Max-Planck-Institut für Astrophysik

IAS Orsay

A brief & biased review on
X-ray background fluctuation analysis

Speaker **Alex Kolodzig**

Affiliation $\leq$08/2018: Max Planck Institute for Astrophysics (MPA), Garching, Germany
$\geq$09/2018: Institut d'Astrophysique Spatiale (IAS), Orsay/Paris, France
→ Nabila Aghanim's ERC group "Baryon Picture of the Cosmos" (ByoPiC)

Collaborators Marat Gilfanov (MPA,IKI), Rashid Sunyaev (MPA,IKI), Gert Hütsi (Tartu Observatory, Estonia), Dominique Eckert (MPE), Nico Cappelluti (University of Miami)

Venue "3rd Anisotropic Universe workshop ", Barolo, Italy, Tu.04.09.2018

Outline

Fluctuation analysis with:

1. Early X-ray surveys (<2000)
2. Modern X-ray surveys (>2000)

Science driver

Fluctuation analysis
with early X-ray surveys

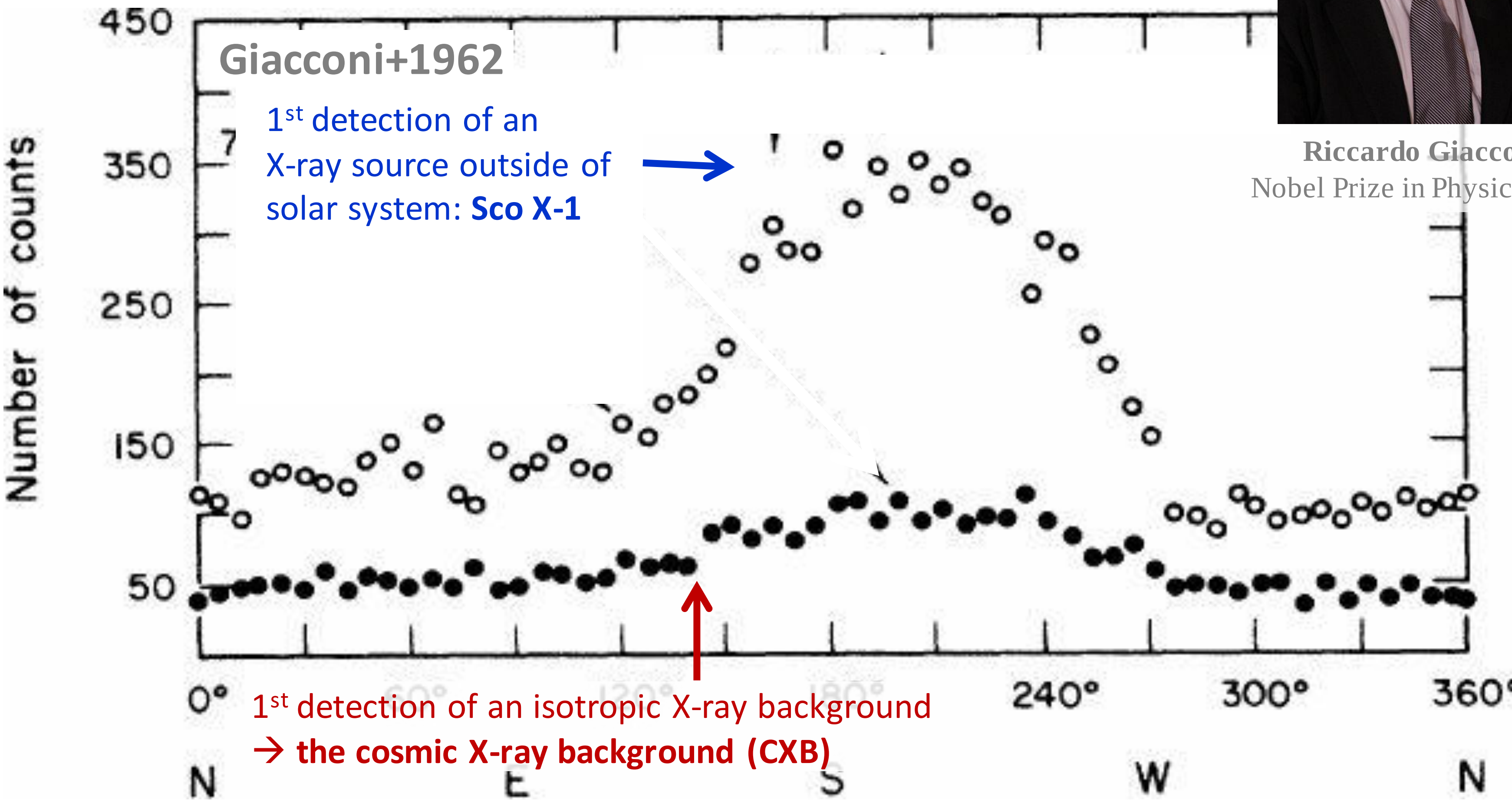
↓

Origin of the (extragalactic)
cosmic X-ray background (CXB)

The birth of X-ray astronomy (~60 years ago)

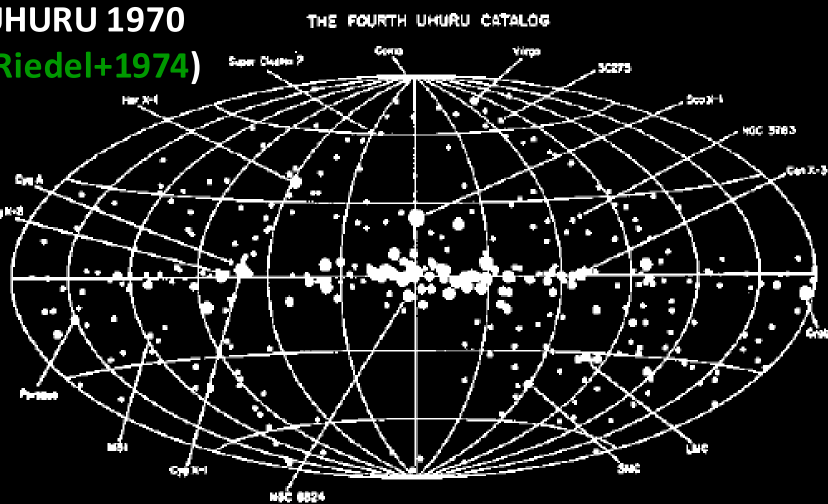
- 1960s - Rocket and Balloon experiments with simple Geiger-Counters

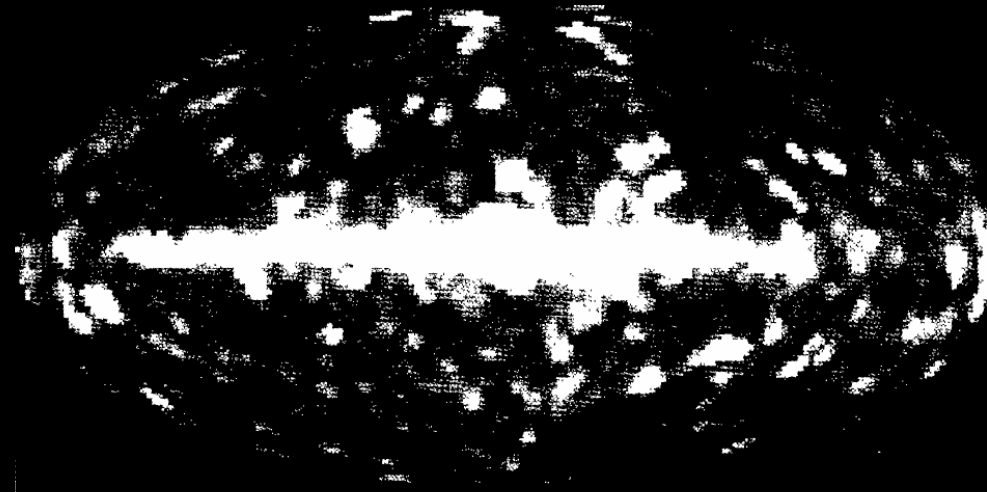
Riccardo Giacconi
Nobel Prize in Physics 2002



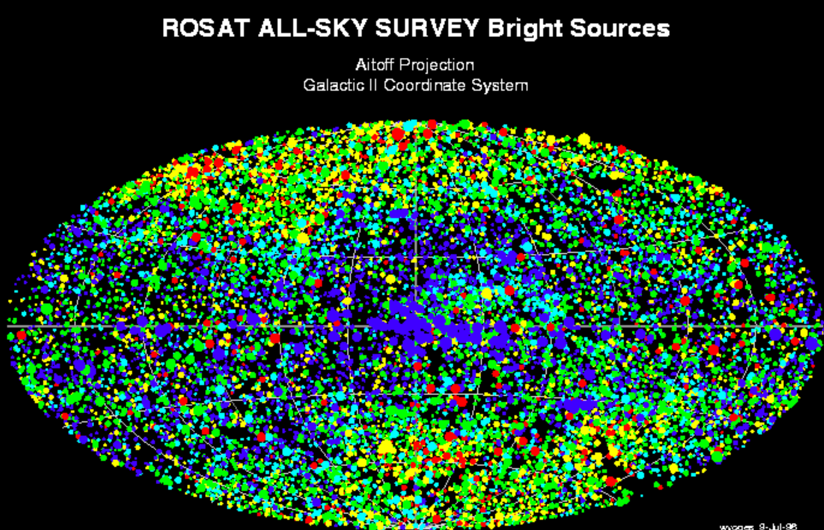
Evolution of X-ray all-sky surveys

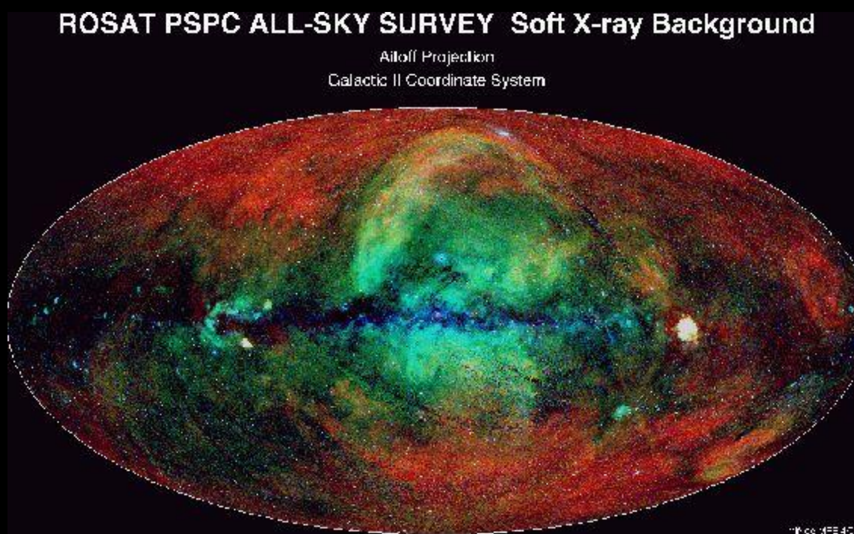
UHURU 1970
(Riedel+1974)





HEAO-1 A2 1980s (2-10 keV) (Fabian & Barcons 1992)

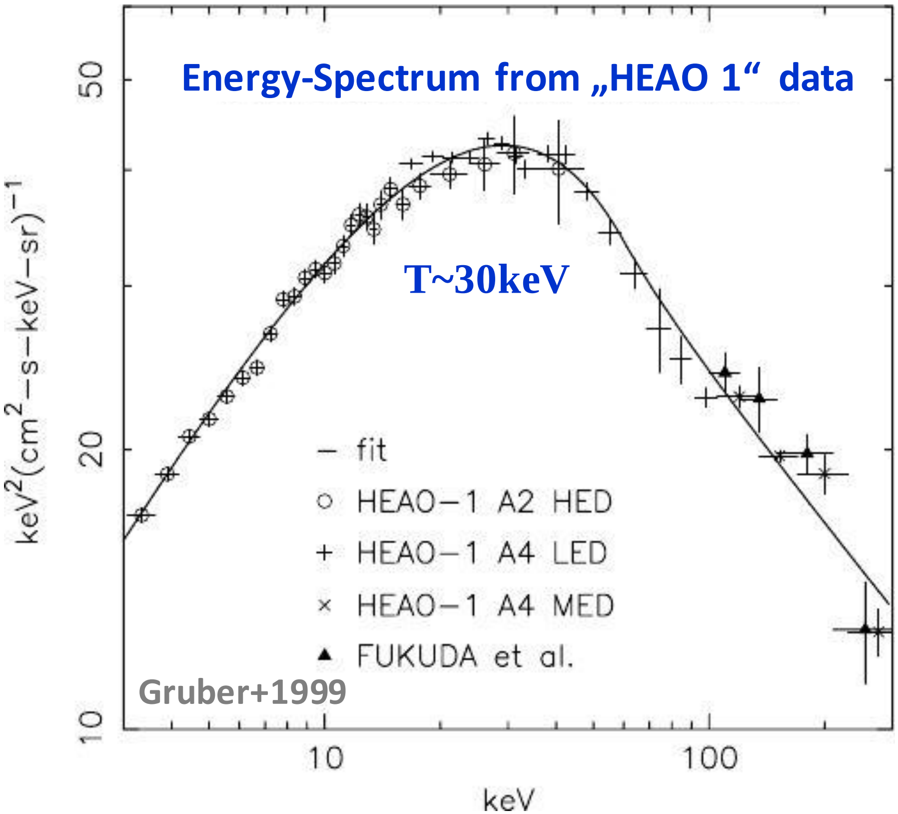




ROSAT 1990s (0.5-2 keV) (Freyberg+1999)

Origin of the extragalactic CXB

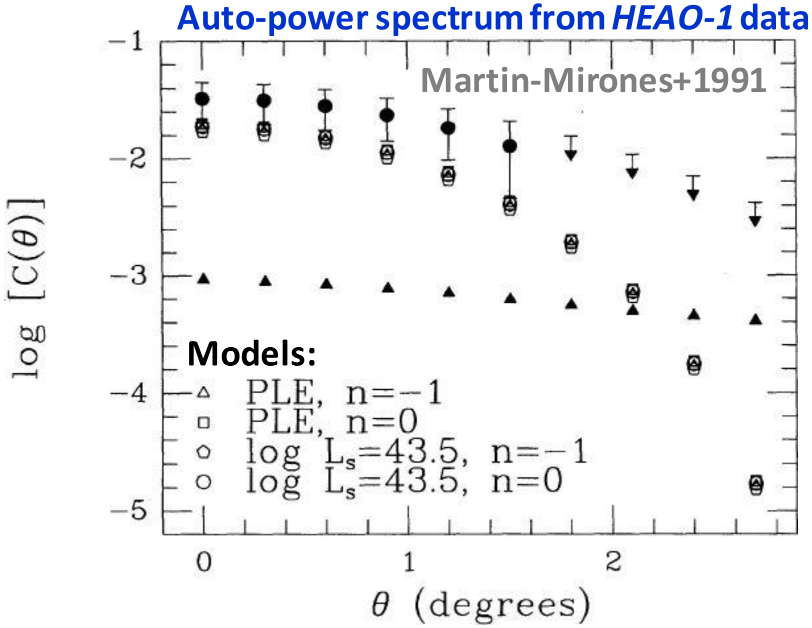
- Energy spectrum: thermal bremsstrahlung model (e.g. Marshall+1980)
- 2 competing theories: (e.g. Shafer & Fabian 1983)
  - Diffuse emission of a universal hot gas
  - Unresolved discrete sources



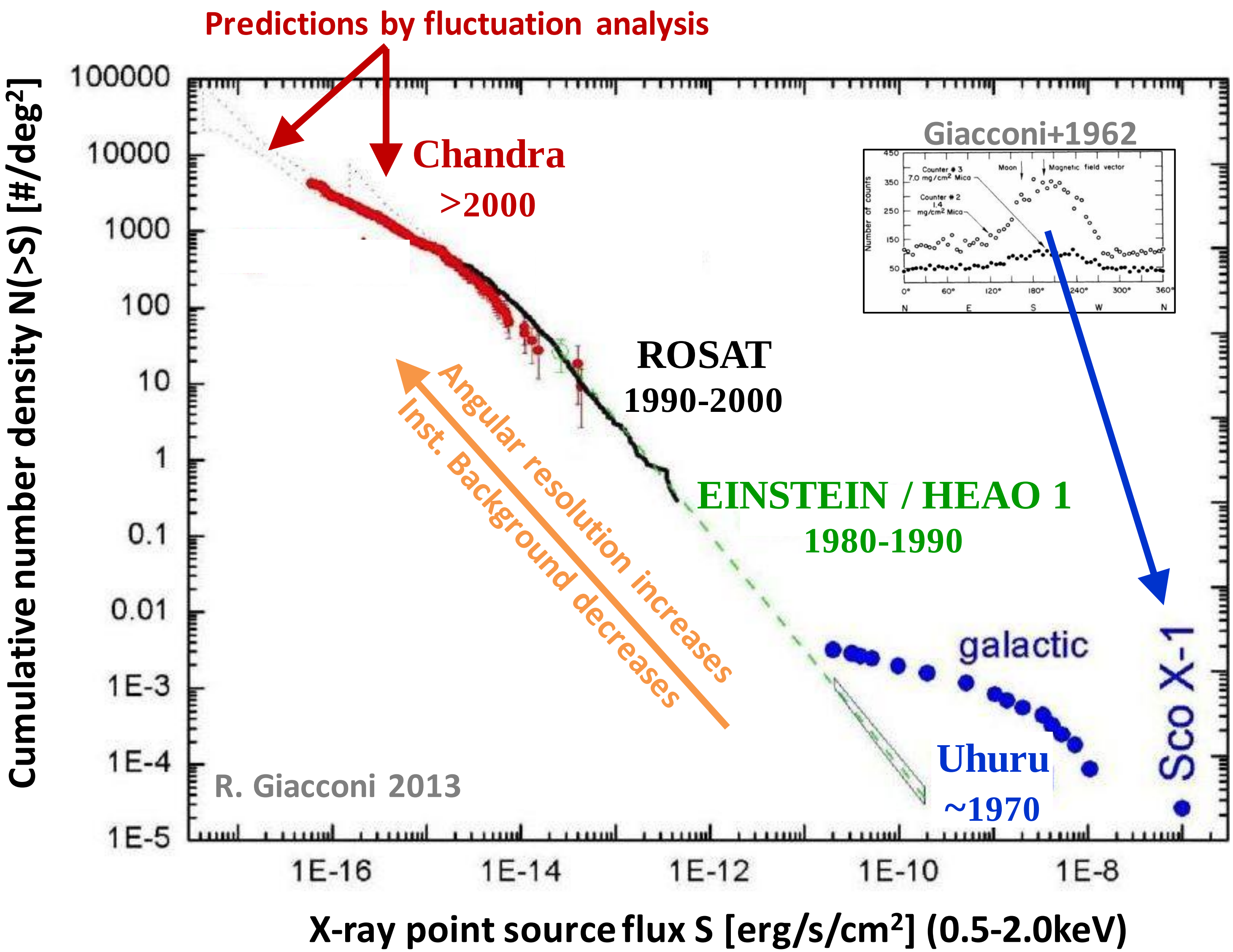
Origin of the extragalactic CXB!

- Major Problem: poor angular resolution of instruments
- Solution: Fluctuation analysis
- Results suggest in ~1980 that the *CXB emission is dominated by point-sources with a redshift distribution similar to optical QSOs but somewhat higher clustering strength* (e.g. Barcons & Fabian 1988)
- Confirmation >20 years later:
  - Discrete nature via very deep, pencil-beam-like surveys of *Chandra* (e.g. Hickox+2006) (*Chandra* on-axis : angular resolution = 0.5 arcsec, 5counts/source = 5σ detection)
  - Clustering strength via 2p-correlation studies with large X-ray source catalogs (e.g. Krumpe+2012)

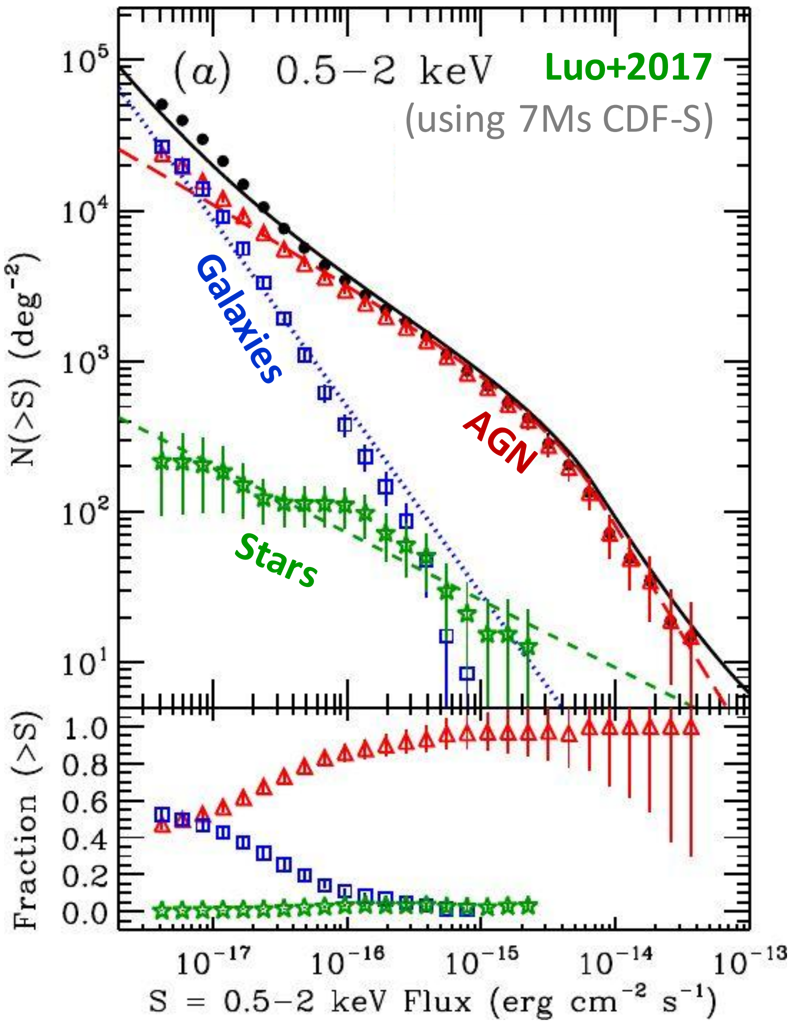
Auto-power spectrum from *HEAO-1* data



Dissolving the CXB into point sources



Extragalactic CXB: Resolved Fraction



Result:

~75% of the CXB emission within 0.5-2.0 keV originates from point sources with fluxes of > ~10^{-17} erg/s/cm^2:

~71% AGN

~3% Normal Galaxies (X-ray binaries)

~1% Stars

Conclusion: *The resolved CXB…*

- *…is the echo of the formation and growth of supermassive black holes over the cosmic time*
- *…plays a crucial role in understanding galaxy evolution*

Max-Planck-Institut für
Astrophysik

Fluctuation analysis
with modern X-ray surveys

(since ~2012)

Applications/Prospects

Fluctuation analysis with modern X-ray surveys

Large (shallow) surveys

Galaxy cluster physics, WHIM, cosmology, DM annihilation

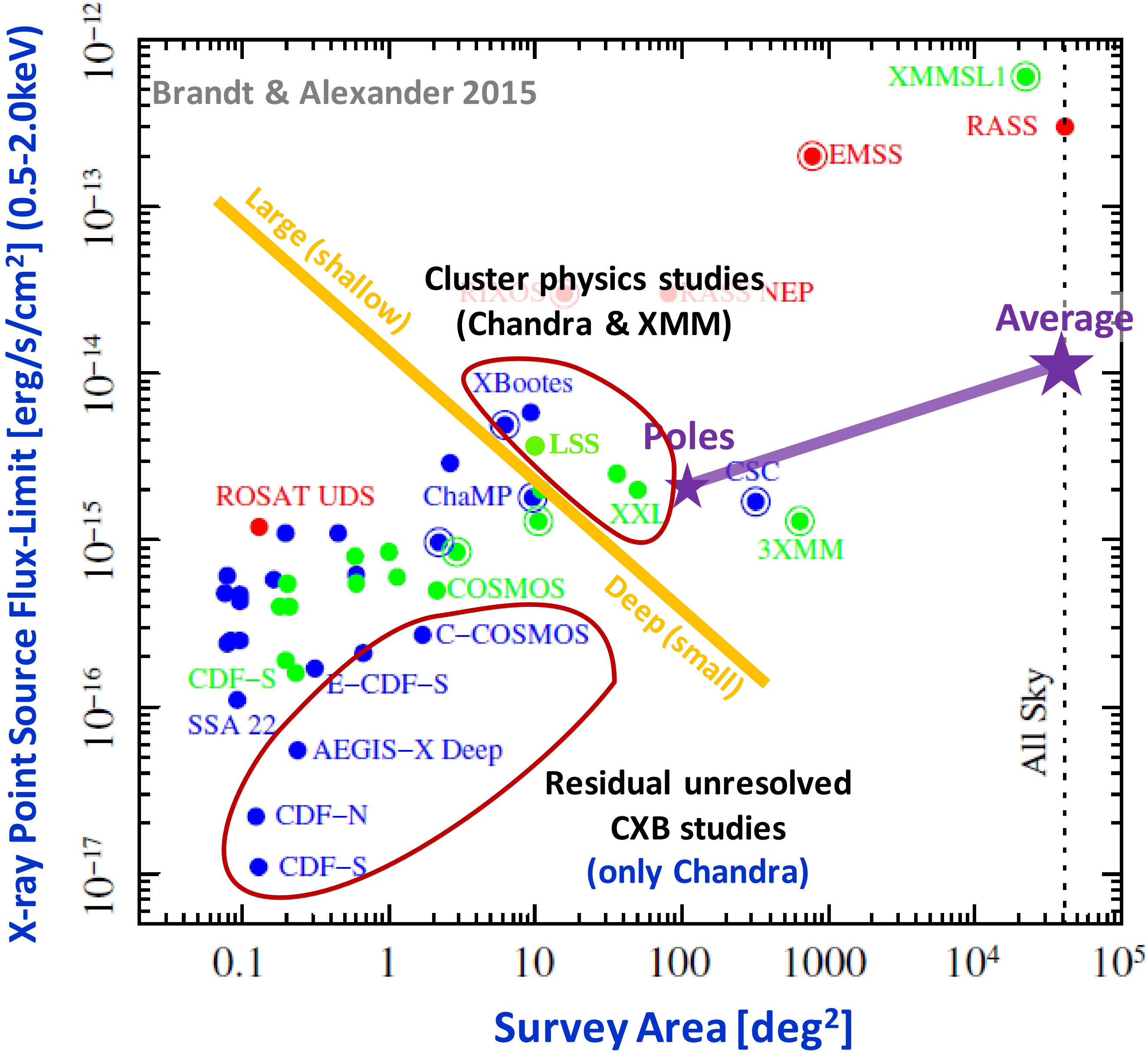
- Studying diffuse/extended emission
- Cross-correlation with SZ data

Deep (small) surveys

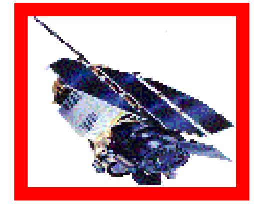
Residual unresolved CXB, SMBH seeds, early galaxy formation

- Studying extremely faint point sources
- Cross-correlation with optical/IR data

X-ray surveys of the last ~25 years

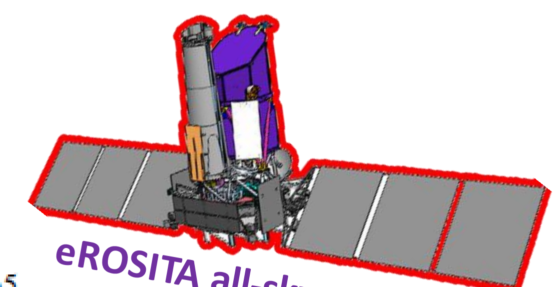


ROSAT



XMM-Newton

Chandra



eROSITA all-sky survey (2020-2025)

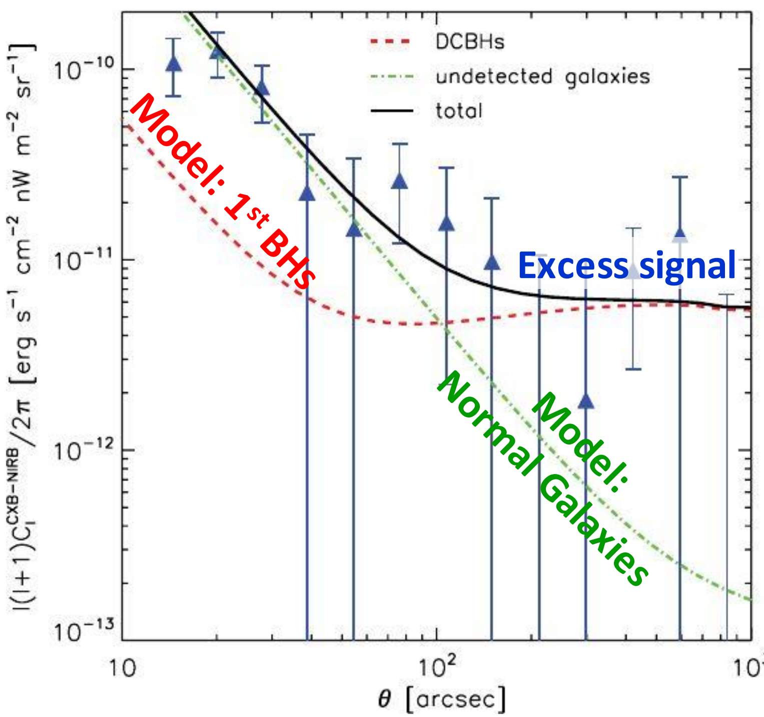
Using **deep** (small) X-ray surveys

- Main science driver:
  - Understanding remaining unresolved CXB
  - Searching for signals of SMBH seeds and early galaxy formation
- Method: cross-correlation with optical/near-IR
- Results: significant (~5σ) excess in various surveys (e.g. Cappelluti+2012,+2013,+2017, Yue+2013, Helgason+2014, Mitchell-Wynne+2016, Li+2018)
- Possible origin:
  - 1st massive BH (~10^5 M_{sun}) created via direct collapse (DCBHs)

  → no consensus yet due to NIRB excess problem

  → **could be an important constrain on SMBH seeds & early galaxy formation**

Yue+2013



Using **large** (shallow) X-ray surveys

- Main science driver:
  - Galaxy cluster physics
  - Searching for Warm-Hot Intergalactic Medium (WHIM)
    - WHIM are best candidate to explain the „Missing Baryon“ Problem
  - Cosmological contraints
  - Searching for DM annihilation signal
- Method: auto-correlation & cross-correlation with CMB

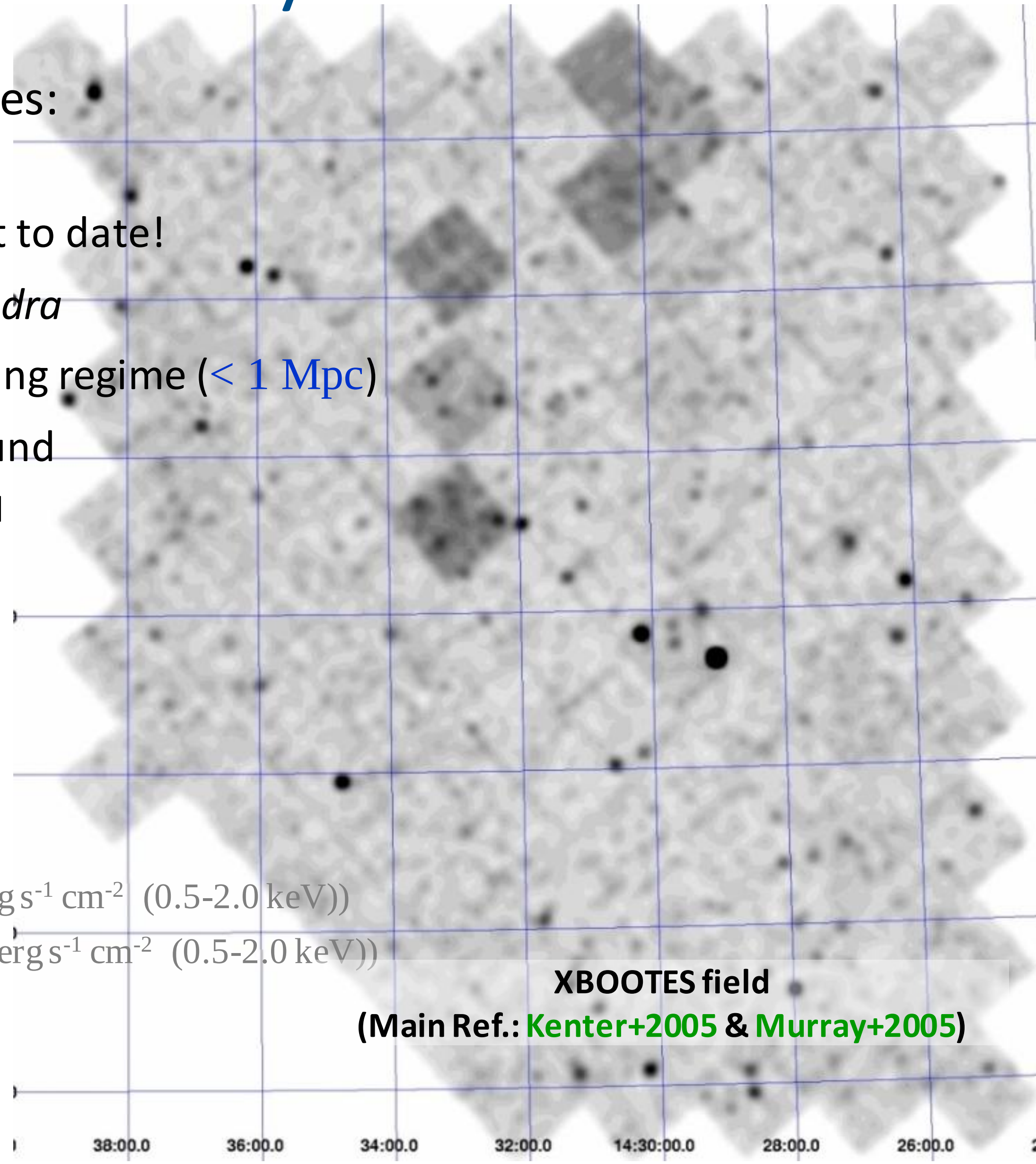
Max-Planck-Institut für Astrophysik

Pilot study with large (modern) X-ray surveys

Collaborators	Prof. Marat Gilfanov (MPA,IKI) Dr. Gert Hütsi (Tartu Observatory, Estonia) Prof. Rashid Sunyaev (MPA,IKI)
Publications	2 papers published (ArXiv: 1609.02941, 1708.00820) 1 paper in preperation

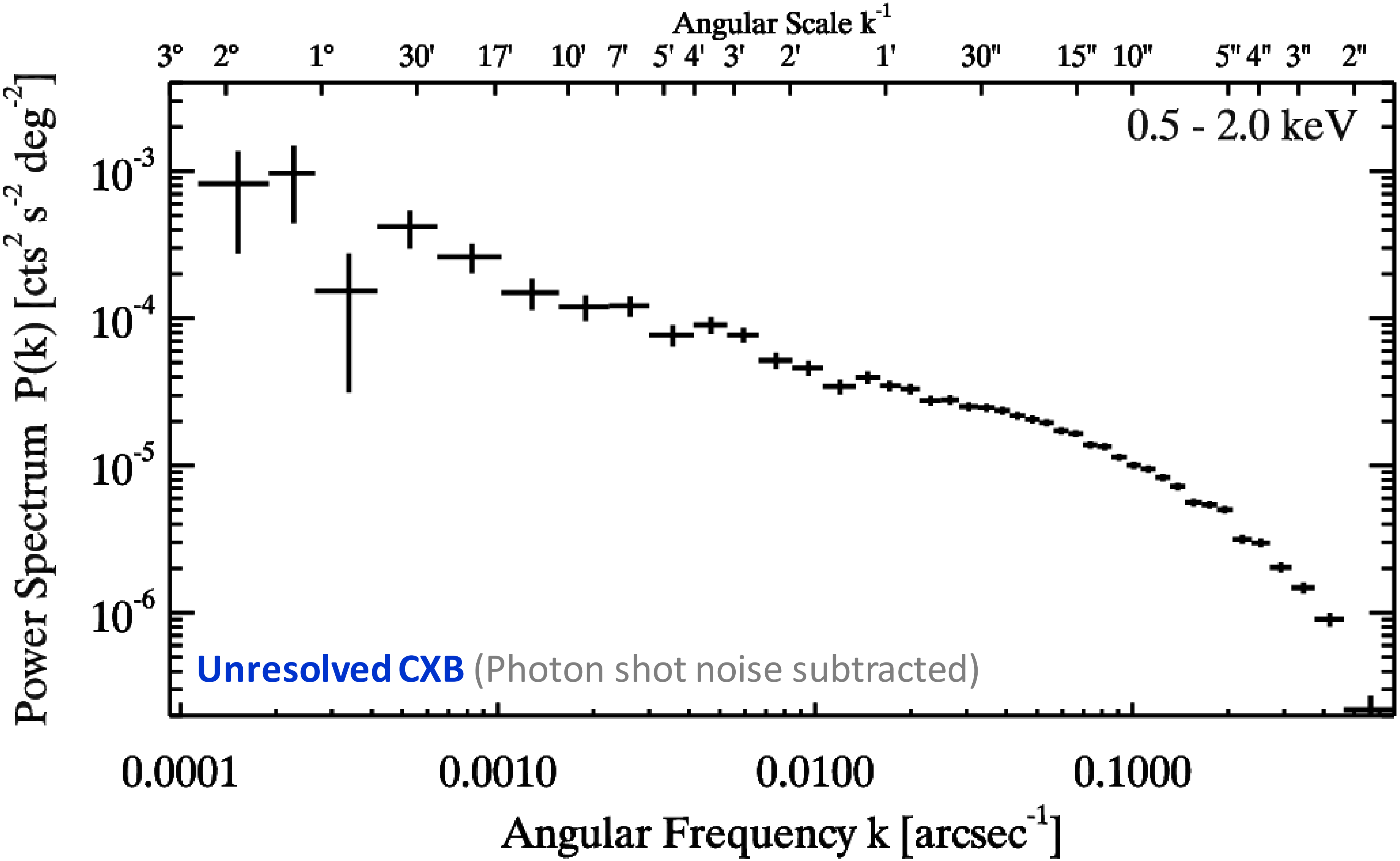
Using ~9 deg^2 XBOOTES survey

- Advantages for fluctuation studies:
  - largest *Chandra* survey
    → most accurate measurement to date!
  - 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)
- 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

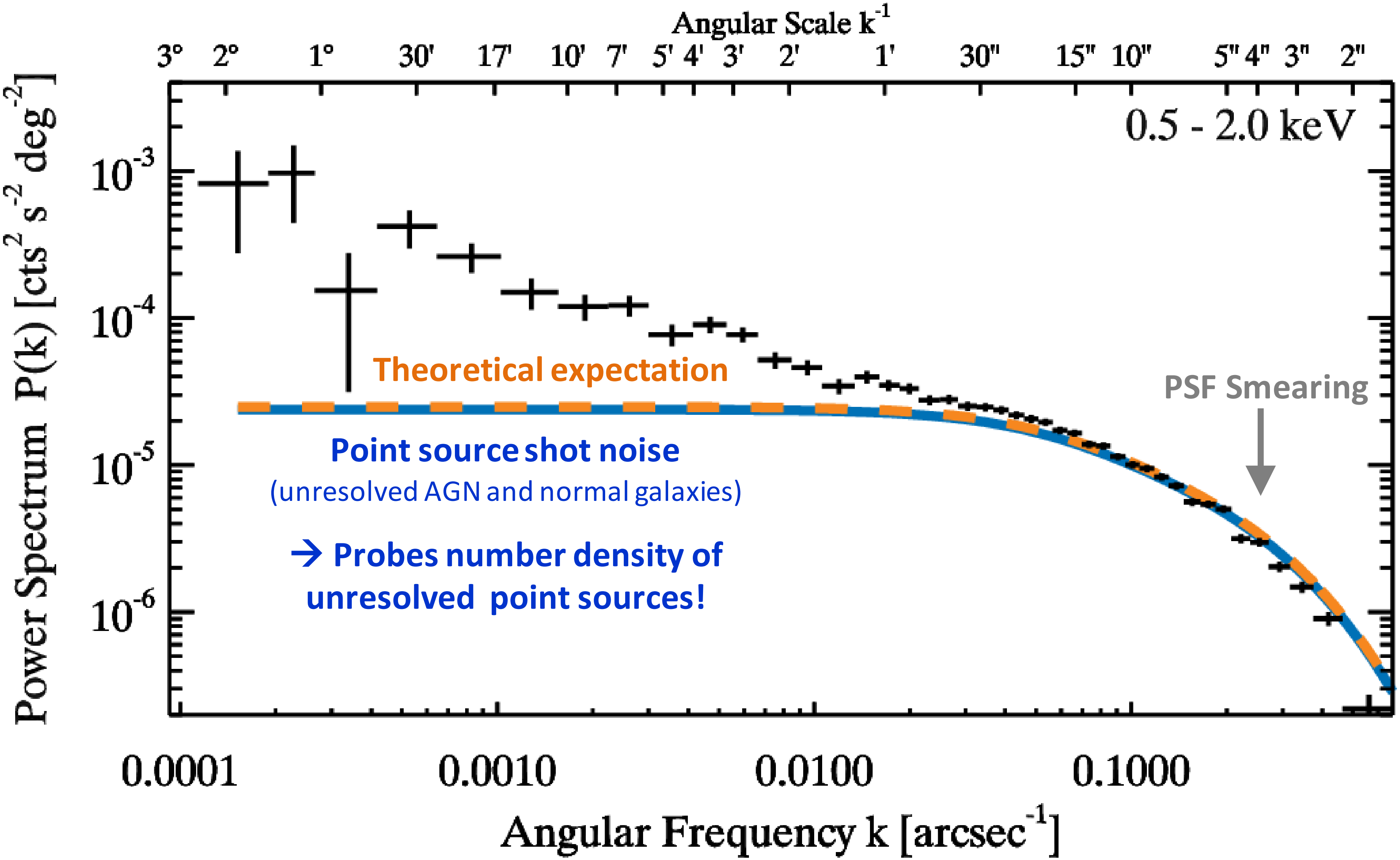


XBOOTES field
(Main Ref.: Kenter+2005 & Murray+2005)

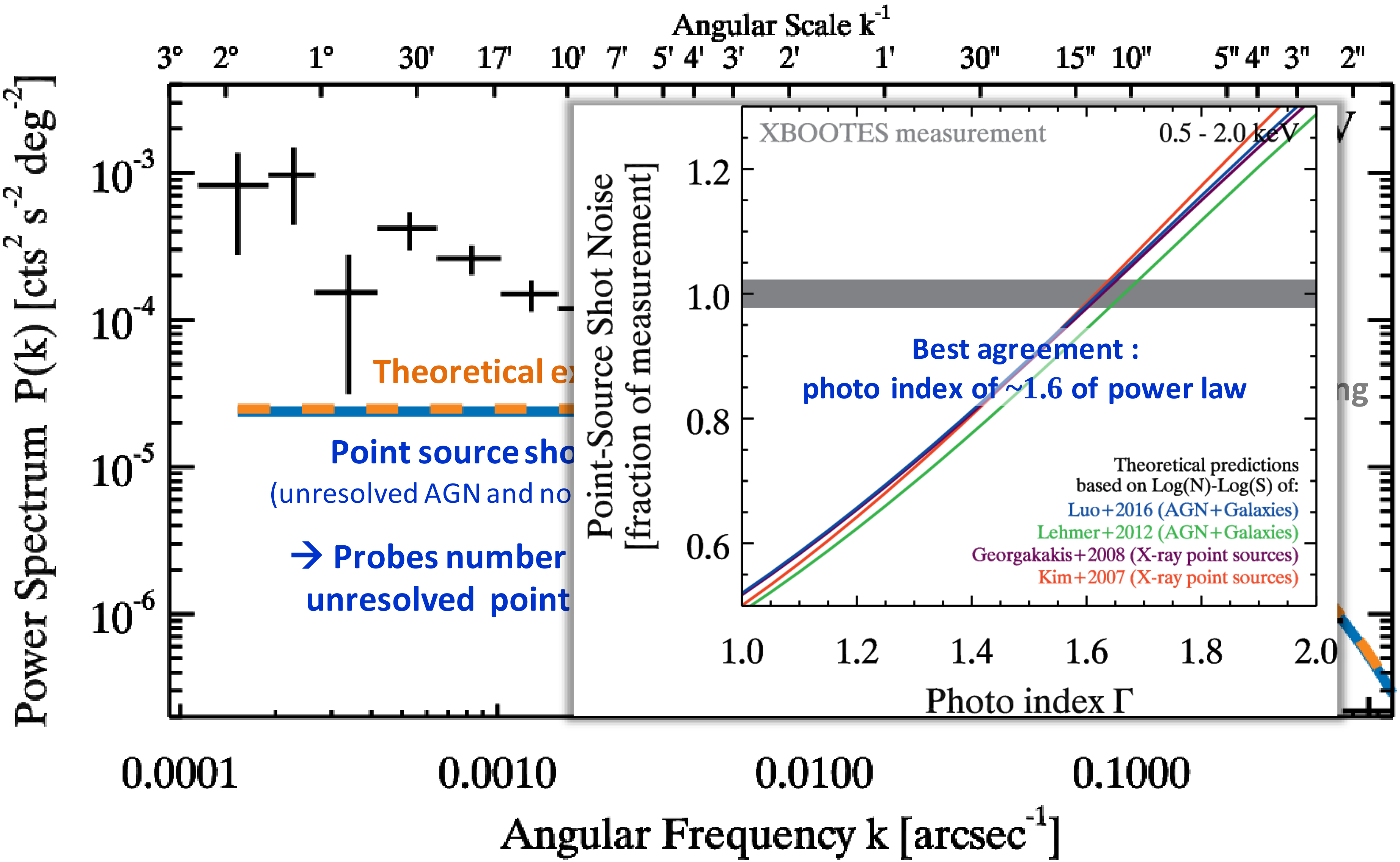
Power spectrum of CXB fluctuations



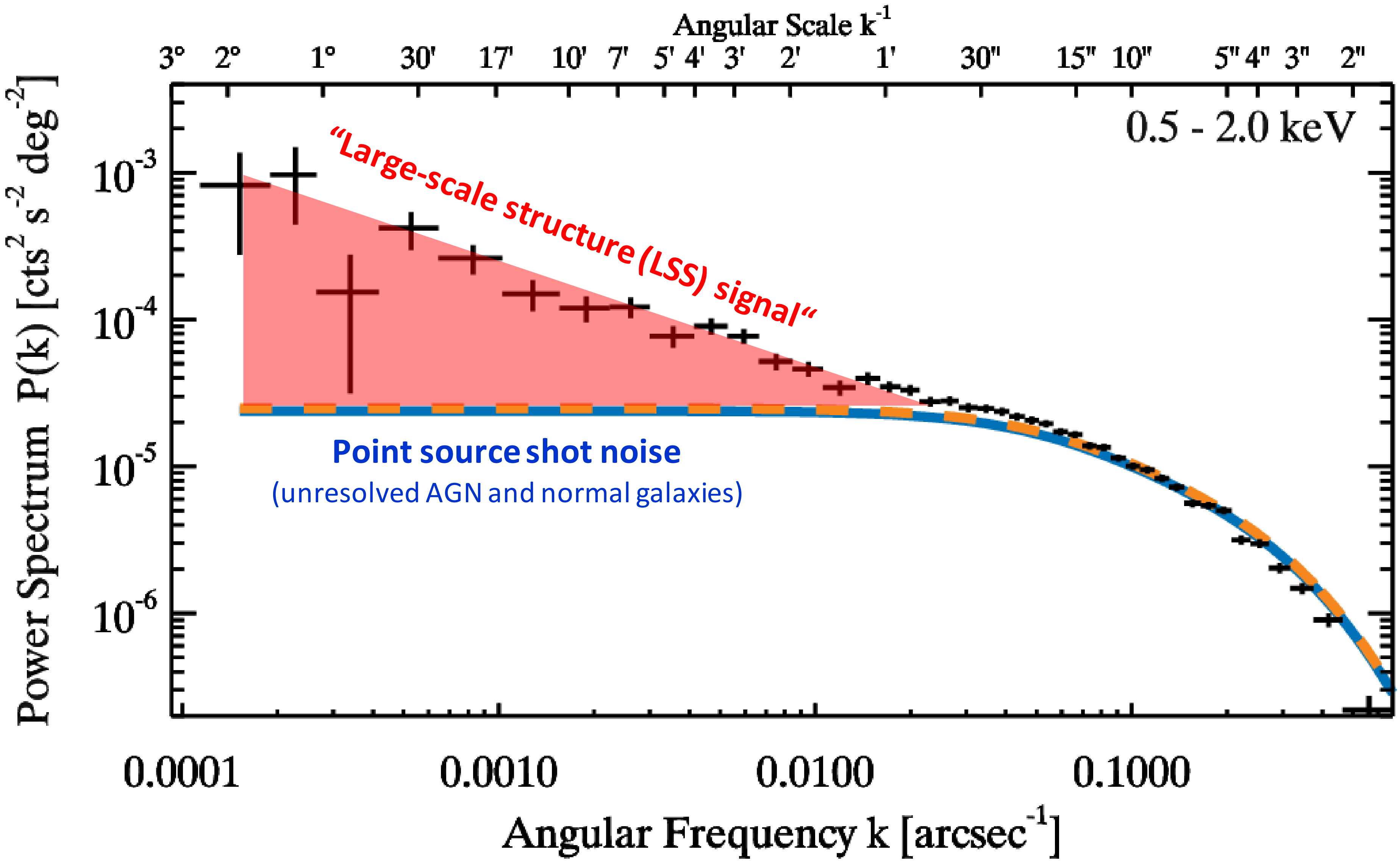
Power spectrum of CXB fluctuations



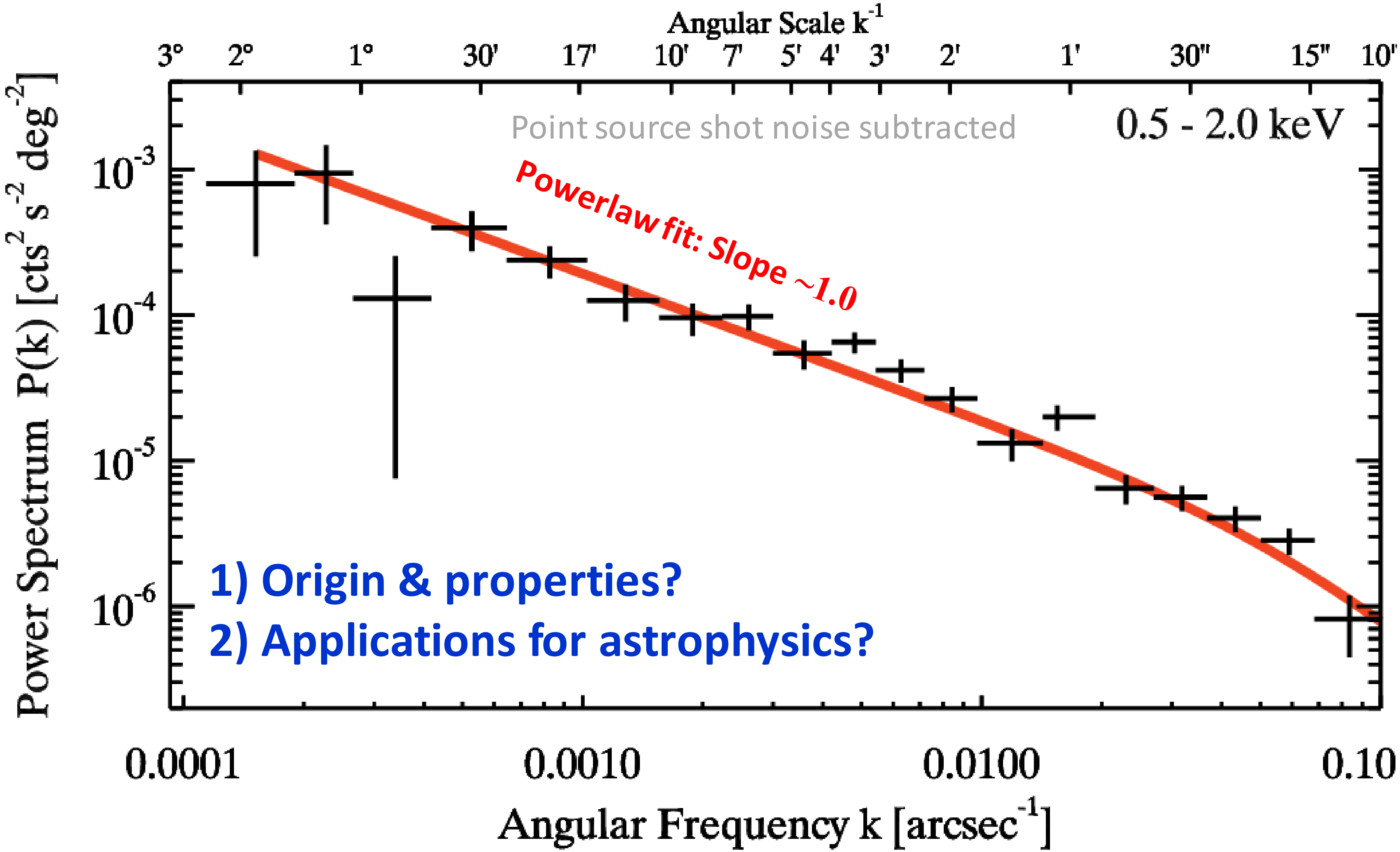
Power spectrum of CXB fluctuations



Power spectrum of CXB fluctuations



LSS signal of unresolved CXB



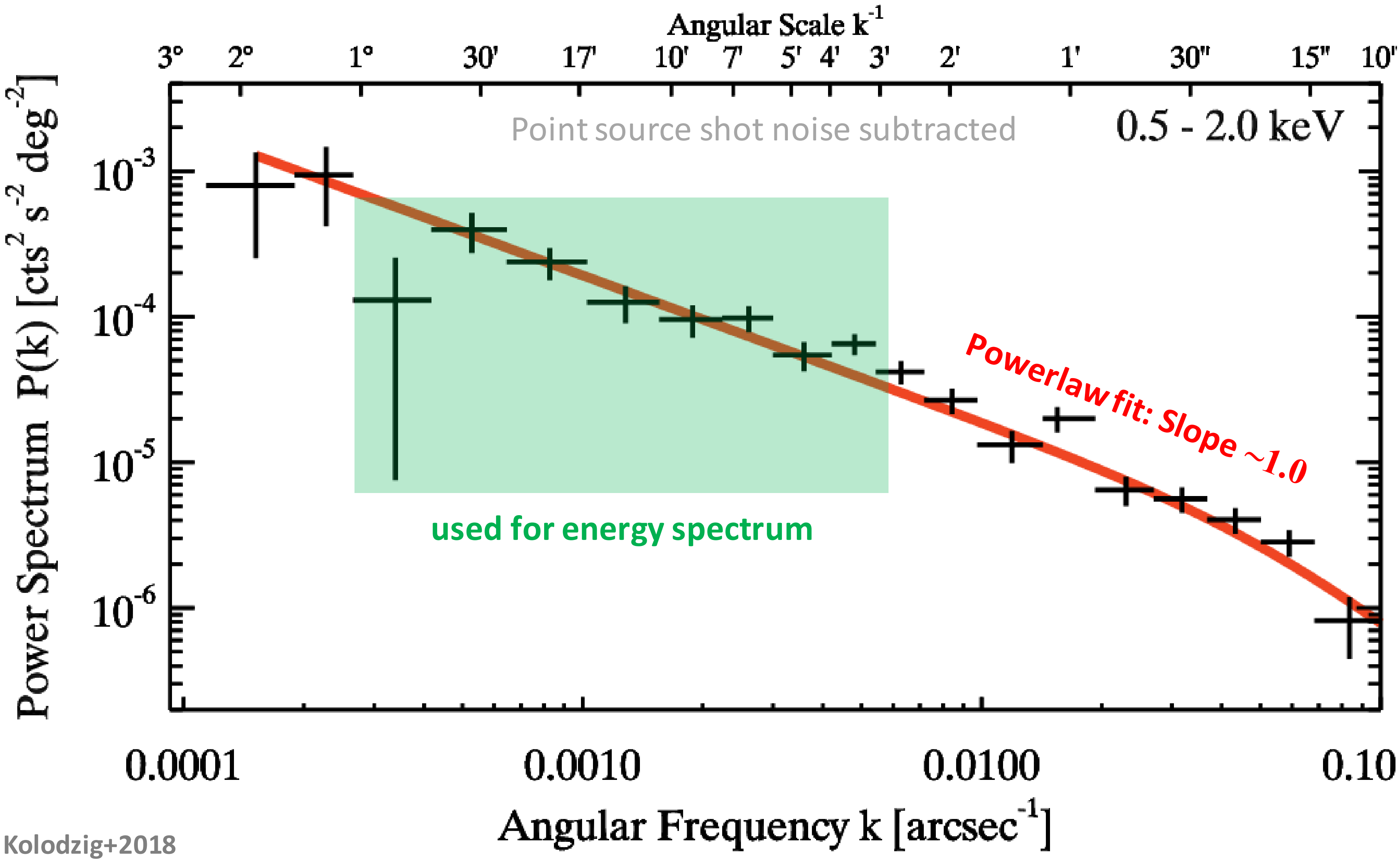
Assessment of systematics
(see Kolodzig+2017)

- 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”)

Strongest observational evidence for origin: energy spectrum

Max-Planck-Institut für Astrophysik

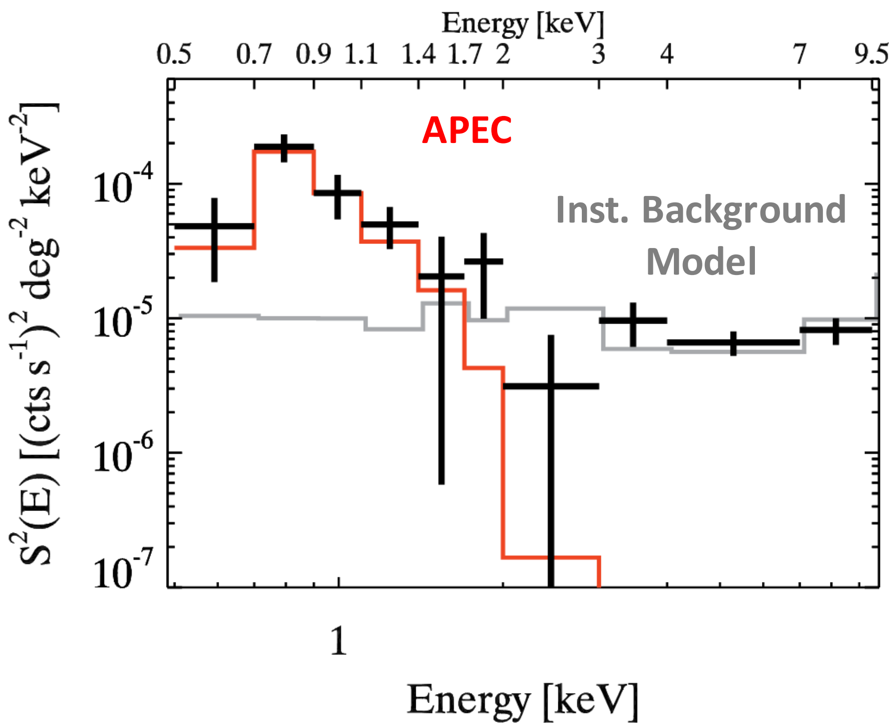
LSS signal of unresolved CXB



Kolodzig+2018

Energy Spectrum of CXB fluctuations

Unresolved CXB



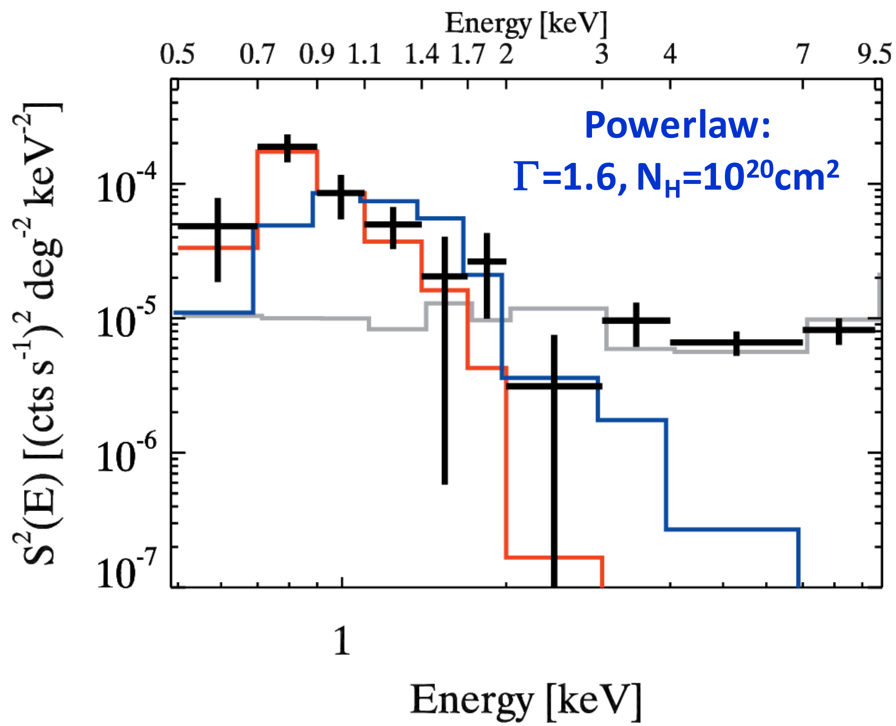
APEC Best-Fit: z=0.40, T=1.3keV

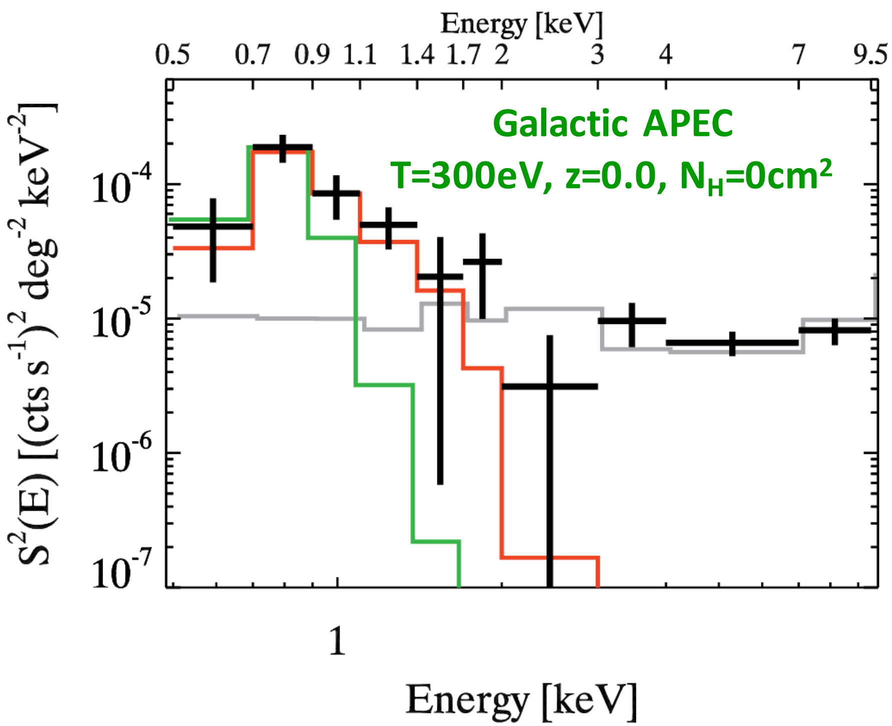
Fixed: $N_H=10^{20}cm^2$, Metal Abundance 0.3

Kolodzig+2018

Energy Spectrum of CXB fluctuations

Unresolved CXB





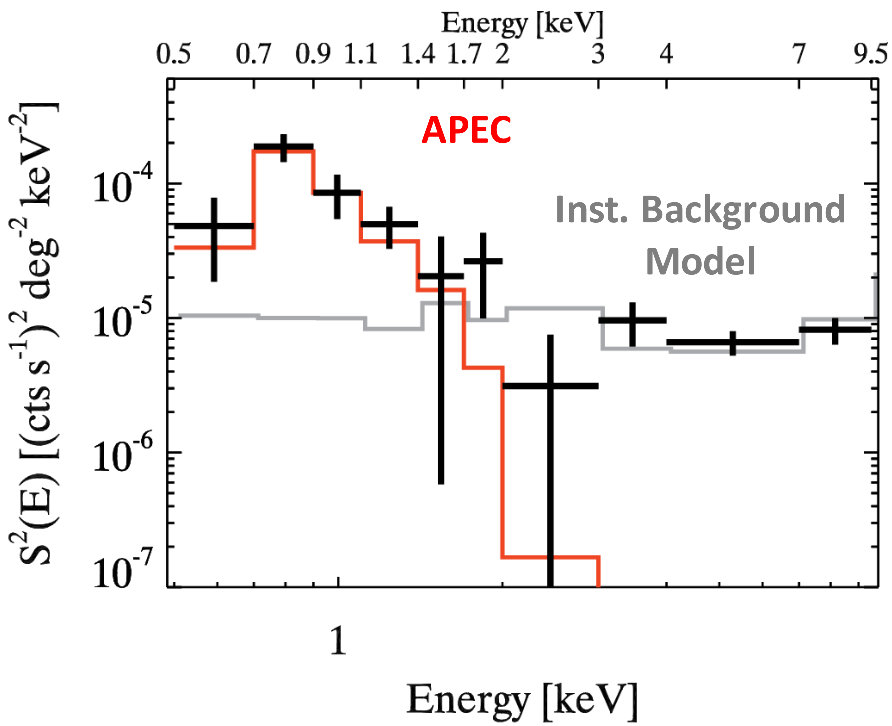
Inconsistent with Powerlaw $\Gamma<3$
(expected from AGN & normal galaxies)

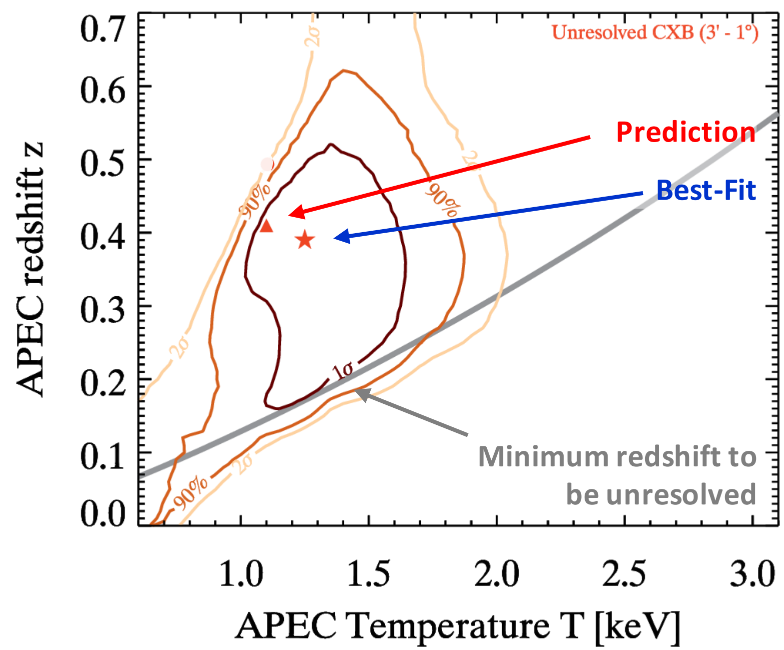
Inconsistent with unabsorbed APEC
(expected from Galactic emission)

APEC: z=0.40, T=1.3keV
$N_H=10^{20}cm^2$, Metal Abundance 0.3

Energy Spectrum of CXB fluctuations

Unresolved CXB





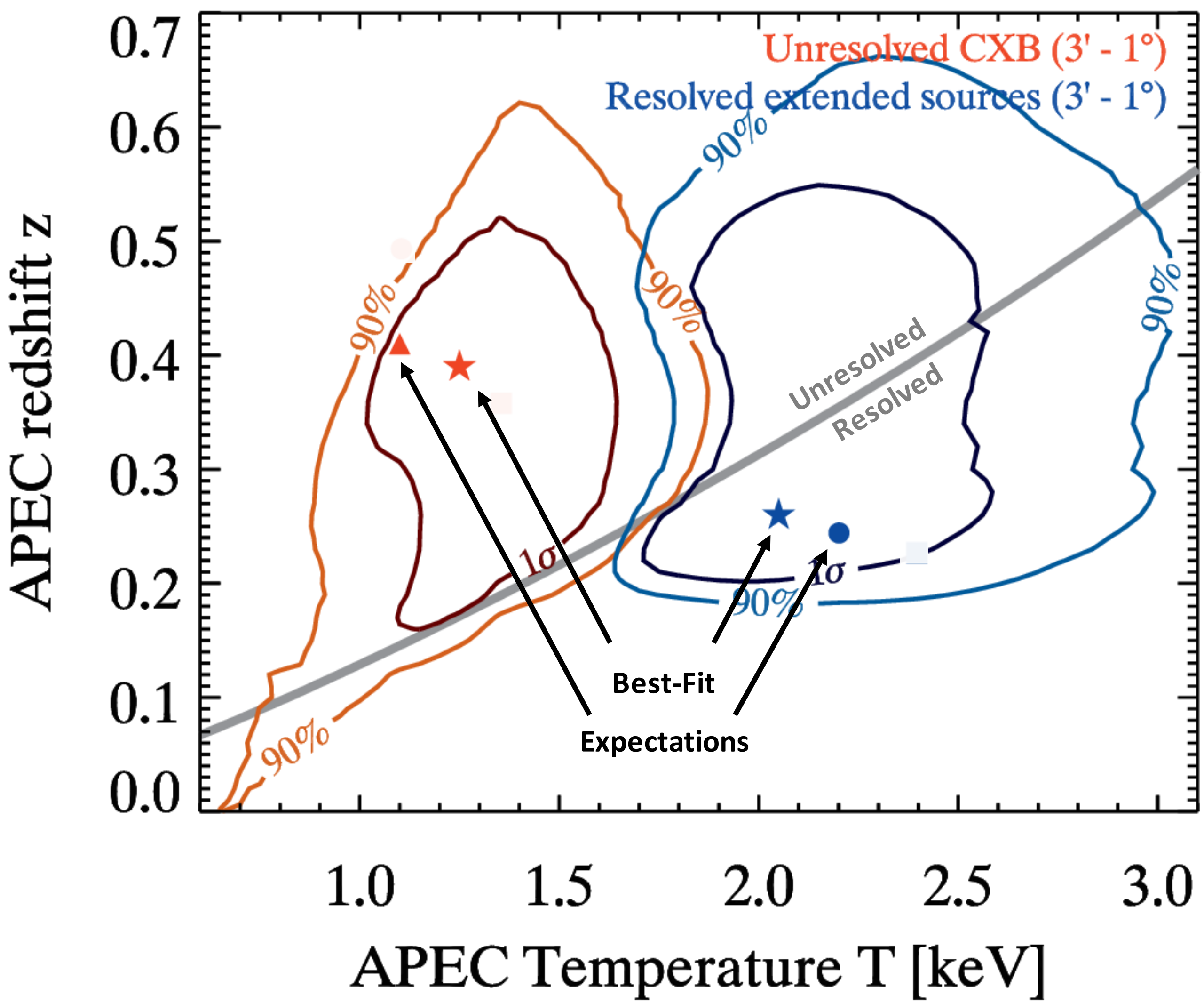
APEC Best-Fit: z=0.40, T=1.3keV

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

Predictions based on XXL's XLF and scaling relations (Pacaud+2016, Giles+2016, Lieu+2016)

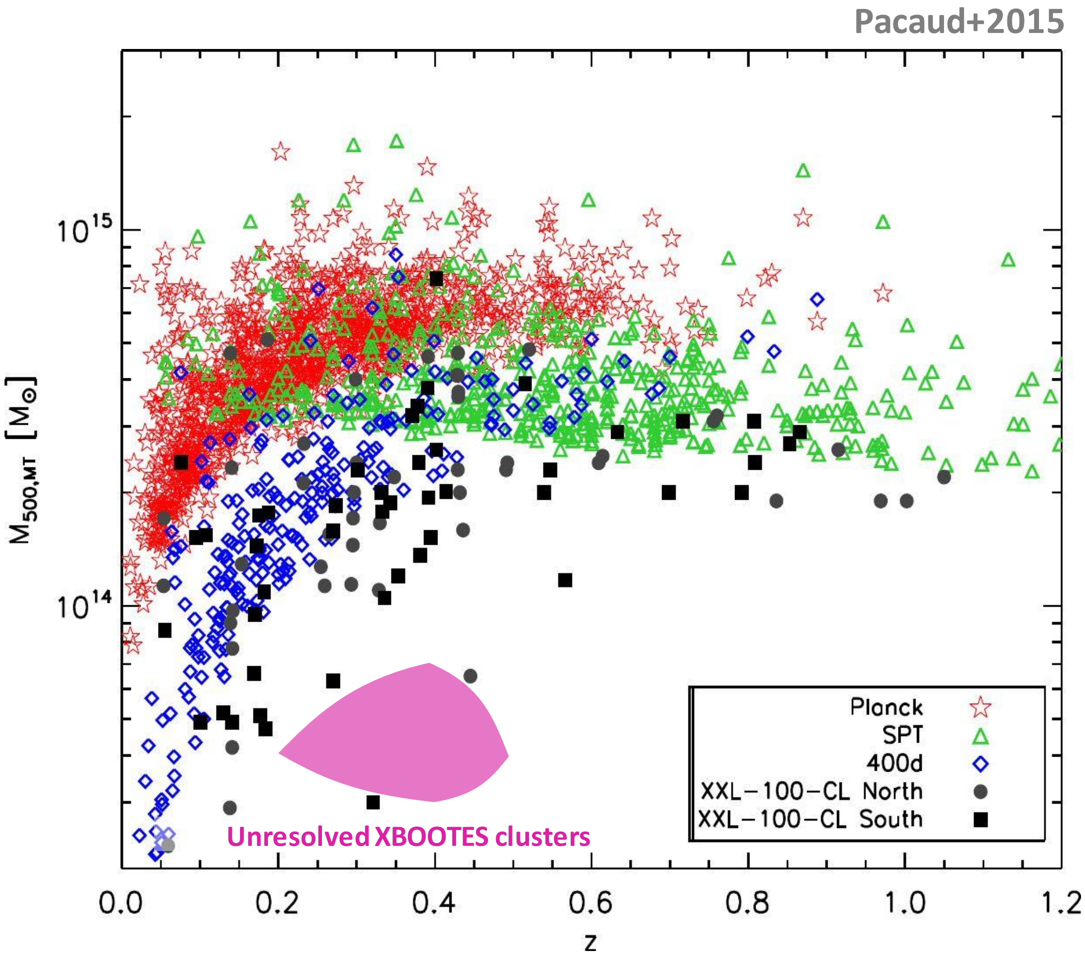
Kolodzig+2018

Energy Spectrum of CXB fluctuations

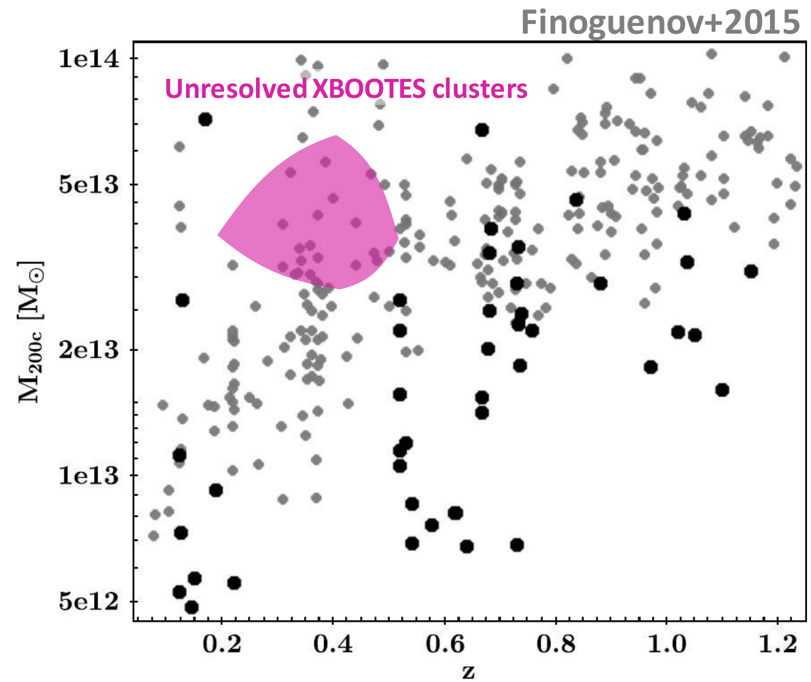


Kolodzig+2018

Studying the faint end



XXL (XMM-Newton 7Ms, 10ks deep 2x25 deg^2)
XBOOTES (Chandra 0.6Ms, 5ks deep, 9deg^2)



ECDF-S (Chandra 4Ms, XMM-Newton 3Ms, 0.3 deg^2)
COSMOS (Chandra 2Ms, XMM-Newton 1.5Ms, 0.9 deg^2)
XBOOTES (Chandra 0.6Ms, 9deg^2)

CXB fluctuations = complementary approach:

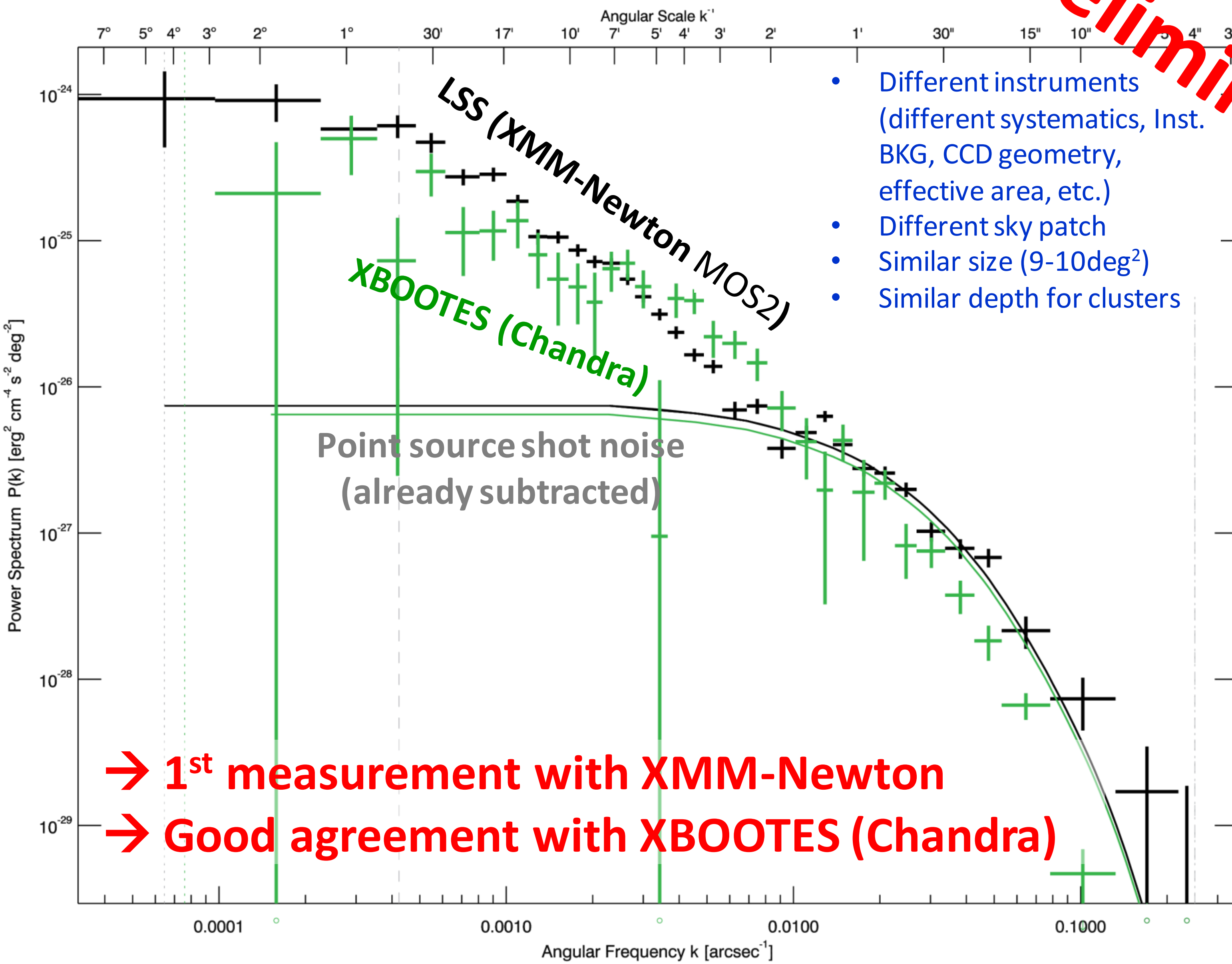
- Data inexpensive, follow-ups not required
- Probes much larger volume than deep surveys

Max-Planck-Institut für
Astrophysik

Comparison with another survey from another X-ray instruments

XBOOTES (Chandra) vs. LSS (XMM)

Preliminary



- Different instruments (different systematics, Inst. BKG, CCD geometry, effective area, etc.)
- Different sky patch
- Similar size (9-10deg^2)
- Similar depth for clusters

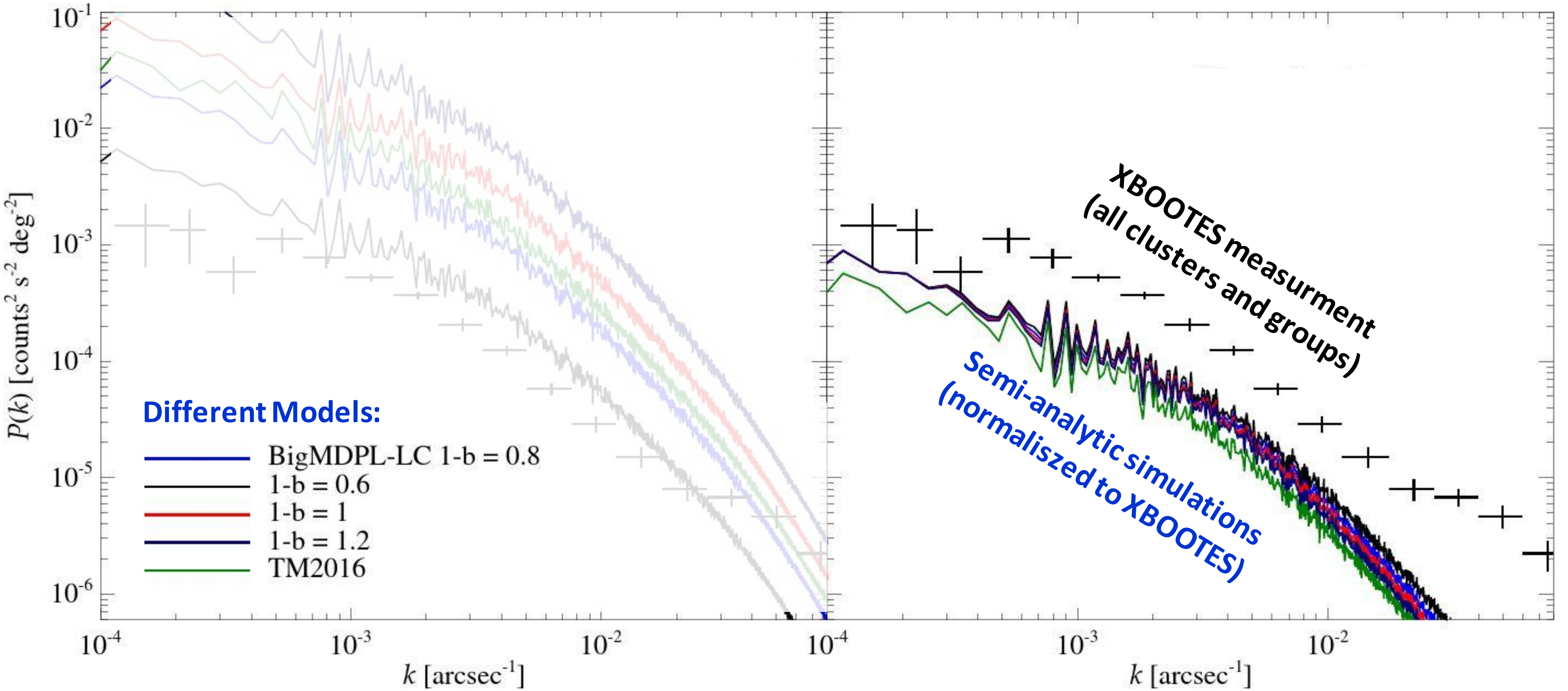
→ 1st measurement with XMM-Newton

→ Good agreement with XBOOTES (Chandra)

Comparison with simulations

Comparison with semi-analytic simulations

Zandanel+2018



Application by comparison studies with

- Semi-analytic simulations: study physical parameters
- Hydro. simulations: new calibration tool

Application: studying faint clusters via fluctuation analysis

Important Pro's:

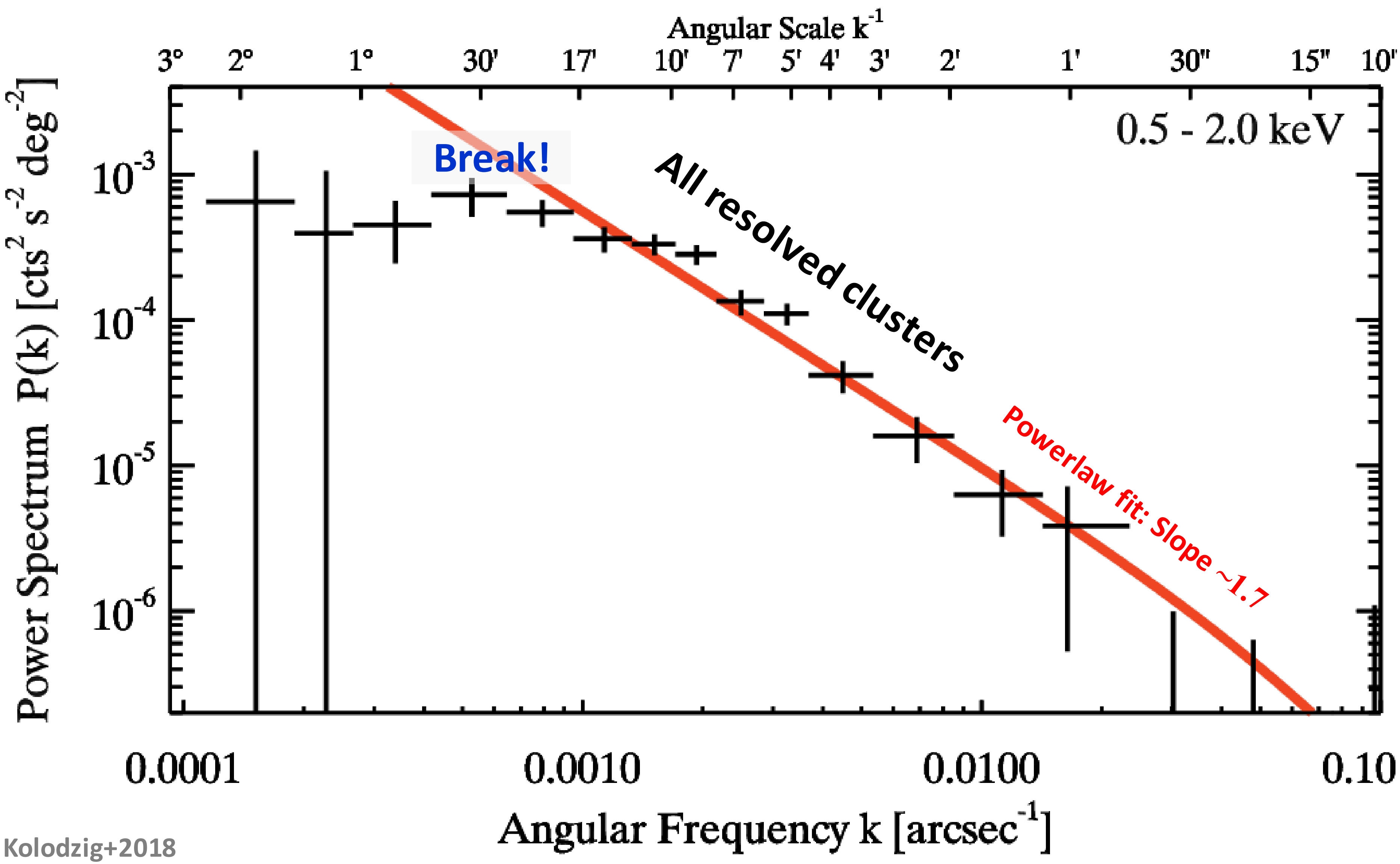
- Able to use all detected source photons
→ Sensible to faint and unresolved sources, aka high-redshift and low-mass clusters
- "Simple" treatment of:
  - fore- & background CXB components
  - Inst. BKG (on scales above FOV)
- Data inexpensive: No follow-up data needed but can be still appreciated (to target specific types of objects, e.g. redshift)
- Study large source population at once and simpler than stacking
- Simple jointed X-ray/SZ analysis via cross-correlations
- Very simple selection function possible
→ most direct comparison with simulations possible

Important Con's:

- Only access to the cumulative emission of many clusters (>20) over a large area (>10deg^2)
- Still dominated by brightest retained sources
→ Survey depth is still important
- Inst. BKG on small scales still important
- No direct access to physical properties
→ Need sophisticated simulations to extract physics

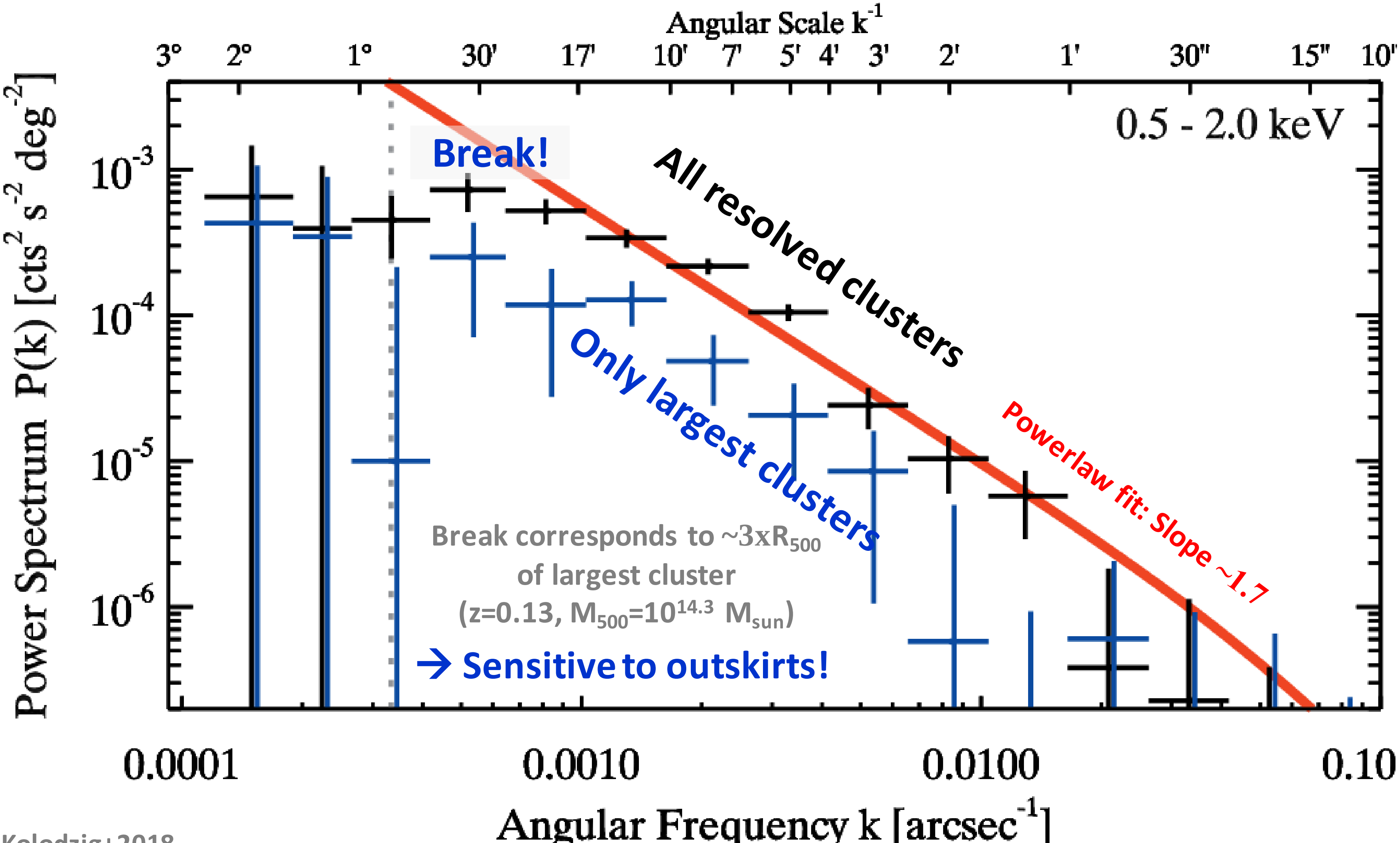
Gas profile of clusters

Break in LSS signal of resolved clusters



Kolodzig+2018

Break in LSS signal of resolved clusters

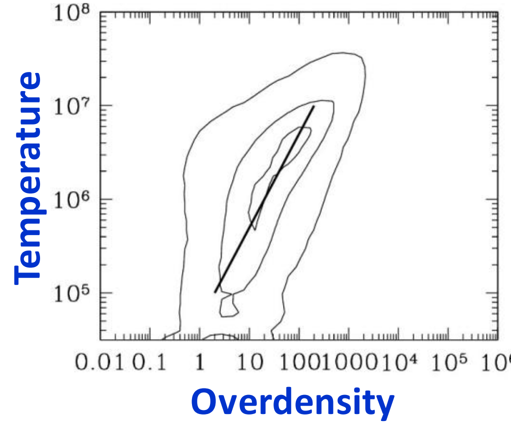


Kolodzig+2018

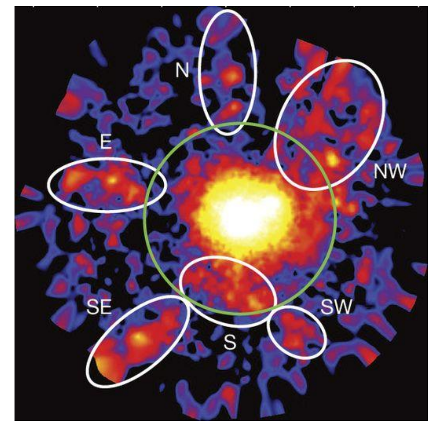
How about WHIM?

WHIM:
State of the art and motivation

- Candidate for explaining missing baryon problem
  (e.g. **Cen & Ostriker 1999**)
- Expected Temperature: $T = 10^5 - 10^7\,\mathrm{K} < \sim 1\,\mathrm{keV}$
  - Hottest close to galaxy clusters
- Challenges from LSS studies with resolved sources:
  - very faint and diffuse: difficult to resolved
  - Observational bias towards galaxy cluster vicinity
- **Angular correlation studies with the CXB:**
  - Sensitive to clustering signal of WHIM?

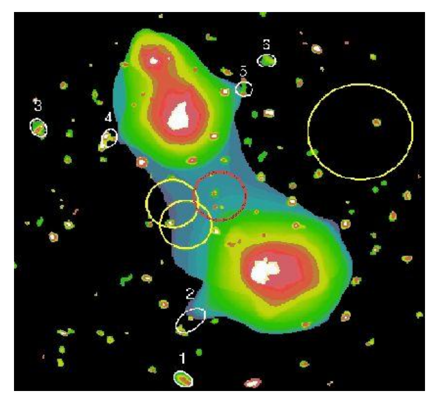


Dave+2001



Eckert+2015

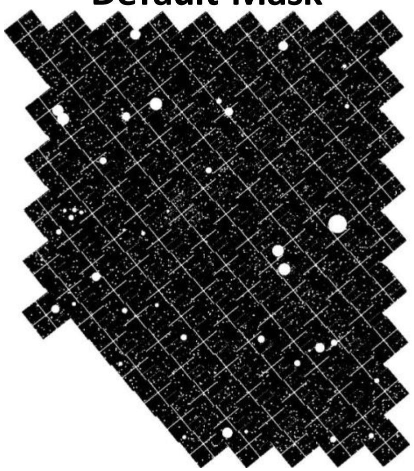
110ks XMM observation


Werner+2008

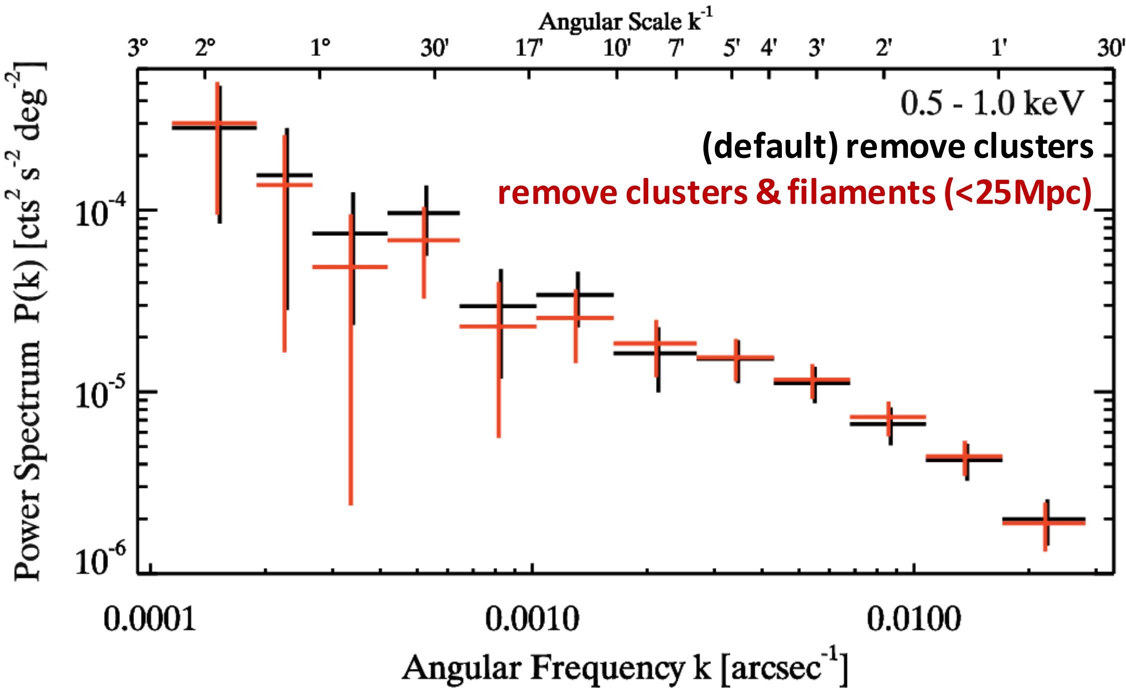
144ks XMM observation

Looking for a signal of WHIM

Default Mask



With Filaments



Conclusion:

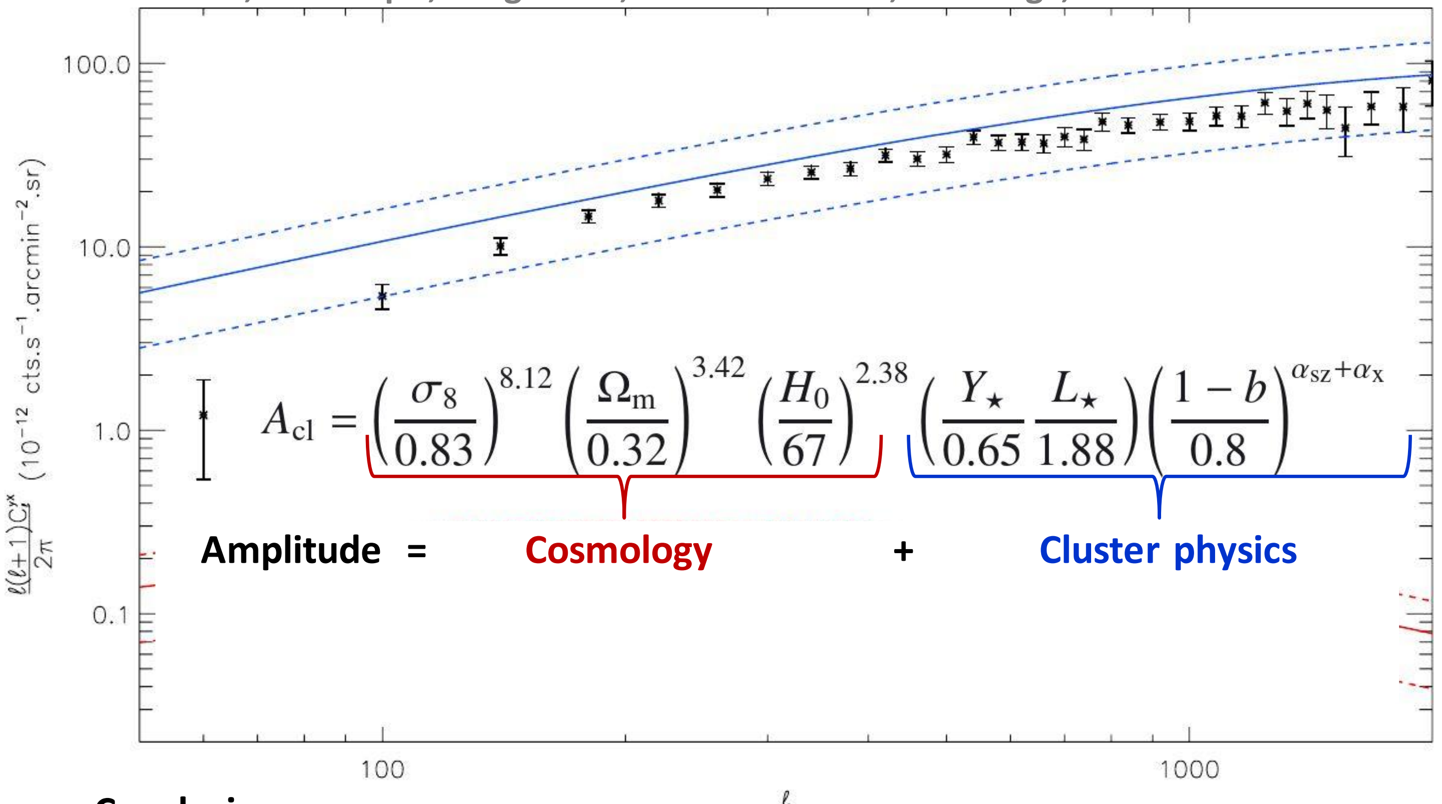
- S/N might be still too low → larger surveys needed
- Need to go to lower energies (<0.5keV)
- Contamination of Galactic emission could be problematic
- Cross-Correlation with ACT & SPT may increase sensibility
- Feasibility test with hydro. simulations needed but difficult

Kolodzig+2018

Cosmology

Cross-Correlation with CMB data: ROSAT vs. Planck

G.Hurier, M.Douspis, N.Aghanim, E.Pointecouteau, J.M.Diego, & J.F.Macias-Perez 2015



$$A_{\rm cl} = \underbrace{\left(\frac{\sigma_8}{0.83}\right)^{8.12}\left(\frac{\Omega_{\rm m}}{0.32}\right)^{3.42}\left(\frac{H_0}{67}\right)^{2.38}}_{\text{Cosmology}}\underbrace{\left(\frac{Y_\star}{0.65}\,\frac{L_\star}{1.88}\right)\left(\frac{1-b}{0.8}\right)^{\alpha_{\rm sz}+\alpha_{\rm x}}}_{\text{Cluster physics}}$$

Amplitude = Cosmology + Cluster physics

Conclusion:

- Possible but degenerated problem: Cosmology & cluster physics
- Breaking it by including smaller scales → more sensitive to cluster physics
- Only possible with X-ray auto-power spectrum from **eRASS**

Future prospects

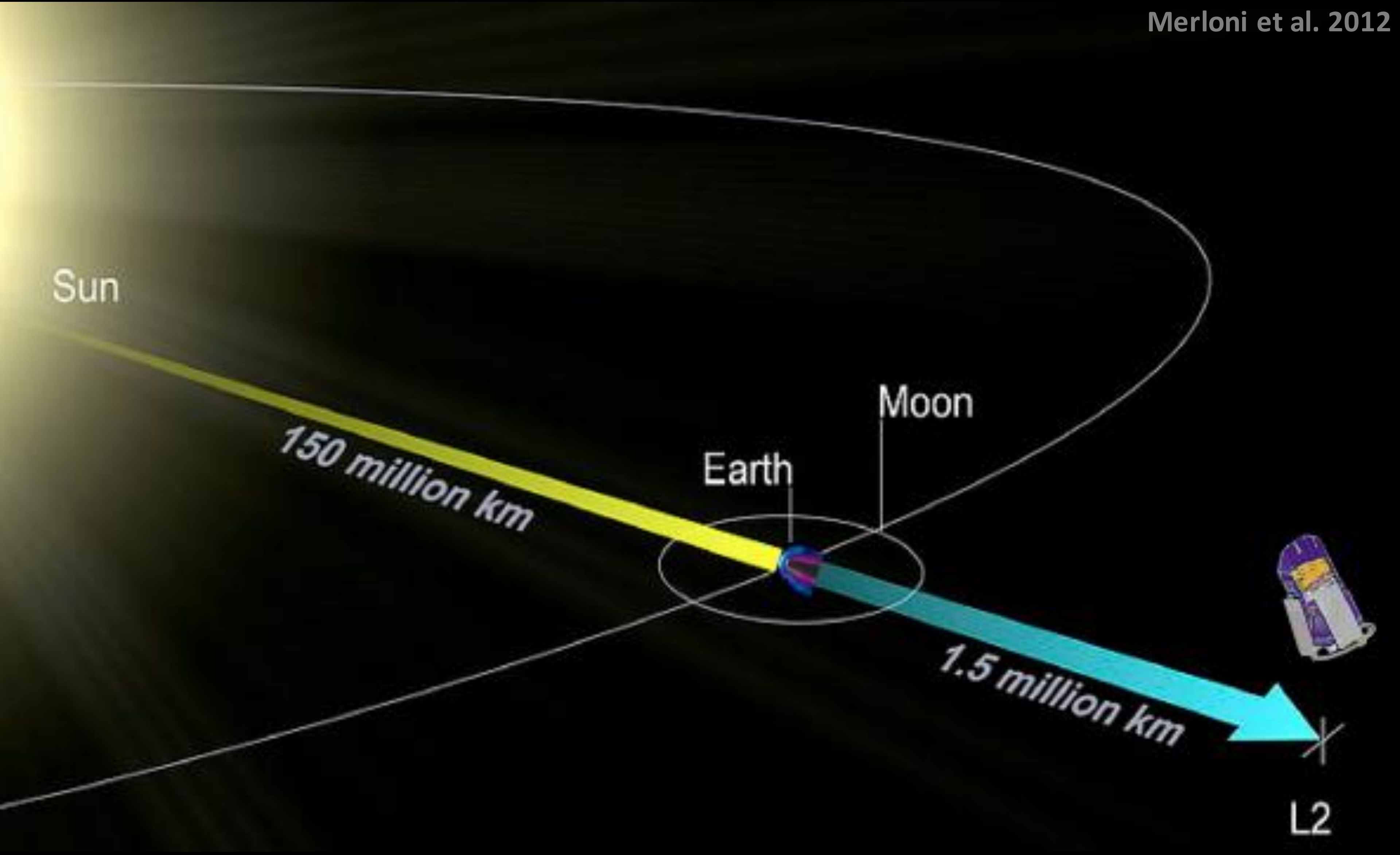
SRG/eROSITA all-sky survey (eRASS)

- Main science Goals:
  - Detecting all galaxy clusters up to $z{\sim}1$
  - Cosmology (Dark Energy, Dark Matter, …)
  - LSS studies with clusters and AGN
- Predecessor of the ROSAT all-sky survey RASS in 1990
  - 30x deeper
  - 10x larger effective area
  - 2x higher angular resolution
  - CCDs instead of proportional counters
- Launch: 03/2019
- Survey completed after 4 years (8 full sky scans)

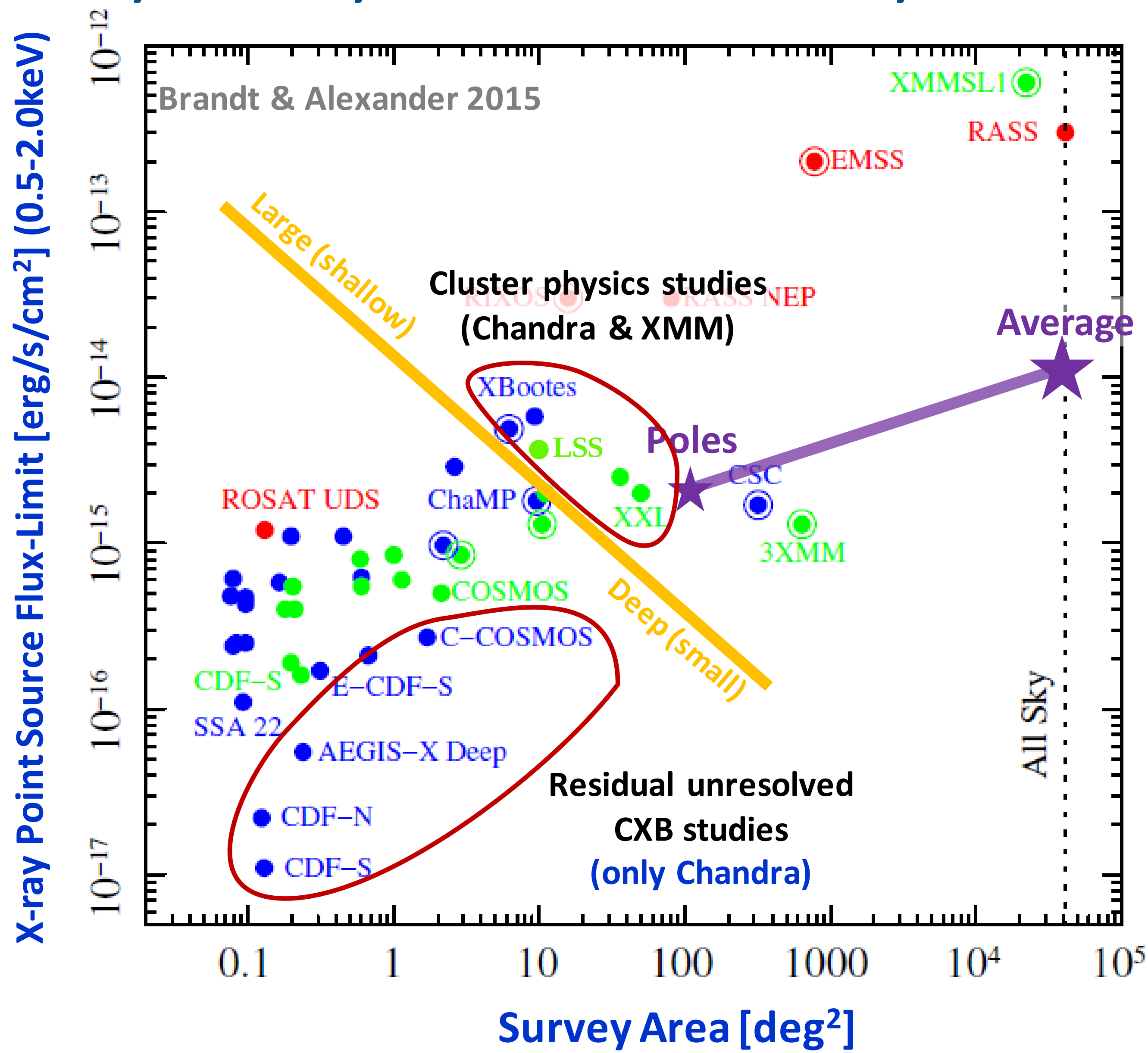
Picture Credits: P. Predehl

eROSIA: First X-ray instrument at L2

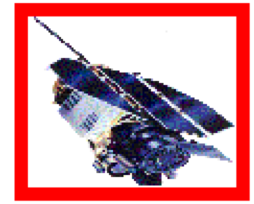
Merloni et al. 2012



X-ray surveys of the last ~25 years

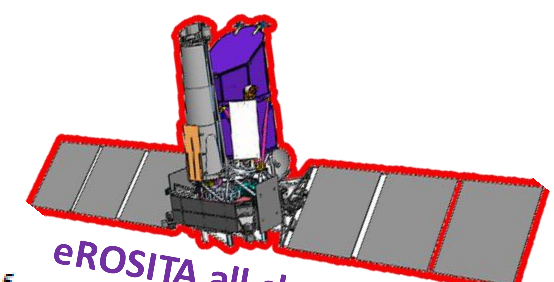


ROSAT



XMM-Newton

Chandra

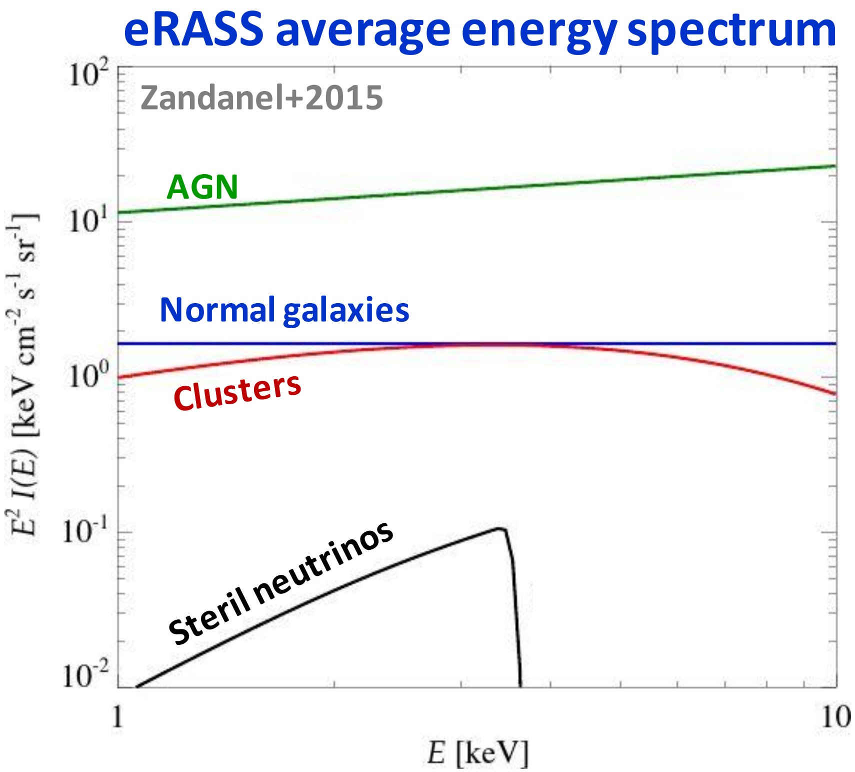


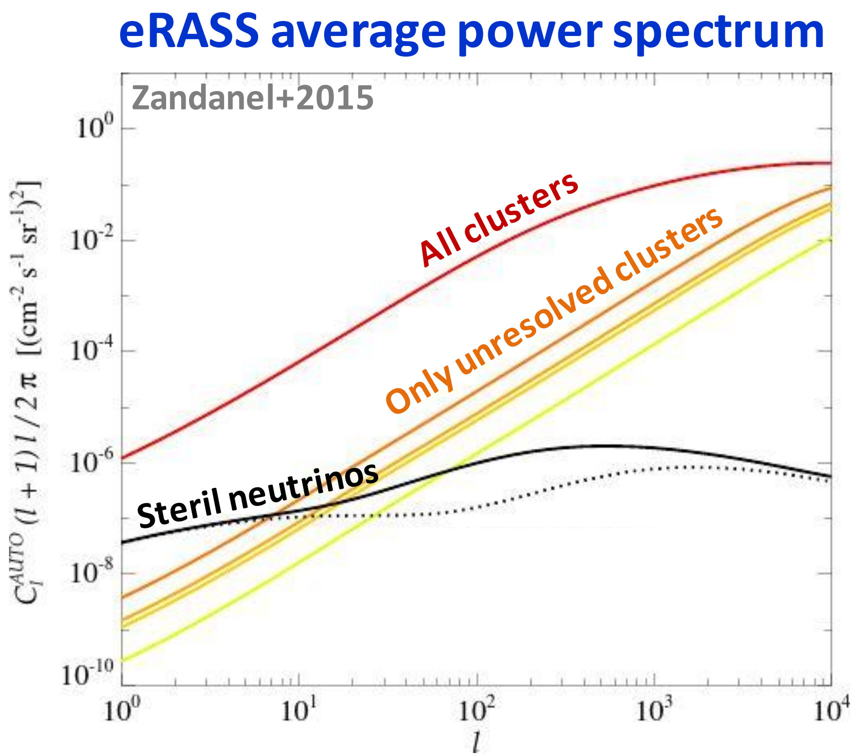
eROSITA all-sky survey
(2020-2025)

eRASS prospects

- Unprecedented statistics:
  – 100’000 detected galaxy clusters
  – 3 Million detected AGN
  → Largest X-ray catalogues
- 50x S/N of the XBOOTES auto-power spectrum
  – Stronger constraints on cluster physics & cosmology
  – Higher chances to detect:
    - WHIM
    - DM annihilation signal
- Cross-Correlation with Planck, ACT & STP surveys

eRASS forecast: DM annihilation signal





Summary/Outlook

- Fluctuation analysis with the **early (<2000)** X-ray surveys:
  - Very successful in understanding the origin of the (extragalactic) CXB
- Fluctuation analysis with **modern (>2000)** X-ray surveys:
  - Still in its infancy
  - Many promising applications in a variety of fields
  - Current surveys are already large/deep enough
  - Several simulations are available
  - For competitive cosmological constraints large surveys needed, e.g. eRASS needed
  - Cross-Correlation very powerful

Backup

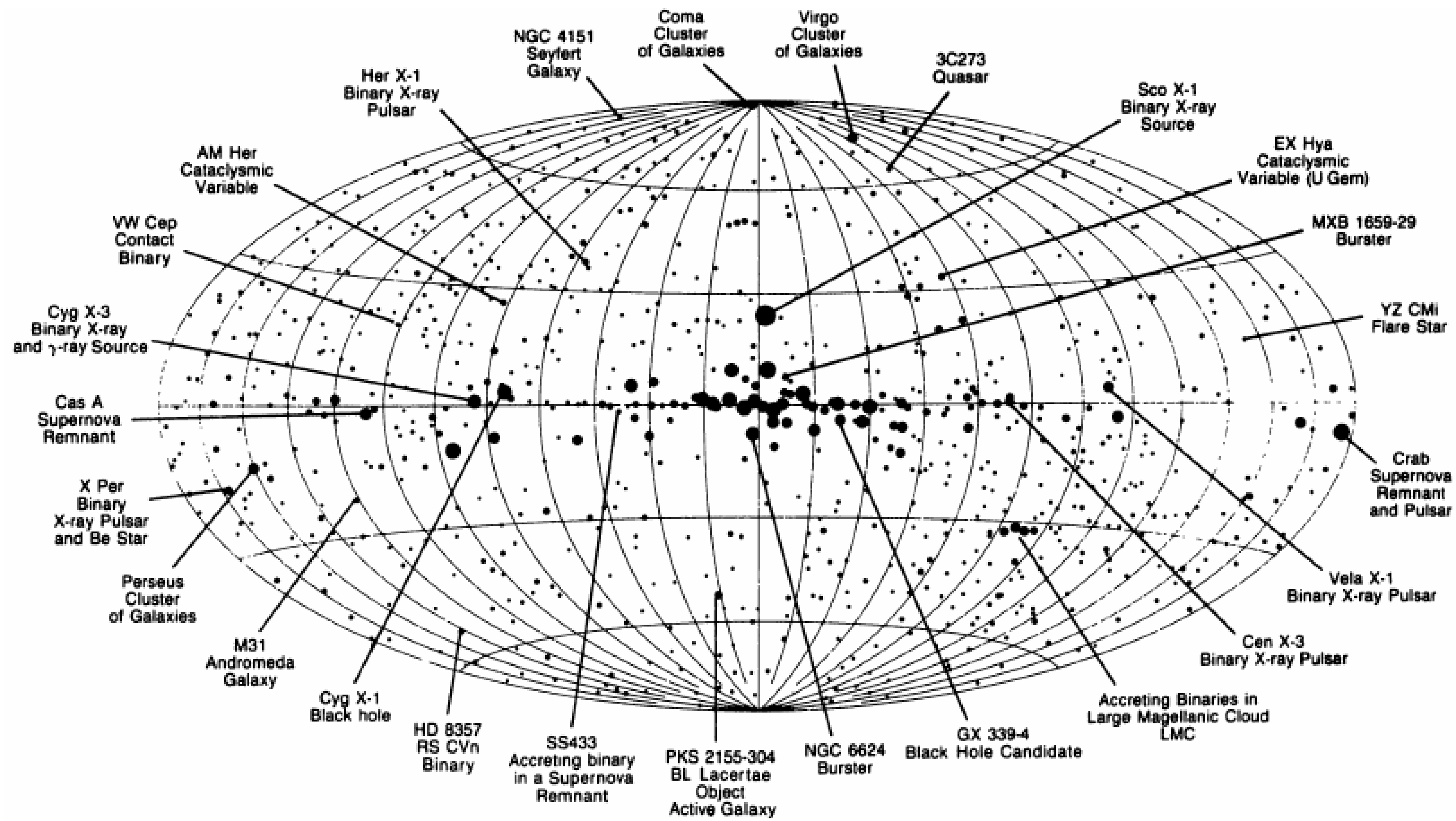
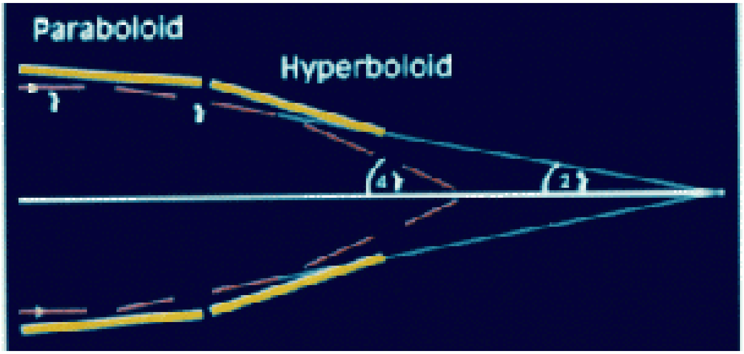
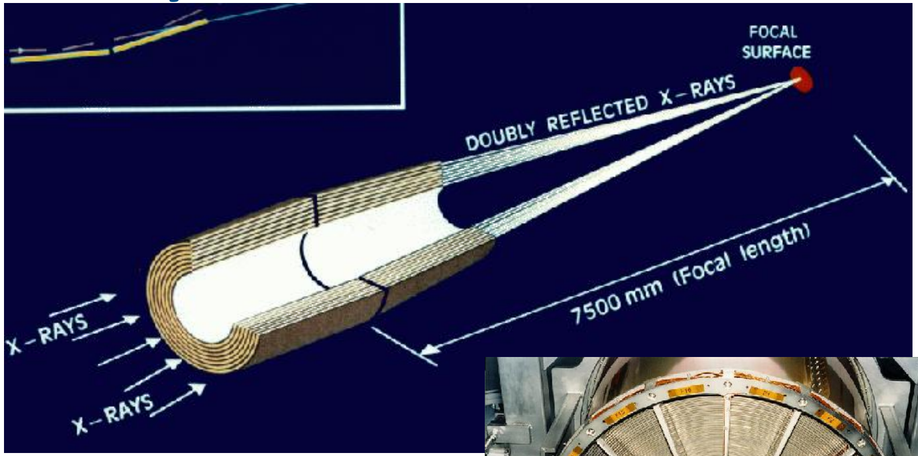
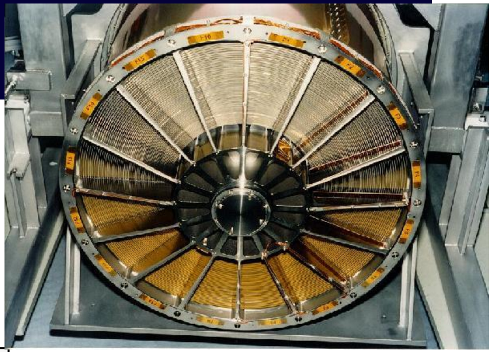


Figure 3 *HEAO-1* sky map of 842 hard X-ray sources (1–20 keV) from the Large Area Sky Survey experiment. (From Wood et al 1984.)

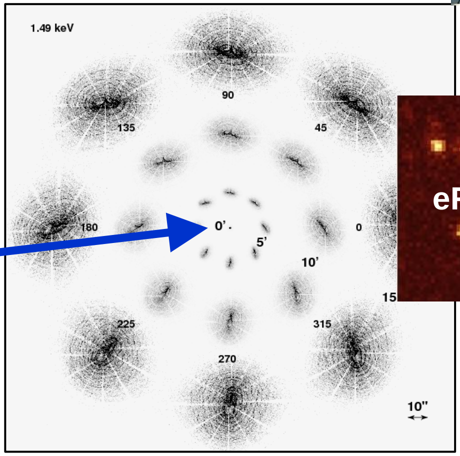
How do we observe X-rays



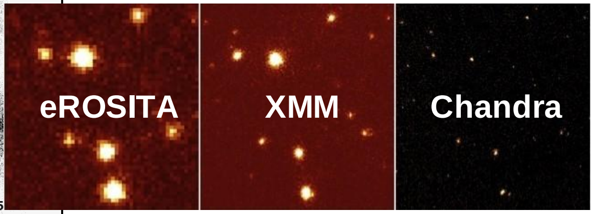




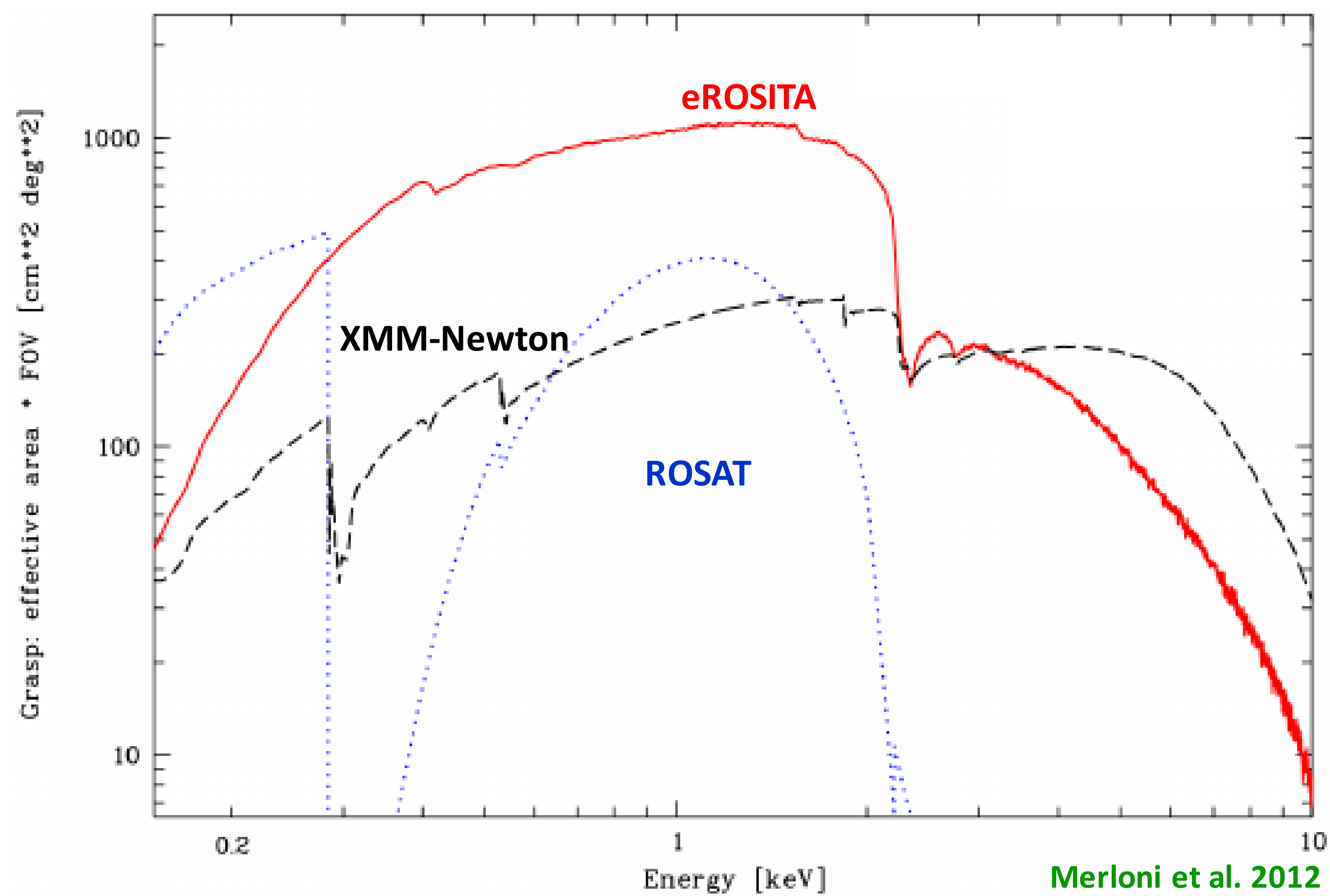
- X-rays are reflected at the grazing angle (<2°), which decreases with energy
- Mirror are gold coated (high atomic number)
- Number of mirror shells defines effectiv area
  - Chandra: 4
  - XMM-Newton: 58
  - eROSITA: 54 per module (7 modules)
- Qualitity of mirrors defines angular resolution (PSF – Point Spread function)
  - Chandra: 0.5'' (on-axis)
  - XMM-Newton: 15'' (on-axis)
  - eROSITA: 16'' (on-axis), 28'' (survey)



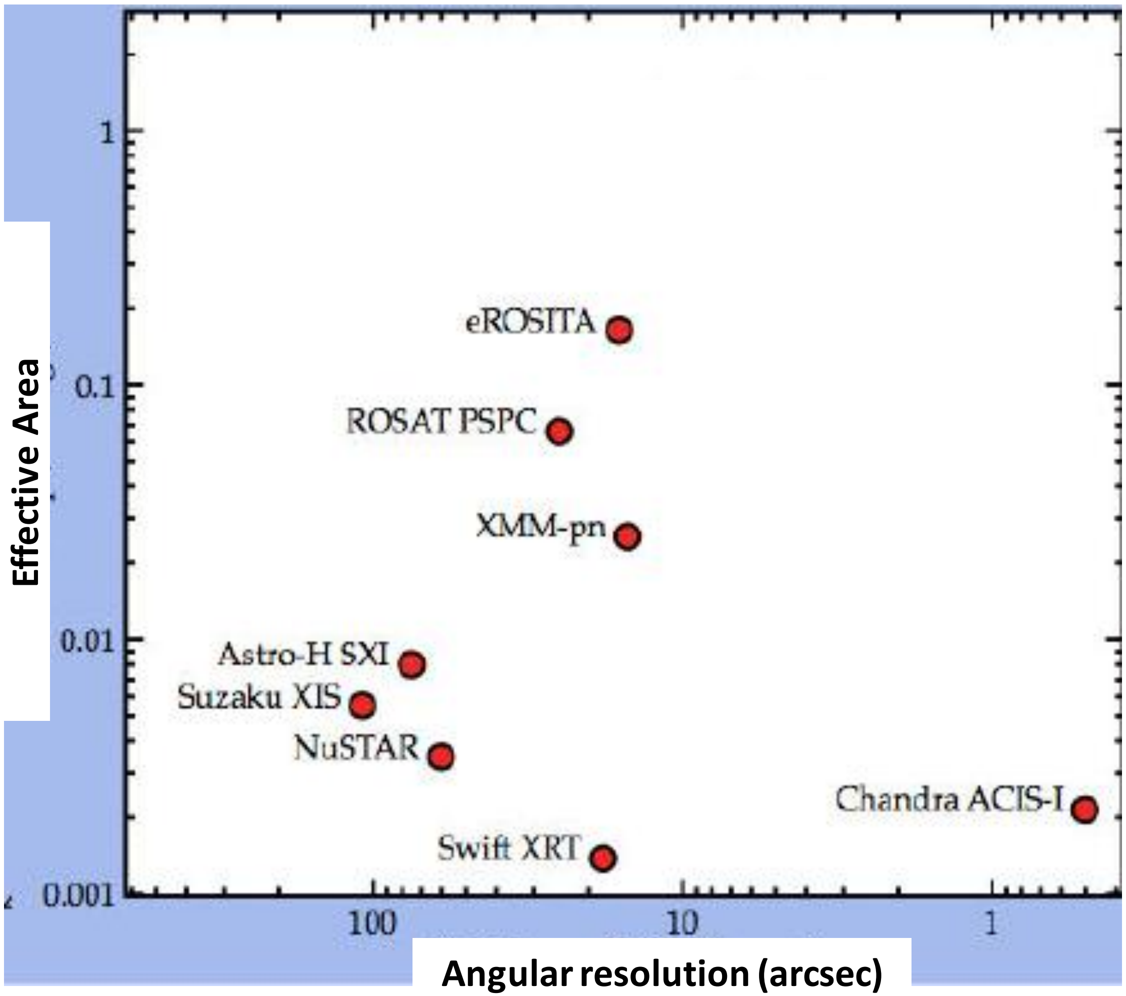
Chandra FOV



Effectiv Area as function of energy



Different current X-ray instruments



Nandra et al. 2013

eROSITA / XMM-Newton:

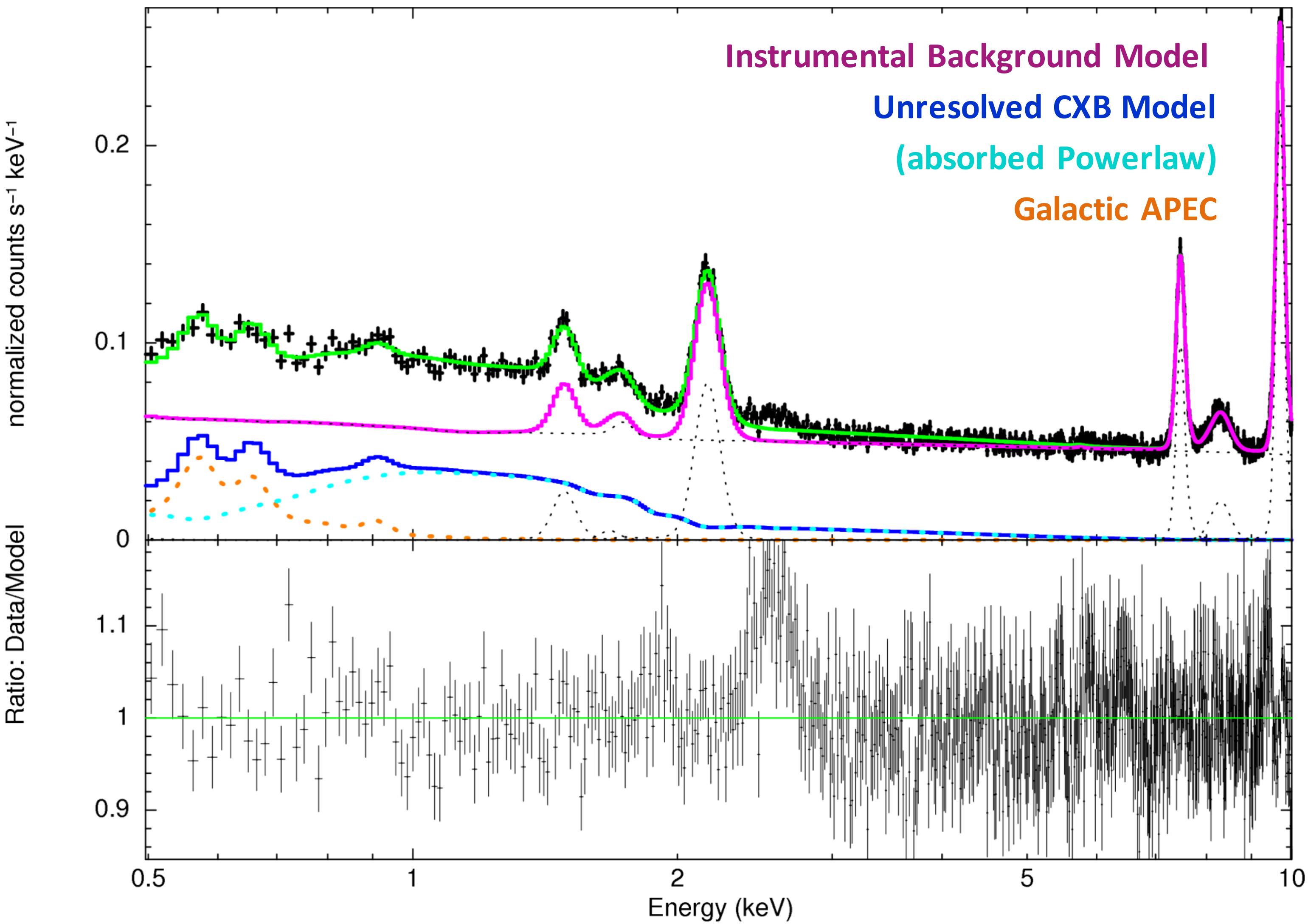
- **Best for wide surveys**
- **Best for extenden source detection**

Chandra:

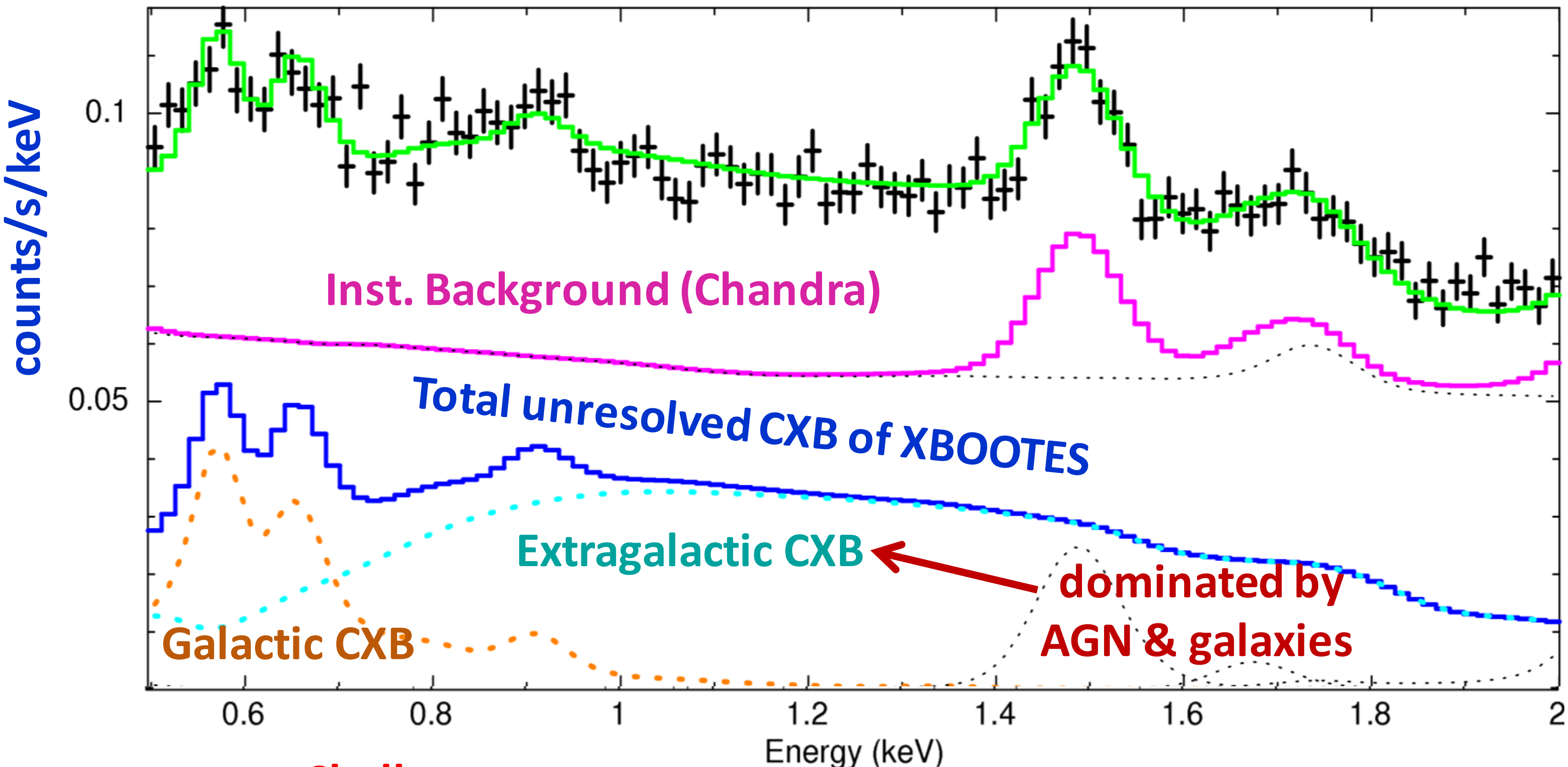
- **Low & stable instrumental background**
- **Best for deep-pencil beam surveys**
- **Best for point-source detection: 4 counts in one pixel → ~5 sigma detection**

BackUp

Energy Spectrum of unresolved emission (0.5 - 10.0 keV)



Challenges for direct detection:



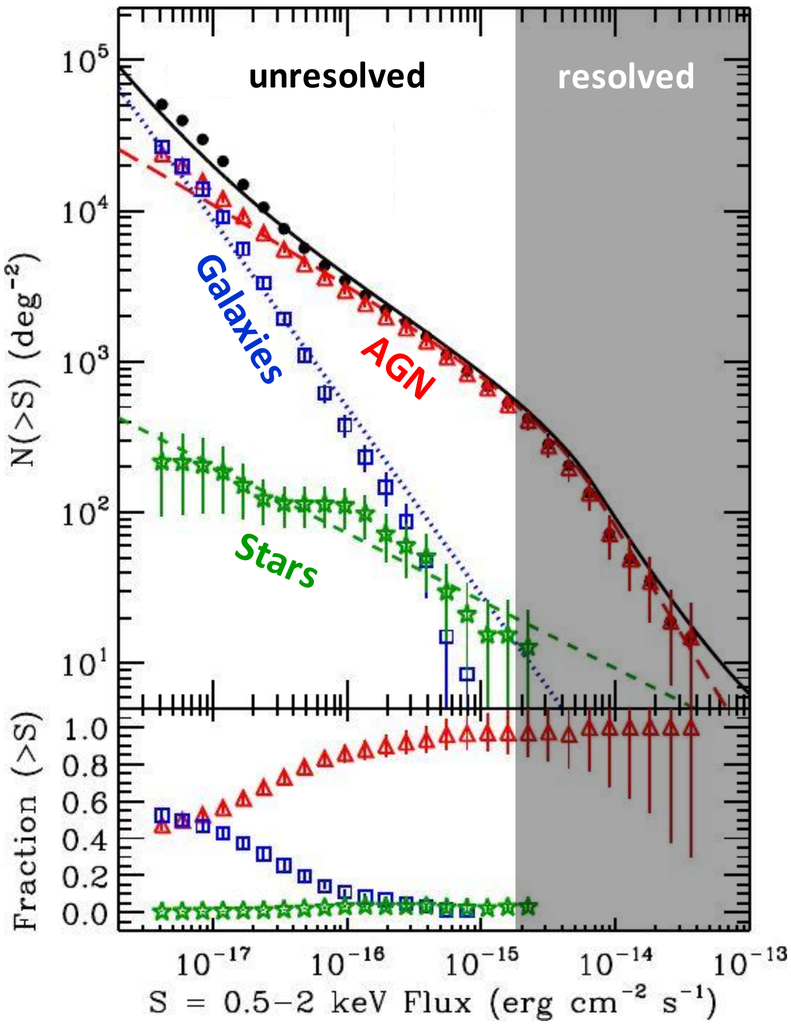
Challenges:

- Low number counts
- Diffuse nature and unknown morphology
- Strong contaminating emission by:
    - Inst. BKG
    - Other CXB components (<10% from clusters)

Kolodzig+2017

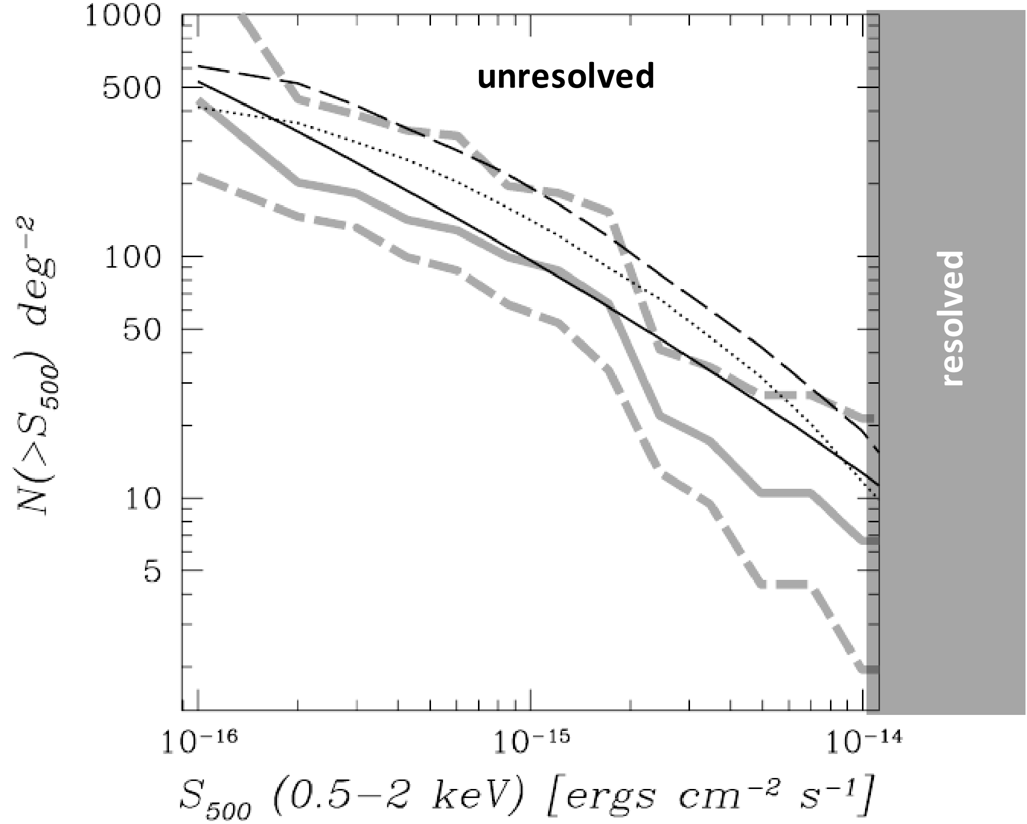
Unresolved extragalactic components

X-ray point sources



Luo+2017 - Chandra: 7Ms , 0.1deg^2

Cluster and groups of galaxies (X-ray extended sources)

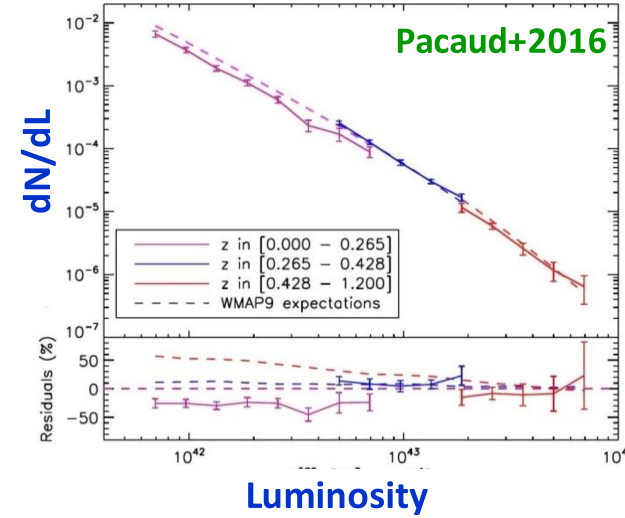


Finoguenov+2015

XMM-Newton 3Ms, Chandra 4Ms, 0.3 deg^2

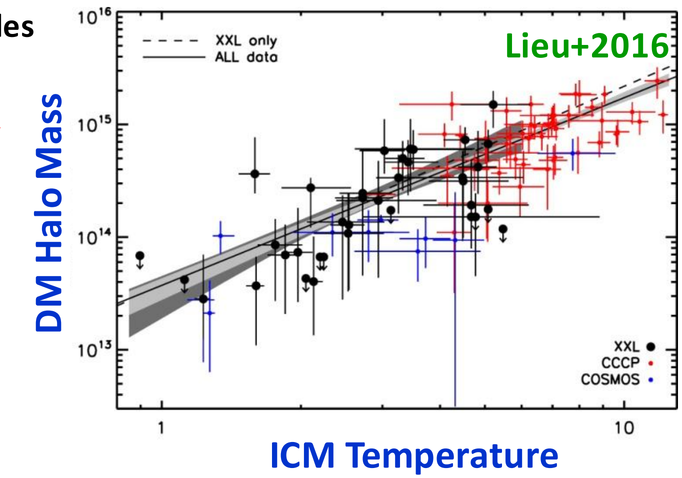
Galaxy clusters:
State of the art and motivation

- X-ray luminosity function: reasonable well known



- Large-scale structure studies:
  - X-rays (and SZ) very efficient detection method
  - Number counts per Mass-Bin → Halo-Mass Function → **Dark Energy probe**

    → Main science driver of largest X-ray surveys: XXL, eRASS
  - Main problem: **calibrating relation between halo mass & ICM observables** (e.g. luminosity, temperature and inferred gas mass)



- Challenges from LSS studies with clusters:
  - Studying entire ICM structure from core to outskirts (1-halo-term)
  - Studying substructure and non-thermal sources (small-scale-clustering)
- **Angular correlation studies with the CXB:**
  - Sensitive to ICM structure from core to outskirts ?
  - High angular resolution: Sensitive to substructure and non-thermal sources ?
  - Additional calibration tool for X-ray observables?

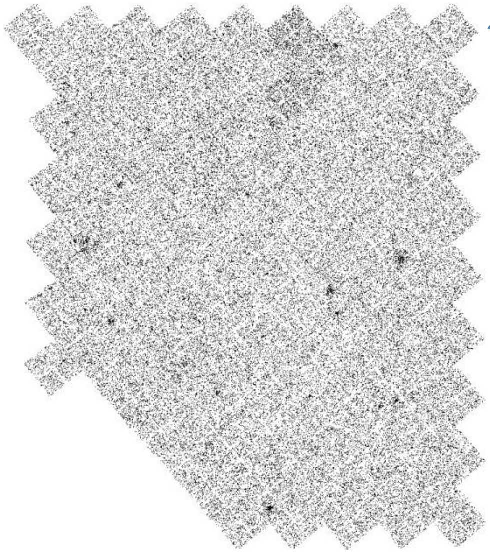
Analyze Technique

Data reduction:

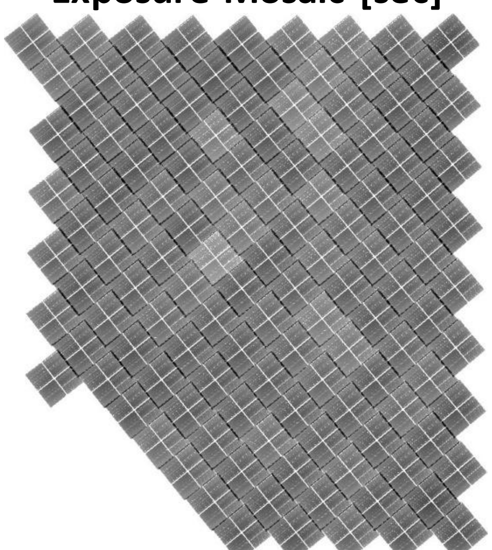
For each Observation:

1. Background flares removed
2. Instrumental background subtracted
3. FOV-Mask applied (removes CCD-edges & -gapes)

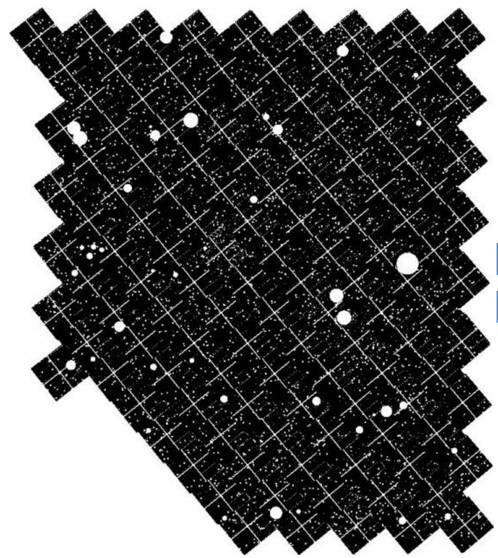
Net-Count Mosaic [cts]



Exposure Mosaic [sec]

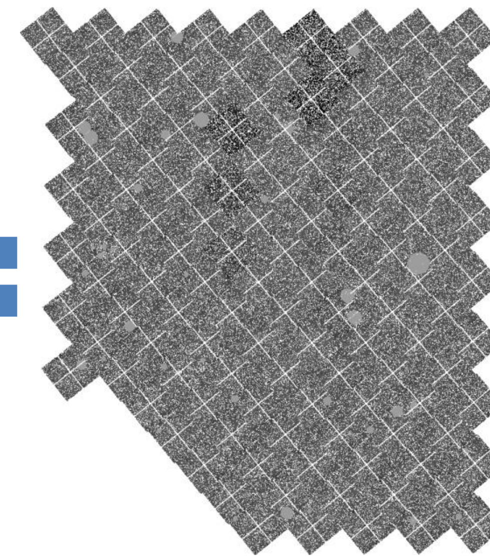


Mosaic Mask



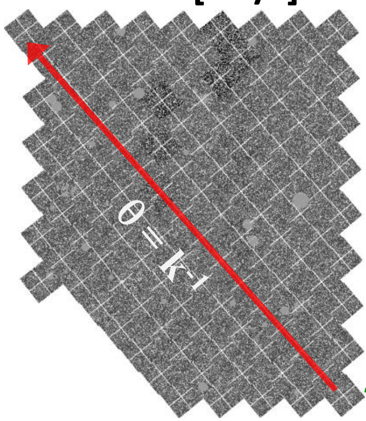
Removes resolved sources and other targets

Masked Count-Rate Mosaic [cts/s]



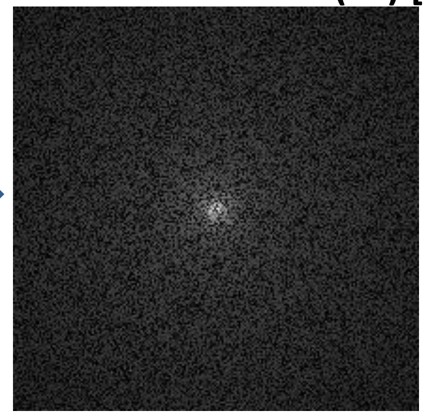
Computing *Mosaic* Power Spectrum:

Masked Count-Rate Mosaic[cts/s]



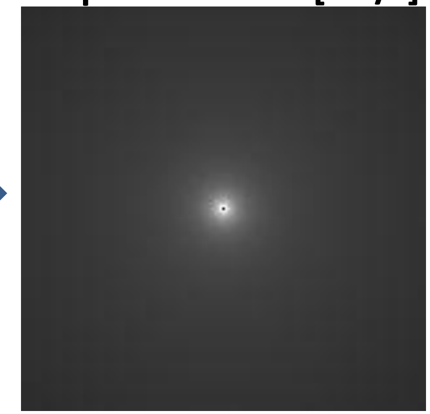
2D DFT

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



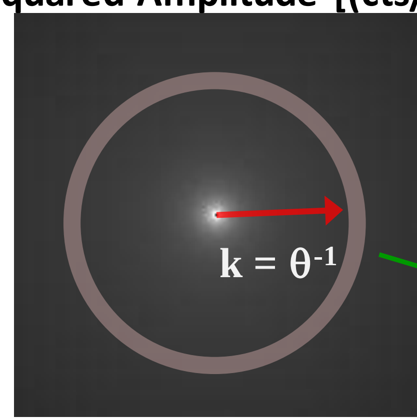
ABS(DFT)

Amplitude of FT [cts/s]



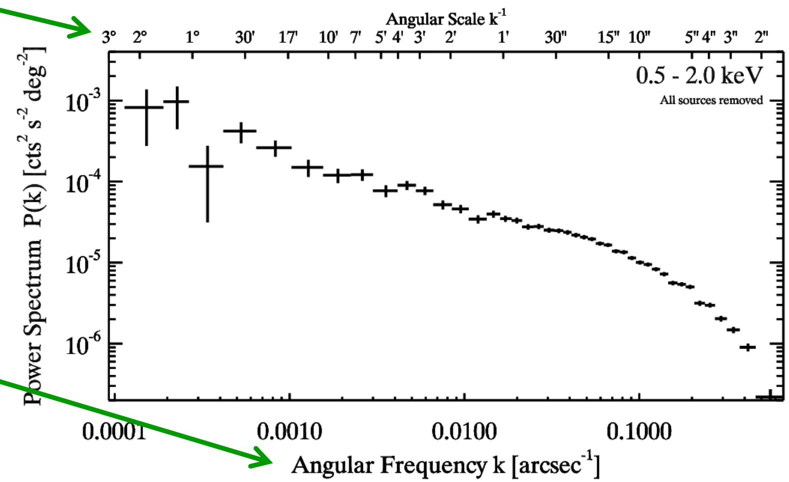
(ABS(DFT))^2

Squared Amplitude [(cts/s)^2]



P(k)

1D Power Spectrum P(k) [(cts/s)^2 deg^{-2}]

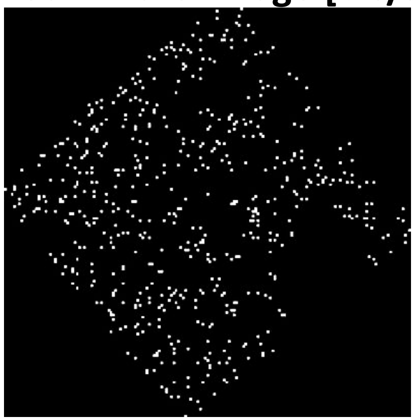


Steps:

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

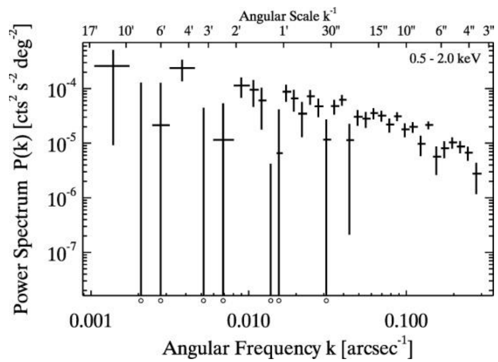
Computing *stacked* Power Spectrum:

Masked Count-Rate Image [cts/s]

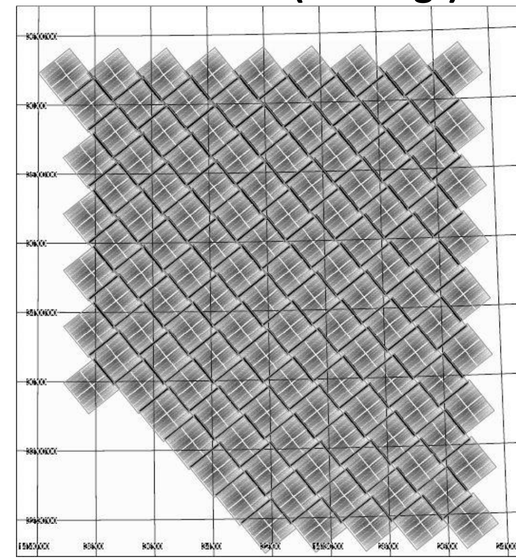


2D DFT

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

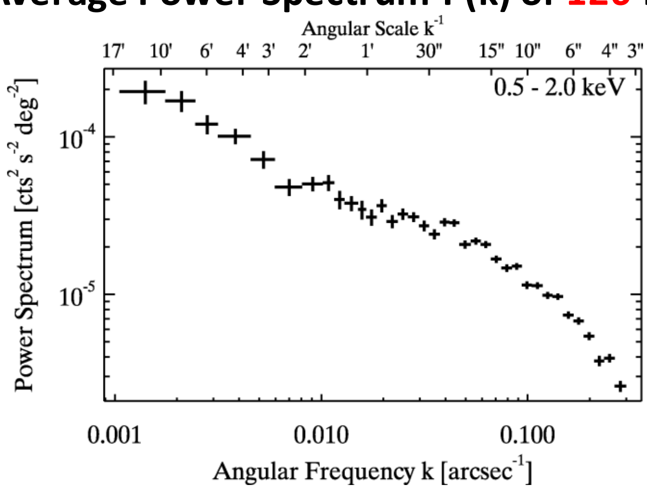


126 Fields (8.7 deg²)



average

Average Power Spectrum P(k) of 126 fields



Application:

study smallest angular scales (<17’)

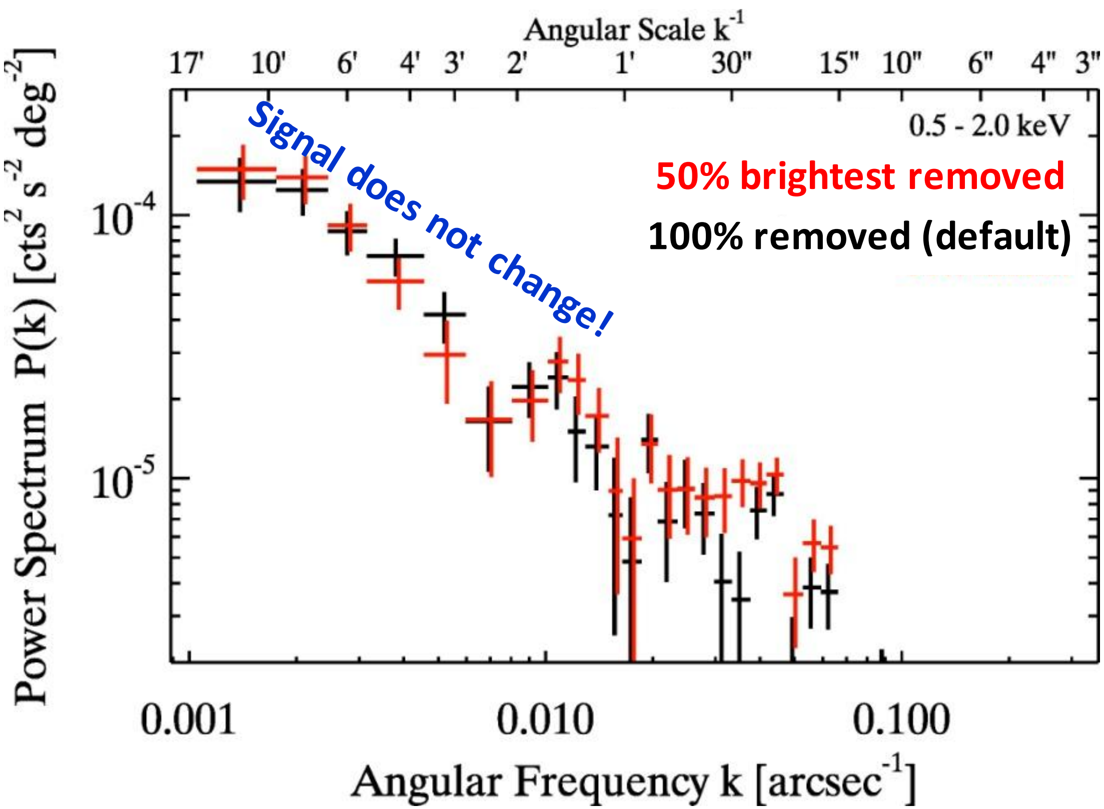
Advantage to Mosaic:

much faster and simpler to compute

Results

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

Fractions of removed resolved point sources

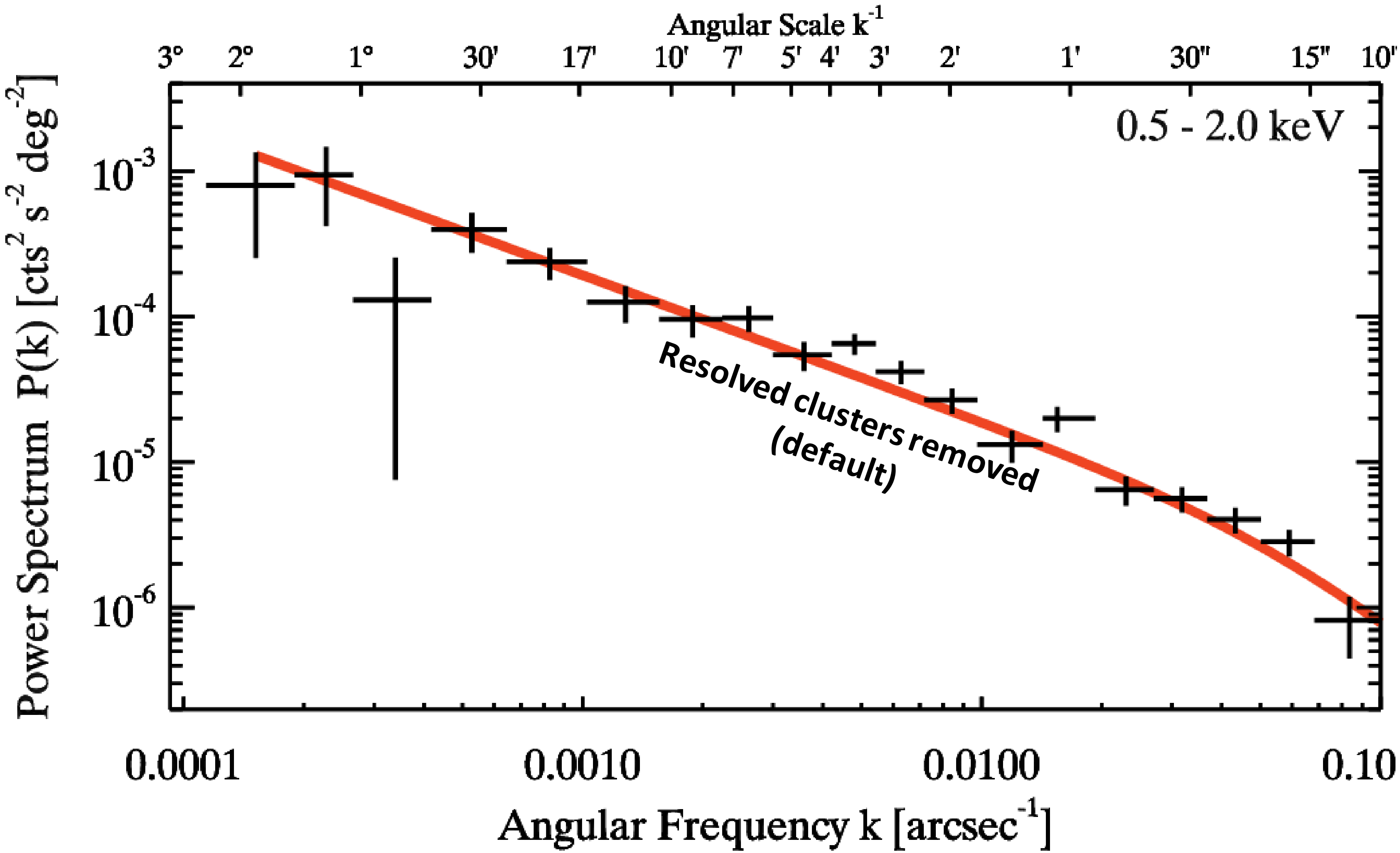


Current summary of evidence:

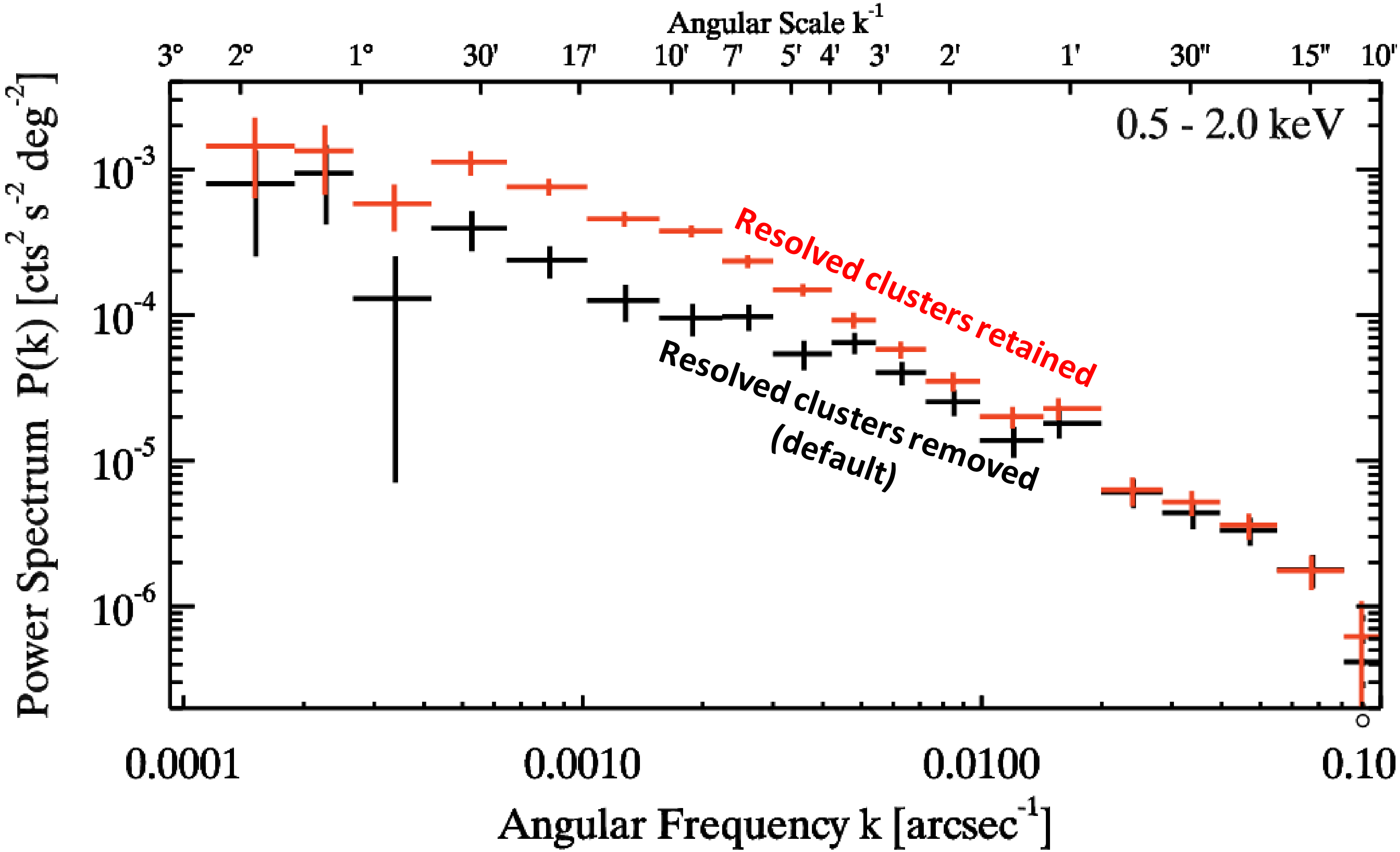
- No known instrumental origin
- Not point sources → extended/diffuse sources? → gas?
- Visible in 1-2keV -> extragalactic? → extragalactic gas?
- Needs to be X-ray bright → hot extragalactic gas?
- Needs to be highly structured → follows dark matter distribution?

→ What about the hot gas within groups and clusters of galaxies, alias the intracluster medium (ICM)?

LSS Signal depends on galaxy clusters ?

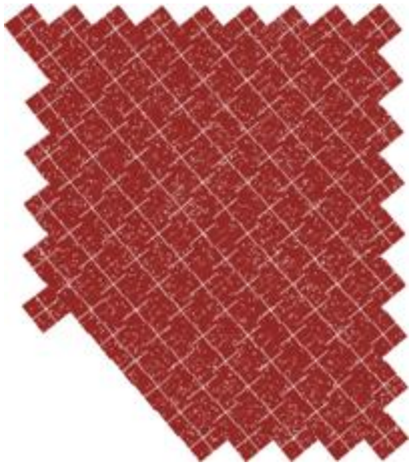


LSS Signal depends on galaxy clusters ?!

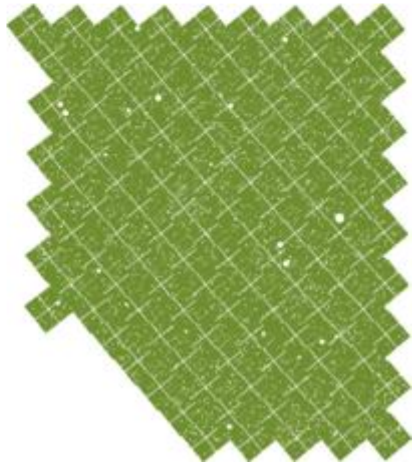


Removing fractional area of resolved clusters

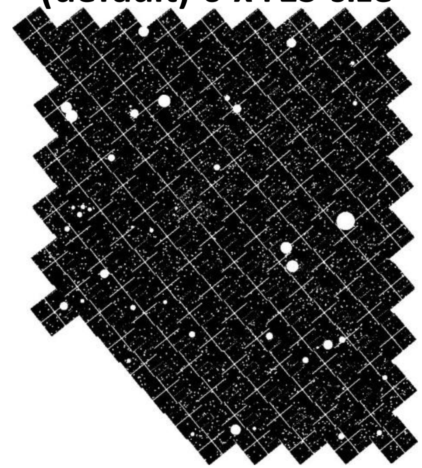
0 x rES-size



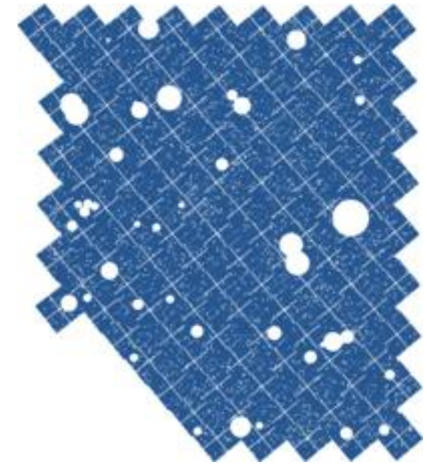
3 x rES-size



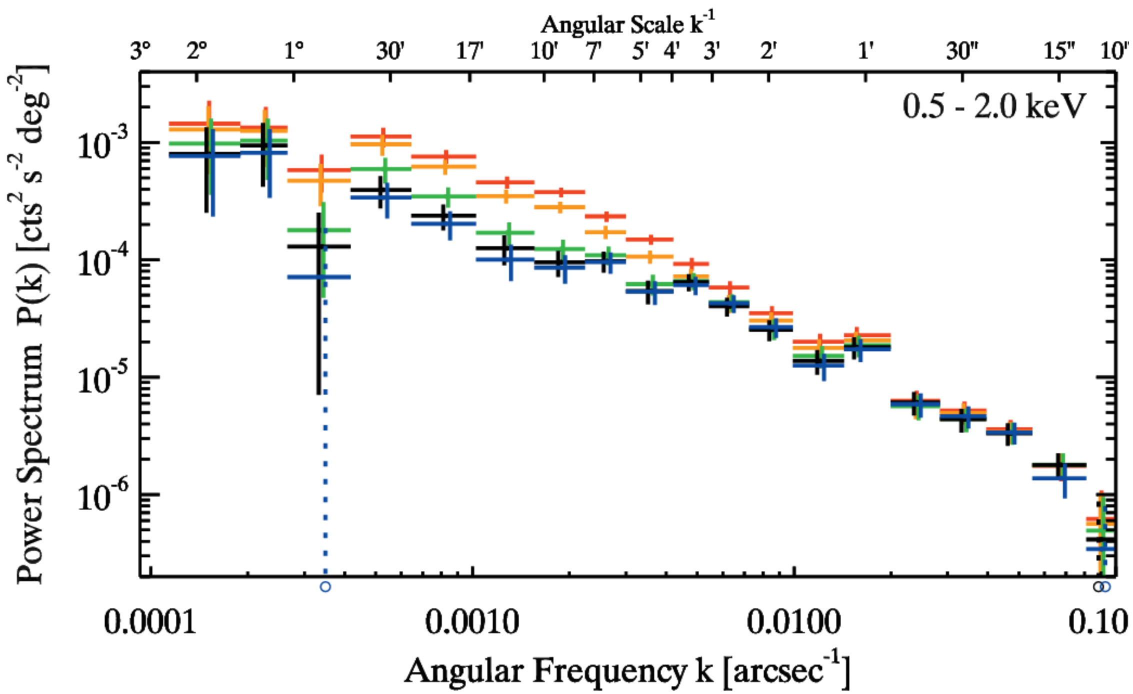
(default) 6 x rES-size



12 x rES-size



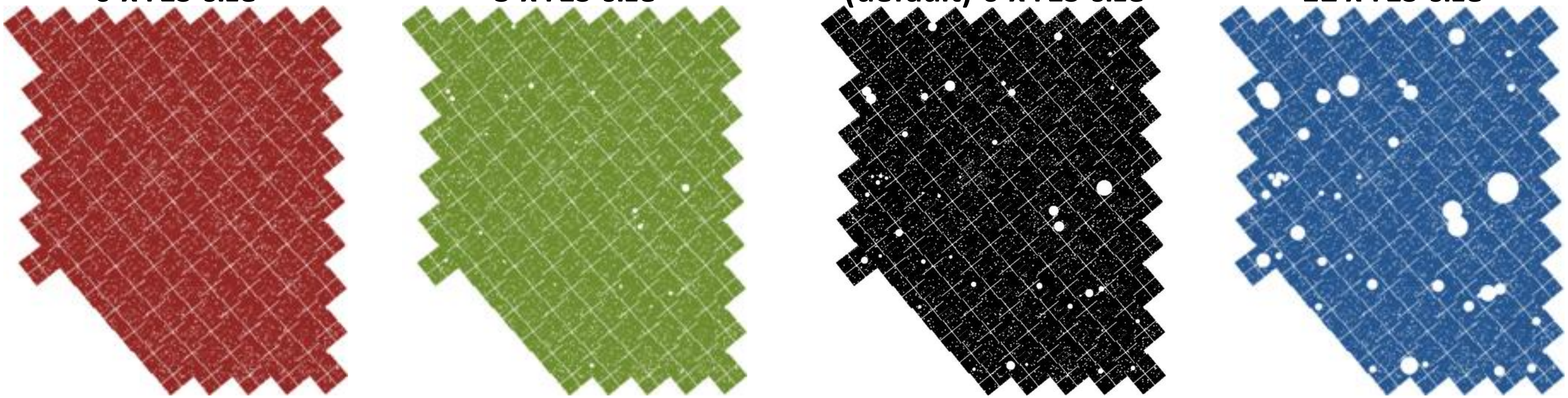
Fractional Radius:
0.0x (All rES retained)
1.0x
3.0x
6.0x (default)
12x



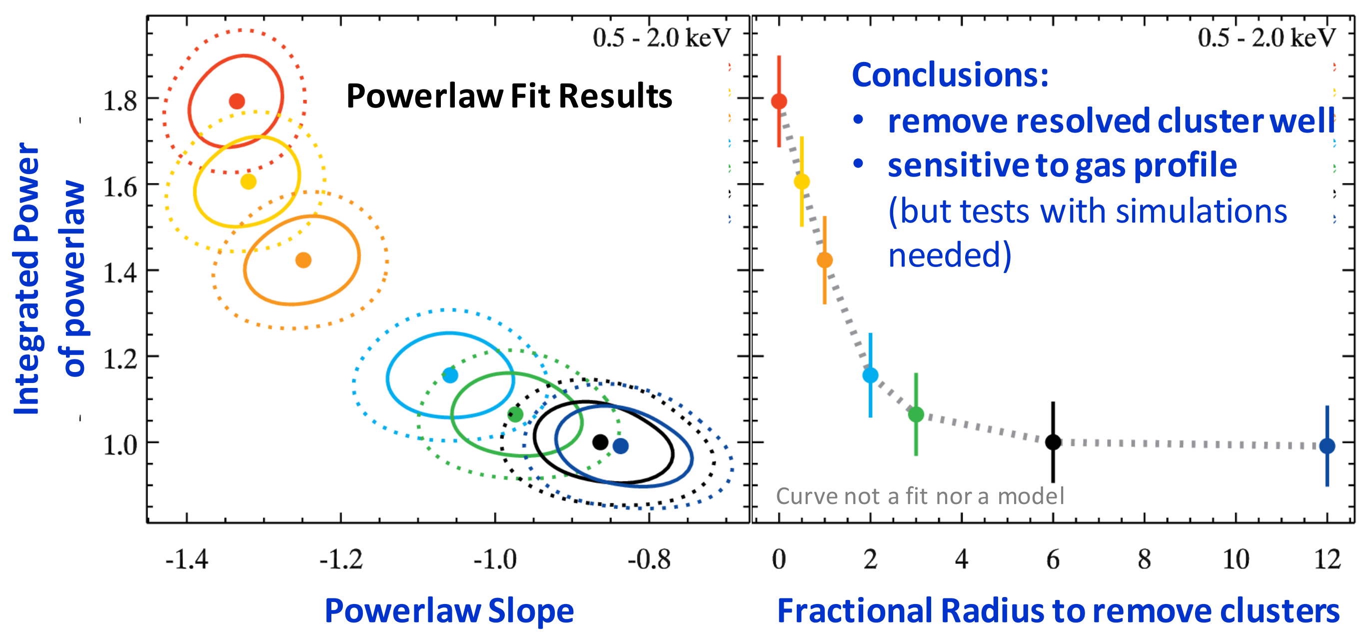
Kolodzig+2018

Removing fractional area of resolved clusters

0 x rES-size | 3 x rES-size | (default) 6 x rES-size | 12 x rES-size



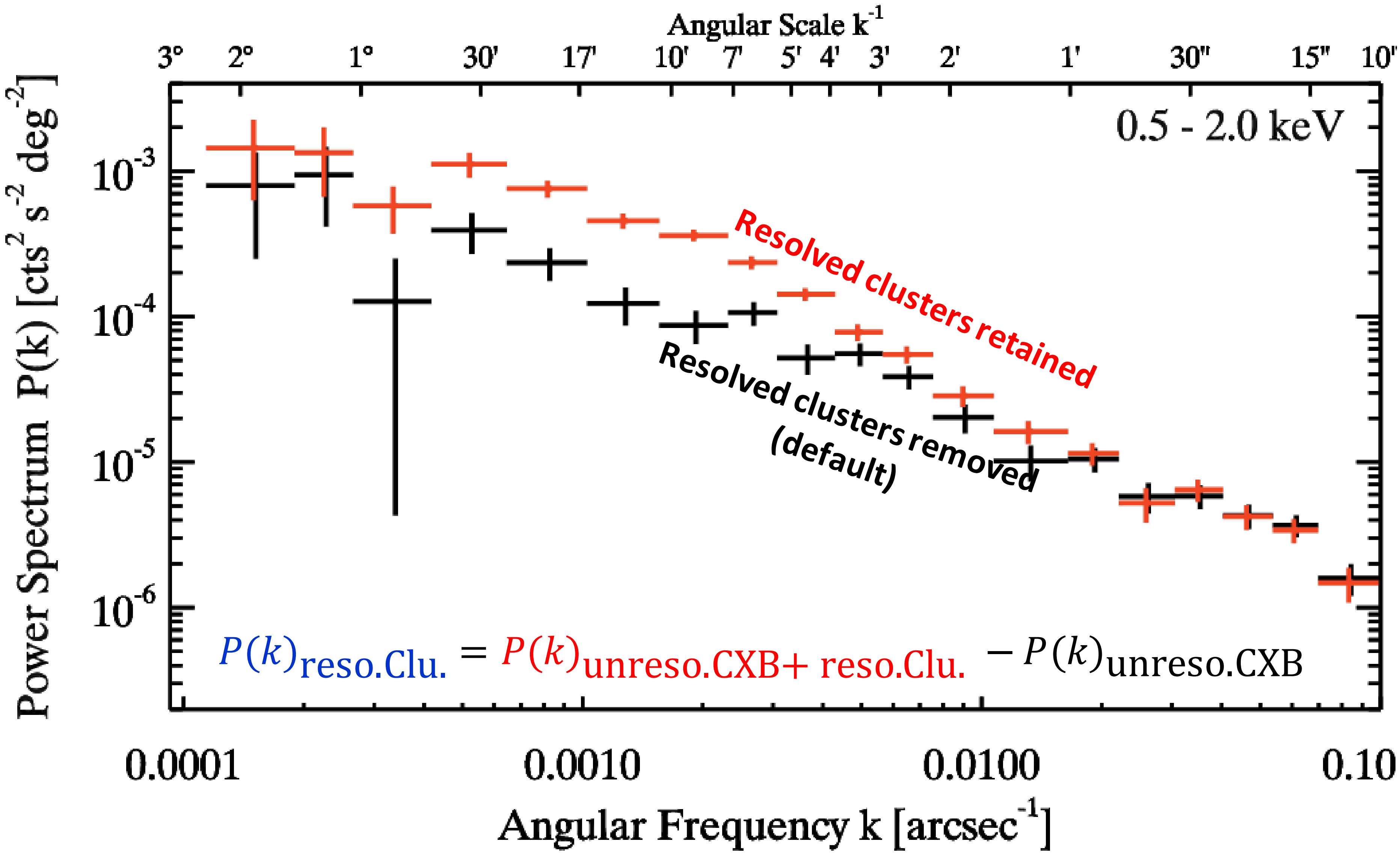
Fractional Radius:
0.0x (All rES retained)
0.5x
1.0x
2.0x
3.0x
6.0x (default)
12x



Kolodzig+2018

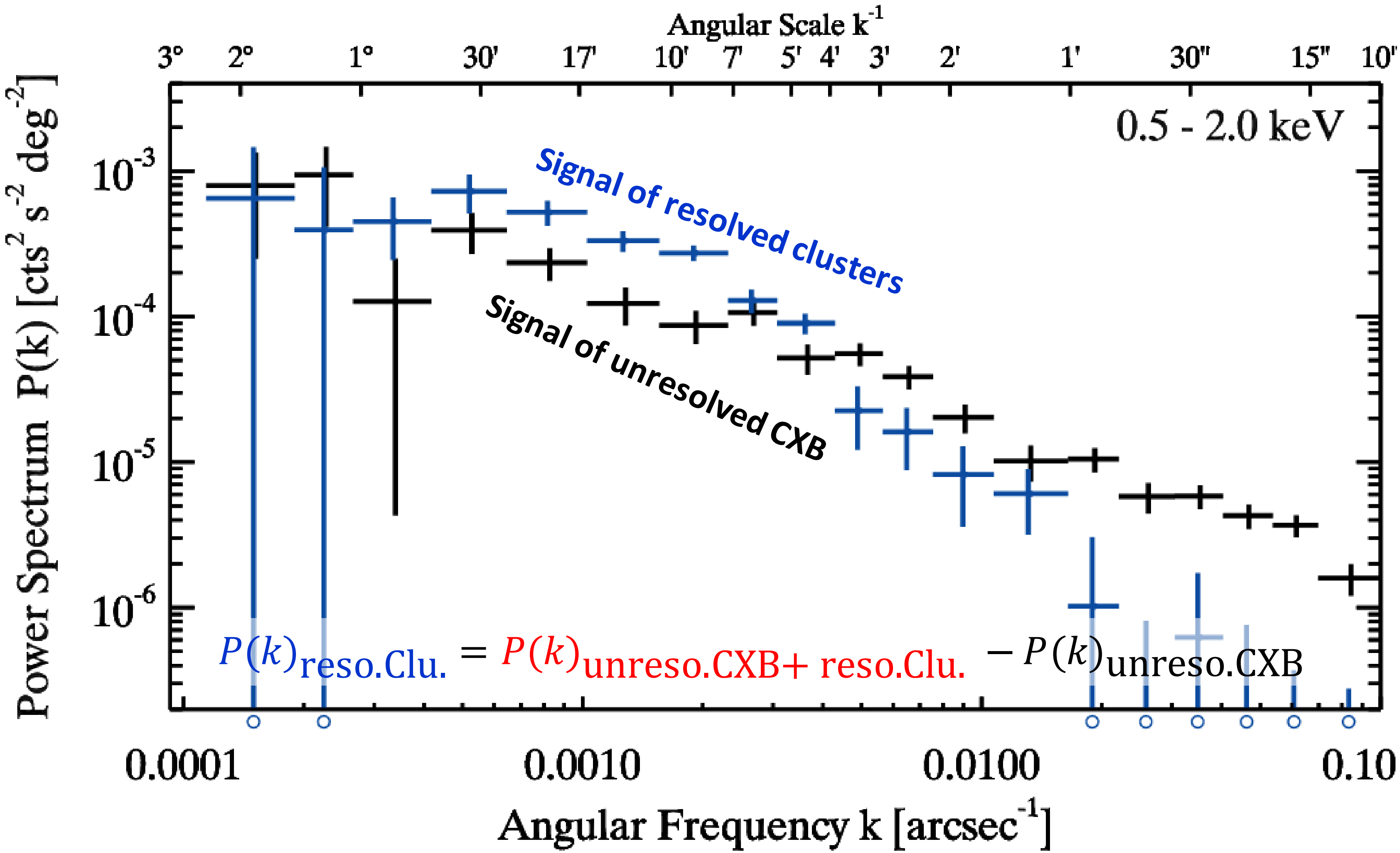
“LSS signal” of resolved clusters

Get LSS signal of resolved clusters

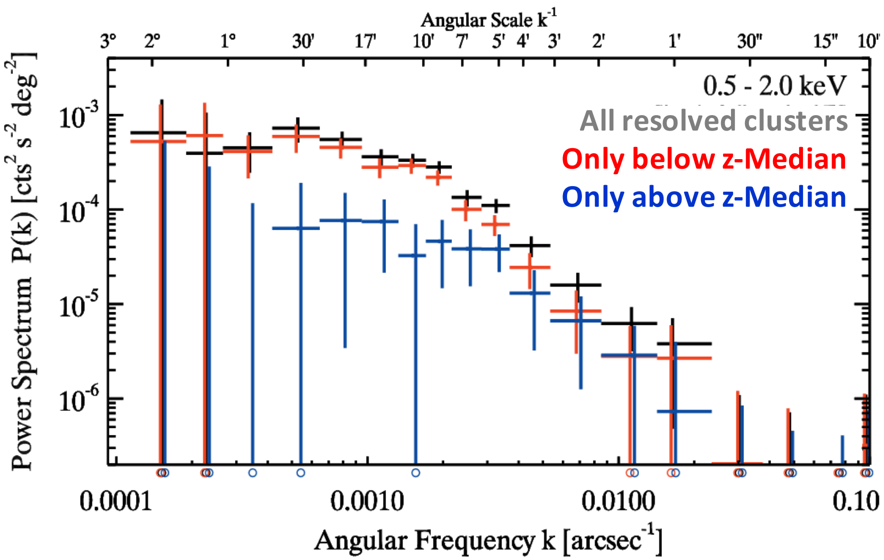


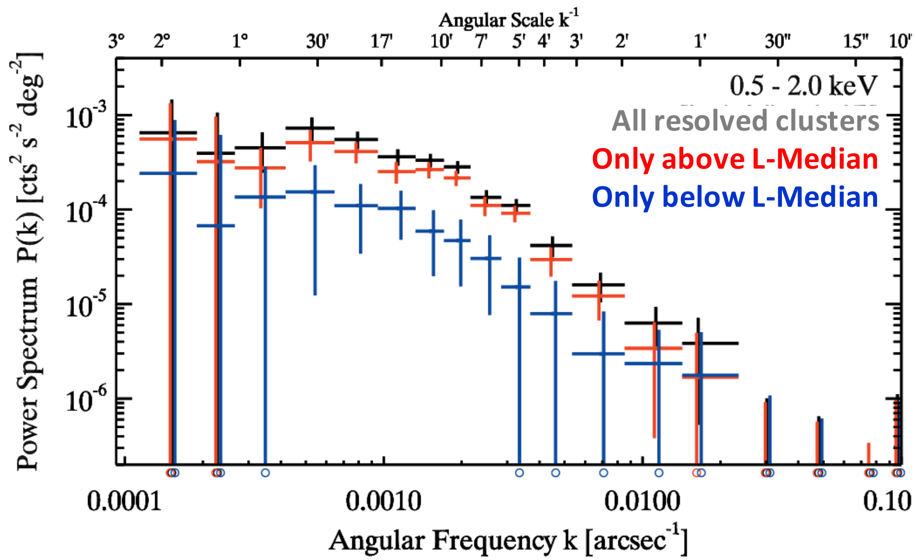
$$P(k)_{\text{reso.Clu.}} = P(k)_{\text{unreso.CXB+ reso.Clu.}} - P(k)_{\text{unreso.CXB}}$$

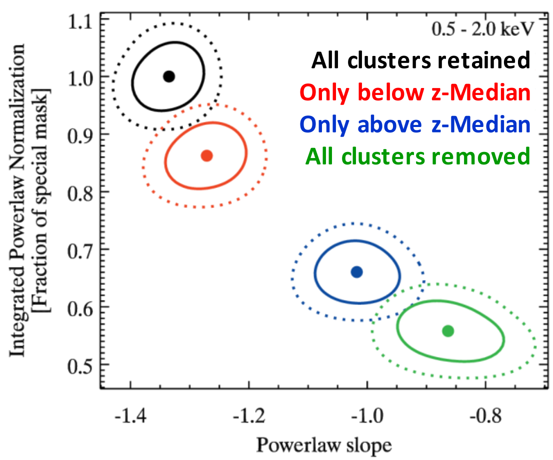
LSS signal: unresolved CXB vs. resolved clusters

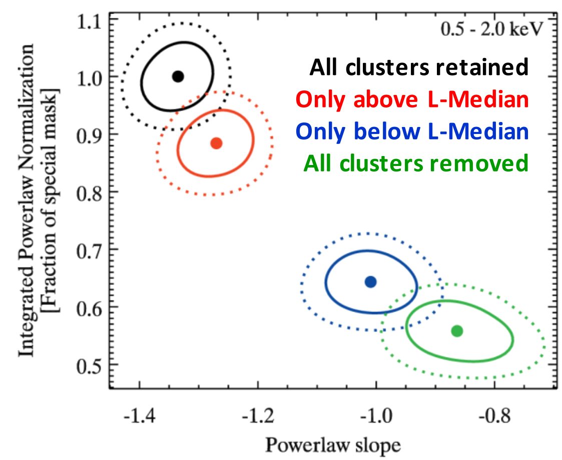


Redshift & luminosity dependence









Conclusion:

"LSS signal of resolved clusters" dominated (as expected) by clusters:

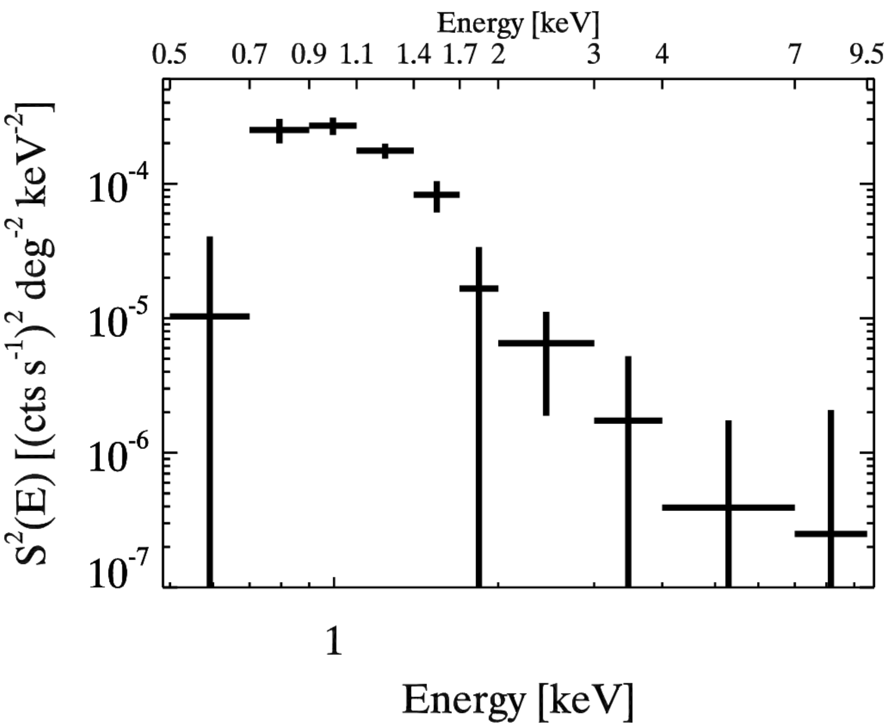
- below z-median (z=0.24)

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

Energy Spectrum of “LSS signal”

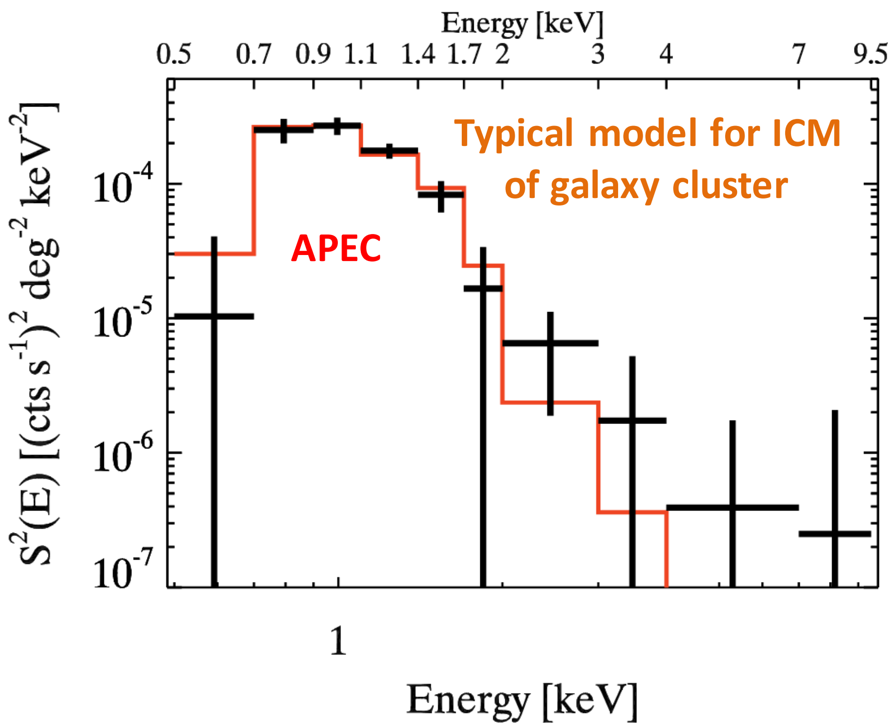
Energy Spectrum of CXB fluctuations

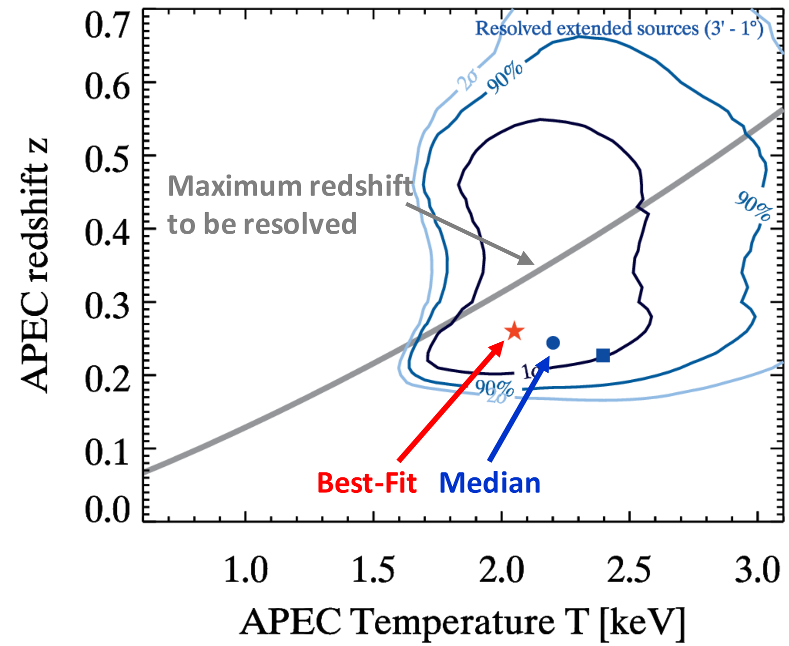
Resolved clusters



Energy Spectrum of CXB fluctuations

Resolved clusters





APEC Best-Fit: z=0.26, T=2.0keV

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

Based on catalog of resolved clusters:

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

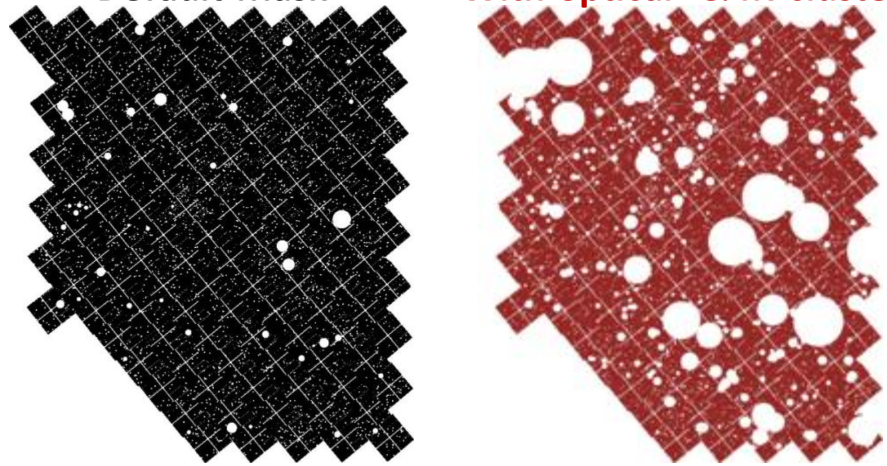
Using L-T-Relation of **Giles+2015** (XXL)

→ method works reliable!

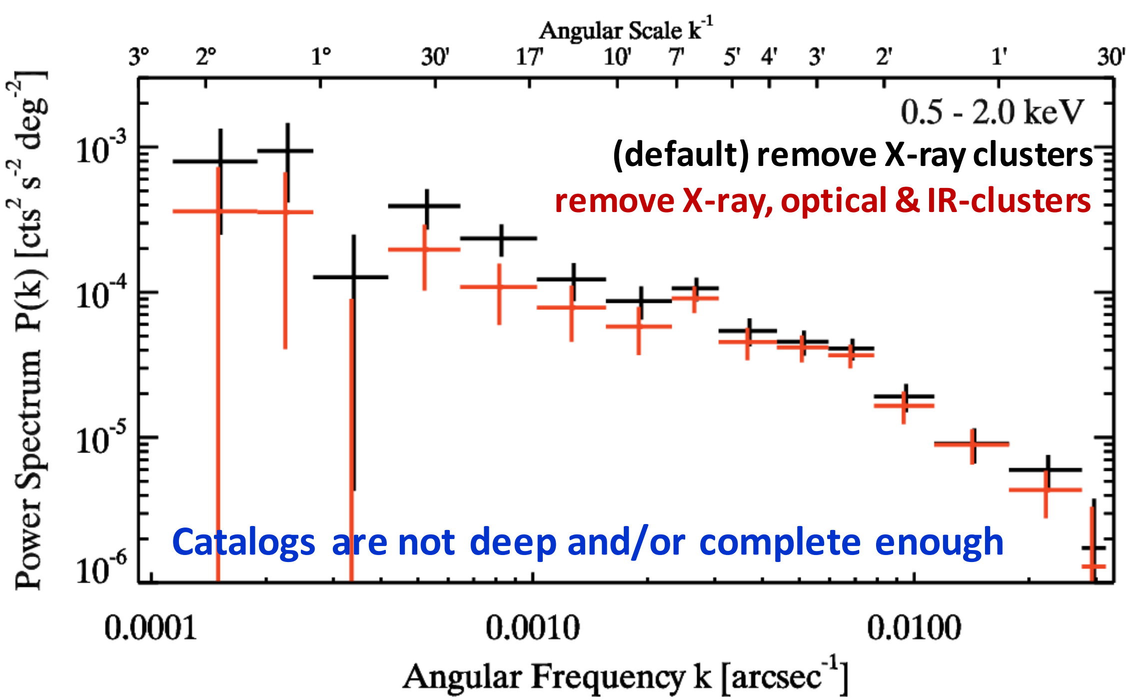
Optical & IR clusters?

Optical- & IR-clusters: minor contribution!

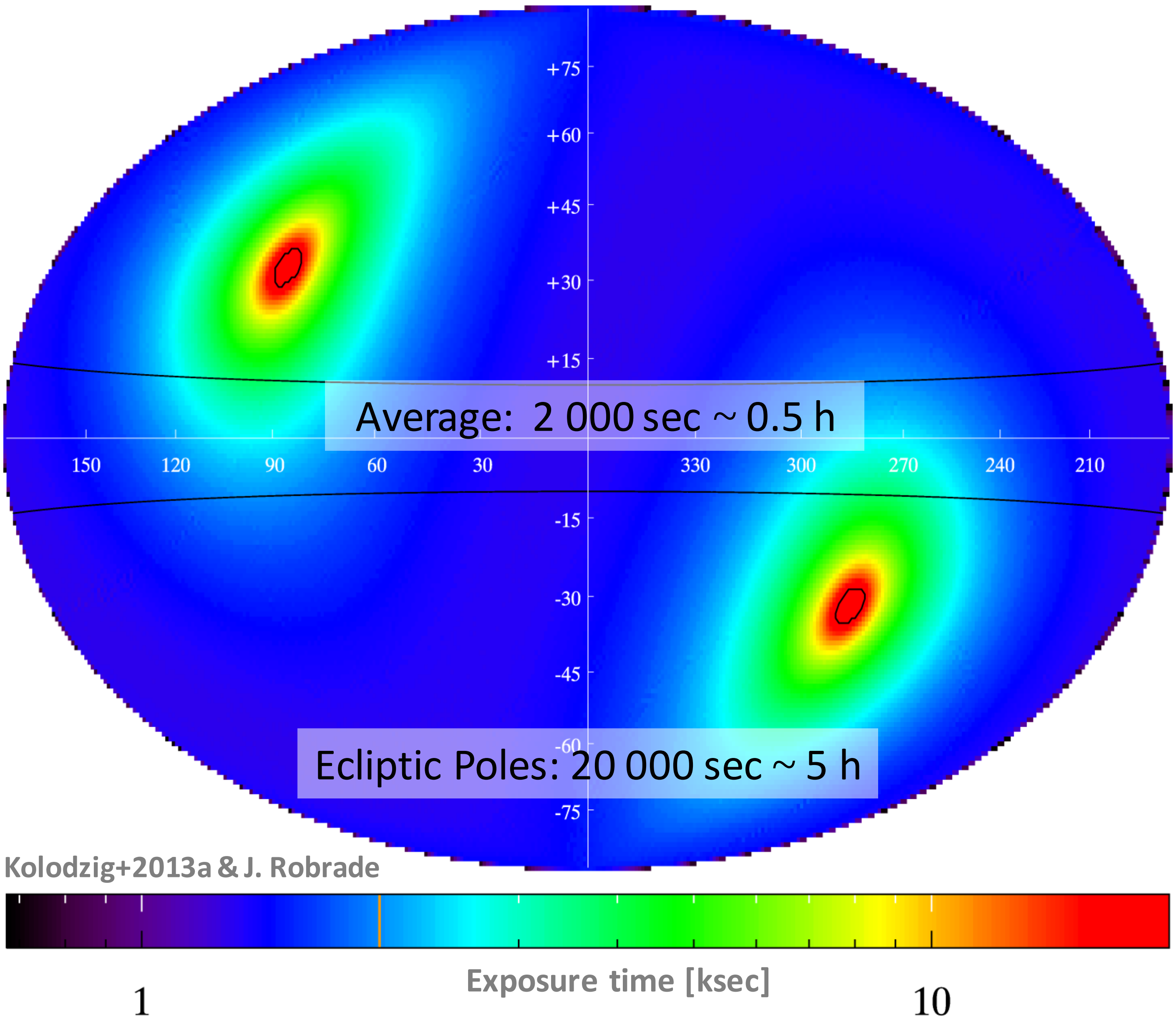
Default Mask | **With optical- & IR-clusters**



Catalogs:
- SDSS-DR12 (z<0.2, r < 18mag)
- SDSS-DR6 (0.1<z<0.7, r < 22mag)
- Spitzer (Eisenhardt+2004)
(f(3.6μm) < 19.1 mag, f(4.5μm) < 18.3mag)



eRASS: effective exposure time



Summary

Full description of CXB fluctuations below 3°