A 5% determination of the local black hole occupation fraction

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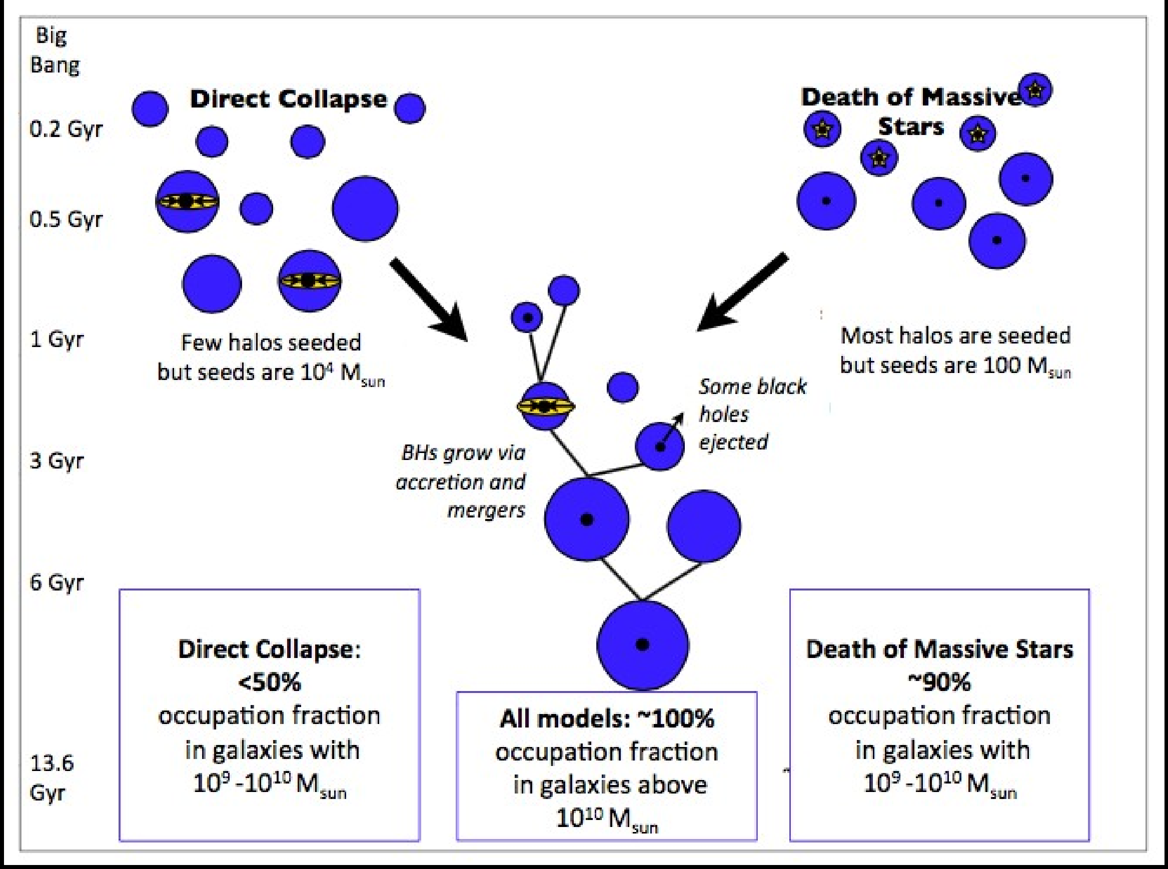
Local BH occupation fraction (f_{occ})

Adapted from Greene 201

Measure of f_{occ} in nearby, low mass galaxies:

- Provides z=0 constraints to numerical simulation work, black hole mass function, and local scaling relations
- May discriminate dominant seed formation mechanism at high z



Observationally need:

- Unbiased sample, clean accretion-powered activity diagnostics
- Broad stellar mass range
- Low Eddington ratios (<<1e-3)

X-ray constraints

- Active fraction => **lower limit** to occupation fraction ($f_{active} < f_{occ}$)
- Observations of nearby active nuclei down to ~1e-8 L_{Edd} indicate a linear relation between $\log(L_x)$ and $\log(M_*)$, with Gaussian scatter
- Since non detections could result from either insufficient sensitivity or the real absence of a BH, fitting simultaneously for the relation's slope and scatter allows to convert f_{active} into f_{occ}

Miller+ 2015

https://arxiv.org/abs/1403.424

1. Assess presence of a relation of the form $L_X \propto A \times M_*^{\alpha}$ and intrinsic scatter σ for the observed sample.
2. Simulate n galaxies with same mass distribution and best-fitting $L_X : M_{star}$ relation as the observed sample.
3. Assume occupation fraction model; Consider fractions bounded by:

$$f_{occ} \cong 0 \text{ for } M_{star} < 10^7 M_{sun}$$

$$f_{occ} \cong 1 \text{ for } M_{star} > 10^{10} M_{sun}$$

and probability of hosting a massive BH:

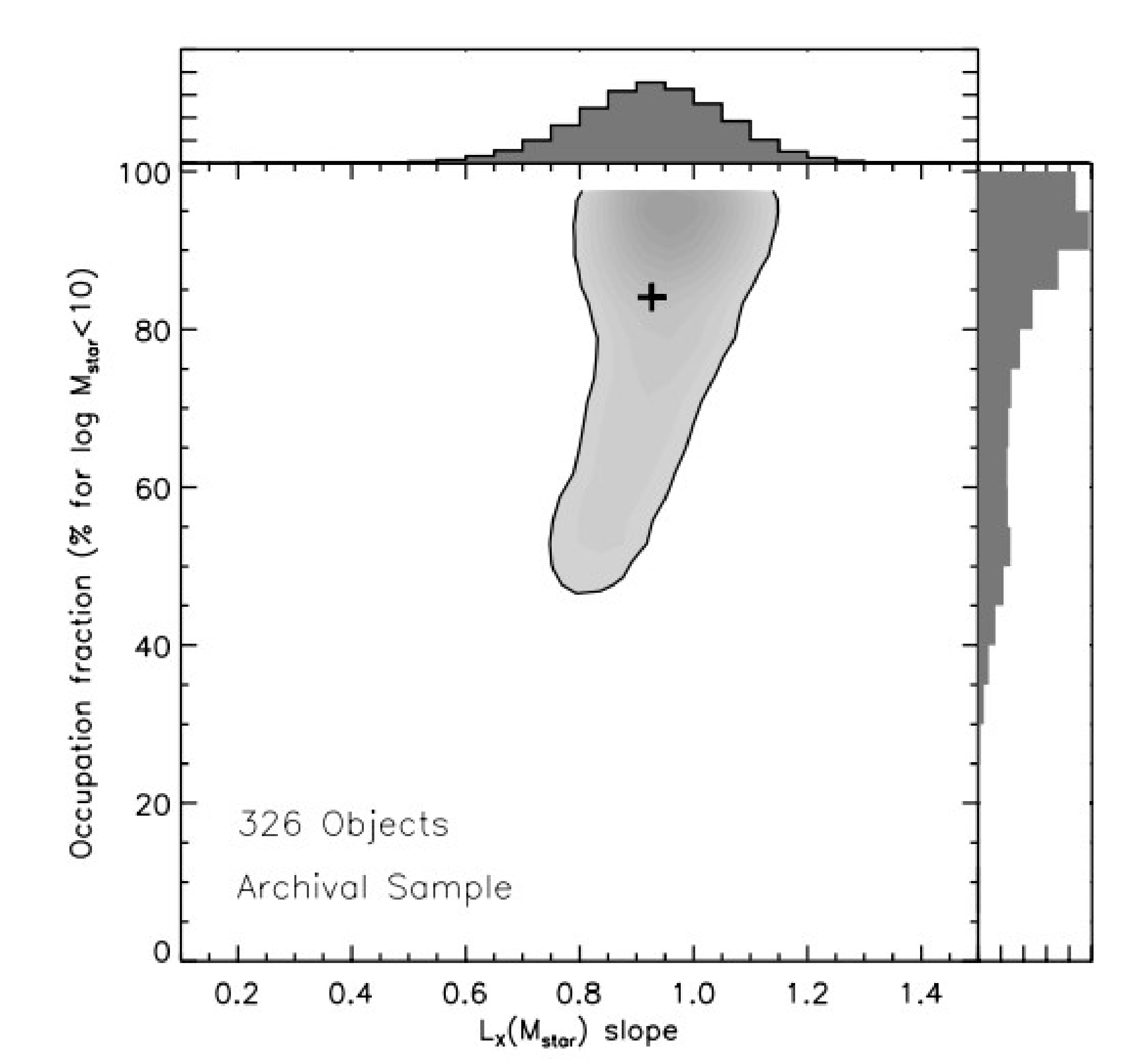
$$0.5 + 0.5 \times \tanh\left(2.5^{|8.9 - \log M_{star,0}|} \log \frac{M_{star}}{M_{star,0}}\right)$$

4. Set detection threshold(s) $\mathcal{L}_{Xlim}$
5. Populate simulated galaxies with BHs according to model curves, setting $Lx \leq \mathcal{L}_{Xlim}$ for galaxies with no BH.
6. Fit simulated sample for occupation fraction (via $M_{0,star}$), and $L_X : M_{star}$ relation (via A, α, and σ).

Occupation fraction vs. Lx:M$_*$ slope: Chandra constraints

- Posterior distribution of the L_x:M_* slope vs. f_{occc} for host stellar masses below $M_* < 1e10\ M_{sun}$
- **f_{occ} > 45% (68% C.L.), with f_{occ} < 25% being ruled out with 99% confidence** (based on 326 nearby early types with Chandra imaging data)

Gallo, Wu+, in prep.



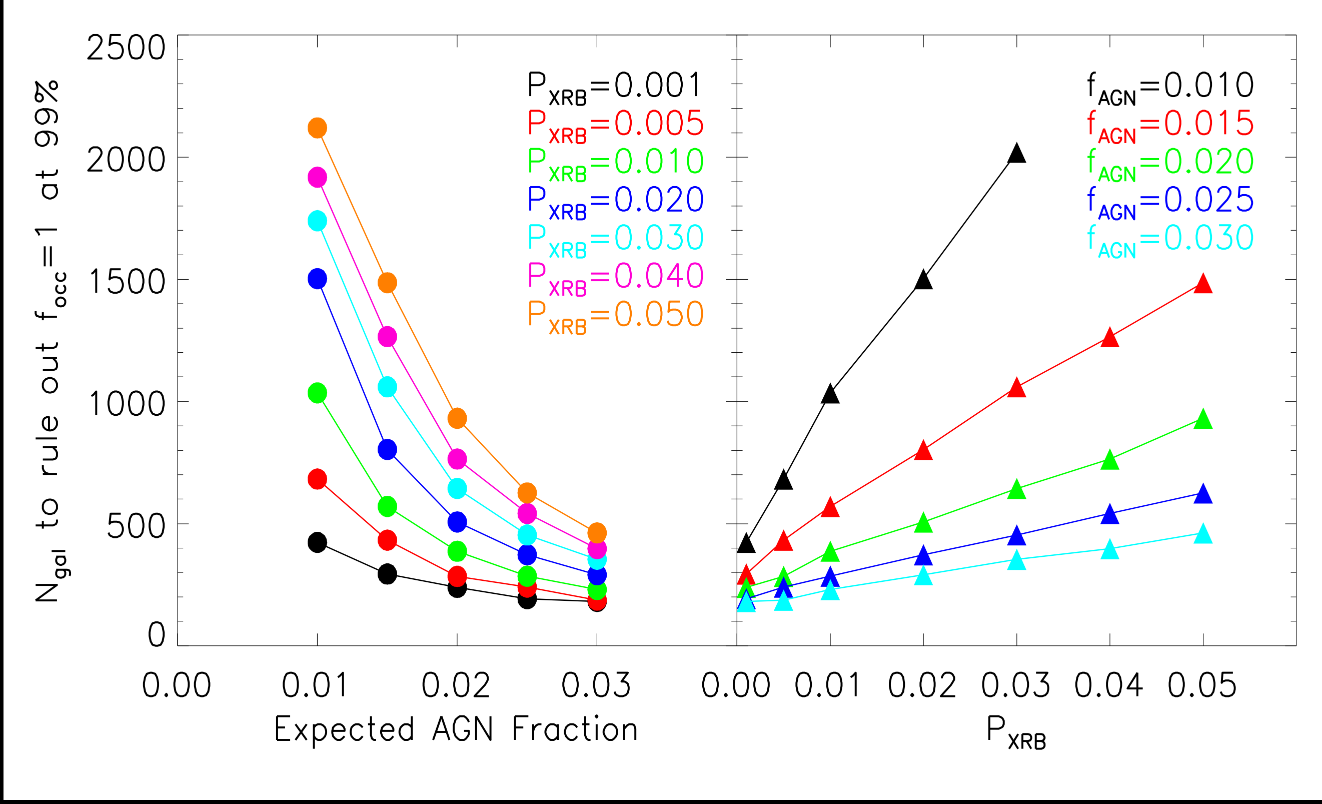
XRB contamination

- Main complication is contamination from high Eddington ratio X-Ray Binaries (XRBs)

$$N_{\rm gal}^{\rm need} \propto P_{\rm XRB}[(L_{X,\rm thresh} - \bar{L}_X)/\sigma]^{-x}$$

P_{XRB} depends on

- fraction of enclosed light (which in turn depends on distance)
- sensitivity (in L_X)
- spatial and luminosity distribution of XRBs (well known; Lehmer+ 2010, 2014 and refs. therein)

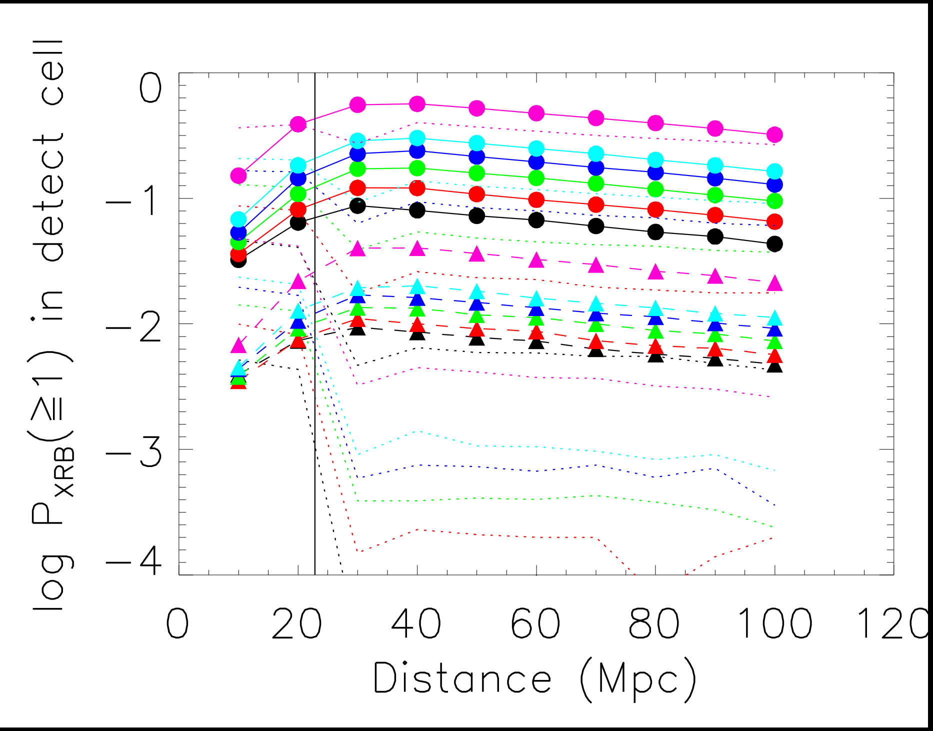


Foord+ 2017

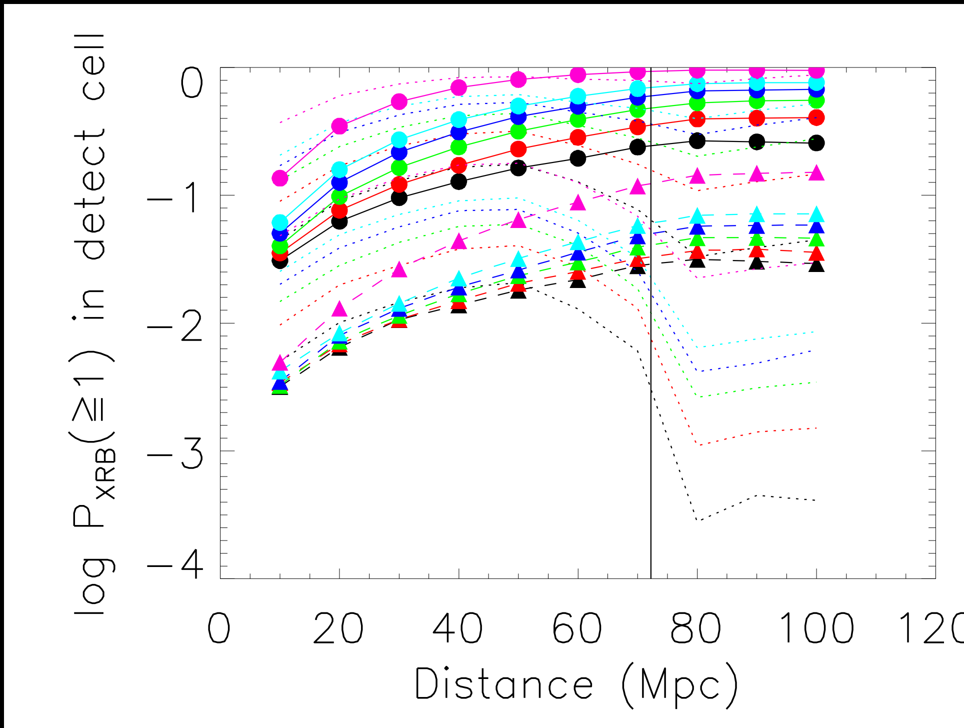
XRB contamination

- 10^5 galaxies with tot. $L_{X,XRB}$=9e28 (M_*/M_{sun})erg/s
- Likelihood of detecting at least 1 nuclear XRB for M_*=1e9 and 1e10 M_{sun} galaxies (triangles and circles) as a function of distance and for resolution θ[0.1-1] arcsec (different colors) assumes A_{eff}=1m^2 and 2 keV photon energy

L_X=1e37 erg/sec



t=10 ksec



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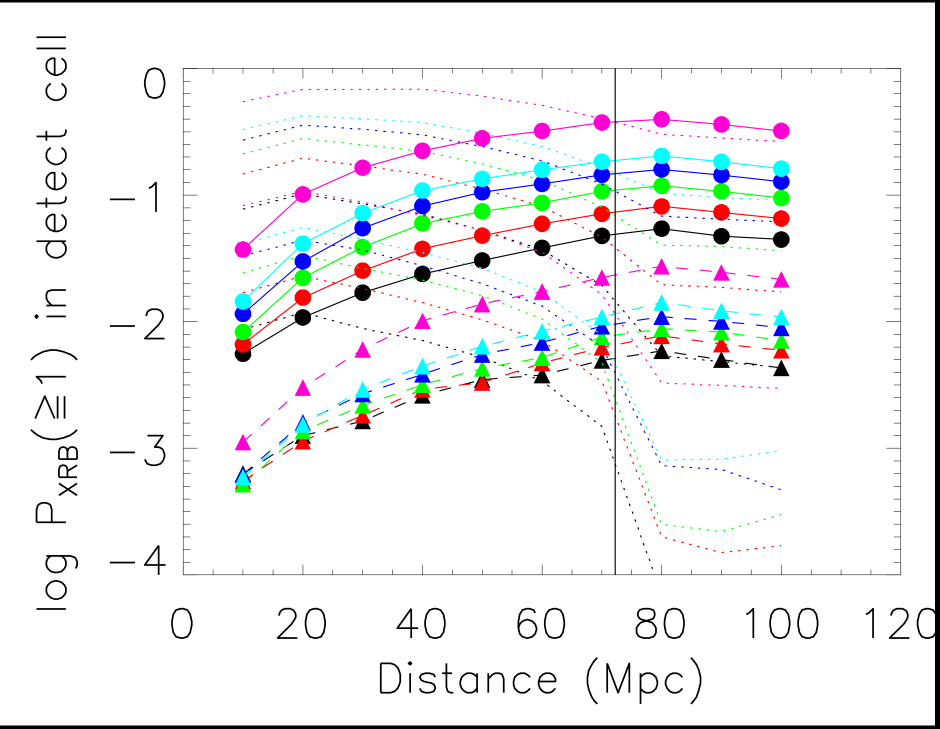
L_X=1e38 erg/sec



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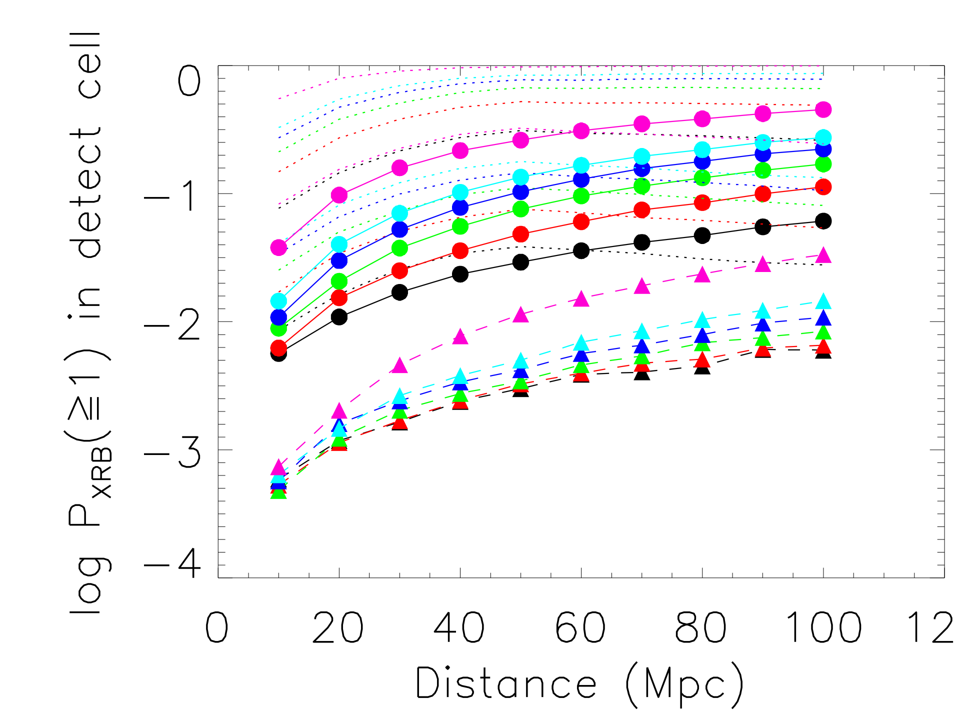


t=100 ksec

XRB contamination

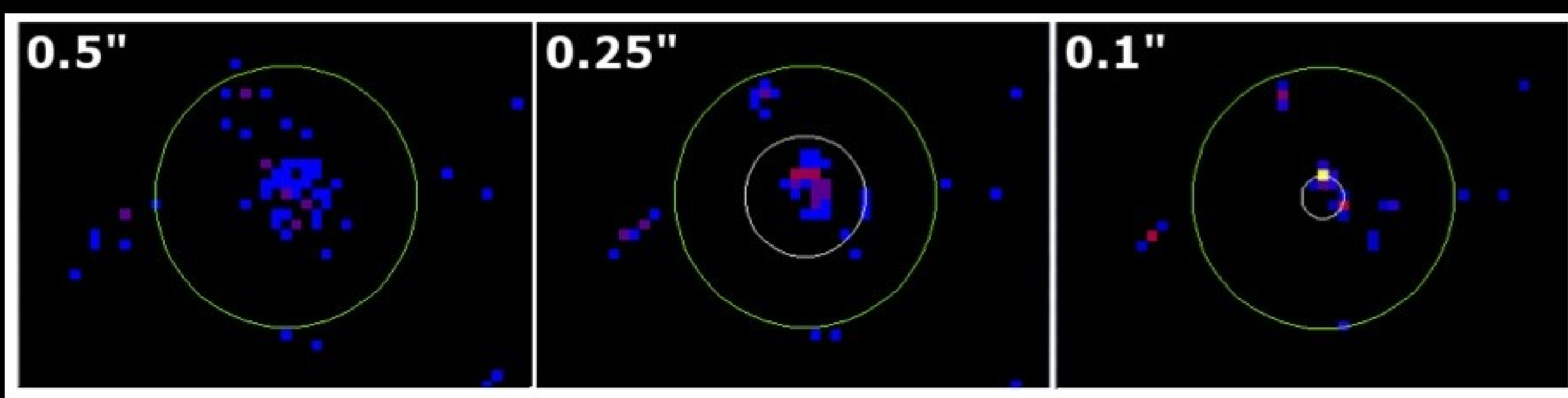
In summary:

$$P_{\mathrm{XRB}} \propto \theta \cdot t_{\mathrm{exp}}^{-1/2} \cdot M_{*} \cdot d \cdot L_{\mathrm{thresh}}^{-\beta}$$

Where β~1 for the adopted XLF and core radius
The exposure time dependence comes from resolving/rejecting more of the “glow”. Then:

$$N_{\mathrm{gal}}^{\mathrm{need}} \propto \theta \cdot t_{\mathrm{exp}}^{-1/2} \cdot M_{*} \cdot d \cdot L_{\mathrm{thresh}}^{-1} \cdot [(L_{X,\mathrm{thresh}} - \bar{L}_X)/\sigma]^{x}$$

Doubling the resolution halves the number of galaxies



2 nuclear sources plus “glow”

Lynx vs. Chandra

Sensitivity:

- With ~50 times greater A_{eff}, Lynx will make dramatic improvements for M_*<1e9M_{sun} galaxies, where XRB contamination is small at any θ but where Chandra obs. are expensive.
- Improvements for high M_* galaxies less dramatic because P_{XRB} is higher for high M_* *and* increases linearly with distance.

Resolution

- Higher resolution decreases the number of galaxies Lynx must observe–key because of the limited number within d < 25 Mpc, where low $L_{X,thresh}$ can be achieved for low masses in short exposures.

Field of View

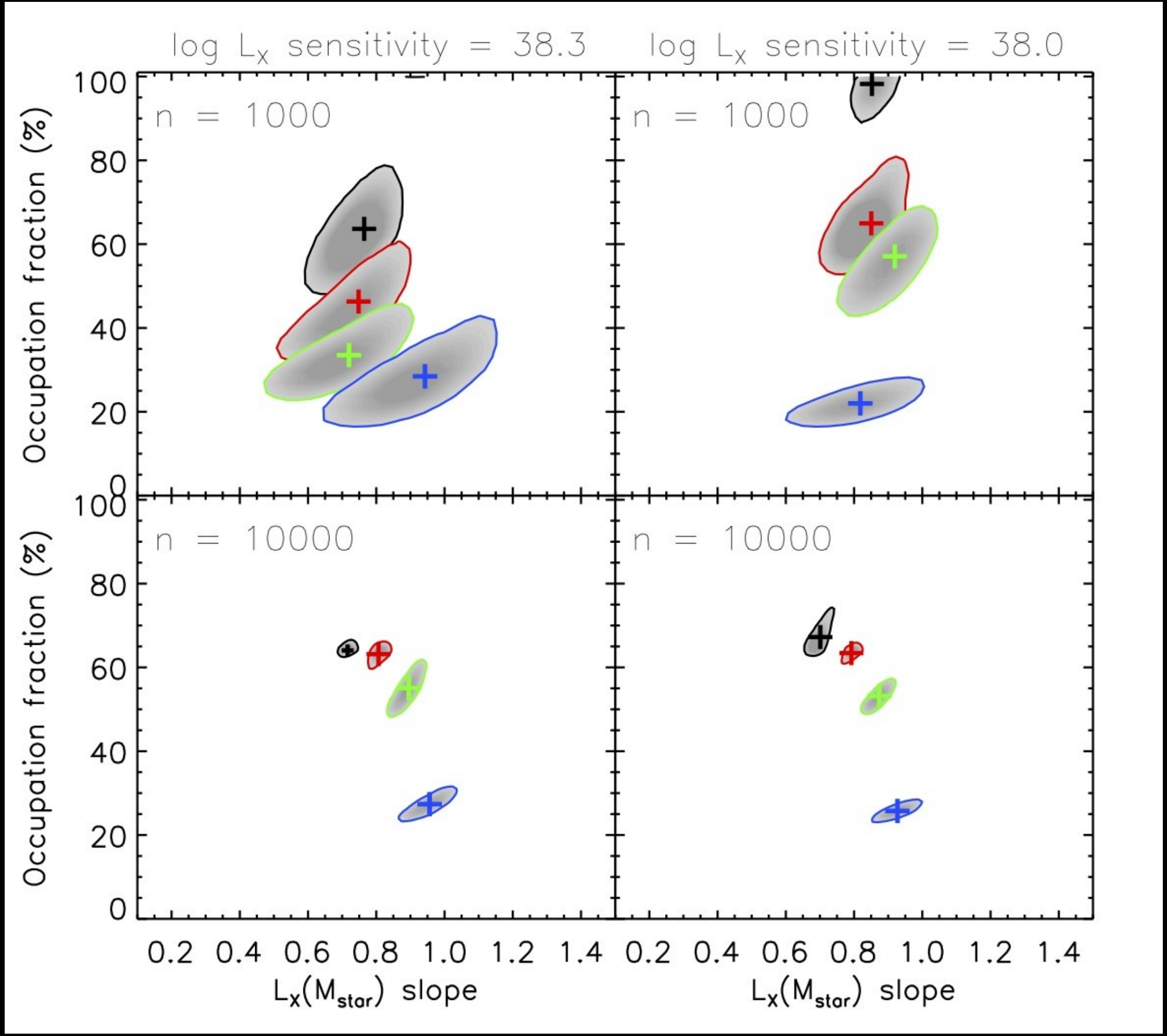
- Chandra PSF distortion leads to large off-axis detection cells (90% energy radius at 6' off-axis is ~4", vs. 1" for Lynx). Current distortion expected for Lynx peaks at ~1.3" at 12' off-axis, hence Lynx will have factor of ~9 greater usable area.
- < 0.5" is only achieved within the interior 4', but high resolution will be important for observations of galaxy clusters and groups.

Galaxy sample and f_{occ} accuracy

- Simulations do not account for P_{XRB}, which acts as a multiplier on N_{need}

- Sample size can be reduced by using a mass-dep. sensitivity that is uniform in the distance from the mean for each bin

A minimum of ~3,500 galaxies needed to achieve a 1–5% accuracy in f_{occ} with 0.1” res. (5-10% with 0.5”)



Program feasibility

$$N_{\rm gal}^{\rm obs} \propto d^3 A_{\rm sky} \propto (A_{\rm eff} t_{\rm exp})^{3/2} R_{\rm HDXI}^2$$

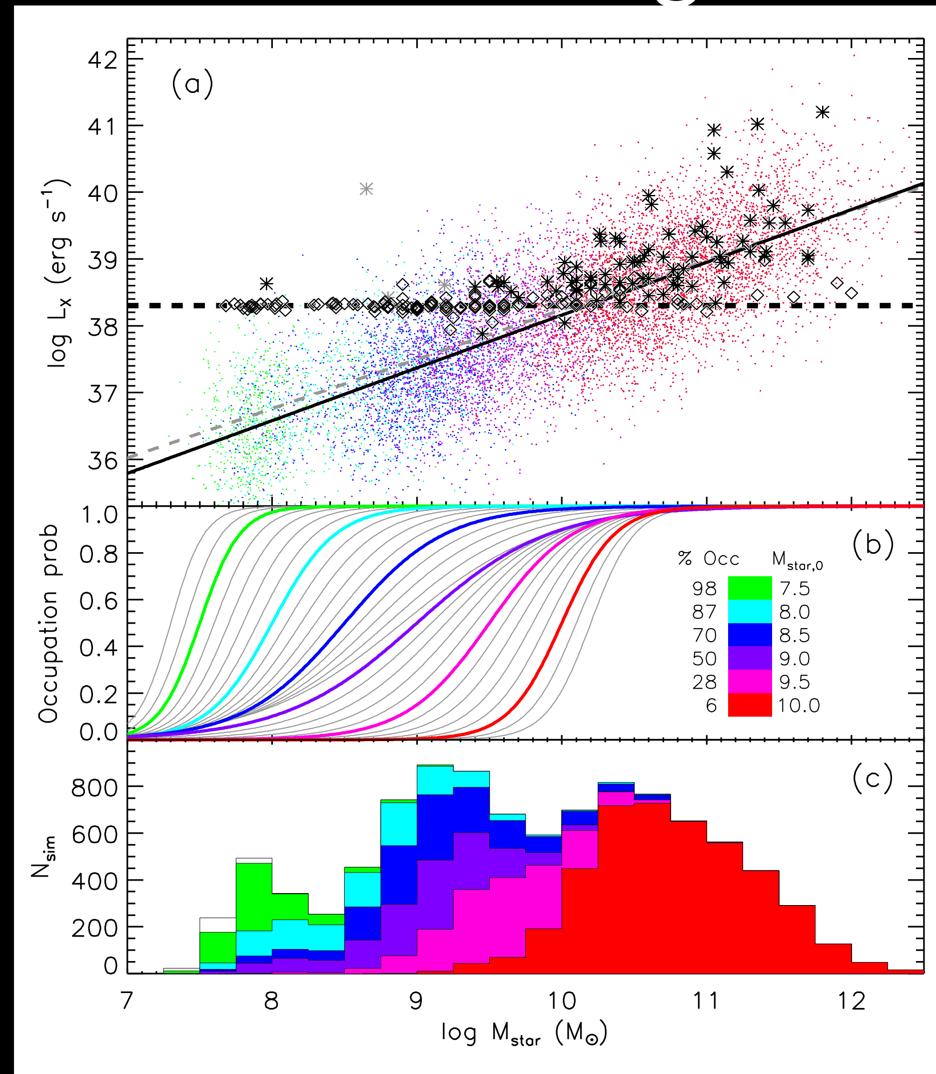
- Roughly 100,000 galaxy available within 100 Mpc (based on SDSS)
- For a Chandra-like observing plan, and including Virgo, Perseus, and Coma, we expect closer to 6,000 galaxies in Lynx fields with t_{exp} 10 ks
- After rejecting of irregulars, objects close to plane and starburts, a rough estimate suggests about 4,000 useful targets within 100 Mpc
- This is a lower limit, but indicates that <0.5 arcsec res. is needed to keep $N_{need} < N_{obs}$
- Better than Chandra resolution is only useful in the central 4 arcmin: While all of the Lynx F.O.V. is useful for <1e9 M_* galaxies, higher res. would primarily be useful for primary targets rather than serendipitous objects.

Active fraction, downsizing & occupation fraction: modeling

- Simulate distribution of 50,000 galaxies (consistent with data)
- Probability of hosting a black hole:

  $0.5+0.5\tanh[\log M_{*}-\log M_{*,0}]\times 2.5^{|8.9-\log M_{*,0}|}$

- Impose sensitivity cut
- Fit simultaneously for
  - L_x/M_* slope & intercept
  - L_x/M_* intrinsic scatter
  - $M_{*,0}$
- Full Bayesian approach, errors & upper limits included



Miller+ 2015