Low-luminosity AGN and Galaxies in X-ray Surveys

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Overview

- X-ray surveys of galaxies (nearby and at z>0)
  - XSINGS (Jenkins et al.), GOALS (Lehmer et al. 2010)
  - Disentangling AGN and SB in soft X-ray band (LaMassa et al.)
  - Evolution of galaxy X-ray emission
  - 4 Ms CDF-S (Lehmer et al. 2012)
- Bayesian joint estimation of obscured / low-luminosity AGN and SB contribution for low S/N X-ray observations
  - Bayesian derivation of number count models, XLFs (work in progress)

Low-X-ray Luminosity Galaxies

- Normal Galaxies
  - SN, hot gas, High-mass X-ray binaries (HMXRB), black-hole candidates (BHC), ultra-luminous X-ray sources (ULXs) correlated with SFR
  - Low-mass x-ray binaries (LMXRB) correlated with galaxy mass (also hot ISM in gas-rich systems)
- Low-luminosity and obscured AGN
  - When $L_X < 10^{42}$ ergs s^{-1}, dominant process can be hard to determine with low S/N spectra
  - Relevance: missed obscured AGN or uncertain AGN contribution to sources with low S/N or ambiguous classification (e.g., composite optical line diagnostics, high-z sources), low accretion rate physics

XSINGS

- Large Chandra program to observe SINGS galaxies (PI: Leigh Jenkins)
- The *Chandra* data cover 55 of the SINGS galaxies (complete to a distance of < 10 Mpc), with a total of 96 ACIS observations and ~1,900 detected point sources (0-230 sources per galaxy, Jenkins et al. 2011a, 2011b, in prep)

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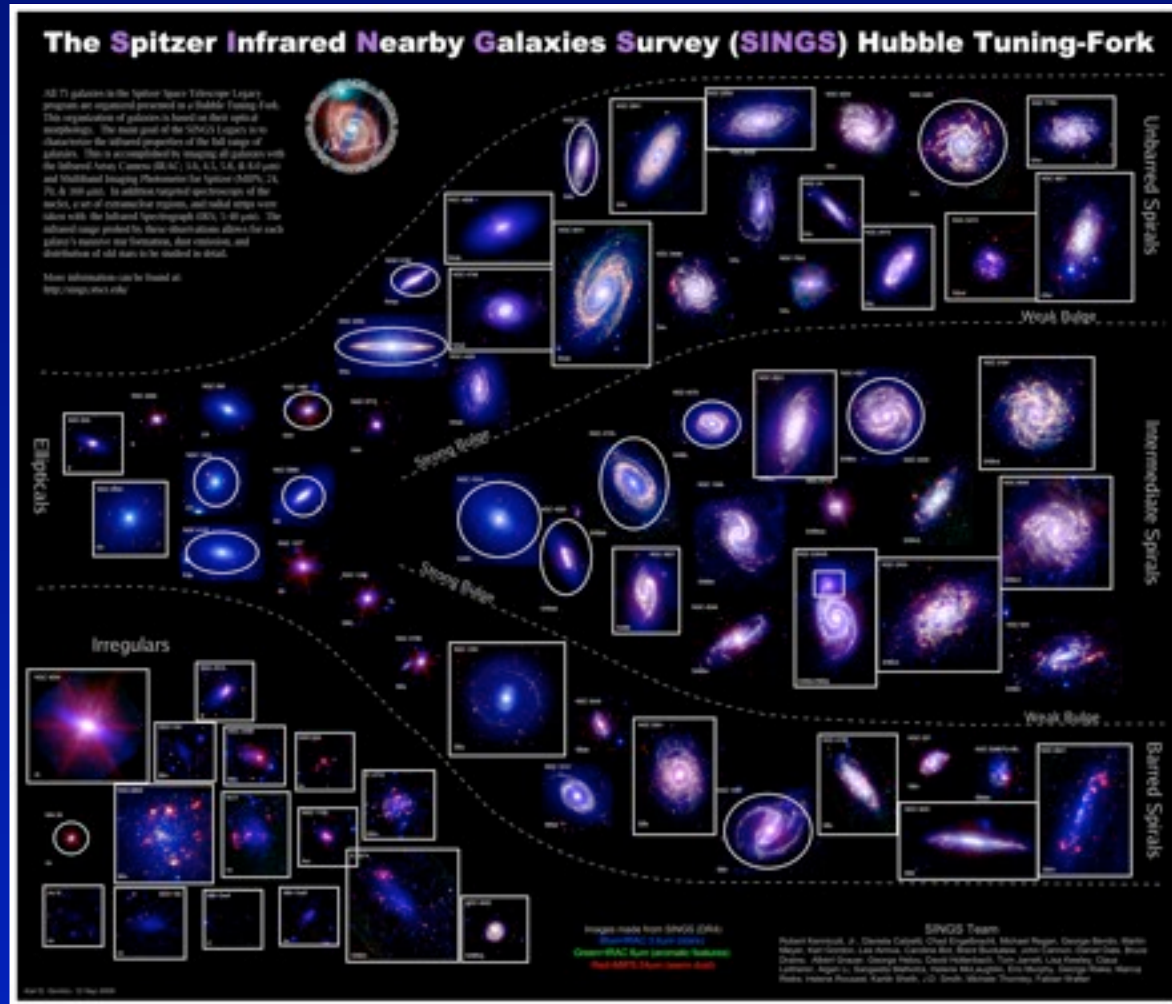
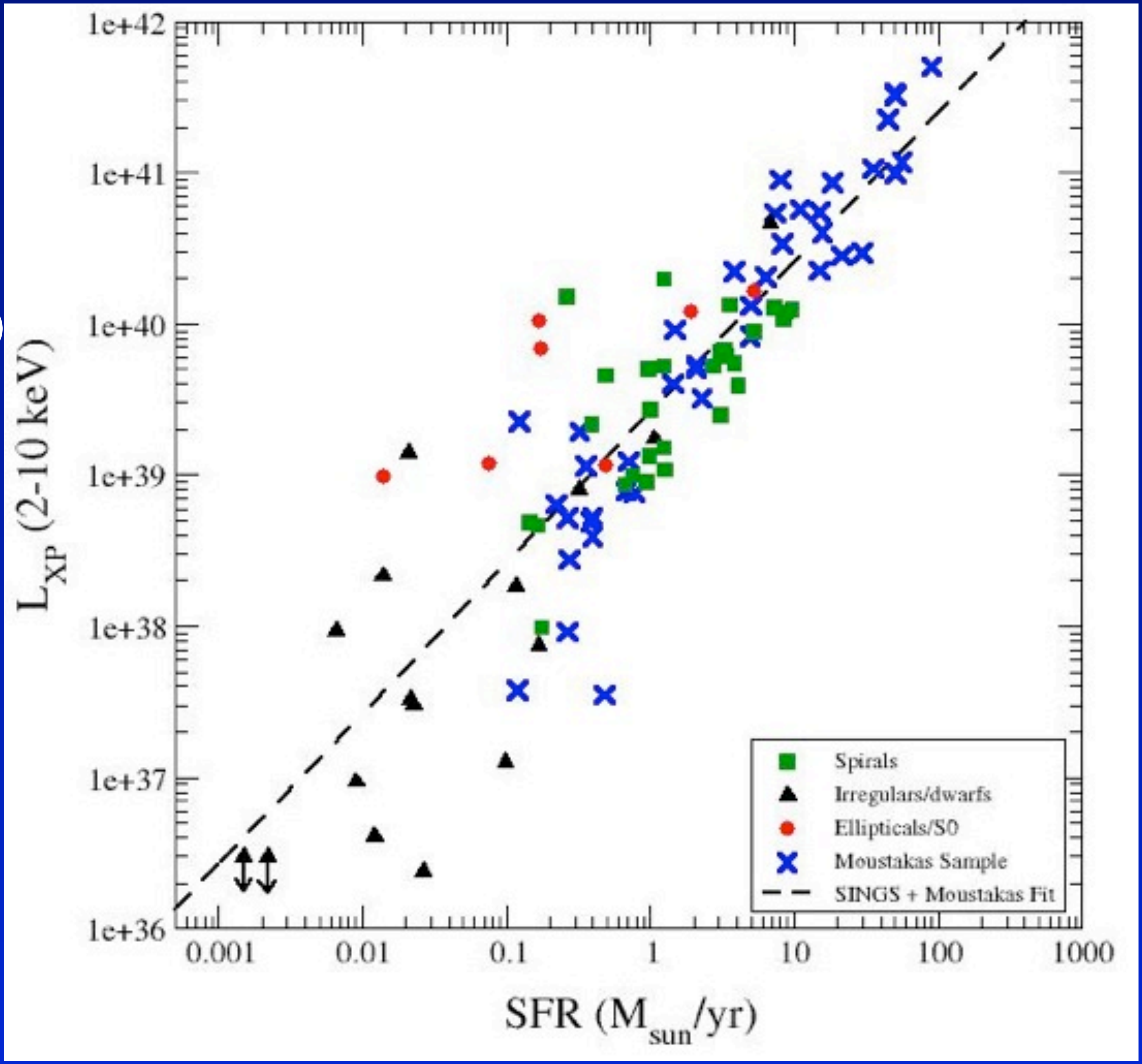
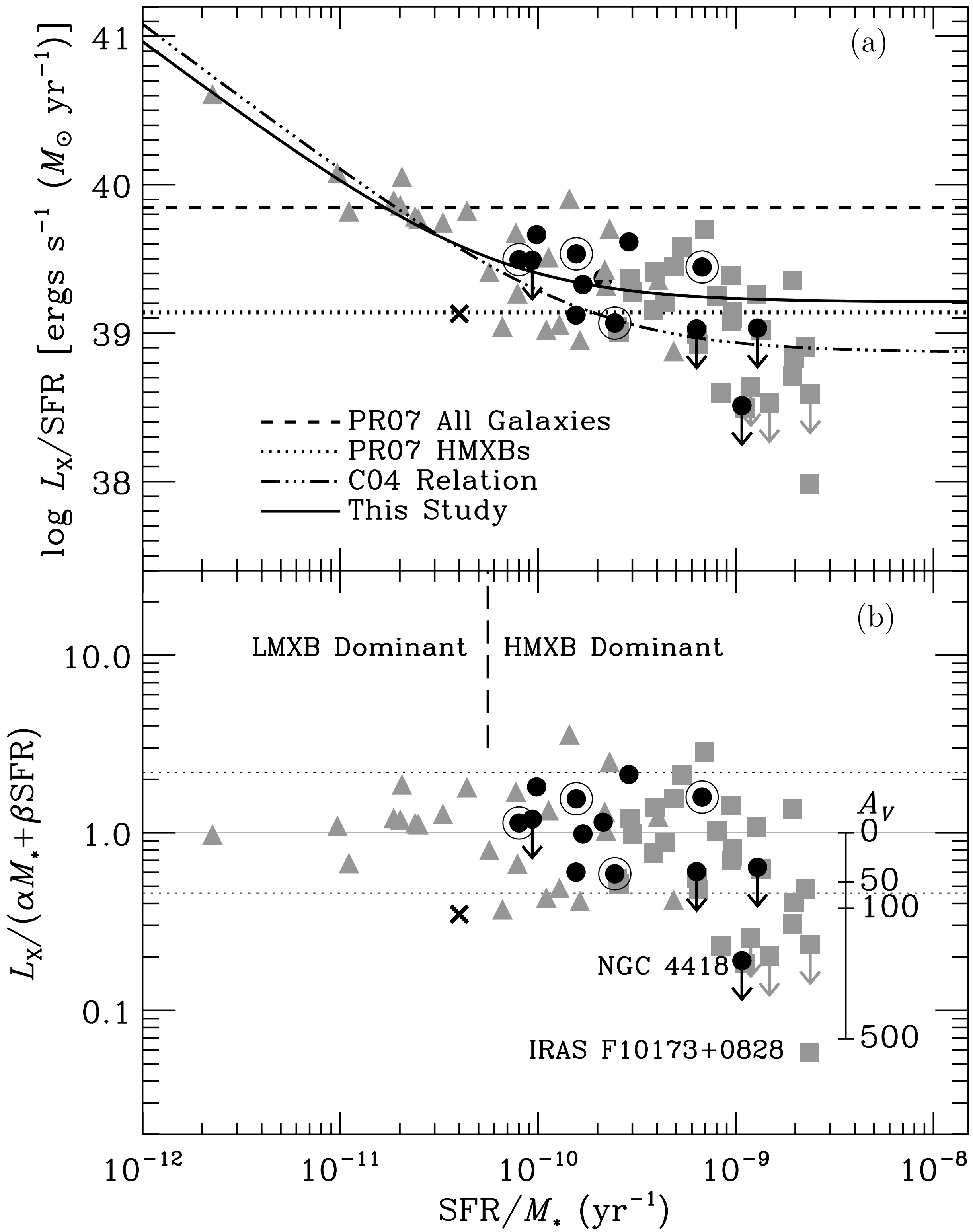


Jenkins et al. (in prep.)

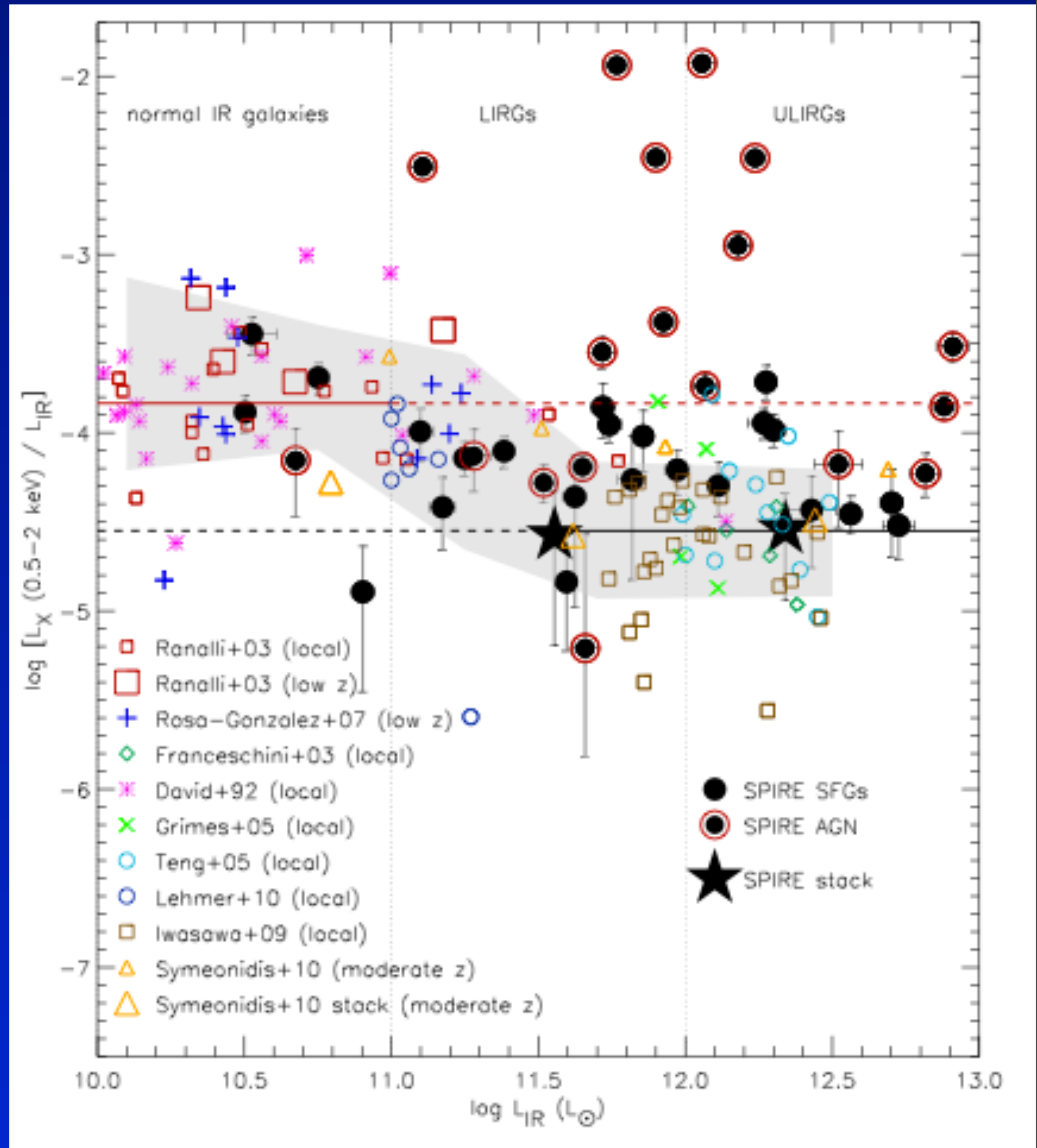


Lehmer et al. (2010)



Symeonidis et al. (2011)

Various studies are showing that L_X vs SFR, M, etc. is not a simple correlation: large statistical samples of normal galaxies and LLAGN are clearly needed

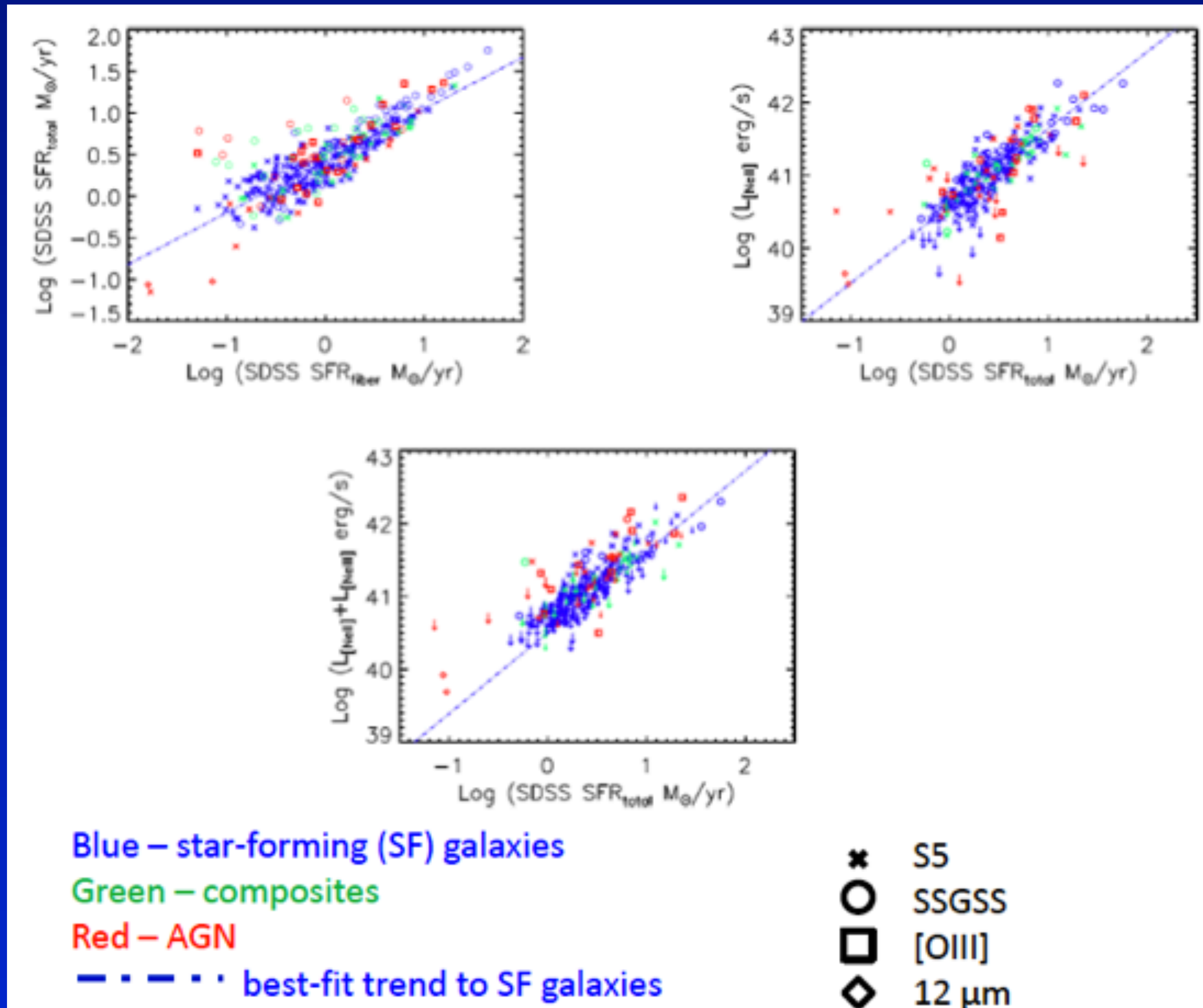


X-ray Observations of [OIII]-Selected and 12 um Sy 2s (Steph LaMassa thesis, LaMassa et al. 2009, 2010, 2011)

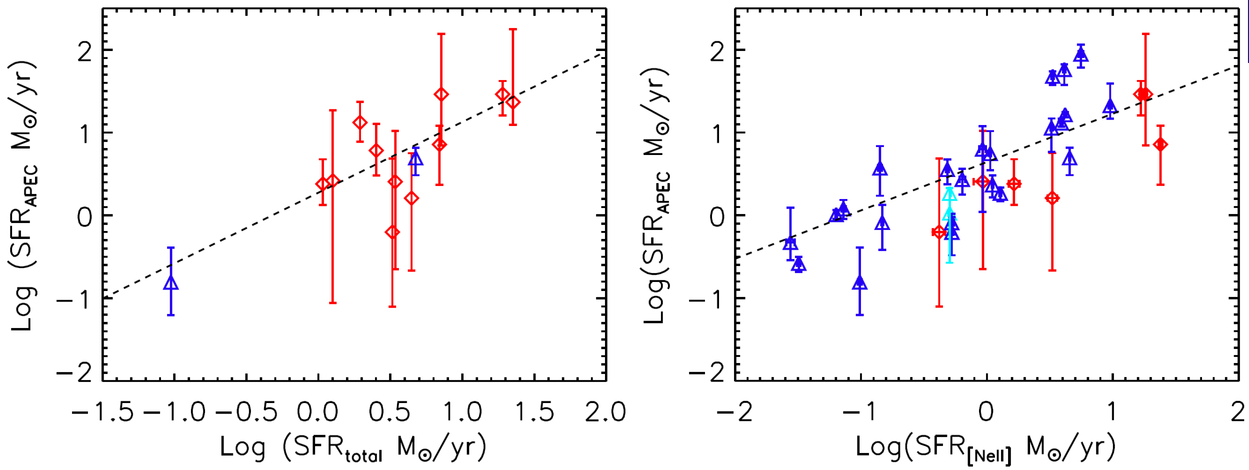
- [OIII] line is ~ isotropic AGN luminosity indicator but can have uncertain extinction corrections
- Selected sources by [OIII] flux from SDSS, 12 um to get unbiased Seyfert 2 samples (see also Brightman & Nandra 2010, 2011 for 12 um)
- Found large range in soft X-ray/hard X-ray components
    - Soft X-ray band usually due to scattered AGN flux but strong evidence for significant contribution from star formation
- Many have low L_X/L[OIII] indicating absorption in excess of fitted N_H
- Also investigated S5 and SGSS starburst galaxies to investigate star formation indicators in more detail

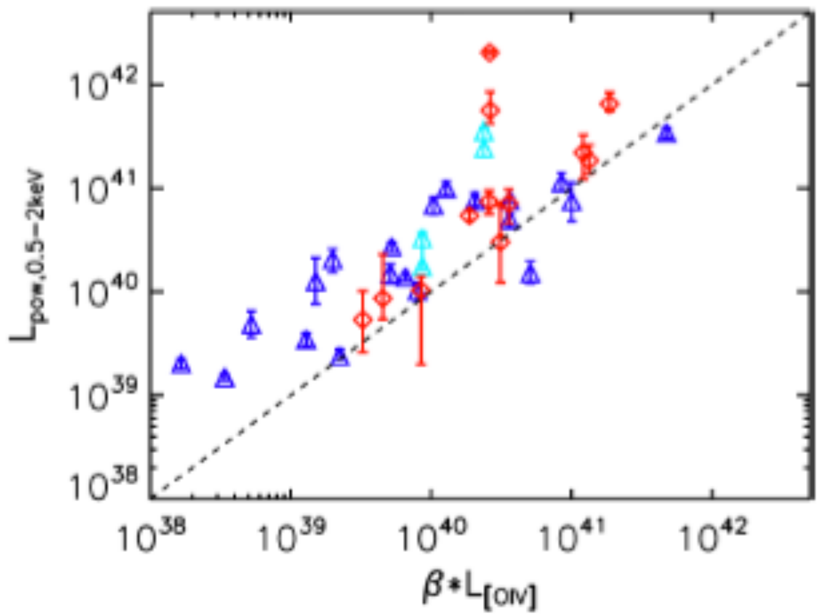
AGN and SF Calibration

SDSS MPA/JHU SFR and [NeII] not affected by AGN but [NeIII] is



AGN + Starburst emission at MIR and X-ray





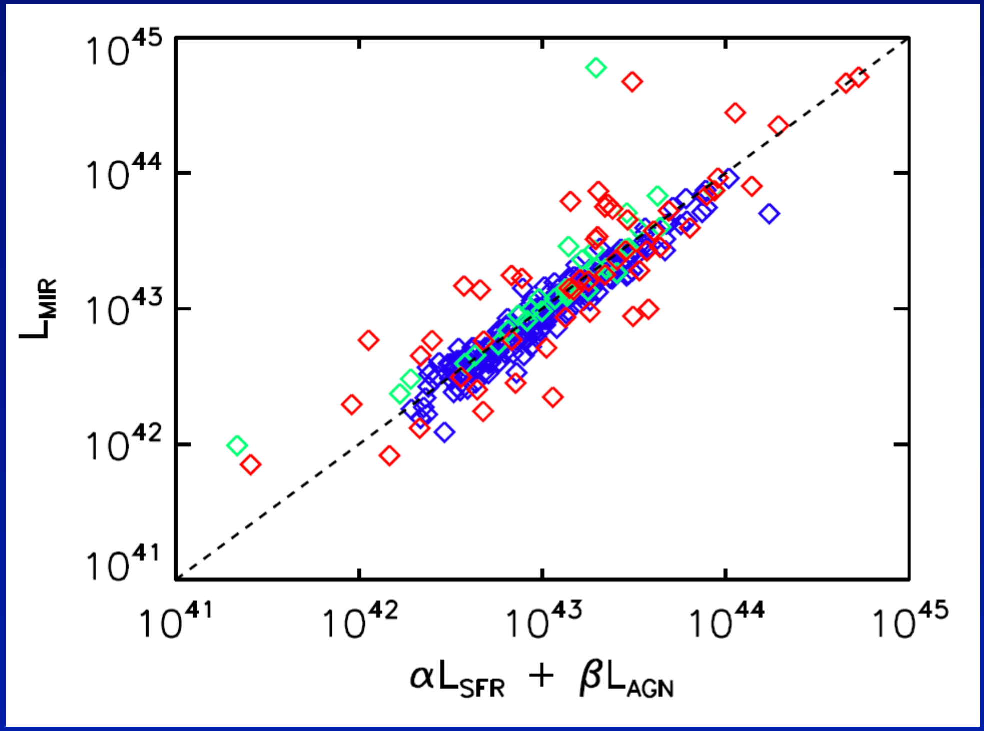
◇ [OIII] sample

△ 12 µm sample

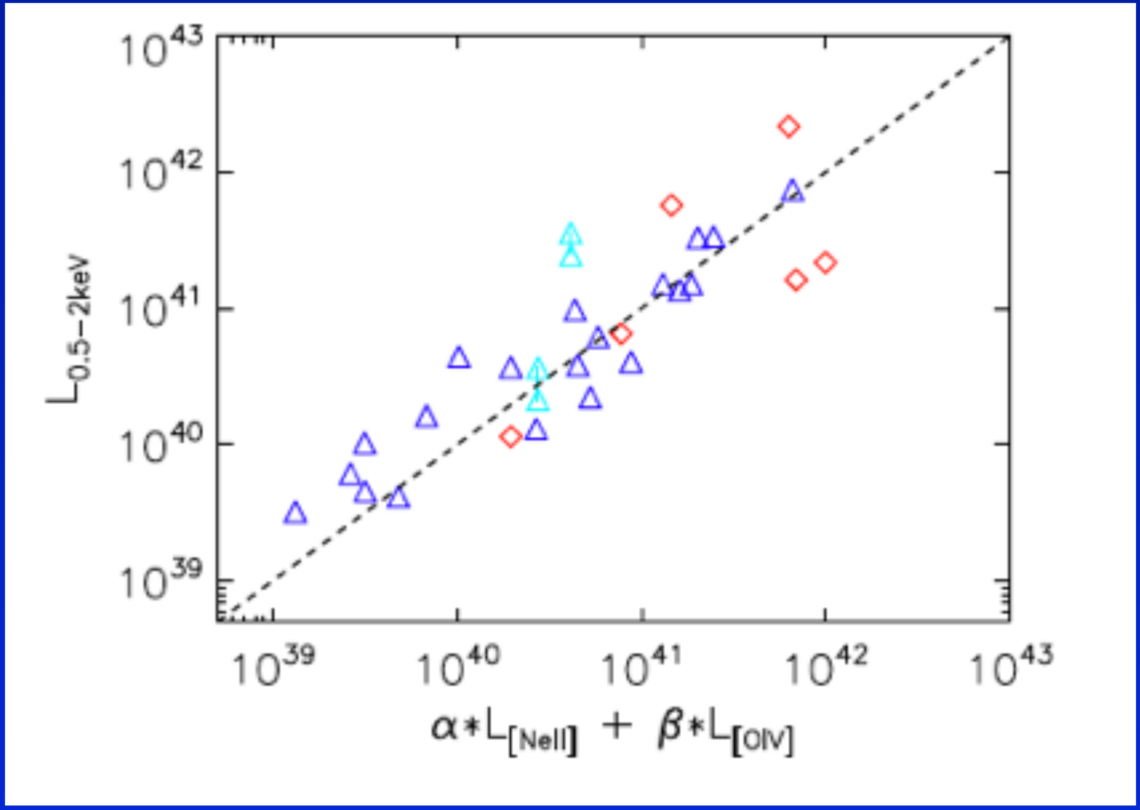
△ X-ray variable 12 µm source

- - - - - Best-fit line using Bayesian approach to linear regression (Kelly 2007)

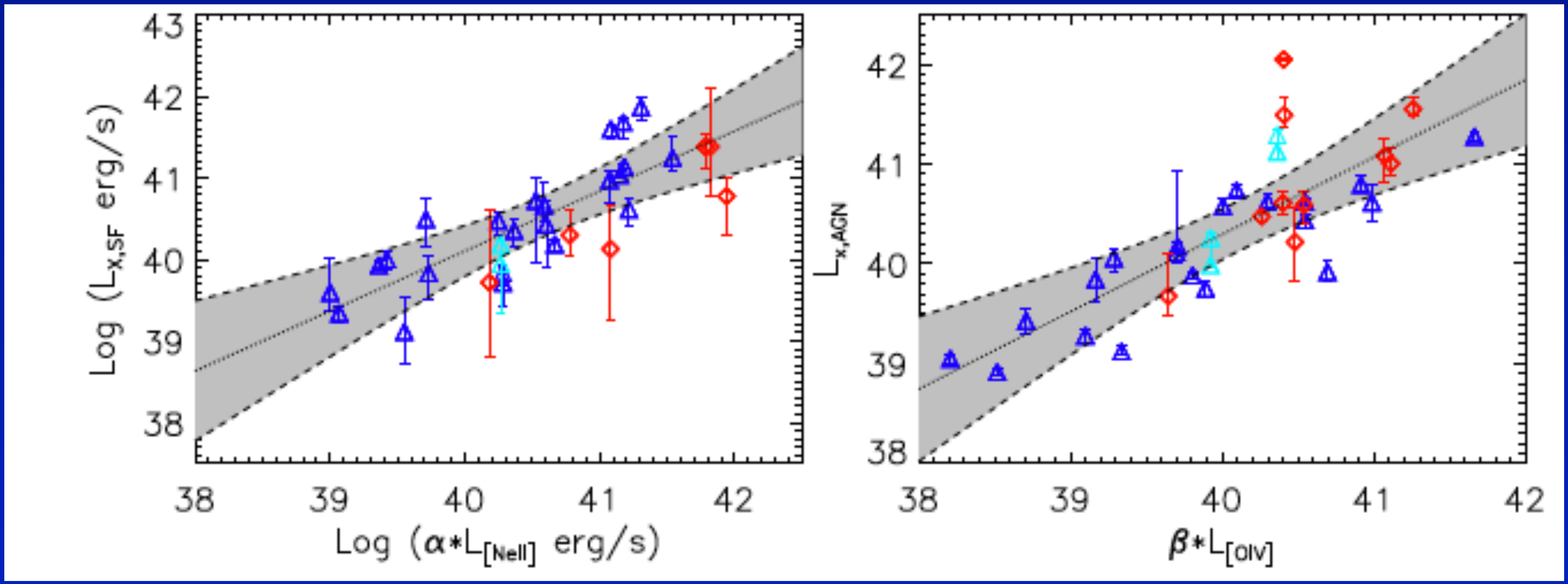
$\alpha = 89$
$\beta = 124$



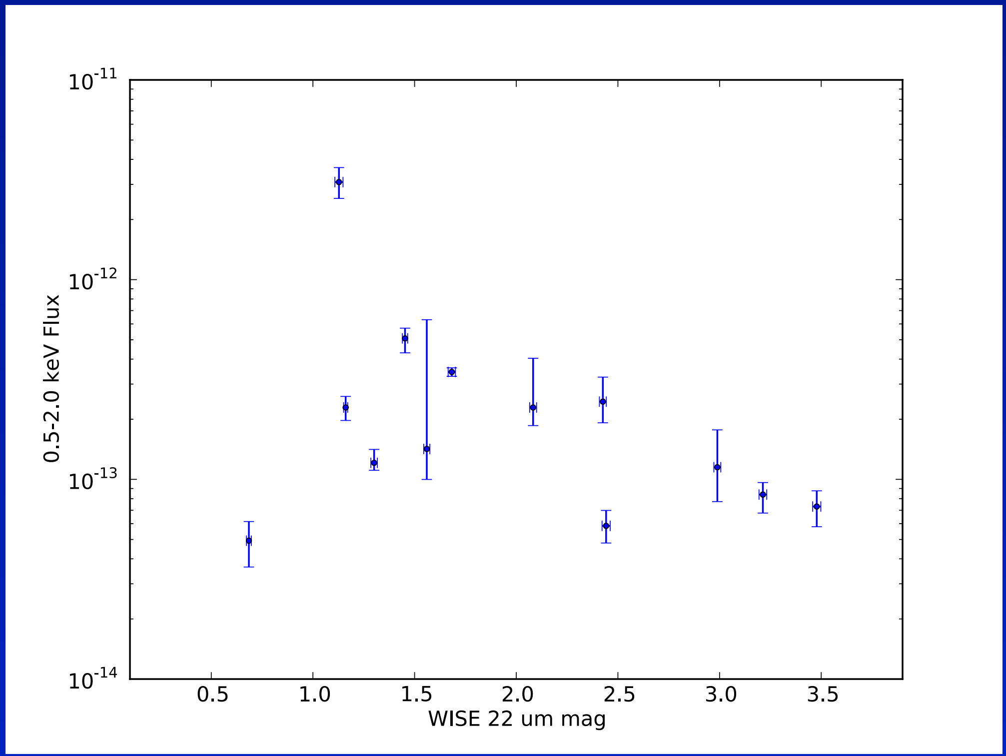
$\alpha = 1.10$
$\beta = 0.13$



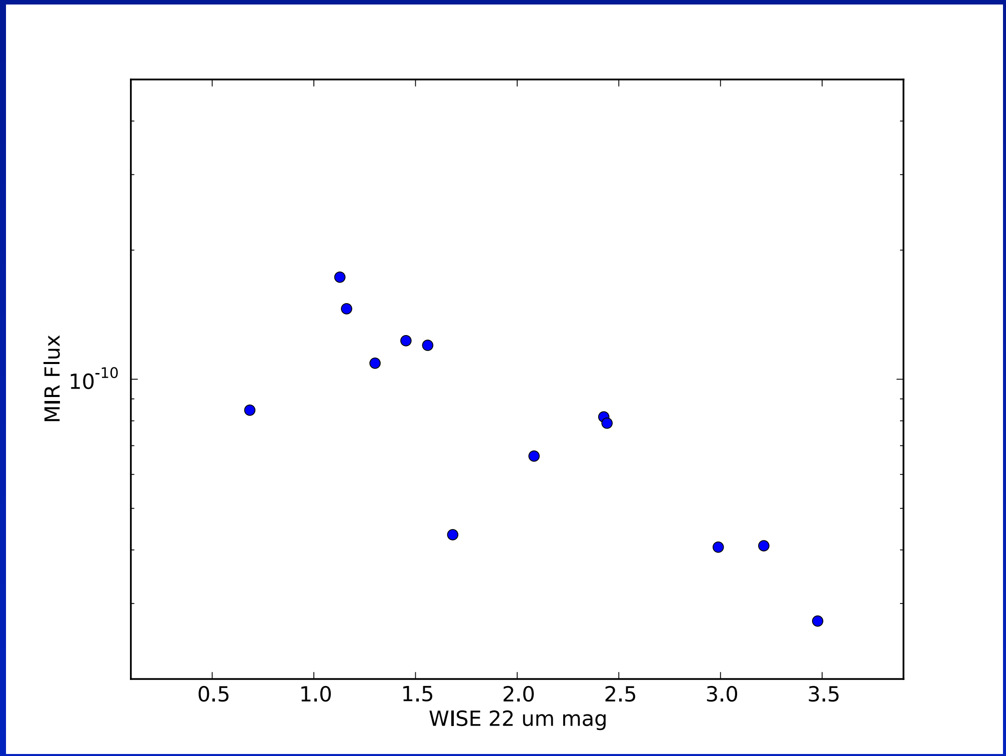
Shaded regions shows 3σ Bayesian posterior confidence intervals (from B. Kelly's regression code)



WISE 22 um



10^{-11}
10^{-12}
10^{-13}
10^{-14}
0.5-2.0 keV Flux
0.5
1.0
1.5
2.0
2.5
3.0
3.5
WISE 22 um mag

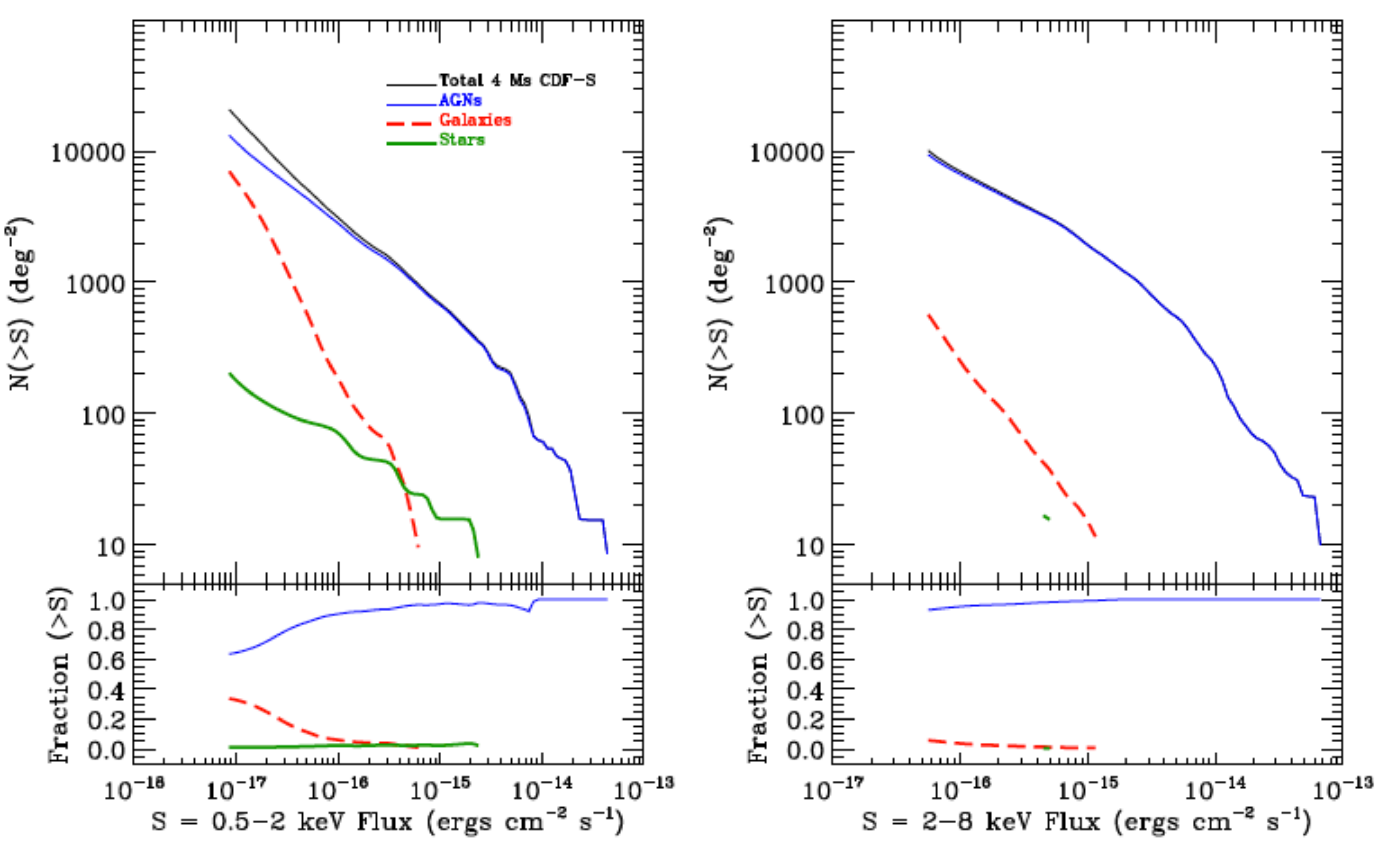


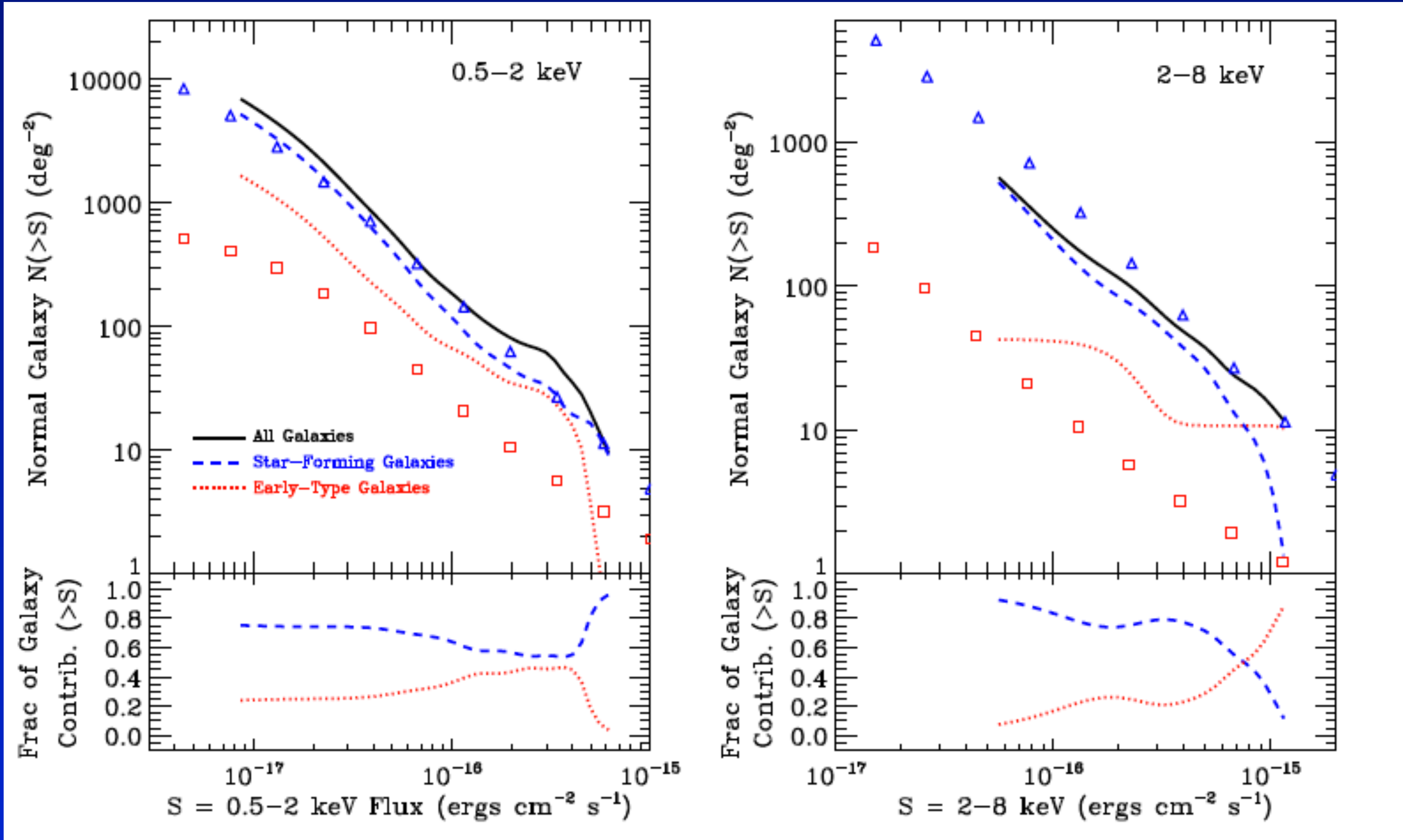
10^{-10}
MIR Flux
0.5
1.0
1.5
2.0
2.5
3.0
3.5
WISE 22 um mag

Galaxy Evolution

- Norman et al. (2004) presented first normal/starburst galaxy X-ray luminosity fns. for z>0
- Used a Bayesian classification algorithm to select normal/ starburst galaxies from CDF-N/S, mainly to take measurement errors into account (faintest sources have <~ 10 photons), expanded in Ptak et al. to include Bayesian fitting of binned luminosity fns.
- Evolution was observed between z~0.25 and z~0.75 consistent with pure luminosity evolution: $(1+z)^3$, with luminosity density dominated by late-type galaxies similar results found by Georgakakis et al, Panayiotis et al. using simple cuts (e.g., FX/Fopt)

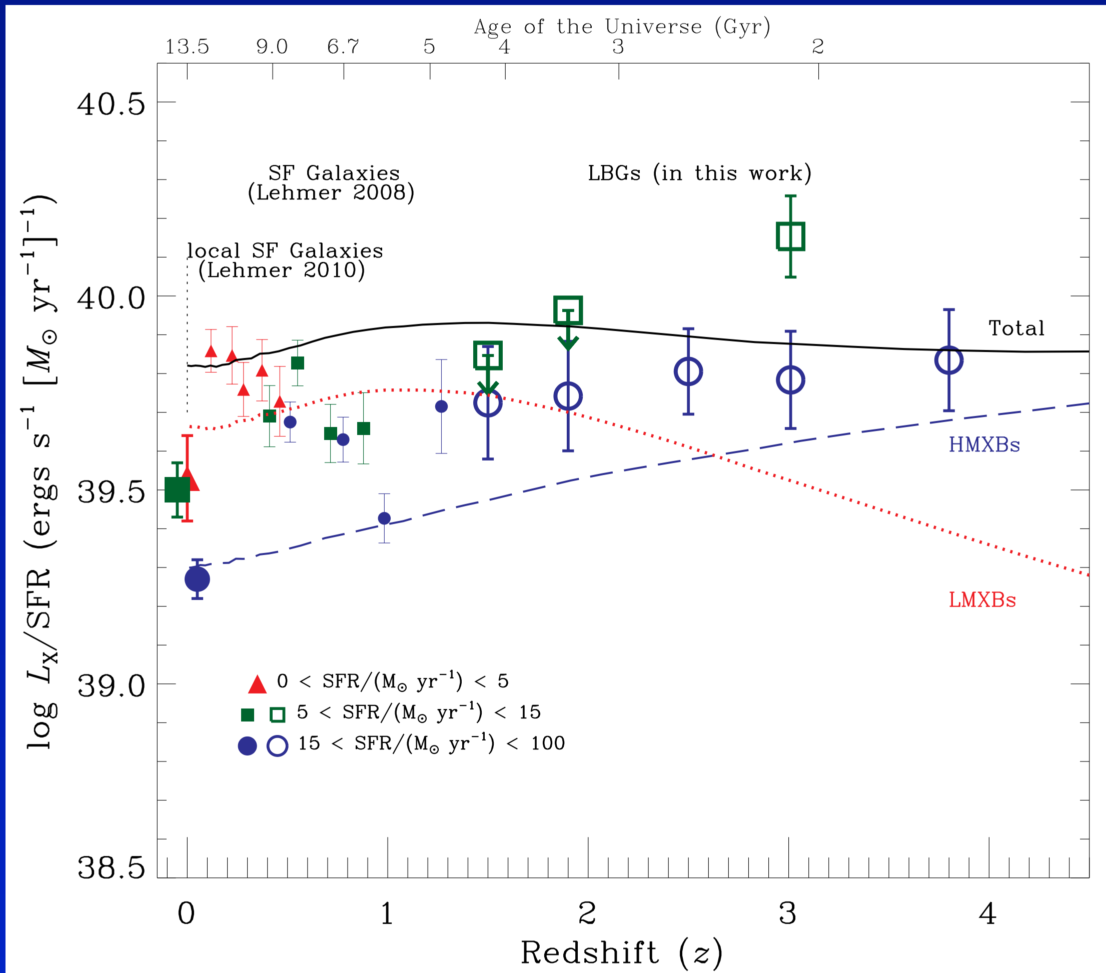
4 Ms Number Counts from Lehmer et al. (in prep.)



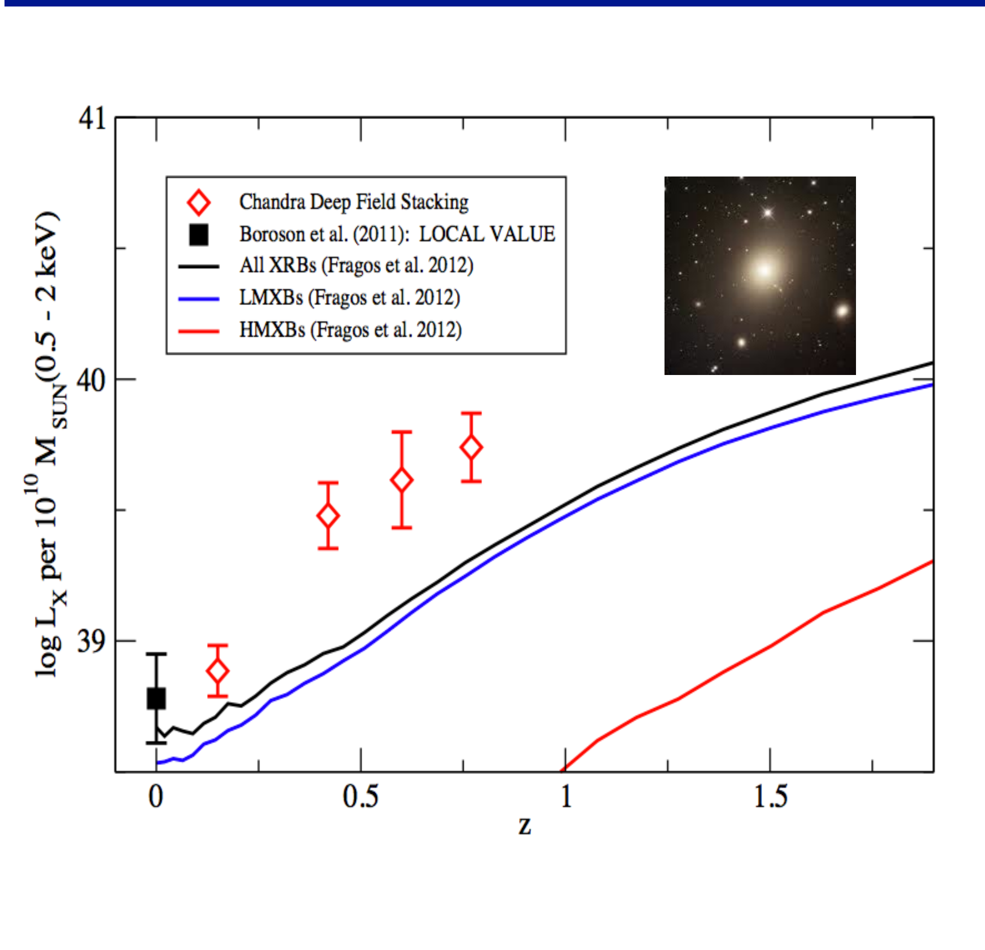


0.5–2 keV
All Galaxies
Star–Forming Galaxies
Early–Type Galaxies
Normal Galaxy N(>S) (deg^{-2})
Frac of Galaxy Contrib. (>S)
S = 0.5–2 keV Flux (ergs cm^{-2} s^{-1})
2–8 keV
S = 2–8 keV (ergs cm^{-2} s^{-1})

X-ray vs. SFR and Mass Evolution from CDF Stacking



Basu-Zych et al. (in prep)



Hornschemieier et al. (in prep.)

Bayesian Galaxy Selection

P_M = "Bayesian evidence" for model M (M=galaxy,AGN1,AGN2)

$$P_M = \int p_M(\vartheta) p_M(D|\vartheta)$$

$$p_M(\vartheta|D) = \frac{p_M(\vartheta) p_M(D|\vartheta)}{p(D)}$$

$p_M(\vartheta)$ = prior distribution of parameter values for model M, computed by taking mean and st. dev. of "training" sample

$$\frac{P_{Galaxy}}{P_{AGN1}} = \frac{\int p_{Galaxy}(\vartheta) p_{Galaxy}(D|\vartheta) d\vartheta}{\int p_{AGN1}(\vartheta) p_{AGN1}(D|\vartheta) d\vartheta}$$

$p_M(D|\vartheta)$ = likelihood function

Assumed N(gal) ~ N(AGN1) ~ N(AGN2)

Contribution Estimator

- Rather than classify, instead calculate posterior probability for contribution of SF and AGN to F(0.5-2.0) and F(2-10) given available SF and AGN estimators *and the likelihoods and priors*
  - Likelihoods
    - Poisson error in X-ray counts
    - Error in indicator measurement (e.g., Hα, [OIII], L_{opt}, L_{radio}, L_{MIR})
  - Priors
    - Dispersion in L_X/indicator
    - Dispersion in X-ray SEDs (including 2 absorbers, galactic contributions of thermal and non-thermal flux)
- Calculate luminosity functions from $L_{X,AGN}$ and $L_{X,Gal}$ with above posterior probabilities now being likelihoods, or "forward-fit" number counts

Bayesian Number Counts

Probability for a source with N_i counts to be included in the survey (Georgakakis et al. 2008):

$$p_i = \frac{\int P(T_i \mid S) P(S) dS}{\int dN/dS\, A(S) dS}$$

$$P = \prod_i p_i$$ = total probability of survey counts

$P(T_i|S)$ = Likelihood for observing *T total* counts given flux S

= Poisson (G08) or binomial (Xue et al. 2011)

$P(S)$ = prior for number count distribution = logN-logS,

e.g., S^{-q}, which has effect of offsetting Eddington bias

dN/dS = number count distribution

$A(S)$ = sky coverage as fn of flux

Vary number count model to maximize P

Expansion to Multiple Contributors to Flux

$P(T_i|S)$ -> $P(T_i|S, \alpha, \beta, SFR, L_{AGN})P(S)*P(\alpha)P(\beta)*$
$P(SFR)P(L_{AGN})$

$P(S)$ = prior given by total logN-logS

$P(\alpha)P(\beta)$ = priors for α, β, *i.e.*, posterior prob. for α, β from regression analysis

$P(SFR)$, $P(L_{AGN})$ = priors for intrinsic SFR and L_{AGN}, can be left as flat (i.e., non-informative)

Bivariate Counts Likelihood

$P(T_i|S)$ -> $P(T_i|S.\ \theta)$, θ = parameters for conversion of flux to total observed counts

m = expected total photons = $t_{exp}*C*S + b$

t_{exp} = exposure time, C = flux to count rate conversion

$P(T_i|S, \alpha, \beta, SFR, L_{AGN}) = Poisson(T_i, m)$

$m = t_{exp}\ [f_{gal}\ C_{gal}\ S + (1-f_{gal})C_{AGN}\ S]+b$

$f_{gal} = \alpha SFR/(\alpha SFR+\beta L_{AGN})$

Maximize final $P=\Pi p_i$ *as before*

Bayesian Luminosity Functions

- Kelly (2008) derived a fully Bayesian LF estimator based on a binomial distribution likelihood function to handle detections vs. non-detections
- Could be expanded to include uncertainties in source fluxes rather than a binary detection threshold, multiple source types
    - posterior probability from X-ray fits or SF or AGN contribution
    - Converting Kelly binomial posterior to multinomial may be promising
- Advantages
    - Minimize statistical biases
    - Posterior probability functions are much more powerful than simple error bars
    - Errors on complex "derived" quantities like luminosity density easily computed

Conclusions

- X-ray dependence on SFR (and M) complex, large samples crucial (see Gilfanov talk and need for even deeper future wide-area X-ray surveys)
- X-ray (and MIR) luminosity can be decomposed into AGN and SF contributions (some SFR indicators unbiased by LLAGN)
  - Broad band indicators should be available for most eRosita galaxies, many should also have optical spectra
- Bayesian analysis can be used to derive statistical-correct number count and luminosity function model parameters
  - Includes input assumptions explicitly, posterior can be examined to assess implications, drive future strategy