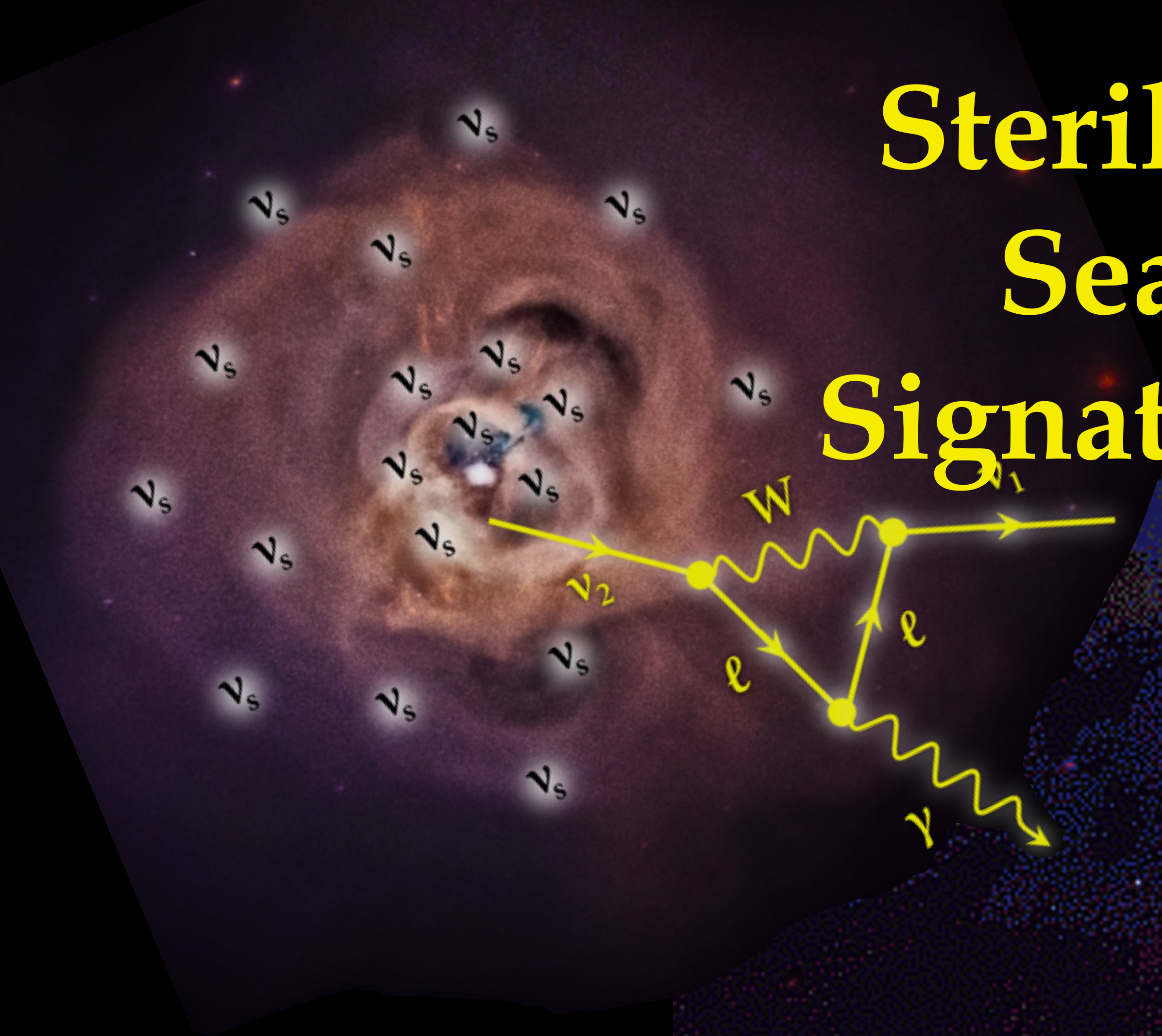
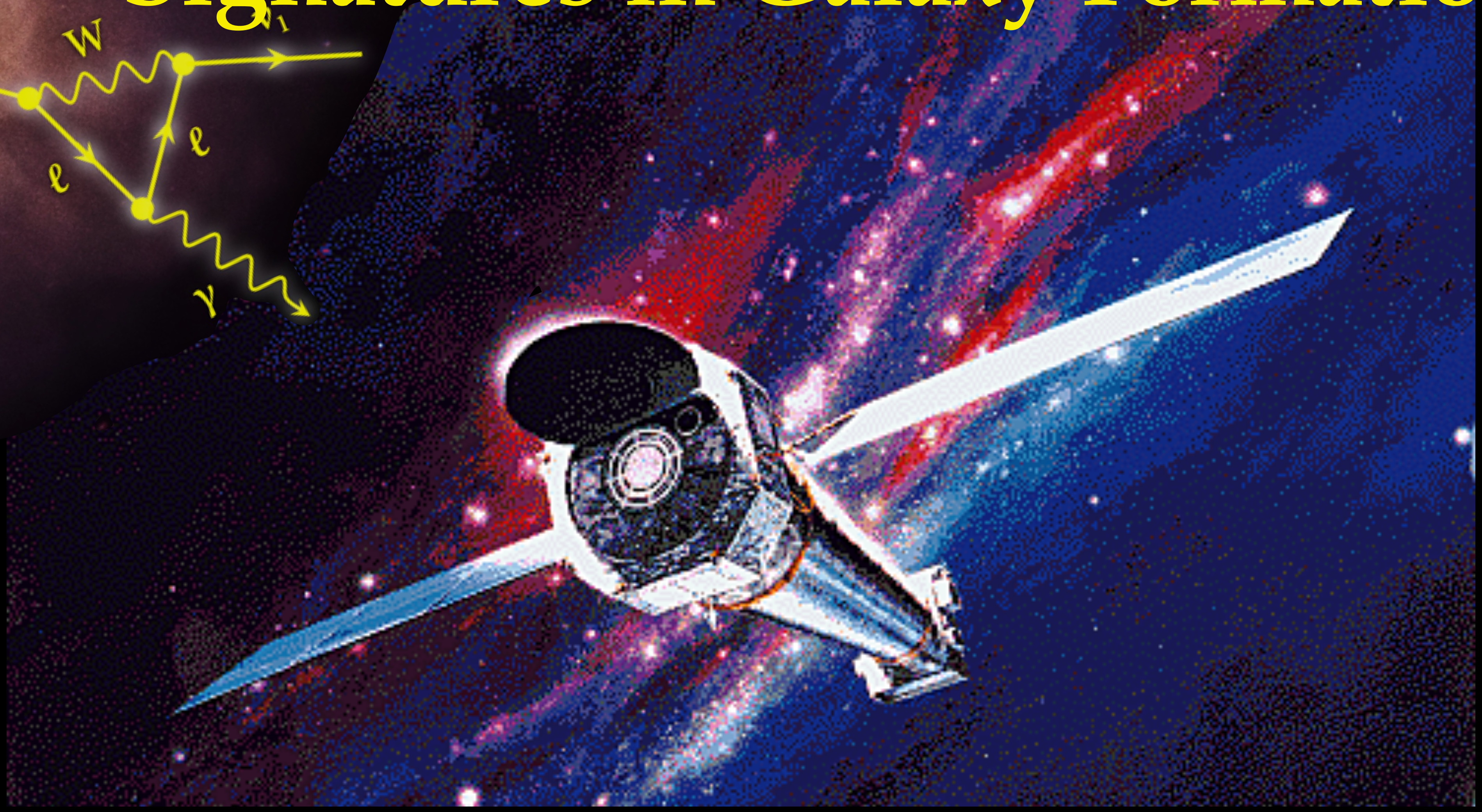
Sterile Neutrino Dark Matter: Searches in the X-ray and Signatures in Galaxy Formation





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University of California, Irvine

May 2, 2018

KITP Conference: Dark Matter Detection or Detectability

Kevork N. Abazajian
@kevaba

3.55 keV X-ray line consistent with DM decay has been seen in multiple sources, several follow-ups planned by future observatories & nuclear decay expts. vs interpretations help w/ galaxies' structure,   TBTF - #KITPDM18 talk tweet - more in review: arxiv.org/abs/1705.01837

10:57 AM - 2 May 2018

1 Like

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Neutrino Mass & Sterile Neutrinos

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

- Two massive (≳100 GeV) sterile neutrinos are required by atmospheric and solar neutrino mass scales

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

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


NEUTRINO

Sterile Neutrino Dark Matter Production

$$\Gamma_\alpha(p) \sim G_F^2 p T^4 \sim T^5$$

$$\Delta^2 \sim p^{-2} \sim T^{-2}$$

$$\Gamma(\nu_\alpha \to \nu_s) \sim \frac{\Gamma_\alpha(p)\Delta^2(p)\sin^2 2\theta}{\Delta^2(p)\sin^2 2\theta + D^2(p) + [\Delta(p)\cos 2\theta - V^L(p) - V^T(p)]^2}$$

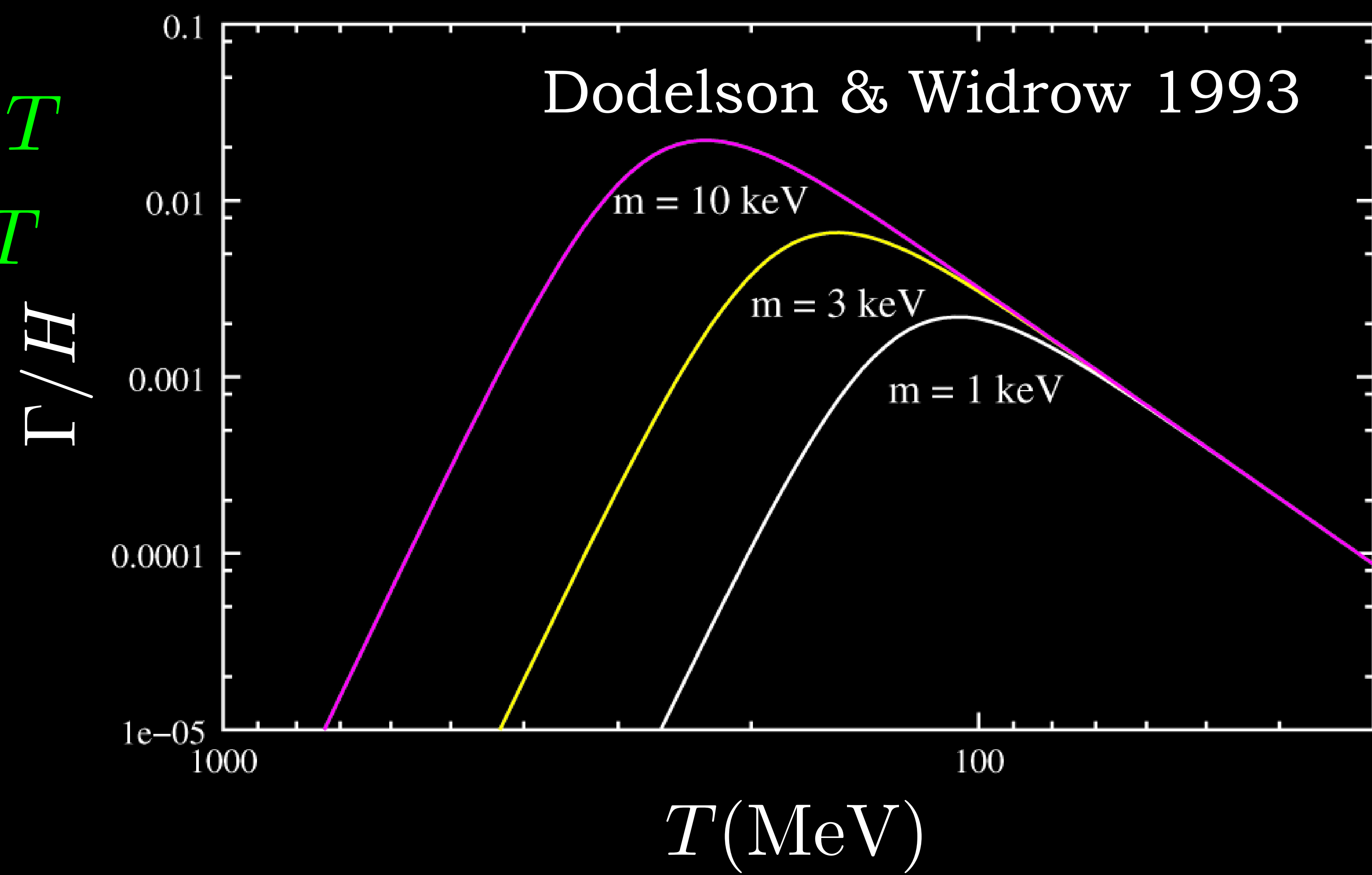
$$D(p)^2 \sim T^{10}$$

$$[V^T]^2 \sim T^{10}$$

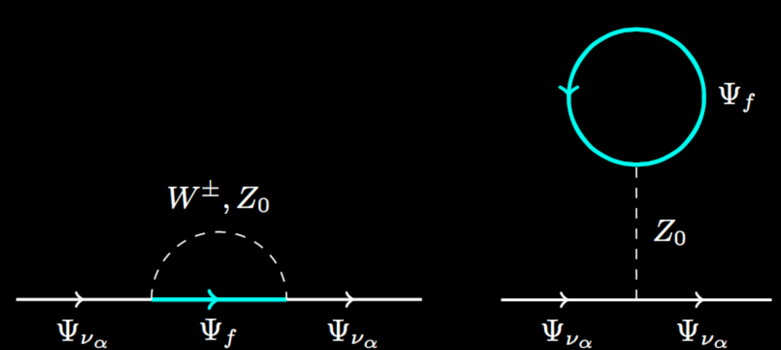
$$H^2 = \frac{8\pi}{3} G\rho \sim T^4$$

Resonance: Shi & Fuller 1998

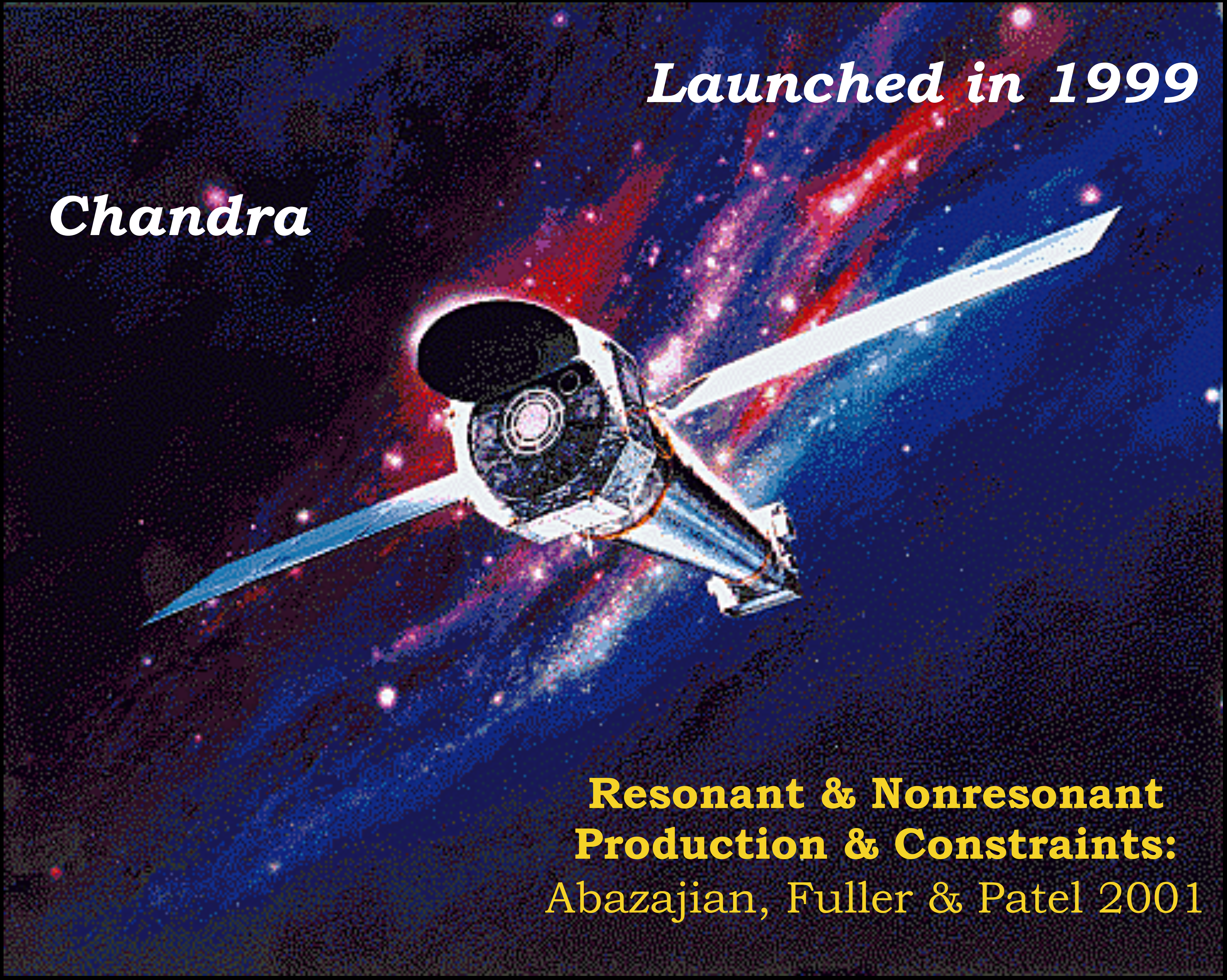
$$\frac{\Gamma}{H} \sim \begin{cases} T^{-9} & \text{High } T \\ T^3 & \text{Low } T \end{cases}$$



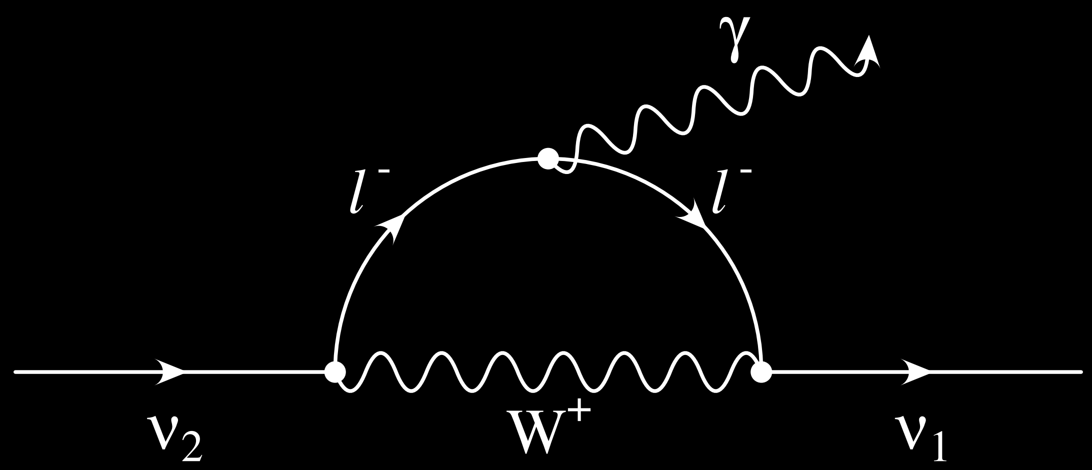
Never in Equilibrium!!



Observing the Sterile Neutrino in the X-ray: *Chandra & XMM-Newton X-ray Space Telescopes*



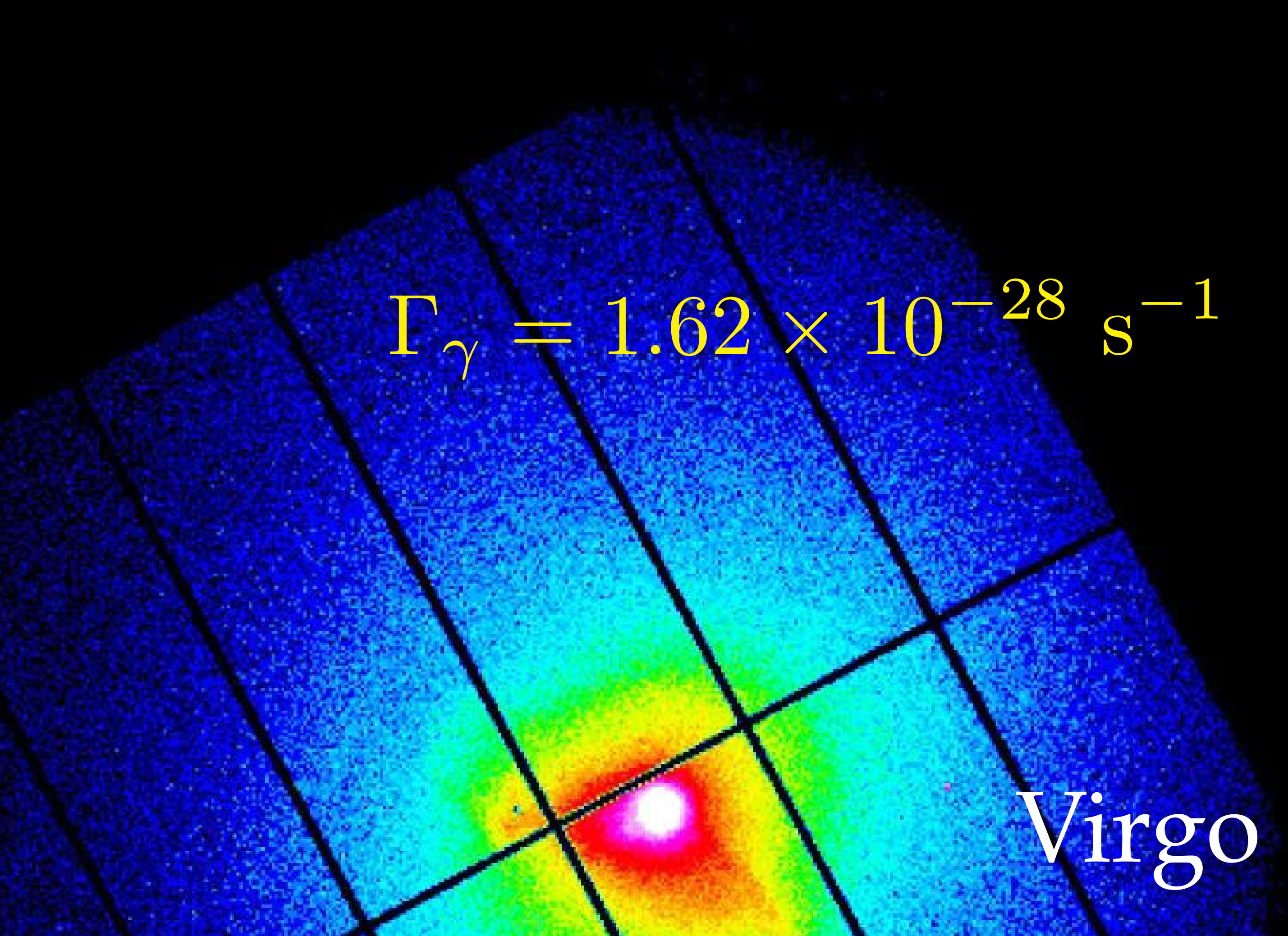
Sterile ν WDM Radiative Decay in the X-ray



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

$$\text{“}\nu_s\text{”} \rightarrow \text{“}\nu_\alpha\text{”} + \gamma$$

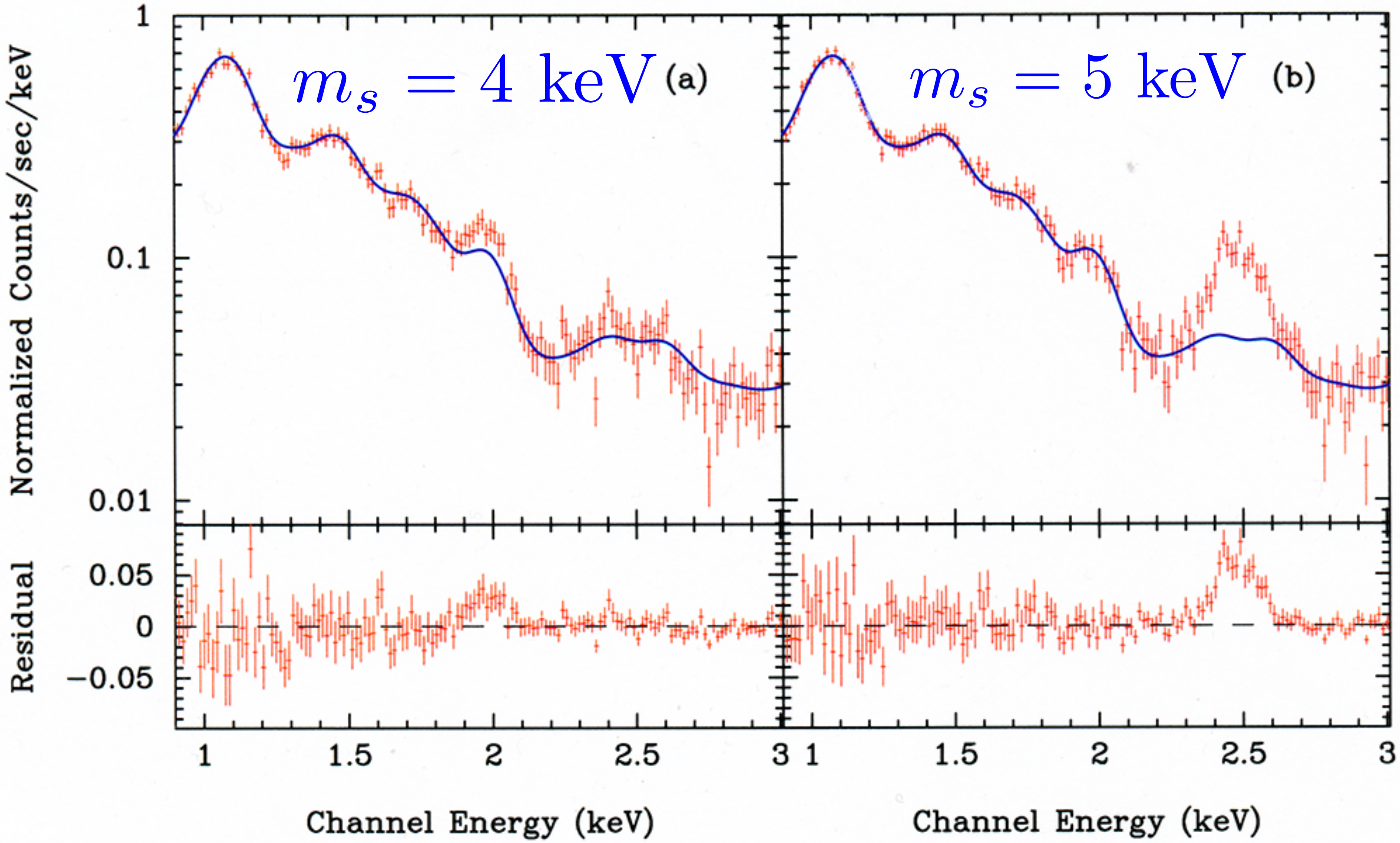
$$E_\gamma = \frac{m_s}{2} \sim 1\ \text{keV}$$



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

Virgo Cluster: 10^{78} DM particles

Slide from 2001



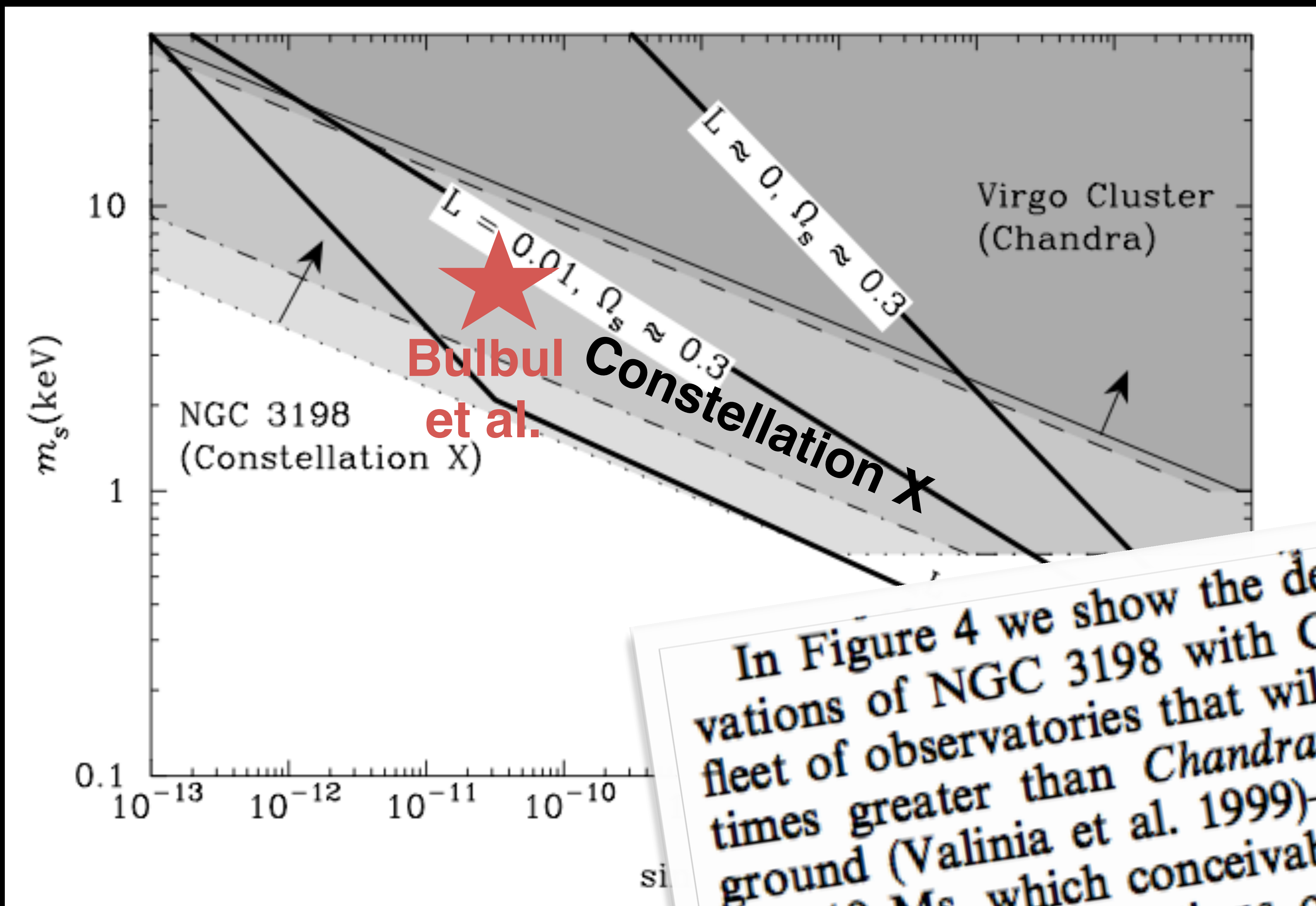
Current Limits

+

Future Detection?

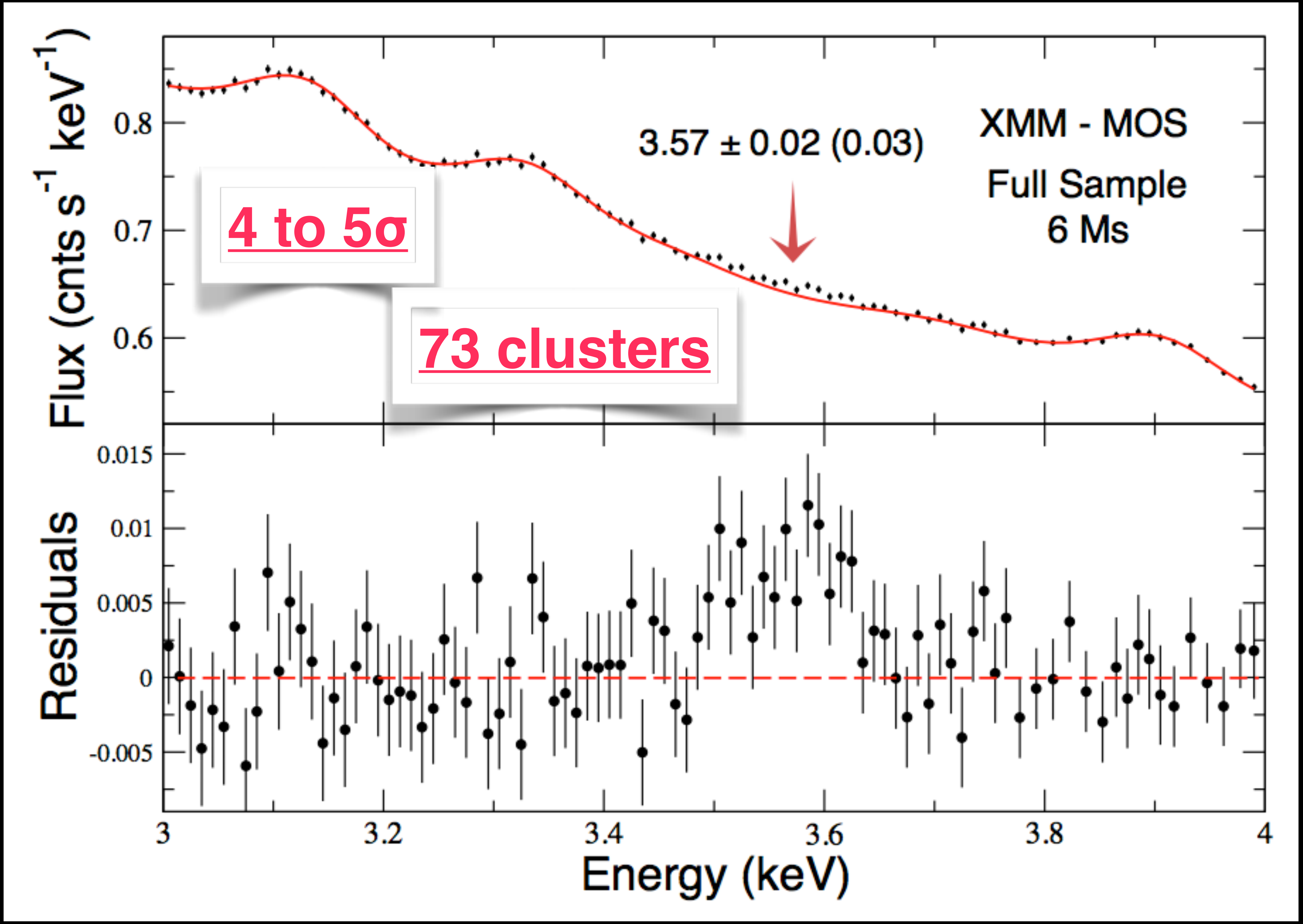
Forecast X-ray Observation Sensitivity for *Constellation-X*

Abazajian, Fuller & Tucker 2001



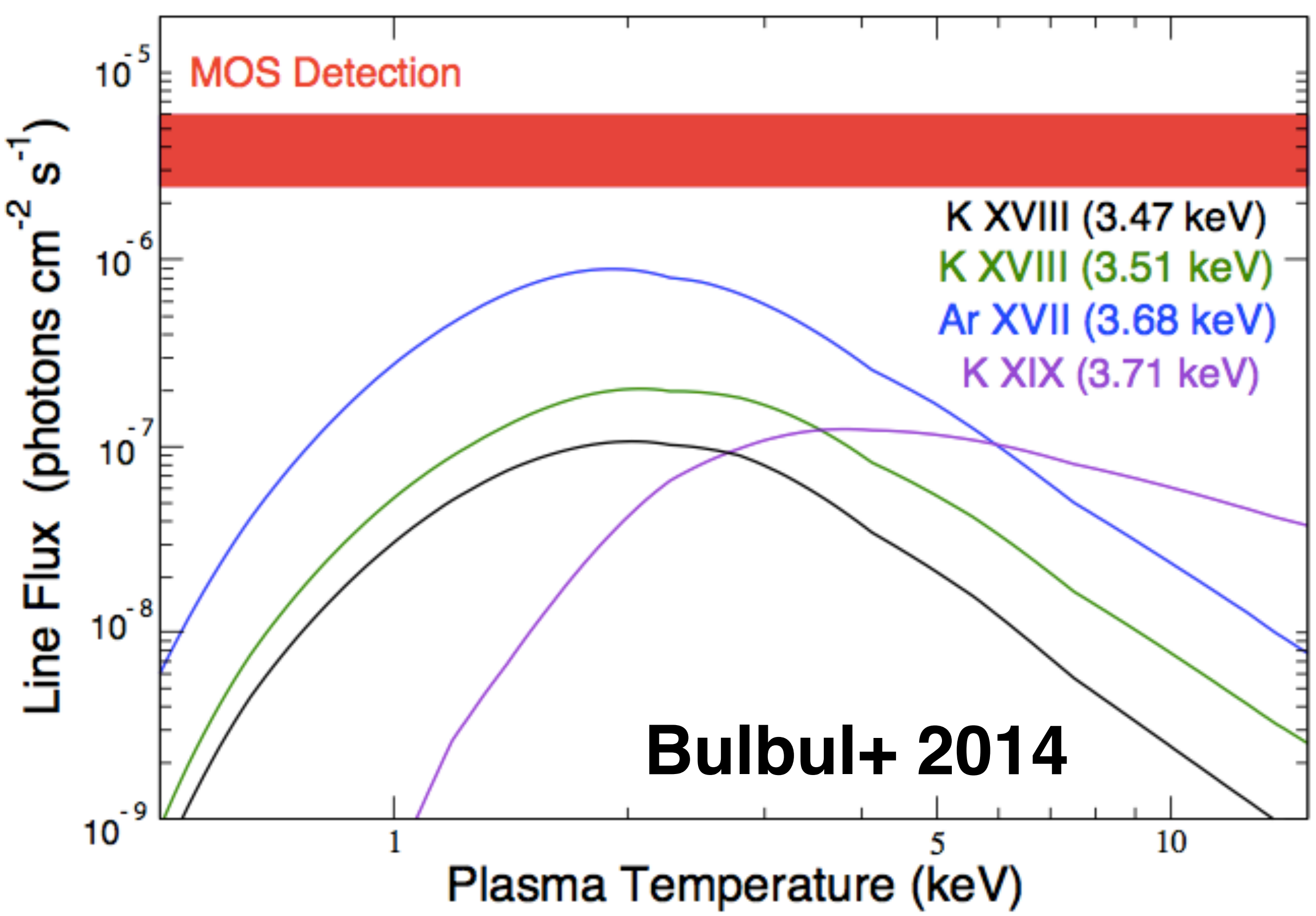
In Figure 4 we show the detectability region for observations of NGC 3198 with Constellation X—a proposed fleet of observatories that will have an effective area ~10 times greater than *Chandra* and no instrumental background (Valinia et al. 1999)—for two integration times, 1 and 10 Ms, which conceivably 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

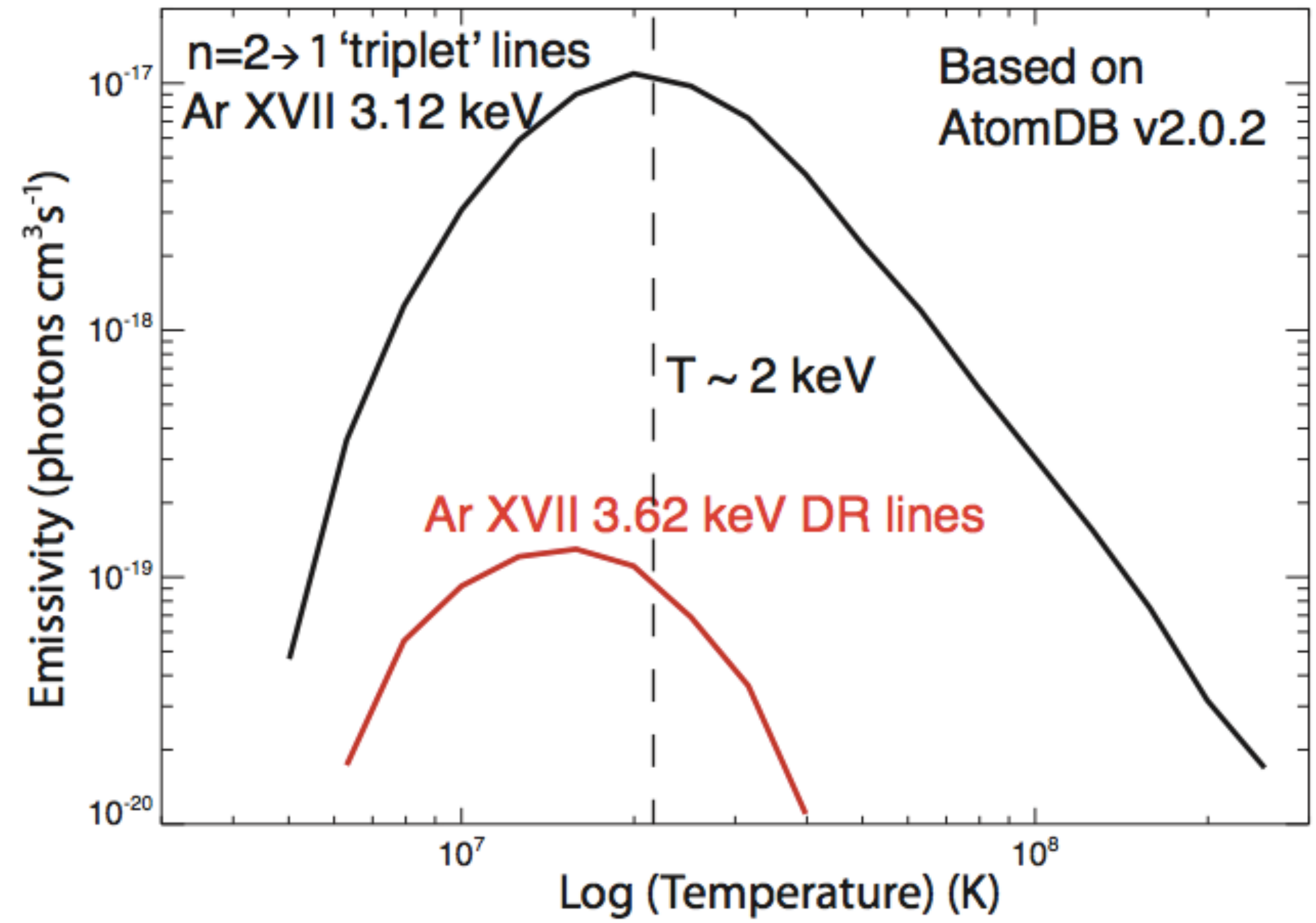
The Detection of an Unidentified Line



Bulbul et al. ApJ 2014

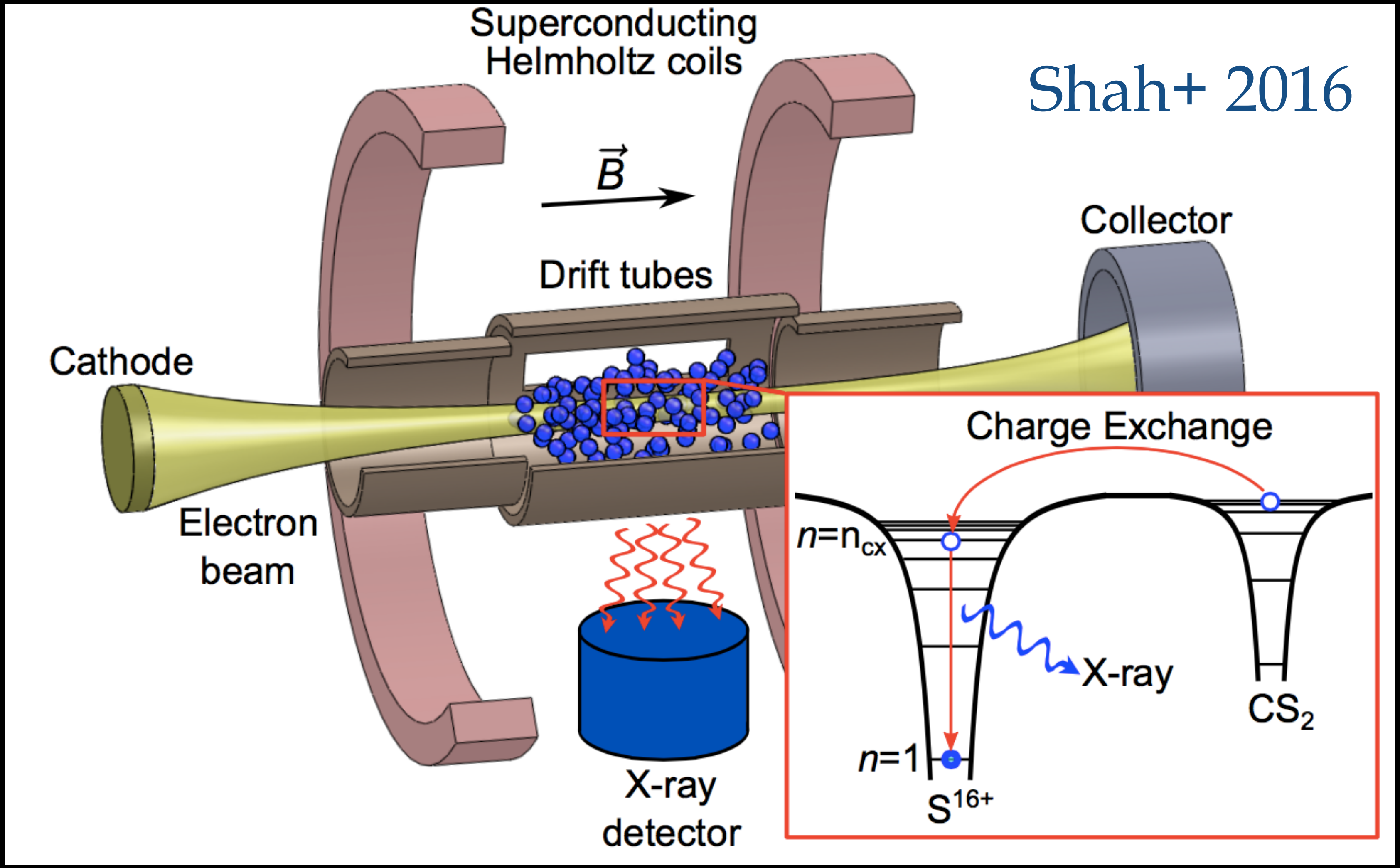
Metal Lines in Clusters at 3.5 keV? *unlikely*





- Most lines at this energy are too low in flux for the typical plasma temperatures
- Those that could be close, Ar XVII DR, would have accompanying lines that make its flux a factor of 30 too low

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)

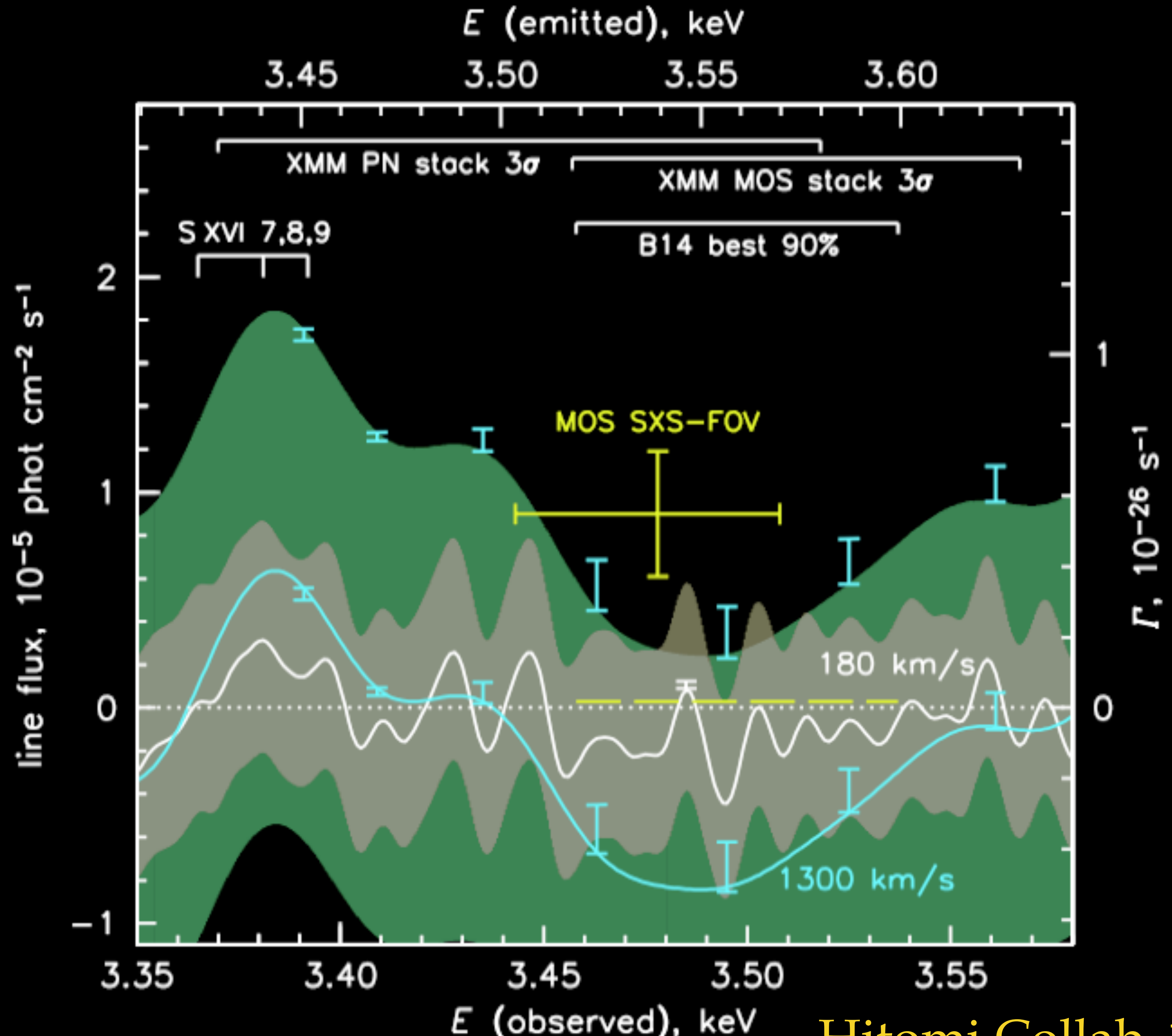
Confirmation hope: Hitomi (Astro-H) X-ray Telescope

Successful launch Feb. 17, 2016

Loss of satellite March 26, 2016

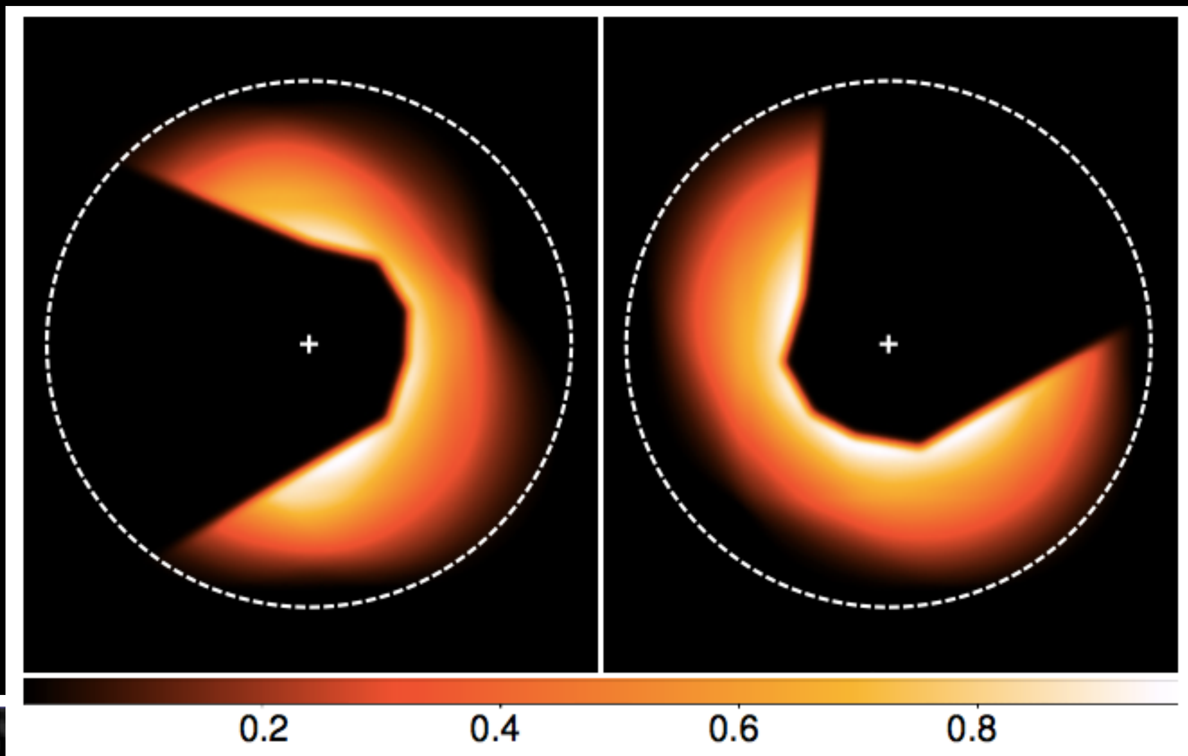
NASA Build-to-print SXS for the X-Ray Astronomy Recovery Mission launch in 2021

Hitomi X-ray Telescope: Expected line or not?



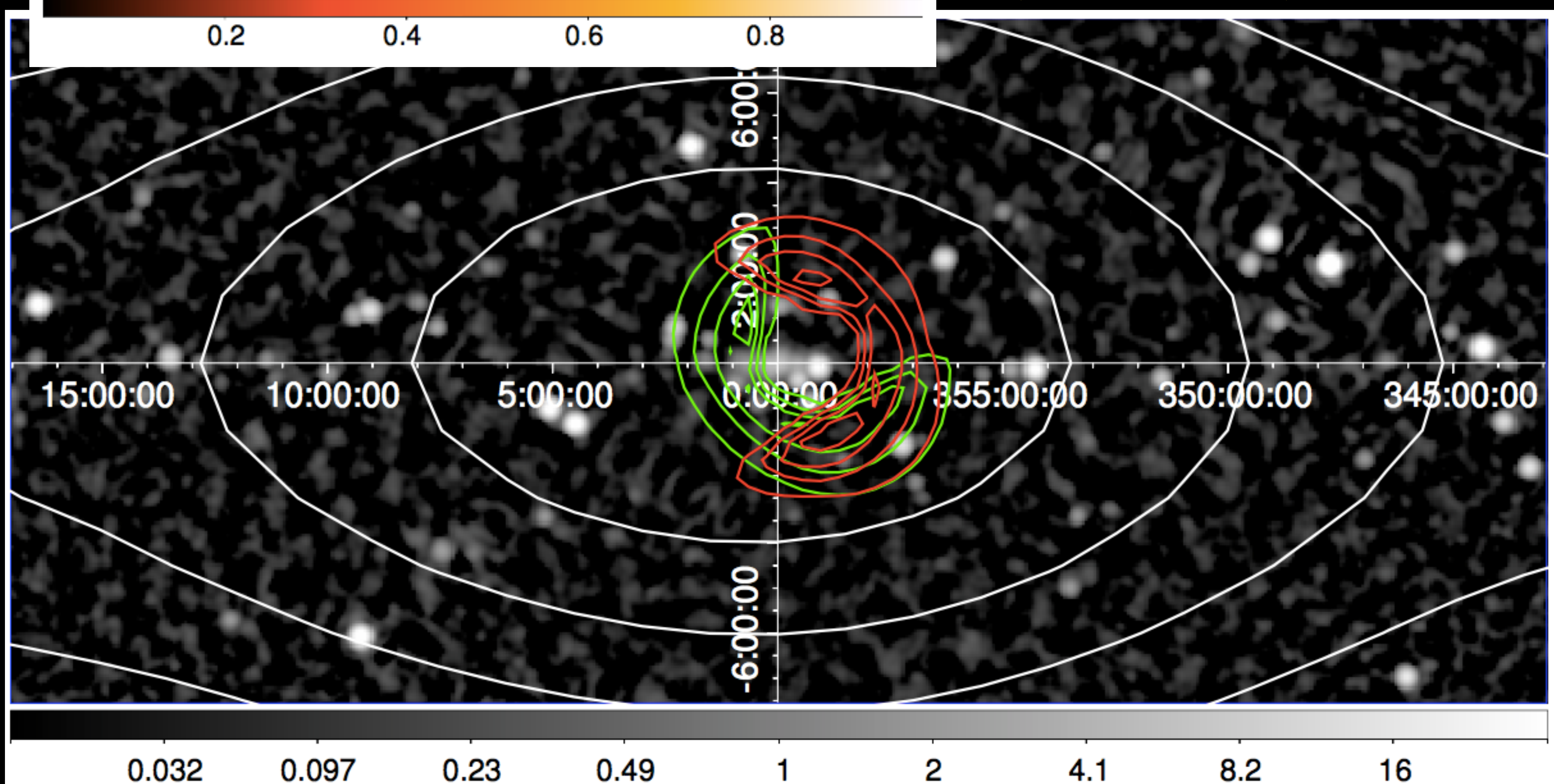
Hitomi Collab. 1607.07420

NuSTAR: the best current telescope?

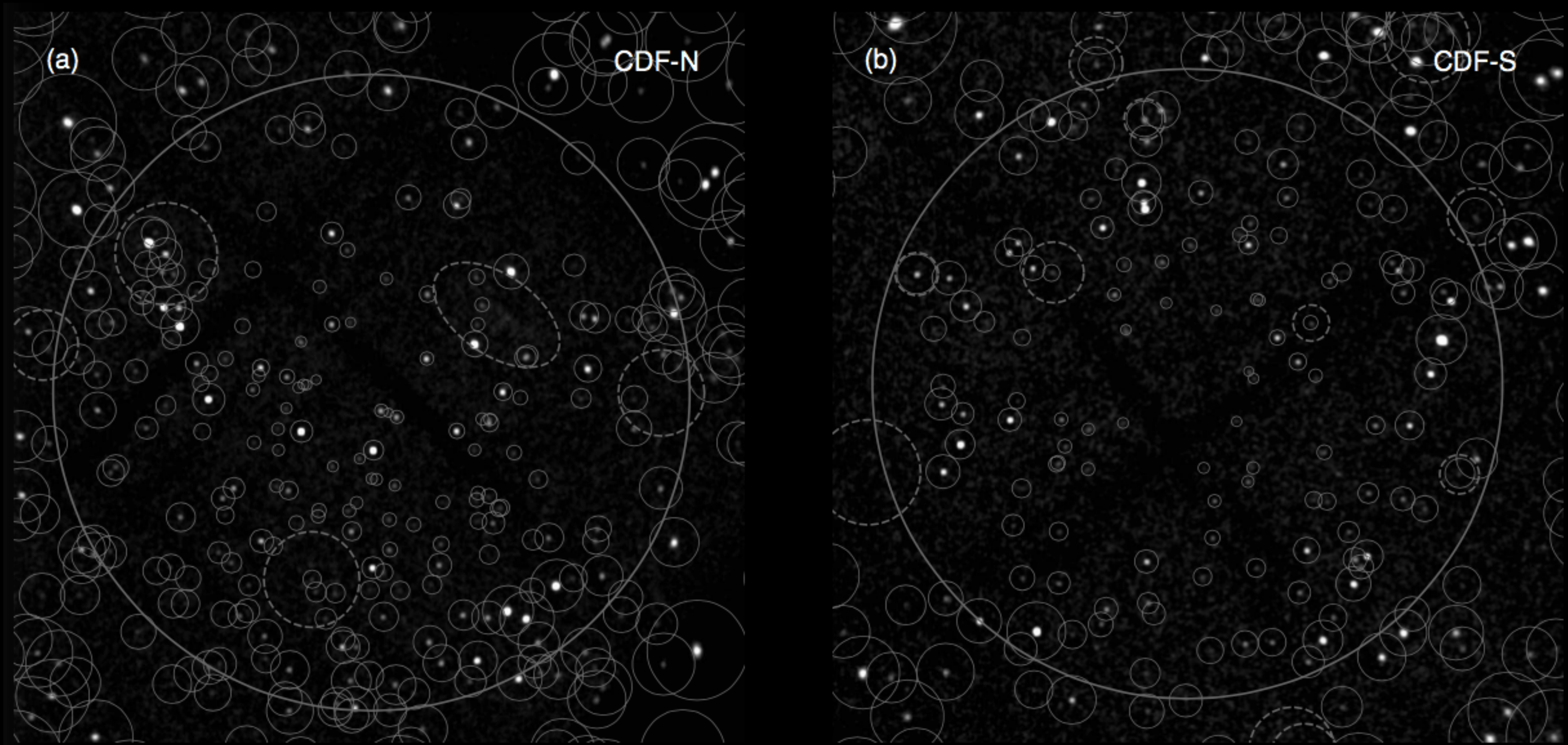


Shielding gap in telescope lets in 0 bounce photons. 37 deg^2 aperture!

Perez+: **GC no signal, limits** (1609.00667)
Neronov+: **Deep field sees 11.1σ 3.5 keV line consistent with DM decay** (1607.07328)



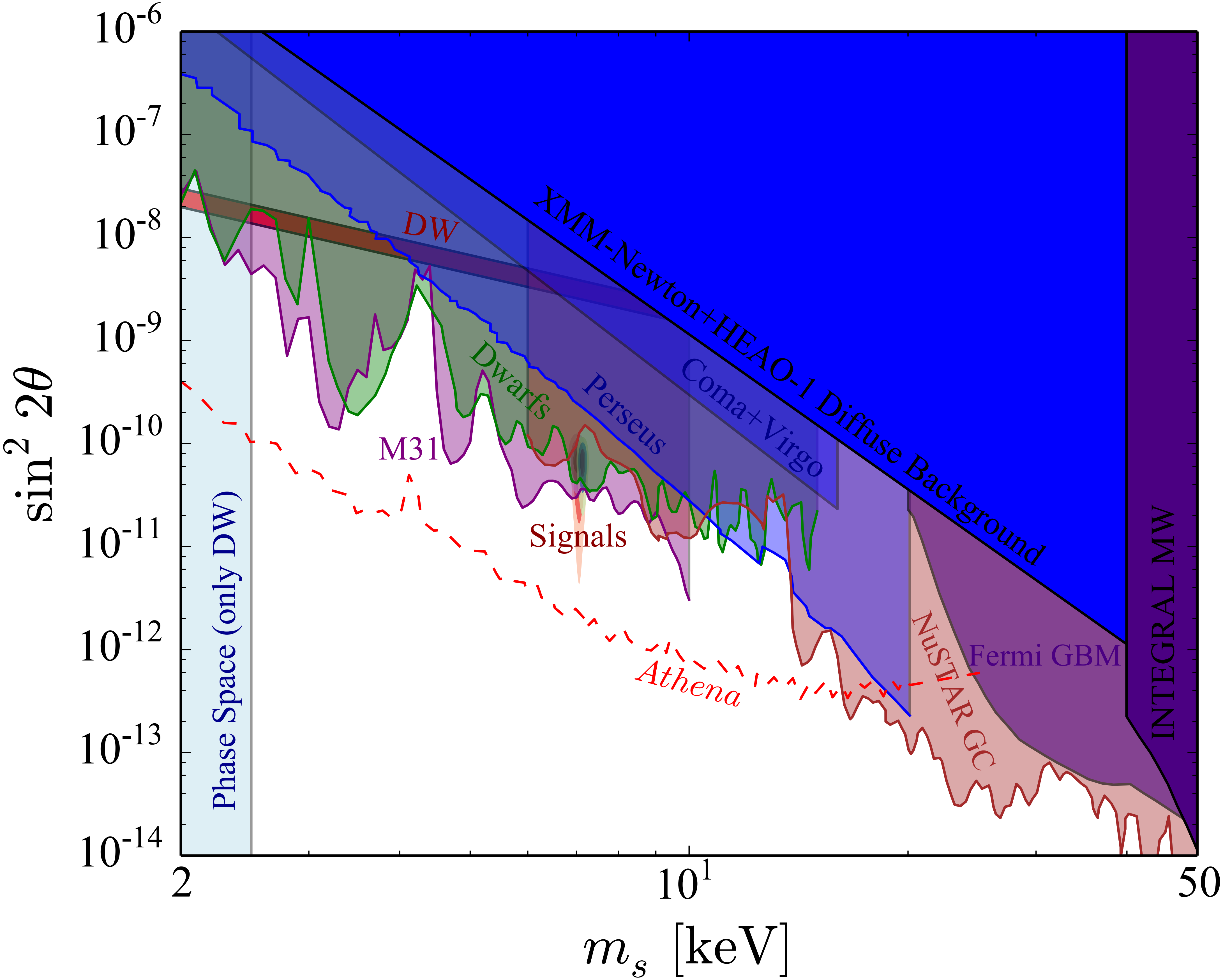
Chandra Deep Fields: 10 Ms of data



Cappelluti+ 2017: see the line at 3σ in ~10 Ms of COSMOS Legacy and Chandra Deep Field South observations,
Rule out instrumental feature based on detailed characterization of response,
Rule out CX & Ar lines due to lack of partner lines
(K shown to be incompatible in 2014)

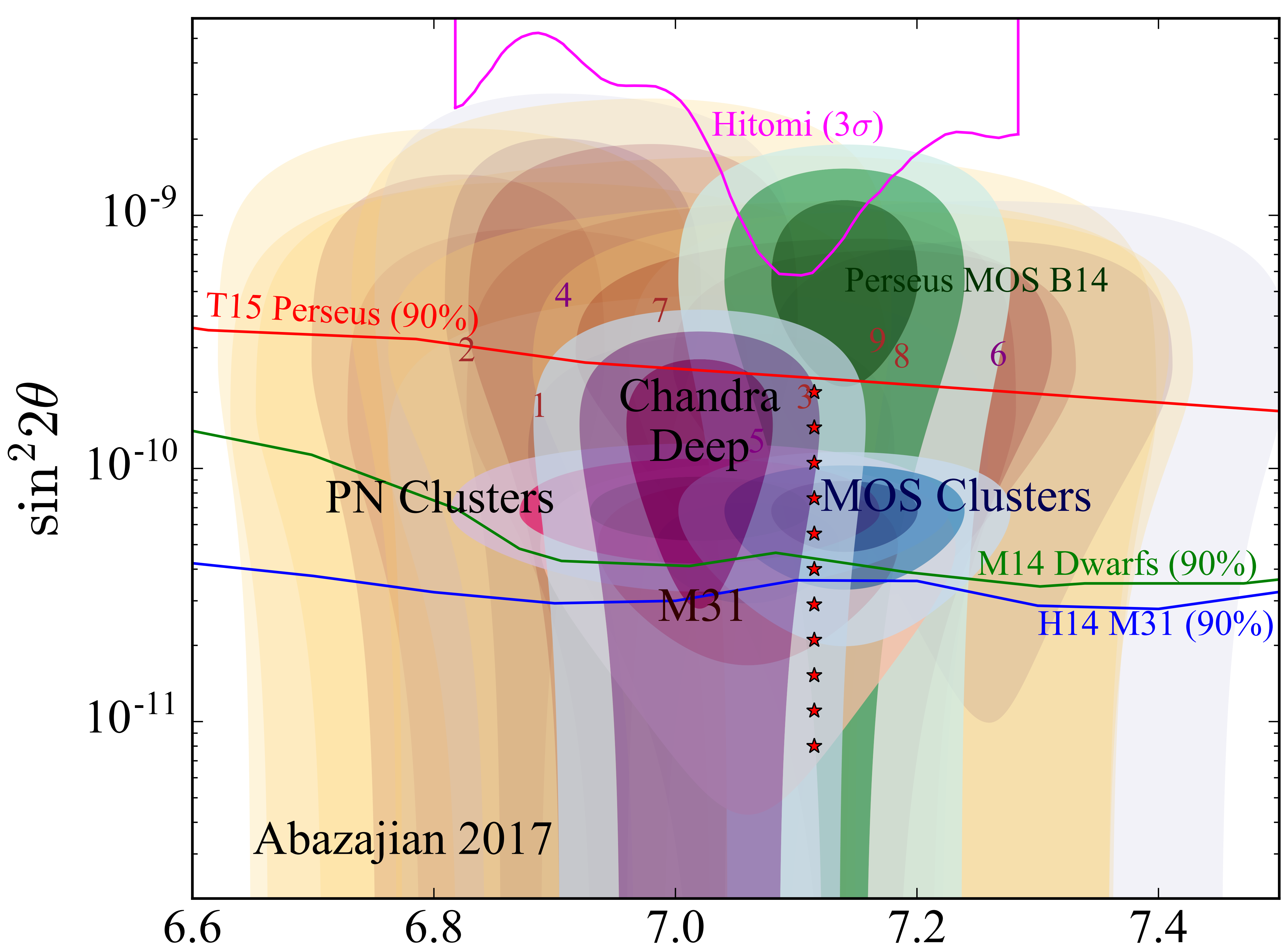
arXiv:1701.07932

Sterile Neutrino Dark Matter: Parameter Space Summary



Abazajian *Physics Reports* arXiv:1705.01837

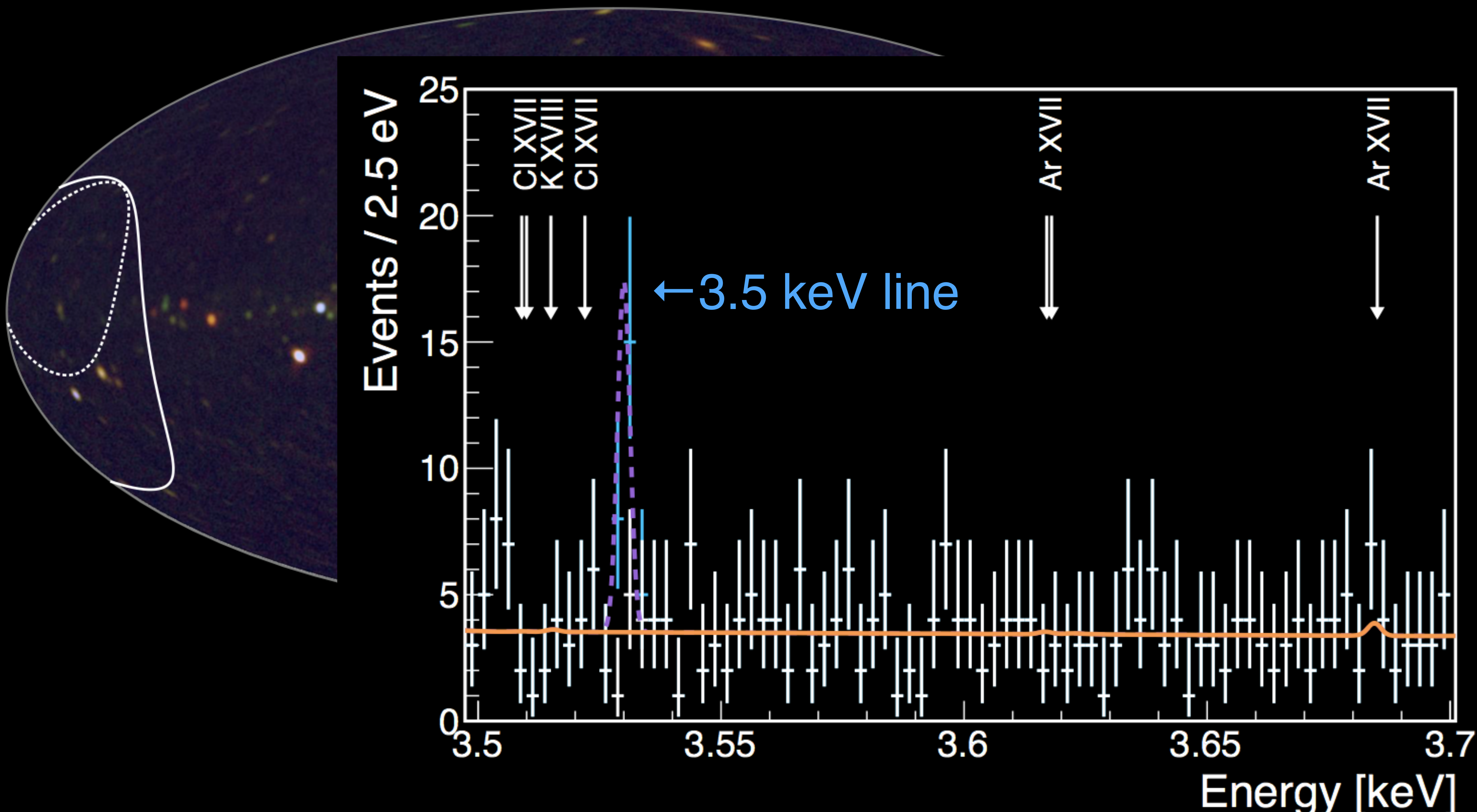
The 7 keV Region Today



arXiv:1705.01837

Cluster search: Iakubovskyi+ 1508.05186

Confirmation? Sounding Rocket X-ray Observations: Micro-X & XQC

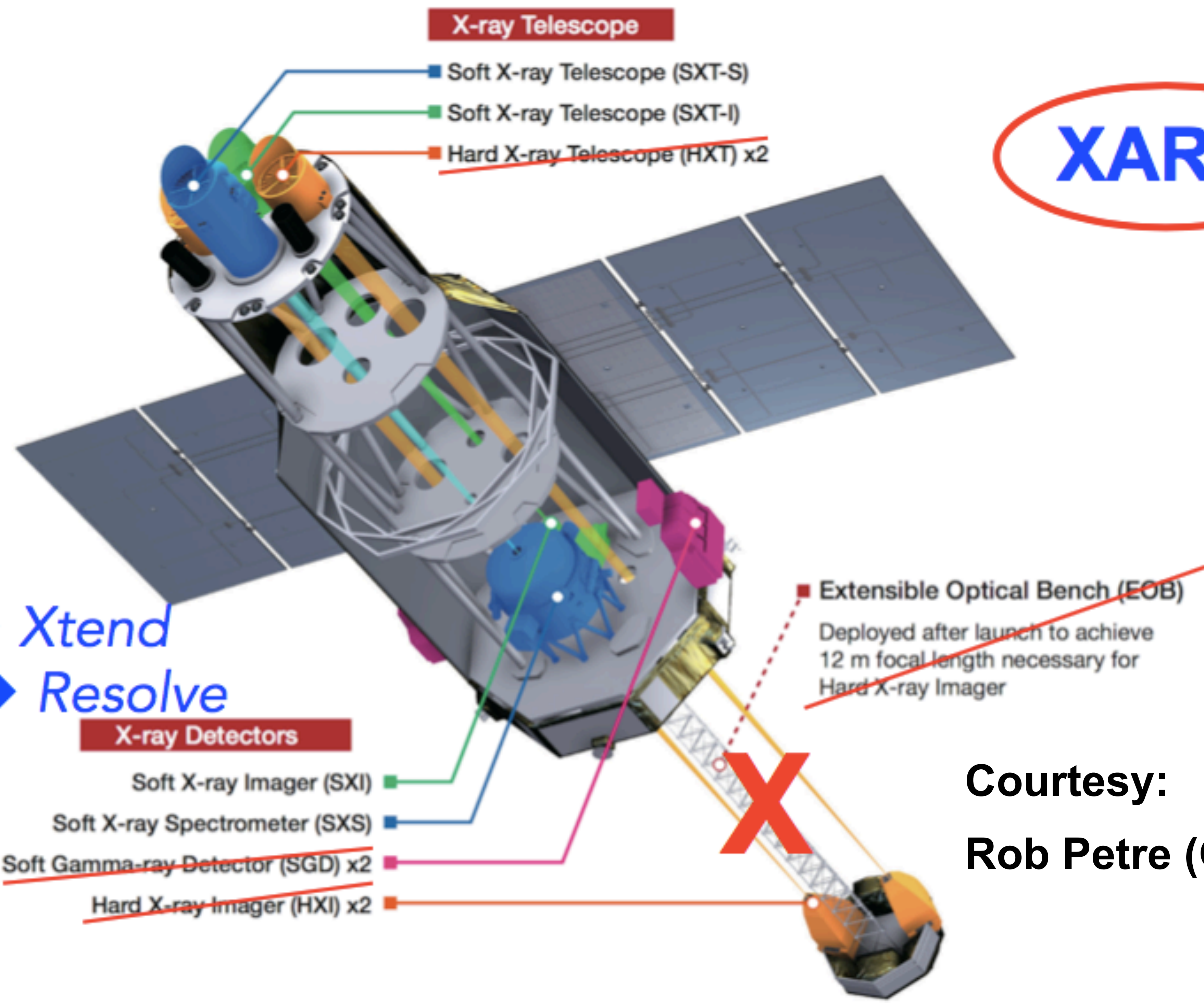


Figueroa-Feliciano+ 1506.05519

Next Space Mission in X-ray Astronomy

X-Ray Astronomy Recovery Mission

XARM
X-ray Astronomy Recovery Mission
Resolve



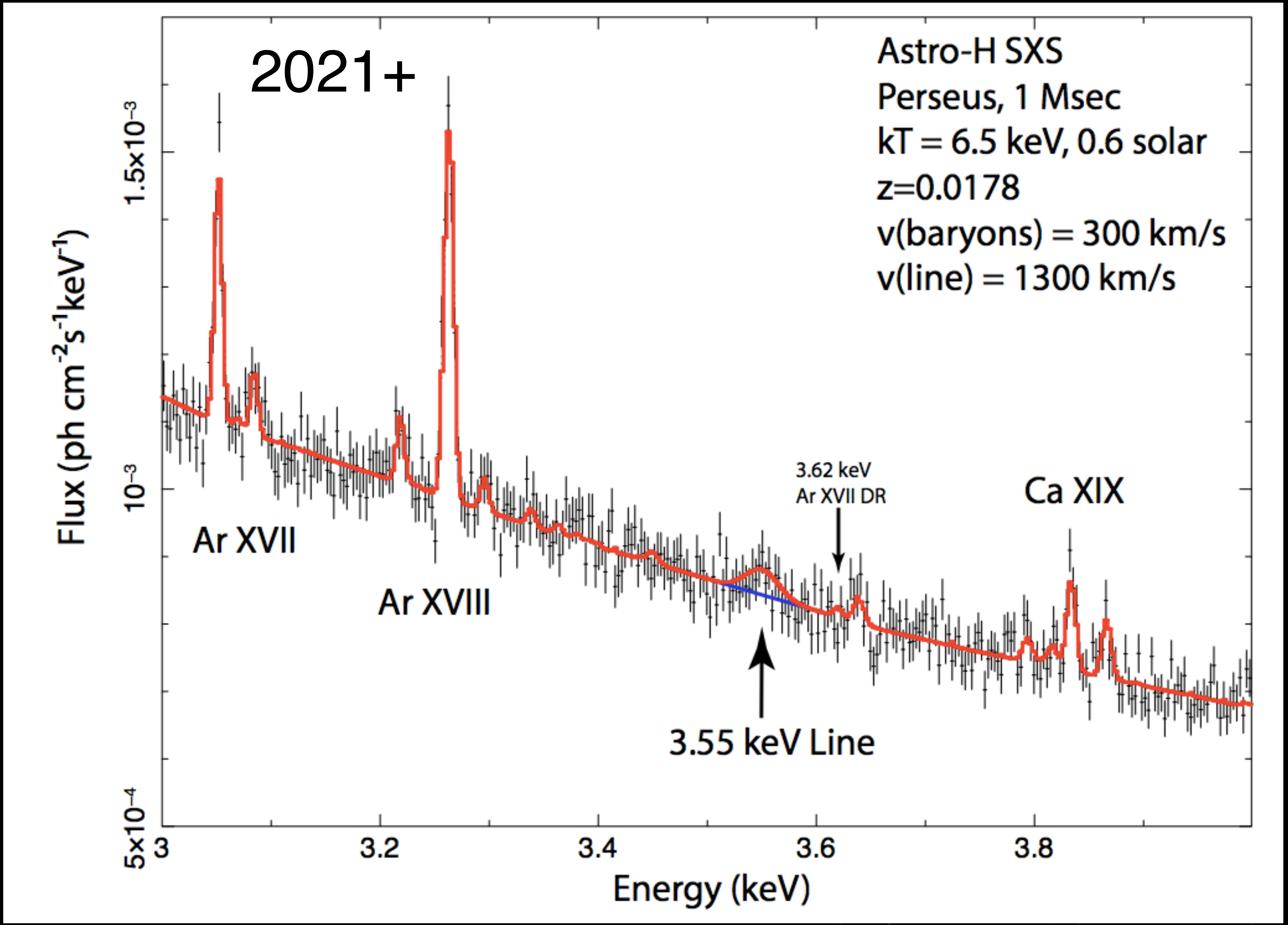
SXI+SXT → *Xtend*

SXS+SXT → *Resolve*

Courtesy:

Rob Petre (GSFC)

Confirmation? XARM



Bulbul et al. ApJ arXiv:1402.2301

Visibility of the Sterile Neutrino

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

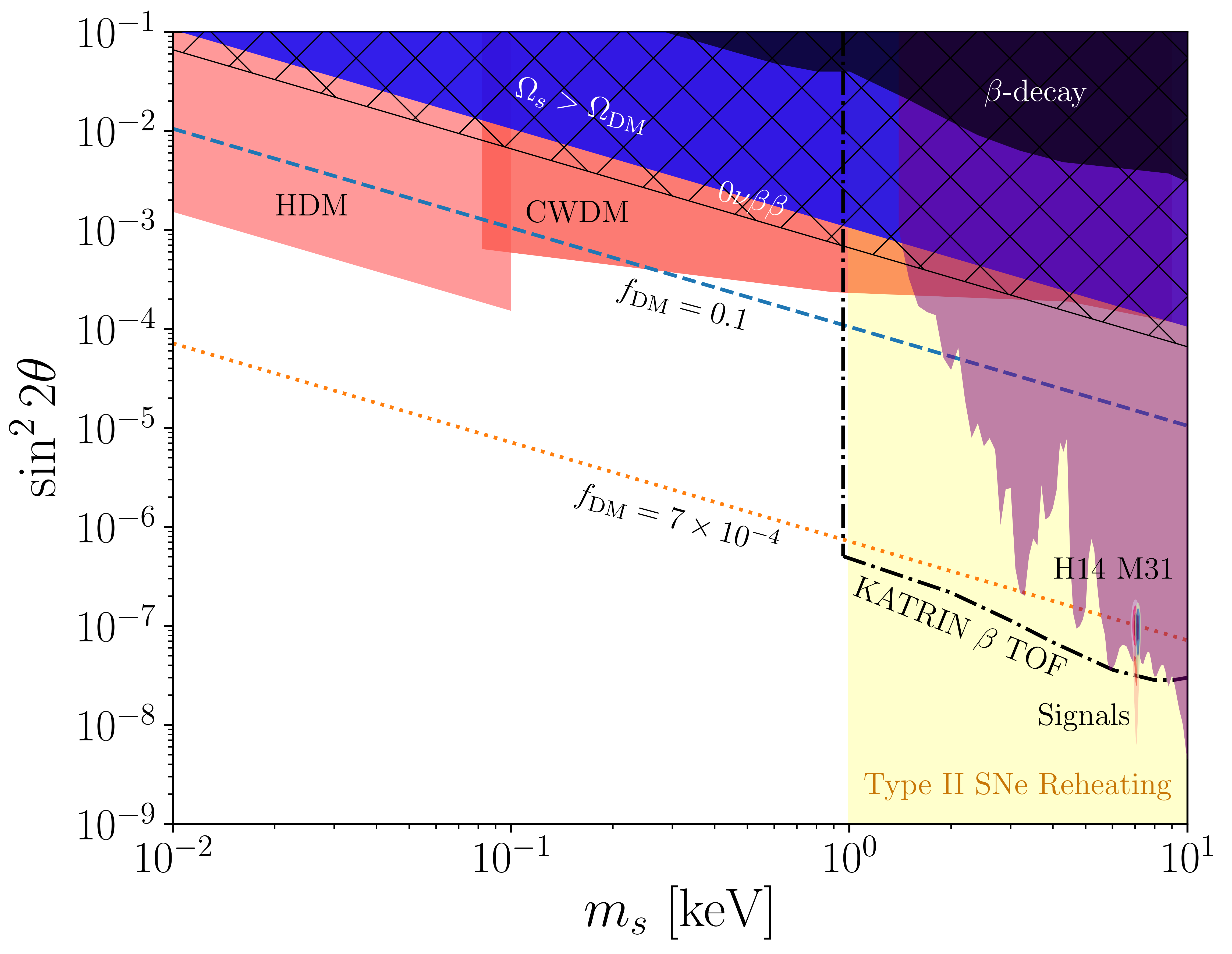
$$\text{Flux} \propto f_{\rm DM} \sin^2 2\theta \quad \text{but: } f_{\rm DM} \propto \left(\sin^2 2\theta\right)^{1.23} \ \text{(Abazajian 2005)}$$

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

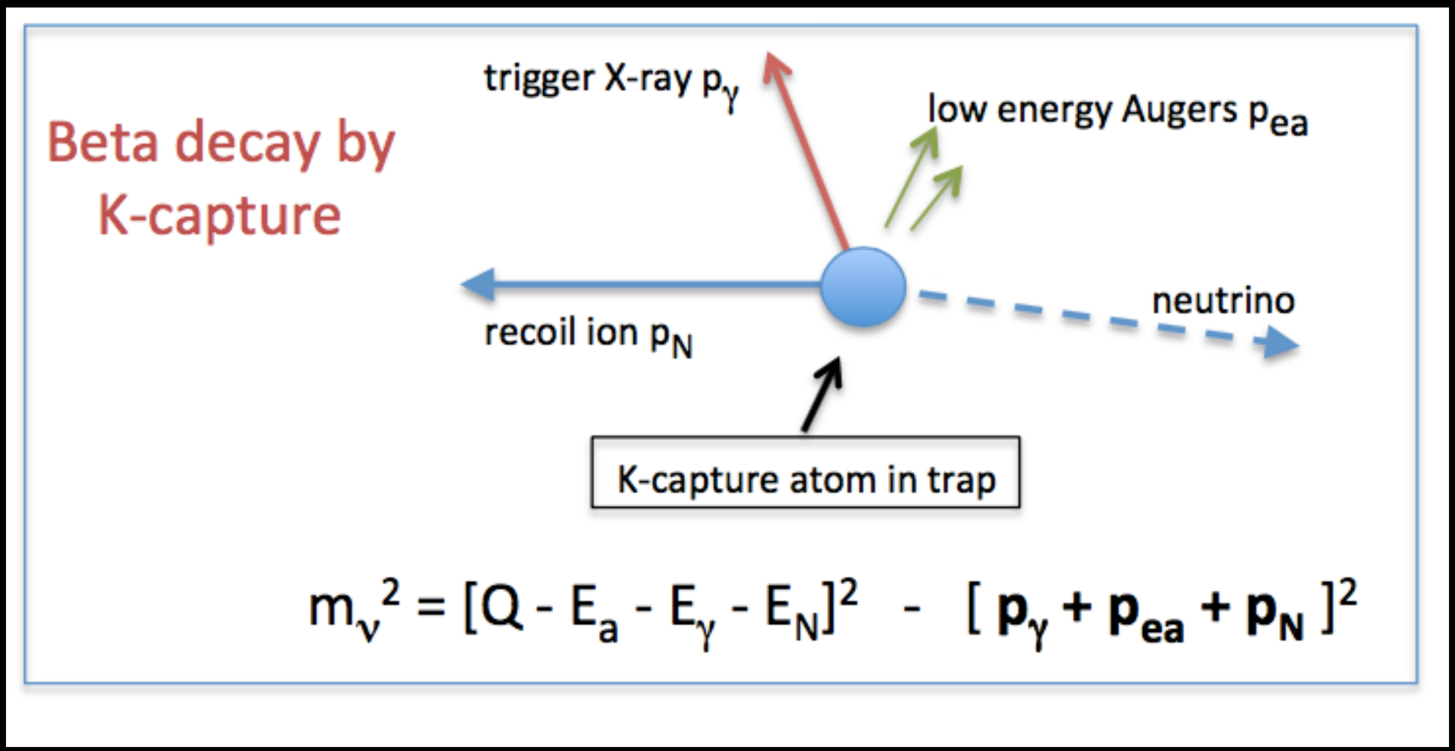
⇒Can achieve even larger mixing angles in low-reheating temperature universes (Gelmini, Palomares-Ruis & Pascoli 2004)

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

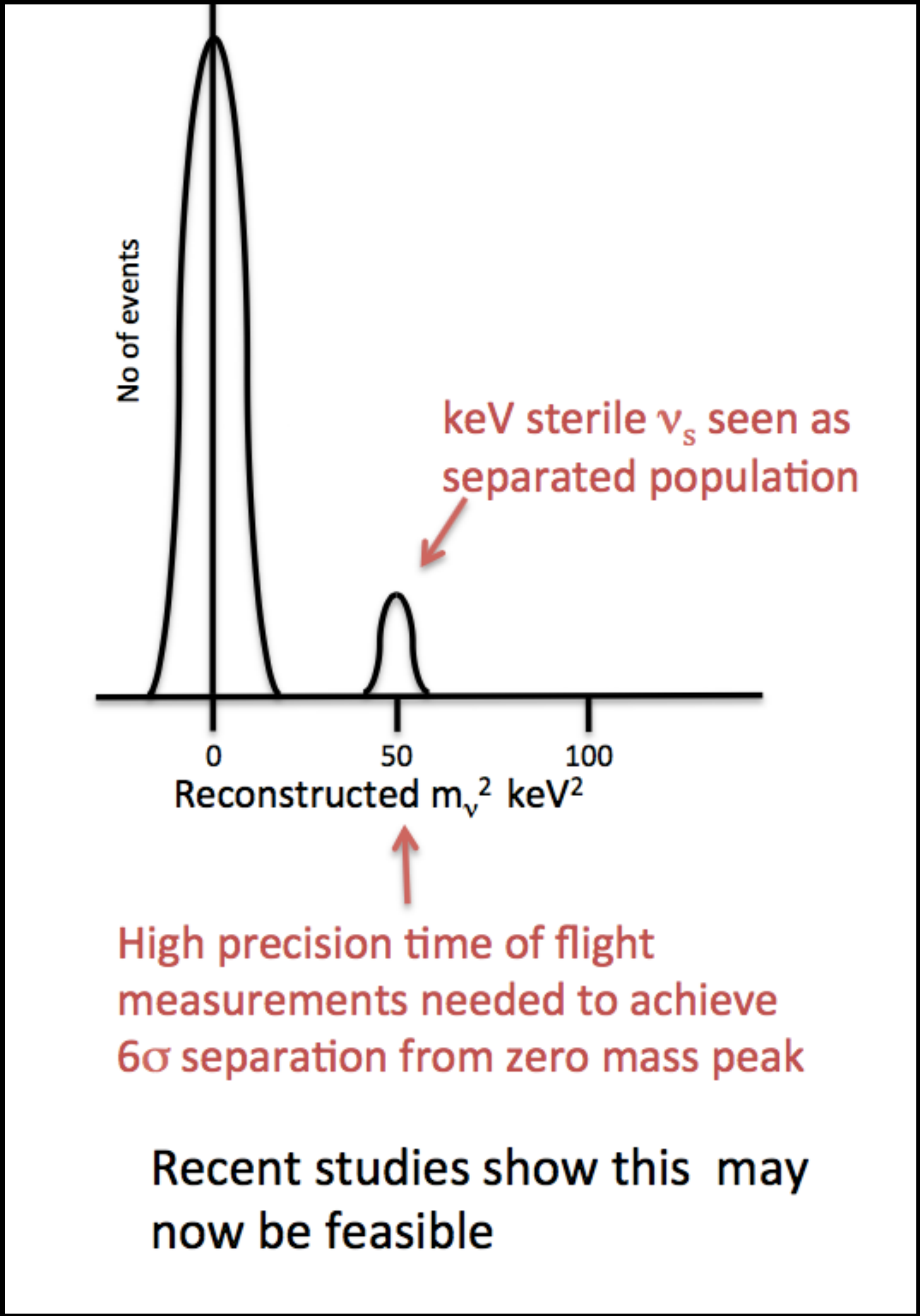
Visible Sterile ν in the Low-Reheat Universe



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



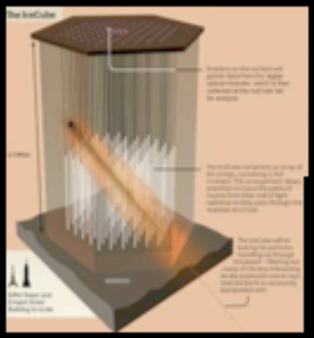
Original studies: Finocchiaro & Shrock 1992

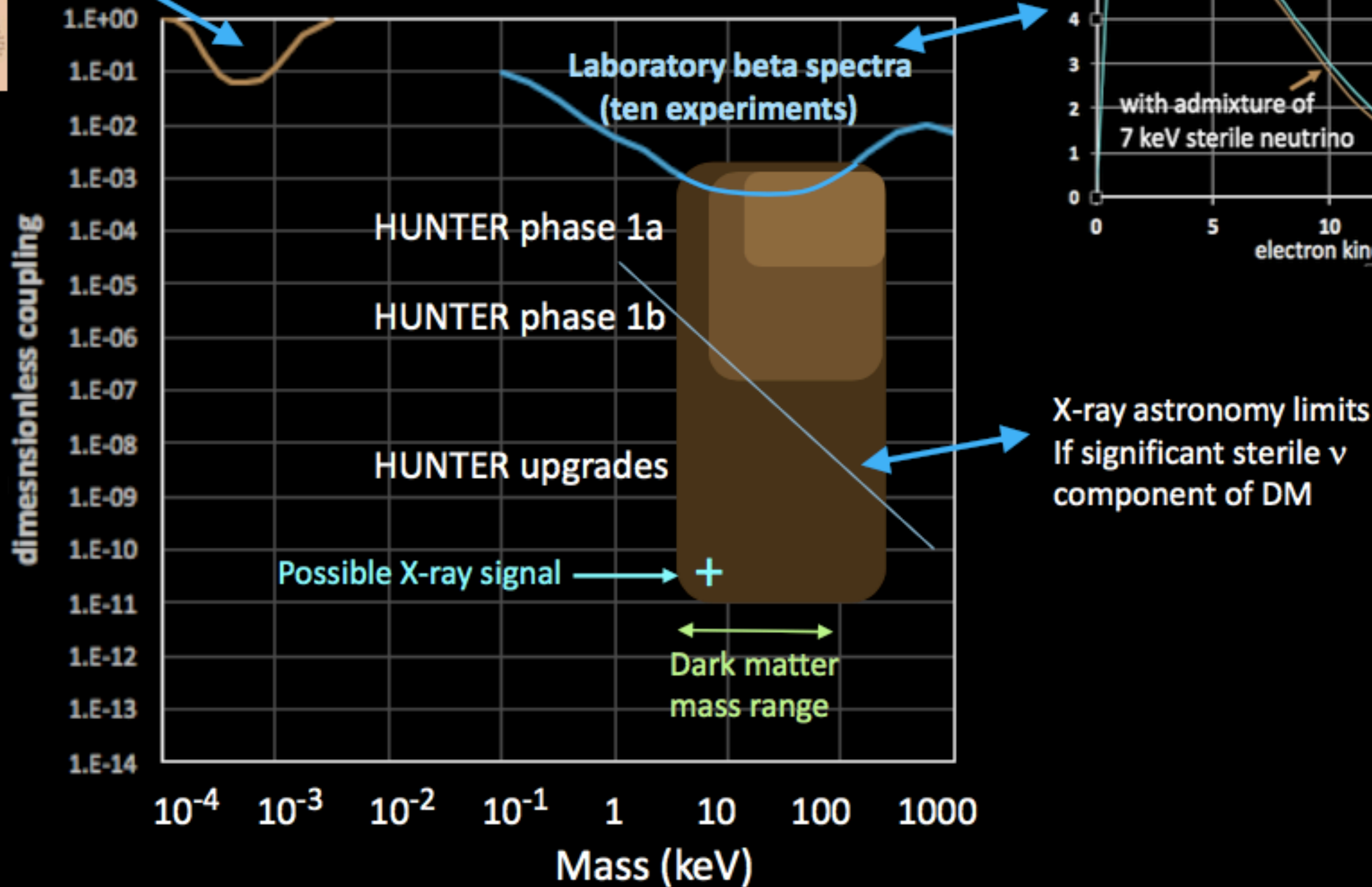


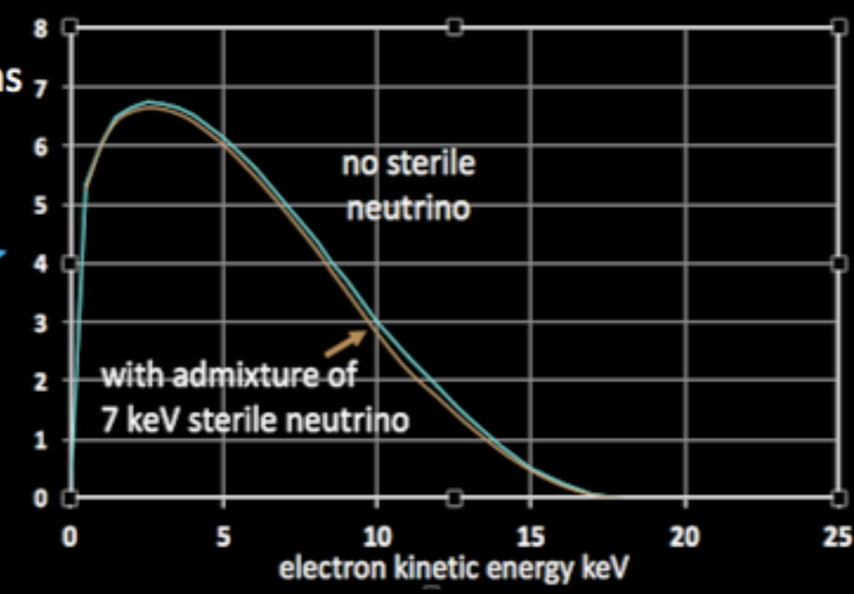
HUNTER experiment (Heavy Unseen Neutrinos by Total Energy-momentum Reconstruction)

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

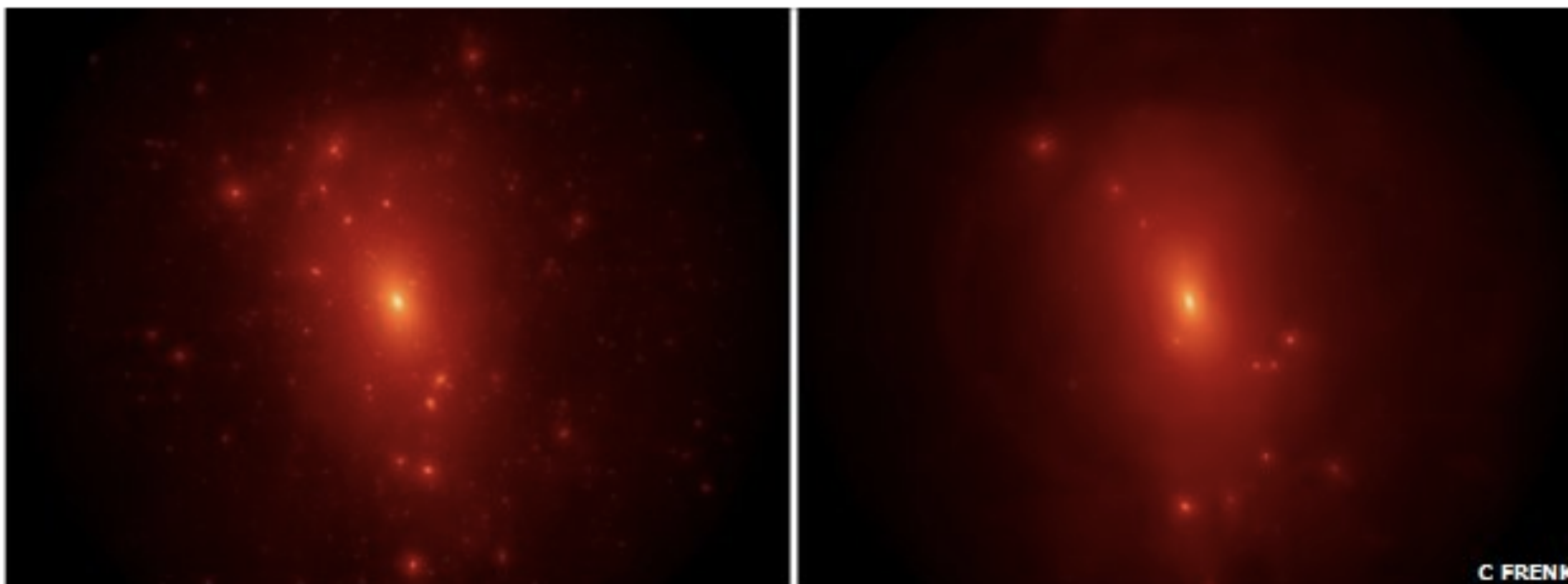
Existing limits and future coverage of HUNTER experiment





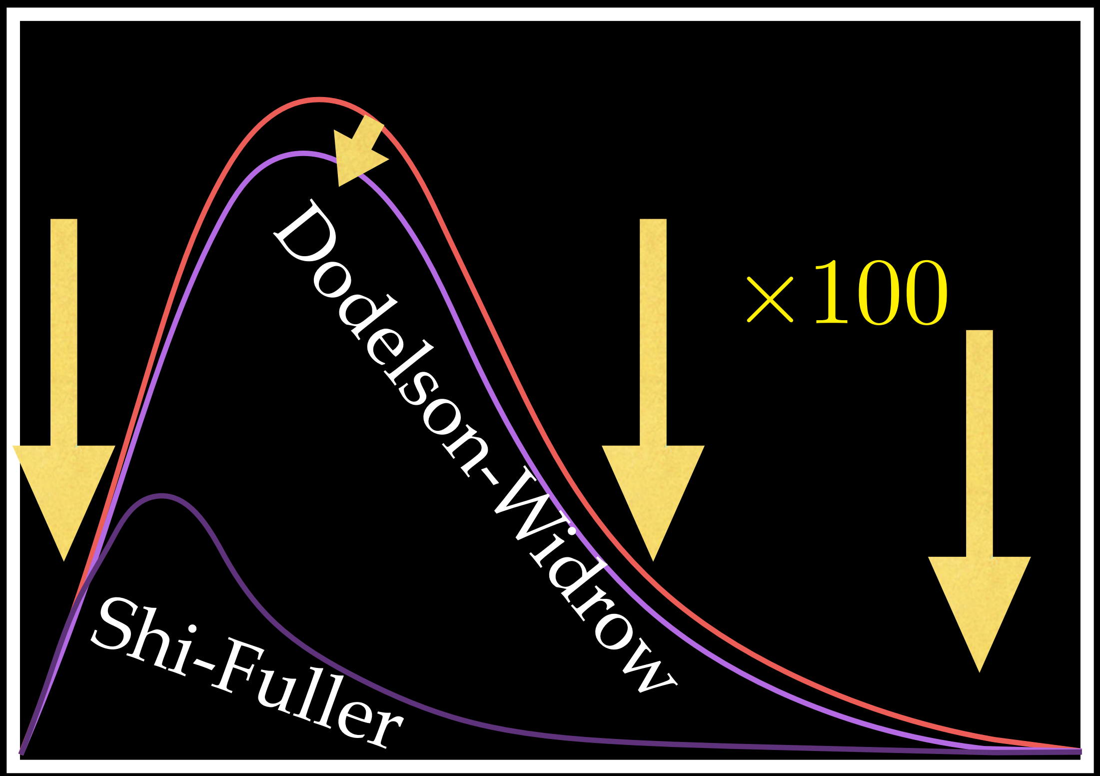


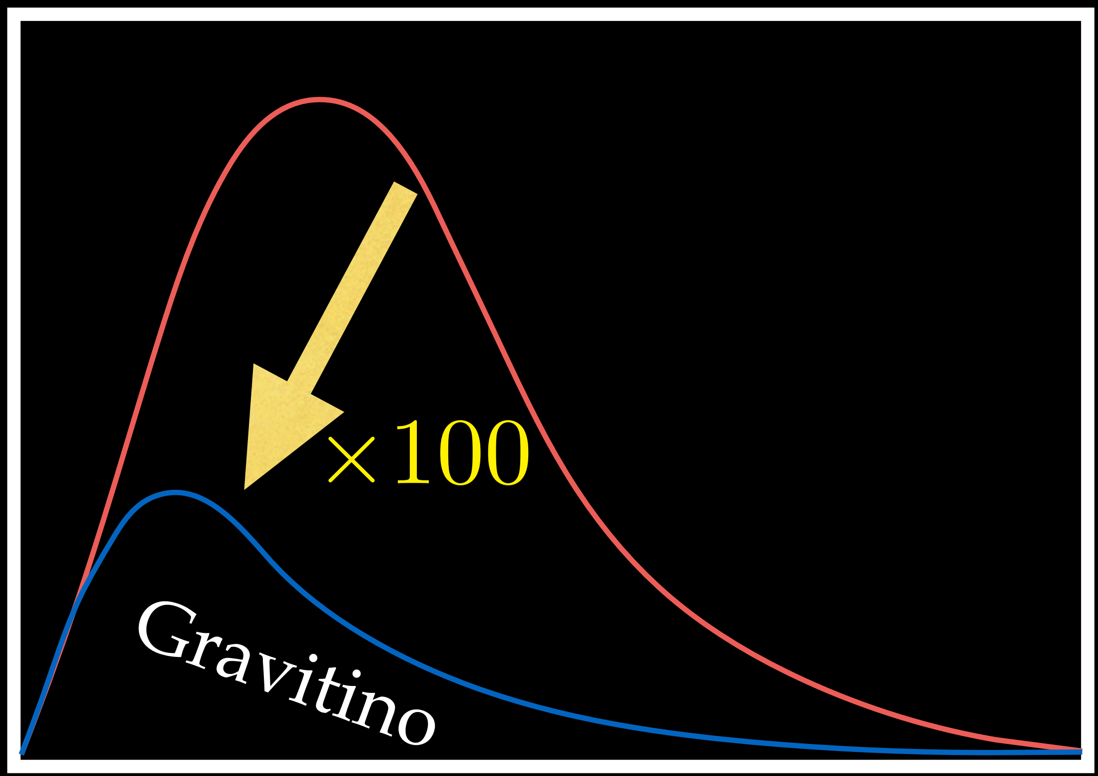
Issues in Cosmological Small-scale Structure?



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

Sterile WDM vs. Thermal WDM





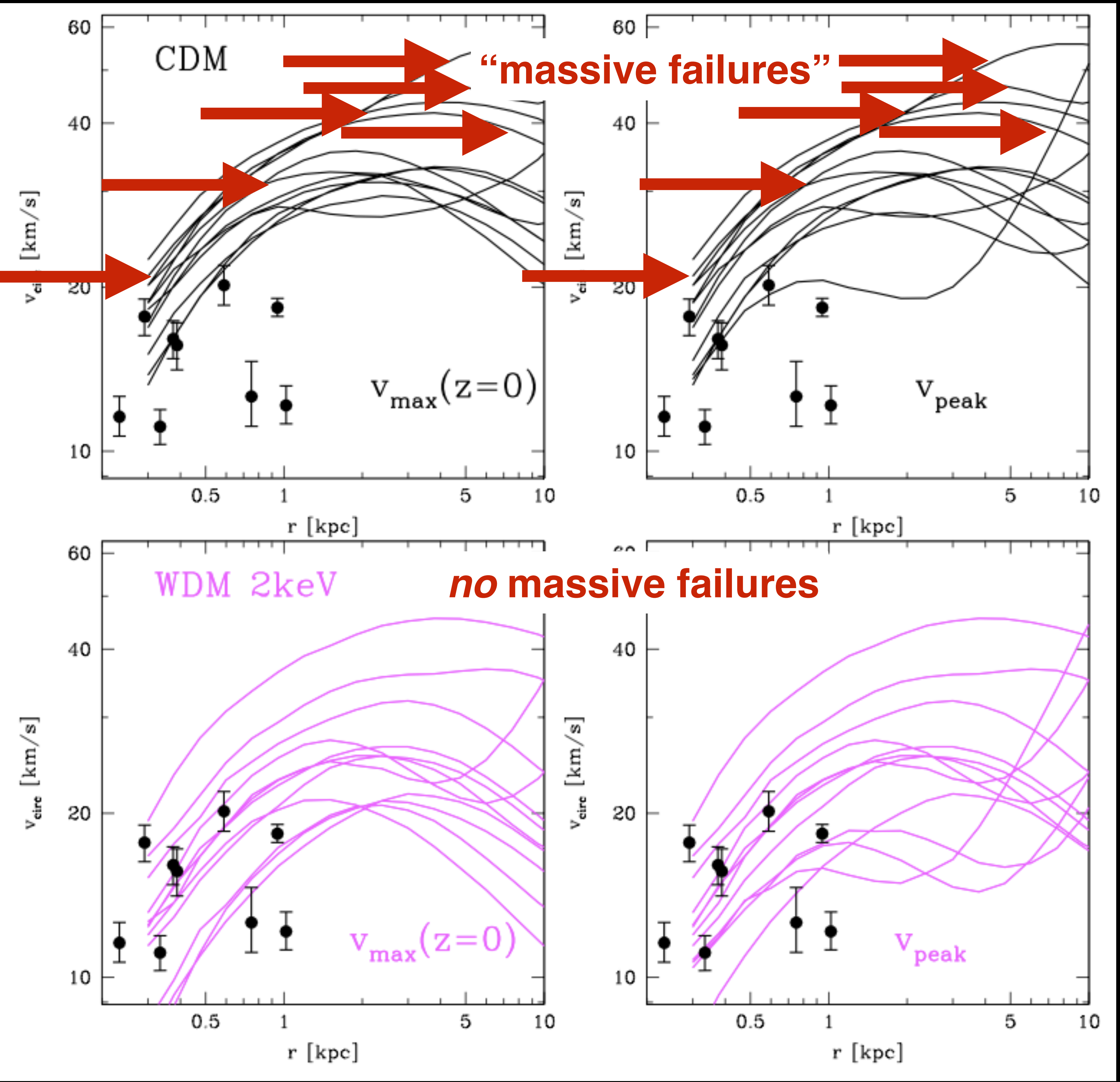
$$m_s\big|_{\text{Dodelson-Widrow,ideal}} \approx 4.46\,\text{keV}\left(\frac{m_{\text{thermal}}}{1\,\text{keV}}\right)^{4/3}$$

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

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

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

WDM Solution to All Local Group Galaxy Properties?

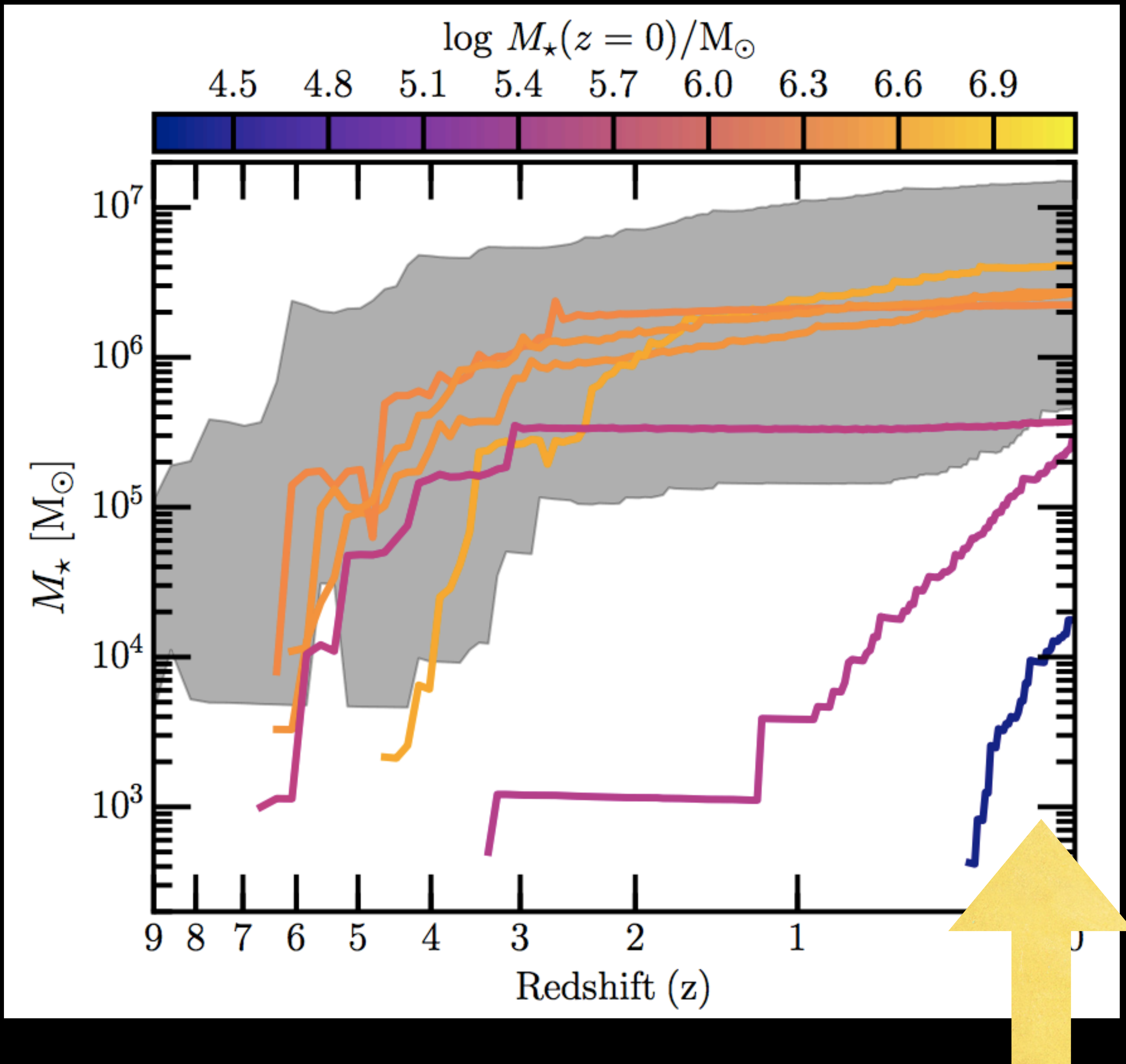


Anderhalden+
arXiv:1212.2967

"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

Signature of WDM in dwarf galaxy formation histories?



Bozek+ arXiv:1803.05424

"The WDM galaxies studied here have a wider diversity of star formation histories (SFHs) than the same systems simulated in CDM… The discovery of young ultra-faint dwarf galaxies with no ancient star formation – which do not exist in our CDM simulations – would therefore provide evidence in support of WDM."

Summary

- Sterile Neutrino Dark Matter has been investigated for 24+ years; indirect detection via cluster & field galaxy searches proposed by yours truly 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 was seen by the same group in the *Perseus* Cluster with *Chandra* data. (Bulbul et al. ApJ 2014). An independent group reported a line at the same energy toward Andromeda (M31) and *Perseus* with *XMM-Newton* (Boyarsky et al. PRL 2014).
- Also seen:
  - in our Milky Way Galactic Center (*XMM-Newton*)
  - with *SUZAKU* X-ray Space Telescope data toward Perseus
  - in 8 more clusters at > 2σ significance
  - Seen in *Chandra* deep fields (Galactic Halo)
- **No consistent astrophysical interpretation exists.**

Summary

- Among the simplest models for the signal are:
  - resonant sterile neutrino production with a cosmological L
  - *a fraction of dark matter as sterile neutrinos*
  - *as well as low-reheating temperature models*.
- The signal crosses a transition region from "cold" dark matter to "warm" dark matter, particularly at a small-scale structure cutoff scale of great interest in galaxy formation of the local group of galaxies, ~2 keV thermal WDM.
- Future Follow up observations:
  - 2019: Micro-X, XQC
  - 2021-2022: XARM
  - 2028+: ATHENA
  - 2030+: X-Ray Surveyor