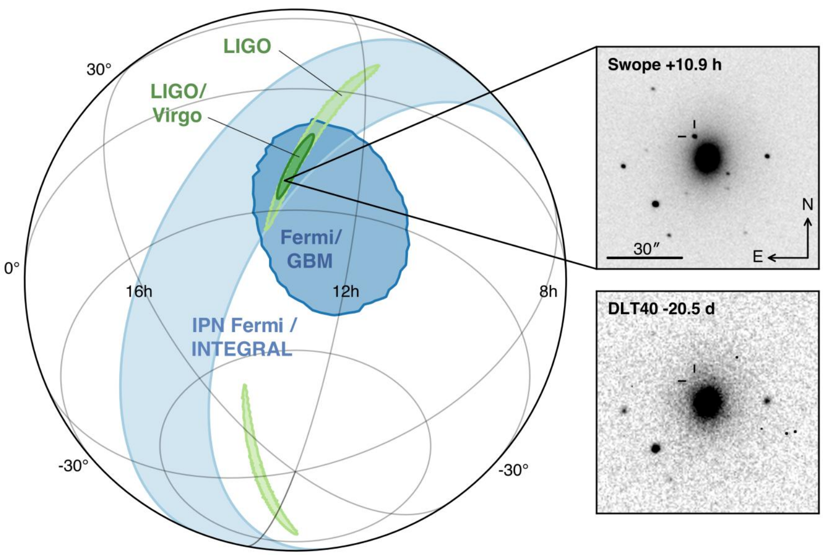
Multimessenger searches of transient sources with Cherenkov telescopes

Alessio Berti
Max Planck Institute for Physics

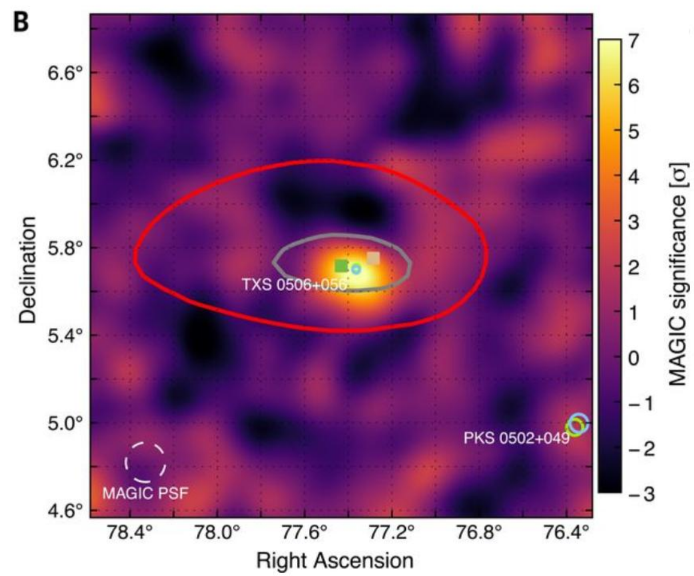
MAX-PLANCK-INSTITUT FÜR PHYSIK

HANDS-ON THE EXTREME UNIVERSE WITH HIGH ENERGY GAMMA-RAY DATA

Introduction



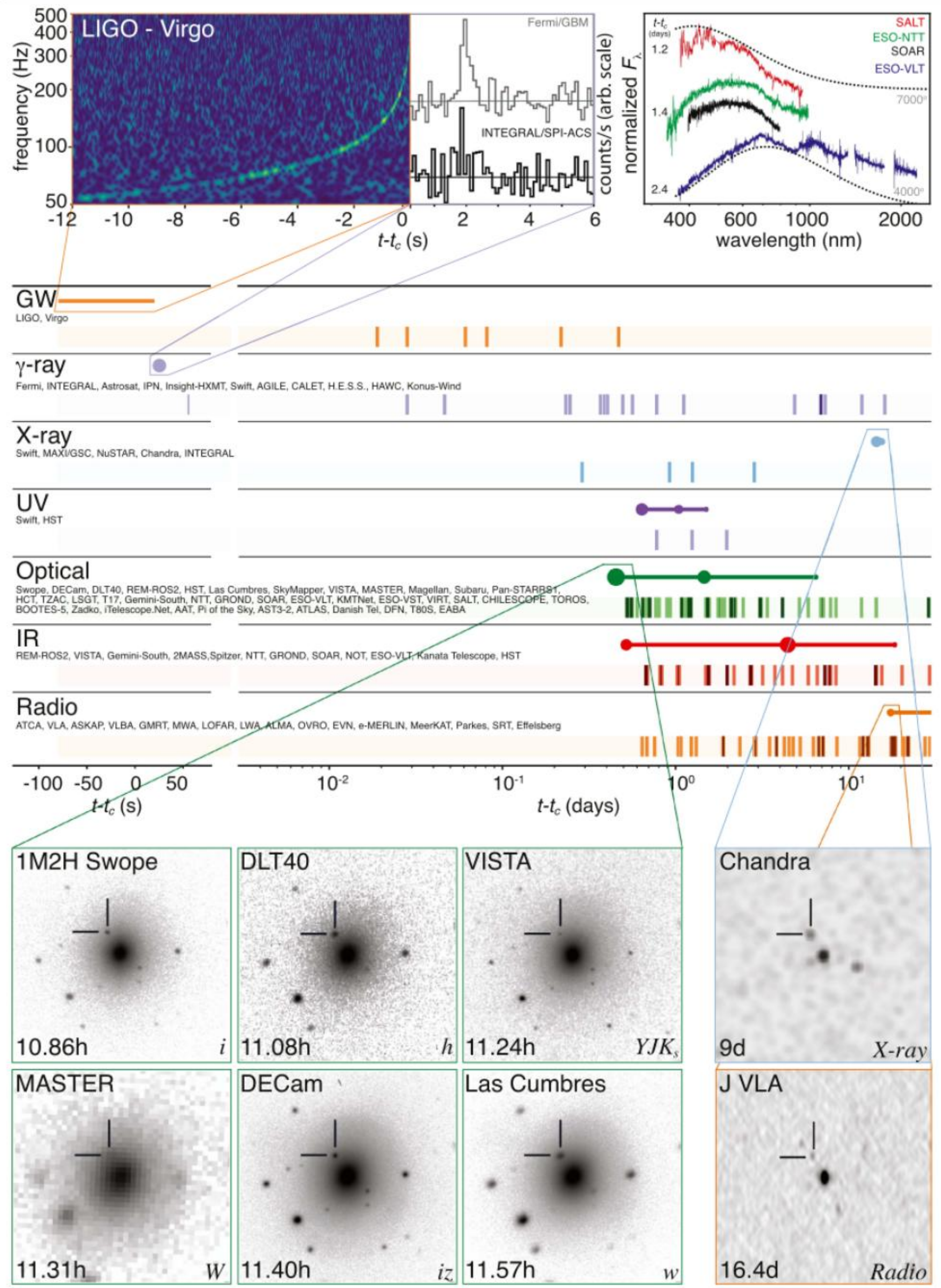
IceCube et al., Science 361, 146 (2018)



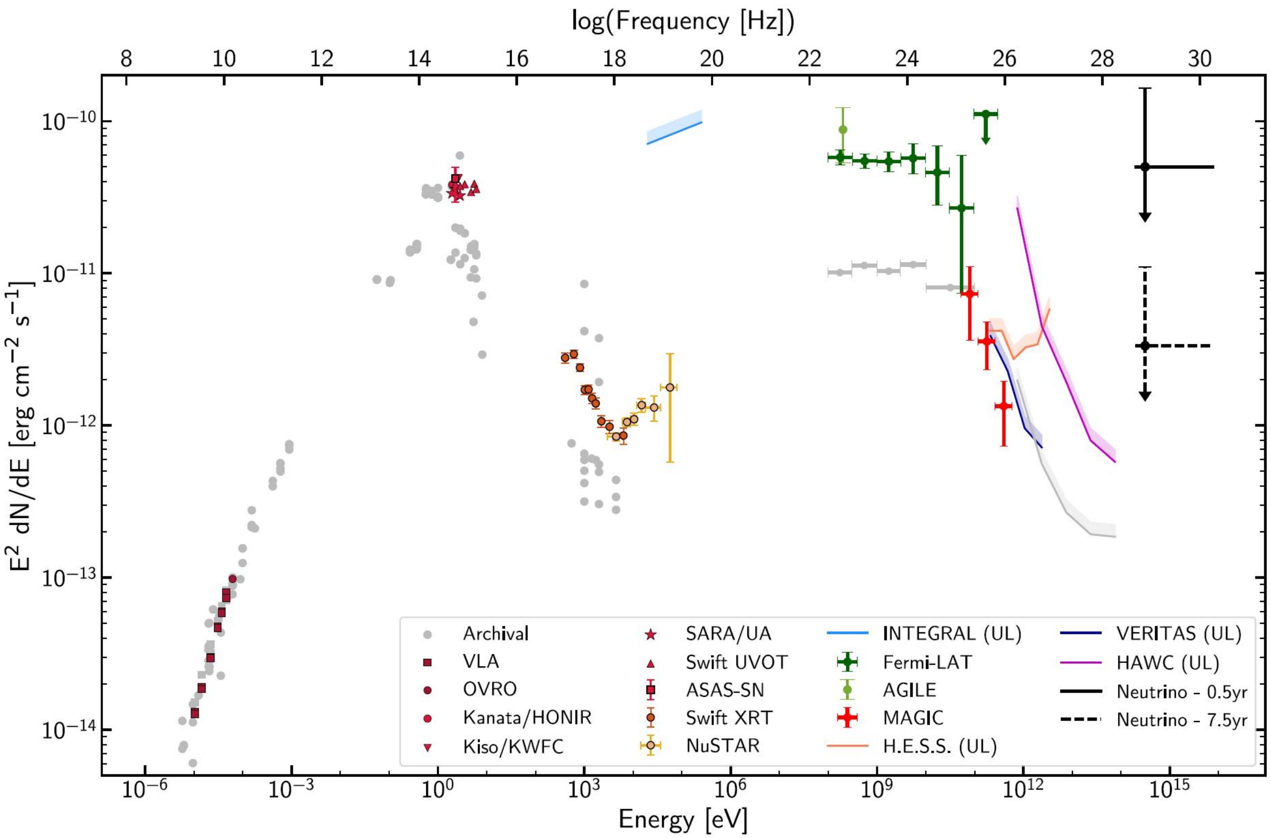
- Multimessenger astrophysics: study an event using information given by different messengers (photons, neutrinos, gravitational waves, cosmic rays)
- Three very famous examples:
  - Sun and SN 1987A (photons+neutrinos)
  - TXS 0506+056 (photons+neutrinos, right figure)
  - GW 170817/GRB 170817A (photons+gravitational waves, left figure)

Introduction

- In many cases, these sources are the result of explosive/catastrophic events e.g. the merging of very compact objects
- Acceleration of particles is expected and so also production of photons at different wavelengths, up to (very) high energies
- GW170817/GRB 170817A is a good example
  - merger results in GRB (off-axis) + kilonova



Introduction

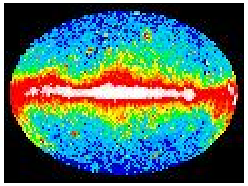


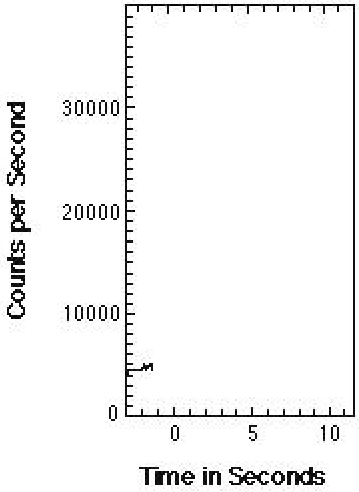
IceCube et al., Science 361, 146 (2018)

- TXS 0506+056 is also a good example
  - presence of neutrino points to acceleration of protons up to UHE

Introduction

- From the previous examples, you can see that these events were connected to **transient sources**
- A transient is an astrophysical event exhibiting time variability on different timescales, from milliseconds to years
- Also their duration may vary, they can be the brightest objects in the sky for few seconds and then fade away
- GRBs are the prototypical transient source, but many more source belong to this category (neutrino events, GWs, flares etc.)

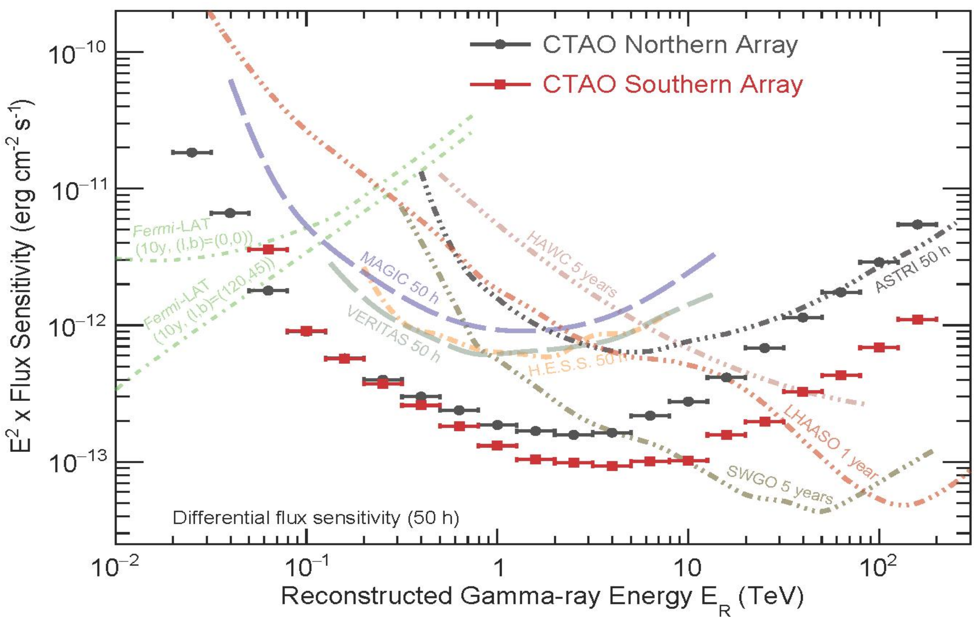


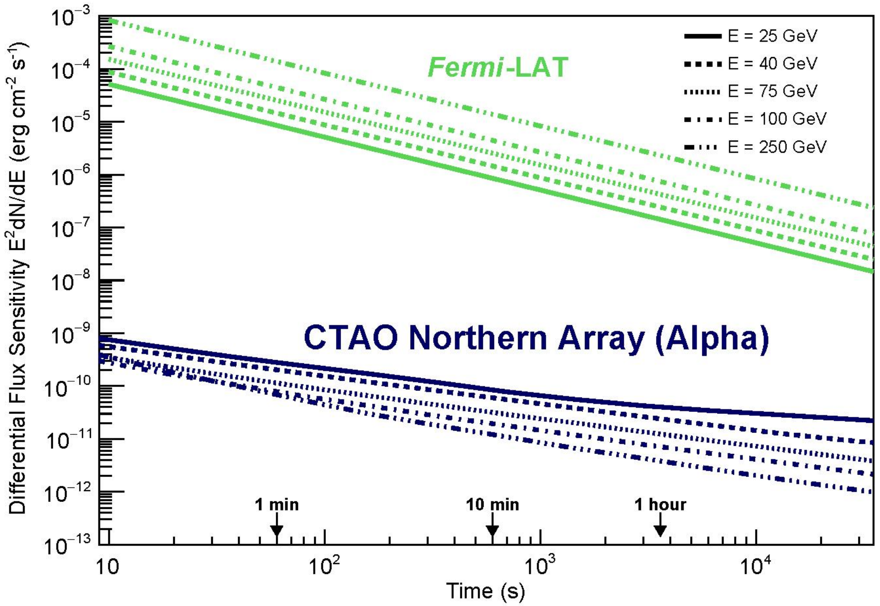


Studying transients with IACTs: why?

- They are very sensitive instrument on a broad energy range --> good characterization of spectra from ~20 GeV to several TeV for CTA
- They are fast instruments, sensitive to short duration events, detecting enough photons thanks to large collection area --> possibility to perform time analysis, searching for variability, change in spectrum, evolution of system

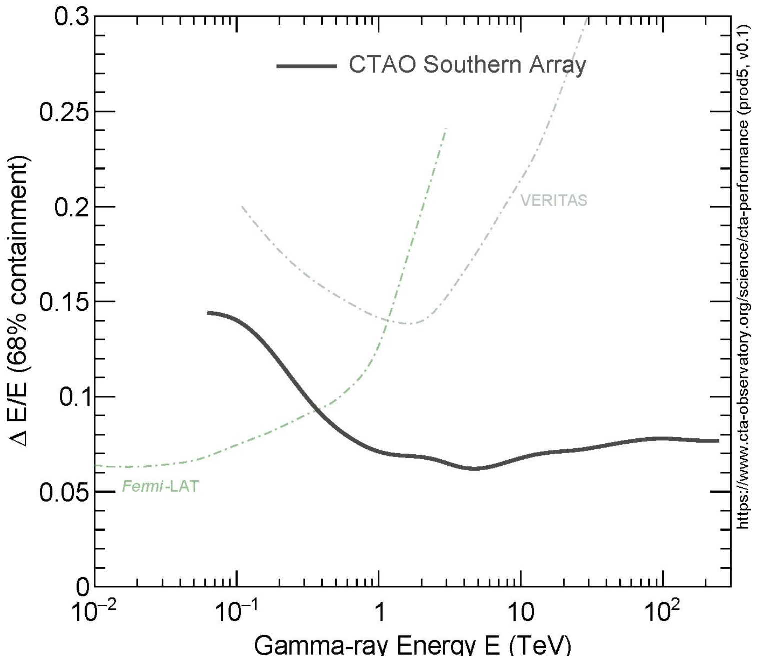
https://www.cta-observatory.org/

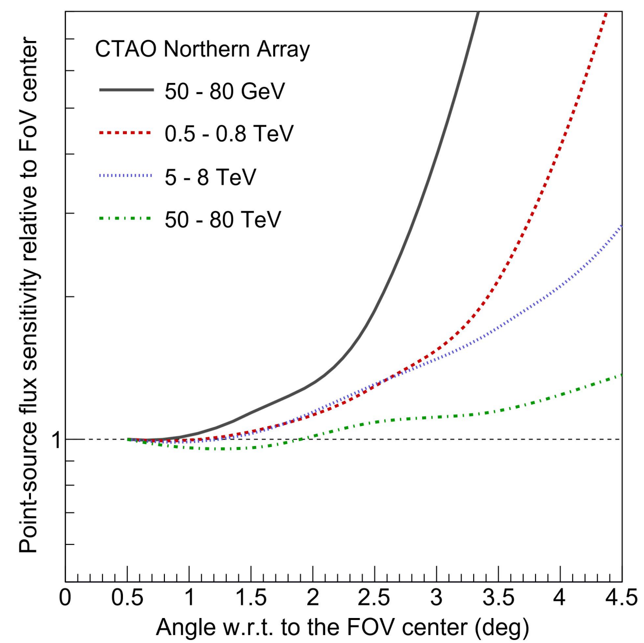




Studying transients with IACTs: why?

- The energy resolution is very good, ensuring reliable energy estimation and spectra
- Also, sources can be detected off-axis, given that degradation of sensitivity is moderate (at least starting from few hundreds of GeV) --> important for not well localized sources like neutrinos or GRBs detected by Fermi-GBM or relatively well localized GW events (O(few 10deg2))





https://www.cta-observatory.org/

Studying GRBs with IACTs: challenges

Observing GRBs with IACTs is challenging...

1. field of view of IACTs is limited (they are pointing instruments), so they need to rely on external facilities to get the GRB coordinates (e.g. from Swift, Fermi)
   - this introduces a delay in the observation, so the most interesting phase of the GRB, the prompt, may be missed

2. GRBs are distant sources (e.g. median redshift for long GRBs is ~2)
   - this translates on a huge absorption of the VHE flux due to the interaction of VHE photons with the ones from the extragalactic background light

3. duty cycle is limited (only nights, with no strong moon, and good weather), so interesting events may happen when IACTs cannot operate or can operate but with worse sensitivity (e.g. strong moon, reduced atmospheric transmission etc.)

4. some instruments provide a large localization, so the best fit position may not be the real position of the source, which can fall outside the field of view

Studying GRBs with IACTs

Given these challenges, how can those be mitigated with IACTs?

- IACTs should be able to repoint fast to the GRB position from any position they were pointing at the moment of the alert, in order to reduce the latency for the beginning of the observation
  - some examples: MAGIC fast mode speed is 7°/s, LST-1 GRB mode speed is ~10°/s i.e. less than ~20s to reach any position in the sky

- IACTs should have a low energy threshold to detect gamma rays in an energy band where EBL absorption is less severe
  - CTA concept implements this with different types of telescopes: in particular, LSTs are those covering the lowest energy range starting from ~20 GeV.
  - Also MAGIC can reach a low energy threshold of ~50 GeV, and H.E.S.S.-II can go down to similar energies as LST-1 (but H.E.S.S.-II will stay mono, while there will be 4 LSTs, so performance is hindered by the worse reconstruction and higher background of monoscopic systems)

Studying GRBs with IACTs

Studying GRBs with IACTs

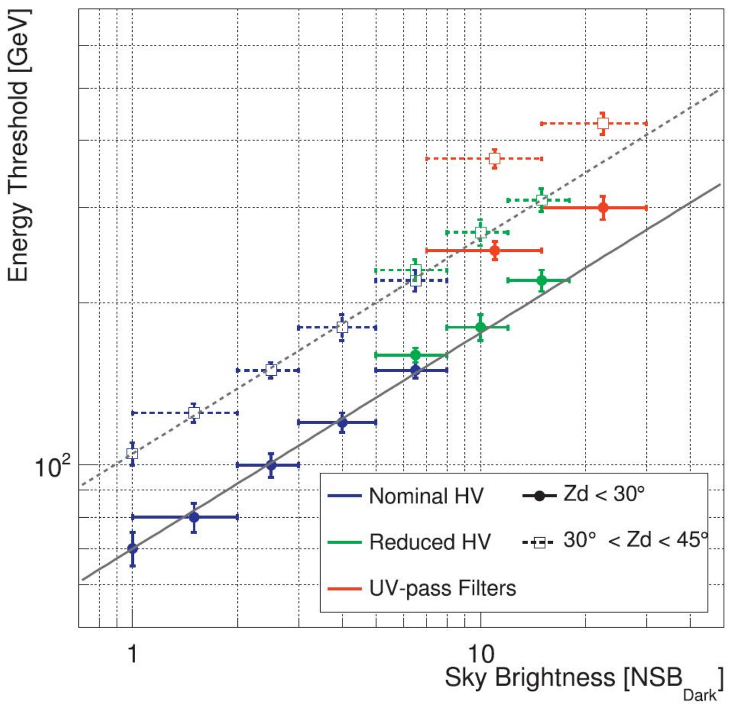
Given these challenges, how can those be mitigated with IACTs?

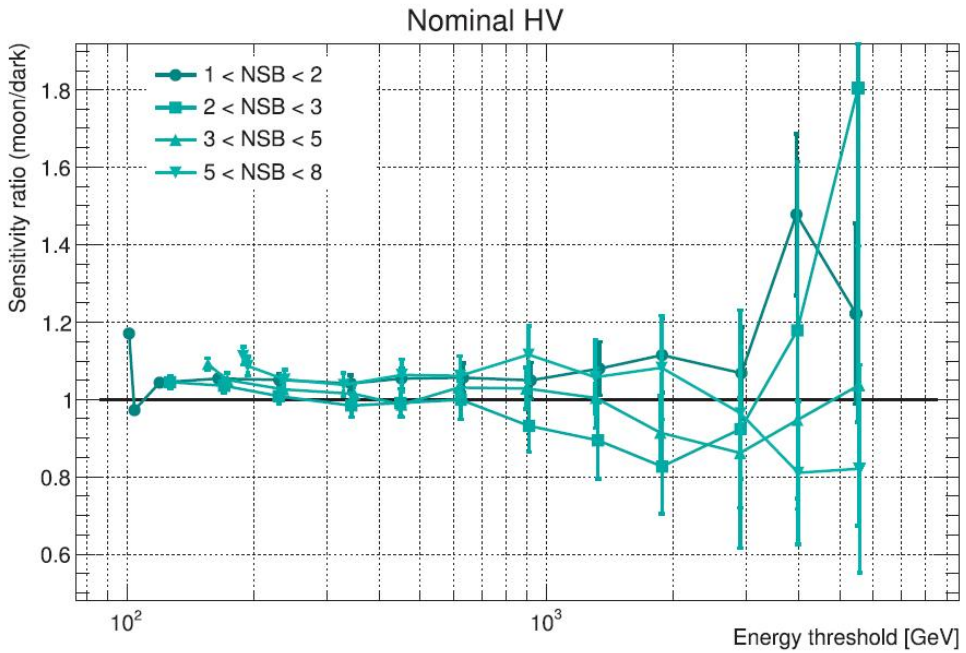
- duty cycle can be increased by performing observations with low/moderate/strong moon and with non perfect atmospheric conditions, at the price of reduced sensitivity
  - for example, MAGIC introduced moon observations by adopting tuned hardware configurations (higher thresholds and/or reduced high voltage of detectors) --> higher threshold, but with a contained worsening of the sensitivity
  - usage of instruments for the monitoring of the atmosphere (e.g. LIDARs) can be used to estimate the transmission of the atmosphere and correspondingly correct the data for this effect

- tiling techniques can be used to cover large areas in order to search for a not-well localized source

Studying GRBs with IACTs

Astroparticle Physics 94 (2017) 29–41

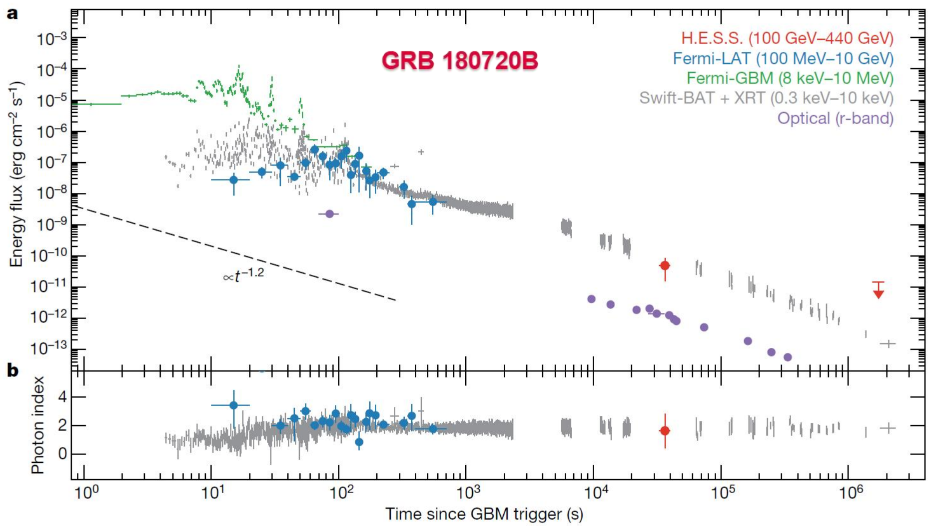




- As expected, energy threshold increases with increasing background
- But, sensitivity drop is moderate up to ~1 TeV

GRBs at VHE with IACTs

Nature, 575, 464 (2019)



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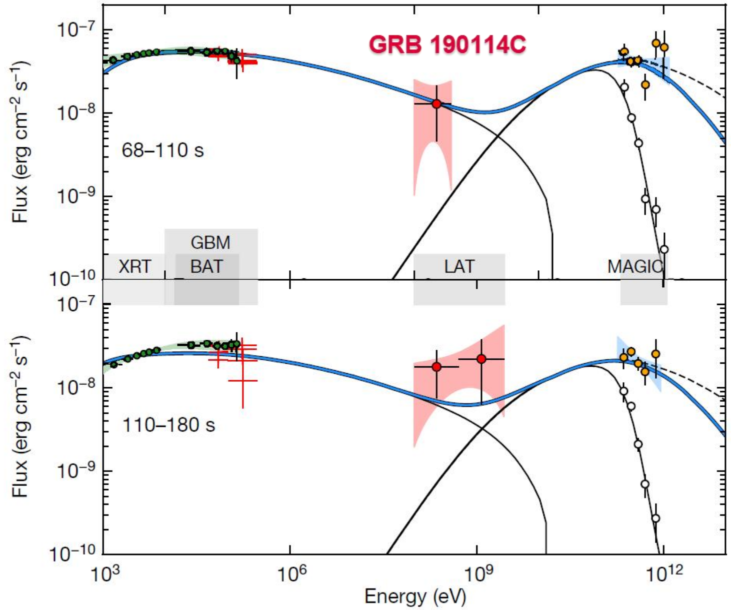
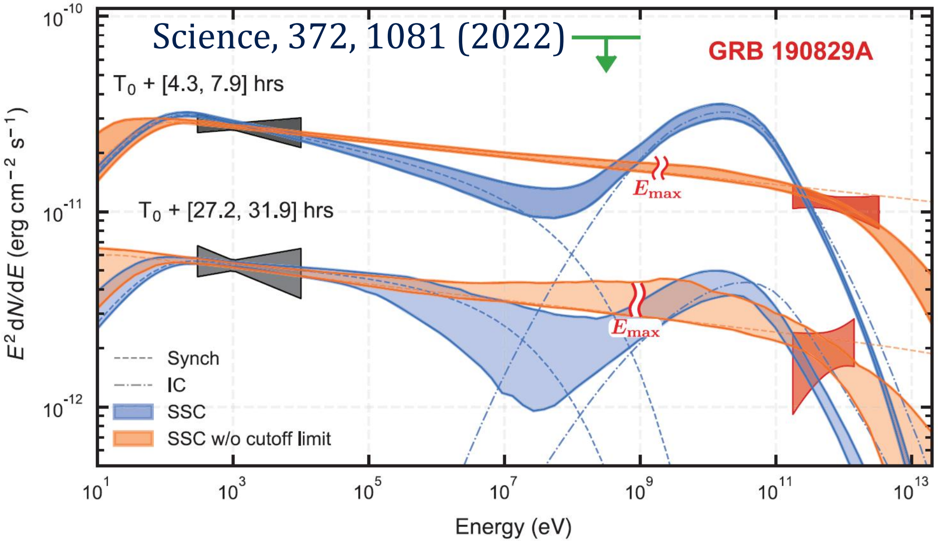
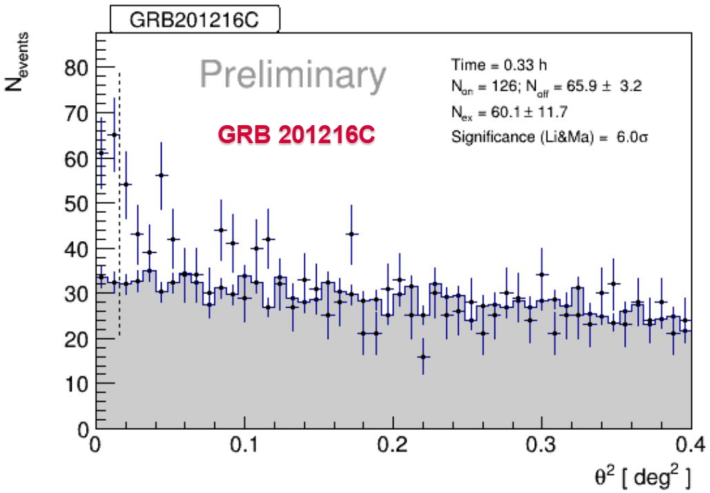


Science, 372, 1081 (2022)





https://pos.sissa.it/395/788/

GRBs at VHE with IACTs: what did we learn?

The 4 detections of GRBs at VHE gave us plenty of information

- GRBs can be detected both in the early and late in the afterglow --> follow-up at early times pays off, but also the one late times can be a winning strategy
- GRBs can be detected at moderate (or high) redshifts if bright enough
  - dim events like GRB 190829A need to be closer
- VHE emission can be produced via the self synchrotron-Compton process e.g. GRB 190114C but GRB 190829A challenges this scenario
  - need more GRBs to understand if new component is there for all GRBs, or if synchrotron (with some revision) can explain part of VHE GRBs
- Similarities between flux level in X-ray and VHE bands, also similar time decay
- MWL data crucial for proper modeling of the emission

GRBs at VHE with IACTs: next challenges

1. Our understanding of the afterglow emission is still uncertain despite the recent detected events
   - synchrotron+SSC vs synchrotron in discussion; alternative models (e.g. hadronic)?
   - **we need more GRBs detected at VHE!**

2. Another major breakthrough would be the detection of VHE emission during the prompt phase
   - crucial info on the emission process, still heavily debated
   - current and new ground-based wide field of view instruments (HAWC, LHAASO, SWGO...) may be better suited for this task

3. VHE emission from short GRBs? Strong hint from GRB 160821B by MAGIC
   - interesting in relation to GW searches (O4 starting early 2023)

4. New physics
   - Lorentz Invariance Violation (we would need a distant GRB detected in the prompt)
   - Axion-like particles (search for signatures in the spectra; GRBs detected at high redshift)
   - EBL studies?

Studying GRBs with IACTs: analysis considerations

Challenges of GRB data analysis with IACTs

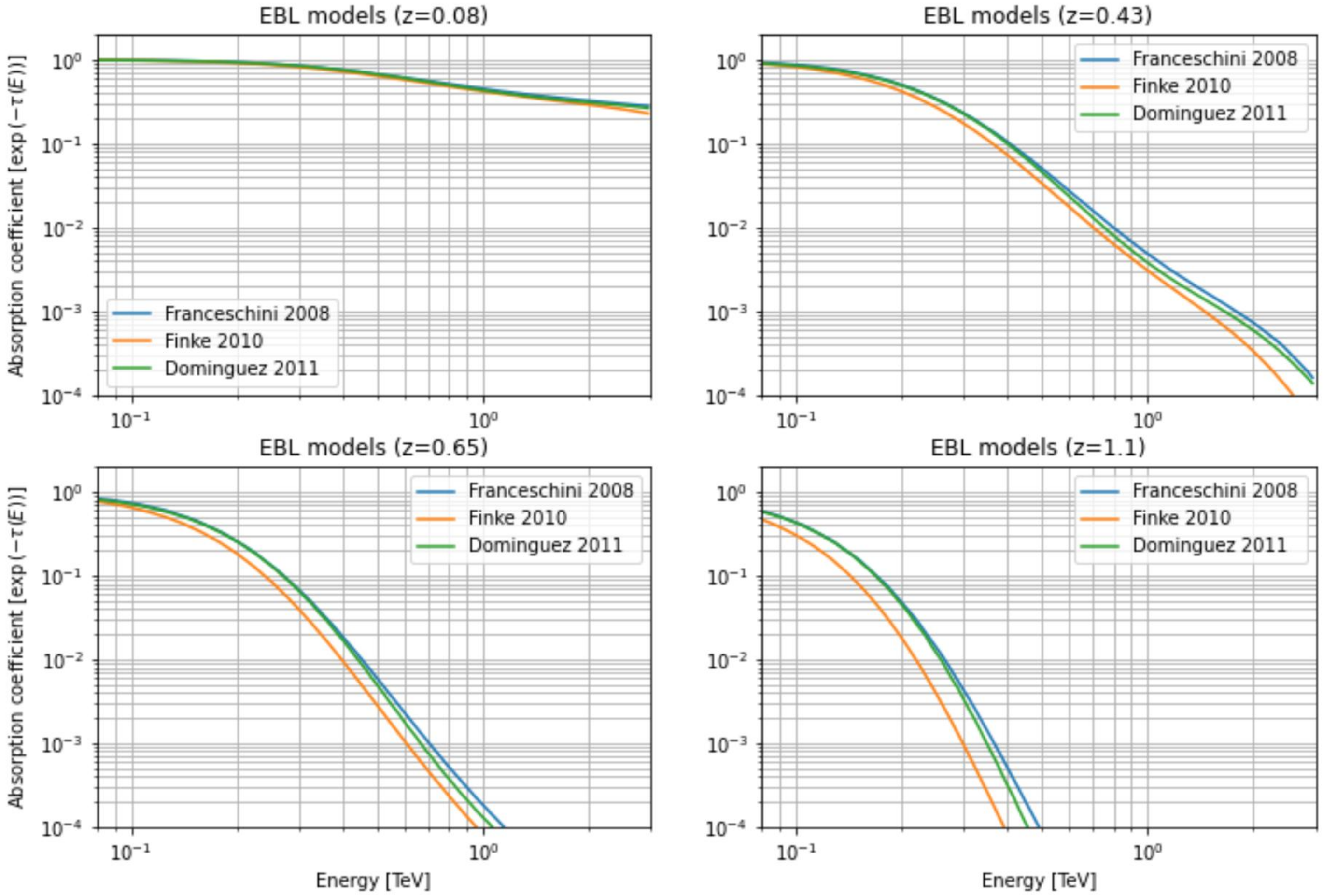
- systematics, especially due to EBL
  - difference on attenuation due to EBL can be large depending on the model, especially for high redshift and high energies (~TeV)
  - systematics due to EBL can be estimated by correcting the observed spectra with different EBL models and checking the resulting index/normalization
  - systematics related to non perfect knowledge of atmosphere transmission, mirror reflectance and PMTs properties --> affects the so-called light scale i.e. amount of light seen by telescopes; there can be mismatches between MCs and real data which affect the resulting spectra (pile-up, event migration)

- trials (e.g. if localization is large or if you start optimizing cuts to get best sensitivity)
  - especially if the level of detection is just above 5 sigma, taking into account trials would inevitably decrease the final detection level
  - for cuts, it is better to have studies a priori, so that some set of cuts can be used and number of trials is not incresed

- very soft spectra leading to difficult unfolding (and also migration matrix can have large tails and migration of low energy event to high energy)

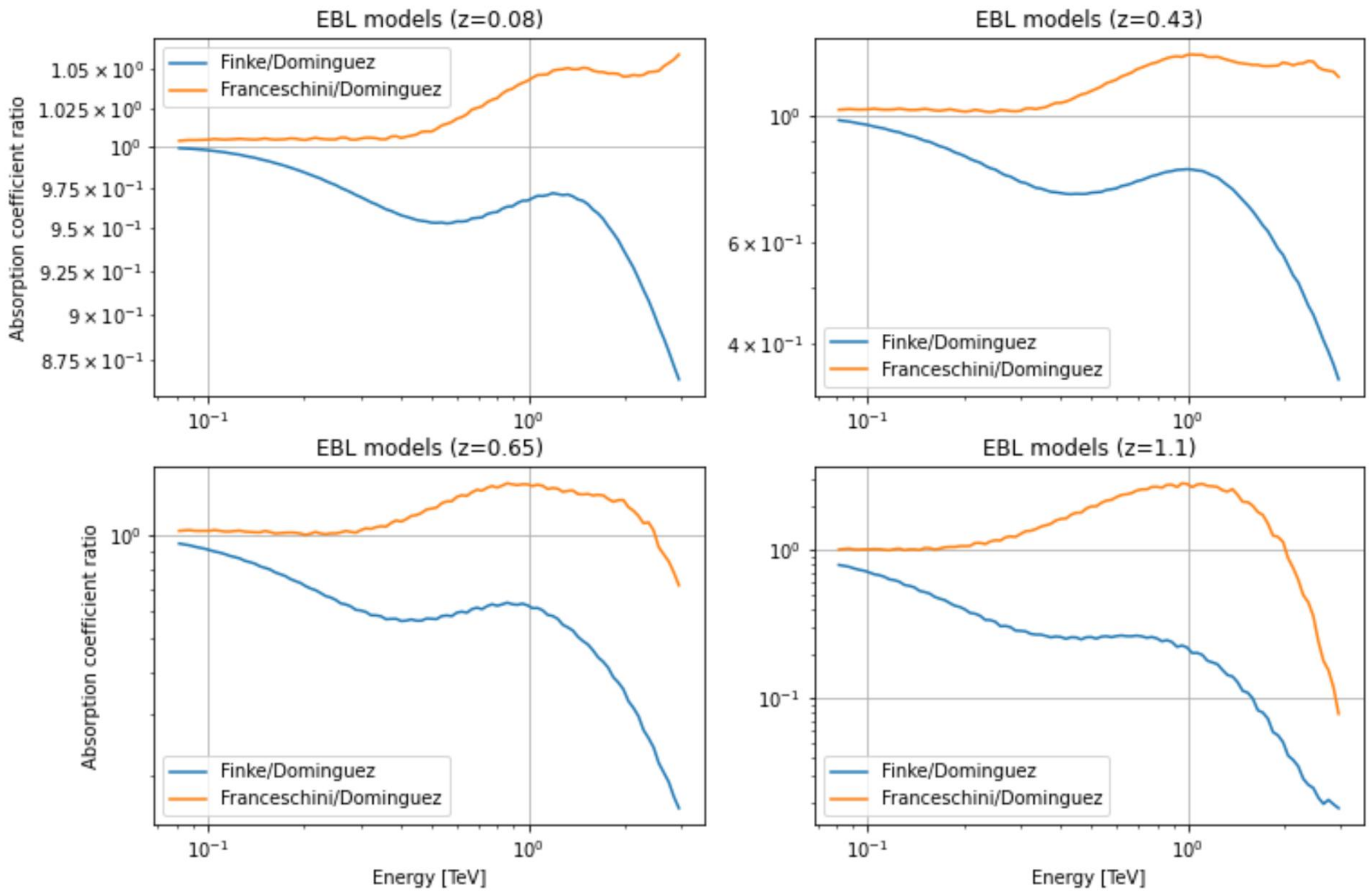
Studying GRBs with IACTs: analysis considerations

Comparison of different EBL models at different redshifts. Small trivia: why this choice of redhifts?



Studying GRBs with IACTs: analysis considerations

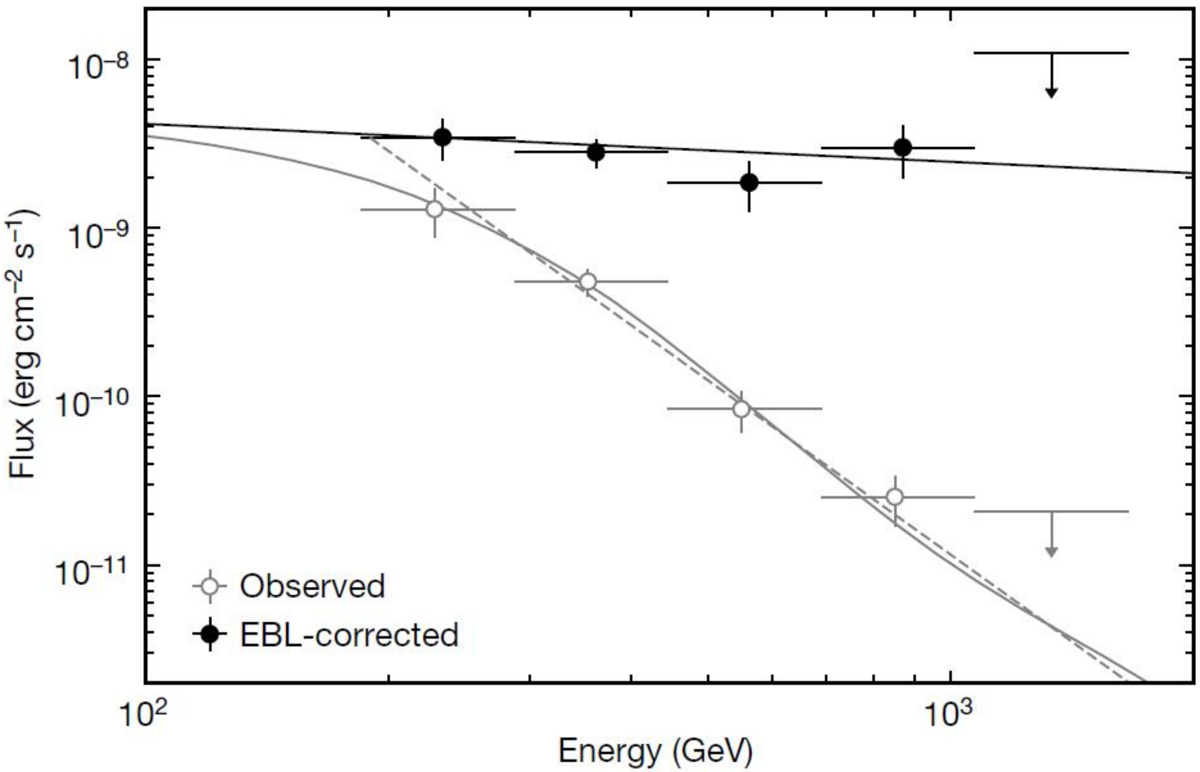
Difference between expected absorption can be quite big especially at high energies...



Studying GRBs with IACTs: analysis considerations

EBL effect: example on GRB 190114C, z=0.42

- factor ~3 at E~200 GeV
- factor ~300 at E~1 TeV

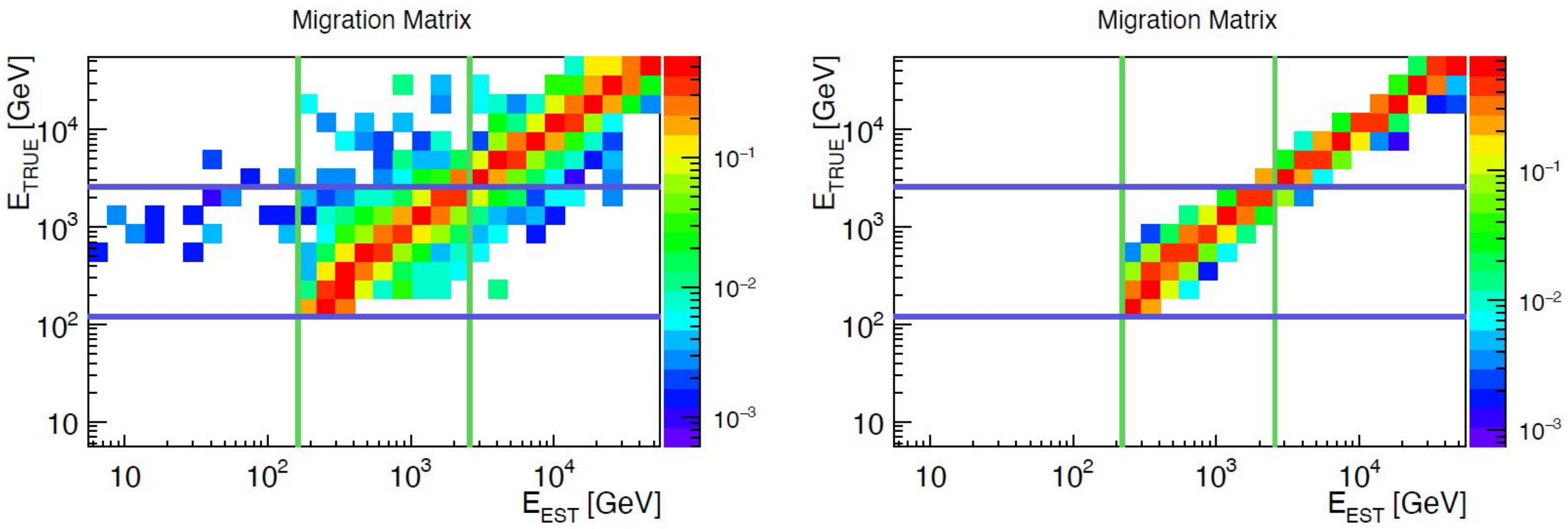


Studying GRBs with IACTs: analysis considerations

With soft spectra, migration matrix can show strange tails

- one way to deal with this is to have better energy estimation methods, see plot below
- left is using energy estimation using Look-Up Tables (LUTs)
- right panel shows the same dataset but energy estimation is performed through Random Forests --> outliers are gone and this helps a lot in the unfolding of the spectra

K. Ishio's PhD thesis

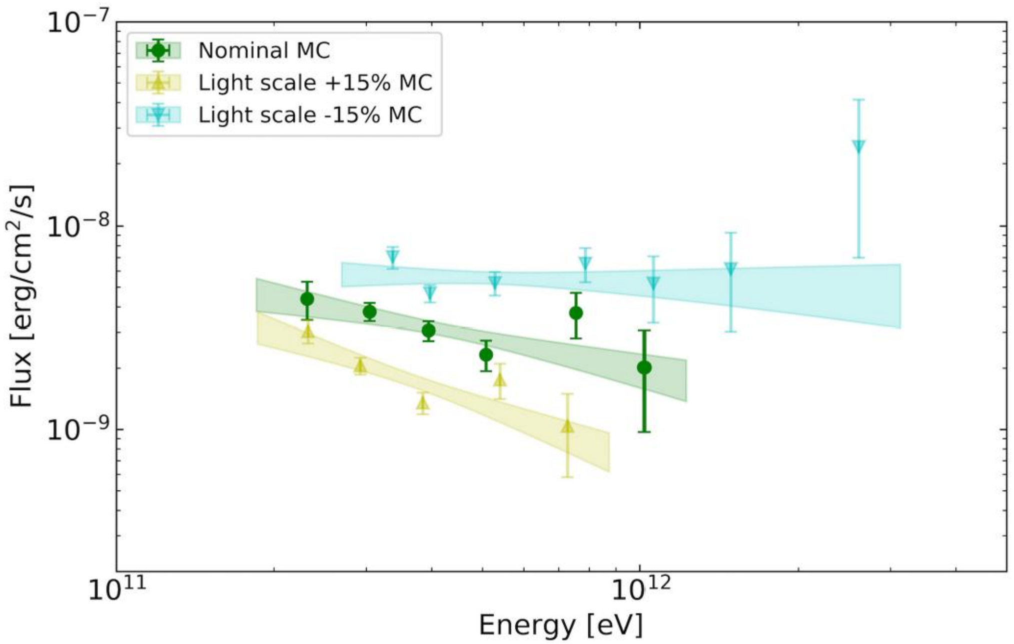


Studying GRBs with IACTs: analysis considerations

Matching of real data and MC is not perfect

- light scale of MCs can be higher or lower than in real data, because of many components that are not perfectly known
- therefore, one can mimic an increased or decreased light scale in MCs and check the effect on the final spectra

Nature, 575, 459 (2019)



Studying GW events with IACTs

Similar challenges as for GRBs affect the follow-up of GW events

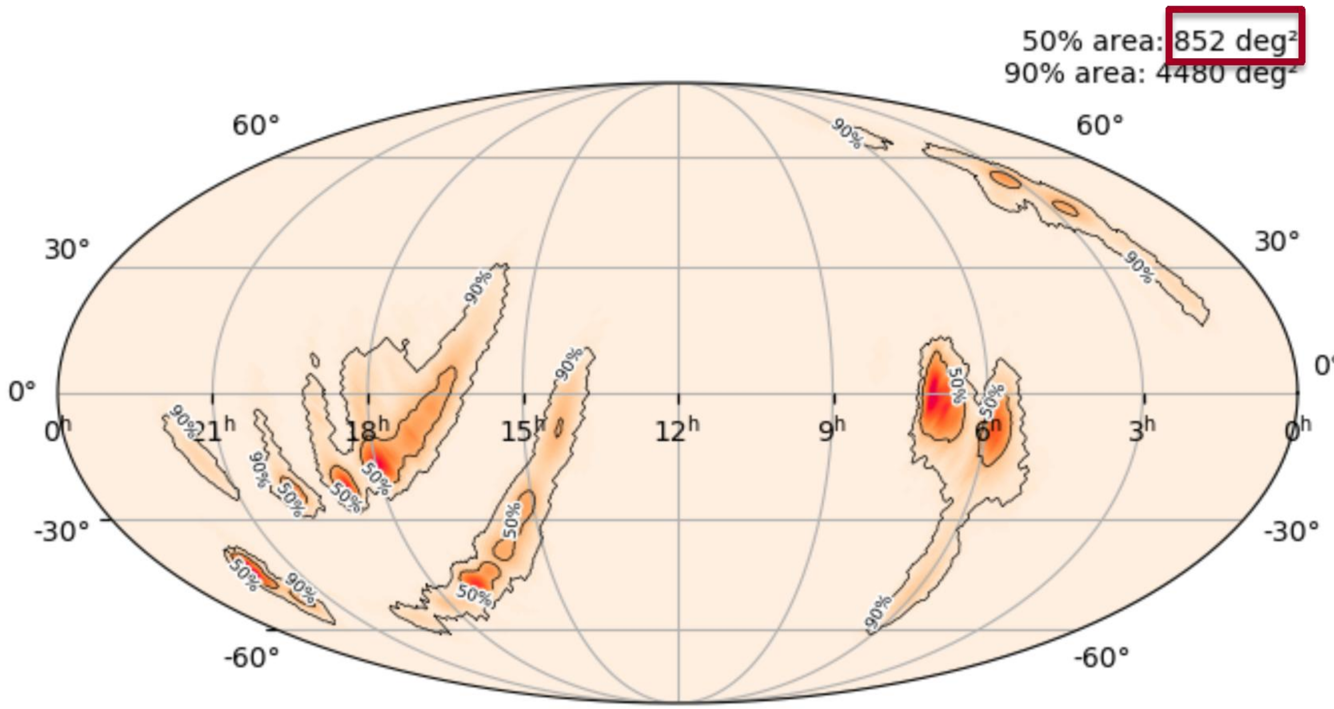
- localization can go from few tens to hundreds/thousands of deg^2, which can be as large as an IACT field of view in the best case scenario --> no clear source

- additional delay introduced to get the signal from interferometers (~few minutes)

- in the case of BNS systems, the resulting GRBs may be off-axis, thus reducing the incoming flux when the jet “opens up” along the line of sight
    - depending on the viewing angle, this may lead to a very faint GRB prompt (e.g. GRB 170817A), or to orphan afterglows

The only way to cope with all these issues is to devise an observational strategy for the follow up of the EM counterpart of GW events

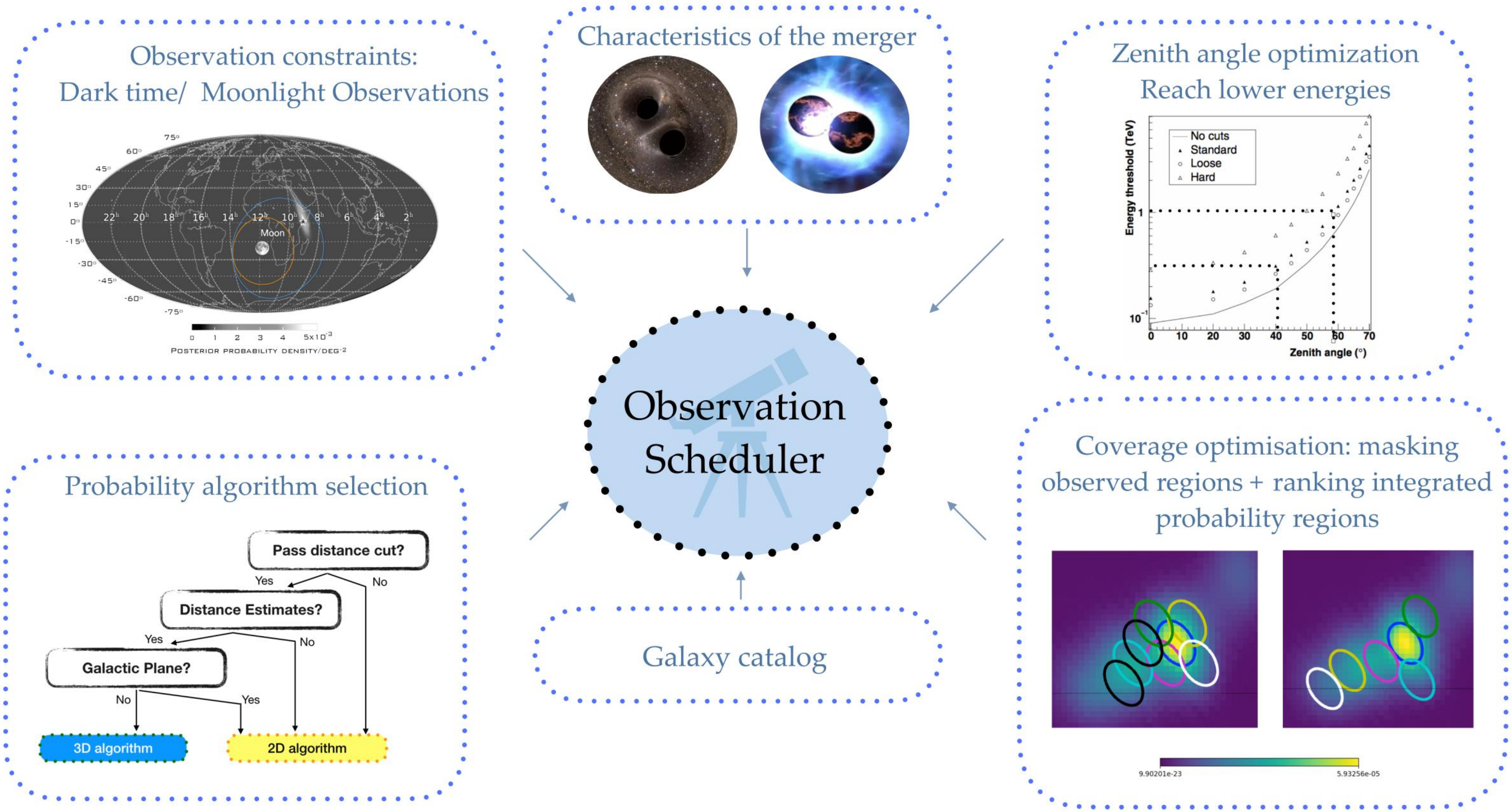
Studying GW events with IACTs



https://gracedb.ligo.org/superevents/S191213g/view/

Example of localization from one BNS event (77%), S191213g, d~200 Mpc, LALInference algorithm

Studying GW events with IACTs: observation scheduler



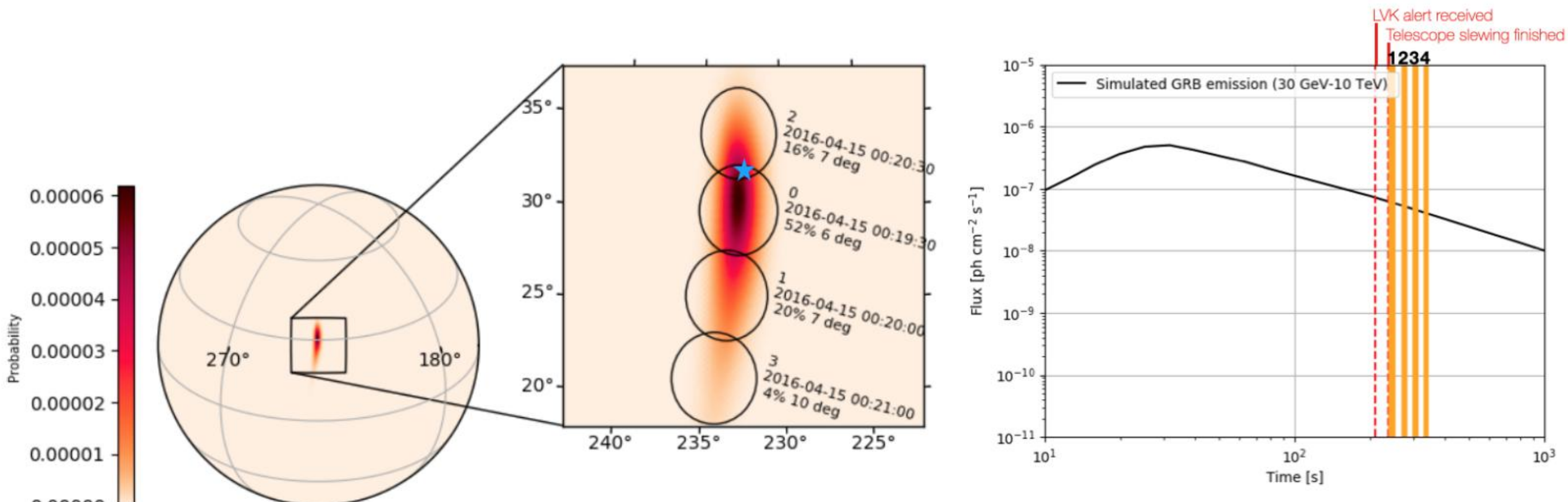
Scheduler algorhitm based on: Ashkar, H., et al. 2021, JCAP 03, 045

Studying GW events with IACTs: observation scheduler

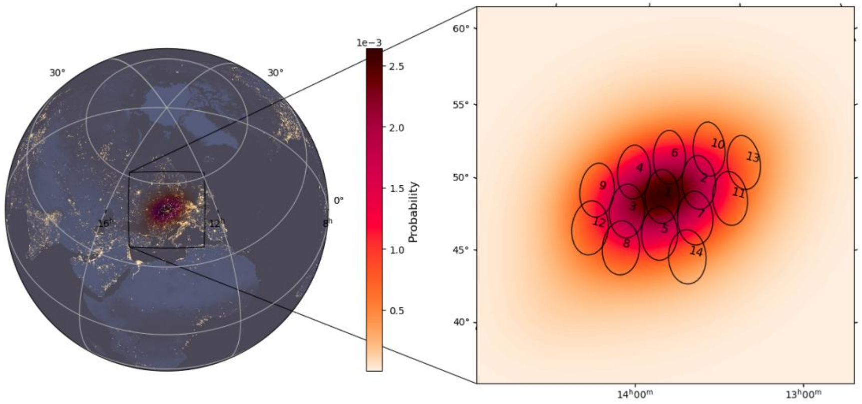
An example of application to a specific event, starting from a simulation of a BNS system (GWCOSMoS, Patricelli et al. 2018, JCAP 5, 056) resulting in a short GRB seen on-axis (E_{iso}~$4x10^{50}$ erg)

- delay in observation: 210s (GW alert 180s + 30s first slewing time; NB: no delay due to scheduler algorhitm to run is considered)
- 4 pointings covering 90% of the region (40 deg^2), each with 10s exposure
- slewing time between pointings: 20s
- CTA-North sensitivity considered
- detection of the GRB (> 5 sigma) for 1st and 3rd pointing

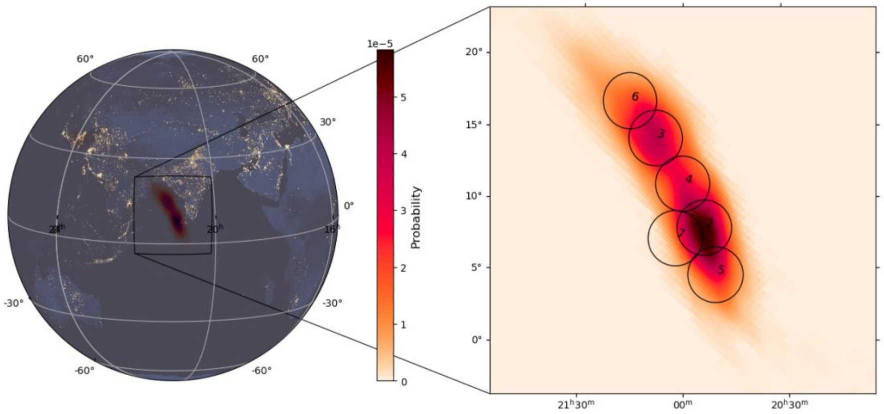
Patricelli et al. 37th ICRC2021, PoS 998, 2021



Studying GW events with IACTs: LST-1 case



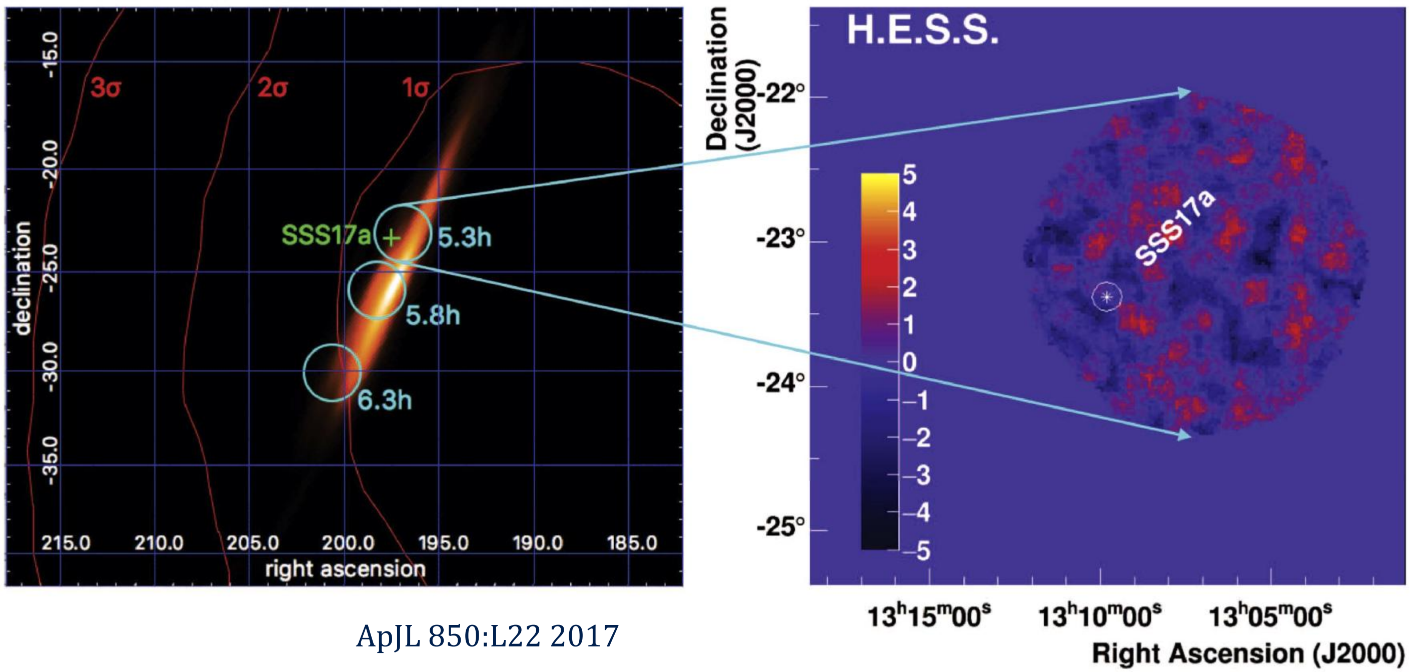
GRB 200303A by Fermi-GBM



GW190915_235702 by LVC

- The aforementioned observation strategy is being implemented within the LST-1 Transient Handler
  - not only GWs, tiling can be applied also to poorly localized GRBs
  - coverage of most of the localization region
  - Real Time Analysis (RTA) will tell if there is a detection and send a science alert to interested parties + change the observation schedule to keep observing the position

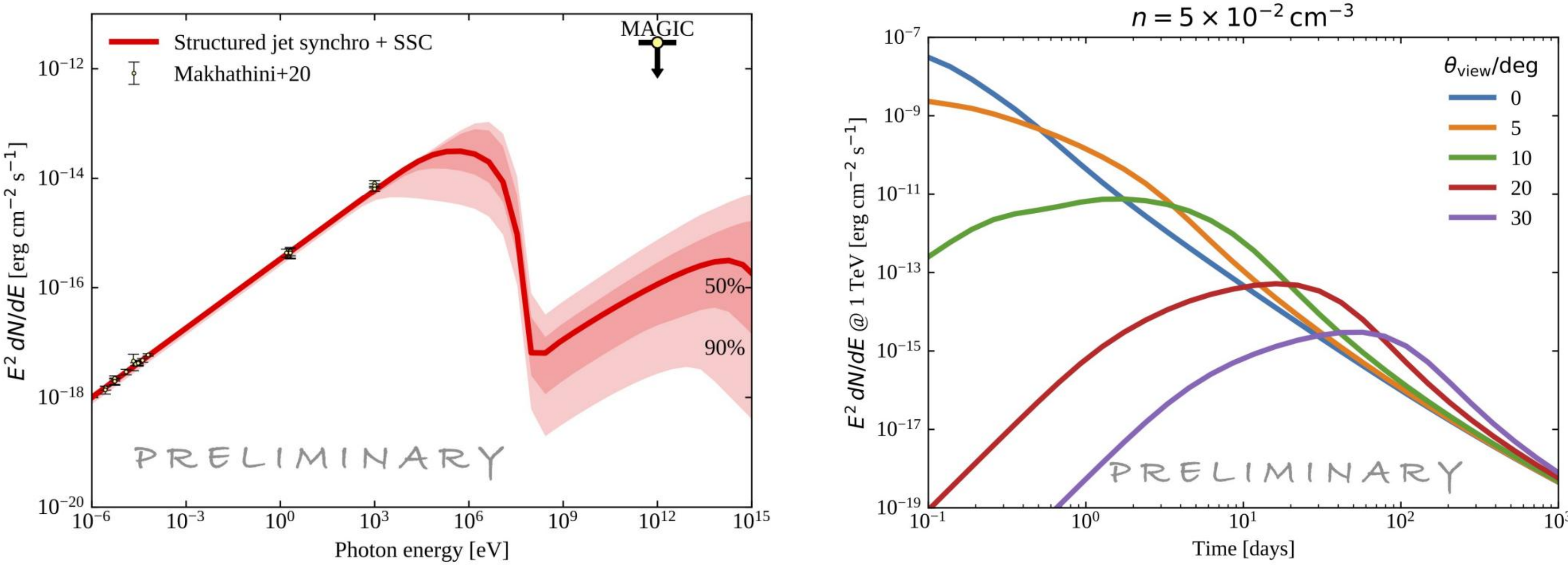
GW events with IACTs



ApJL 850:L22 2017

- H.E.S.S. follow-up of GW170817A
  - scheduling covered the region where the EM counterpart, SSS17a, was later confirmed to be
  - delay of ~5h because alert came during day
  - further follow-up in the following days focused on the EM source

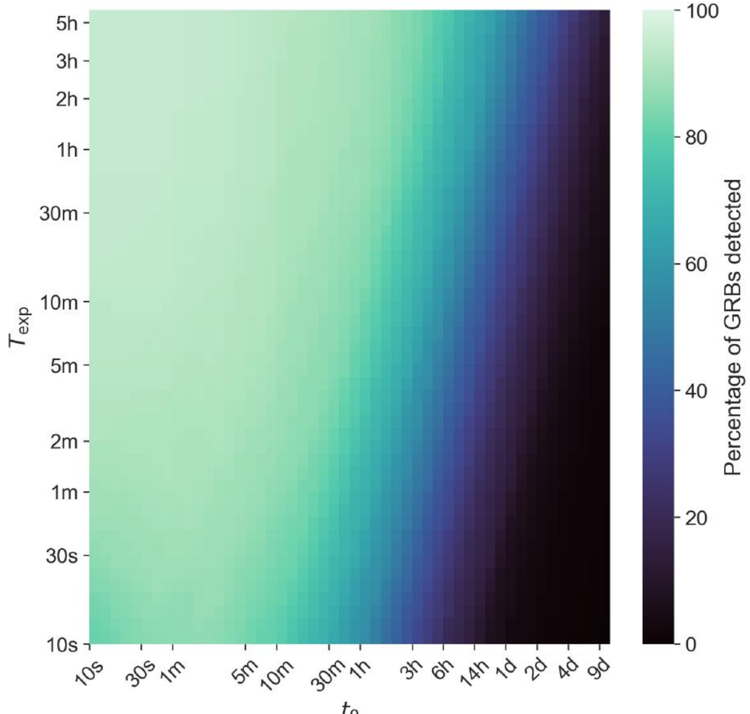
GW events with IACTs



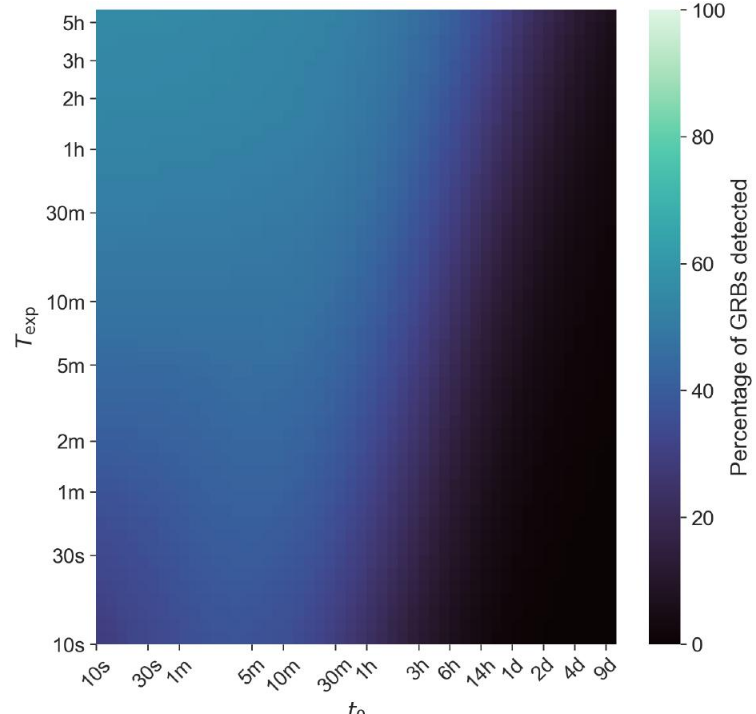
https://pos.sissa.it/395/944/

- MAGIC follow-up of GW170817A
  - at the time of the alert, the EM counterpart was too low on the horizon
  - follow-up ~150 days after merger, but UL not sensitive to constrain possible TeV emission
  - a larger medium density and smaller viewing angle make the emission brighter, and so possibly detectable

GW events with IACTs



(c) CTA North, z20°, ($\theta_{\text{view}} < 10°$)



(d) CTA North, z20°, ($\theta_{\text{view}} < 45°$)

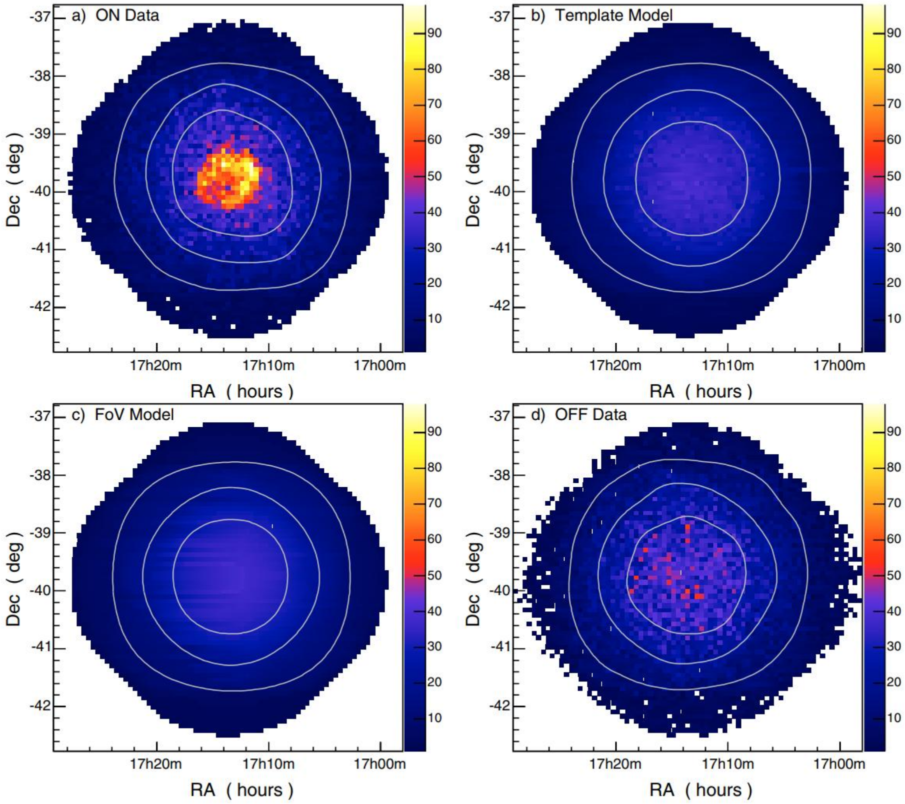
Patricelli et al. 37th ICRC2021, PoS 998, 2021

- Delay ~30s: ~94% (52%) detections with exposure time ≤ 30 minutes for on (off) axis GRBs
- Delay ~10min: ~92% (54%) detections with exposure time of few hours for on (off) axis GRBs

Studying GW events with IACTs

Background modeling for skymaps e.g. for ULs of NToO/GWs

- in such cases, one may need to know the background on a large part of the FoV, if not all of it --> Berge et al., A&A, 466, 2007 is a great reference for this

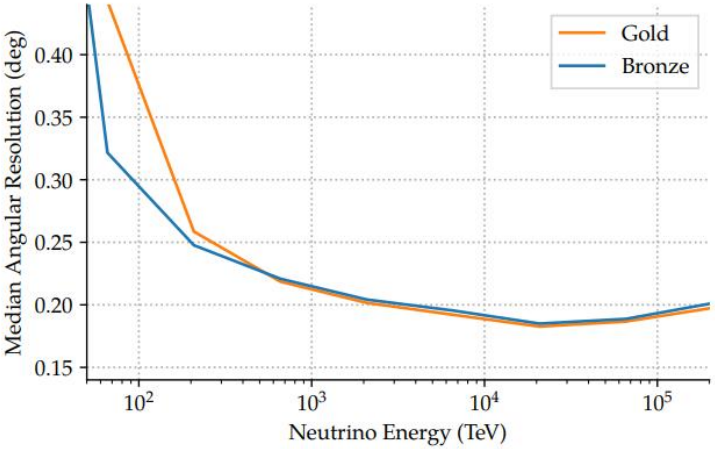


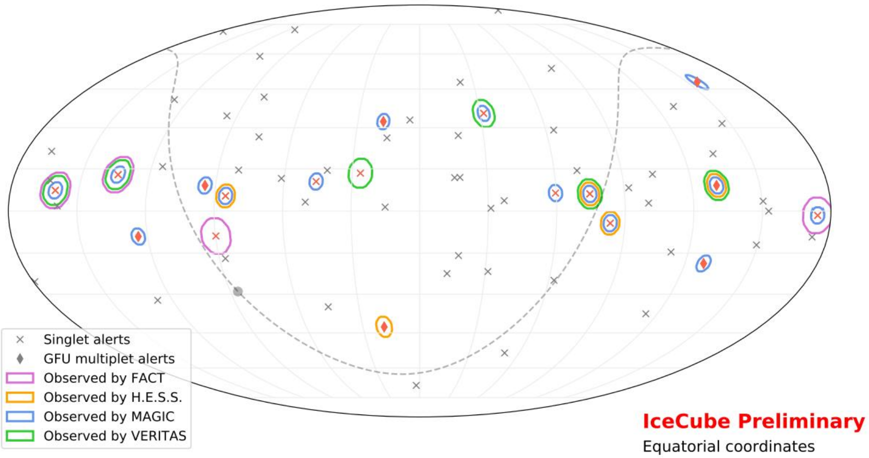
Studying neutrino events with IACTs

The case of neutrino combines a bit the challenges from GRBs and GWs
- no prediction on their arrival
- localization can be of the order of ~1deg, depending on energy of the neutrino

IceCube is the experiment currently sending neutrino alerts
- two public streams
  - GOLD, events having on average 50% probability of being astrophysical
  - BRONZE, events having on average 30% probability of being astrophysical

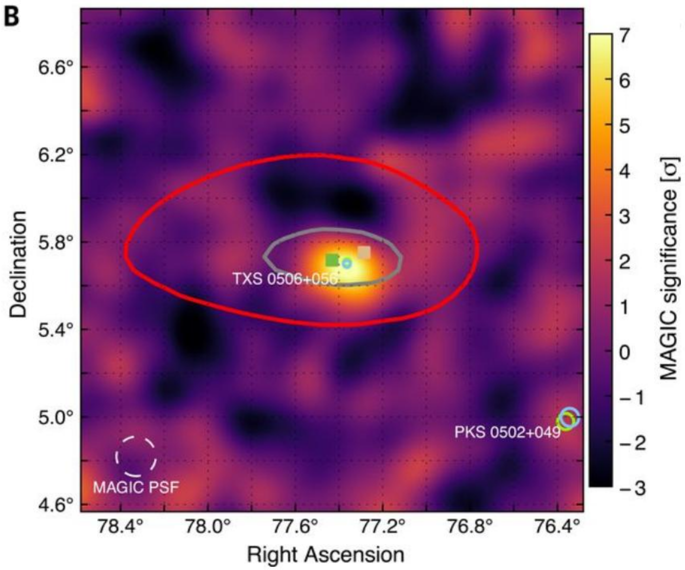
- two private streams (through a memorandum of understanding between interested parties), soon (?) to become public
  - multiplets coming from specific source
  - all-sky multiplets

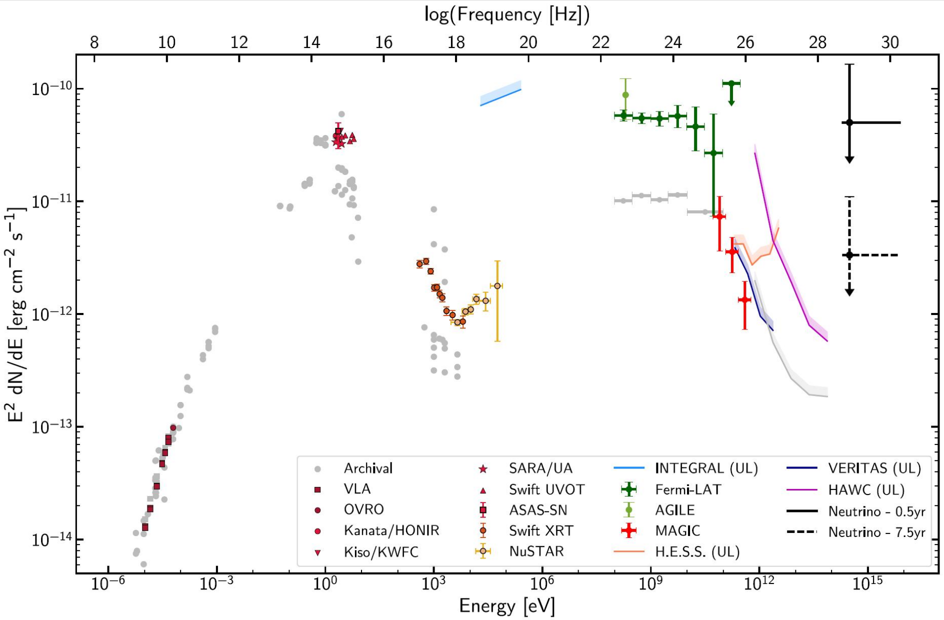




https://pos.sissa.it/395/960/

Studying neutrino events with IACTs



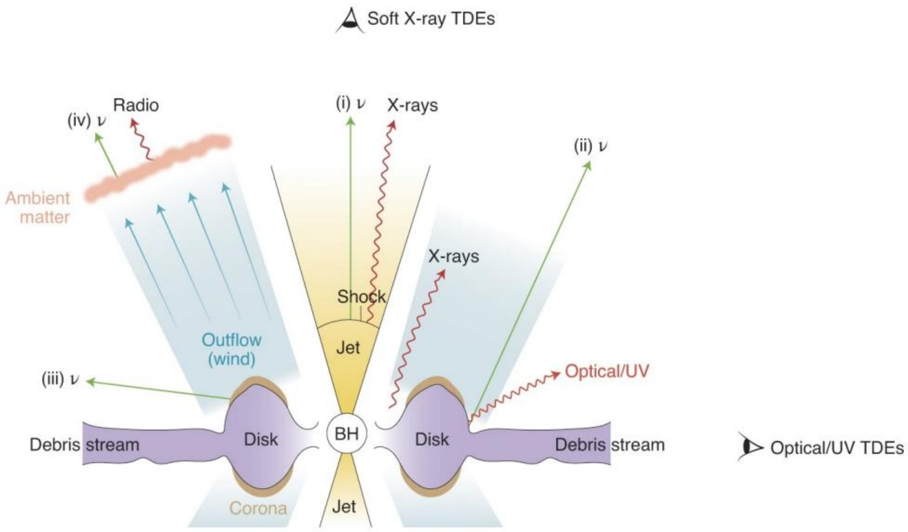


IceCube et al., Science 361, 146 (2018)

- Most famous example: TXS 0506+056, where emission of (V)HE gamma rays was detected by Fermi-LAT, MAGIC and VERITAS
  - chance coincidence of neutrino and flare disfavored at 3sigma level
  - hadronic model is needed to account for the production of neutrinos, and for this acceleration of protons up to UHE is needed --> blazar may be accleration sites for UHECRs
- But, picture is more complicated...
  - blazar may contribute to only part of the neutrinos
  - sources may be faint in gamma rays
  - other sources may contribute to neutrino flux e.g. tidal disruption events (AT2019dsg)

Studying neutrino events with IACTs

https://pos.sissa.it/395/009/



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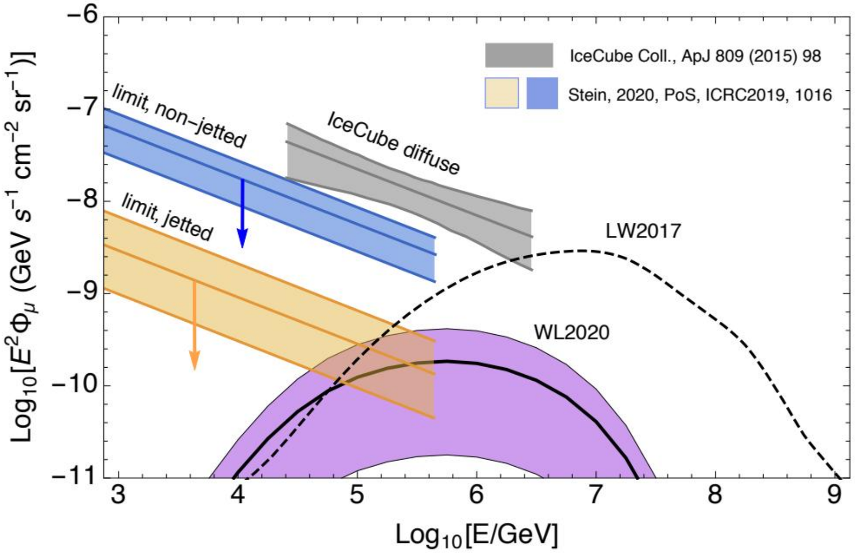
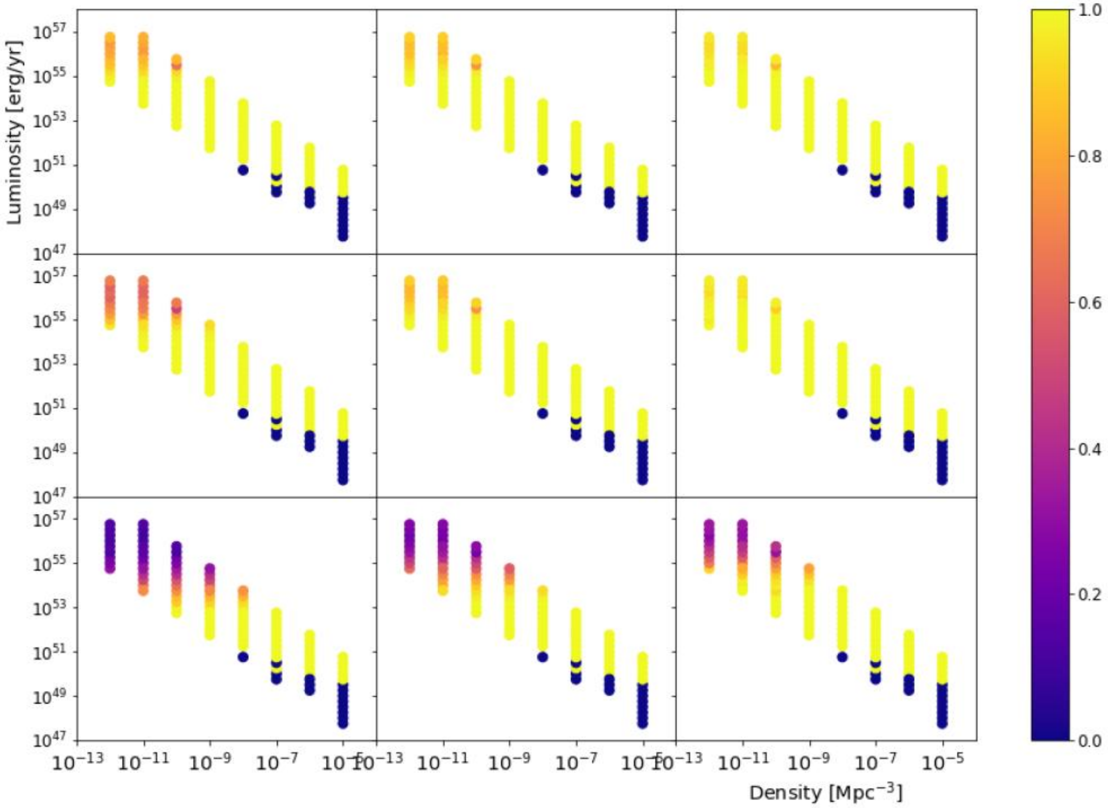


- Jetted TDE are possible neutrino emitters (left picture)
- Current models predict a contribution at the ~few % level of the total diffuse neutrino flux
- Current (ZTF, iPTF) and future facilities (e.g. Vera Rubin) will detect more TDEs, giving the opportunity of testing such scenario

Neutrino events with IACTs: prospects with CTA

Simulation of two class of sources using FIRESONG code

- steady sources of neutrinos, following a specific star formation rate model



For low zenith (20°- 40°), all sources with density down to 10^{-9} Mpc^{-3}

For high zenith, there is a large loss of performance, up to 65%

30min observation, CTA North

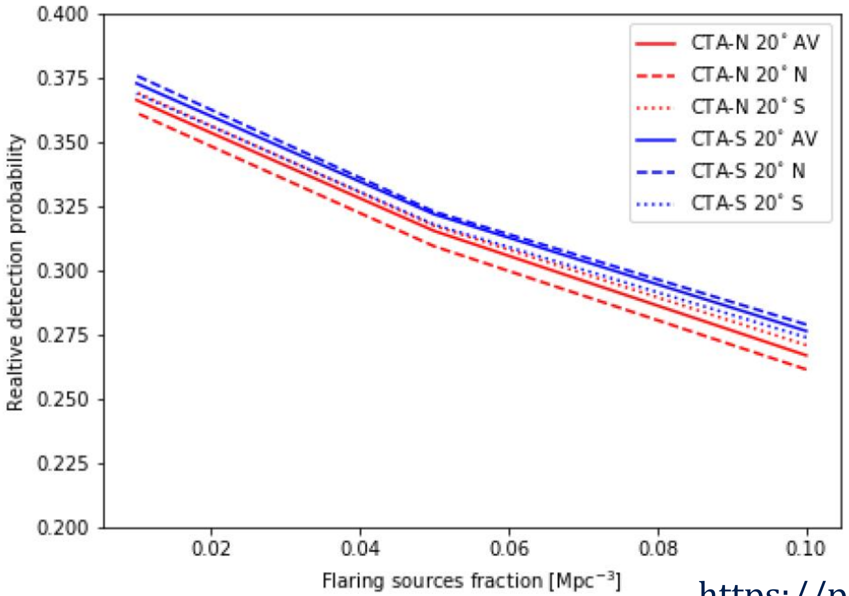
https://pos.sissa.it/395/975/

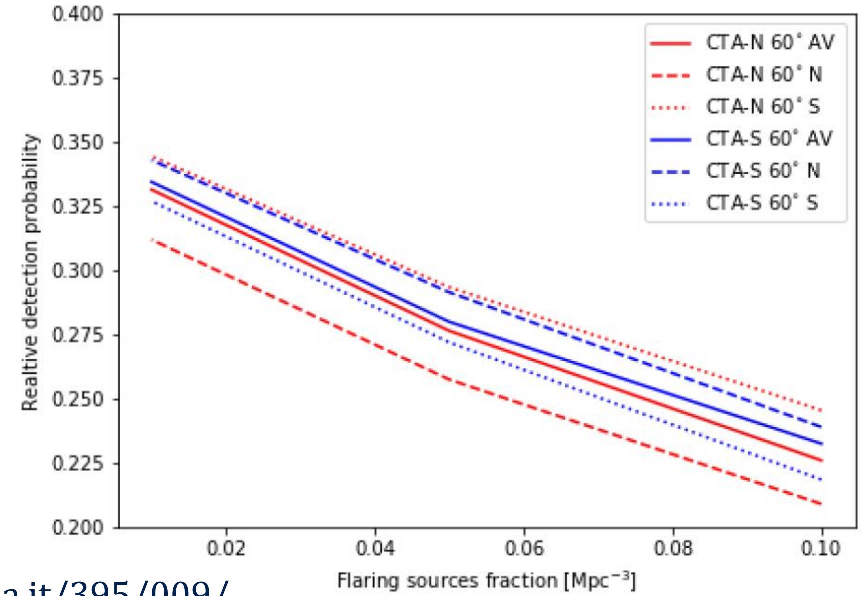
Neutrino events with IACTs: prospects with CTA

Simulation of two class of sources using FIRESONG code

- TXS-like flaring sources, following model of neutrino flare from TXS 0506 from 2014-2015, assumes only part of blazars are responsible for the neutrino flux

30min observation



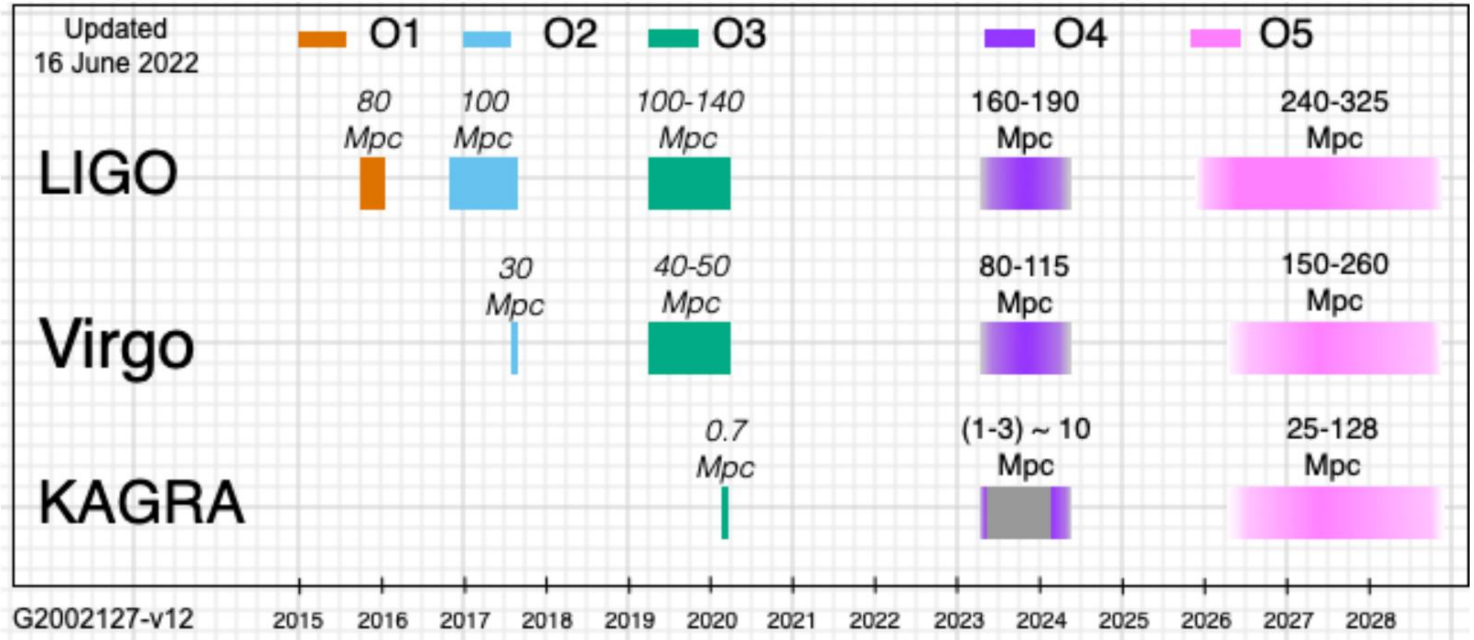


https://pos.sissa.it/395/009/

Not much difference between different zenith ranges
Detection probability grows with lower flaring sources fraction because single flare becomes brighter for lower fraction

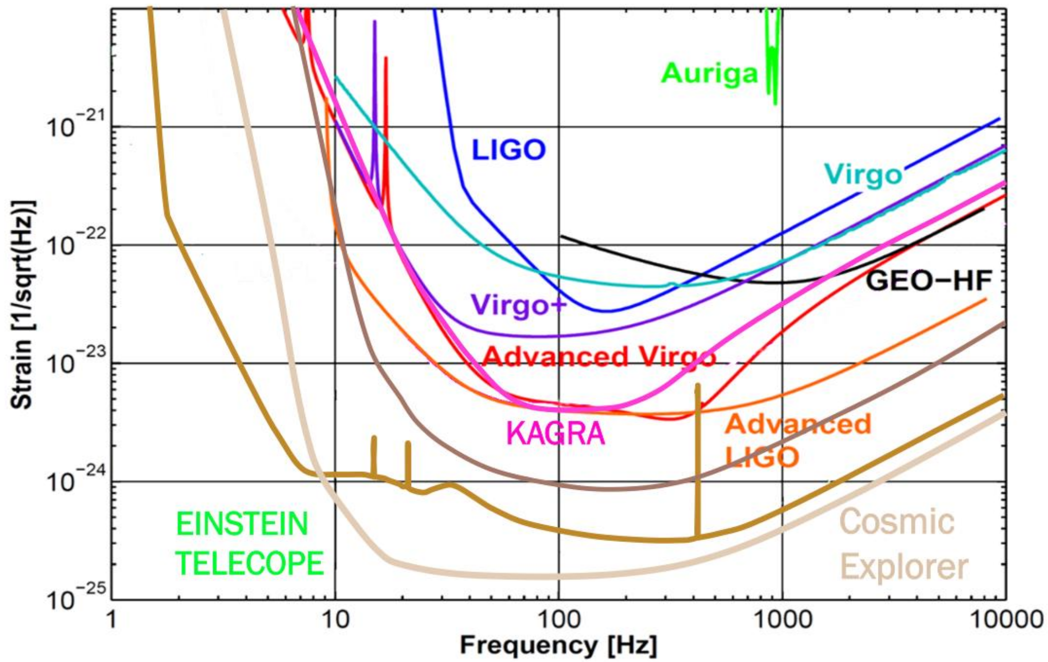
Future of MM astrophysics: GWs

https://observing.docs.ligo.org/plan/



- O4 should start in March 2023, 1 month engineering run, O4 duration ~1 year with 1 month break
- KAGRA not at full sensitivity
- As in previous runs, alerts will be sent via GCN (not clear if also early warning alerts will be sent)

Future of MM astrophysics: GWs



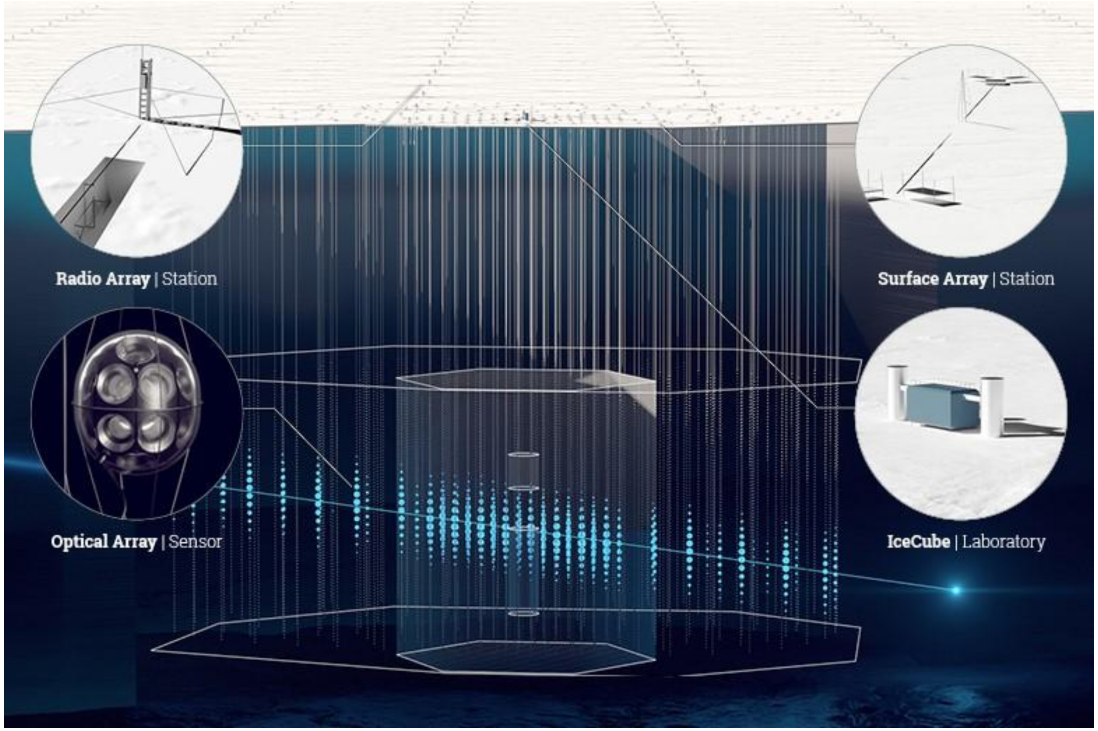
Einstein Telescope and Cosmic Explorer will be much more sensitive than current generation interferometers

- more alerts
- GW can be detected before the actual merger, giving already a rough localization to ground telescopes --> better follow-up!

Future of MM astrophysics: neutrinos

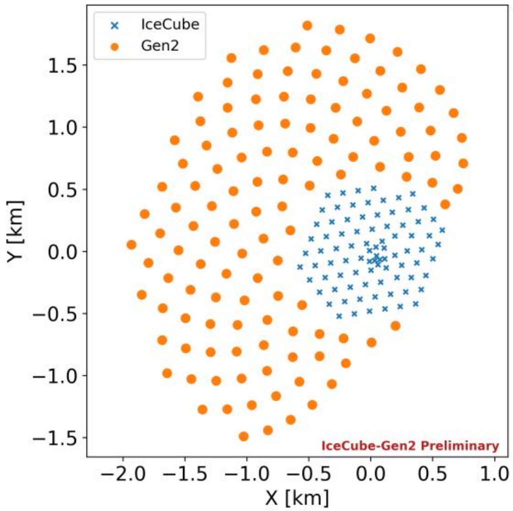
IceCube-Gen2

https://www.icecube-gen2.de



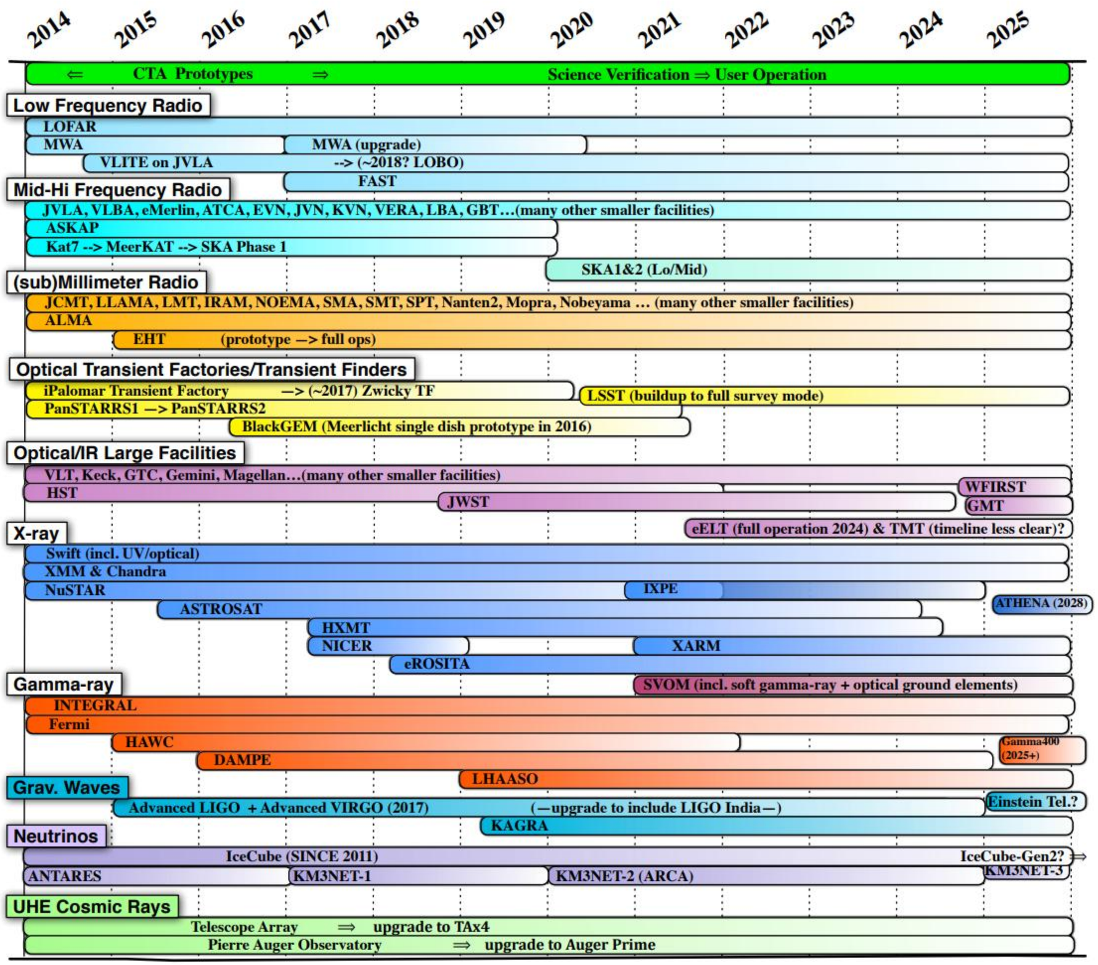
IceCube-Gen2 as an upgrade of IceCube

- ~8km^3, 1 order of magnitude more than IceCube
- 120 more optical modules
- radio array for >100 PeV neutrinos
- surface array for CR studies



https://pos.sissa.it/395/1186/

Future of MM astrophysics



arXiv:1709.07997

Summary

- MM astrophysics is blossoming, and future facilities will improve the outcome of such searches
  - But, need for coordination between facilities
- Already some key results, we can only improve from here
- Did not mention FRBs, Galactic transients (e.g. SGRs, novae) due to time, but they are very hot topics right now
- A lot of topics where young researchers can work for their bachelor/master, PhD, postdoc, both for theory, instrumentation, observations etc.

BACKUP