

NuSTAR X-ray observations and multi-wavelength investigations of Galactic TeV sources



7th Heidelberg International Symposium
on High Energy Gamma-Ray Astronomy

2022
BARCELONA

SCIENTIFIC ORGANIZING COMMITTEE

Felix Aharonian (OJAS / MPEK, chair)
 Elena Amato (INAF - Osservatorio Astrofisico di Arcetri)
 Xavier Barcons (ESO)
 Valenti Bosch-Ramon (Universitat de Barcelona / ICCUB)
 Zhen Cao (HEP-KITP and Cosmic Ray Research Center)
 Catherine Cesarsky (AIM, DAp, Université Paris Saclay)
 Paola Coppi (Yale University)
 Emma De Ona Wilhelmi (ICE / DESY)
 Jim Hinton (MPEK)
 Werner Hofmann (MPEK)
 Michael Kramer (MPIR)
 Mireia Latorre (IAE-CNRG / Sorbonne Université)
 Josep Martí (Universitat de Jaén)
 Mireia Martínez (IFAE-BIST)
 Reshmi Mukherjee (Barnard College, Columbia University)
 Josep M. Paredes (Universitat de Barcelona / ICCUB, co-chair)
 Elena Pian (INAF-OAGS)
 Elisa Resconi (Technische Universität München)
 Gustavo Romero (ARC-CONICET / OGDPA)
 Gavin Rowell (The University of Adelaide)
 Samir Salhi (The University of Maryland)
 Eun-uk Seo (University of Maryland)
 Ronald Shearer (CEPP)
 Joe Silk (MPEK)
 Christian Stegmann (DESY)
 Marco Tavani (INAF)
 Masahiro Teshima (ICRR, University of Tokyo / MPIR)
 Jacco Vink (Anton Pannekoek Institute, University of Amsterdam)
 Xiang Yu Wang (Nanjing University)
 Roberta Zanin (CTA Observatory GmbH)

LOCAL ORGANIZING COMMITTEE

Arnau Aguasca Cabot
 Valenti Bosch-Ramon
 Pol Bordas
 Masashi Iwagawa
 Edgar Molina
 Josep M. Paredes (chair)
 Marc Ribó
 Preeti Singhani (co-chair)
 Xinyi Zhang

Anna Argüeso
 Anna Böttcher
 Mar Carratero-Castillo
 Eleni Kefaua
 Pilar Montes
 Esther Pallares
 Gabriele Weese

Barcelona, July 4-8, 2022

<https://indico.icc.ub.edu/e/gamma2022>
 Contact: gamma2022@icc.ub.edu

MAX PLANCK INSTITUTE
FÜR EXPERIMENTELLE
KOSMOPHYSIK

ICCUB

Institut de Ciències del Cosmos
UNIVERSITAT DE BARCELONA

2022-07-04
10:00 AM
10:00 AM

IEEC³
Español de Catalunya

Kaya Mori
(Columbia University)
7/4/2022

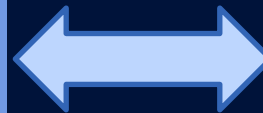
X
2022



X-ray views of TeV sources: synchrotron radiation

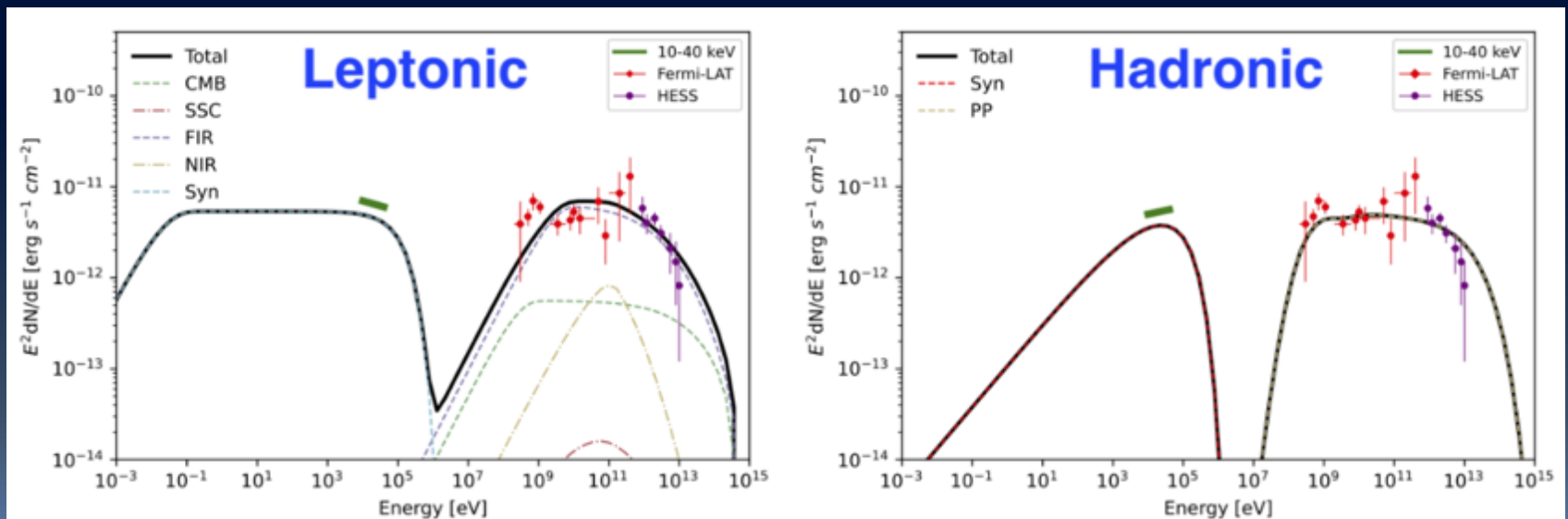
- Energetic gamma-ray sources produce TeV-PeV electrons
 - Primary electrons (leptonic accelerators)
 - Secondary electrons from p-p collisions (hadronic accelerators)

X-ray synchrotron radiation:
100-TeV electrons + 10 μ G B-field
 \Rightarrow 4-keV X-rays



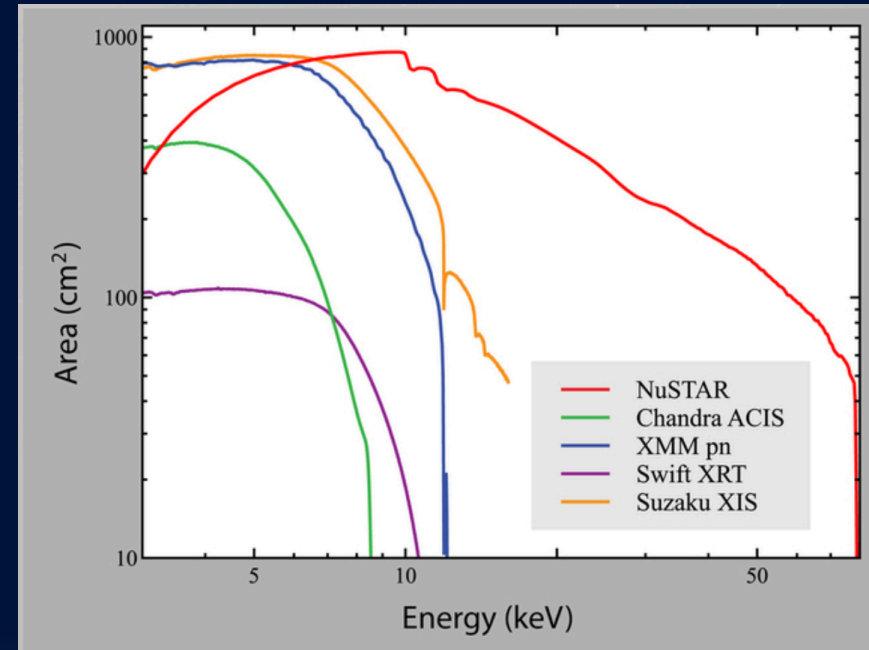
Gamma-ray emission:
inverse Compton scattering
or pion decays

SED models for star cluster Westerlund 2 (Mori et al. NuSTAR proposal)



NuSTAR telescope's 10th anniversary

- NuSTAR observed ~30 TeV sources
- We are leading...
 - NuSTAR Galactic Survey team (10 yr)
 - Galactic TeV source collaboration (5 yr)
 - X-ray probe mission (HEX-P) – Galactic Survey, SNRs, PWNe, TeV sources...



NuSTAR's effective area compared to other x-ray satellites.

Energy Band	3 - 79 keV
Angular Resolution	58" (HPD), 18" (FWHM)
Focal Plane Size	12' x 12'
Energy Resolution	0.4 keV at 6 keV, 0.9 keV at 60 keV (FWHM)
Temporal Resolution	0.1 msec

Cagliari, Italy, June 20-22, 2022

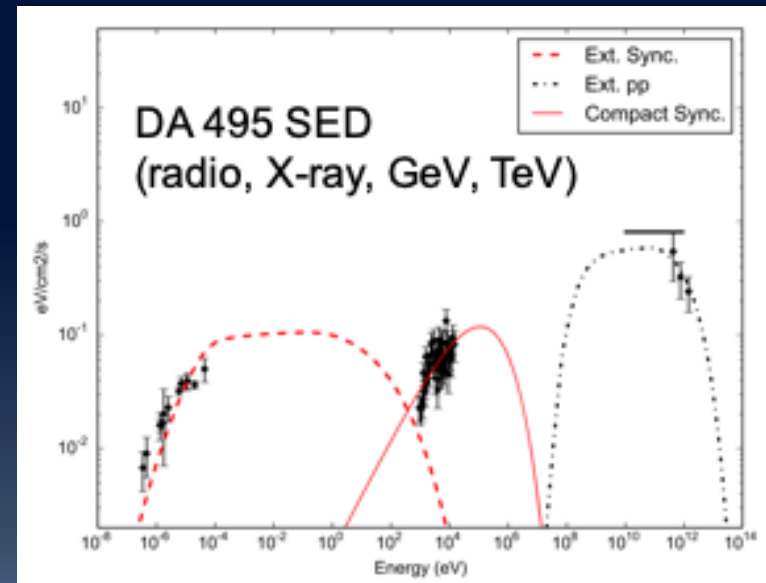
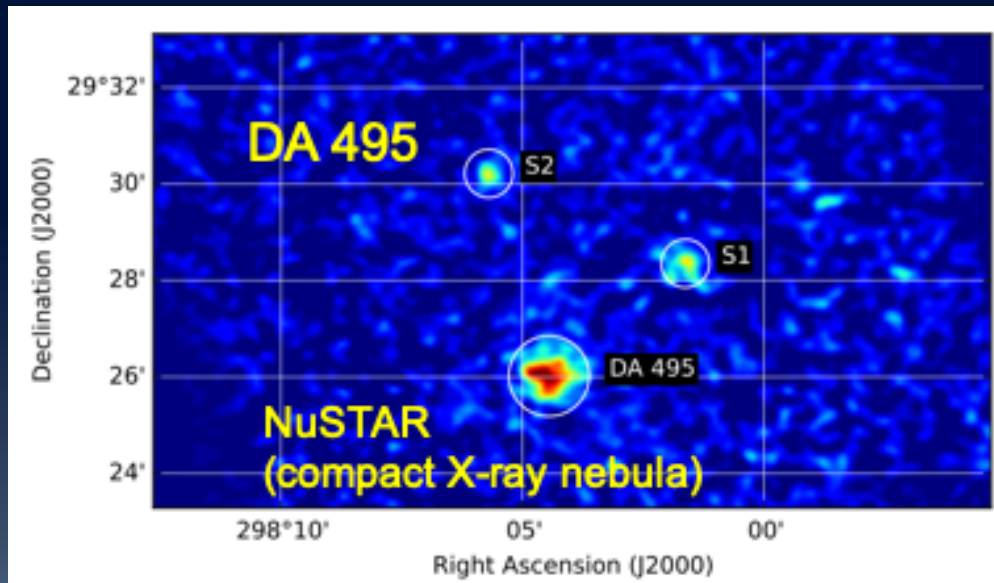
Ten years of High-Energy Universe in focus: NuSTAR 2022

Organizing committee:
 Matteo Bachetti (INAF - OA Cagliari)
 Daniel Stern (NASA/JPL)

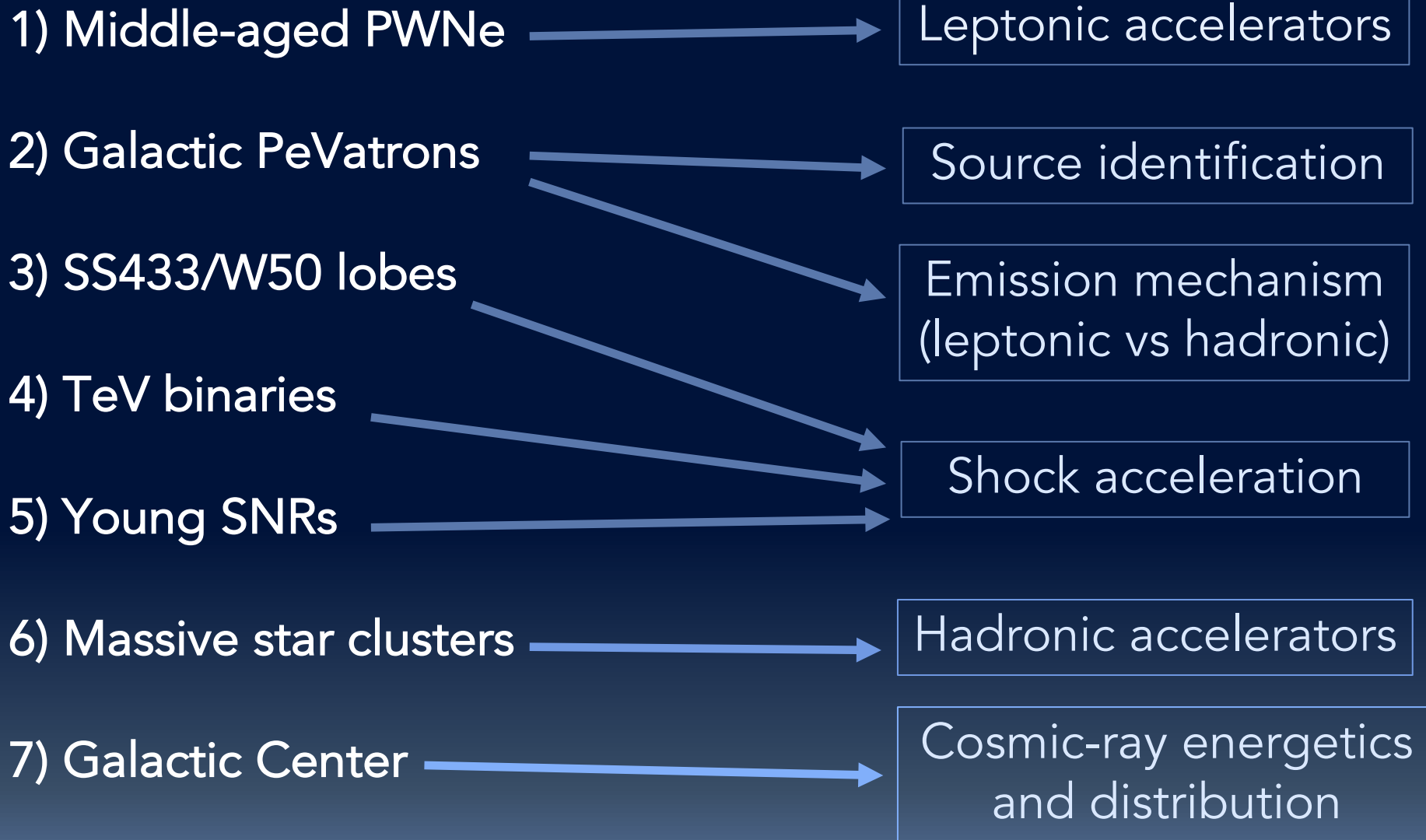
Logos: NASA, JPL, Caltech, INAF, OAC, Osservatorio Astronomico di Cagliari, Cassiopea group

NuSTAR's unique roles for exploring TeV sources

- Hard X-ray morphology (1 arcmin angular resolution)
 - Tracks spatial distribution of sub-PeV electrons
 - Synchrotron electron cooling => energy-dependent X-ray size
- Broad-band X-ray spectroscopy (3-79 keV)
 - Multi-wavelength SEDs => leptonic vs hadronic model.
 - Spectral cutoff/rollover

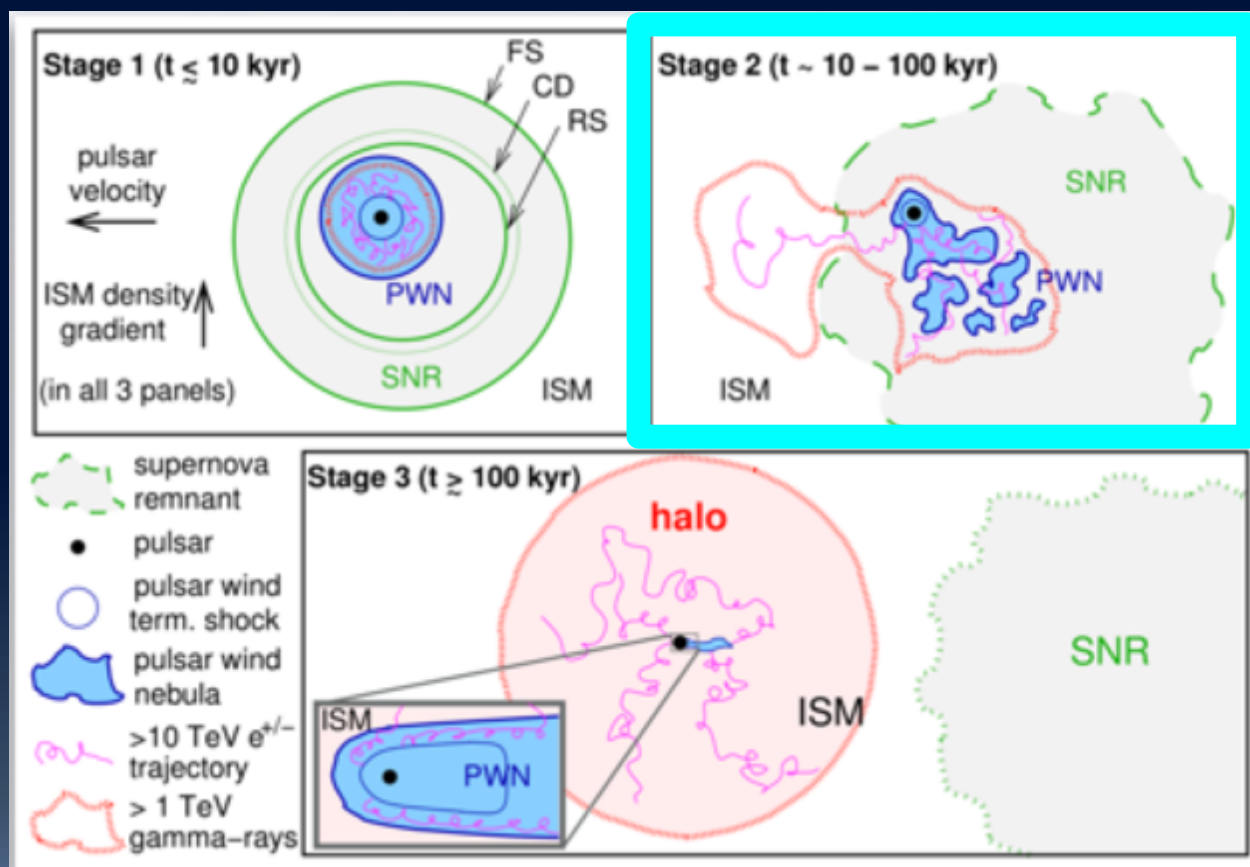


On-going X-ray investigations of Galactic TeV sources



(1) NuSTAR observations of middle-aged PWNe

- Age $\sim 10 - 100$ kyr
- Interacting with supernova remnants
- Diverse morphology and spectra in multi-wavelength bands



8 middle-aged PWNe associated with TeV sources

- NuSTAR LP observation campaign in 2021-22
- 4 PeVatron candidates detected by HAWC/LHAASO
- See Nahee Park's talk on Boomerang PWN (Tuesday)

PWN name	TeV source name	Lead	Status
G106.6+2.9 (Boomerang)	VER J2227+608	I. Pope (CU)	Paper in prep
G18.5-0.4 (Eel)	HESS J1826-130	D. Burgess (CU)	Published in ApJ
G313.54+0.23	HESS J1420-607	H. An (Chungbuk U)	Paper in prep
G313.3+0.1 (Rabbit)	HESS J1418-609	H. An (Chungbuk U)	Submitted to ApJ
G309.92-2.51	HESS J1356-645	S. Safi-harb (U of Manitoba)	SED modeling
G75.2+0.1 (Dragonfly)	VER J2019+368	J. Woo (CU)	Paper in prep
G32.64+0.53	HESS J1849+0000	S. Silverman (CU)	SED modeling
G0.9+0.1	HESS J1747-281	M. Nynka (MIT)	SED modeling

Eel pulsar wind nebula

- Published in ApJ (Burgess et al. 2022)
- Featured in Sky and Telescope magazine

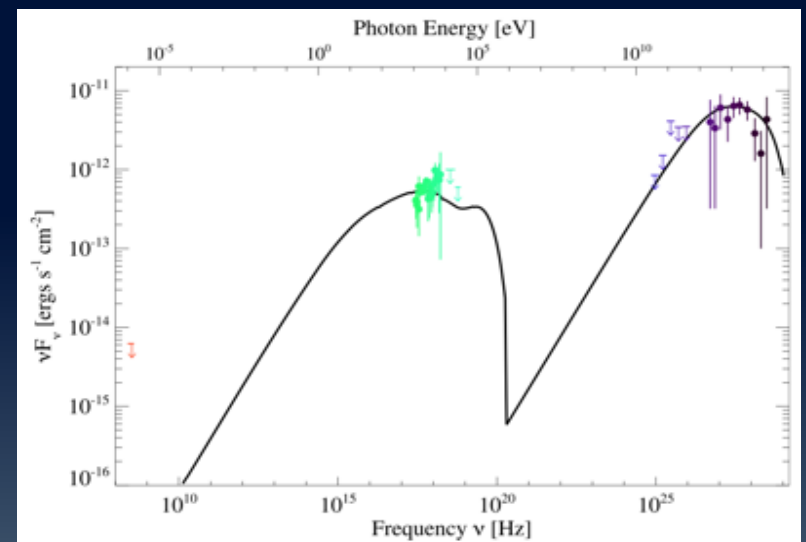
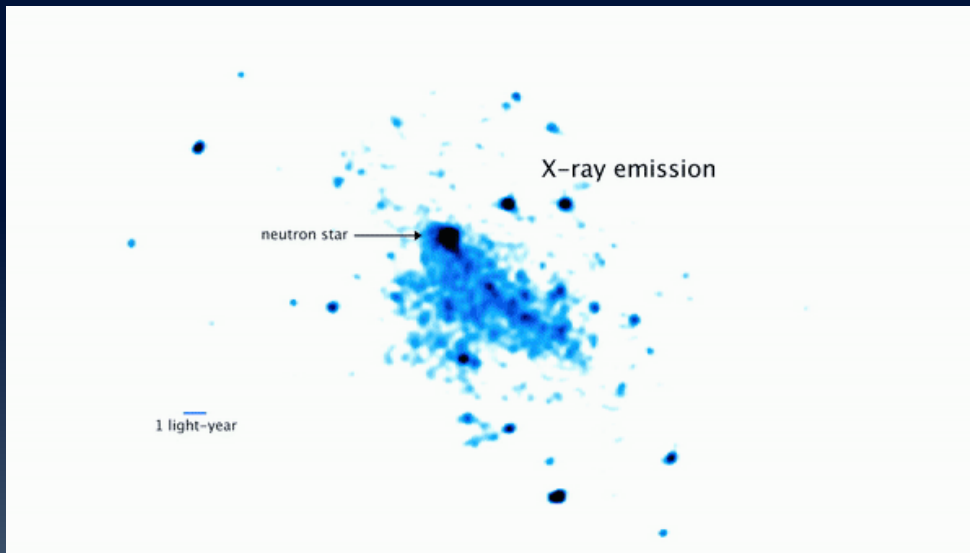


ASTRONOMY & OBSERVING NEWS

Seeing Inside a Cosmic Superaccelerator

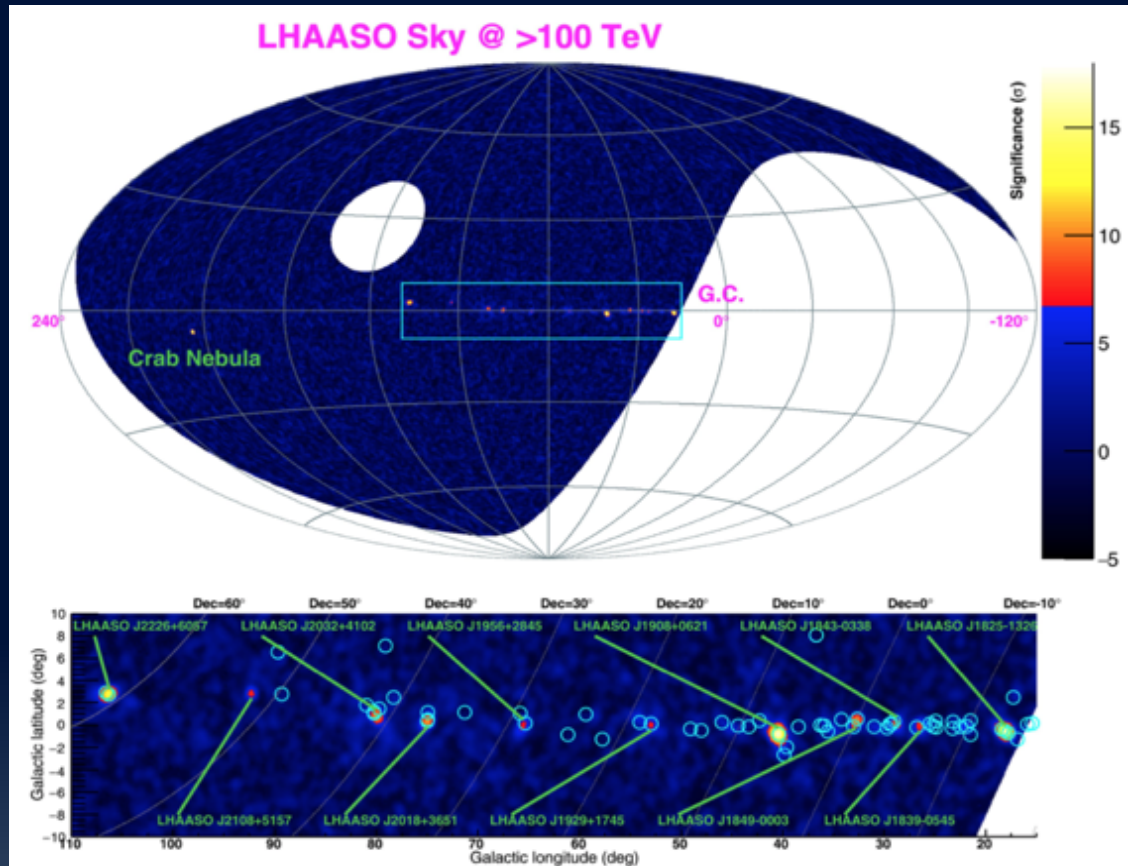
Astronomers are exploring a celestial particle accelerator in the Eel Nebula that surrounds a distant pulsar.

BY: MONICA YOUNG | MAY 19, 2022



(2) Unidentified Galactic PeVatrons

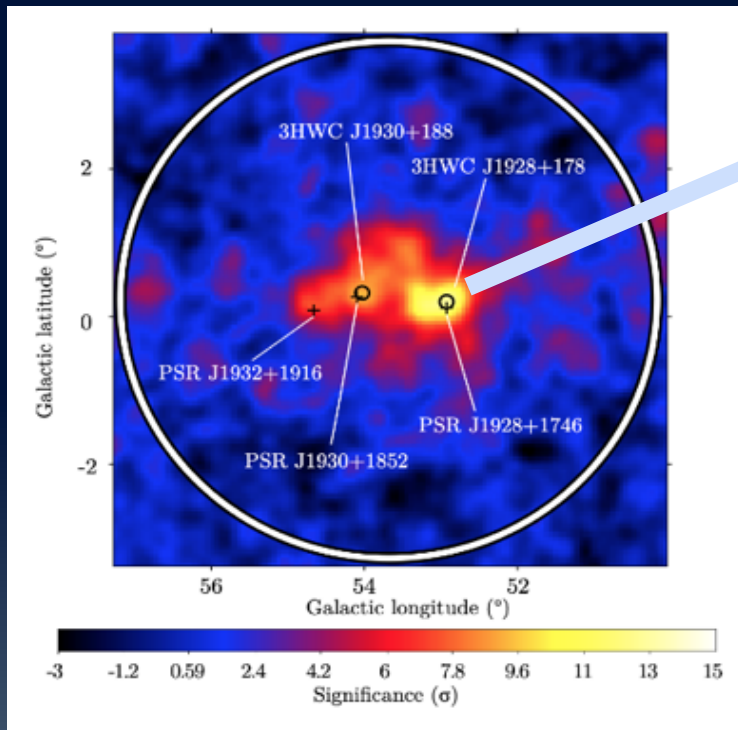
- LHAASO detected 13 sources above ~ 100 TeV \Rightarrow PeVatrons
- Only one of them is identified (Crab nebula)
- On-going X-ray studies with NuSTAR and XMM-Newton



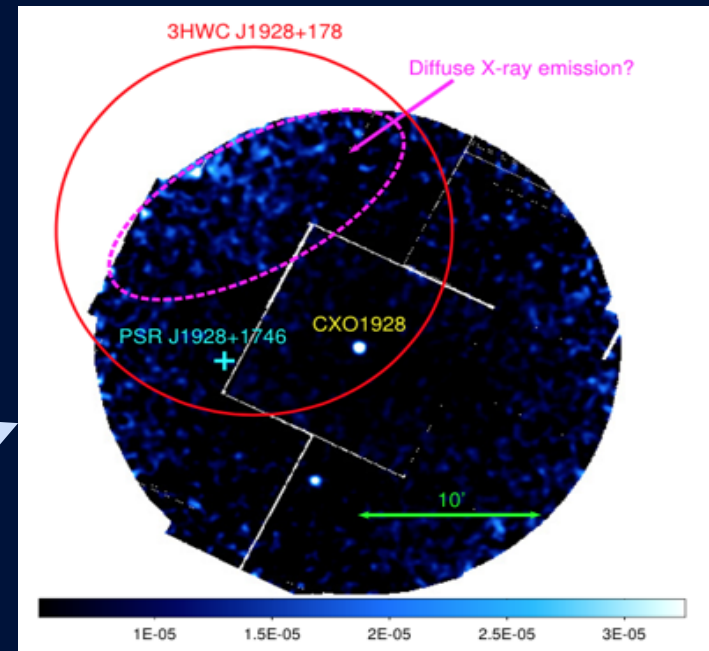
Cao et al. 2021

LHAASO J1929+1745 / 3HWC J1928+178

- TeV binary or dark accelerator (Mori et al. 2020)?
- A variable X-ray source with high mass companion => TeV binary?



TeV (HAWC)



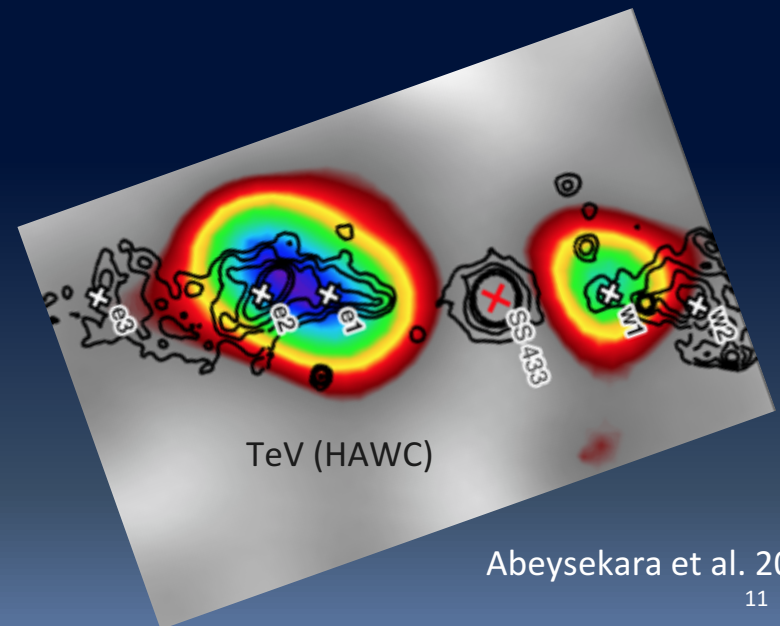
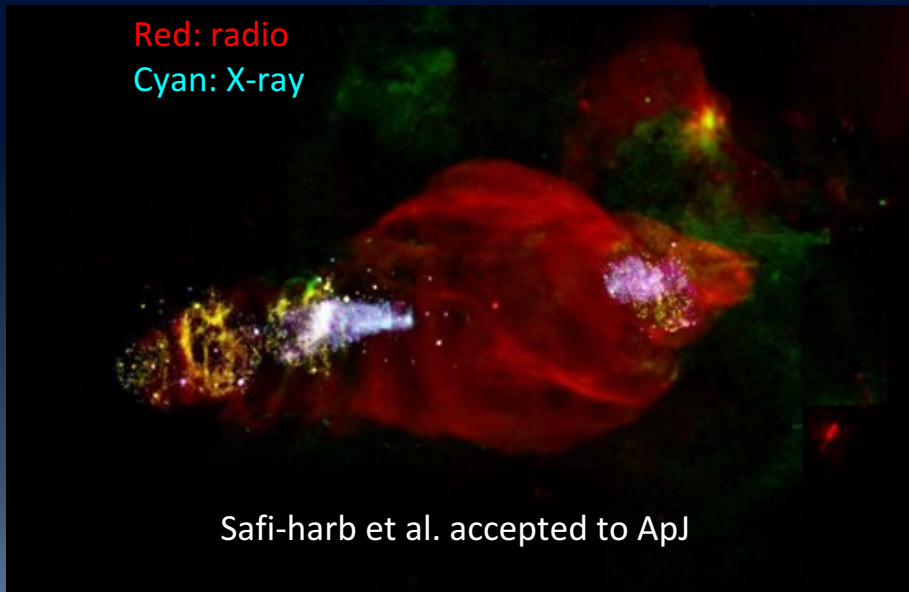
X-ray (XMM)

- Diffuse X-ray emission coinciding with the HAWC source?
- XMM follow-up observations scheduled this year

(3) SS433/W50 lobes: Microquasar jets

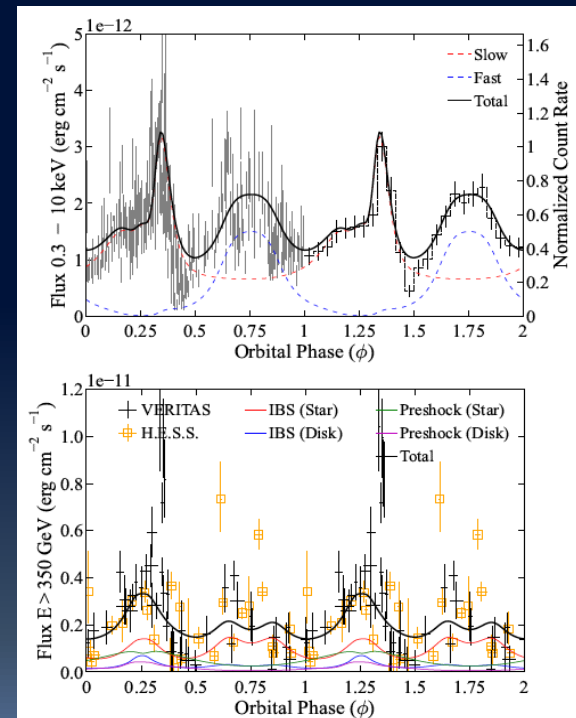
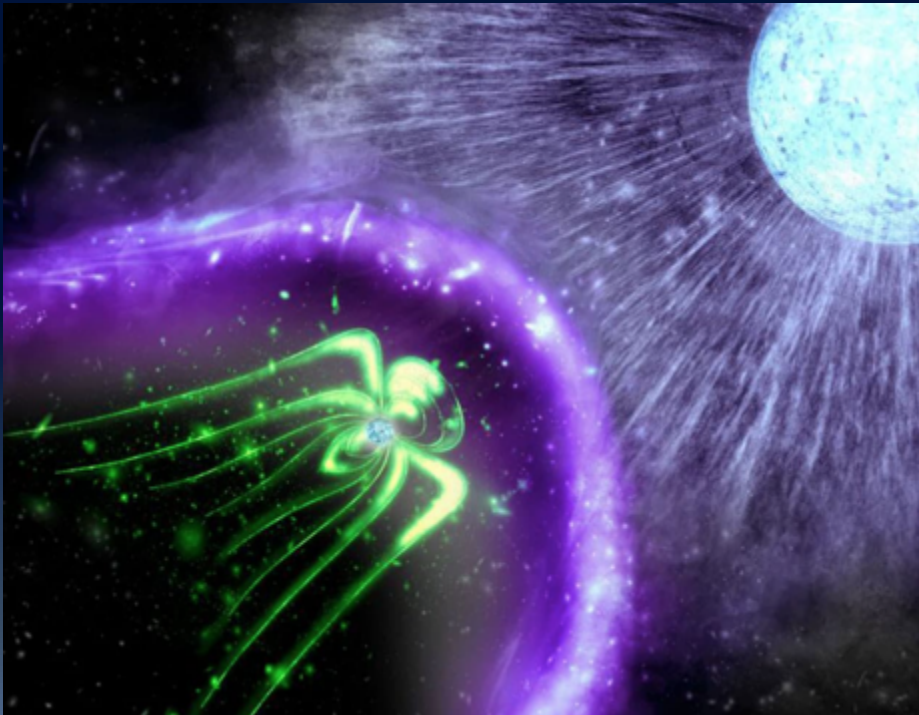


- Microquasar jets interacting with the ISM
- HAWC TeV detection of W50 lobes
- See S. Safi-harb's talk on Monday
- On-going NuSTAR + XMM analysis of the western lobe
- Chandra and ALMA observations scheduled (led by N. Tsuji)



(4) TeV gamma-ray binaries: HESS J0632+053

- Pulsar + stellar wind collisions cause intra-binary shock => TeV emission
- NuSTAR + VERITAS observations (Archer+ 2020, Tokayer+ 2021)
- Refined MW lightcurve and SED modeling (Kim et al. submitted to ApJ)
- NuSTAR observation of the gamma-ray spike scheduled in April 2023

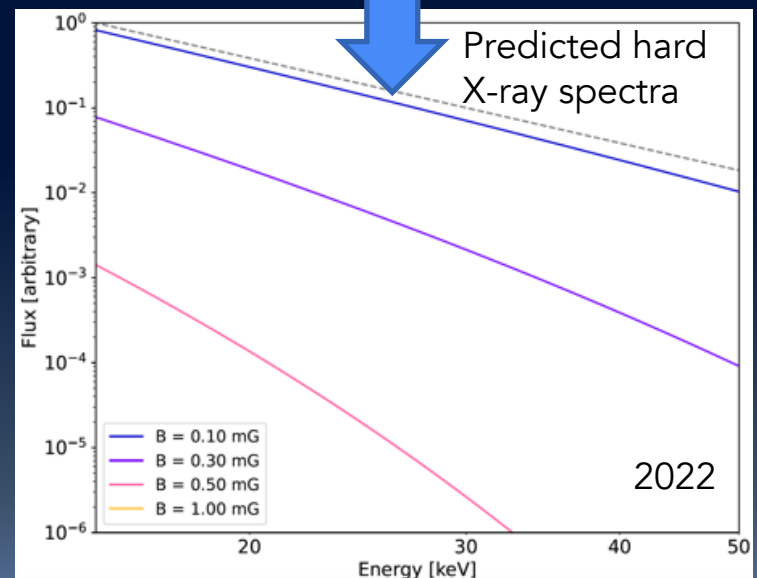
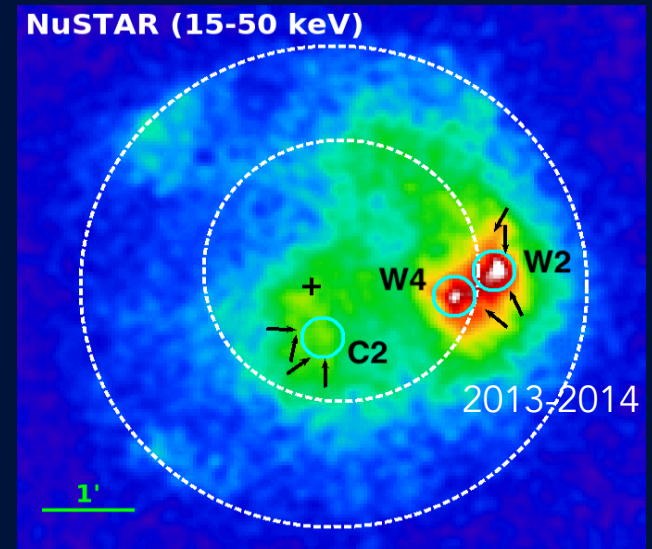


X-ray

TeV

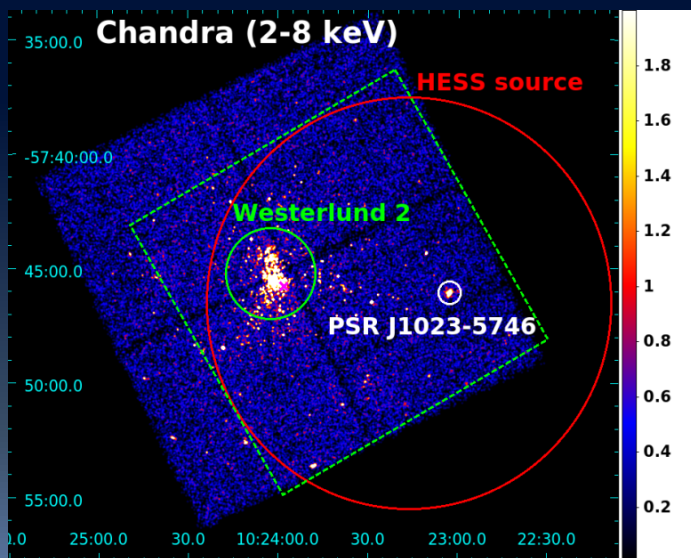
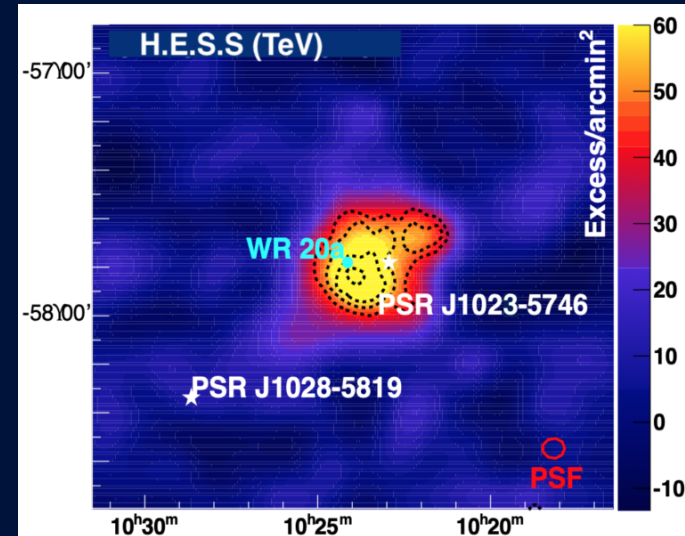
(5) Young supernova remnants: Cassiopeia A

- 2.6 Msec NuSTAR legacy observations in 2013-2014:
 - Ti44 line and X-ray continuum mapping (Grefenstette+ 14, 15)
 - Hard X-ray knots => most energetic particle acceleration sites
- NuSTAR follow-up observation scheduled in July 22
 - Hard X-ray variability over ~20 yr due to synchrotron cooling

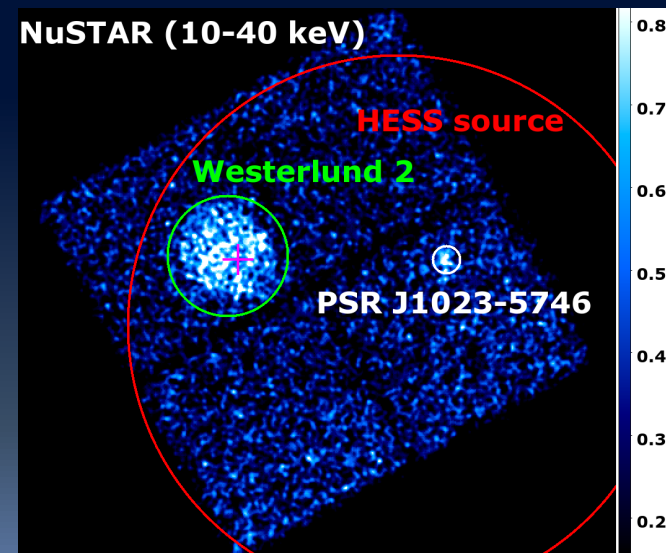


(6) Massive star clusters: Westerlund 2

- MSCs as one of the primary classes of hadronic accelerators (Aharonian et al. 2019)
- Some MSCs produce large-scale gamma-ray cocoons over $\sim 100\text{-}200$ pc (Yang et al. 2019)
- NuSTAR observation of Westerlund 2 approved
 - Is the X-ray emission non-thermal?
 - Leptonic or hadronic origin?



Simulation



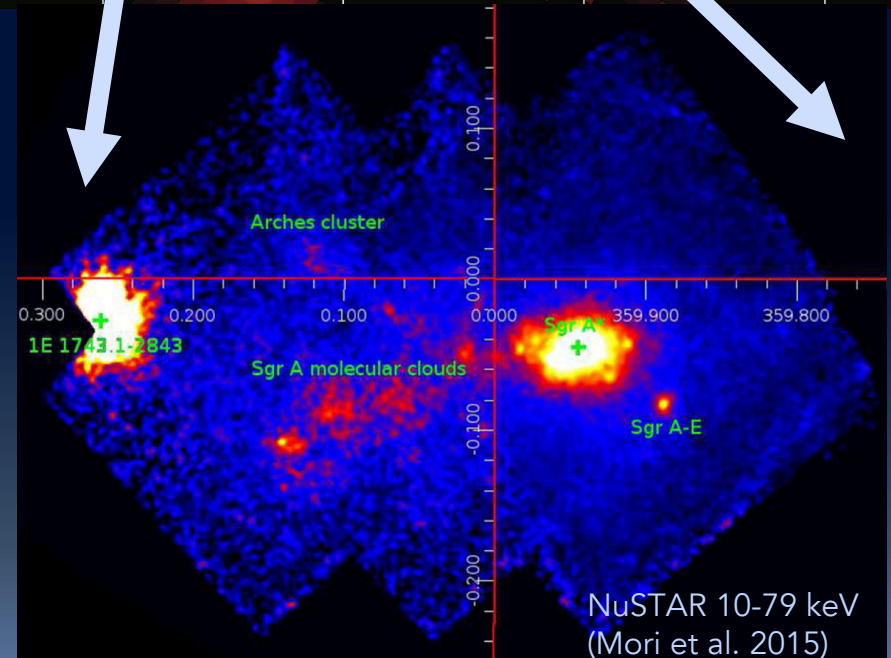
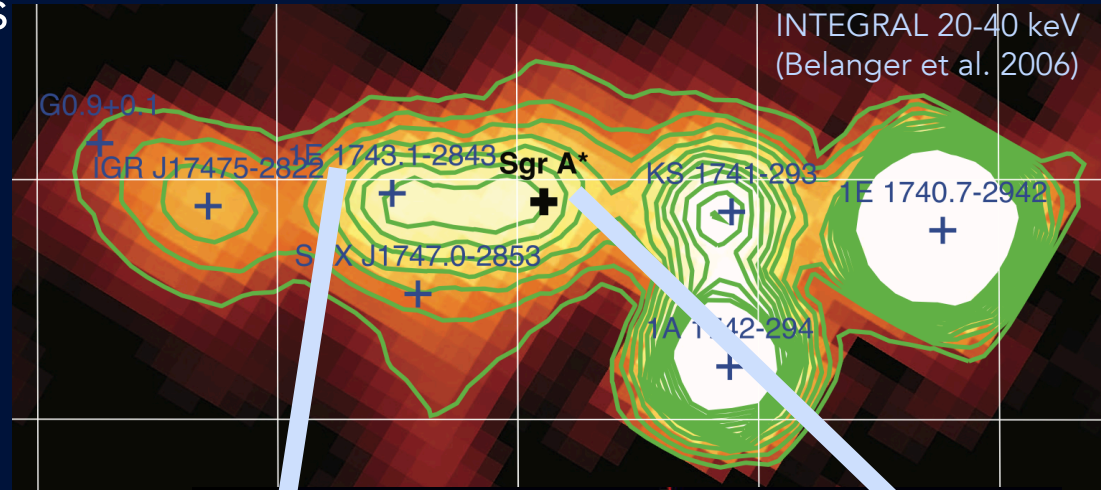
(7) Hard X-ray views of the Galactic Center

- NuSTAR resolved various hard X-ray sources

- PWN
- X-ray filaments
- Star clusters
- Molecular clouds
- X-ray binaries
- Magnetic CVs

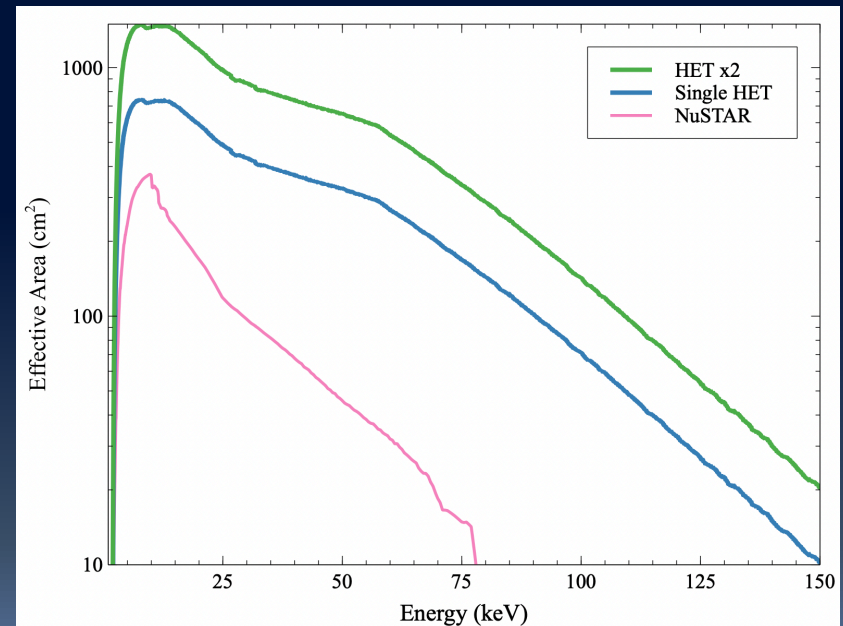
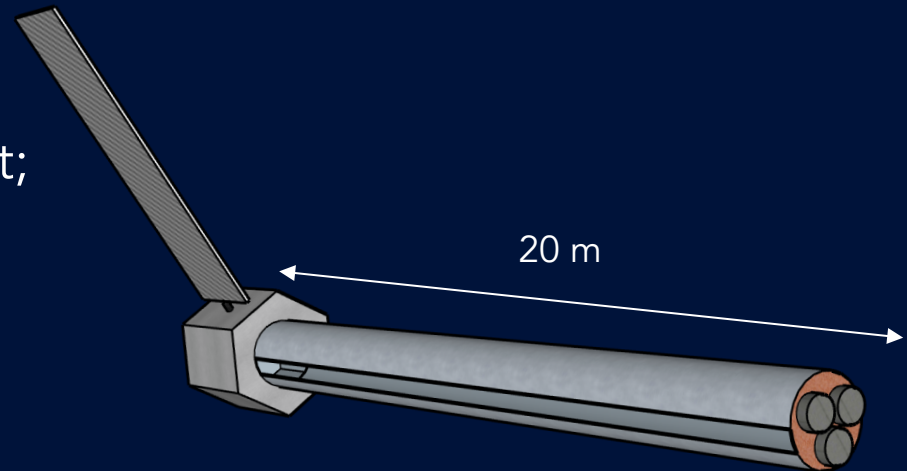
- Upcoming NuSTAR observations (led by S. Zhang)

- Sgr A* flares (with EHT, Gravity)
- Sgr A clouds, filaments



Future: High energy X-ray probe

- One of NASA's X-ray probe mission candidates (~\$1B budget; to be launched in early 2030s)
- PI: Daniel Stern (JPL/Caltech)
- Baseline telescope design
 - Energy band: 0.1-150 keV
 - Angular resolution: 5 arcsec
- Check out: HEXP.org



Summary

- 10 years of NuSTAR mission => observing gamma-ray sources
- MW observations of Galactic TeV sources => source ID and emission mechanisms
- Multiple publications, approved X-ray observations and student projects
- We work on transients, too.
 - ICECUBE blazar ToOs with NuSTAR + VERITAS (led by Q. Feng and R. Mukherjee)
 - X-ray transients
- Questions? Collaboration? Contact Kaya Mori (kaya@astro.columbia.edu)