Max-Planck-Institut für Astrophysik

CXB surface brightness fluctuations:
A new frontier of ICM structure & outskirts studies of (un)resolved galaxy clusters

Speaker	**Alexander Kolodzig** (Kavli-Fellow at KIAA/Peking University) **For hire from 10/2018 ;-)**
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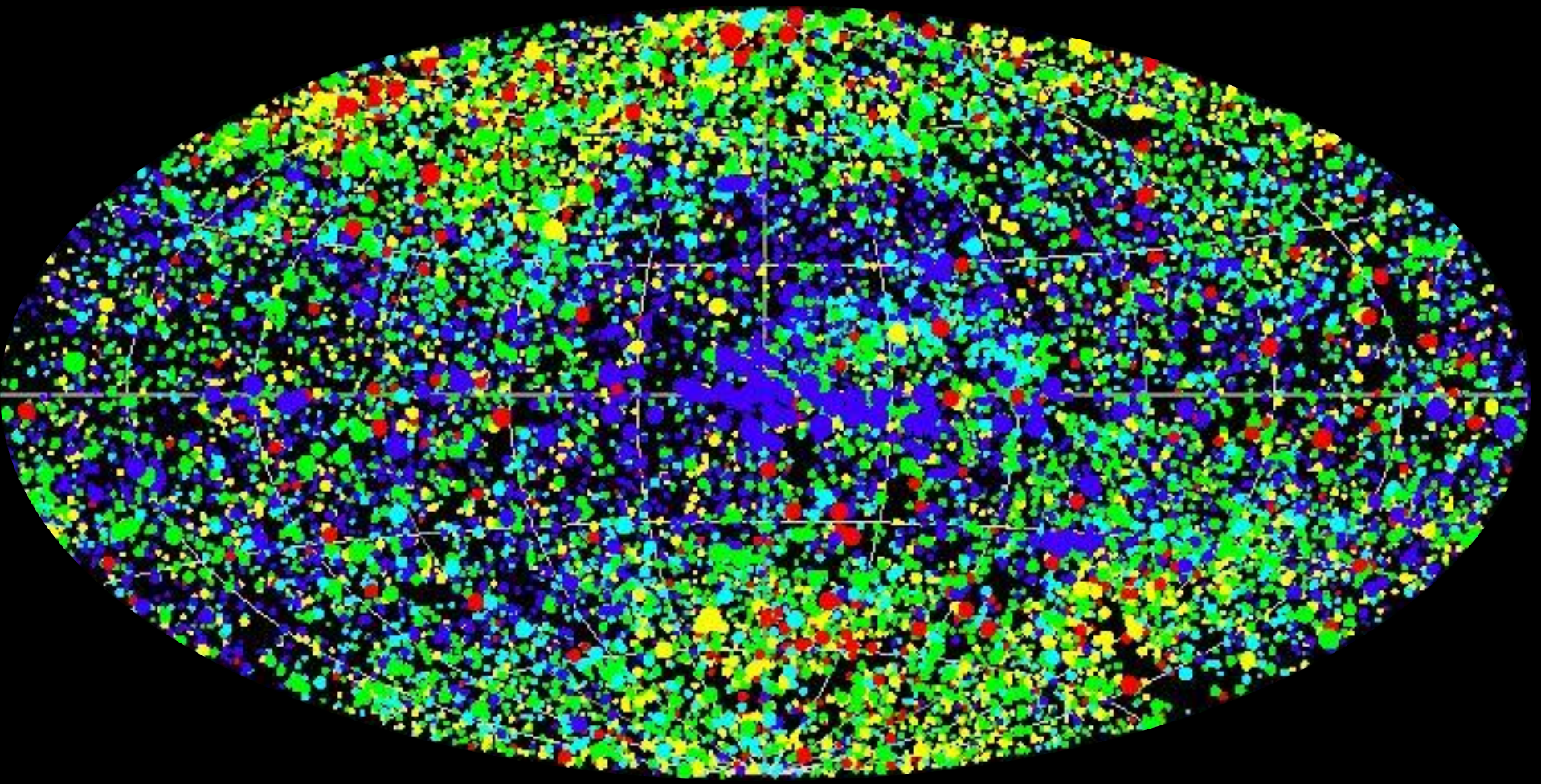
Publications	1st published in MNRAS (01/2017), 2nd submitting in July! ;-)
Meeting	“The X-ray Universe 2017”, Rome, Italy, Th.08.06.2017

Intro

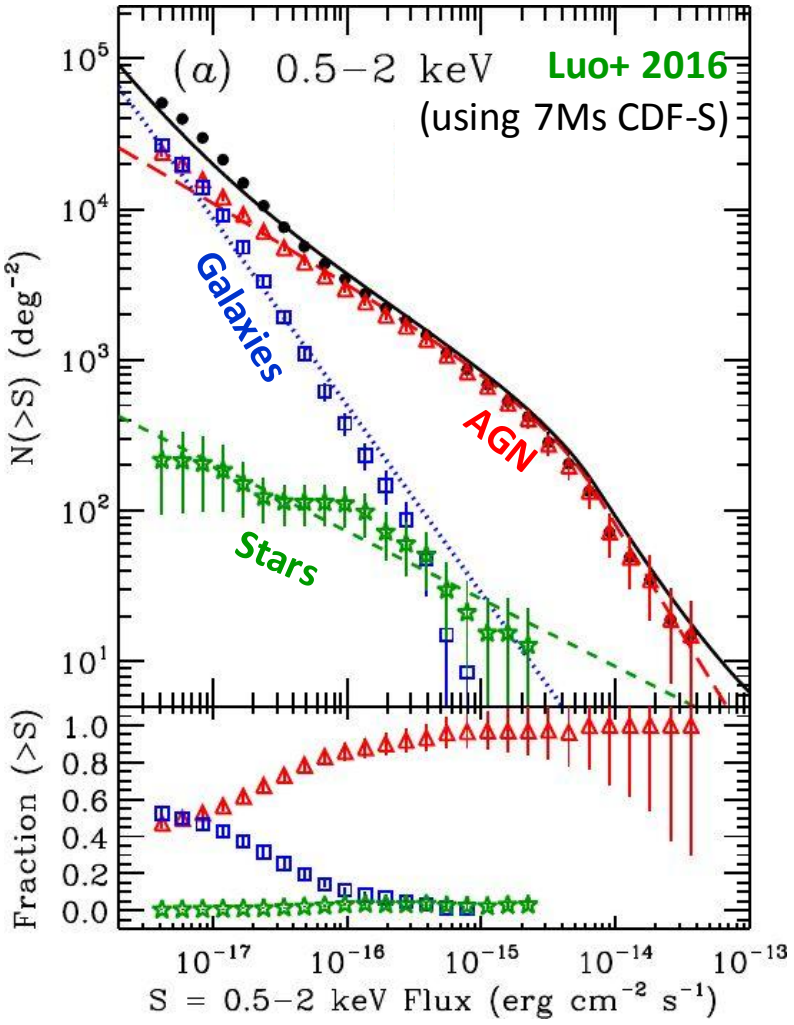
Resolved cosmic X-ray background (CXB)

(ROSAT All-Sky survey)



ROSAT PSPC All-Sky: (Trumper 1990, Freyberg+1999, MPE)

Extragalactic CXB: Resolved Fraction



~75% resolved into point sources

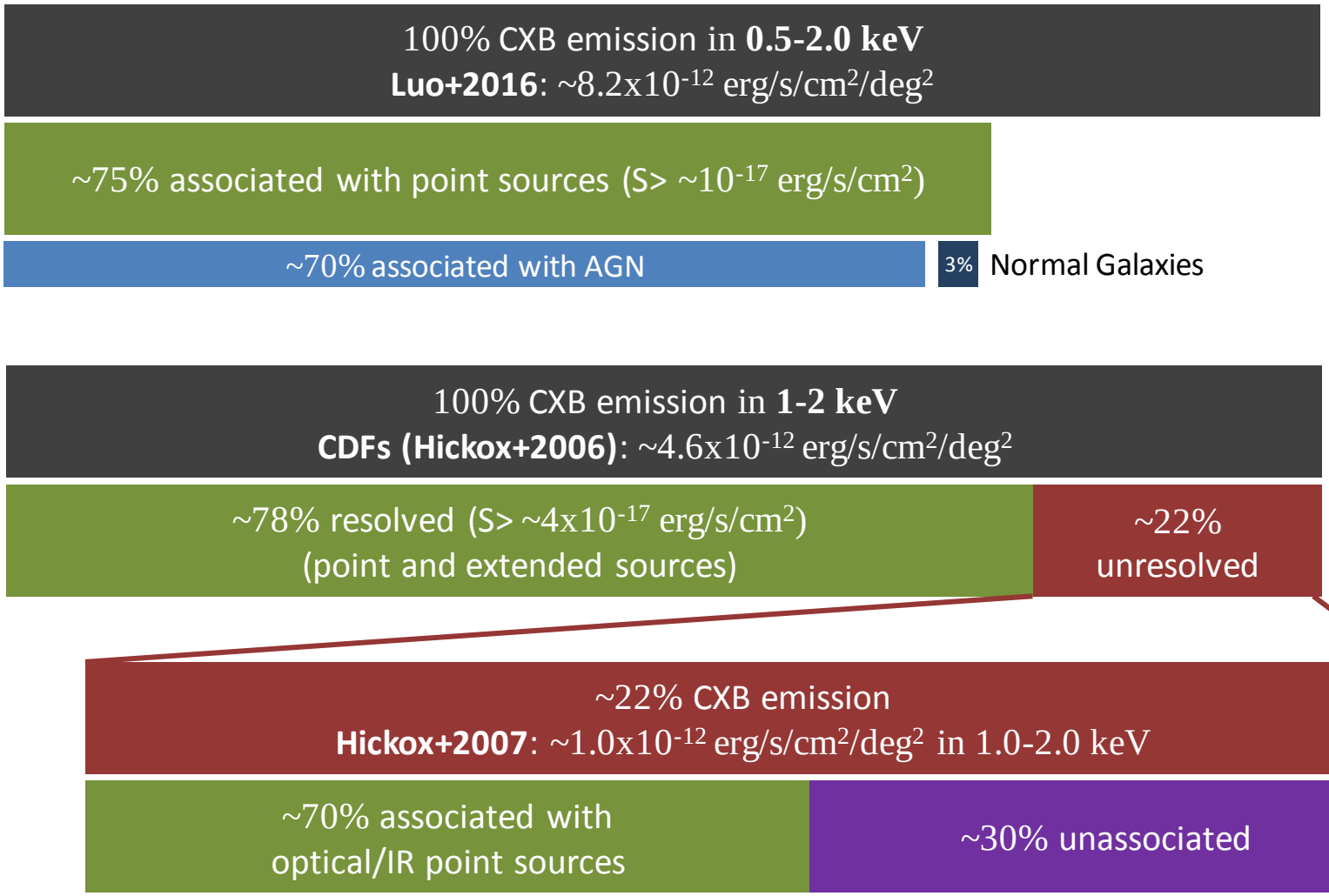
for 0.5-2.0 keV (> ~10^{-17} erg/s/cm^2):

~70% AGN

~3% Normal Galaxies

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

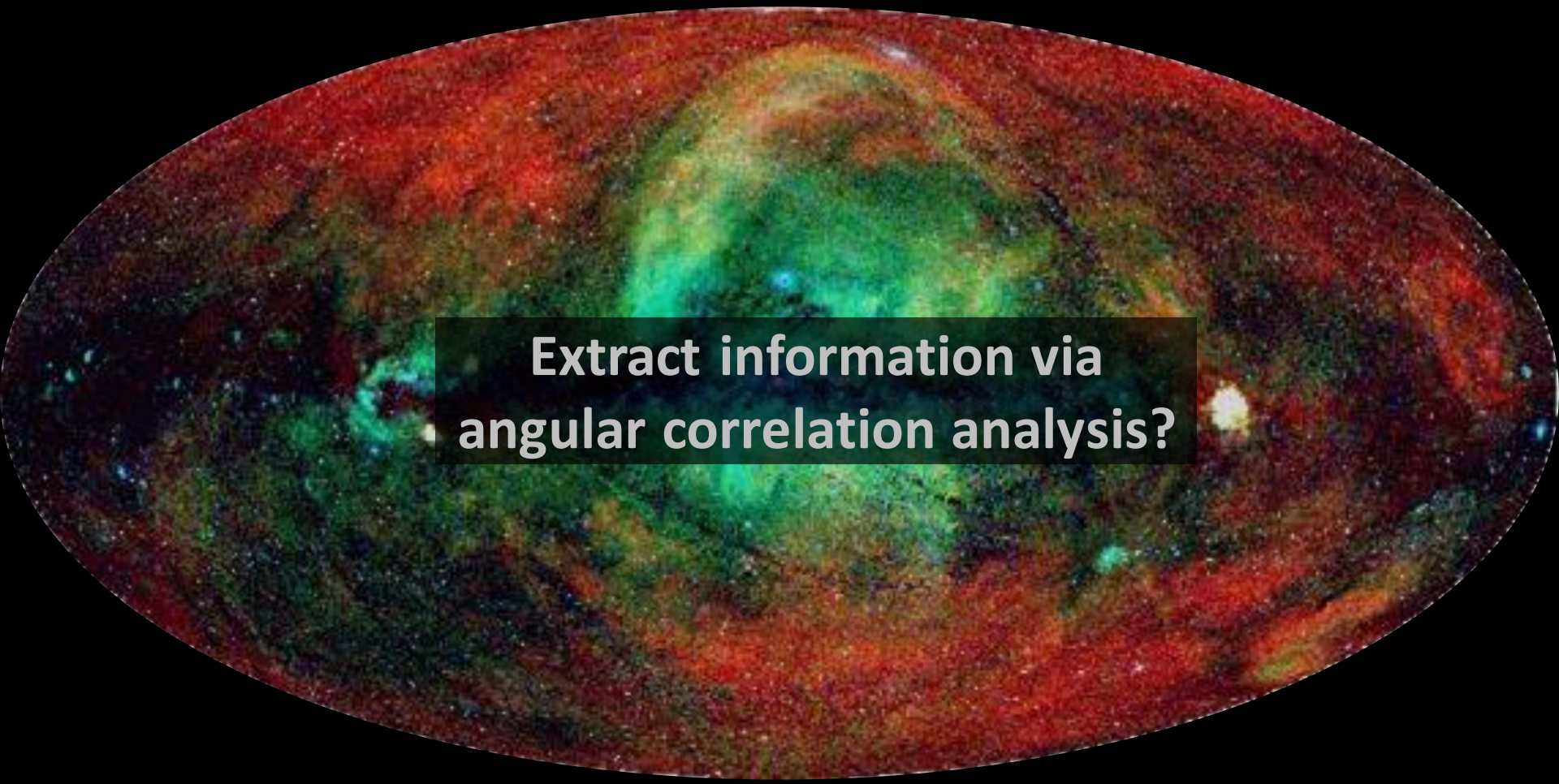
Extragalactic CXB: **Un**resolved Fraction



→ ~10% of CXB remain unassociated

(based on 0.02 deg^2 → cosmic variance!!!)

Unresolved/diffuse CXB contains unique information!



ROSAT PSPC All-Sky: (Trümper 1990, Freyberg+1999, MPE)

Studying source populations in the (un)resolved CXB with angular correlation studies

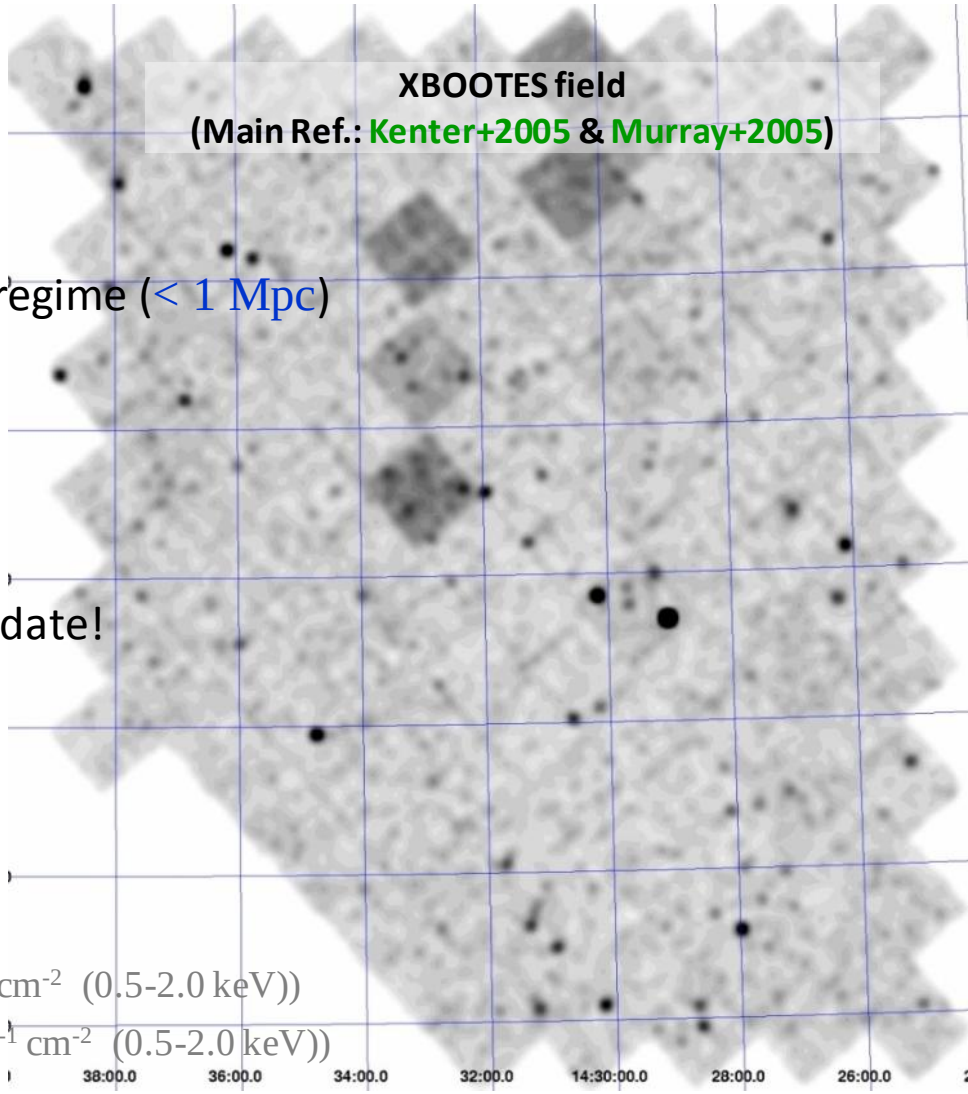
- Point sources:
  - AGN (active galactic nuclei) → **very successful!**

    (e.g. Scheuer 1974; Hamilton & Helfand 1987; Shafer & Fabian 1983; Barcons & Fabian 1988; Soltan & Hasinger 1994; Vikhlinin & Forman 1995; Miyaji & Griffiths 2002, Cappelluti+2012,+2013, Helgason+2014, Mitchell-Wynne+2016)
- Extended/Diffuse sources:
  - Galaxy clusters (ICM) → **feasible?**
  - Warm Hot Intergalactic Medium (WHIM) → **feasible?**
  - Galactic emission → **feasible?**

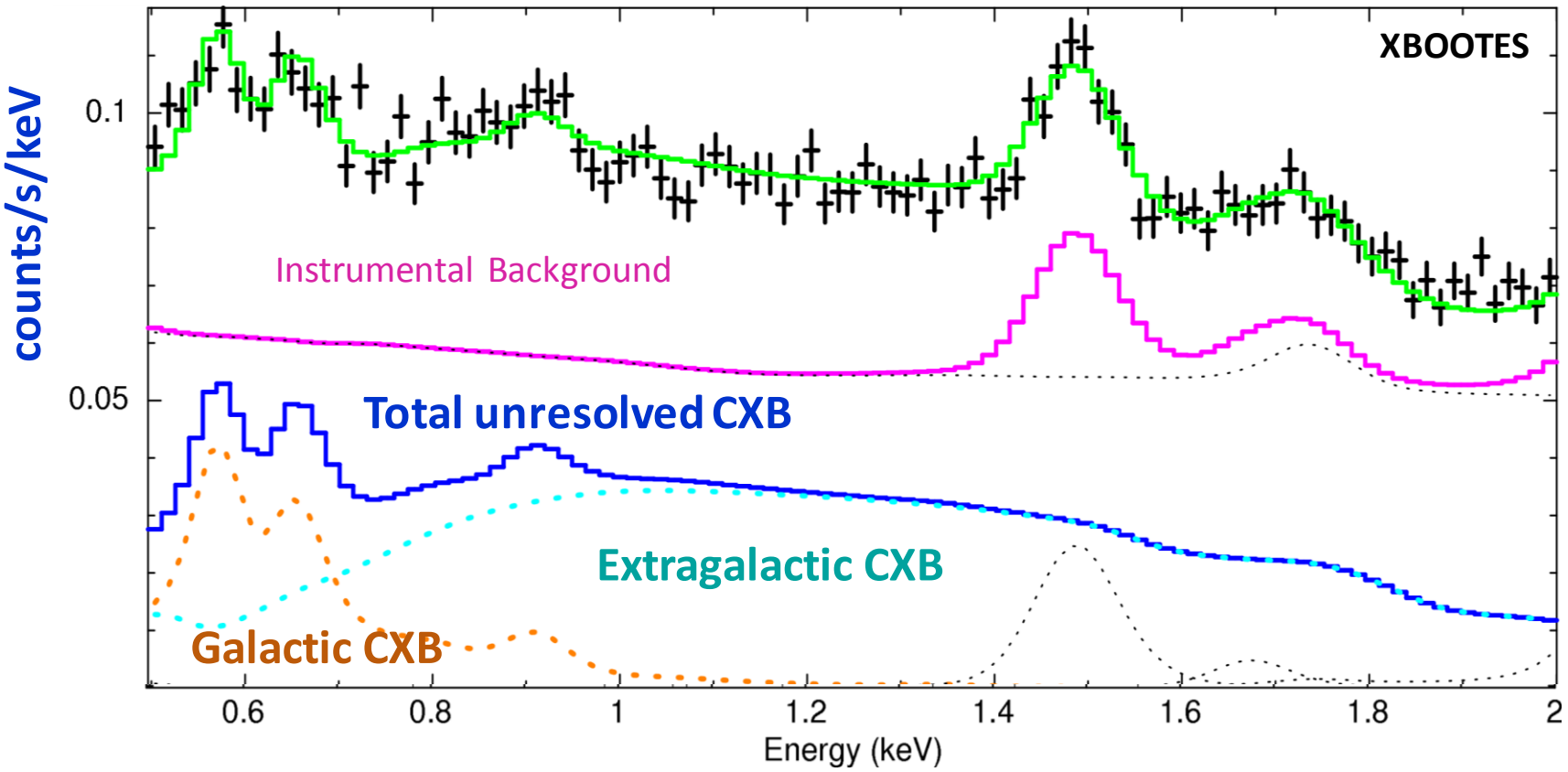
Our Data

Our Data: ~9 deg^2 XBOOTES survey

- Advantages for fluctuation studies:
  - high angular resolution of *Chandra*
    → access to small-scale clustering regime (< 1 Mpc)
  - *Chandra* Instrumental Background
    - low, stable, and well understood
      (e.g. Hickox & Markevitch 2006)
  - largest *Chandra* survey
    → most accurate measurement to date!
- Properties:
  - 126 contiguous observations
  - ~5 ksec average exposure time
  - ~50% of CXB emission resolved
    - ~3300 point-sources (>~2×10^{-15} erg s^{-1} cm^{-2} (0.5-2.0 keV))
    - ~40 extended sources (>~3×10^{-14} erg s^{-1} cm^{-2} (0.5-2.0 keV))
  - ~8.3 deg^2 of unresolved emission



Unresolved CXB of XBOOTES

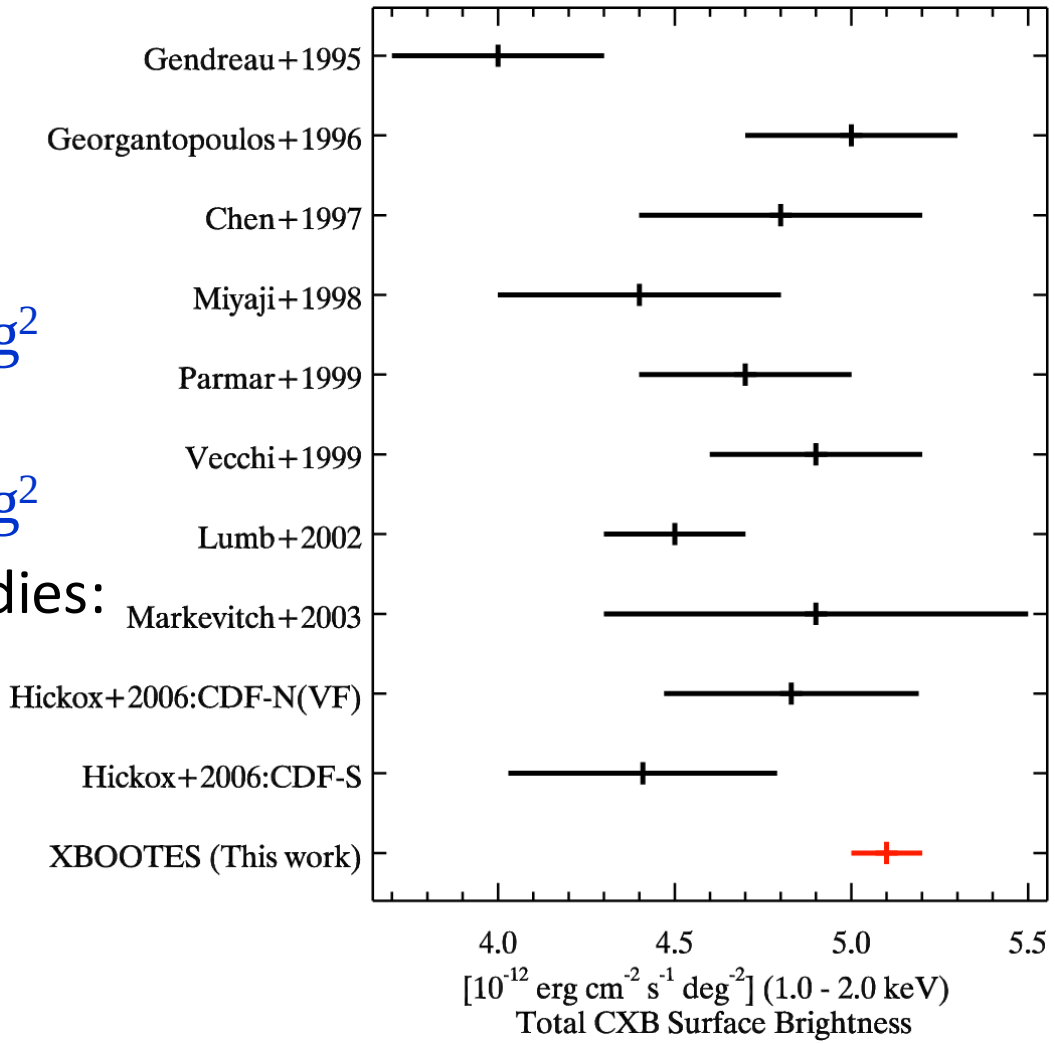


Galactic	**APEC:** $T = 164 \pm 3$ eV
Extragalactic	**Powerlaw:** $\Gamma = 1.74 \pm 0.03$, $N_H = 10^{20}$ cm^{-2}

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

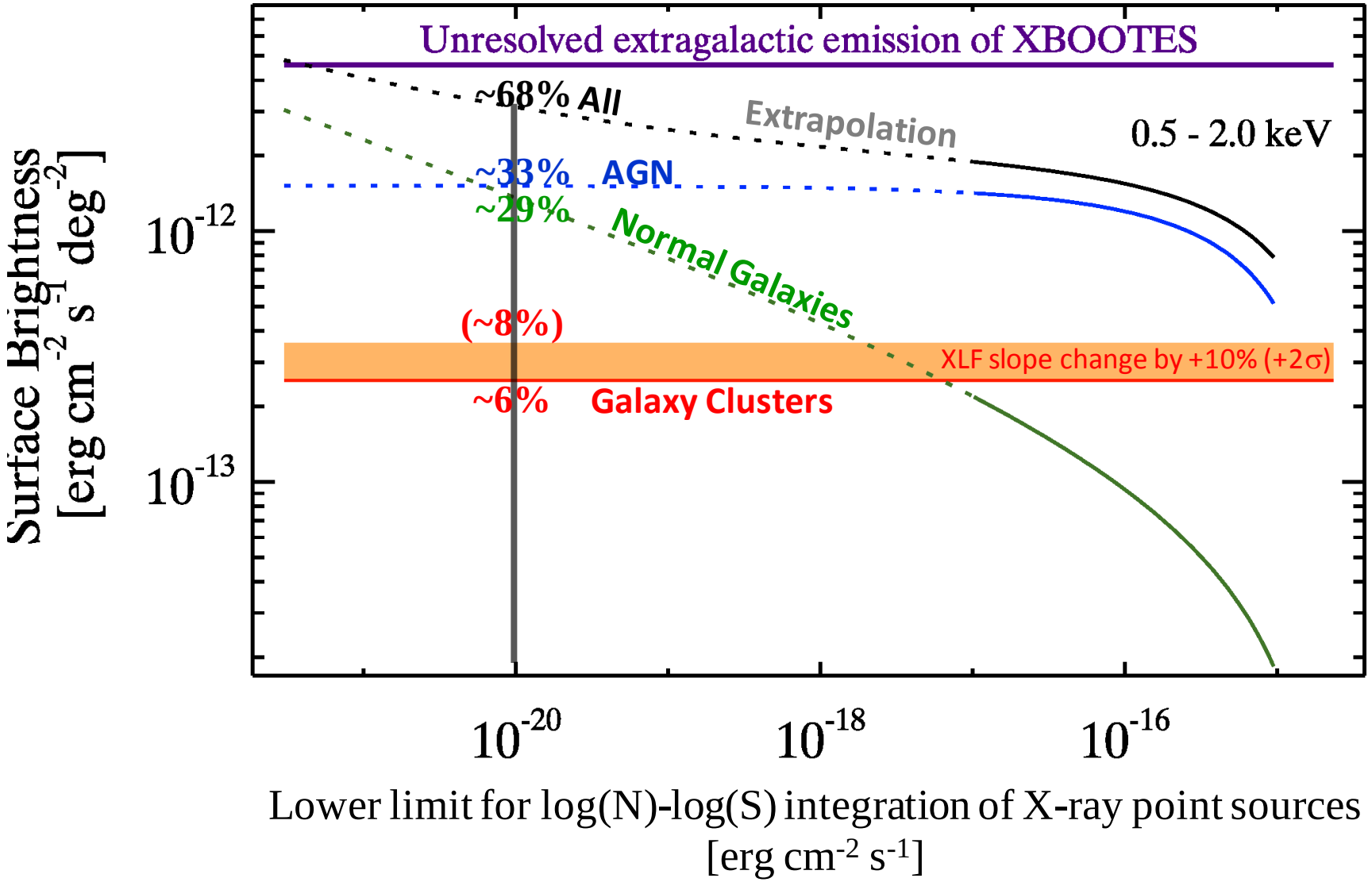
Total extragalactic emission (resolved and unresolved):

- 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)



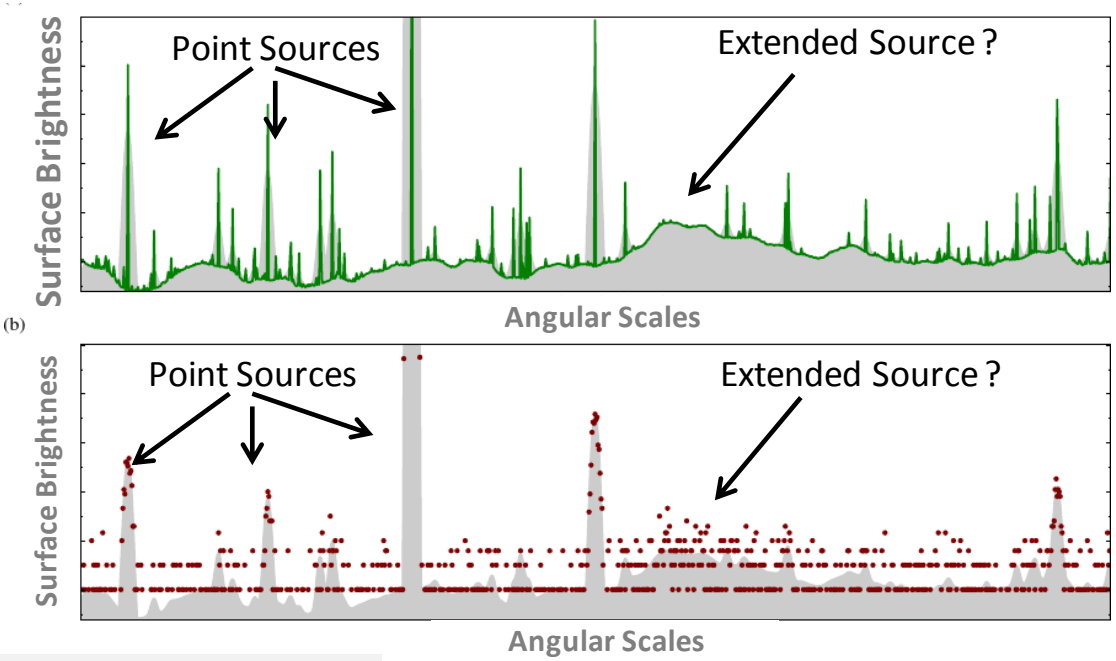
Unresolved extragalactic components

(0.5 - 2.0 keV)



Analyze Technique

Angular correlation studies with the CXB

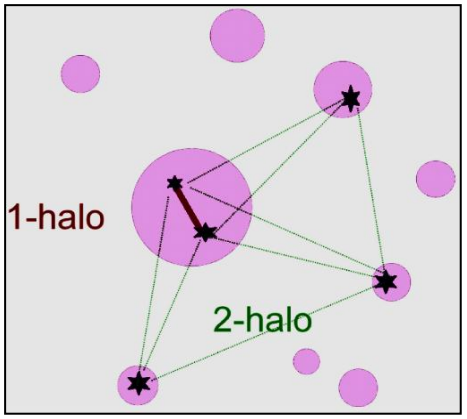


Expected Signal

Measurement (Counts)

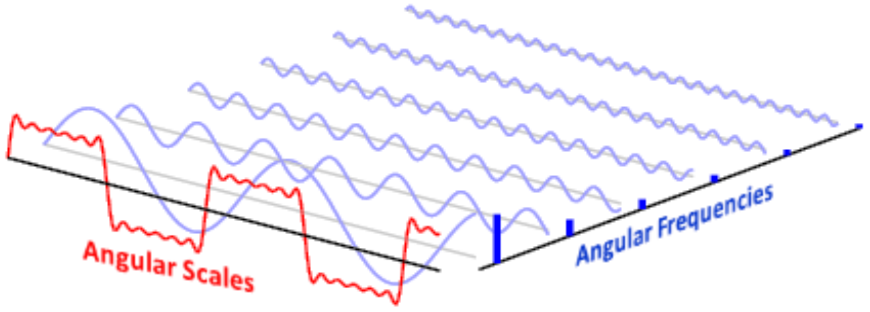
Selig+2016

Counts of different sources correlate differently for a given angular scale!
(Inst. BKG counts are ~uncorrelated)

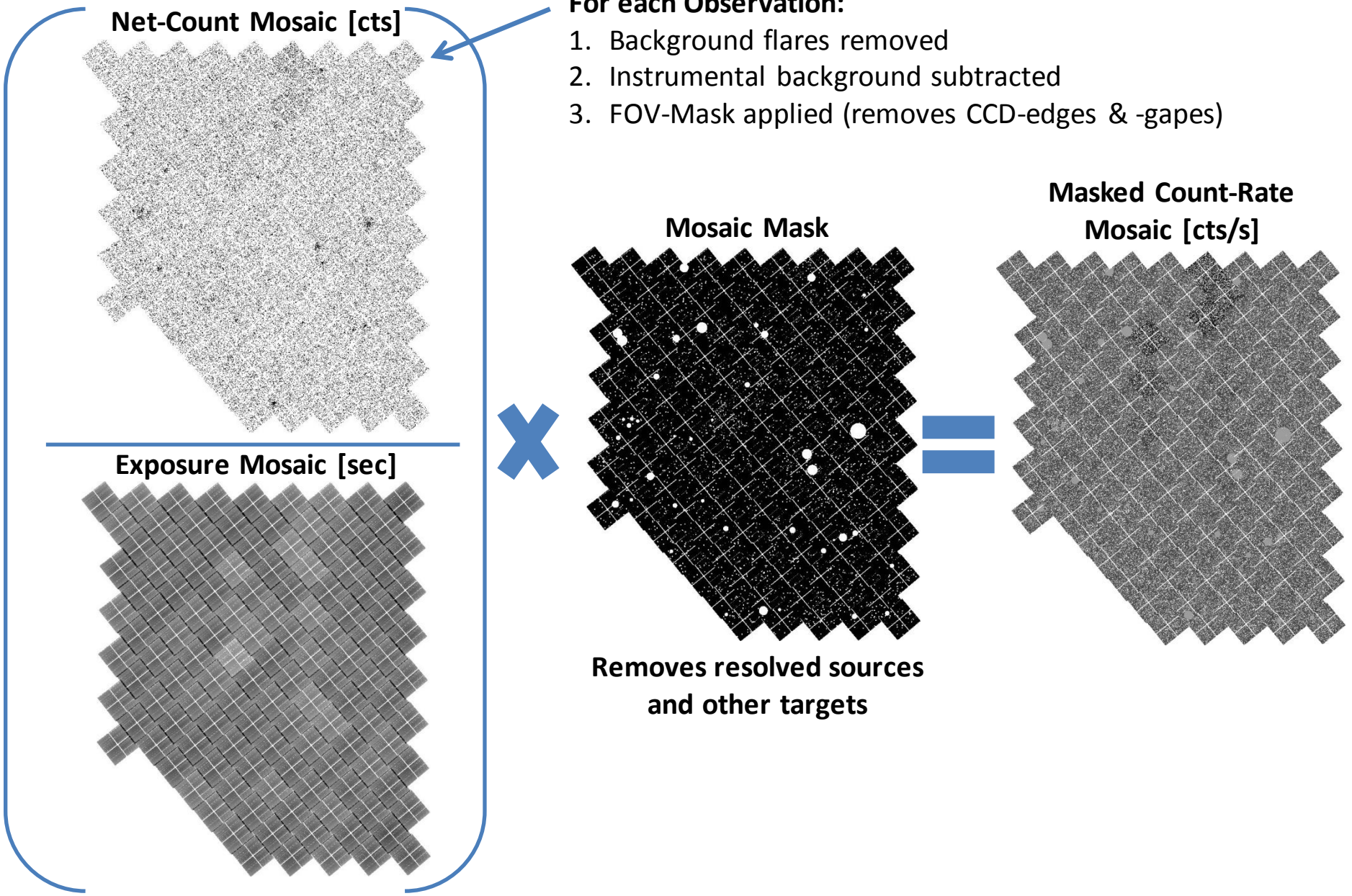


Krumpe+2014

Measure correlation amplitude via Fourier Transform
→ Compute Power Spectrum

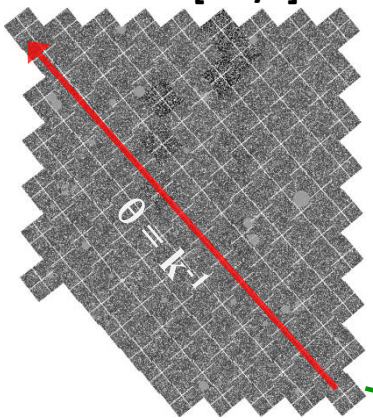


Data reduction:



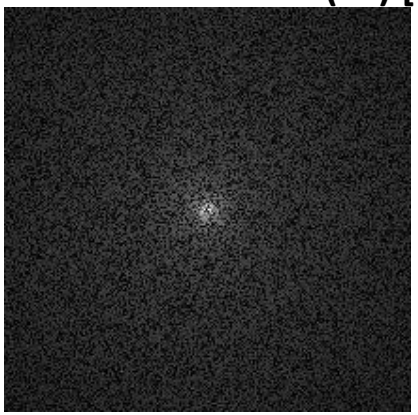
Computing *Mosaic* Power Spectrum:

Masked Count-Rate Mosaic[cts/s]



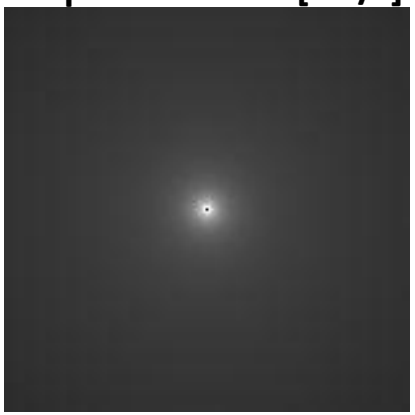
2D DFT

2D Fourier Transform (FT) [cts/s]



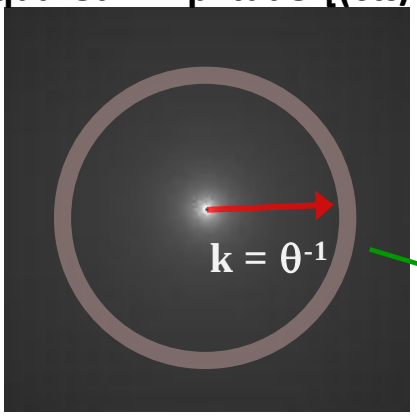
ABS(DFT)

Amplitude of FT [cts/s]



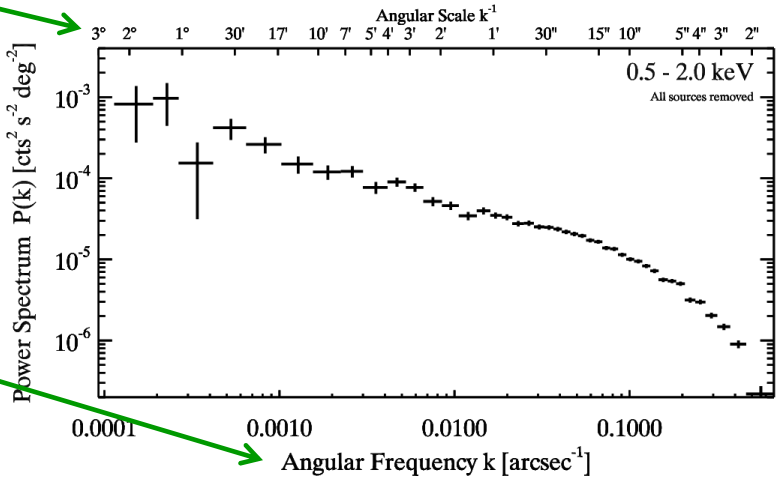
(ABS(DFT))²

Squared Amplitude [(cts/s)²]



P(k)

1D Power Spectrum P(k) [(cts/s)² deg⁻²]

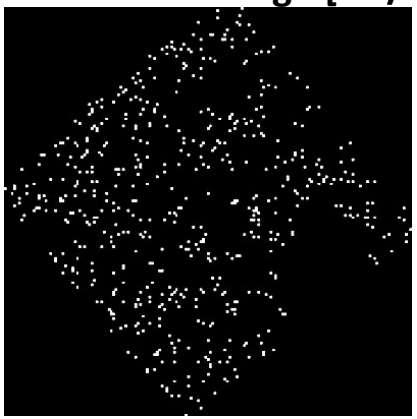


Steps:

1. Compute 2D discrete Fourier-Transform (DFT)
2. Take only amplitude
3. Compute 1D Power Spectrum [(cts/s)²/deg²] (assuming isotropy)

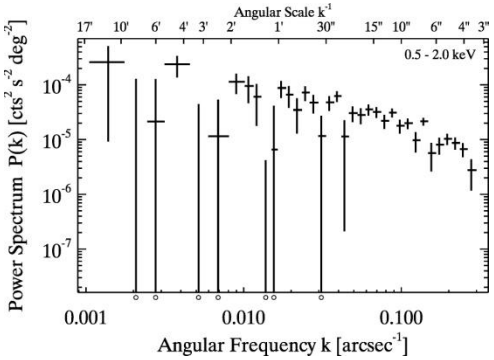
Computing *stacked* Power Spectrum:

Masked Count-Rate Image [cts/s]

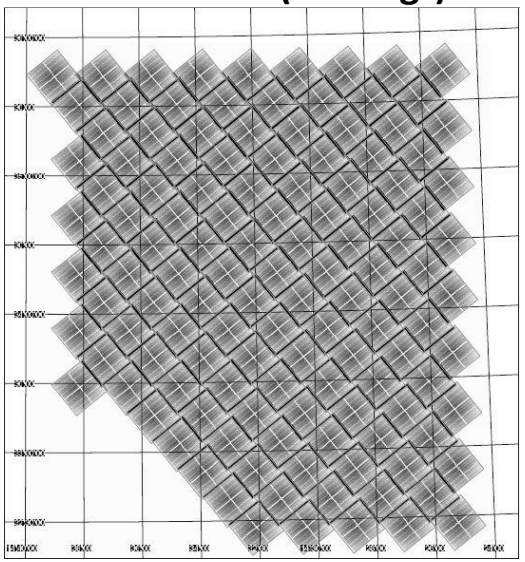


2D DFT

Power Spectrum P(k) of 1 field 17' x 17' (0.07 deg²)

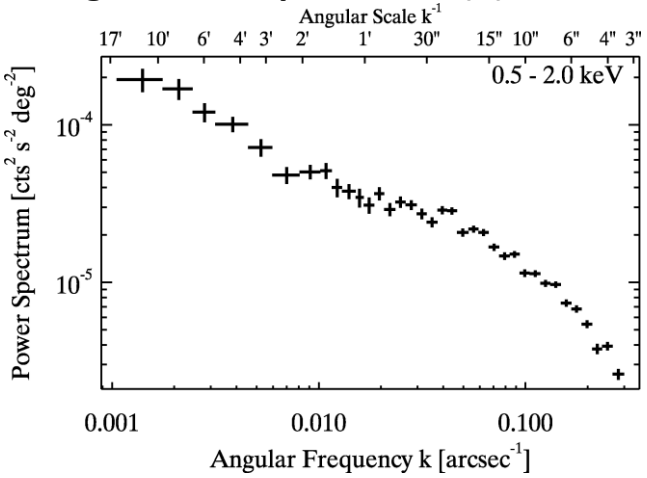


126 Fields (8.7 deg²)



average

Average Power Spectrum P(k) of 126 fields



Application:

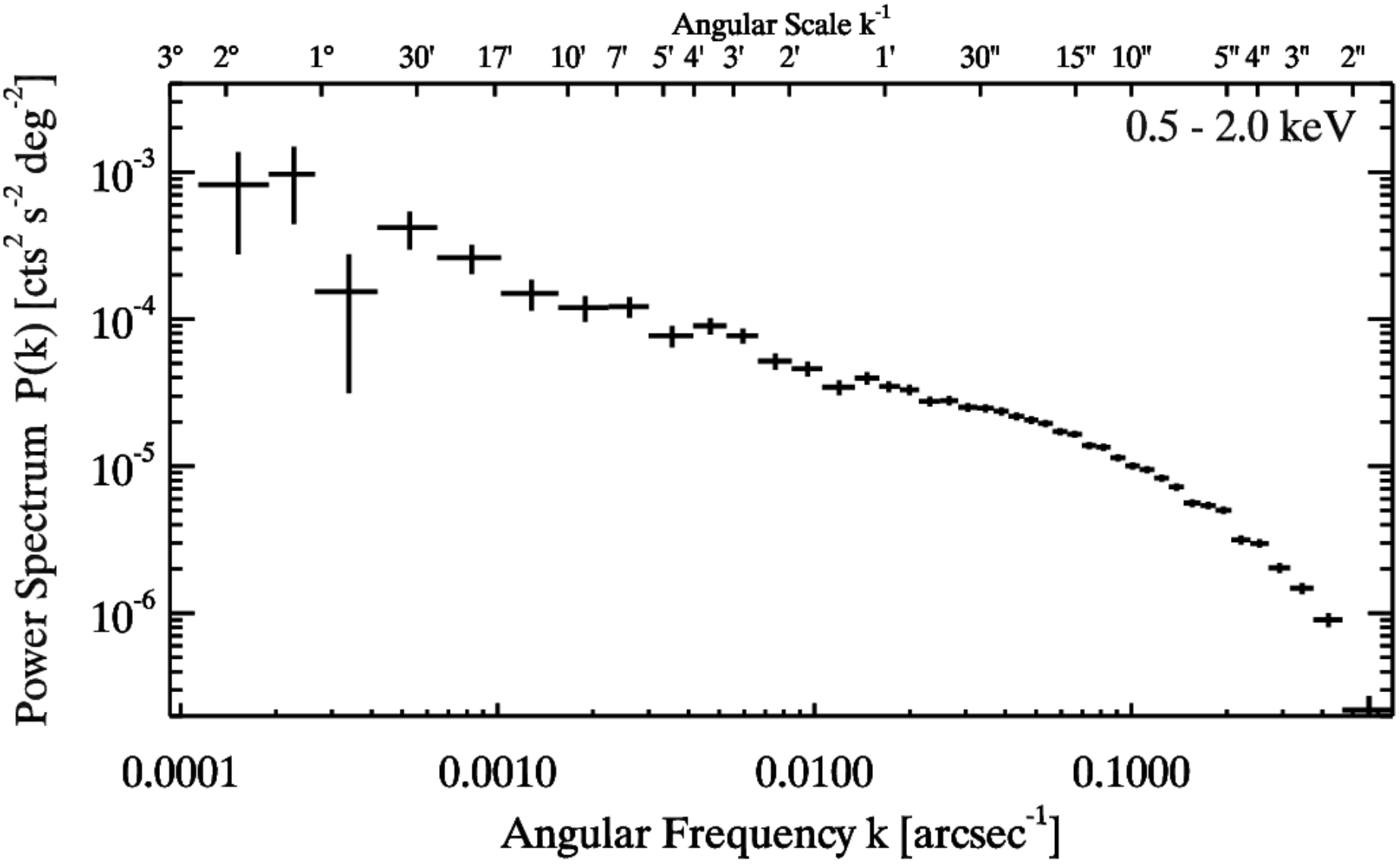
study smallest angular scales (<17')

Advantage to Mosaic:

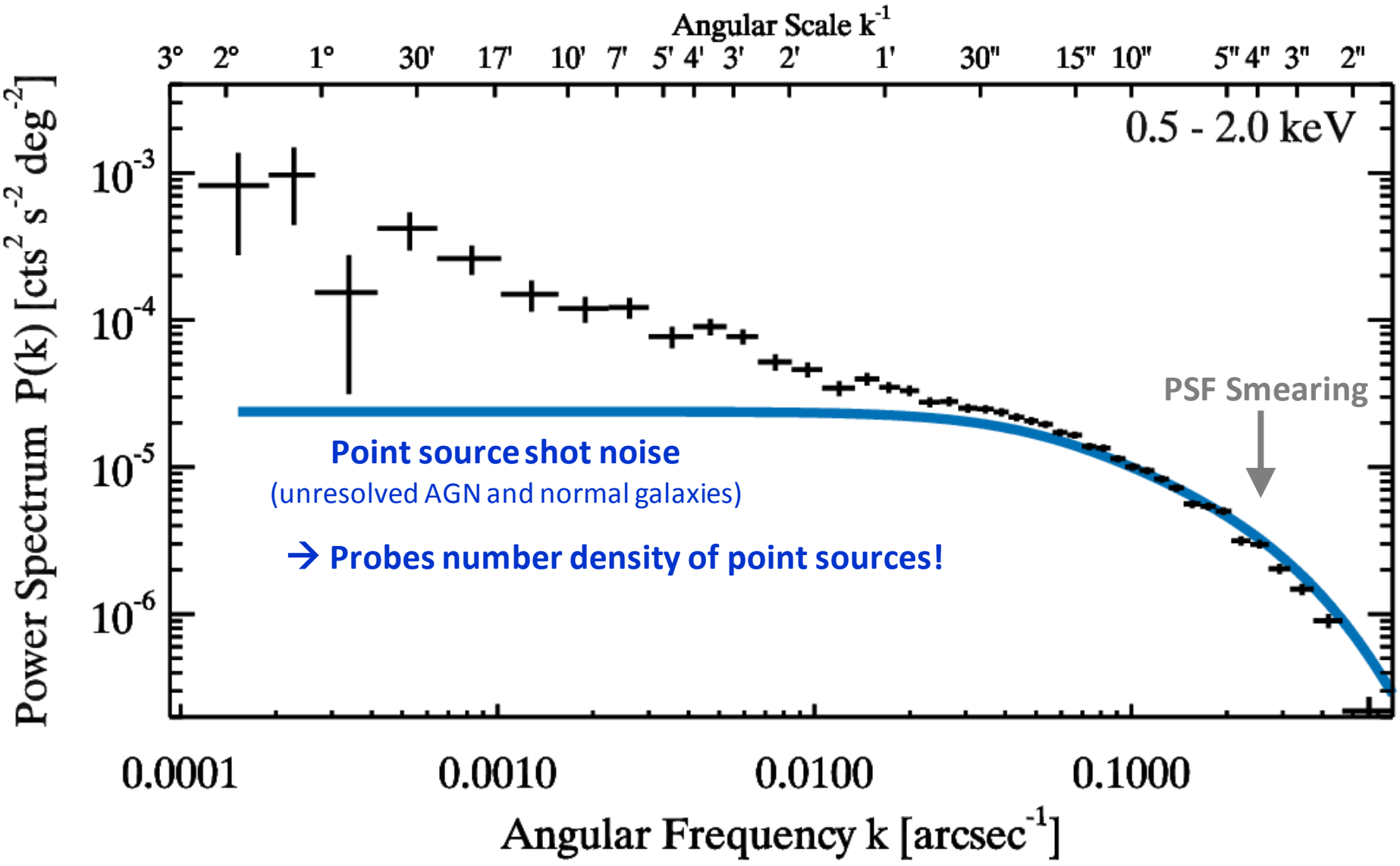
much faster and simpler to compute

Results

Power spectrum of CXB fluctuations

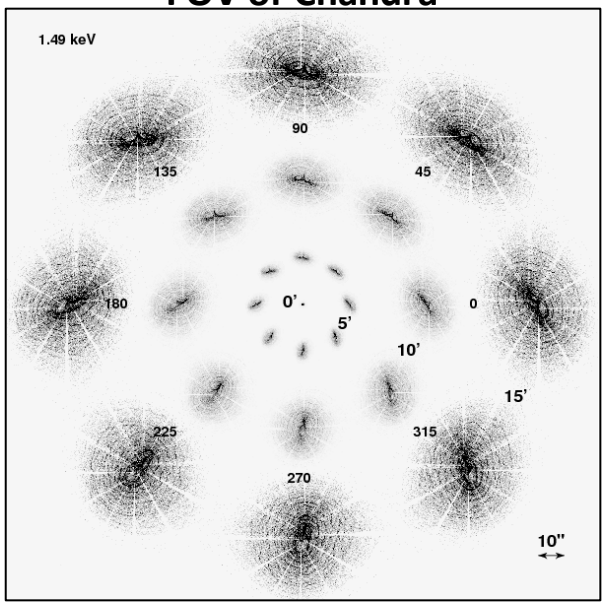


Power spectrum of CXB fluctuations



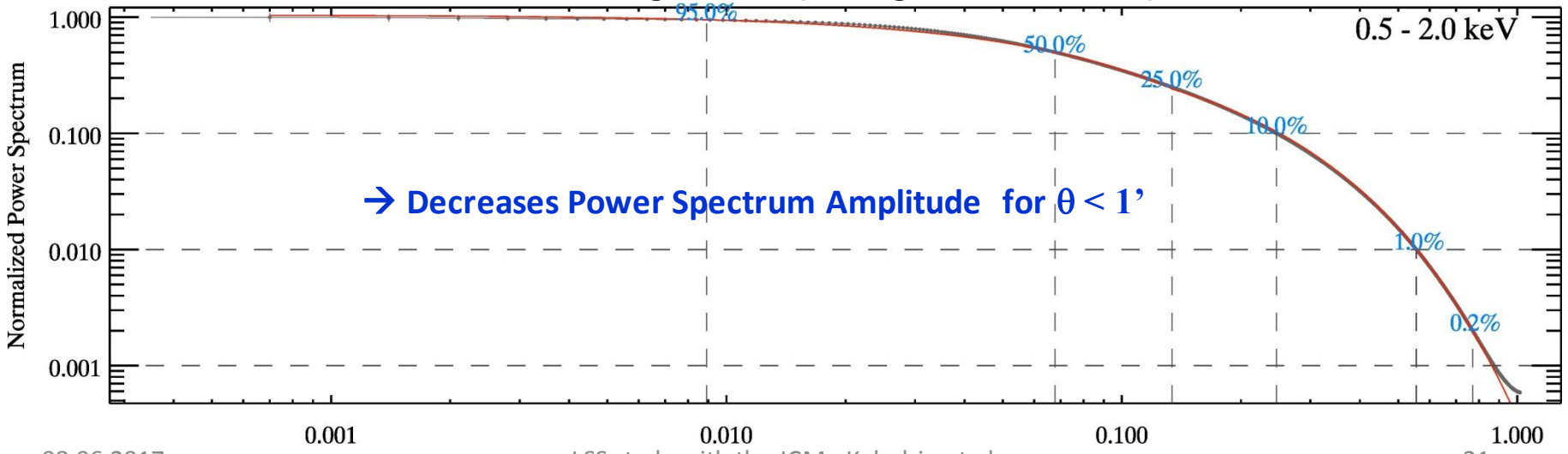
PSF-Smearing

FOV of Chandra

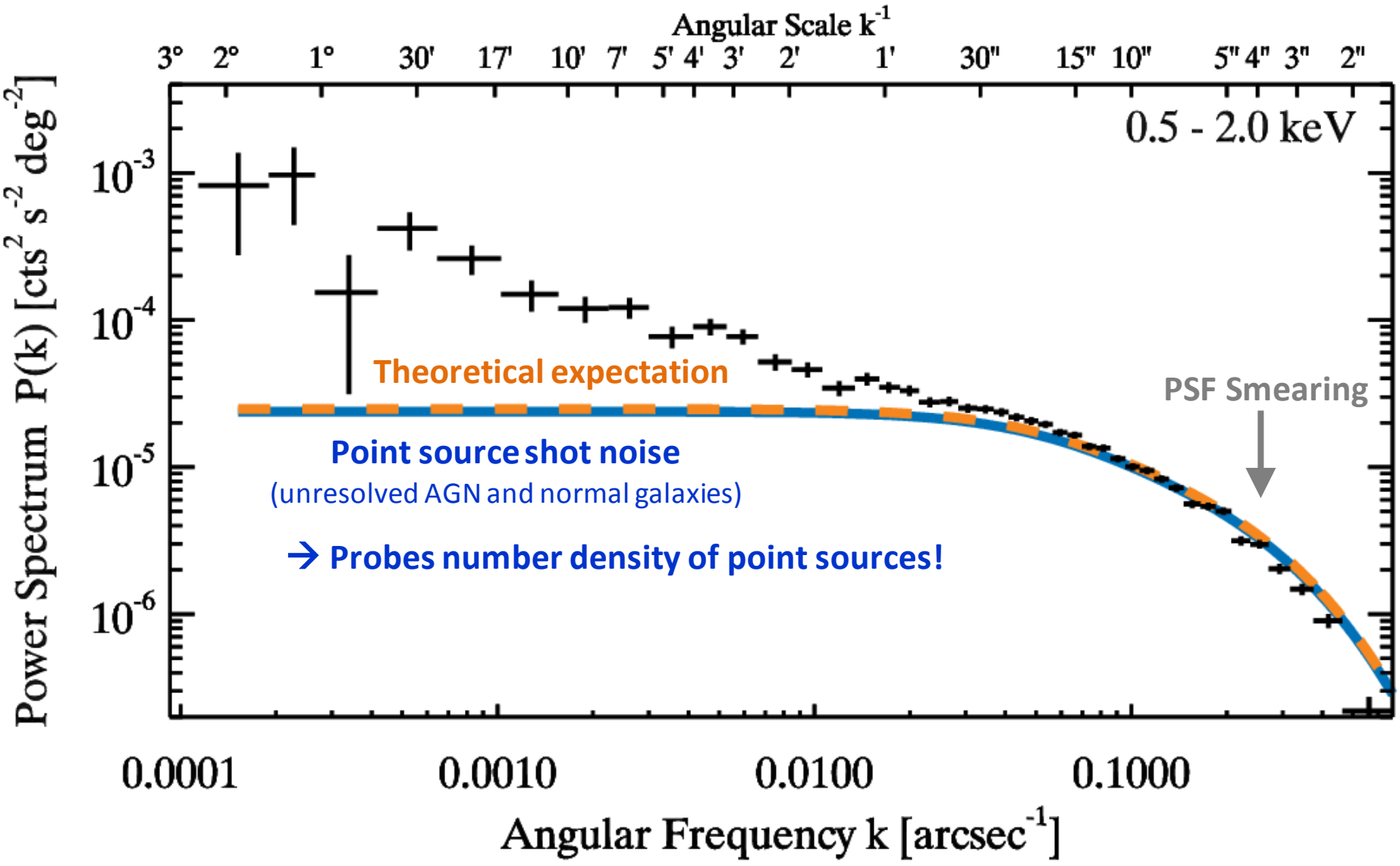


- PSF-Smearing increases with off-set angle

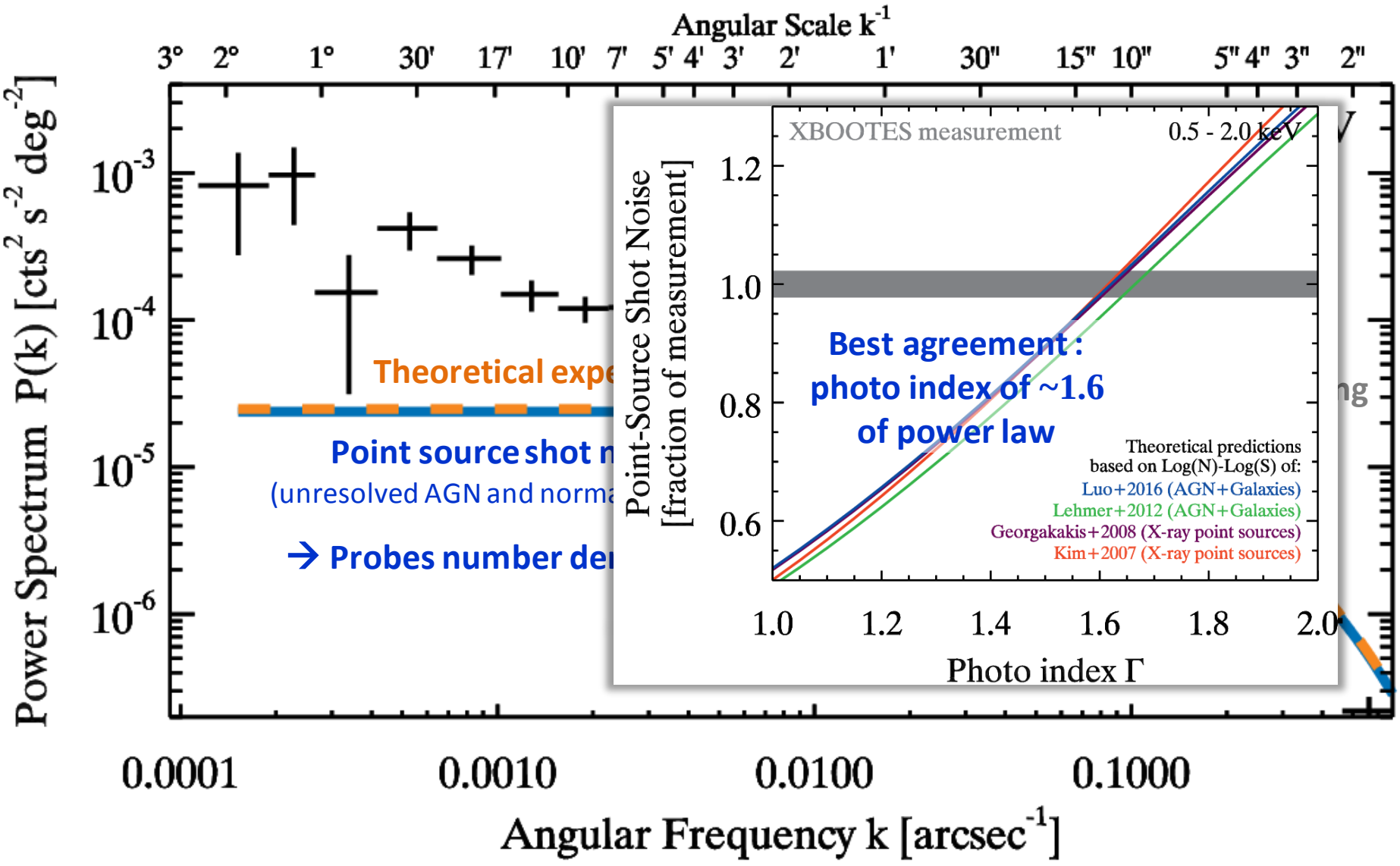
Our PSF-Smearing-Model (average for entire FOV)



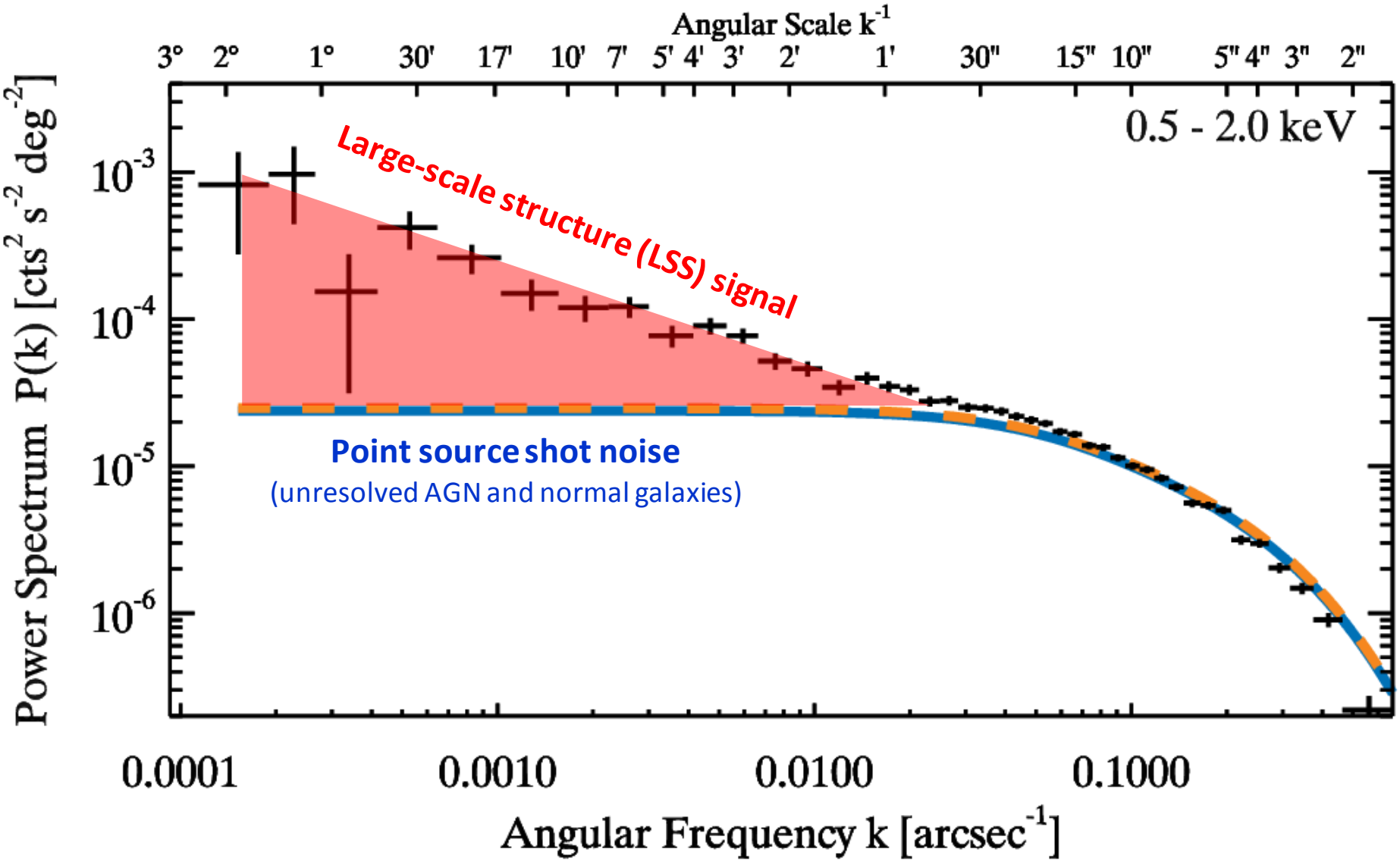
Power spectrum of CXB fluctuations



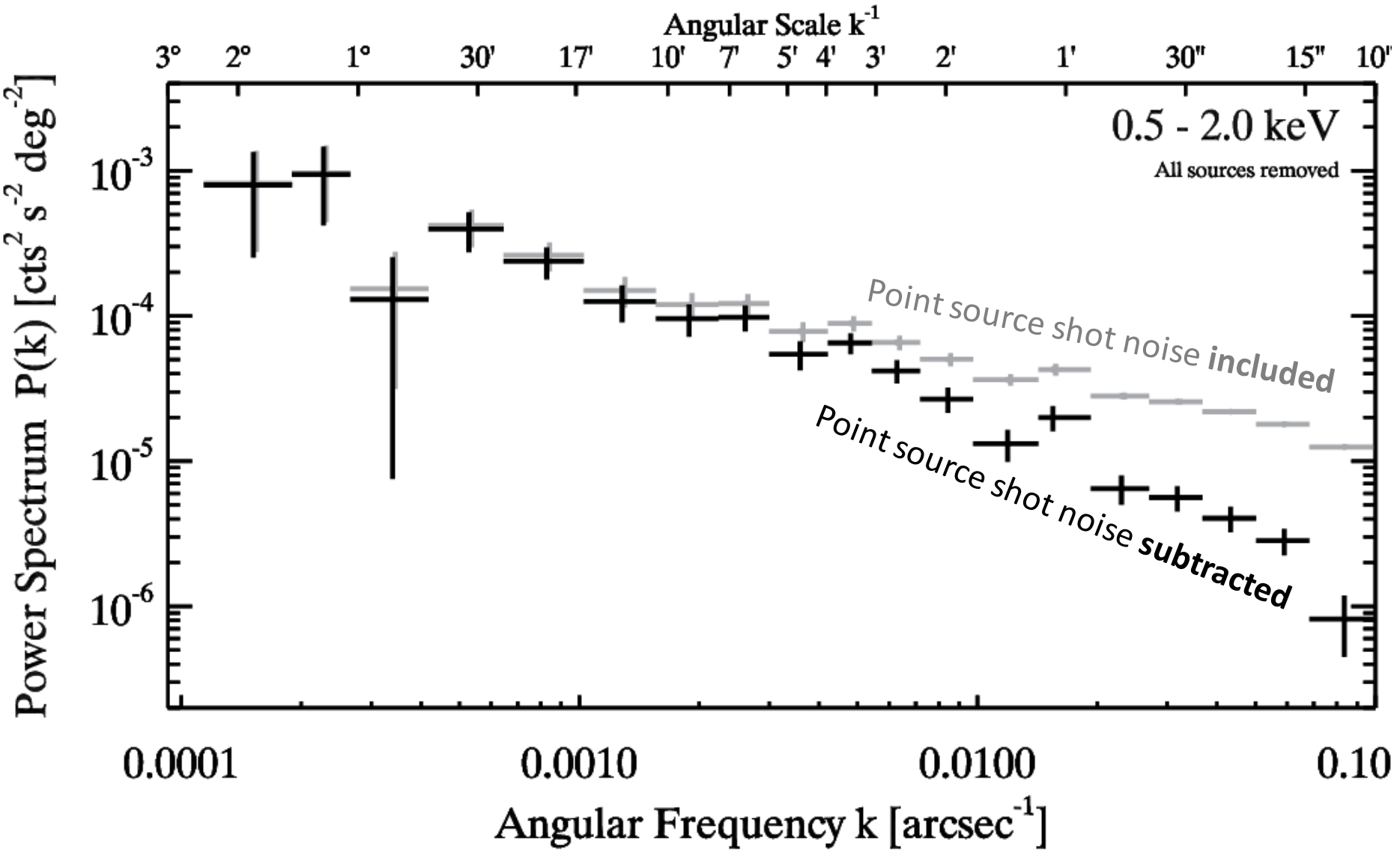
Power spectrum of CXB fluctuations



Power spectrum of CXB fluctuations

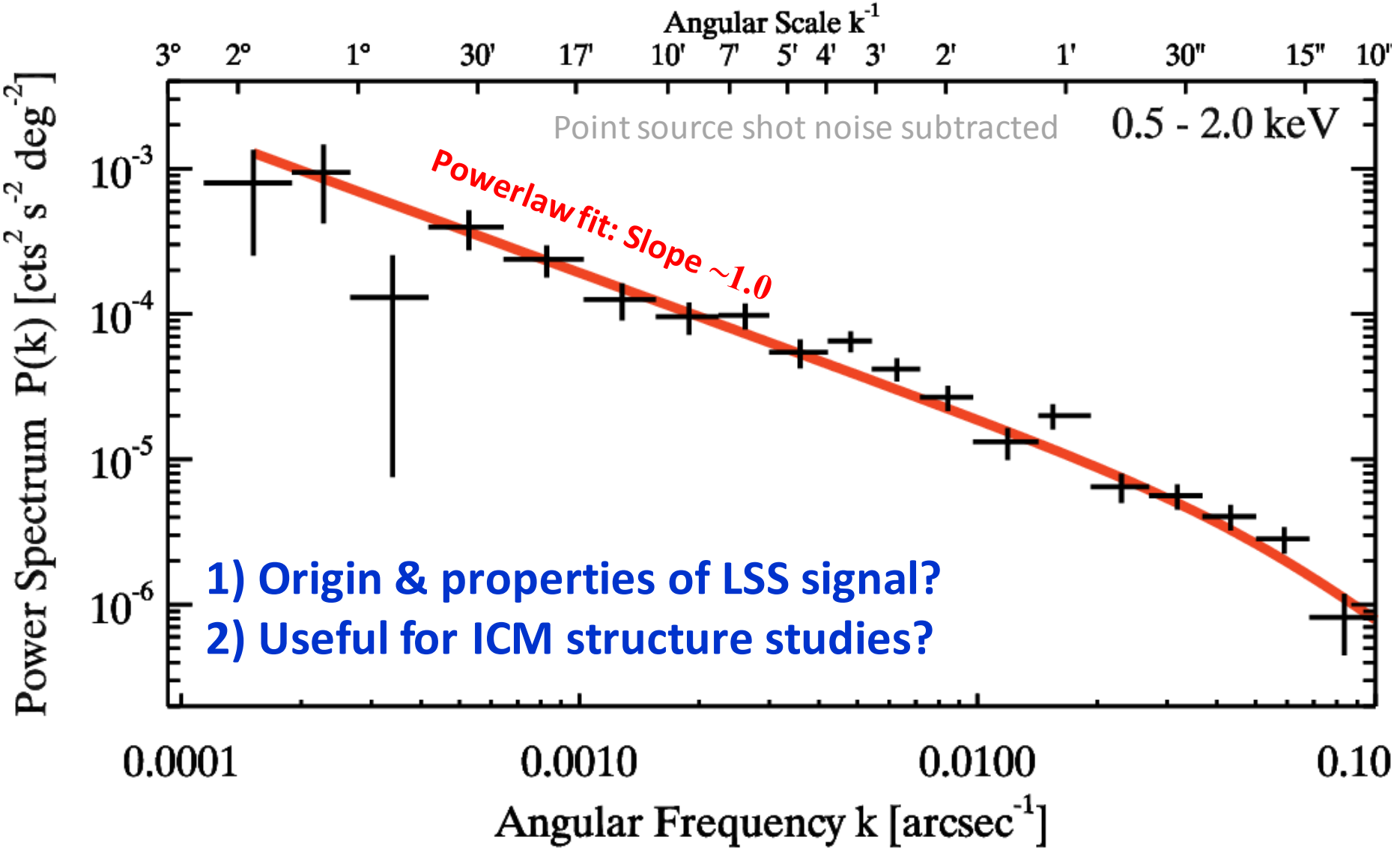


LSS signal of unresolved CXB



LSS signal of unresolved CXB

(Point source shot noise subtracted power spectrum)



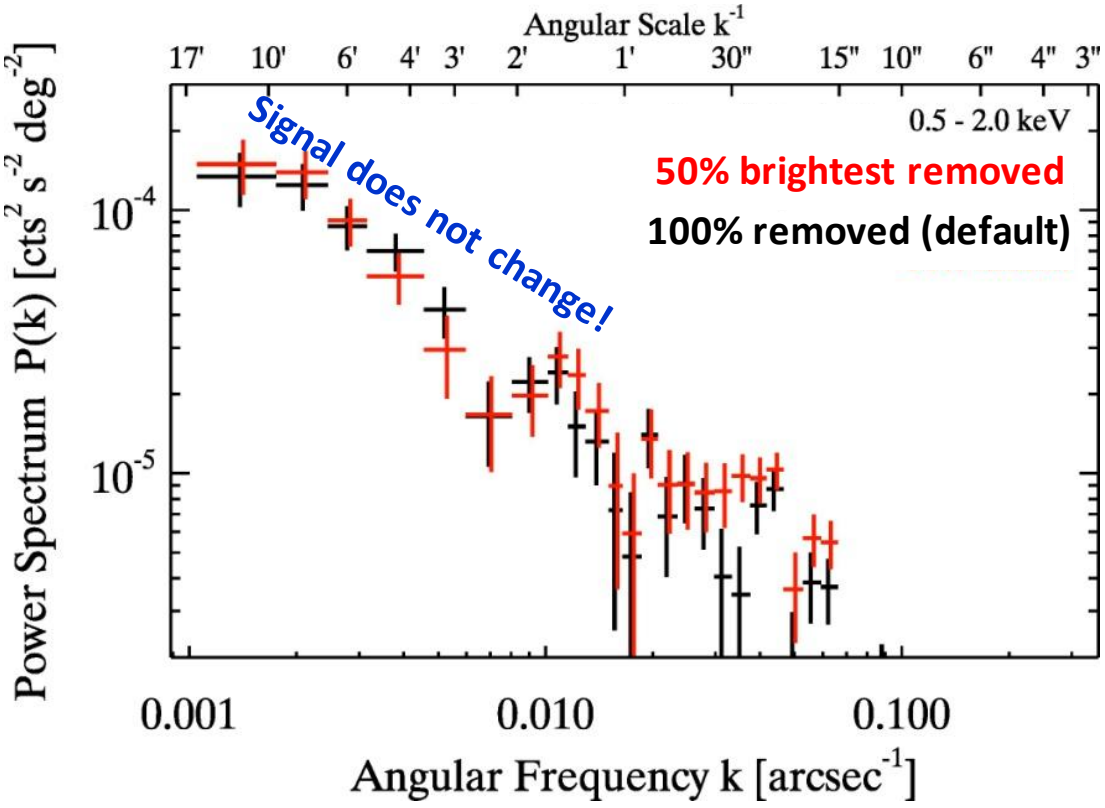
Assessment of systematics
(see Kolodzig+2017a)

- Quiescent instrumental background → negligible
- Instrumental background flares → negligible
- Mask effects → minor effect on largest scales
- PSF-Smearing Model → not important for large scales (>3")
- Residual counts of removed point-sources → negligible
  - Can be modeled with good knowledge of PSF
- Point source shot-noise estimate → sufficiently accurate (at given S/N)
- Photon-shot-noise estimators → not important for large scales (>2")

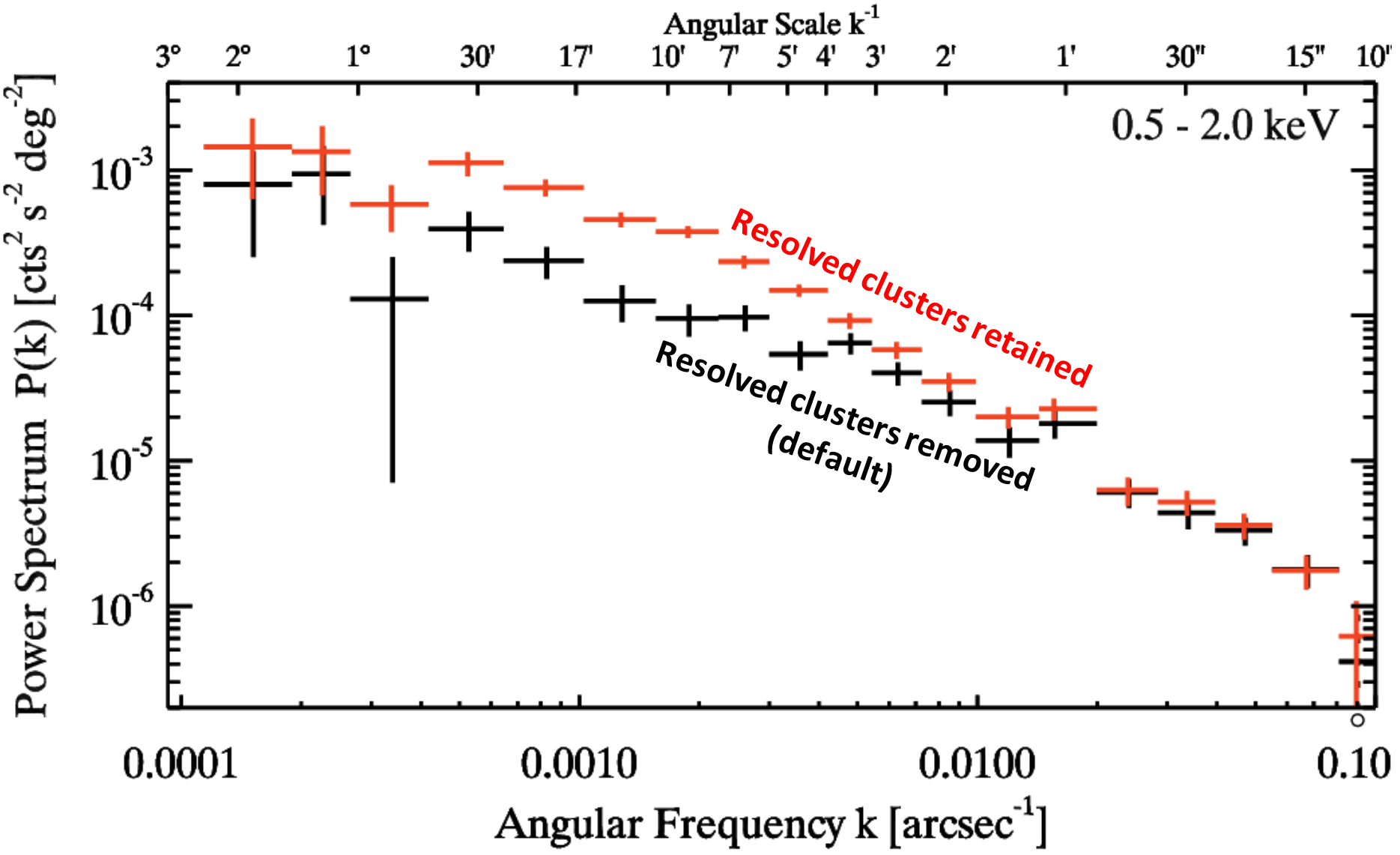
LSS signal:
Observational evidence

LSS Signal does **not** depend on point sources!

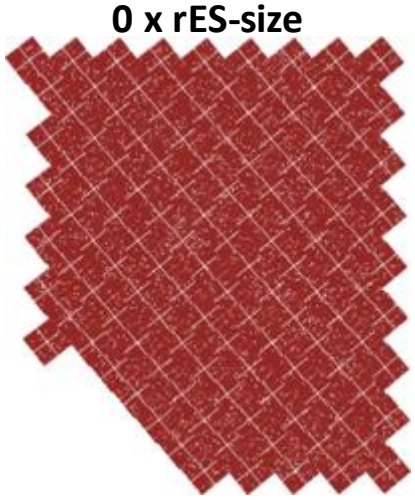
Fractions of removed resolved point sources

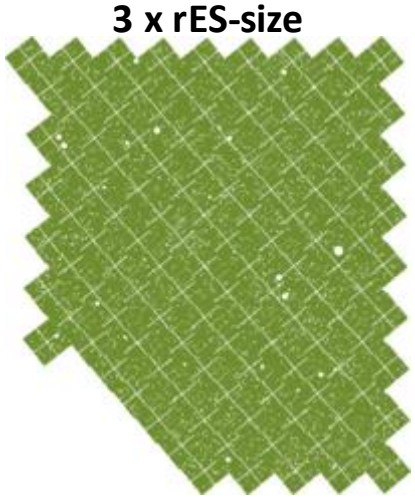


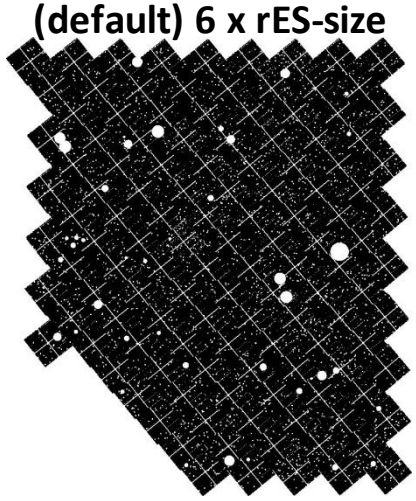
LSS Signal depends on galaxy clusters !

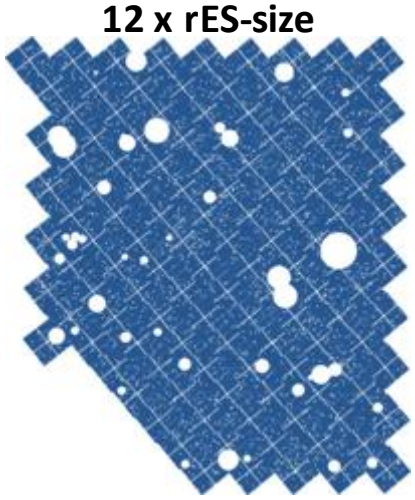


Removing fractional area of resolved clusters

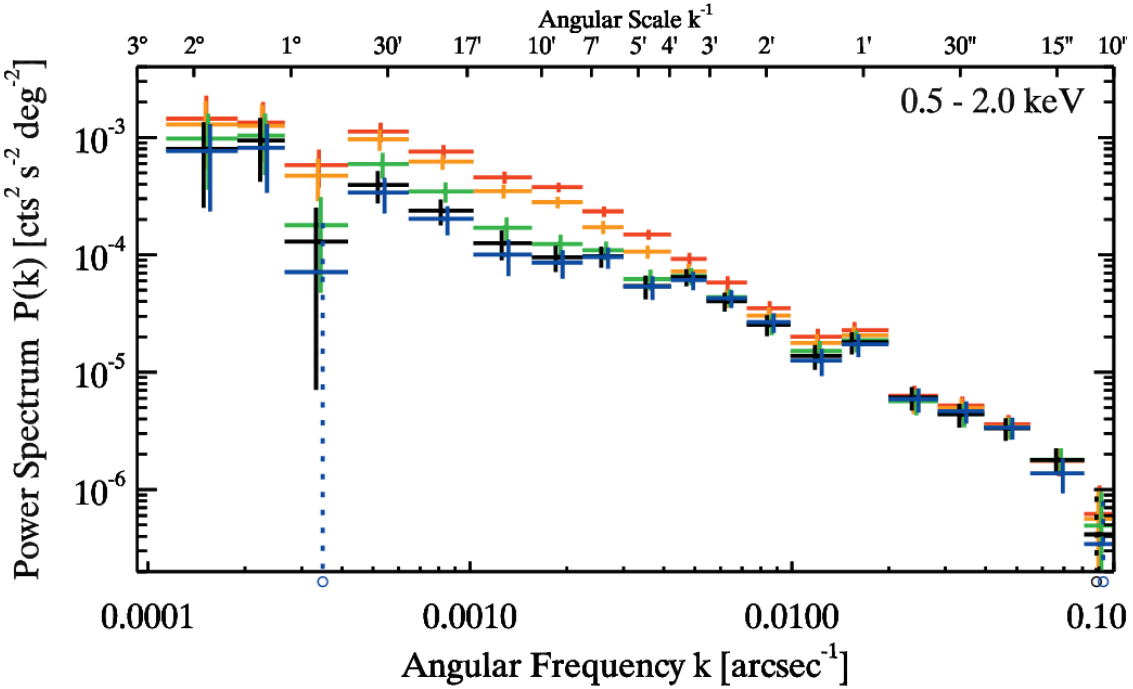




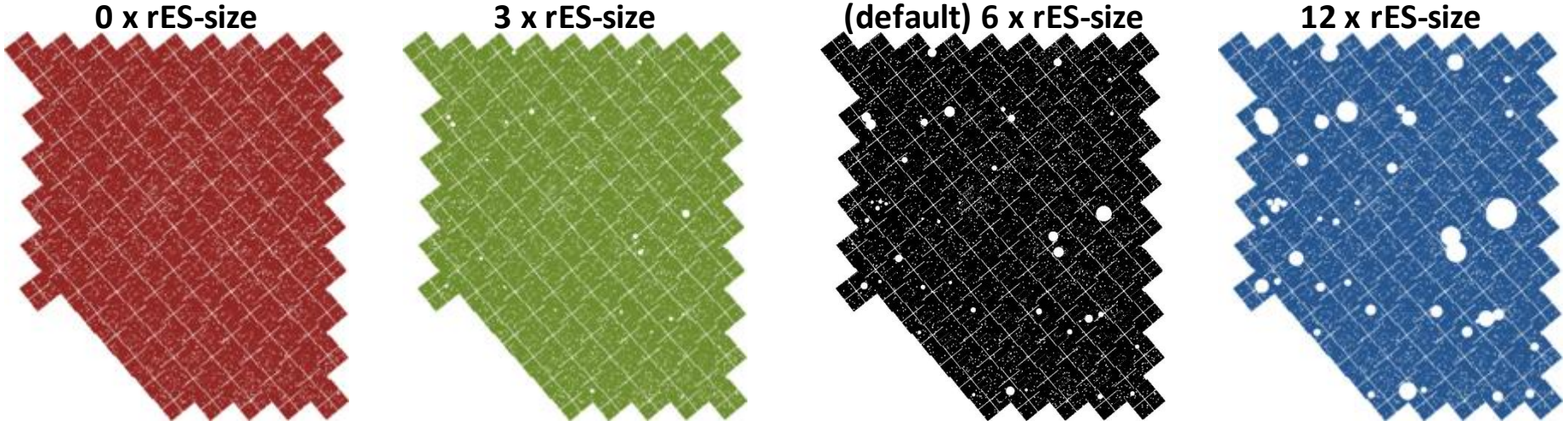




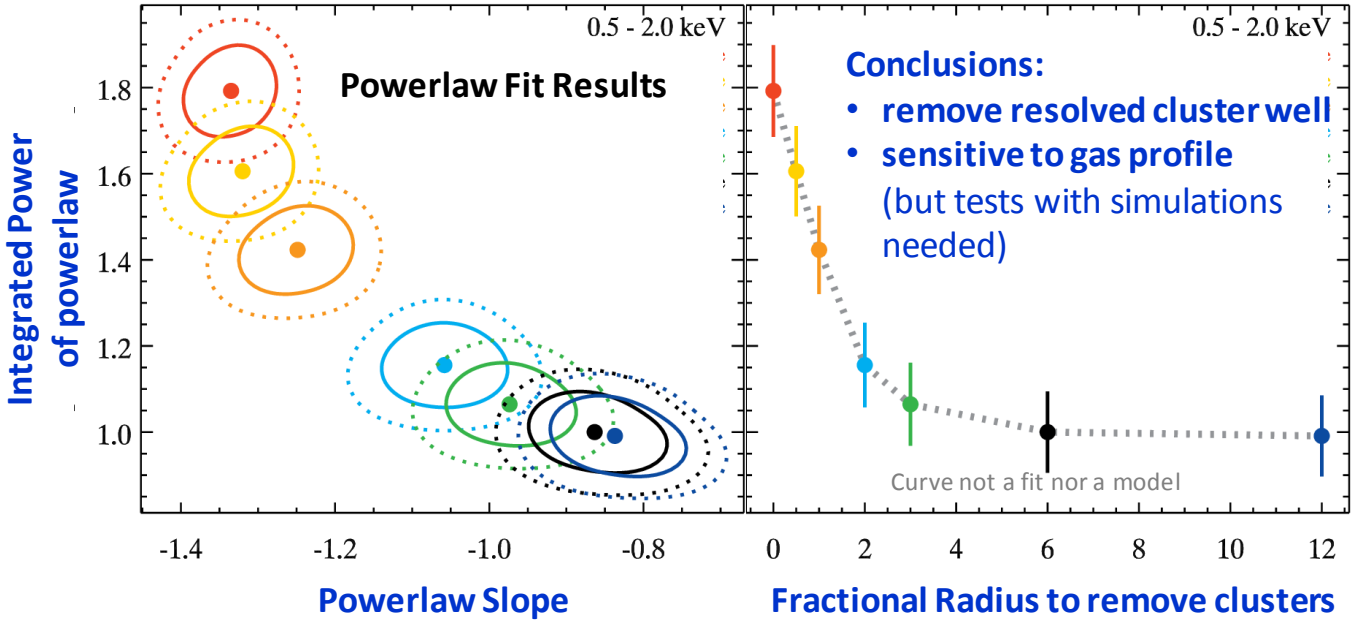
Fractional Radius:
0.0x (All rES retained)
1.0x
3.0x
6.0x (default)
12x



Removing fractional area of resolved clusters



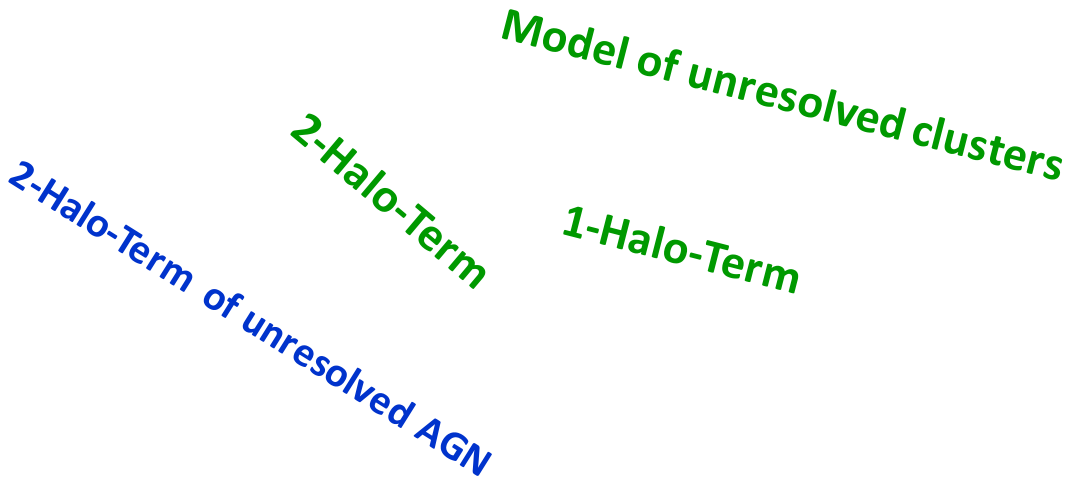
Fractional Radius:
0.0x (All rES retained)
0.5x
1.0x
2.0x
3.0x
6.0x (default)
12x



LSS signal:
Theoretical evidence

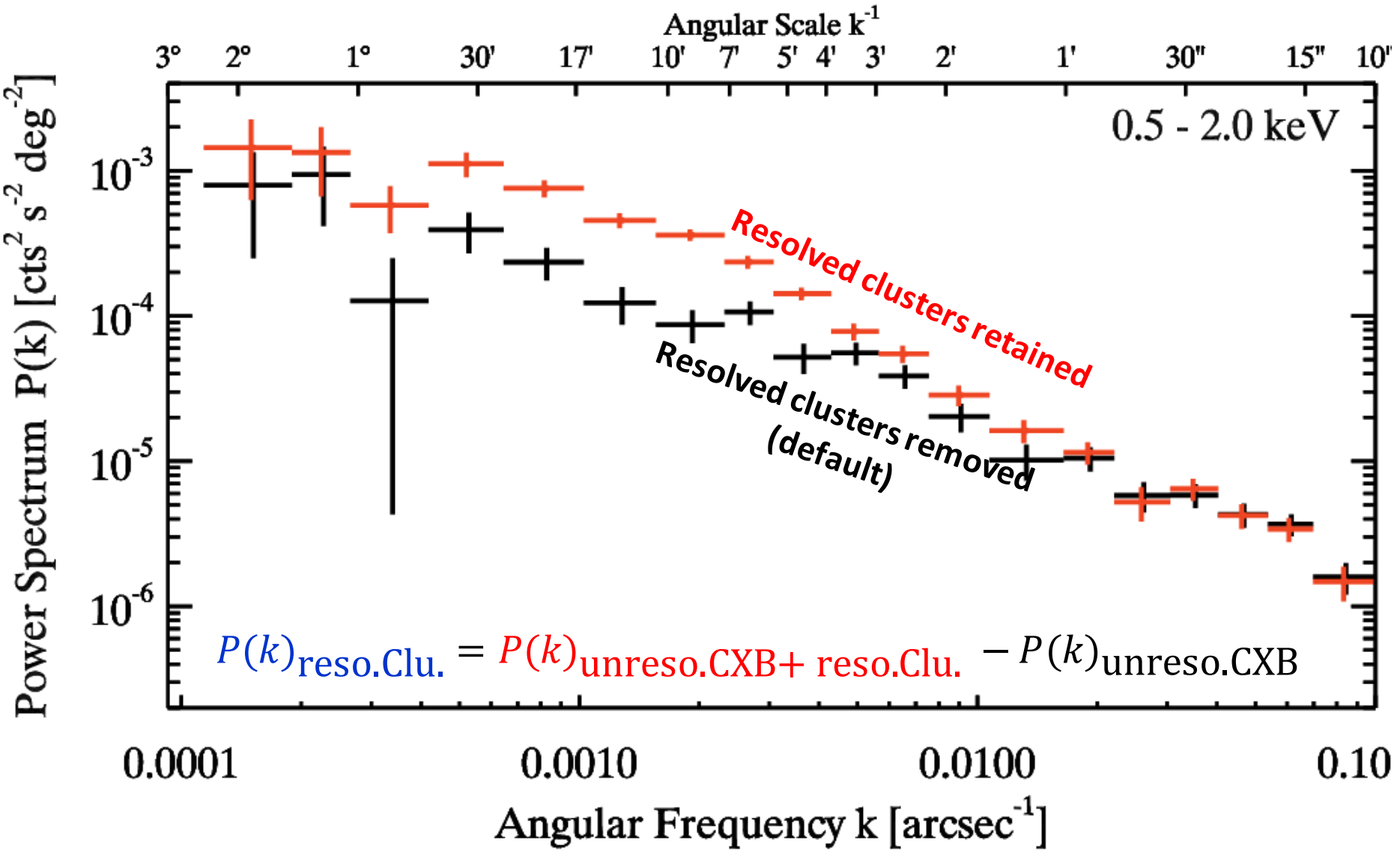
Unresolved CXB: observation vs. model

Preliminary

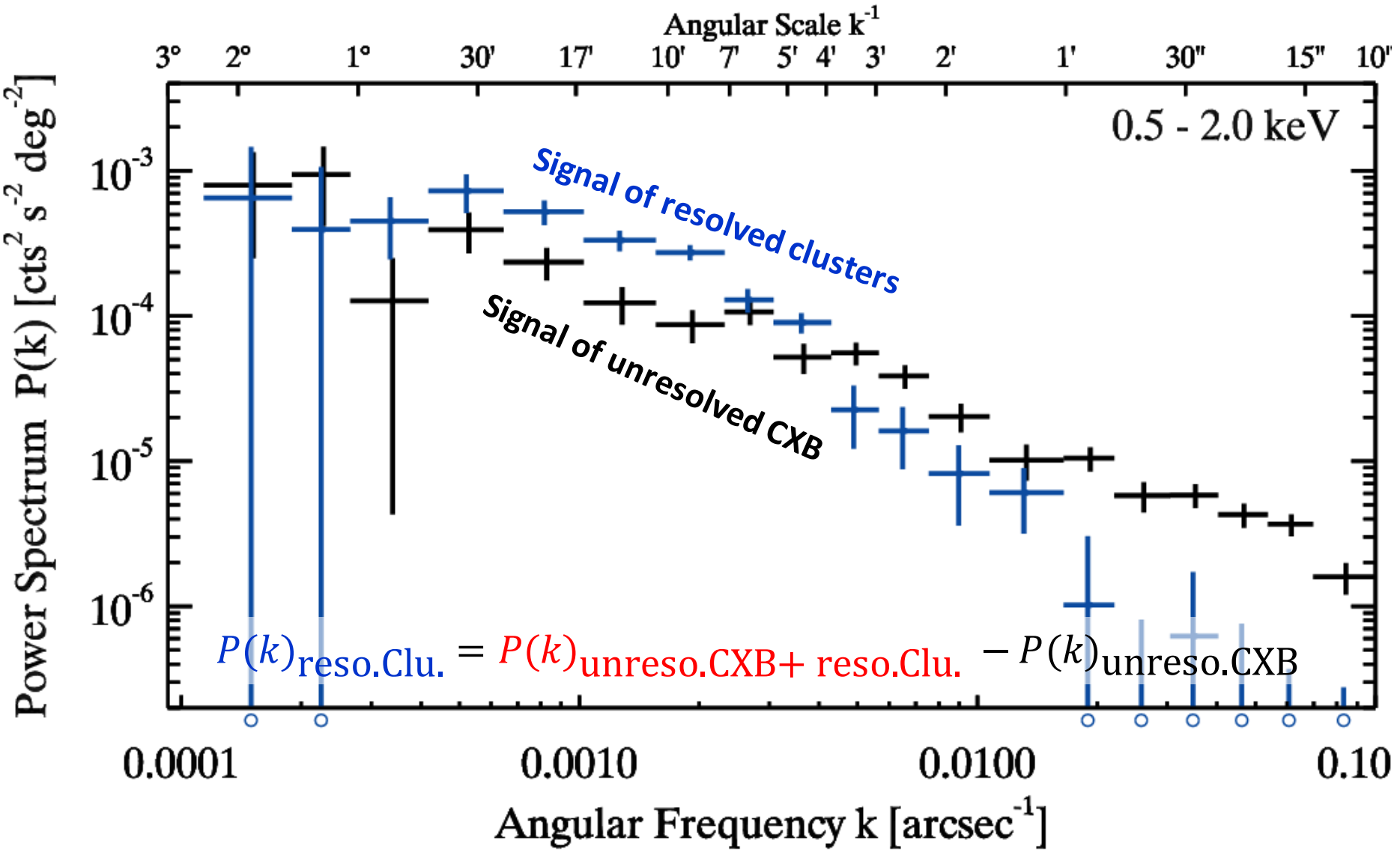


LSS signal of resolved clusters

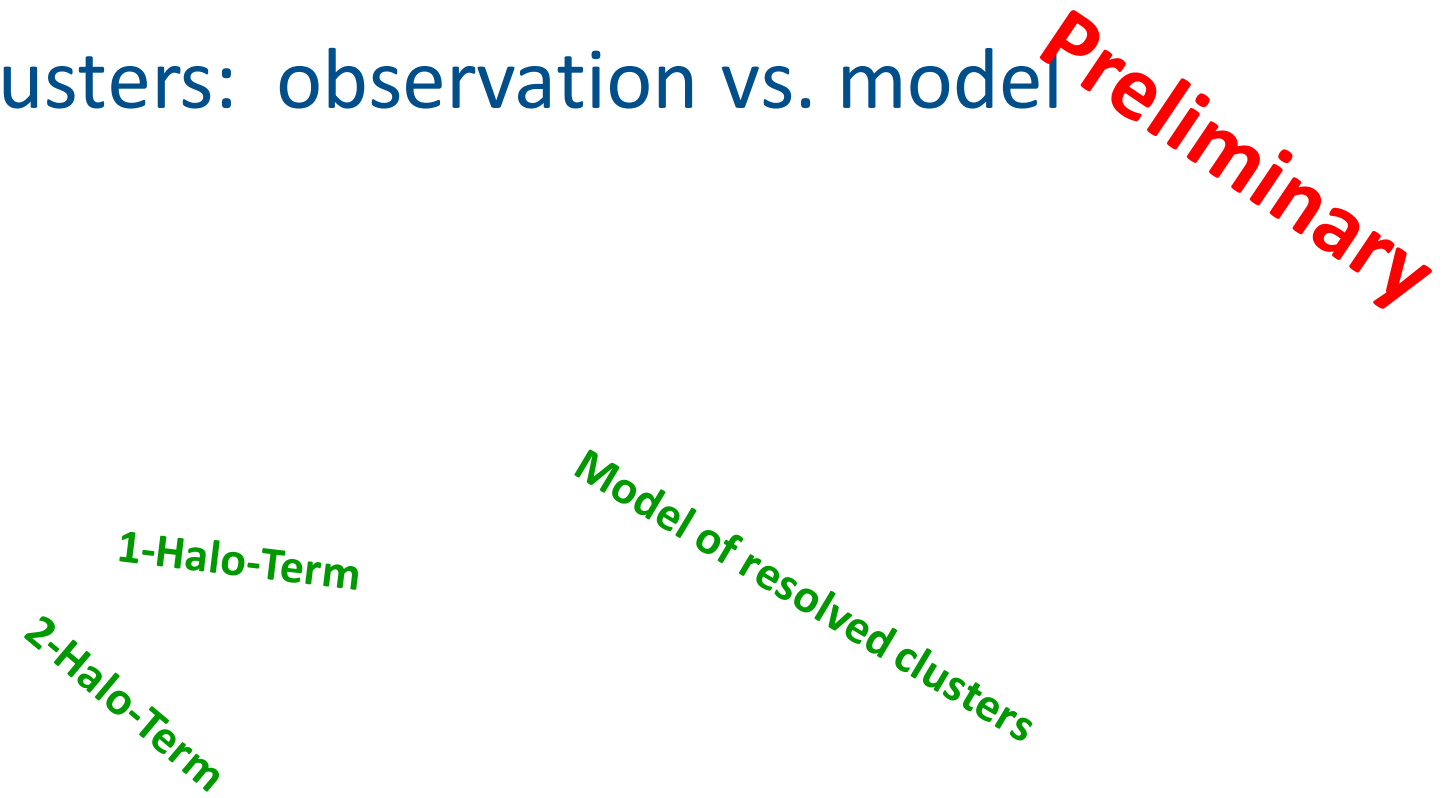
Get LSS signal of resolved clusters



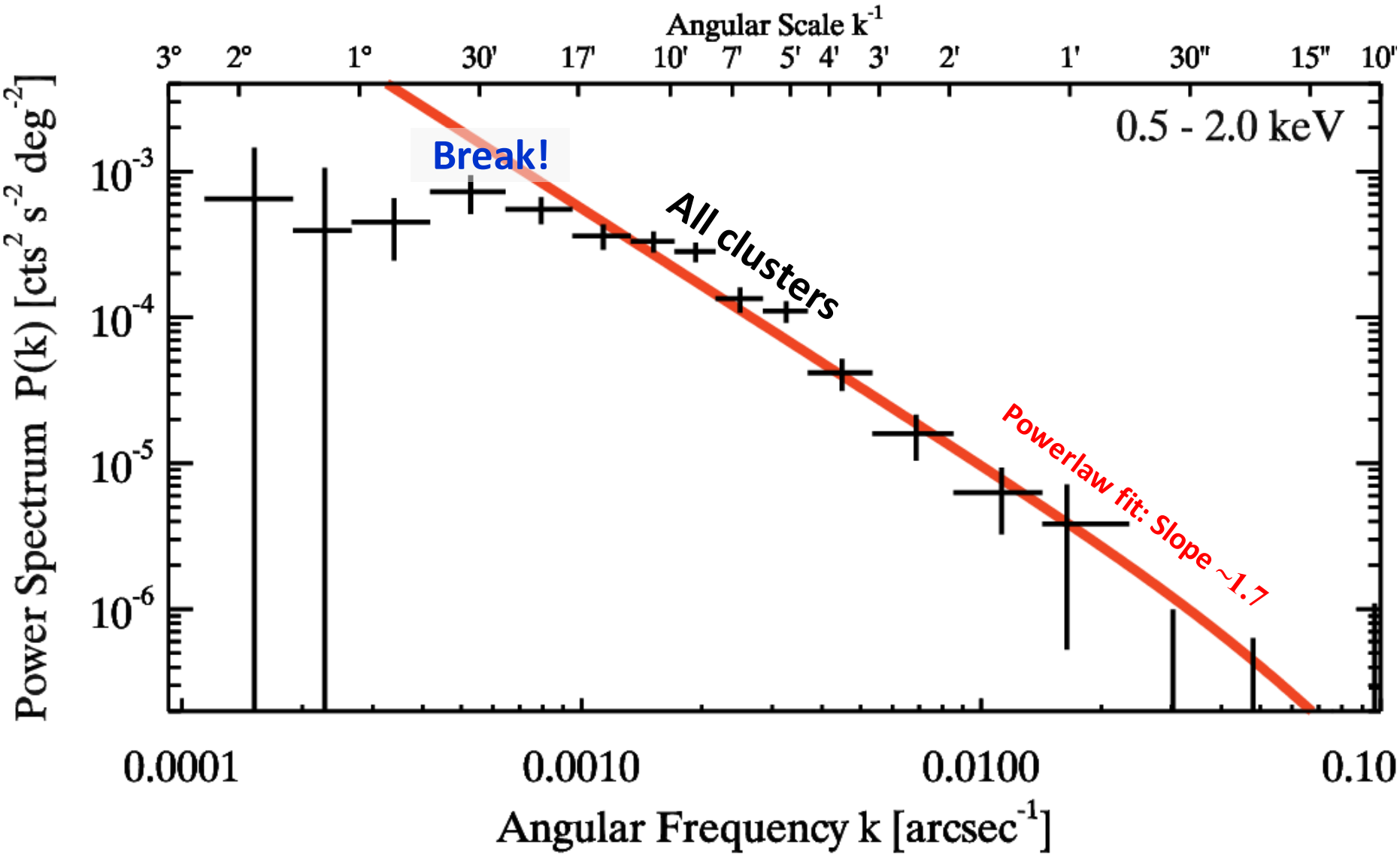
LSS signal: unresolved CXB vs. resolved clusters



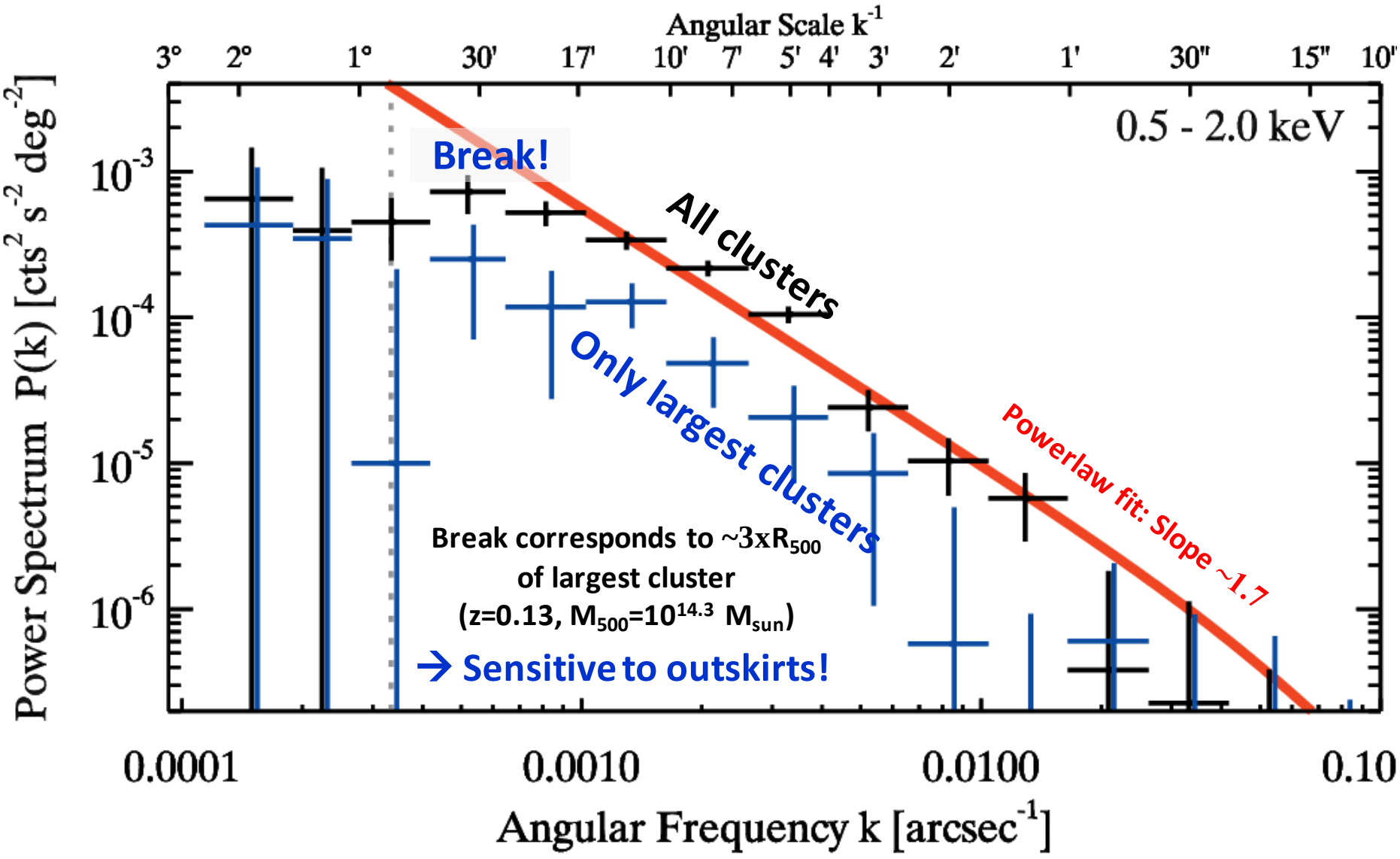
Resolved clusters: observation vs. model



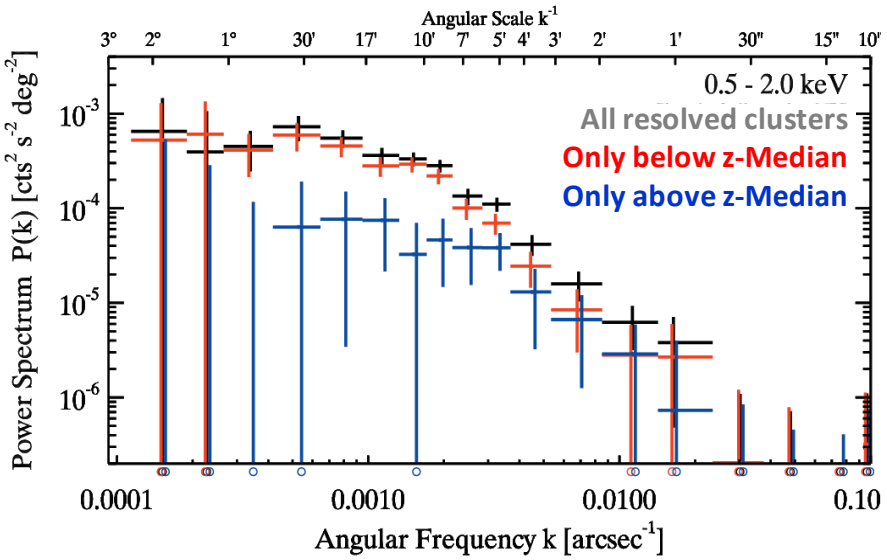
Break in LSS signal of resolved clusters

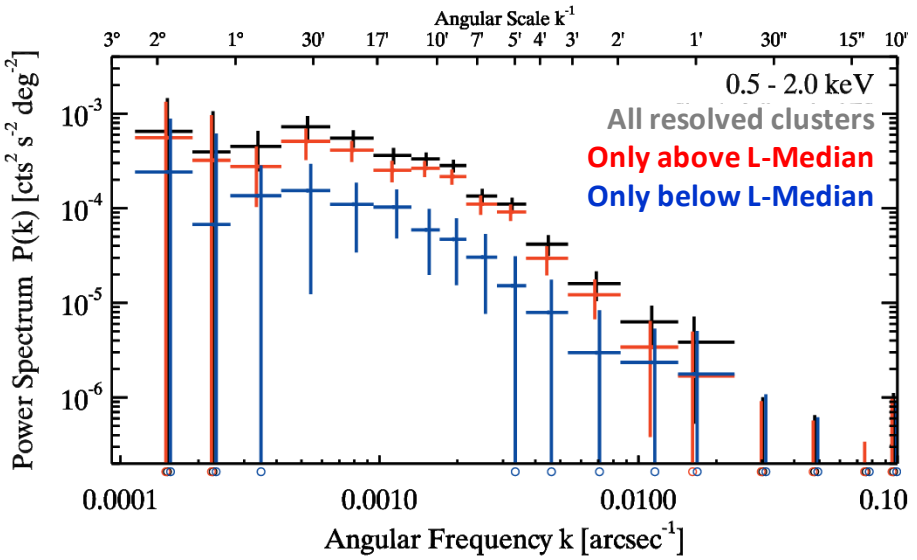


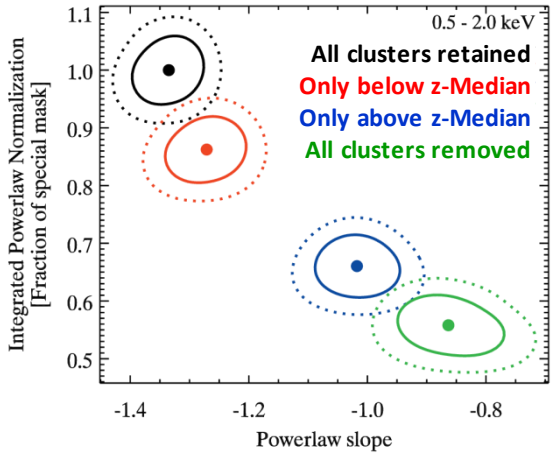
Break in LSS signal of resolved clusters

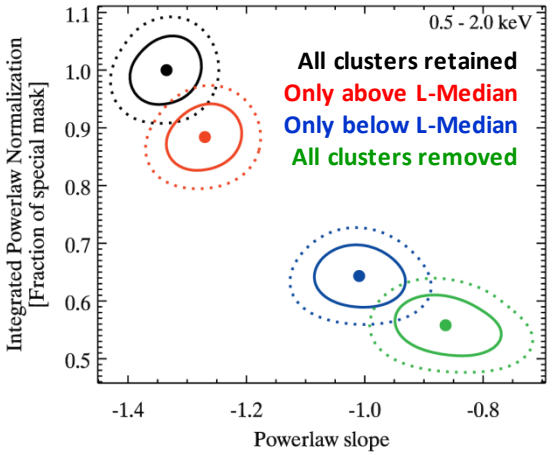


Redshift and luminosity dependence









Conclusion:

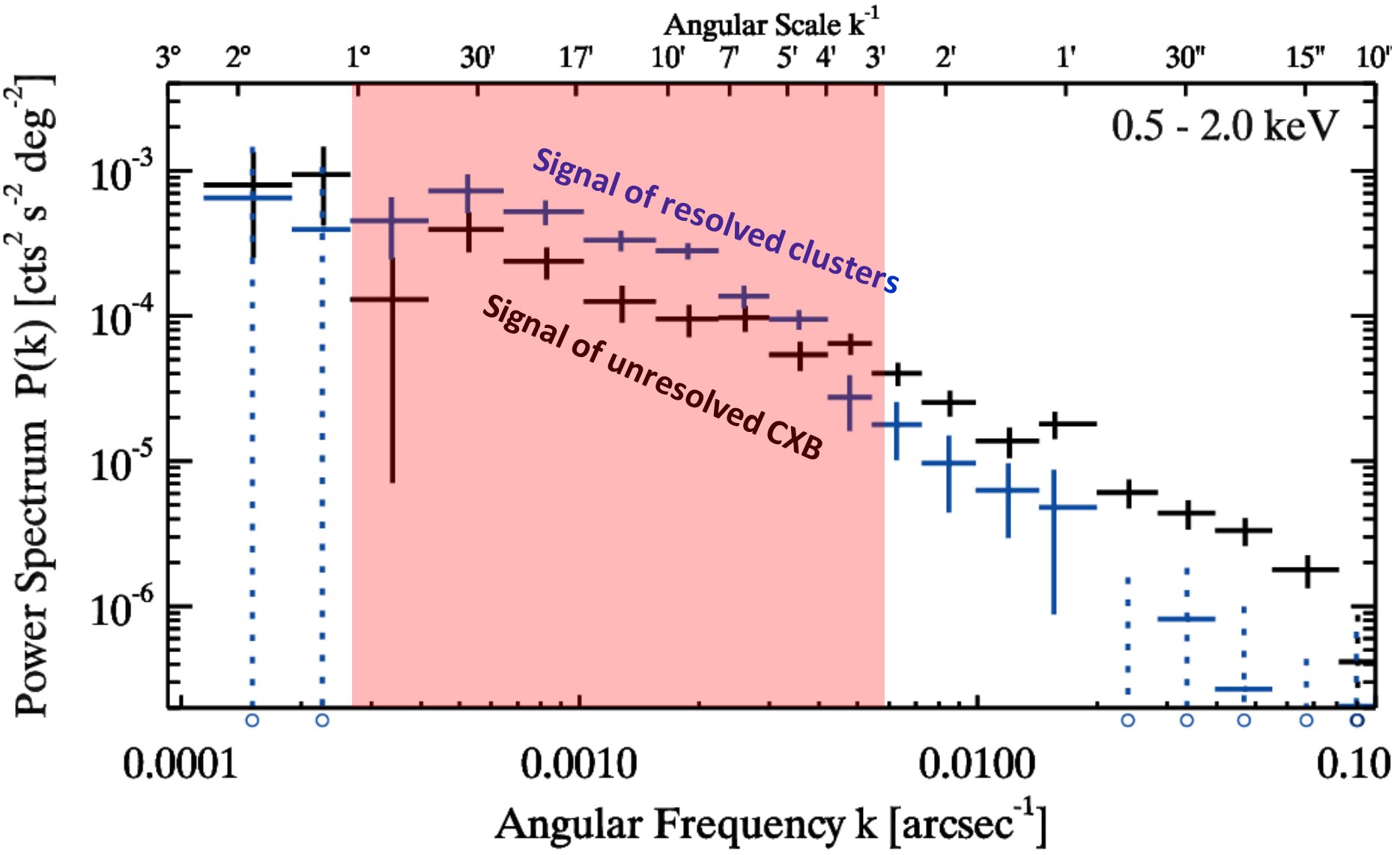
LSS signal of resolved clusters dominated by clusters:

- below z-median (z=0.24)

- above L-median (L_{bol}=2.2x10^{43} erg/s)

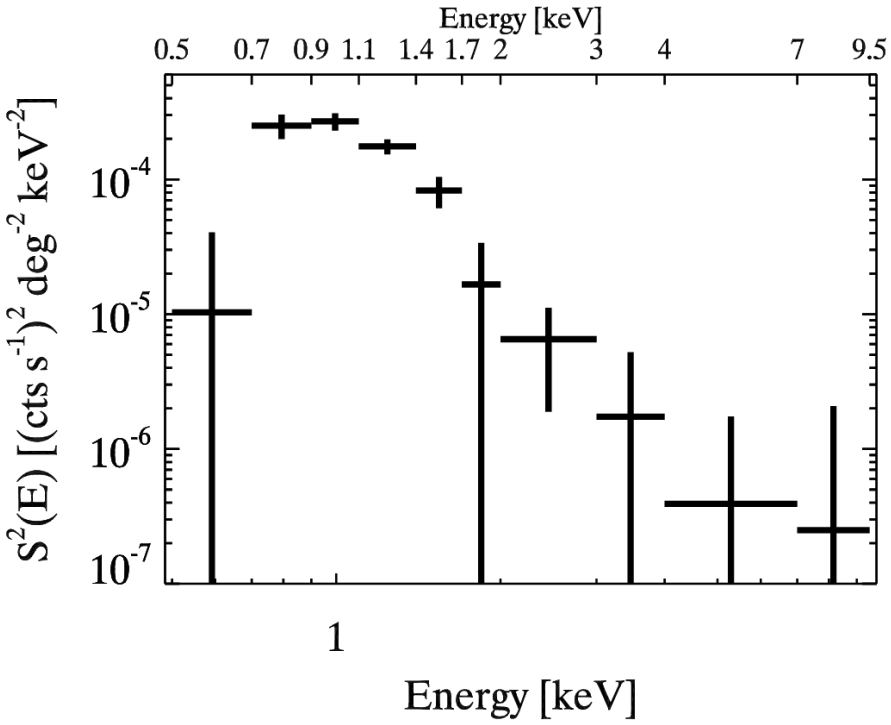
Energy Spectrum of LSS signal

LSS signal: Unresolved CXB & resolved clusters



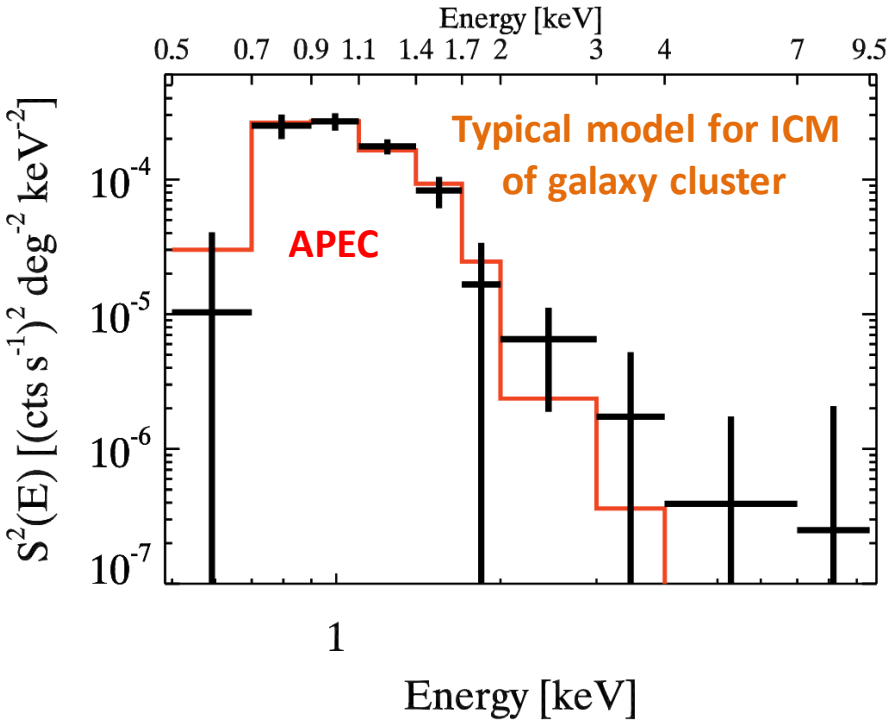
Energy Spectrum of CXB fluctuations

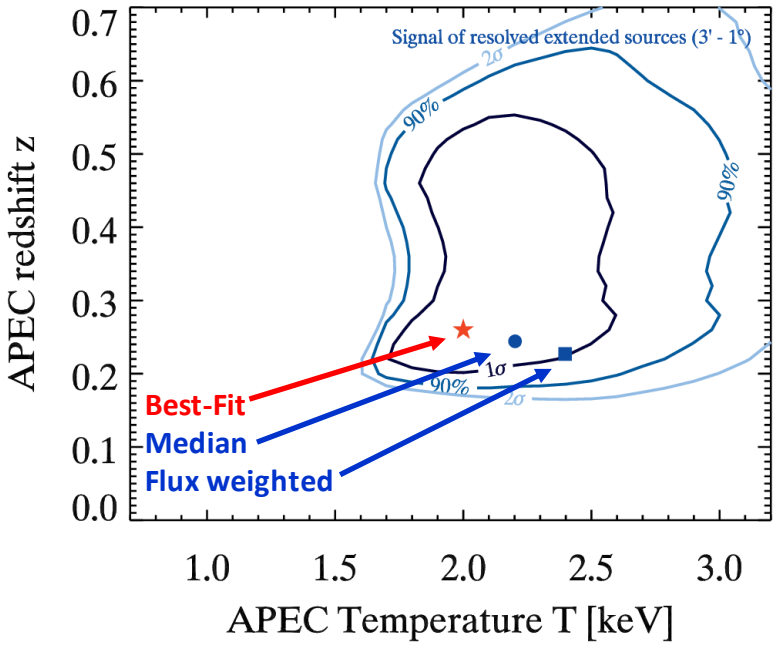
Resolved clusters



Energy Spectrum of CXB fluctuations

Resolved clusters





APEC: z=0.26, T=2.0keV

N_H=10^{20}cm^2 , Metal Abundance 0.3

Based on resolved clusters:

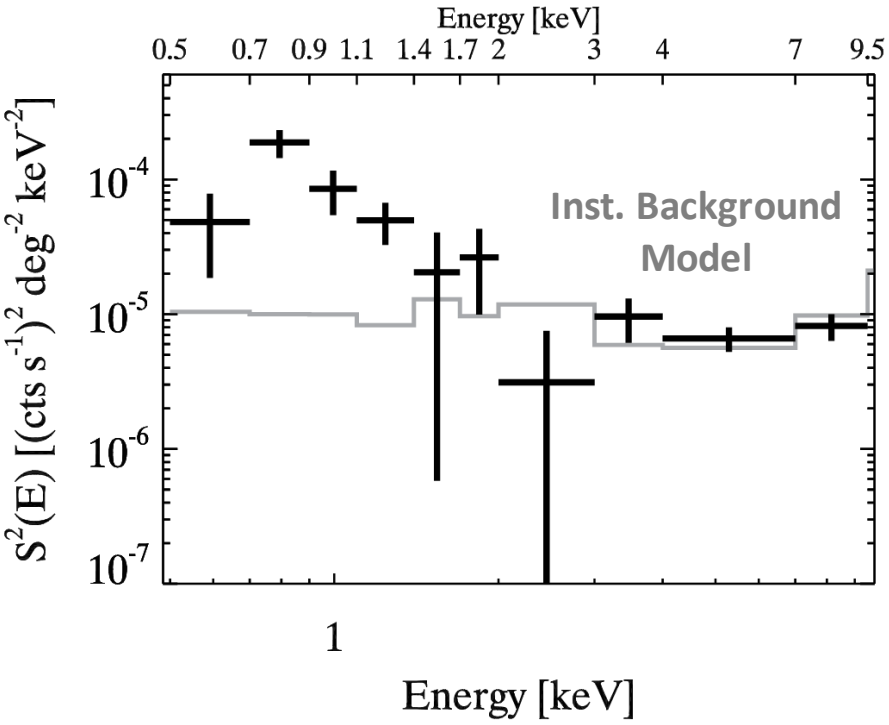
- **Median z~0.24,**
- **Flux weighted z~0.23**
- **Mass M_{500} ~ $10^{14.0}$ M_{Sun}**
- **T_{ICM} ~ 2.2keV based on L~$10^{43.1}$ erg/s**

Using L-T-Relation of **Giles+2015** (XXL)

→ method works reliable!

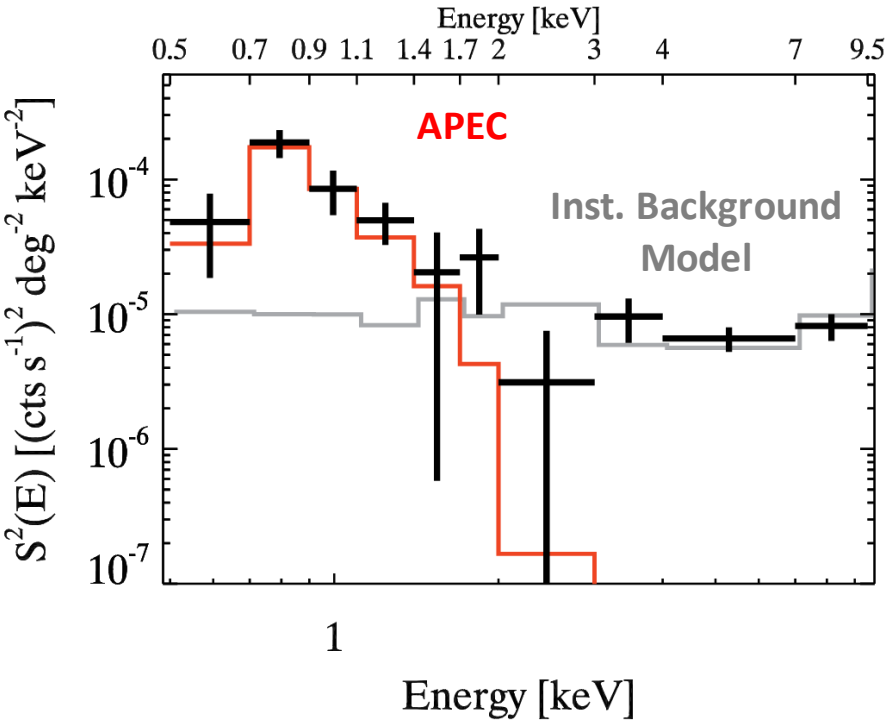
Energy Spectrum of CXB fluctuations

Unresolved CXB



Energy Spectrum of CXB fluctuations

Unresolved CXB

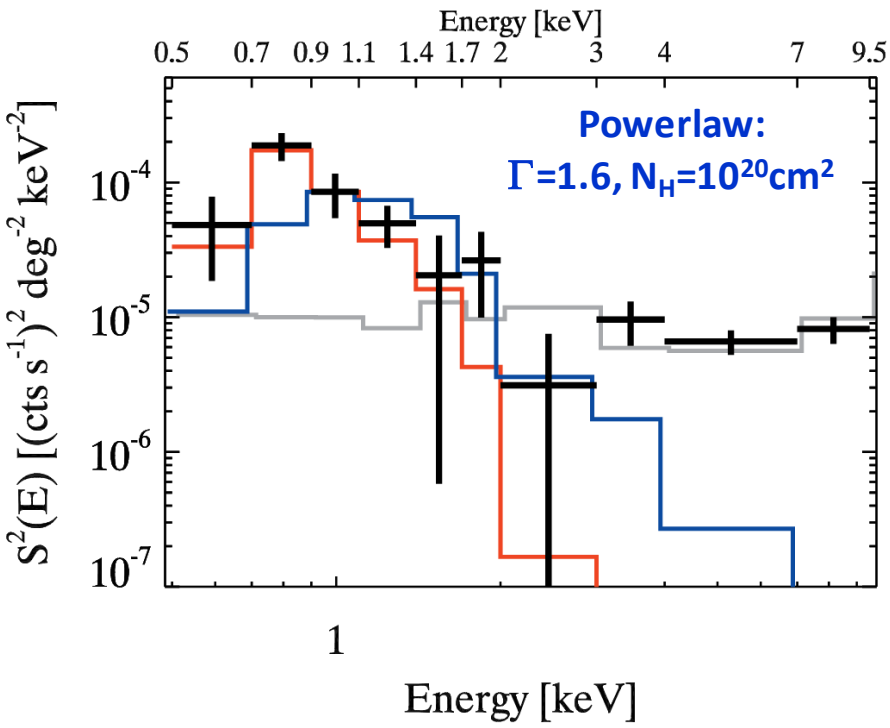


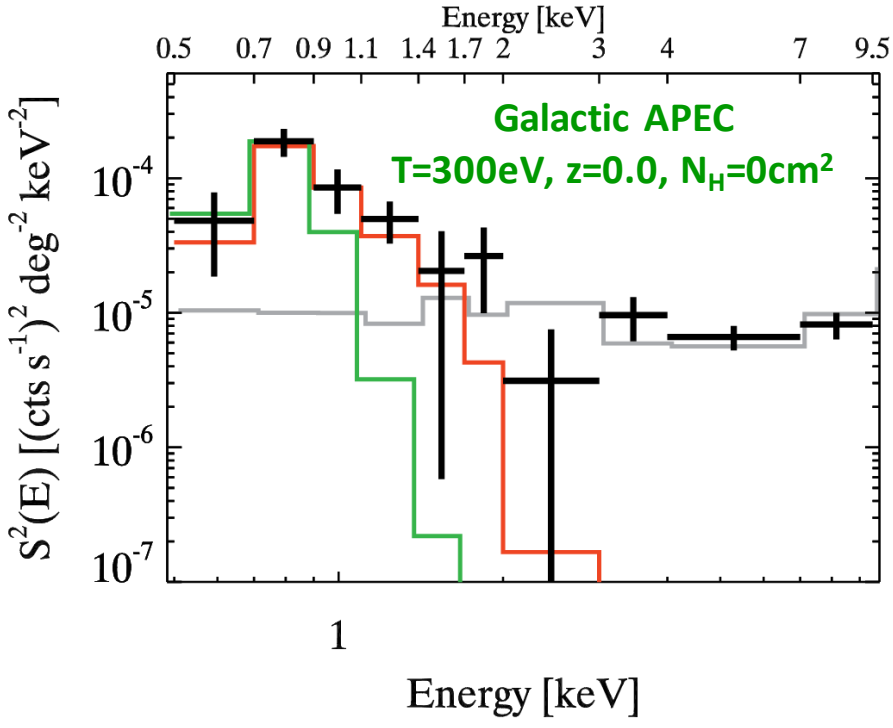
APEC: z=0.40, T=1.3keV

N_H=10^{20}cm^2 , Metal Abundance 0.3

Energy Spectrum of CXB fluctuations

Unresolved CXB





Inconsistent with Powerlaw Γ<3
(expected from AGN & normal galaxies)

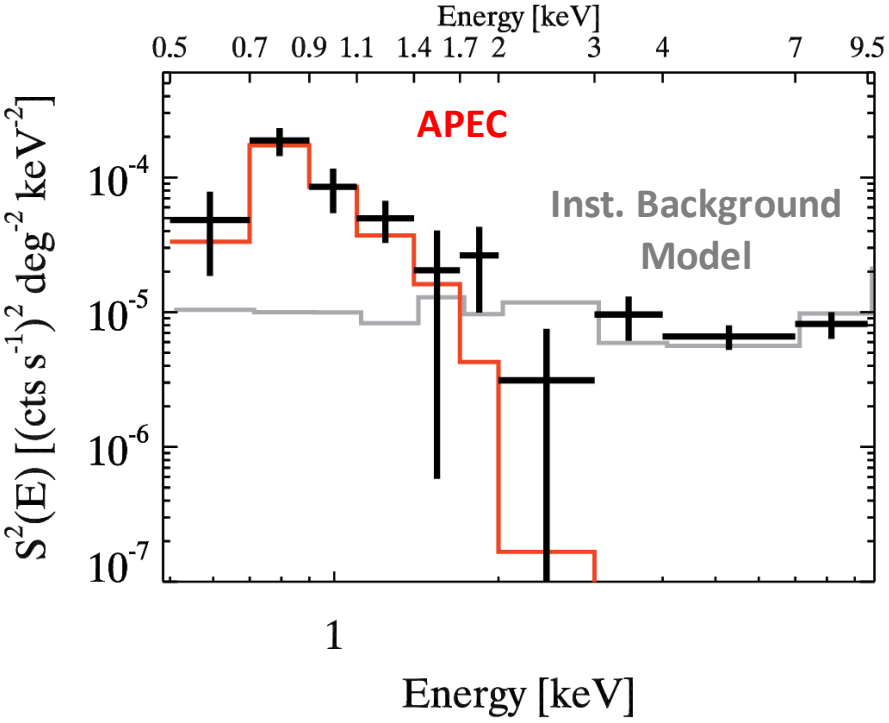
Inconsistent with unabsorbed APEC
(expected from Galactic emission)

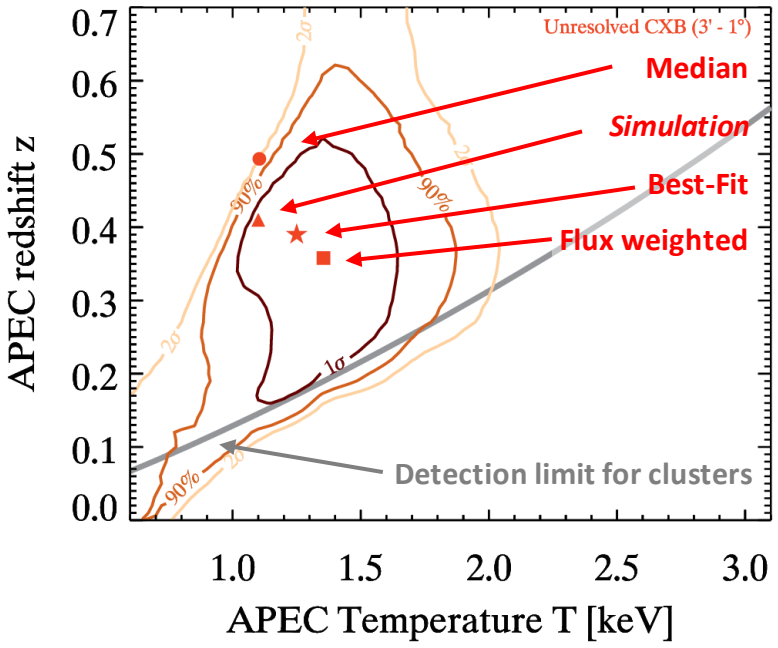
APEC: z=0.40, T=1.3keV

$N_H=10^{20}cm^2$, Metal Abundance 0.3

Energy Spectrum of CXB fluctuations

Unresolved CXB





APEC: z=0.40, T=1.3keV

N_H=10^{20}cm^2 , Metal Abundance 0.3

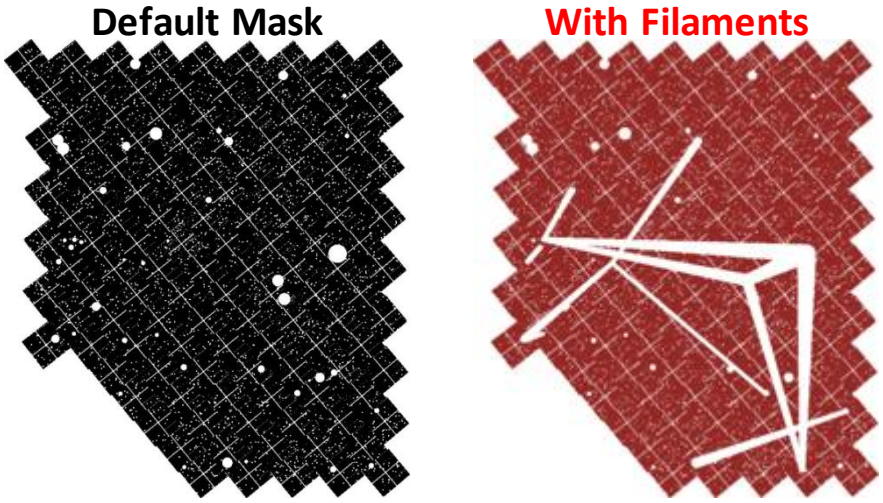
Based on XLF for unresolved clusters:

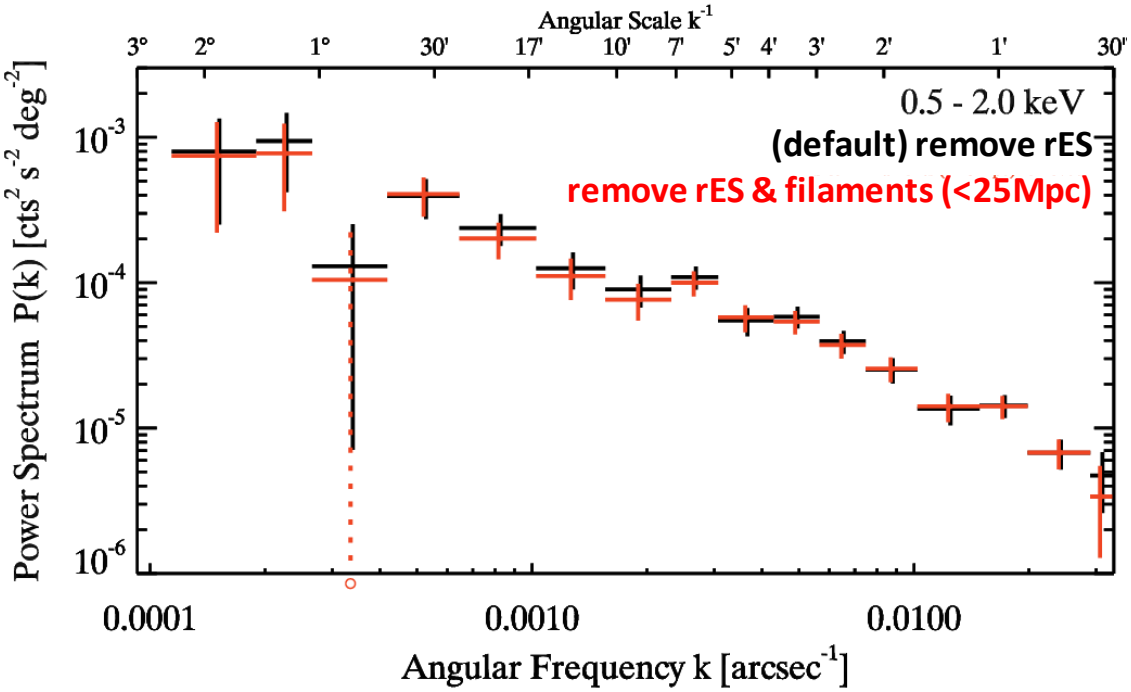
- **Median z~0.49**
- **Flux weighted z~0.35**
- **Median Mass M_{500} ~ $10^{13.5}$ M_{Sun}**
- **T_{ICM} ~ 1.1keV based on L~$10^{42.3}$ erg/s**

→ Strongest evidence for the origin of the LSS signal!

WHIM:
No observational evidence!

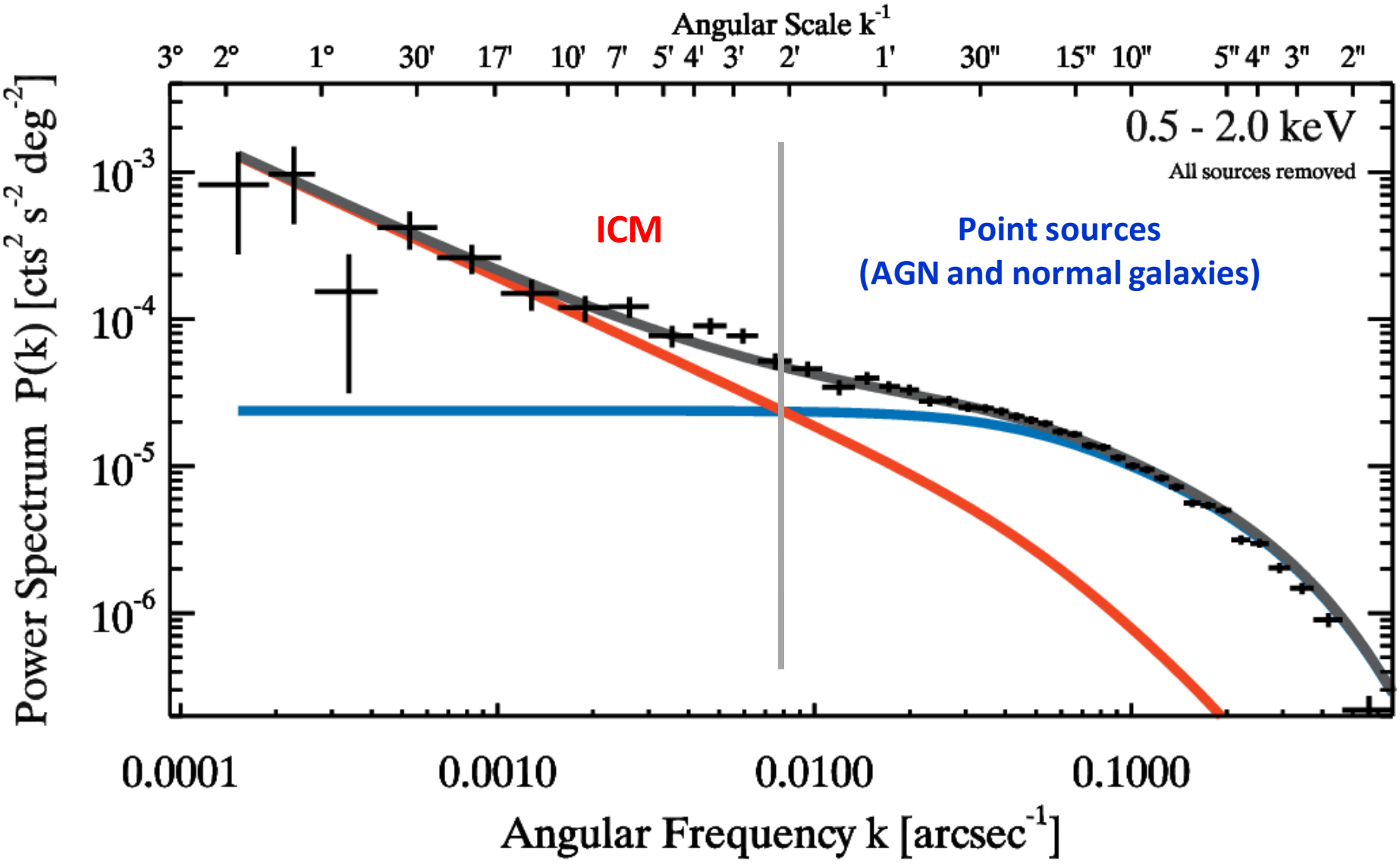
Removing filaments has no effect





Summary

Full description of CXB fluctuations below 3°



Summary

Max-Planck-Institut für Astrophysik

Surface brightness fluctuations of the CXB with XBOOTES:

- **LSS signal** (for >2'):
  - Resolved source retained:
    - Amplitude and negative slope increases for extended sources
    - no change for point sources (not shown)
  - Energy spectrum:
    - in agreement with expectations from (un)resolved galaxy cluster & groups
    - no agreement with extragalactic power law nor with galactic thermal emission
  - Clustering models (*preliminary*):
    - Shape in reasonable agreement with 1-halo-term of (un)resolved galaxy cluster & groups
    - Possible signal of cluster substructure
    - Signal of resolved clusters: sensitive up to outskirts!
    - No agreement with AGN 2-halo-term

→ **Conclusion: LSS signal originates from the ICM of (un)resolved galaxy clusters & groups**

– No evidence for signal of WHIM at given S/N

Application: New tool to study the ICM structure of galaxy cluster & groups up to the outskirts

Great potential for large surveys, e.g. Stripe 82X, XXL, SRG/eRosita all-sky survey !

Outlook: using CXB angular correlations analysis for ICM structure studies

Pro's:

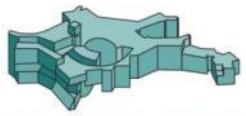
- Unique access to faint & low-luminosity sources
- Survey area more important than survey depth → ideal for XXL and eRASS!
- No requirement of other data (but appreciated)
- Study large source population at once (and simpler than stacking)
- Measure entire gas profile from core to outskirts ($>R_{500}$)
- "Simple" treatment of fore- & background CXB components
- "Simple" treatment of BKG (on scales above FOV)
- redshift information optional (use XLF instead)

Features:

- Energy-resolved study feasible
- SZ cross-correlation has great potential too

Con's:

- Require large survey area ($>9 deg^2$) with relative homogenous depth
- Spatial variation of inst. BKG may be important (on scales below FOV)
- Difficult to use for individual sources (need to be bright and nearby)
- For unresolved sources:
  - No direct measurement of properties
  - Rely on XLF and scaling relations
- Modeling challenging
  - many theoretical unknowns
  - Measure one- and two-halo term simultaneously at best



Backup

Energy Spectrum of unresolved emission (0.5 - 10.0 keV)