CTAO
Cherenkov Telescope Array Observatory

Which are the CTAO-WST synergies?

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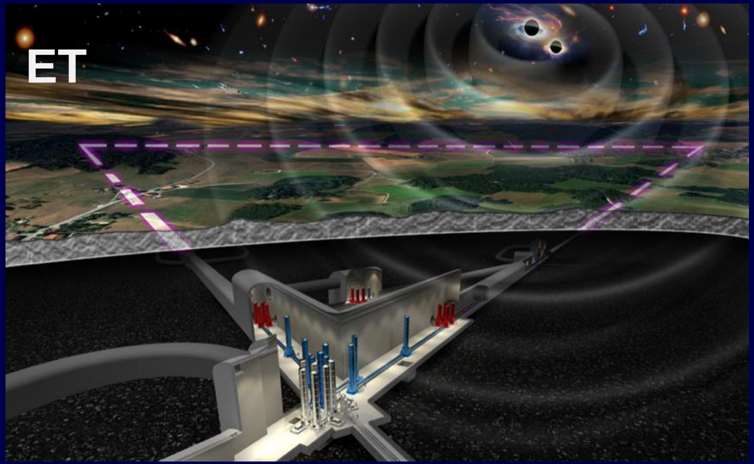
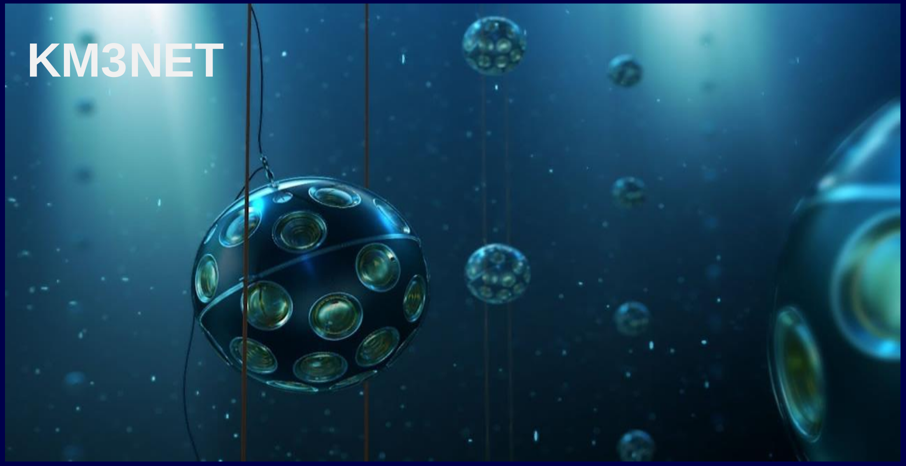
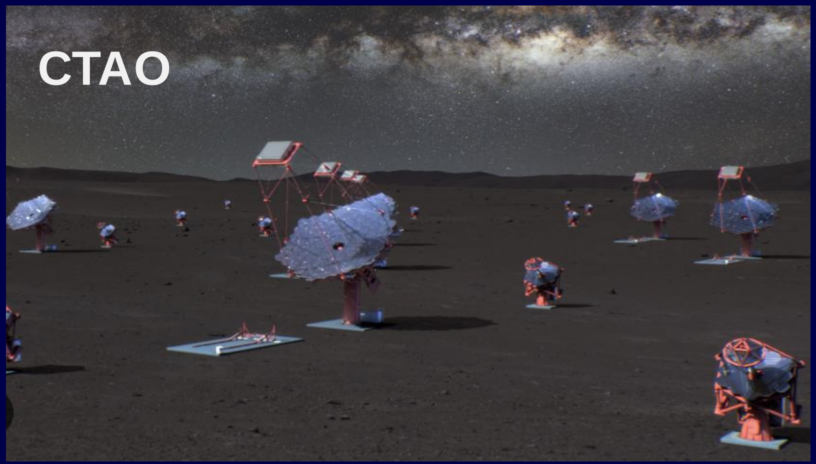
Napoli - March 10, 2025

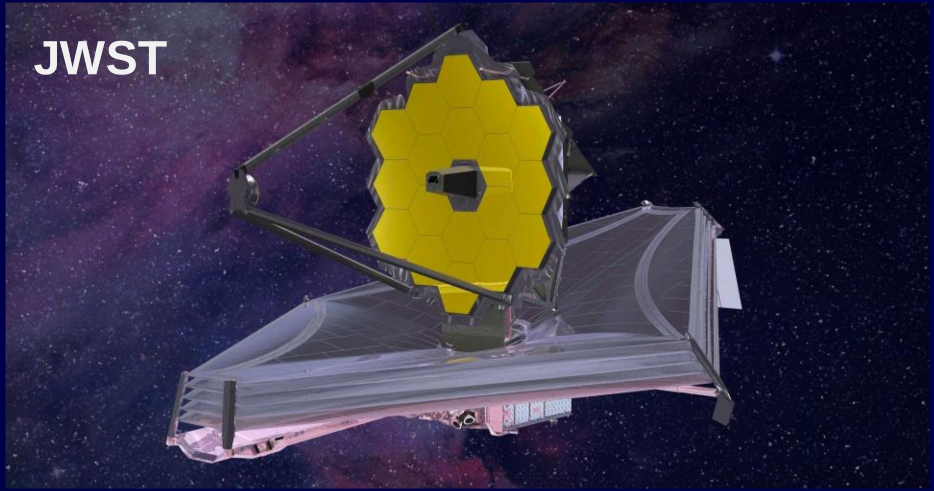
Next decays in astronomy

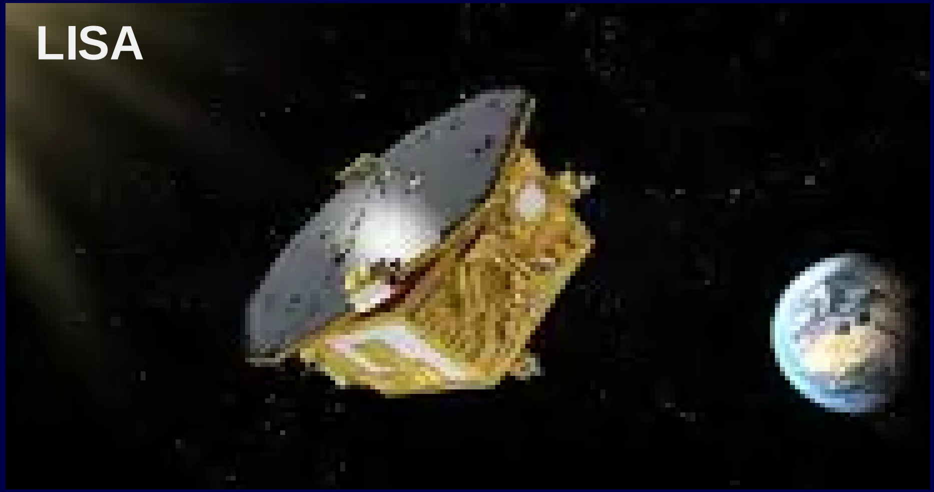






Next decays in astronomy





Next decays in astronomy

- **Huge amount of high-quality imaging data**
- **Alerts from non-γ messengers**
- **Giant leap in survey capabilities**

a complete scientific exploitation requires characterization and understanding of these data

CTAO SKAO Athena WST

multi-wavelength /multi-messenger

VHE gamma-ray astronomy

γ rays: $m_e c^2$ →

meV … eV … keV … MeV … GeV … TeV … PeV … EeV .. ZeV

astronomy

astroparticle physics

Photons detection

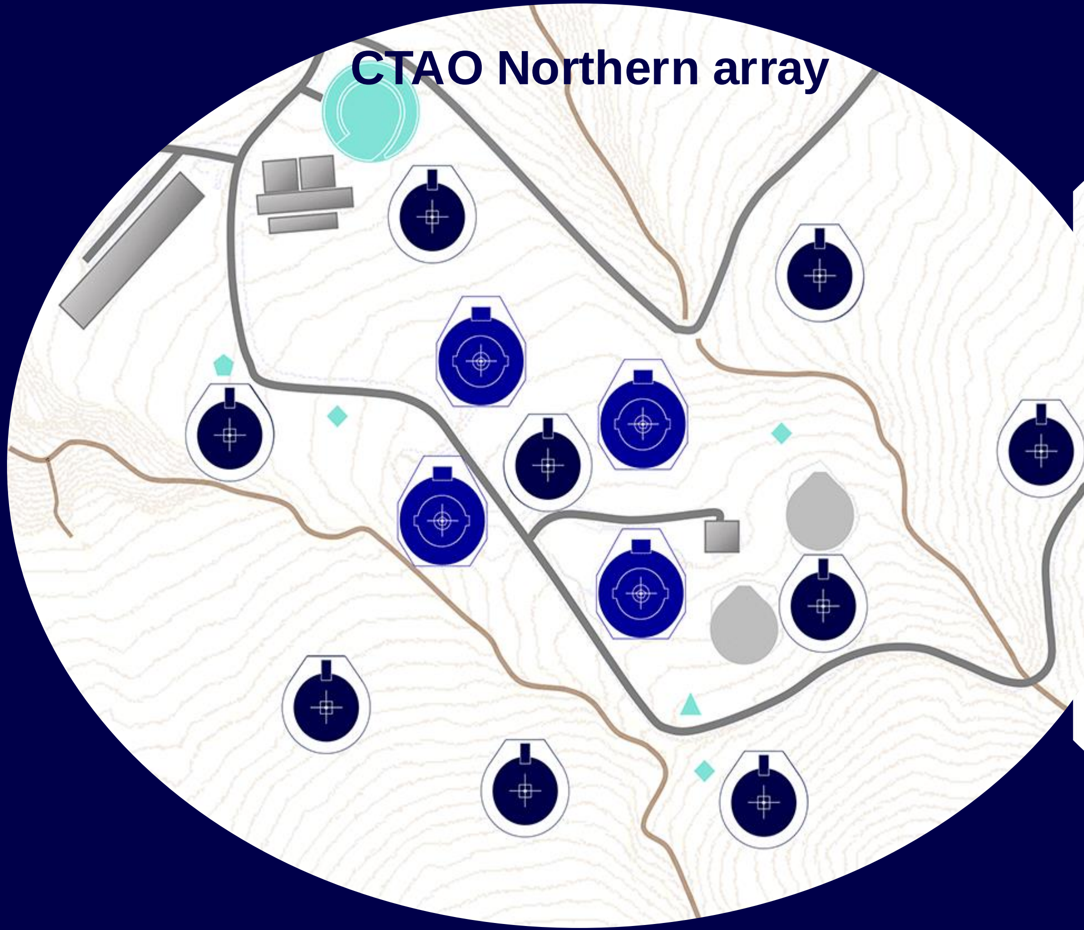
CR Charge particles detection

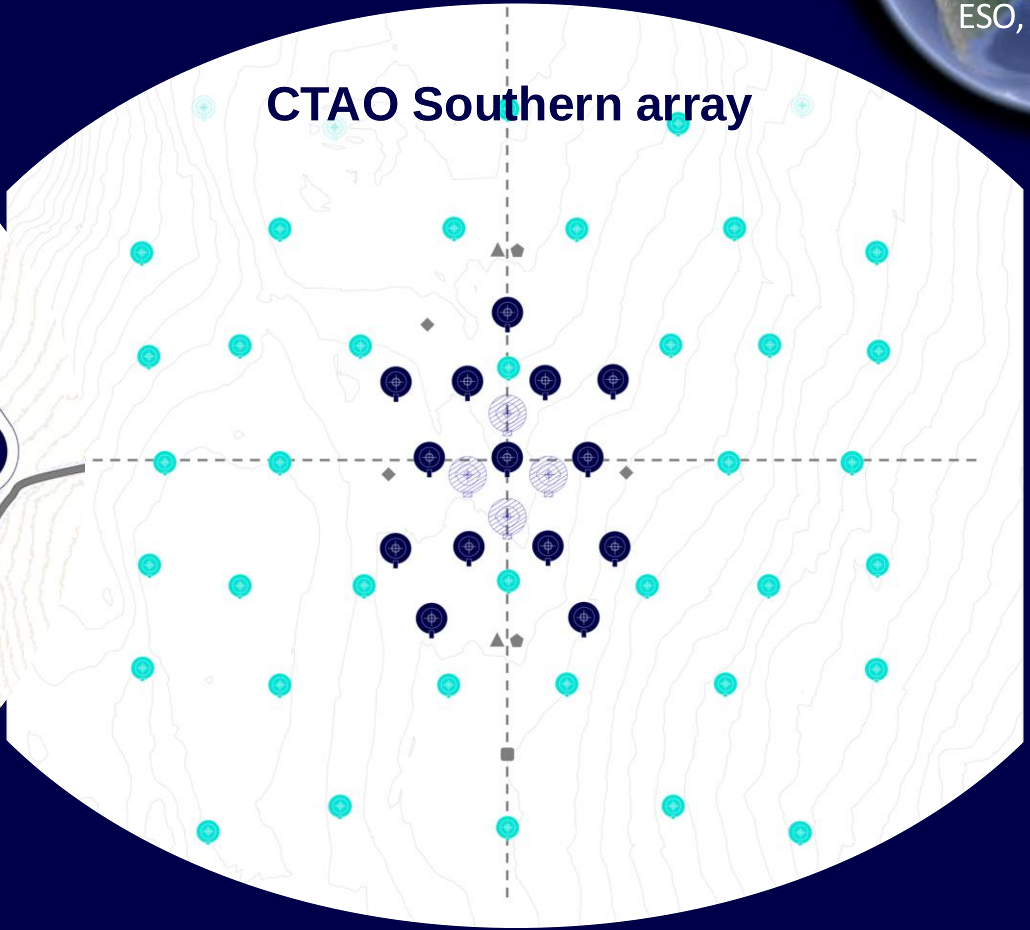
Neutrino signals

CTAO: VHE gamma-ray observatory

The two arrays

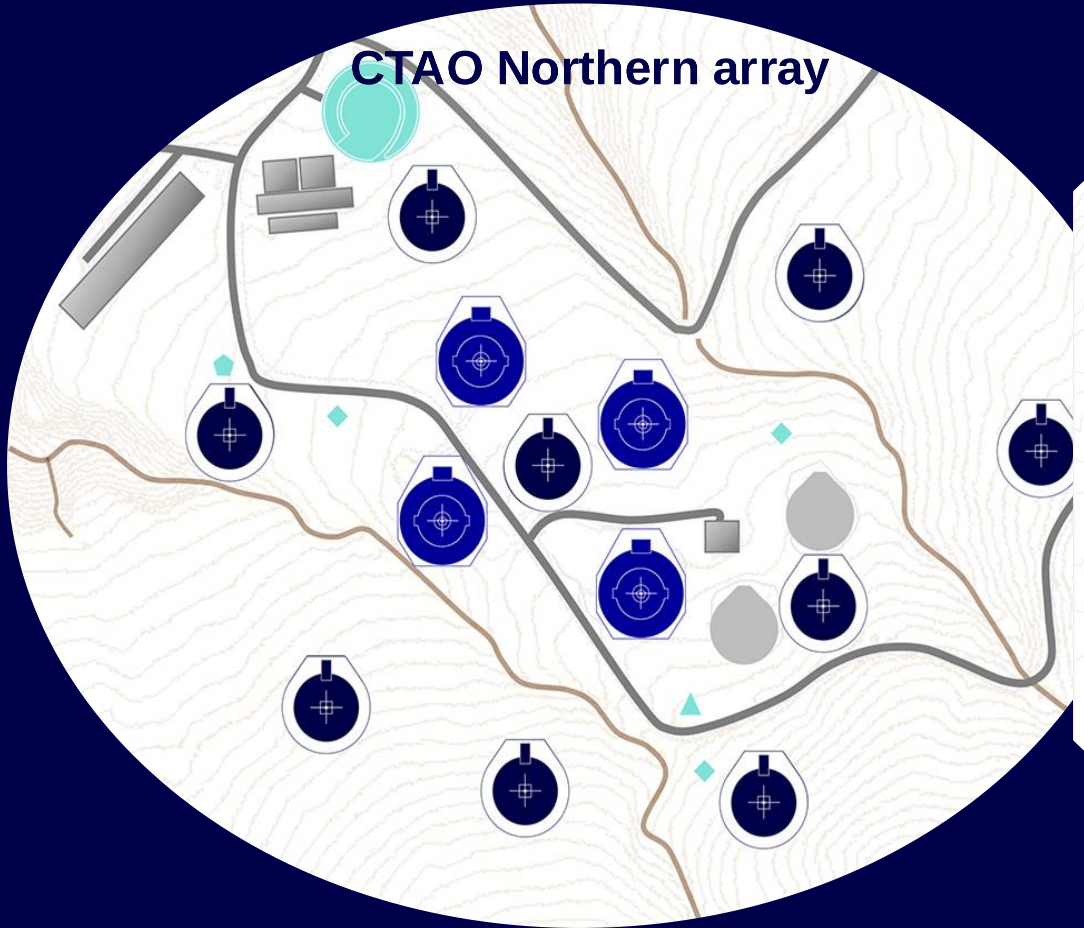
Alpha Configuration

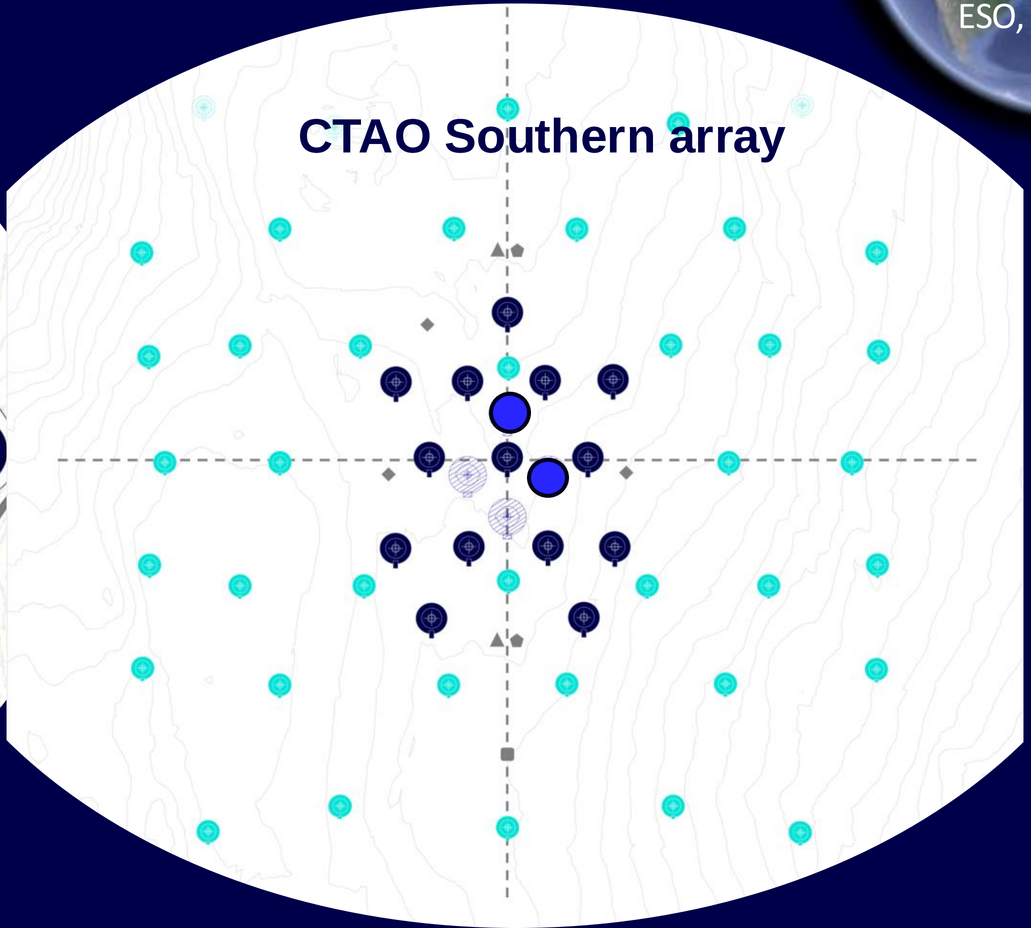




The two arrays

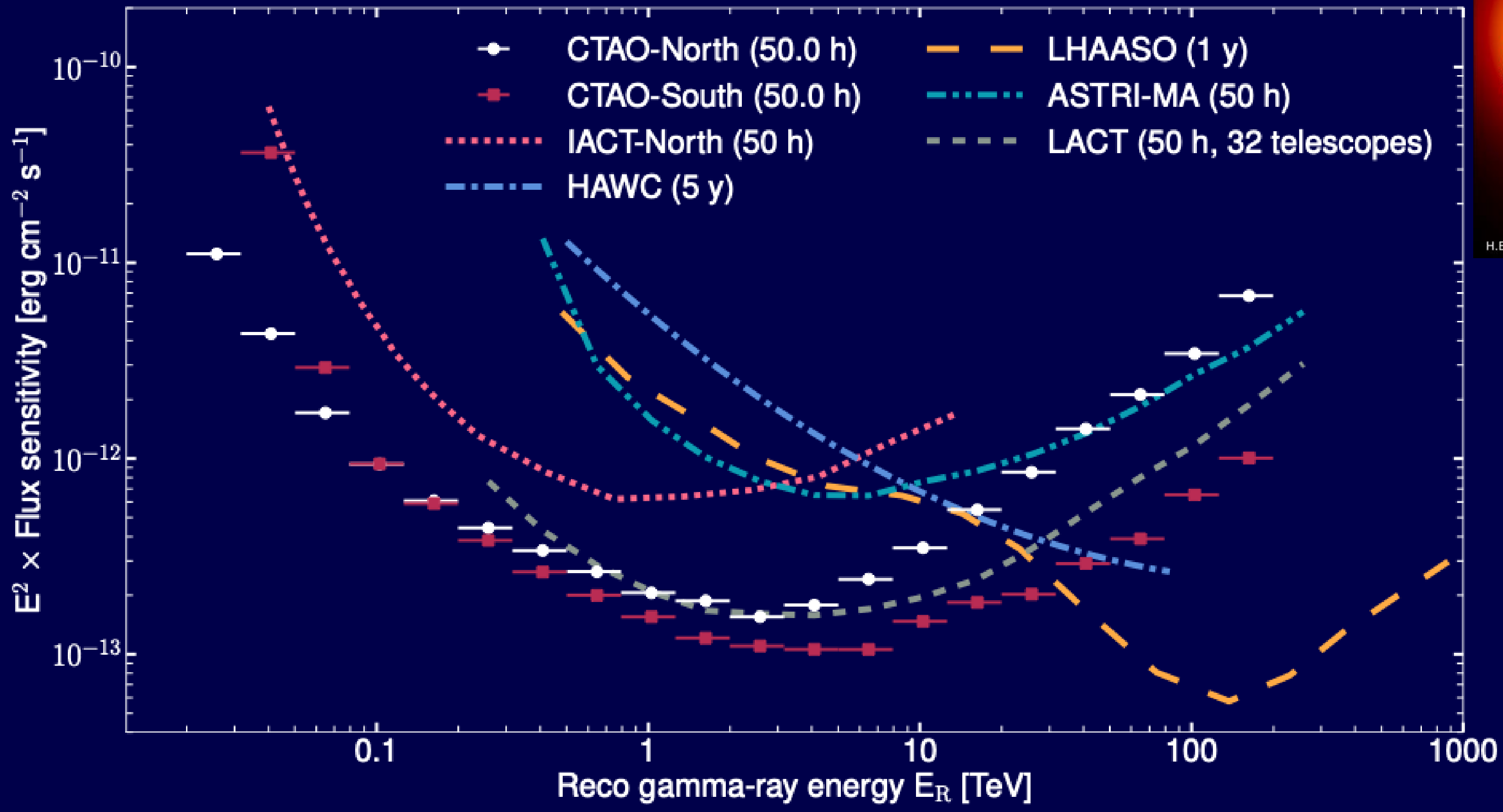
Beta Configuration

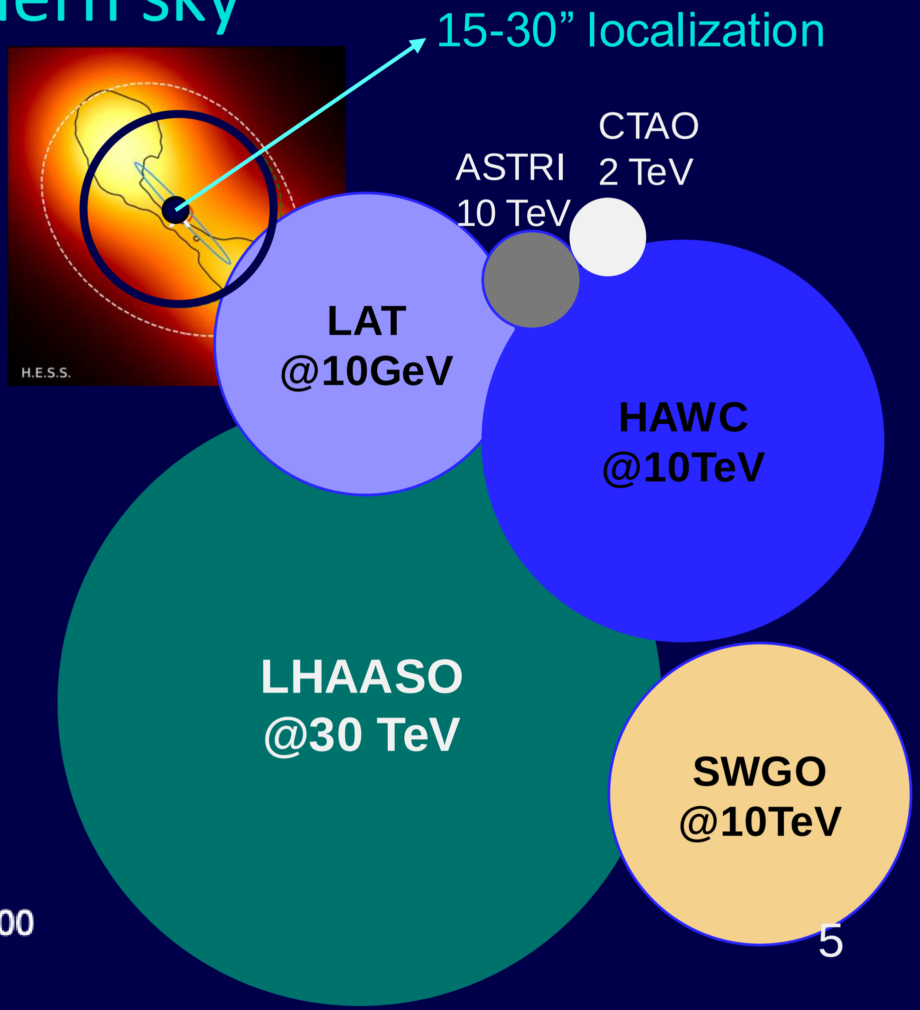




CTAO steady-source performance

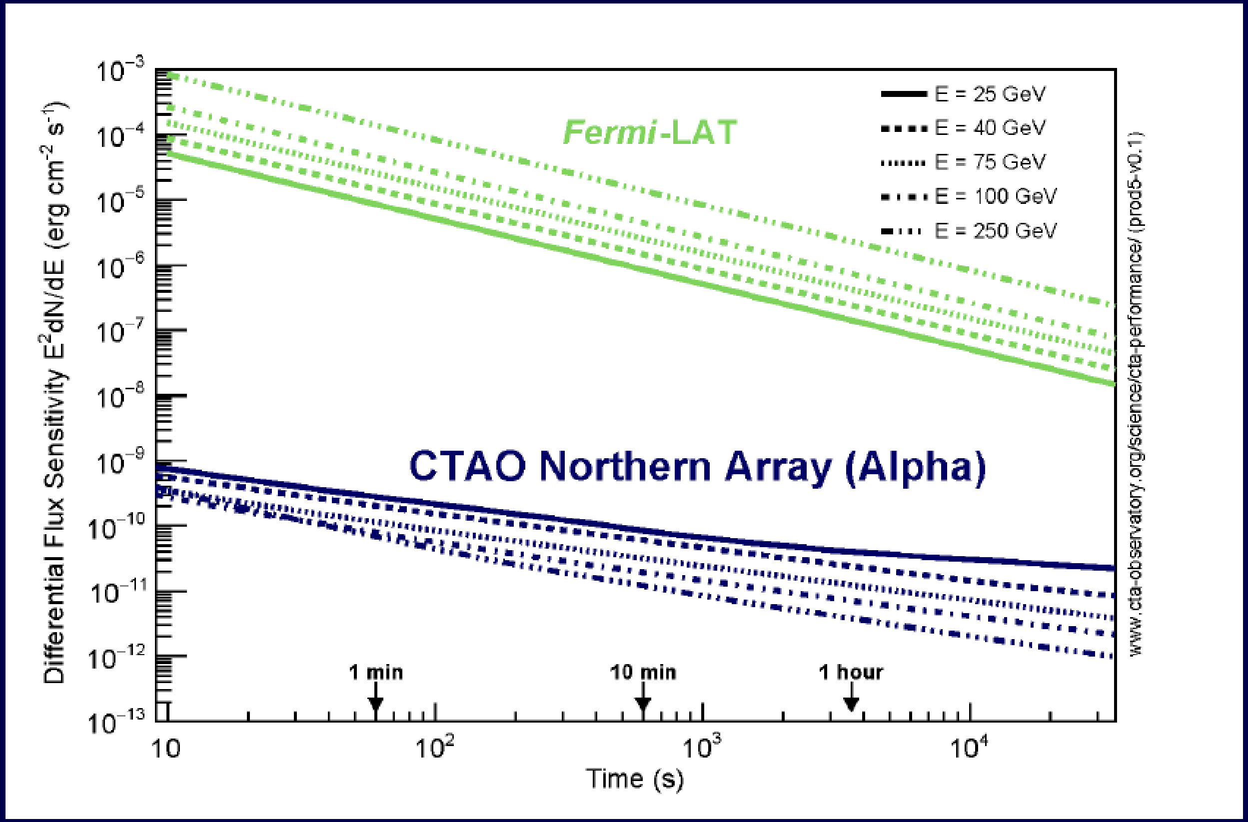
Opening up the multi-TeV science to the Southern sky





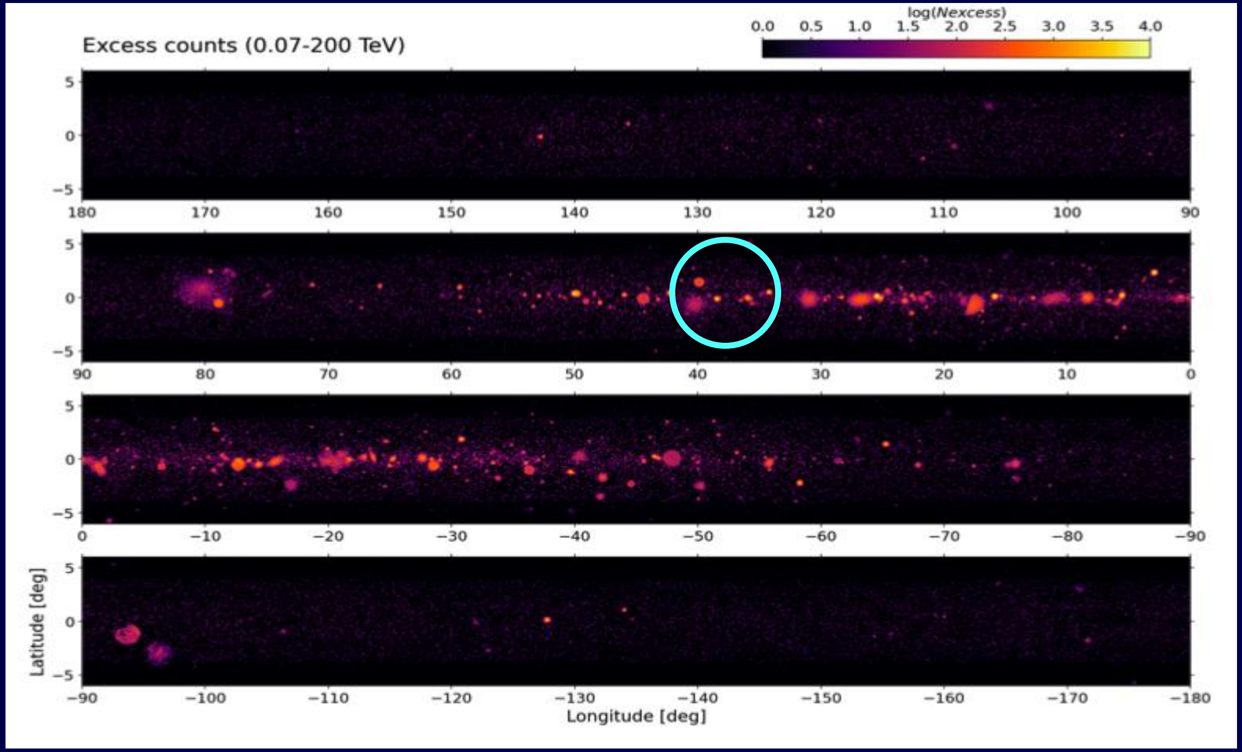
CTAO short-term obs performance

Transients are key science cases



- LSTs can repositioning any point in the sky in 20”
- Real-time analysis that can issue science alerts in 30”

Other CTAO capabilities

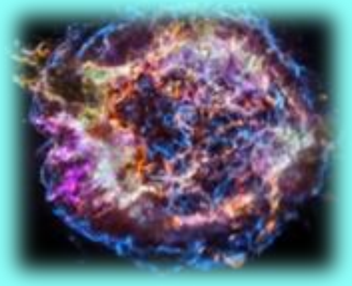


6º γ-ray FoV

Themes of the VHE astronomy

COSMIC PARTICLE ACCELLERATION

- How & where particles are accelerated?
- How do they propagate?
- What is their impact on the environment?



PROBING EXTREME ENVIROMENTS

- Which are the processes close to neutron stars and black holes?
- Which are the processes in relativistic jets, winds and explosions?
- What are the cosmic voids?

PHYSICS FRONTIERS - BEYOND THE STANDARD MODEL

- What's the nature of the dark matter? How is it distributed?
- Do axion-like particles exist?

VHE – optical astronomy

proportional to needed obs time

	Time domain	Stellar populations	BH jet/ accretion	Dark Matter
COSMIC RAYS				
EXTREME ASTROPHYSICAL ENVIORMENTS				
FUNDAMENTAL PHYSICS				

AGNs: still many astrophysical quests

- How/where to convert gravitational energy into particle acceleration?

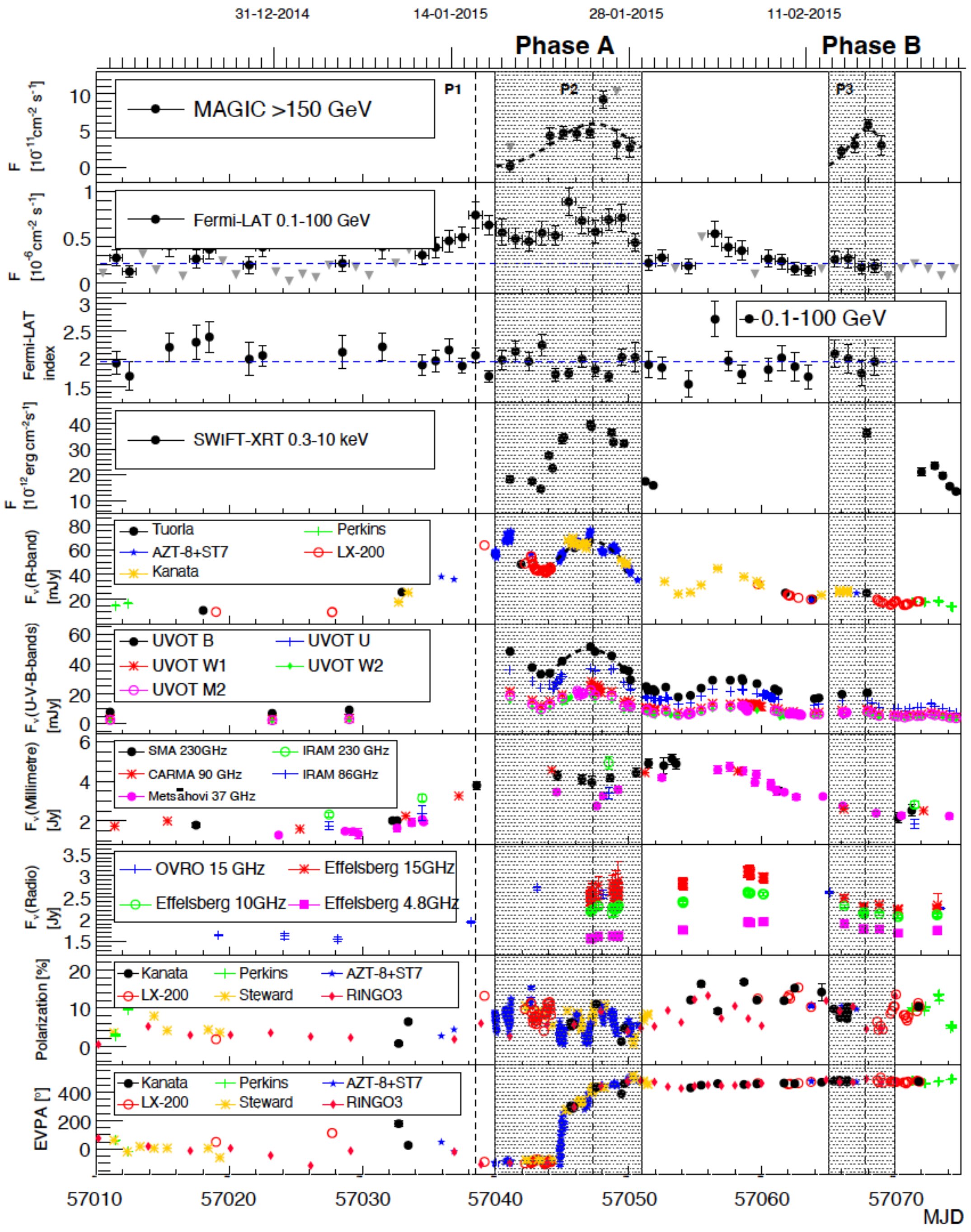
… VHE angular resolution does not help: it is flux variability & opacity arguments that do the game

simulataneous lower frequencies measurements add further dimensions to the study:

- Time lags → co-spatiality (EC vs SSC)
- Variability timescales in two bands → comparison of emission region size
- Polarization → magnatic field orientation

OPTICAL MOST PROFITABLE WAVEBAND TO TARGET SO FAR

- **relatively "cheap" from ground**
- **not absorbed → several correlations found (mainly for LBLs)**



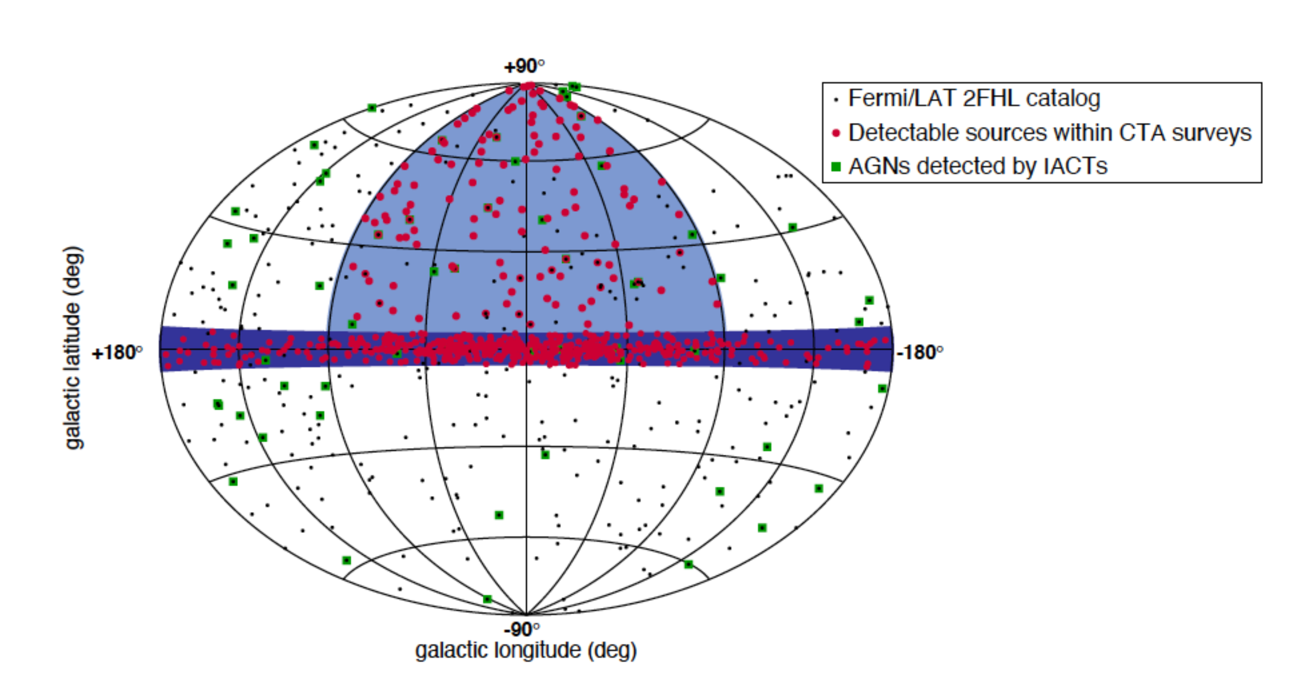
MAGIC Coll. 2018

AGNs

- Optical photometry used as trigger criterium
  → so far a very biased sample
- Simultaneous observations to study the broad band behaviour

MAINLY KNOWN TARGETS → JOINT OBS CAMPAIGNS

CTAO extragalactic survey



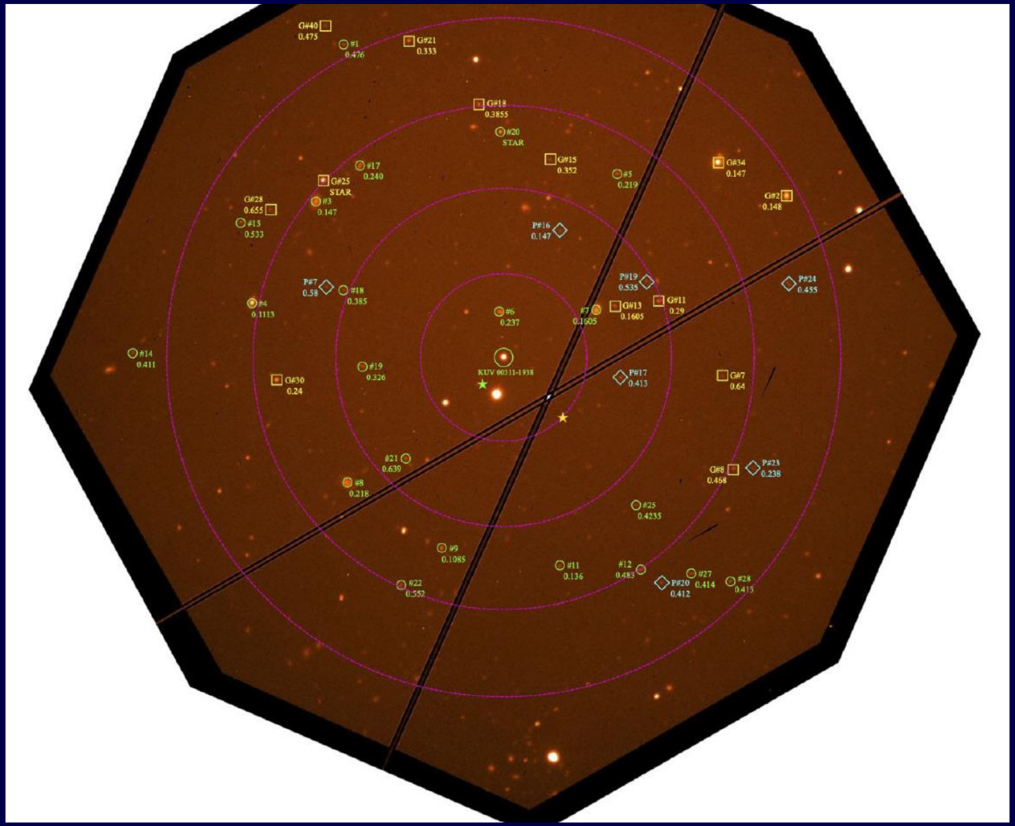
- First blind extragalactic survey with arrays of IACTs
  - remove observational biases in population studies
- New window of exploration on minute timescale variability!

SIMULTANEOUS OPTICAL PHOTOMETRY & JOINT HIGH-CADENCE COVERAGE

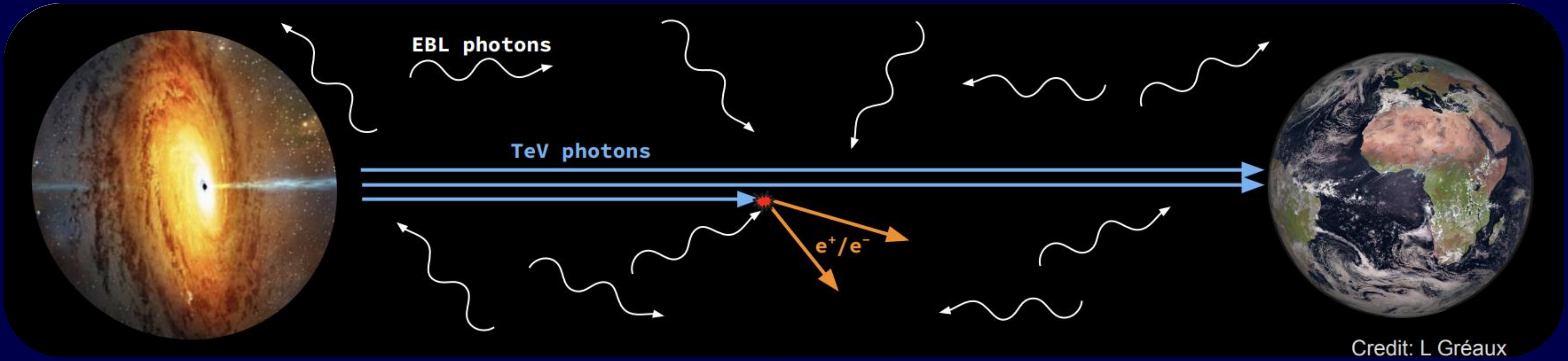
Needed redshift measurements

- In general if position is known, no need for MOS
  - It could be easier during a low flux state when AGN/host galaxy luminosity descrease
- Although when redshift cannot be extracted from the optical spectrum of the blazar, searches for groups of galaxies around the blazar

  → ~10 arcmin FoV is enough!



Why distance matters?

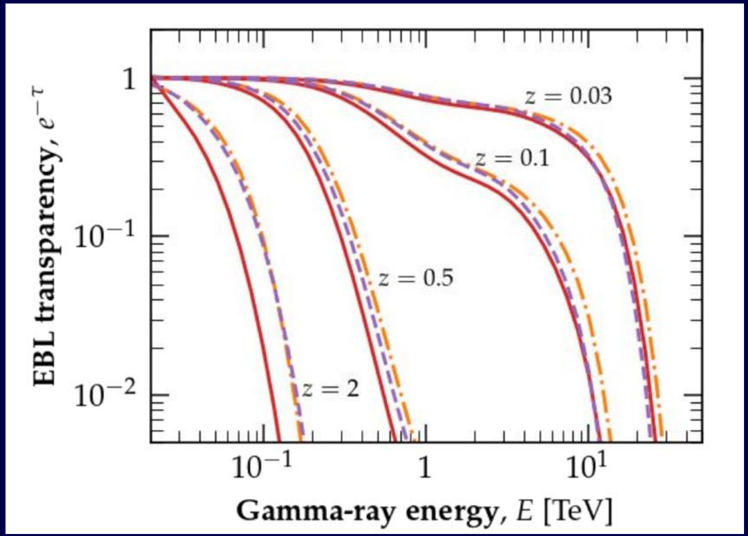


$\phi_{obs} = \phi_{int}(E) \times e^{-\tau(E,z)}$

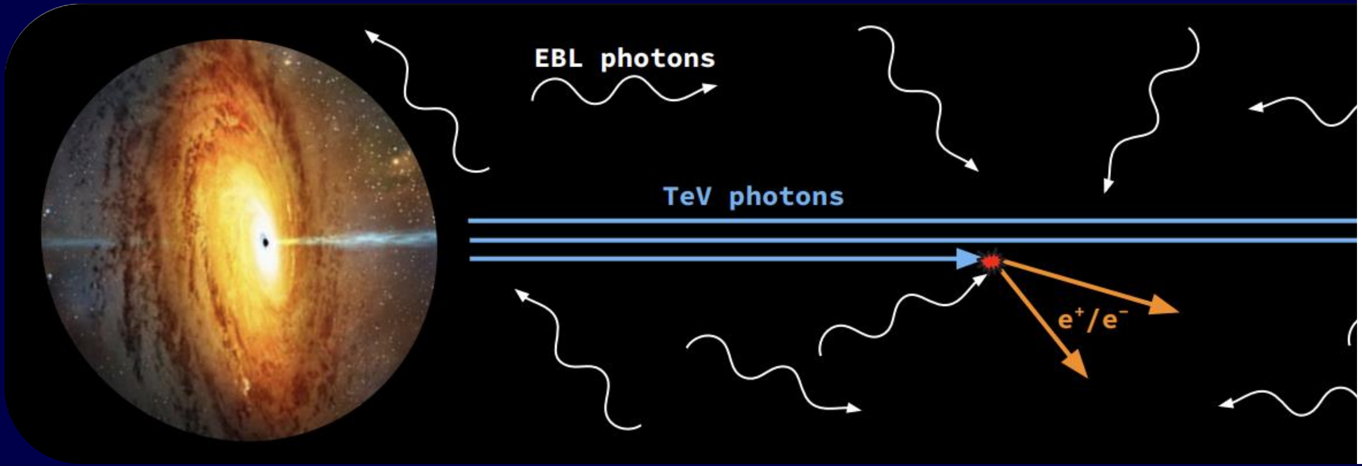
- Absorption features observed in gamma-ray spectra

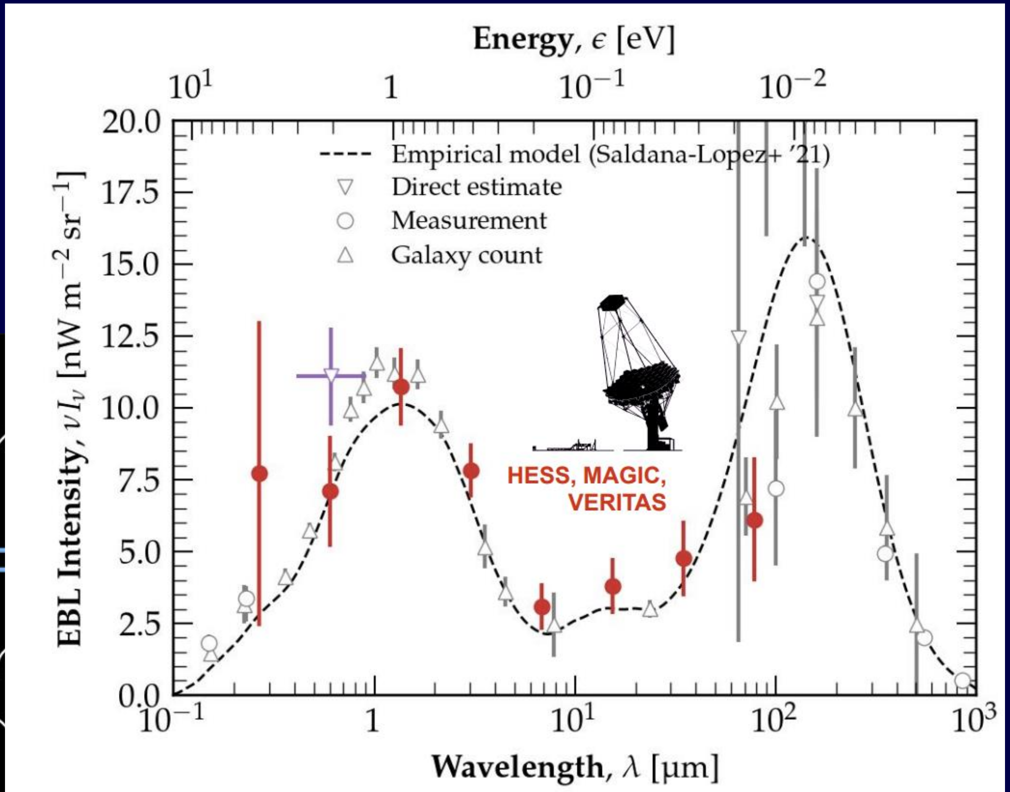
- To discriminate absorption feautures from intrinsic spectral feautures we need large sample of jetted source per redshift bin

- Redshift measurements of extraoridnary importance!



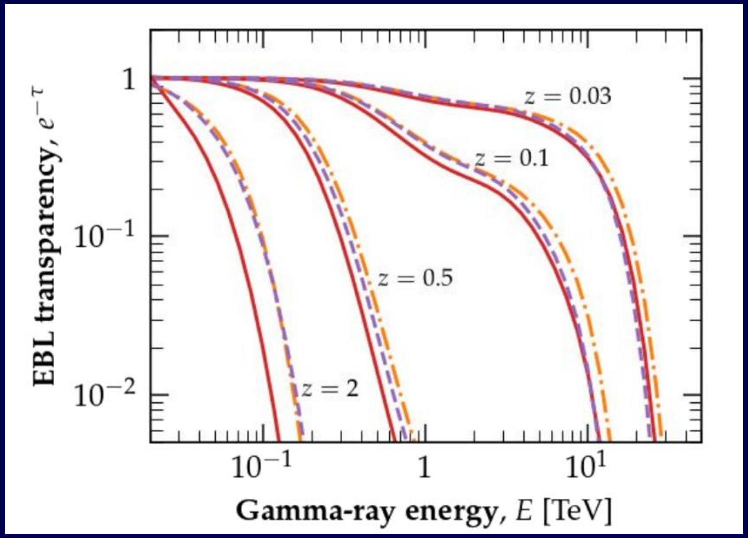
Why distance matters?





Credits Greaux & Biteau

$$\phi_{obs} = \phi_{int}(E) \times e^{-\tau(E,z)}$$



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For the AGN-related science cases, optical coverage is essential but a 12m large FoV MOS is “excessive”

Time-domain is the real point of synergy

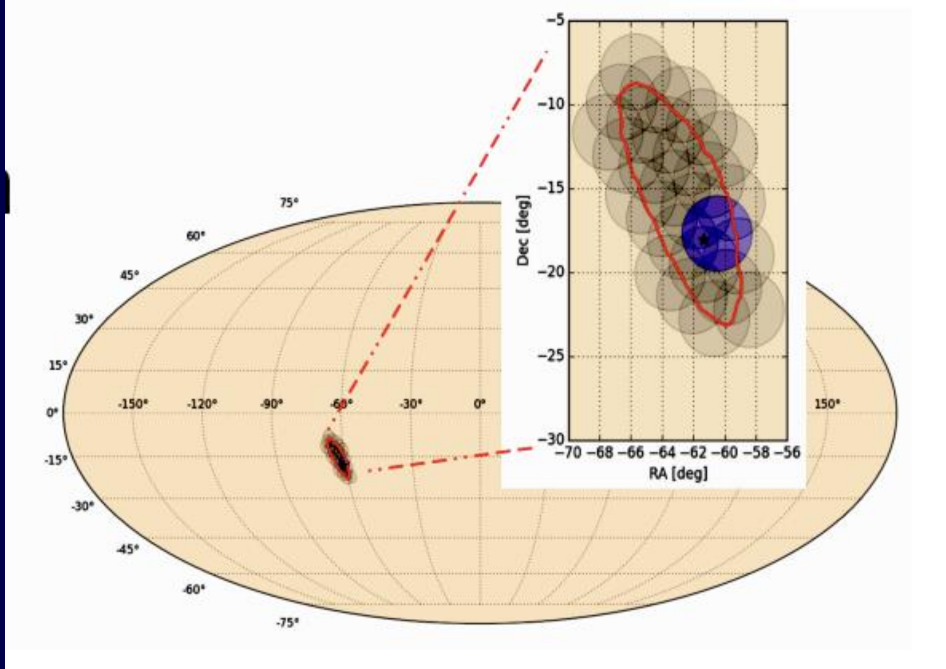
Serendipitous discoveries &

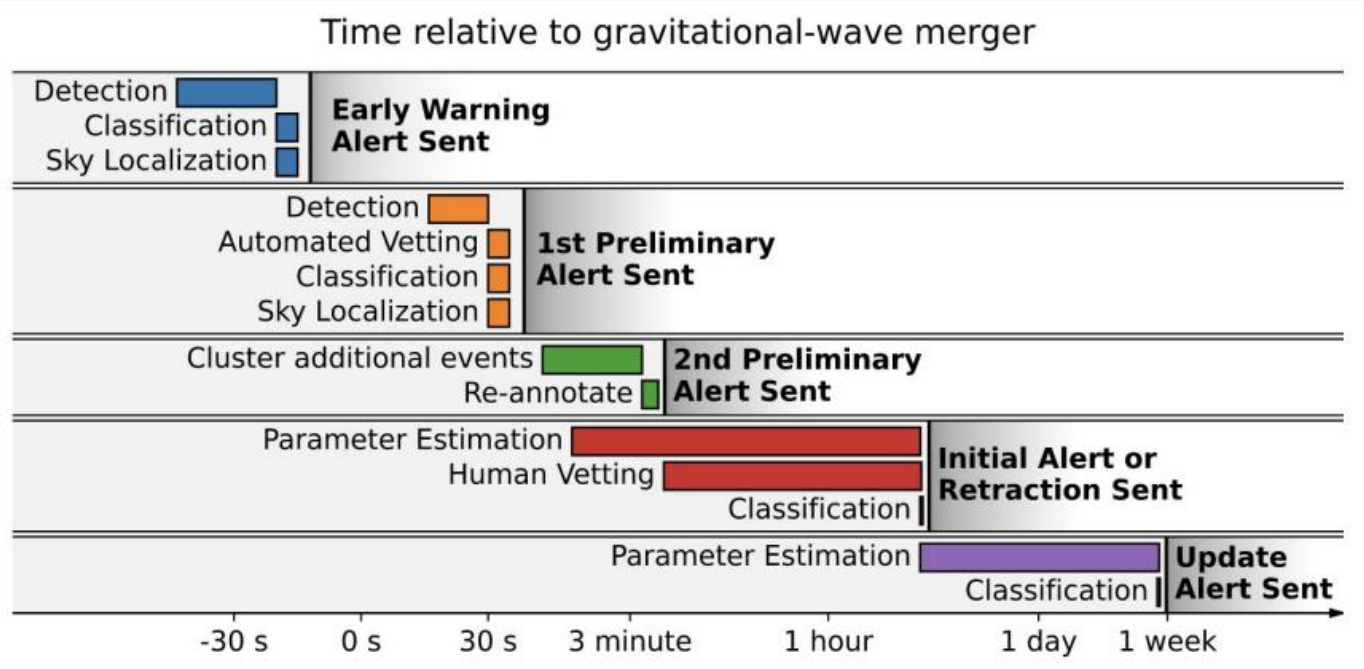
science alerts with large localization uncertainties

Wide-FoV optical transient factories

GW & UHE astrophysical neutrinos follow ups

GW science alerts

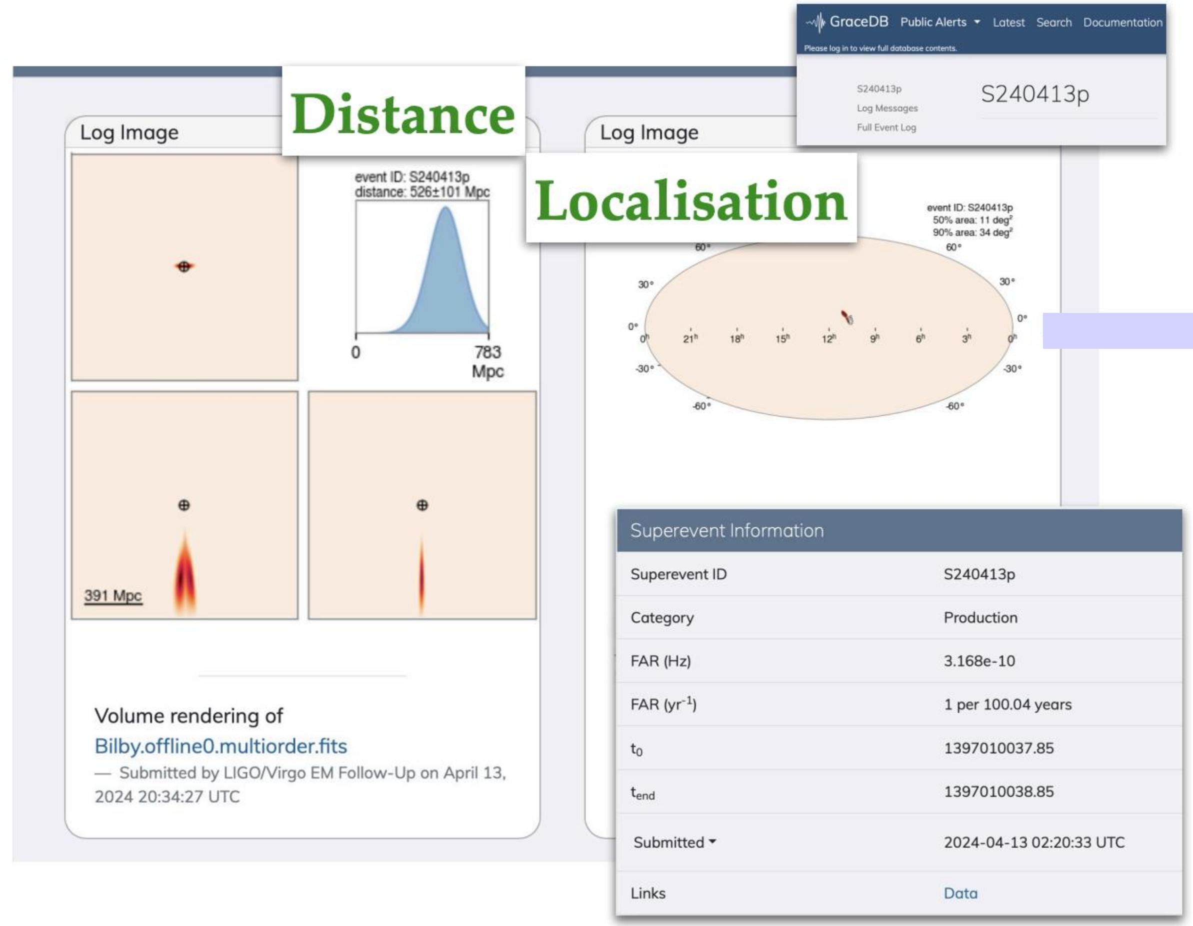




LOCALIZATION UNCERTAINTY: 10-1000 deg^2

ALERT LATENCY: minutes

GW science alerts



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

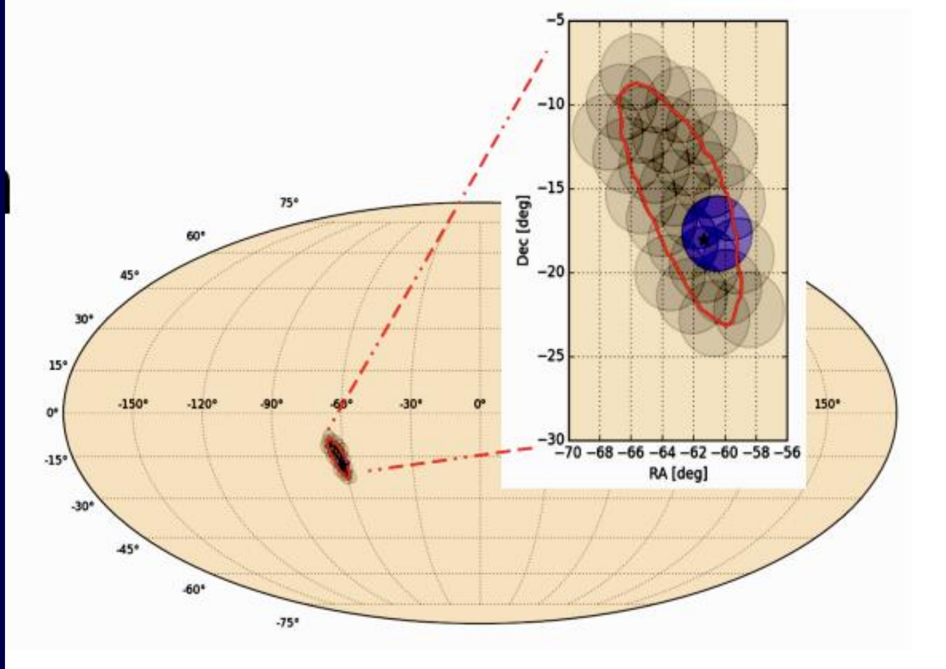
First significant event in O4b (including Virgo): April 13, 2024 – BBH @526 Mpc

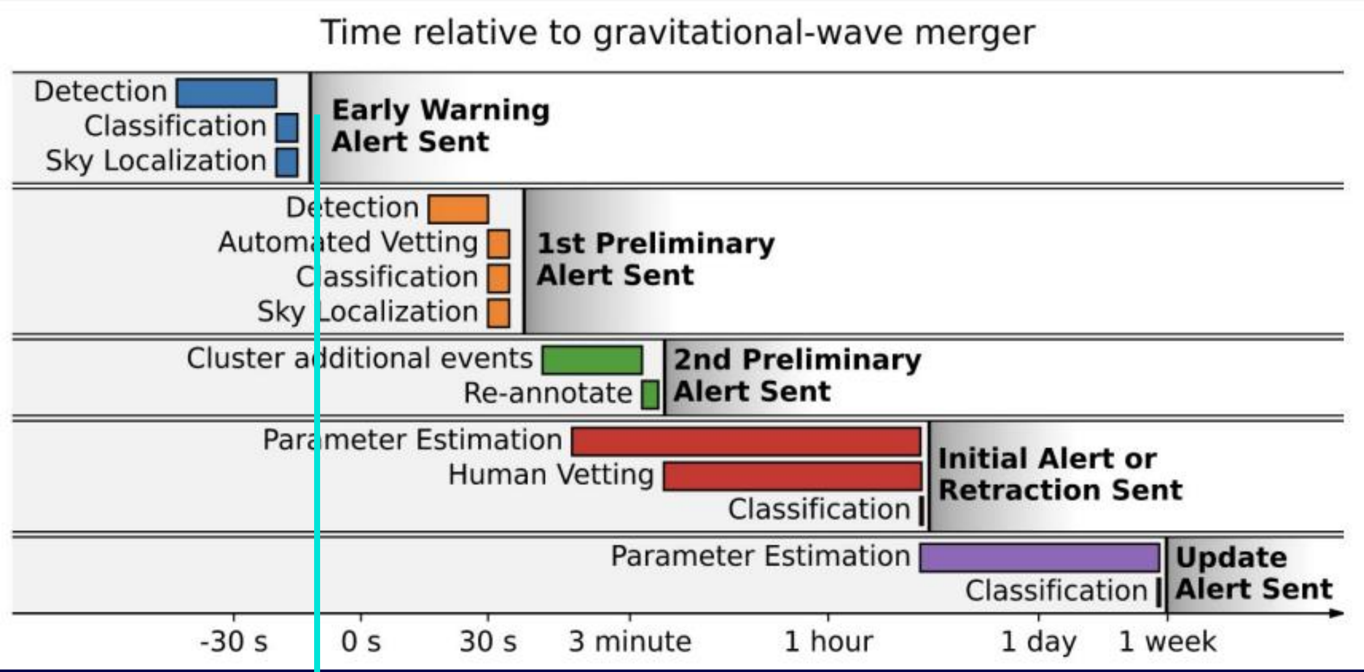
Evt ID: S20413p
50% area: 11 deg^2
90% area: 34 deg^2

CTAO CAN COVER IT WITH JUST FEW POINTINGS!

- **How to choose the first pointing?**
- **For how long?**

GW science alerts





LOCALIZATION UNCERTAINTY: 10-1000 deg^2

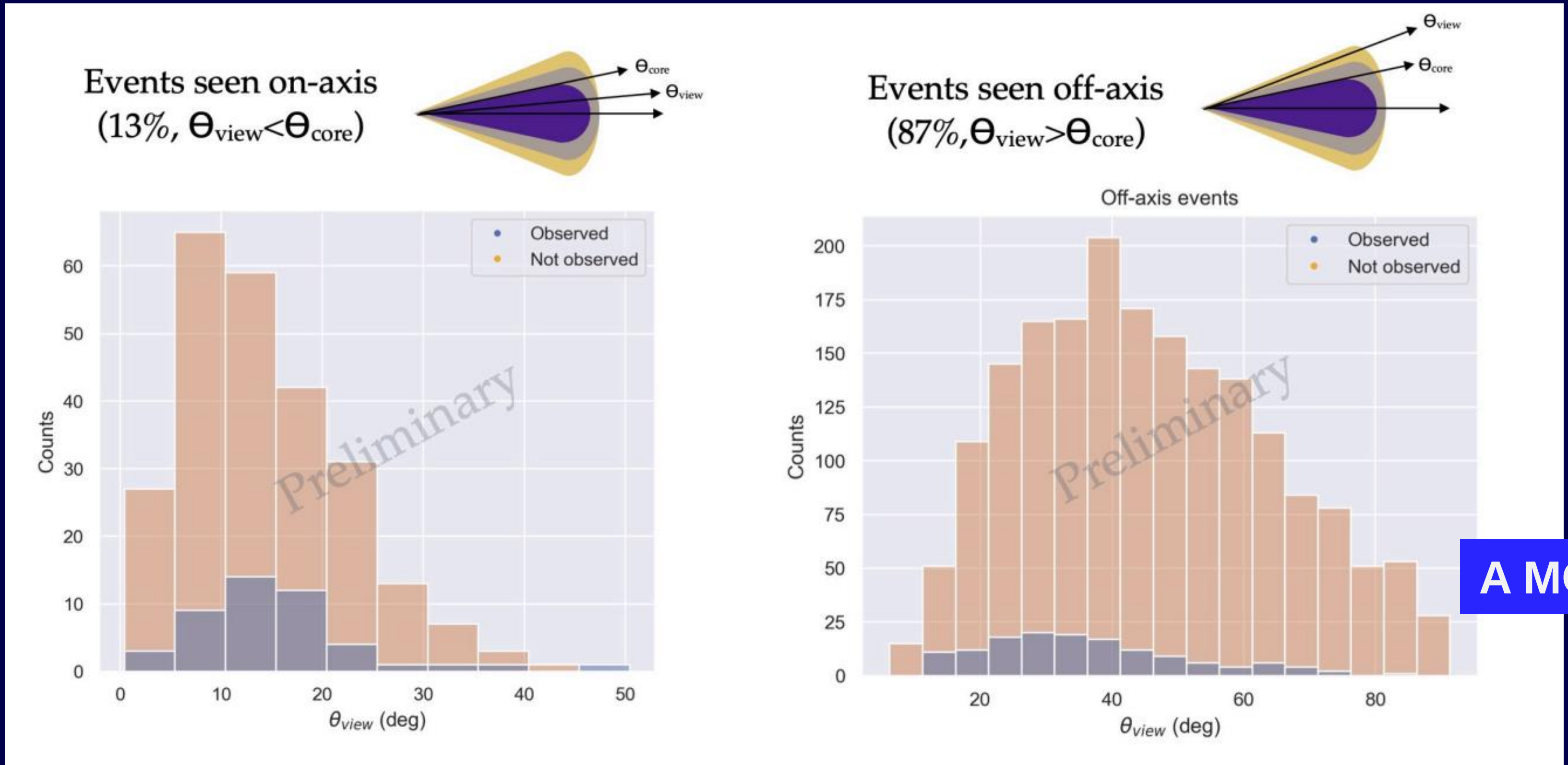
ALERT LATENCY: minutes

Essential for prompt emission detecton

Tiling algorithm starting already here?

GW science alerts

Current simulations on O5 prove that 10%(4%) of the on-axis (off-axis) events are covered at the true location



For the detactability is fundamental to observe within 20' – 1hr

Redshift estimation becomes essential with ET

A MOS like WST becomes essential!

M. Seglar-Arroyo+ 2023

Other transients

- A completely new discovery space with the upcoming Optical Fransient Factory: FBOTs or other even more rare with luminosities comparable with those of core-collapse SNe but with day-raising timescales
  - Identification of these new transients require spectroscopy and multi-wavelength information with short term sensitivities capabilities

- Serendipitous discoveries by CTAO will also invoke for follow up MWL observations, although in this case the locations would be better than 30”.

Molecular clouds and ISM

- Determination of the clumpiness of the ISM at different scales is relevant for the Cosmic ray propagation studies
- Molecular cloud spectroscopy as a tool to study the effect of the CR penetrating the molecular clouds
- One of the main open question for gamma-ray astronomy is about the identification of the sources accelerating CR up the maximum energies within our Galaxy: new emerging scenario are young stellar clusters (collective winds vs wind-to-wind shocks)

Conclusions

- Among the various MWL bands, the optical one plays a key role for the exploitation of the VHE science cases
  - Trade-off between costs (observing time competition) and needed capabilities

- Great most of these cases, we know the source localization with precision of tens of arcseconds
  - Small robotics optical telescopes for triggering and monitoring
  - 4-8m optical telescopes for redshift determination of a relative small number of sources

- The main scientific case for the CTAO-WST synergies is in the TIME-DOMAIN,
  - particularly for alerts with large localization uncertainties.
    In these cases, the combination of a wide FoV and spectrographic capabilities is crucial for providing essential information for multi-wavelength (MWL) follow-ups
  - serendipitous discoveries

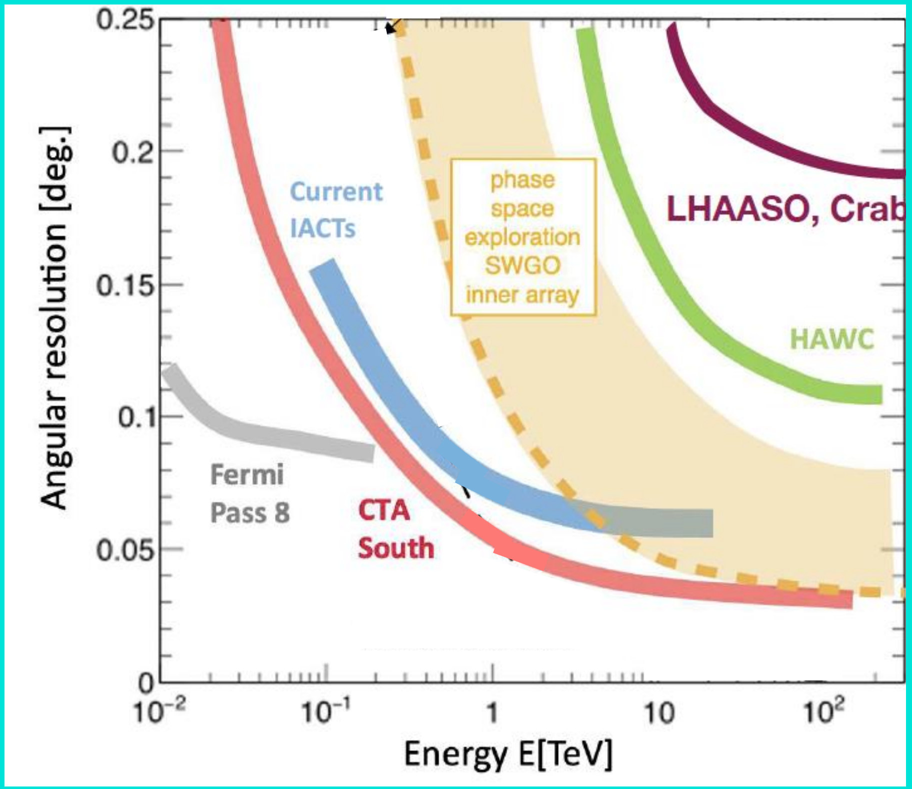
- It certainly offers a significant benefit in advancing our understanding of star-forming regions, molecular clouds, and ISM, and in turn of the CR propagation dynamics.

Cherenkov Telescope Array Observatory

Thank you

Angular & energy resolution

angular resolution



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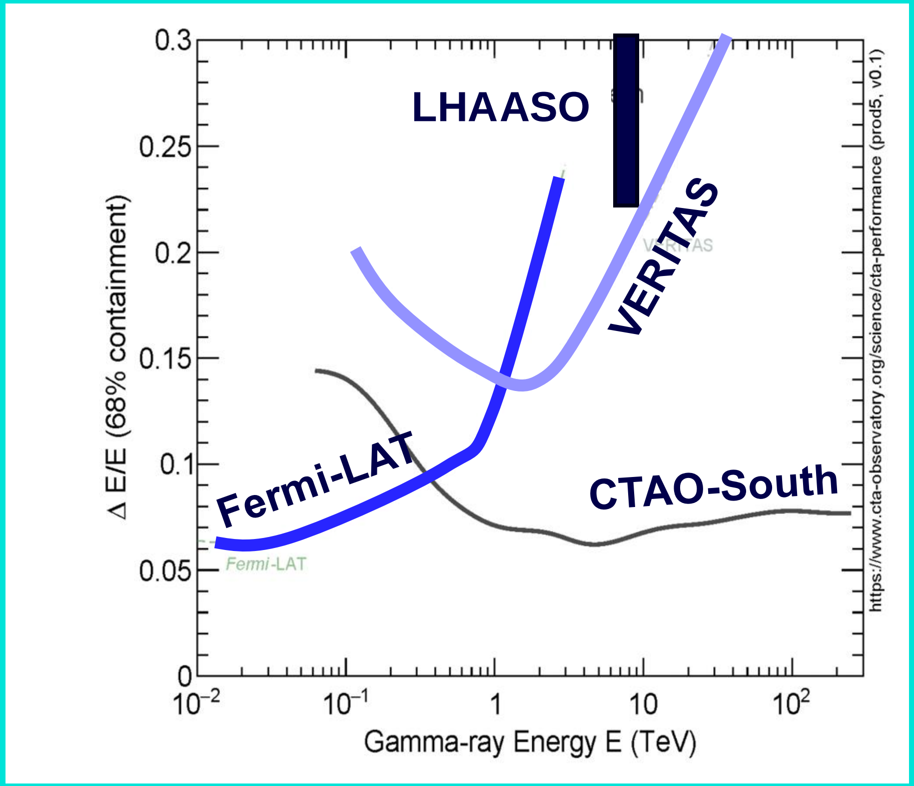
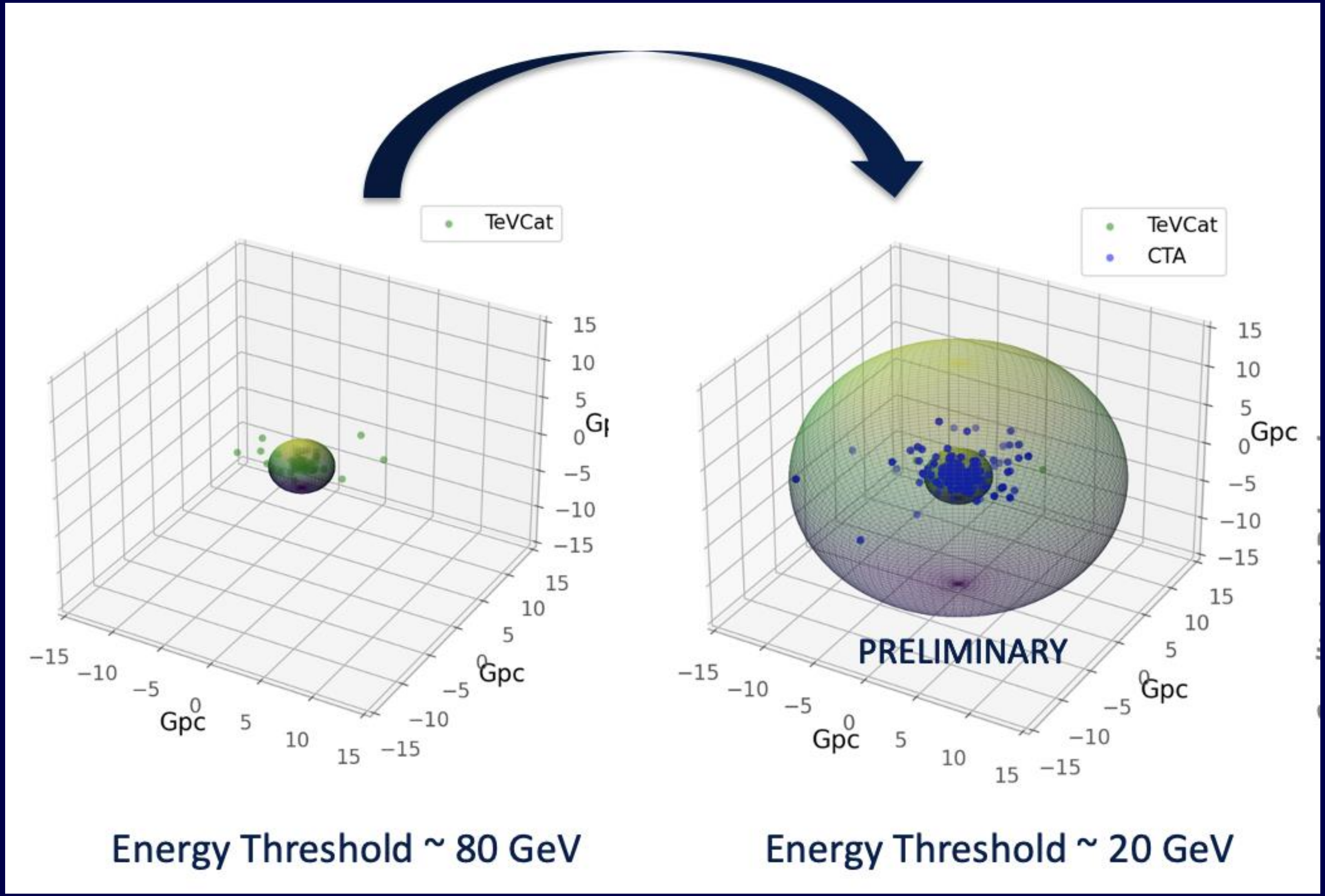


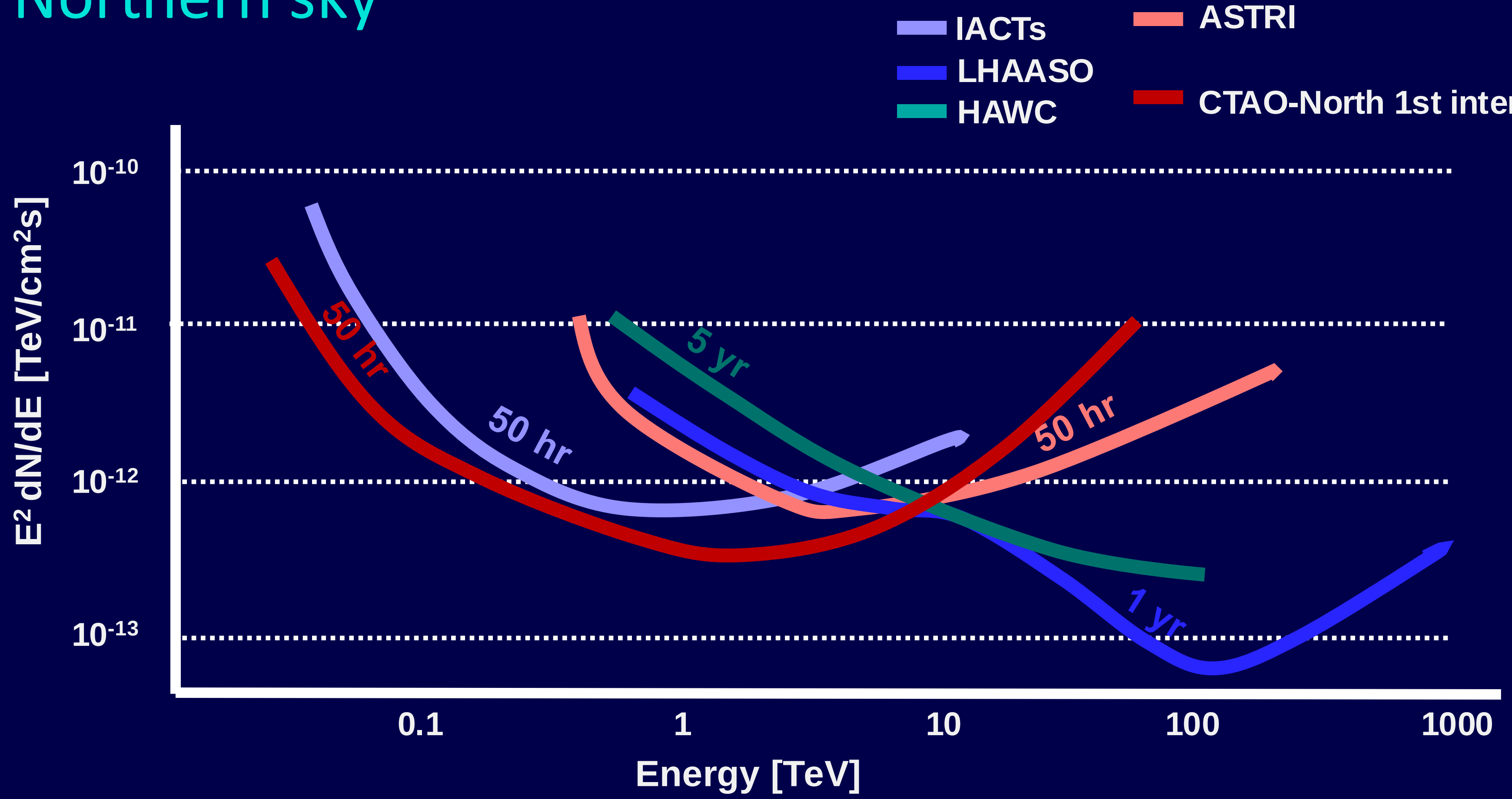
Universe volume

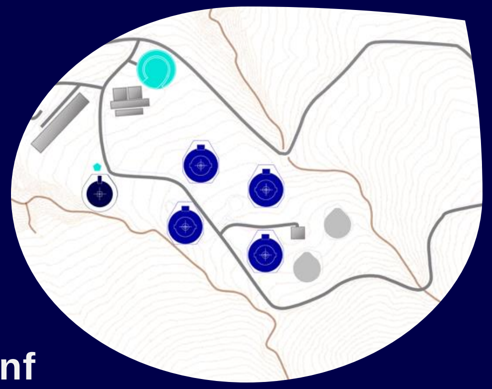
Credits J.P Lenain



In 3 years from now

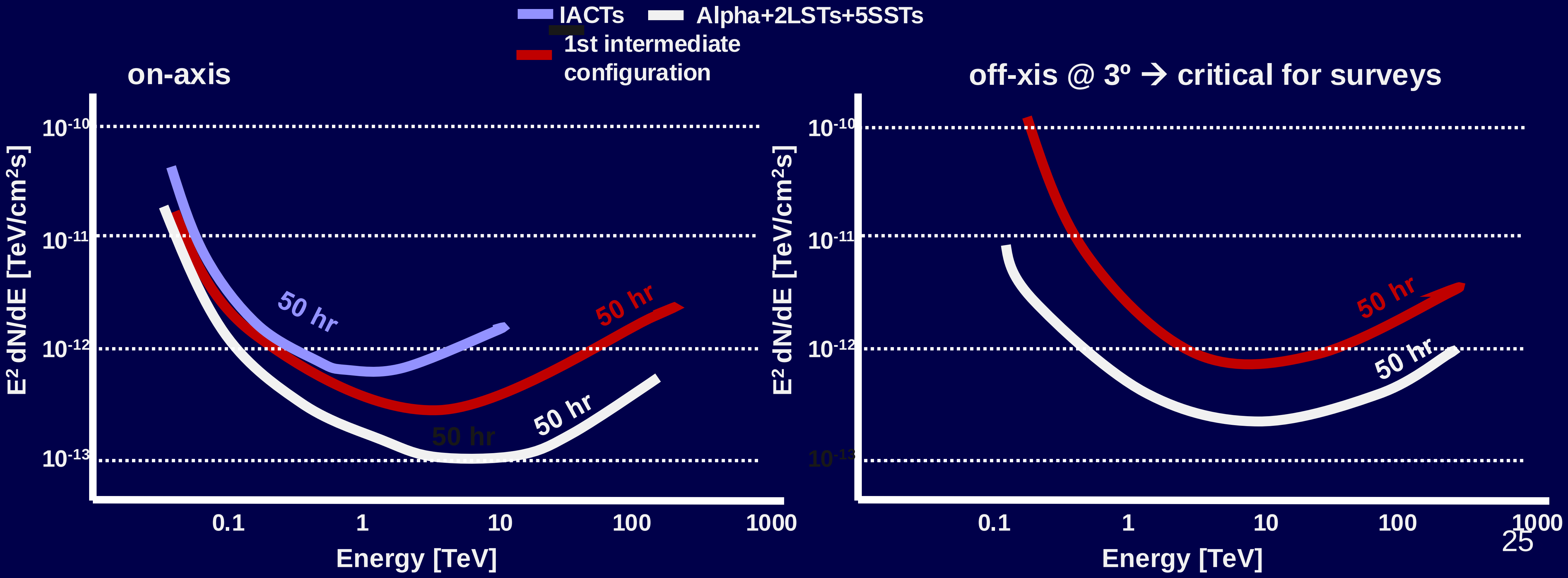
Northern sky





In 3 years from now

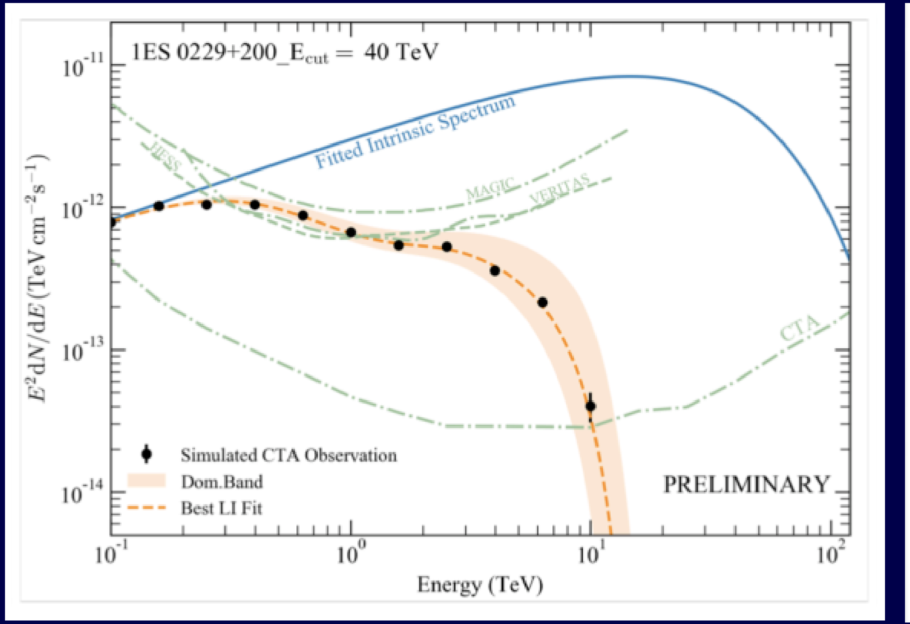
Southern sky

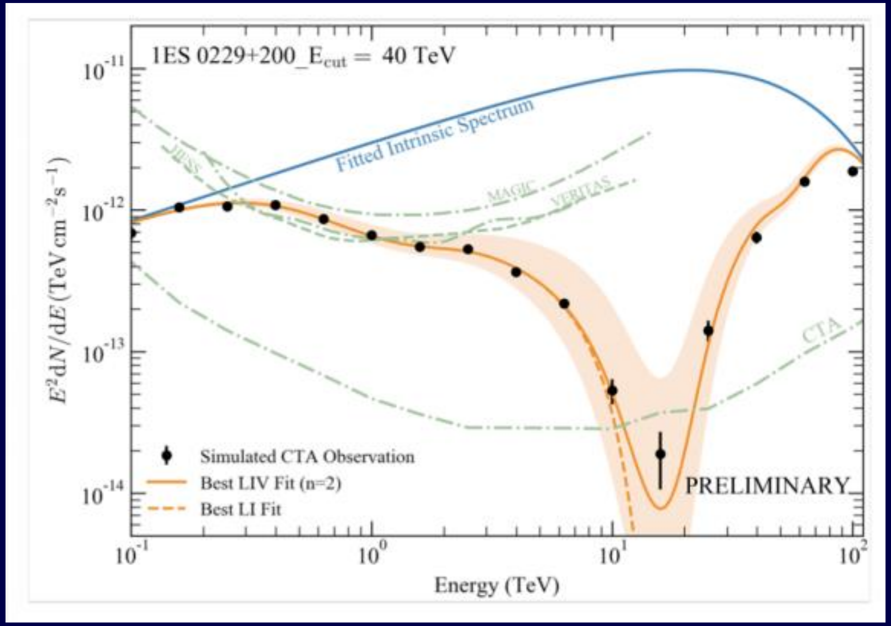


Lorentz Invariance Violation

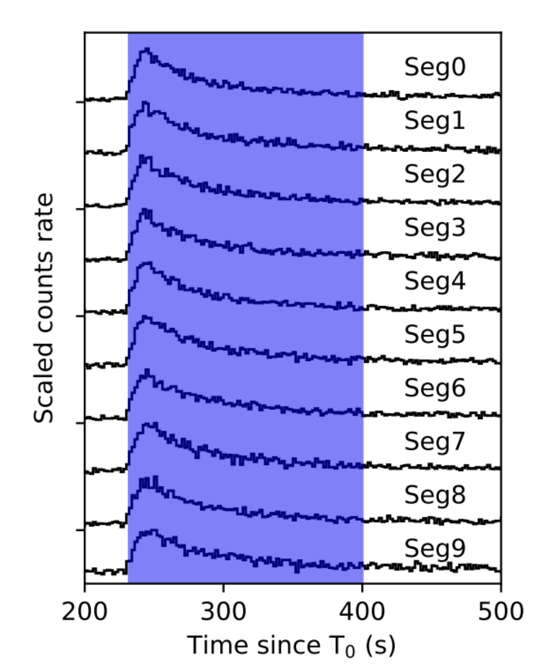
- A recovery of the TeV spectrum

Martinez-Huerta+2024





The BOAT

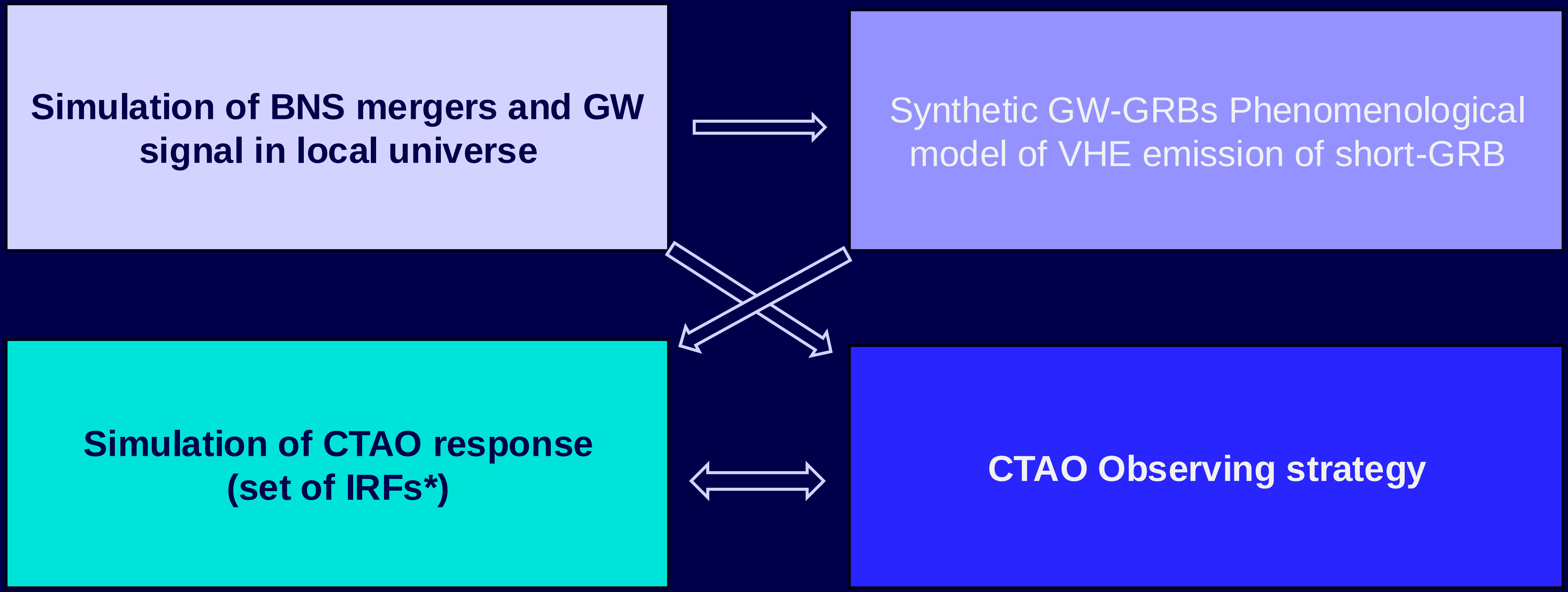


LHAASO Coll 2024

- An energy-dependent modifications to the photon dispersion *(MAGIC Coll. 2008)*

LIVelihood *(Bolmont+2022)* a software package computing the expected time delays *(Rosales de Leon+2024)*

GW follow up

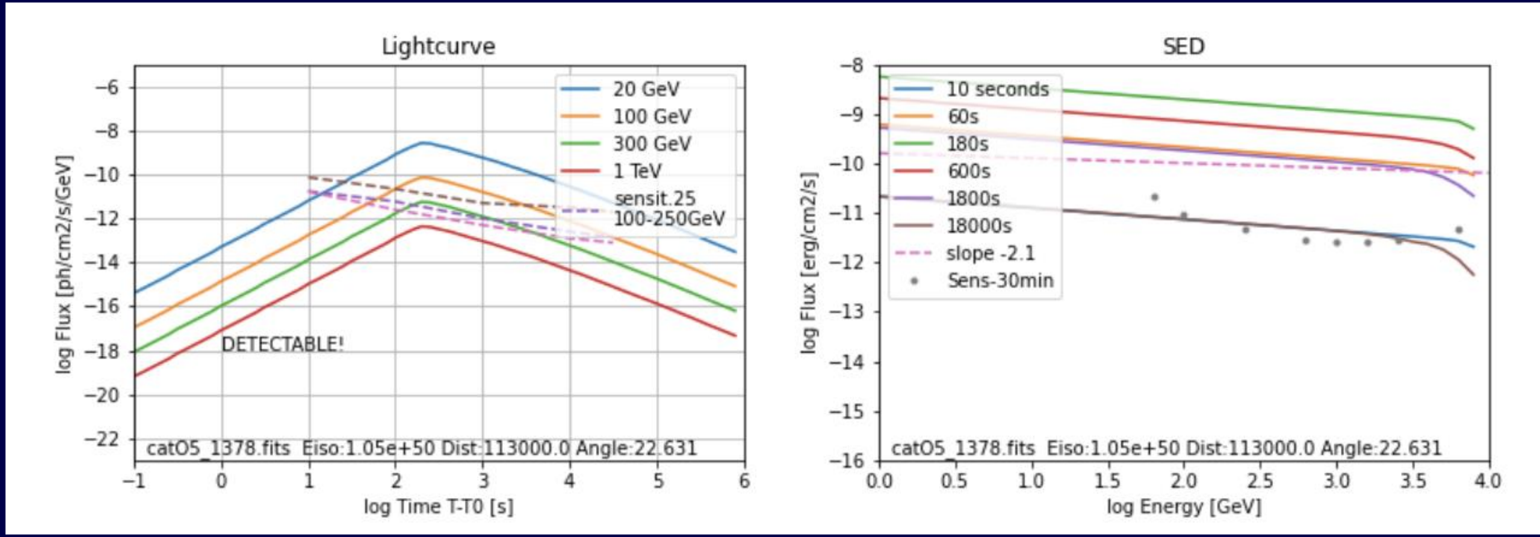


- Gravitational wave catalogue of simulated binary neutron star (BNS) mergers from Petrov+2022 for O5 (O6) •
- ~2300 (8160) compact binaries in O5 (O6*) detected

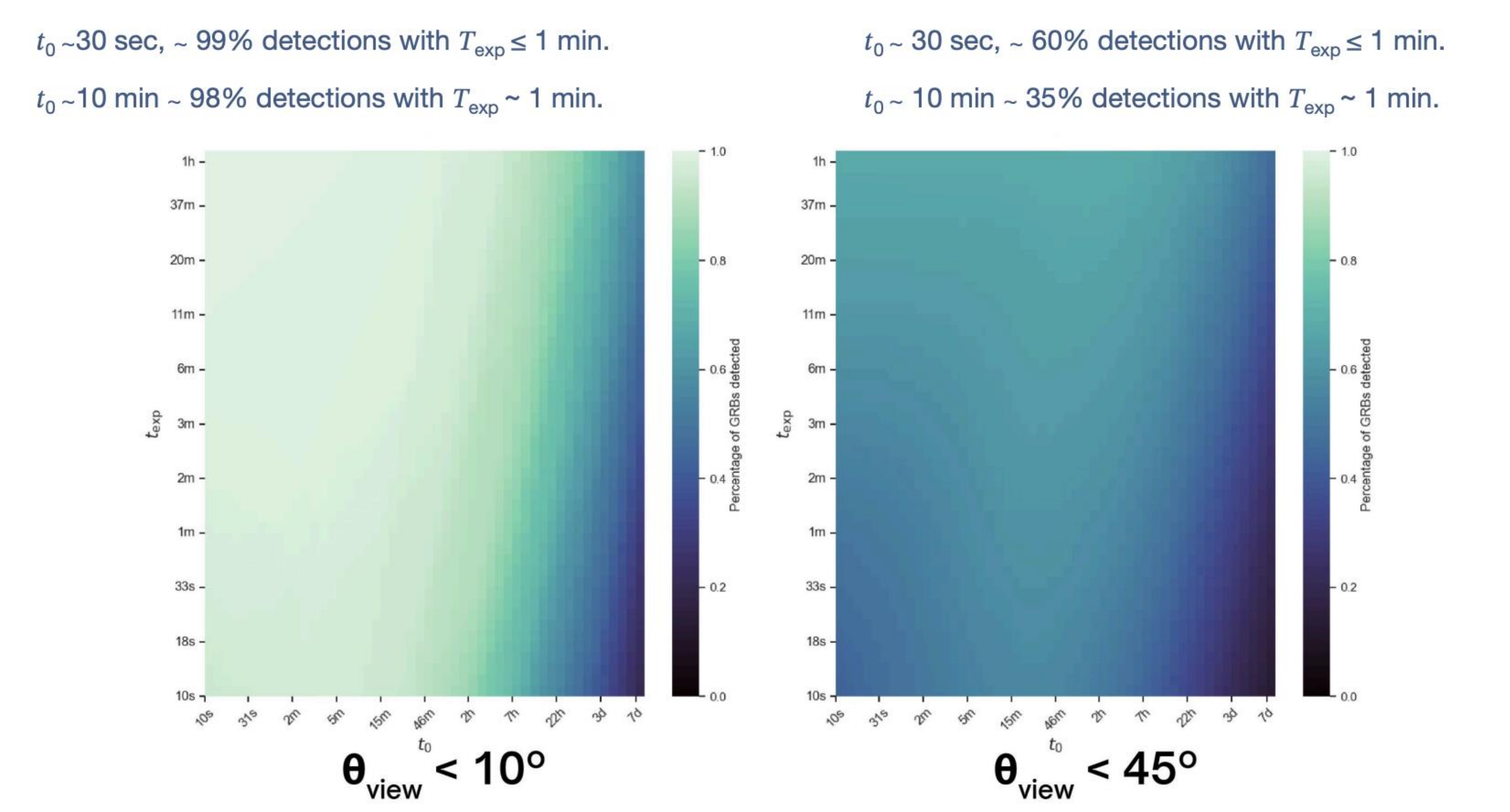
GW follow up

Phenomenological simulations of afterglow emission from short GRBs

- Jet opening angle inferred from short-GRBs seen on-axis, average:~14deg
- Viewing angle from the inclination of the BNS
- Lightcurve: follows deceleration phase + similar temporal decay as in X-rays
- Spectrum: Photon index ~-2; Density of the external medium ~0.1 cm-3
- Jet structure: Gaussian distribution for both energy and Lorentz factor



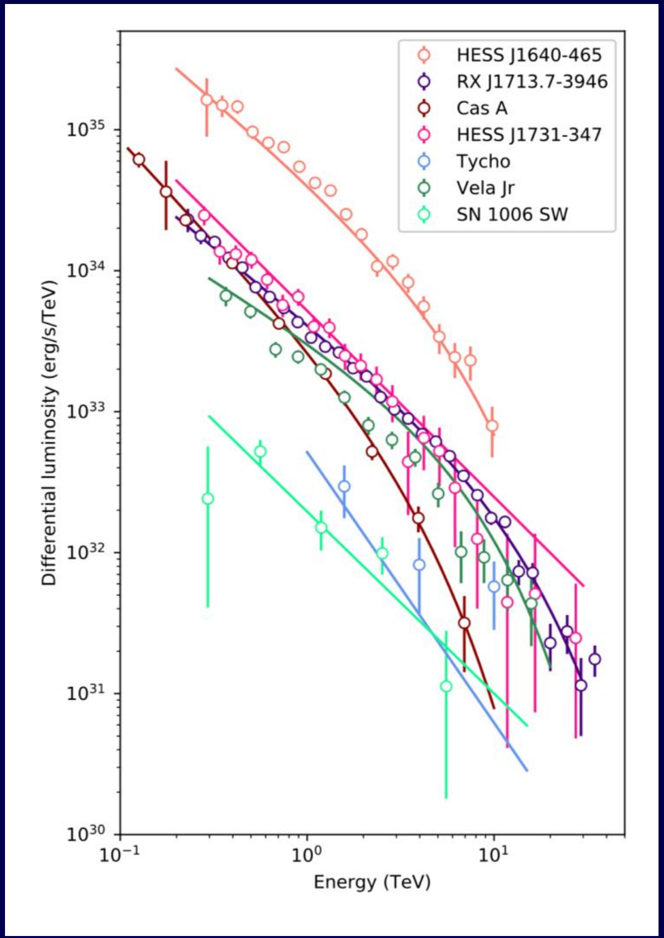
GW follow up



Credits to A. Stamerra

Molecular clouds and ISM

Open point: CR maximum energy



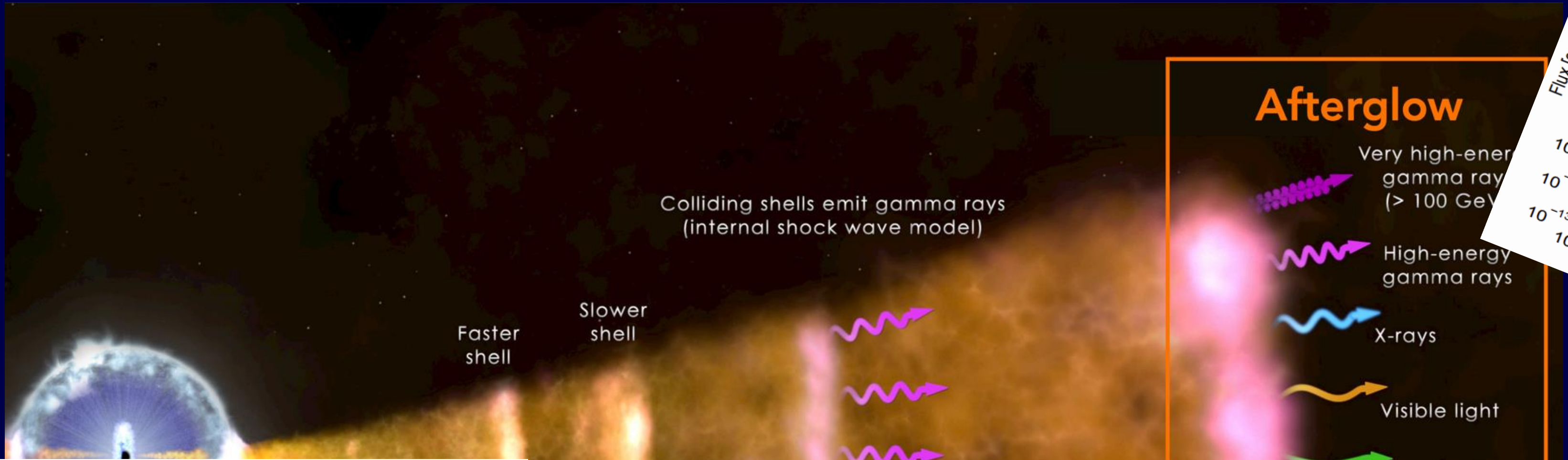
Aharonian et al 2019

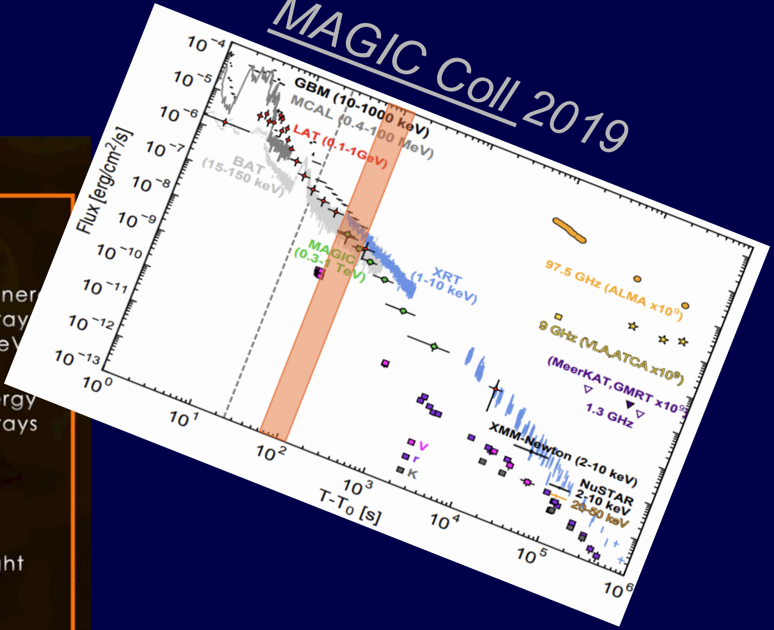
- **Young SNRs display energy cutoff below 100 TeV** in agreement with theoretical models *(Bell+ 2013, Cardillo+2015)* unless extreme conditions are assumed *(Cristofari+2022)*
- They **could be PeVatrons only for a short period** after the SN explosion *(Cristofari+2020)*
- It could be easier to detect CR escaping and interacting with nearby molecular clouds *(Gabici+2007, Gabici+2009, Casanova+2010)*

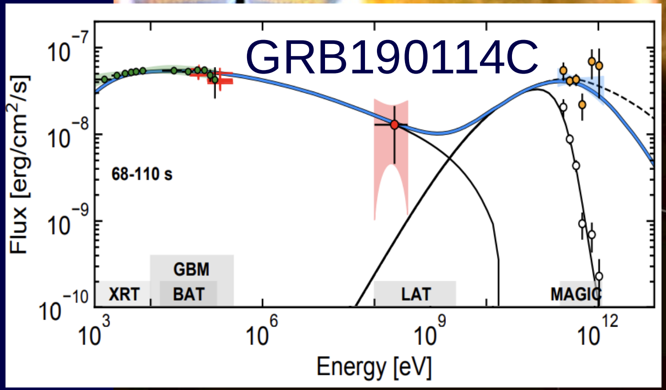
sub-
Tev

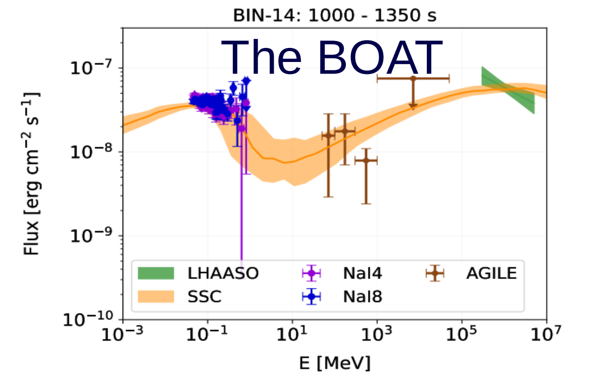
Transient extreme phenomena

Gamma-ray bursts







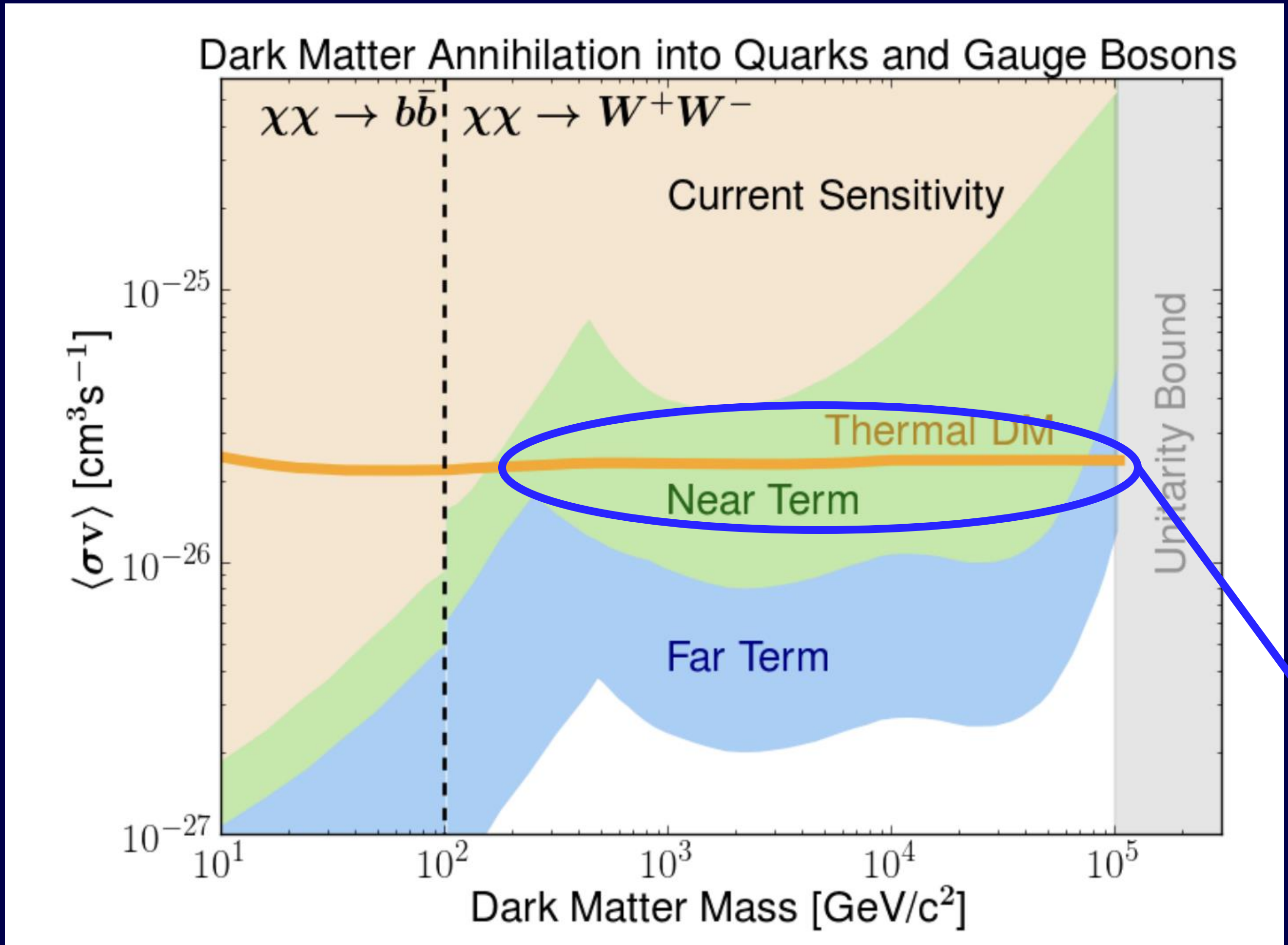


MAGIC Coll 2019

Banerjee+2024

MWL info is what is needed.
Gamma rays allow to estimate:
- max electron energy
- energy budget
- magnetic field
- acceleration efficiency

Thermal dark matter

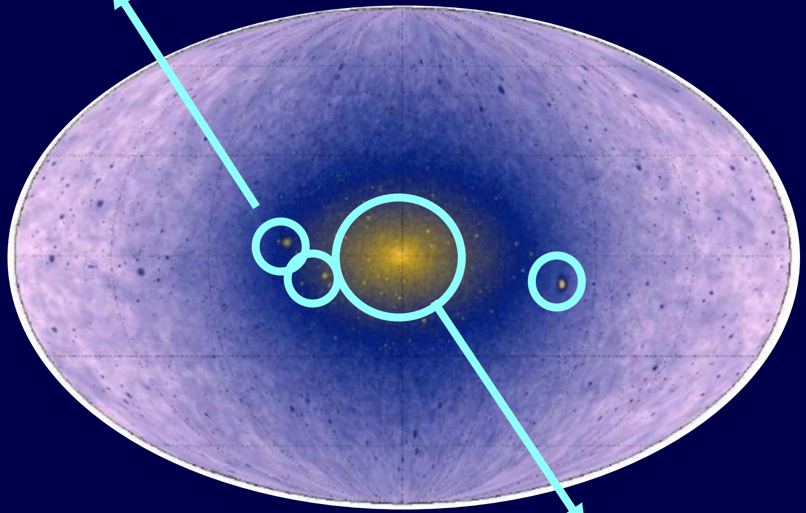


unexplored mass range that is accessible by the next generation of VHE facilities down to the thermal cross section

MW satellites

LMC CTAO Consortium,2023

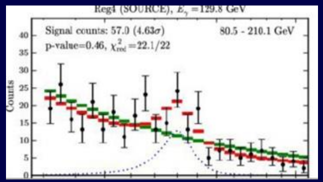
dSph CTAO Consortium,2023



adapted from Kuhlen+ 2008

Spectral signatures

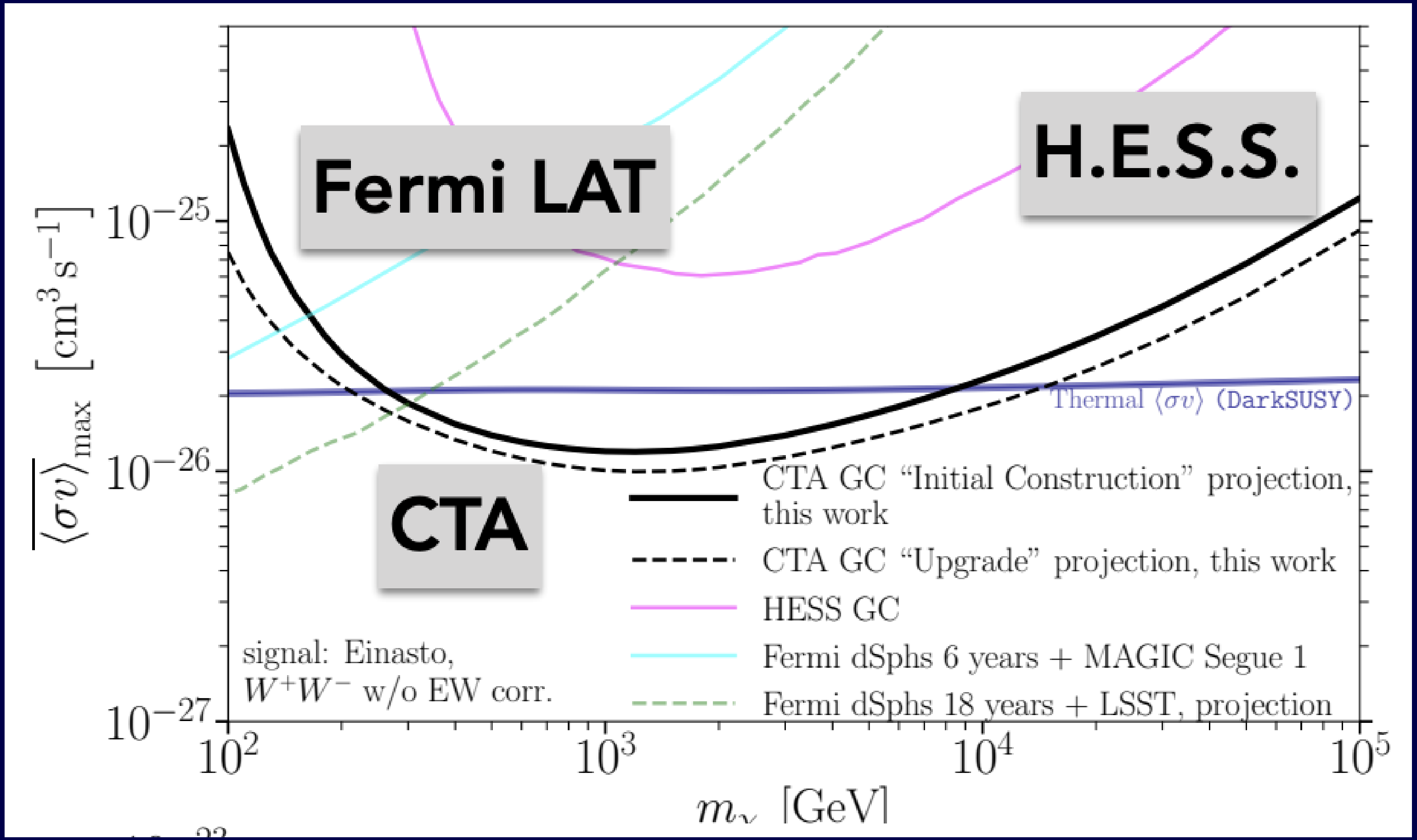
CTAO Consortium,2024



Galactic center

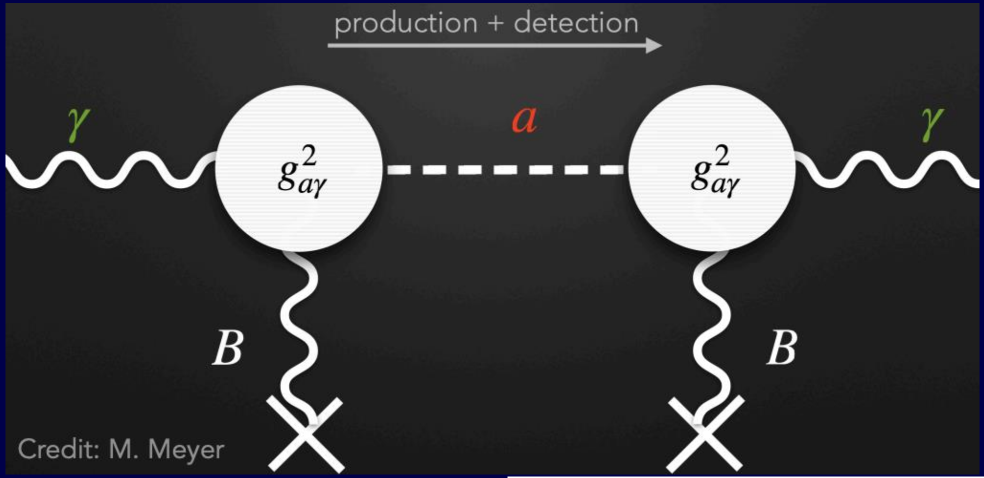
CTAO Consortium,2021

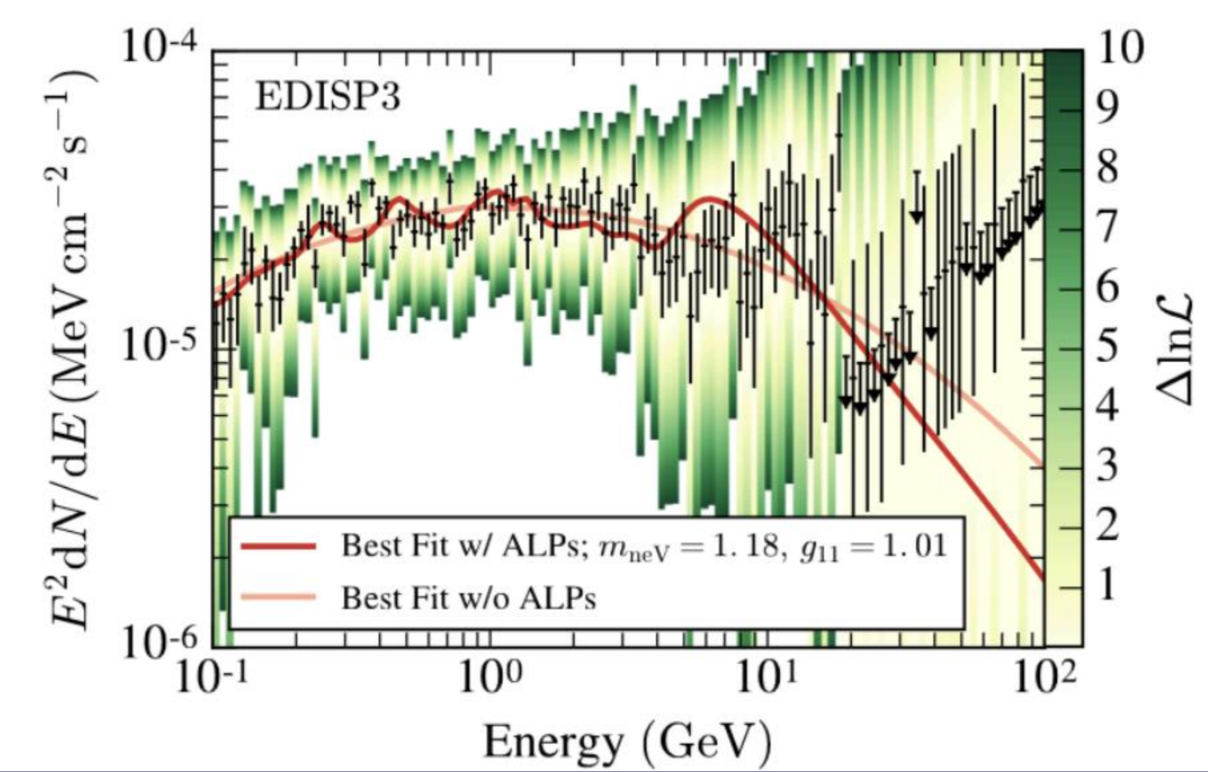
Thermal dark matter

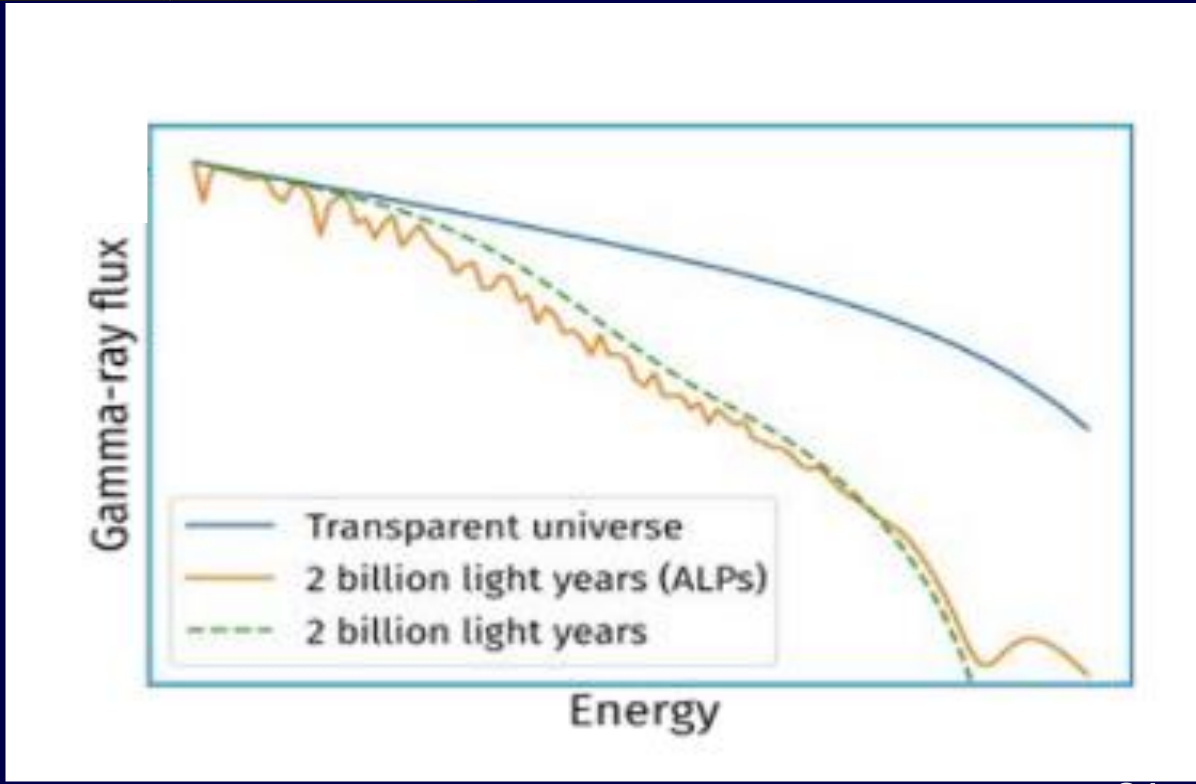


CTAO Consortium 2021

Axions





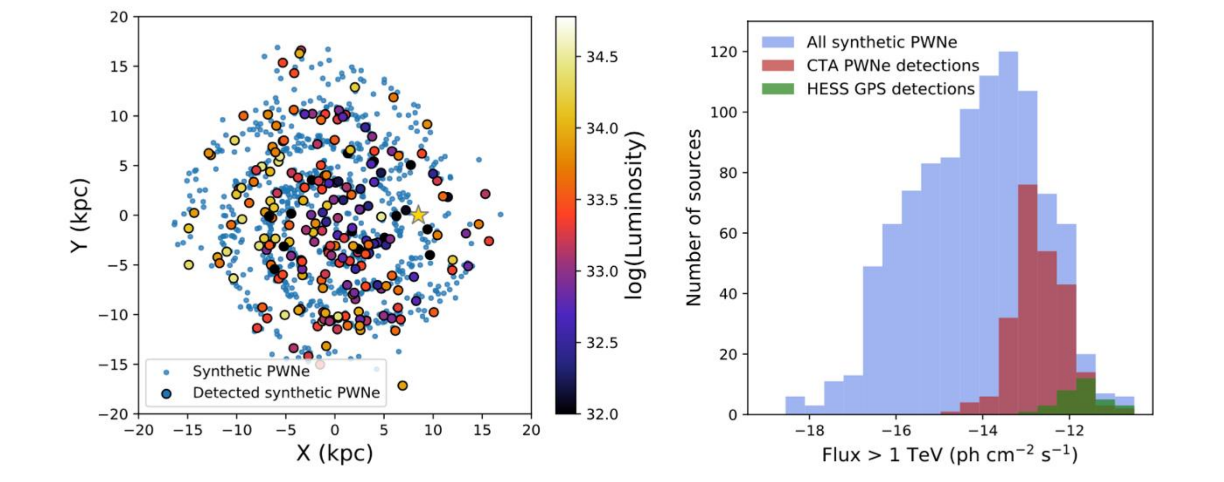


Mayer+

Credits to J. Biteau

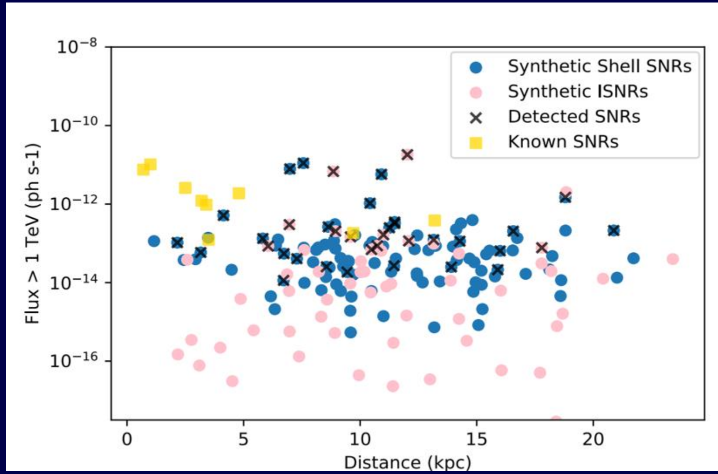
Population studies

PWNe



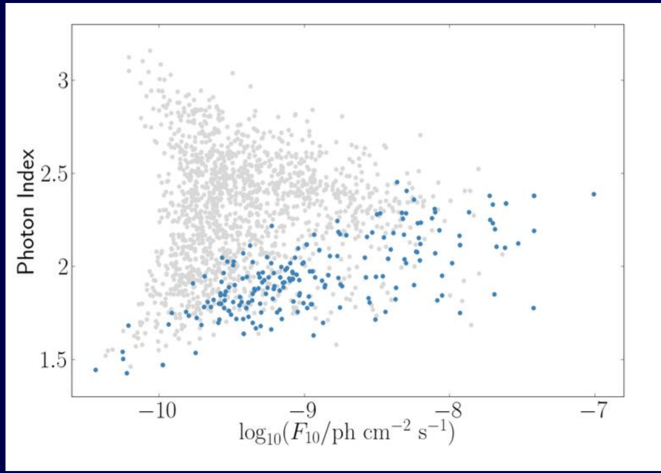
- transformational jump in population size to the PWNe field

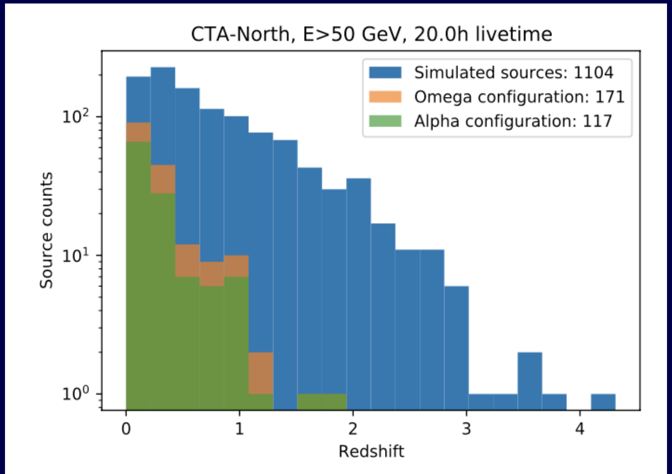
SNRs



- SNRs up to other side of the Galaxy
- 5-10 times better flux sensitivity

AGNs





- factor >2 detected non-flaring AGNs
- enlarge the γ-ray horizon up to z$\simeq$2

When will the scientific impact begin?