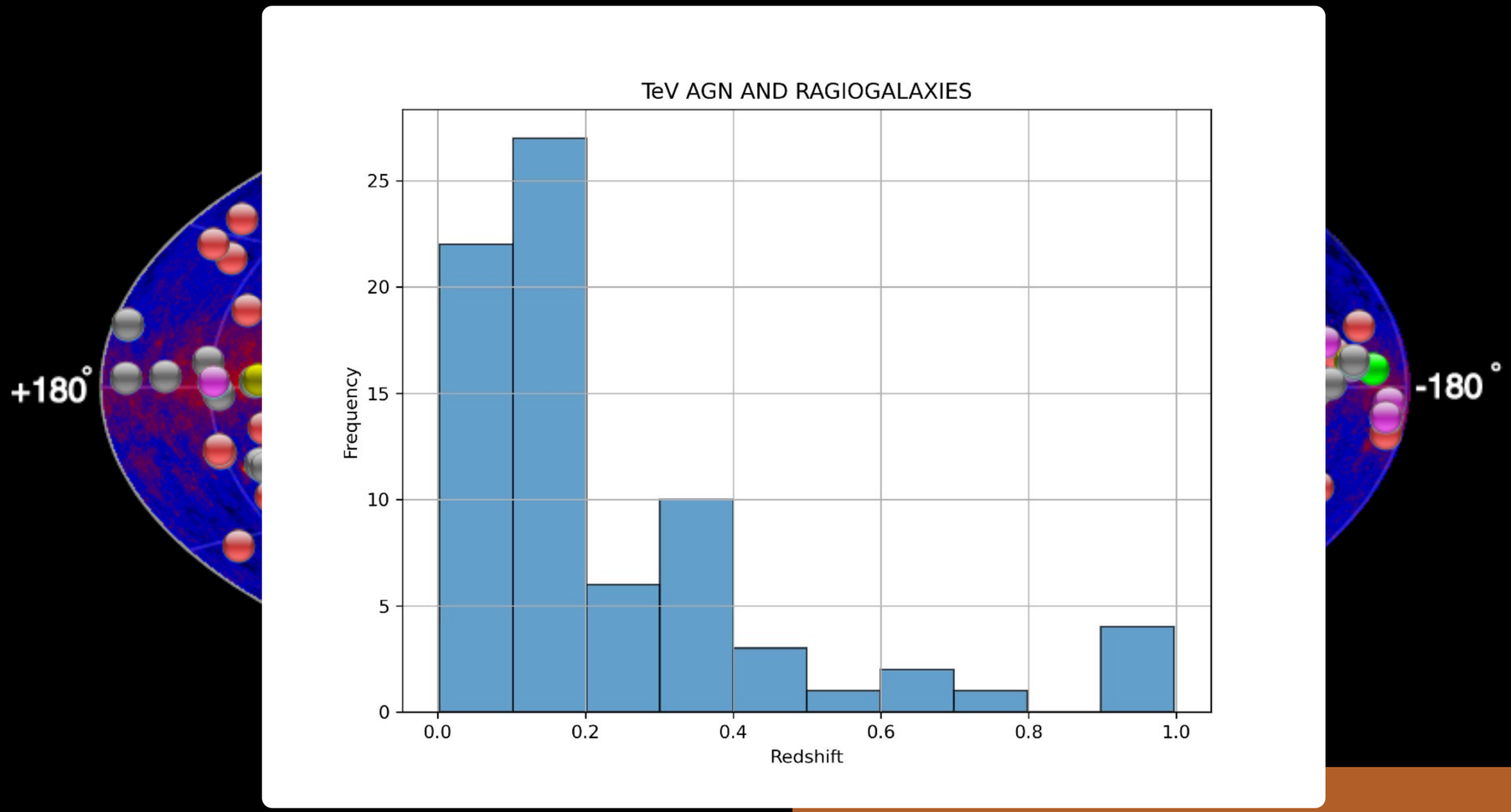

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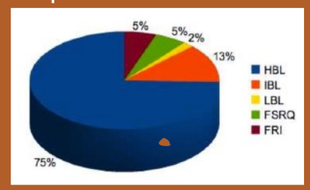
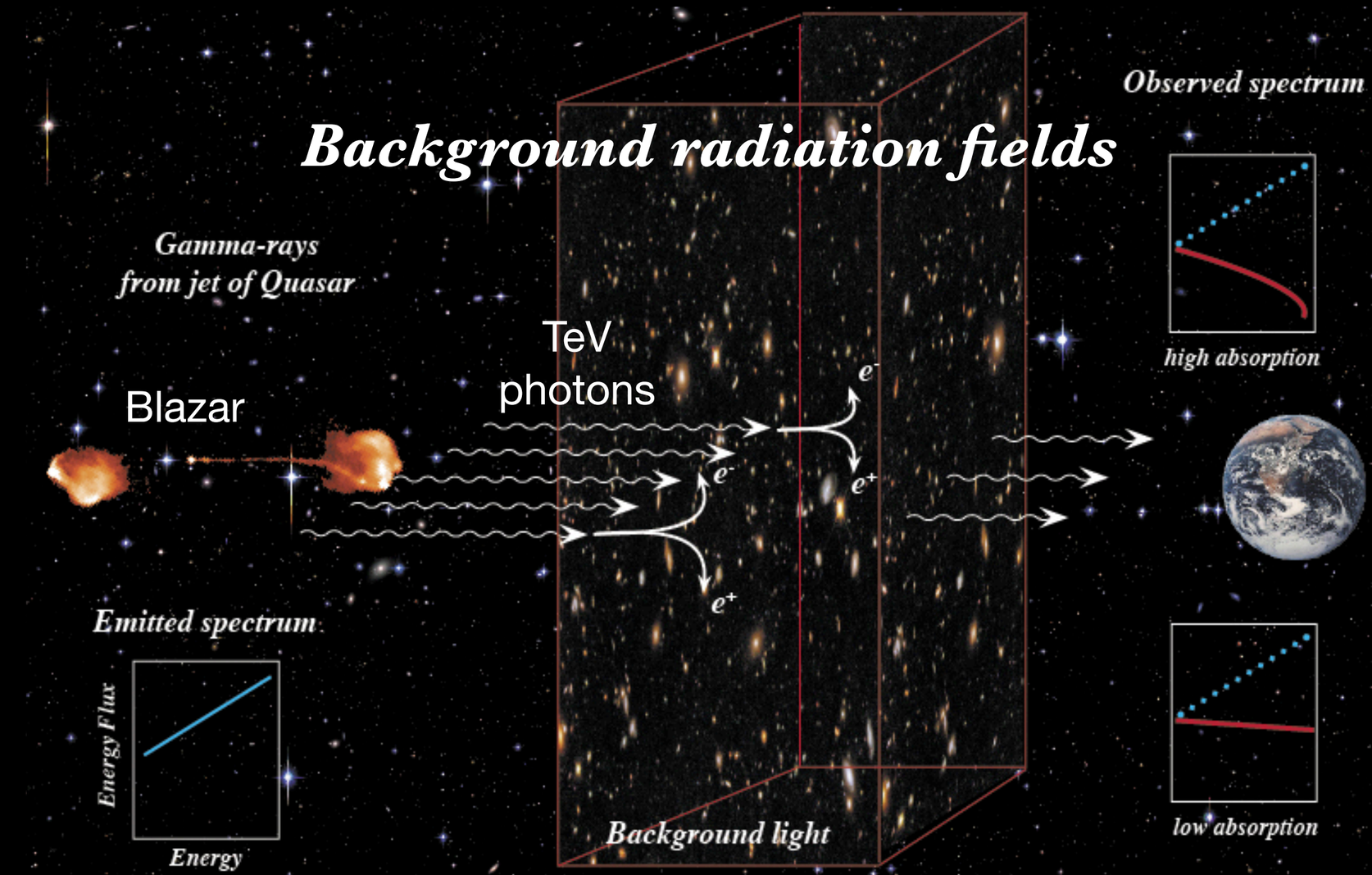
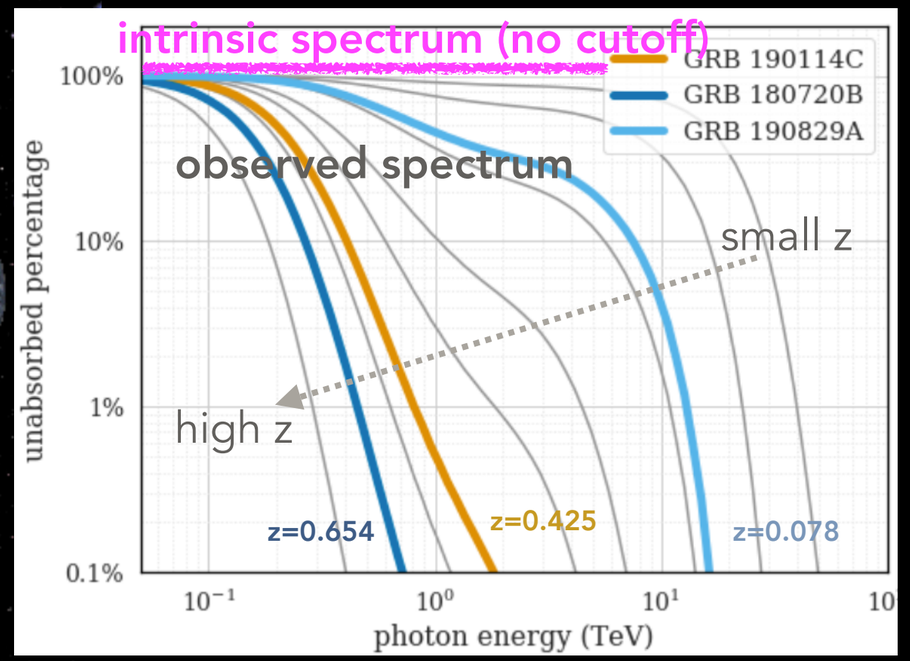


http://tevcat.uchicago.edu

EBL absorption of TeV photons

EBL: extragalactic Background Light





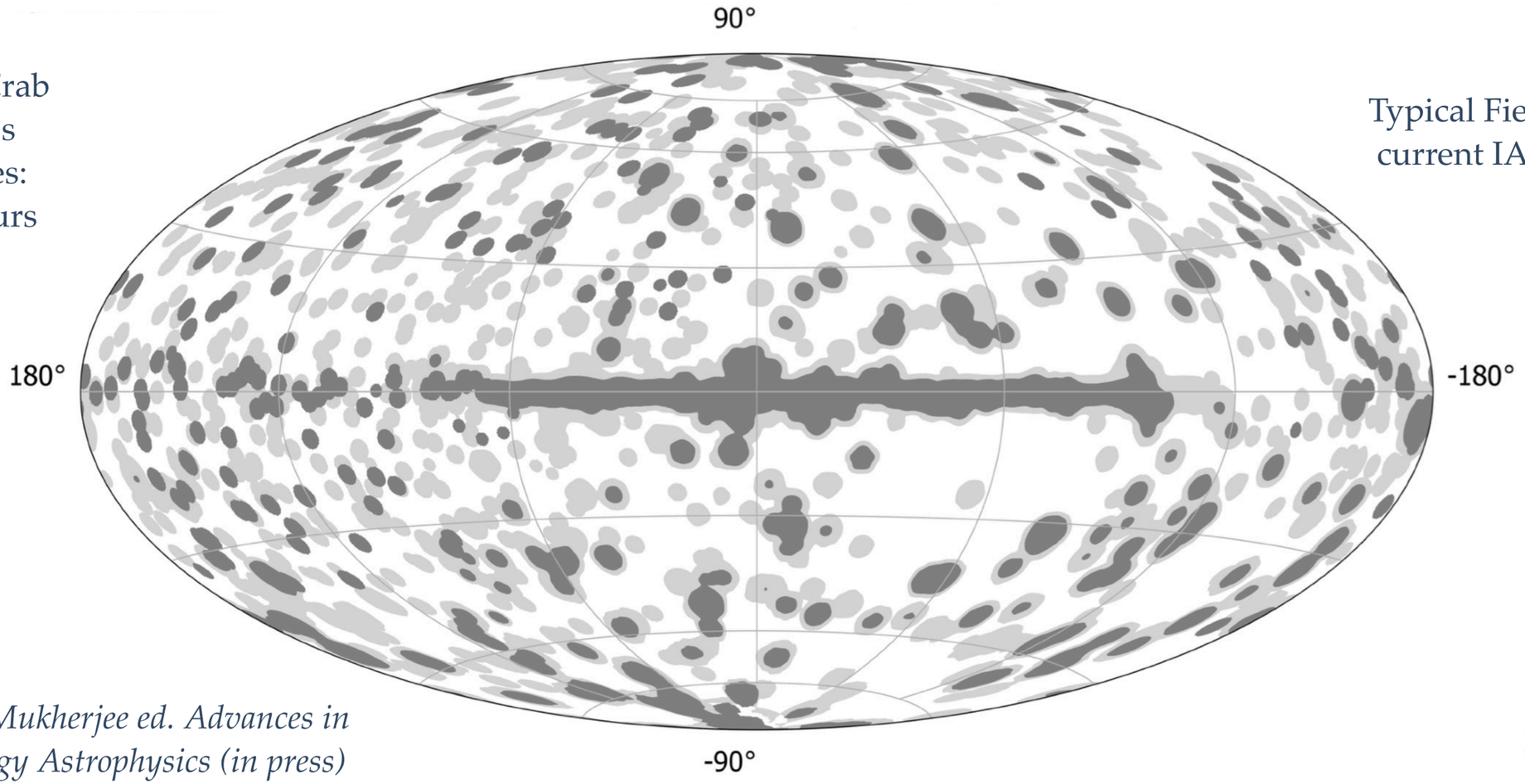
$$\Phi_\gamma^{obs}(E) = \Phi_\gamma^{source}(E) \times \mathrm{e}^{-\tau(E_\gamma, z)}$$

opacity gamma-ray horizon (z<~1 E>100 GeV)

Why an extragalactic survey at TeV energies?

- The extragalactic TeV sky is biased due to non-uniform observations, primarily driven by target-based monitoring and triggers on flaring sources in other wavelengths.

Sensitivity ~1% Crab
~10^{-12} erg/cm^2/s
Typical exposures:
few to tens of hours



Typical Field of View of current IACTs: 3-5 deg

R. Zanin&R. Mukherjee ed. Advances in very high energy Astrophysics (in press)

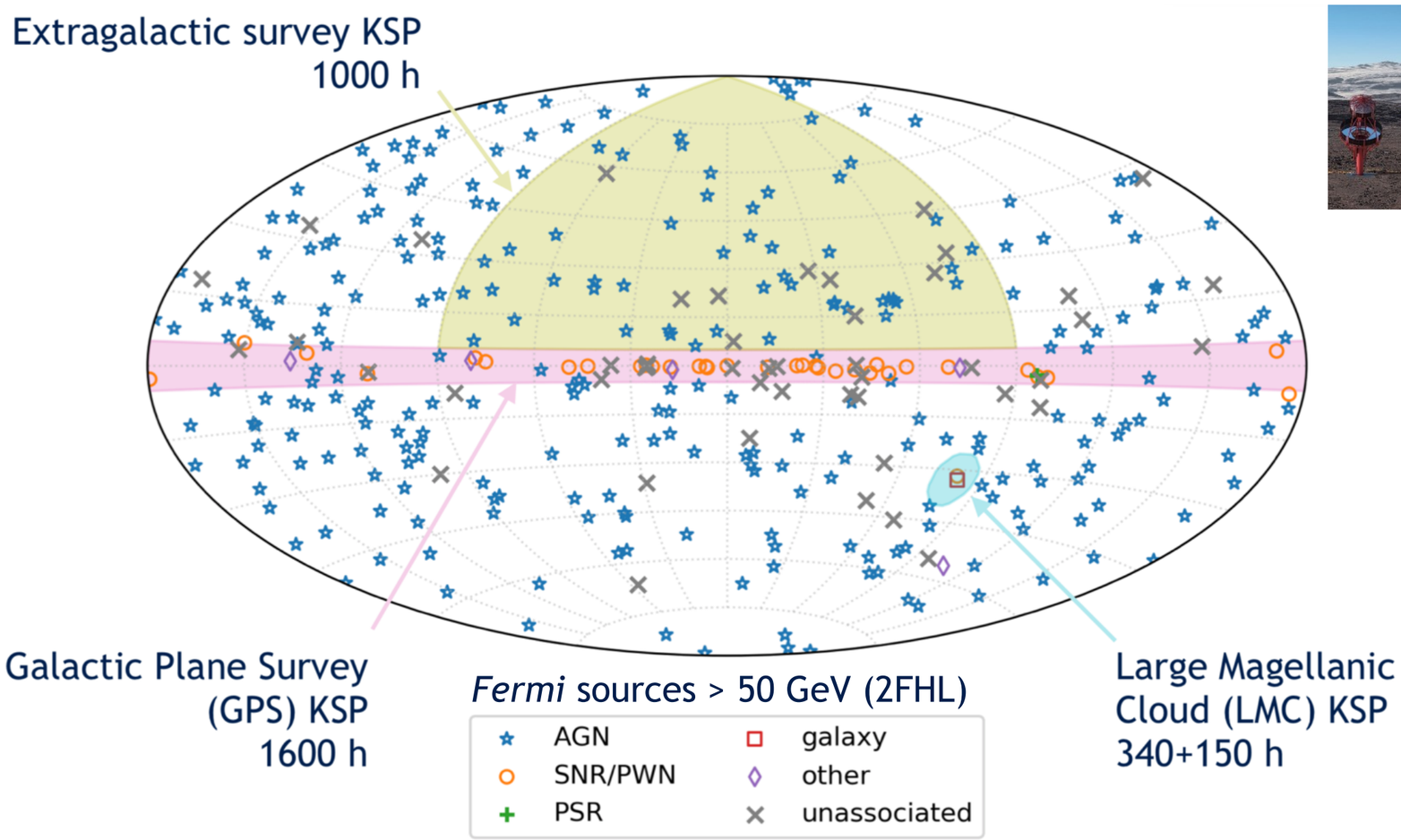
Why an extragalactic survey at TeV energies?

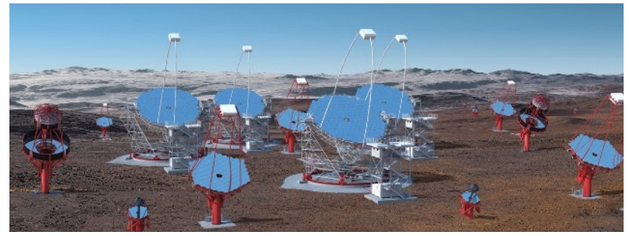
- 1st LHAASO catalogue with exposure: 1.5 yrs
  - 90 sources; 4(5) blazars
- Limiting flux ~1% Crab at >1 TeV
- Severe EBL absorption
  - WCDA: >1 TeV, KM2A: >25 TeV

*Zhen Cao et al 2024 ApJS **271** 25*

Planned surveys with the Cherenkov Telescope Array Observatory CTAO

- Unbiased survey on 1/4 of the sky, 1000 hours. Sensitivity 6 mCrab (~3x10^{12} ph/cm^2/s >125 GeV)
- ✓ derive the LogN-LogS and Luminosity function of TeV blazars
- ✓ Detect sources in flaring state —> Duty cycle
- ✓ Serendipitous new sources; extreme blazars; exotic:dark sources; GRB



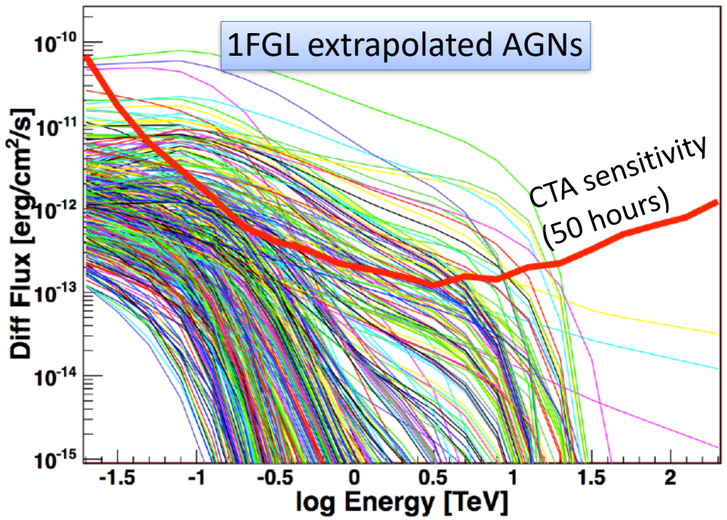


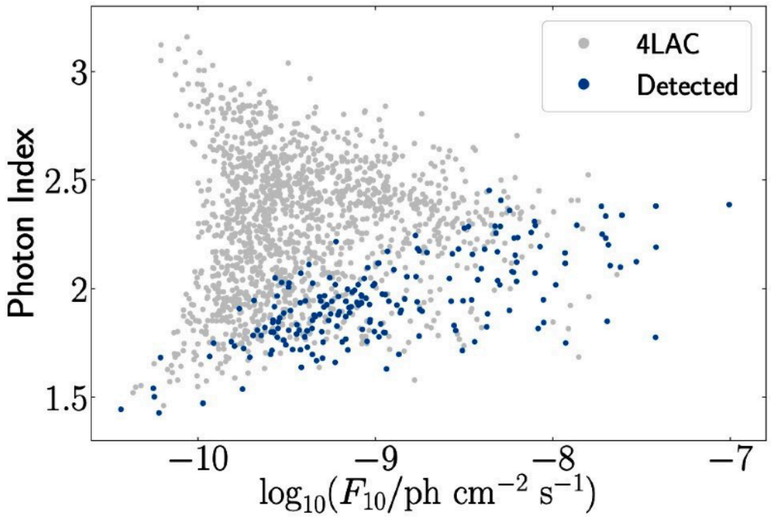
CTAO

Field of view of CTAO telescopes: ~8 deg

The TeV extragalactic survey: predictions

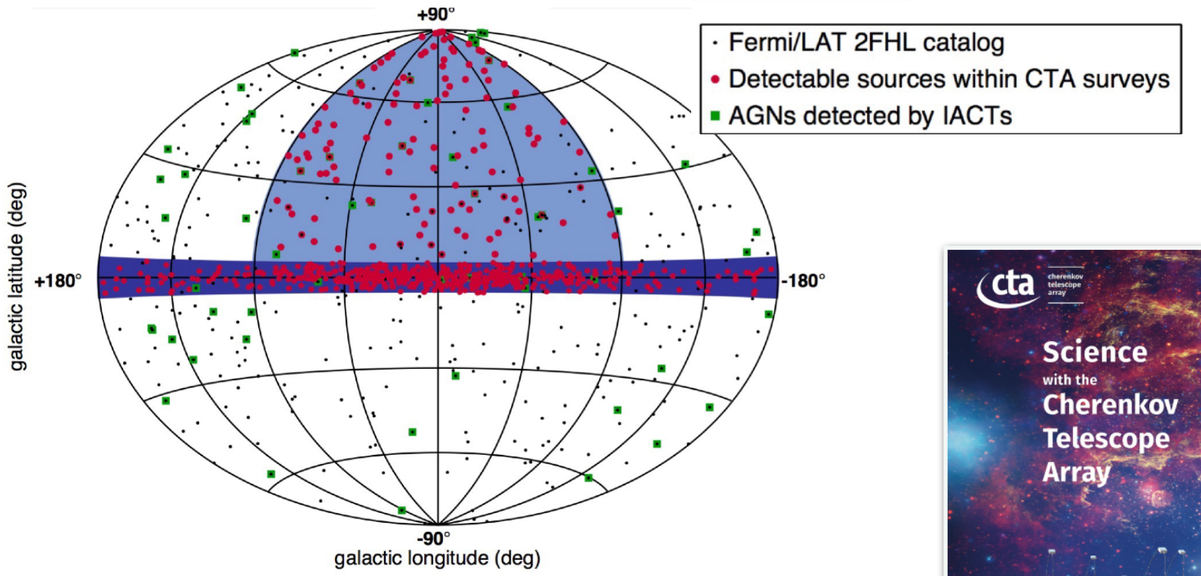
- Simple extrapolation from 1FGL/2FGL with EBL
- 120/400 AGN detectable in 50 hrs @ z_{max}~1.8
- 30-120 AGN detectable in the extragalactic survey
- More recent studies with 4FGL catalogue confirms these figures (alpha/omega configurations)





Southern alpha array	100 GeV	300 GeV	500 GeV	1 TeV
5 hour - PL	50	72	72	53
20 hour - PL	100	124	125	96
5 hour - LP	30	45	46	39
20 hour - LP	57	78	74	56

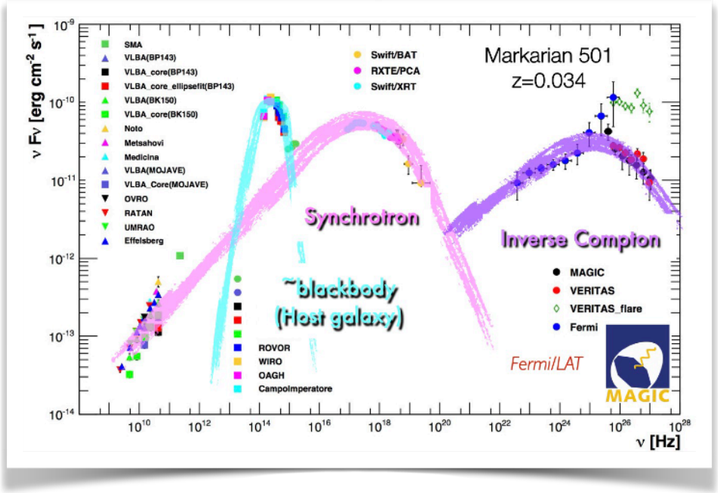
Brown et al. (CTAO-consortium) ICRC 2021



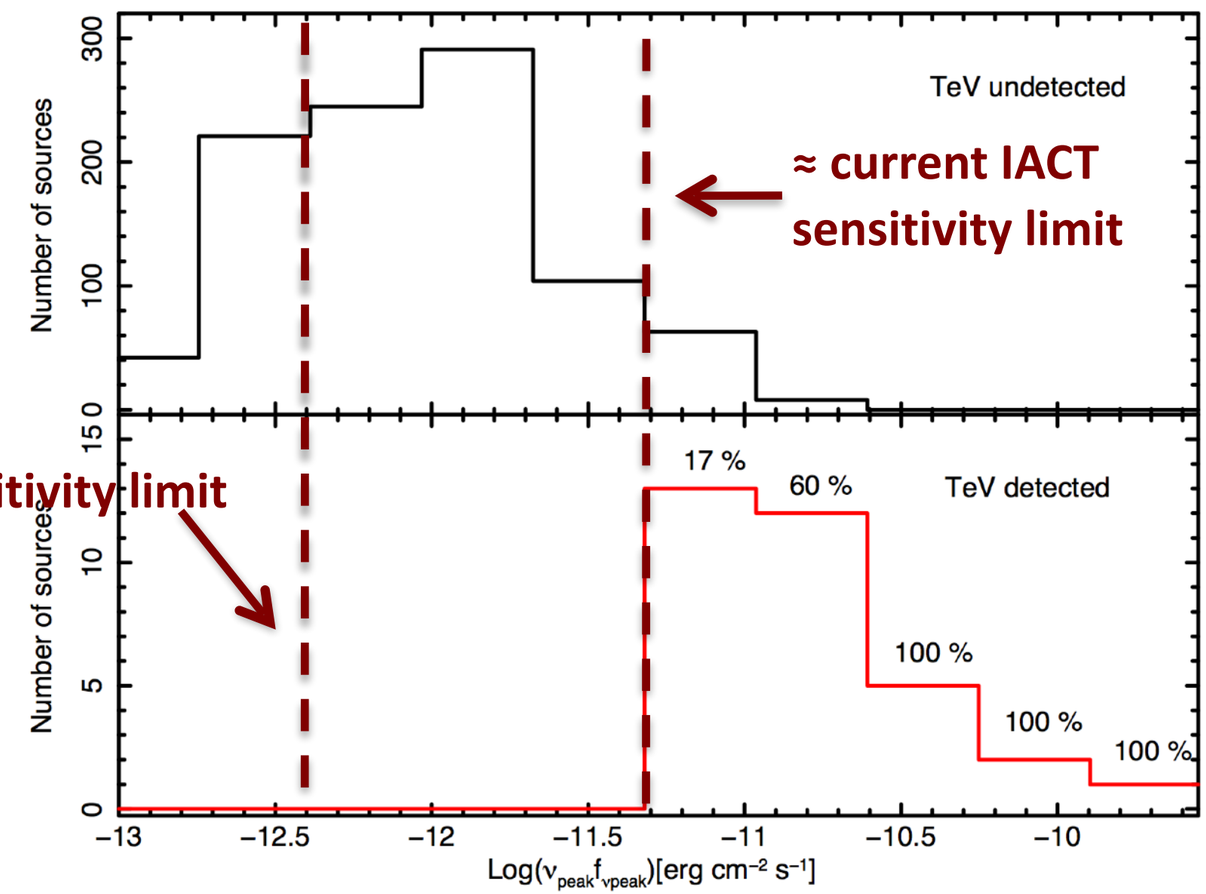
CTAO-consortium (2019)
https://doi.org/10.1142/10986

The TeV extragalactic survey: predictions

- WISE IR and X-ray data
  - Figure-of-Merit for TeV sources from synchrotron peak flux



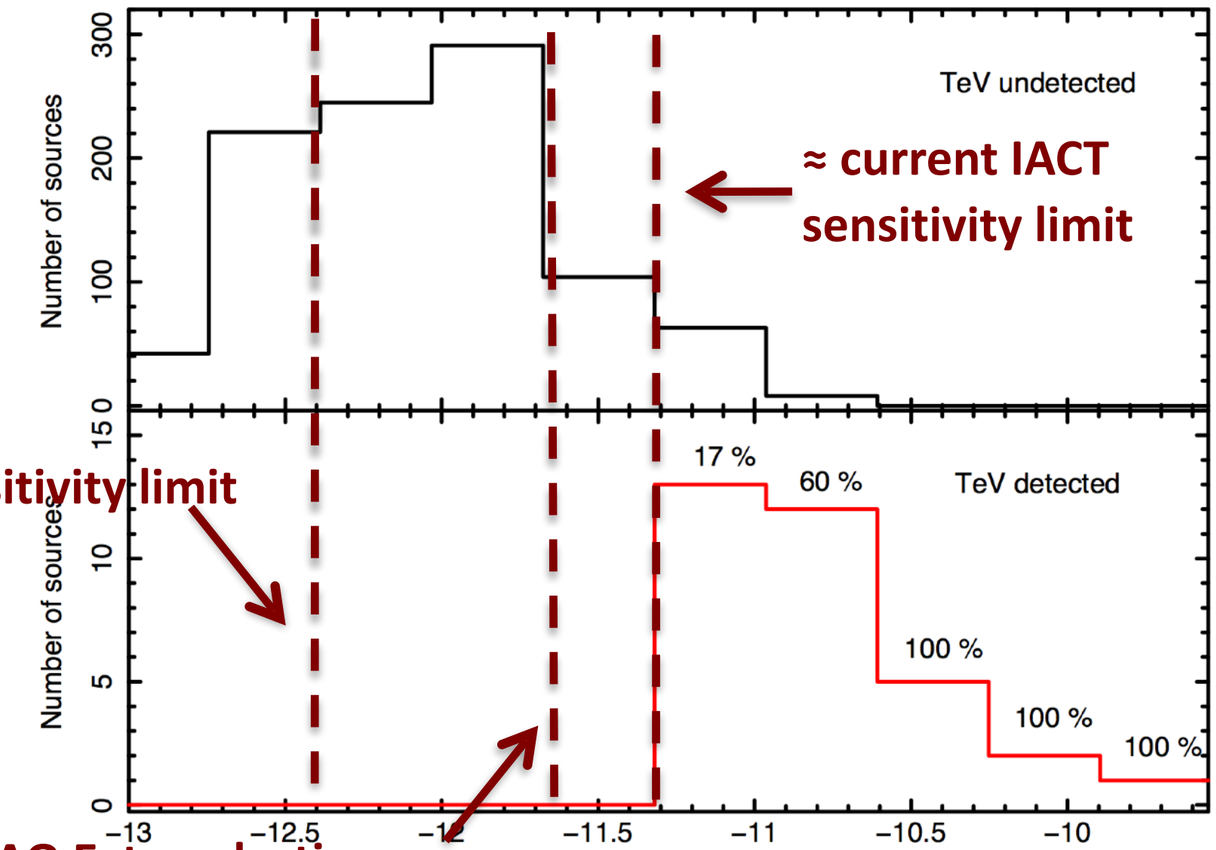
≈ **CTAO sensitivity limit**



Arsioli, Fraga, Glommi et al. 2017

The TeV extragalactic survey: predictions

- WISE IR and X-ray data
  - Figure-of-Merit for TeV sources from synchrotron peak flux
  - CTAO survey: >100 blazars expected for detection



Arsioli, Fraga, Glommi et al. 2017

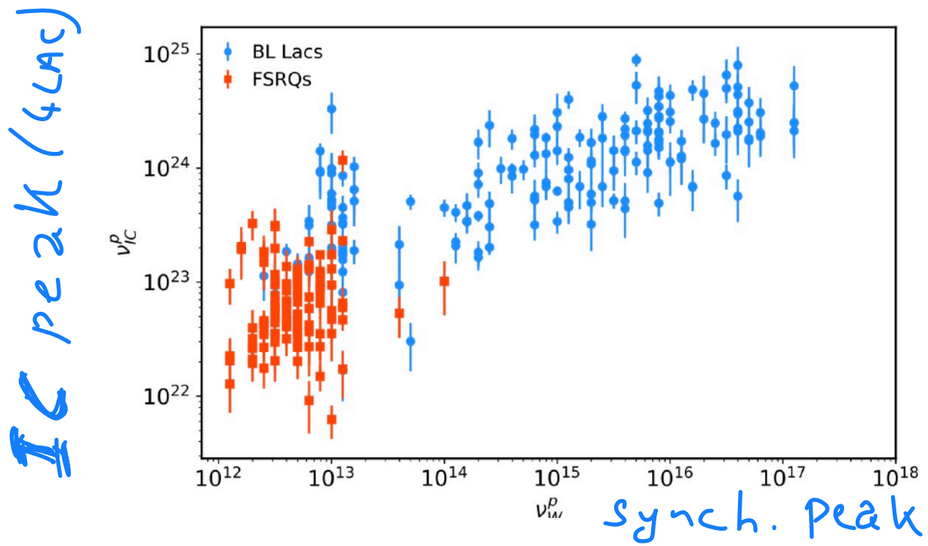
≈ CTAO sensitivity limit

CTAO Extragalactic survey

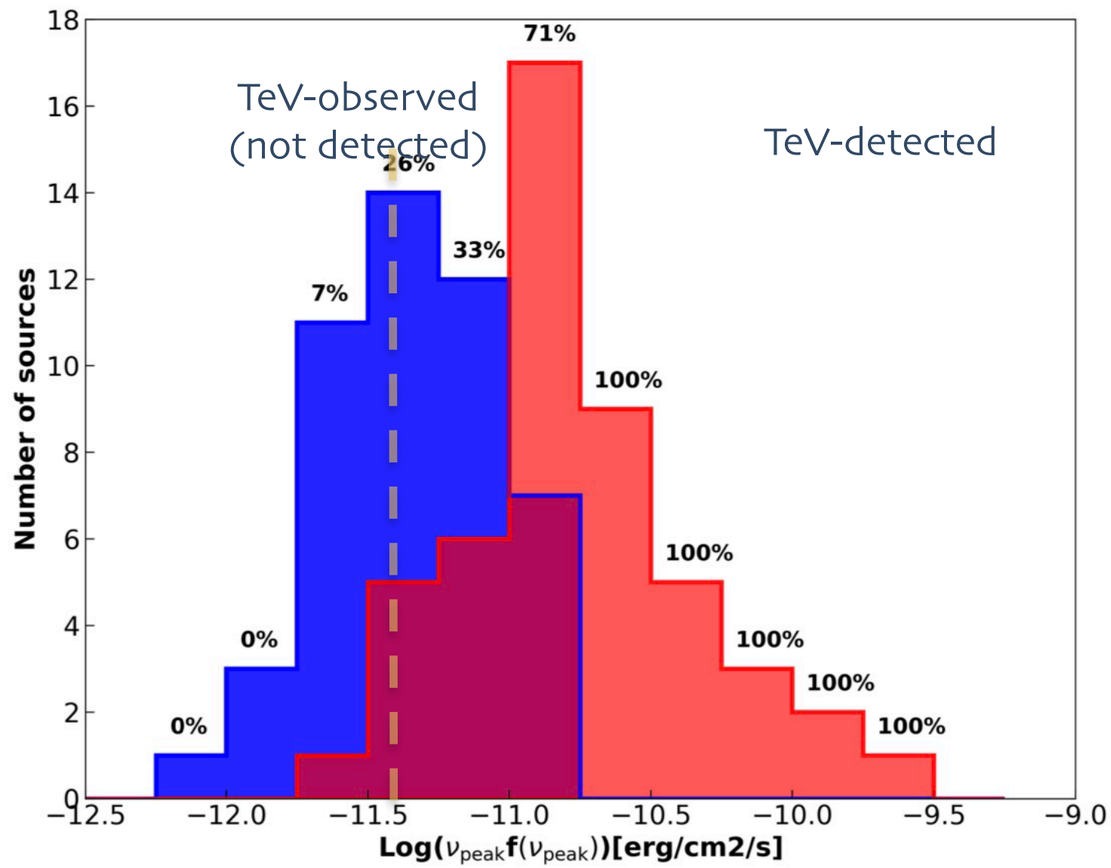
Sensitivity limit *2.5x10^{-12} erg/cm2/s E>100 GeV*

The TeV extragalactic survey: predictions

- Estimation based on IR-synchrotron-IC predictions (from Fermi/LAT 4LAC-DR3) and current TeV observations
- 158 expected detectable blazars with the CTAO survey



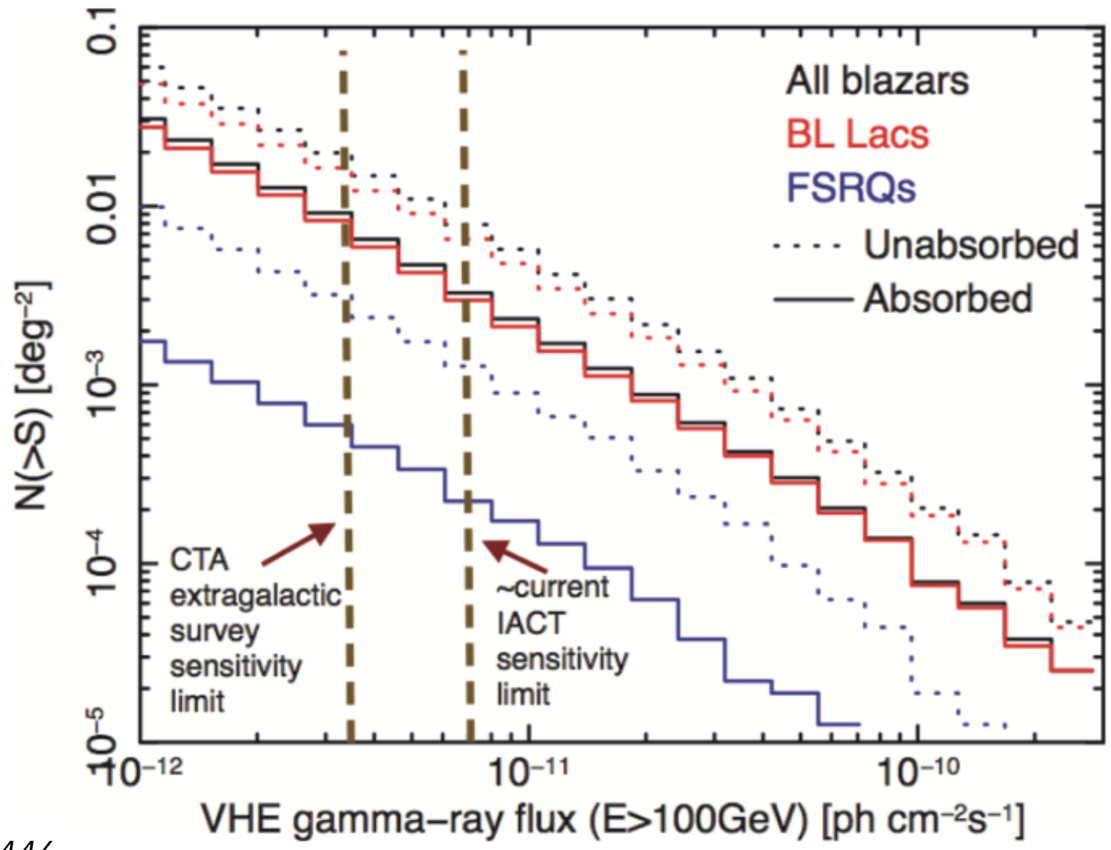
Log($\nu F\nu$) bin	p	No. of blazars in bin	Expected detections in 1,100 sq deg	Expected detections in 10,000 sq deg
> -11.25	100%	3	3	27
-11.25 to -11.50	71%	7	5	45
-11.50 to -11.75	33%	10	3.3	30
-11.75 to -12.00	26%	17	4.4	40
-12.00 to -12.25	7%	25	1.8	16
< -12.25	0%	47	0.0	0
Total				158



Giommi, Sahakyan et al. 2024, ApJ, 963

The TeV extragalactic survey: predictions

- TeV flux from simulated SED (*simplified view of blazars*)
- Extrapolation to GeV-TeV using Fermi/LAT and observed properties of TeV blazars
- ~100 detections with CTAO survey



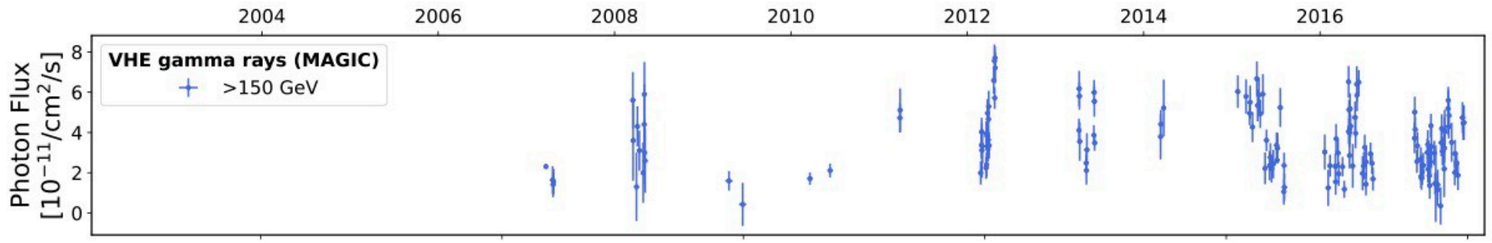
Padovani&Giommi 2015, MNRAS, 446

Derive properties of TeV blazars

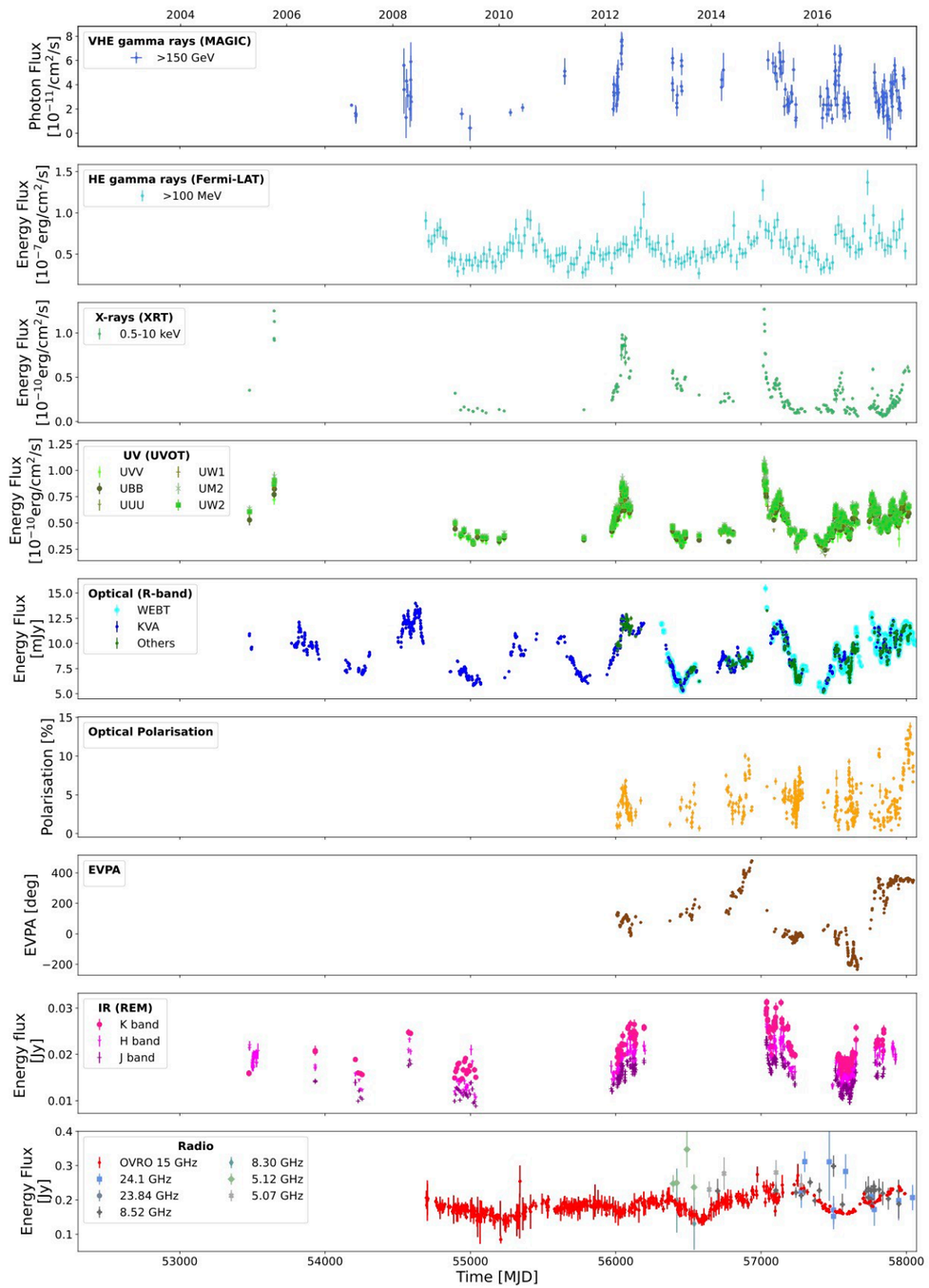
- Derive General properties of TeV blazars (e.g. Senturk+2013)
- An unbiased monitoring on a few TeV blazars (e.g. PG1553+113, since 2015)
- Correlation studies and precise SED modelling; PSD; Duty cycle.

Work in progress!

(E. Prandini, G. Silvestri)



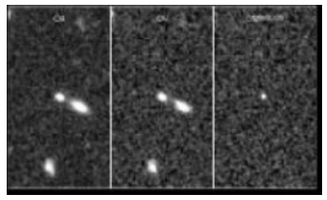
MAGIC Collaboration, 2024, MNRAS, 649



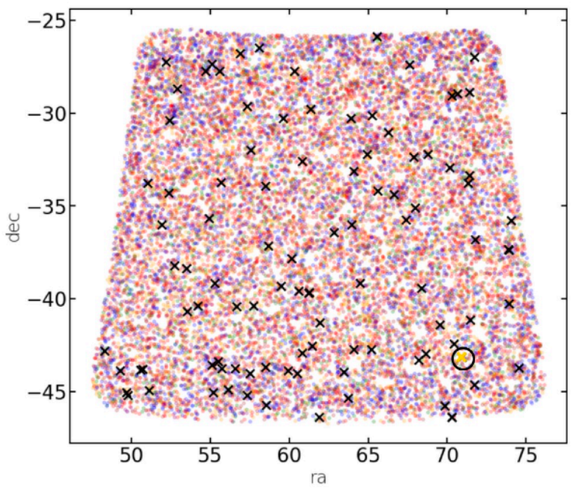
High-energy and TeV counterparts and follow-up in the LSST era


- A bridge between the high-energy observations and the LSST
  in-kind project PI: A.L. Antonelli. OAR-INAF - G. Altavilla, SSDC-INAF
- GOAL: LSST TVS analysis in a multi-frequency and multi-messenger context to allow the maximum exploitation of the astrophysical information contained in the data in a high-energy and very-high-energy field

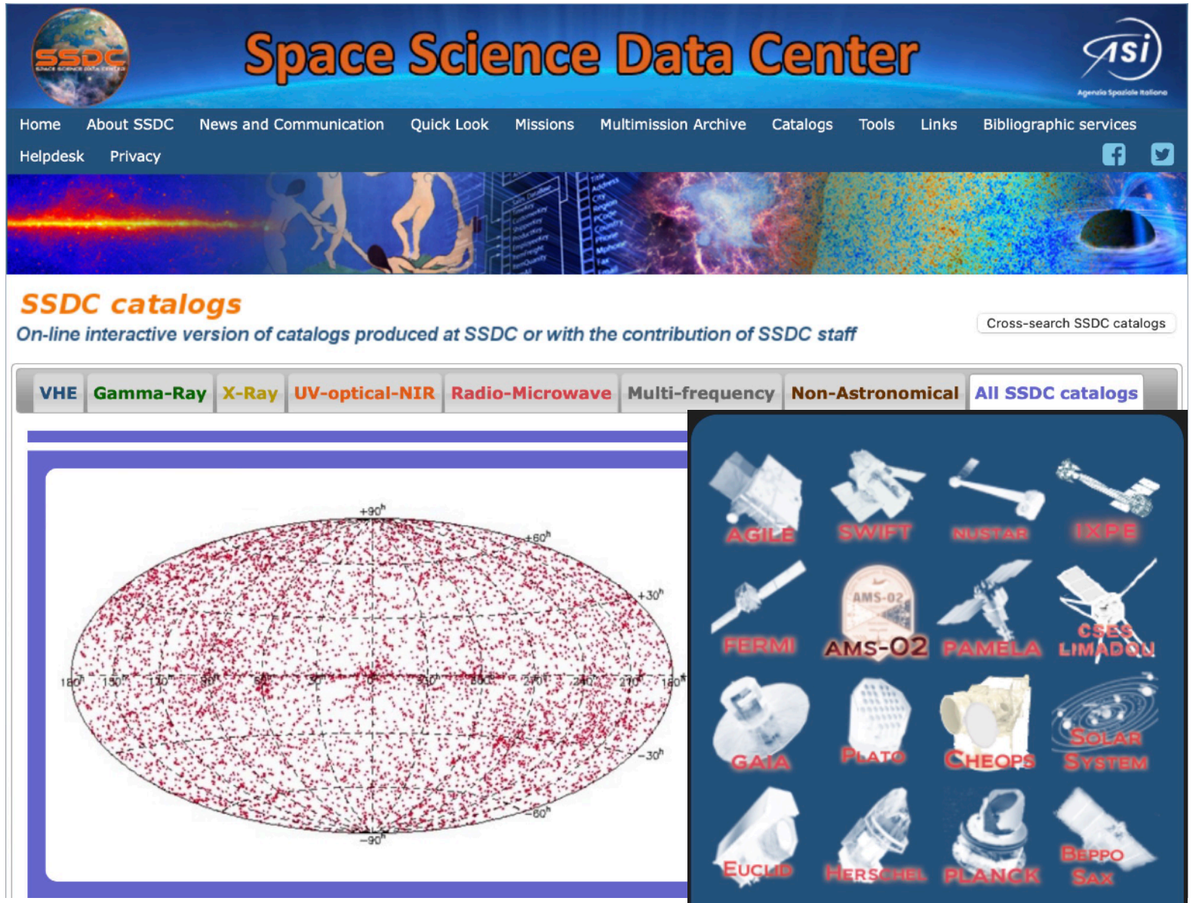
METHOD



Alerts



RAW-DP0-data



https://www.ssdc.asi.it/SSDC_source_catalogs.html

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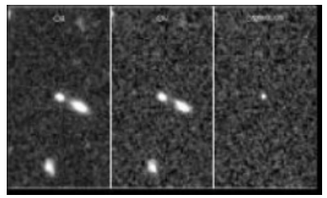

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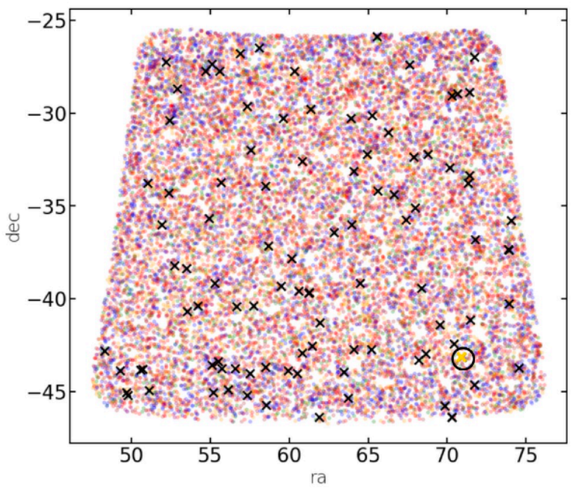

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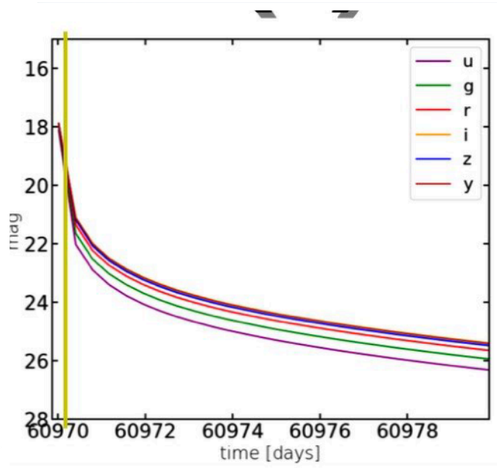

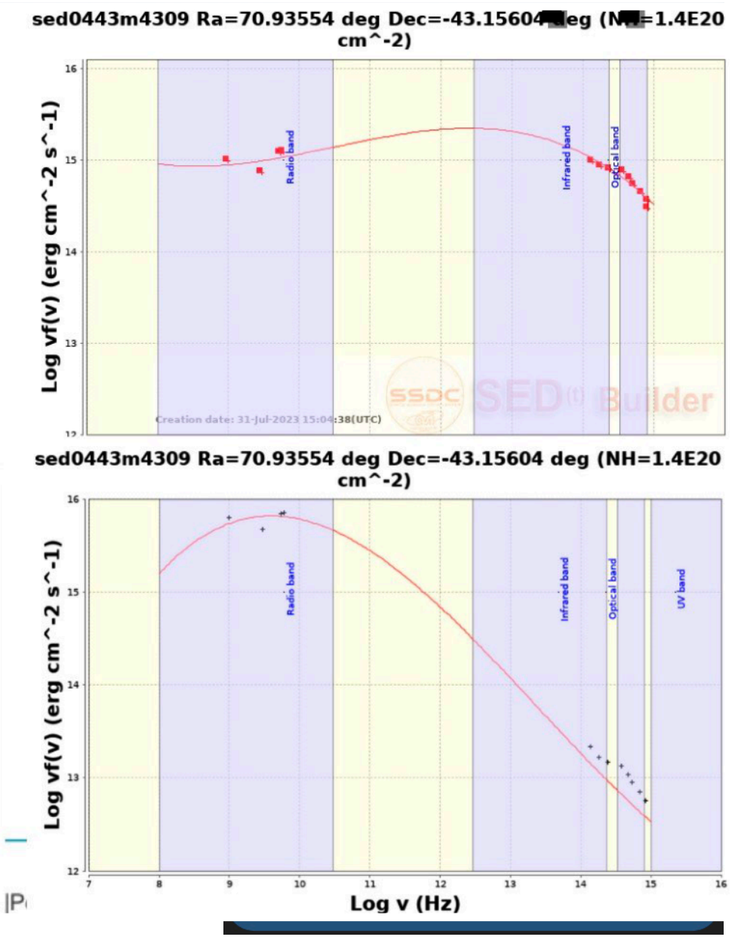

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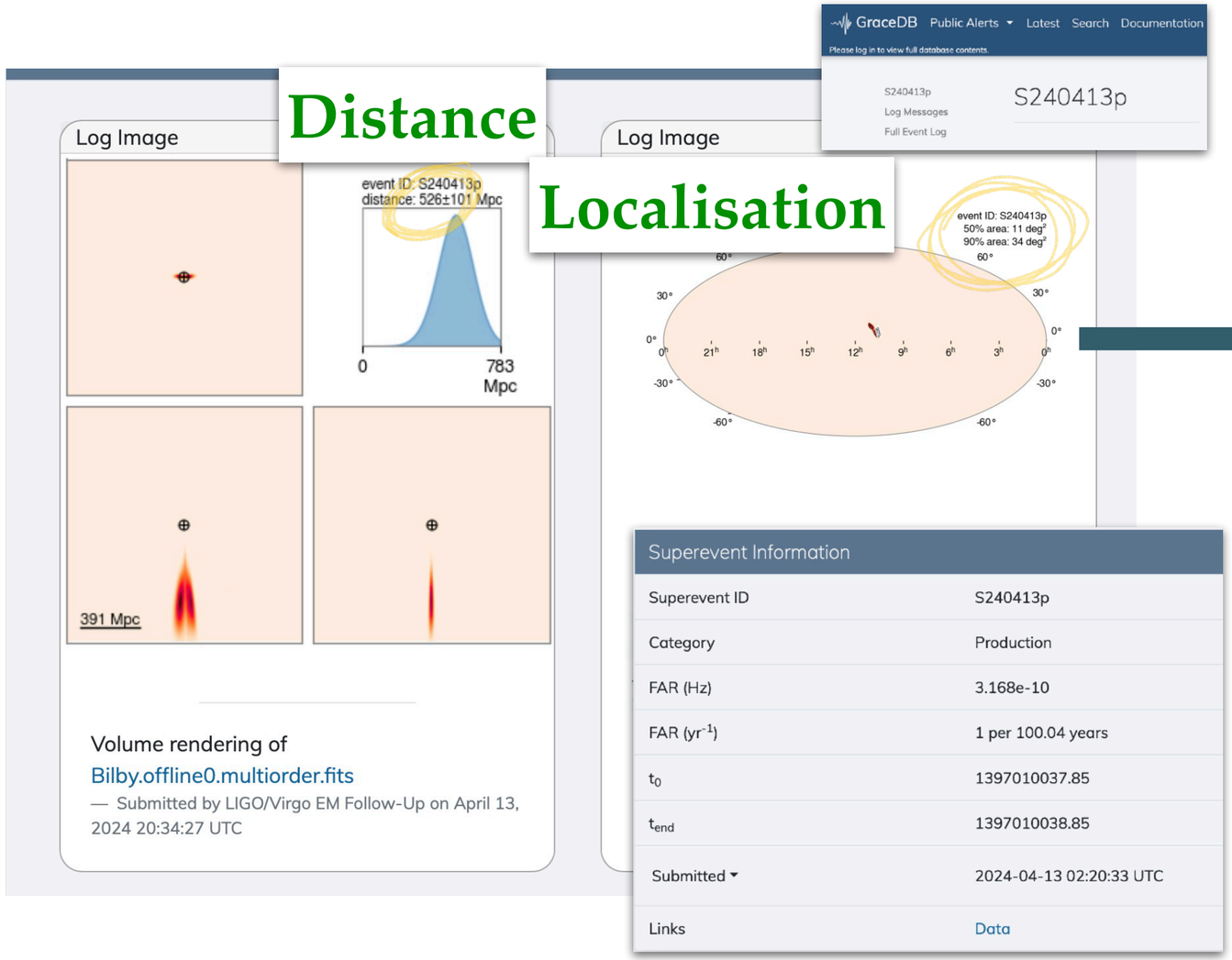
Gravitational wave surveys

- Scientific runs with GW interferometers



First significant event in O4b, including Virgo
April 13, 2024 - BBH @526 Mpc

event ID: S240413p
50% area: 11 deg²
90% area: 34 deg²

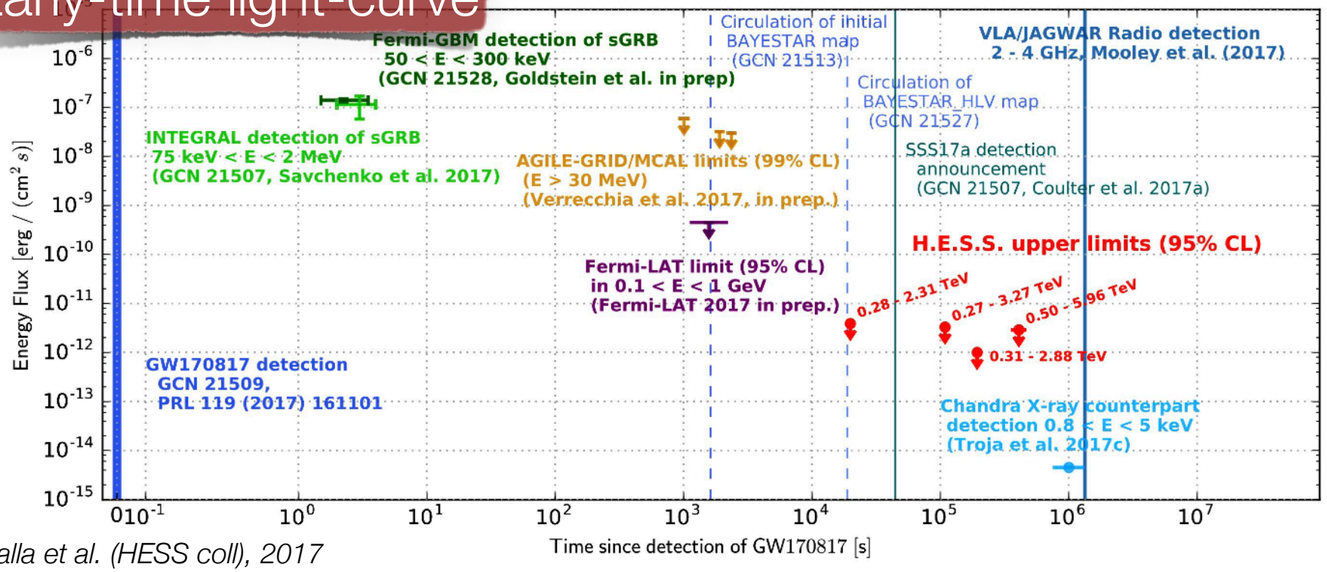
CTAO could cover most of the region with a single or a few pointings!

https://gracedb.ligo.org/superevents/S240413p/view/

Gravitational Wave counterparts at TeV energies

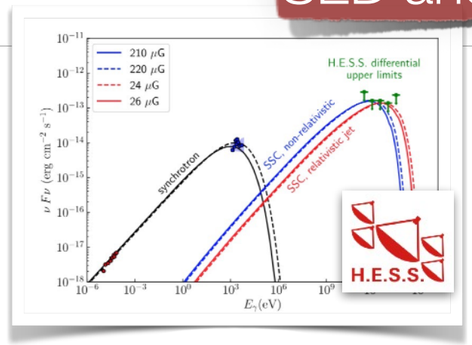
No detection of GeV-TeV emission from the counterpart of GW170817/GRB170817A

Early-time light-curve

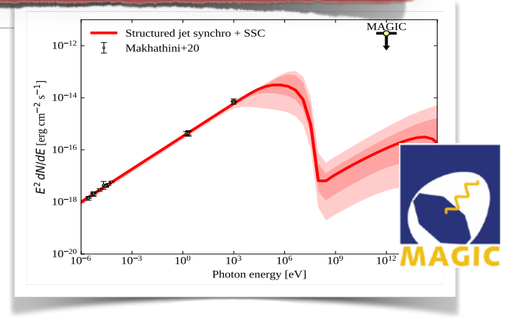


Abdalla et al. (HESS coll), 2017

SED and spectral models



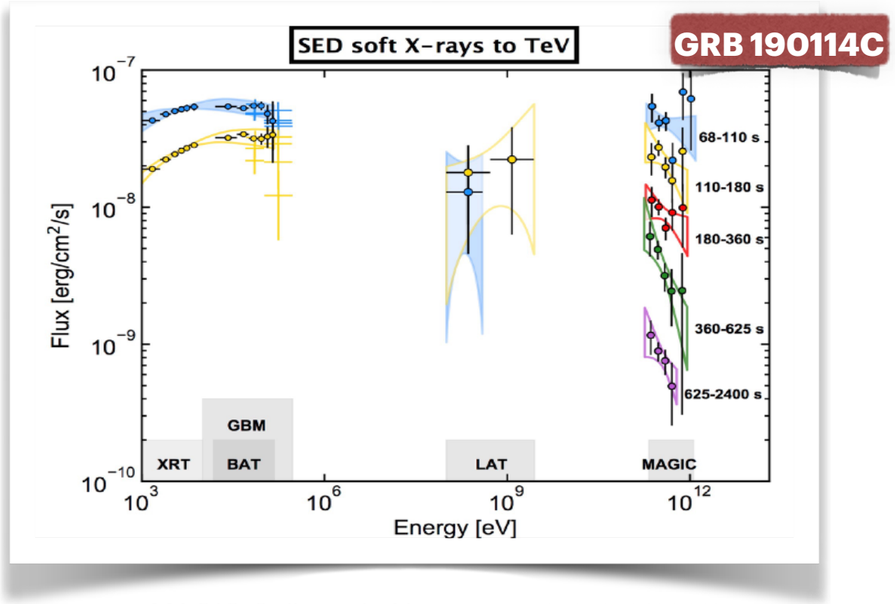
H.E.S.S. coll., 2020 ApJL, 894



AS, Salafia O. S., et al. 2021a, PoS, 944

But, GRBs have been detected at TeV energies since 2019

GRB190114C, GRB190825A, GRB201216C, GRB180720B, GRB221009A



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

A Dedicated Study on the CTAO's Prospects on GW Follow-ups

CTAO

G O A L S

Compute the joint GW and CTAO detection rates from binary neutron star (BNS)

Explore the parameter space of the GW-GRBs detectable by CTAO

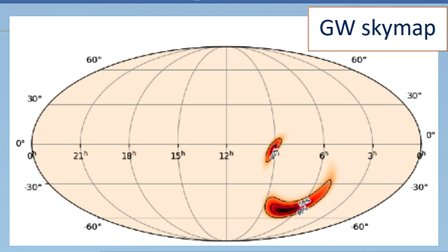
- Physical parameters (luminosity, jet opening angles and jet orientation, spectral slope)
- Observational parameters (time delays, exposures)

Optimise the observing strategy

- Maximise the detection rate
- Maximise the physical interpretation return
- Evaluate the amount of observing time

An evolved multi-messenger scenario on GWs and TeV-GRBs

Prospects on GW followups at TeV energies with CTAO

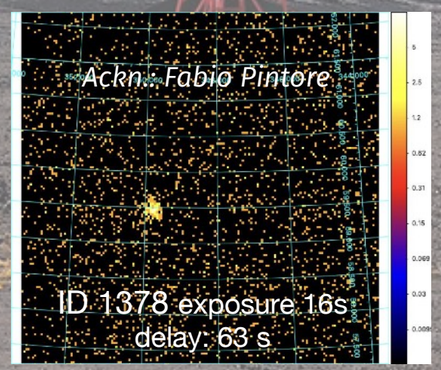


Simulation of BNS mergers
and GW signal in local universe

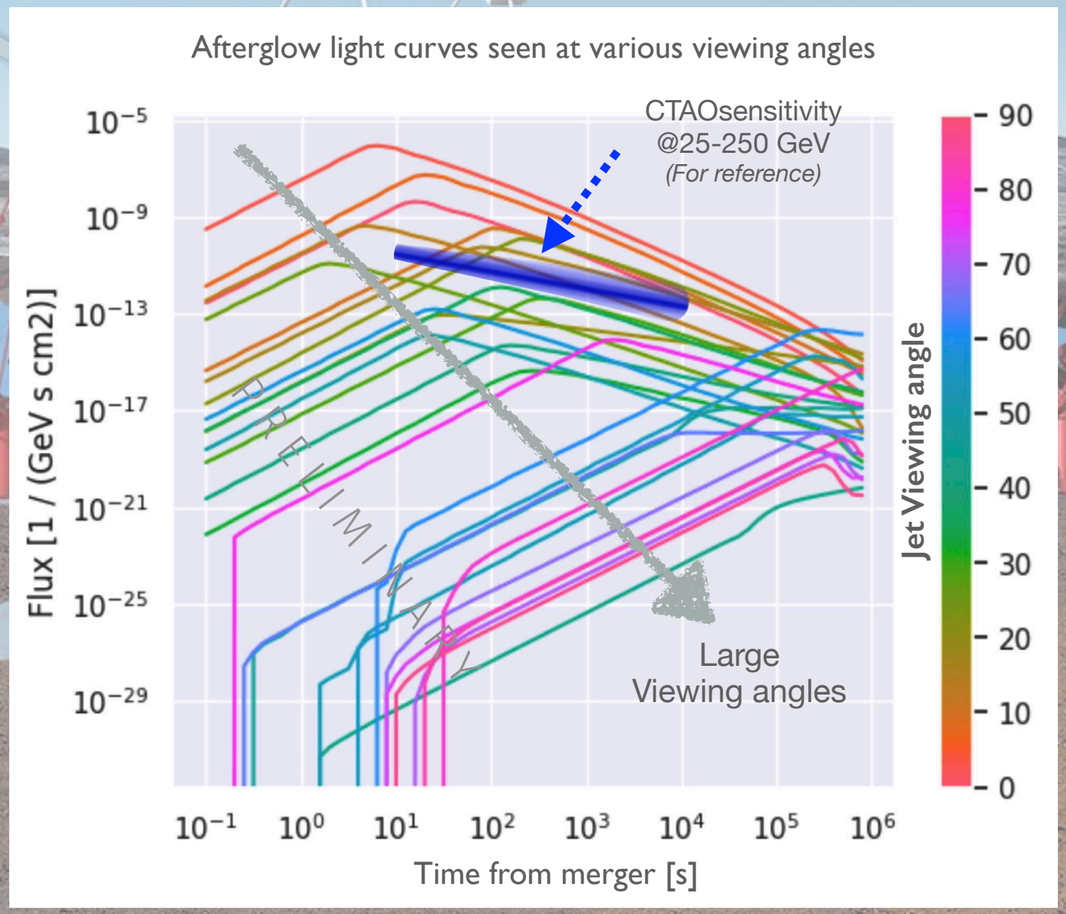
Synthetic GW-GRBs
Phenomenological model of VHE emission of short-GRB

Simulation of CTAO response (set of IRFs*) *gammapy, ctools*

* IRF: Instrument Response Function



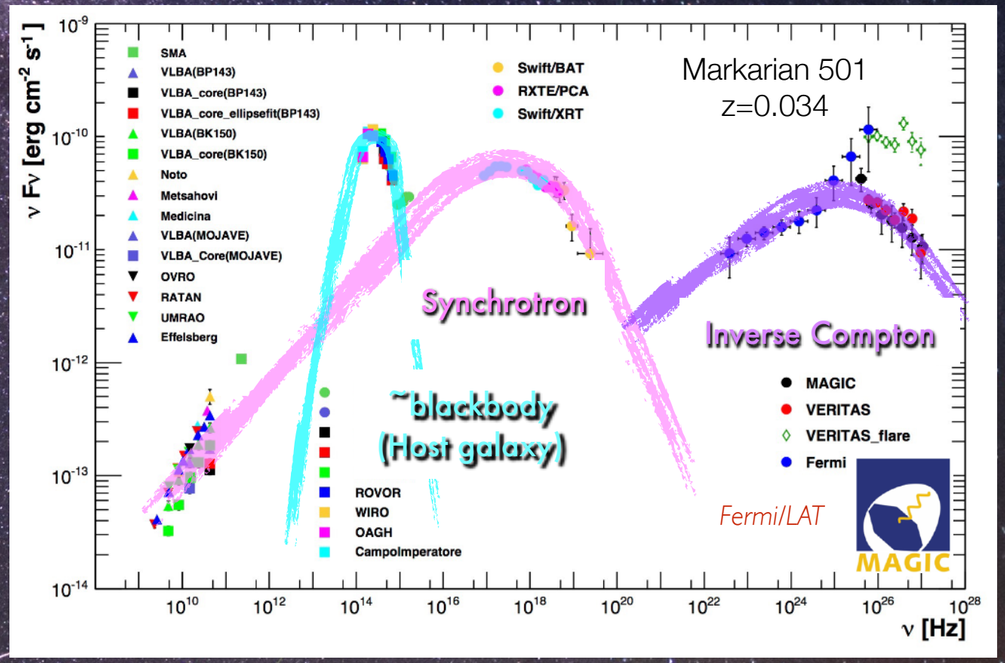
- Computation of CTAO sensitivity tailored on the GW-GRB models, including EBL absorption
- CTAO Alpha configuration

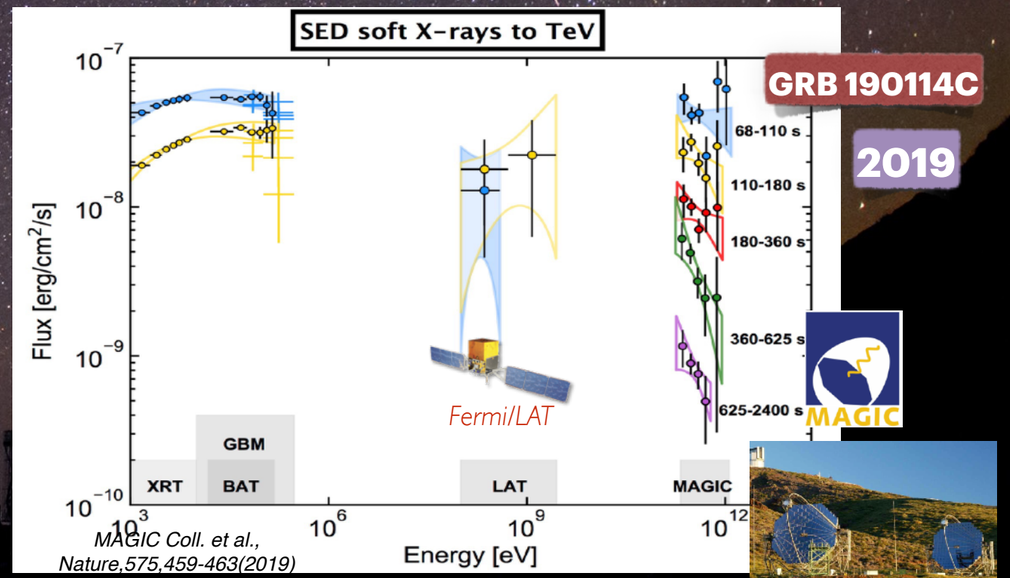


J. Green, L. Nava, B. Patricelli, M. Seglar-Arroyo

Surveys using TeV observations: summary

- TeV observations are crucial for understanding extreme sources such as blazars and gamma-ray bursts, which are dominated by non-thermal emission.
- Cherenkov telescopes have a sufficient field of view to cover approximately 1/4 of the sky at ~6 mCrab sensitivity between 20 GeV and a few TeV for redshifts z< ~2
- An extragalactic survey at TeV energy is currently lacking.
- The CTAO extragalactic survey is expected to detect around 100 sources, including flaring events and various source classes. Further studies are needed to improve precision power and to optimize the survey strategy.
- Project ongoing to utilize TeV archival data and follow-up observations for the LSST program on transients and AGN.
- A new landscape of gravitational waves and TeV-GRBs has emerged, leading to an expanded science program that will be proposed for CTAO.





Surveys using TeV observations: summary

- TeV observations are crucial for understanding extreme sources such as blazars and gamma-ray bursts, which are dominated by non-thermal emission.
- Cherenkov telescopes have a sufficient field of view to cover approximately 1/4 of the sky at ~6 mCrab sensitivity between 20 GeV and a few TeV for redshifts z< ~2
- An extragalactic survey at TeV energy is currently lacking.
- The CTAO extragalactic survey is expected to detect around 100 sources, including flaring events and various source classes. Further studies are needed to improve precision power and to optimize the survey strategy.
- Project ongoing to utilize TeV archival data and follow-up observations for the LSST program on transients and AGN.
- A new landscape of gravitational waves and TeV-GRBs has emerged, leading to an expanded science program that will be proposed for CTAO.

Share your insight!

MAGIC

CTAO CONSORTIUM


Elisa


Giuseppe


Jarred


Barbara


Lara

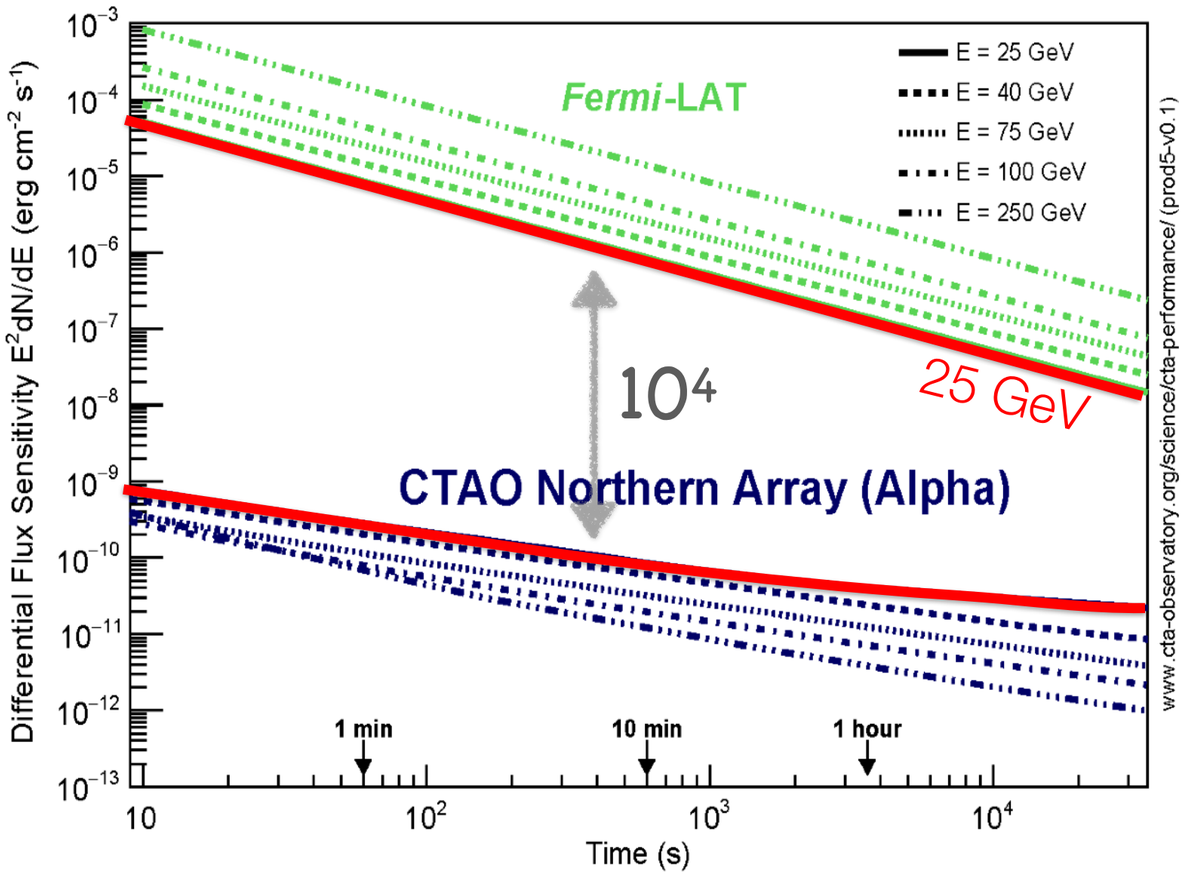

Monica


Antonio

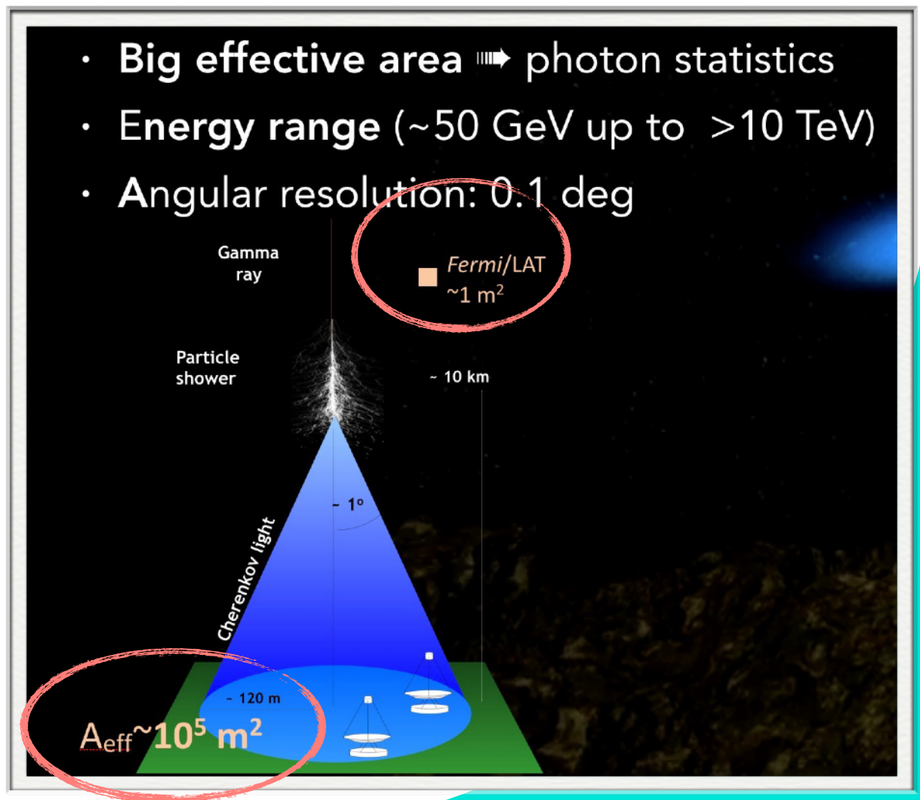
INAF
ISTITUTO NAZIONALE DI ASTROFISICA

ICSC
Centro Nazionale di Ricerca in HPC, Big Data and Quantum Computing

CTAO performances: Sensitivity to transient and flaring sources



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

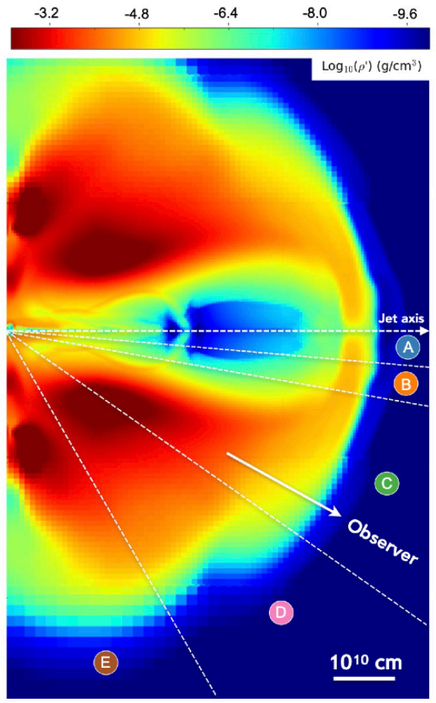


The Role of Off-axis Observations and structured Jet

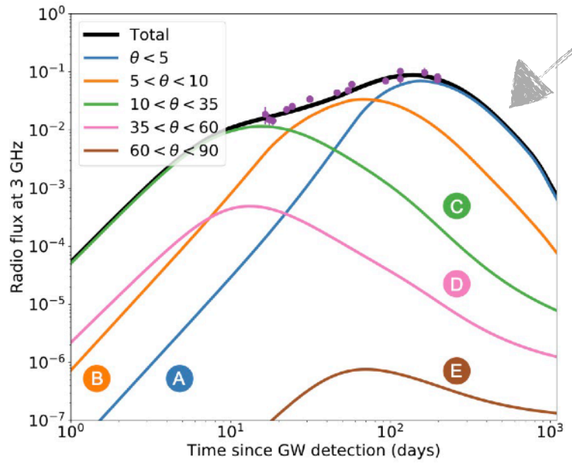
GeV-TeV emission is expected from the relativistic outflow (jets)

In GW-counterparts, the jet is seen preferentially **off-axis:** small Lorentz factor

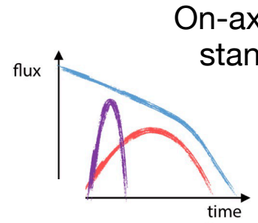
- ➡ intensity <u>weaker</u> 10^{-4} to 10^{-6} times than on-axis emission
- ➡ light curve <u>delayed</u> (hours/days/months, depending on θ_{view})

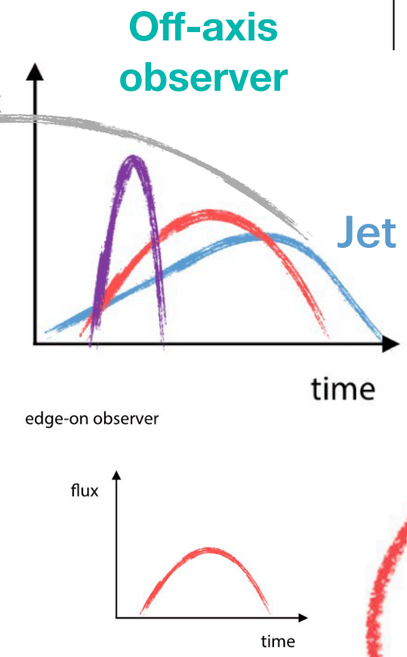


Off-axis observer and STRUCTURED JET



Hydrodynamical simulation of a short GRB (Lazzati+2018)





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