AGN Clustering and Environments in X-ray Surveys

A review

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Scope of the Talk

1. Large Scale Structure in X-ray AGNs: Intro
2. Two point Correlation Function Measurements from X-ray data: Basics and Practice
3. Summary of Correlation Function results from various surveys
4. Some Cosmological Implications
5. Other approaches
6. Summary

1. Large Scale Structure in X-ray Surveys: Introduction

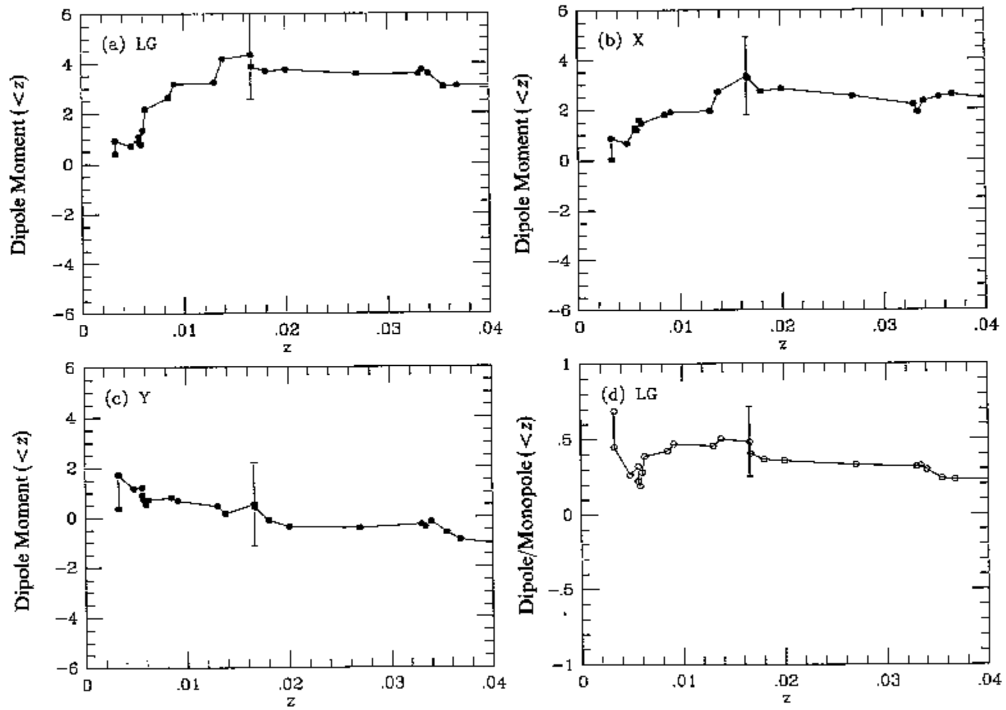


FIG. 2.—Dipole growth curves (eq. [1]) for the components in three orthogonal directions are shown in (*a*)–(*c*). Fig. 2*d* shows growth curve of the ratio of dipole/monopole (eq. [2]) for LG direction. Error bars show statistical sampling errors.

Miyaji & Boldt 1990

- Matter in the universe has a structure. Galaxies, AGNs, Clusters of galaxies etc. trace the underlying structure in mass.

- Clustering properties of AGNs provide yet another clue to understanding the formation and evolution of Supermassive Blackholes (SMBH).
- Simple characterization of how AGNs trace underlying mass: bias parameter

$$b_{\mathrm{AGN}}=(\delta\rho/<\rho>)_{\mathrm{AGN}}/(\delta\rho/<\rho>)_{\mathrm{mass}}$$

(contrast enhancement factor)

- Bias b >1 when a tracer samples high tips of underlying mass density (Kaiser '84).
- Biasing of theoretical Dark Matter Halos (DMH) depends is mass dependent.

2. Two-point Correlation Function on X-ray data: Basics and Practice

- Excess number of pairs separated by *r* or θ over random distribution
- Joint probability δP of finding an object in both of the solid angle elements separated by r/θ is represented by:

  Angular: $\delta P = n^2[1+\underline{w(\theta)}]\,\delta\Omega_1\delta\Omega_2$, 3D: $\delta P = n^2[1+\underline{\xi(r)}]\,\delta V_1 \delta V_2$

- Two point 3-D correlation function is related to bias parameter by:

$$\xi_{\mathrm{AGN}}(r) = b_{AGN}^{\ 2}\ \xi_{\mathrm{mass}}(r)$$

- Estimators (DD, RD, and RR are *normalized* numbers of source-source, source-random and random-random pairs respectively):
  - $w_{est}(\theta)$=(DD/RD)-1 (Efstathiou+ 1991)
  - $w_{est}(\theta)$=(DD RR)/(DR DR)-1 (Hamilton 1993)
  - $w_{est}(\theta)$=(DD-2RD-RR)/RR (Landy & Szalay 1996)
  - They give basicly the same results, with some different error properties.

Depending on the availability of redshift information

- **Angular Correlation function $w(\theta)$**, poor man's measure, signal diluted by projection effects. No redshift information, but redshift distribution can be modeled. Use Limber's equation to de-project to $\xi(r)$
- **Projected distance correlation function $w_p(r_p)$**

  Redshift information, even photo-z. Use with redshift-divided samples to improve S/N.
- Correlation function in 2 paramater space (projected dist and redshift space) $\xi(r_p,\pi)$
- 3-D correlation function in redshift space $\xi(s)$ with $s^2=r_p^2+\pi^2$ used when spect-z's are available. Redshift distortion ...

Technicalities

- Error/Covariance Matrix Estimations
  - Poissonian of the number of pairs (1+w)/sqrt(DD) or full Poisson expression (fit with C-stat) if the number of pairs are small
  - Jackknife resampling (can create covariance matrix) (needs large number of independent regions)
  - Random Monte-Carlo scaled by (1+w) (TM+,'07)
  - Monte-carlo using mock catalogs (including clustering)
- Integral constraint gives an offset to w for estimated in finite area. Correction is model dependent.

$$\int\int w_{\rm est}\, d^2\Omega = 0.$$

- Amplification bias (Vikhlinin & Forman '95) due to PSF smoothing: several percent effect for typical medium-depth XMM survey (Basilakos04,05;TM+'07). Negligible in Chandra Surveys
- Random sample generation

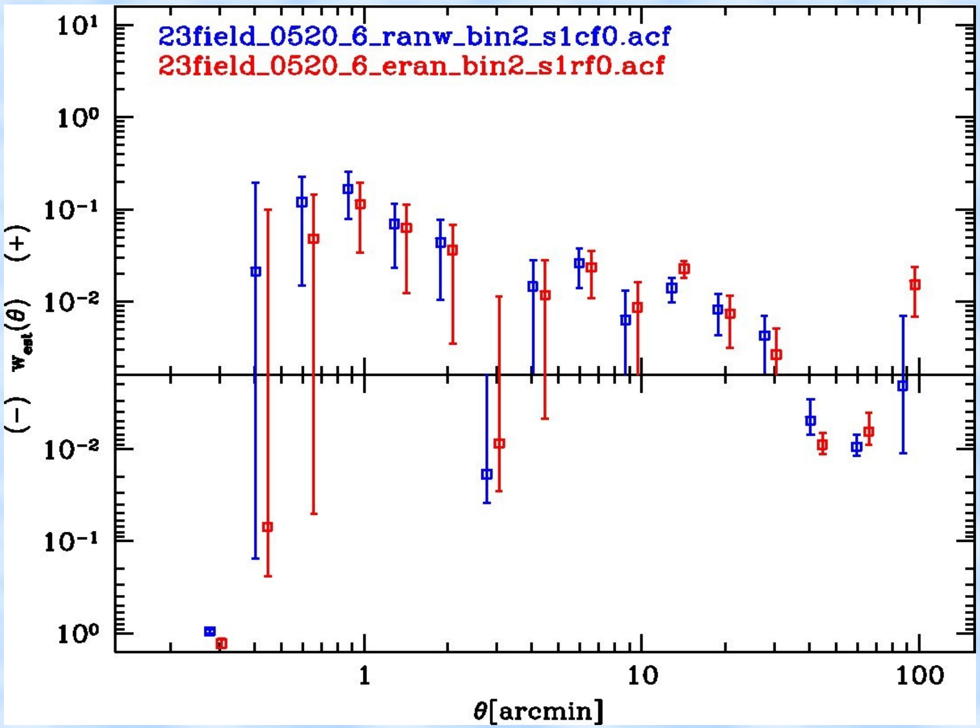
Random Sample Generations

- Sensitivity varies over the field, possibly producing spurious clustering signal.
- **This can be compensated by applying the same sensitivity cut to the random sample.**

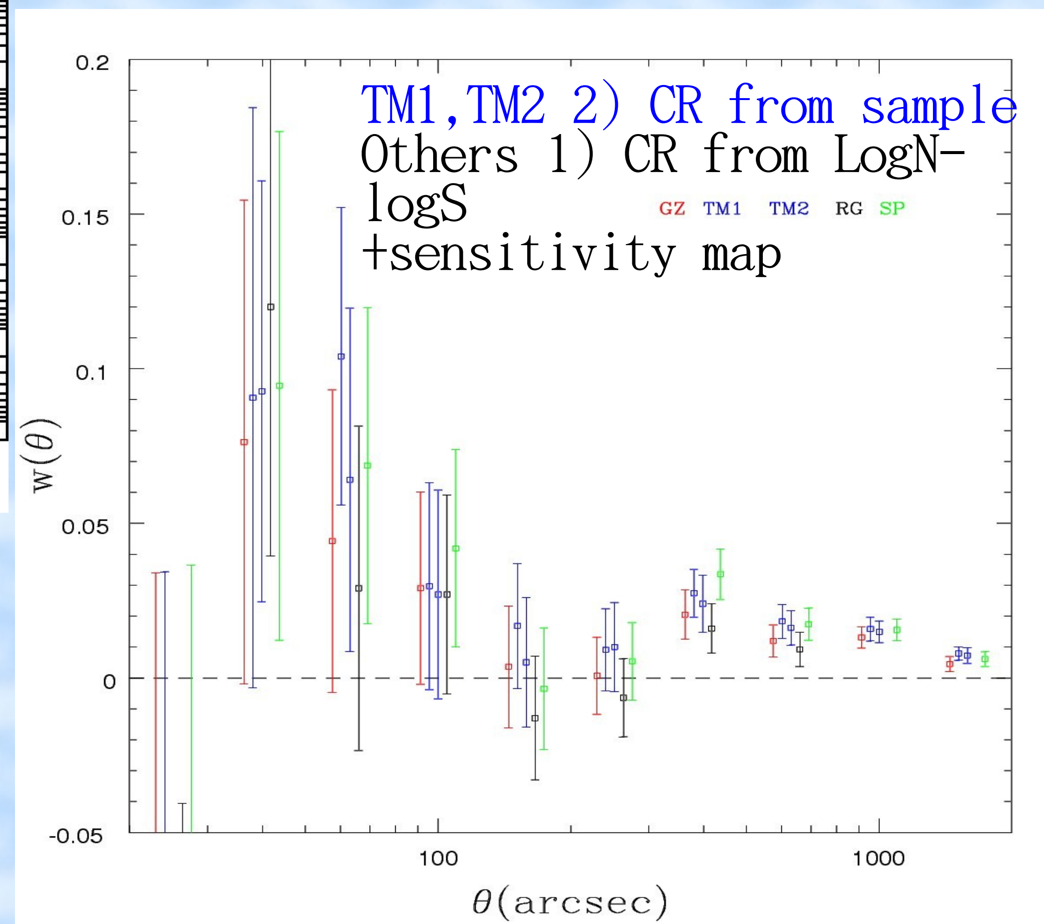
1. **Full X-ray Image simulation and source detection** (Murray+'06,Gandhi+'06,TM+'07,Carrera+submitted)
   Requires a Log N-Log S model/Computationally demanding.
2. **The CR of the random source is drawn from an externally given Log N-Log S relation** (Basilakos+'04, Pucetti+'06,Carrera+)
   1.Good sensitivity map and Log N-Log S model.
3. **Take the Countrate (CR) distribution from actual sources** (TM+ '07)
   Good sensitivity map. Good for, e.g., investigate subsamples.
4. **Make survey as uniform as possible by dense tiling (XMM-COSMOS year-2, C-COSMOS)**

Comparing Random Sample Methods (XMM-COSMOS 23 field data)

Having a Good Sensitivity map and a hood log N-log S model, different methods give consistent results.



2) CR from Sample+sensitivity map vs 3) Simulated random



Limber De-Projection to 3D-Correlation Function

The 2-D ACF is a projection of the real-space 3-D ACF of the sources ($\xi(r)$) along the line of sight. The relation is expressed by the Limber's equation:

$$w(\theta) N^2 = \int \left(\frac{dN}{dz}\right)^2 \int \xi(\sqrt{[d_{\rm A}(z)\theta]^2 + l^2})(dz/dl)\, dl\, dz,$$

where $d_{\rm A}(z)$ is the angular distance at the redshift z, N is the total number of sources and dN/dz is the redshift distribution (per z) of the sources. The redshift evolution of the 3-D correlation function is customarily expressed by:

$$\xi(r,z) = (r/r_0)^{-\gamma}(1+z)^{-3-\epsilon}.$$

Clustering evolution

In the above expression, $\epsilon = -3$ corresponds to the case where the correlation length is constant in the physical coordinates and $\epsilon = \gamma - 3$ corresponds to the case the clustering is constant in the comoving coordinates.

The relationship between zero-redshift 3-D correlation length r_0 and the 2-D correlation length θ_c is then:

$$r_0^\gamma = (N^2/S)\,\theta_c^{\gamma-1},$$

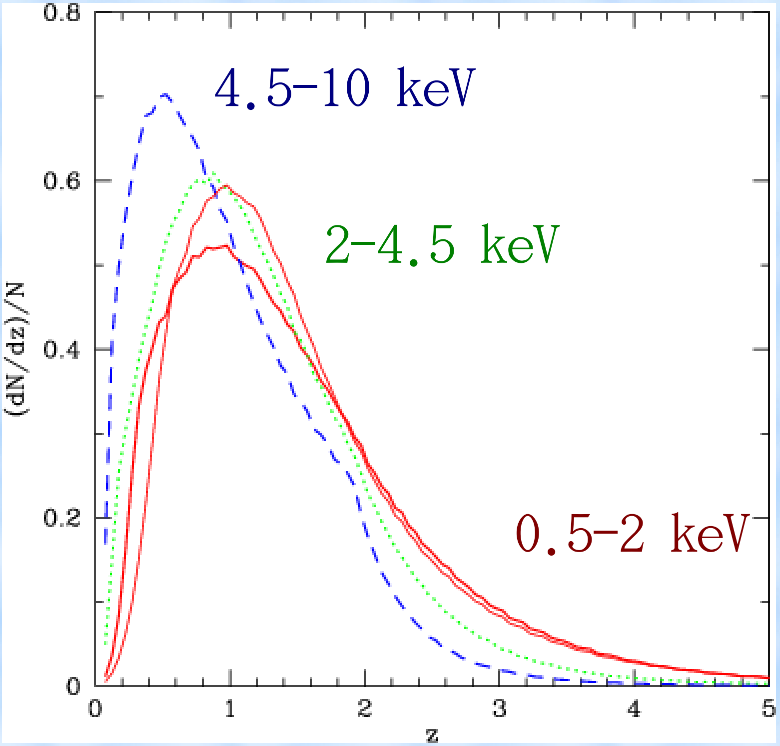
$$S = H_\gamma \int \left(\frac{dN}{dz}\right)^2, \left(\frac{c\,d\tau(z)}{dz}\right)^{-1} d_{\rm A}^{1-\gamma}(1+z)^{-3-\epsilon} dz$$

$$H_\gamma = \frac{\Gamma[(\gamma-1)/2]\Gamma(1/2)}{\Gamma(\gamma/2)},$$

where $\tau(z)$ is the look back time. All dependences on cosmological parameters are included in $d_{\rm A}(z)$ and $\tau(z)$.

Model Redshift Distribution

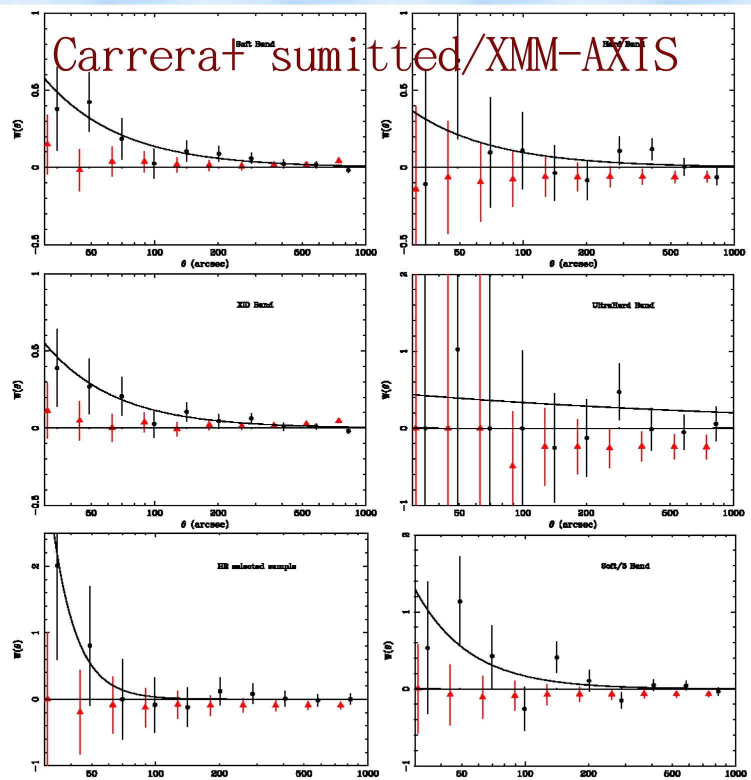
For de-projection of the angular ACF/CCF, we need the redshift distribution of the sources.

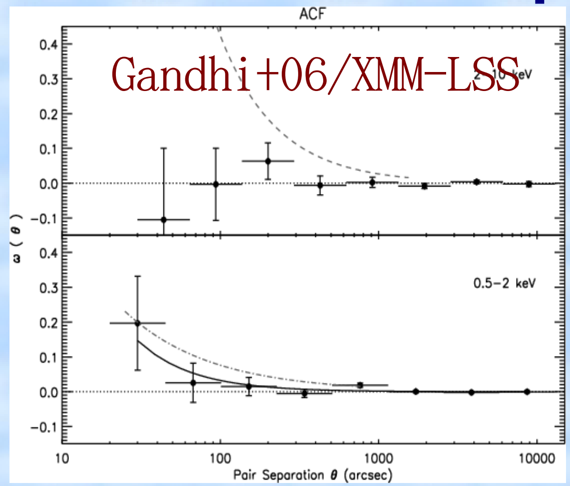


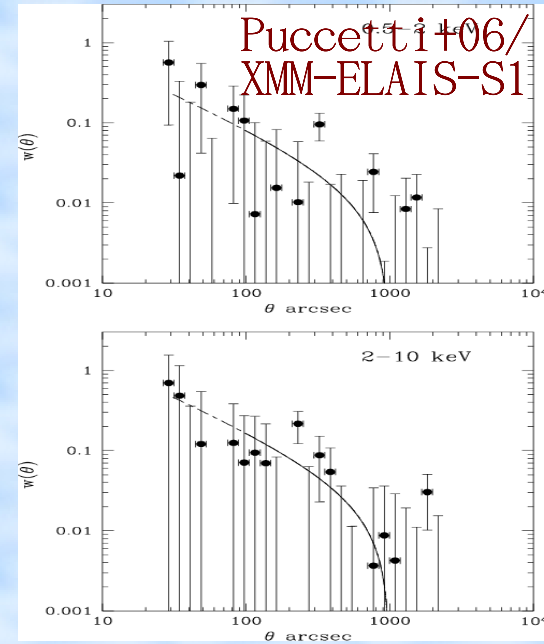
Redshift distributions of the XMM-COSMOS X-ray sources detected in the three bands used in the de-projection, calculated using Ueda et al. (2003, ApJ 598, 886;U03) model except the thin red solid line, which is from Hasinger, Miyaji, Schmidt (2005, A&A 441, 417;H05)

From TM+'07 for XMM-COSMOS

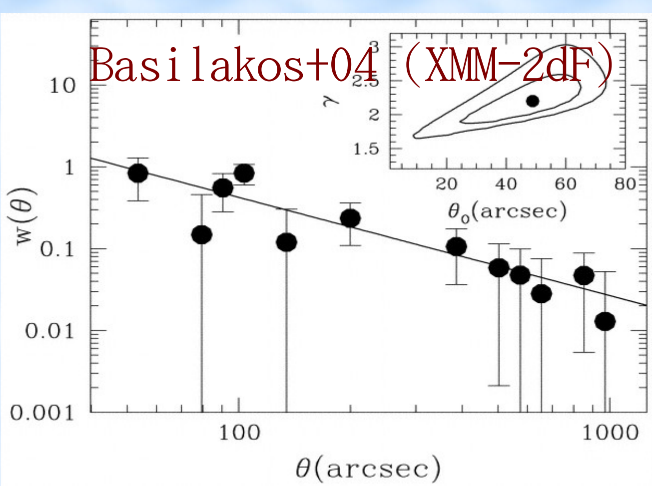
3. AGN/QSO Correlation Function Measurements and Comparisons

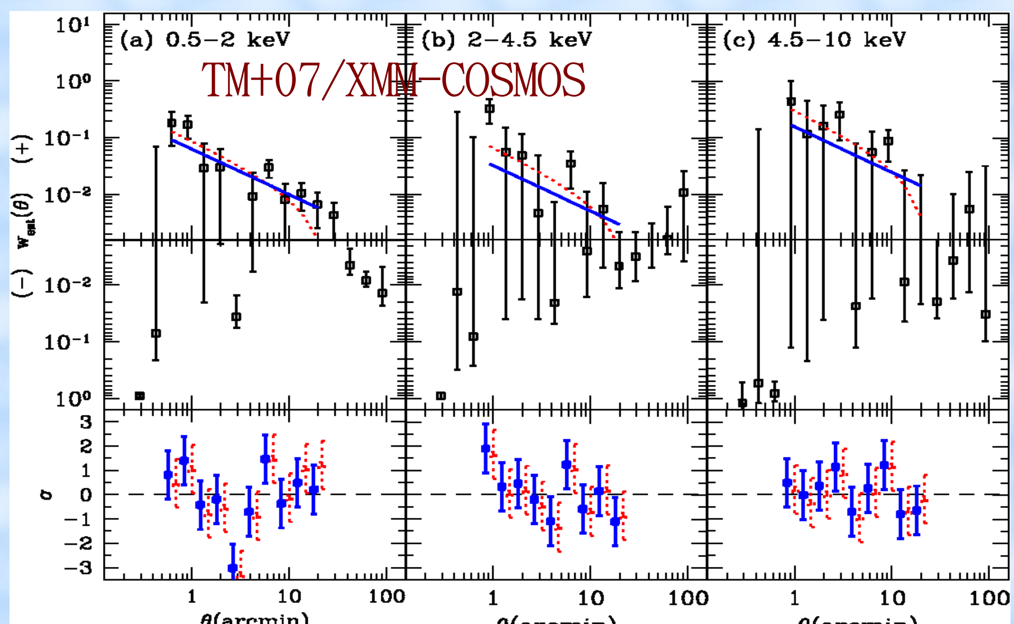




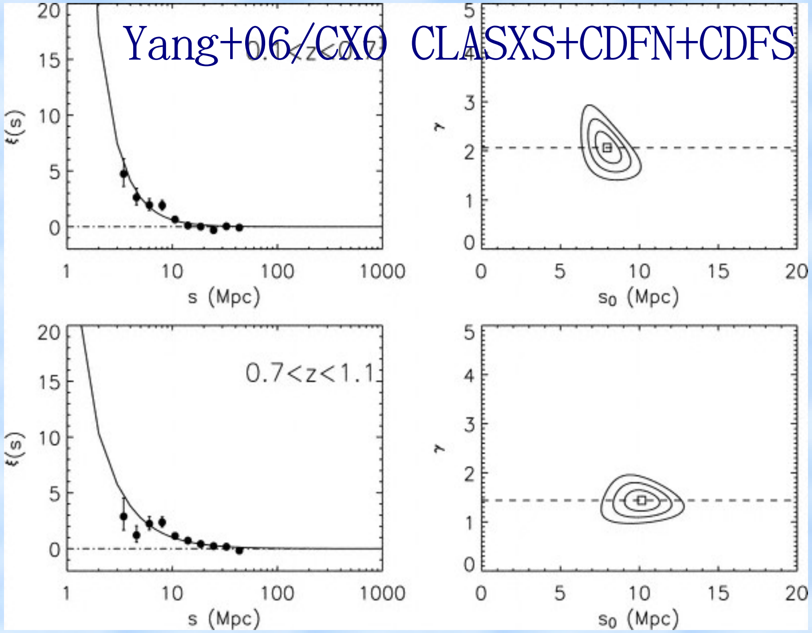


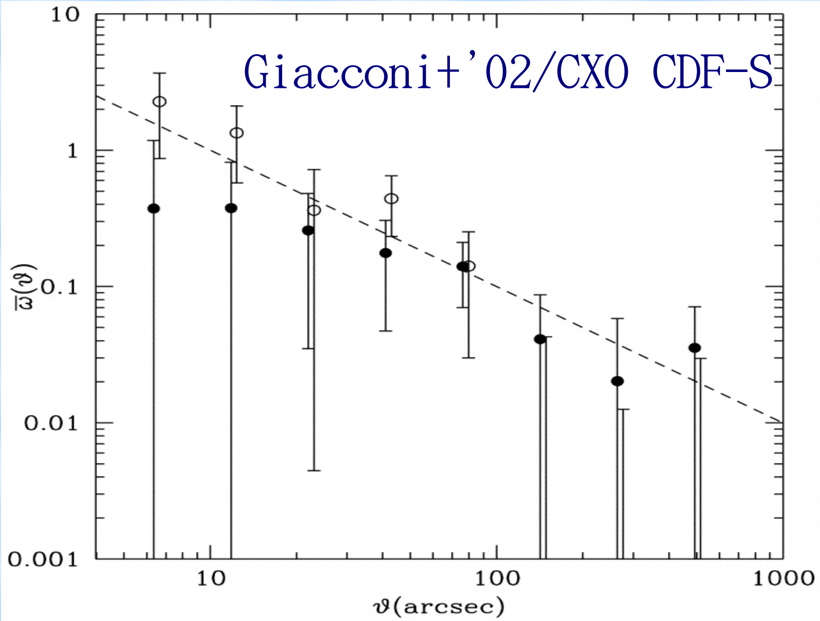
XMM-NEWTON

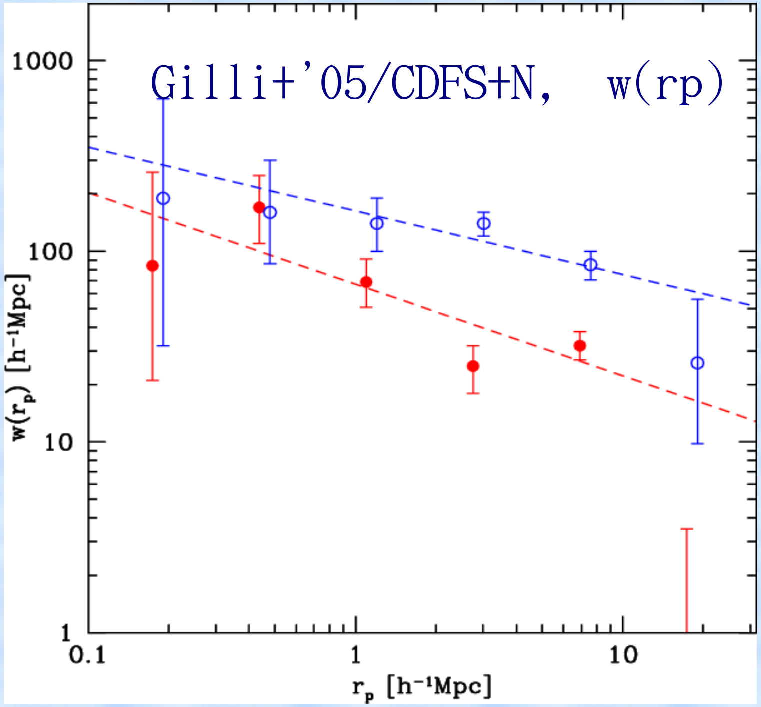


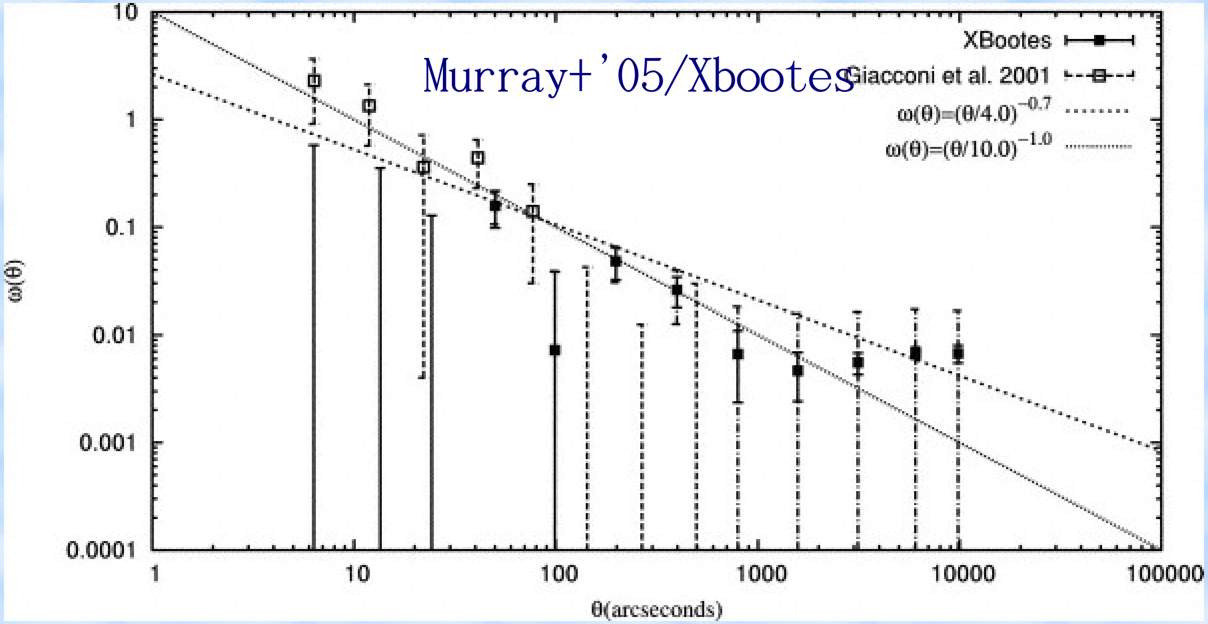


Chandra


Yang+06/CXO CLASXS+CDFN+CDFS 3D
0.7<z<1.1
ξ(s)
s (Mpc)
γ
s0 (Mpc)


Giacconi+'02/CXO CDF-S
ϖ(ϑ)
ϑ(arcsec)


Gilli+'05/CDFS+N, w(rp)
w(rp) [h⁻¹Mpc]
rp [h⁻¹Mpc]


Murray+'05/Xbootes
XBootes
Giacconi et al. 2001
ω(θ)=(θ/4.0)^-0.7
ω(θ)=(θ/10.0)^-1.0
ω(θ)
θ(arcseconds)

Summary of Correlation Lengths

Survey	Band	N_{src}	$\langle z \rangle$	Method	γ	r_0/s_0 h^{-1} Mpc	Ref
RASS	0.1-2.4 keV	2096	0.15	$w(\theta)$	1.8*	6.5±1.0	Akylas+'00
AERQS	0.1-2.4 keV	392 w/z	0.06	$\xi(s)$	1.56	8.6±2.0	Grazian+'04
RASS-NEPS	0.1-2.4 keV	219 w/z	0.22	$\xi(s)$	1.8*	7.4±1.8	Mullis+'04
XMM-2dF	0.5-2 keV	432	1.19	$w(\theta)$	1.8*	16.4±1.3	Basilakos+,'05
"	2-10 keV	171	0.75	"	1.8*	19.0±3.0	Basilakos+,'04
XMM-COSMOS	0.5-2 keV	1037	1.07	"	1.8*	9.4±0.8	TM+'07
"	2-4.5 keV	545	0.87	"	1.8*	6.9(+2.2;-3.1)	"
"	4.5-10 keV	151	0.60	"	1.8*	12.7(+2.3;-2.7)	"
XMM-ELAIS S1	0.5-2 keV	395	1.00	"	1.8*	12.8±4.2	Puccetti+'06
"	2-10 keV	205	0.85	"	1.8*	17.9±4.8	"
CXO-CLASXS+CDF	2-8 keV	168 w/z	0.45	$\xi(s)$	1.9±0.3	7.9±0.9	Yang+'06
"	"	151 w/z	0.92	"	1.4±0.2	10.1(+1.1;-1.0)	
"	"	77 w/z	1.26	"	2.0±0.7	8.4(+1.8;-2.4)	"
"	"	89 w/z	2.07	"	1.7±0.5	12.4(+2.7;-3.4)	"
CXO-CDFS	0.5-10 keV	97 w/z	0.84	$w_p(r_p)$	1.33±0.14	10.3±1.7	Gilli+'05
CXO-CDFN	"	160 w/z	0.96	"	1.50±0.12	5.5±0.6	"

- $\xi(r)=(r/r_0)^{-\gamma}$ (real-space) or $\xi(s)=(s/s_0)^{-\gamma}$ (redshift-space),
- comoving coordinates
- Assuming clustering evolution fixed in comoving coord.

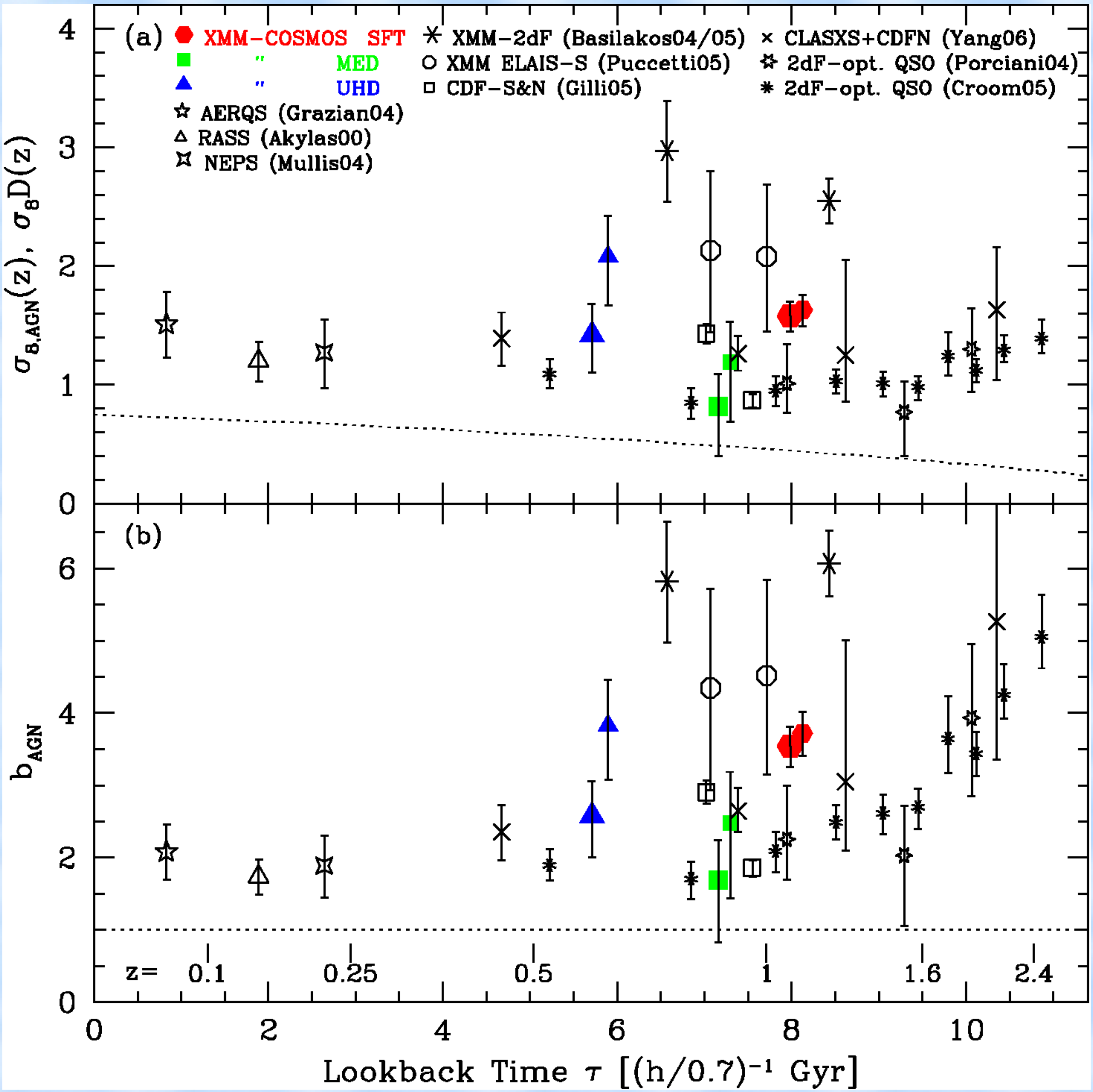
Comparison with Other work and Bias Parameters of AGN clustering
(TM+07 approach)

- Convert the 3-D correlation functions to the RMS density fluctuations in 8h^{-1} Mpc^{-1} : $\sigma_{8,\mathrm{AGN}}(z)$

$$\sigma^2_{8,\mathrm{AGN}} = \int\int \xi(|\mathbf{r}_1 - \mathbf{r}_2|) dV_1 dV_2 / V^2$$

- Direct comparison with DM fluctuation: $\sigma_8 D(z)$.
- Insensitive to assumed slope, when γ is fixed.
- Convert AGN/QSO ACF mesurements from literature to the same $\sigma_{8,\mathrm{AGN}}(z)$.
- Plot against the effective mean redshift of the sample from various works.

Density Fluctuation and Bias



- **Convert $\xi(r,z)$ to $\sigma_{8,\mathrm{AGN}}(z)$**: the rms fluctuation in the $8h^{-1}$ Mpc sphere. Comparison on the common ground.
- **Comparison with $\sigma_8 D(z)$** mass distribution from the linear theory with WMAP σ_8.
- **Bias parameter** of the X-ray AGN distribution $b_{\mathrm{AGN}}=\sigma_{8,\mathrm{AGN}}(z)\,/\sigma_8 D(z)$

Trends

- No evidence for difference between obscured and unobscured AGNs (by X-ray colors) (directly by Gilli+'05, Yang+'06, indirectly by some XMM $w(\theta)$'s)
- CDF-S has stronger clustering amplitude ($\approx \times 1.6$) than HDF/CDF-N (Gilli+'05).. Cosmic Variance
- A weak dependence of clustering amplitude with Lx (Yang +'06)

4. Some Cosmological Implications

Typical Mass of Dark Matter Halo that these AGNs reside

- Typical Mass of the Dark Matter Halo is a function of bias parameter (e.g. Mo & White 1996; Sheth, Mo, Tormen 2001)

$$b(M,z) = 1 + \frac{1}{\sqrt{a}\delta_c(z)}\left[a\nu^2\sqrt{a} + 0.5\sqrt{a}(a\nu^2)^{(1-c)} - \frac{(a\nu^2)^c}{(a\nu^2)^c + 0.5(1-c)(1-c/2)}\right]$$

Sheth, Mo, Tormen 2001

- For XMM-AGNs along with some CXO AGNs in literature:

$b_{AGN} \approx 2\text{–}4, M_{halo} \approx 10^{13}\text{–}10^{14}\ M_{\odot}$

$n(>\sim M_{halo}) \approx 10^{-3}\text{–}10^{-4}\ h^{-1}\ \mathrm{Mpc}^{-3}$ (Halo MF by Jenkins+2001, Warren+2006)

This is 1-10 times the number density of AGNs (unobscured+obscured) (log Lx>≈42.5 at z≈1) approximately represented by the sample.

cf. Luminous Optical QSOs: M_{halo} = a few $\times 10^{12}\ M_{\odot}$ (e.g. Croom+05,)

Lifetime of AGN activity

Lifetime of QSO activity t_Q (Martini & Weinberg 01; Haimann & Hui 01) can be estimated assuming....

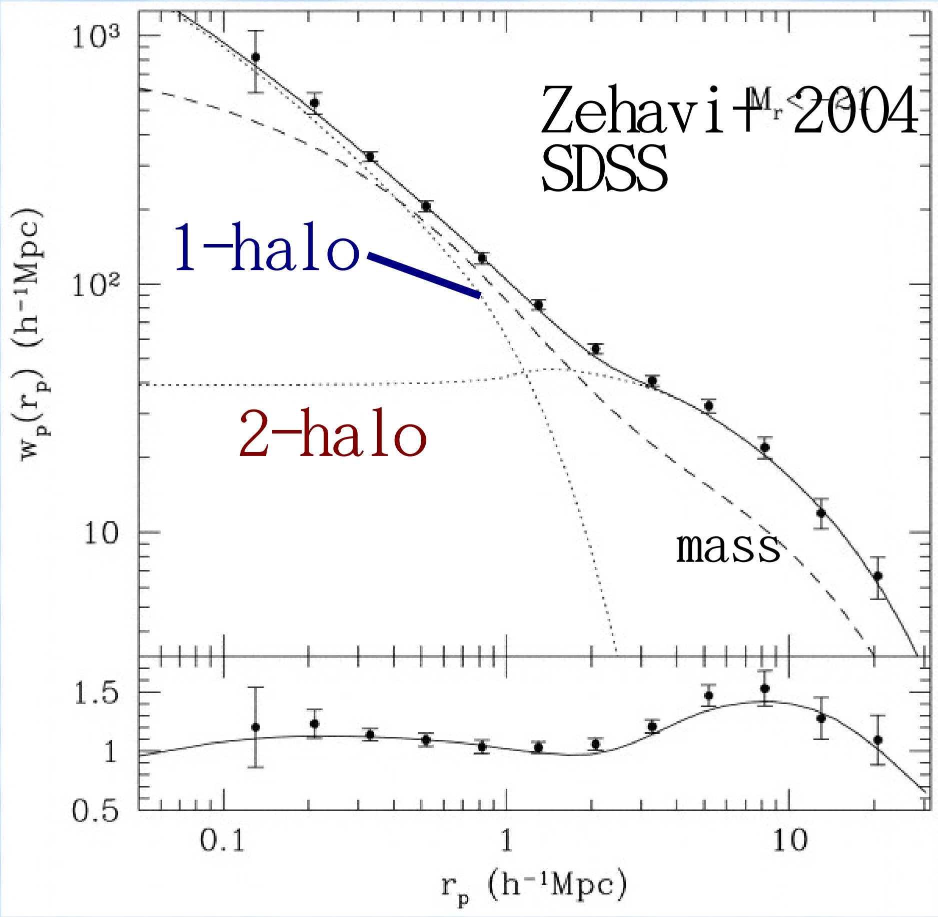
1. At most one active QSO at a time in a halo.
2. QSO luminosities are associated with halo mass monotonically
3. The existence of SMBH is the only requirement for QSO activity

$$\text{QSO Bias} \rightarrow \langle M_{\text{halo}} \rangle$$

$$\text{Duty cycle} \approx n(>L_{\text{QSO,min}})/n(>M_{\text{halo,min}}) \approx t_Q/t_{\text{halo}}$$

- Works for luminous QSOs, (e.g Croom+05, $t_Q \approx 10^7$yr)
- **Crudely for XMM-Newton X-ray AGNs at $z \approx 1$, $\log L_x > \approx 42.5$, $n \approx$ a few $\times 10^{-4}\ h^{-1}\ \text{Mpc}^{-3}$, duty cycle ≈ 0.1–1**
- At $0.8 < z < 2$, $t_{AGN} \approx$ Gyr
- Some of the above assumptions are not valid. (A single halo contains multiple galaxies and each of them has a SMBH)

Current popular halo model for galaxies



- Two point Correlation Function=

  1-halo term+2-halo term

- Fit with Halo Occupation Model $N_{gal}(M_{halo})$ (Cooray & Sheth'02 for review)
- For local SDSS galaxies, more than one galaxy per halo for M_{halo}> a few x10^{-12} $M_{\odot}$
- A similar result at 0.4<z<0.8 (e.g. Phelps+'06/Combo-17)
- Apply to X-ray AGN to galaxy Cross-correlation?

Further Cosmological Implications?

Cosmological Parameters from the Likelihood Analysis

Data	Ω_m	w	σ_8	b_0	χ^2/dof
XMM-Newton	0.28 ± 0.03	$w = -1$	0.75 ± 0.03	$2.0^{+0.20}_{-0.25}$	0.90
XMM-Newton/SN Ia	0.26 ± 0.04	$-0.90^{+0.10}_{-0.05}$	0.73	2.0	0.87

Basilakos & Plionis 2006

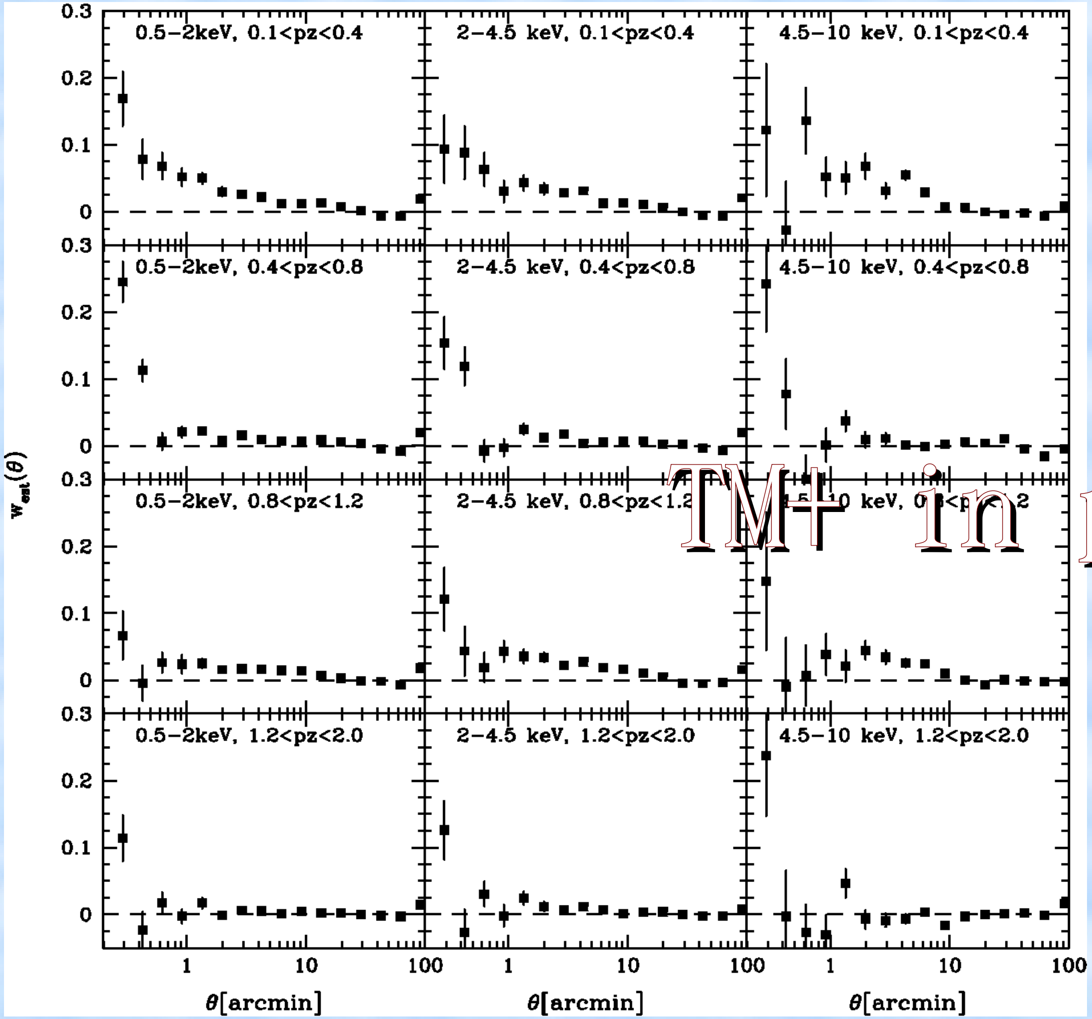
- Basilakos & Plionis (2005, 2006) went further by fitting $w_{\mathrm{AGN}}(\theta)$ with a model involving cosmological parameters assuming:
  - Linear biasing (b (z)) is scale independent. here is a redshift dependence.
  - AGN bias at z=0 (b_0) is a free parameter of fit.
  - Dependence of cosmology is solely in slope/shape of ACF
    - Sensitivity of the results to linear biasing assumption?
  - In excellent agreement with the WMAP results!

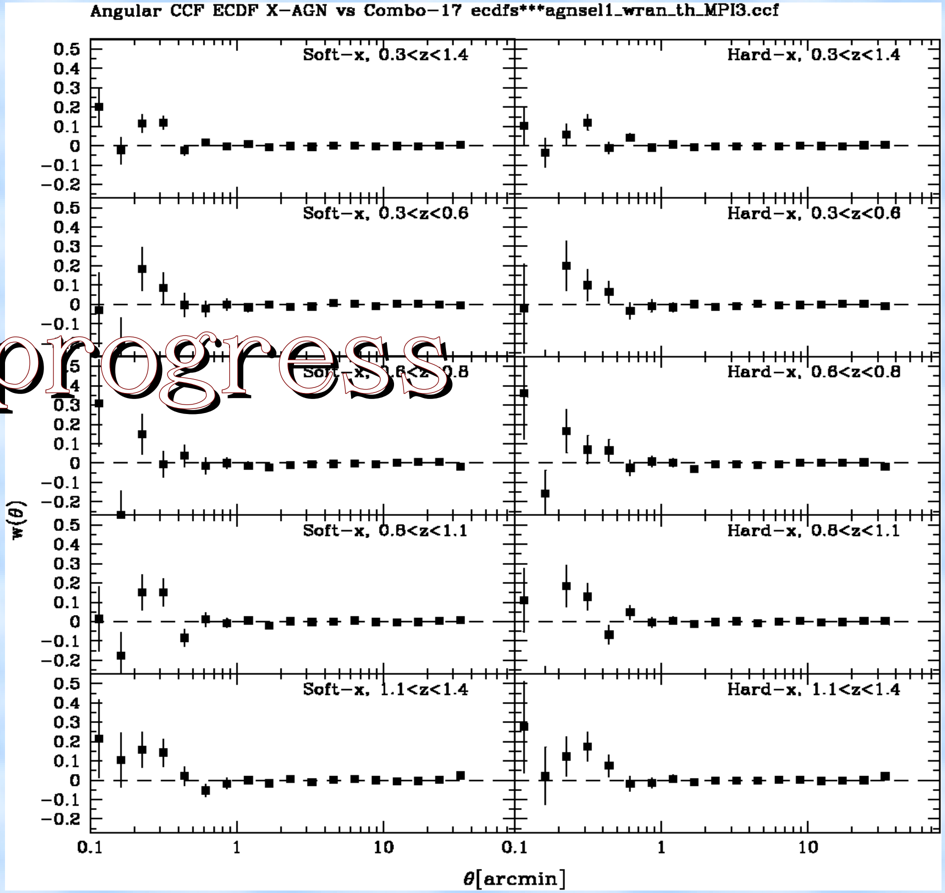
5. Other Approaches

- Cross-correlation function with other classes of objects:
  - $\xi_{agn\text{-}gal}=b_{agn}b_{gal}\xi_{mass}$
  - With clusters:
    - Cappelluti+'05 in cluster fields,+'07 in NEPS.
  - With galaxies (better statistics for precise investigations, also traces more local environments):
    - TM+ in XMM-COSMOS/E-CDFS
    - Coil+ in EGS (this session)
    - Francke+ poster

      Ly-break gal vs X-ray src $b_{AGN}\approx 6$ @ $z=3$
    - See also Cheng, Kauffmann+'06 (SDSS NLAGN+Galaxies)

Galaxies vs X-ray Source



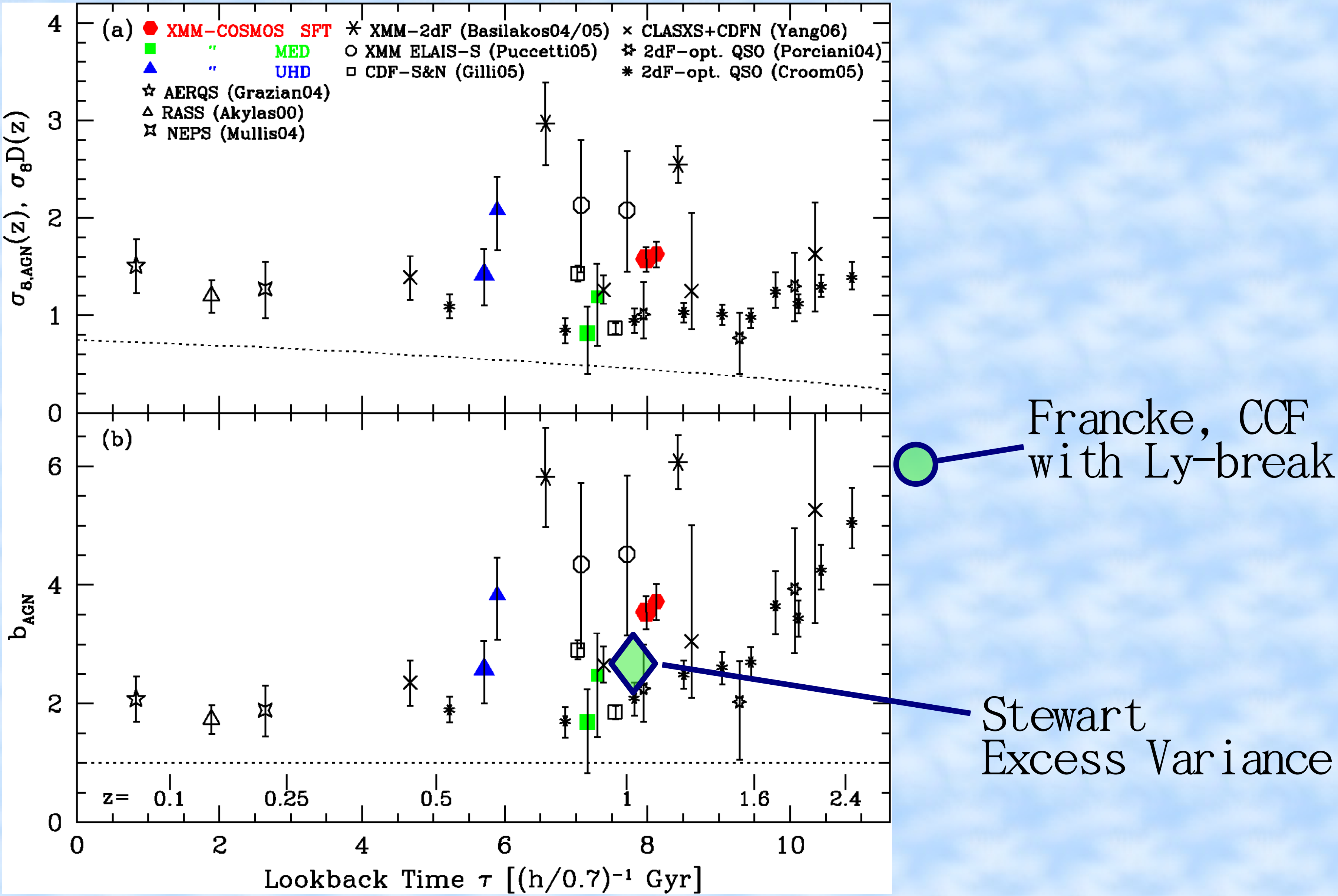


TM+ in progress

XMM-COSMOS vs Galaxies

ECDFS AGN vs Combo-17 galaxies

- Eccess Variance
  - Yang+'03, LHNW (CLASXS): **hard band sources are more strongly clustered**, but see their own recent $\xi(s)$ studies...
  - Stewart, poster: 2XMM catalog. 16% of excess variance for Sx>1e-14 cgs, $b_{AGN}\approx$**2.6 @z≈1-2**.
- **Galaxy counts around X-ray AGNs** and comparison with environments of non-AGN galaxies
  - 31 AGNs in 0.4<z<0.6 have the same local environmet (<500 kpc) as galaxies with similar morphologies. Minor merger for fueling (Waskett+ 06)?
  - 53 X-ray AGNs at z≈1 avoid underdense regions. AGN with blue host reside in denser environment than galaxies in AEGIS (Georgakakis+'06)



(a)
XMM-COSMOS SFT
" MED
" UHD
AERQS (Grazian04)
RASS (Akylas00)
NEPS (Mullis04)
XMM-2dF (Basilakos04/05)
XMM ELAIS-S (Puccetti05)
CDF-S&N (Gilli05)
CLASXS+CDFN (Yang06)
2dF-opt. QSO (Porciani04)
2dF-opt. QSO (Croom05)
$\sigma_{8,AGN}(z)$, $\sigma_8 D(z)$
(b)
b_{AGN}
z= 0.1 0.25 0.5 1 1.6 2.4
Lookback Time τ [(h/0.7)$^{-1}$ Gyr]
Francke, CCF with Ly-break
Stewart Excess Variance

Summary

- Current status of correlation function and environmental studies in X-ray surveys are reviewed.
- Technical aspects of of two-point correlation functions are discussed
- $b_{AGN} \approx 2$ in local universe, $b_{AGN} \approx 2-6$ at $z>1$
- The b_{AGN} values of AGNs at $z \approx 1$ suggest associations with 10^{13}–10^{14} $M_{\odot}$ dark matter halos.
- Cross-correlation with galaxies and galaxy counts around AGNs are starting to give clues to local environment, leading to the understanding of fueling mechanism.