Giornate INAF 2023 - Napoli 2-5 maggio

New detection in VHE

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Summary

Galactic sources

- **PeVatrons**

  In 2021 LHAASO has detected 12 potential PeVatrons [Cao et al. Nature (2021)]

- **Diffuse emission**

  Tibet ASγ and LHAASO have detected sub PeV diffuse emission

  [Amenomori et al. PRL (2021)]

Extra-galactic sources

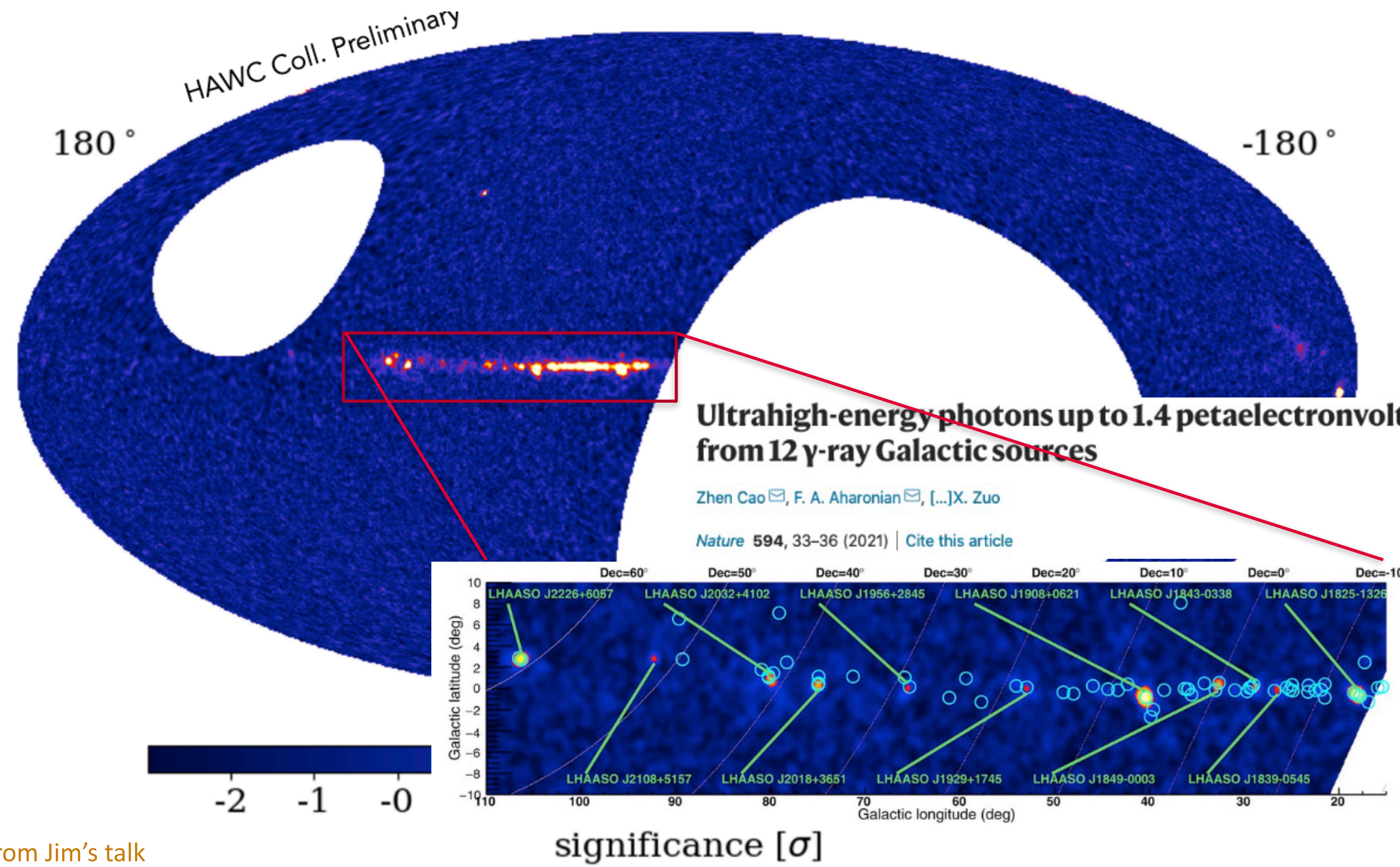
- **GRBs**

  Starting from 2018 GRBs have been detected in VHE

- **Starbursts**

  PAO confirmed correlation between UHECRs and SBGs at 4.7σ

The VHE sky in the present



Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources

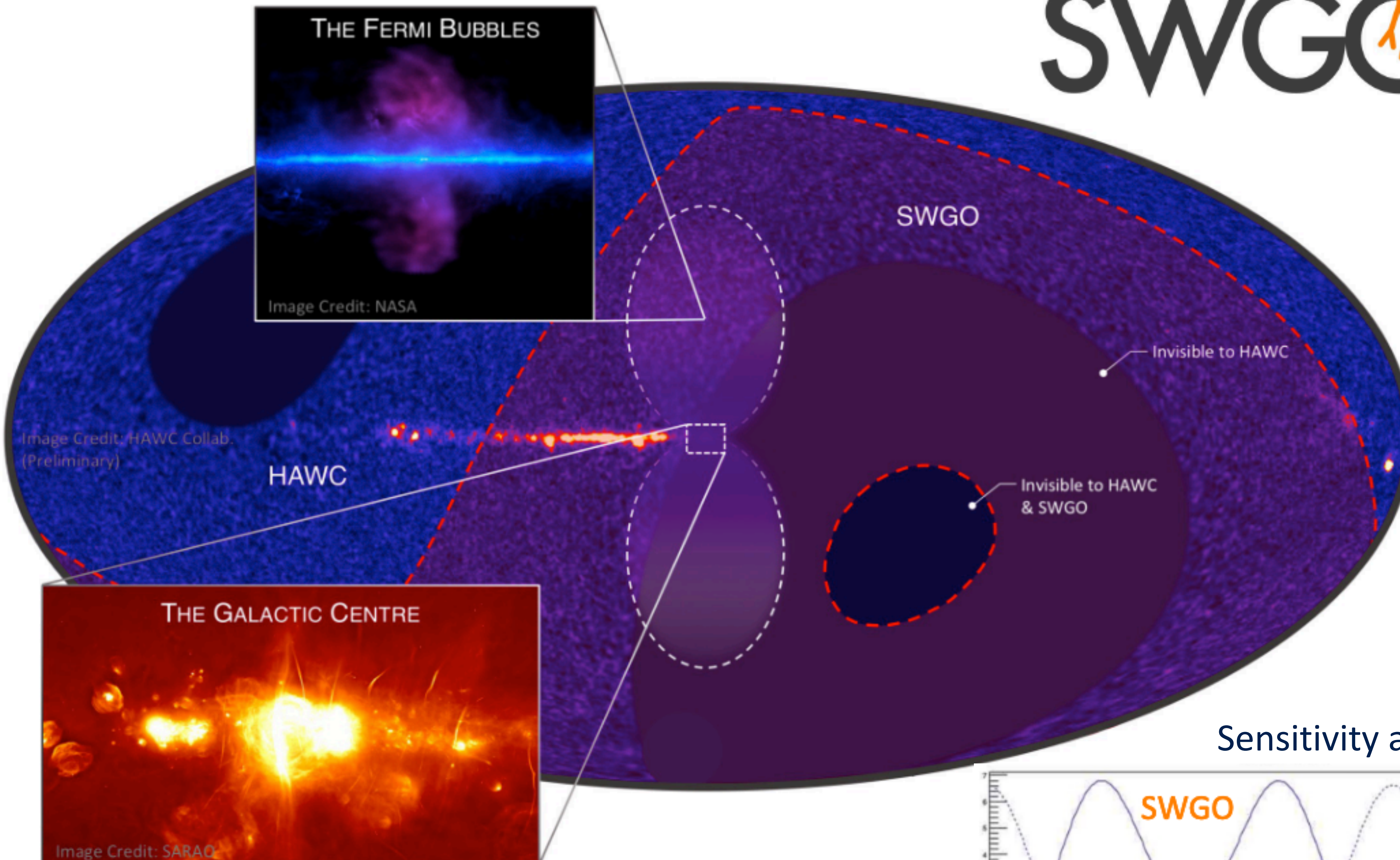
Zhen Cao, F. A. Aharonian, […]X. Zuo

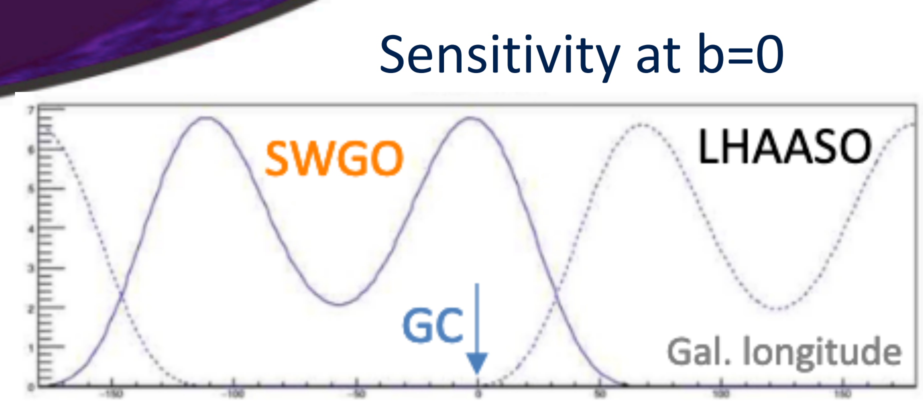
Nature **594**, 33–36 (2021) | Cite this article

Slide from Jim's talk

The VHE sky in the future

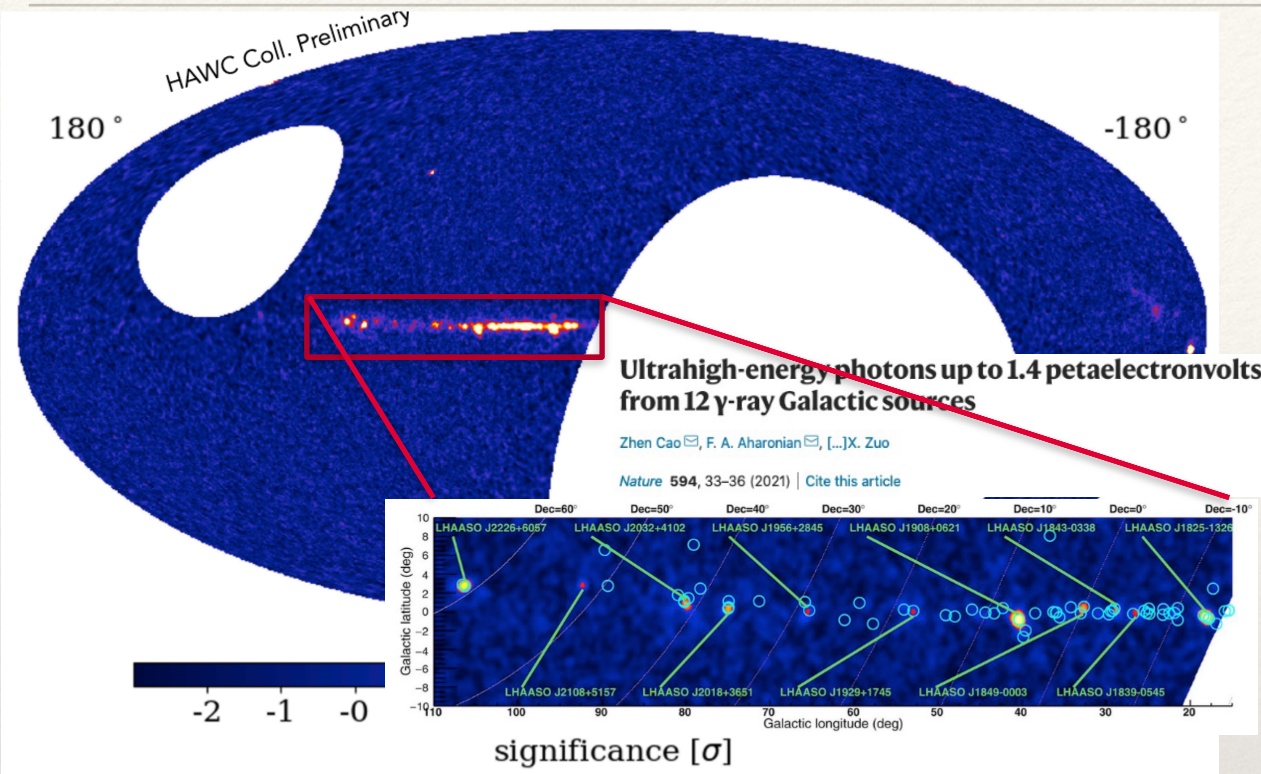
www.swgo.org





Slide from Jim’s talk

LHAASO sources



Z. Cao et al. Nature (2021)

LHAASO observed 12 sources with gamma-ray emission at E> 100 TeV

- Majority of associations with PSR
- Few SNRs (4/12)
- 2 Star clusters

Uncertain association due to pour angular resolution

Need to have much better angular resolution

LHAASO Source	Possible Origin	Type	Distance (kpc)	Age (kyr)[a]	L_s (erg/s)[b]	Potential TeV Counterpart[c]
LHAASO J0534+2202	PSR J0534+2200	PSR	2.0	1.26	4.5×10^{38}	Crab, Crab Nebula
LHAASO J1825-1326	PSR J1826-1334	PSR	3.1 ± 0.2^d	21.4	2.8×10^{36}	HESS J1825-137, HESS J1826-130,
	PSR J1826-1256	PSR	1.6	14.4	3.6×10^{36}	2HWC J1825-134
LHAASO J1839-0545	PSR J1837-0604	PSR	4.8	33.8	2.0×10^{36}	2HWC J1837-065, HESS J1837-069,
	PSR J1838-0537	PSR	1.3^e	4.9	6.0×10^{36}	HESS J1841-055
LHAASO J1843-0338	SNR G28.6-0.1	SNR	9.6 ± 0.3^f	$< 2^f$	—	HESS J1843-033, HESS J1844-030, 2HWC J1844-032
LHAASO J1849-0003	PSR J1849-0001	PSR	7^g	43.1	9.8×10^{36}	HESS J1849-000, 2HWC J1849+001
	W43	YMC	5.5^h	—	—	
LHAASO J1908+0621	SNR G40.5-0.5	SNR	3.4^i	$\sim 10 - 20^j$	—	MGRO J1908+06, HESS J1908+063,
	PSR 1907+0602	PSR	2.4	19.5	2.8×10^{36}	ARGO J1907+0627, VER J1907+062,
	PSR 1907+0631	PSR	3.4	11.3	5.3×10^{35}	2HWC 1908+063
LHAASO J1929+1745	PSR J1928+1746	PSR	4.6	82.6	1.6×10^{36}	2HWC J1928+177, 2HWC J1930+188,
	PSR J1930+1852	PSR	6.2	2.9	1.2×10^{37}	HESS J1930+188, VER J1930+188
	SNR G54.1+0.3	SNR	$6.3^{+0.8\ d}_{-0.7}$	$1.8 - 3.3^k$	—	
LHAASO J1956+2845	PSR J1958+2846	PSR	2.0	21.7	3.4×10^{35}	2HWC J1955+285
	SNR G66.0-0.0	SNR	2.3 ± 0.2^d	—	—	
LHAASO J2018+3651	PSR J2021+3651	PSR	$1.8^{+1.7\ l}_{-1.4}$	17.2	3.4×10^{36}	MGRO J2019+37, VER J2019+368,
	Sh 2-104	H II/YMC	$3.3 \pm 0.3^m/4.0 \pm 0.5^n$	—	—	VER J2016+371
LHAASO J2032+4102	Cygnus OB2	YMC	1.40 ± 0.08^o	—	—	TeV J2032+4130, ARGO J2031+4157,
	PSR 2032+4127	PSR	1.40 ± 0.08^o	201	1.5×10^{35}	MGRO J2031+41, 2HWC J2031+415,
	SNR G79.8+1.2	SNR candidate	—	—	—	VER J2032+414
LHAASO J2108+5157	—	—	—	—	—	—
LHAASO J2226+6057	SNR G106.3+2.7	SNR	0.8^p	$\sim 10^p$	—	VER J2227+608, Boomerang Nebula
	PSR J2229+6114	PSR	0.8^p	$\sim 10^p$	2.2×10^{37}	

LHAASO sources: candidate

❖ *Hadronic sources*

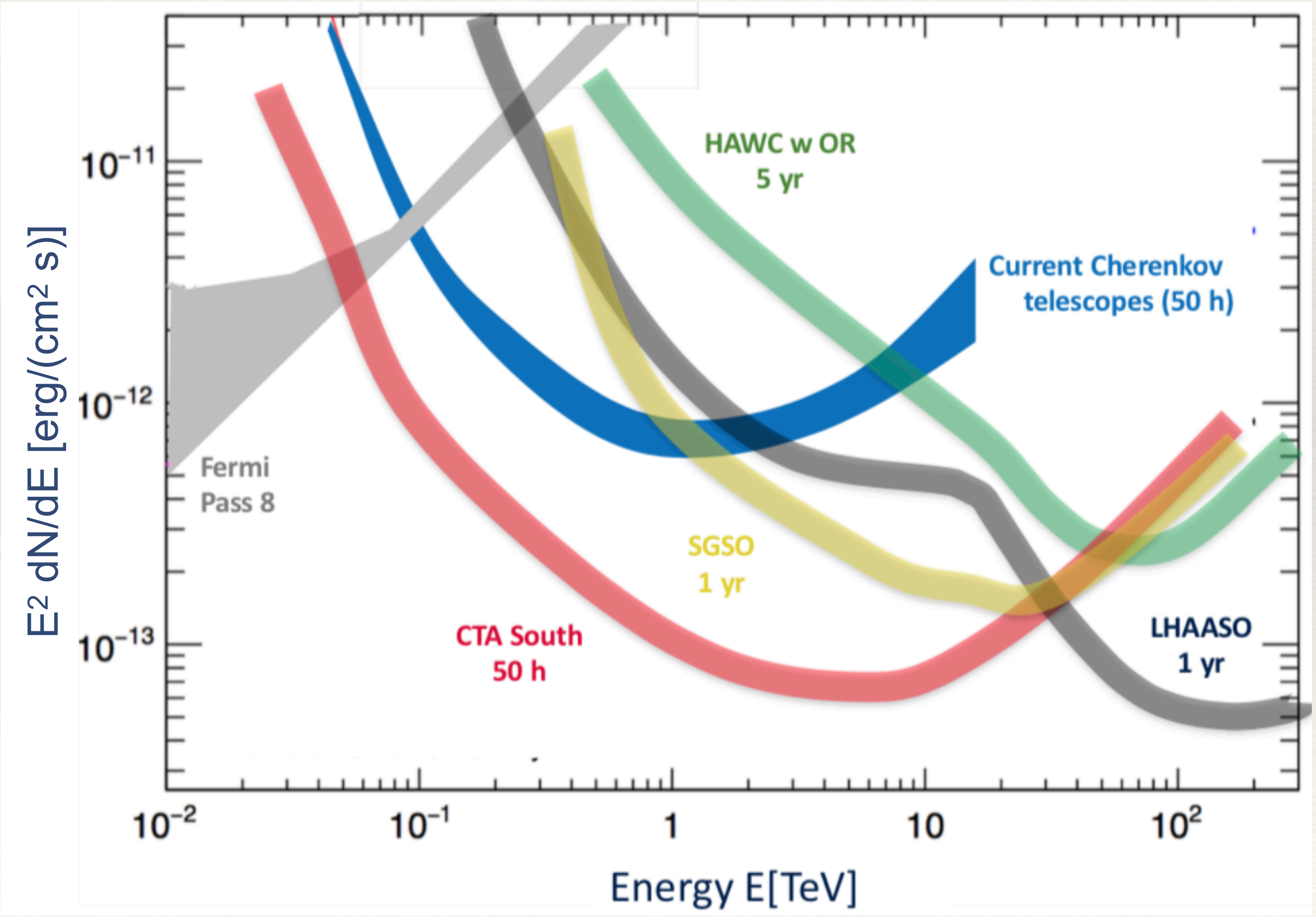
- SNRs: the (not any more?) preferred candidate
  - not many (4 possible associations)
  - All middle aged - possible interaction with molecular clouds
  - No evidence for acceleration > 100 TV even in young SNRs
  - From theory only very powerful and rare SNR can reach PeV
- Massive young stellar clusters (2 associations)
  - Several YSC have been associated to gamma-rays
  - LHAASO detected ~1.4 PeV photon in coincidence with Cygnus OB2
  - Theoretical models still immature:
    - do not explains emission at $\gtrsim 1\,\mathrm{PeV}$)

❖ *Leptonic sources*

- Pulsars and PWNe
- All LHAASO sources are close to pulsars (not a surprise due to the large angular resolution)
- Leptonic origin of gamma-rays > 100 TeV is possible but requires peculiar conditions
  - requires low magnetic field ($\lesssim 3\mu G$)
  - not easy to accomodate for young PWNe
  - need to separate acceleration from cooling zones
- **PWNe as hadronic accelerators?**

Sensitivity curves of VHE observatories

LHAASO opened a new window thanks to its high sensitivity at $E \gtrsim 30\,\mathrm{TeV}$



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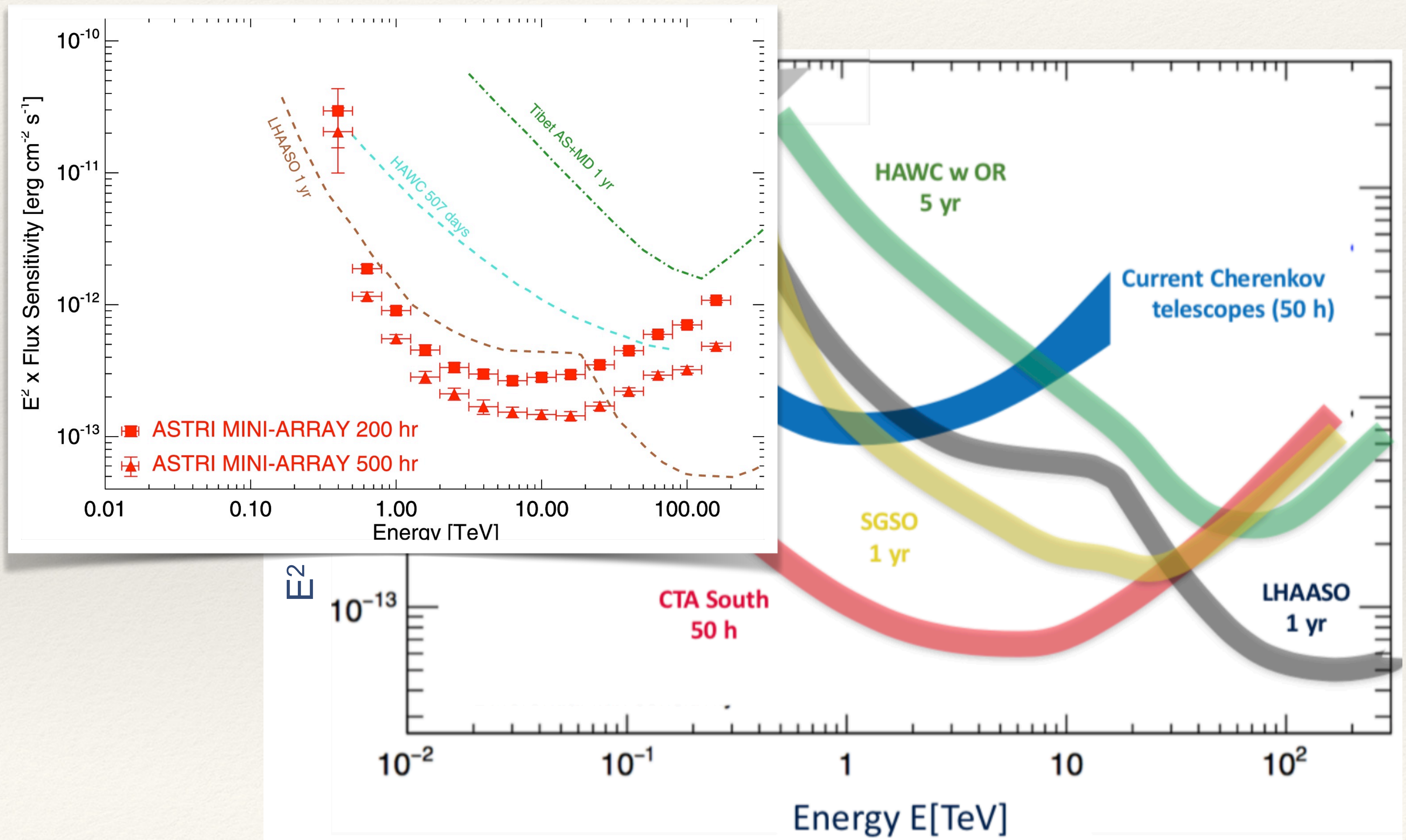
Comparison with ASTRI- Mini-Array

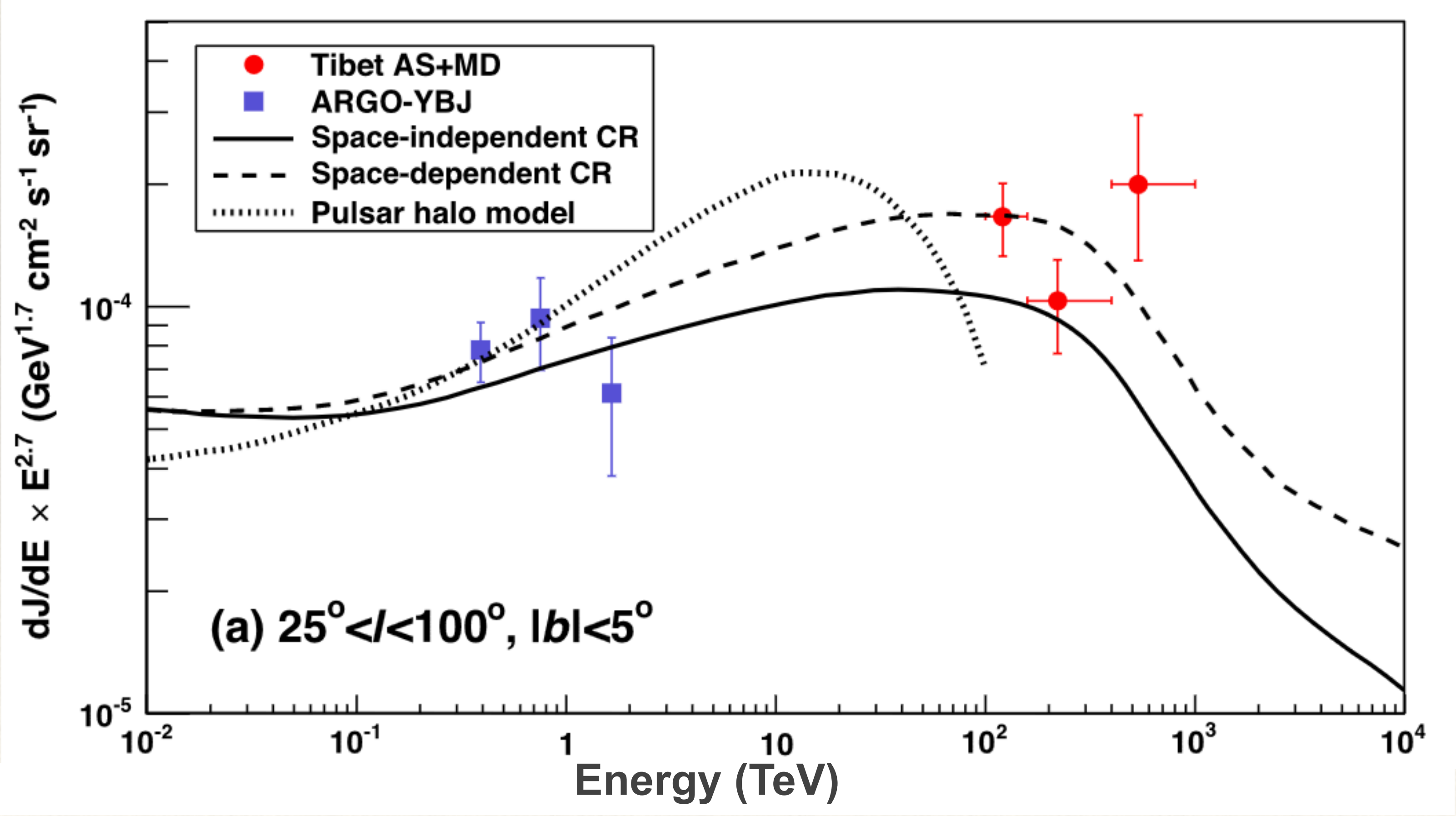


Galactic diffuse emission at VHE

Tibet ASγ and LHAASO have detected sub PeV diffuse emission [Amenomori et al. PRL (2021)]

Real diffuse component *or* unresolved sources?

Diffuse γ-ray emission compared with different models of CR propagation and PWN halo model



Galactic diffuse emission at VHE

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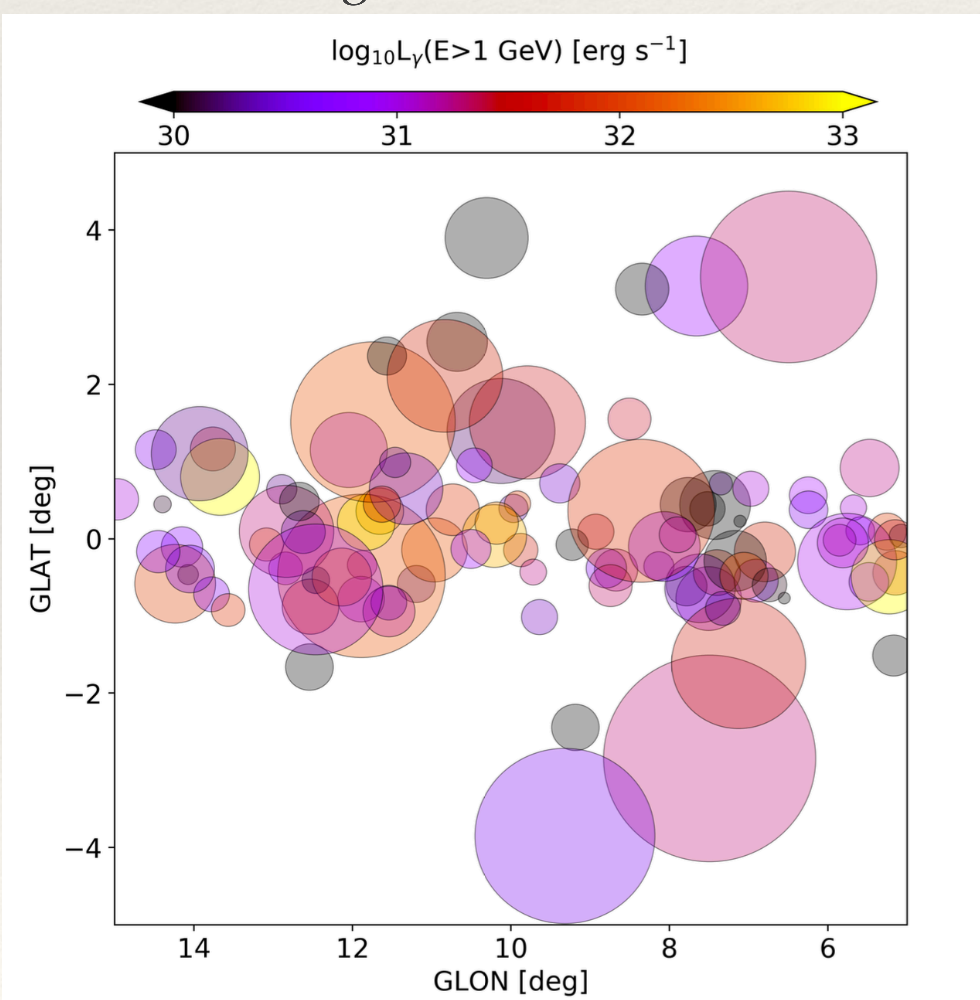
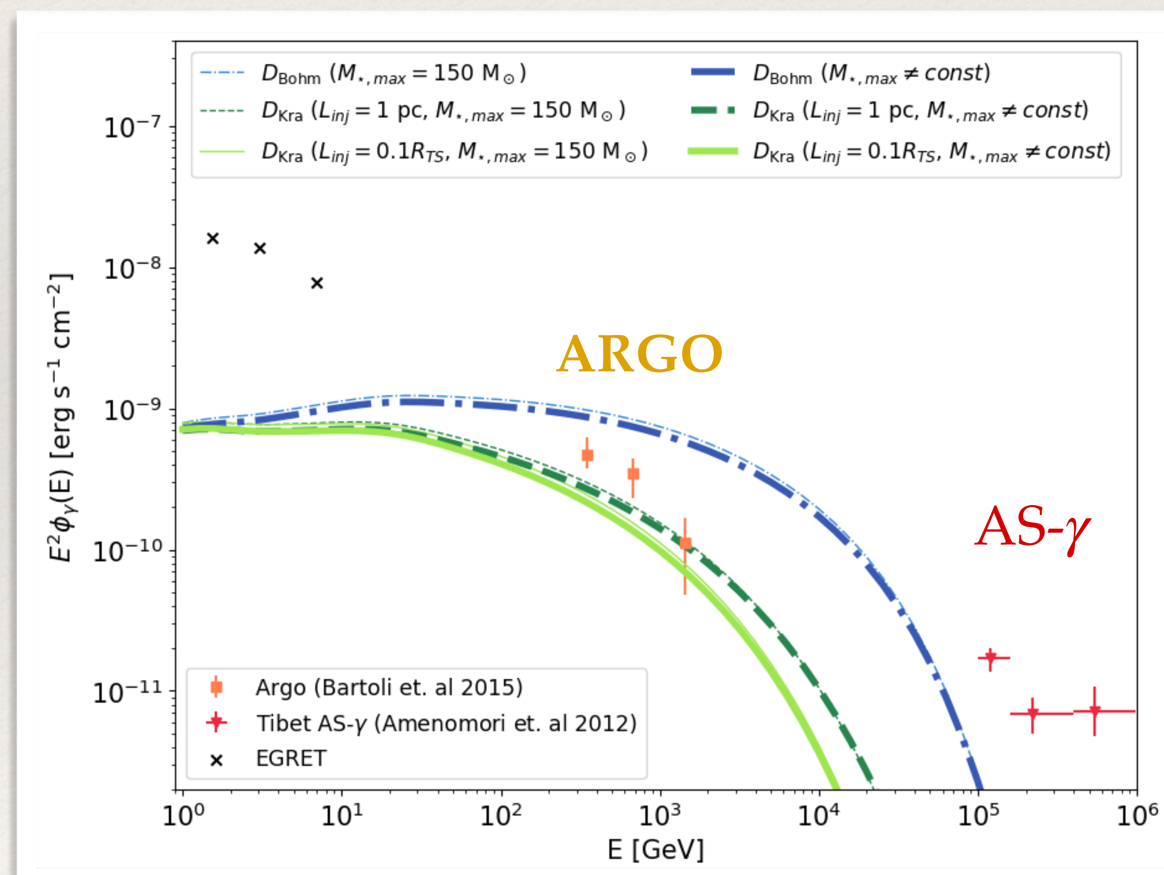
Real diffuse component *or* unresolved sources?

S. Menchiari (PhD thesis, 2023)

Estimated number of stellar clusters in a region 10°×10°



Contribution from unresolved Stellar Clusters



GRBs @ VHE

GRBs detected in VHE gamma-rays since 2018

GRB	Redshift	$E_{g,iso}$	Range [TeV]	T_{90} [s]	VHE detector
180720B	0.653	6×10^{53}	0.1 – 0.4	49	HESS
190114C	0.4245	3×10^{53}	0.2 – 1	25	MAGIC
190829A	0.0785	2×10^{50}	0.2 – 4	63	HESS
201015A	0.423	1.1×10^{50}	> 0.14	10	MAGIC
201216C	1.1	5.79×10^{53}	~ 0.100	30	MAGIC
221009A	**0.151**	$\mathbf{3 \times 10^{54}}$	**0.5-18**	**600**	**LHAASO-WCDA** **LHAASO-KM2A**

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201216C	1.1	5.79×10^{53}	~ 0.100	30	MAGIC
221009A	**0.151**	$\mathbf{3 \times 10^{54}}$	**0.5-18**	**600**	**LHAASO-WCDA** **LHAASO-KM2A**

- LHAASO detected > 5000 γ-rays with $E > 500\,\mathrm{GeV}$
- The highest energy γ-ray has 18 TeV! [Huang et al.(2022)]

Explaining the GRB 221009A

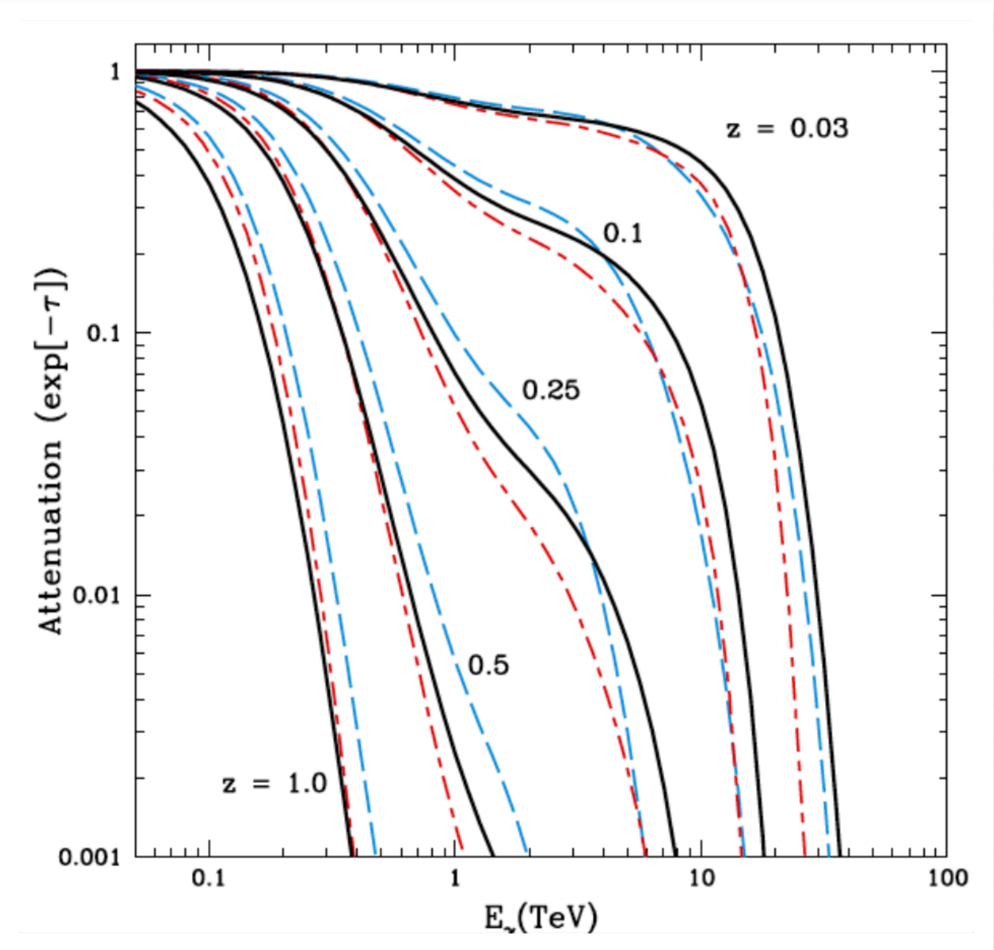
Possible mechanism to explain the VHE emission, especially up to 18 TeV:

Standard physics:

- Synchrotron Self-Compton (SSC) in the afterglow [e.g. Ren et al.(2023)]
- Proton synchrotron at the reverse shock [Zhang et al. (2023)]
- Shower due to UHECR produced in the GRB [Das & Razzaque (2022)]
- Correction to EBL

Beyond Standard Physics

- Axion-like particles (ALP)
- Lorents Invariance violation (LIV)

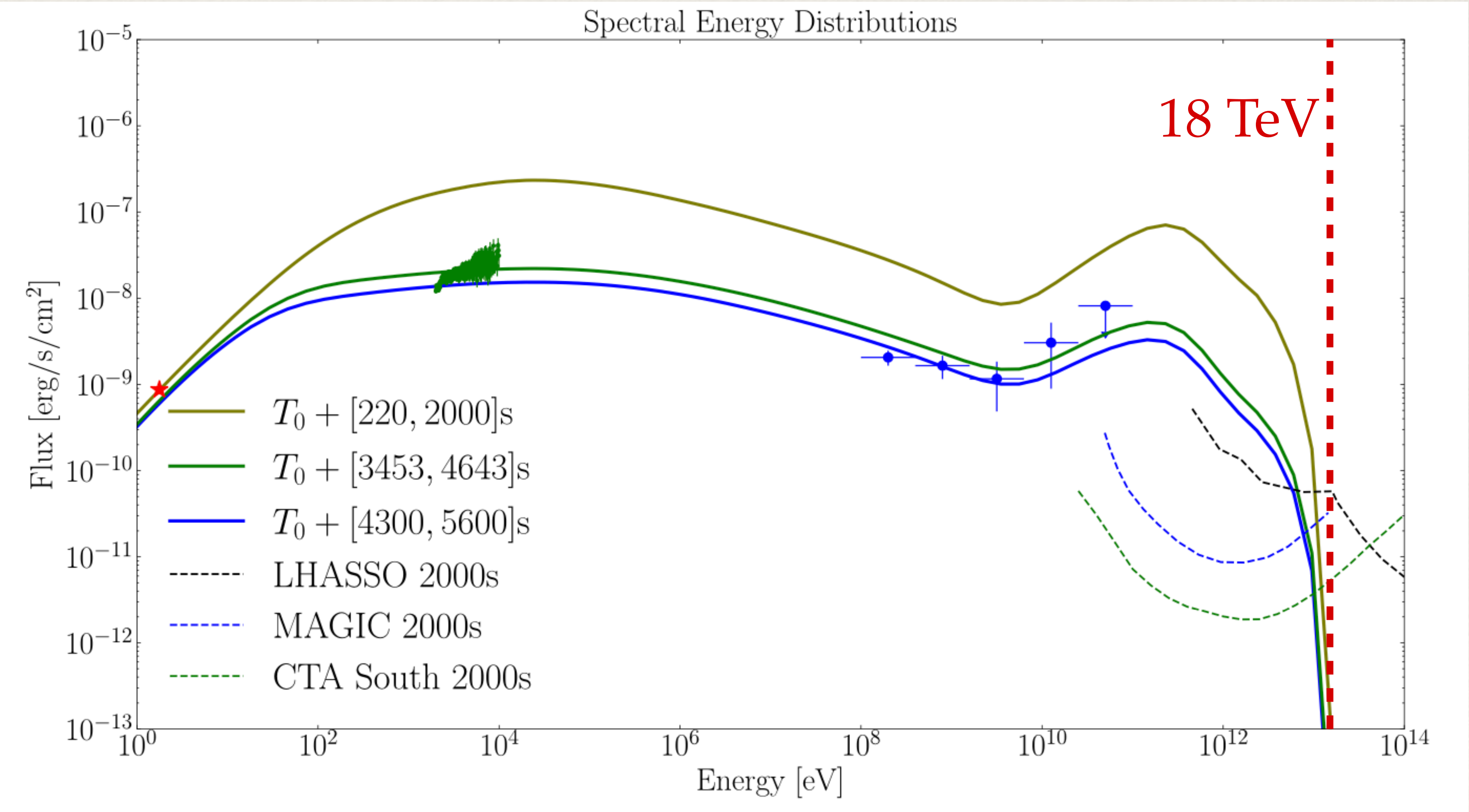


γ-rays are absorbed by interaction with the EBL

Explaining the GRB 221009A

- SSC is very unlikely to produce 18 TeV photons due to EBL absorption

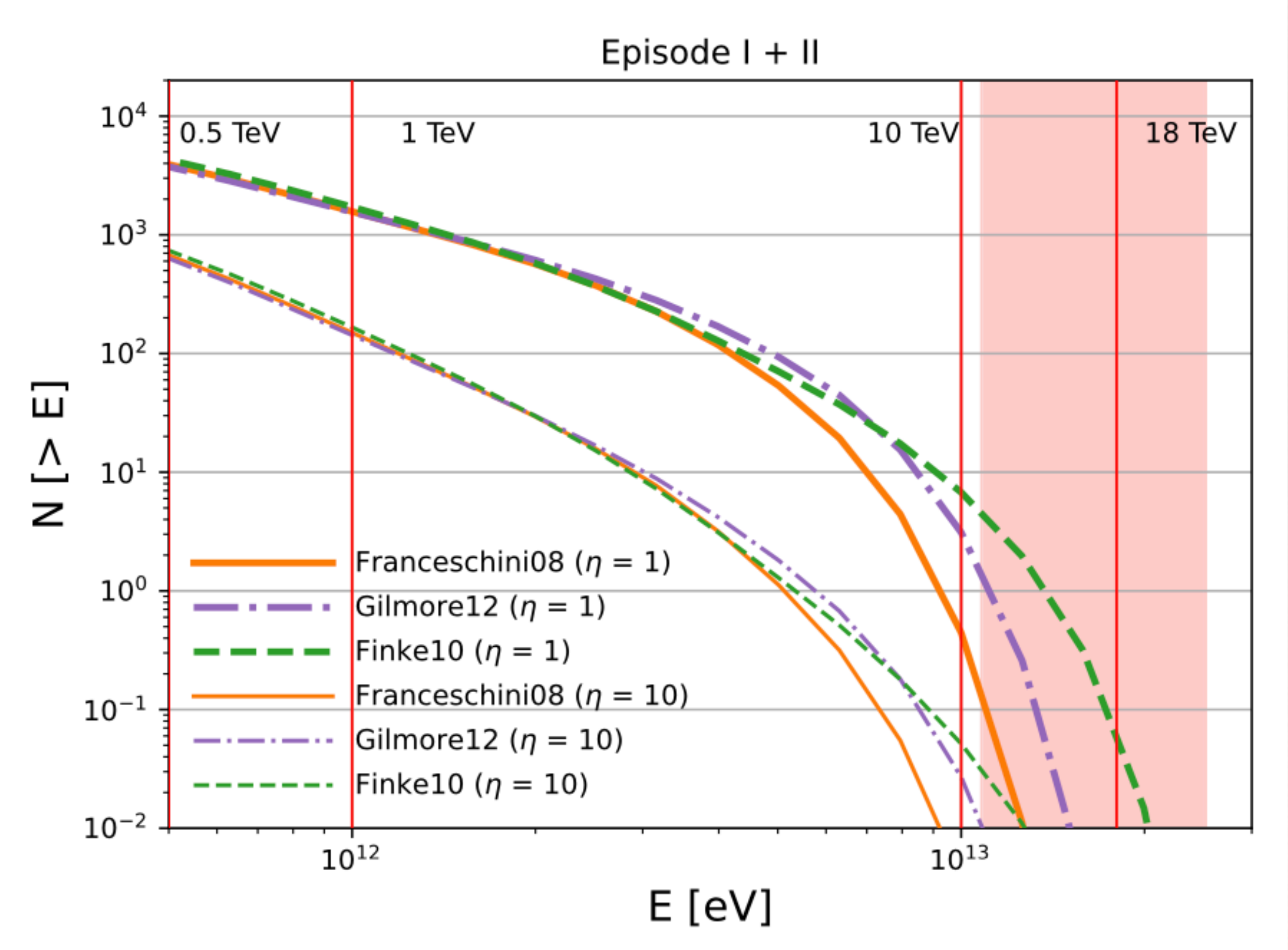
Ren et al. (2023)



Explaining the GRB 221009A

- SSC is very unlikely to produce 18 TeV photons due to EBL absorption
- Proton Synchrotron from the reverse shock may explain photons up to $\gtrsim$ 10 TeV but 18 TeV remains difficult

Zhang et al. (2023)



Explaining the GRB 221009A

- SSC is very unlikely to produce 18 TeV photons due to EBL absorption
- Proton Synchrotron from the reverse shock may explain photons up to $\gtrsim$ 10 TeV but 18 TeV remains difficult
- UHECR produced at the reverse shock may start a cascade; gamma-rays from this cascade may explain photons at >18 TeV

Das & Razzaque (2023)

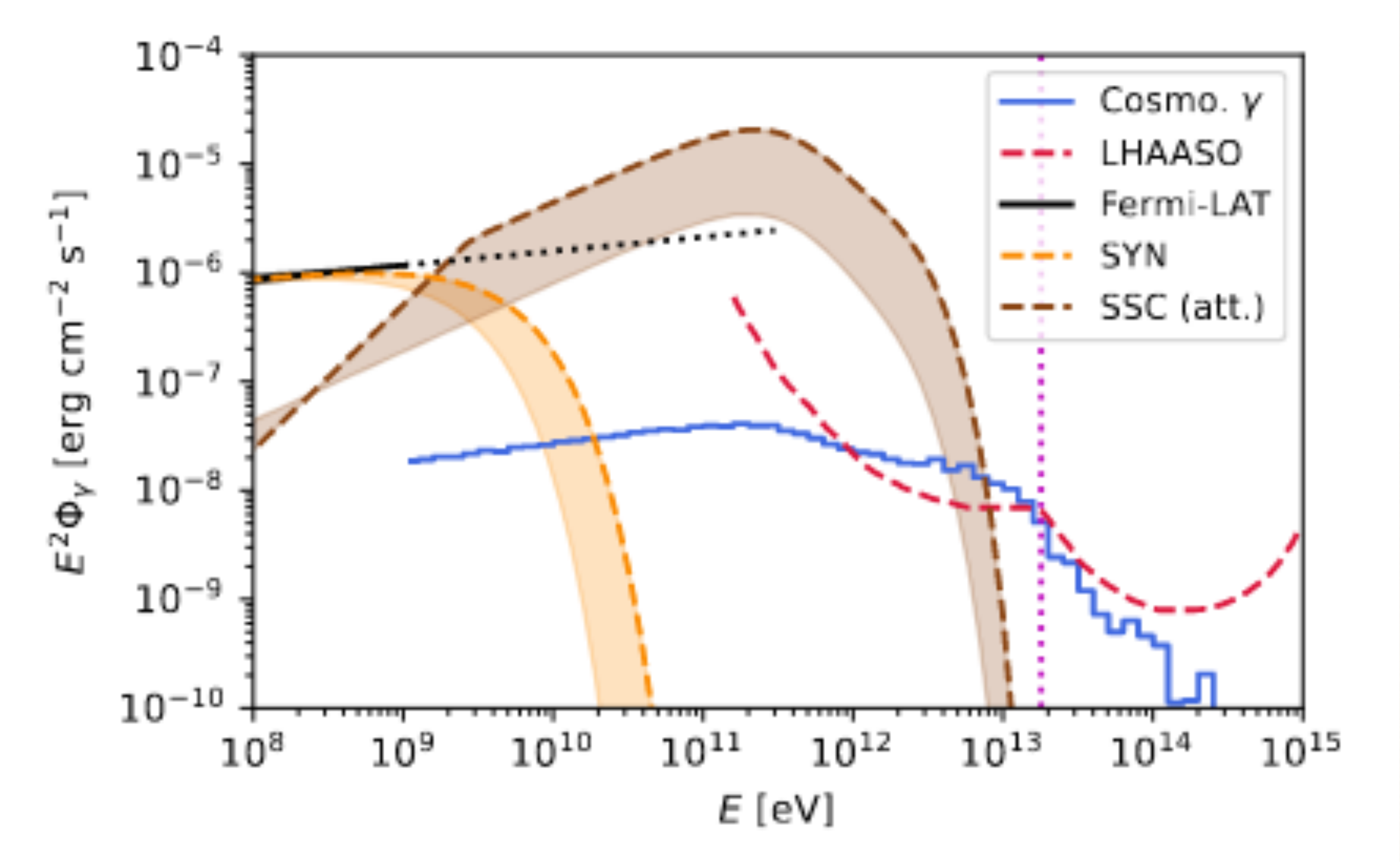
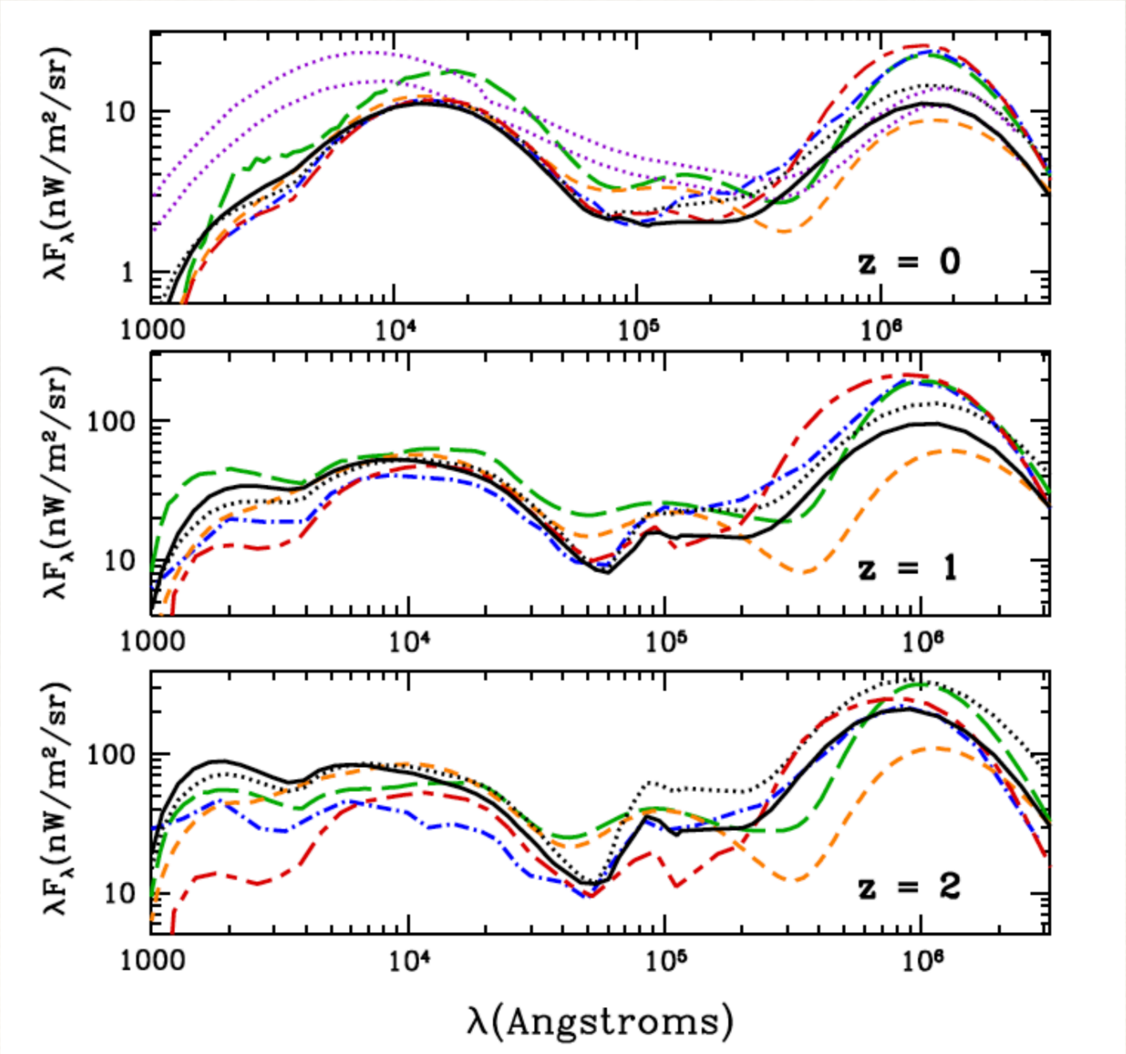


Fig. 2. Line-of-sight cosmogenic γ-ray flux from UHECR interactions (blue curve). The black solid line corresponds to the Fermi-LAT preliminary flux estimate from GRB 221009A (Pillera et al. 2022). The red dashed curve indicates the LHAASO sensitivity corresponding to 2000 s of observation. The dotted vertical line corresponds to the highest energy detection by LHAASO. The synchrotron and SSC emission components are shown as orange and brown dashed curves, respectively.

Explaining the GRB 221009A

- SSC is very unlikely to produce 18 TeV photons due to EBL absorption
- Proton Synchrotron from the reverse shock may explain photons up to $\gtrsim$ 10 TeV but 18 TeV remains difficult
- UHECR produced at the reverse shock may start a cascade; gamma-rays from this cascade may explain photons at >18 TeV
- Correction to EBL models

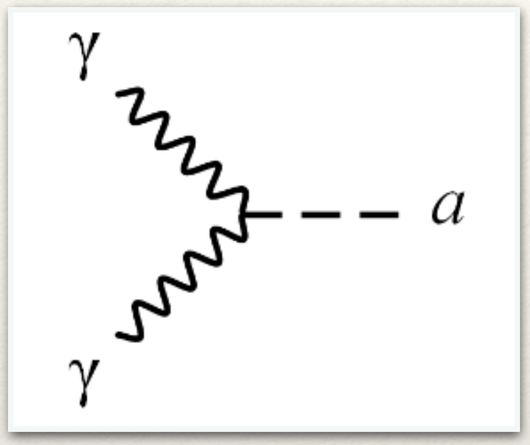
GRB @ 10 TeV may be the way to better constrain the EBL



Primack et al. (2011)

GRB 221009A: beyond the standard physics - ALPs

See, e.g. Galanti & Roncadelli (2022)



Axion-like particles (ALP) are pseudo-scalar boson that can couple to photons with coupling constant $g_{a\gamma\gamma}$

Photon-ALP coupling in a magnetic field

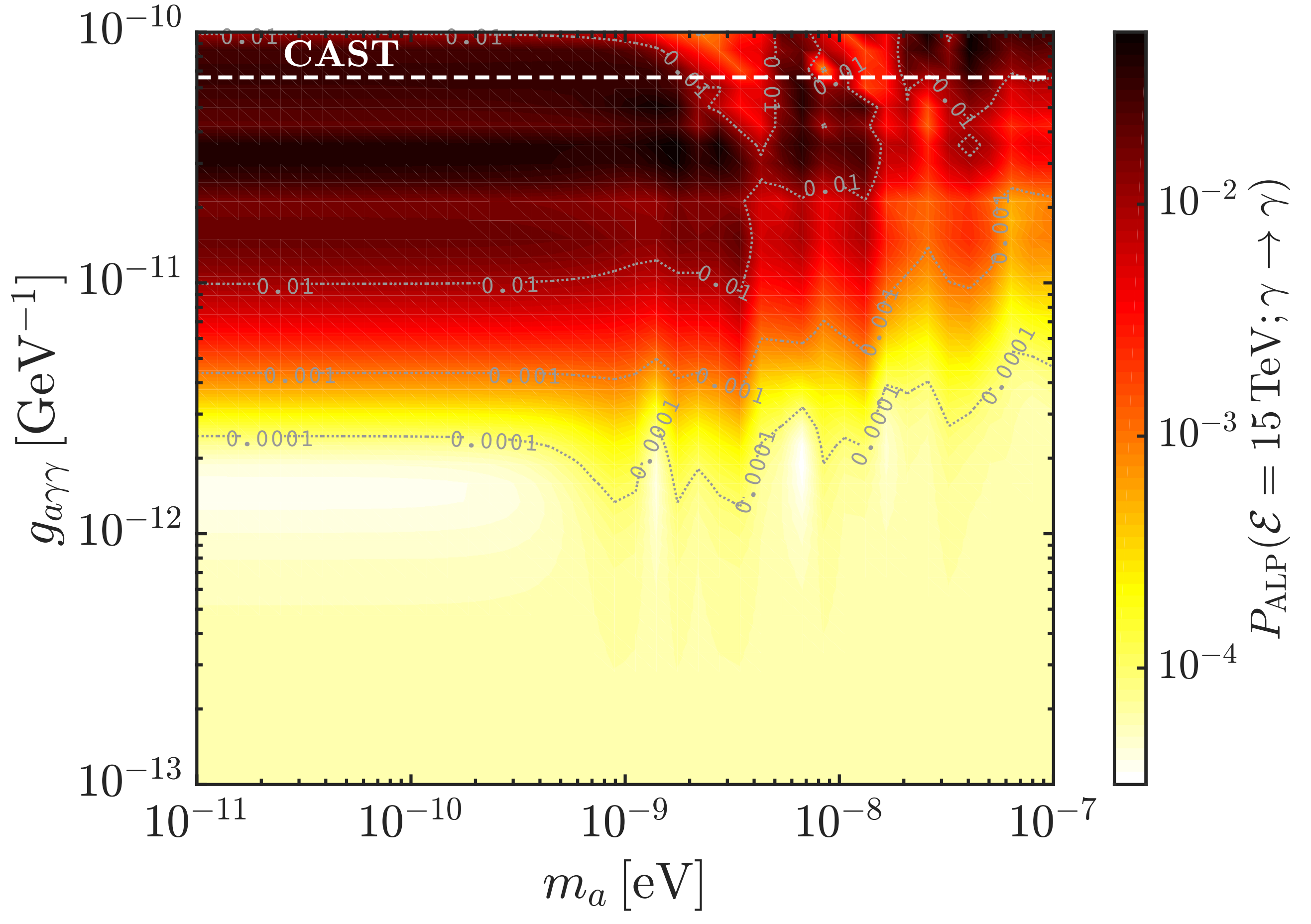
First conversion in the source galaxy

Second conversion in the Milky Way

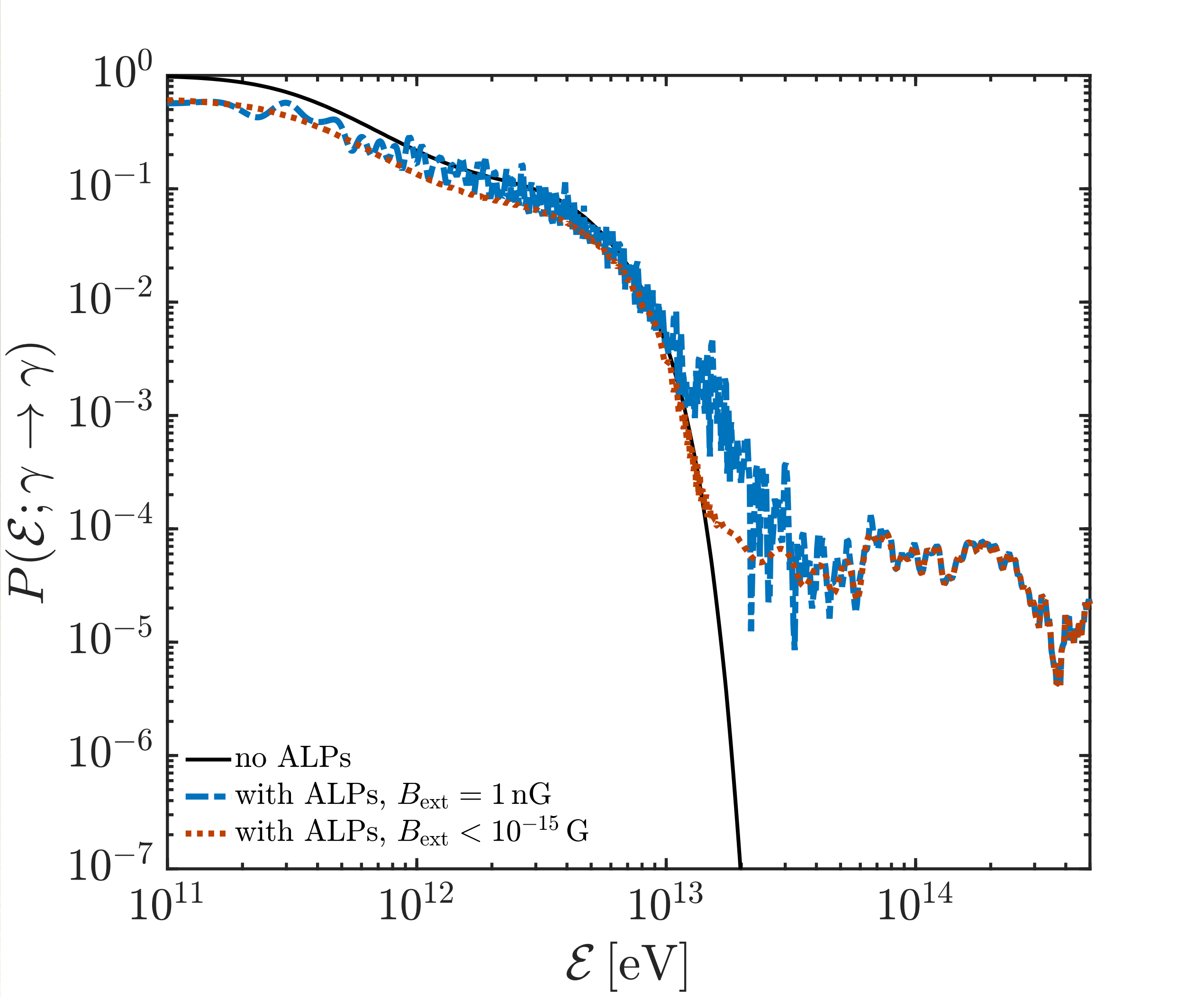
GRB 221009A: beyond the standard physics - ALPs

Galanti, Nava, Roncadelli, Tavecchio (2023, submitted)

Survival probability $[e^{-\tau(m_a, g_{a\gamma\gamma})} @ 15 TeV]$
with EBL model from Franceschini et al. (2017)
Magnetic field inside the source from starburst model.

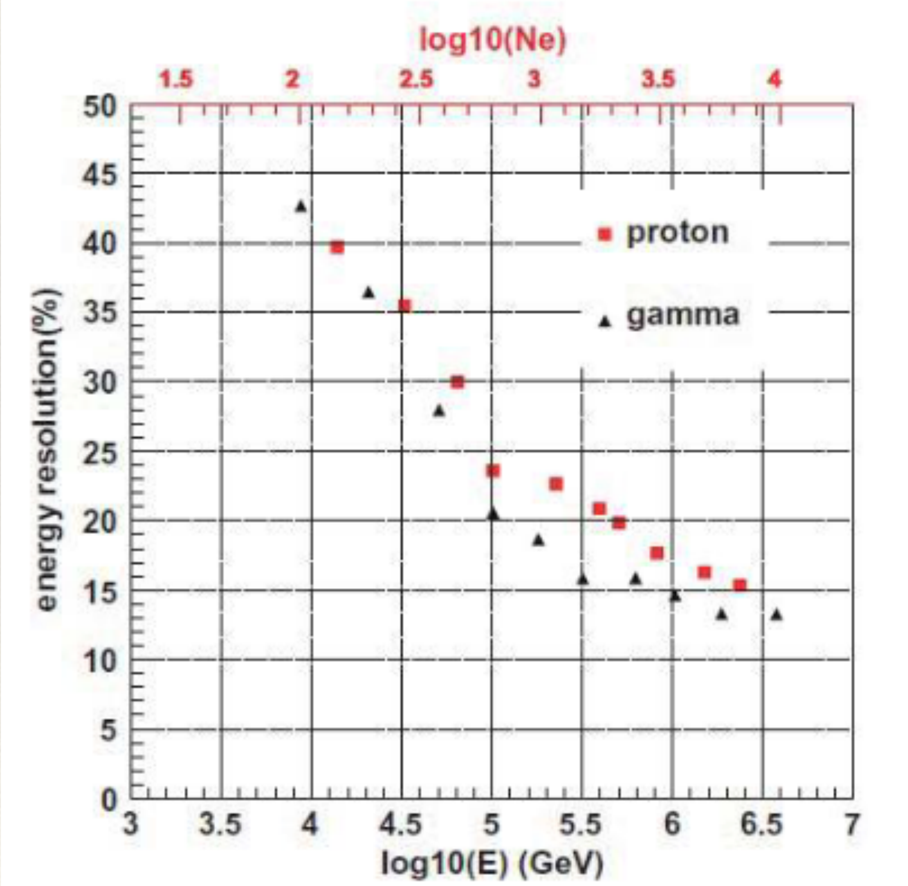


Survival probability with:
$m_a = 10^{-10}$ eV
$g_{a,\gamma\gamma} = 5 \times 10^{-12}$ GeV^{-1}
EBL from Franceschini et al. (2017)

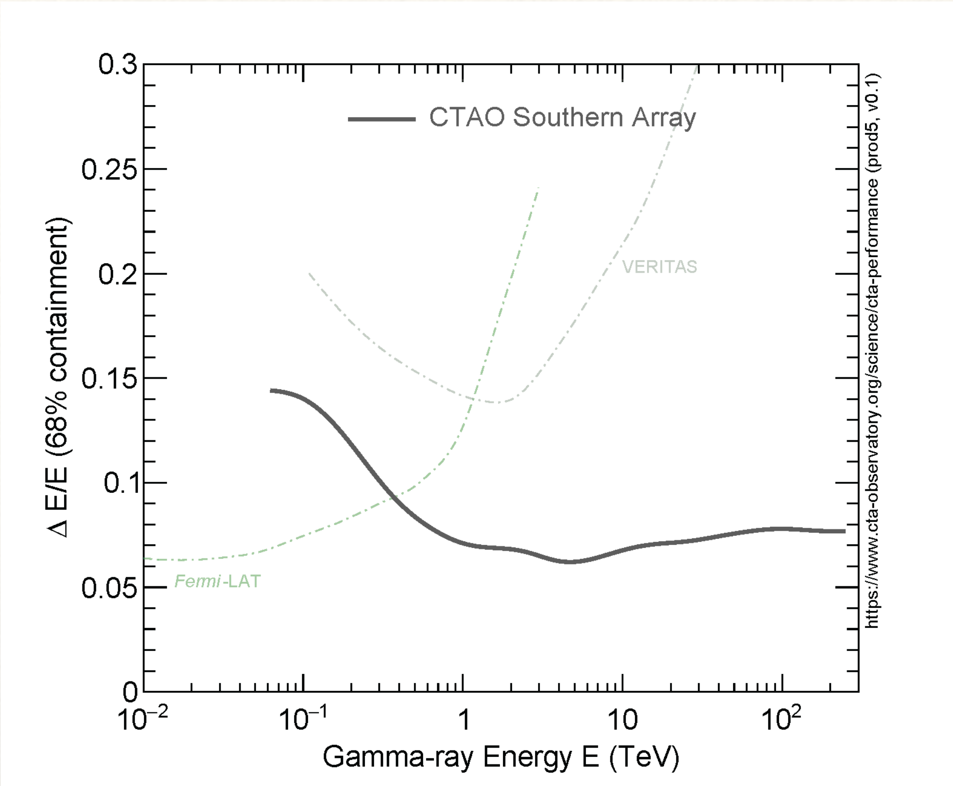


Importance of energy resolution

LHAASO-KM2A energy resolution @18 TeV ~40%
[Xin-Hua Ma et al.(2022)]



CTAO's Energy resolution for the Alpha configuration



ASTRI Miny-Array

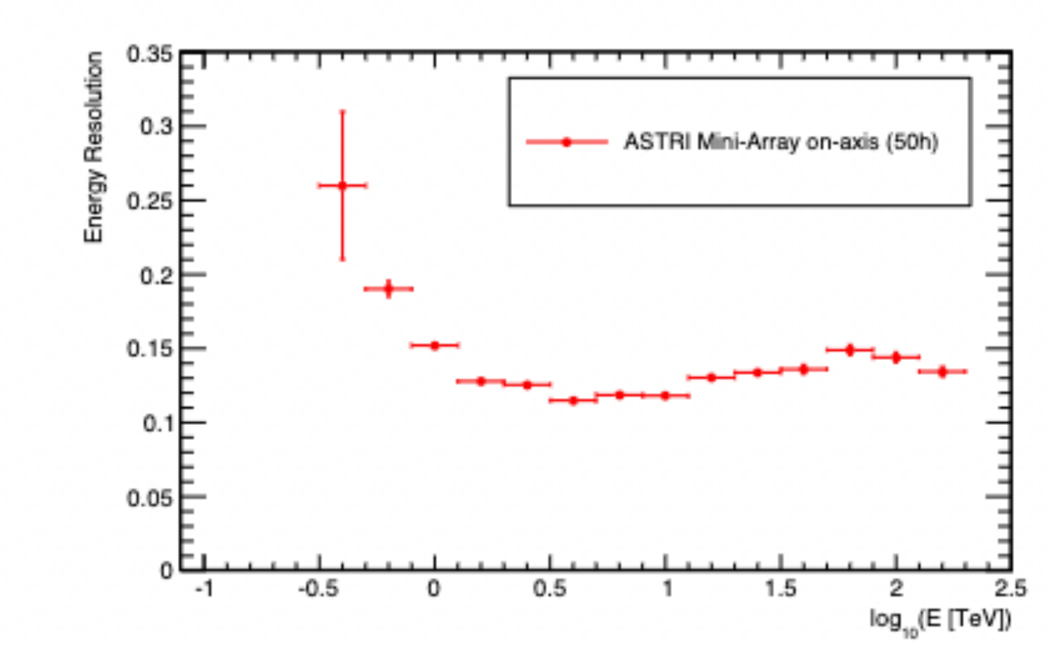


Figure 2: On-axis energy resolution of the ASTRI Mini-Array as a function of the energy between ≃ 0.3 TeV and ≃ 200 TeV.

Role of the ASTRI Mini-Array

["ASTRI Mini-Array Core Science", S. Vercellone et al. (2022)]

Prediction for a GRB with prompt energy 3×10^{53} erg with
z=0.078, 0.25, 90.42
⇒ detection possible up to 20-30 TeV

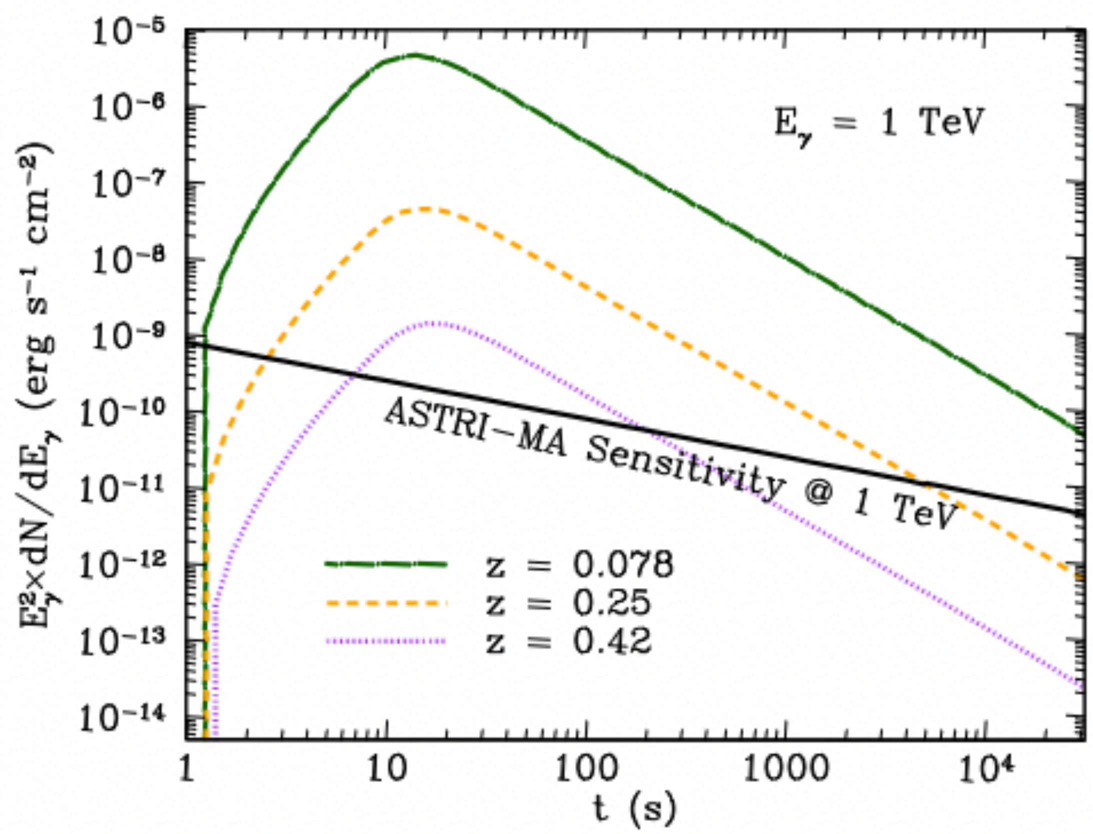


Figure 33: Synthetic light curves at 1 TeV of the three simulated GRBs, obtained adopting GRB 190114C ($z = 0.42$) as a template and moving the GRB at shorter distances ($z = 0.25$ and $z = 0.078$), as described in the text. The black line shows the sensitivity of the ASTRI Mini-Array at 1 TeV, rescaled for the corresponding integration time on the x-axis.

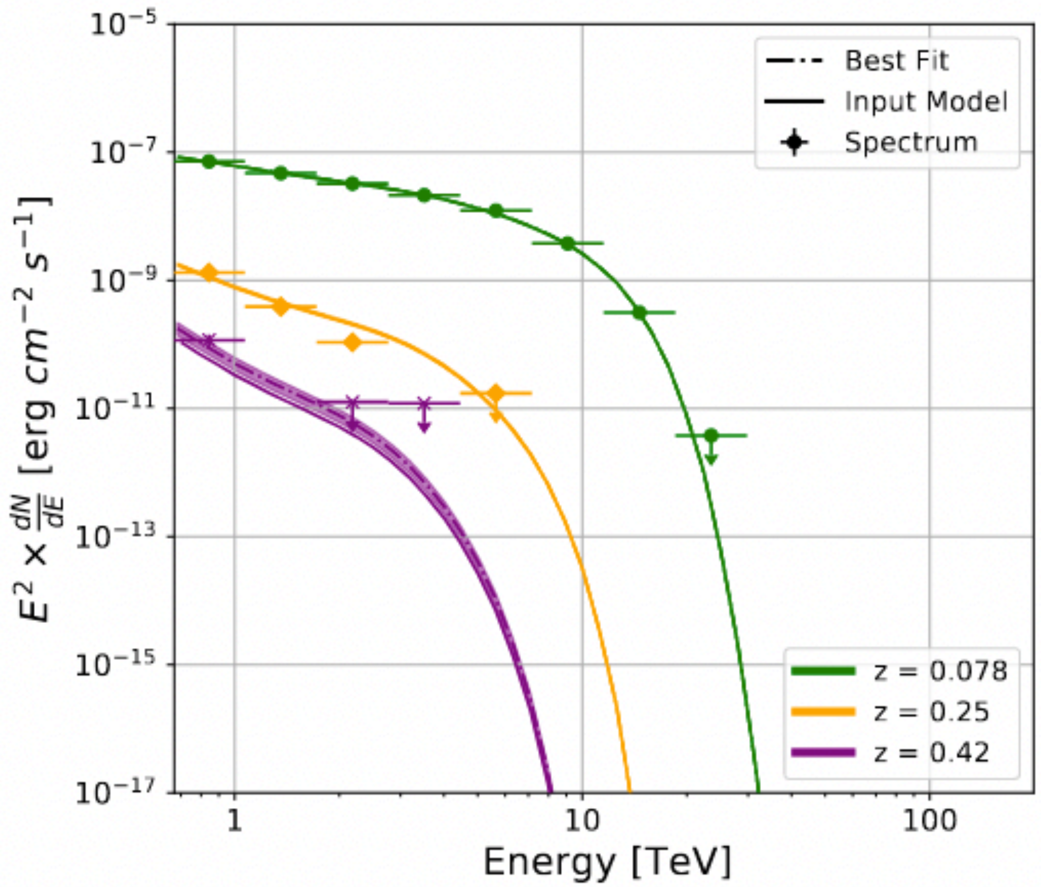


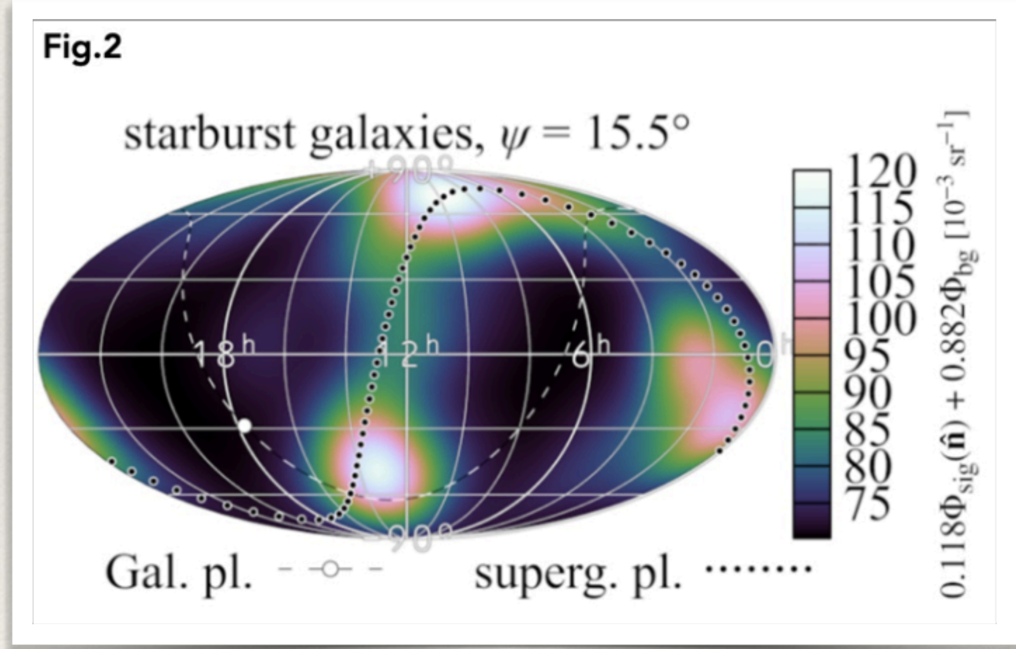
Figure 35: Simulated response of the ASTRI Mini-Array to the emission from three GRB 190114C-like bursts, at three different redshifts, $z = 0.078$, $z = 0.25$ and $z = 0.42$. The simulation considers an observation started at $t \sim 200$ s after the initial burst, with flux decaying according to the lightcurves in Fig. 33, integrated for ~ 600 s.

Starburst Galaxies and UHECRs

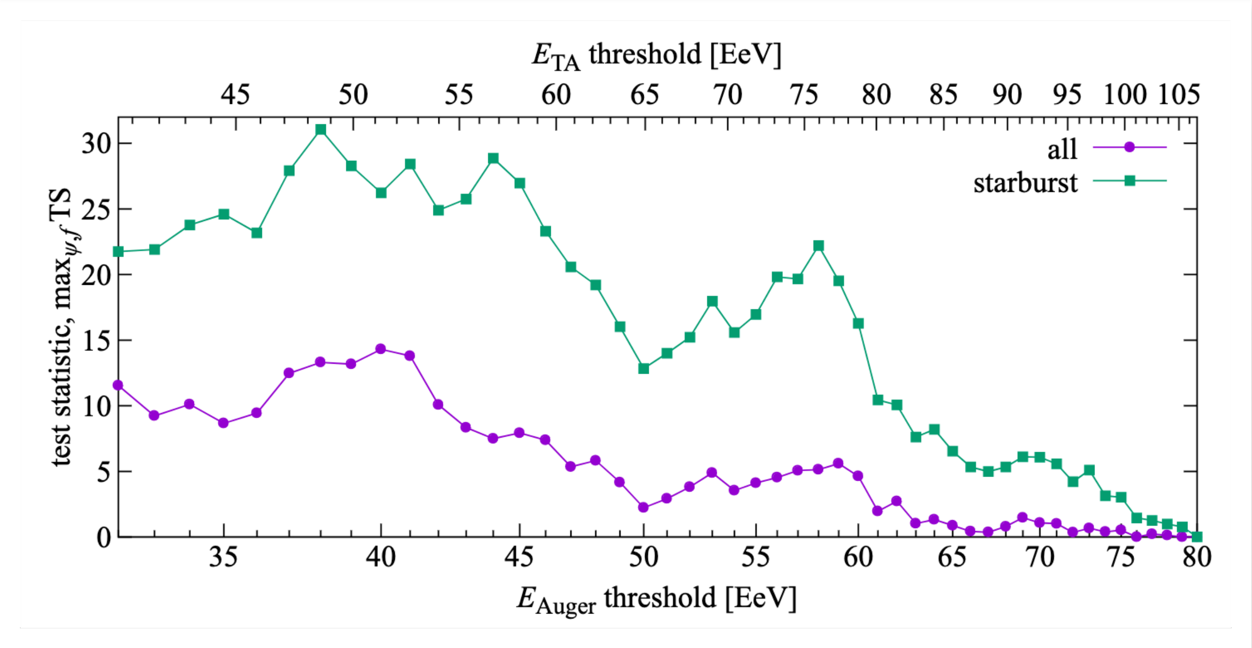
A. di Matteo et al. (2023)

Pierre Auger and Telescope Array collaborations reported strong evidence for a correlation between the highest energy cosmic rays and nearby starburst galaxies, with a global significance post-trial of **4.7 σ** (previous analysis reports 4.2 σ)

- NGC4945, M83 in the CenA region
- NGC253 towards Gal. South Pole



Test Statistics as a function of energy threshold



Future development:

- TA is undergoing an upgrade (TA×4) which will increase its area by a factor of 4
- Auger will be upgraded to AugerPrime: new scintillation and radio detectors are being added to the existing water-Cherenkov and fluorescence detectors

Starburst Galaxies and UHECRs

Why UHECRs correlate with SBGs?   Unclear…

Acceleration models invoke

- Termination shock of winds from SB nuclei;
- Turbulence and multiple SNR shock interaction;

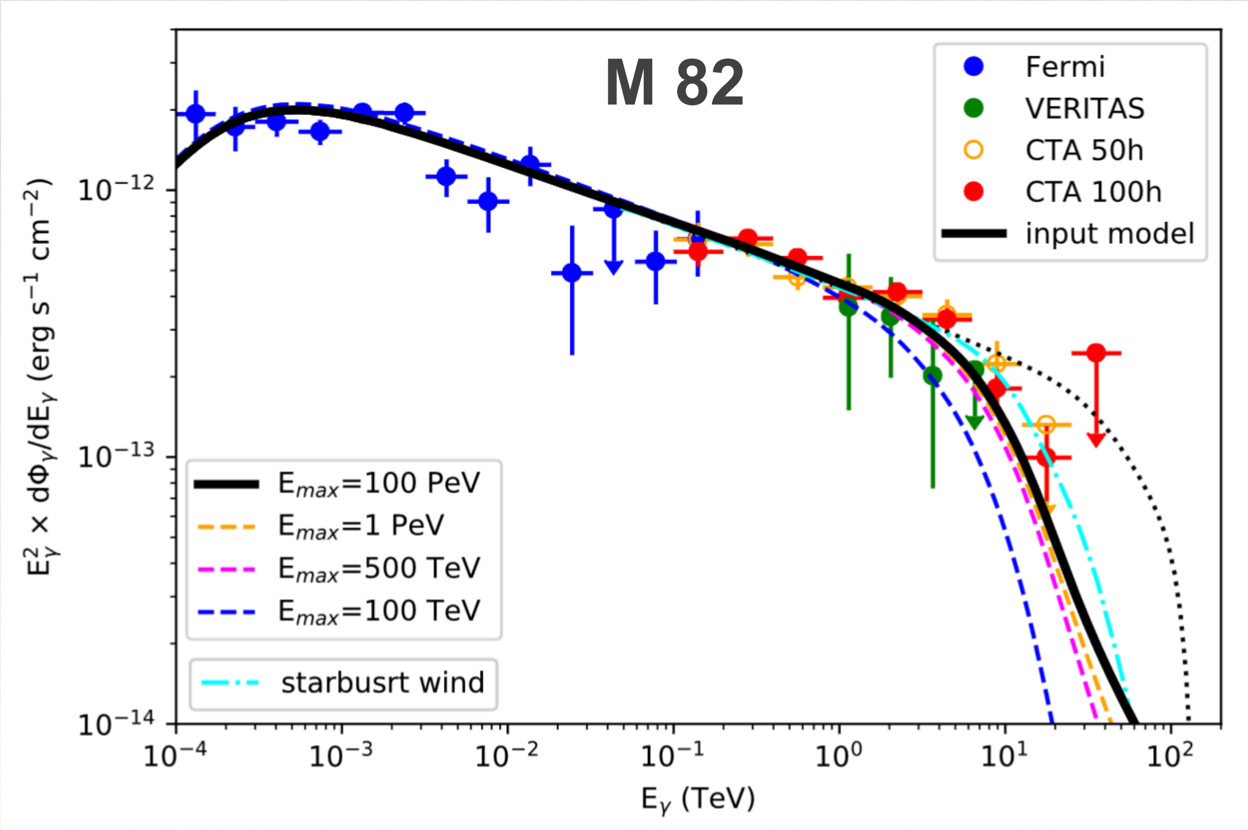
$\}$ $E_{\max}$ seems not enough

- Further possibility: Ultra Fast Outflow (UFO) powerful winds driven by the central AGN

CTA study on star-forming regions (in preparation):
Model by Peretti et al.(2019)
Simulations by A. Lamastra

Role of INAF

- Theoretical study on wind-acceleration models
- Simulations for CTA and ASTRI Mini-Array
- Theoretical study on UFOs



Conclusions

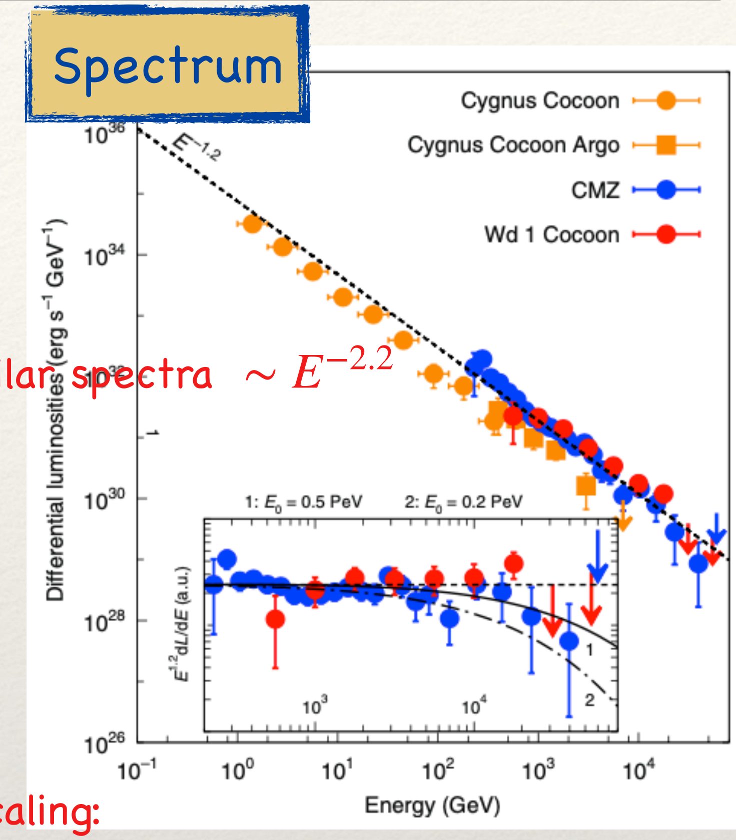
	Requirements	Better instrument	Strategy
PeVatrons	High sensitivity at >50TeV	LHAASO	Synergies between CTA, LHAASO and SWGO
	Good angular resolution	CTA	
Diffuse emission	Resolving source confusion/ angular resolution	CTA	Synergies between CTA, LHAASO and SWGO
	Wide FOV	LHAASO CTA (7-8°) ASTRI-MA (~10°)	
GRBs	Good energy resolution @1-10 TeV	CTA (ASTRI-MA)	
SBGs	High sensitivity @~10 TeV	CTA	Multi-wavelength/multi-messenger analysis

Additional slides

Highlights: ammassi stellari come sorgenti di raggi cosmici

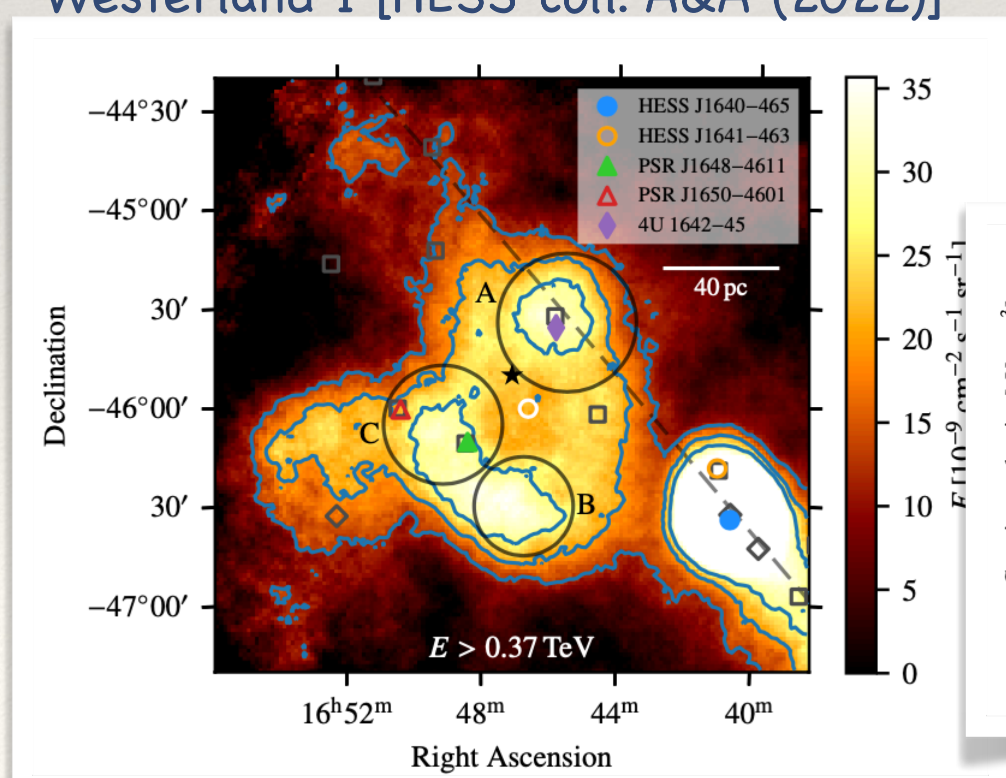
Negli ultimi anni ~10 ammassi stellari giovani sono stati associati a sorgenti gamma

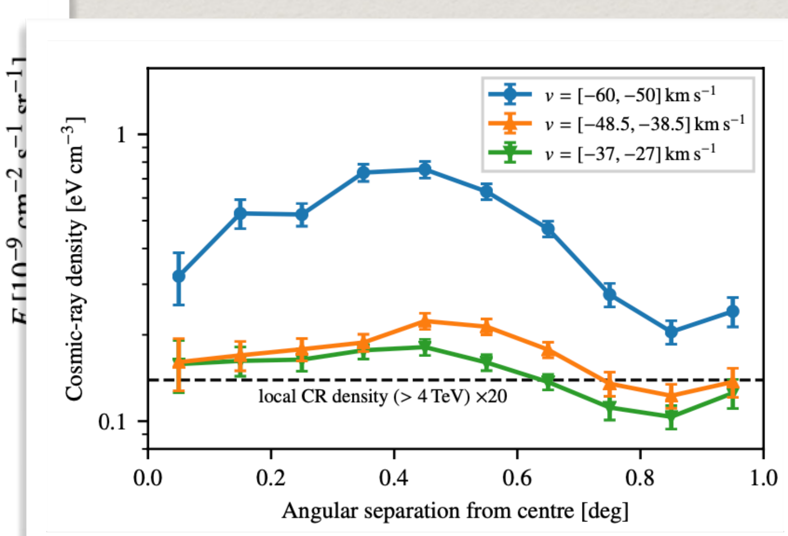
- Sorgenti estese ⇒ difficili da studiare
- Profilo spaziale piatto o decrescente $\propto 1/r$ ⇒ competizione tra avvezione e diffusione?
- Spettri relativamente duri $\propto E^{-2.2}$ ⇒ probabile origine adronica
- Energia massima > 100 TeV ⇒ candidati PeVatroni



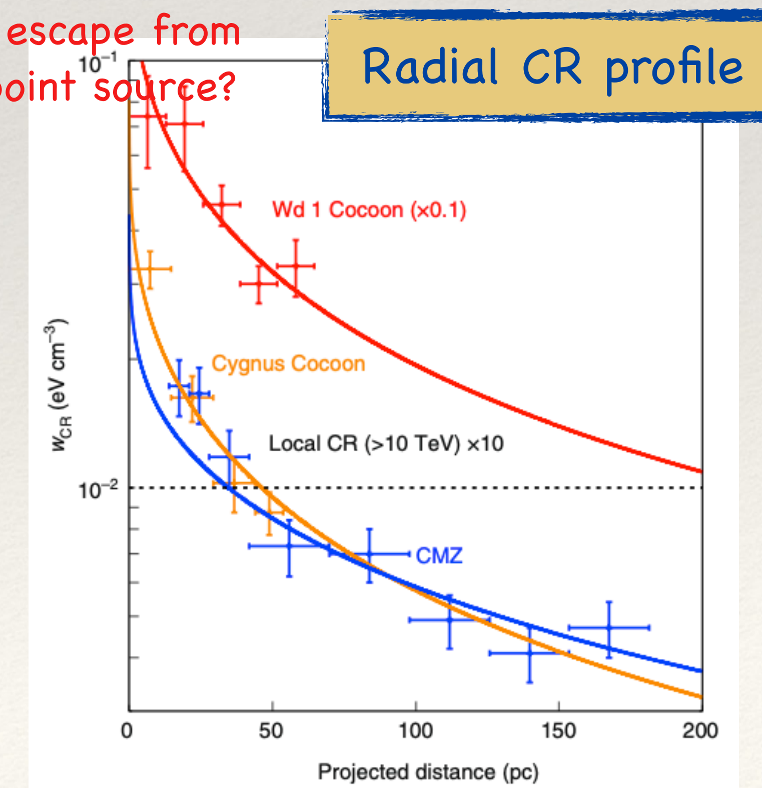
Similar spectra $\sim E^{-2.2}$

Westerland 1 [HESS coll. A&A (2022)]





1/r scaling:
CR diffusive escape from continuous point source?



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Tibet ASγ and LHAASO have detected sub PeV diffuse emission [Amenomori et al. PRL (2021)]

Real diffuse component *or* unresolved sources?

Diffuse γ-ray emission compared with different models of CR propagation

de la Torre Luque et al. (2022)