VHE gamma-ray counterparts to GWs

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AstroParticle Symposium

Astroparticle symposium - Paris-Saclay, 16 November 2021

Week 5 Gravitational waves and compact objects: experiments meet theories

Outline

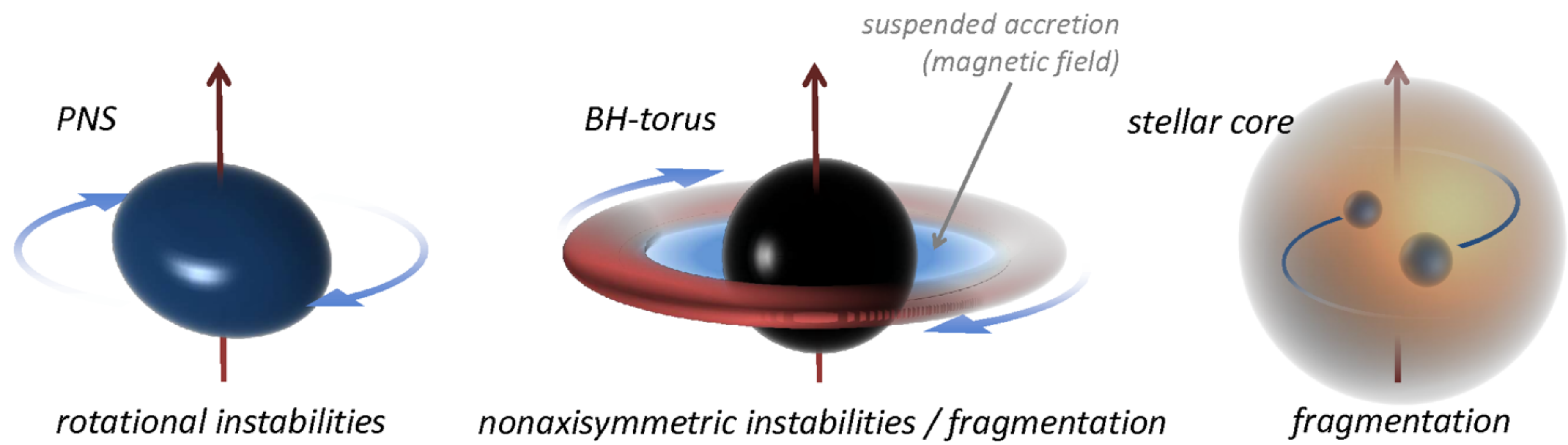
- GW at VHE: what
  - What do we know of the VHE emission from GW counterparts
  - What do we learn searching for VHE emission of GW counterparts How GW at VHE
- GW at VHE: how
  - How do we detect VHE transients?
  - How do we see a GW event in VHE?
  - How do we maximise the chance of detection of the VHE counterpart of GW events?
- GW at VHE: when
  - now - The GW follow-ups performed at VHE by present IACTs
  - future - The prospects for the GW-followup at VHE

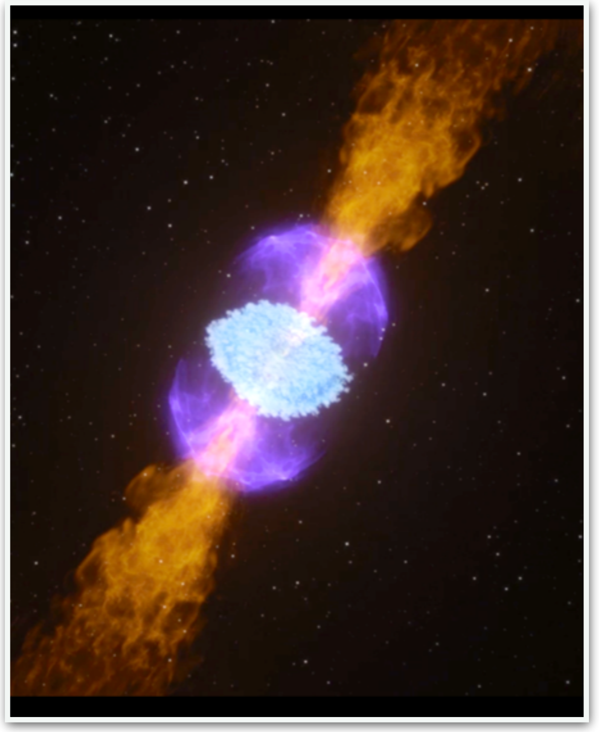
GW at VHE: what

- What do we know of the VHE emission from GW counterparts
- What do we learn searching for VHE emission of GW counterparts

GW e.m. counterparts

- Binary Neutron star mergers (BNS) ➔ **short GRB**, suggested (since Eichler+1989), expected (GRB050724) 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)





What do we learn searching for VHE emission from GW (theory)

- ✤ BNS association to short-GRB ➔ study VHE emission from short-GRB
- ➡ long/short GRBs show GeV emission (e.g. Nava+2018)
- ➡ Questions that the VHE constraints can address:
  - is GeV to TeV emission an extension of the synchrotron component?
  - or from Inverse Compton emission? which seeds?
  - proton-synchrotron radiation? Proton induced cascades? (➔ high-energy neutrinos)

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- ✤ While for long-GRB evidence is emerging on the last option thanks also to VHE observations, not clear the case for short GRB. VHE observations can shed light (thanks also to their highest sensitivity for transients).
- ✤ Theoretically, different scenarios and processes envisaged to bring to VHE emission

some literature

- Takami K., High-energy radiation from remnants of neutron star binary mergers, 2014, Phys. Rev. D, 89, 063006
- Veres P., & Meszaros P., Prospects for Gev–Tev detection of short γ-ray bursts with extended emission, 2014, ApJ, 787, 168.
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- ✤ **Caveat**: the e.m. beamed (jetted) afterglow emission of a GW events is usually observed off-axis

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- **Caveat**: the e.m. beamed (jetted) afterglow emission of a GW events is usually observed off-axis

16:30 **Refined analysis of GW170817's off-axis afterglow observation and flux predictions at higher energies**

Speaker: Clément PELLOUIN (Institut d'Astrophysique de Paris)

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What do we know of VHE emission from GW counterparts (observations)

- no VHE emission detected from GW counterparts, yet. (see next slides)

    but:

- ✓ long GRBs detected up to few TeV (GRB190825A, GRB190114C)
    - ✓ long GRBs associated SN ➔ GW emission?
    - ✓ jet formation and interaction similar for long and short GRB ➔ short GRB plausible VHE emitters, too.

- hint of VHE emission from short GRB 160821B

GW at VHE: how

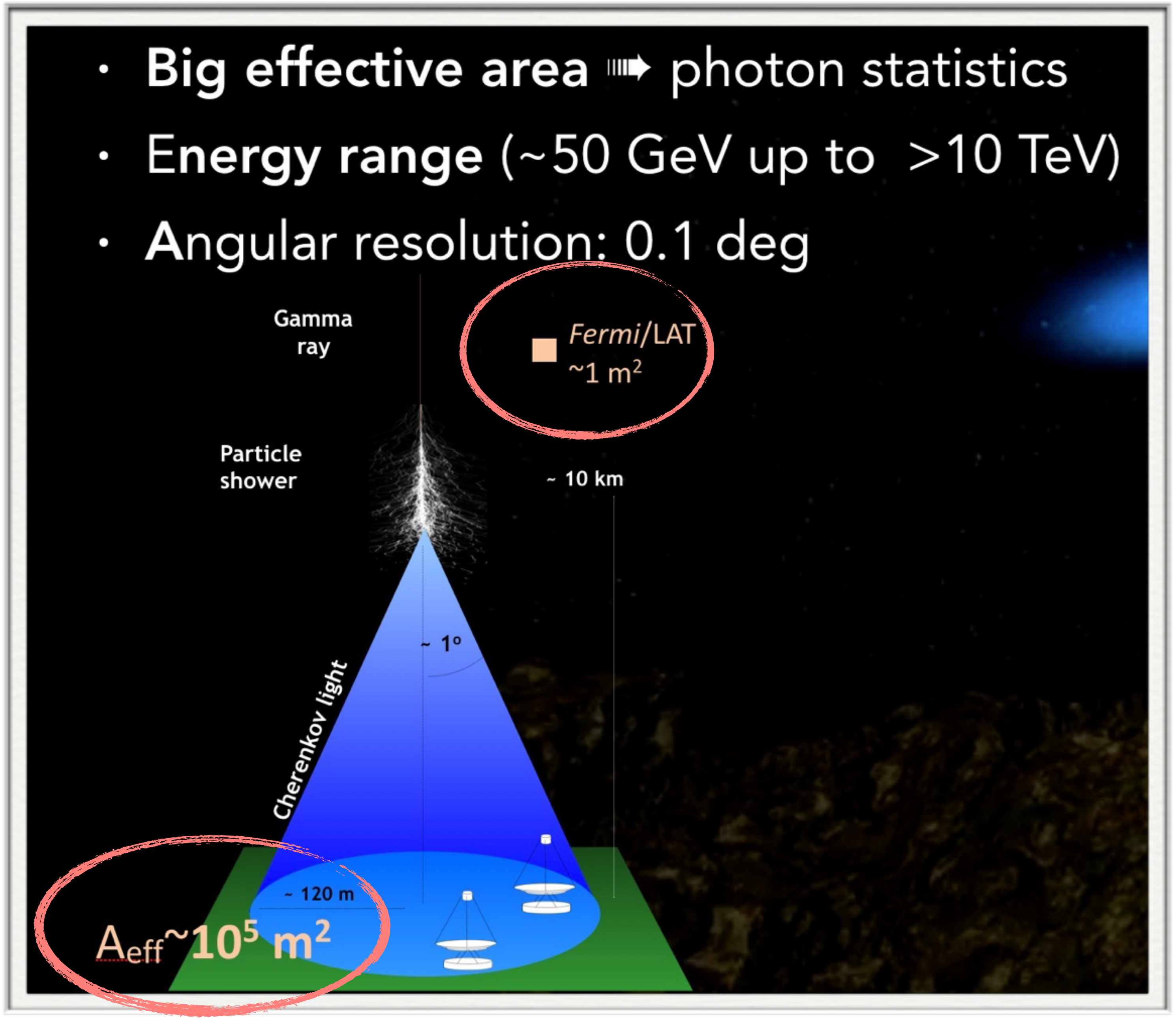
How do we detect VHE transients?

How do we see a GW event in VHE?

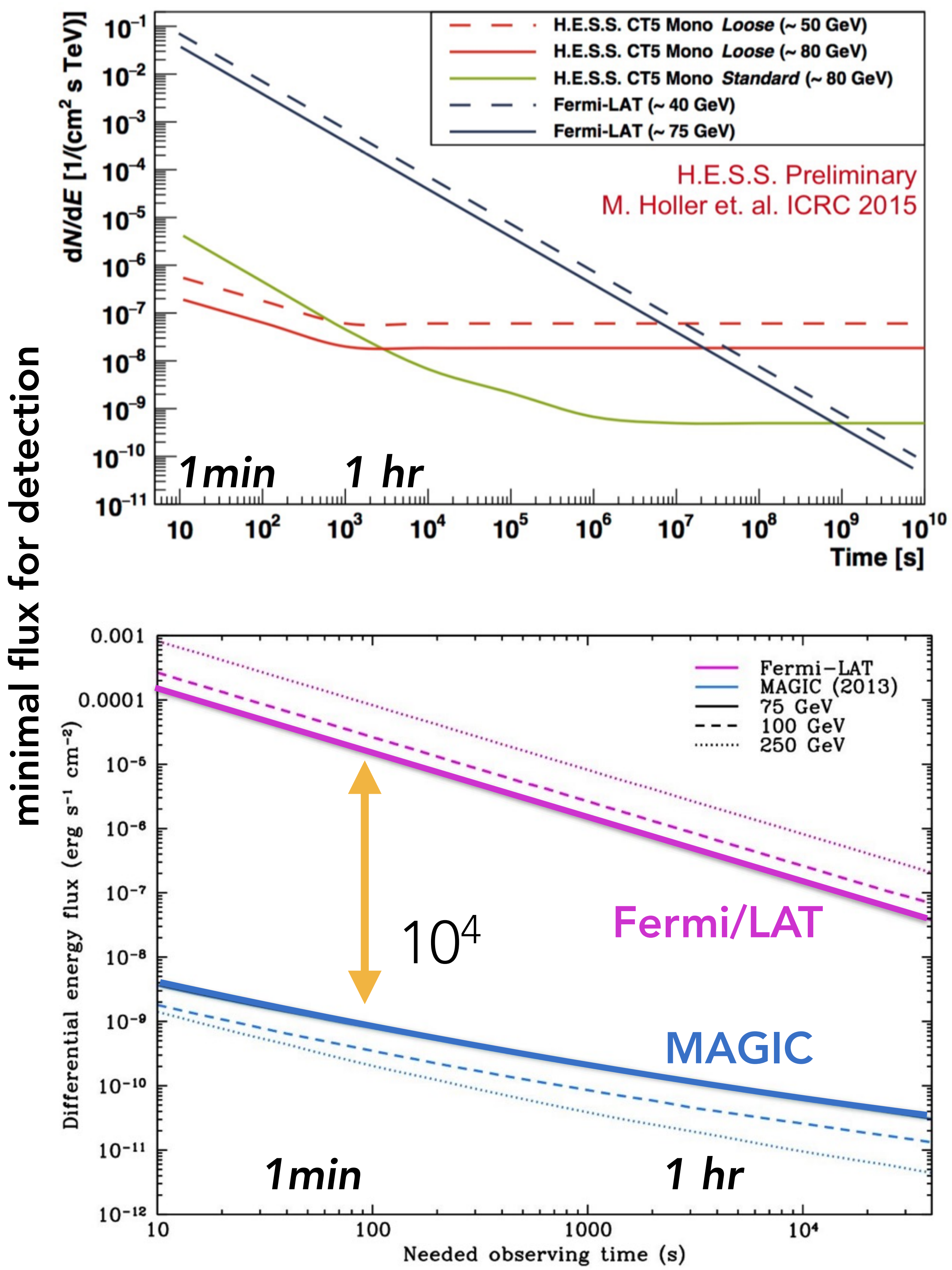
How do we maximise the chance of detection of the VHE counterpart of GW events?

Detect VHE emission from transients: IACTs

- Imaging Air Cherenkov telescopes (IACT)
- IACT sensitivity to transients



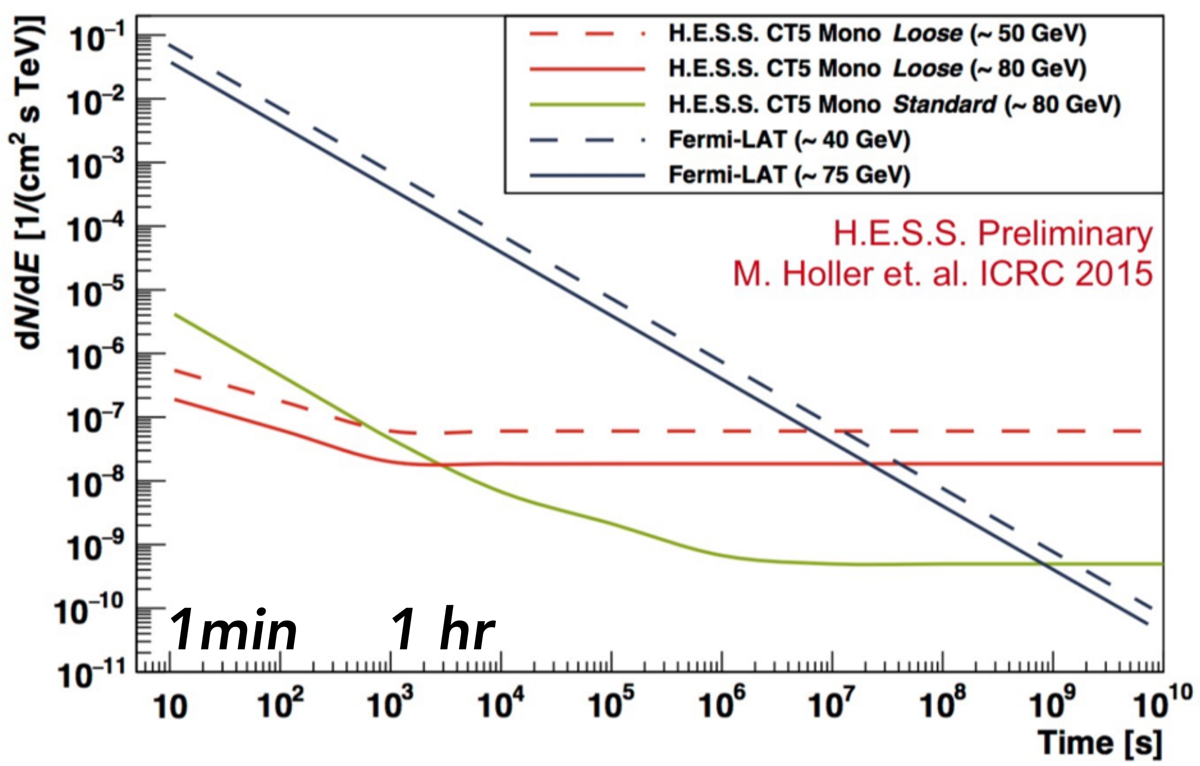
sensitivity limits vs integration time

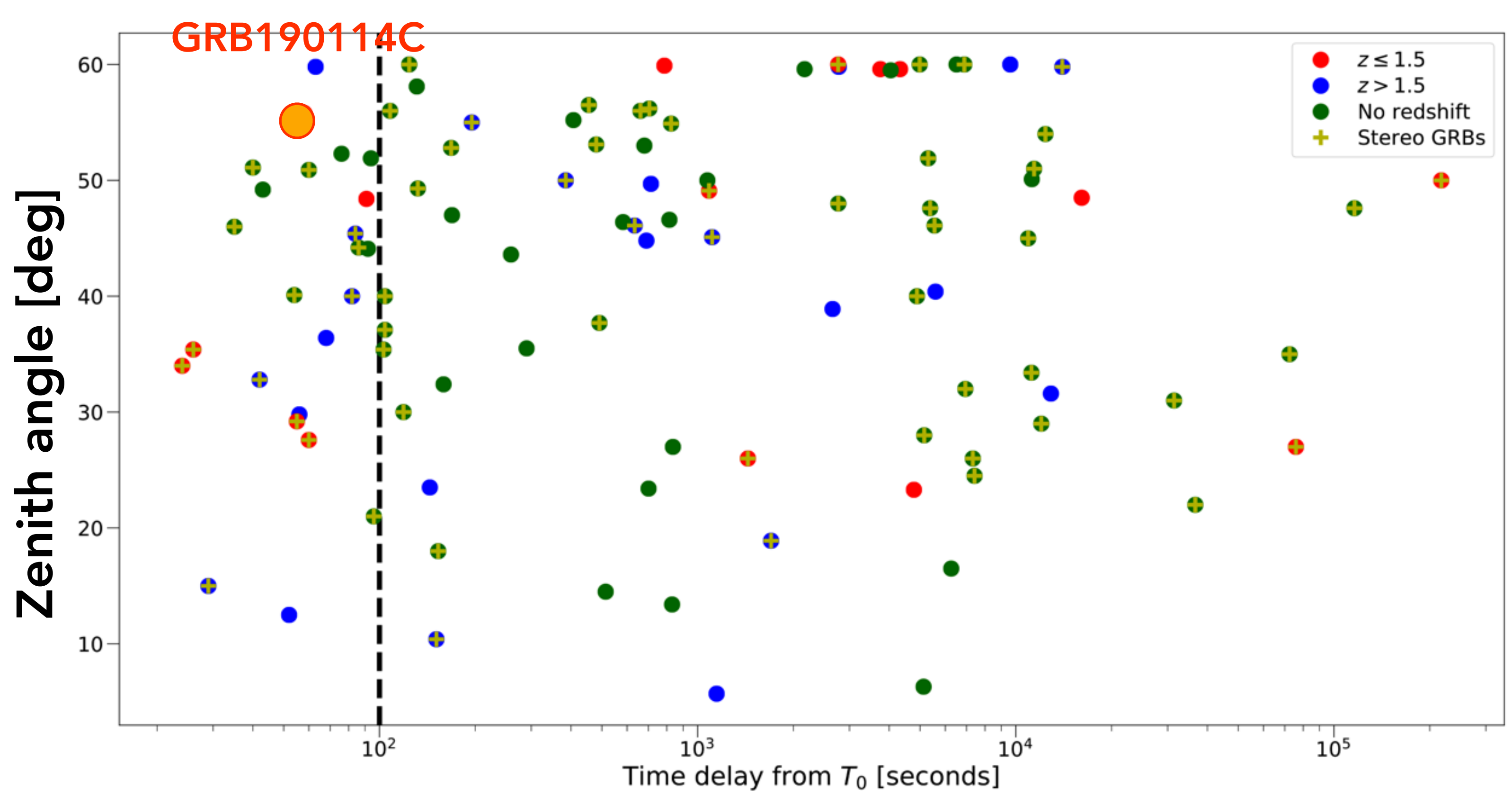


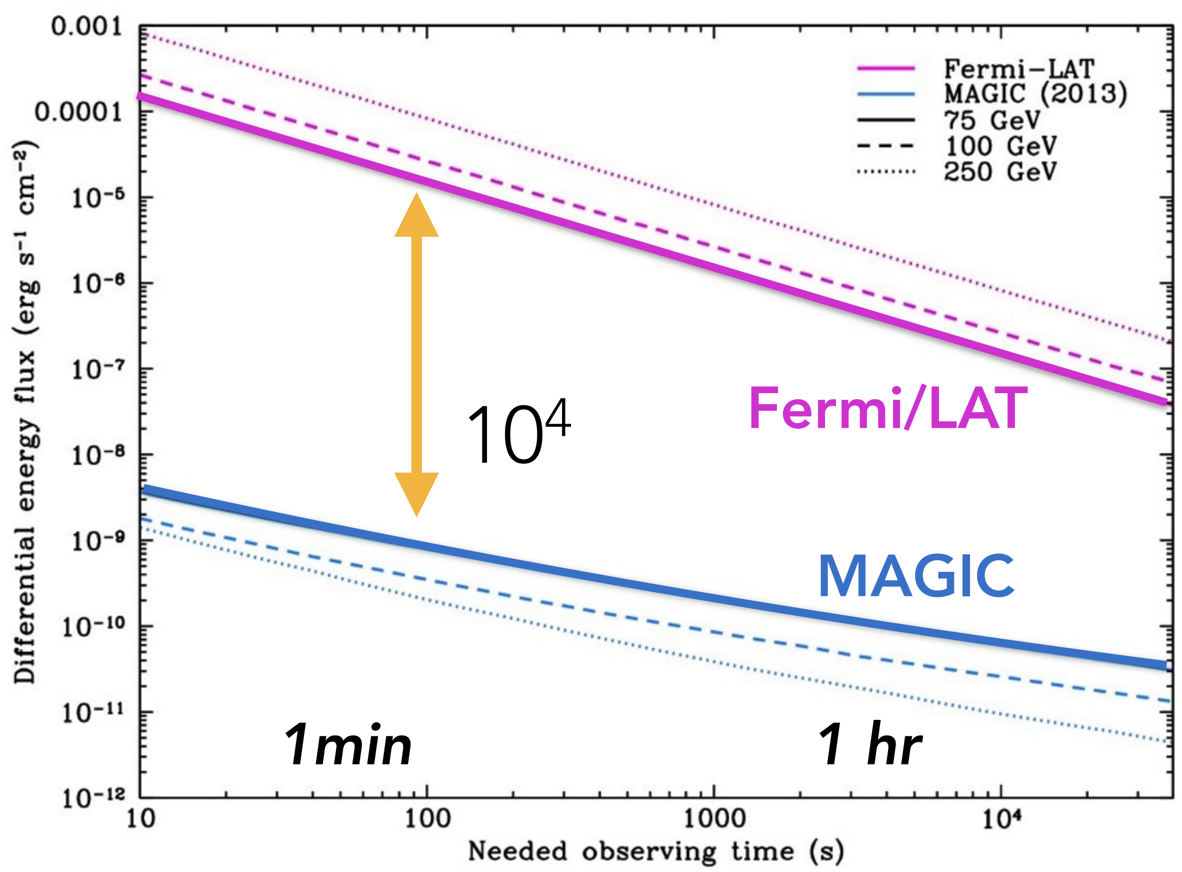
Detect VHE emission from transients: IACTs

- Imaging Air Cherenkov telescopes (IACT)
- IACT sensitivity to transients
- Fast and automatic repositioning
  - Afterglow decays fast ~$t^{-1.5}$

sensitivity limits vs integration time



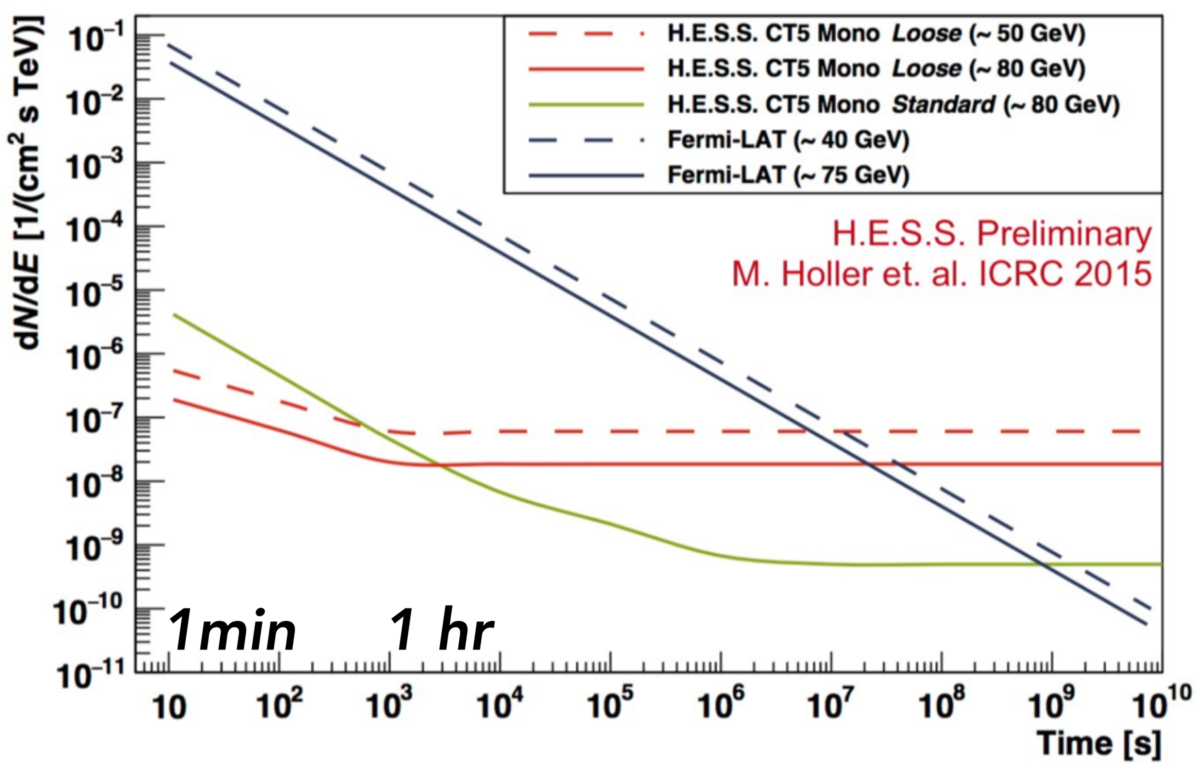


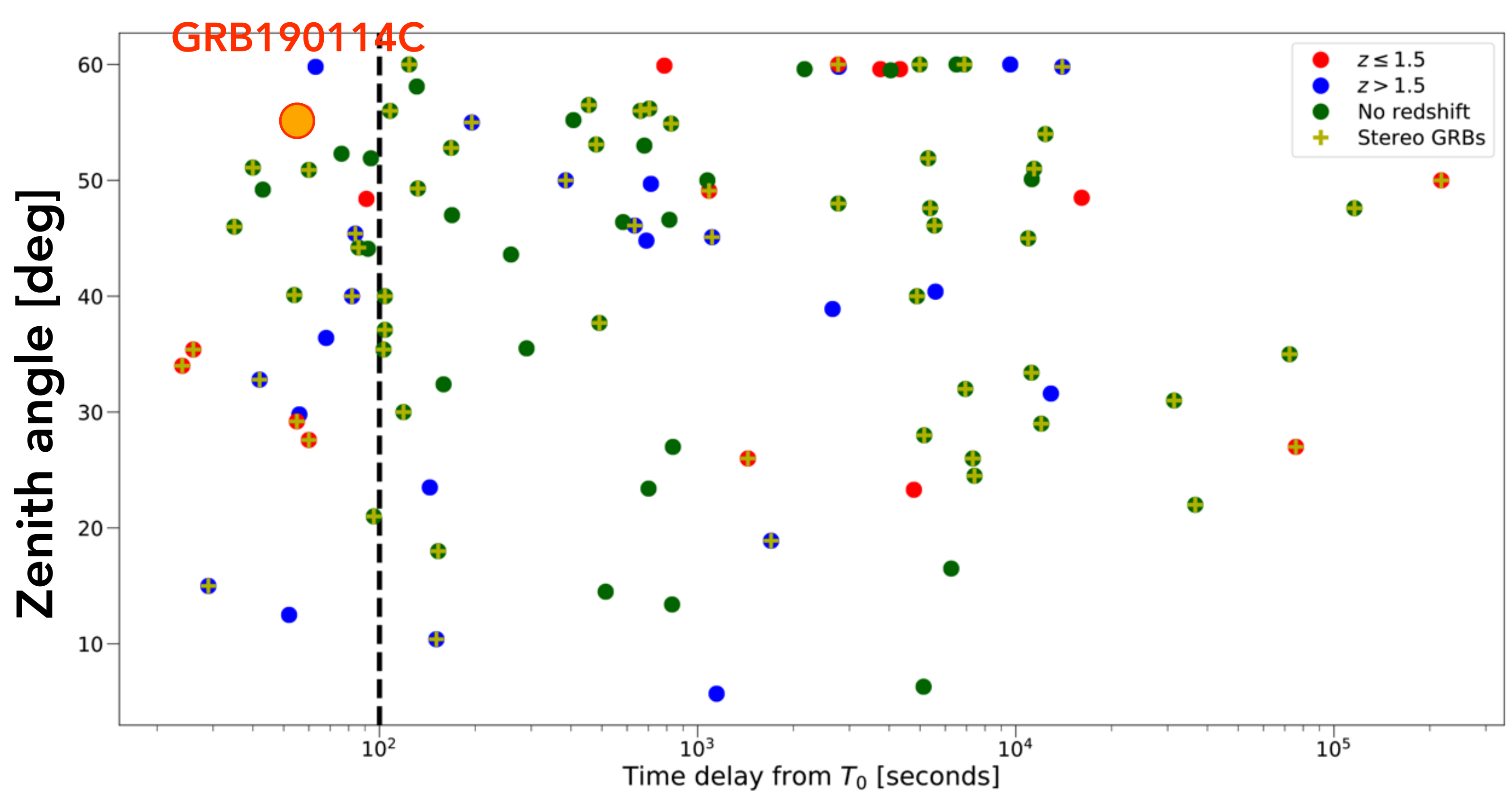


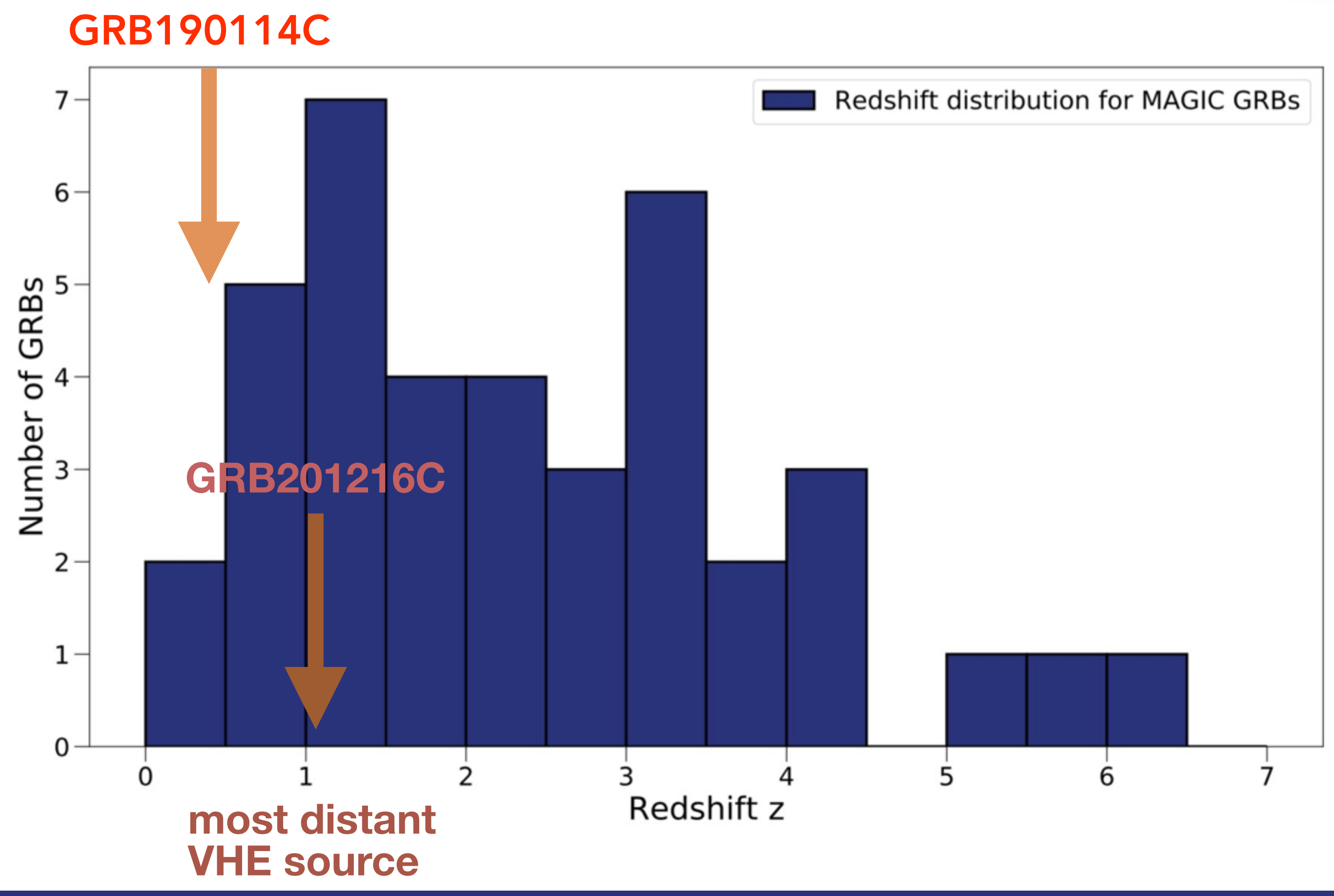
Detect VHE emission from transients: IACTs

- Imaging Air Cherenkov telescopes (IACT)
- IACT sensitivity to transients
- Fast and automatic repositioning
- Extragalactic background light (EBL) affecting distant sources
- but GW horizon (03-04) ~few hundreds Mpc, z<~0.1

sensitivity limits vs integration time

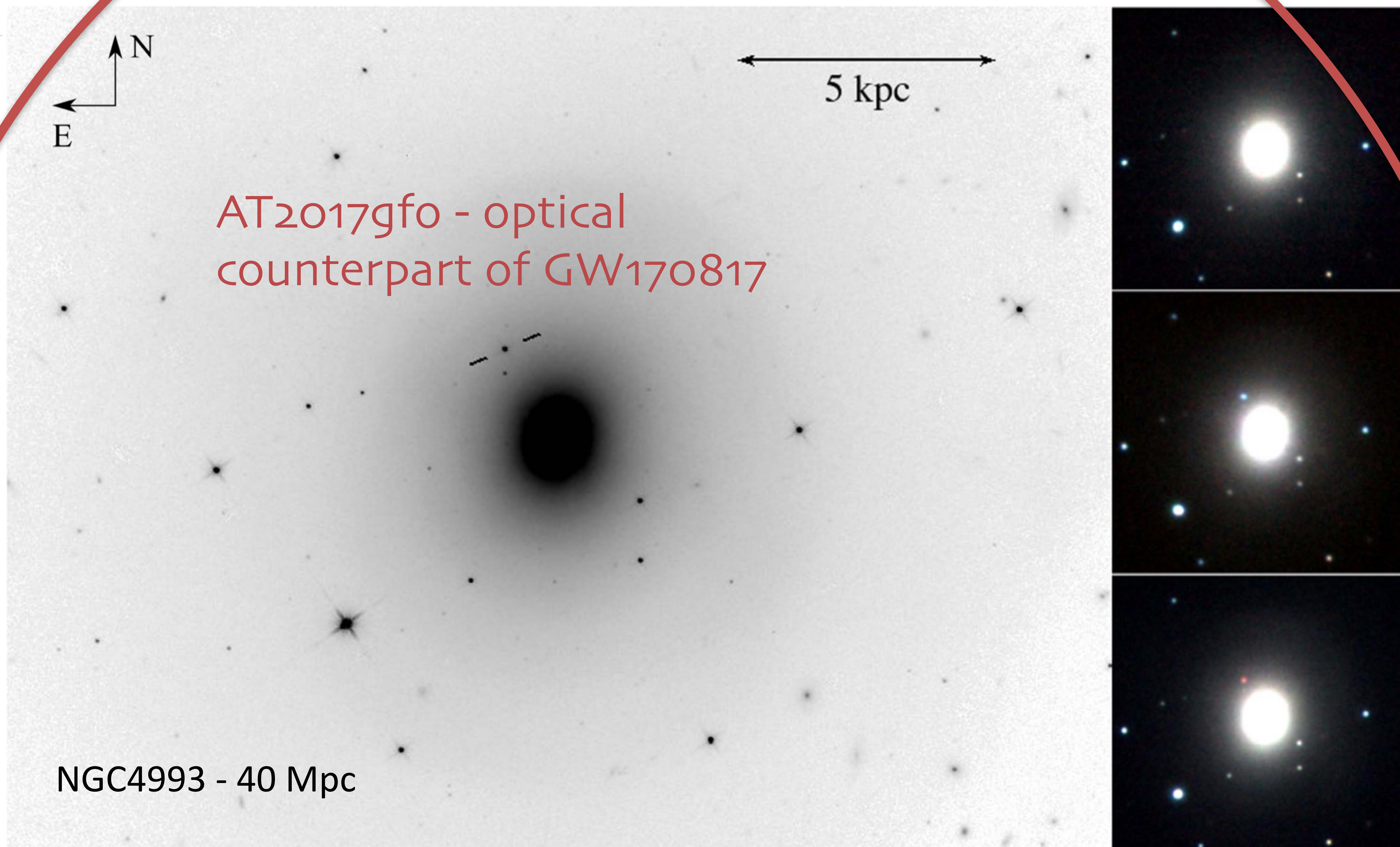






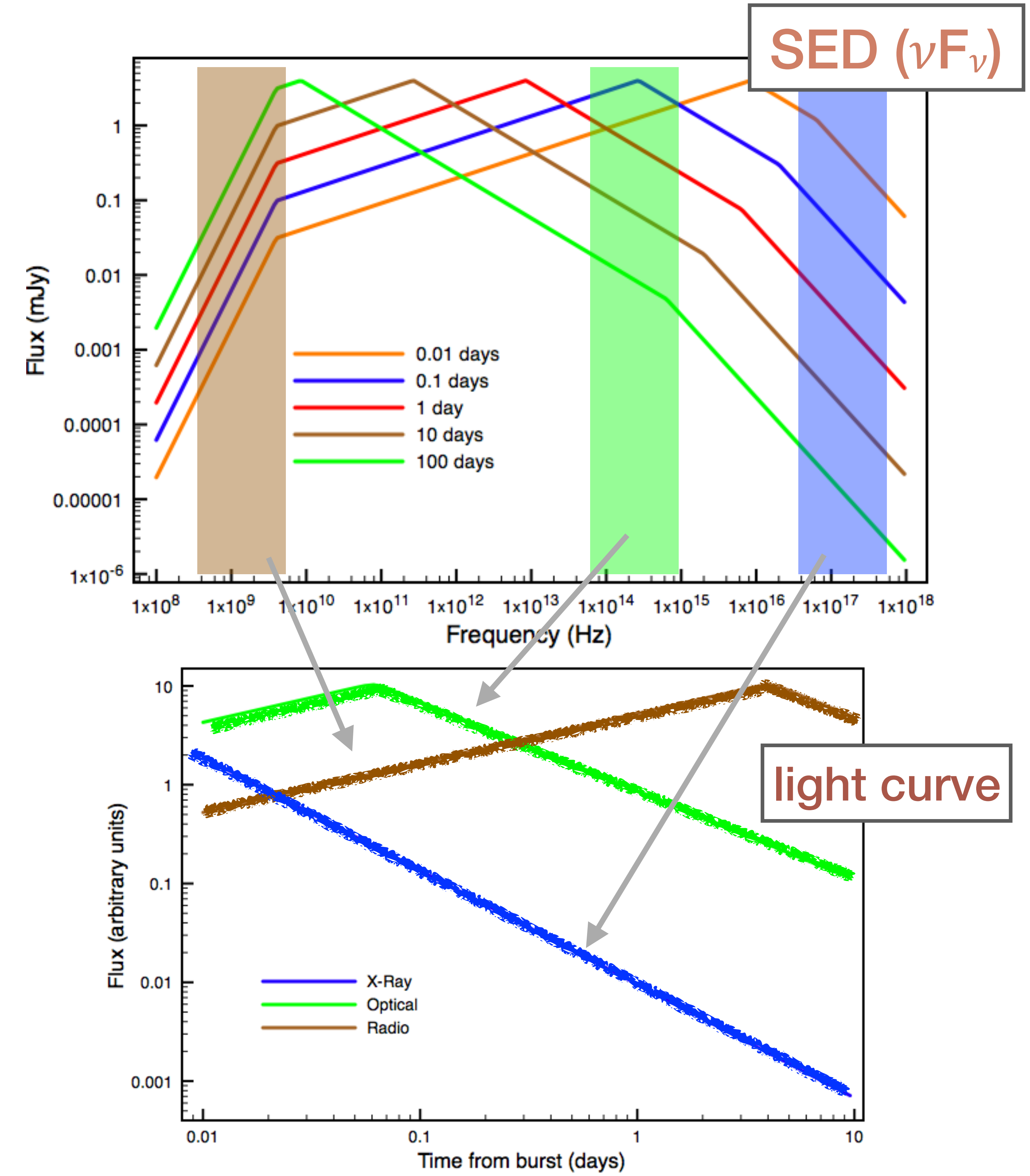
Detect VHE emission from transients: IACTs

MAGIC (IACT)
PSF



VHE emission from GW counterparts: an off-axis GRB

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



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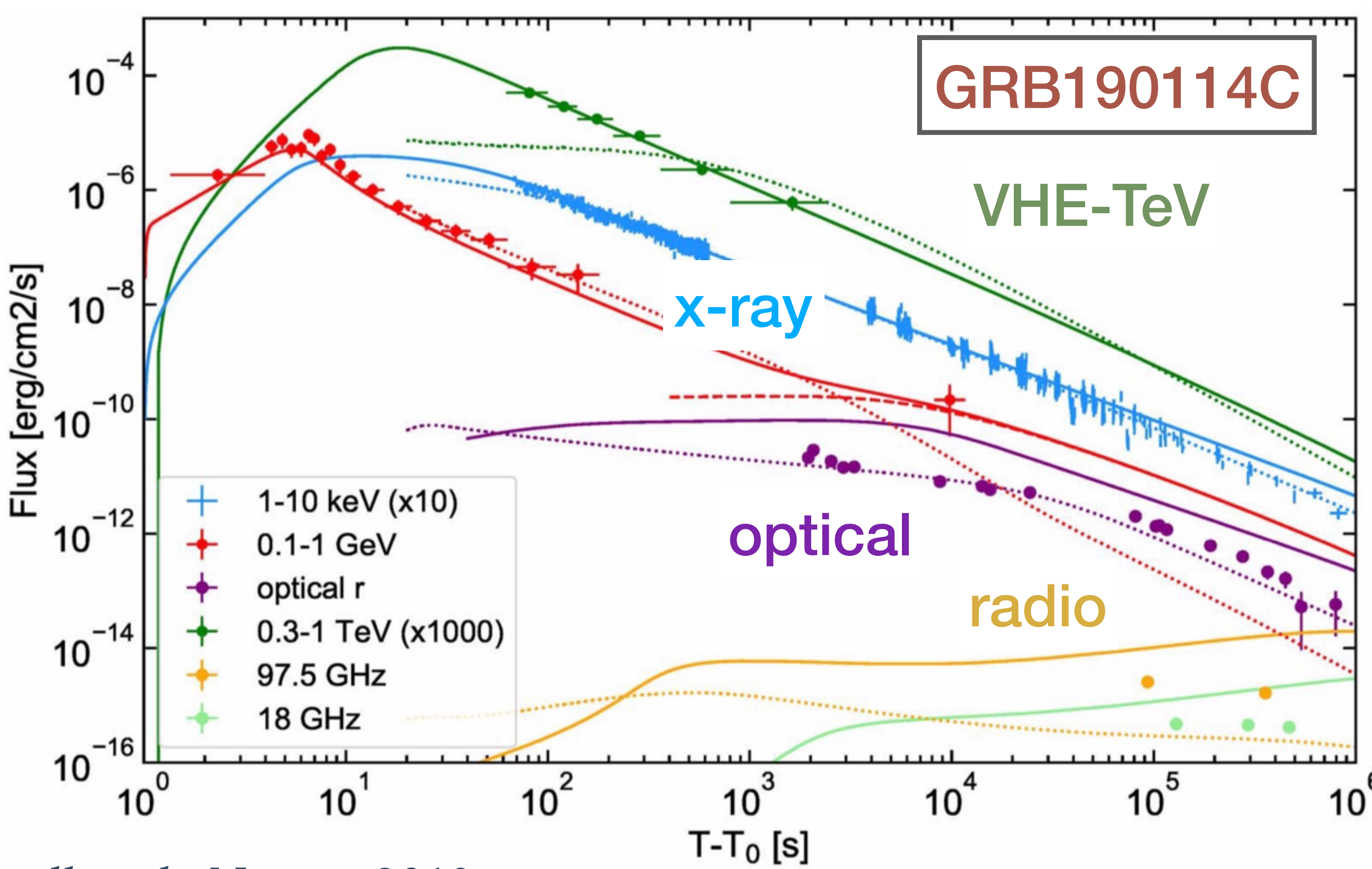

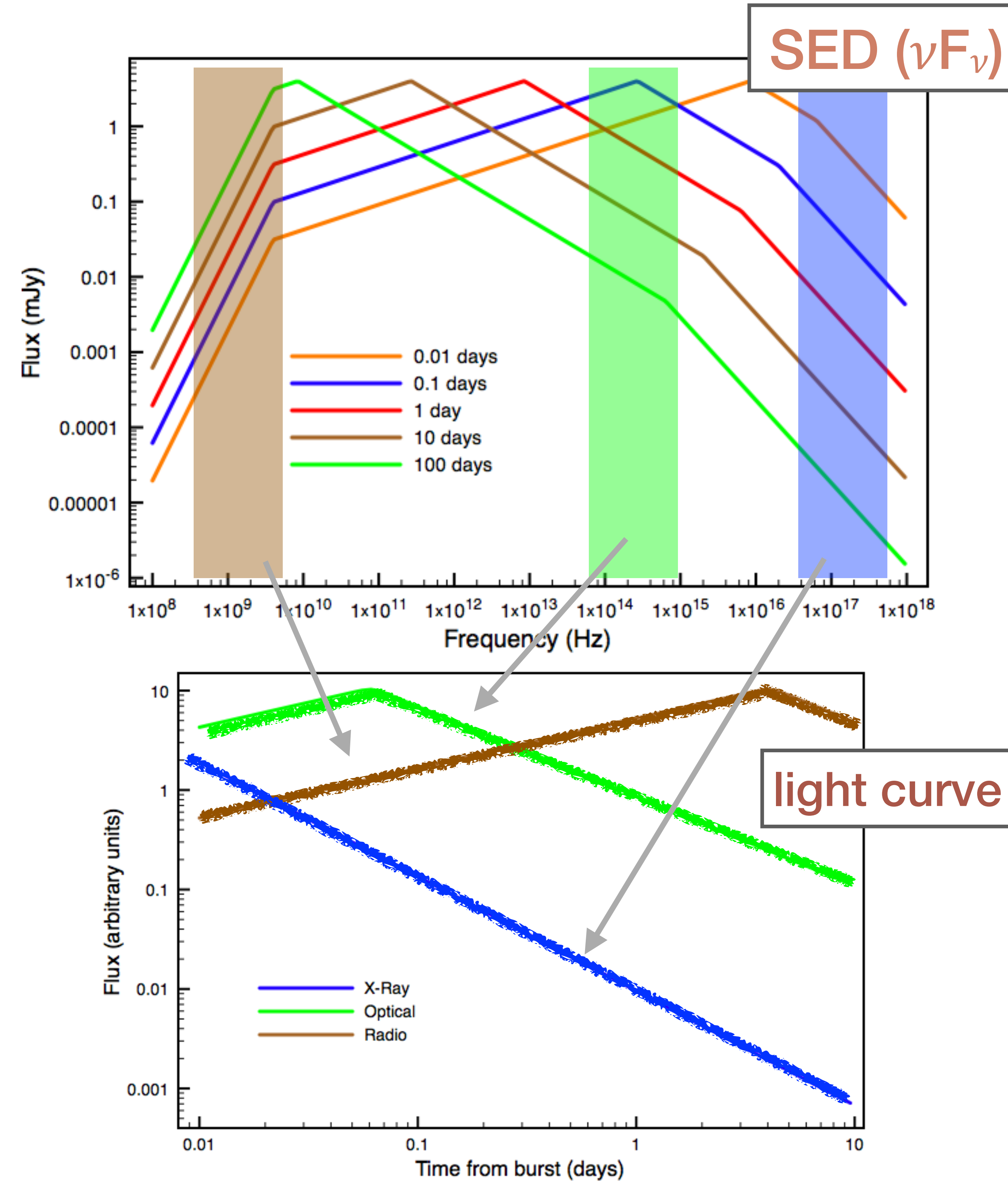

MAGIC coll.et al., Nature, 2019

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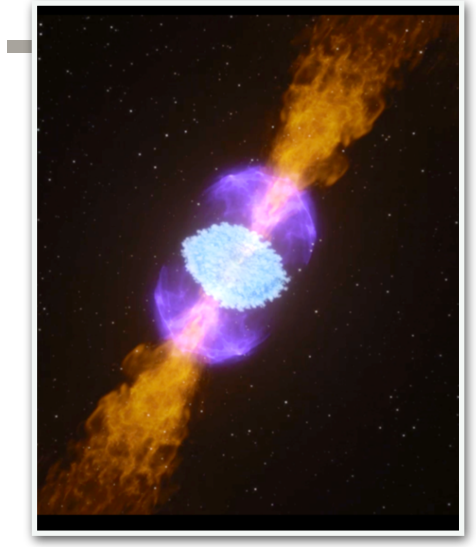
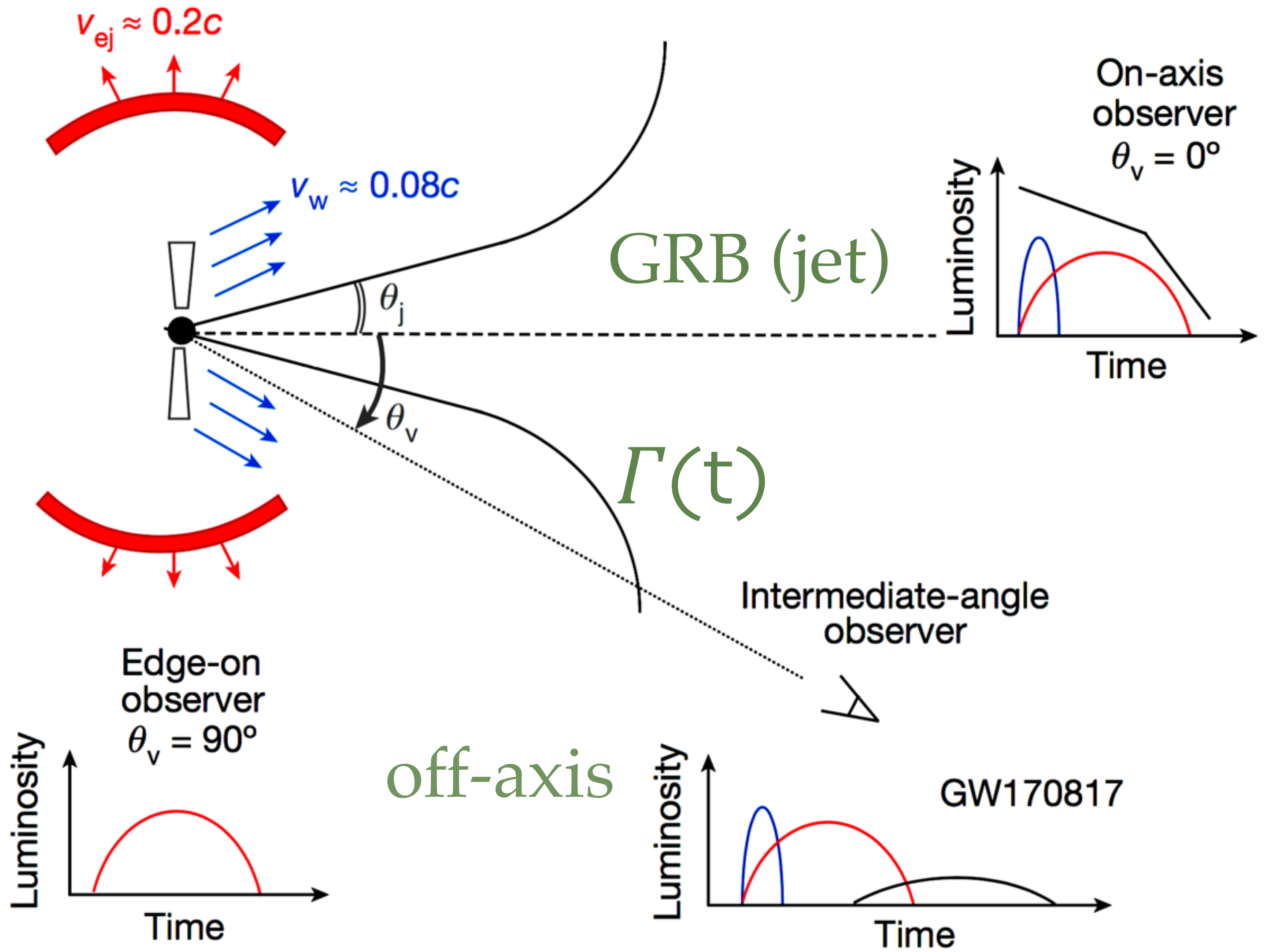
- High energy emission from GW counterparts is seen **off-axis**, $\Gamma\sim$a few
  - intensity weaker $10^{-4,-6}$
  - light curve Delayed (hours-days-months, depending on θ_{view})





Troja, Piro+2017

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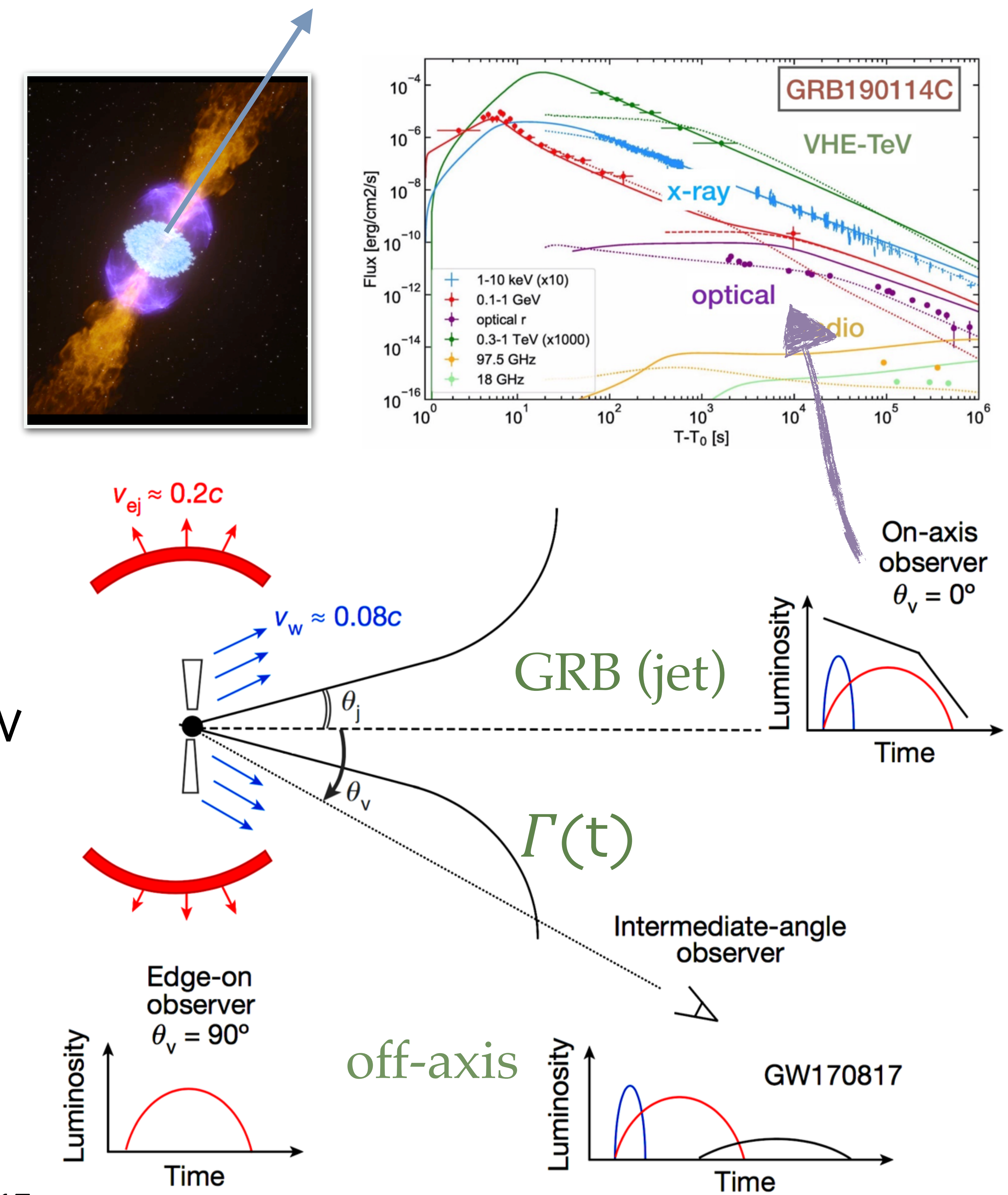

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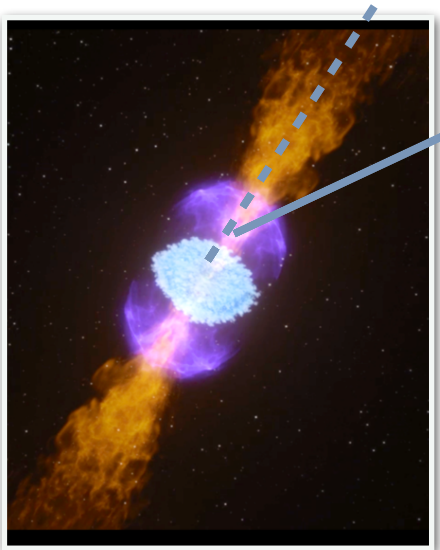
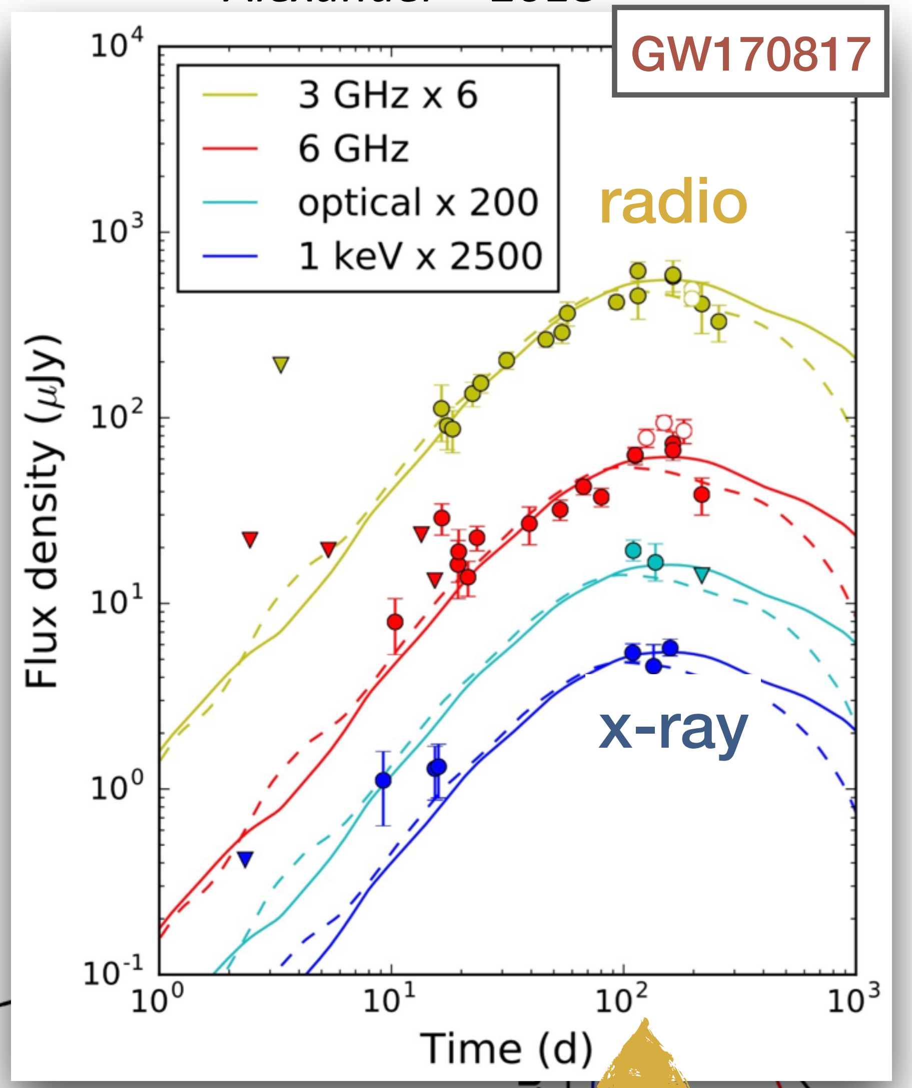
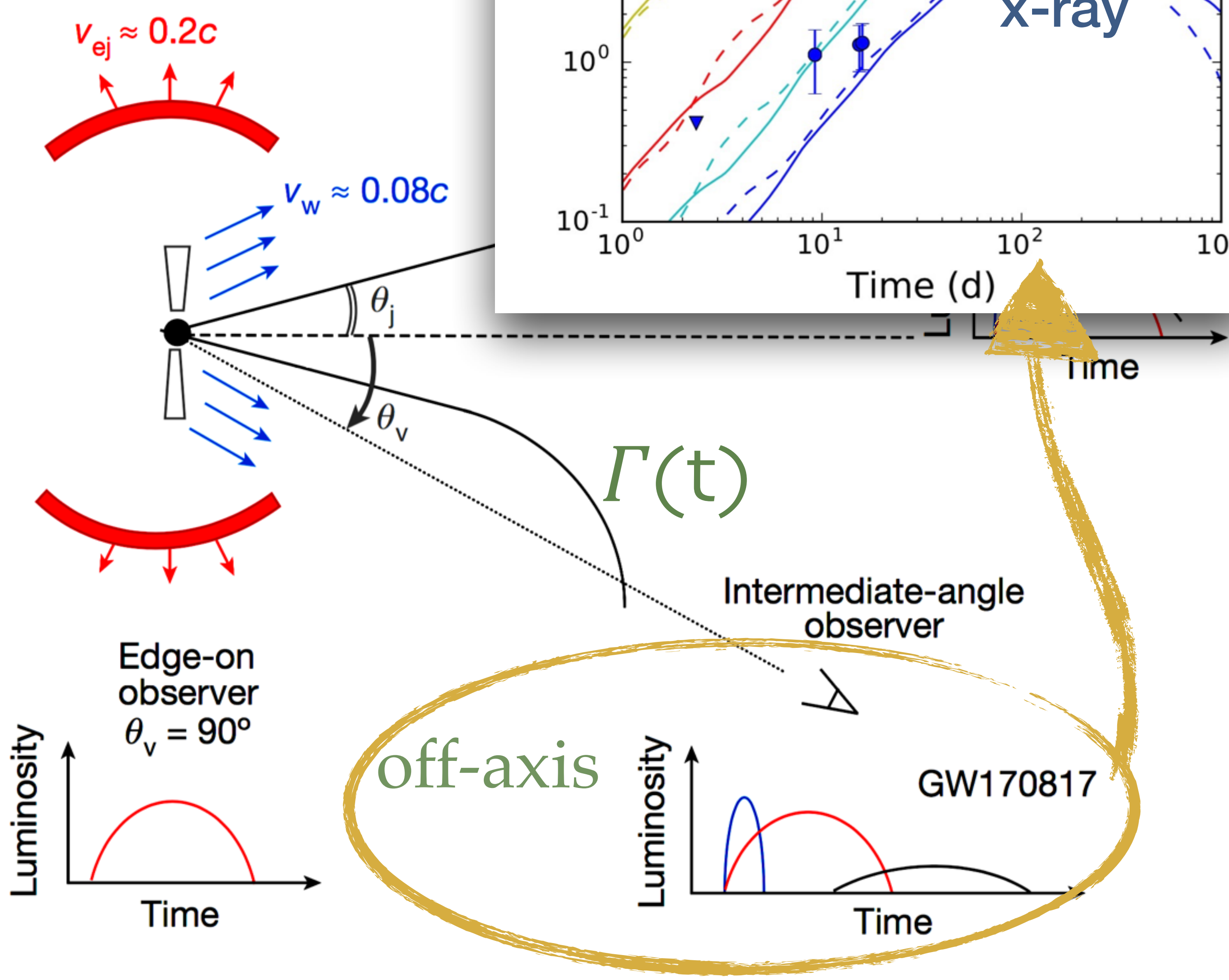
Alexander + 2018



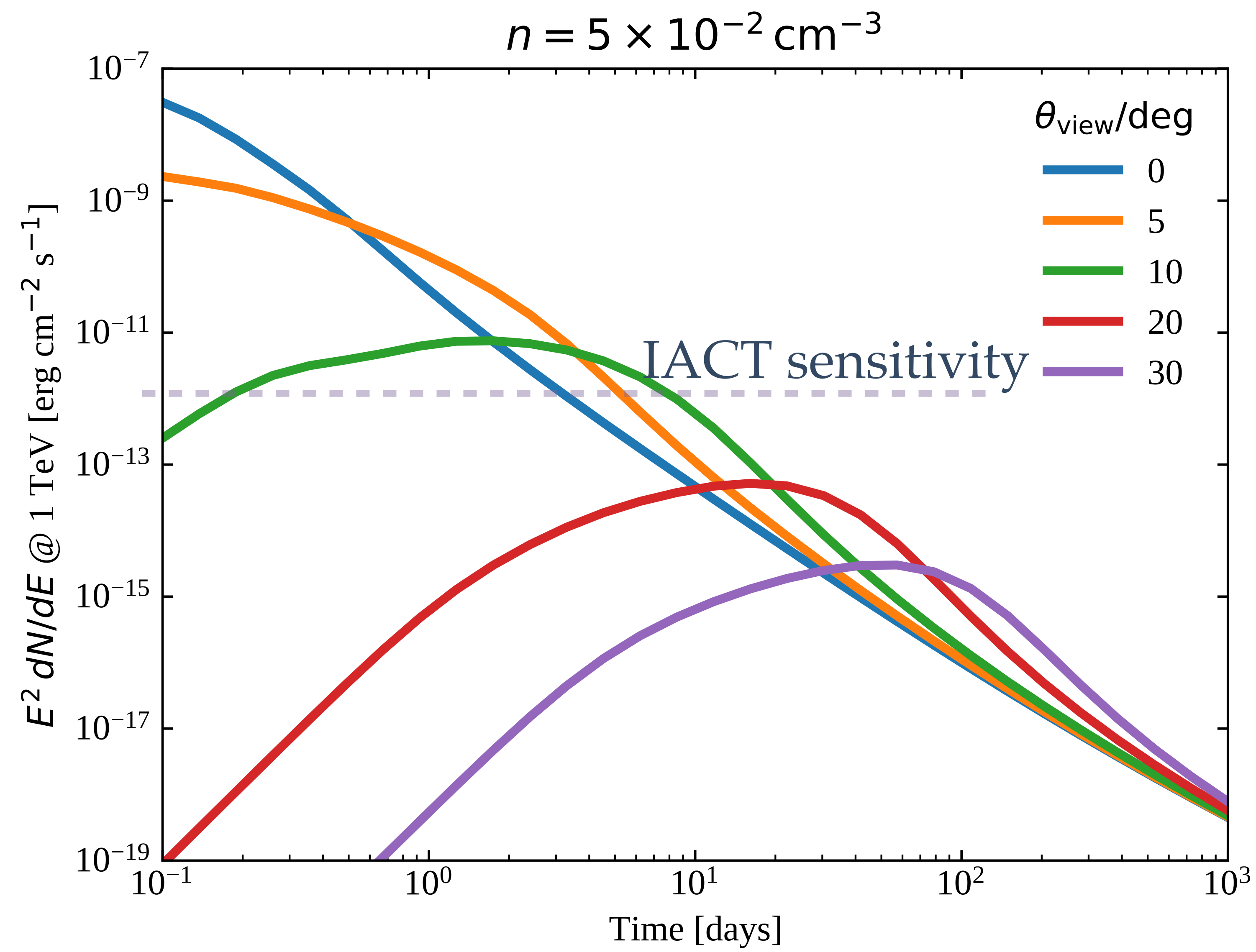




Troja, Piro+2017

Chasing the VHE counterpart of GW: strategies and optimisation

- Small viewing angle: bright, steady fading
  - ➡ Fast reaction
- larger viewing angle: weak, delayed emission



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

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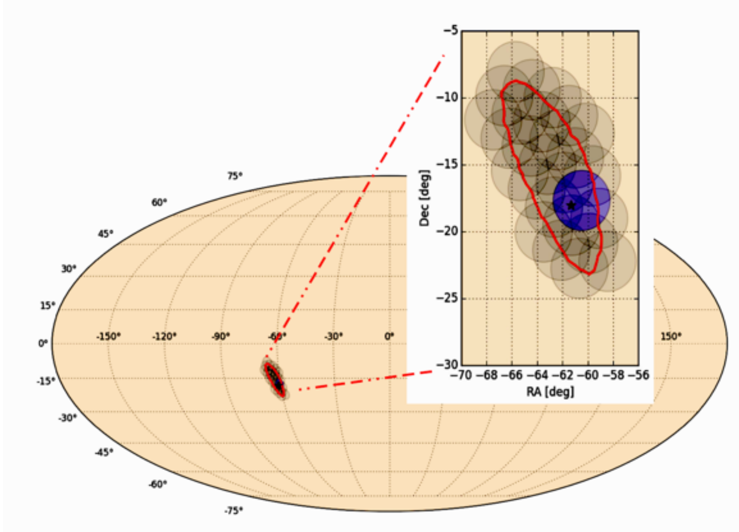
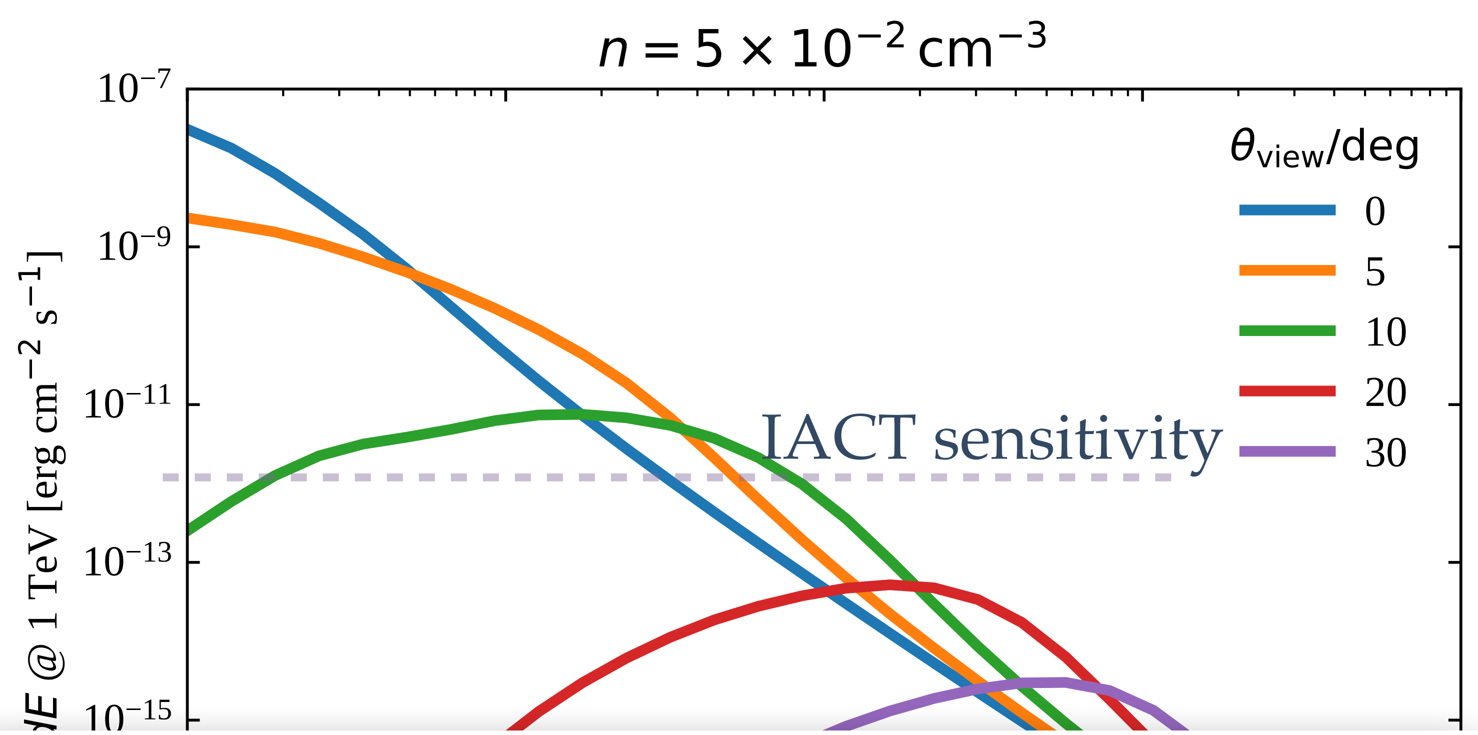
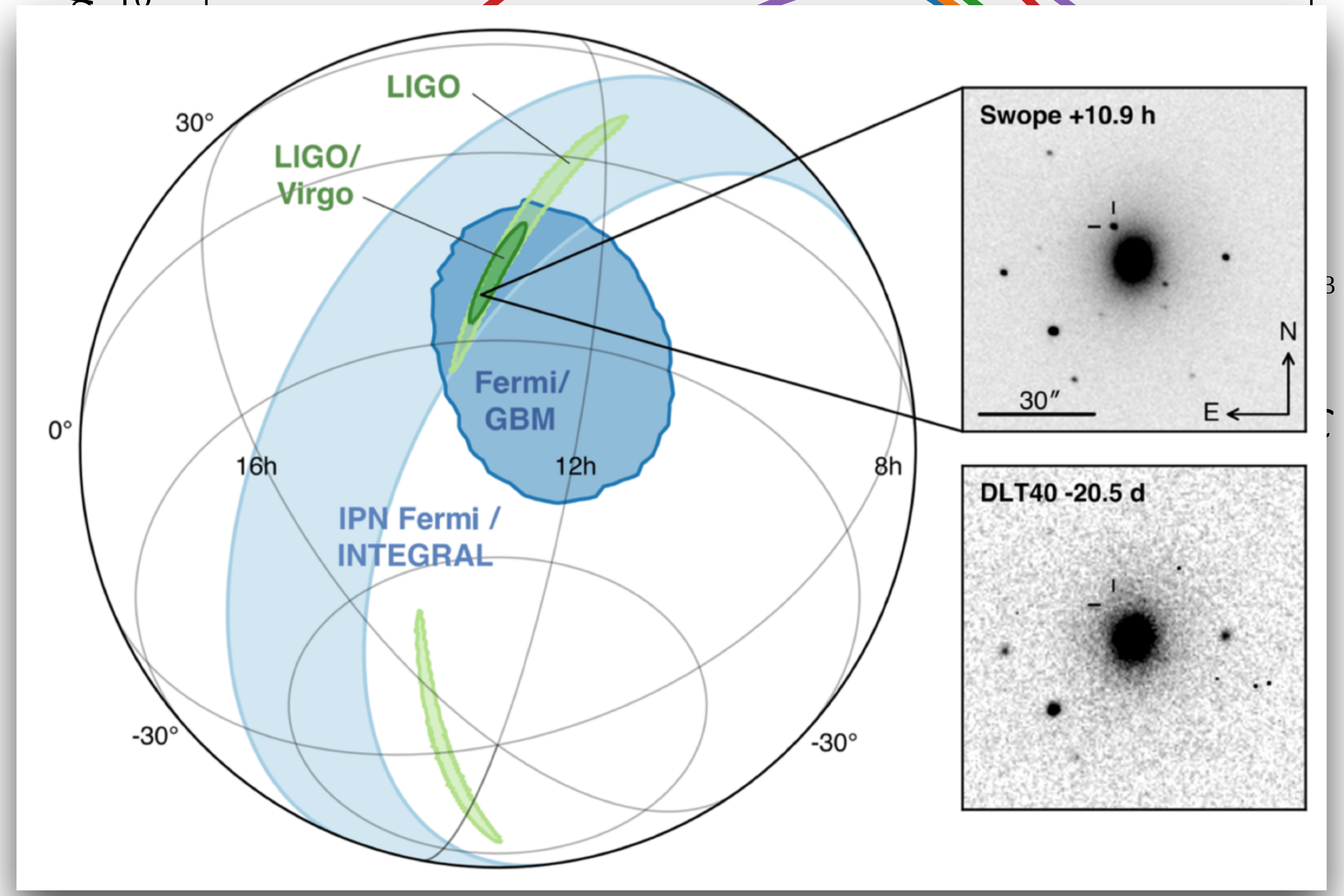
- larger viewing angle: weak, delayed emission
- GW uncertainty location
  - ➡ optimise observations/tiling







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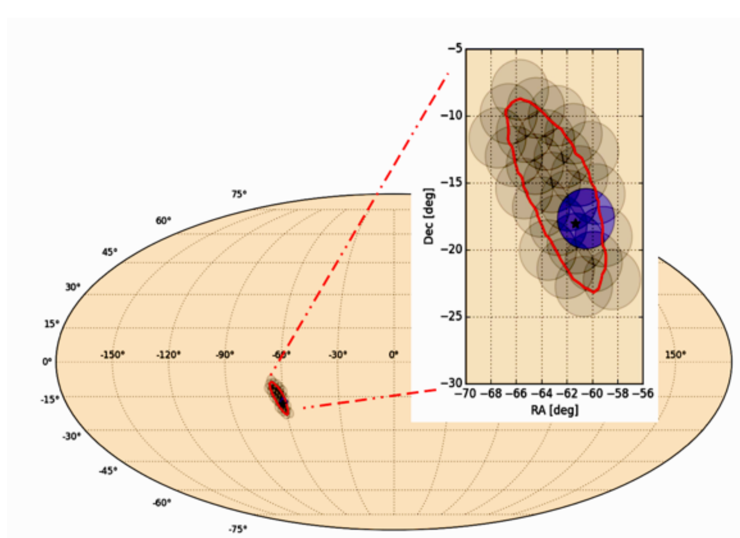
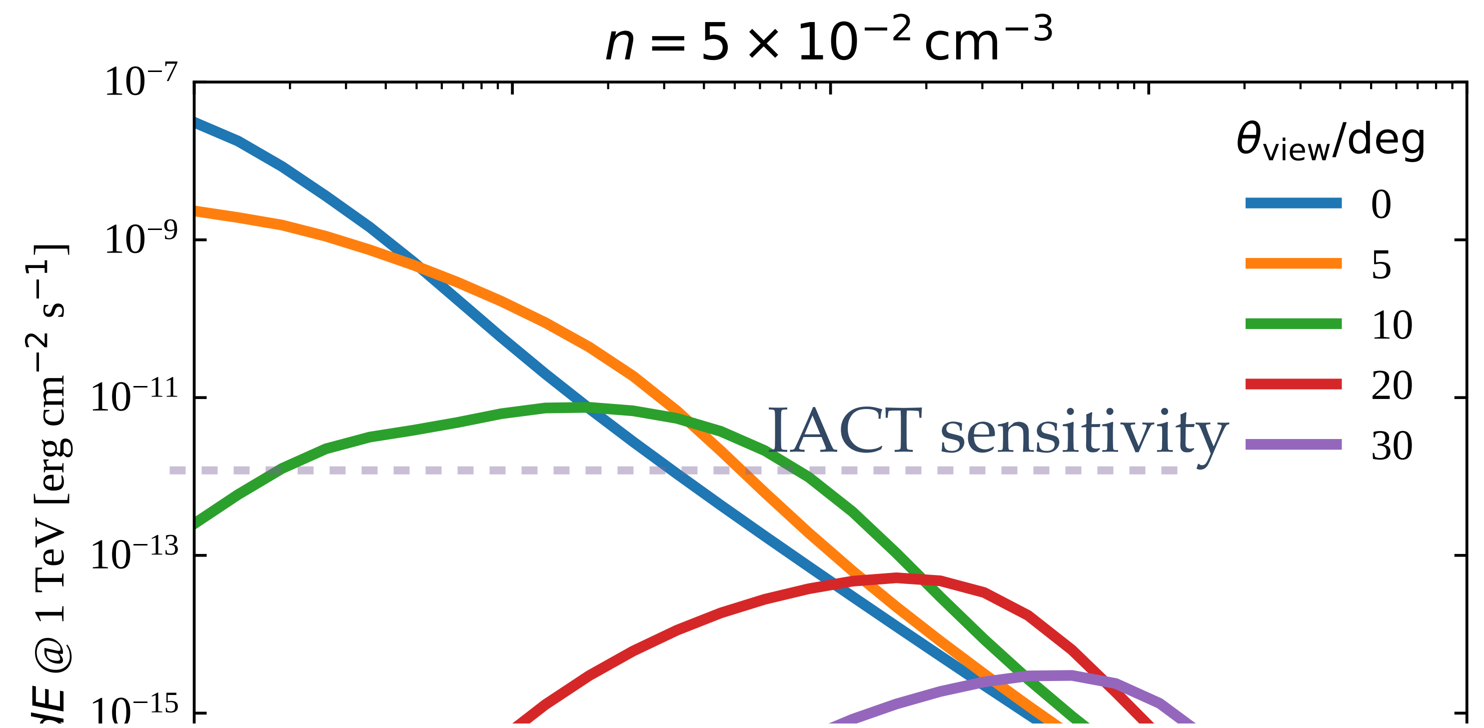
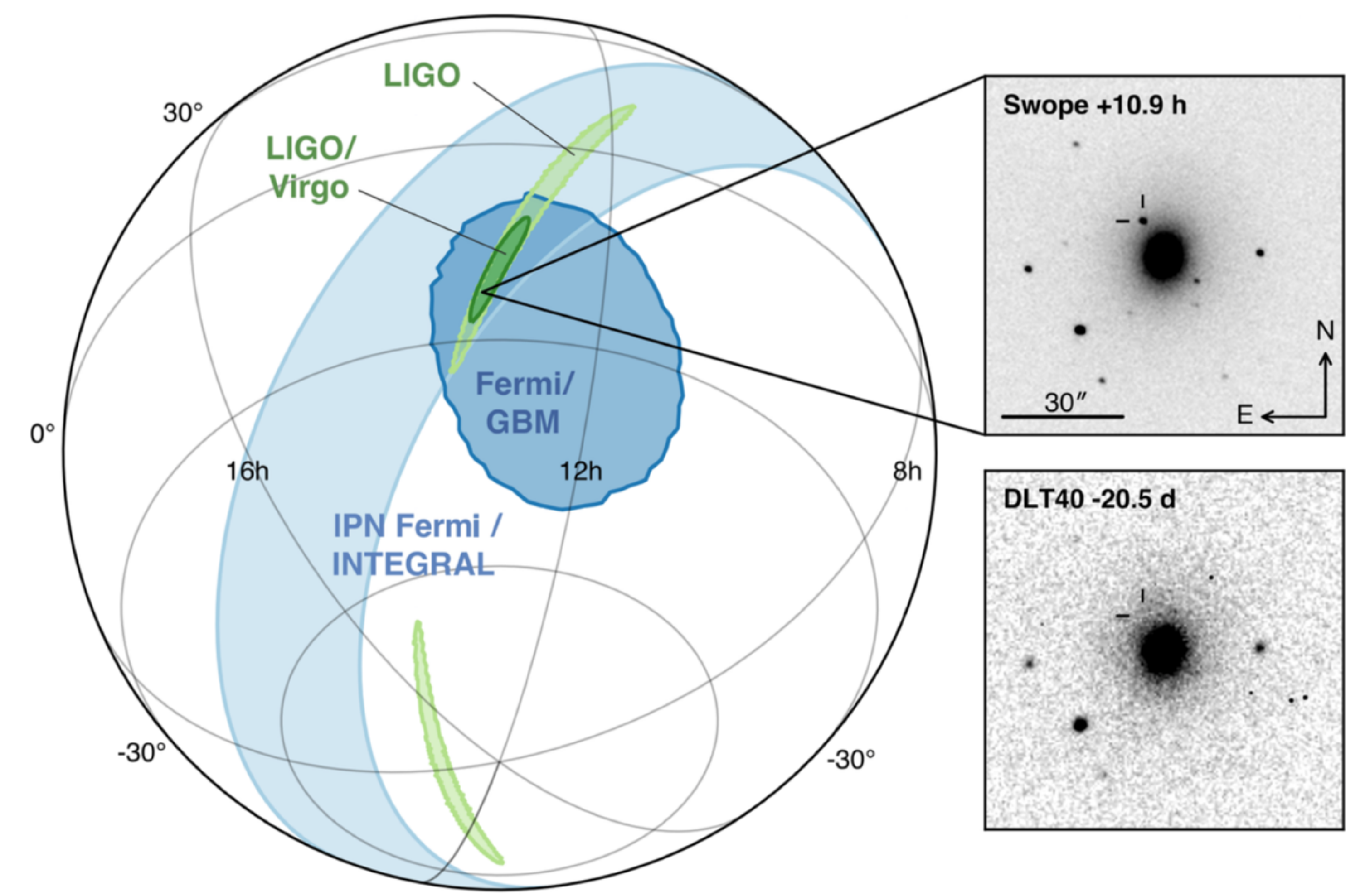
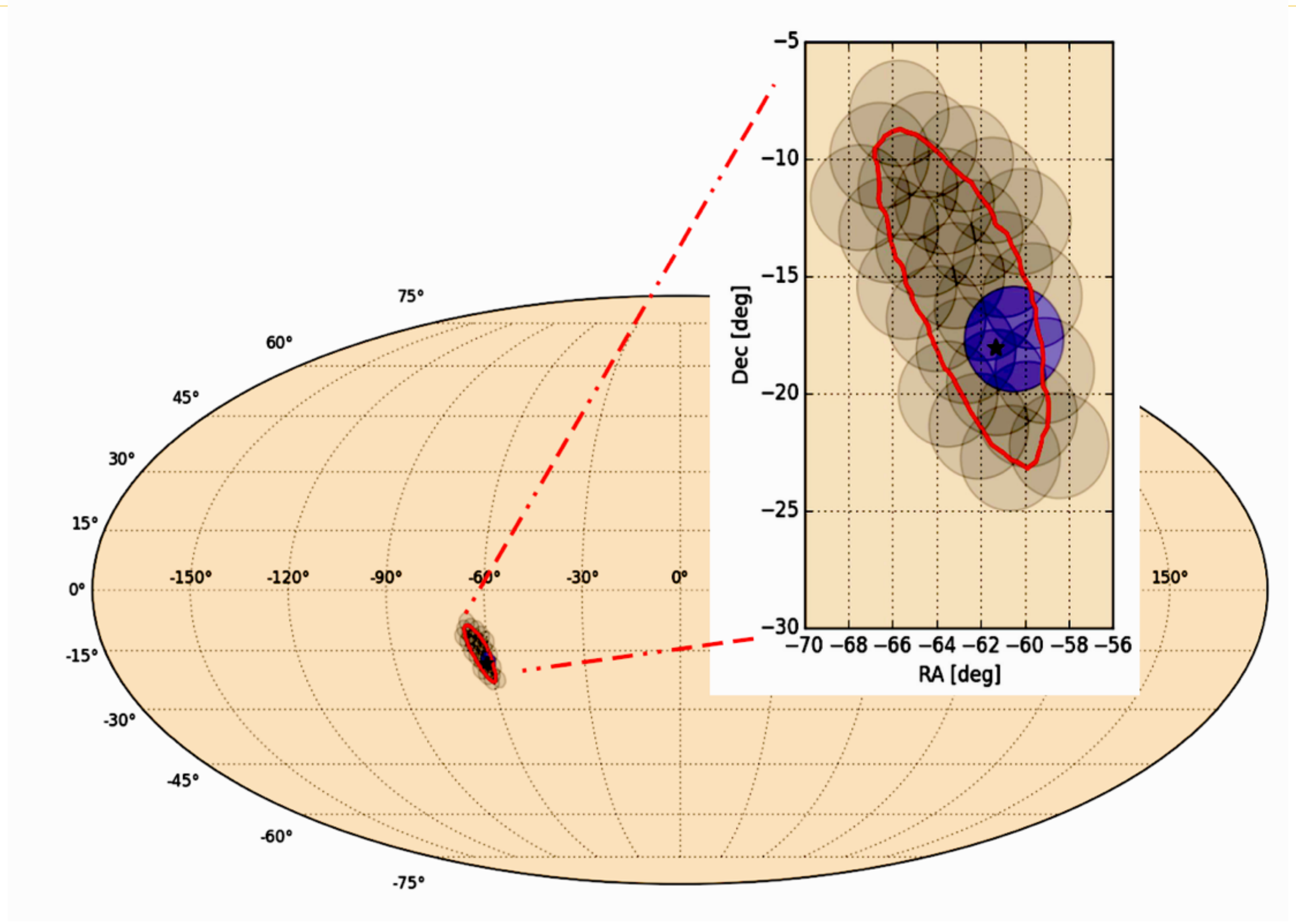






- GW Skymap 2D (probability)
  - tiles on FoV ~3 deg ∅
  - equal observing time

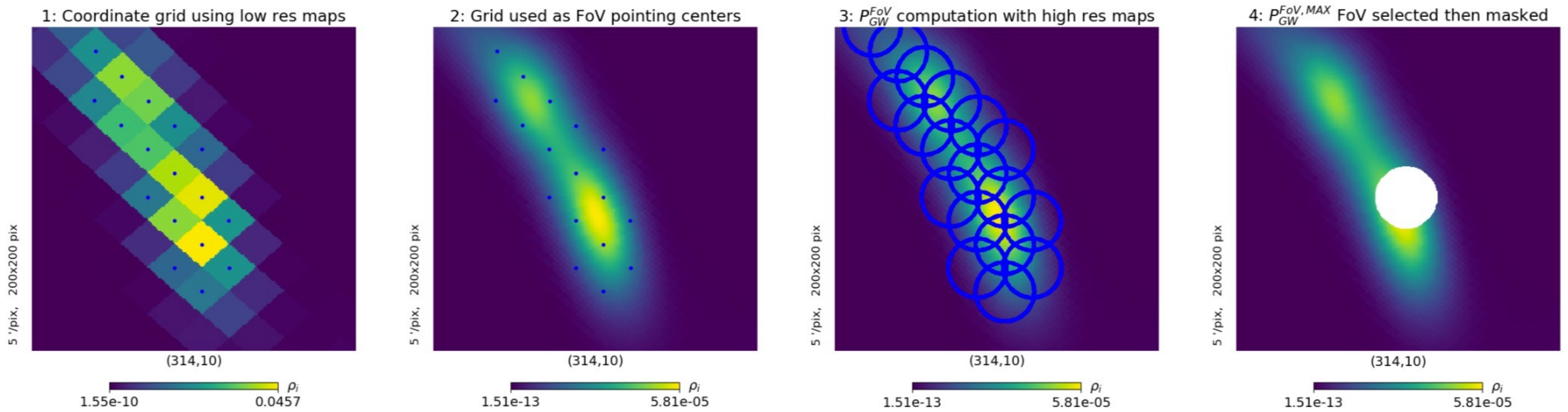


integration over FoV

Probability GW in FoV
$$P_{\mathrm{GW}}^{\mathrm{FoV}} = \int_0^{2\pi} \int_0^{r_{\mathrm{FoV}}} \rho(r,\phi)\, \mathrm{d}r \mathrm{d}\phi$$

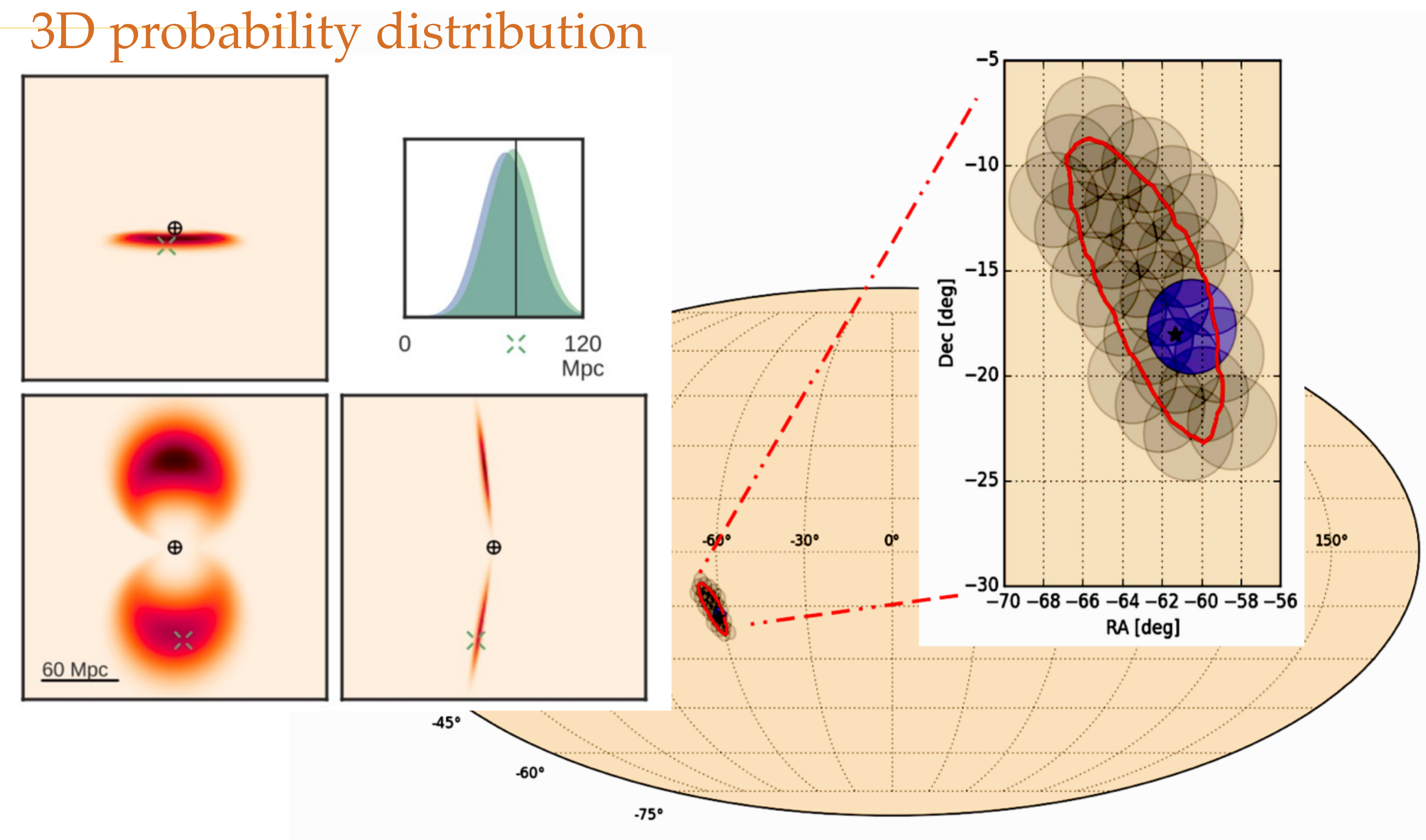
probability in GW map

Halim Ashkar et al JCAP03(2021)045



Chasing the VHE counterpart of GW: strategies and optimisation

- 3D GW maps:
  - distribution of probability with distance
  - map galaxy distribution



probability in GW map at given distance

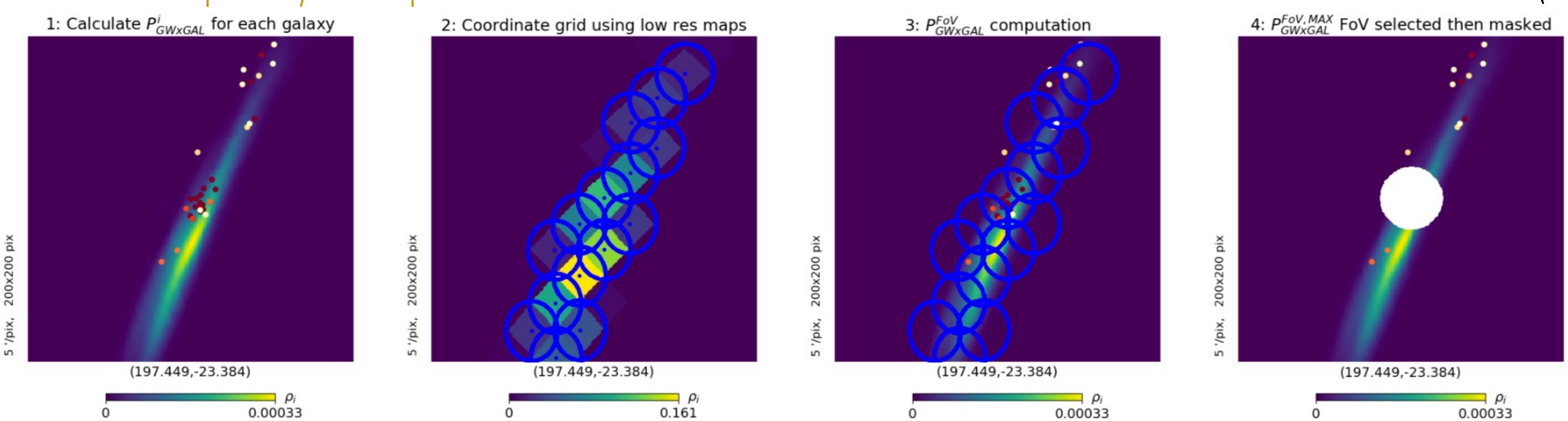
$$\Delta P(r, \hat{\mathbf{n}}_i)\, \Delta r = \rho_i \frac{N_i}{\sqrt{2\pi}\sigma_i} \exp\left[-\frac{(r-\mu_i)^2}{2{\sigma_i}^2}\right] r^2\, \Delta r.$$

to be integrated over all galaxies

distance

probability in GW map

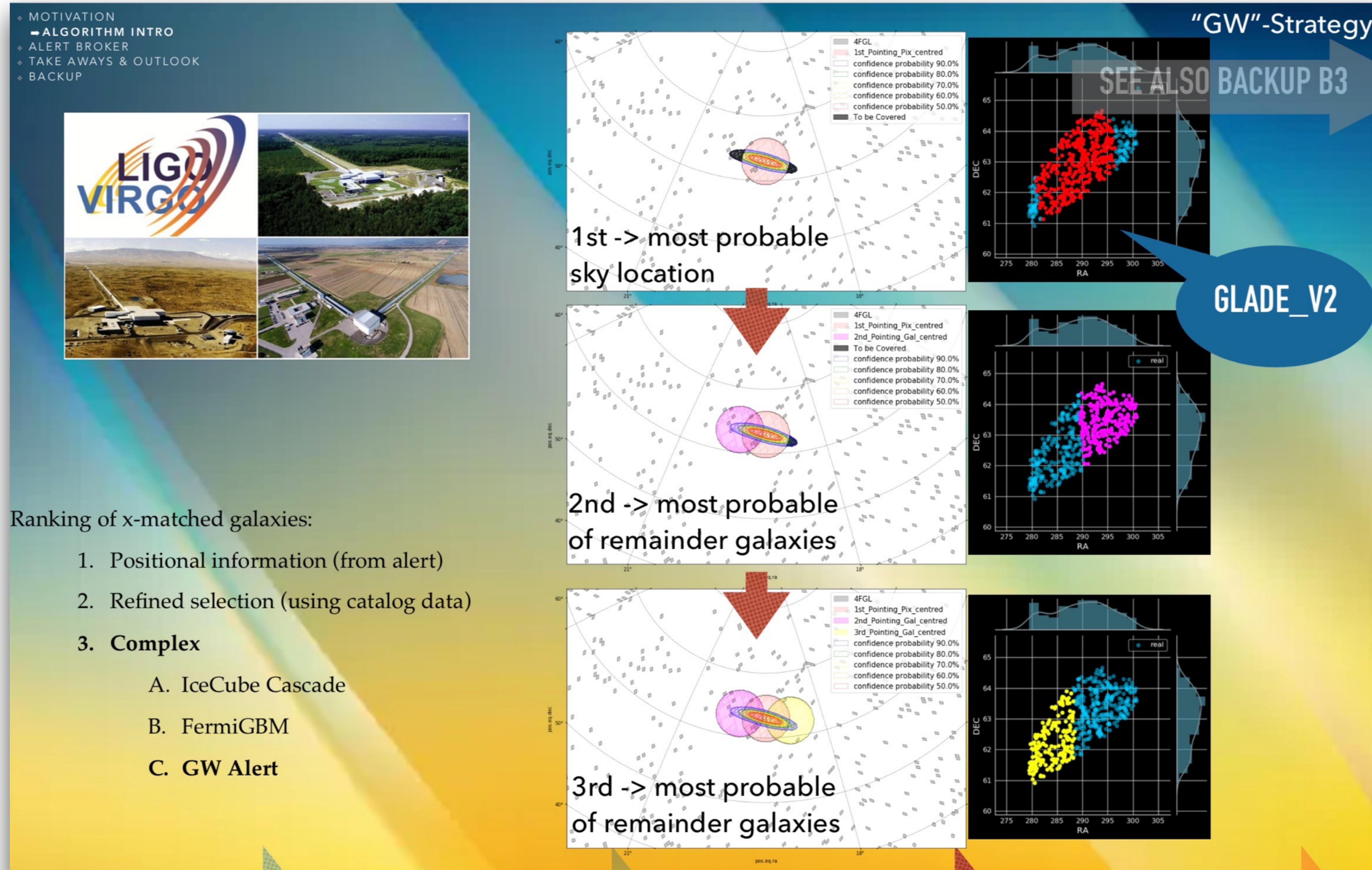
Halim Ashkar et al JCAP03(2021)045



Chasing the VHE counterpart of GW: strategies and optimisation

MAGIC - selection of pointings

(credits:Manuel Artero)

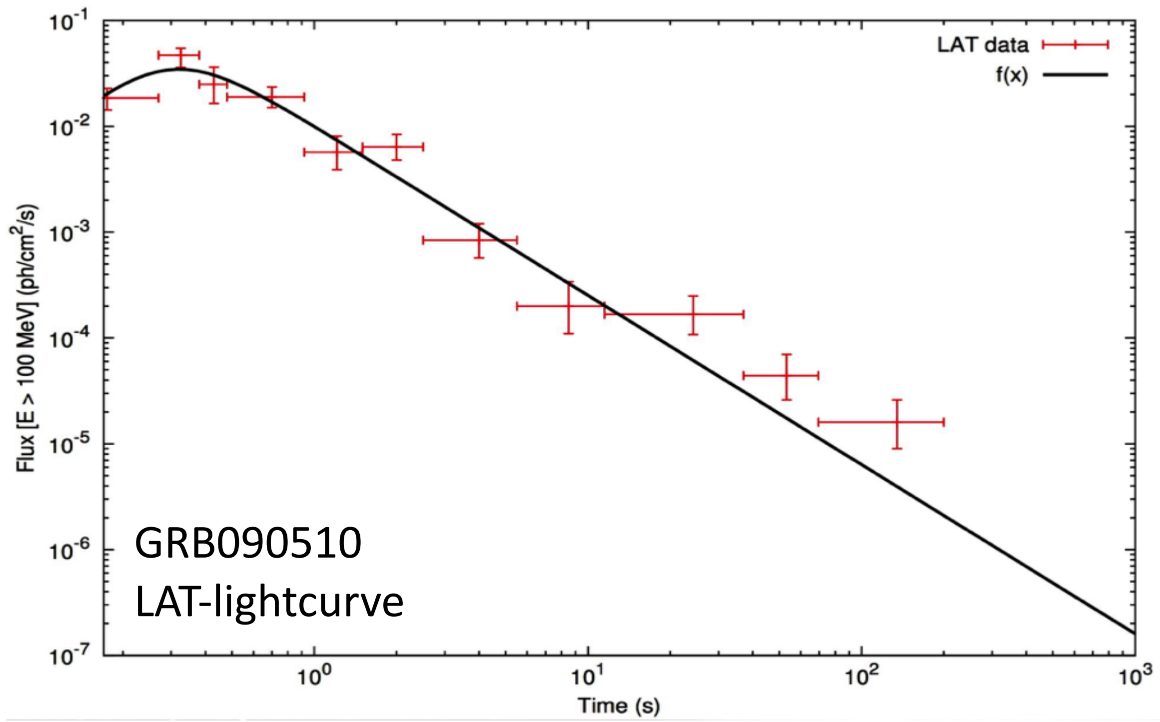


Chasing the VHE counterpart of GW: strategies and optimisation

- GW 3D map

and

- **time dependent and model dependent observing time**



Light curve: $$F(t) = A\,\frac{(t/t_{peak})^{\alpha}}{1+(t/t_{peak})^{\alpha+\omega}}$$

Spectrum (+cutoff): $N(E) \propto E^{\beta}$, β=-2.1

- **Flux normalised for E_{iso} and rescaled to the GW distance**
- **flux extrapolated to higher energies assuming a power-law with exponential cut-off spectrum**
- **time sequence of tiles:**
  - **each ΔT_i chosen to have a fluence for the simulated GRB equal to the CTA sensitivity at that ΔT_i**
  - **Sets the max number of observations (tiles)**

Chasing the VHE counterpart of GW: strategies and optimisation

- GW 3D map

and

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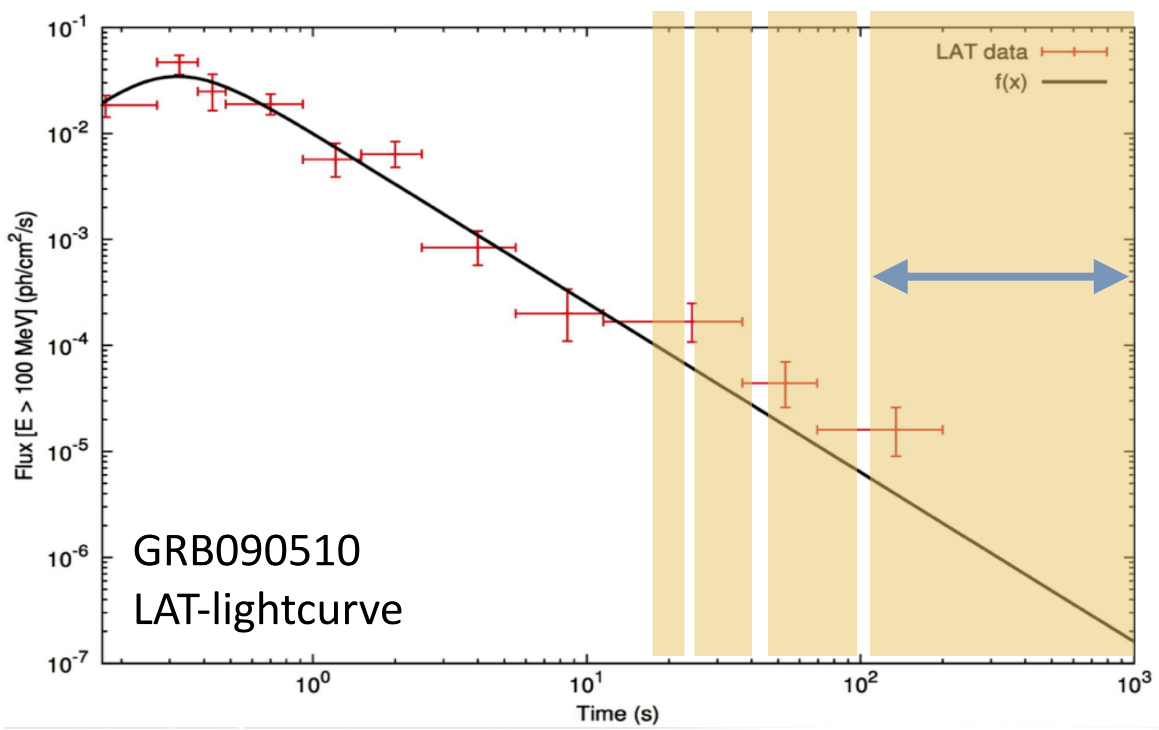
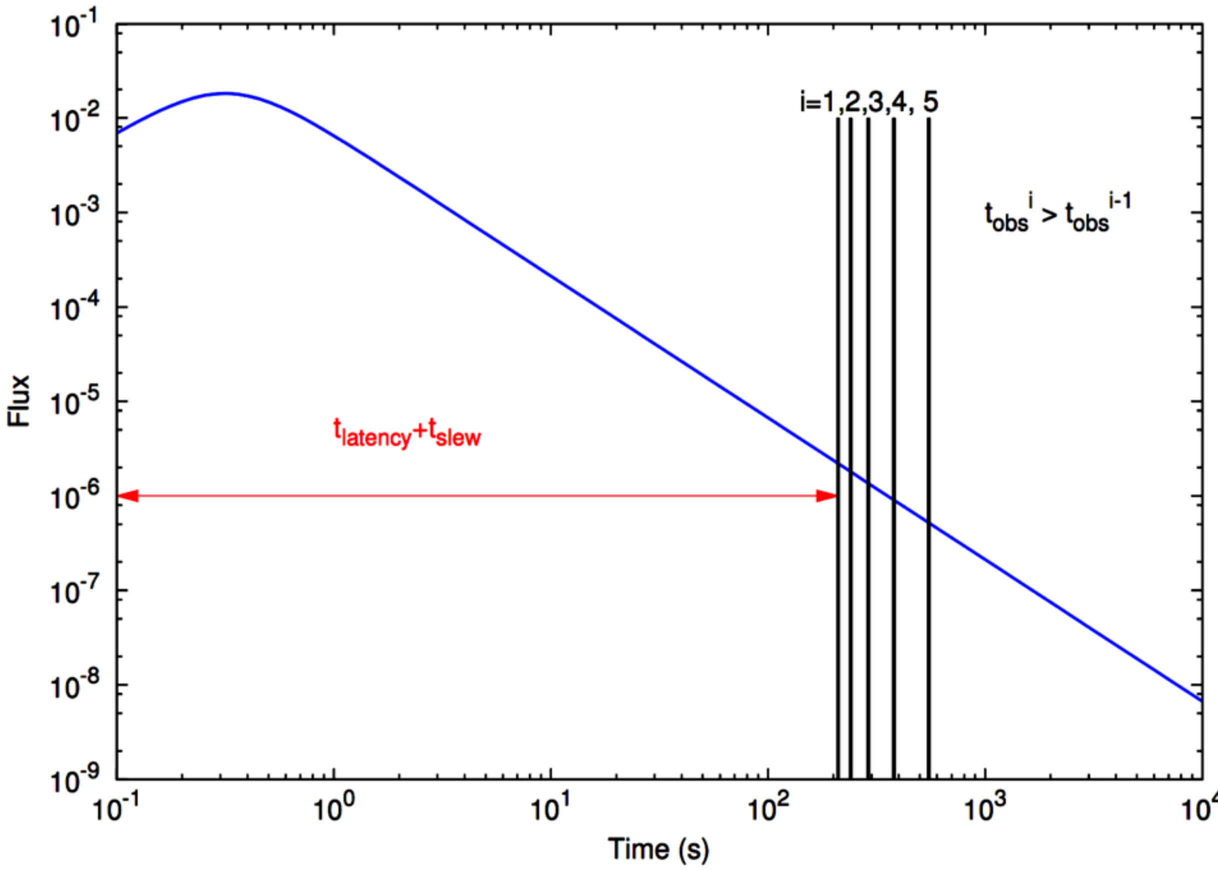


integration time securing the detection



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Chasing the VHE counterpart of GW: strategies and optimisation

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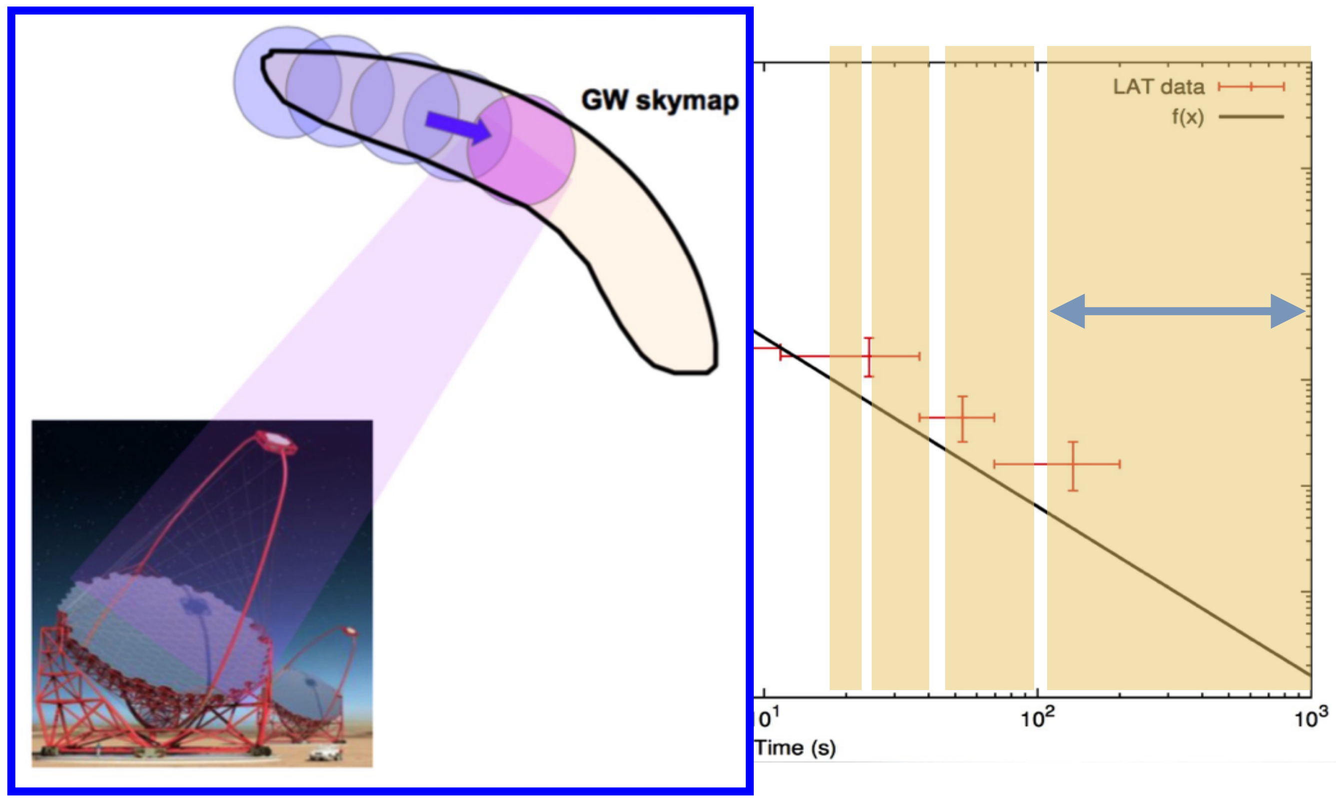
and

- **time dependent and model dependent observing time**



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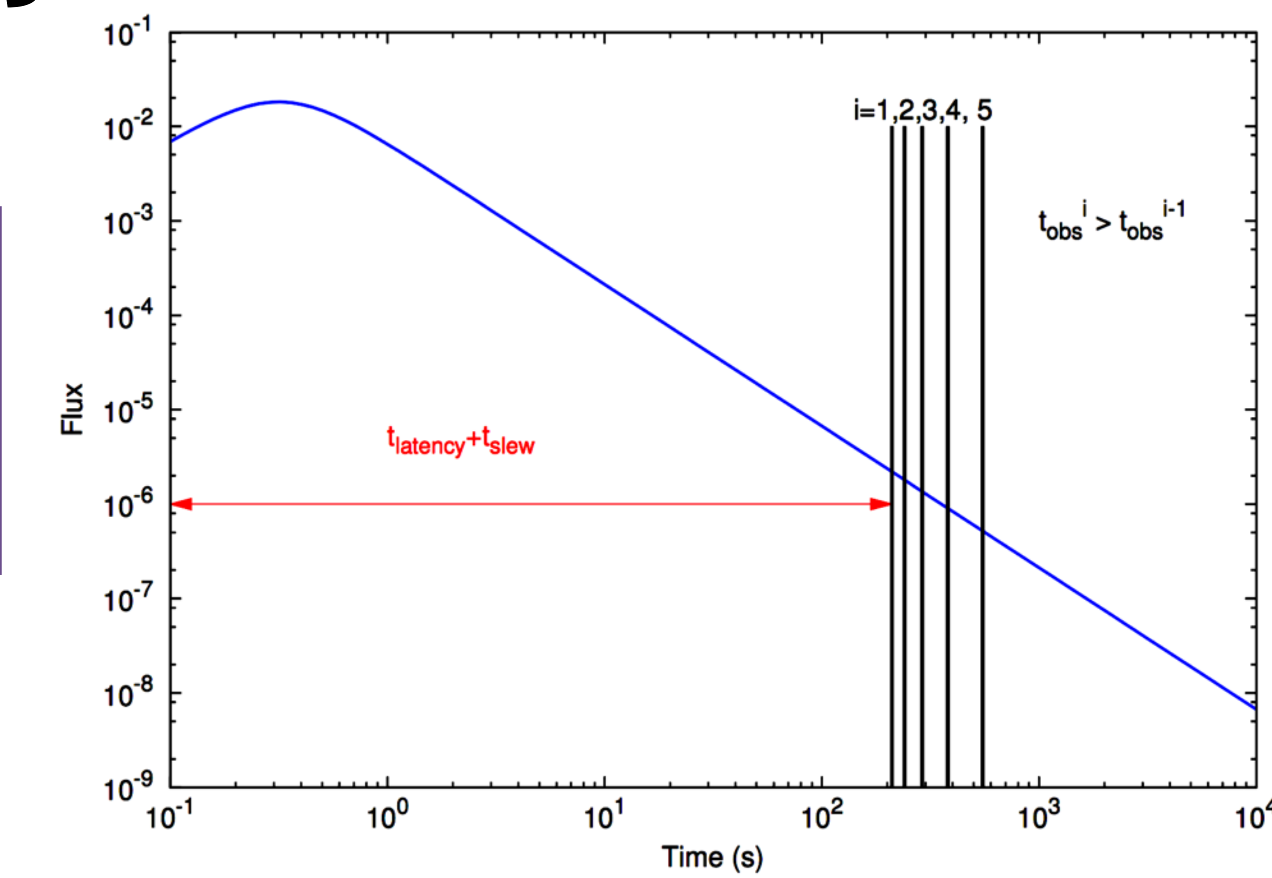

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GW at VHE: when

- now: the GW follow-ups performed at VHE by present IACTs
- future: the prospects for the GW-followup at VHE

GW follow-ups with present IACTs

MAGIC: GW151226 - the second BBH merger

- few pointings on MASTER and VST optical observations (moonlight conditions)
- GCN#18776, De Lotto et al. (MAGIC Coll.), IAU Symposium 324 (2017)

VERITAS: GW170104

- 39 pointings (5min each) covering ~27% of the localization region (GCN #21153)

H.E.S.S.: GW170814, the first GW event detected by 3 interferometers

- First complete coverage of the localization region, H. Ashkar et al. (H.E.S.S.), arXiv: 1906.10426

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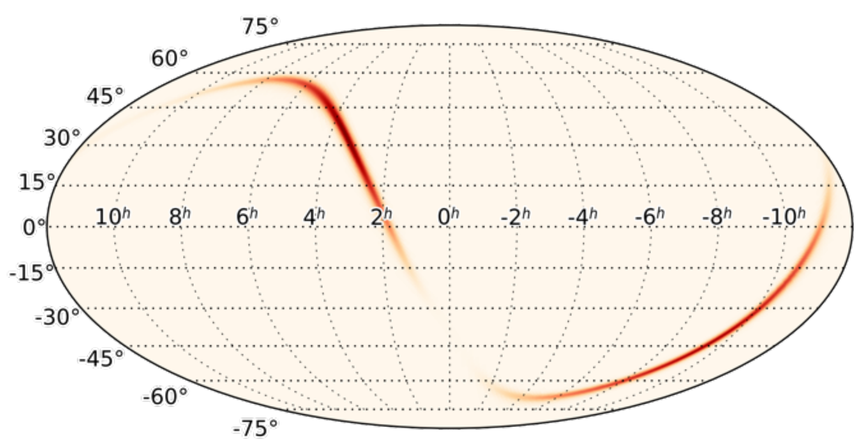
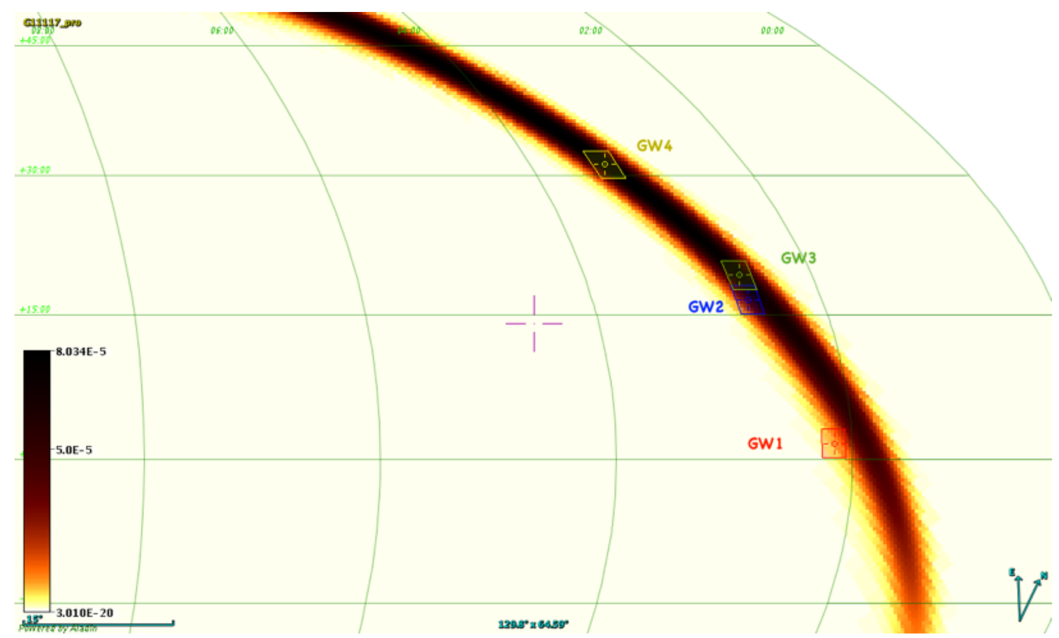
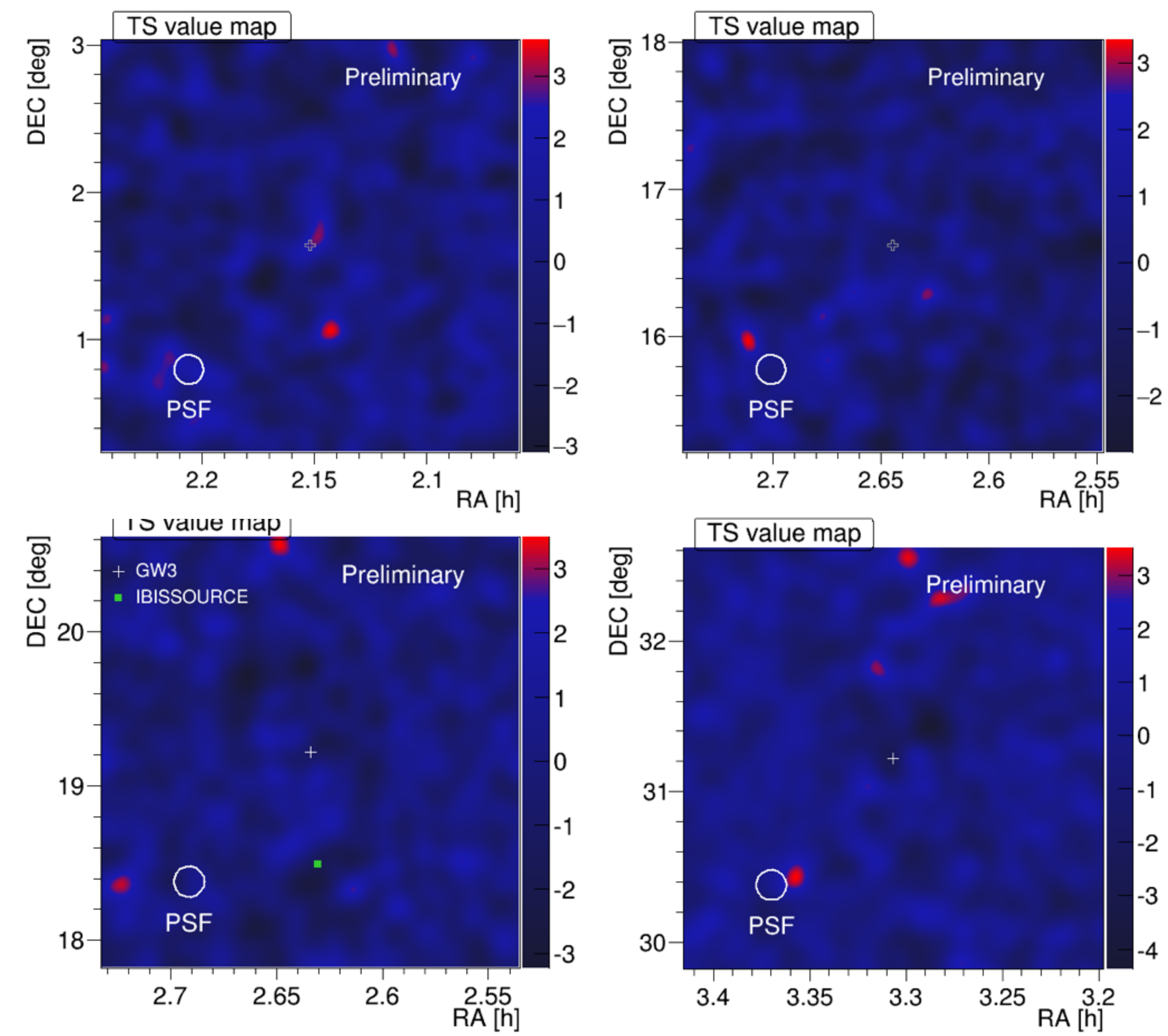
- GCN#18776, De Lotto et al. (MAGIC Coll.), IAU Symposium 324 (2017)







- T_0: 2015-12-26 03:38:53.648 UT (internal GCN Circular)
- T_{notice}: 2015-12-27 17:40:00 UT
- 90% (50%) credible region: 1337 deg^2 (430 deg^2)
- Observation ~ 66 h after T0 (on 28th December 21 UT): 4 pointings

MAGIC: GW151226 - the second BBH merger

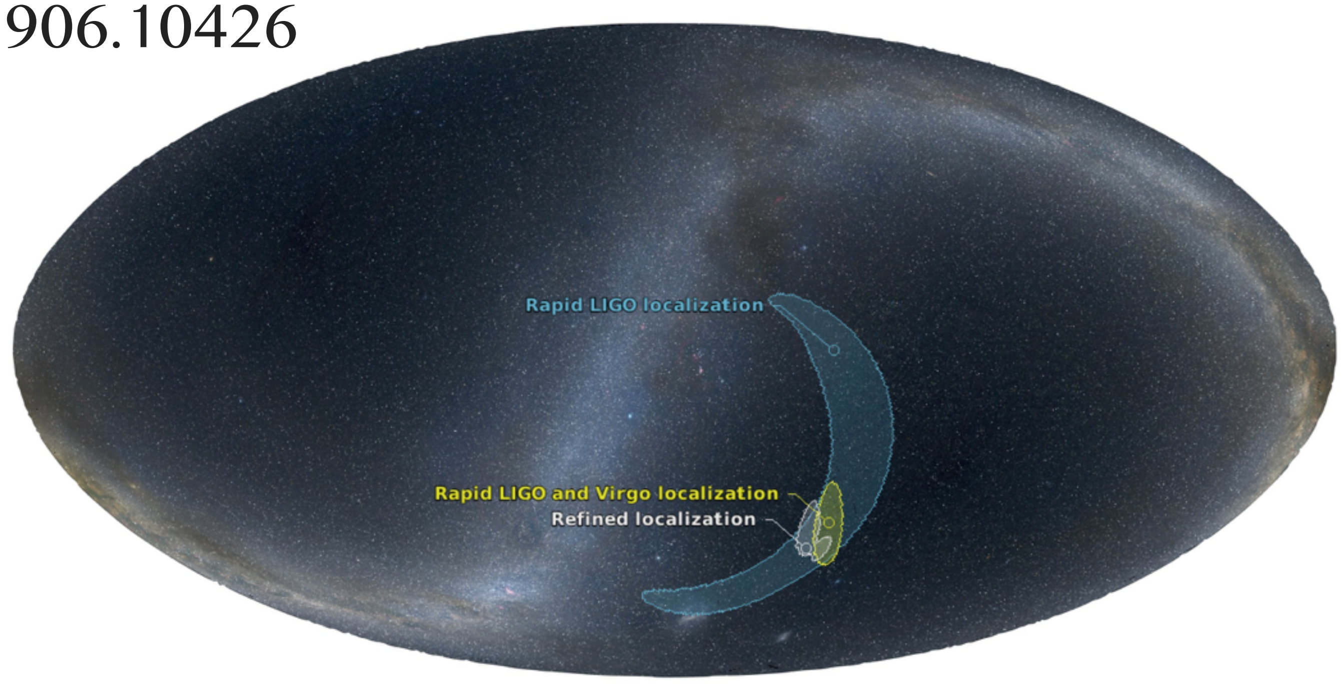
- few pointings on MASTER and VST optical observations (moonlight conditions)
- GCN#18776, De Lotto et al. (MAGIC Coll.), IAU Symposium 324 (2017)

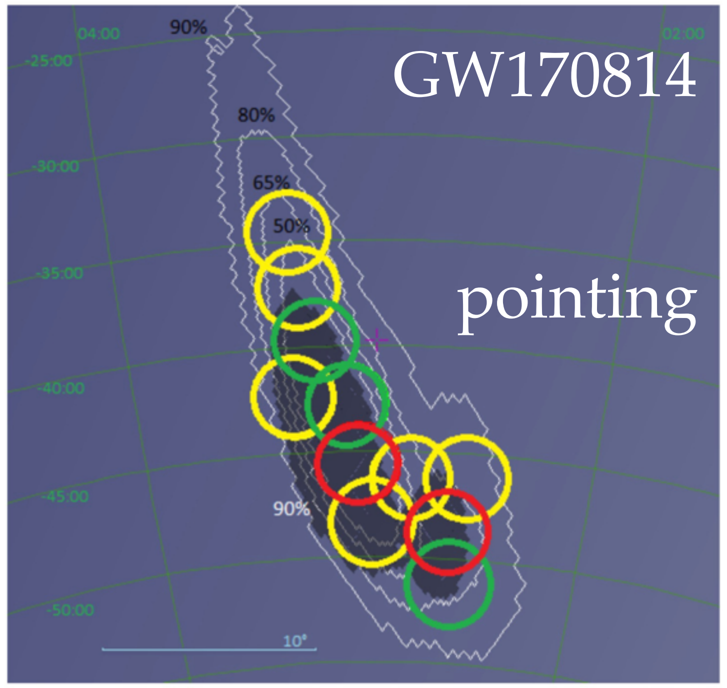
VERITAS: GW170104

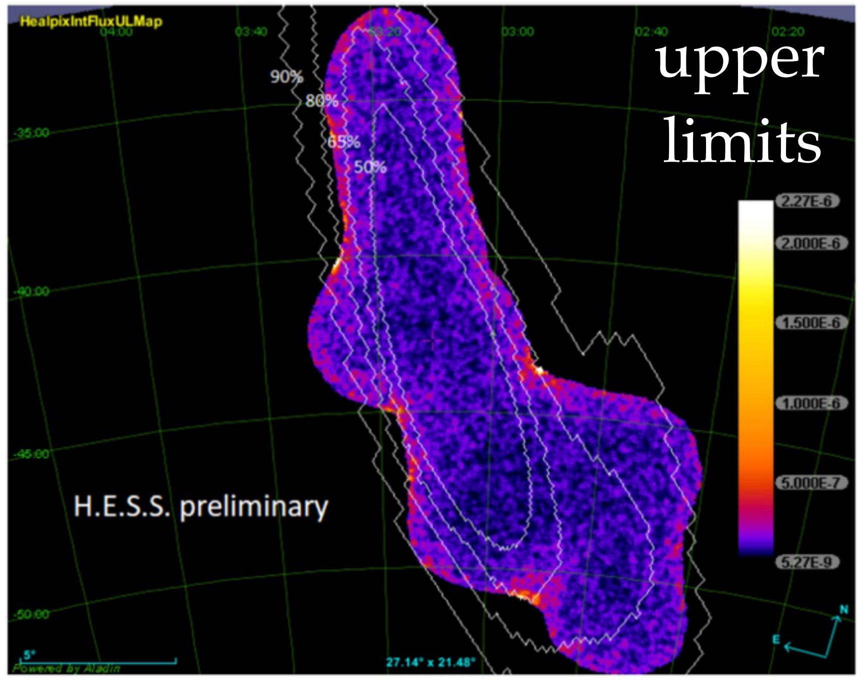
- 39 pointings (5min each) covering ~27% of the localization region (GCN #21153)

H.E.S.S.: GW170814, the first GW event detected by 3 interferometers

- First complete coverage of the localization region, H. Ashkar et al. (H.E.S.S.), arXiv: 1906.10426



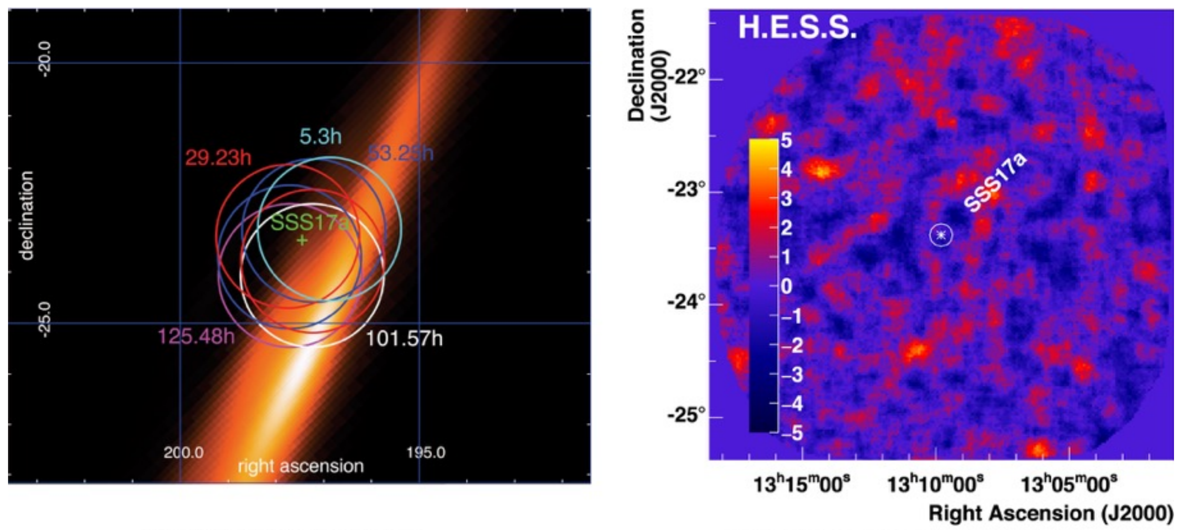




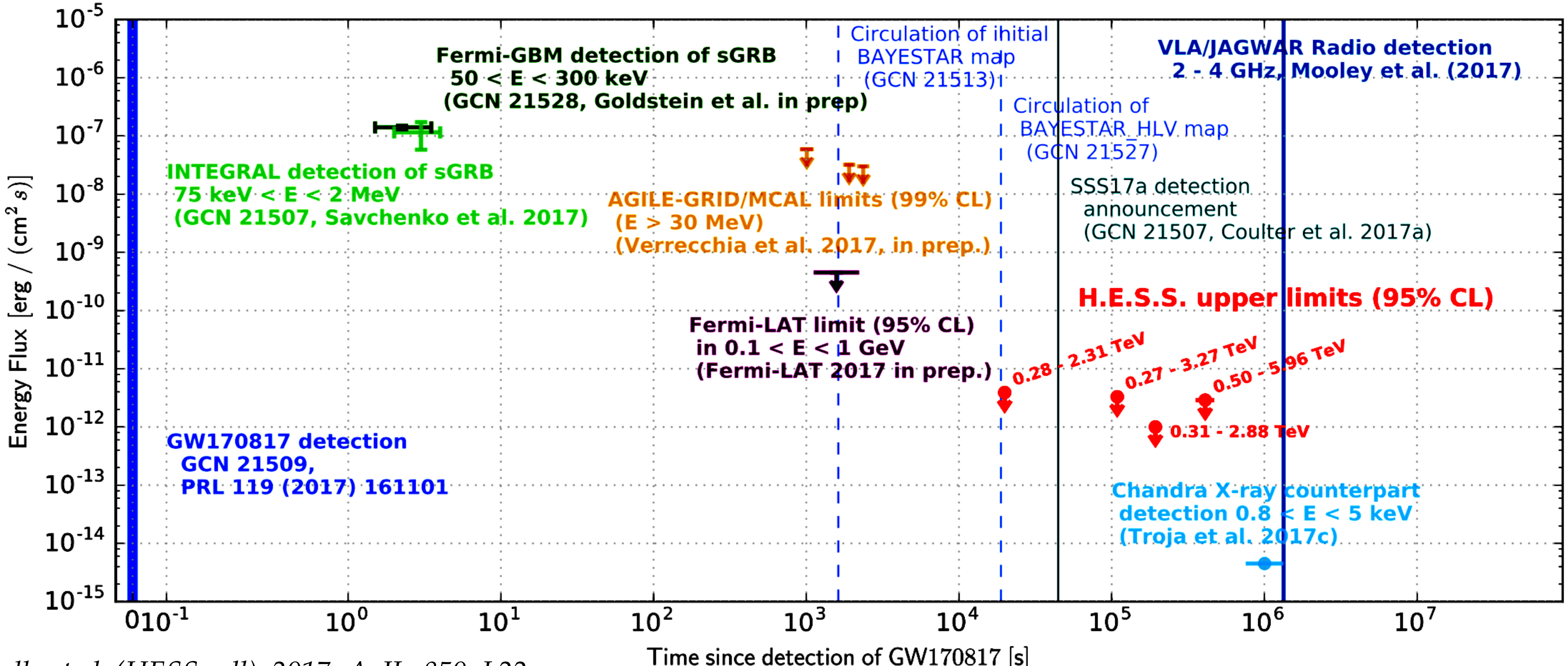
GW follow-ups with present IACTs: prompt follow-up of GW170817

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

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



(a) SSS17a: H.E.S.S. pointings (b) SSS17a: H.E.S.S. significance map



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

GW follow-ups with present IACTs: late follow-up of GW170817

- HESS observations 124-272 days from T0 (December 2017 - May 2018)
- Tot.: ~55 hrs ZA: ~24 deg
- E_{thr}: 130 GeV

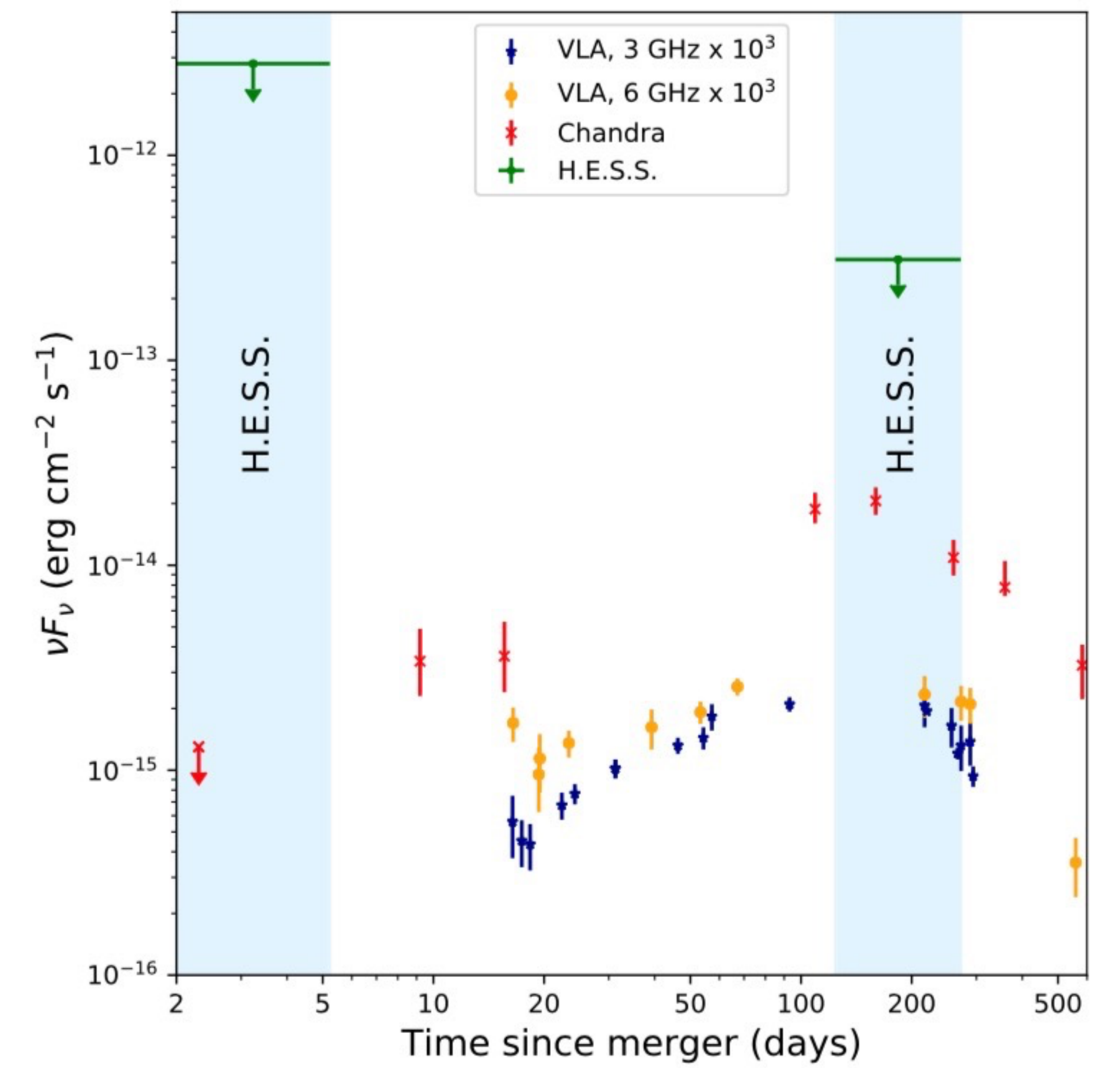
The Astrophysical Journal Letters, 894:L16 (5pp), 2020 May 10 https://doi.org/10.3847/2041-8213/ab8b59

Probing the Magnetic Field in the GW170817 Outflow Using H.E.S.S. Observations

H. Abdalla[1], R. Adam[2], F. Aharonian[3,4,5], F. Ait Benkhali[3], E. O. Angüner[6], M. Arakawa[7], C. Arcaro[1], C. Armand[8], T. Armstrong[9], H. Ashkar[10,41], M. Backes[1,11], V. Baghmanyan[12], V. Barbosa-Martins[13], A. Barnacka[14], M. Barnard[1], Y. Becherini[15], D. Berge[13], K. Bernlöhr[3], R. Blackwell[16], M. Böttcher[1], C. Boisson[17], J. Bolmont[18], S. Bonnefoy[13], J. Bregeon[19], M. Breuhaus[3], F. Brun[10], P. Brun[10], M. Bryan[20], M. Büchele[21], T. Bulik[22], T. Bylund[15], S. Caroff[18], A. Carosi[8], S. Casanova[3,12], M. Cerruti[18,42], T. Chand[1],

Table 1
Properties of the H.E.S.S. Data Sets on GW170817/GRB 170817A and Analysis Results

$T - T_0$ (days)	Exposure (hr)	Energy Range (TeV)	$F(>E_{th})$ (erg cm^{-2} s^{-1})	F(1–10 TeV) (erg cm^{-2} s^{-1})	Zenith Angle (deg)
0.22–5.23	3.2	0.27–8.55	$<1.5 \times 10^{-12}$	…	58
0.22–5.23	3.2	0.56–17.8	$<4.7 \times 10^{-12}$	$<2.8 \times 10^{-12}$	58
124–272	53.9	0.13–23.7	$<1.6 \times 10^{-12}$	$<3.2 \times 10^{-13}$	24



GW follow-ups with present IACTs: late follow-up of GW170817

- HESS observations 124-272 days from T0 (December 2017 - May 2018)
- Tot.: ~55 hrs ZA: ~24 deg
- E_{thr}: 130 GeV
- Assumed SSC emission, with:
    - isotropic non-relativistic expansion
        - $R_{iso} \sim \beta c \Delta t$ $\beta=0.2$
    - relativistic jet
        - $\boldsymbol{\Gamma}=3$, $\theta_{jet} \sim 5$ $\theta_{obs} \sim 20$ $\delta=\Gamma=3$
        - $E_X \sim E_e^2 B$ $N_e \sim \delta^{-3}$

$$L_{IC} \approx 10^{46} \left(\frac{\theta'_{jet}}{5^\circ}\right)^{-2} \left(\frac{\beta \Delta t}{0.94 \times 110 \text{ days}}\right)^{-2} \left(\frac{\delta}{3}\right)^{-5.25} \text{erg s}^{-1}. \text{ IC}$$

THE ASTROPHYSICAL JOURNAL LETTERS, 894:L16 (5pp), 2020 May 10 https://doi.org/10.3847/2041-8213/ab8b59

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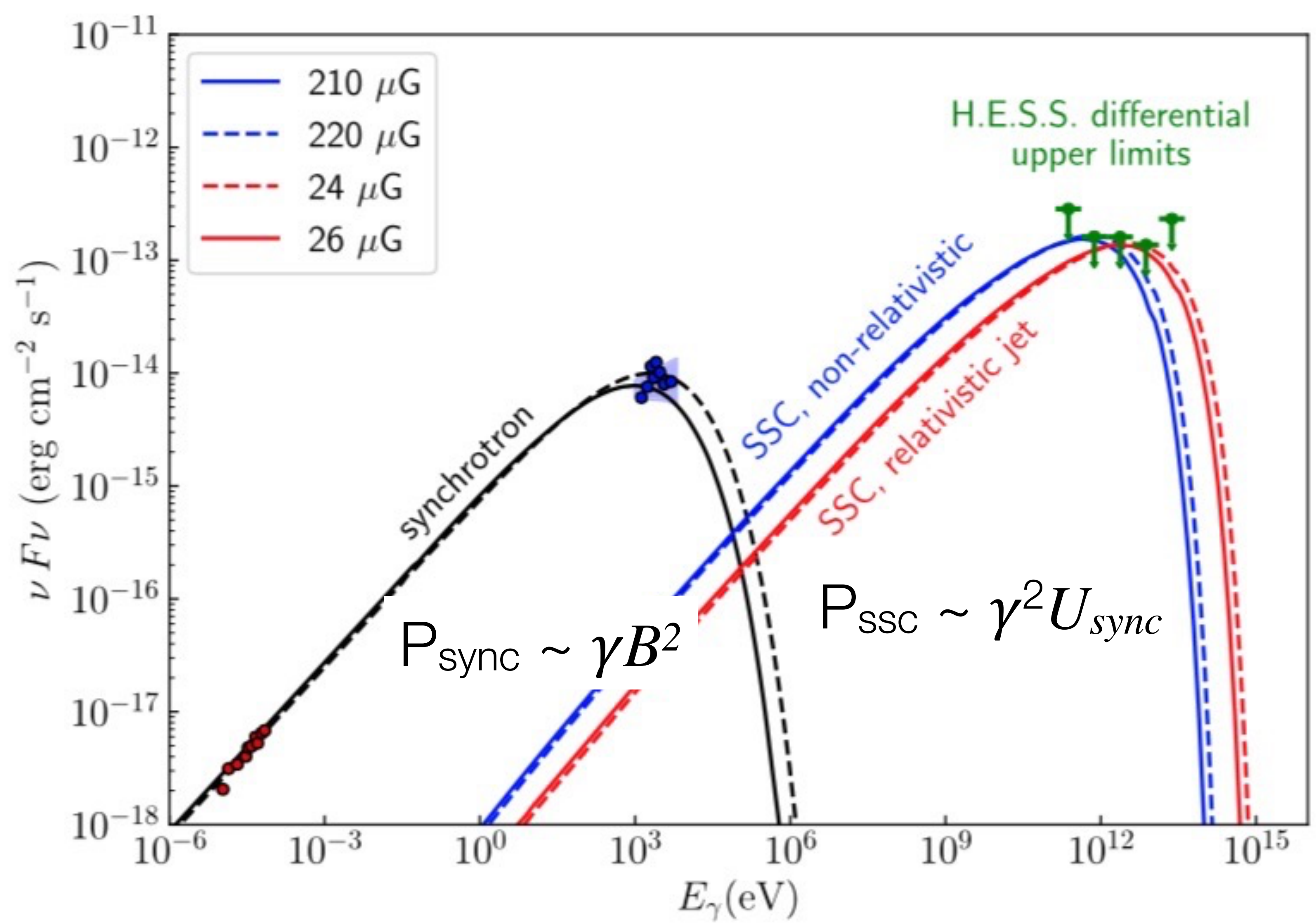
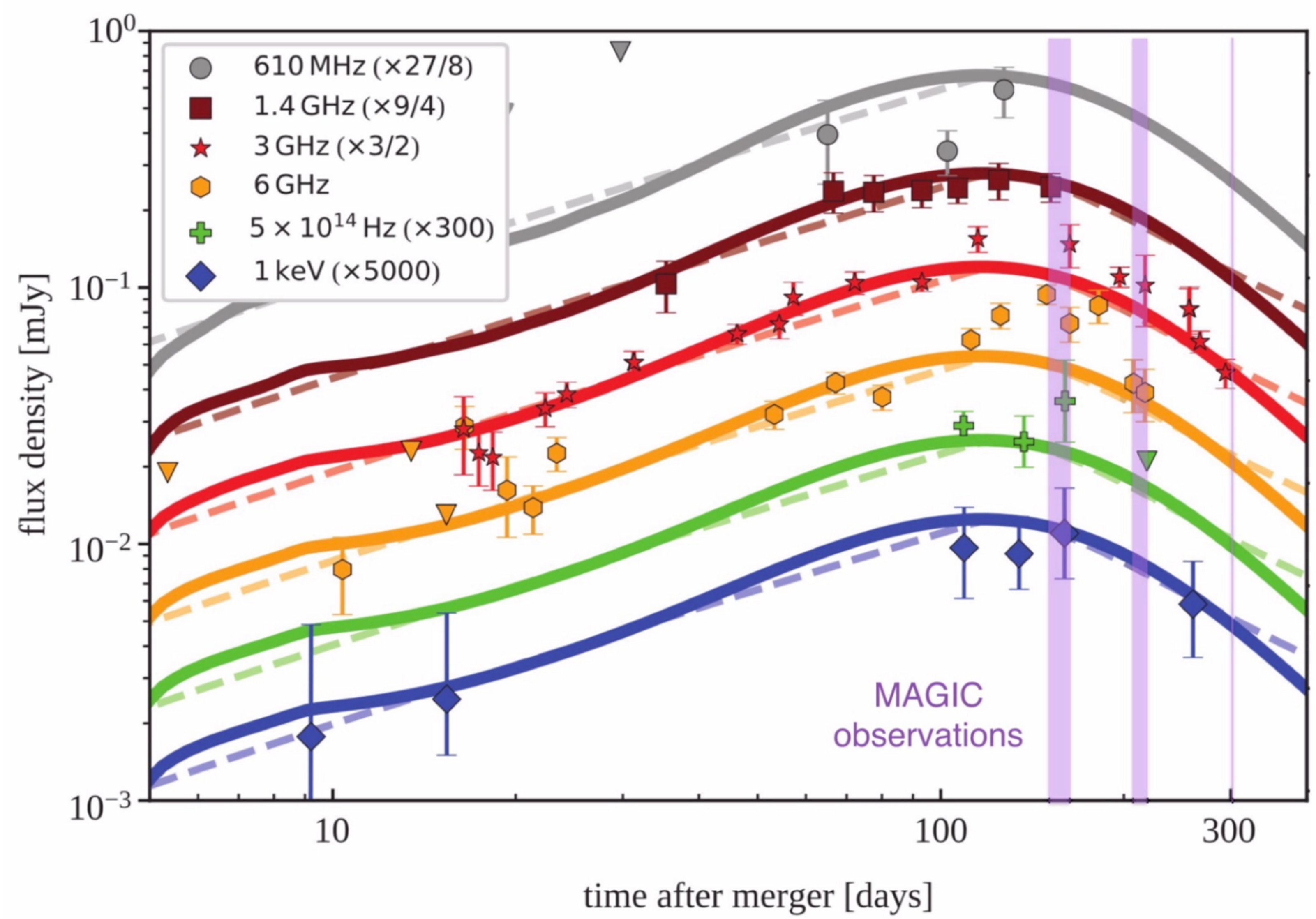


Constrains on the minimum magnetic field strength

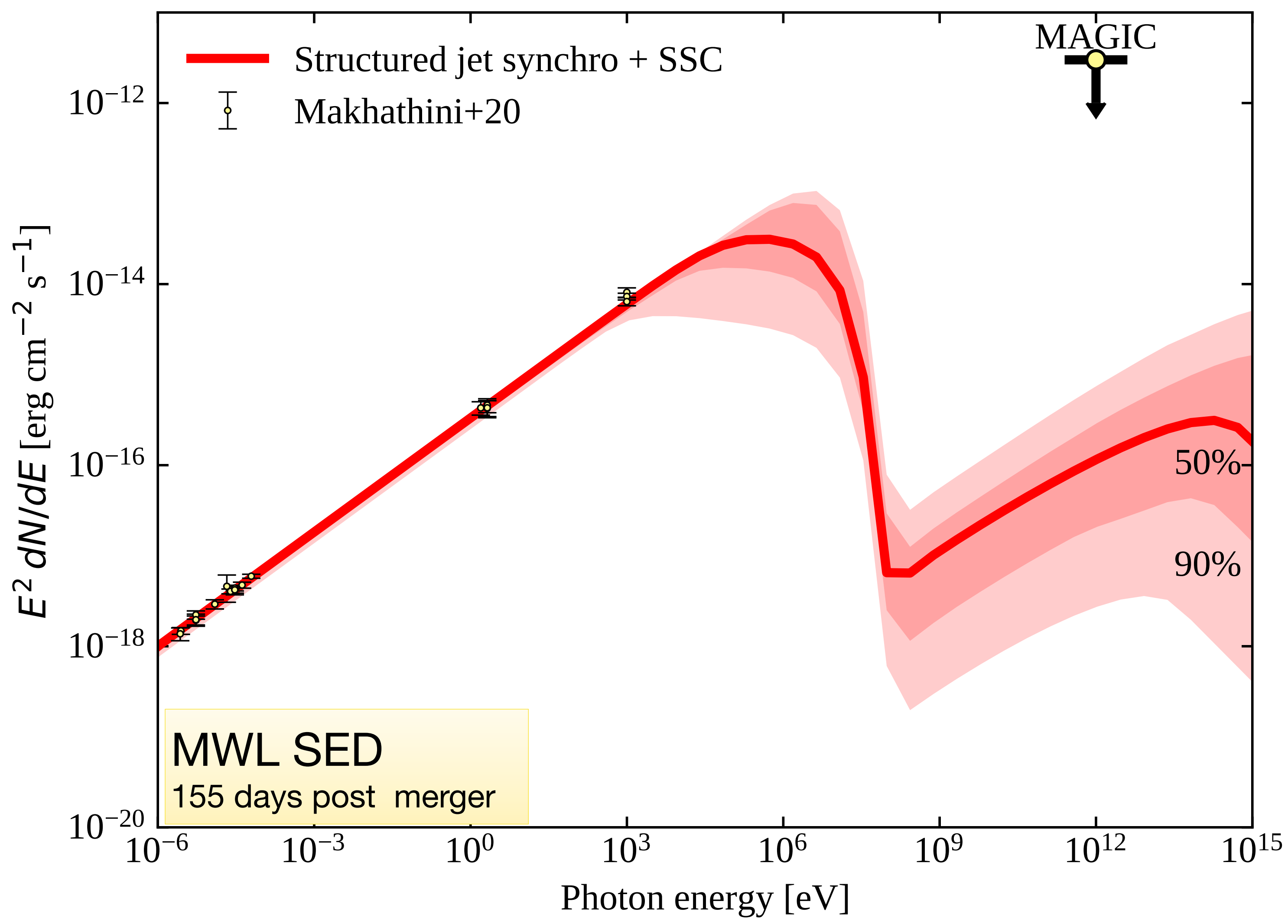
GW follow-ups with present IACTs: late follow-up of GW170817

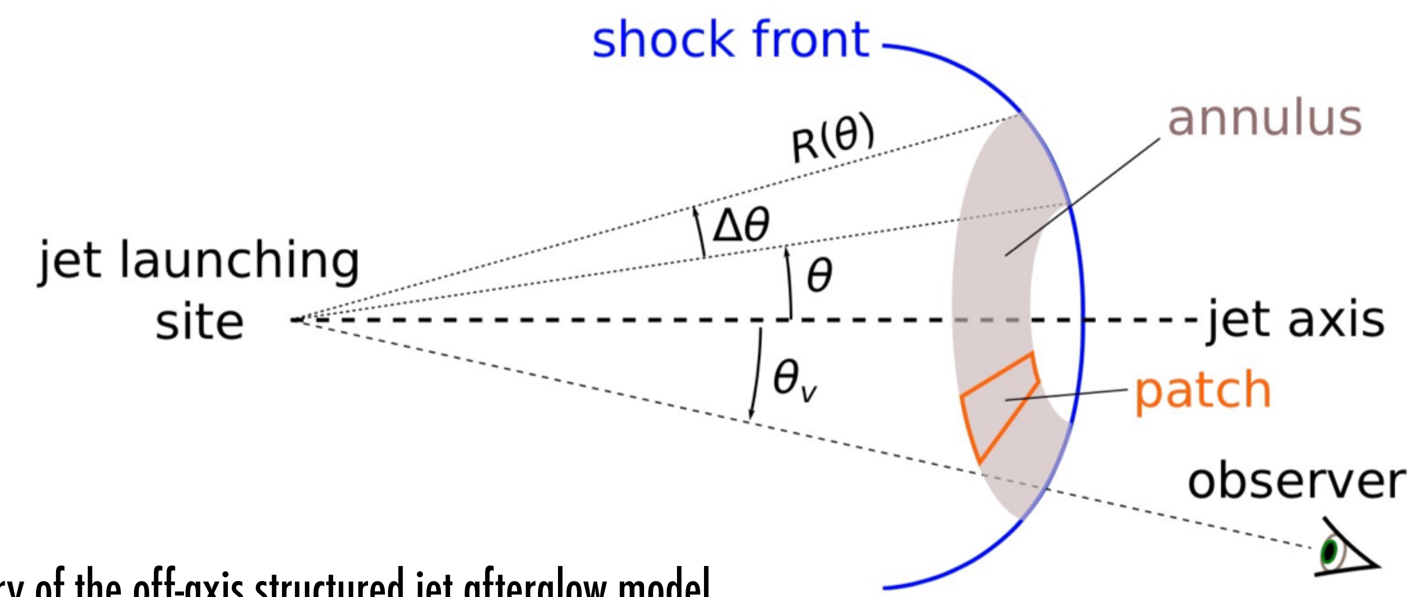
- MAGIC follow-up observations: 10 hours, from Jan to June 2018.
- Large zenith angles>50 deg
  - E_{thr} >400 GeV



GW follow-ups with present IACTs: late follow-up of GW170817

- MAGIC follow-up observations: 10 hours, from Jan to June 2018.
- Large zenith angles>50 deg
  - E_{thr} >400 GeV
- Build the multi-wavelength spectral energy distribution (SED), using the available radio, optical and X-ray data.
- Expected TeV emission computed from a self-synchrotron Compton (SSC) model built on an **evolving structured jet**, seen off-axis.





Geometry of the off-axis structured jet afterglow model.

GW follow-ups with present IACTs: late follow-up of GW170817

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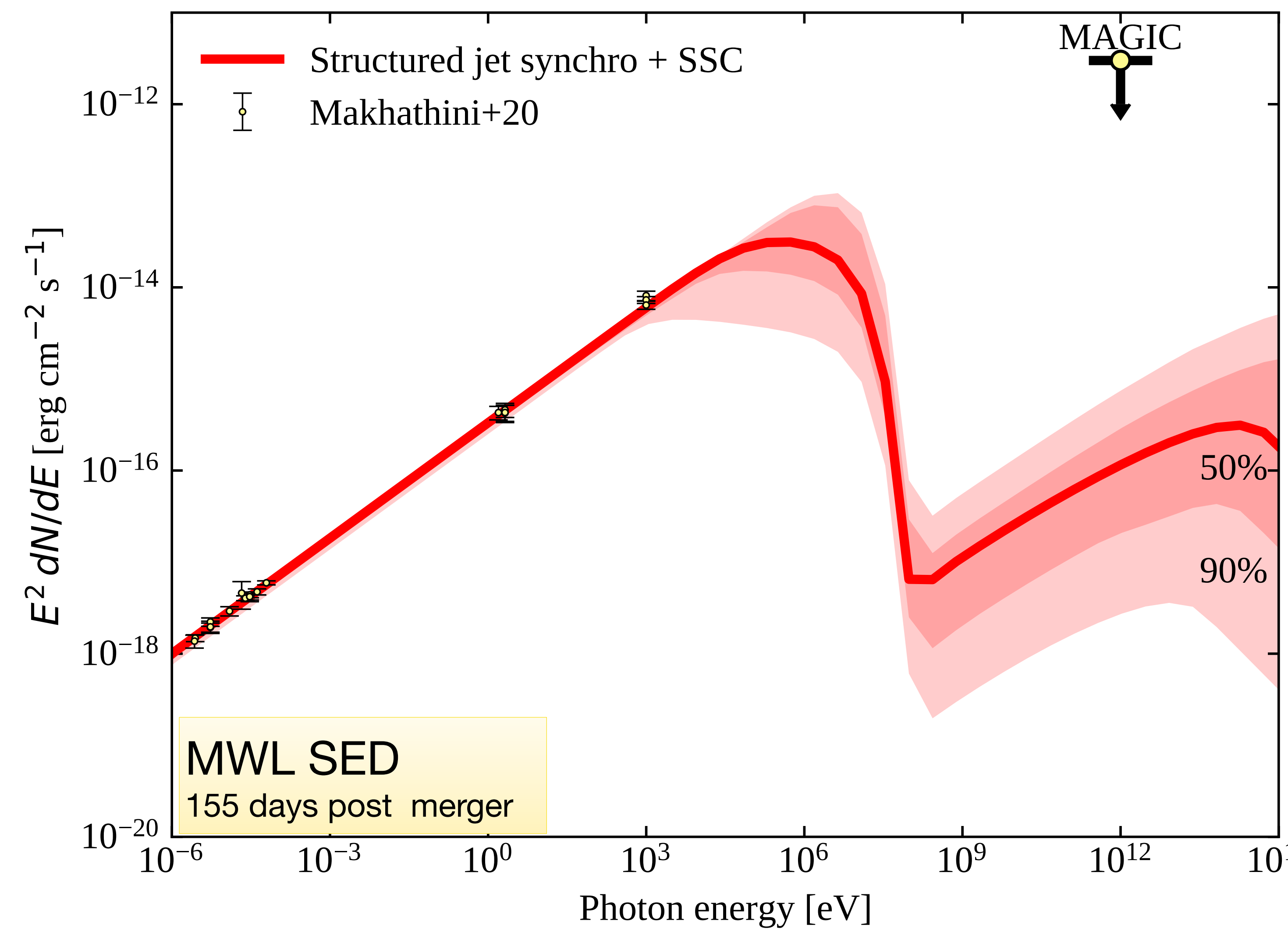
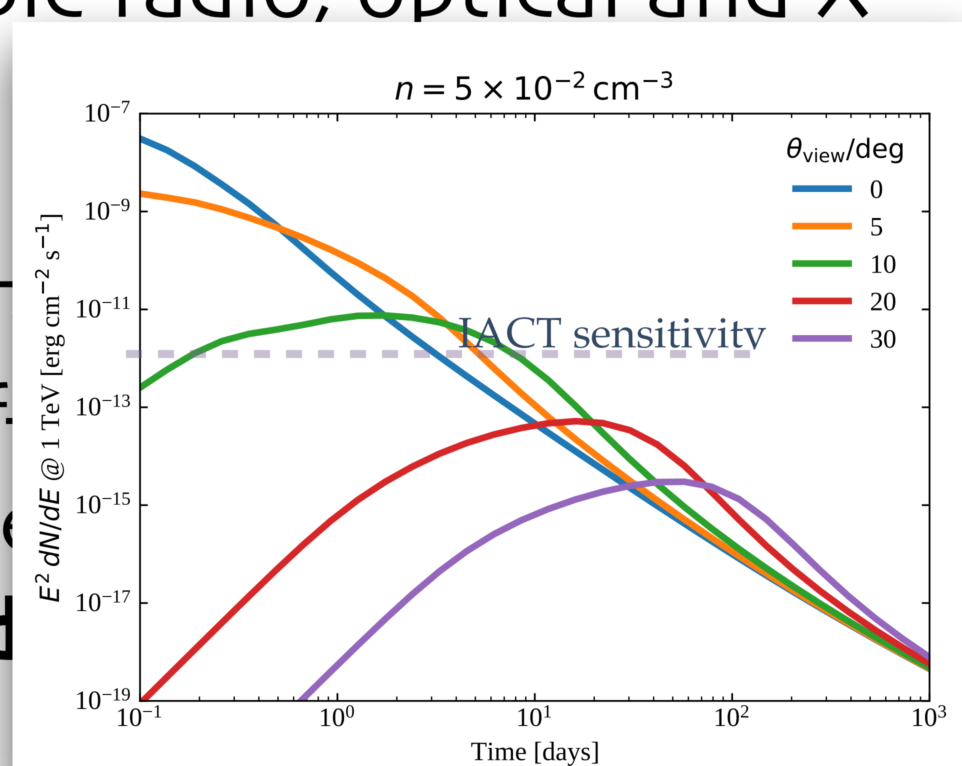
- Build the multi-wavelength spectral energy distribution (SED), using the available radio, optical and X-ray data.
- Expected T… from a self… (SSC) mode… **structured…**





TeV emission from short-GRBs seen off-axis (>10-20 deg) is challenging for the present generation of Cherenkov telescopes.

The detection of an energetic component from GW and BNS counterparts by Cherenkov telescopes is expected with either smaller off-axis angle <~10 deg and denser interstellar medium density, or an additional emission component.

future: the prospects for the GW-followup at VHE

CTA in a nutshell

Energy range: 30 GeV to 300 TeV

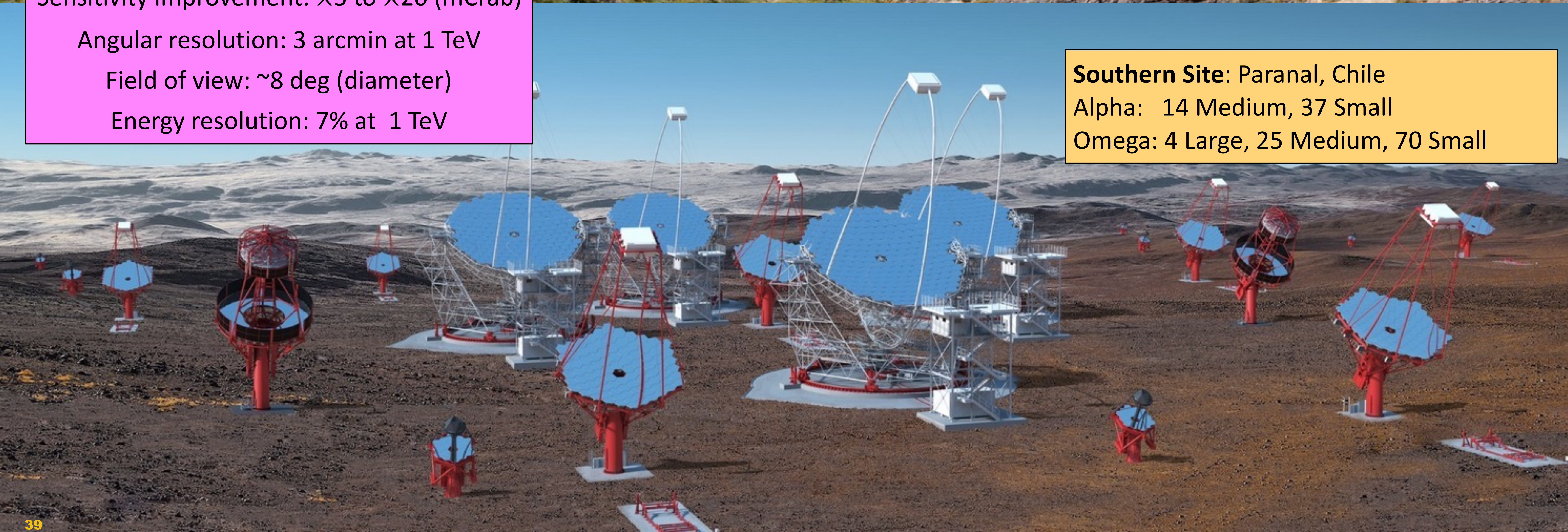
Sensitivity improvement: ×5 to ×20 (mCrab)

Angular resolution: 3 arcmin at 1 TeV

Field of view: ~8 deg (diameter)

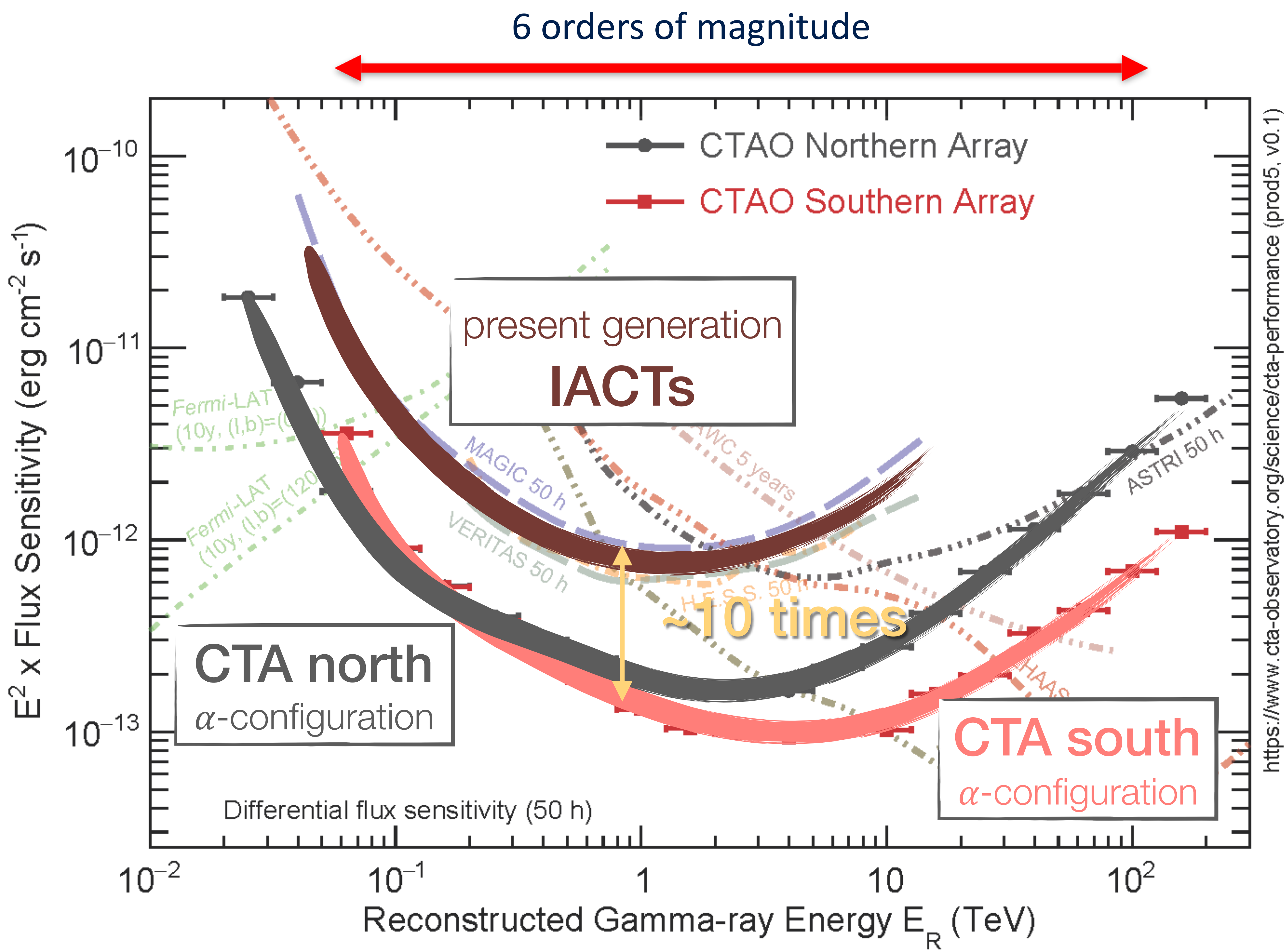
Energy resolution: 7% at 1 TeV

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

CTA performances: Sensitivity - transient and flaring sources

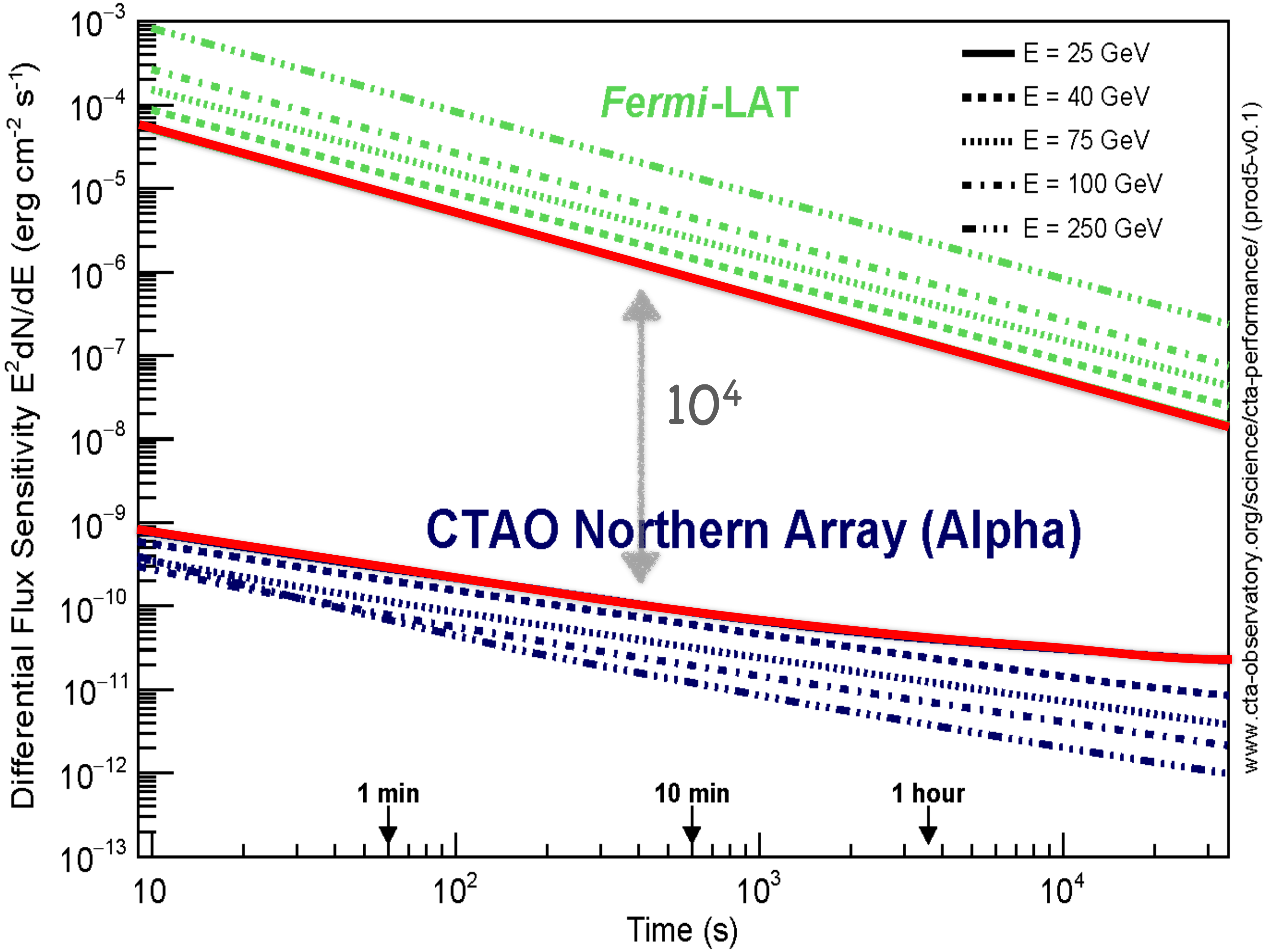


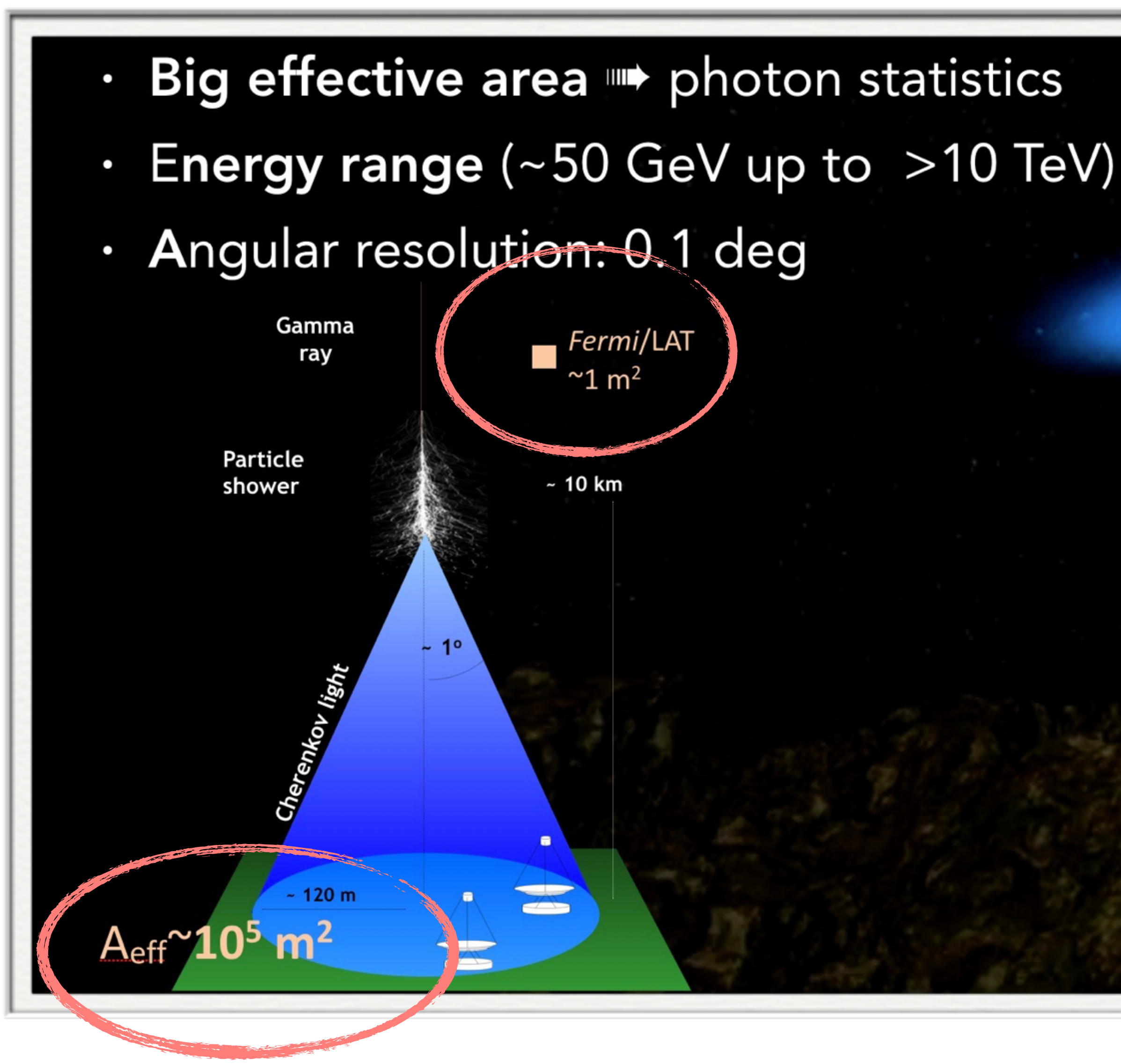
- precision astronomy
- detection of weaker sources
  - population studies
- transients/flares

Alpha configuration

CTA performances: Sensitivity - transient and flaring sources

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





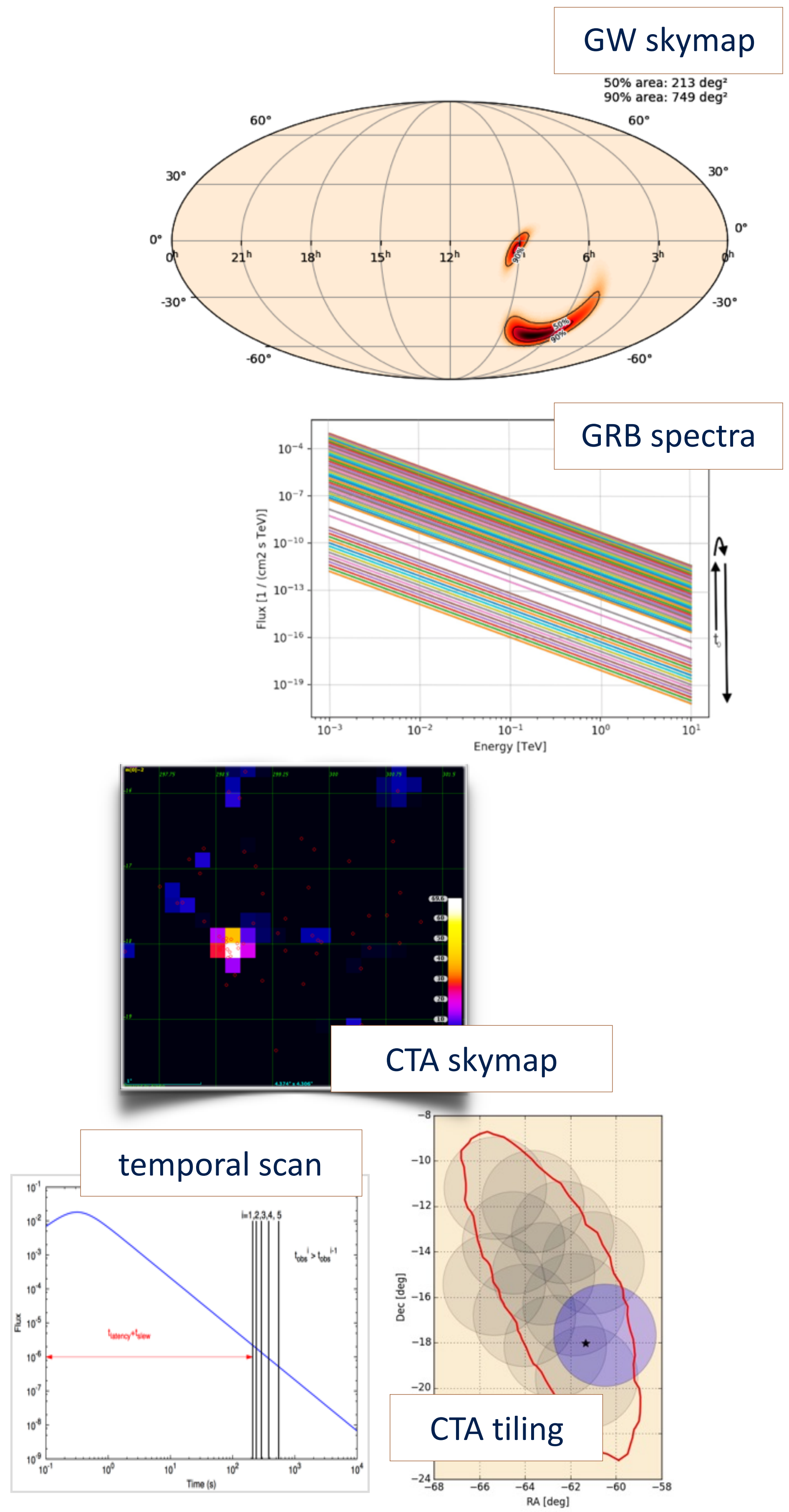
Study of prospects in searching GW counterparts in CTA

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



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

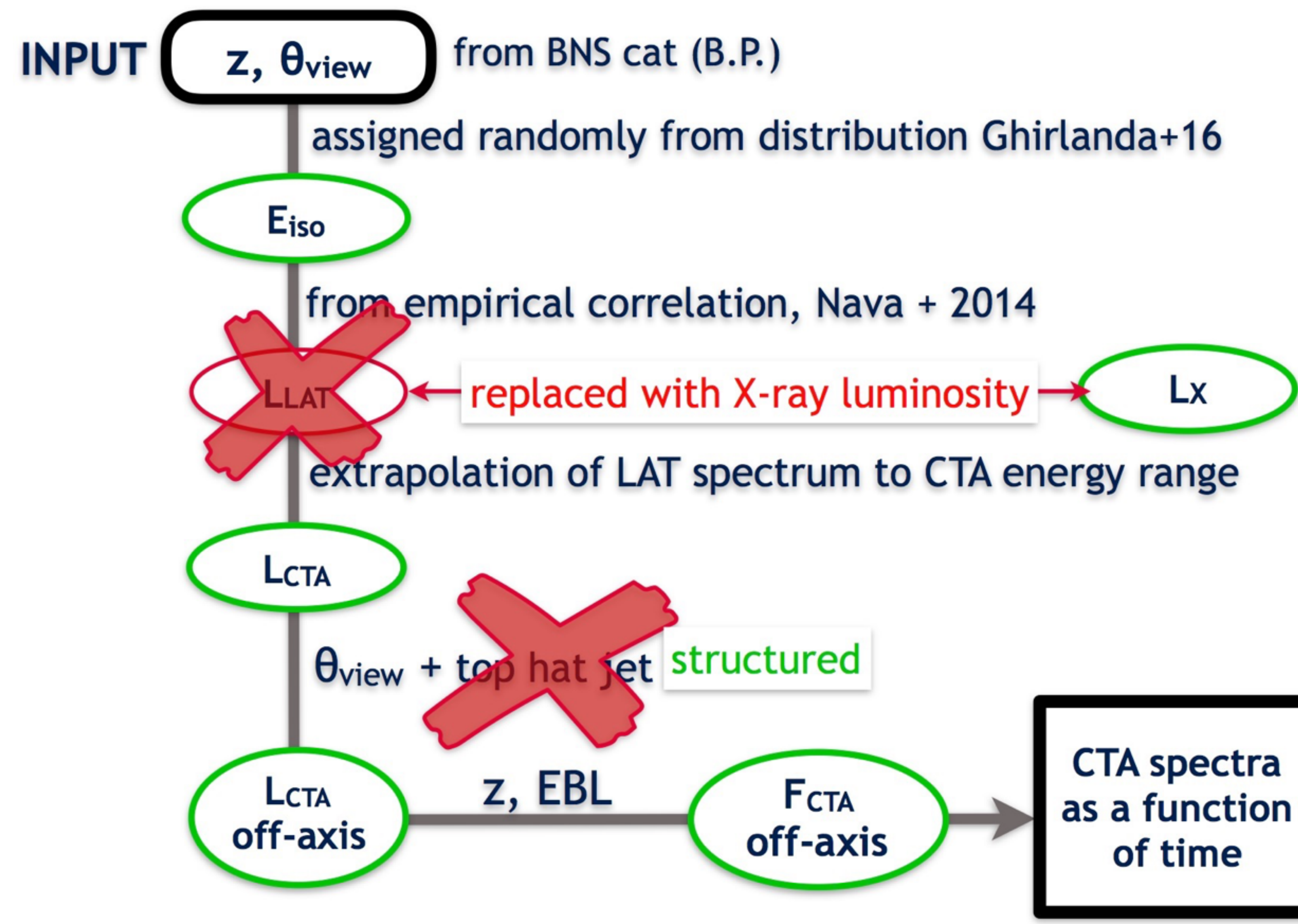
Patricelli, AS et al. 2018 JCAP05(2018)056.
M. Seglar-Arroyo et al., ICRC 2019, https://pos.sissa.it/358/790/

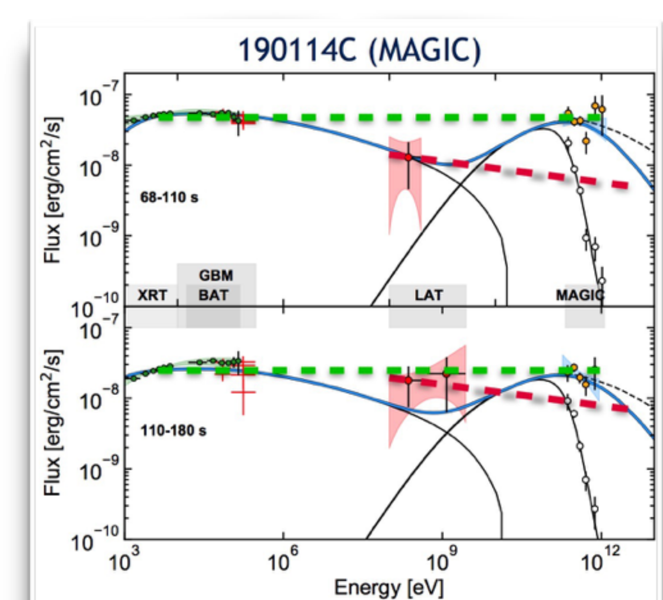
The synthetic-GRB module

- GRB catalogue containing models for each GW-event with the expected emission in the CTA energy range
    - empirical (model-independent) light-curves and spectra
    - E_{iso} distribution
    - $L_{X\text{-ray}} \rightarrow L_{TeV(CTA)}$ (+EBL)
    - top-hat jet model and gaussian jet model

★ Results on GRB 190114C (MAGIC) and GRB180720B (H.E.S.S.)

➡ empirical relations on the TeV emission based on X-ray luminosity.



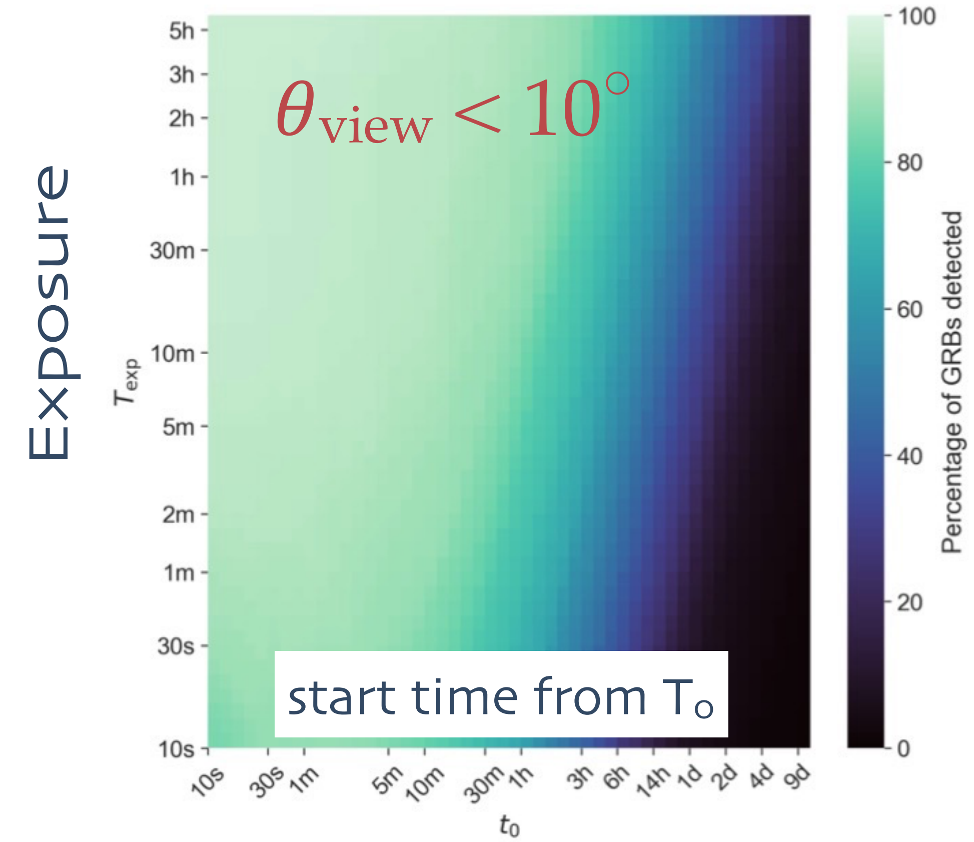


future: the prospects for the GW-followup at VHE

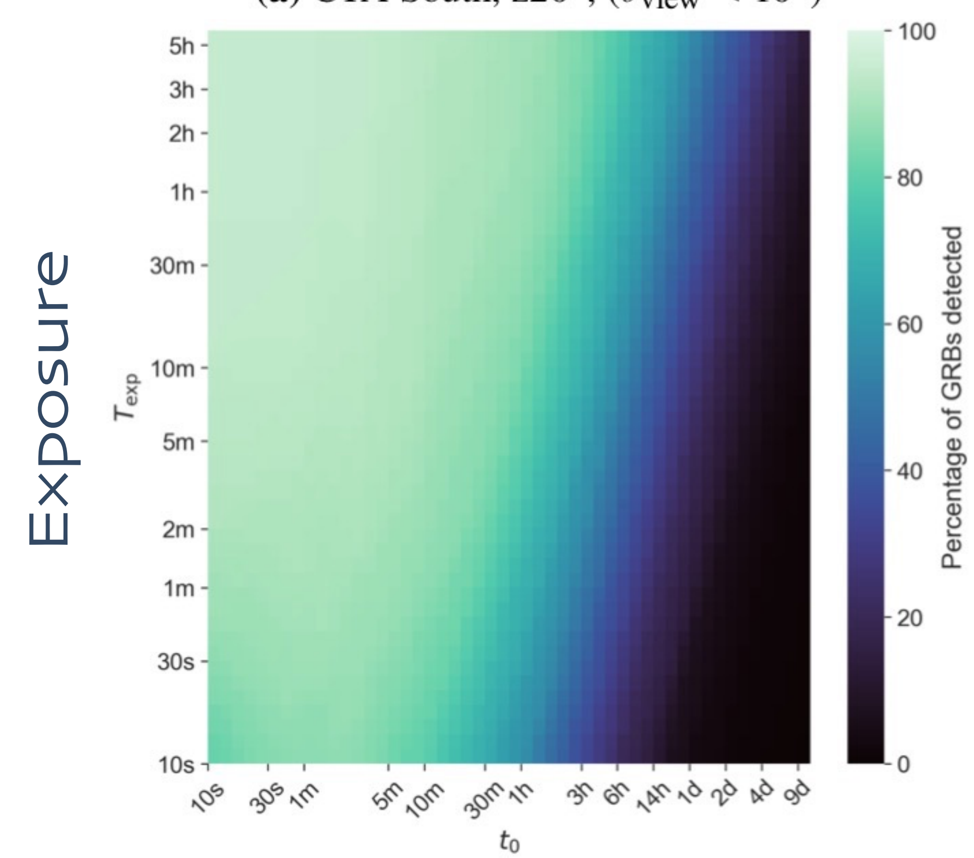
Detectability vs exposure time and start time

Viewing angle <10 deg (on-axis)

- for t_0~30s, ~94% of the GRBs can be detected with T_{exp}≤30 minutes
- for t_0~10min, ~92% of the GRBs can be detected with T_{exp}~few hours



(a) CTA South, z20°, ($\theta_{\rm view} < 10^\circ$)



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

future: the prospects for the GW-followup at VHE

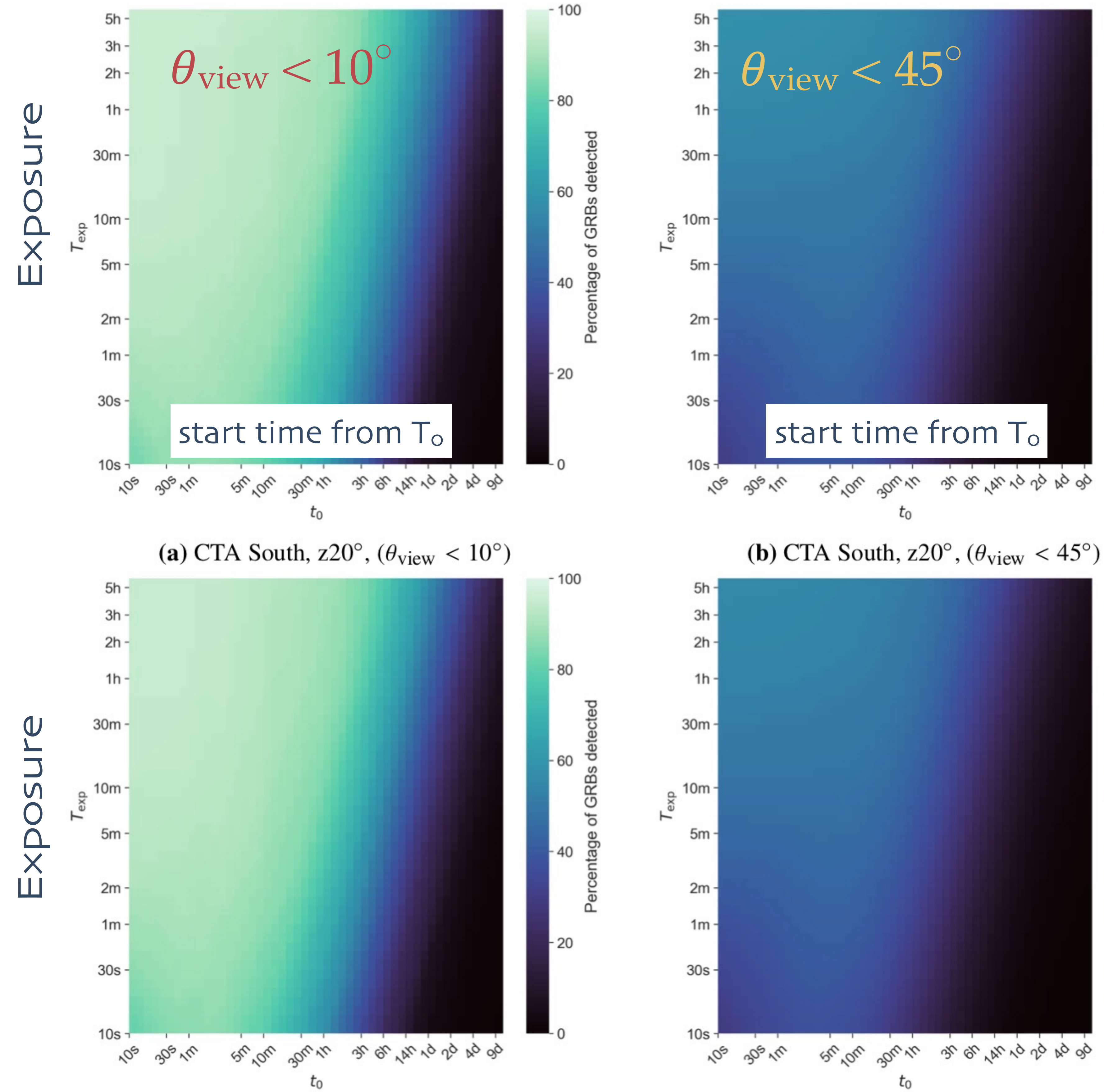
Detectability vs exposure time and start time

Viewing angle <10 deg (on-axis)

- for t_0~30s, ~94% of the GRBs can be detected with T_{exp}≤30 minutes
- for t_0~10min, ~92% of the GRBs can be detected with T_{exp}~few hours

Viewing angle <45 deg

- for t_0~30s, ~52% of the GRBs can be detected with T_{exp}≤30 minutes
- for t_0~10min, ~54% of the GRBs can be detected with T_{exp}~few hours



(a) CTA South, z20°, ($\theta_{view} < 10^\circ$)

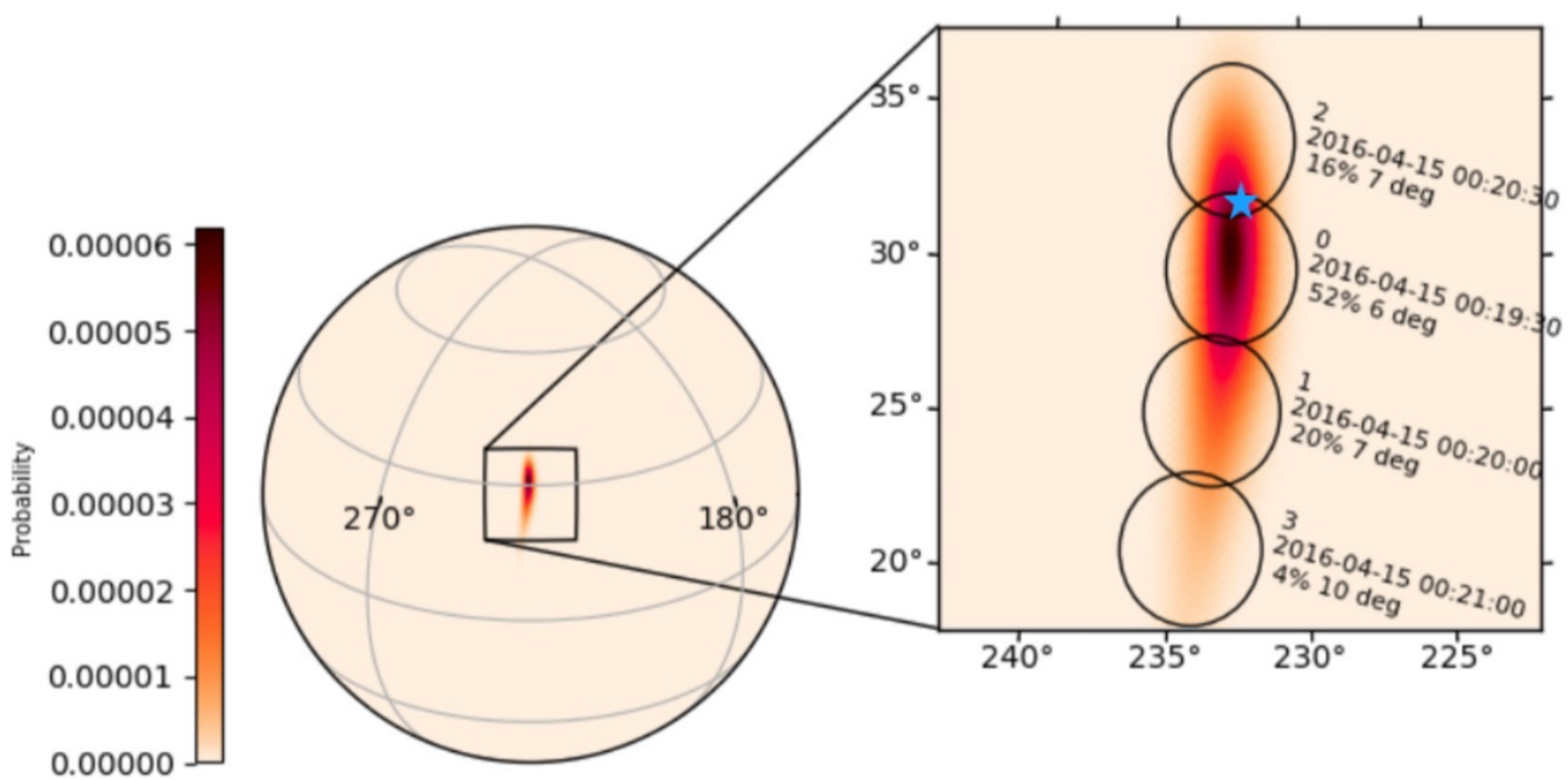
(b) CTA South, z20°, ($\theta_{view} < 45^\circ$)

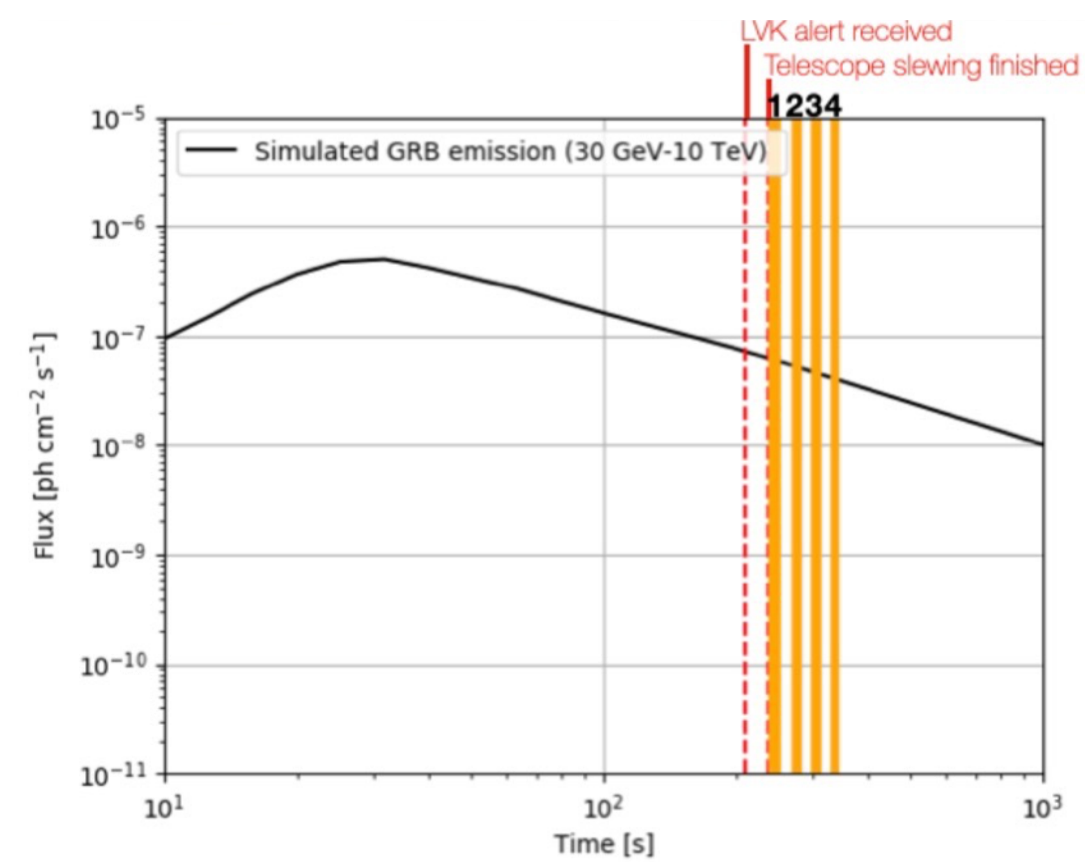
(c) CTA North, z20°, ($\theta_{view} < 10^\circ$)

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

future: the prospects for the GW-followup at VHE

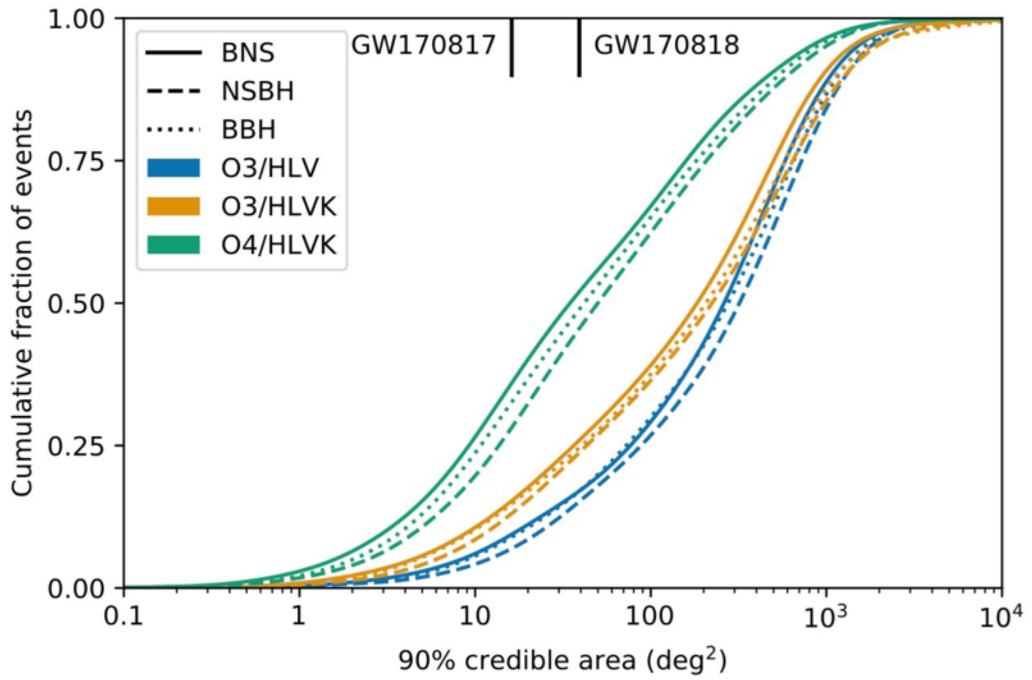
- **Scheduler** optimising observing conditions, site, sky position, and their evolution
- determine set of pointings maximising the probability in the FoV (with or without galaxies)
- determine the best integration time according to a given assumed model and off-axis angle
- A test case
  - $E_{iso} \sim 4 \times 10^{50}$ erg;
  - t_0: 210 s (3+0.5min); inter-slewing time: 20 s
  - scheduler: 4 tiles, ~90 % GW-region(~ 40 deg^2) in just 2 minutes after t_0

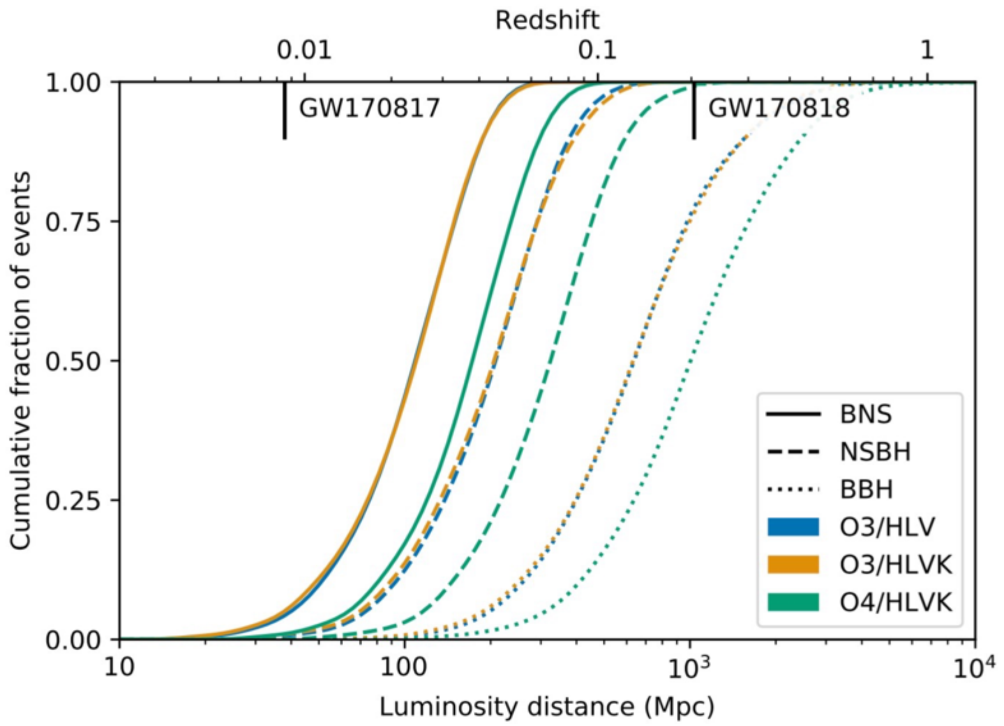




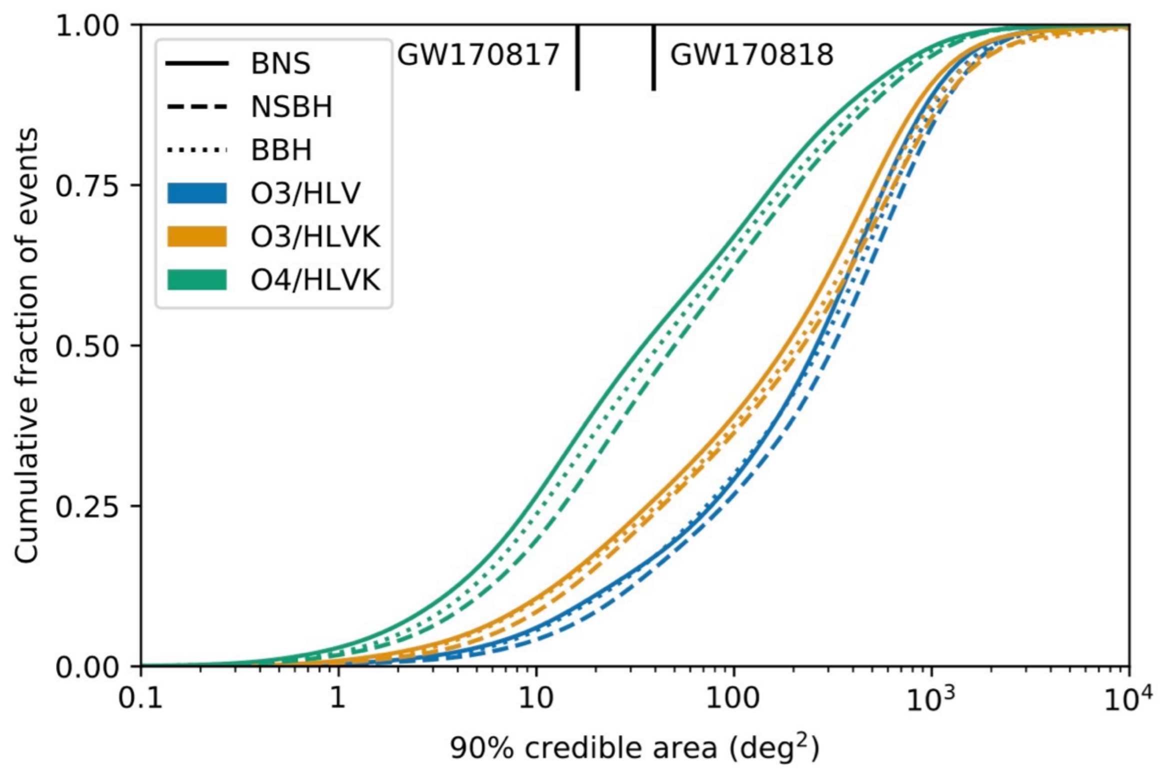
Conclusions and overview

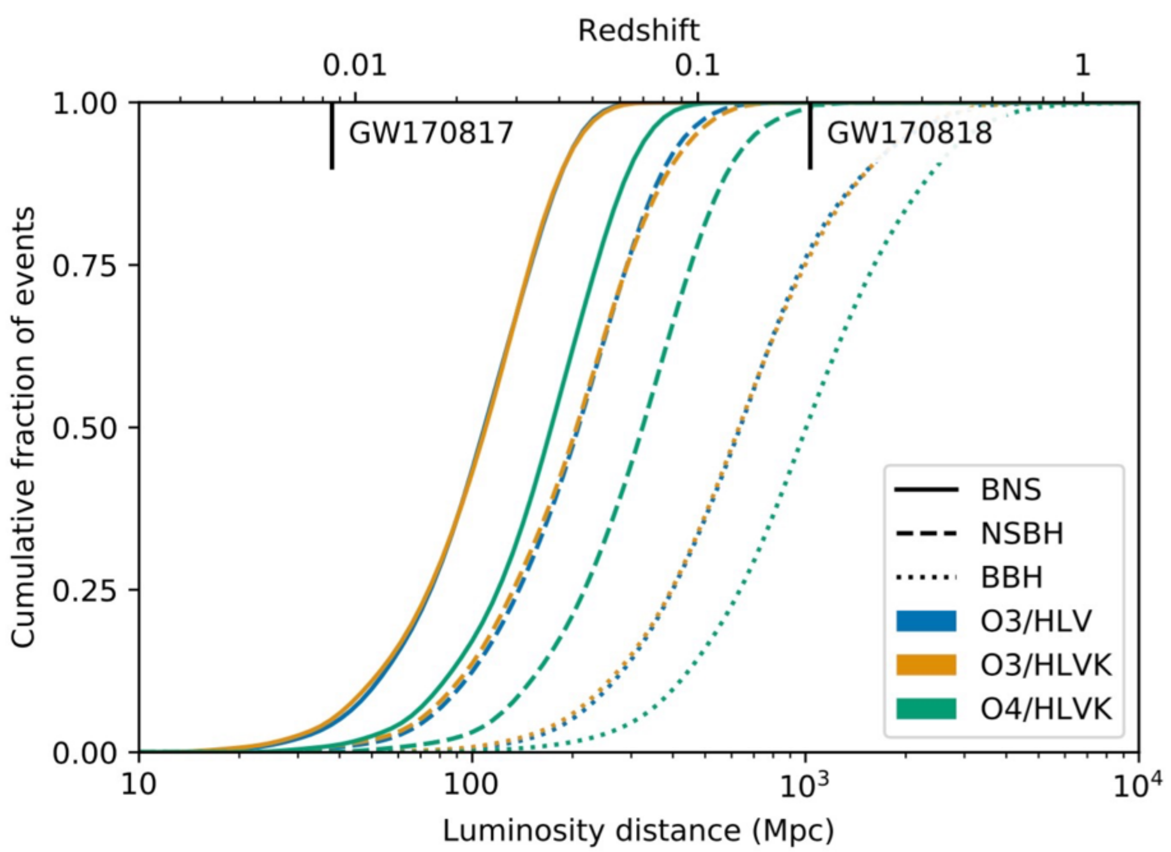
- Counterparts at VHE-TeV energies of GW events (BNS, BH-NS, CCSN) are the next frontier of gamma-ray/multimessenger astronomy
  - VHE emission provides a new insight in transient and multimessenger phenomena
    - new component in GRB emission; constraints on hadronic emission
- IACT demonstrated to be ideal transient factories in the multi messenger era
  - big effective area, sensitivity
  - fast reaction
  - dedicated GRB, neutrino and GW follow-up programs
- CTA is sensitive is sensitive enough to detect both on-axis and off-axis GRBs with time delay up to ~ 10 minutes
  - work in progress
- Next scientific run 04 (present IACTs) and O5 (CTA) will pose great challenges in selecting, scheduling an optimising the GW follow-ups.





Expected rates in O4

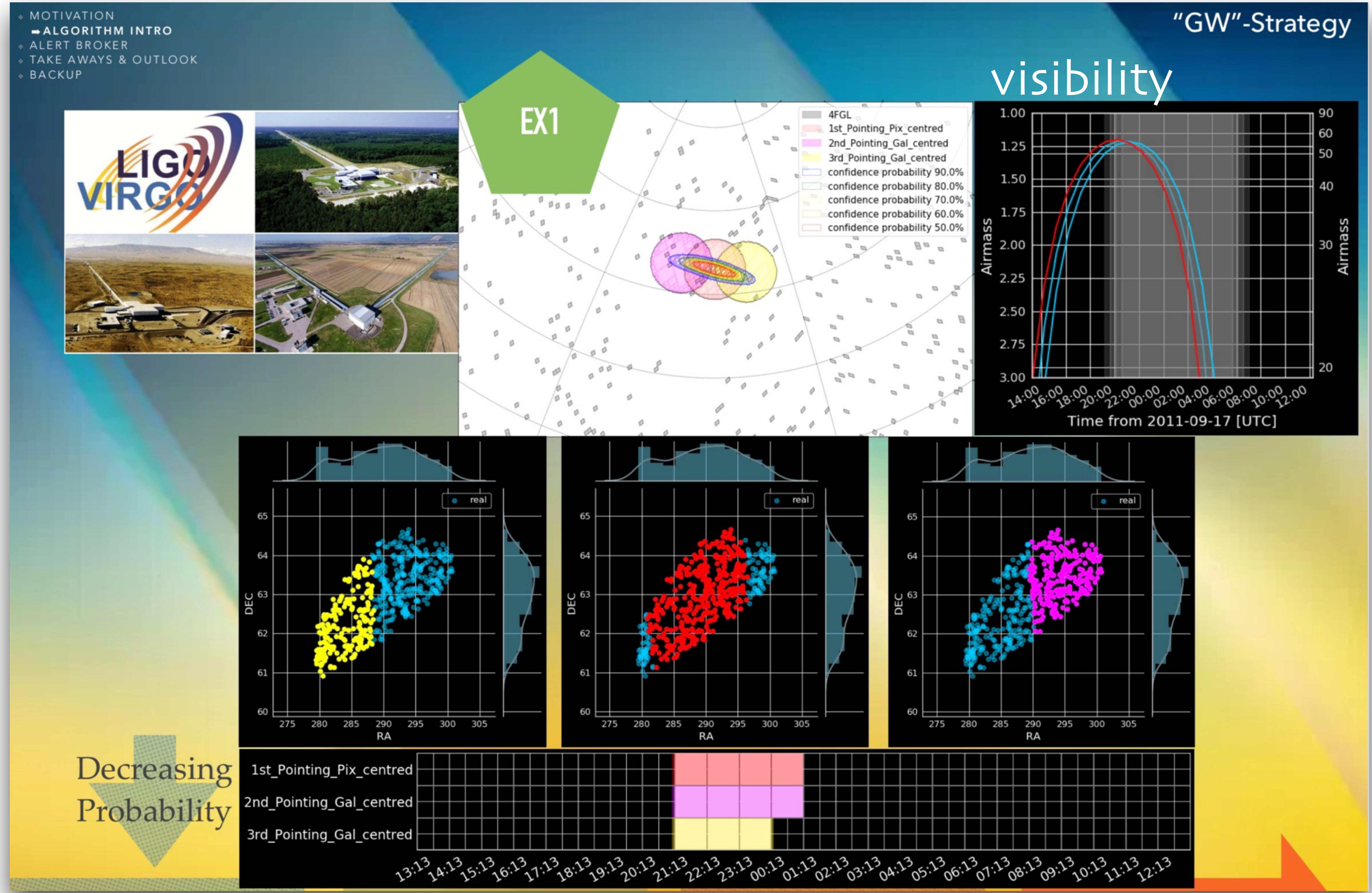




Observation Run	Network	Expected BNS Detections	Expected NSBH Detections	Expected BBH Detections
O3	HLV	1^{+12}_{-1}	0^{+19}_{-0}	17^{+22}_{-11}
O4	HLVK	10^{+52}_{-10}	1^{+91}_{-1}	79^{+89}_{-44}
		Area (deg^2) 90% c.r.	Area (deg^2) 90% c.r.	Area (deg^2) 90% c.r.
O3	HLV	270^{+34}_{-20}	330^{+24}_{-31}	280^{+30}_{-23}
O4	HLVK	33^{+5}_{-5}	50^{+8}_{-8}	41^{+7}_{-6}
		Comoving Volume (10^3 Mpc^3) 90% c.r.	Comoving Volume (10^3 Mpc^3) 90% c.r.	Comoving Volume (10^3 Mpc^3) 90% c.r.
O3	HLV	120^{+19}_{-24}	860^{+150}_{-150}	16000^{+2200}_{-2500}
O4	HLVK	52^{+10}_{-9}	430^{+100}_{-78}	7700^{+1500}_{-920}

Chasing the VHE counterpart of GW: strategies and optimisation

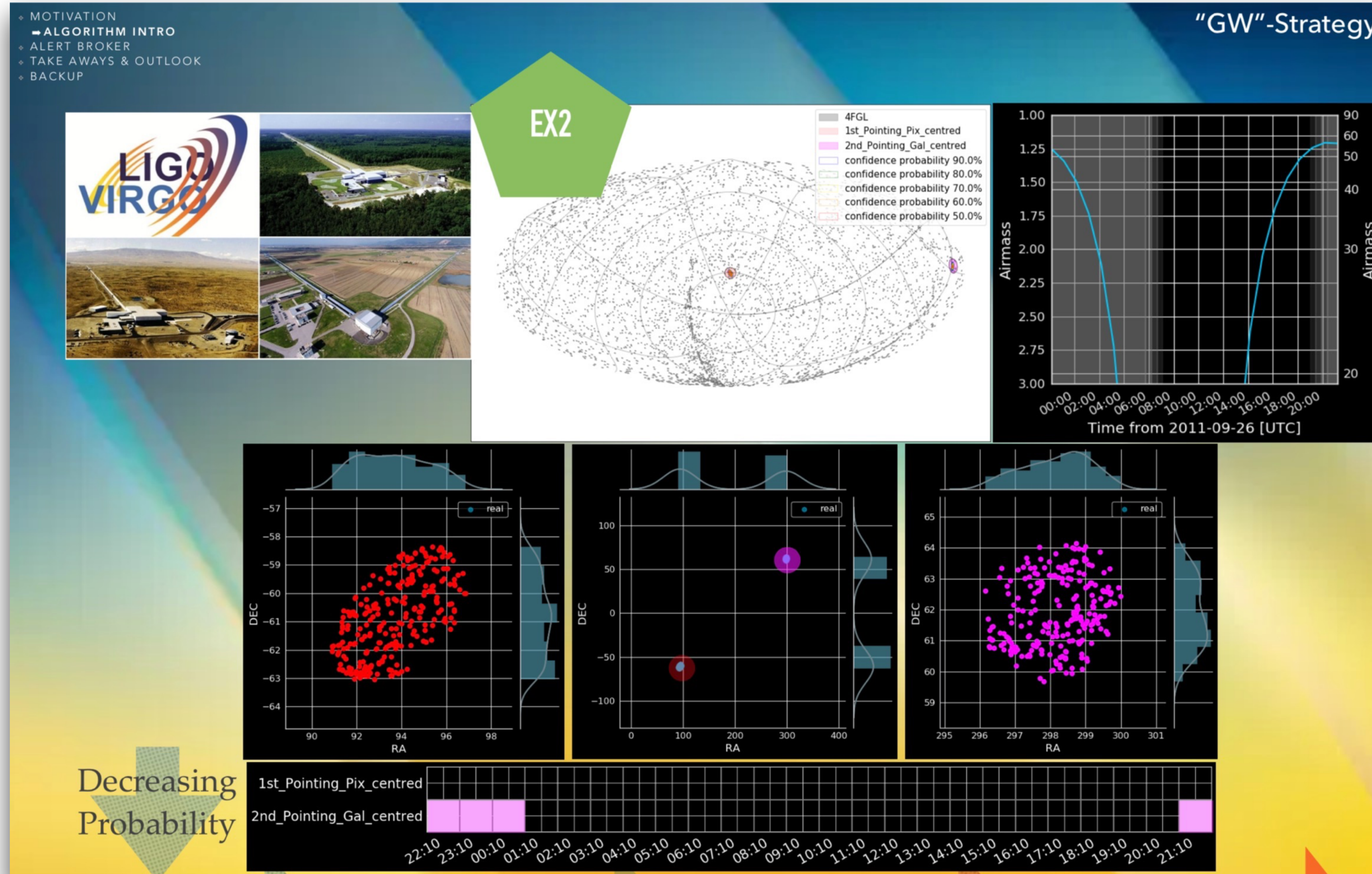
MAGIC - scheduling *(credits:Manuel Artero)*



Chasing the VHE counterpart of GW: strategies and optimisation

MAGIC - scheduling

(credits:Manuel Artero)



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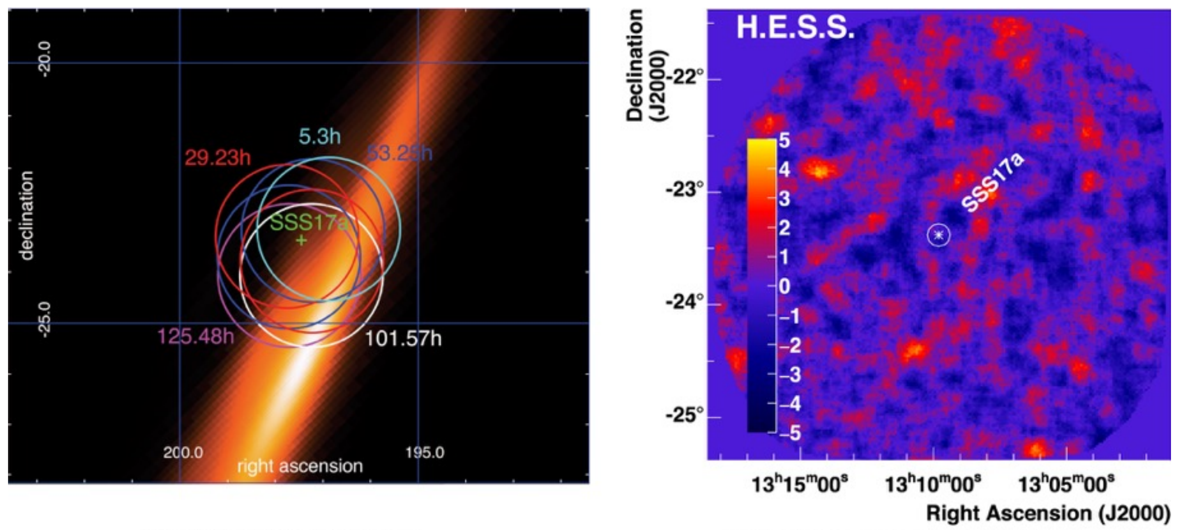
- First ground telescope to point to the source location (NGC4993)



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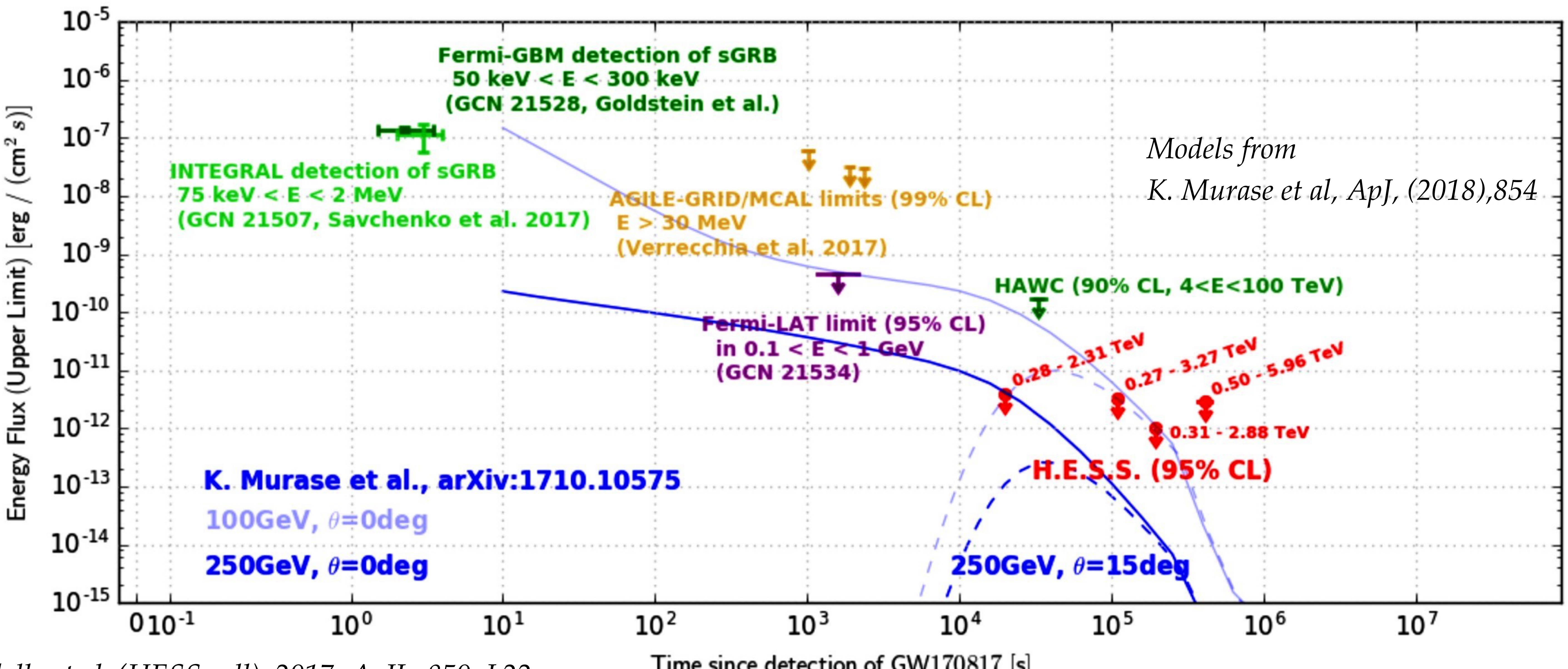
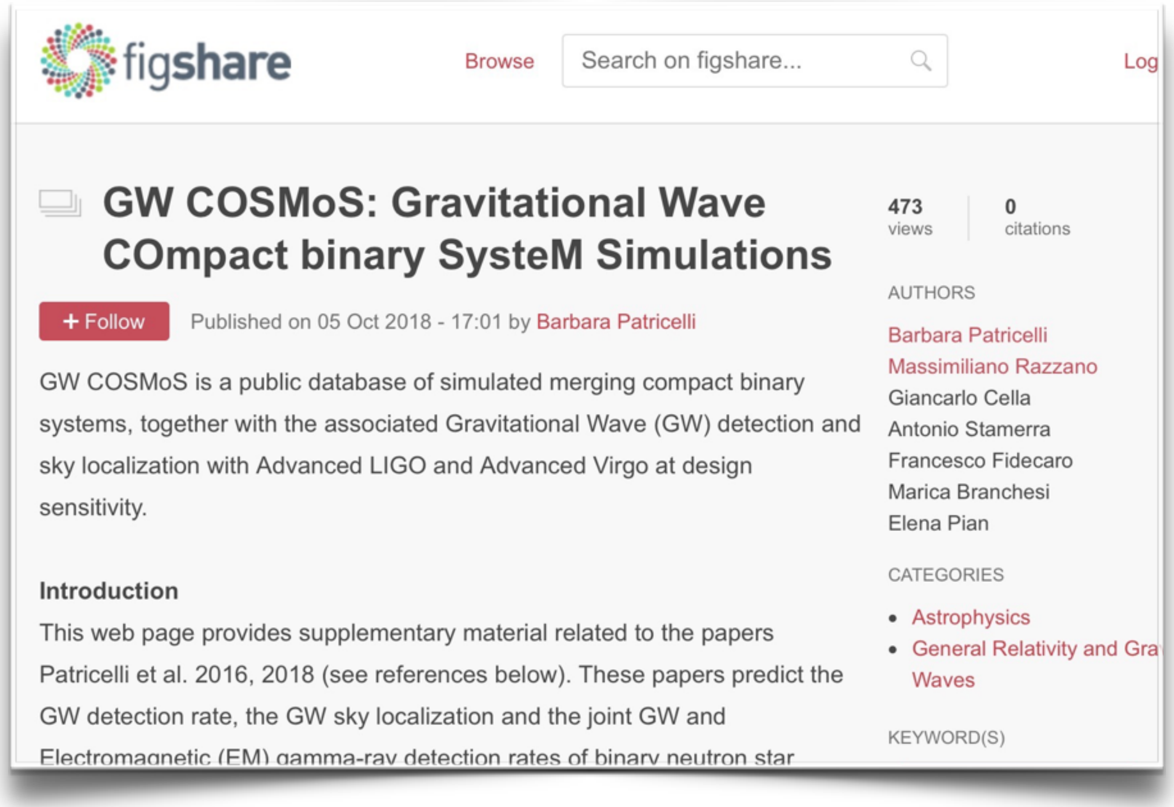


Models from K. Murase et al, ApJ, (2018),854

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

The GW module

- GW COSMoS: simulated merging compact binary systems (BNS), together with the GW detection and sky localization with Advanced LIGO and Advanced Virgo
    - OUTPUT: 2D GW skymaps, RA, Dec, Distance, inclination angle of the BNS
- 3D GW skymaps generated from 2D GW skymaps with the error on the distance of the GW detected sources (ongoing)
- Clumpiness: subsample using the GLADE galaxy catalogue (important to investigate galaxy targeted searches)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GW COSMoS: Gravitational Wave COmpact binary SysteM Simulations

473 views | 0 citations

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GW COSMoS is a public database of simulated merging compact binary systems, together with the associated Gravitational Wave (GW) detection and sky localization with Advanced LIGO and Advanced Virgo at design sensitivity.

Introduction

This web page provides supplementary material related to the papers Patricelli et al. 2016, 2018 (see references below). These papers predict the GW detection rate, the GW sky localization and the joint GW and Electromagnetic (EM) gamma-ray detection rates of binary neutron star

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Marica Branchesi
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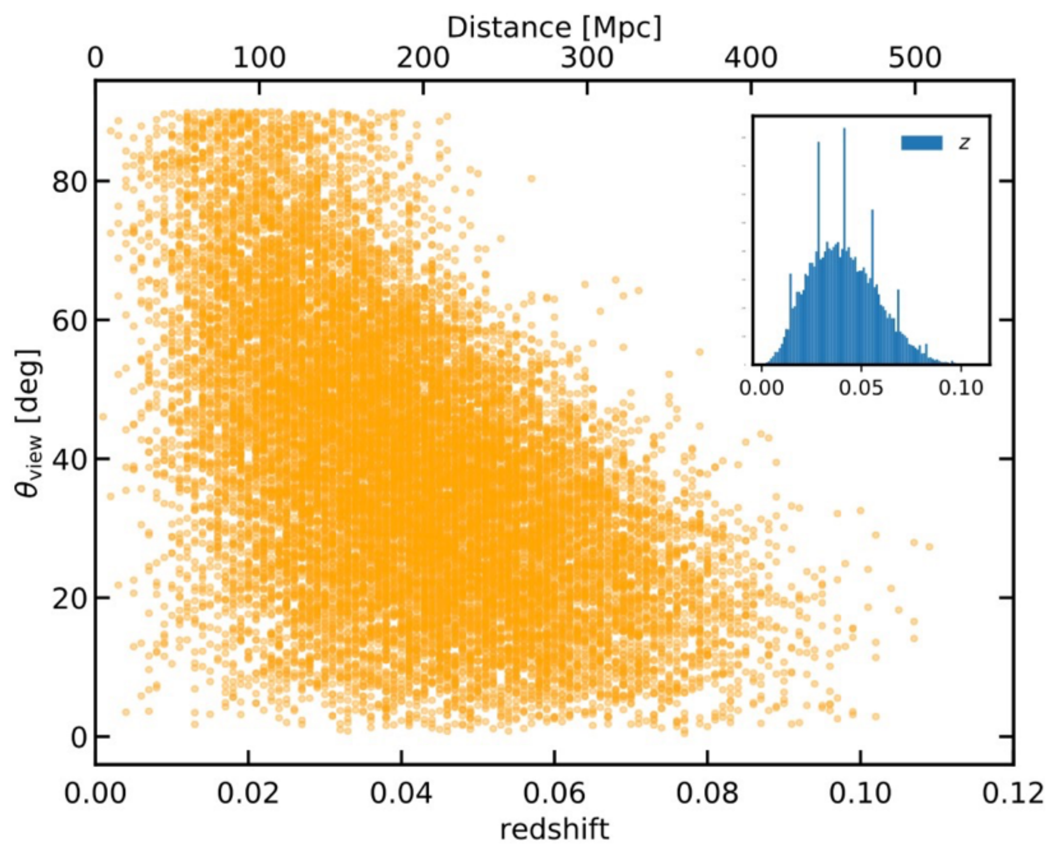
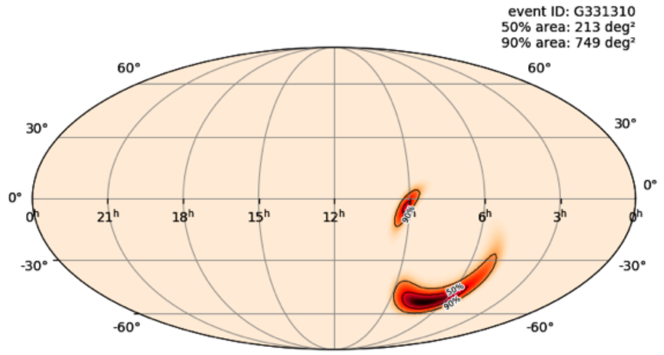
CATEGORIES

- Astrophysics
- General Relativity and Gra[vitational] Waves

KEYWORD(S)

https://doi.org/10.6084/m9.figshare.c.4243595

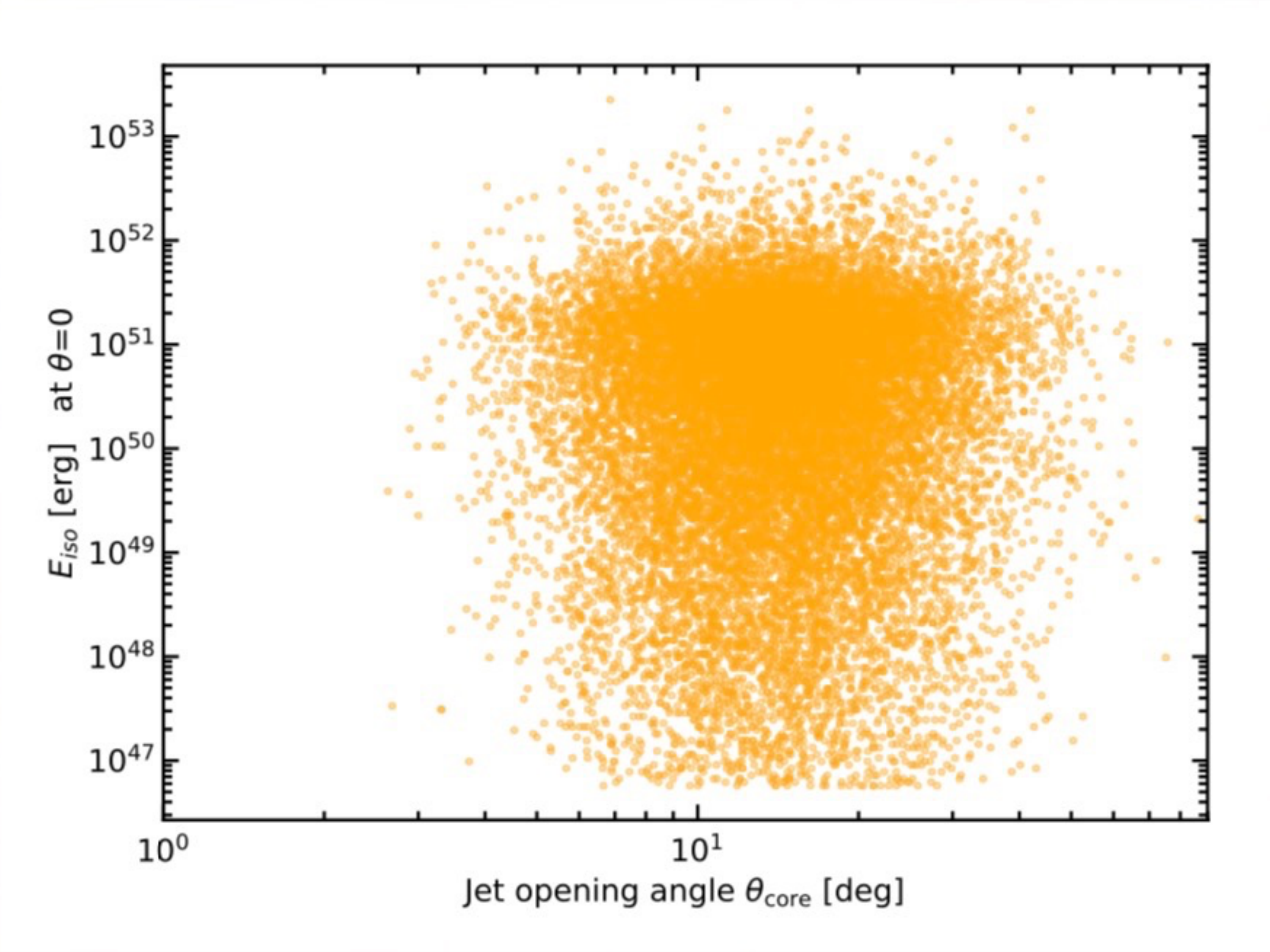




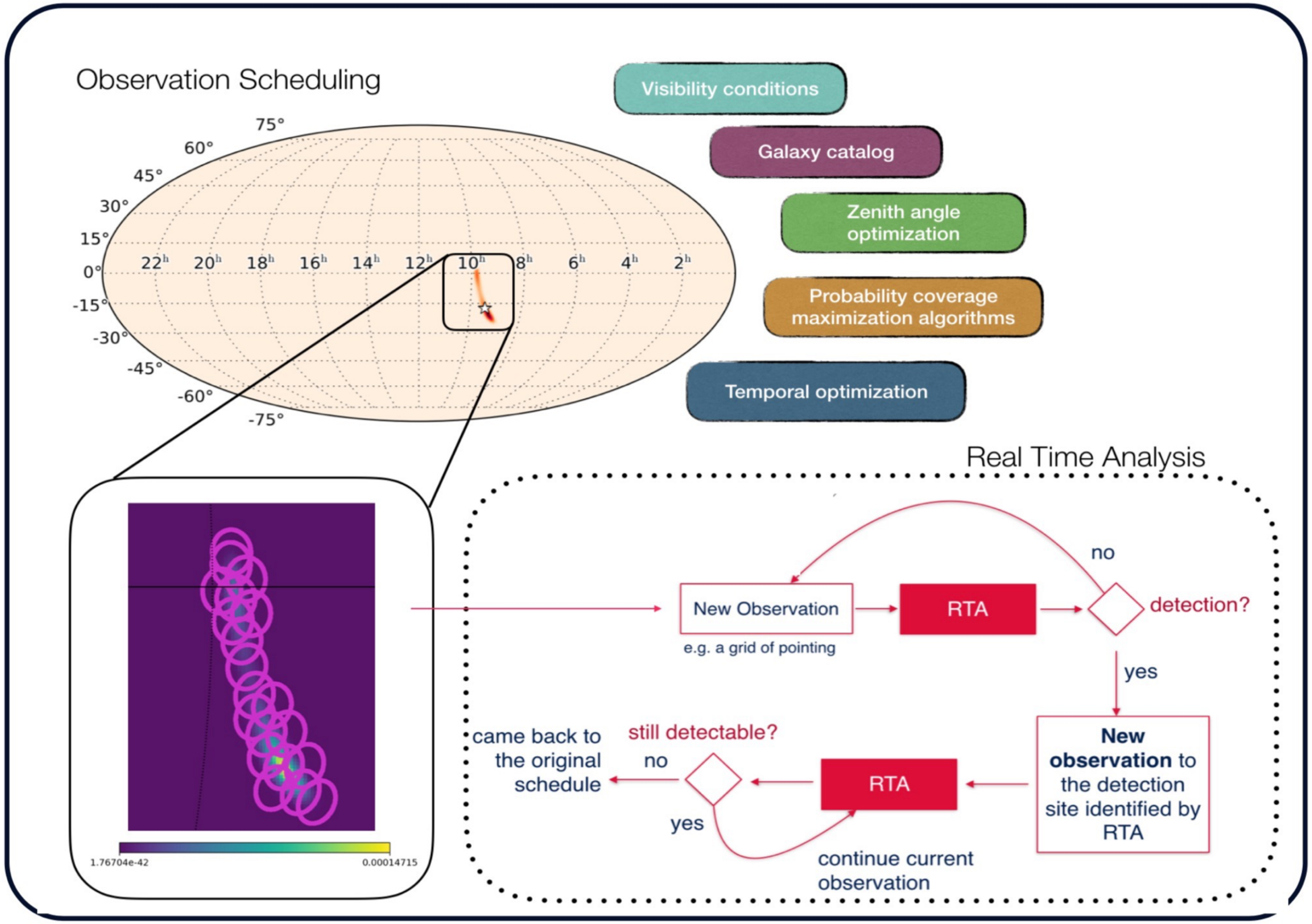
future: the prospects for the GW-followup at VHE

We assume that all BNS mergers are associated to a short GRB with VHE emission, simulated with an empirical approach

- E_{iso}: distribution inferred from short GRB observations (Ghirlanda et al. 2016)
- Structured (gaussian) jet
- θ_{core}: distribution inferred from short GRB observations (Fong et al. 2015)
- θ_{view}: it is given by the inclination of the BNS systems
- Light curve modeled taking into account the X-ray afterglows of short GRBs and the recent GRB detections at VHE
- Spectrum: power-law with photon index ~-2.2 (consistent with GRB 190114C)



The scheduler and optimisation module



Simulation of BNS and GW detection

BNS mergers

- **$\rho_{galaxies}$=0.0116 Mpc^{-3}** *(Kopparapu et al. 2008)*
- **Maximum distance: 500 Mpc**
- **Merging systems: Synthetic Universe**[1] *(Dominik et al. 2012)*
- **Bimodal distribution in metallicity: half at $Z=Z_{\odot}$ and half at $Z=0.1\cdot Z_{\odot}$** *(Panter et al. 2008)*
- **Merger rate: 830 Gpc^{-3}yr^{-1} (within the range in** *Abbott et al. 2017***)**

GW emission and detection

- **Non spinning systems; TaylorT4 waveforms** *(Buonanno et al. 2009)*
- **Matched filtering technique** *(Wainstein 1962)*
- **aLIGO and AdV at design sensitivity, with 80 % independent duty cycle** *(Abbott et al. 2016)*
- **Trigger: at least 2 detectors; combined SNR threshold: 12**
- **GW localization with BAYESTAR** *(Singer et al. 2014)*

Patricelli et al., JCAP 11, 056 (2016)

Simulation of GRB emission with CTA

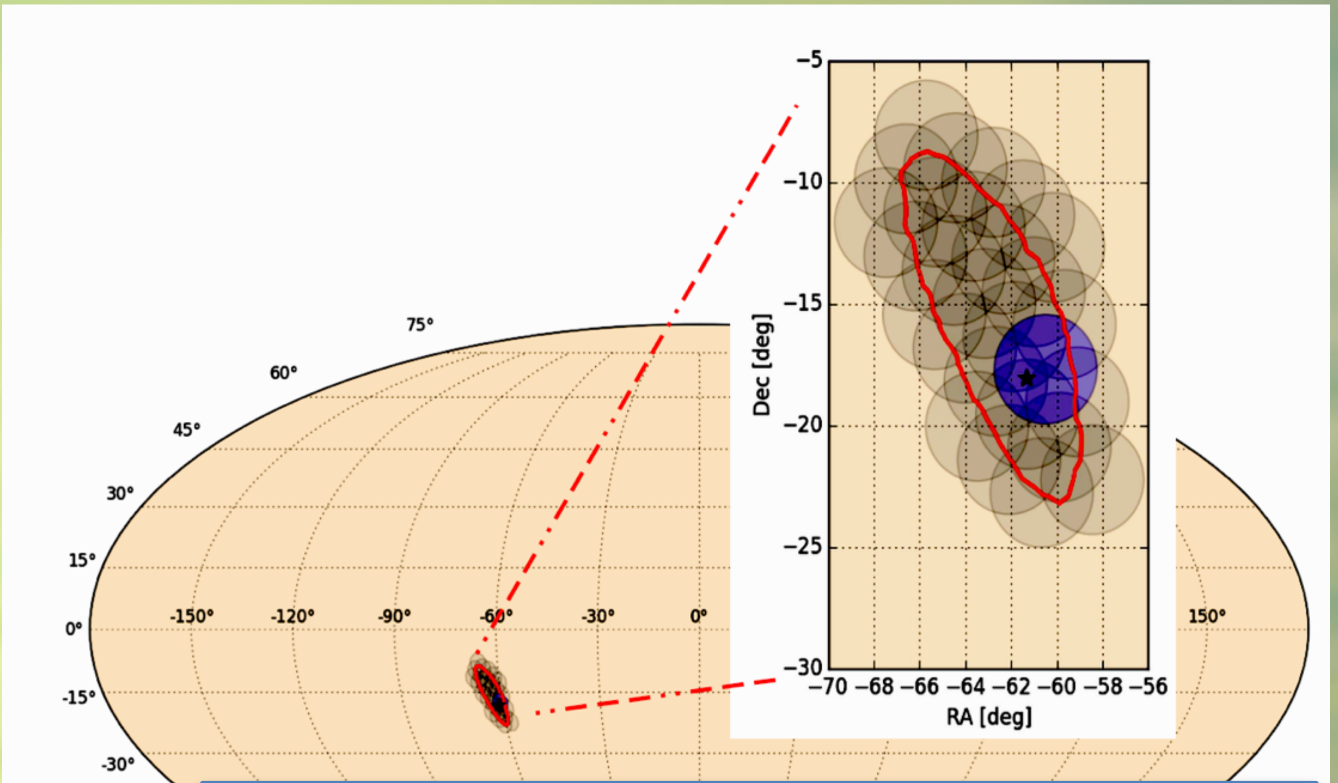
Observation time:

Latency to send the GW alert t_l=3 minutes; slewing time t_{slew}=30 s

Sensitivity:

CTA response functions of baseline configurations; ctools package

Duty cycle of ~ 10 %



SNR=18; 90 % C.R.~ 56 deg2

E_{ISO} = 10^{51} ergs; $E_{cut-off}$ =100 GeV

Patricelli, AS et al. 2018 JCAP 05(2018)056.

(http://cta.irap.omp.eu/ctools/; in this work we used the ctools version 1.4.0)

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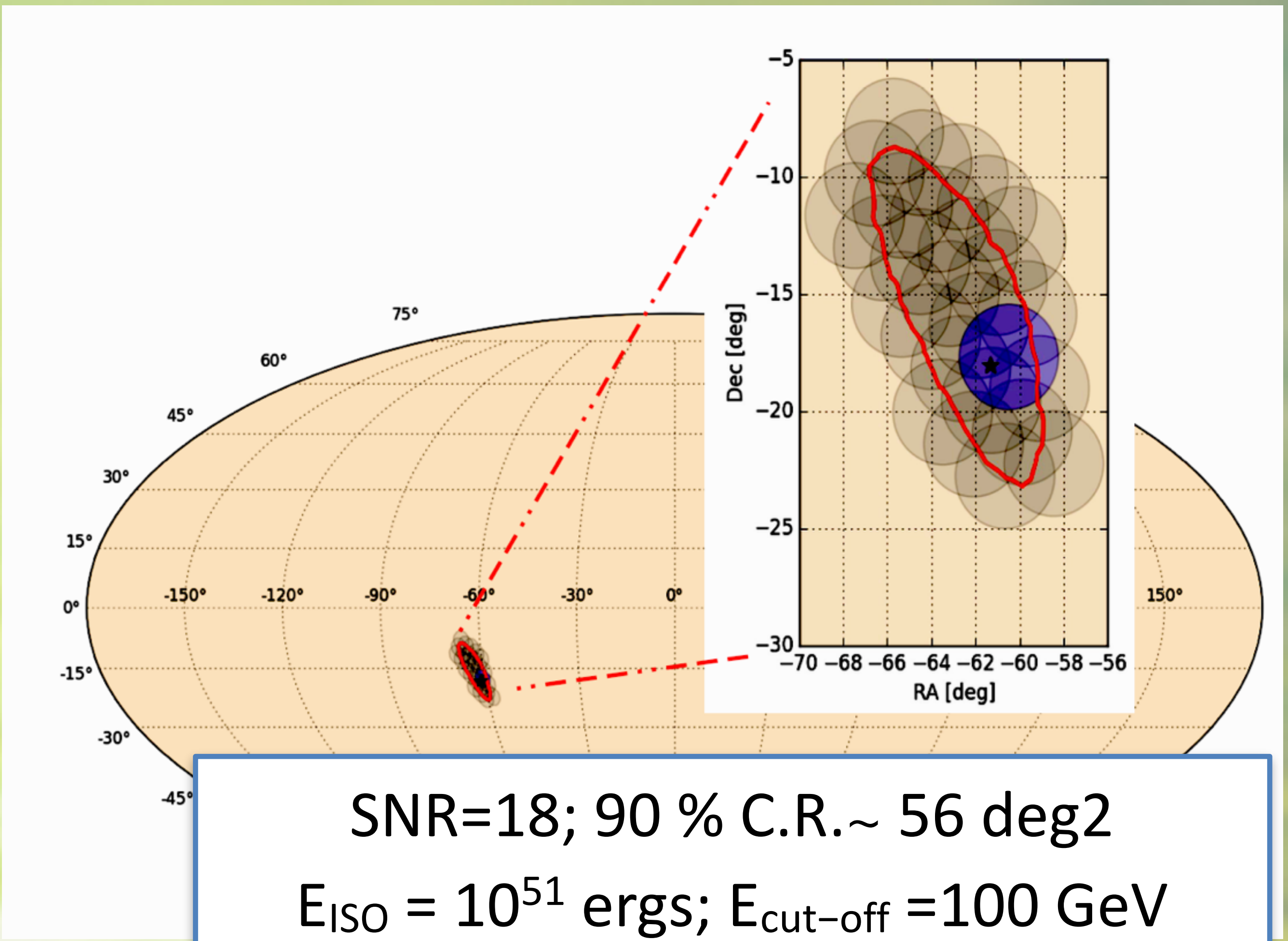
CTA Detection:

A source is detected if located within a maximum displacement of 1 deg with respect to the pointing coordinate



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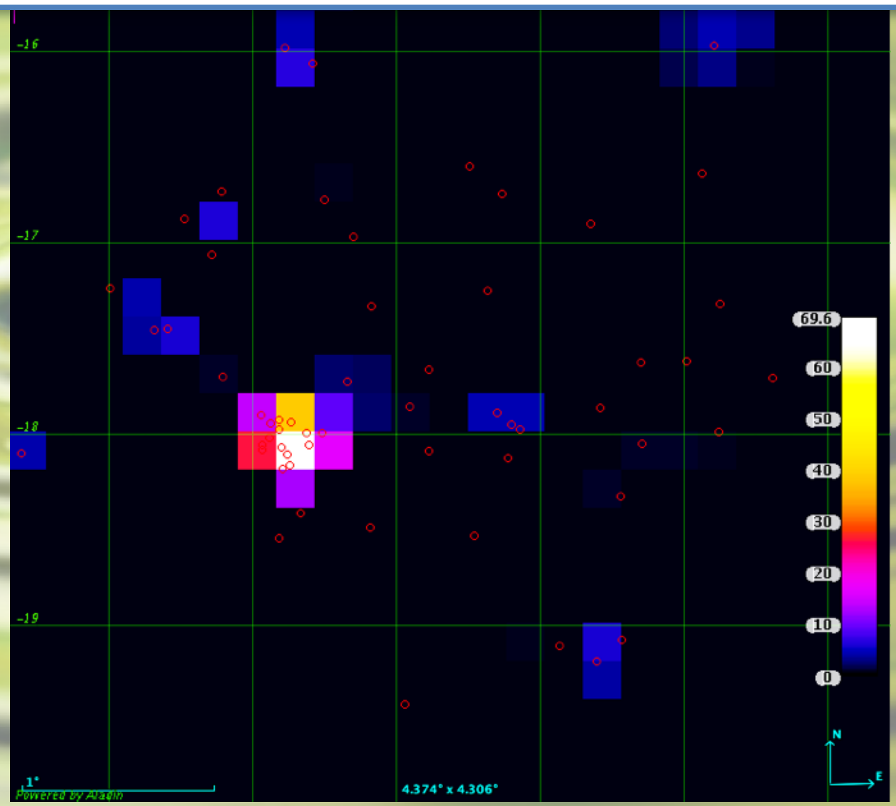

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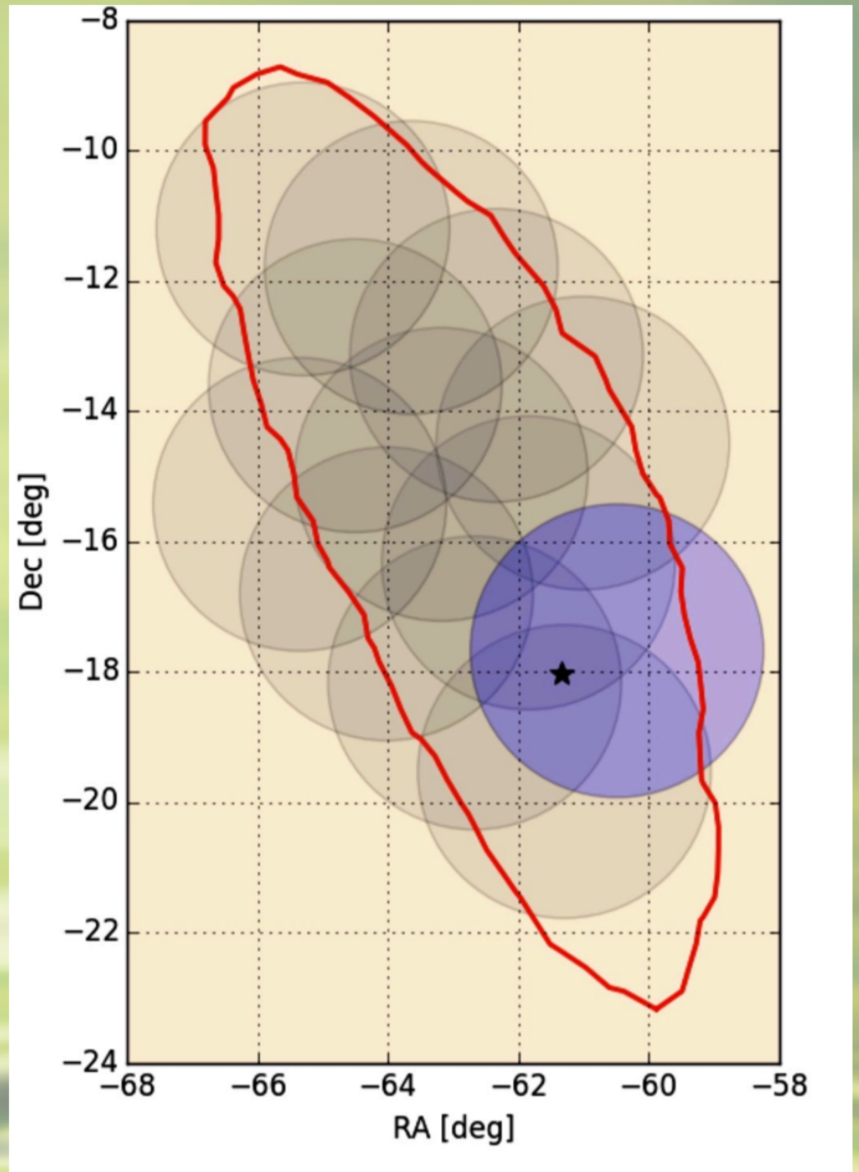


SNR=18; 50 % C.R.~ 56 deg2

E_{ISO} = 10^{50} ergs; $E_{cut-off}$ =100 GeV

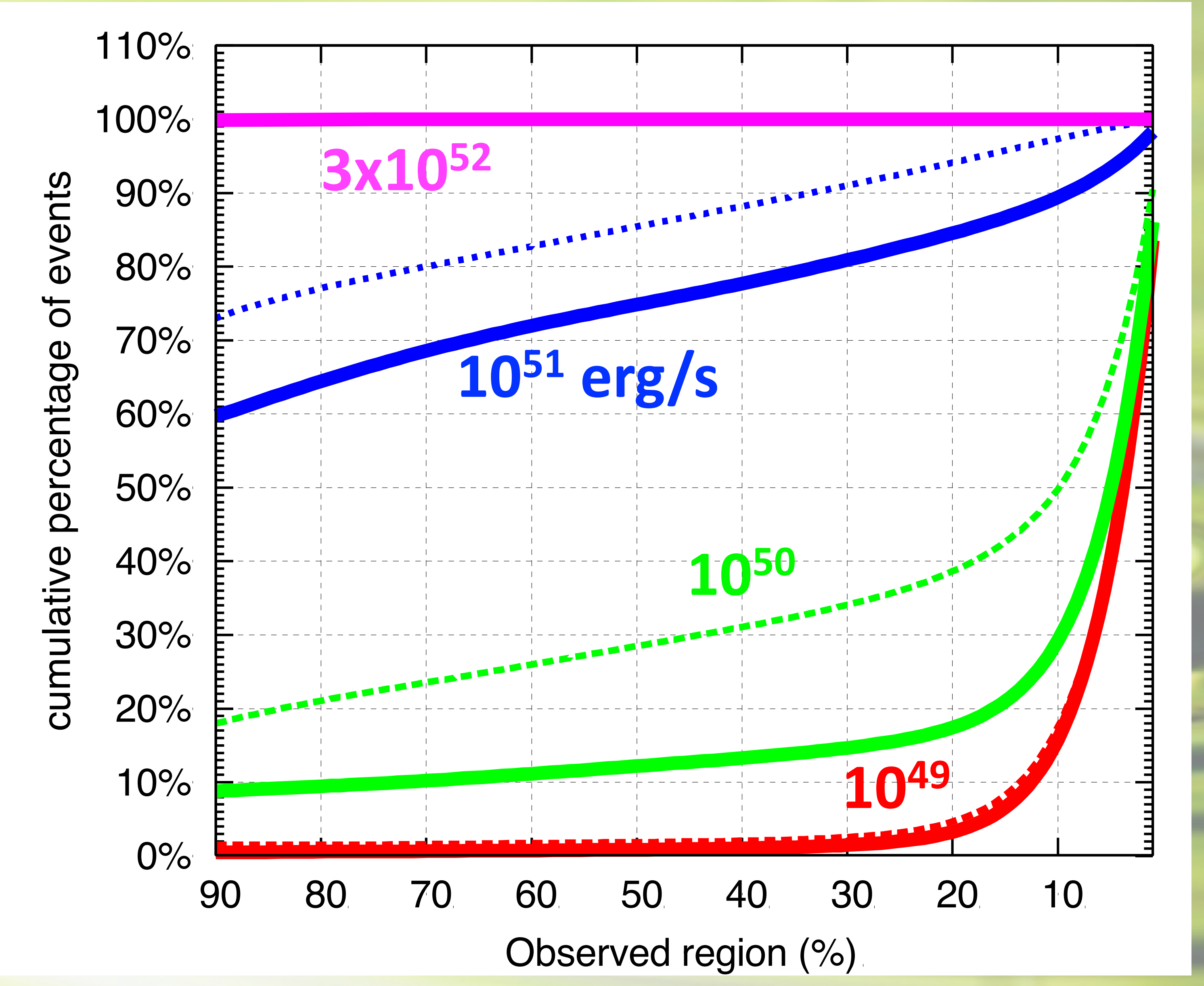
Patricelli, AS et al. 2018 JCAP 05(2018)056.

(http://cta.irap.omp.eu/ctools/; in this work we used the ctools version 1.4.0)

GW-CTA BNS joint rates

- **Coverage** of detectable BNS mergers
- Expected rate up to **0.08 yr^{-1}** for most luminous GRB

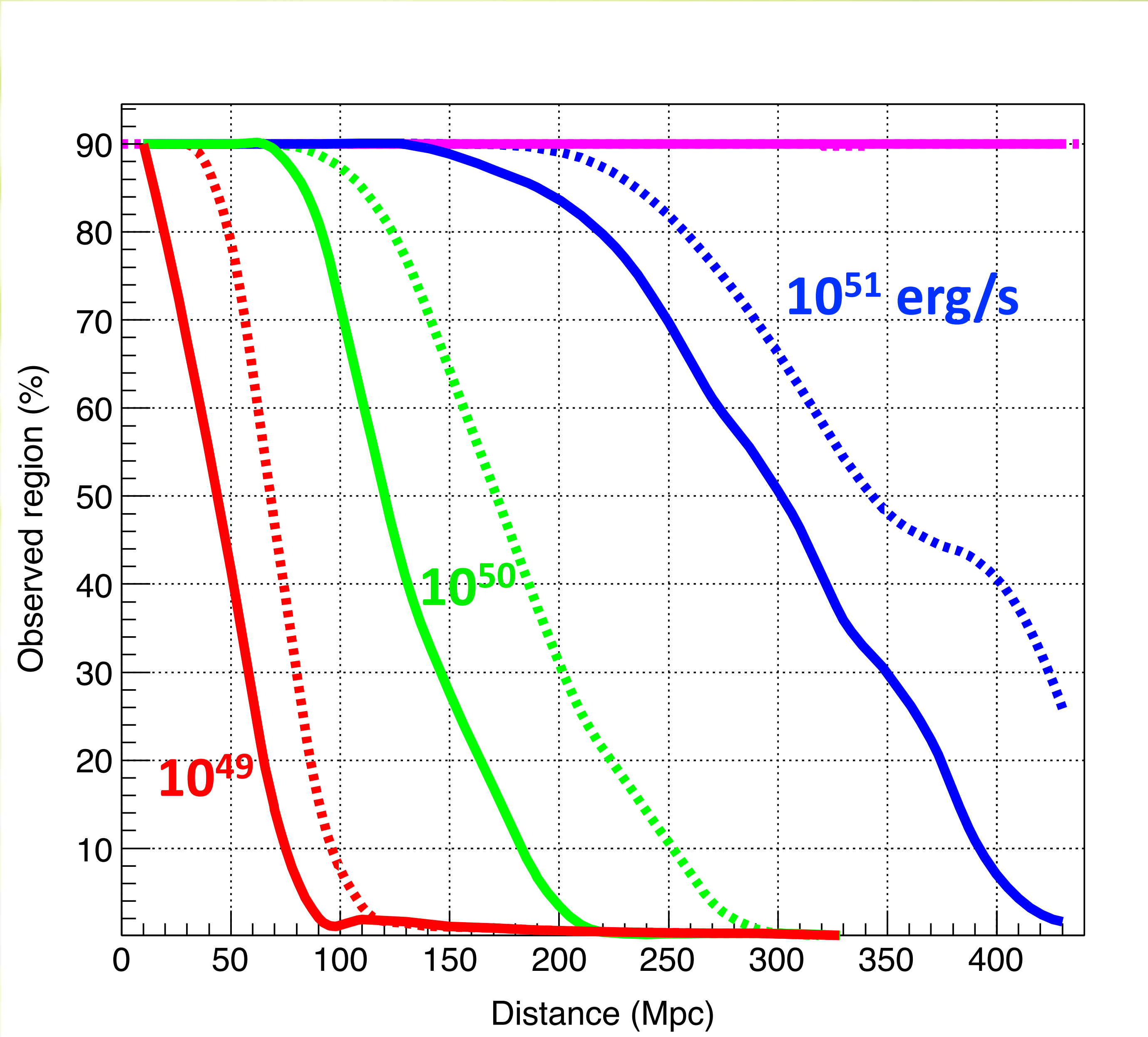
coverage



GW-CTA BNS joint rates

- **Max distance** of detectable BNS mergers
- Expected rate up to **0.08 yr^{-1}** for most luminous GRB

Distance



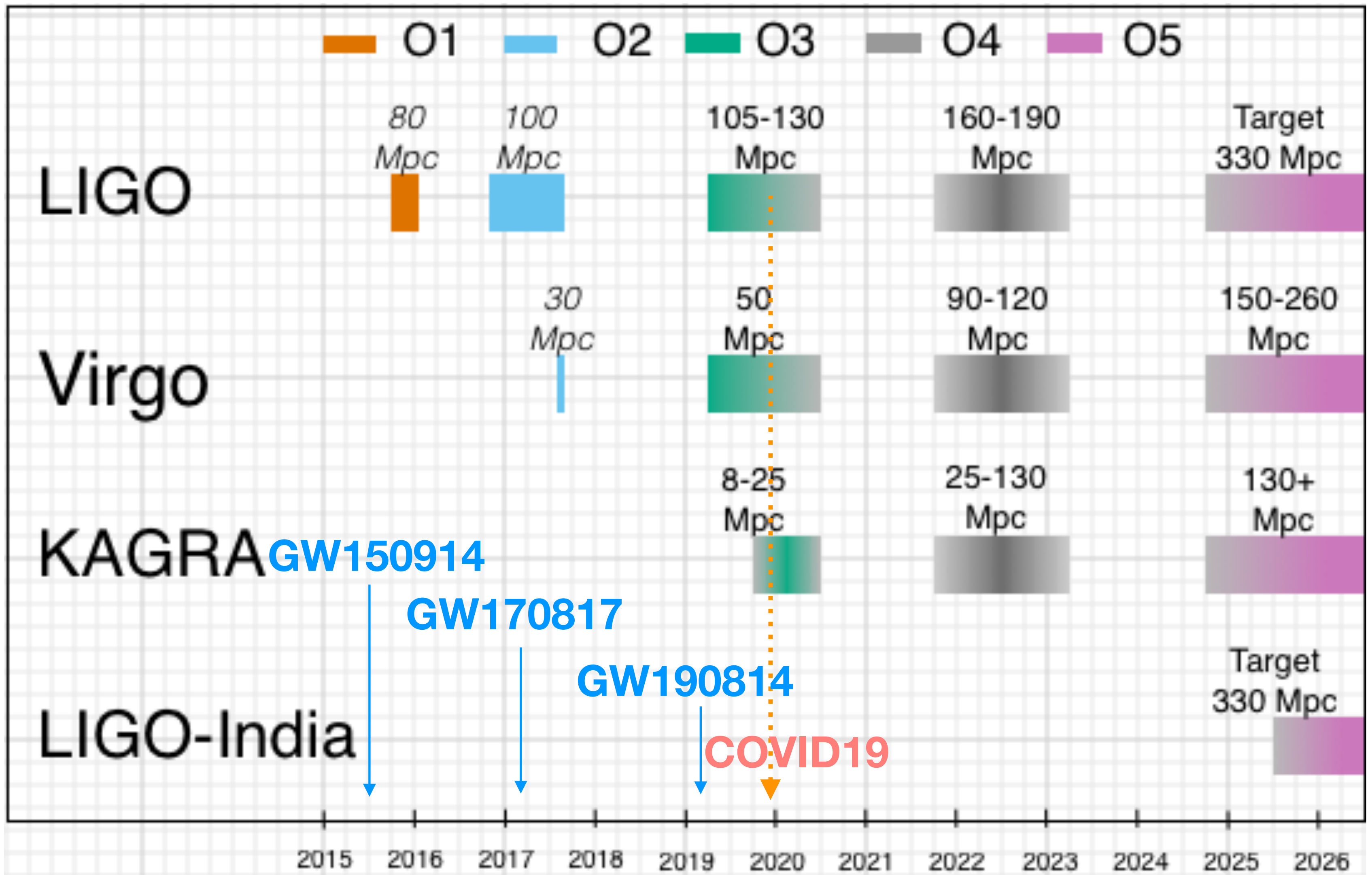
rates

E_{iso} (ergs)	cut-off (GeV)	EM and GW (yr^{-1})
10^{49}	30	$< 10^{-3}$
	100	0.001
10^{50}	30	0.01
	100	0.03
10^{51}	30	0.06
	100	0.07
3.5×10^{52}	30	0.08
	100	0.08

GW detector timeline - scientific runs

- Run 01 (2x LIGO)
  Sept 2015 - Jan. 2016
  First GW (BH-BH) event!
- Run 02 (LIGO + VIRGO)
  2016-2017; 6 months; VIrgo: Aug2017
  First e.m. counterpart of BNS merger!
- Run 03 (LIGO + VIRGO) -advanced phase
  February 2019; 1 year - O3a / O3b
  First NS-BH events!
  March 27th: stop due to COVID19... (O3c?)
- Run O4 - (LIGO+VIRGO+KAGRA)
  exp. January 2022
- Run O5 - AdV+ phase (LIGO+VIRGO+KAGRA + LIGO-India)
  2024/2025-2026

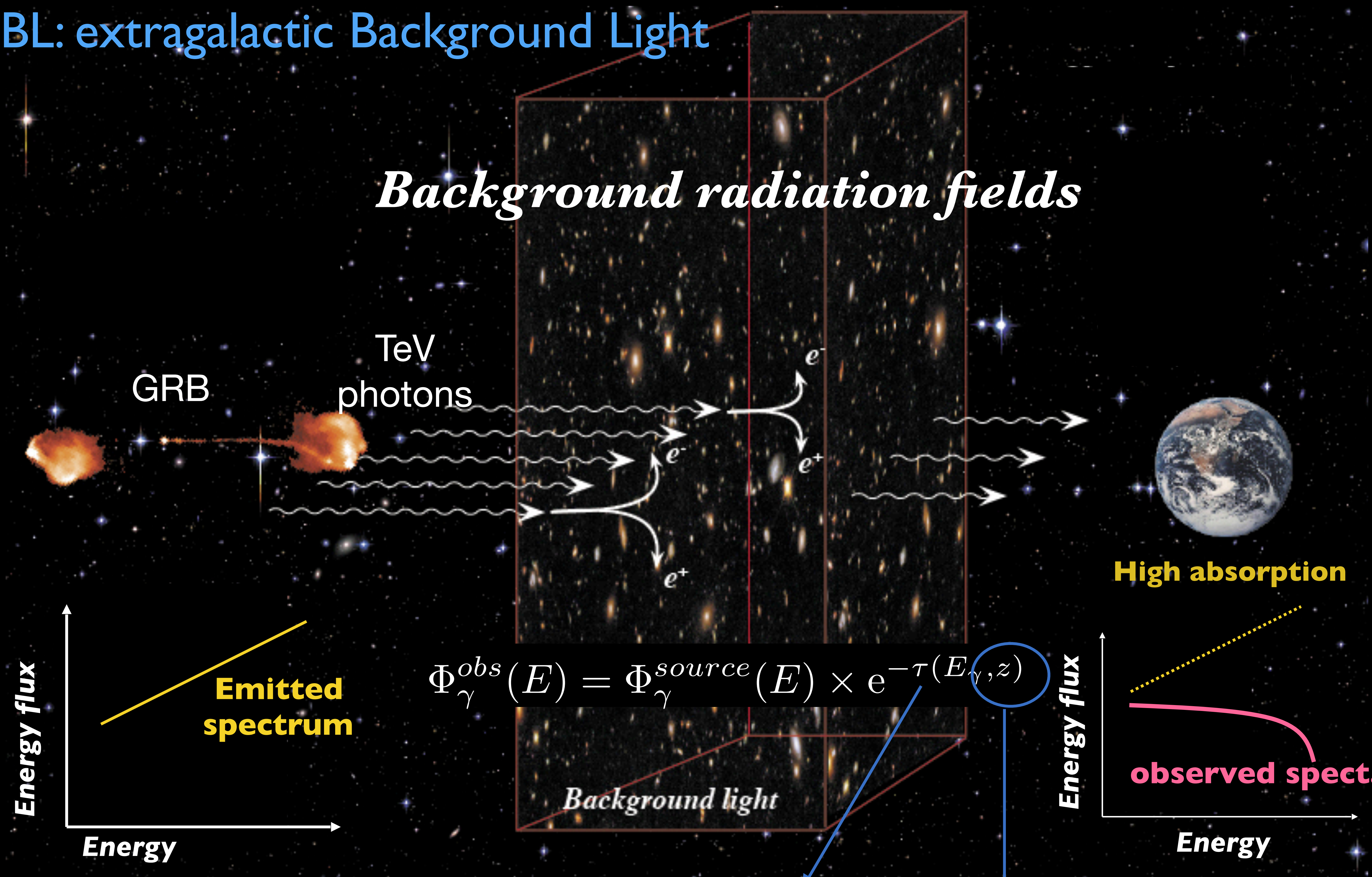
https://www.ligo.org/scientists/GWEMalerts.php



https://arxiv.org/pdf/1304.0670.pdf

EBL absorption of TeV photons

EBL: extragalactic Background Light



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

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