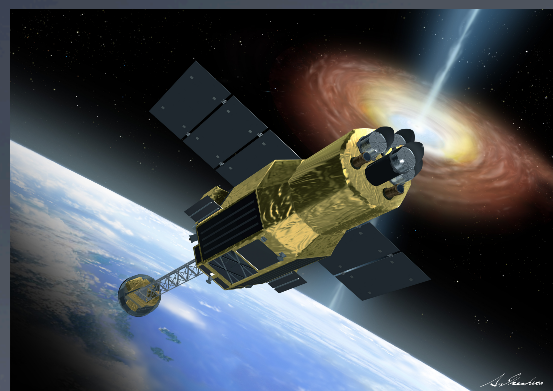
Search for Light Dark Matter with X-rays and Implications of a Possible Detection

Michael Loewenstein (Univ. of Maryland/CRESST/NASA-GSFC)



Suzaku

Chandra

XMM-Newton

ADAP

Search for Light* Dark Matter with X-rays and Implications of a Possible Detection

Short Subject -- Search: Motivation, Targets…
[w/ A. Kusenko (UCLA/IPMU), T. Yanagida (IPMU)…]

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

Brief Intermission

Coming Attractions – **Next Steps**
[*Astro-H* Instrument, and Software & Calibration Teams,
A-H Science Working Group]

*0.000000001 TeV

Short Subject

The Search: What to Look *for*

Focus on NRP Sterile Neutrino Light DM

Most extensions to the Standard Model that explain the neutrino mass include right-handed (***sterile***) neutrinos.

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

- WDM: $m_{thermal} \sim 0.33\ \mathrm{keV} (m_{ster\text{-}\nu}/\mathrm{keV})^{3/4}\ \mathrm{s}^{-1}$

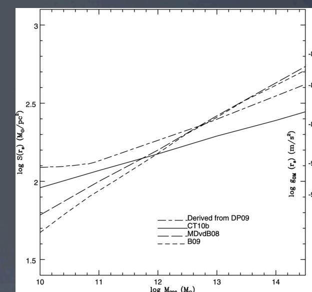
$$\Gamma_\gamma(m_s, \theta) = 1.38 \times 10^{-29}\ \mathrm{s}^{-1} \left(\frac{\sin^2 2\theta}{10^{-7}}\right)\left(\frac{m_s}{1\ \mathrm{keV}}\right)^5$$

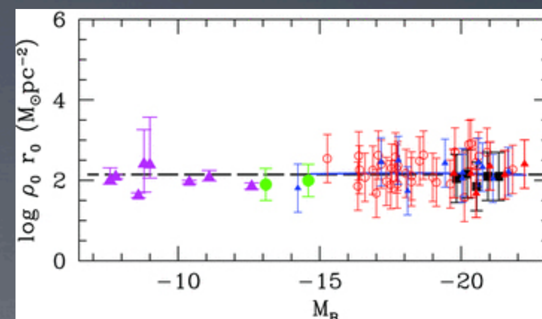
Dodelson & Widrow (1994), Kusenko (2009), Kusenko, Takahashi, and Yanagida (2010), Boyarsky, Iakubovskyi, and Ruchayskiy (2012)...

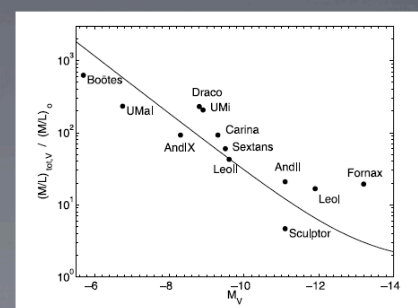
The Search: What to Look *at*

(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?

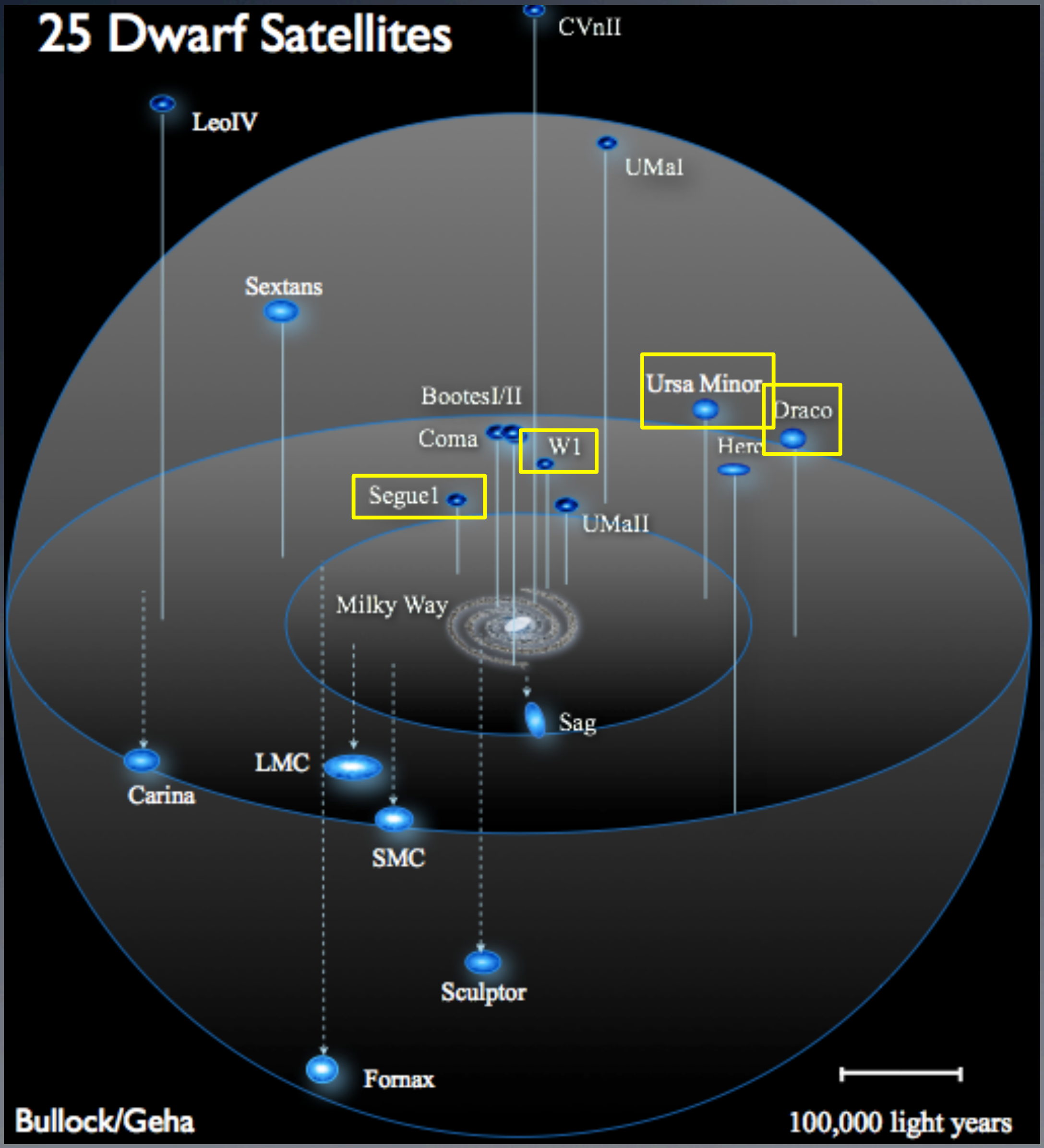






Dsphs (Gillmore et al.);
Galaxies (Salucci et al.);
Clusters (Popolo et al.)

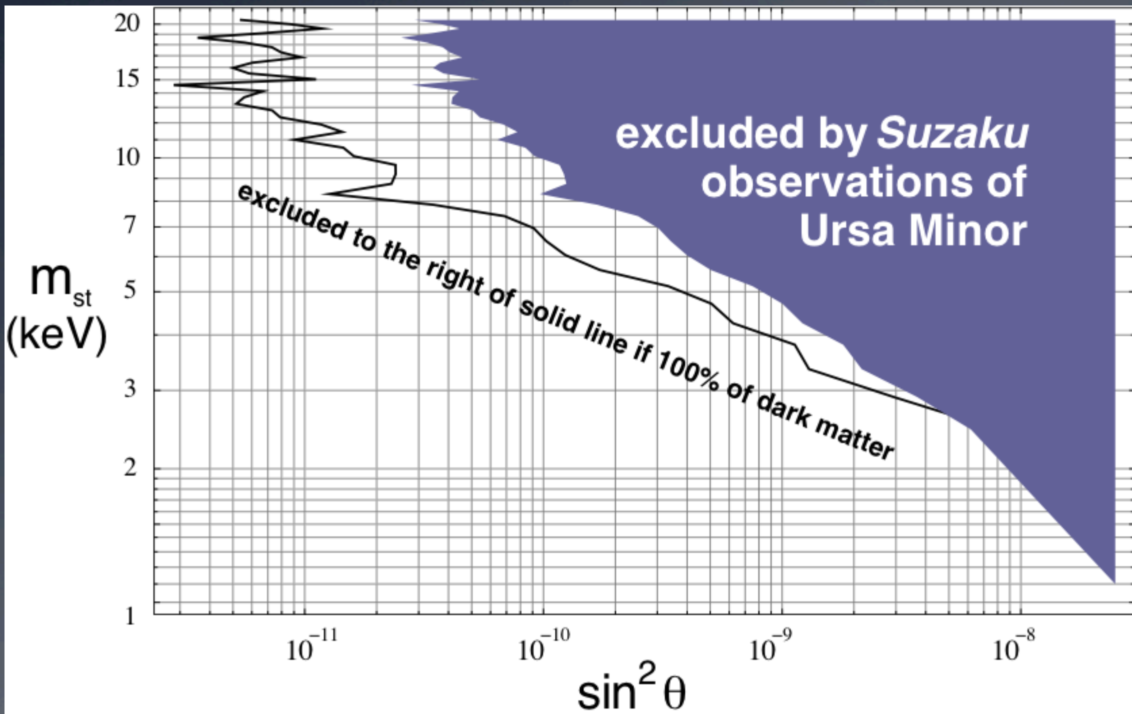
The Search: What to Look *with*



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…

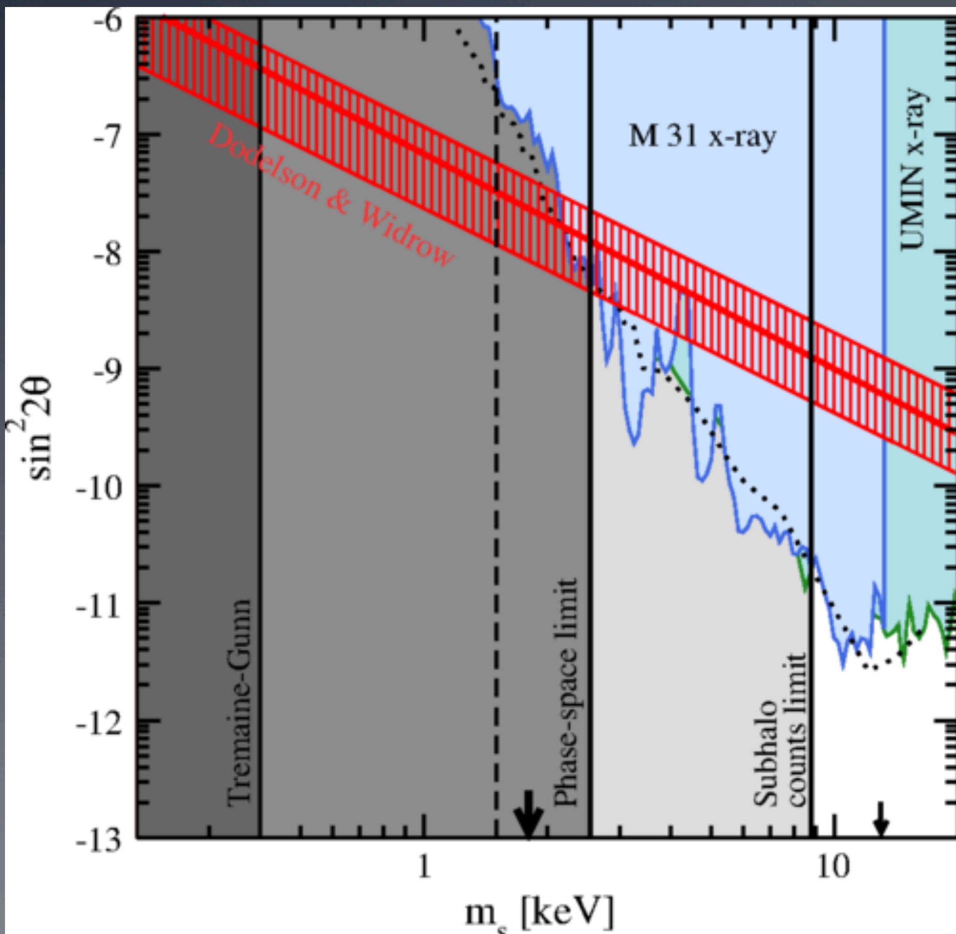


Draco, Will-1, Seg-1 (ML/AK in prep) similar

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.

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:

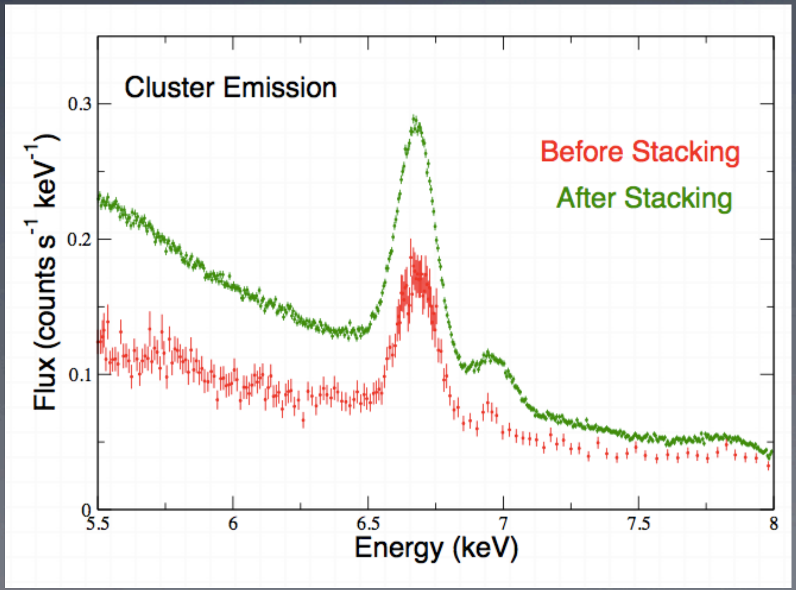
- **Other ways of making sterile neutrinos**
- **Other X-ray-line emitting DM candidates**

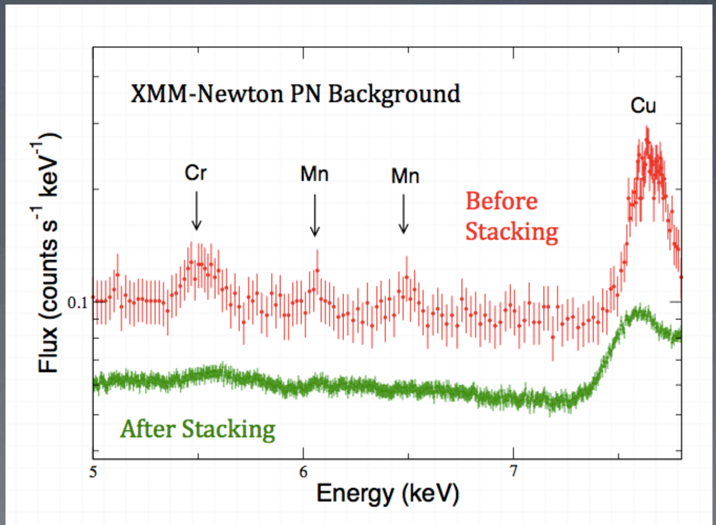
Feature Presentation

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.

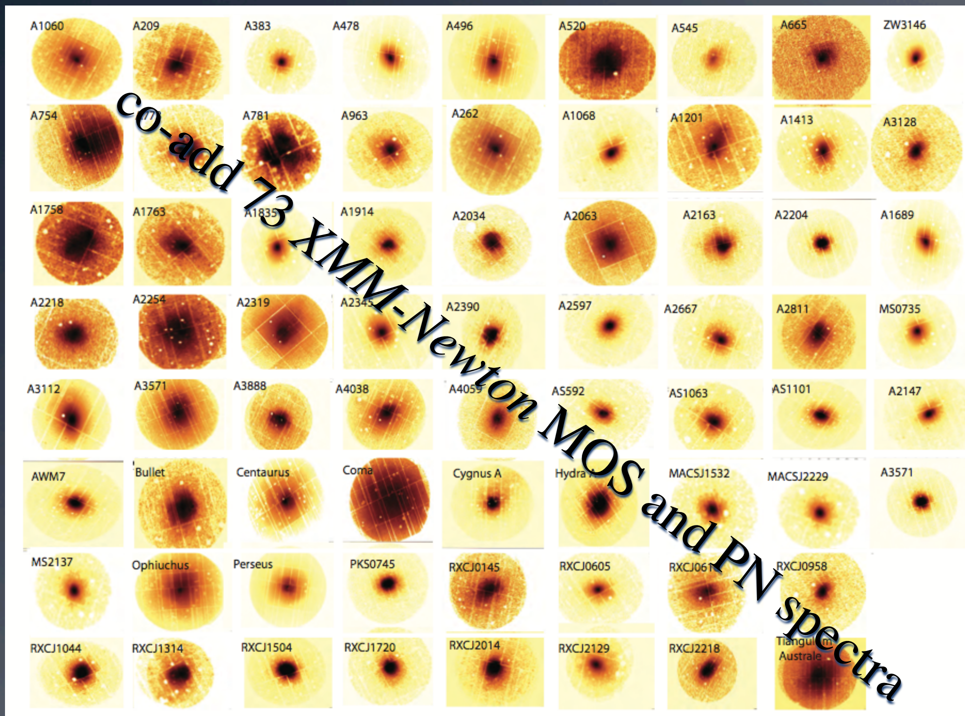




MOS and PN are two different CCD detectors on XMM-Newton

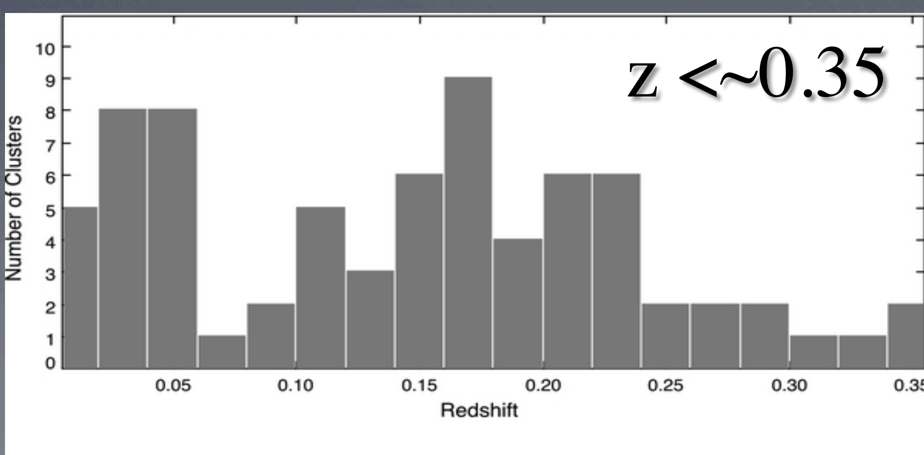
ApJ, 789, 13

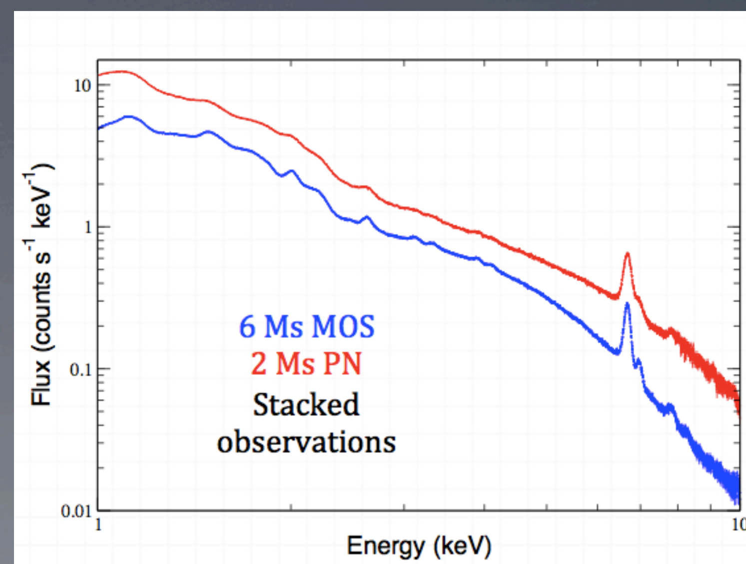
Galaxy Cluster Stacking: The Sample



M~10^14 -10^15+
(well-determined)

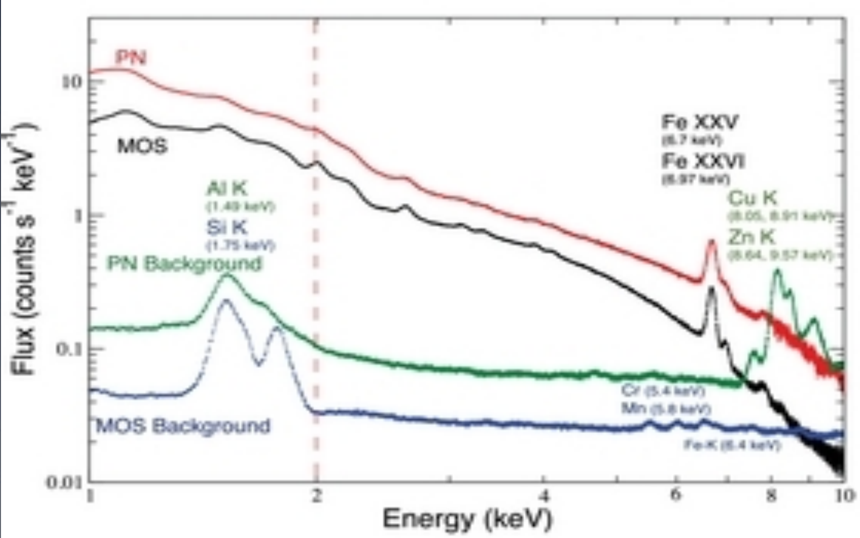
kT~3-10 keV
fgas~0.13, Fe~0.3 solar
lots of emission lines!



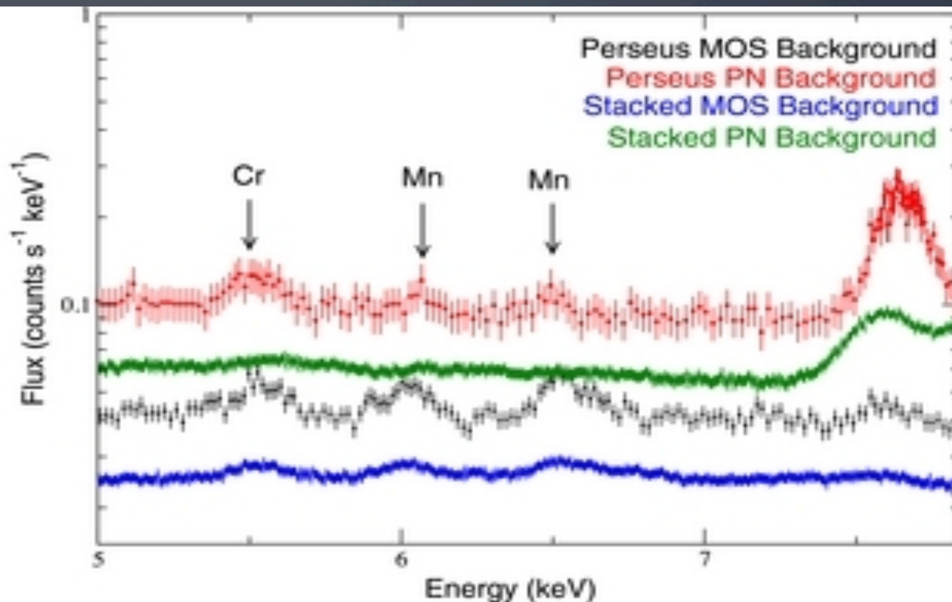


Basic Analysis Steps:

(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

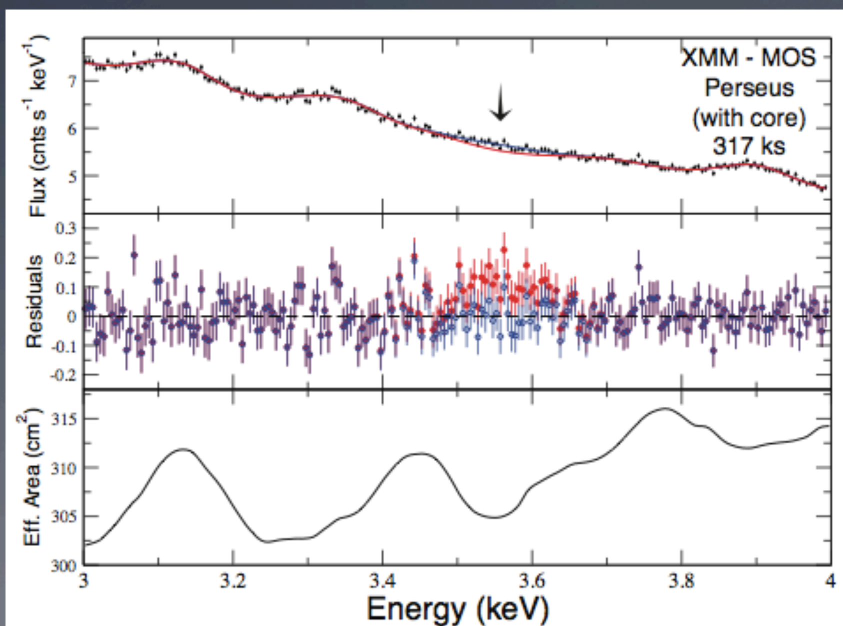


Unmatched High S/N

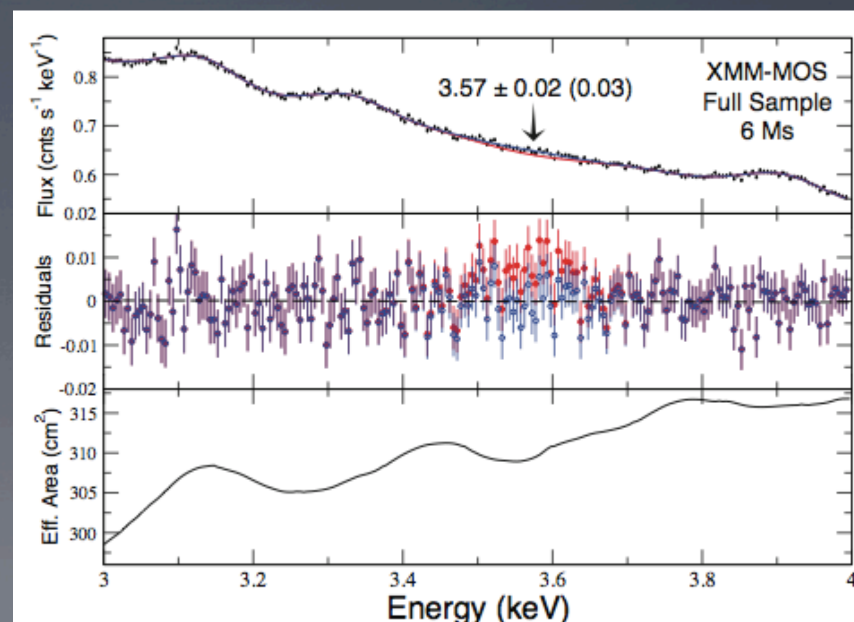
Smeared Instrumental Bkg

(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...

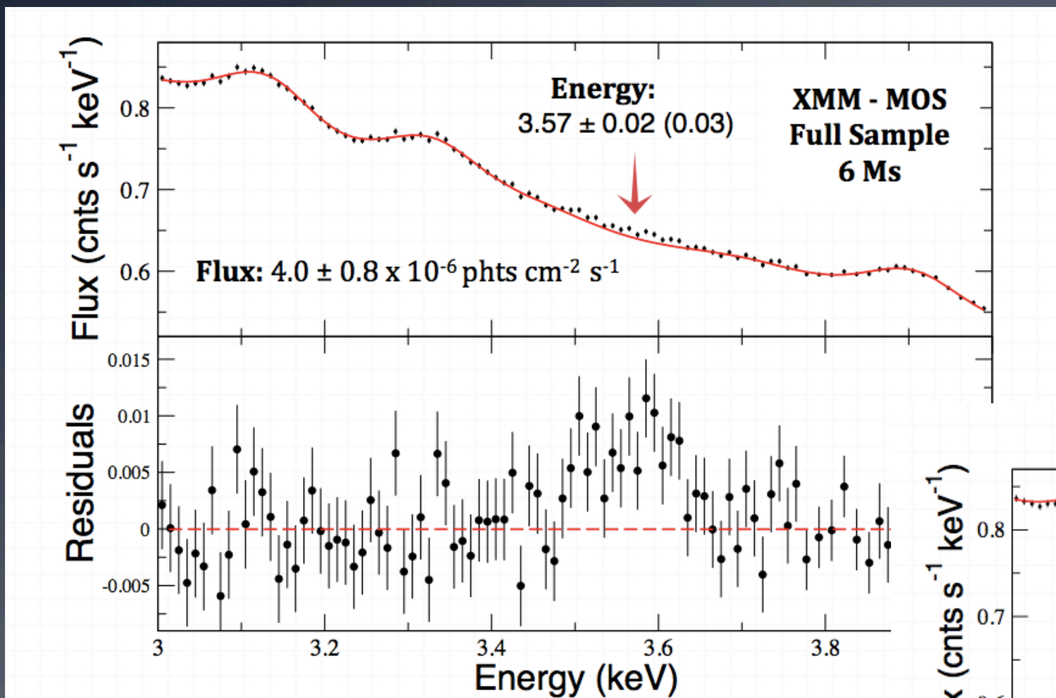


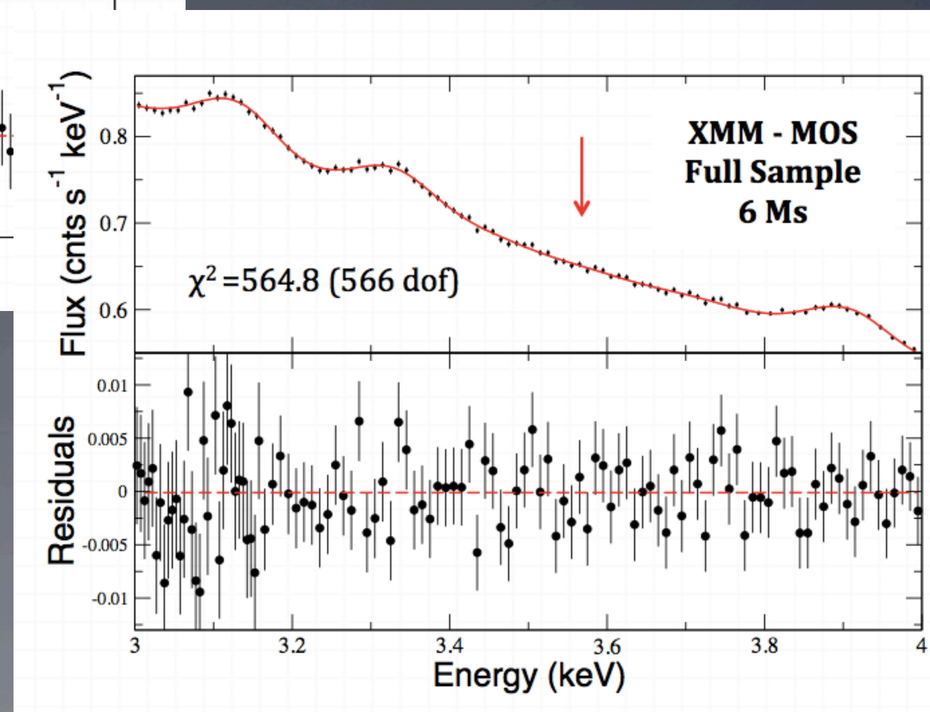
single cluster spectrum



stacked cluster spectrum

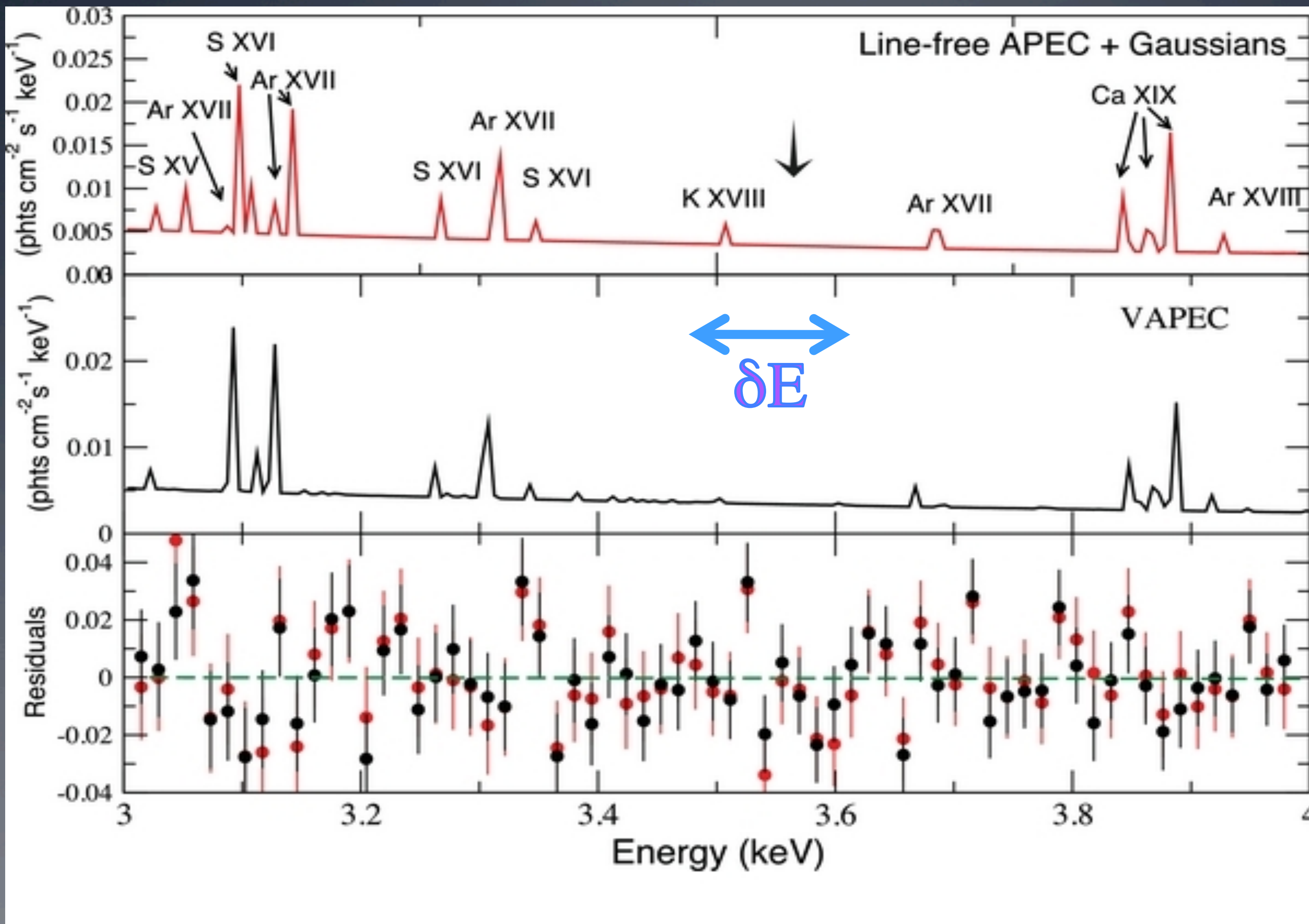
(4) Search for "extra" features in 2-10 keV band (<2 keV too crowded).





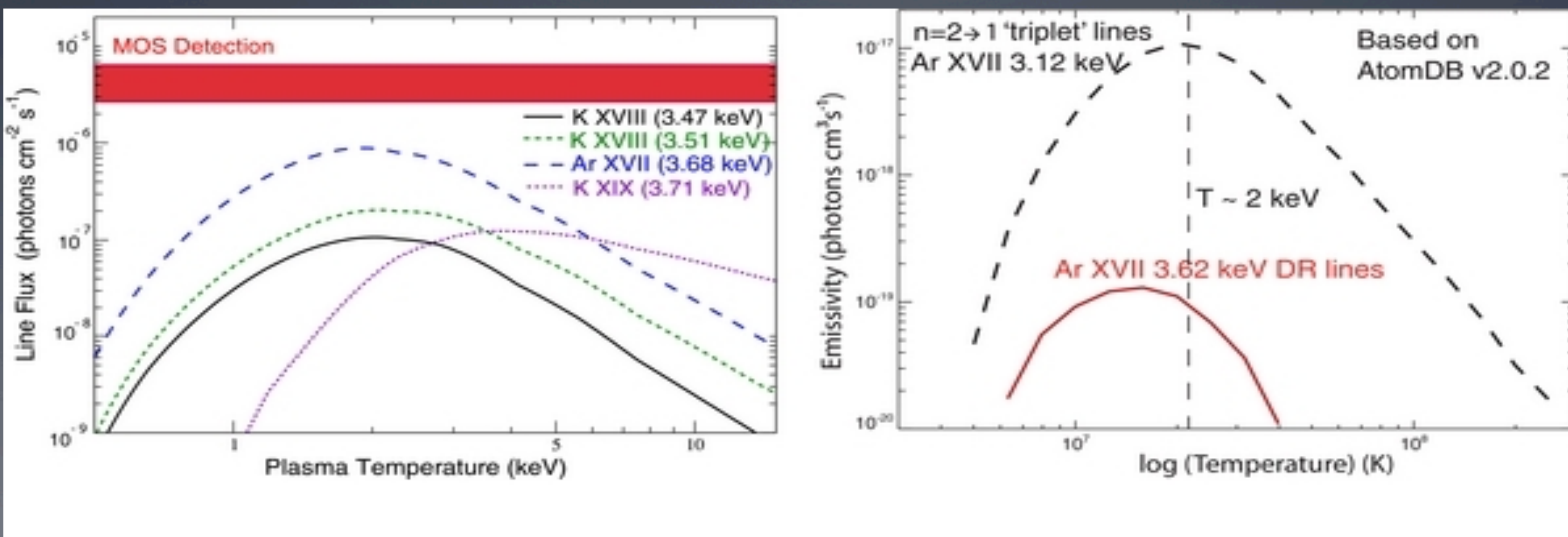
Detection of unidentified emission line at ~3.57 keV at ~5σ

- 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.



subsamples, etc.

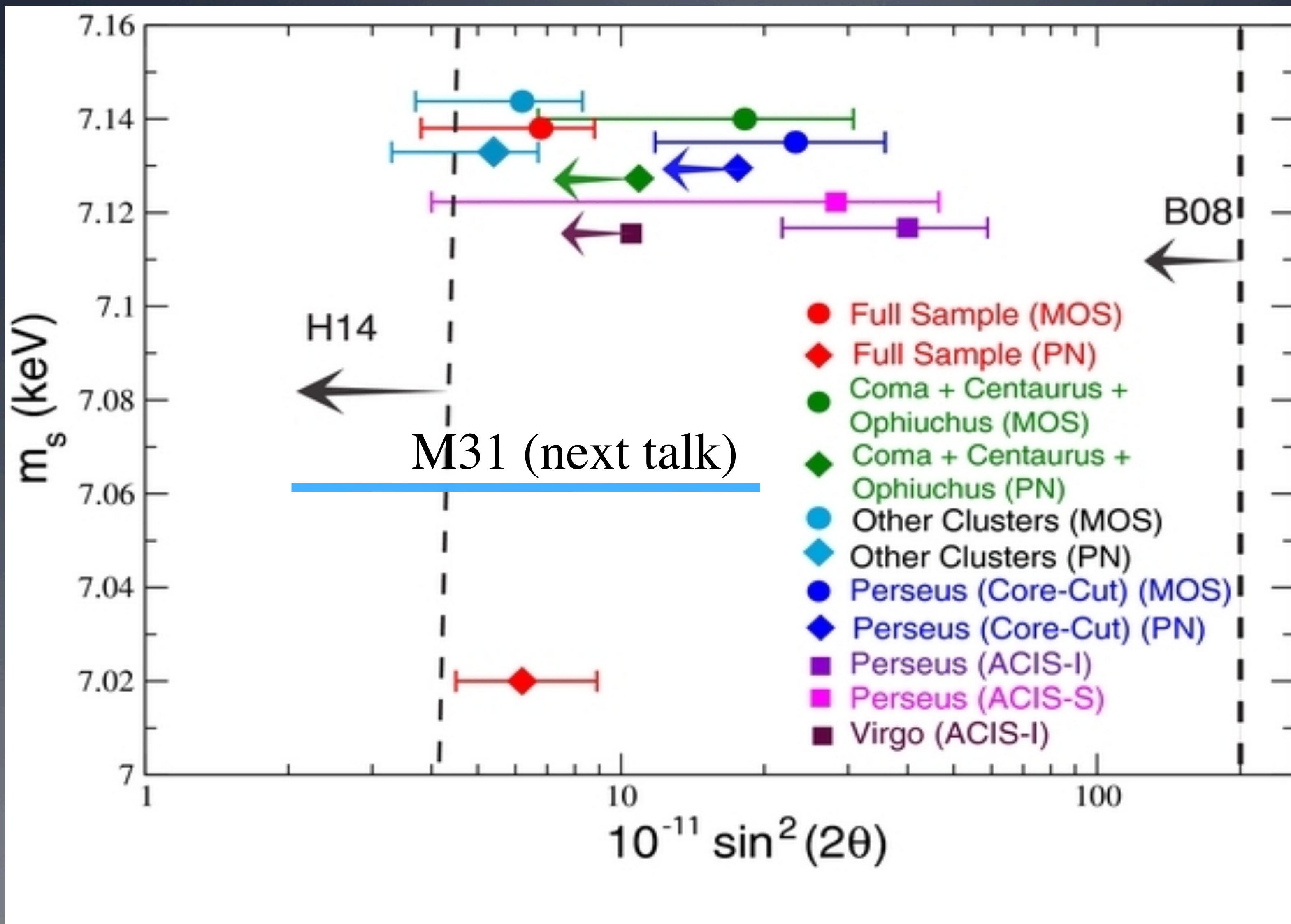
sample	Flux	$\Delta\chi^2/\Delta\nu$	10^{11} $\sin^2(2\theta)$
full XMM/MOS	4.0 (-0.8,+0.8)	22.8/2	6.8 (-1.4,+1.4)
full XMM/PN	3.9 (-.1.0,+0.6)	13.9/2	6.7 (-1.0,+1.7)
full XMM/PN*	2.5(-0.7,+0.6)	11.2/1	4.3 (-1.0,+1.2)
Perseus XMM/MOS* (1)	21.4 (-6.3,+7.0)	12.8/1	23.3 (-6.9,+7.6)
Perseus XMM/PN*	<16.1	...	<17.6
bright XMM/MOS* (2)	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* (3)	2.1 (-.0.5,+0.4)	16.5/1	6.0 (-1.4,+1.1)
Others XMM/PN* (4)	2.0 (-0.5,+0.3)	15.8/1	5.4 (-1.3,+0.8)
Perseus Chandra/ACIS** (5)	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

*E fixed at 3.57 keV

**E=3.56 ±0.02

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

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



Final Remarks on Cluster Stacking Analysis

Concerns

- Lines are weak
- 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

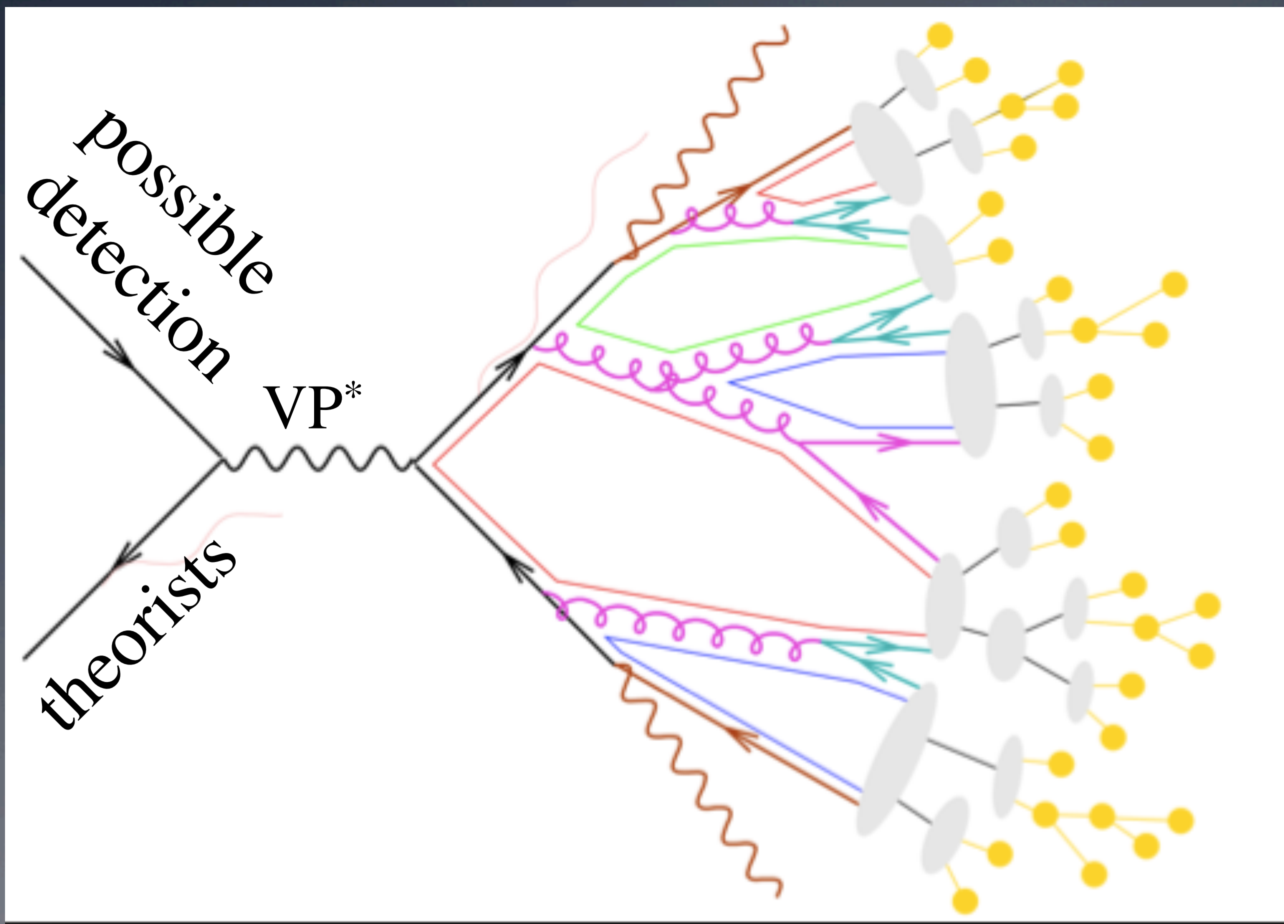
- Is this line emitted by all DM halos (this is a unique dataset)? [MW? Riemer-Sorenson, arXiv 1405.7943]
- Is the line emitted by DM particles?
- If so, which DM particle?

Intermission

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)
Moduli (arXiv:1403.1398, 1403.1733)
eXciting Dark Matter(arXiv:1402.6671)
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)
Axino (arXiv:1403.1536, arXiv:1403.1782, 1403.6621)
Radiative Neutrino (arXiv:1403.1710, 1404.4795, 1404.3676)
Effective field theory (arXiv:1403.1240)
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)
Light non-thermal DM (arXiv:1403.5717)
Sgoldstino (1404.1339)

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

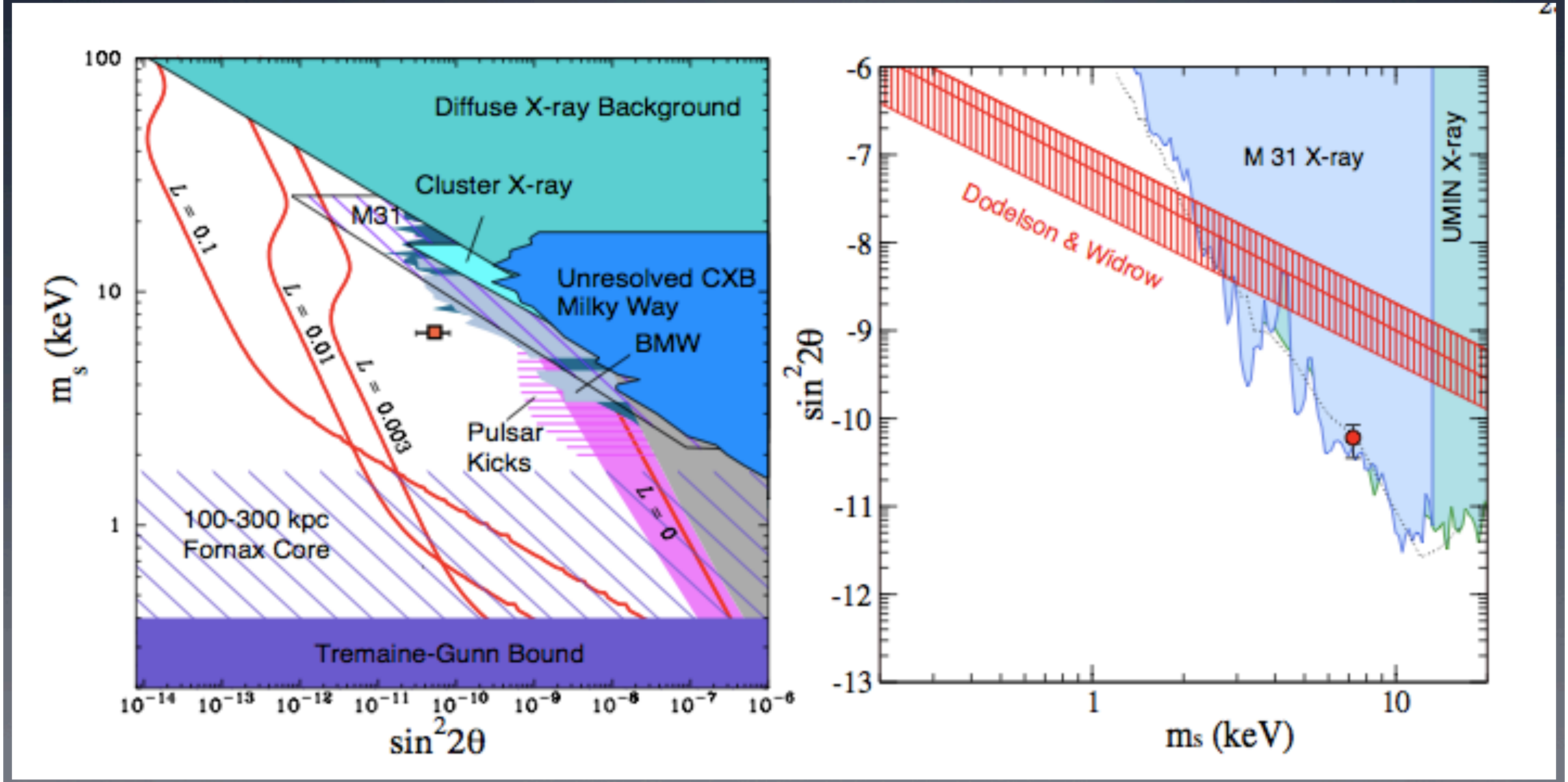


shower of new models and DM candidates

*VP=virtual preprint

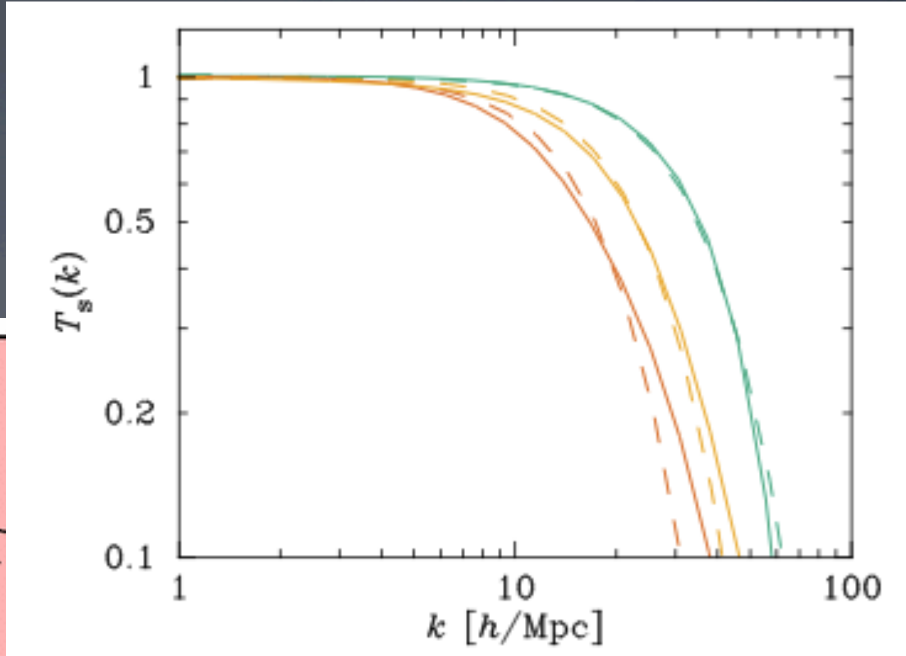
quantumdiaries .org

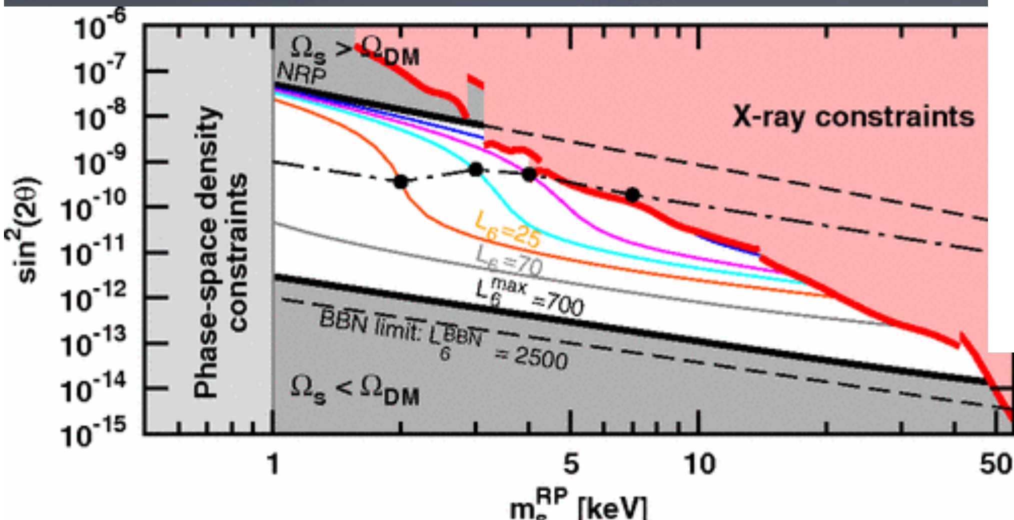
Sterile Neutrinos Still Viable



Sterile Neutrinos Still Viable

< 25% produced by non-resonant oscillations (DW)
(<10% if all DM is sterile neutrinos)
Resonant oscillations, other production (singlet Higgs, inflaton decay, split seesaw) ok

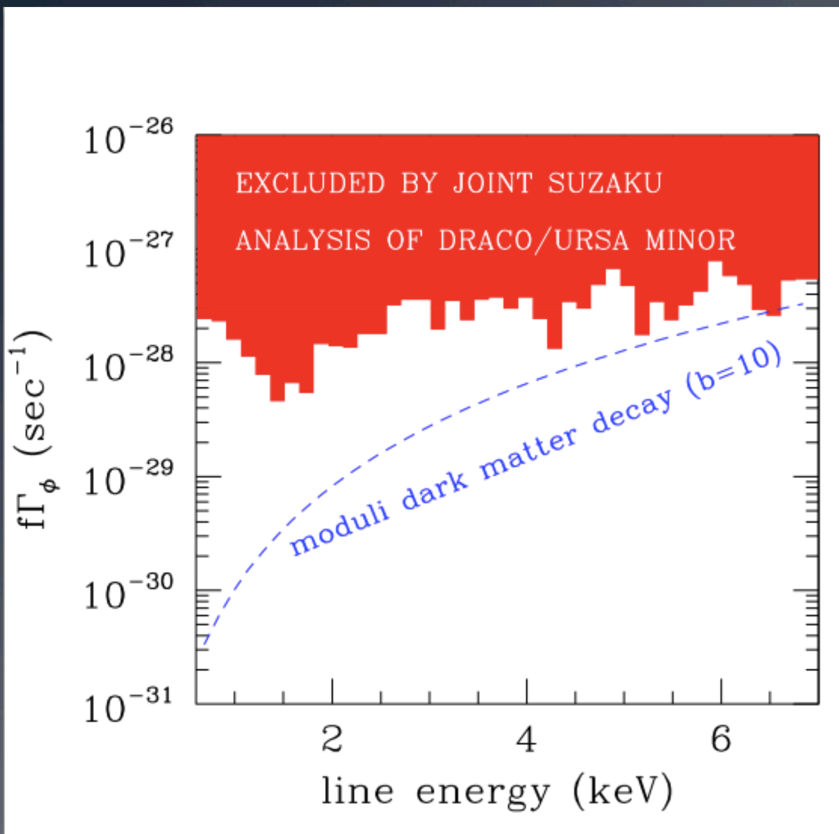


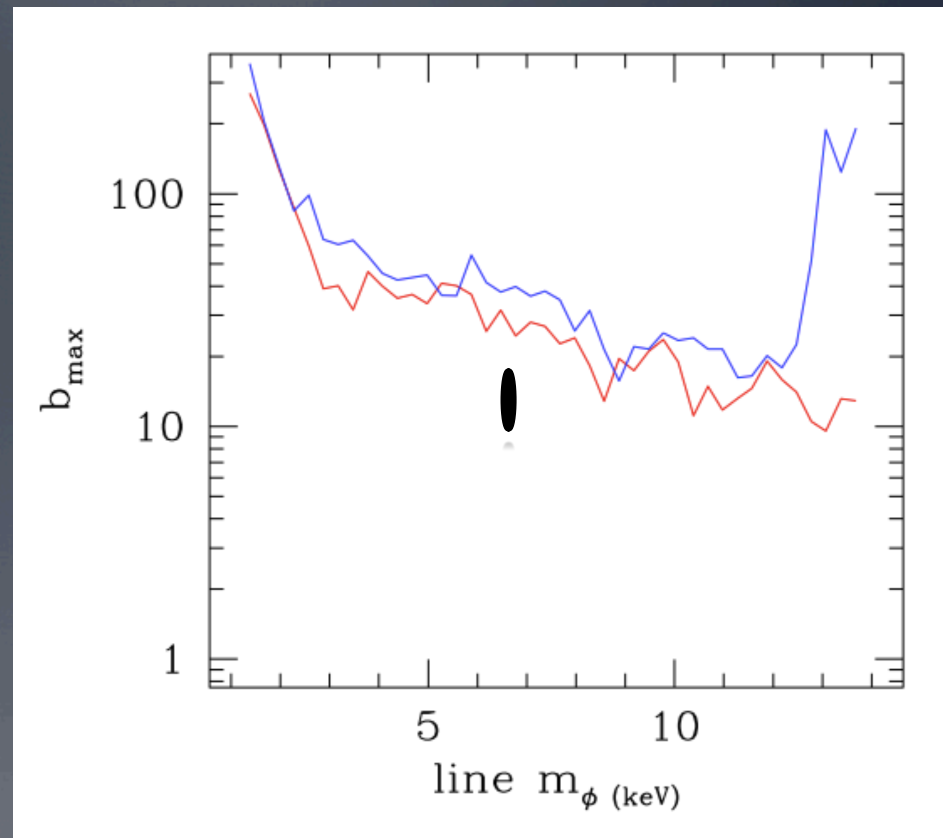


Boyarksy et al. 2009

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

As is Moduli DM





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

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

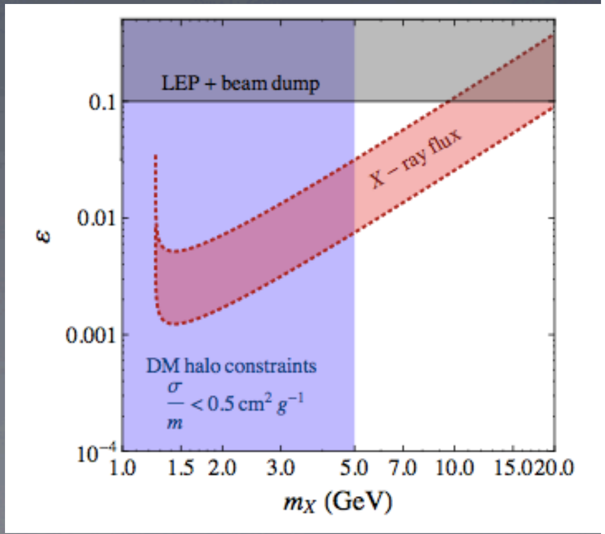
Ursa Minor and Draco

Kusenko, Loewenstein, and Yanagida 2013

How Can We Distinguish These Candidates?

- Other particle physics considerations, e.g. "naturalness" vs fine-tuning
- Cosmological implications (N_{eff})

- Clustering (structure on galaxy scales)
  Most keV DM candidates are WDM, but...
  -- sterile neutrinos: CDM and/or WDM
  -- moduli, eXciting DM: CDM
  -- axion: CDM or CDM+HDM
- Self-interaction (e.g., mili-charged DM)



Fransden et al. 2014

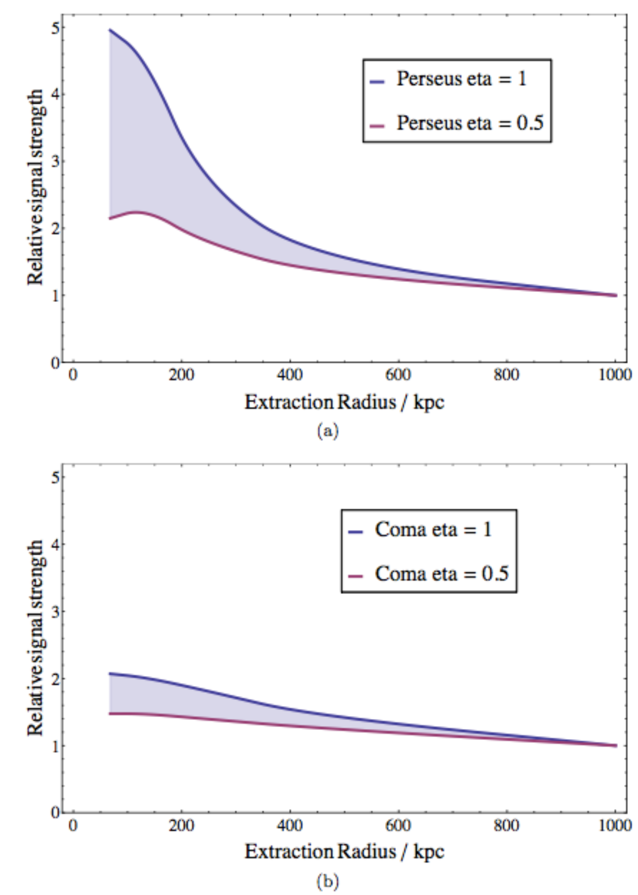
How Can We Distinguish These Candidates?

Dependence on density (i.e. DM concentration *between* halos, *radius* within halos) and environment* –

-- 2-body [annihilating, *eXciting, atomic LDM] vs

-- 1-body interactions [decay]

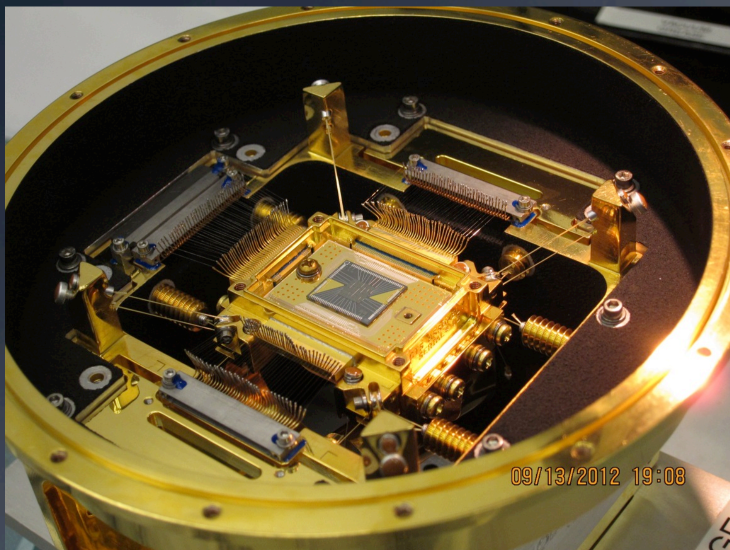
Dependence on B-fields (DM→ALP→X-ray) – (explain diversity among clusters, between MW and M31; Conlon and Day/Powell)

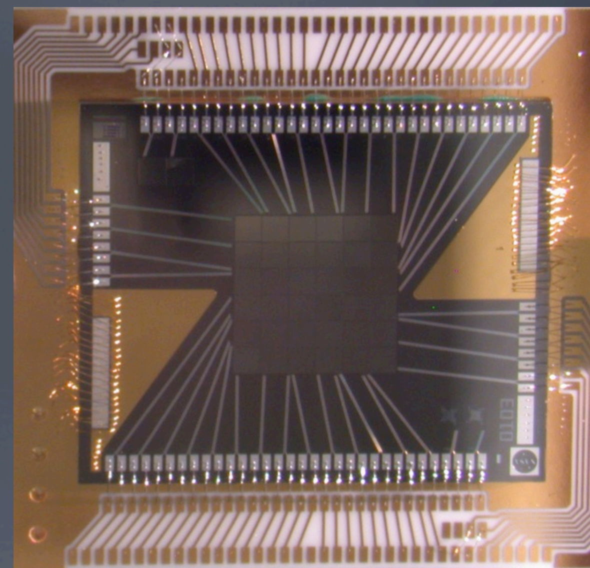


$\eta == d\ln B/d\ln(n_e)$

Coming Attractions

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

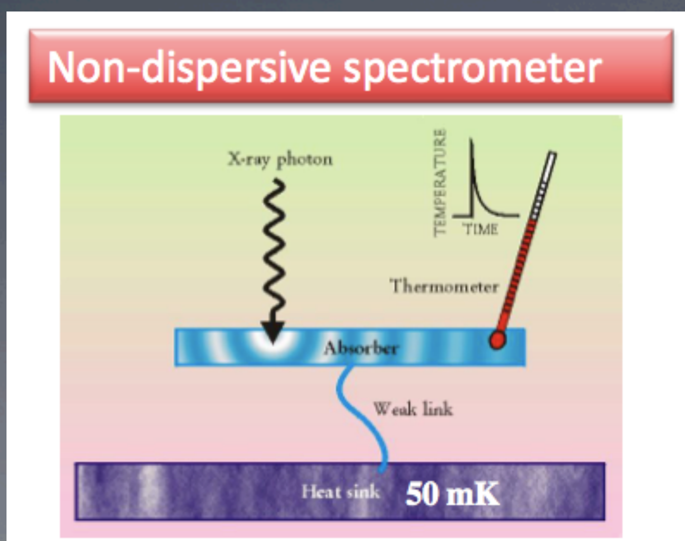


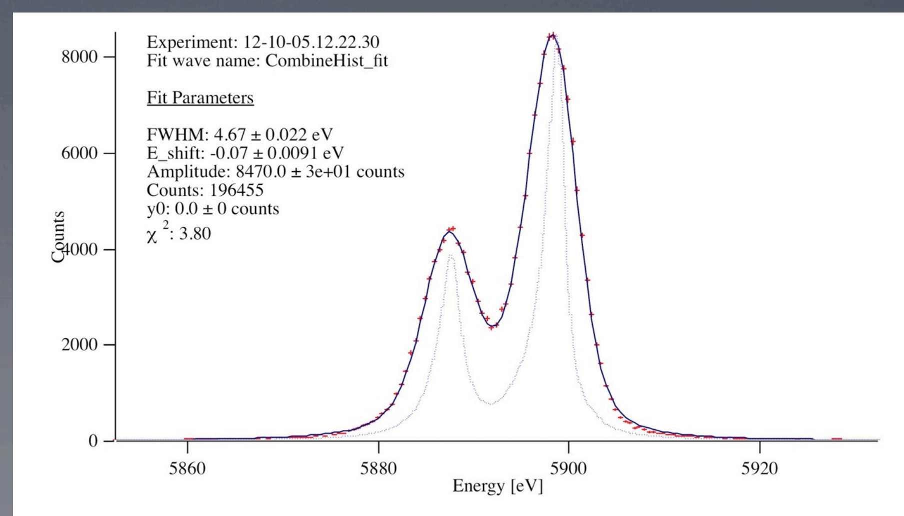


6 × 6

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/□′**

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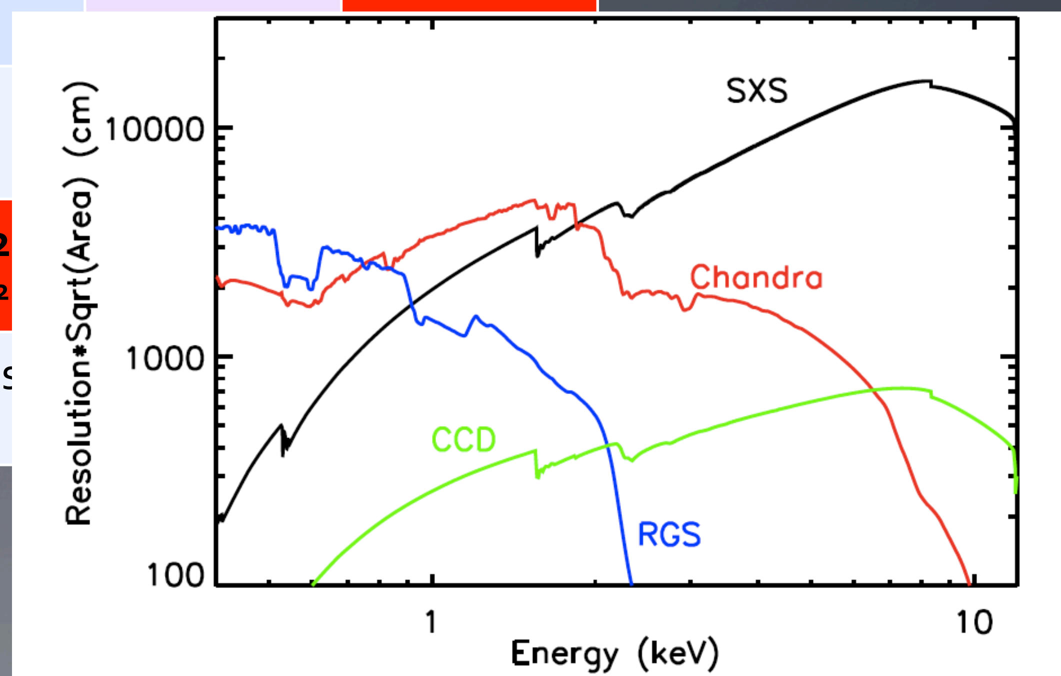

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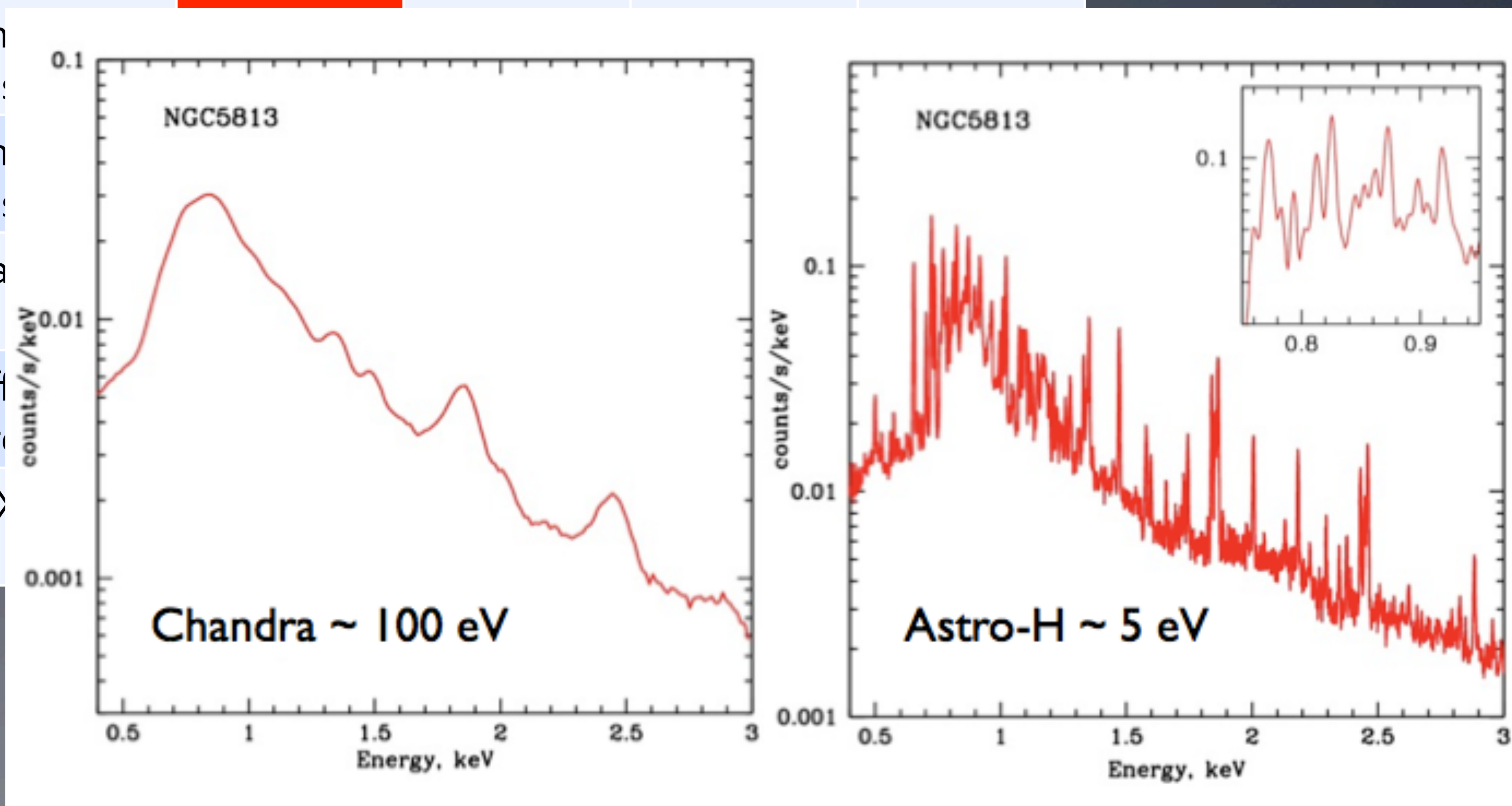
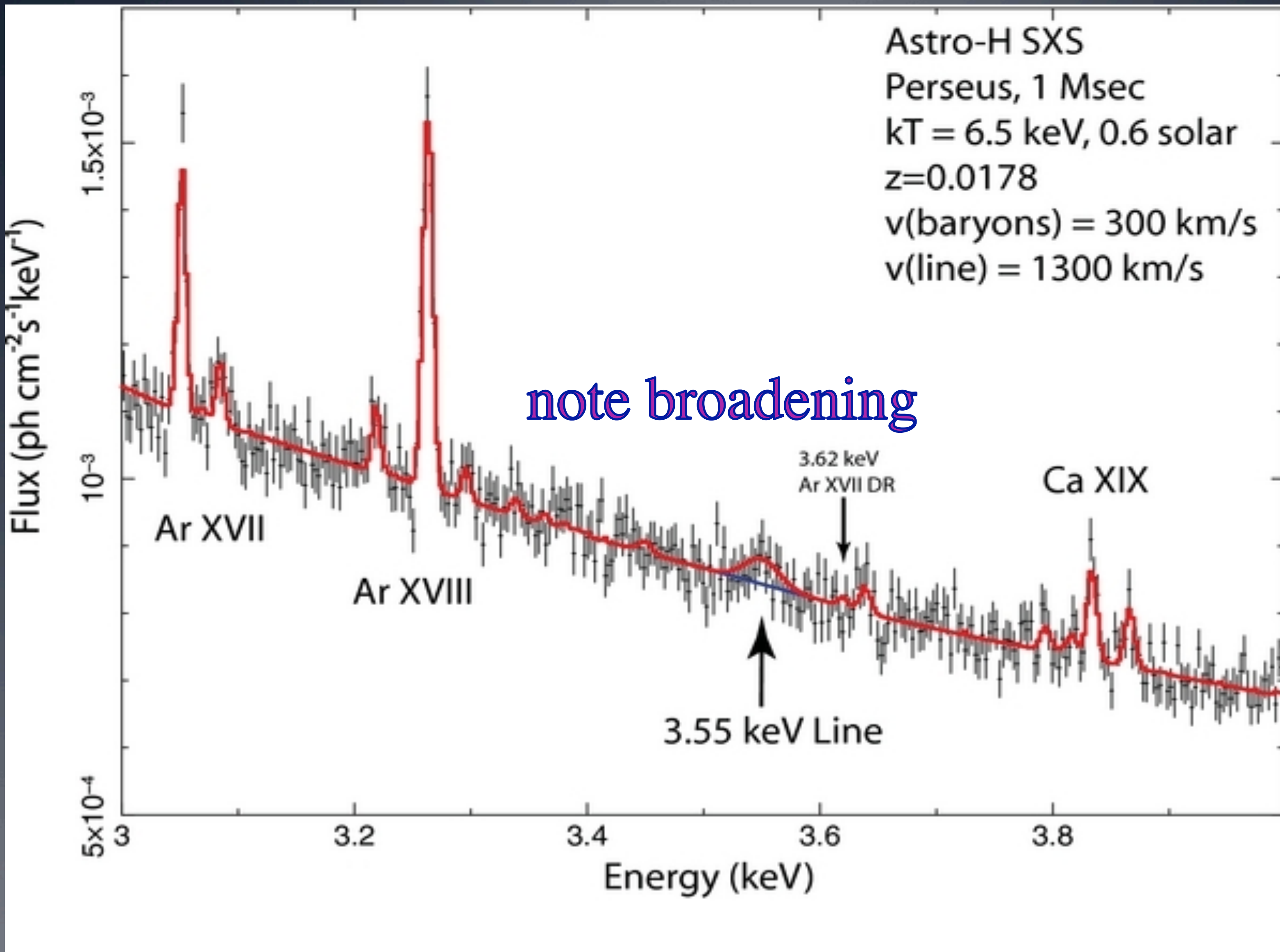
I. Zhuravleva
(Snowcluster '13)





clear and distinct...

Final Remarks

• Two independent groups find evidence of an unidentified X-ray emission line consistent with LDM decay – in our case at at >3σ in 5 statistically independent spectra.

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

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

• 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.

HARVARD-SMITHSONIAN CENTER FOR ASTROPHYSICS

Mysterious X-ray Signal Intrigues Astronomers

Tuesday, June 24, 2014
News Feature

A mysterious X-ray signal has been found in a detailed study of galaxy clusters using NASA's Chandra X-ray Observatory and ESA's XMM-Newton. One intriguing possibility is that the X-rays are produced by the decay of sterile neutrinos, a type of particle that has been proposed as a candidate for dark matter.

While holding exciting potential, these results must be confirmed with additional data to rule out other explanations and determine whether it is plausible that dark matter has been observed.

Astronomers think dark matter constitutes 85% of the matter in the universe, but does not emit or absorb light like "normal" matter such as the protons, neutrons, and electrons that make up the familiar elements observed in planets, stars, and galaxies. Because of this, scientists must use indirect methods to search for clues about dark matter.

The latest results from Chandra and XMM-Newton consist of an unidentified X-ray emission line, that is, a spike of intensity at a very specific wavelength of X-ray light. Astronomers detected this emission line in the Perseus galaxy cluster using both Chandra and XMM-Newton. They also found the line in a combined study of 73 other galaxy clusters with XMM-Newton.

"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."

The authors suggest this emission line could be a signature from the decay of a "sterile neutrino." Sterile neutrinos are a hypothetical type of neutrino that is predicted to interact with normal matter only via gravity. Some scientists have proposed that sterile neutrinos may at least partially explain dark matter.

"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."

One source of uncertainty is that the detection of this emission line is pushing the capabilities of the two observatories in terms of sensitivity. Also, there may be explanations other than sterile neutrinos if this X-ray emission line is deemed to be real. There are ways that normal matter in the cluster could have produced the line, although the team's analysis suggested that all of these would involve unlikely changes to our understanding of physical conditions in the galaxy cluster or the details of the atomic physics of extremely hot gases.

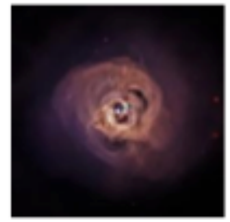
The authors note that even if the sterile neutrino interpretation is correct, their detection does not necessarily imply that all of dark matter is composed of these particles.

"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."

Because of the tantalizing potential of these results, after submitting to *The Astrophysical Journal* the authors posted a copy of the paper to a publicly accessible database, arXiv. This forum allows scientists to examine a paper prior to its acceptance into a peer-reviewed journal. The paper ignited a flurry of activity, with 55 new papers having already cited this work, mostly involving theories discussing the emission line as possible evidence for dark matter. Some of the papers explore the sterile neutrino interpretation, but others suggest different types of candidate dark matter particles, such as the axion, may have been detected.

Only a week after Bulbul et al. placed their paper on the arXiv, a different group, led by Alexey Boyarsky of Leiden University in the Netherlands, placed a paper on the arXiv reporting evidence for an emission line at the same energy in XMM-Newton observations of the galaxy M31 and the outskirts of the Perseus cluster. This strengthens the evidence that the emission line is real and not an instrumental artifact.

Chandra X-ray Observatory Press Release



This image shows a new view of the Perseus cluster, one of the galaxy clusters included in the new study.
NASA/CXC/SAO/E.Bulbul, et al.

"BICEP2 effect"

From the6/24 PR

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