The angular power spectrum and eROSITA's potential role for sterile neutrino searches

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ongoing work with
S. Ando, CW, F. Zandanel, arXiv:15MM.NNNNN

Wednesday 15th April 2015
Off the beaten tracks Workshop, Trieste, Italy

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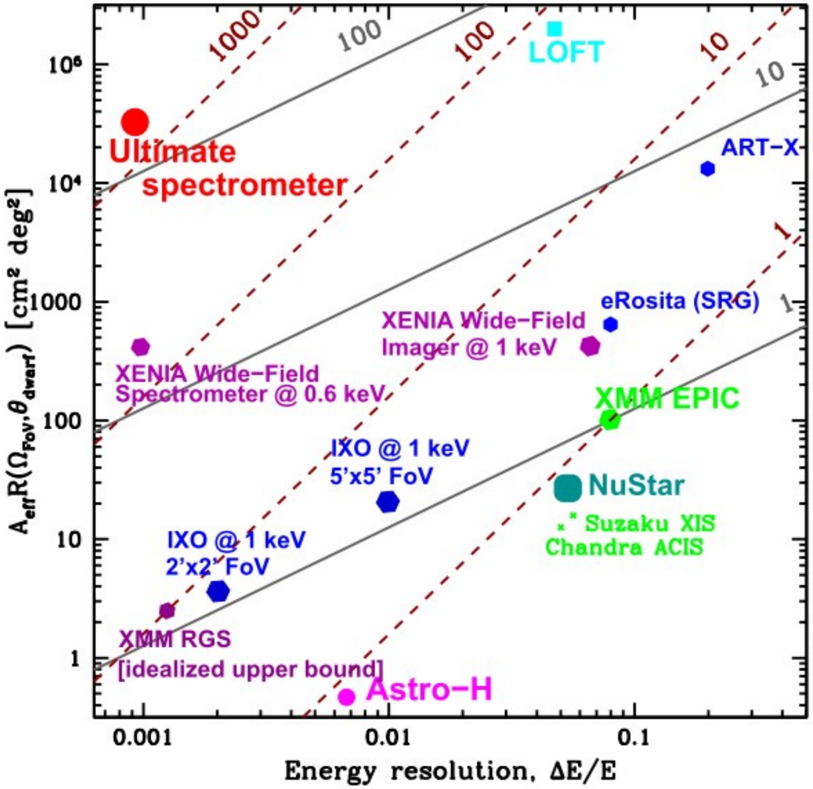
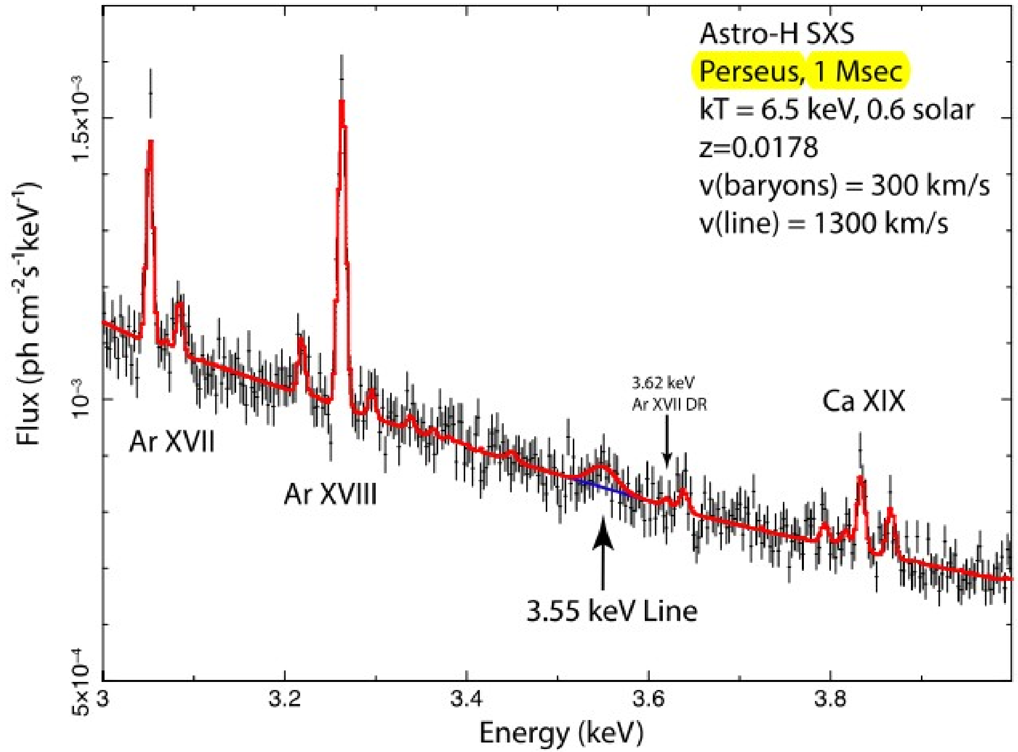
eROSITA and the grasp of X-ray satellites

[Boyarsky+ 2012]



[Bulbul+ 2014]

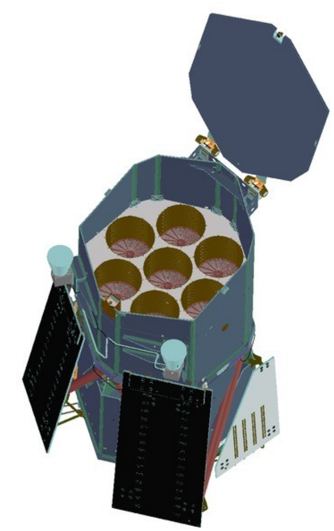


eROSITA

- Primary instrument on-board the Russian SRG satellite
- Launch from Baikonur 2016, placed in L2 orbit
- Will perform *first imaging all-sky survey in the medium X-ray energy range, up to 10 keV*

- Average observation time after four years: **about 3 ksec**

Can one do DM searches with such a shallow survey?



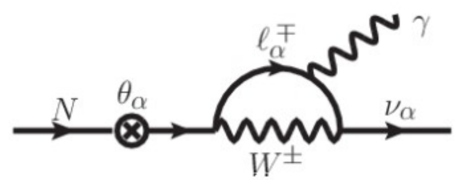
The averaged signal

Sky-averaged spectrum

- Cosmological signal

$$I_{\nu_s}(E, \chi \boldsymbol{n}) = \frac{\Gamma_{\nu_s}}{4\pi m_{\nu_s}} \int_0^\infty \frac{dz}{H(z)} \rho_{\nu_s}(z, \chi \boldsymbol{n}) \, \delta_{\rm D}\left[(1+z)E - \frac{m_{\nu_s}}{2}\right]$$

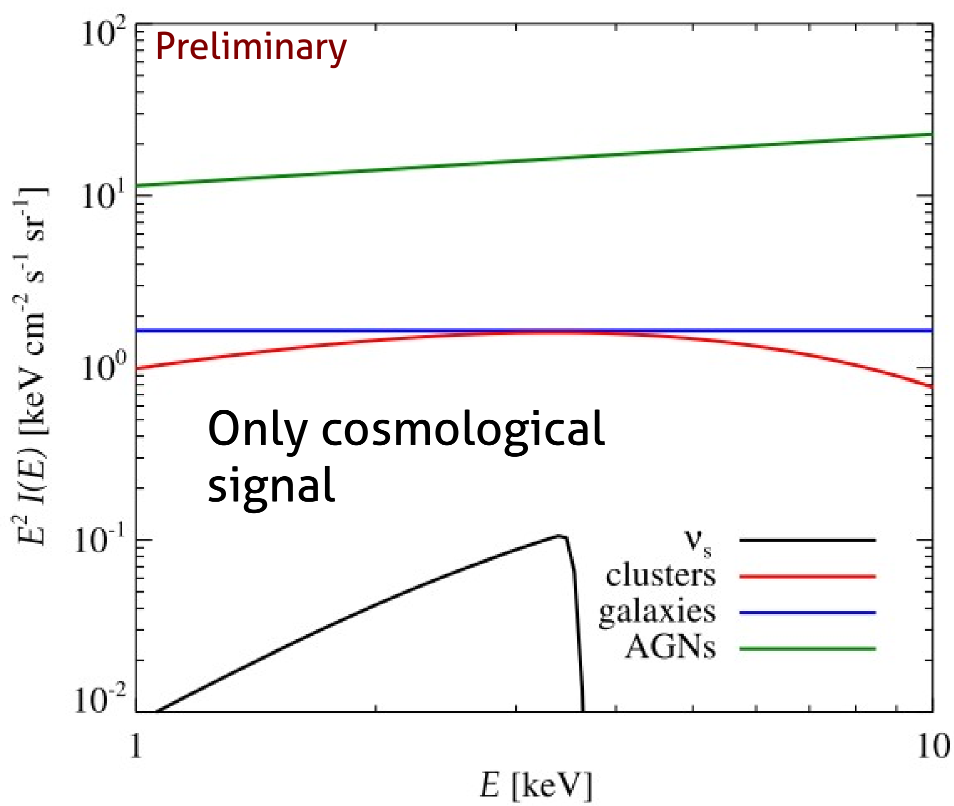
$$\Gamma_{\nu_s} \simeq (7.2 \times 10^{29}\ \mathrm{s})^{-1} \left(\frac{\sin^2 2\theta}{10^{-8}}\right) \left(\frac{m_{\nu_s}}{1\ \mathrm{keV}}\right)^5$$



- Backgrounds
  - Diffuse
    - Galaxy clusters
  - Unresolved point sources
    - Blazars
    - Star-forming galaxies
  - Instrumental background

Signal-to-background << 1%

→ Systematics limited searches



Fisher information & auto-correlation

Unbinned maximum likelihood method

- No information loss due to binning
- Well behaved in case of Poisson noise

Linear model:

$$\mathcal{L} = e^{-N_{\rm tot}} \prod_i \Phi_{\rm tot}(\Omega_i)$$

$$\Phi_{\rm tot}(\Omega) = \sum_{i=1}^{N_{\rm comp}} \alpha_i \Phi_i(\Omega)$$

Product over observed photons

Units: $\Phi_i\,[\mathrm{ph\,sr^{-1}}]$

Fischer information:

- General definition

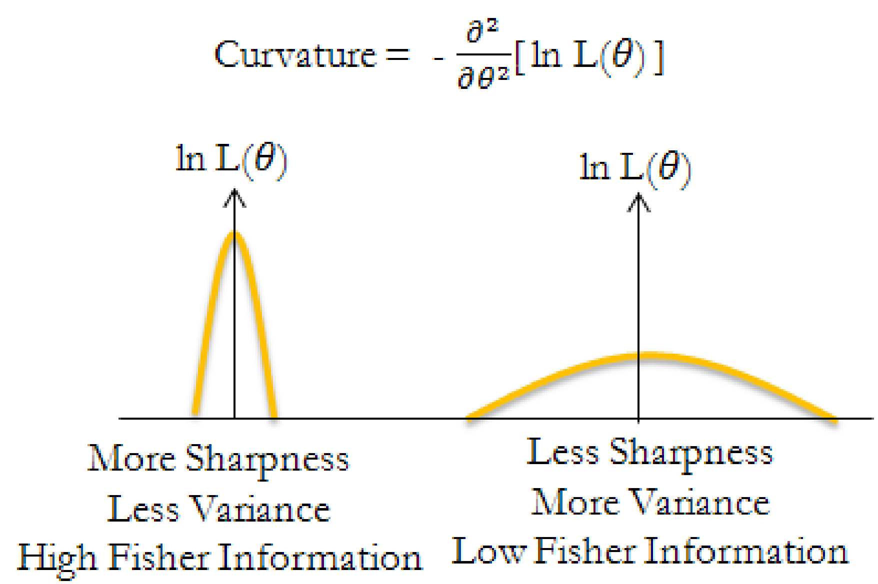
$$\mathcal{I}_{ij} = -\left\langle \frac{\partial^2}{\partial\alpha_i\partial\alpha_j} \ln\mathcal{L} \right\rangle$$

- Here:

$$\mathcal{I}_{ij} = \int d\Omega \frac{\Phi_i \Phi_j}{\Phi_{\rm tot}}$$

- Connection with standard deviation:

$$\sigma_\chi^2 = (\mathcal{I}^{-1})_{\chi\chi}$$



[CW+, in preparation]

Fisher information & Auto-correlations

If we forget (for a moment) about all other backgrounds, the only relevant quantity is:

$$\mathcal{I}_{\chi\chi} = \frac{1}{\Phi_{\rm tot}} \int d\Omega \, \Phi_\chi^2$$

This can be rewritten in terms of the auto-correlation angular power spectrum.

$$\mathcal{I}_{\chi\chi} = \frac{N_{\rm sig}^2}{4\pi N_{\rm tot}} \sum_{\ell=0}^{\infty} (2\ell+1) C_\ell$$

with the usual definitions:

$$C_\ell = \langle |a_{\ell m}|^2 \rangle$$

$$a_{\ell m} = \int d\Omega \, \Phi_\chi(\Omega) Y_{\ell m}^*(\Omega)$$

In this case, the ***differential Fisher information*** is given by

$$\frac{d\mathcal{I}_{\chi\chi}}{d\ln \ell} \propto \frac{(\ell+1)\ell}{2\pi} C_\ell$$

Hence → calculate auto-correlation power spectrum.

Dark matter signal auto-correlation

Using the large-sky limit and the Limber approximation, of finds

$$C_\ell^A(E) = \int_0^\infty \frac{d\chi}{\chi^2}\, W_A([1+z]E, z)^2\, P_A\left(k = \frac{\ell}{\chi}, z\right)$$

Power spectrum of sources.

The auto-correlation power spectrum

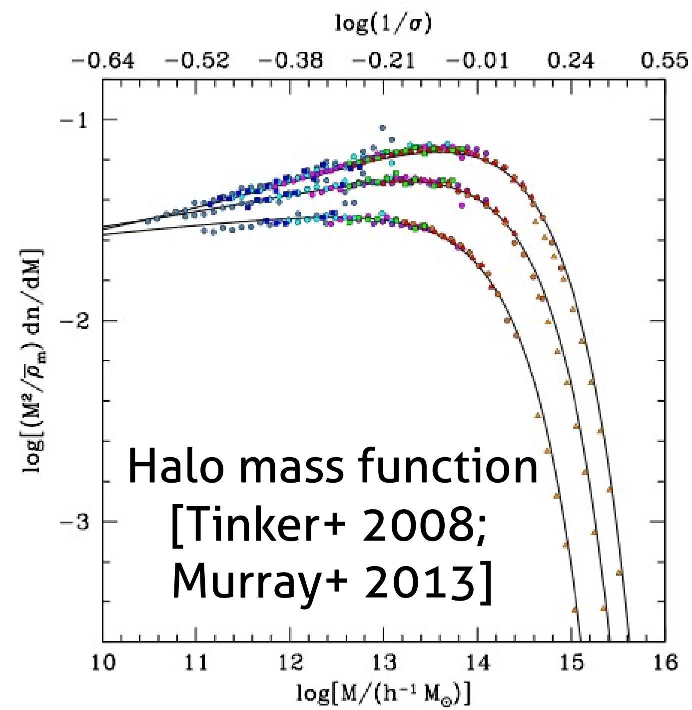
- …splits into two main contributions

$$P_{\rm A} = P_{\rm A}^{\rm 1h} + P_{\rm A}^{\rm 2h}$$

- One halo term (mostly halo shapes)

$$P_{\nu_s}^{\rm 1h} = \left(\frac{1}{\Omega_{\rm dm}\rho_{\rm c}}\right)^2 \int dM_{200} \frac{dn}{dM_{200}} \left[\int 4\pi r^2 dr\, \rho_{\rm dm}(r) \frac{\sin(kr)}{kr}\right]^2$$

- Two halo term (mostly halo grouping)



Halo mass function [Tinker+ 2008; Murray+ 2013]

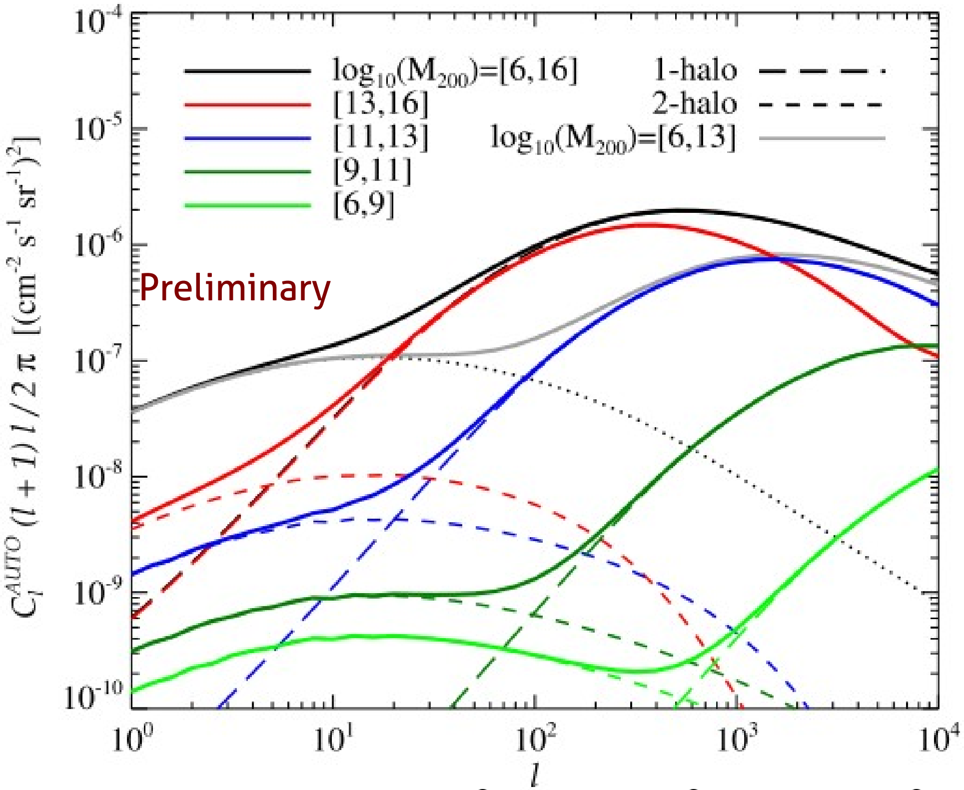
$$P_{\nu_s}^{\rm 2h} = \left[\left(\frac{1}{\Omega_{\rm dm}\rho_{\rm c}}\right) \int dM_{200} \frac{dn}{dM_{200}}\, b(M_{200}, z) \int 4\pi r^2 dr\, \rho_{\rm dm}(r) \frac{\sin(kr)}{kr}\right]^2 \times P_{\rm lin}(k, \chi)$$

DM profiles: NFW with concentration mass relation from [Prada+ 2011]

Contributions from different mass scales

Contributions
- One-halo term dominates (except at the largest scales)
- Most relevant contributions appear at scales 0.1 – 10 deg
- Cluster-sized halos carry most of the information
- Information carried by Galaxy-sized halos is still very significant

Note: Uncertainties (halo model vs. non-linear power spectrum method) are of the order of ~O(2)



10° 1° 0.1°

Dominated by MW
[Ibarra+ 2010]

$$\theta \sim \frac{\pi}{\ell}$$

[See also e.g.: Cuoco+ 2006; Ibarra+ 2010; Fornengo+ 2013, Camera+ 2014]

Cluster calculation

X-ray emission from Galaxy clusters

- From ambient gas, intra-cluster medium (ICM)
- Mostly Bremsstrahlung emission
- Future missions are expected to resolve all Galaxy clusters (eROSITA)

$$I_{\rm cl}(E) = \int_0^\infty d\chi \; W_{\rm cl}([1+z]E, z) \langle \rho_{\rm gas}^2 \rangle$$

$$\langle \rho_{\rm gas}^2 \rangle = \left(\frac{1}{\Omega_{\rm b} \; \rho_{\rm c}} \right)^2 \int dM_{200} \frac{dn}{dM_{200}} \int dV \, \rho_{\rm gas}^2 (r | M_{200})$$

density

ICM temperature and gas density from [Zandanel+ 2014], reproduce X-ray and SZ scaling relations.

ICM

temperature

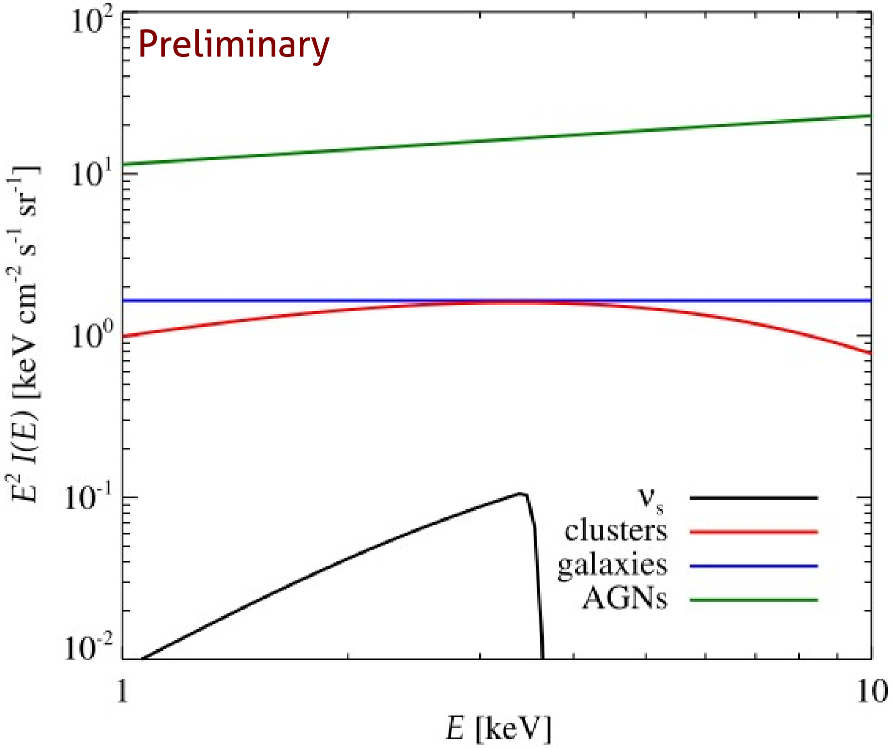
$$W_{\rm cl}(E,z) = \frac{(1+z)^3}{4\pi} (\Omega_b \; \rho_c)^2 \, k_{\rm ff} \; \frac{(k_{\rm B} T_{\rm gas})^{-1/2}}{E} \; \exp\left(\frac{E}{k_{\rm B} T_{\rm gas}} \right)$$

Note: We neglect atomic line transitions in the medium, since we want to explore the power of a mostly *spatial* analysis.

Unresolved point sources

Unresolved point sources as main contributions to the Cosmic X-ray Background (CXB)

- AGNs are believed to provide the dominant contribution to the measured CXB
- We adopt XLF from LADE [Aird+ 2010]
- Galaxies are X-ray sources as they host X-ray binaries. We adopt XLF from [Ptak+ 2007].



In the case of AGNs (similar for galaxies):

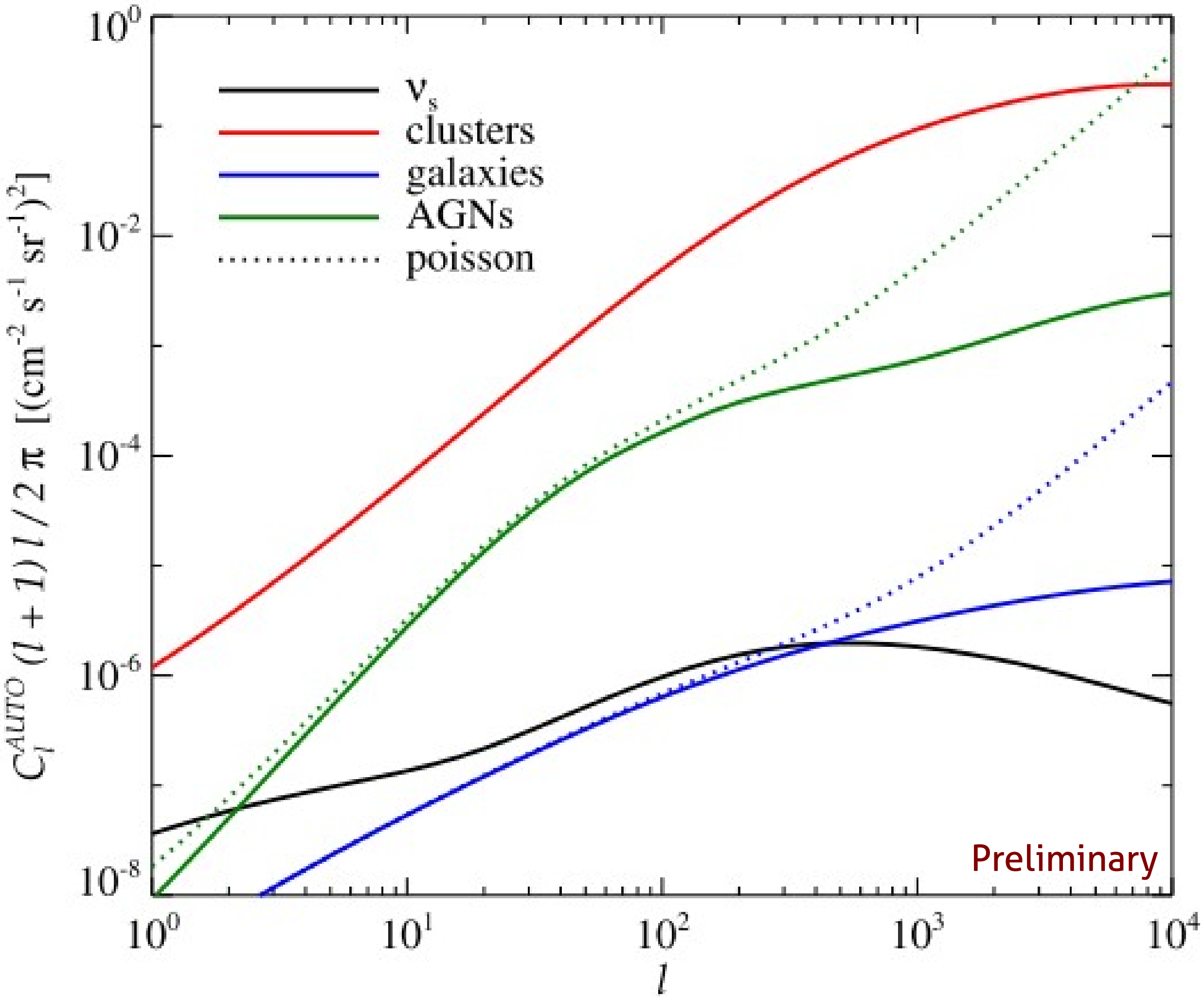
$$I_{\rm AGN}(E) = \int_0^\infty d\chi\; W_{\rm AGN}([1+z]E, z)$$

$$W_{\rm AGN}(E,z) = \frac{1}{4\pi \ln 10} \int_{L_{\rm X,min}}^{L_{\rm X,max}} \frac{dL_{\rm X}}{L_{\rm X}} \Phi_{\rm AGN}(L_{\rm X}, z) \mathcal{L}_{\rm X}(E,z)$$

There is an additional Poisson noise term because of the discreteness of sources:

$$C_{\rm P}^{\rm AGN,gal}(E) = \frac{1}{(4\pi)^2 \ln 10} \int_0^\infty \frac{d\chi}{\chi^2} \int_{L_{\rm X,min}}^{L_{\rm X,max}} \frac{dL_{\rm X}}{L_{\rm X}} \Phi_{\rm AGN,gal}(L_{\rm X}, z) \mathcal{L}_X(E,z)^2$$

Total auto-correlation power spectrum



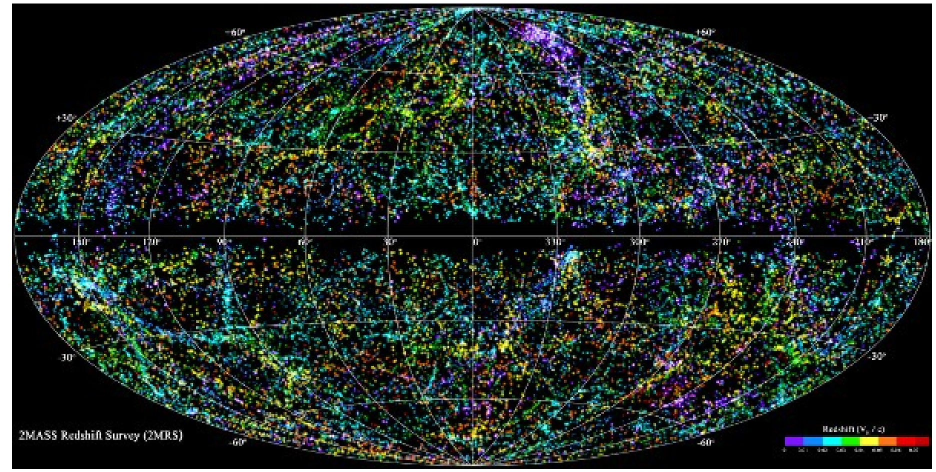
Components in the 3.4 – 3.6 keV energy band

- Clusters vastly dominate the overall auto-correlation.
- As expected, a benchmark dark matter signal contributes with a few orders-of-magnitude below the cluster fluctuation.

Enhancing the DM signal by cross-correlations

Galaxies of the 2MASS redshift survey [Huchra+ 2012] as tracer for DM

$$C_\ell^X = \langle |a_{\ell m}^X a_{\ell m}^{g,*}| \rangle$$

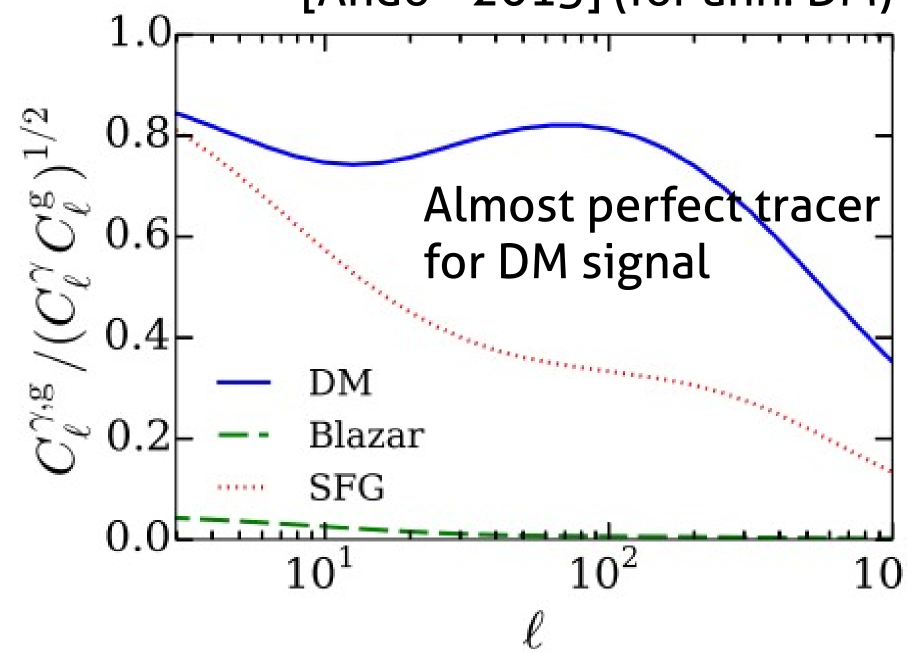


Connection with unbinned likelihood analysis & Fisher information

- Analyzing the cross-correlation angular power spectrum is equivalent, *as long as we have a perfect tracer*
- It turns out that the 2MRS galaxy catalog is a very good tracer already, up to some scales.

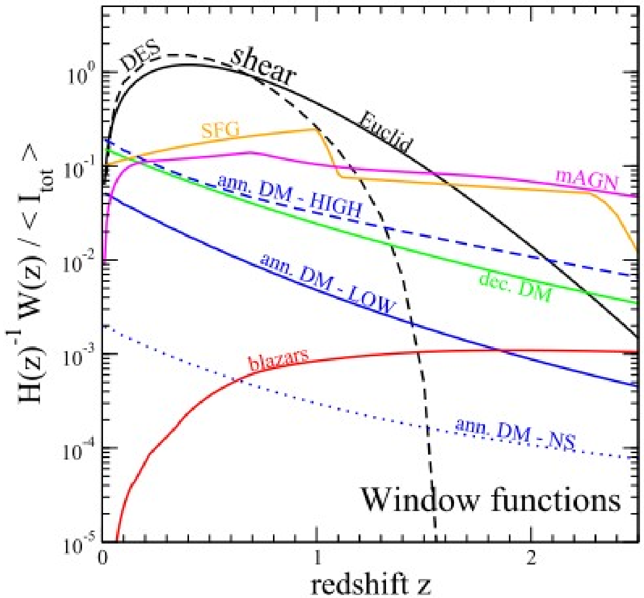
  43500 galaxies, up to z ~ 0.1

[Ando+ 2013] (for ann. DM)



Dark matter signal

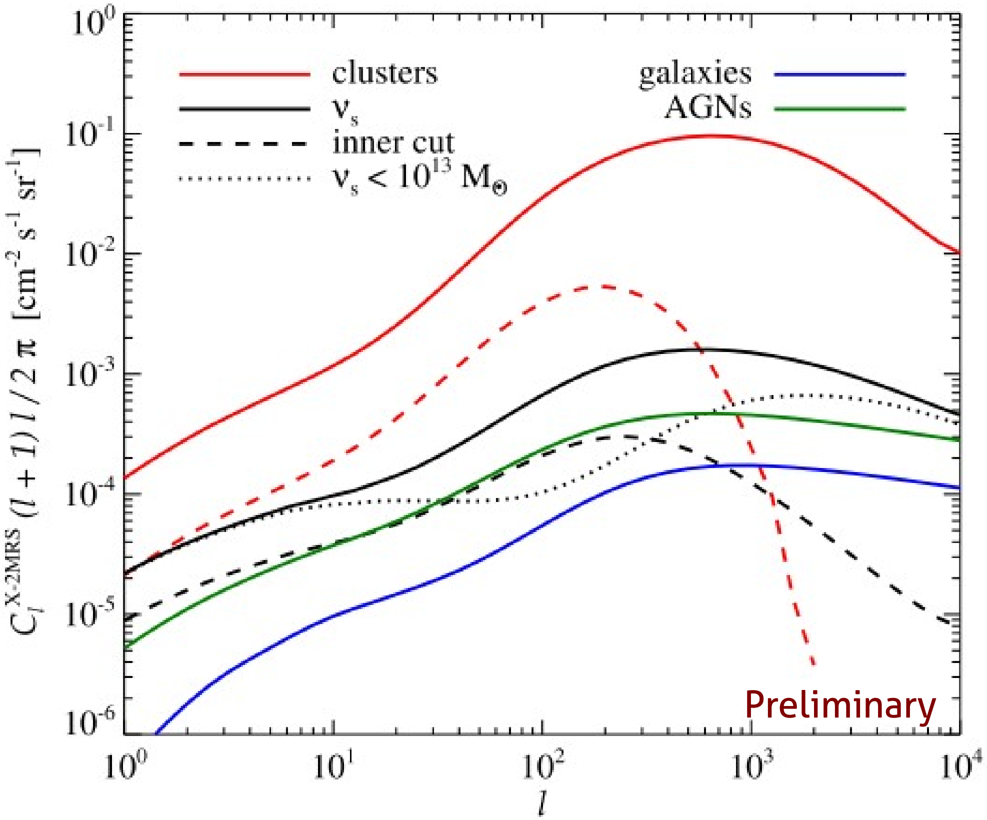
Cross-correlation angular power spectrum depends on
- Window functions
- power spectrum of the two components

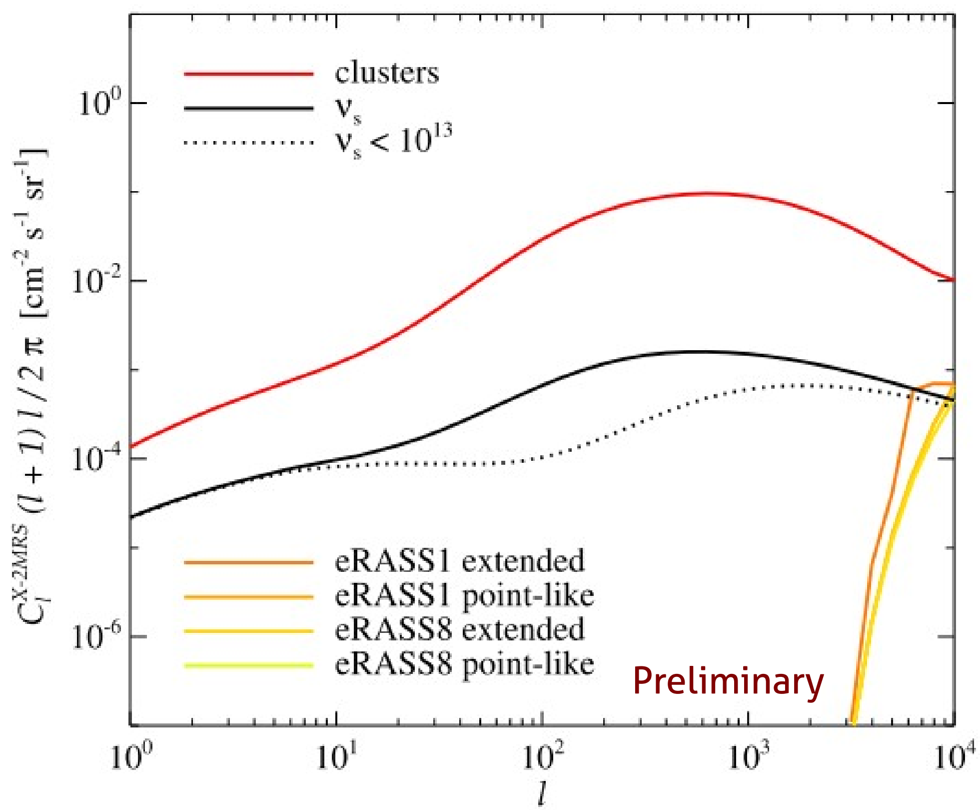


$$C_\ell^{X=A,B}(E) = \int \frac{d\chi}{\chi^2} W_A([1+z]E, z) W_B(\chi) P_{\rm A,B}\left(k = \frac{\ell}{\chi}, \chi\right)$$

$$\begin{aligned} P^{\rm 1h}_{\rm cl,B} &= \left(\frac{1}{\Omega_{\rm b}\rho_{\rm c}}\right)^2 \frac{b_{\rm gal}(z)}{\Omega_{\rm dm}\rho_{\rm c}} \int dM_{200} \frac{dn}{dM_{200}} \times \\ &\times \left[\int 4\pi r^2 dr \rho^2_{\rm gas}(r) \frac{\sin(kr)}{kr}\right] \left[\int 4\pi r^2 dr \rho_{\rm dm}(r) \frac{\sin(kr)}{kr}\right], \\ P^{\rm 2h}_{\rm cl,B} &= \left[\left(\frac{1}{\Omega_{\rm b}\rho_{\rm c}}\right)^2 \int dM_{200} \frac{dn}{dM_{200}} b(M_{200}, z) \int 4\pi r^2 dr \rho^2_{\rm gas}(r) \frac{\sin(kr)}{kr}\right] \times \\ &\times \left[\frac{b_{\rm gal}(z)}{\Omega_{\rm dm}\rho_{\rm c}} \int dM_{200} \frac{dn}{dM_{200}} b(M_{200}, z) \int 4\pi r^2 dr \rho_{\rm dm}(r) \frac{\sin(kr)}{kr}\right] \times P_{\rm lin}(k, \chi) \end{aligned}$$

Cross-correlation signal





Results

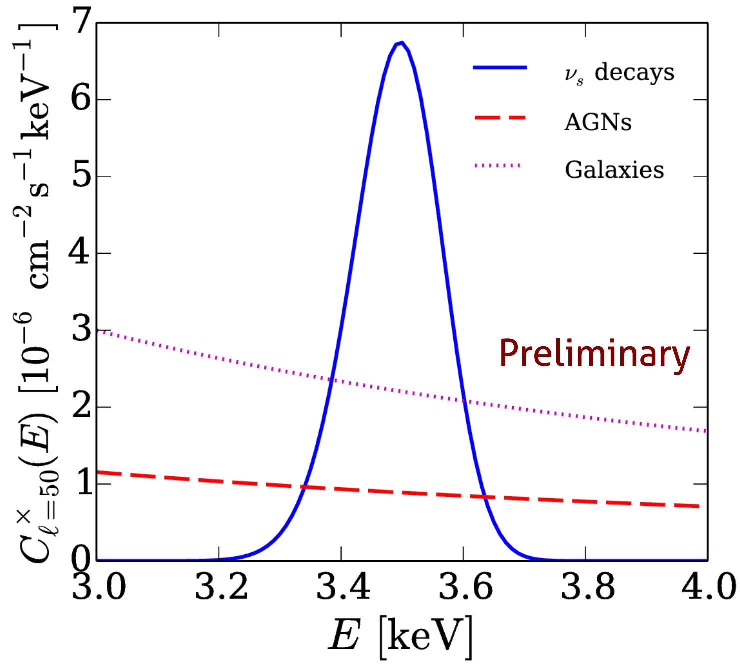
- The DM signal is significantly enhanced w.r.t. AGN and galaxy contributions
- The X-ray cluster emission still dominates
- *However*, even cutting away all clusters does reduce the DM CC power spectrum only by a factor of 2 to 4.

Statistical method

Chi-squared analysis of cross-correlation angular power spectrum:

$$\chi^2 = \sum_\ell \frac{(\bar{C}_\ell^{\gamma,g} - C_\ell^{\gamma,g}(\theta))^2}{(\delta C_\ell^{\gamma,g})^2}$$

Simultaneous fit in three energy ranges:
3.0 – 3.3, 3.4 – 3.6 , 3.7 – 4.0 keV sidebands

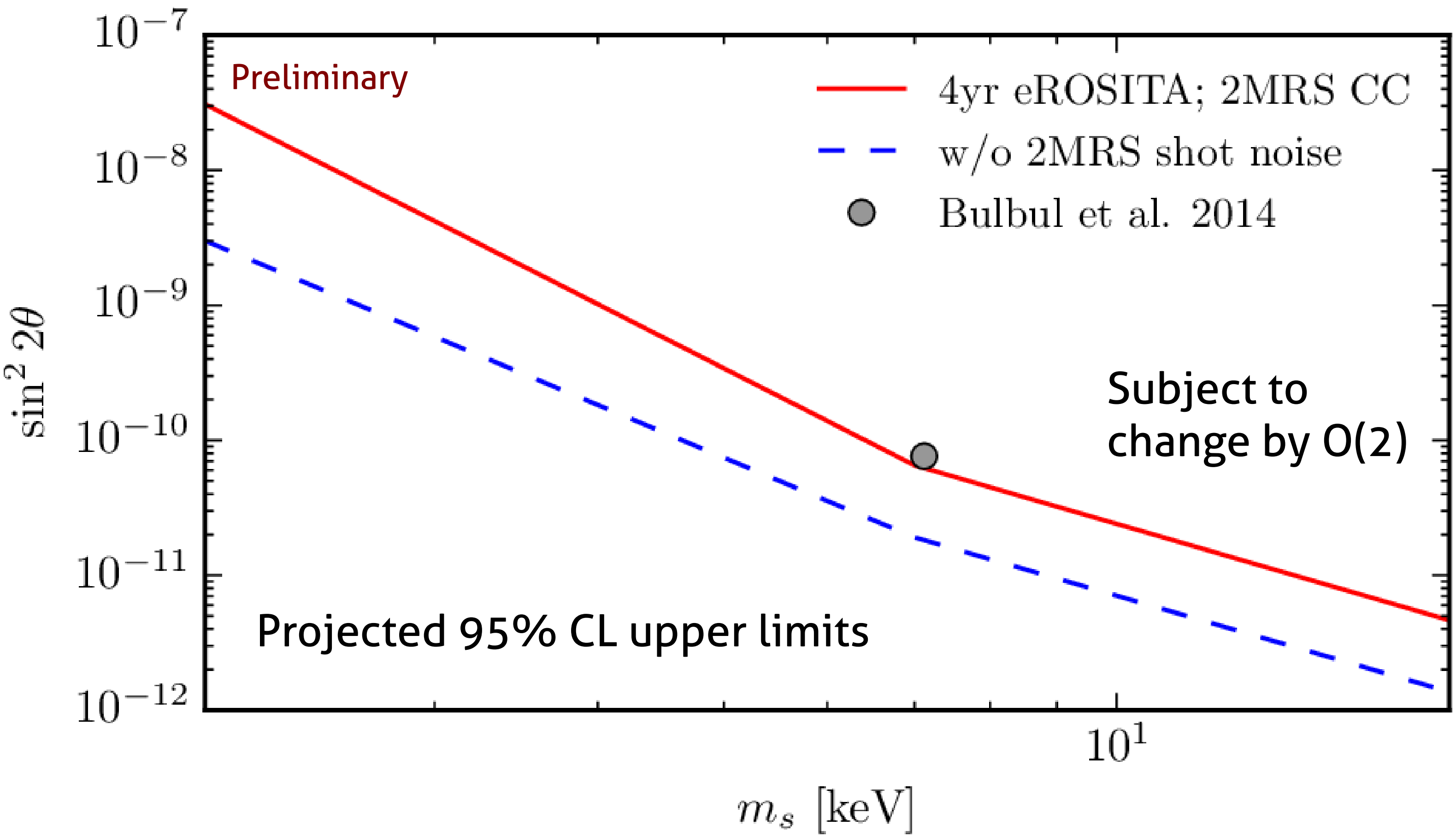


The variance is determined by photon and galaxy catalogue shot noise:

$$\delta C_\ell^{\gamma,\mathrm{g}} = \sqrt{\frac{1}{(2\ell+1)f_{\mathrm{sky}}}}\left[\frac{C_N^\gamma}{W_\ell^2}\cdot C_\ell^{\mathrm{g}} + C_\ell^\gamma \cdot C_N^{\mathrm{g}} + \frac{C_N^\gamma}{W_\ell^2}\cdot C_N^{\mathrm{g}}\right]^{1/2}$$

(NB: The expression used in the recent literature on cross-correlations in e.g. gamma rays has a wrong additional term, that falsely accounts for cosmic variance.)

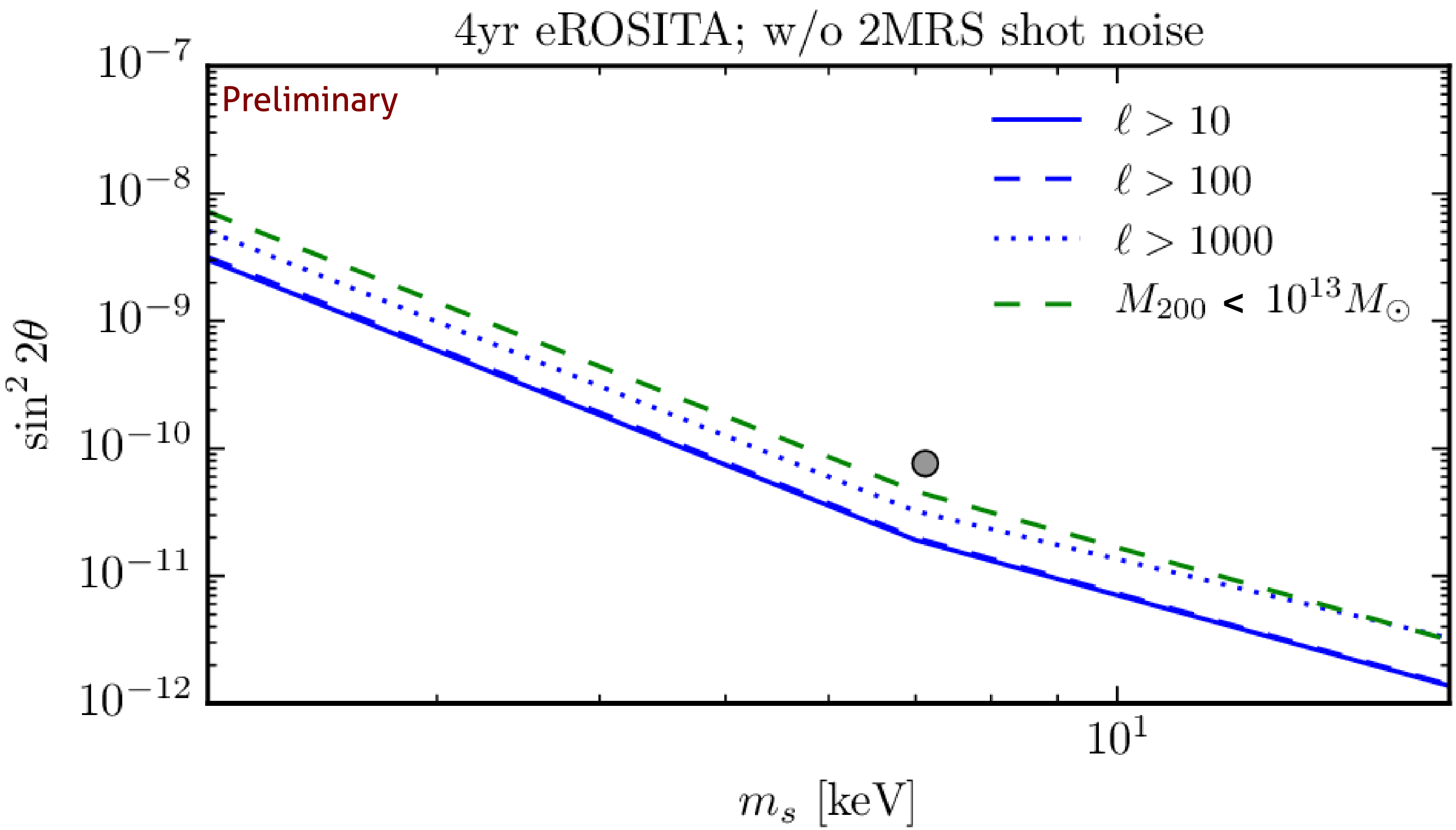
Preliminary Results



Results

- Upper limits that can be obtained by cross-correlating eROSITA with 2MRS catalog barely touch the benchmark point
- The limiting factor is not the number of X-ray photons, but the shot noise from the 2MRS
- In an optimal situation, limits & sensitivity could be stronger by a factor of 5.
  → Enough to confirm putative X-ray line

Preliminary Results



Results

- Limits come mostly from angular scales below theta ~ pi/100
- Masking out all halos with masses above 1e13 Msol decreases sensitivity by factor of two

Conclusions

- The angular power spectrum of the sterile neutrino signal indicates that structures at the O(deg), corresponding to nearby Galaxy clusters, are the most relevant targets in the extragalactic sky.
- A cross-correlation of the angular power spectrum of full-sky X-ray surveys with tracers of the dark matter distribution can significantly enhance the contrast with respect to the most relevant backgrounds.
- Even after cross-correlation, the thermal emission from Galaxy clusters provides the dominant background to DM searches with sterile neutrinos.
- Using a sideband analysis, projected limits for 4 years of eROSITA observations just touch the putative 3.5 keV line
- The limiting factor is however the shot noise of the tracer, not the data → Lots of room for improvement until eROSITA data becomes availabe.

Thank you!