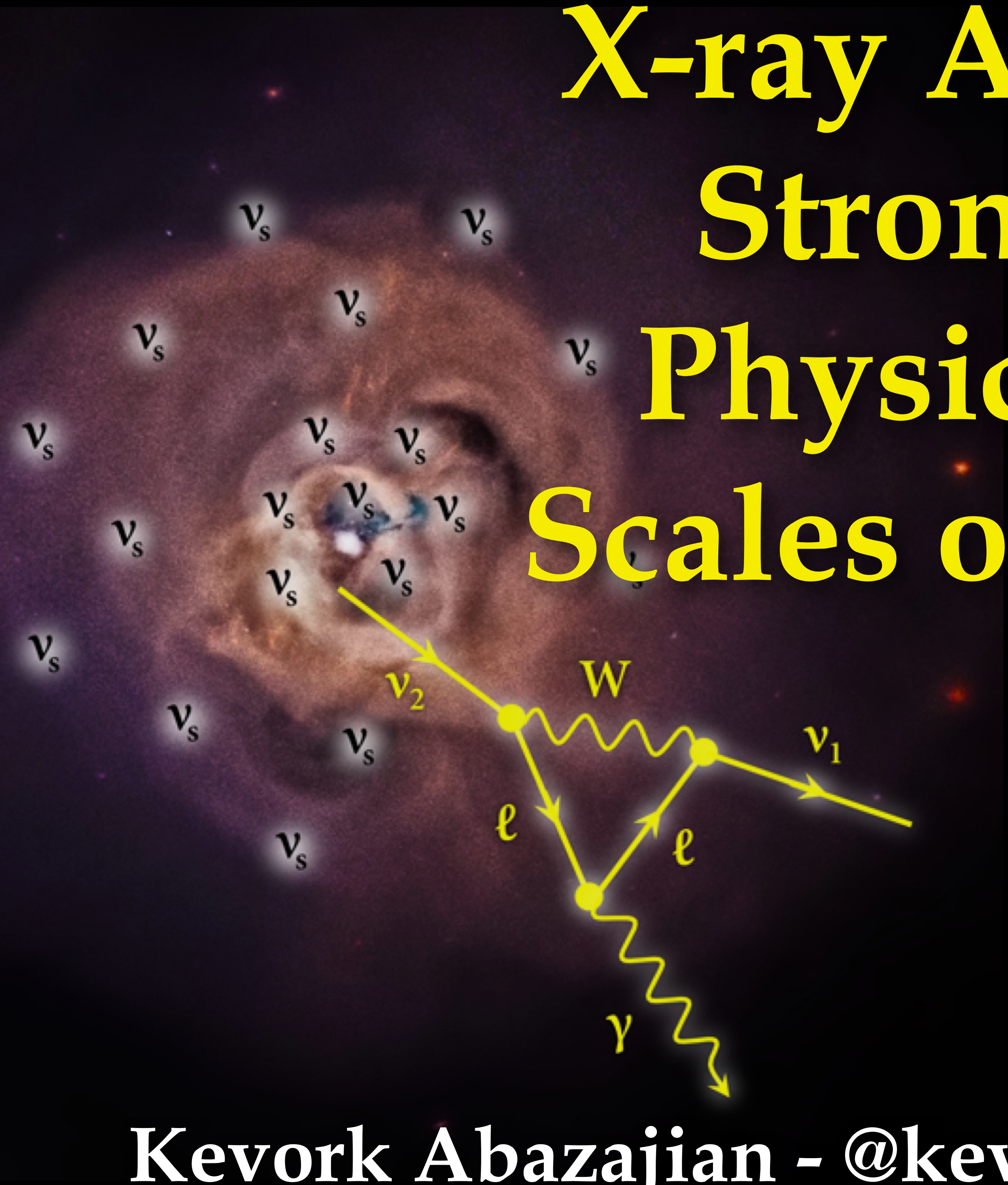
X-ray Astronomy: A Very Strong Probe of New Physics at Super-Weak Scales of Sterile Neutrinos



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XCalibur 2019 Workshop

Neutrinos ν_α !

The second most abundant particle in the Universe*
From thermal physics:

$$n_\gamma = \frac{\zeta(3)}{\pi^3}\, g\, T^3 \approx 411\,\mathrm{cm}^{-3}$$

$$n_\nu = N_\nu \times \left(\frac{3}{11}\right) n_\gamma \approx 340\,\mathrm{cm}^{-3}$$

*depends on dark matter particle mass...

Neutrino mixing (& oscillations)!

Flavors

$$|\nu_e\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$
$$|\nu_\mu\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$$

Masses

Propagate as:

$$e^{i(\vec{k}\cdot\vec{x}-\omega t)} = e^{i(\vec{k}\cdot\vec{x}-\sqrt{m_i^2+k^2}t)}$$

$$k \gg m \Rightarrow \sqrt{m_i^2+k^2} \sim k\left(1+\frac{m_i^2}{2k^2}\right)$$

$$|\nu(t)\rangle = e^{i(\vec{k}\cdot\vec{x}-(m_1^2+m_2^2)t/4k)}$$
$$\times\left[\cos\theta|\nu_1\rangle e^{i\delta m^2 t/4k} + \sin\theta|\nu_2\rangle e^{-i\delta m^2 t/4k}\right]$$
$$(\delta m^2 \equiv m_2^2 - m_1^2)$$

Neutrino mixing (& oscillations)!

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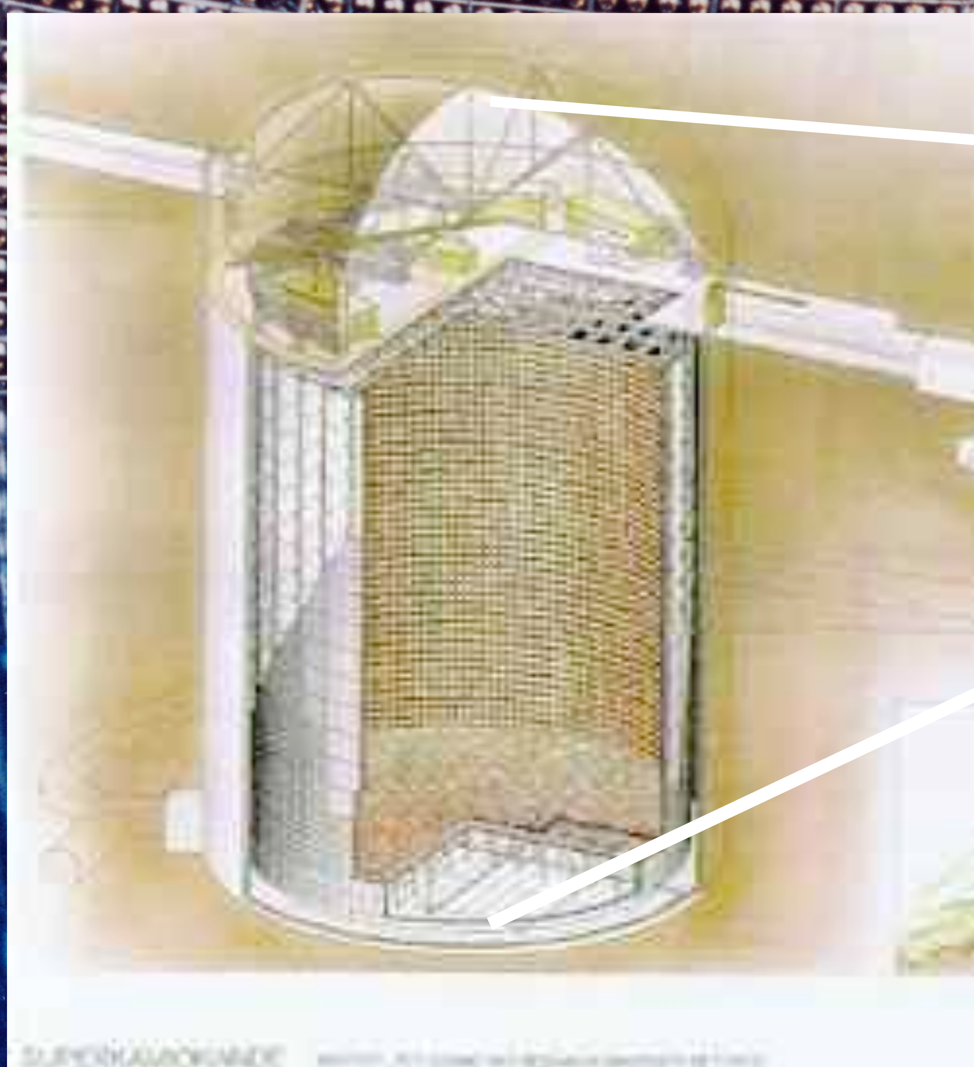
$$\left(\delta m^2 \equiv m_2^2 - m_1^2\right)$$

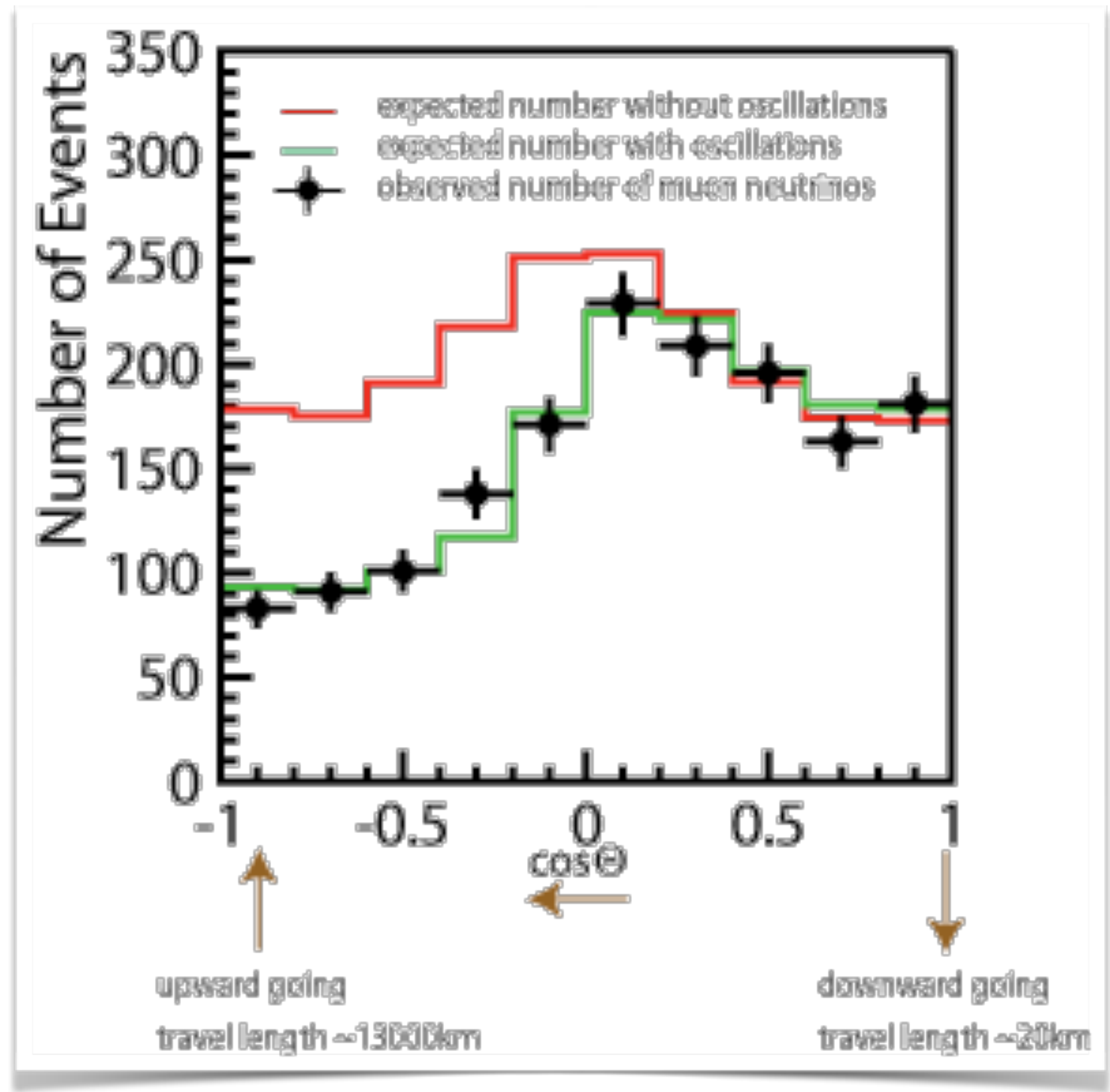
$$P_{\nu_e}(t) = |\langle\nu_e|\nu(t)\rangle|^2$$

$$= 1 - \sin^2 2\theta \sin^2\left(\frac{\delta m^2 t}{4k}\right)$$

Breakthrough in Fundamental Physics: *Neutrino Mass*

Atmospheric Neutrinos





Neutrino Mass Generation: An Original Hidden Sector Theory

- Simplest models of neutrino mass introduce sterile neutrinos that generate small active neutrino mass scales from very massive sterile neutrinos (Seesaw models)

- Phenomenological Insertion of Majorana & Dirac Mass Terms:

$$\mathcal{L} \supset -y_{\alpha i} L_\alpha N_i H - \frac{1}{2} M_{ij} N_i N_j + H.c.$$

(e.g. νSM de Gouvêa 2005; νMSM Asaka et al 2005; L_e-L_μ-L_τ Lindner+ 2010)

- Two massive (≳10 GeV) sterile neutrinos are required by atmospheric and solar neutrino mass scales. *Only hidden sector model with evidence for its existence!*

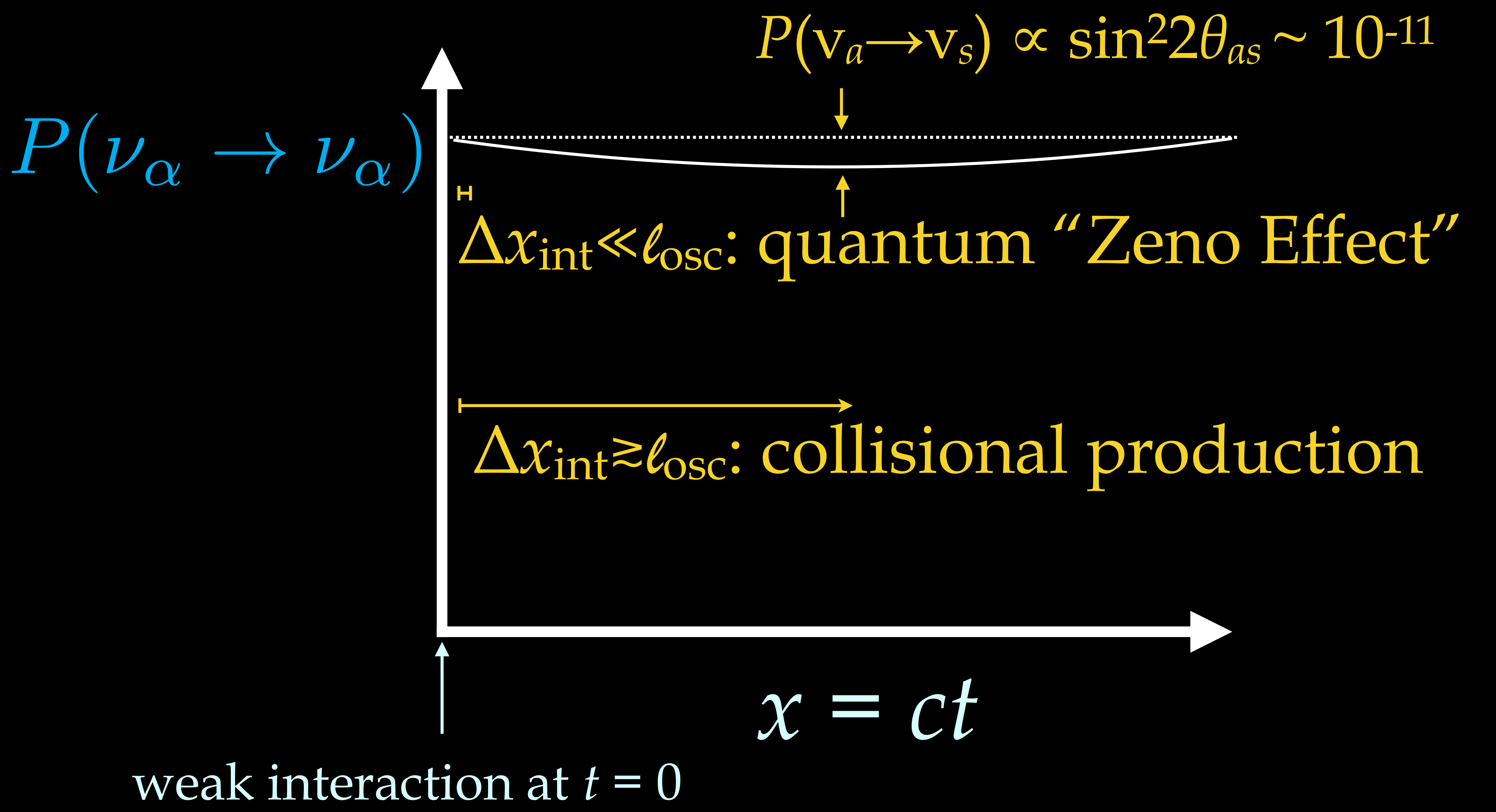
- 3rd sterile neutrinos has complete freedom. In simplest formulations, since lowest mass light ν is unbounded from below, so is the mixing of the lightest sterile neutrinos with the active ν.

$$\theta \sim \sqrt{\frac{m_\alpha}{M}}$$

Sterile Neutrinos as Dark Matter: History

- *Sterile* neutrinos [Dodelson & Widrow, 1993]: No SM interactions beyond mass terms, inclusion of finite-temperature modifications to self-energy, lack of thermalization. **keV mass scale.** WDM.
- *Resonant* sterile neutrinos [Shi & Fuller, 1999]: Finite temperature production with non-zero lepton number resonant enhanced production. WDM to CDM. "Cool" Dark Matter.
- *Precision* Sterile Neutrino Dark Matter & **Proposal for X-ray Detection** [Abazajian, Fuller & Patel 2001; KA 2005]: Full momentum-space production description with QCD transition corrections, resonant to non-resonant solutions as a continuum in lepton number.

Oscillation Sterile Neutrino Dark Matter Production: Dodelson-Widrow & Shi-Fuller, *Simplified*



The Miracle Production Mechanism

The sterile neutrino is given mass via a **Singlet Higgs** which is in thermal equilibrium in the early Universe and produces the sterile neutrino dark matter via **Decay Production** $S \to N\,N$.

The coupling required to produce keV masses,

$$m_1 = f_1 \langle S \rangle \sim \text{keV} \Rightarrow f_1 \sim 10^{-8}$$

the electroweak scale $\langle S \rangle \sim 100$ GeV and decay time in the early Universe

$$\tau \sim M_0/T^2 \sim M_0/m_S^2$$

gives an abundance of sterile neutrino dark matter of the observed amount $\Omega_{\rm DM} \sim 0.25$

(Kusenko 2006; Petraki & Kusenko 2007)

Visibility of Sterile Neutrinos

The observed flux is proportional to the amount of dark matter in the form of a sterile neutrino and the mixing angle

$$\text{Flux} \propto f_{\rm DM} \sin^2 2\theta \qquad \text{but: } f_{\rm DM} \propto \left(\sin^2 2\theta\right)^{1.23} \ \text{(Abazajian 2005)}$$

Nonresonant production (DW) can provide signal with ~13% of dark matter as 7.1 keV sterile neutrino, evades all constraints including structure formation, with ~7 times stronger mixing angle

⇒Can achieve even larger mixing angles in low-reheating temperature universes (Gelmini, Palomares-Ruis & Pascoli 2004)

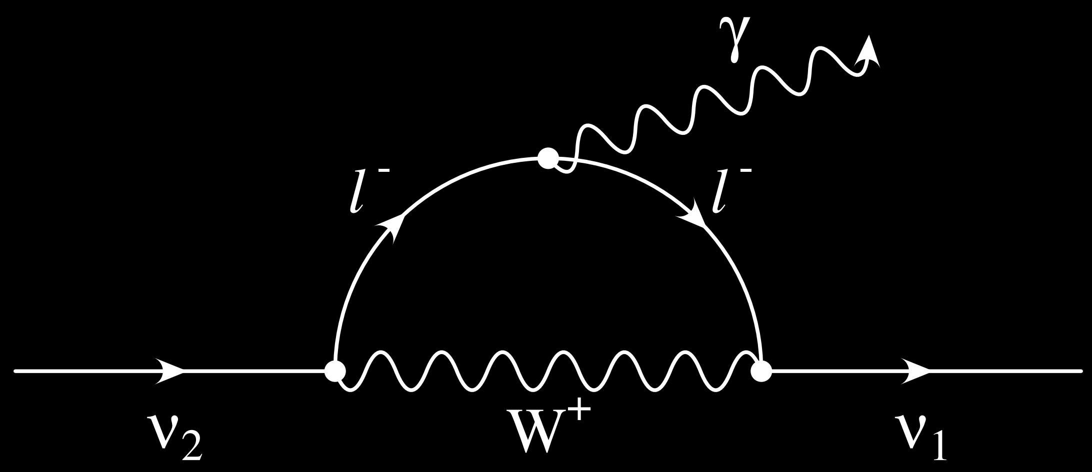
⇒ Low-reheating temperature universe can produce 3.5 signal with **$7{\times}10^{-4}$ of DM** as sterile neutrino

Other Production Mechanisms

- **GUT-Scale Split See-Saw Out of Equilibrium Production:**
  Kusenko, Takahashi, & Yanagida 2010

- **Production by Generic Scalar Decay** (Adhikari+ 2017) **or Vector Decay** (Schuve+ 2014)

Dark Fermion WDM Radiative Decay in the X-ray

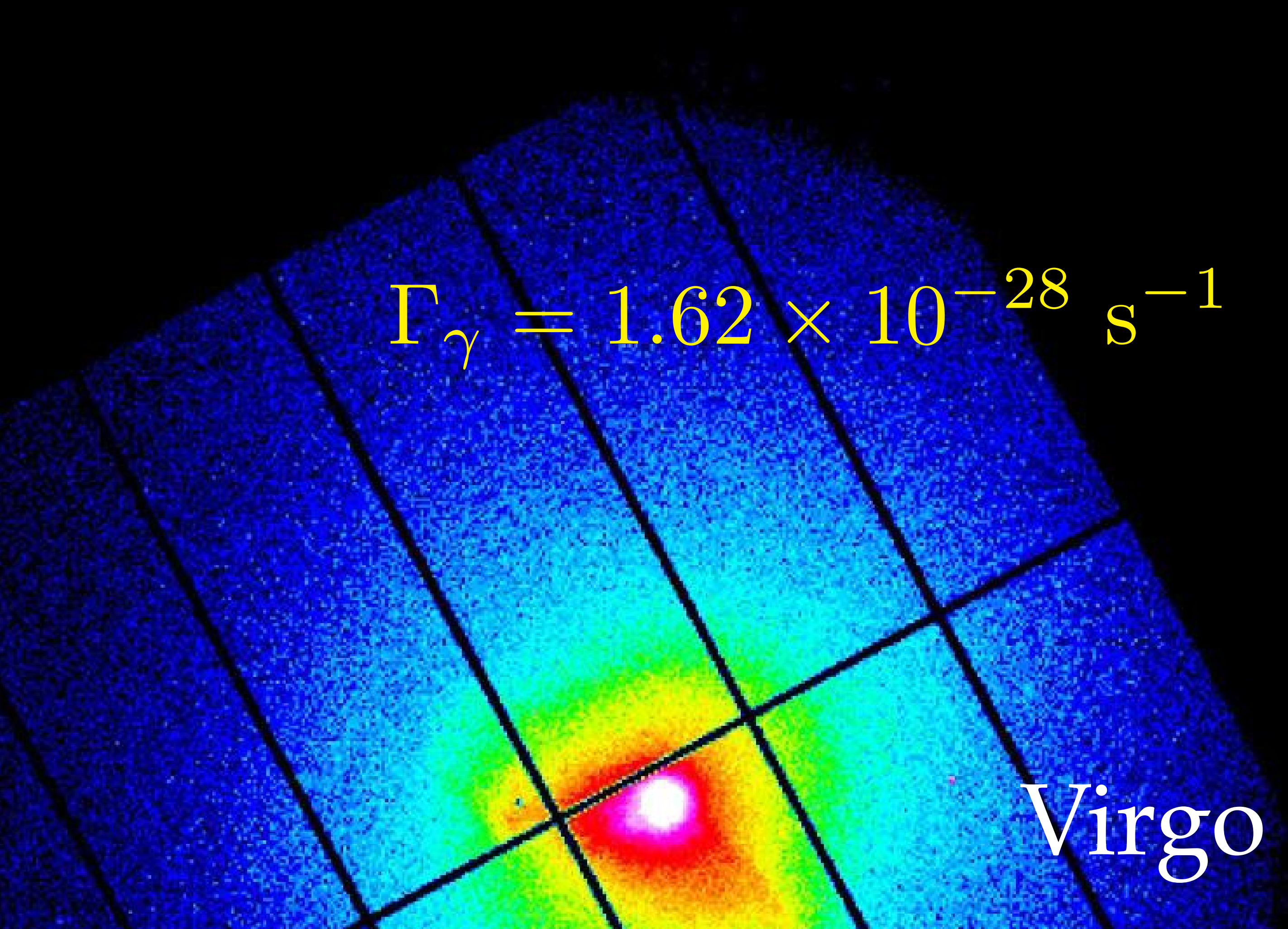


Decay: Shrock 1974; Pal & Wolfenstein 1981; Barger, Philips & Sarkar 1995
X-ray: Abazajian, Fuller & Tucker 2001

$$\text{``}\nu_s\text{''} \rightarrow \text{``}\nu_\alpha\text{''} + \gamma$$

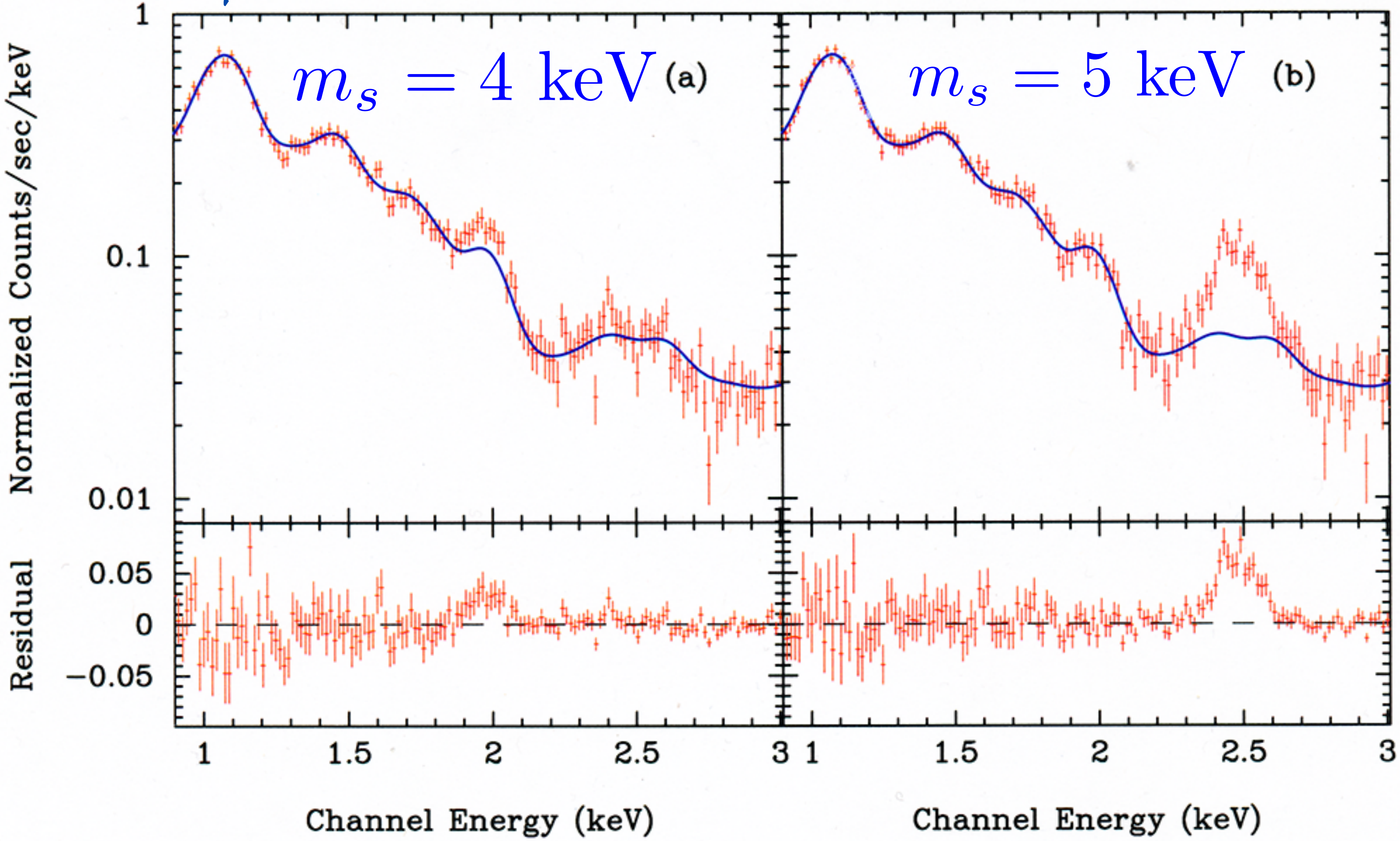
$$E_\gamma = \frac{m_s}{2} \sim 1 \text{ keV}$$

$$\Gamma_\gamma = 1.62 \times 10^{-28}\ \text{s}^{-1} \left(\frac{\sin^2 2\theta}{7 \times 10^{-11}}\right)\left(\frac{m_s}{7\ \text{keV}}\right)^5$$



Virgo Cluster: 10^{78} DM particles

Slide from 2001



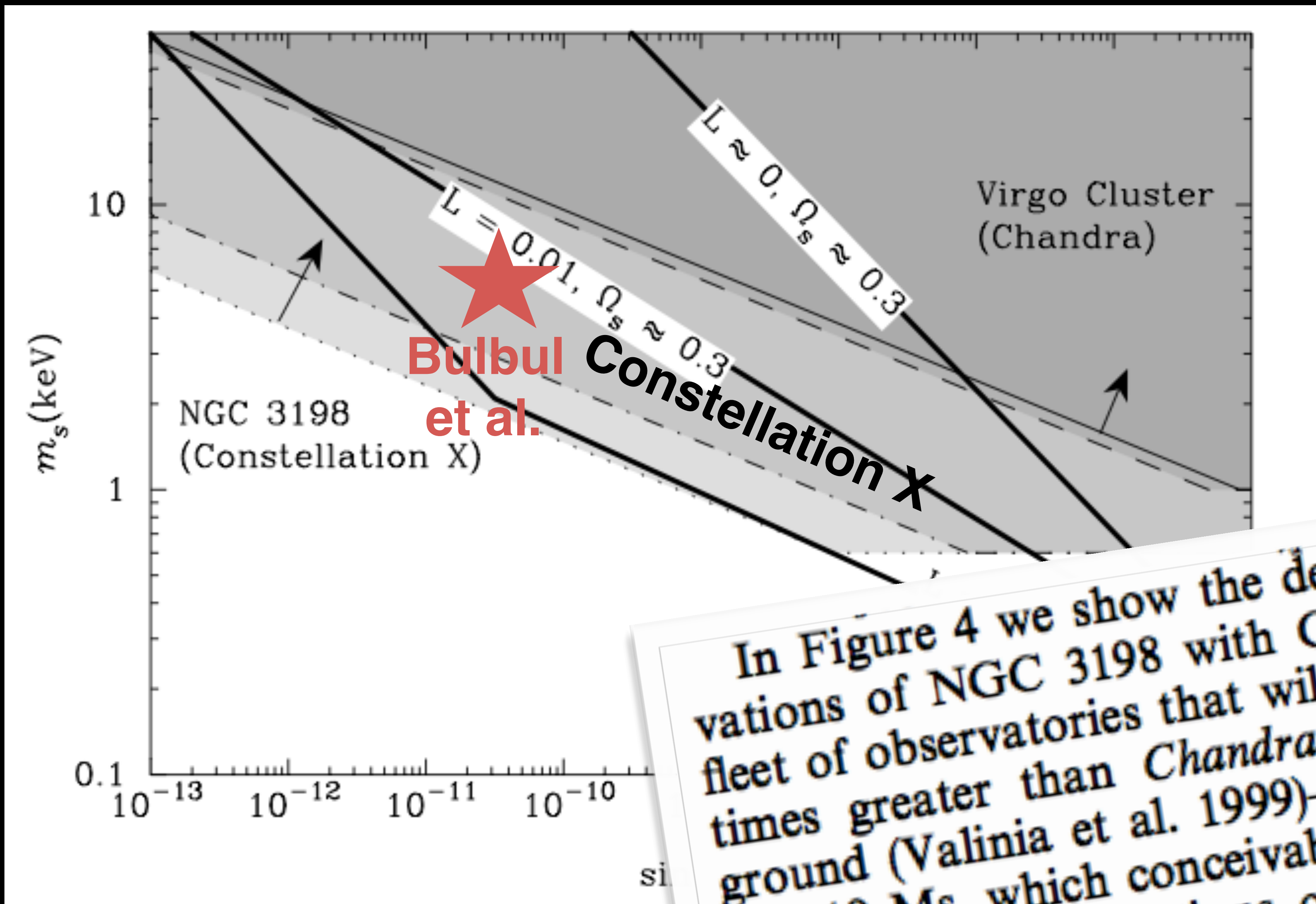
Current Limits

+

Future Detection?

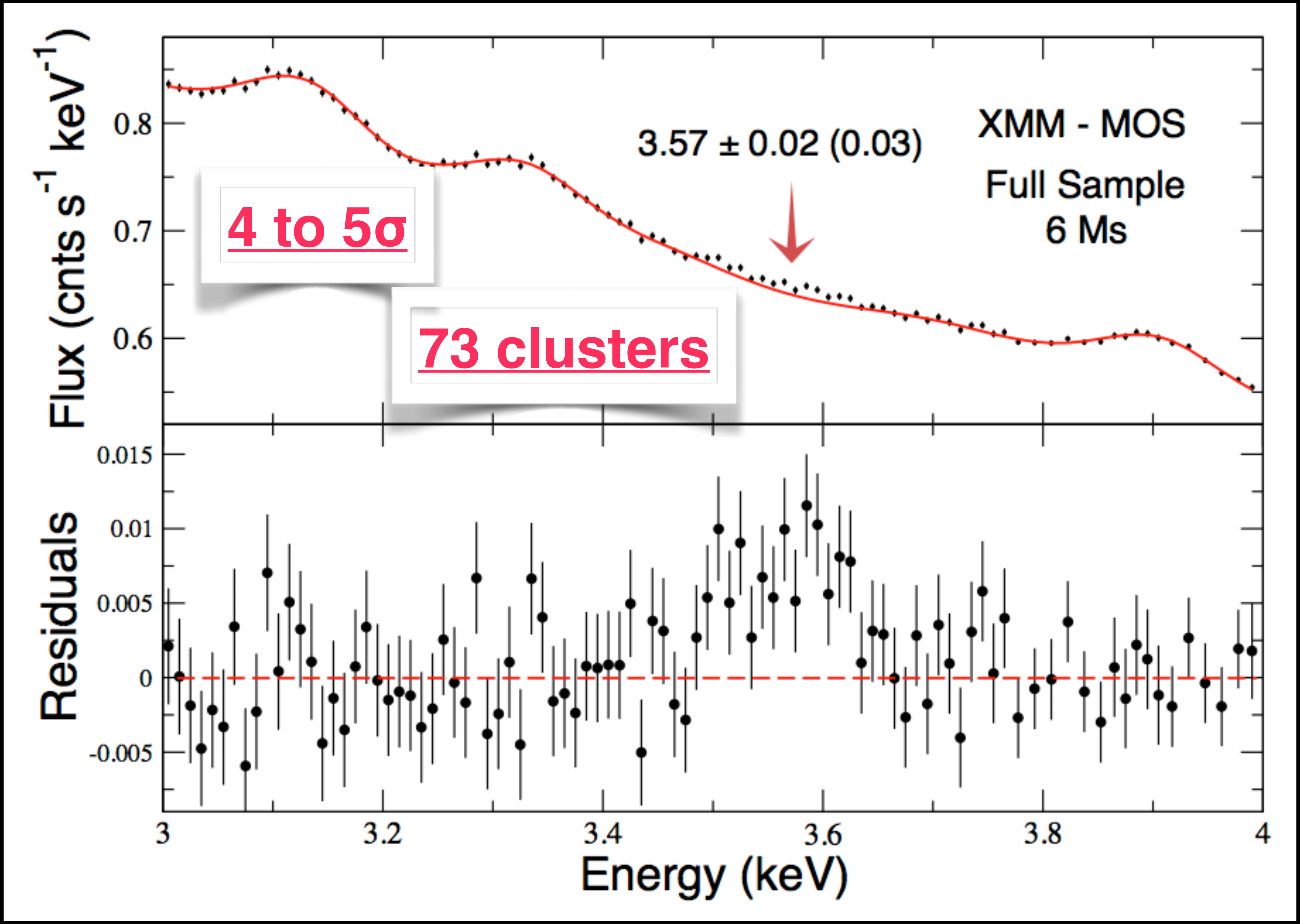
Forecast X-ray Observation Sensitivity for *Constellation-X*

Abazajian, Fuller & Tucker 2001



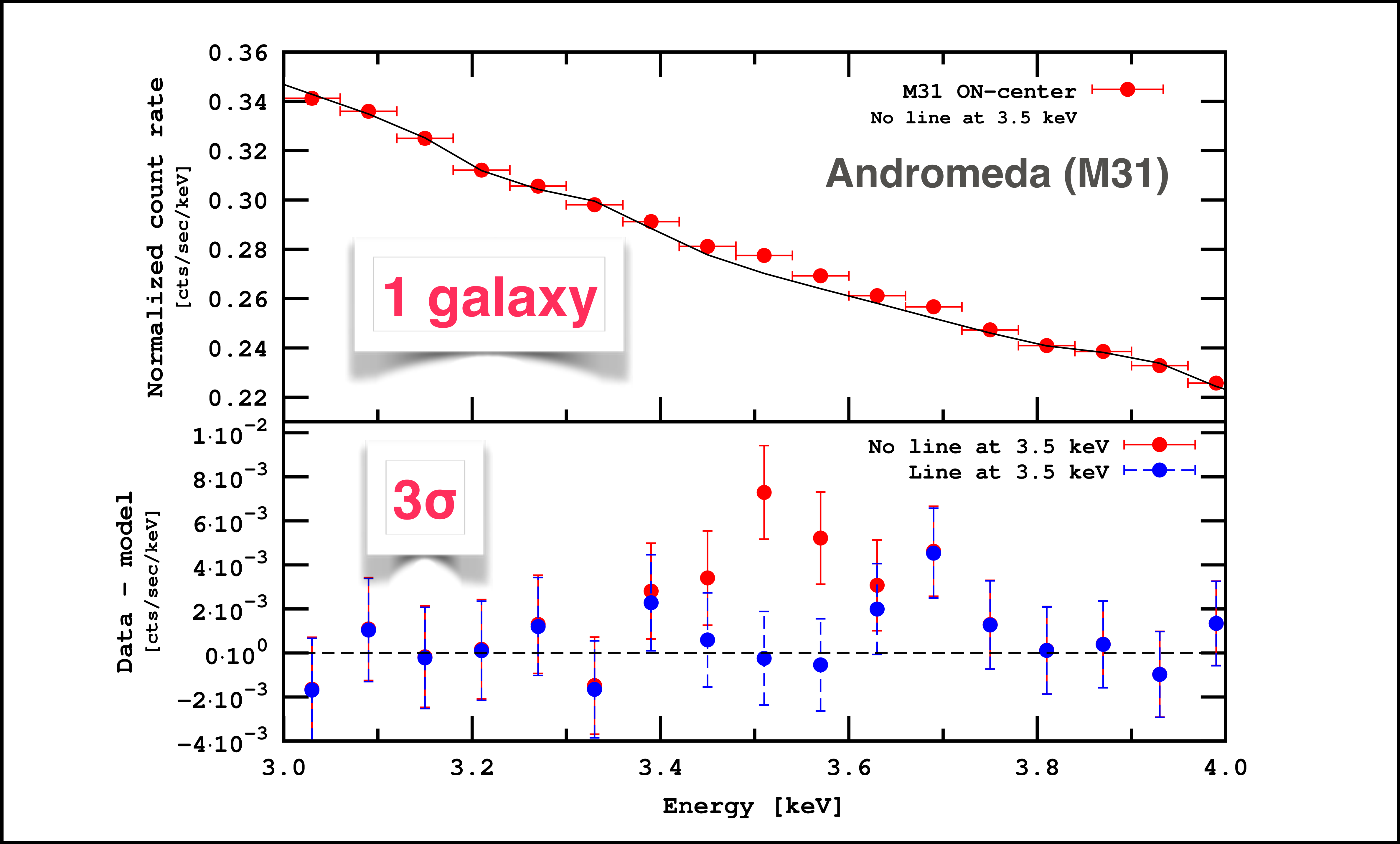
In Figure 4 we show the detectability region for observations of NGC 3198 with Constellation X—a proposed fleet of observatories that will have an effective area ~10 times greater than *Chandra* and no instrumental background (Valinia et al. 1999)—for two integration times, 1 and 10 Ms, which conceivably could be achieved through several long observations over a few years. An exposure equivalent to this could be obtained by a stacking analysis of the spectra of a number of similar clusters (see, e.g., Brandt et al. 2001; Tozzi et al. 2001). Constellation X, with very long integration times, holds out the prospect of covering nearly the entire WDM parameter space of interest for

The Detection of an Unidentified Line



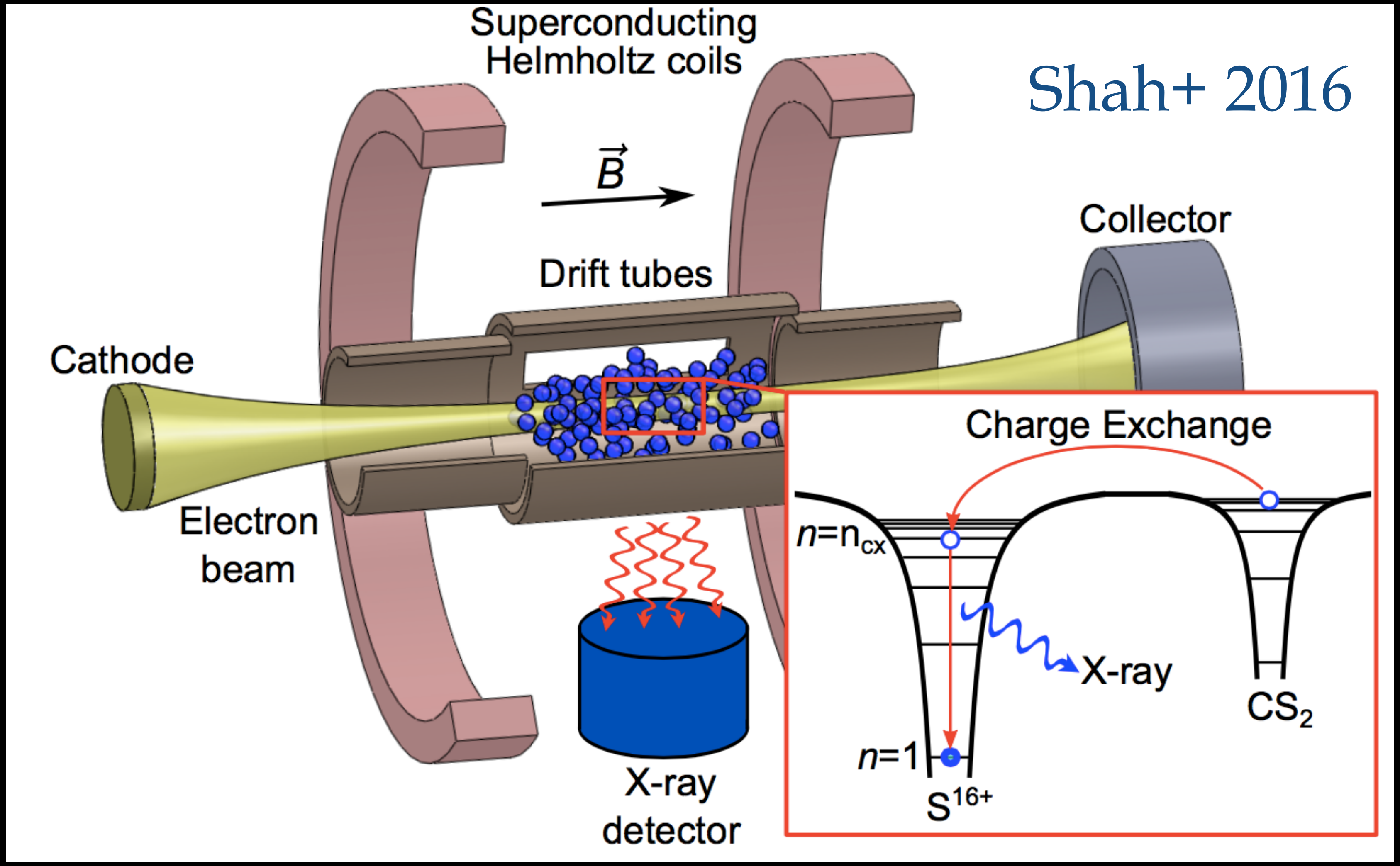
Bulbul et al. ApJ 2014

The Detection of an Unidentified Line II



Boyarsky et al. PRL 2014

CX lines at ~3.5 keV?



Betancourt-Martinez+ 2014; Gu+ 2015; Shah+ 2016

CX line(s) at 3.44 - 3.47 keV while unidentified line at

- 3.57±0.025 keV (Perseus)
- 3.57±0.02 keV (MOS stack)
- 3.51±0.03 keV (PN stack)

3.55 keV line consistent with DM in field of view seen

- in Andromeda (M31) with *XMM-Newton* (Boyarsky+ 2014)
- Perseus with *XMM-Newton, Chandra and Suzaku* ≳3σ (Bulbul+ 2014, Boyarsky+ 2014, Urban+ 2014)
- in 8 more clusters at > 2σ significance (*XMM-Newton*) (Iakubovskyi+ 2015)
- Milky Way Galactic Center out to > 10° (*XMM-Newton*) (Boyarsky+ 2014, 2018)
- Milky Way Galactic Center at 1.5° at Galactic Bulge limiting window (*Chandra*) (Hofmann & Wegg 2019)
- *NuSTAR* observations of Deep Fields at **11.1σ** and Galactic Center (Neronov+ 2016, Perez+ 2016)
- *Chandra* Deep Fields at 3σ (Cappelluti+ 2017): rule out CX, Ar or instrumental

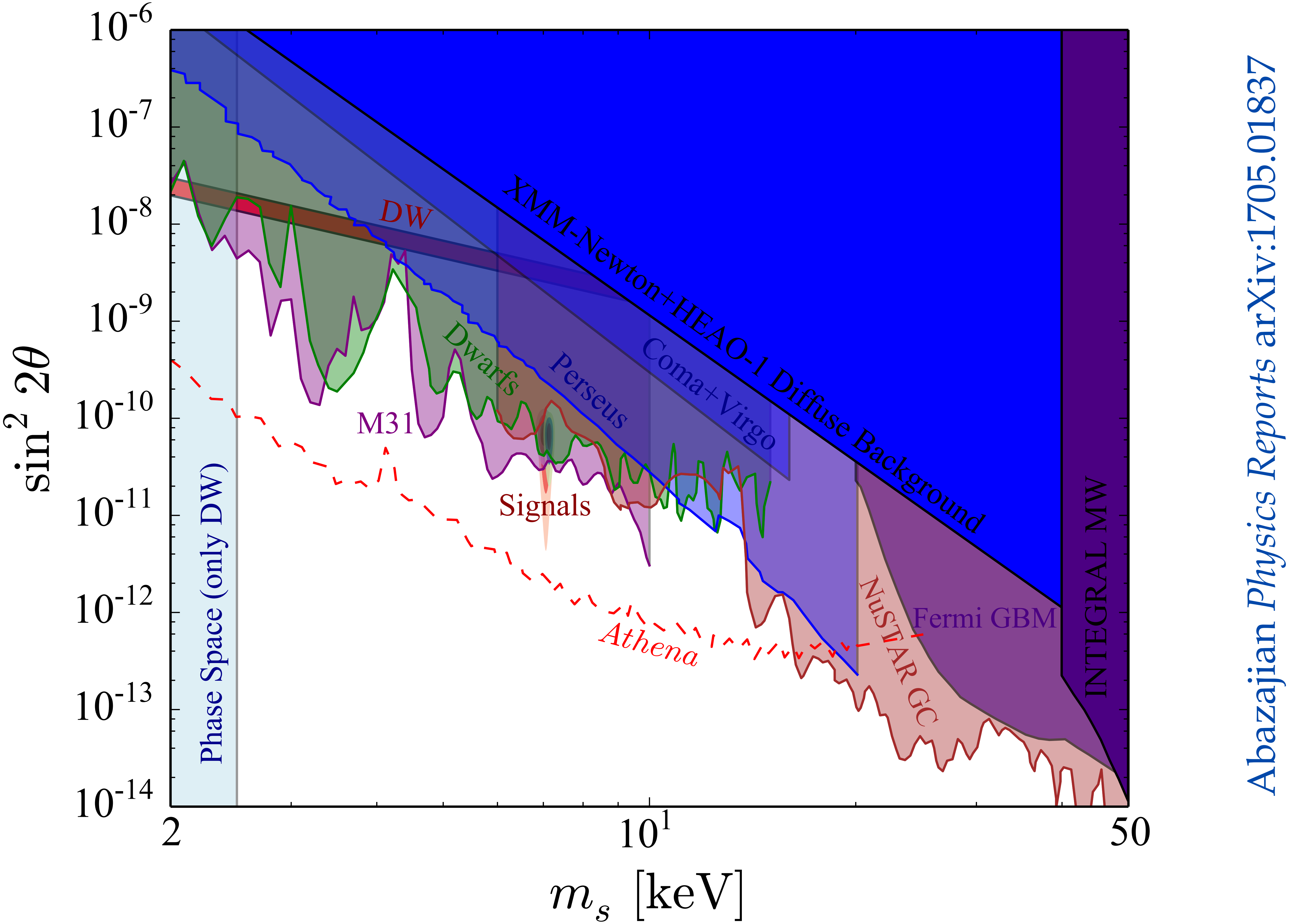
3 places it may have been expected

- **Draco 1 Ms exposure:** not seen in MOS detectors, at lower than expected flux in PN. But, ***"We conclude that this Draco observation does not exclude the dark matter interpretation of the 3.5 keV line in those objects."***
  Boyarsky+ arXiv:1512.07217

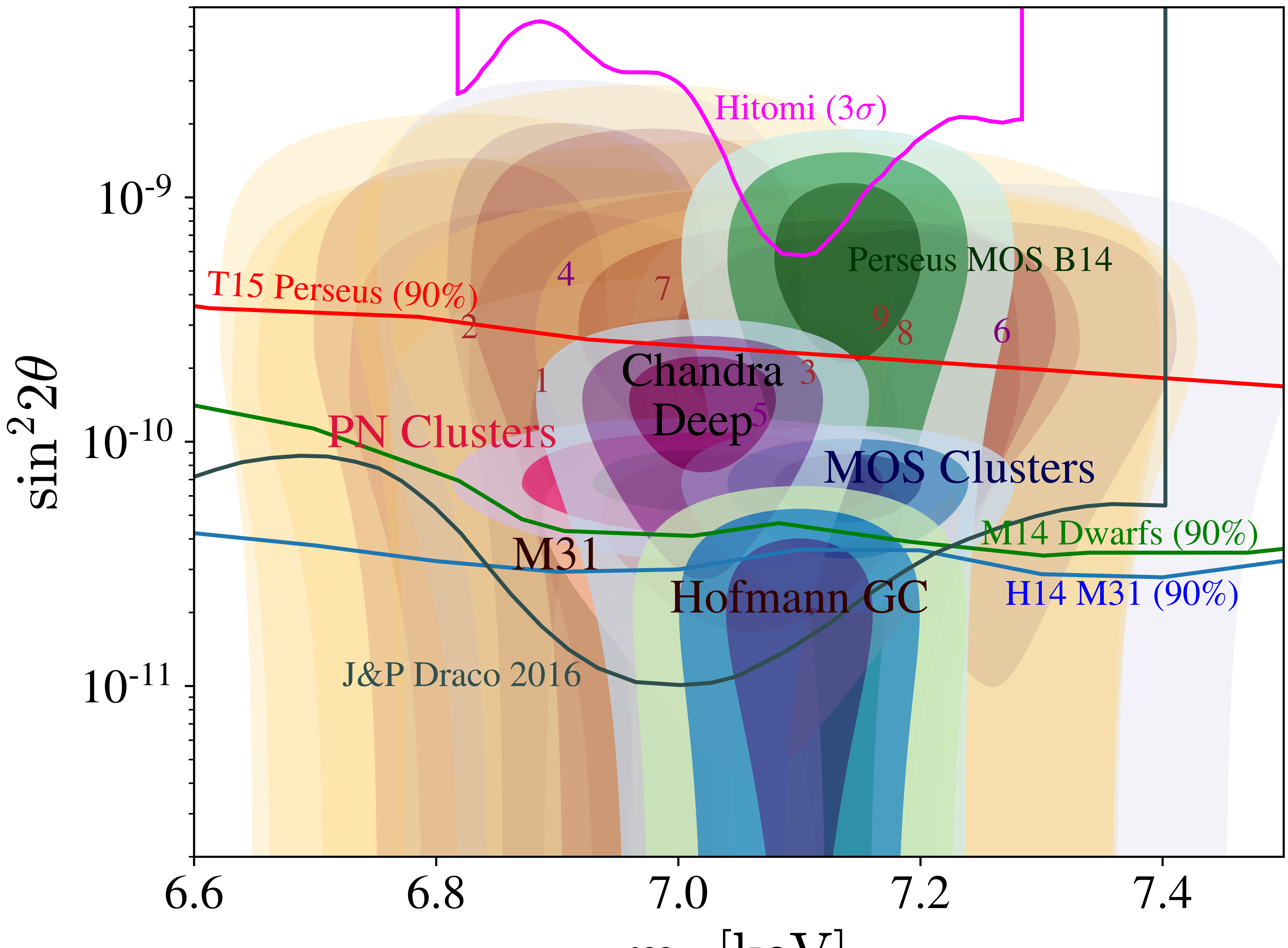
- **Stacked galaxies:** 81 with Chandra and 89 with *XMM-Newton*, using outskirts of the galaxies:
  Anderson, Churazov & Bregman arXiv:1408.4115.
  ➥***Systematic continuum errors are of order the uncertainties on detected*** $\boldsymbol{\sin^2 2\theta}$

- **Stacked blank sky:** 30 Ms *XMM-Newton* data, 0.5 keV energy window analysis.
  Dessert, Rodd & Safdi arXiv:1812.06976

Sterile Neutrino Dark Matter: Parameter Space Summary



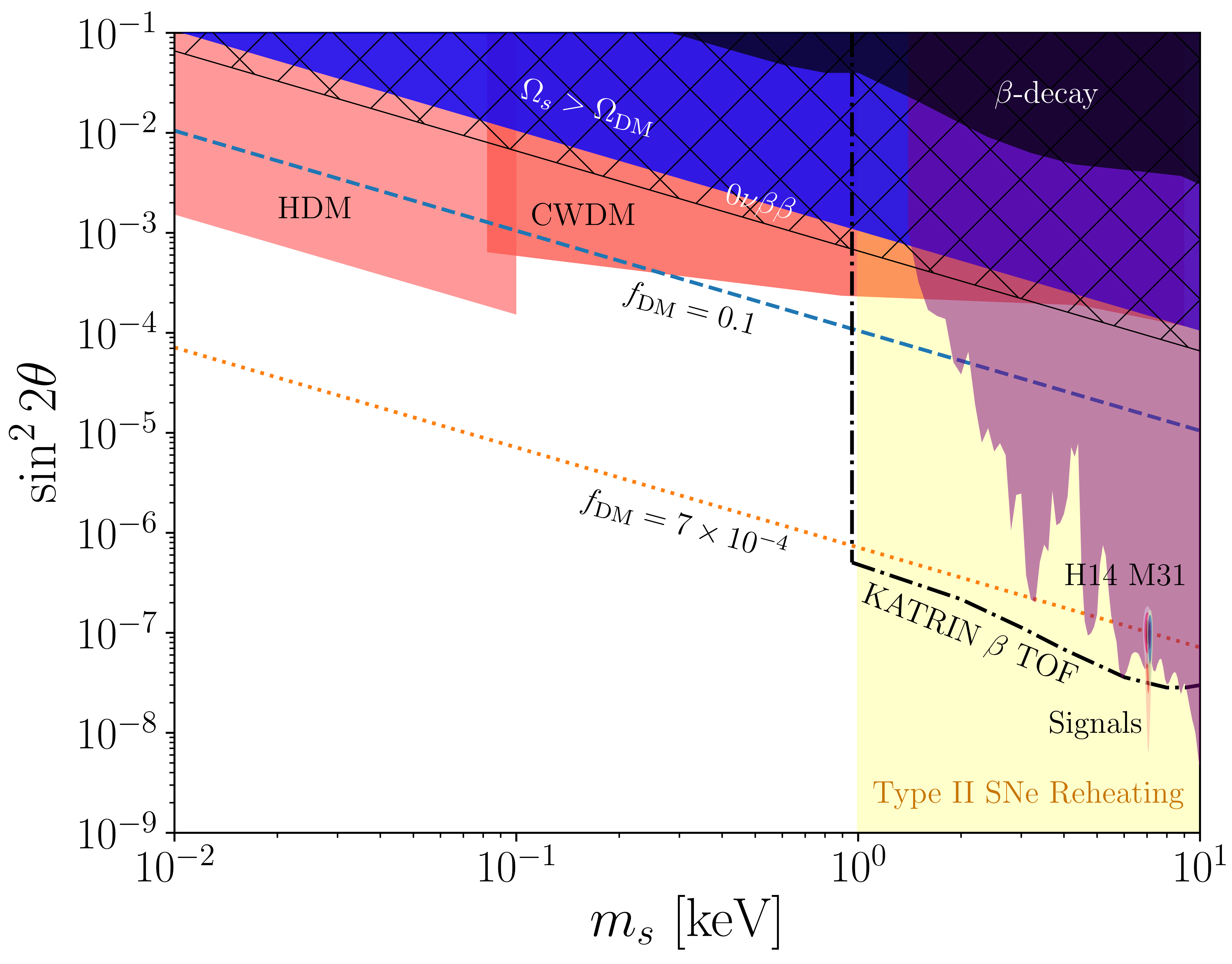
The 7 keV Region Today



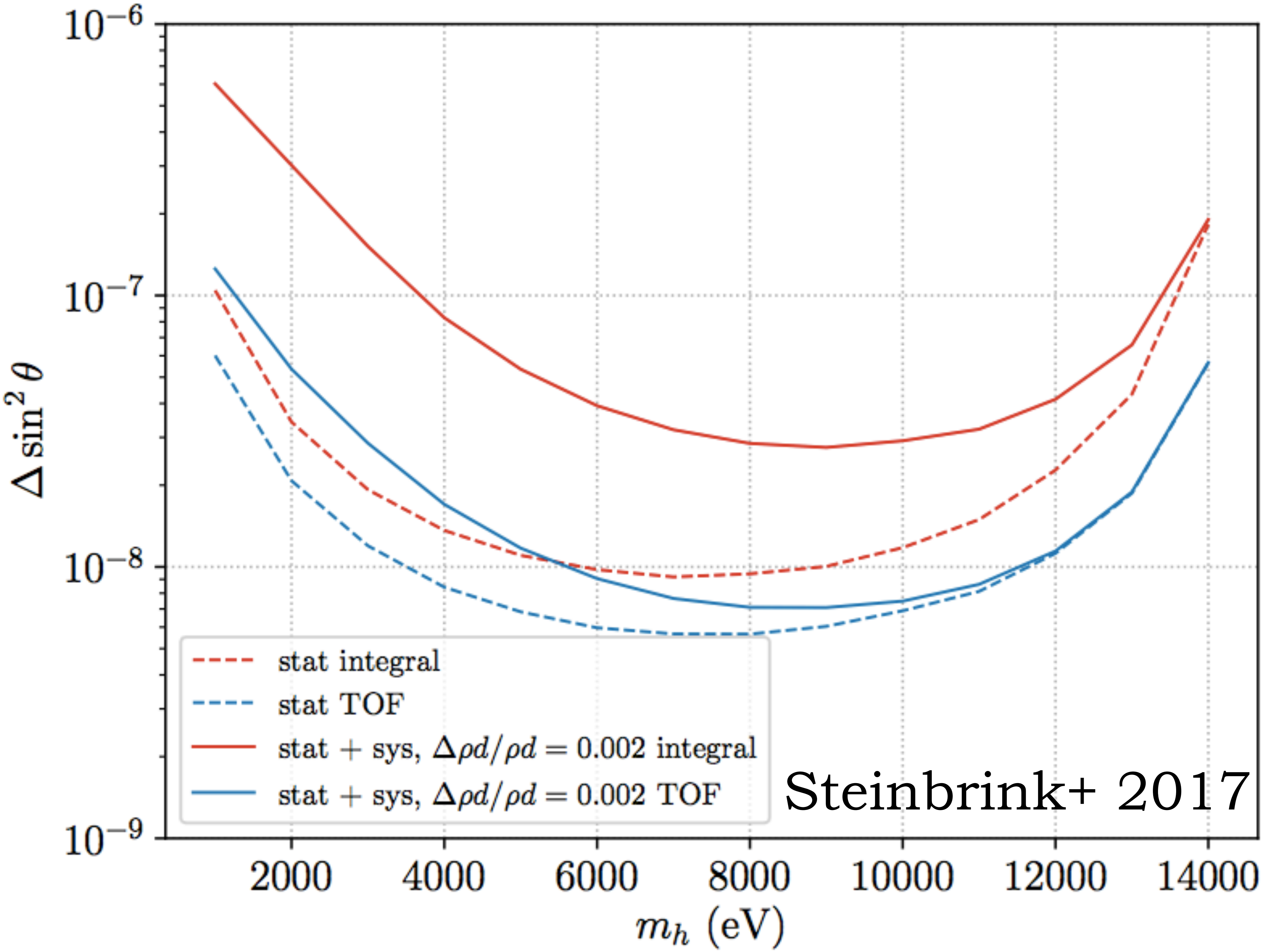
Updated from Abazajian 2017

arXiv:1705.01837

Visible Sterile ν in the Low-Reheat Universe

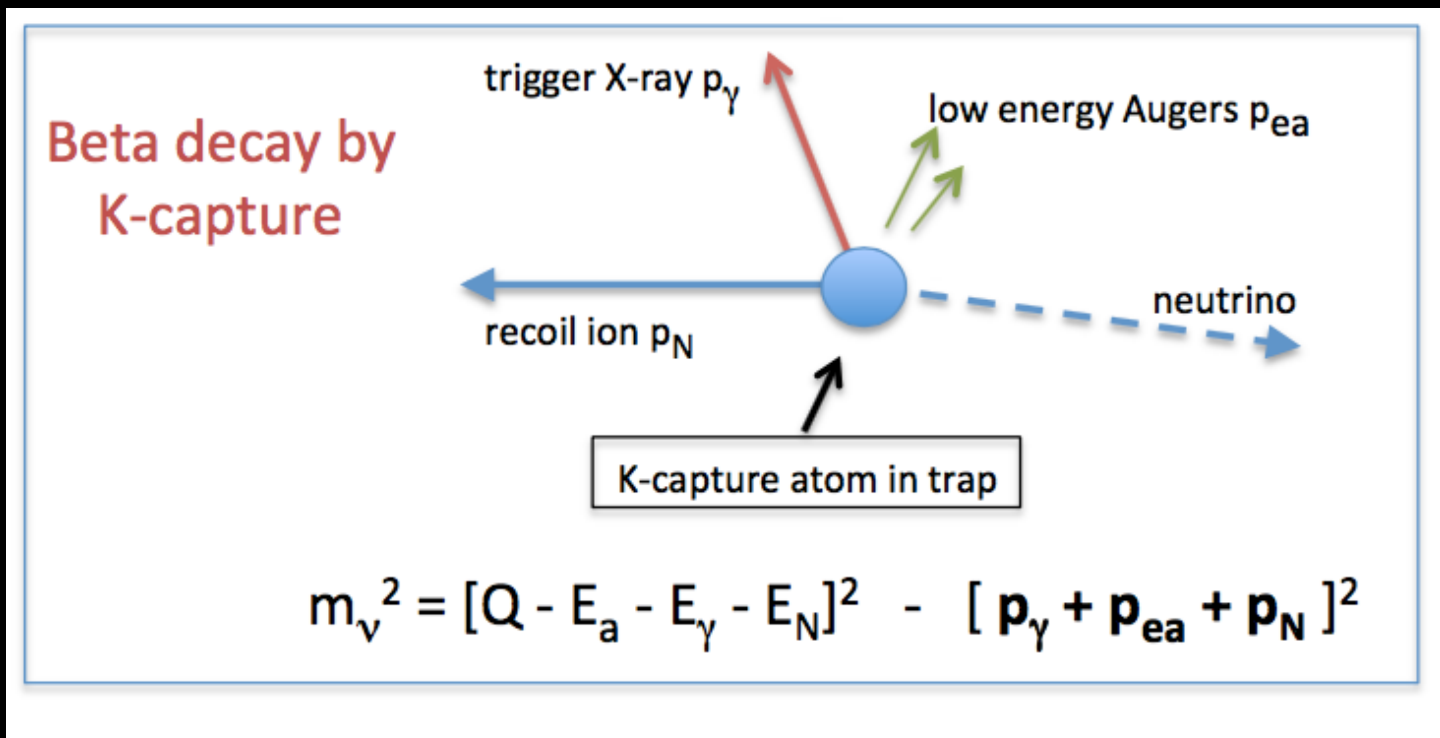


Confirmation? kinematic searches in nuclear β-decay



Steinbrink+ 2017

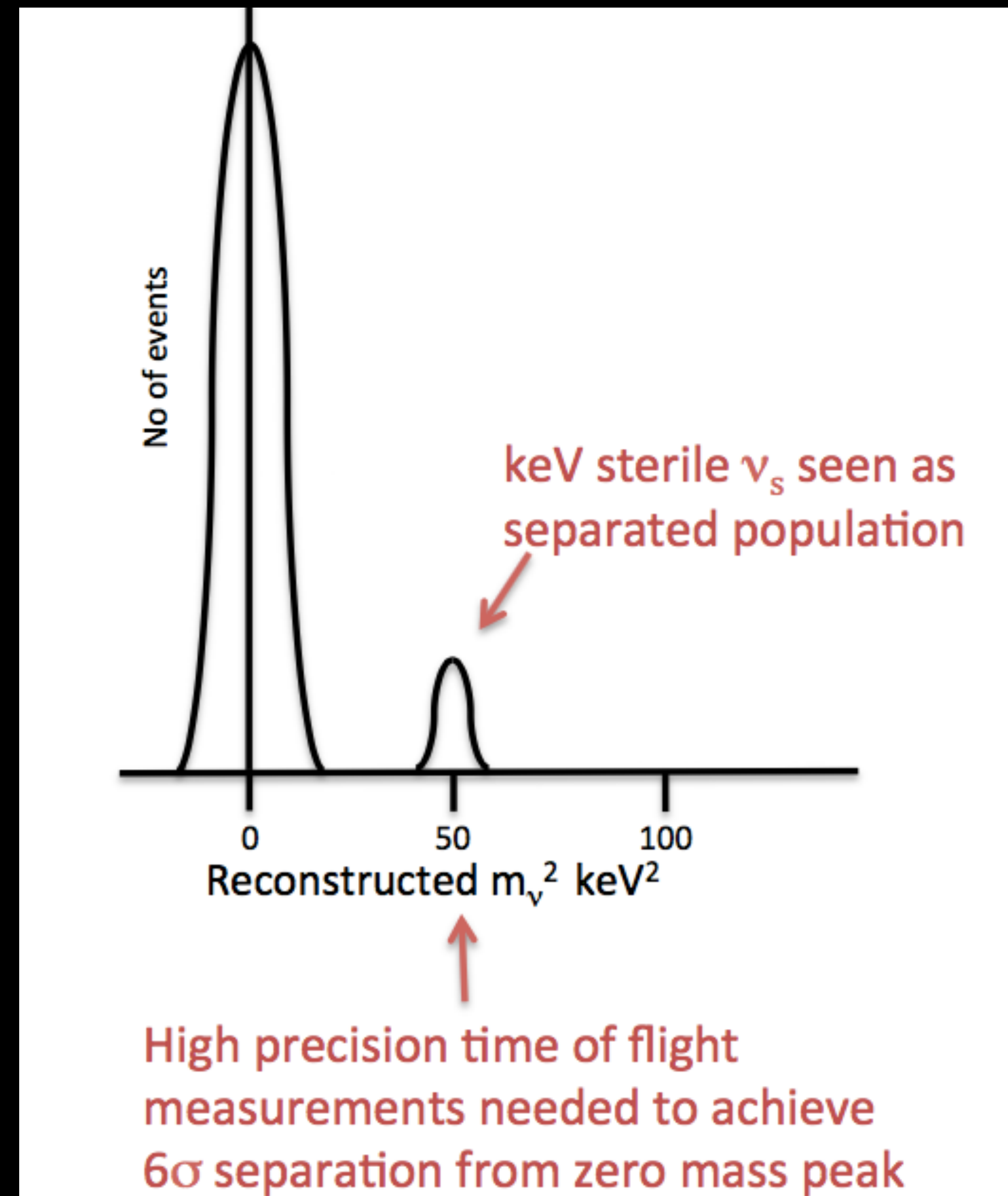
Laboratory Method: full kinematic reconstruction of K-capture nuclear decay



Original studies: Finocchiaro & Shrock 1992

HUNTER experiment (Heavy Unseen Neutrinos by Total Energy-momentum Reconstruction)

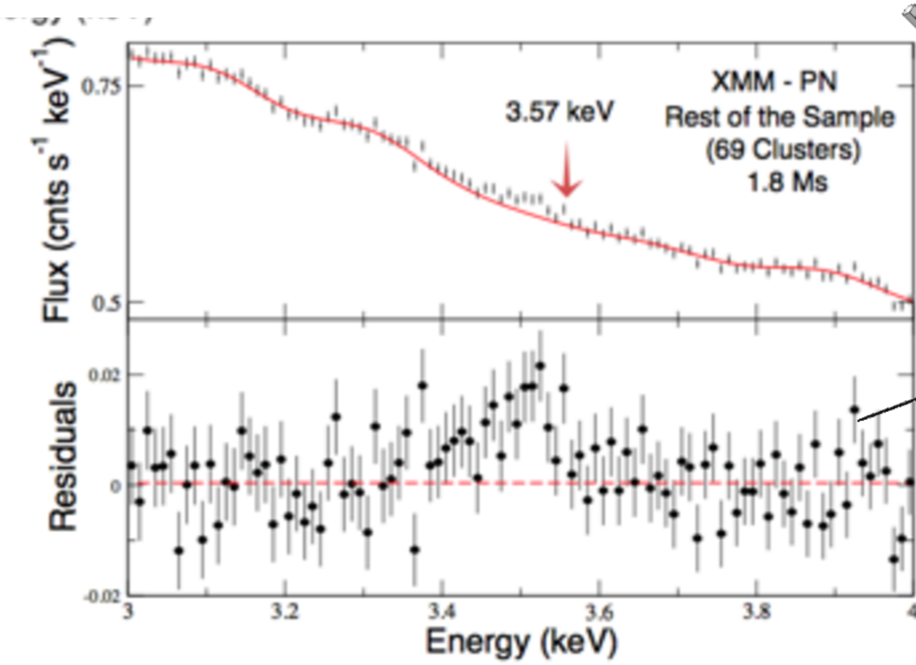
^{131}Cs Ion trap proposal:
Peter Smith+ arXiv:1607.06876

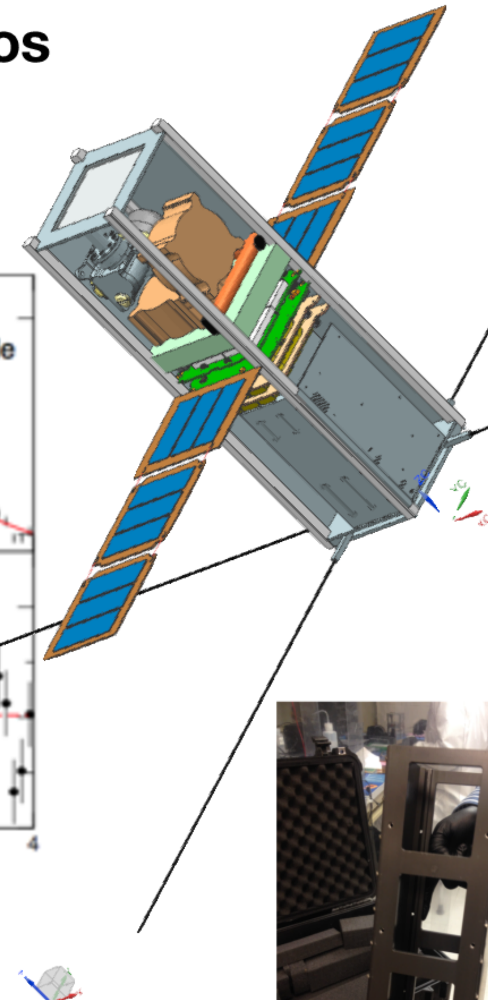


Recent studies show this may now be feasible

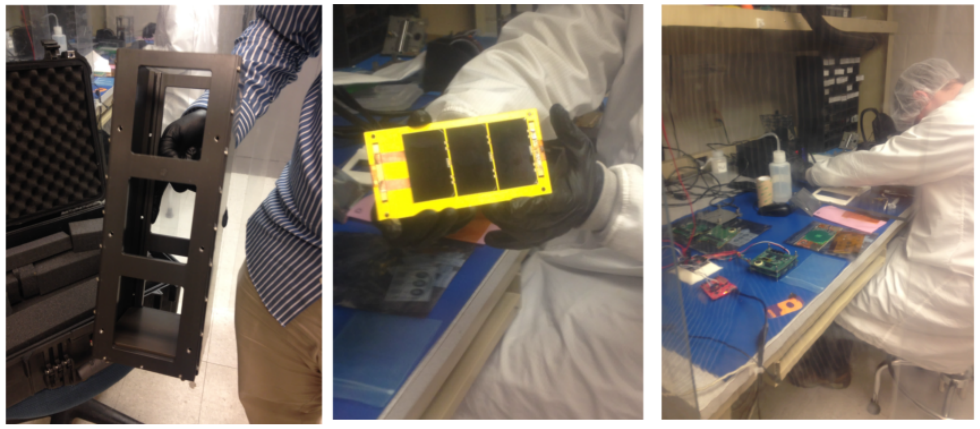
New Technology: New CCDs plus CubeSats

observed 3.5 keV X-ray line could be produced by keV sterile neutrinos annihilation.

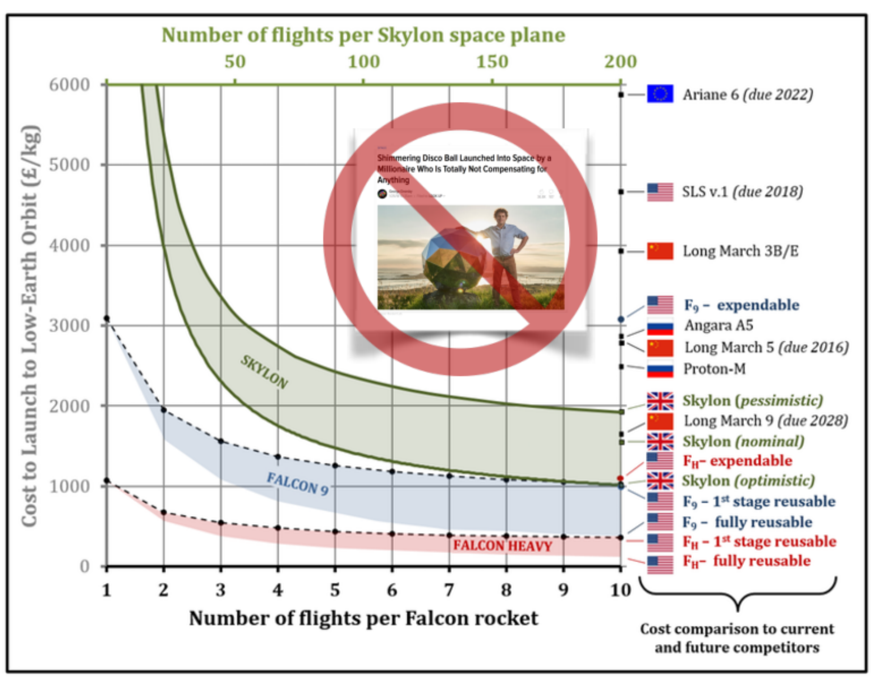




A cubeSat with a large CCD detector (DESI size) with good energy resolution (maybe skipper) in low earth orbit could go after this signal in our own galaxy. Others (Tali et al) are planning to do this with a "CDMS" detector in a rocket. A couple of summer students work on a conceptual design.



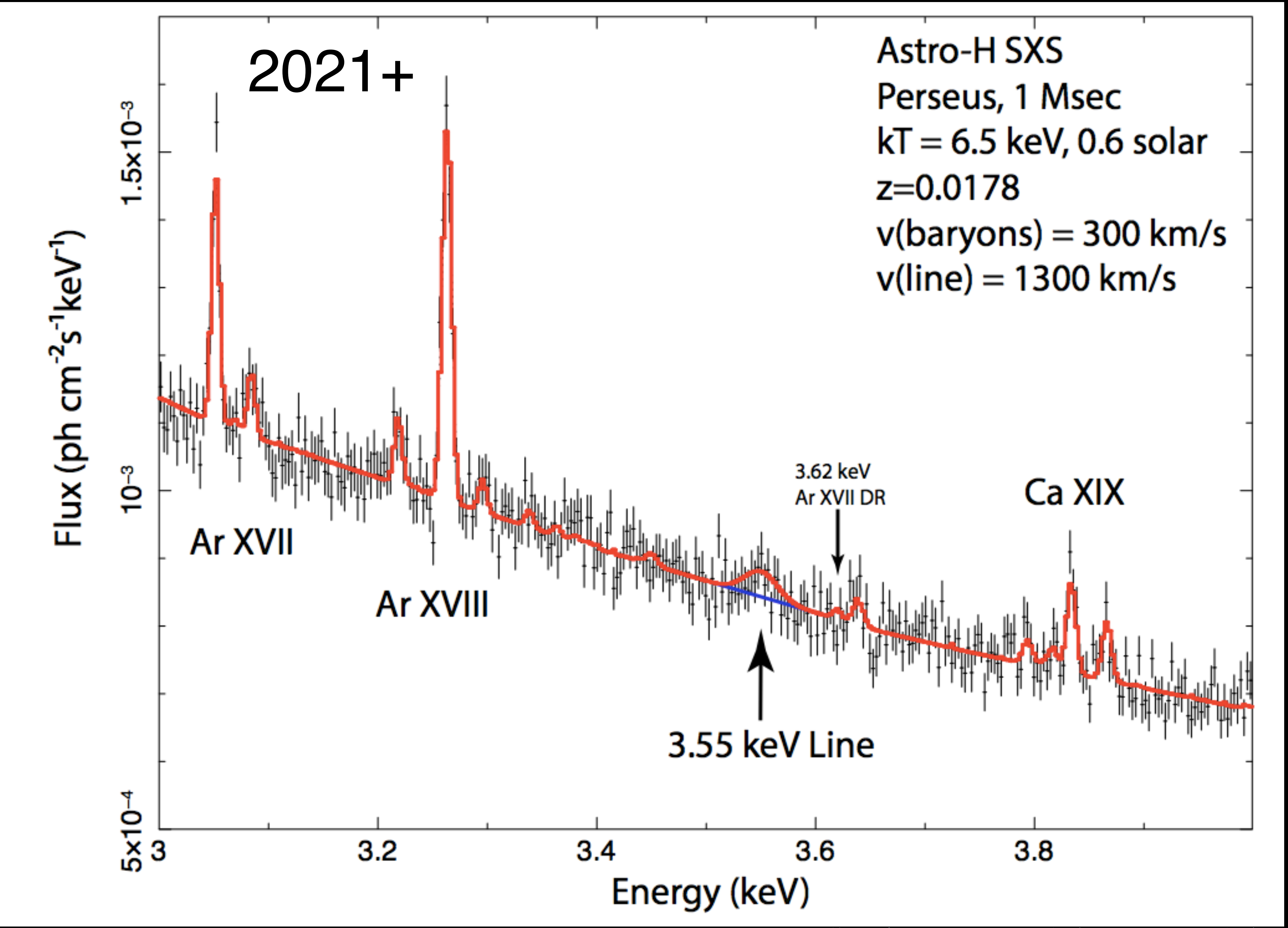
partnership with UIUC (aerospace)



opportunity:

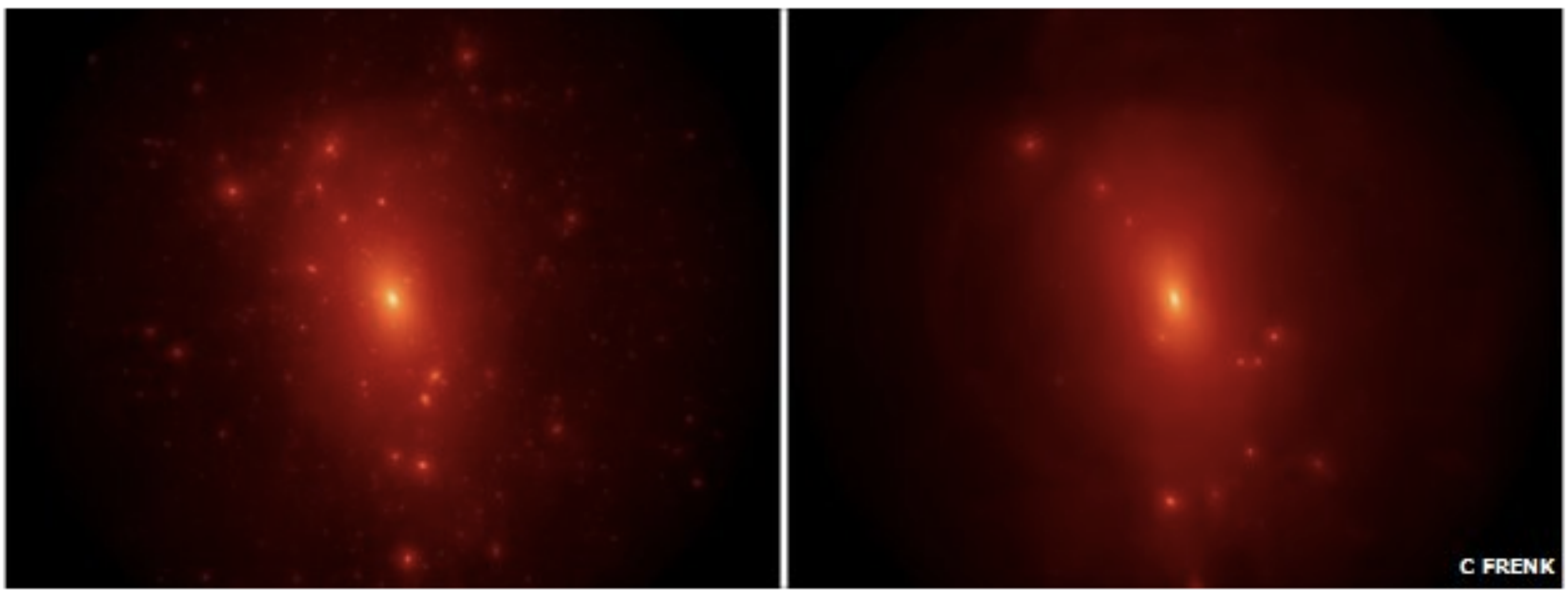
- look for 3.5 signal
- train our engineers in space applications
- new partnerships
- **get in better shape to take advantage of "cheap space"**

XRISM Space Telescope



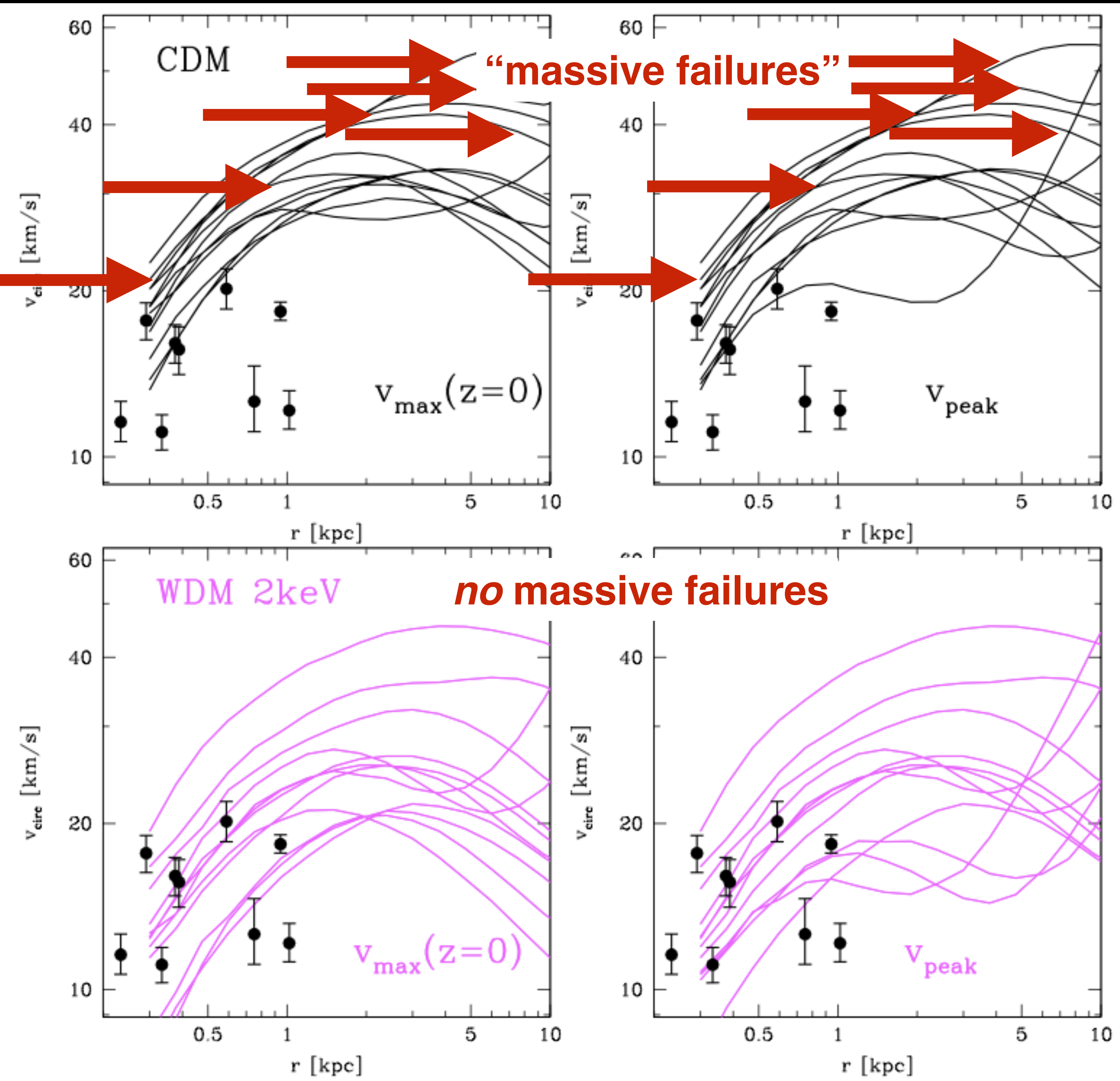
Bulbul et al. ApJ arXiv:1402.2301

Issues in Cosmological Small-scale Structure?



Dwarf galaxies around the Milky Way are less dense than they should be if they held cold dark matter

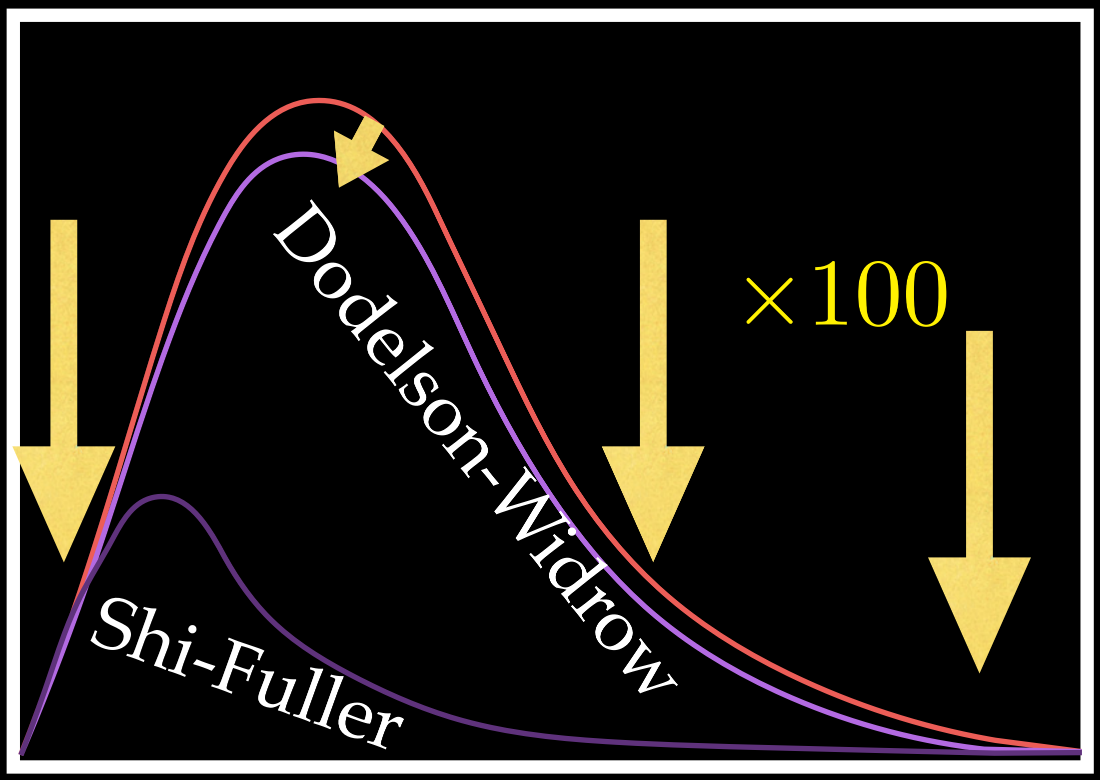
WDM Solution to Local Group Galaxy Properties?

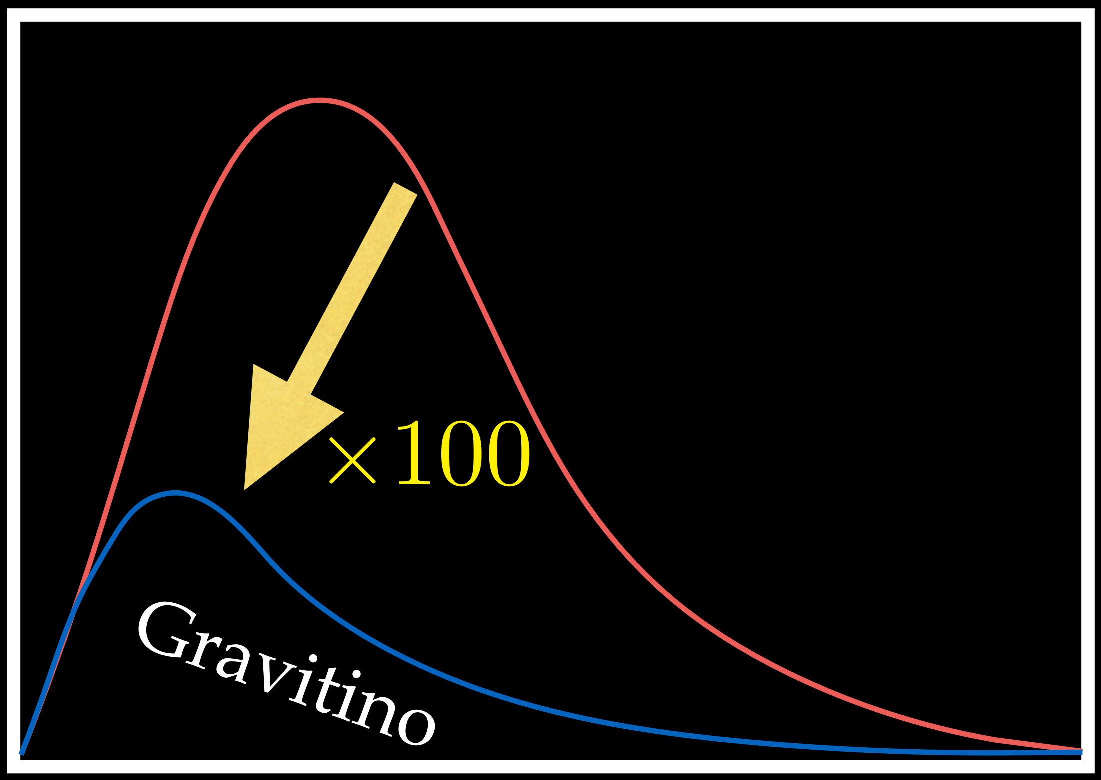


Lovell+ arXiv:1104.2929.
Anderhalden+ arXiv:1212.2967:
"It seems that only the pure WDM model with a 2 keV [thermal] particle is able to match the all observations" of the Milky Way Satellites: "the total satellite abundance, their radial distribution and their mass profile" (or TBTF)

Sterile Neutrino DM:
Horiuchi+ arXiv:1512.04548
Bozek+ arXiv:1512.04544

Sterile WDM vs. Thermal WDM





$$m_s\big|_{\text{Dodelson-Widrow,ideal}} \approx 4.46\,\text{keV}\left(\frac{m_{\text{thermal}}}{1\,\text{keV}}\right)^{4/3}$$

$$m_s\big|_{\text{Shi-Fuller}} < m_s\big|_{\text{Dodelson-Widrow}}$$

$$m_{\text{thermal}} = 2\,\text{keV} \Rightarrow m_s\big|_{\text{DW,ideal}} \approx 11\,\text{keV} \Rightarrow m_s\big|_{\text{Shi-Fuller}} \approx 7\,\text{keV}$$

Colombi, Dodelson & Widrow astro-ph/9505029;
Abazajian 2005; arXiv:1705.01837; Venumadhav+ 2016

Summary

- Sterile Neutrino Dark Matter has been investigated for 26+ years; indirect detection via cluster & field galaxy searches proposed in 2001.
- An unidentified line has been detected at 4σ to 5σ in two independent samples of stacked X-ray clusters with *XMM-Newton*. It has been seen in several followup observations.
- At least two nuclear physics laboratory experiments are following up sterile neutrino dark matter interpretations.
- The signal crosses a transition from “cold” dark matter to “warm” dark matter, at a cutoff scale of great interest in galaxy formation
- Future Follow up observations:
  - 2020: *eROSITA*
  - 2021: *Micro-X, XQC*, X-ray CubeSAT
  - 2022: *XRISM*
  - 2030+: *ATHENA*, *Lynx*