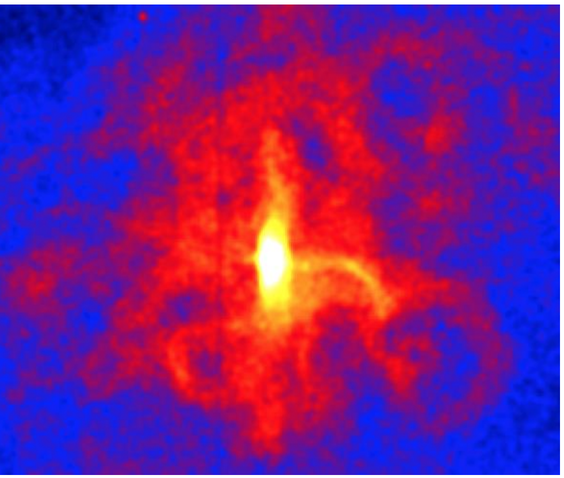
Exploiting Athena Capabilities in the Field of PWNe



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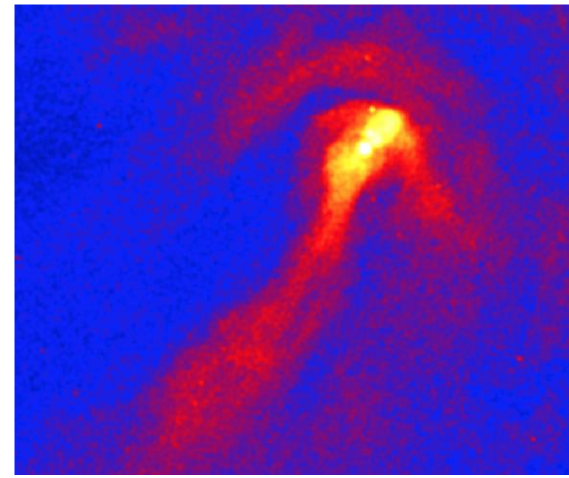
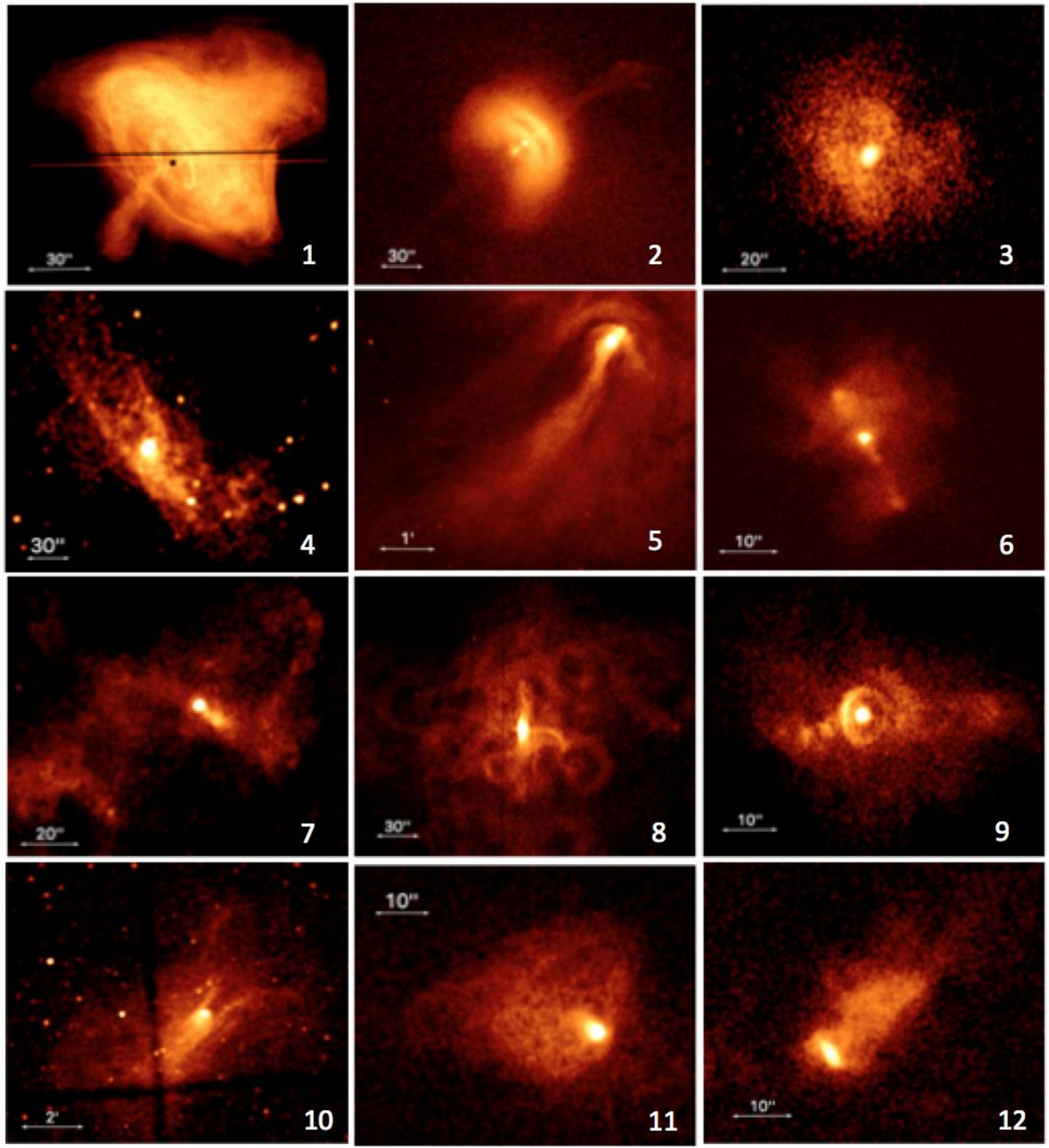


Exploring the Hot and Energetic Universe:
The second scientific conference dedicated to the Athena X-ray observatory
24-27 September 2018, Palermo, Italy

ATHENA

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

PWNe Observed with *Chandra*



- >100 PWNe have been discovered, primarily with *Chandra*, thanks to its *high resolution optics* and *low detector background*
- Observations reveal variety of morphologies and structures formed by anisotropic pulsar winds

Left: sample images of PWNe powered by pulsars still residing in their host SNRs

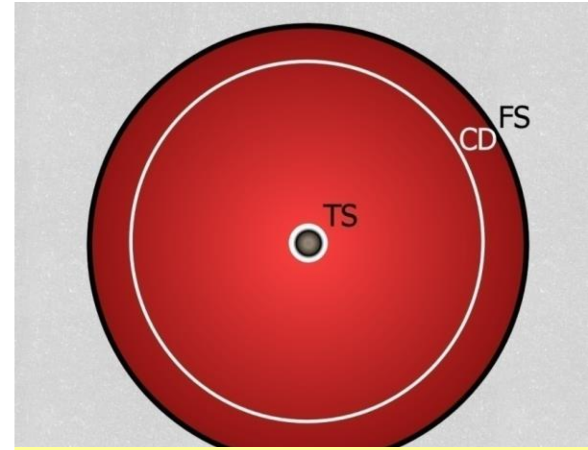
Athena's *high sensitivity*, *time resolution*, and *large field of view* will enable us to:

- obtain high-S/N images allowing spatially-resolved spectroscopy on arcsec scales
- detect/resolve very faint extended sources or structures
  - “misaligned” outflows of PWNe produced by supersonic pulsars (SPWNe)
  - faint PWNe associated with TeV sources, old/distant SNRs

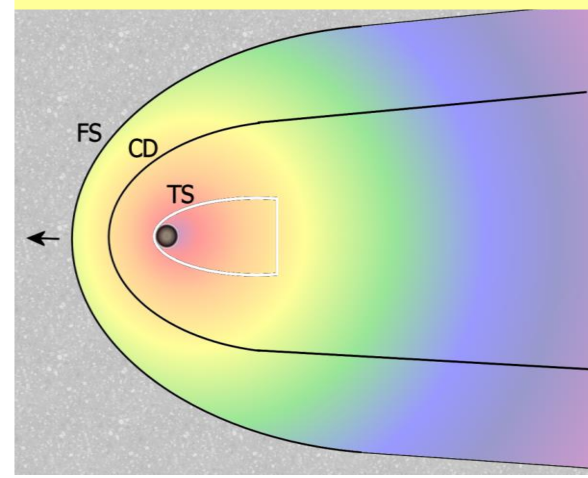
- detect the thermal components of pulsars in soft X-rays (<1 keV)
  → constrain NS cooling models
- produce high-quality X-ray light curves
  → probe magnetospheric X-ray emission, constrain magnetospheric models
- arcsecond localization
  → measure velocities of pulsars using ~30+ yr baselines established with *Chandra*
  → discovery of compact objects via multiwavelength matching and analysis, accurately measure the spectra of objects embedded in complex backgrounds (e.g., pulsars/PWNe inside SNRs, CCOs, objects in crowded clusters)

PWN Morphologies & PSR Velocities

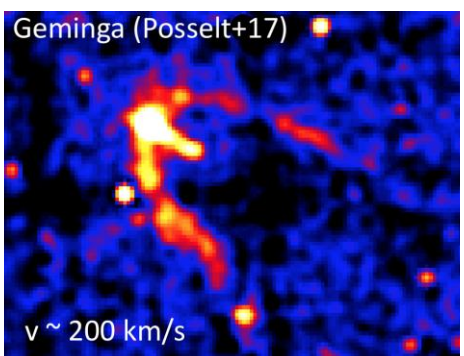
- v_{PSR} ~ a few * 100 km/s
- Inside SNR → PSRs are usually subsonic
  - Isotropic wind ("spherical cow") → spherical PWN
  - In reality: wind is highly anisotropic → equatorial + polar outflows (torus + jets)
- Outside SNRs → PSRs usually supersonic
  - $c_{s,ISM}$ ~ a few – a few * 10 km/s
  - Mach number $\mathcal{M} = v_{PSR}/c_{s,ISM}$ ~ a few × (1-10)
  - ISM exerts ram pressure on wind →
    - wind confined behind PSR, structures deformed



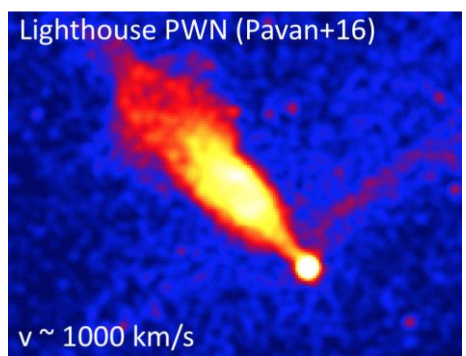
TS – termination shock
CD – contact discontinuity
FS – forward shock



$\mathcal{M} \gtrsim 1$: jets/tori get bent back

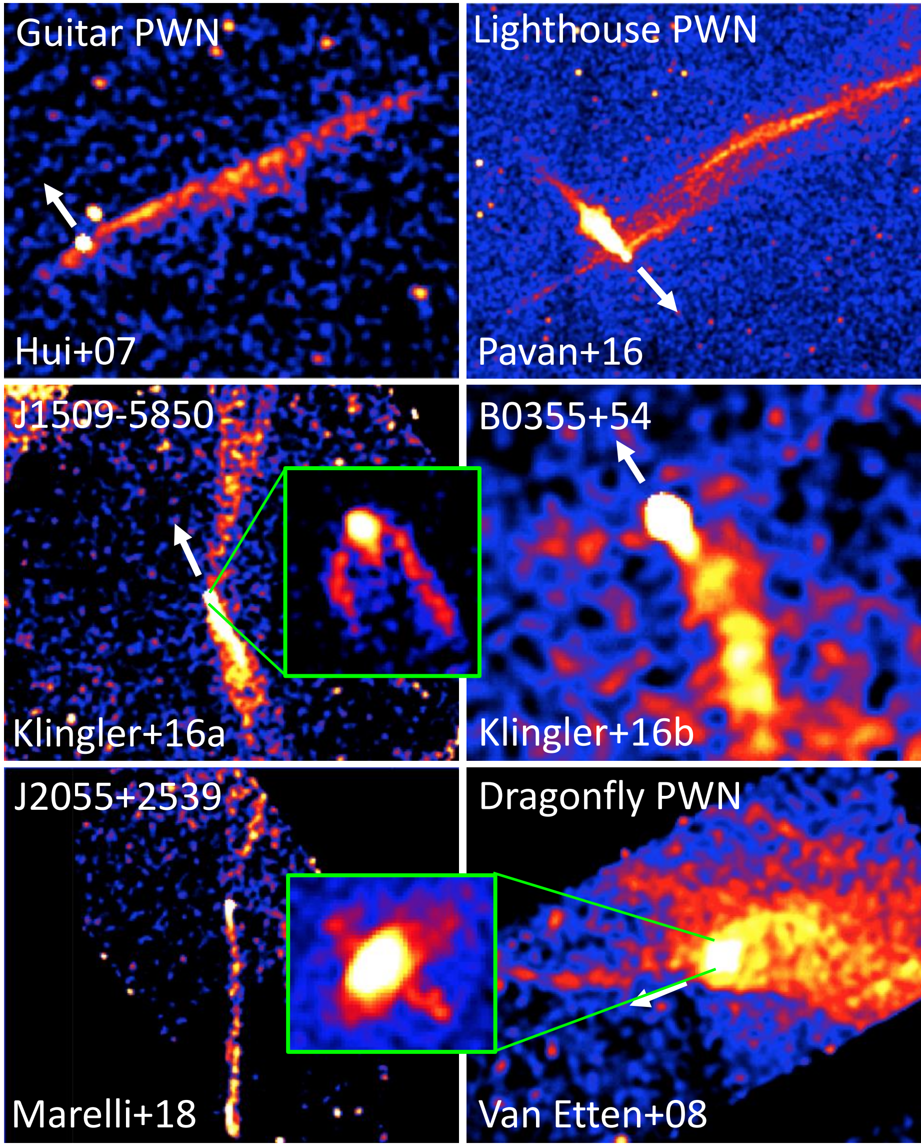


$\mathcal{M} \gg 1$: jets/tori get crushed and mixed together



Misaligned Outflows of SPWNe

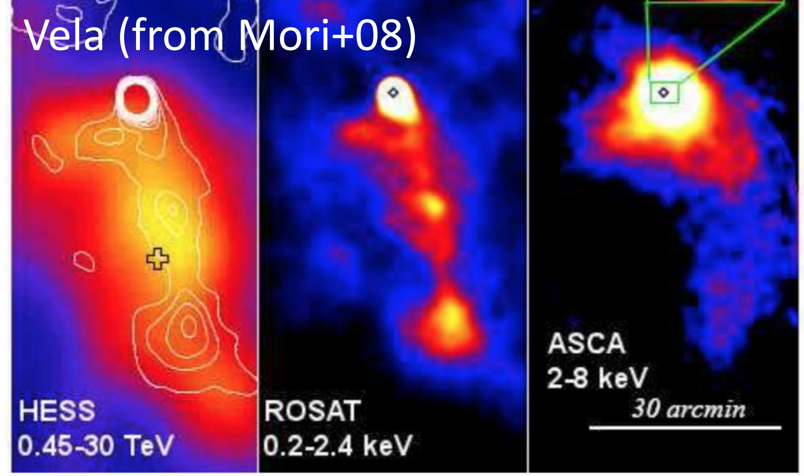
- Collimated structures offset from direction of pulsar motion
  - unexpected -- MHD suggests outflows should be bent back by ram pressure, contained within bow shock
  - caused by leakage of high-E particles into ISM B-field (Bandiera 2008), magnetic reconnection of PWN and ISM B-field (Bucciantini 2018)
  - allow us to probe the often difficult-to-study ISM B-field strengths and directions
- Challenges
  - very faint; ≳100 ks usually needed to detect with CXO; few times longer to study spectral evolution with distance
  - only 6 have been detected; too few for meaningful population studies

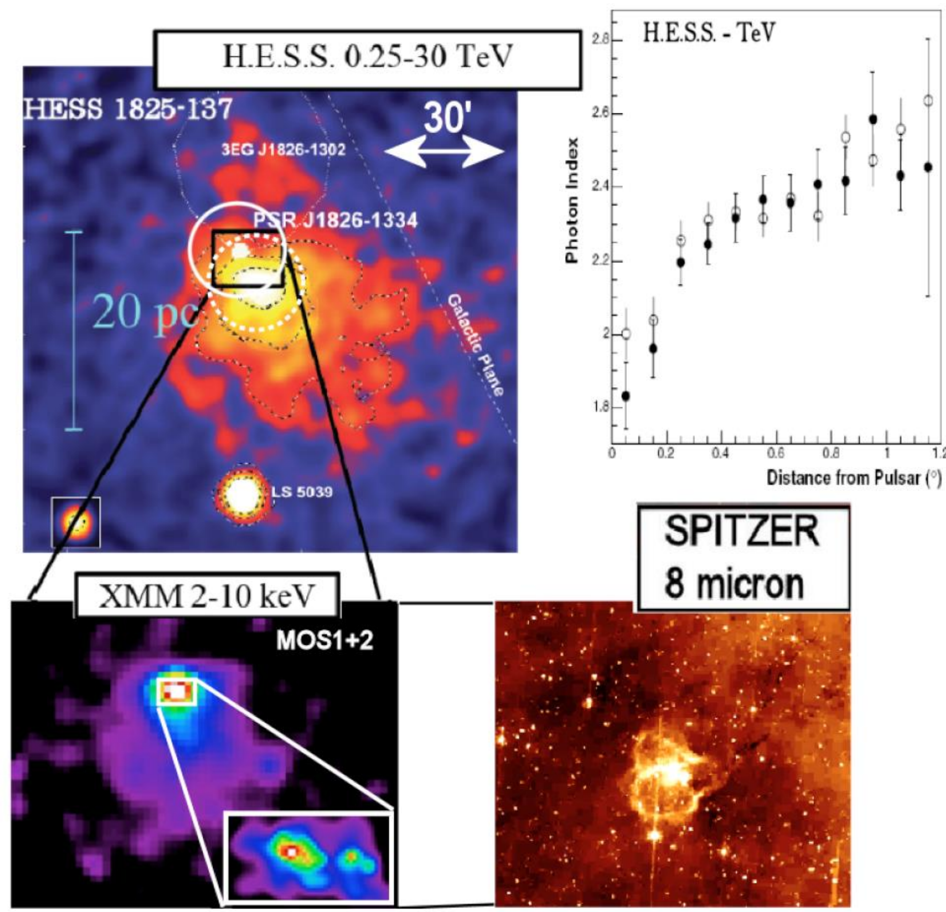


Athena will be uniquely suited for studying this unexpected and interesting phenomenon, and will enable expanding the small currently-known population

TeV PWNe

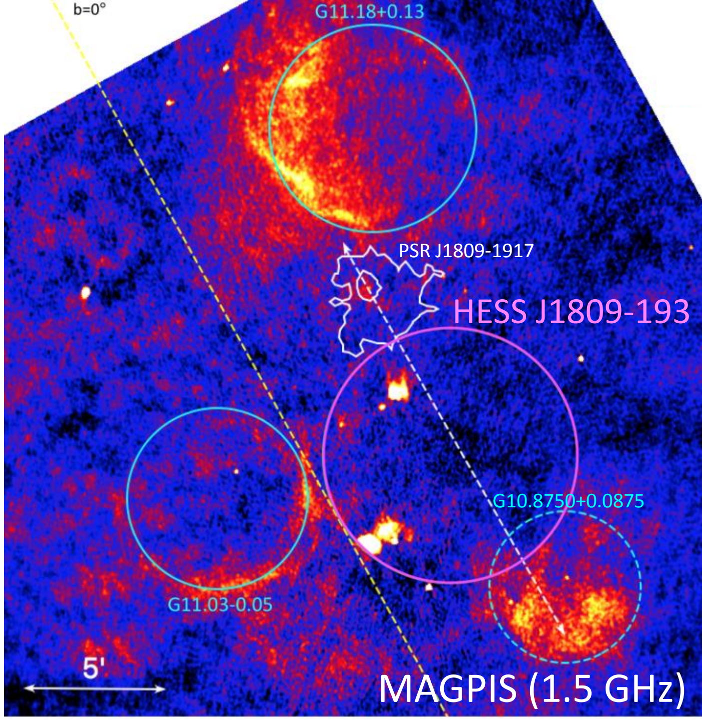
- the most populous class of galactic TeV sources
- produced by inverse-Compton upscattering of background photons (CMB, IR, starlight)
- the aged electron populations which produce IC-emission have lower energies and longer cooling timescales (~10 kyr) than X-ray synchrotron-emitting electrons; thus, they can:
  - → diffuse/advect to parsec-scale distances
  - → be positionally-offset from their pulsars by ~10s of arcmin
- this poses a challenge in associating PSRs/PWNe with their TeV counterparts
  - ~50% of galactic TeV sources remain unidentified

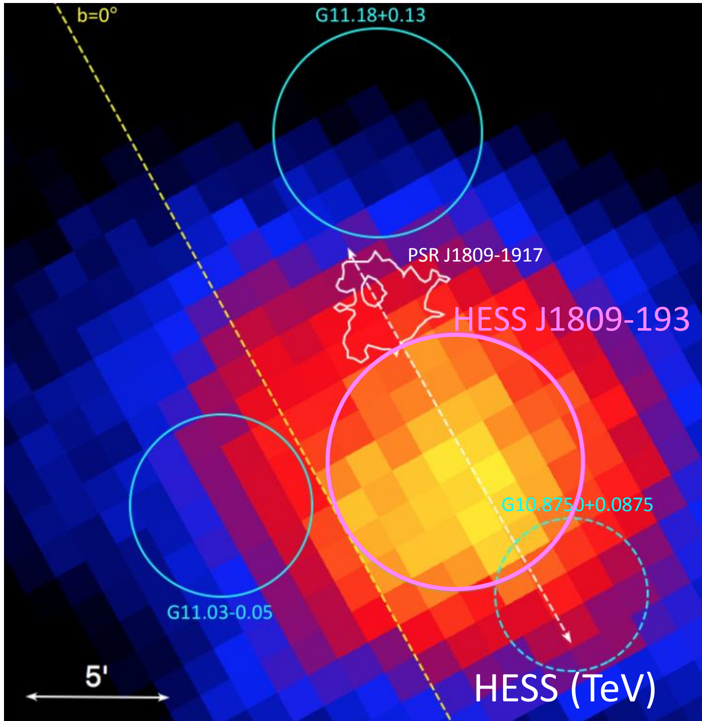




TeV PWNe & X-ray Counterparts

- offset TeV PWNe can have faint extended X-ray counterparts
- in crowded fields, associations are not always clear
  - deep X-ray images can help confirm associations





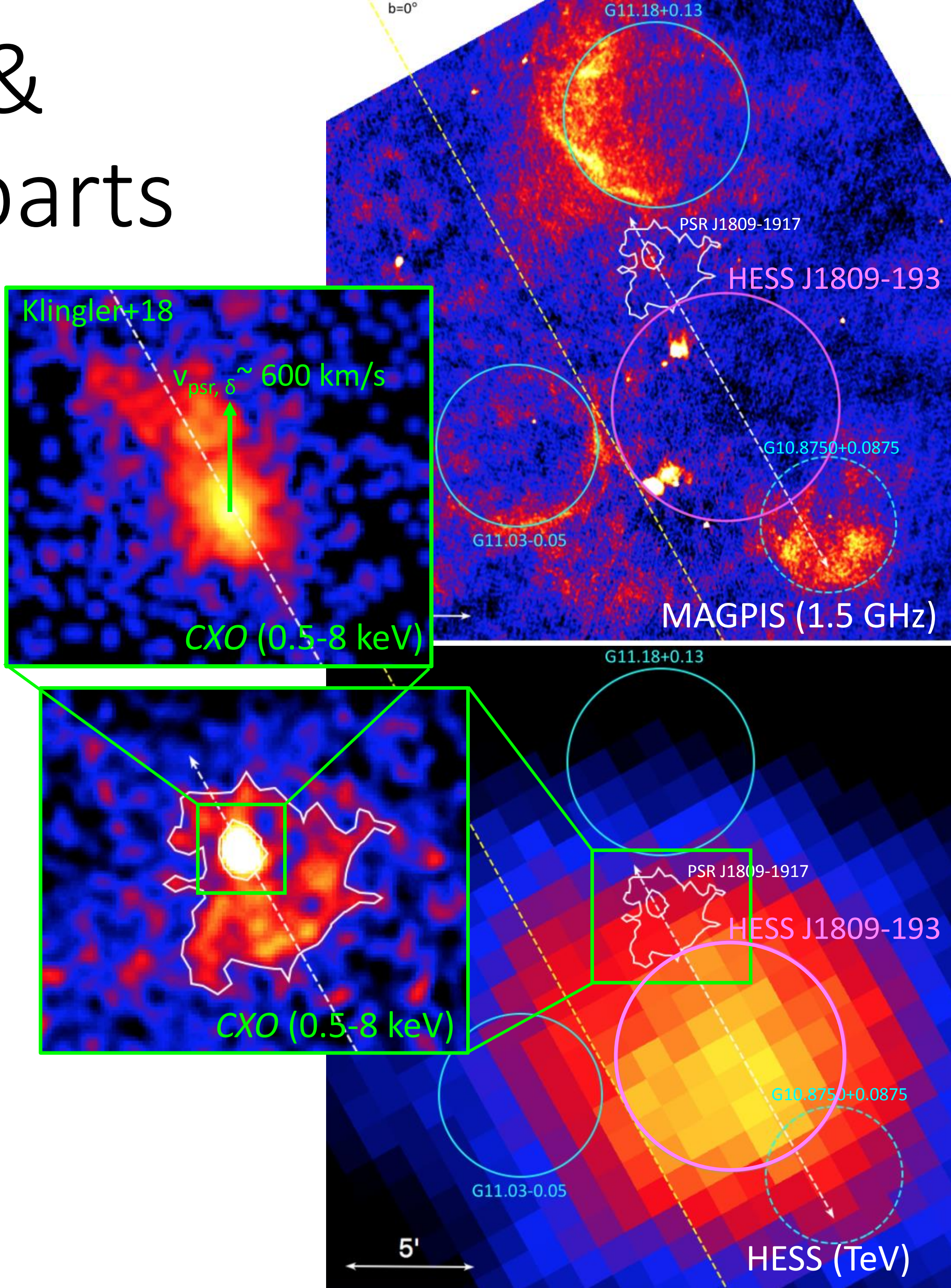
- Detecting/resolving the faint extended PWNe will allow us to better constrain how electron SEDs age/evolve

  → modeling of TeV emission, wind SED, dynamics, and energetics

TeV PWNe & X-ray Counterparts

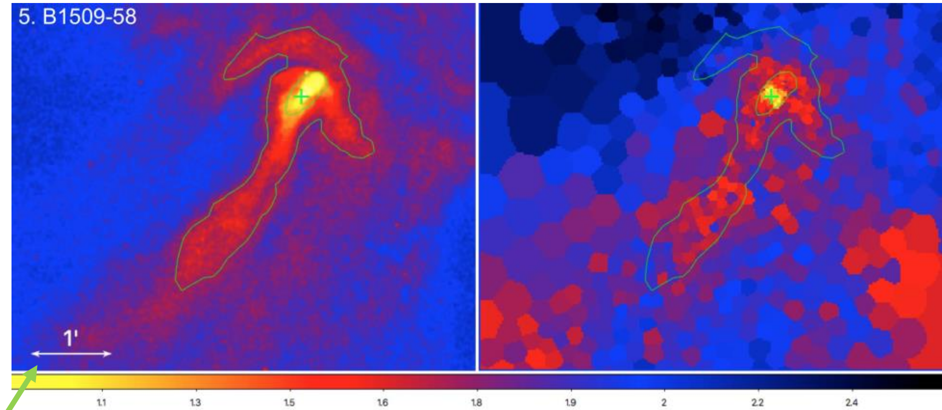
- offset TeV PWNe can have faint extended X-ray counterparts
- in crowded fields, associations are not always clear
  - deep X-ray images can help confirm associations
  - e.g., X-ray morphology of J1809-1917 PWN suggests association with HESS J809-193
  - Athena's large FOV will allow the fields of TeV sources to be thoroughly searched, shed light on "dark" TeV sources with no currently-seen extended X-ray counterparts
- Detecting/resolving the faint extended PWNe will allow us to better constrain how electron SEDs age/evolve

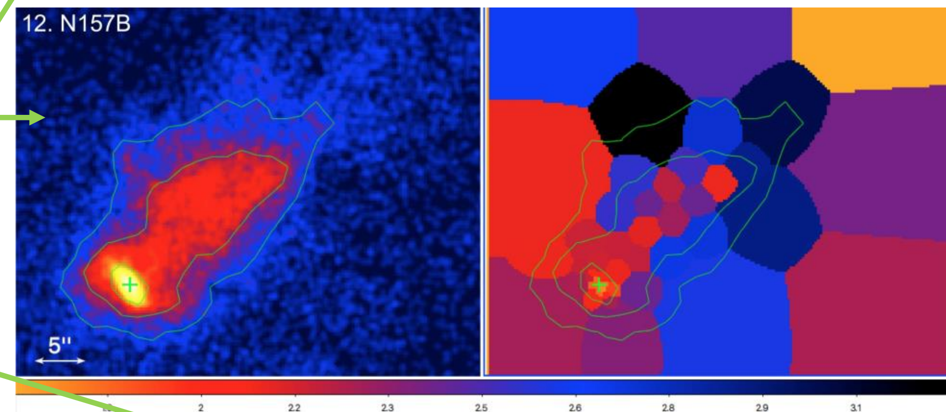
  → modeling of TeV emission, wind SED, dynamics, and energetics

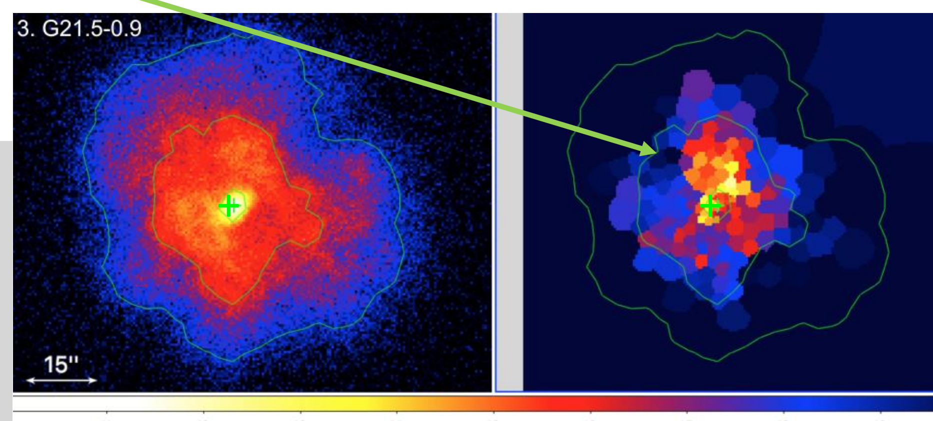


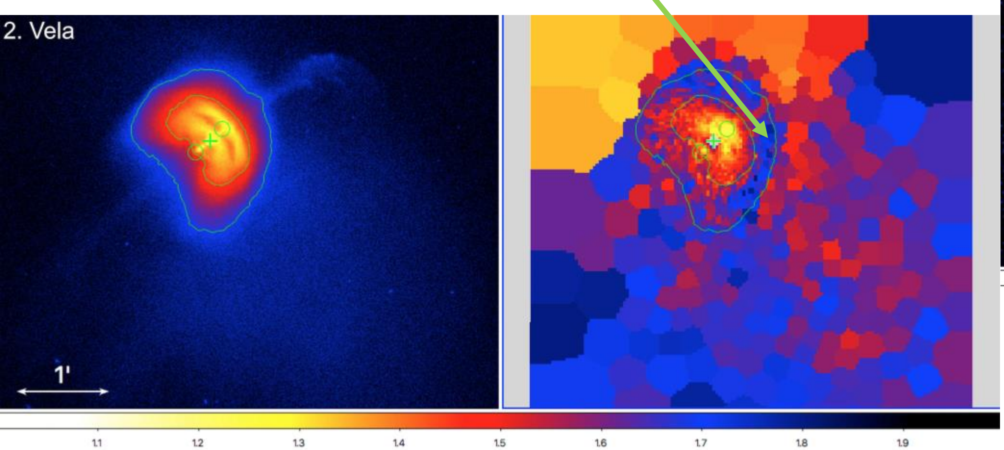
Spectral Maps

- spatially-resolved spectroscopy: characterize how e^- population evolves with time/distance
- spectral maps allow us to:
  - determine the injection spectra of the uncooled electrons
  - study varying dependences of spectral cooling (Γ) with distance from the pulsar
  - detect phenomena that are not visible in counts images, e.g.:
    - spectral anisotropy of wind
    - in-situ particle reacceleration sites (reconnection?)
  - Discern connections between pulsar magnetospheric parameters and PWN spectra/energetics







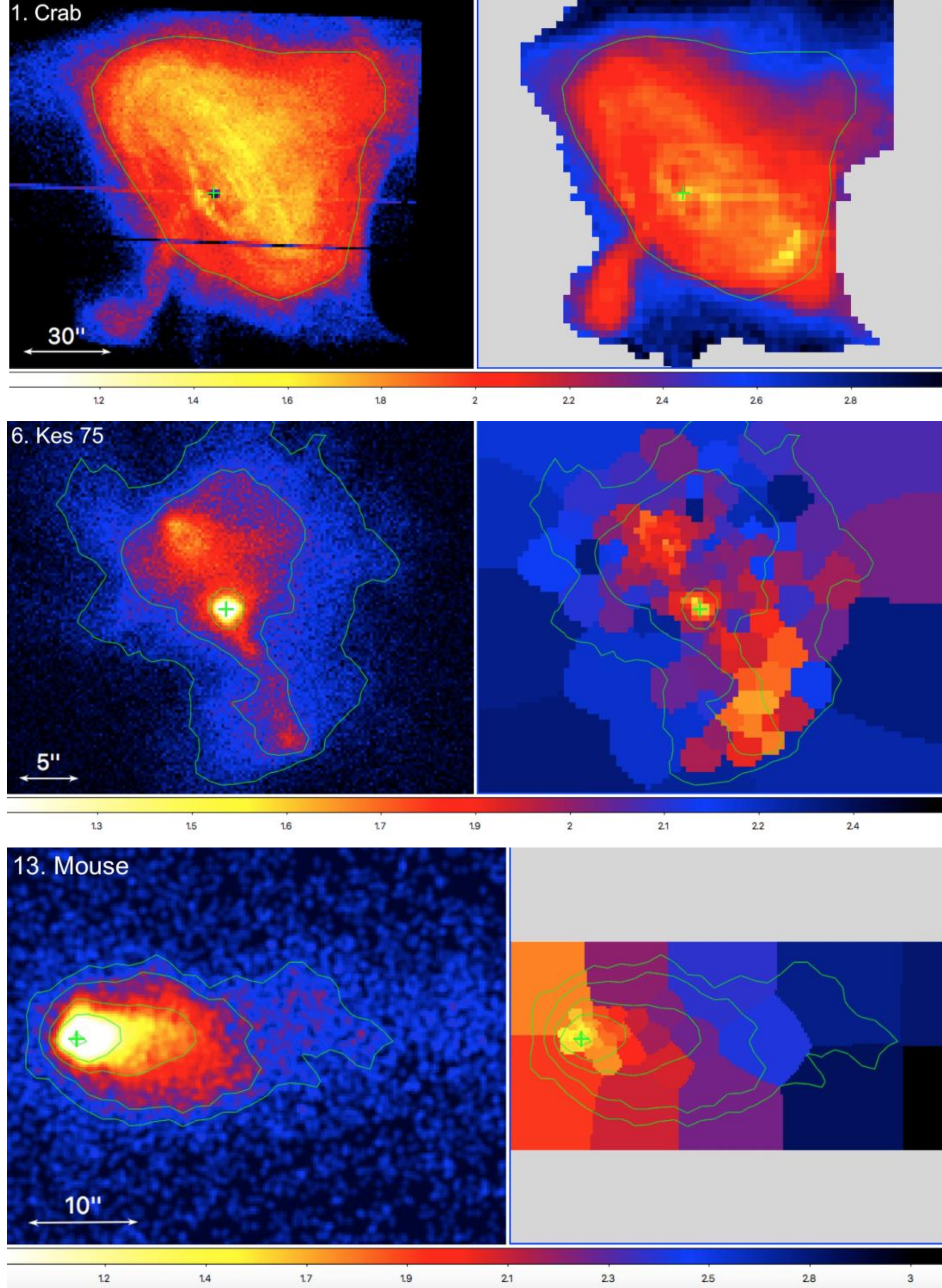


Spectral Maps

- *CXO* provides:
  - arcsecond-scale resolution for extremely bright (Crab-like) sources
  - satisfactory resolution (~few arcsec) in bright sources (e.g., Vela, Kes 75)
  - but inadequate resolution in fainter sources (e.g., the Mouse PWN: some bins >10 arcsec), due to low S/N

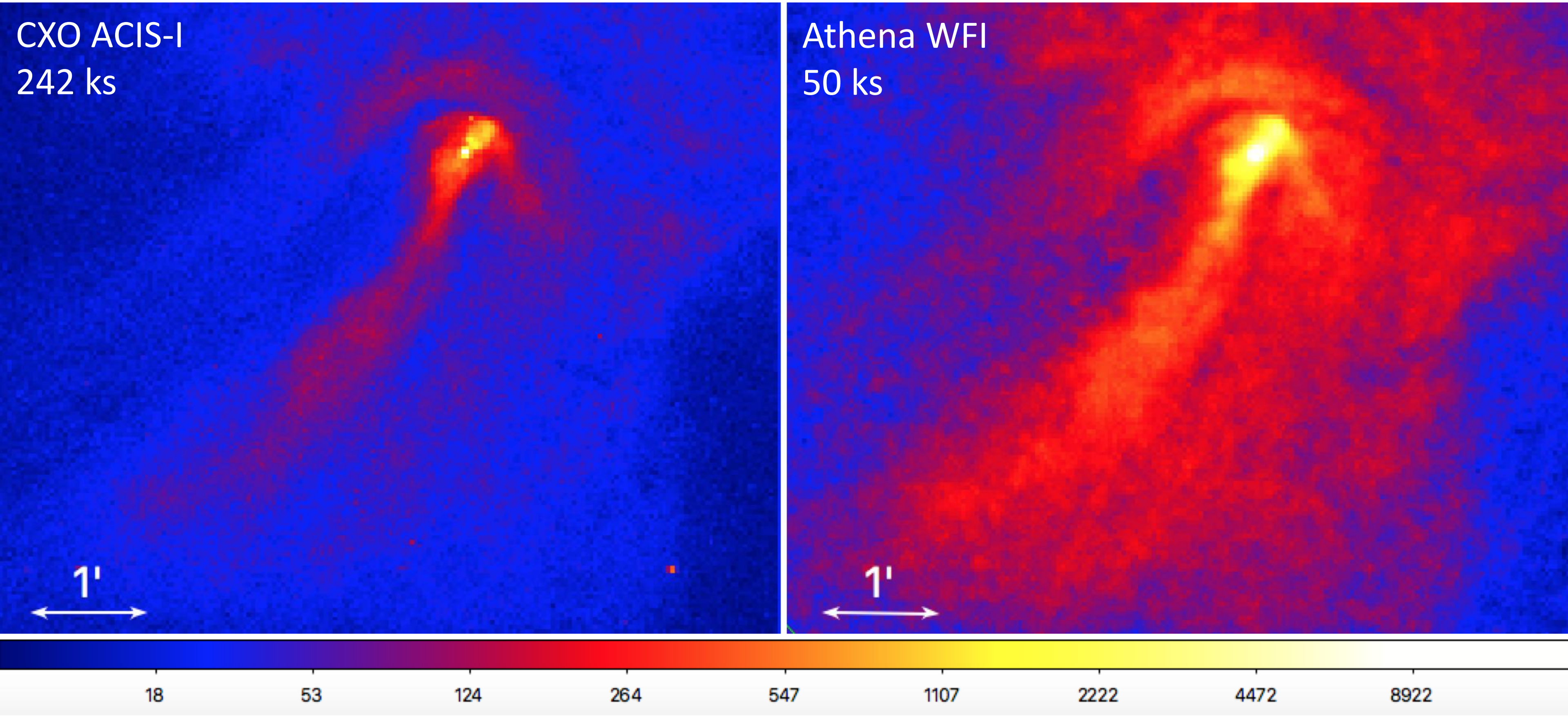
- Only a dozen PWNe are bright enough for spectral mapping with *CXO* (Kargaltsev+17)
  - uncertainties $\Delta\Gamma \sim 0.1$-0.2

- Athena's higher sensitivity will:
  - at least double the sample of mappable PWNe
    - → population studies (N>25), detect statistically-meaningful trends
  - greatly enhance quality of current sample
    - spatial bins → 2-4 arcsec
    - uncertainties → likely $\Delta\Gamma < 0.05$



Simulations: What We Can Expect

PSR B1509-58

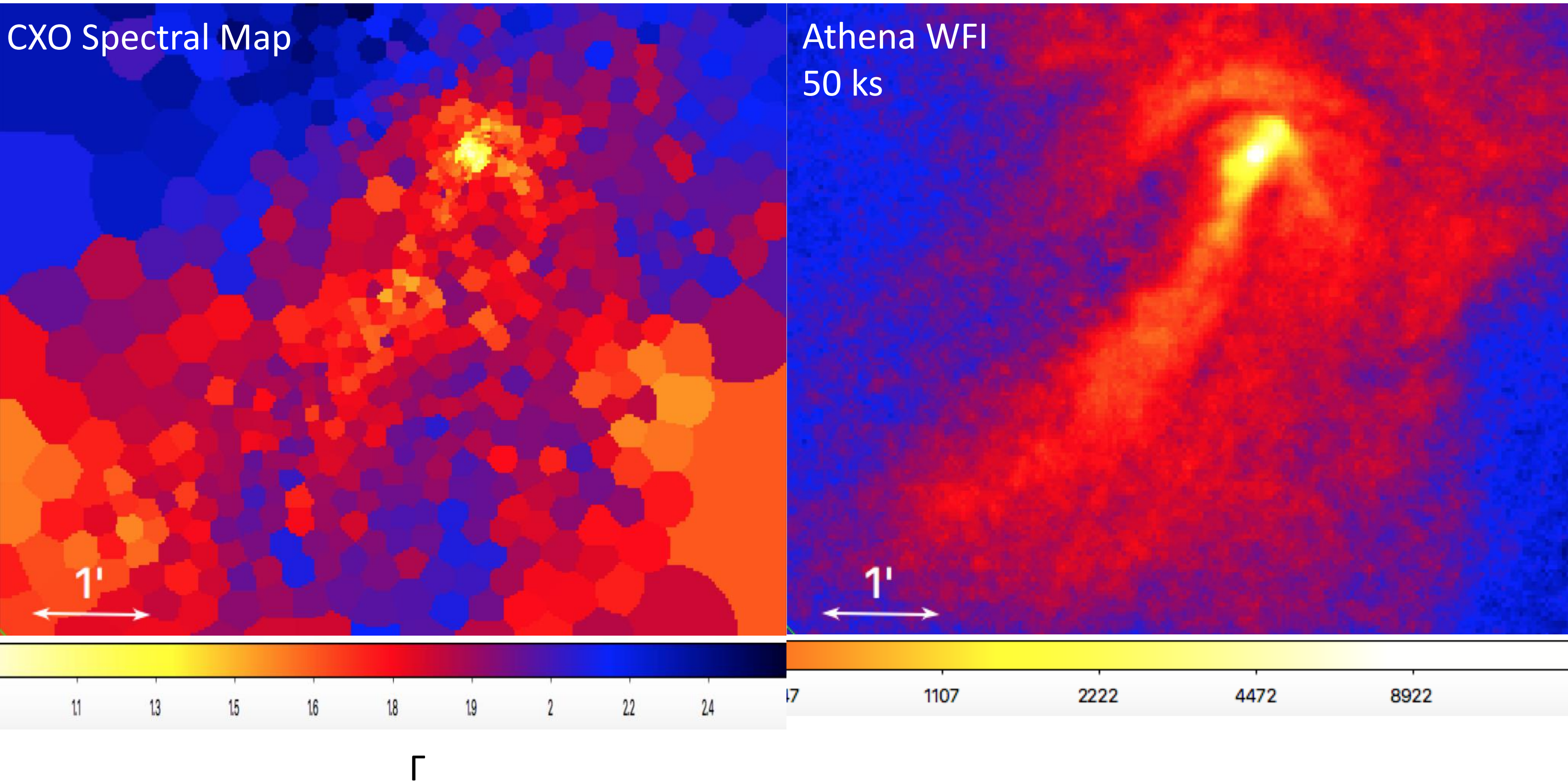


Counts/pixel

(CXO image binned to Athena pixel size for comparison)

Simulations: What We Can Expect

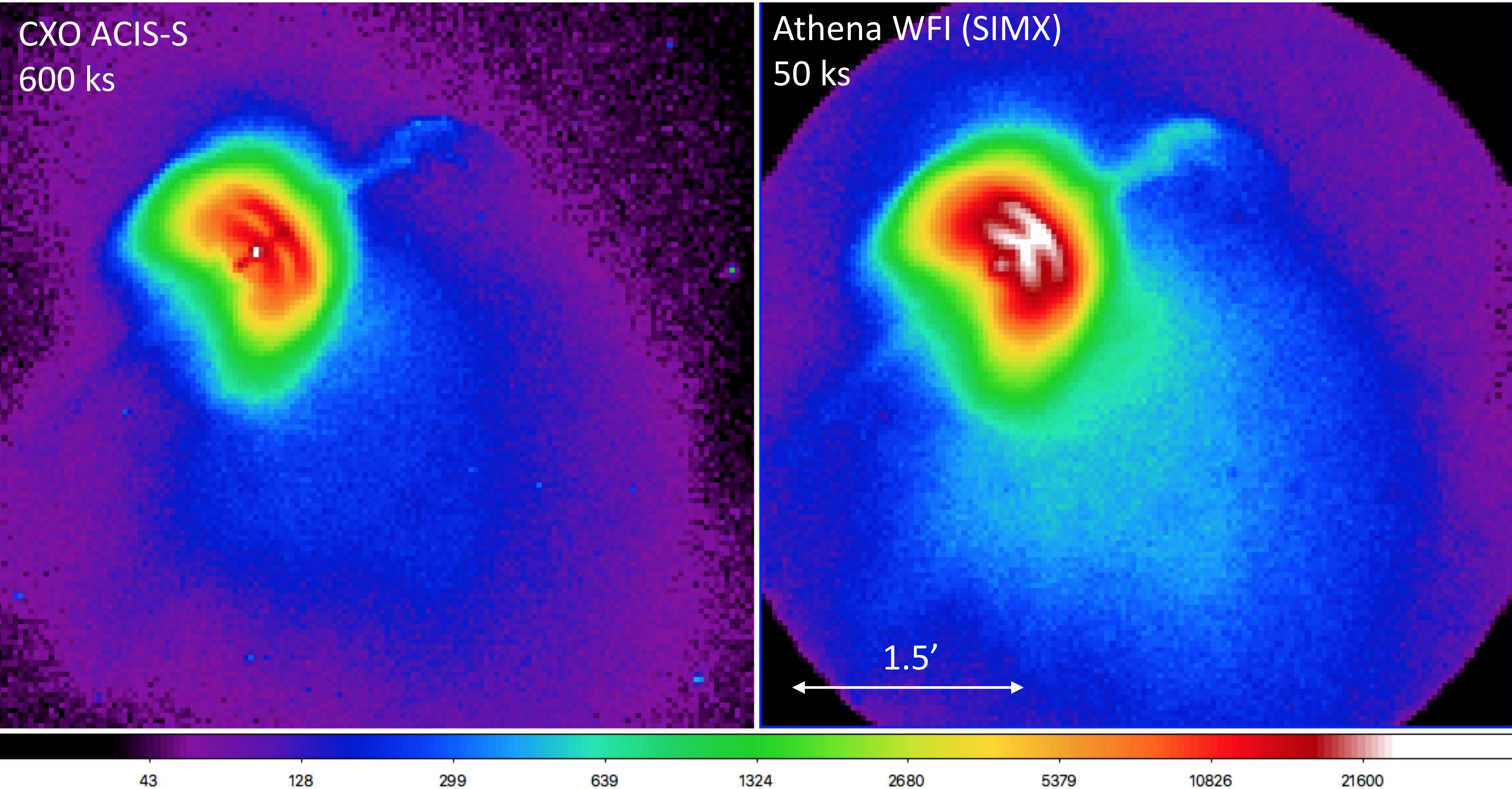
PSR B1509-58



Spectral mapping pipeline is currently being adapted to preview the resolution Athena spectral maps. The largest spatial bins will be a fraction the size of Chandra's

Simulations: What We Can Expect

Vela



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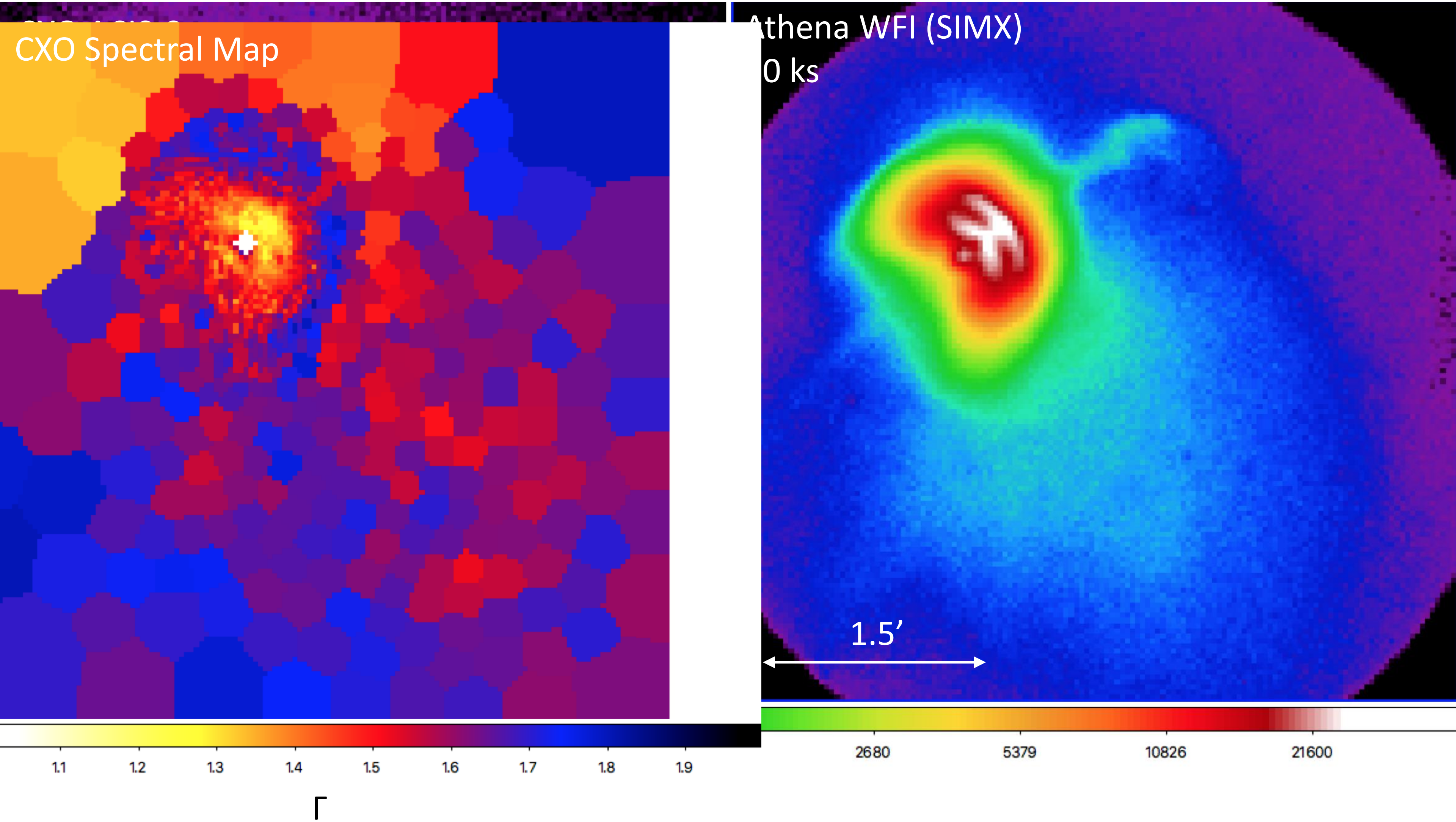
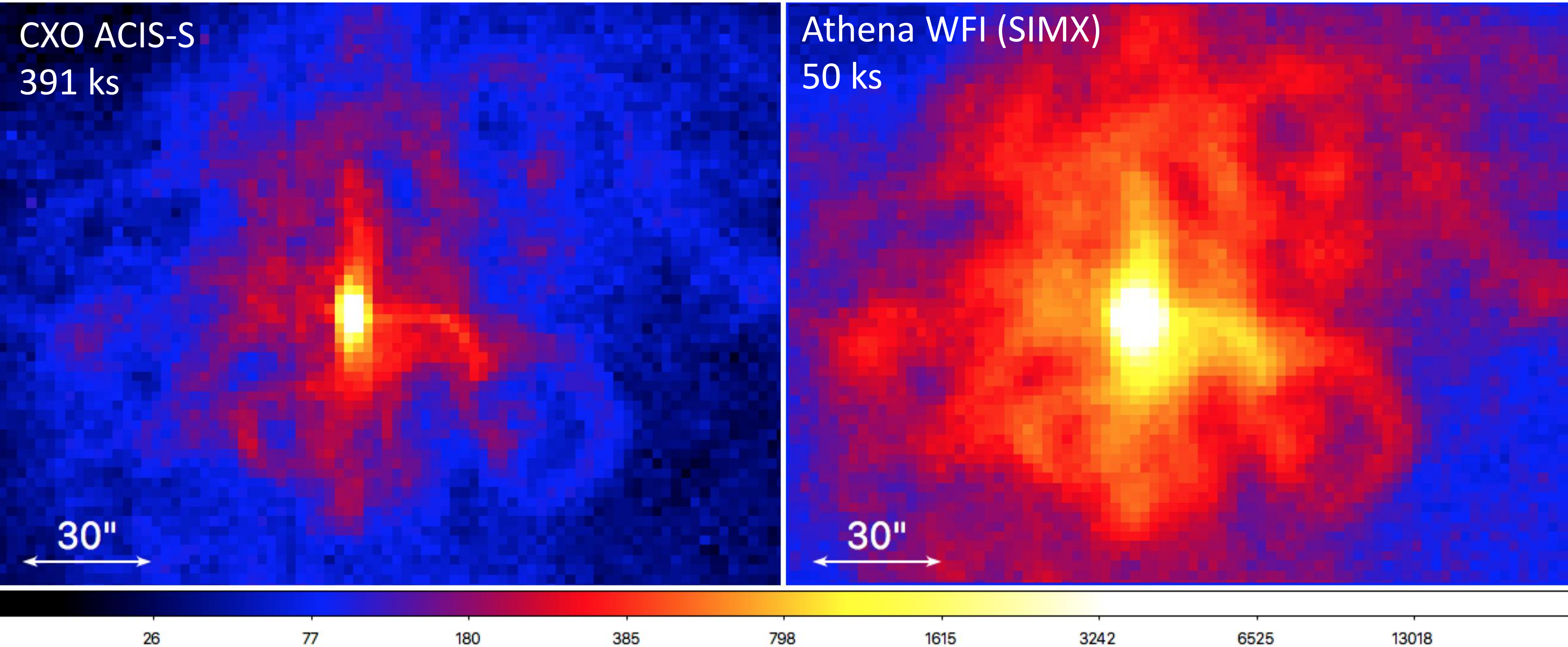
Simulations: What We Can Expect

Vela



Simulations: What We Can Expect

3C 58



Counts/pixel

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Simulations: What We Can Expect

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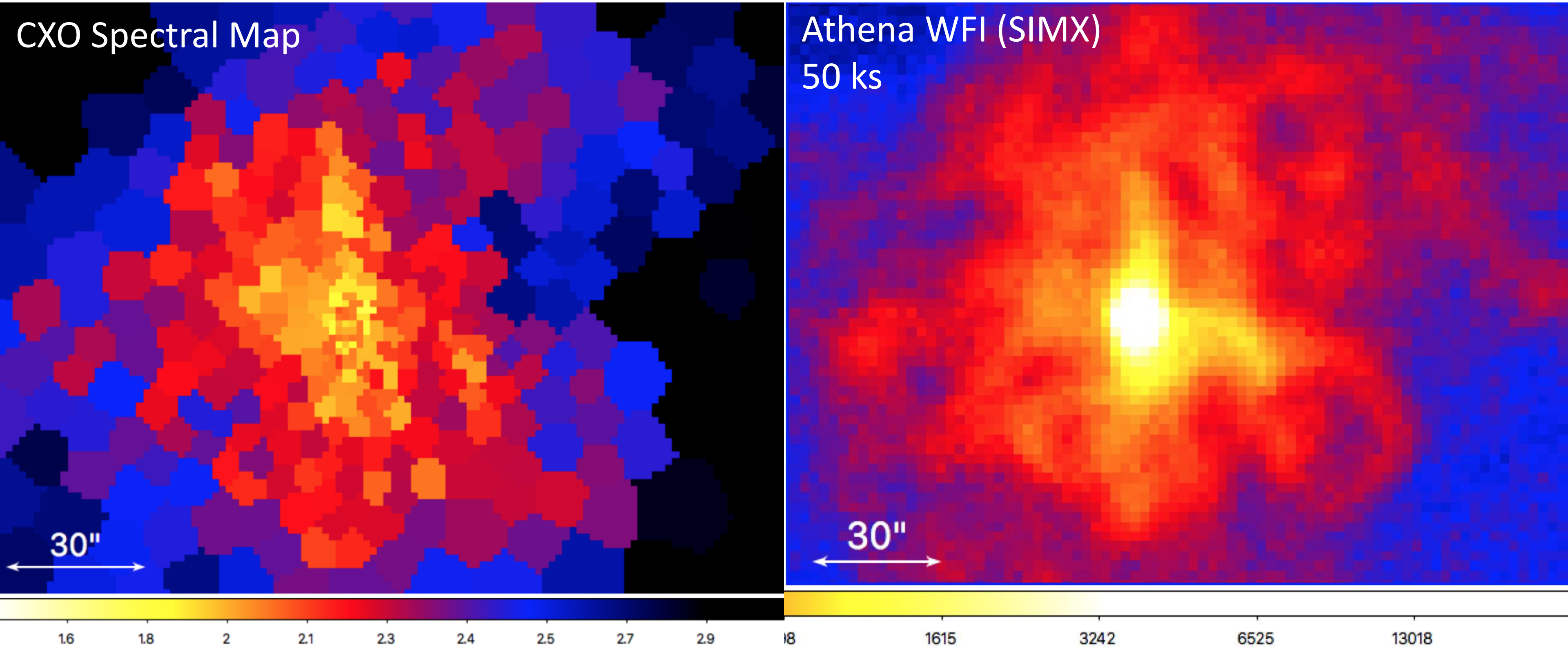
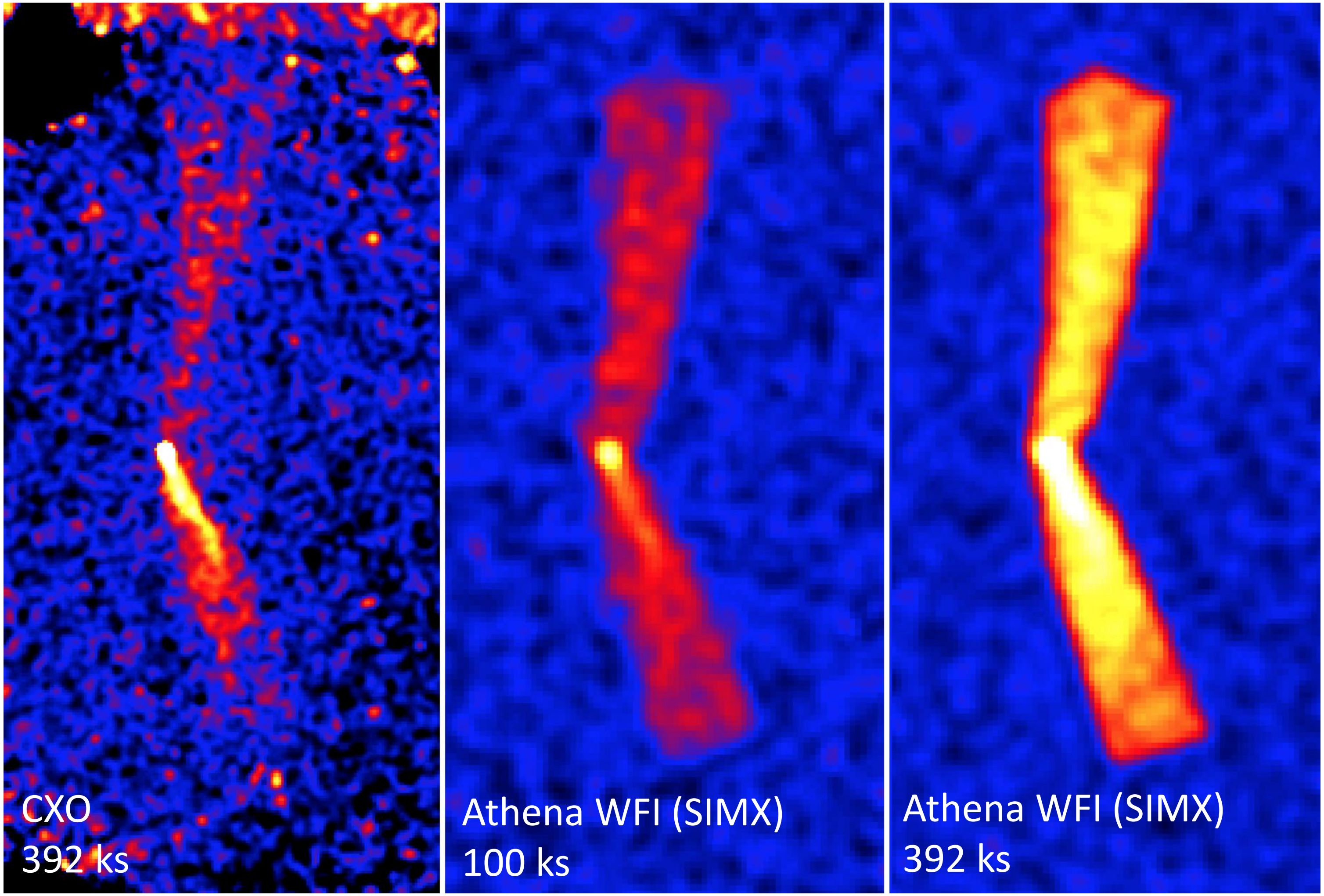


Γ

Simulations: What We Can Expect

J1509-5850



instrumental and cosmic X-ray backgrounds included

Caveat: simulations limited by what *Chandra* can currently detect/resolve. There could be fainter structures that only Athena can reveal.

Additional Benefits of Athena

- High time resolution of WFI will allow the study of both PWN and the pulsar in the same observation

  → enables collection of a large number of X-ray pulse profiles, further advancing out understanding of magnetospheric emission

- Athena will probe the poorly-known faint end of the pulsar X-ray luminosity function by detecting fainter pulsars in X-rays