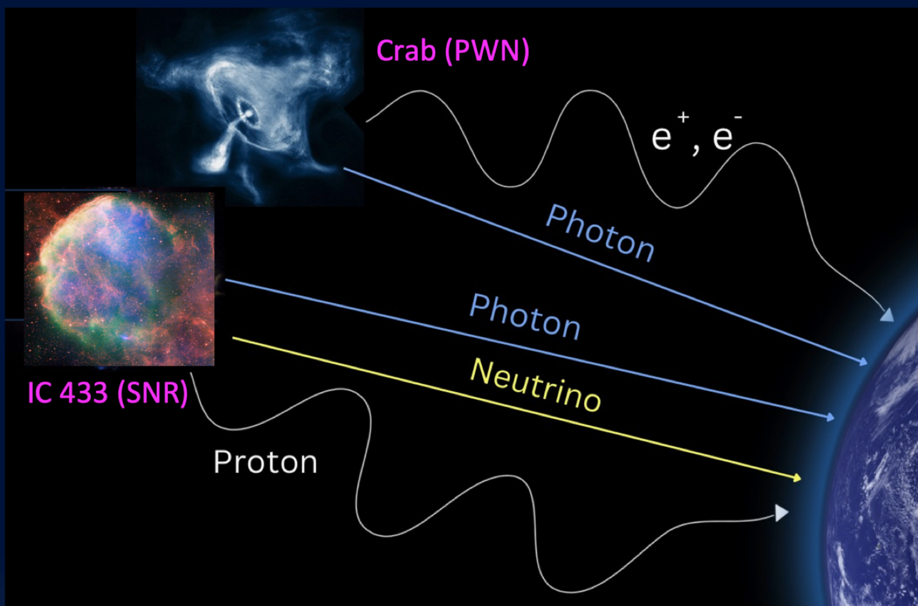
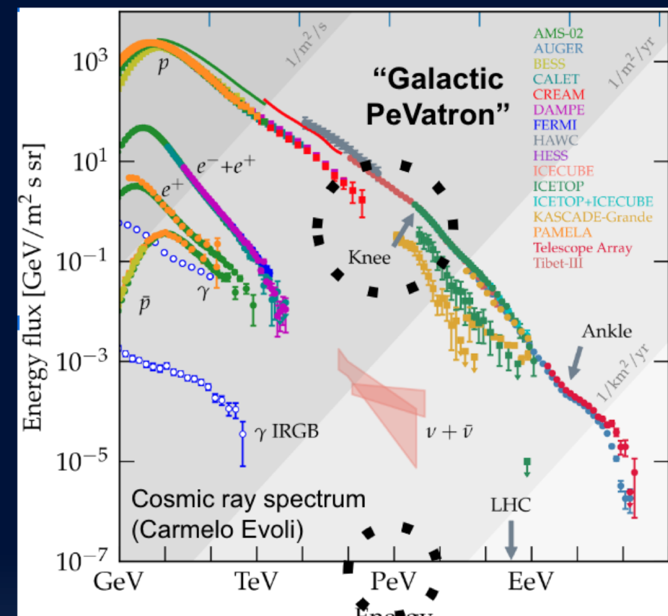
Multi-wavelength observations of Galactic PeVatrons





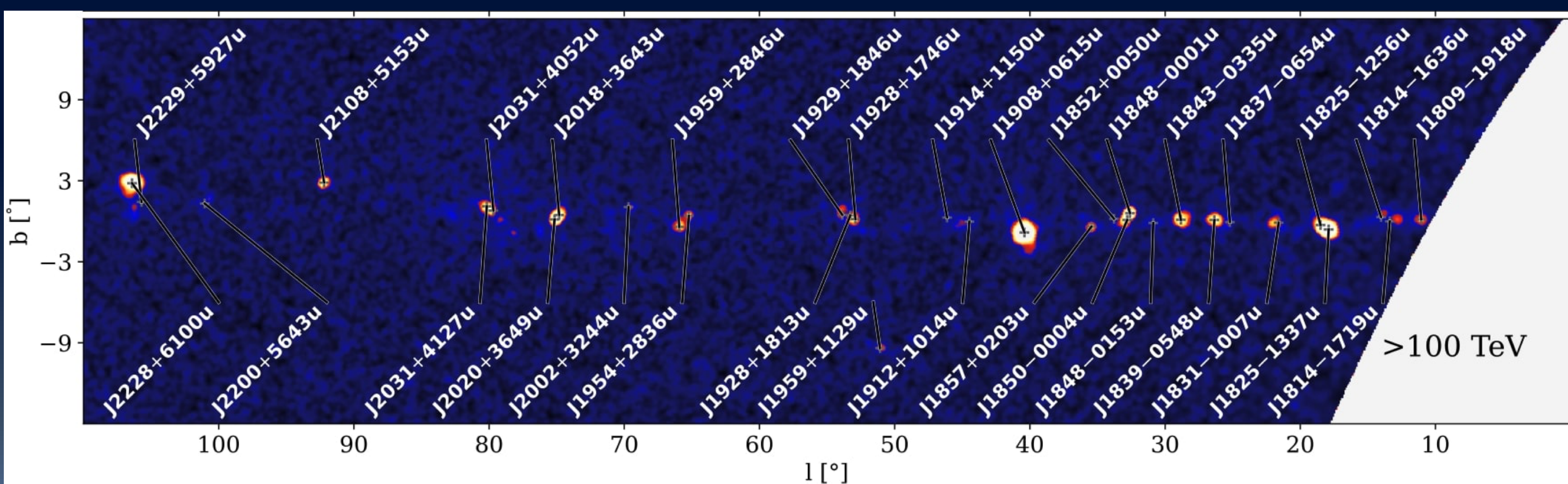
Kaya Mori
(Columbia University)

June 14, 2024

PeVatron astrophysics in 2024: where do we stand?

- See Fabio Acelo’s talk
- 2023 is the revolutionary year of PeVatron astrophysics
  - 43 UHE sources (E > 100 TeV; LHAASO, HAWC, Tibet AS-g)
  - Hadronic PeVatrons exist in our galaxy (IceCube)
- The field is in an early stage and rapidly growing.

LHAASO E > 100 TeV sky map (Cao et al. 2023)



Galactic PeVatron observations: 3 steps

PeVatron finders (E > 100 TeV)	PeVatron locators (E = 0.1-100 TeV)	PeVatron identifiers (MW bands)
LHAASO	H.E.S.S.	TeV
HAWC	VERITAS	GeV
Tibet AS-g	MAGIC	X-ray
	CTAO	Radio

Galactic TeV source multi-messenger collaboration

- ~50 members including observers in radio, IR, X-ray, gamma-ray bands, neutrino astrophysics and theorists

HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

VERITAS

ICECUBE
NEUTRINO OBSERVATORY

Fermi
Gamma-ray
Space Telescope

Nuclear Spectroscopic Telescope Array
NuSTAR
Bringing the High Energy Universe into Focus

esa
xmm-newton

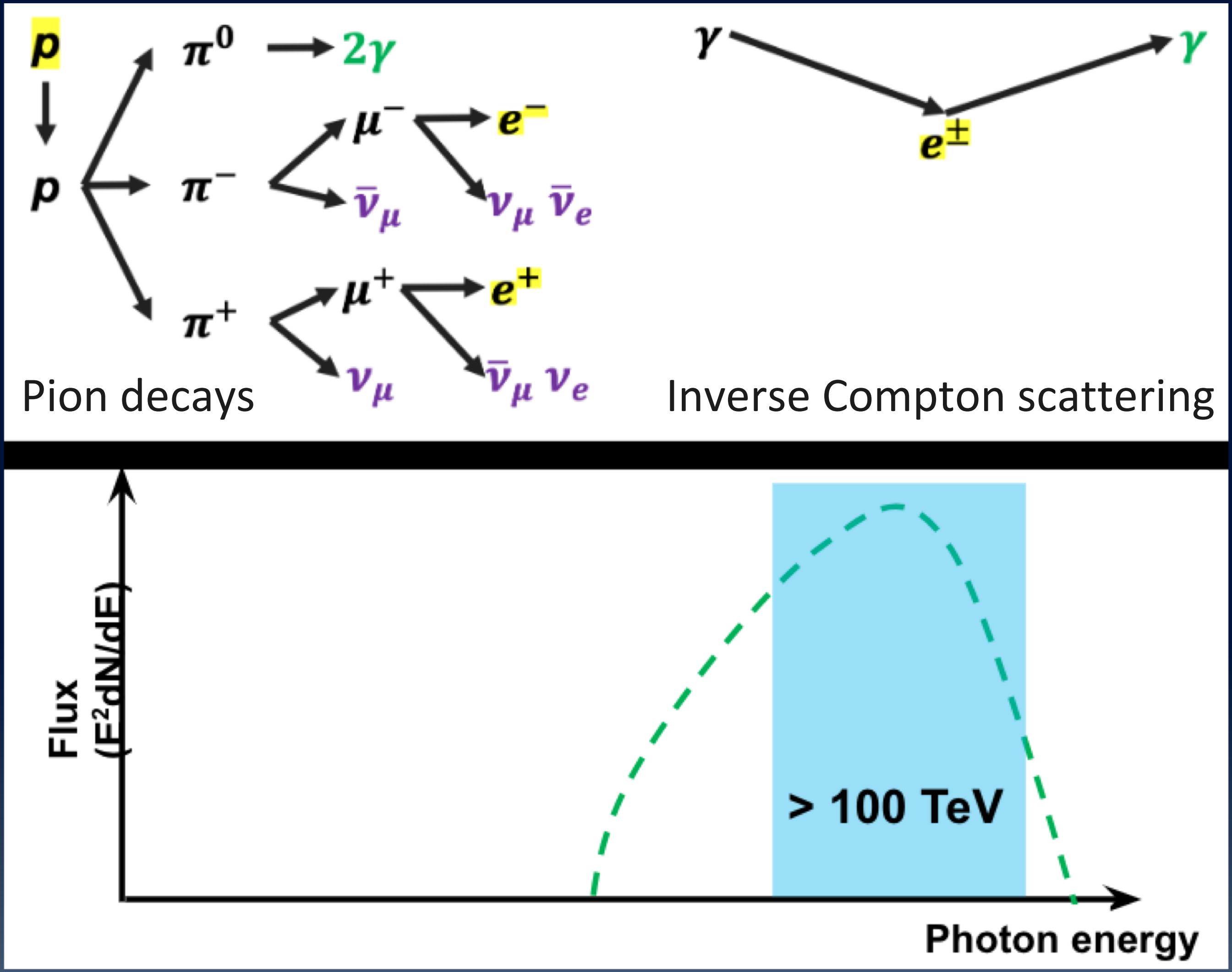
What we are working on…

1) Young SNRs
2) Middle-aged PWNe
3) Unidentified Galactic PeVatrons
4) Gamma-ray binaries
5) SS433 microquasar jet lobes
6) Star clusters
7) Globular clusters
8) Galactic Center (Sgr A*, clouds, filaments…)

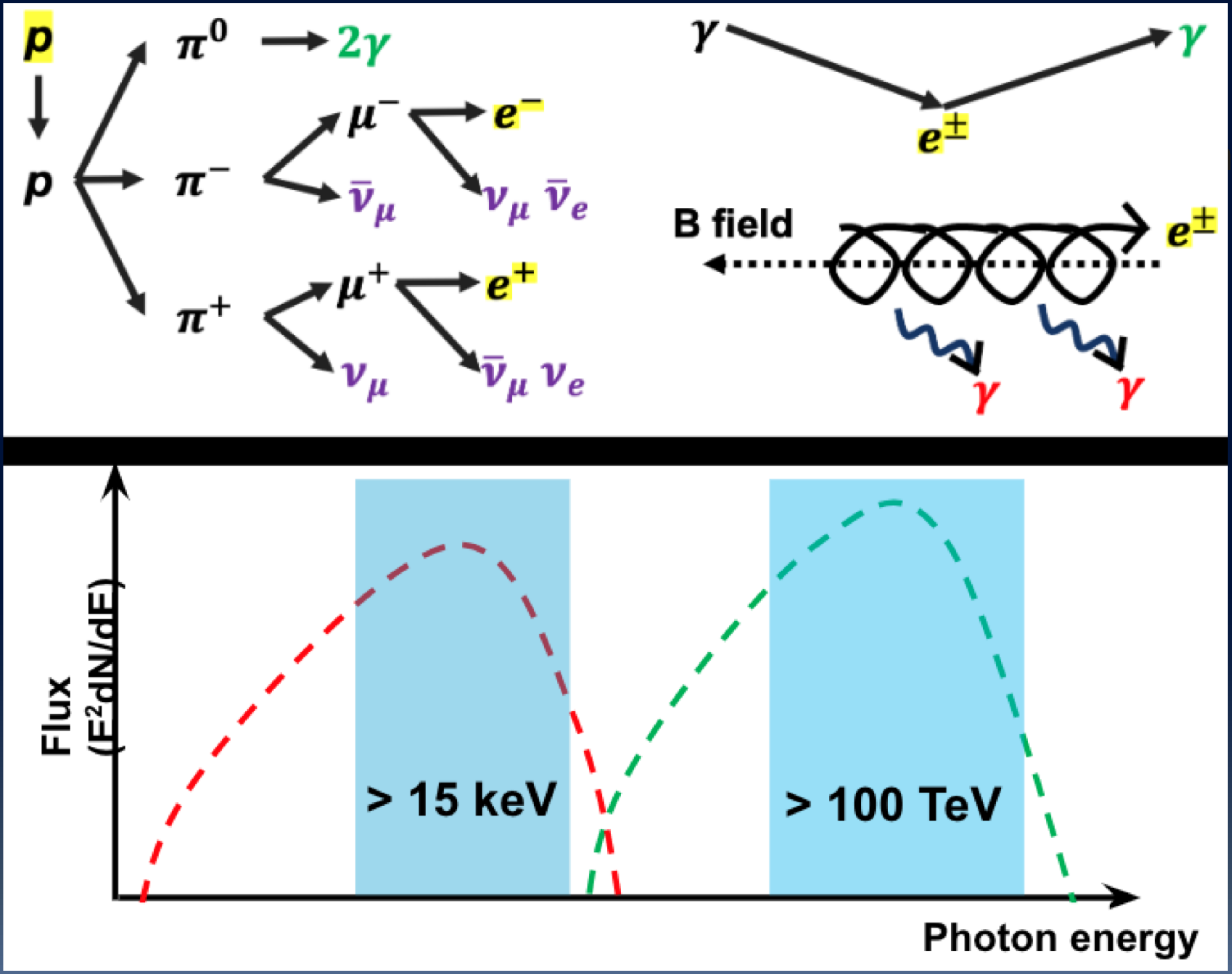
SNR 2024 posters from our collaborators

- J. Alford (S7.1): CTA 1 PWN
- B. MacIntyre (S8.6): SS433 lobes
- I. Sander (S8.7): Salamander PWN
- N. Tsuji (S8.8): Molecular clouds around LHAASO J0341
- J. Woo (S8.9) : Cas A hard X-ray variability
- M. Abdelmaguid (S9.2): Kes 75 and HESS J1640 PWNe

Hadronic vs leptonic process for producing gamma-rays

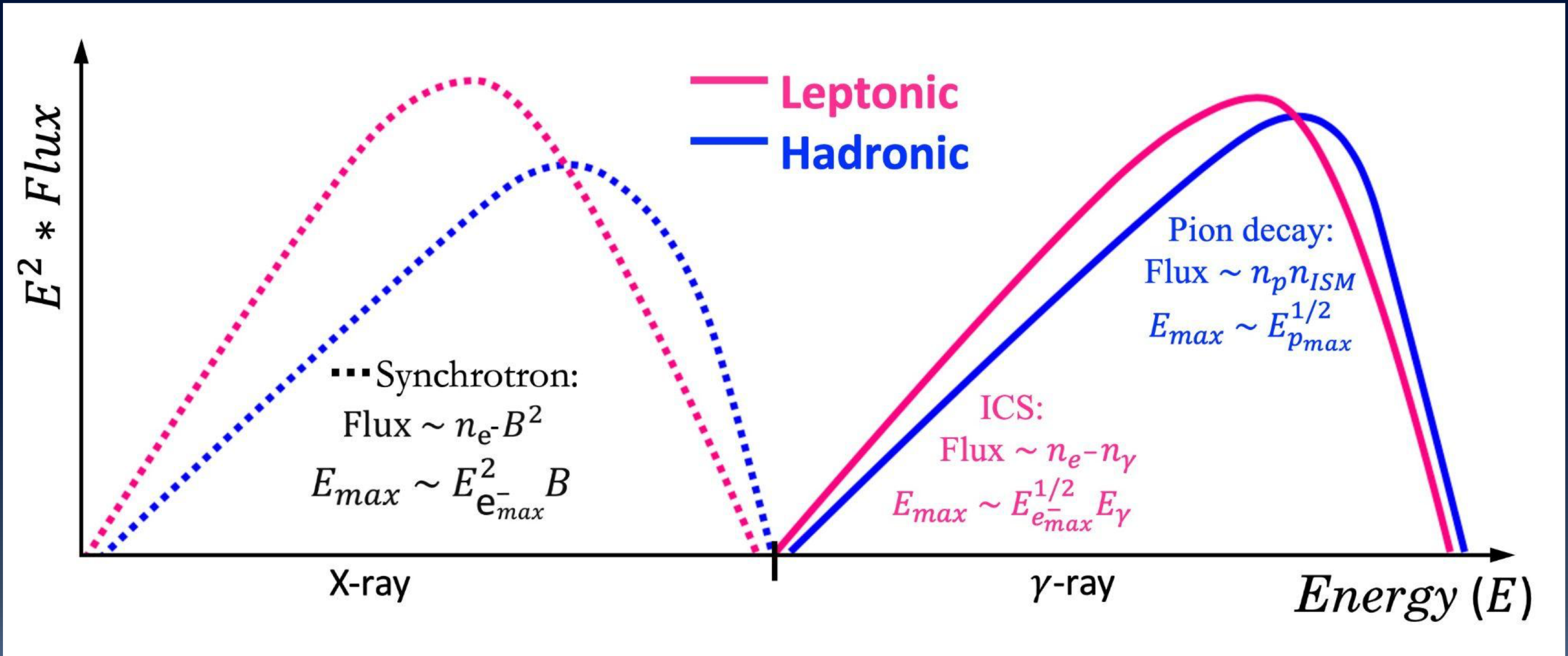


Synchrotron radiation in radio to X-ray band



Multi-wavelength spectral energy distribution

- Fitting MW SED data => determining key parameters
  - Emax, particle spectrum, B-field, ambient density…



Key questions addressing through MW observations

1. Leptonic or Hadronic accelerator?

1. Which types of accelerators (SNRs, PWNe)?

1. Any interaction targets (molecular clouds)?

1. Intrinsic particle energy distributions (e.g., Emax, spectral index)?

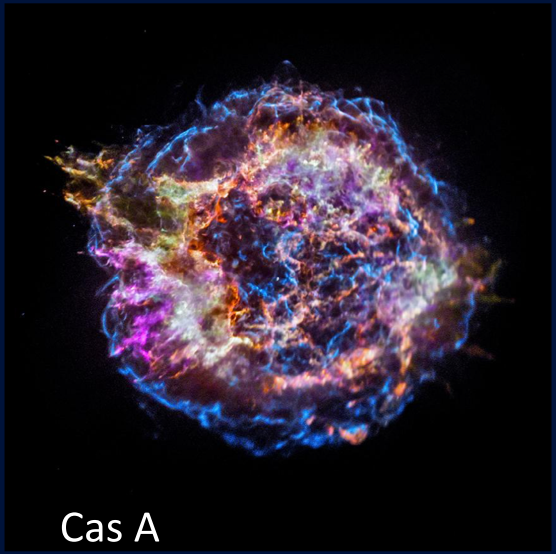
1. Environmental parameters (B-field , density)?

Investigating Two types of Galactic CR accelerators

- Known particle accelerators:

  Are they PeVatrons?

  – SNRs, PWNe, Star clusters, compact object binaries or something else

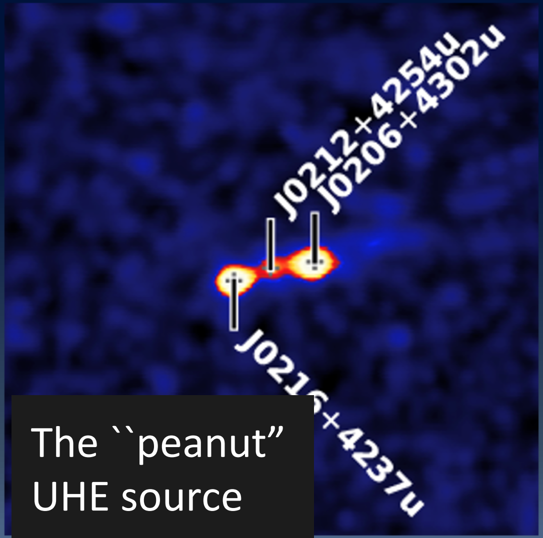


Cas A

- Unidentified PeVatrons:

  What are they?

  – Nearly all of the 43 UHE sources are still unidentified



The ``peanut" UHE source

Is my favorite gamma-ray source a PeVatron?

Hadronic accelerators:

Emax (proton) > 1 PeV ?

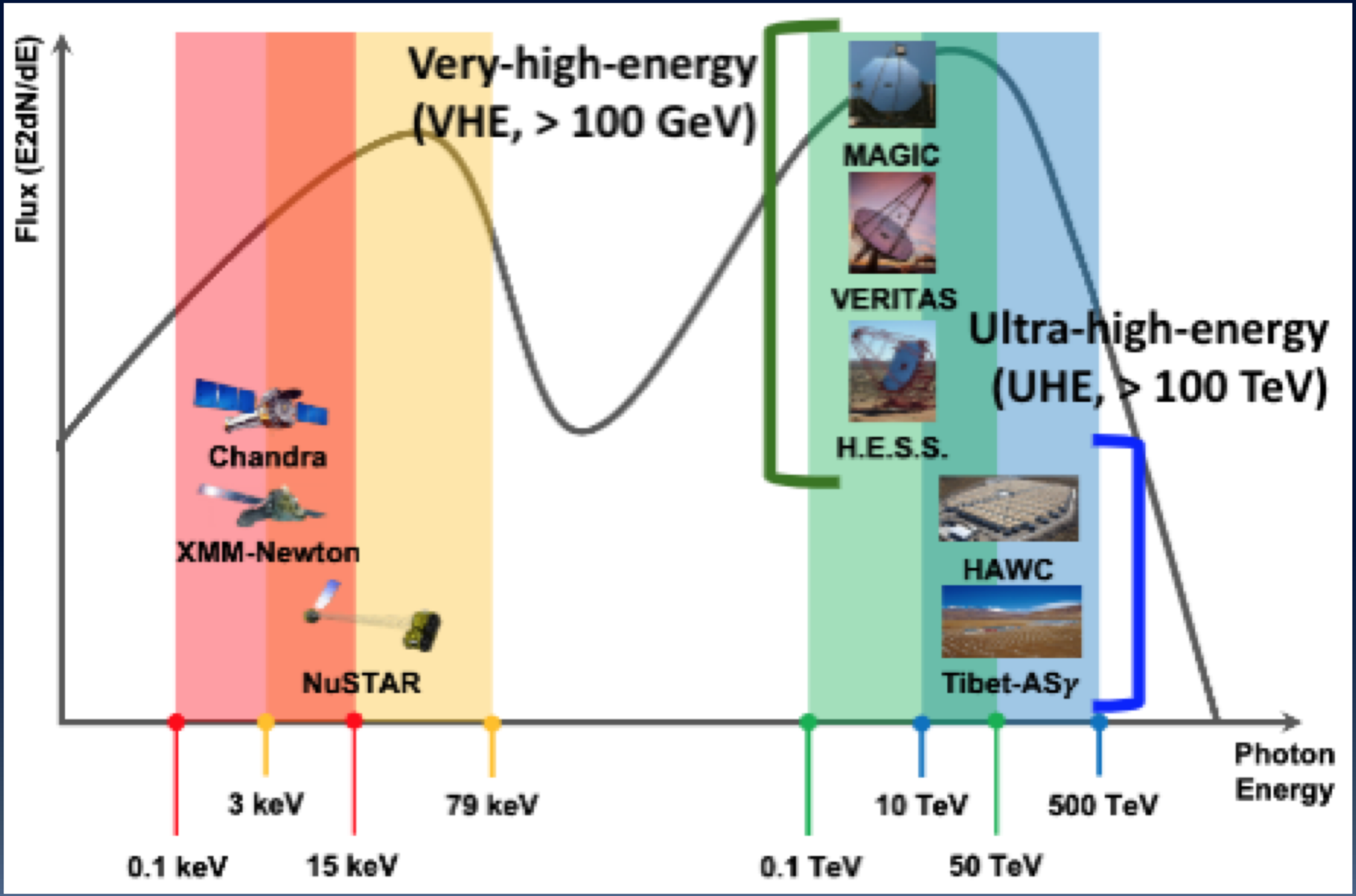
* Emax > 3 PeV above the knee

Leptonic accelerators:

Emax (e^+/e^-) > 1 PeV ?

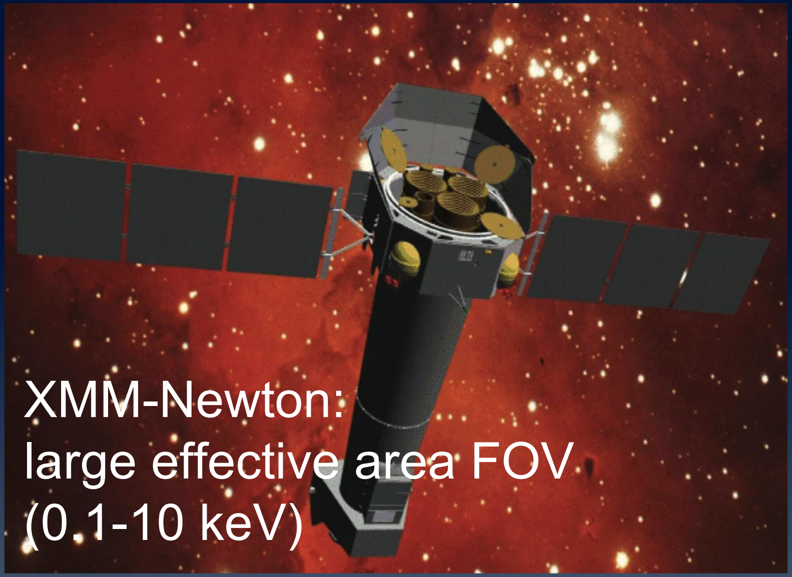
*after taking into account cooling

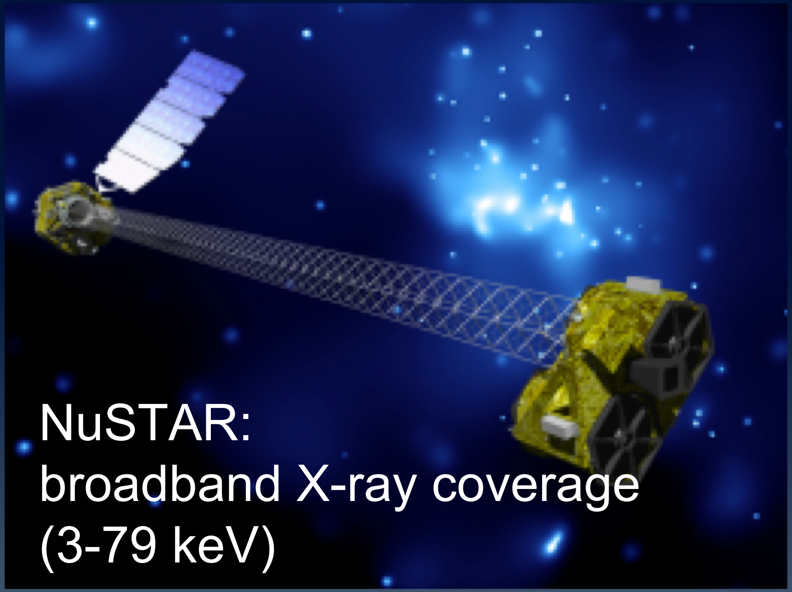
X-ray and UHE data are important for exploring TeV-PeV particles and determining Emax



X-ray telescopes for studying diffuse X-ray emission

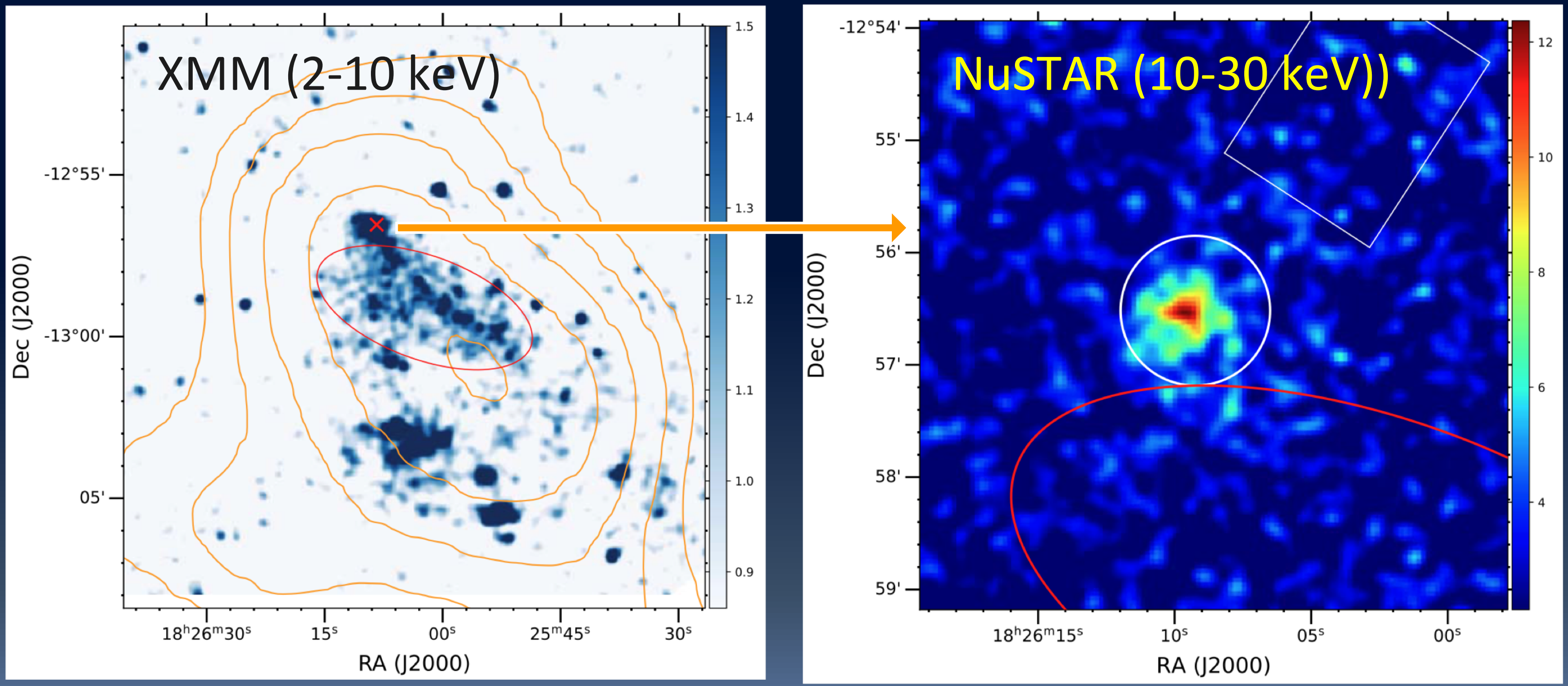
- XMM-Newton and NuSTAR are best-suited for studying non-thermal diffuse X-ray emission
- Chandra (Oleg’s PWN talk), eROSITA, INTEGRAL, Suzaku





X-ray telescopes detect synchrotron radiation from TeV-PeV electrons

- XMM large FOV survey => NuSTAR hard X-ray follow-up
- Hard X-ray band (> 10 keV) explores more energetic particles
  - Esyn = 40 keV (Ee/100 TeV)^2(B/0.1 mG) => Sensitive to Emax
  - Tsyn = 1.2 yr (B/0.1 mG)$^{-3/2}$(Esyn/10 keV)$^{-1/2}$ => Faster variability

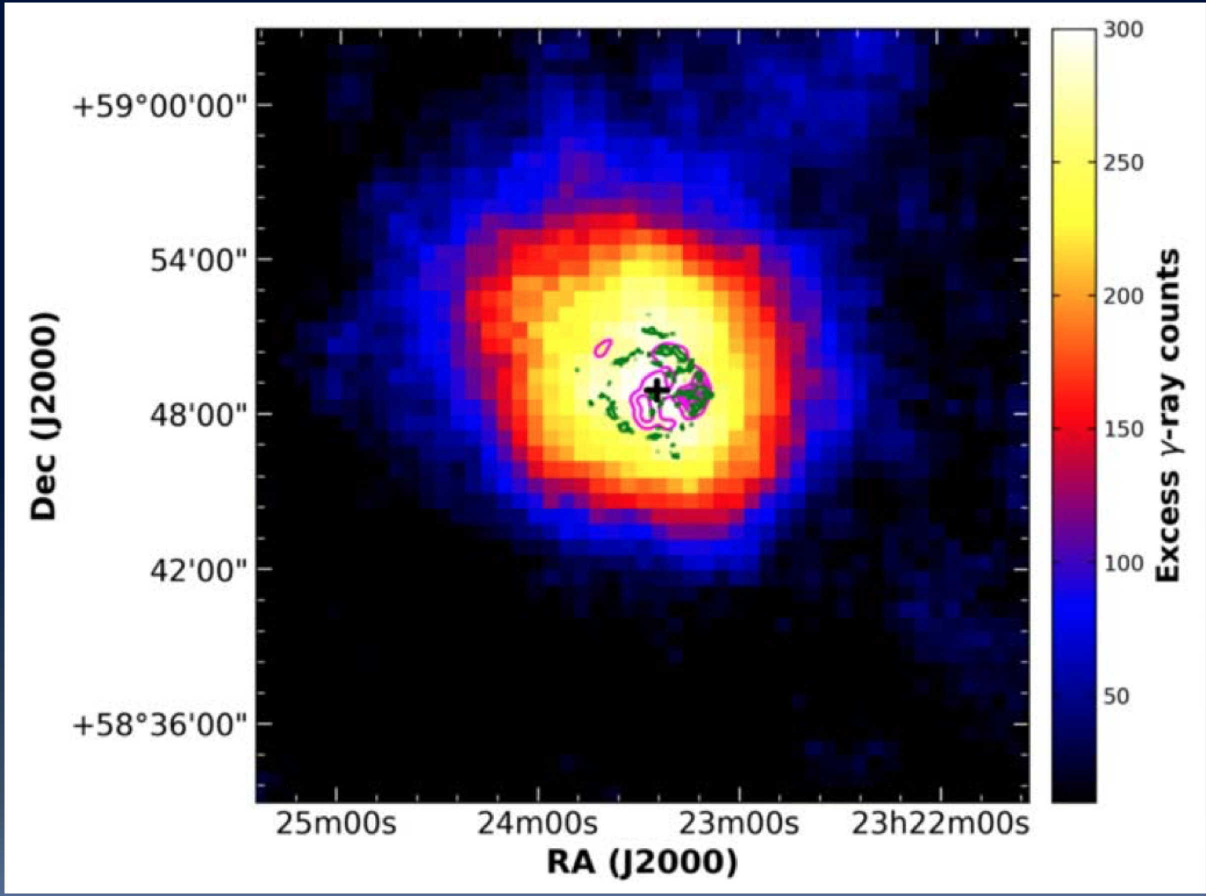


HESS J1826-130 = Eel PWN (Burgess+ 22)

Young supernova remnants

Are we sure that young SNRs are not PeVatrons?

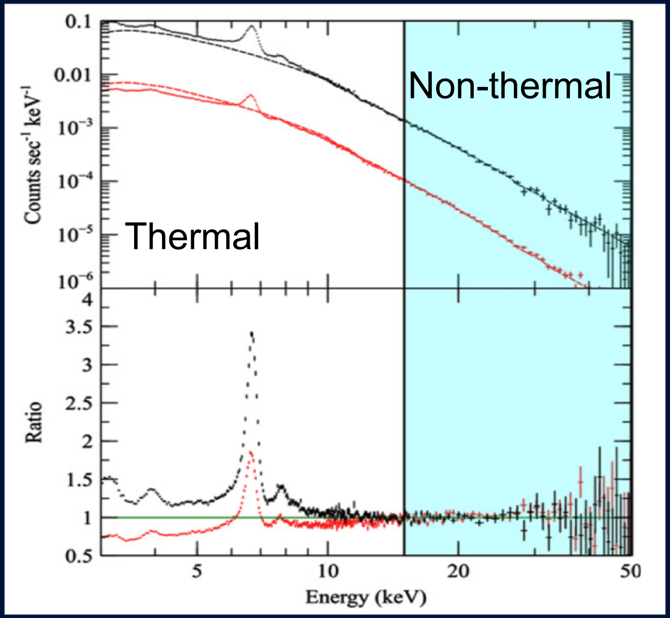
- No detection above ~10 TeV (Talks by Acero and Yang)
- Any local PeVatrons not resolved in the TeV band?



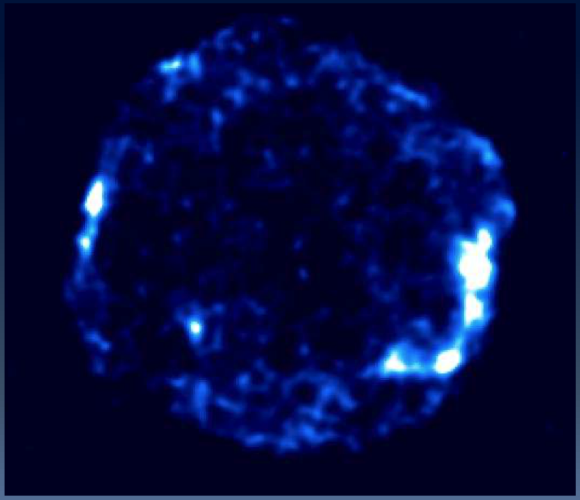
VERITAS TeV image of Cas A (Abeysekara+ 20)

NuSTAR traces the most energetic electrons above 15 keV

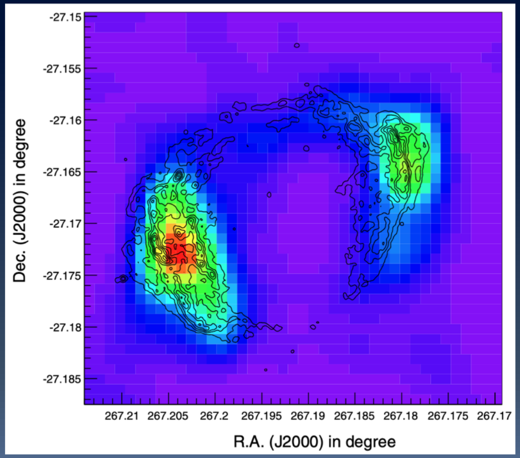
- Dissecting synchrotron X-ray emission from thermal emission at E > 15 keV



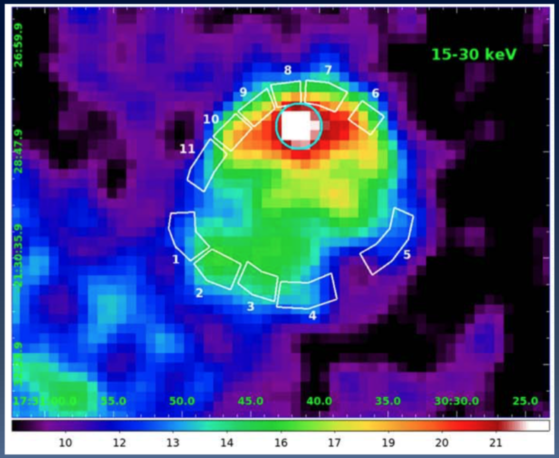
Tycho (Lopez+ 15)



G1.9+0.3 (Zoglauer+ 15)

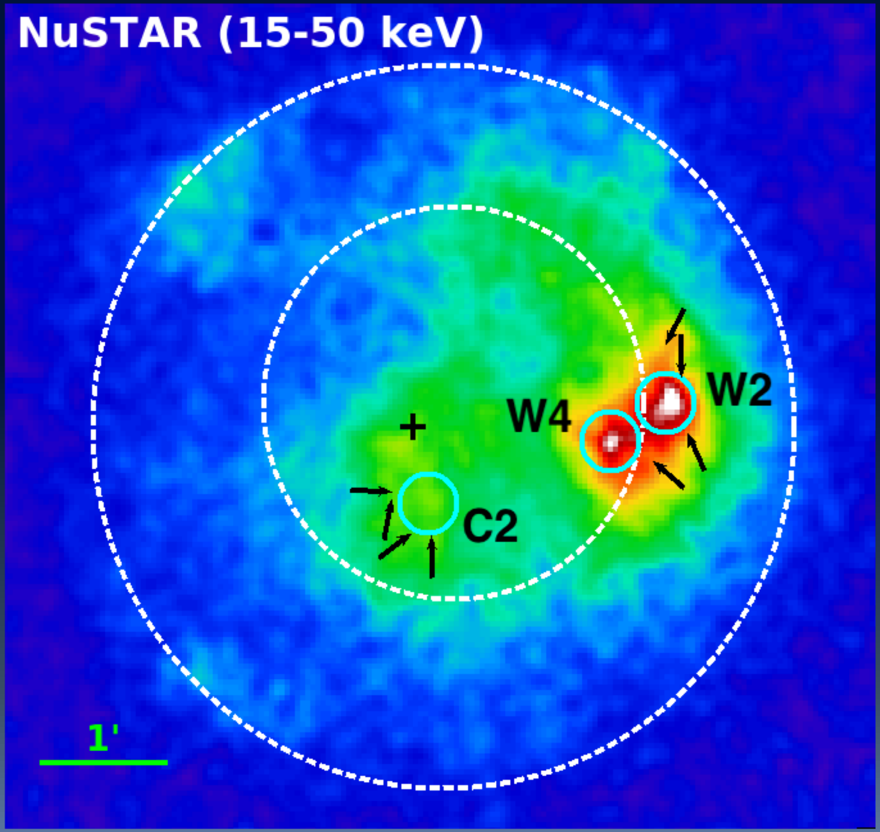


Kepler (Sapienza+ 22)



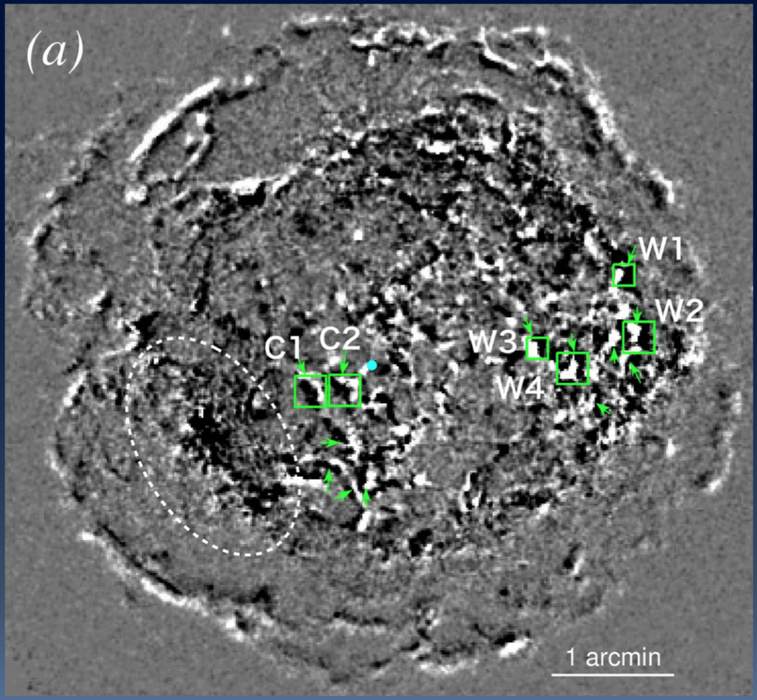
Cas A: NuSTAR view of non-thermal-only X-ray emission

- NuSTAR observations in 2012-13 (2.4 Ms; Grefenstette+15)
- Hard X-ray knots = most energetic electron sites
- Different morphology from radio and thermal X-ray emission



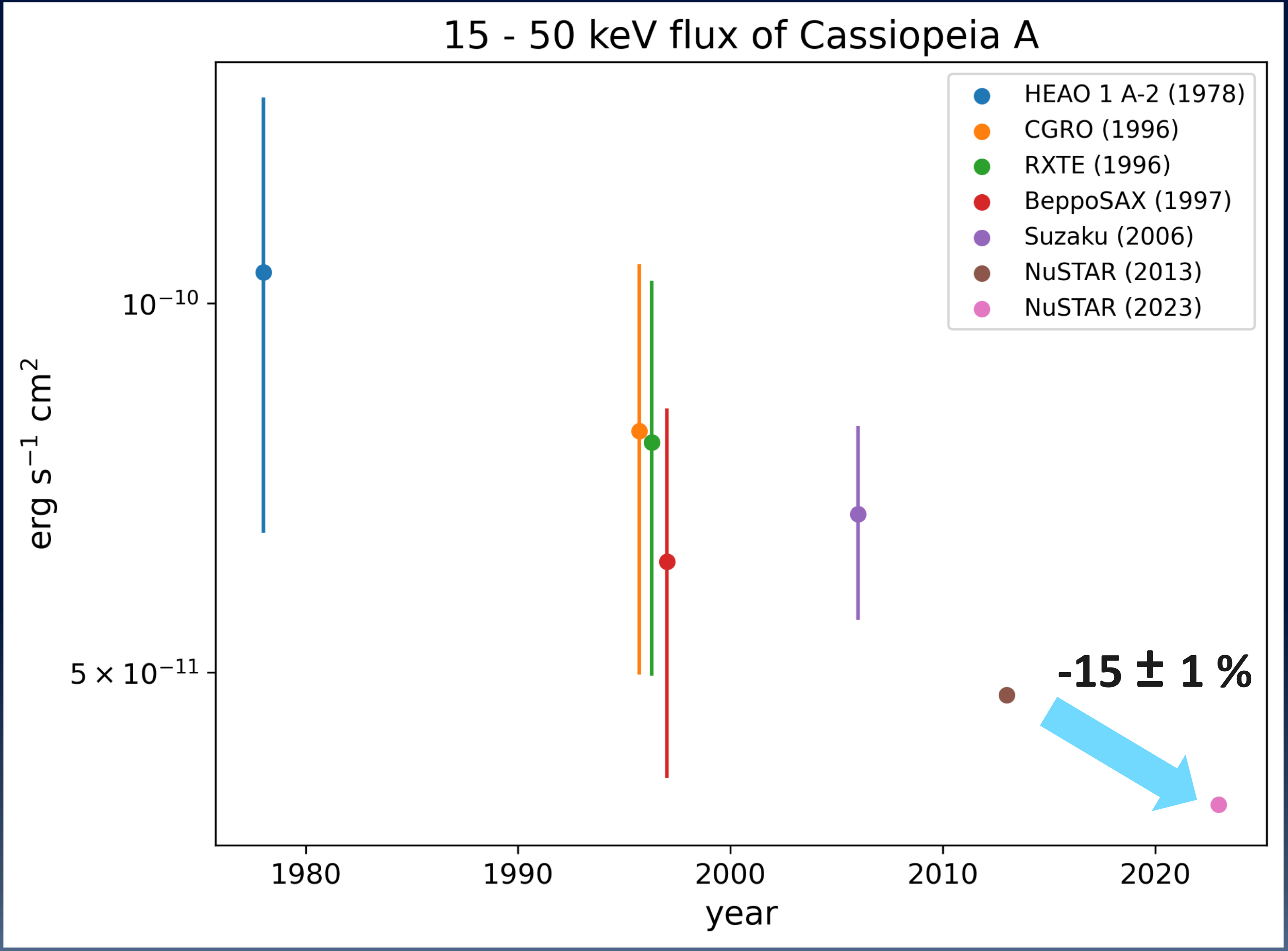
SNRs are dynamical sources with year-scale variabilities

- Multi-epoch MW observations
  - Proper motions and variabilities in Chandra 4-6 keV narrow band
    => V, dV/dt, B-field (Sato+ 17, Tanaka+ 21, Vink+ 22 + many papers)
- The brightest hard X-ray knot coincides with the reflected shock region

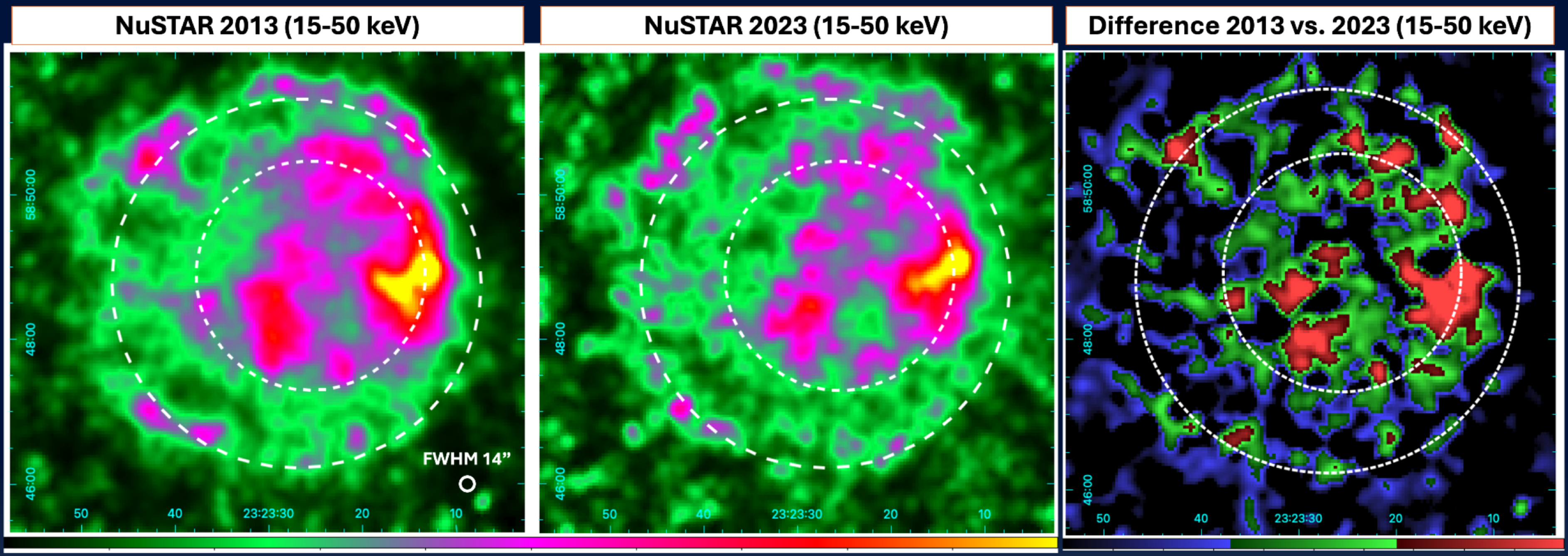


Cas A: Chandra 4-6 keV difference image between 2000 and 2014 (Sato+ 2017)

Cas A: NuSTAR observation in 2023 detected 15% decrease above 15 keV

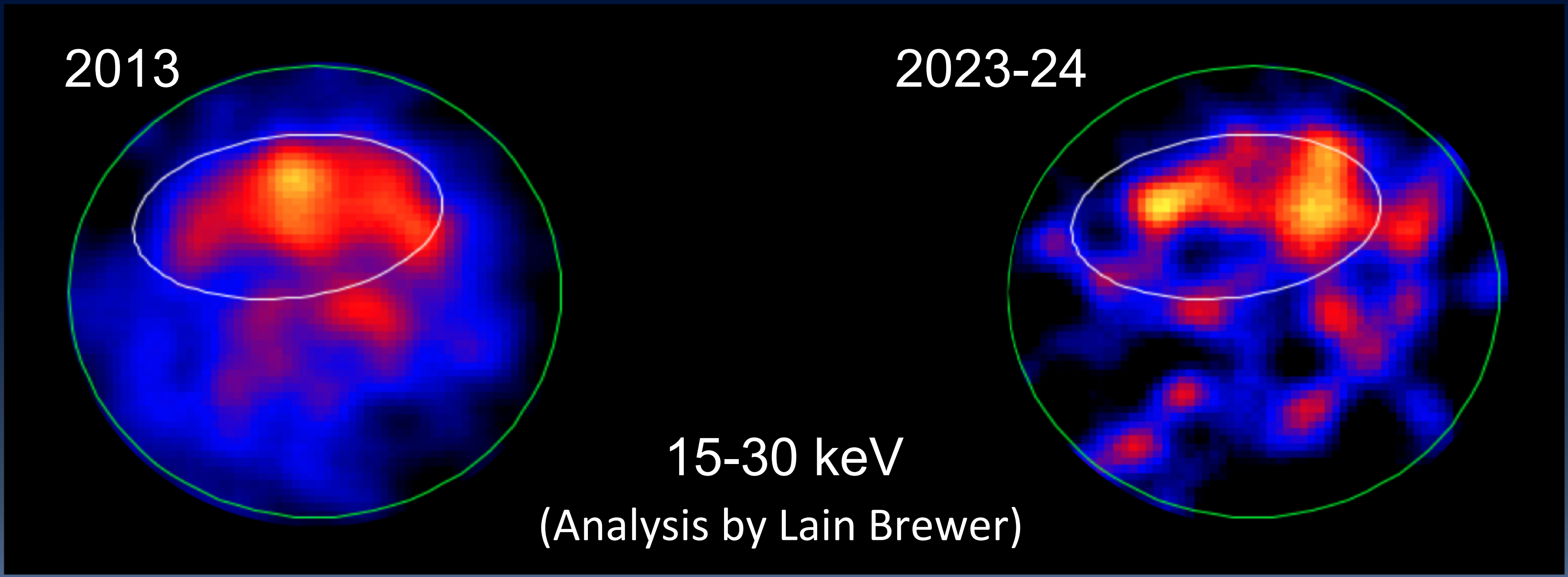


Cas A: hard X-ray knots remained bright after 10 years



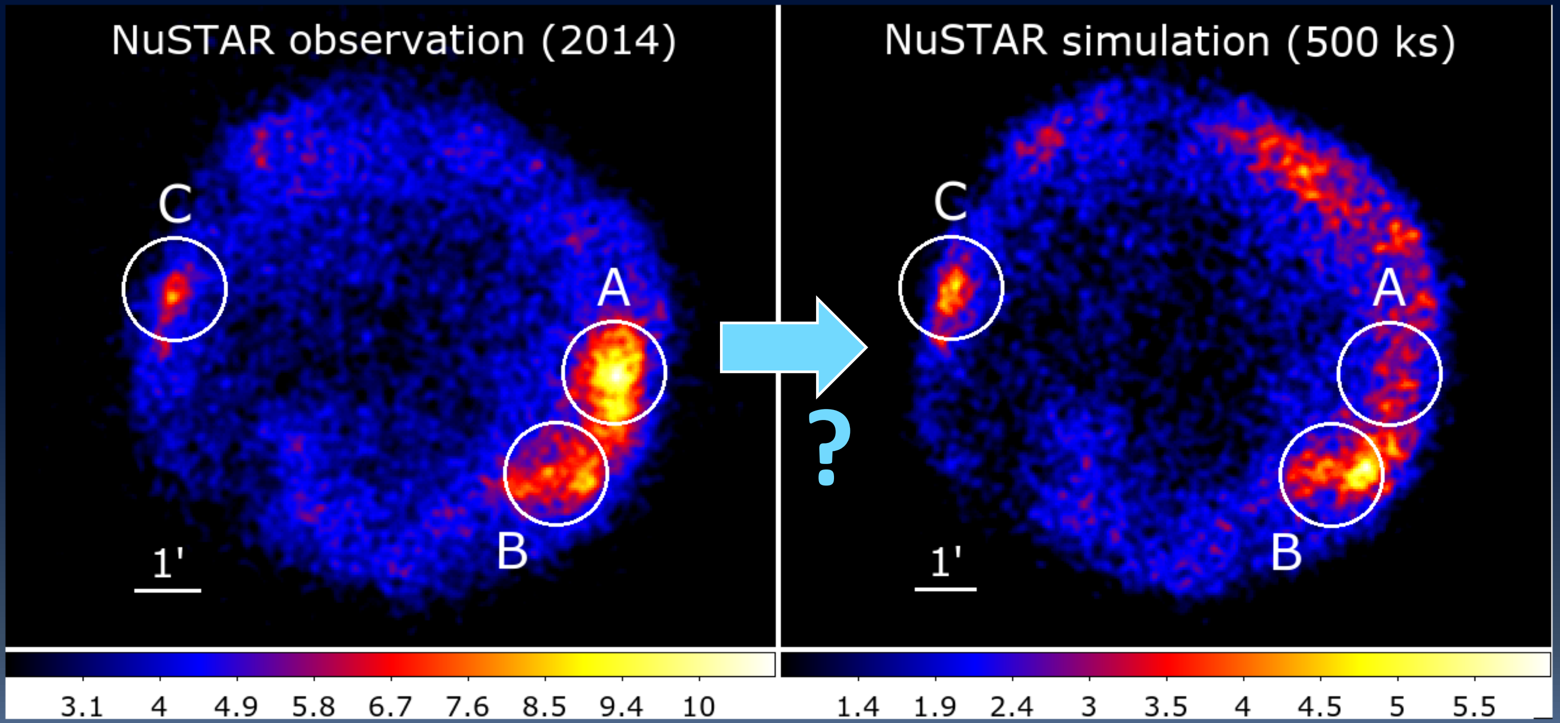
Kepler: 13% (?) flux decrease in the hard X-ray knot

- NuSTAR observed Kepler as a calibration source multiple times
- NuSTAR detected 13 ± 6% flux decrease in the northern region
- Chandra X-ray variability study (See Sapienza's poster)



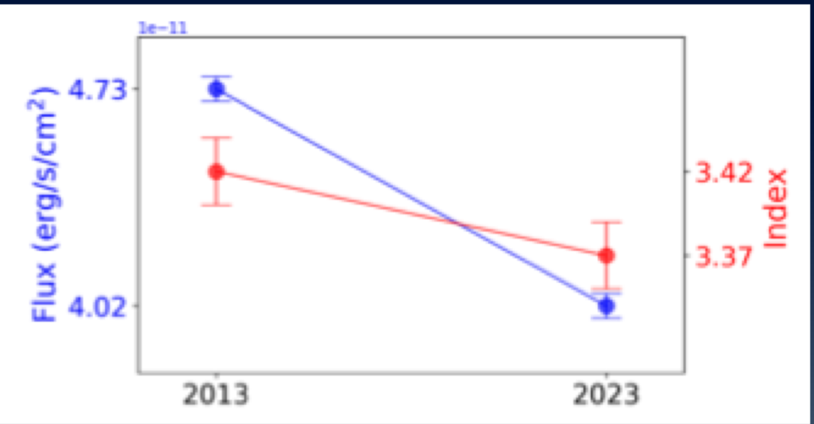
Tycho: new NuSTAR observation scheduled in 2025

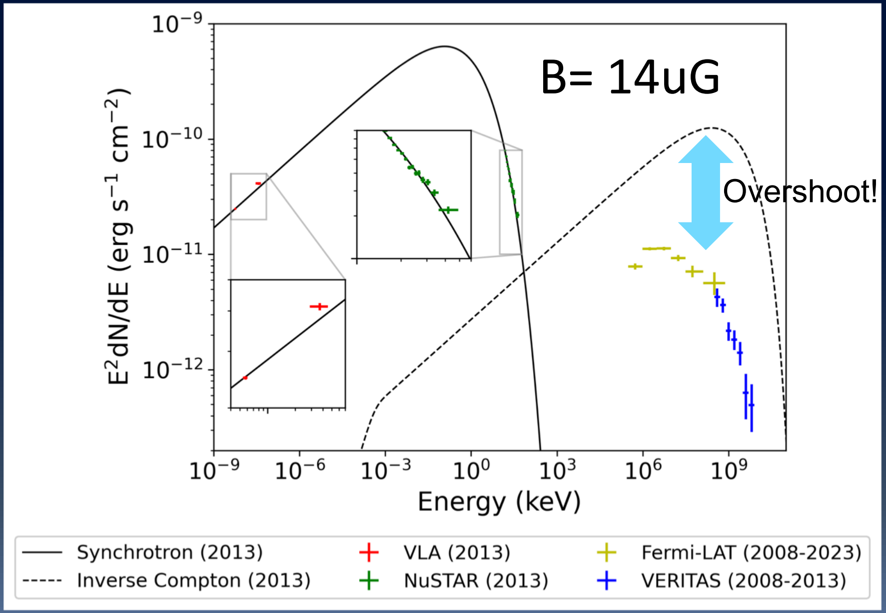
- Easier to resolve the remnant than Cas A and Kepler
- 500 ks approved through NuSTAR AO-10 large program



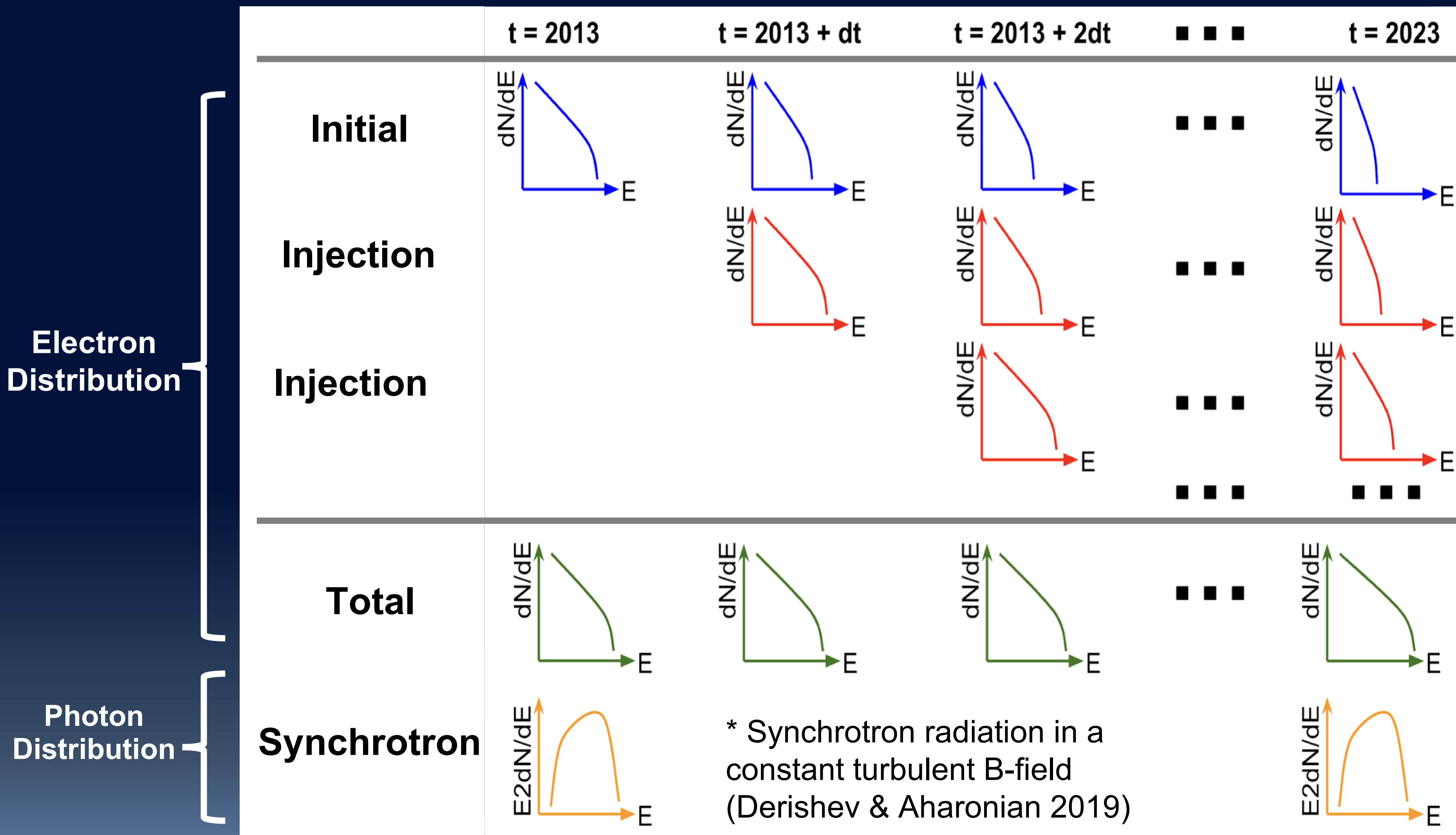
Cas A: What does 15% hard X-ray flux decrease indicate?

- See Jooyun Woo's poster S8.9
- If we assume only synchrotron cooling,
  - B = 14 uG << B ~100 uG ~ few mG (from other estimates)
  - Spectral softening is expected ≠ not observed
  - Predicted ICS flux >> TeV data
- B >> 14 uG & electron injection is required!



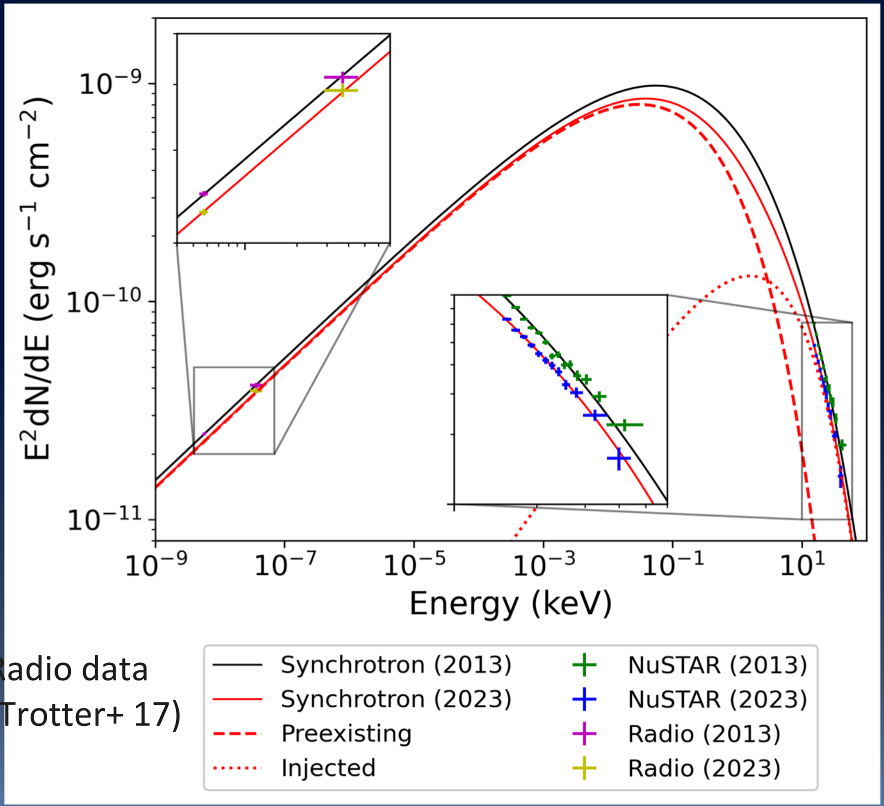


Modeling electron injection and cooling for the past 10 yrs



Cas A: Constraining injected electron spectrum

- Thanks to hard X-ray spectral variability measured by NuSTAR
- Emax (e) = 10-40 TeV => Emax (p)?
- We = 0.1-1% injected over last 10 years
- α_e = 1.9-2.2 => DSA theorists?



Radio data (Trotter+ 17)

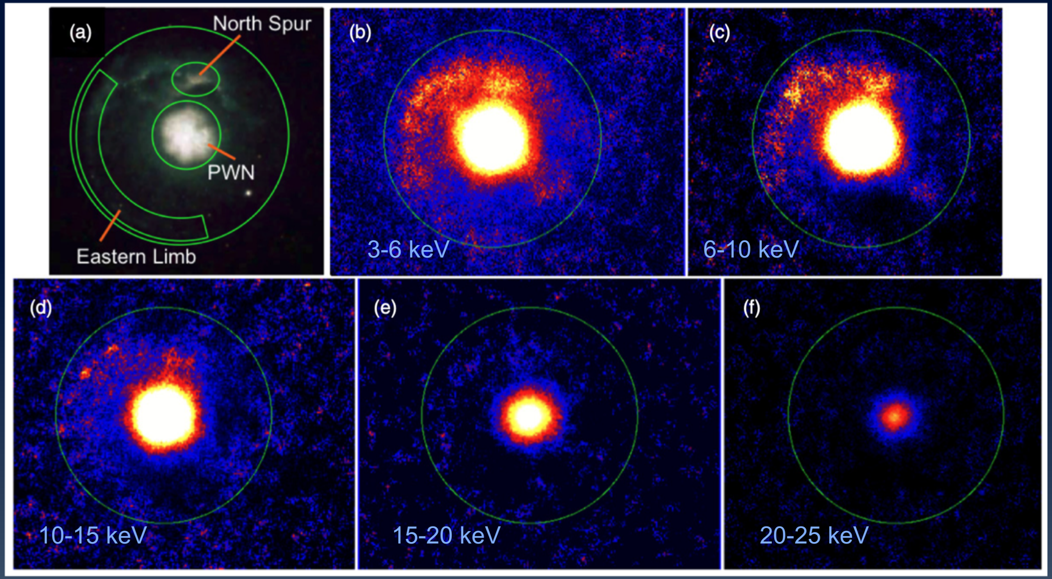
Multi-epoch radio and hard X-ray SED data fit by our electron injection+cooling model

Pulsar wind nebulae

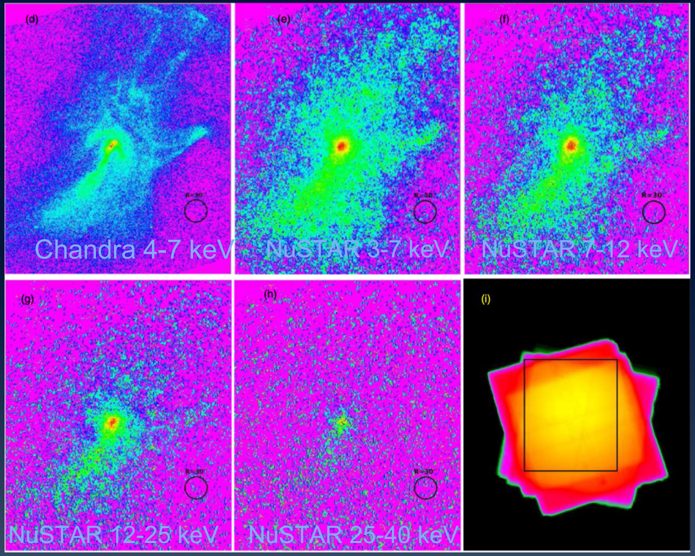
NuSTAR hard X-ray views of young PWNe

- Hard X-ray emission: compact and concentrated around the pulsars
- Synchrotron burnoff effect

G21.5 (NuSTAR; Nynka+ 15)

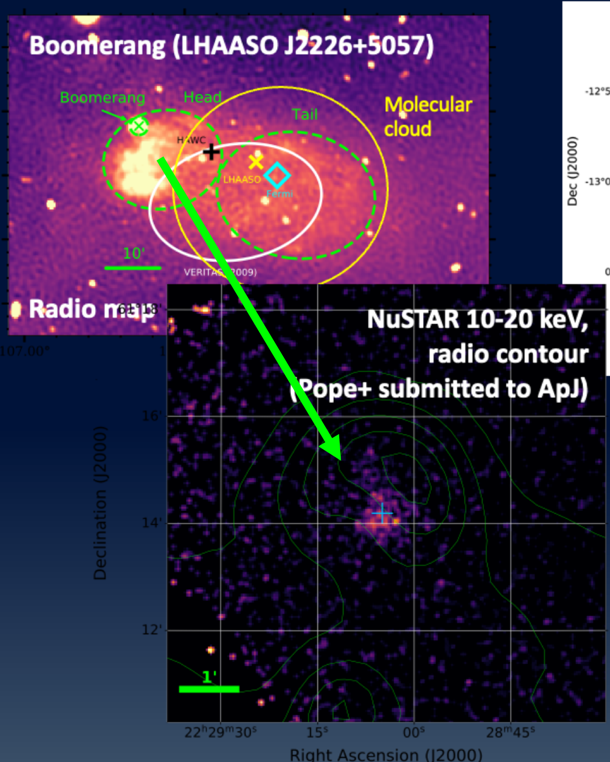


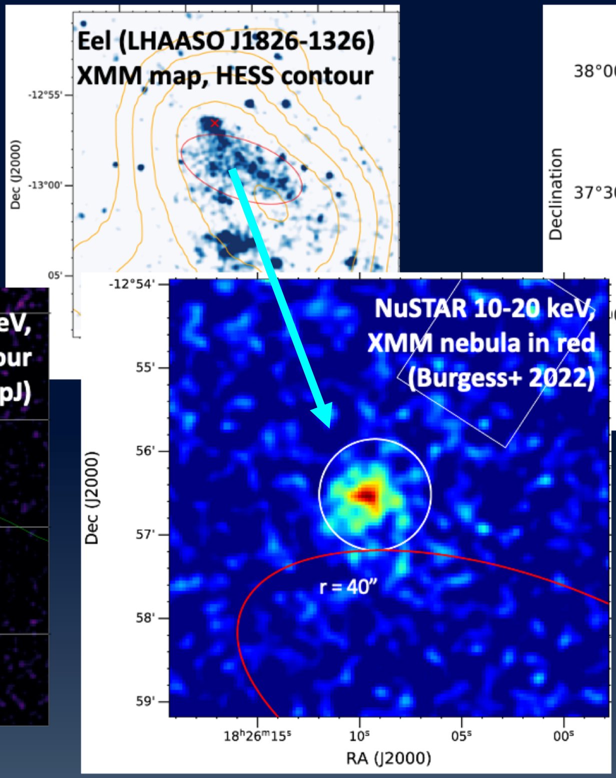
“Hand of God” MSH 15-52 (An+ 14)

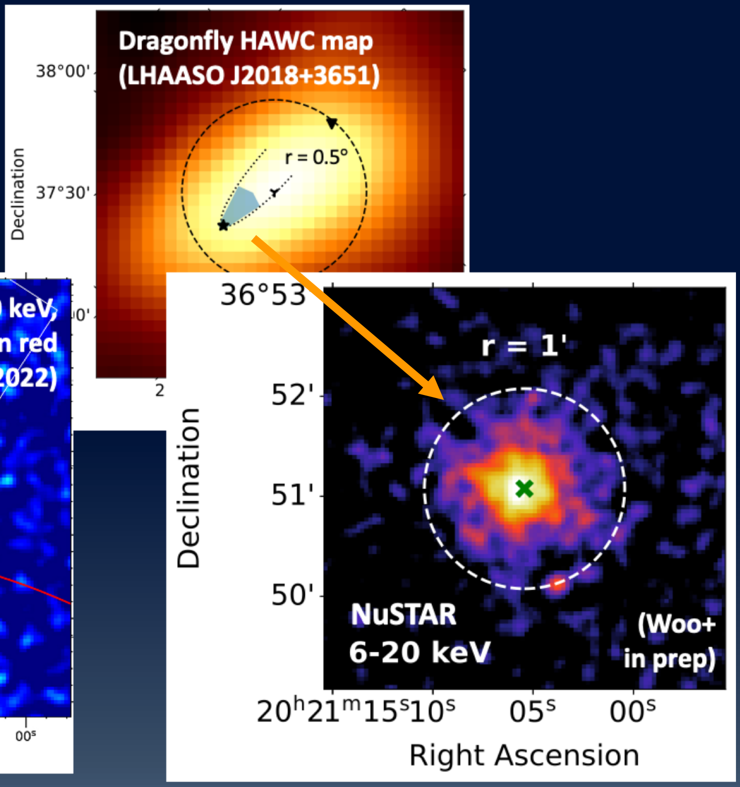


NuSTAR hard X-ray views of middle-aged PWNe

- Some 10-100 kyr old PWNe are associated with UHE sources
- NuSTAR detected compact, hard X-ray PWNe around the pulsars





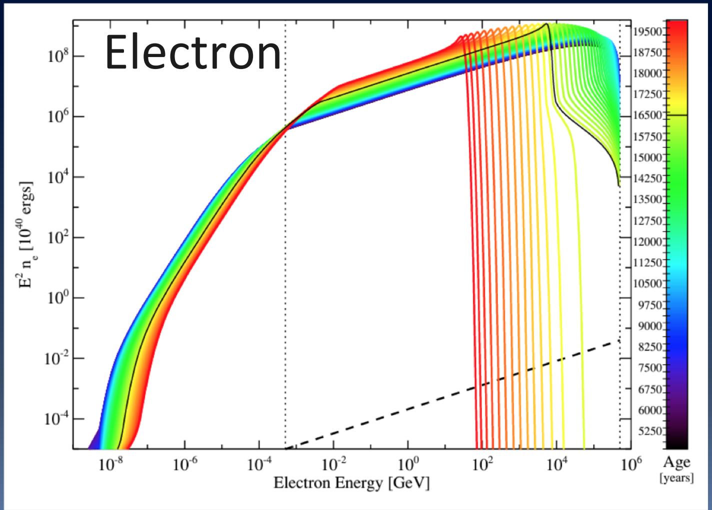


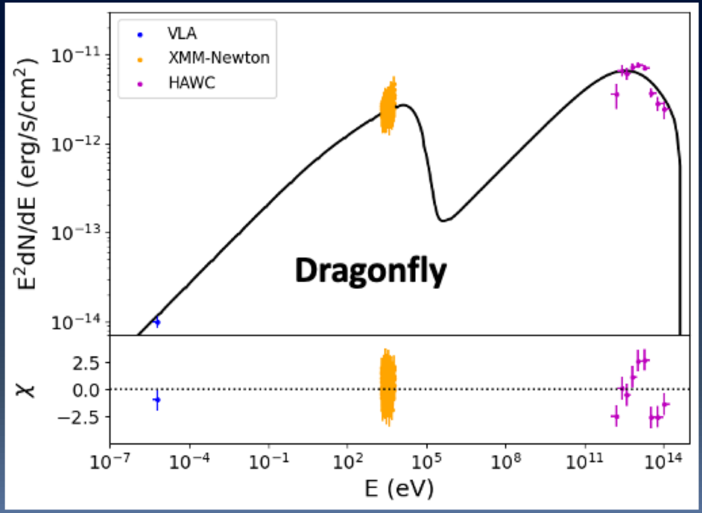
Modeling MW emission from PWNe (1)

- One-zone time-evolution model (Gelfand+ 2009)
  - Inject pulsar's spin-down energy into PWNe and account for particle cooling => electron and photon SEDs
  - Fit MW SED and PWN radius (usually radio/TeV size)

$$\dot{E}(t) = \dot{E}_0 \left(1 + \frac{t}{\tau_{sd}}\right)^{-\frac{p+1}{p-1}} \longrightarrow E_{\mathrm{pwn,e}}(t) = \eta_{\mathrm{e}}\dot{E}(t), E_{\mathrm{pwn,i}}(t) = \eta_{\mathrm{i}}\dot{E}(t), E_{\mathrm{pwn,B}}(t) = \eta_{\mathrm{B}}\dot{E}(t)$$

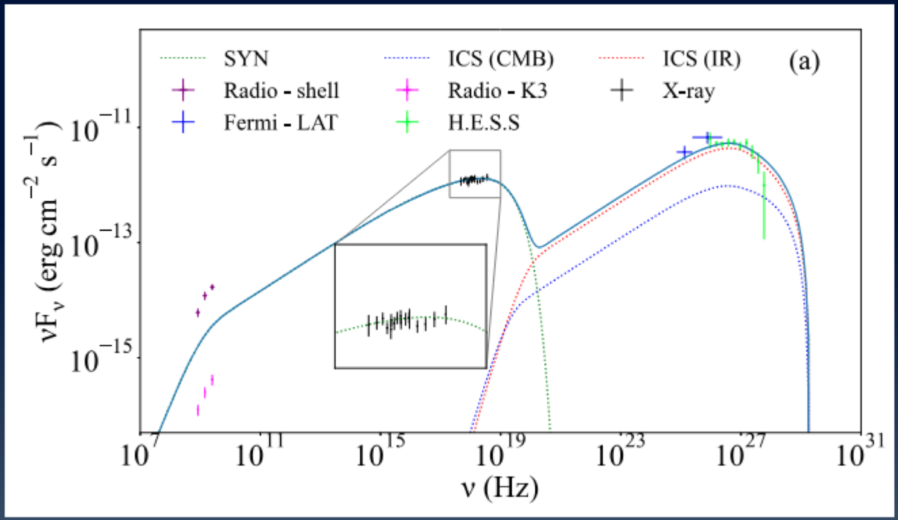
$$n_e = n_{0,e}\left(\frac{E}{E_0}\right)^{-\gamma_e} \text{ electrons s}^{-1}\text{ keV}^{-1},\ \dot{E}_{\mathrm{inj,e}} \equiv \int_{E_{e,\min}}^{E_{e,\max}} n_e E\, dE$$

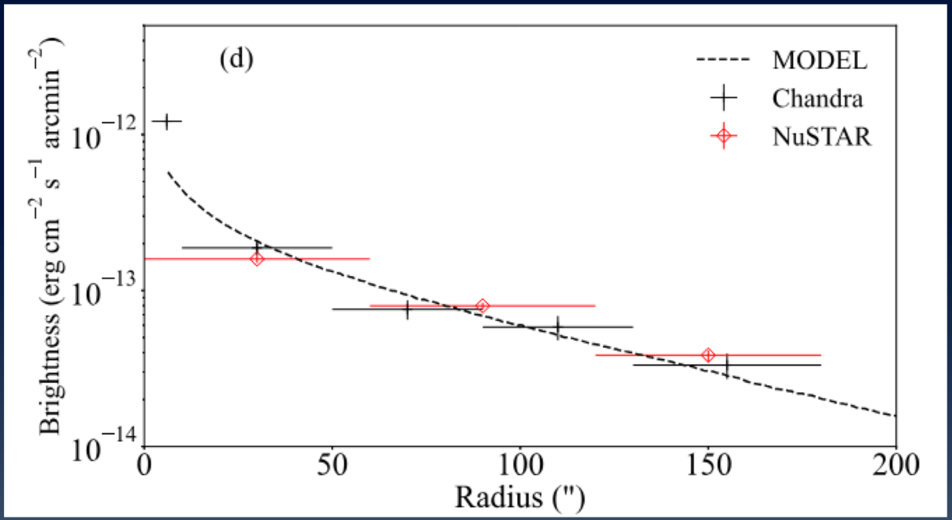




Modeling MW emission from PWNe (2)

- Multi-zone PWN model (Park+ 2023, 2024)
  - Prescribe B(r) and v(r) in a power-law form
  - Inject particles from the pulsar and advect/diffuse them out while cooling
  - Fit both MW SED and X-ray radial profile





Are middle-aged PWNe PeVatrons?

- Emax ~ 0.4-2 PeV indicates PeVatron PWNe
- 6 papers published in ApJ (2023-25)
- Next steps: model comparison, p-degeneracy, error estimation

PWN name	Edot [erg/s]	Spin-down age [kyr]	**Emax [PeV]**	B [uG]
Eel	3.6×10^{36}	14	**2**	1
Dragonfly	3.4×10^{36}	17	**1**	3
Boomerang	2.2×10^{37}	10	**1**	3
G32.6+0.53	9.8×10^{36}	43	**0.4**	7
Kookaburra	1×10^{37}	13	**0.9**	5
Rabbit	5×10^{36}	10	**1**	12

Blue: one-zone time-dependent model
Red: multi-zone model

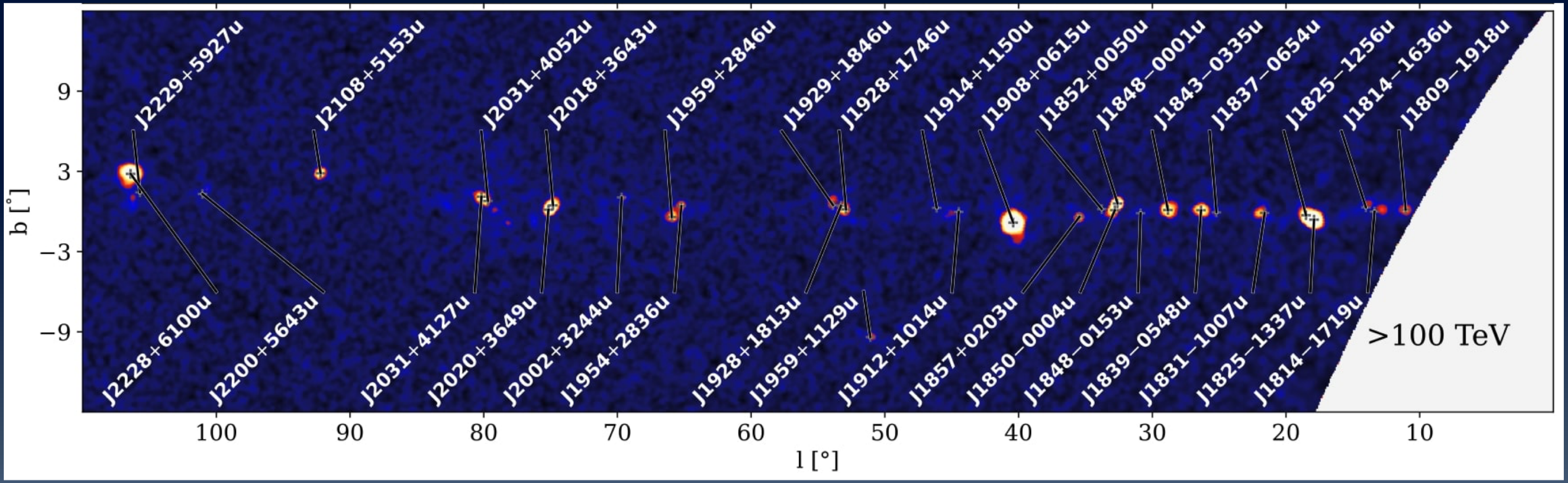
Unidentified Galactic PeVatron candidates

Searching for counterparts of Galactic PeVatrons

- Some of the UHE sources are dark PeVatron candidates:
  - no low-energy counterparts and no SNRs/PWNe nearby

- Recent XMM observations of 5 UHE sources (~100 ks per source) => exploratory X-ray survey

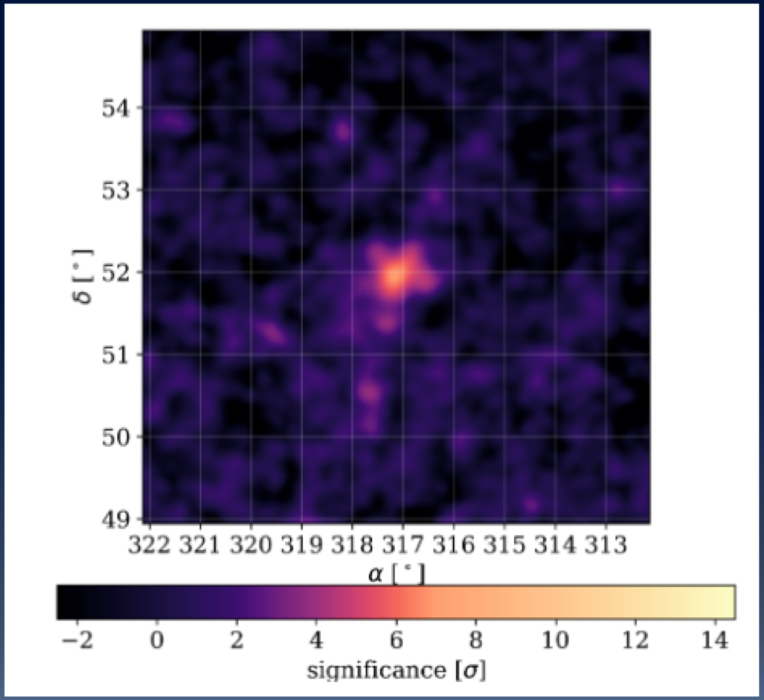
LHAASO E > 100 TeV sky map (Cao et al. 2023)



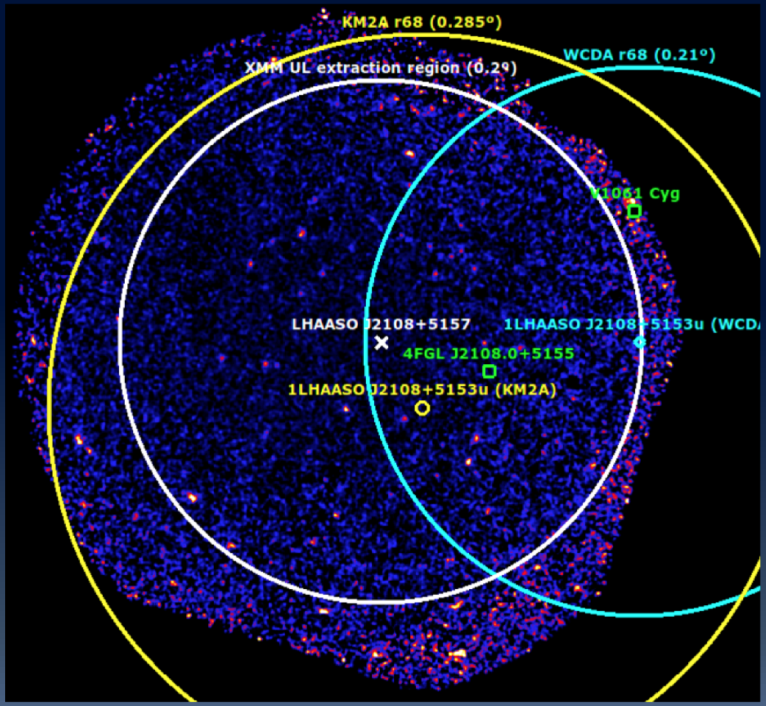
LHAASO J2108+5157: Dark PeVatron?

- One of the brightest UHE sources and dark PeVatron
- New XMM observation (100 ks) => No X-ray detection (!)
- No X-ray detection also from 3HWC J1928+178

HAWC TeV map

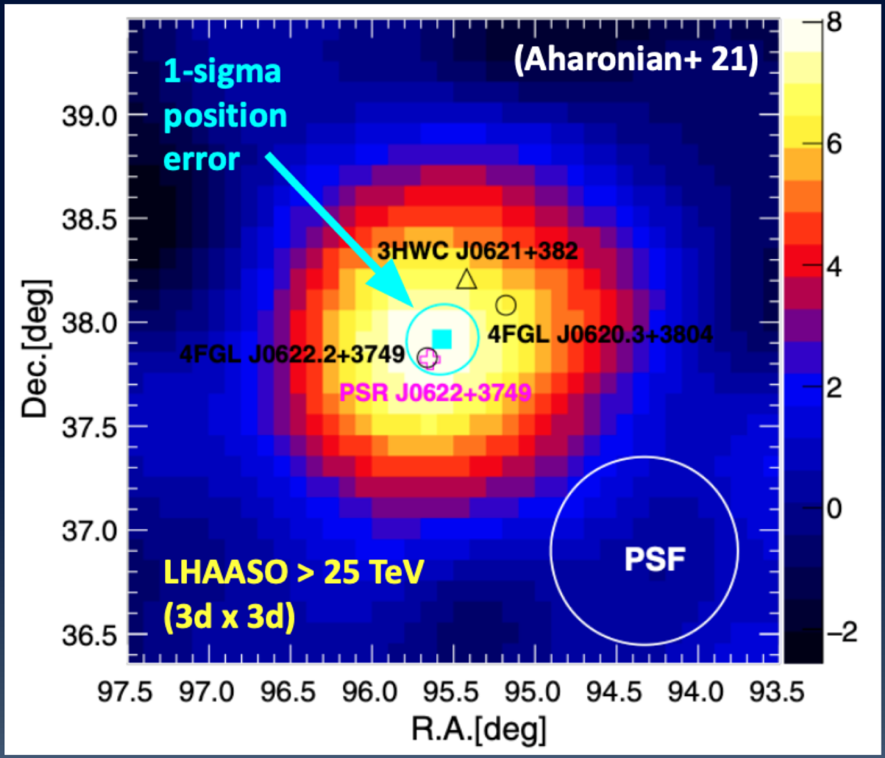


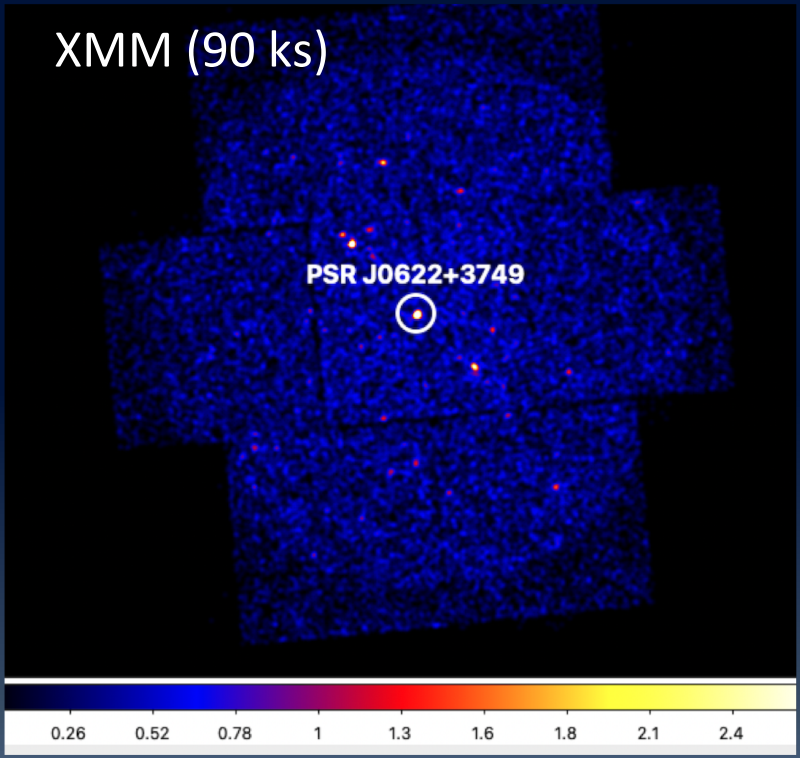
XMM (100 ks)



LHAASO J0622+3754 : PeVatron pulsar halo?

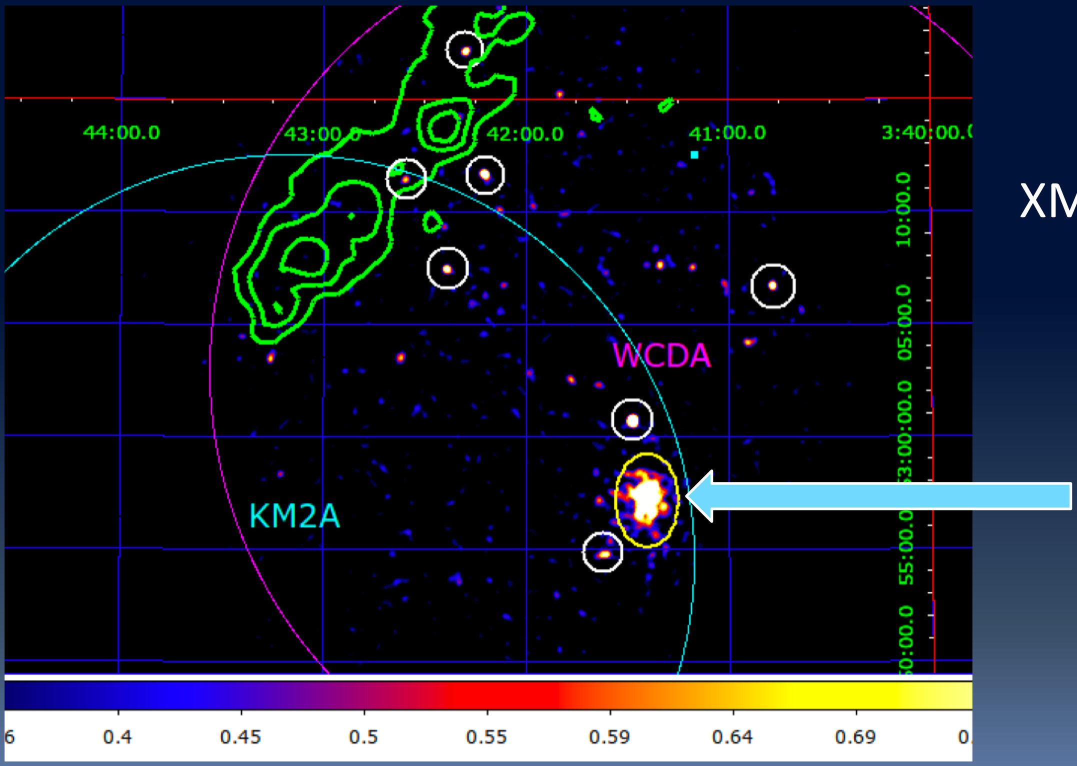
- The pulsar (Edot = 3.7×10^{34} erg/s) was detected by XMM
- Searching for diffuse X-ray emission





LHAASO J0343+5254: diffuse X-ray emission detected

- Molecular cloud detections (Naomi's poster S8.8)
- Diffuse X-ray emission detected by XMM! => 60 ks more to come (analysis led by Shuo Zhang)
- The diffuse X-ray source does NOT coincide with the molecular clouds or known pulsars



XMM (30 ks)

?

What we have learned so far…

- No X-ray detection from 2 PeVatron sources
  - Diffuse X-ray emission may be faint and extended
  - Low B-field environment?
  - Hadronic accelerators?

- Diffuse X-ray source detected from LHAASO J0343
  - Non-thermal X-ray emission? What is it?

- Will reassess our observation strategies

- We need continuing community effort, covering MW bands, and communicate across collaborations

PeVatron science in the 2030s

NASA's X-ray probe mission candidates

HEX-P
HIGH ENERGY X-RAY PROBE

0.2-80 keV

0.2-2 keV

< 1.5 keV

STROBE-X

0.2-30 keV (non-focusing)

LEM

0.2-2 keV

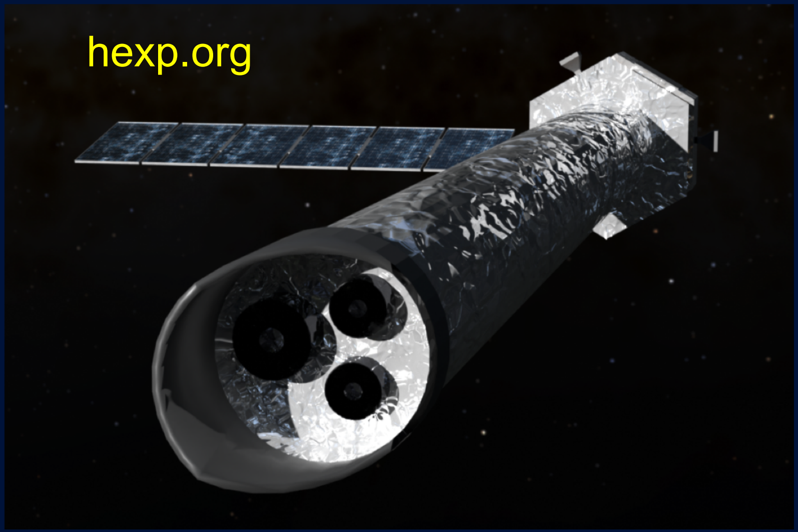
ARCUS

E < 1.2 keV

AXIS
Advanced X-ray Imaging Satellite

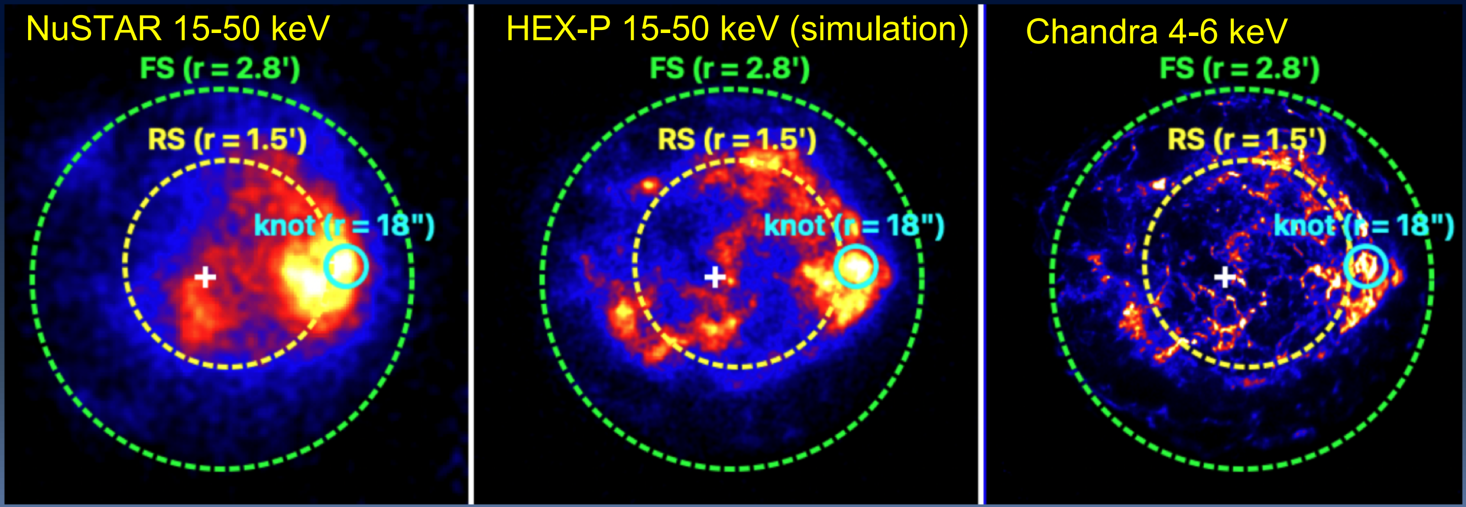
0.2-10 keV

HEX-P: next-generation all-purpose X-ray telescope



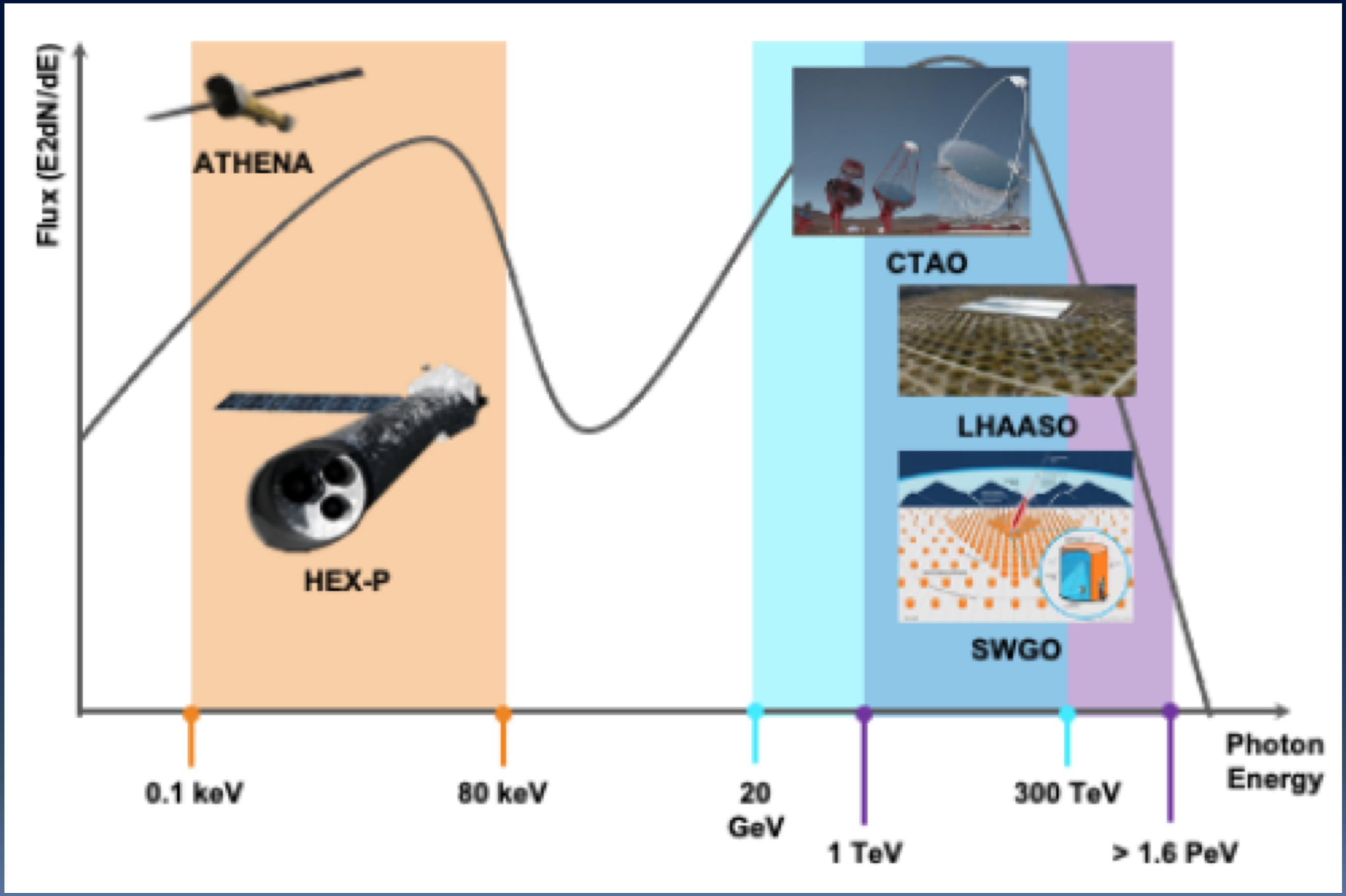
	HEX-P		NuSTAR
	LET	**HET**	
E-band	**0.2-20 keV**	**2-80 keV**	3-79 keV
PSF (HPD)	**2.5-3”**	**15-20”**	58”

Cas A images



PeVatron science landscape in the 2030s

- LHAASO and HAWC will find more PeVatrons
- CTAO and HEX-P will be a golden duo to explore PeVatrons in the early 2030s (Mori+ 23, Reynolds+ 23)



Summary

- Galactic PeVatrons are a new, profound, unresolved problem in high-energy astrophysics and cosmic-ray physics.
- Multi-wavelength SED and morphology studies are essential for identifying Galactic PeVatrons and particle acceleration mechanisms.
- SNRs:
  - Ongoing hard X-ray variability studies of Cas A, Kepler and Tycho
- PWNe:
  - More NuSTAR analysis/observations of G0.9+0.1, CTA1, CTB 87 and Taz
  - Model comparison/upgrade and systematic error estimation
- Unidentified PeVatrons:
  - Working on MW data of 5 sources => plan to observe more UHE sources
- Multi-messenger PeVatron astrophysics in the 2030s
  - HEX-P, CTAO, next-gen neutrino telescopes…