「高エネルギーガンマ線でみる極限宇宙2021」

The extreme Universe viewed in very-high-energy gamma rays 2021

GRB detection with the Cherenkov Telescope Array

Preliminary results

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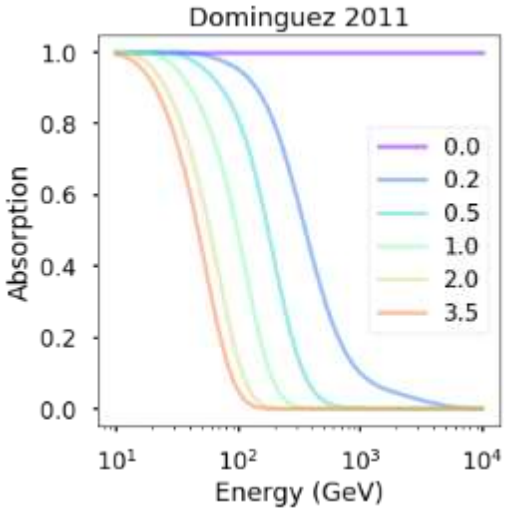
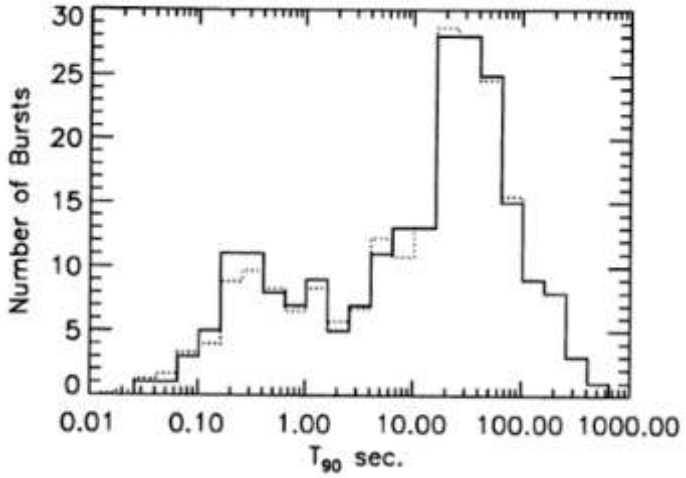
This work was conducted in the context of the CTA Consortium. We gratefully acknowledge financial support from the agencies and organizations listed here: http://www.cta-observatory.org/consortium_acknowledgments

GRB detection rates with CTA

- **Strategy : external alert and LSTs**
  - Fast repointing
    - Prompt 0.1–1000s; Afterglow in ~1/t
  - Get low E ⇐ EBL absorption (~100 GeV)
- **Present rates**
  - Inoue et al. 2013, ~ **a few yr^{-1}**
  - Since July 2018, 4 detected by IACT
    ⇒ ~ **1 yr^{-1}**
    - All long GRBs
    - No prompt detected
    - z < 1.1
- **How much will CTA do better ?**
  - First results with 1000 bright long GRBs
    - $P_{SWIFT}(15\text{–}150\ keV) > 2.6\ \gamma\ cm^{-2}\ s^{-1}$
  - <u>No Prompt simulated</u>



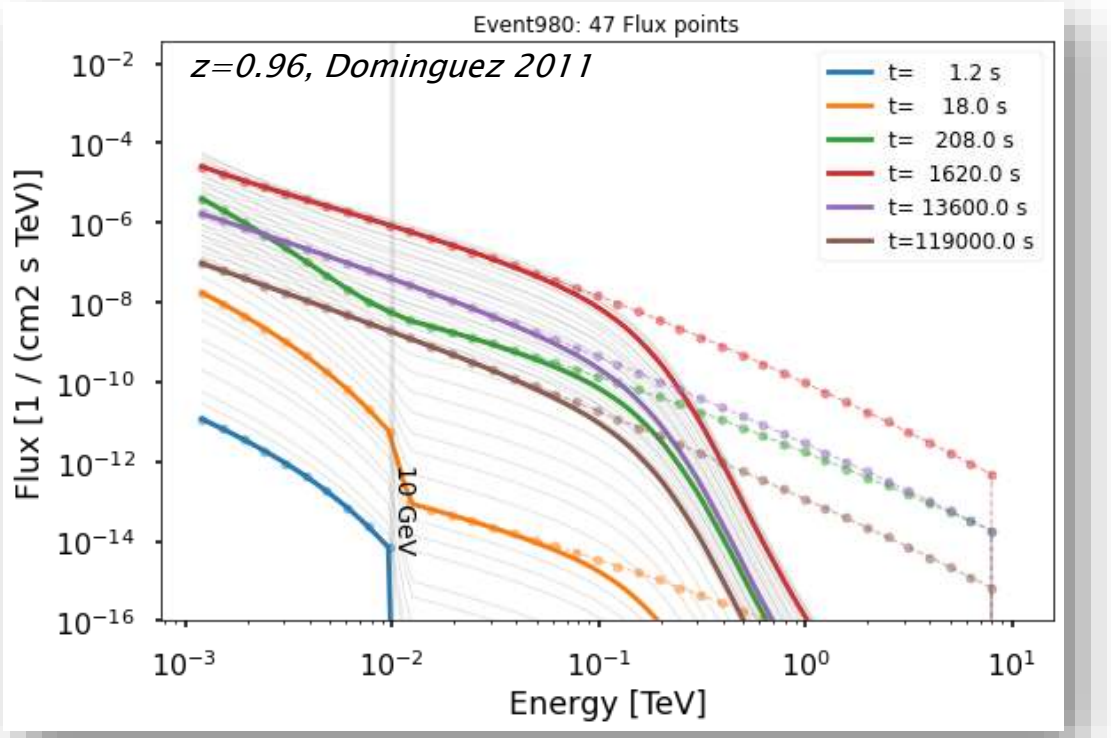


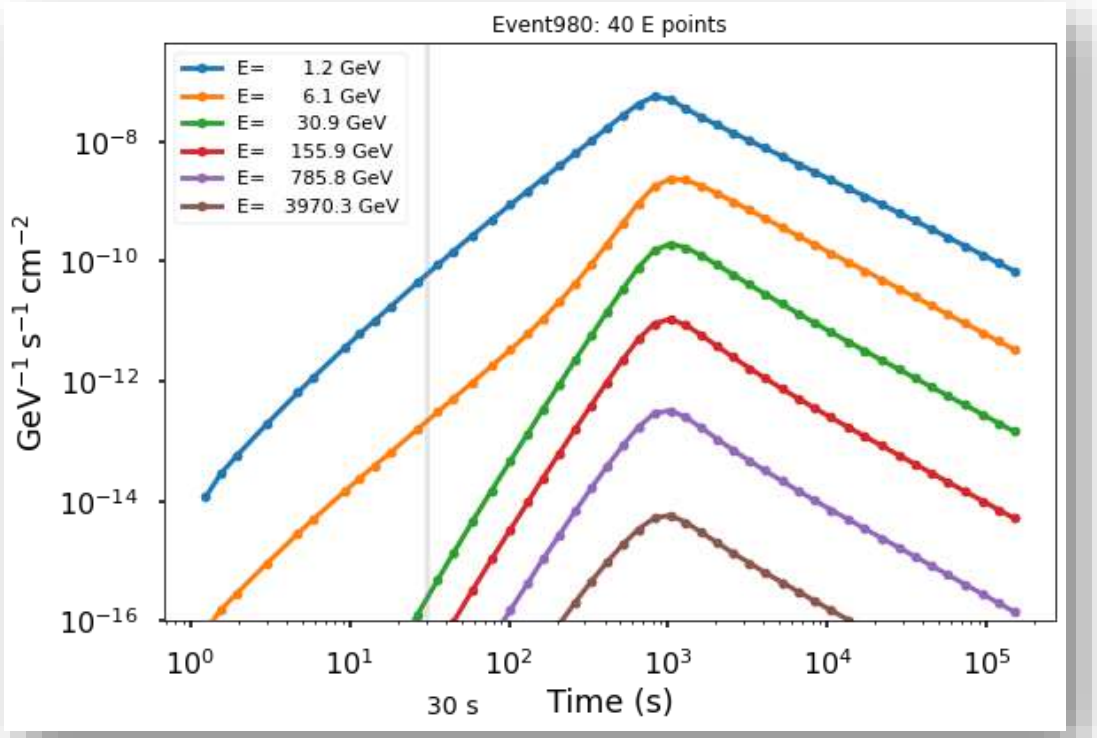
Name	Obs.	σ_{max}	Delay	E range	T90 (s)	Eiso (erg)	z
180720B	**H.E.S.S.**	5.3	10 hr	100 - 400 GeV	49	6 x 10^{53}	0.654
190114C	**MAGIC**	50	1'	0.2 - 1 TeV	25	2.5 x 10^{53}	0.4245
190829A	**H.E.S.S.**	22	4h20'	0.2 - 3 TeV	63	2 x 10^{50}	0.0785
201216C	**MAGIC**	>5	57"	100 GeV	30	5 x 10^{53}	1.1

Input files : 1000 Long GRB afterglows

- From G. Ghirlanda population model : E_{iso} & E_{peak}, z, t_{90}, Γ (Lorentz factor)
- *ra*, *dec*, t_0
- Afterglow spectra from L. Nava.

44 yr of Swift alerts





1 GeV ⟷ 10 TeV

~ 1 s ⟷ ~2 days

Telescope arrays

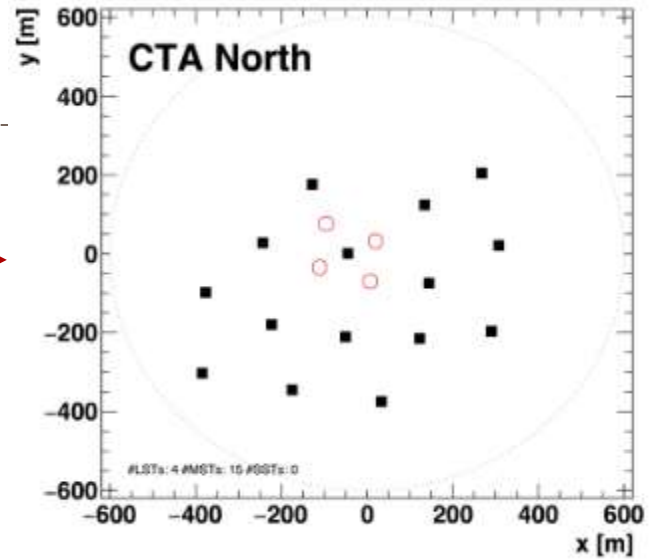
Omega
The ultimate goal

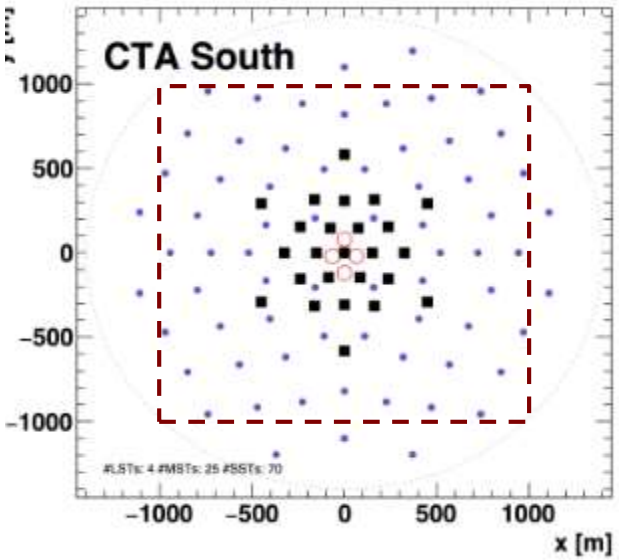
- **North**: 4 LSTs, 15 MSTs
- **South**: 4 LSTs, 25 MSTs, 70 SSTs

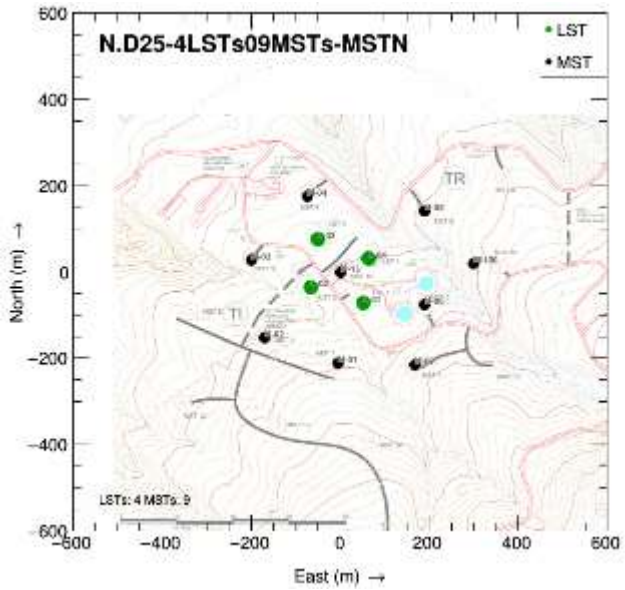
Note:
- *Not the "final" arrays – optimisation is ongoing*
- *Alpha layout is not a strict subset of Omega*
- *Slight variations in telescope simulations*

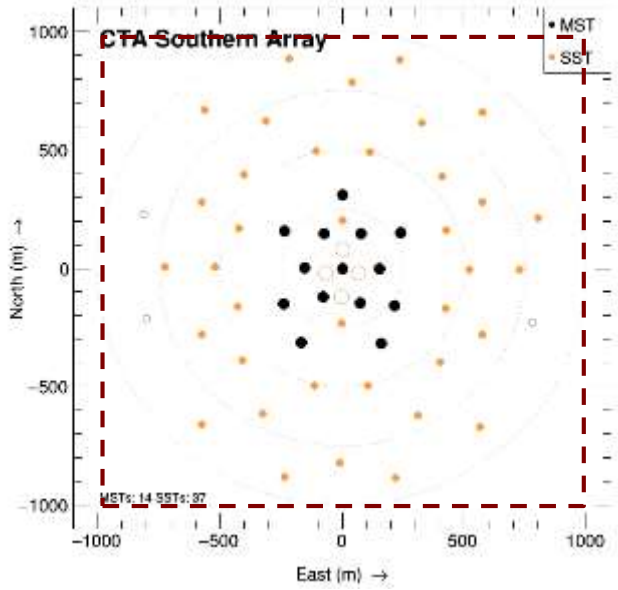
Alpha
The starting (funded) point

- **North**: 4 LSTs, 9 MSTs
- **South**: 0 LST, 14 MSTs, 37 SSTs
  ⇒ *Slewing times and E-thresholds increased*









Reference simulation, ω

- ✓ **EBL model : Dominguez 2011**
- ✓ **IRF : Full ω Array (N, S)**
  - Variable zenith (20°, 40°, 60°)
  - Variable observation time (100 s, 30', 5 h, 50 h)
  - Average azimuth
- ✓ **Visibility**
  - Moon veto whatever its phase (altitude < −0.25°)
  - GRB altitude > 24° (CTA requirements)
- ✓ **Delays**
  - ✓ Slewing : 30 s (LST)
    - MST additional delays neglected (<90 s)
  - ✓ Alert : 77 s (Swift mean δt)

⇒ **Total delay : $\Delta t_0 = 107$ s**

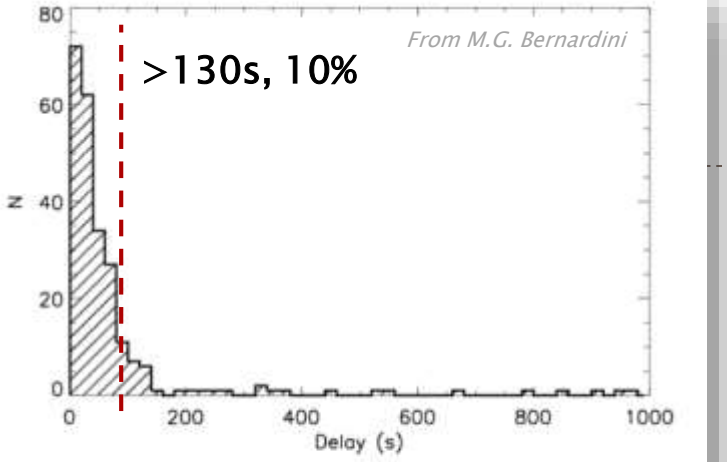


Figure 6: Swift latency as obtained from [9]. The minimum delay is 12 s, the mean 77 s and the median 34s. Delays of 65% of the GRBs are shorter than 52 s, 90% shorter than 130 s.

Slewing test in March 2019
34' for a complete turn

Simulation & Analysis principle

Based on Gammapy A Python package for gamma-ray astronomy

https://github.com/tstolarczyk/SoHAPPy

- **Visibility above horizon (Astroplan 0.8)**
- Apply detection delays

⇒ Recompute time slices
Get "best" IRF (Δt, θ)

Loop over slices

- Fluctuate S, B
- Cumulate S, B

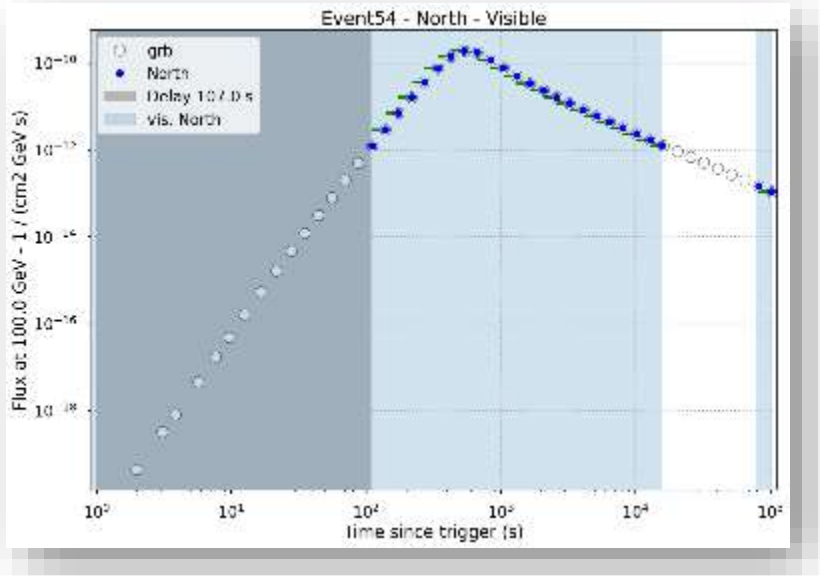
⇒ Significance σ(Li & Ma)

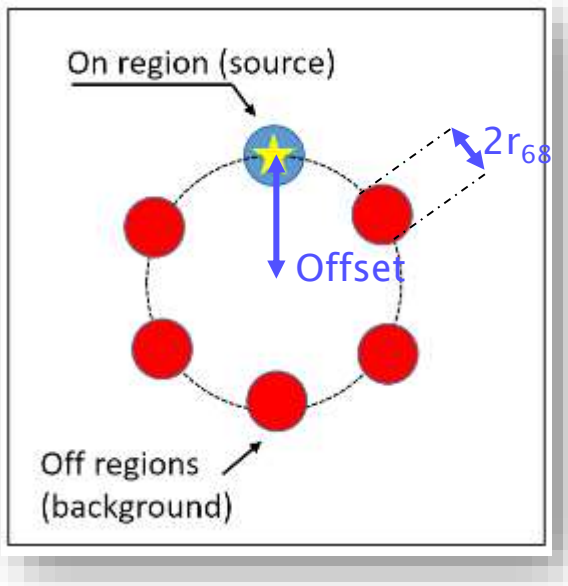
→ σ_{max} @ t_{max}
→ Δt for 3 σ & 5 σ

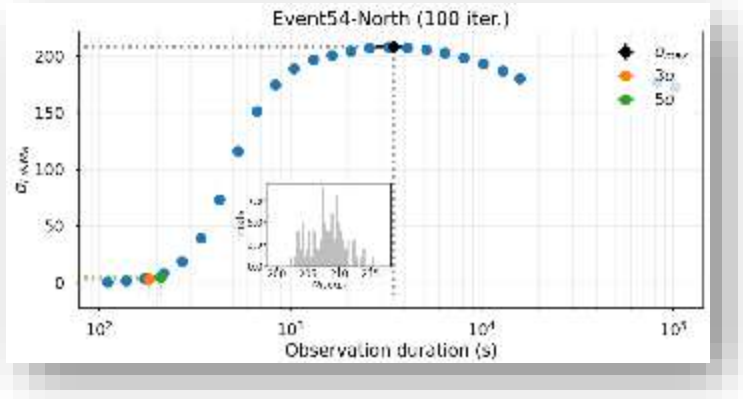
Repeat 100 times

Detected 3/5 σ if 90% of the trials are successful

- Mean σ_{max} @ mean t_{max}
- t of 3σ / 5σ







Simulation & Analysis principle

Based on γπ A Python package for gamma-ray astronomy

- **Visibility above horizon (Astroplan 0.8)**
- Apply detection delays

⇒ Recompute time slices
Get "best" IRF (Δt, θ)

Loop over slices

- Fluctuate S, B
- Cumulate S, B

⇒ Significance σ(Li & Ma)

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Detected 3/5 σ if 90% of the trials are successful

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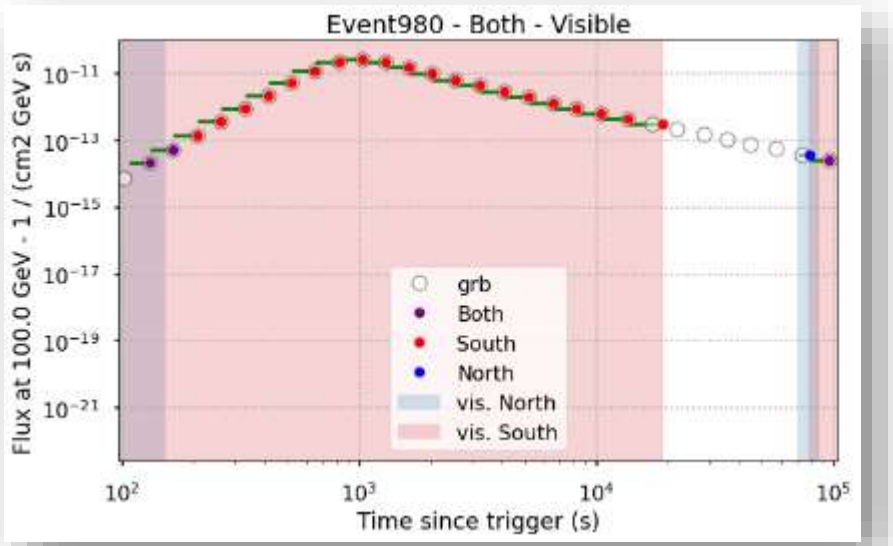
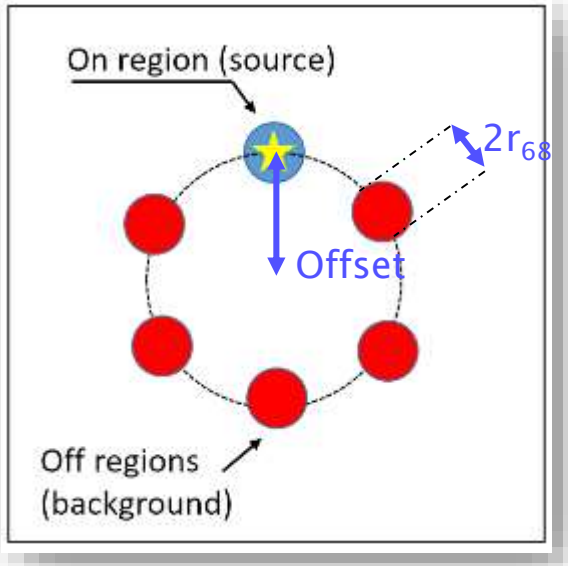
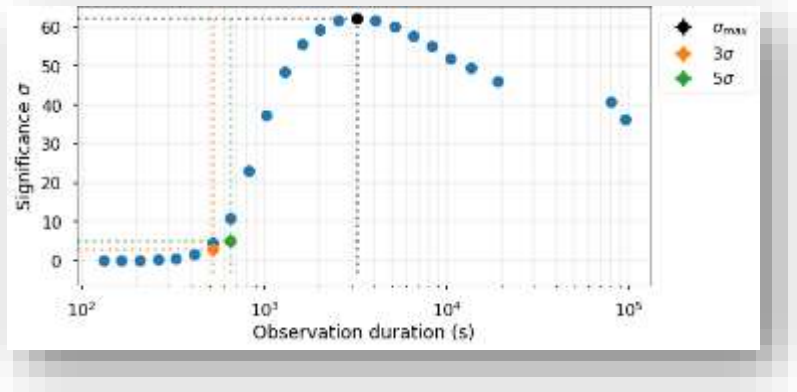






Detection rates – Reference simulation, ω

Rate		N	S
Vis.	Counts	*446 ± 21*	*452 ± 21*
	yr^{-1}	**10.1 ± 0.5**	**10.3 ± 0.5**
	@trig	13%	11%
3σ	Counts	*64 ± 8*	*53 ± 7*
	yr^{-1}	**1.5 ± 0.2**	**1.2 ± 0.2**
	@trig	48%	49%
5σ	Counts	*57 ± 8*	*46 ± 7*
	yr^{-1}	**1.3 ± 0.2**	**1.0 ± 0.2**
	@trig	51%	50%

– 20%

PRELIMINARY

3/5σ detection easier if start seen

- *Over 1000 initial GRB : 45% visible*
- *÷ 44 years*
- *Fraction starting in a visible window*

  $\Rightarrow$ *prompt ~visible if t90 > Δt_0 = 107 s*
- *Detected at ≥ 3σ in ≥ 90% of the trials*
- *Detected at ≥ 5 σ in ≥ 90% of the trials*

Detection rates – Reference simulation, ω

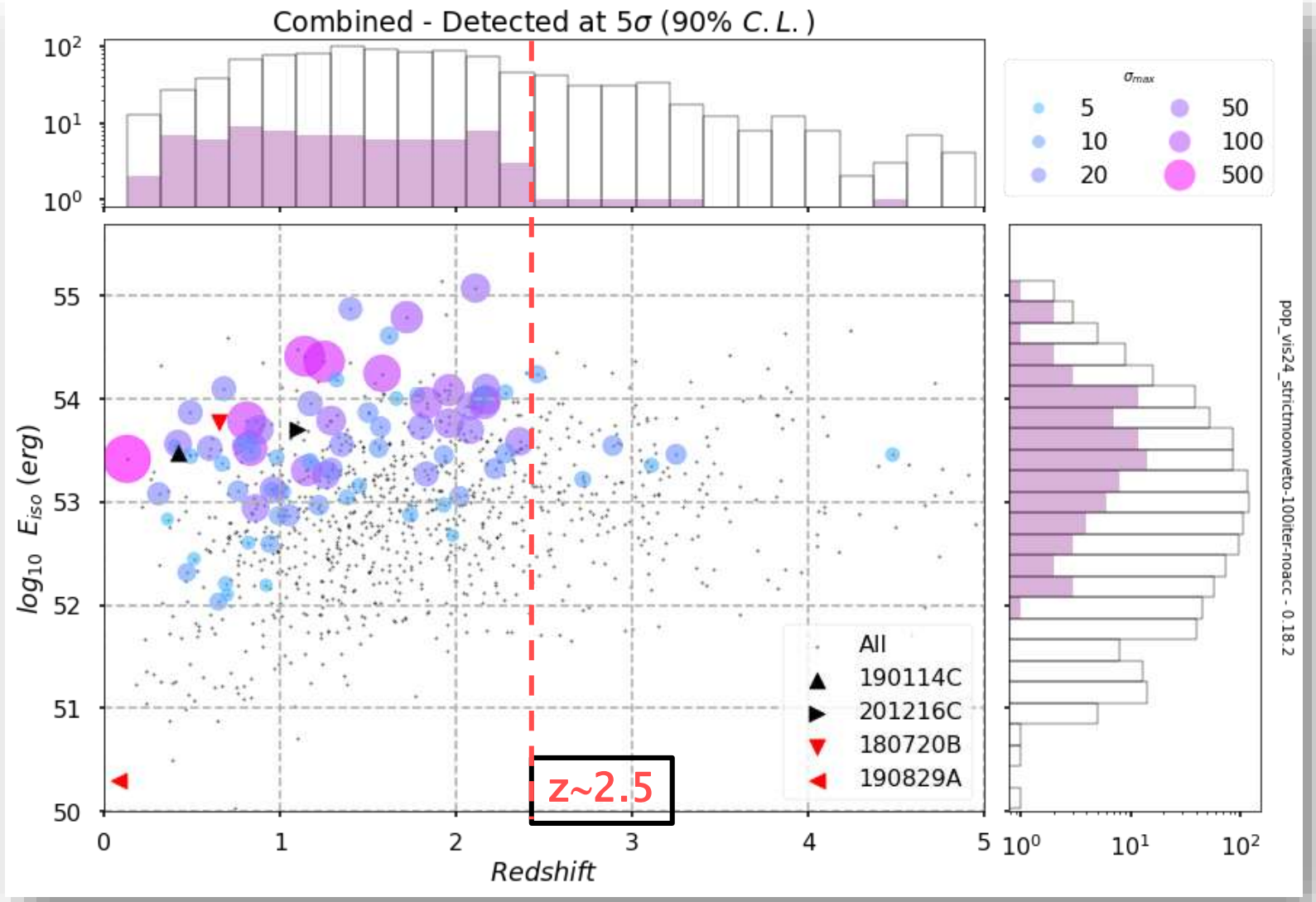
Rate		N	S	N only	S only	Both	Total
Vis.	Counts	*446 ± 21*	*452 ± 21*	*159 ± 13*	*165 ± 13*	*287 ± 17*	*611 ± 25*
	yr^{-1}	**10.1 ± 0.5**	**10.3 ± 0.5**	**3.6 ± 0.3**	**3.8 ± 0.3**	**6.5 ± 0.4**	**13.9 ± 0.6**
	@trig	13%	11%	10%	10%		
3σ	Counts	*64 ± 8*	*53 ± 7*	*19 ± 4*	*13 ± 4*	*64 ± 8*	*96 ± 10*
	yr^{-1}	**1.5 ± 0.2**	**1.2 ± 0.2**	**0.4 ± 0.1**	**0.3 ± 0.1**	**1.5 ± 0.2**	**2.2 ± 0.2**
	@trig	48%	49%	58%	54%		
5σ	Counts	*57 ± 8*	*46 ± 7*	*17 ± 4*	*11 ± 3*	*53 ± 7*	*81 ± 9*
	yr^{-1}	**1.3 ± 0.2**	**1.0 ± 0.2**	**0.4 ± 0.1**	**0.2 ± 0.1**	**1.2 ± 0.2**	**1.8 ± 0.2**
	@trig	51%	50%	65%	64%		

PRELIMINARY

- 50% are detected at 5σ 90%CL in <10'
- σ_{max} reached after 1.3 hours (median)

Population covered

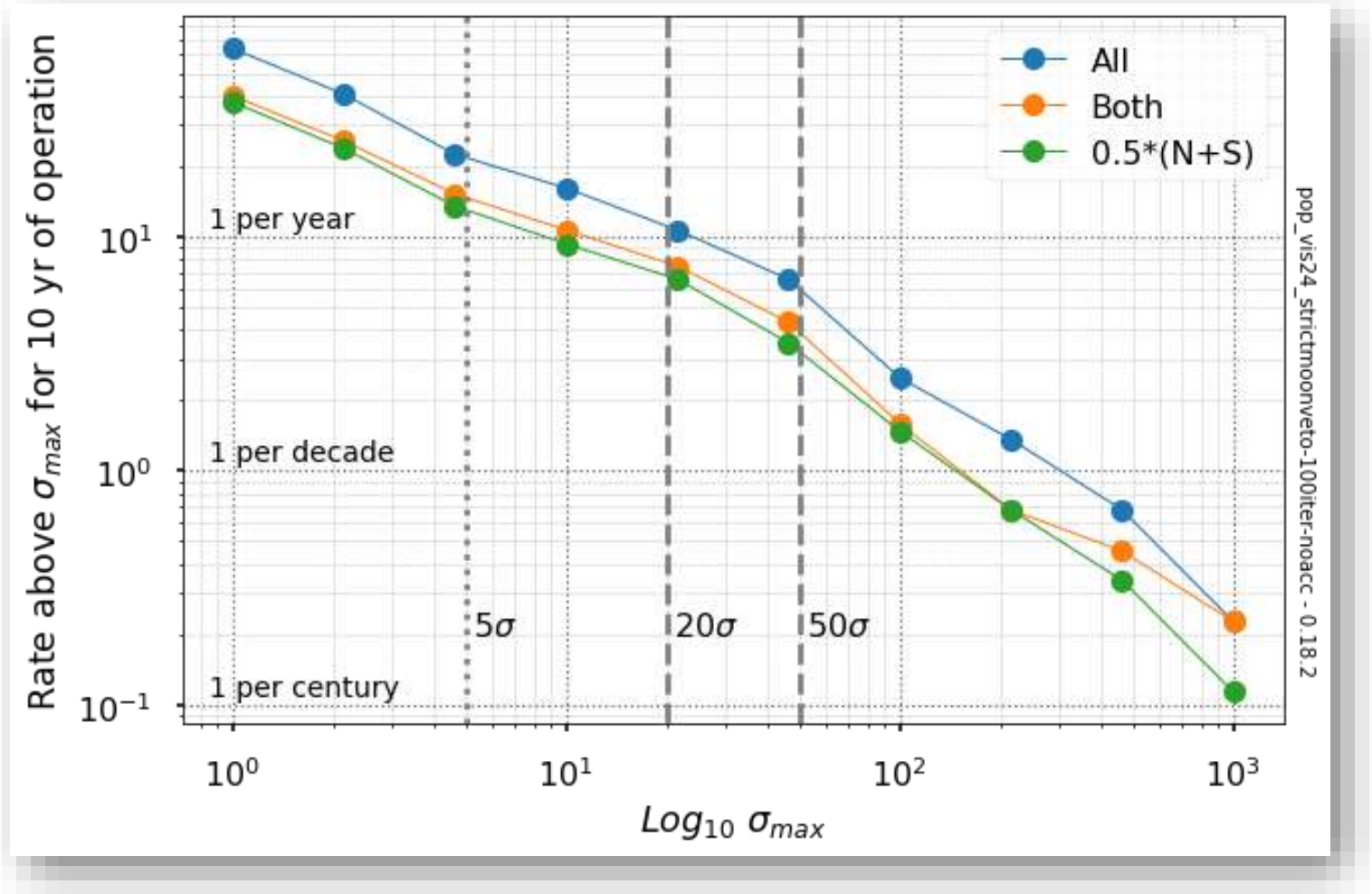
Reference ω
$\Delta t_0 = 30 + 77$ s



PRELIMINARY

Maximal significances

Reference ω
$\Delta t_0 = 30 + 77$ s



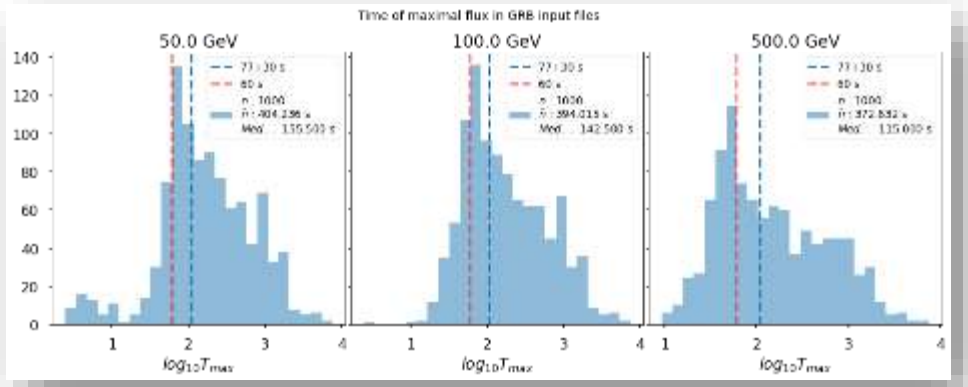
≥ 5σ : ~ 2 per year
≥ 20σ : ~ 1 every year
≥ 50σ : ~ 1 every 2 years

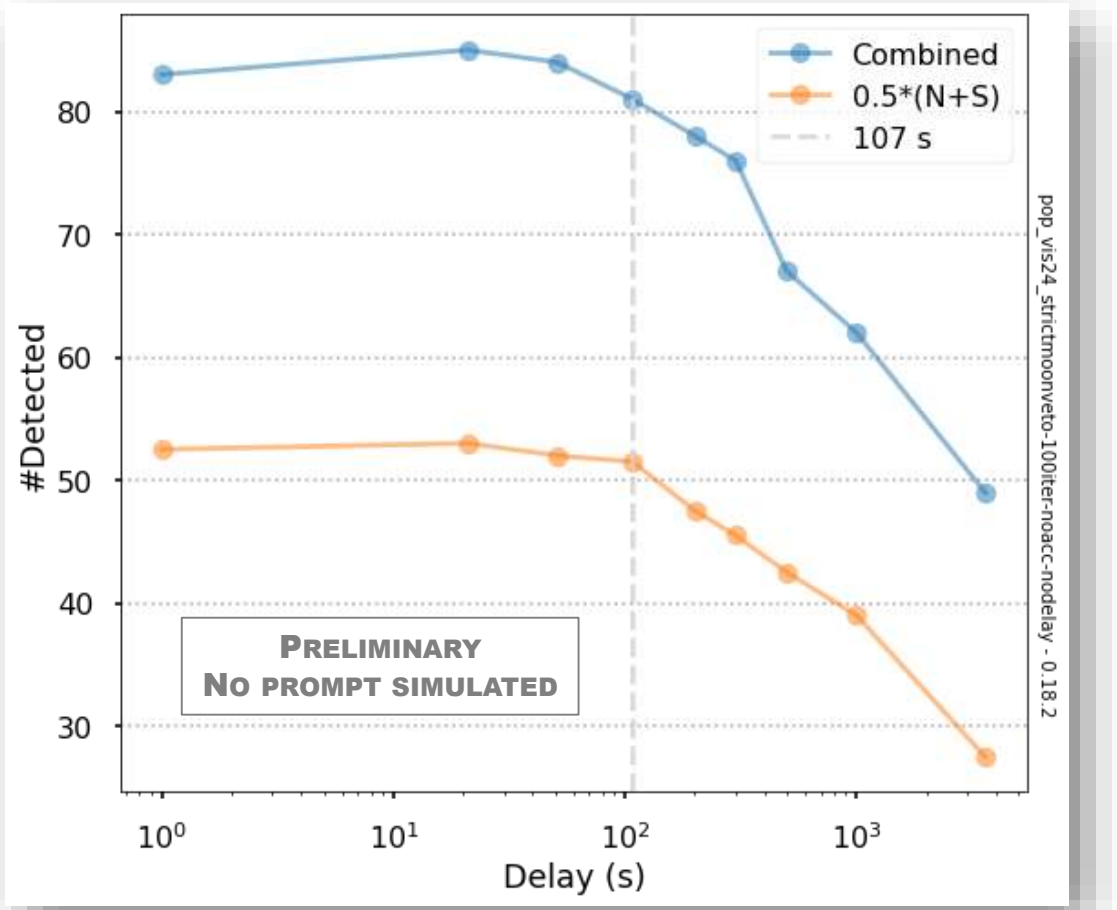
Detection vs Δt_0

Reference ω

- ✓ **LST Slewing**
  - Depends on source position
  - Can be as low as ~10s (?)
- ✓ **Alert delay (Swift)**
  - Can be as low as 12s
- ✓ **Delays of ~20 s are possible**

Detection rate stable until ~100s
⇐ GRB max. flux time ~50–100 s



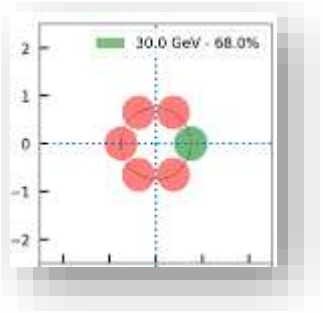


** For zenith at 20°, 40°, 60° resp.*

From ω to α — Analysis changes

Omega

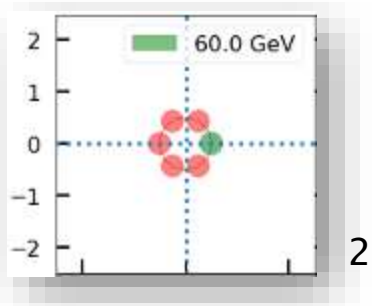
- **North : 4 LST, 15 MST**
  - IRF dominated by **LST**
  - Slewing : 30 s
  - On-region / offset : 0.4° / 0.75°
  - Thresholds* : 30, 40, 110 GeV
- **South : 4 LST, 25 MST, 70 SST**
  - Same as in North



20°, 100 s

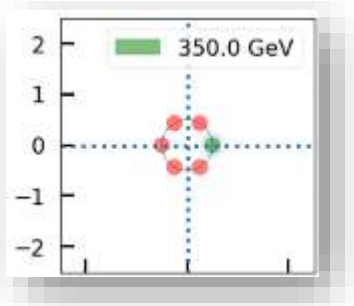
Alpha

- **North: 4 LST, 9 MST**
  - Same as Omega (dominated by LST)
- **South : 0 LST, 14 MST, 37 SST**
  - IRF dominated by **MST**
  - Slewing : 90 s
  - On-region / Offset : 0.25° / 0.5°
  - Thresholds* : 60, 110, 350 GeV



20°, 100 s

60°, 50 h



From ω to α : Detection rates

Rate	N			S			Nonly			Sonly			Both			Total			
5σ	*54*	*±*	*7.3*	*37*	*±*	*6.1*	*16*	*±*	*4*	*5*	*±*	*2.2*	*49*	*±*	*7*	*70*	*±*	*8.4*	
yr^{-1}	**1.2**	**±**	**0.2**	**0.8**	**±**	**0.1**	**0.4**	**±**	**0.1**	**0.1**	**±**	**0.1**	**1.1**	**±**	**0.2**	**1.6**	**±**	**0.2**	α
Réf.	*1.3*	*±*	*0.2*	*1.0*	*±*	*0.2*	*0.4*	*±*	*0.1*	*0.2*	*±*	*0.1*	*1.2*	*±*	*0.2*	*1.8*	*±*	*0.2*	ω

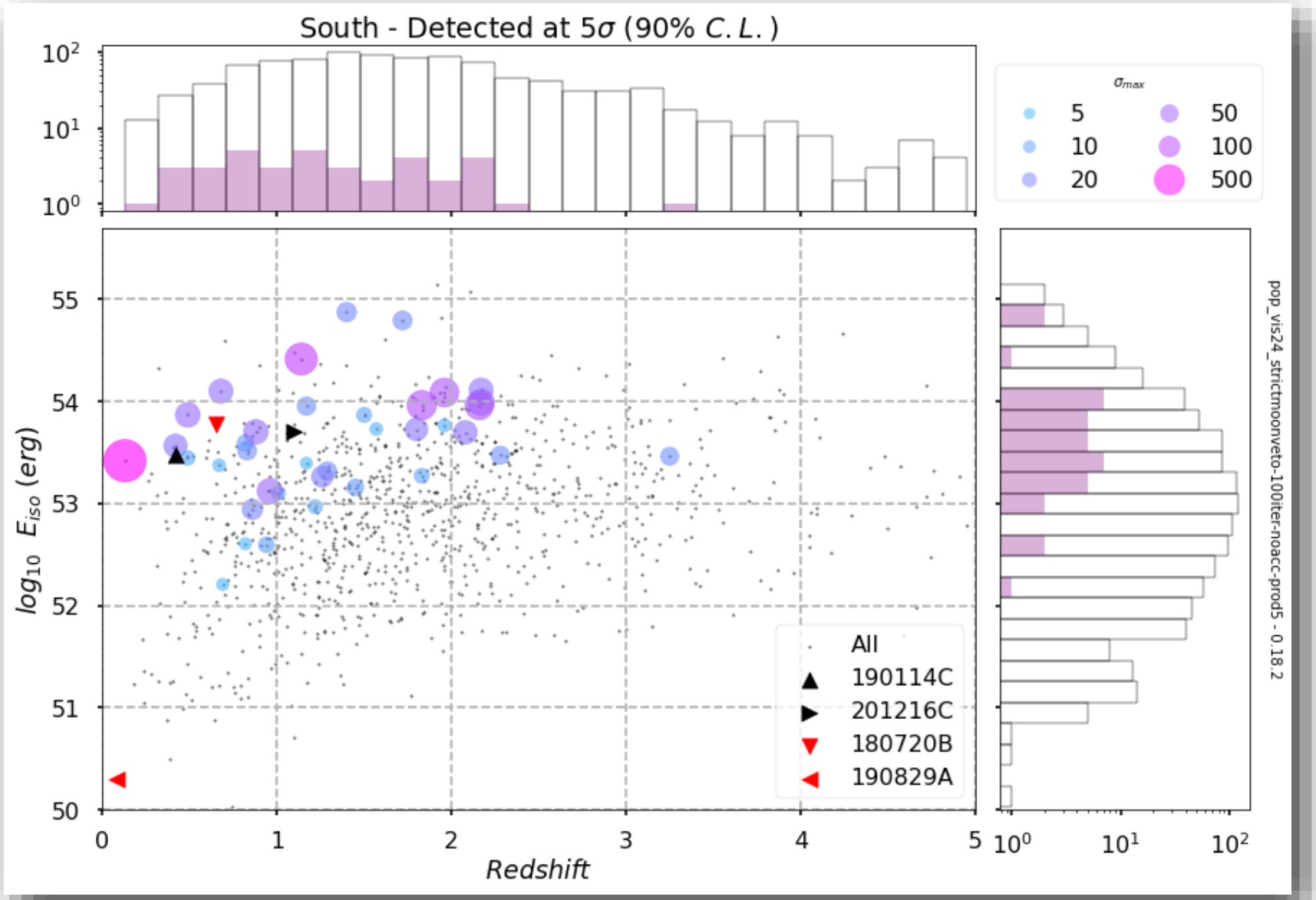
PRELIMINARY - NO PROMPT SIMULATED

Conclusion on the detection rates compared to the Omega configuration

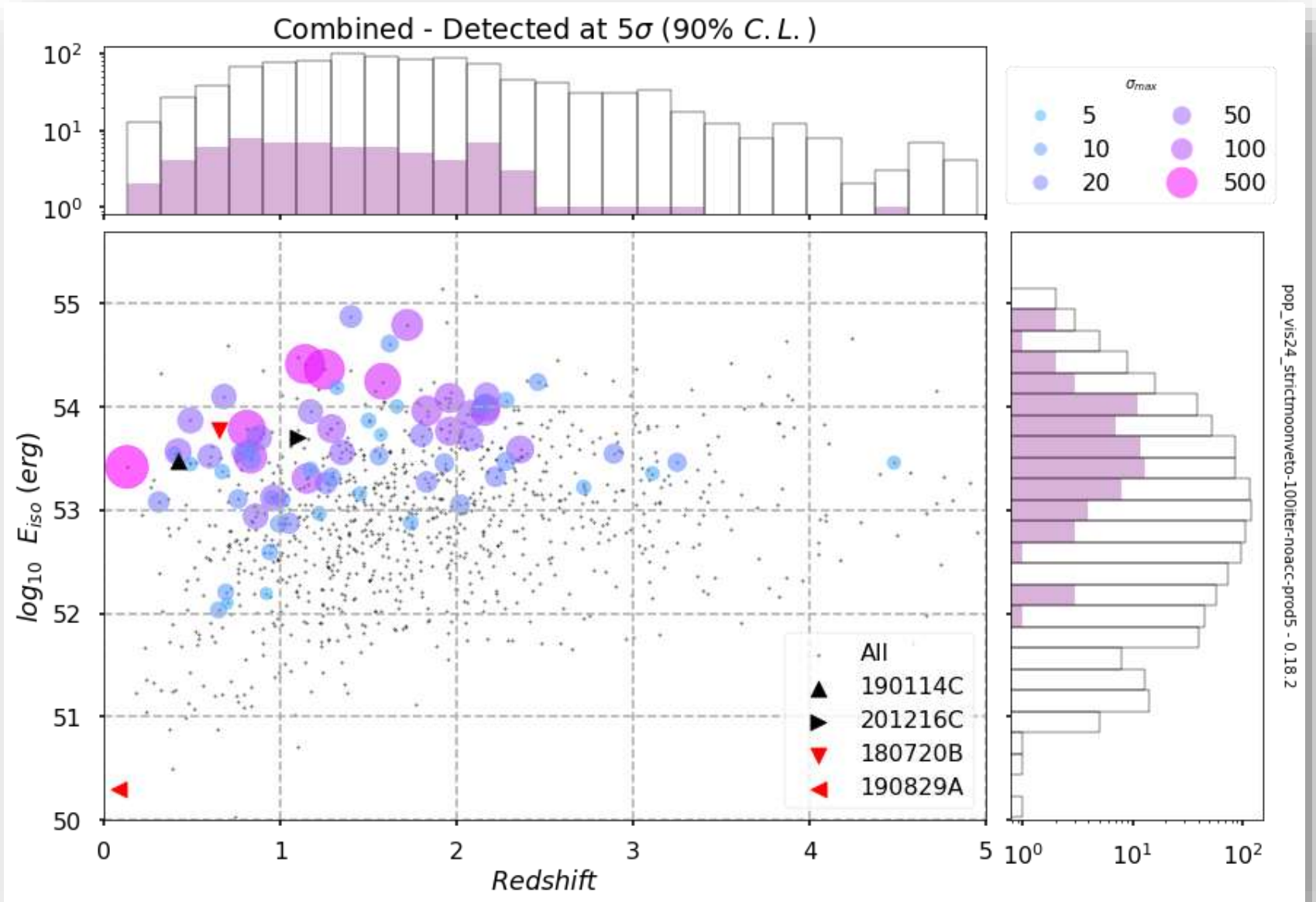
- North : -5% Almost identical (-3/57)
- South : -20% 1.0 to 0.8 GRB per year (-9/46)
- Both : -8% Compensates South loss (-4/53)
- Total : -14% (-11/81)

South

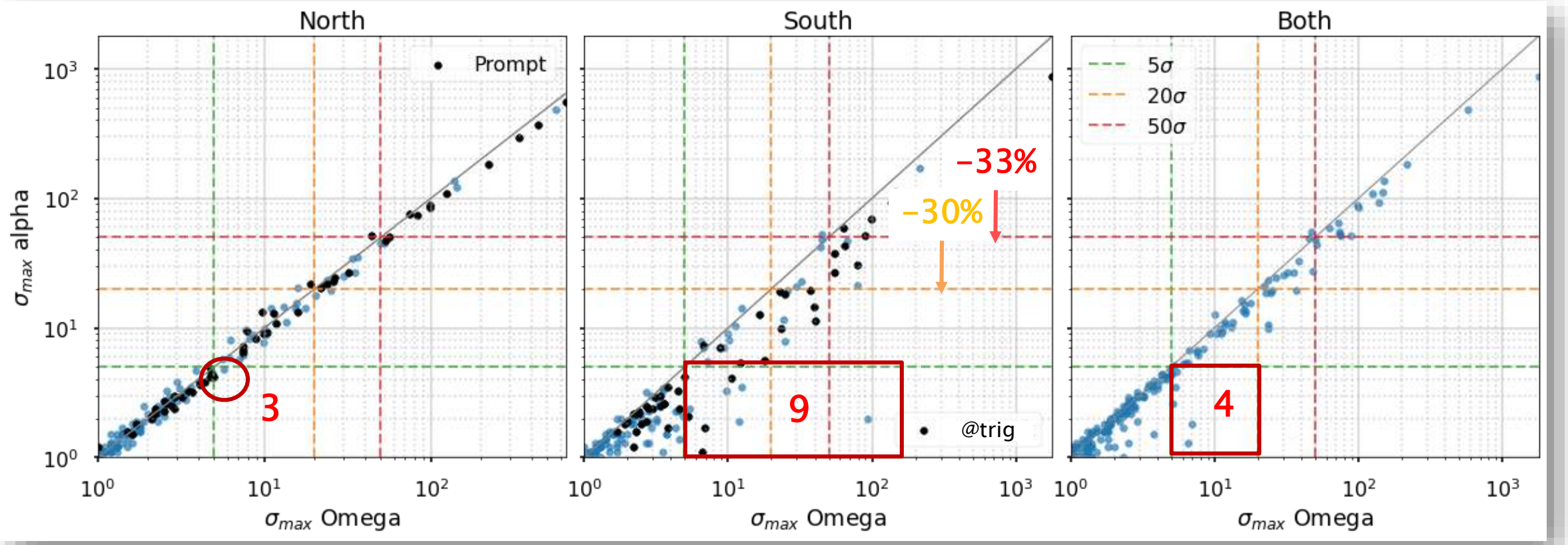
Alpha


South - Detected at 5σ (90% C.L.)
10^2
10^1
10^0
σ_{max}
5
10
20
50
100
500
55
54
53
52
51
50
log_{10} E_{iso} (erg)
All
190114C
201216C
180720B
190829A
0
1
2
3
4
5
Redshift
10^0
10^1
10^2
pop_vis24_strictmoonveto-100iter-noacc-prod5 - 0.18.2

Alpha

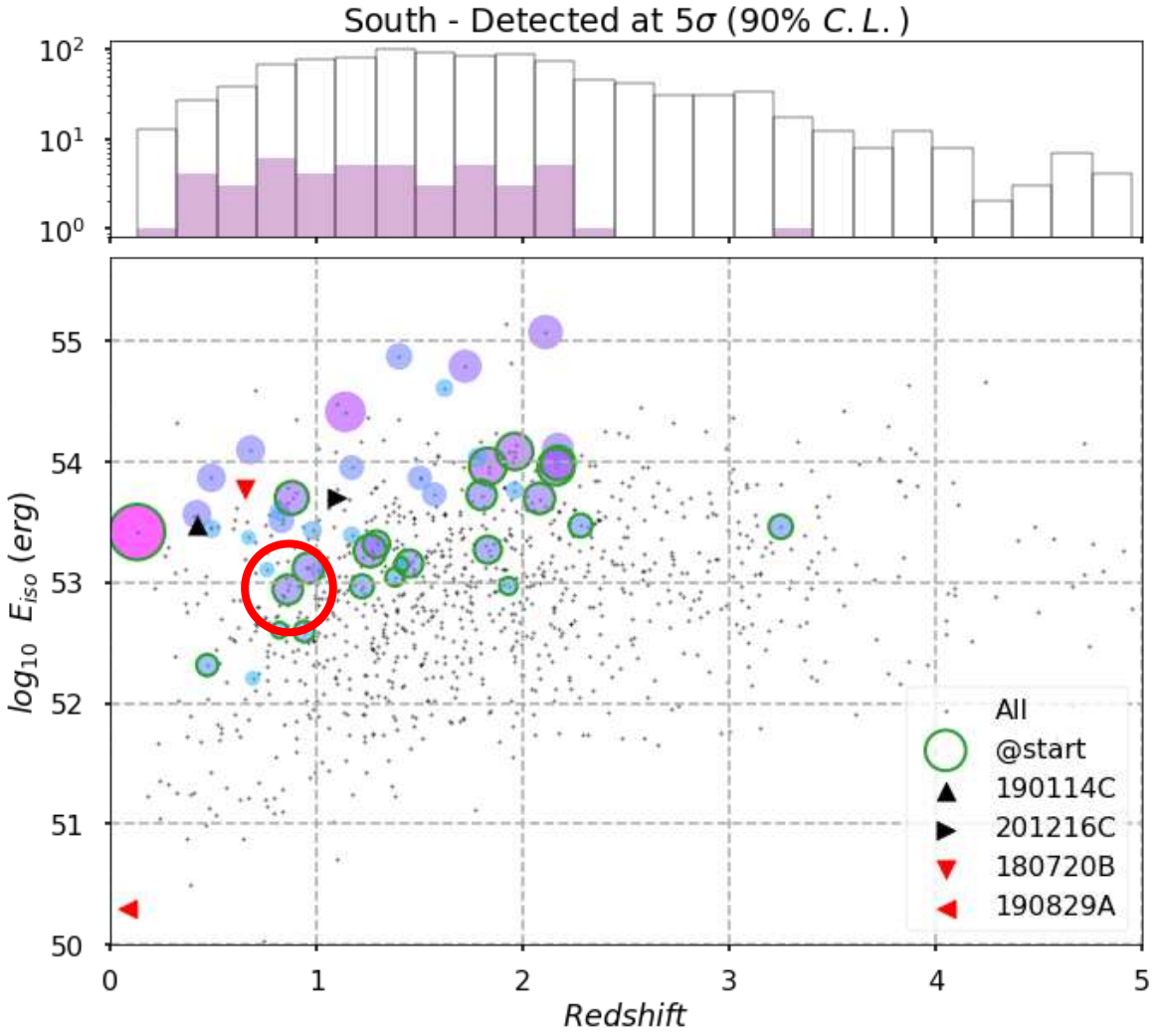

Combined - Detected at 5σ (90% C.L.)
10^2
10^1
10^0
σ_{max}
5
10
20
50
100
500
55
54
53
52
51
50
log_{10} E_{iso} (erg)
All
190114C
201216C
180720B
190829A
0
1
2
3
4
5
Redshift
10^0
10^1
10^2
pop_vis24_strictmoonveto-100iter-noacc-prod5 - 0.18.2

From ω to α : changes in $\bar{\sigma}_{max}$



A look to some spectra
(Preliminary)

980 – South



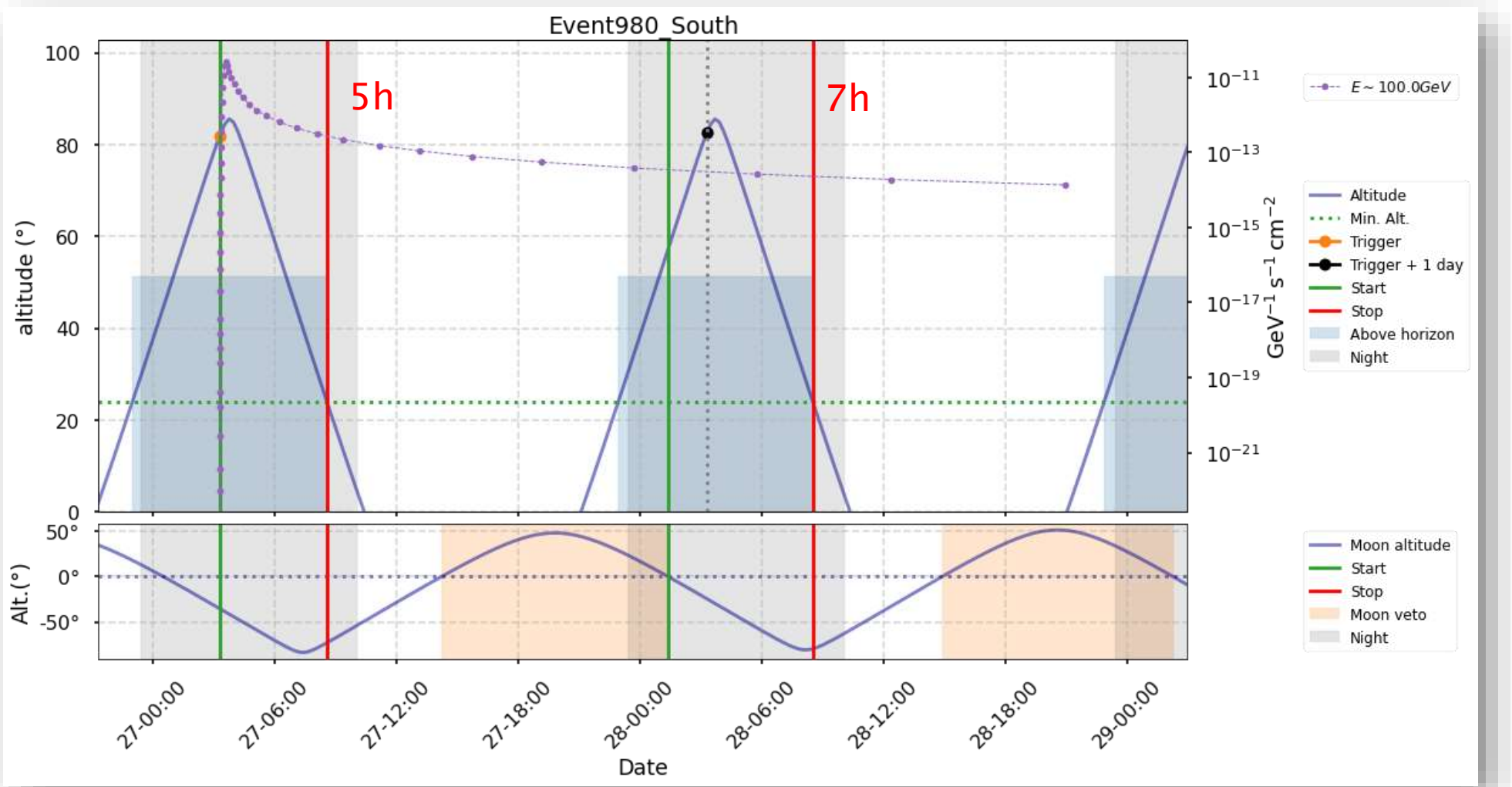
z = 0.96
Eiso = 1.32e+53 erg

Omega
σ_{max} : 63 @ 54′
5 sigma @ 10′

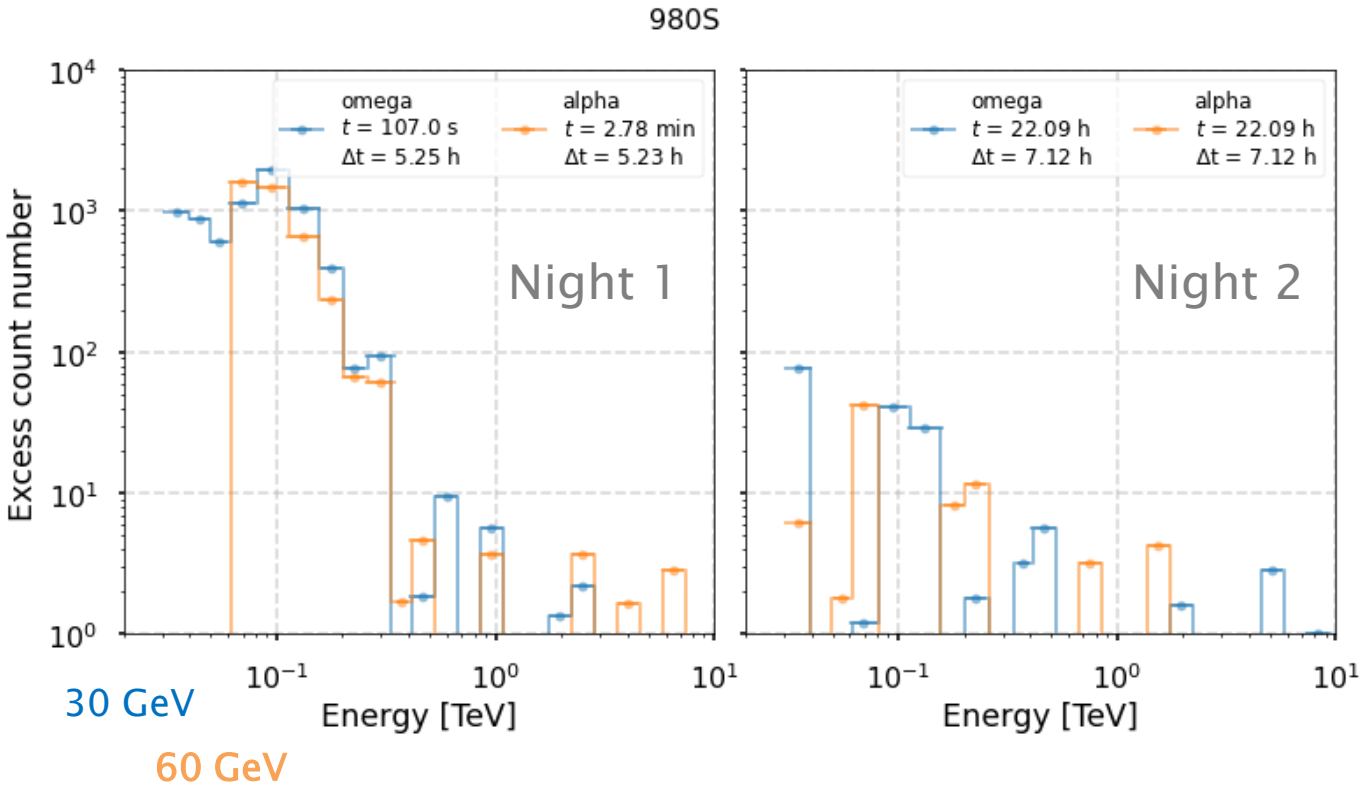
Alpha
σ_{max} : 60 @ 53′
5 sigma @ 9′

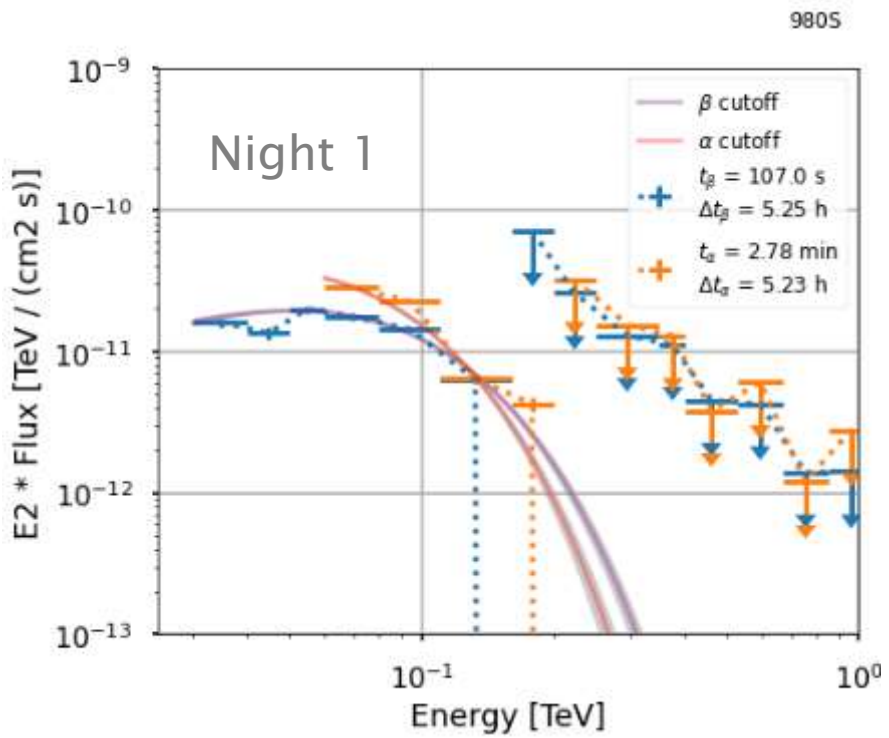
980 – South

- ✓ Visible from start (107s)
- ✓ Large visibility periods
- ✓ High altitude (low thresholds)

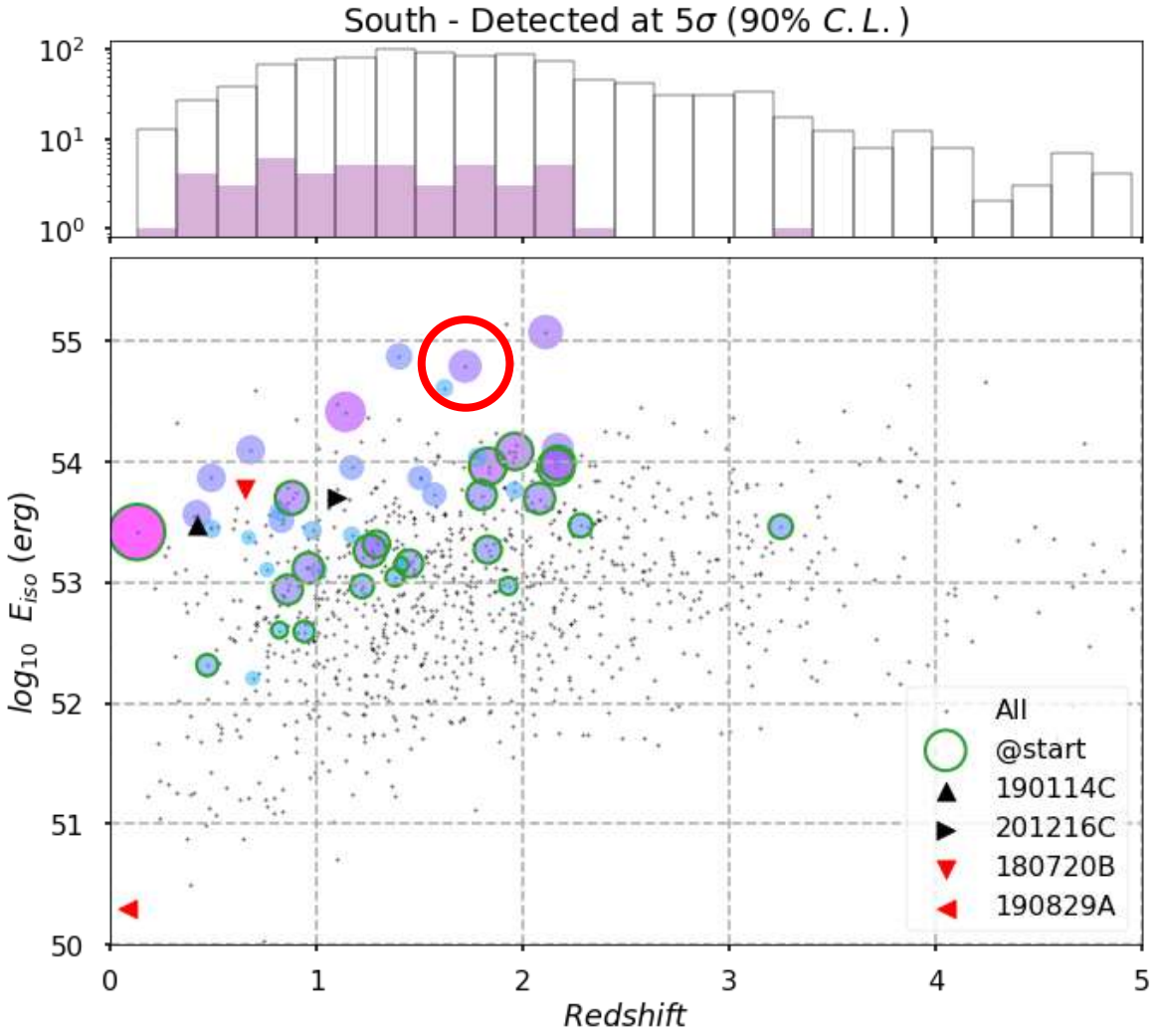


980 South


980S
Excess count number
omega
t = 107.0 s
Δt = 5.25 h
alpha
t = 2.78 min
Δt = 5.23 h
Night 1
omega
t = 22.09 h
Δt = 7.12 h
alpha
t = 22.09 h
Δt = 7.12 h
Night 2
Energy [TeV]
Energy [TeV]
30 GeV
60 GeV


980S
Night 1
β cutoff
α cutoff
t_β = 107.0 s
Δt_β = 5.25 h
t_α = 2.78 min
Δt_α = 5.23 h
E2 * Flux [TeV / (cm2 s)]
Energy [TeV]

465 – South



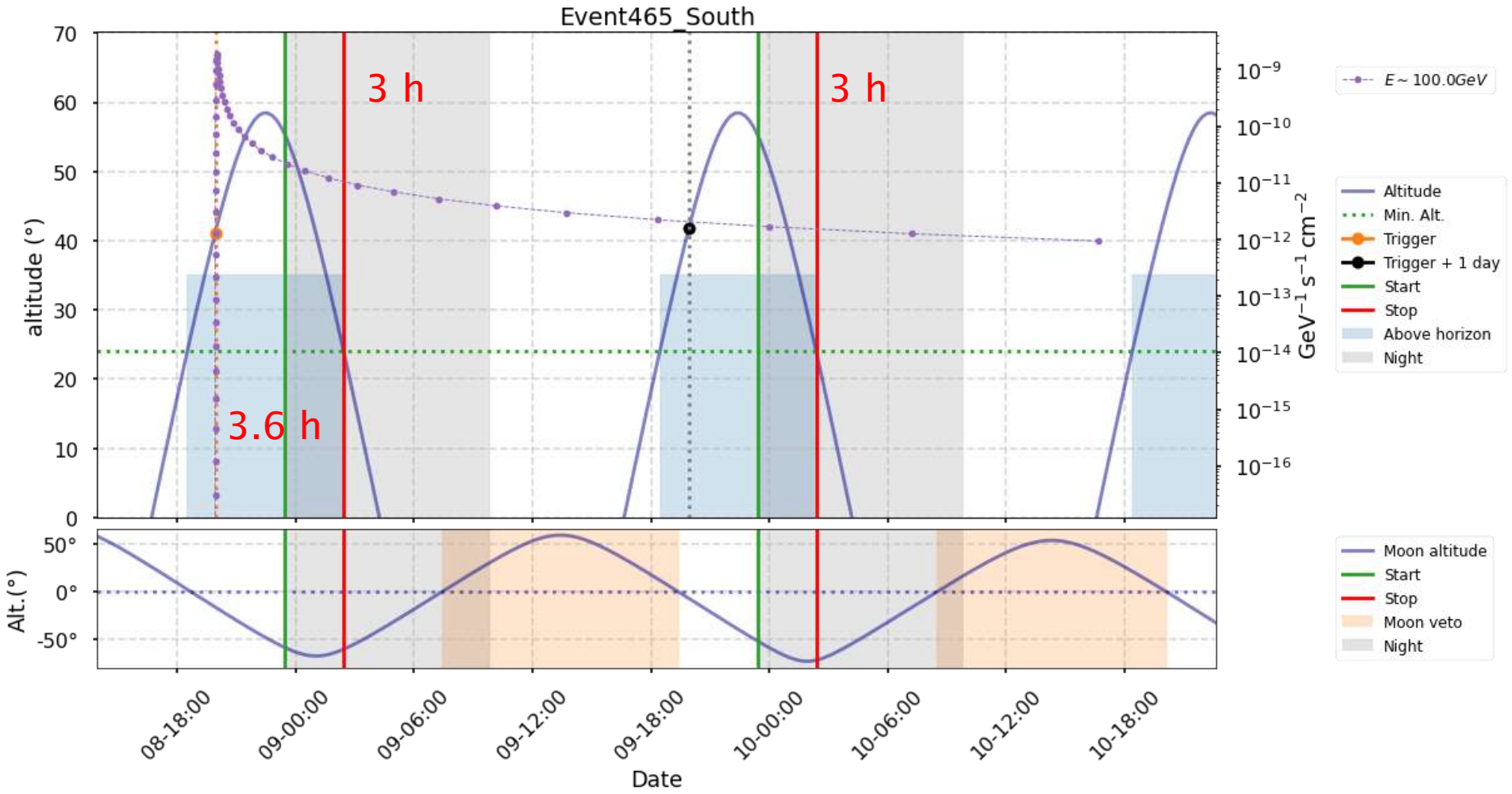
z = 1.72
Eiso = 6.21e+54 erg

Omega
σ_{max} : 78 @ 5.7 h
5 sigma @ 3.6 h

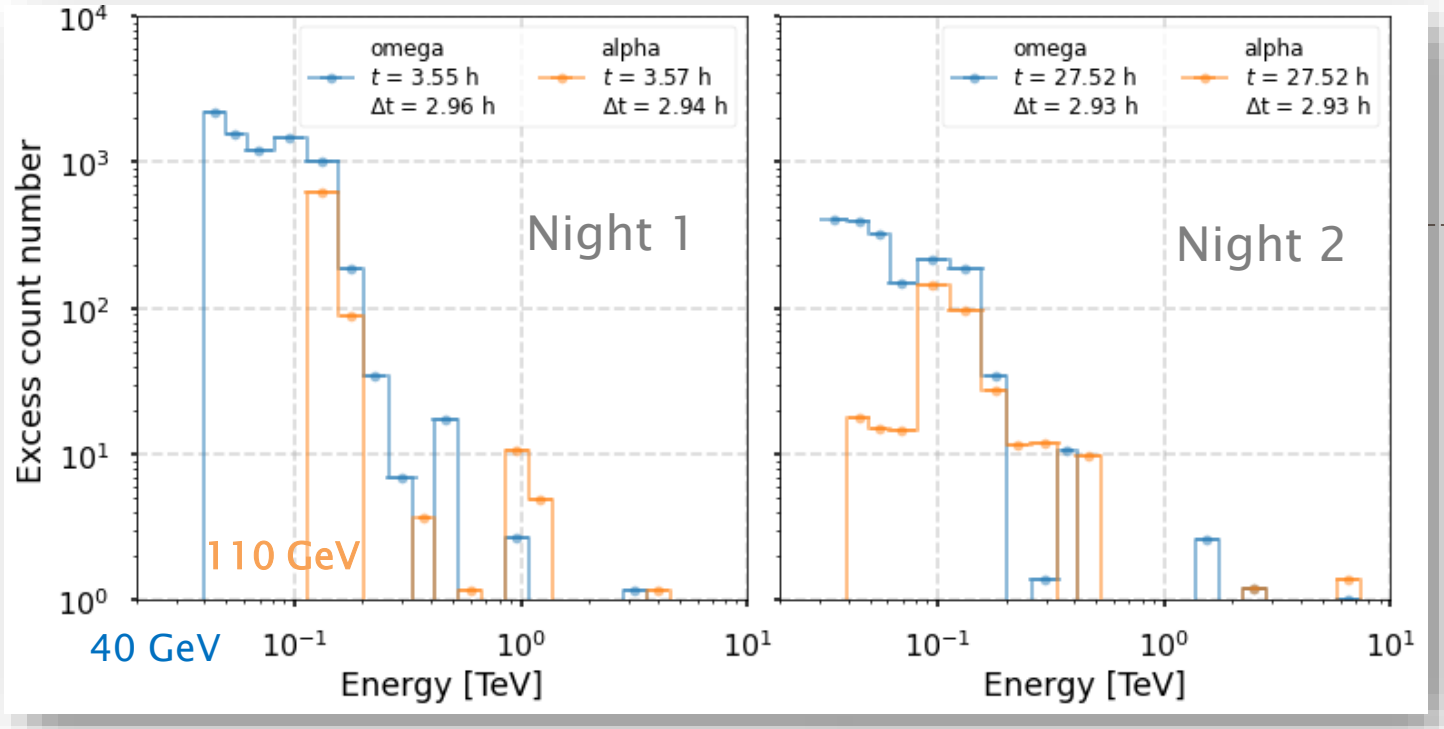
Alpha
σ_{max} : 21 @ 5.9 h
5 sigma @ 4.0 h

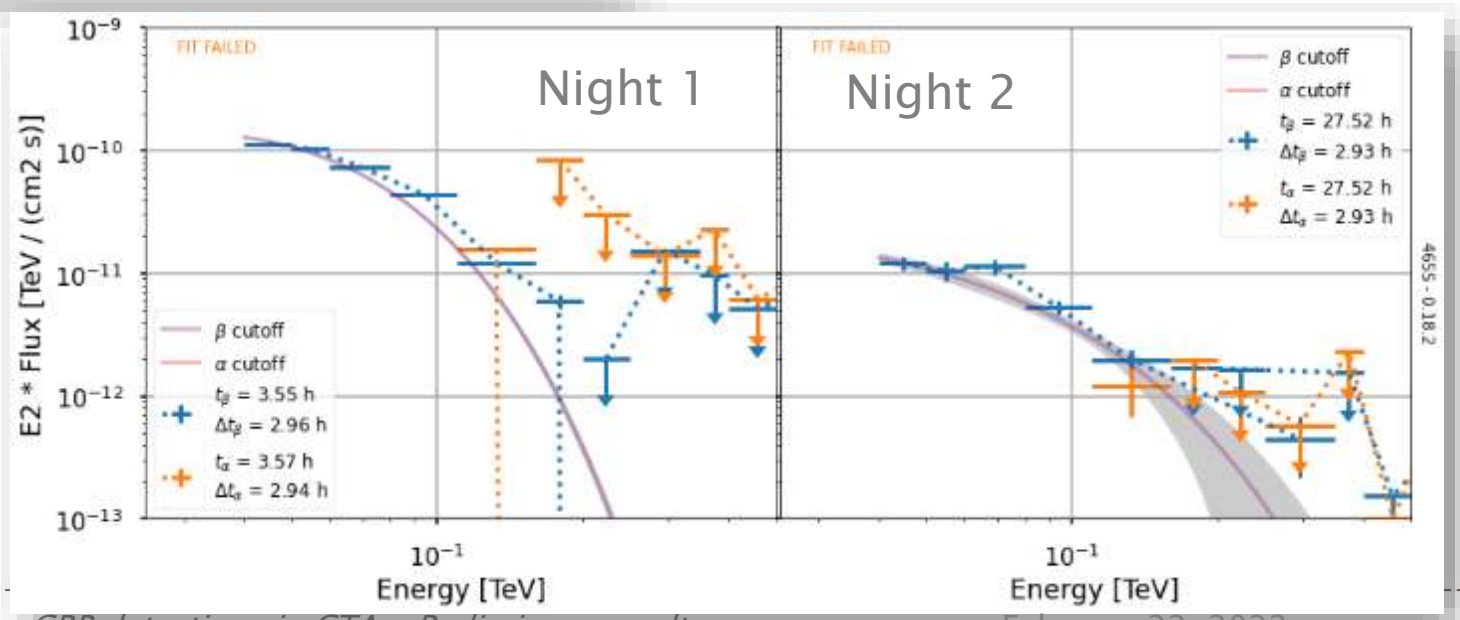
465 South

- ✓ 4h of delays
- ✓ 3h visibility periods
- ✓ Mid altitude

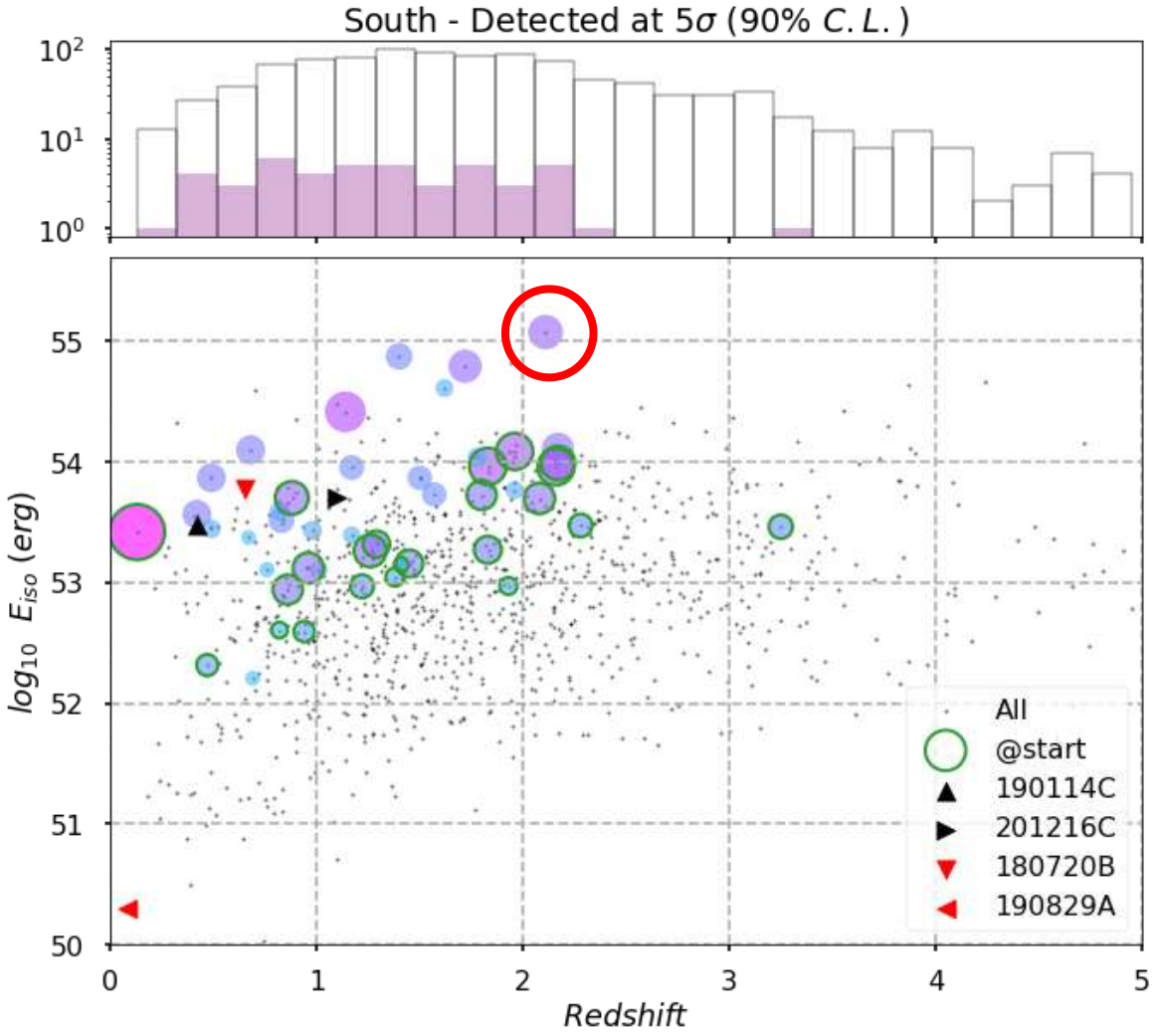


465 South


omega
t = 3.55 h
Δt = 2.96 h
alpha
t = 3.57 h
Δt = 2.94 h
Night 1
omega
t = 27.52 h
Δt = 2.93 h
alpha
t = 27.52 h
Δt = 2.93 h
Night 2
Excess count number
110 GeV
40 GeV
Energy [TeV]
Energy [TeV]


FIT FAILED
Night 1
FIT FAILED
Night 2
β cutoff
α cutoff
t_β = 27.52 h
Δt_β = 2.93 h
t_α = 27.52 h
Δt_α = 2.93 h
β cutoff
α cutoff
t_β = 3.55 h
Δt_β = 2.96 h
t_α = 3.57 h
Δt_α = 2.94 h
E2 * Flux [TeV / (cm2 s)]
Energy [TeV]
Energy [TeV]
4655 - 0.18.2

GRB 785 – South



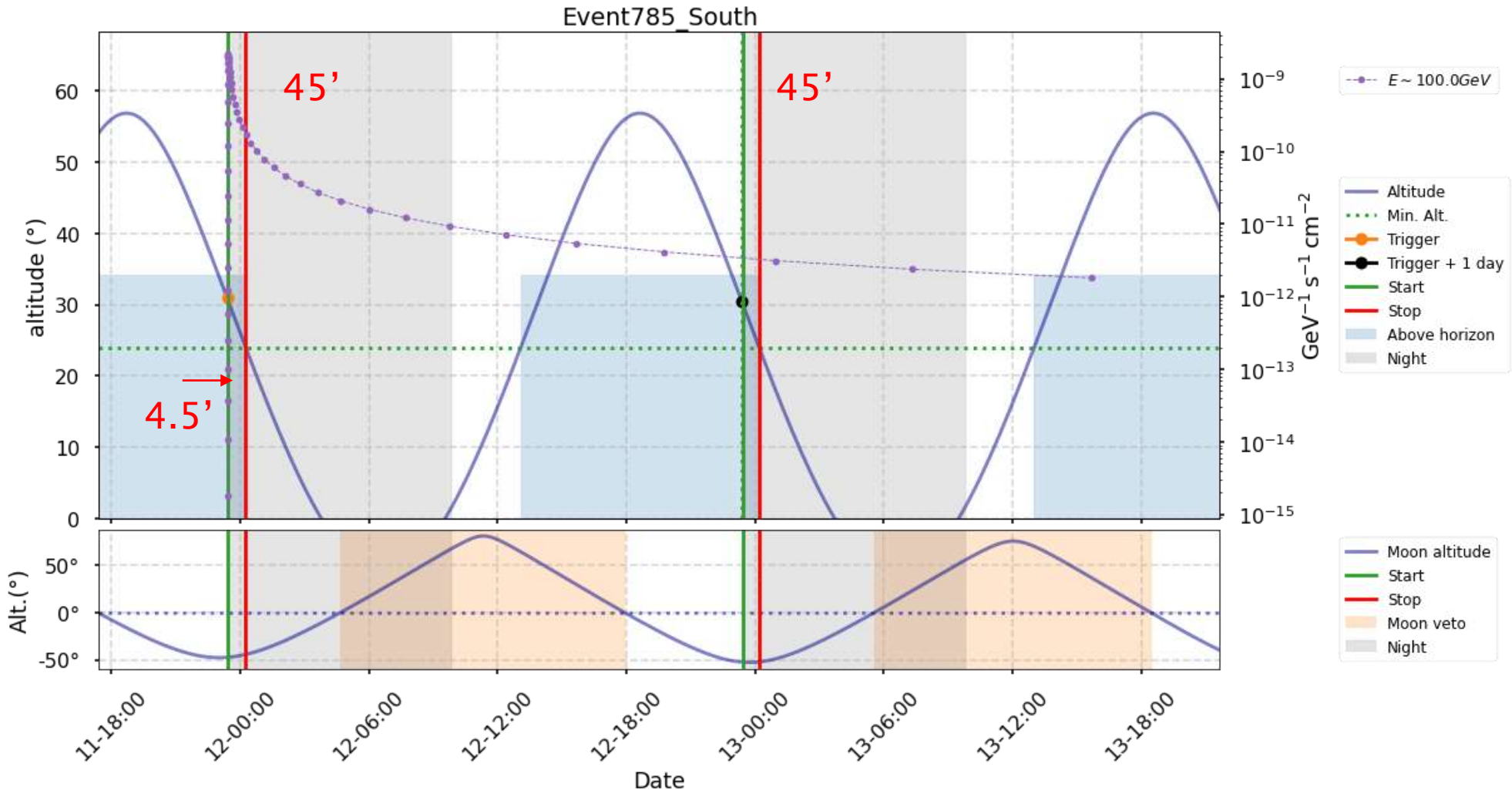
z = 2.11
Eiso = 1.19e+55 erg

Omega
sigmax : 92 @ 51 min
5 sigma @ 4.5 min

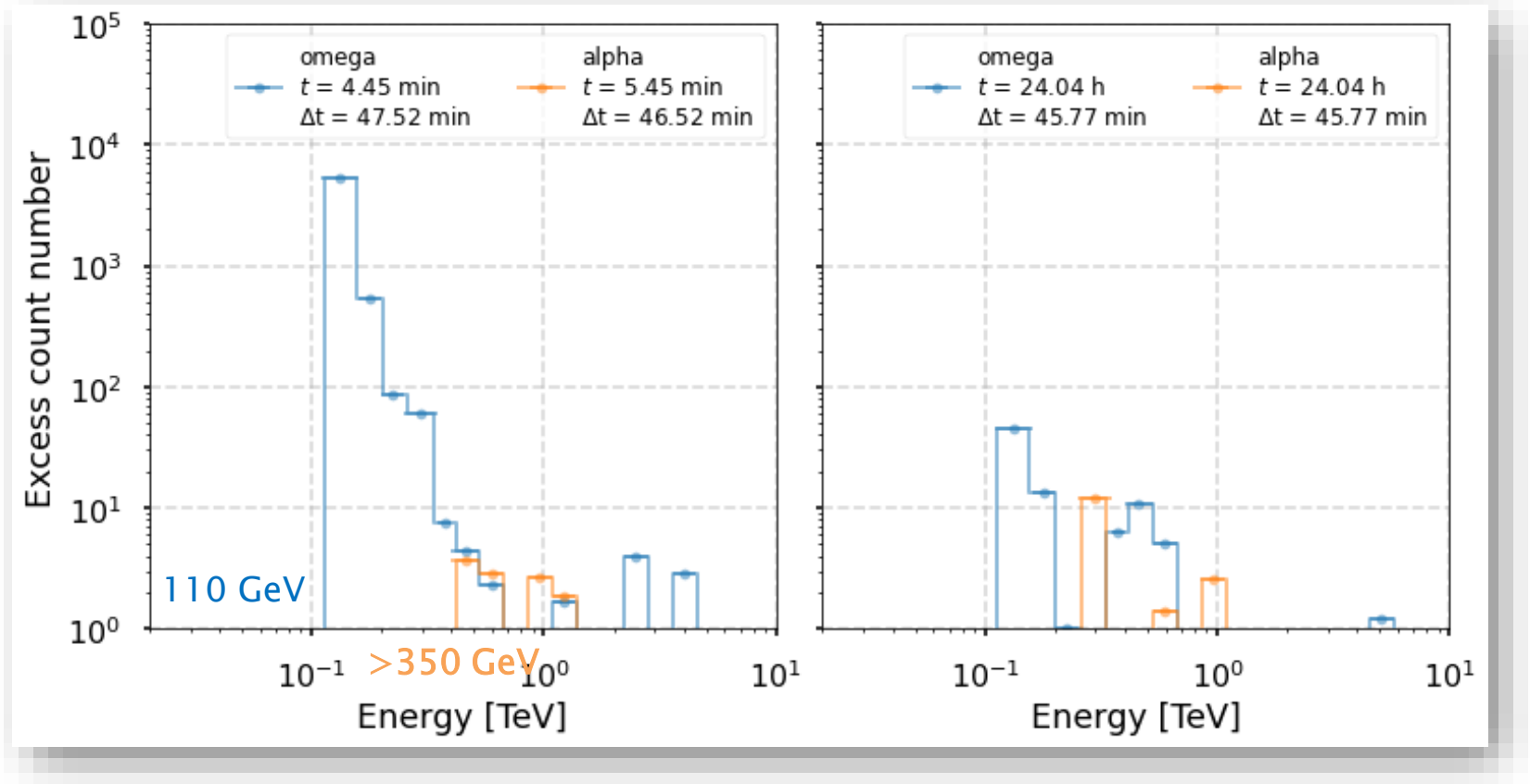
Alpha
sigmax : 2
5 sigma @ not detected

GRB 785 – South

Low altitude → high threshold

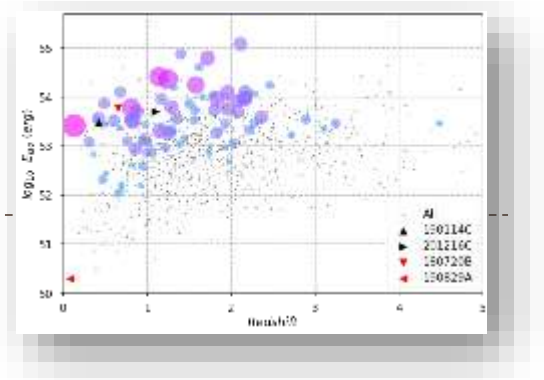


GRB 785 – South



Omega : Difficult to get spectral information, but alert can be resent “immediately”
Alpha : not detected

Conclusion



- **Preliminary GRB population**
  - 1000 long GRB + afterglows
    - Only high luminosity Swift GRB
  - No short GRBs
- **Conservative simulation**
  - Delays = 107 s
  - Maximal moon vetoing, no extra-low altitude
  - No prompt signal included
- **Detection rate is 1.8 ± 0.2 stat per year**
  - "Bright" GRBs are common
    - 1 event per year >20σ, every 2 years >50σ
  - Rate is stable with delays < 100-150 s
  - EBL has small effect except Gilmore (-21%)
  - ~10% of population detected (81/1000)
    - ~ duty cycle
  - 1 per year, per site (~ H.E.S.S., MAGIC (x2?))
- **Loss with α configuration**
  - Moderated for rates : South -20%, Total: 14%
    - But -30% >20 sig
  - Spectral information : Can be dramatic
    - Higher energy threshold reduce high z Science
    - Higher delays limit access to prompt
- **Still to be done – Population**
  - Increase statistics
  - also lower (Eiso, z) values (HESS 190829A)
  - Add short GRBs
- **Next steps – Analysis**
  - Find back HESS / MAGIC detections ?
  - Combine N & S in spectral analysis
  - Add prompt component
  - Add moonlight period (+ ~15-20% expected)
  - Study systematics