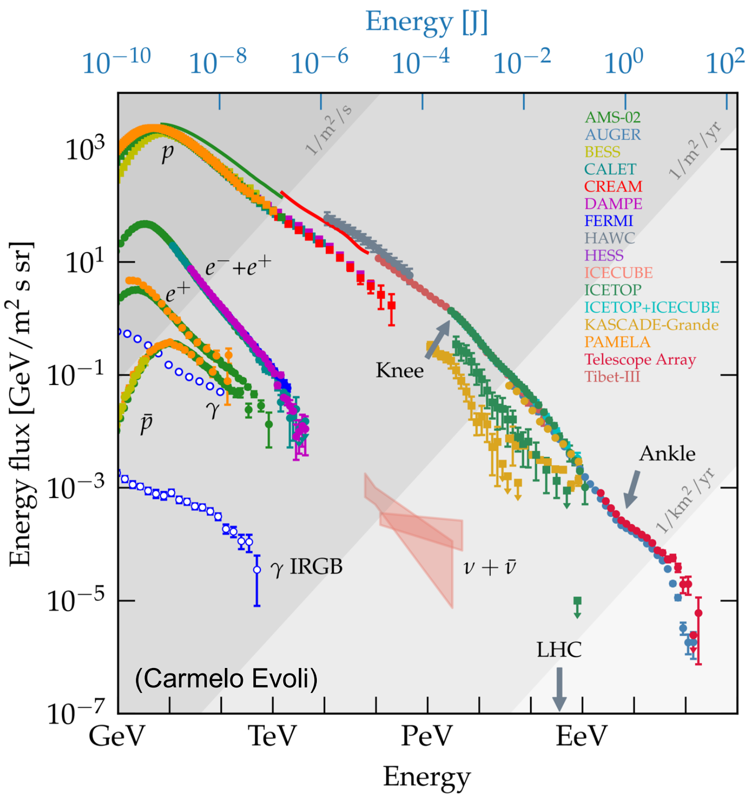
“The Ultimate Hard X-ray Probe of the Most Energetic Galactic Particle accelerators”

Jooyun Woo (Columbia University)
On behalf of HEX-P Galactic SNR/PWN Group
9/14/2023 @ TeVPA 2023 - Napoli, Italy

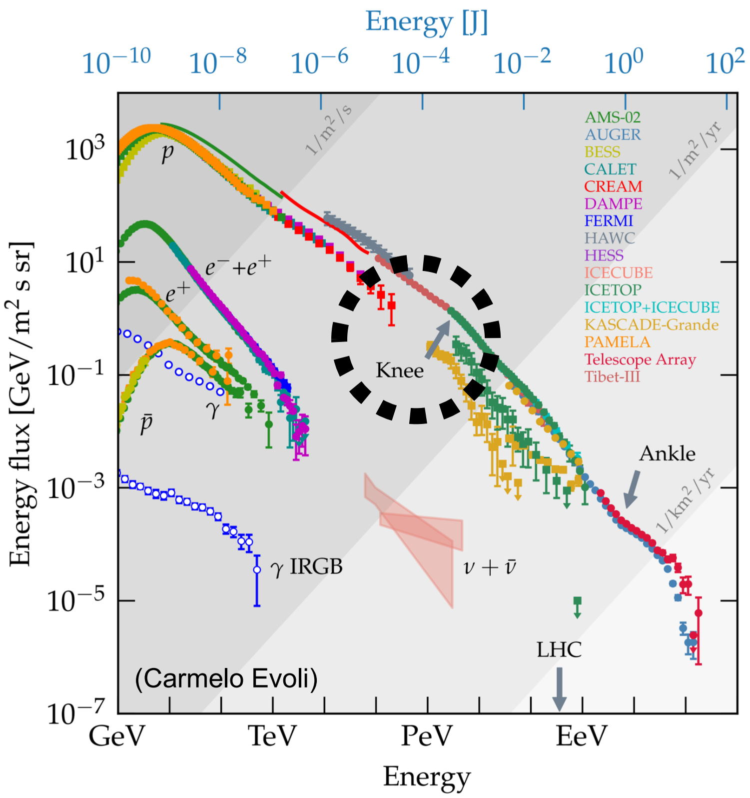
X-ray and gamma-ray observations bear the key to the mysteries of cosmic rays.

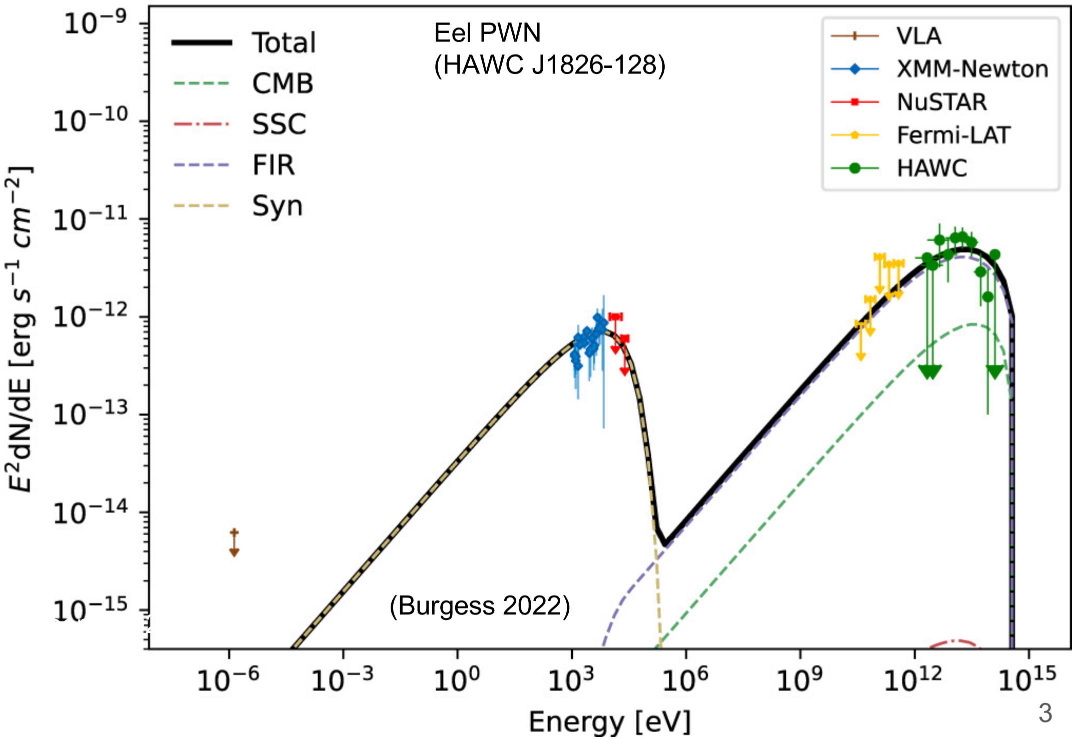
HEX-P
HIGH ENERGY X-RAY PROBE



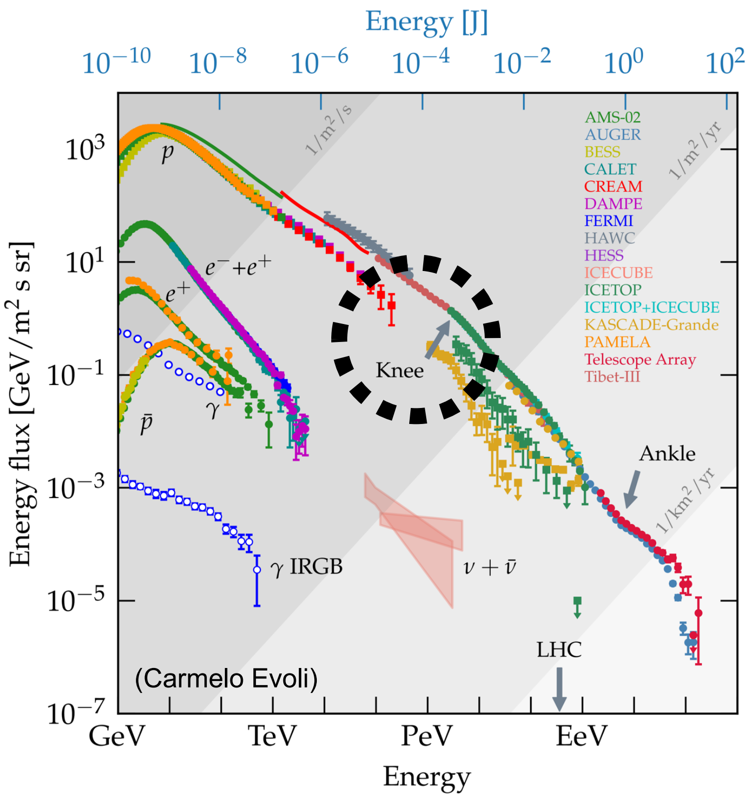
- Where are they coming from?
  “Source localization / identification”
- How are they accelerated?
  “Particle acceleration”
- How do they get to Earth?
  “Particle transport”
- What happens on the way to Earth?
  “Particle cooling”

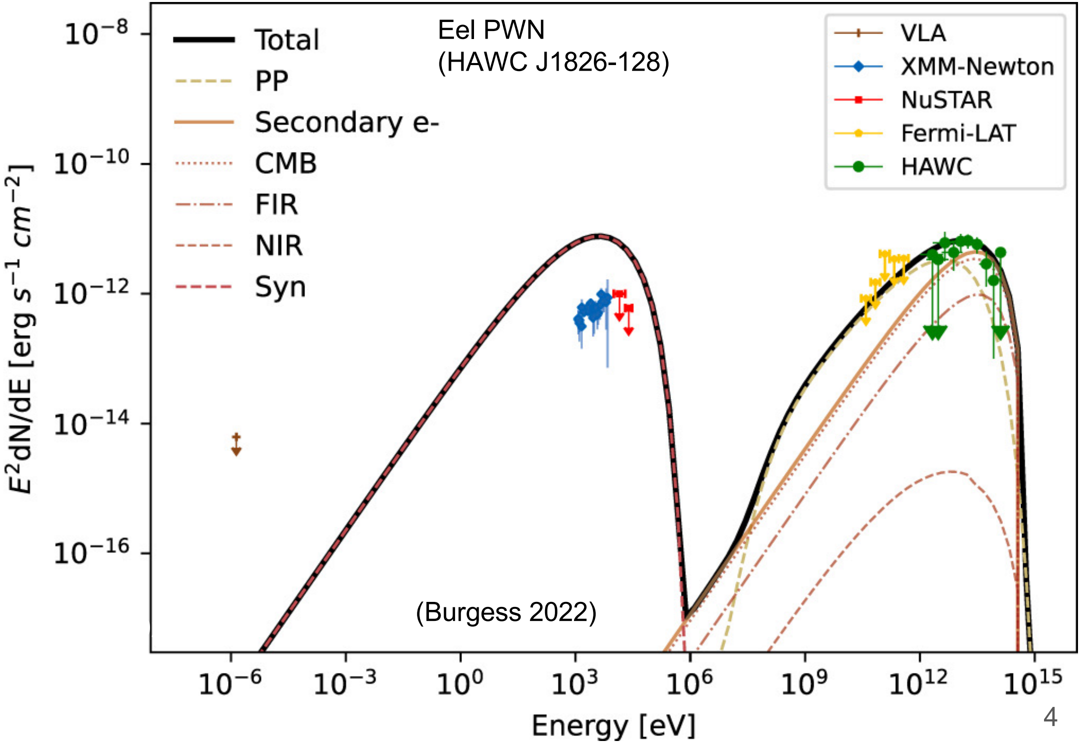
Leptonic PeVatron: gamma-ray from inverse Compton scattering, X-ray from synchrotron radiation





Hadronic PeVatron: gamma-ray from pion decay, X-ray from secondary lepton's synchrotron emission





X-ray's recipe for Galactic PeVatron science: measure particle Emax, B-field, Vshock

- **"PeVatron" accelerates particles to the maximum energy > 1 PeV**
- acceleration time > cooling time / system's characteristic time scale

→ **Maximum particle energy = f(magnetic field, shock velocity)**

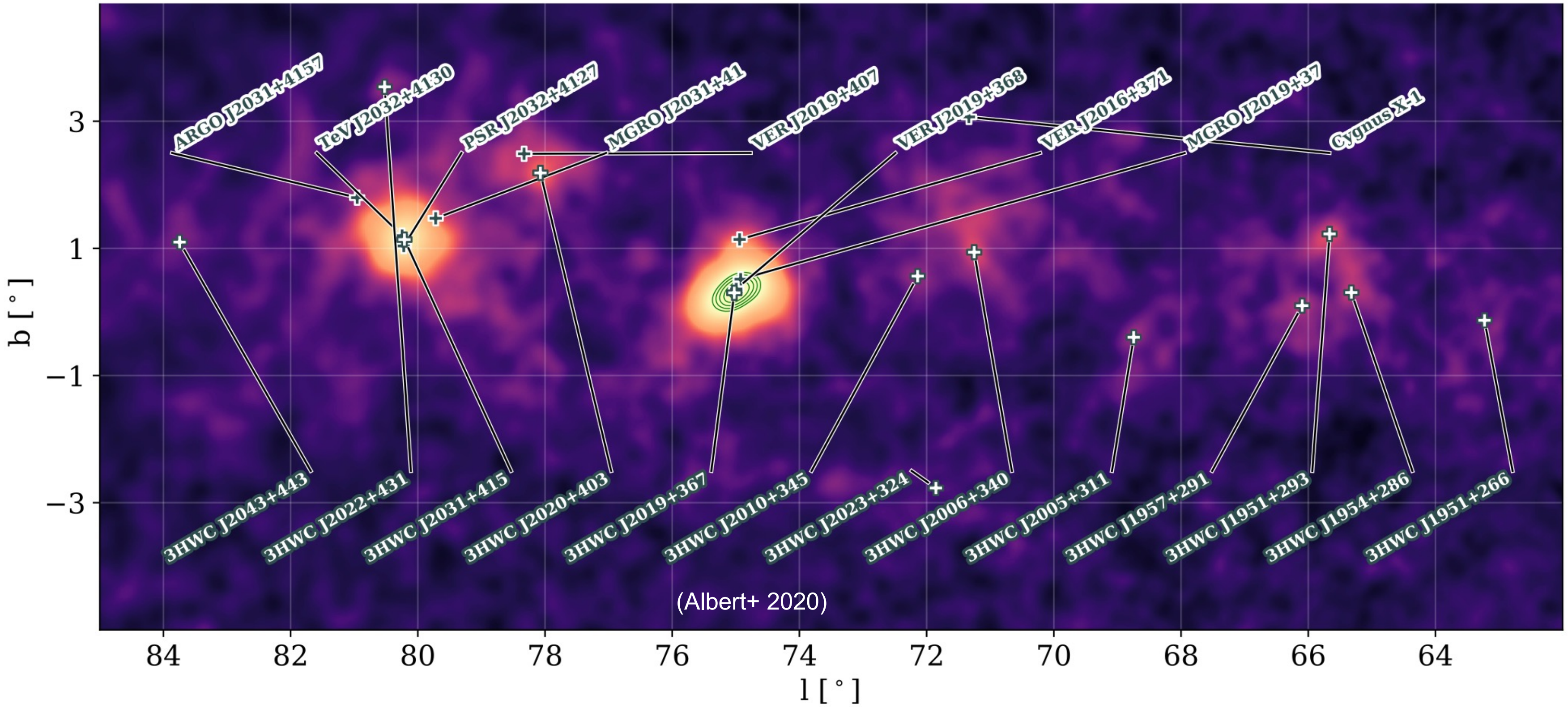
① Directly measure maximum particle energy from synchrotron cutoff

② Deduce magnetic field and shock velocity from (energy-dependent) morphology at different regions of the source

→ **For Galactic PeVatron science, X-ray instruments need**

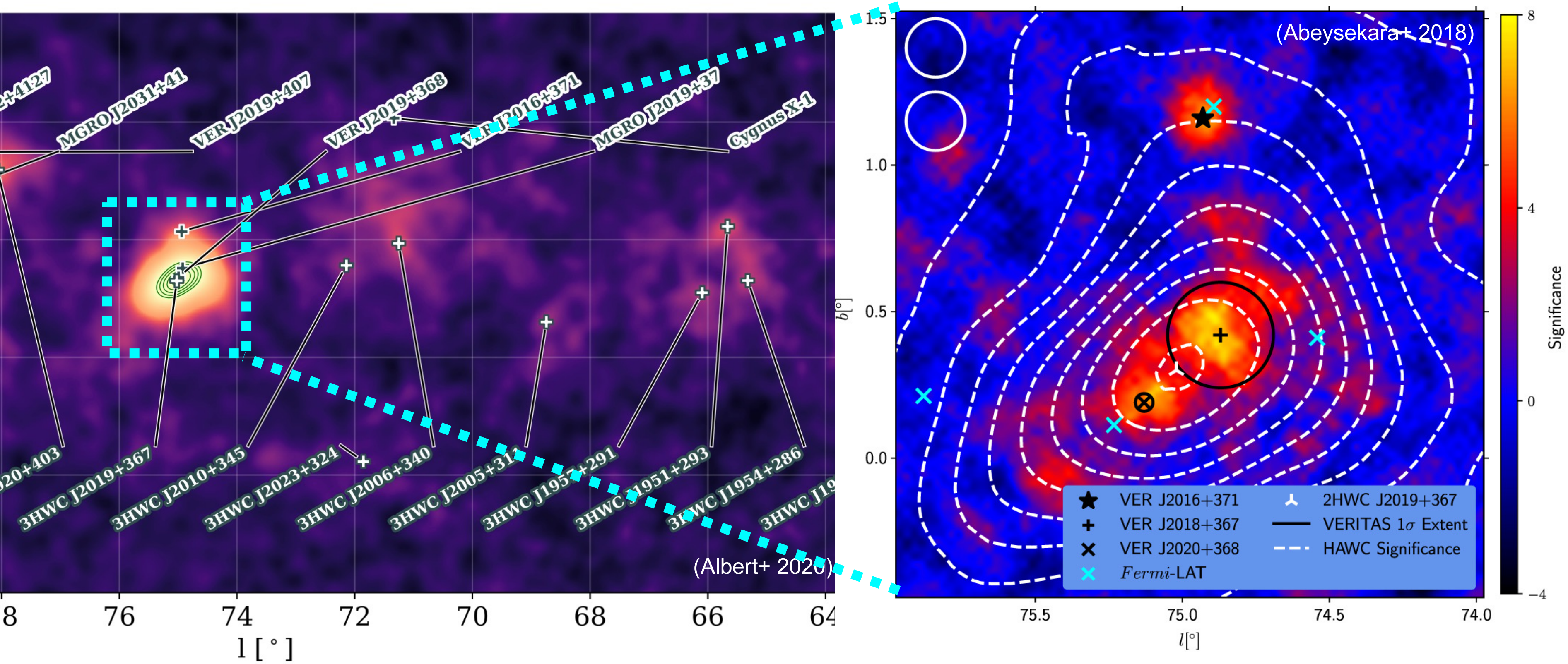
  - **Broadband hard X-ray coverage**
  - **Fine angular resolution**
  - **High sensitivity**

Extensive air shower arrays: Locate PeVatrons by ultra-high-energy gamma-rays

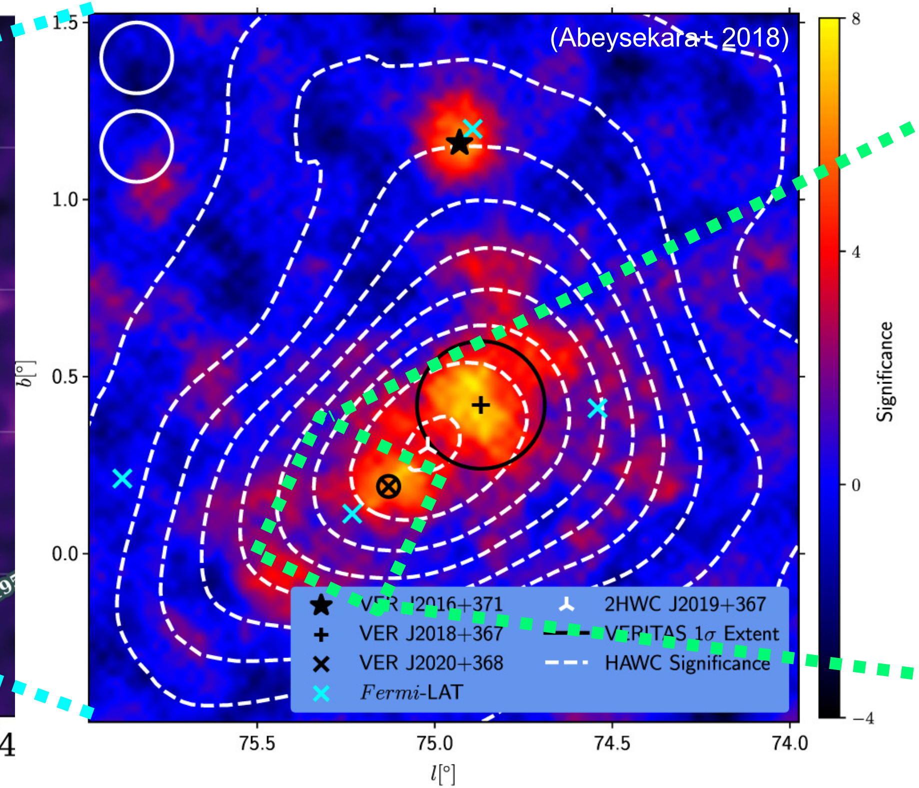


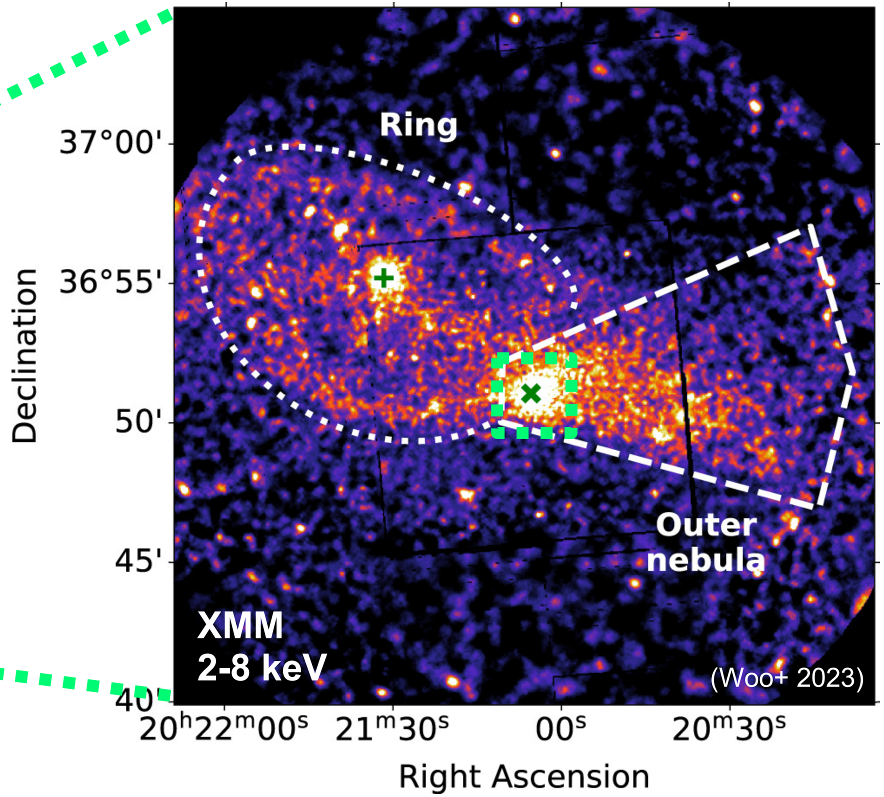
(Albert+ 2020)

Imaging air Cherenkov telescopes: Resolve source confusion, decode ambient density

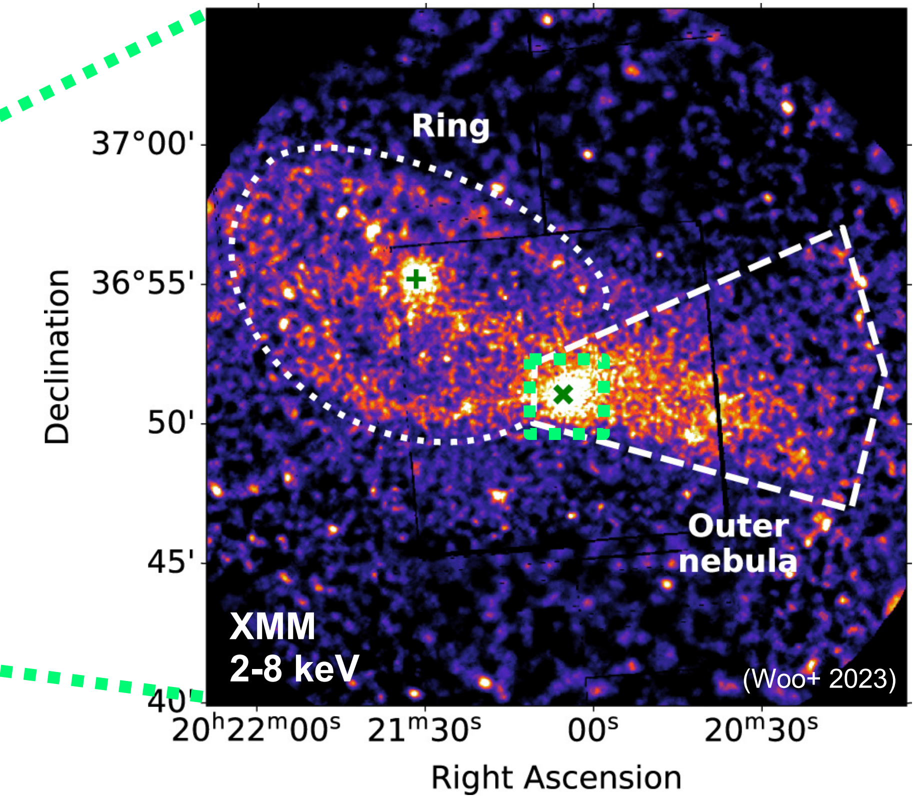


Wide-field-of-view soft X-ray telescope: Study morphology, decode particle diffusion



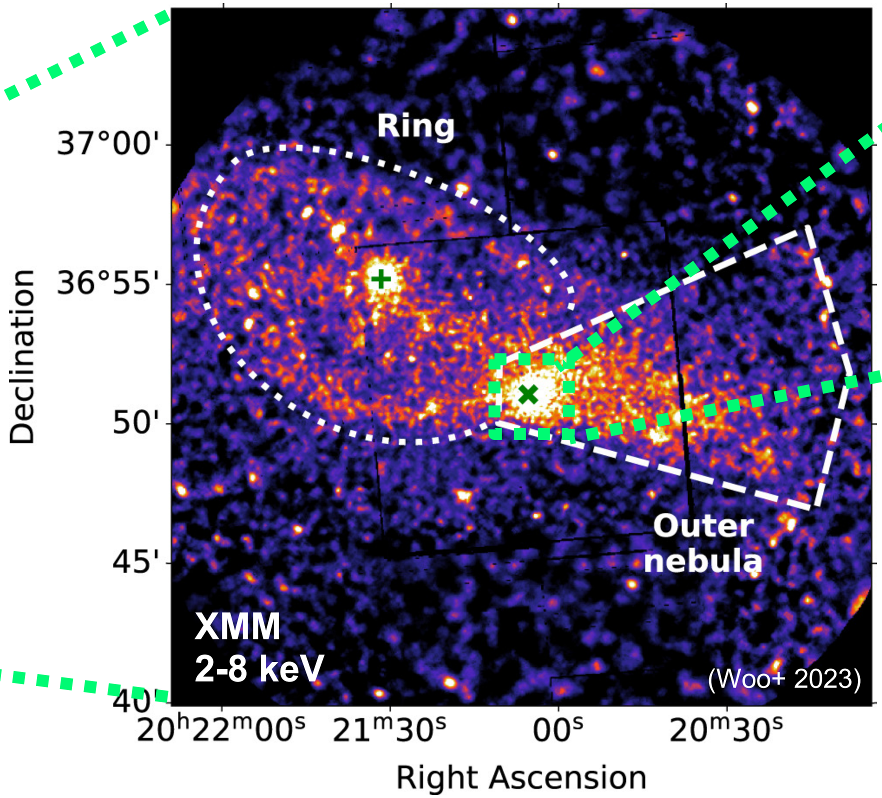


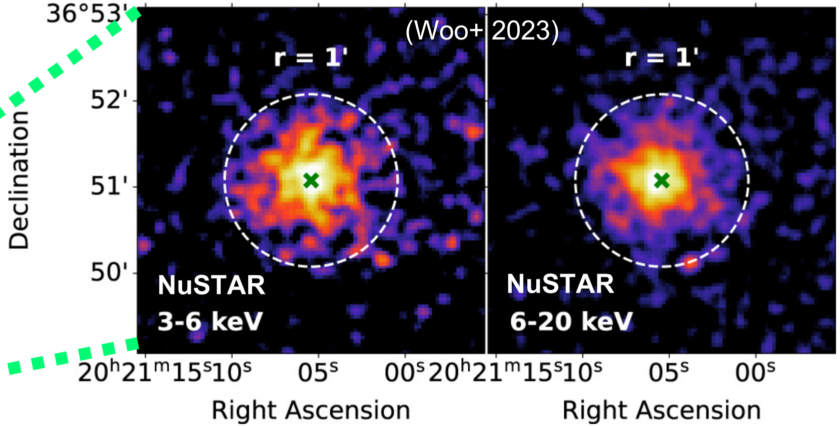
Broadband hard X-ray telescope: Resolve the acceleration site, decode shock mechanism



- Detection of synchrotron cutoff
  - Maximum particle energy
- Finely resolved energy-dependent morphology
  - Magnetic field
  - Shock / advection velocity

Current hard X-ray telescope can't resolve the acceleration site or decode shock mechanism.



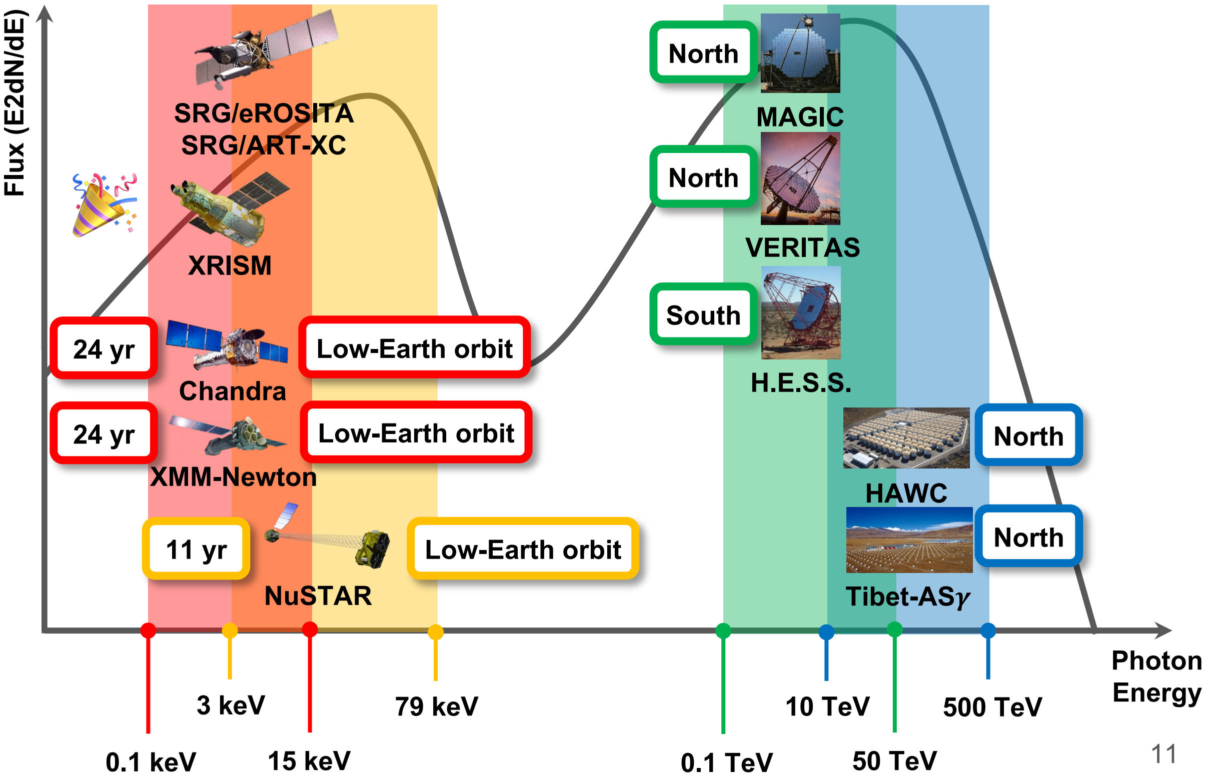


- ❌ Detection of synchrotron cutoff
  - Maximum particle energy
- ❌ Finely resolved energy-dependent morphology
  - Magnetic field
  - Shock / advection velocity

What we need for X-ray and gamma-ray instruments vs. What we have now

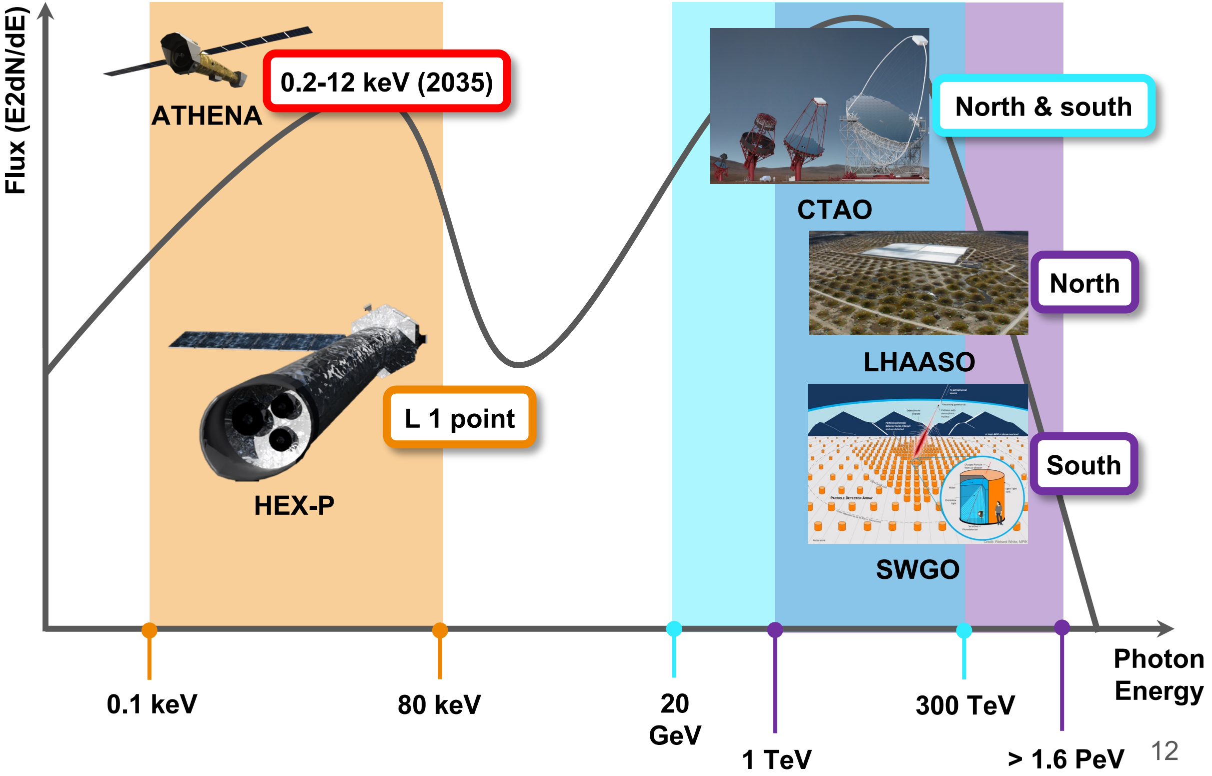
HEX-P HIGH ENERGY X-RAY PROBE

- Broad spectral coverage
  - Single instrument: ✅ broad bandpass
  - Multi-instrument: ✅ multiwavelength observation
- Broad / long sky coverage
  - Ground observatories: northern + southern ⚠ hemisphere
  - Space observatories: uninterrupted view ❌
- **High sensitivity**
  - **Large effective area** ⚠
  - **Low background** ❌
- **Fine angular resolution** ❌



What we will have in 2030s:
Ultimate synergy for Galactic PeVatron science

- Broad spectral coverage
  - Single instrument: 🌟 broad bandpass
  - Multi-instrument: 🌟 multiwavelength observation
- Broad / long sky coverage
  - Ground observatories: northern + southern ✅ hemisphere
  - Space observatories: uninterrupted view ✅
- High sensitivity
  - Large effective area ✅
  - Low background ✅
- Fine angular resolution ✅



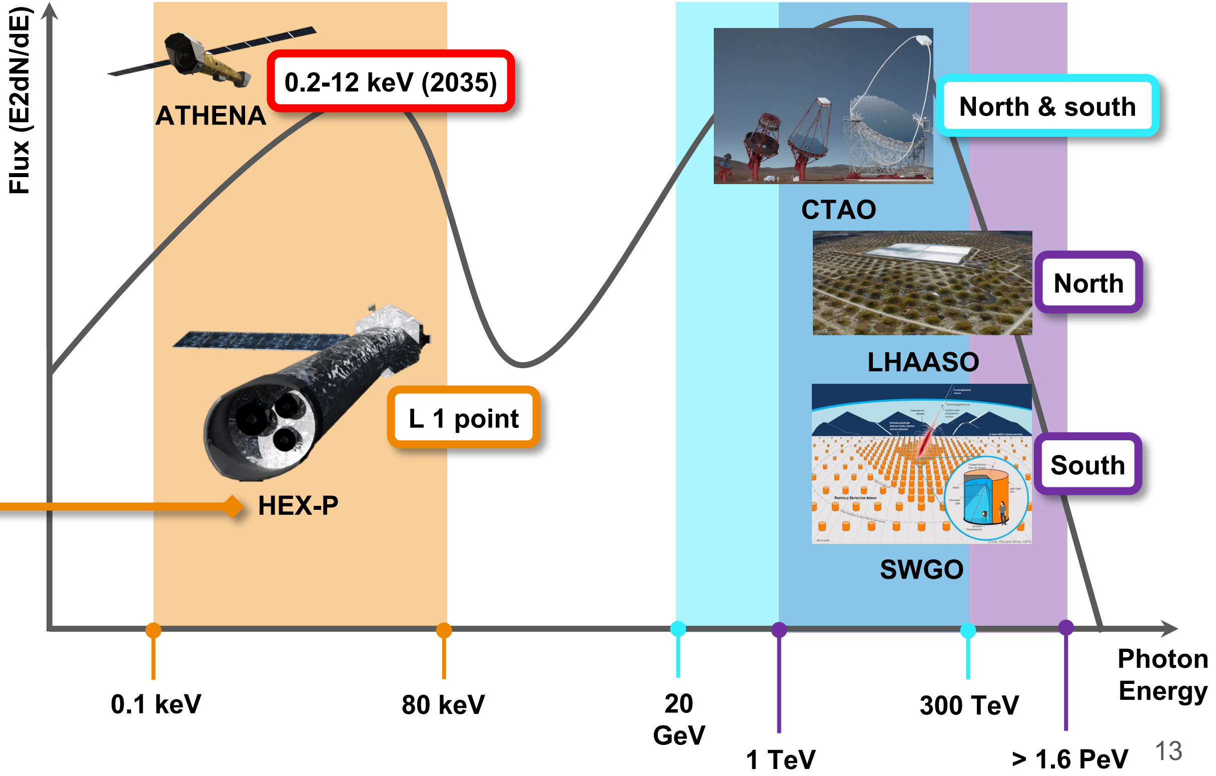
What we will have in 2030s: Ultimate synergy for Galactic PeVatron science

HEX-P HIGH ENERGY X-RAY PROBE

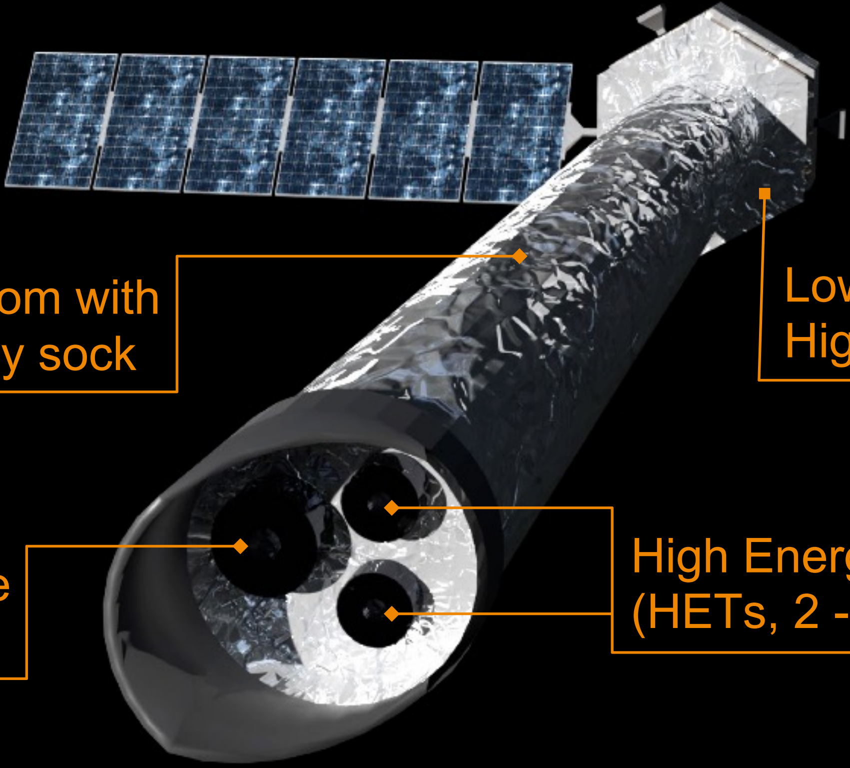
NASA 2023 Astrophysics Probe Explorer (APEX) program ($1B)

- Respond to Astro2020
- Selection in 2025, launch in 2030s
- Far-infrared or **X-ray mission**
- **X-ray candidates: HEX-P,** AXIS, Strobe-X, LEM, Arcus

- PI: Daniel Stern (JPL/Caltech)
- Deputy PI: Kristin Madsen (GSFC)
- Project scientist: Javier Garcia (Caltech)
- Managing center: JPL
- Partners: Northrop Grumman, **ASI**, GSFC, MPE Garching, Caltech



HEX-P instrument overview



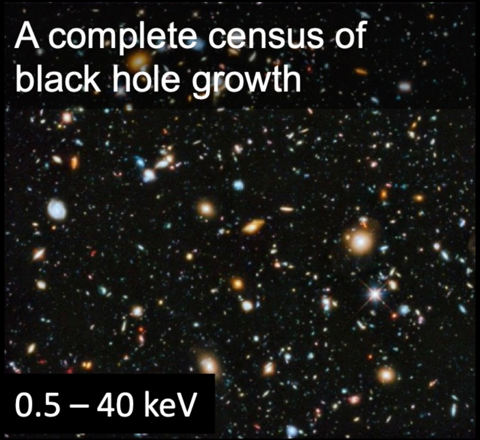
HEX-P: All-purpose workhorse

HEX-P
HIGH ENERGY X-RAY PROBE

- Baseline mission lifetime: 5 years
- $\geq$ 70% Guest Observatory facility
- Non-cryogenic
- ToO response time: 24 hrs
- Orbit: L1 (long uninterrupted stares)

	HEX-P		NuSTAR
	LET	**HET**	
🌟 Bandpass	**0.2-20 keV**	**2-80 keV**	3-79 keV
Spectral resolution (FWHM)	$\leq$ 70 eV @ 1 keV $\leq$ 140 eV @ 6 keV	$\leq$ 0.5 keV @ 6 keV $\leq$ 1 keV @ 60 keV	600 eV @ 6 keV 1.2 keV @ 60 keV
🌟 PSF (HPD)	5”	**15”**	58”
Timing resolution	**$\leq$ 2 ms**	**1 μs**	1 μs
Field of view	11.3’ x 11.3’	13.7’ x 13.7’	13’ x 13’
🌟 Sensitivity	**2 x XMM**	**4 x NuSTAR**	-

HEX-P Science Pillars

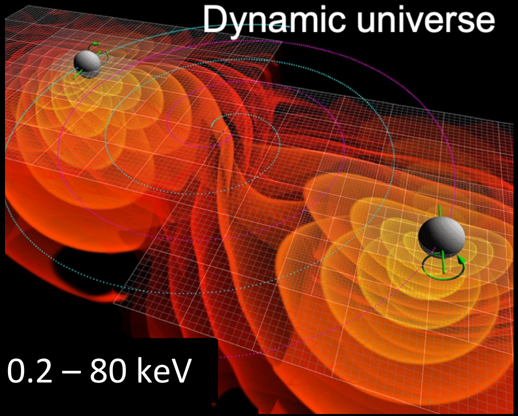


Pillar leads:
Francesca Civano
Peter Boorman

Galactic PeVatrons

Pillar leads:
Bret Lehmer
Kaya Mori

Pillar leads:
Javier García
Dom Walton



Pillar leads:
Murray Brightman
Raffaella Margutti

Recipe for Galactic PeVatron science: measure particle Emax, B-field, Vshock with HEX-P

- **"PeVatron" accelerates particles to the maximum energy > 1 PeV**
- acceleration time > cooling time / system's characteristic time scale

→ **Maximum particle energy = f(magnetic field, shock velocity)**

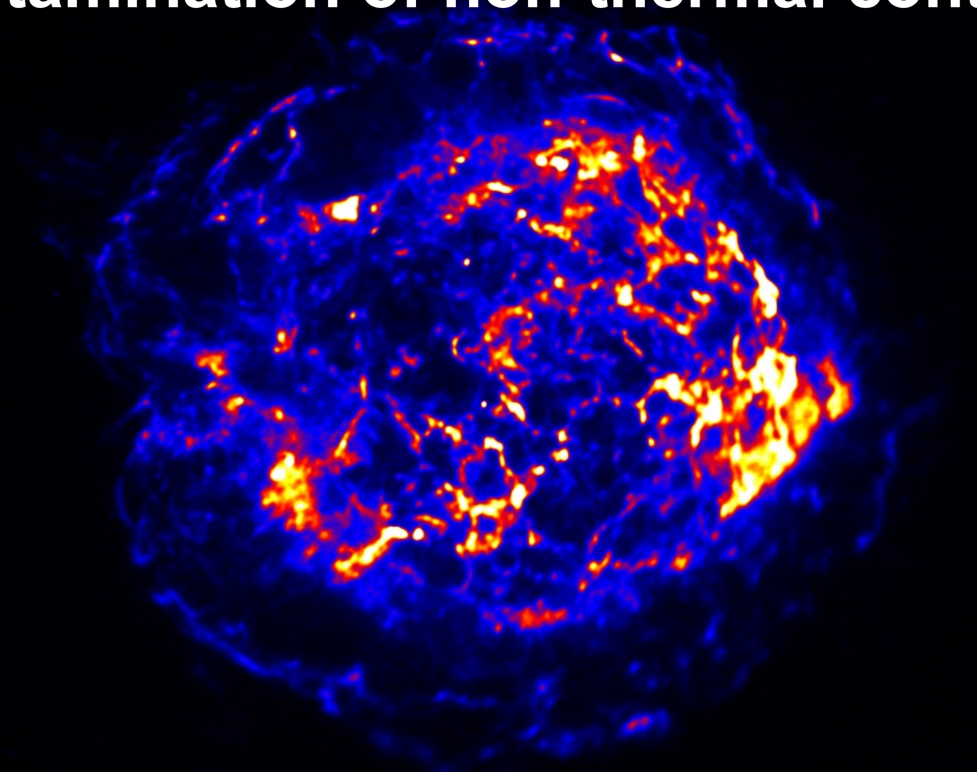
① Directly measure maximum particle energy from synchrotron cutoff

② Deduce magnetic field and shock velocity from (energy-dependent) morphology at different regions of the source

→ **Galactic PeVatron science with HEX-P's**

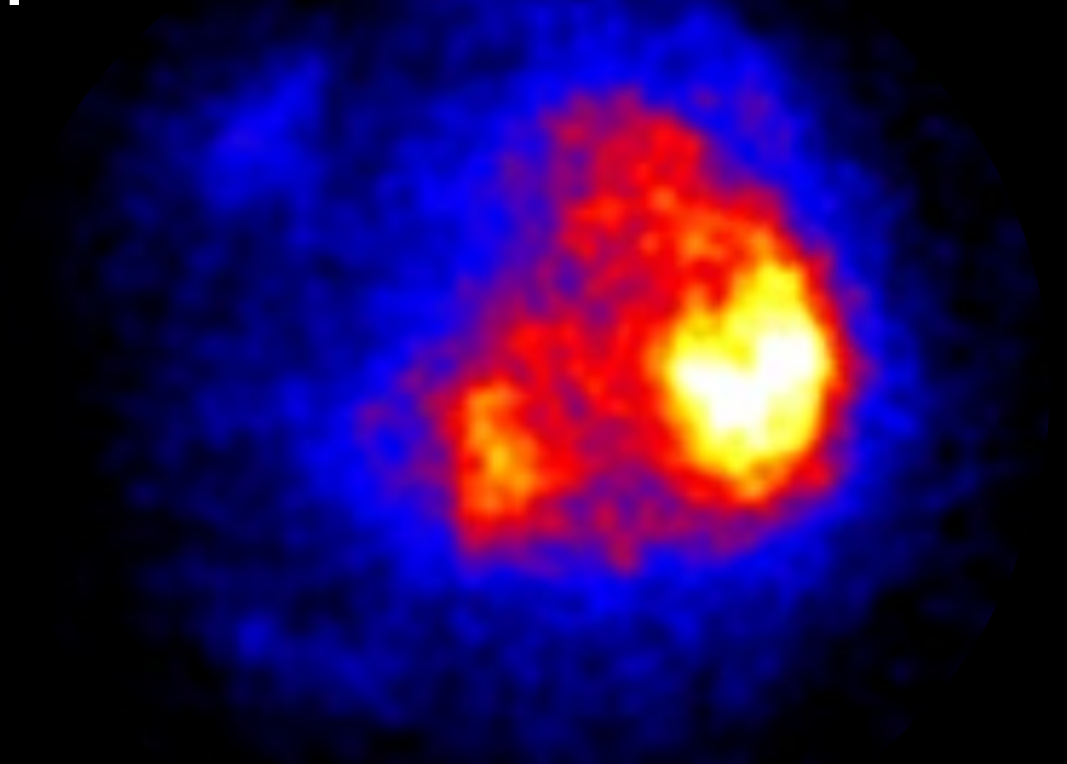
  - **Broadband hard X-ray coverage**
  - **Fine angular resolution**
  - **High sensitivity**

SNRs: Thermal emission in the soft X-ray band causes contamination of non-thermal continuum.



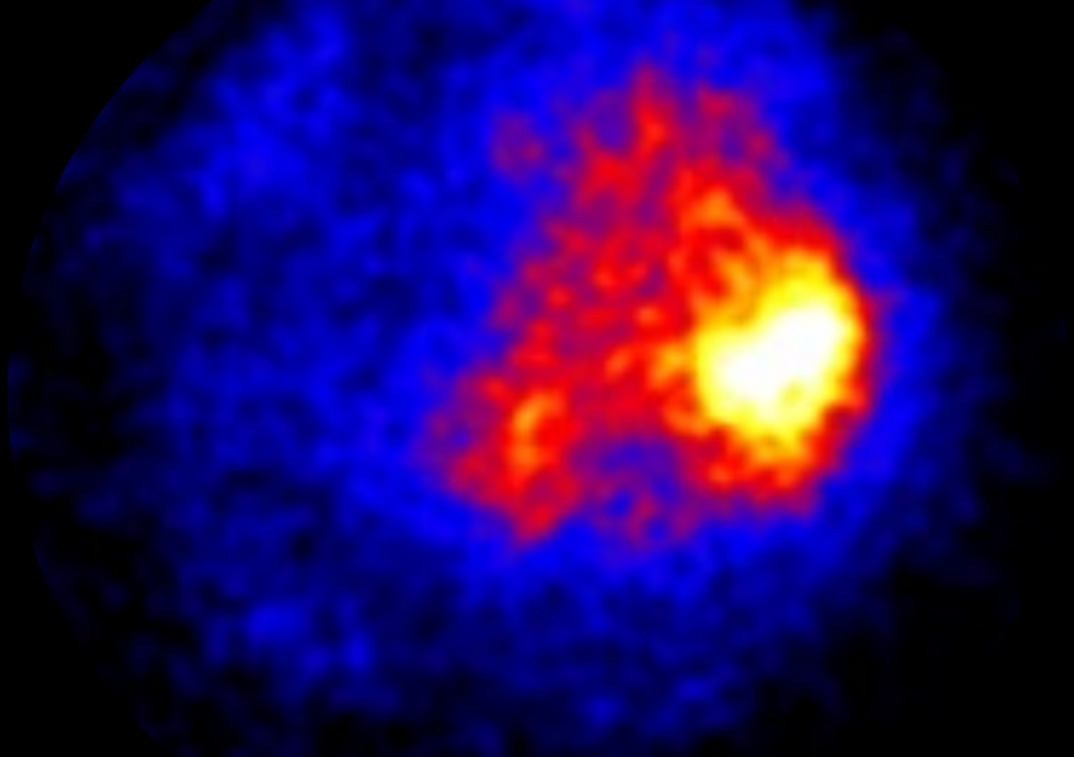
Cassiopeia A: Chandra 4.2-6 keV (image: Toshiki Sato)

NuSTAR detected hard X-ray knots up to 40 keV indicating particle acceleration and enhanced B-field.



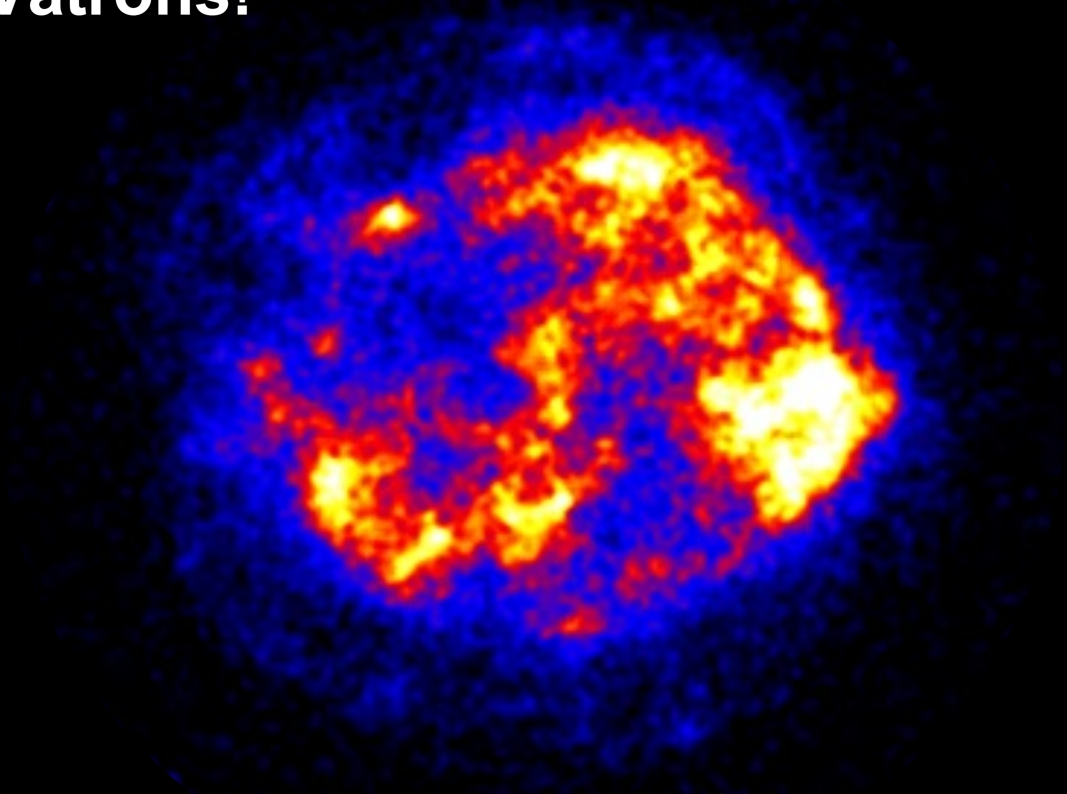
Cassiopeia A: NuSTAR 15-50 keV (2012)

Knot flux and size variability due to synchrotron cooling will provide clues to acceleration mechanism.



Cassiopeia A: NuSTAR 15-50 keV (2023)

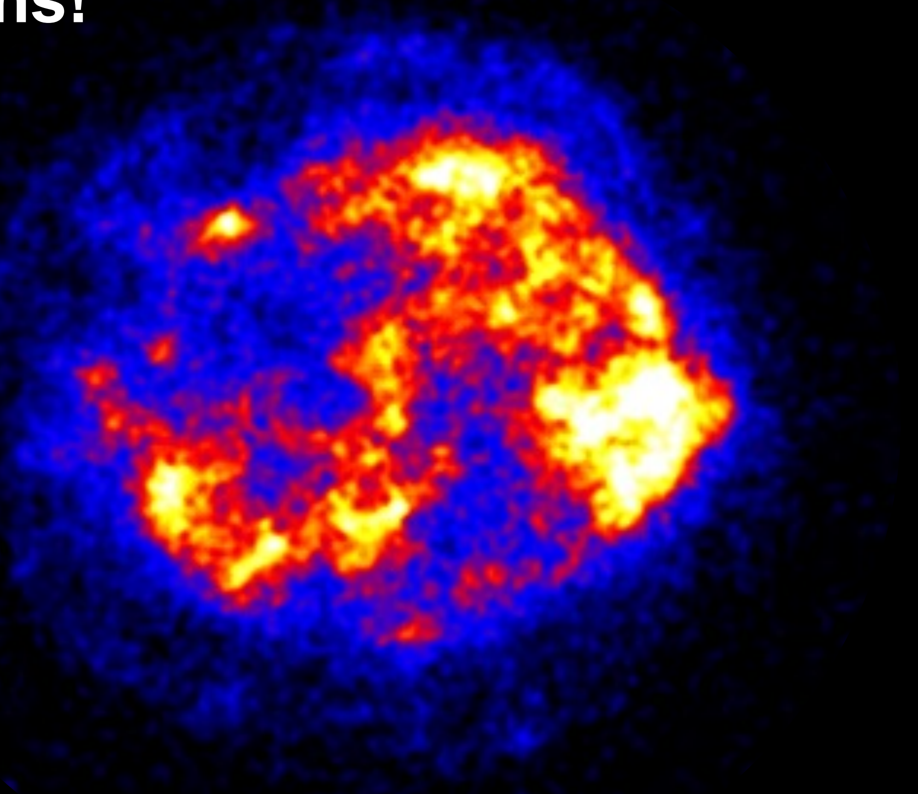
HEX-P will find out whether young SNRs are (local) PeVatrons!



Cassiopeia A: HEX-P 15-50 keV (simulated, 200 ks)

HEX-P will find out whether young SNRs are (local) PeVatrons!

- Monthly monitoring young SNRs → building baseline for temporal morphology and spectral study
- Finely resolving hard X-ray knots up to. > 50 keV

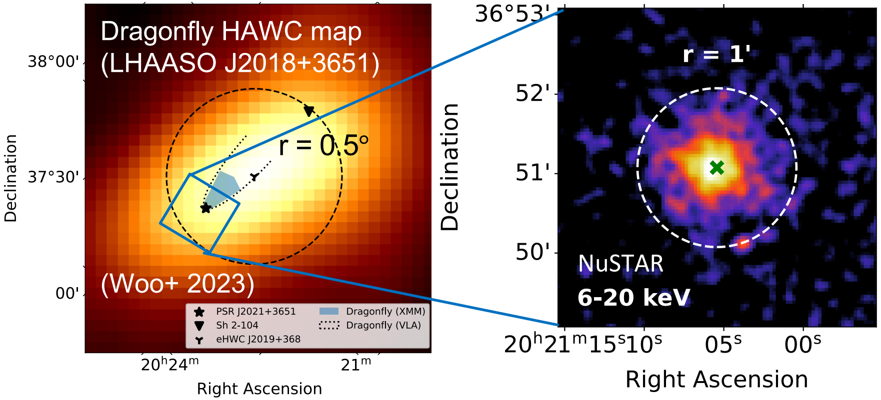


Cassiopeia A: HEX-P 15-50 keV (simulated, 200 ks)

Maximum particle energies of the PeVatron PWNe were not constrained by NuSTAR.

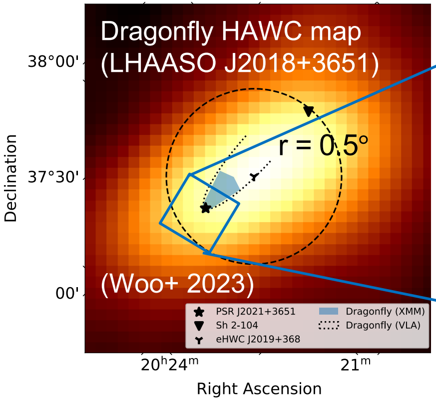
HEX-P HIGH ENERGY X-RAY PROBE

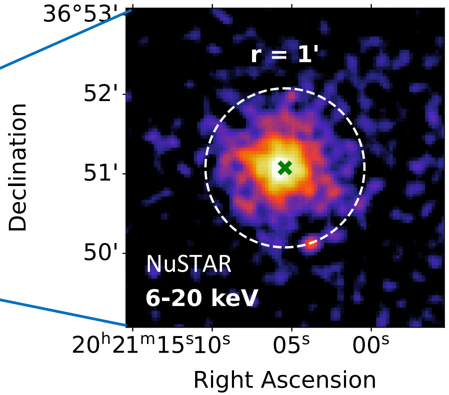
- Energetic ($\dot{E} > 10^{34}$ erg/s) pulsars near half of the UHE sources
- **NuSTAR spectra dominated by background > 20 keV**
  - **No cutoff up to 20 keV, maximum particle energies remain unconstrained**

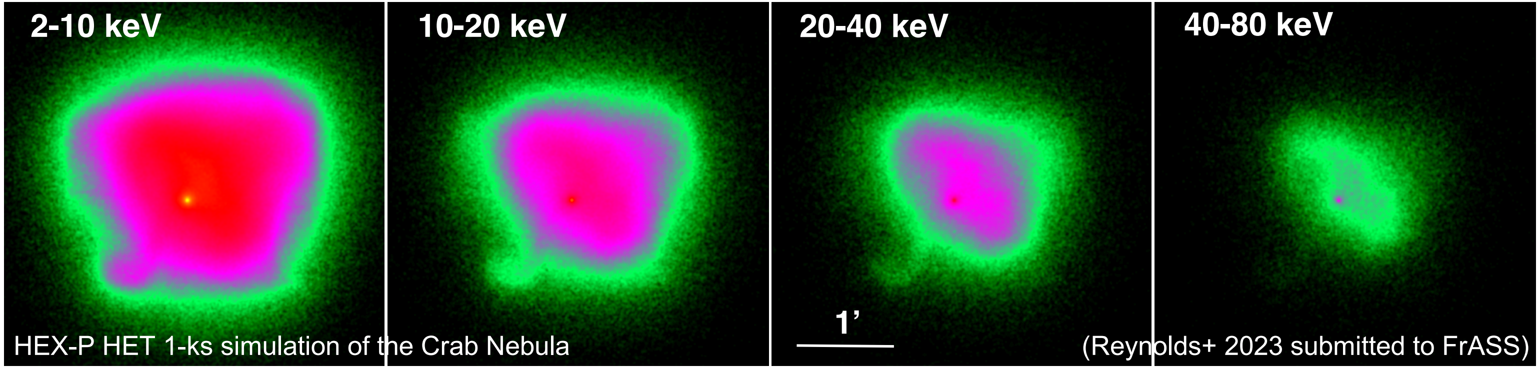


HEX-P will enable broadband multi-zone modeling of PWNe without pulsar contamination.

- **Constrain maximum particle energy** by
  - Detecting **spectral cutoff > 20 keV (low background, broadband coverage)**
  - Deducing magnetic field from energy-dependent morphology (synchrotron burnoff)
- **Multi-zone broadband SED with gamma-ray** (fine angular resolution)



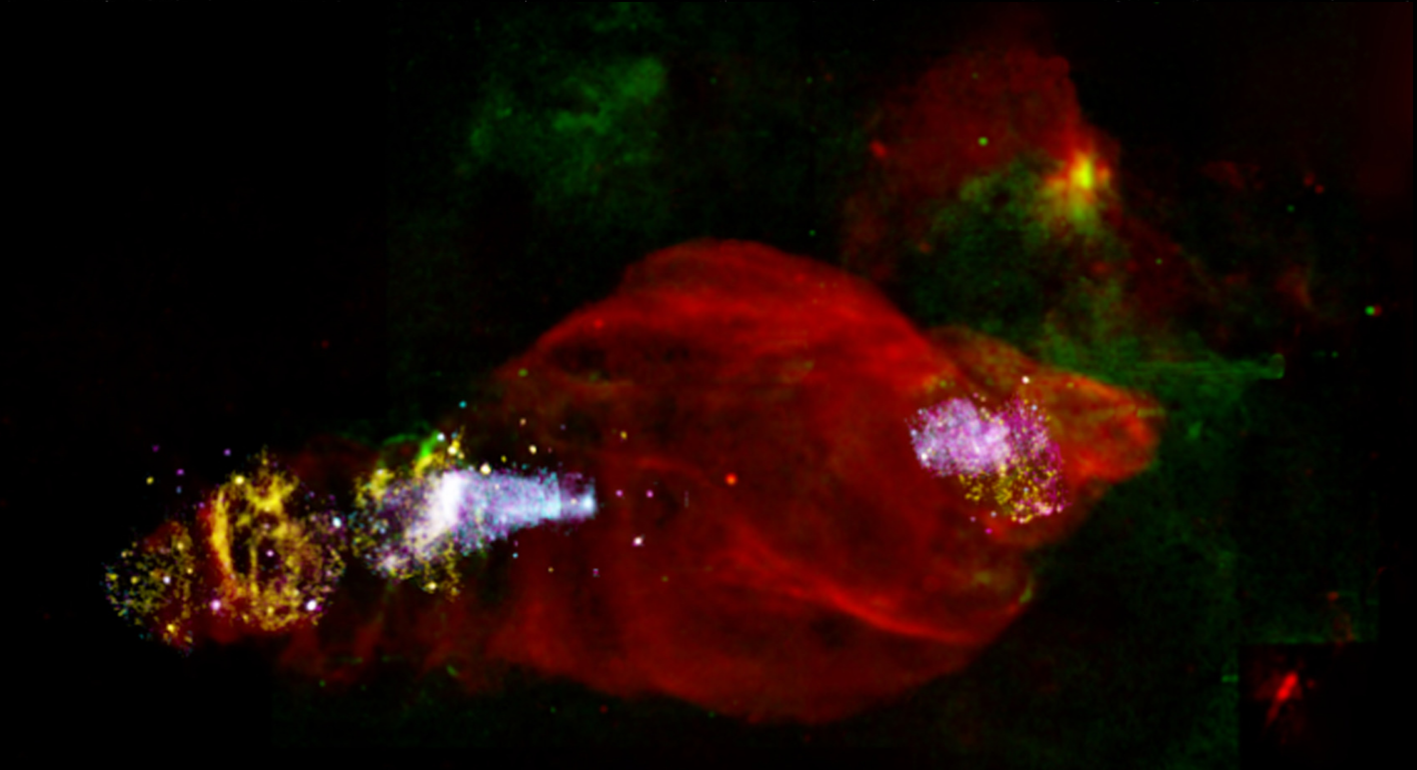




HEX-P HET 1-ks simulation of the Crab Nebula

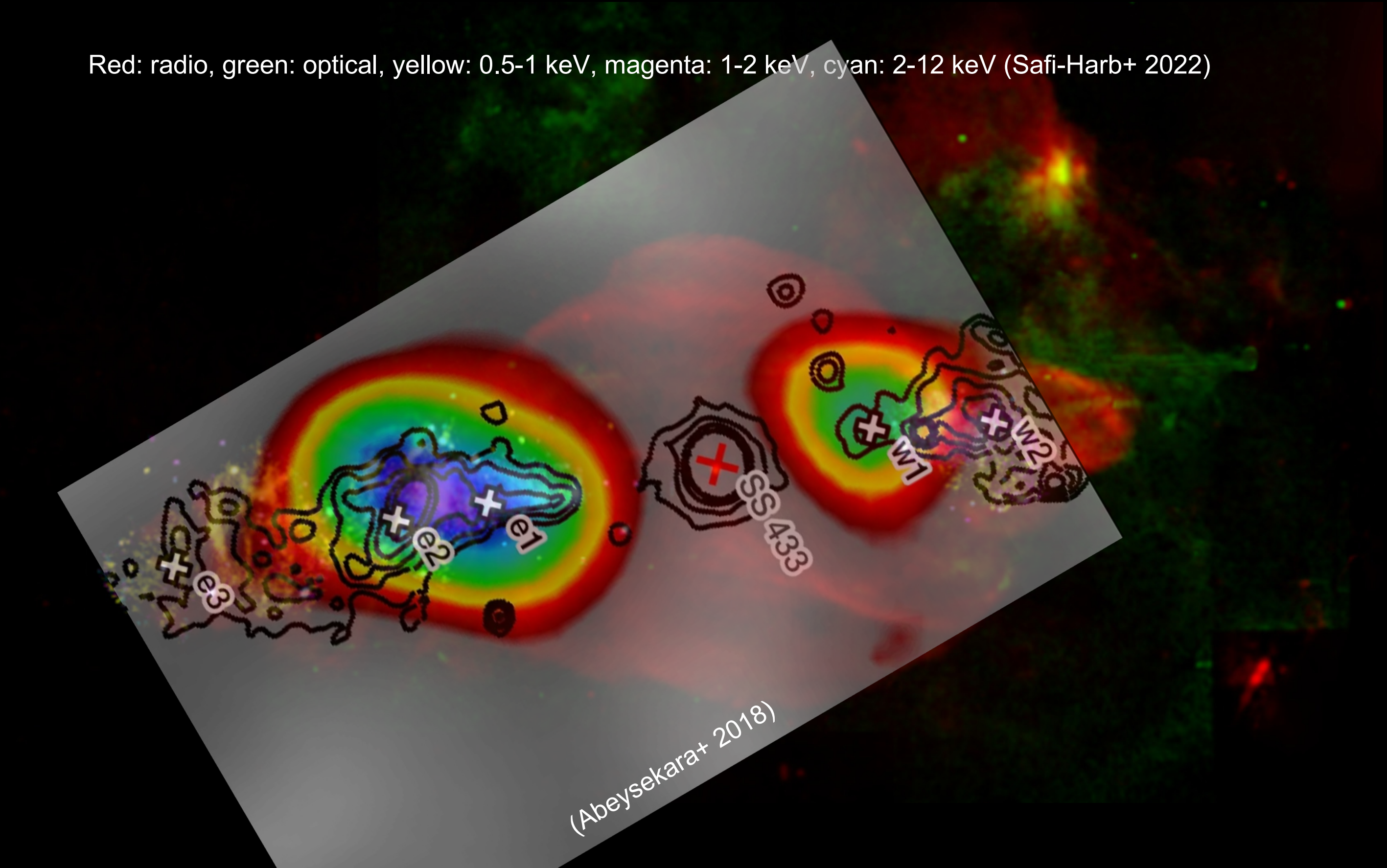
(Reynolds+ 2023 submitted to FrASS)

SS 433 is a microquasar with bipolar jets which interact with an SNR W50 and ISM.



Red: radio, green: optical, yellow: 0.5-1 keV, magenta: 1-2 keV, cyan: 2-12 keV (Safi-Harb+ 2022)

UHE and VHE gamma rays were detected from knots in the east and western lobes.



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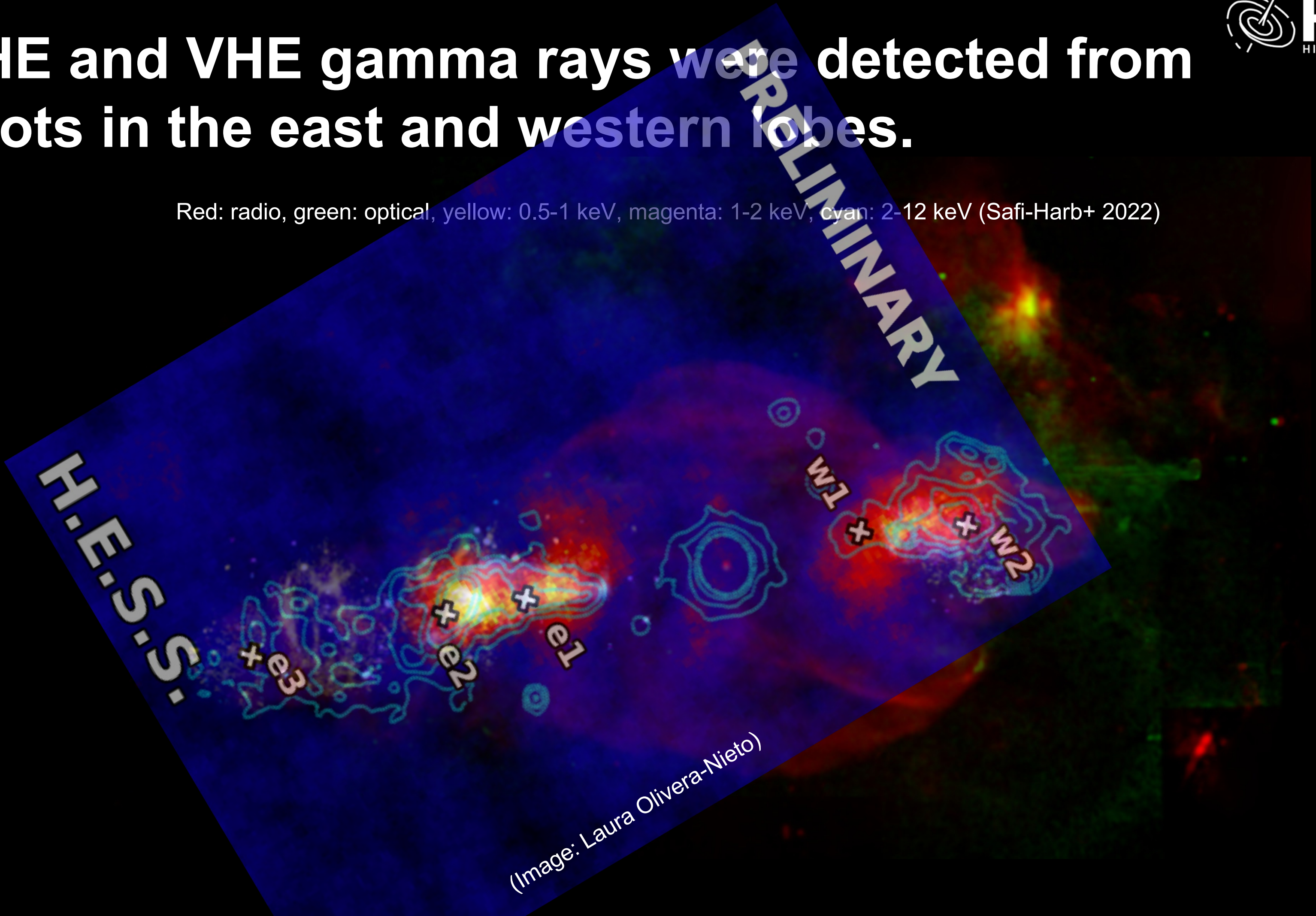
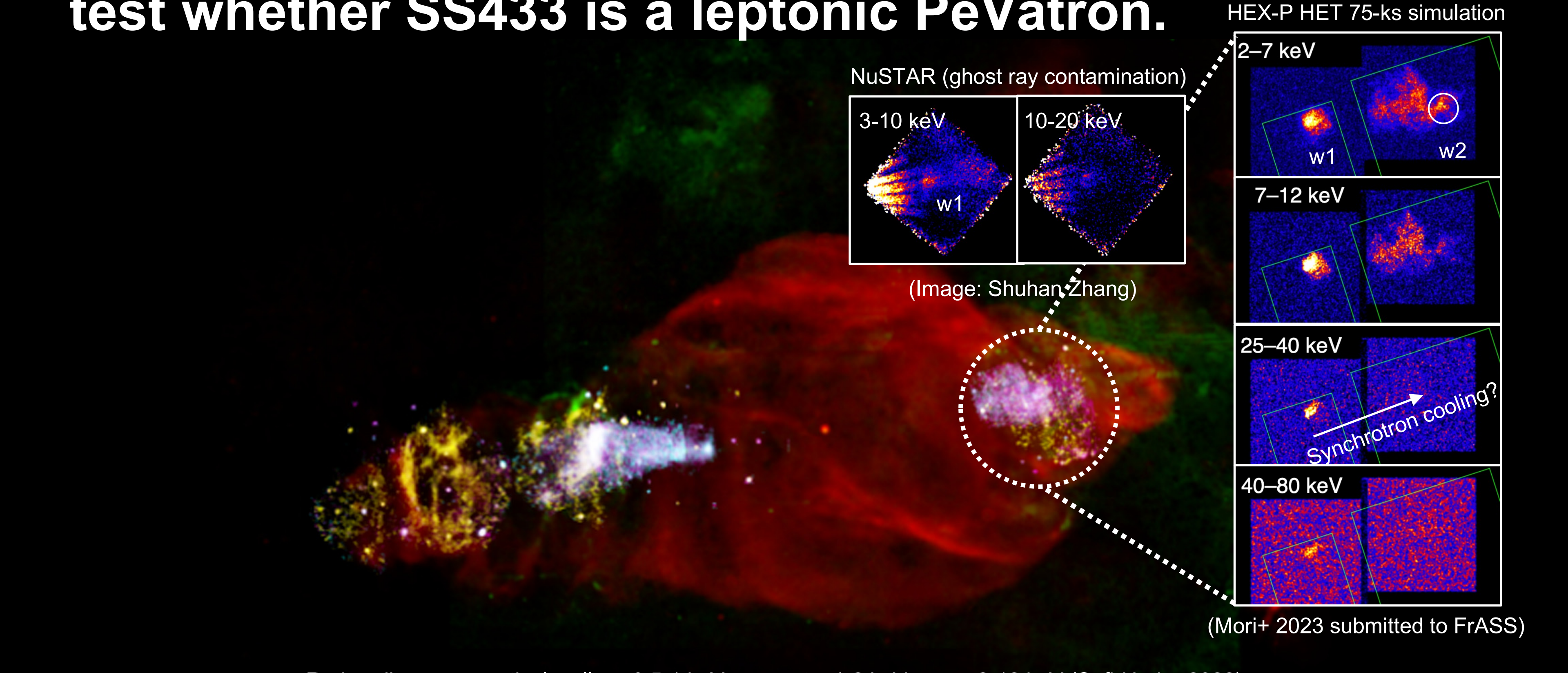
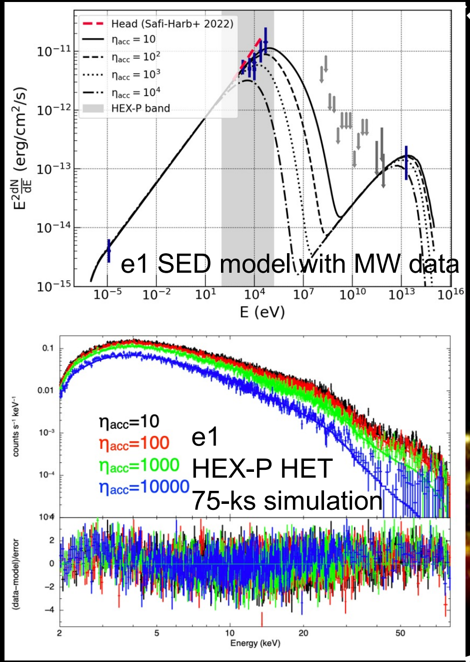


HEX-P will resolve the western lobe up to > 40 keV, test whether SS433 is a leptonic PeVatron.

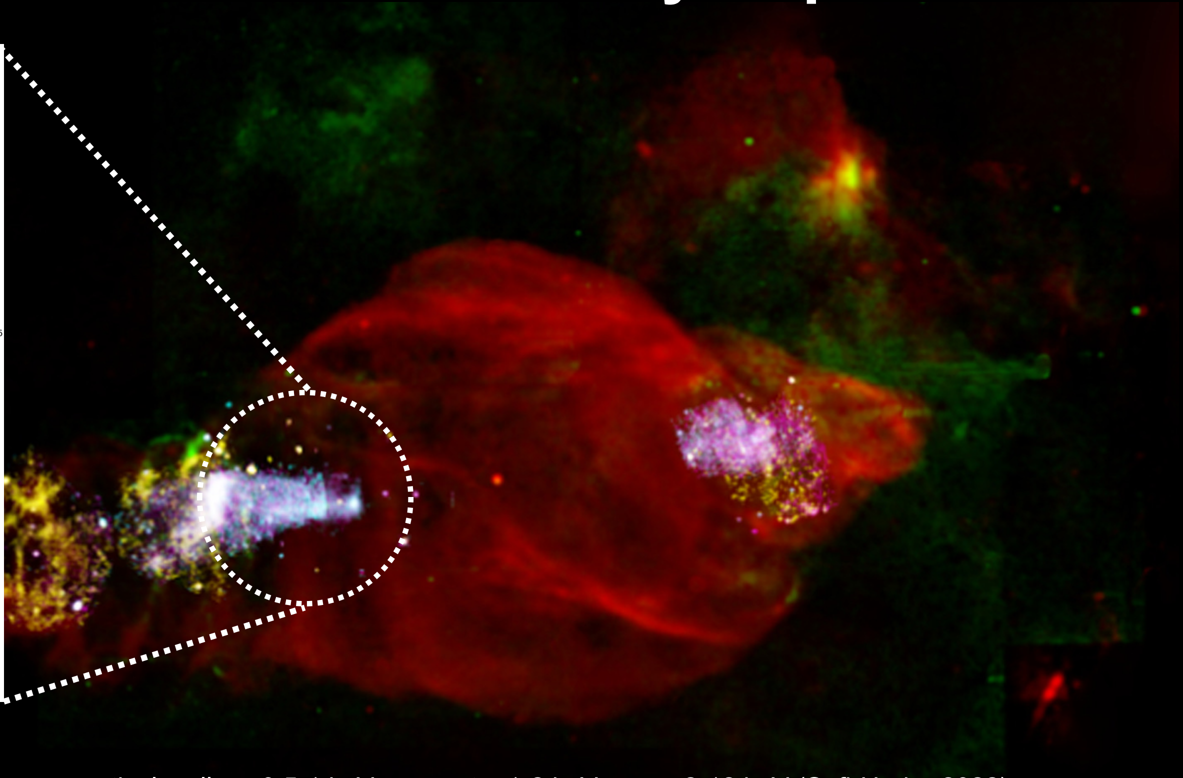


Red: radio, green: optical, yellow: 0.5-1 keV, magenta: 1-2 keV, cyan: 2-12 keV (Safi-Harb+ 2022)

HEX-P will detect synchrotron cutoff to directly measure the acceleration efficiency → particle Emax



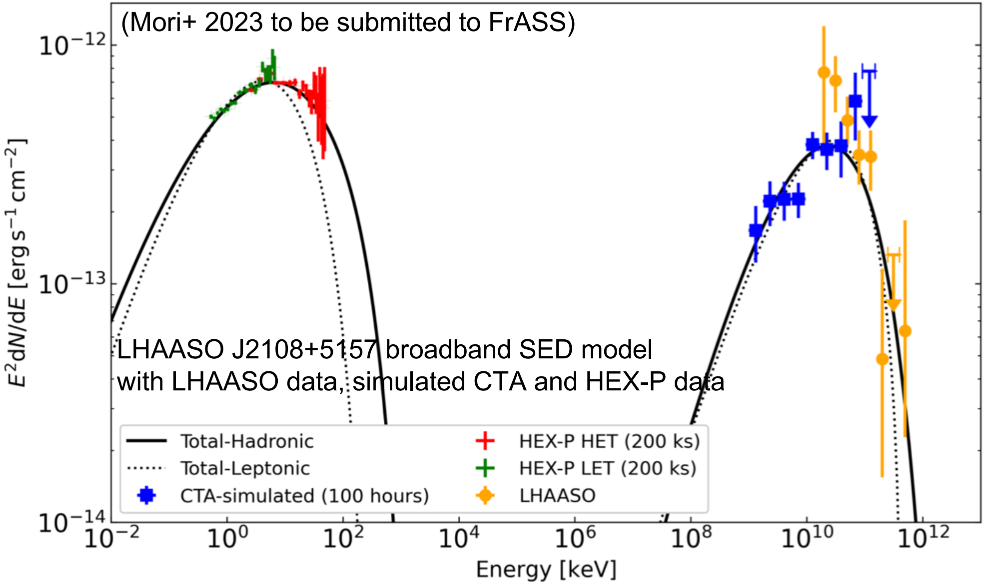
(Mori+ 2023 submitted to FrASS)



Red: radio, green: optical, yellow: 0.5-1 keV, magenta: 1-2 keV, cyan: 2-12 keV (Safi-Harb+ 2022)

HEX-P will help identify ”dark PeVatrons” by discriminating between leptonic and hadronic case.

- 10 UHE sources without known MW counterparts detected by LHAASO
- **Similar gamma-ray vs. distinct X-ray spectra for different cases**
- Extra synergy with IceCube-Gen2 for hadronic PeVatrons

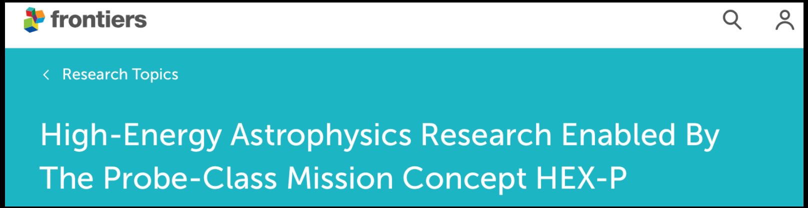


HEX-P Galactic baseline program will explore various particle acceleration sites and mechanisms.

- **Supernova remnants**: forward / reverse shock
- **Pulsar wind nebulae**: termination shock
  - Interaction of SNRs vs. PWNe
  - Interaction between SNR/PWN and dense environment
- **Gamma-ray binaries**: intrabinary shock
- **Star clusters**: colliding wind shock
- **Microquasars**: jet-driven shock
- **"Dark PeVatrons"**: leptonic or hadronic?

HEX-P will open a new chapter of Galactic PeVatron science in synergy with gamma ray observatories.

- NASA 2023 APEX mission candidate
- **Uniquely suited for PeVatron science**
  - **Broad bandpass (0.2-80 keV)** covering synchrotron emission from ~ PeV CRs
  - **Fine angular resolution (LET 5”, HET 18”)** enabling spatially resolved spectroscopy
  - Superior timing resolution (1 μs) allowing to remove pulsar contamination
- Synergy with CTAO, LHAASO, SWGO
- 10 science cases to be published



frontiers

‹ Research Topics

High-Energy Astrophysics Research Enabled By The Probe-Class Mission Concept HEX-P

HEX-P
HIGH ENERGY X-RAY PROBE

The High Energy X-ray Probe

The Next Generation All Purpose X-ray Observatory.

https://hexp.org

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Silvia Celli, Rebecca Diesing, Jordan Eagle, Chris L. Fryer, Stefano Gabici,
Joseph Gelfand, Brian Grefenstette, Javier Garcia, Chanho Kim, Roman Krivonos,
Sajan Kumar, Ekaterina Kuznetsova, Brydyn Mac Intyre, Kristin Madsen,
Silvia Manconi, Yugo Motogami, Melania Nynka, Hayato Ohsumi, Barbara Olmi,
Jaegeun Park, Gabriele Ponti, Toshiki Sato, Ruo-Yu Shang, Daniel Stern,
Yukkikatsu Terada, Naomi Tsuji, George Younes, and Andreas Zoglauer

HEX-P
HIGH ENERGY X-RAY PROBE

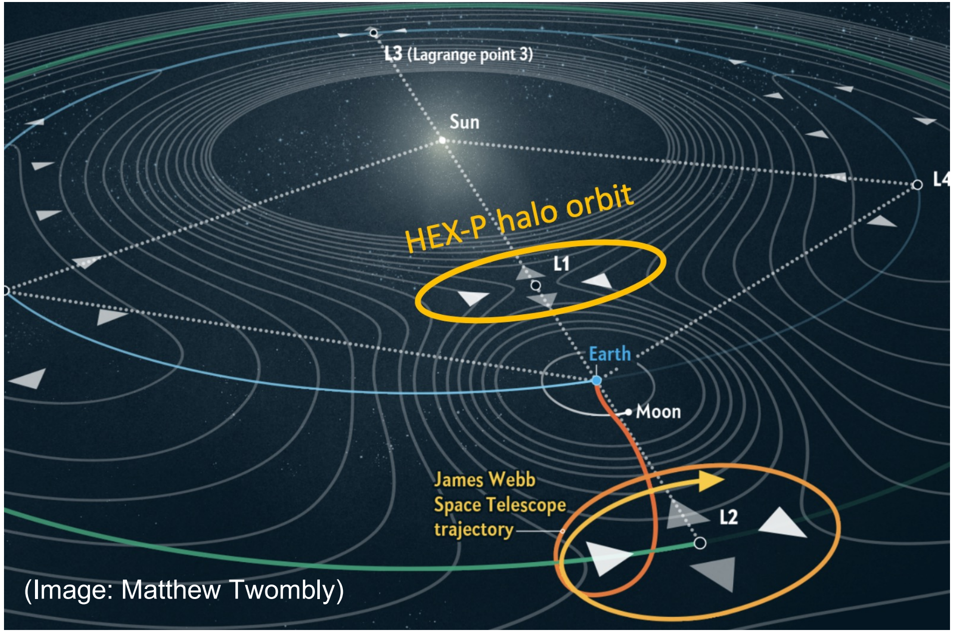
The High Energy X-ray Probe

The Next Generation All Purpose X-ray Observatory.

Backup slides

HEX-P orbit: L 1 point

- Long uninterrupted stares, large field of regard
- Benign thermal environment (vs. L2: Earth's geomagnetic tail)



(Image: Matthew Twombly)