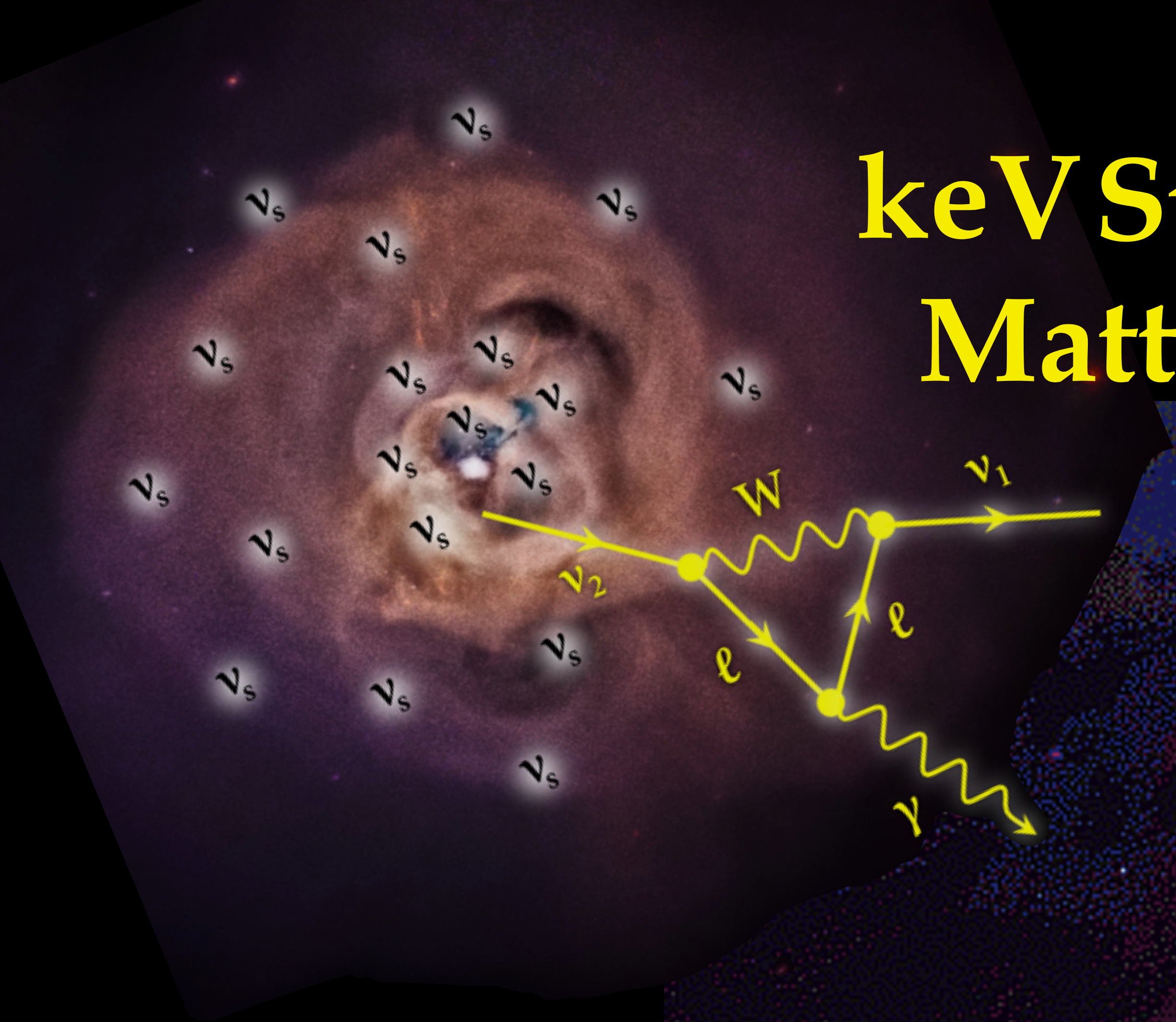
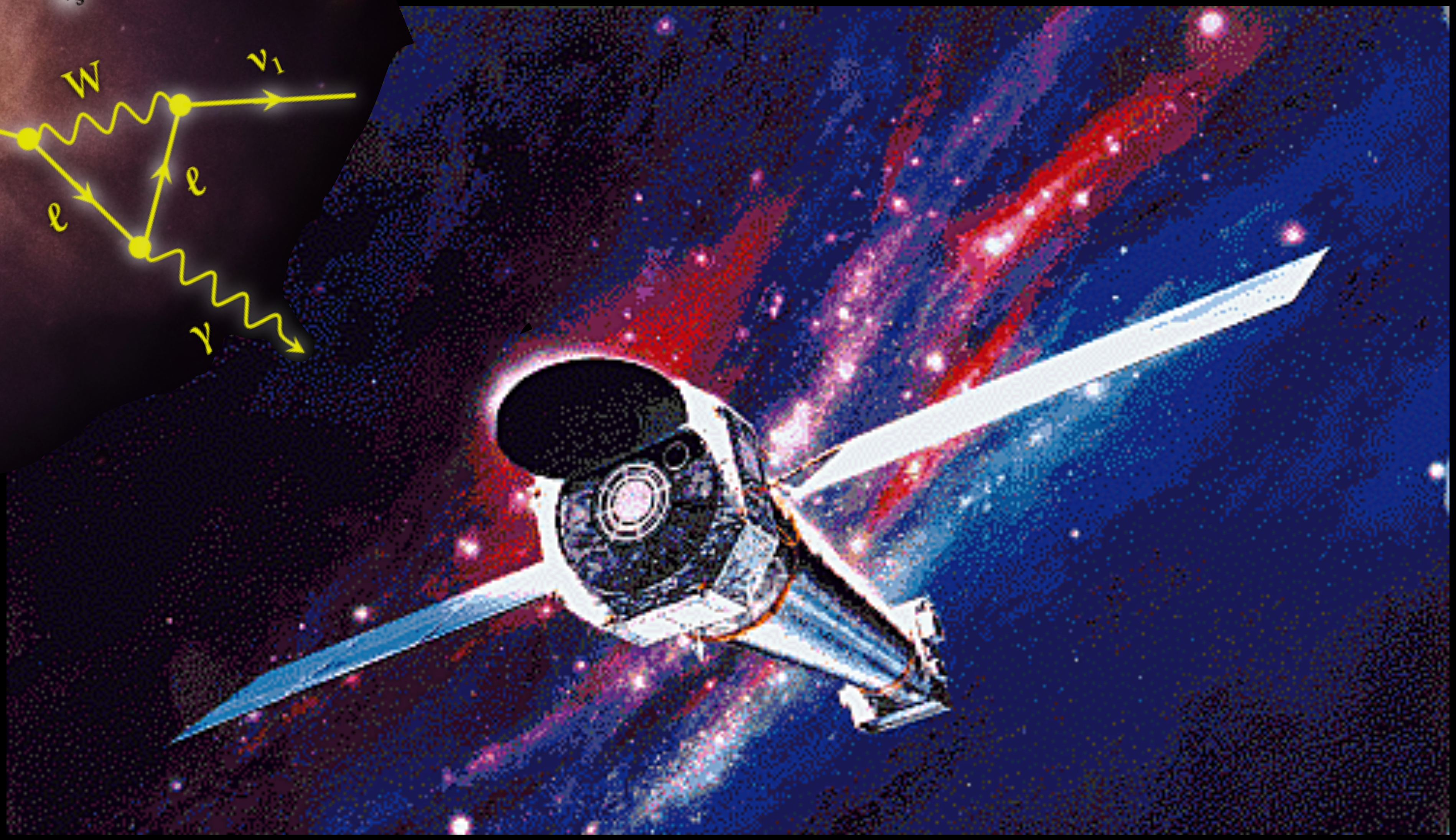
keV Sterile Neutrinos as Dark Matter and the 3.5 keV Line





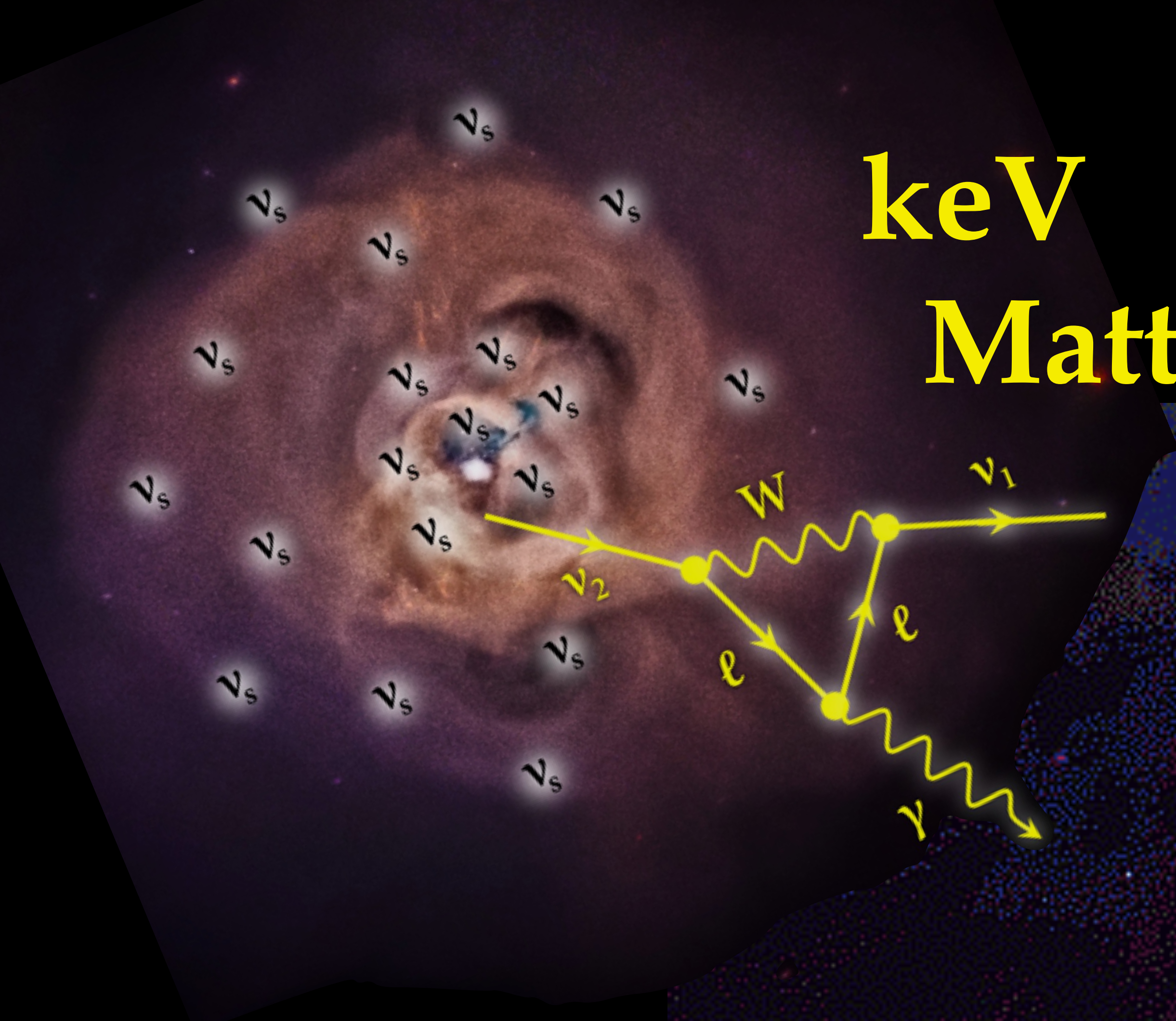
Kev Abazajian - @kevaba - /kevork.abazajian

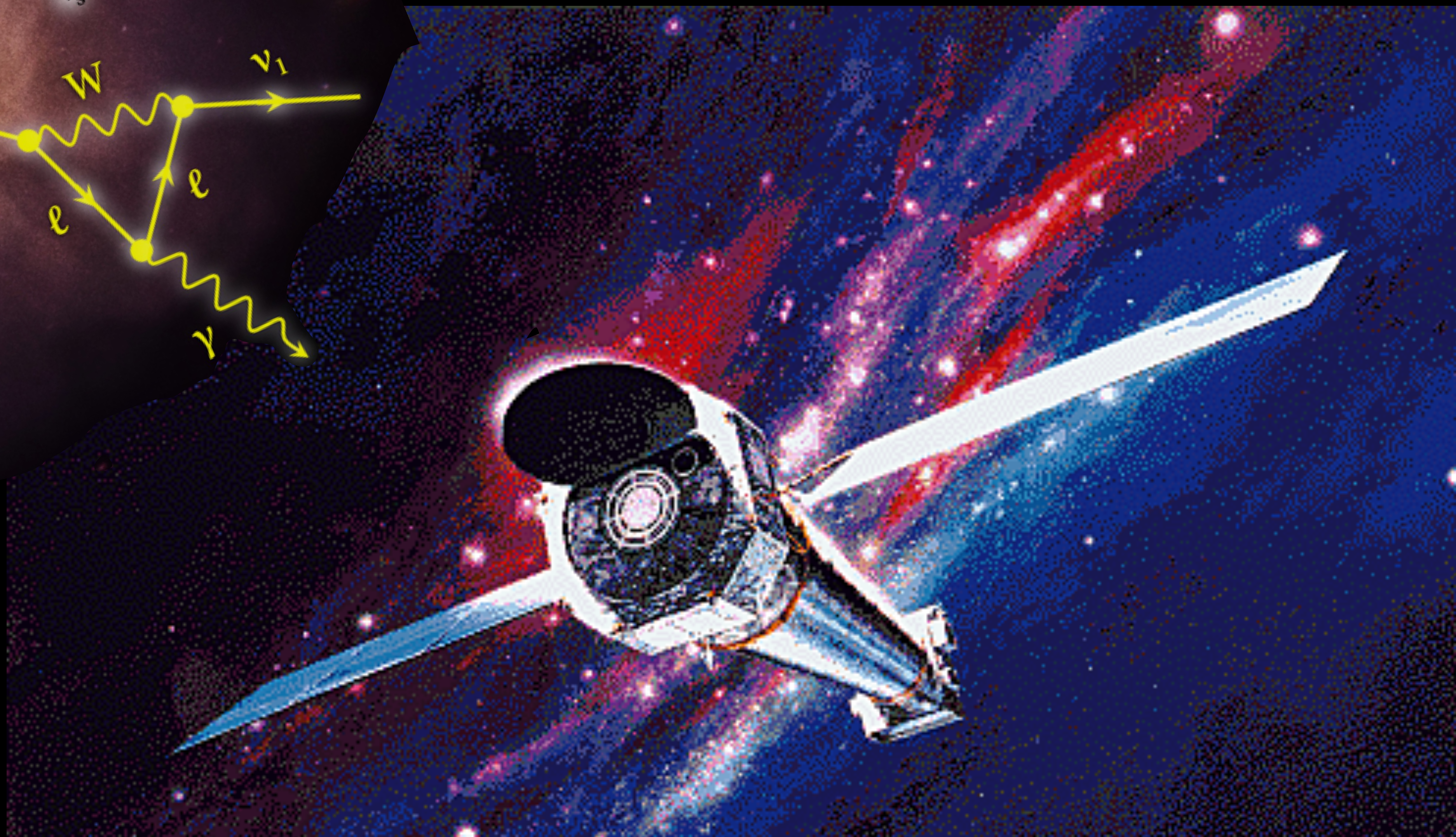
University of California, Irvine

May 31, 2018

CIPANP 2018 - Thirteenth Conference on the Intersections of Particle and Nuclear Physics

keV as Dark Matter and the 3.5 keV Line





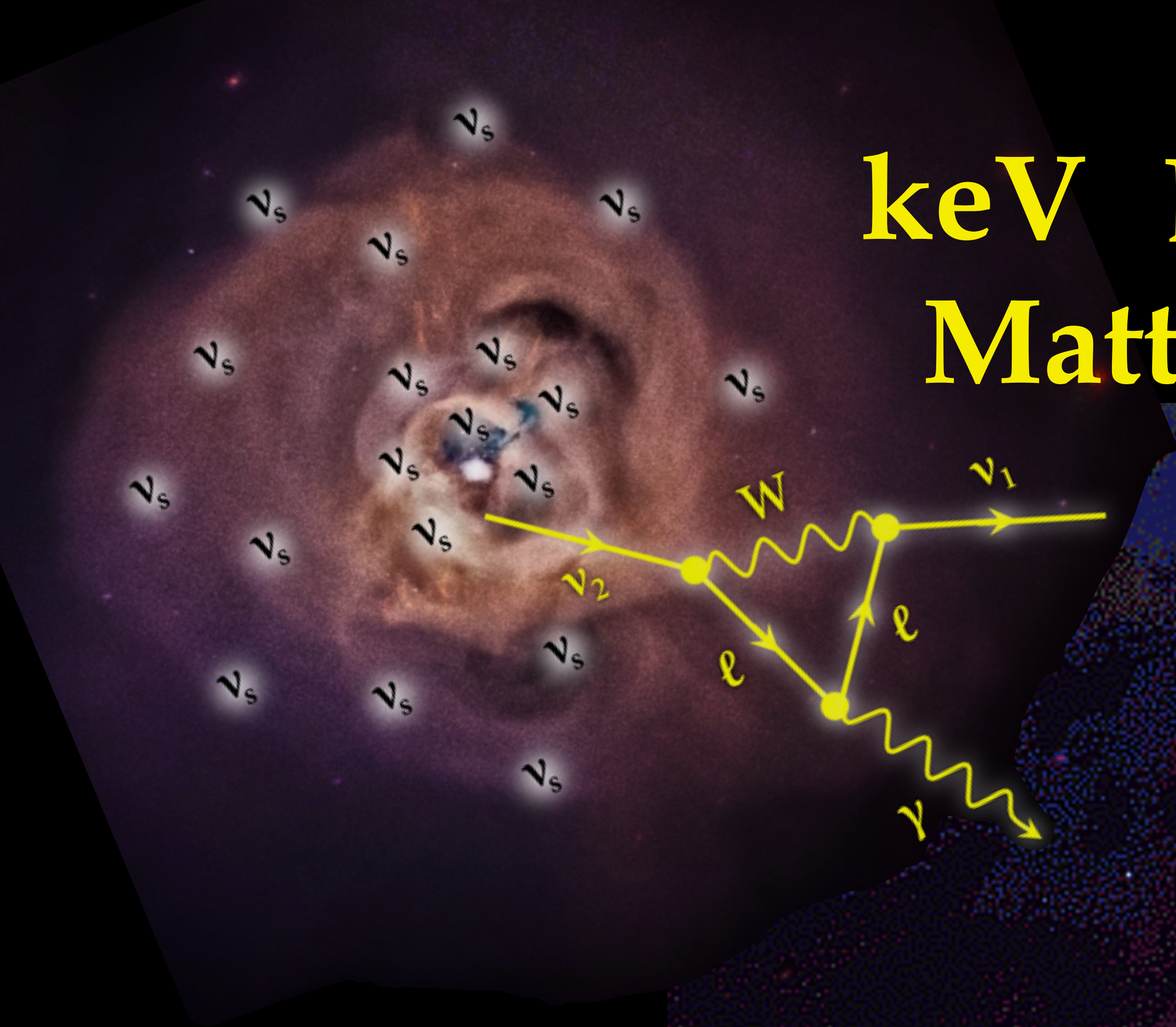
Kev Abazajian - @kevaba - /kevork.abazajian

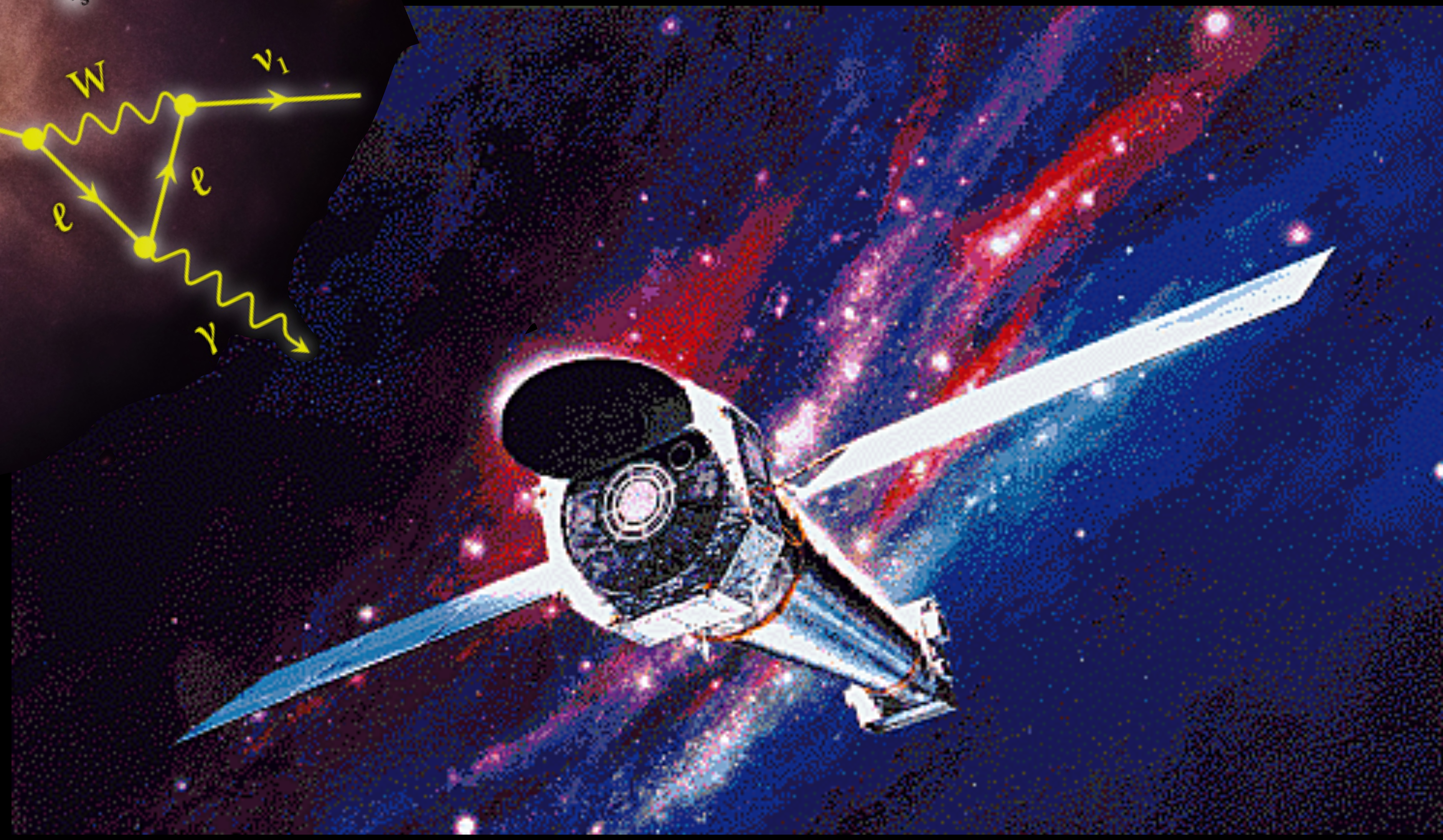
University of California, Irvine

May 31, 2018

CIPANP 2018 - Thirteenth Conference on the Intersections of Particle and Nuclear Physics

keV Dark Fermions as Dark Matter and the 3.5 keV Line





Kev Abazajian - @kevaba - /kevork.abazajian
University of California, Irvine

May 31, 2018

CIPANP 2018 - Thirteenth Conference on the Intersections of Particle and Nuclear Physics

Neutrino Mass Generation: An Original Hidden Sector Theory

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)

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)

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)

- Two massive (≳100 GeV) sterile neutrinos are required by atmospheric and solar neutrino mass scales. *Only hidden sector model with evidence for its existence!*

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)

- Two massive (≳100 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.

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)

- Two massive (≳100 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.

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

Neutrino Mass Generation: An Original Hidden Sector Theory

- Simplest models of neutrino mass introduce dark fermions that generate small active neutrino mass scales from very massive dark fermions (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) dark fermions are required by atmospheric and solar neutrino mass scales. *Only hidden sector model with evidence for its existence!*

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

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

Dark Fermion Neutrino Mixing Dark Matter Production

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

Dark Fermion Neutrino Mixing Dark Matter Production

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

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

Dark Fermion Neutrino Mixing Dark Matter Production

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

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

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

Dark Fermion Neutrino Mixing Dark Matter Production

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

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

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

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

Dark Fermion Neutrino Mixing Dark Matter Production

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

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

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

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

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

Dark Fermion Neutrino Mixing Dark Matter Production

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

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

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

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

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

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

Dark Fermion Neutrino Mixing Dark Matter Production

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

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

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

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

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

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

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

Dark Fermion Neutrino Mixing Dark Matter Production

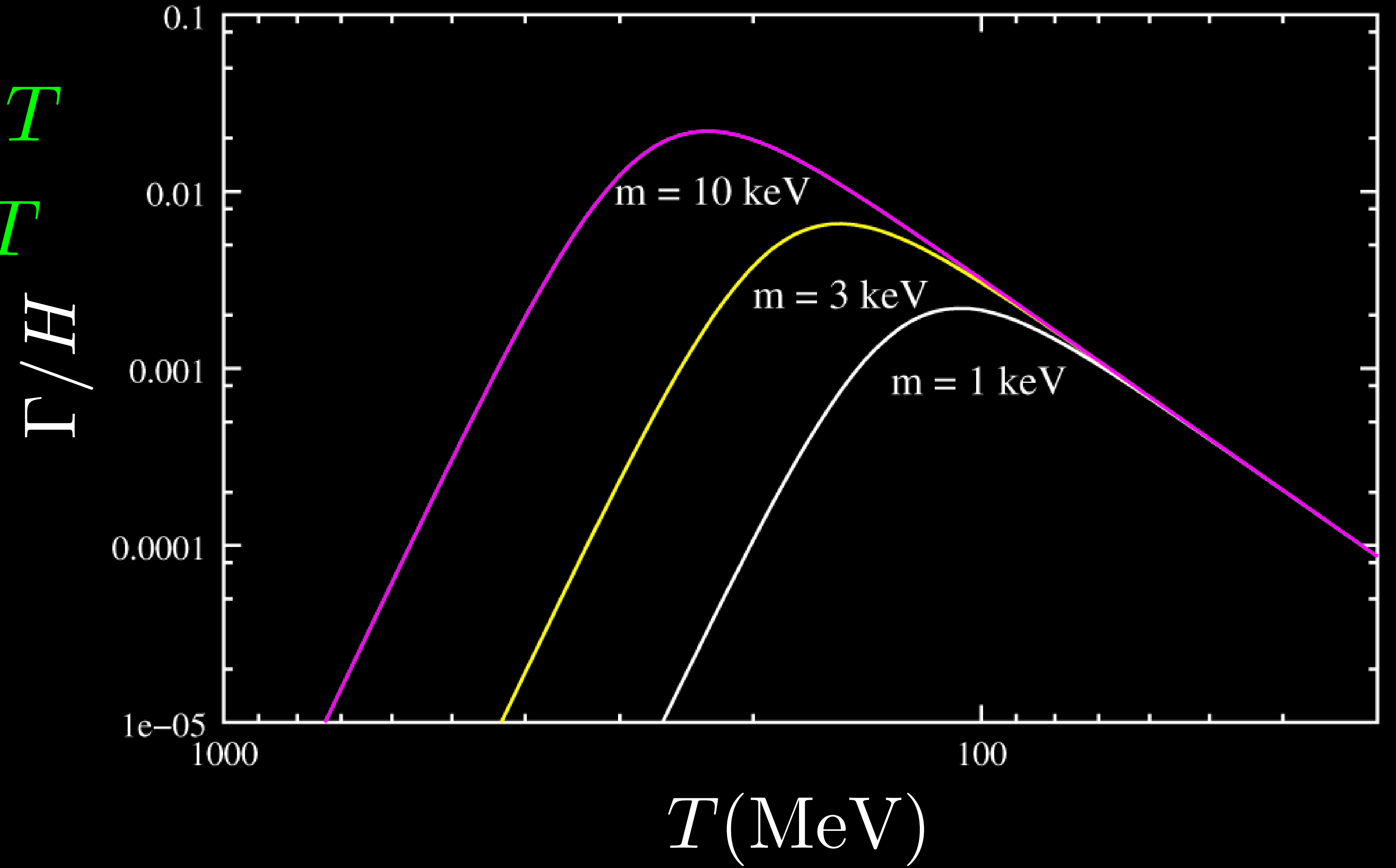
$$\Gamma_\alpha(p) \sim G_F^2 p T^4 \sim T^5 \qquad \Delta^2 \sim p^{-2} \sim T^{-2}$$

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

$$D(p)^2 \sim T^{10} \qquad [V^T]^2 \sim T^{10}$$

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

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



Dark Fermion Neutrino Mixing Dark Matter Production

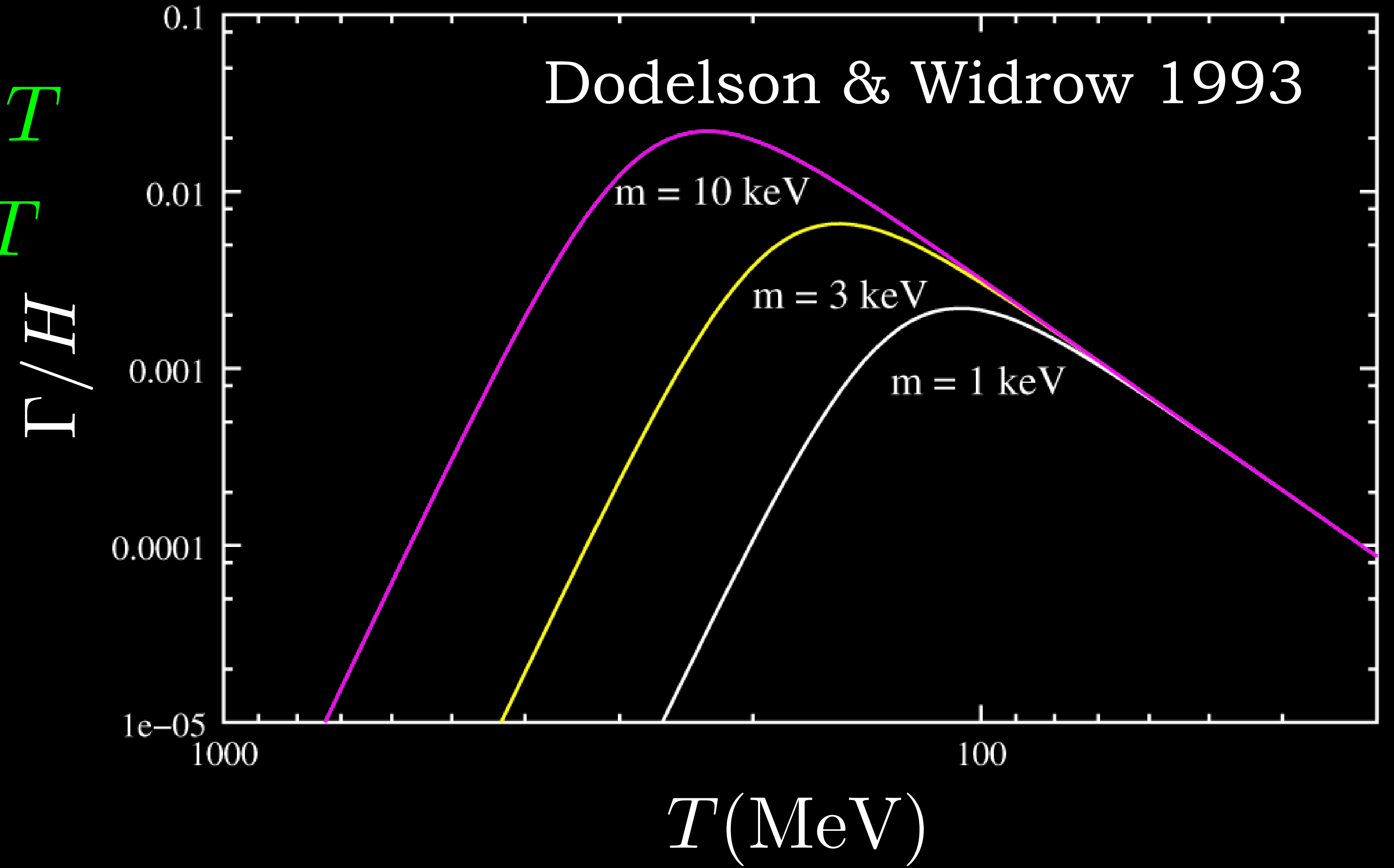
$$\Gamma_\alpha(p) \sim G_F^2 p T^4 \sim T^5 \qquad \Delta^2 \sim p^{-2} \sim T^{-2}$$

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

$$D(p)^2 \sim T^{10} \qquad [V^T]^2 \sim T^{10}$$

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

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



Dark Fermion Neutrino Mixing Dark Matter Production

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

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

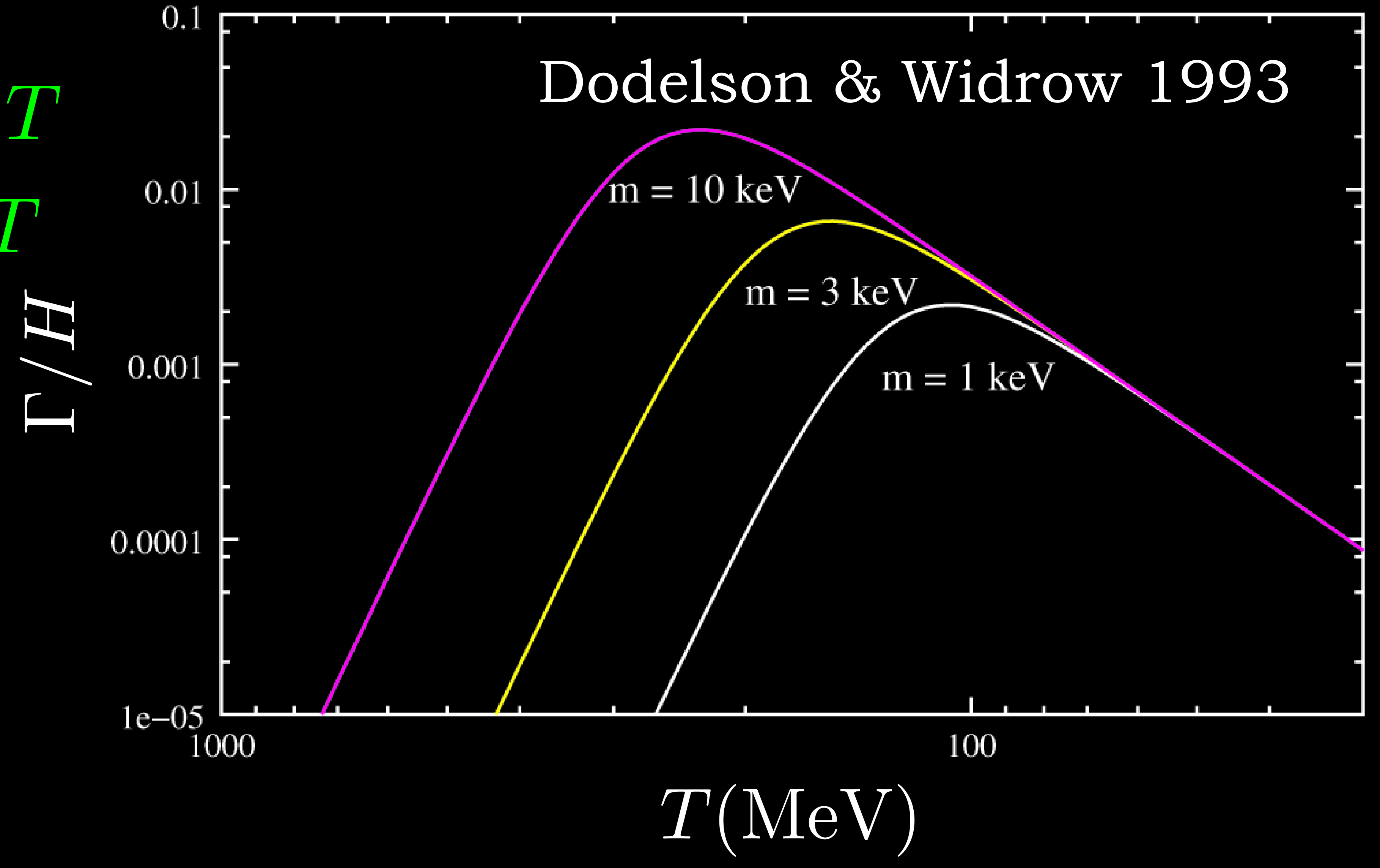
$$\Gamma(\nu_\alpha \to \nu_s) \sim \frac{\Gamma_\alpha(p)\Delta^2(p)\sin^2 2\theta}{\Delta^2(p)\sin^2 2\theta + D^2(p) + [\Delta(p)\cos 2\theta - V^L(p) - V^T(p)]^2}$$

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

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

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

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



Dark Fermion Neutrino Mixing Dark Matter Production

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

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

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

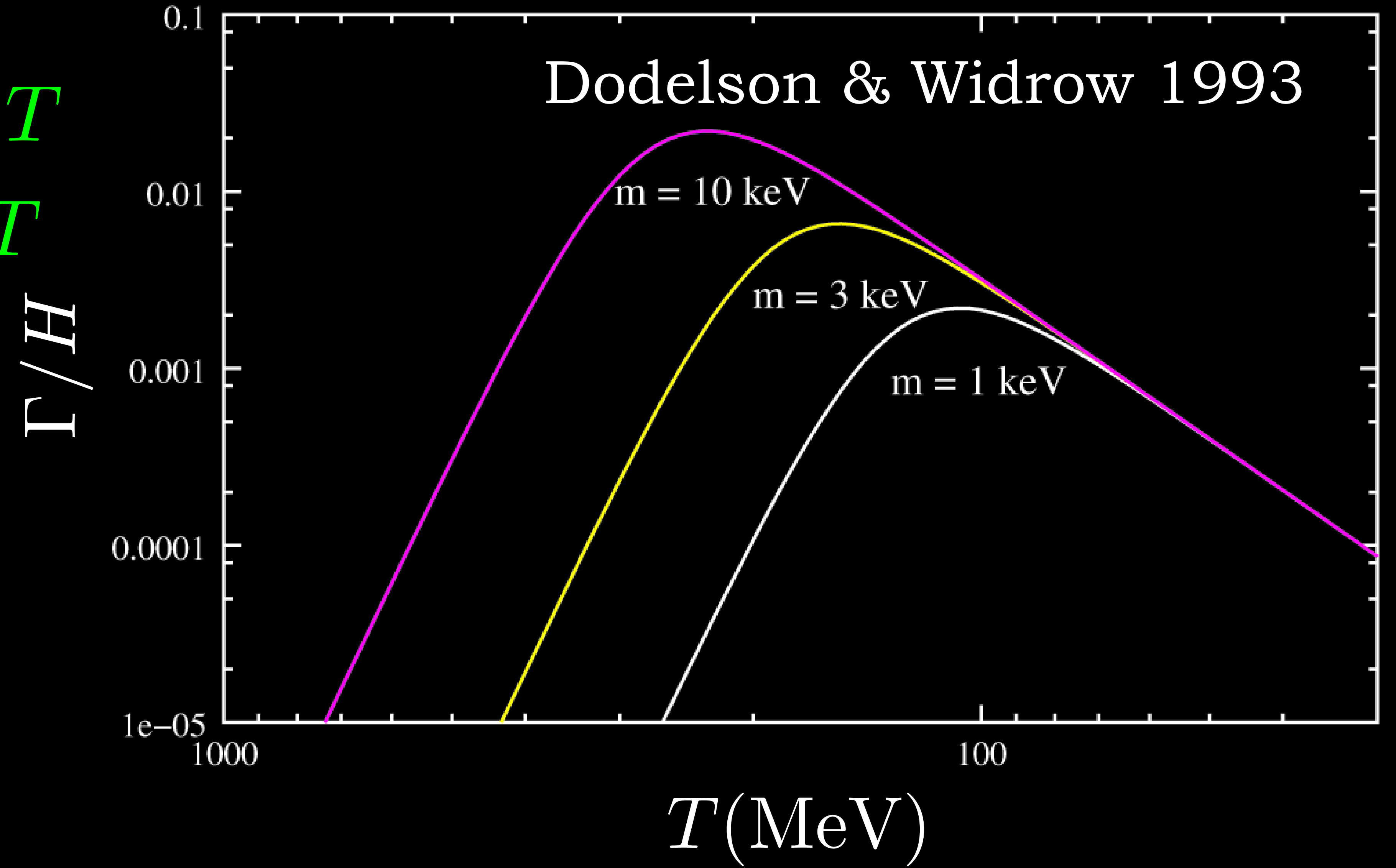
$D(p)^2 \sim T^{10}$

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

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

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

Resonance: Shi & Fuller 1998



Dark Fermion Neutrino Mixing Dark Matter Production

$$\Gamma_\alpha(p) \sim G_F^2 p T^4 \sim T^5 \qquad \Delta^2 \sim p^{-2} \sim T^{-2}$$

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

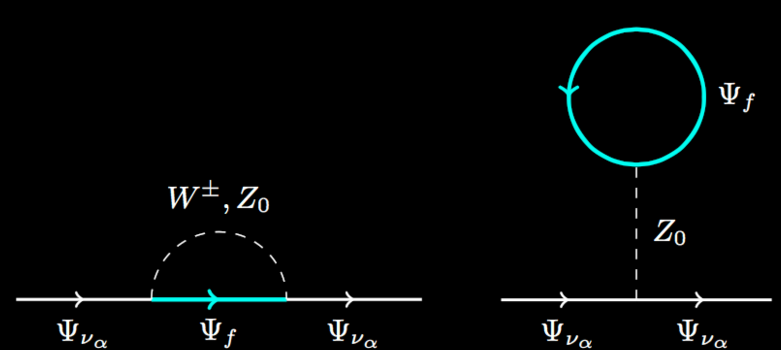
$$D(p)^2 \sim T^{10} \qquad [V^T]^2 \sim T^{10}$$

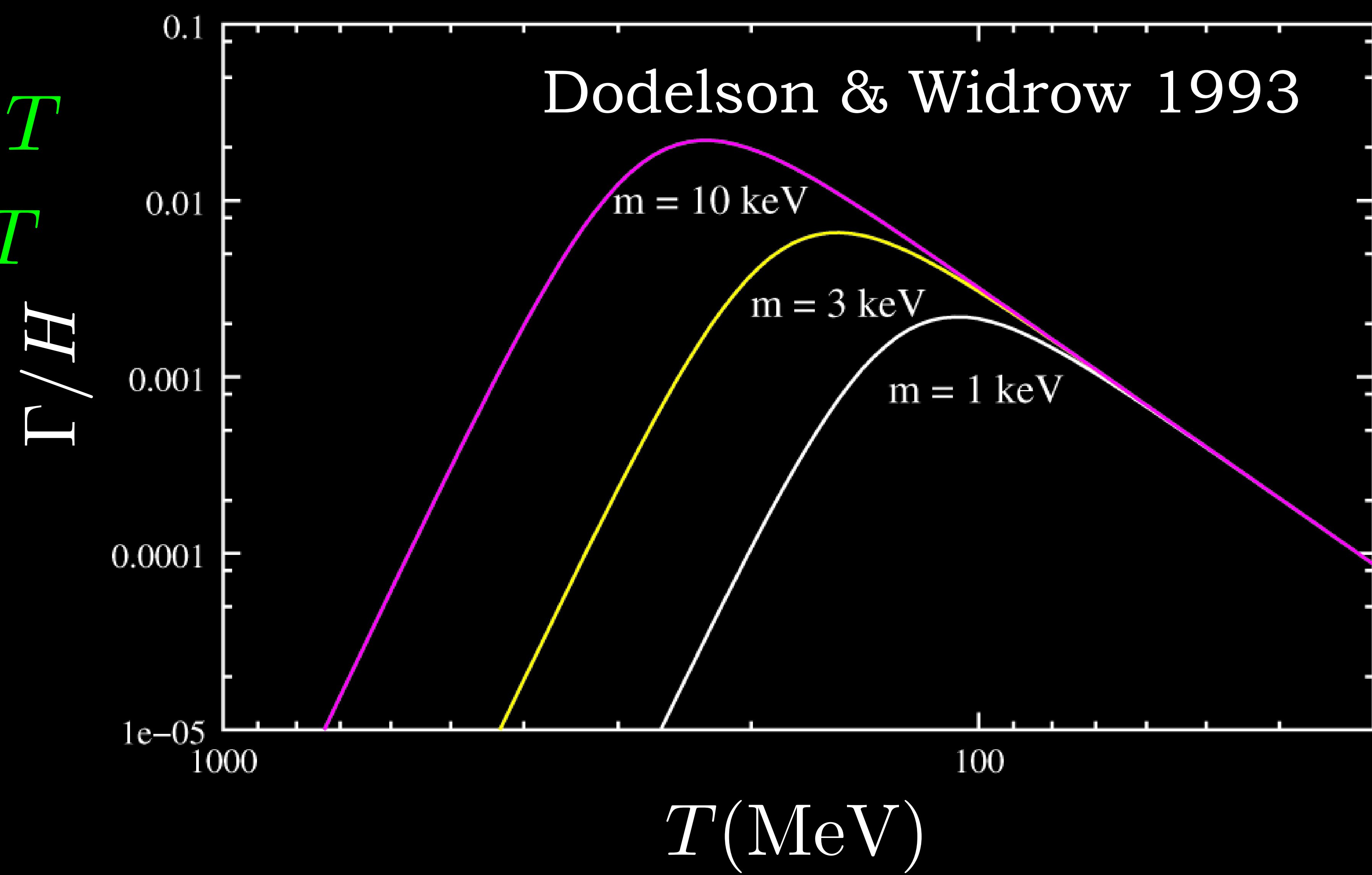
Resonance: Shi & Fuller 1998

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

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

Never in Equilibrium!!

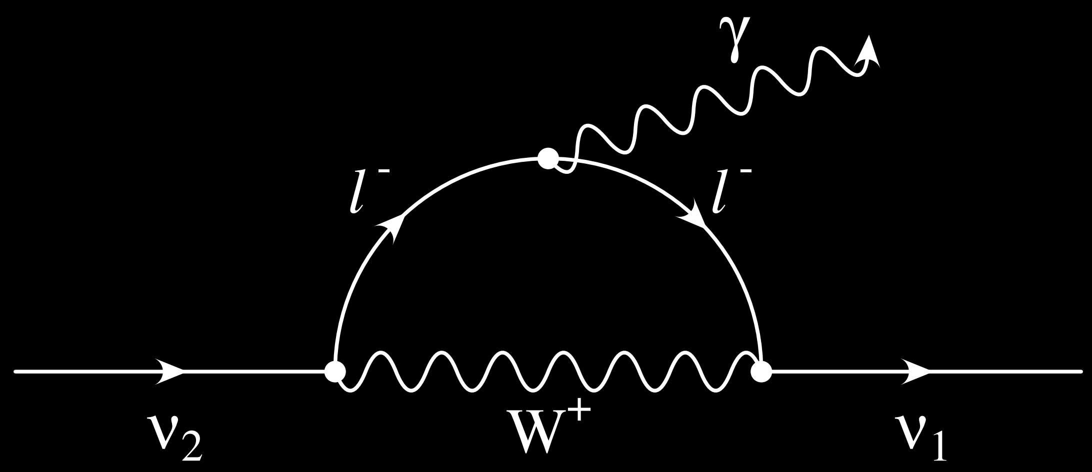




Observing Dark Fermions in the X-ray: *Chandra* & *XMM-Newton X-ray Space Telescopes*

Observing Dark Fermions in the X-ray: *Chandra* & *XMM-Newton X-ray Space Telescopes*

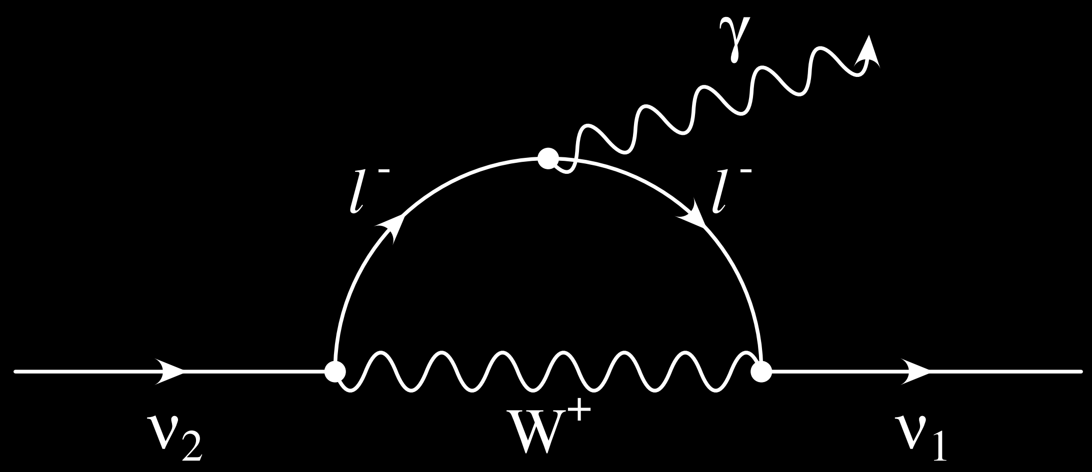
Dark Fermion WDM Radiative Decay in the X-ray



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

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

Dark Fermion WDM Radiative Decay in the X-ray

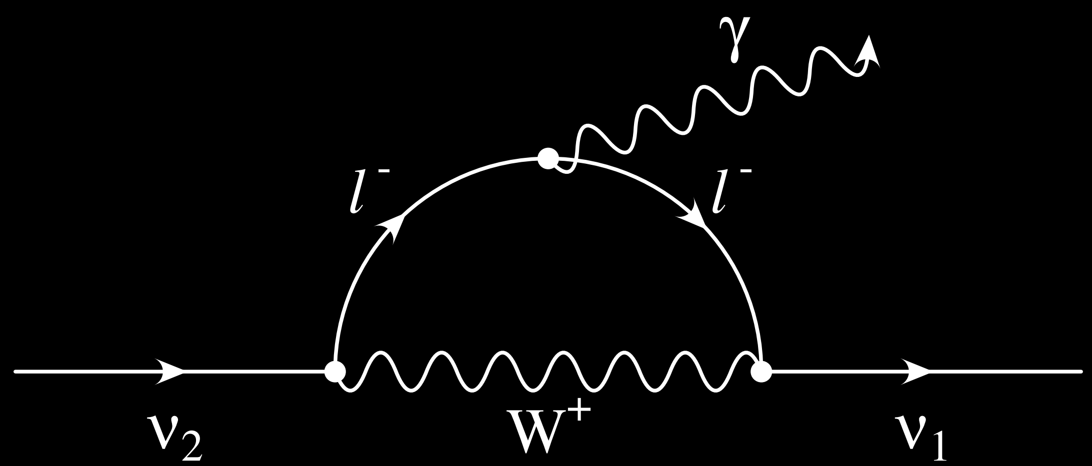


Decay: Shrock 1974; Pal & Wolfenstein 1981; Barger, Philips & Sarkar 1995
X-ray: Abazajian, Fuller & Tucker 2001

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

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

Dark Fermion WDM Radiative Decay in the X-ray



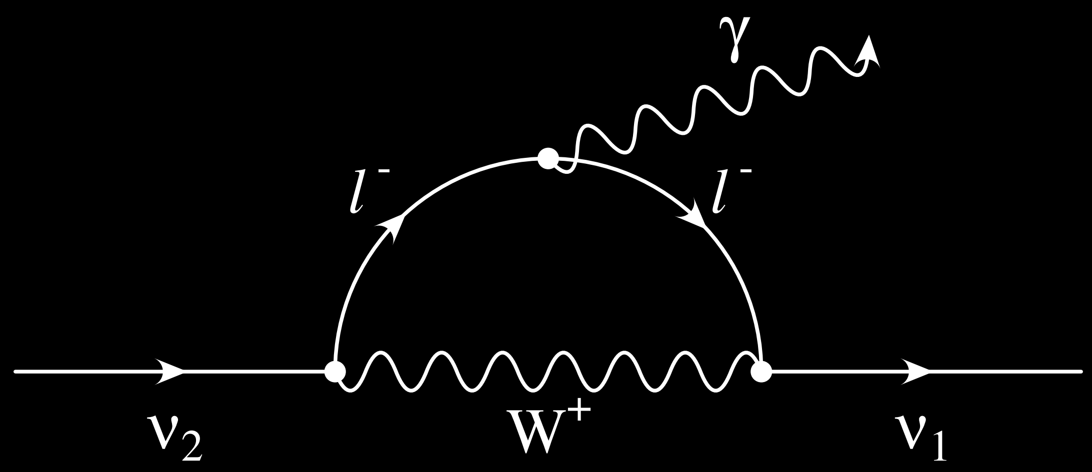
Decay: Shrock 1974; Pal & Wolfenstein 1981; Barger, Philips & Sarkar 1995
X-ray: Abazajian, Fuller & Tucker 2001

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

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

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

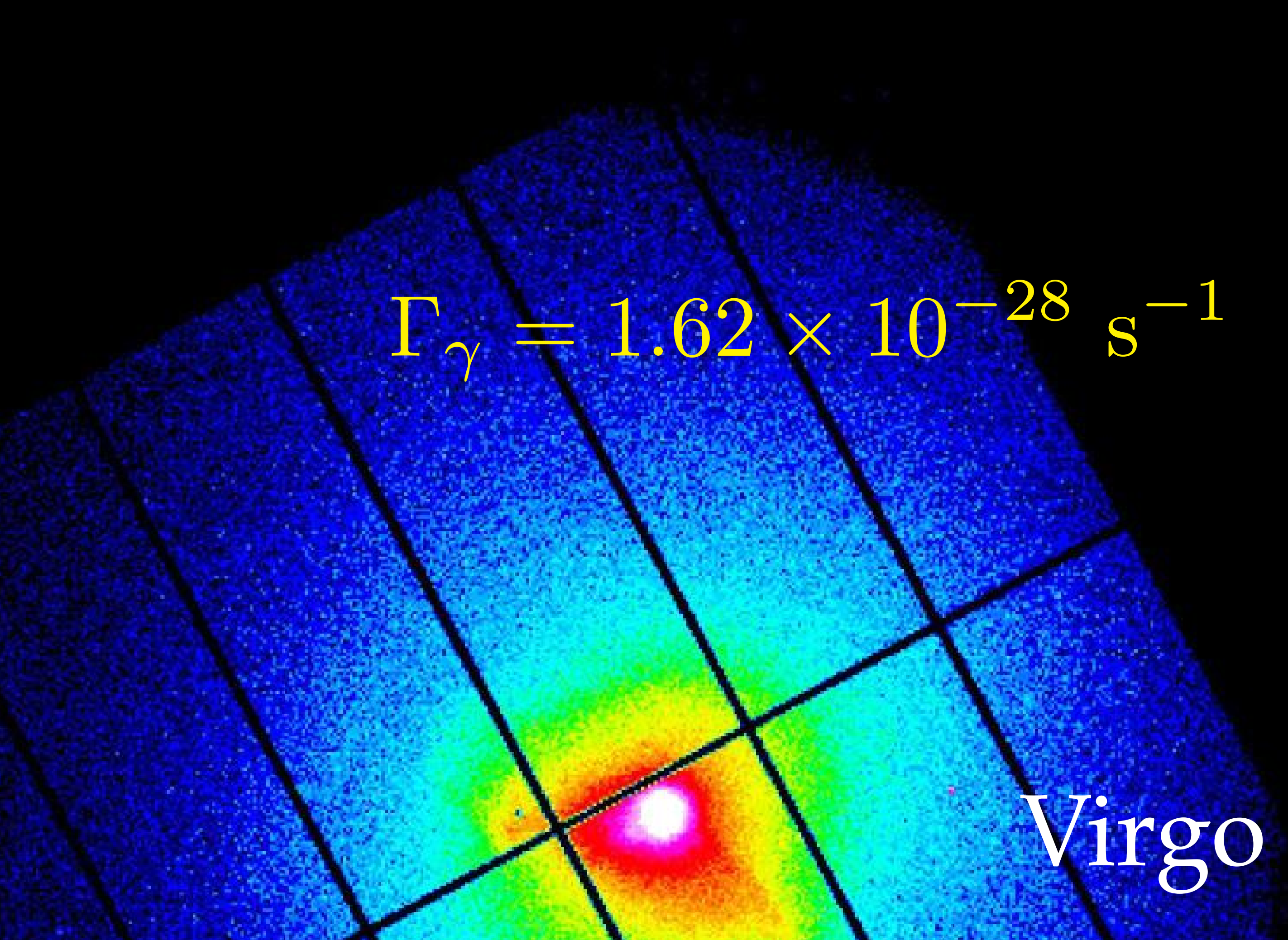
Dark Fermion WDM Radiative Decay in the X-ray



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

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

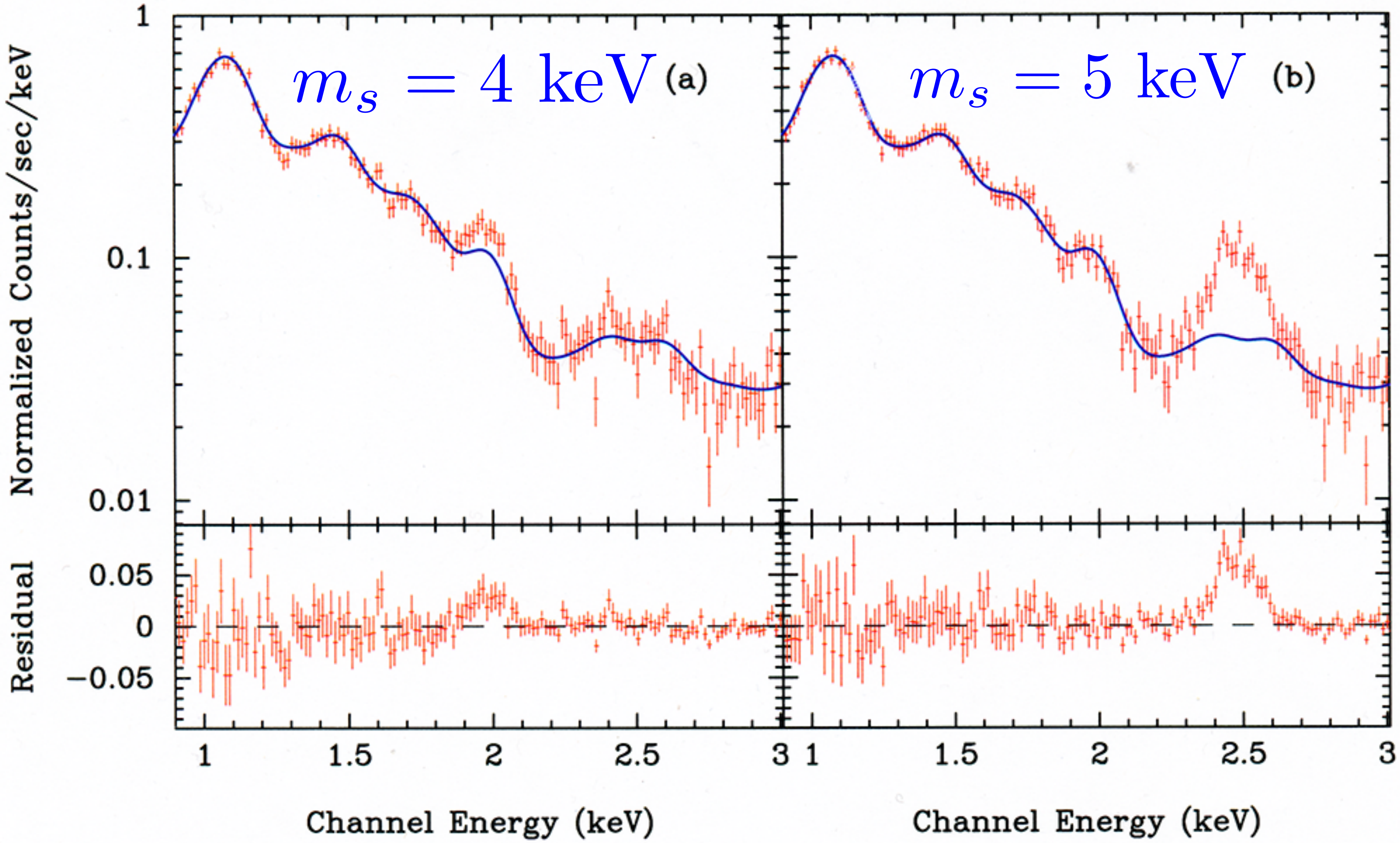
$$E_\gamma = \frac{m_s}{2} \sim 1\ \mathrm{keV}$$



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

Virgo Cluster: 10^{78} DM particles

Slide from 2001



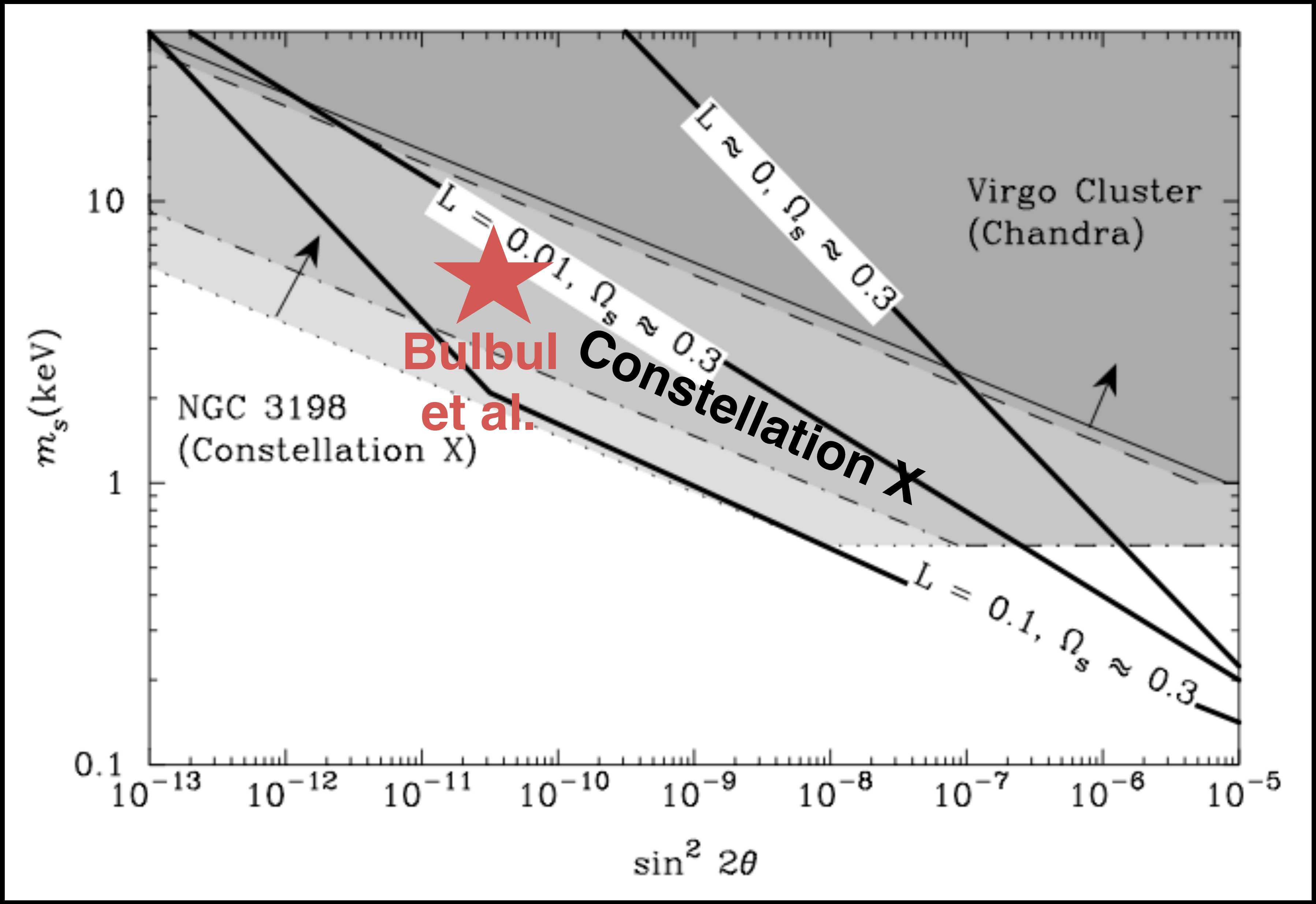
Current Limits

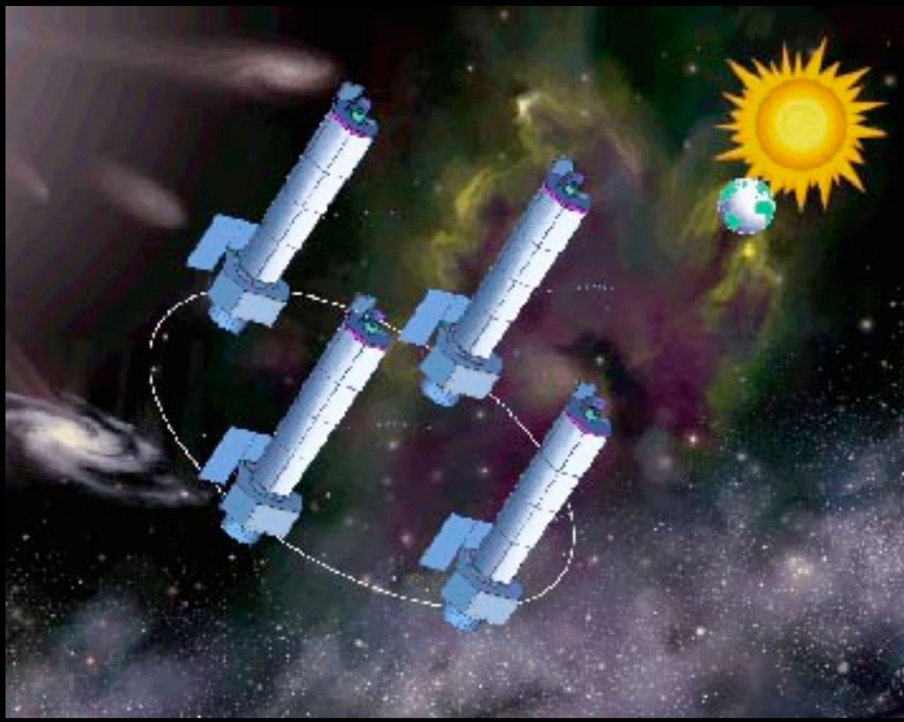
+

Future Detection?

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

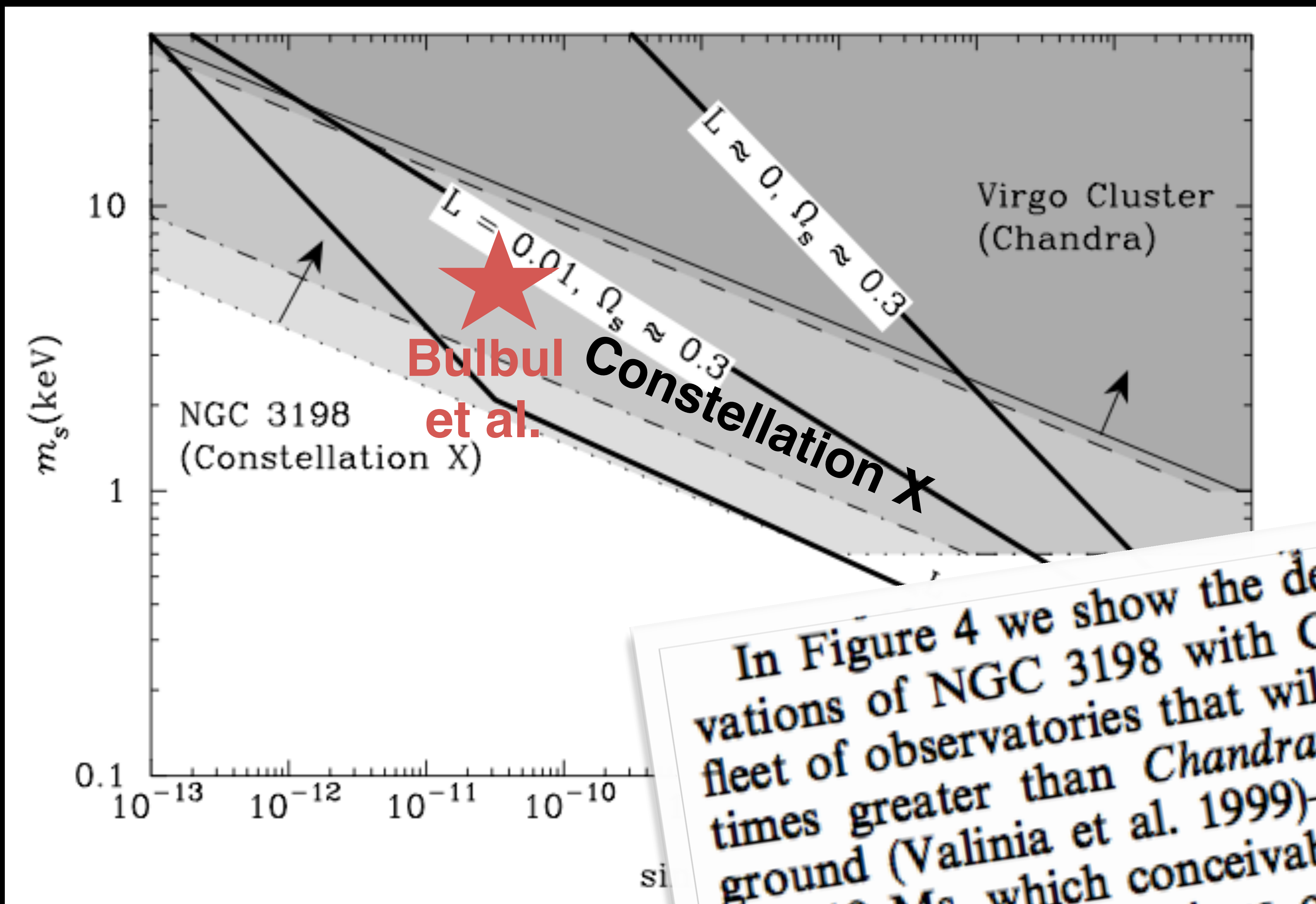
Abazajian, Fuller & Tucker 2001

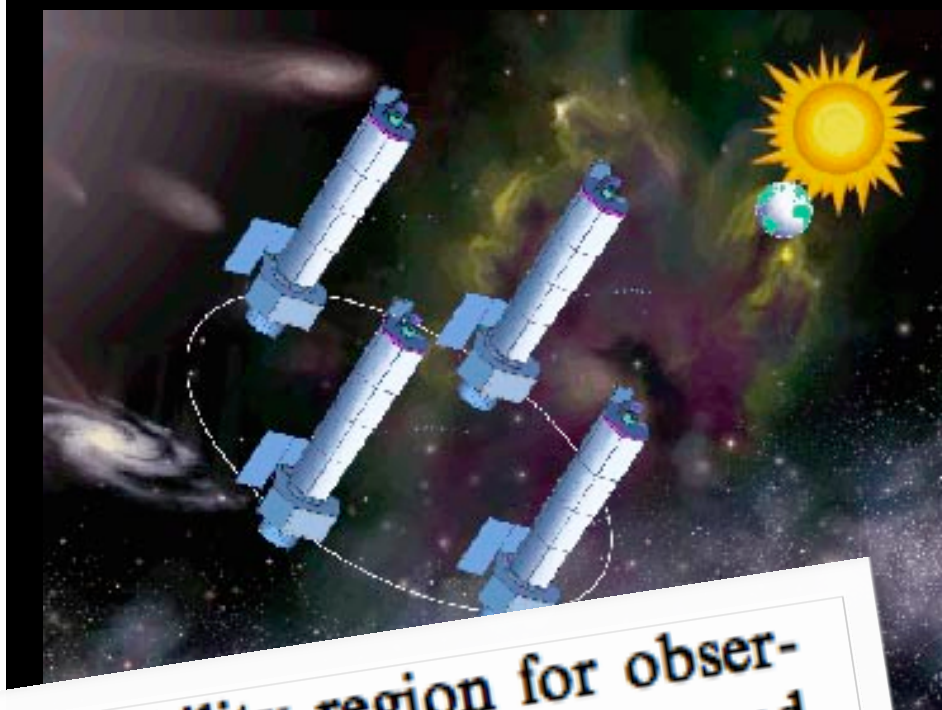




Forecast X-ray Observation Sensitivity for *Constellation-X*

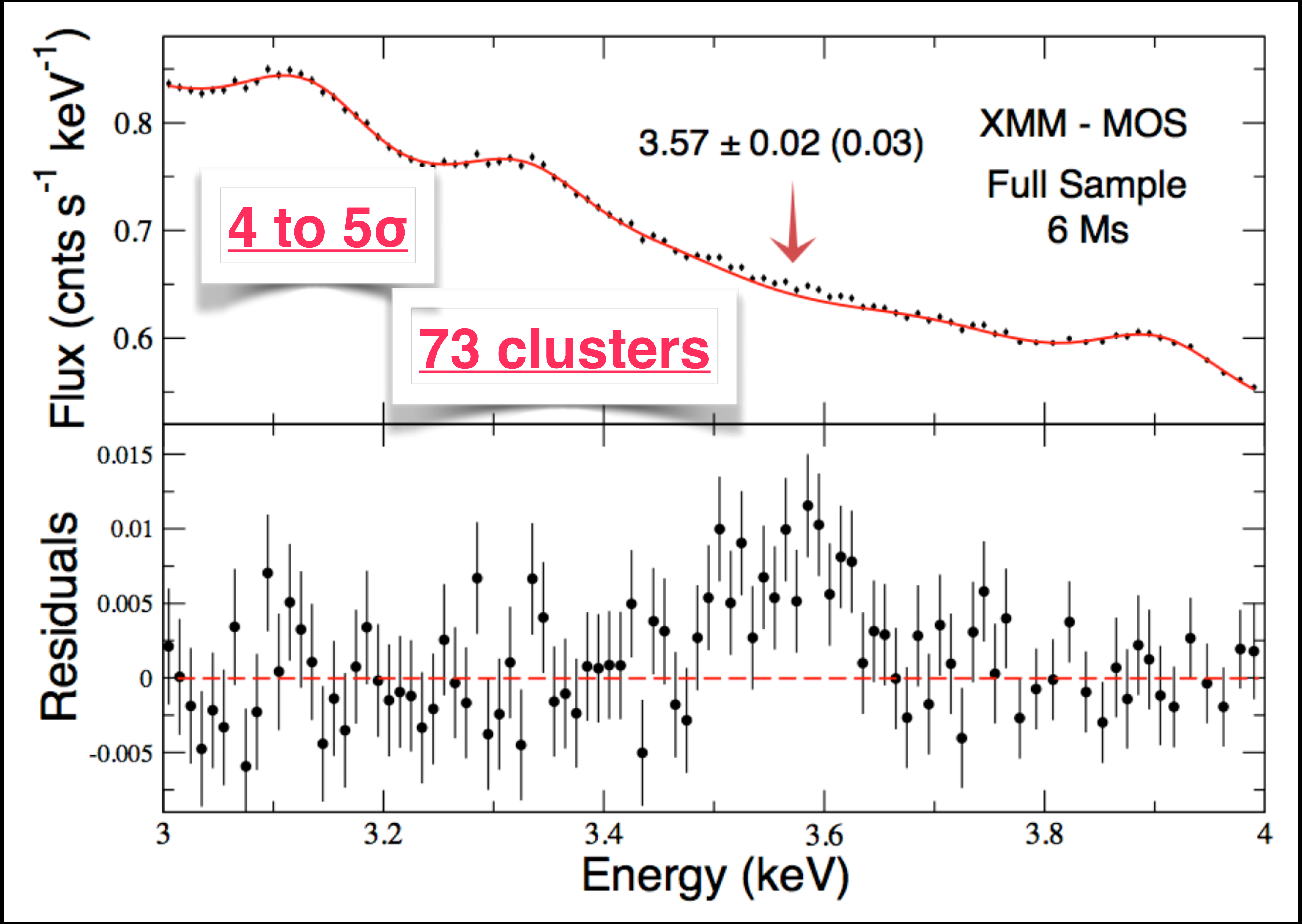
Abazajian, Fuller & Tucker 2001





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

3.55 keV line consistent with DM in field of view seen

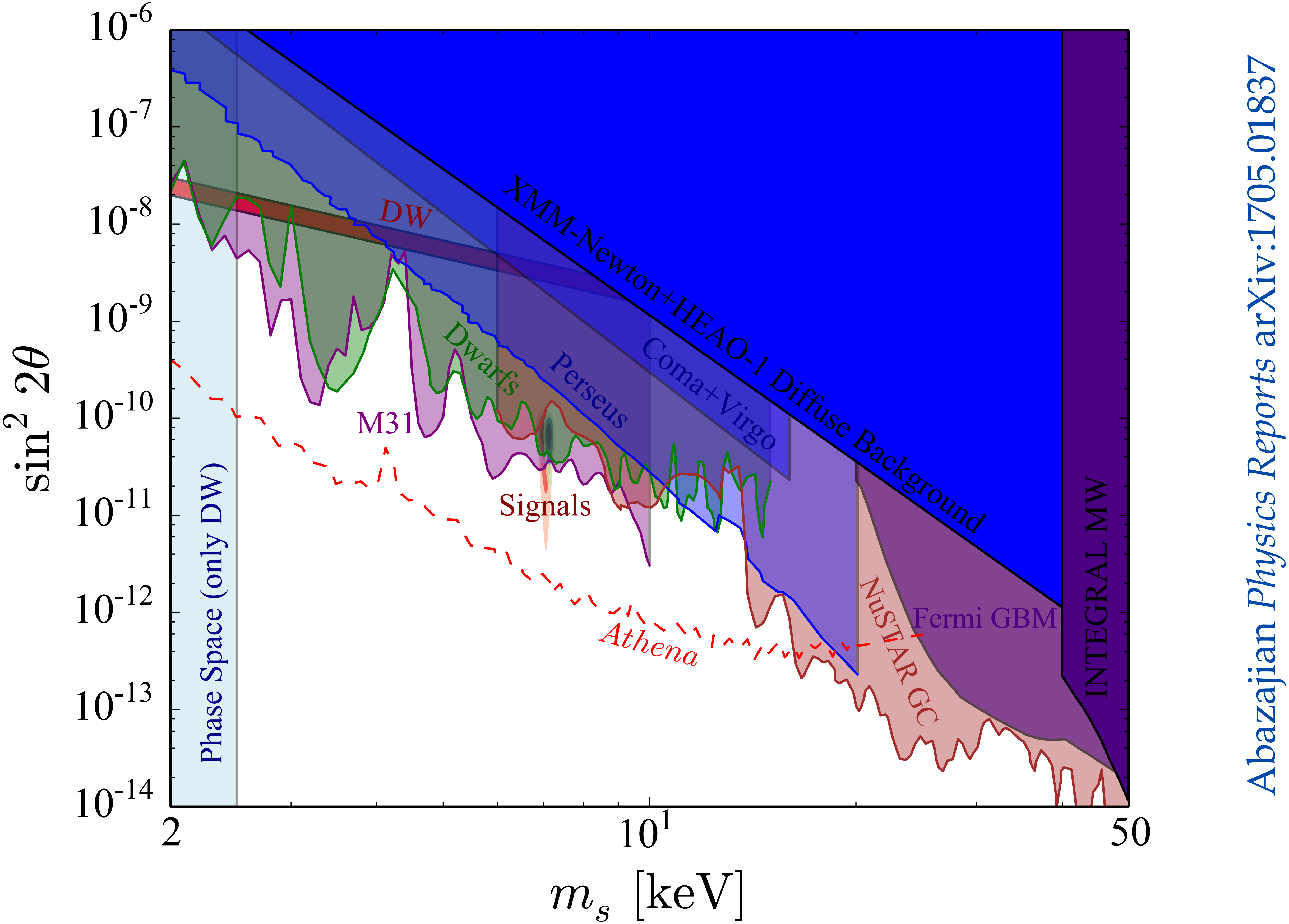
- in Andromeda (M31) with *XMM-Newton* (Boyarsky+ 2014)
- Perseus with *XMM-Newton, Chandra and Suzaku* ≳3σ (Bulbul+ 2014, Boyarsky+ 2014, Urban+ 2014)
- in our Milky Way Galactic Center (*XMM-Newton*) (Boyarsky+ 2014)
- in 8 more clusters at > 2σ significance (*XMM-Newton*) (Iakubovskyi+ 2015)
- *NuSTAR* observations of Deep Fields at **11.1σ** and Galactic Center (Neronov+ 2016, Perez+ 2016)
- *Chandra* Deep Fields at 3σ (Cappelluti+ 2017)

Two places it may have been expected

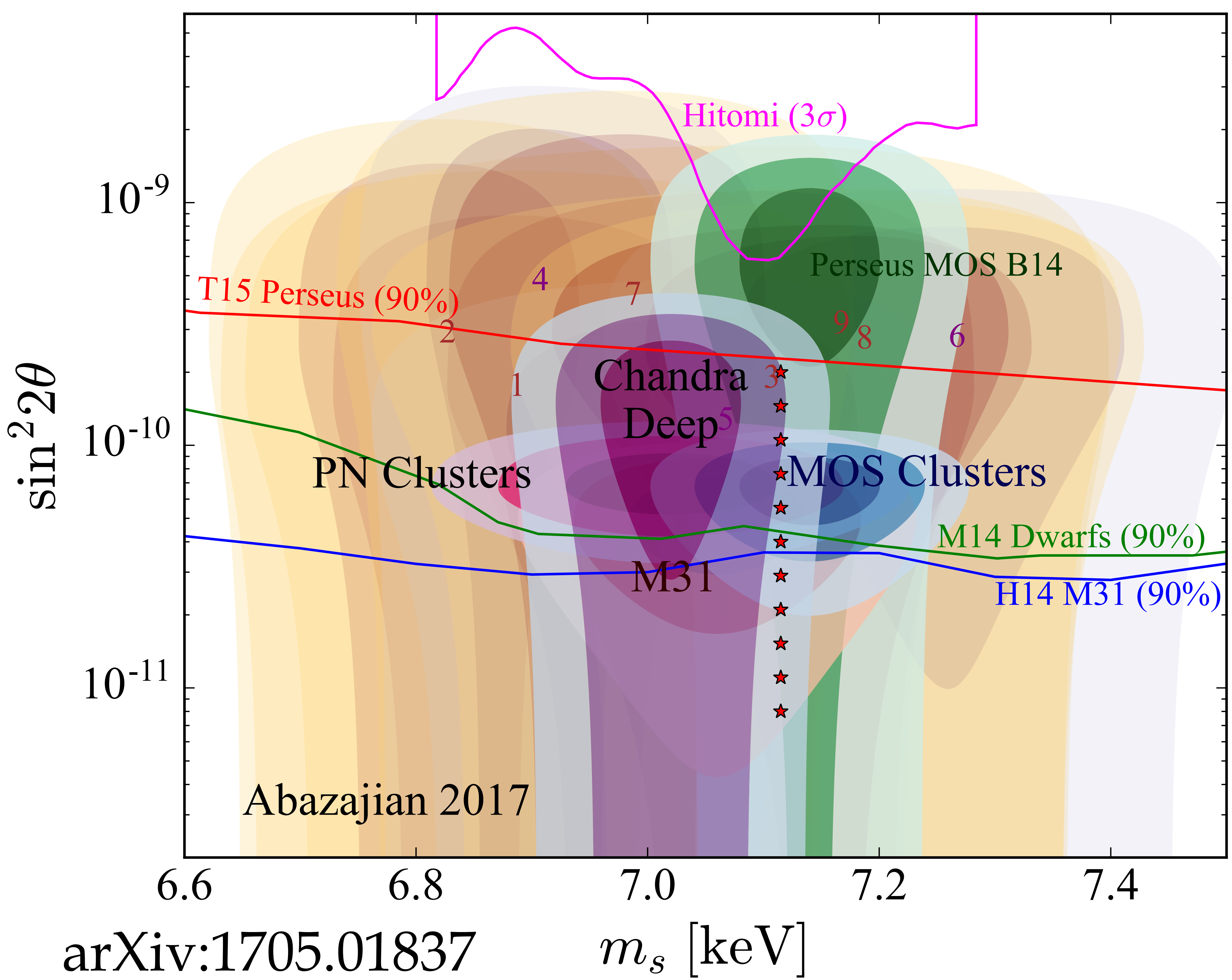
- **Draco 1 Ms exposure:** not seen in MOS detectors, at lower than expected flux in PN. But, ***"We conclude that this Draco observation does not exclude the dark matter interpretation of the 3.5 keV line in those objects."*** Boyarsky+ arXiv:1512.07217

- **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*** $\sin^2 2\theta$

Sterile Neutrino Dark Matter: Parameter Space Summary



The 7 keV Region Today



arXiv:1705.01837

Visibility of Dark Fermions

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

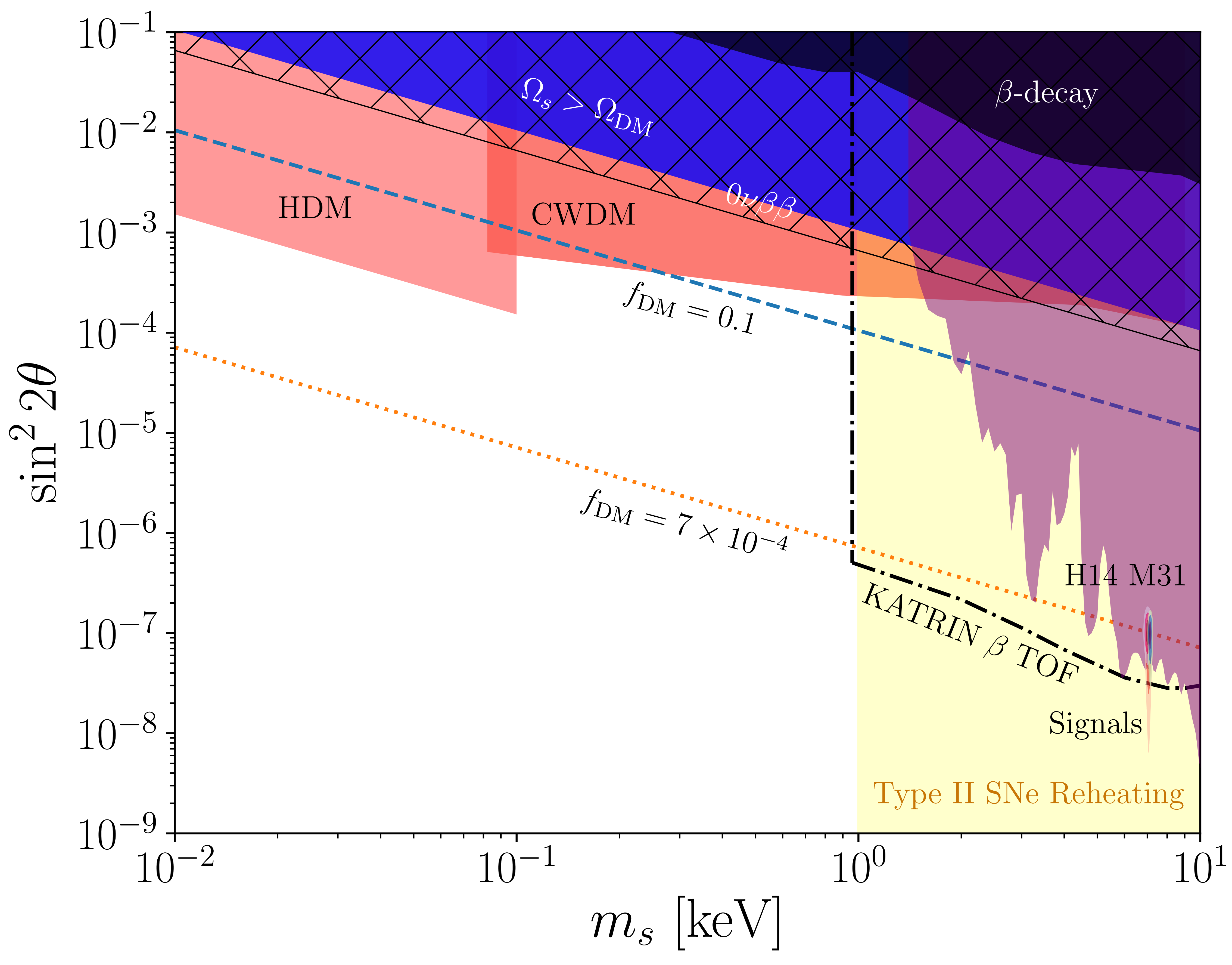
$$\text{Flux} \propto f_{\text{DM}} \sin^2 2\theta \qquad \text{but: } f_{\text{DM}} \propto \left(\sin^2 2\theta\right)^{1.23} \text{ (Abazajian 2005)}$$

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

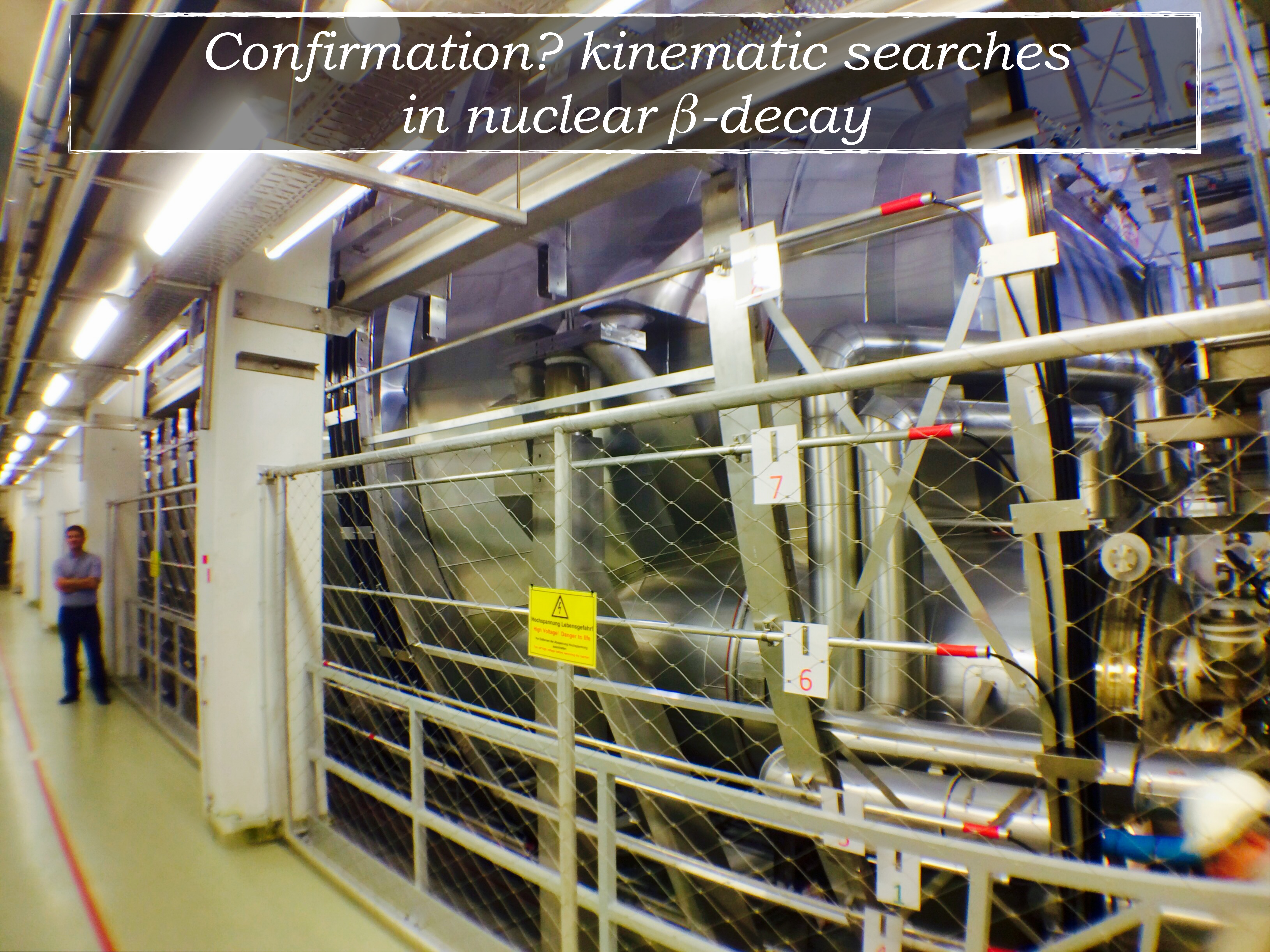
⇒Can achieve even larger mixing angles in low-reheating temperature universes (Gelmini, Palomares-Ruis & Pascoli 2004)

⇒ Low-reheating temperature universe can produce 3.5 signal with **7×10^{-4} of DM** as dark fermions

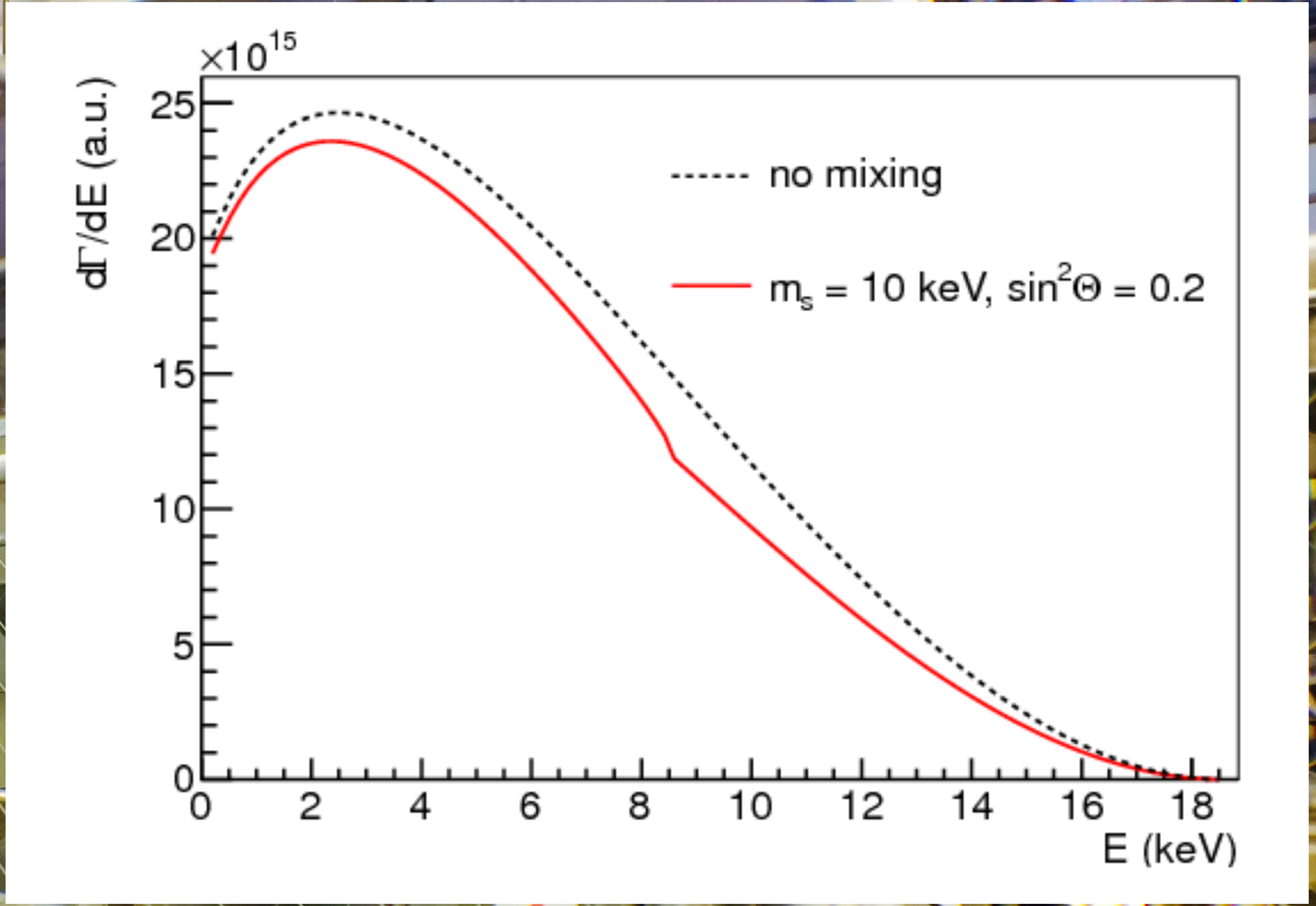
Visible Sterile ν in the Low-Reheat Universe



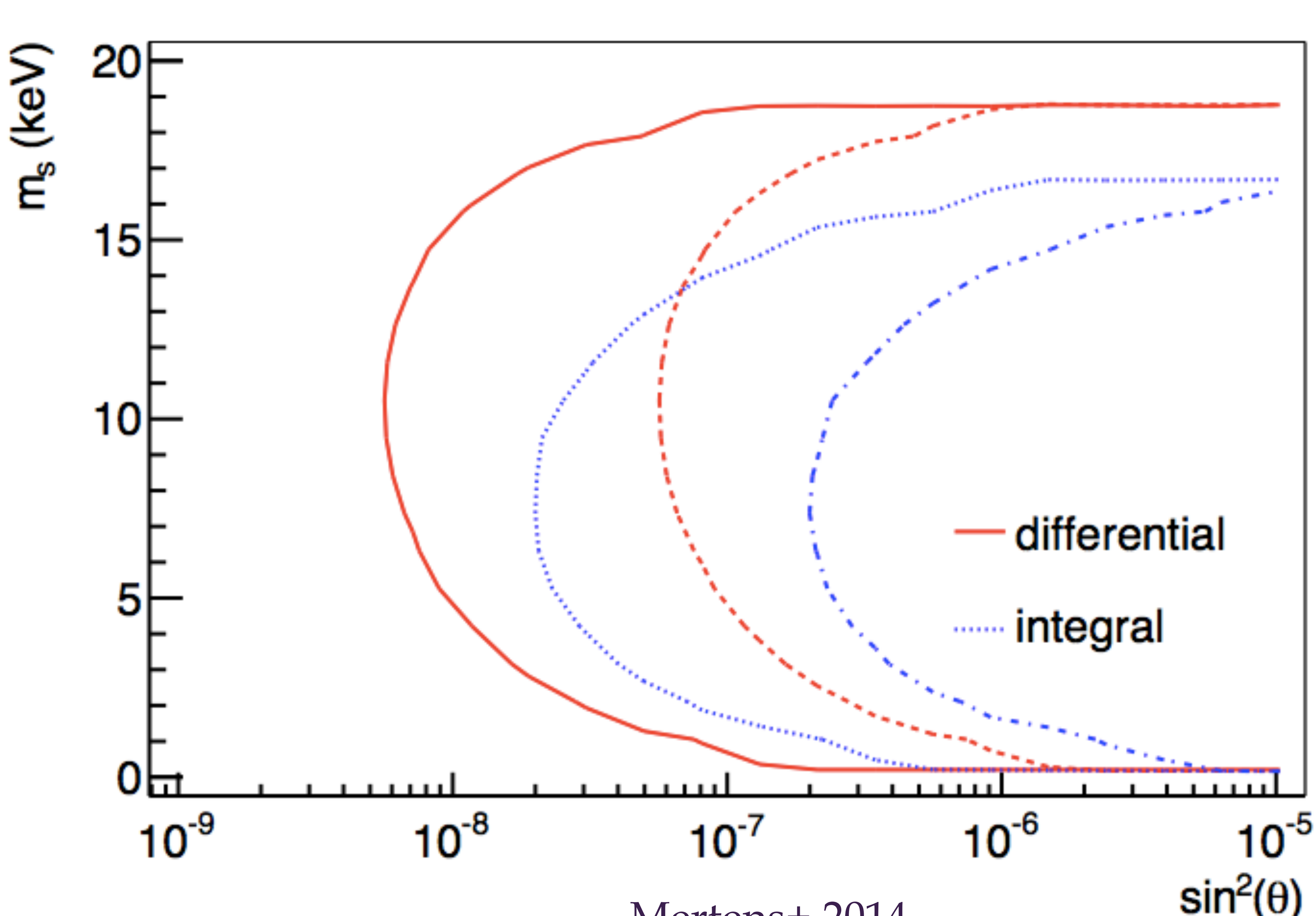
Confirmation? kinematic searches in nuclear β-decay



Confirmation? kinematic searches in nuclear β-decay

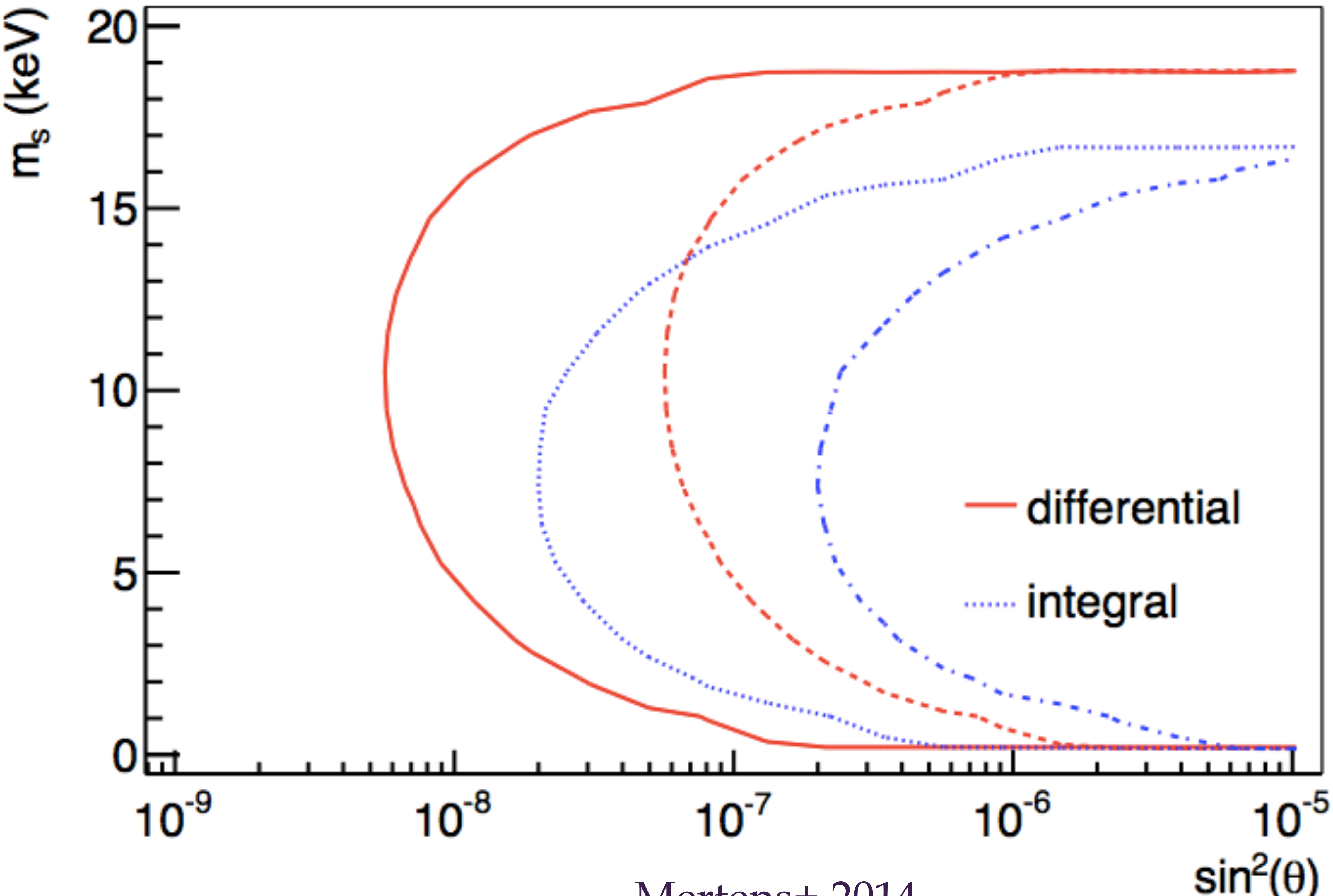


Confirmation? kinematic searches in nuclear β-decay



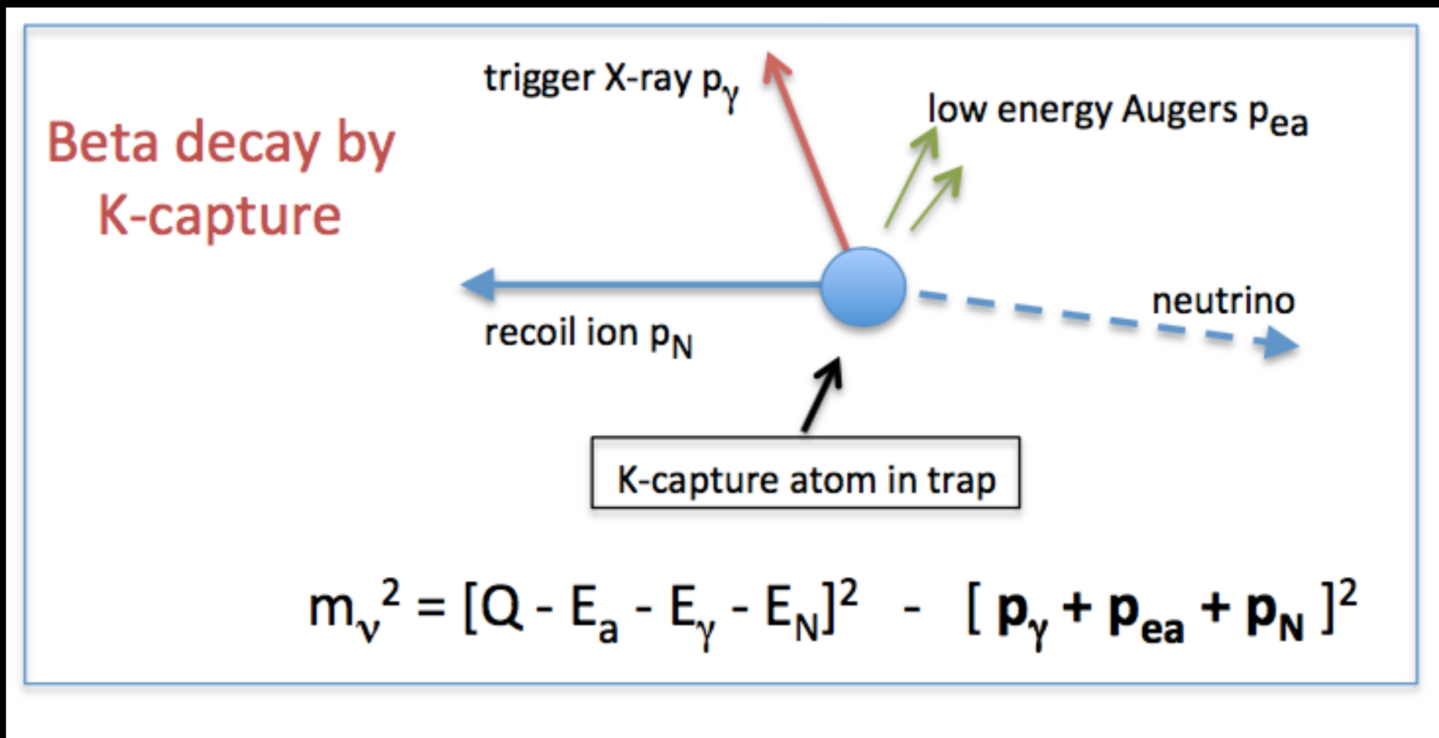
Mertens+ 2014

Confirmation? kinematic searches in nuclear β-decay



Mertens+ 2014

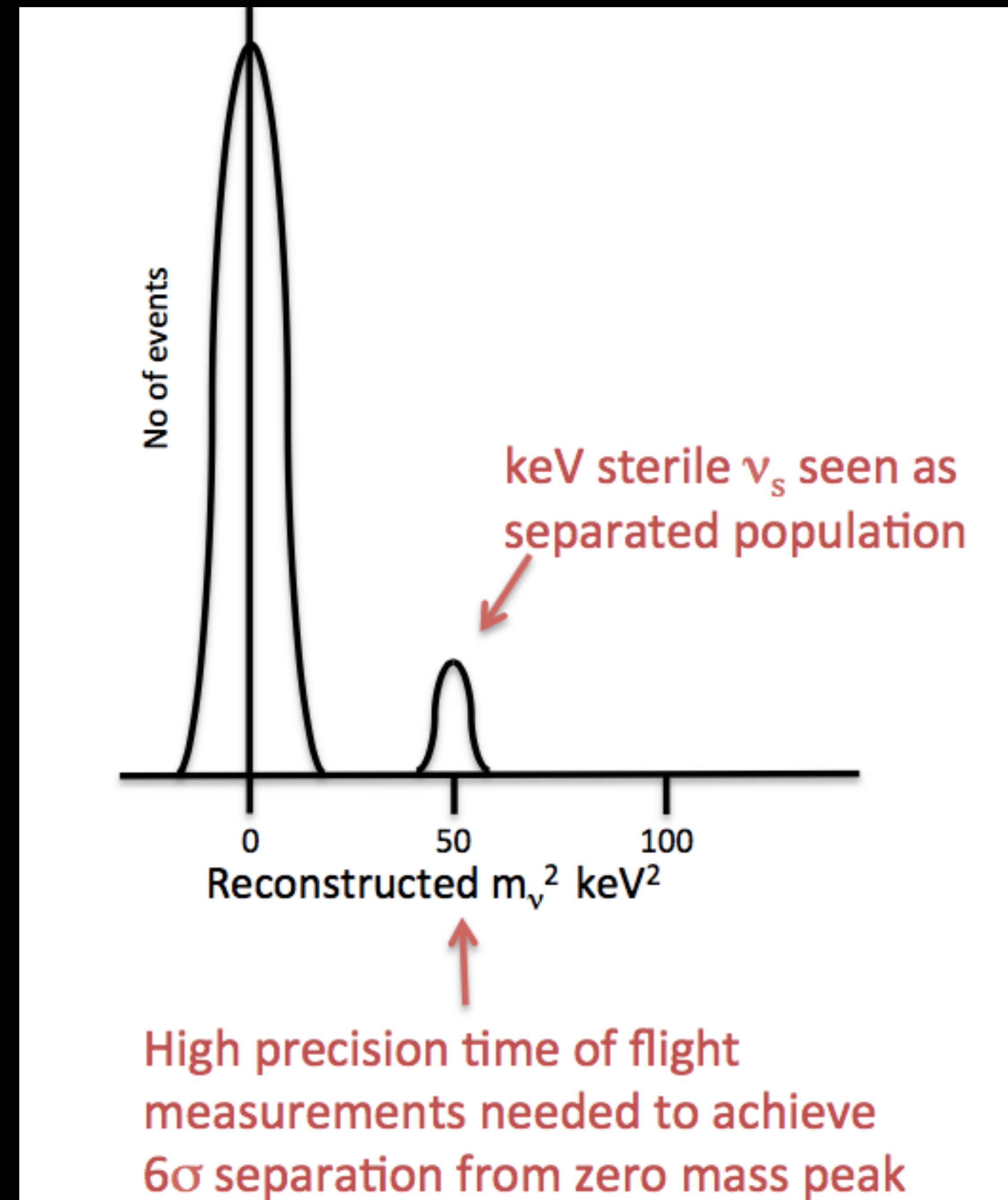
Laboratory Method: full kinematic reconstruction of K-capture nuclear decay



Original studies: Finocchiaro & Shrock 1992

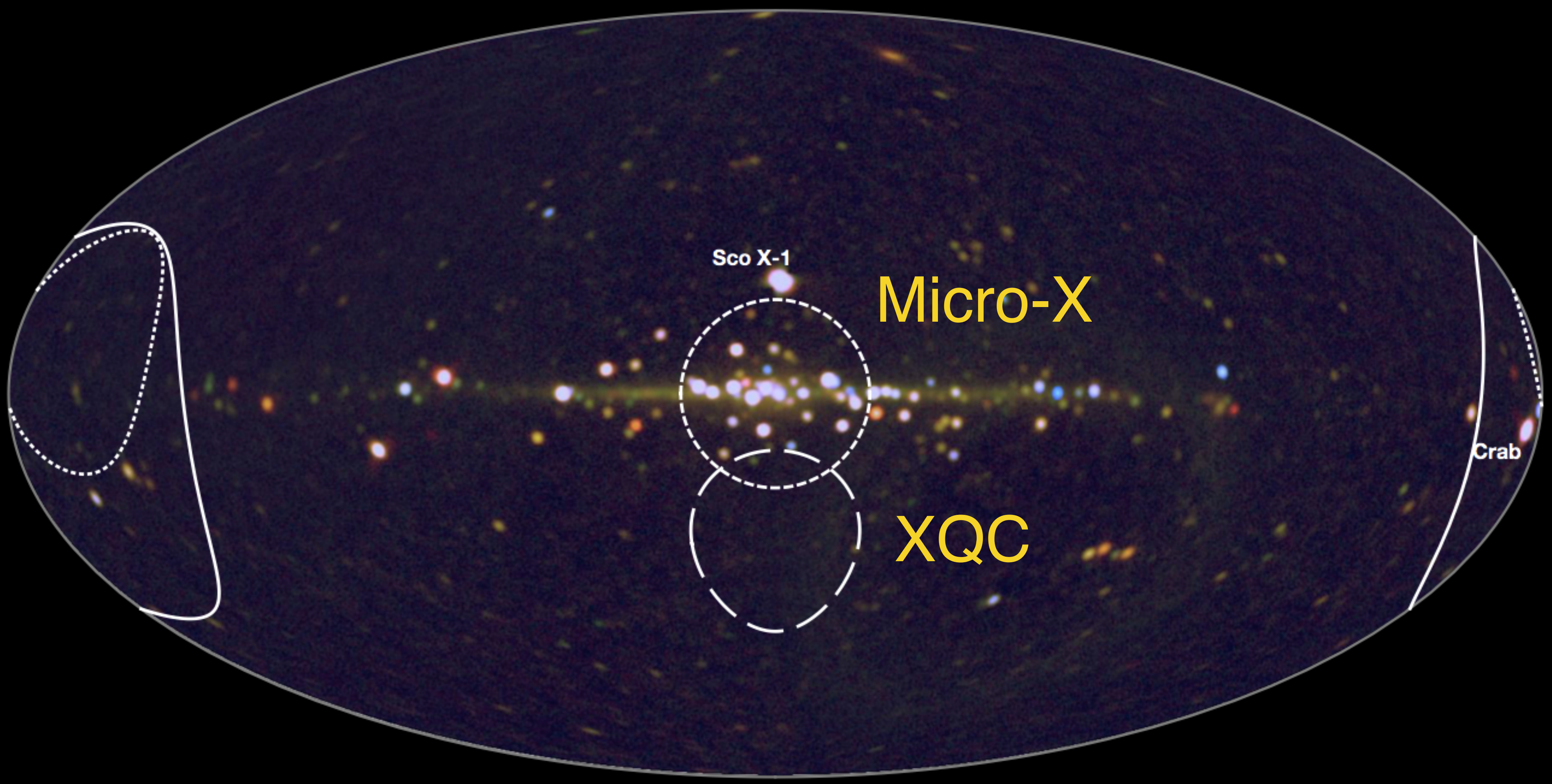
HUNTER experiment (Heavy Unseen Neutrinos by Total Energy-momentum Reconstruction)

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



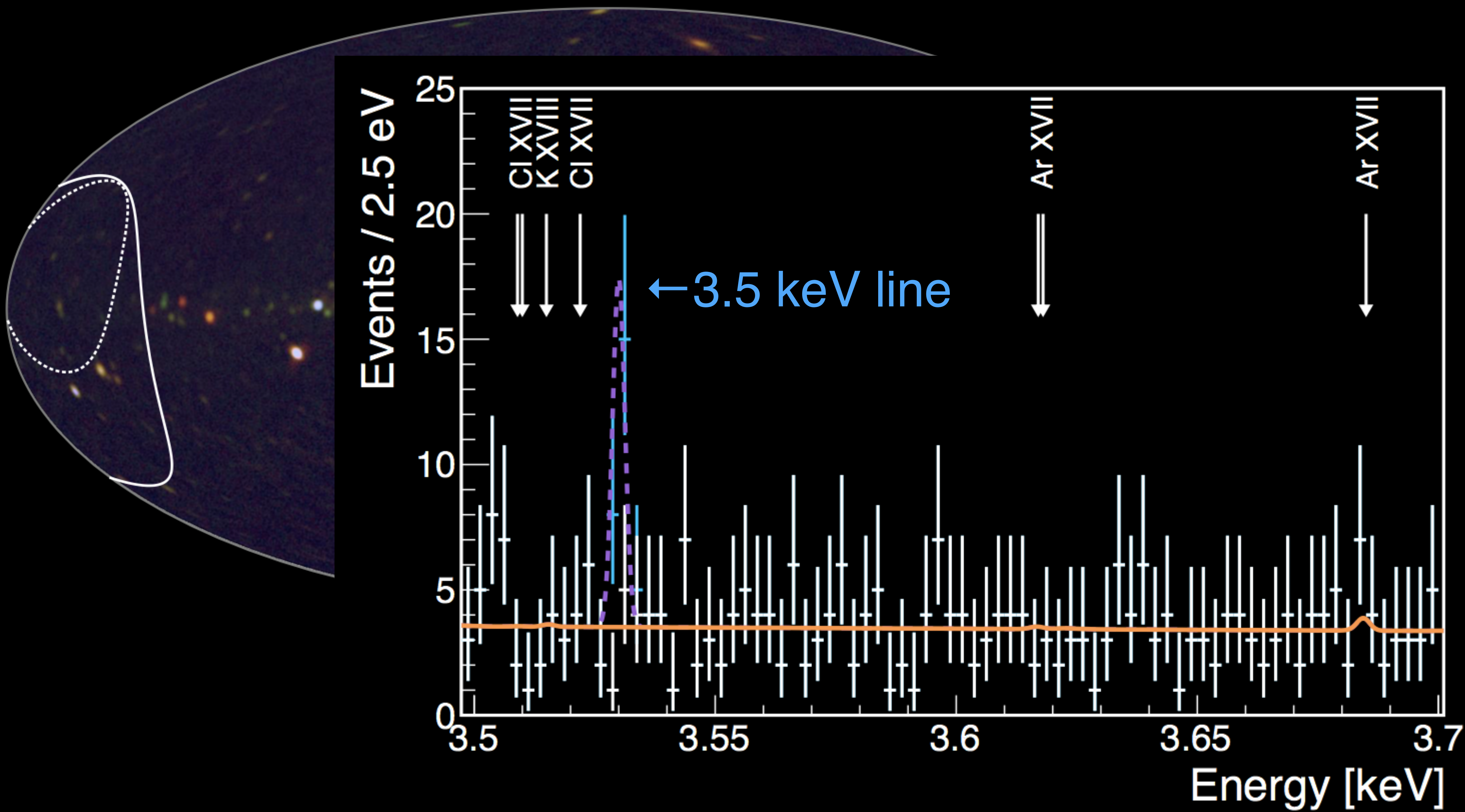
Recent studies show this may now be feasible

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



Figueroa-Feliciano+ 1506.05519

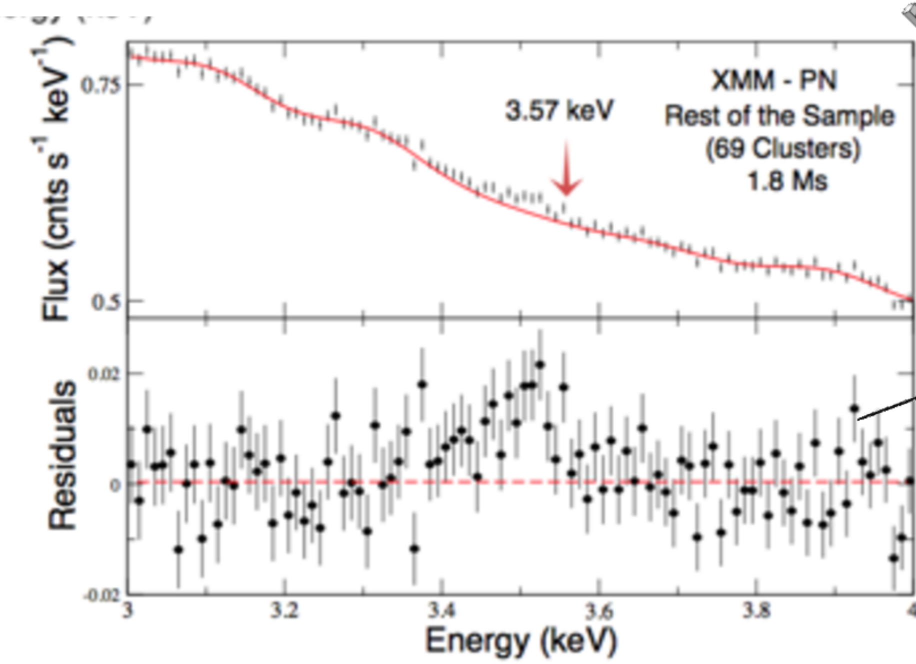
Confirmation? Sounding Rocket X-ray Observations: Micro-X & XQC

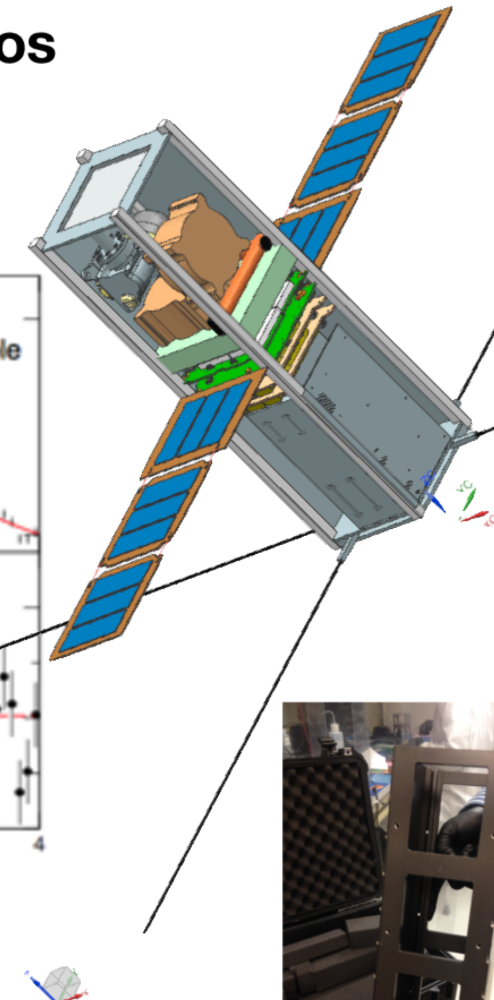


Figueroa-Feliciano+ 1506.05519

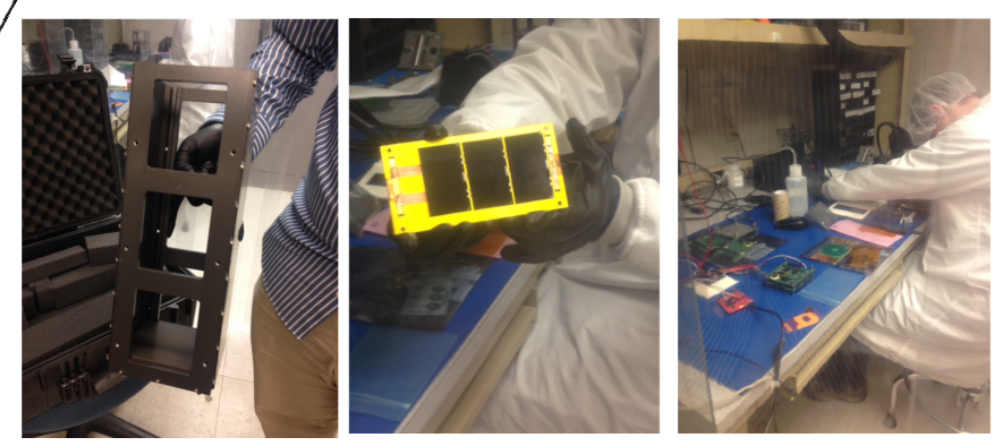
New Technology: New CCDs plus CubeSats

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

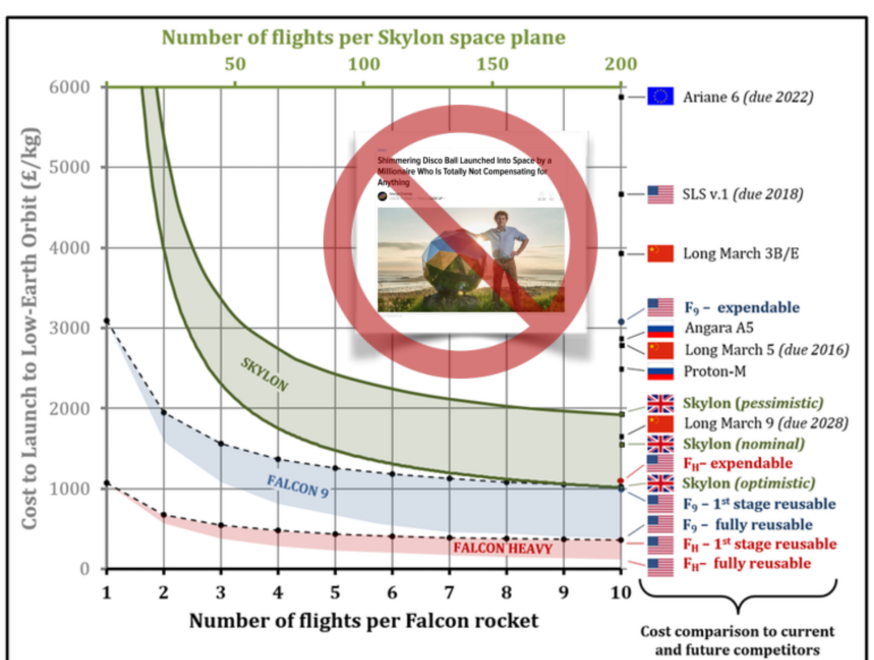




A cubeSat with a large CCD detector (DESI size) with good energy resolution (maybe skipper) in low earth orbit could go after this signal in our own galaxy. Others (Tali et al) are planning to do this with a "CDMS" detector in a rocket. A couple of summer students work on a conceptual design.



partnership with UIUC (aerospace)



opportunity:

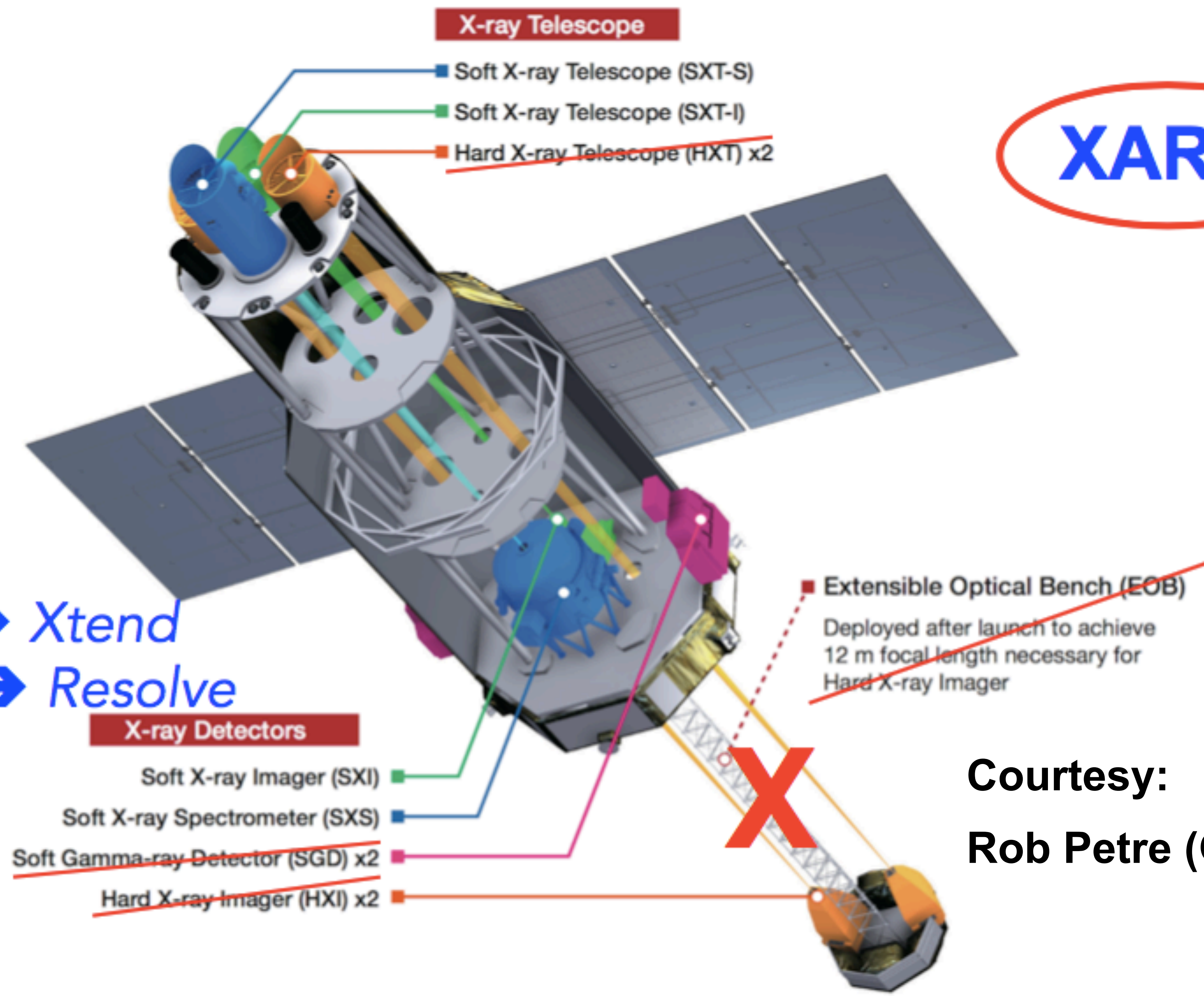
- look for 3.5 signal
- train our engineers in space applications
- new partnerships
- **get in better shape to take advantage of "cheap space"**

Next Space Mission in X-ray Astronomy

X-Ray Astronomy Recovery Mission

XARM
X-ray Astronomy Recovery Mission
Resolve

XARM



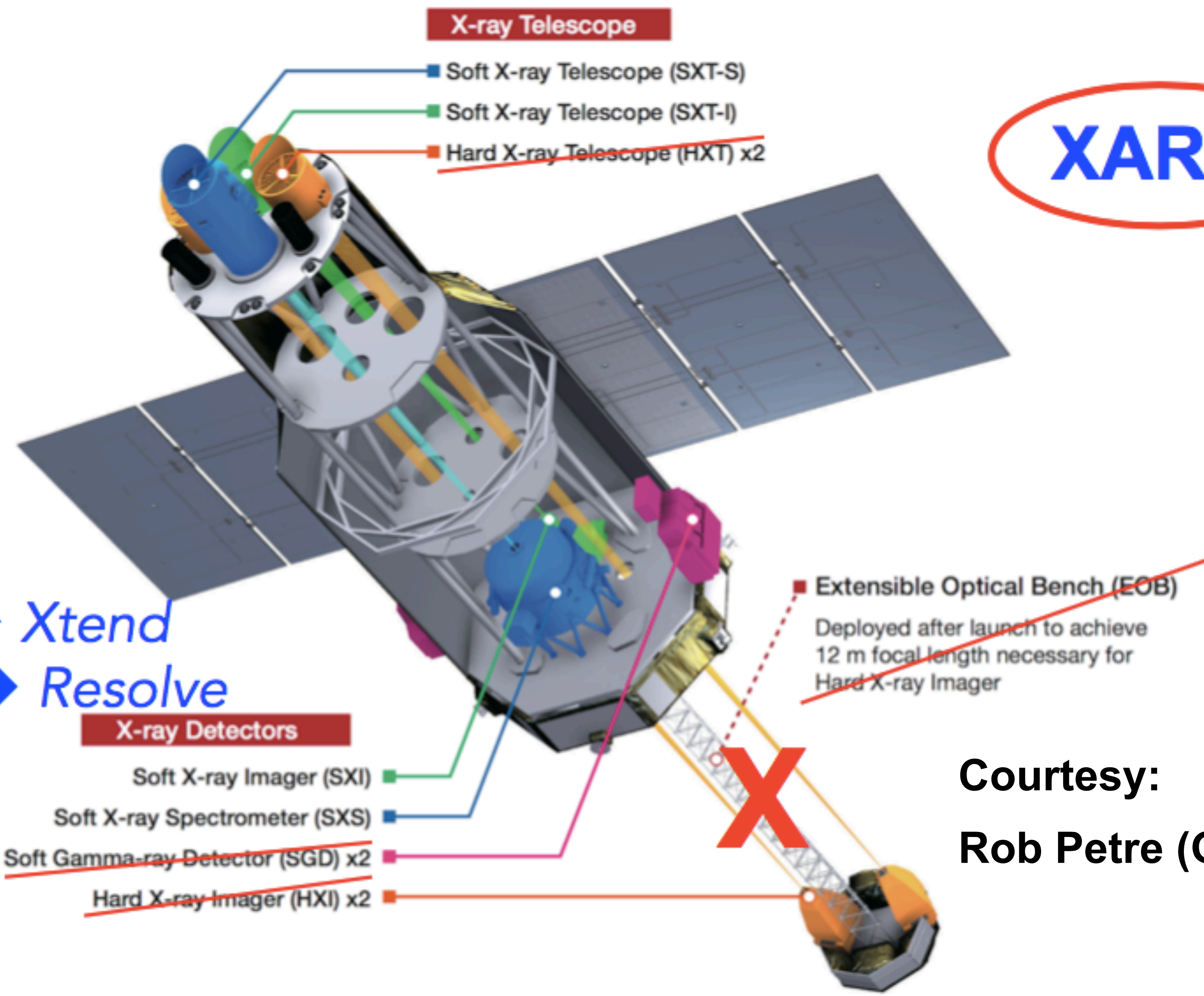
SXI+SXT → *Xtend*
SXS+SXT → *Resolve*

Courtesy:
Rob Petre (GSFC)

Next Space Mission in X-ray Astronomy

X-Ray Astronomy Recovery Mission

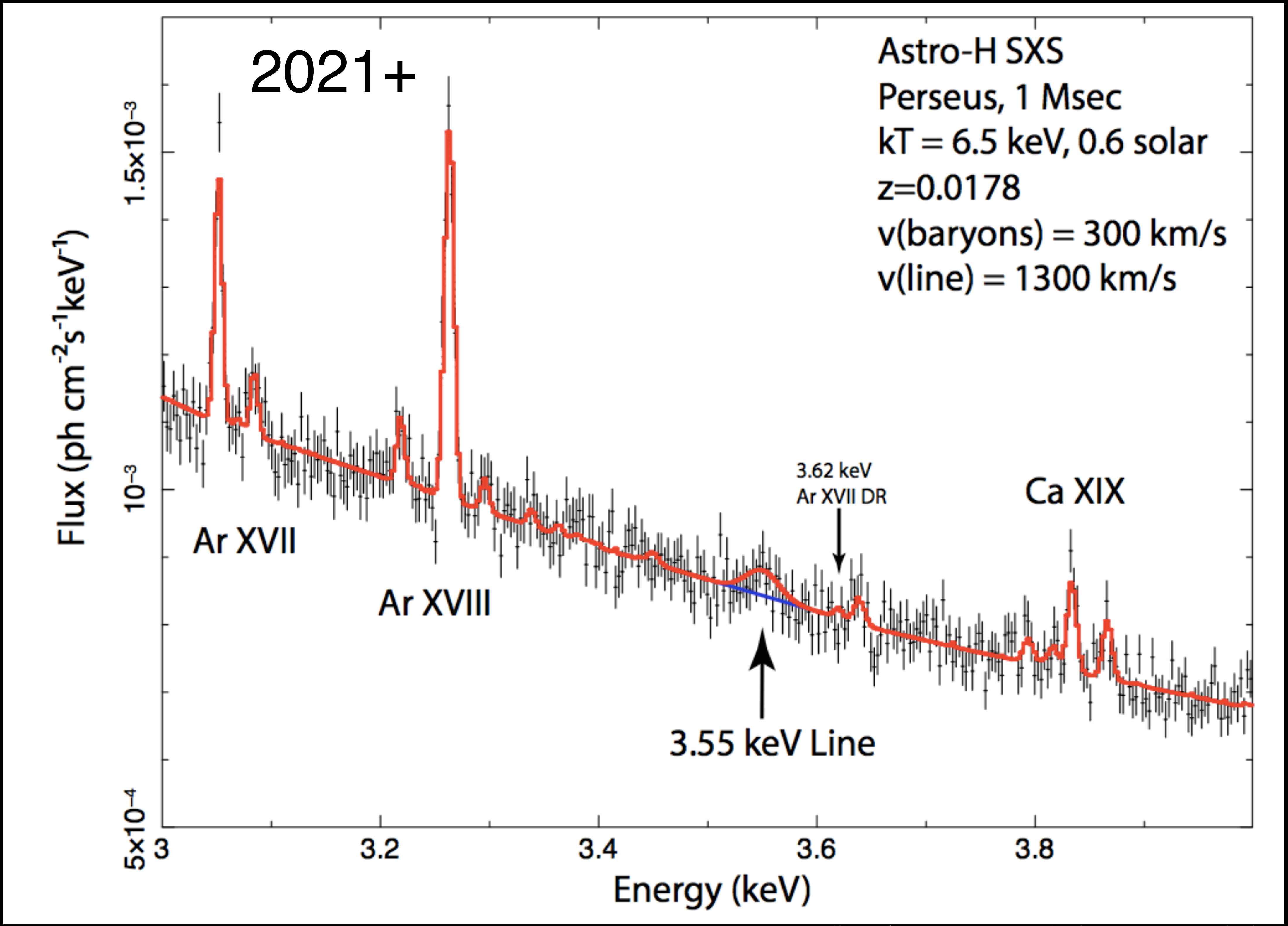
XARM
X-ray Astronomy Recovery Mission
Resolve



Courtesy:

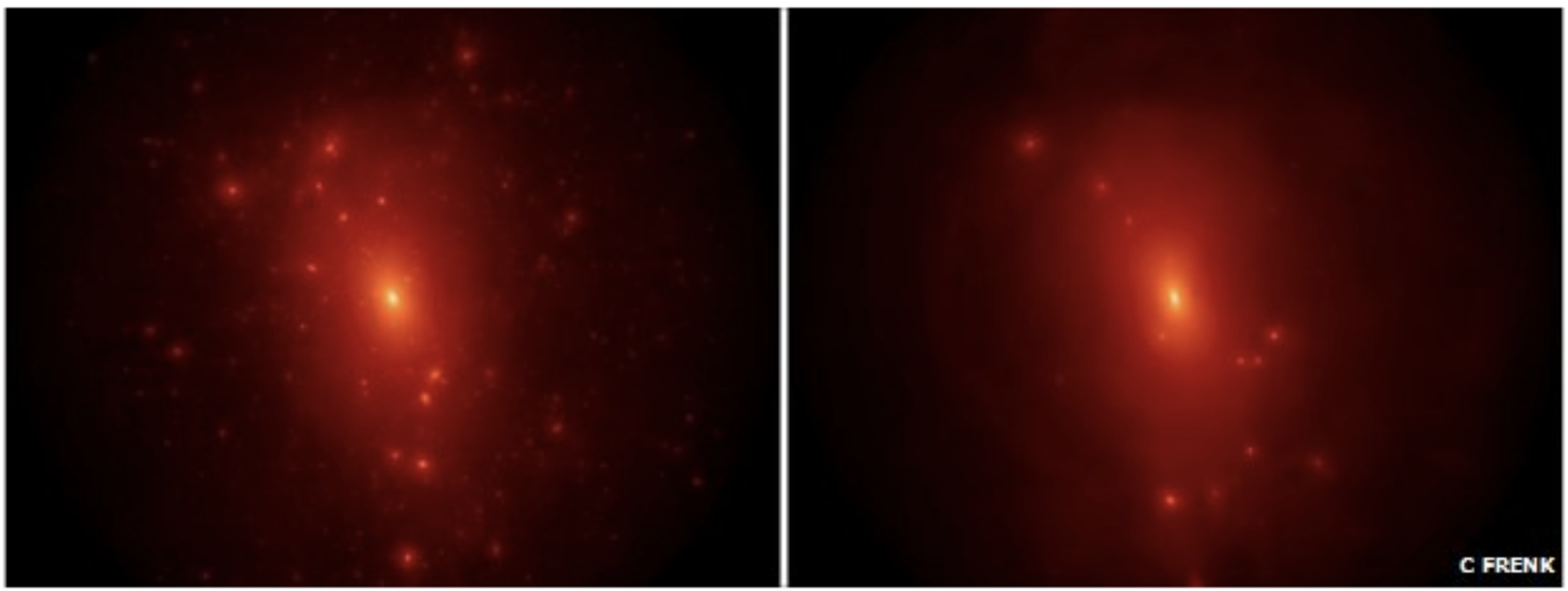
Rob Petre (GSFC)

Confirmation: XARM Space Telescope



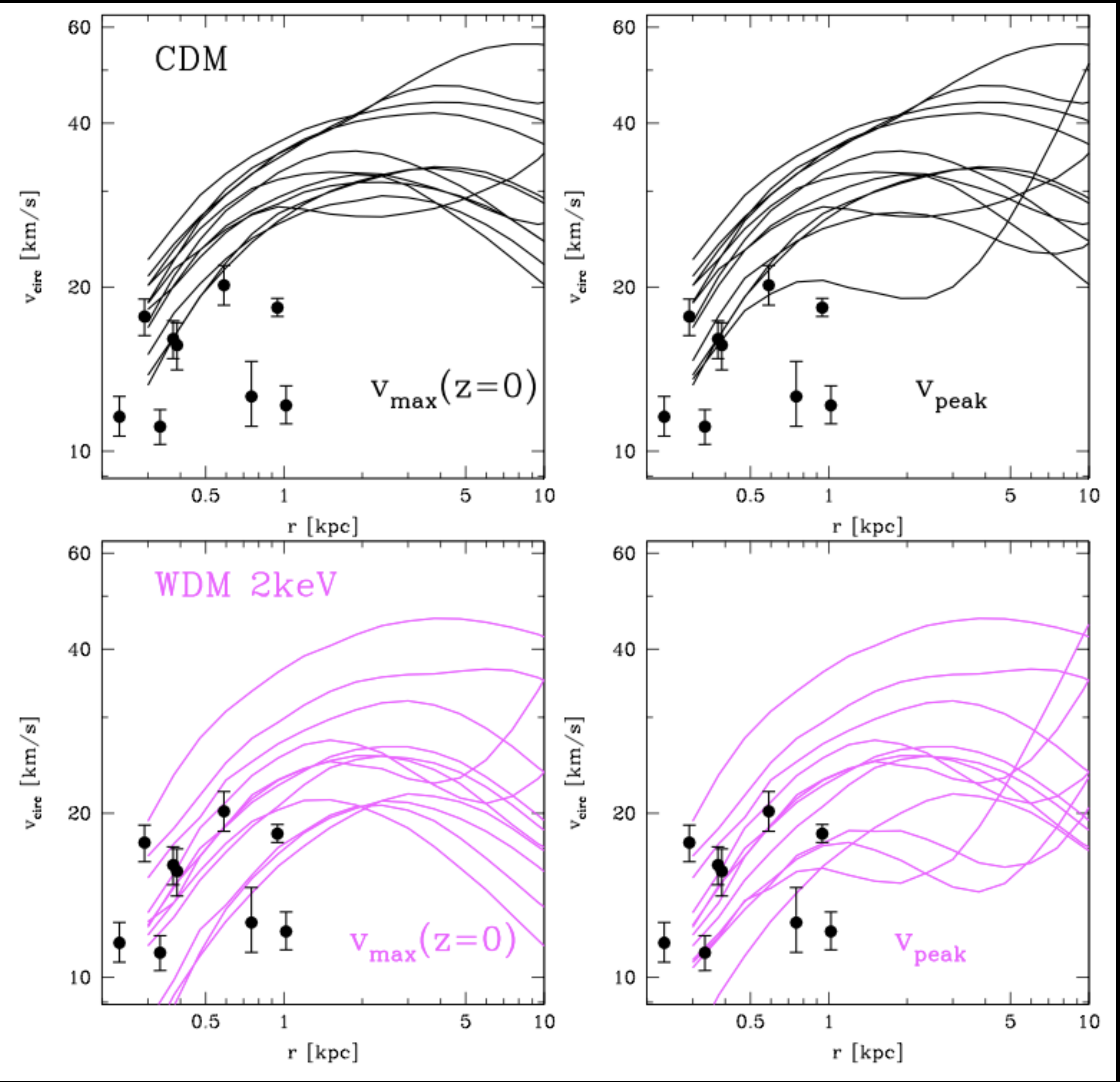
Bulbul et al. ApJ arXiv:1402.2301

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

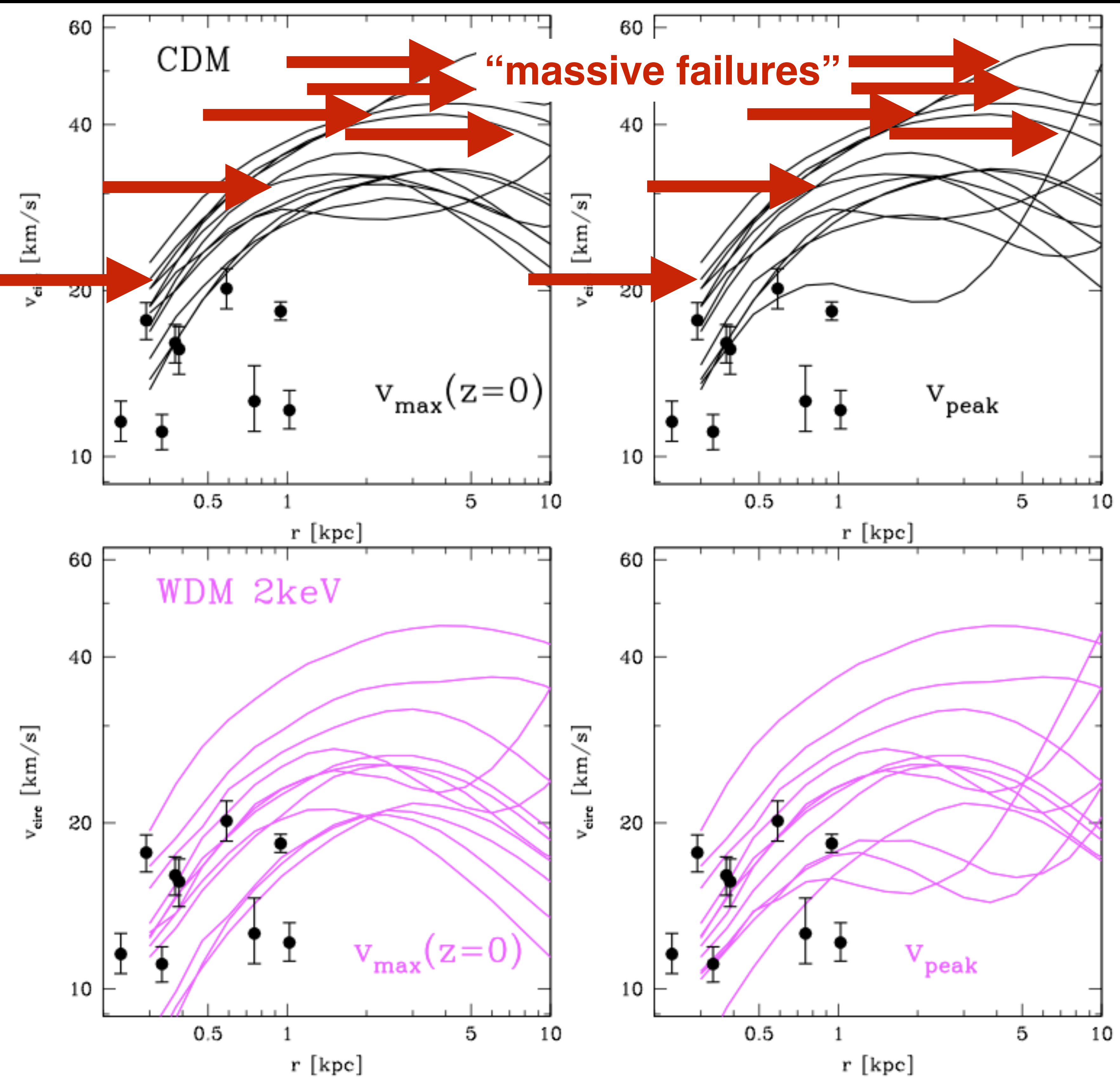
WDM Solution to Local Group Galaxy Properties?



Lovell+ arXiv:1104.2929.
Anderhalden+ arXiv:1212.2967:

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

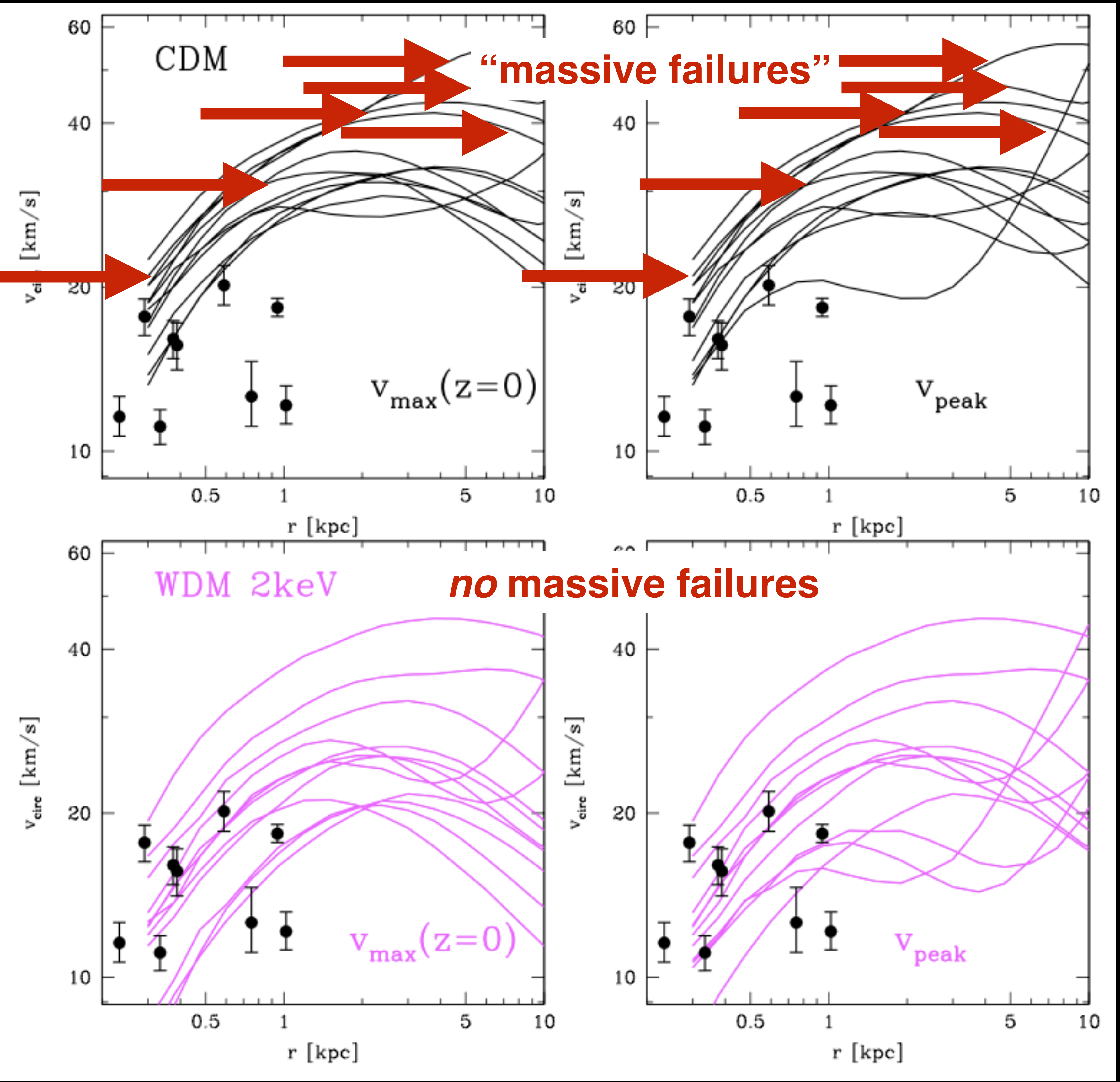
WDM Solution to Local Group Galaxy Properties?



Lovell+
arXiv:1104.2929.
Anderhalden+
arXiv:1212.2967:

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

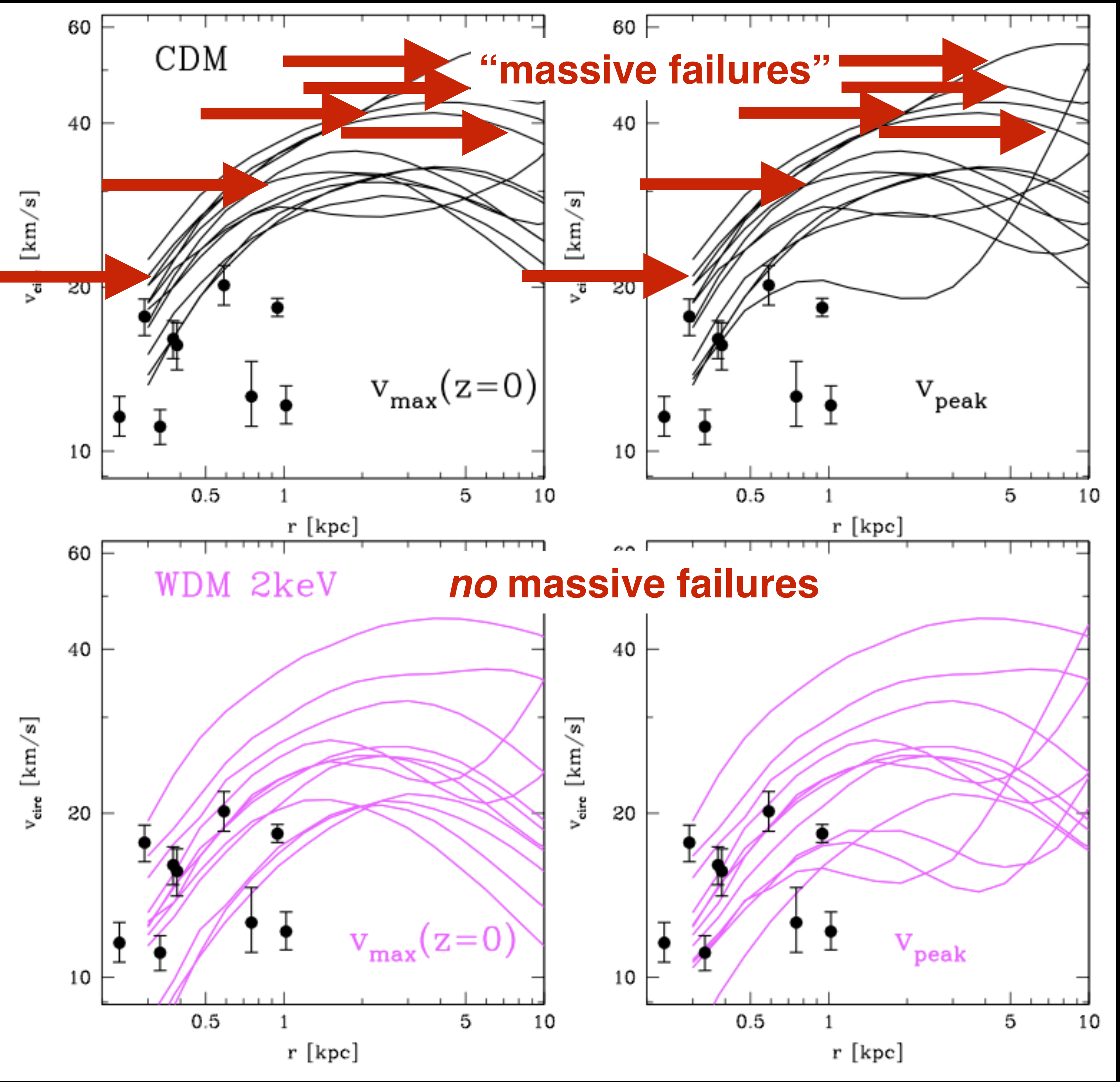
WDM Solution to Local Group Galaxy Properties?



Lovell+
arXiv:1104.2929.
Anderhalden+
arXiv:1212.2967:

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

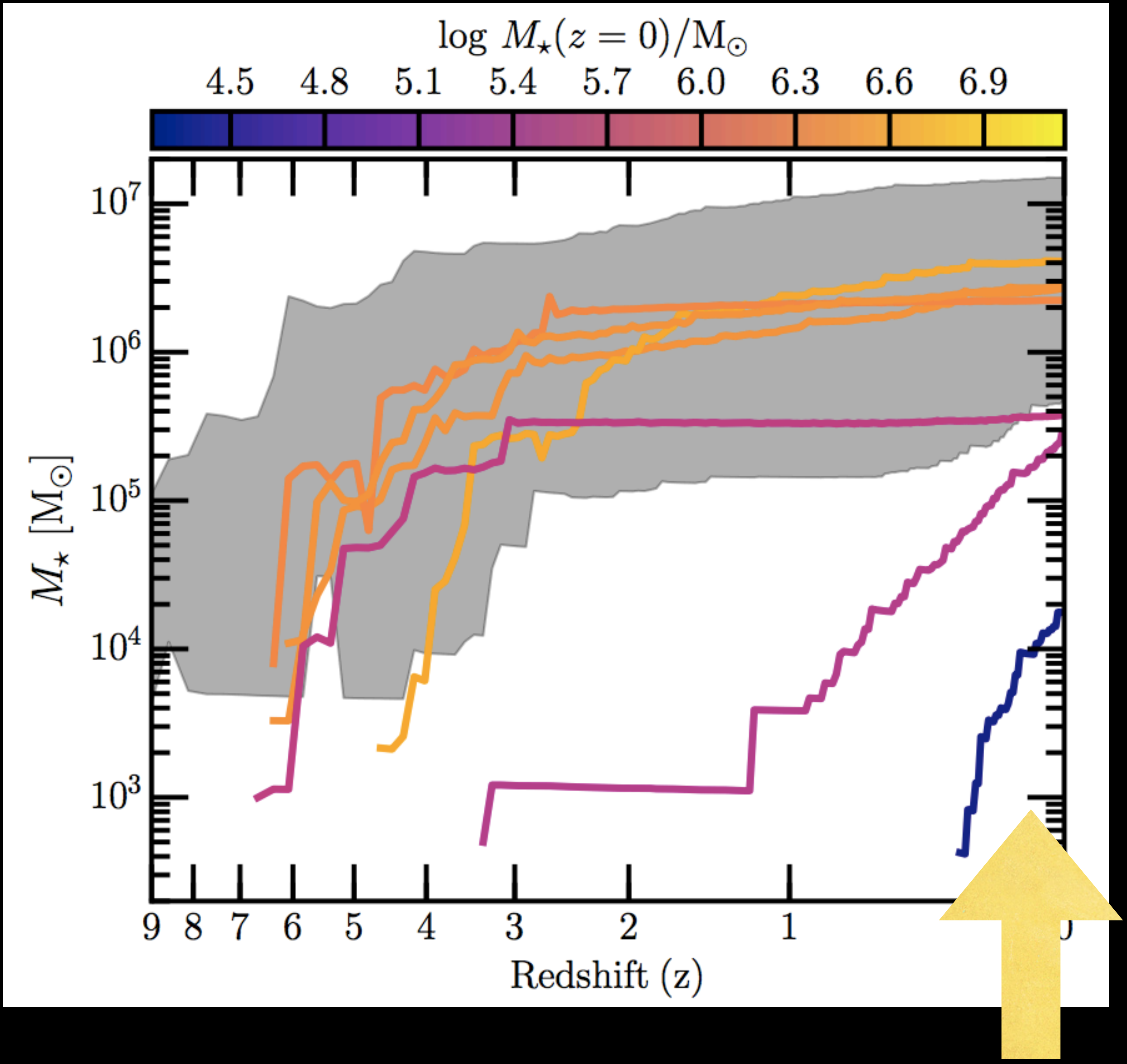
WDM Solution to Local Group Galaxy Properties?



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)

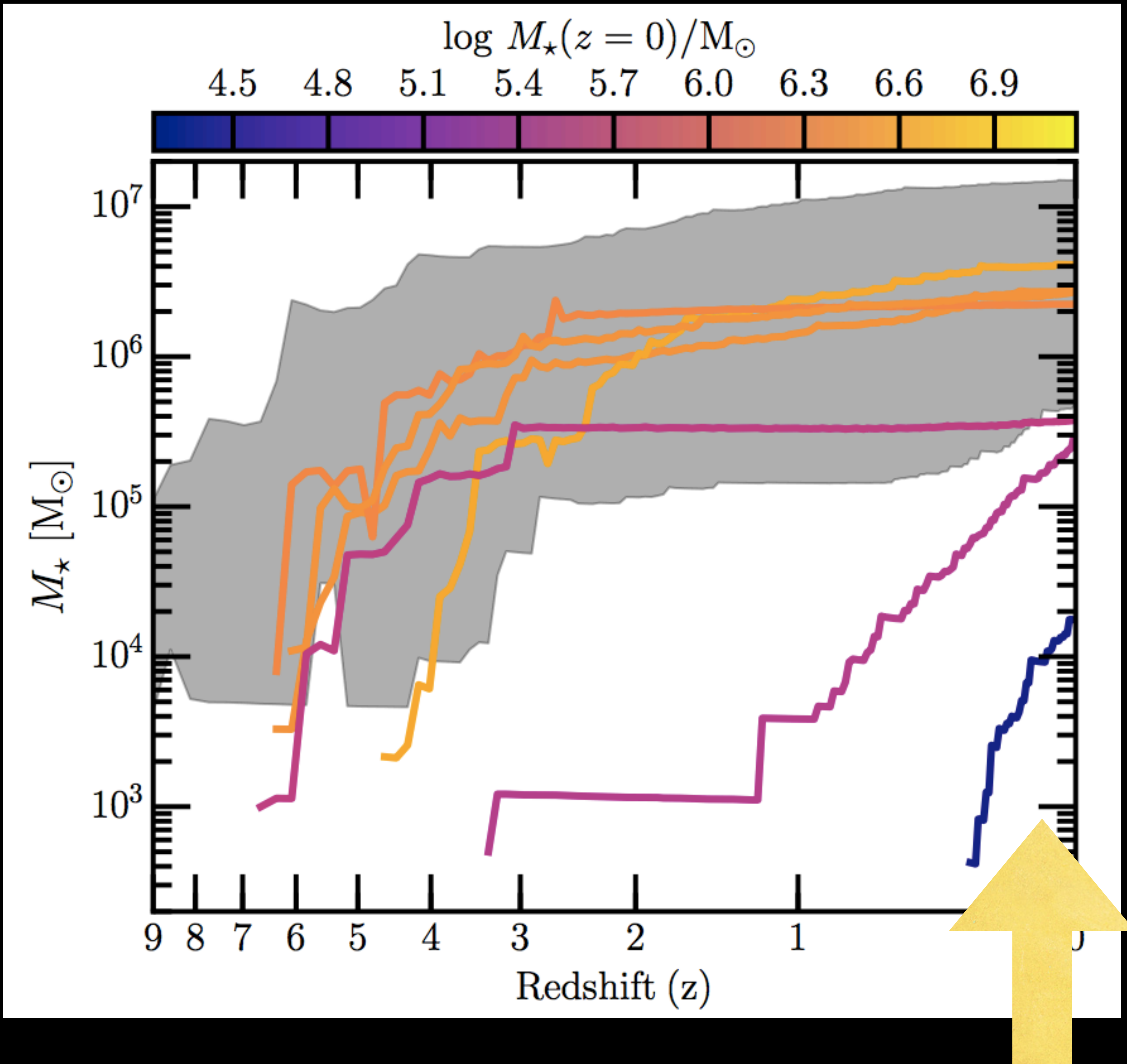
Sterile Neutrino DM:
Horiuchi+ arXiv:1512.04548
Bozek+ arXiv:1512.04544

Signature of WDM in dwarf galaxy formation histories?



Bozek+
arXiv:1803.05424

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

Summary

- Sterile Neutrino Dark Matter has been investigated for 24+ years; indirect detection via cluster & field galaxy searches proposed by yours truly in 2001.

Summary

- ~~Sterile Neutrino~~ Dark Matter has been investigated for 24+ years; indirect detection via cluster & field galaxy searches proposed by yours truly in 2001.

Summary

- *Dark fermion* ~~Sterile Neutrino~~ Dark Matter has been investigated for 24+ years; indirect detection via cluster & field galaxy searches proposed by yours truly in 2001.

Summary

- *Dark fermion* ~~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 has been seen in several followup observations.

Summary

- *Dark fermion* ~~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 has been seen in several followup observations.
- **No consistent astrophysical interpretation exists.**

Summary

Summary

- Among the simplest models for the signal are:

Summary

- Among the simplest models for the signal are:
  - resonant sterile neutrino production with a cosmological L

Summary

- Among the simplest models for the signal are:
  - resonant ~~sterile neutrino~~ *dark fermion* production with a cosmological L

Summary

- Among the simplest models for the signal are:
  - resonant ~~sterile neutrino~~ *dark fermion* production with a cosmological L
  - *a fraction of dark matter as dark fermions*

Summary

- Among the simplest models for the signal are:
  - resonant ~~sterile neutrino~~ *dark fermion* production with a cosmological L
  - *a fraction of dark matter as dark fermions*
  - *low-reheating temperature models*

Summary

- Among the simplest models for the signal are:
  - resonant ~~sterile neutrino~~ *dark fermion* production with a cosmological L
  - *a fraction of dark matter as dark fermions*
  - *low-reheating temperature models*
  - *singlet Higgs decay models*

Summary

- Among the simplest models for the signal are:
    - resonant ~~sterile neutrino~~ *dark fermion* production with a cosmological L
    - *a fraction of dark matter as dark fermions*
    - *low-reheating temperature models*
    - *singlet Higgs decay models*
- At least two nuclear physics laboratory experiments are following up sterile neutrino dark matter interpretations.

Summary

- Among the simplest models for the signal are:
  - resonant ~~sterile neutrino~~ *dark fermion* production with a cosmological L
  - *a fraction of dark matter as dark fermions*
  - *low-reheating temperature models*
  - *singlet Higgs decay models*
- At least two nuclear physics laboratory experiments are following up sterile neutrino dark matter interpretations.
- The signal crosses a transition region from "cold" dark matter to "warm" dark matter, at s cutoff scale of great interest in galaxy formation of the local group of galaxies,

Summary

- Among the simplest models for the signal are:
  - resonant ~~sterile neutrino~~ *dark fermion* production with a cosmological L
  - *a fraction of dark matter as dark fermions*
  - *low-reheating temperature models*
  - *singlet Higgs decay models*
- At least two nuclear physics laboratory experiments are following up sterile neutrino dark matter interpretations.
- The signal crosses a transition region from "cold" dark matter to "warm" dark matter, at s cutoff scale of great interest in galaxy formation of the local group of galaxies,
- Future Follow up observations:

Summary

- Among the simplest models for the signal are:
  - resonant ~~sterile neutrino~~ *dark fermion* production with a cosmological L
  - *a fraction of dark matter as dark fermions*
  - *low-reheating temperature models*
  - *singlet Higgs decay models*
- At least two nuclear physics laboratory experiments are following up sterile neutrino dark matter interpretations.
- The signal crosses a transition region from "cold" dark matter to "warm" dark matter, at s cutoff scale of great interest in galaxy formation of the local group of galaxies,
- Future Follow up observations:
  - 2019: X-ray CubeSAT, Micro-X, XQC

Summary

- Among the simplest models for the signal are:
  - resonant ~~sterile neutrino~~ *dark fermion* production with a cosmological L
  - *a fraction of dark matter as dark fermions*
  - *low-reheating temperature models*
  - *singlet Higgs decay models*
- At least two nuclear physics laboratory experiments are following up sterile neutrino dark matter interpretations.
- The signal crosses a transition region from "cold" dark matter to "warm" dark matter, at s cutoff scale of great interest in galaxy formation of the local group of galaxies,
- Future Follow up observations:
  - 2019: X-ray CubeSAT, Micro-X, XQC
  - 2021-2022: XARM

Summary

- Among the simplest models for the signal are:
  - resonant ~~sterile neutrino~~ *dark fermion* production with a cosmological L
  - *a fraction of dark matter as dark fermions*
  - *low-reheating temperature models*
  - *singlet Higgs decay models*

- At least two nuclear physics laboratory experiments are following up sterile neutrino dark matter interpretations.

- The signal crosses a transition region from "cold" dark matter to "warm" dark matter, at s cutoff scale of great interest in galaxy formation of the local group of galaxies,

- Future Follow up observations:

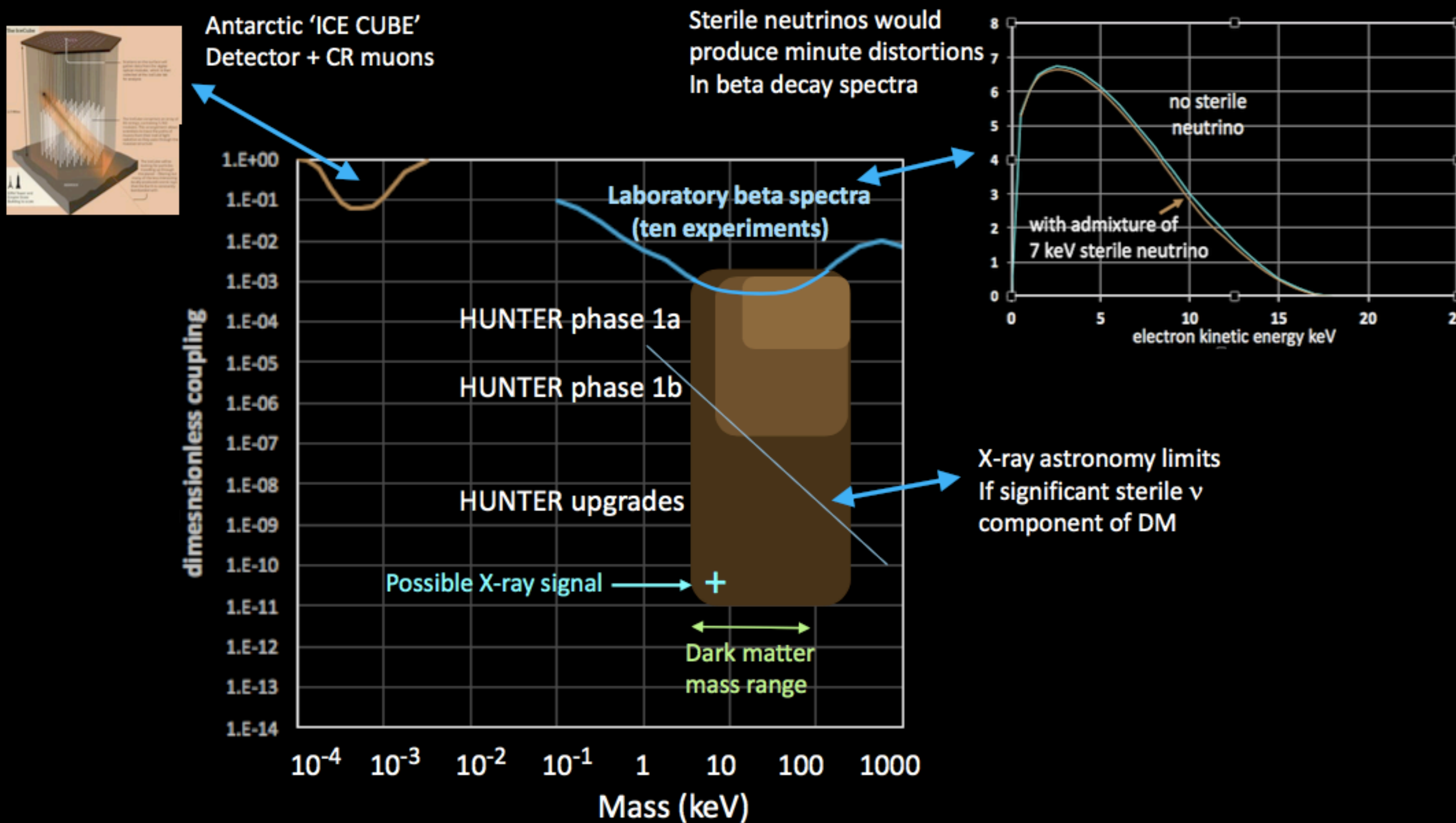
  - 2019: X-ray CubeSAT, Micro-X, XQC
  - 2021-2022: XARM
  - 2028+: ATHENA

Summary

- Among the simplest models for the signal are:
  - resonant ~~sterile neutrino~~ *dark fermion* production with a cosmological L
  - *a fraction of dark matter as dark fermions*
  - *low-reheating temperature models*
  - *singlet Higgs decay models*
- At least two nuclear physics laboratory experiments are following up sterile neutrino dark matter interpretations.
- The signal crosses a transition region from "cold" dark matter to "warm" dark matter, at s cutoff scale of great interest in galaxy formation of the local group of galaxies,
- Future Follow up observations:
  - 2019: X-ray CubeSAT, Micro-X, XQC
  - 2021-2022: XARM
  - 2028+: ATHENA
  - 2030+: X-Ray Surveyor

Backup Slides

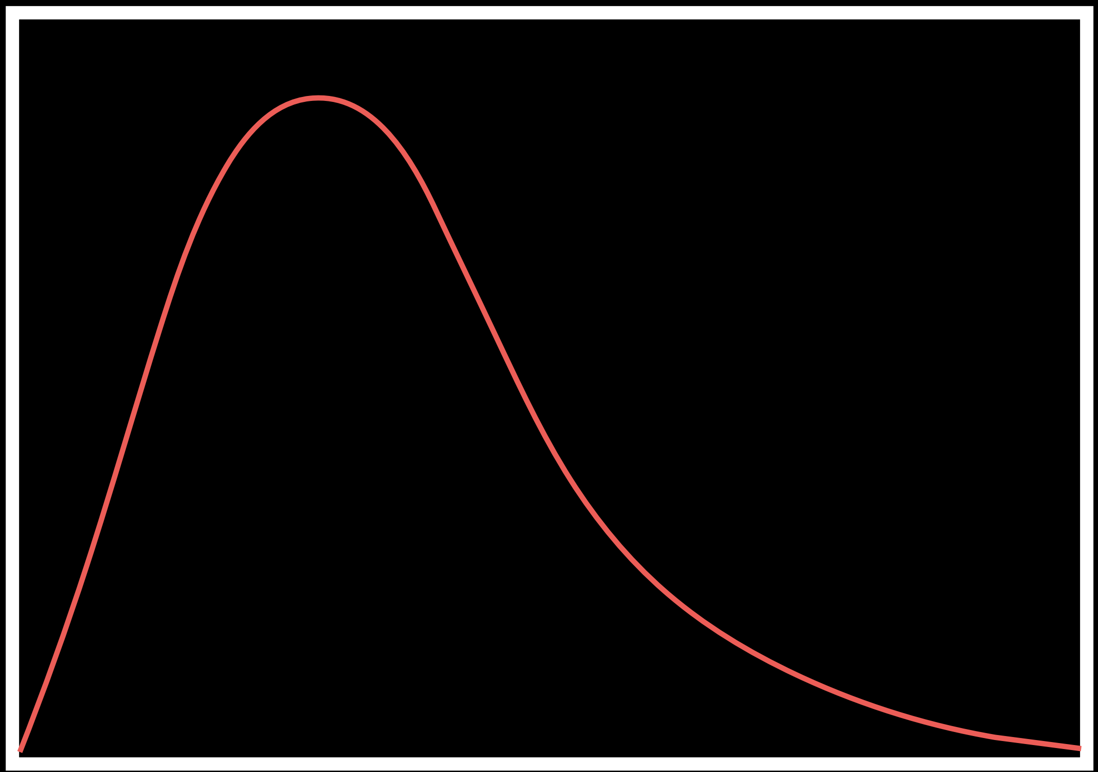
Existing limits and future coverage of HUNTER experiment



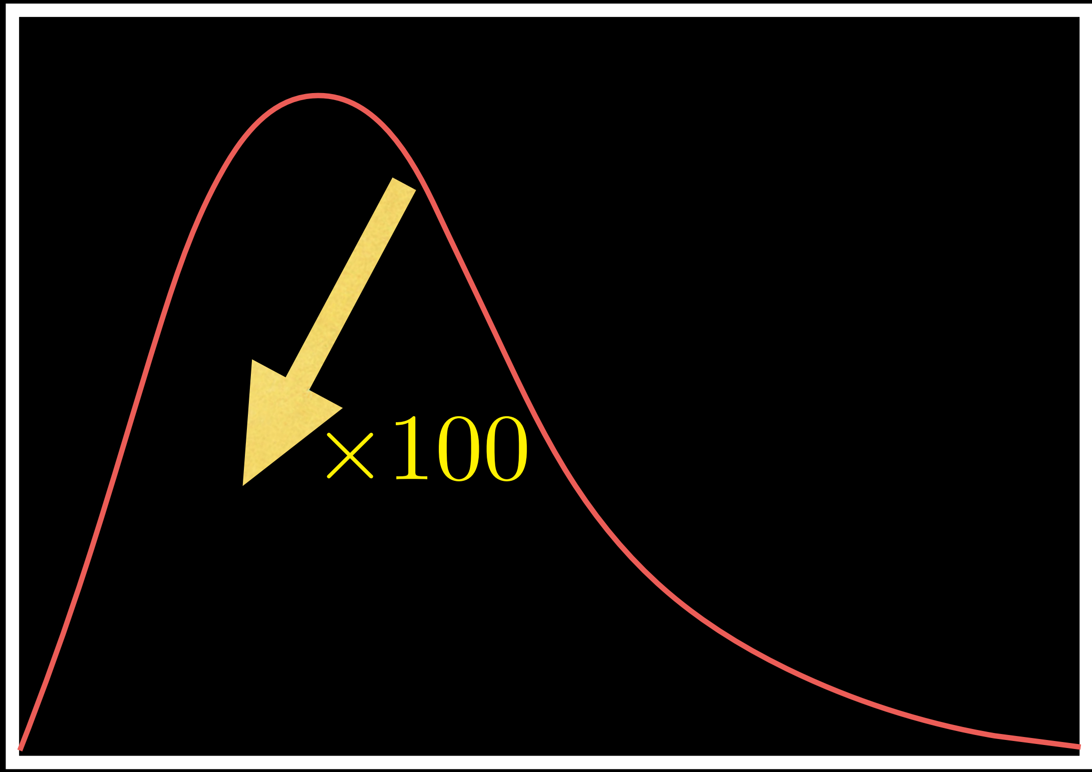
Thermal WDM

Thermal WDM

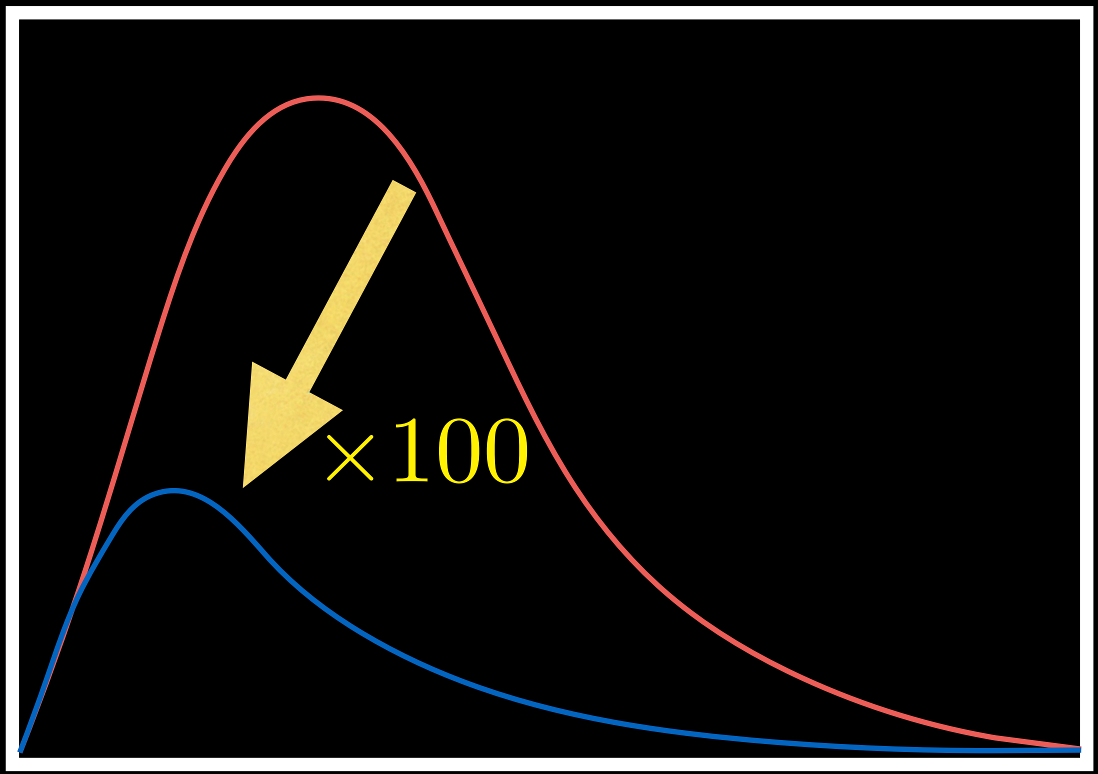
Thermal WDM



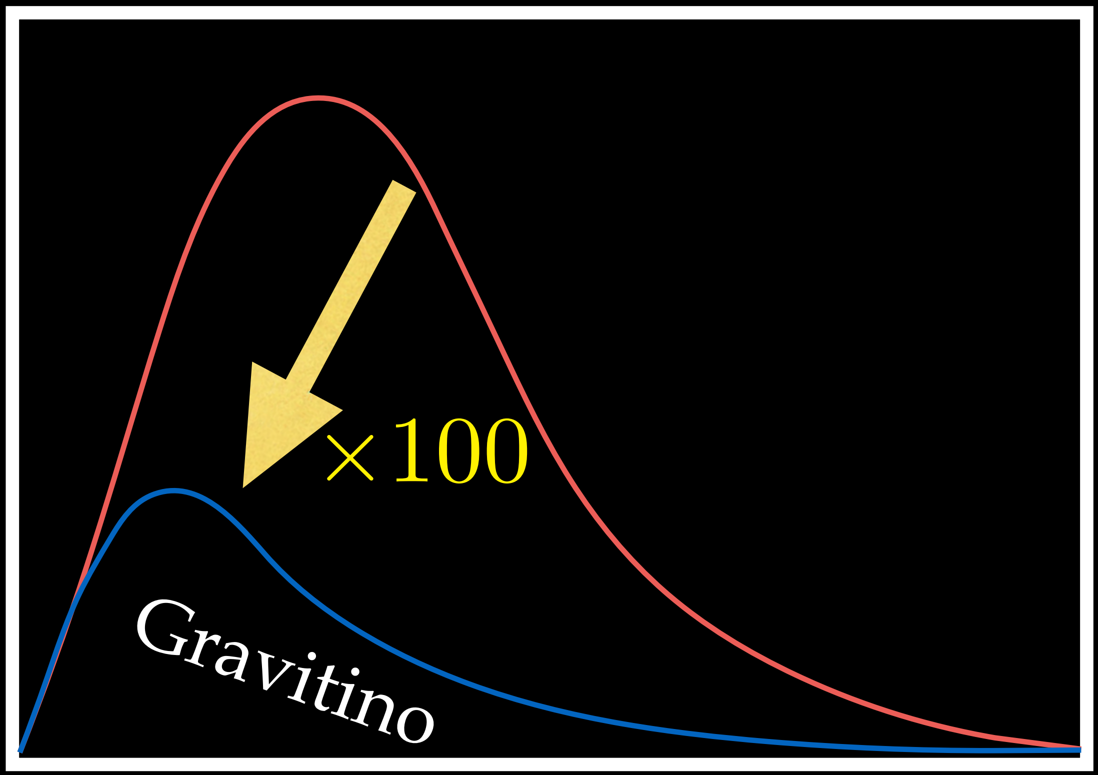
Thermal WDM



Thermal WDM

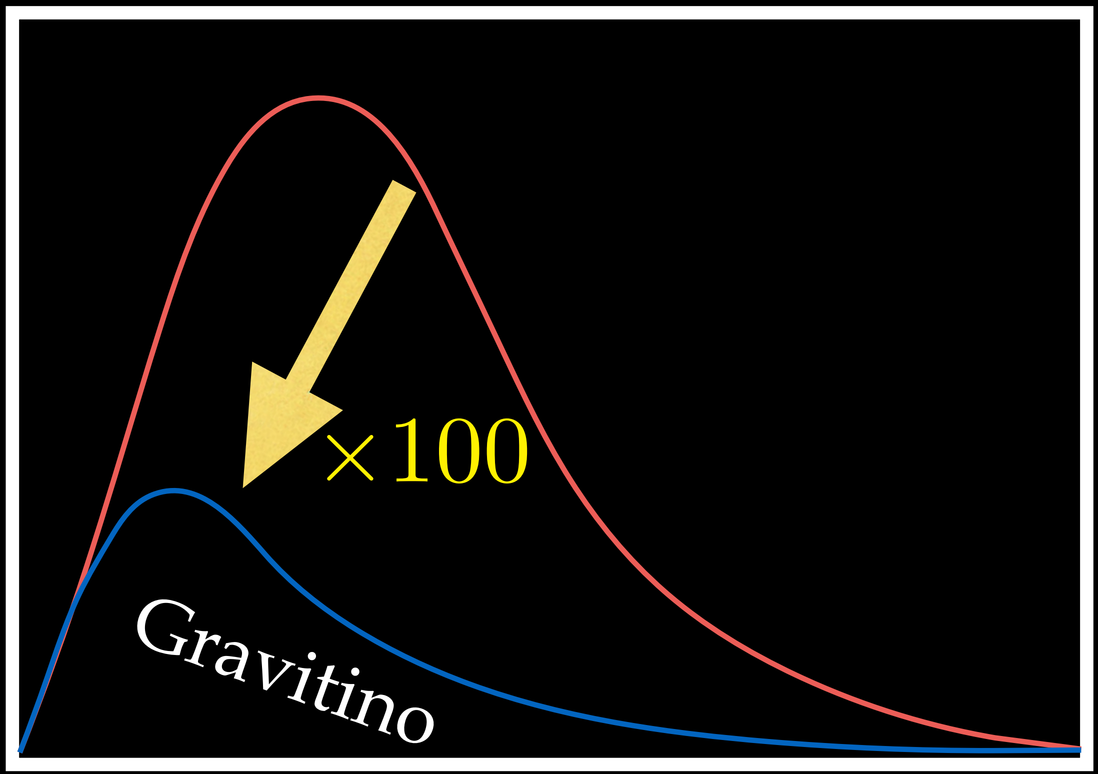


Thermal WDM



Sterile WDM

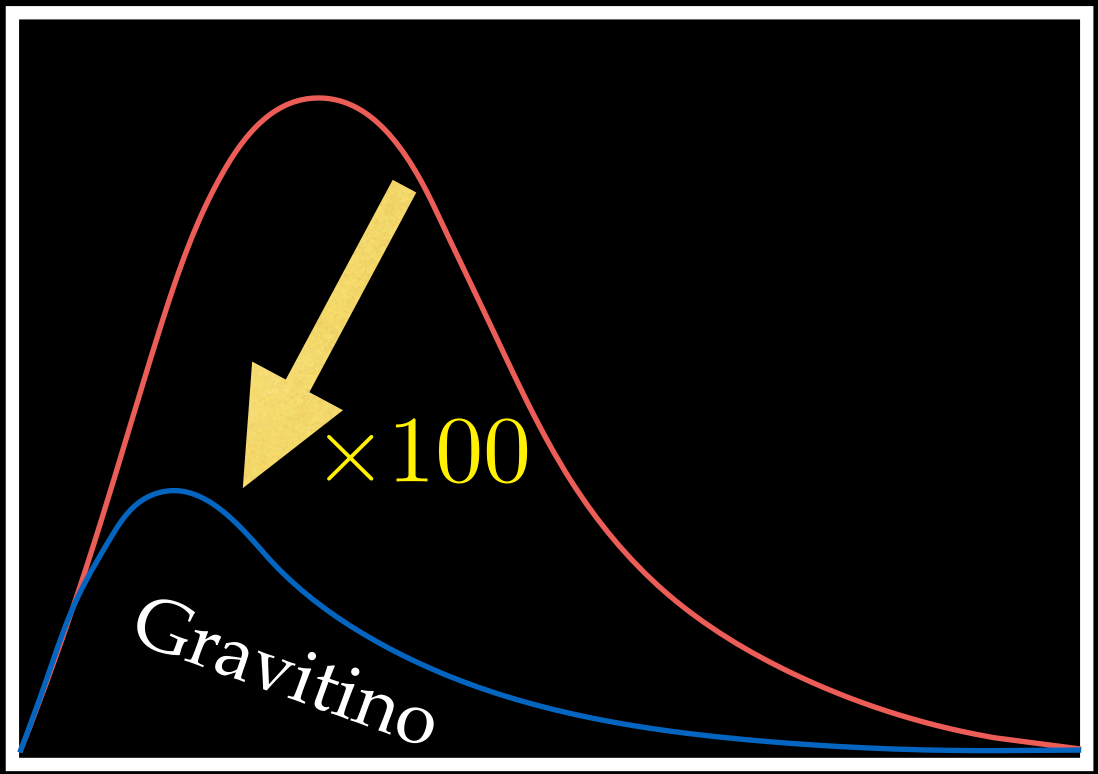
Thermal WDM



Sterile WDM

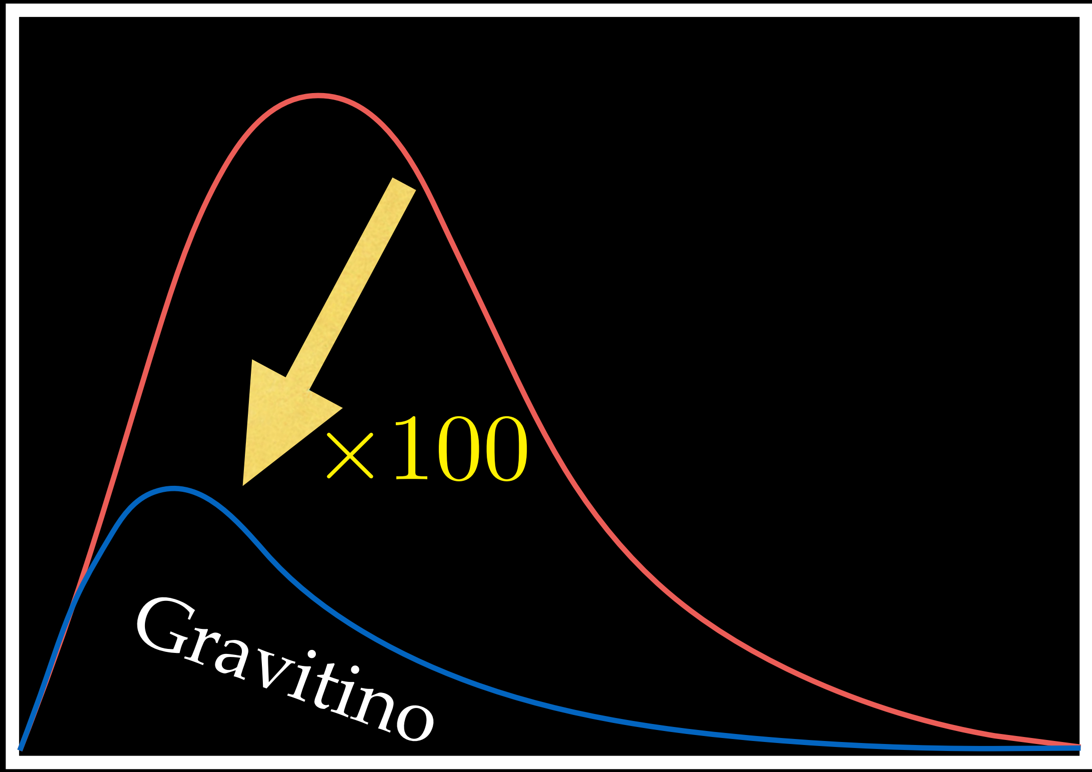
Dark Fermion

Thermal WDM



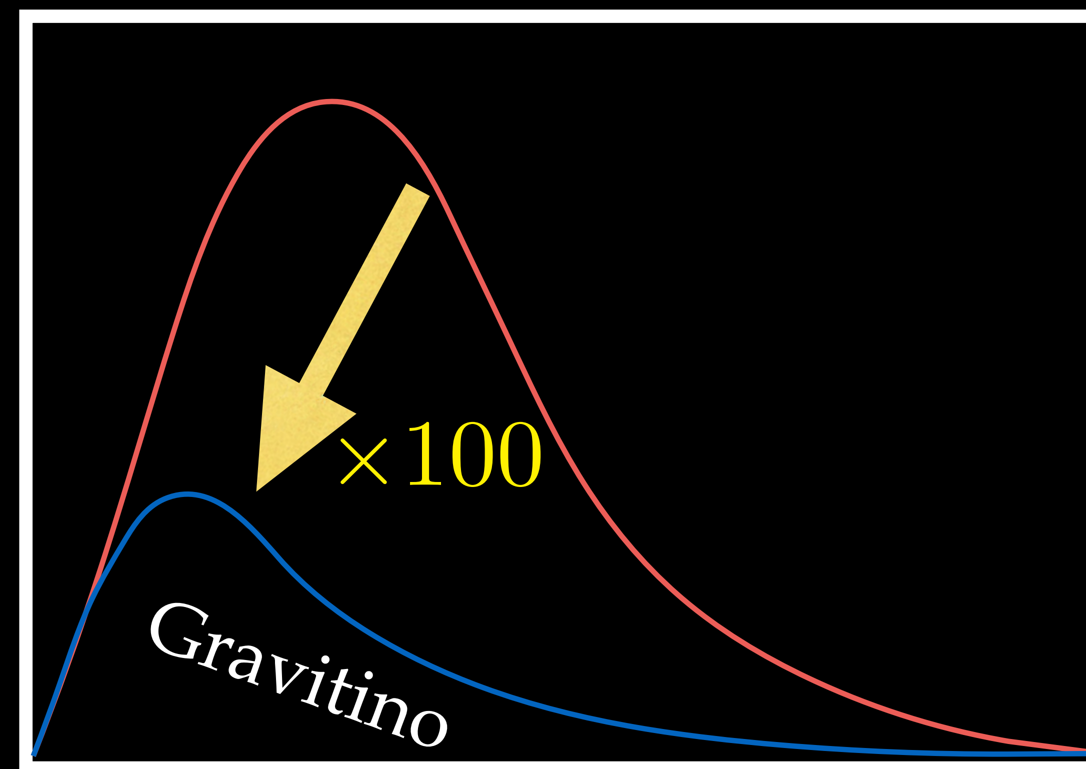
Sterile WDM vs. Thermal WDM

Dark Fermion



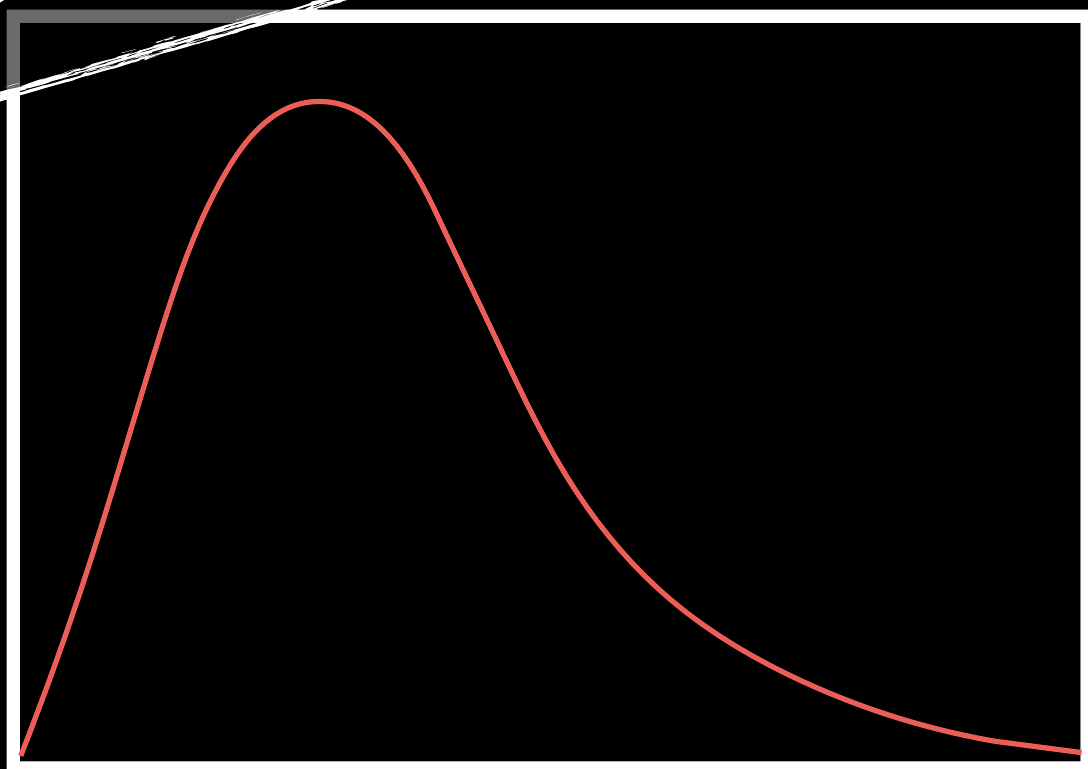
Dark Fermion

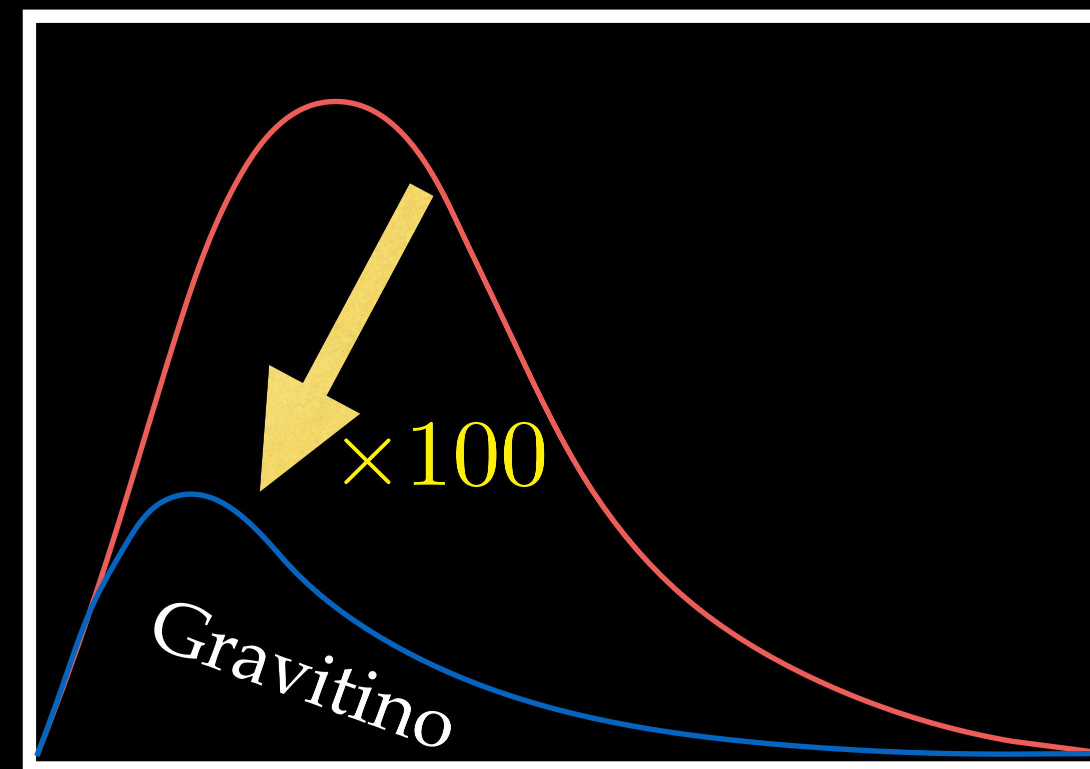
Sterile WDM vs. Thermal WDM



Sterile WDM vs. Thermal WDM

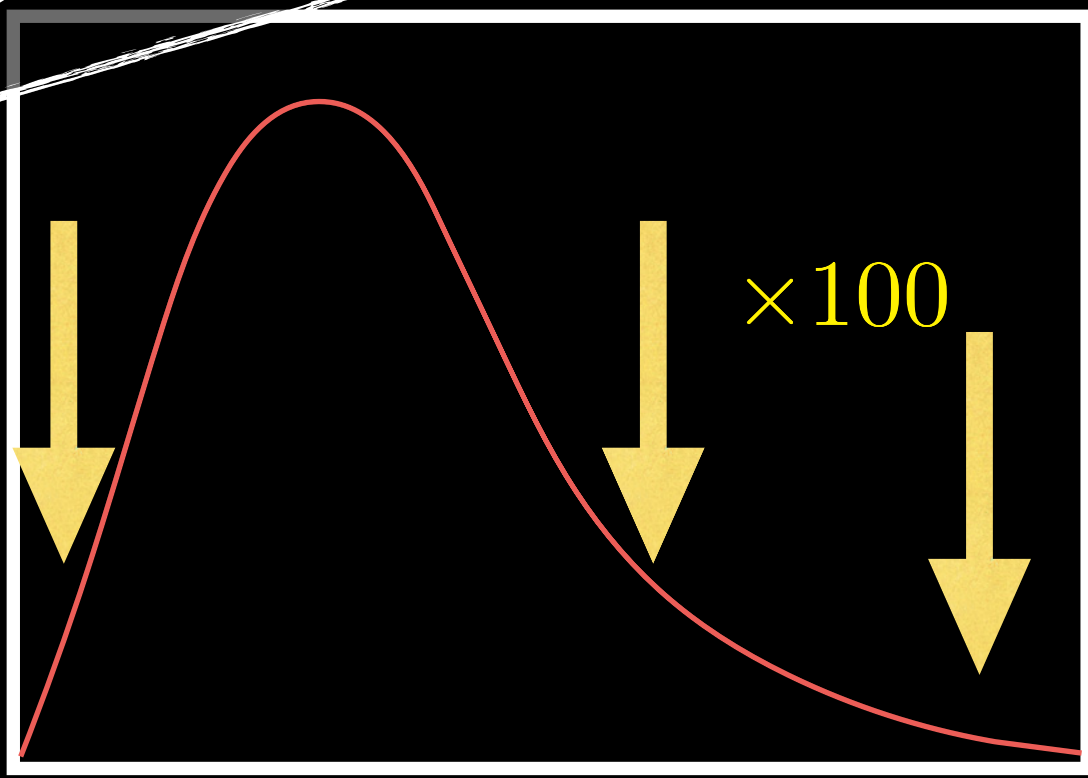
Dark Fermion

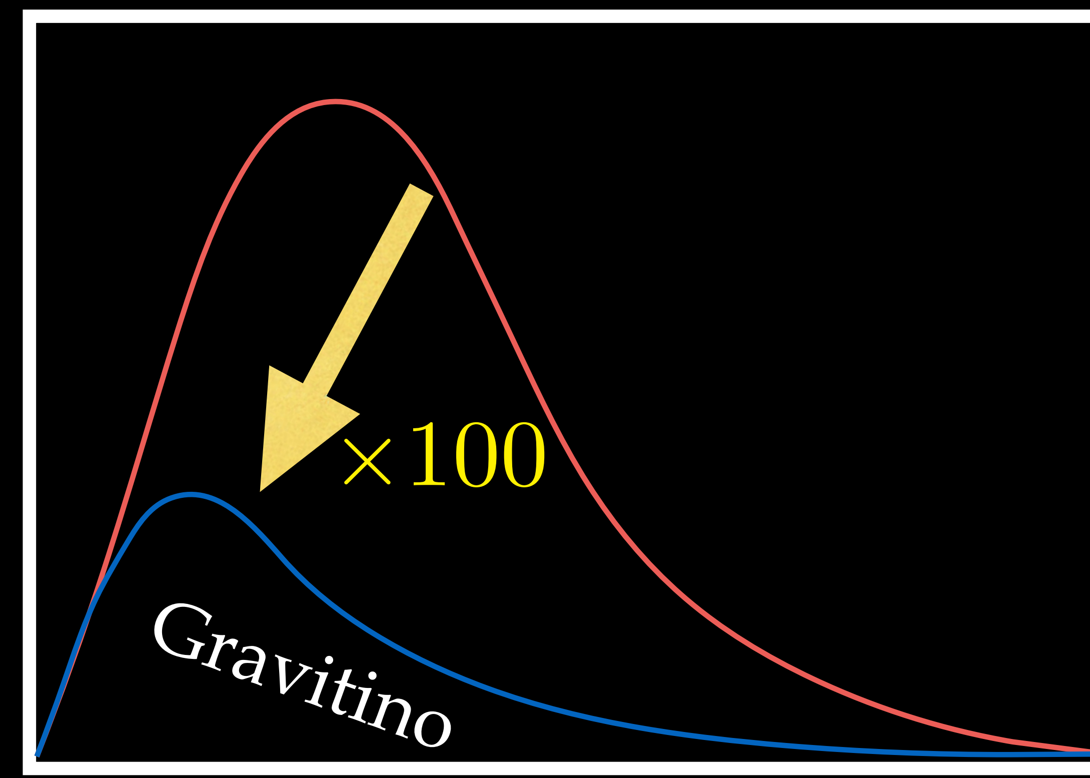




Sterile WDM vs. Thermal WDM

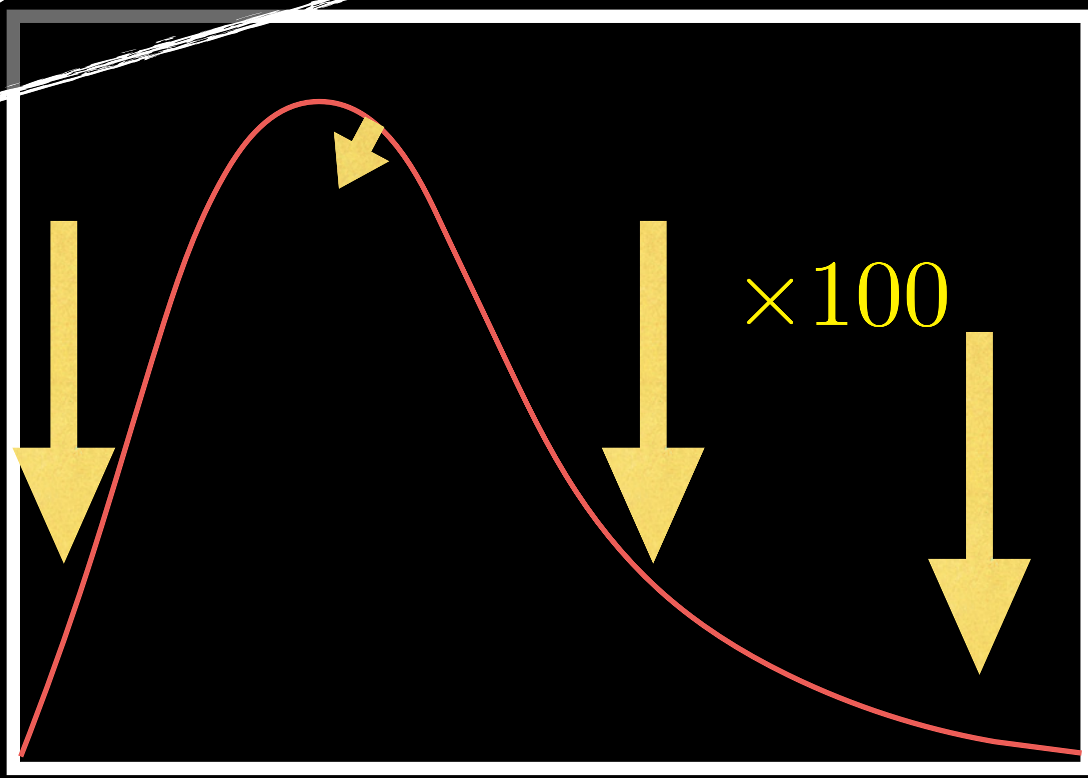
Dark Fermion

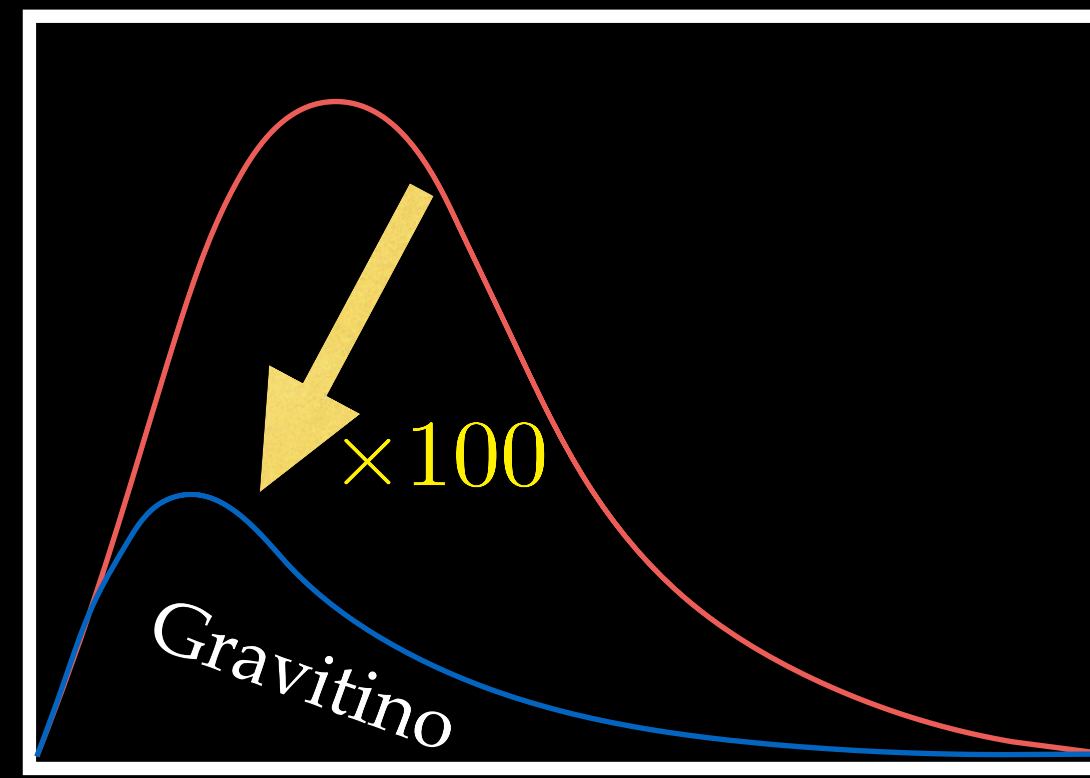




Sterile WDM vs. Thermal WDM

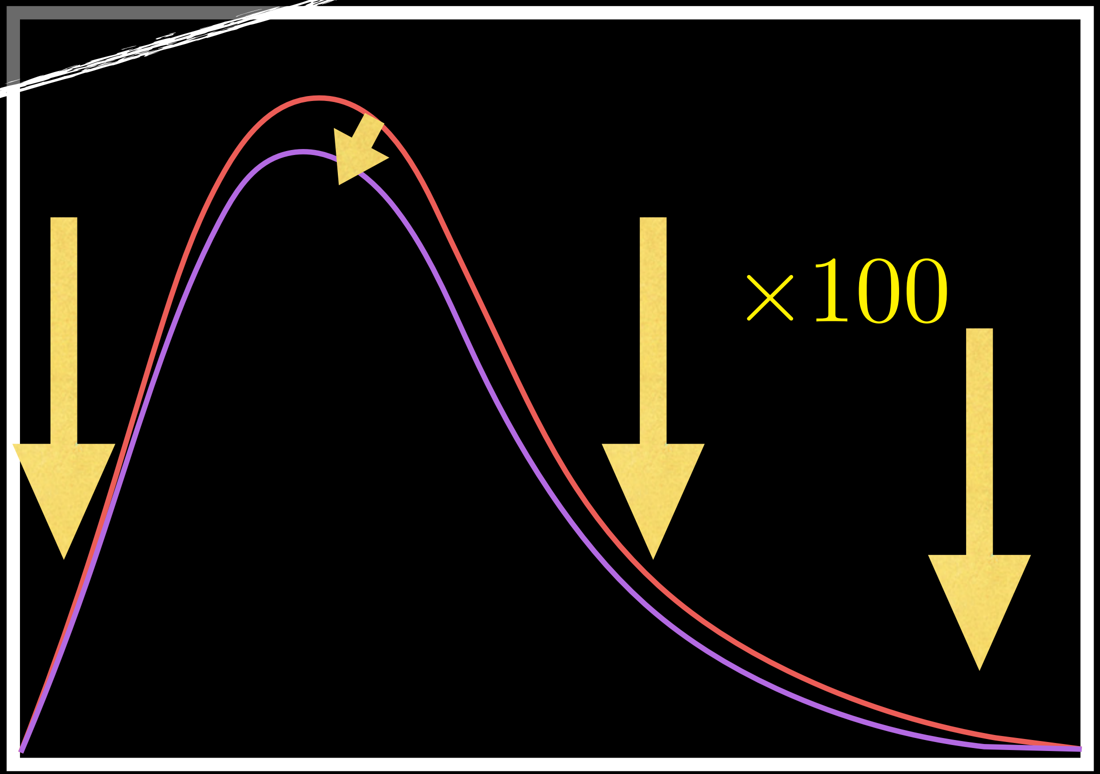
Dark Fermion

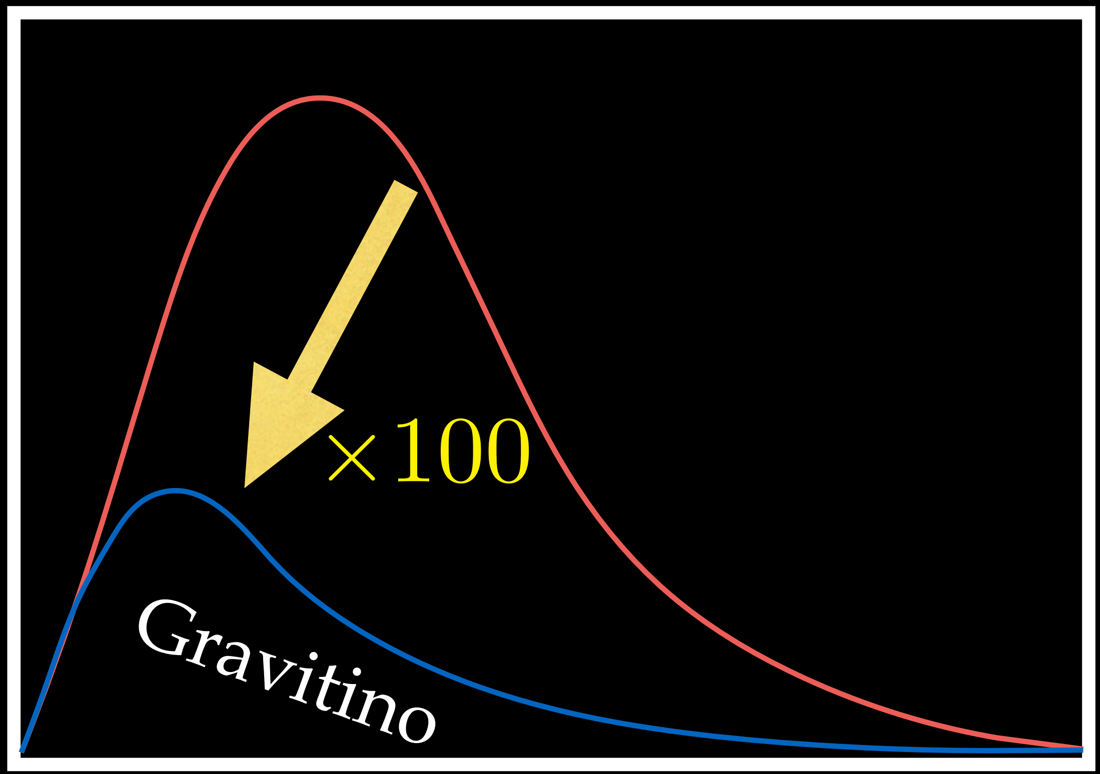




Sterile WDM vs. Thermal WDM

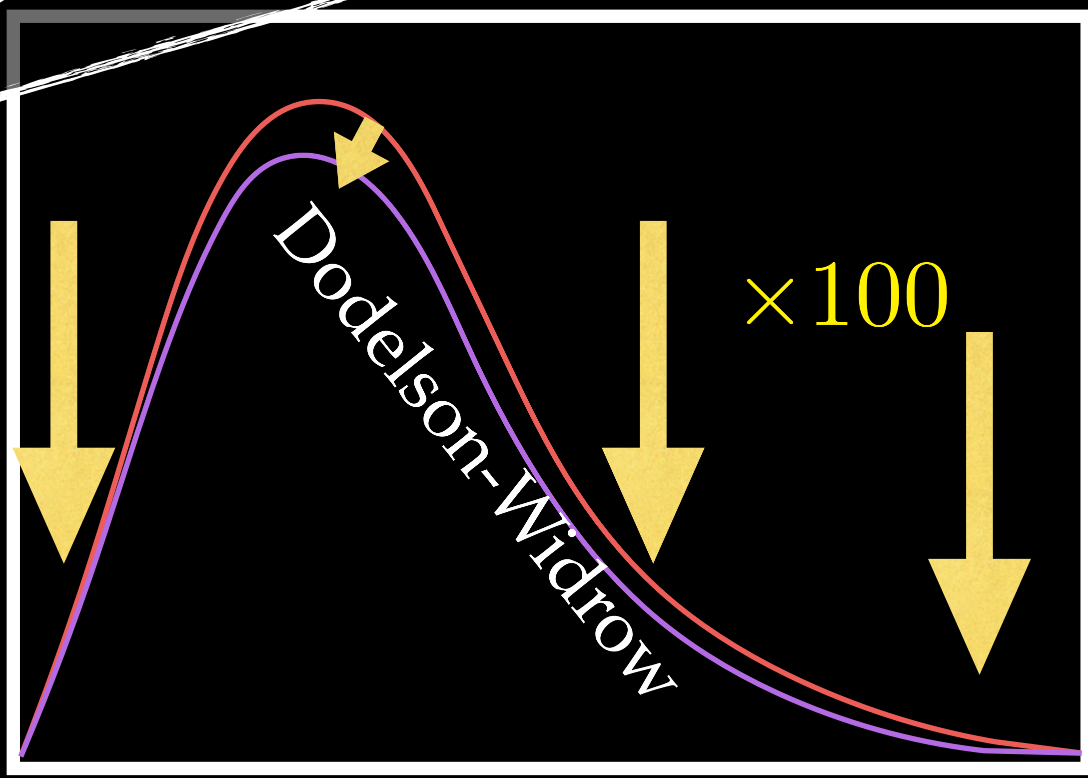
Dark Fermion

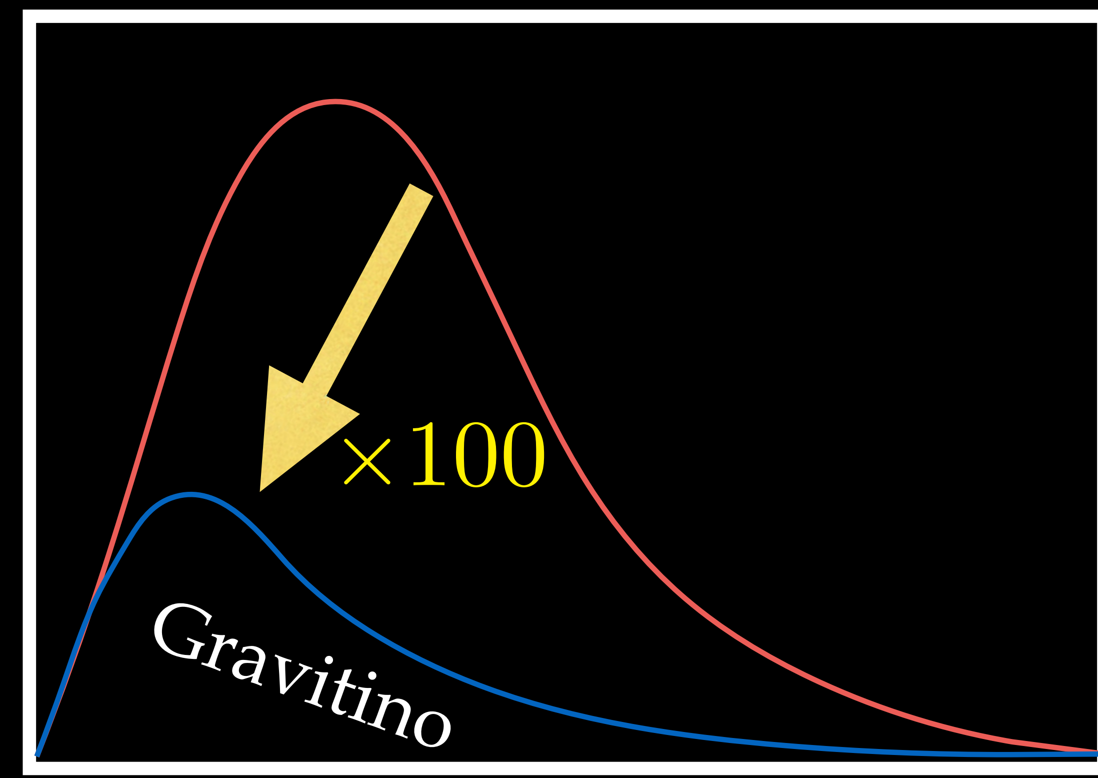




Sterile WDM vs. Thermal WDM

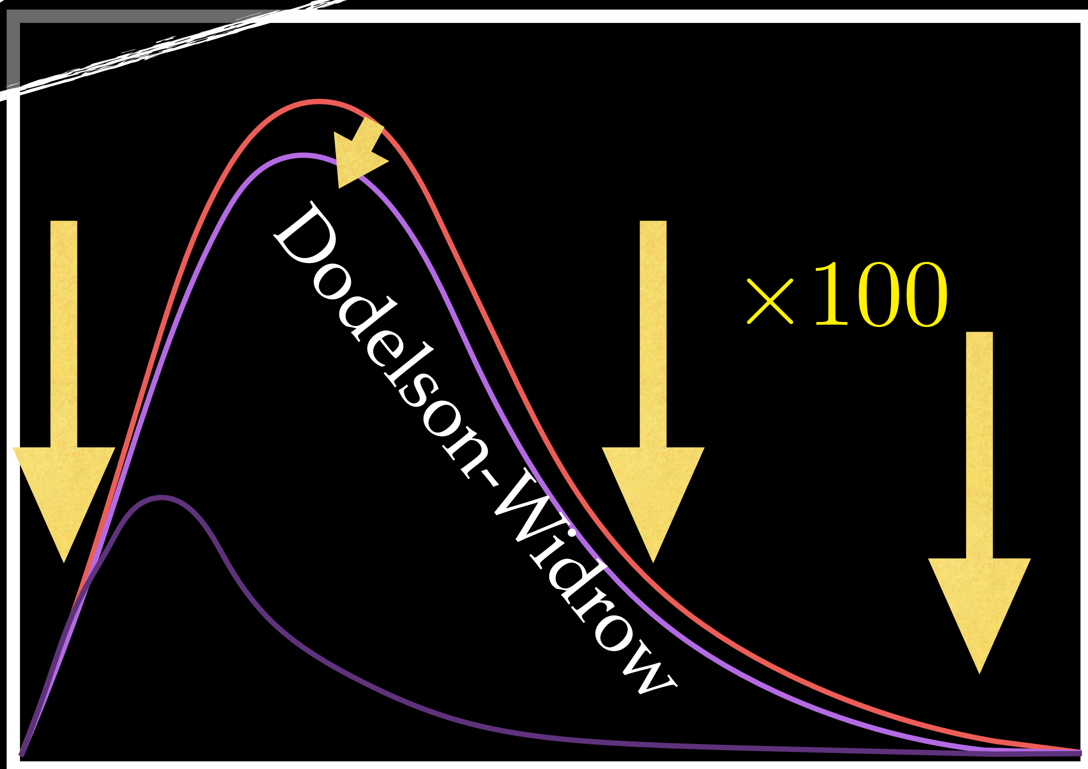
Dark Fermion

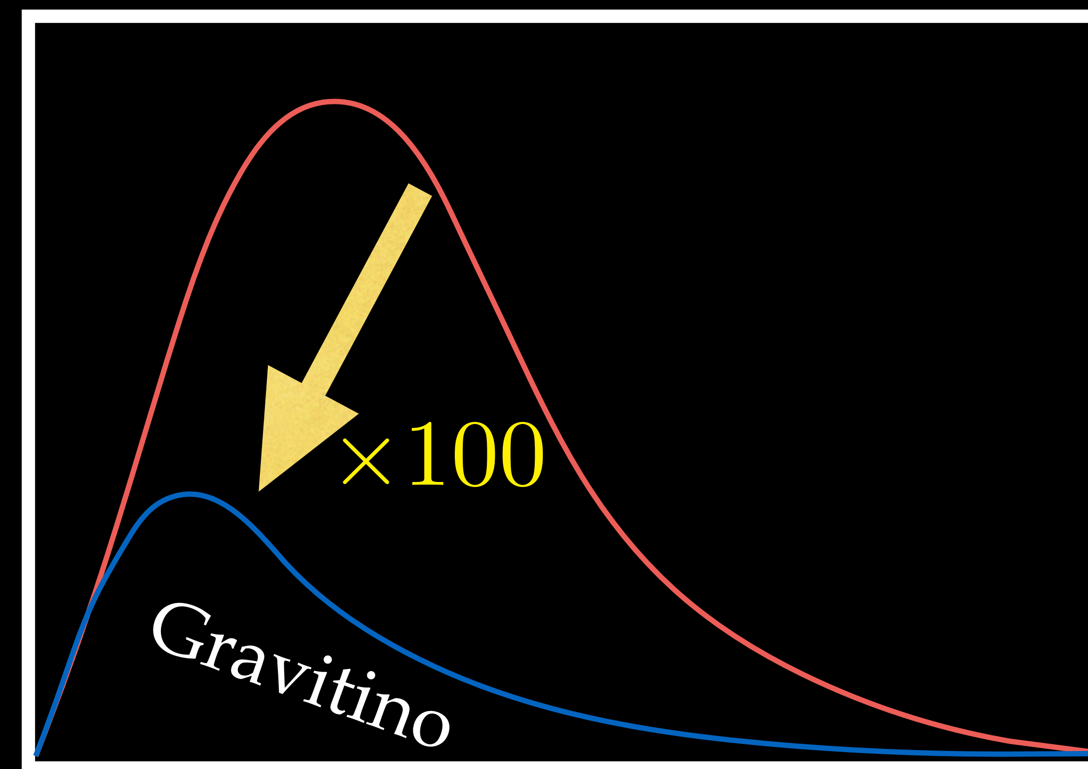




Sterile WDM vs. Thermal WDM

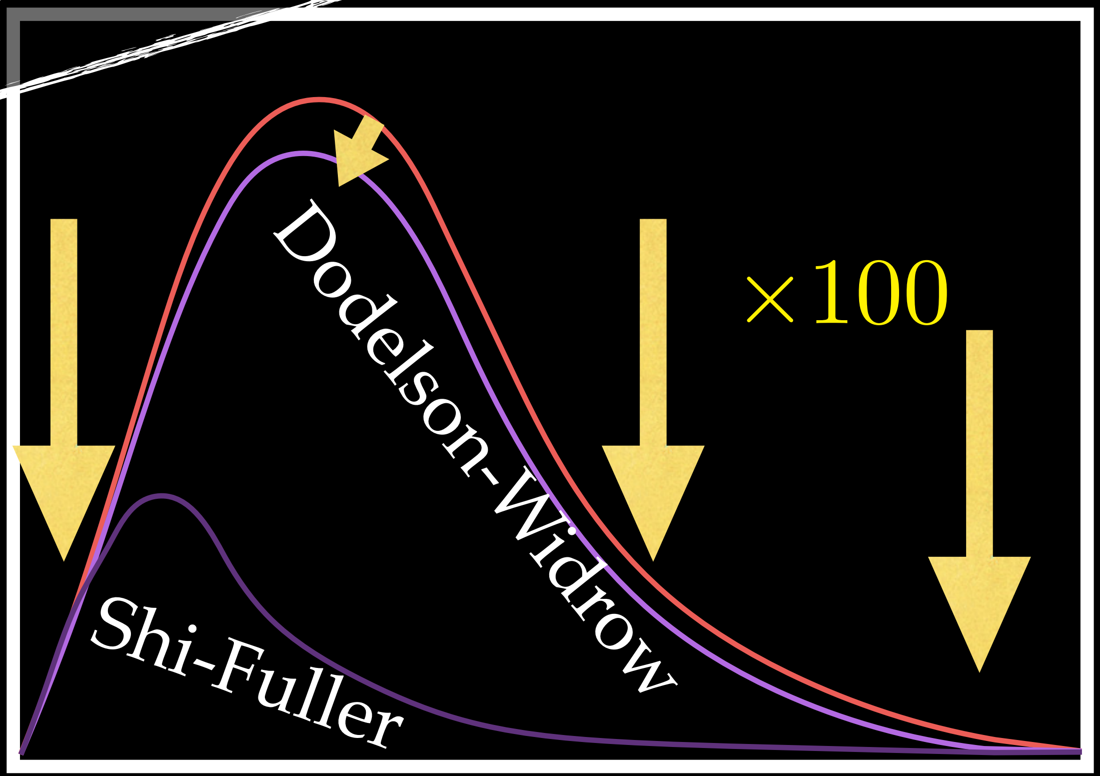
Dark Fermion

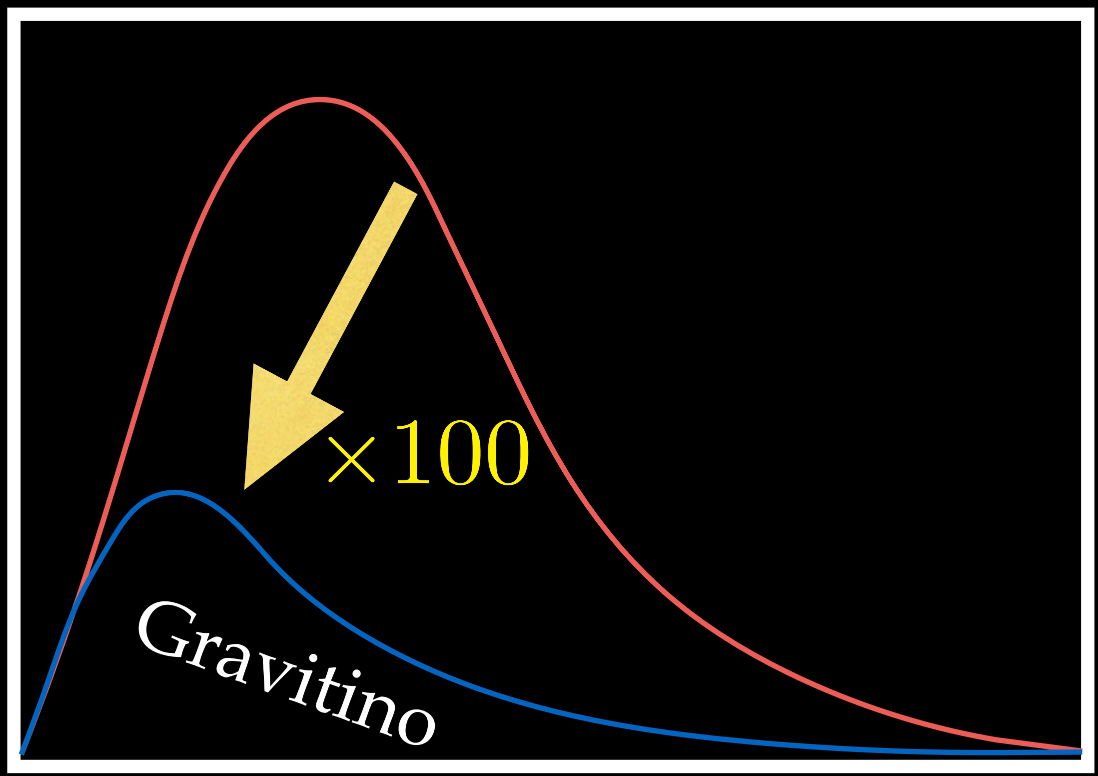




Sterile WDM vs. Thermal WDM

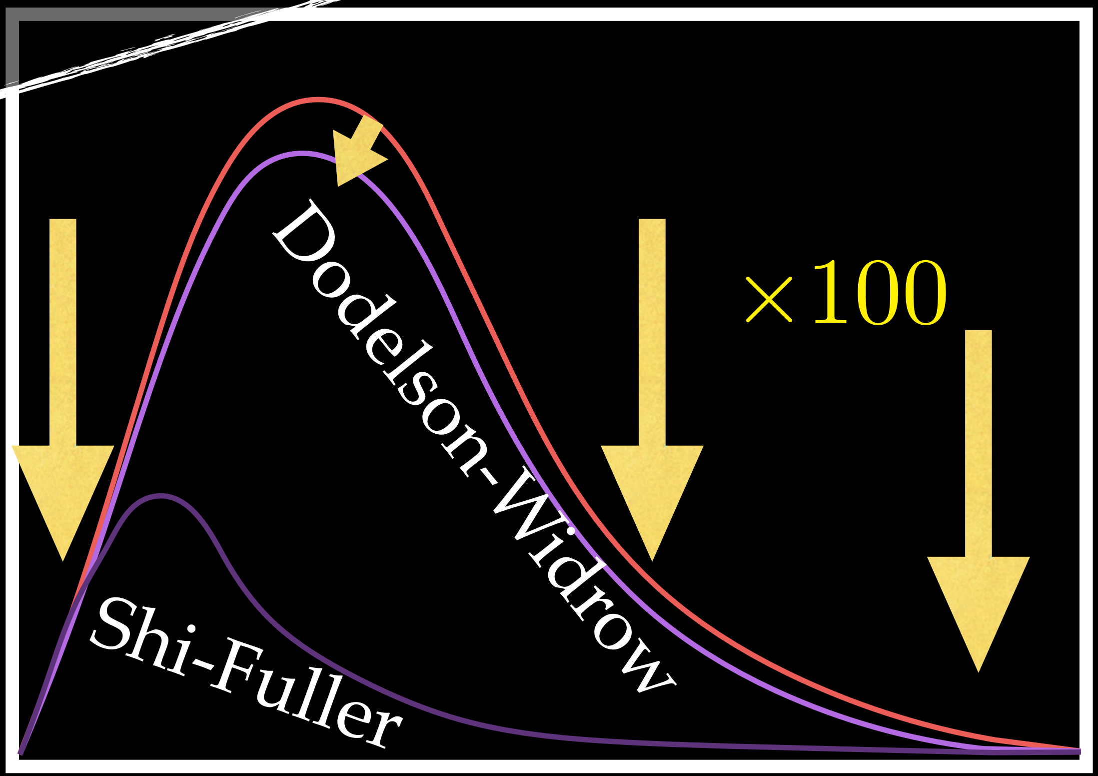
Dark Fermion

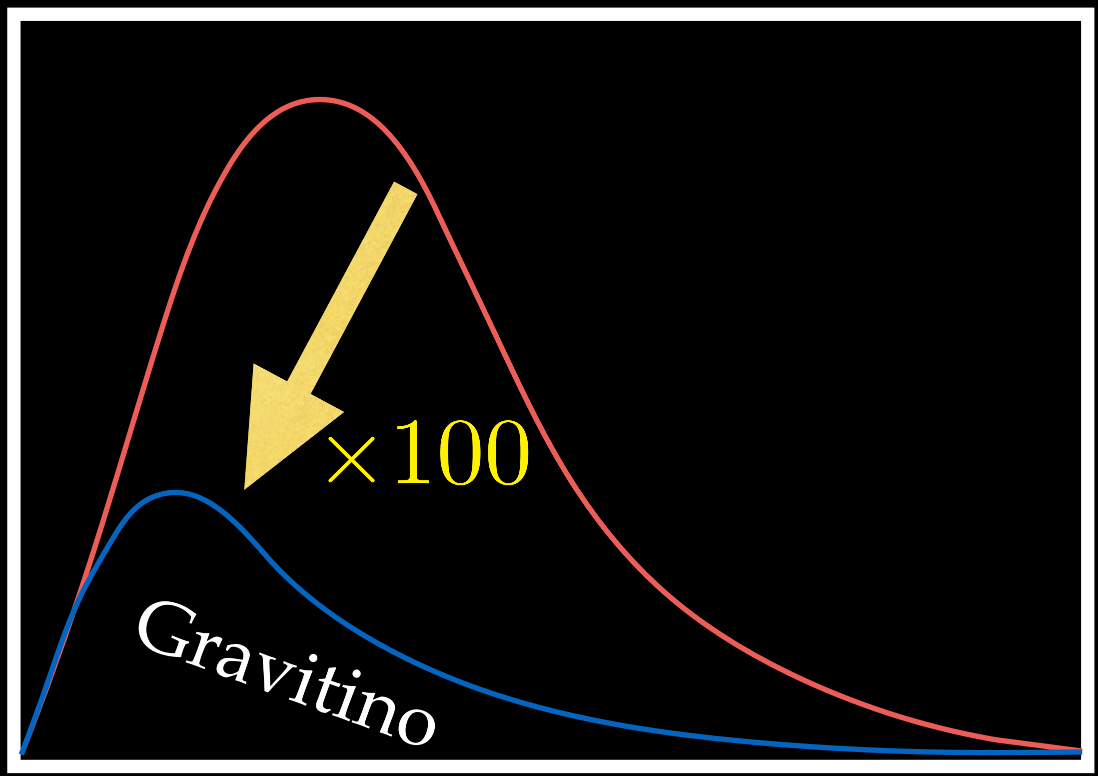




Sterile WDM vs. Thermal WDM

Dark Fermion

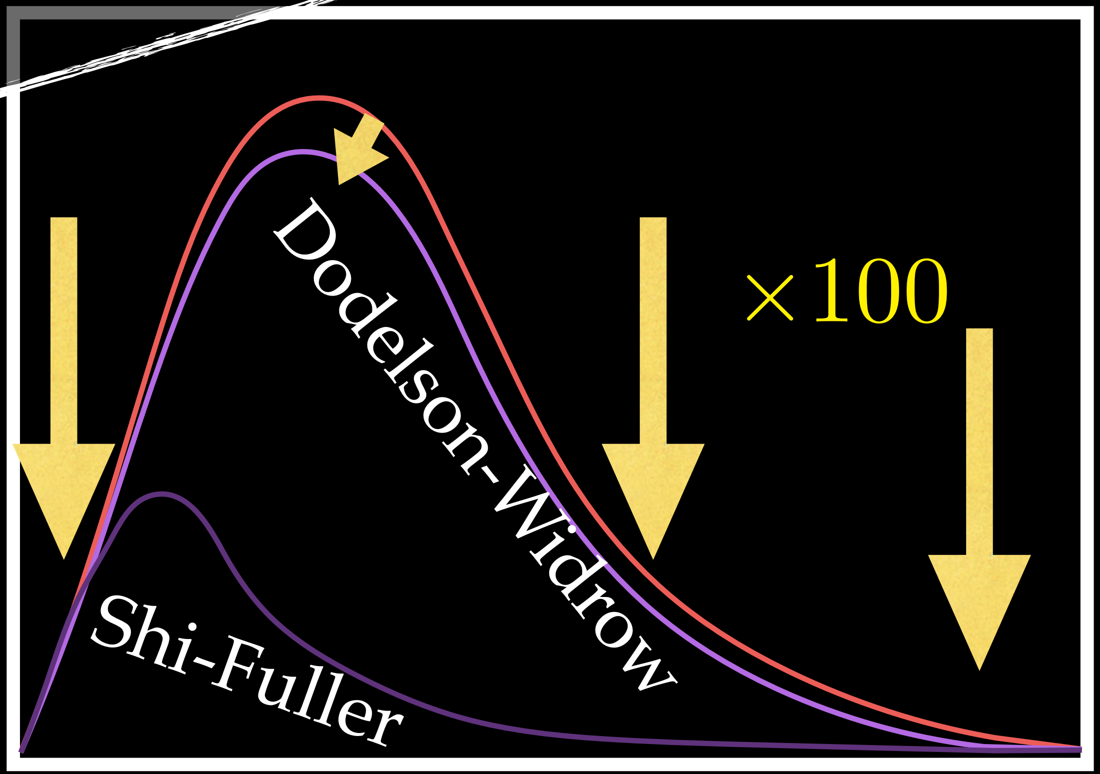


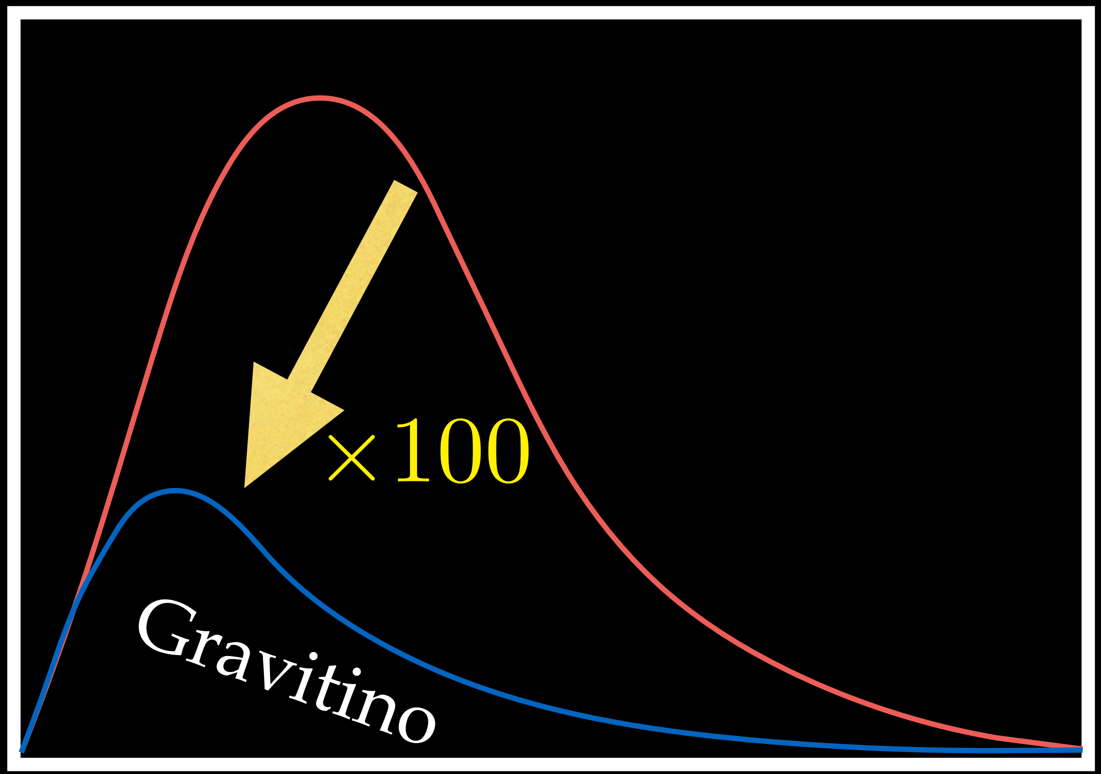


$$m_s\big|_{\text{Dodelson-Widrow,ideal}} \approx 4.46\,\text{keV}\,\left(\frac{m_{\text{thermal}}}{1\,\text{keV}}\right)^{4/3}$$

Sterile WDM vs. Thermal WDM

Dark Fermion



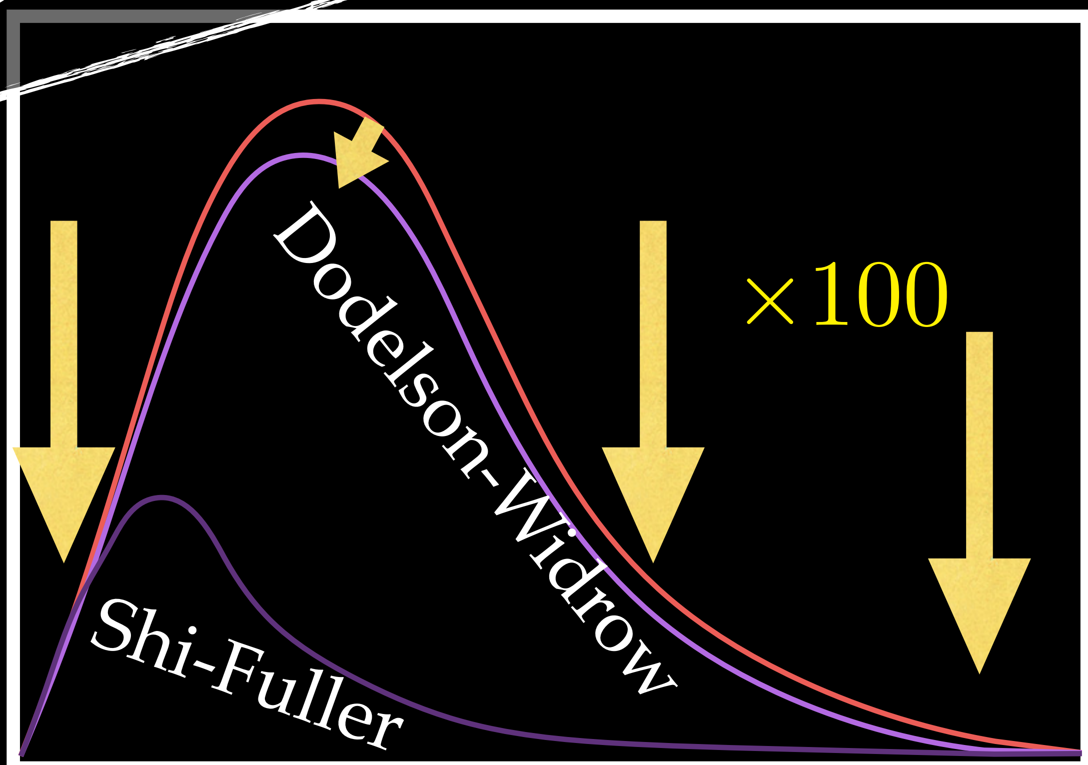


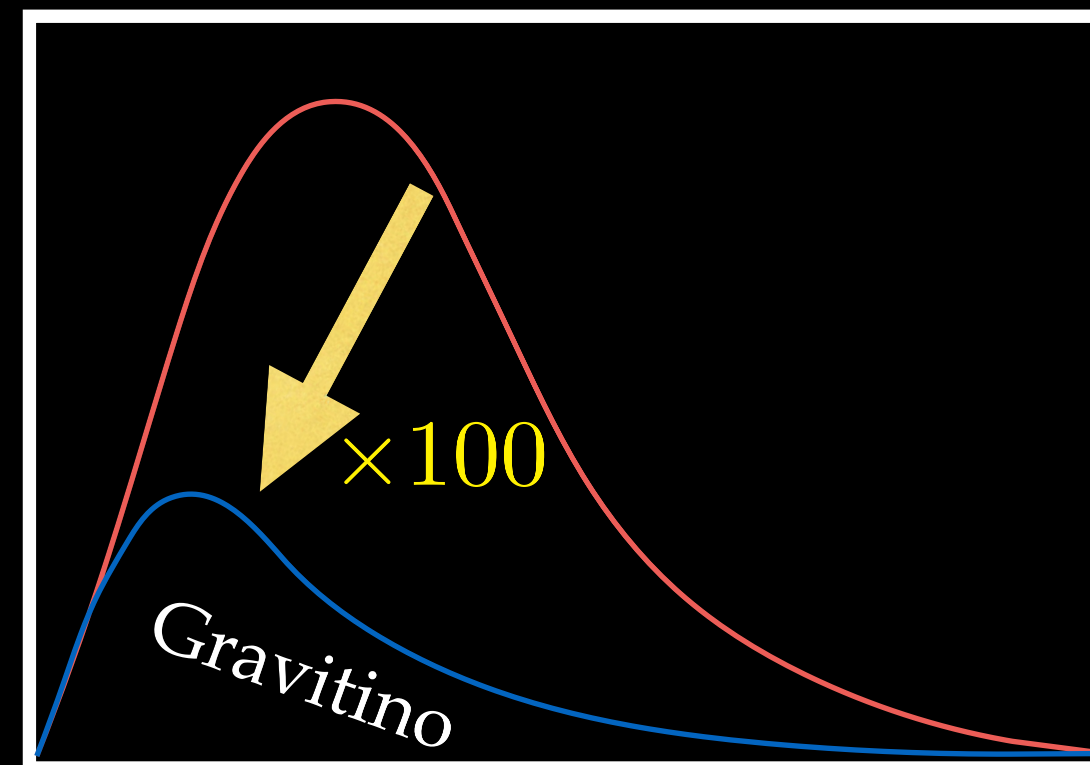
$$m_s\big|_{\text{Dodelson-Widrow,ideal}} \approx 4.46\,\text{keV}\,\left(\frac{m_{\text{thermal}}}{1\,\text{keV}}\right)^{4/3}$$

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

Sterile WDM vs. Thermal WDM

Dark Fermion





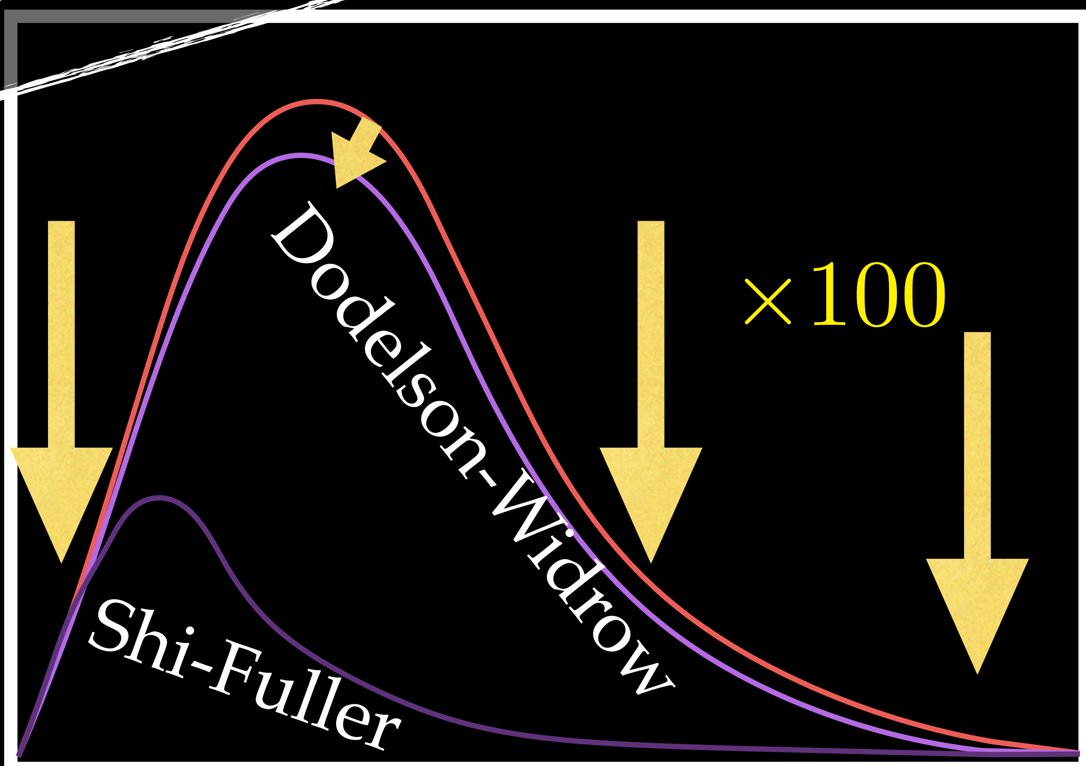
$$m_s\big|_{\text{Dodelson-Widrow,ideal}} \approx 4.46\,\text{keV}\,\left(\frac{m_{\text{thermal}}}{1\,\text{keV}}\right)^{4/3}$$

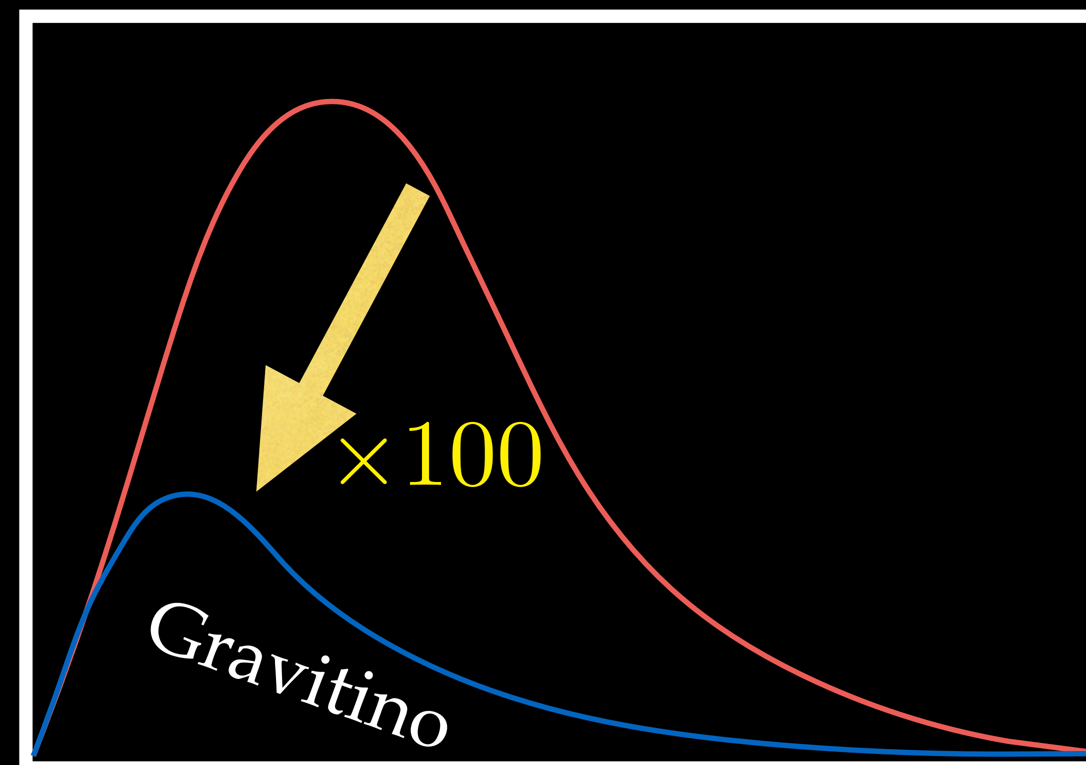
$$m_s\big|_{\text{Shi-Fuller}} < m_s\big|_{\text{Dodelson-Widrow}}$$

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

Dark Fermion

Sterile WDM vs. Thermal WDM





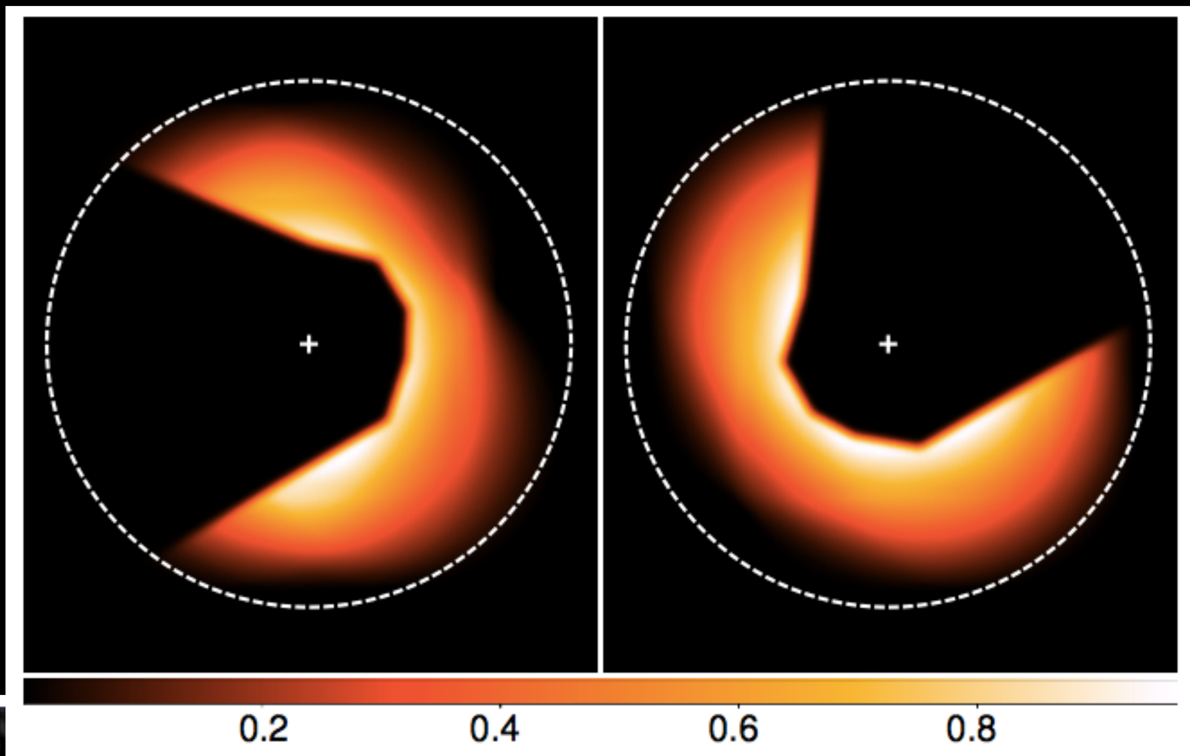
$$m_s\big|_{\text{Dodelson-Widrow,ideal}} \approx 4.46\,\text{keV}\,\left(\frac{m_{\text{thermal}}}{1\,\text{keV}}\right)^{4/3}$$

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

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

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

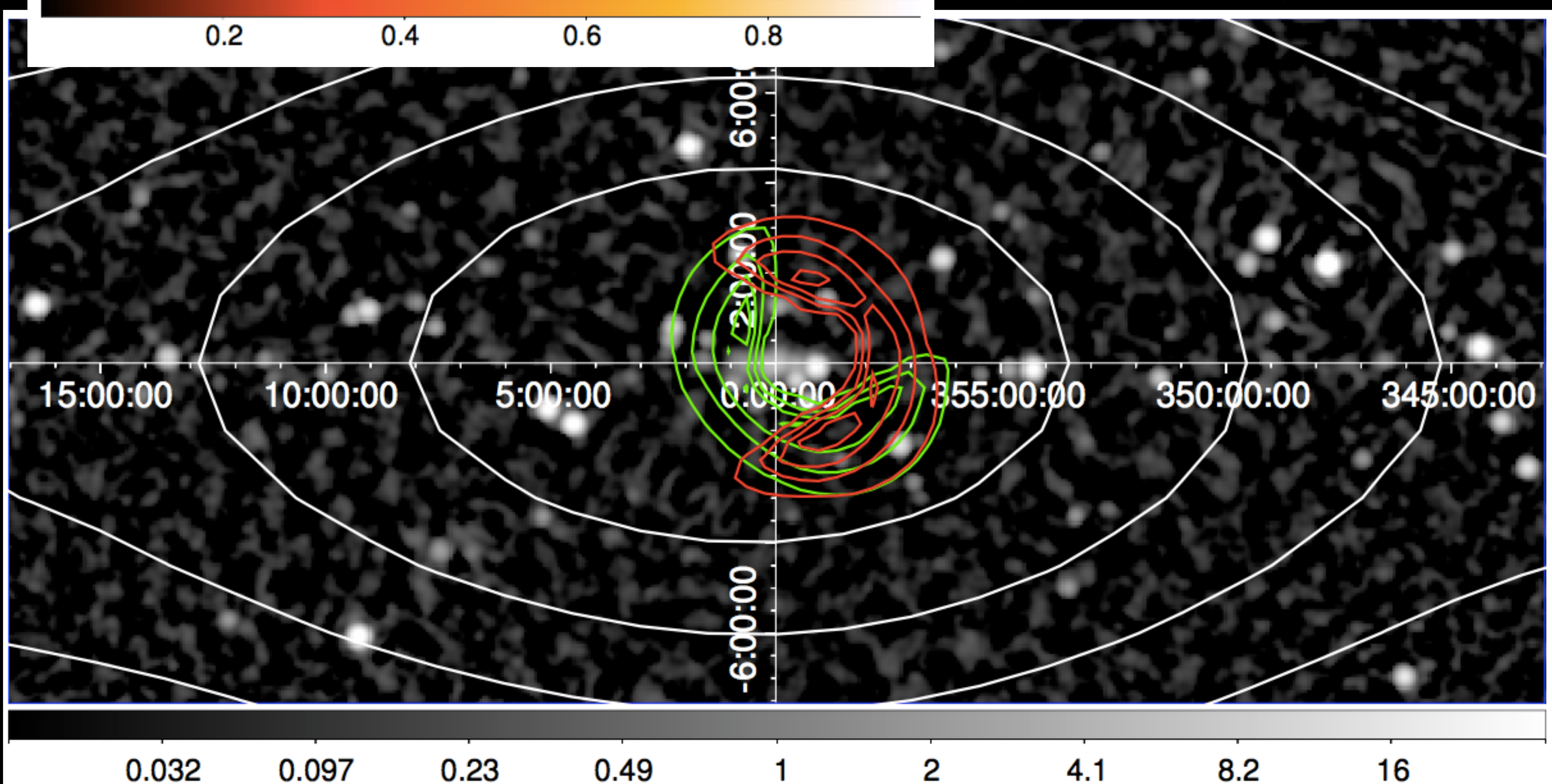
NuSTAR: the best current telescope?



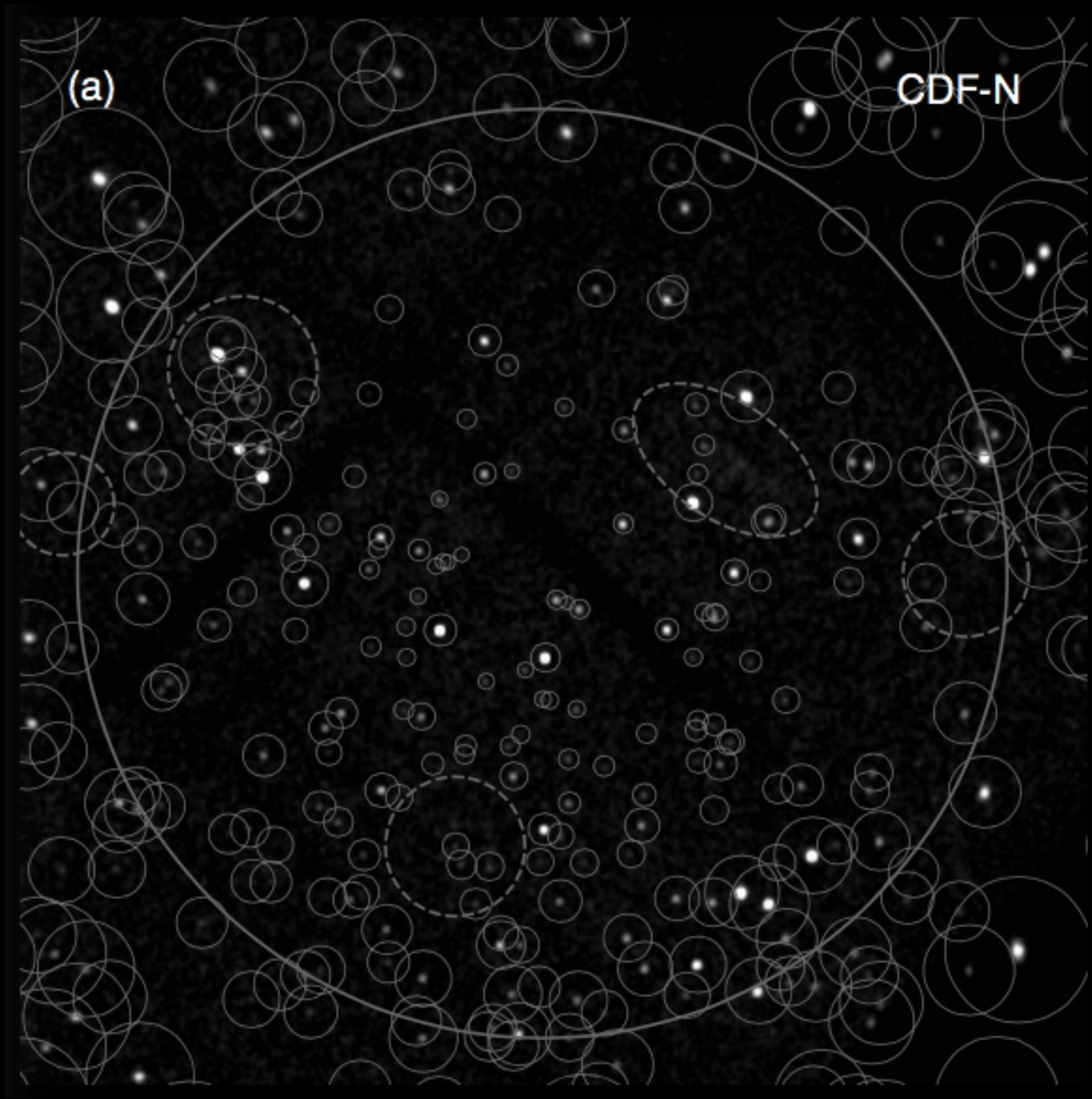
Shielding gap in telescope lets in 0 bounce photons. 37 deg² aperture!

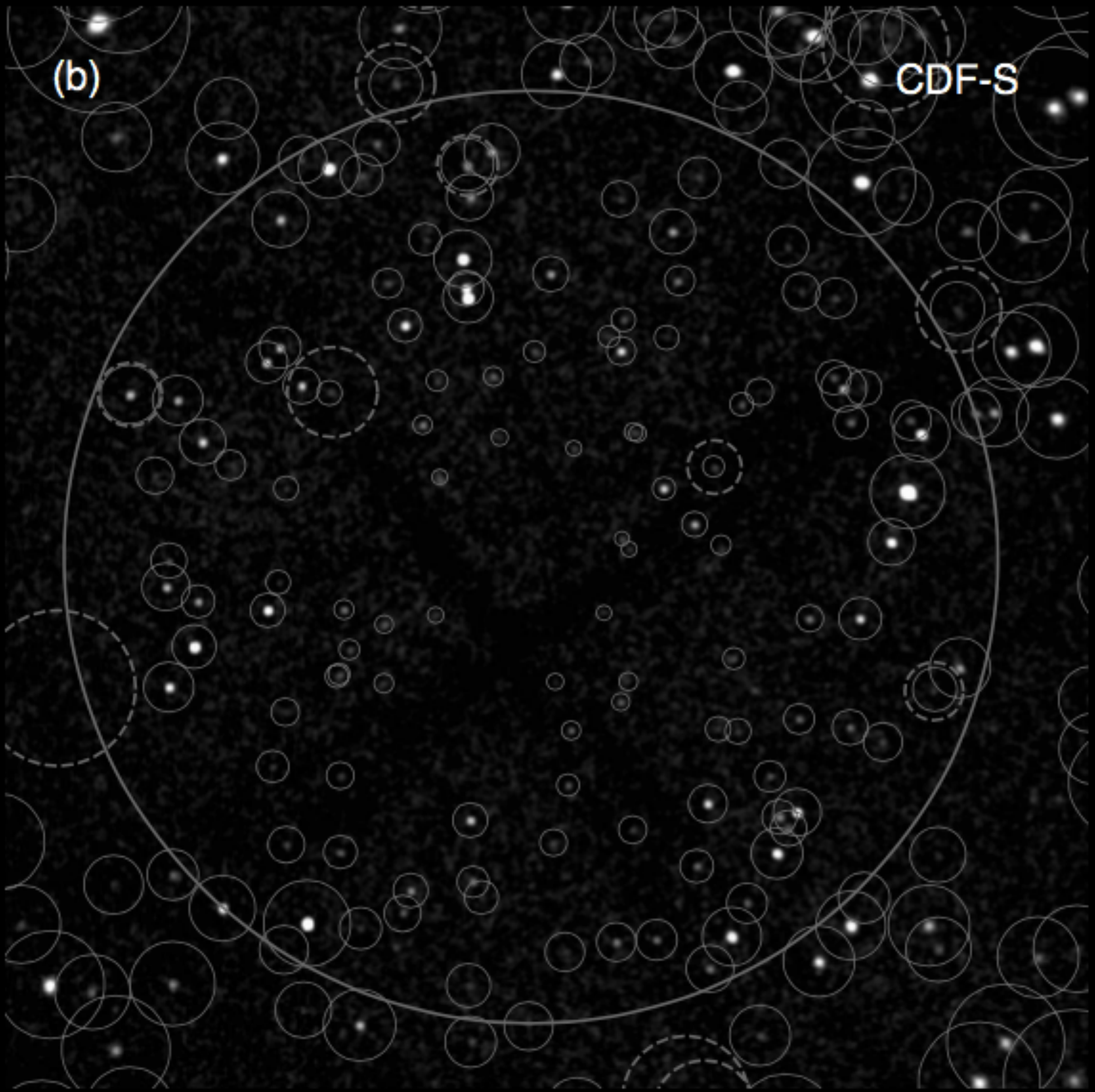
Perez+: **GC no signal, limits** (1609.00667)

Neronov+: **Deep field sees 11.1σ 3.5 keV line consistent with DM decay** (1607.07328)



Chandra Deep Fields: 10 Ms of data

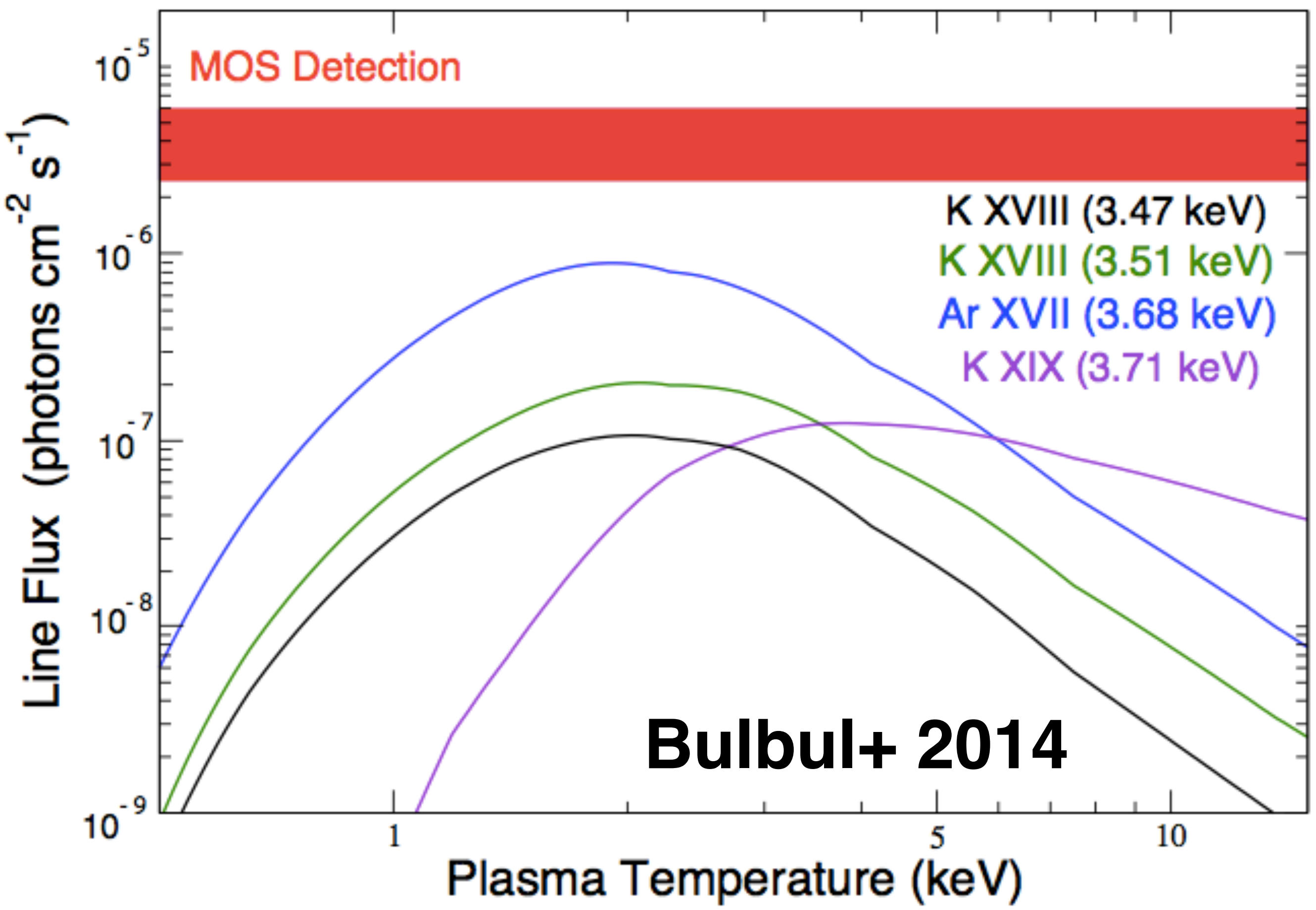


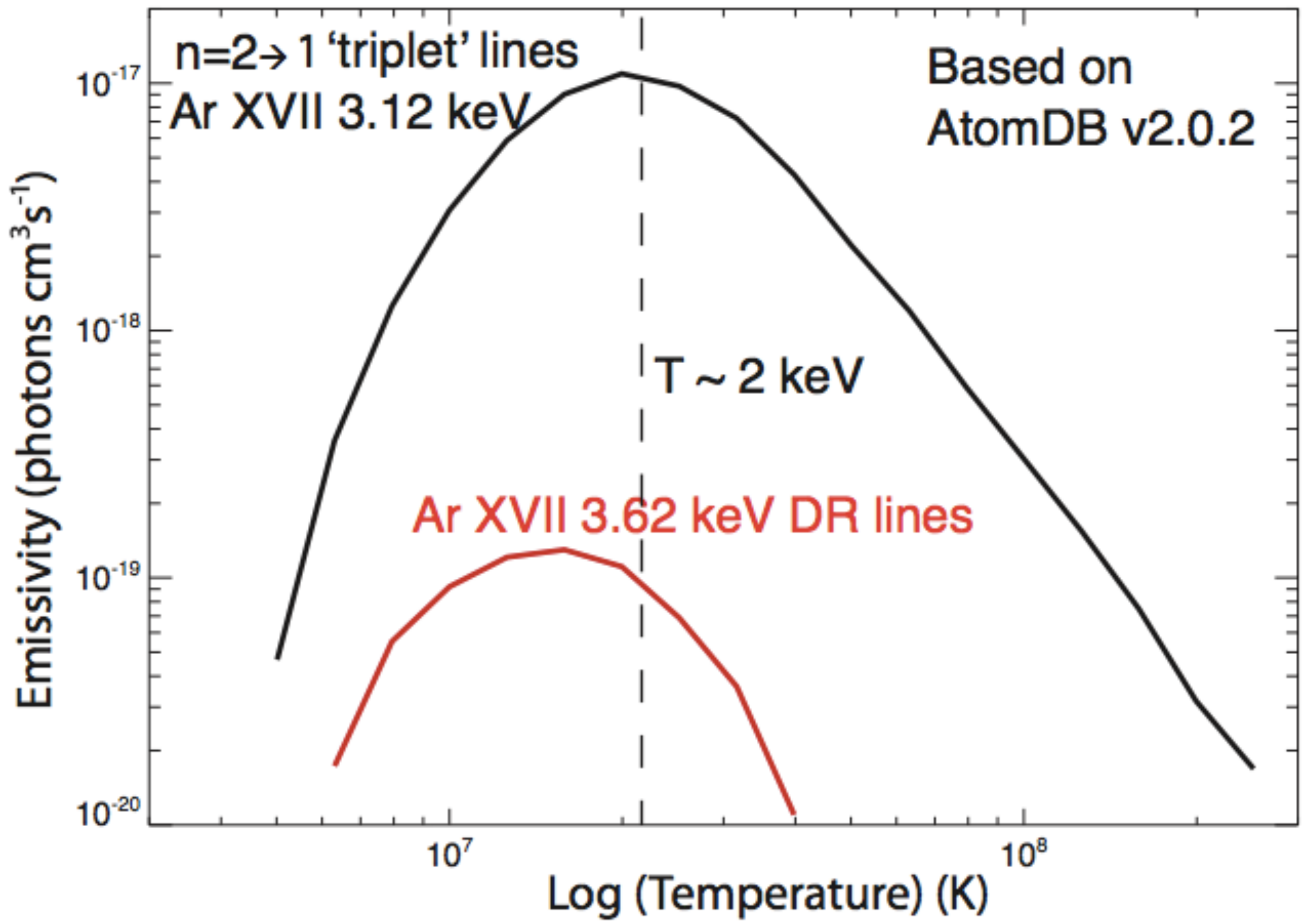


Cappelluti+ 2017: see the line at 3σ in ~10 Ms of COSMOS Legacy and Chandra Deep Field South observations,
Rule out instrumental feature based on detailed characterization of response,
Rule out CX & Ar lines due to lack of partner lines
(K shown to be incompatible in 2014)

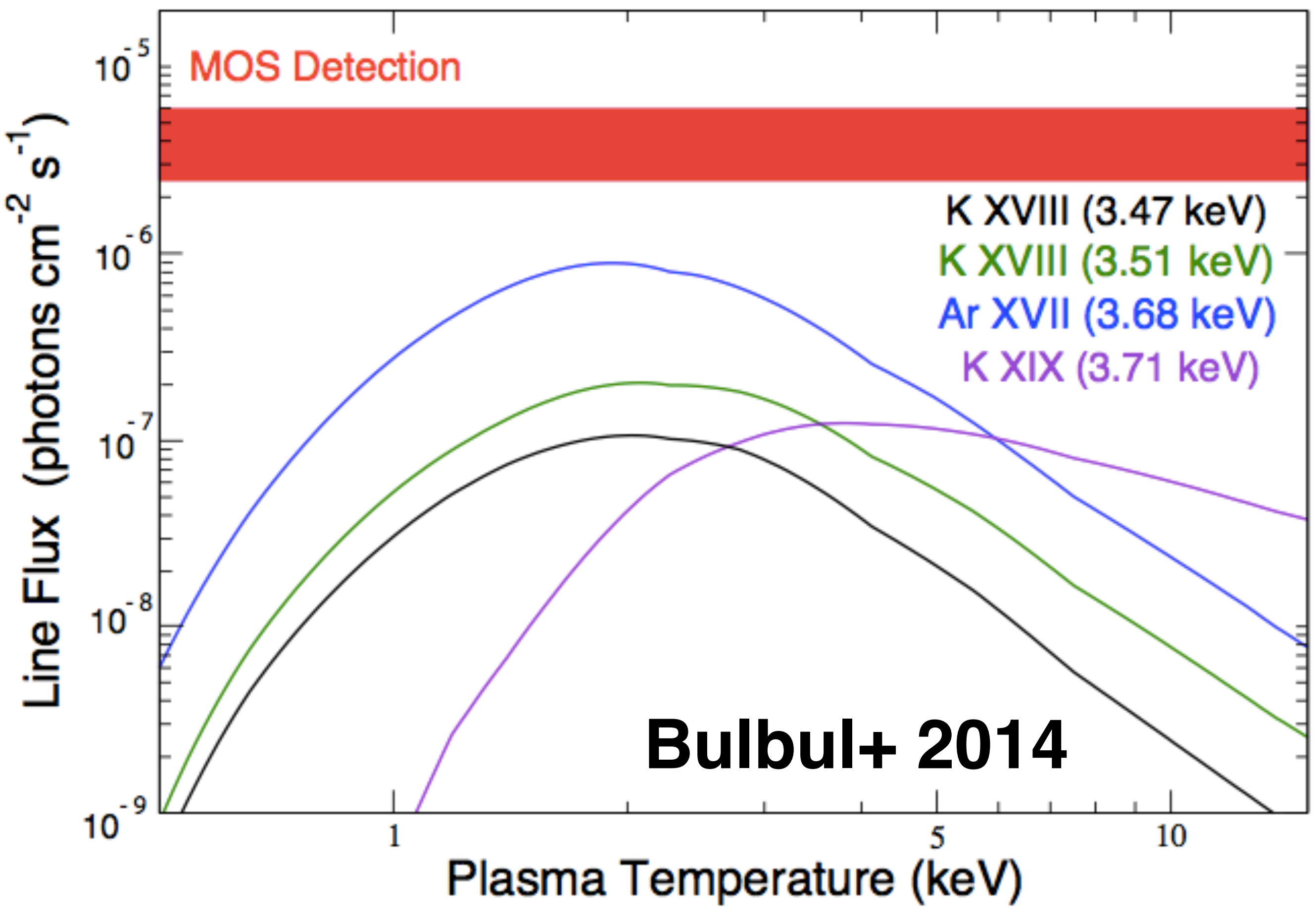
arXiv:1701.07932

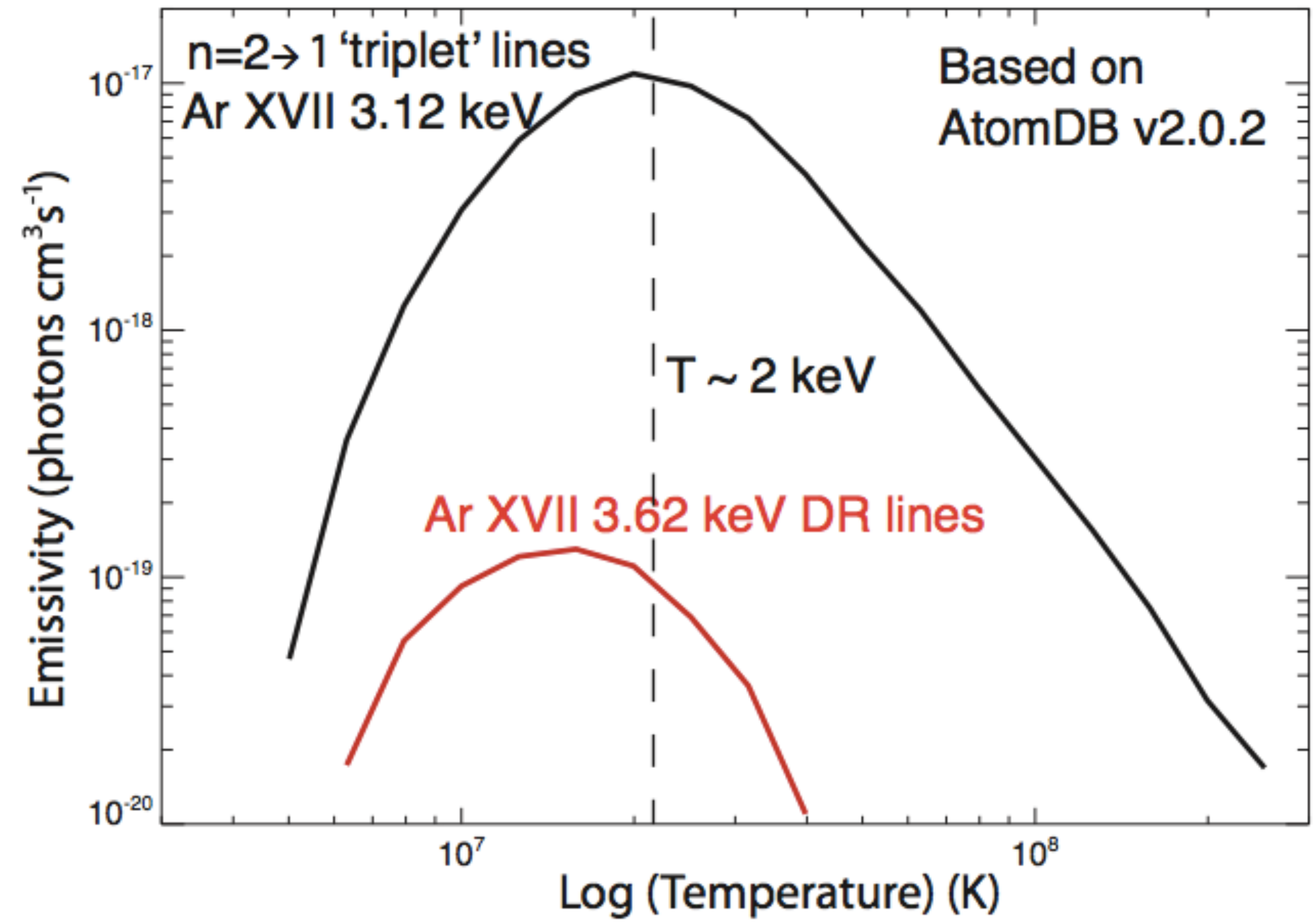
Metal Lines in Clusters at 3.5 keV? *unlikely*





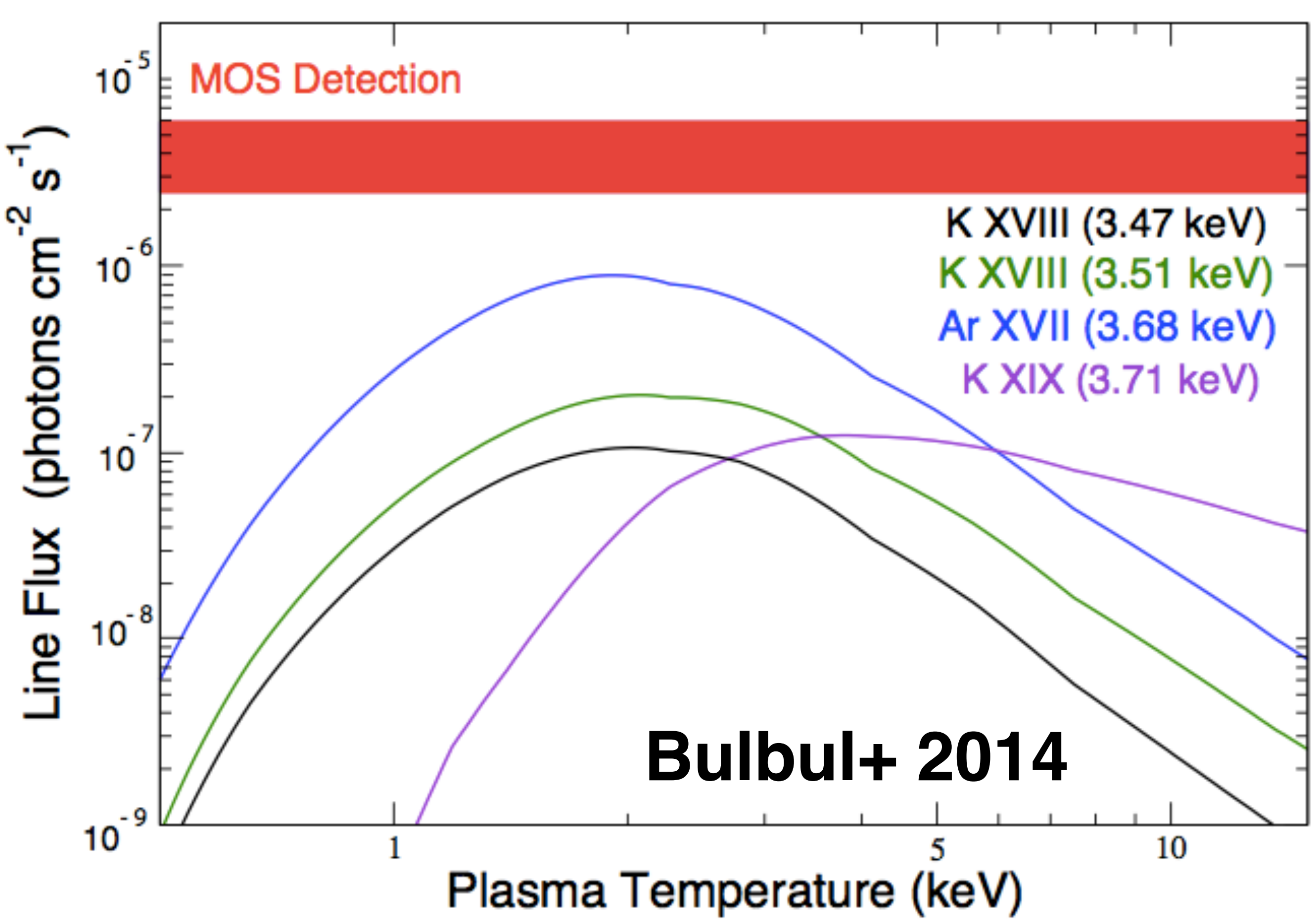
Metal Lines in Clusters at 3.5 keV? *unlikely*

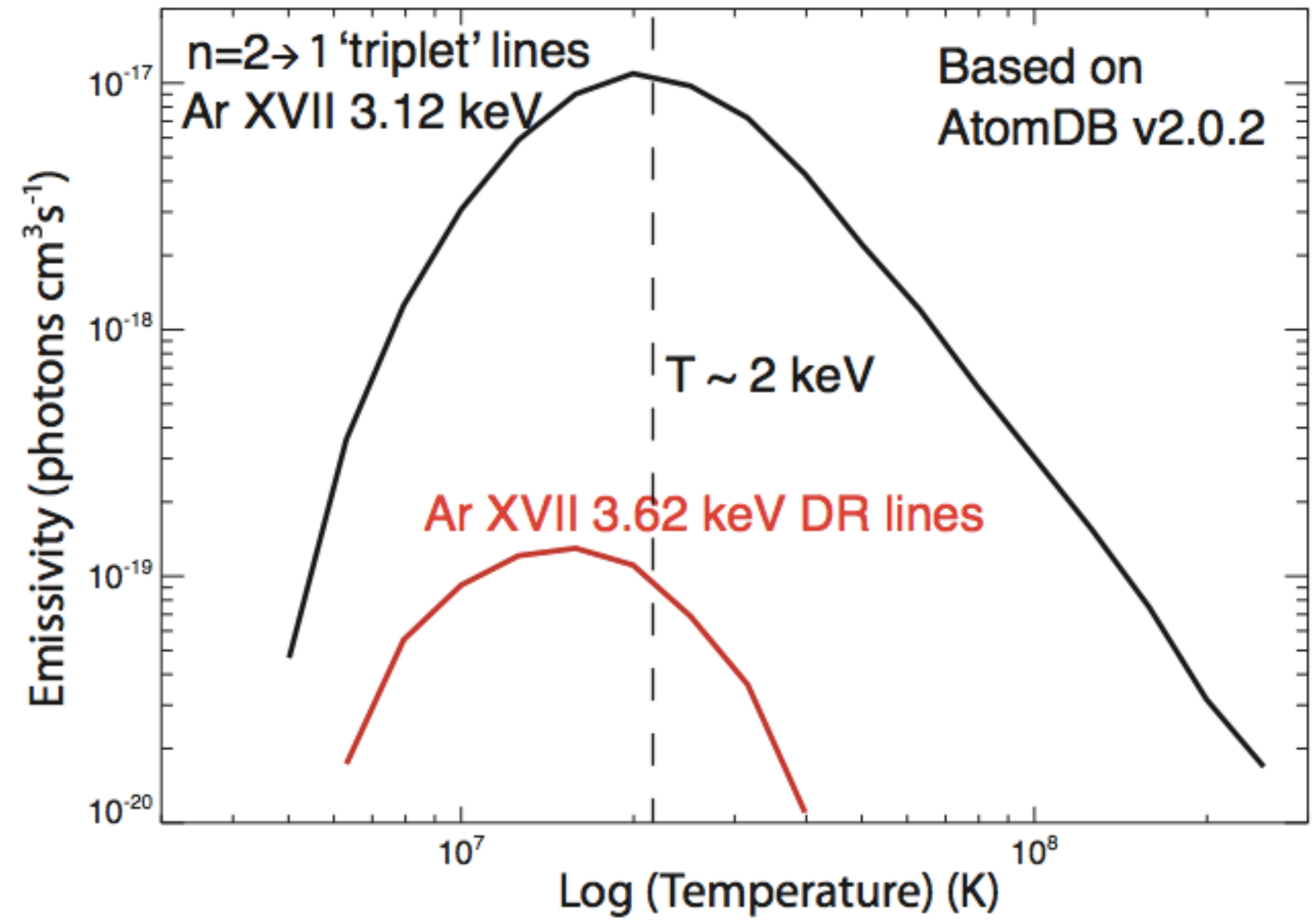




- Most lines at this energy are too low in flux for the typical plasma temperatures

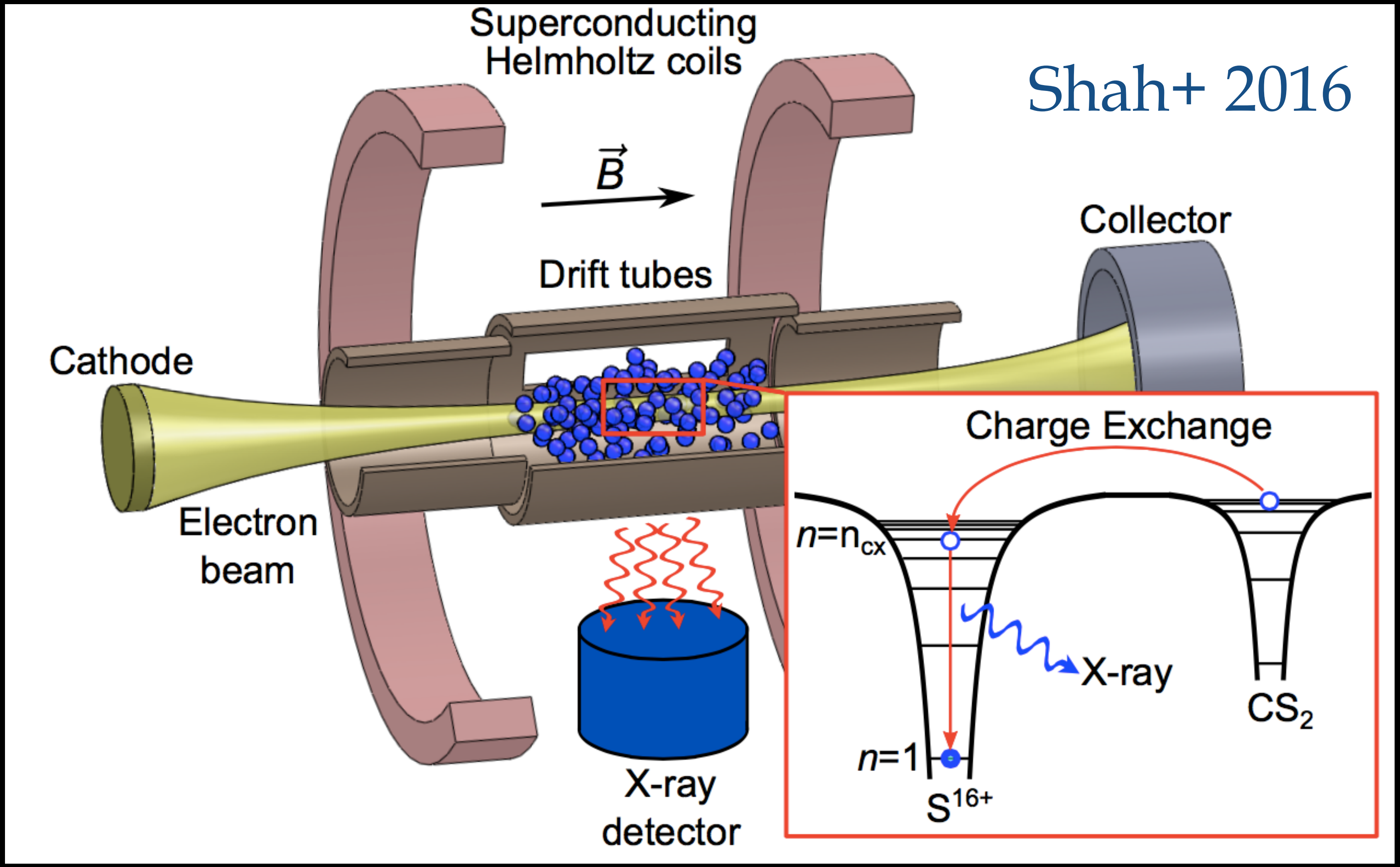
Metal Lines in Clusters at 3.5 keV? *unlikely*





- 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)

Galactic Center X-ray Constraints? Potassium Lines? M31?

Galactic Center X-ray Constraints? Potassium Lines? M31?

“Dark Matter Searches Gone Bananas” Potassium paper by Jeltema & Profumo arXiv:1408.1699 (JP) called into question Bulbul+ and Boyarsky+ results:

Galactic Center X-ray Constraints? Potassium Lines? M31?

“Dark Matter Searches Gone Bananas” Potassium paper by Jeltema & Profumo arXiv:1408.1699 (JP) called into question Bulbul+ and Boyarsky+ results:

- ν_s JP claim that the Galactic Center excludes a dark matter interpretation

Galactic Center X-ray Constraints? Potassium Lines? M31?

"Dark Matter Searches Gone Bananas" Potassium paper by Jeltema & Profumo arXiv:1408.1699 (JP) called into question Bulbul+ and Boyarsky+ results:

- ν_s JP claim that the Galactic Center excludes a dark matter interpretation
  - » JP makes the assumption of all of the 3.5 keV flux coming from K XVIII, and then placing constraints on dark matter decay from the Galactic Center after this assumption. The flux from the Galactic Center is in fact consistent with the dark matter mass within the region [Boyarsky+ arXiv:1408.2503].

Galactic Center X-ray Constraints? Potassium Lines? M31?

“Dark Matter Searches Gone Bananas” Potassium paper by Jeltema & Profumo arXiv:1408.1699 (JP) called into question Bulbul+ and Boyarsky+ results:

- ν_s JP claim that the Galactic Center excludes a dark matter interpretation
  - » JP makes the assumption of all of the 3.5 keV flux coming from K XVIII, and then placing constraints on dark matter decay from the Galactic Center after this assumption. The flux from the Galactic Center is in fact consistent with the dark matter mass within the region [Boyarsky+ arXiv:1408.2503].
- ν_s JP claim that there is less than 2σ evidence for the line in XMM-Newton data of M31

Galactic Center X-ray Constraints? Potassium Lines? M31?

"Dark Matter Searches Gone Bananas" Potassium paper by Jeltema & Profumo arXiv:1408.1699 (JP) called into question Bulbul+ and Boyarsky+ results:

- ν_s JP claim that the Galactic Center excludes a dark matter interpretation
  - » JP makes the assumption of all of the 3.5 keV flux coming from K XVIII, and then placing constraints on dark matter decay from the Galactic Center after this assumption. The flux from the Galactic Center is in fact consistent with the dark matter mass within the region [Boyarsky+ arXiv:1408.2503].
- ν_s JP claim that there is less than 2σ evidence for the line in XMM-Newton data of M31
  - » The Boyarsky team showed how the JP M31 analysis is flawed in using much too narrow of an energy window in their line search modeling, which allows the continuum to float excessively [arXiv:1408.4388].

Galactic Center X-ray Constraints? Potassium Lines? M31?

"Dark Matter Searches Gone Bananas" Potassium paper by Jeltema & Profumo arXiv:1408.1699 (JP) called into question Bulbul+ and Boyarsky+ results:

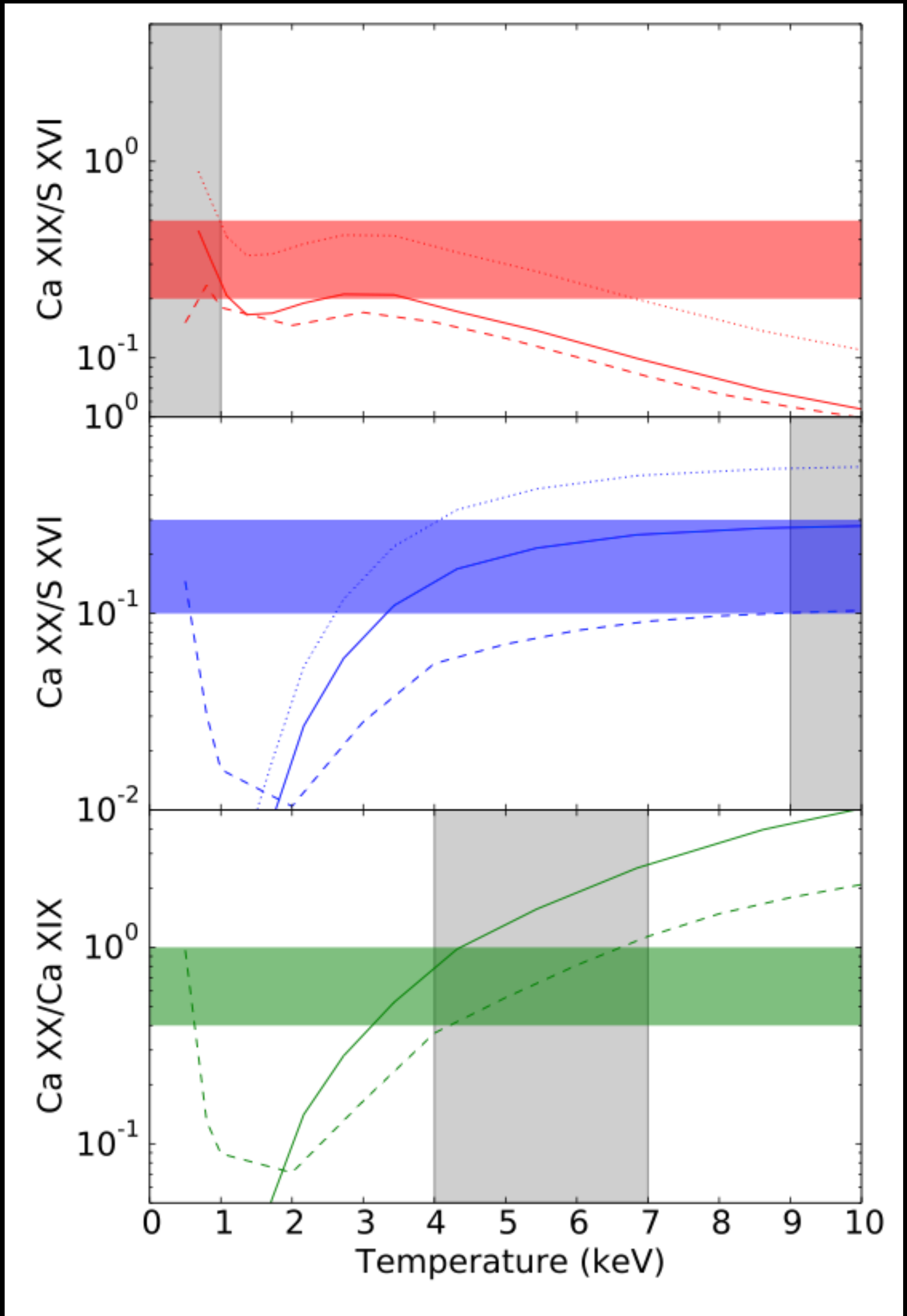
- ν_s JP claim that the Galactic Center excludes a dark matter interpretation
  - » JP makes the assumption of all of the 3.5 keV flux coming from K XVIII, and then placing constraints on dark matter decay from the Galactic Center after this assumption. The flux from the Galactic Center is in fact consistent with the dark matter mass within the region [Boyarsky+ arXiv:1408.2503].
- ν_s JP claim that there is less than 2σ evidence for the line in XMM-Newton data of M31
  - » The Boyarsky team showed how the JP M31 analysis is flawed in using much too narrow of an energy window in their line search modeling, which allows the continuum to float excessively [arXiv:1408.4388].
- ν_s JP claim line ratios in the cluster data do not allow for a consistent model for the temperature of Perseus

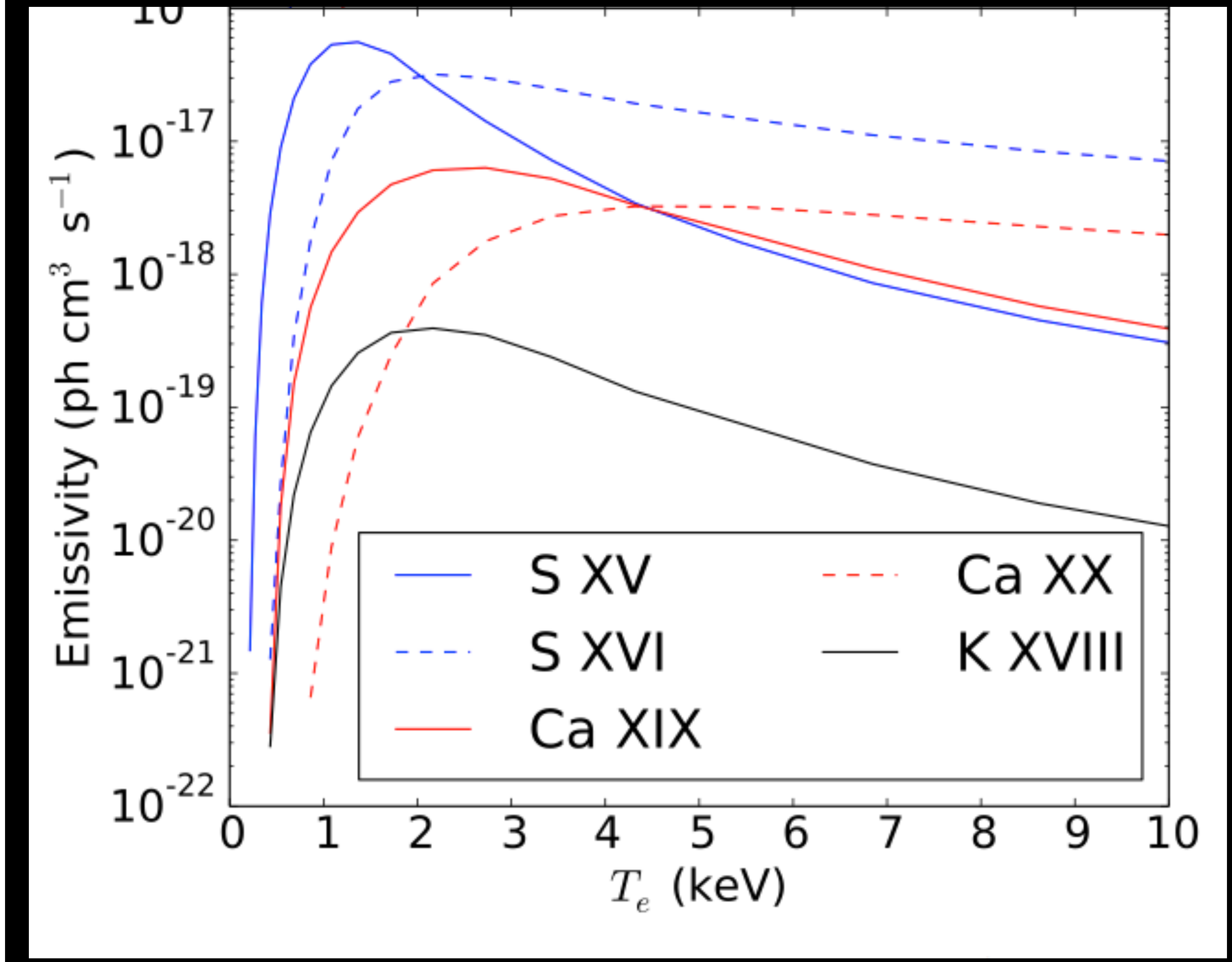
Galactic Center X-ray Constraints? Potassium Lines? M31?

"Dark Matter Searches Gone Bananas" Potassium paper by Jeltema & Profumo arXiv:1408.1699 (JP) called into question Bulbul+ and Boyarsky+ results:

- ν_s JP claim that the Galactic Center excludes a dark matter interpretation
  - » JP makes the assumption of all of the 3.5 keV flux coming from K XVIII, and then placing constraints on dark matter decay from the Galactic Center after this assumption. The flux from the Galactic Center is in fact consistent with the dark matter mass within the region [Boyarsky+ arXiv:1408.2503].
- ν_s JP claim that there is less than 2σ evidence for the line in XMM-Newton data of M31
  - » The Boyarsky team showed how the JP M31 analysis is flawed in using much too narrow of an energy window in their line search modeling, which allows the continuum to float excessively [arXiv:1408.4388].
- ν_s JP claim line ratios in the cluster data do not allow for a consistent model for the temperature of Perseus
  - » The Bulbul+ team showed that JP use over-simplified single-temperature model arguments with incorrect line ratios in their X-ray cluster modeling [arXiv:1409.0920].

Inconsistent T? Potassium Line? (JP)



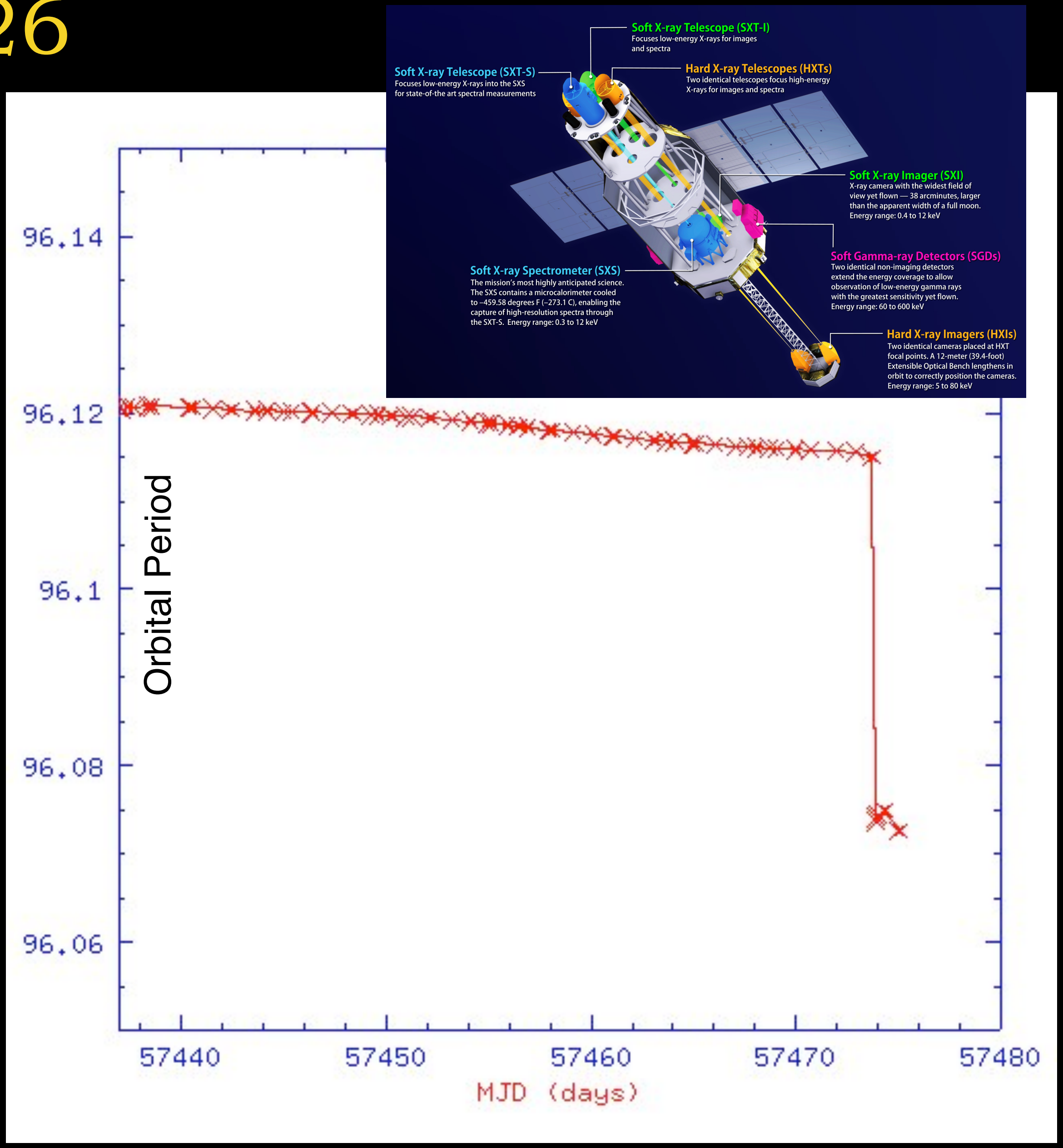


Bulbul+: “An independent consideration is the observed absolute line fluxes. Because the Ca XX, Ca XIX and S XVI emissivities drop steeply at low temperatures (lower panel in Fig. 3), any cool component would have to have a very high abundance of those elements to contribute significantly to the observed line fluxes. For example, to produce all of the observed Ca XX line in the Perseus MOS spectrum with a T = 1 keV plasma, the Ca abundance would have to be over 100 times solar (which is unlikely given the observed values of 0.3 – 2 solar in clusters, including their cool cores).”

Communication anomaly of X-ray Astronomy Satellite “Hitomi” (ASTRO-H) - March 26

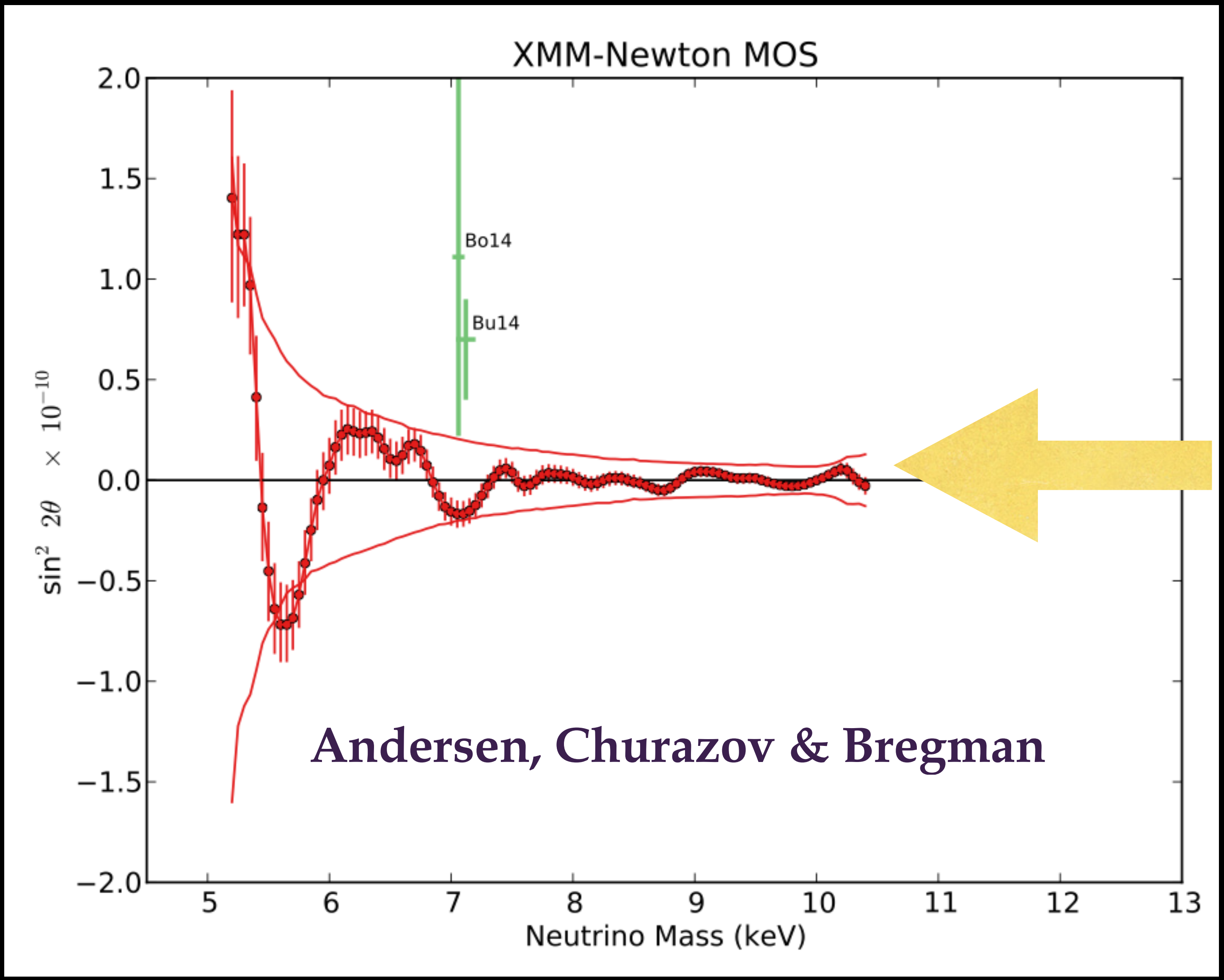
JAXA Press Releases:

- loss of orbit altitude
- loss of communication
- debris reported by JSpOC (Joint Space Operations Center)
- estimated rotation period calculated from the light curve is about 5.2 seconds



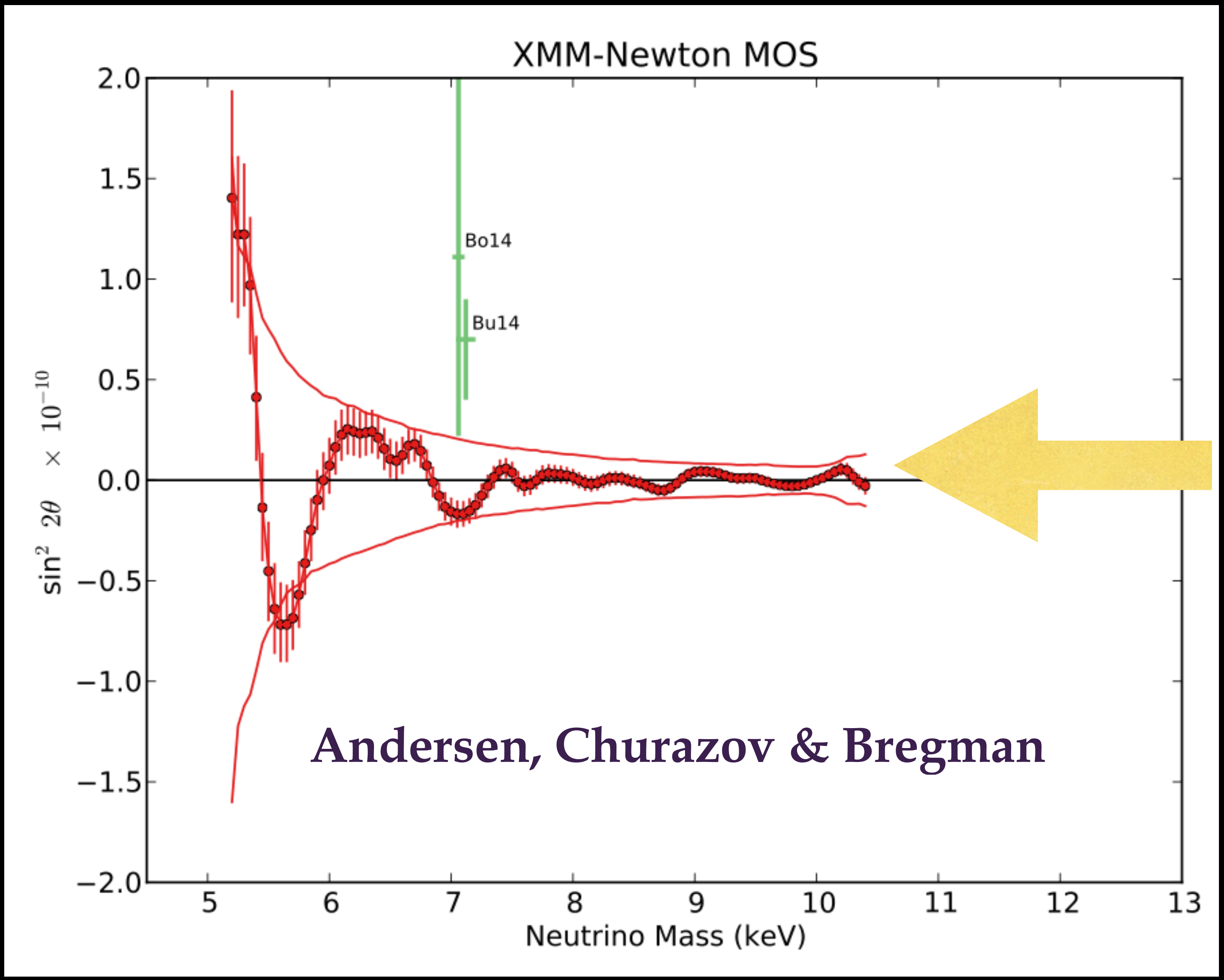
- JAXA: “cause for this fast rotations is anomaly in attitude control system. Based on information from several overseas organizations indicating the separation of the two SAPs from ASTRO-H, JAXA concluded that the functions of ASTRO-H could not be restored. Accordingly, JAXA ceased efforts to recover the satellite and turned to investigating the cause of the anomaly.”

Stacked Observations: Galaxies



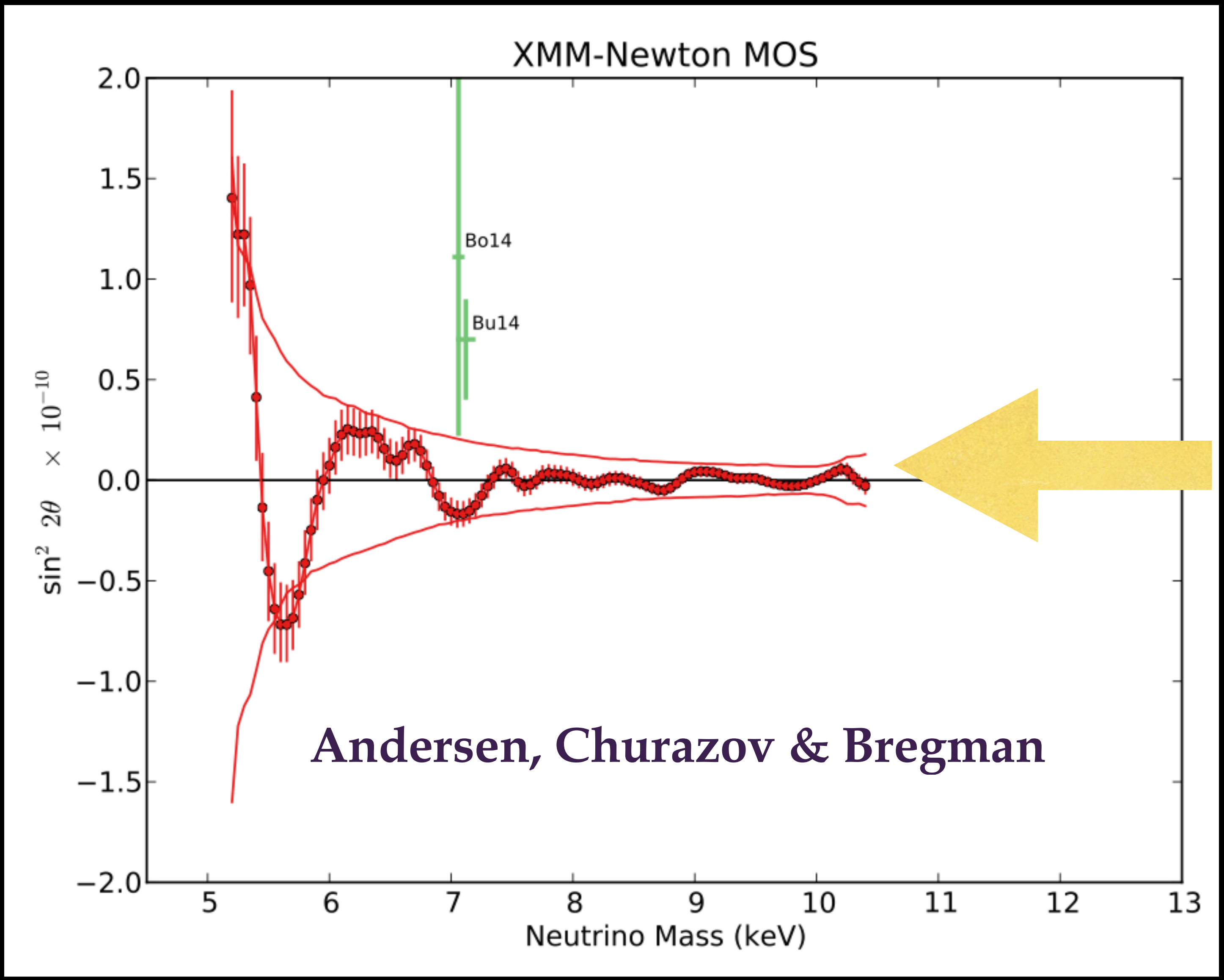
Stacked Observations: Galaxies

Sample of 81 galaxies observed with Chandra and a sample of 89 galaxies observed with XMM-Newton, using outskirts of the galaxies (Andersen, Churazov & Bregman 2014)

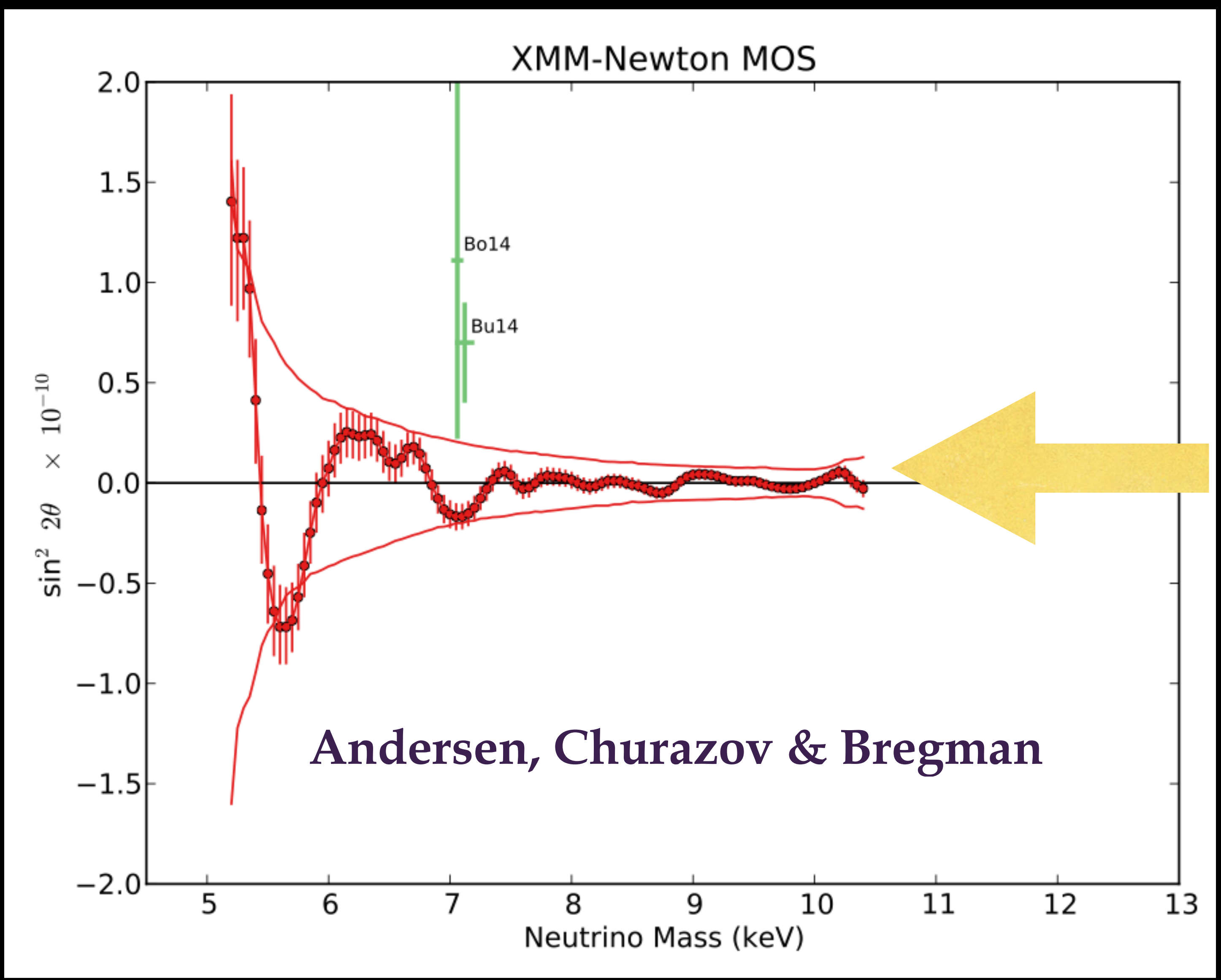


Stacked Observations: Galaxies

Sample of 81 galaxies observed with Chandra and a sample of 89 galaxies observed with XMM-Newton, using outskirts of the galaxies (Andersen, Churazov & Bregman 2014)



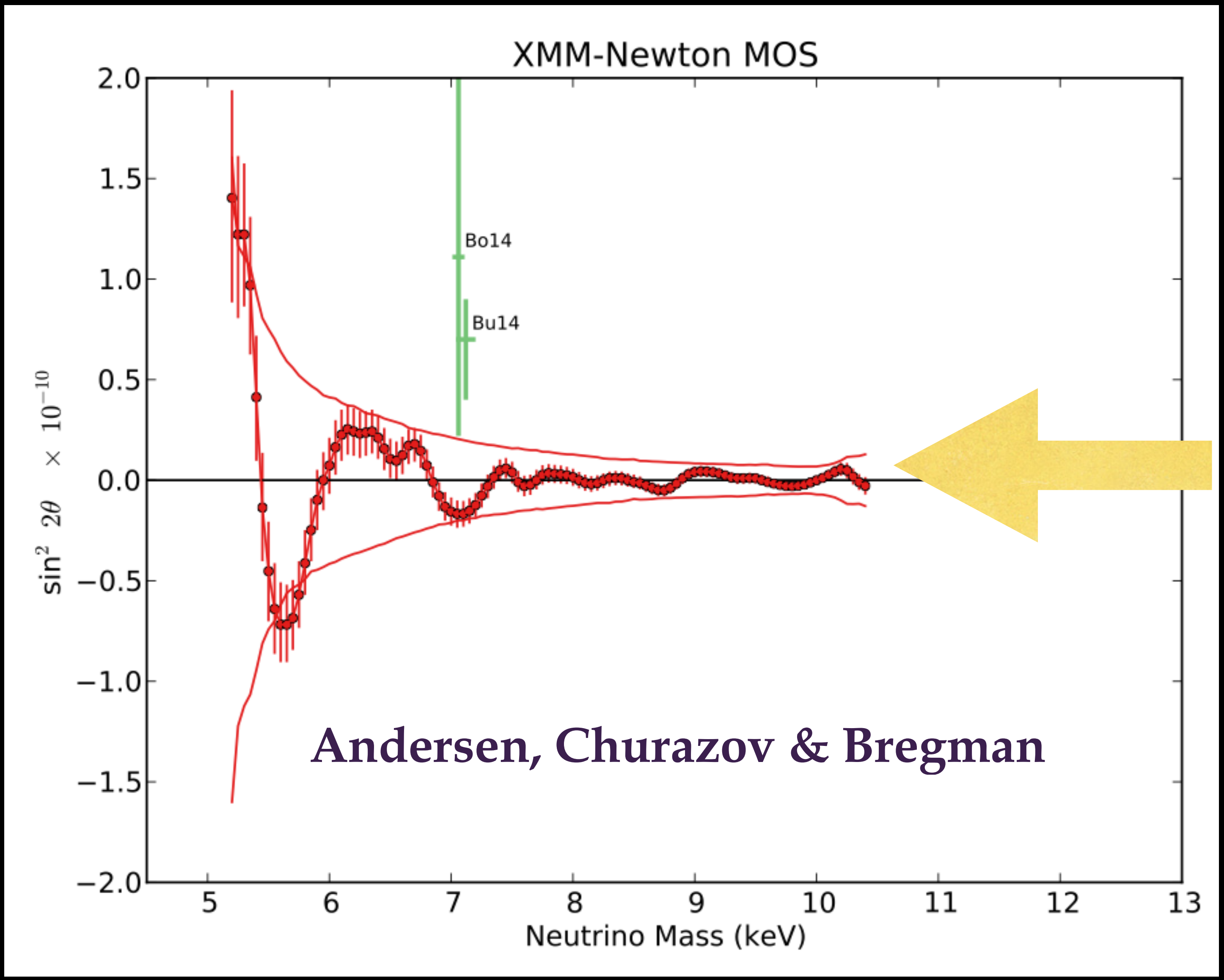
Stacked Observations: Galaxies



Sample of 81 galaxies observed with Chandra and a sample of 89 galaxies observed with XMM-Newton, using outskirts of the galaxies (Andersen, Churazov & Bregman 2014)

Quoted exclusion of the 3.5 keV line at fixed $\sin^2 2\theta$ by 11.8σ

Stacked Observations: Galaxies

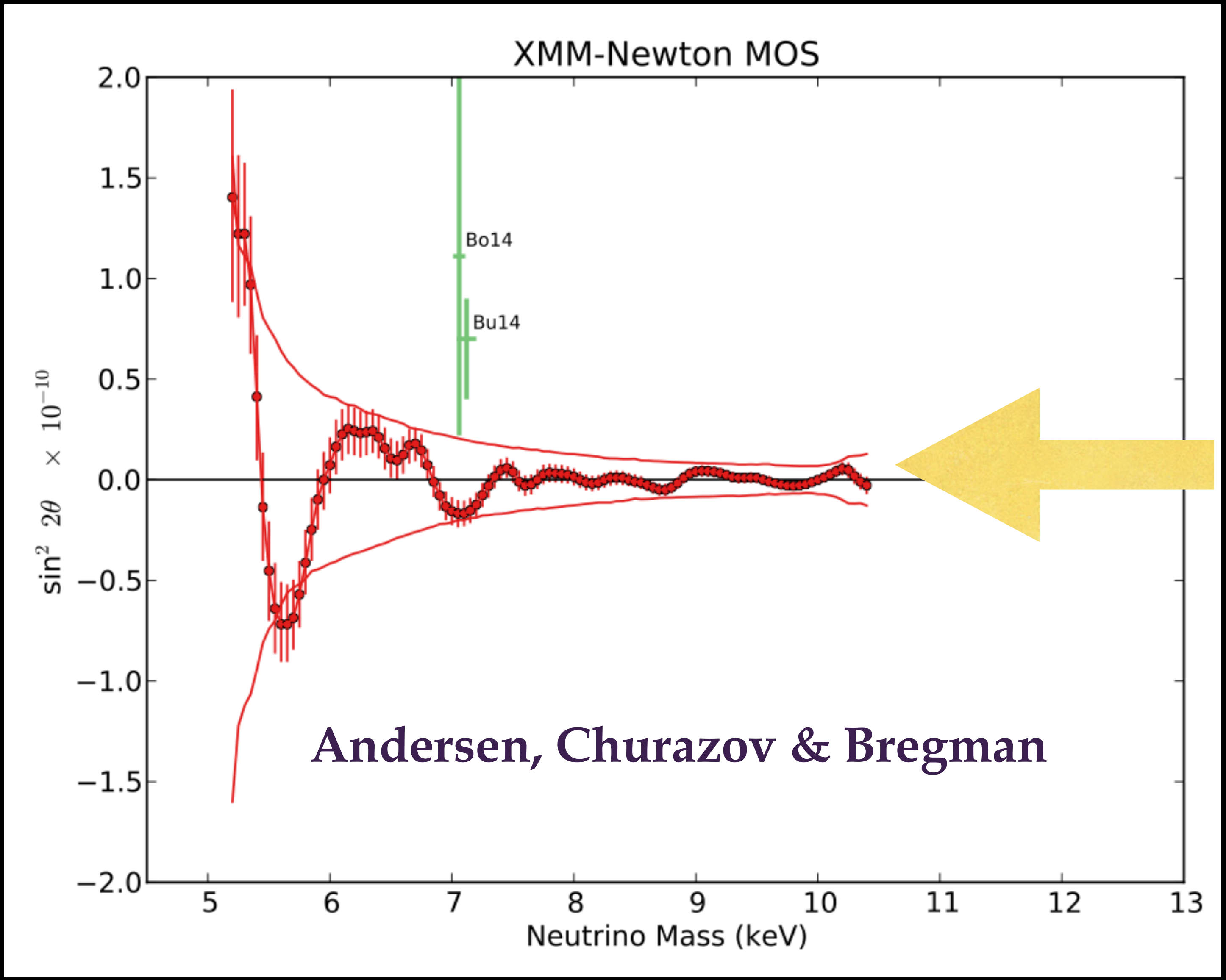


Sample of 81 galaxies observed with Chandra and a sample of 89 galaxies observed with XMM-Newton, using outskirts of the galaxies (Andersen, Churazov & Bregman 2014)

Quoted exclusion of the 3.5 keV line at fixed $\sin^2 2\theta$ by 11.8σ

Systematic errors are of order the uncertainties on detected $\sin^2 2\theta$

Stacked Observations: Galaxies



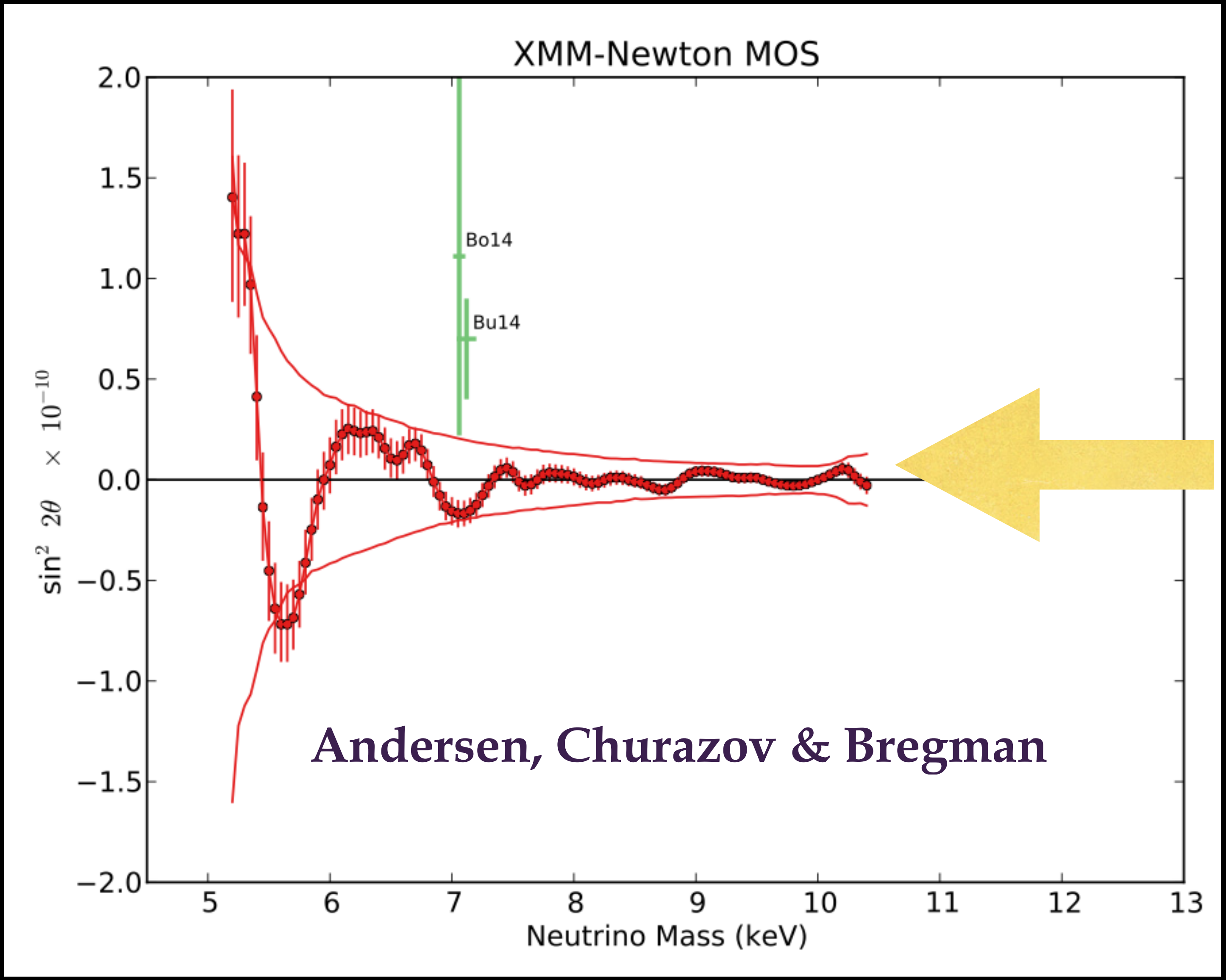
Sample of 81 galaxies observed with Chandra and a sample of 89 galaxies observed with XMM-Newton, using outskirts of the galaxies (Andersen, Churazov & Bregman 2014)

Quoted exclusion of the 3.5 keV line at fixed $\sin^2 2\theta$ by 11.8σ

Systematic errors are of order the uncertainties on detected $\sin^2 2\theta$

Despite overwhelming systematic uncertainties that are of order the signal, the authors quote statistical errors only.

Stacked Observations: Galaxies



Sample of 81 galaxies observed with Chandra and a sample of 89 galaxies observed with XMM-Newton, using outskirts of the galaxies (Andersen, Churazov & Bregman 2014)

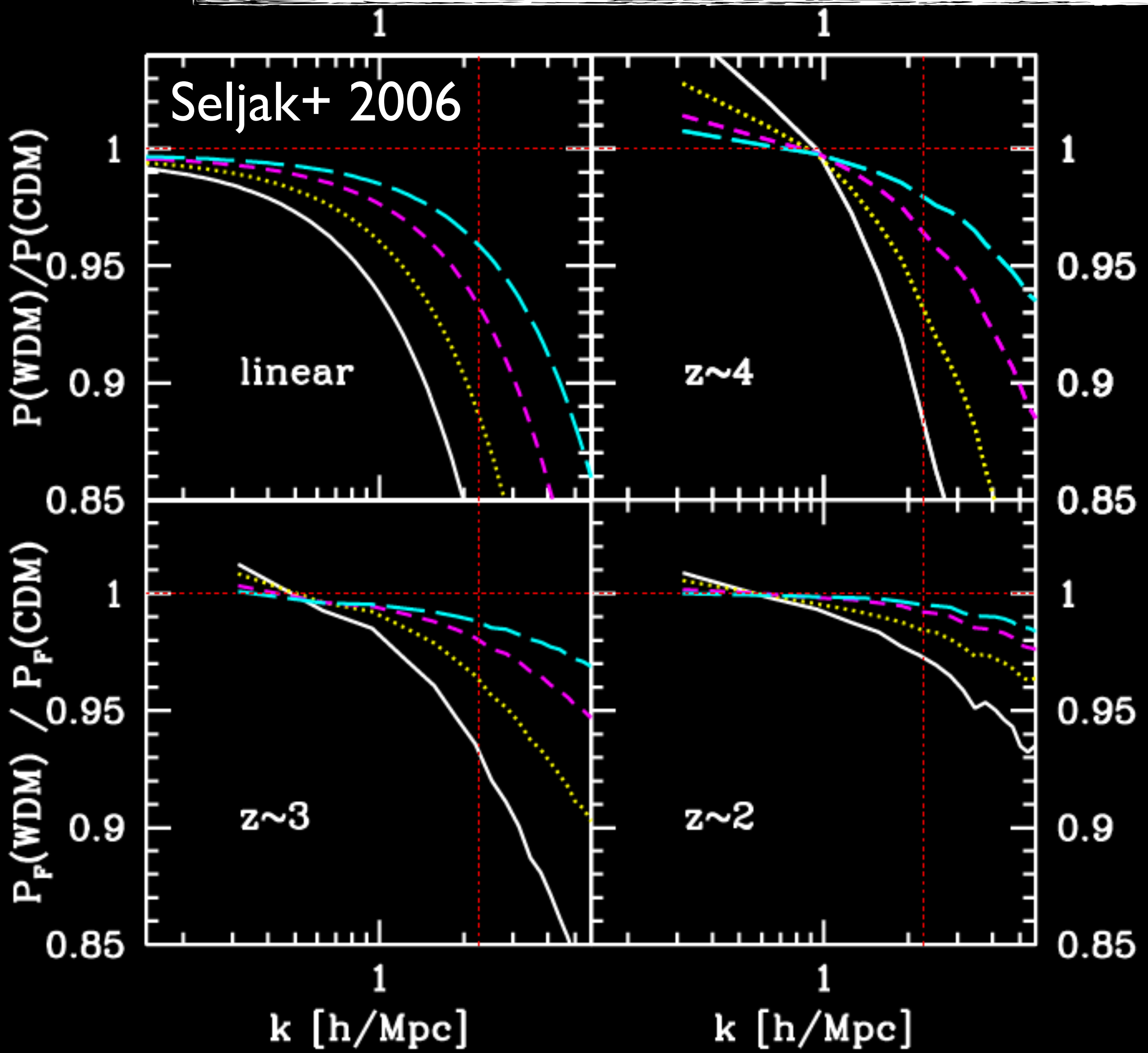
Quoted exclusion of the 3.5 keV line at fixed $\sin^2 2\theta$ by 11.8σ

Systematic errors are of order the uncertainties on detected $\sin^2 2\theta$

Despite overwhelming systematic uncertainties that are of order the signal, the authors quote statistical errors only.

Proper methodology would find a more robust, less systematics dominated method & not quote irrelevant statistical evidence which reach an invalid conclusion.

Lyman-α Forest Constraints on WDM

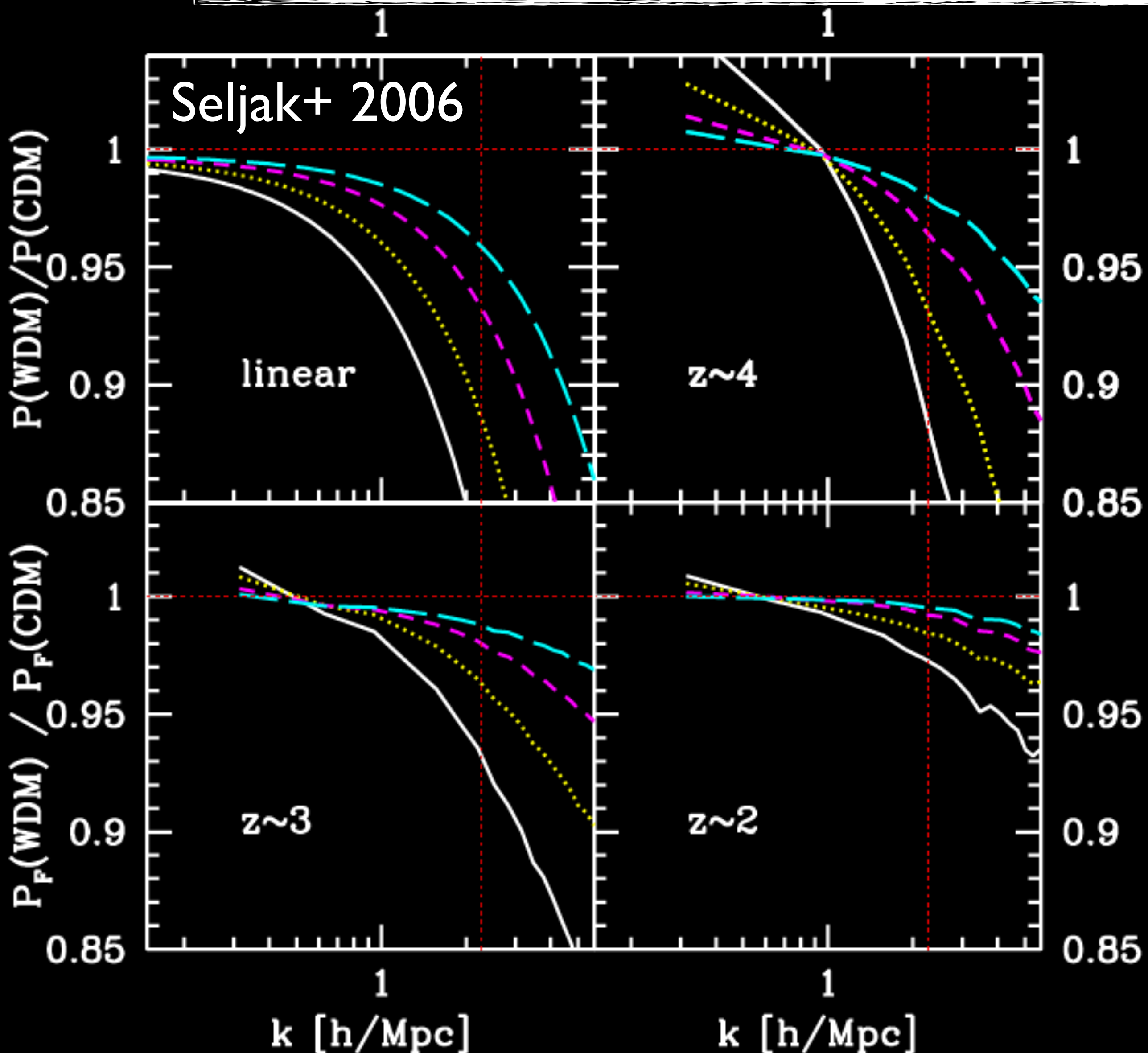


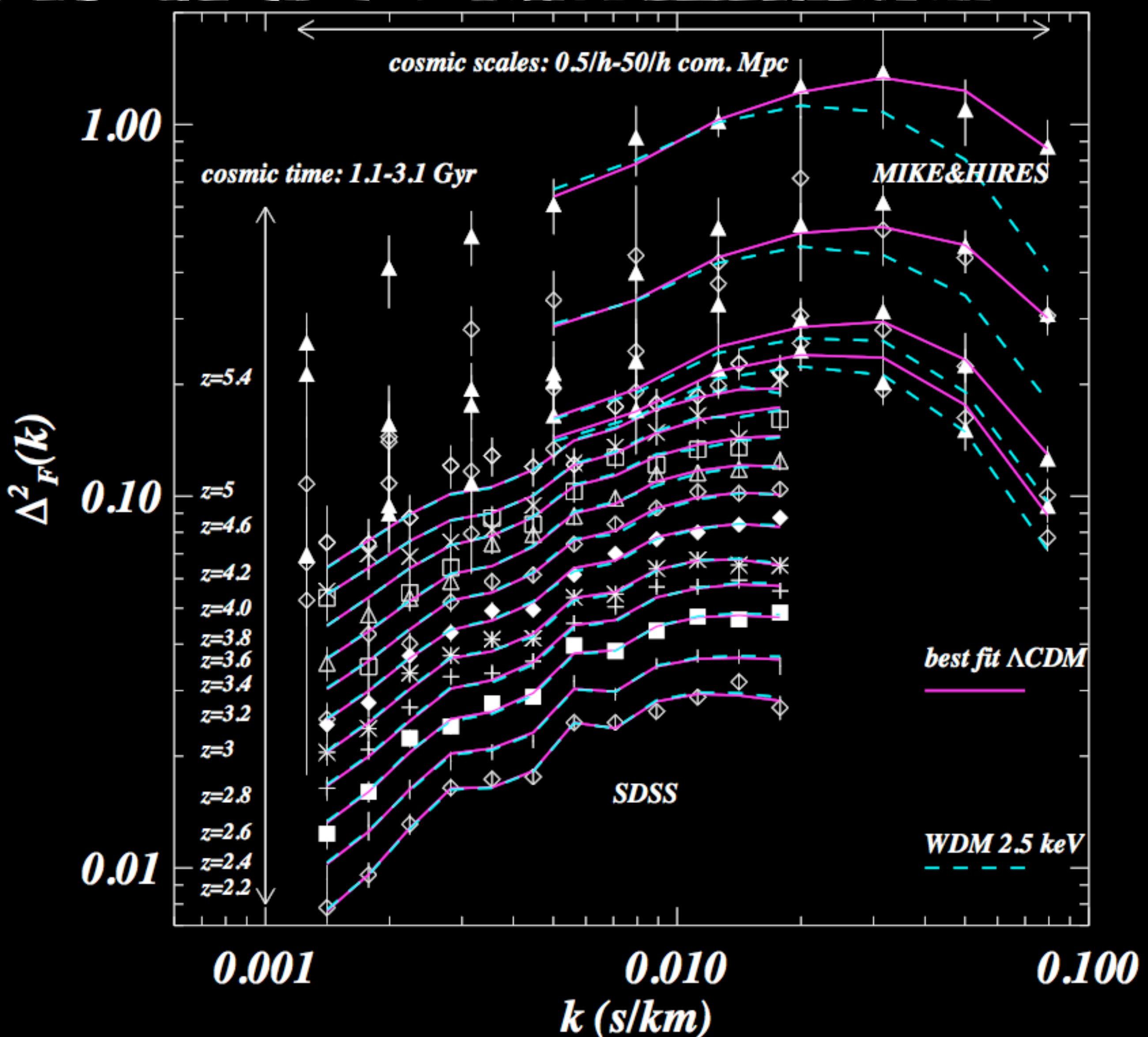
m > 3 keV (WDM)   (95% CL)

[m_s > 16 keV]

(Baur et al. 2015: SDSS III)

Lyman-α Forest Constraints on WDM



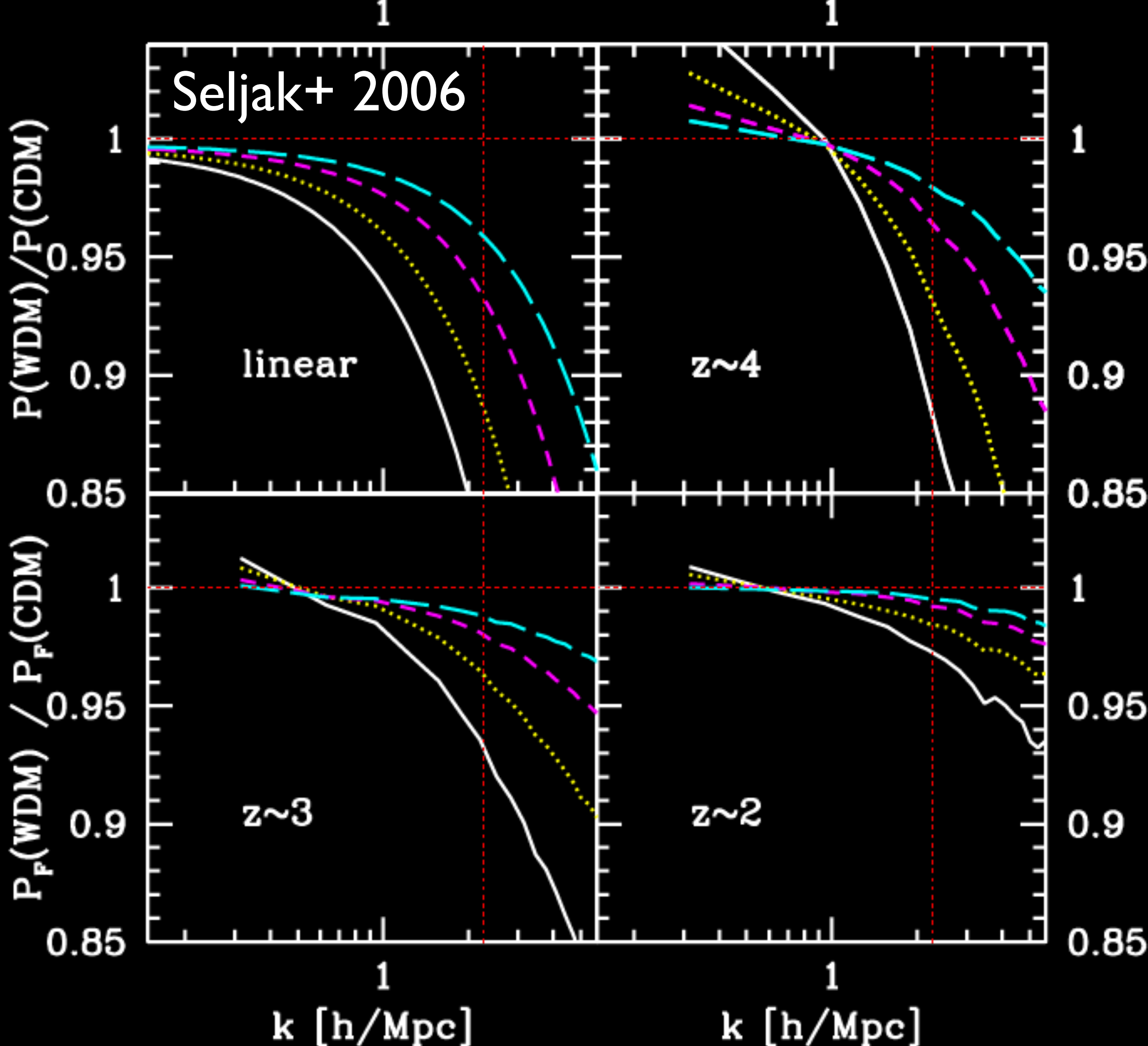


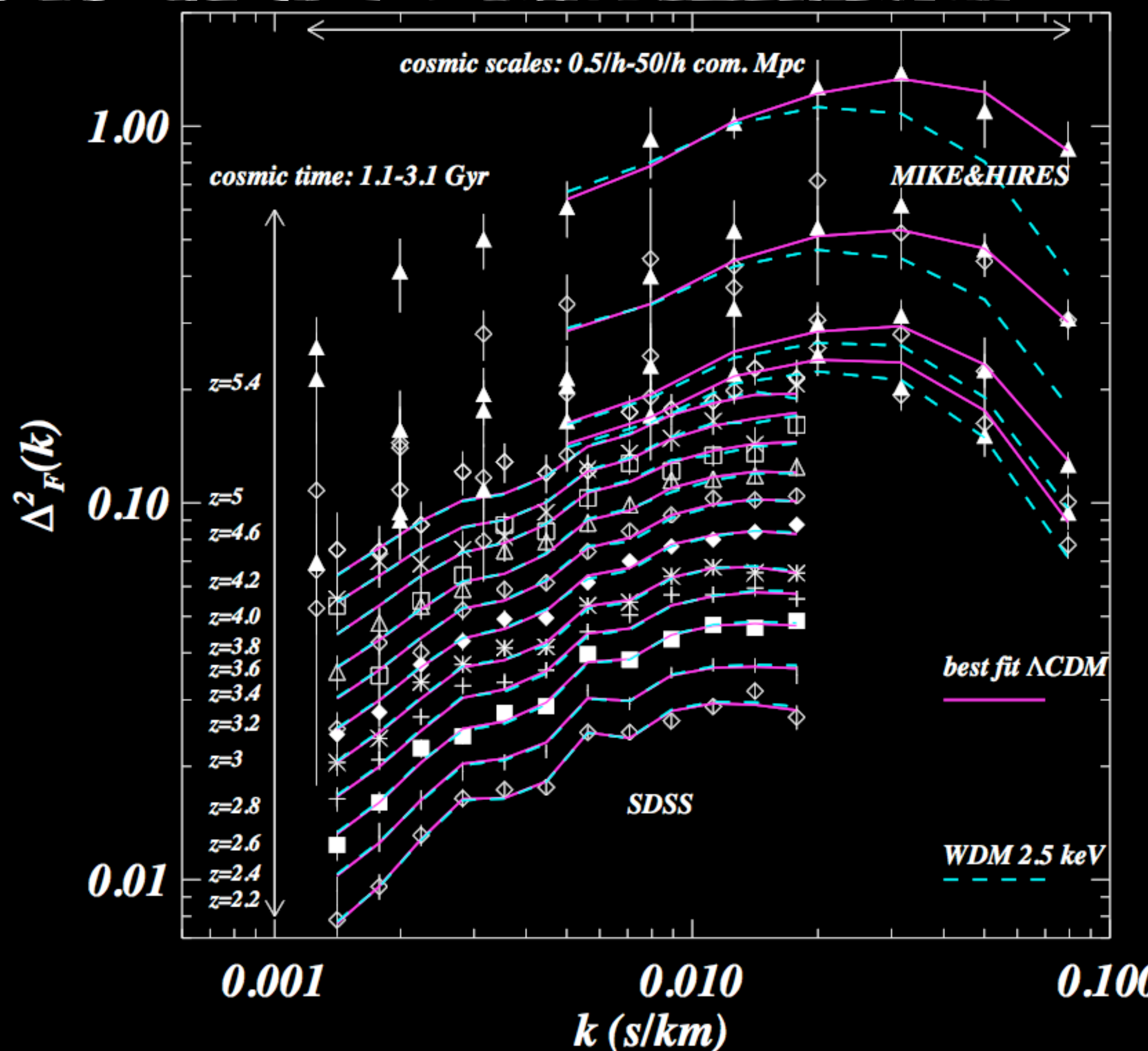
m > 3 keV (WDM) (95% CL)

[m_s > 16 keV]

(Baur et al. 2015: SDSS III)

Lyman-α Forest Constraints on WDM





$m > 3$ keV (WDM)   (95% CL)

[$m_s > 16$ keV]

(Baur et al. 2015: SDSS III)

$\lambda_{FS} < 42$ kpc $M_{FS} < 3 \times 10^6$ $M_\odot$ (Abazajian & Koushiappas 2006)

The Lyman-α Forest: Powerful & Challenging

THE ASTROPHYSICAL JOURNAL, 812:30 (15pp), 2015 October 10 KULKARNI ET AL.

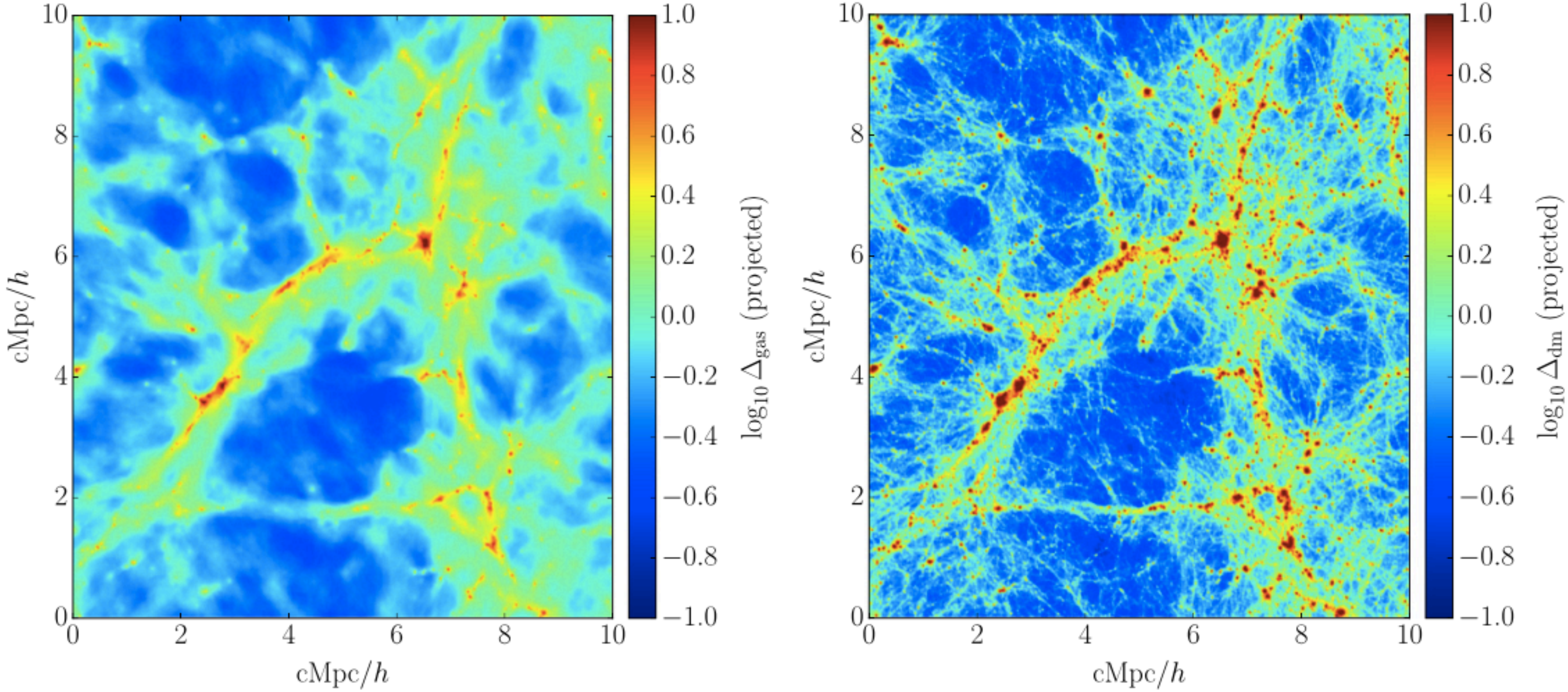
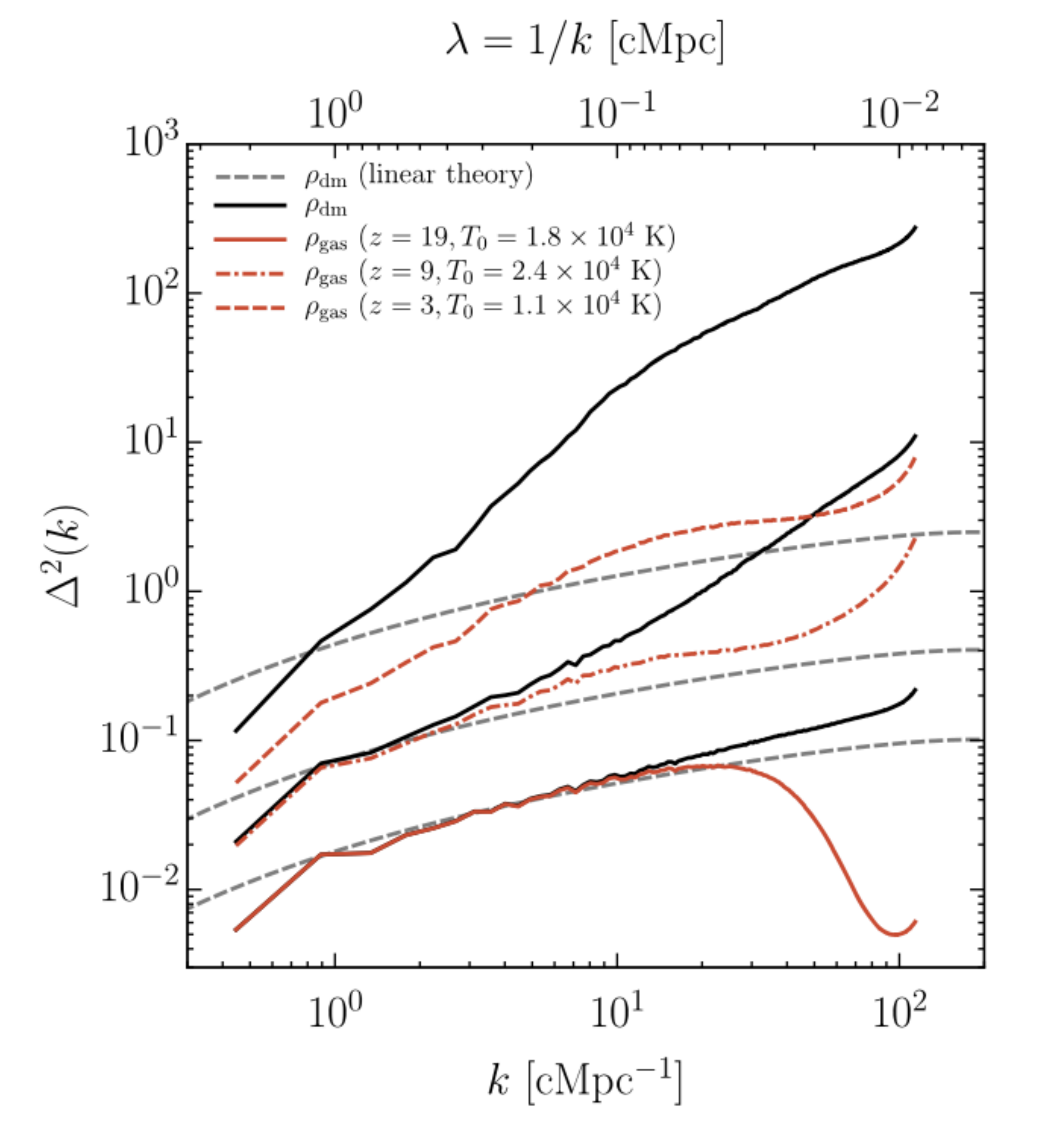


Figure 1. Projected density distributions of gas (left) and dark matter (right) at $z = 3$ in our fiducial simulation, showing pressure smoothing of gas relative to dark matter. The density at each point is an average for a column approximately 5 Mpc/h long.

Kulkarni et al. arXiv:1504.00366:

First hydro resolution simulation of pressure free streaming scale at high *z*.

The Lyman-α Forest: Powerful & Challenging



Kulkarni+: "The structure of the IGM in hydrodynamical simulations is very different from linear theory expectations at redshifts probed by the Lyα forest."… "the temperature–density relation should be augmented with a third pressure smoothing scale parameter λ_F"

Oñorbe et al. arXiv:1703.08633: use Lyα to probe reionization (not DM)