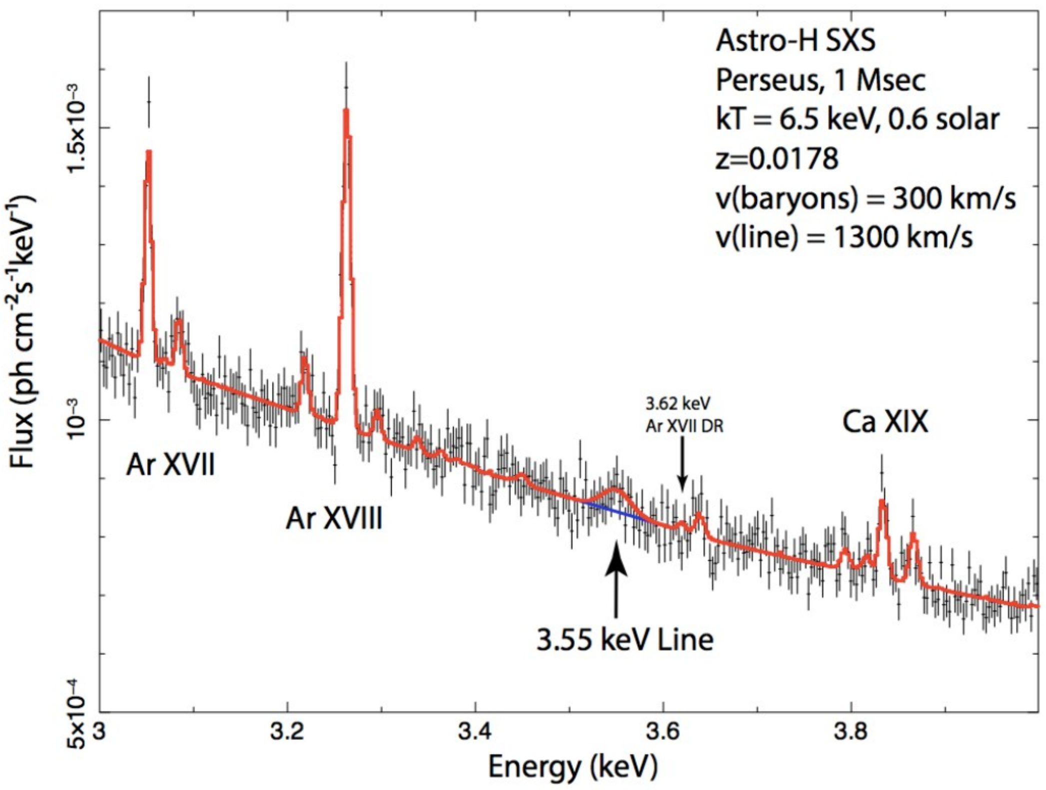
Sterile Neutrino Dark Matter



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Physics 290E
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Outline

- Sterile neutrinos
- ...as dark matter?
- Advantages over cold DM
- X-ray astronomy evidence for 7 keV particle
- Future prospects

Sterile neutrinos: Motivation

- Oscillations imply neutrino mass
- Mass can come from *Majorana* and/or *Dirac* terms:
  - Majorana: $\mathcal{L} \supset \overline{\nu}^c_R \nu_L$ $\nu^c_R \equiv C\gamma^{0T}\nu^*_L$ Not allowed in gauge-invariant Lag.! ν_L carries weak charge! But we *can* add such a term for a new sterile N_R!
  - Dirac: $\mathcal{L} \supset \overline{N}_R \nu_L$ Requires new N_R field!
- Since we can't insert a Majorana term for the active neutrinos ν_L, we “need” at least one sterile field N_R
- If N_R has a Majorana term, EWSB generates three effective Majorana terms for the ν_L, leading to 0νββ
- Otherwise, just Dirac masses, no 0νββ

Sterile neutrinos: Motivation

- Smallness of neutrino masses is unnatural.
  Solution: *Seesaw mechanism*

(many models; here's one example)

$$\underset{\text{mass mixing}}{\mathcal{M}} = \begin{array}{cc} \begin{pmatrix} 0_{3x3} & D_{3x3} \\ D_{3x3} & M_{3x3} \end{pmatrix} & \begin{array}{l} \text{active} \\ \text{sterile} \end{array} \\ \begin{array}{cc} \text{active} & \text{sterile} \end{array} & \end{array}$$

$$m_{\text{heavy}} \approx \frac{1}{2}\left(|M| + \sqrt{|M|^2 + 4|D|^2}\right) \approx |M|$$

$$m_{\text{light}} \approx \frac{1}{2}\left(|M| - \sqrt{|M|^2 + 4|D|^2}\right) \approx \frac{|D|^2}{|M|}$$

- With |*D*| near EW scale, |*M*| near Planck scale, light neutrinos emerge naturally!
- Ability to solve naturalness problem thus another motivation for sterile neutrinos (also: every other SM particle has both chiralities!)

Sterile neutrinos: Summary

- *A priori*, masses could be anywhere from eV to Planck scale (although many models like Seesaw prefer heavier masses)
- Could be any number of them; 3 is most natural, but not required
- Some could be light and others could be heavy
- Some oscillation experiments (but not others) hint at ~eV species
    - Too light to be DM
- Astrophysical observations hint at ~keV species (DM candidate!)

Neutrino dark matter?

- SM neutrinos too light! Unable to form density perturbations
  - Tremaine-Gunn bound: $m_{\mathrm{DM}} > 400$ eV
- What about sterile neutrinos?
  - If too heavy, then too unstable ($\Gamma \sim M^5$)
  - keV scale is the sweet spot
- keV DM can be warm or “cool” (but not cold!), depending on production conditions
  - Warm DM has multiple advantages over standard cold DM!

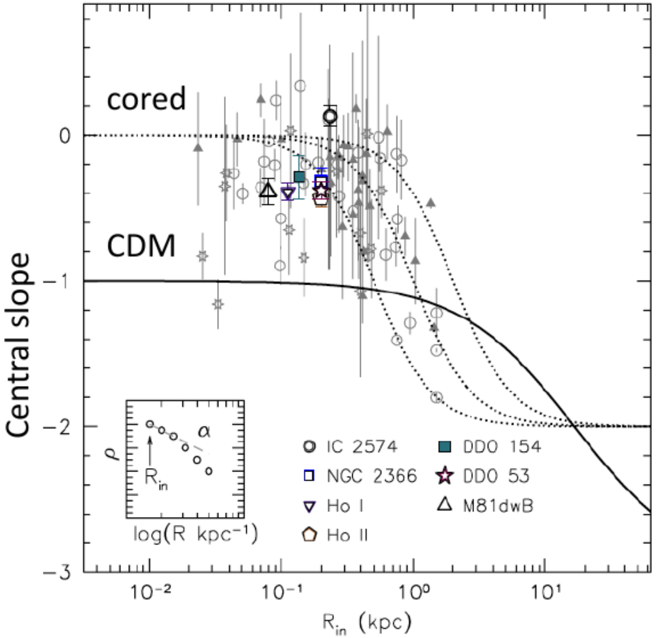
Production in early Universe

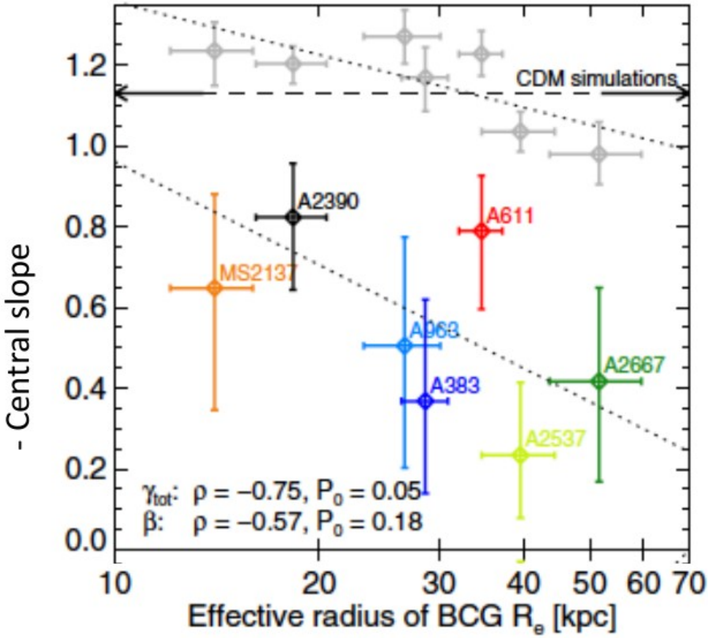
- Neutrino oscillations
  - Off-resonance → near-thermal spectrum
  - On-resonance (MSW) → non-thermal, cooler spectrum
- Decays
  - Inflaton, etc.
  - (Extended) Higgs decays! (Same coupling can generate mass)

$$\mathcal{L} = \mathcal{L}_{SM} + \bar{N} i \partial\!\!\!/ N + \frac{1}{2}(\partial S)^2 - y H \bar{L} N - \frac{f}{2} S \bar{N}^c N - V(H,S) + h.c.$$

Cold DM: Troubles at small scales

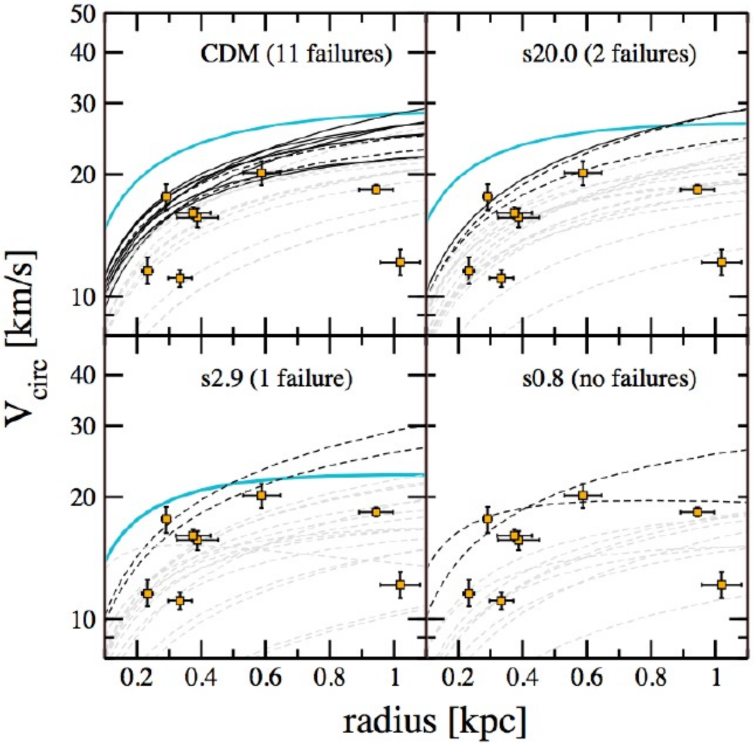
- Cold DM has various unresolved issues *at small scales,* including:
  - Core/cusp problem: CDM predicts a galactic inner density slope that is too steep
  - Satellite galaxies: CDM predicts more satellite galaxies than observed, off by ~10
  - Massive halos: CDM overpredicts density
  - Pure disk galaxies: Not predicted by CDM

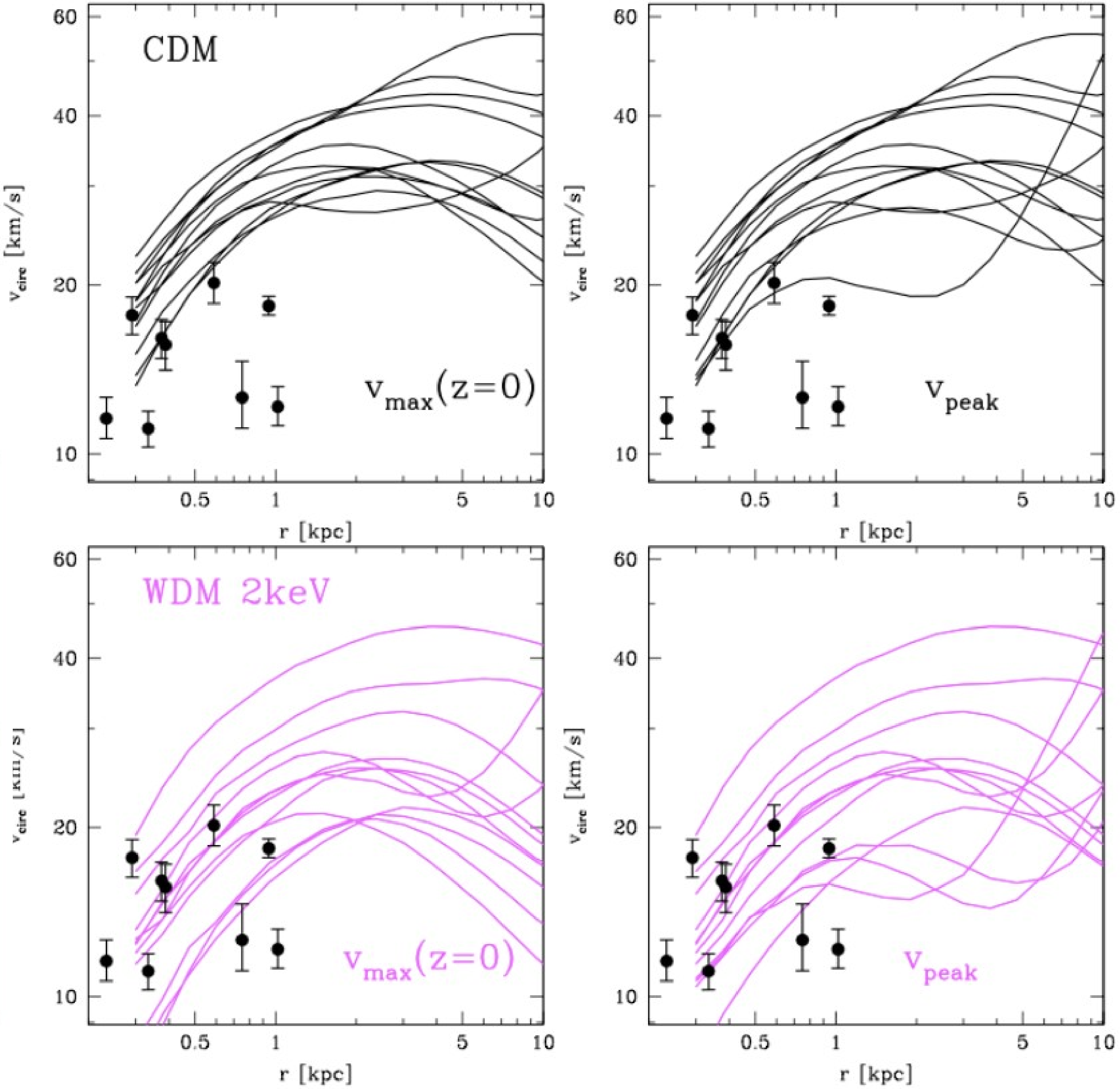




Warm DM to the rescue!

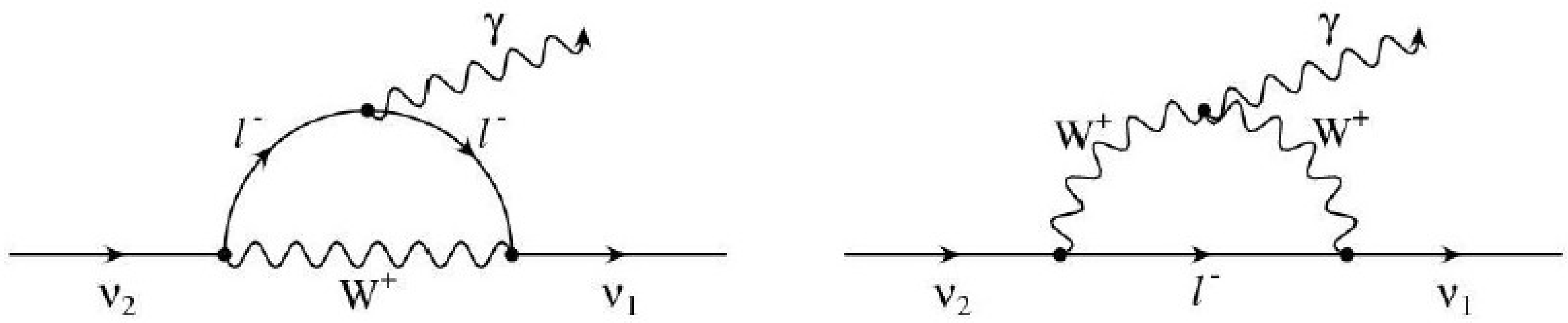
At keV scale, WDM largely resolves small-scale issues of CDM





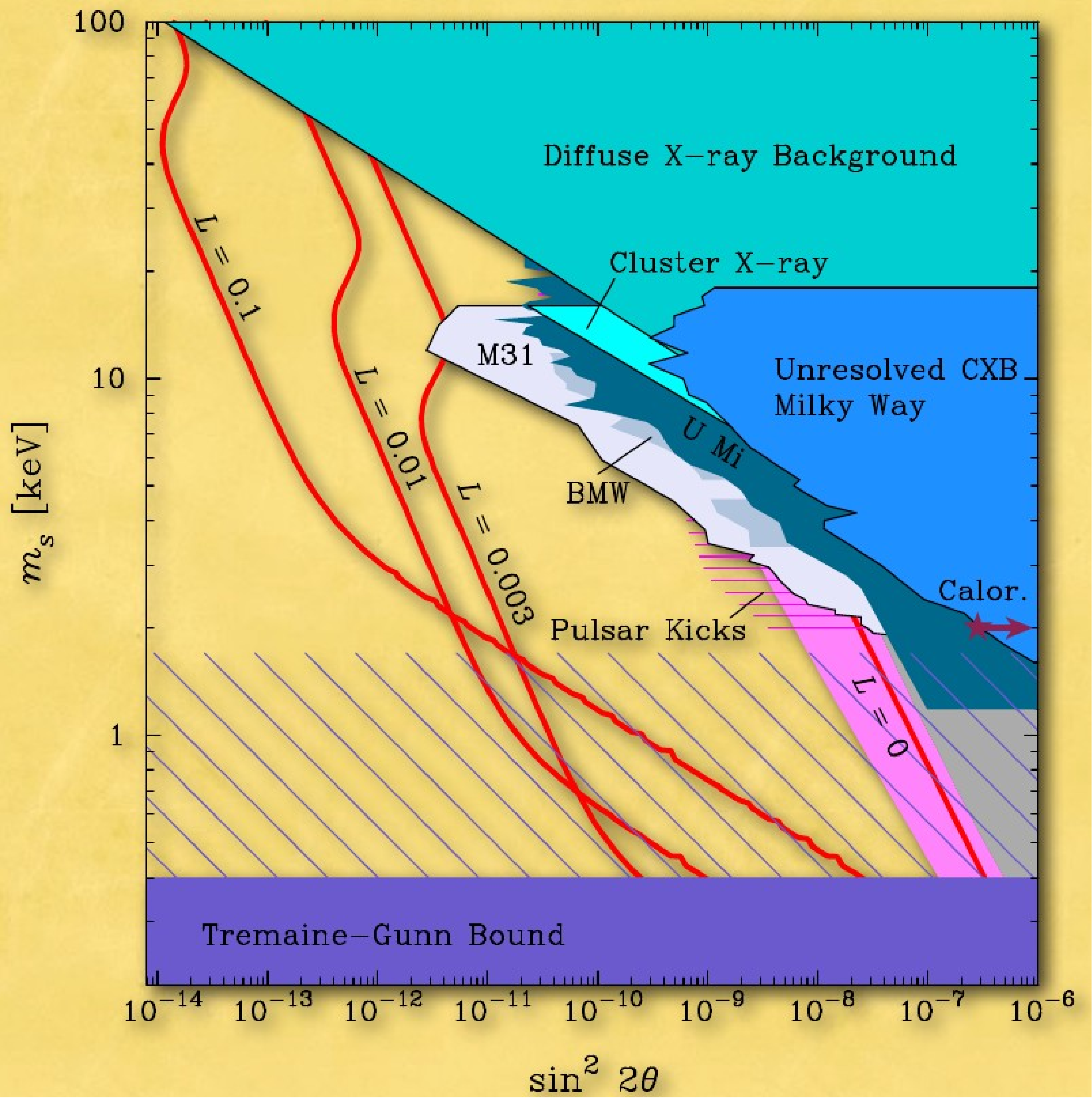
Detection

- Sterile neutrinos can decay into a lighter neutrino + photon:



- Gamma energy = m/2
- At keV-scale, lifetime greater than age of Universe, but there's a lot of DM out there!
- Detect using standard X-ray astronomy

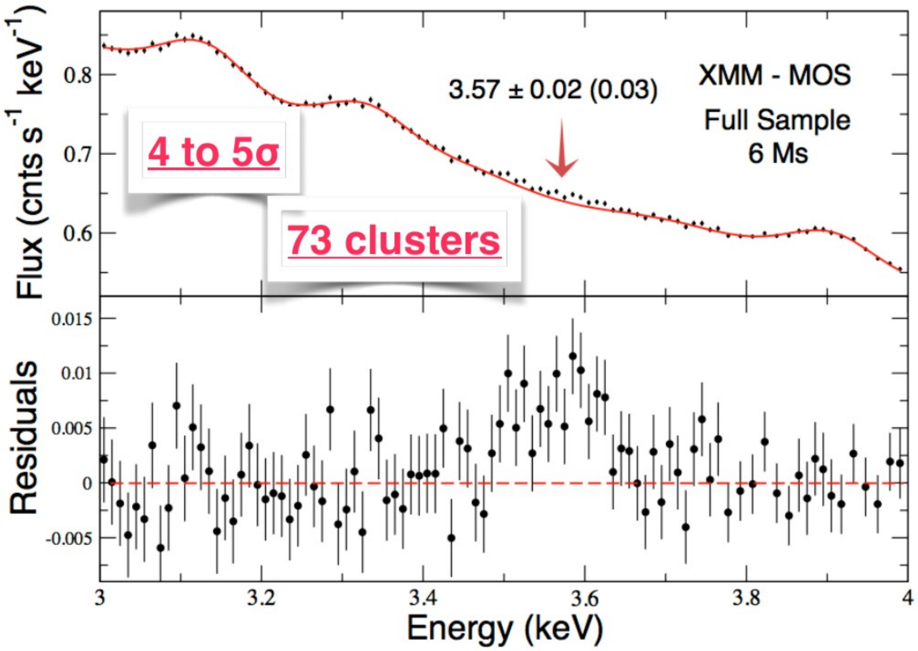
Constraints as of 2012



- Colored regions excluded
- θ is mixing angle
- Many regions remain(ed) viable!

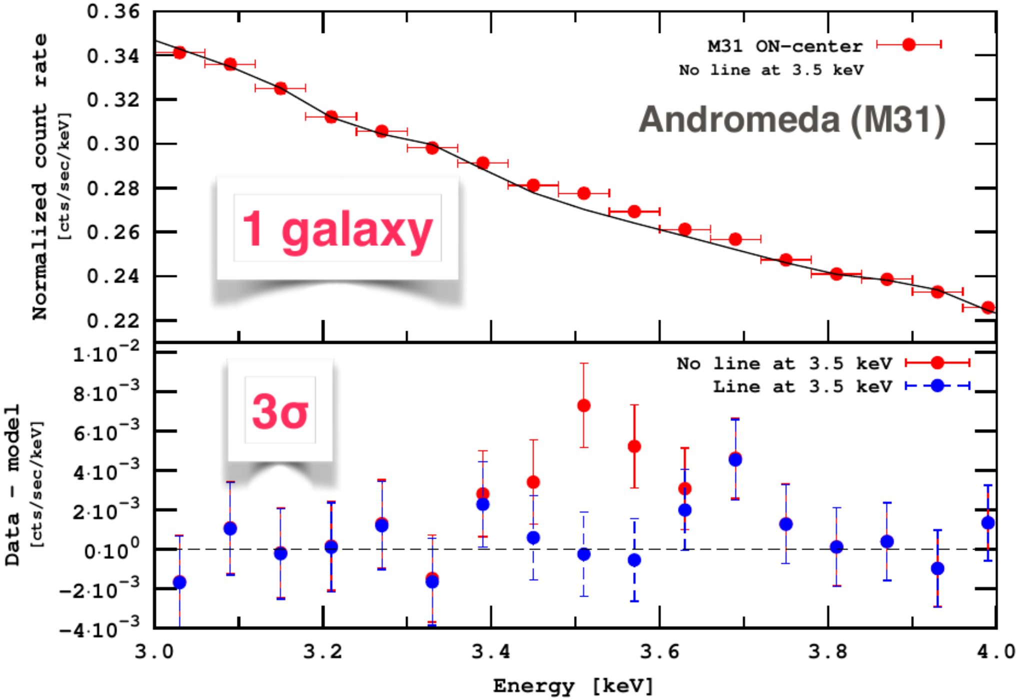
XMM-Newton observations

- Feb 2014: Bulbul *et al.* discover 3.55 keV line in X-ray spectra of 73 clusters at “4-5σ”
- One week later: Boyarsky *et al.* sees line in Perseus cluster (2.3σ), Andromeda (3σ), total 4.4σ



4 to 5σ

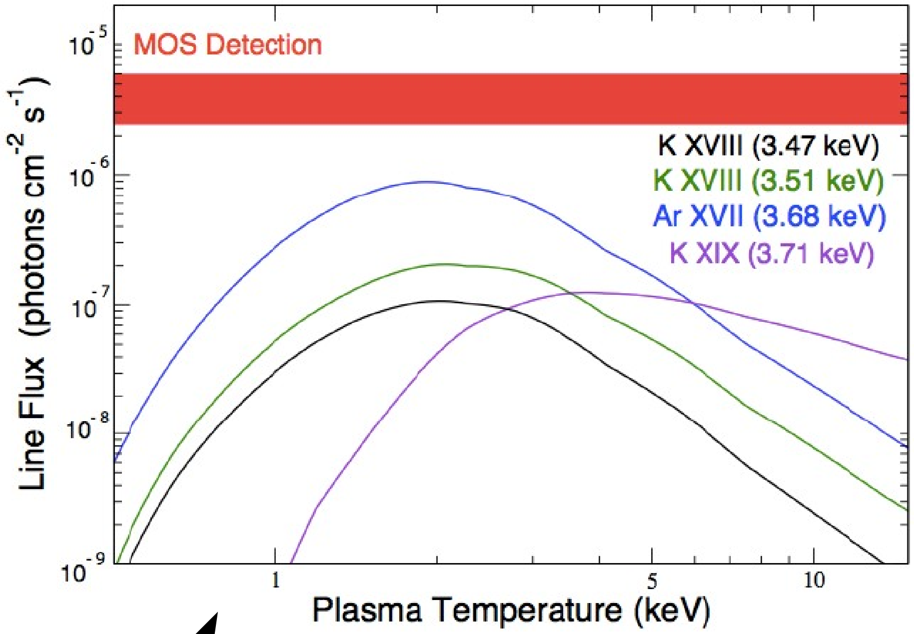
73 clusters

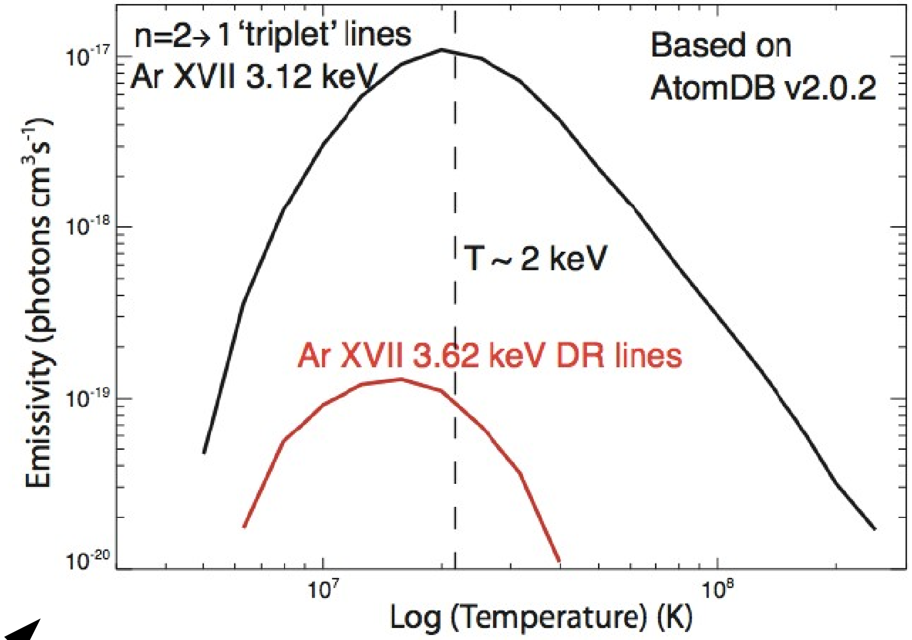


1 galaxy

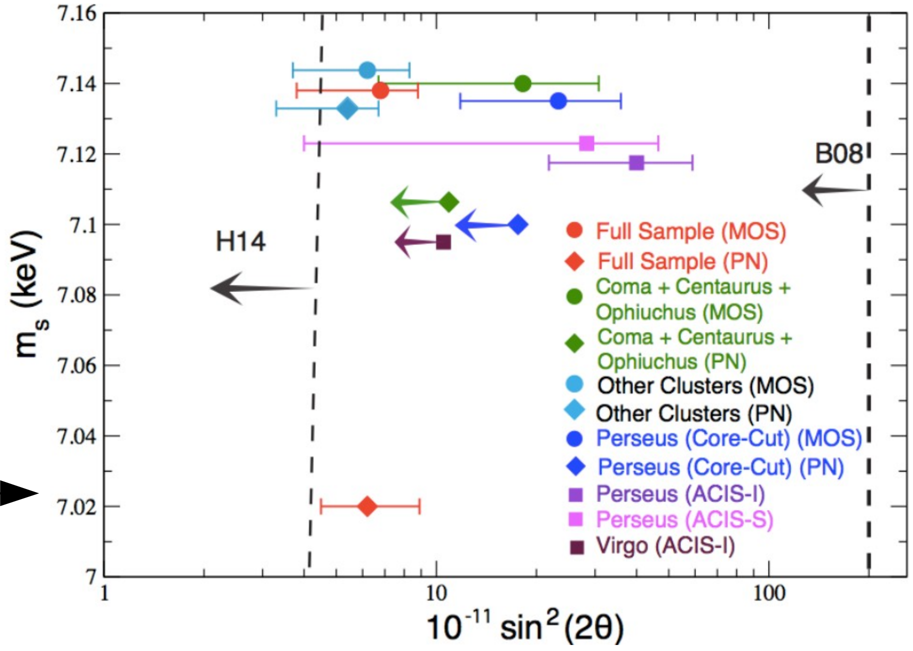
3σ

Does it hold up?



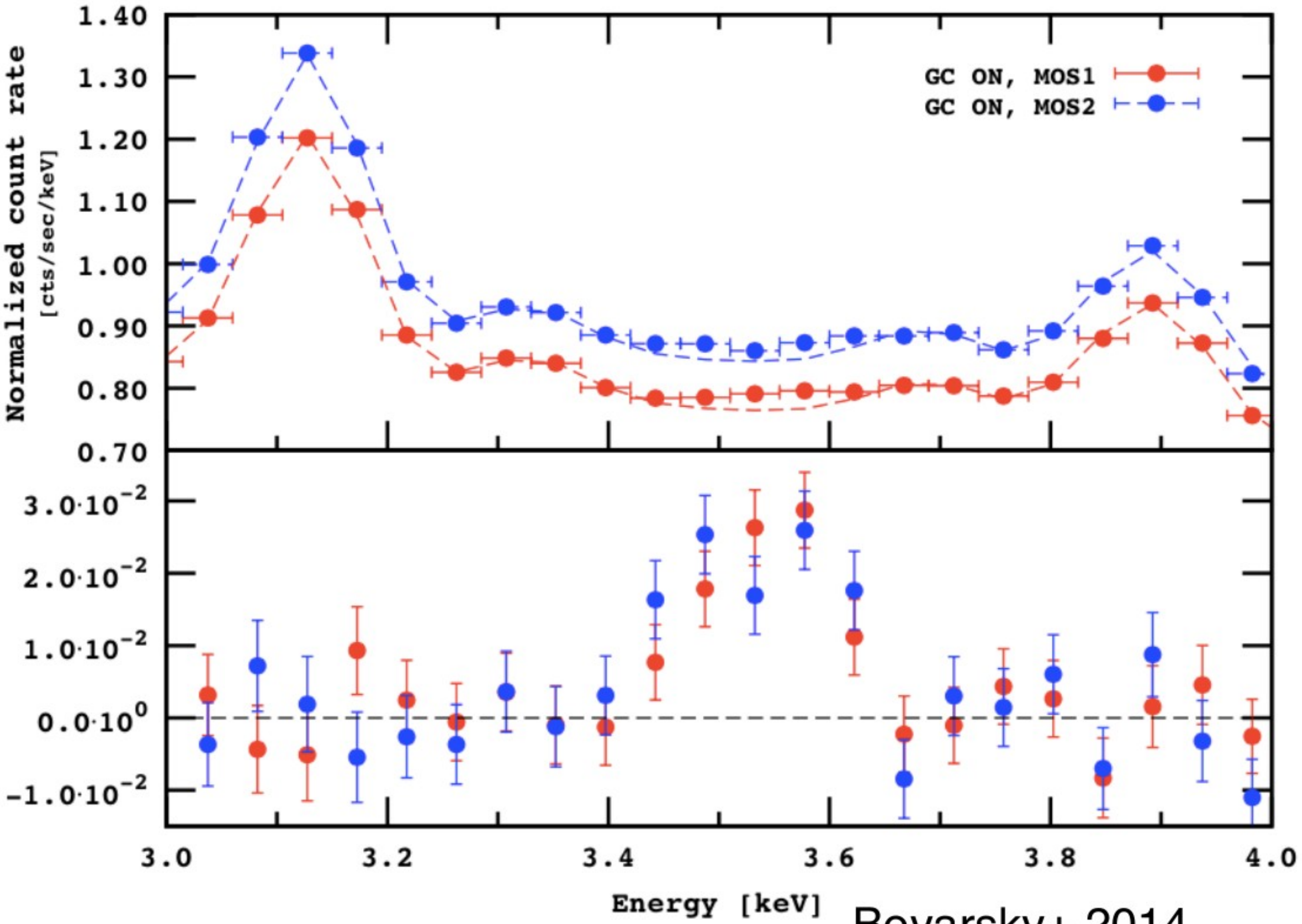


Atomic transitions too weak to explain signal



Signal (or limits) consistent between subsamples

What about galactic center?

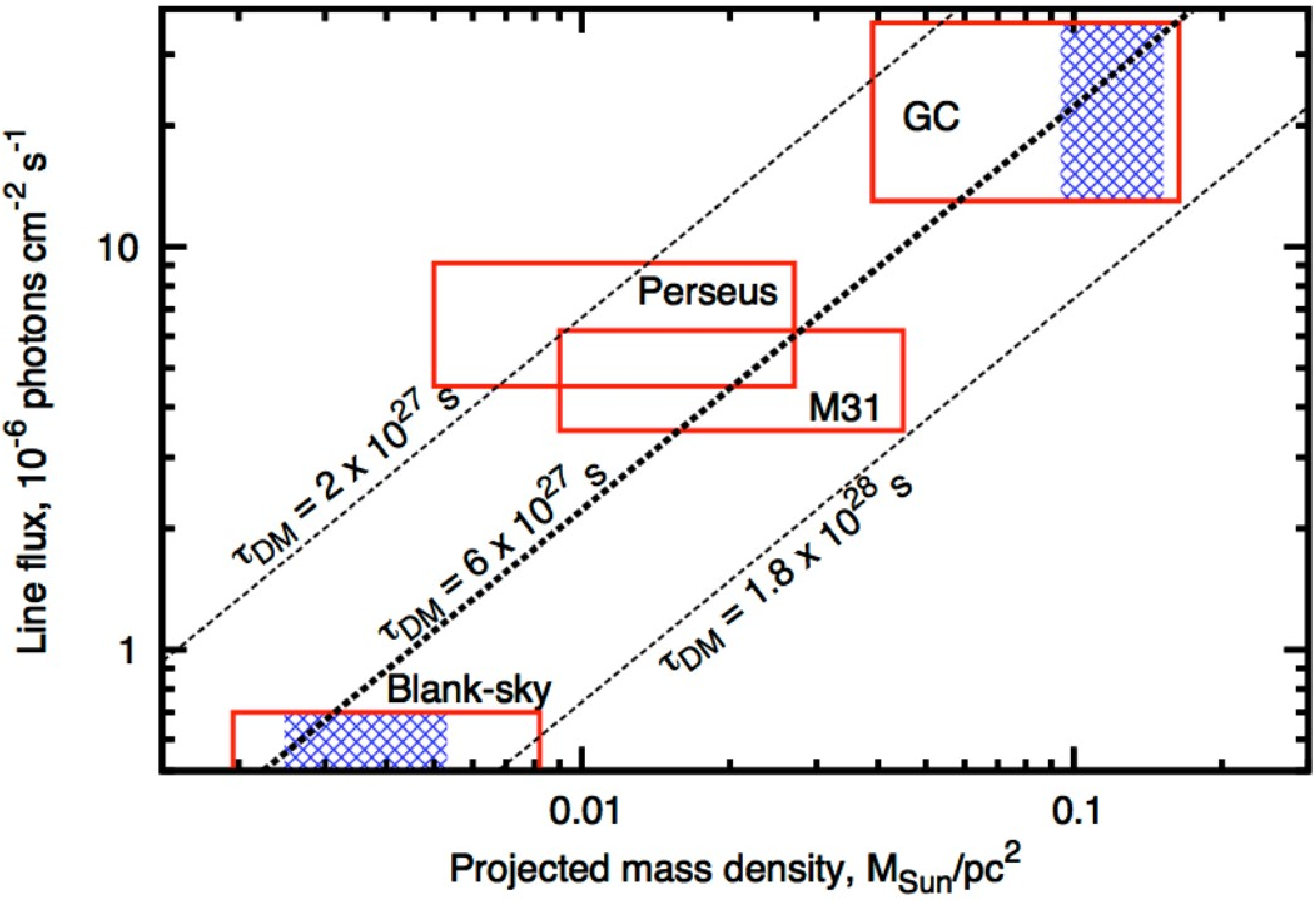


Boyarsky+ 2014

Signal is here, too, although there's been some controversy over background modeling

Boyarsky+ published series of papers addressing (refuting?) these objections

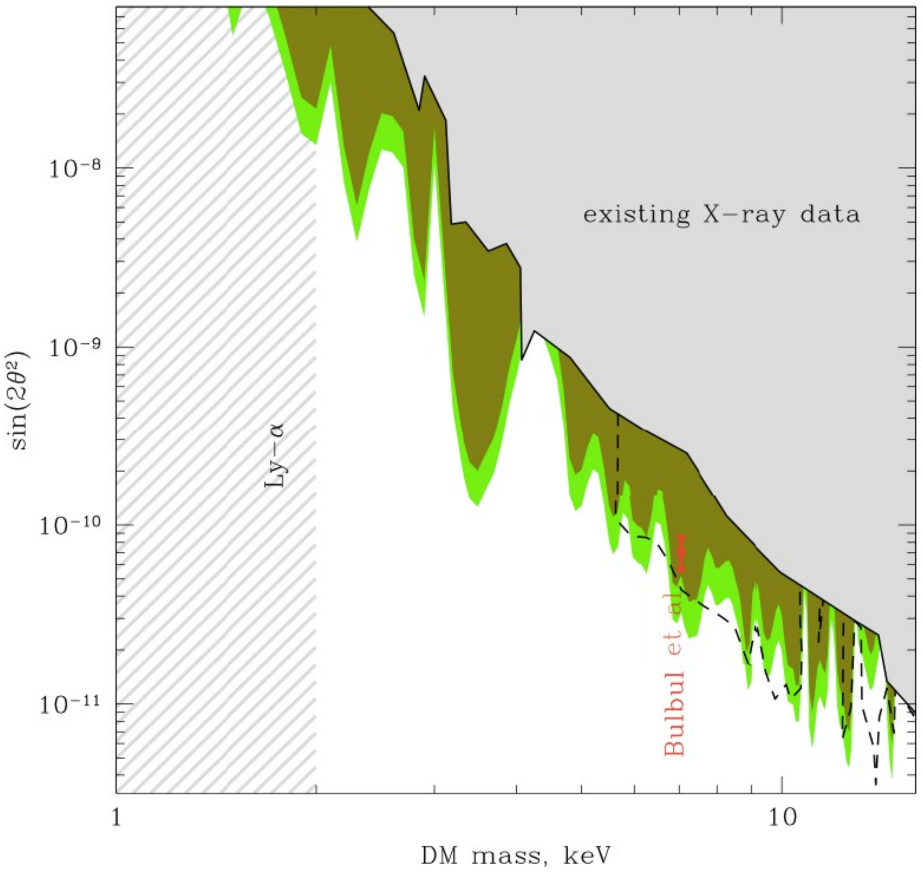
Consistent decay lifetime

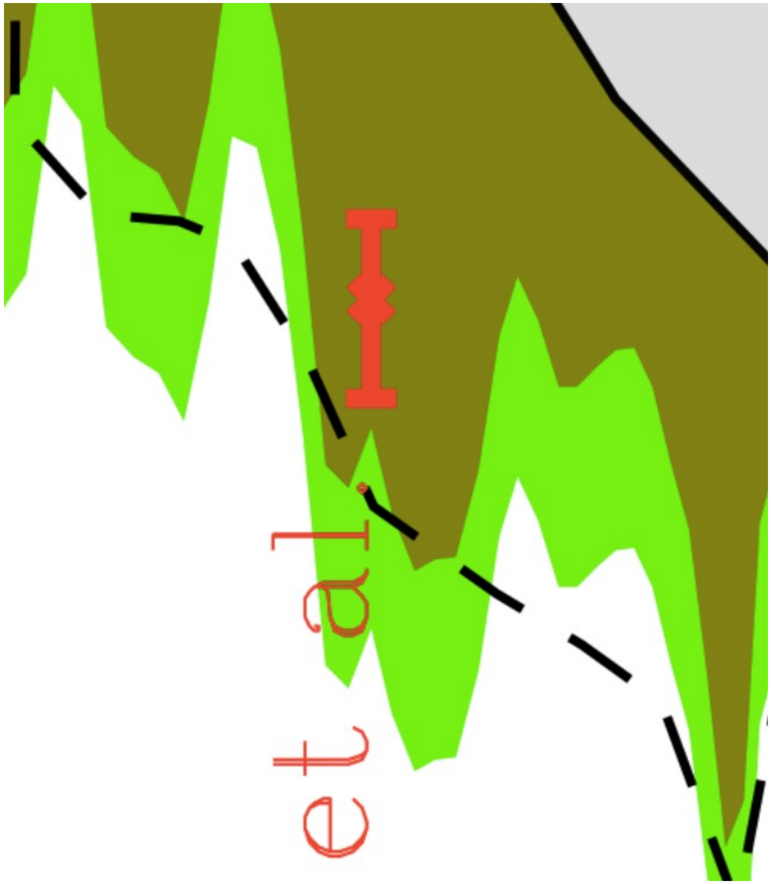


Constraints from dwarf galaxies

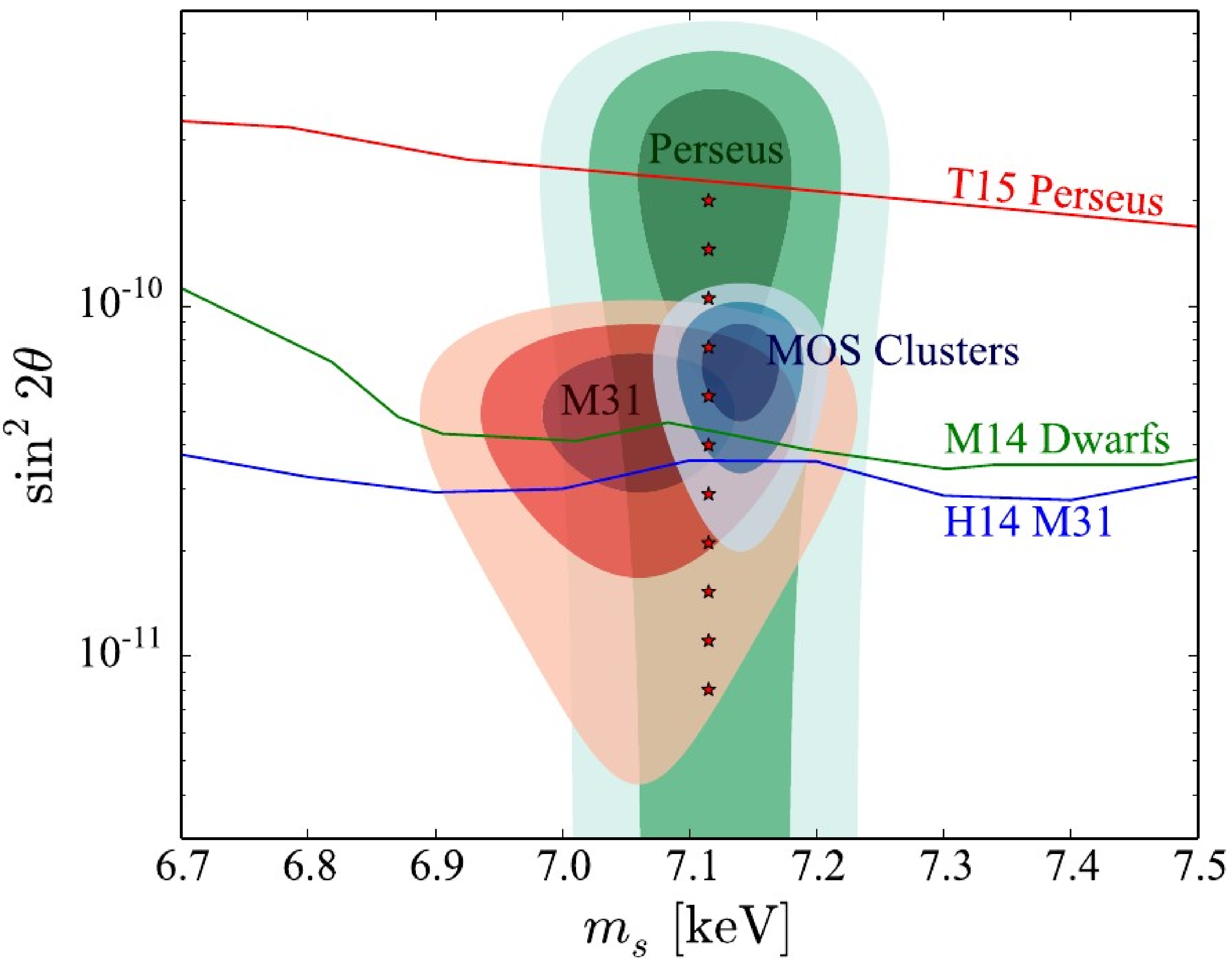
2014: Analysis of 8 dwarf galaxies with XMM-Newton

Signal lies at edge of excluded region



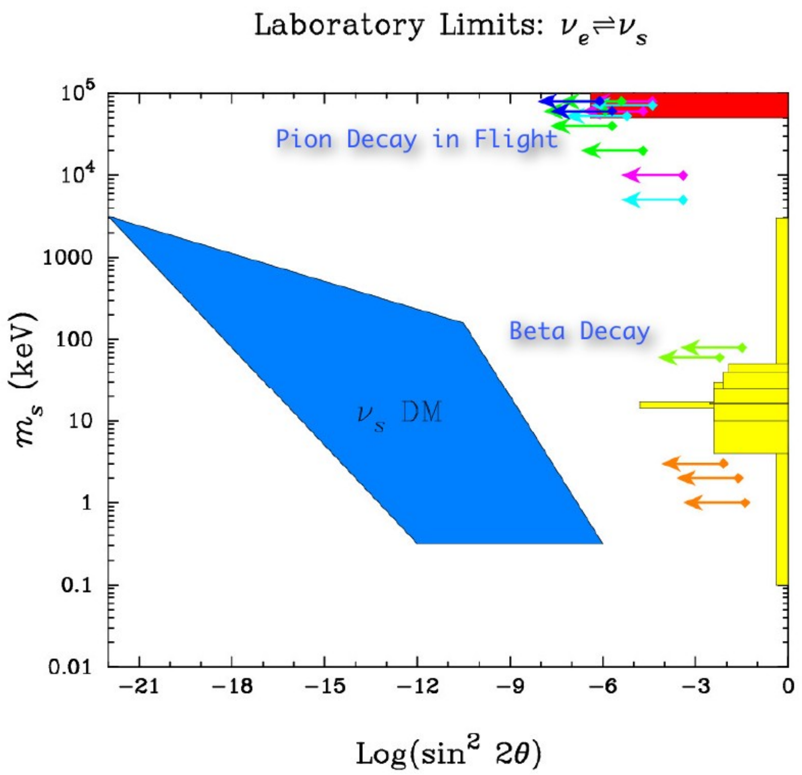


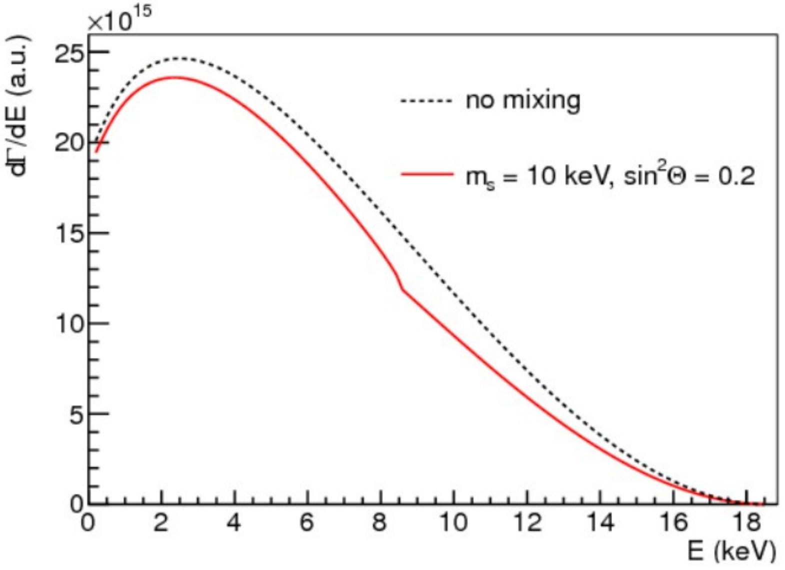
“Global” picture



Future prospects

- Astro-H X-ray observatory to be launched in 2016
- NASA sounding rocket program
  - Micro-X and XQC spectrometers
- Deeper observations of local group
- Kink searches in β decay, electron capture (tricky!)





Summary

- Sterile neutrinos are well motivated by theory
- Masses could lie anywhere from eV to Planck scale
- A keV sterile neutrino is an ideal candidate for warm/cool dark matter
- It could resolve numerous small-scale issues with cold dark matter's predictions
- X-ray astronomy has provided a tantalizing hint of a 7 keV state
- Further evidence may come sooner rather than later!

Thanks!

- https://indico.cern.ch/event/373156/session/1/contribution/22/attachments/1141576/1635409/Abazajian_SSI_2015.pdf
(XMM-Newton observations, etc.)
- http://lss.fnal.gov/conf/C0911181/Petraki_CosPA09.pdf (overview of sterile neutrino dark matter)
- http://arxiv.org/abs/1204.5379 (sterile neutrino white paper)
- http://arxiv.org/abs/1402.2301 (XMM-Newton, Bulbul *et al.*)
- http://arxiv.org/abs/1402.4119 (XMM-Newton, Boyarsky *et al.*)