Chandra's Detailed View of Supernova Remnants & the Hot ISM

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CCAPP

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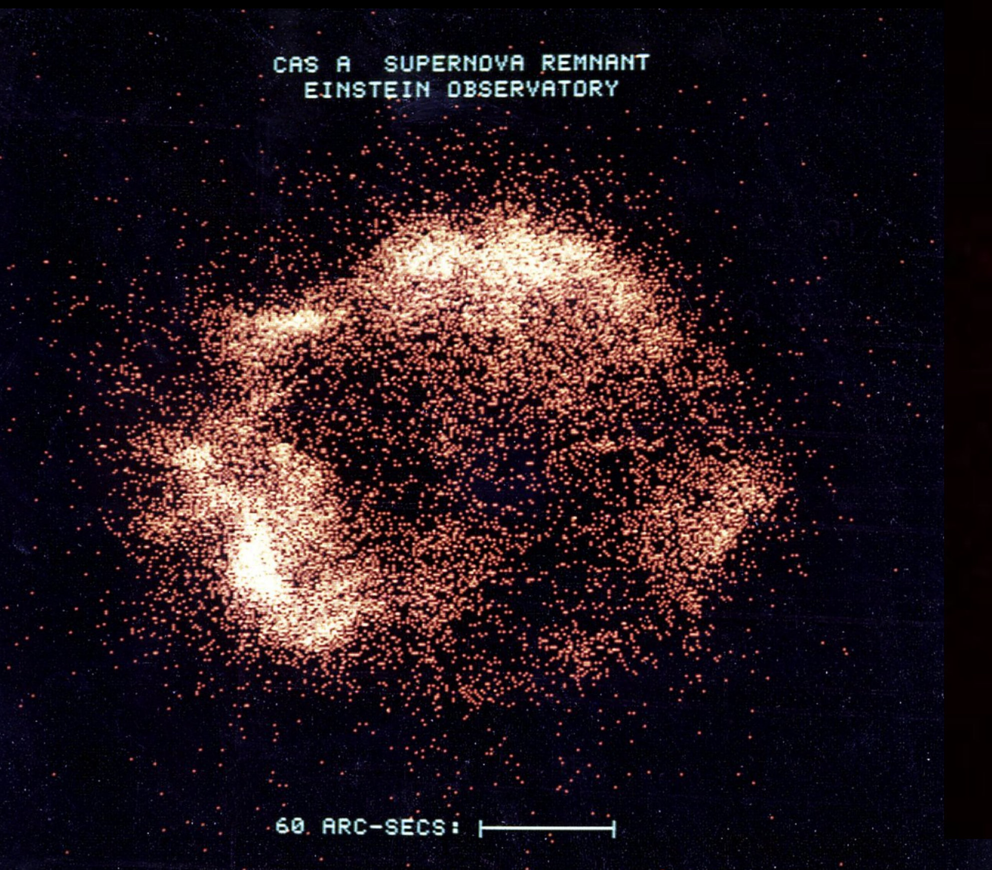
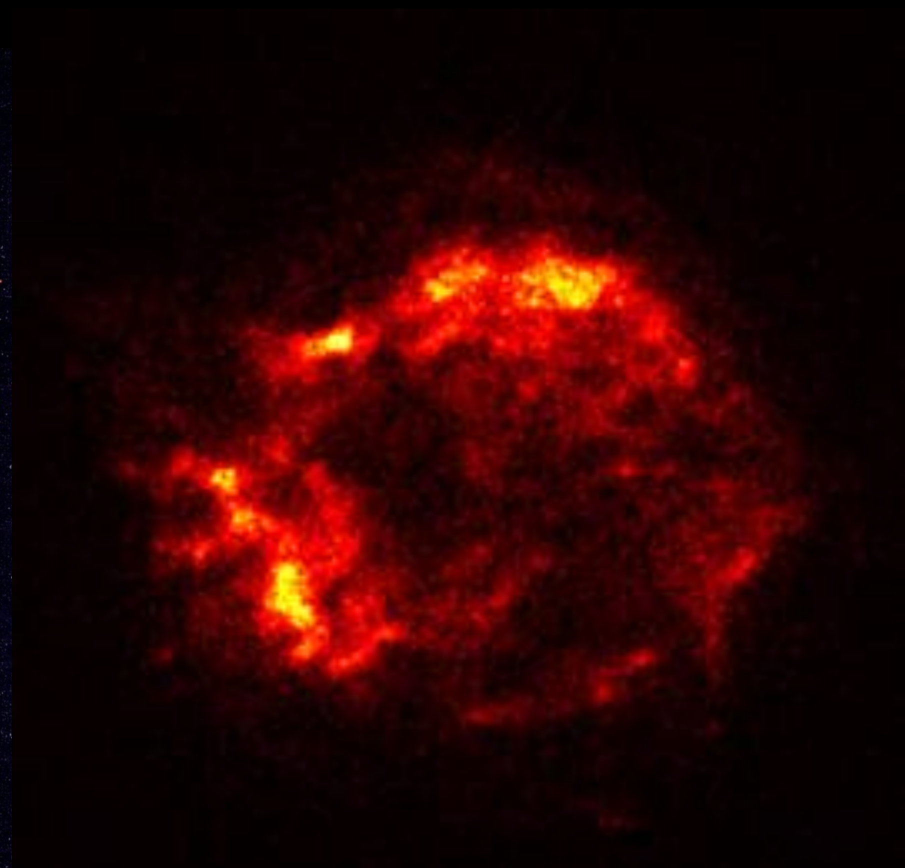
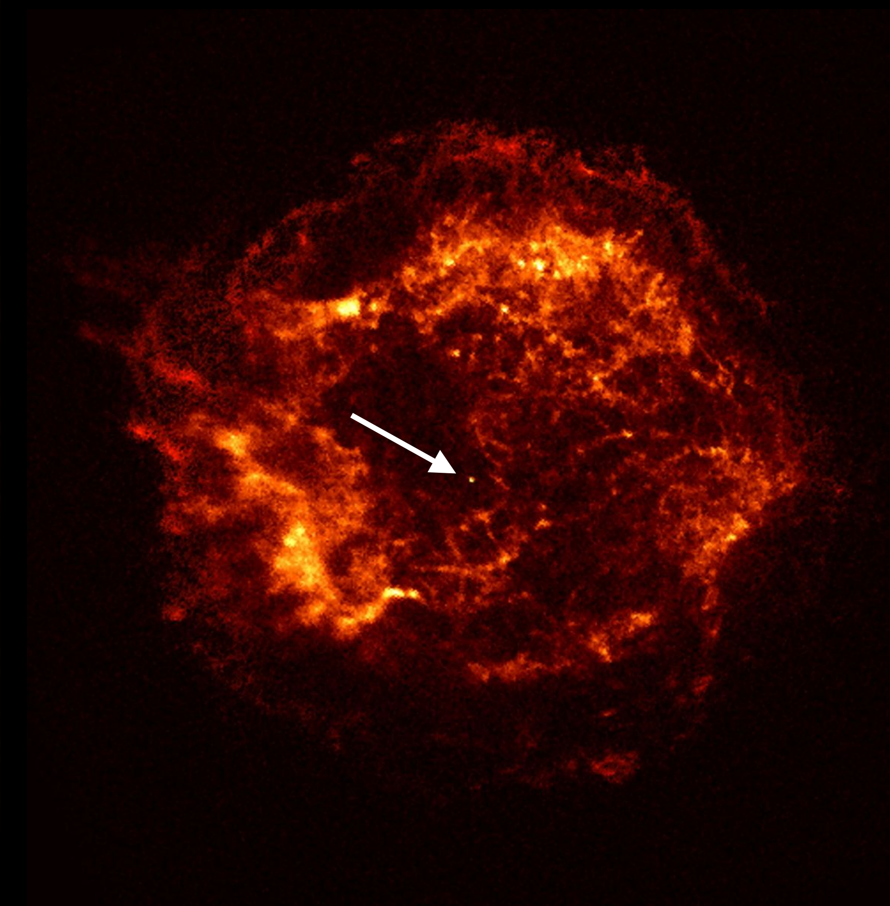
Improving our X-ray Vision



Einstein (1980)

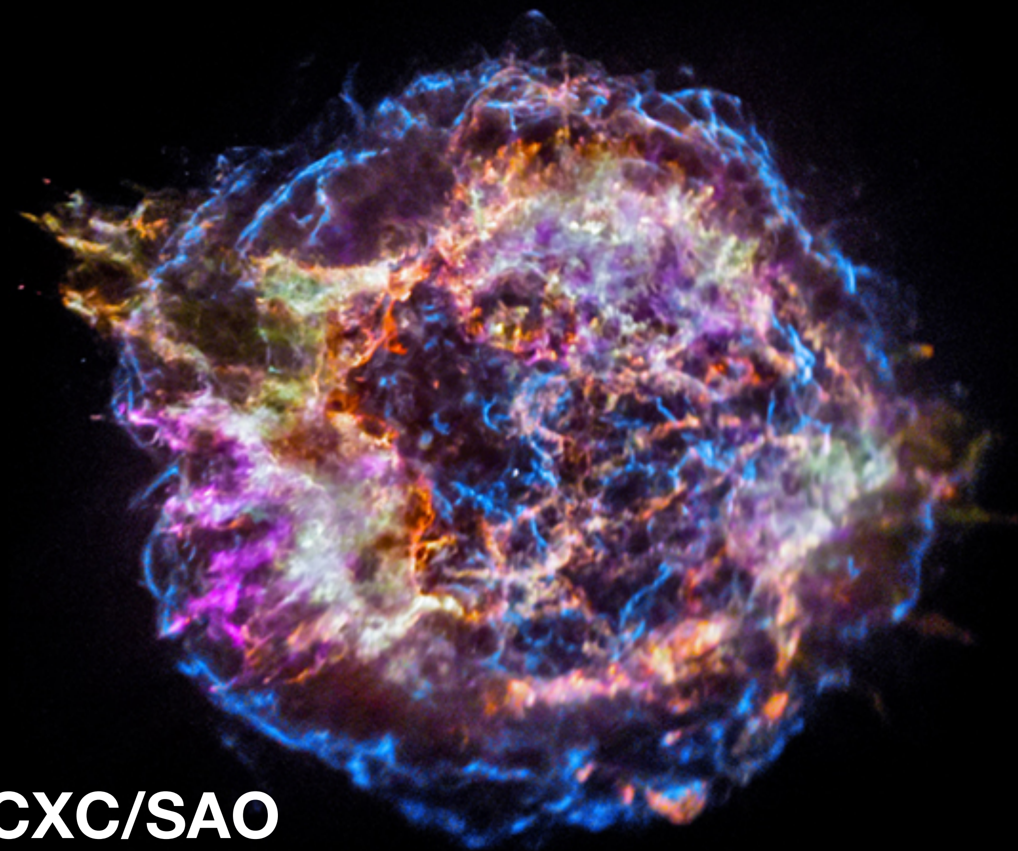


ROSAT HRI
(1995)

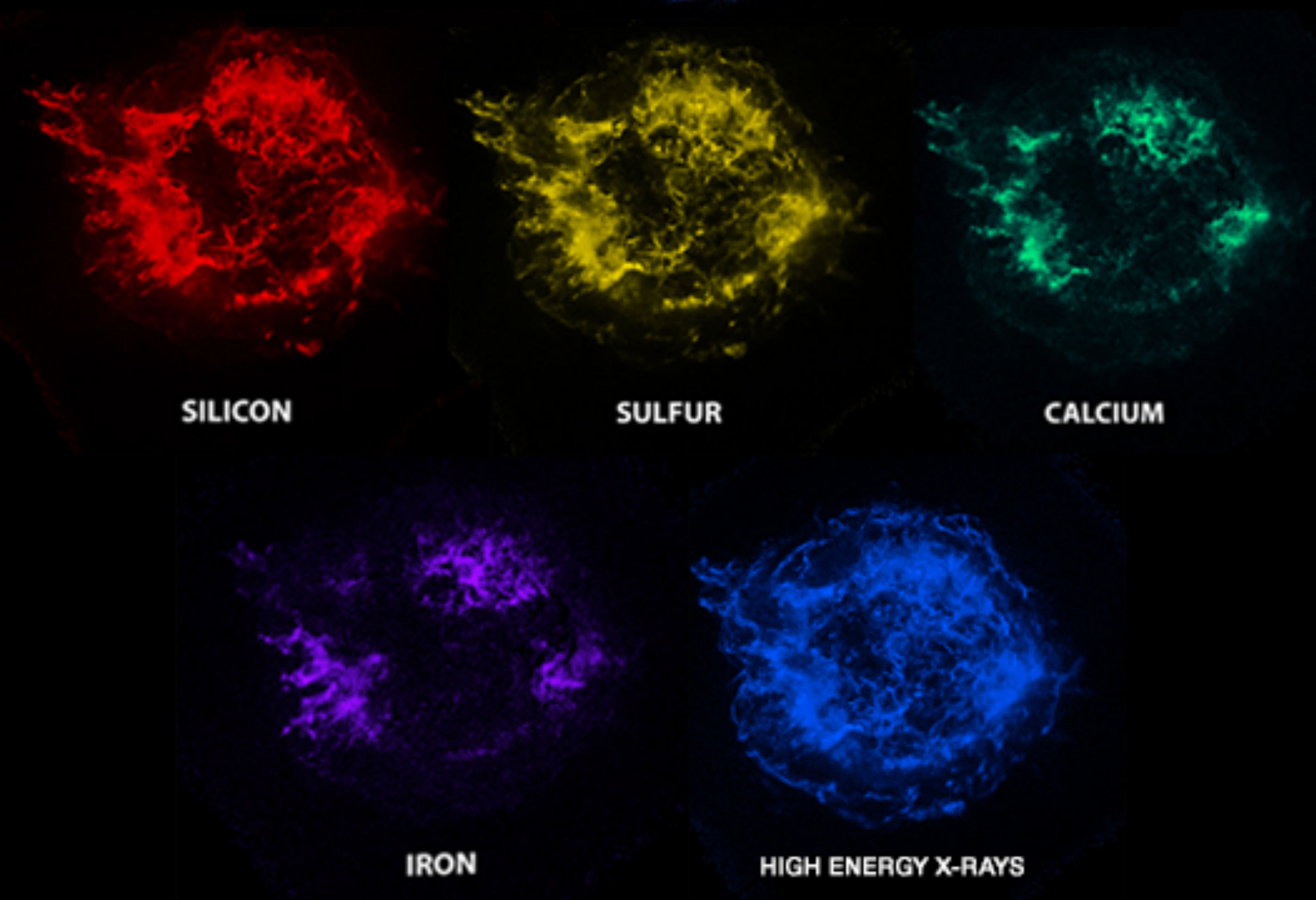


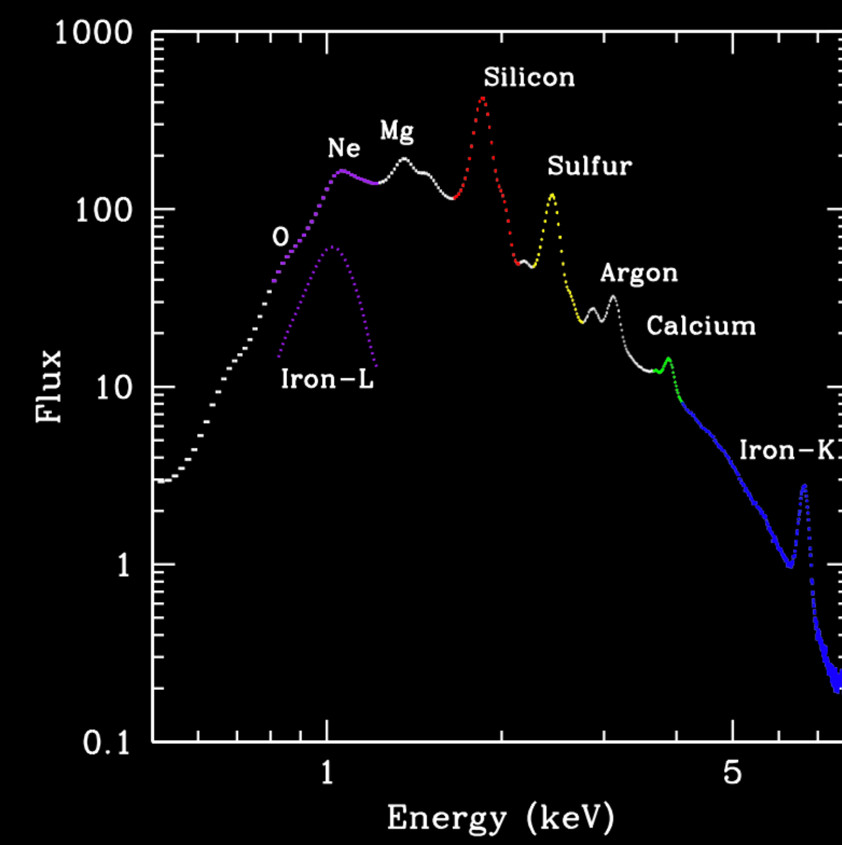
Chandra (1999)

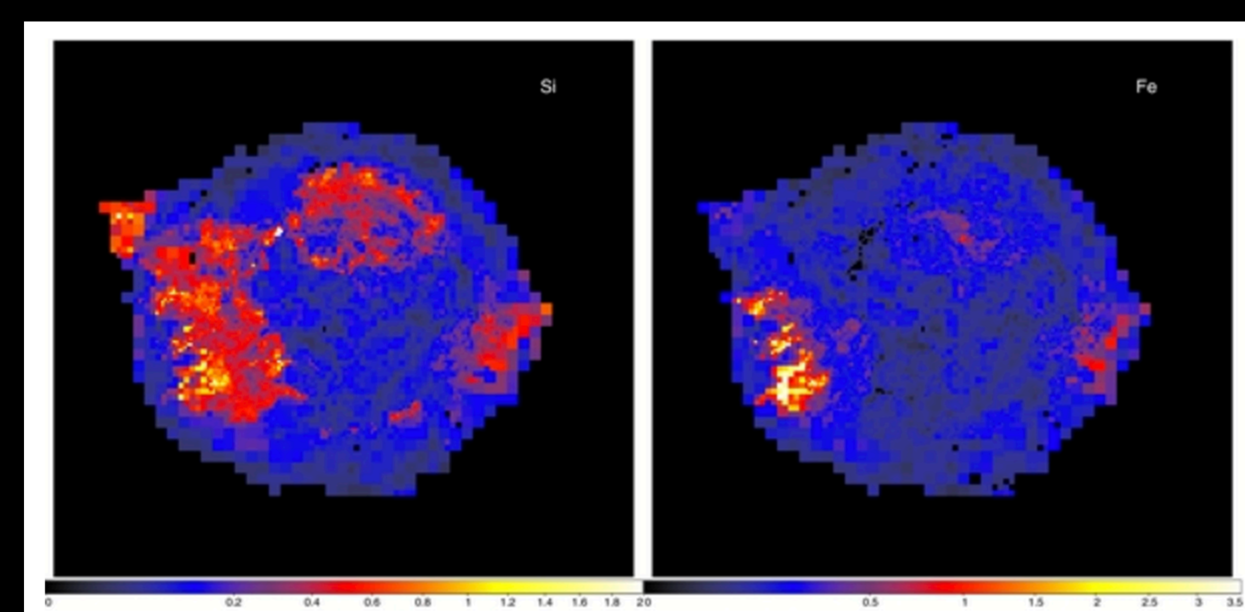
Spectro-Imaging



NASA/CXC/SAO

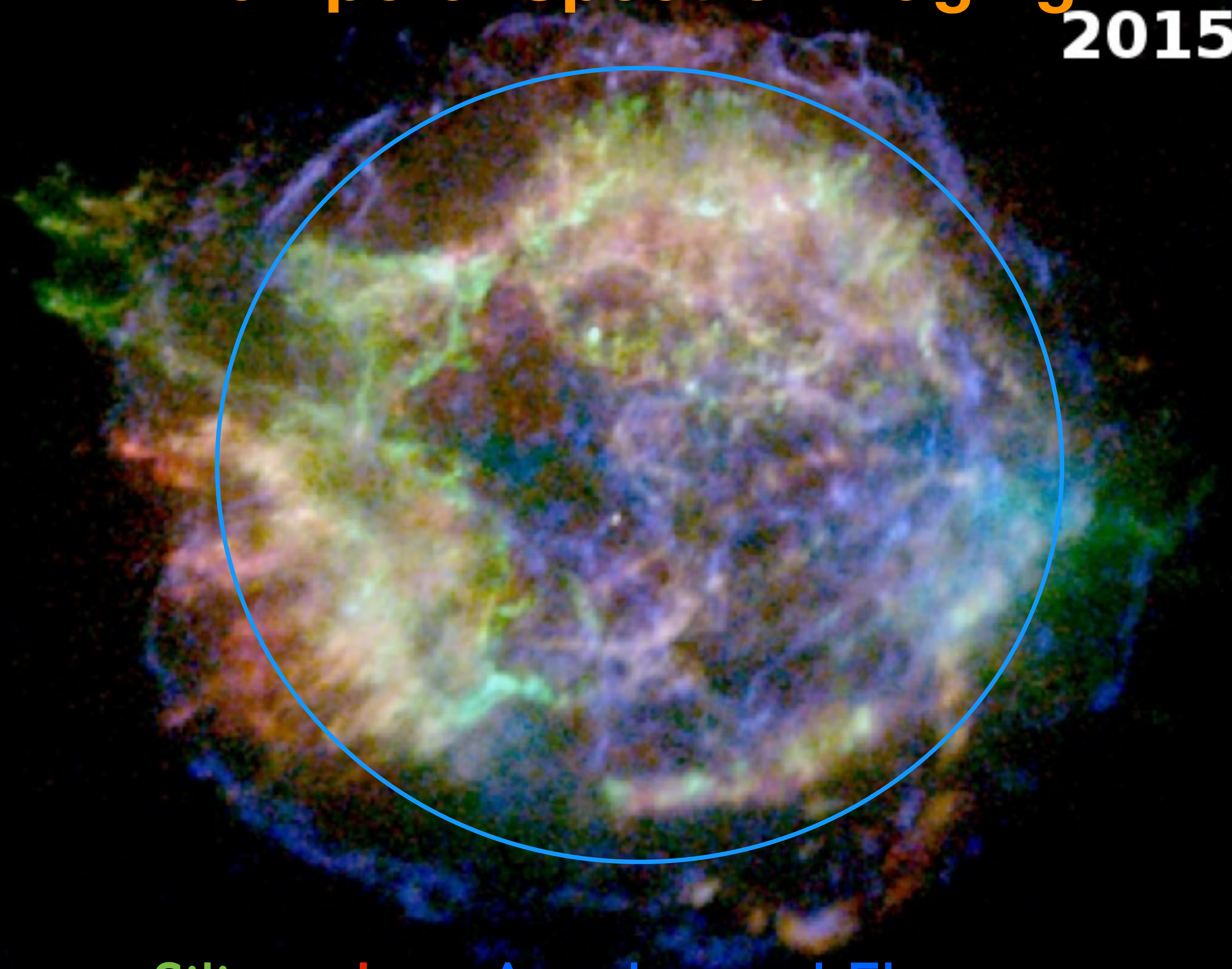






Hwang & Laming 2012

Temporal Spectro-Imaging



Adapted from NASA/CXC/SAO/D. Patnaude

Silicon Iron Accelerated Electrons

Tying SNRs to Their Explosions

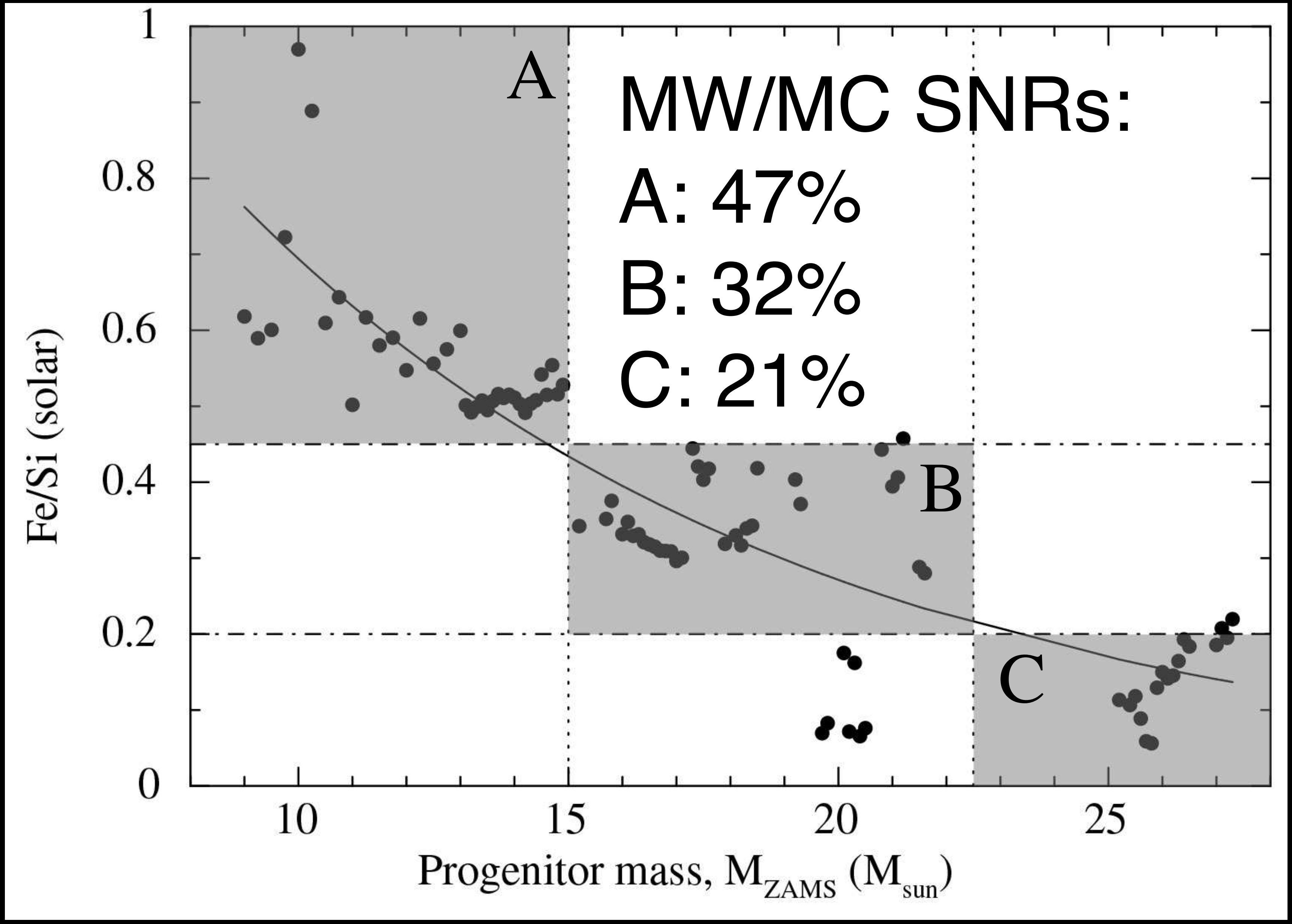
SNe are typed based on light weeks after an explosion.

Ways to classify explosions of SNRs (Type Ia versus core-collapse):

1. Identification of a central neutron star
2. Light echoes (Rest+2005, 2008; Krause+2008)
3. Metal abundances (e.g., O/Fe)
4. Environment (e.g., nearby molecular clouds, CSM)
5. Nearby stellar populations (young or old stars)
6. X-ray morphologies (Type Ia SNRs are more symmetric; Lopez+2009b, 2011)
7. Fe line centroid energy (Type Ia SNRs have lower Fe ionization state; Yamaguchi+2014)

Tying SNRs to Progenitors Using Nucleosynthesis

Nucleosynthetic yields of CC SNe depend on progenitor mass (e.g., Sukhbold et al. 2016).



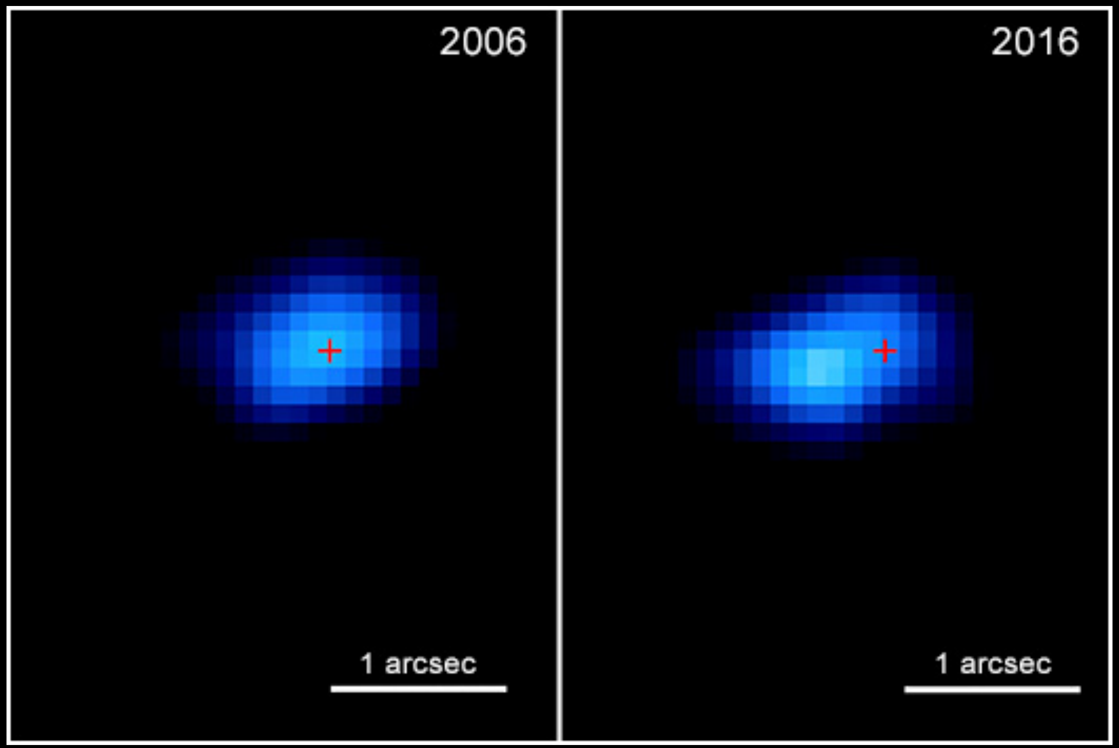
Katsuda et al. 2018b, using models of Sukhbold et al. 2016

Neutron Star Proper Motions

Typical velocities of neutron stars are ~400 km/s, corresponding to proper motions of 0.03”/yr (0.45”/15 yrs) at a distance of 3 kpc.

After 25 years, Chandra has sufficient spatial resolution to map changes in neutron star positions.

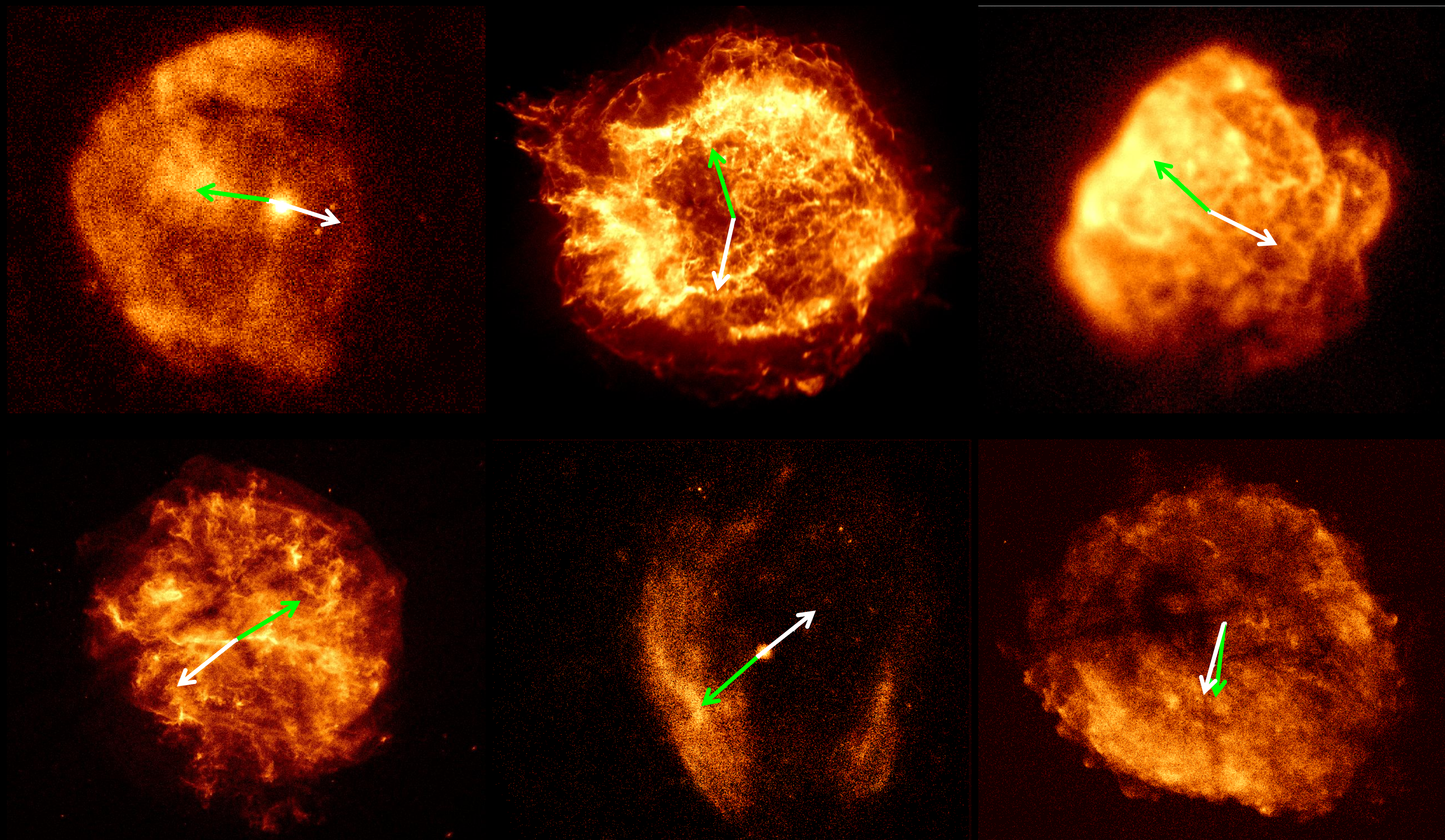
~20 neutron stars have velocity measurements within SNRs, with direct proper motion measurements (~7) or measuring distances from explosion sites to current NS position (~13)



G292.0+1.8:
612+-152 km/s

X. Long+ 2022

NS Kicks in Supernova Remnants

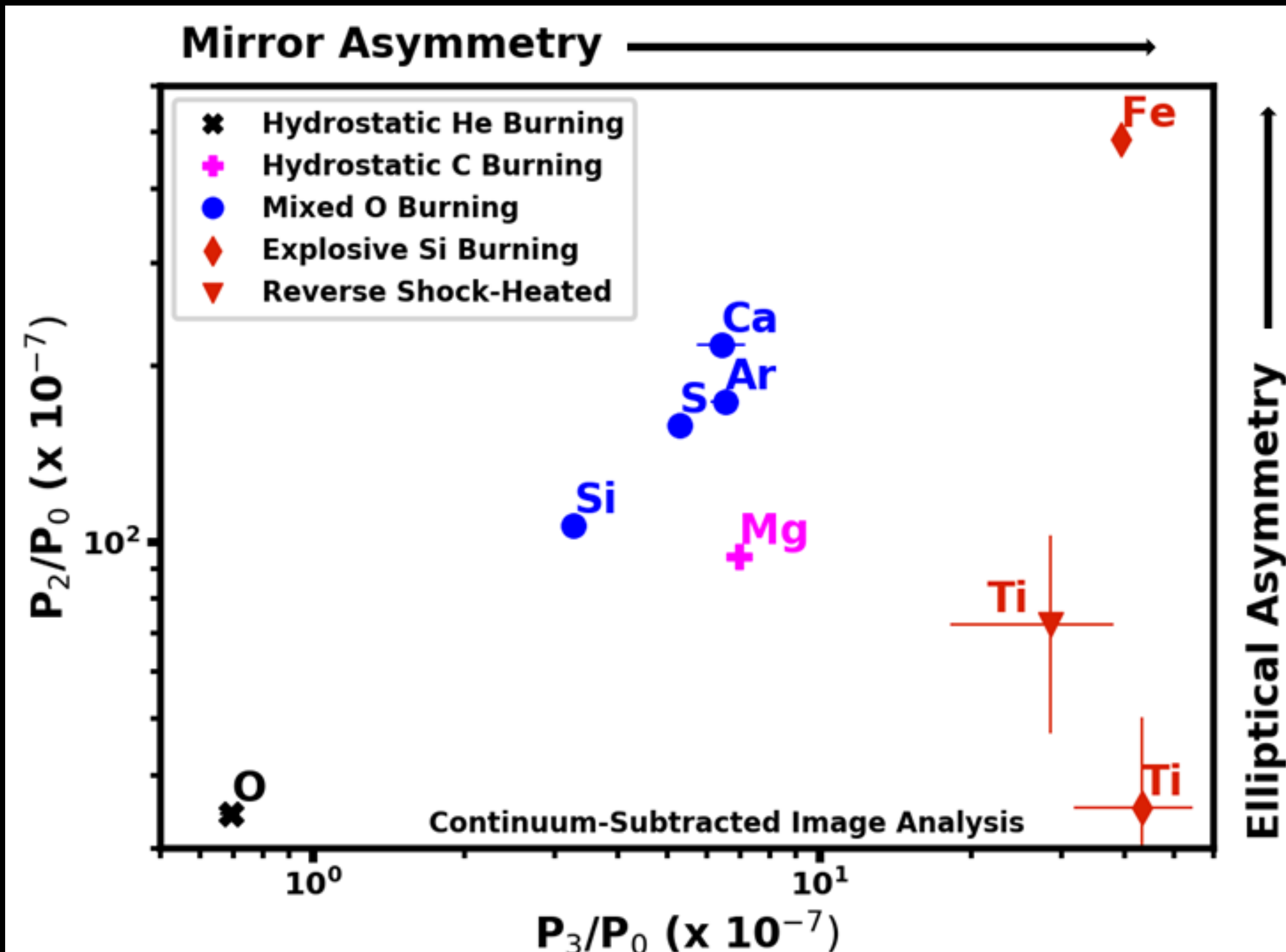


Holland-Ashford+ 2017

Neutron Star direction; X-ray Emission

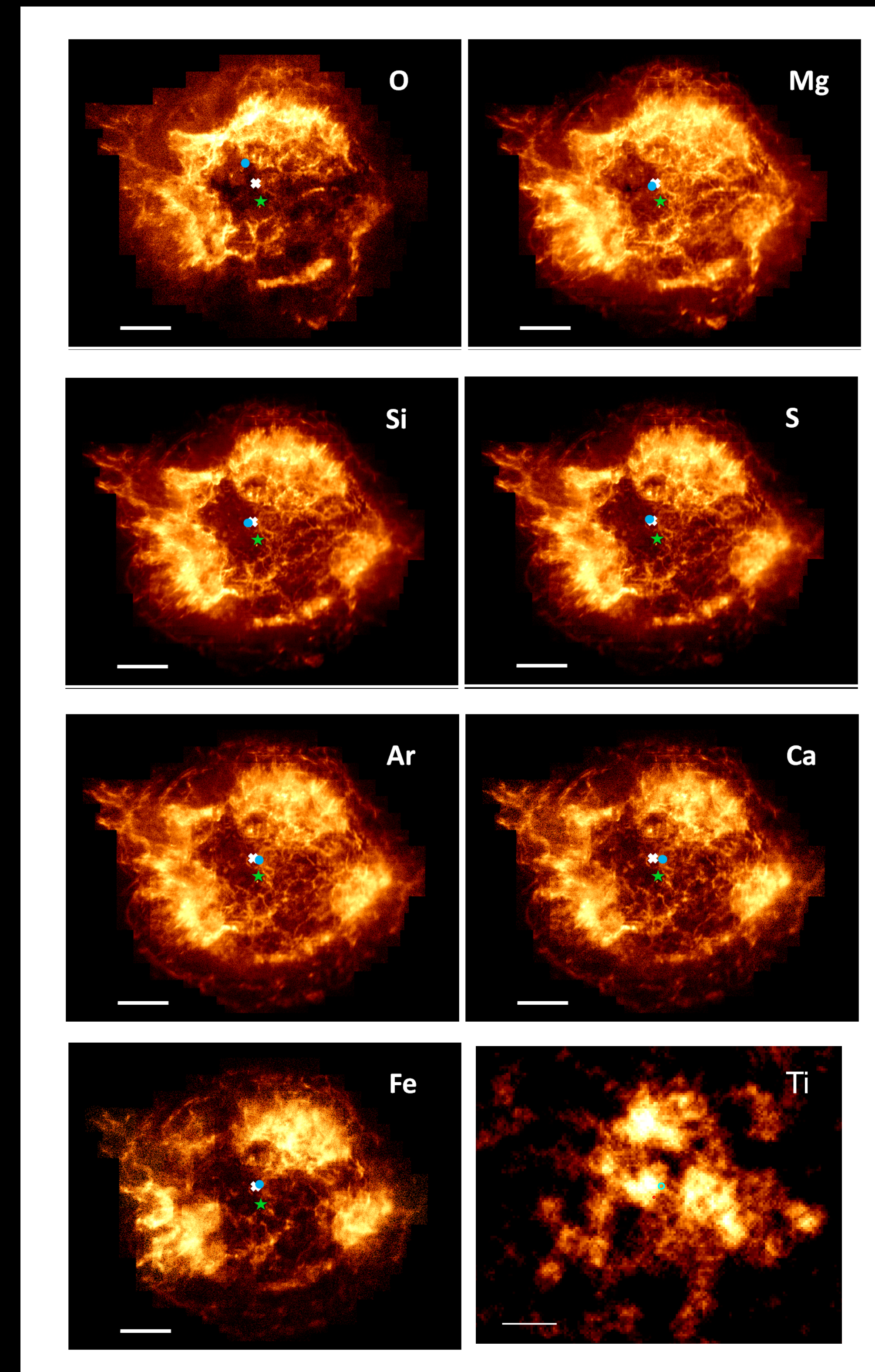
Neutron stars are ‘kicked’ by the SN explosion opposite to the bulk of the X-ray emission / ejecta, consistent with NS kicks originating from hydrodynamical instabilities

Elemental Spatial Distributions Vary



Holland-Ashford, Lopez, & Auchettl 2020

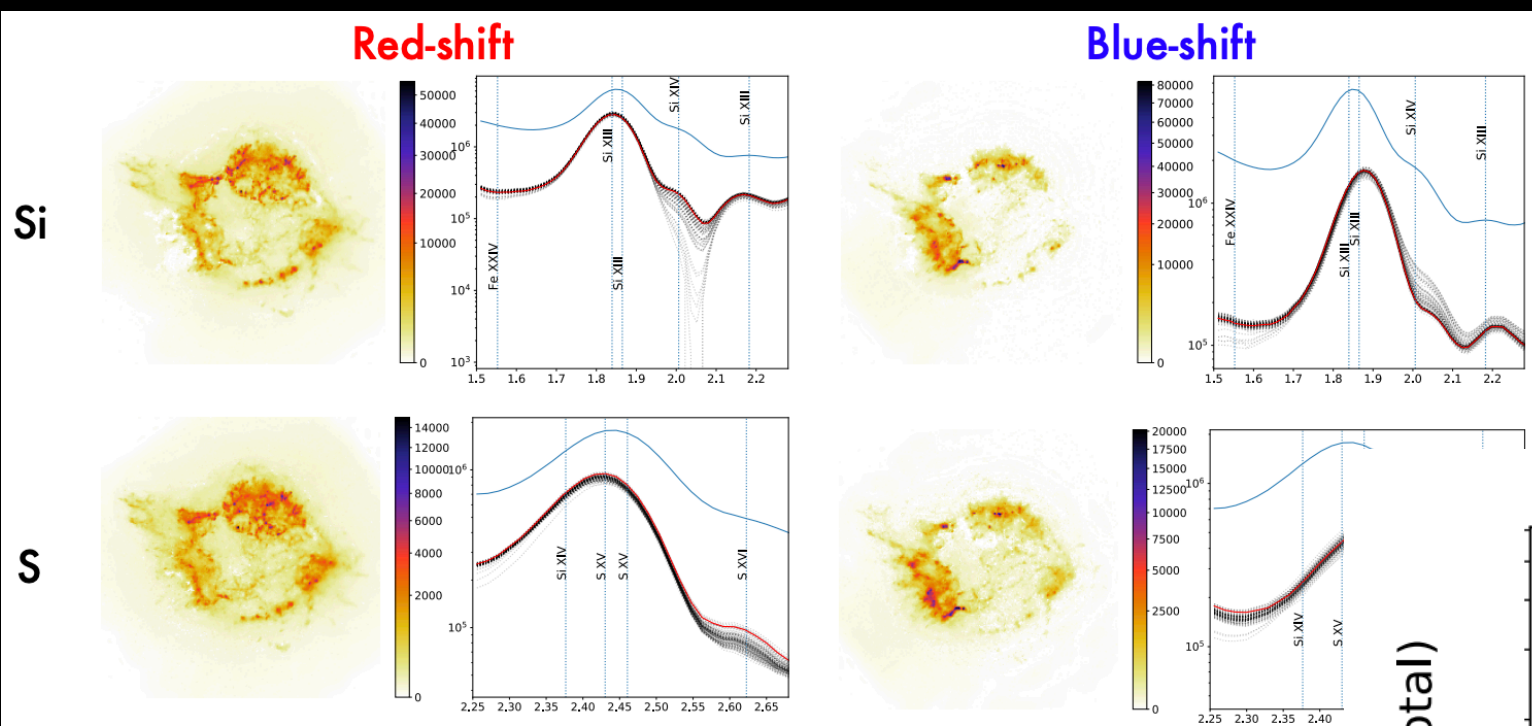
Burning processes from Woosley, Heger, Weaver 2002; Curtis+2019

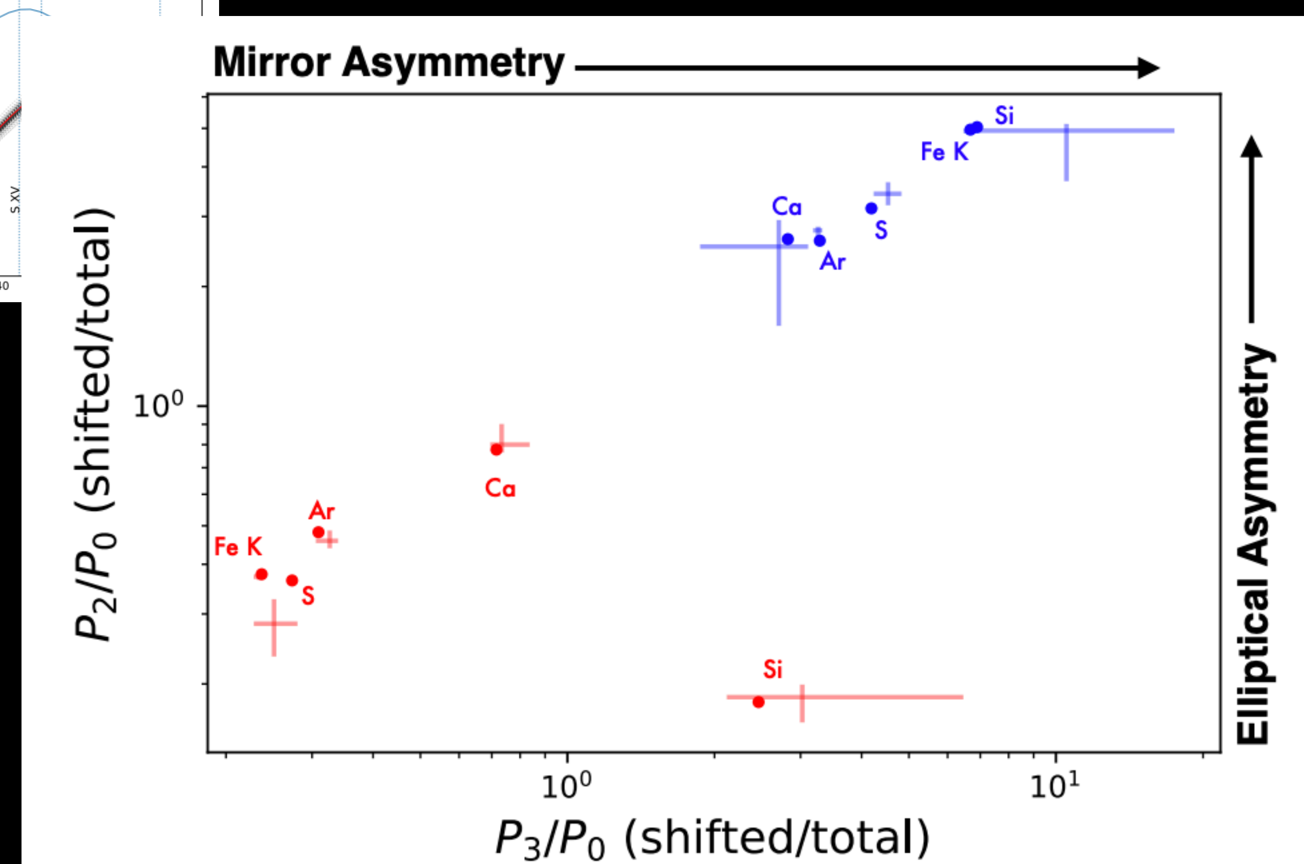


NS motion is more directly opposed to heavier elements (Ar, Ca, Fe, Ti) than lighter elements (O, Mg, Si)

2D to 3D with Chandra CCD Data

Use techniques (general morphological component analysis) to separate the red- and blue shifted components in the Chandra X-ray images of Cas A





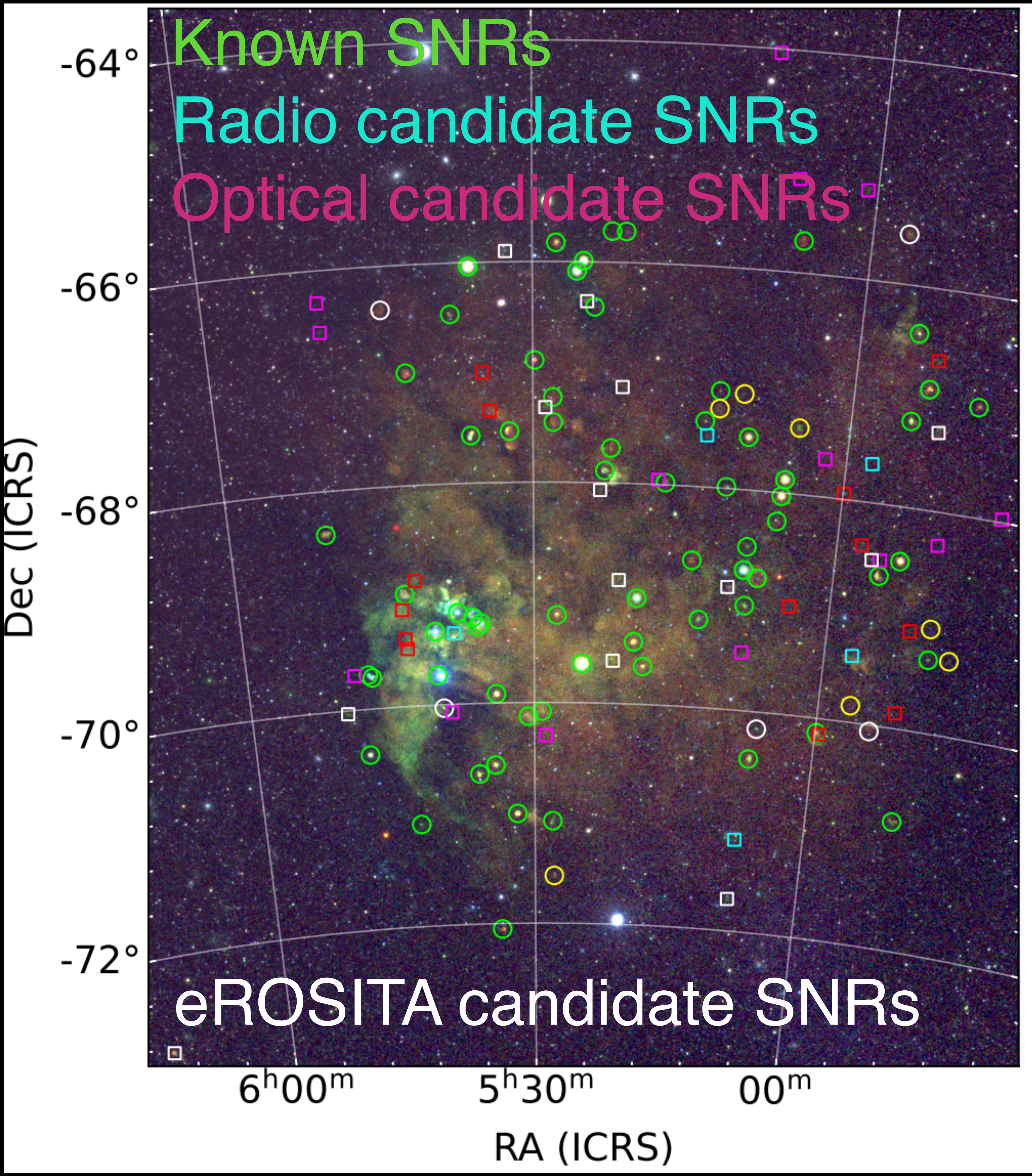
Redshifted ejecta is more symmetric/circular and dominates the emission

Picquenot+2021

Future

Follow-up Chandra observations to get expansion velocities, neutron star kicks, variability of emission to probe shock heating and particle acceleration

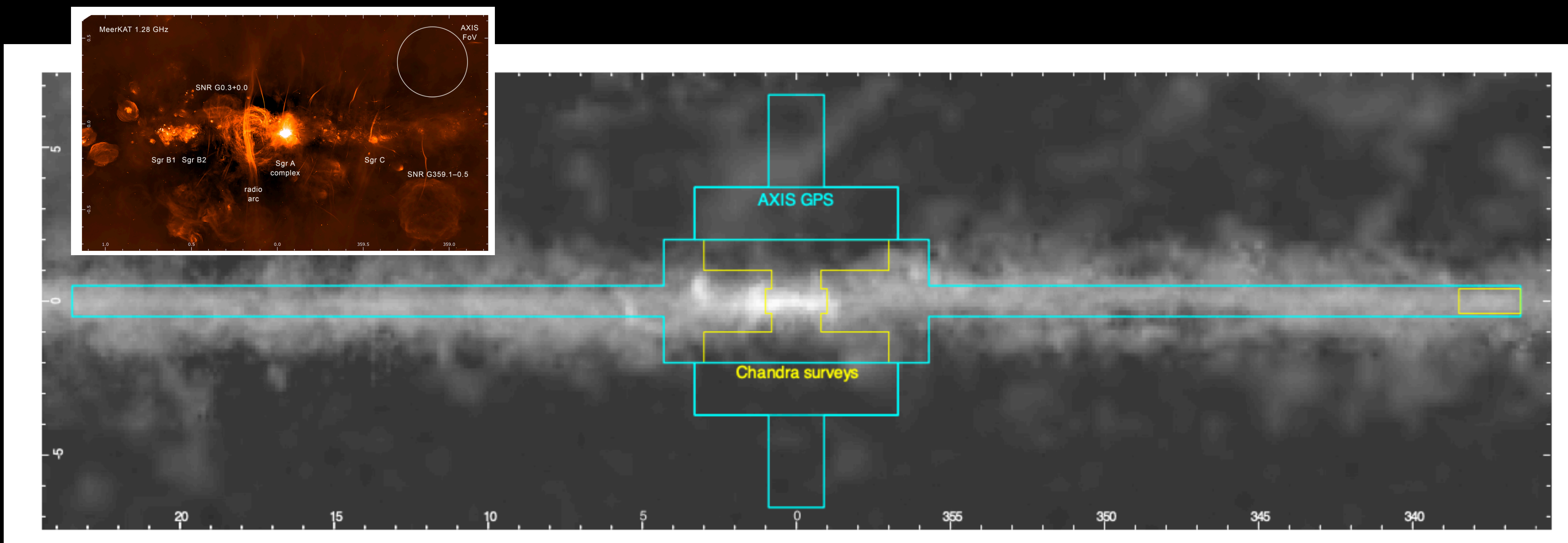
New Chandra observations of SNRs discovered with eROSITA or at other wavelengths

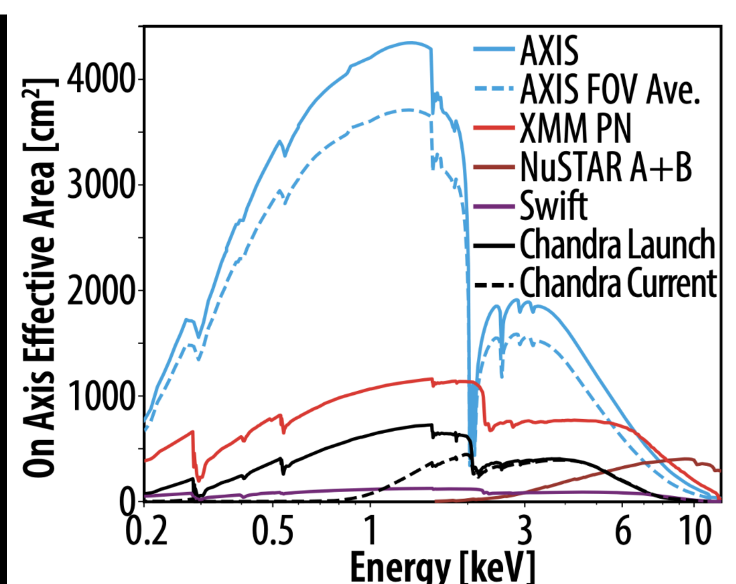


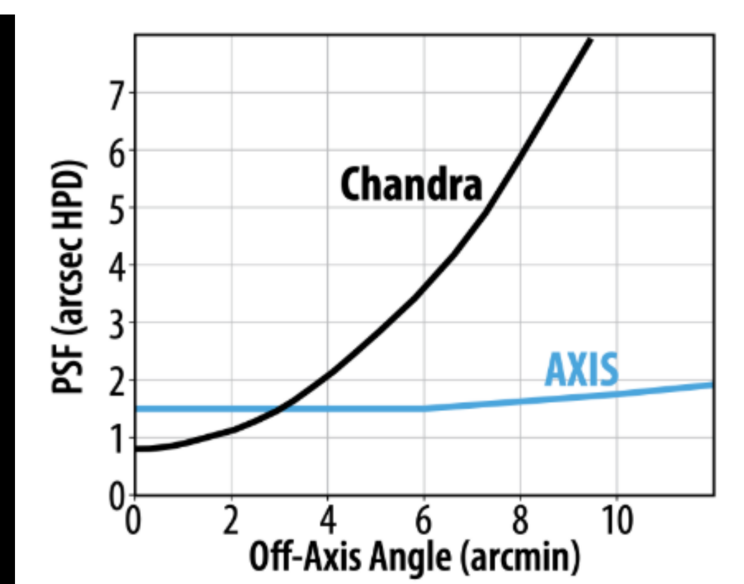
Zangrandi+24

Future with AXIS

AXIS Galactic Plane Survey (cyan) will include dozens of known SNRs. Will discover new neutron stars, measure proper motions/expansions, get chemical abundances







Safi-Harb+24

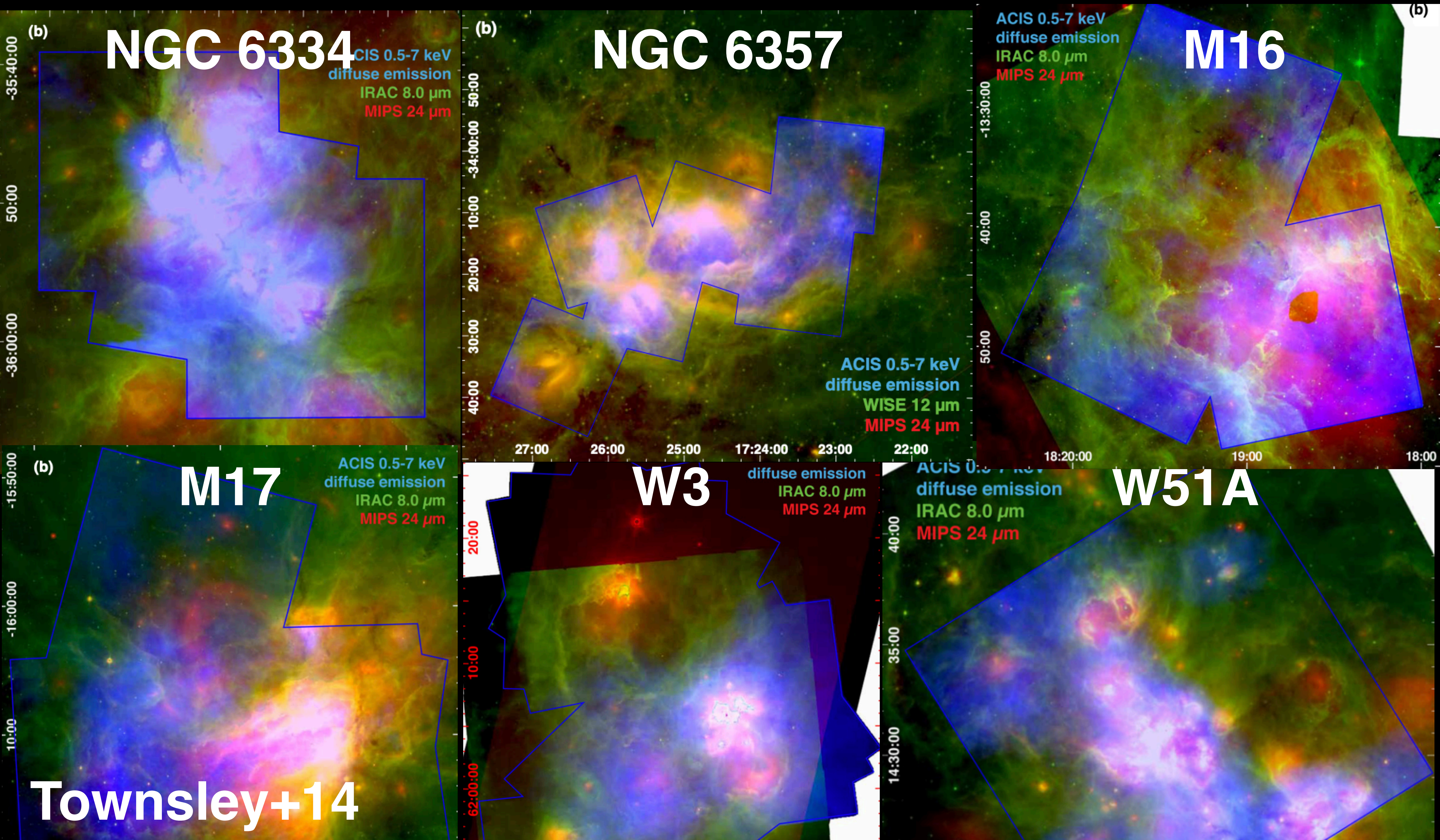
Conclusions

Chandra has given detailed view of SNRs in Milky Way and nearby galaxies, probing metal distribution, dynamics, nucleosynthesis, and their connection to progenitors and neutron star kicks.

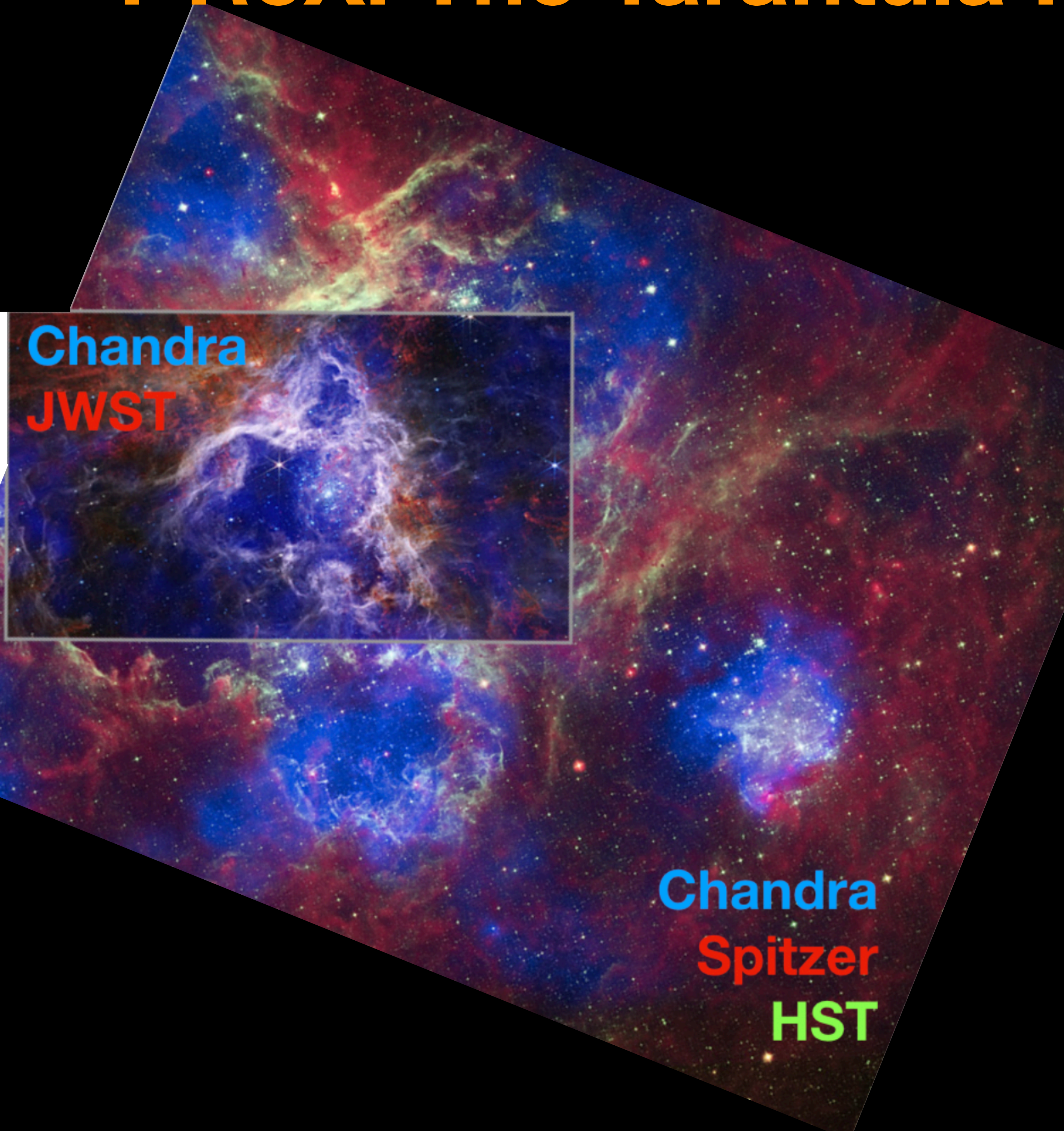
Future Chandra studies are critical for longer dynamics baselines and to probe explosions & progenitors of newly-discovered SNRs. AXIS will offer even more detail on larger populations of SNRs.

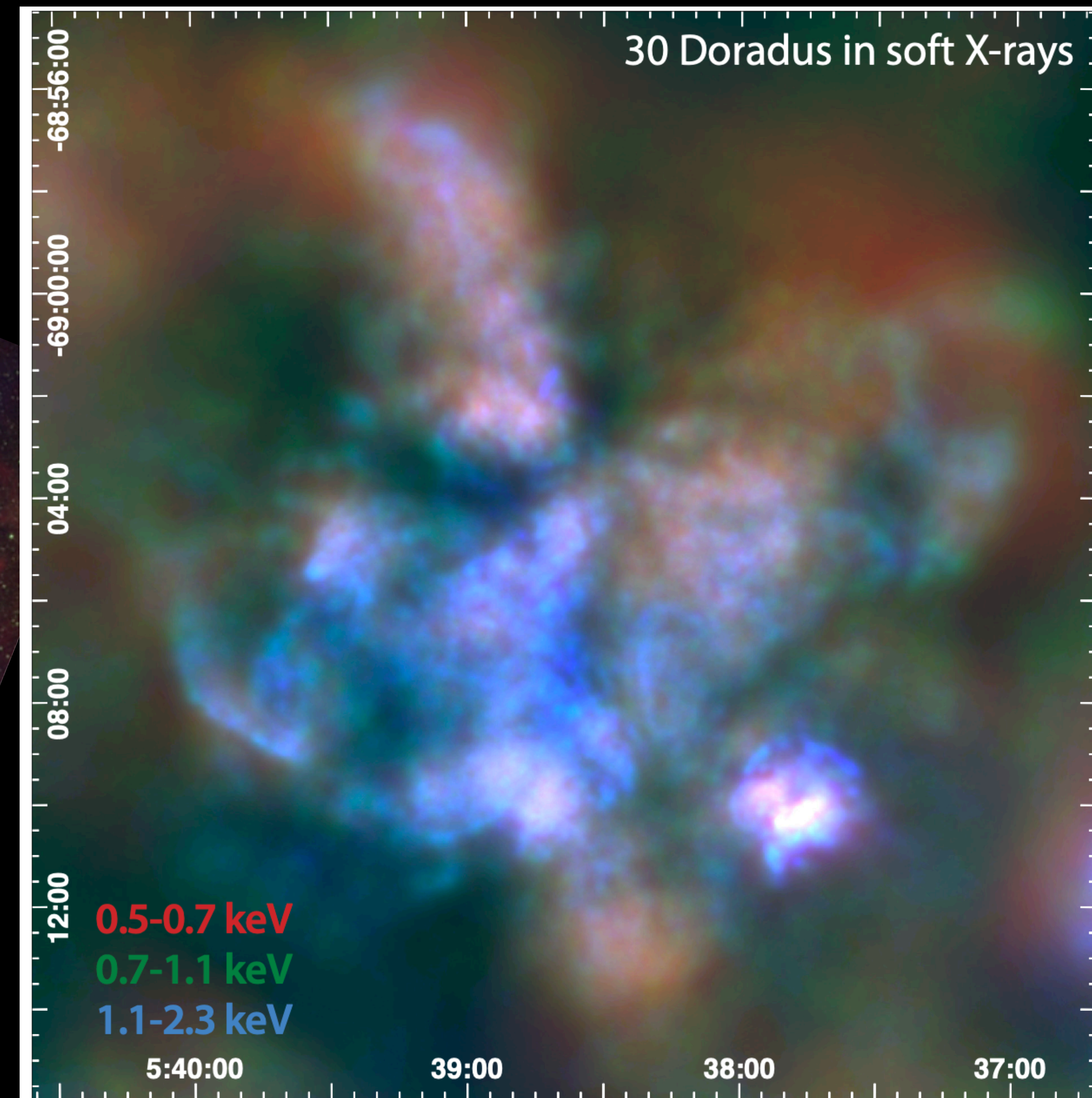
Galactic Star-Forming Regions

Chandra has revealed diffuse, shock-heated gas from stellar winds & SNe in Milky Way and MC HII regions.



T-ReX: The Tarantula Revealed in X-rays

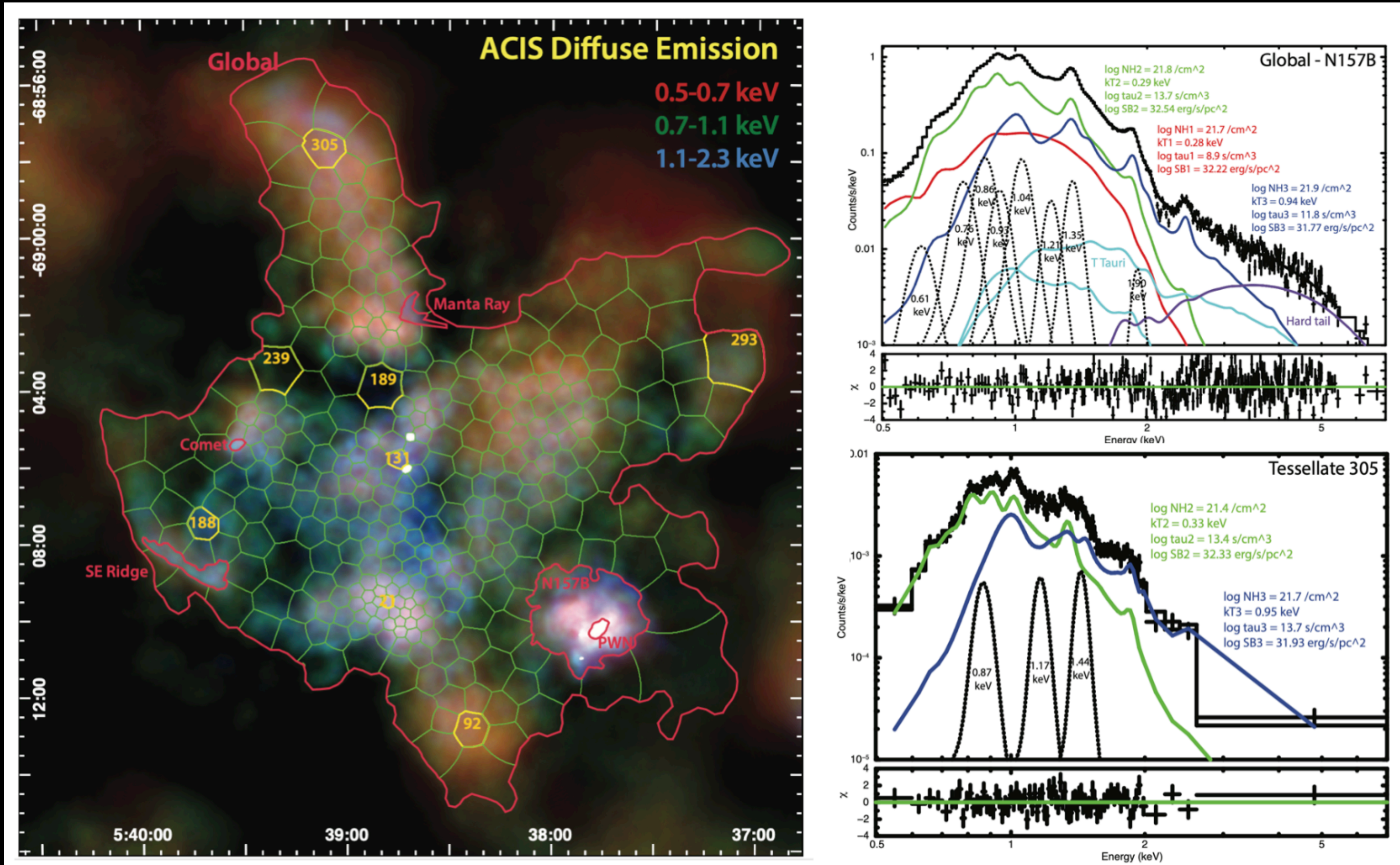




Townsley, Broos, & Povich+24

Chandra observed 30 Doradus for 2 Ms, revealing detailed view of complex hot gas distribution.

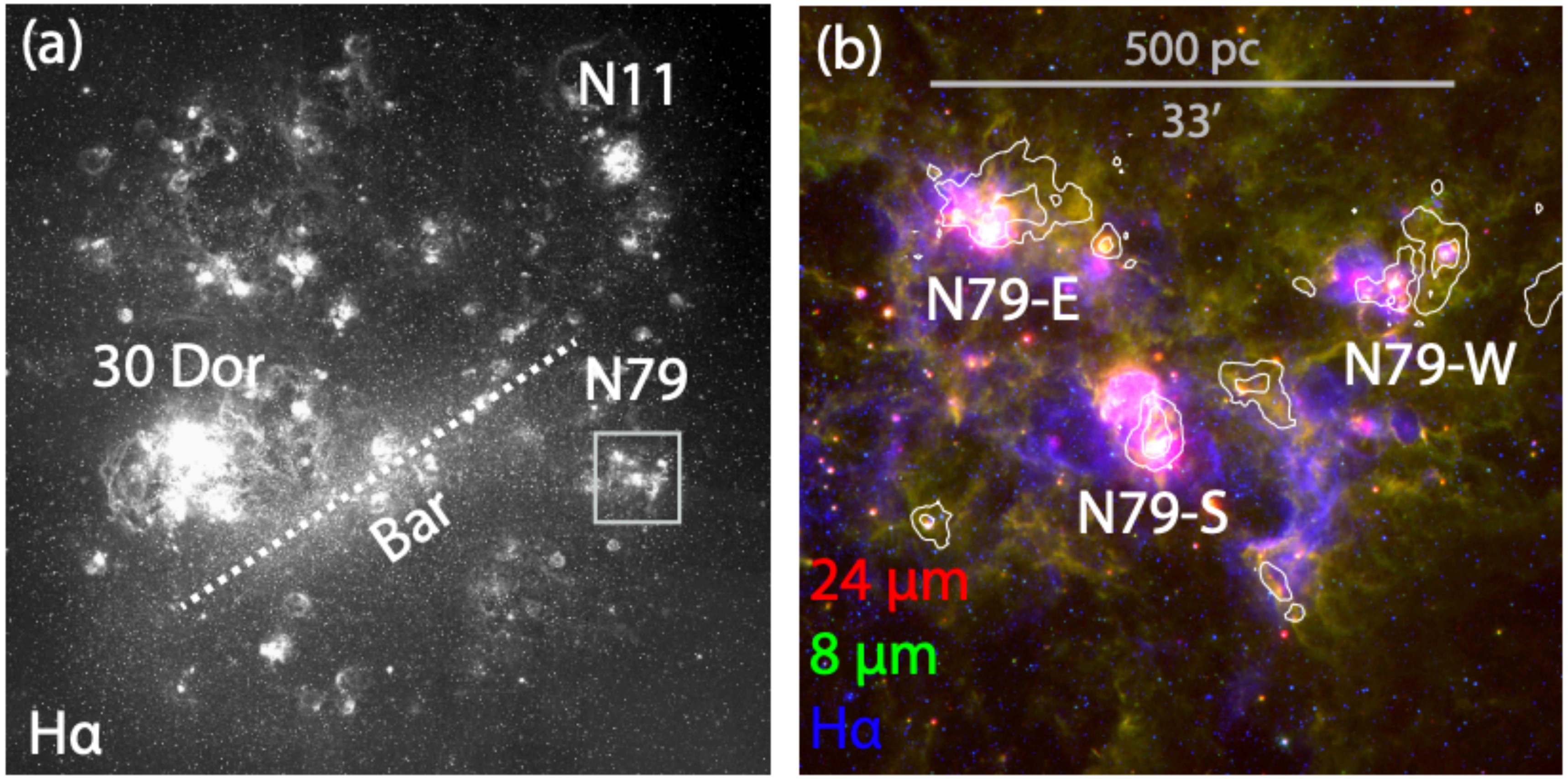
T-ReX: The Tarantula Revealed in X-rays



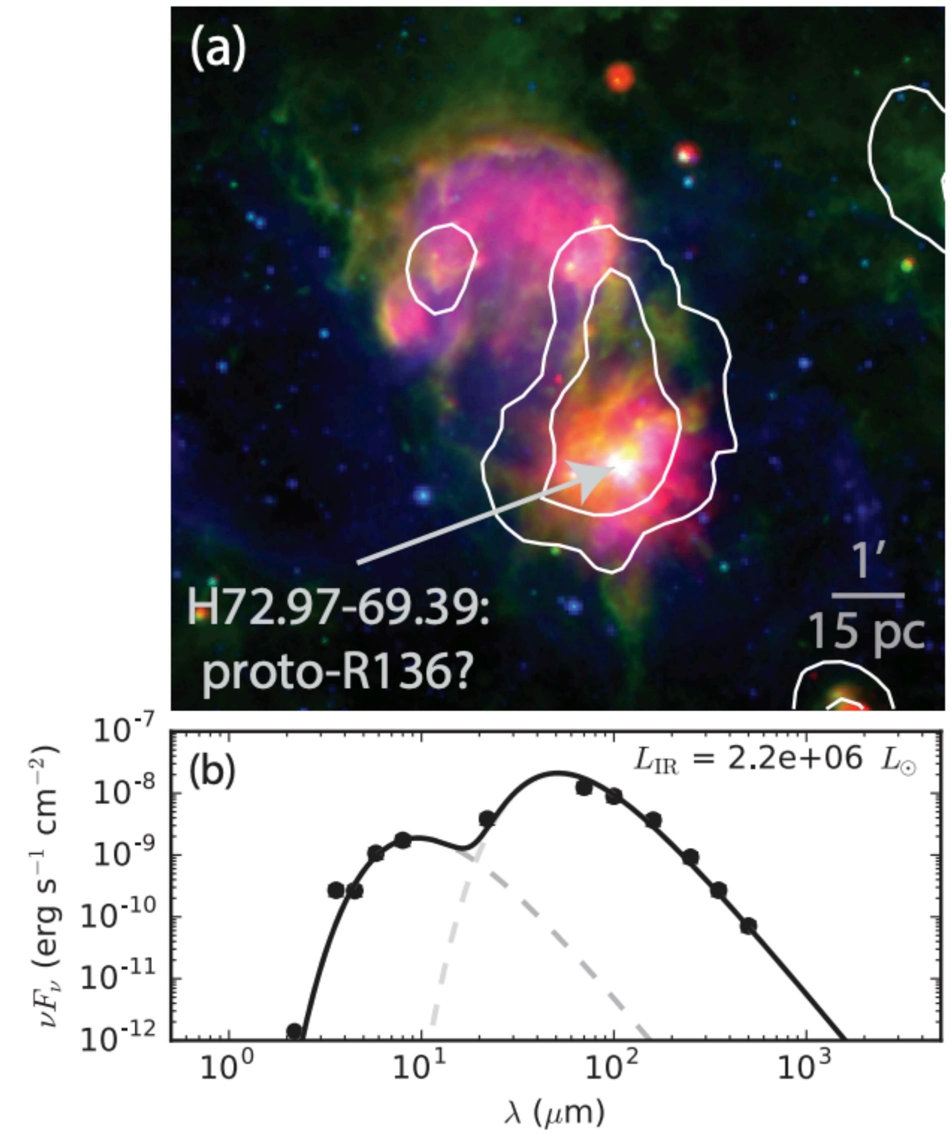
Townsley, Broos, & Povich 24

Compare hot gas properties (L_x, kT, n_e) with warm gas and dust to explore wind and SN energy loss channels — test to see how stellar feedback couples to the ISM.

A Proto-30 Dor: N79

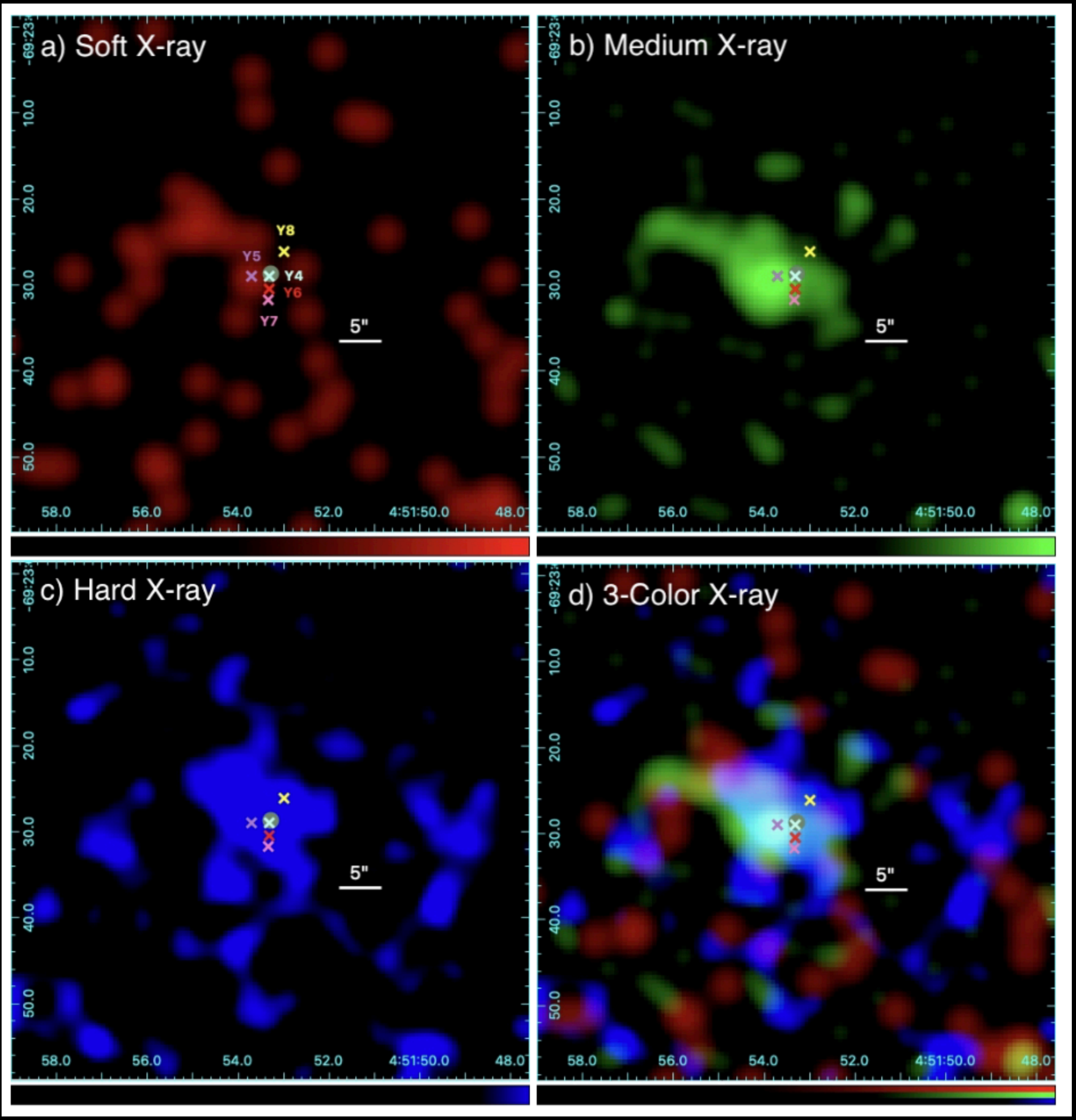


Ochsendorf+17



N79 has an accelerating star-formation rate for the last 0.5 Myr, Ochsendorf posited that the possible super-star cluster could be a proto-30 Doradus of age 0.1-0.5 Myr.

A Proto-30 Dor: N79



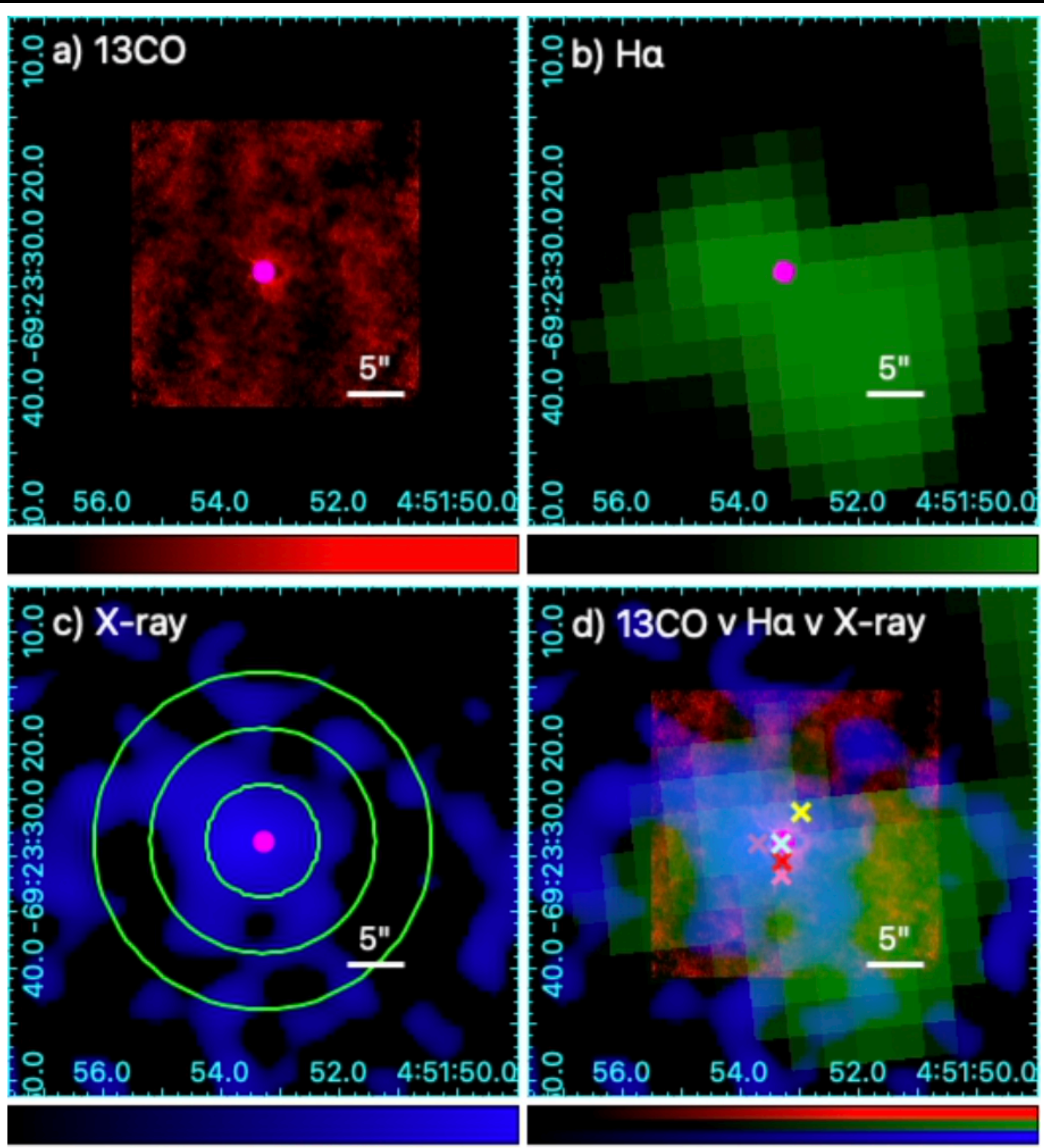
Observed with Chandra for 100 ks.

Diffuse X-rays extend 10” ~ 2.4 pc; peak is offset from YSOs identified with JWST.

Stellar winds do produce hot gas at earliest stages.

Webb, Rodriguez, Lopez+24

A Proto-30 Dor: N79



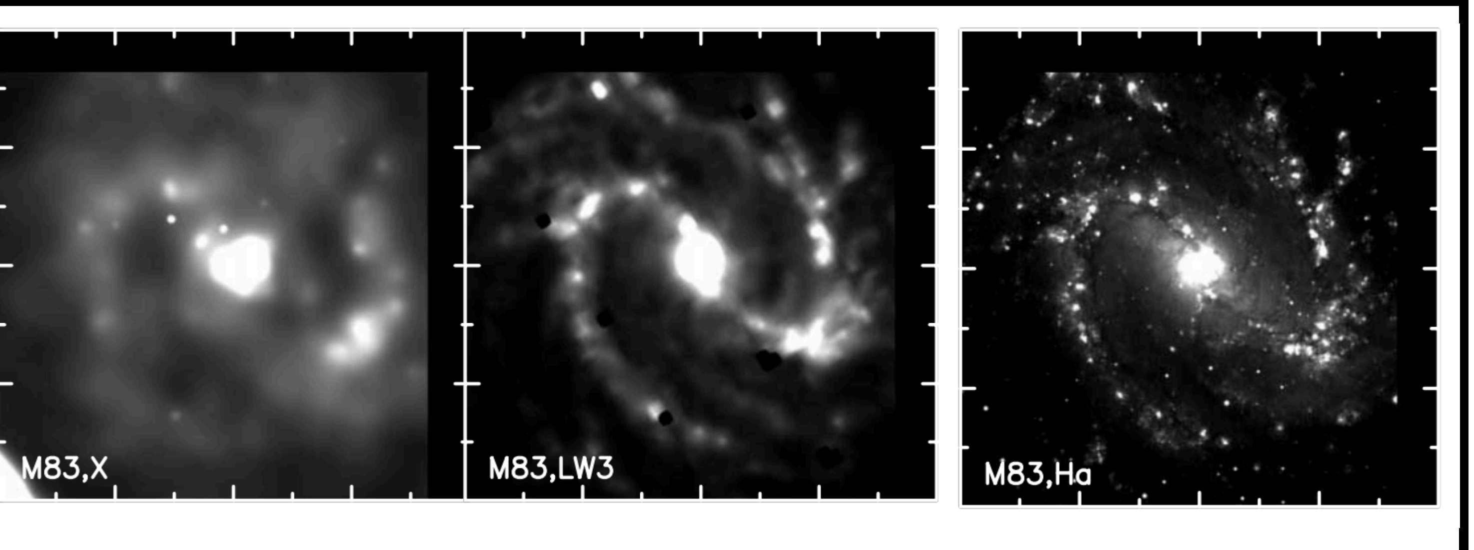
X-rays fill the cavities seen in ^{13}CO from ALMA.

X-ray luminosity is 20x below predictions if hot gas was fully confined.

Wind energy lost via turbulent mixing, radiative cooling, leakage.

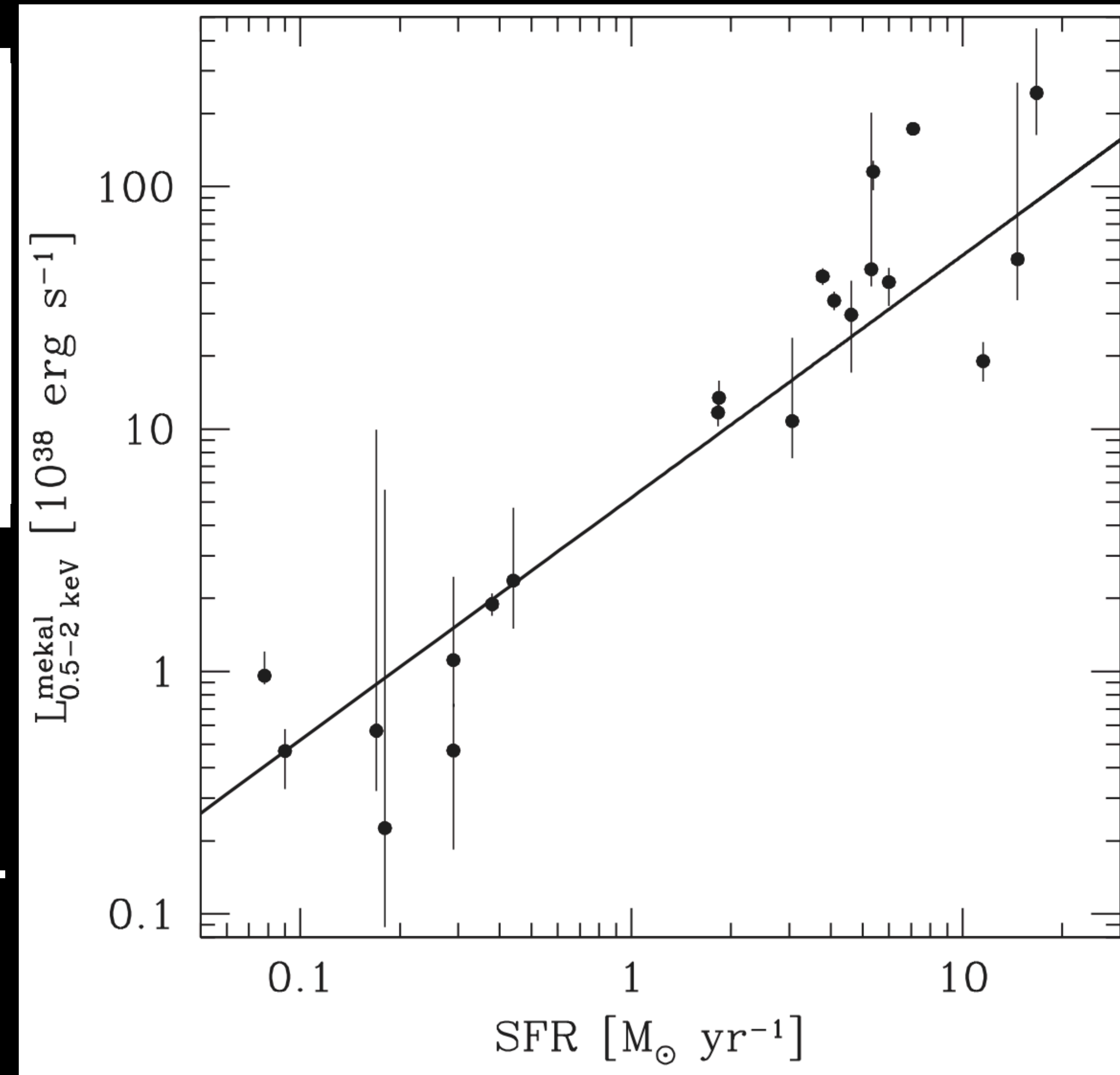
Webb, Rodriguez, Lopez+24

Hot ISM on Galactic Scales



Tyler+04

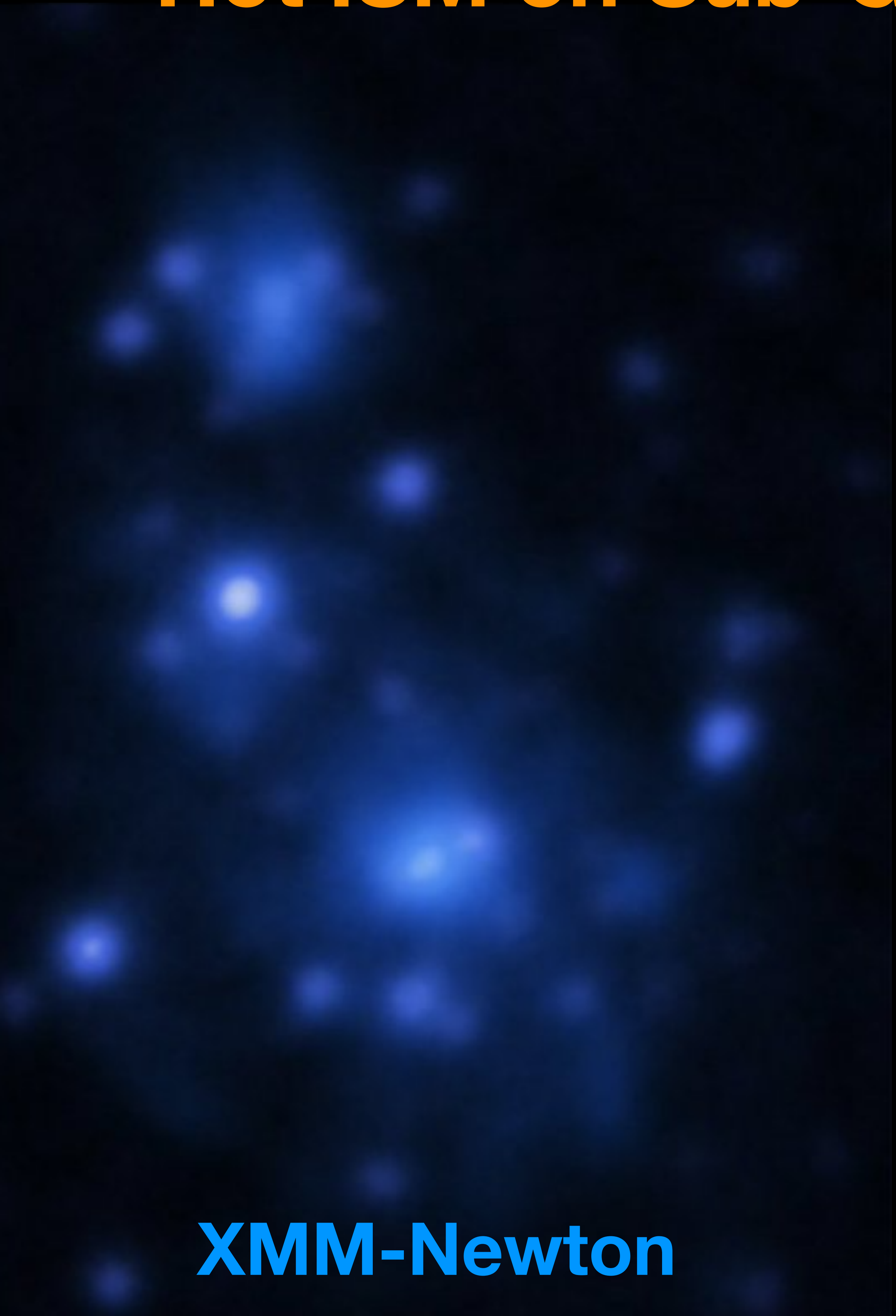
X-ray morphology traces spiral arms (similar to H-alpha and mid-IR; Tyler+04) and correlates with SFR (Mineo+12)

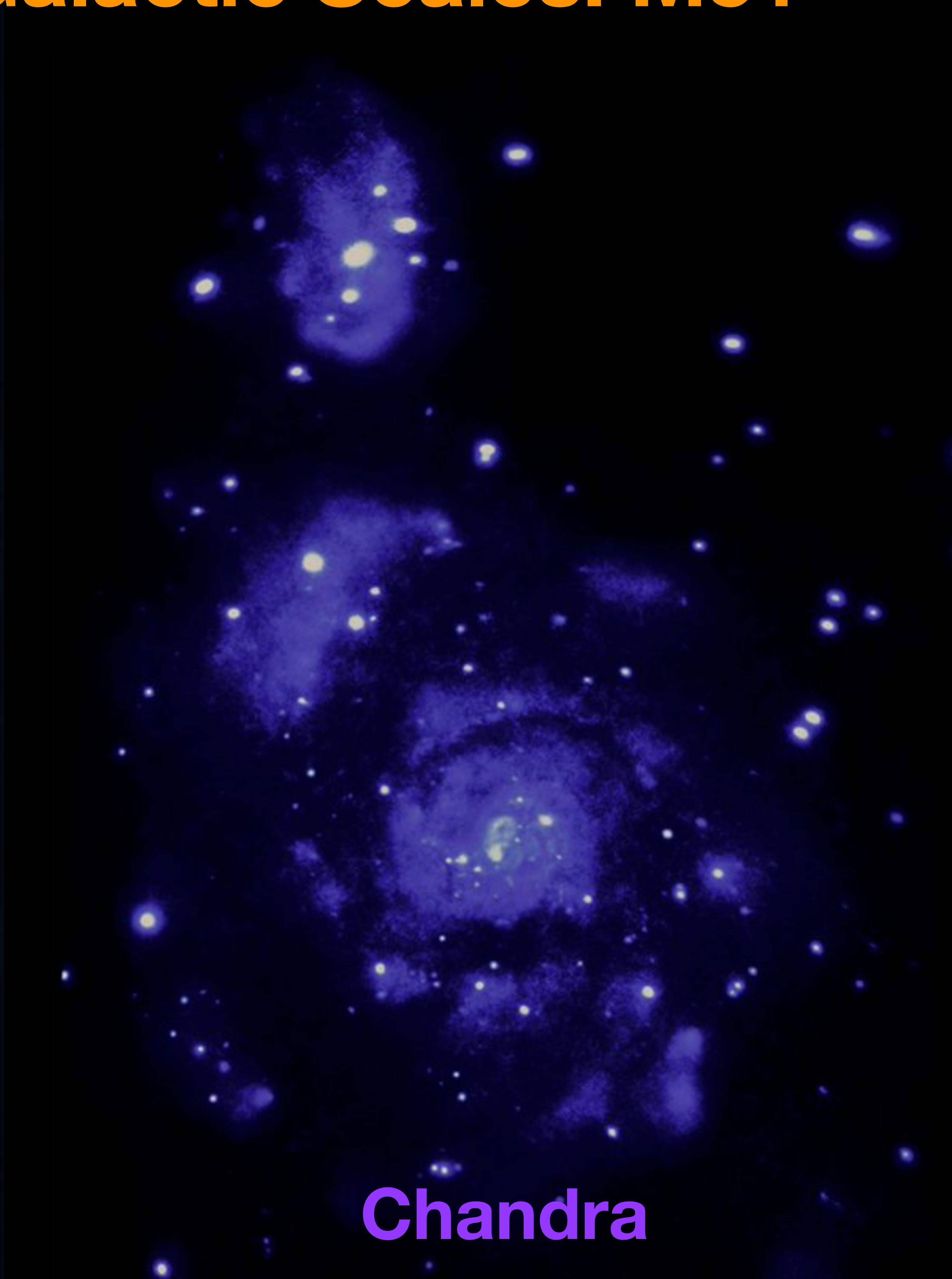


Mineo+12

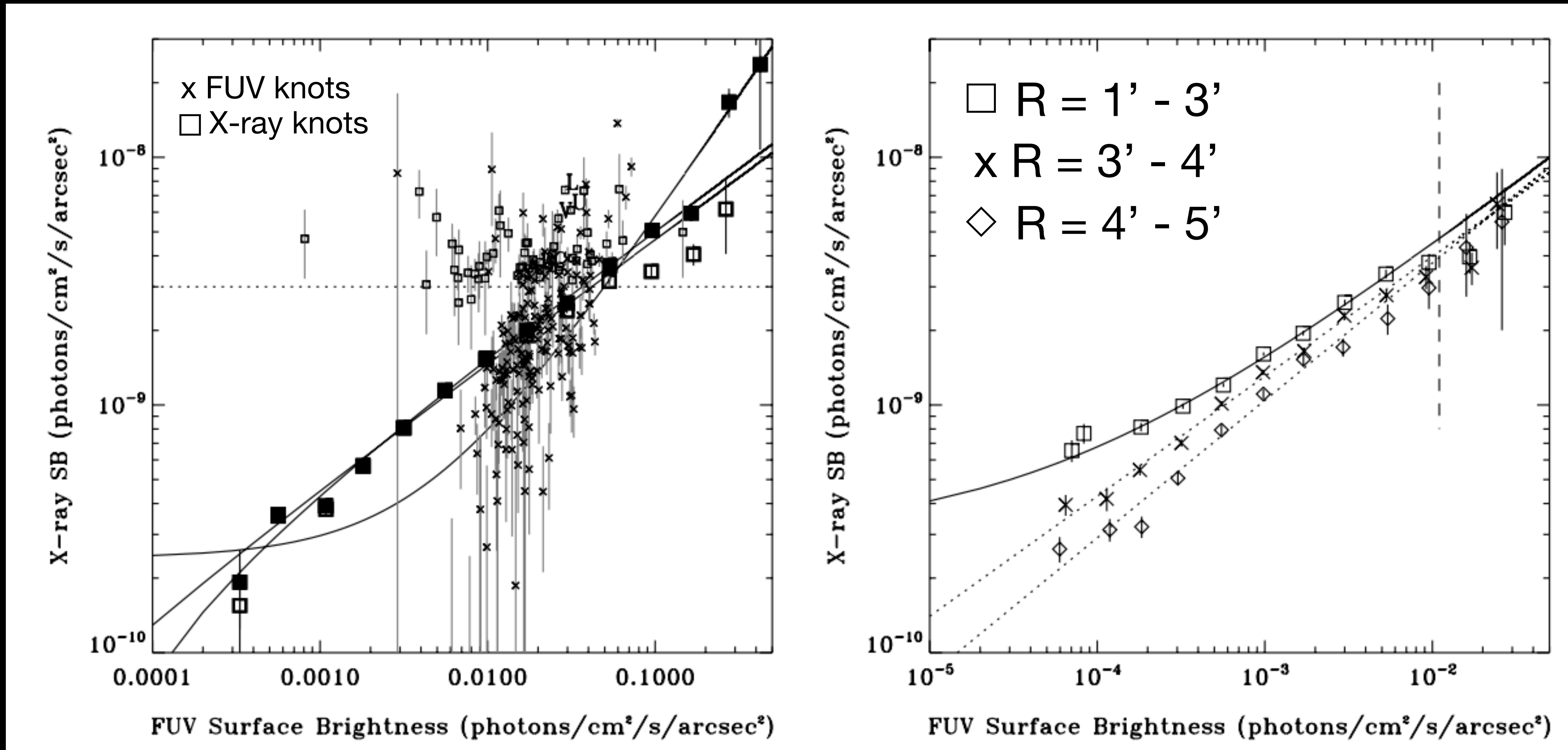
To date, limited work on diffuse hot gas on a subgalactic scale in nearby galaxies (though see posters of Erik Monson, Luan Luan, Junfeng Wang, Ryder Smith)

Hot ISM on Sub-Galactic Scales: M51





Hot ISM on Sub-Galactic Scales: M101

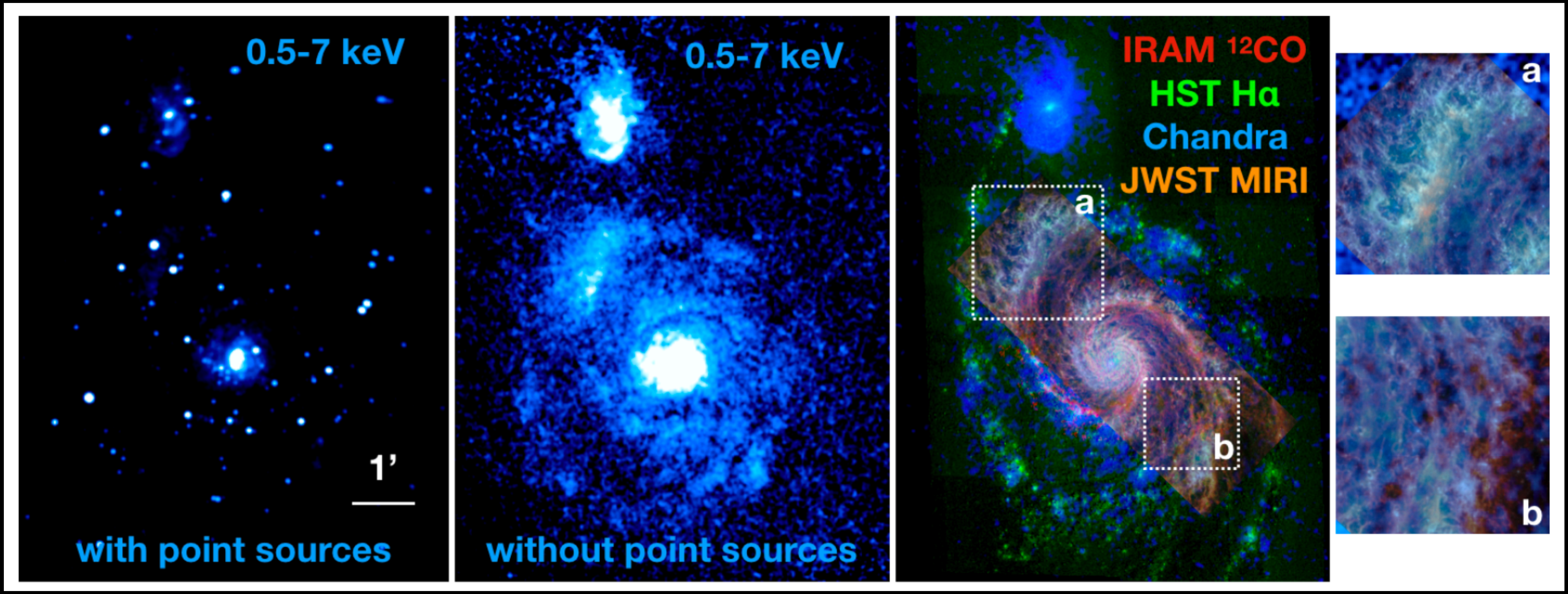


Kuntz & Snowden10

X-rays and FUV are correlated but are non-linear. Spatial relationship between wavelengths can reveal insights about stellar population ages.

Hot ISM on Sub-Galactic Scales: M51

Many nearby galaxies have been observed deeply by Chandra to study X-ray binaries, and Chandra spatial resolution enables removal of point sources to map diffuse hot gas. We are examining the relationship of the hot gas to other ISM tracers, stars, environment.



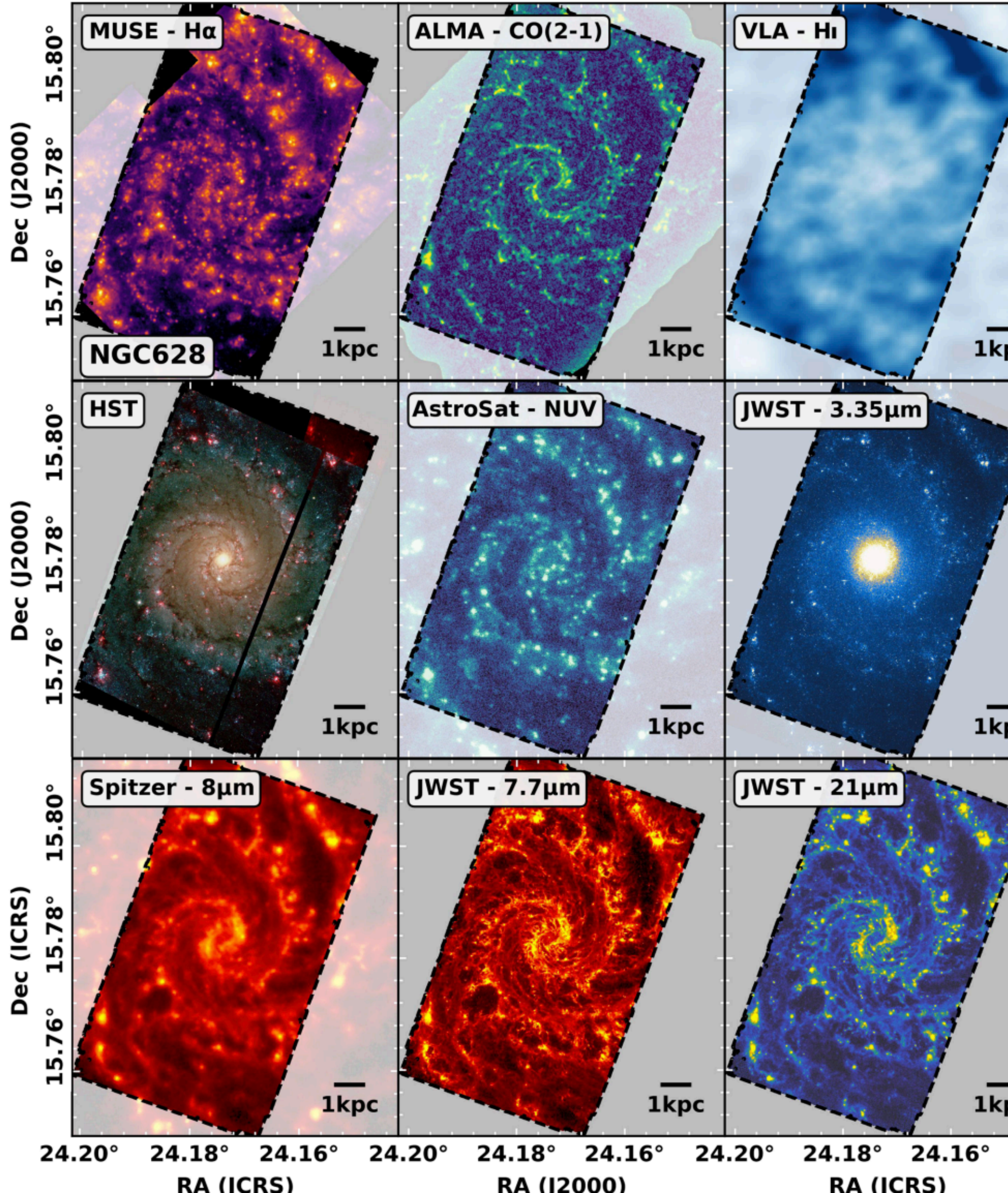
Rodriguez, Lopez+25 in prep

Nearby Galaxies - PHANGS

Physics at High Angular Resolution In Nearby Galaxies (PHANGS) has surveyed 74 star-forming, face-on galaxies <30 Mpc at ~100 pc resolution.

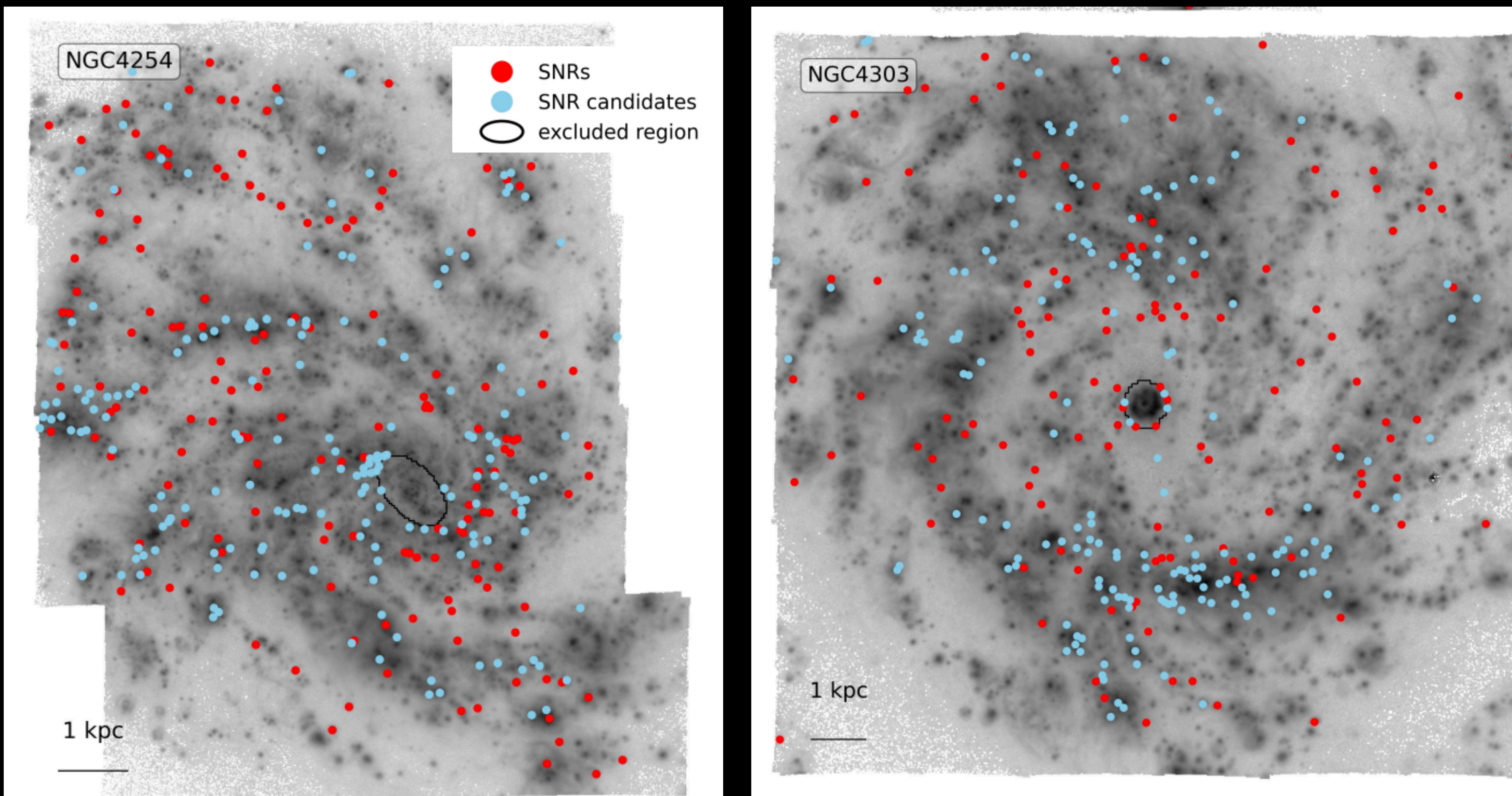
ALMA, MUSE, HST, JWST, Chandra - complete view of ISM

Watkins+23



Identifying SNRs in the Optical

Identified ~2200 new SNRs in PHANGS-MUSE galaxies using optical line diagnostics + kinematics. 35% overlap with HII regions.



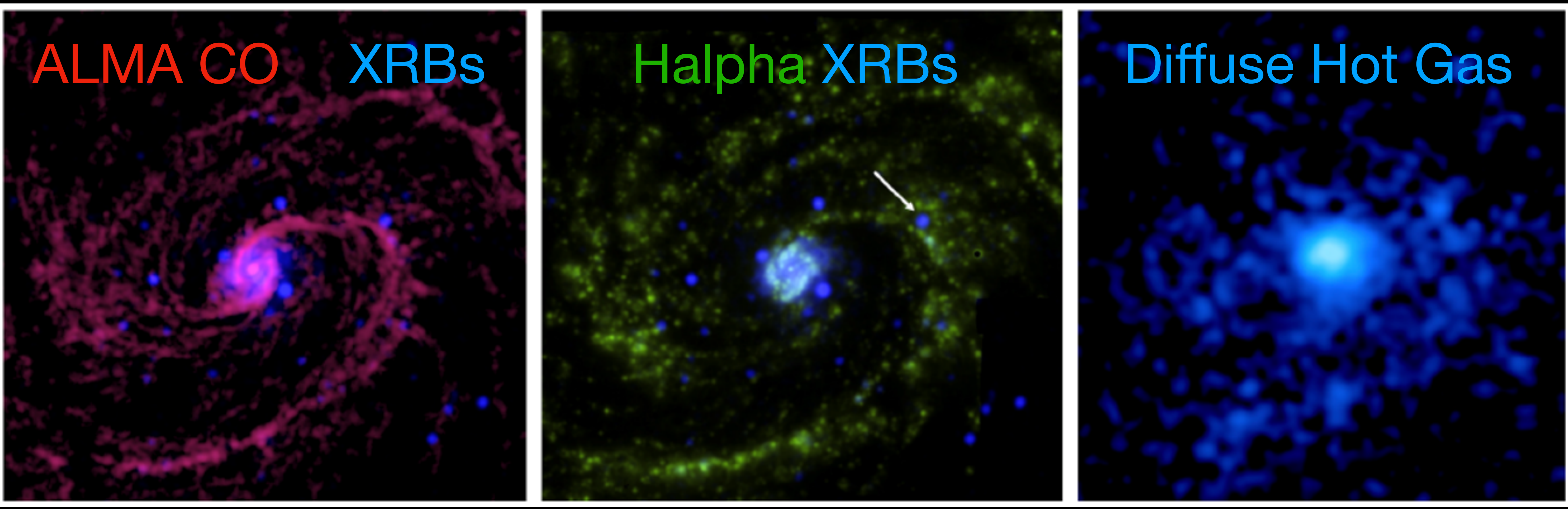
Jing Li+24

PHANGS-Chandra

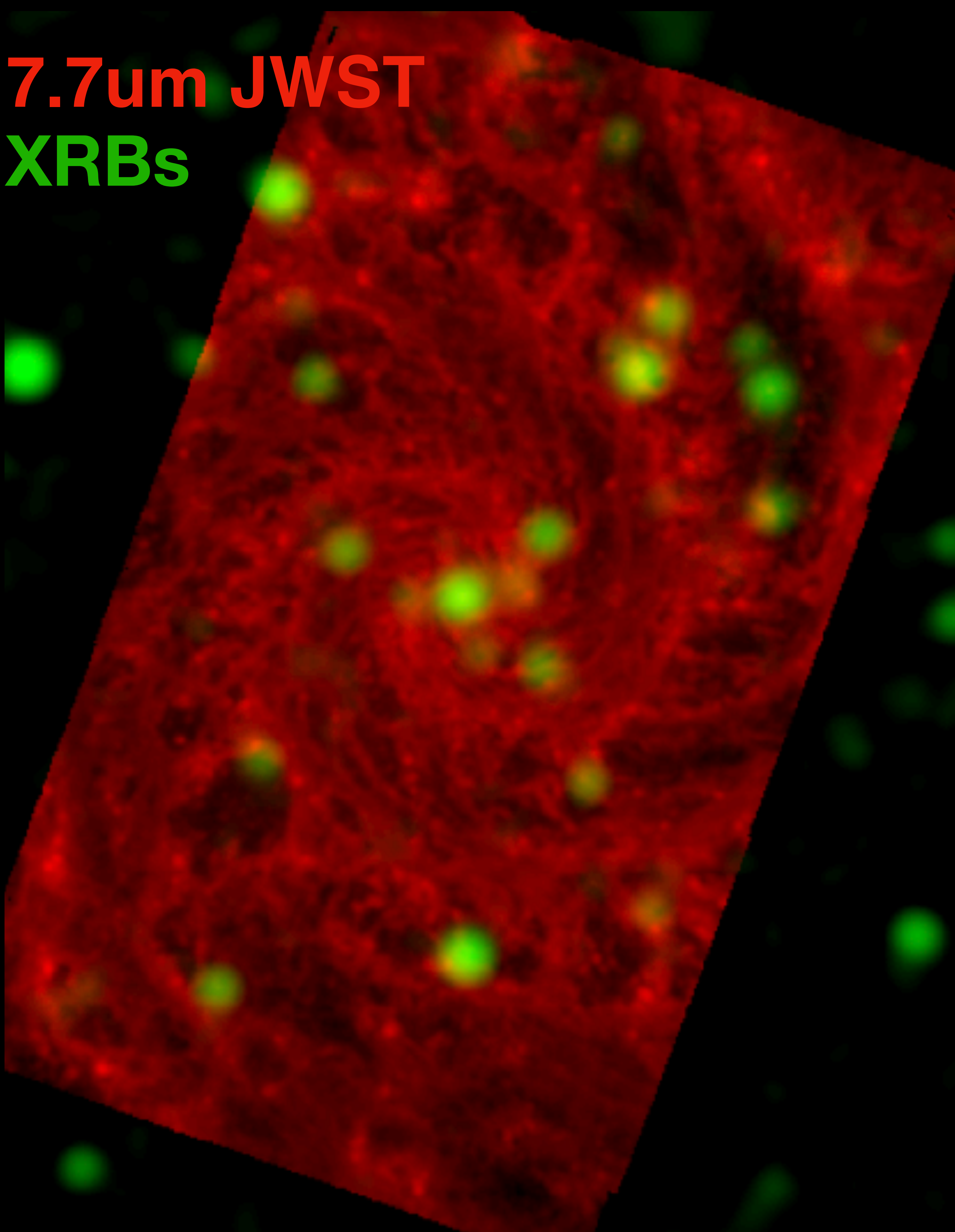
33 of the 74 PHANGS galaxies have been observed already or will be this year with Chandra, including all of the PHANGS-JWST “first 19” (PIs: Lehmer, Lopez)

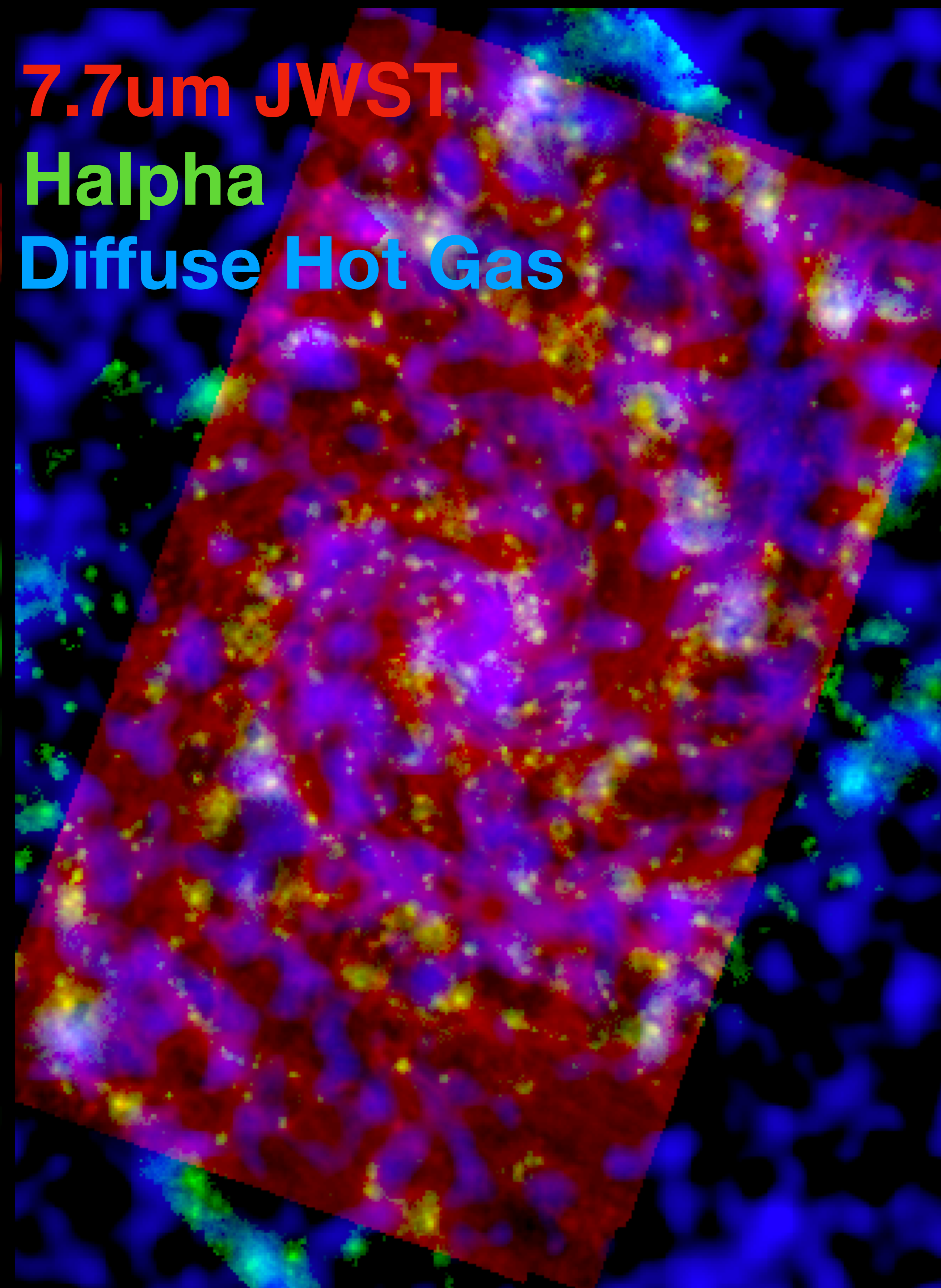
~Half of emission is from X-ray binaries, other half is diffuse hot gas. Must remove XRBs to see diffuse gas.

NGC 4321



NGC 628

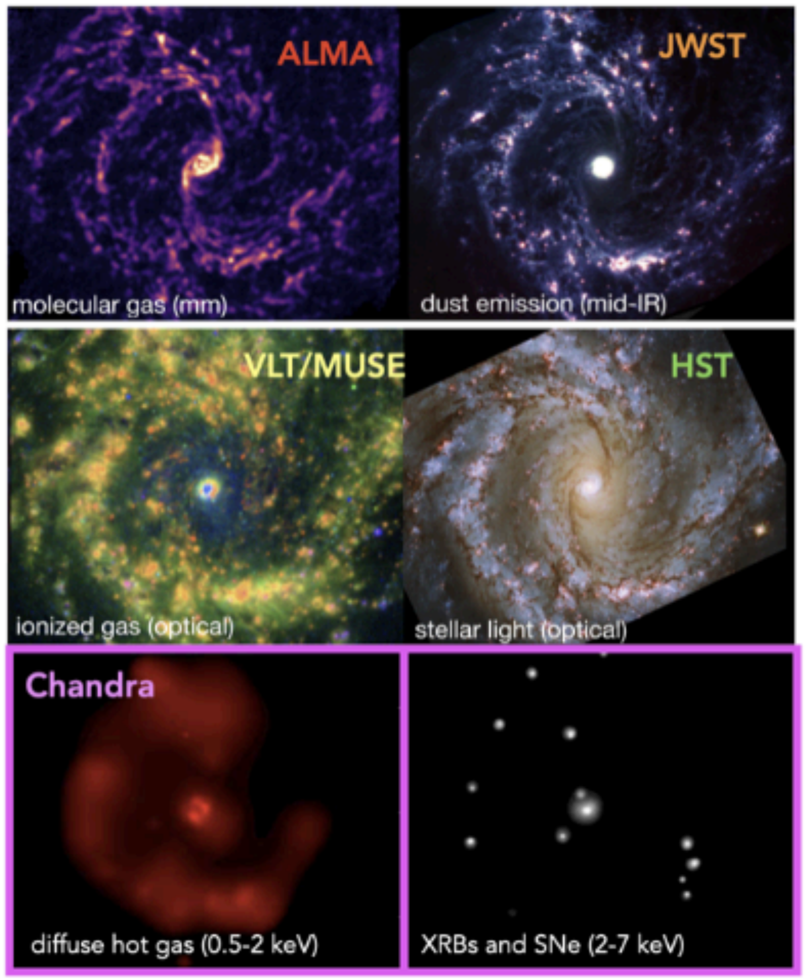


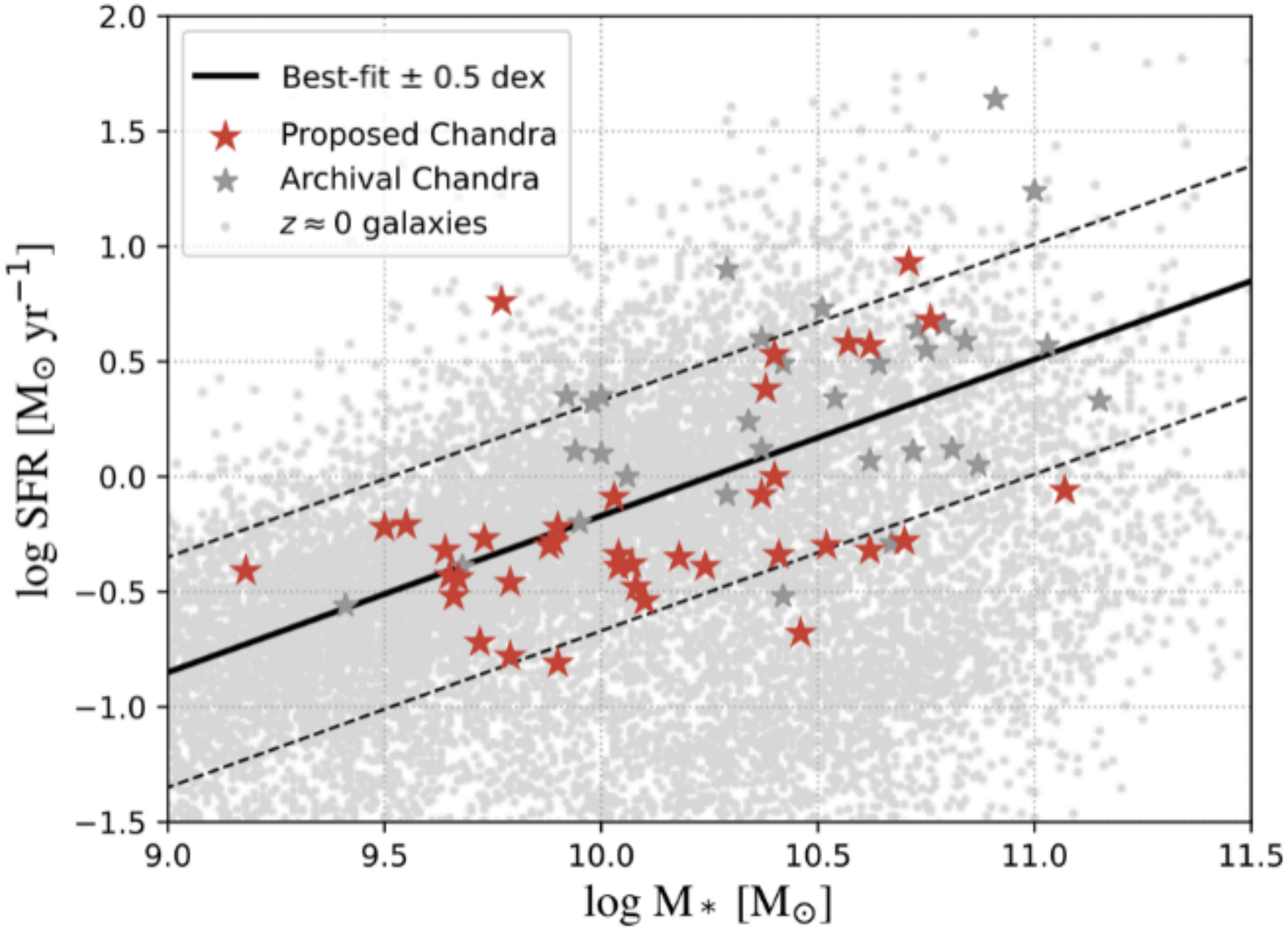


Future: PHANGS-Chandra

Awarded 3 Ms Chandra Legacy Program to observe the other ~40 PHANGS galaxies (PIs: Mathur, Lehmer, Lopez), down to $L_X \sim 3 \times 10^{37}$ erg/s

NGC 4303



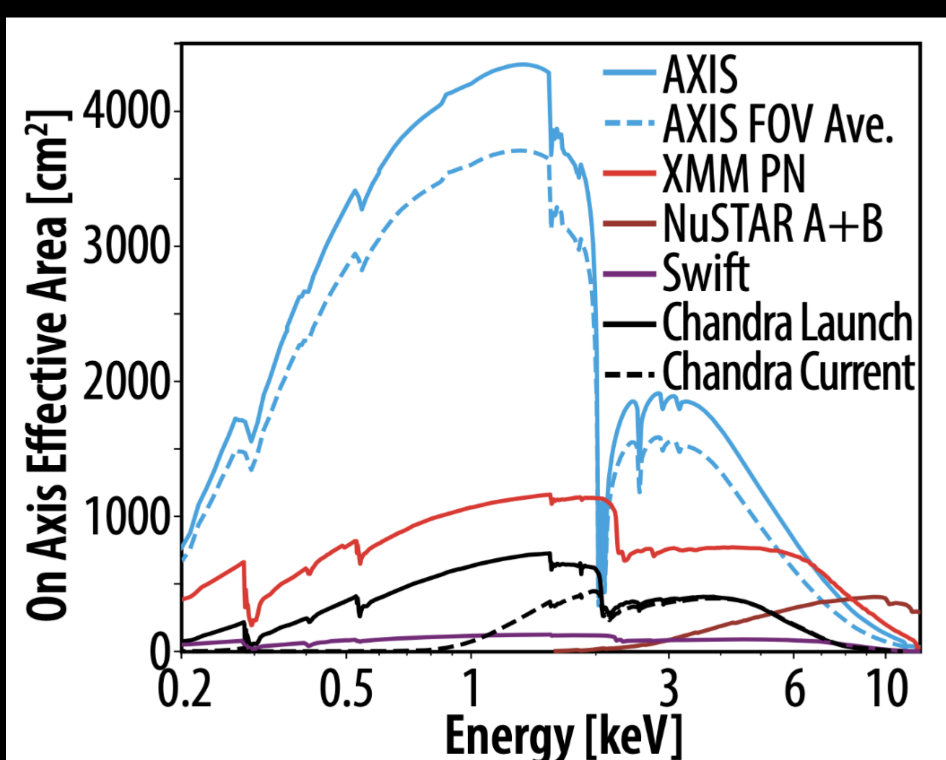


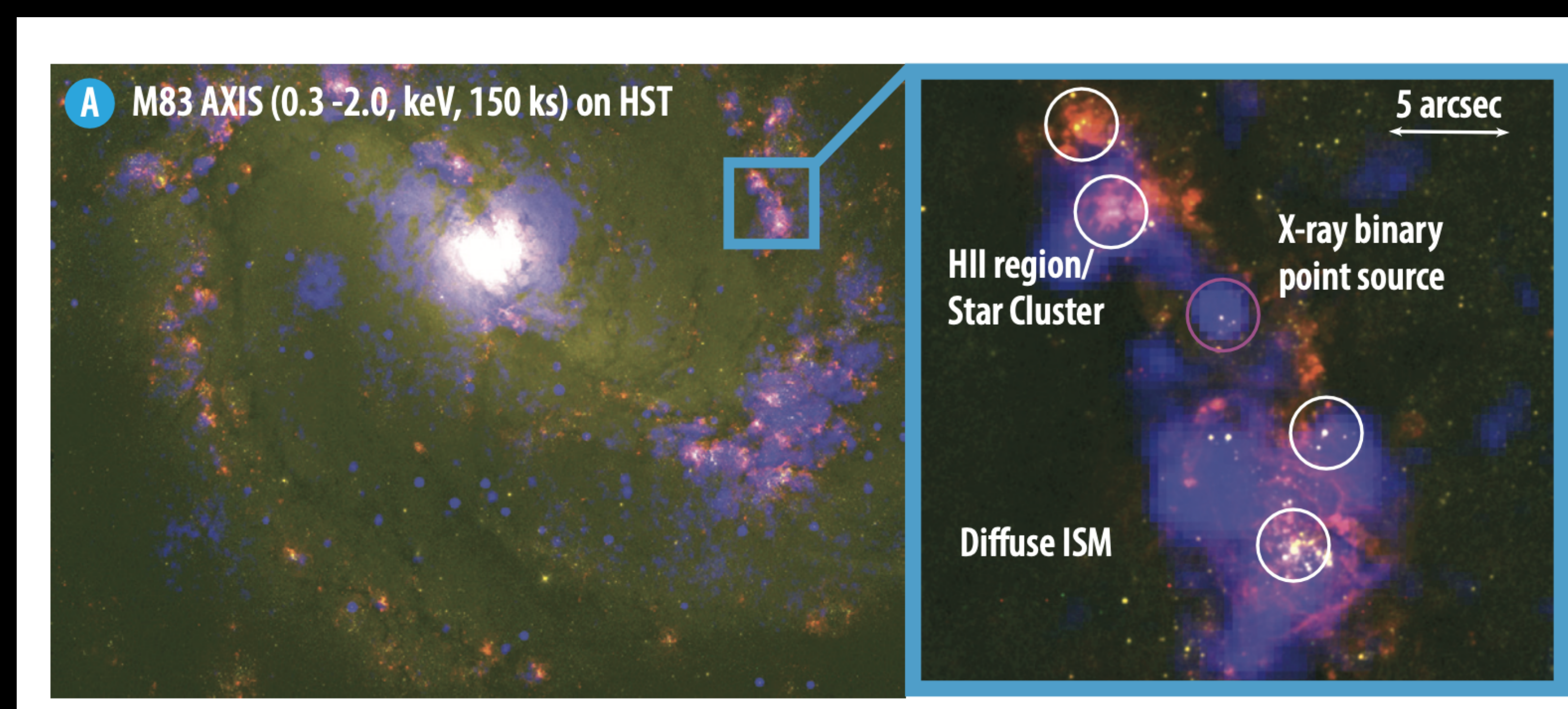
Data will be taken 2025-2026.

Future: AXIS

AXIS, with 1.5” PSF and 24’ field of view, will be much more sensitive than Chandra.

Feedback in/out of galaxies is an important part of science plan: will cover 5000 star clusters in galaxies <7 Mpc away and will detect $L_x > 3 \times 10^{34}$ erg/s, create the first X-ray luminosity function of star clusters/HII regions.





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Future Chandra studies are critical for longer dynamics baselines and to probe explosions & progenitors of newly-discovered SNRs. AXIS will offer even more detail on larger populations of SNRs.

Hot ISM from stellar winds and SNe fill star-forming regions; Chandra resolution key to separate point sources from diffuse ISM. Most studies have focused on Milky Way and Magellanic Clouds; need larger samples to explore how feedback is deposited to ISM.

Little done on hot ISM within galaxies. PHANGS-Chandra will be first to look on sub-galactic scales across a large sample to get complete ISM topology across many galaxies.

AXIS will enable first statistical sample of hot ISM around star clusters in nearby galaxies.