CTAO
Cherenkov Telescope Array Observatory

CTAO LST–1 Observations Of Magnetar SGR 1935+2154: Deep Limits On Sub-second Bursts And Persistent TeV Emission

Advances in Modeling HE Astrophysical Sources

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The CTAO and LST-1

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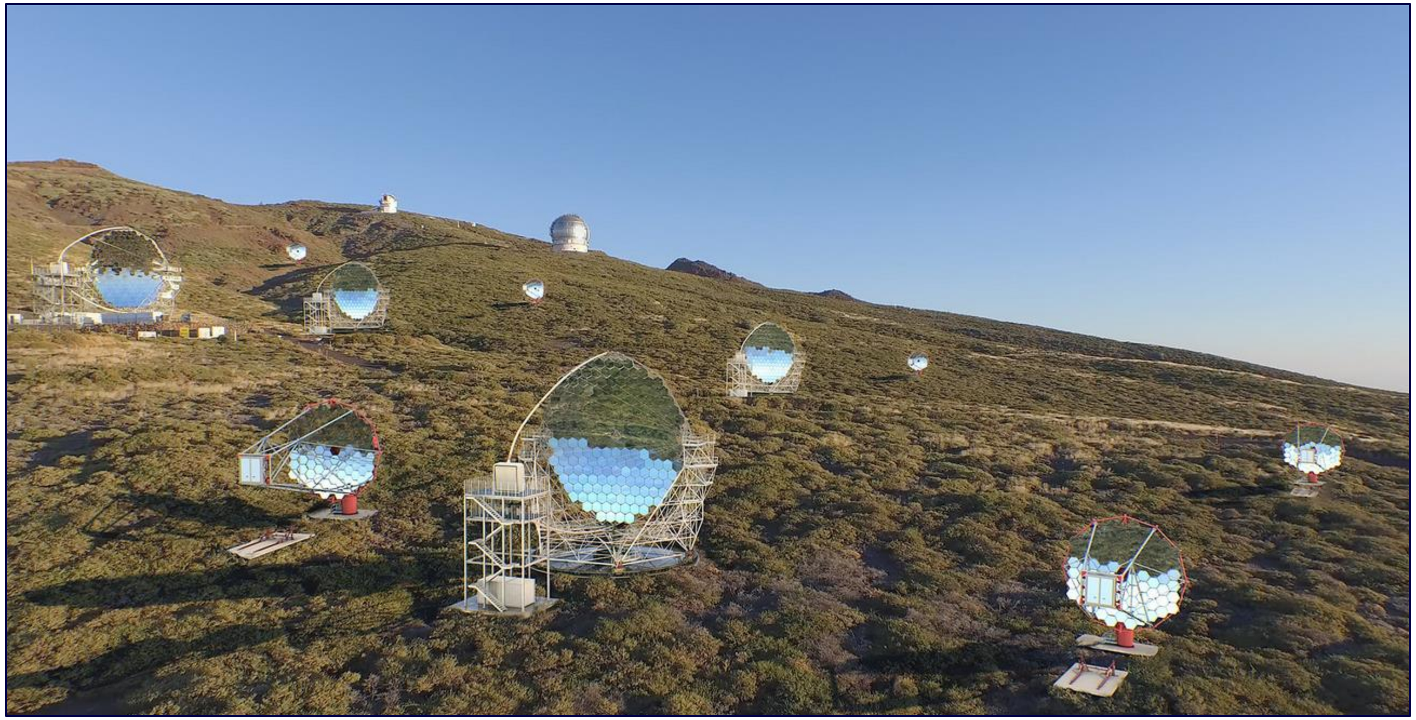
The CTAO

- Cherenkov Telescope Array Observatory
- > 60 telescopes, sensitivity ×10 improvement
- Full-sky Coverage from 2 sites (La Palma, Chile)
- Wide Field of View (>5°)
- Broad Energy Range (20 GeV – 300 TeV)
- Fast repointing time (< 30s)

The LST-1

- Large-Sized Telescope Prototype (LST-1)
- Active since 2019
- Energy Range: 20 GeV – 10 TeV



Artistic Rendering of CTAO North site (La Palma), with LST-1 on far left

Magnetars

Magnetars

- Subclass of Isolated Neutron Stars (NSs)
  - High Magnetic Field $B \sim 10^{14-15} G$, Twisted Magnetosphere
  - Large Rotation Period $\sim 1 - 12\ s$
- $\approx$ 30 in Galaxy and Magellanic Clouds
- Powered by $\boldsymbol{B}$ Decay: Persistent and Bursting emission

Bursting Emission

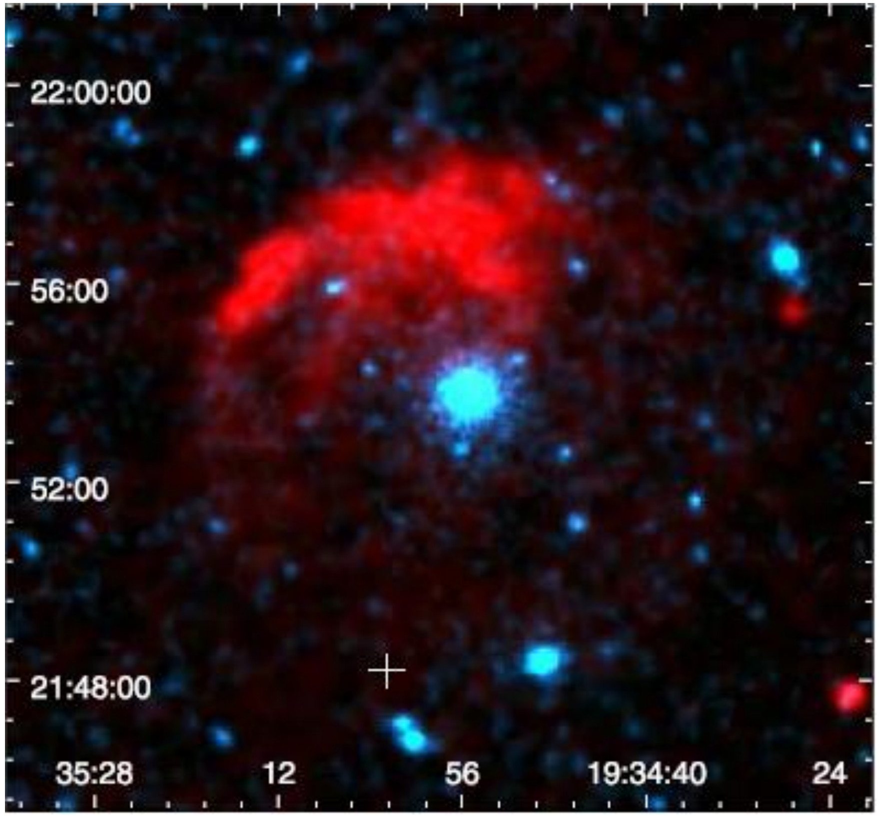
- Outburst periods $\sim weeks\ (keV - MeV)$
- Short Bursts $\sim 0.1\ s$, $\mathrm{L} \sim 10^{36-43} erg\ s^{-1}$
  - $\boldsymbol{B}$ Stress cracks NS crust → Hot plasma ejection
  - Cut-off Power Law / 2 Black Body
- Intermediate, Giant Flares (MGF) $\mathrm{L} \sim 10^{44-47} erg\ s^{-1}$

Persistent Emission

- X-ray, pulsed emission
- Soft X-ray Thermal Component
  - Heating powered by $\boldsymbol{B}$ decay
  - Peak at $\sim 0.5\ keV$
- Hard X-ray Power-Law Component
  - Inner magnetosphere e^- scatter thermal photons
  - Multiple Resonant Cyclotron Scattering
- Cut-off $\sim 1\ MeV$ not observed
  - COMPTEL MeV Upper Limits $\sim 10^{-10} erg\ s^{-1} cm^{-2}$
  - Fermi-Lat GeV Upper Limits $\sim 10^{-12} erg\ s^{-1} cm^{-2}$

SGR 1935+2154

- Galactic Magnetar in SNR G57.2+0.8 with SGR activity
- Discovered in 2014, many outburst periods
  - Period $\sim 3.24\ s$, Age $\sim 3.6\ kyr$, Distance $\sim 4.4\ kpc$
  - BB Temperature $(0.47 \pm 0.02)\ keV$, PL index (1.8 ± 0.5)
- FRB 20200428D
  - Detected X-ray and Radio bursts simultaneously!
  - Magnetars can produce FRBs!
- Is there TeV emission in coincidence of SGR 1935 activity?
  - LST-1 Observations: $33\ h$ in July, September 2021, June 2022
  - 9 simultaneous X-ray Bursts
  - Reconstruction adapted for real Observing Conditions



SNR G57.2+0.8 environment
SGR 1935+2154 in the center
THOR 1.4 GHz, XMM Newton
(Zhou et al., 2020)

SGR 1935+2154

Persistent Emission

Persistent Emission

- Standard Analysis on 25h of good-quality observations: 2021 (July-Sept.), 2022 (June)
- Standard Stacked Analysis (0.1 – 10 TeV) for Significance, Flux
- No detection overall (**Figs. 1, 2**) -> Upper Limits (ULs)
  - No nightly variability

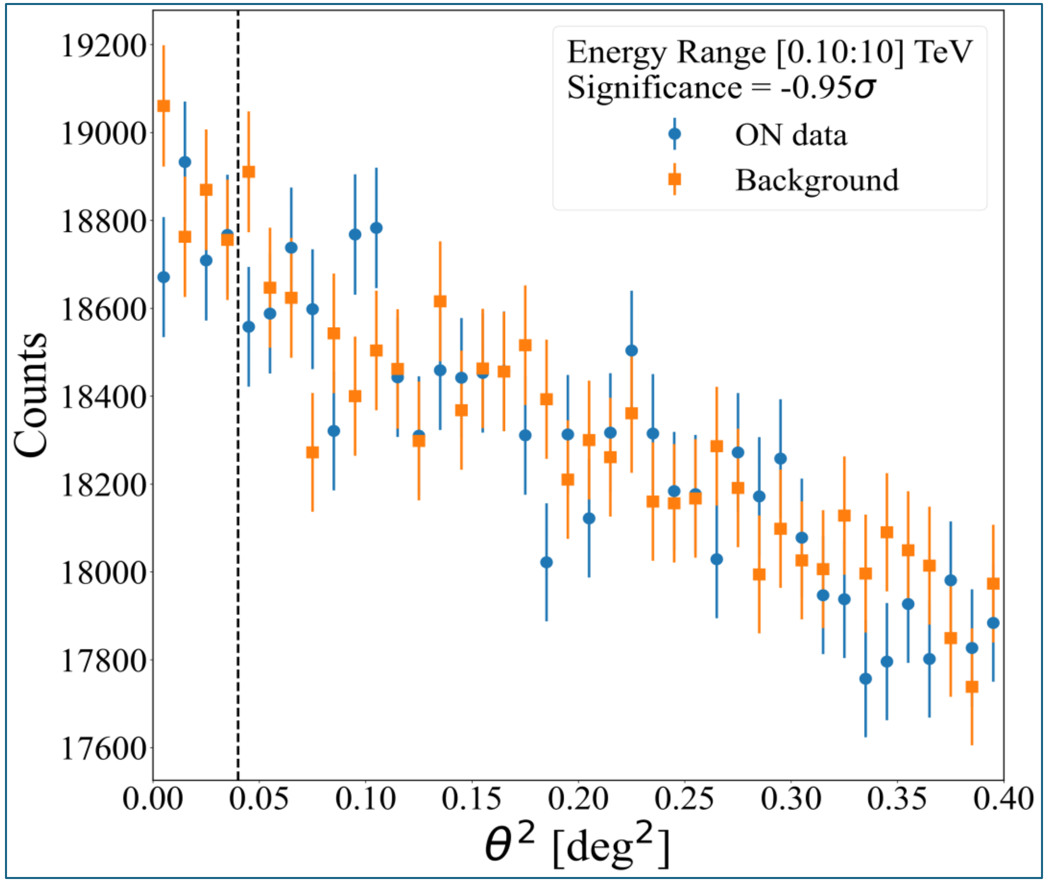


Figure 1
Stacked θ^2

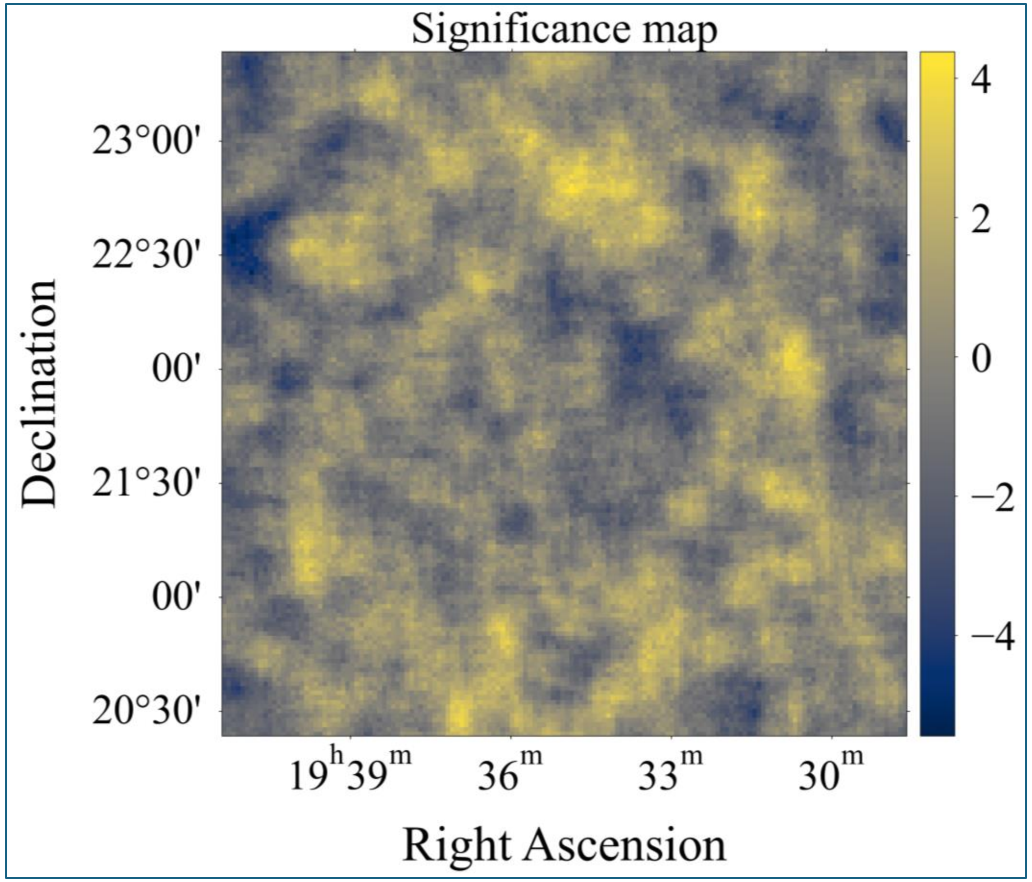


Figure 2
Significance Map

Persistent Emission

- TeV ULs ~ X-ray flux
  - LST-1 improves H.E.S.S. ULs (Index=−2.5, 95% CL)
- Agreement with Magnetar Models
  - Emission break expected in MeV
  - Current MeV ULs $\sim 10^{-10} erg\ s^{-1} cm^{-2}$
  - Current GeV ULs $\sim 10^{-12} erg\ s^{-1} cm^{-2}$
- Emission Detection of FRB Progenitors?
  - PRSs likely powered by pulsar/magnetar in nebulae
  - FRB Progenitors might emit VHE γ-rays (PWNe or SNRs)
- Interesting targets for CTAO

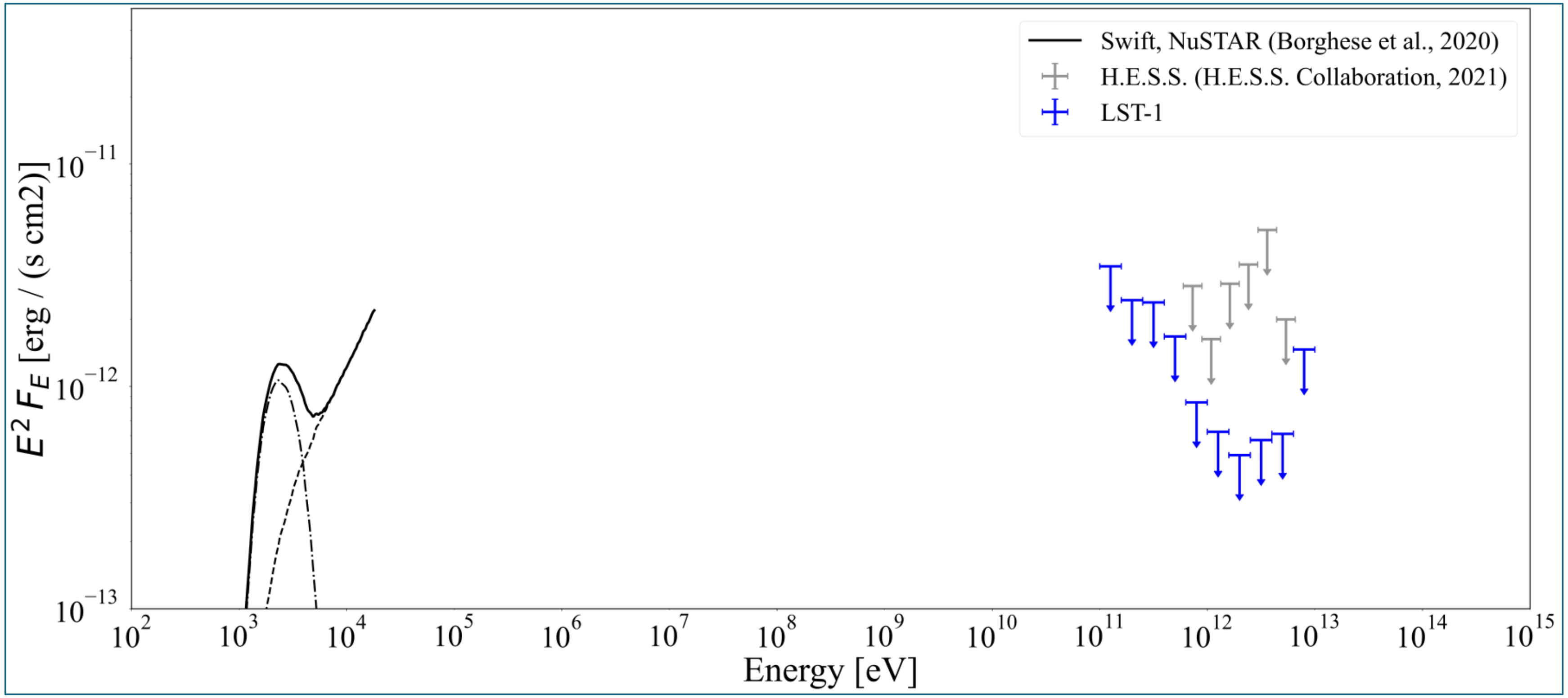


Figure 3
Spectral Energy Distribution

SGR 1935+2154

Bursting Emission

Bursting Emission

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Data Analysis

- Burst Analysis developed
  - Signal: a $\mathbf{0.1s}$ Burst above a Poisson Background
  - New dataset obtained with optimized Cherenkov Cuts
- **9** X-ray Bursts simultaneous to Observations

Results

- No detection -> Bayesian Burst ULs $[0.1 - 10]\ TeV$
  - Sensitivity $\approx 3.0 \cdot 10^{-8}\ ph\ s^{-1} cm^{-2}$
- Unbiased Burst Search: No detection
  - Sensitivity $\approx 6.2 \cdot 10^{-8}\ ph\ s^{-1} cm^{-2}$

#	Time of Alert ISOT UTC	Instrument	LST-1 R_{BKG} s^{-1}	$N_{5\sigma}$	N_{ON}	Flux UL $10^{-8} s^{-1} cm^{-2}$	Fluence UL $10^{-9}\ erg\ cm^{-2}$
1	2021-07-07 00:33:31.670	Fermi-GBM	0.81±0.02	4	0	2.01	1.50
2	2021-09-10 23:40:34.460	Fermi-GBM	1.05±0.03	4	0	1.95	1.45
3	2021-09-11 22:51:41.600	GECAM	0.95±0.03	4	0	2.03	1.51
4	2021-09-11 23:55:45.872	NICER	1.01±0.03	4	0	1.94	1.45
5	2021-09-12 00:34:37.450	GECAM	0.61±0.03	4	0	1.97	1.47
6	2021-09-12 00:45:49.400	GECAM	0.66±0.03	4	0	1.96	1.46
7	2021-09-12 22:16:36.200	GECAM	0.68±0.02	4	1	3.61	2.69
8	2021-09-12 23:19:32.080	Fermi-GBM	1.04±0.03	4	0	2.02	1.51
9	2021-09-13 00:27:25.200	GECAM	1.04±0.03	4	0	1.95	1.45
	STACKED $\delta t = 0.9s$		0.87±0.04	8	1	0.30	0.20

Table 1
VHE ULs simultaneous to external alerts on a 0.1s time scale.

Bursting Emission

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Discussion

- TeV ULs $\sim 10^{-3}$ X-ray Flux
  - First X-TeV Magnetar Burst SED on $0.1s$ (**Fig. 4**)
- Agreement with Magnetar Models
  - No TeV emission from “regular” short bursts
- Magnetar systems more complex than SGR 1935+2154 may emit High-Energy Gamma Flashes (HEGF)

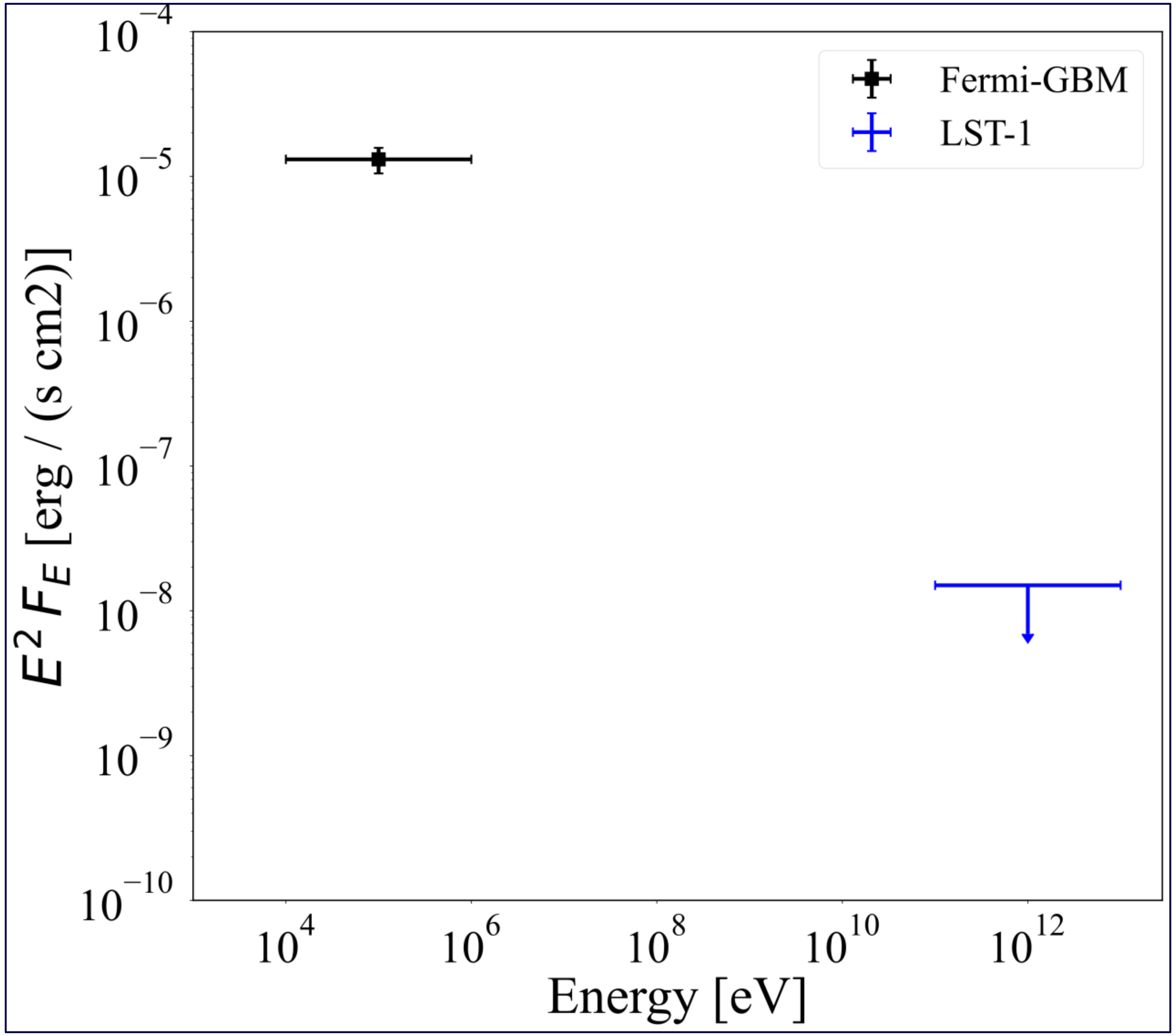

Figure 4. Burst #1 Spectral Energy Distribution

Bursting Emission

Discussion: FRBs

- Magnetar Burst + PWN can produce FRB + HEGF
- Murase, 2016: TeV Burst Fluence φ can constrain $E_{outflow}$
- SGR 1935+2154 example:
  - $\varphi_{UL} \sim 1.5 \cdot 10^{-9}\ erg\ cm^{-2} \rightarrow E_{outflow} < 3.6 \cdot 10^{37}\ erg$

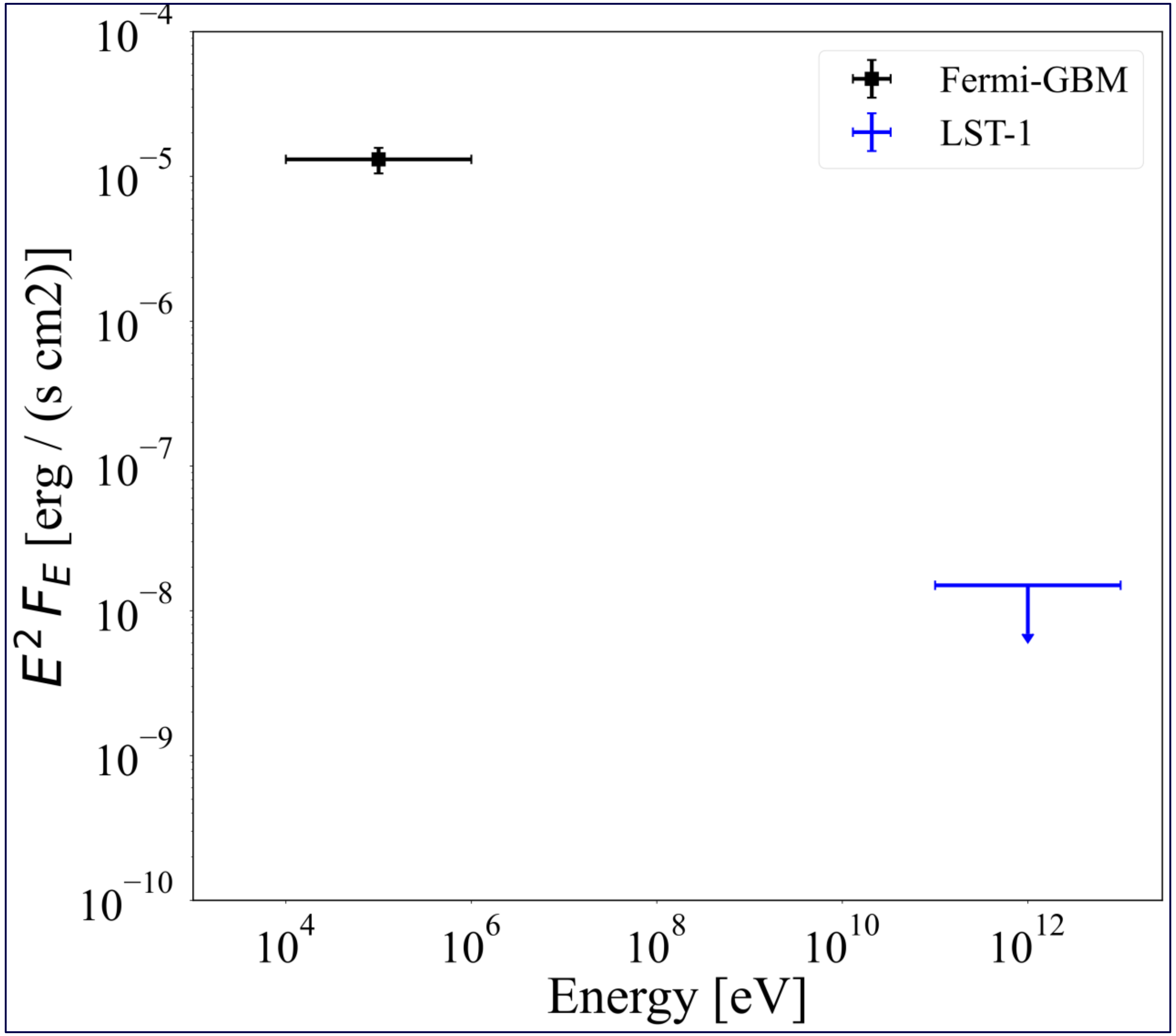

Figure 4. Burst #1 Spectral Energy Distribution

Bursting Emission

Discussion: Candidate MGF detected at GeV

- Ajello, 2021 detected MGF at GeV from Sculptor Galaxy
  - Flux $\Phi(> 0.1\ GeV) = (4.1 \pm 2.2) \cdot 10^{-6} s^{-1} cm^{-2}$
  - Distance $d = 3.5\ Mpc$
  - Power Law Index = -1.7 ± 0.3
- Scaled Flux: $\Phi(> 0.1\ TeV) \approx 2 \cdot 10^{-3} s^{-1} cm^{-2}$, **IF**
  - Power Law Extends to TeV
  - Source is at $d = 4.4\ kpc$
- LST-1 can detect a similar burst up to a few Mpc
- Caveats:
  - Observation conditions can degrade sensitivity
  - Spectral Model extension uncertain
  - Flare duration may be different

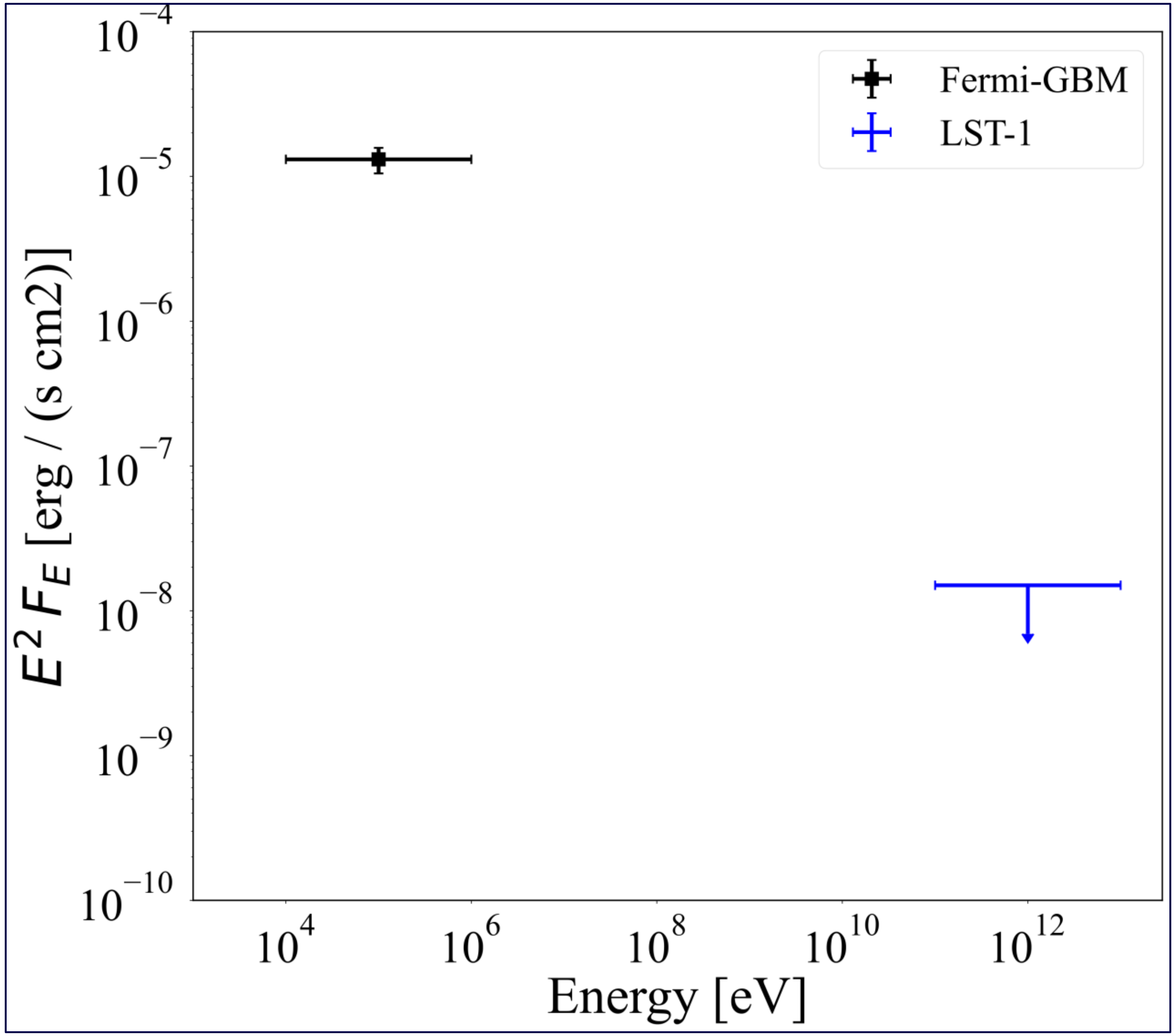

Figure 4. Burst #1 Spectral Energy Distribution

SGR 1935+2154

Conclusions

Conclusions

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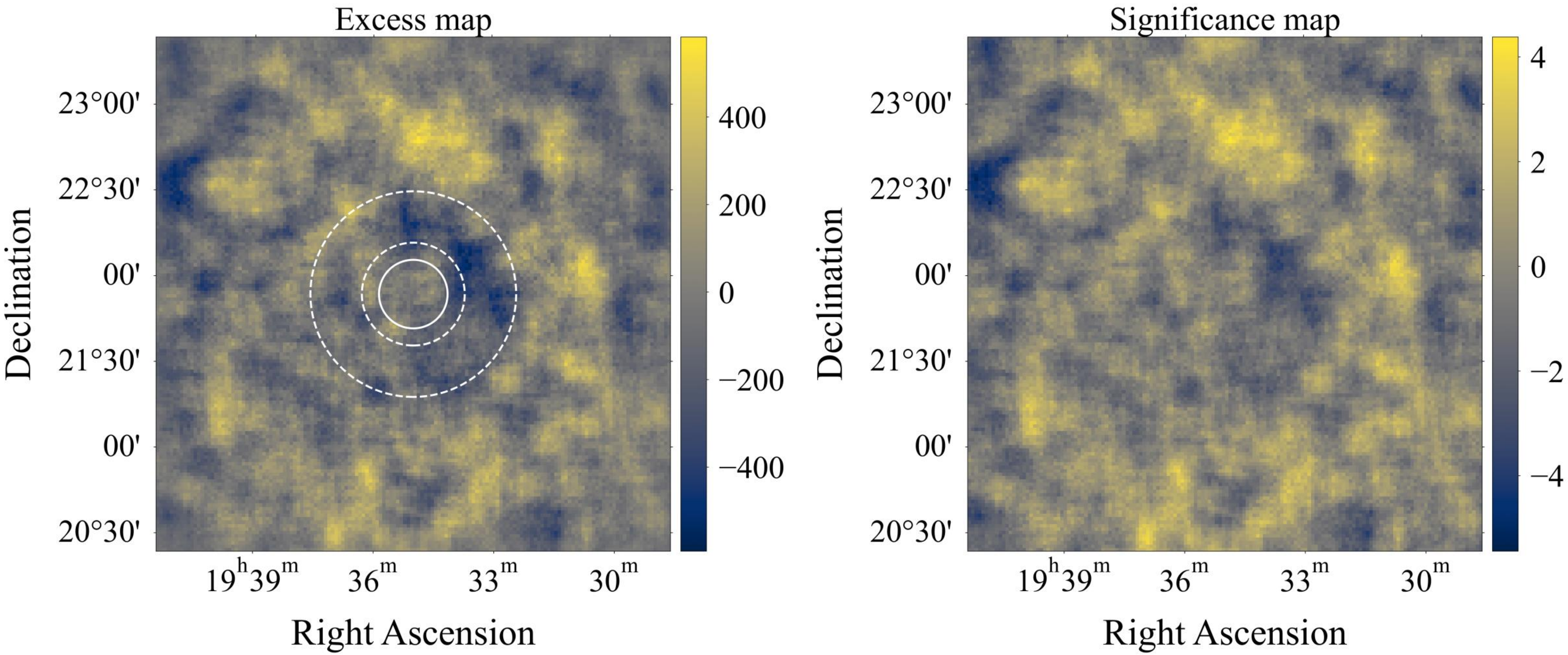
- We analysed >25h of good-quality LST-1 observations
- No persistent TeV emission detected, in agreement with observations and models.
  - Cutoff expected at MeV for magnetars.
  - TeV ULs ~ X-ray flux
- We developed the **Burst Analysis** for short transients with low-photon-statistics
- No TeV Burst emission detected for 9 bursts simultaneous to LST-1 observations
  - Burst TeV ULs $\sim 10^{-3}$X-ray Burst Flux
- TeV emission not ruled out for other similar sources (e.g., progenitors of FRBs)
  - Magnetars, GMFs, FRBs, short GRBs, fast transients… remain interesting targets for CTAO, LST-1
- Non-Consortium Scientific Paper to A&A

Thank you

CTAO

Extra

Persistent Emission



LST–1 Observations Of Magnetar SGR 1935+2154:
Deep Limits On Sub-second Bursts And Persistent TeV Emission

- Aims.
  - Search for potential TeV counterpart to SGR 1935+2154 emission (persistent, bursting)
  - Insights on mechanisms of magnetar emission and Very-High Energy (VHE) processes
- Methods.
  - Stacked spectral analysis (25h) for persistent emission (2021-2022 observations)
  - ***Burst Analysis*** in 9 windows (0.1s) for transient emission [in *low-photon-statistics* regime]
- Results
  - No persistent nor transient VHE emission detected
  - TeV Upper Limits (ULs) to *short magnetar burst emission* simultaneous to X-ray bursts.
- Conclusions
  - If TeV emission exists, conditions not covered by observations
  - Burst Analysis development for LST-1, can be applied to fast transients (e.g. FRBs)

The low-photon-statistics regime

- Significance, Flux Estimation require $\gtrsim$ 10 photons
  - Wilks' Theorem
- Not possible in low-photon-statistics regime
  - For **LST-1**: $\lesssim$ **10s**
  - Short GRBs, Fast Radio Bursts (FRBs), Magnetar Bursts and Flares
- We developed the Burst Analysis for CTAO LST-1
  - Based on Poisson statistics
- Science Case: Magnetar Bursts of SGR 1935+2154

↕ Soft Gamma Repeater

The CTAO LST-1

Transient Emission

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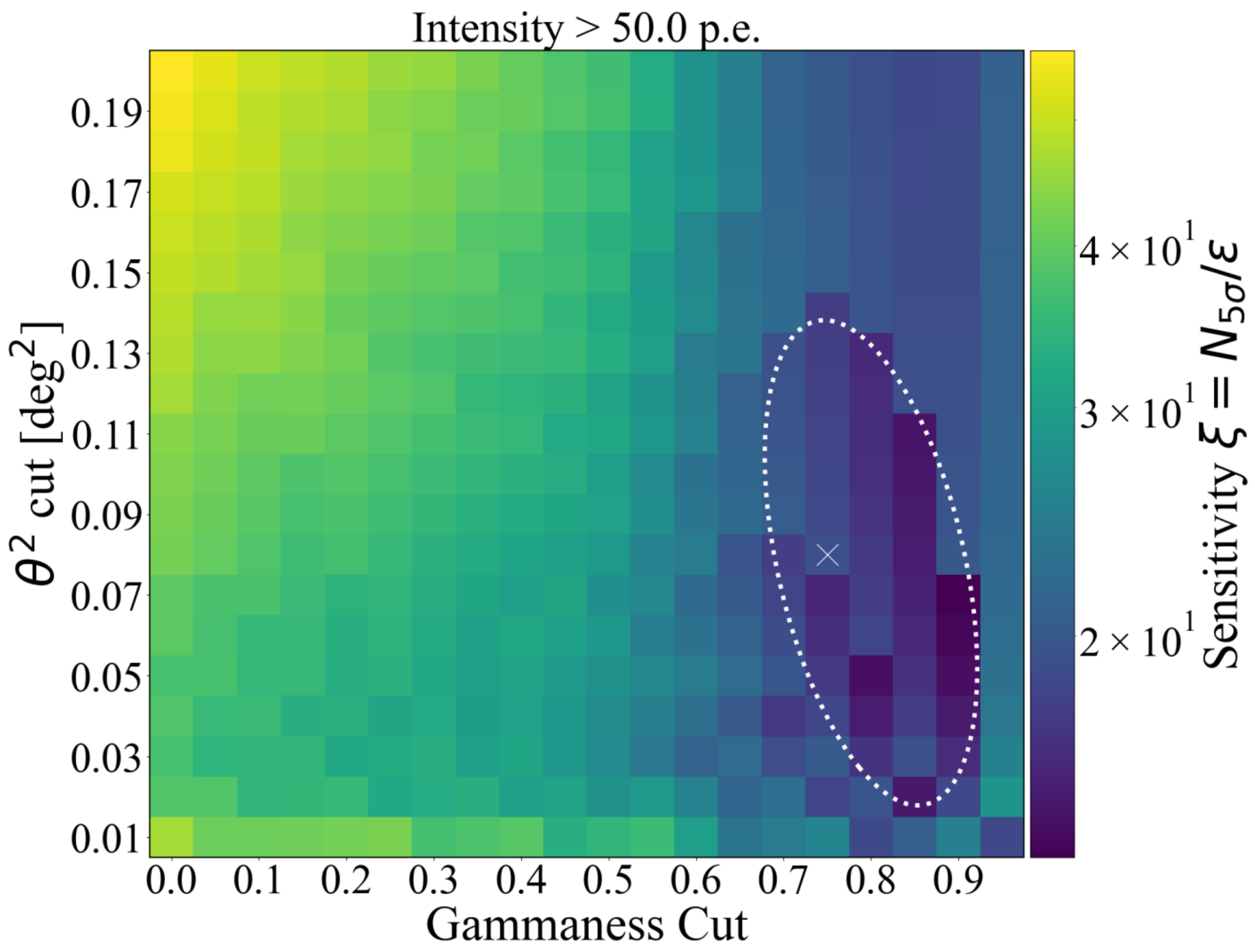
Burst Analysis Cuts (Not in paper)

- Li&Ma, MLE not applicable on 0.1s time scale due to *low-photon-statistics* regime
- Must redefine sensitivity and optimise cuts

- Hypothesis Test: *Poisson* Background
  - $N_{5\sigma}$: counts to have a detection in a 0.1s bin above a constant background rate measured from OFF region.
  - ε: cuts Efficiency on γ-rays, measured from MC simulations
  - Sensitivity $\xi = {}^{N_{5\sigma}}/_{\varepsilon}$

- Optimal Burst Cuts: $g_{cut} = 0.75$, $i_{cut} = 50\ p.e.$, $\theta^2_{cut} = 0.08\ deg^2$



Burst Analysis Sensitivity and Optimal Cuts to detect a 0.1s burst

Transient Emission

$$\mu_{s,UL} = \frac{1}{2} F_{\chi^2}^{-1}(p|2(N_{ON} - 1)) - \mu_{BKG}$$

$$p = 1 - \alpha \left(F_{\chi^2}(2\mu_{BKG}|2(N_{ON} - 1)) \right)$$

Flux UL = $\boldsymbol{\mu_{s,UL}}$ **/ Exposure**

- $\alpha = 0.95$ Confidence Level
- F Cumulative Distribution Function of χ^2
  - $\mathrm{DOF} = 2(N_{ON} - 1)$