“X射线天文学60周年及中国X射线天文研究” 研讨会：
时域与多信使天文学时代的X射线天文研究

X-ray view of galaxies near and far

- **Introduce various types of X-ray sources in galaxies**
- **Give broad astrophysical context for some time-domain X-ray studies**
- **Highlight a couple of such studies that seem to be under-represented in the workshop program**

王青德 (Qingde Daniel Wang)
University of Massachusetts

In memory of 高煜 (Gao Yu) – my former postdoc and friend, as well as an accomplished astronomer

Gao Yu was a pioneer in studying HLXs!

THE ASTROPHYSICAL JOURNAL, 596:L171–L174, 2003 October 20

NONNUCLEAR HYPER/ULTRALUMINOUS X-RAY SOURCES IN THE STARBURSTING CARTWHEEL RING GALAXY

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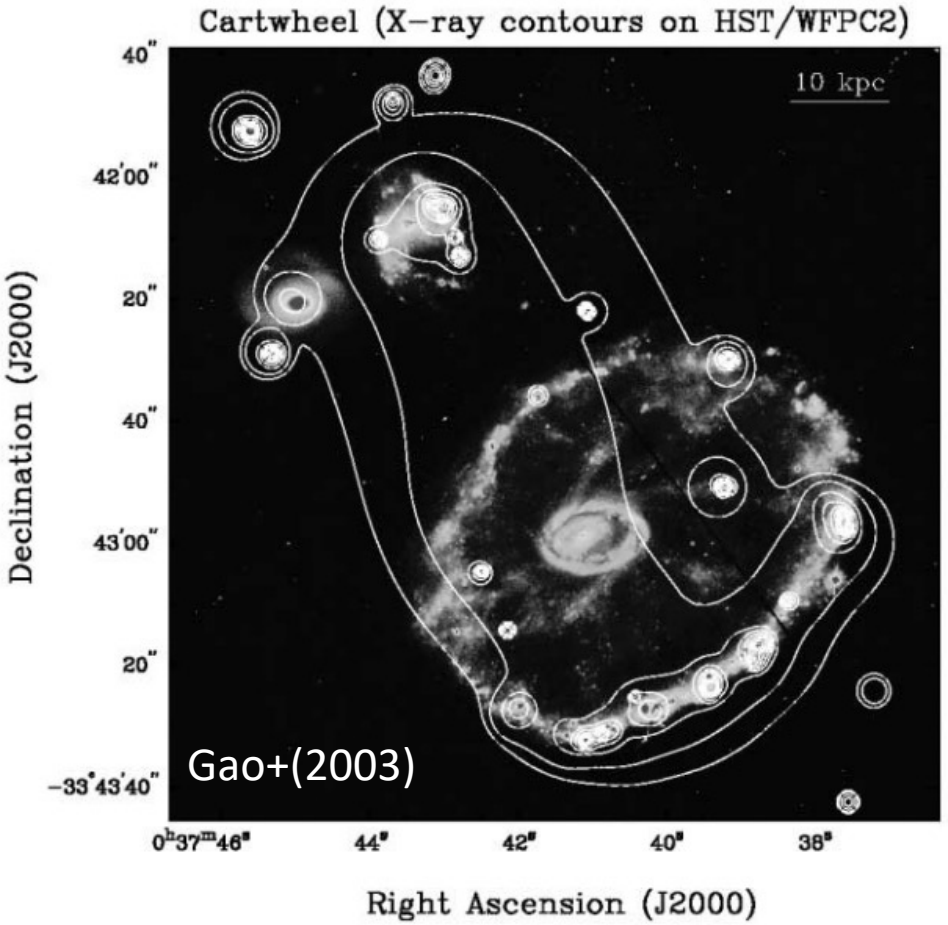
ABSTRACT

We report the *Chandra*/ACIS-S detection of more than 20 ultraluminous X-ray sources (ULXs; $L_{0.5-10\,\mathrm{keV}} \gtrsim 3 \times 10^{39}$ ergs s^{-1}) in the Cartwheel collisional ring galaxy system, of which over a dozen are located in the outer active star-forming ring. A remarkable hyperluminous X-ray source (HLX; $L_{0.5-10\,\mathrm{keV}} \gtrsim 10^{41}$ ergs s^{-1} assuming isotropic radiation), which dominates the X-ray emission from the Cartwheel ring, is located in the same segment of the ring as most ULXs. These powerful H/ULXs appear to be coincident with giant H II region complexes, young star clusters, and radio and mid-infrared hot spots: all strong indicators of recent massive star formation. The X-ray spectra show that H/ULXs have similar properties as those of the *most luminous* ULXs found in the nearest starbursts and galaxy mergers such as the Antennae galaxies and M82. The close association between the X-ray sources and the starbursting ring strongly suggests that the H/ULXs are intimately associated with the production and rapid evolution of short-lived massive stars. The observations represent the most extreme X-ray luminosities discovered to date associated with star-forming regions—rivaling the X-ray luminosities usually associated with active galactic nuclei.

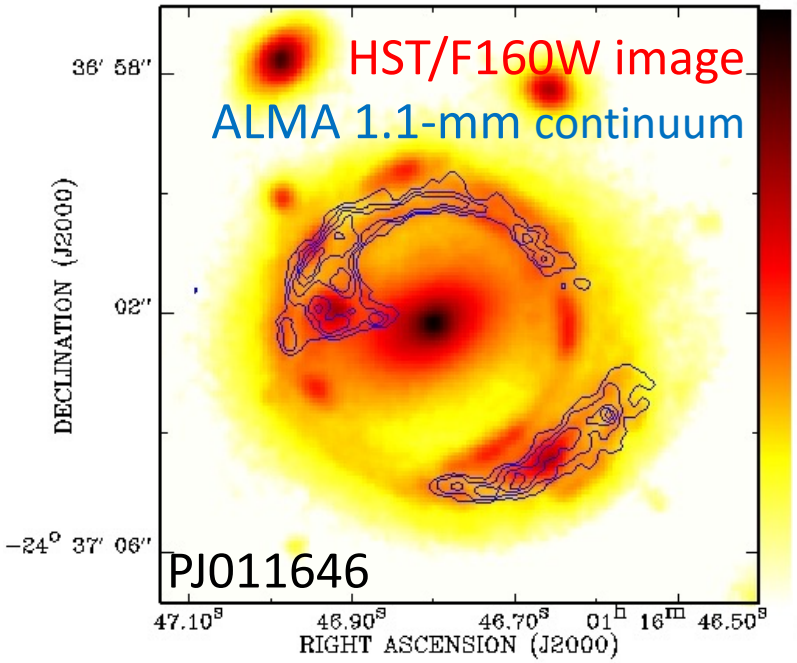
X-ray emission from active star forming galaxies: massive stellar end-products

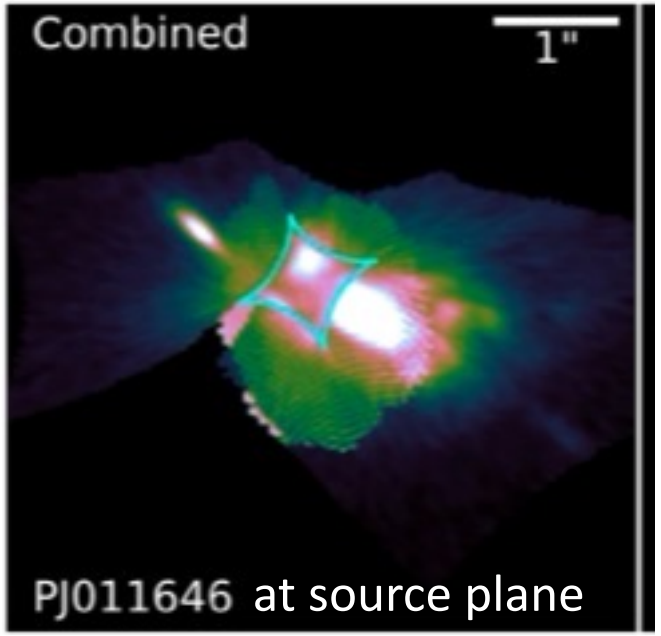


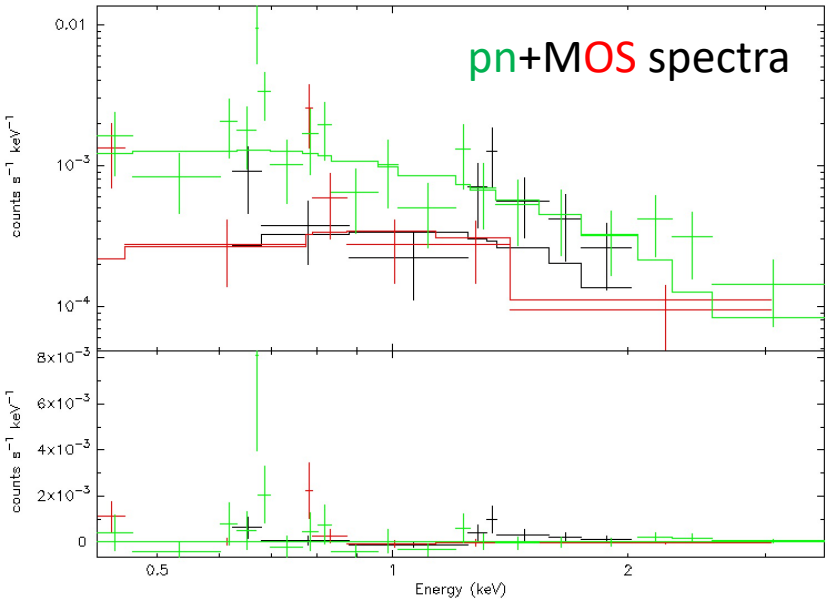
Some of (H)ULXs vary strongly with time!

- Large pop. of the (H)ULXs in the Cartwheel ring is most likely due to the low metallicity in the outer region.
- Some ULXs are probably X-ray-beaming or apparent super-Eddington accretors of stellar mass objects (e.g., pulsars; later talks by 孔令达 and 侯贤).
- HLXs may be accreting intermediate-mass black holes (R. Soria's talk) or progenitors of massive BH binary mergers as observed in gravitational wave detections.
- Such X-ray sources could have played a major role in the cosmic re-ionization and heating.

X-raying strongly lensed hyper-luminous dusty galaxies (z=2.1-3.5)



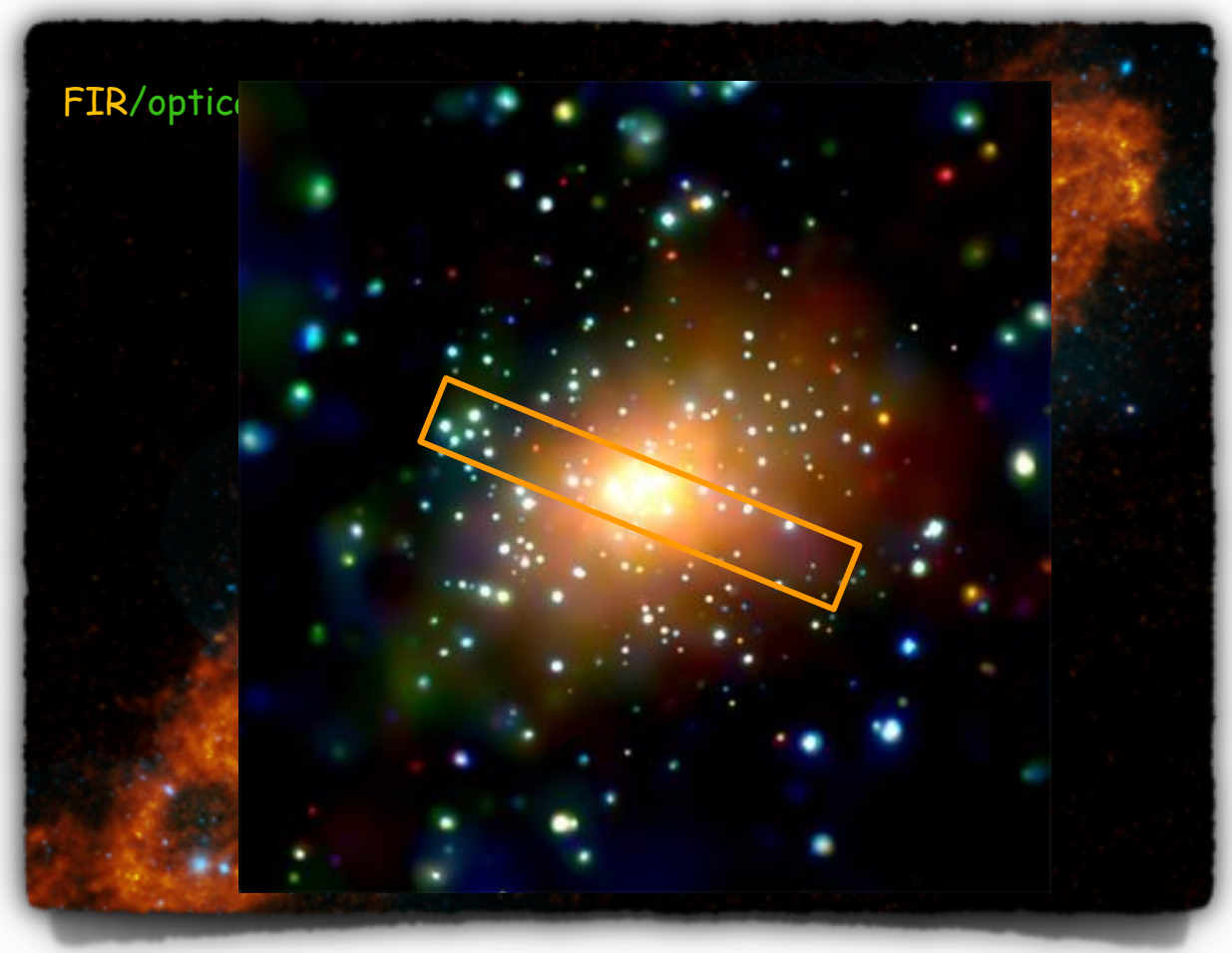


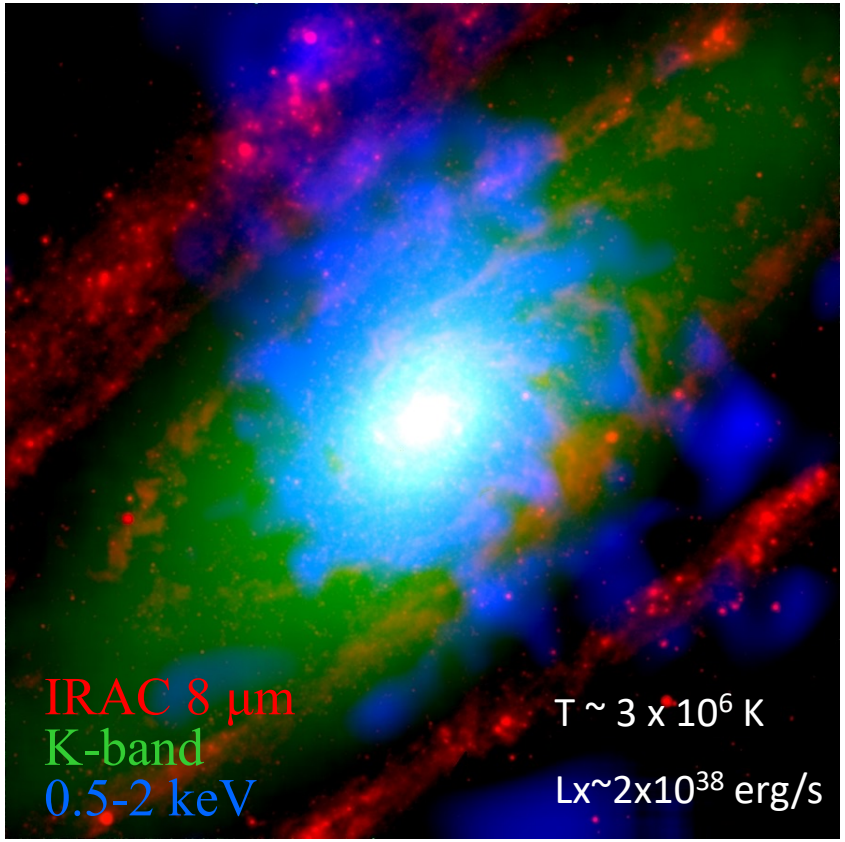


- Large XMM-Newton project -- part of the multi-wavelength PASSAGES Collaboration -- aimed to determine the Lx/SFR ratio of (H)ULXs and to constrain the IMF shape of massive stars in these extreme star-forming galaxies (SFR > 10^3 Msun/yr).
- High-res X-ray imaging may detect strongly amplified individual (H)ULXs!

Wang+2022 in prep

X-ray emission from quiescent galaxies: M31 bulge

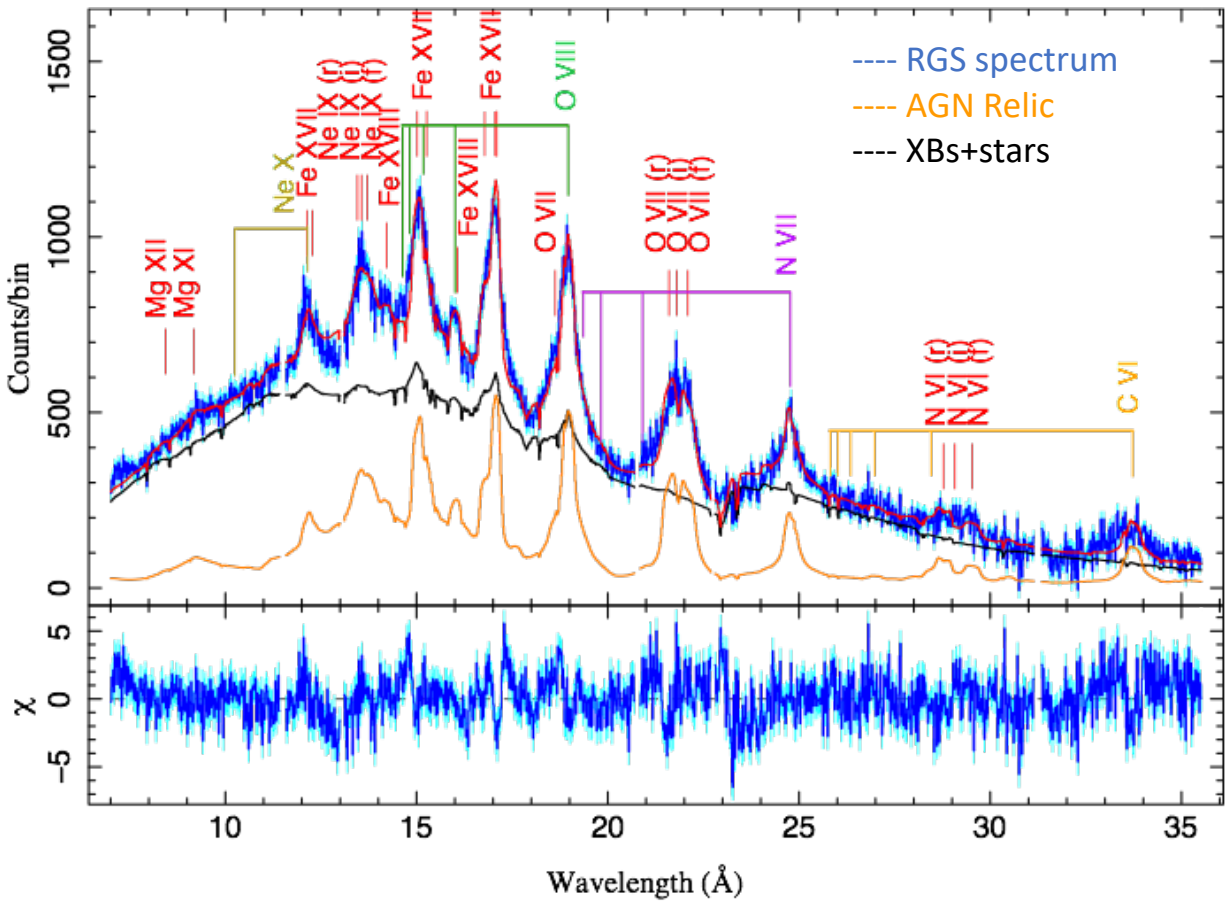




- Little cool gas and no recent star formation.
- Enhanced X-ray source population largely due to low-mass X-ray binaries formed dynamically.

Apparent large-scale hot gas outflow is likely driven by Ia SNe (Li & Wang 2007), but may also be linked to recent AGN (Zhang+2014).

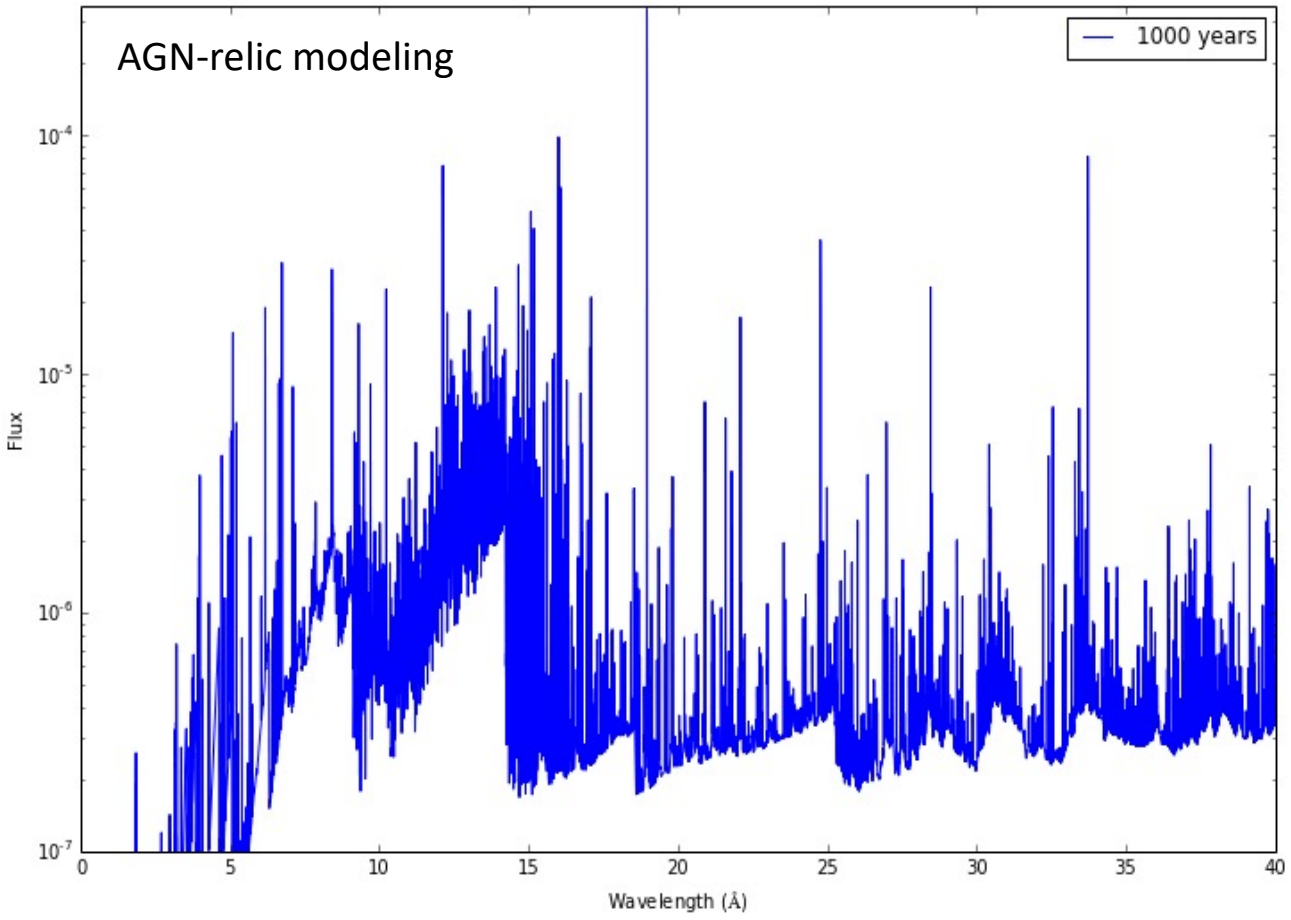
X-ray spectroscopy of M31 bulge: AGN relic



- G =(f+i)/r ratios of Kα triplets of He-like ions are far too large to be consistent with optically-thin CIE plasma.
- Also unexpected are high Lyβ/Lyα for H-like N and O and high iron line ratios (Fe XVIII 14.2Å/Fe XVII 17Å and Fe XVII 15Å/17 Å).
- Instead, the spectrum is well explained by the presence of an AGN of Lx~10^{44} erg/s about half Myr ago, which led to over-ionization of the gas.

Zhang, Wang+. 2018

X-ray spectroscopy as a tool to infer the recent AGN history in nearby galaxies

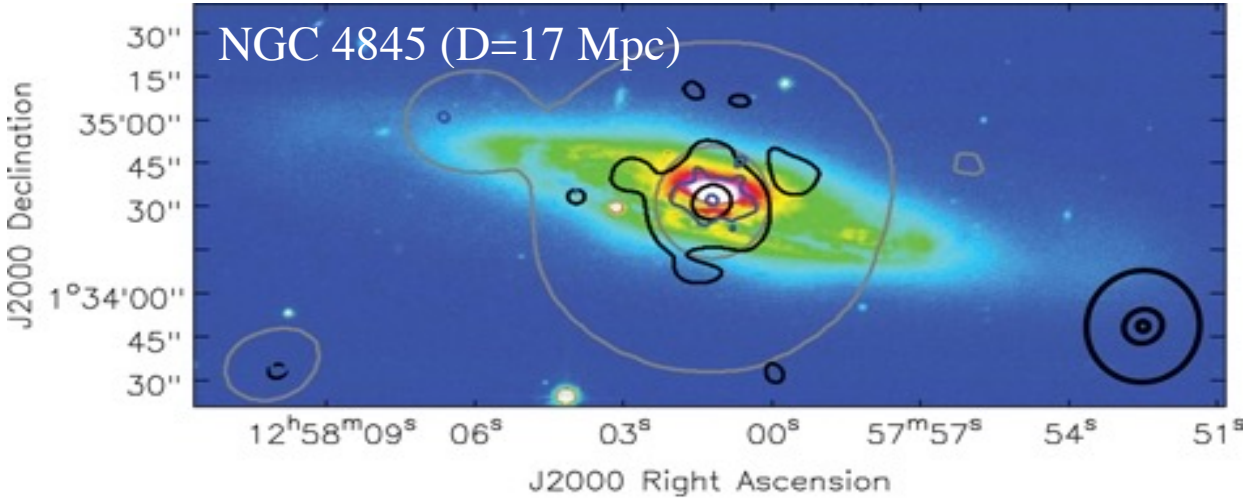


Zhang, Wang+ (2018)

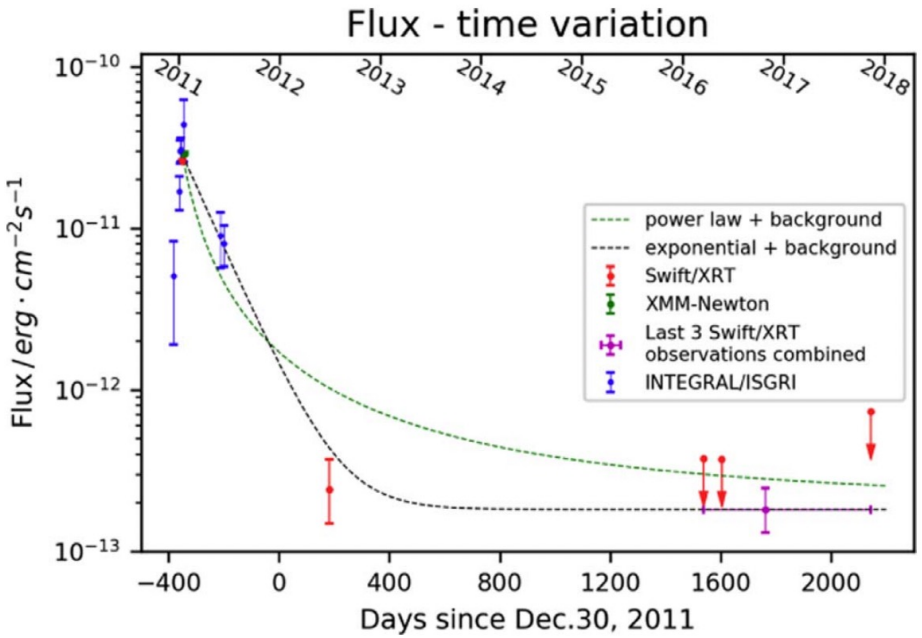
- Recombination continuums (or edges) are key diagnostics of AGN relics, detectable by HUBS.
- Timescale to reach ionization equilibrium can be > time interval between AGN episodes.
- Such spectroscopic studies can complement direct time-domain observations of AGN to statistically infer their variability behaviors.

Other galactic nuclear activity: TDEs

Check out Lixin DAI's talk for more thorough discussion on TDEs.

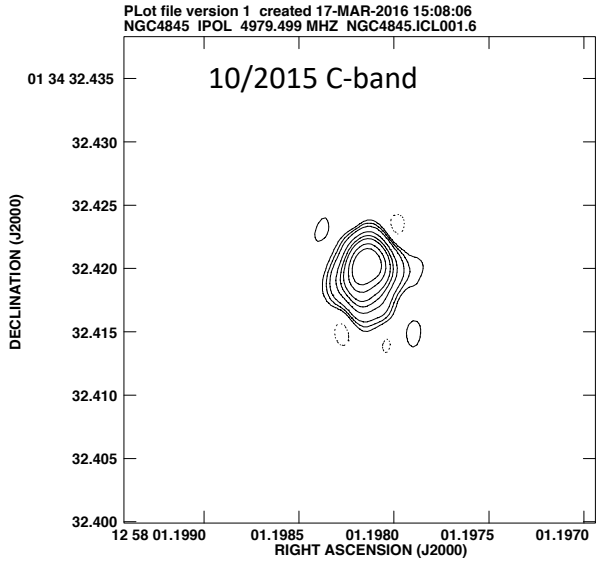


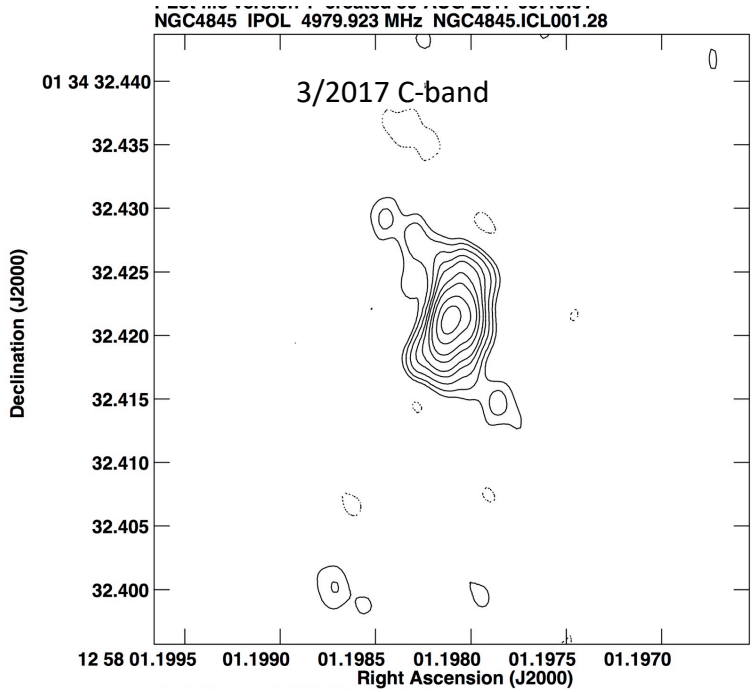
Irwin+ (2015)

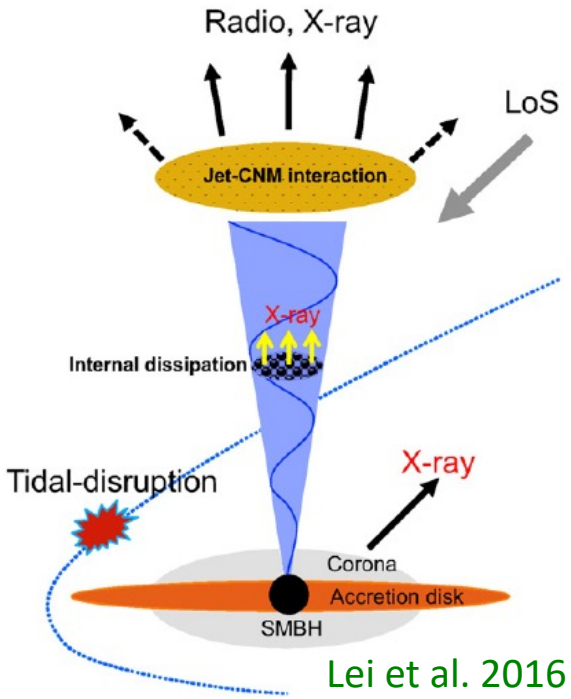


- IGR J12580+0134 – **the nearest TDE of a super-Jupiter** -- discovered in X-ray by INTEGRAL and XMM-Newton in 11/2010 (Walter et al. 2011) and serendipitously in radio by VLA (Irwin+, 2015) and in mm by Planck (Yuan, Wang+ 2016).
- Follow-up observations by VLA, VLBA, ALMA and Swift (e.g., Perlman+ 2017, 2021).

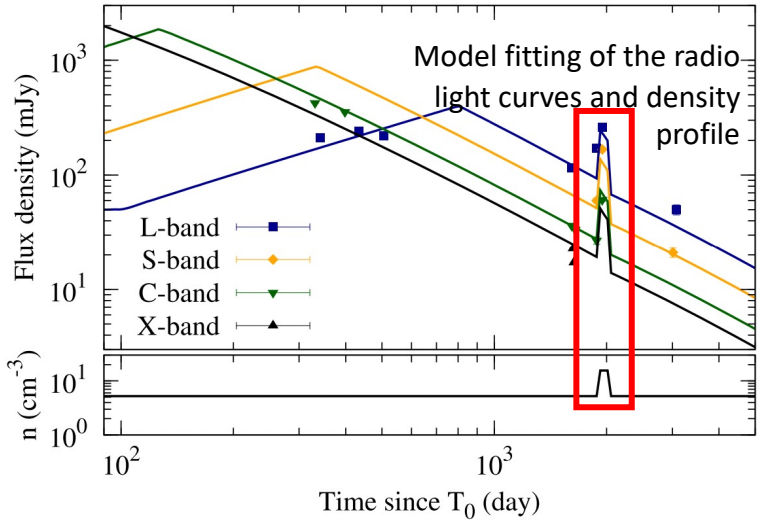
IGR J12580+0134: Nearest TDE event







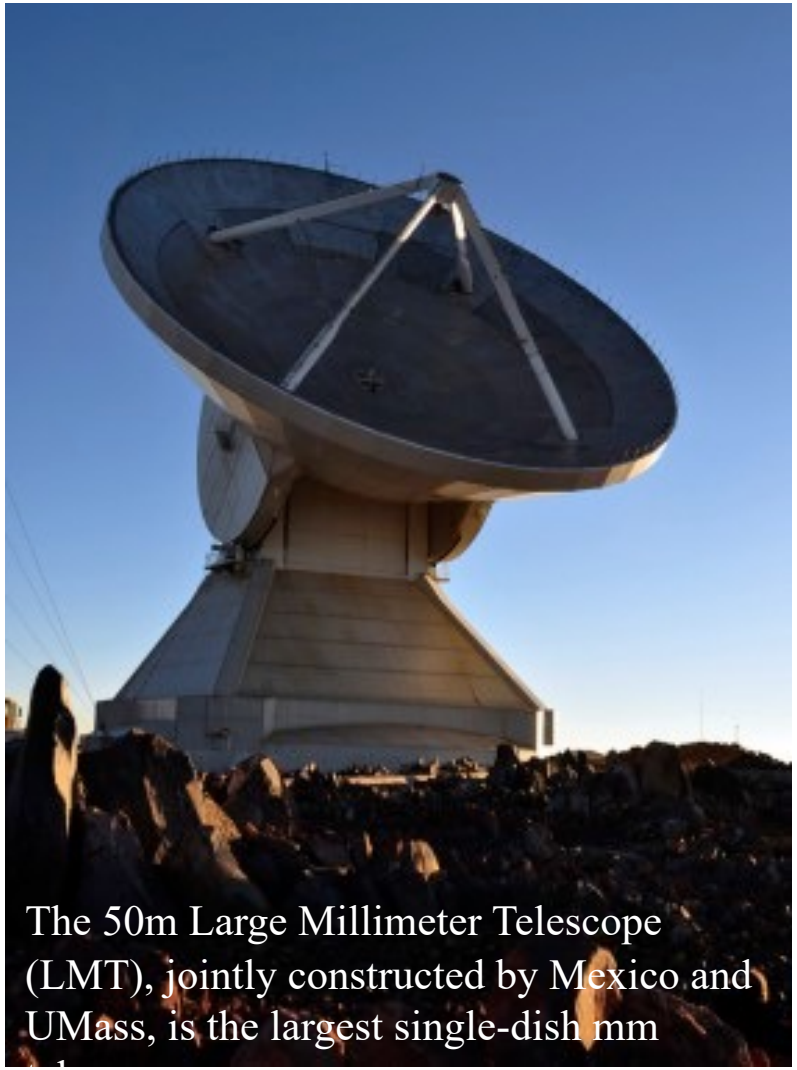
Lei et al. 2016



- Detection of **spatially resolved circular polarization** of the radio emission -- first time for any TDEs
- Decreasing L-band circular polarization from ~2% in 2011 to ~1% in 2015, likely due to the decreasing Faraday depth with time.
- Radio observations can be well explained by jets, **observed off-axis, interact with circumnuclear medium**.

Perlman+(2017,2021)

Need an organized trigger, mm, and radio campaign for TDEs!

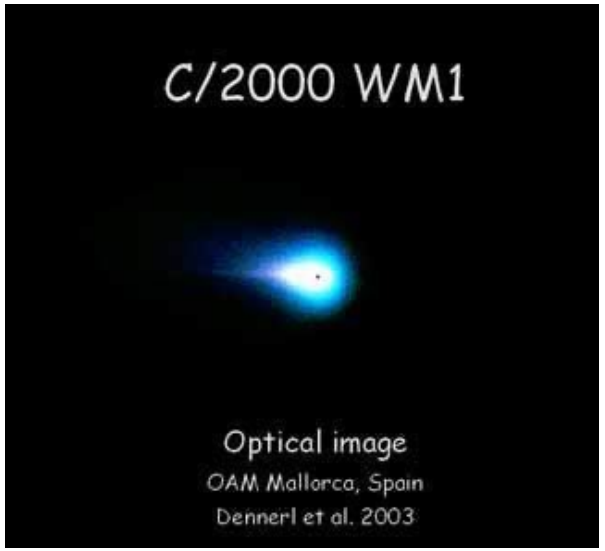

The 50m Large Millimeter Telescope (LMT), jointly constructed by Mexico and UMass, is the largest single-dish mm

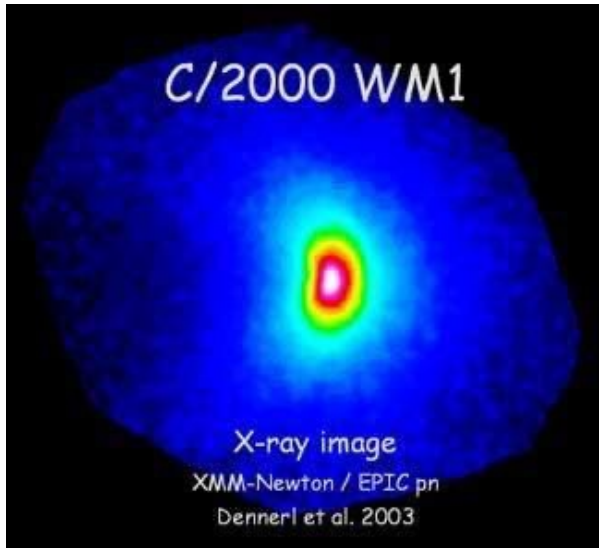
- Triggered by Einstein Probe, Rubin, Euclid, Roman, etc.
- Timely (sub)mm snapshots will help to determine if a jet is launched and its early (radio optically-thick) evolution and to initiate observations at longer wavelengths (e.g., using FAST, JVLA, VLBA, etc.)
- Ideal for studying jet properties (energetics, opening angle, etc.) and circumnuclear medium properties (density and B-field structure, cosmic ray acceleration, etc.)

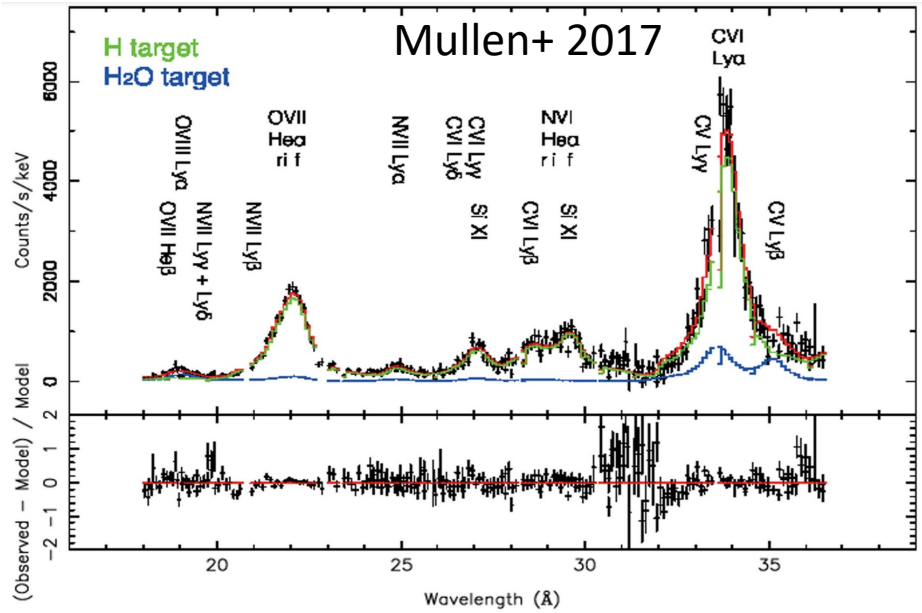
Yuan, Wang+ (2016).

Essentially, everything in a galaxy emits X-ray!

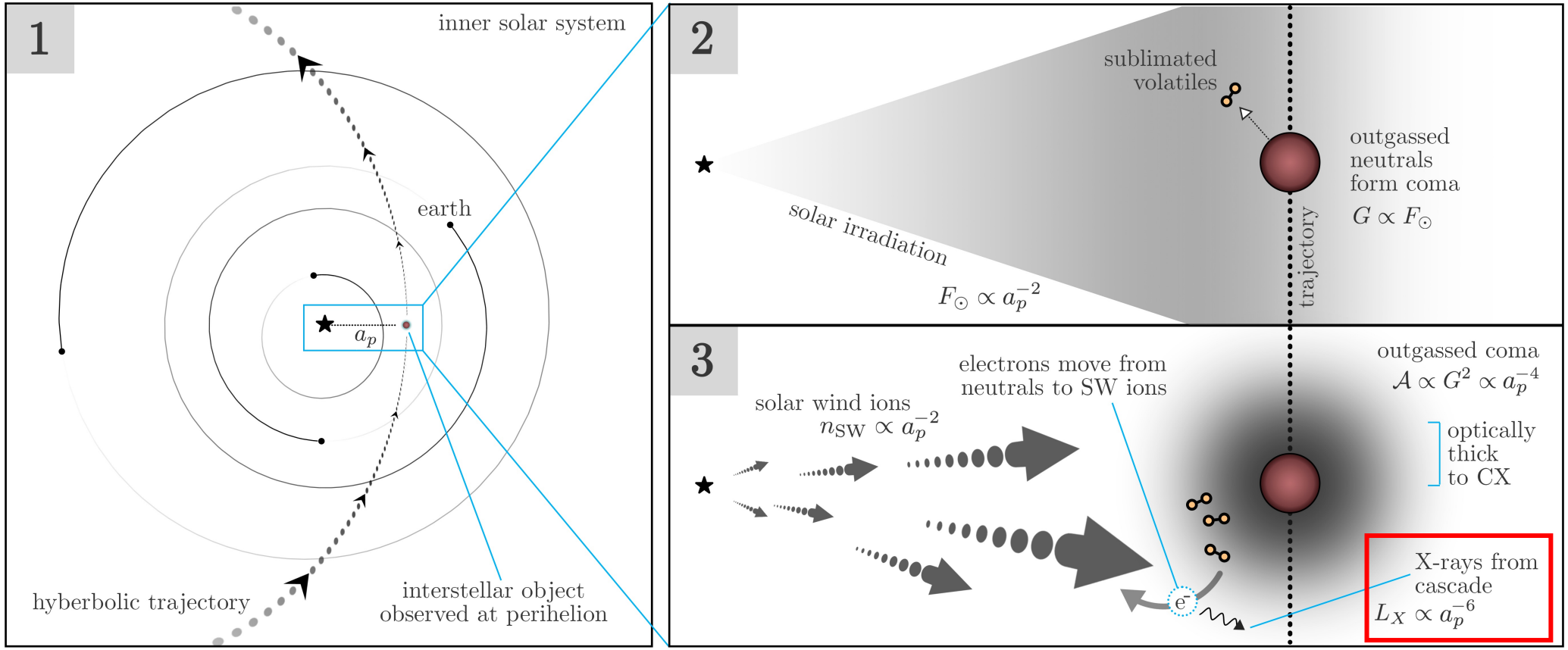
- Including normal stars (e.g., our Sun). Low-mass stars tend to be disproportionally bright in X-ray, because of strong magnetic field activities, affecting the habitability of their planets.
- Even comets can be X-ray emitters due to charge exchange (CX) with solar winds.
- X-ray spectra of comets can be used to probe their chemical composition and hence their origins or even the formation process of the solar system.







X-ray emission of comets via charge exchange



Calbot, Wang, & Seligman (2022)

Interstellar objects (ISOs) from extrasolar systems

- Non-gravitational acceleration are observed, probably due to outgassing.
- Oumuamua, discovered with Pan-STARRS data, could have been detected in X-ray by XMM-Newton during its perihelion passage.
- X-ray detectability, extent, and spectroscopy of ISOs will provide insight into the earliest stages of planet formation in extrasolar systems.
- ~2 ISOs per year are expected from Rubin Observatory (LSST), many of which could be detectable in X-ray, depending on the composition and perihelion distance.
- SMILE may be well suited for observing ISOs (If interested, talk to 纪丽 (Li Ji) at PMO).

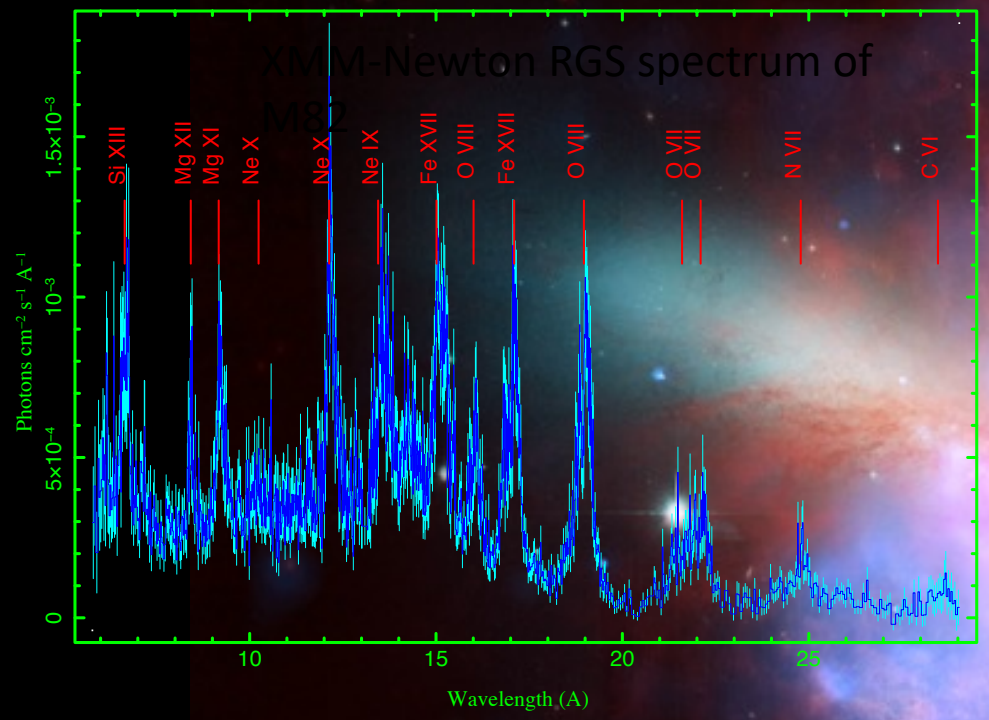
Calbot, Wang, & Seligman (2022)

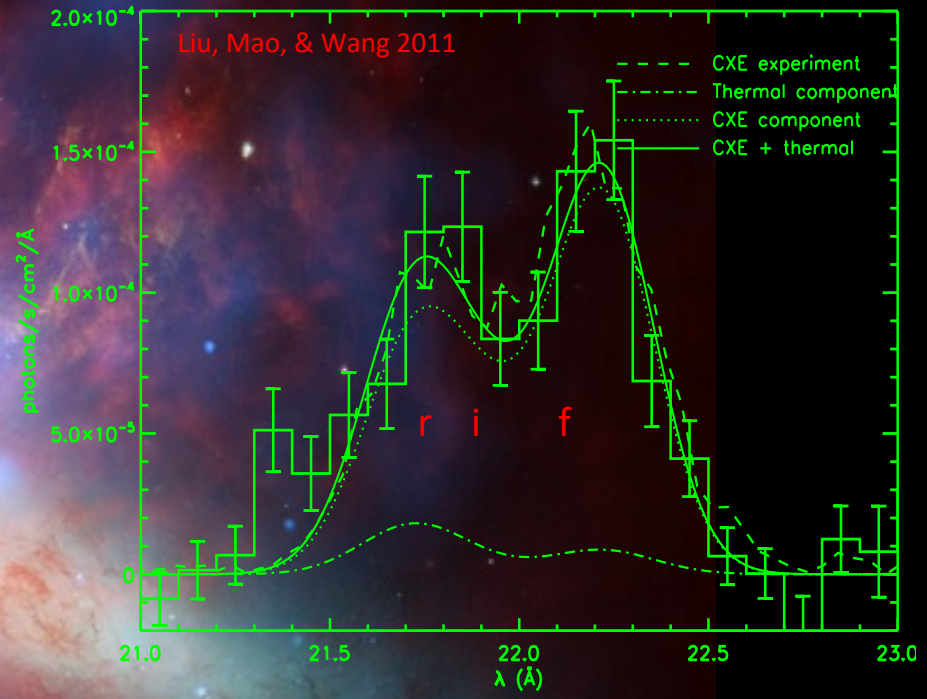
Summary

- X-ray emission in a galaxy traces chiefly stellar end-products or accreting compact stars, SNe, even IMBHs, cataclysmic variables, as well as normal stars and diffuse hot ISM/CGM.
- Variability of X-ray sources, especially AGN, can have strongly effects on the ionization state of diffuse hot ISM/CGM.
- **Well-coordinated mm to radio campaigns** of nearby TDEs will allow for studying the density and magnetic field structures of circumnuclear medium.
- **Via strong gravitational lensing**, X-ray emission can be observed from high-z galaxies, not only AGN, but potentially X-ray binaries as well, collectively or even individually!
- X-ray observations of **interstellar objects** can potentially yield insights into the formation processes of extrasolar systems.

Questions and comments are welcome! wqd@umass.edu; people.umass.edu/wqd

Charge exchange X-ray emission in the ISM





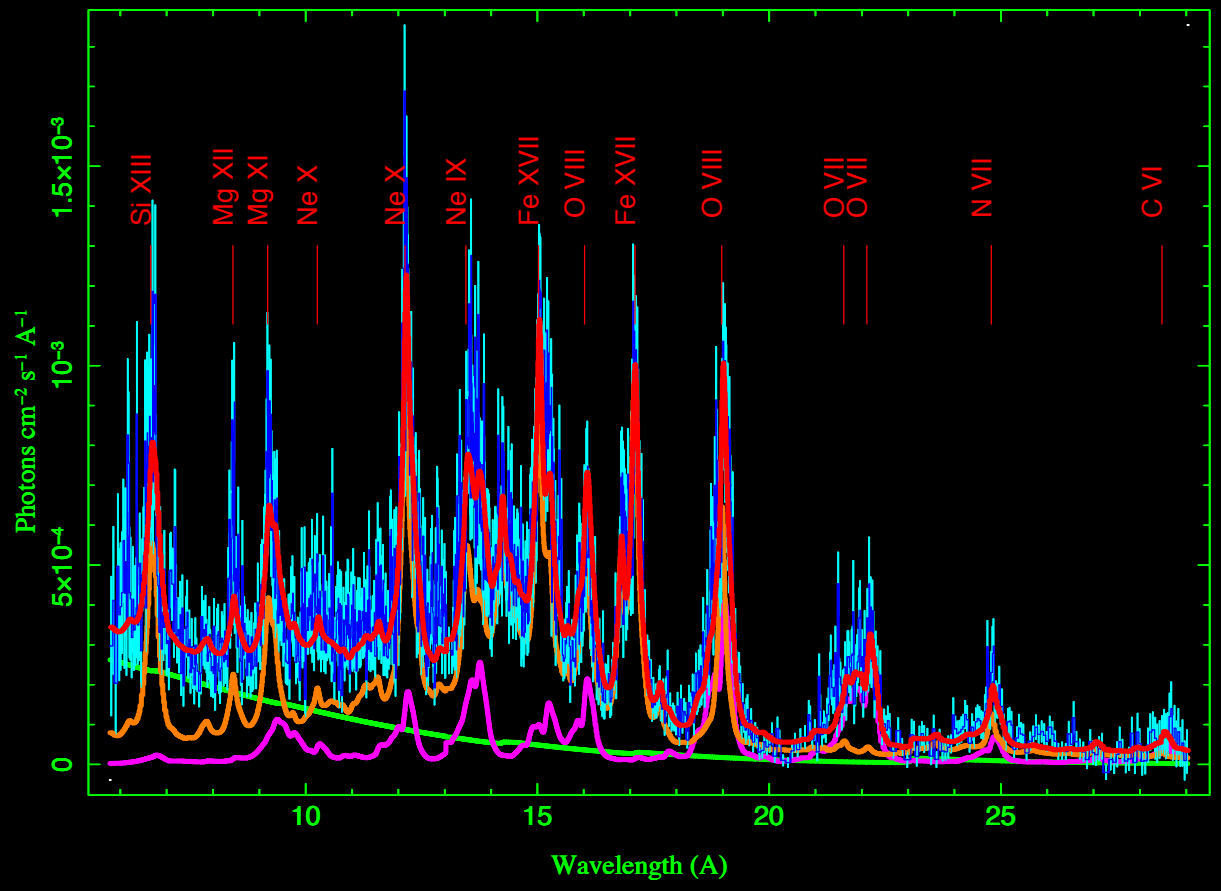
G =(f+i)/r ratios of He-like Kα triplets are far too large to be consistent with optically-thin CIE plasma emission.

Soft X-ray arises at least partly from the interplay between hot gas outflow and entrained cool gas clouds, as part of the mass-loading process

Composite of optical (HST), infrared (Spitzer), and X-ray (Chandra) images

Zhang, Wang, Li, Smith, & Foster (2014)

Thermal plasma+charge exchange modelling leads to diagnostics of interface astrophysics



- Explains the spatial correlation between hot and cool gas tracers.
- Accounting for the CX is important for determining the thermal and chemical properties of the hot plasma.
- CX is proportional to the ion flux and **the effective area of the hot/cold gas interface**.

Zhang, Wang, Ji, Smith, & Foster (2014)