Observational Constraints on the Growth and Evolution of AGN

Franz Bauer (PUC, MAS, EMBIGGEN)

Following Einstein and HEAO-I A2 Observatory discoveries in ~1980 that most resolved extragalactic sources were AGN….

Sołtan Argument (1982)

If AGNs are powered by black-hole accretion then cosmic AGN accretion history (Cosmic X-ray background or AGN luminosity function + assumptions) should match the black-hole mass density in local Universe

$$\int_0^\infty M n_M(M, t_0) dM = \int_0^{t_0} \mathrm{d}t \int_0^\infty \mathrm{d}L \frac{(1-\varepsilon) L_{\mathrm{bol}}}{\varepsilon c^2} \psi(L, t);$$

local accreted

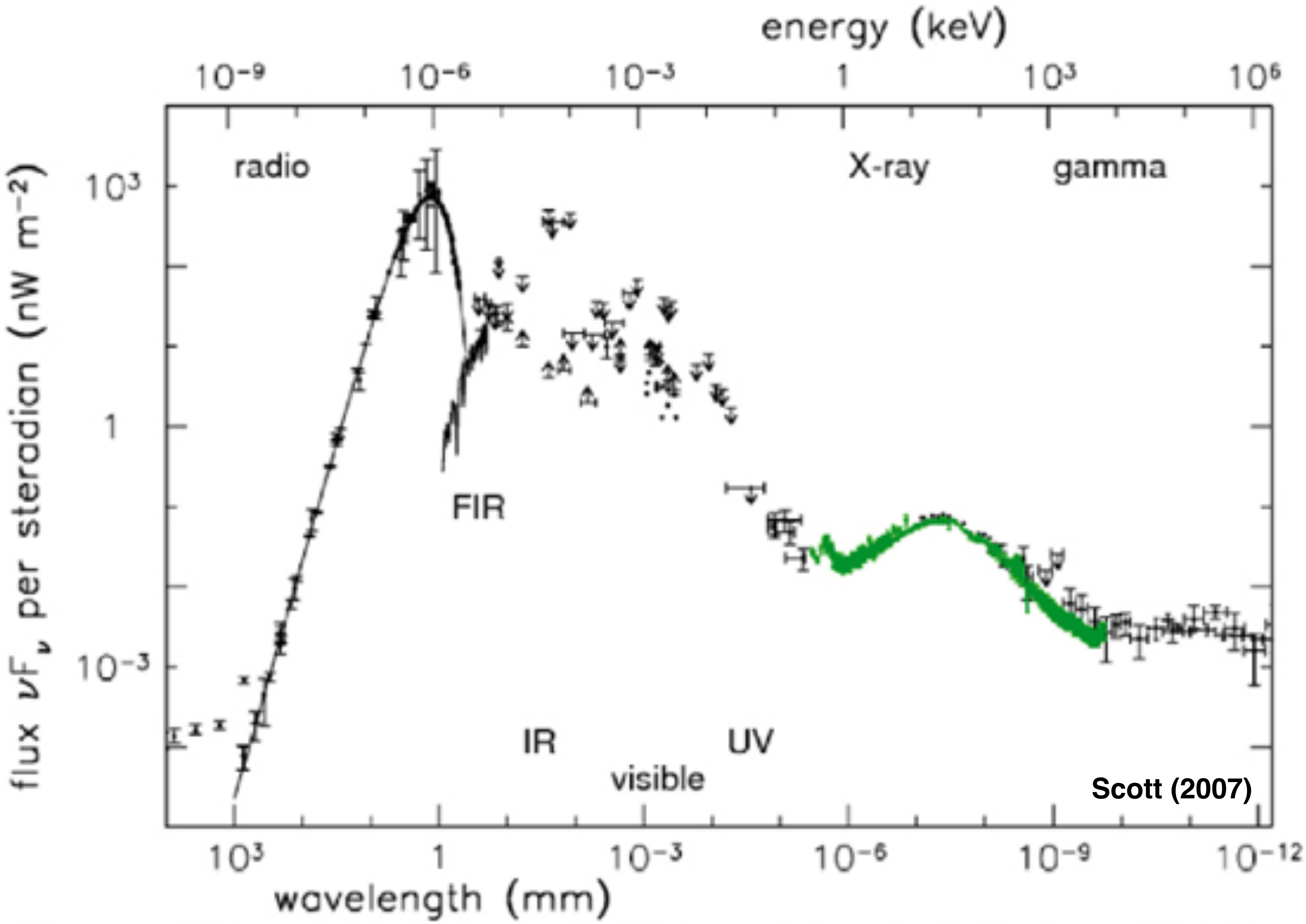
$n_M(M, t_0)$: local BH mass function,

$\psi(L, t)$: QSO luminosity function,

$$\varepsilon : \text{efficiency}, \quad \dot{M} = \frac{(1-\varepsilon) L_{\mathrm{bol}}}{\varepsilon c^2}.$$

We've talked a lot about CMB, but what about rest of EBL?

While only a small fraction of EBL in the universe emerges in X-rays, this emission is largely due to AGN and thus provides the most direct window on black hole evolution



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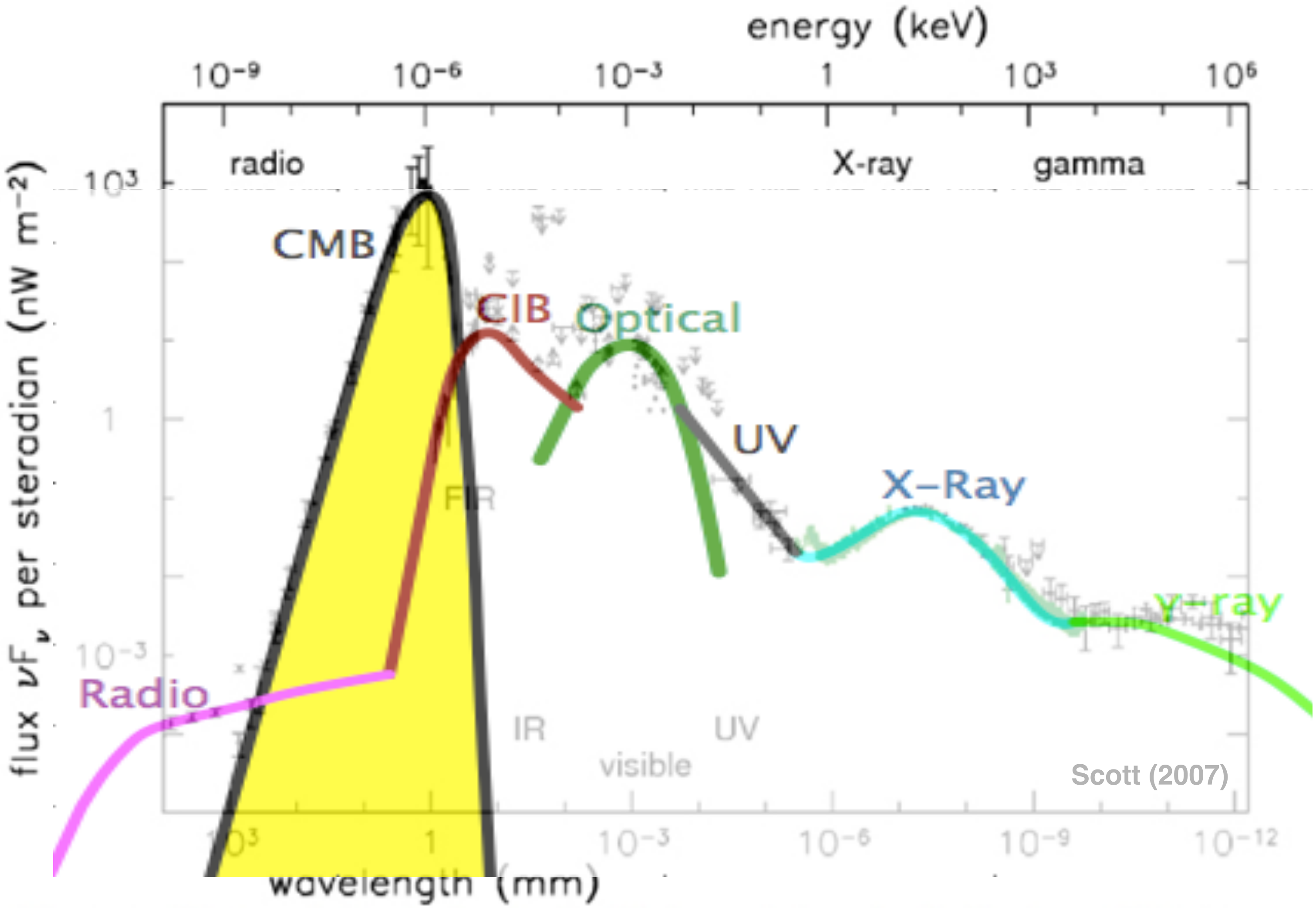
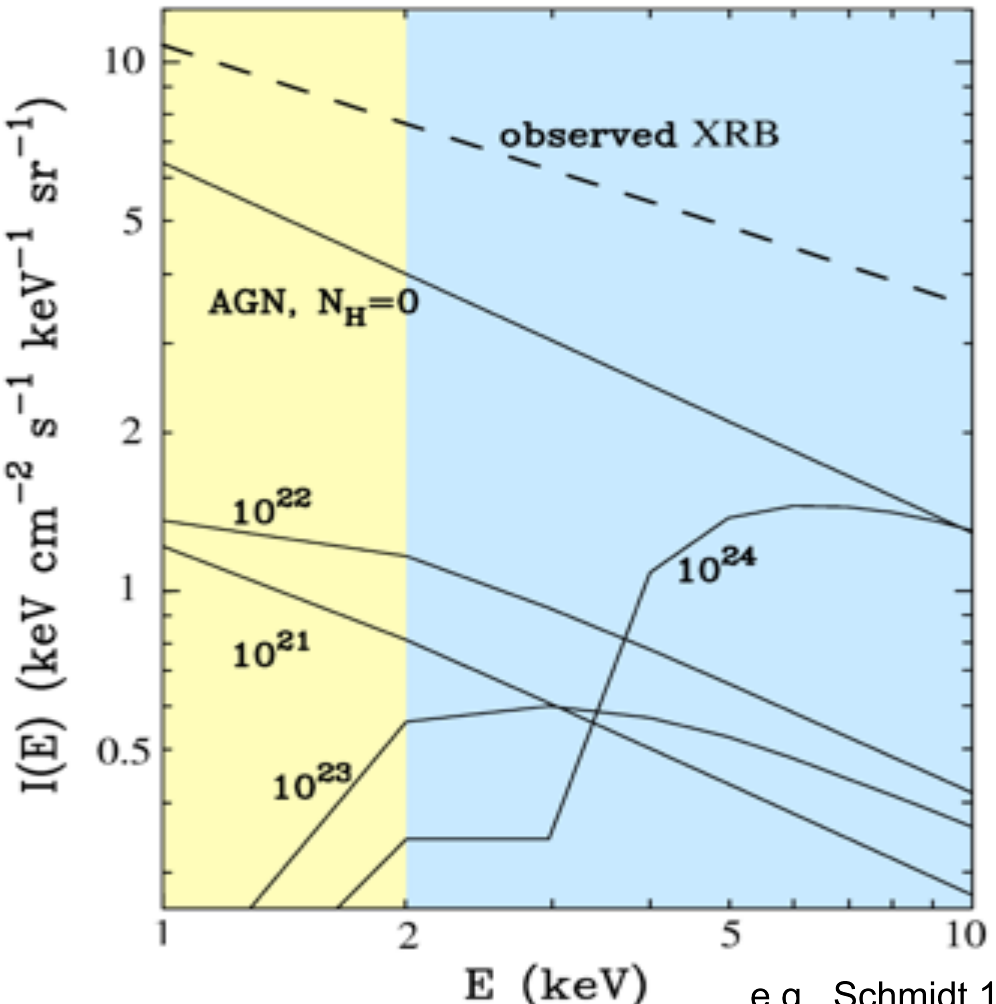
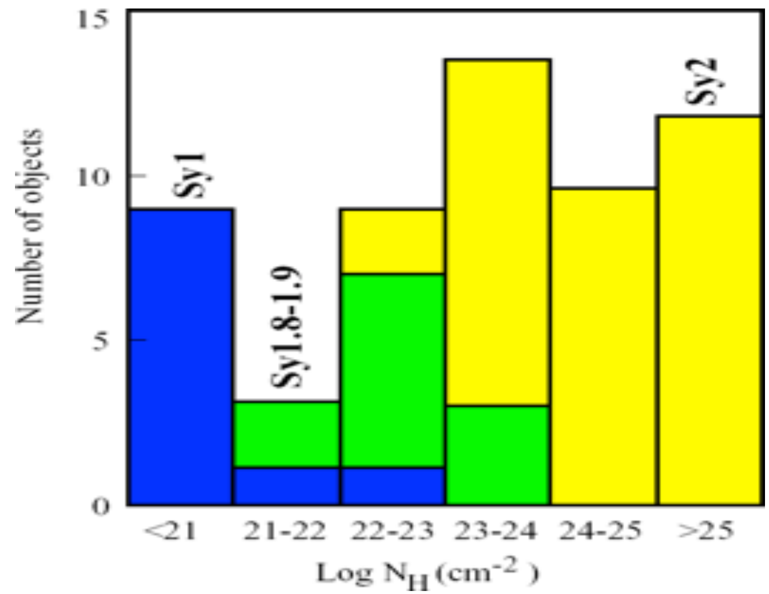


Modelers could predict what one should find (e.g., a population of obscured quasars at z=2-3).

BUT, considerable degeneracy exists from uncertain N_H and z distributions.

ALSO, not even X-ray telescopes are not sensitive to N_H>~10^{25}



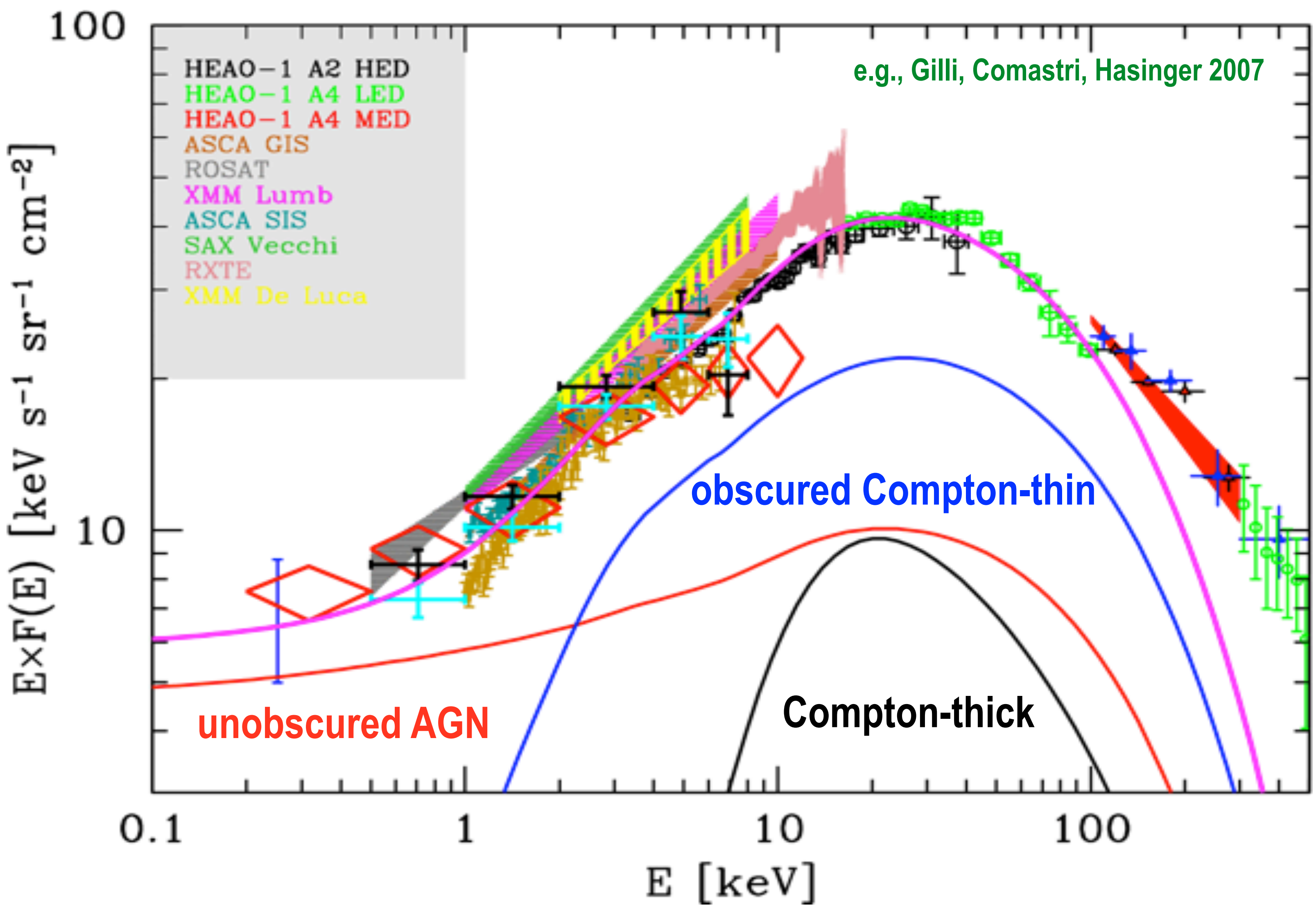


Distribution of N_H column densities of local AGN

(i.e., neutral hydrogen material between us and source, particles per cm^2)

e.g., Schmidt 1998

It has been hypothesized that CT AGN can contribute up to ~25% of the XRB

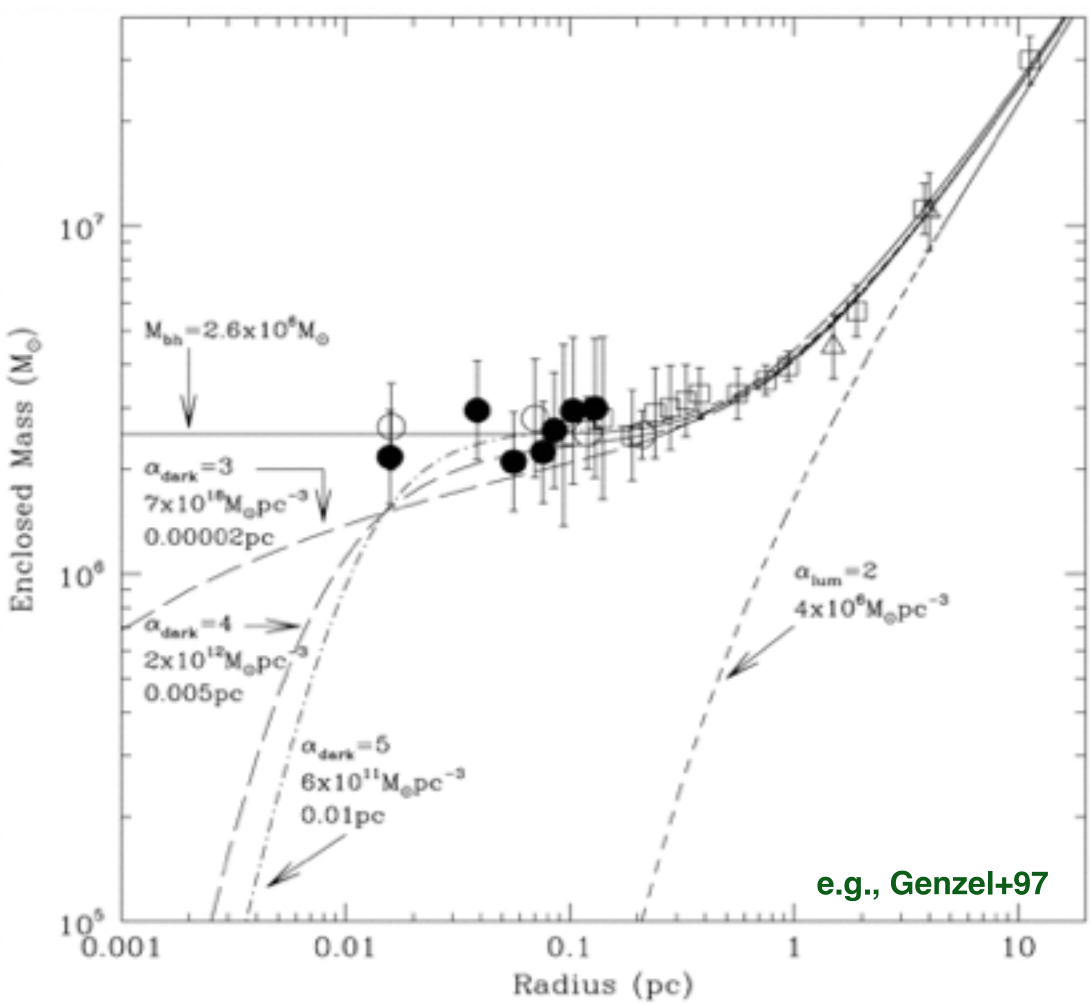


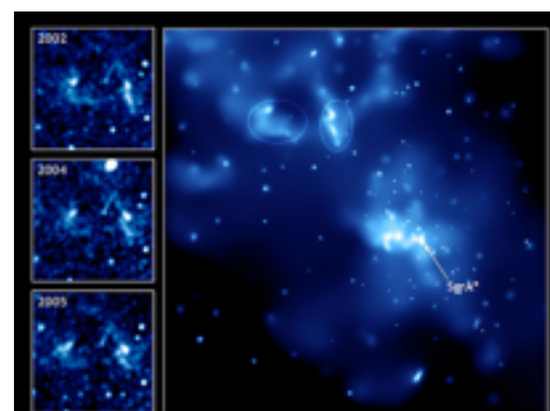
CTAGN important, but need redshift, luminosity, accretion rate distributions.

Around the same time…

Black Holes in Every Large Galaxy…

Sgr A* is supermassive black hole with $3\times10^6\ M_\odot$ and past “Seyfert” level activity $\sim10^2$-10^4 yrs ago





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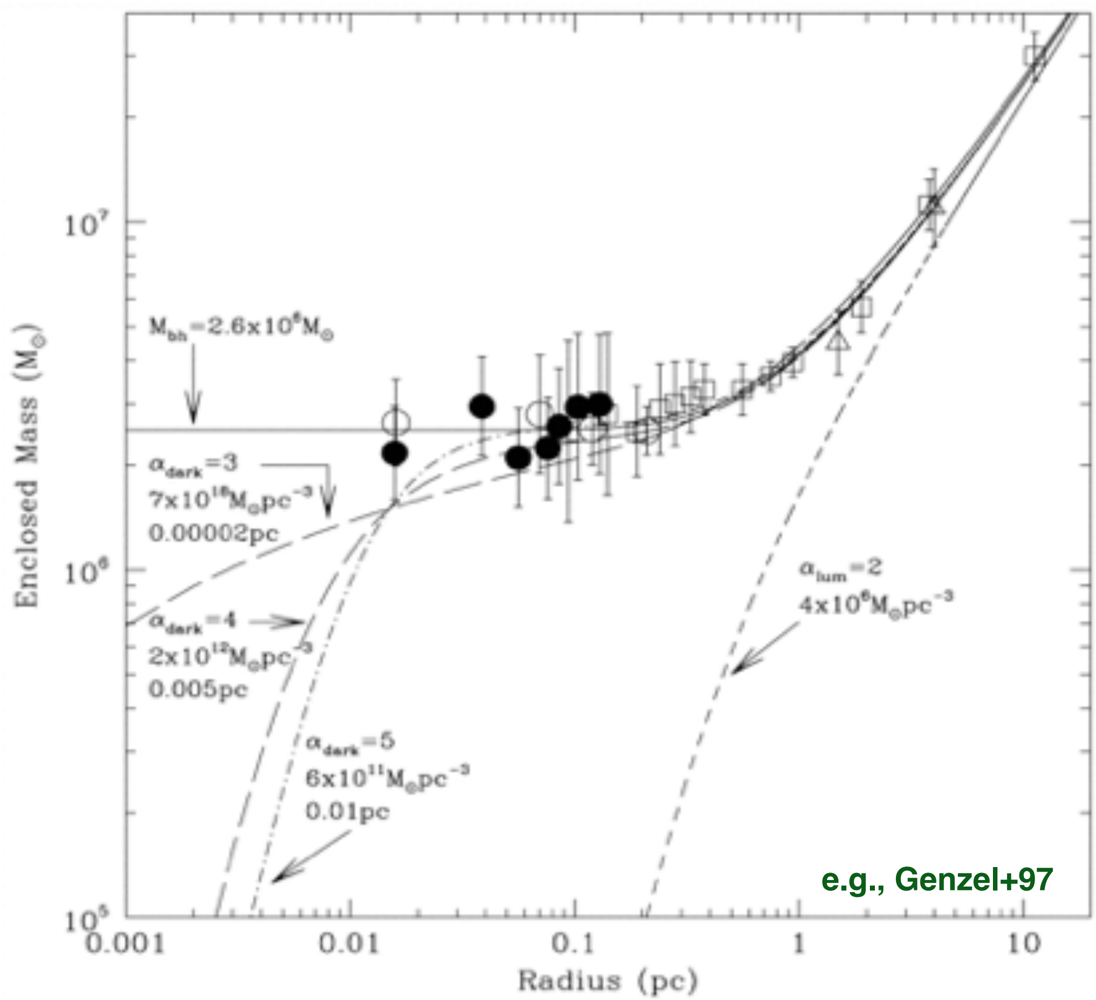
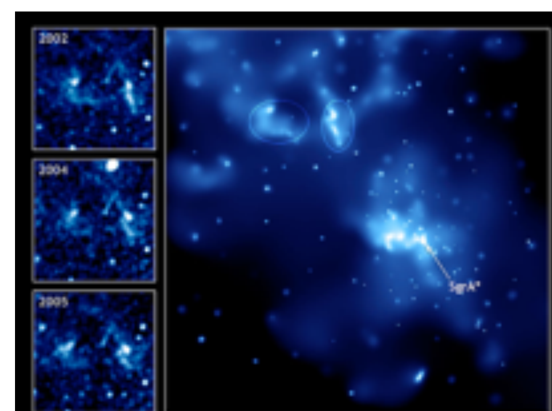
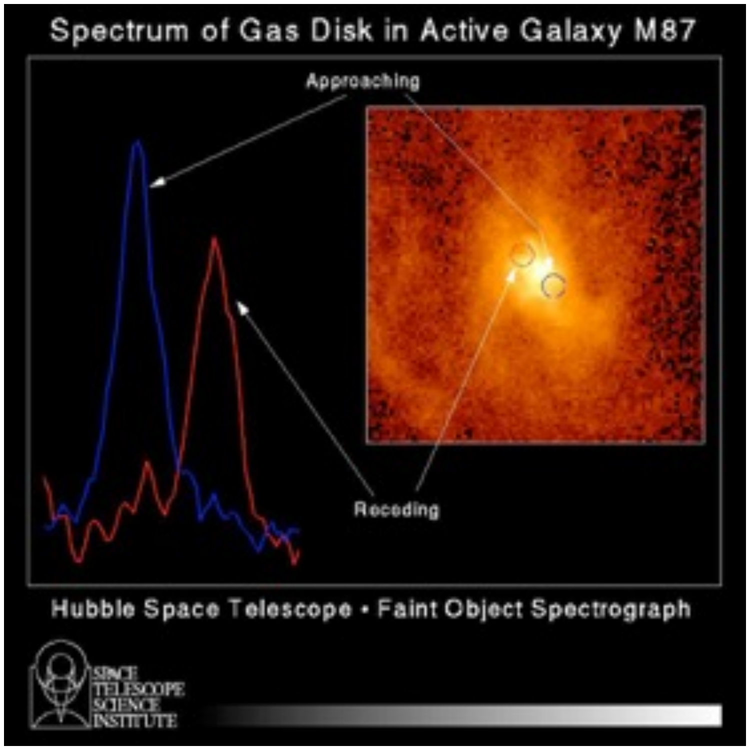




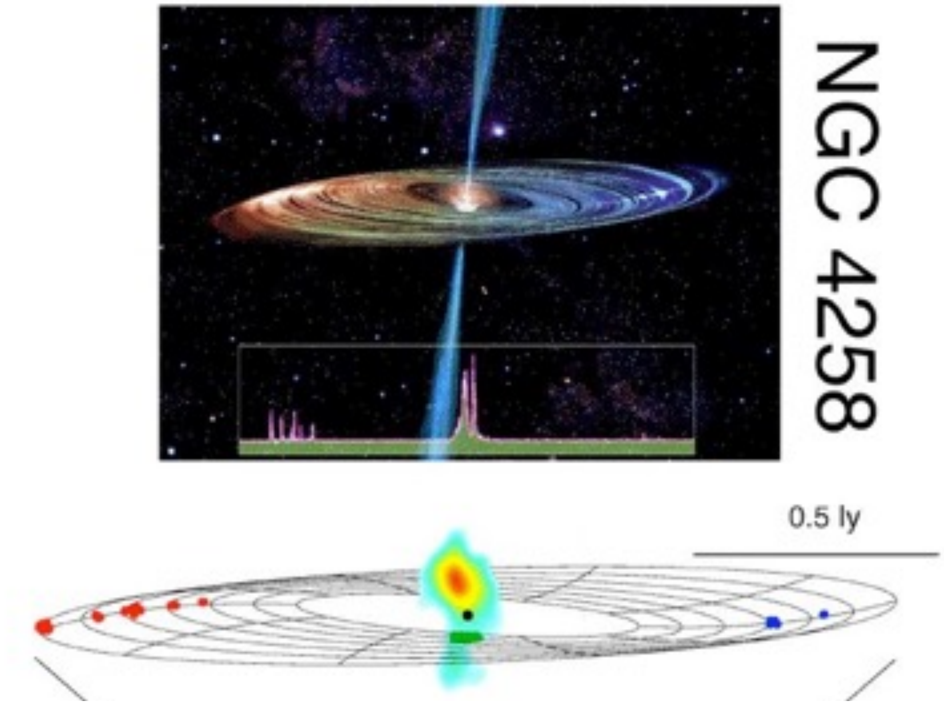
Black Holes in Every Large Galaxy…

Other galaxies - less accurate measurements, but measurements none the less



Ford et al. 1994

Braatz et al. 1994



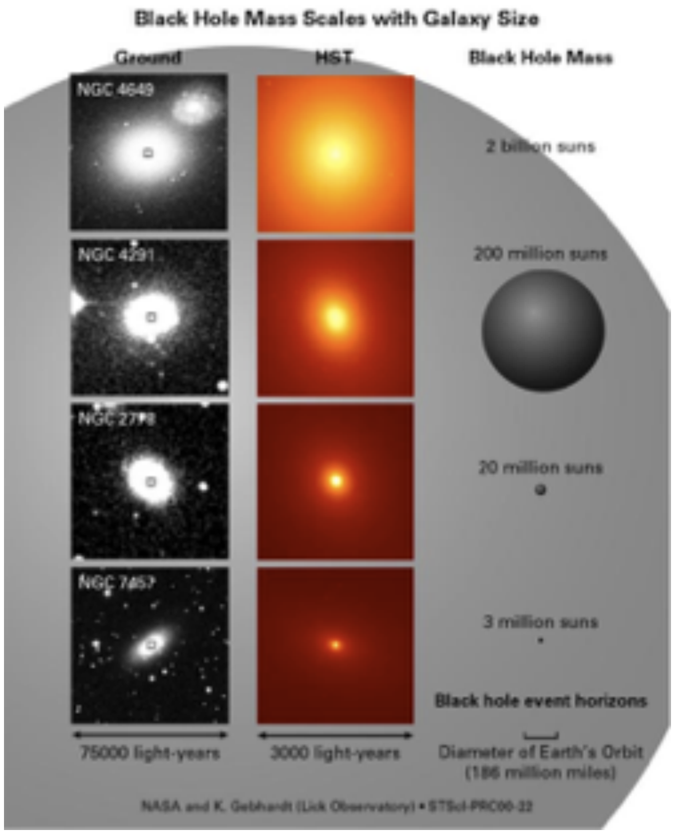
HST Legacy project (few dozen) spatially-resolved optical spectroscopy

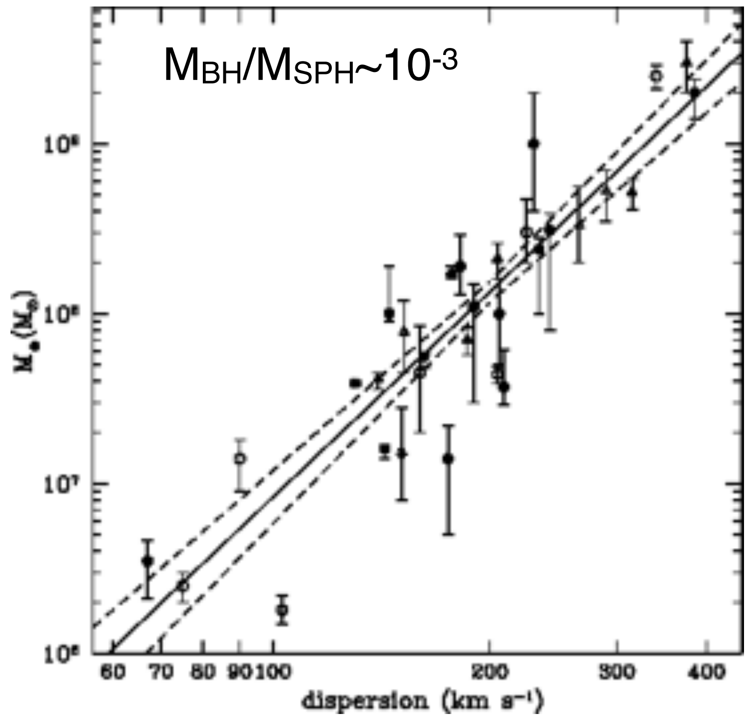
For favorably orientated AGN, radio monitoring of MASER emission

Black Hole / Galaxy Relationship

Begin to see relationship by comparing M_{BH}-σ, M_{BH}-L_{bulge}, M_{BH}-M_{bulge}, M_{BH}-M_{halo}
These imply stars and SMBH roughly grow together

=> Now non-AGN astronomers must care about AGNs!

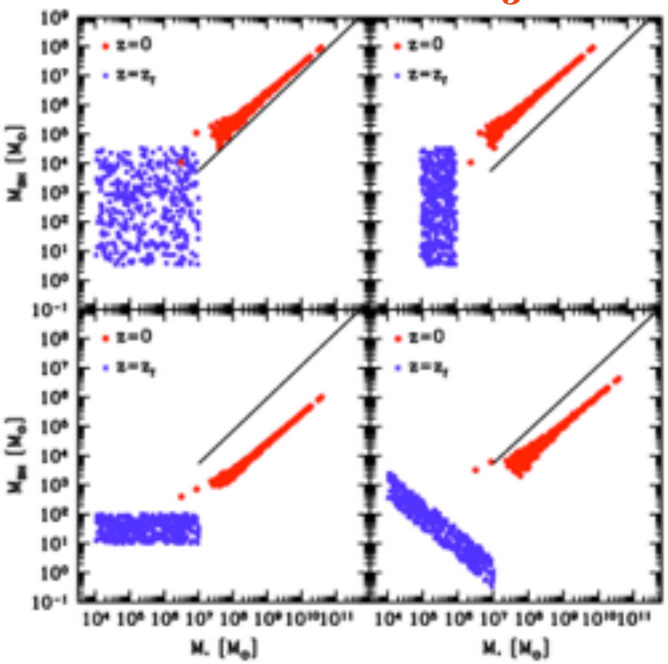




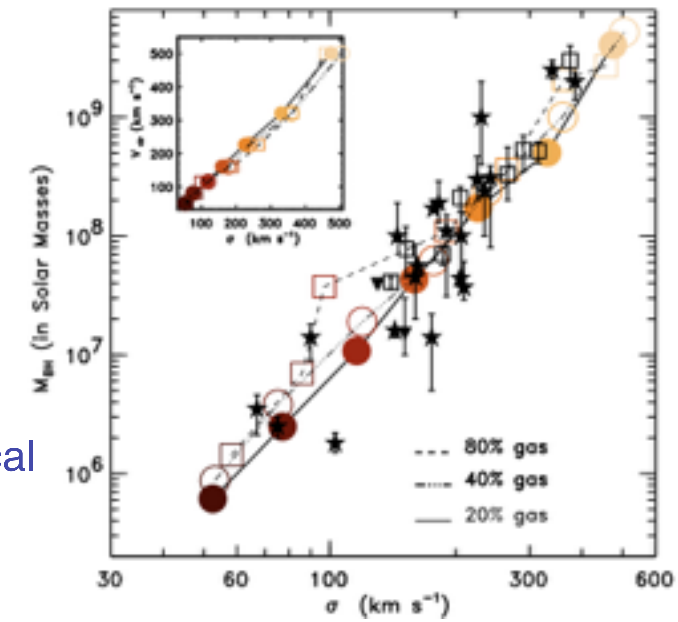
Want to understand how something so small can scale with something so large (9 orders of magnitude difference in size scale)?

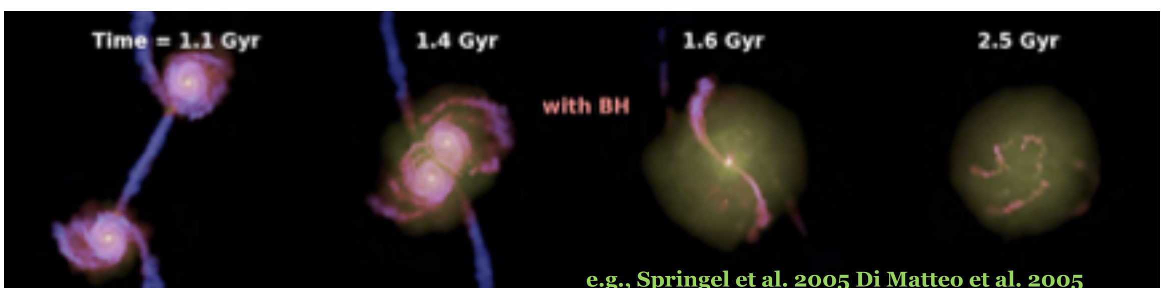
To 1st order, we could get these relations from merging. However, the frequency of mergers is not that high, so not enough time to "lock-in" relation. Moreover, the exact slope (2nd order) critically requires fine-tuning (halting) of star formation. Is there room for the black hole to start/stop star-formation in the galaxy via some feedback process?

Janhke 2013



Hydrodynamical simulations

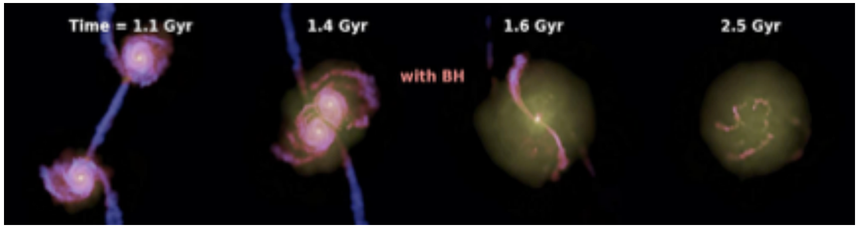


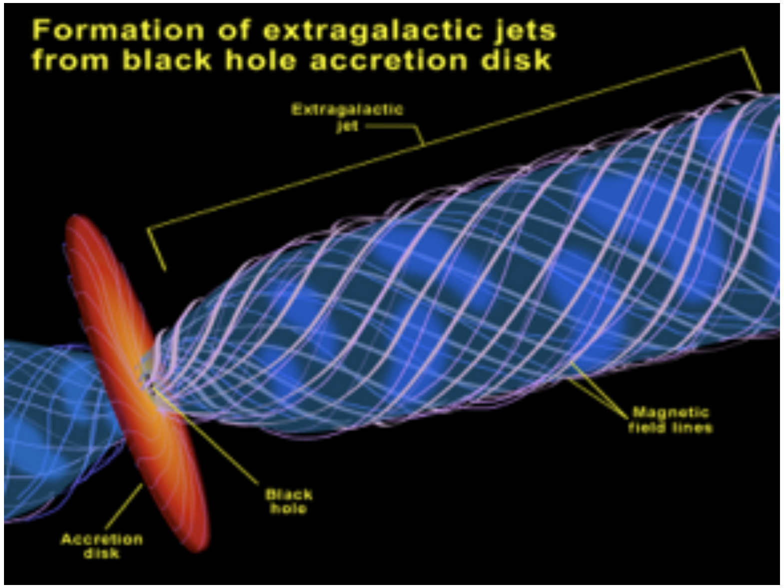


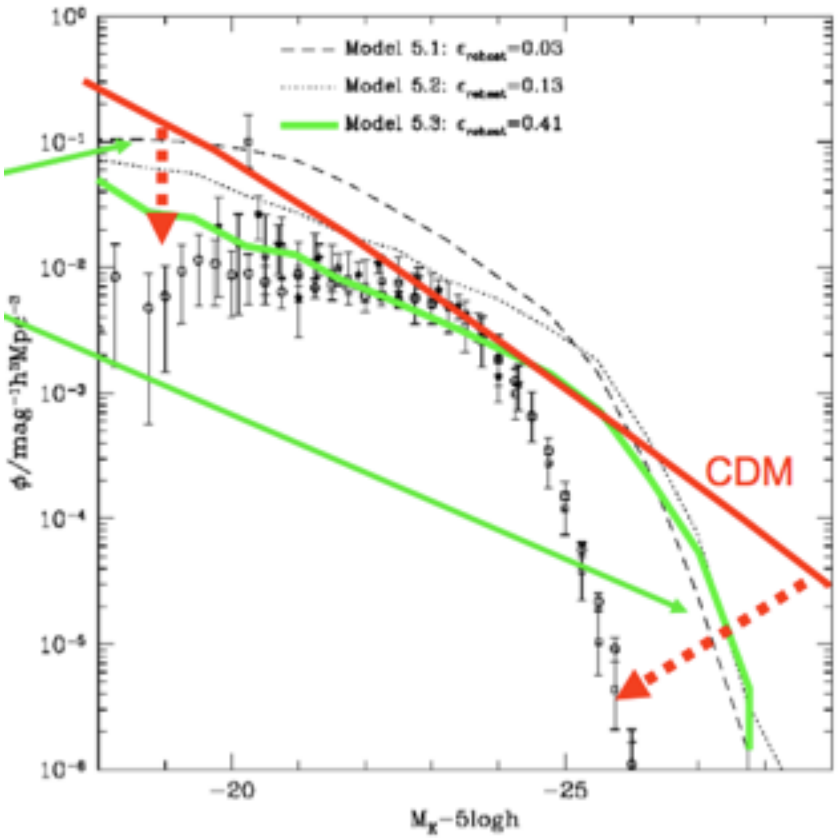
Need energetic feed-back that requires no star-formation itself

Outflows: the Black-Hole Arm?

An arm for the black hole to “orchestrate” star formation: potential to get over the factor of a billion difference in size scale. Possibility of BH to affect evolution of galaxy => could help shape galaxy luminosity function!





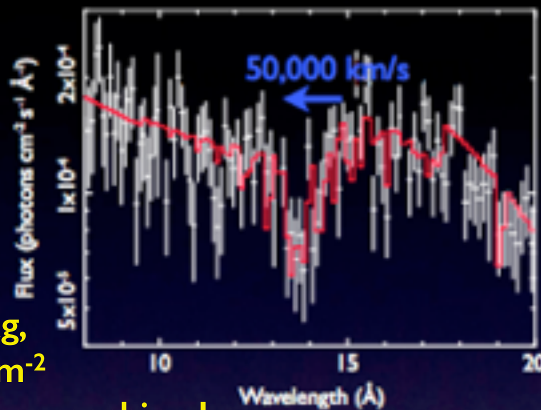


Need energetic feed-back that requires no star-formation itself

Black Hole / Galaxy Relationship

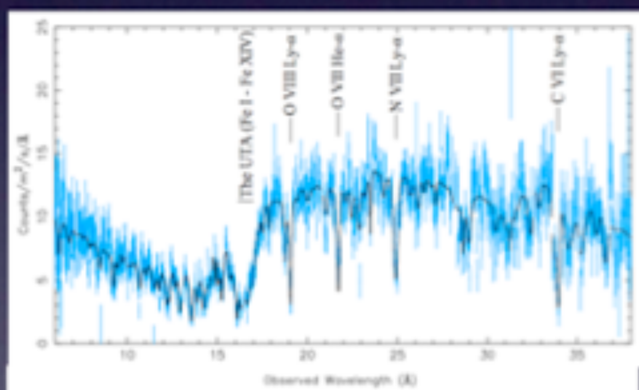
Evidence for Outflows: Spectroscopy

(BAL) QSOs

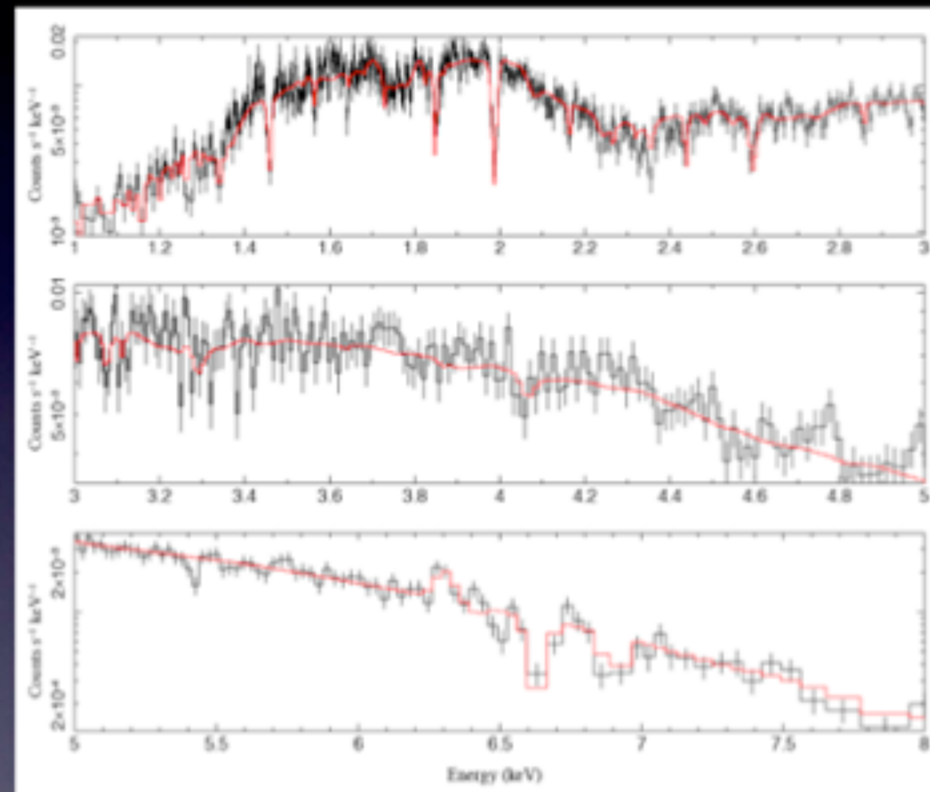


PDS 456 - Reeves et al. (2003)

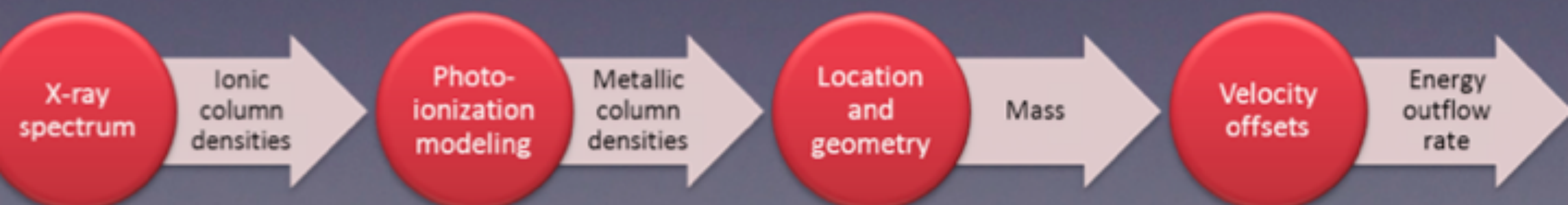
0.1-0.2c,
from 100Rg,
$N_H > 10^{23}$ cm^{-2}
-> power approaching L_{bol}



N3516 - Mehdipour et al. (2010)

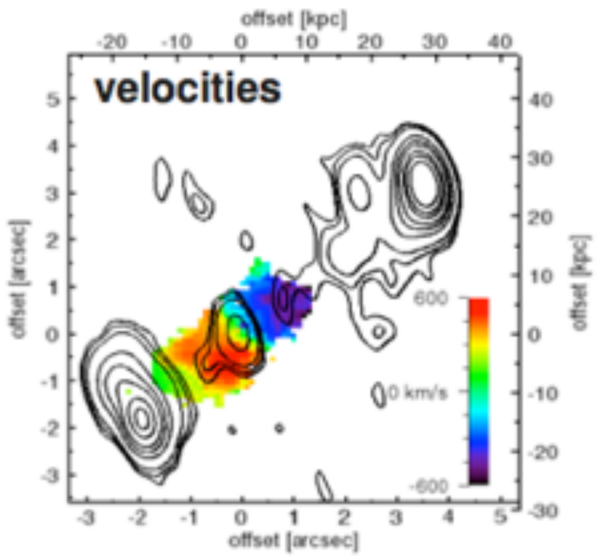


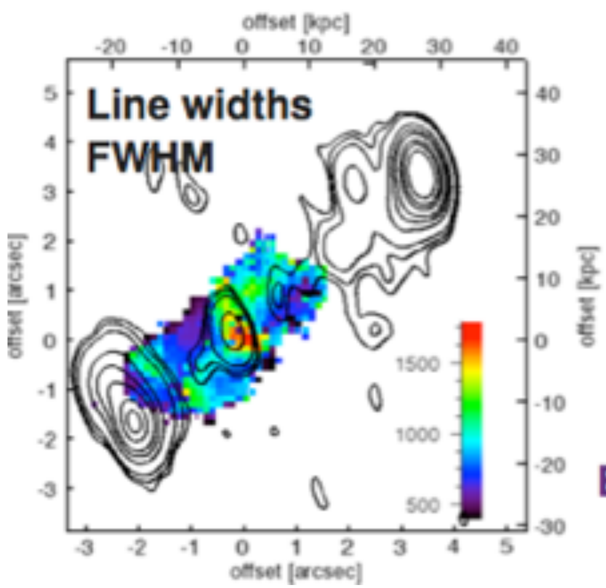
ESO 323 - Evans et al. (in prep.)



High-ionization X-ray gas has large columns and filling factors

Jet-Mode: Radio-loud quasars w/ extended [OIII]





(e.g., Nesvadba+08, +09, +11)

Characteristic: blue / redshifted bubbles
- velocity offset 1000 km s^{-1} (>> rotation)
- Line widths ~ 1000 km s^{-1}

Gas extends along jet axis to $R >> R_{stars}$
- only extended gas where extended radio sources
- velocity along the jet axis

$M_{gas,ion}$ ~ 10^{10} M_s ~ $M_{gas,\,mol}$
- Hα flux, extinction, electron densities measured
- starburst galaxies: M_{mol} / M_{ion} ~ $10^{2\text{-}3}$

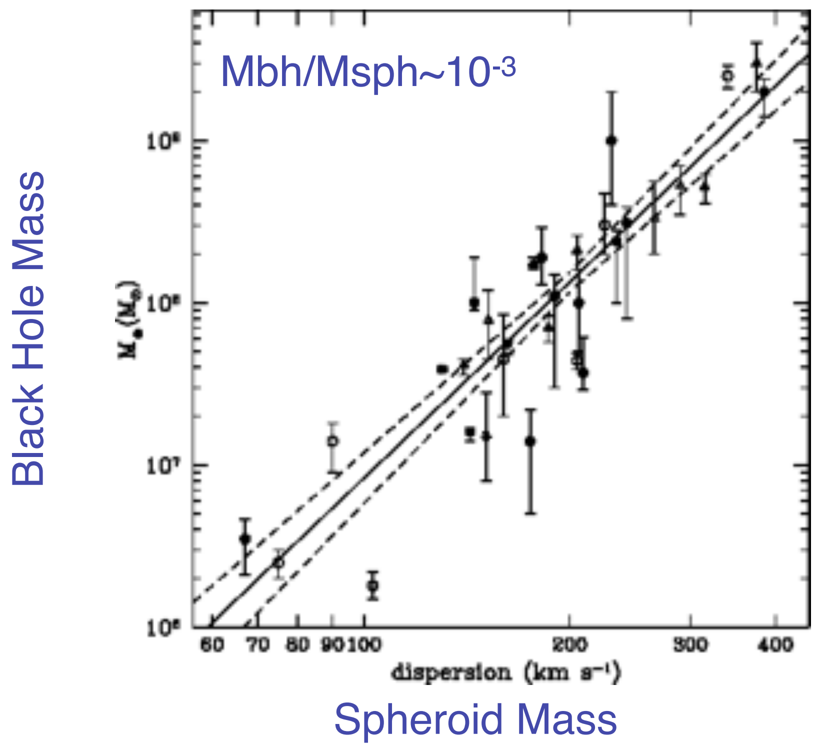
$E_{kin,gas}$ ~ $10^{59\text{-}60}$ erg
- ~ binding energy of a massive host galaxy
- 0.1 - 0.2 % of the rest-mass energy equivalent of the SMBH
- 1-10% of the jet power

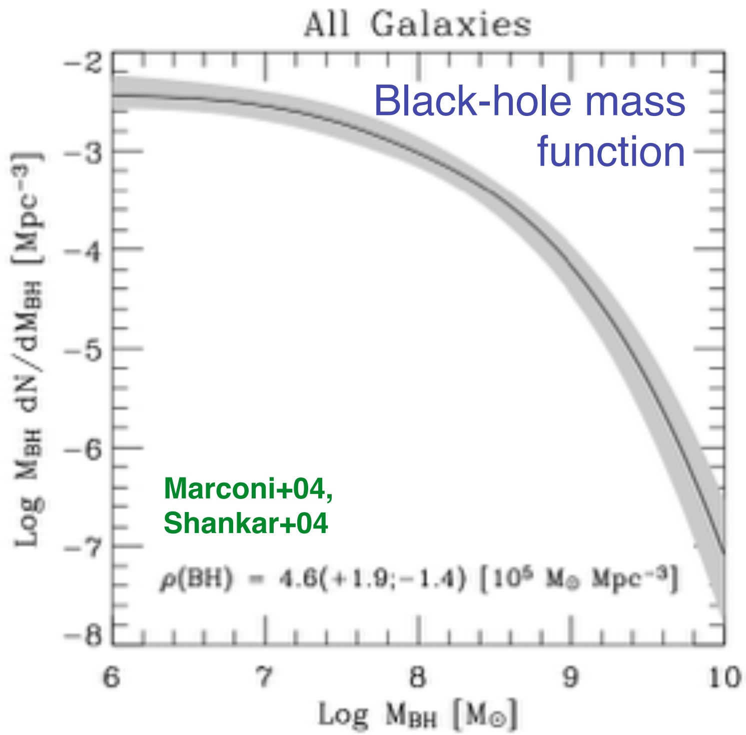
$T_{outflow}$ few x 10^7 yrs ~ AGN lifetime
- characteristic time of a starburst ~ 10^8 yrs

Expected characteristics of AGN-driven winds quenching intense starbursts in massive high-z galaxies

Sołtan Argument Revisited

e.g., Magorrian et al. 1998; Ferrarese & Merritt 2000; Marconi & Hunt 2003

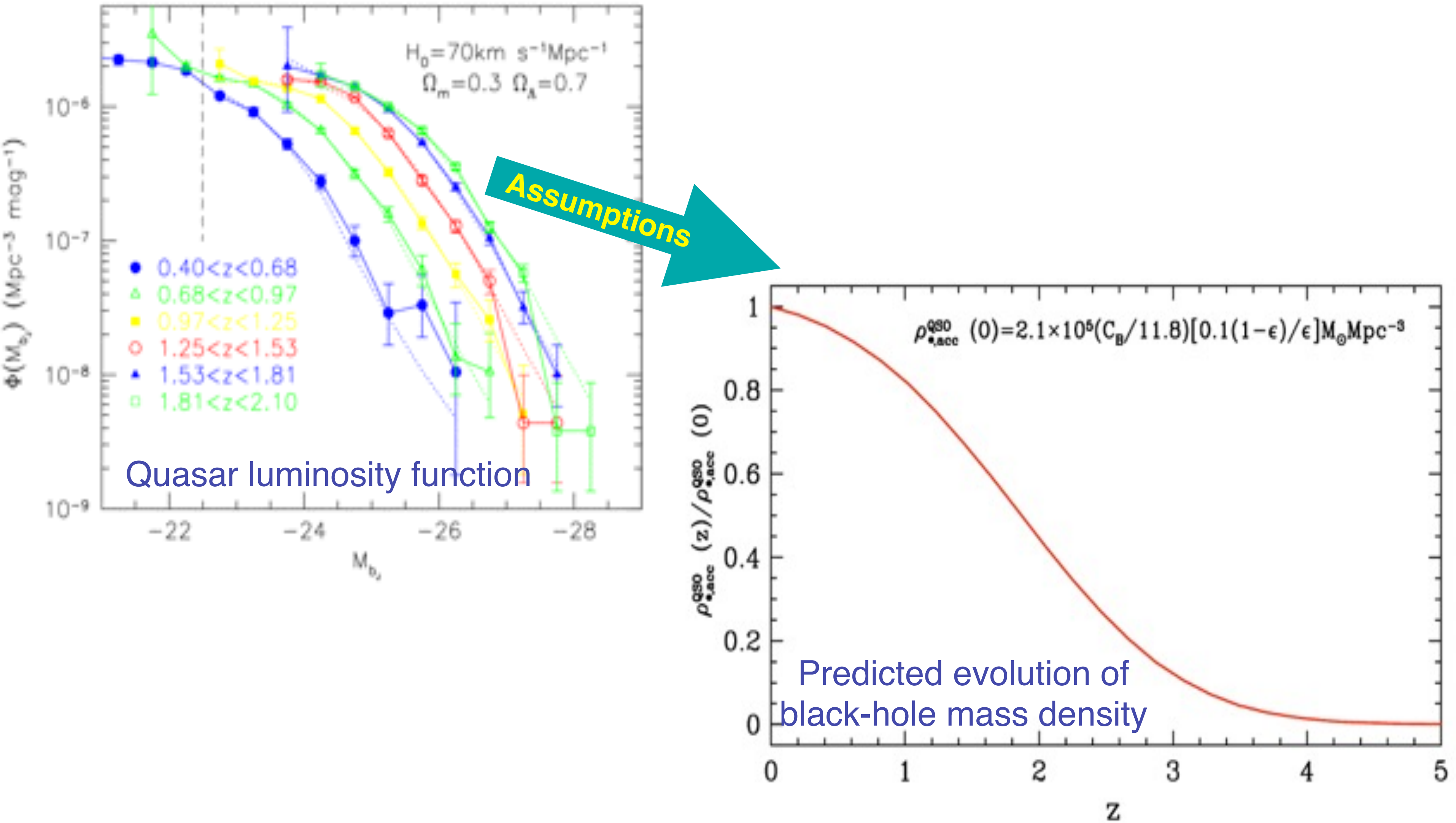




=> can calculate **local SMBH density distribution**

ALSO only 1-5% are active now, so black-hole growth is transient:
<u>there is a substantial "duty cycle" of black-hole growth</u>

Sołtan Argument Revisited

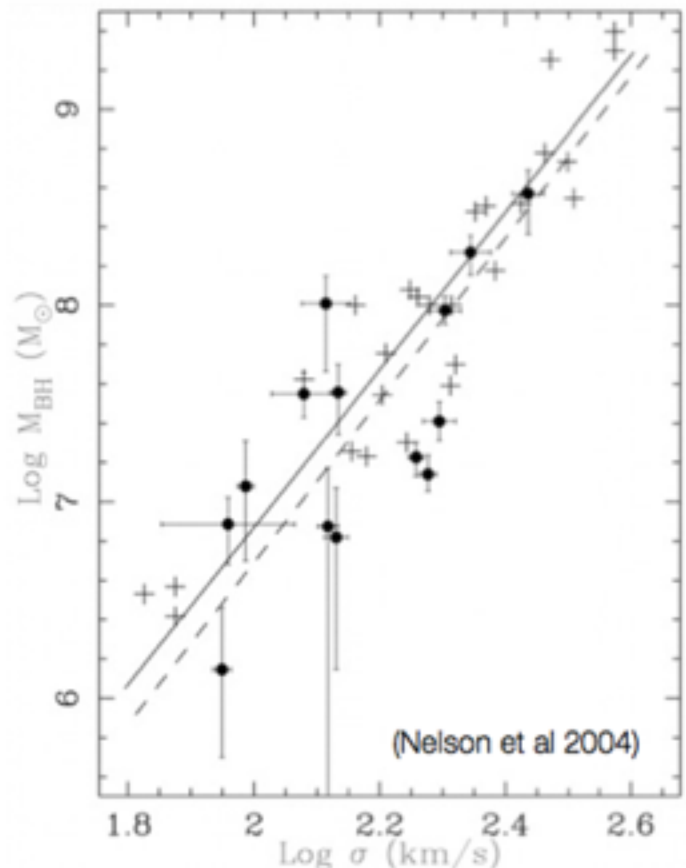


Values roughly consistent (e.g., Fabian & Iwasawa 1999; Yu & Tremaine 2002; Marconi 2003 + MANY OTHERS)

But wait…Reverberation Mapping!

- If the broad-line kinematics are dominated by gravity, we can derive a virial estimate the central mass using the lag time Δt and the broad-line width:

$$M_{BH} = f\frac{rv^2}{G}$$
$$= f\frac{(c\Delta t)[\mathrm{FWHM}(\mathrm{H}\beta)]^2}{G}$$



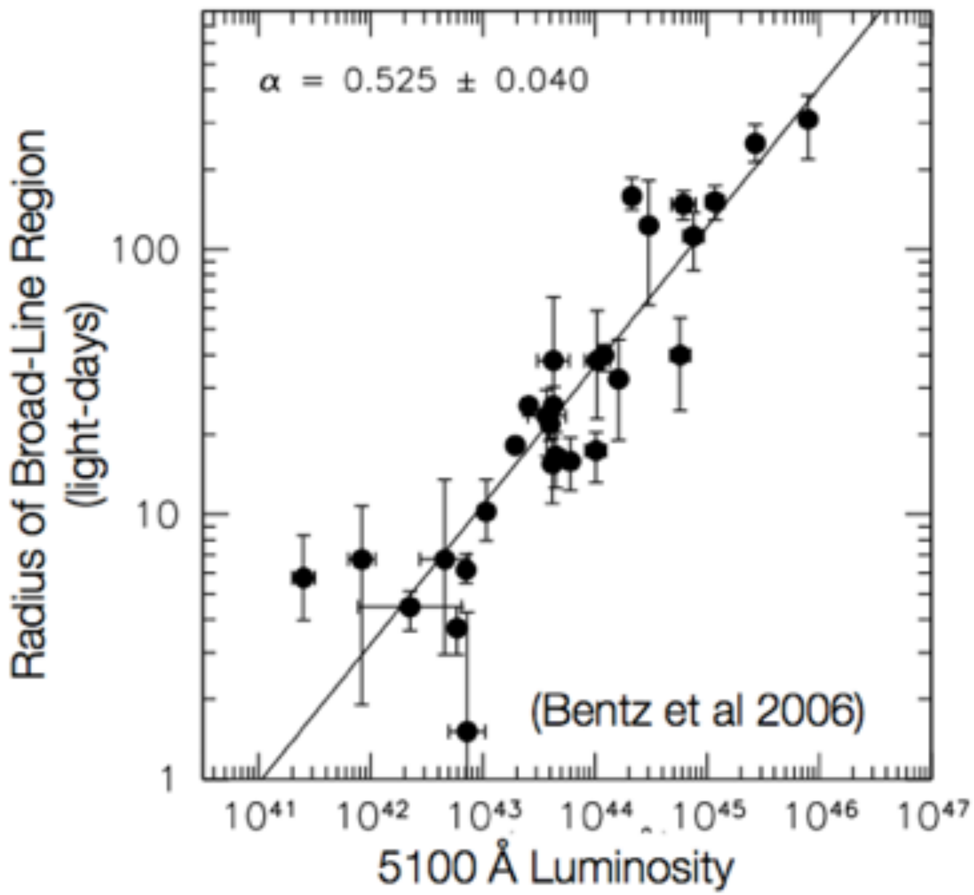
- Hβ reverberation data available for ~35 low-redshift Seyferts & quasars (Kaspi et al. 2000; Peterson et al. 2004)

- Mass estimates from this technique are claimed to be accurate to typically a factor of ~~~3~~ (Onken et al 2004, Nelson et al 2004, Peterson et al 2004, Vestergaard et al 2006) => more likely ~5

- this allows to extend SMBH estimates well beyond regime where spatially-resolved optical spectroscopy applicable
  => still need to monitor variability though

But wait…Reverberation Mapping!

- The broad-line region size is correlated with AGN continuum luminosity:



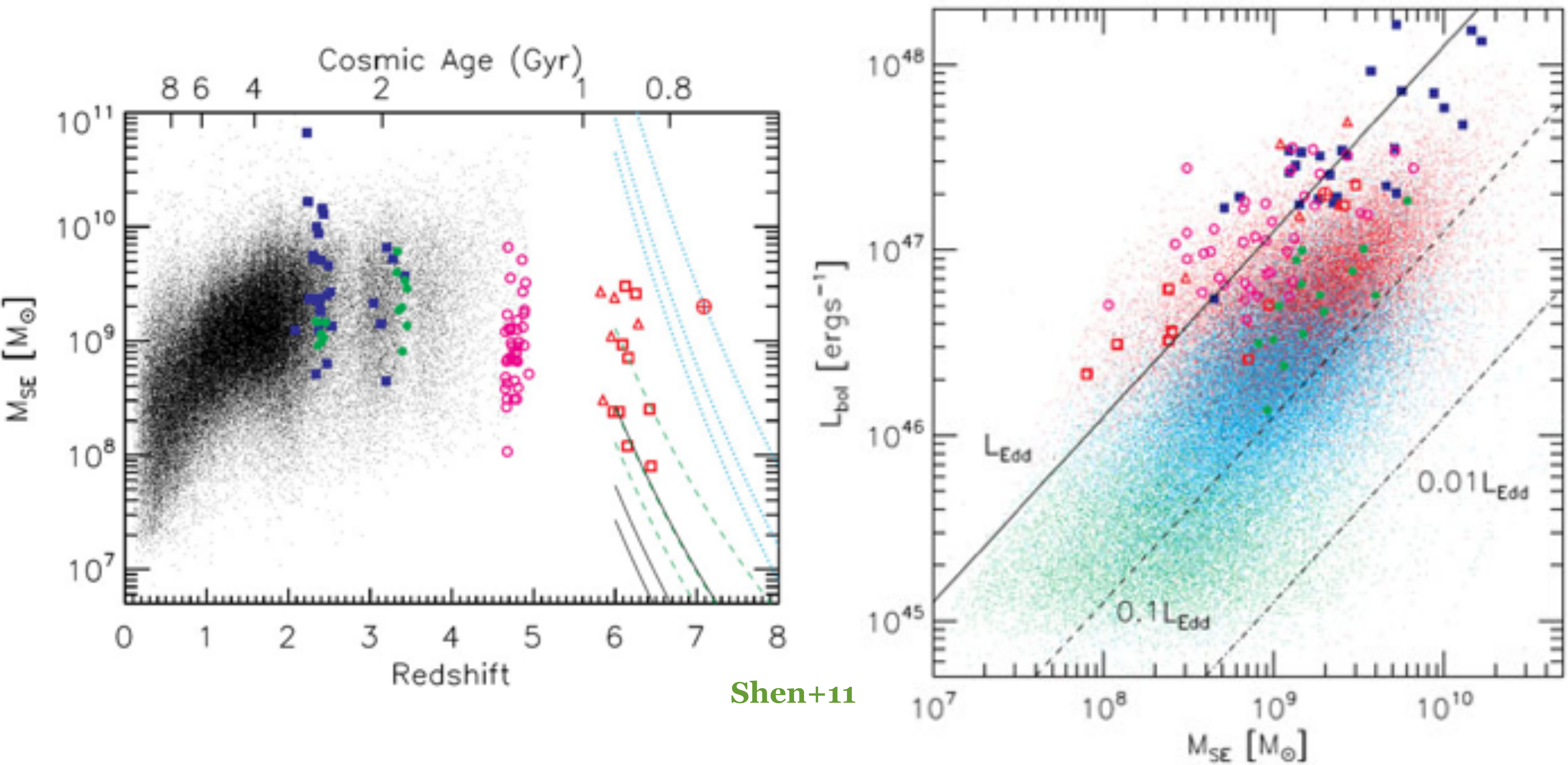
- This provides a quick way to estimate black hole masses in AGNs
- From a single spectrum, can measure both linewidth and continuum luminosity
- Use L to estimate r(BLR), then apply the virial relation to estimate M

(e.g., Laor 1998; Wandel et al. 1999; McLure & Dunlop 2001; Vestergaard 2002; Woo & Urry 2002; Shields et al. 2003; Netzer 2003, many others....)

=> AGN broad lines become a proxy for M_{BH}

M_{BH} for 10^5-10^6 AGN!

e.g., McLure+02, 04; Vestergaard+06; Shen+08, 11; Assef+11 and MANY MORE



Shen+11

Supermassive black-holes range from ~10^4-10^{10} solar masses

Most massive black hole “confirmed”: OJ287 with 1.8×10^{10} solar masses!!!

This makes things significantly more interesting, because we can now try to investigate SMBH growth as a function of **redshift**, **accretion rate**, **SMBH mass**, **host type**, **environment**, **etc**.

However, there are still several details to be worked out and error budgets need to be treated and propagated properly:

SEDs => Bolometric corrections for all AGN

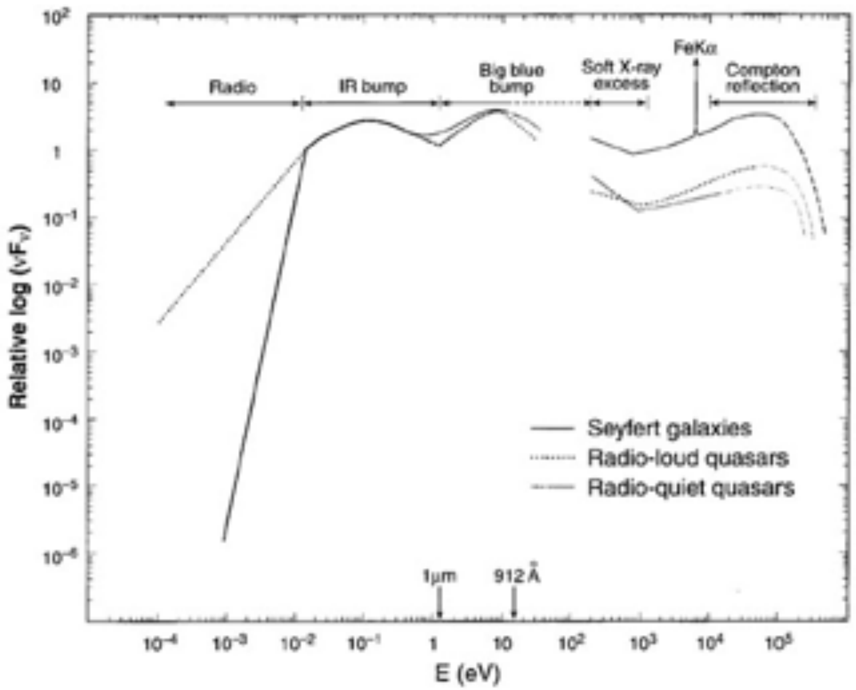
Demographics => census of all AGN vs z

Spectral modeling => understand/correct physics

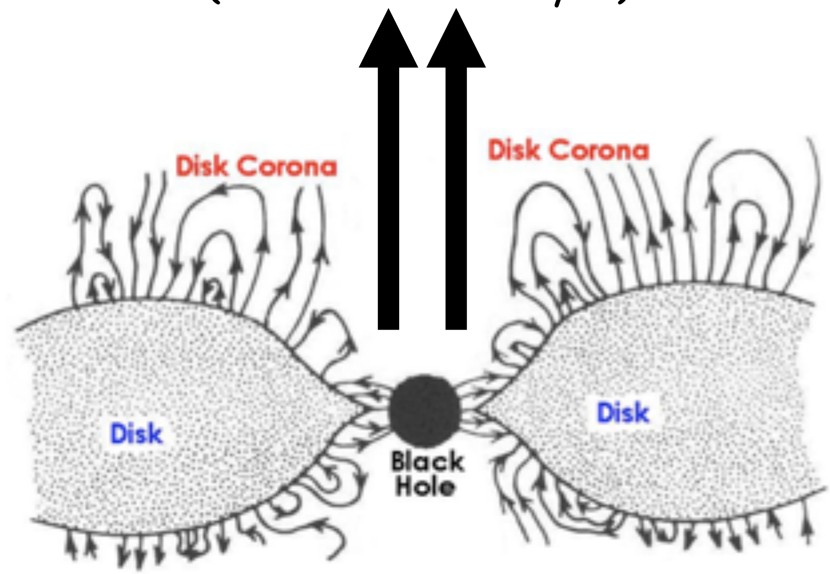
Modeling Luminosity Function

STRUCTURE => SED

First must understand how AGN are powered



Particle jets
(sometimes? always?)



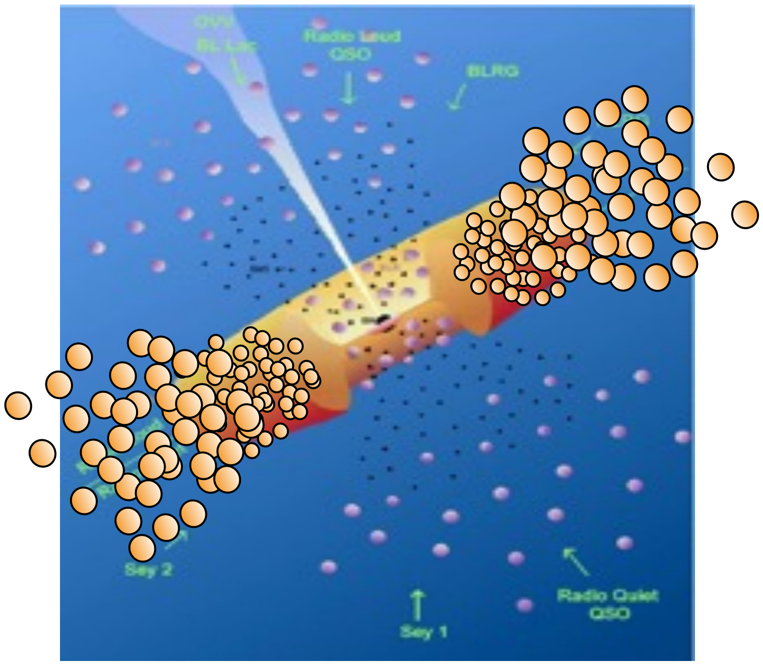
Accretion disk (soft X-ray-UV-optical emission)

thin-disk accretion model
Shakura & Sunyaev (1973)

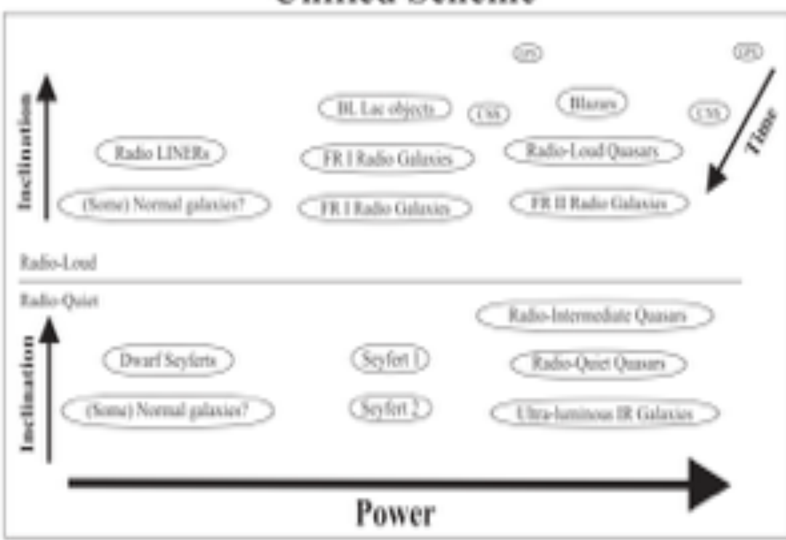
slim-disk?
ADAF?
RIAF?

$$\dot{m}_{\rm BH} = 0.15\left(\frac{\epsilon}{0.1}\right)\left(\frac{L_{\rm bol}}{10^{45}{\rm ergs}^{-1}}\right)M_{\odot}yr^{-1},$$

Corralling the AGN Zoo => Unification?



Unified Scheme



AGN properties driven by

- orientation of a dusty (clumpy) torus (obscuration)
- and jets (beaming),
- mass inflow/accretion type (availability of gas)
- Possible cyclical and evolutionary temporal components?

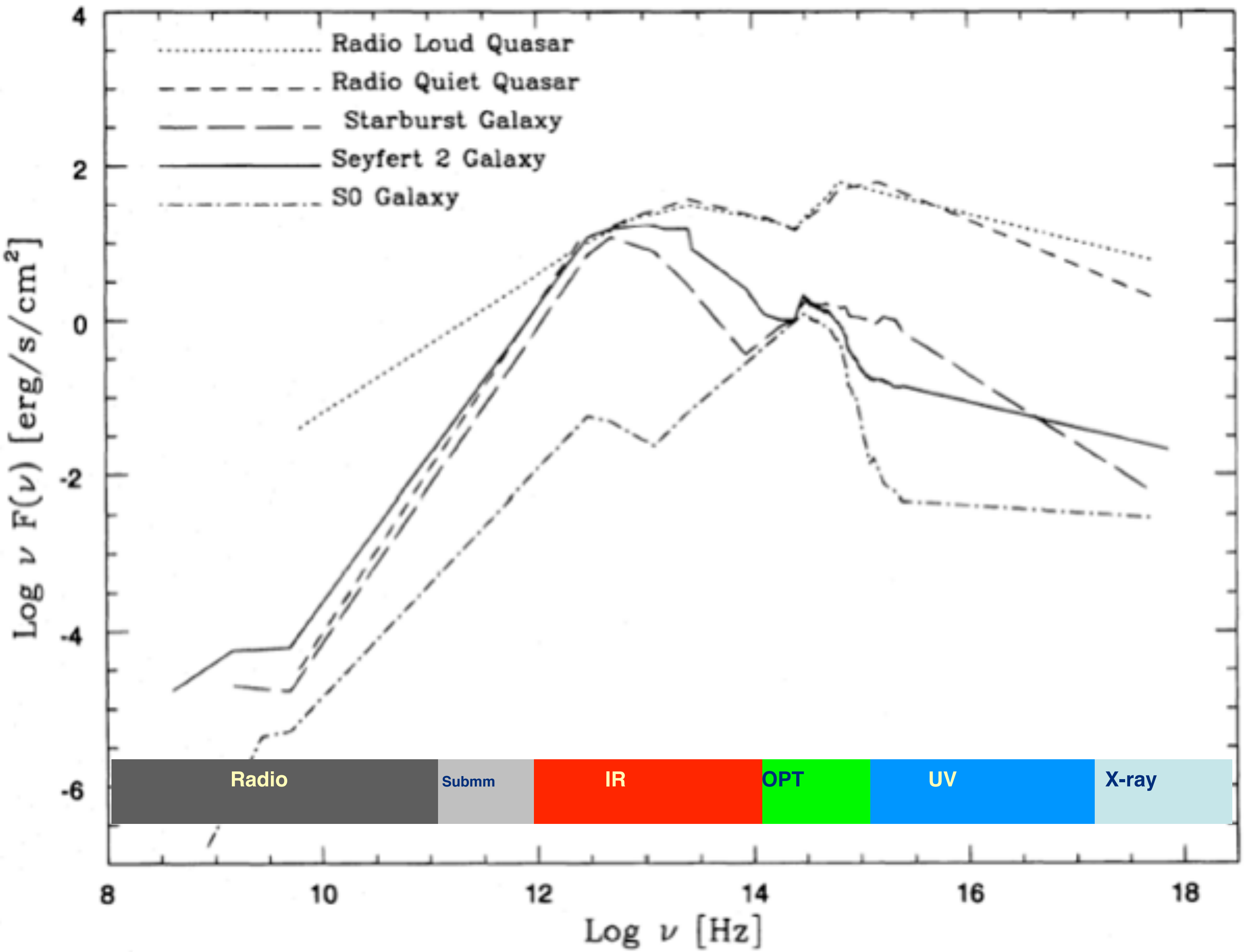
(all of which may be linked)?

Radio loudness: black hole spin, mass accretion rate?

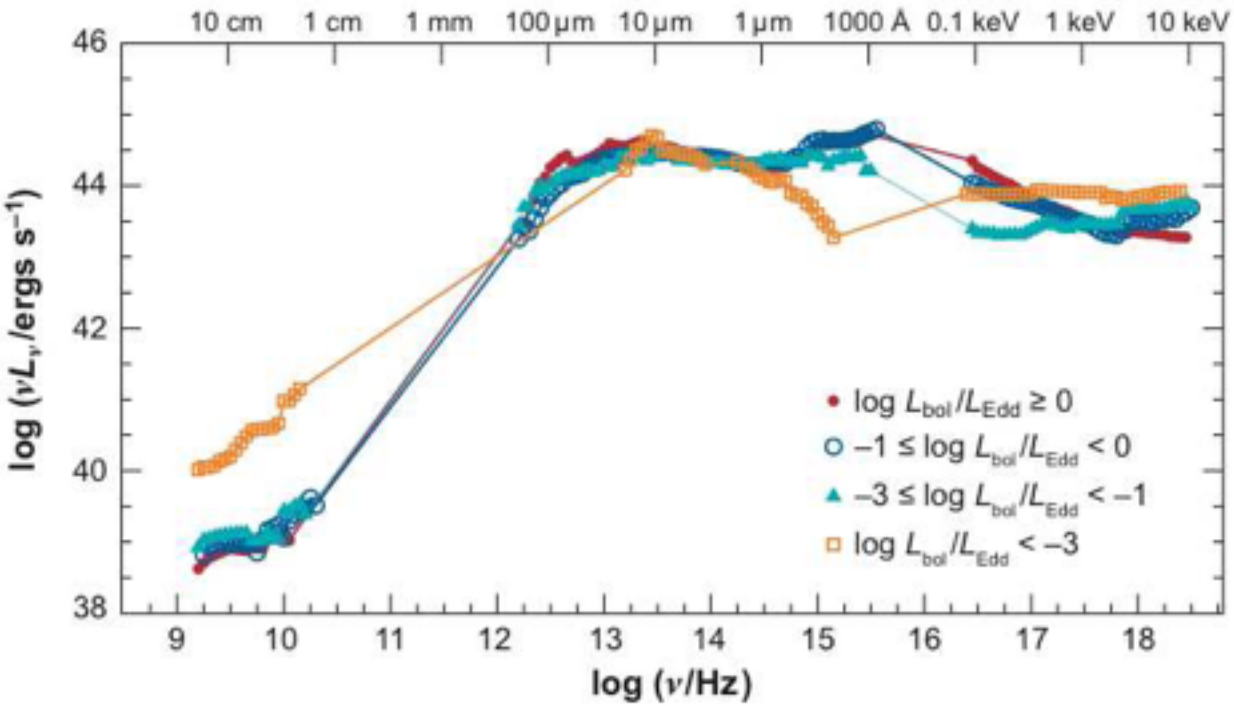
Broad range of possible properties means it is challenging to find ALL AGNs…

need **multi-wavelength** observations

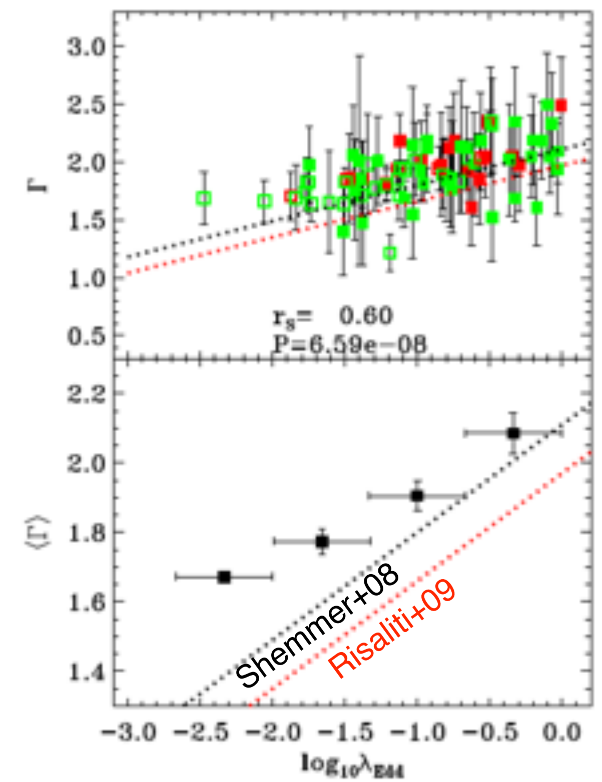
Corralling the AGN SED Zoo



Corralling the AGN SED Zoo



Ho 08

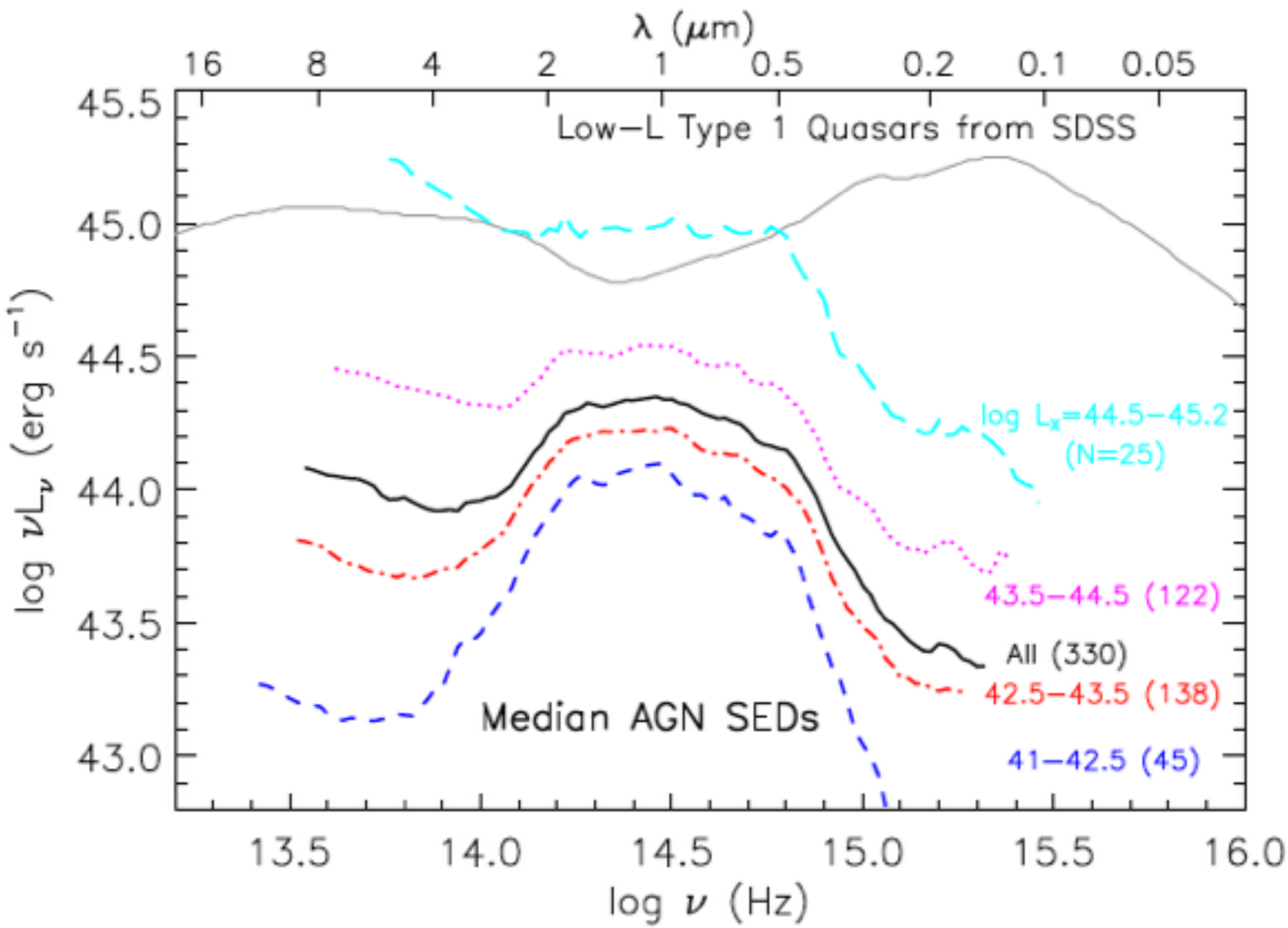


Brightman+13

Accretion rate dependence (in thin-disk regime?)

M_{BH} assessment critical (yields offsets)

Corralling the AGN SED Zoo



Luo+10

The result is that the bolometric correction is likely non-trivial to calculate

bias/error factors of 2-5x easily possible

full multi-wavelength constraints and SED modeling absolutely necessary + M_{BH} => expensive

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Also need to be careful about double counting disk and torus emission

bias/error factors of 1.5-2 possible

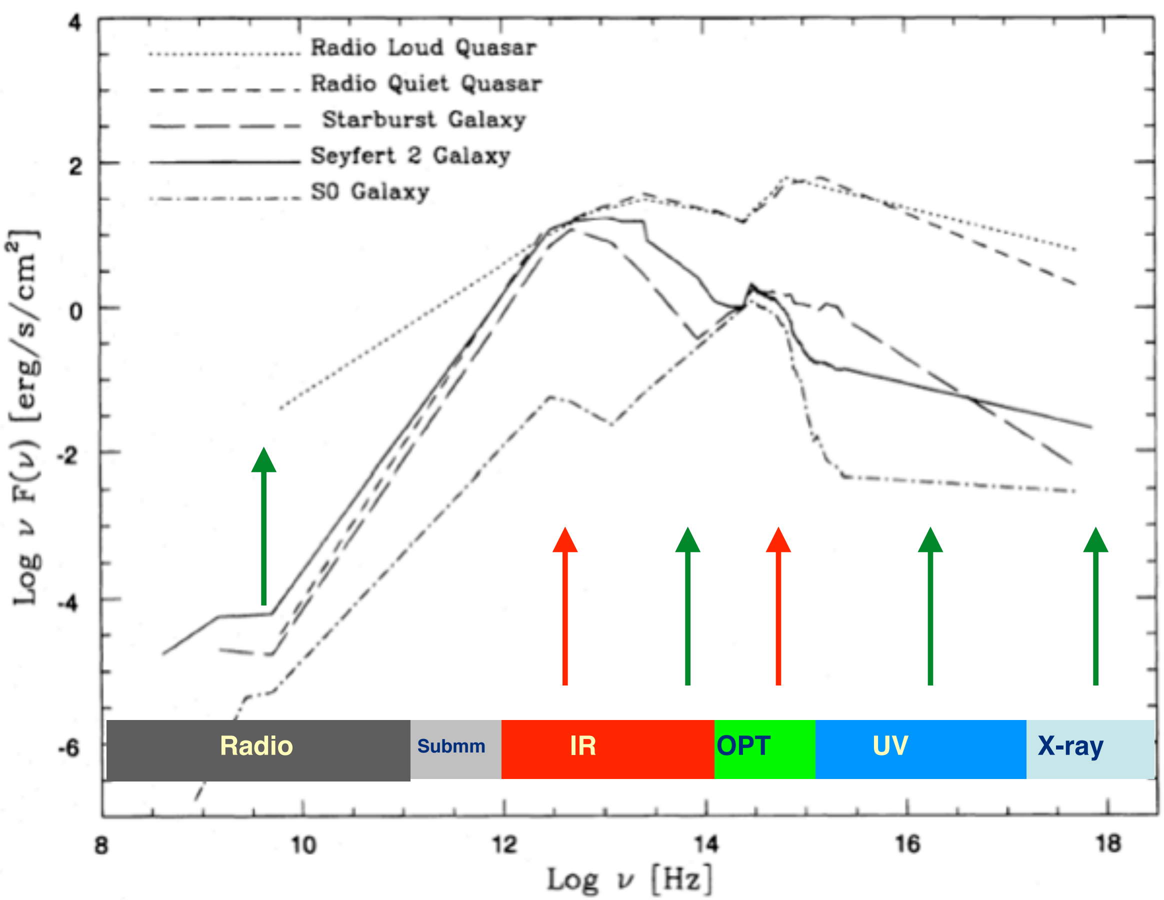
Better torus models needed.

Demographics

(aka how to find AGN)

Evidence for an AGN: SED "Contrast"

Use properties of SED (strength or colors) in particular band which 'identify" AGN versus contaminants (galaxies, stars, etc).



X-rays, UV, mid-IR have best contrast

(+radio when loud)

Optical, far-IR have worst contrast

(limited to intrinsically brighter objects)

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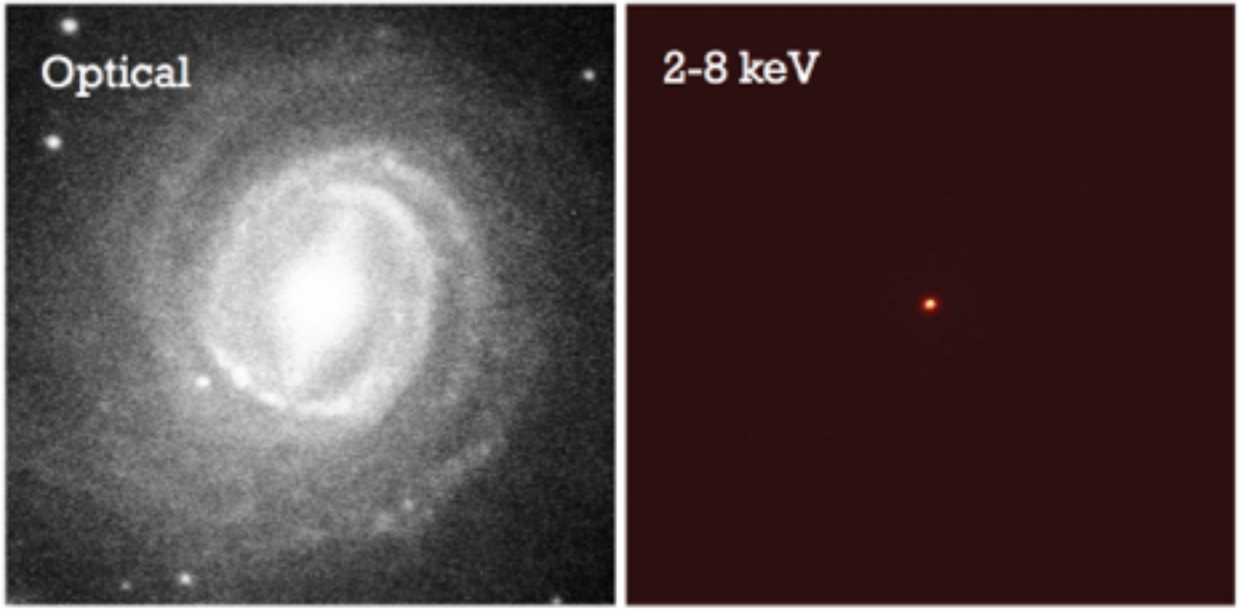

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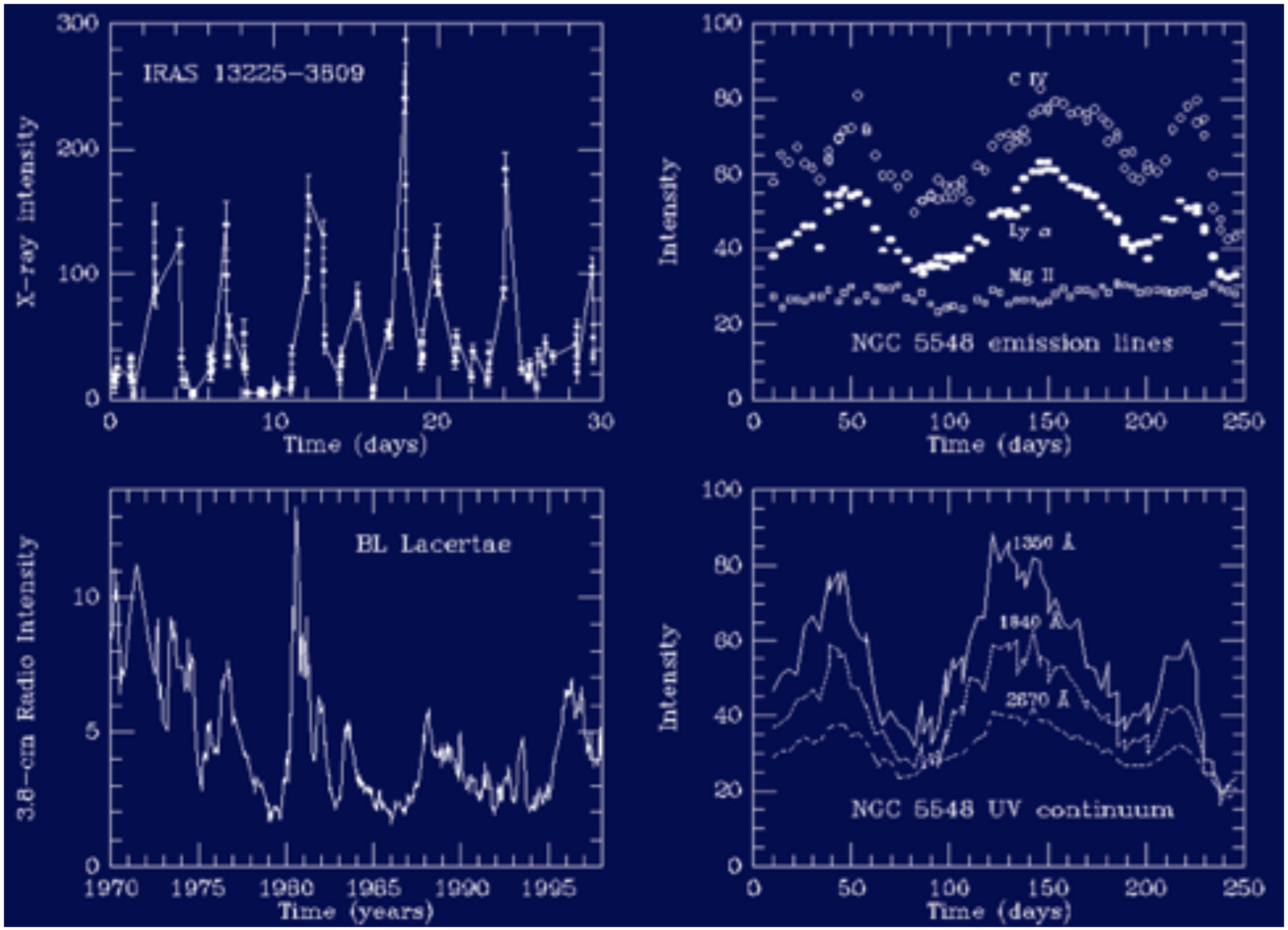
Evidence for an AGN: Variability

Rapid Variability

→ Luminous rapidly variable emission -> small region that can produce powerful emission

X-ray

UV emission lines



Radio (core)

UV

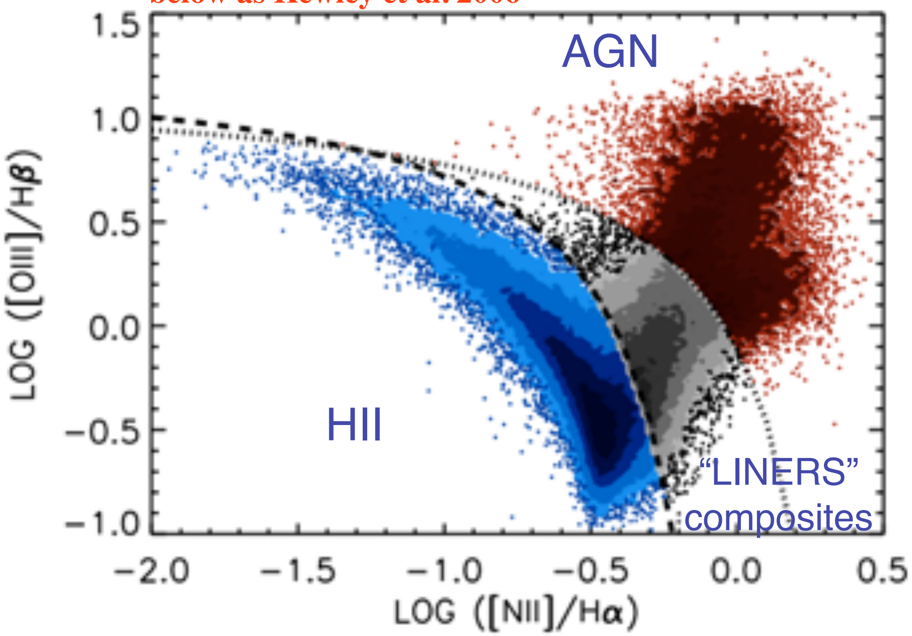
(can be expensive. only find mostly type I?)

Evidence for an AGN: Optical/NIR Spectra

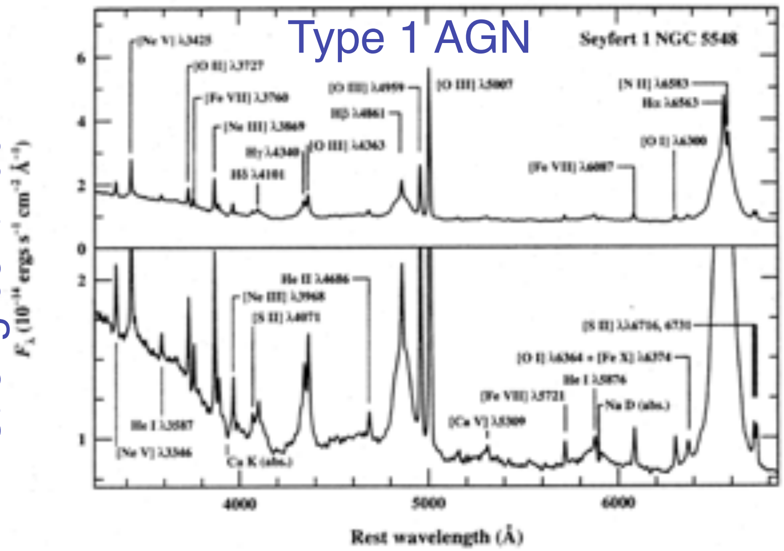
"BPT" classification diagram:
i.e., quantifying Seyfert 1943

Trouille, Barger & Tremonti 2011

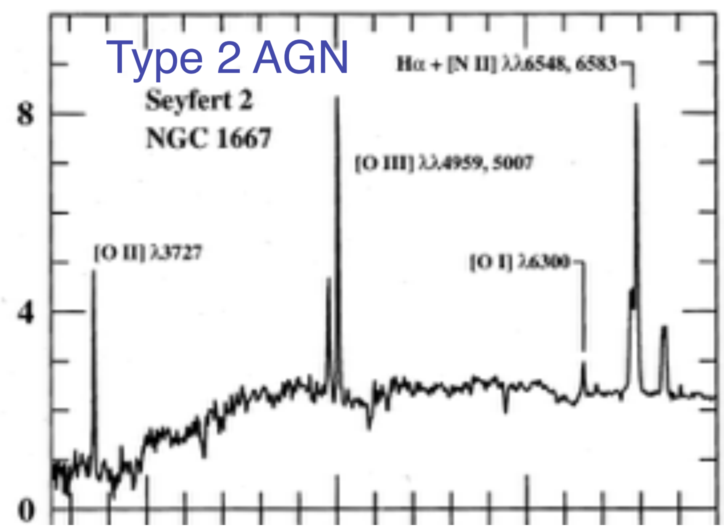
Baldwin, Phillips, and Terlevich 1981
below as Kewley et al. 2006



Broad permitted lines
strong continuum



Narrow permitted lines
host galaxy dominated
continuum



General identifiers:

- → Strong, broad H and He lines (+ others)
- → Strong, high-ionization narrow lines in elements of [C], [N], [O], [Ne], [Fe]
- → both inconsistent with being powered by star formation
- → Other indicators in UV and IR

(again can be expensive)

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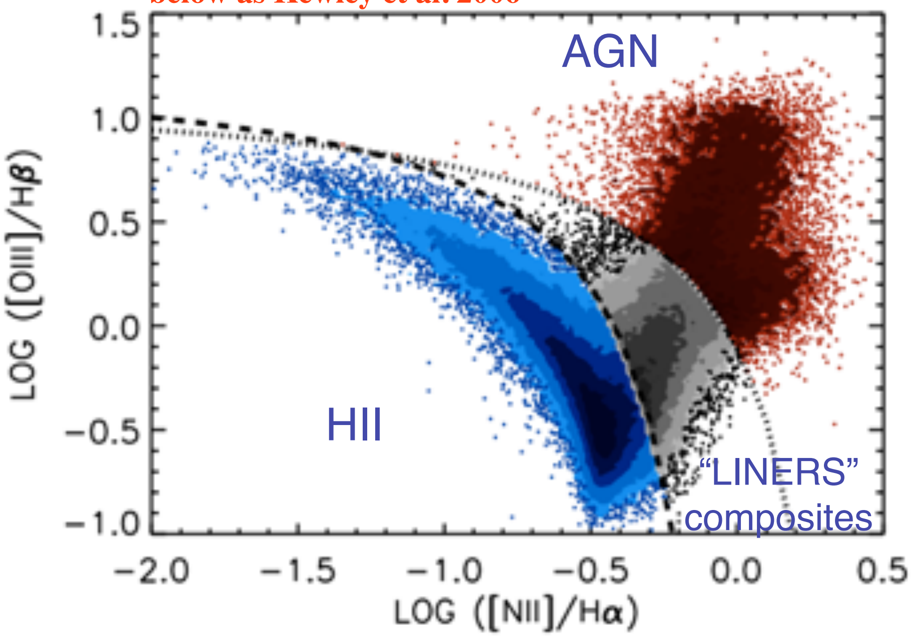

Trouille, Barger & Tremonti 2011

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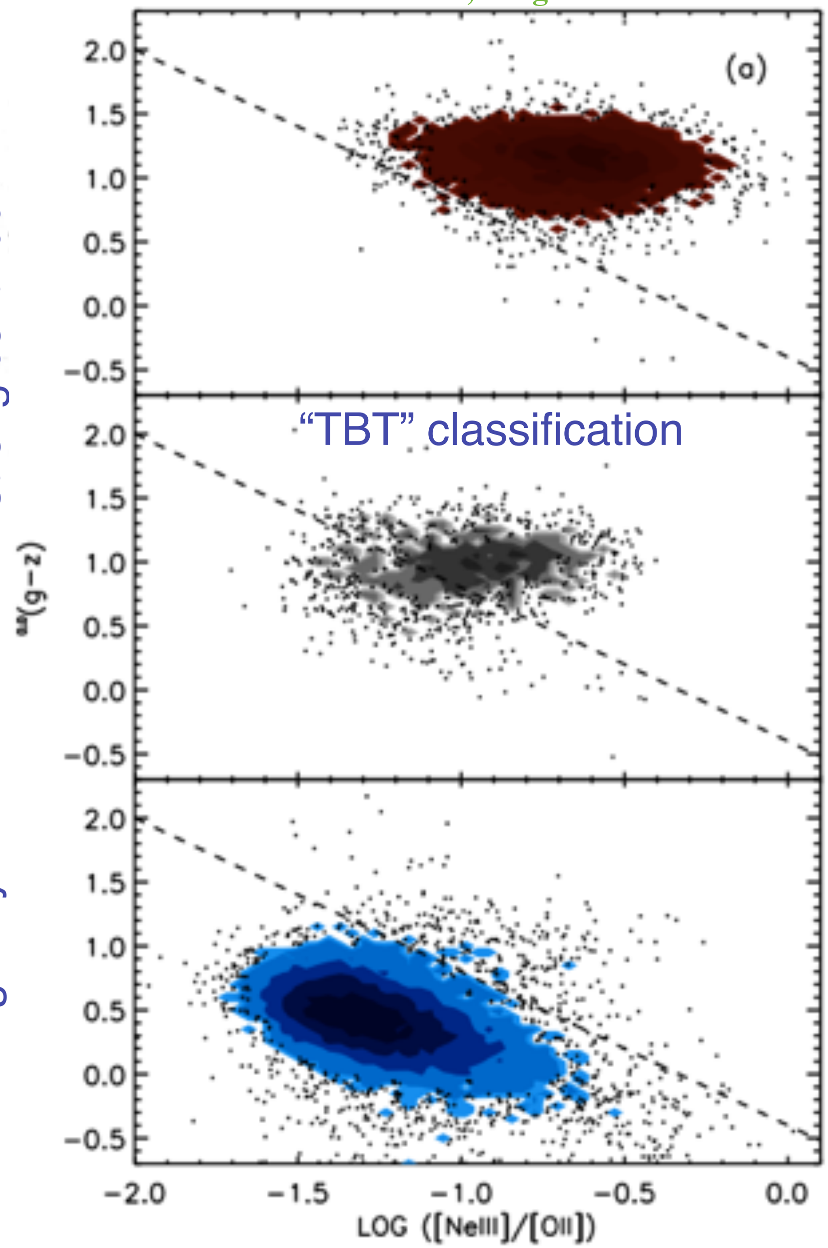

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Local AGN Demographics (AGN fraction)

First-order statistics on AGNs:

→ Optically, ~5% of massive galaxies host an obvious, luminous AGN:

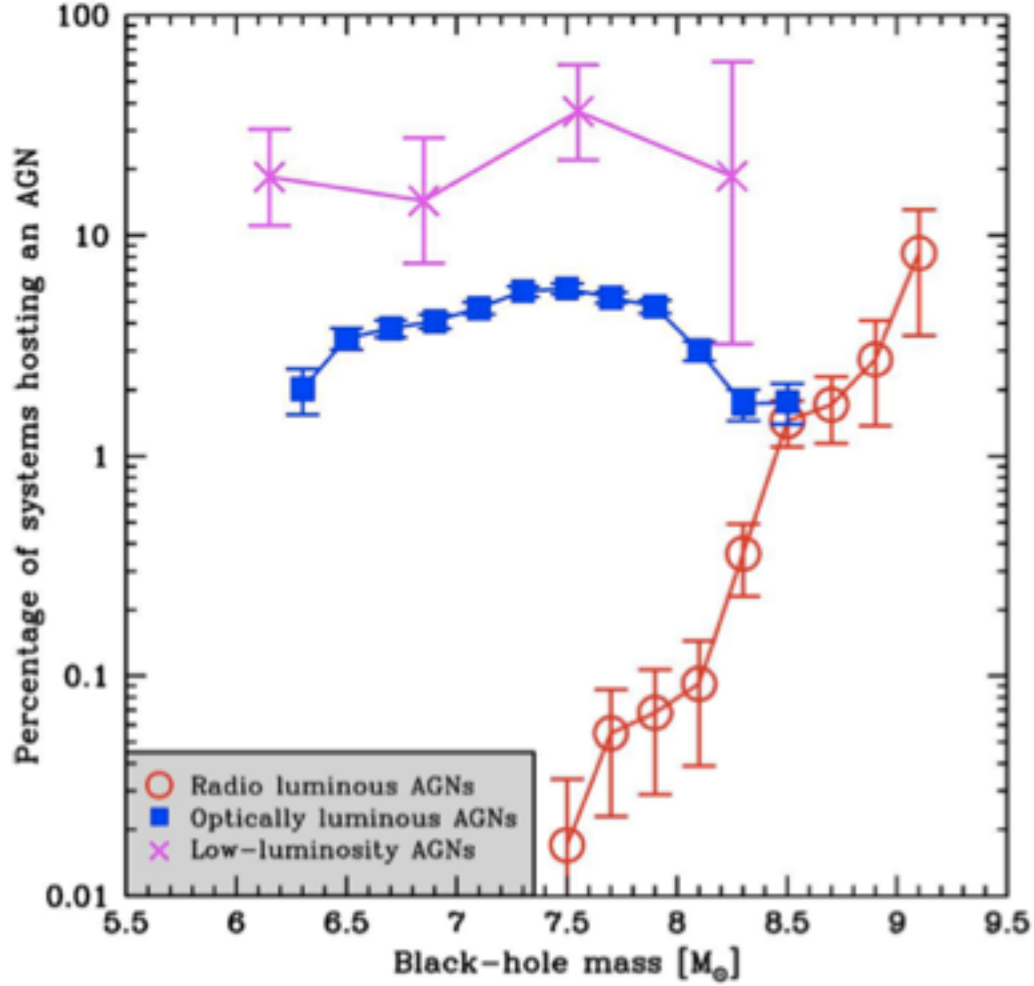
~4x more Type 2 than Type 1 AGNs

→ However, up to ~30-40% of galaxies may show at least faint evidence for AGN activity (either line emission or at IR/X-ray wavelengths).

→ ~10% of luminous AGNs are “radio loud”, although this is clearly dependent on black hole mass!

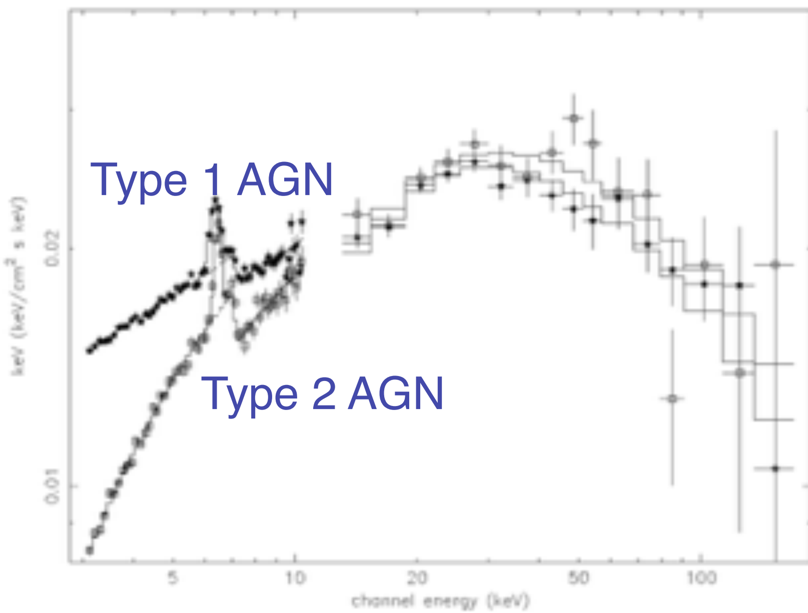
Informs us about duty cycle and torus structure

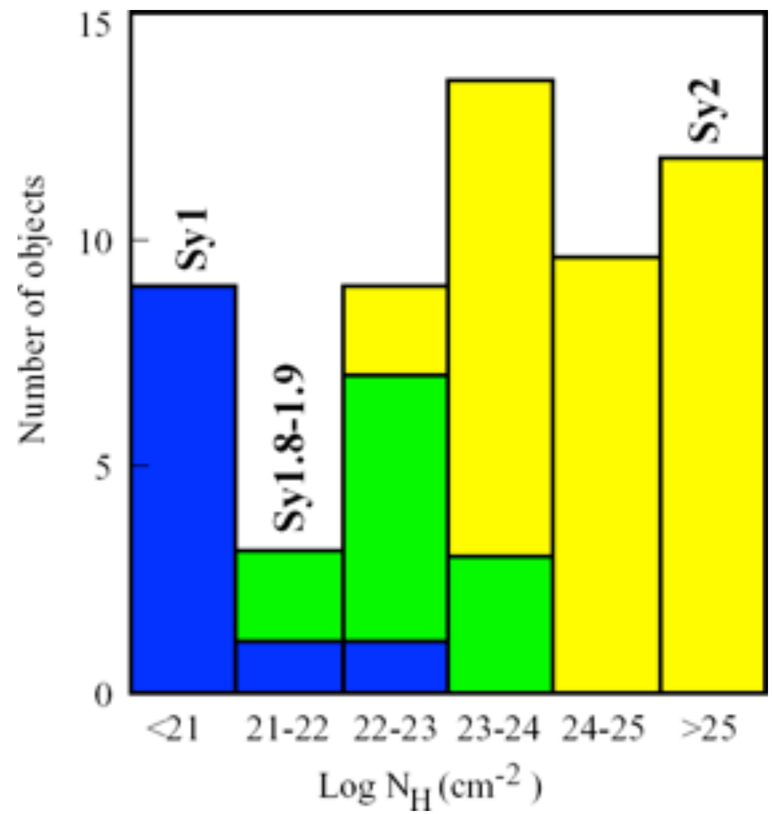
Alexander & Hickox 2011



Local AGN Demographics (N_H)

X-ray observations show Type 2 AGNs have larger column densities of gas than Type 1 AGNs (they are more absorbed)





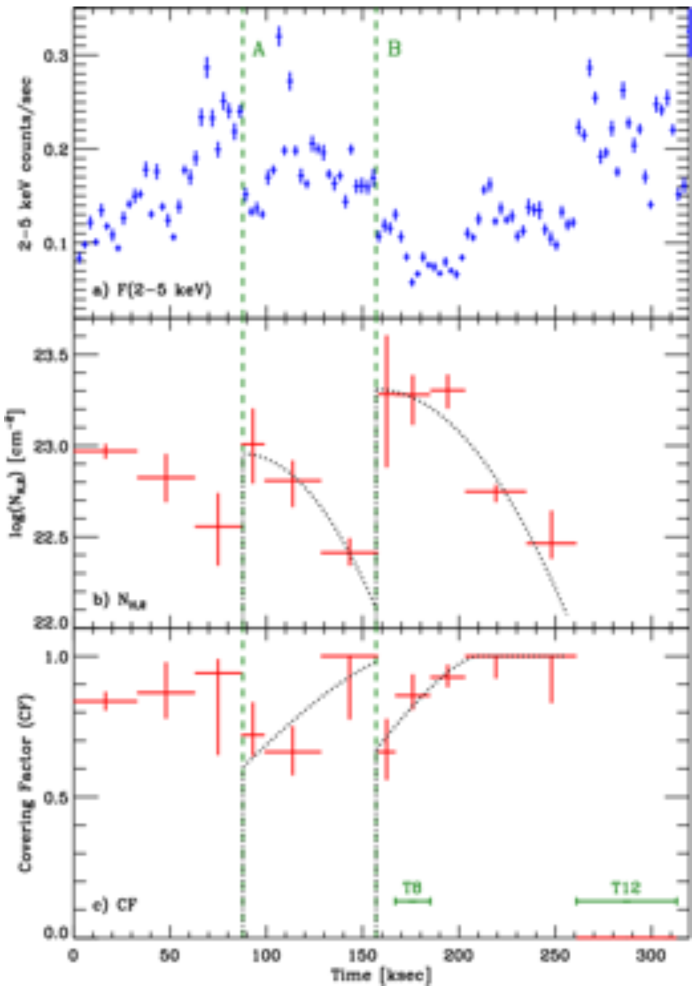
About 3-10 times more obscured AGN than unobscured AGN

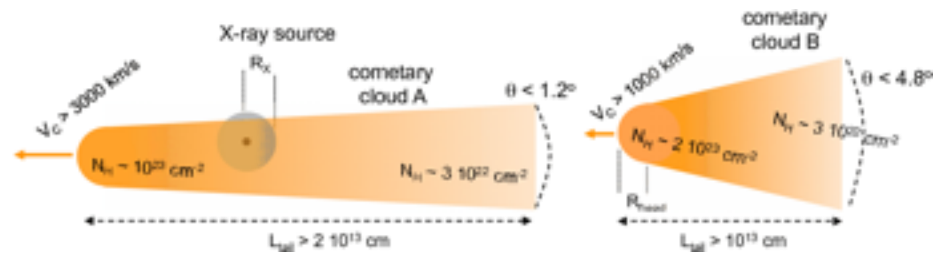
Local AGN Demographics (Structure)

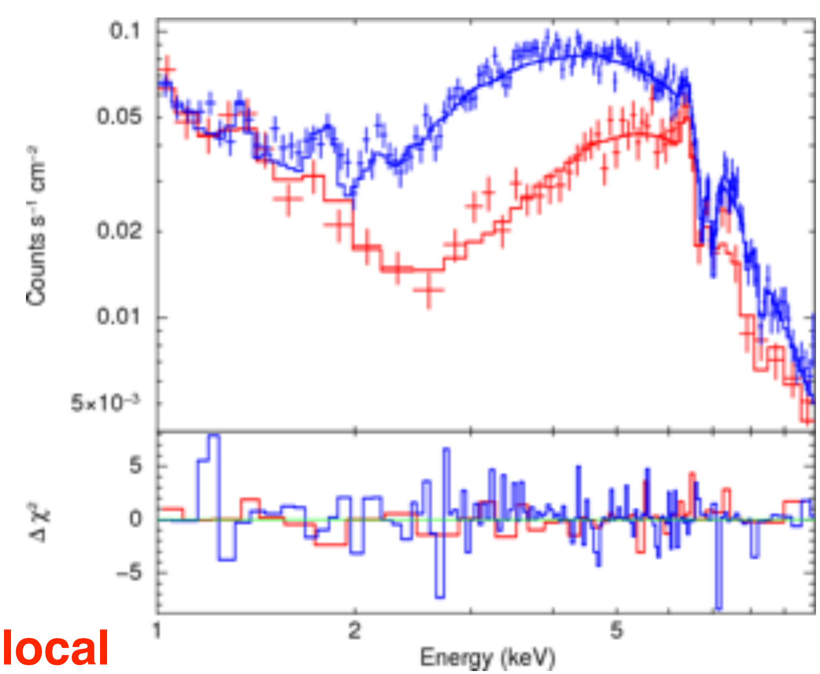
Recently, changing look AGN found.

Absorber in one object has been shown to be “comet”-like...with a concentrated head and gradually weakening tail.

Maiolino et al. 2010







Still unclear about frequency (10-20% of local AGN?), but complicates corrections for sure!

X-ray selection is by far the simplest. But can miss fully Compton-thick (CT) AGN (factors of 10-100 dimmer) and issues with corrections for changing-look AGN.

bias/error factors of 1.5x possible

Must complement with mid-IR or line emission to try to get these.

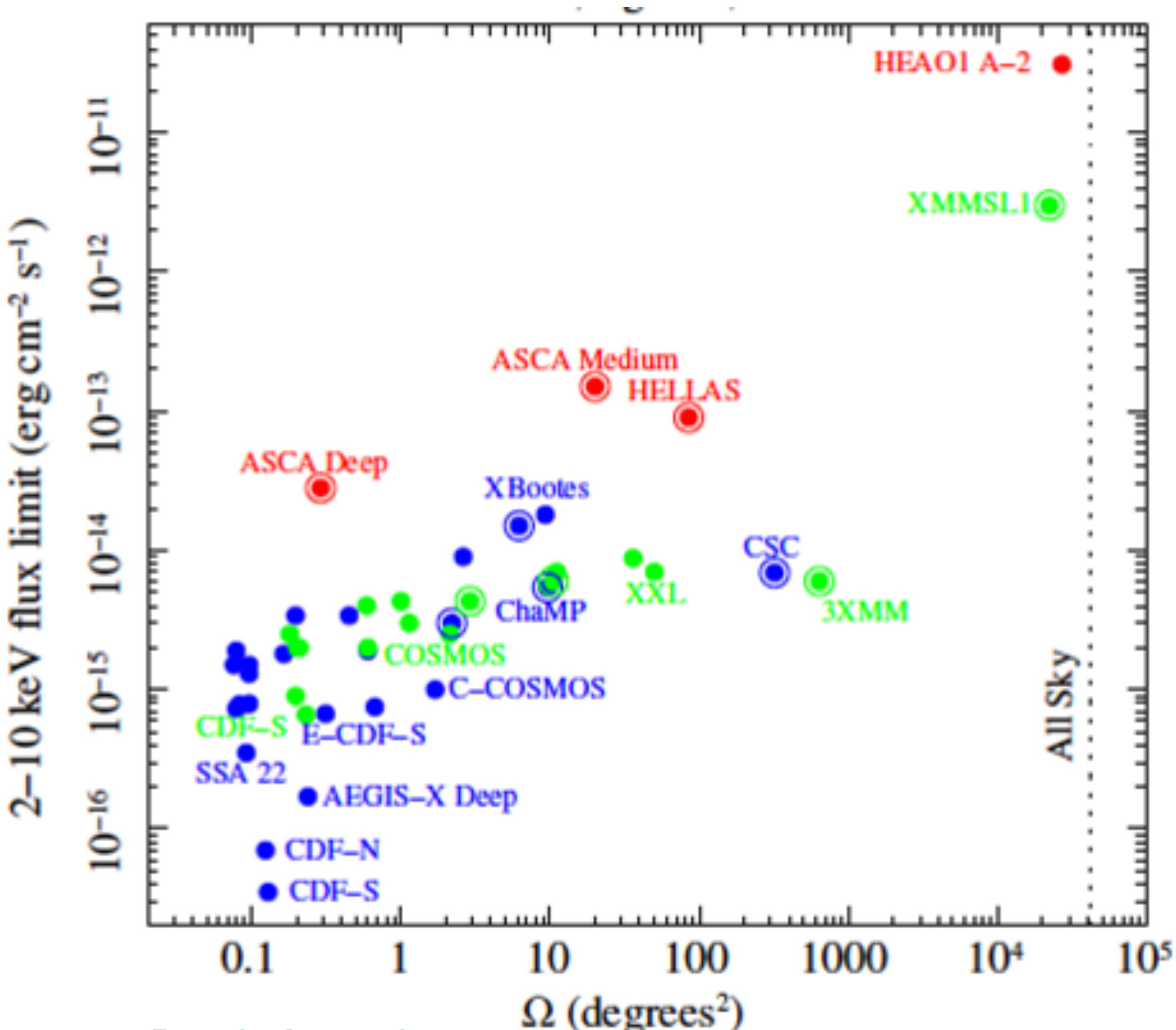
Assumes degree of unification. Does not address if accretion is different in most obscured AGN (open question)

bias/error factors of 1-10x possible?

Better understanding and identification of super-Edd accretion needed (Marta Volonteri et al. solving this for us).

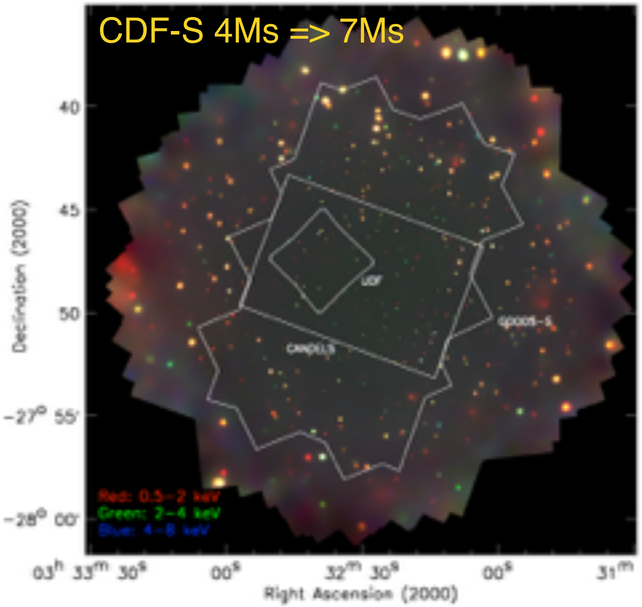
Distant AGN Demographics

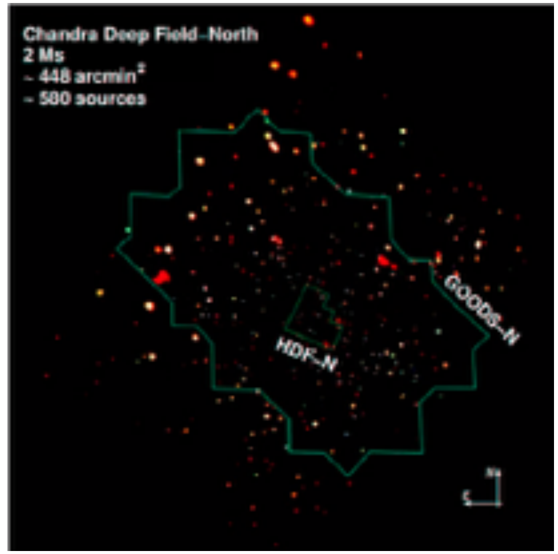
Prior to Chandra / XMM-Newton (1999), demographics established only for luminous type 1 QSOs in 0.5-2.0 band => evolve strongly over cosmic time, peaking in number density at z~2.

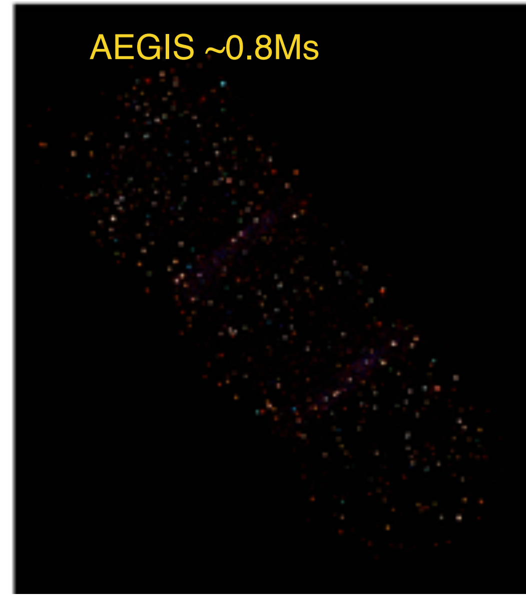


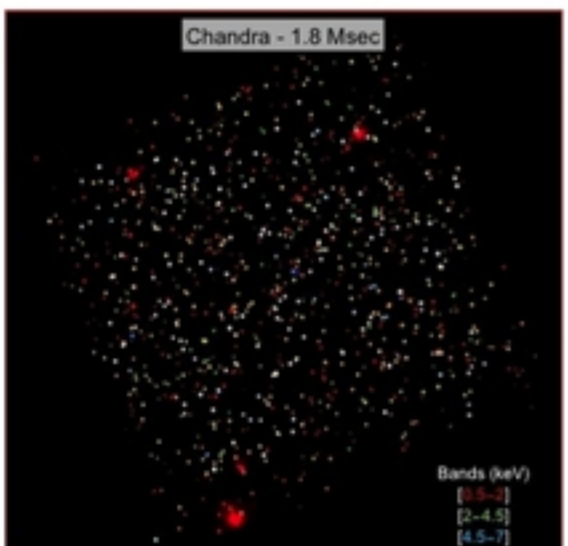
Brandt+Alexander15

Distant AGN Demographics





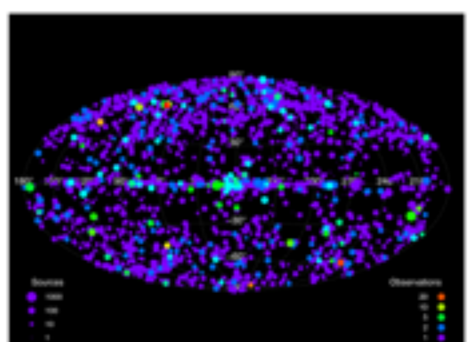


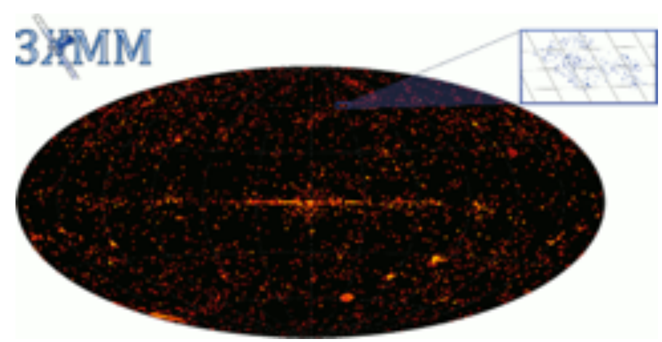


Handful of ~1Ms fields with excellent multi-λ data

Many shallow ~50ks fields with ok multi-λ data

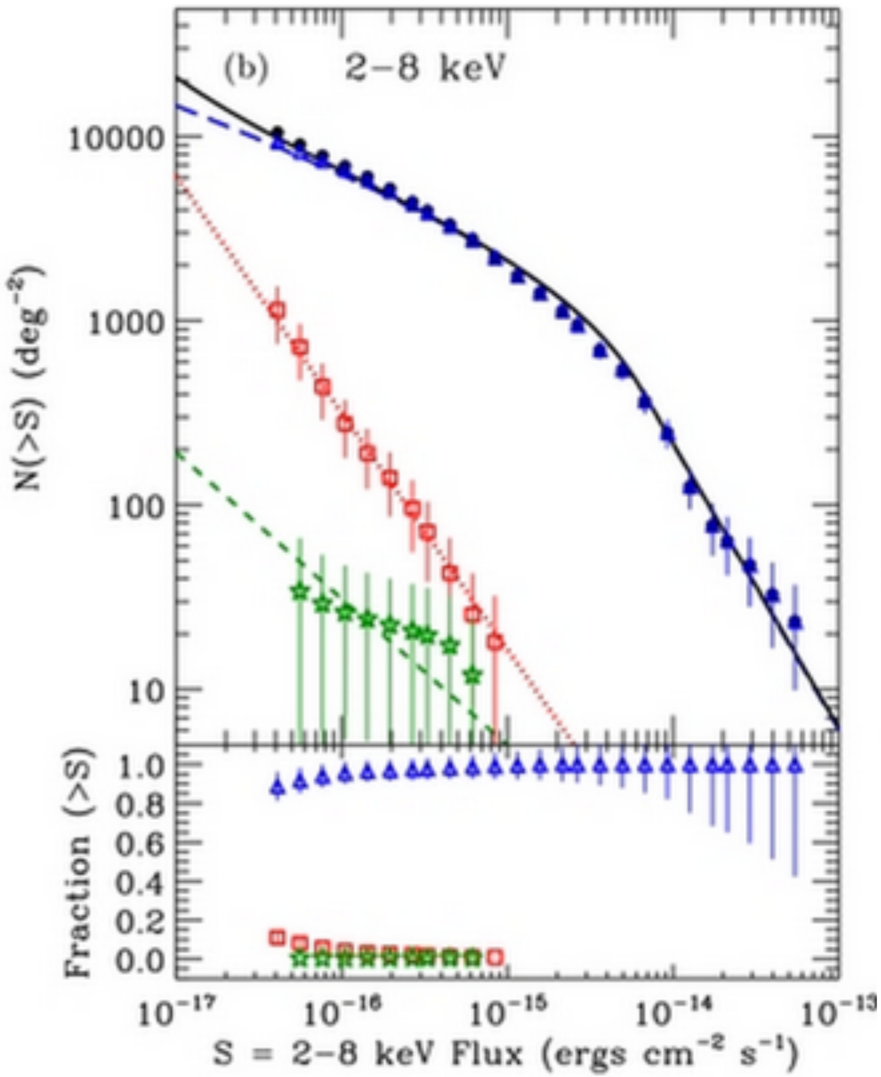
Few % of sky serendipitous fields with bad multi-λ data

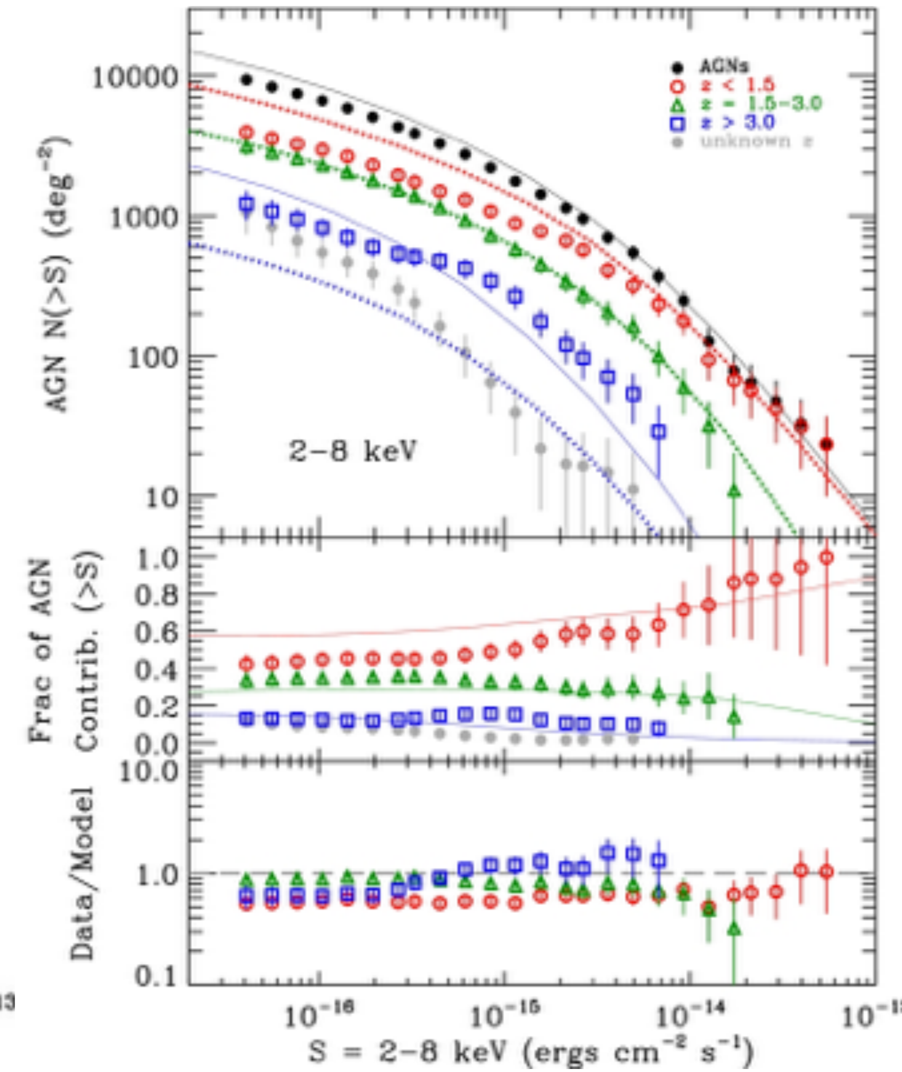




Distant AGN Demographics

Lehmer+10

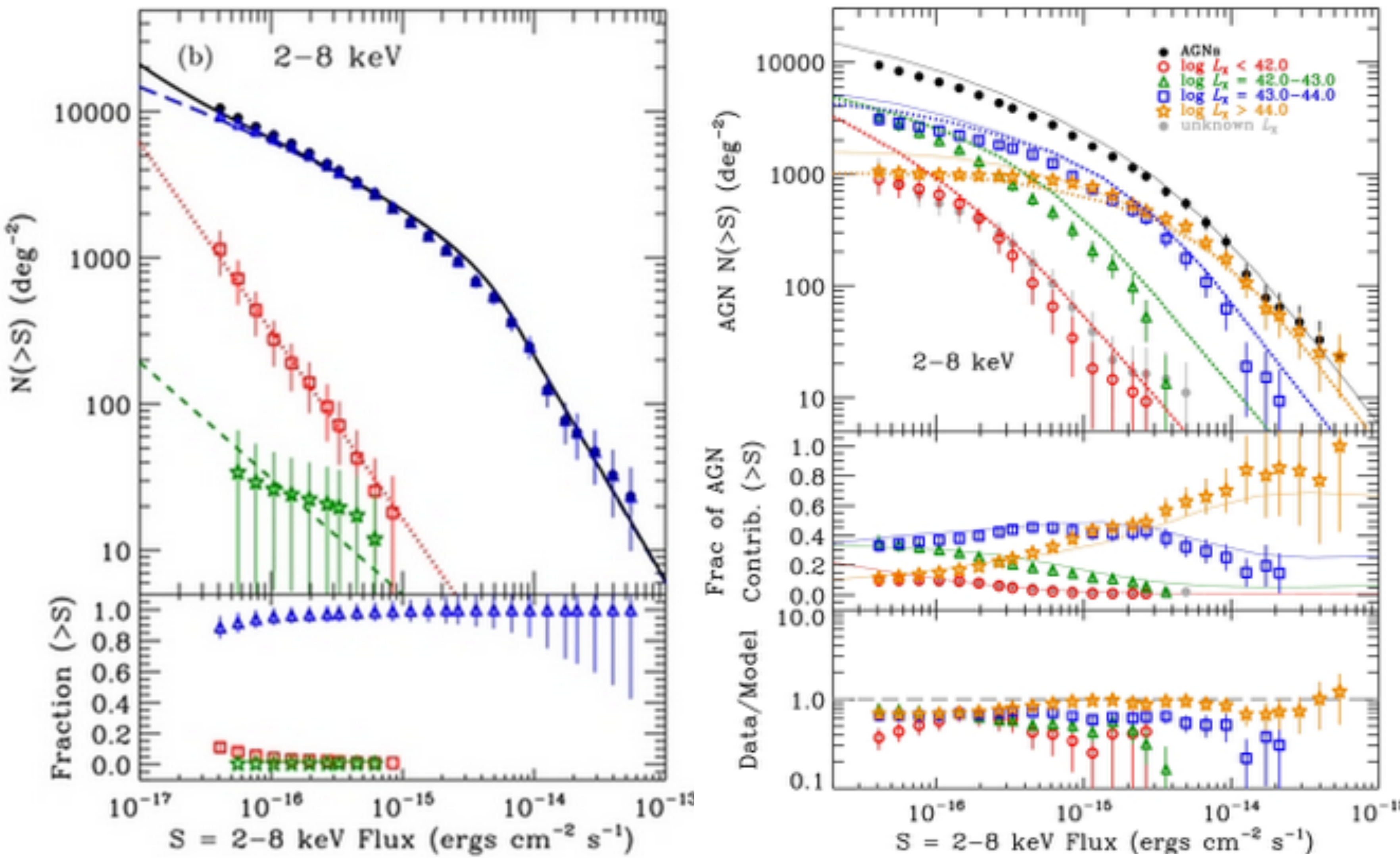




For reference: 5 x 10^{-17} erg/s/cm^2 equates to ~2 x 10^{43} erg/s at z=6

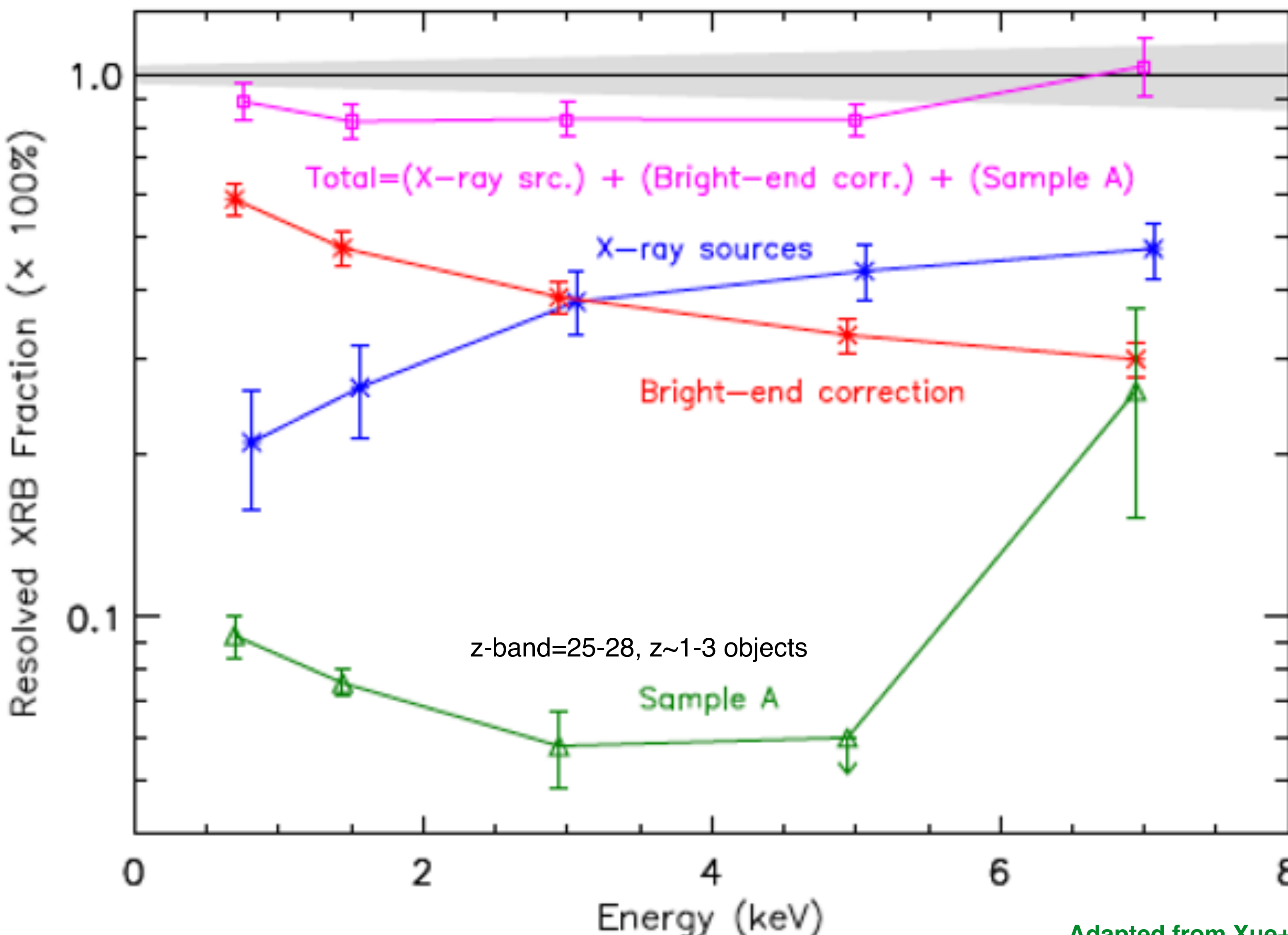
Distant AGN Demographics

Lehmer+10



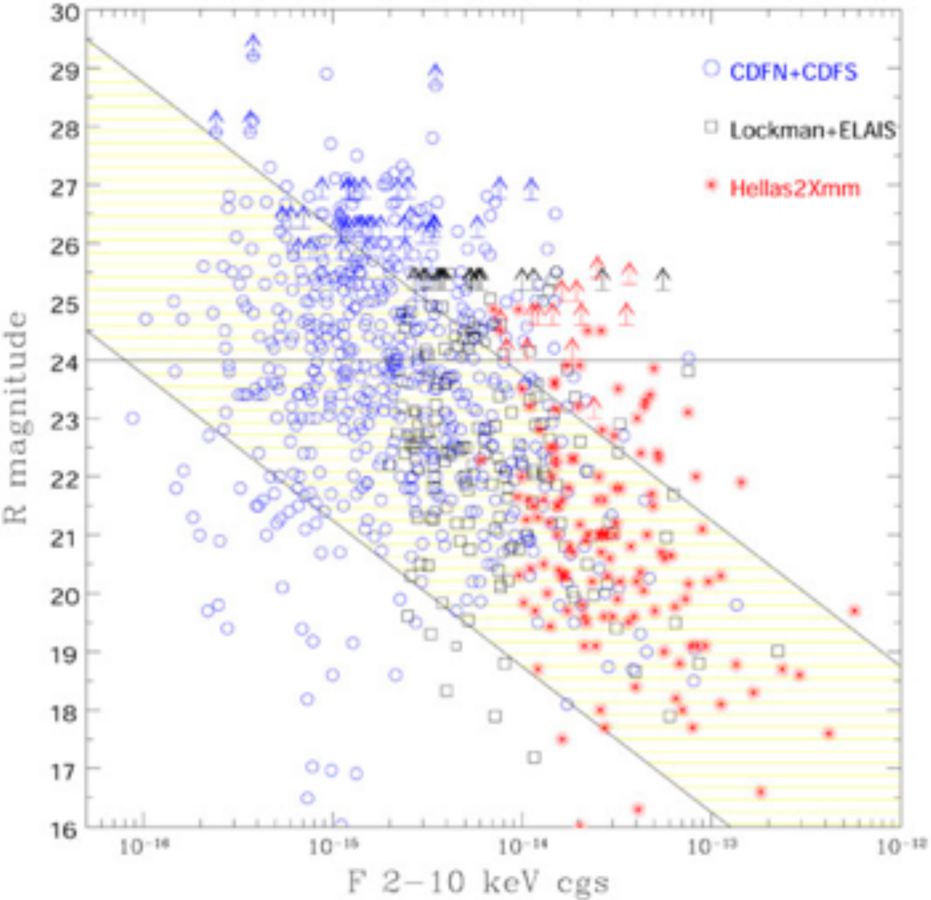
For reference: 5×10^{-17} erg/s/cm^2 equates to ~2×10^{43} erg/s at z=6

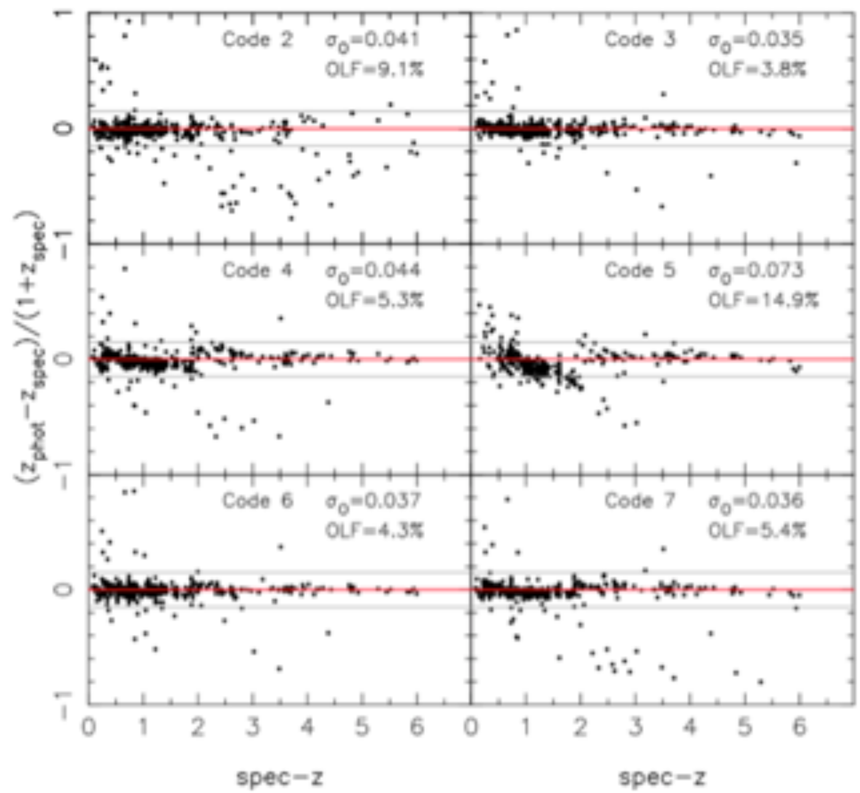
Distant AGN Demographics



Adapted from Xue+12

Distant AGN Demographics





90% spectra completeness for R<24, but require photo-z's for R>24
(strong dependence on code, and parent templates)

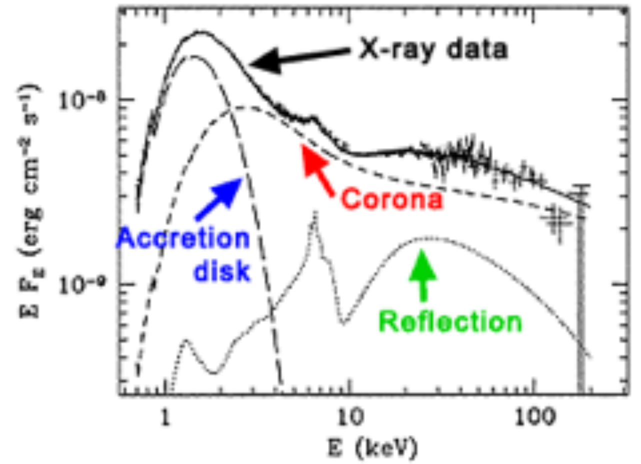
bias/error factors of several possible

SPECTRAL MODELING
LUMINOSITY FUNCTION

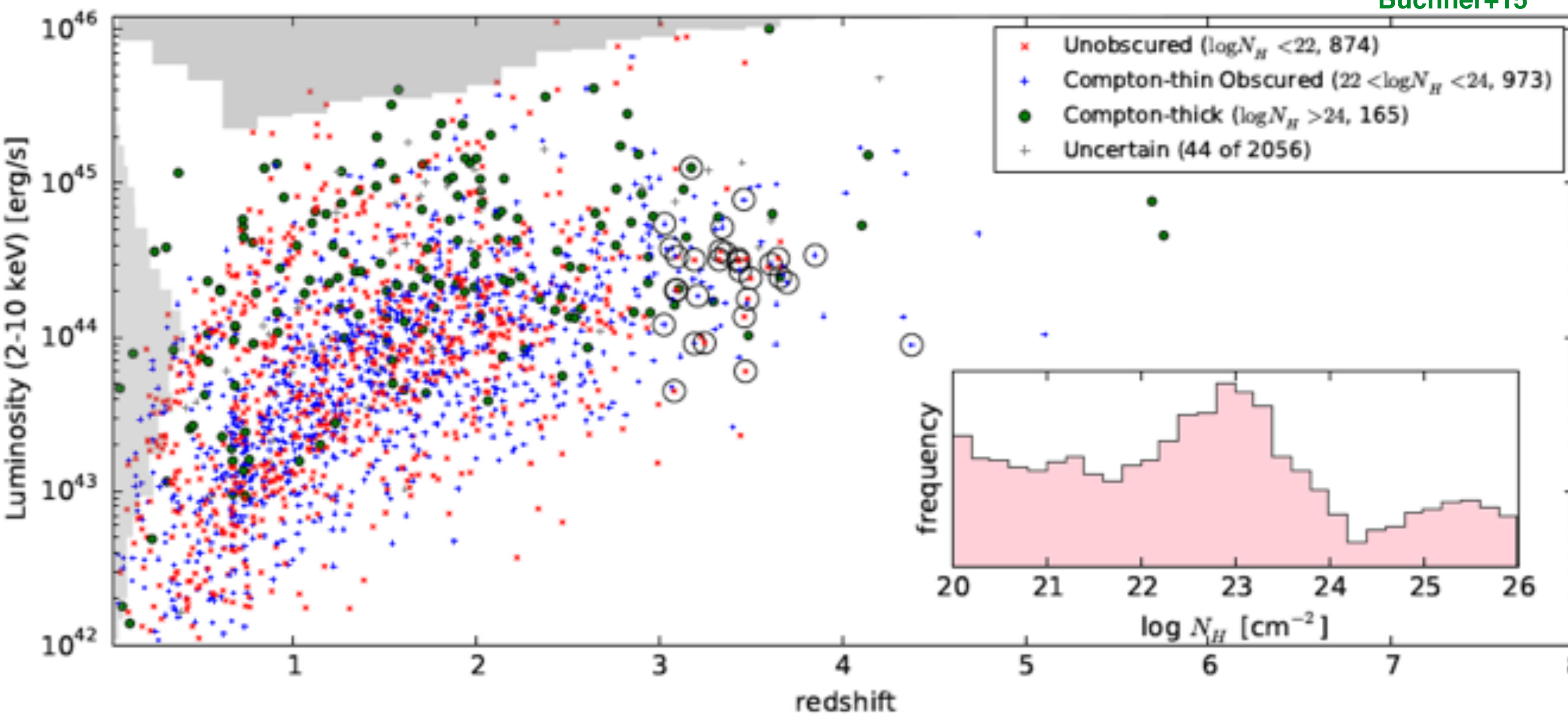
Spectral Modeling and distributions

Must fit or assume spectral model to get flux/luminosity
Must assume z, Lx, Nh distributions to correct for unseen
(strong dependence models)

bias/error factors of 1.5-10x possible

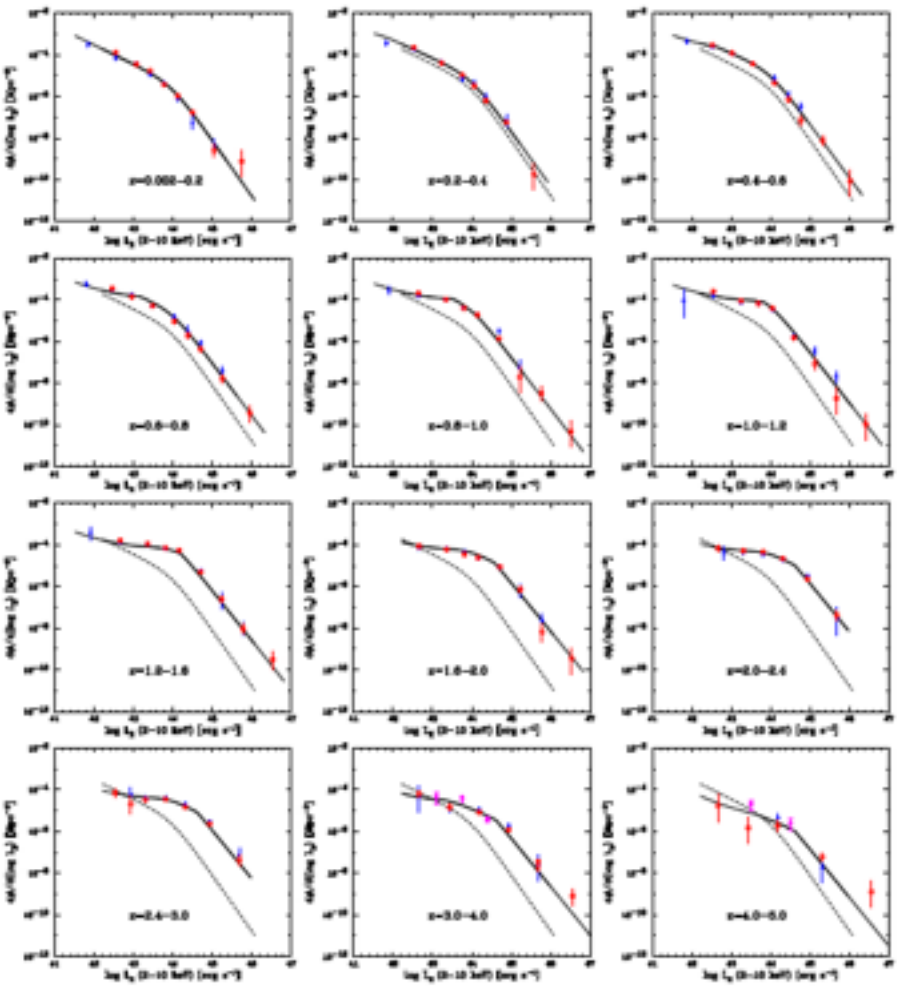


Buchner+15

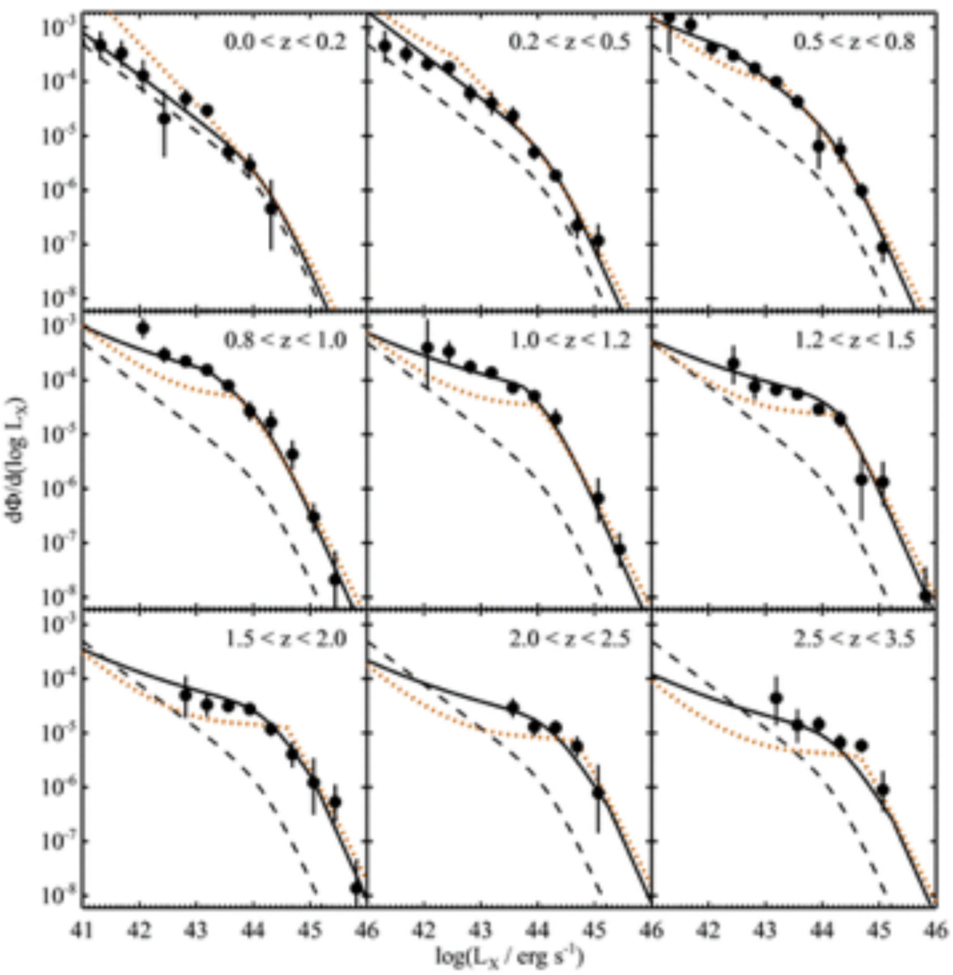


And presto…X-ray Luminosity Functions

Ueda+14

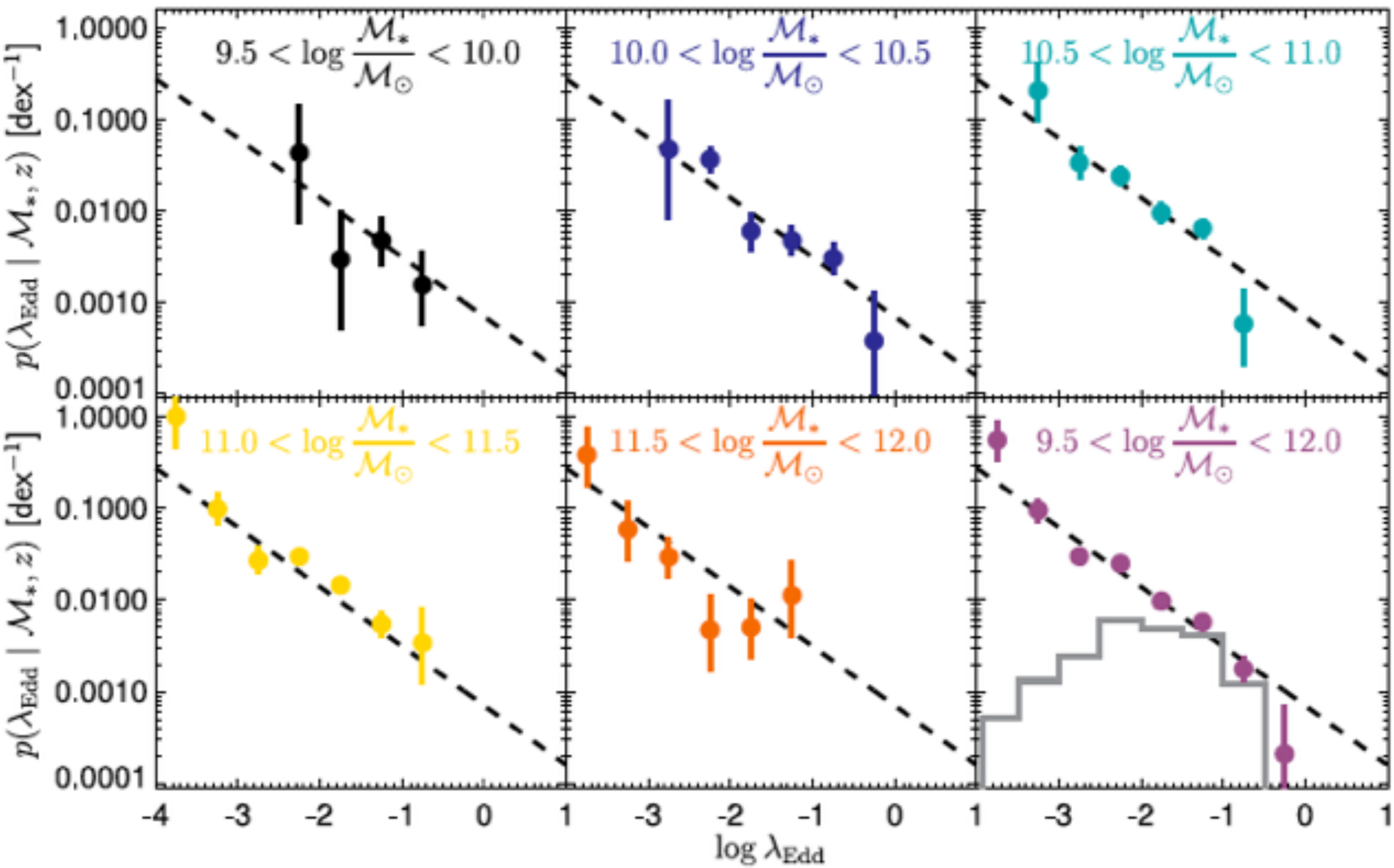


Aird+10



Great *(although many parametrizations here)*

Modulo Accretion Rates



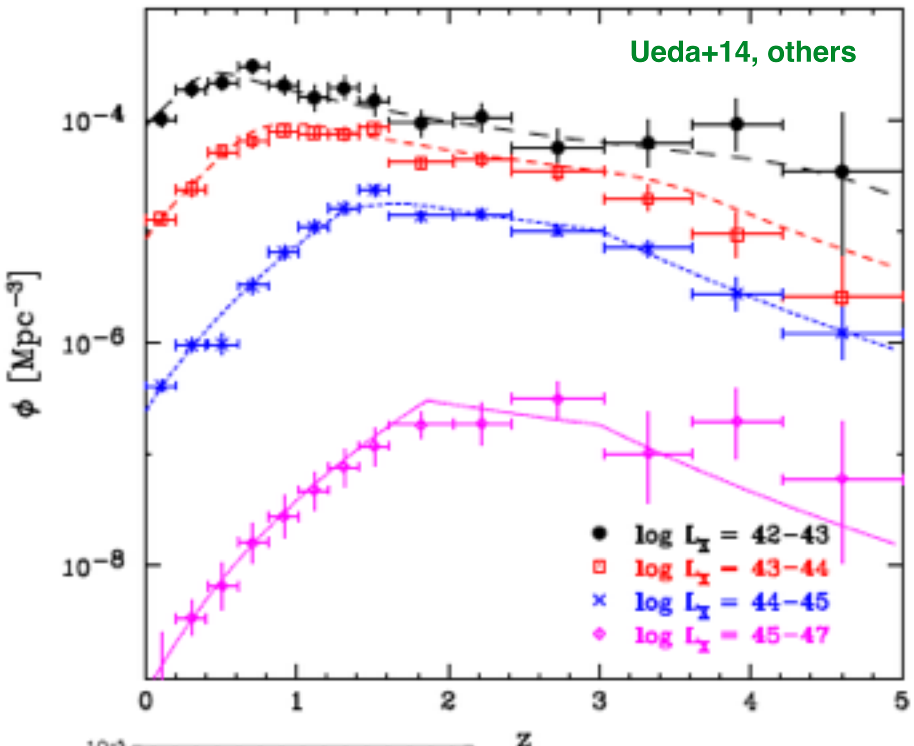
Aird+12

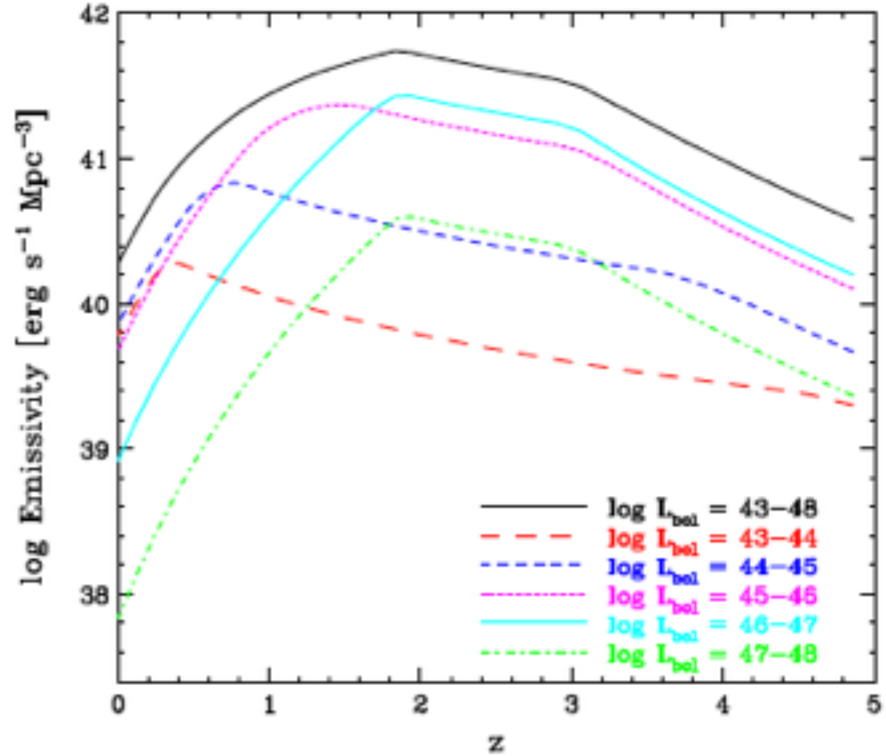
Using only objects with broad lines => extrapolating blindly to obscured objects

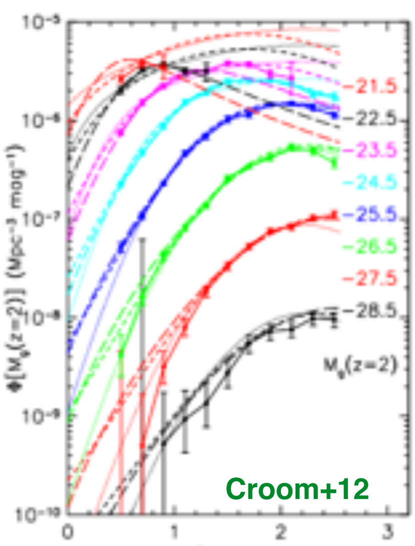
Not probing any super Edd accretion (legitimate to extrapolate to it?)

Interesting to see what happens if we tweak growth formula for these instances?

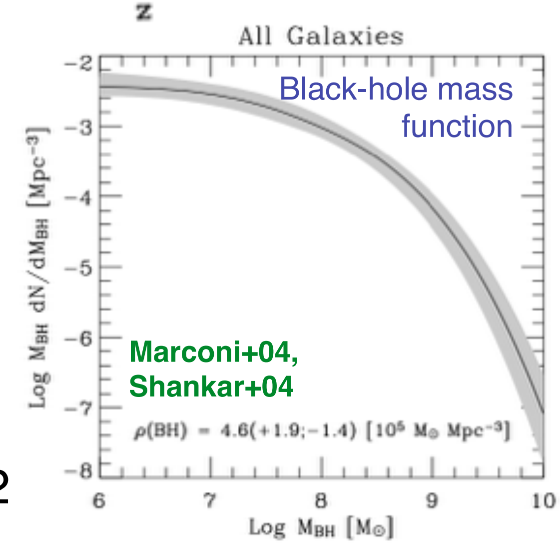
Space and Emissivity Densities







Integrating these….

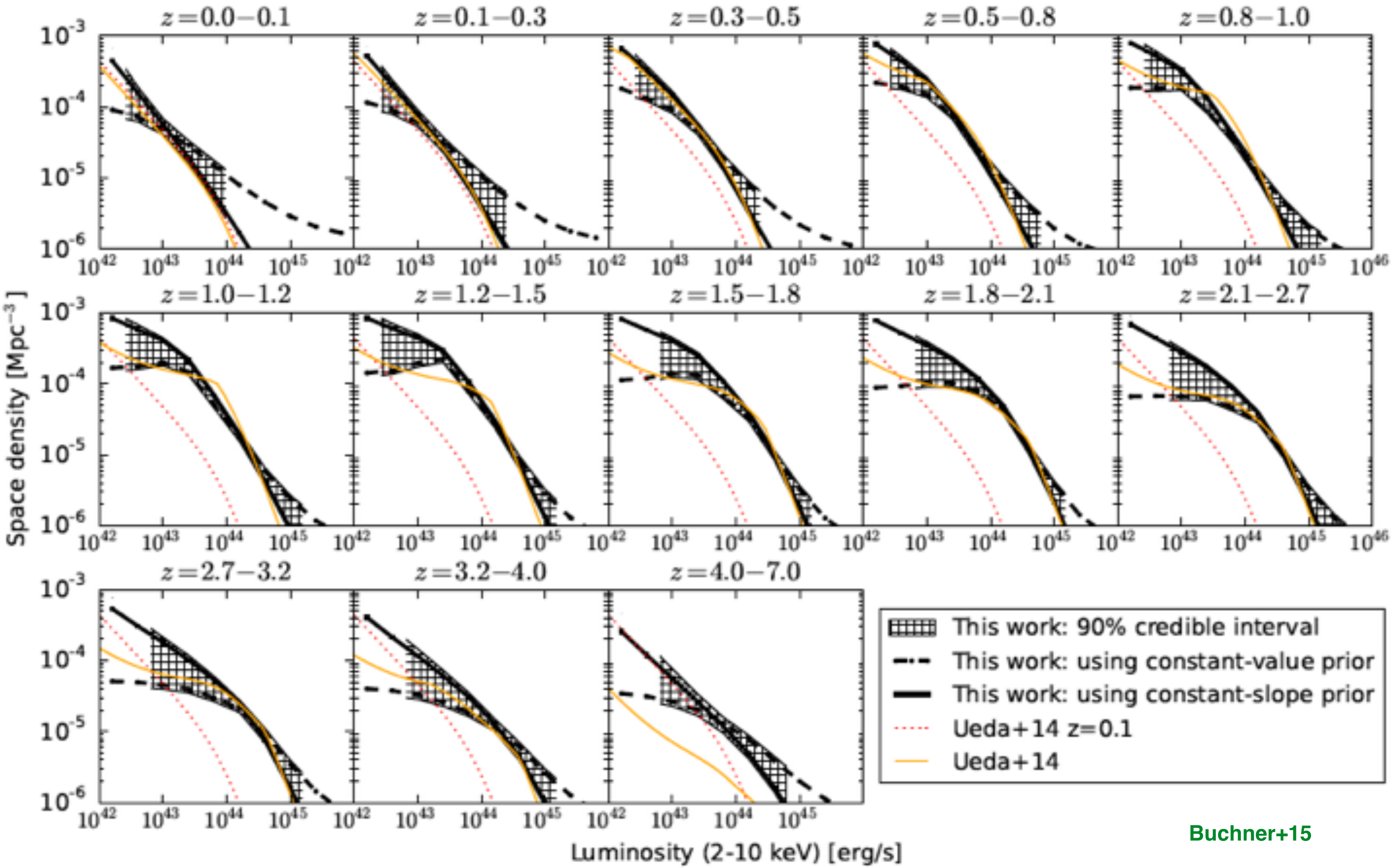


Find agreement to with factor of ~2

But wait…what about all those errors you mentioned???

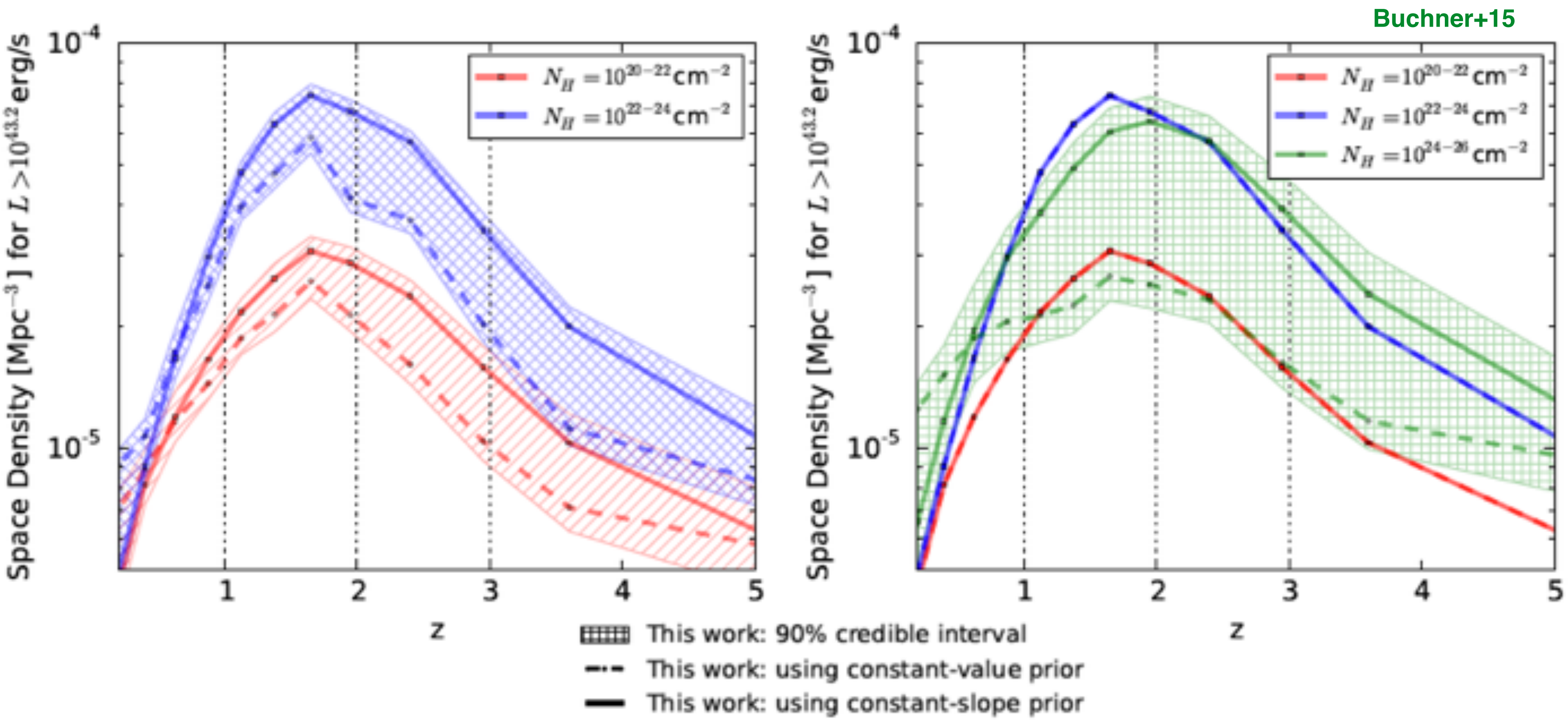
X-ray Luminosity Functions Revisted

Propagating the error distributions through and choosing different models makes a BIG difference!



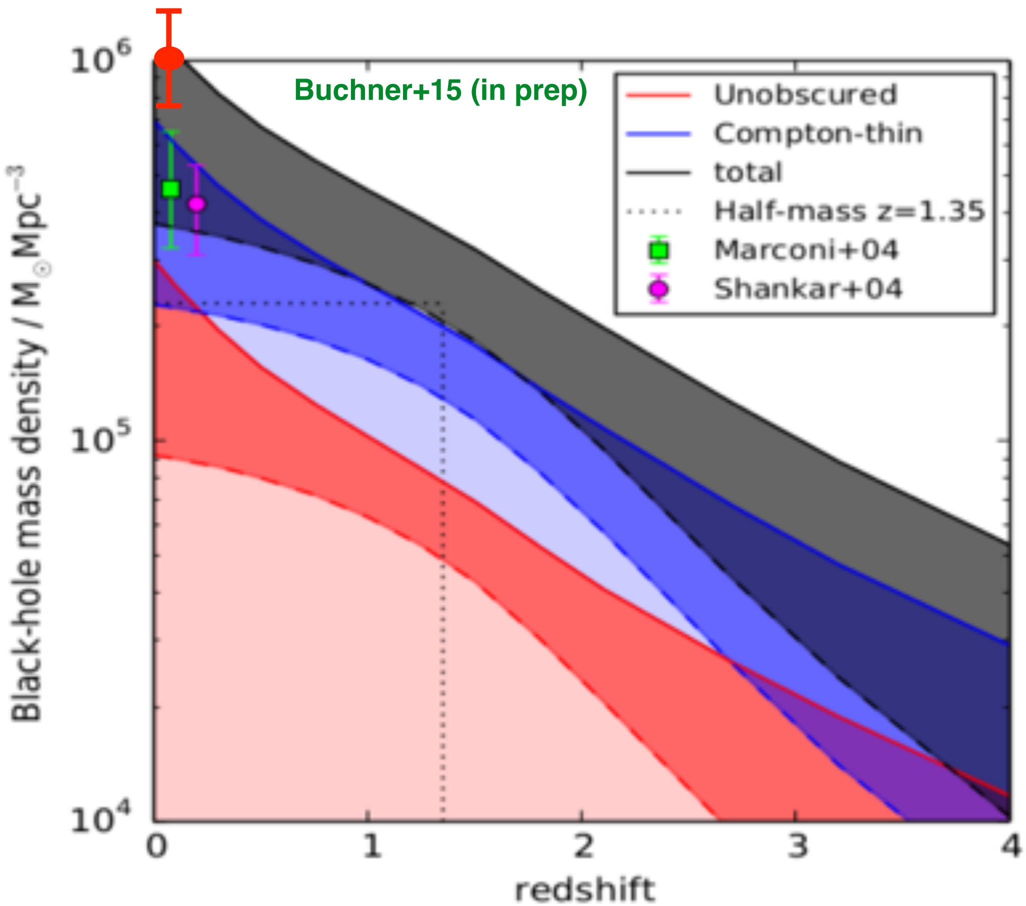
Buchner+15

Space and Emissivity Densities Revisited



At any given redshift, the error distribution generates approx. factor of 2-3 uncertainty!

SMBH Mass Density Revisited

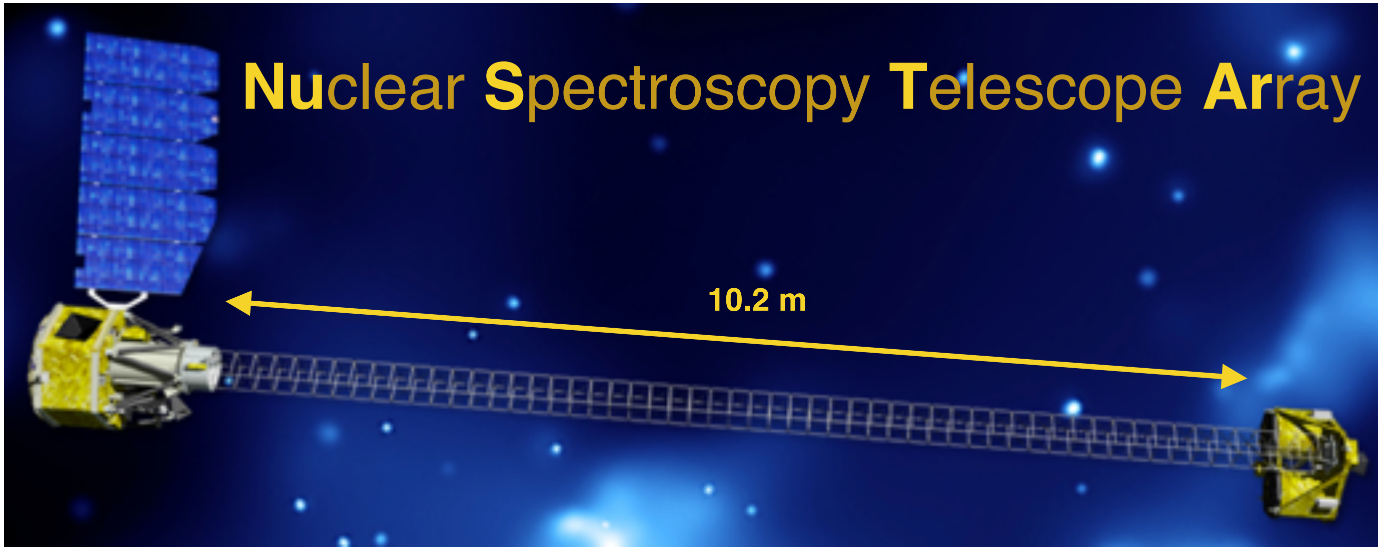


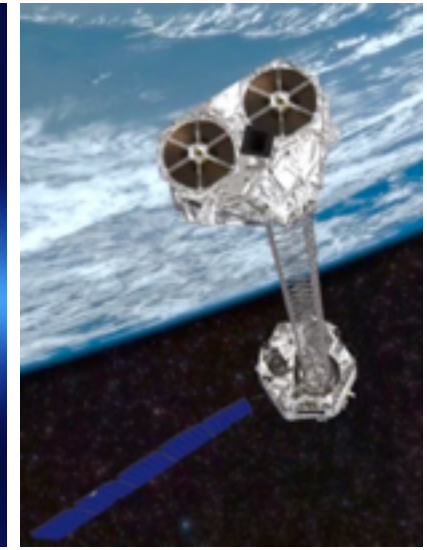
New calculations over-predict mass density!

But wait….A recent revision of black hole scaling relations (Kormendy & Ho 2013), indicates that the local mass density in black holes should be revised upwards by a factor of 2-4 also!

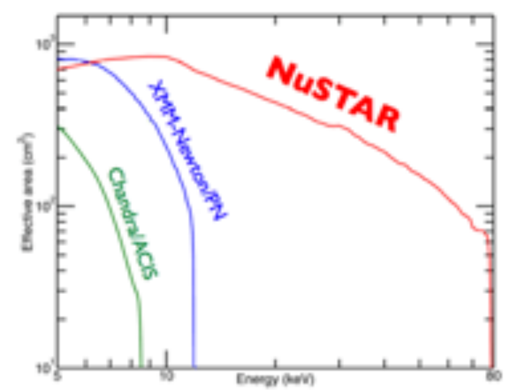
Buchner (now at PUC) is working on a sequel combining a larger dataset and propagating further uncertainties into final calculation (stay tuned)

What about pushing to harder energies, closer to CXRB peak at 30 keV?





- **SMall EXplorer (1 of only 3 NASA SMEX missions funded pre-JWST in 2018!!)**
- **Energy Band:** 5 - 80 keV
- **Angular Resolution:** ~50" (HPD), ~18" (FWHM) => ~100 improvement!!!!
- **Field of View:** 12.5’ x 12.5’
- **Energy Resolution:** 0.5 keV at 6 keV, 1.0 keV at 60 keV (FWHM)
- **Orbit:** 550 km x 600 km, 6 degree inclination
- **Launch date:** June, 2012



Obscured AGN working group

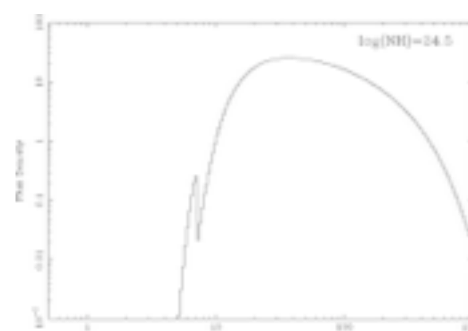
=> 1-2Ms on Compton-Thick AGN, ULIRGs, BALQSOs

=> From marginal detections to strong spectral constraints

Extragalactic survey team

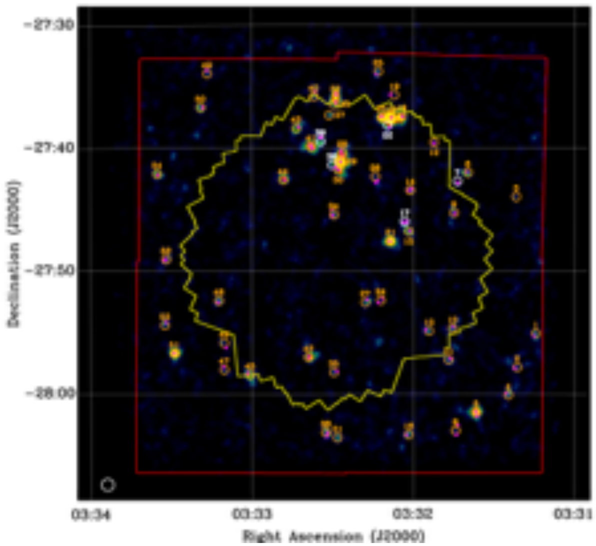
=> 2Ms survey to resolve CXRB at 30keV peak

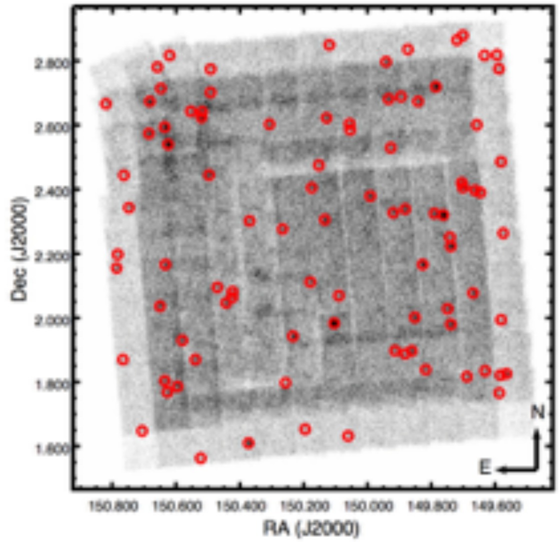
=> Number cnts, XLF, stacking constraints using Chandra srcs

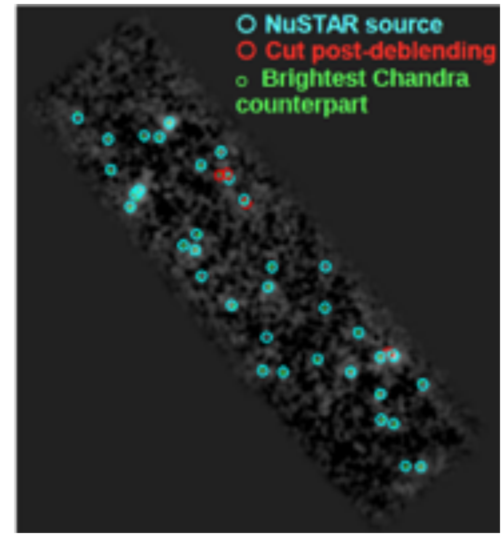


NuSTAR Observations of Deep Fields

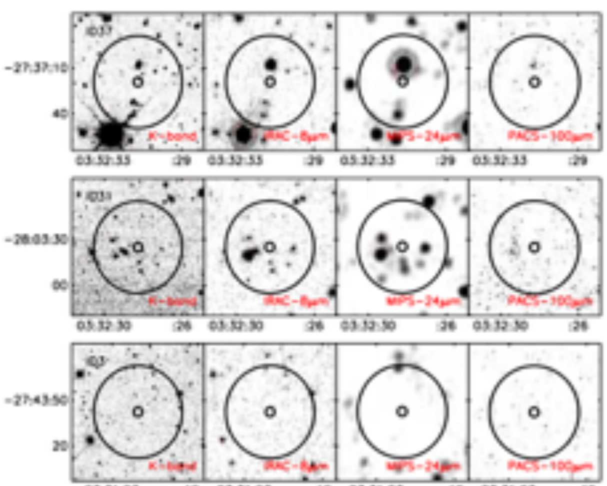
ECDFS, COSMOS, EGS done. CDF-N and UDS in progress

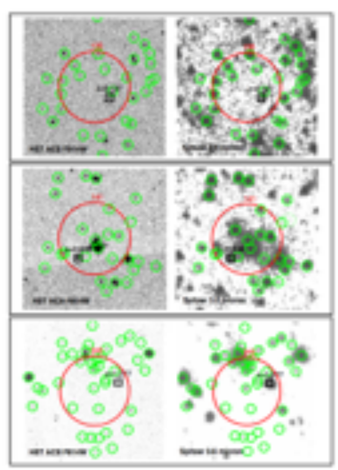


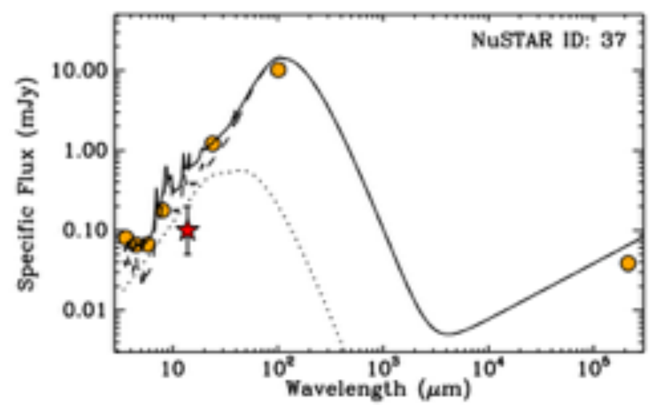




3 NuSTAR sources per field with no Chandra / XMM-Newton counterparts



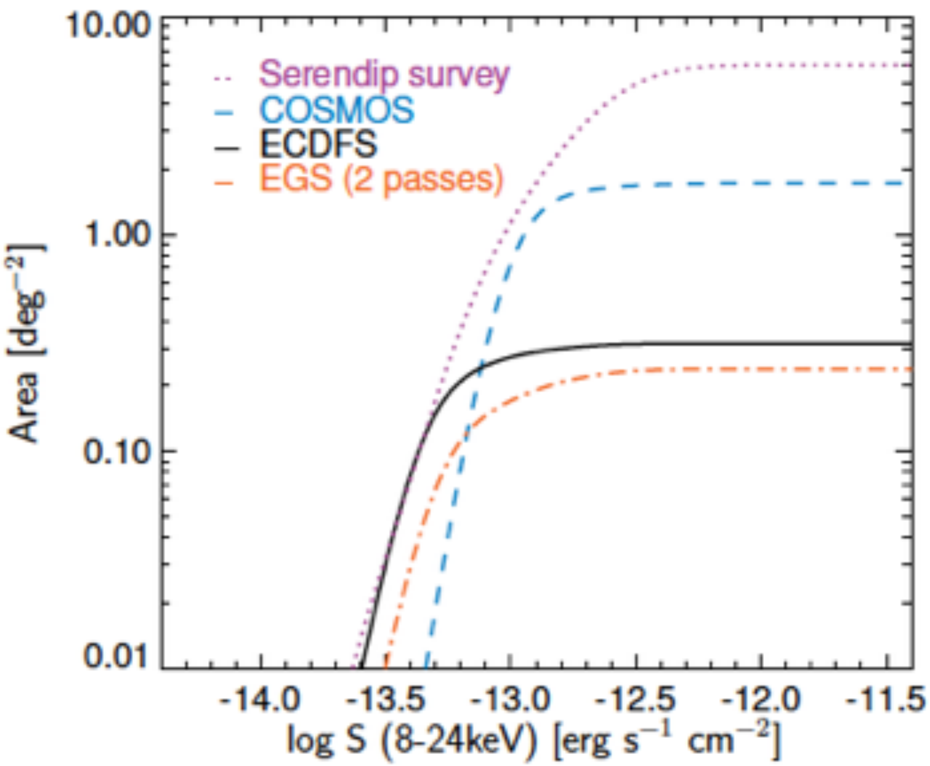


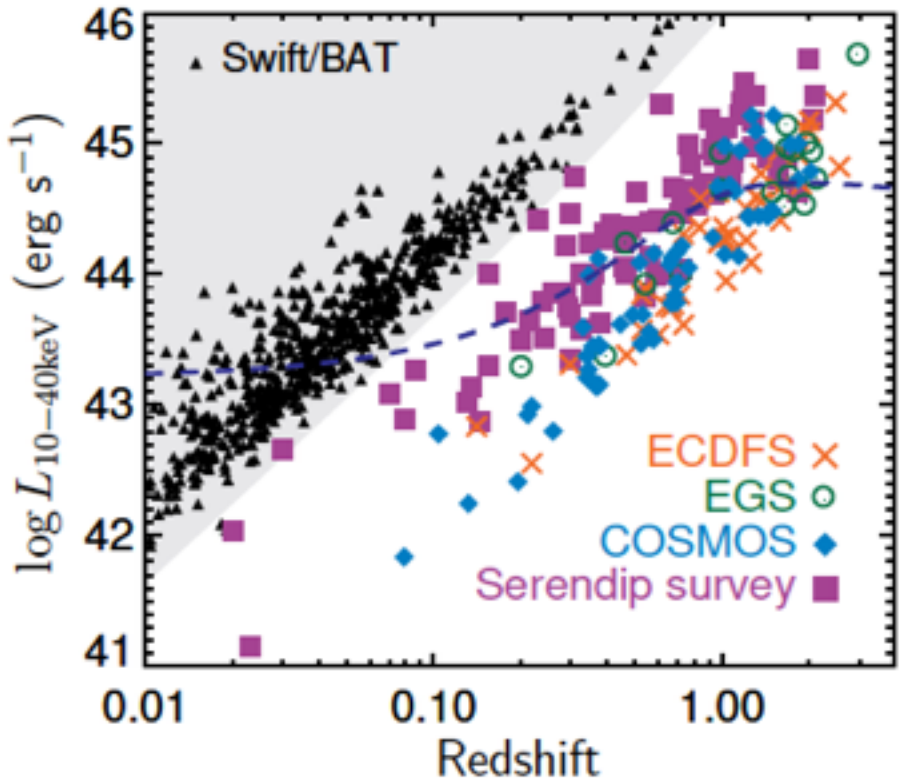


(consistent w/ noise, but few real?)

NuSTAR Observations of Deep Fields

Harrison+15 (in prep)



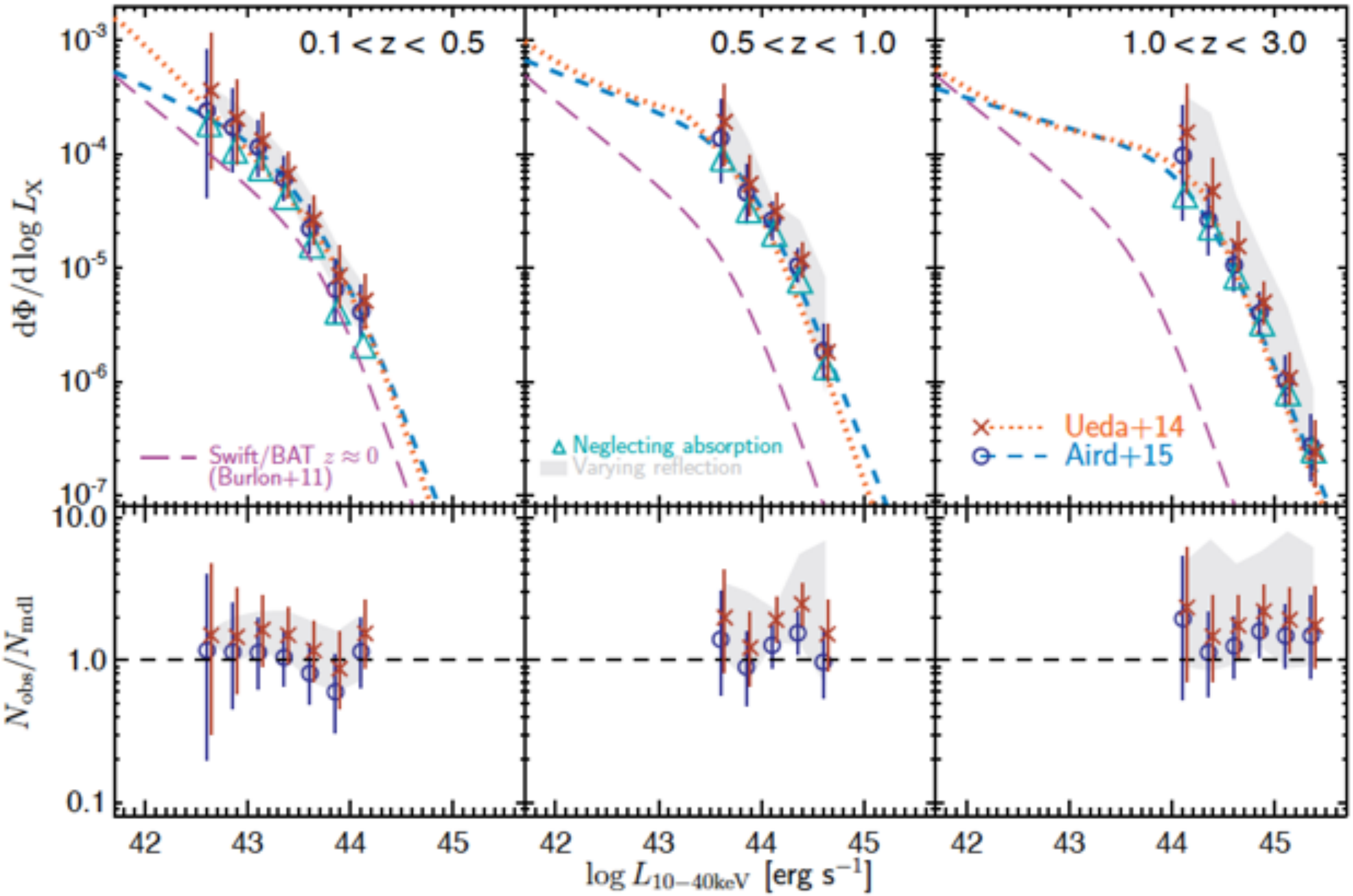


go from resolving 1-2% of CXRB at 30 keV with BAT/INTEGRAL to 30-50% with NuSTAR!

Redshift distribution MUCH higher (sampling "cosmic" AGN population)

NuSTAR Observations of Deep Fields

Aird+15 (in prep)

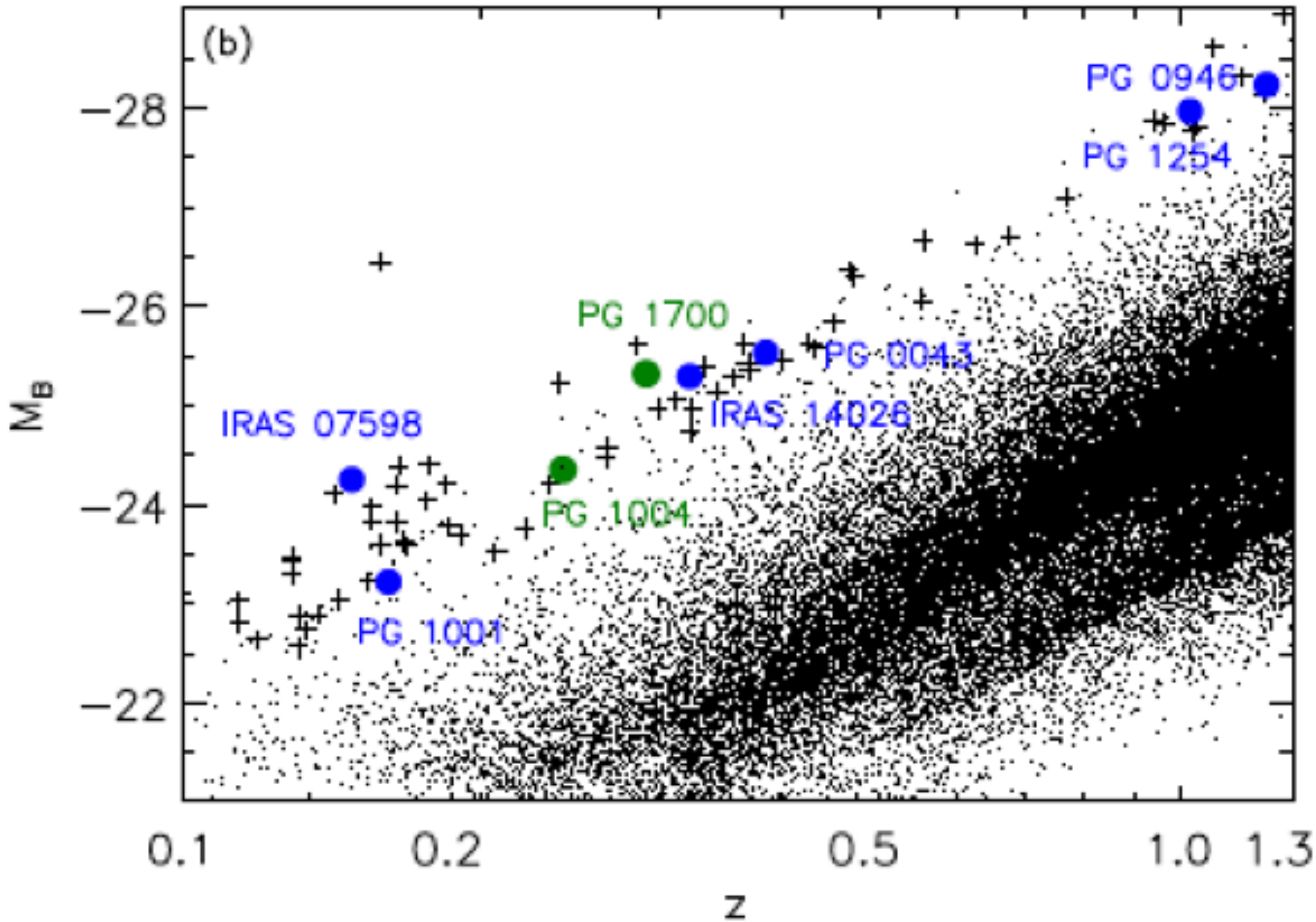


To current depths, not much deviation compared to Chandra/XMM results.

Possible shift due to spectral complexity. What will 2-4x depth bring?

Something
strange afoot?

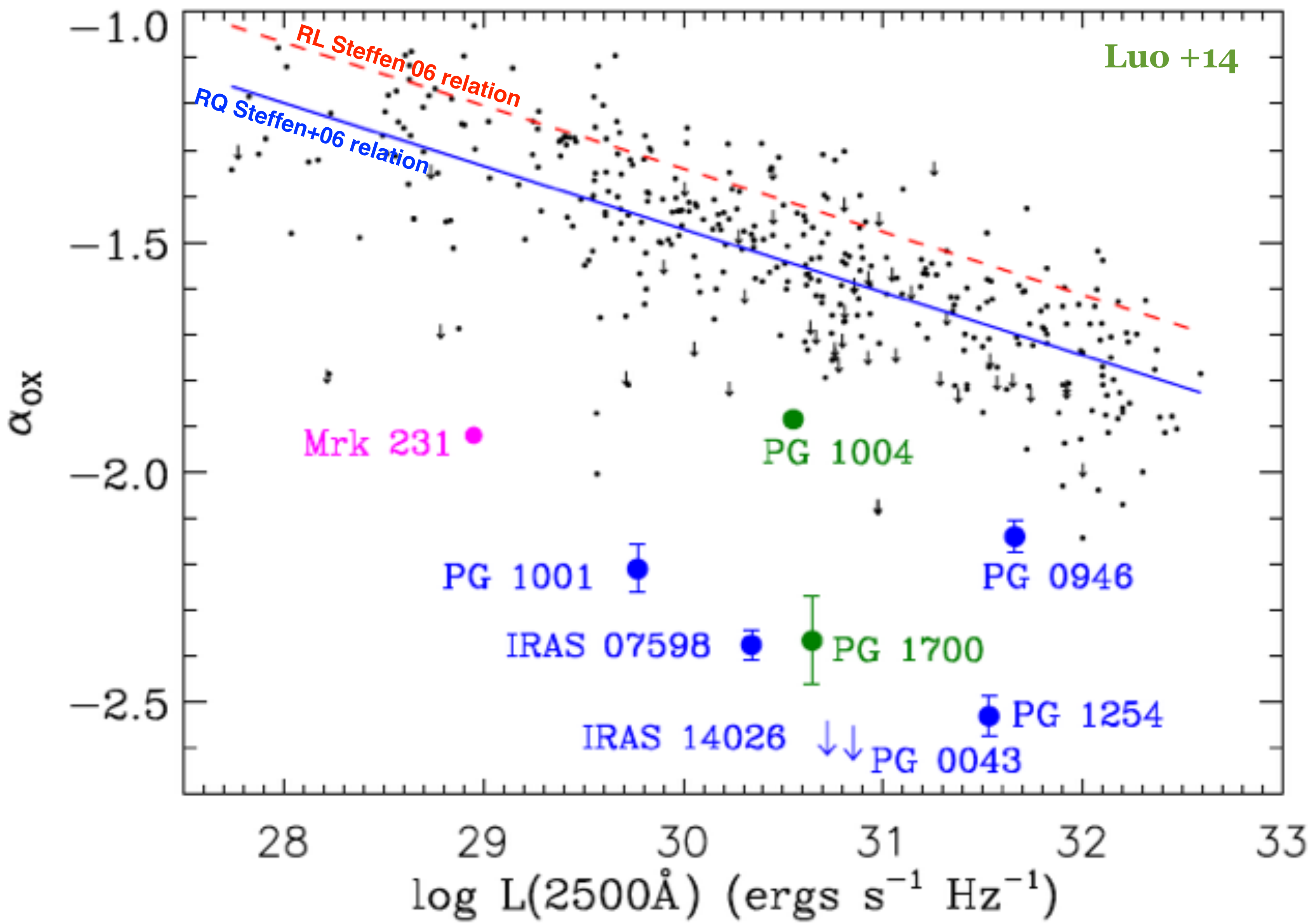
NuSTAR observations of Radio-Quiet, X-ray faint BALQSOs



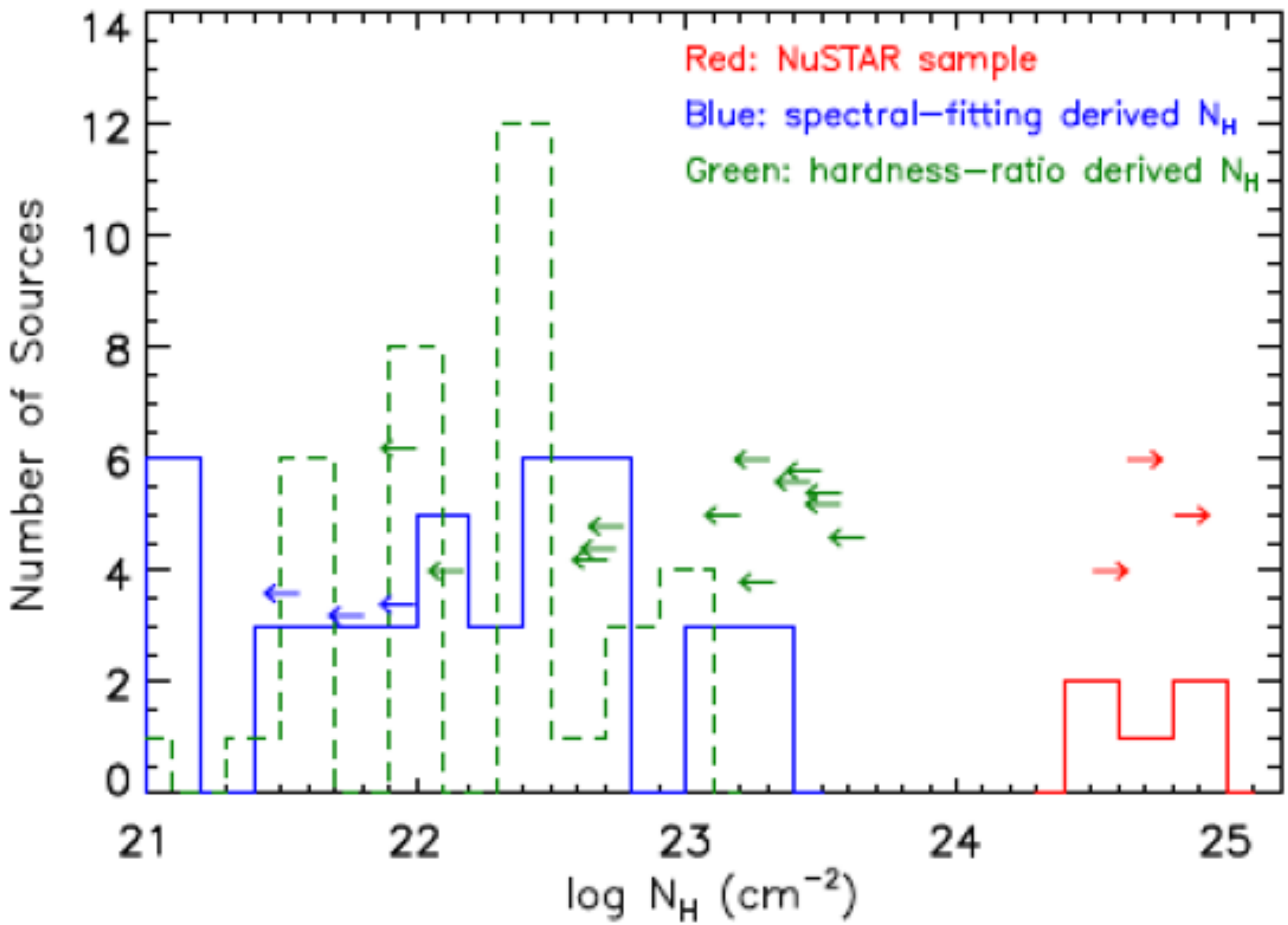
Luo +14

- Targets are among most UV luminous for distance,
- Have L/L_{EDD} = 1.5-7.7 (although double-counting IR)

NuSTAR observations of Radio-Quiet, X-ray faint BALQSOs



NuSTAR observations of Radio-Quiet, X-ray faint BALQSOs



Luo +14

All targets are either marginally or not detected by *NuSTAR*…

NuSTAR observations of Radio-Quiet, X-ray faint BALQSOs

Luo +14

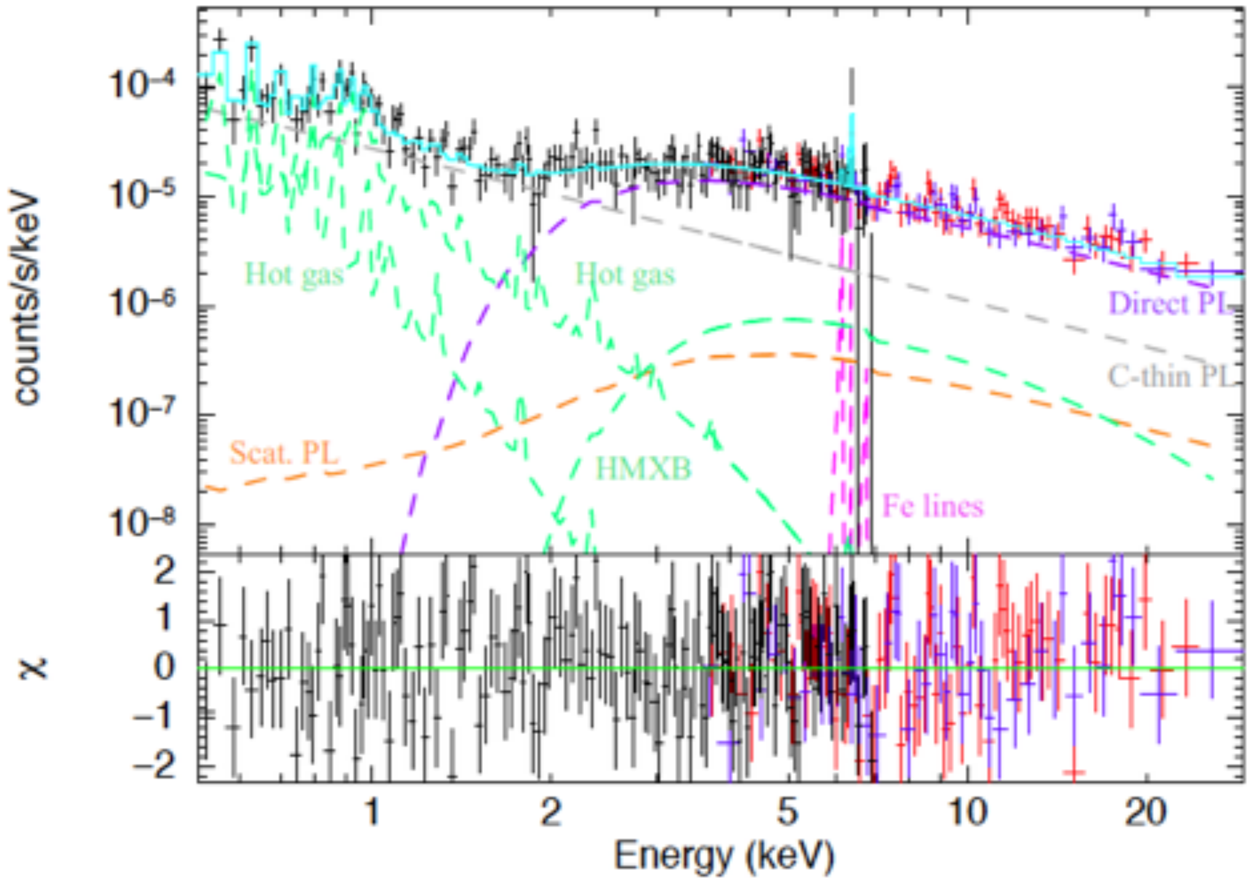
- *NuSTAR* estimated fluxes indicate significant hard X-ray (8–24 keV) weakness or CT absorption.
- Stacking and joint spectral analyses indicate a soft Γ, disfavoring Compton-thick absorption.
- Fraction of BAL quasars that are intrinsically X-ray weak is poorly constrained (~17–40%). Still dominated by low N statistics
- **Implication may be that the disk winds in intrinsically X-ray weak quasars have large covering factors, so sources would be preferentially observed as BAL quasars.**

Luo +14

NuSTAR observations of ULIRG Mrk 231

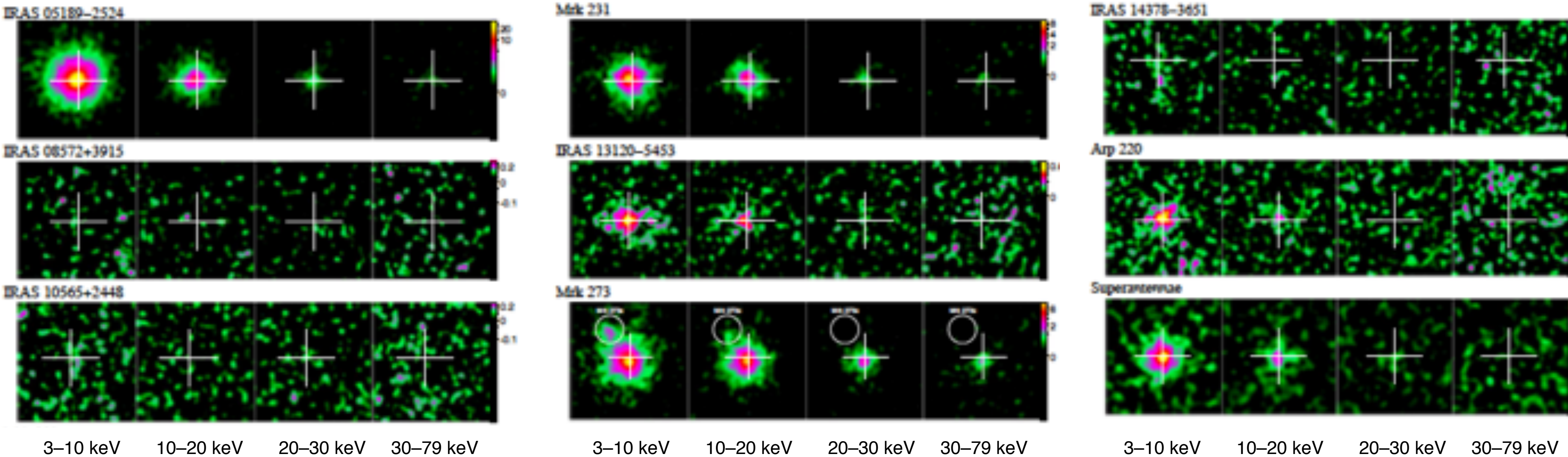
Teng +14

- The direct AGN emission appears absorbed and scattered by a patchy Compton-thin torus with N_H = (1.2 +/- 0.3) x 10^{23} cm^{-2} and Γ=1.4 +/- 0.1.
- Fe line very faint, with EW= 0.16+/-0.1
- X-ray emission is 0.1% L_{bol}

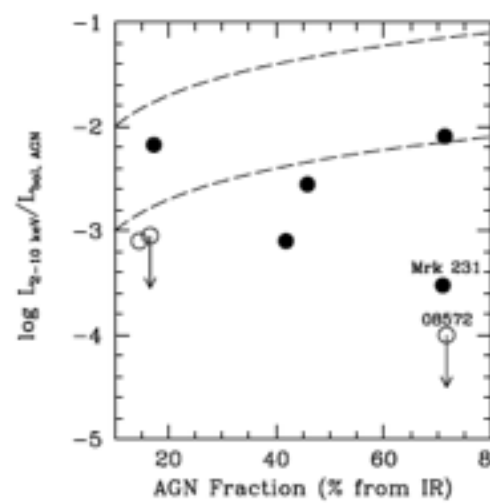


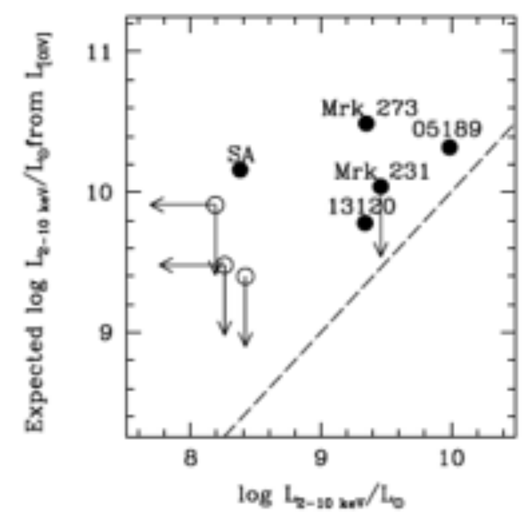
NuSTAR observations of other nearby ULIRGs

Teng +15



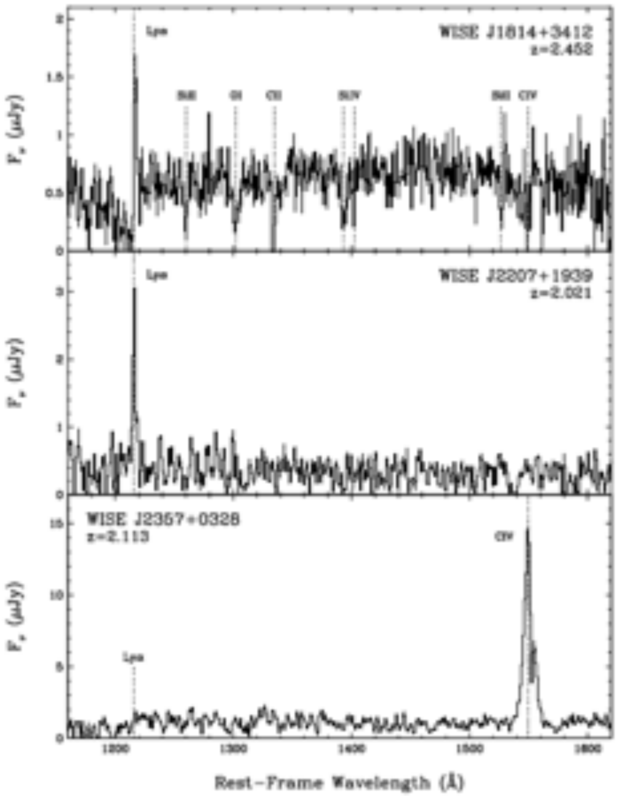
- ULIRG AGN largely Compton-thin (6/9)
- X-ray emission is generally <1% L_{bol}

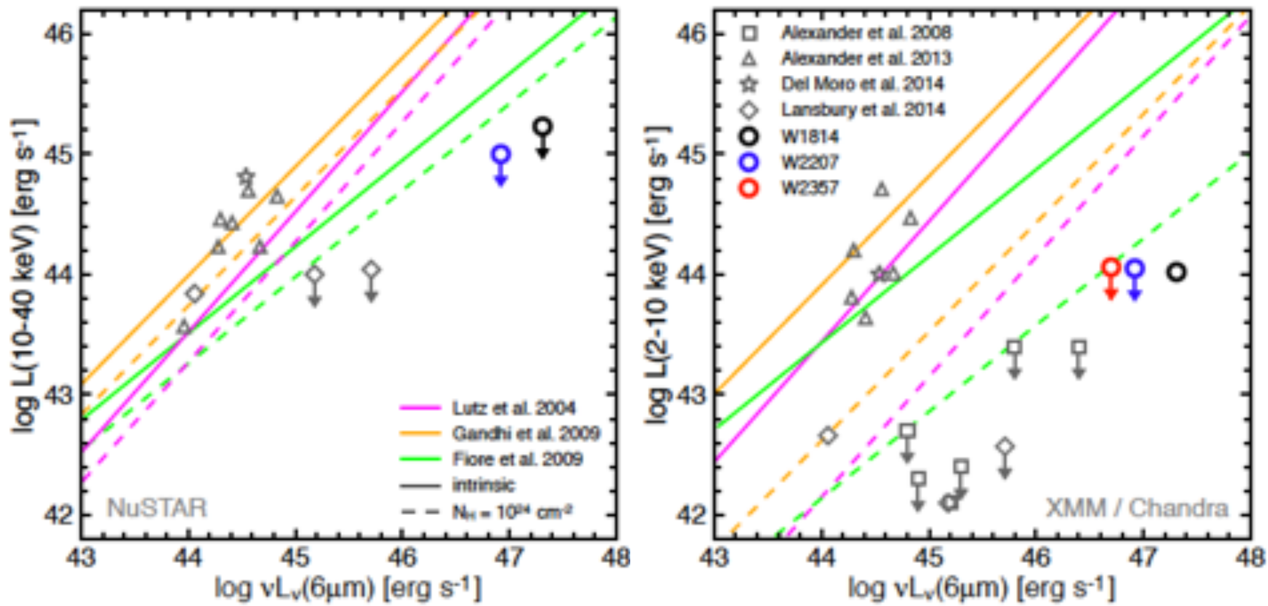




X-ray observations of WISE QSOs

Stern +14

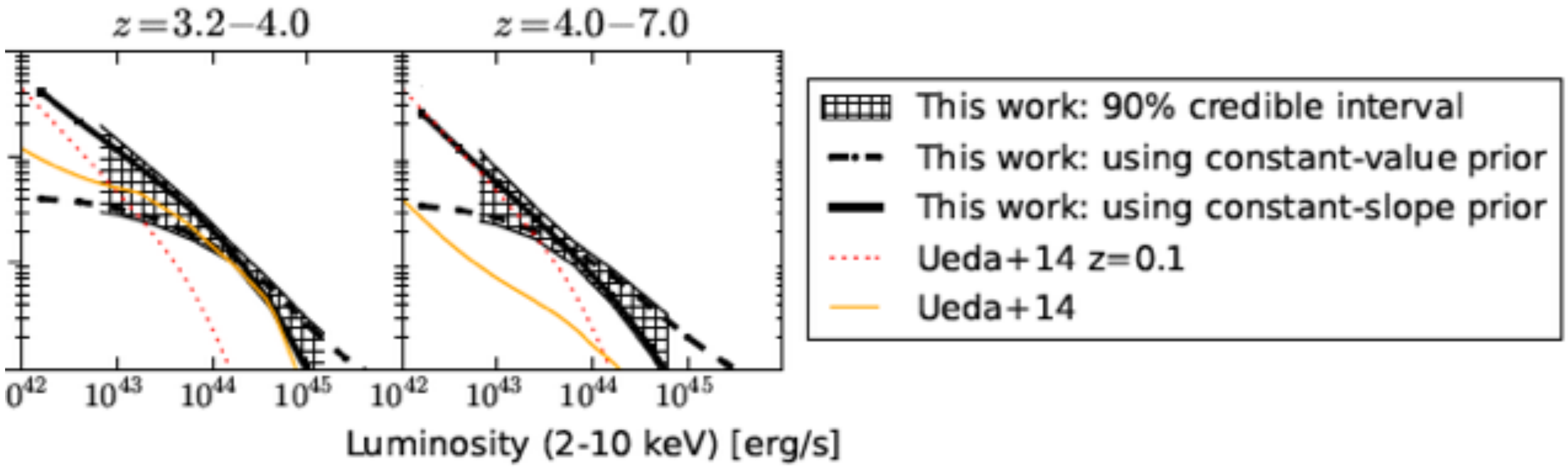




- "W1W2-dropouts" => z~2 with $L_{bol} \sim 10^{14}\ L_{\odot}$.
- *Optical spectra suggest type II*
- X-ray faint => **either CTAGN or X-ray weak.**

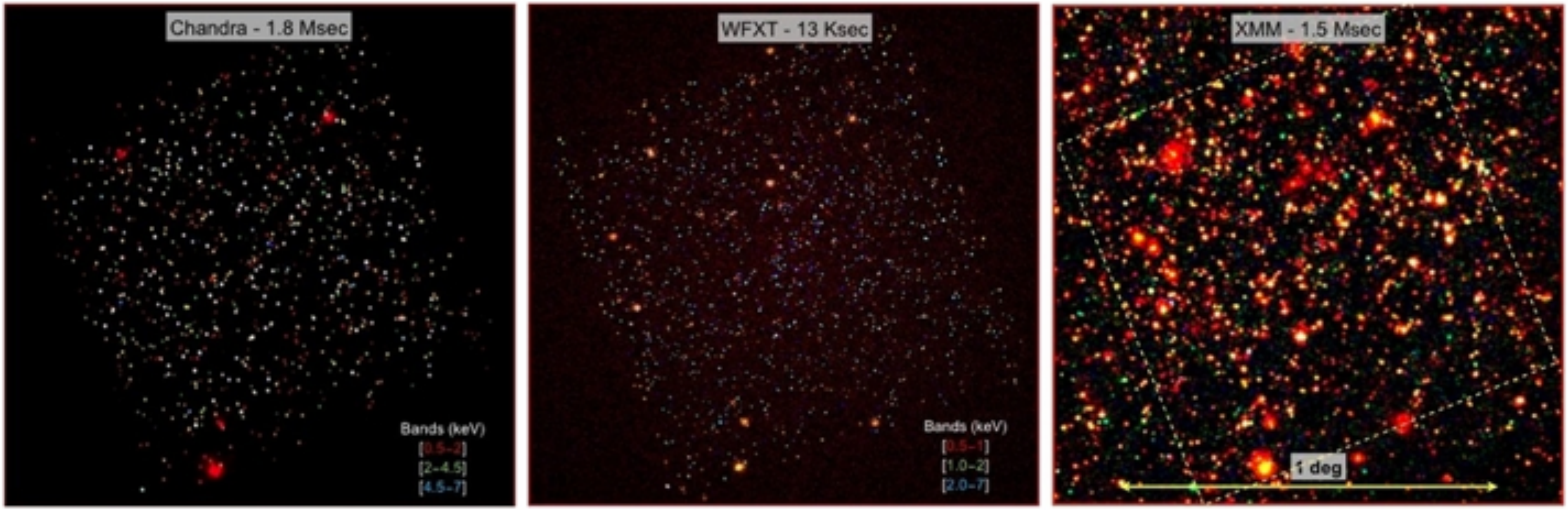
What about SMBHs at high-z?

High-z AGN prospects?



- As detailed in talk by Marta Volonteri, have several dozen QSOs at z>6 (many X-ray detected)
- However, as yet, no viable X-ray detected/selected AGN (e.g., Treister+13, Weigel+15)
- Dangerous to extrapolate there (e.g., Aird+13, Treister+13)
- Certainly seem to be much rarer than can be observed in deep fields, despite sensitivity

High-z AGN prospects?



- Ultimately, wide-field missions like WXFT, SMART-X are best best to find them

  => Athena+ or JWST would have to get lucky.

- But must be coupled with deep ancillary data to weed out closer objects

Summary

- Picture of SMBH growth and evolution shaping up nicely

  => Still need to be concerned with details and propagate errors properly

  => otherwise extrapolations dangerous

- There are some clear areas where lots of work need

  => super Edd accretion, X-ray weak AGN, highly obscured accretion

  => pushing out to high-z to see how seeds form and grow