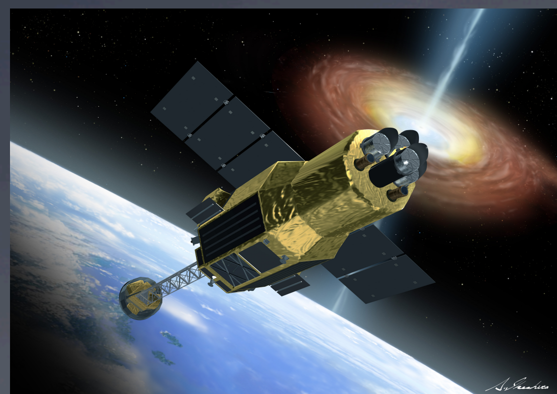
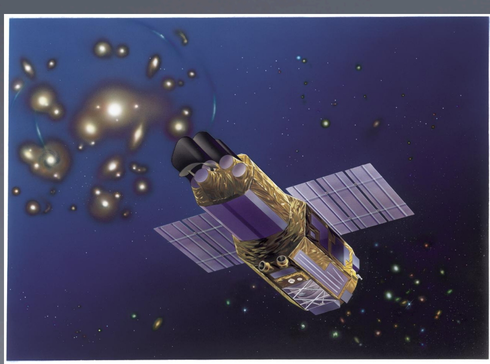
Possible X-ray Detection of Sterile Neutrino Dark Matter

Michael Loewenstein (Univ. of Maryland/CRESST/NASA-GSFC; *Astro-H* SCT/SWG)





Suzaku

Chandra

XMM-Newton

ADAP

Search for Light Dark Matter with X-rays: Status

Search: Background, Motivation, Targets
[w/ Alexander Kusenko (UCLA/IPMU), Tsutomu Yanagida (IPMU)...]

"Detection of an unidentified emission line in the stacked X-ray spectrum of galaxy clusters" (ApJ, 789, 13)
[E. Bulbul (Harvard/CFA) , M. Markevitch (NASA/GSFC),
A. Foster (CFA), R. Smith (CFA), M. Loewenstein, S. Randall (CFA)]

Observational Response: Confirmations, Refutations, Refutations of Confirmations, Refutations of Refutations...

Theoretical Response: Sterile Neutrinos and other interpretations

Concluding Remarks: Where we are, where we go from here [*Astro-H* Instrument, and Software & Calibration Teams, *A-H* SWG]

1) Candidates and their Signatures

Motivation for considering light dark matter

- No Standard Model particle can be the dark matter.

- There is no definitive CDM/WIMP detection.

- Light dark matter may behave as WDM; WDM may be in better accord with structure on <<Mpc scales ("too big to fail" satellite, core-cusp, void... problems).

- There are well-motivated alternative candidates (e.g., **sterile neutrinos**) that emit X-ray radiative decay lines that are *potentially detectable* using current X-ray observatories (i.e. without a dedicated experiment).

1) Candidates and their Signatures

General considerations for decaying light dark matter

- No *a priori* preferred m_{DM} ⟹ E_γ ($E_\gamma = m_{DM}c^2/2$) (decay line energy) unknown.
- Emission line width ~ σ_{DM}; Line intensity ~ Σ_{DM}.
- For Σ_{DM}~300-500 $M_\odot/pc^2$, detectability by current X-ray observatories requires $10^{-28}\ s^{-1} < \Gamma_{decay} < 1/t_{hubble}$.

1) Candidates and their Signatures

Focus on NRP Sterile Neutrino Light DM

- Standard Model Extensions that explain nonzero neutrino mass often include right-handed ***(sterile)*** neutrinos.

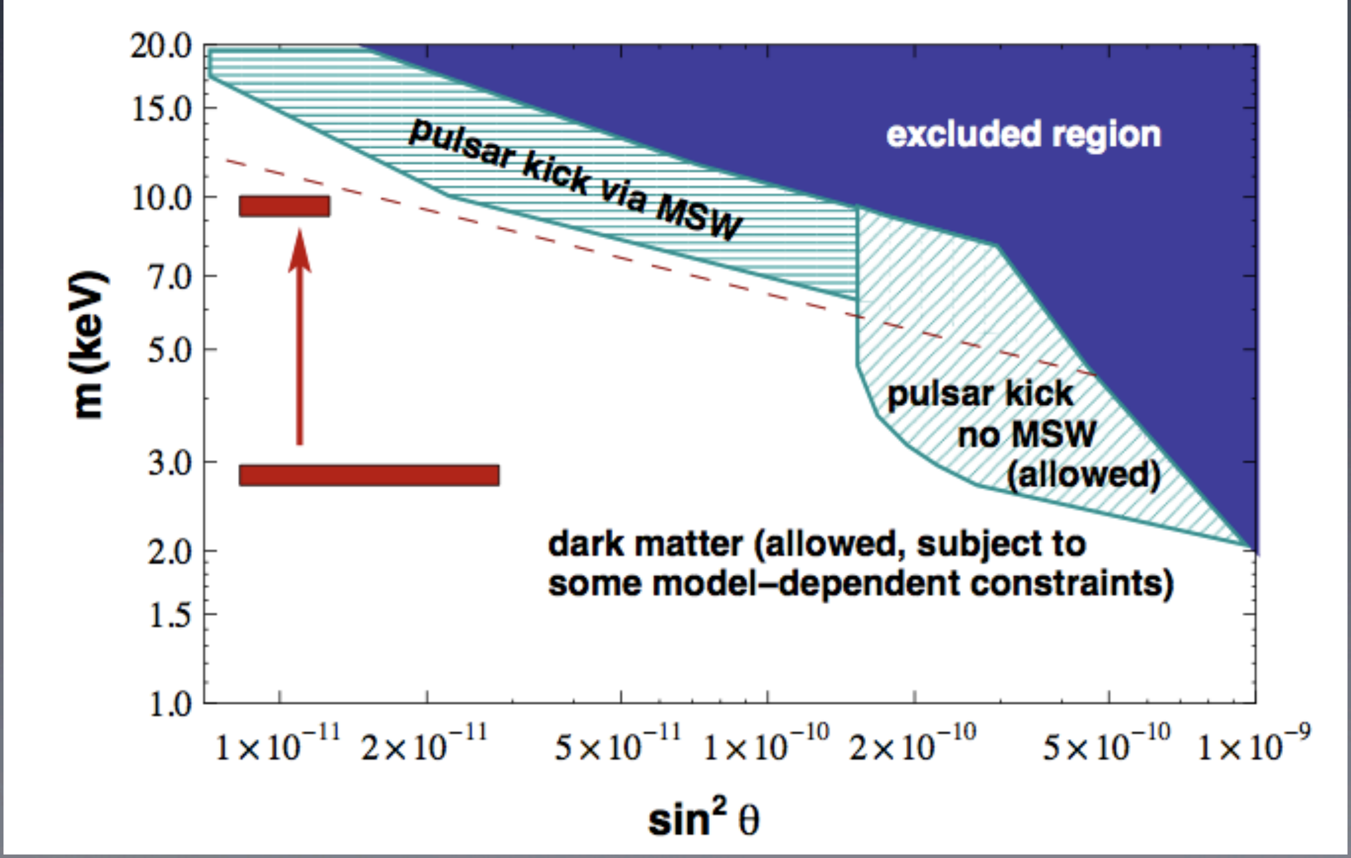
- These are produced via non-resonant oscillations ("DW") at rate $\Gamma_{st\text{-}\nu,DW} \sim 10^{-29} f_{dm/st\text{-}\nu}(m_{ster\text{-}\nu}/keV)^{3.4}\ s^{-1}$.

- WDM: $m_{thermal} \sim 0.33\ keV(m_{ster\text{-}\nu}/keV)^{3.4}\ s^{-1}$.

Dodelson & Widrow (1994), Kusenko (2009), Kusenko, Takahashi, and Yanagida (2010), Boyarsky, Iakubovskyi, and Ruchayskiy (2012)...

1) Candidates and their Signatures

Focus on NRP Sterile Neutrino Light DM



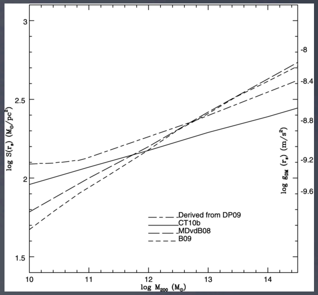
can account for DM, and explain pulsar kicks for $m_{ster\text{-}\nu} \sim 1 - 20$ keV, $\theta_{mix} \sim 10^{-4} - 10^{-5}$

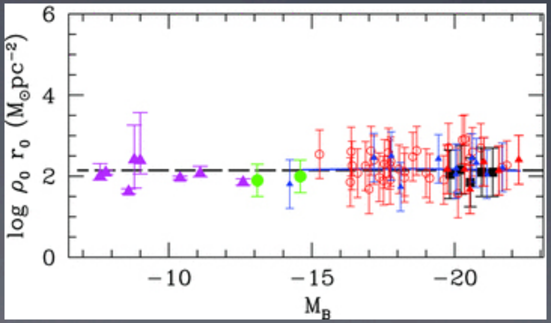
2) Prospective Targets

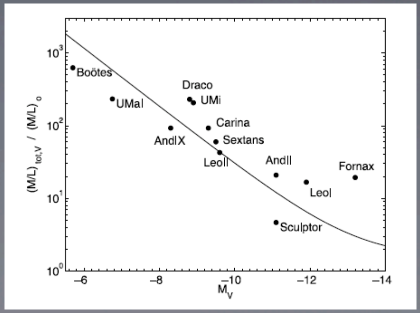
(1) maximize dark matter surface density

(2) minimize competing intrinsic sources of X-rays.

targets	on one hand…	on the other…
galaxy clusters	photons! DM profile	ICM
galaxies	abundance	intrinsic sources mass decomposition
MW and M31	proximity	absorption mass decomposition
dwarf spheroidals	proximity no intrinsic sources	DM profile/extent?







dSphs (Gillmore et al.);
Galaxies (Salucci et al.);
Clusters (Popolo et al.)

3) Current X-ray Searches

$$S/N = I_{line}(\Omega A_{det} T_{obs}/2I_{back}\Delta E)^{1/2}(1+I_{line}/2I_{back}\Delta E)^{-1/2}$$

$$I_{line} \sim \langle \Sigma_{DM} \rangle_{\Omega}$$

(T. Tamura)

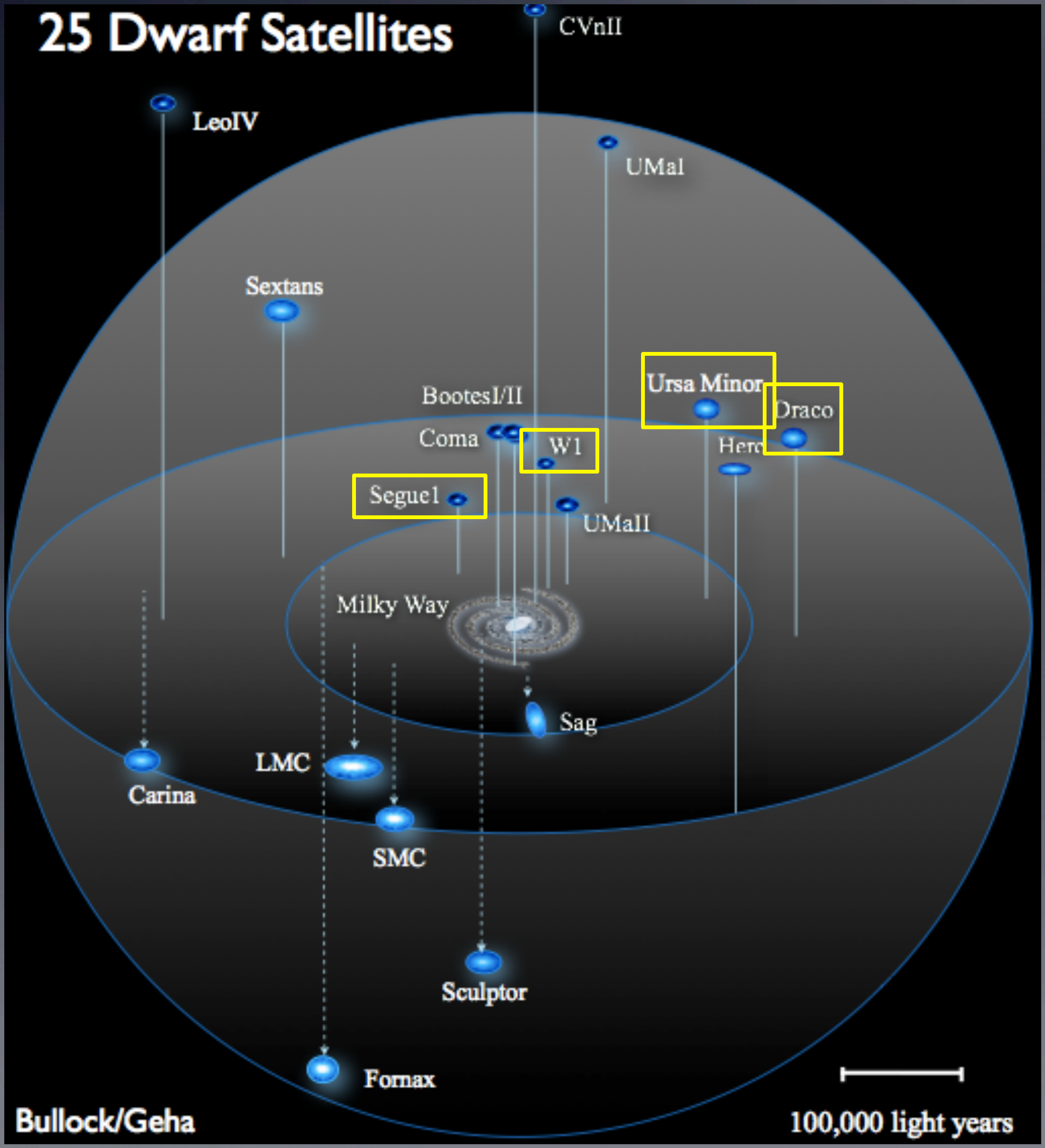
	Chandra (I-array)	XMM-Newton	Suzaku
field of view	17' X 17'	30' X 30'	18' X 18'
angular resolution	**1''**	6''	90''
energy resolution	~50	~50	~50*
bandpass	0.4 – 8 keV	0.2 – 12 keV	0.3 – 12 keV
effective area	400 cm²	**1200 + 2 X 900 cm²**	400 X 3 cm²
NXB rate	~0.01 cts/sec/□' *	~0.01 cts/sec/□'	**~0.001 cts/sec/□'**

Chandra for compact dSphs, galaxies

Suzaku for dSphs, clusters

XMM-Newton for dSphs, clusters

Dedicated Indirect DM X-ray Search Using dSphs



Clean signal

Little or no (ultra-faints) reason, otherwise, to observe these…

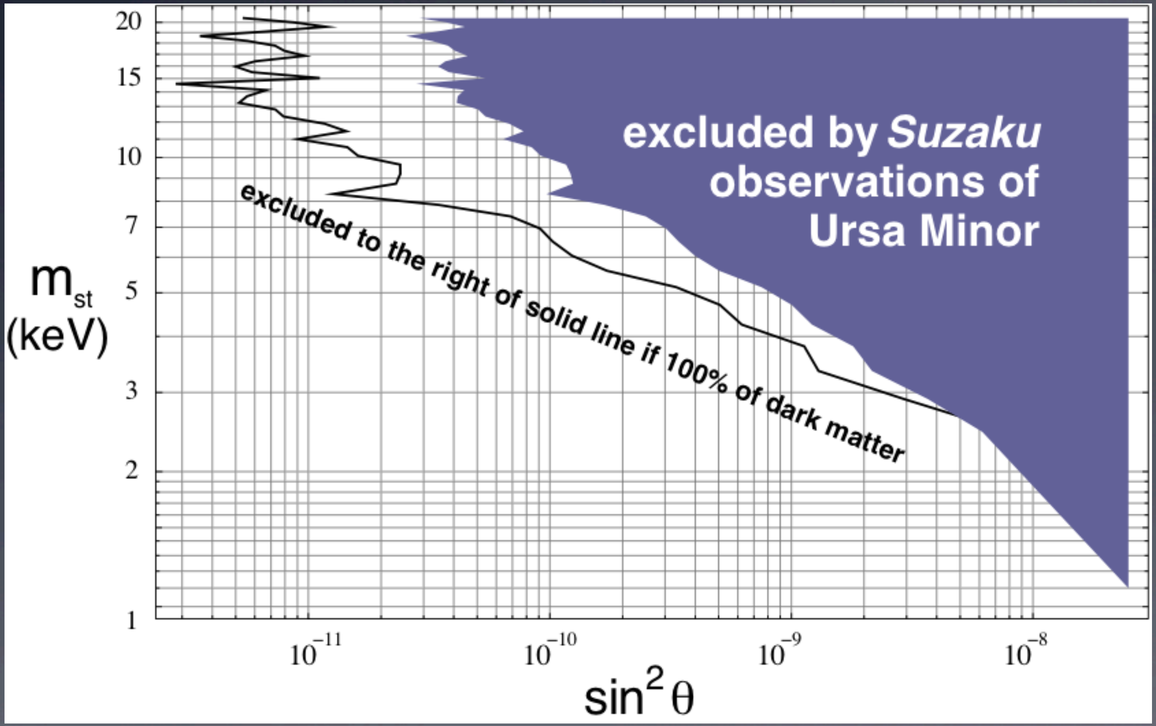
Utilize the full "fleet" --

XMM-Newton: Will-1

Chandra: Will-1

Suzaku: Dra, UMi, Seg-1

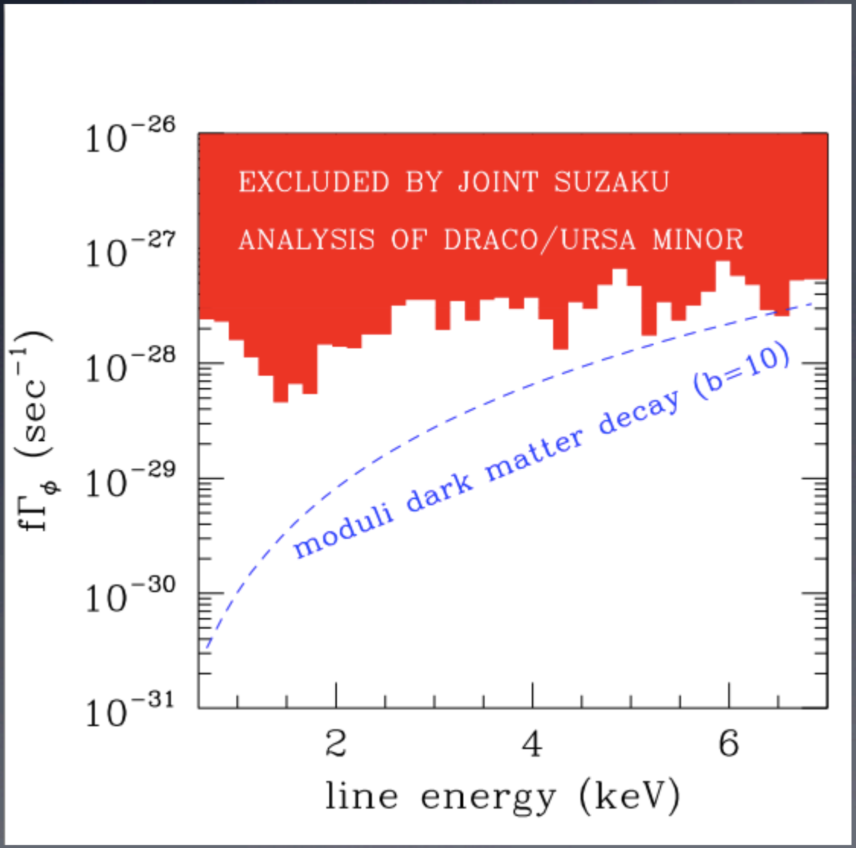
Suzaku Constraints on Sterile Neutrinos…

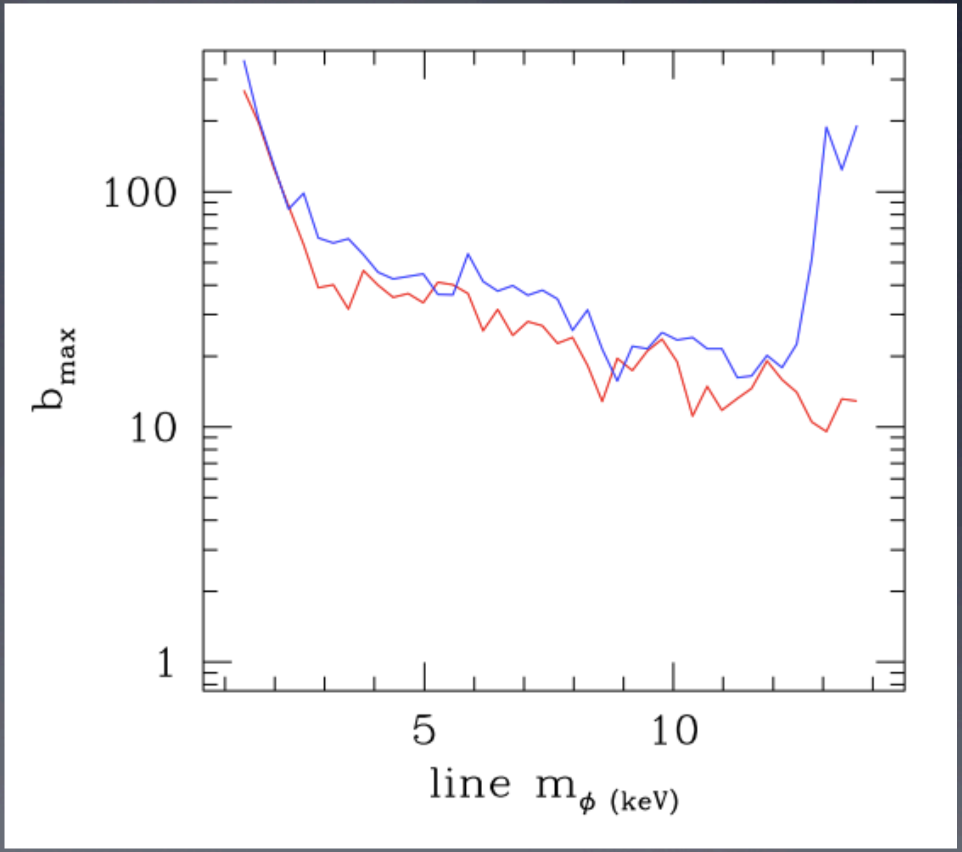


Draco, Will-1, Seg-1 (ML/AK in prep) similar

The region to the right of the solid curve is excluded if 100% of DM is sterile neutrinos; in the solid exclusion region the minimum abundance produced by oscillations overproduce the X-ray emission (LKB 2009). Allowed regions expand for L>0 (f_{st}=1), or subdominant.

Constraints on Moduli DM





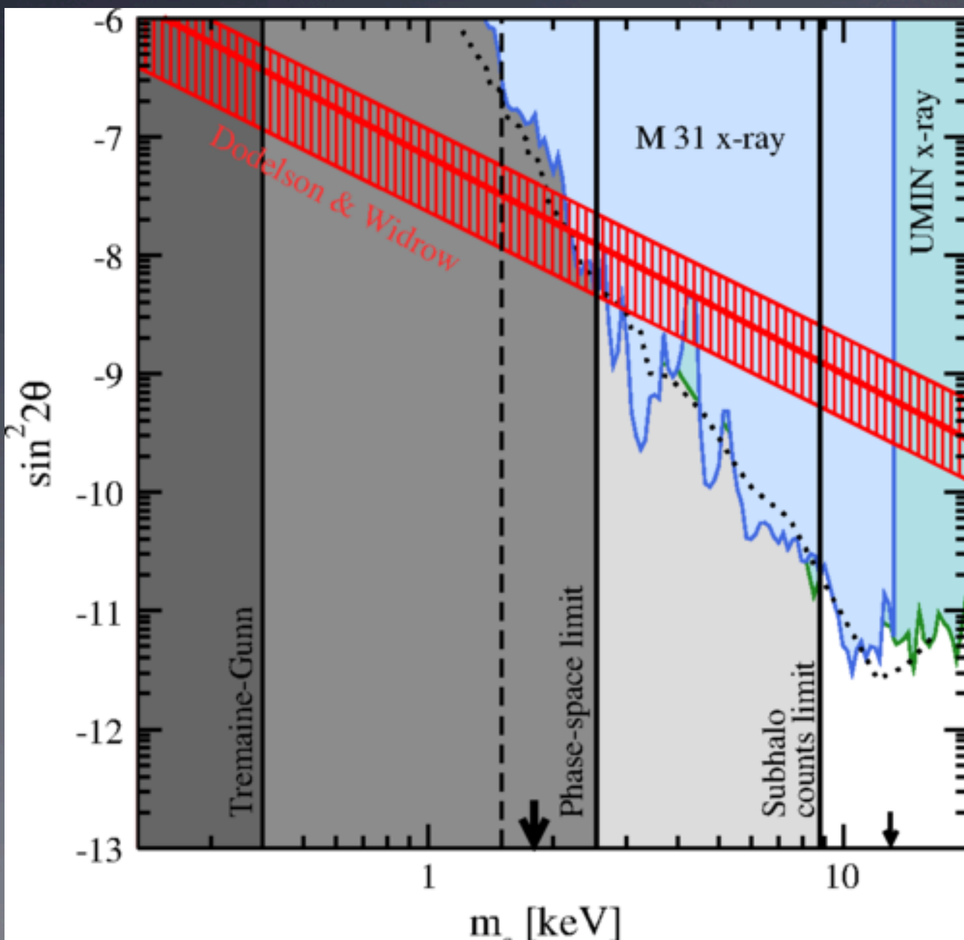
$$\Gamma_{\phi\to\gamma\gamma} = b^2 \frac{m_\phi^3}{64\pi M_G^2}.$$

$$b \equiv M_G/\Lambda_{eff}.$$

Ursa Minor and Draco
Kusenko, Loewenstein, and Yanagida 2013

Ruling Out Sterile Neutrinos Produced by DW

M31 *Chandra Redux* (plus MW dwSph phase space, M31 subhalo counts) [Horiuchi et al. 2014]



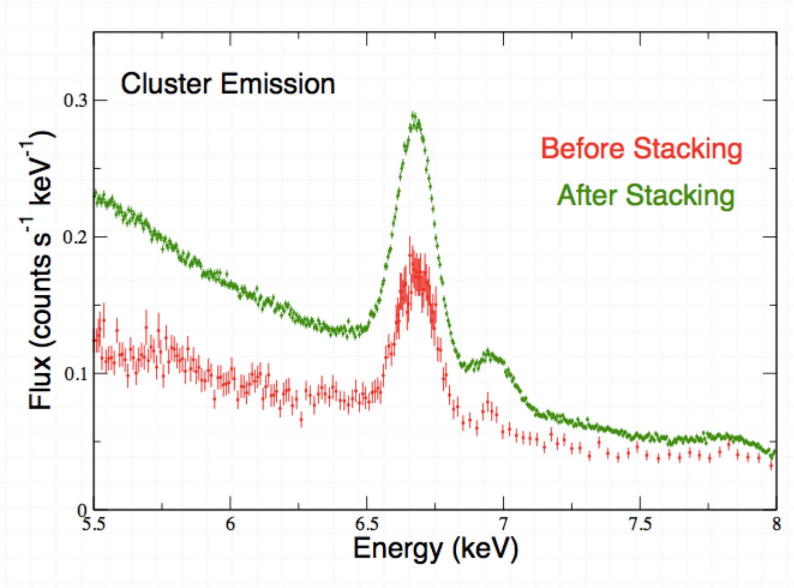
Not the end of the story:

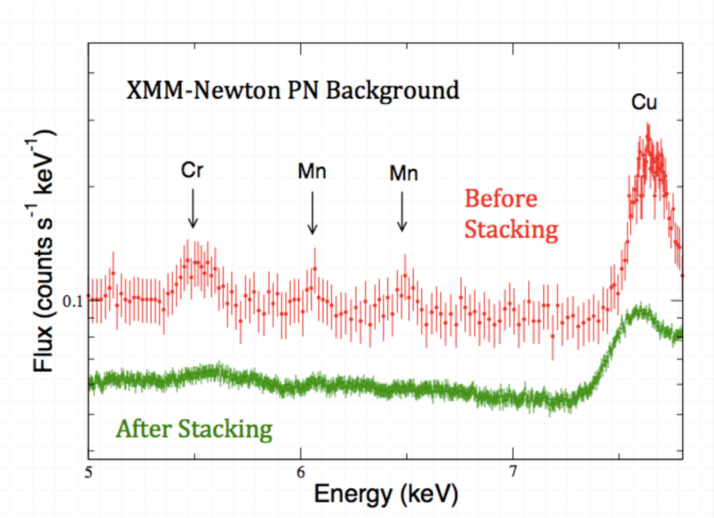
- Other ways of making sterile neutrinos
- Other X-ray-line emitting DM candidates

Doing Better *(w/ existing data)*:
Galaxy Cluster Stacking

E. Bulbul, **M. Markevitch,** A. Foster, R. K. Smith, ML, S. Randall

- Stacking (Abazajian et al. 2001) increases the S/N.
- Because the clusters are at a range of redshifts, instrumental features (but not the putative signal!) are smoothed out.

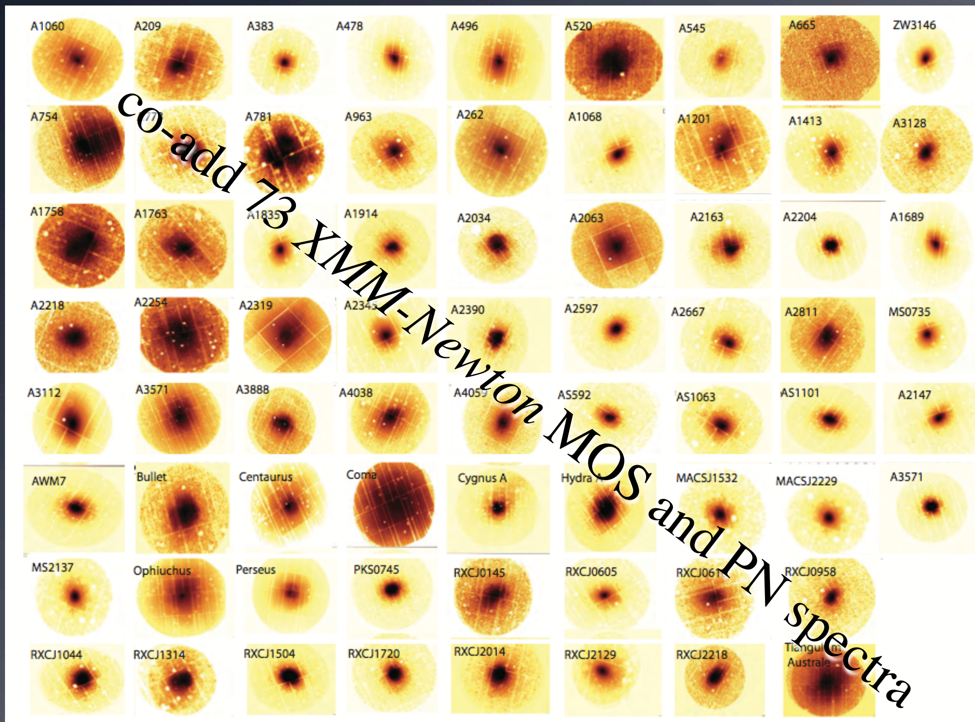




MOS and PN are two different CCD detectors on XMM-Newton

ApJ, 789, 13

Galaxy Cluster Stacking: The Sample

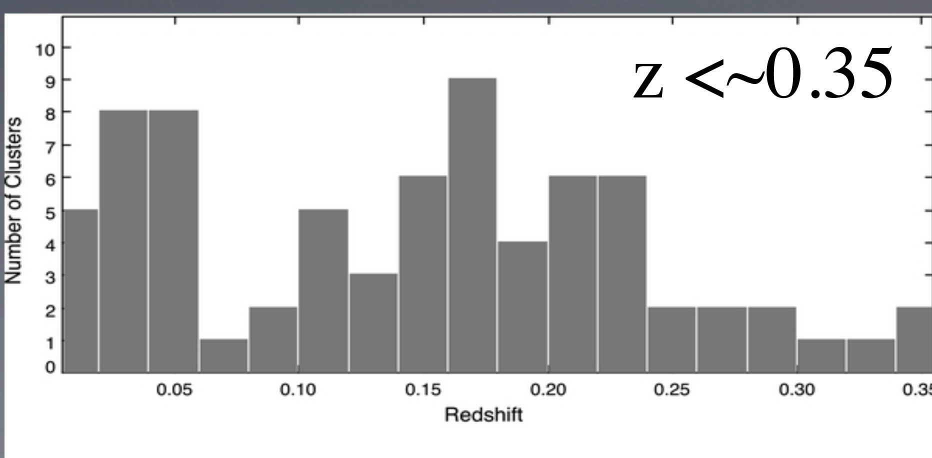


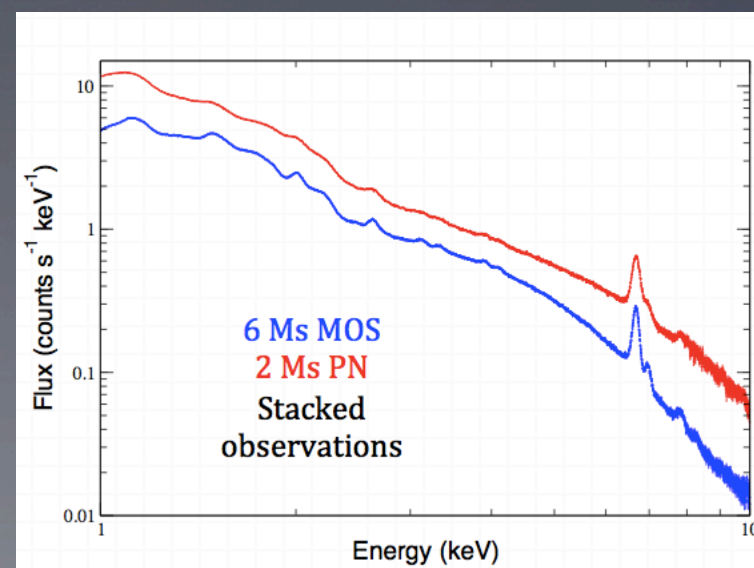
$M \sim 10^{14}$–$10^{15}\ M_\odot$ (well-determined)

kT~3-10 keV

fgas~0.13, Fe~0.3 solar

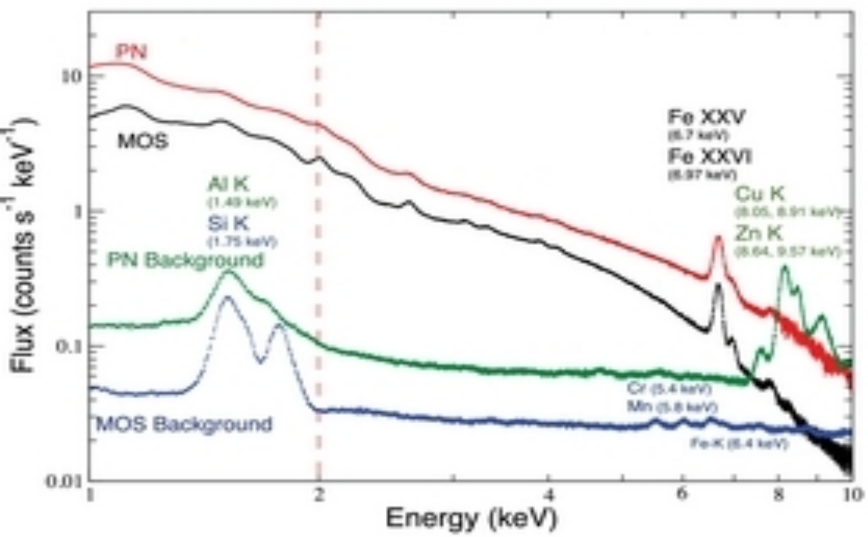
lots of emission lines!

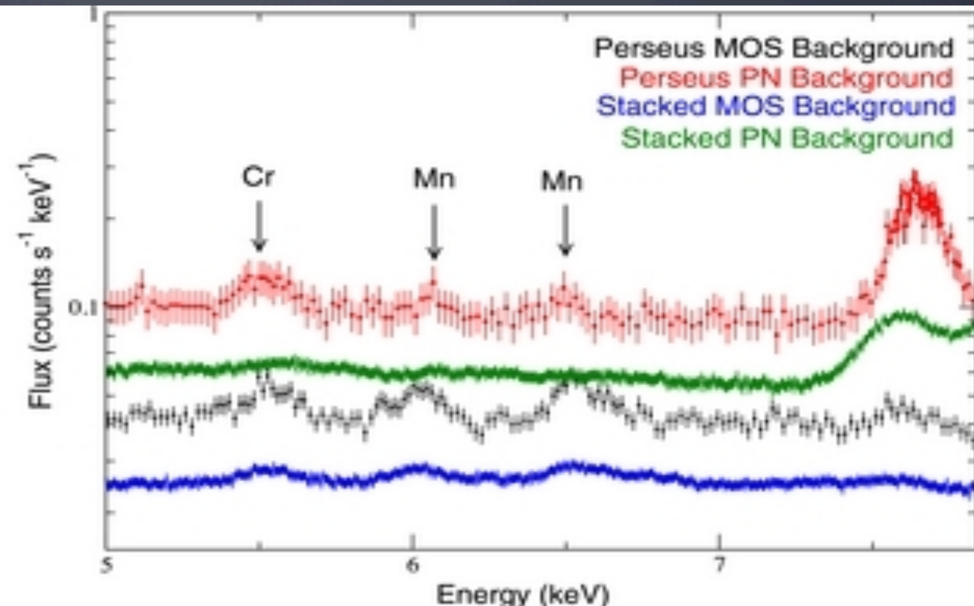




Basic Analysis Steps:

(1) Construct the de-redshifted stacked spectra, the weighted response, and the summed (smoothed) particle background.
(2) Subtract the summed particle background.





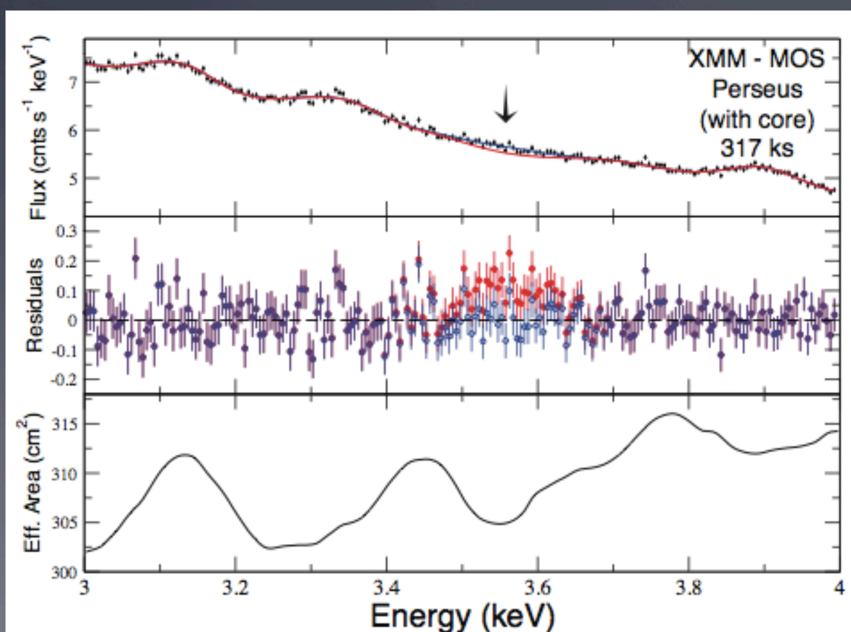
MOS: 6 Msec, 8.6 Mcts; PN: 2 Msec; 5.1 Mcts

Unmatched High S/N

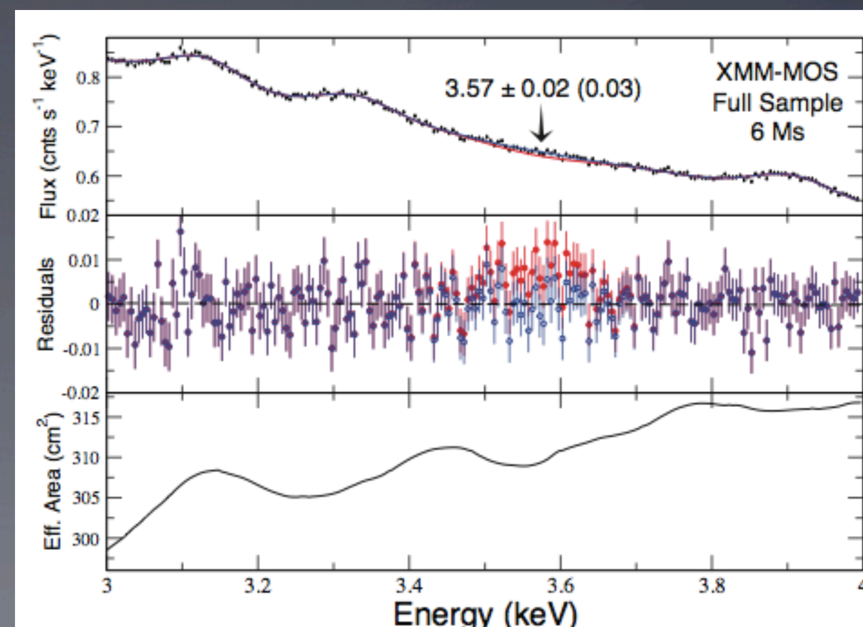
Smeared Instrumental Bkg

(3) Fit the stacked spectra of the entire sample (and various subsets) to a – (multi-temperature) thermal plasma *continuum* plus known emission *lines* with unconstrained fluxes.

Note the smoothing out of the effective area curve...

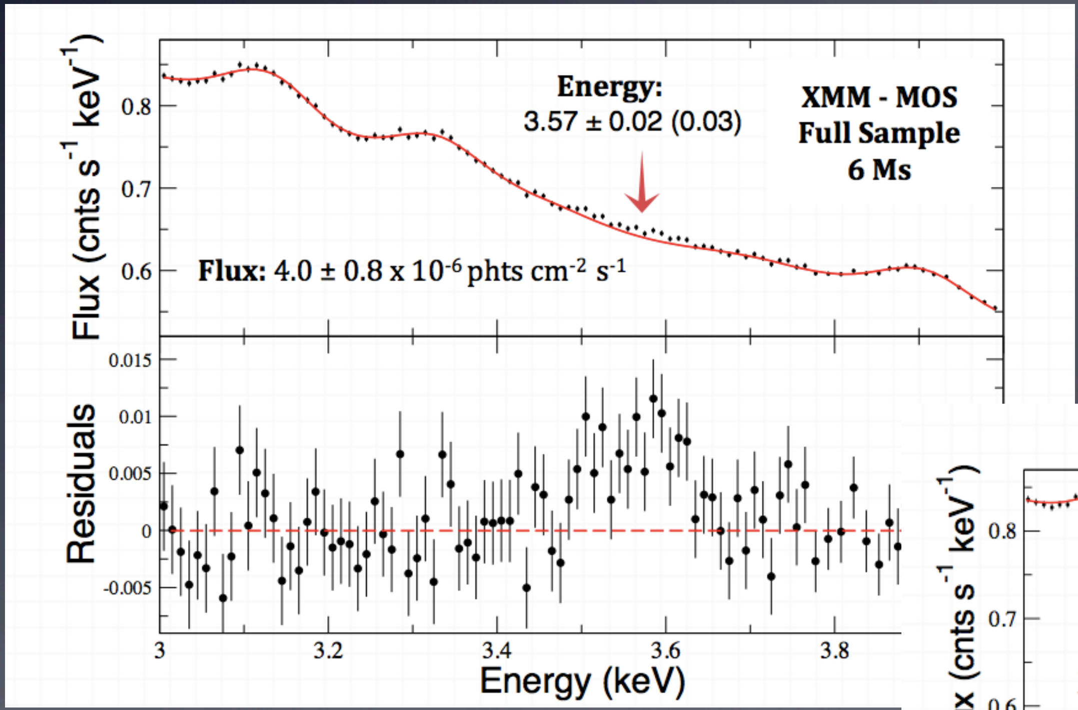


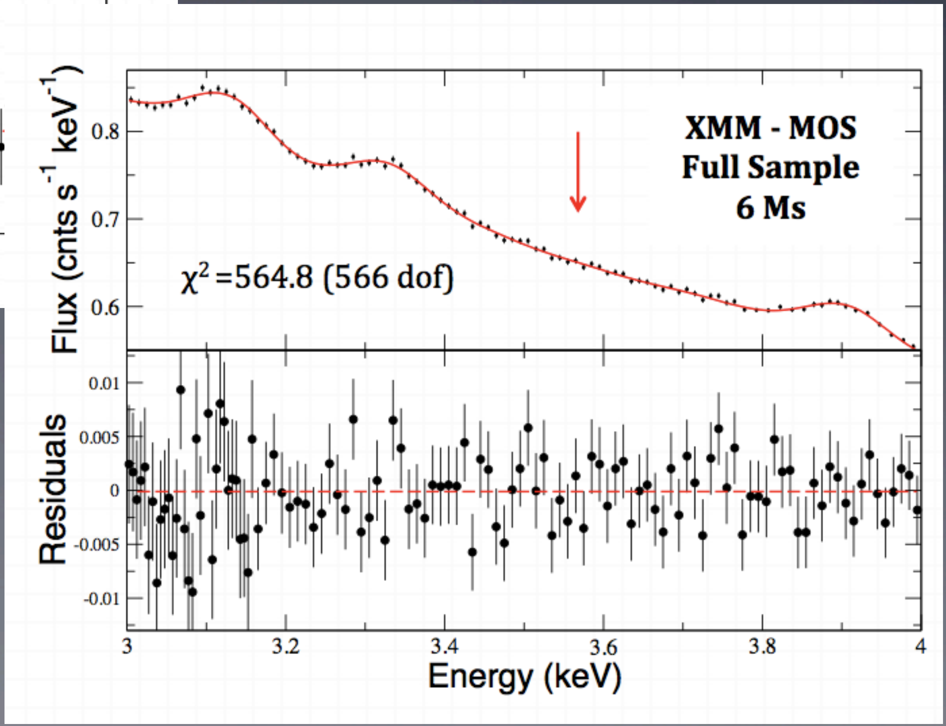
single cluster spectrum



stacked cluster spectrum

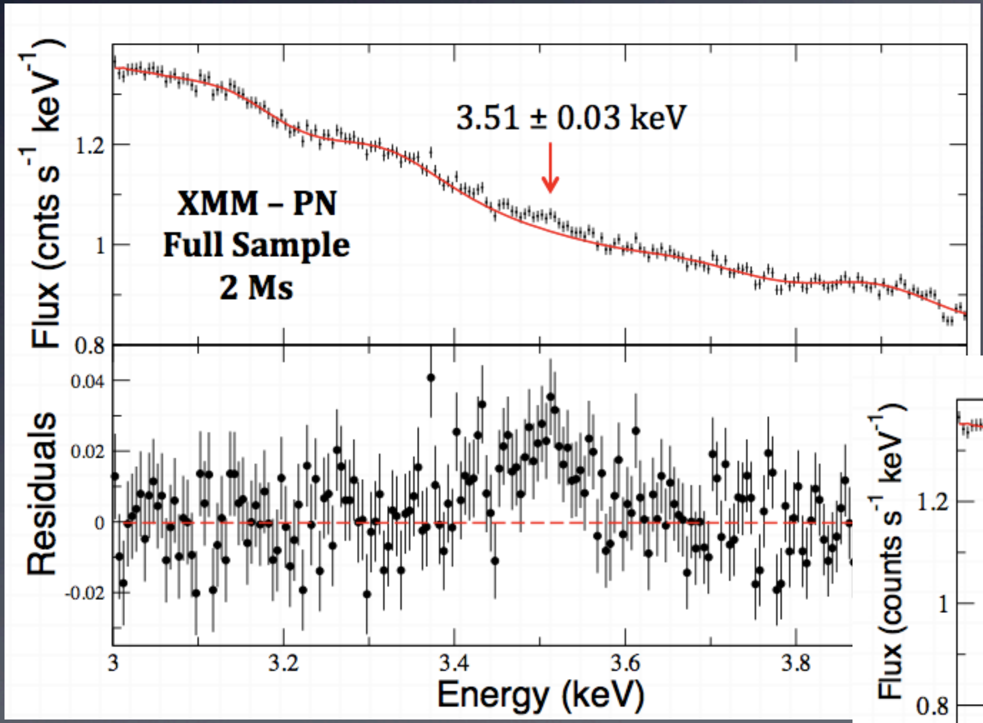
(4) Search for "extra" features in 2-10 keV band (<2 keV too crowded).

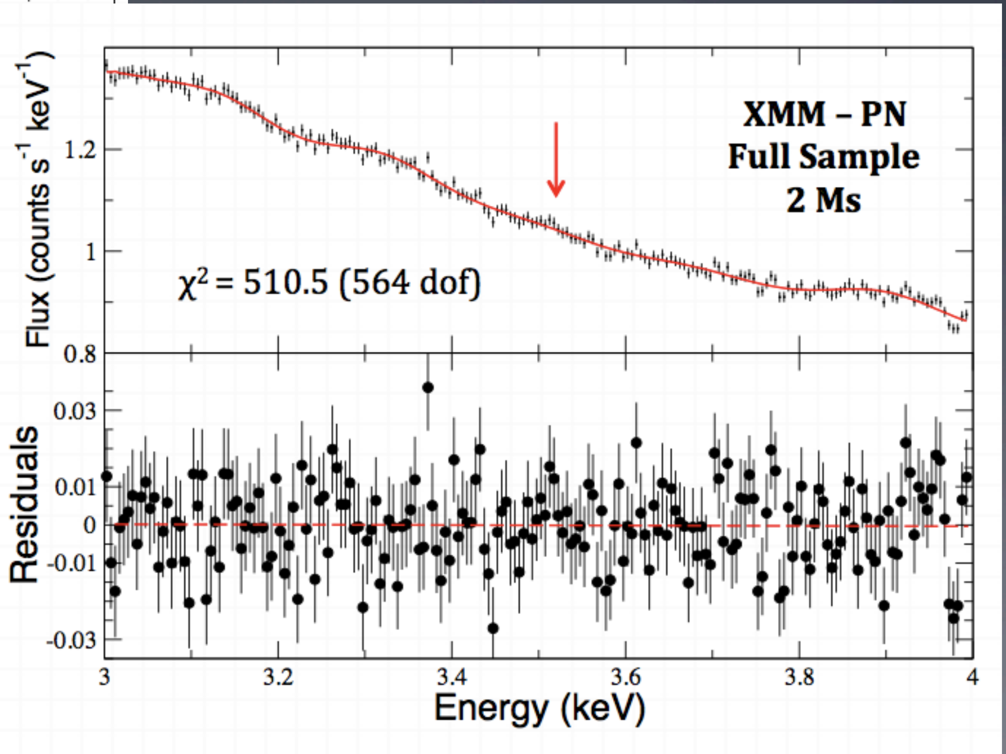




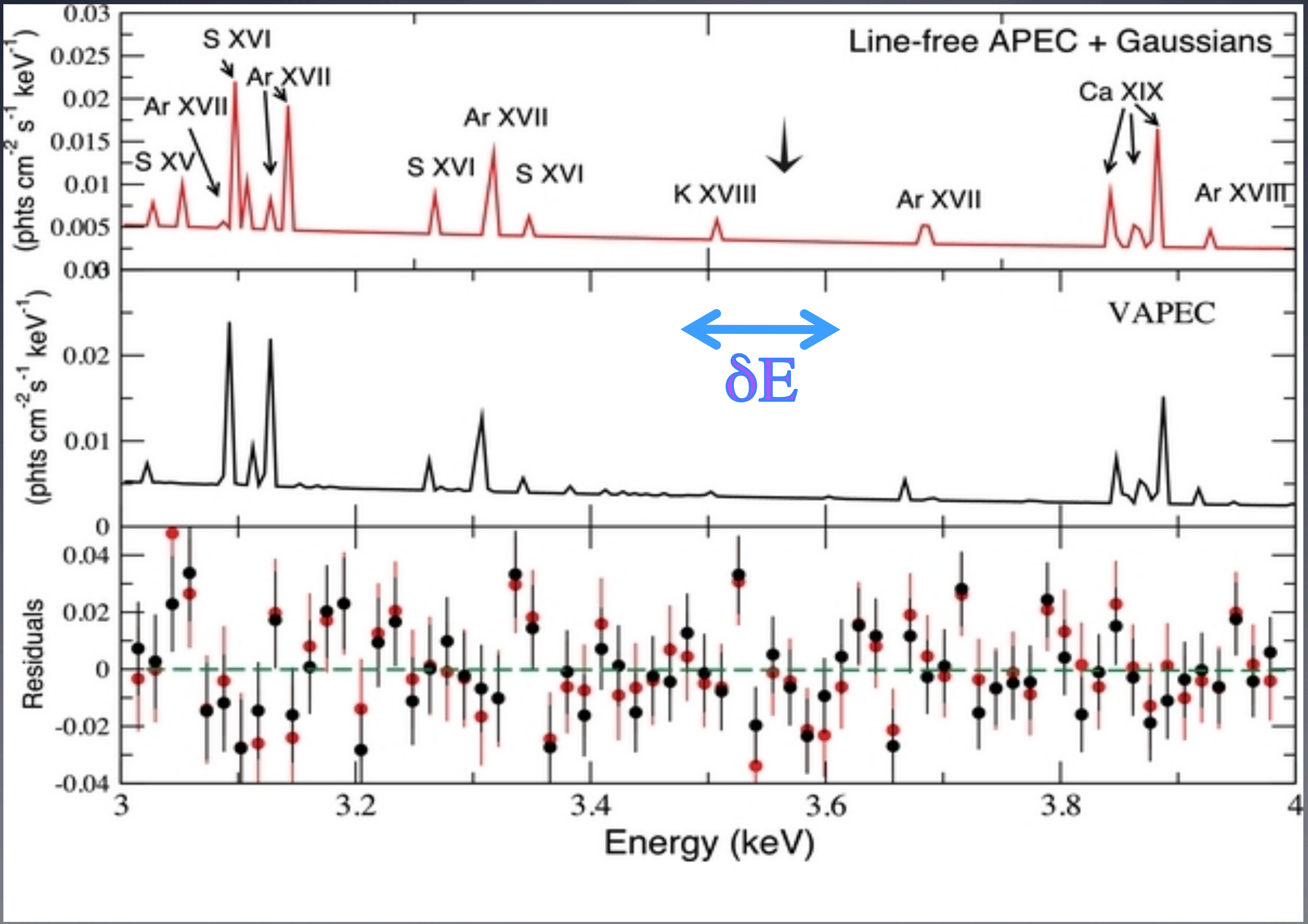
Detection of unidentified emission line at ~3.57 keV at ~5σ

... also seen in PN with consistent flux, slightly discrepant (2.5σ) energy):



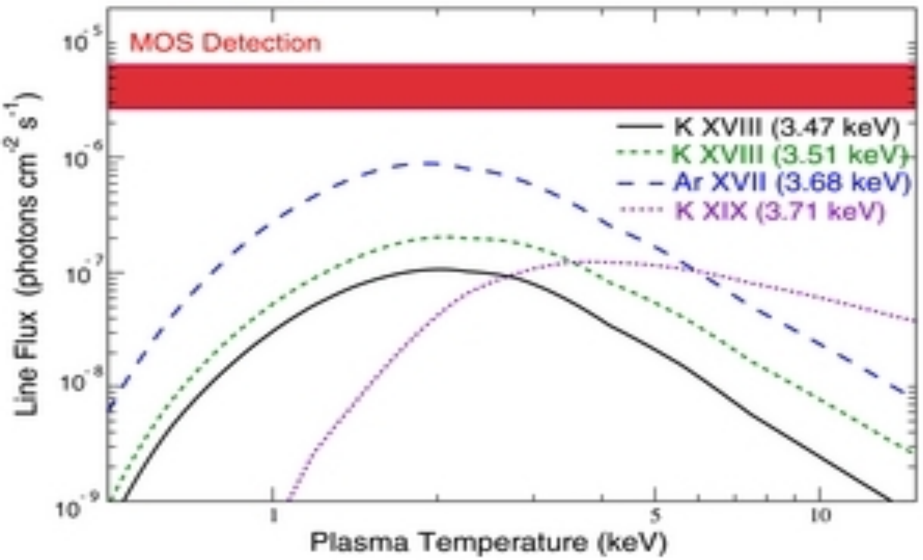


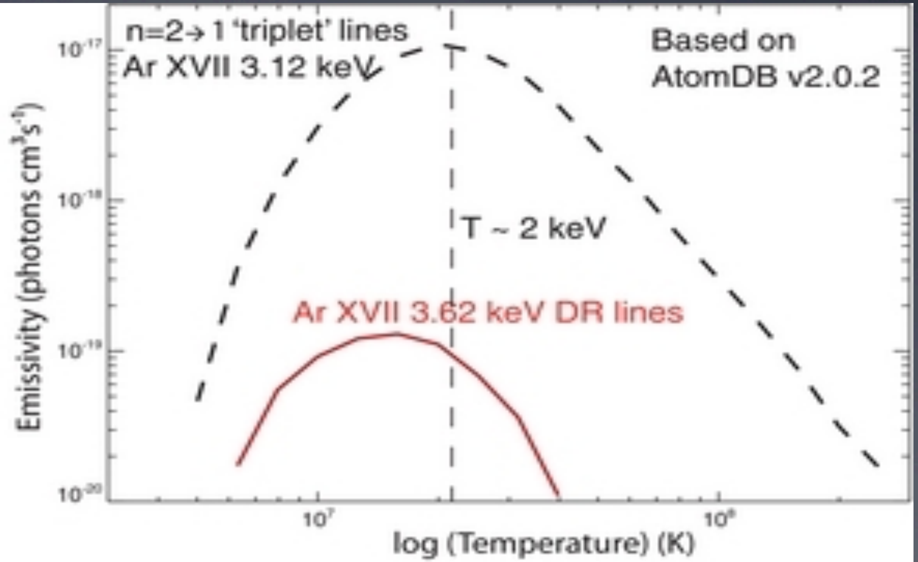
- Many lines in a single kT ~ 3-10 keV thermal plasma.
- Many kT's (ionization states) in the stacked spectrum.



Final energies and fluxes are derived using 3-6 keV band

- with a *weighting appropriate for dark matter decay*,
- allowing the strengths of atomic features in this band to vary over a ***conservatively*** large range.





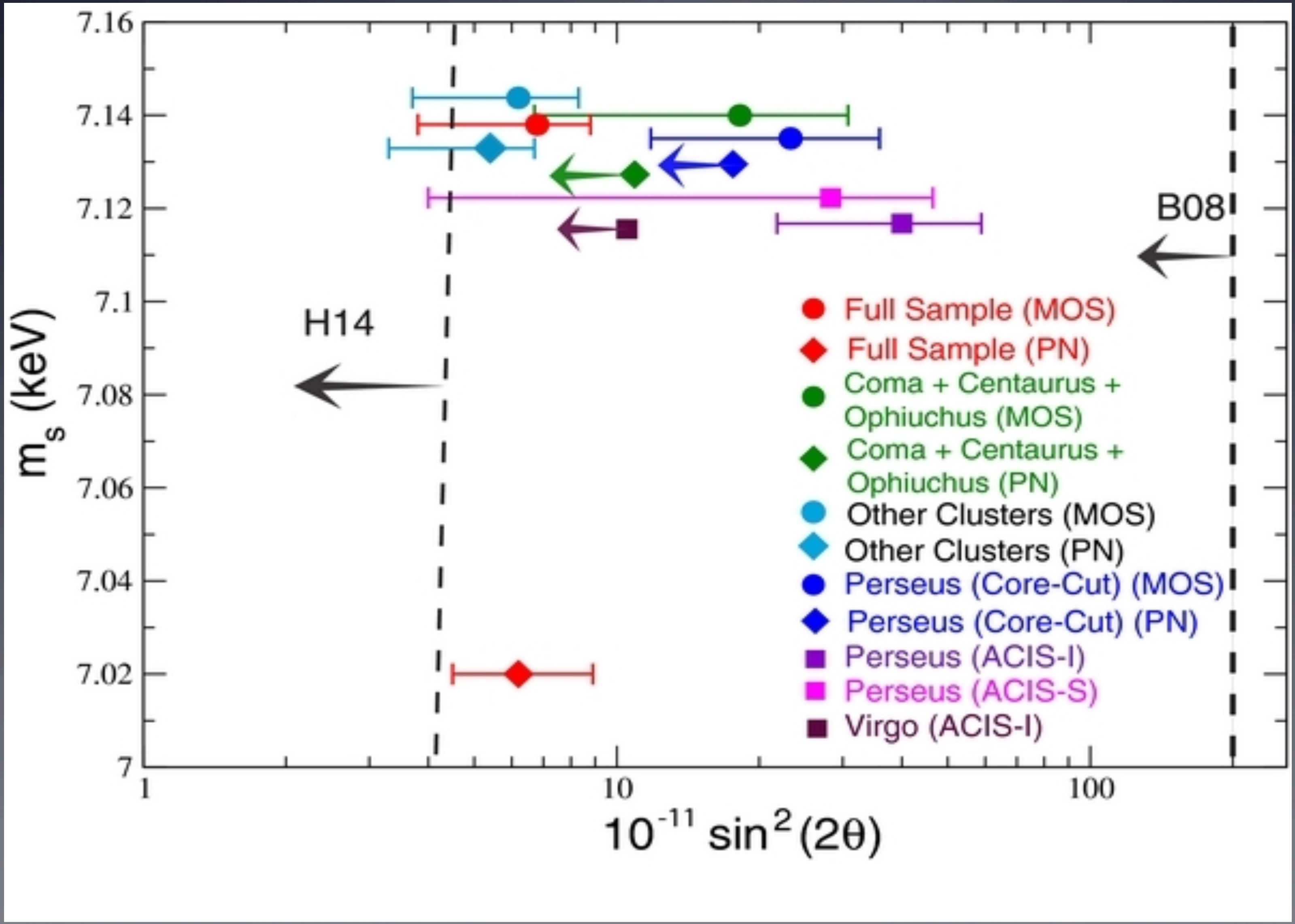
Perseus line can be fit with enhanced (by 30)Ar XVII 3.62 keV, but the remaining sample still requires an extra line at 2.5σ.

sample	Flux	$\Delta\chi^2/\Delta\nu$	10^{11} $\sin^2(2\theta)$
full XMM/MOS***	4.0 (-0.8,+0.8)	22.8/2	6.8 (-1.4,+1.4)
full XMM/PN****	3.9 (-.1.0,+0.6)	13.9/2	6.7 (-1.0,+1.7)
full XMM/PN*	2.5(-0.7,+0.6)	11.2/1	4.3 (-1.0,+1.2)
Perseus XMM/MOS*	21.4 (-6.3,+7.0)	12.8/1	23.3 (-6.9,+7.6)
Perseus XMM/PN*	<16.1	...	<17.6
bright XMM/MOS*	15.9 (-.3.8,+3.4)	17.1/1	18.2 (-3.9,+4.4)
bright XMM/PN*	<9.5	...	<10.9
Others XMM/MOS*	2.1 (-.0.5,+0.4)	16.5/1	6.0 (-1.4,+1.1)
Others XMM/PN*	2.0 (-0.5,+0.3)	15.8/1	5.4 (-1.3,+0.8)
Perseus Chandra/ACIS**	10.2 (-3.5,+3.7)	11.8/2	40.1 (-13.7,+14.5)
Perseus Chandra/ACIS-I*	18.6(-8.0,+7.8)	6.2/1	28.3 (-12.1,+11.8)
Virgo Chandra/ACIS-I*	<9.1	...	<10.5

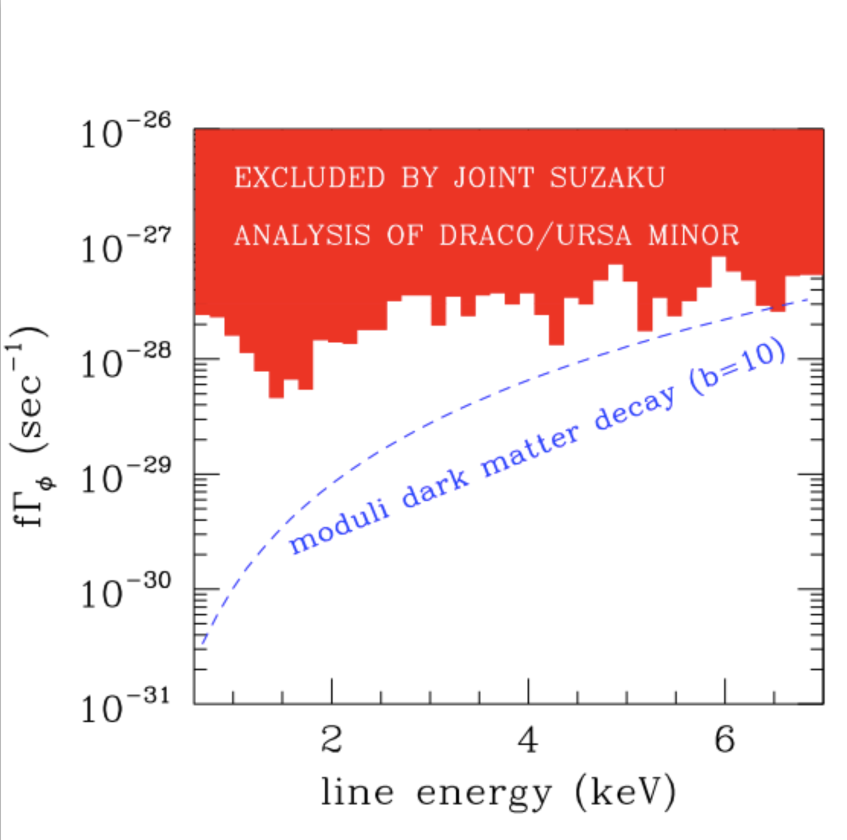
notes: perseus Perseus XMM w/o core,
"bright" = Coma +Centaurus + Ophiuchus,
flux in 10^{-6} photons cm^{-2} sec^{-1}

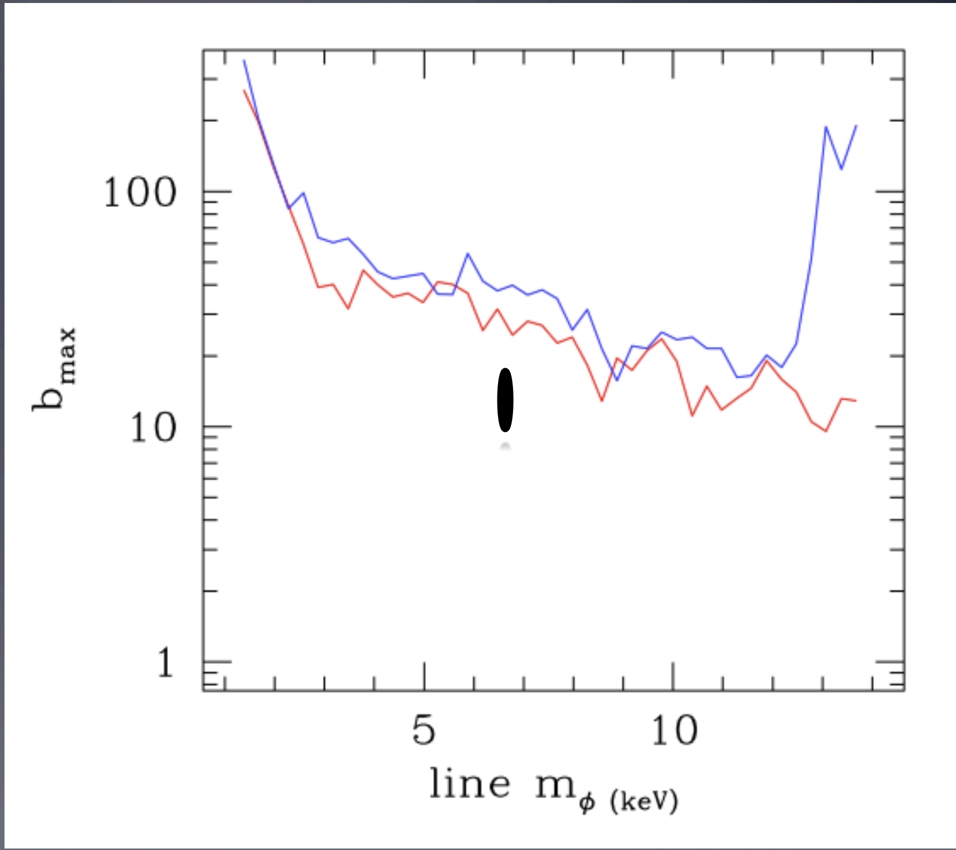
*E fixed at 3.57 keV
**E=3.56 ±0.02
***E=3.57 ±0.02
****E=3.51 ±0.03

Line detected at ~consistent energy at >3σ in 5 statistically independent spectra



Moduli DM Consistency w/ Cluster Stacking





$$\Gamma_{\phi\to\gamma\gamma} = b^2 \frac{m_\phi^3}{64\pi M_G^2}.$$

$$b \equiv M_G/\Lambda_{eff}.$$

Ursa Minor and Draco

Kusenko, Loewenstein, and Yanagida 2013

Notes on Cluster Stacking Analysis

Concerns

- Lines are weak
- Other ICM features within 50-110 eV
- ICM emission is bright. complex, and diverse
- Energy/flux discrepancies among subsamples

✓ **Our Suzaku stacking program should partially address these**

What we Know

- There is an unidentified feature in the spectra of most (consistent with all) clusters that is…
- … not a background feature
- … not an instrumental line
- … not a detector feature
- … not a modeling artefact

Final Remarks on Cluster Stacking Analysis

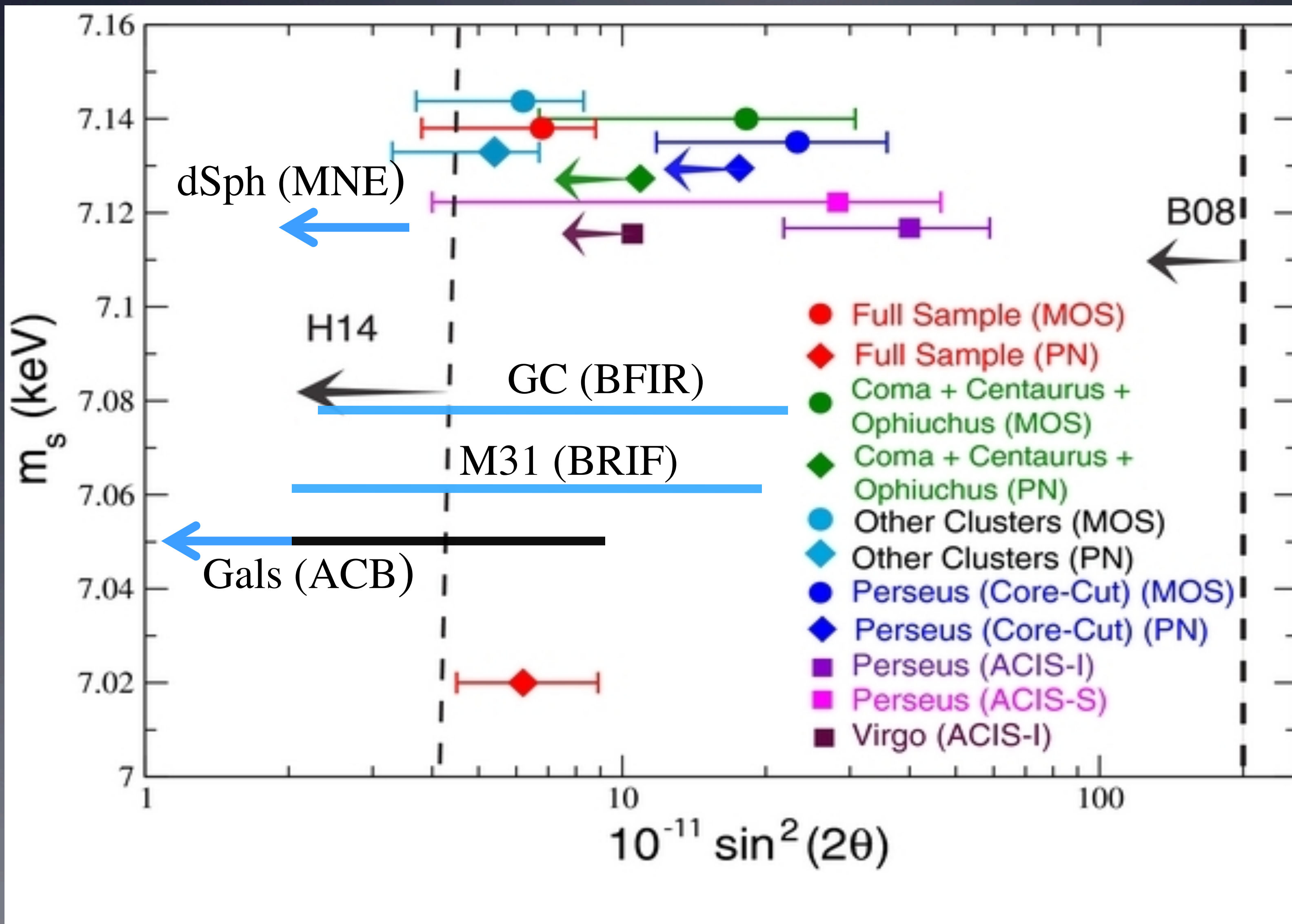
What we Know

- There is an unidentified feature in the spectra of most (consistent with all) clusters that is…
- … not a background feature
- … not an instrumental line
- … not a detector feature
- … not a modeling artefact

What we Don’t Know

- Is this line present in all DM halos (this is a unique dataset)?
- Is the line emitted by DM particles? Thermal plasma line is highly implausible (despite recent claims to the contrary).
- If so, which DM particle?

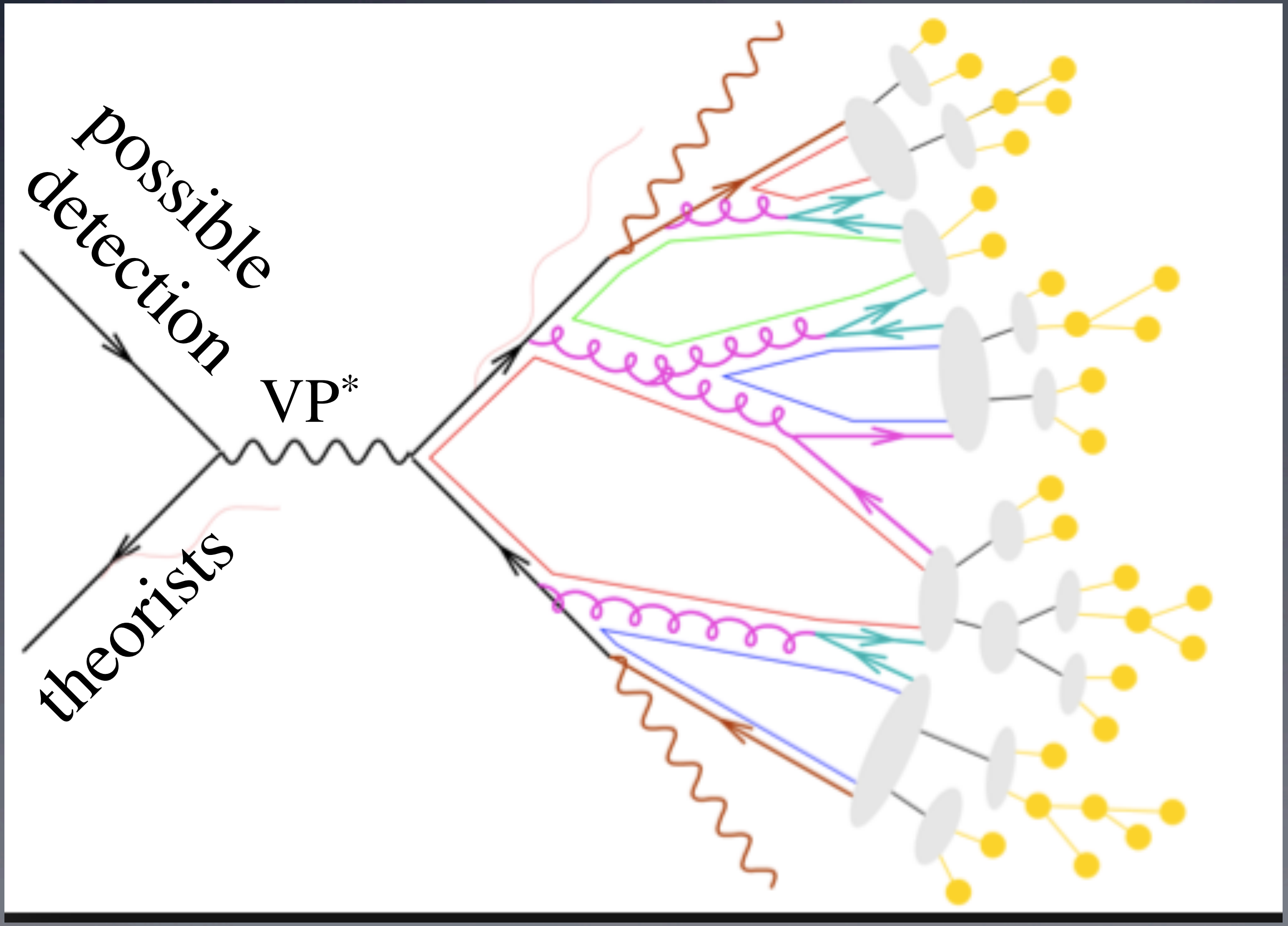
Line detected at ~consistent energy at >3σ in 8 statistically independent spectra



incomplete (and possibly inaccurate) list of candidates, explanations, scenarios...

Sterile Neutrinos (arXiv:1403.0954,1402.5837, 1403.2727, 1403.4368, 1404.5198, 1404.5955, 1404.7118, 1405.6967, 1406.004, 1409.3656)
Moduli (arXiv:1403.1398, 1403.1733)
eXciting Dark Matter(arXiv:1402.6671, 1410.7766)
Radiative decays of excited levels of SIMPLe dark matter (arXiv:1408.6532)
Millicharged dark matter (arXiv:1403.1280, 1403.1570)
Dark atoms (arXiv:1404.3729)
Axion/ALP (arXiv:1402.6965, 1402.7335, 1403.0865, 1403.2370, 1403.5760, 1404.7741, 1406.0660, 1406.5518, 1409.7918, 1410.1867)
Axino (arXiv:1403.1536, arXiv:1403.1782, 1403.6621)
Radiative Neutrino (arXiv:1403.1710, 1404.4795, 1404.3676)
Inflaton (arXiv:1403.4638)
Gravitino (arXiv:1403.6503, 1403.7742,)
Scalar Dark Matter (arXiv:1404.2220, 1406.0687)
Magnetic dark matter (arXiv:1404.5446)
Annihilating dark matter (arXiv:1404.1927, 1405.3730)
Pseudo Nambu-Goldstone bosons (arXiv:1403.7390, 1404.1400)
Sparticles (arXiv:1403.5580)
Sgoldstino (1404.1339)
Decaying scotogenic dark matter (arXiv:1408.5887)

DM candidate production is resonantly enhanced in the presence of a claimed detection ("arXiv-mediated hep-phino production")



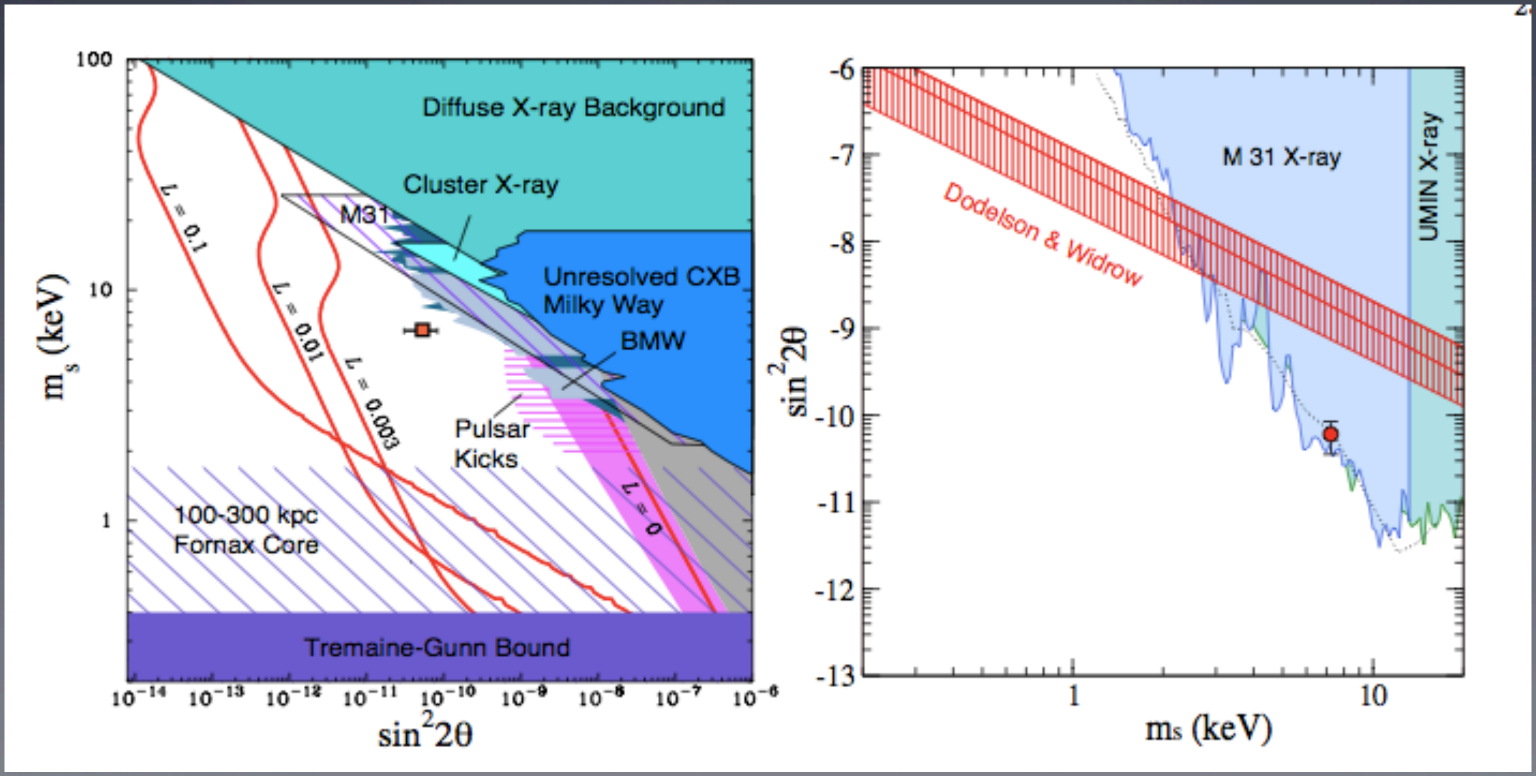
shower of new models and DM candidates

*VP=virtual preprint

Sterile Neutrinos Viability

< 25% produced by non-resonant oscillations (DW) (<10% if all DM is sterile neutrinos)

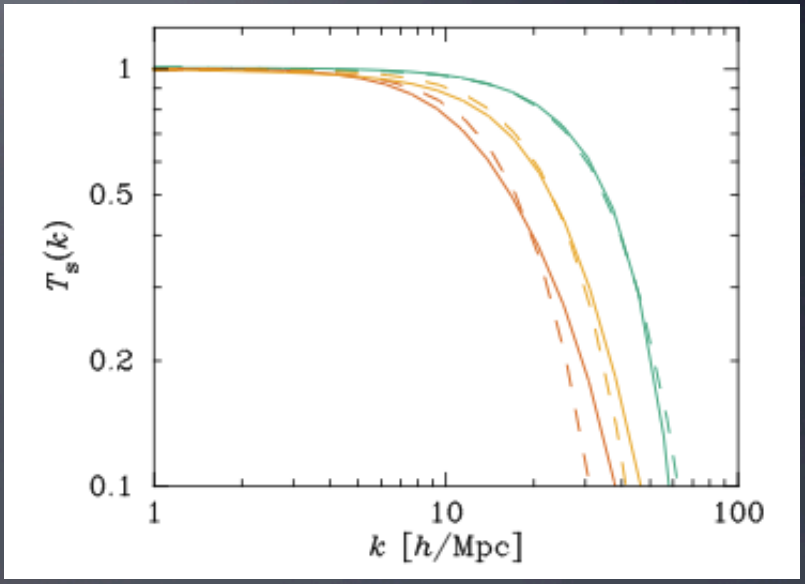
Resonant oscillations, other production (singlet Higgs, inflaton decay, split seesaw, split flavor) allowed.



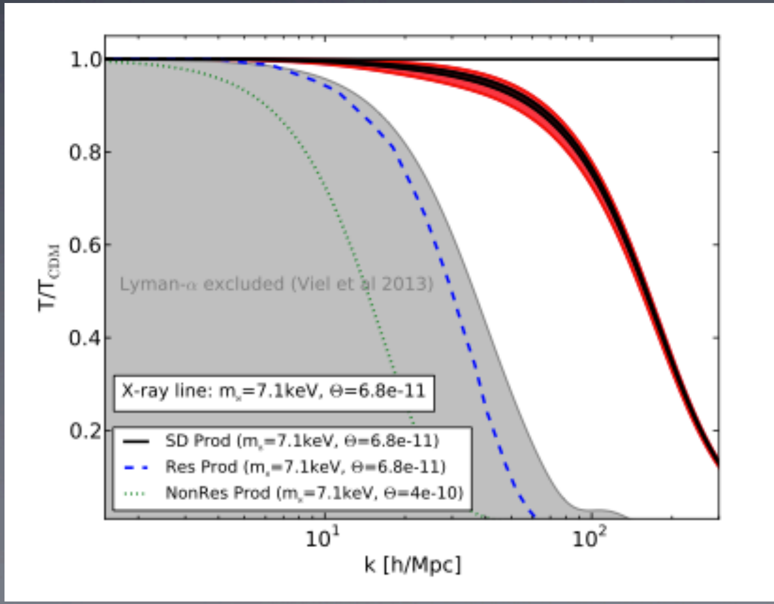
Sterile Neutrinos	interactions	clustering	comments
non-resonant oscillations	one-body (decay)	$k_{1/2}$~7.5/Mpc	<10%
resonant oscillations	one-body (decay)	$k_{K1/2}$~20/Mpc	lepton asymmetry at production L~0.0004-0.0008
singlet Higgs inflaton decay Z' decay	one-body (decay)	$k_{1/2}$~40/Mpc	
split seesaw	one-body (decay)	cool DM	baryogenesis small neutrino mass
split flavor	one-body (decay)	cool DM	neutrino mass predicts 100 Tev gravitino

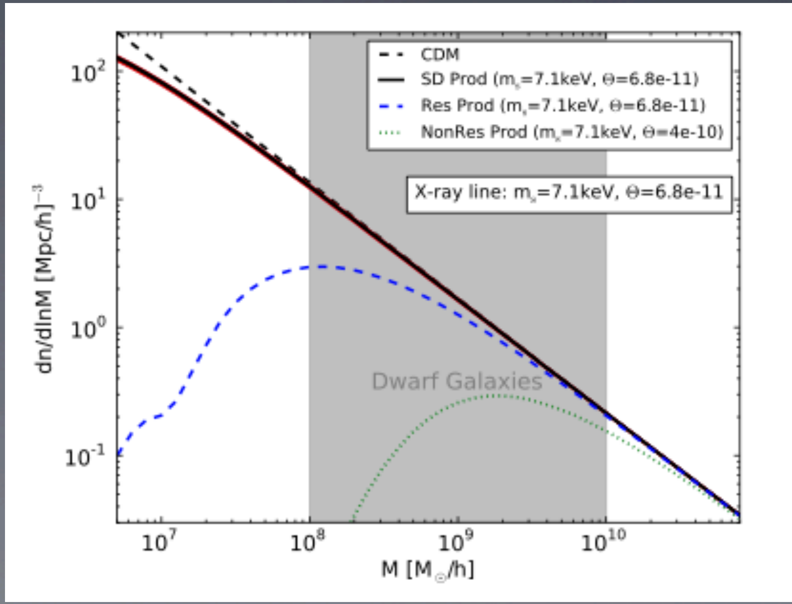
look to the lab... look to the sky...

The Sky: Different Production → Different Clustering



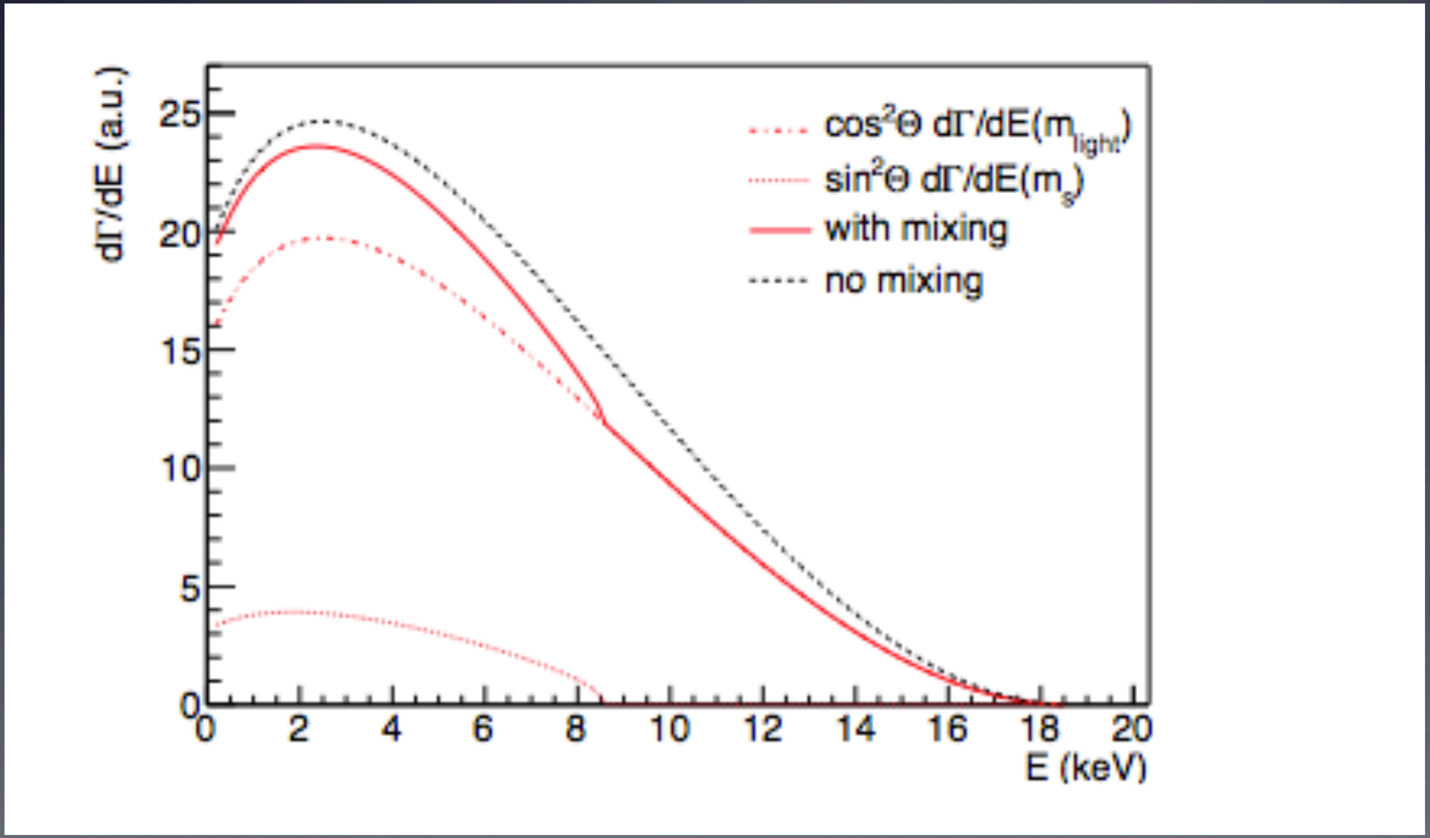
$L \sim 7 \times 10^{-4}$, $m_{thermal} \sim 2$ keV
(Abazajian 2014)





Merle and Schneider, arXiv:1409:6311

The Lab: Direct detection (???), effect on β-decay -



Mertens et al. (arXiv:1410.7684, Monday; Barry et al. 2014)

"challenging" at such a small mixing angle....

How Can We Distinguish Other Candidates -- From Sterile Neutrinos, and from Each Other?

- Other particle physics considerations, (theory and experiment); Cosmological implications (N_{eff})

- Clustering (structure on galaxy scales), e.g.
  - -- sterile neutrinos: CDM and/or WDM
  - -- moduli, eXciting DM: CDM
  - -- axion: CDM or CDM+HDM

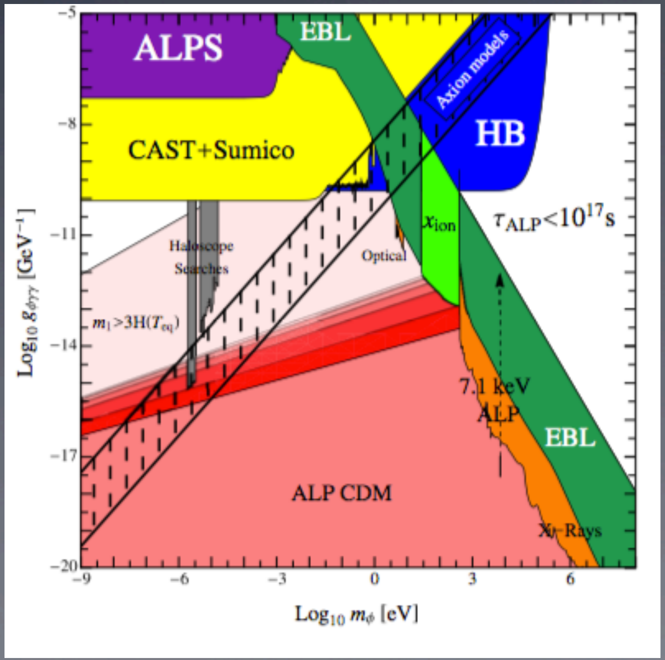
- Dependence on density (i.e. DM concentration *between* halos, *radius* within halos) and environment –
  - -- 2-body [annihilating] vs
  - -- 1-body interactions [decay] vs
  - -- 1.5-body [scattering: eXciting DM, dark atoms]

Axion –Like Particles?

DM→ALP→X-ray

$$\mathcal{F}_{\psi\to\nu\gamma} = \frac{\Gamma_{\mathrm{DM}\to a}}{4\pi} \int_{\mathrm{FOV}} \varrho\, \mathrm{d}\varrho\, \mathrm{d}\phi \int_{\mathrm{l.o.s.}} \frac{\rho_{\mathrm{DM}}(l,\varrho,\phi)}{m_{\mathrm{DM}}} P_{a\to\gamma}(l,\varrho,\phi)\, \mathrm{d}l,$$

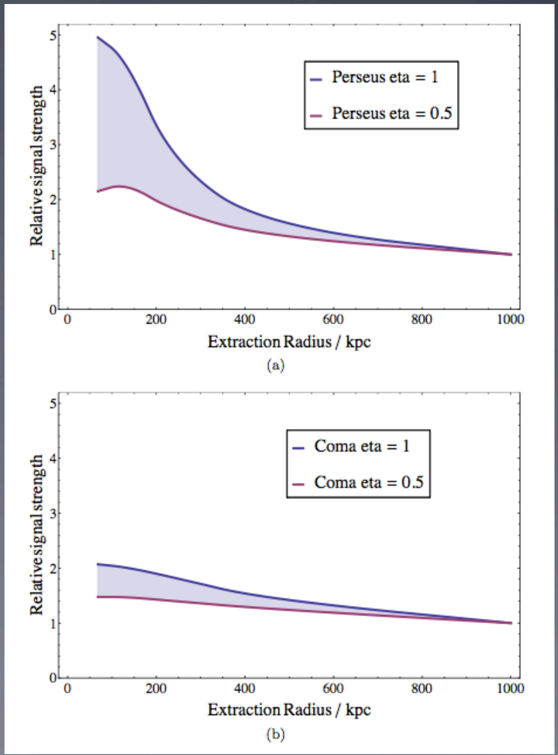
Explain radial dependence within and diversity among clusters and galaxies; Alvarez et al. arXiv:1410.1867



Joerg et al. 2014

$\eta == \mathrm{dlnB/dln}(n_e)$

Conlon et al. 2014



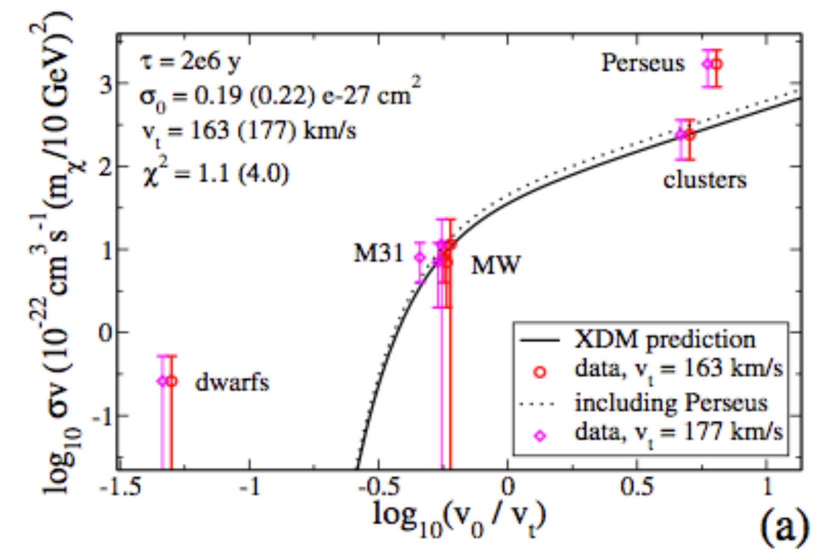
eXciting Dark Matter, Dark Atoms, etc.

- Emissivity depends on kinetic energy of particles: mean and "peculiar" velocities of particles.
- Scaling with DM density depends on decay time relative to dynamical time.

Excited dark matter reconciles conflicting observations of 3.5 keV X-rays

James M. Cline
Department of Physics, McGill University, 3600 Rue University, Mc

Andrew R. Frey
Department of Physics and Winnipeg Institute for T
University of Winnipeg, Winnipeg, Manitoba, Ca



- Can work for fast or intermediate decay particles
- GC γ-ray excess

Finkbeiner et al. (arXiv:1402.671)

What next??

At the current ~100 eV energy resolution, data is background limited

⇨

to improve sensitivity need a big increase in T_{obs} or...
a big decrease in ΔE

$$S/N = I_{line}(\Omega A_{det} T_{obs}/2I_{back}\Delta E)^{1/2}(1+I_{line}/2I_{back}\Delta E)^{-1/2}$$

	Non-X-ray (NXB)	Galactic (GXB)	Cosmic (CXB)
origin	particles	halo and LHB	AGN
determining factors	orbit, design	direction	angular resolution
measurement	look at nothing	look at blank sky*	look at blank sky*
correction	subtract (or fit)	subtract* or fit	resolve/sub.* or fit

*understand your background, but don't subtract your signal !

4) Future X-ray Searches: *Astro-H*

1. High Resolution Spectroscopy by a micro-calorimeter array

ASTRO-H is the first mission to carry out high resolution spectroscopy of extended objects at Fe-K

2. Wide Band /High Sensitivity Observation

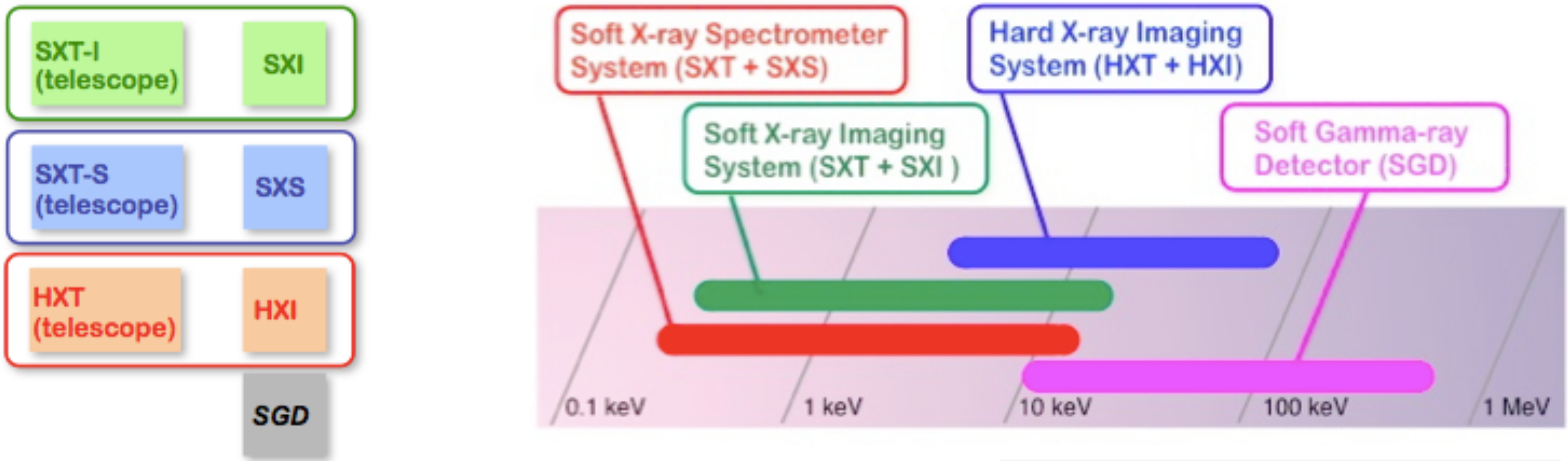
0.3 keV - 600 keV : Four Instruments including Hard X-ray Focusing optics

SXS+SXT: Micro Calorimeter
SXI+SXT: X-ray CCD
HXI (two sets)+HXT:
Si and CdTe Hybrid
SGD(two sets):
Si/CdTe Compton Camera

4) Future X-ray Searches: *Astro-H*

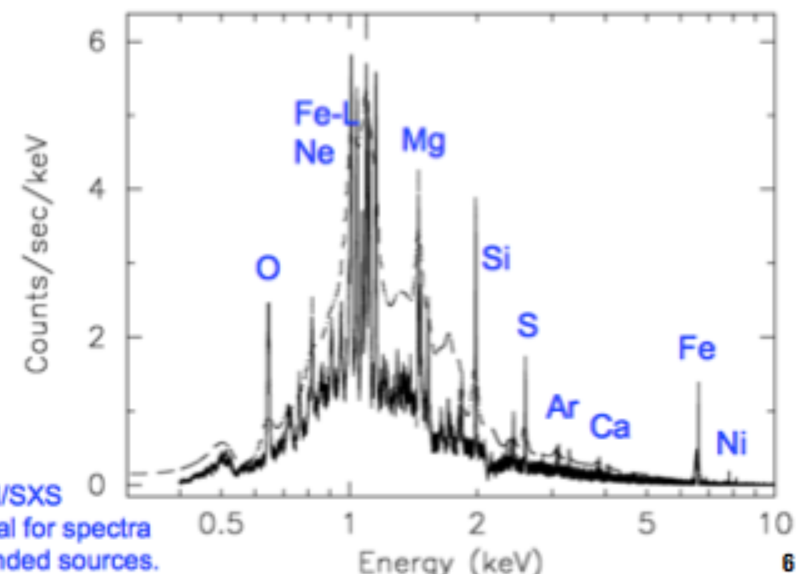
1. Wide Band /High Sensitivity Observation

0.3 keV - 600 keV : Four Instruments including Hard X-ray Focusing optics



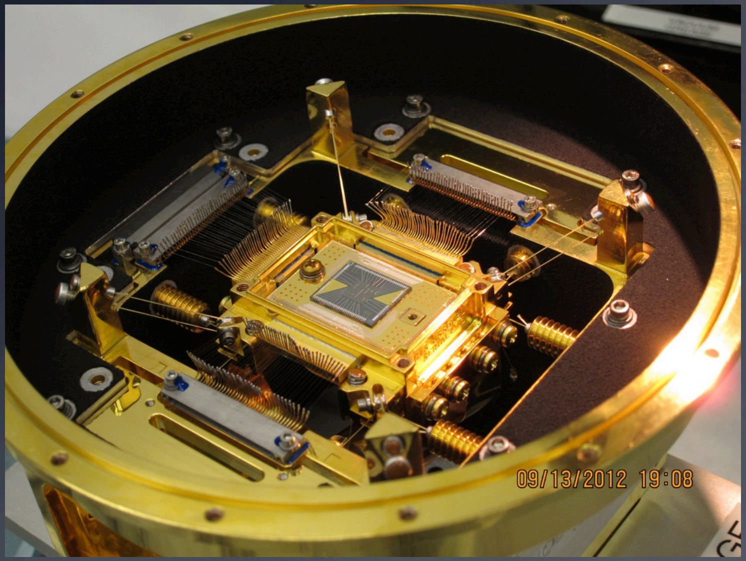
2. High Resolution Spectroscopy by a micro-calorimeter array

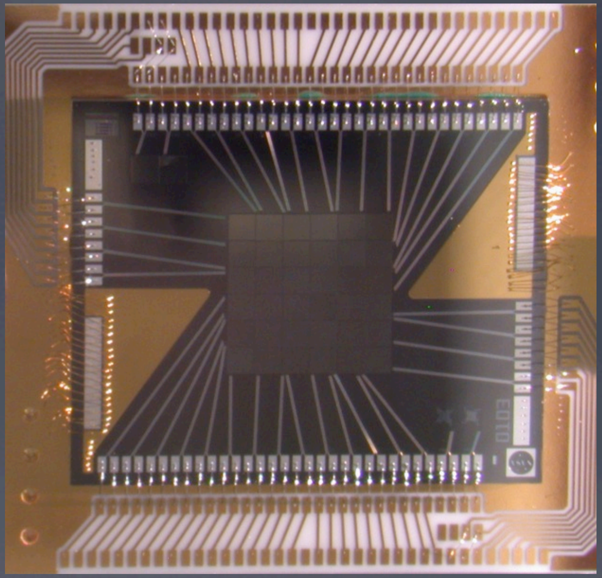
5 eV (FWHM) @ 6 keV



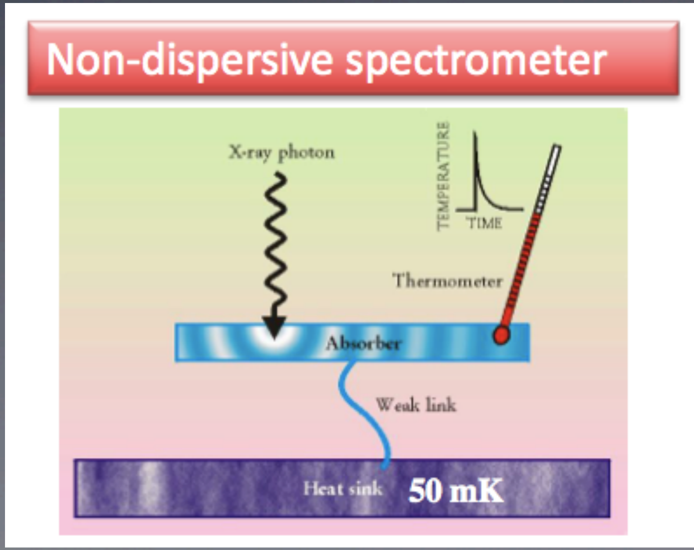
Astro-H/SXS essential for spectra of extended sources.

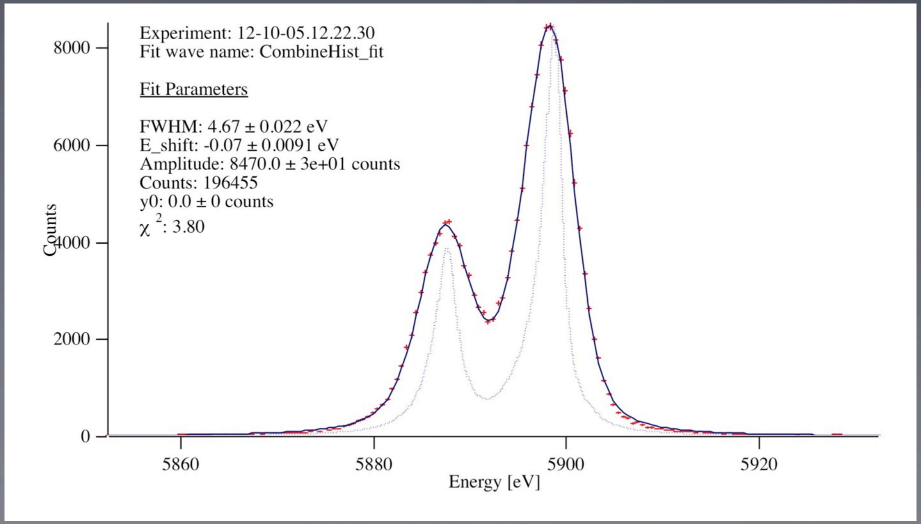
Future X-ray Searches: *Astro-H* Microcalorimeter Array – High Energy Resolution Imaging Spectroscopy





6 × 6
0.5′ × 0.5′
pixels



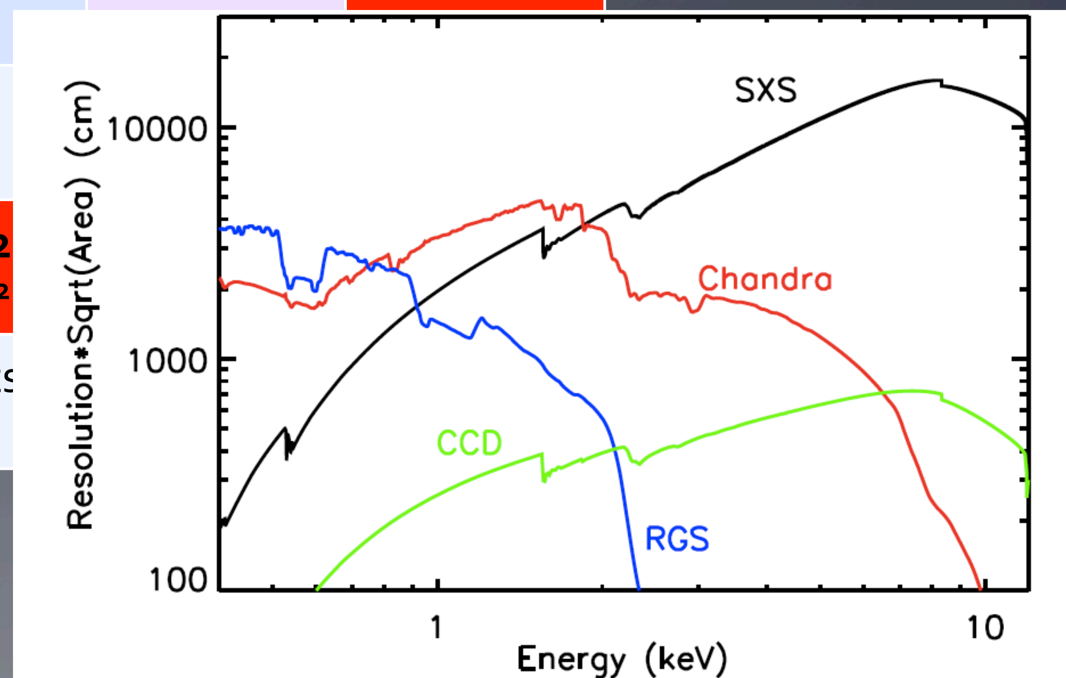


4) Future X-ray Searches: *Astro-H*

	Chandra (I-array)	XMM-Newton	Suzaku	ASTRO-H SXS
field of view	17' X 17'	30' X 30'	19' X 19'	3' X 3'
angular resolution	**1''**	6''	90''	60"
energy resolution	~50	~50	~50*	~1000
bandpass	0.4 – 8 keV	0.2 – 12 keV	0.3 – 12 keV	0.3-12 keV
effective area	400 cm^2	**1200 + 2 X 900 cm^2**	400 X 3 cm^2	200 cm^2
NXB rate	~0.01 cts/sec/□' *	~0.01 cts/sec/□'	**~0.001 cts/sec/□'**	**~0.001 cts/sec/□'**

4) Future X-ray Searches: *Astro-H*

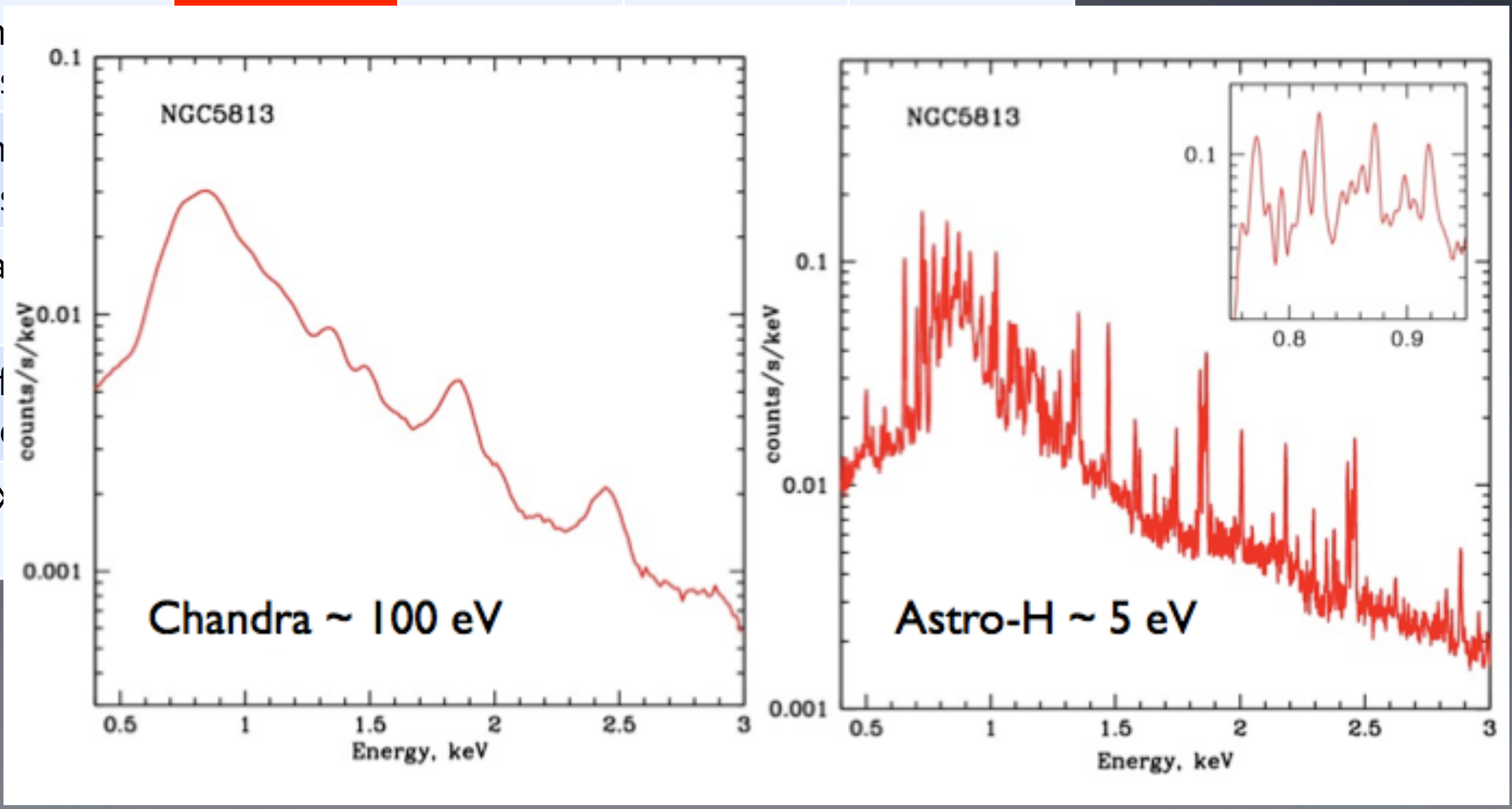
	Chandra (I-array)	XMM-Newton	Suzaku	ASTRO-H SXS
field of view	17' X 17'	30' X 30'	19' X 19'	3' X 3'
angular resolution	**1''**	6''	90''	60"
energy resolution	~50	~50	~50*	~1000
bandpass	0.4 – 8 keV	0.2 – 12 keV		
effective area	400 cm²	**1200 + 2 900 cm²**		
NXB rate	~0.01 cts/ sec/□' *	~0.01 cts sec/□'		

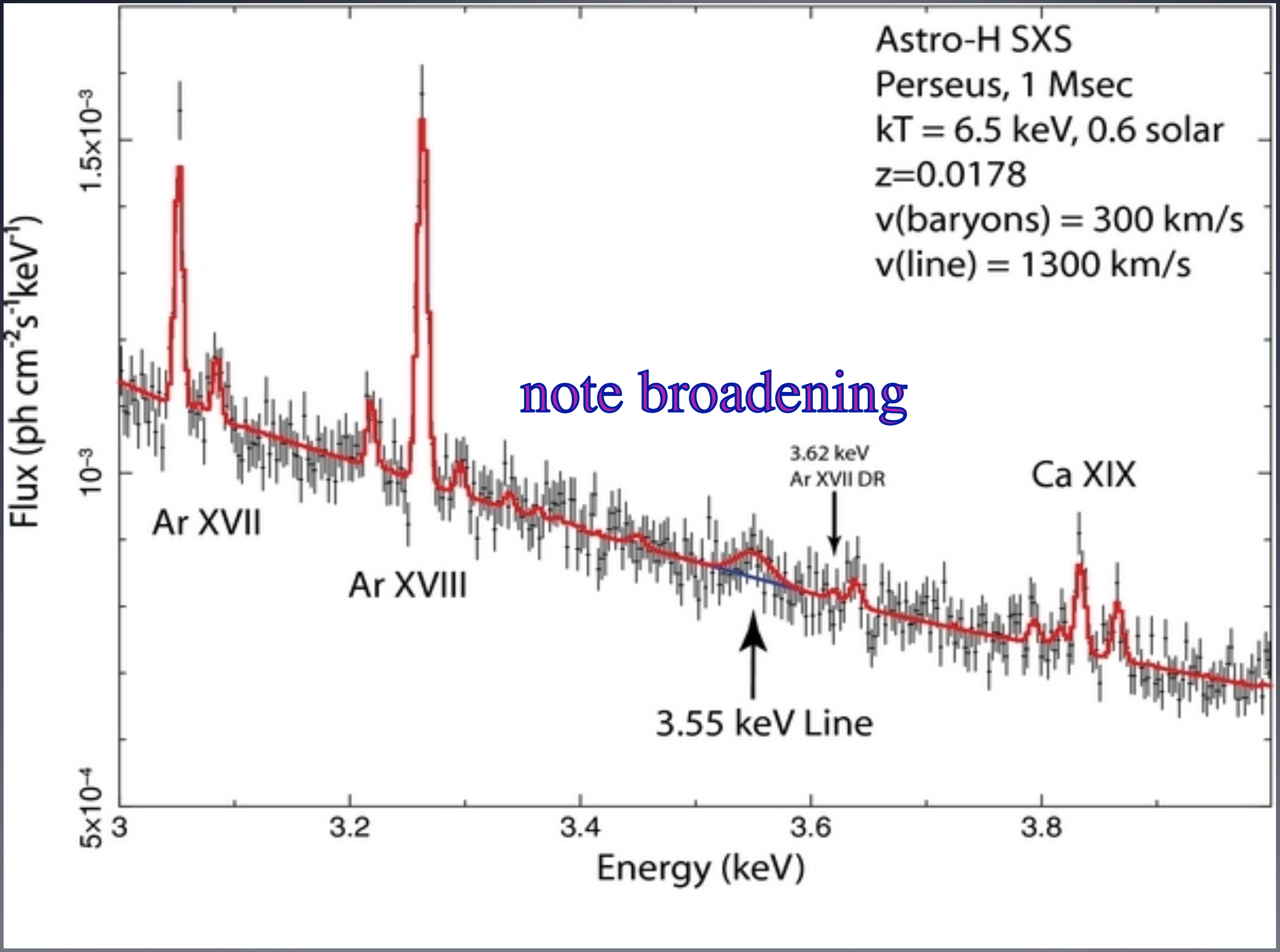


4) Future X-ray Searches: *Astro-H*

	Chandra (I-array)	XMM-Newton	Suzaku	ASTRO-H SXS
field of view	17' X 17'	30' X 30'	19' X 19'	3' X 3'
an res				
en res				
ba				
eff ar				
NX				

I. Zhuravleva (Snowcluster '13)





clear and distinct...

Final Remarks

• Cluster stacking method is unique in spanning a sufficient range of redshifts to mitigate systematics.

• Two independent groups find evidence of an unidentified X-ray emission line consistent with LDM decay – 8 statistically independent $>3\sigma$ detections. Weak, but unlikely to have instrumental origin.

• There are (suddenly) many plausible particle models that can explain this line, including sterile neutrinos.

• These may be distinguished in a number of ways – in some cases based on the variation of line strength with environment/density/magnetic field.

• Conflicts among analysis may imply (1) anomalous plasma line emission in ICM, (2) underestimated systematic errors in low-z samples, (3) DM with velocity/B-field dependent emission.

"We know that the dark matter explanation is a long shot, but the pay-off would be huge if we're right," said Esra Bulbul of the Harvard-Smithsonian Center for Astrophysics (CfA) in Cambridge, Mass., who led the study. "So we're going to keep testing this interpretation and see where it takes us."

"We have a lot of work to do before we can claim, with any confidence, that we've found sterile neutrinos," said Maxim Markevitch, a co-author from NASA's Goddard Space Flight Center in Greenbelt, Maryland. "But just the possibility of finding them has us very excited."

"Our next step is to combine data from Chandra and JAXA's Suzaku mission for a large number of galaxy clusters to see if we find the same X-ray signal," said co-author Adam Foster, also of CfA. "There are lots of ideas out there about what these data could represent. We may not know for certain until Astro-H launches, with a new type of X-ray detector that will be able to measure the line with more precision than currently possible."

• A conclusive answer on the nature of the line will arrive via from Astro-H (launch: 2015).

• If confirmed, future (high-energy good-angular resolution, large collecting area) X-ray missions will map out dark matter in the universe and point the way to physics beyond the Standard Model.