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Max-Planck-Institut für Astrophysik

Angular correlation studies of the cosmic X-ray background:

A new frontier of LSS studies with X-ray surveys

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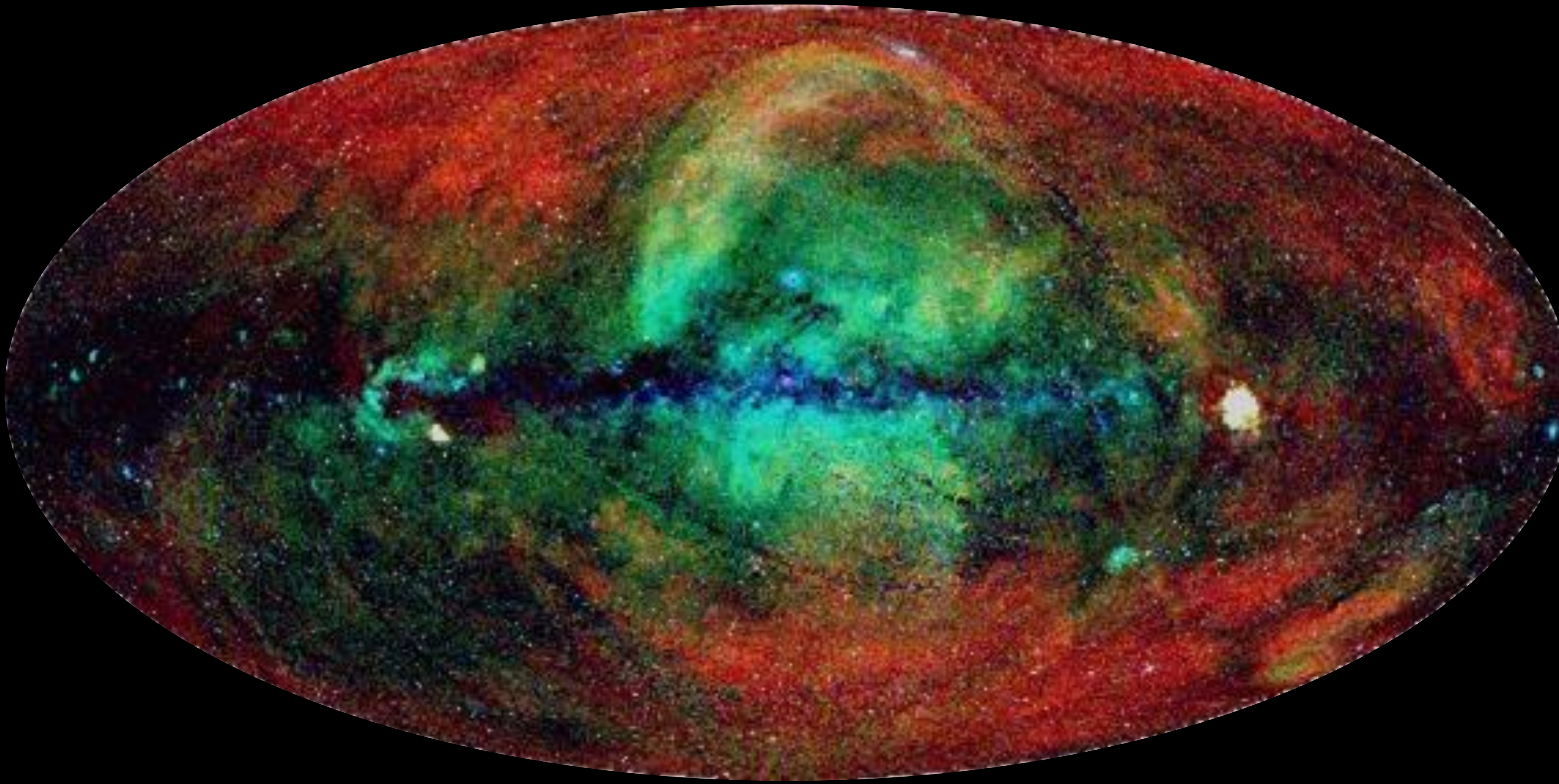
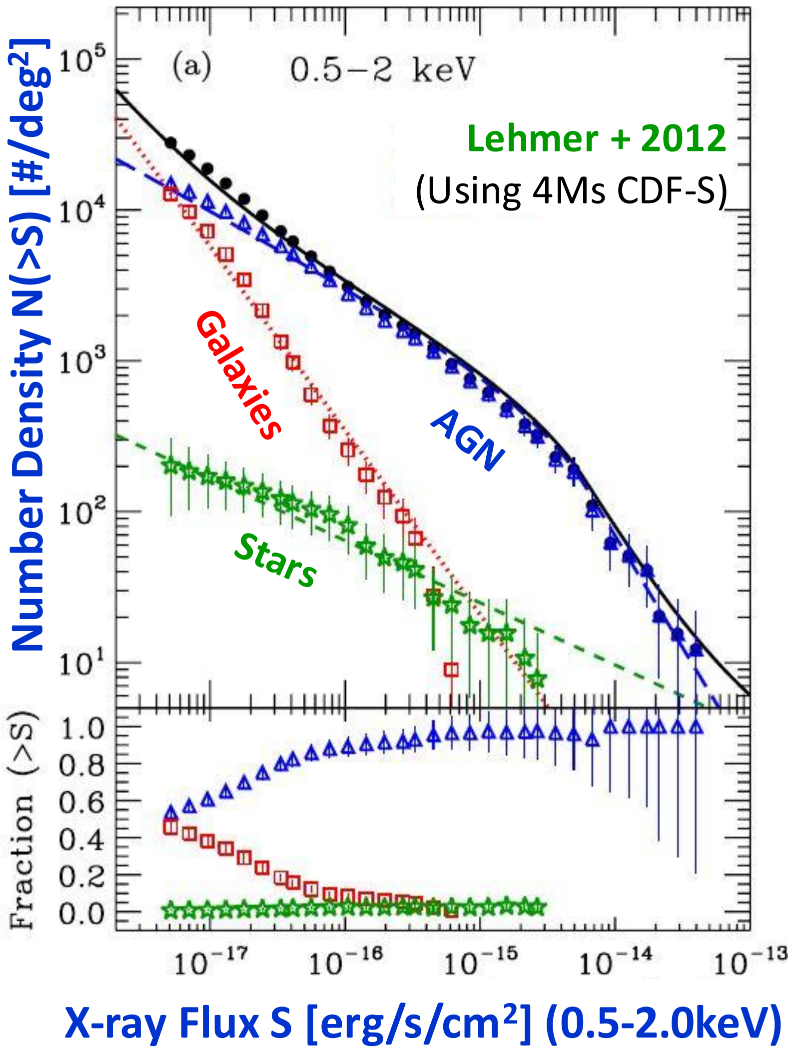
Meeting Hot spots in the XMM sky, Conference, Mykonos Island, Greece, 15.06.2016

Cosmic X-ray background (CXB)



ROSAT PSPC All-Sky: Soft X-ray Background (Trümper 1990, Freyberg+1999)

The resolved CXB – state of the art



- **~75%** of CXB emission is due to point sources with fluxes of **> ~10^{-17} erg/s/cm^2 (0.5-2.0 keV)** (based on 4Msec Chandra-Deep-Field-South (CDFS) , **Xue+2011**)
- Seperated into source types:
  - **~71%** Active Galactic Nuclei (AGN)
  - **~3%** Normal Galaxies
  - **~1%** Stars

→ Resolved CXB shows the formation and accretion history of SMBHs over cosmic time

The unresolved CXB

Lehmer+2012: ~8.2x10^{-12} erg/s/cm^2/deg^2 in 0.5-2.0 keV (based on Hickox+2006)
100% CXB emission

~75% associated with point sources
(S> ~10^{-17} erg/s/cm^2)

~70% associated with AGN

3% Normal Galaxies

CDFs (Hickox+2006): ~4.6x10^{-12} erg/s/cm^2/deg^2 in 1.0-2.0 keV
100% CXB emission

~78% resolved (S> ~4x10^{-17} erg/s/cm^2)
(point and extended sources)

~22% unresolved

Hickox+2007: ~1.0x10^{-12} erg/s/cm^2/deg^2 in 1.0-2.0 keV
~22% CXB emission

~50% associated with optical/IR point sources

~50% unassociated

→ ~10% of CXB remain unassociated

(based on 0.02 deg^2 → cosmic variance)

Our CXB study

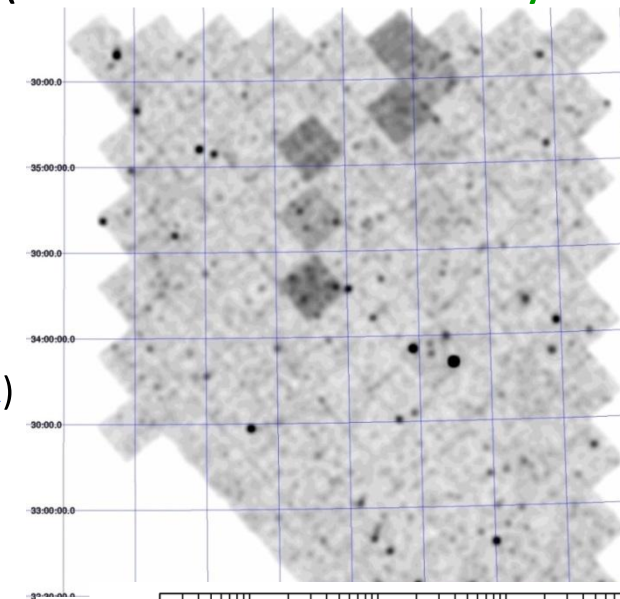
Our Data: 9 deg^2 XBOOTES survey

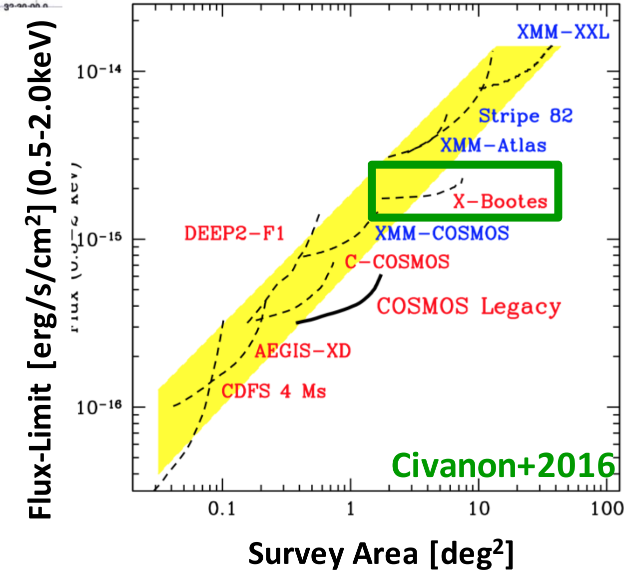
- Advantages for angular correlation studies:
  - largest *Chandra* survey
    - most accurate measurement of CXB fluctuations to date
    - previous studies : ~0.1 deg^2 (e.g. Helgason+2014)
  - *Chandra*'s angular resolution: highest in X-rays
    - measure angular scales down to arcsec-regime!

  → unique access to small-scale clustering regime (< 1 Mpc)
  - *Chandra* Instrumental Background:
    - low, stable, well understood (e.g. Hickox & Markevitch 2006)

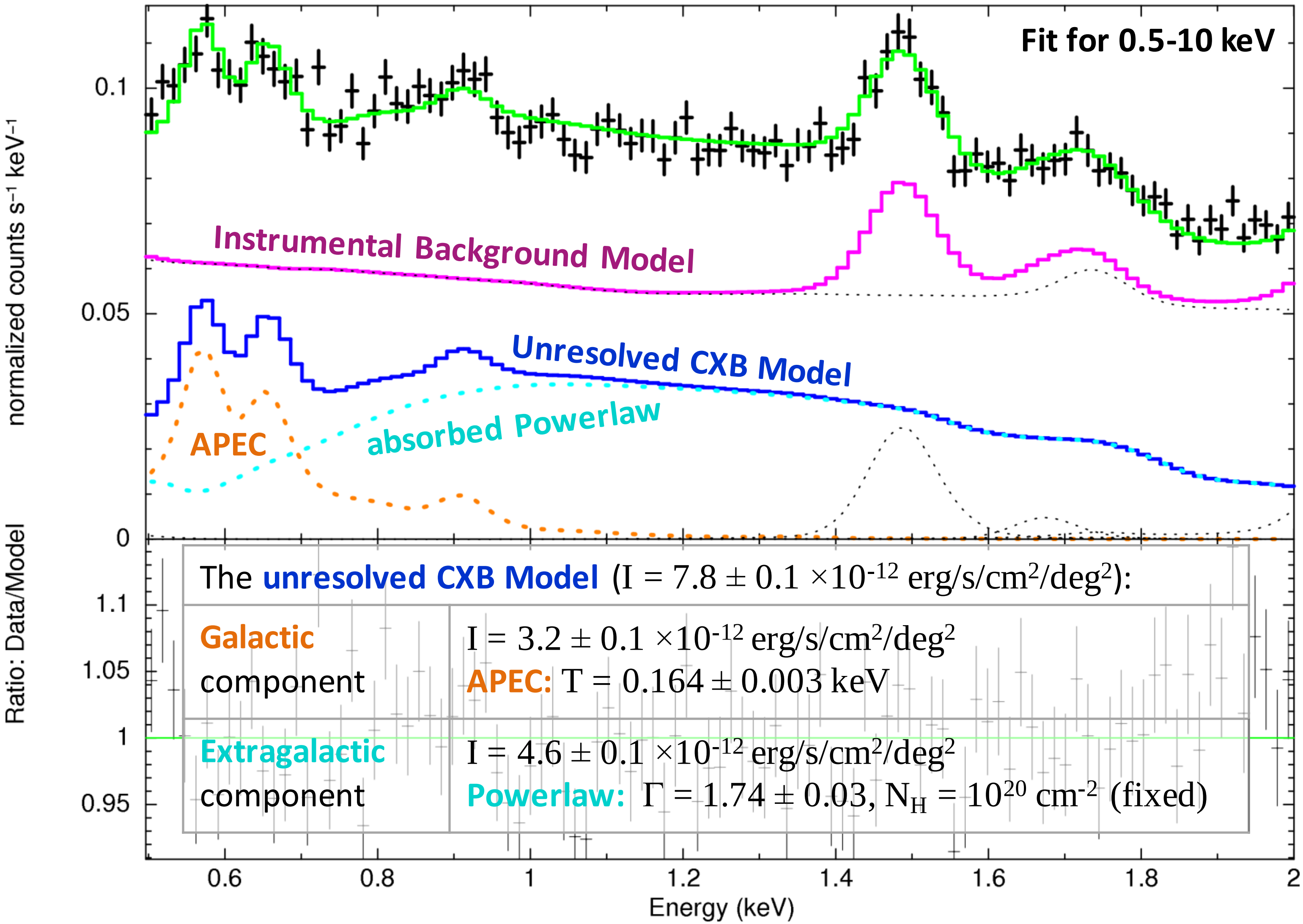
- Properties:
  - 126 contiguous observations (use 118)
  - Unresolved emission:
    - Total Surface Area: ~7 deg^2 (82%)
    - Ave. Exposure Time per Obs.: ~4.3 ksec
    - Total Exposure Time: ~0.5 Msec
    - Point-Source sensitivity: ~2×10^{-15} erg s^{-1} cm^{-2} (0.5-2.0 keV)

XBOOTES field
(Main Ref.: Kenter+2005 & Murray+2005)





Energy Spectrum of unresolved emission (0.5 - 2.0 keV)

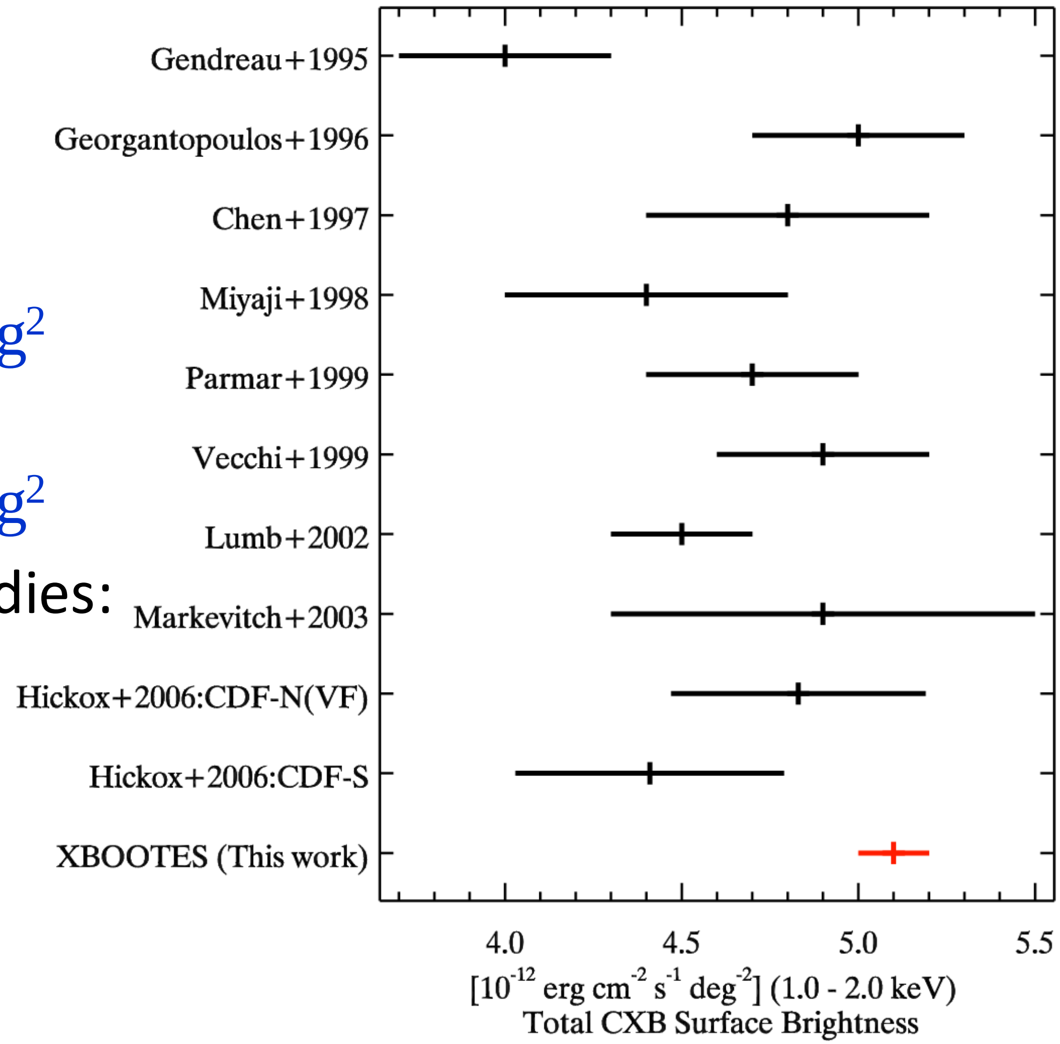


The **unresolved CXB Model** ($I = 7.8 \pm 0.1 \times 10^{-12}$ erg/s/cm^2/deg^2):	
Galactic component	$I = 3.2 \pm 0.1 \times 10^{-12}$ erg/s/cm^2/deg^2 **APEC:** $T = 0.164 \pm 0.003$ keV
Extragalactic component	$I = 4.6 \pm 0.1 \times 10^{-12}$ erg/s/cm^2/deg^2 **Powerlaw:** $\Gamma = 1.74 \pm 0.03$, $N_H = 10^{20}$ cm^{-2} (fixed)

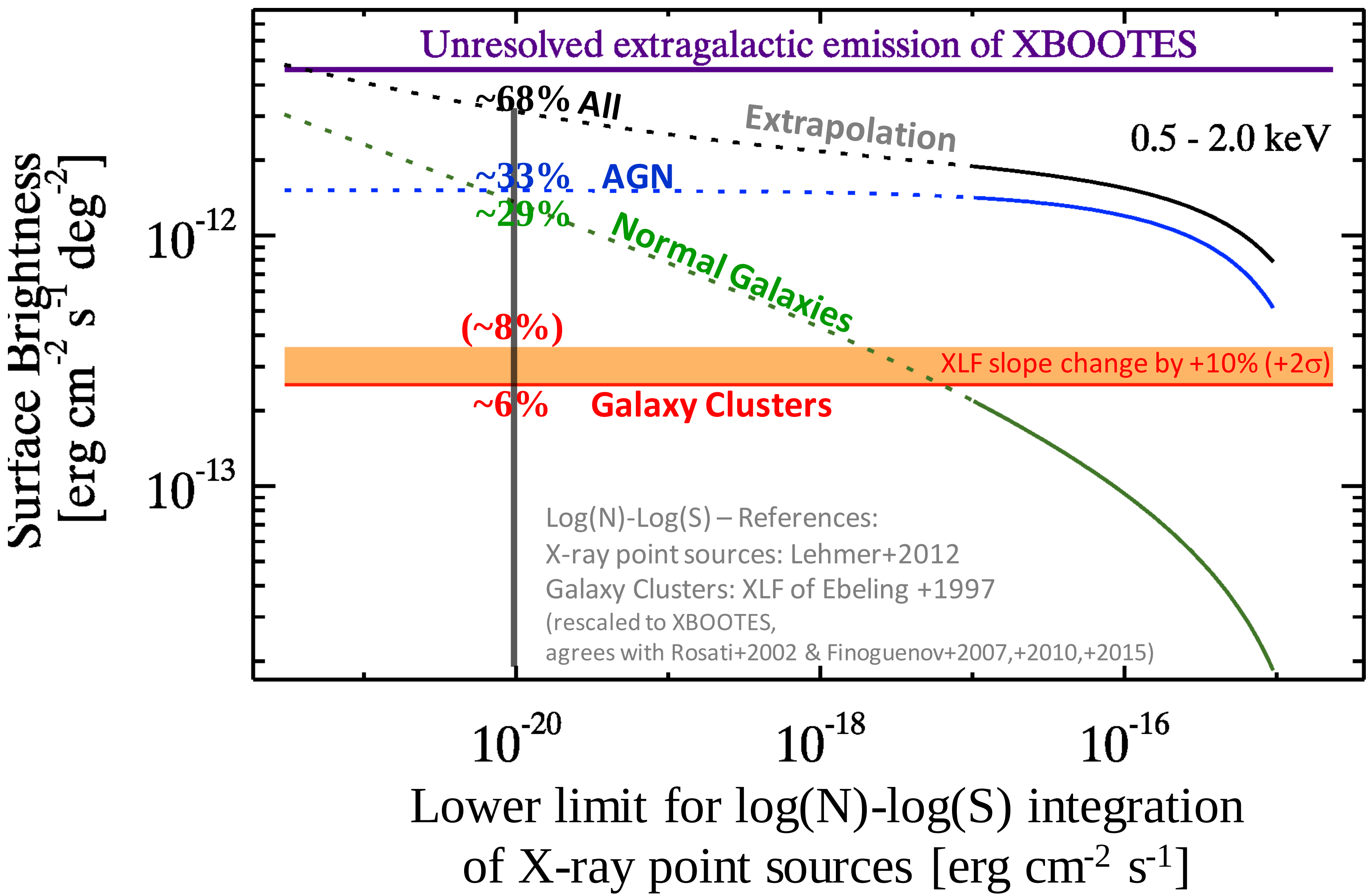
Total extragalactic emission: consistent with previous studies (1.0 - 2.0 keV)

Total extragalactic emission (resolved and unresolved):

- 0.5 – 2.0 keV:
  $9.0 \pm 0.1 \times 10^{-12}$ erg/s/cm^2/deg^2
- 1.0 – 2.0 keV:
  $5.1 \pm 0.1 \times 10^{-12}$ erg/s/cm^2/deg^2
- Agreement with other studies:
  <15% (expect for one)



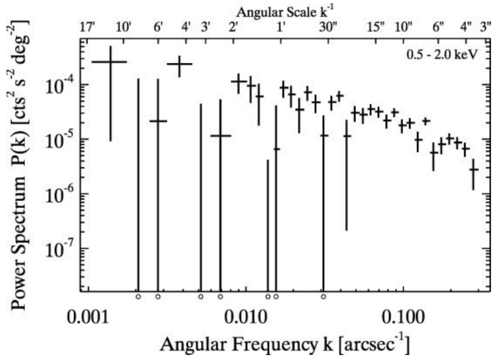
Unresolved extragalactic emission: Components
(0.5 - 2.0 keV)



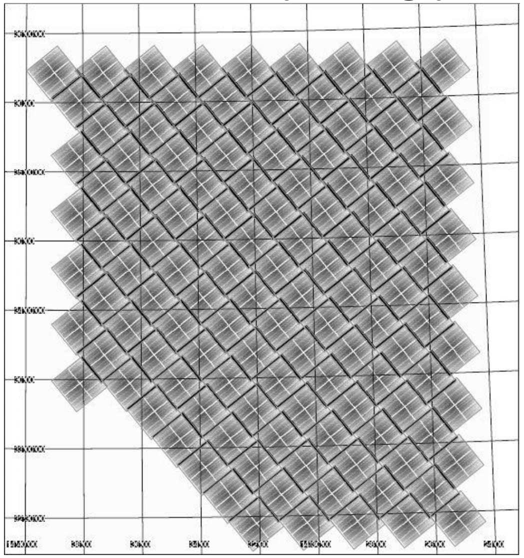
Angular correlation studies of the unresolved CXB

Computing Power Spectrum:

Power Spectrum P(k)
of one field 17’ x 17’ (0.06 deg²)

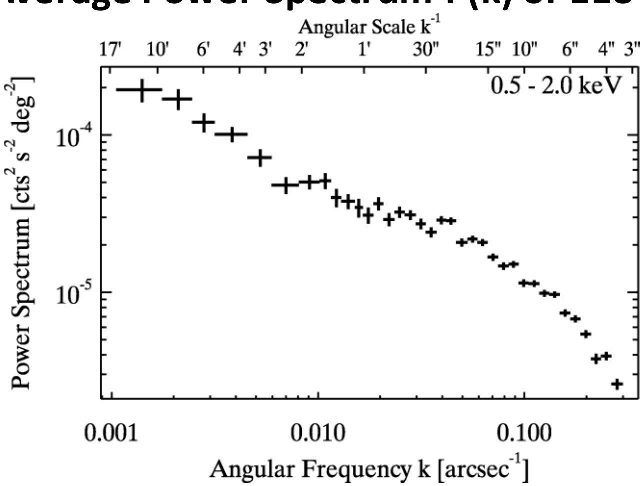


118 Fields (7.2 deg²)

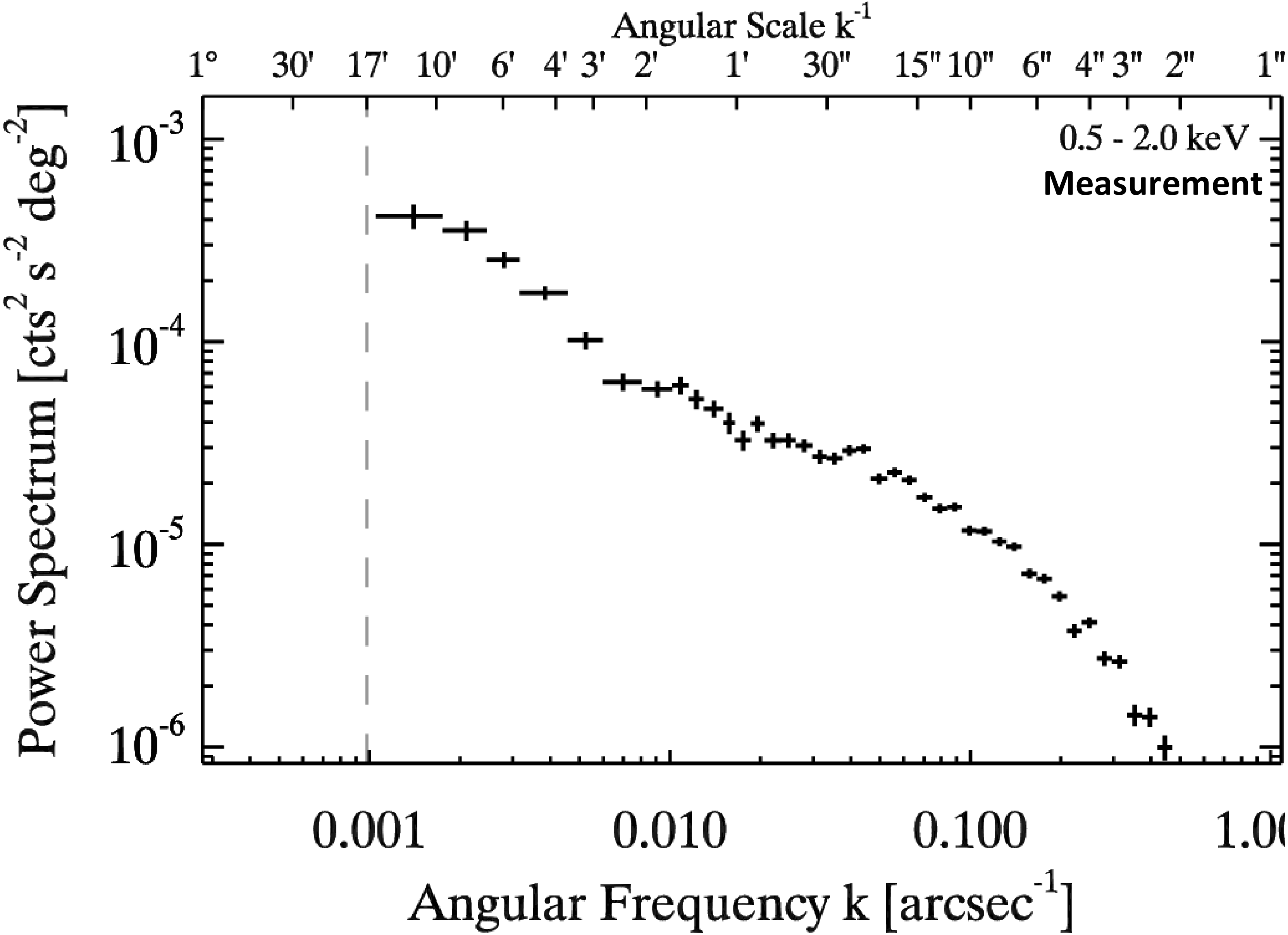


average

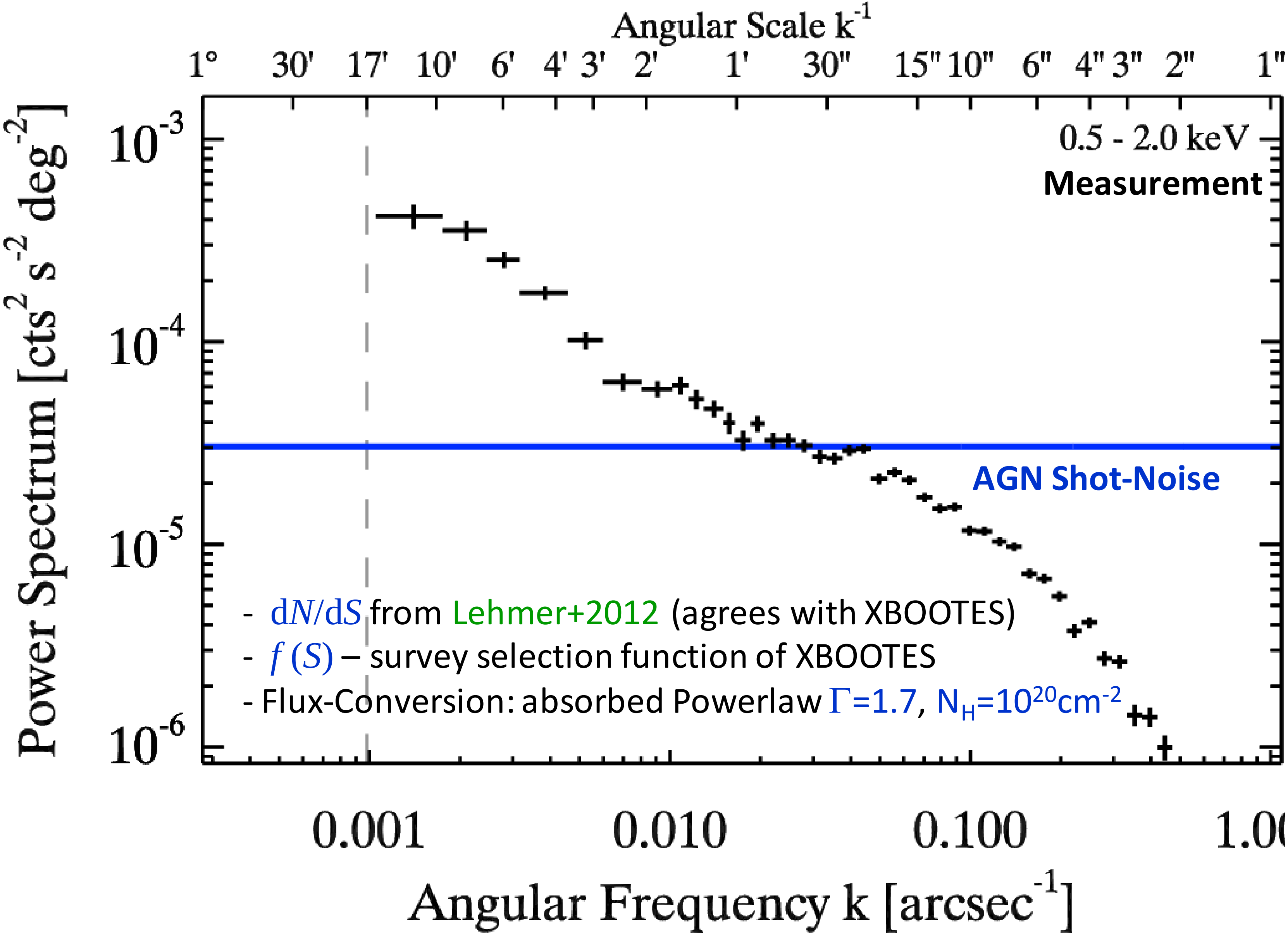
Average Power Spectrum P(k) of 118 fields



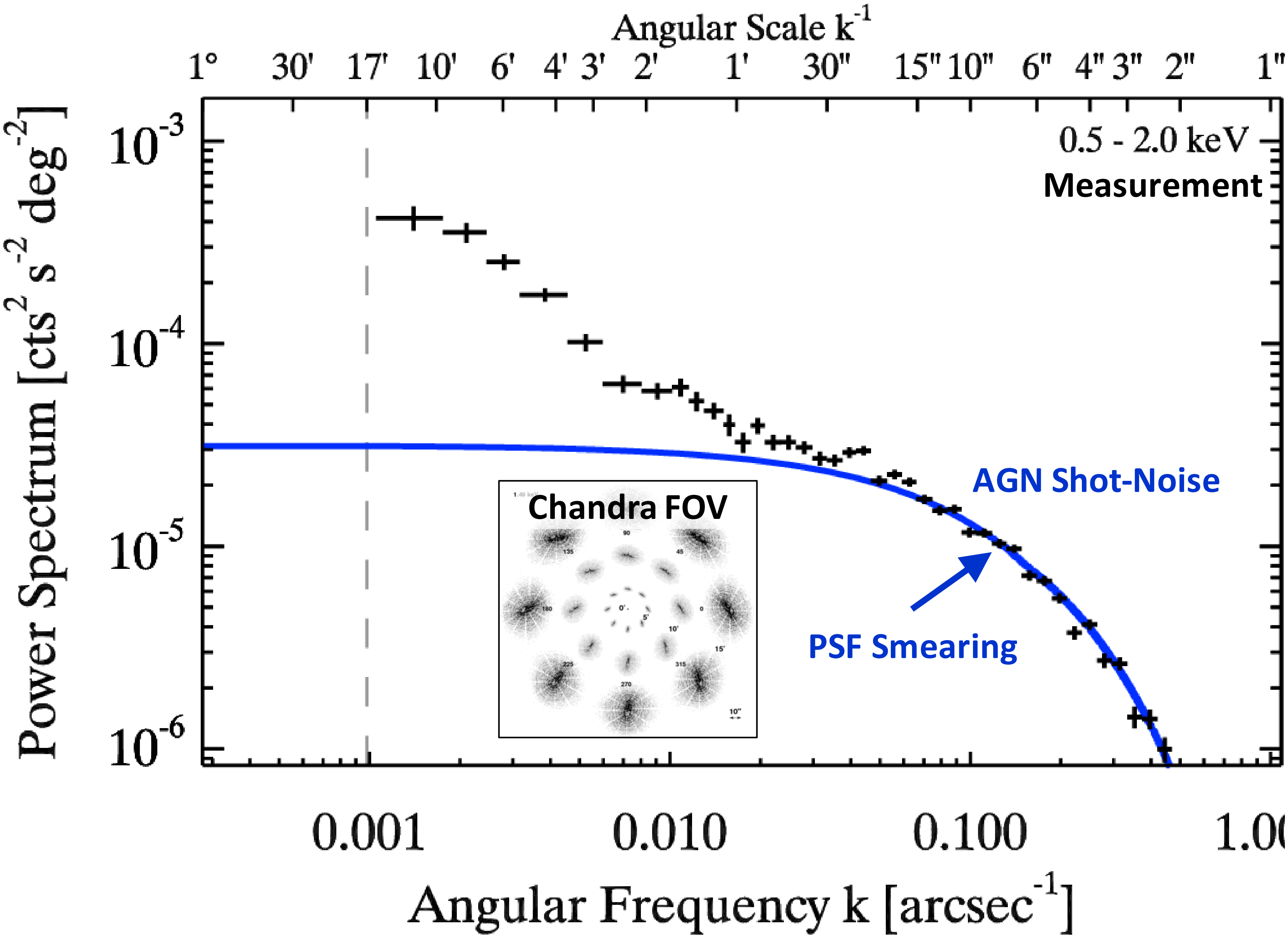
CXB fluctuations for <17‘



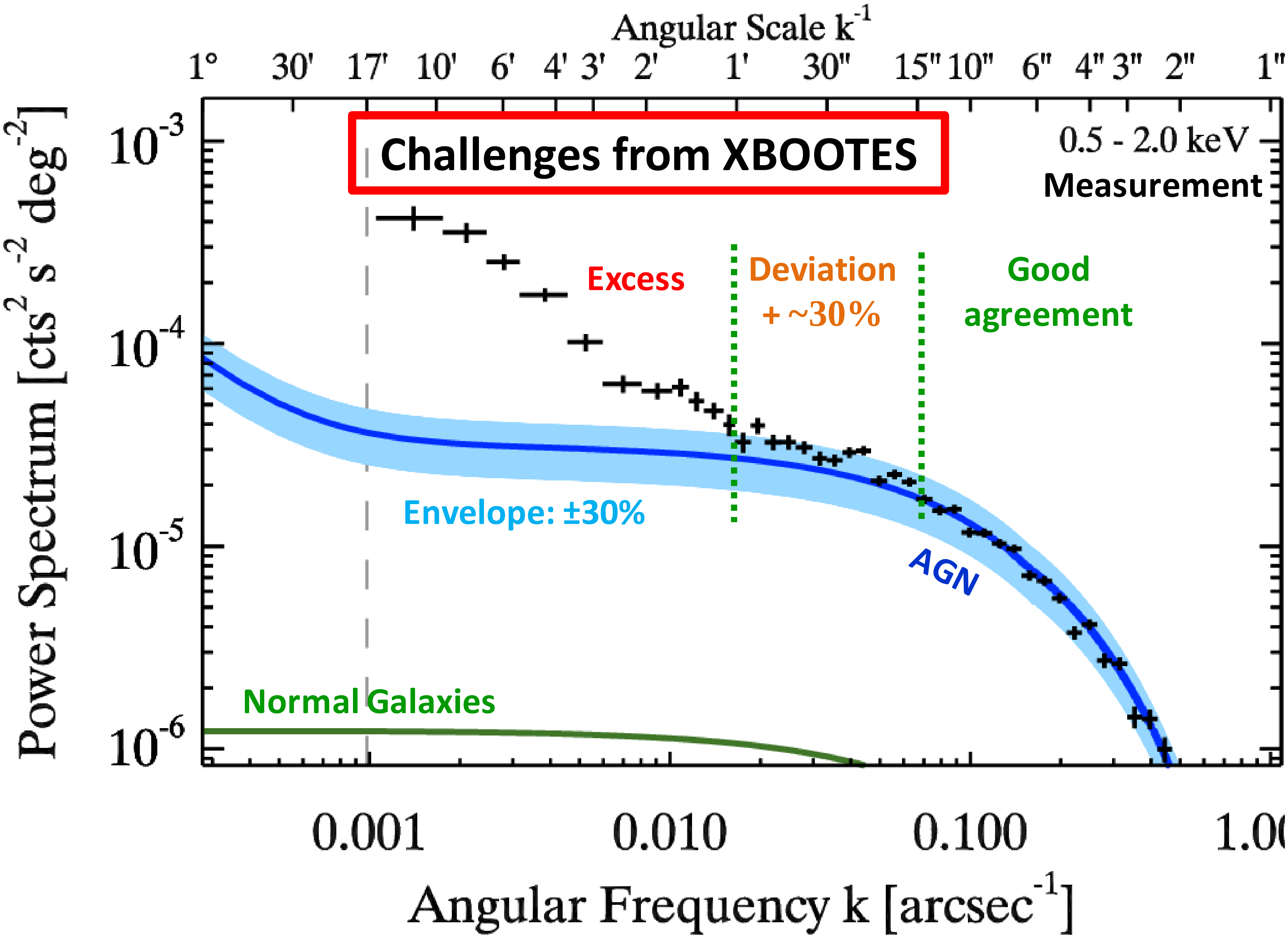
CXB fluctuations for <17‘



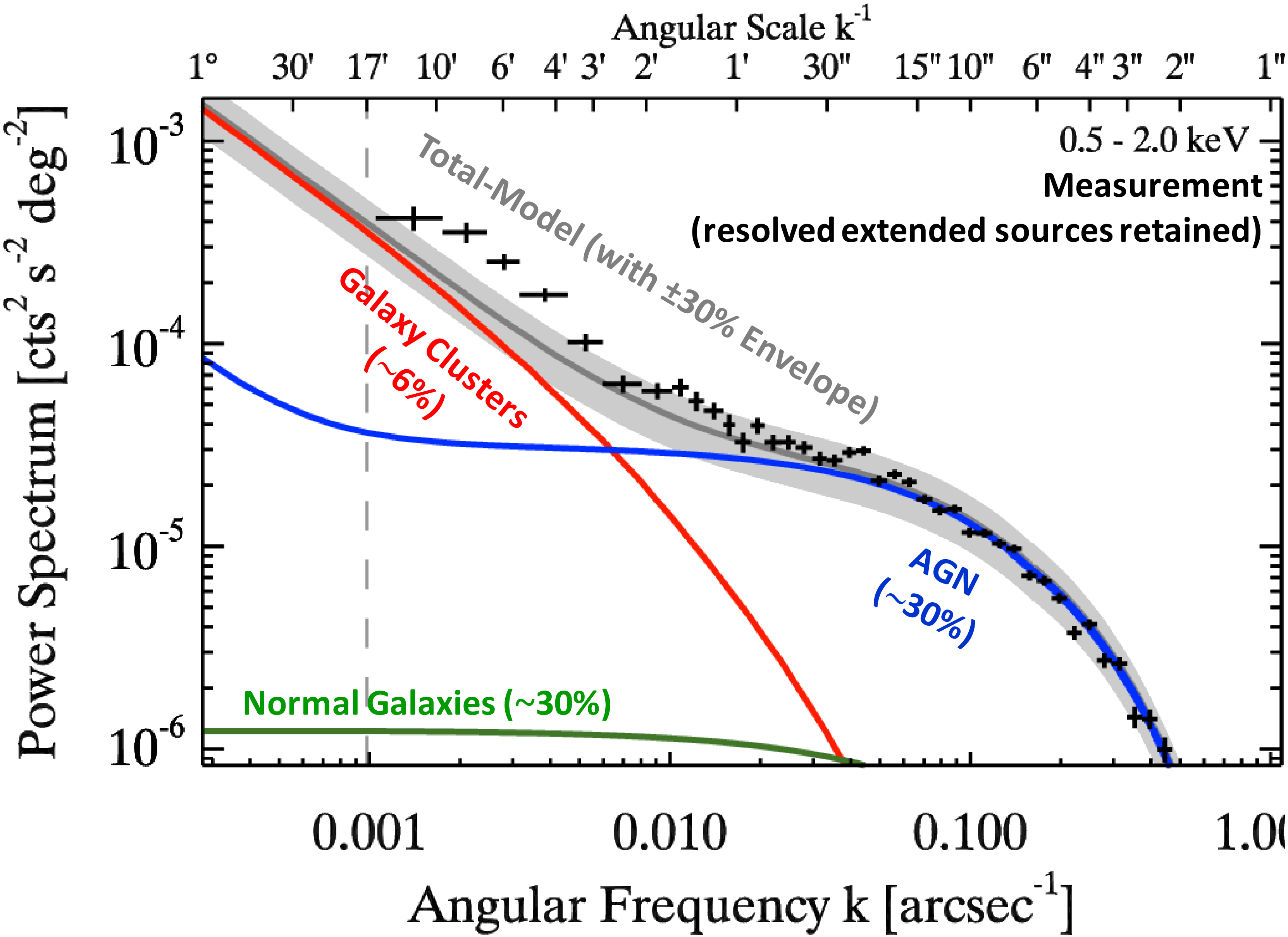
CXB fluctuations for <17‘



CXB fluctuations for <17‘



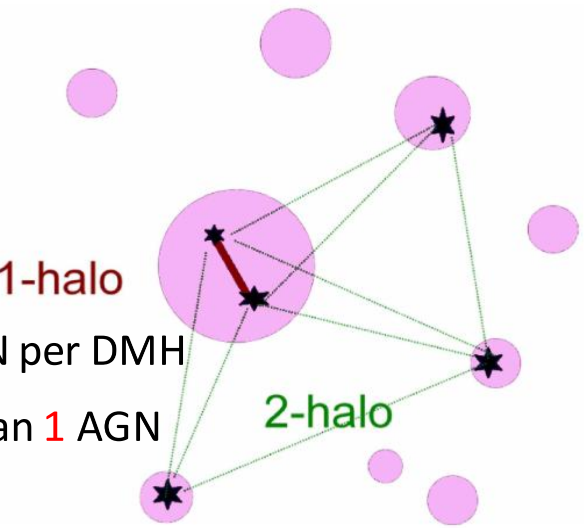
CXB fluctuations for <17‘: first full describtion



Unresolved AGN population of XBOOTES

- Properties:
  - Contribution to unresolved CXB: **~30%**
  - Redshift: Median **$z \sim 1.0$** (67%: **$0.4 < z < 2.3$**)
  - Luminosity: Median **$L \sim 10^{42.6}$ erg/s** (67%: **$10^{41.0} < L < 10^{43.6}$ erg/s**)
- Model uncertainties:
  - Flux-Conversion: **< ~30%**
  - Log(N)-Log(S): **< ~15%** (for shot-noise term)
  - Clustering model:
    - $\theta < 2'$ for $z<1$ corresponds to < 1.3 Mpc/h → 1-halo
    - Theoretical prediction & our assumption: 1 AGN per DMH
    - Possibility: some fraction of DMH with more than 1 AGN

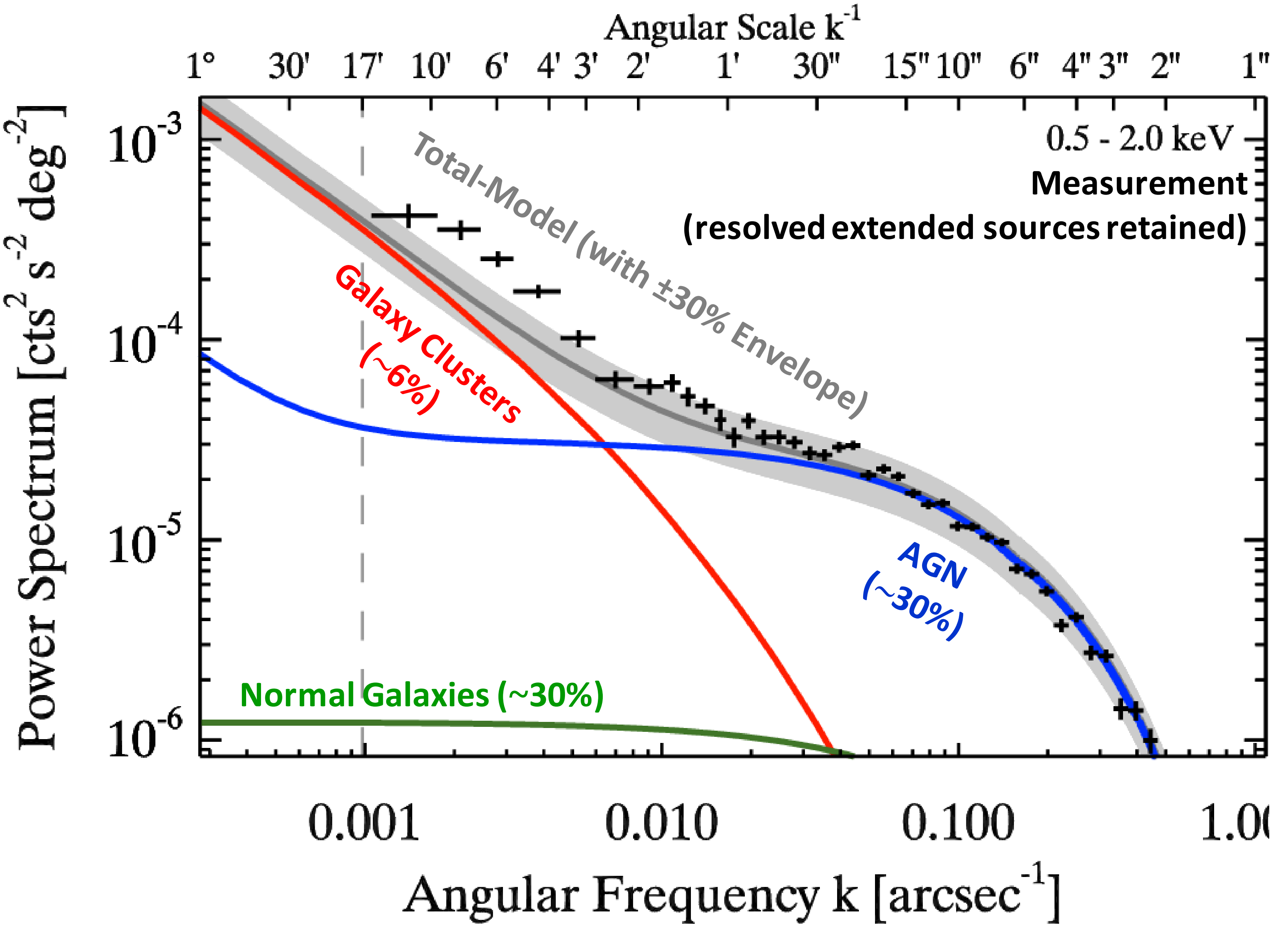
    → higher accuracy and better modeling needed



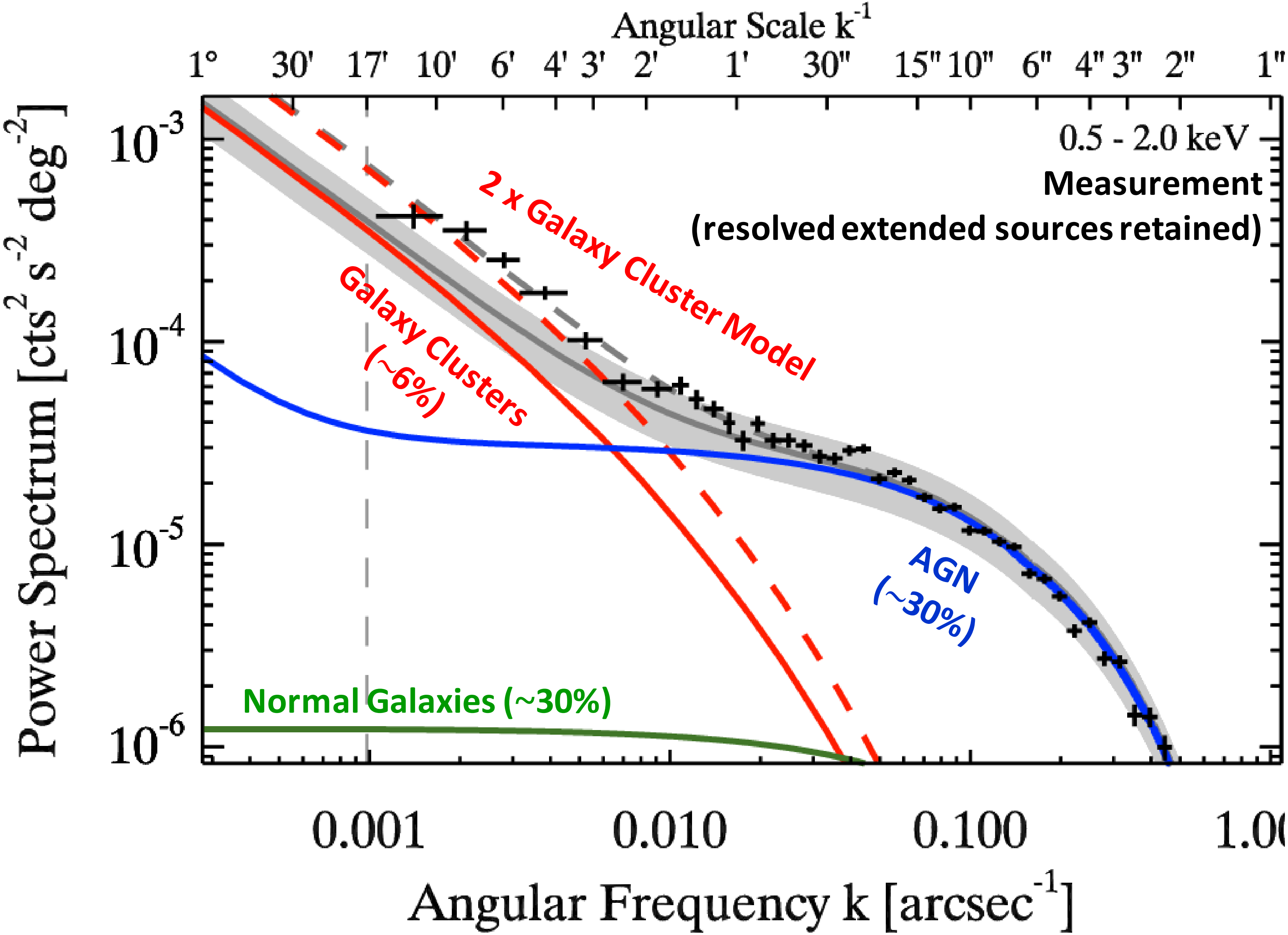
Krumpe+2014

Galaxy clusters cause the excess for $>2'$?!

CXB fluctuations for <17‘: first full describtion



CXB fluctuations for <17‘: first full describtion



Assessment of systematics

- Fluctuations of instrumental background → negligible
- Tested efficiency of removing resolved point-sources:
  - Residual counts: ~1% of unresolved CXB → negligible
- Tested mask effects (but not corrected) → not important (for now)
- Tested different photon-shot-noise estimators → results are robust
- Tested vignetting effects → not important (at given S/N)
- Tested deflaring → not important (at given S/N)

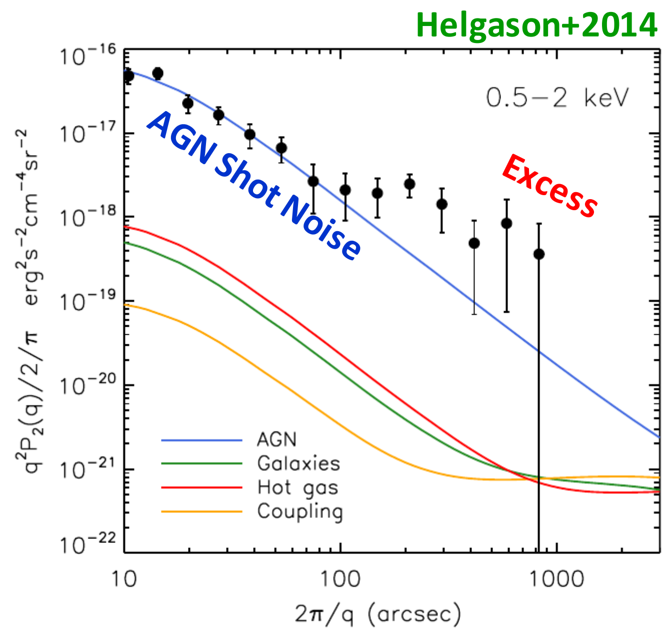
Extragalactic Origin

- Studies with smaller surveys:

  EGS (~0.1 deg^2): Helgason+2014

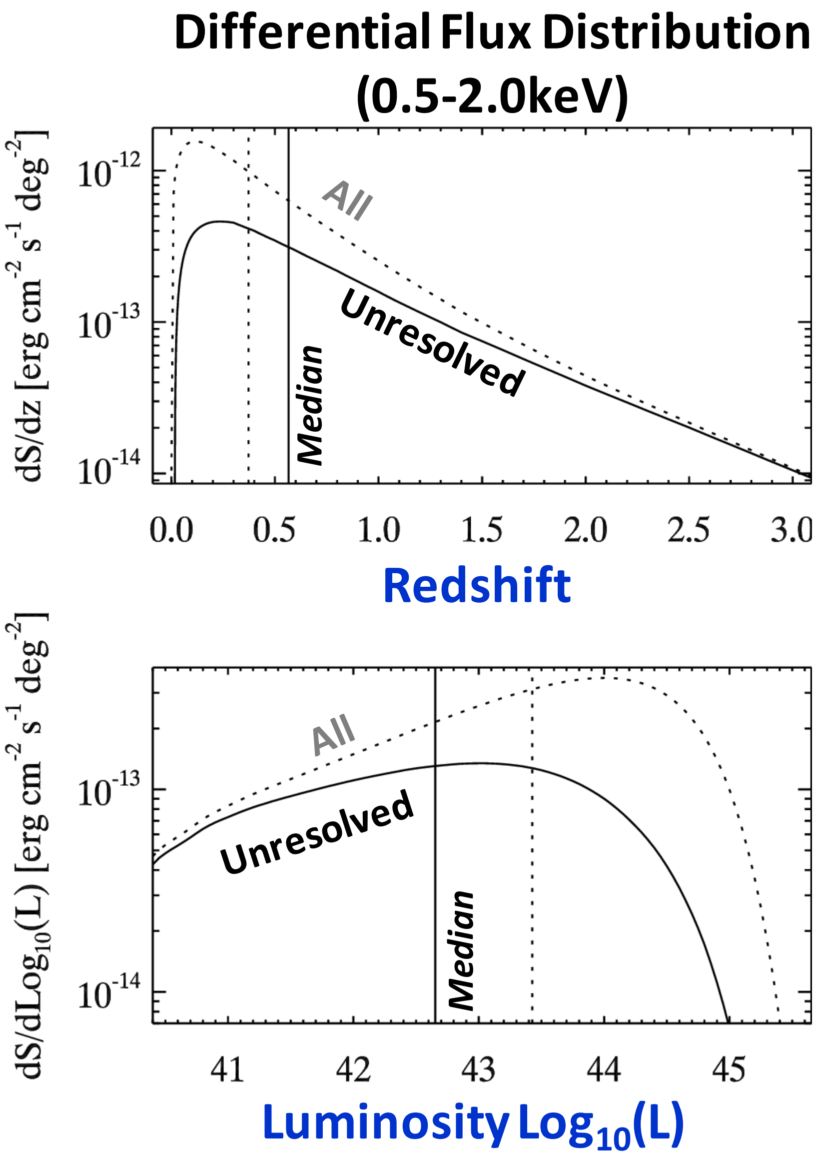
  COSMOS (~2 deg^2): Li,Hasinger+2016, in prep.

  → **Universal feature on the sky ?!**



- Detect in 1-2keV energy band → **Extragalactic origin ?!**

Unresolved galaxy cluster population



Redshift:
Median: $z \sim 0.6$
67%: $0.2 < z < 1.3$

Luminosity:
Median: $L \sim 10^{42.7}$ erg/s
67%: $10^{41.4} < L < 10^{43.8}$ erg/s

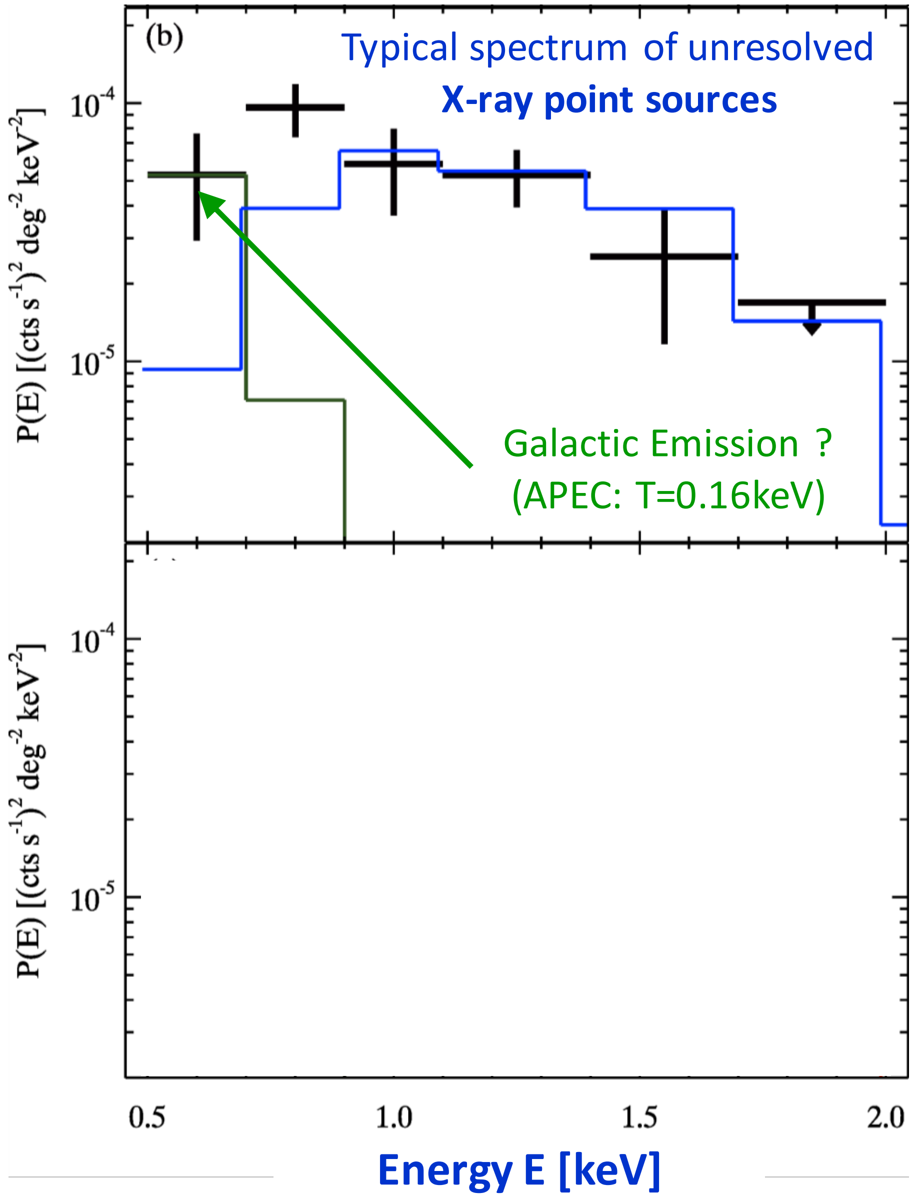
Derived average Parameters:
Temperature: **$T \sim 1.4$ keV (1.6×10^7 K)**
Mass : **$M_{500} \sim 10^{13.5} M_{Sun}$**

Based on XLF of Ebeling +1997
(rescaled to XBOOTES.
agrees with with Rosati+2002,
Finoguenov+2007,+2010,+2015)

Excess: Spectral shape

Average Power per energy bin for 3'-8'
(AGN Shot-Noise subtracted)

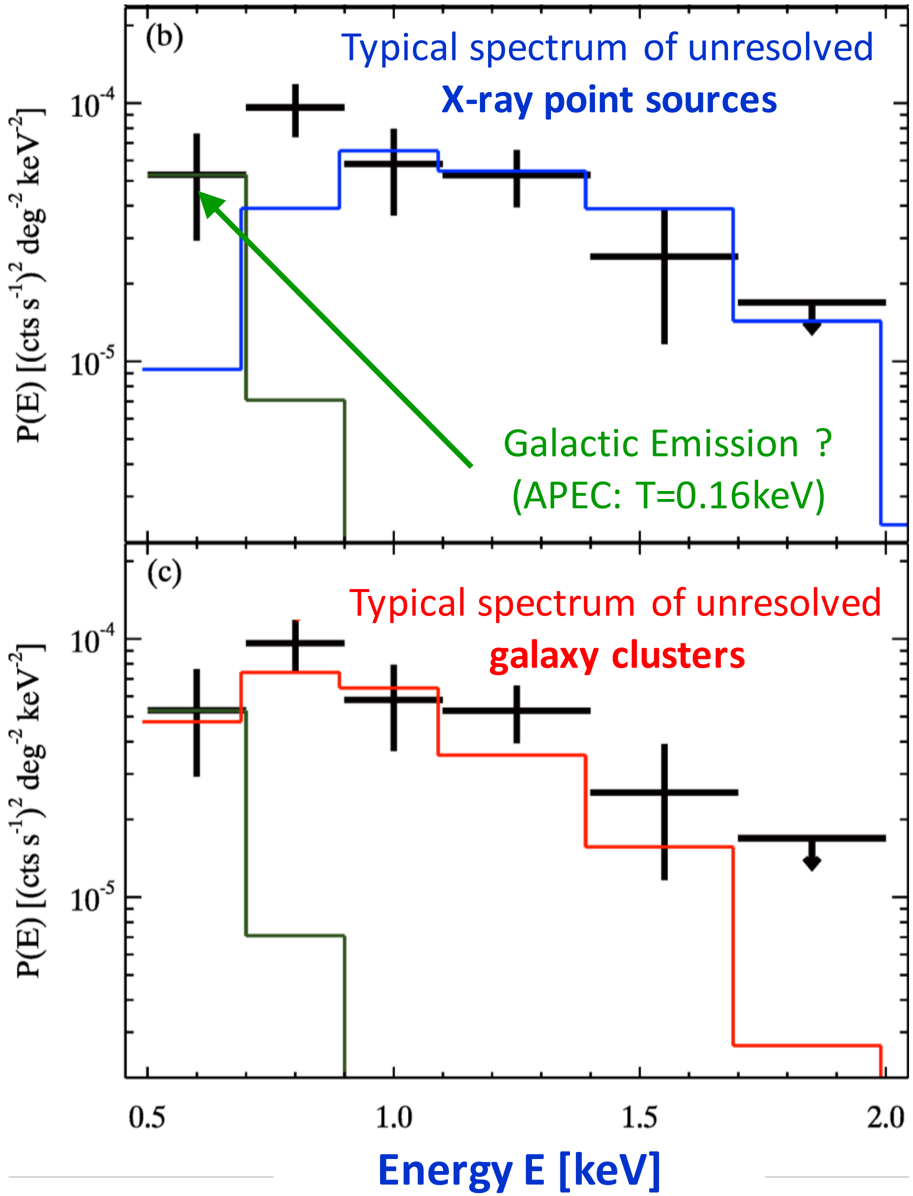
$$P(E) = \frac{\langle P(k) \rangle}{(\Delta E)^2}$$



Excess: Spectral shape agrees with galaxy clusters

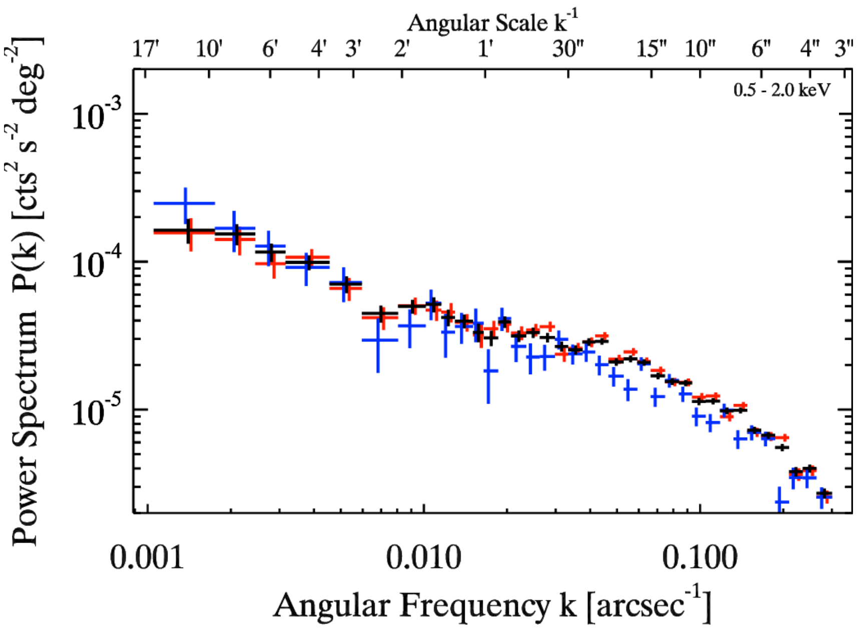
Average Power per energy bin for 3'-8'
(AGN Shot-Noise subtracted)

$$P(E) = \frac{\langle P(k) \rangle}{(\Delta E)^2}$$



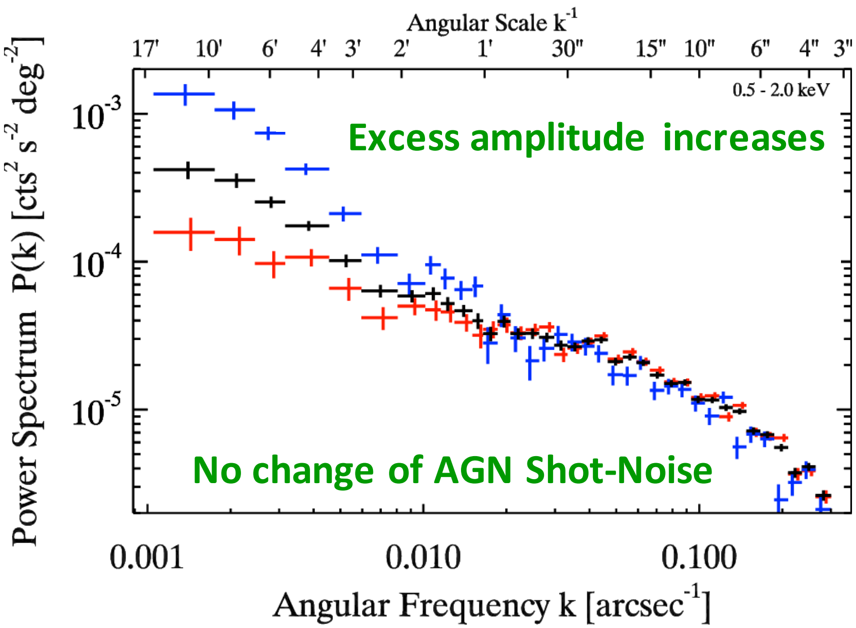
Does the excess depend on extended source sensitivity limit? **YES!**

A) Resolved extended sources removed



B) Resolved extended sources retained

(as shown before)



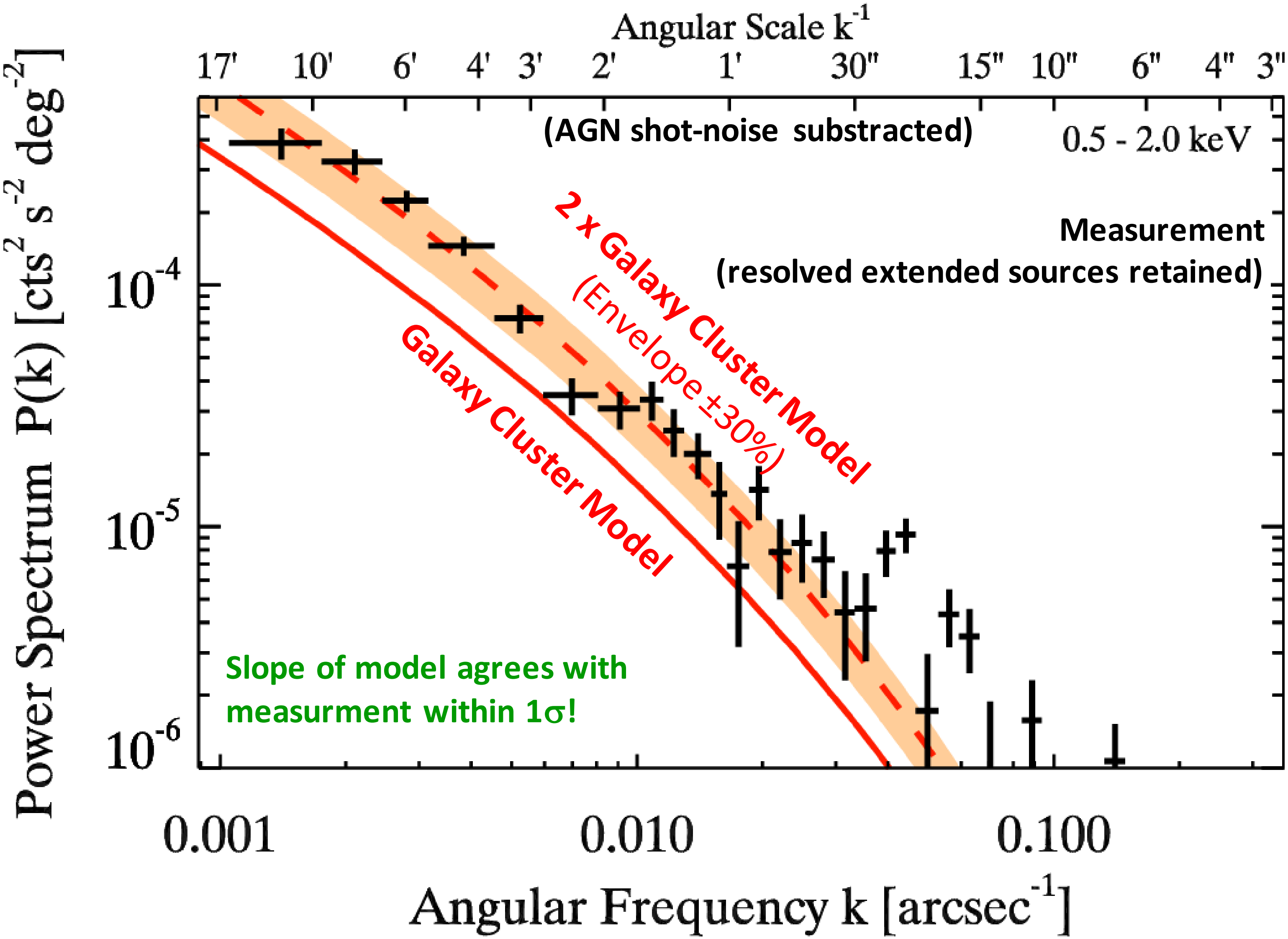
Three selections of XBOOTES fields:

118 fields (default) - some contain resolved extended sources

26 fields - all contain resolved extended sources

76 fields (control) - none contains a resolved extended source

Excess can be explained by galaxy clusters down to ~30”



Clustering Model of galaxy clusters

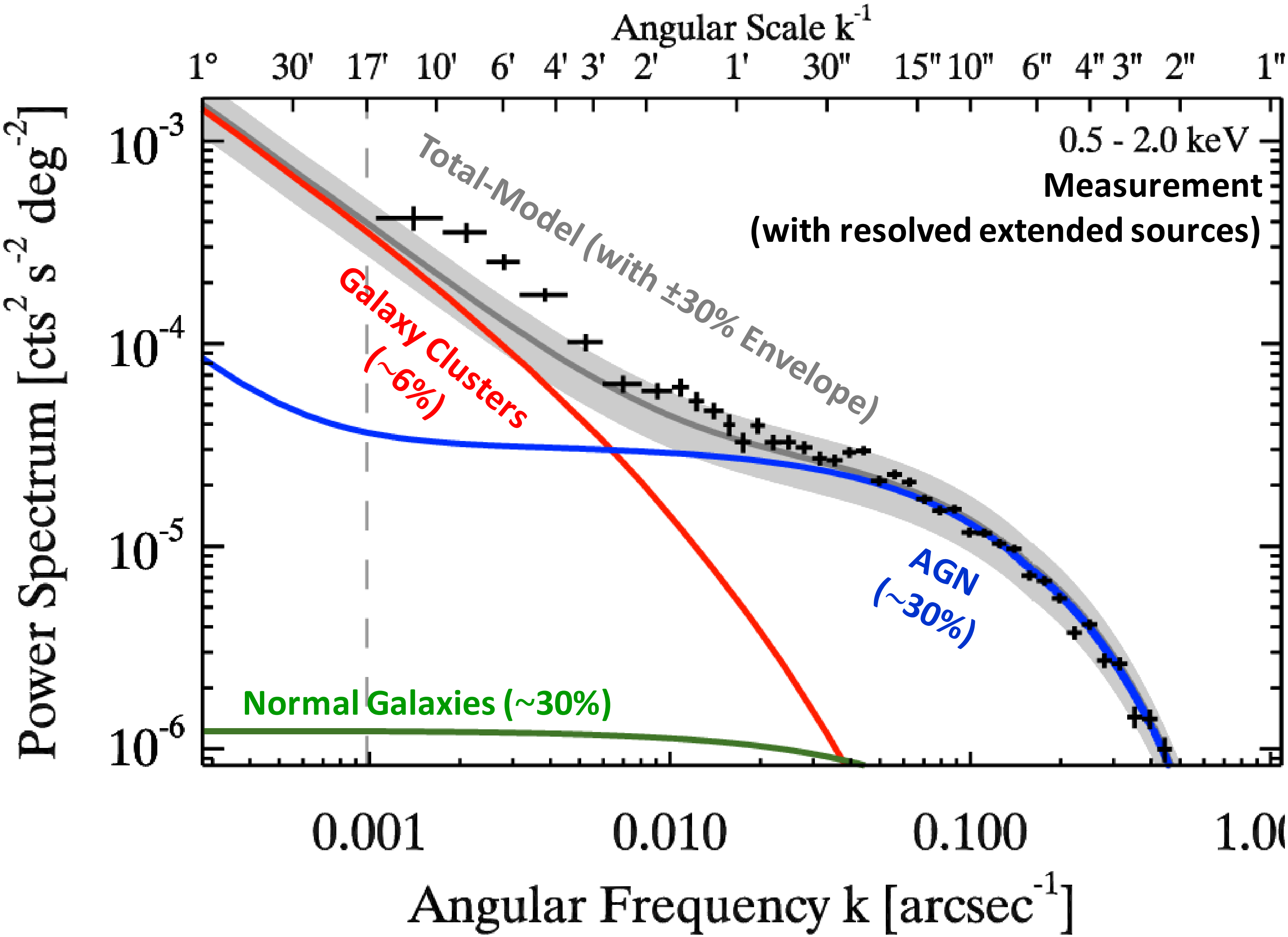
- Uncertainties for Model amplitude:
  - Flux-Conversion: < ~15%
  - Surface brightness estimate:
    - Log(N)-Log(S) observationally quite uncertain for unresolved part
    - Amplitude increases by factor of ~2, if XLF slope changes by +10% (+2σ)
  - Clustering properties of ICM (one-halo-term):
    - **Cheng+2004**: Assumes hydrostatic equilibrium of ICM
    - Amplitude can be increased by any non-gravitational effect
    - Observationally and theoretical uncertainties for these effects

    → Our measurement can be utilized to test models with different effects implemented
- Potential:
  - Shape of model defined by spatial structure of ICM (convolved with redshift distribution of galaxy clusters)

  → Measure average ICM profile beyond R_{500} for all nearby galaxy clusters ($z<\sim0.1$)

Summary

CXB fluctuations for <17‘: first full describtion



Lessons learned

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- Chandra survey of ~5ksec and >9deg^2 can measure CXB fluctuations below <17' to <~30% accuracy
  - Important systematics understood (instrumental background negligible)
- Origin of CXB fluctuations below ~17':
  - Angular scales below ~2': **AGN shot noise**
    - No need of AGN one-halo-term (at given accuracy)
      → consistent with theory (e.g. Fanidakis+2013, Leauthaud+2015)
  - Angular scales above ~2': **Galaxy clusters (one-halo-term)**
    - Discrepancy by factor ~2 between theory and observation

    → New observational constraints, needs to be utilized
    - **Potential**: Measure average ICM profile beyond R_{500} for all nearby galaxy clusters ($z<\sim 0.1$)
- Future surveys:
  - Larger surveys (>9deg^2) :

    → Larger angular scales -> study more massive nearby galaxy clusters

    → higher accuracy → better constraints (also on AGN one-halo-term)
  - Deeper surveys (>5ksec): → study galaxy clusters at higher redshift

eROSITA forecast (~50 times better S/N than XBOOTES)