GALAXIES
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Galaxy Science with AXIS

• How does gas get into and out of galaxies?
  – How important is hot accretion for L* or larger galaxies?
  – How does star formation/black hole growth regulate itself?
Galaxy Science with AXIS

• Distant
  – Feedback, AGN in galaxies near the peak of SF
  – (ULXs, LBAs as local analogs of high-z feedback; present in the future)

• Local
  – Hot CGM R>50 kpc
  – Low-level AGN feedback, closing feedback cycle
  – (Galactic not-so-superwinds; present in the future)
  – Others?
z>0.5 Galaxies/Feedback

• (How) did feedback shut down intense star formation? What happened to feedback material?
  – Most of the energy in thermal (SNe) feedback is in the X-rays
  – It remains unclear how much wind material escapes $R_{\text{vir}}$
  – What is the hot contribution to the “missing metals” problem (Peeples et al. 2014)?

• Sample:
  – >25 galaxies with SFR>100 $M_\odot$/yr detected with ALMA, SKA, JWST...
  – Nearby ULIRGs, superwind galaxies to better understand low-z analogs
  – Measure $kT$, $Z$ with isothermal models in distant systems

• Why AXIS?
  – High resolution and low background are critical to measuring diffuse hot gas at z>0.5 (especially if there is a quasar)
  – At characteristic temperatures, AXIS can probe to z~1.5 (emission lines are redshifted into the Galactic shadow)
Stellar Mass/Halo Mass vs. Halo Mass

Dwarf Galaxies

Massive Galaxies

Milky Way (most efficient star formation)

Moster+2010

\[ \log_{10}(m/M) \]

\[ \log_{10}(M/M_\odot) \]
Need high luminosity, but also high resolution to isolate diffuse gas
NGC 6240 (a LIRG with LX~$10^{43}$ erg/s) is a local analog to galaxies common at $z>0.5$. 
Project NGC 6240 to $z=0.5$, $z=1.0$
Arp220 (ULIRG) is a fainter analog

Project Arp220 to $z=0.5$, $z=1.0$
AXIS can resolve a quasar in a ULIRG at z=1...
Chandra barely does

(X-ray binaries must be accounted for spectroscopically)
Hot CGM

• Competing claims of baryon closure in the CGM:
  – Mostly hot (>10^{11} M_\odot; Gupta et al. 2011; Faerman et al. 2016; Nicastro et al. 2016; Planck Collaboration XI, 2013)
  – Mostly warm (2\times10^{11} M_\odot; Werk et al. 2014)
  – Not closed (Bregman et al. 2017, subm.)
• Uncertainty in hot mass from radial profile for R>50 kpc
  – Take \beta-model around Milky Way, which is a good fit at R<50 kpc:
    • Shallow slope (\beta\sim0.2-0.3) \rightarrow baryon closure (Faerman et al. 2016; Nicastro et al. 2016)
    • Steep slope (\beta\geq0.5) \rightarrow <10^{10} M_\odot (Miller & Bregman 2015; Hodges-Kluck et al. 2016)
  – External galaxies consistent with \beta\sim0.5 (e.g., Anderson & Bregman 2011), but at R<50 kpc
• Solve the problem by measuring \beta(R) to >0.5 R_{vir}
  – Isolated, L* or bigger galaxies (v_c > 240 km/s, \sigma>200 km/s) within a few hundred Mpc (<10 early-type, <10 late-type)
• Why AXIS?
  – Low background, high A_{eff} and high resolution to remove all contaminating point sources (first two more important)
  – Can measure to R\sim150 kpc in \sim100 ks
• Fit to whole halo >15 kpc is sufficient to get metallicity for a quasi-isothermal hot halo
The hot mass inferred from massive spirals differs from the expectation from the stacked SZ sample of central galaxies. (How) are massive spirals strange?
ISM: \( kT = 0.3 \) keV, \( Z = 0.3 \), \( L_X = 1 \times 10^{40} \) erg/s, \( \beta = 0.5 \), \( r_c = 3 \) kpc \([d=100 \text{ Mpc}]\)

Bkg: Snowden SXRB (Local Bubble, Galactic Halo, CXB)

NXB: LEO or HEO

**AXIS** performs much better than Chandra because of higher soft \( A_{\text{eff}} \), lower NXB
AXIS allows direct measurement to about 80 kpc.

A more sophisticated approach (e.g., Anderson & Bregman 2014) can reach ~150 kpc. This is sufficient to determine changes in $\beta$ with radius.
100 ks with AXIS distinguishes between solar, 0.2 solar metallicity from accreted material or feedback ejecta.

For large areas, the SXRB must be included in the fit (i.e., no on-field subtraction)
AGN Feedback in Galaxies

• Massive galaxies need AGN feedback; it may occur in small galaxies

• How is feedback tuned in low-mass halos?
  – Survey of gas-rich, early-type galaxies within d<200 Mpc
  – Census of kpc-scale cavities

• How is the feedback cycle closed?
  – Mini-survey of massive early-type galaxies to measure kT, Z on <kpc scales and search for sites of rapid cooling (t_{cool}/t_{ff} < 10)
  – Athena pathfinder

• Why AXIS?
  – 0.3” resolution, soft A_{eff}, low background isolate the hot gas near the galactic center
  – Contamination from LMXBs is the major problem at small R
Cavity “power” is correlated with X-ray luminosity (in groups and clusters)

Cavity size is correlated with distance from the AGN (including in individual galaxies)
Near the center, XRBs can confuse deep images

**ISM:** \(kT=0.8 \text{ keV}, Z=1, L_X=2 \times 10^{40} \text{ erg/s}, \beta=0.5, r_c=2 \text{ kpc}\)

**XRBs:** Gilfanov et al. (2004) XLF, \(L_{\text{tot}}=10^{40} \text{ erg/s (10^{11} M_\odot)}\), Sérsic \(n=4, \Gamma=1.8, N_H=10^{21} \text{ cm}^{-2}\)

**AGN:** \(10^{40} \text{ erg/s, } \Gamma=1.8, N_H=10^{21} \text{ cm}^{-2}\)

**Bkg:** Snowden SXRB (Local Bubble, Galactic Halo, CXB)
A “color” analysis is feasible, and strongly improved by removing more XRBs.
Do Weak Winds Matter?

• Several wind models (cf. Heckman 2017)
  – Thermal winds (SNe driven)
    • Adiabatic, radiative flavors
  – Cosmic ray-driven winds
  – Radiation pressure from ISRF
  – They are not mutually exclusive, nor on/off

• Need high resolution, high sensitivity to see the less spectacular winds, relic winds
  – AXIS acts as an Athena pathfinder

• Edge-on galaxies are the best place to look, but still need high resolution (for XMM, the 90% EEF is often wider than the galaxy disk)
XMM-Newton reveals a relic outflow around NGC 891, a nearby (d=10 Mpc) Milky Way analog (Hodges-Kluck et al., in prep). NGC 891 is the X-ray brightest normal galaxy—is this common?