Ultra Hard X-ray Luminosity Function of AGN

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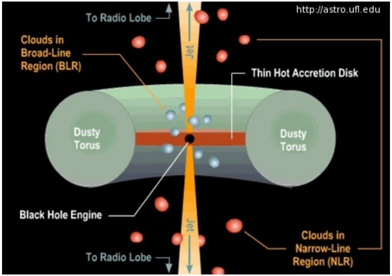
Active Galactic Nuclei

- powered by accretion onto super-massive black hole,
- growth of black hole,
- extreme X-ray radiation from the nucleus
- selection criterion:

$$L_x > 10^{42} \mathrm{erg/sec}$$



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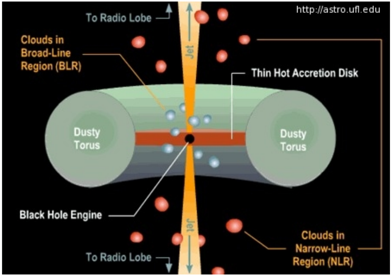

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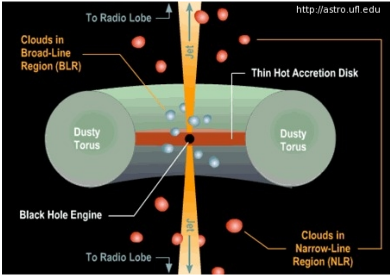

Interplay between host galaxy and AGN, co-evolution? feedback?

How do AGN evolve with redshift?

How do AGN evolve?

The luminosity function is the number of AGN per unit comoving volume, per unit luminosity:

$$\frac{d\Phi(L_x, z)}{dLogL_x} = \frac{dN(L_x, z)}{dV_c\, dLogL_x}$$

The comoving volume is the volume traced by coordinates fixed on the Hubble flow:

$$dV_c = D_H \frac{(1+z)^2 D_A^2}{E(z)} d\Omega dz$$

Computing the LF

Non-parameteric

- $1/V_{max}$ – binned

  (Page & Carrera 2000)

  For each (L_x-z) bin:

$$\phi(L_x, z) = \frac{sources}{\int\int \frac{dV_c}{dz} dLogL_x dz}$$

Parametric – not binned

- Maximum Likelihood

  (Marshall et al., 1985)

  Assume a functional form

  Find the best parameters, minimizing:

$$L = -2 \sum ln \frac{N(LogL_{x,i}, z_i)}{\int\int N(LogL_x, z) dLogL_x dz}$$

where $N(LogL_x, z) = \frac{d\Phi^{model}}{dLogL_x} \frac{dV_c}{dz}$

Previous works

	energy range (keV)	best model	no. param.
Miyaji et al. (2000)	0.5 - 2.0	LDDE1 LDDE2	8 9
Ueda et al. (2003)	2.0 - 10.0	LDDE	8 (U03)
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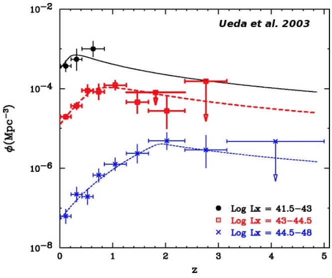

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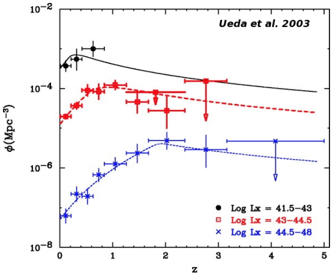

Question 1: What happens at low luminosities?

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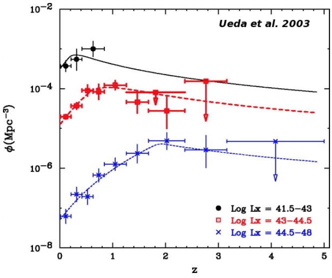
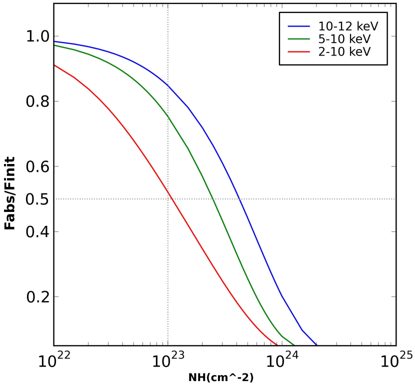


Question 1: What happens at low luminosities?
Question 2: What happens at high redshift?

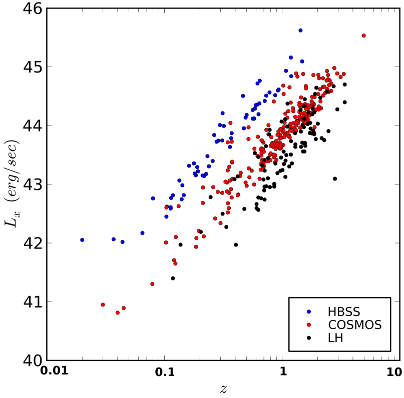
Ultra Hard X-ray (5-10keV) – motivation

- Little absorption, even for edge-on torus, z=0 $NH \sim 10^{23} cm^{-2}$
    - $5 - 10\,\mathrm{keV} \sim 20\%$ flux lost
    - $2 - 10\,\mathrm{keV} \sim 50\%$ flux lost
- Compton thick objects



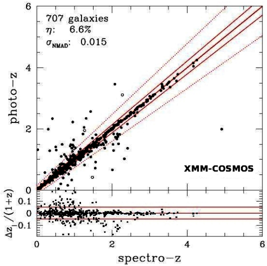
Ultra Hard X-ray (5-10keV) – dataset

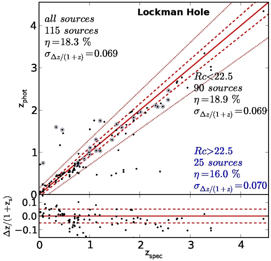
- Only XMM fields used:
  - Hard Bright Sample $\sim 25\,\mathrm{deg}^2$
    $\mathrm{F_{x,lim}} = 7 \cdot 10^{-14}\,\mathrm{erg/s/cm^2}$
    (Della Ceca et al. 2004, Caccianiga et al. 2008)
  - XMM-Cosmos $\sim 2\,\mathrm{deg}^2$
    $\mathrm{F_{x,lim}} = 1.3 \cdot 10^{-14}\,\mathrm{erg/s/cm^2}$
    (Cappelluti et al. 2009, Brusa et al 2010, Salvato et al. 09)
  - Lockman Hole $\sim 0.2\,\mathrm{deg}^2$
    $\mathrm{F_{x,lim}} = 1.8 \cdot 10^{-15}\,\mathrm{erg/s/cm^2}$
    (Brunner et al. 2008, Rovilos et al. 2011, Fotopoulou et al. 2011)
- Good coverage of the L_X-z plane, ~400 sources
- 98% redshift complete



Ultra Hard X-ray (5-10keV) – dataset

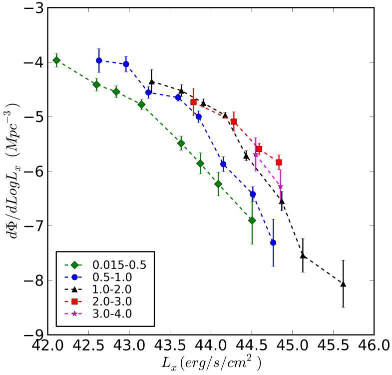
- Redshift information:
  - Hard Bright Sample
    63 spec-z
  - XMM-Cosmos
    191 spec-z, 55 phot-z
  - Lockman Hole
    52 spec-z, 42 phot-z
- photoz tuned for AGN:
  - XMM - and *Chandra*-COSMOS: Salvato et al., 2009, 2011 (G41)
  - Lockman Hole: Fotopoulou et al., 2011





Ultra Hard X-ray (5-10keV) – First results

- $1/V_{max}$ method- Non parametric
- No function assumed
- Broken power law at low z
- Complicated evolution with z



Ultra Hard X-ray (5-10keV) – Model crash test

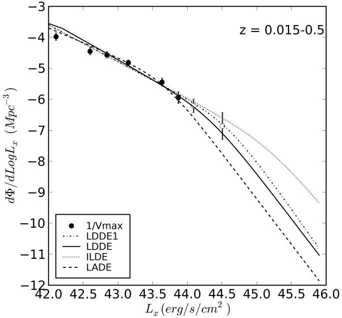
Akaike Information Criterion (AIC),

$$AIC = -2ln(L) + 2k$$

Minimum value preferred, also models with

$$AIC_{model} - AIC_{min} < 2$$

should be considered.



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Ueda et al. 2003	LDDE	8	1065.226
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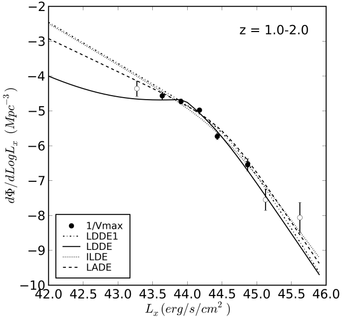

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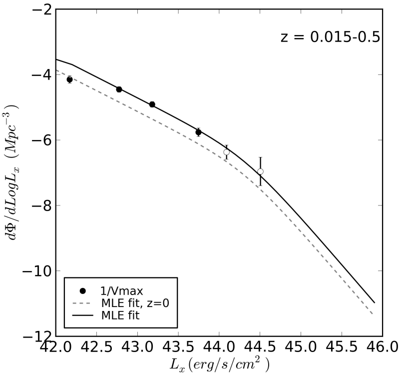

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— solid black line: fitted LDDE model at median z of the redshift bin

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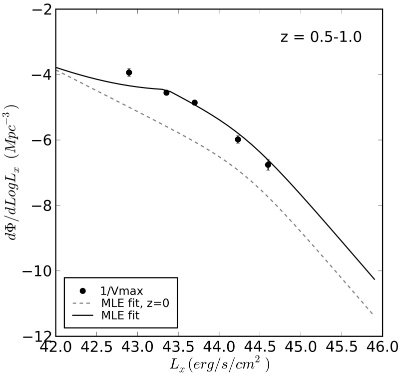

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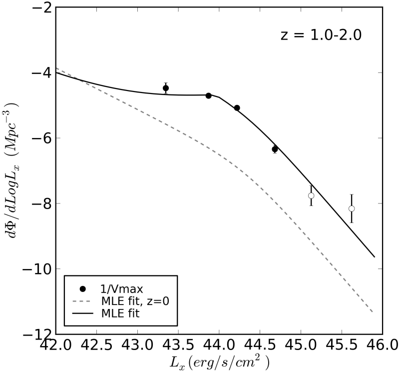

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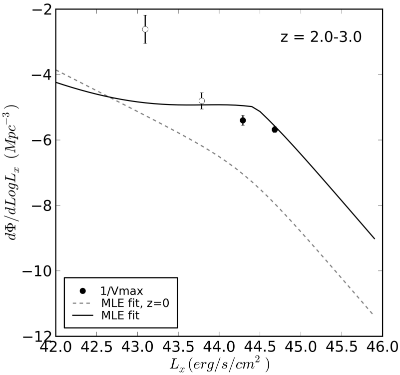

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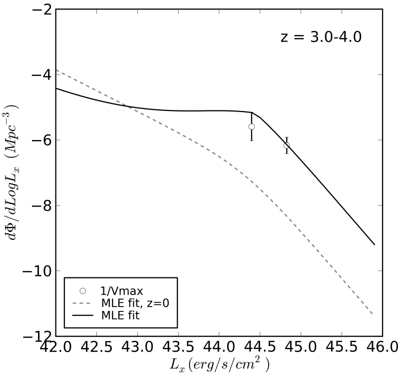

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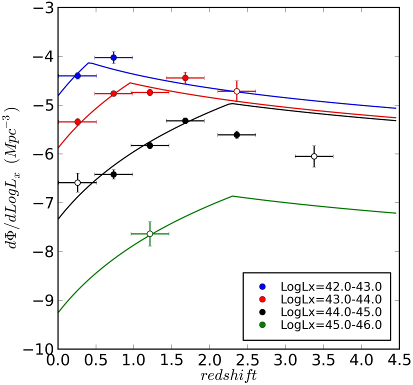
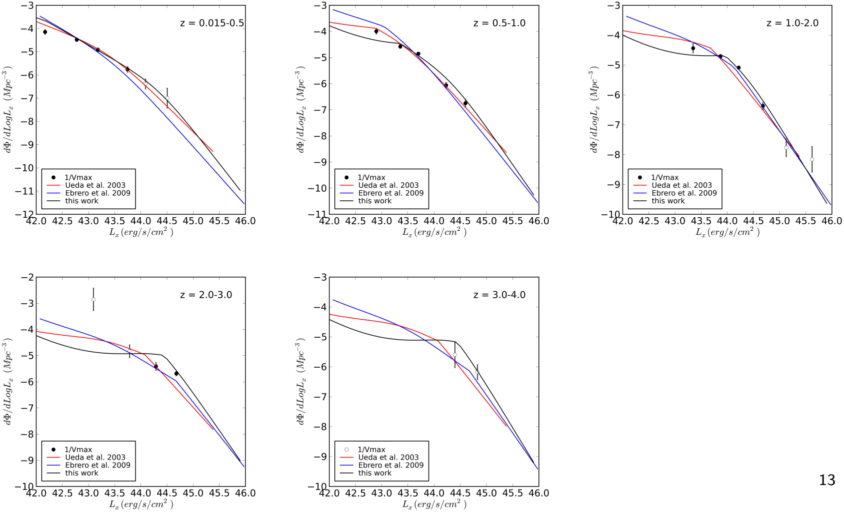
LDDE best fit parameters

L_*	44.32±0.07	L_a	44.44±0.02
γ_1	1.27±0.02	γ_2	2.9±0.1
p_1	4.61±0.18±	p_2	-1.6±0.5
z_c	2.319±0.009	α	0.444±0.006



Comparison with previous works



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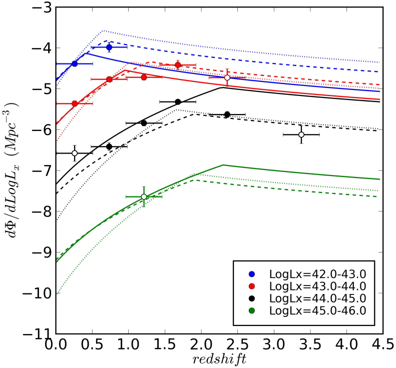
- Some agreement with previous LFs.
- **Question 1:** What happens at low luminosities?
- **Question 2:** What happens at high redshift?
- High redshift and low luminosity are still unclear.



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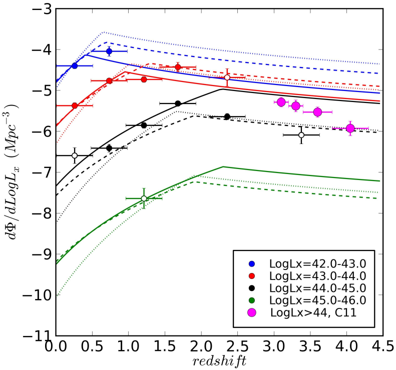

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magenta points: $1/V_{max}$ estimates $L_x > 10^{44} erg/sec$, Civano et al., 2011 (G07)

Outlook

Can we use the 5 - 10 keV band to study LFs?

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- Stronger evolution with redshift than lower X-ray bands.
- Number density decreases at high redshift(?)

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What else is there to explore?

- Soft X-ray Band: up to 80-90% of the Cosmic X-ray Background has been resolved to discrete sources (Miyaji et al., 2000).
- Ultra Hard X-ray Band: only 50-70% has been resolved (Worsley et al., 2004).

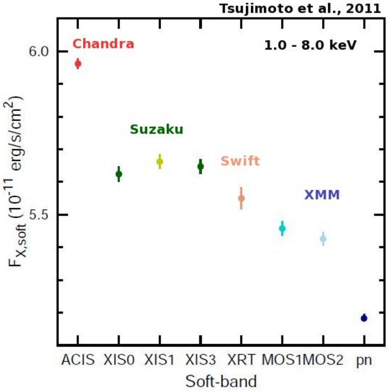
Thank you!

XMM - *Chandra* cross calibration

- Lumb et al. 2001,
  "We find a slight evidence that the XMM-determined fluxes are in excess of the CHANDRA estimated fluxes by about 10 (20)% in the soft (hard) band."
- Tsujimoto et al. 2011,
  "We identify systematic differences in the best-fit parameter values unattributable to statistical scatter of the data alone." (20% for 1-8keV for XMM and Chandra)

- Moretti et al. 2003,
  "[...] we artificially increased and reduced the flux of each survey (one by one) by a 10% factor (modifying the corresponding sky coverage). We found that we have typical differences of 2% of the total CXB (and never larger than 3%)."

XMM - *Chandra* cross calibration



Luminosity Function

$$\frac{d\Phi(LogL_x, z)}{dLogLx} = A \cdot [(\frac{L_x}{L_*})^{\gamma_1} + (\frac{L_x}{L_*})]^{-1} \cdot evolution$$

Pure Luminosity Evolution: $\frac{d\Phi(LogL_x, z)}{dLogLx} = \frac{d\Phi(LogL_x/\mathbf{e}(z), z=0)}{dLogLx}$

Pure Density Evolution: $\frac{d\Phi(LogL_x, z)}{dLogLx} = \frac{d\Phi(LogL_x, z=0)}{dLogLx} \cdot \mathbf{e}(z)$

$$e(z) = \begin{cases} (1+z)^{p1} & z <= z_c, \\ e(z_c) \cdot (\frac{1+z}{1+z_c})^{p2} & z > z_c \end{cases}$$

Luminosity Depended Density Evolution: $\frac{d\Phi(LogL_x, z)}{dLogLx} = \frac{d\Phi(LogL_x, z=0)}{dLogLx} \cdot \mathbf{e}(z, L_x)$

$$e(z, L_x) = \begin{cases} (1+z)^{p1} & z \leq z_c(L_x), \\ e(z_c) \cdot (\frac{1+z}{1+z_c(L_x)})^{p2} & z > z_c(L_x) \end{cases} \qquad z_c(L_x) = \begin{cases} z_c^* & L_x \geq L_a, \\ z_c^* \cdot (\frac{L_x}{L_a})^a & L_x < L_a \end{cases}$$

Likelihood minimization determines: L_*, γ_1, γ_2, z_c, L_a, p_1, p_2, a