On the Nature of the 0.3-30 keV Spectrum of the Low-Metallicity Starburst Galaxy VV 114 Based on *Chandra*, *XMM*, and *NuSTAR*

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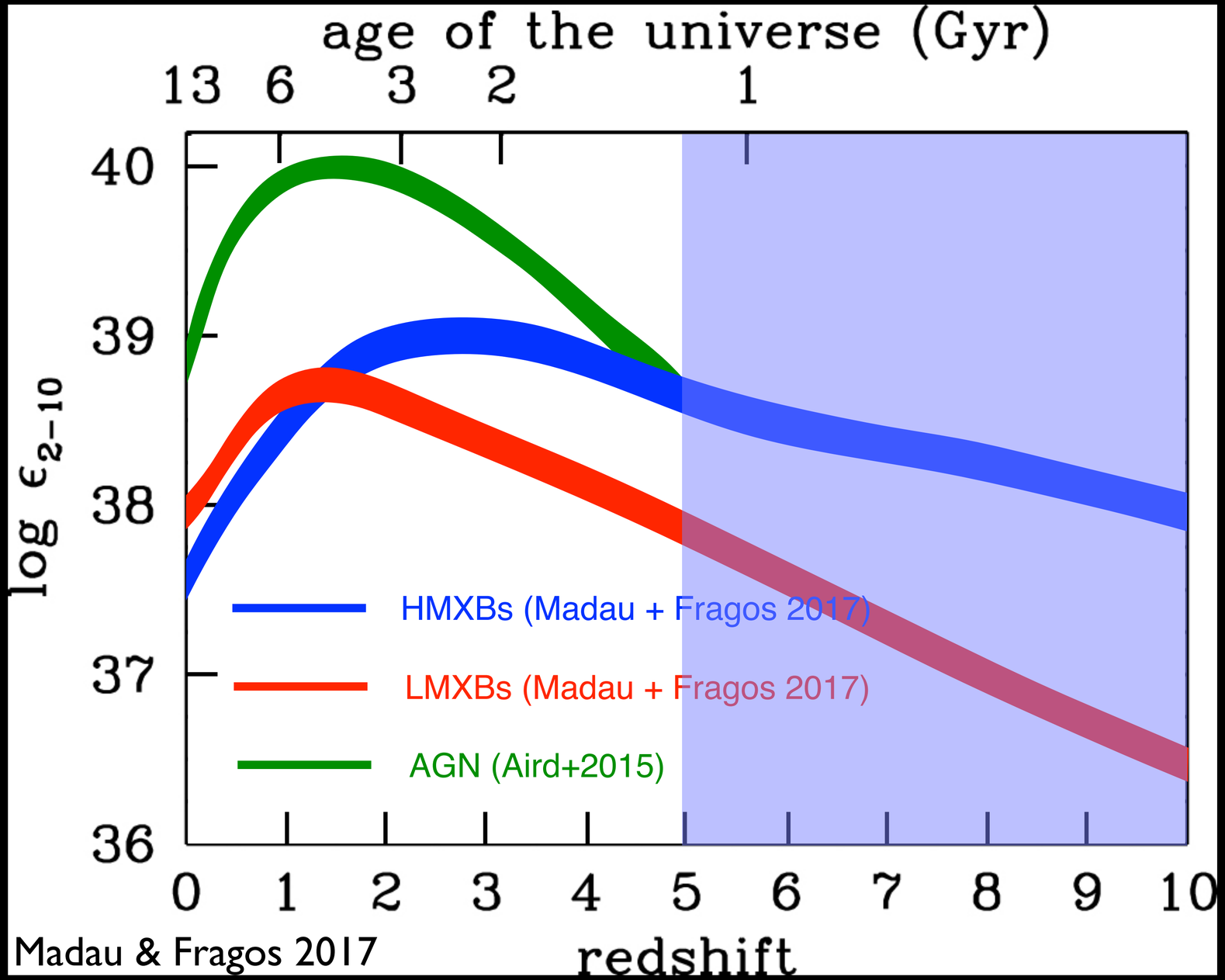
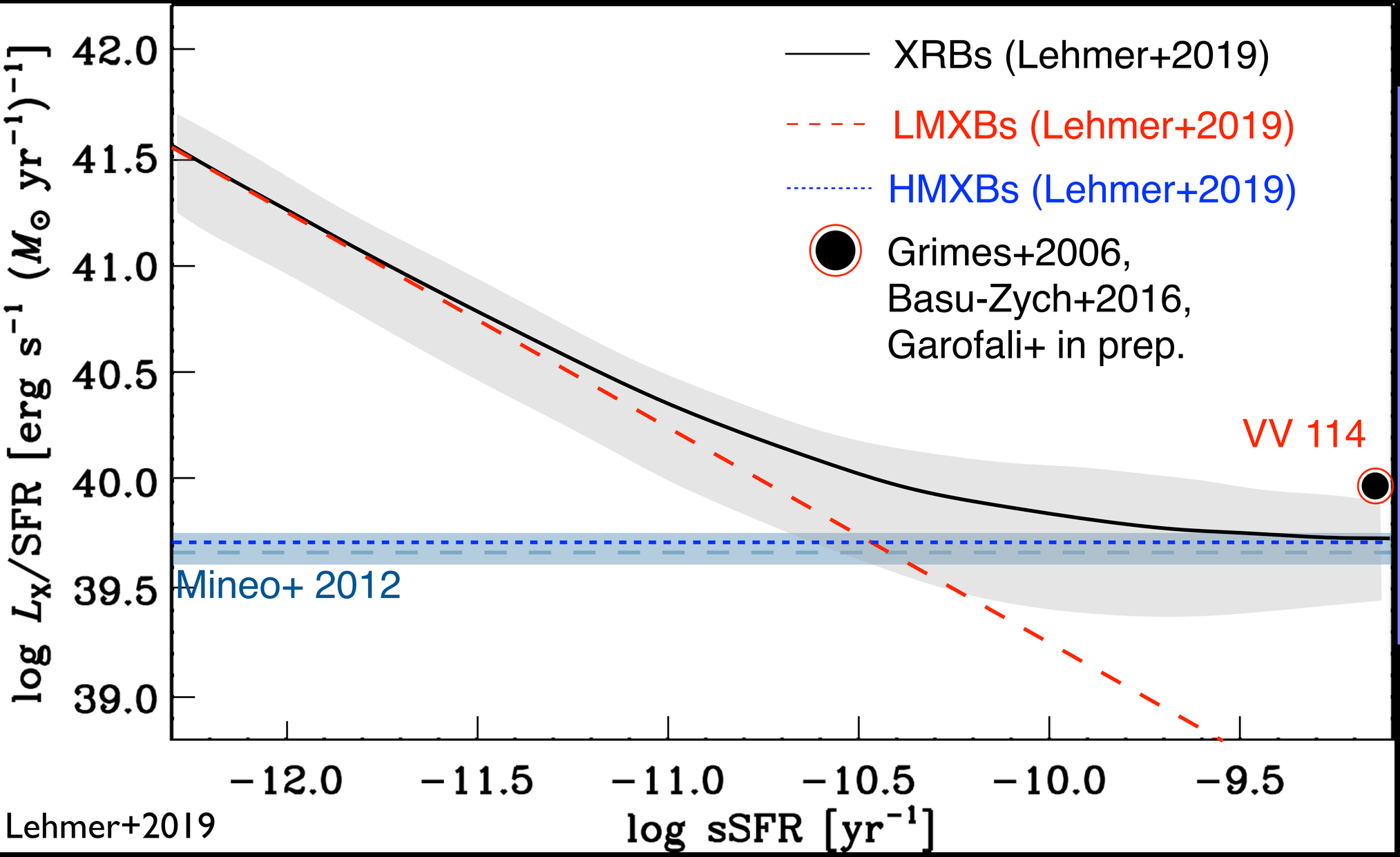
Importance of X-ray Binaries in the Early Universe



Madau & Fragos 2017

- HMXBs dominate normal galaxies at $z \gtrsim 1-2$ (Fragos+2013a, Madau & Fragos 2017)
- Normal galaxy emissivity (XRBs) may dominate AGN at $z \gtrsim 5$ (Fragos+2013b, Madau & Fragos 2017)
  - Declining metallicity and mean stellar population age
- XRB impact on: IGM heating, future 21 cm measurements (e.g., Das+2017, Greig & Mesinger 2017)

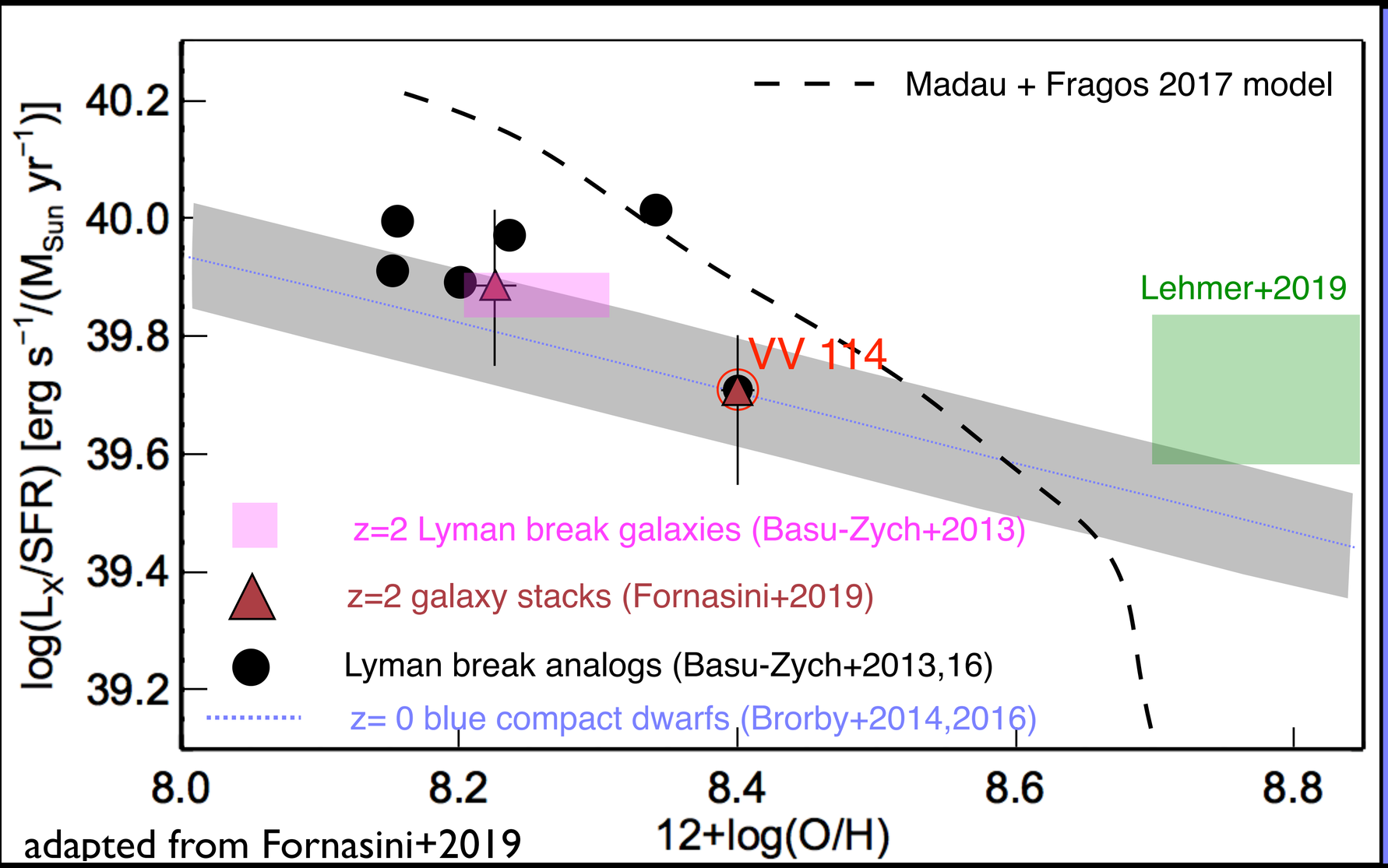
X-ray Binary Populations in Star-Forming Galaxies



- Lx scales with SFR (HMXBs) and stellar mass (LMXBs) (Lehmer+2010,19, Mineo+2012)
- Some galaxies (e.g., VV 114) elevated Lx per unit SFR
  - Overabundance of ULXs a metallicity effect?

note: based on 0.5-8 keV fluxes

Effect of Metallicity on X-ray Binary Populations

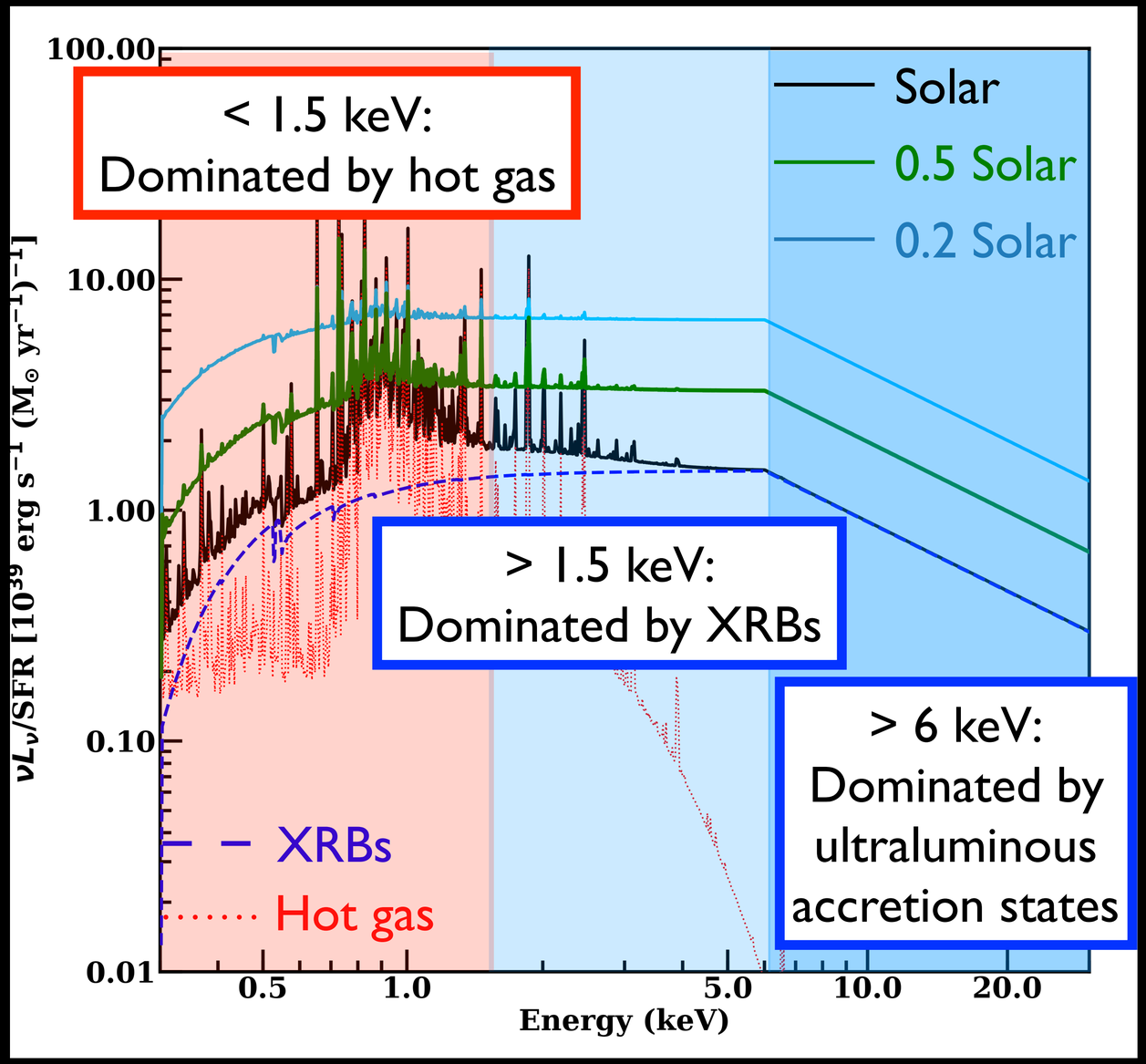


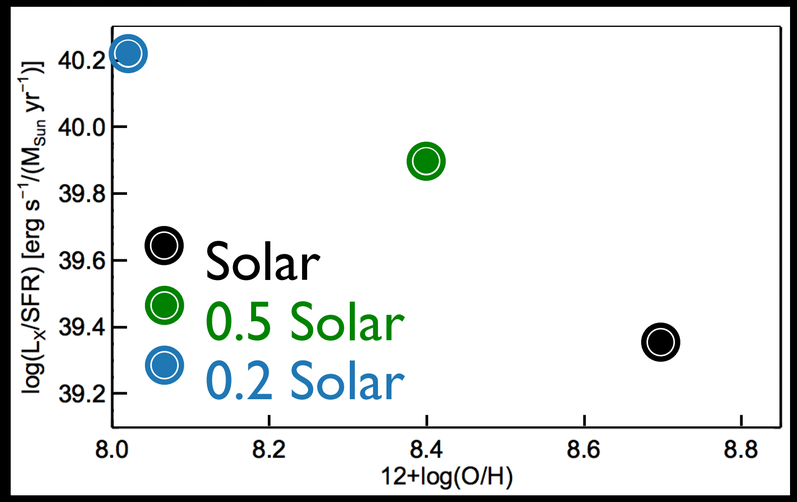
adapted from Fornasini+2019

- Lx per unit SFR *increases* with decreasing metallicity (e.g., Basu-Zych+2013,16, Prestwich+2013, Brorby+2014,16, Douna+2015)
  - Weaker stellar winds —> more massive compact objects (e.g., Mapelli+2010)
  - More compact binaries —> bright RLOF systems (e.g., Belczynski+2010, Linden+2010)
- Lx per unit SFR *increases* with increasing redshift (e.g., Basu-Zych+2013, Lehmer+2016, Aird+2017)
  - Driven by metallicity evolution (empirical: Fornasini+2019, theoretical: Fragos+2013)

note: based on 2-10 keV fluxes

X-ray Binary Spectral Energy Distribution





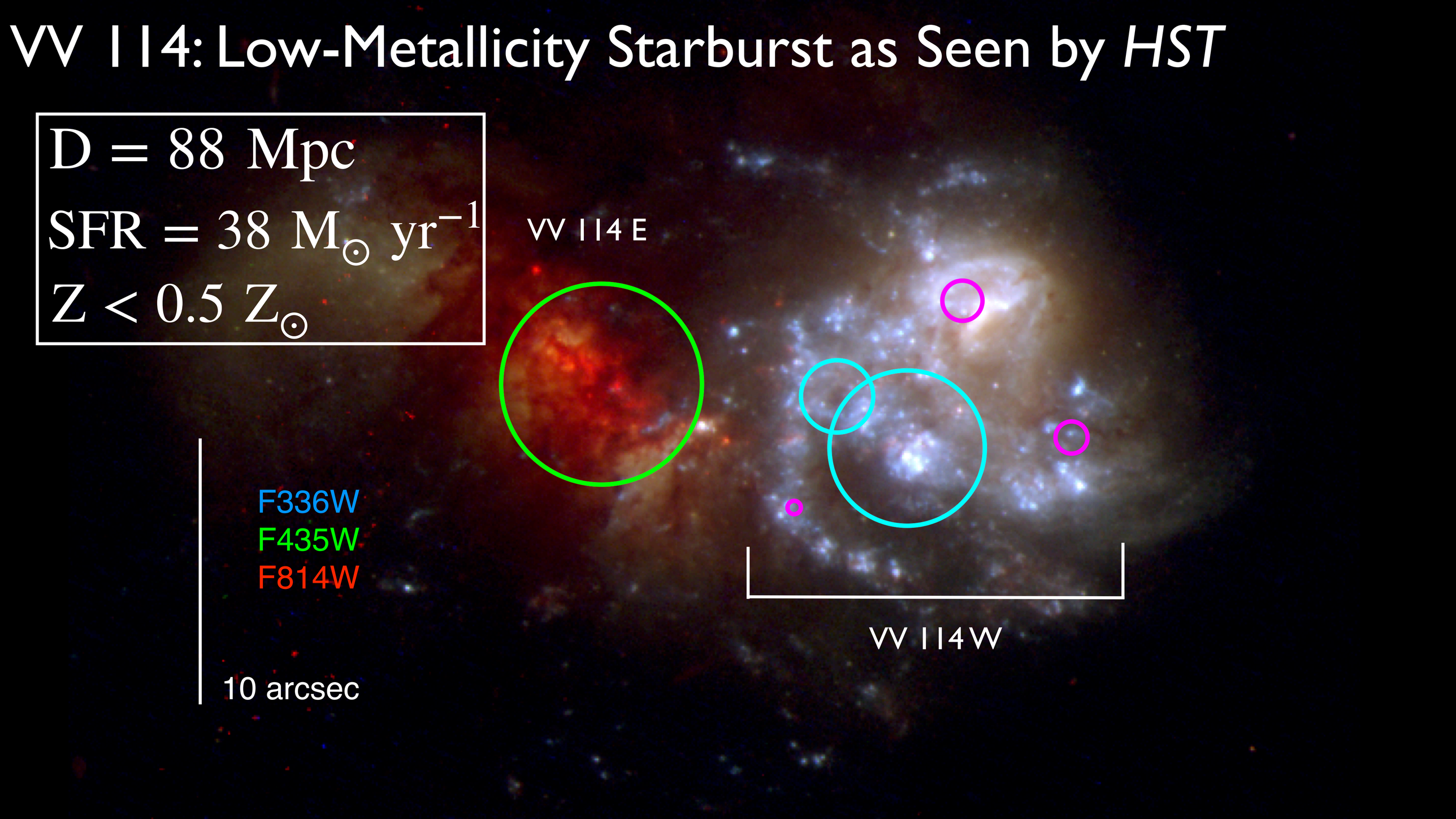
- General SED shape: hot gas + XRBs + ultraluminous accretion states (e.g., Gladstone+2009, Walton+2013,14, Wik+2014)
- Overall SED normalization should vary with metallicity given Lx-SFR-metallicity plane
- How do hot gas and XRB contributions scale with change in metallicity and SFR?
  - VV 114 to constrain low-metallicity SED properties

VV 114: Low-Metallicity Starburst as Seen by *HST*

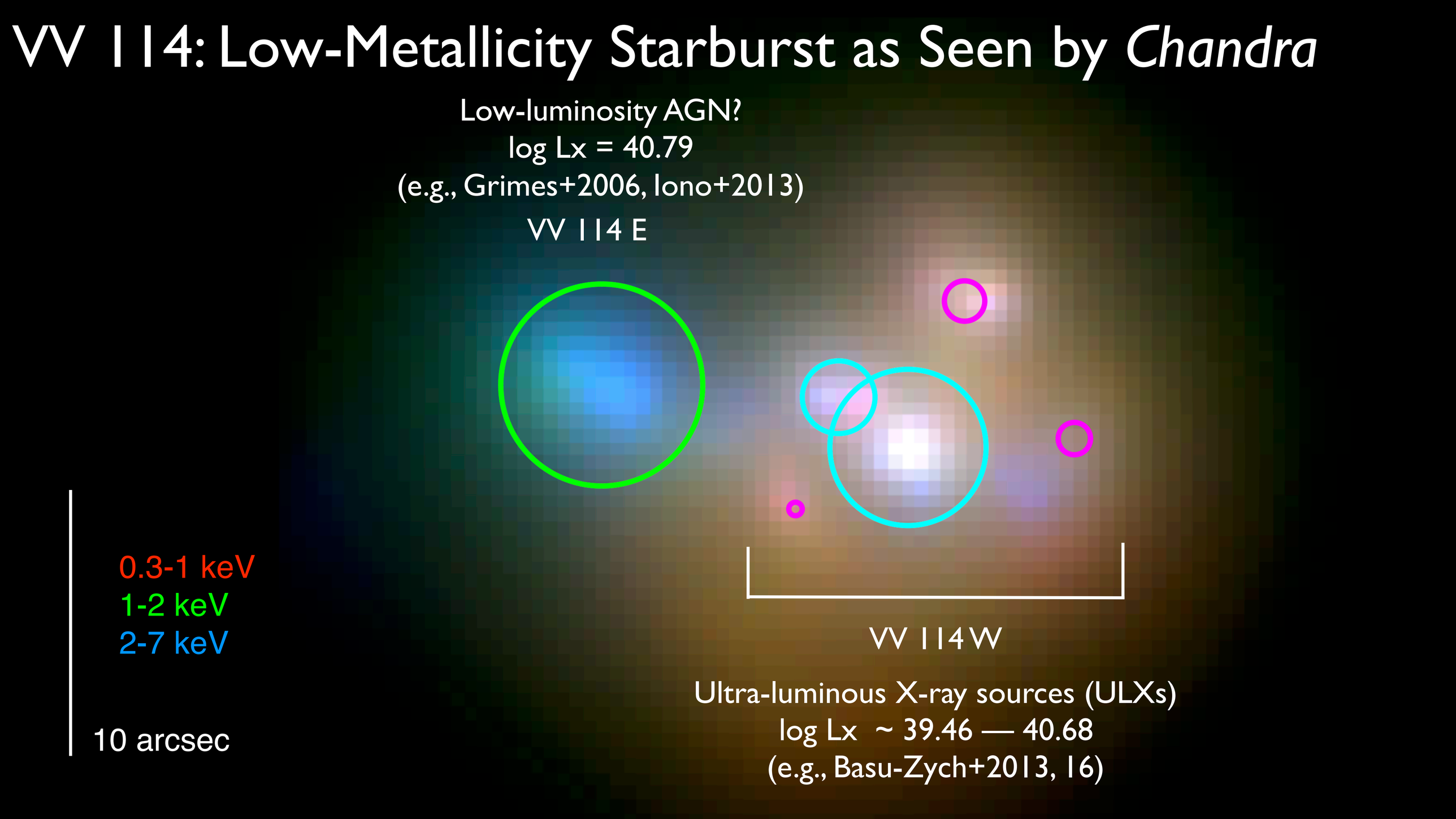
$D = 88$ Mpc

$SFR = 38\ M_\odot\ yr^{-1}$

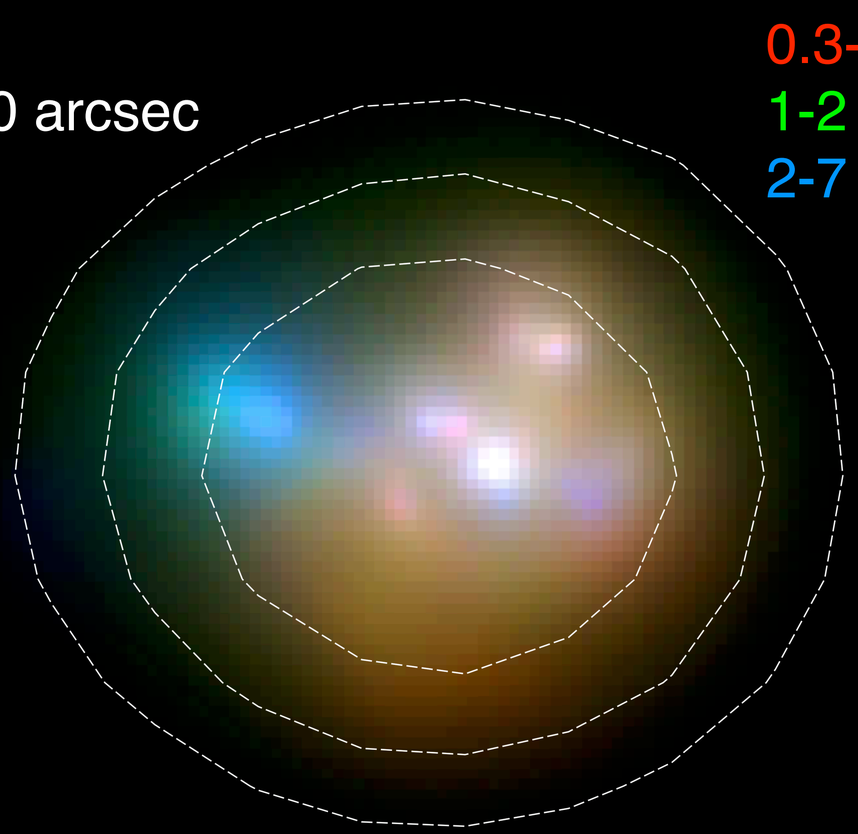
$Z < 0.5\ Z_\odot$



VV 114: Low-Metallicity Starburst as Seen by *Chandra*



Combined Power of *Chandra*, *XMM*, and *NuSTAR*

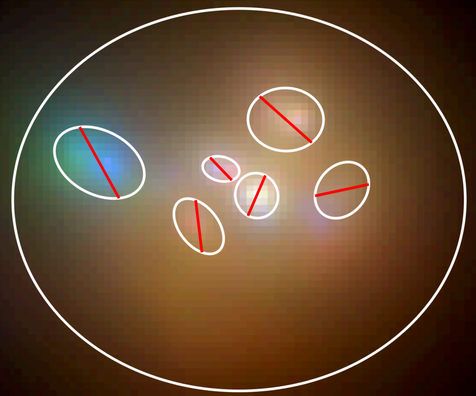


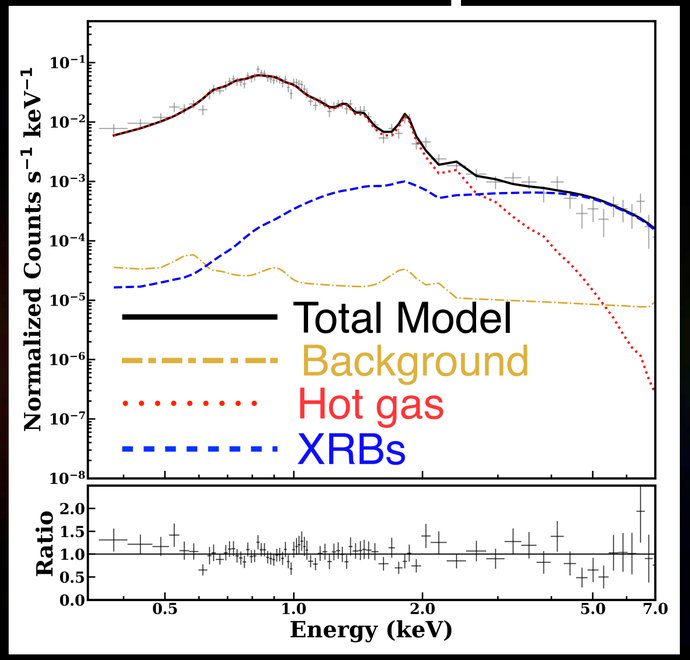
near simultaneous

- 60 ks *Chandra* (PI: Heckman): point source decomposition
- 30 ks *XMM-Newton* (PI: B. Lehmer): hot gas components
- 200 ks *NuSTAR* (PI: B. Lehmer): > 8 keV XRB contribution

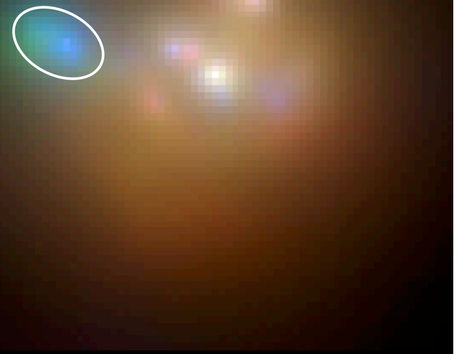
Chandra Point Source Spectral Decomposition

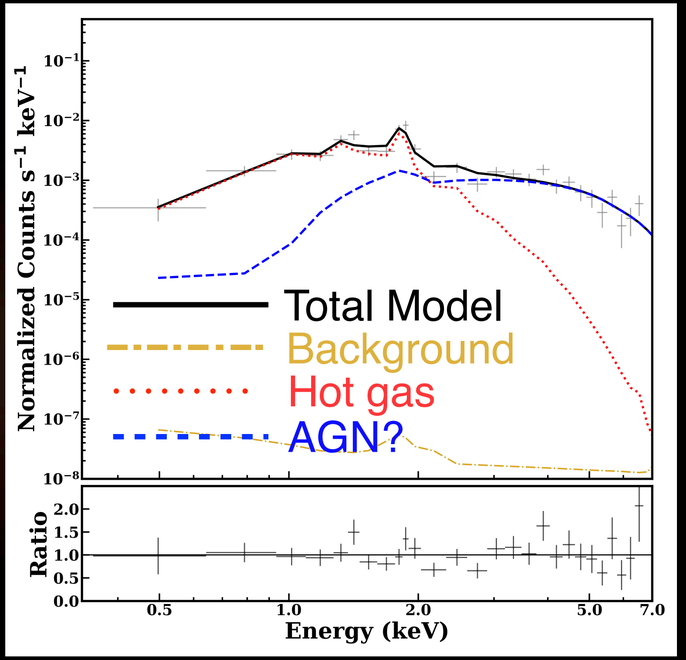
VV 114 Diffuse Emission



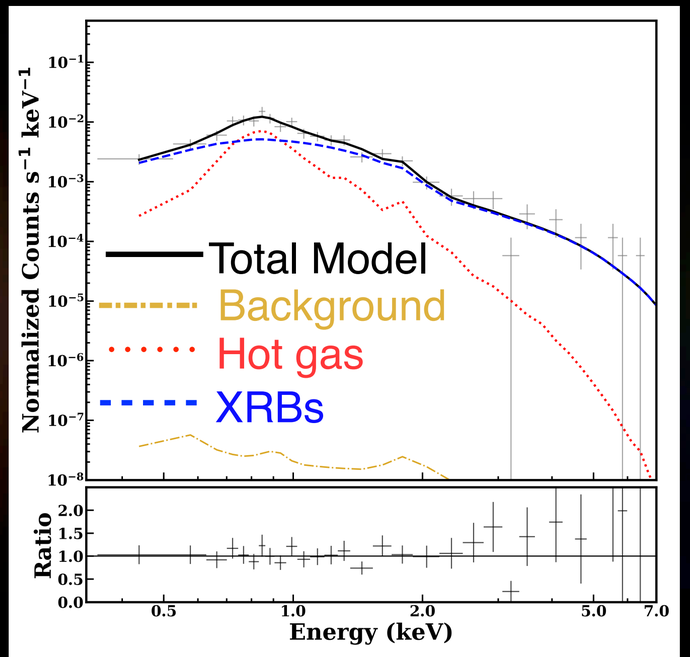


VV 114E: AGN?

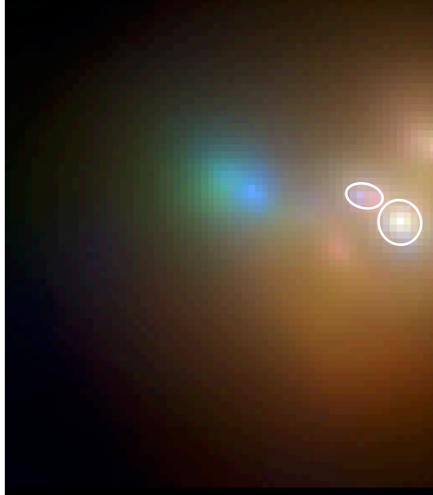


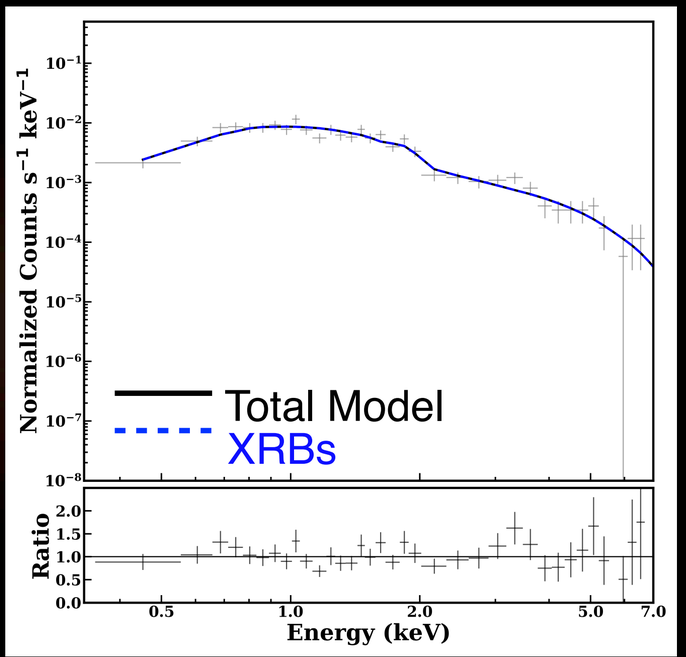


ULX + Hot gas

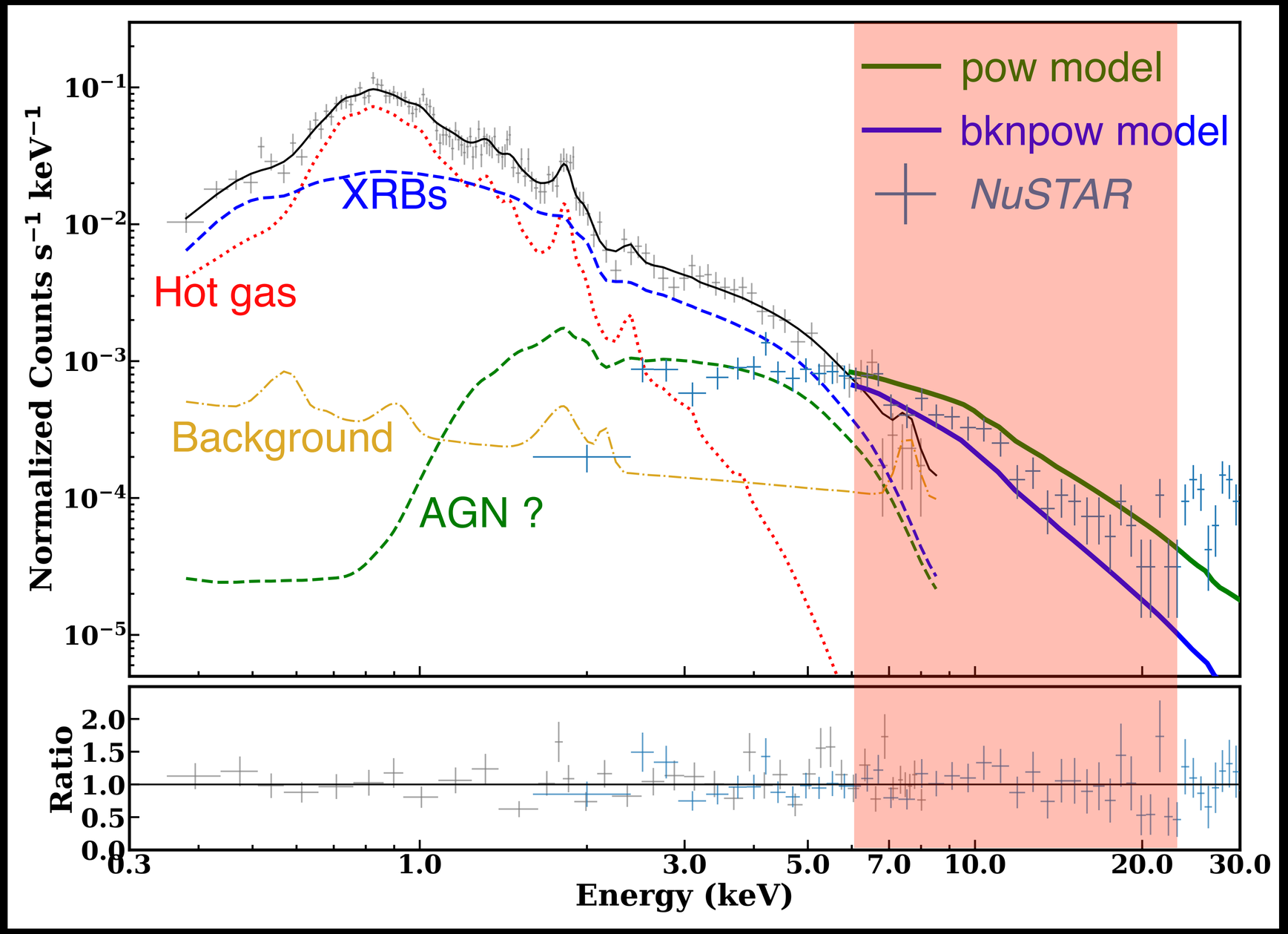


VV 114W: ULX



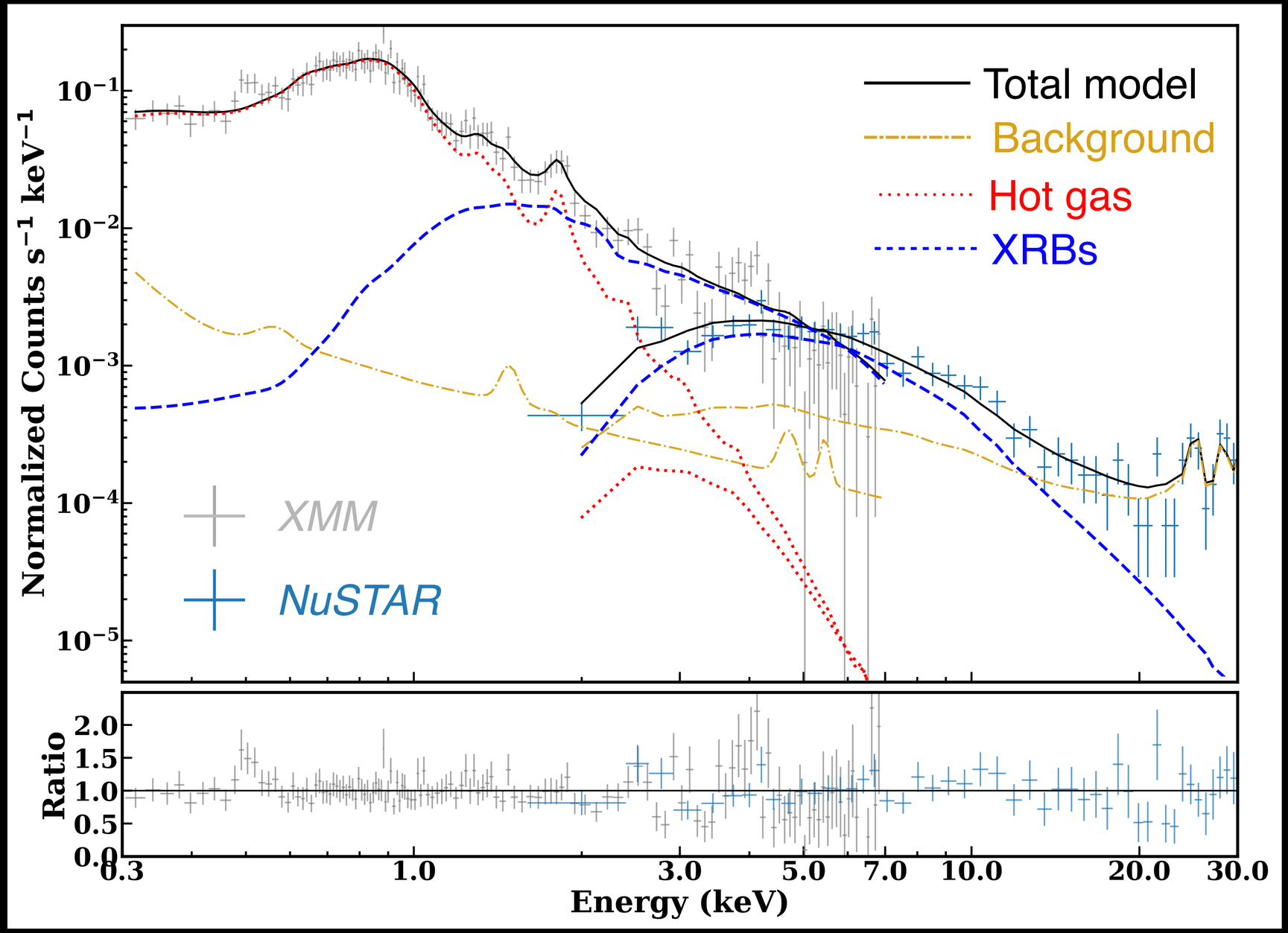


Extrapolating *Chandra* Spectral Fit to *NuSTAR*

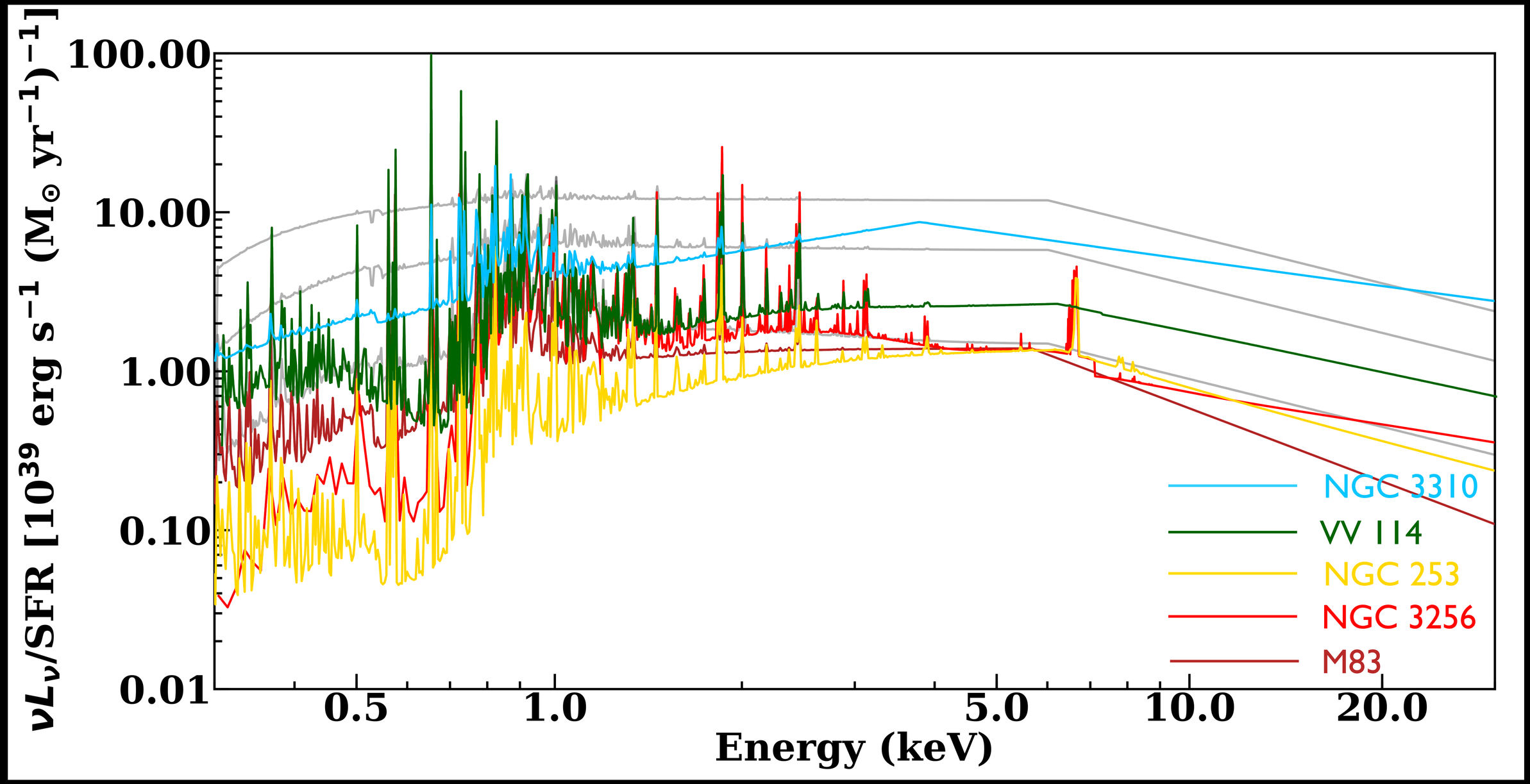


- *NuSTAR* reveals high energy turnover ~ 6 keV
  - Photon indices and turnover consistent with ULX population (e.g., Gladstone+2009)

NuSTAR & *XMM* Reveal Dominant ULX Population

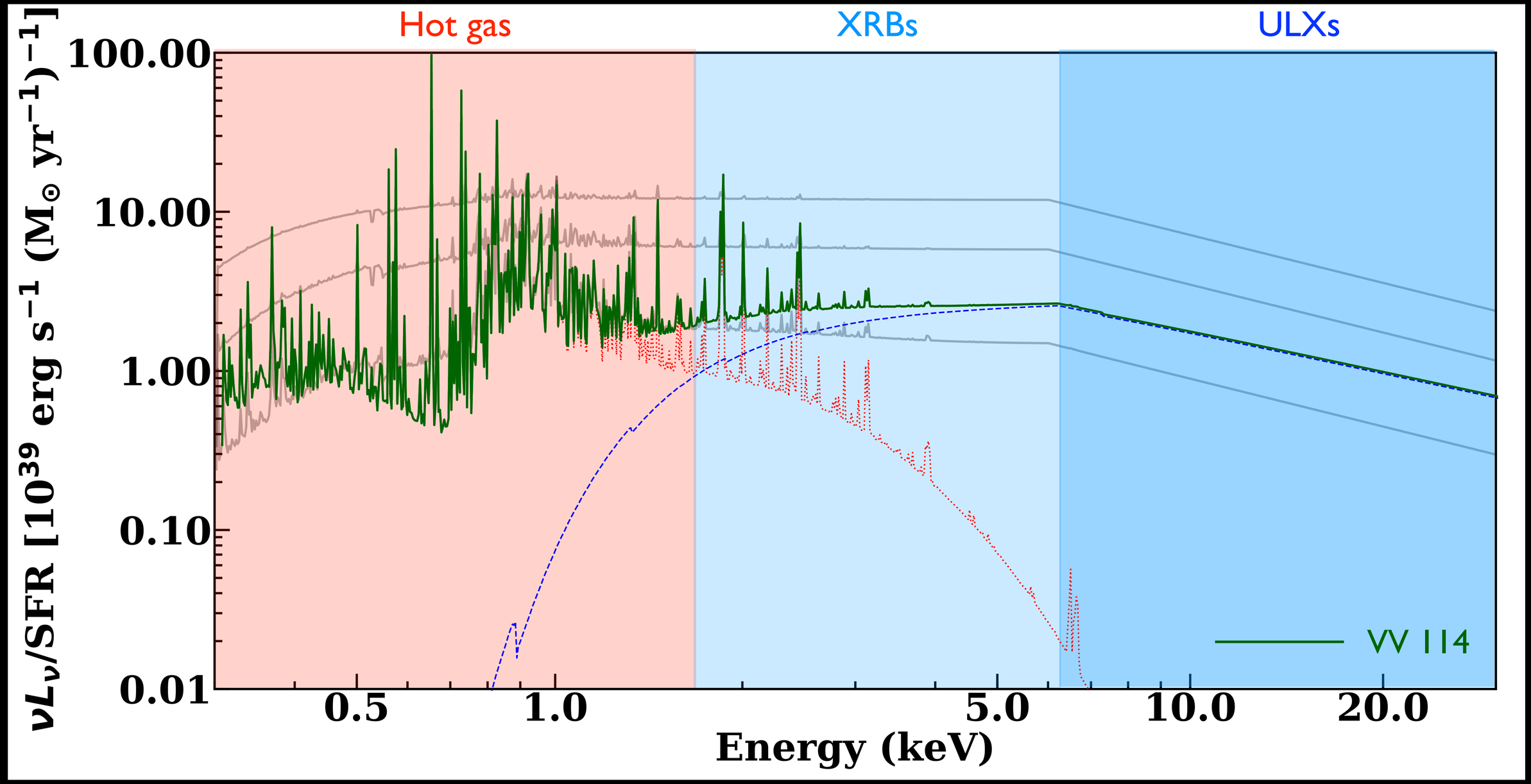


The 0.3-30 keV SED of VV 114



M83, NGC 253: Wik+2014, Yukita+2016; NGC 3256, NGC 3310: Lehmer+2015; VV 114: Garofali+ in prep.

The 0.3-30 keV SED of VV 114



Summary & Future Directions

- Combined *Chandra*, *XMM*, and *NuSTAR* reveal VV 114 spectrum as hot gas + XRBs, with spectral turnover at higher energies
  - Consistent with population dominated by ULXs (e.g., Gladstone+2009)

- VV 114 0.3-30 keV SED shows elevated normalization relative to solar metallicity SEDs
  - Elevated Lx/SFR driven by metallicity —> increase in ULX emission
  - Empirical SED at lower metallicity: conversion for theoretical mass accretion rates from models to XRB emissivity

- Poster by Lacey West: joint *Chandra* & *NuSTAR* constraints on X-ray emission in NGC 7552 for star-forming knots of known SFR and age

- Future directions: empirical constraints on XRB emission scalings with SFR, metallicity, and stellar population age
  - constrain models, improve predictions for importance of XRBs in early universe