The High Energy X-Ray Probe (HEX-P)

Galactic PeVatrons, supernova remnants, pulsar wind nebulae and nuclear astrophysics

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Overview:

HEX-P is a probe-class mission concept that will combine high spatial resolution X-ray imaging (<10 arcsec FWHM) and broad spectral coverage (0.1-150 keV) with an effective area far superior to current facilities (including XMM-Newton and NuSTAR) to enable revolutionary new insights into a variety of important astrophysical problems.

- HEX-P is ideally suited to address important problems in the physics and astrophysics of supernova remnants (SNRs) and pulsar wind nebulae (PWNe).
- For shell SNRs, HEX-P can greatly improve our understanding in several areas, including detections of, or limits on, ^{44}Ti in the youngest supernova remnants and better spectral characterization and localization of nonthermal X-ray emission from both nonthermal-dominated SNRs and those containing both thermal and nonthermal components.
- For PWNe, HEX-P can fill in a large gap in the spectral-energy distributions (SEDs) of many objects observed in radio, soft X-rays, and gamma rays, constraining the maximum energies to which electrons can be accelerated, with implications for the nature of the Galactic PeVatrons required by the spectrum of Galactic cosmic rays.

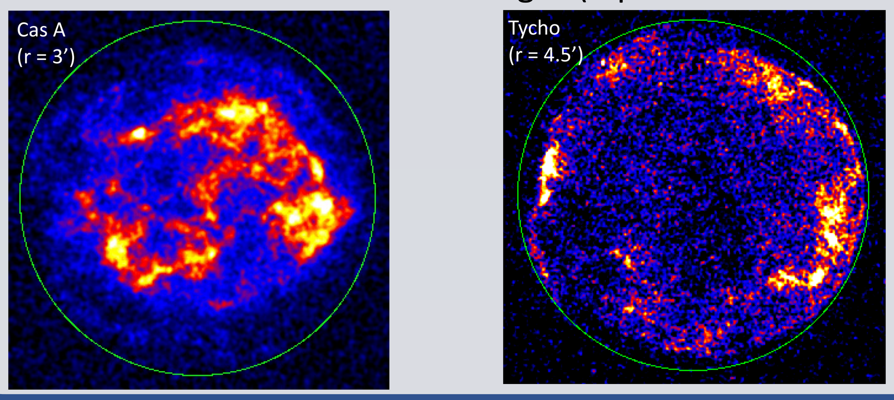
Galactic PeVatrons: New frontier in astroparticle physics

- LHAASO detected 14 gamma-ray sources in the Galactic Plane above ~100 TeV (Cao+ 21a&b, Aharonian+ 21).
- What are these PeVatrons? Only Crab PWN is identified.
  - Leptonic or hadronic origin?
  - SNRs, PWNe, star clusters, TeV binaries, microquasar jets, Sgr A* or something unknown?
- In the leptonic case (e.g., PWNe), primary electrons are accelerated to PeV energies. In the hadronic case (e.g., SNR-cloud systems), secondary electrons are produced by pionic showers when PeV protons hit clouds.
- In either case, PeV electrons emit synchrotron X-rays in the hard X-ray band: $E_{syn} \sim 120$ keV $(E_e/\mathrm{PeV})^2(B/3\ \mathrm{uG})$.
- Particle acceleration, propagation and cooling all in play → MW SED and morphology data are crucial.
- Multi-messenger PeVatron science in the 2030s
  - HEX-P (X-ray) and CTA (TeV) will be a golden duo to identify PeVatrons and explore acceleration/emission mechanisms.
  - ICECUBE gen 2 (neutrino) will probe hadronic PeVatrons in our galaxy

Young supernova remnants: New insights on shock acceleration

- Young SNRs (Cas A, Tycho, Kepler…) exhibit highly asymmetric thermal and non-thermal emission.
- NuSTAR spotted three hard X-ray knots coinciding with the inward-moving shocks detected by Chandra → most energetic acceleration sites in Cas A (Grefenstette+ 15, Sato+ 18)
- HEX-P can determine fundamental parameters from synchrotron X-ray emission in the knots, filaments and forward/reverse shock regions (Diesing+ 21)
  - E > 15keV: uncontaminated non-thermal emission
  - Year-scale hard X-ray variability due to fast synchrotron cooling → B-field
  - Photon index → electron spectral index
  - Spectral cutoff → Maximum electron energy
- HEX-P's sensitive survey for non-thermal X-ray emission from older SNRs

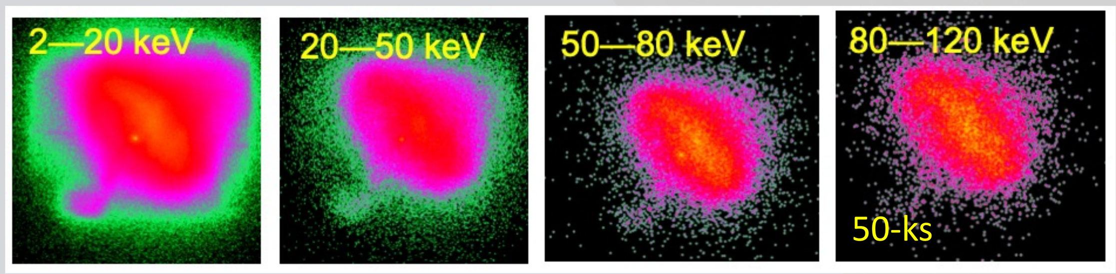
Figure 1: Simulated HEX-P 15-60 keV images (input: Chandra 4-6 keV images)



Pulsar wind nebulae: Multi-zone and multi-band approach

- Multi-wavelength SEDs are characterized by synchrotron (radio to X-ray) and inverse Compton scattering (GeV to TeV) components.
- ICS emission is suppressed by Klein-Nishina effect above ~100 TeV → Hard X-ray band for determining Emax.
- Both young (e.g., Crab) and middle-aged PWNe (Eel, Dragonfly etc.) are PeVatron candidates – see J. Woo's talk in the PWN special session (session ID 201).
- Particle advection/diffusion and SNR-PWN interactions produce complex multi-wavelength morphological patterns → multi-zone SED model + spatially-resolved, multi-band SED data with HEX-P + CTA
- HEX-P can excise pulsar emission and characterize broad-band X-ray spectra in multiple PWN regions as a single telescope from 0.1 to 150 keV.

Figure 2: Simulated HEX-P HET images of the Crab nebula



SN1987A: Thermal emission, PWN, pulsar search and ^{44}Ti lines altogether

- A very young SNR in the LMC exploded in 1987. The central compact object is not yet detected: NS or BH?
- A PWN in SN1987A suggested by NuSTAR data (Greco+ 22)
- An excellent example of HEX-P's capabilities
  - Characterizing three thermal components (kT 0.4, 0.8 and 3 keV) and their time evolution → LET spectral data
  - X-ray emission from the SNR's core is highly absorbed by high-Z ejecta elements (Alp+ 21)→ HET spectral data
  - Detecting a pulsar? → HET timing data
  - ^{44}Ti emission line shift and width measurements (Boggs+ 15) → HET's 65-80 keV coverage

Figure 3: Chandra image of SN1987A and putative pulsar cartoon (Greco+ 22)

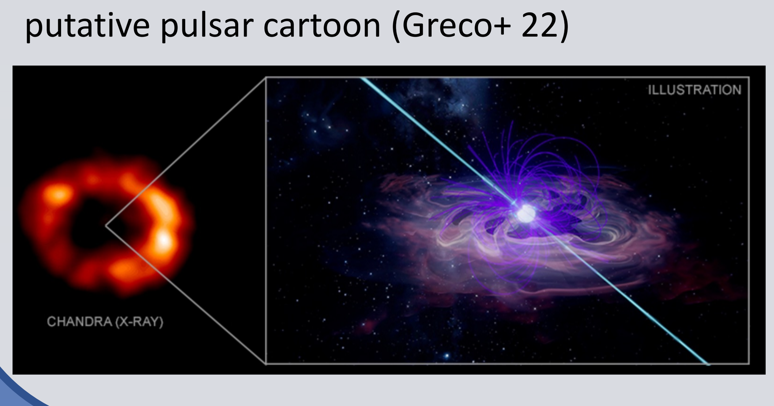
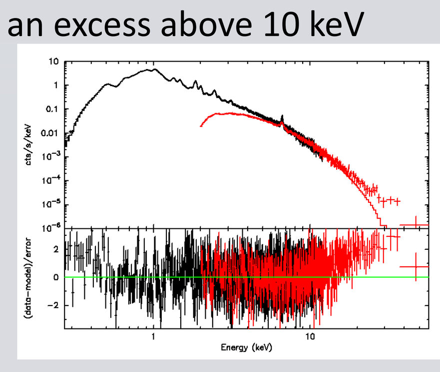


Figure 4: Simulated HEX-P LET and HET spectra of SN1987A: the PWN component shown as an excess above 10 keV



References: Cao+ 2021 Nature 594 33; Cao+ 2021 ApJL 917 L4; Aharonian+ 2021 PRL 126 241103; Grefenstette+ 2015 ApJ 802 15; Sato+ 2018 ApJ 853 46; Diesing+ 2021 ApJ 922 1; Greco+ 2021 ApJ 931 132; Alp+ 2021 ApJ 916 76; Boggs+ 2015 Science 348 670; Grefenstette+ 2014 Nature 506 339; Grefenstette+ 2017 ApJ 834 19; Kosakowski+ 2023 MNRASL 519 74; Terada+ 2022 ApJ 933 111

Nuclear astrophysics in the Milky Way: Supernova and kilonova explosions

- ^{44}Ti emission lines from young SNRs:
  - NuSTAR detections for Cas A (Grefenstette+ 14) and SN1987A (Boggs+ 15)
  - Mapping of ^{44}Ti emission line flux, width and shift → 3D Doppler tomography → SN explosion mechanism (Grefenstette+ 17)
  - New ^{44}Ti line detections possibly from G350.1-0.3, Kes 75 and Tycho by HEX-P (SIXTE simulations)
  - Tycho, Kepler, G1.9+0.3 → constrains Type Ia SN progenitor type (Kosakowski+ 23)

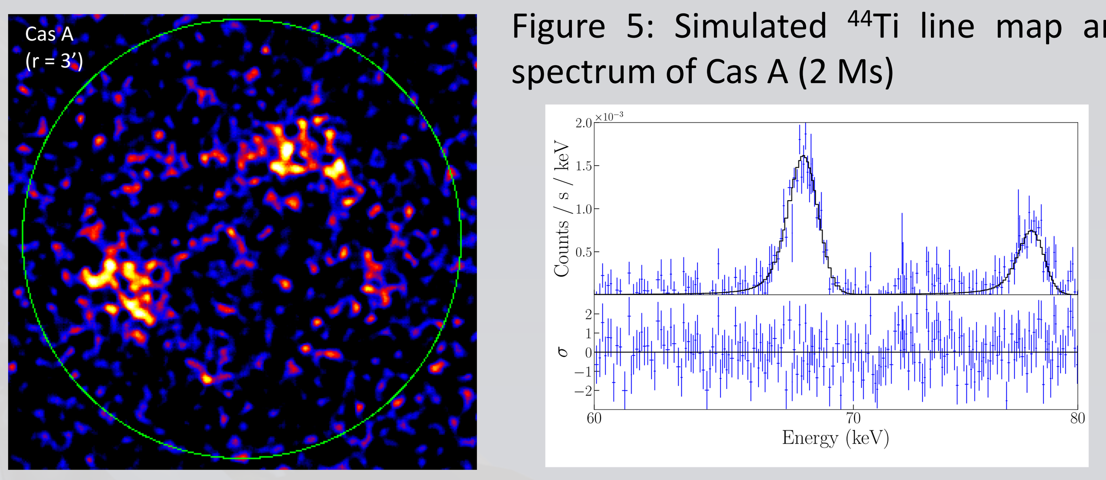


Figure 5: Simulated ^{44}Ti line map and spectrum of Cas A (2 Ms)

- Nuclear lines from double NS merger remnants
  - Kilonovae from DNS mergers produce exotic nuclei via r-process nucleosynthesis (Korobkin+ 20, Terada+ 22).
  - Nuclear lines in 11 to 75 keV are detectable by HEX-P
  - Complementary to COSI MeV telescope

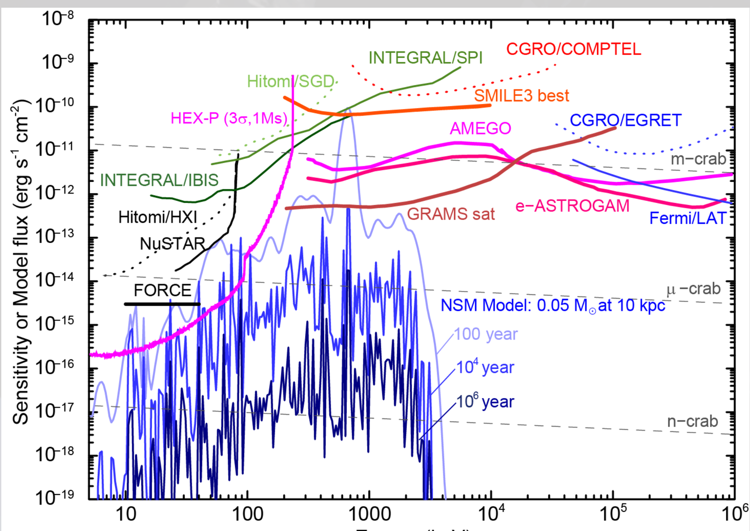


Figure 6: Model nuclear line spectra and sensitivity limits.

Table 1: Nuclear emission lines detectable by HEX-P

Line Energy (keV)	Nuclei
11.26	^{229}Th
23.4, 88.2	^{126}Sn
26.8, 59.6	^{241}Am
40.3	^{225}Ra
43.9, 74.4	^{243}Am

Other Galactic diffuse X-ray sources:

- ~150 Galactic TeV sources detected by VERITAS, HAWC, H.E.S.S and MAGIC, and more to come with CTA
- Star clusters (Westerlund 1 & 2, Arches…)
- SS433's jet interaction with SNR W50
- Galactic Center (see HEX-P poster ID 116.57 by S. Mandel)

Do you have ideas for how HEX-P would revolutionize your science? Get in touch!

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