AGNs Over Cosmic Time: The Demography, Physics, and Ecology of Growing SMBHs as Revealed by X-ray Surveys

Niel Brandt (Penn State)

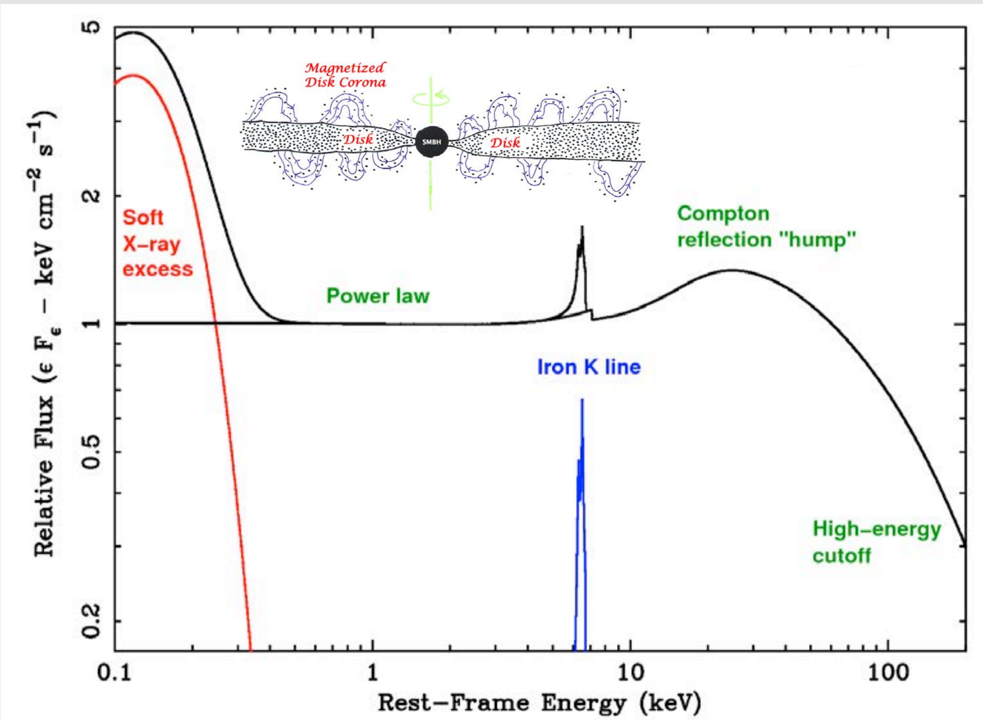
In X-ray surveys to date, AGNs are the main source population in terms of numbers and integrated power.

Now more than 500 substantial papers from ~ 25 ongoing surveys!

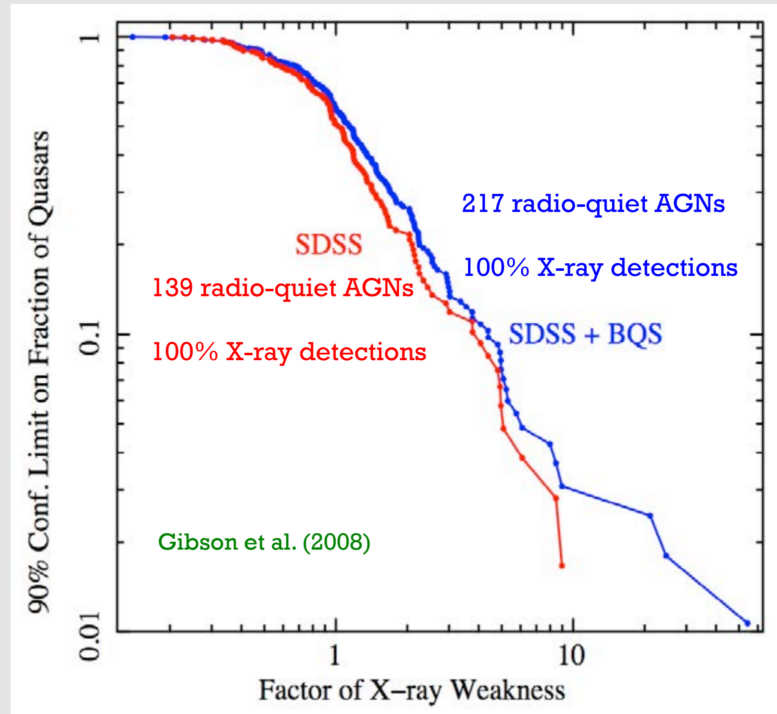
Utility of X-ray AGN Surveys

(1): X-ray Emission is Nearly Universal from Luminous AGNs

Typical AGN X-ray Spectral Energy Distribution



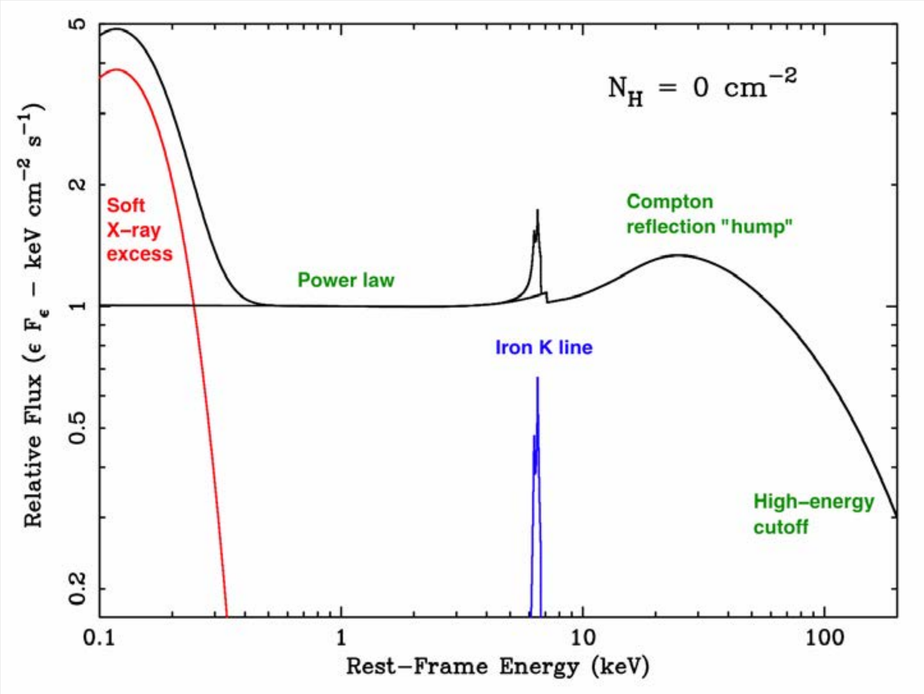
X-ray Luminosities of Optically Selected AGNs



Optically, infrared, and radio-selected AGNs almost always show strong X-ray emission.

Accretion disk + corona is empirically *robust*, even if poorly understood.

(2): X-ray Emission is Penetrating with Reduced Absorption Bias



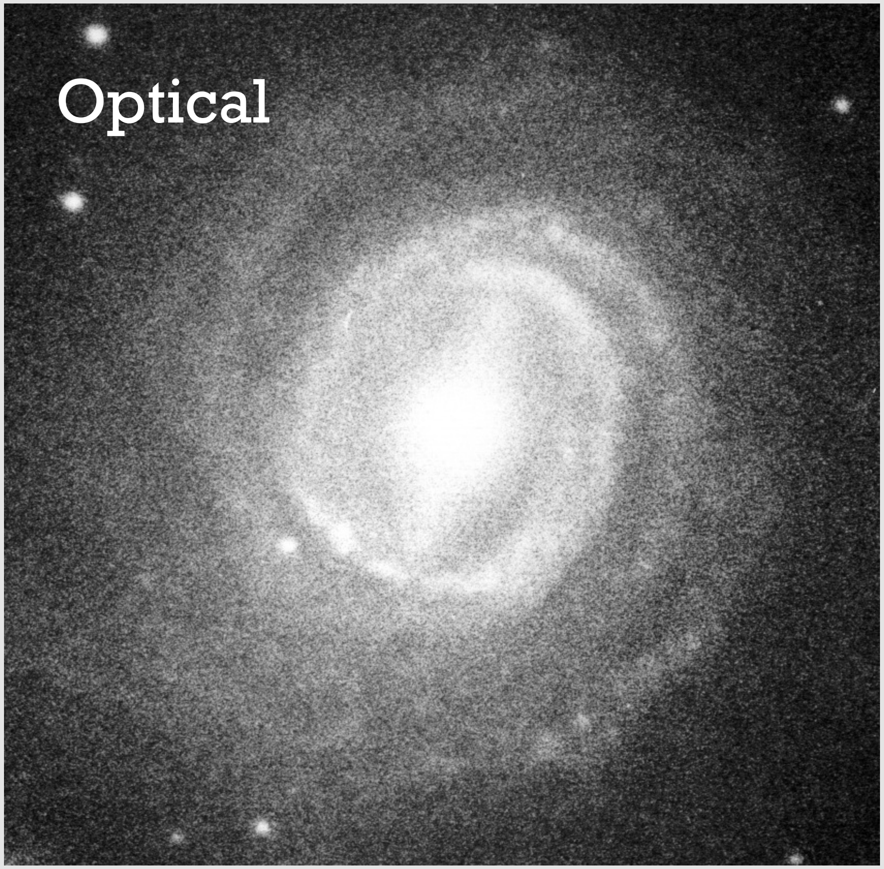
X-ray emission can penetrate and measure large column densities. Hand ($10^{23}\ cm^{-2}$), chest ($10^{24}\ cm^{-2}$).

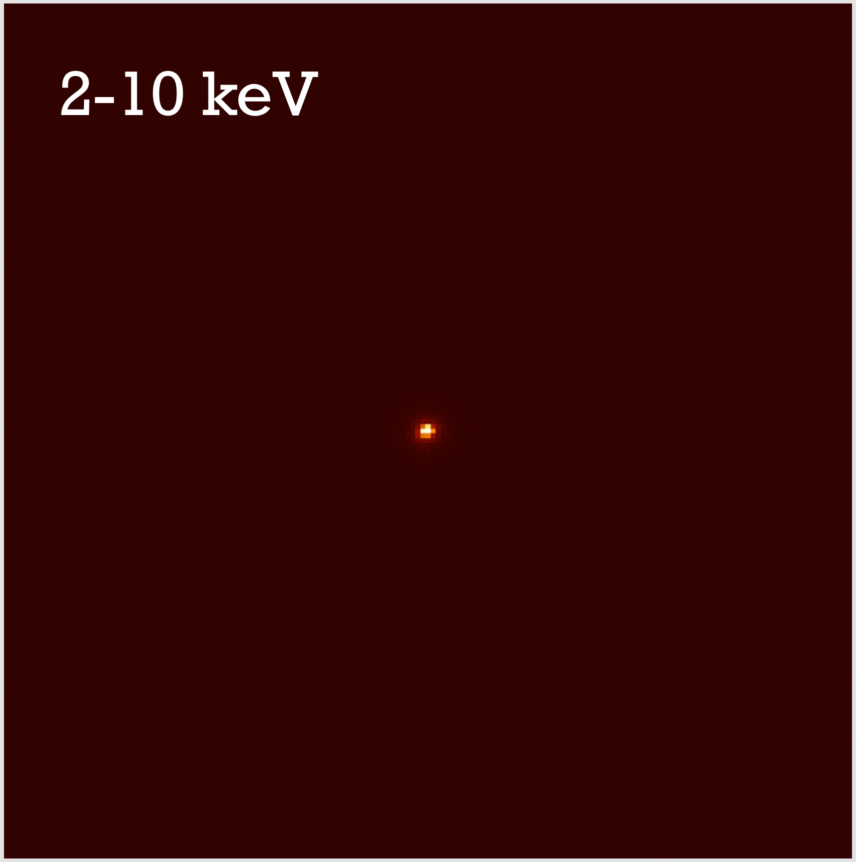
Critically important - majority of active galaxies are absorbed.

Absorption bias drops going to high redshift.

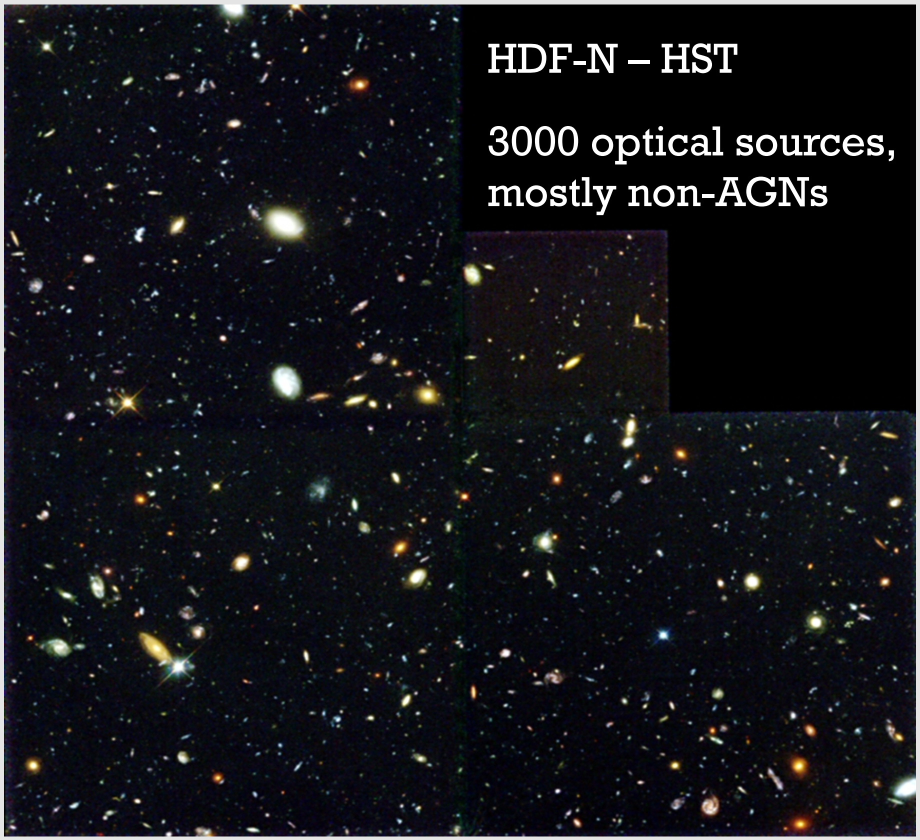
(3): X-rays Have Low Dilution by Host-Galaxy Starlight

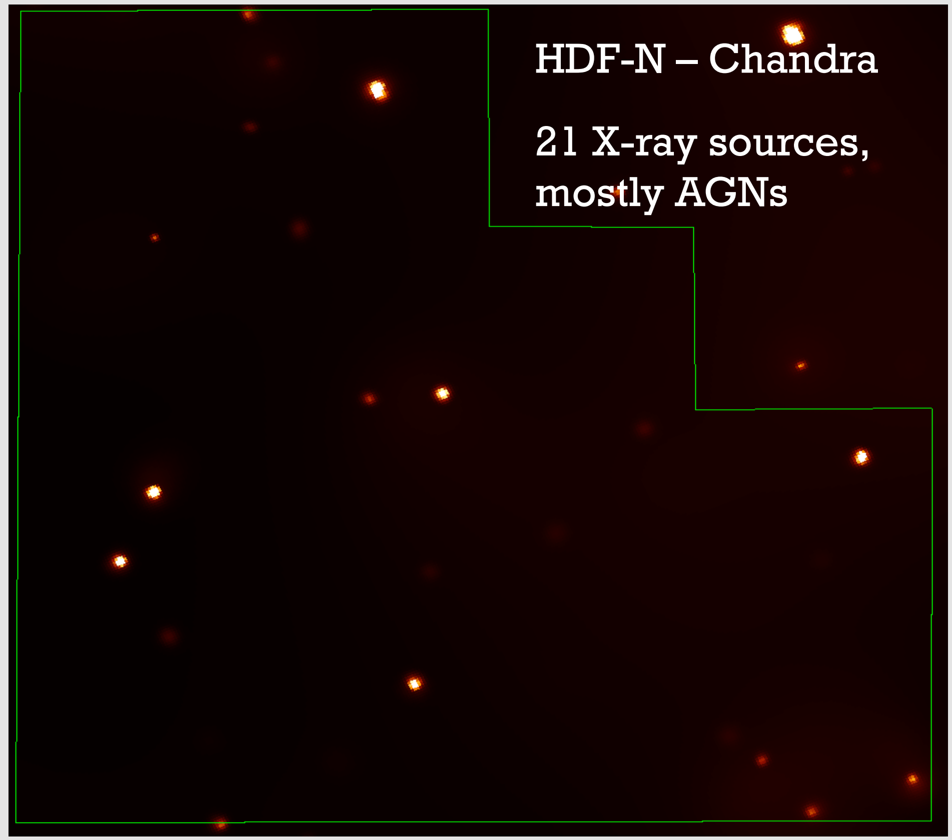
Optical vs. X-ray Emission from a Local Seyfert Galaxy (NGC 3783)





(3): X-rays Have Low Dilution by Host-Galaxy Starlight

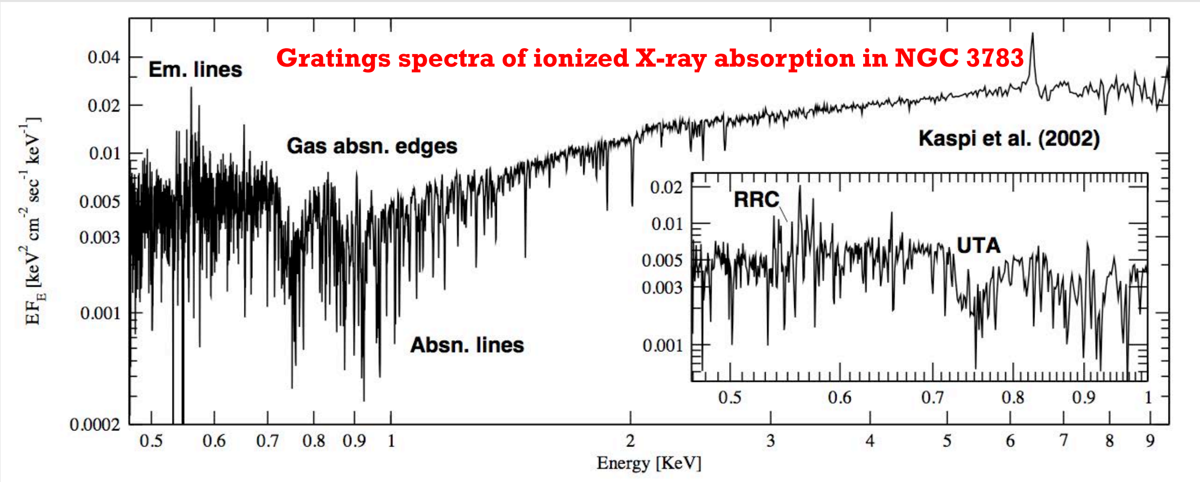


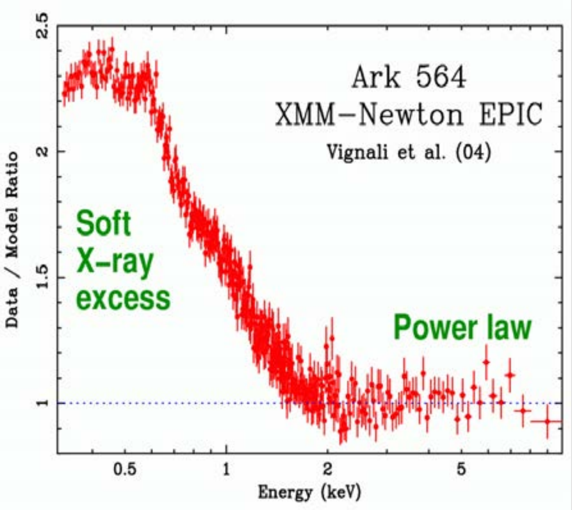


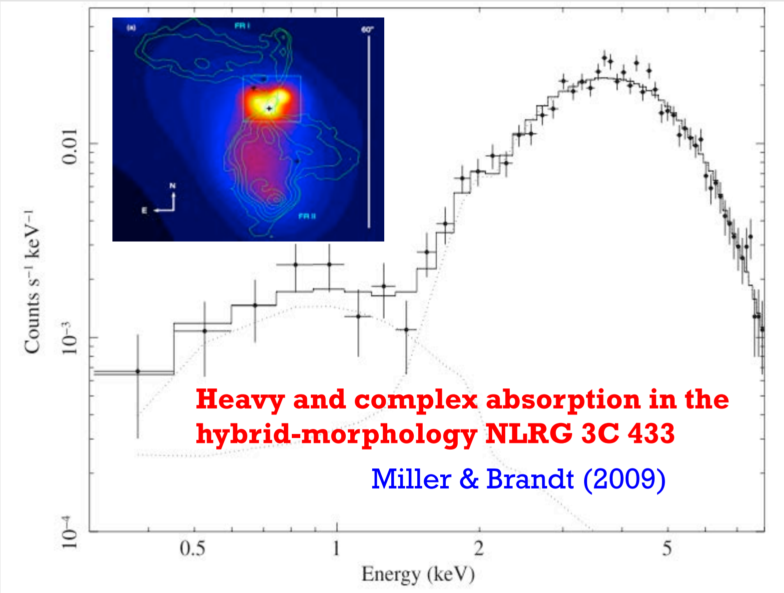
At high redshift cannot spatially resolve AGN light from host-galaxy starlight.

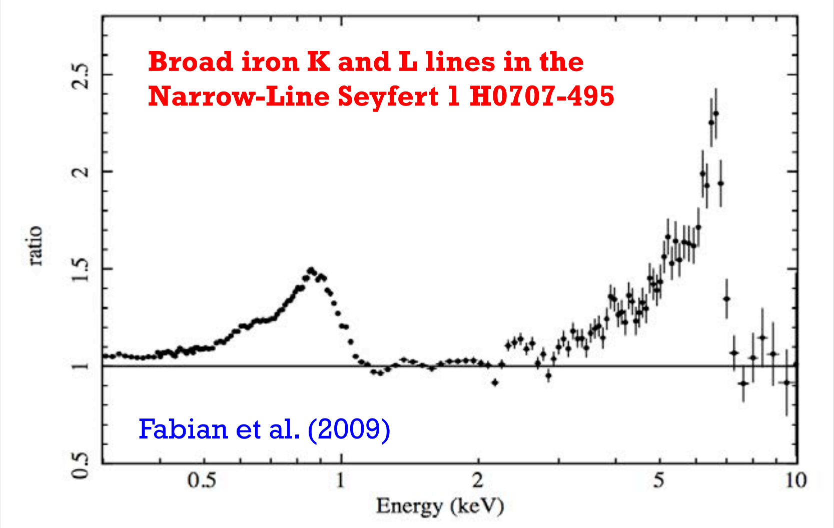
X-rays maximize contrast for "cleanest" samples.

(4): X-ray Spectra of AGNs Are Rich with Diagnostics





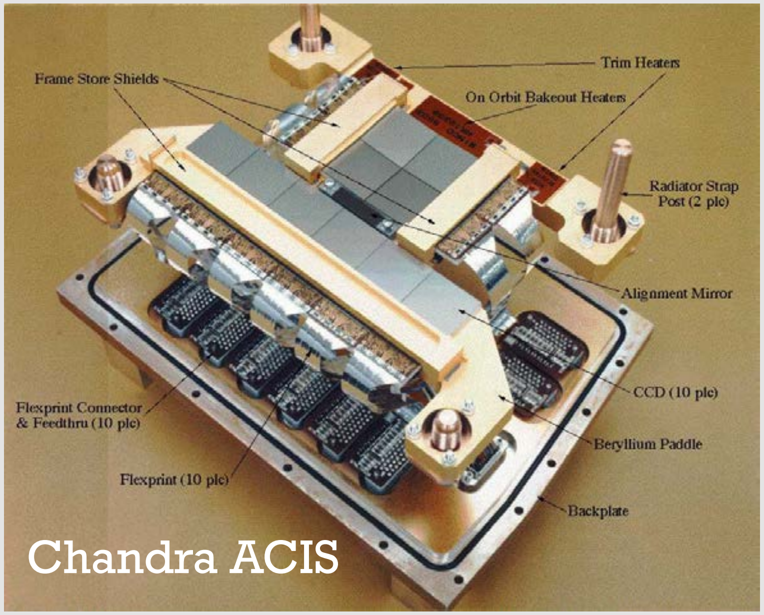


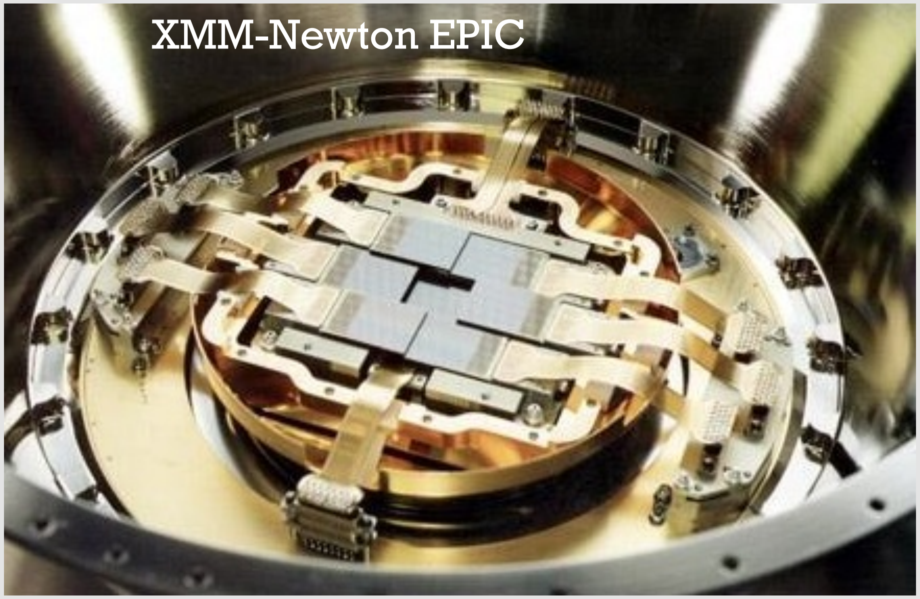


Current X-ray Surveys and Their Multiwavelength Follow-Up

Capabilities of Chandra and XMM-Newton for Surveys

Good-to-great angular resolution – Broad bandpass – Respectable FOVs





Great sensitivity – Up to 80-400 times that of previous missions.

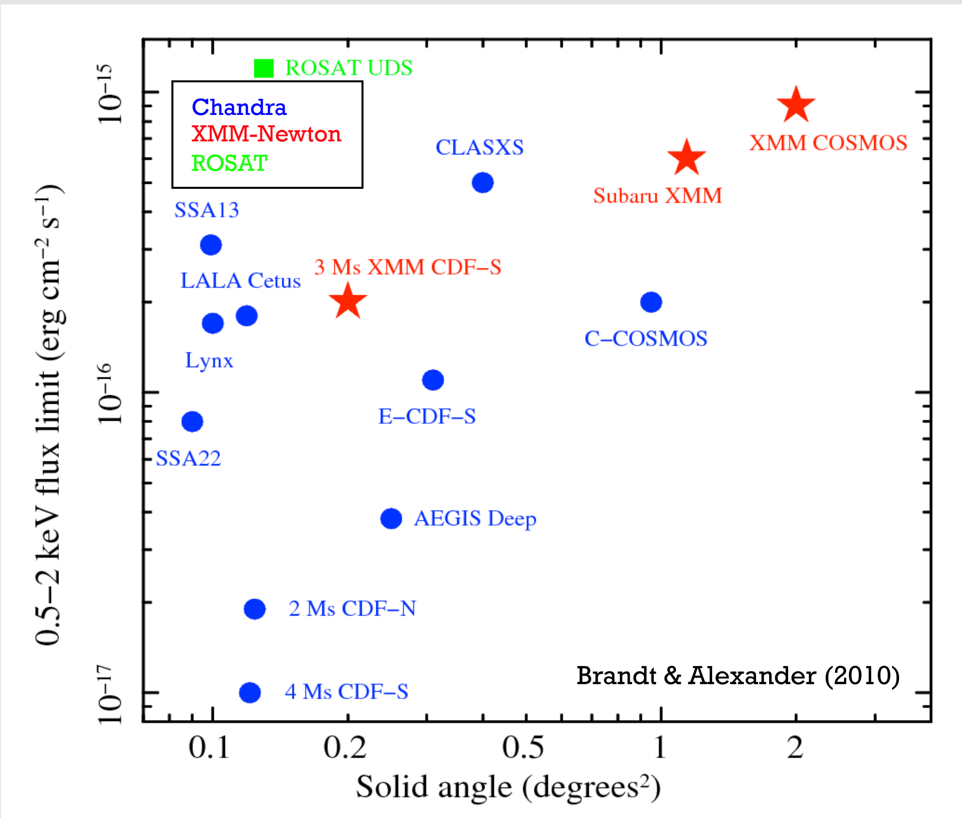
Good-to-great positions – 0.2-2.5 arcsec. *Essential* for reliable follow-up work at faint fluxes.

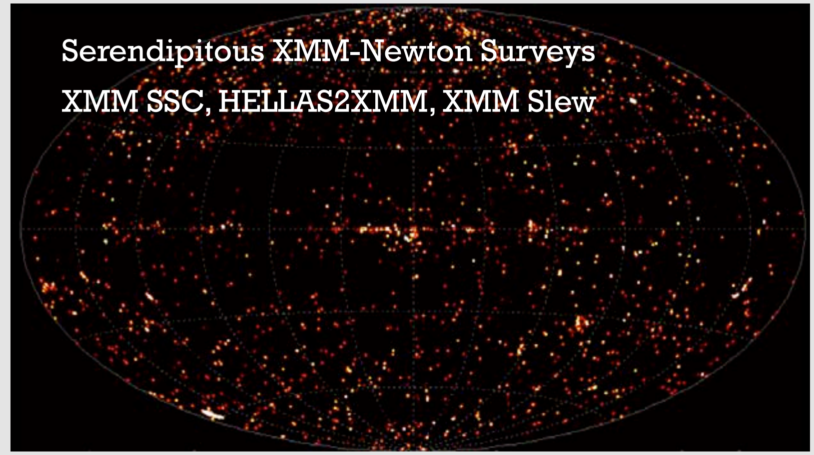
Large samples – Hundreds-to-thousands of sources for powerful statistical studies.

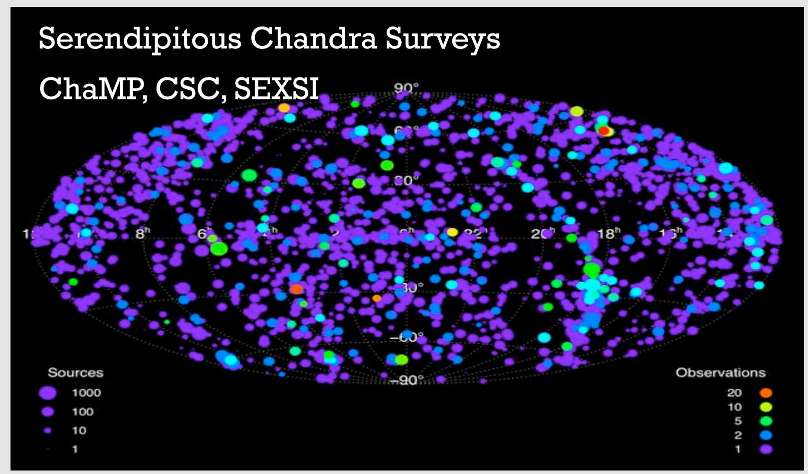
Good archiving practices – Allows effective survey federation by anyone.

Multitude of X-ray AGN Surveys

Some Recent Contiguous Deep X-ray Surveys



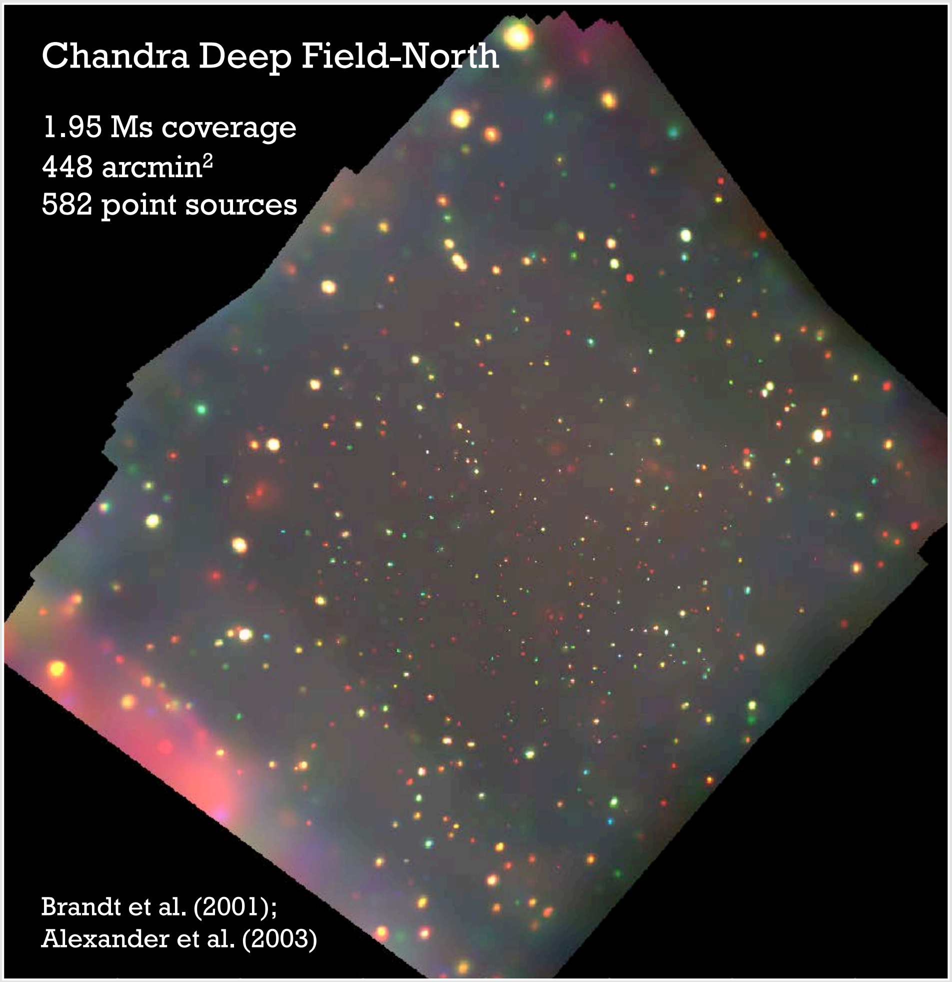


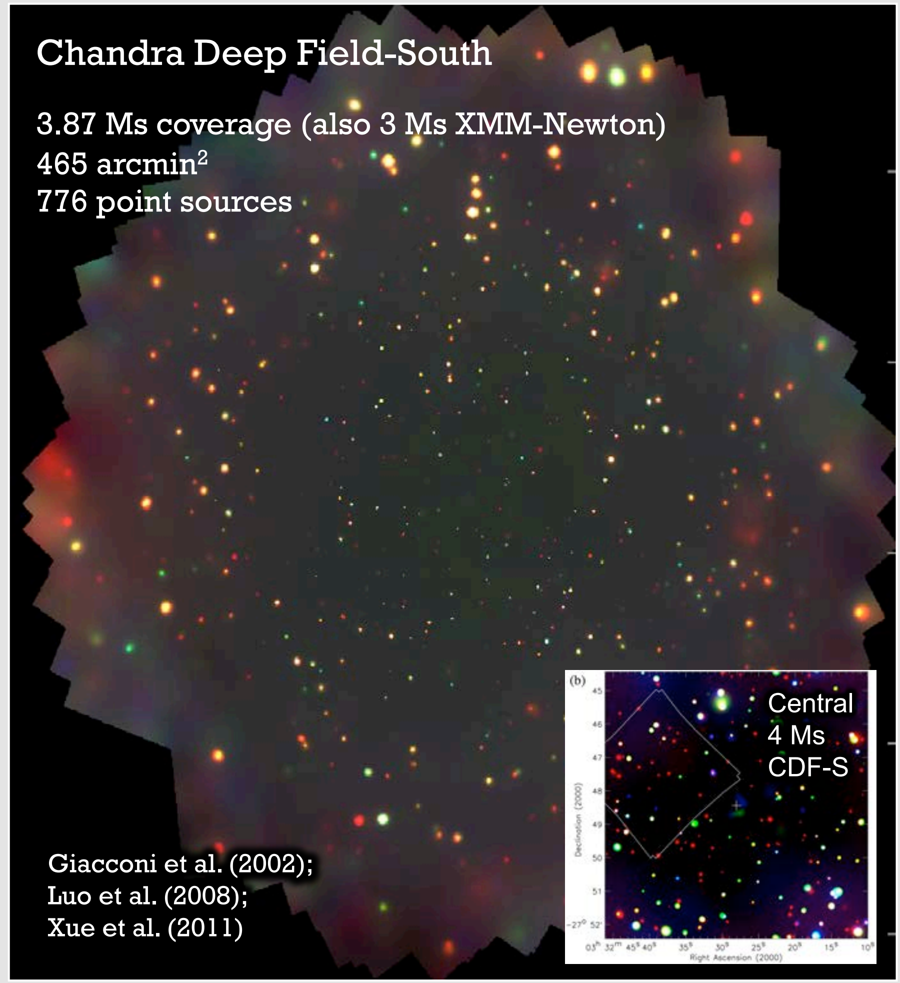


~ 25 ongoing Chandra and XMM-Newton surveys cover most of the practically accessible sensitivity vs. solid-angle "discovery space."

Together are providing a complete understanding of X-ray source populations.

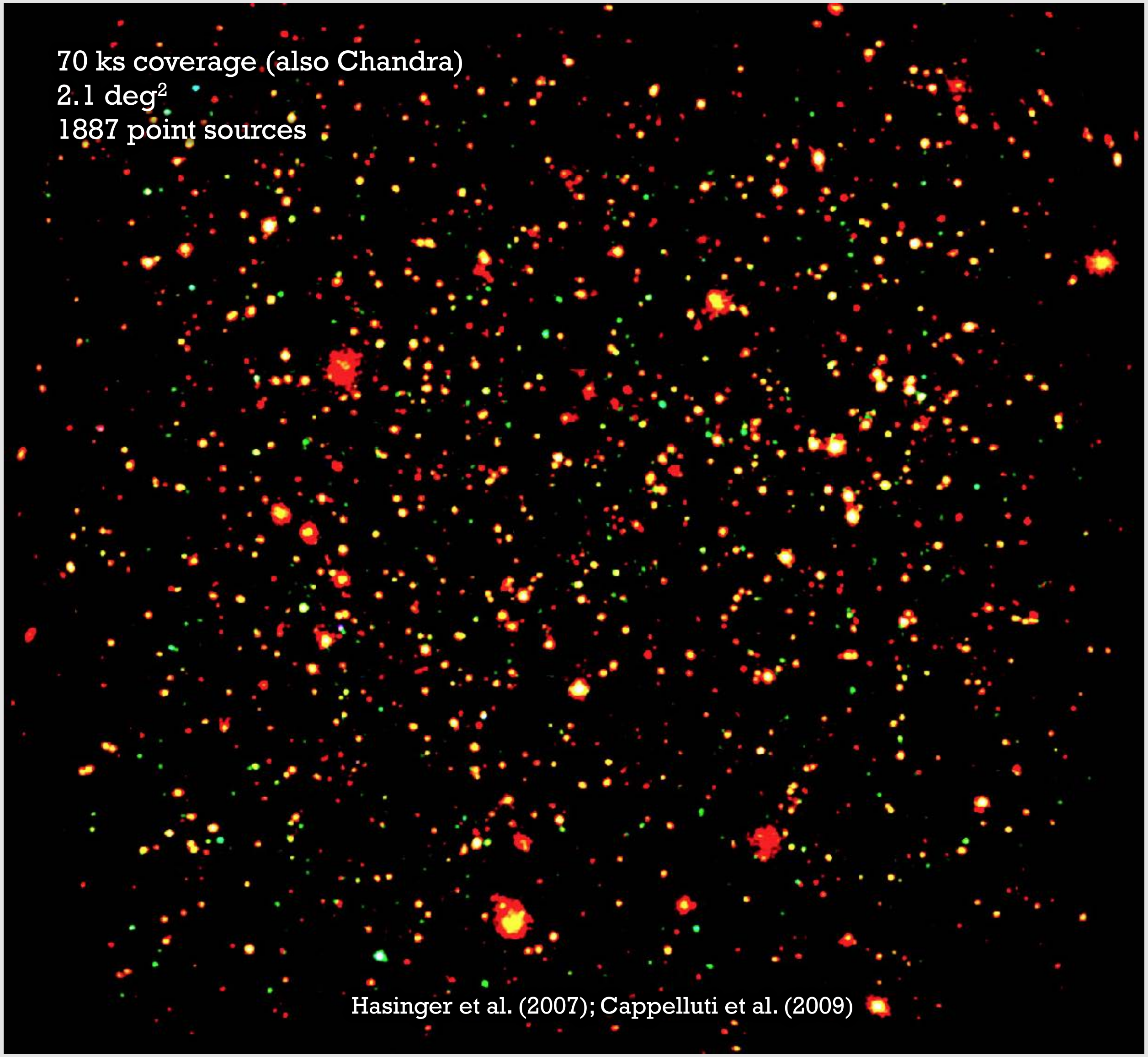
The Chandra Deep Fields



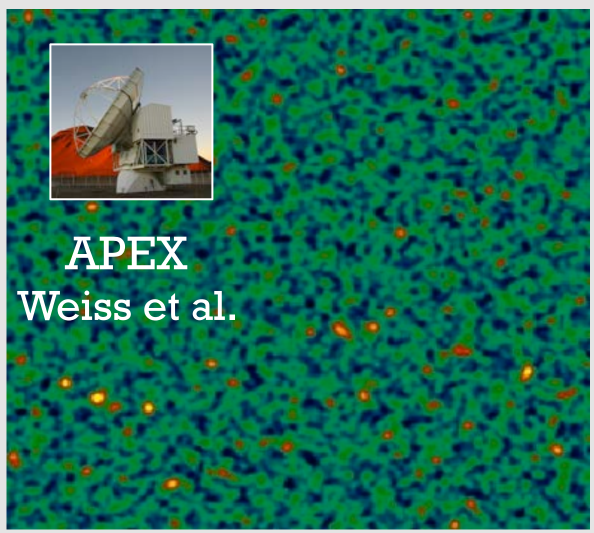


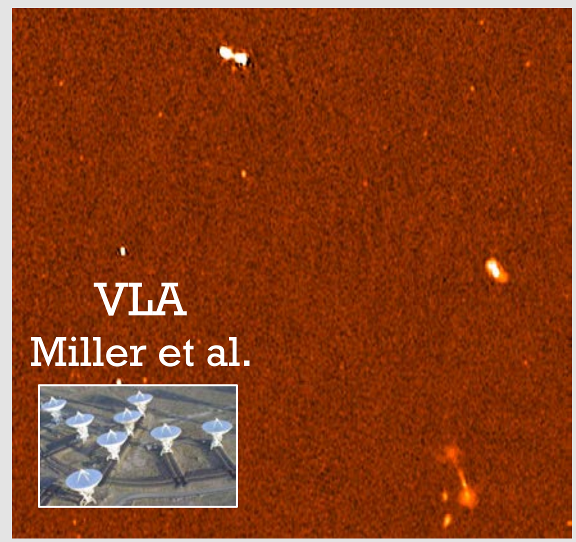
Faintest sources have 1 count per ~ 7 days!

The XMM-Newton COSMOS Field



Ultradeep Multiwavelength Coverage (CDF-S)

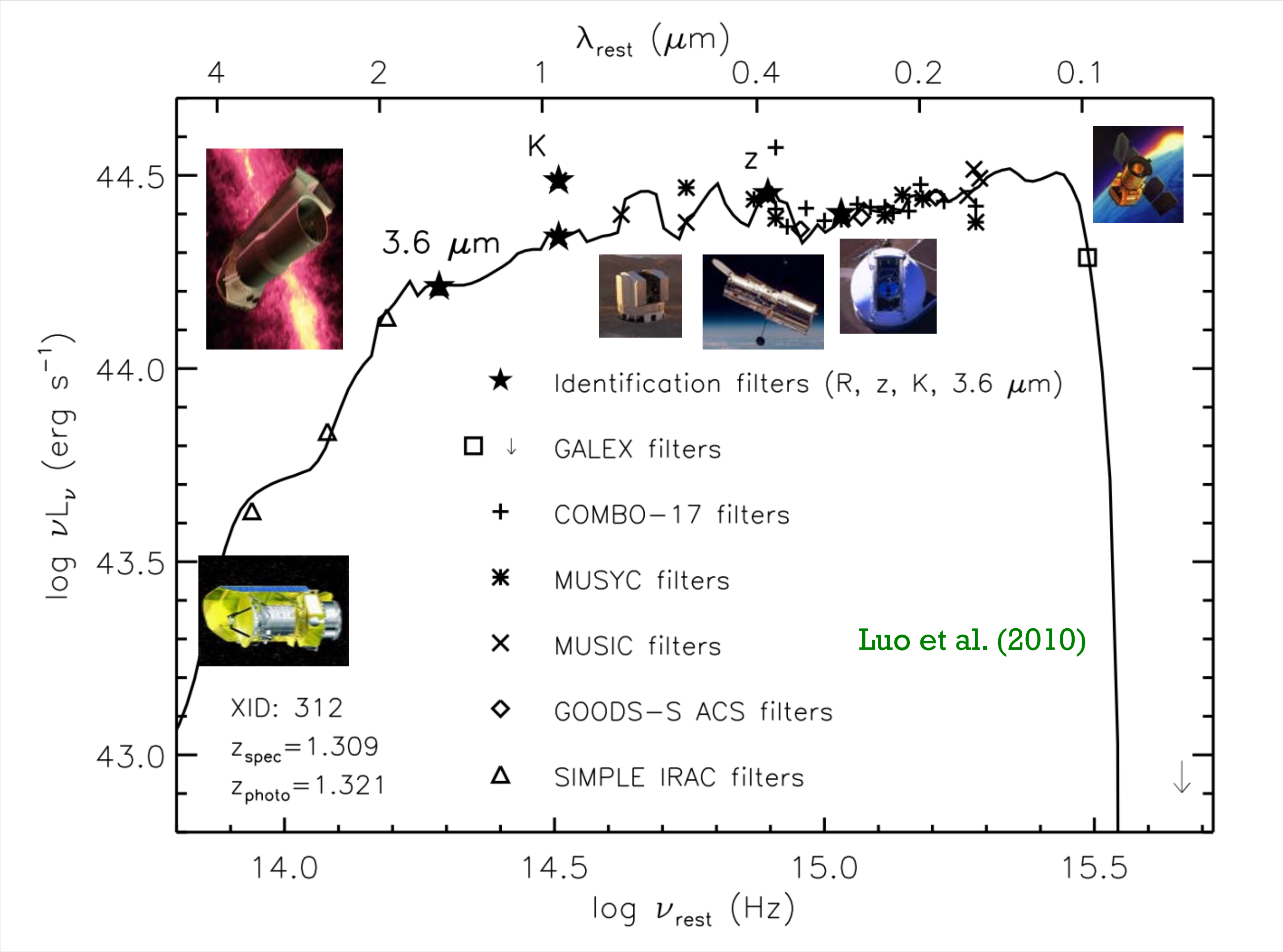




Extraordinary multiwavelength supporting data continue to grow. In the future NuSTAR, ALMA, EVLA, JWST, LSST, ELTs.

Roles of the Multiwavelength Data

Example IR-to-UV SED with Fitted Template



Source identification

Photometric redshifts (often 15-40 bands)

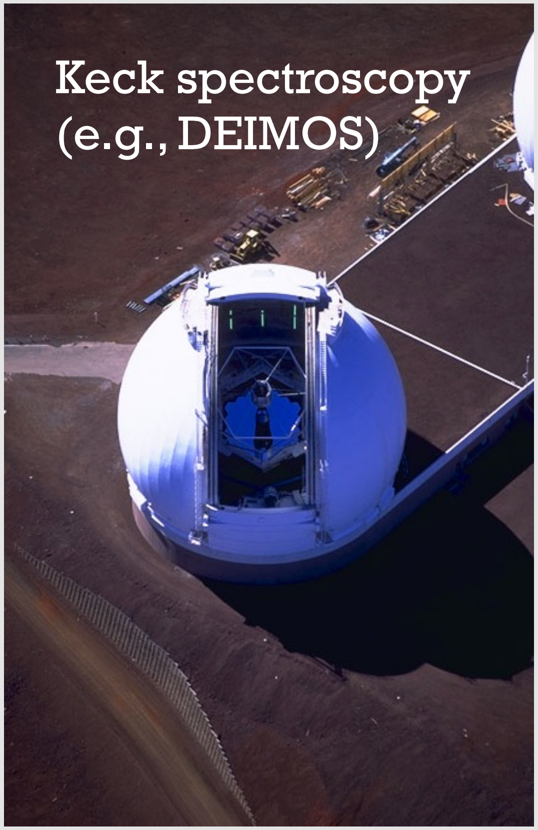
AGN accretion physics

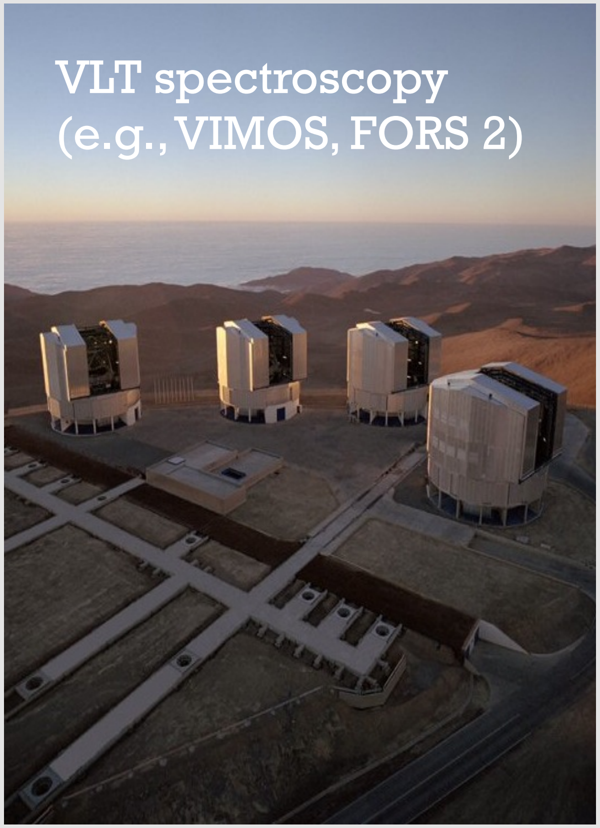
AGN vs. SFR power

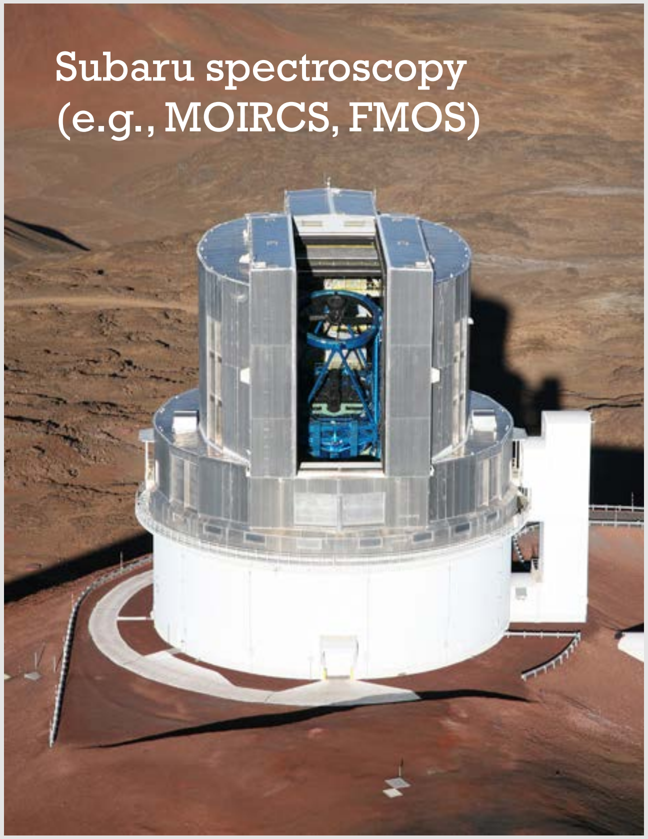
Host-galaxy properties

X-ray missed AGNs

X-ray Source Spectroscopic IDs







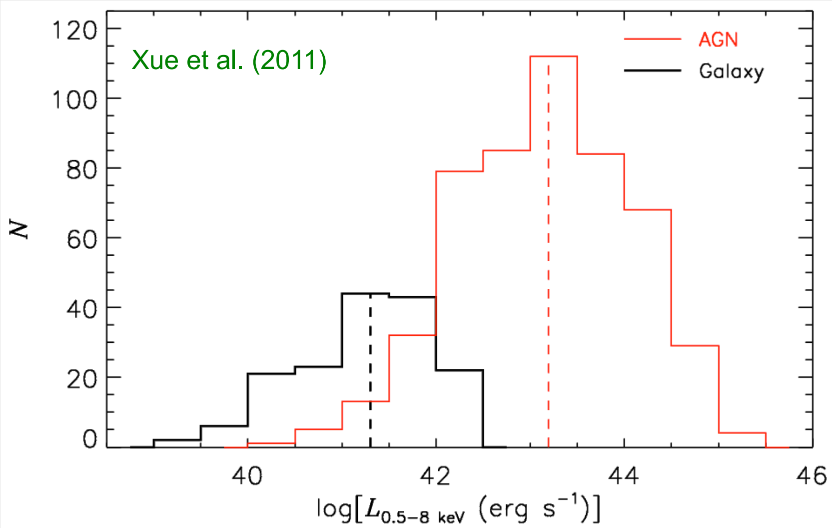
Enormous progress over the past decade using multi-object spectrographs, but remains a persistent challenge and bottleneck (especially at $R \sim 24$-28).

Driver for future large spectroscopic facilities (e.g., ELTs).

Good photometric redshifts often derived to $R \sim 26$-27.

Selection of AGNs from the X-ray Source Population

X-ray Luminosity Distribution for CDF-S Sources



Select AGNs using

- X-ray luminosity
- X-ray-to-optical flux ratio
- X-ray spectral shape
- X-ray variability
- Follow-up spectroscopy
- SED fitting

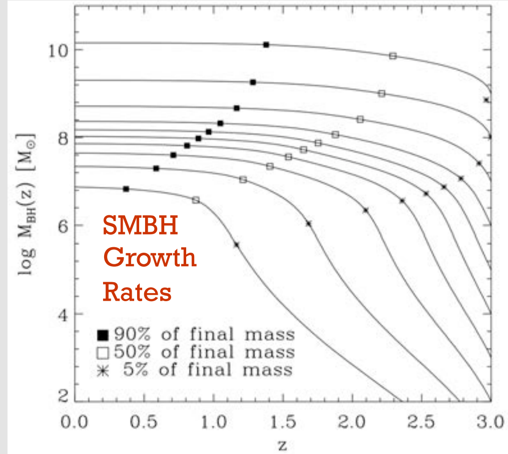
Multiple independent cross-checks provide "cleanest" possible AGN selection.

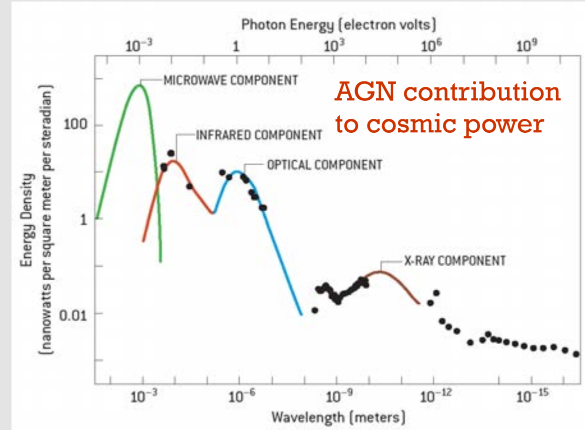
Typically 75-90% of the X-ray sources are AGNs.

Other X-ray point source populations are starburst galaxies, normal galaxies, and stars.

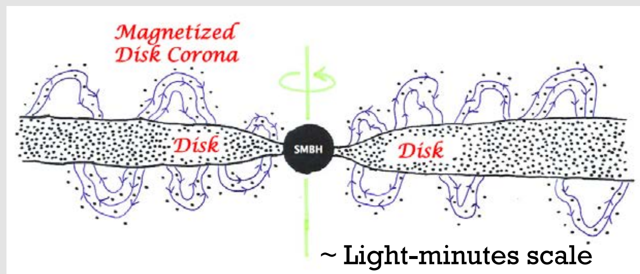
Selected AGN Science Results

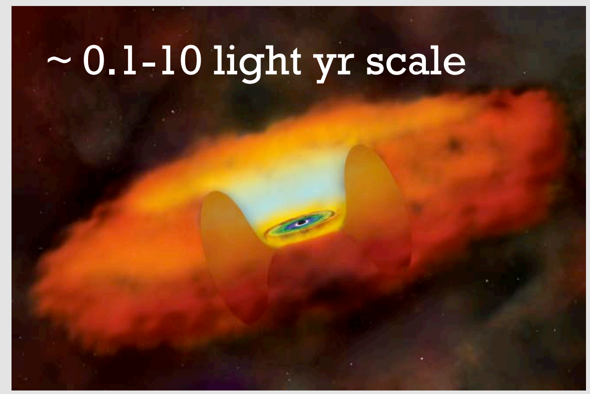
Demography



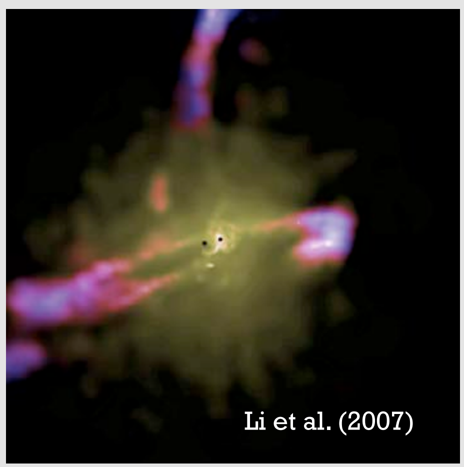


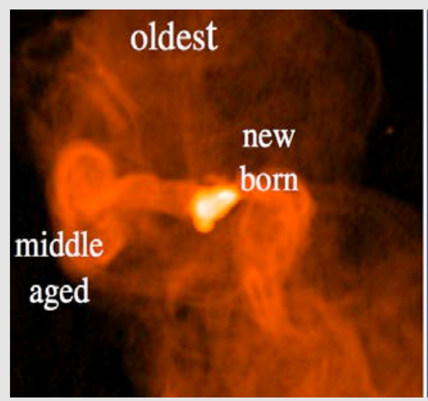
Physics

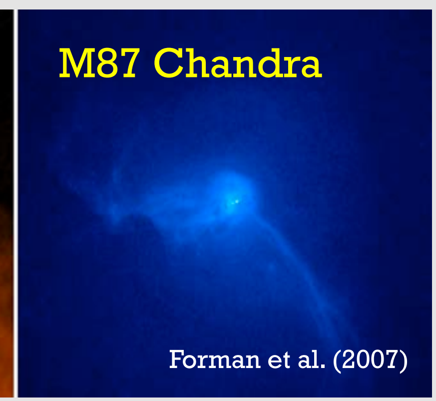




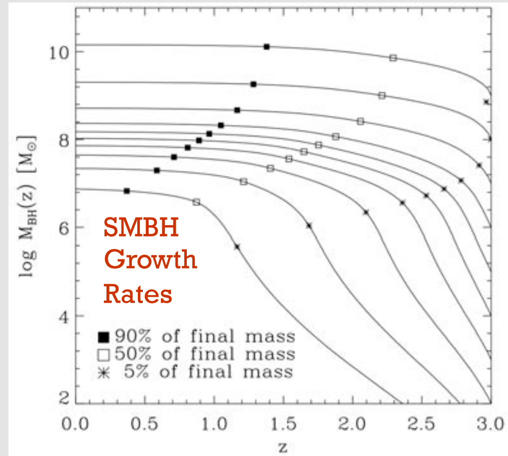
Ecology

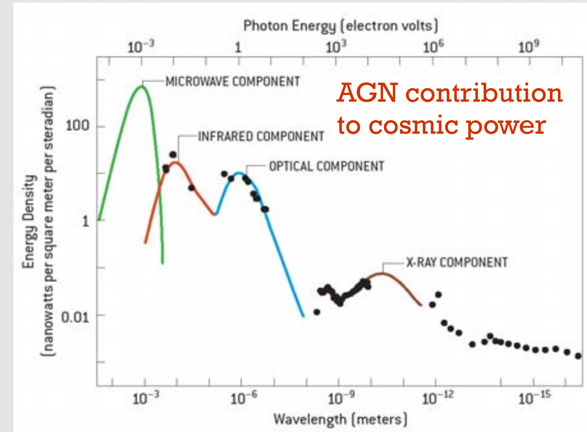




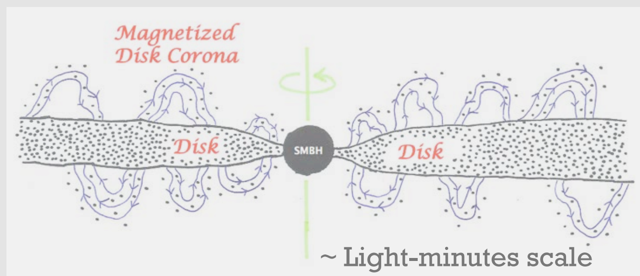


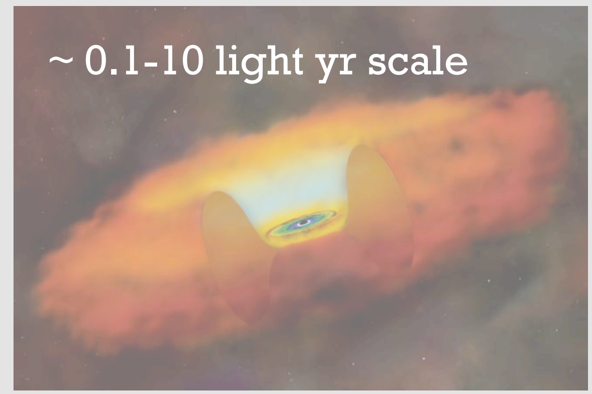
Demography



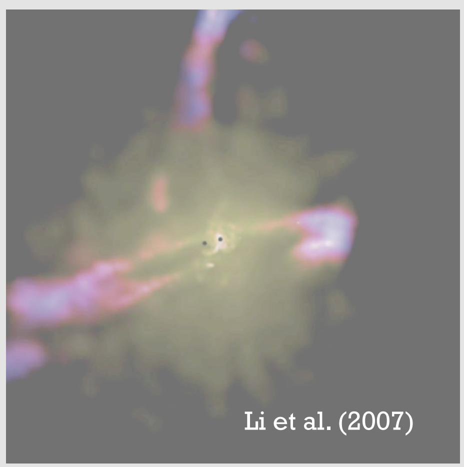


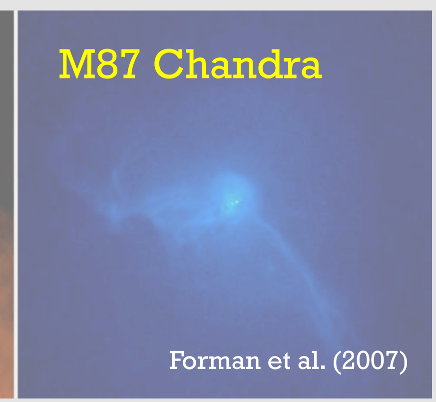
Physics





Ecology





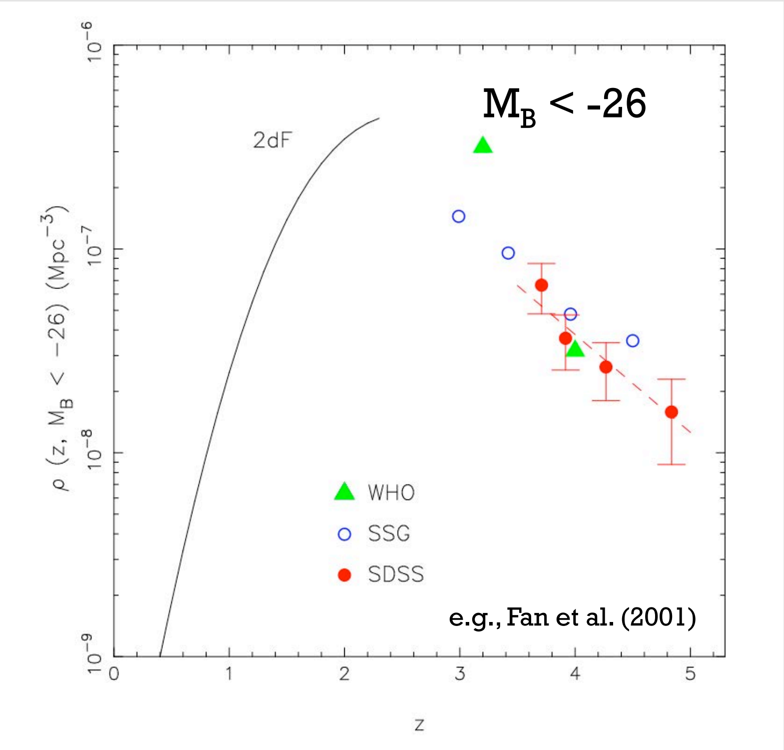
Demography: Pre-Chandra/XMM Status

1960s – 1990s: Dominated by wide-field surveys of rare, luminous quasars.

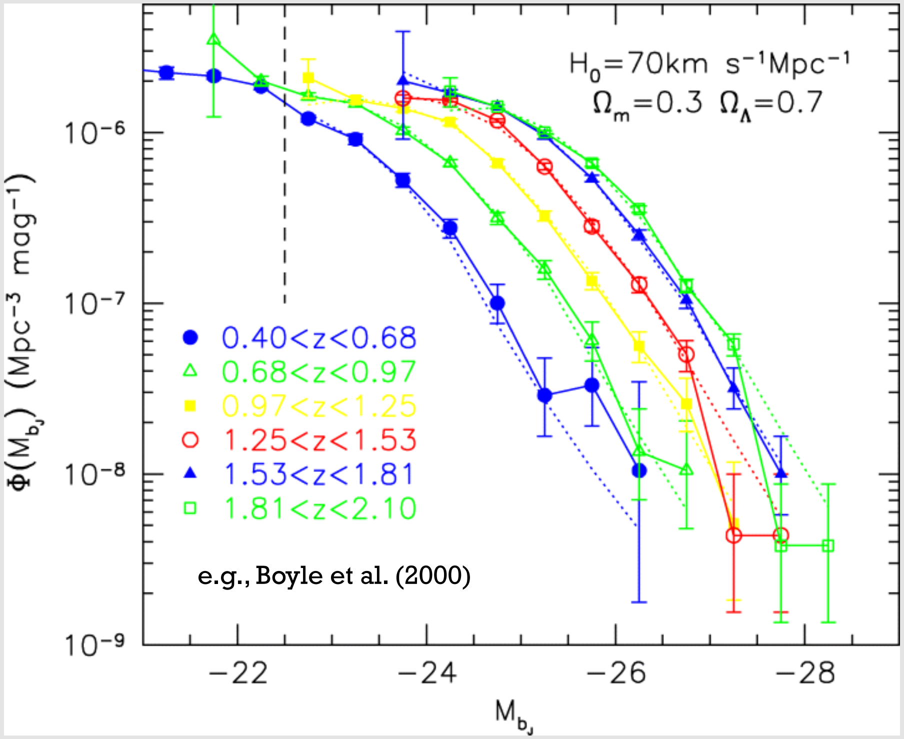
Luminous quasars peak at $z \sim 2\text{-}3$ and consistent with pure luminosity evolution.

How do *most* AGN evolve? Suggestions from ROSAT surveys of LDDE,
but limited statistics and concerns about obscuration bias.

SDSS Luminous Quasar Evolution



2QZ Quasar Luminosity Function



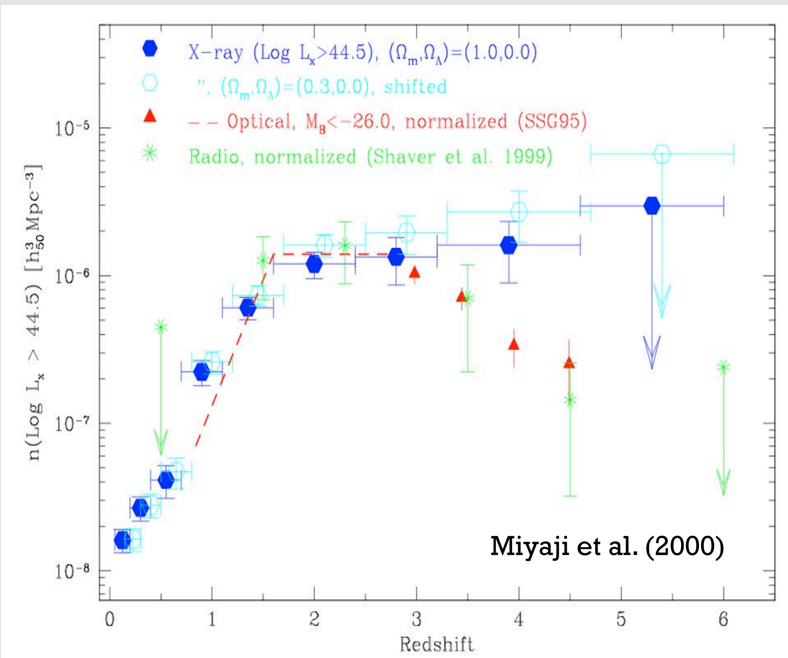
Demography: Pre-Chandra/XMM Status

Constraints on high-redshift (z > 3.5) demography *highly* uncertain.

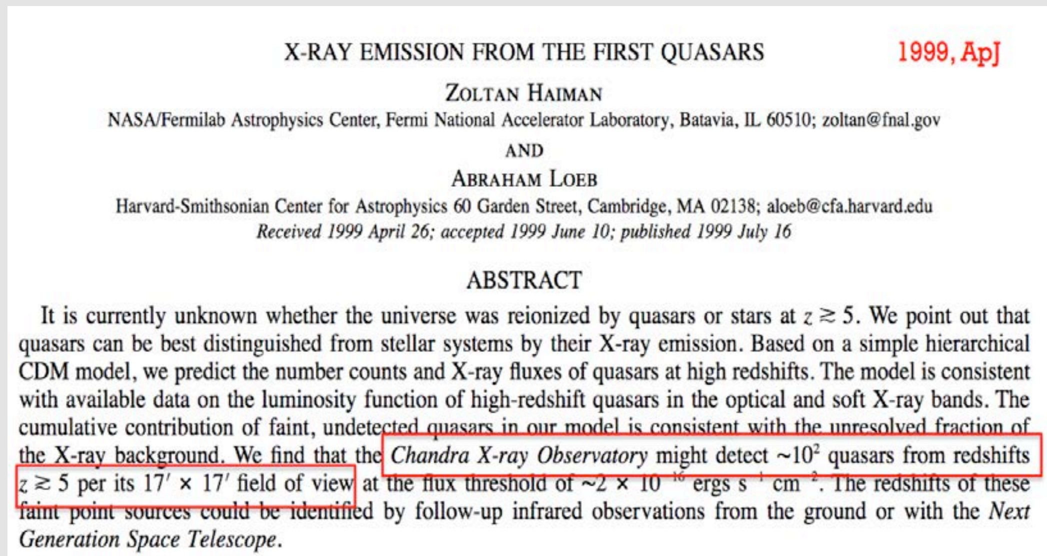
Hints of no decline in the X-ray quasar number density at high redshift.

AGNs plausibly dominated cosmic reionization.

No Decline of X-ray Quasars at High Redshift?



One 1999 prediction for Chandra and XMM-Newton...



X-RAY EMISSION FROM THE FIRST QUASARS

1999, ApJ

ZOLTAN HAIMAN

NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, IL 60510; zoltan@fnal.gov

AND

ABRAHAM LOEB

Harvard-Smithsonian Center for Astrophysics 60 Garden Street, Cambridge, MA 02138; aloeb@cfa.harvard.edu

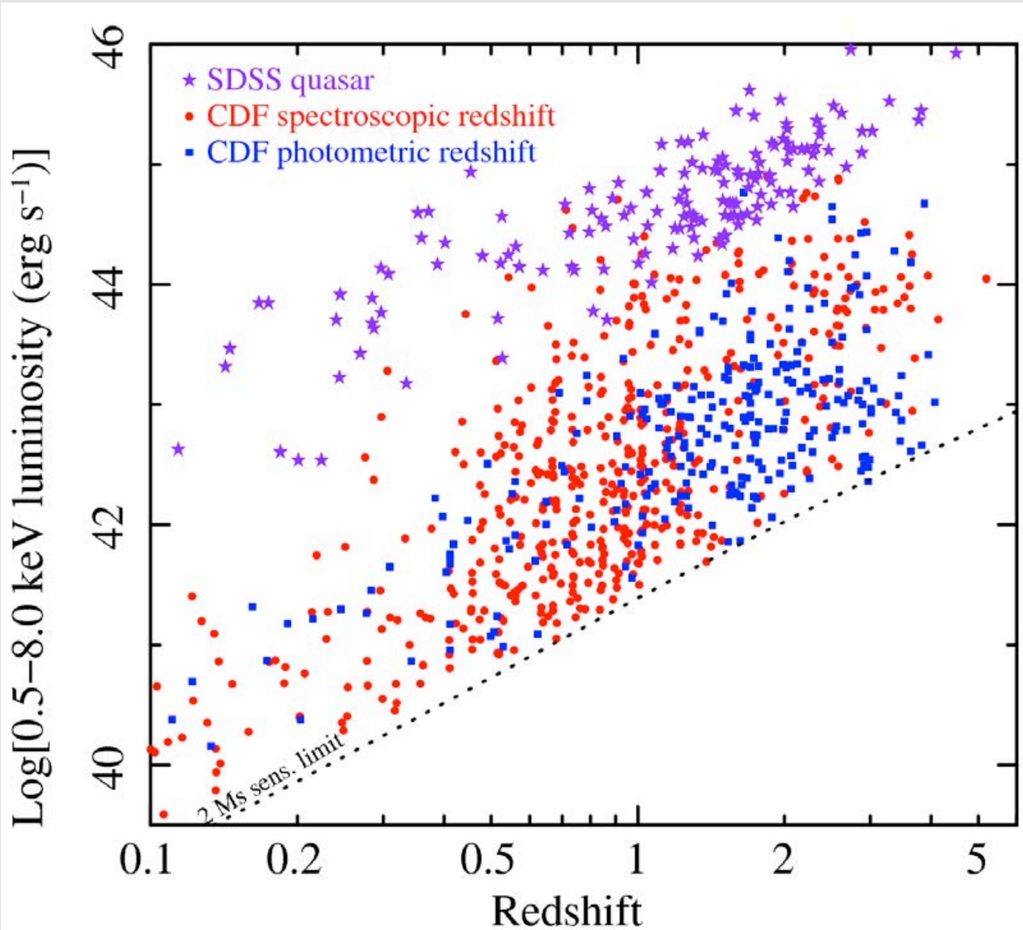
Received 1999 April 26; accepted 1999 June 10; published 1999 July 16

ABSTRACT

It is currently unknown whether the universe was reionized by quasars or stars at $z \gtrsim 5$. We point out that quasars can be best distinguished from stellar systems by their X-ray emission. Based on a simple hierarchical CDM model, we predict the number counts and X-ray fluxes of quasars at high redshifts. The model is consistent with available data on the luminosity function of high-redshift quasars in the optical and soft X-ray bands. The cumulative contribution of faint, undetected quasars in our model is consistent with the unresolved fraction of the X-ray background. We find that the *Chandra X-ray Observatory* might detect ~10^2 quasars from redshifts $z \gtrsim 5$ per its 17′ × 17′ field of view at the flux threshold of ~2×10^{-16} ergs s^{-1} cm^{-2}. The redshifts of these faint point sources could be identified by follow-up infrared observations from the ground or with the *Next Generation Space Telescope*.

Typical AGNs in the High-Redshift Universe

Chandra Deep Fields AGNs vs. SDSS Quasars



X-ray surveys allow AGN selection about 100 times fainter than wide-field optical surveys.

These AGNs are ~ 500+ times more numerous.

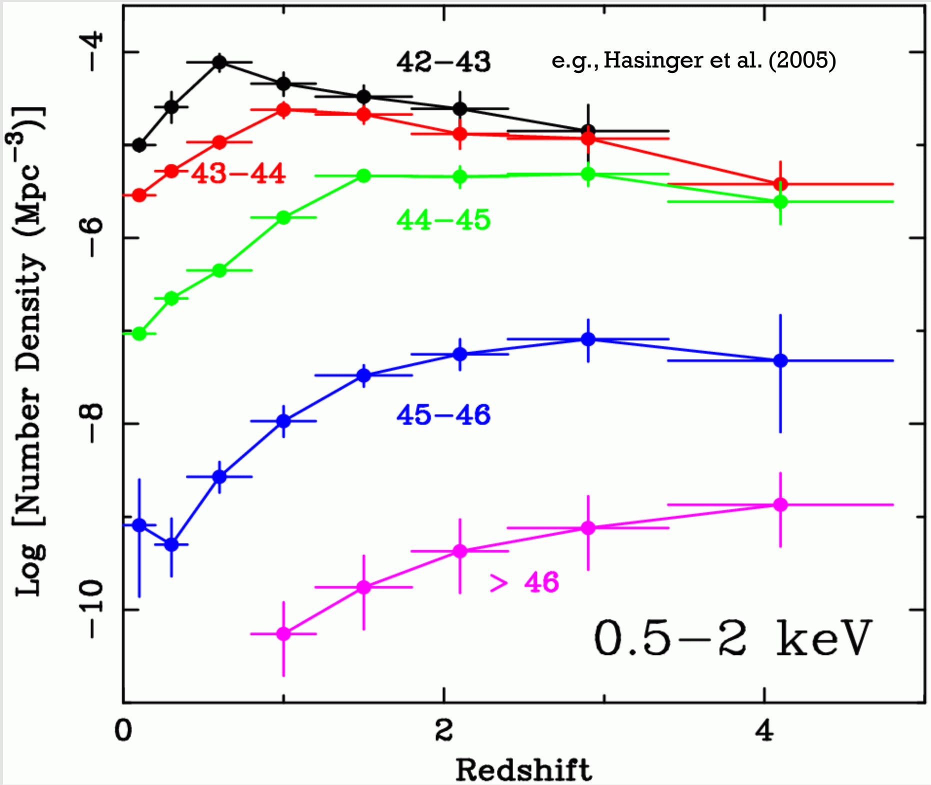
Equally important, do this with minimized obscuration bias.

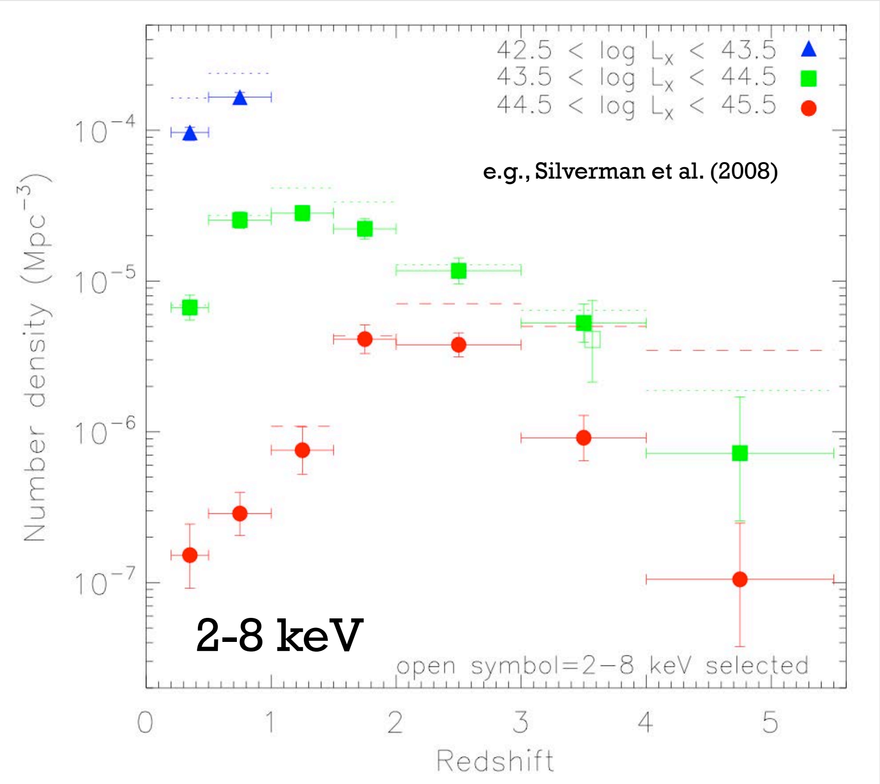
AGN number counts now ~ 9800 deg^{-2} in CDFs, about 12 times those from ROSAT ultradeep surveys.

The key new discovery space!

Luminosity Dependent AGN Evolution

Number-Density Changes with Luminosity





Lower luminosity AGNs peak at later cosmic times - "cosmic downsizing."

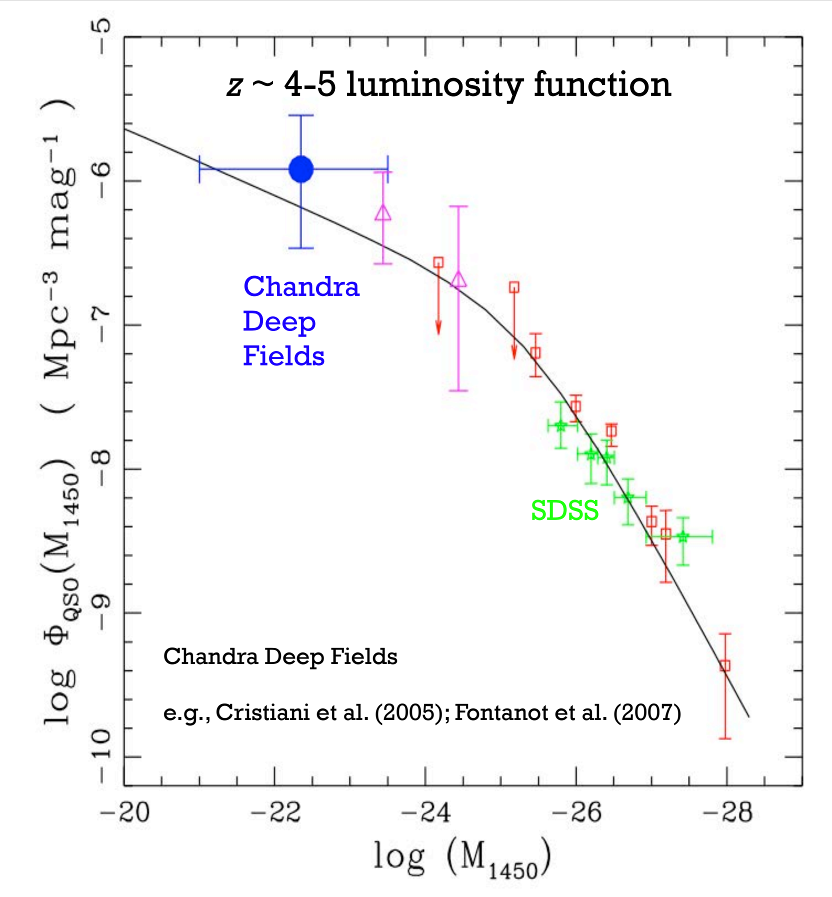
Basic result robust, but details uncertain due to detection incompleteness, source identification issues, follow-up incompleteness, and X-ray spectral complexity.

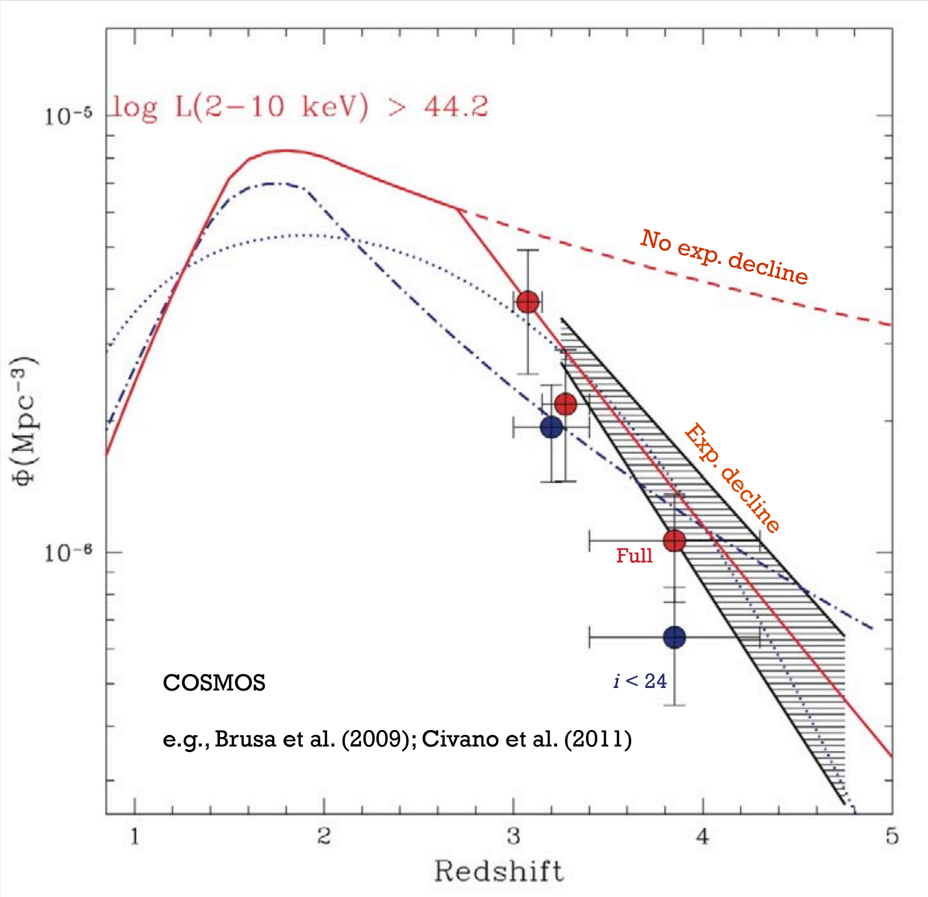
Peak of SMBH power production at $z \sim 1$-1.5 and not $z \sim 2$-3.

High-Redshift Demographic Constraints

Roughly exponential decline of X-ray quasar number density required.

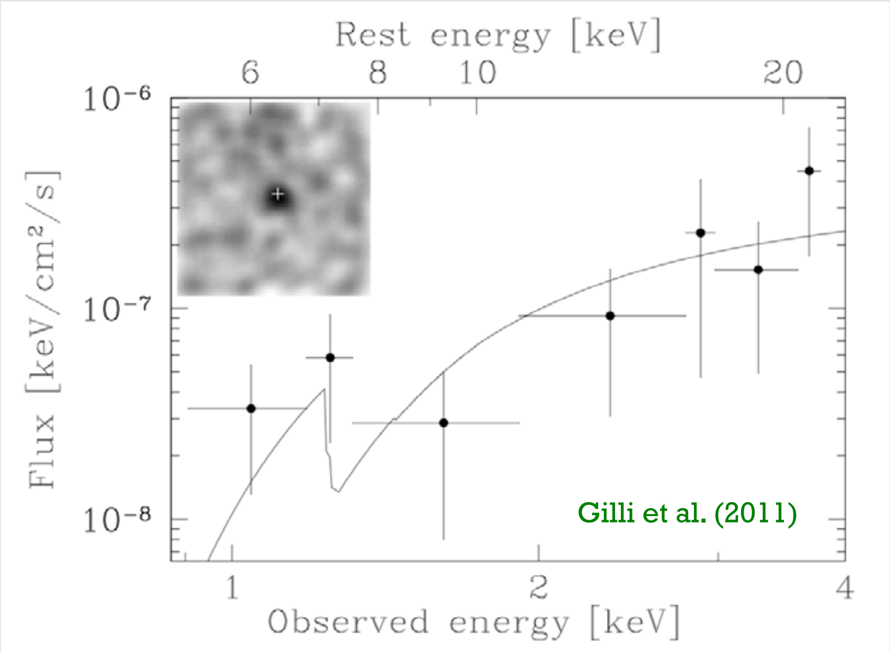
Luminous AGNs unlikely to have dominated cosmic reionization.



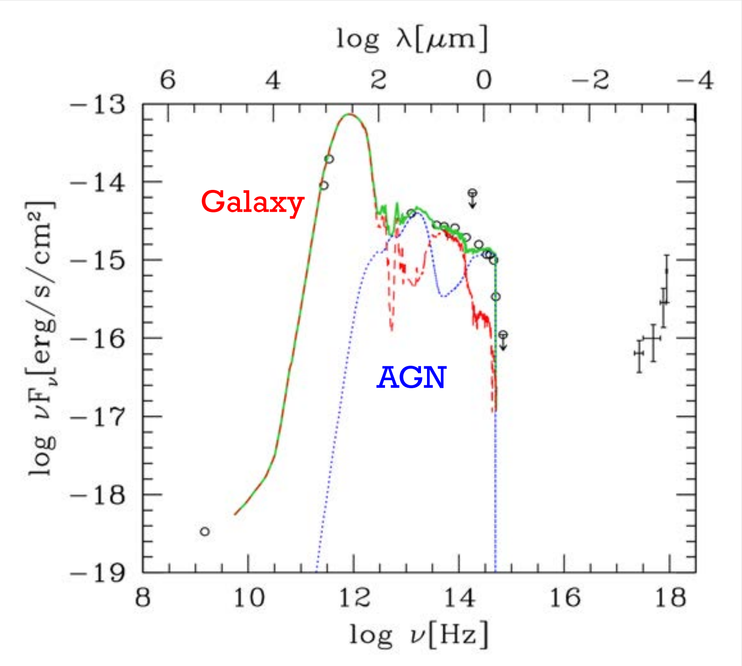


New Compton-Thick Quasar at $z = 4.76$ in the 4 Ms CDF-S

Best-Fit Chandra Spectral Model



Strongly Star-Forming Host Detected by APEX LABOCA



Key phase in SMBH / galaxy co-evolution where obscured SMBH rapidly growing in forming bulge (e.g., Granato et al. 2006; Hopkins et al. 2006)?

The Soltan Argument

Mon. Not. R. astr. Soc. (1982) **200**, 115–122

Masses of quasars

Andrzej Sołtan *N. Copernicus Astronomical Centre, Bartycka 18, 00-716 Warsaw, Poland*

Received 1981 October 18; in original form 1981 August 19

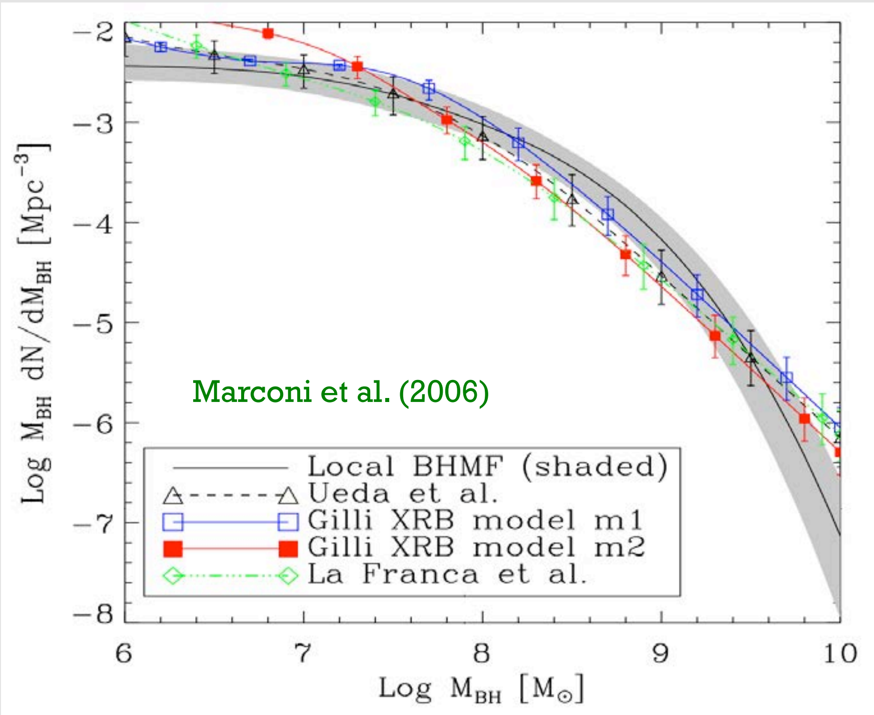
Summary. Quasar masses are investigated assuming that accretion on to massive black holes is the ultimate source of energy produced by quasars. Lower limit for the total energy emitted and the mass accumulated in black holes in 1 Gpc^3 is calculated using various data on quasar counts and bolometric luminosities. The energy produced is at least 8.5×10^{66} erg Gpc^{-3}. This result is independent of the cosmological model. Assuming that quasars reside in nuclei of giant galaxies it is shown that minimum masses of dead quasars are of the order of $10^8 M_\odot$, close to the observational threshold for ground-based telescopes.

$$E = \eta M c^2$$

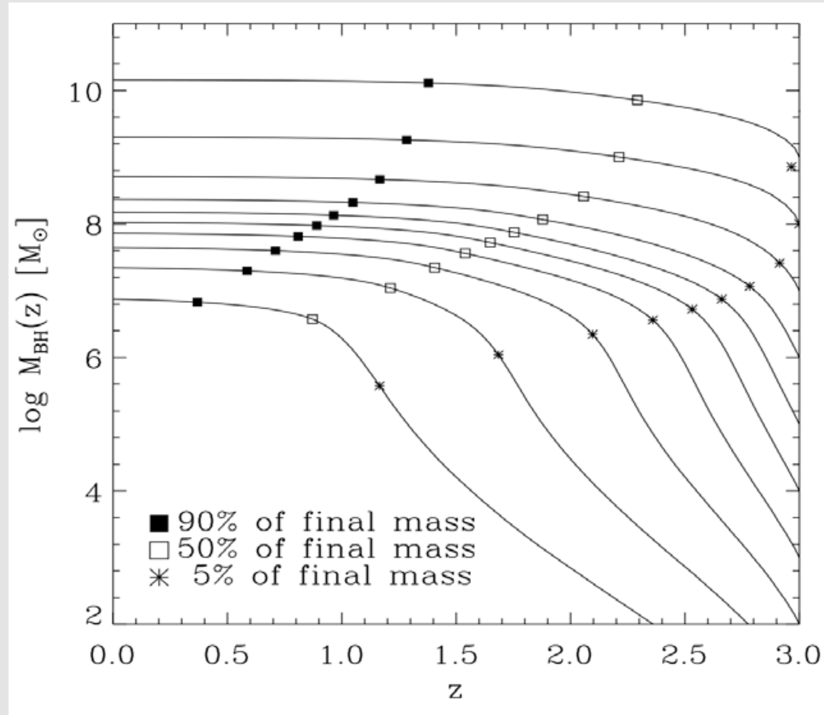
$$\epsilon_{\mathrm{rad}}(1+\bar{z}) = \eta \rho_\bullet c^2$$

Soltan Argument with X-ray AGNs

Local vs. Expected Black-Hole Mass Function



Growth History for Different SMBH Masses



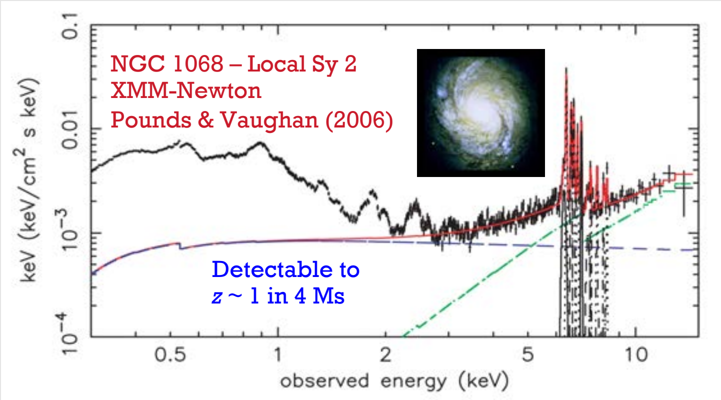
Soltan argument with X-ray luminosity function gives plausible agreement with local SMBH density (3-5 x 10^5 $M_\odot$ Mpc^{-3}).

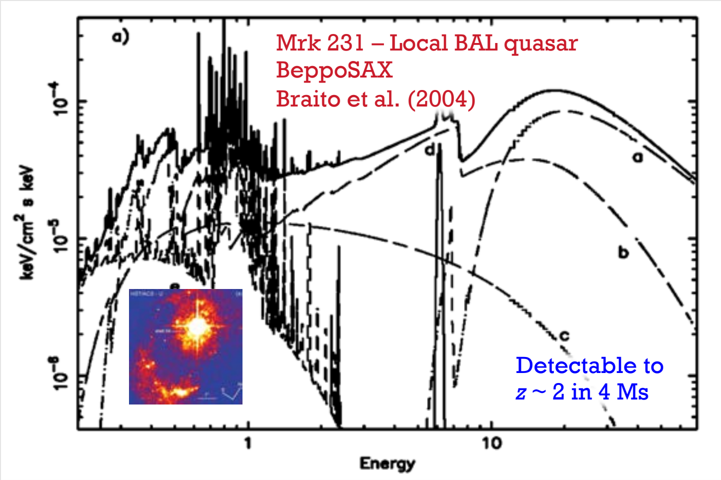
Radiatively efficient accretion likely drives most SMBH growth.

More massive SMBHs generally grew earlier.

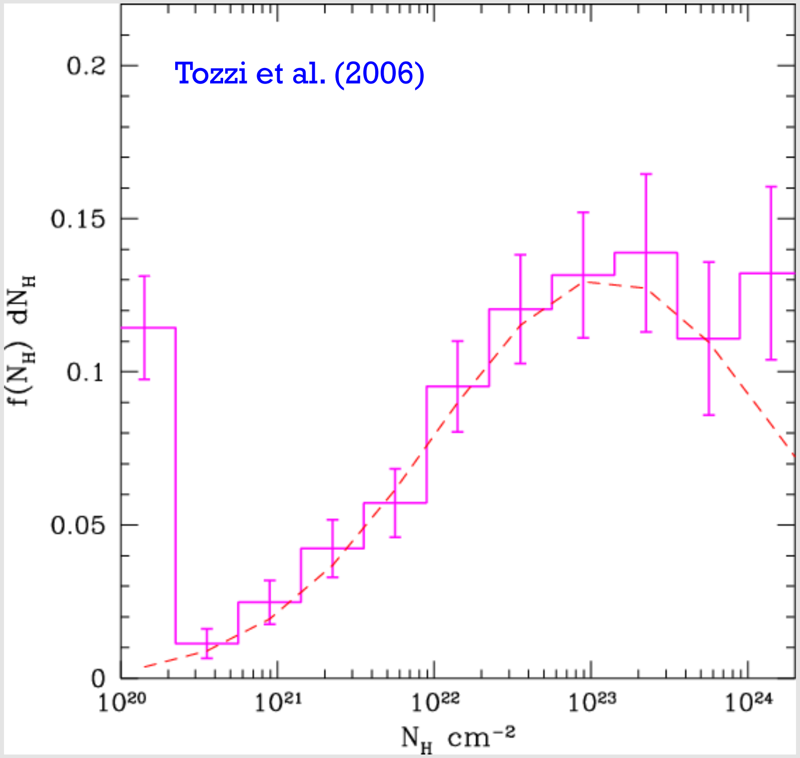
But uncertainties limit potency of test: ρ, η, L_{Bol}, $f_{C\text{-thick}}$.

How Many AGNs Being Missed?





Column-Density Distribution for CDF-S



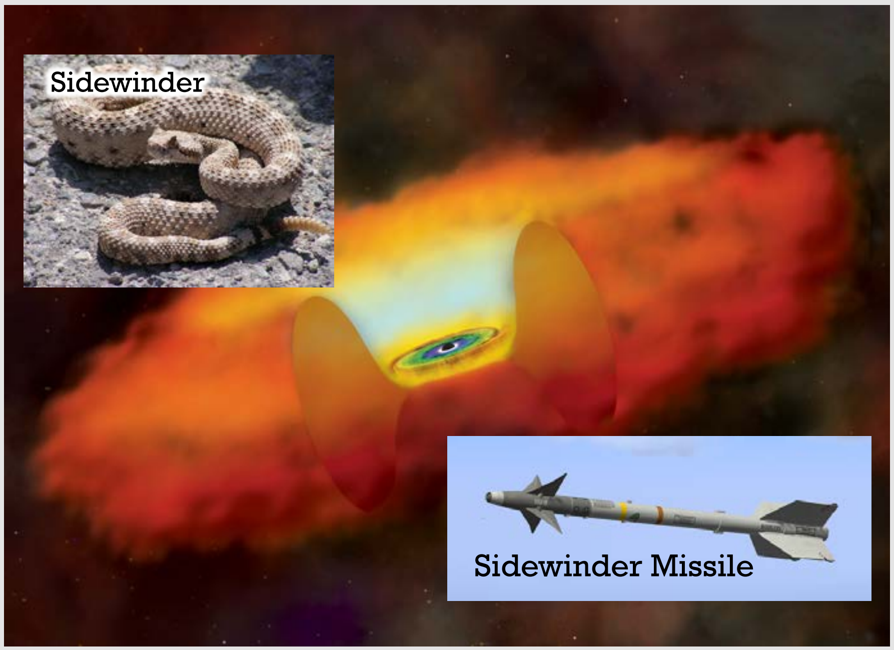
Not surprising – consider local luminous, but highly obscured, AGNs.

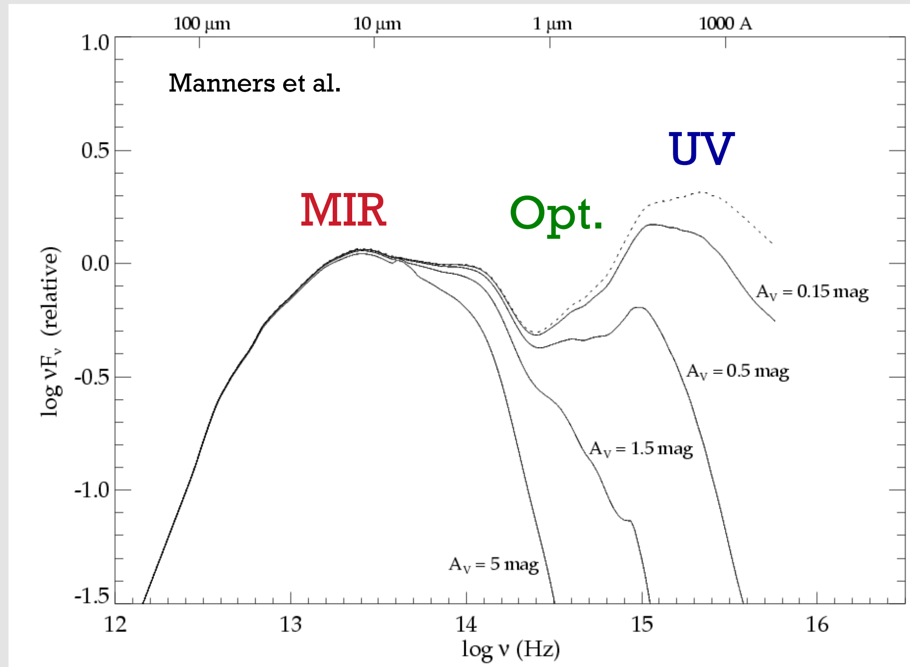
X-ray spectra show many highly obscured AGNs in deep fields. Expect many Compton-thick.

Missed obscured AGNs could add ~ 3000 deg^{-2} (30%) to the number counts.

How to Find Missed AGNs?

Home in on the waste heat – AGN heated dust.

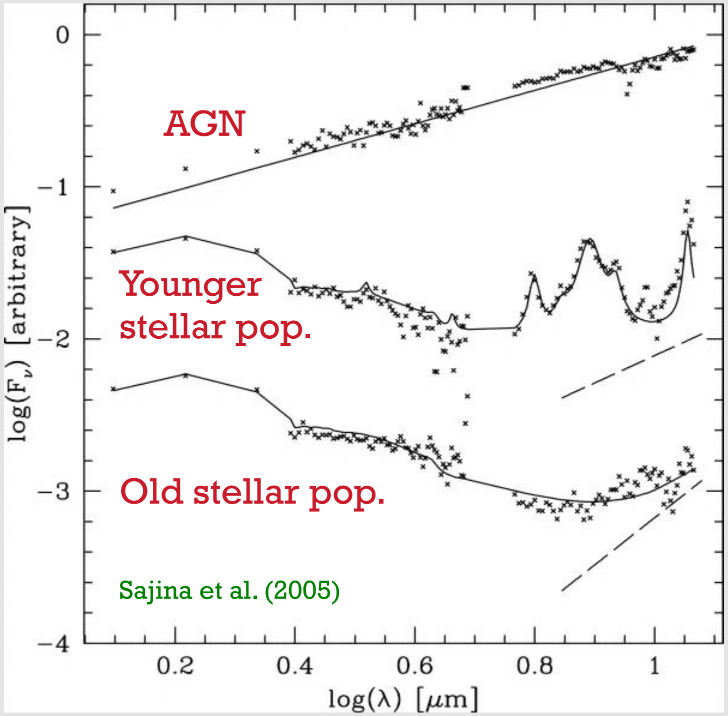




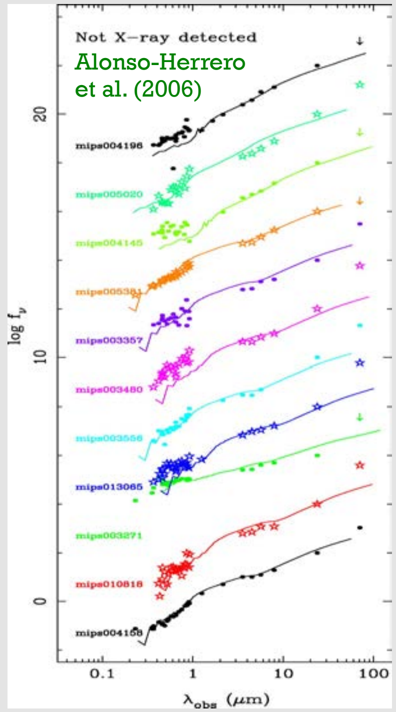
(Also highly sensitive hard X-ray surveys.)

Infrared AGN Selection Methods

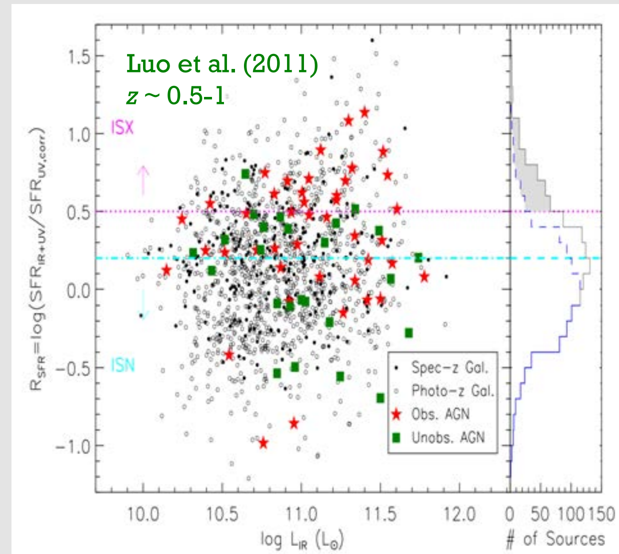
Infrared Power-Law Selection



CDF-S Examples



Mid-IR Excess



24 micron excess compared to expectation from SFR (UV, radio).

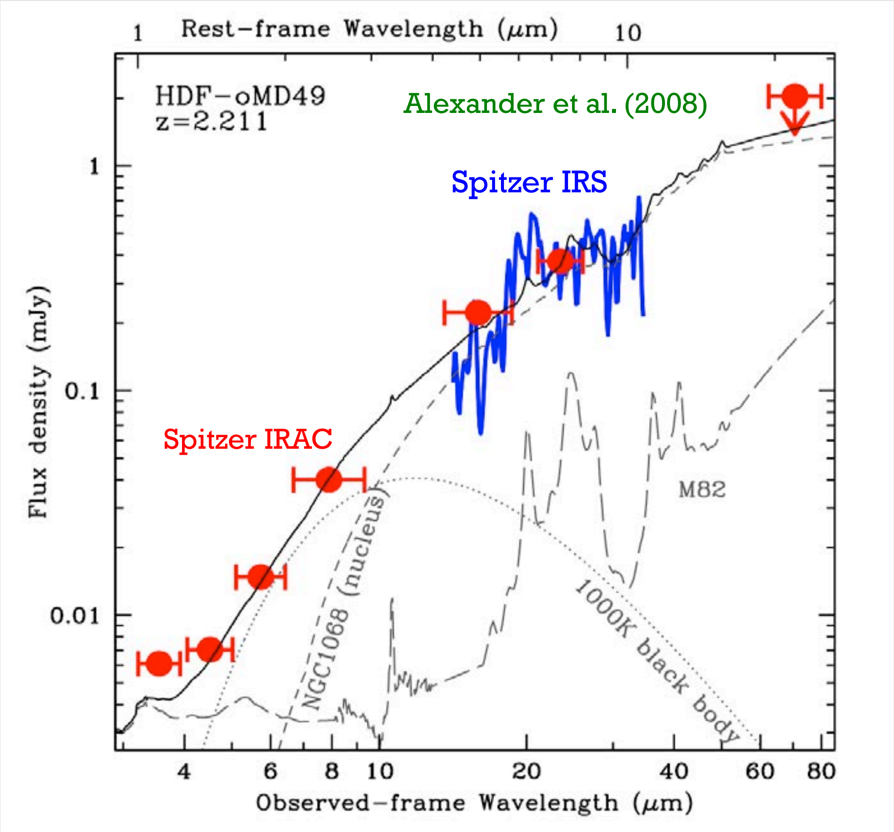
Some AGNs clearly confirmed by X-ray stacking studies and spectroscopy.

Not as "clean" as X-ray selection. AGN frequency and luminosities often unclear.

Also see, e.g., Stern et al. (2005, 2007); Polletta et al. (2006); Daddi et al. (2007); Donley et al. (2007, 2008); Hickox et al. (2007); Steffen et al. (2007); Alexander et al. (2008, 2011); Cardamone et al. (2008); Fiore et al. (2008, 2009); Treister et al. (2010); Georgantopoulos et al. (2011).

Reliable Identifications for a Few Compton-thick Quasars

Narrow-line AGN in CDF-N



Barely X-ray detected in 2 Ms.

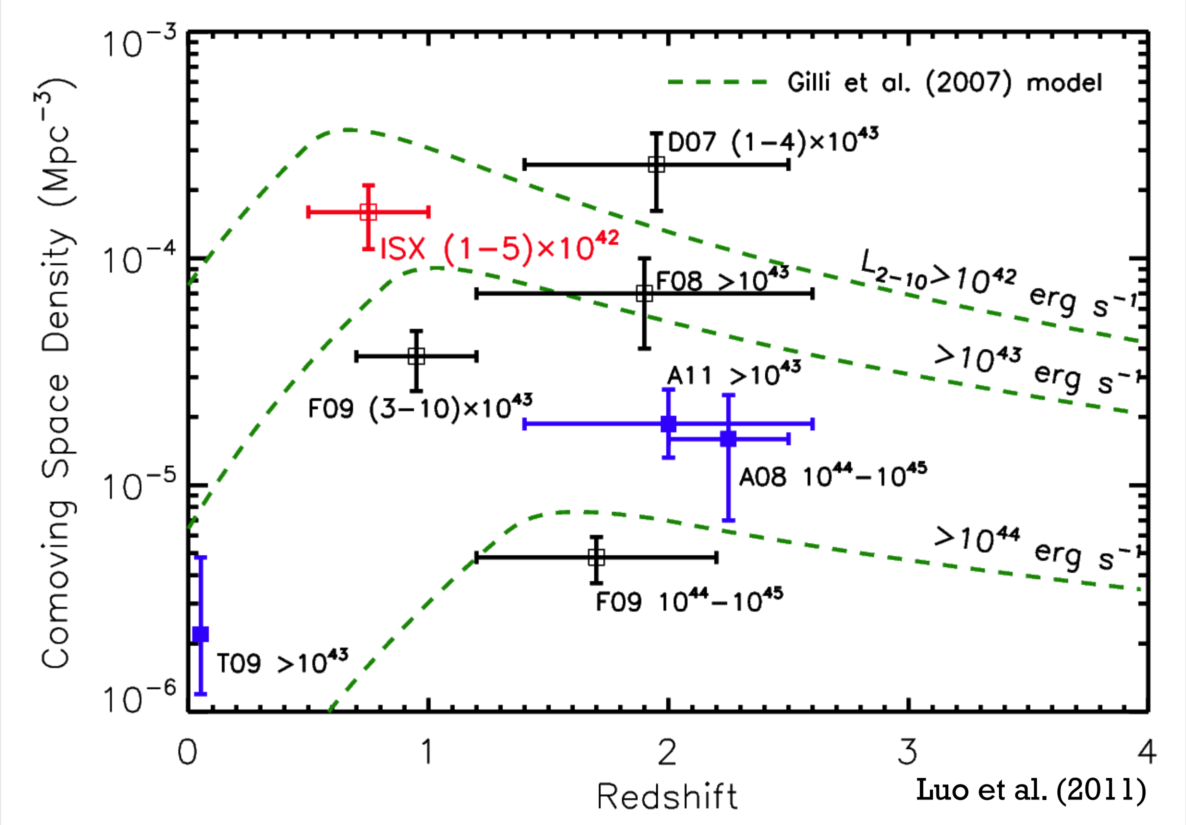
Infrared SED is AGN dominated, and no PAH features.

6 micron + line luminosities indicate Compton-thick quasar with $L_{2\text{-}10} \sim 3 \times 10^{44}$ erg s^{-1}.

Though difficult, more such detailed source characterization required to assess AGN contributions.

How Many Missed Compton-Thick AGNs?

Space Density Estimates / Limits



Preliminary estimates indicate considerable z ~ 1-3 SMBH growth in Compton-thick AGNs.

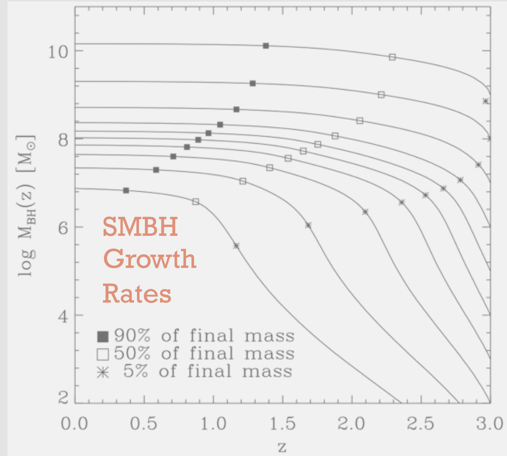
Substantial systematic and statistical uncertainties often present in the samples.

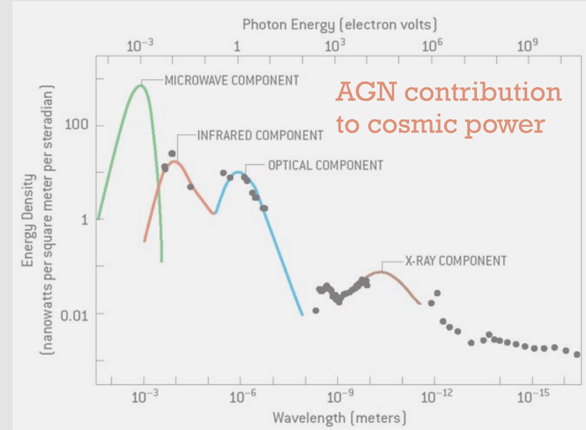
Even in the same luminosity class, different authors get factor ~ 5 discrepancies.

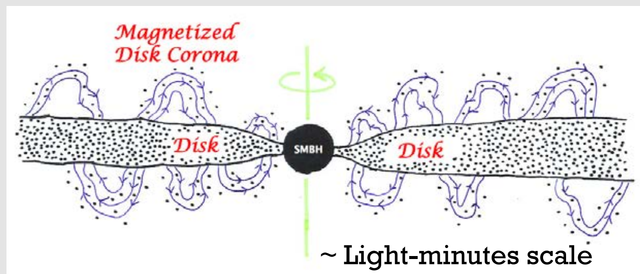
Demography

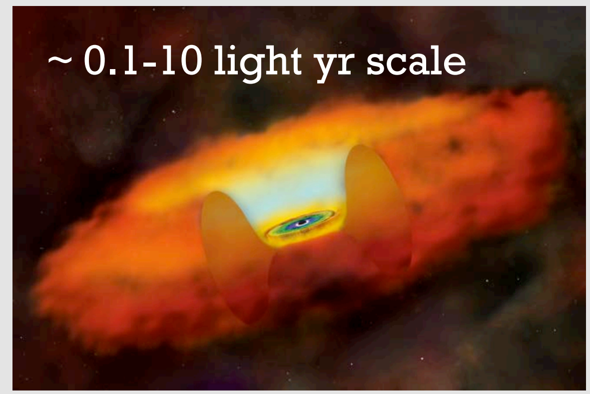
Physics

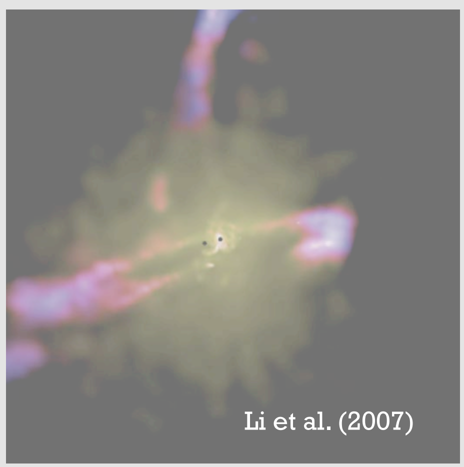
Ecology

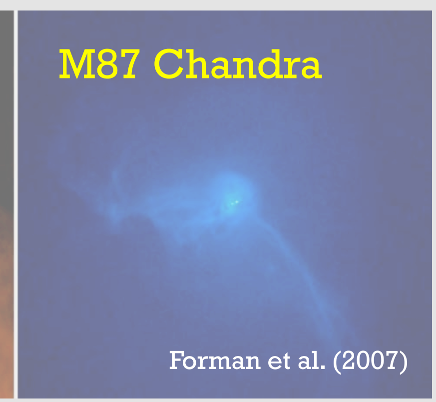






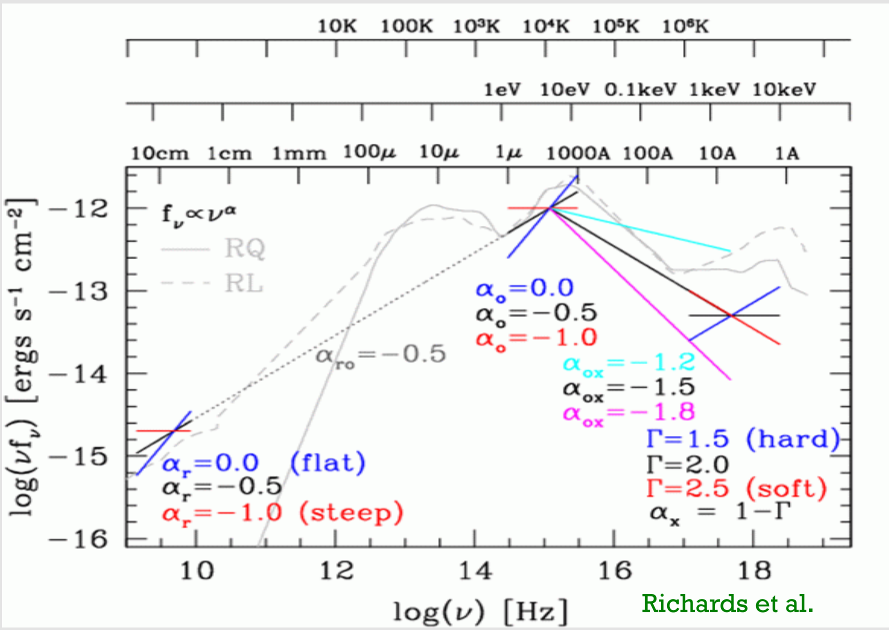


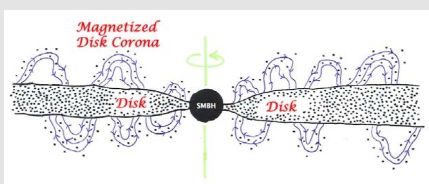




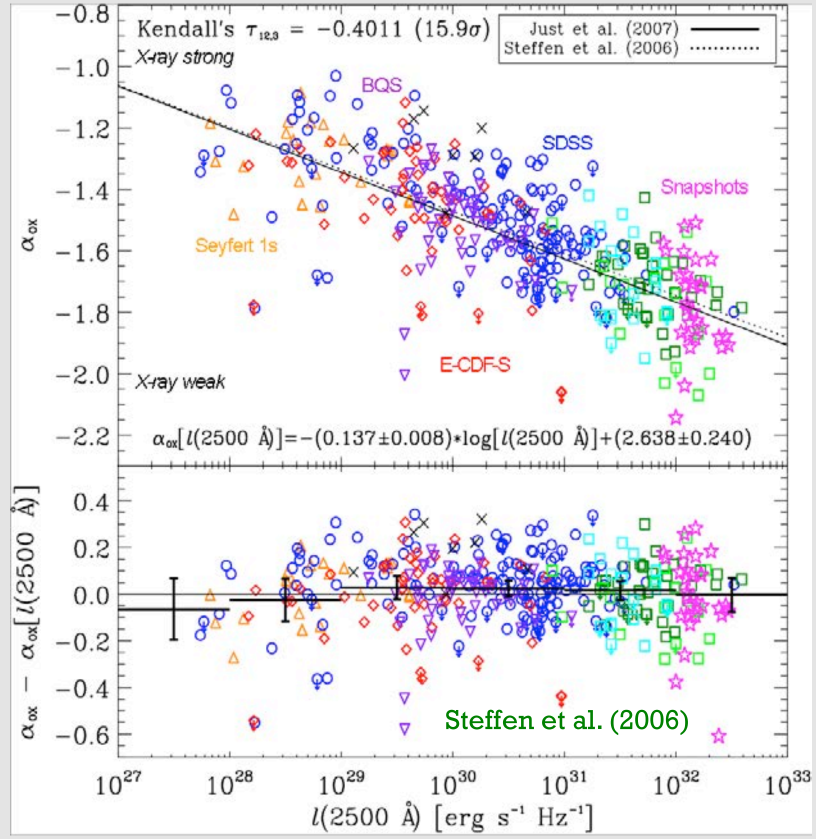
Are Distant AGNs Growing in Same Way?

Typical AGN Spectral Energy Distribution (SED)





Intrinsic α_{ox} Versus Luminosity



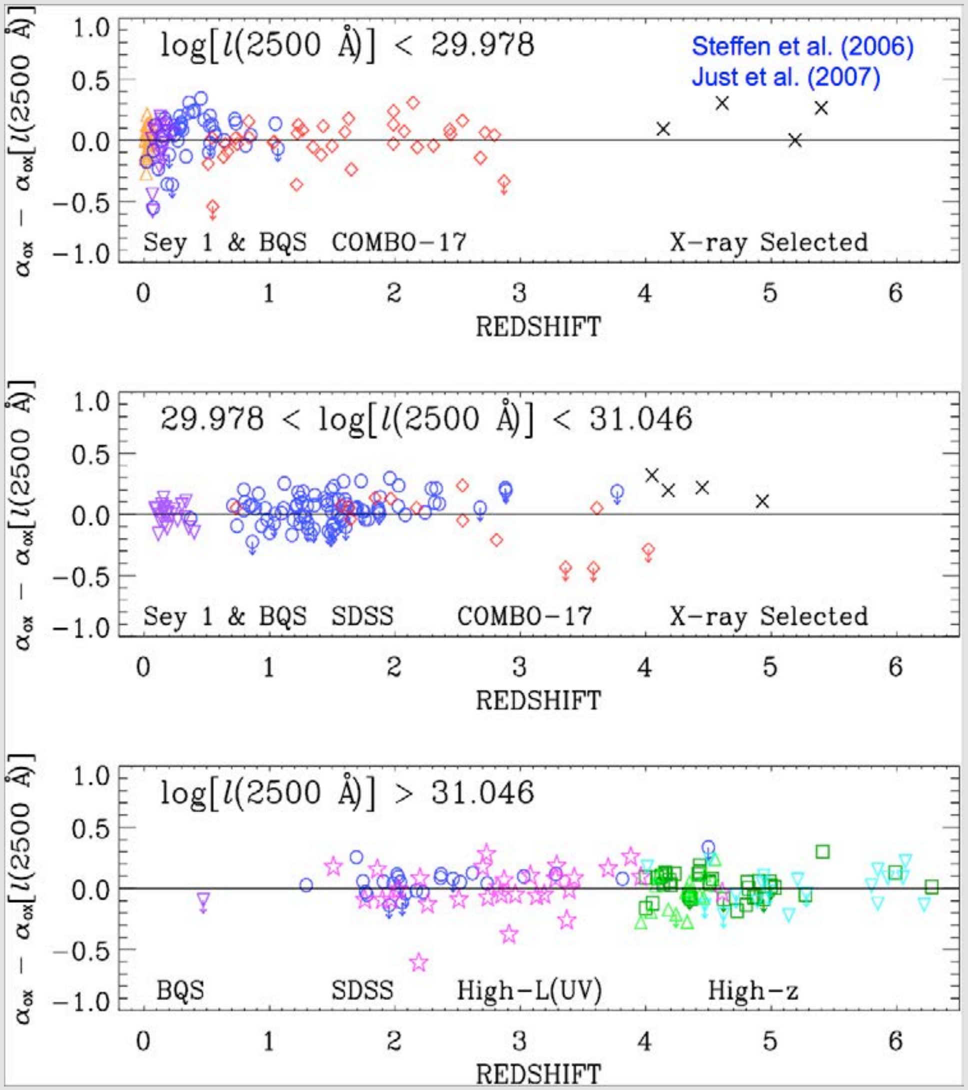
Accretion changes should cause SED changes. For example, *intrinsic* α_{ox} probes disk vs. corona power.

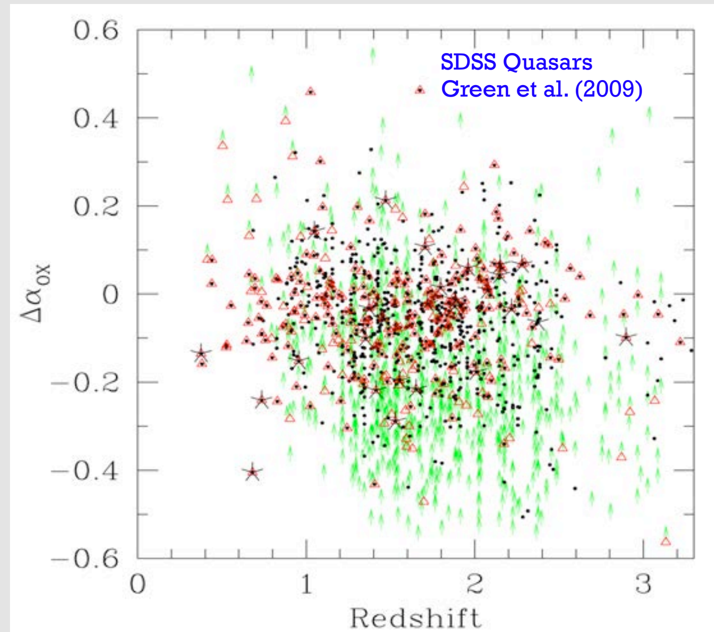
Sensitive surveys provide coverage of majority population of AGNs over most of cosmic time.

Clear luminosity dependence - L_X / $L_{Opt.}$ declines with rising luminosity over range of ~ 100,000 in luminosity (probably non-linearly). Not well understood physically.

No Redshift Dependence of SED

Constraints on Redshift Evolution of α_{ox}





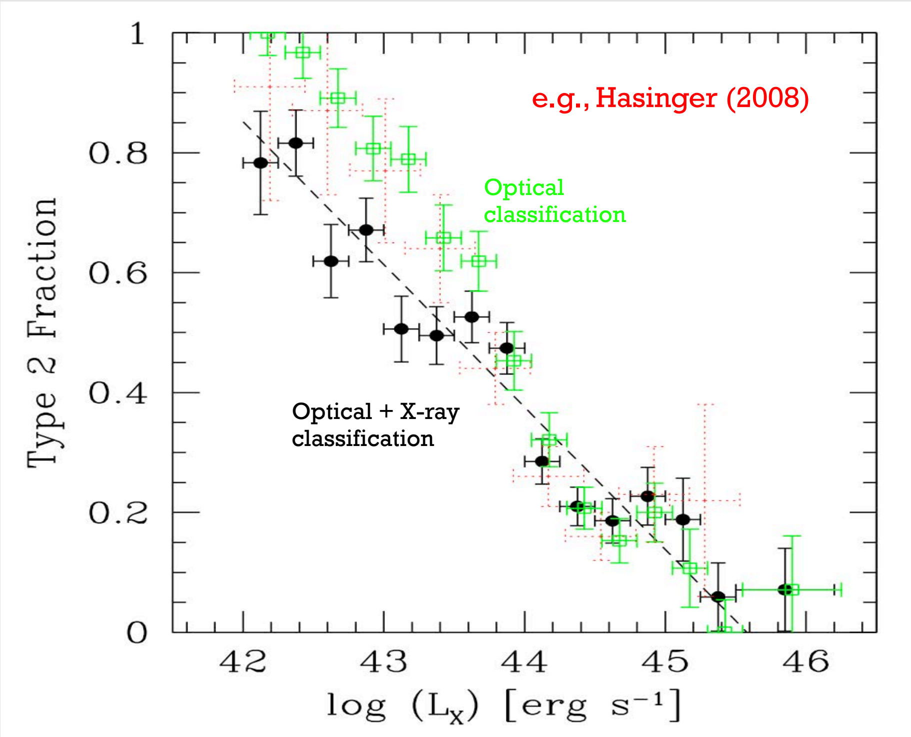
Generally no detectable redshift dependence (some counterclaims).

X-ray-to-optical ratios change by less than 30% from $z \sim$ 0-5.

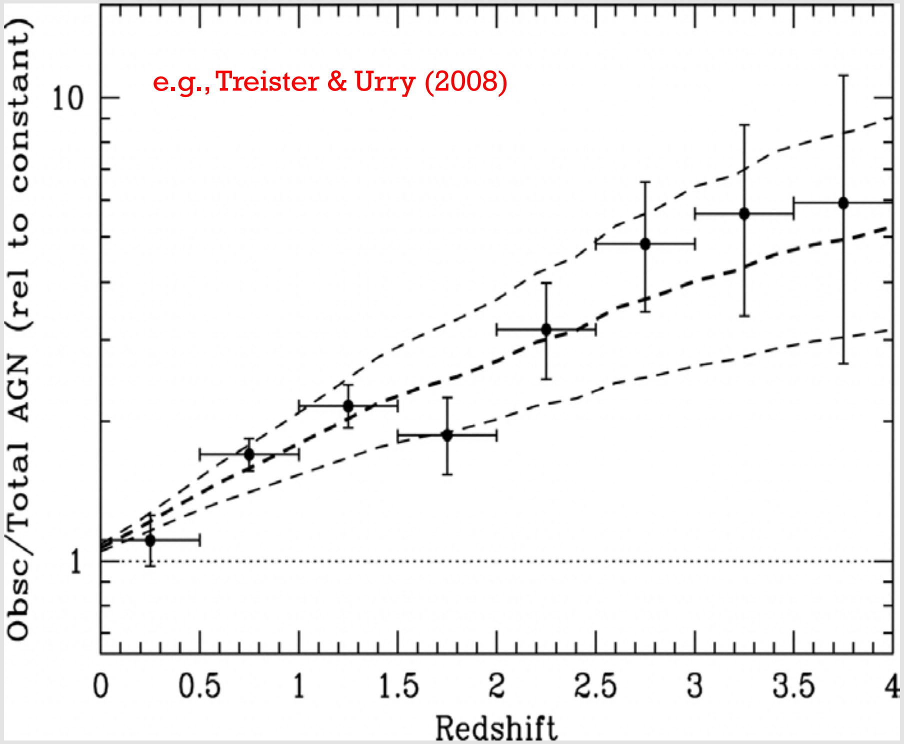
Basic emission processes of AGN appear remarkably stable, in spite of large number-density changes.

Obscuration Dependences

Obscured AGN Fraction Drops with Luminosity



Obscured AGN Fraction Rises with Redshift



Useful, and long-expected, refinement of AGN unification models. More luminous AGNs can evacuate their environments better.

Obscured fraction scales as $(1+z)^{0.3\text{-}0.7}$, at least up to $z \sim 2$. Torus evolves but inner disk does not? More available gas and dust at early times?

Cosmic Balance of Power

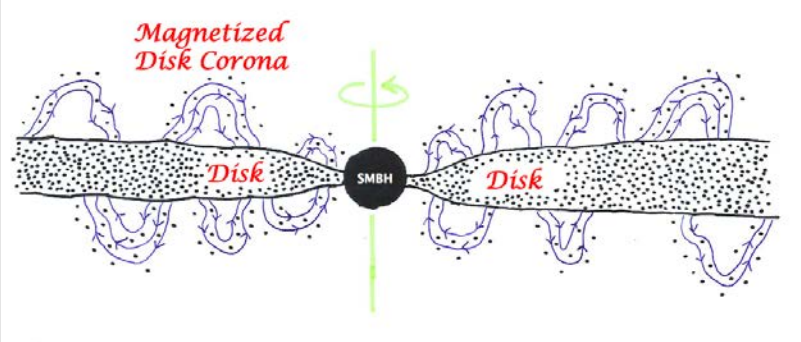
King Alfred the Great

vs.

The Vikings (and NGC 6251)

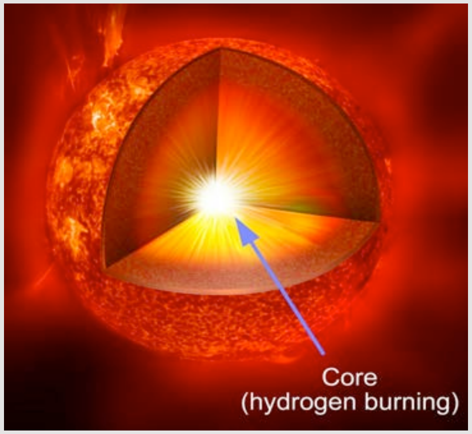
Cosmic Balance of Power

Supermassive Black Hole Accretion



vs.

Stellar Fusion



Predictions from around the Chandra and XMM-Newton launches…

Black Holes May Supply Up to Half the Universe's Energy Output

Contact:
Christopher Wanjek
wanjek@gsfc.nasa.gov
301-286-4453

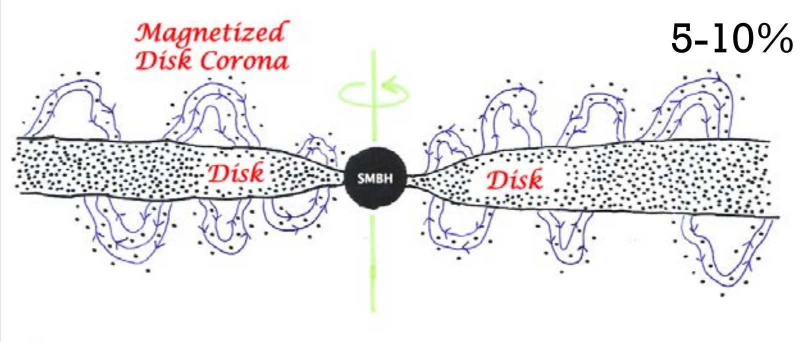
September 10, 1999

Greenbelt, Md. -- Massive black holes, long-thought to produce only a mere fraction of the universe's total energy output, may actually be the force behind half of the universe's radiation produced after the Big Bang, chipping away the coveted power monopoly believed to be held by ordinary stars.

Details of this energy theory, based on measurements of background X-ray radiation and the gas-obscured growth of massive black holes, are presented today by the University of Cambridge Institute of Astronomy theorist Dr. Andrew Fabian at the X-ray Astronomy 1999 meeting in Bologna, Italy. The meeting is being chaired by Dr. Nicholas White, head of NASA Goddard Space Flight Center's (Greenbelt, Md.) X-ray Astrophysics Branch in the Laboratory for High Energy Astrophysics.

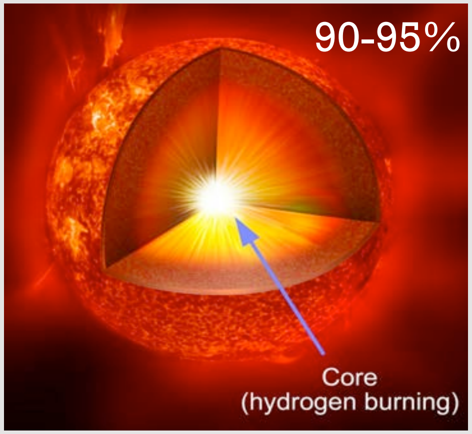
The Economical X-ray Universe

Supermassive Black Hole Accretion



vs.

Stellar Fusion

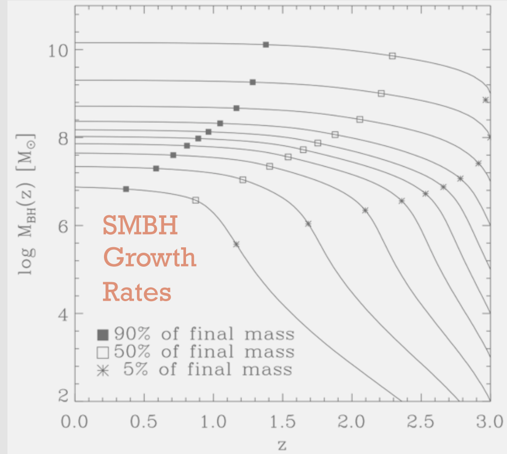


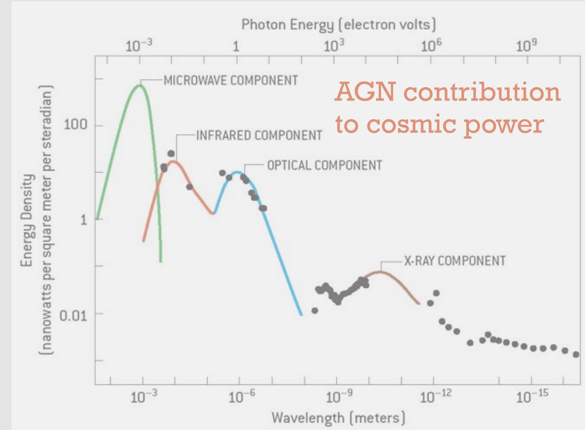
Chandra and XMM-Newton results show we live in a remarkably economical X-ray universe, more so than expected a few years ago.

X-ray background not dominated by powerful obscured quasars at $z \sim 2$-4. Moderate-luminosity, obscured AGNs at $z \sim 0.5$-2 dominate.

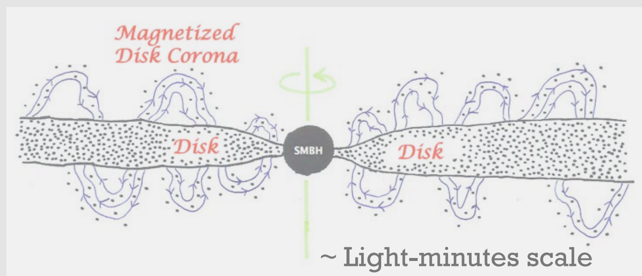
SMBH accretion makes ~ 5-10% of cosmic power since galaxy formation.

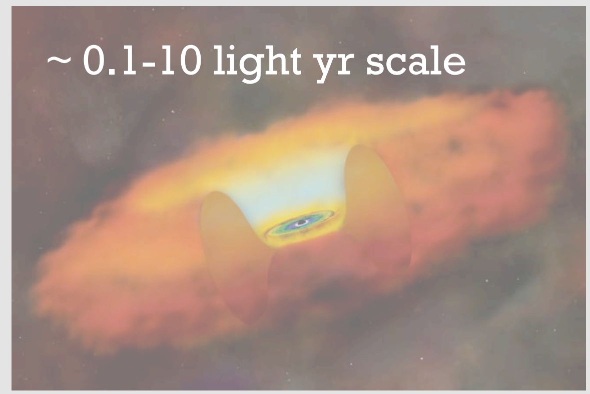
Demography



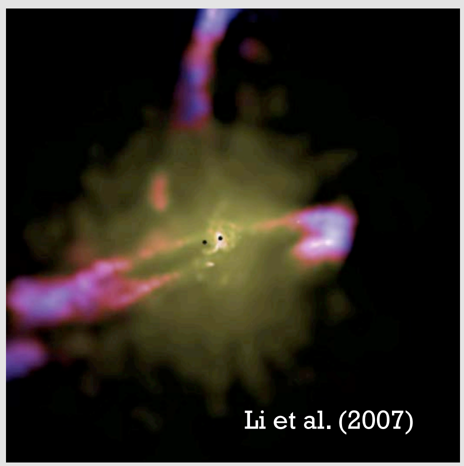


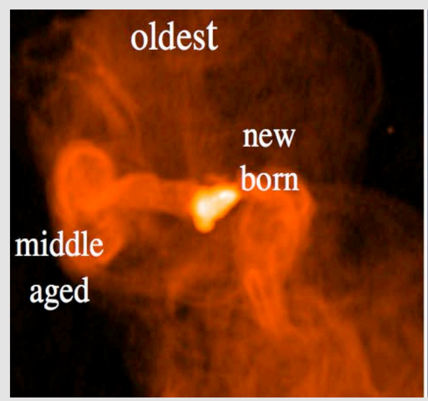
Physics

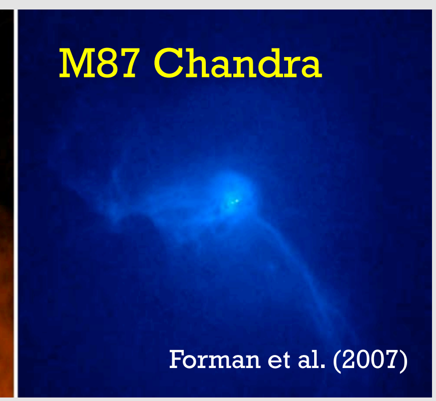




Ecology



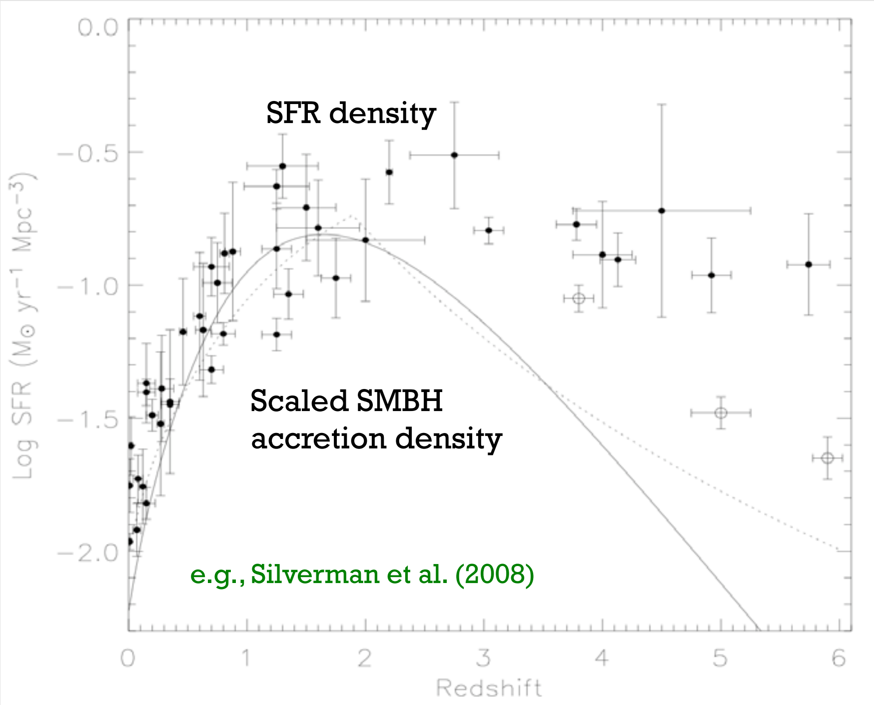




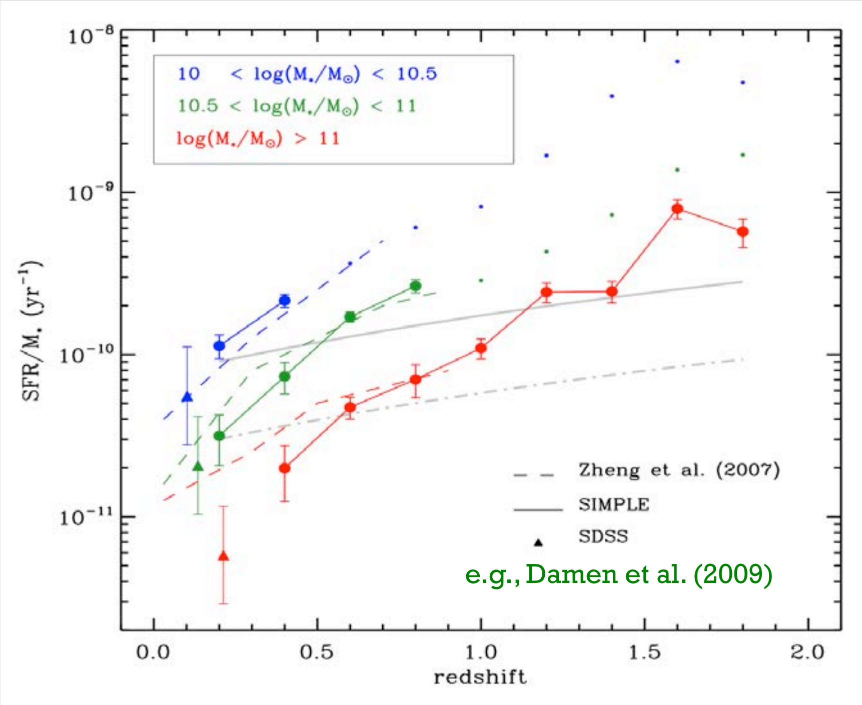
Role of AGNs in Galaxy Evolution

Relevant order-of-magnitude energies: $E_{\mathrm{SMBH}} \sim$ 30-100 $E_{\mathrm{Galaxy\ Binding}}$

Broadly Similar AGN-SFR Evolution for Most of Cosmic Time (z < 2)



Downsizing of Star Formation in Galaxies



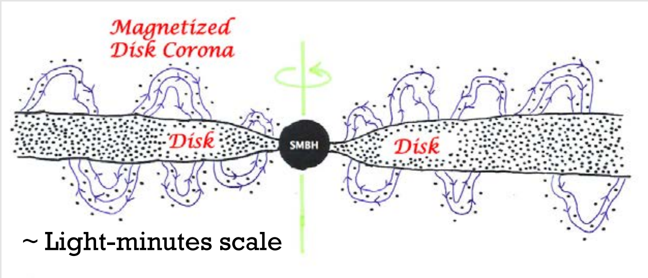
Also SMBH-spheroid relations.

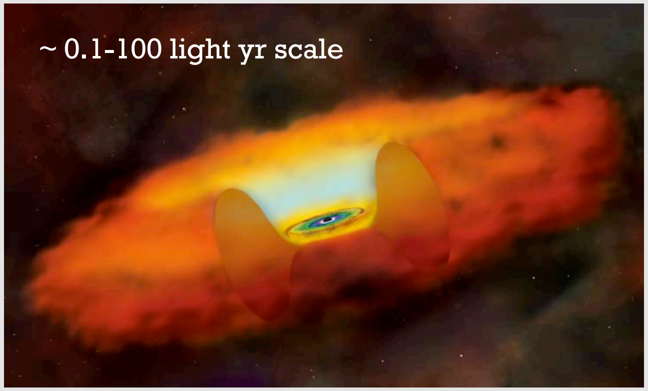
Want to understand how SMBHs and their hosts have co-evolved and interacted.

Use multiwavelength survey data to describe co-eval SMBH-host growth.

Relevant Observable Quantities

Black-Hole and Torus Regions



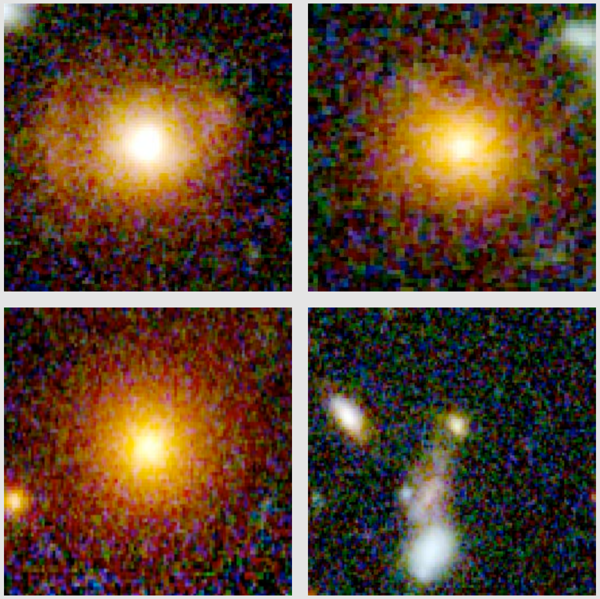


AGN Luminosity
SMBH Accretion Rate
Obscuration Properties
SMBH Mass

Fueling and Obscuration

Feedback

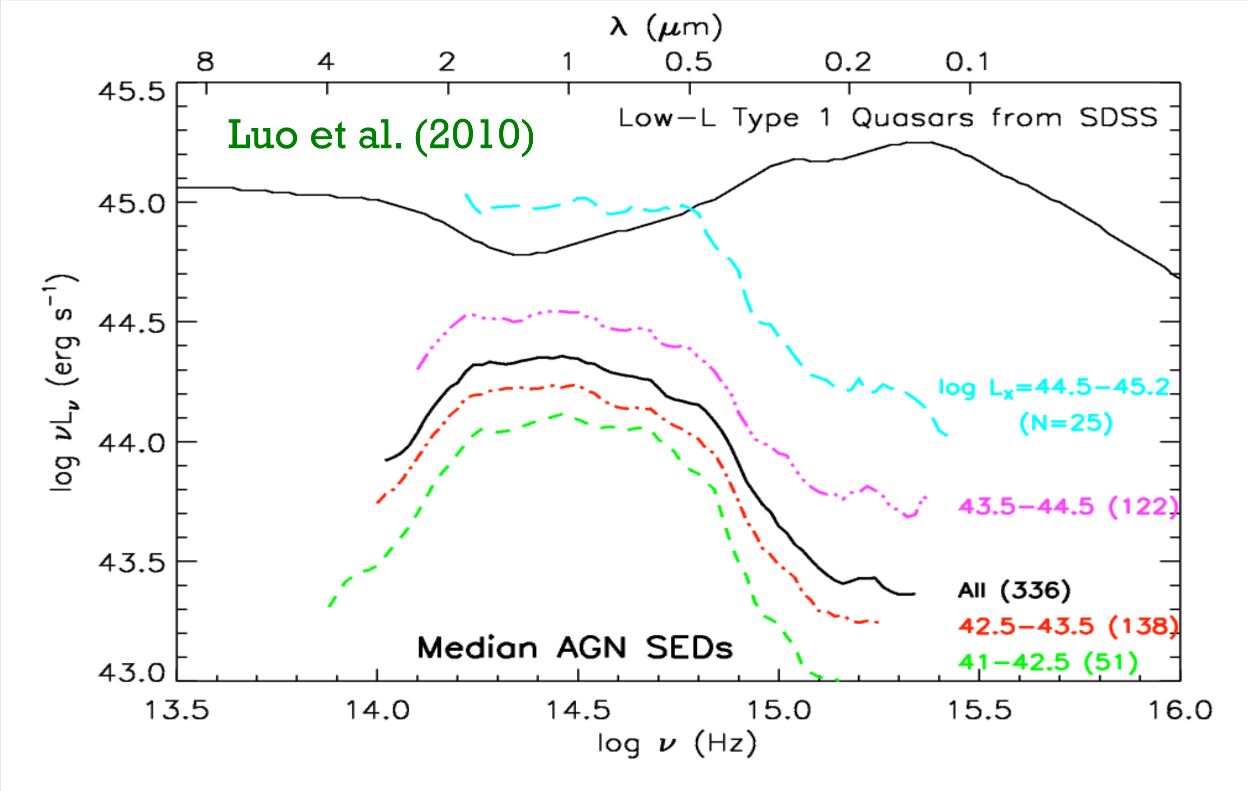
AGN Host Galaxies



Stellar Luminosity
Stellar Mass
Morphology
Companions
Colors
Star-Formation Rate

Feasibility of Host-Galaxy Measurements

Mean AGN SEDs in Chandra Deep Field-South (15-35 Bands)



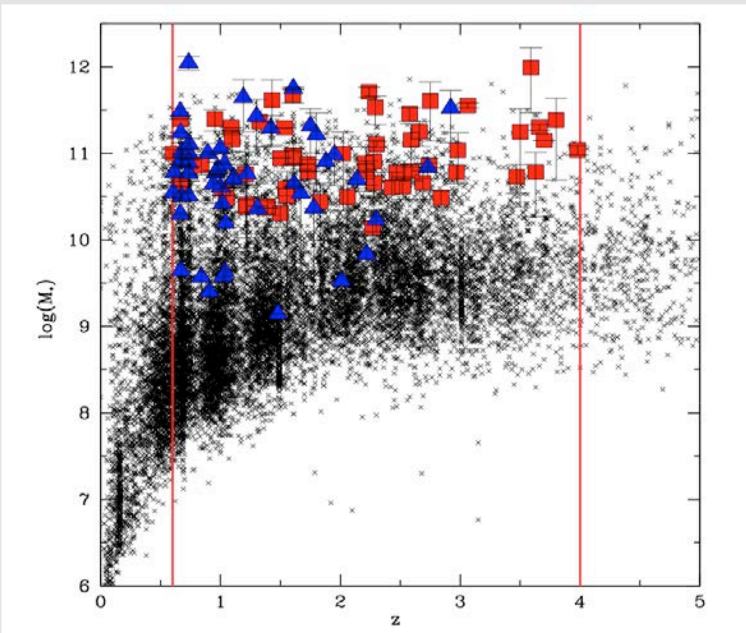
Many X-ray AGNs, especially those that are obscured, have rest-frame UV, optical, and infrared emission dominated by host starlight.

Still must be wary of problems due to AGN light – subtract when possible.

Assess with SED fitting, HST imaging, optical spectroscopy, and correlation analyses.

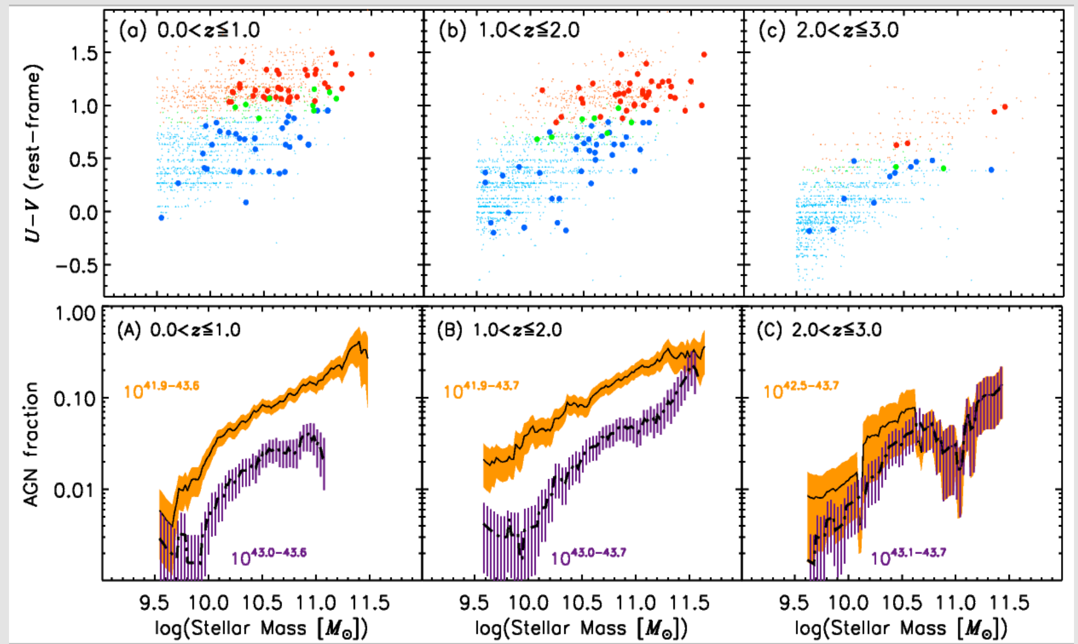
Hosts are Luminous and Massive

Stellar Mass vs. Redshift for CDF-S AGNs



e.g., Brusa et al. (2009)

AGN Fraction Increases Toward High Stellar Mass – AGNs Are Large Dots

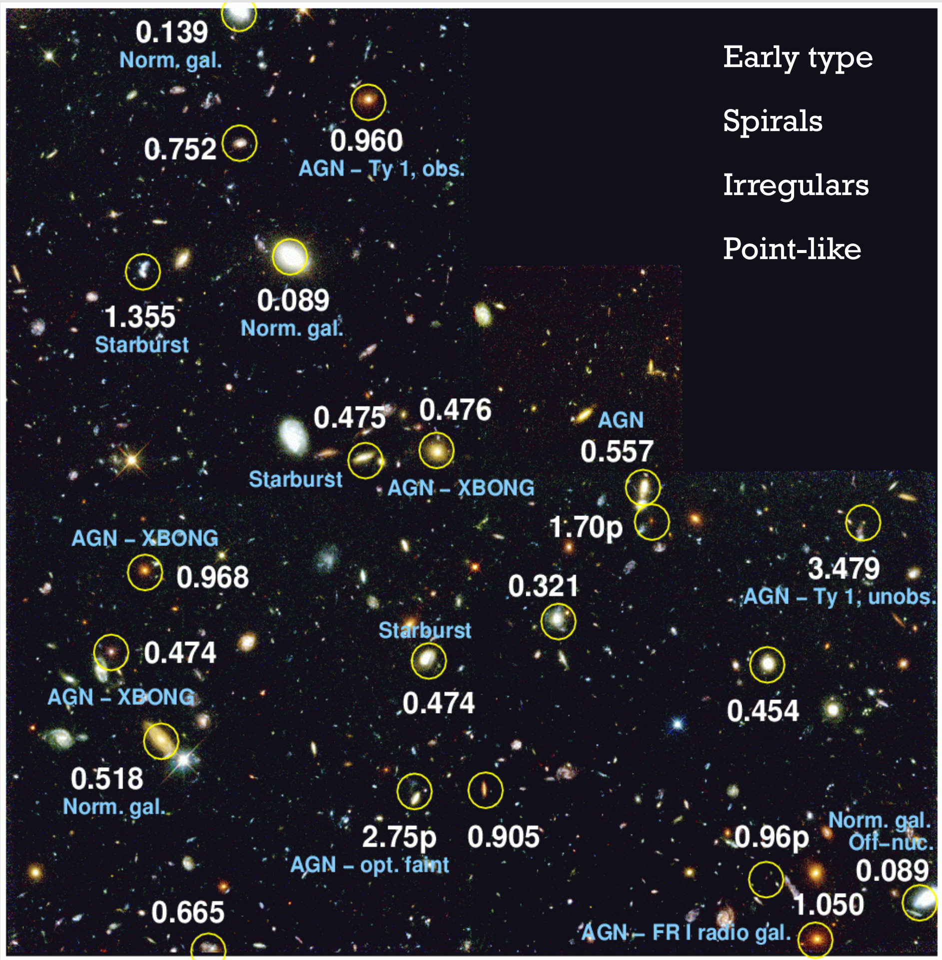


e.g., Xue et al. (2010)

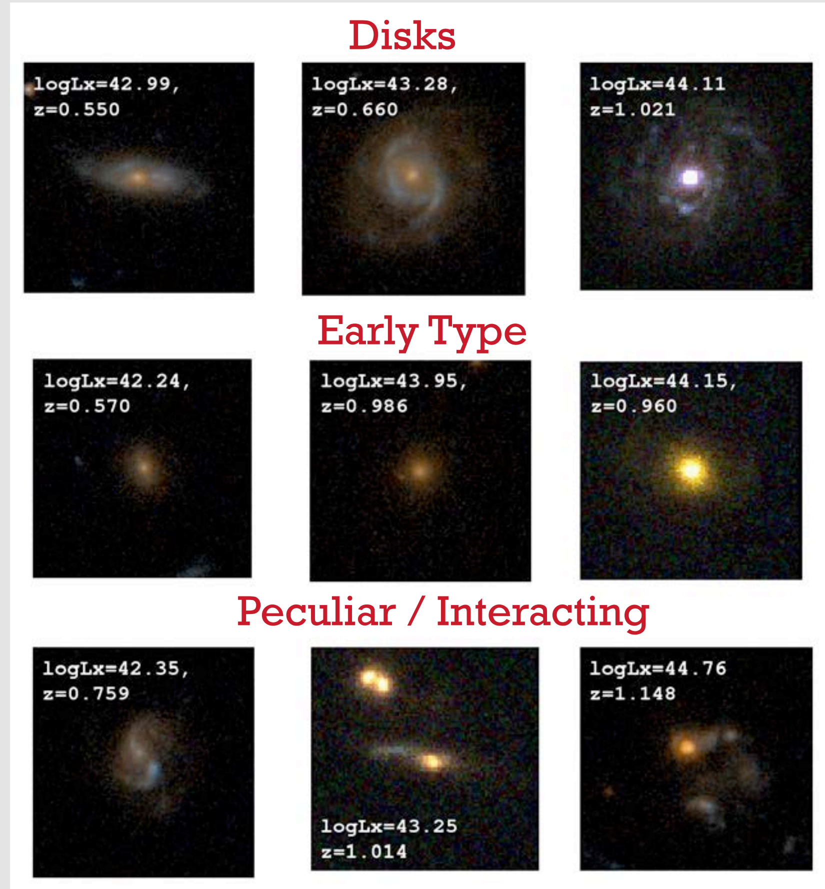
Strongest result found at z = 0-3 – factor of ~ 40.

Arguably affects some of the other claims about AGN host galaxies.

Wide Diversity of Morphological Types



e.g., Brandt et al. (2001); Koekemoer et al. (2002)

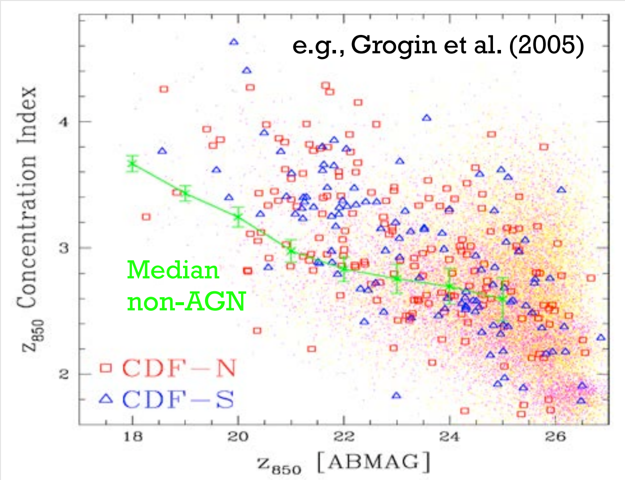


Georgakakis et al. (2009)

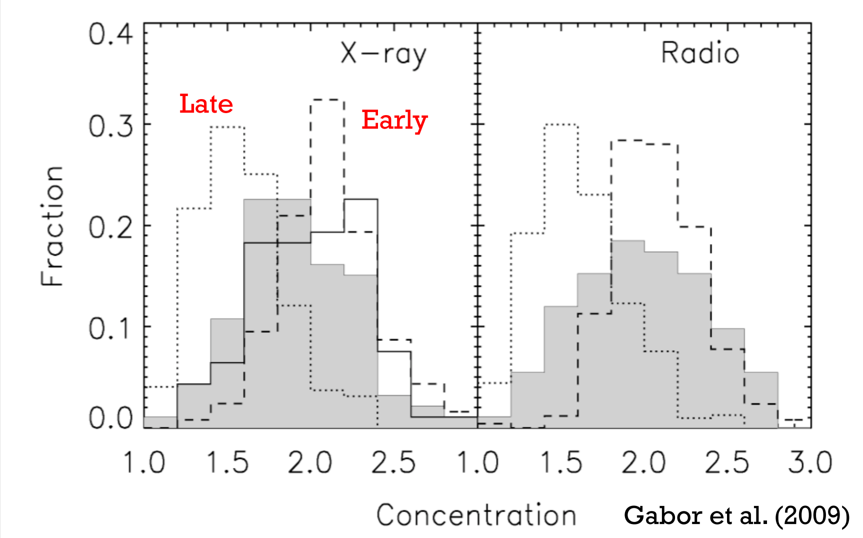
Broadly speaking, about 40-50% early types, 20-30% late types, rest irregular or point-like.

Host Concentrations for X-ray AGNs

Concentrations of GOODS AGNs



Concentrations of COSMOS AGNs



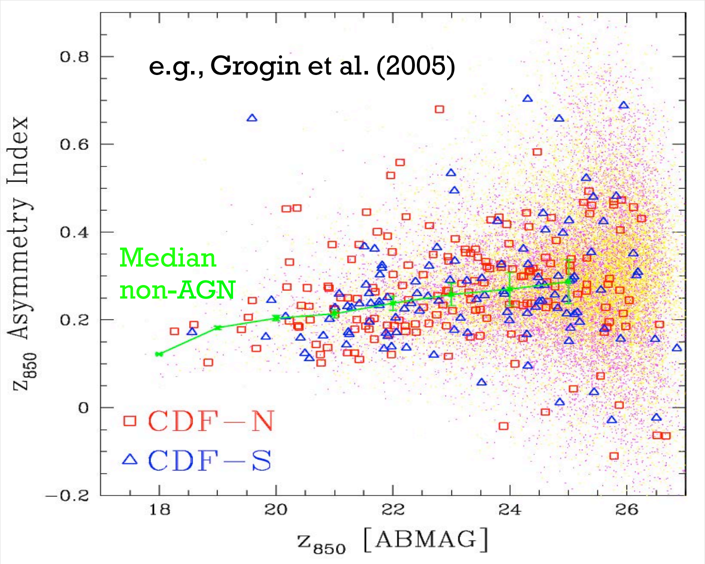
Broad range of concentrations seen.

X-ray AGNs prefer galaxies with higher concentrations to $z \sim 1.5$.

Tend to be more bulge dominated than the galaxy population overall, consistent with local results.

Host Asymmetries for X-ray AGNs

Asymmetries of GOODS AGNs



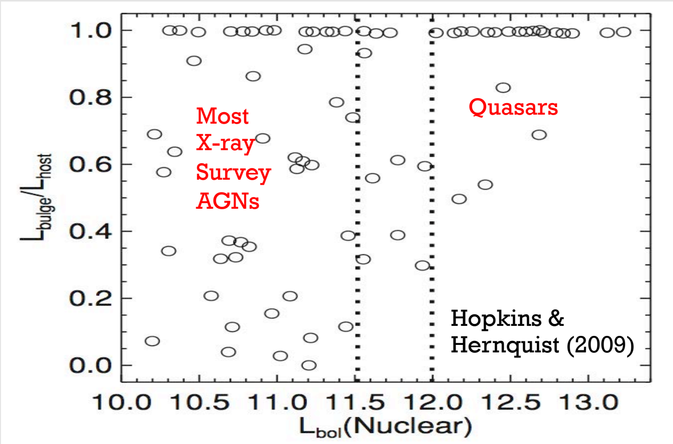
X-ray AGNs show no strong asymmetry vs. non-AGNs; most in relatively undisturbed systems.

No obvious connection between recent strong galaxy mergers and moderate-luminosity AGNs.

Merger signatures may fade before onset of AGN.

Secular host-galaxy processes probably lead to much of the SMBH fueling in these systems.

Bulge Fraction vs. AGN Luminosity

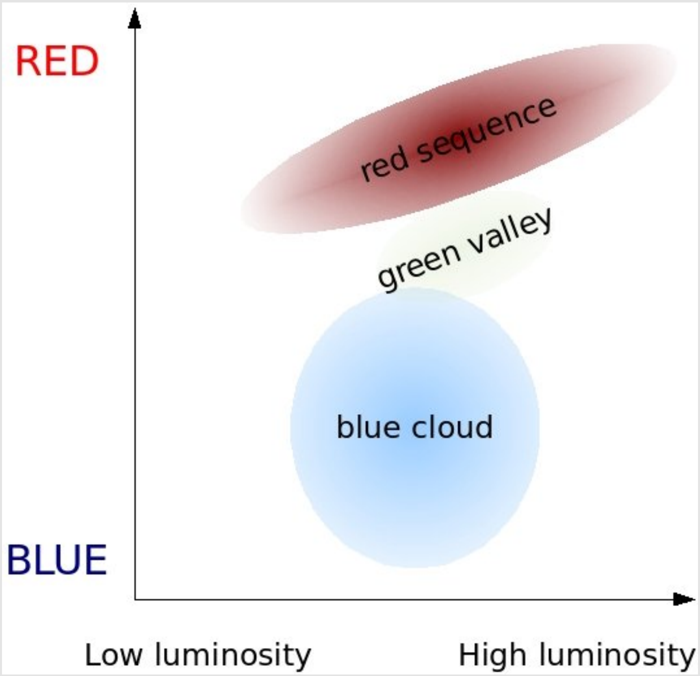


Likely contrasts with high-luminosity quasars.

These often show merger activity and are hosted largely in "merger remnant" ellipticals.

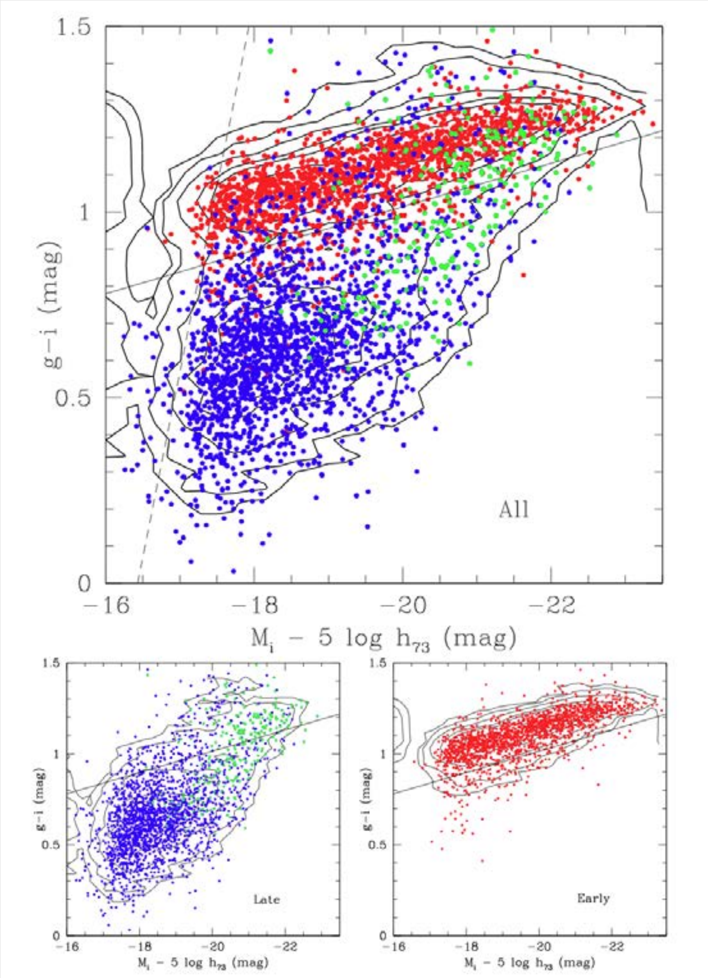
Color-Magnitude Diagrams

Simple CMD Schematic



e.g., Strateva et al. (2001); Bell et al. (2004)

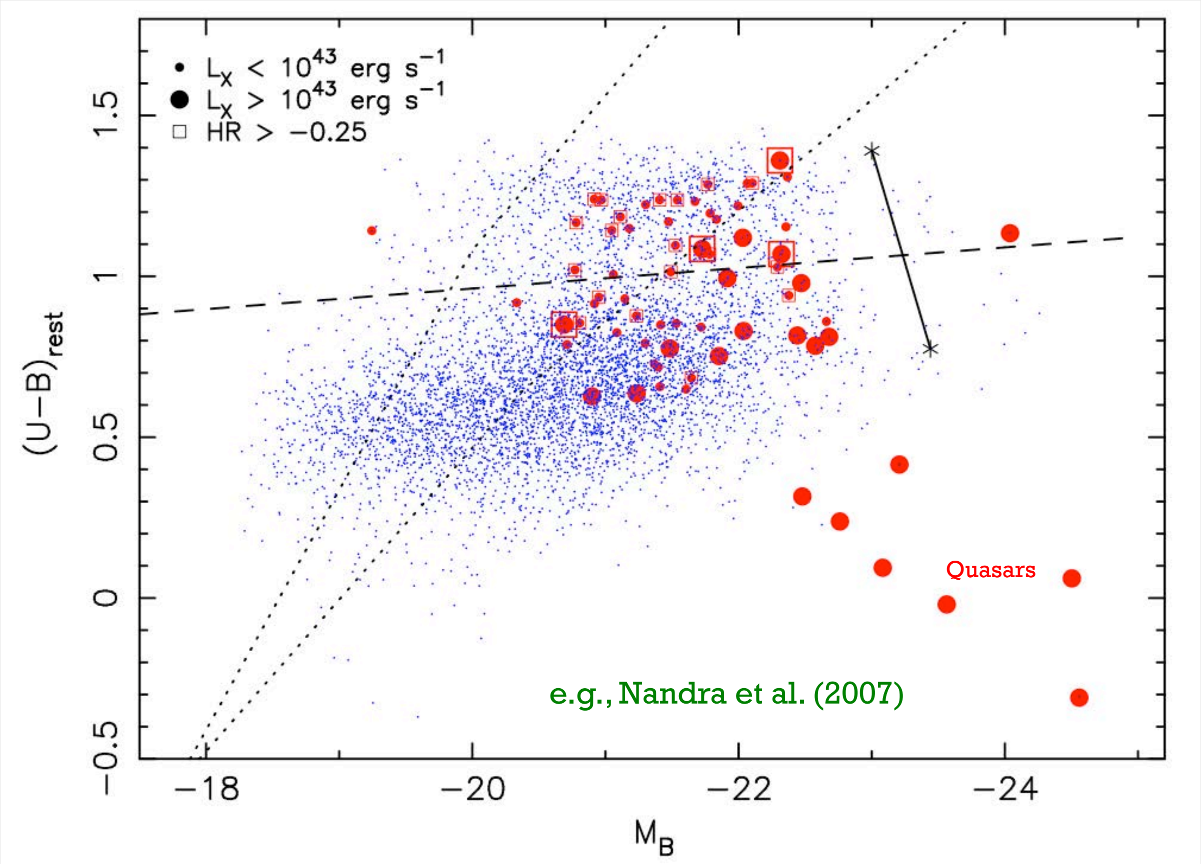
Example CMD



e.g., Gavazzi et al. (2010)

Apparent "Clustering" of AGNs in the Color-Magnitude Diagram

CMD with AGNs Marked as Large Dots (z = 0.6-1.4)



AGN hosts have broad color range, but AGN fraction peaks in "green valley" or "red sequence".

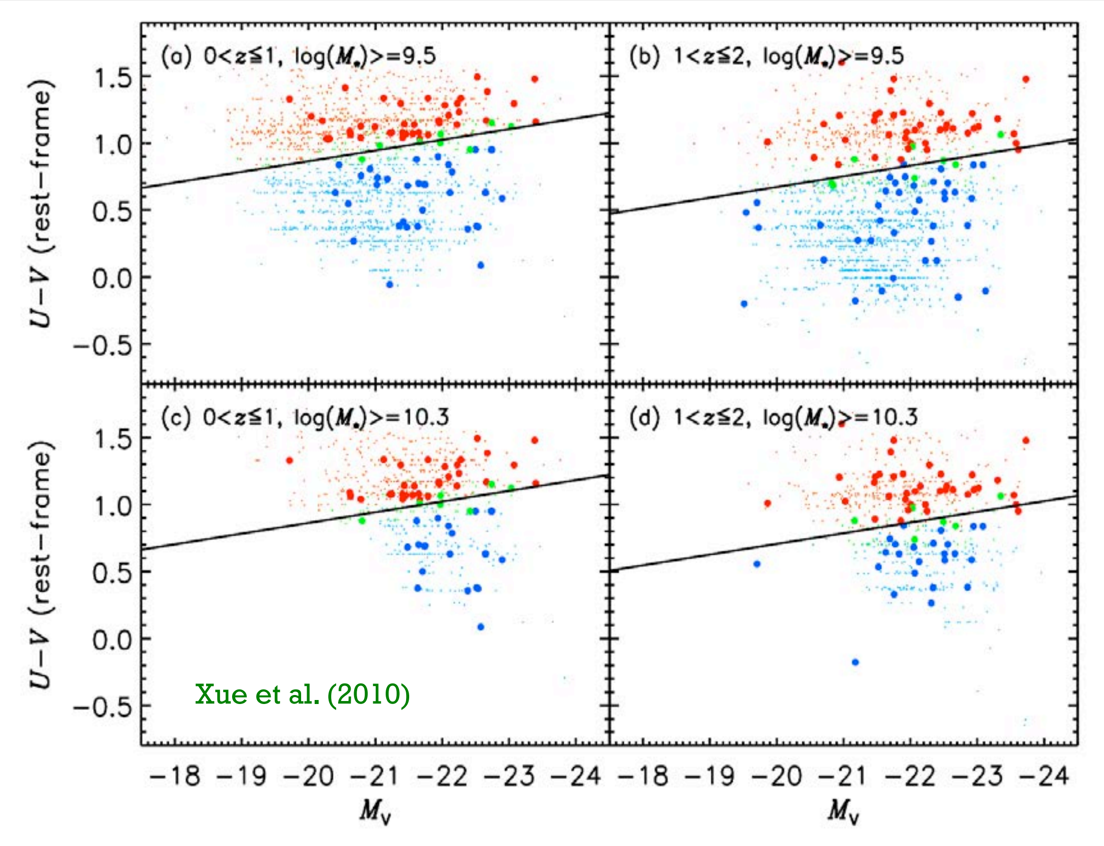
AGN playing a role in transitioning galaxies from blue cloud to red sequence via "quenching" of star formation?

Rejuvenation of bulge-dominated systems by addition of a gas-rich disk over cosmic time (e.g., Hasinger 2008)?

Issues with sample construction (e.g., Silverman et al. 2009)?

No Real AGN Clustering in CMDs?

CMDs for Mass-Selected Samples

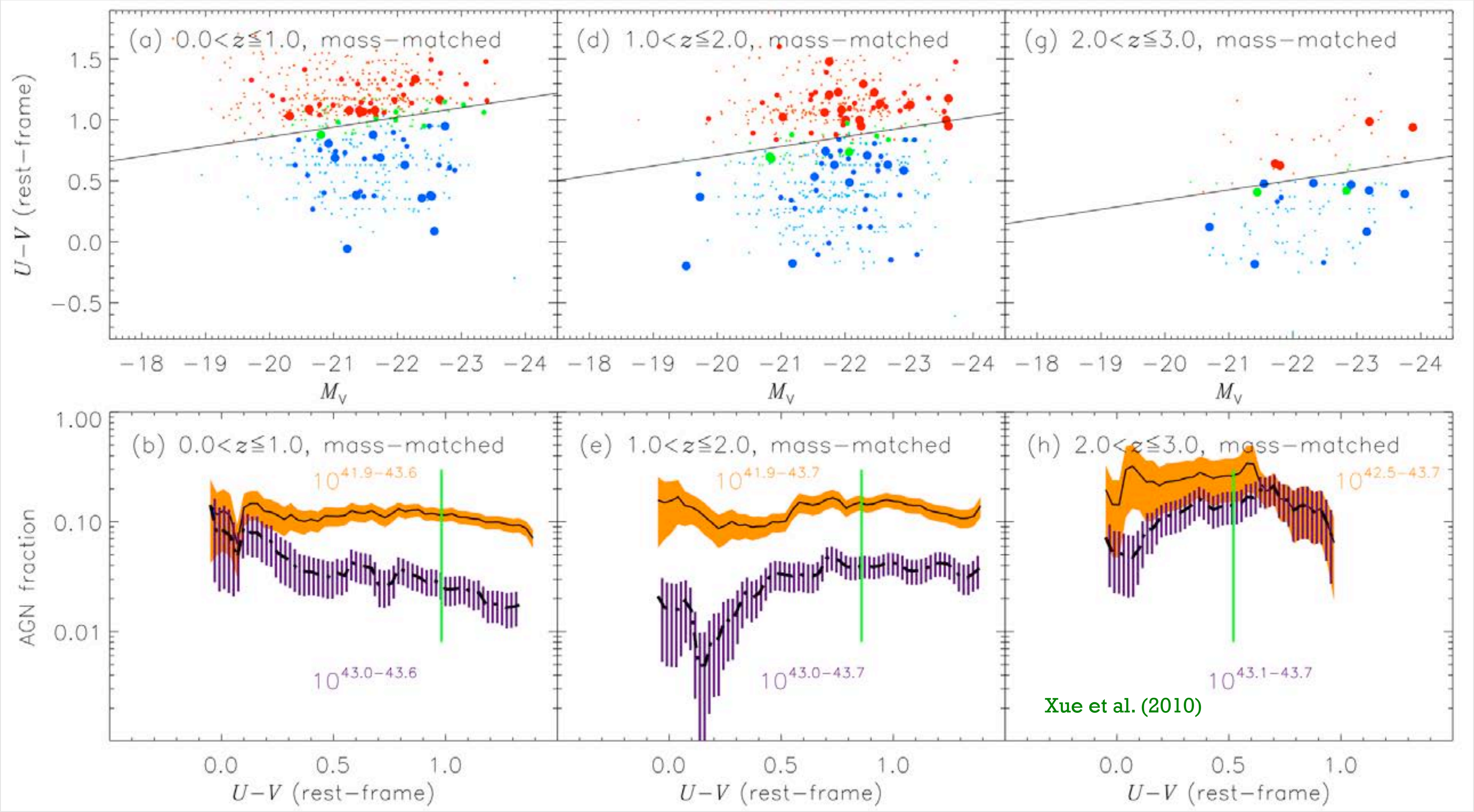


Given that AGNs prefer more massive hosts, it is not surprising that they tend to be redder.

The higher the mass cut applied, the more similar the AGN and non-AGN distributions appear in CMDs.

The color-mass correlation may *entirely* account for apparent special clustering of AGNs in CMDs.

Mass-Matched Sample Results



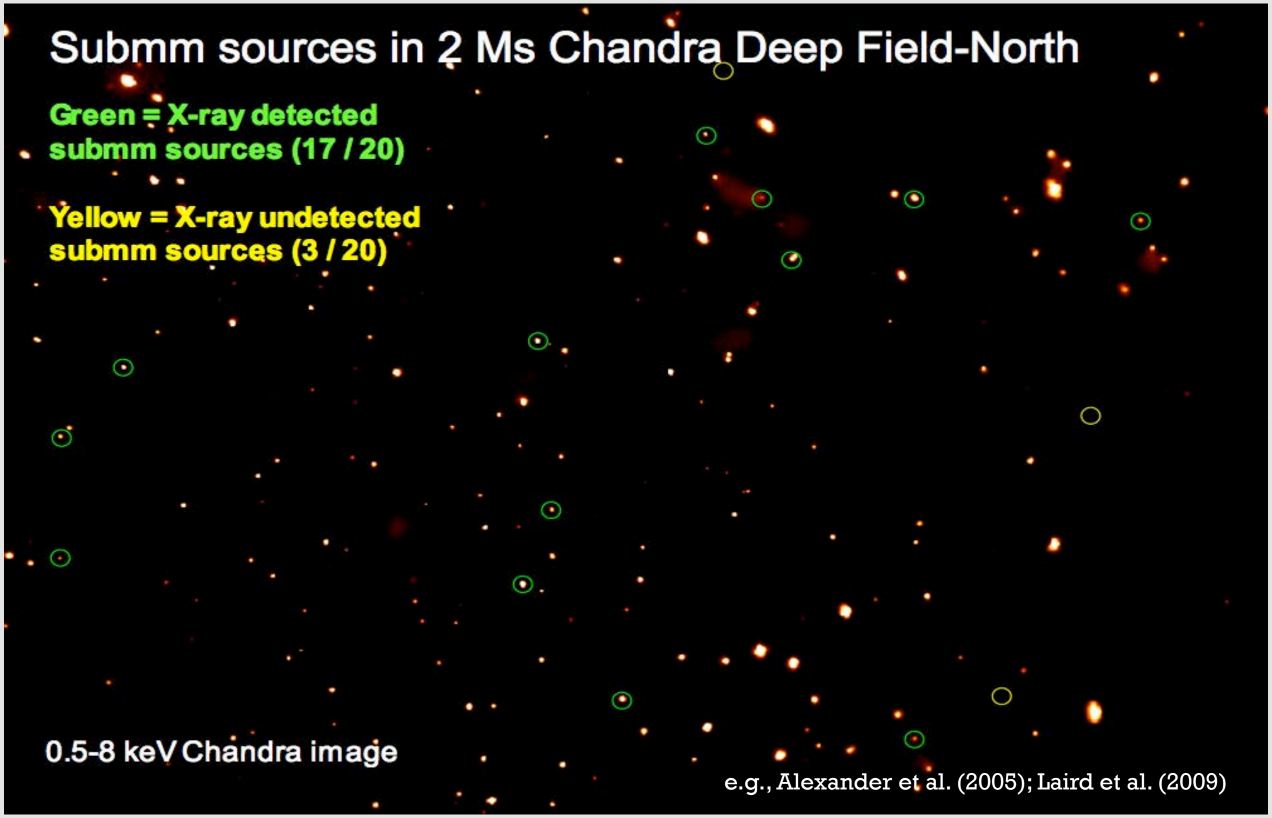
Constructed a mass-matched sample via random draws from galaxy population (10 galaxies per AGN).

AGNs no longer occupy a distinctive location in the color-magnitude diagram, out to $z \sim 3$.

AGN fractions flat or declining toward red colors, rather than rising.

Accretion luminosity also does not change significantly with host color.

AGNs in Submillimeter Galaxies



High fraction of submm galaxies at $z \sim$ 1-4 are X-ray detected in deepest X-ray surveys.

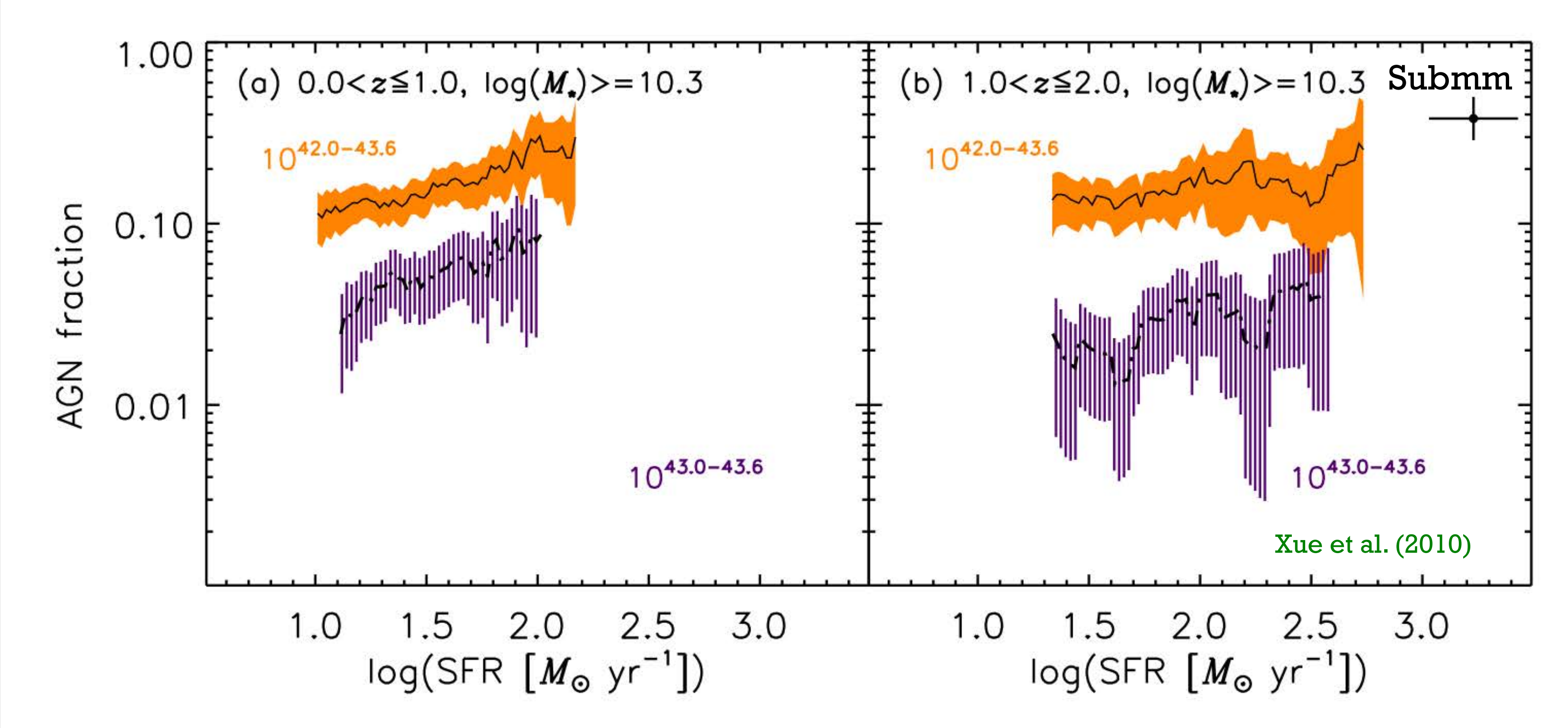
Often evidence for AGN activity. AGN fraction ~ 20-35%.

Suggests high duty cycle of SMBH growth in forming spheroids – SFR-accretion connection?

But submm galaxies also massive.

AGN Fraction vs. SFR for Mass-Matched Samples

(Derived using 139 AGNs within 1468 galaxies)

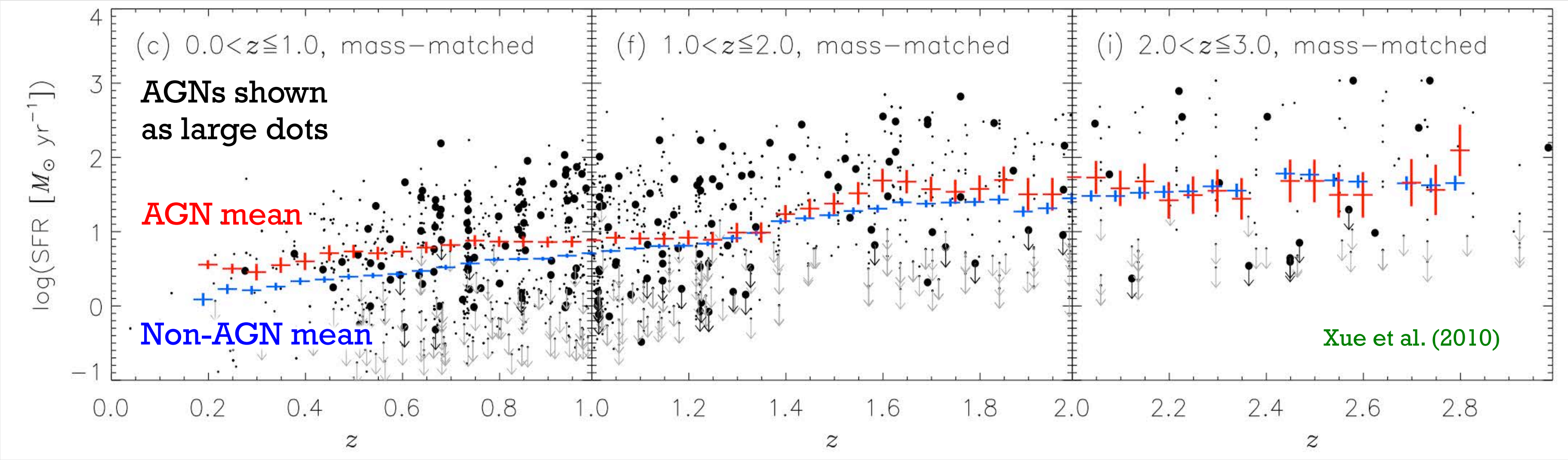


Dependence of AGN fraction upon SFR for mass-matched samples (i.e., SSFR) becomes modest (at z ~ 0-1) or largely vanishes (at z ~ 1-2).

High AGN fraction of submm galaxies may be due to high masses instead of high SFRs.

SFRs of AGNs vs. Non-AGNs

SFR for AGNs and Non-AGNs in a Mass-Matched Sample (Using a Sliding Bin of Width $\Delta z = 0.5$)



SFRs of both AGN hosts and non-AGN galaxies rise with redshift, as expected.

SFRs of AGN hosts are ~ 2-3 times higher than those of non-AGN galaxies up to $z \sim 1$, but no significant difference at higher redshifts.

The SFR difference at $z < 1$ diminishes if only star-forming populations are considered; this finding may help to explain the overall behavior.

Future Hopes

Some Big Unresolved Questions

Missed highly obscured AGNs and their contribution to SMBH growth.

SMBH growth and feedback at $z \sim 4$-10.

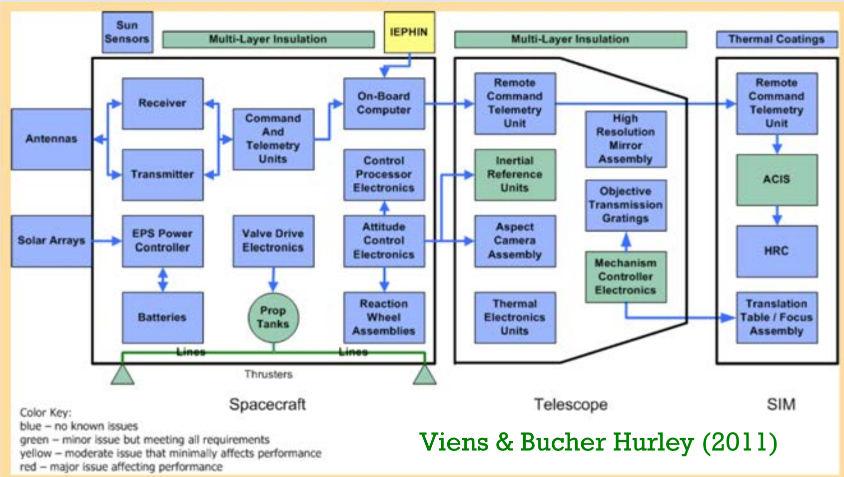
What sets the SMBH coronal X-ray luminosity?

Co-evolution of SMBH and galaxy stellar populations through the $z \sim 1$-3 formation era.

Effects of large-scale cosmic environment.

Chandra and XMM-Newton Are Healthy

State of Health for Major Chandra Subsystems



A 20+ year Chandra mission appears entirely feasible.

Some XMM-Newton Mission Operations Parameters

Fuel	Remaining Use per year Estimated lifetime	71 kg <6 kg >2020
Solar array power	Maximum required Current margin Margin 2020	1350 W 550 W >400 W
Battery	Same capacity as launch	Reconditioning can be repeated
Gyros/(IMUs)	Usage	<20%
Reaction wheels	Usage	<38%
RCS FCV	Usage (A,B)	~50% A, B only ESAM
RF switches **Transponder switches**	Usage	Possibly stuck at one position Back up not used instead transponders are switched TX A /B switching <300 (Qualified to 25000)

Parmar et al. (2011)

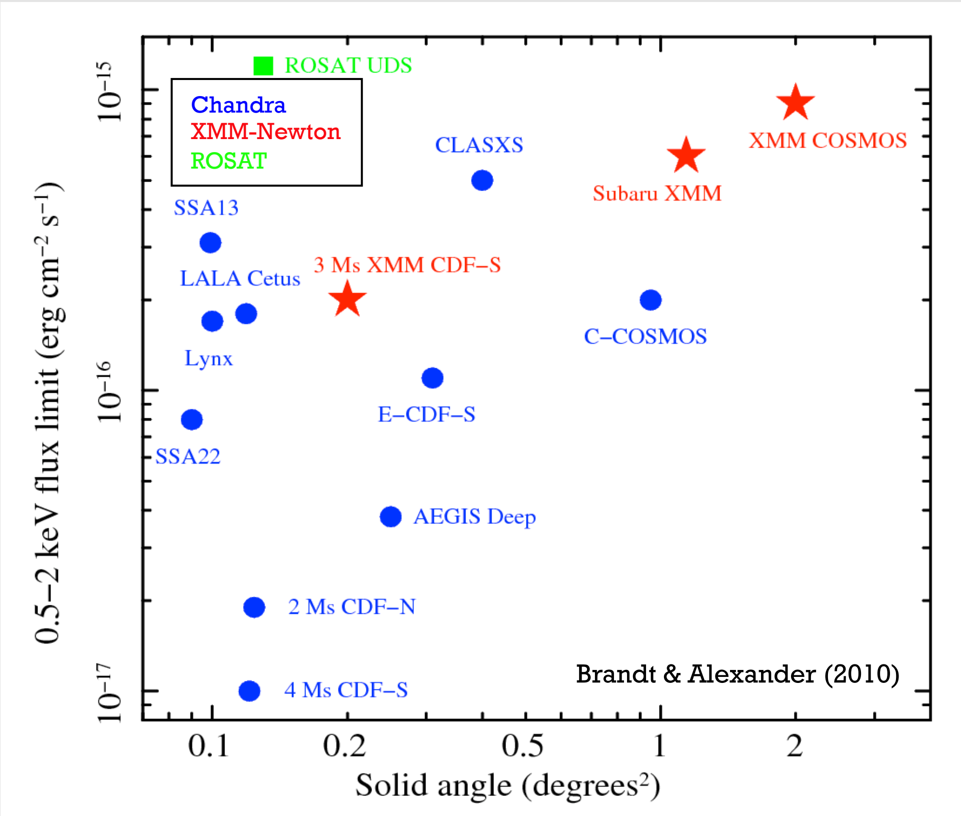
XMM-Newton mission status is very good.

Consumable fuel good to 2020, and likely beyond with conservation.

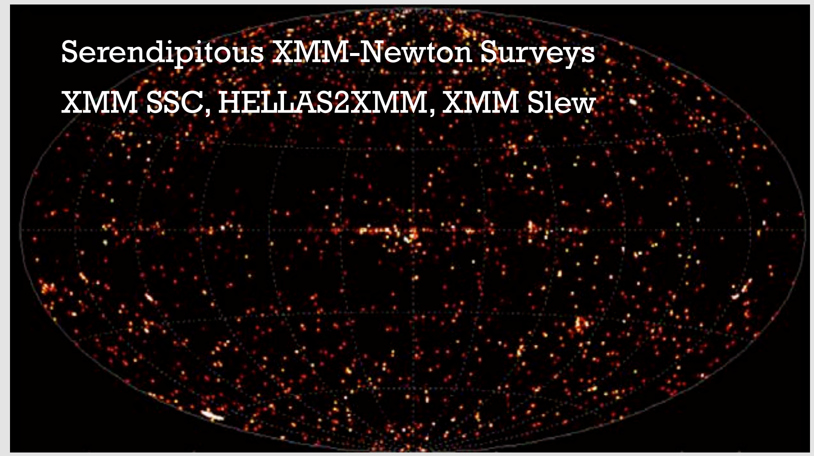
Must maintain outstanding science output to maintain mission funding; e.g., aggressive large-scale projects that break new ground.

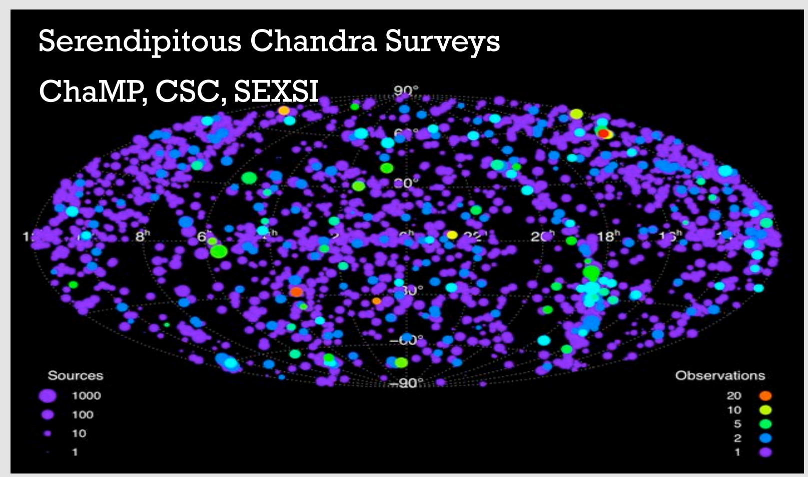
Let's Hope for Another Great Decade of Chandra and XMM-Newton Surveys!

Some Recent Contiguous Deep X-ray Surveys

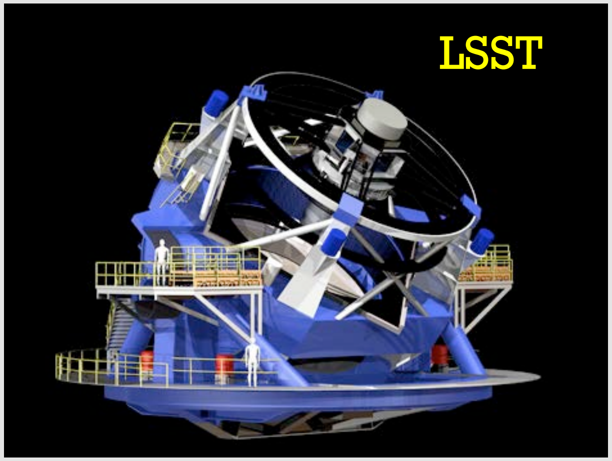


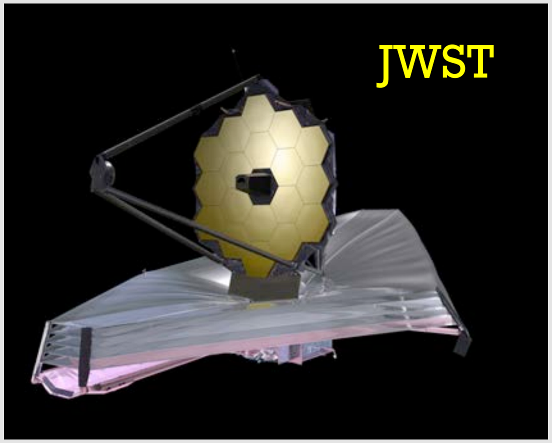
Can aim to push both deeper and wider.

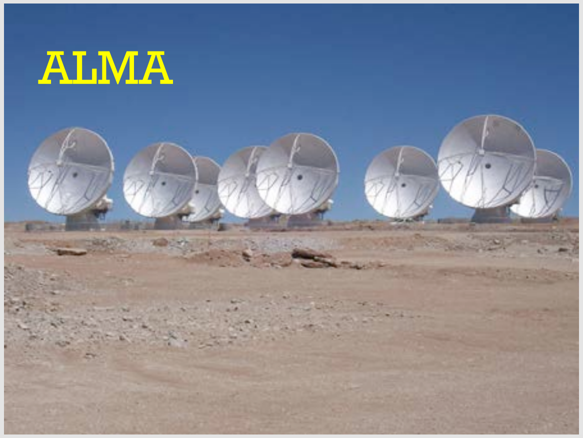


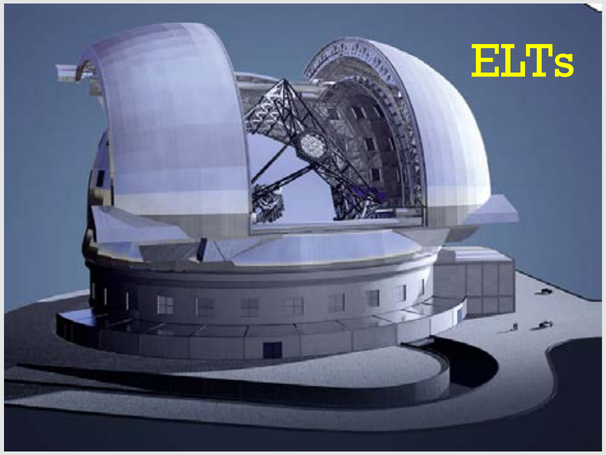


With Lots of New Complementary Multiwavelength Data Flooding In!



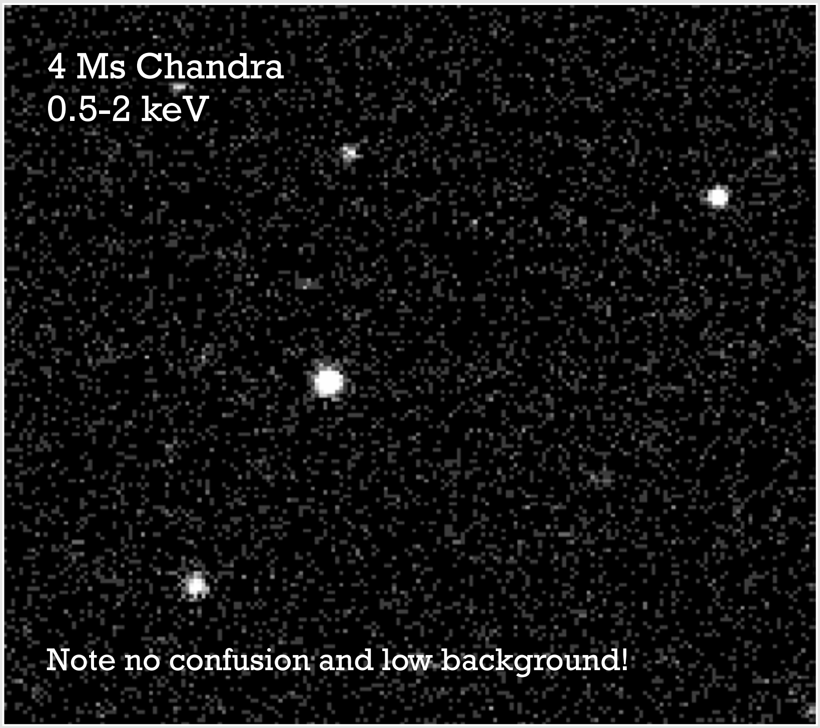




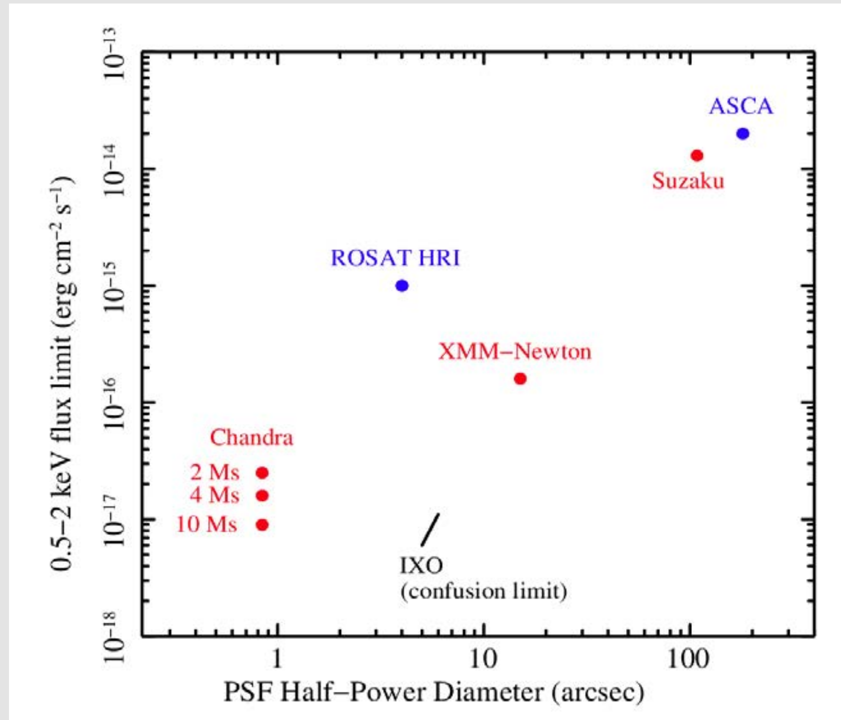


One Direction: Pushing Deeper with Chandra

Central Chandra Deep Field-South



Missions – Depth vs. PSF Quality



Chandra can still go deeper while remaining confusion free.

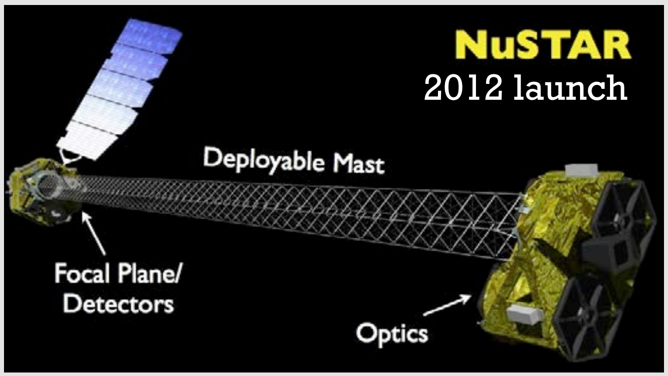
In 10 Ms can reach depths that were planned for IXO and go deeper than Athena.

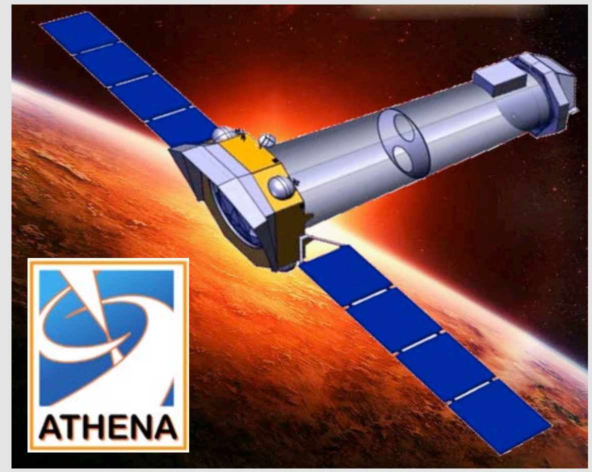
A 20+ year legacy for Chandra.

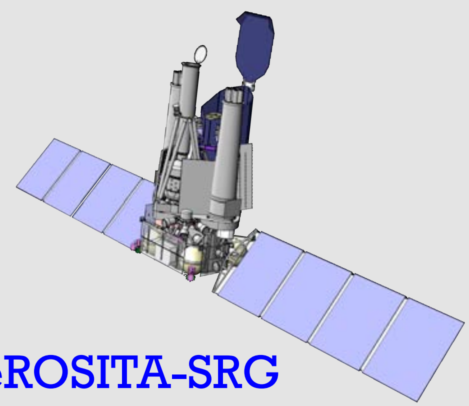
Angular resolution and *positions* likely unmatched even by next generation missions.

Better photon statistics improve spectral and variability studies for hundreds of sources.

Near-Term and Long-Term New Surveyors of the X-ray Universe







eROSITA-SRG
2013 launch