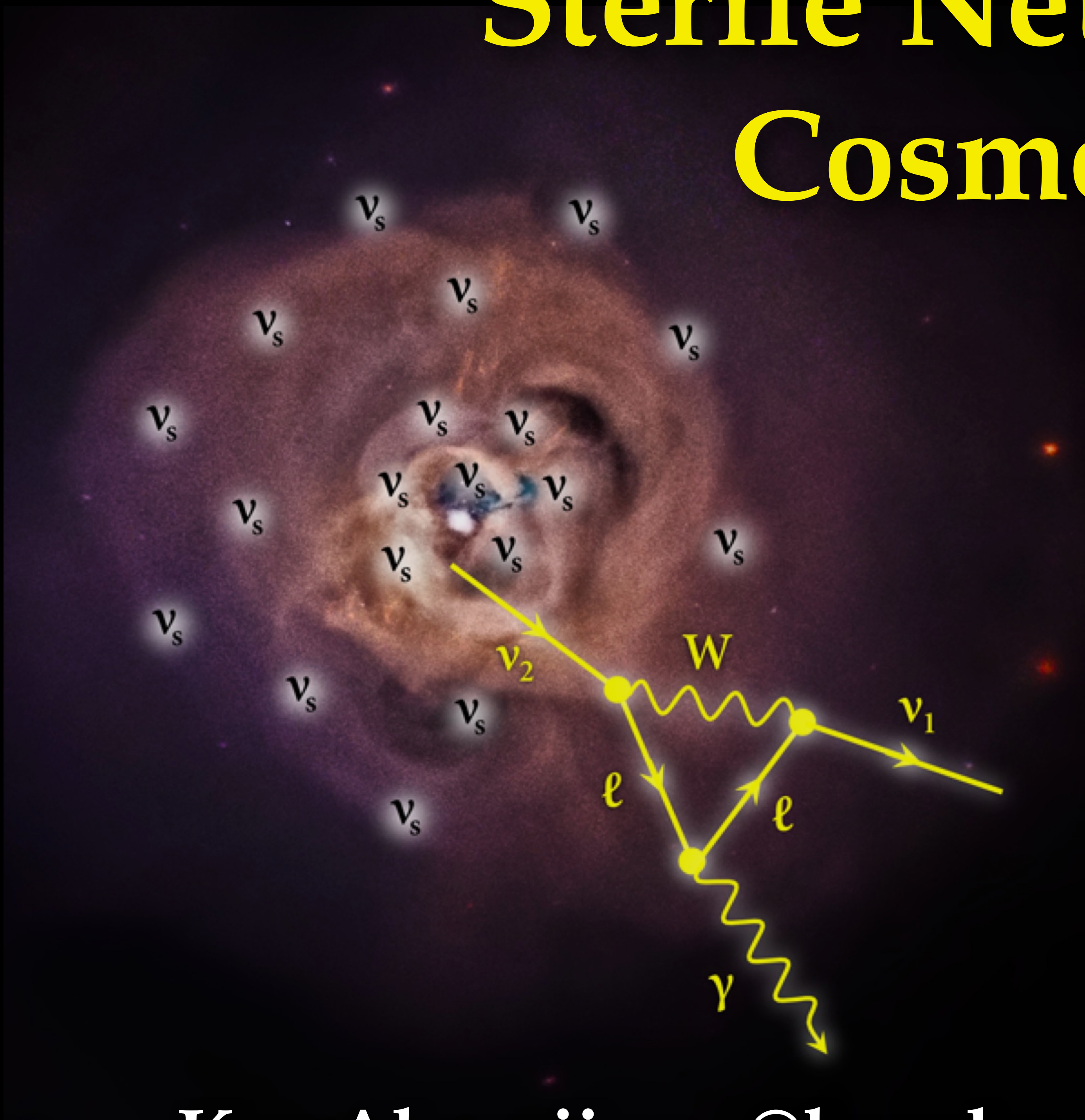
Sterile Neutrinos in Cosmology



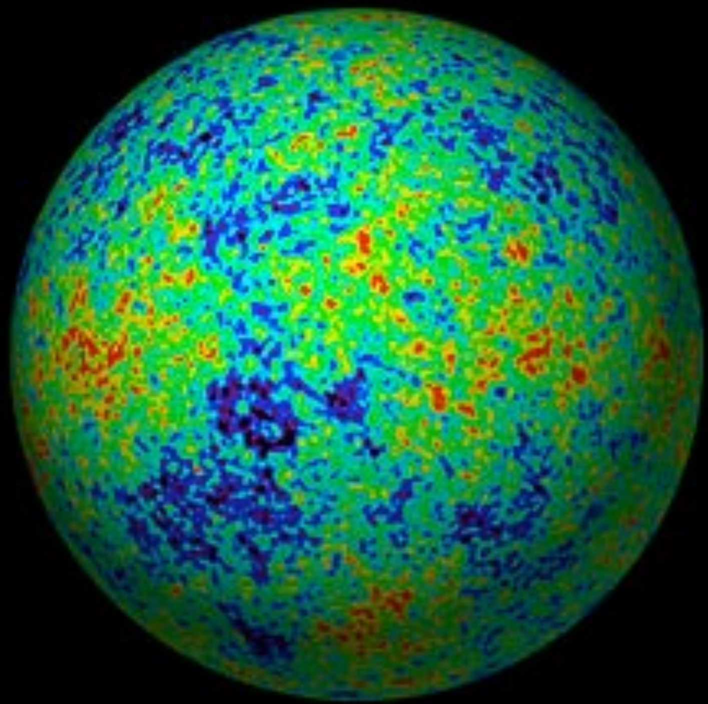
Kev Abazajian - @kevaba - /kevork.abazajian

University of California, Irvine

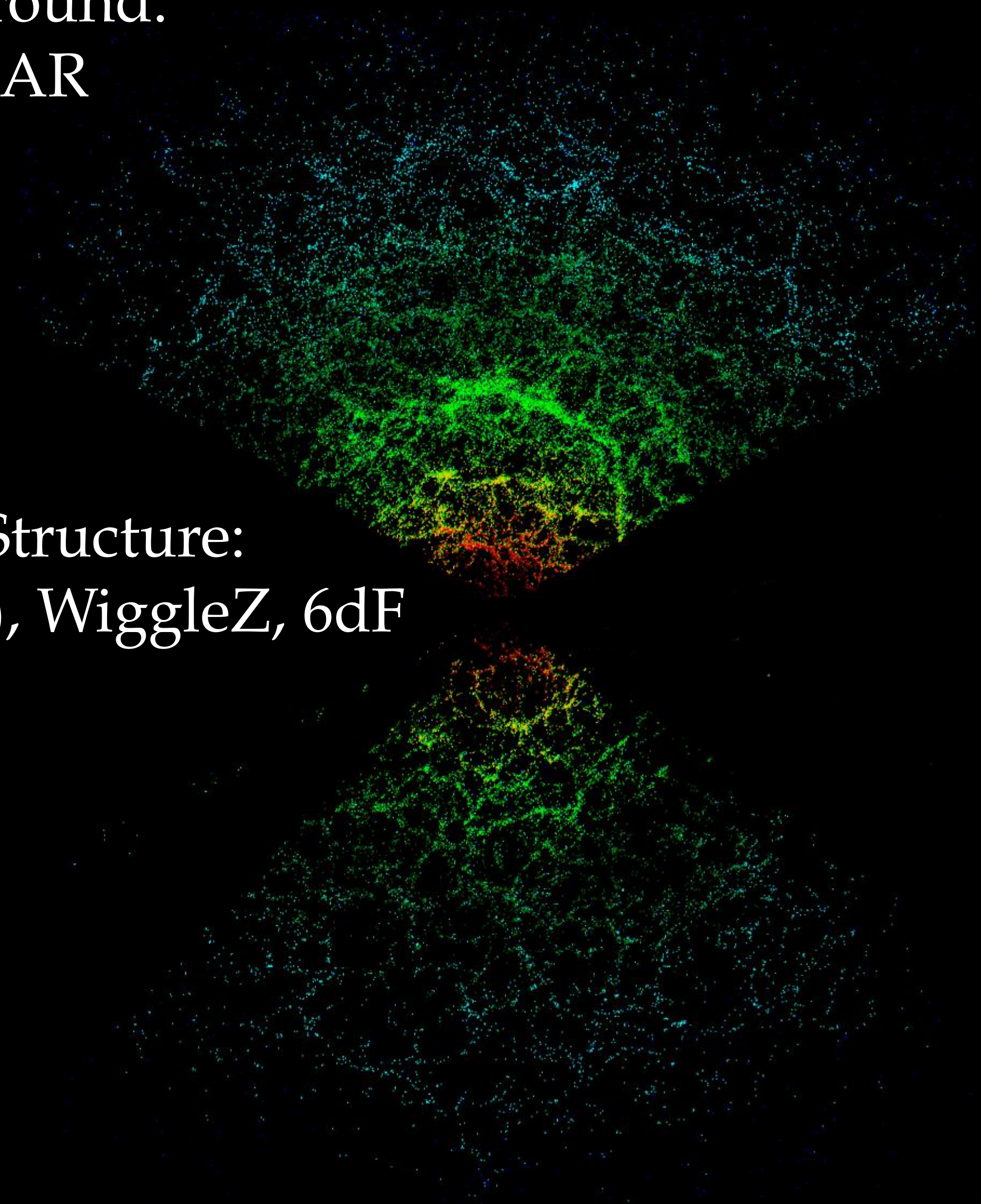
September 23, 2019

NEPLES - KIAS

Dark Matter Today: from large scale cosmology



Cosmic Microwave Background:
Planck, SPT, ACT, PolarBEAR



Large Scale Structure:
SDSS (BOSS), WiggleZ, 6dF

$$\Omega_{\rm DM} \equiv \frac{\rho_{\rm DM}}{\rho_{\rm crit}} = 0.259 \pm 0.002$$

Planck 2015 + BAO + SNe + H_0
(Planck Collab. 2015)

Neutrino Mass Generation: An Original Hidden Sector Theory

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

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- "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.


NEUTRINO

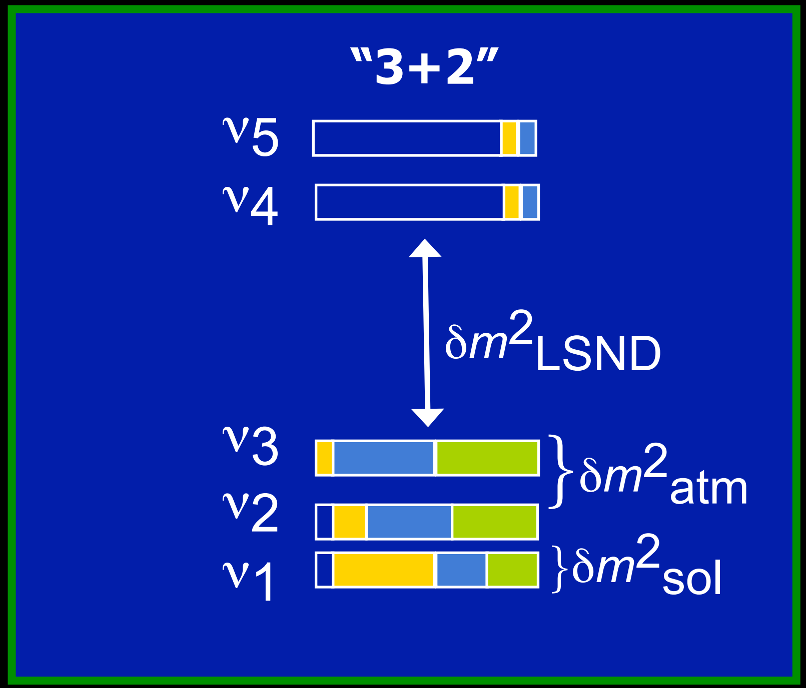
Dark Matter Neutrinos

Sterile Neutrino Dark Matter ν_6

$$|\nu_\alpha\rangle = \cos\theta|\nu_a\rangle + \sin\theta|\nu_b\rangle$$
$$|\nu_s\rangle = -\sin\theta|\nu_a\rangle + \cos\theta|\nu_b\rangle$$

~ 1 keV

$\sin^2 2\theta \lesssim 10^{-7}$



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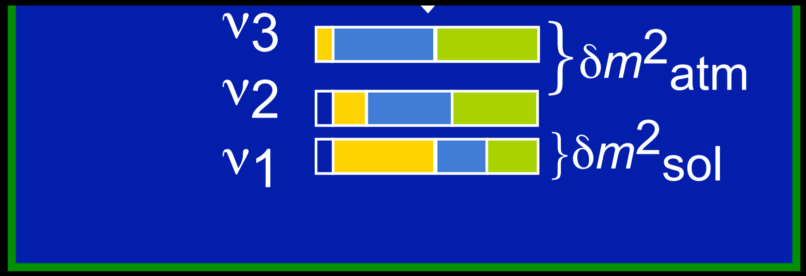

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Sterile Neutrino Dark Matter ν_4

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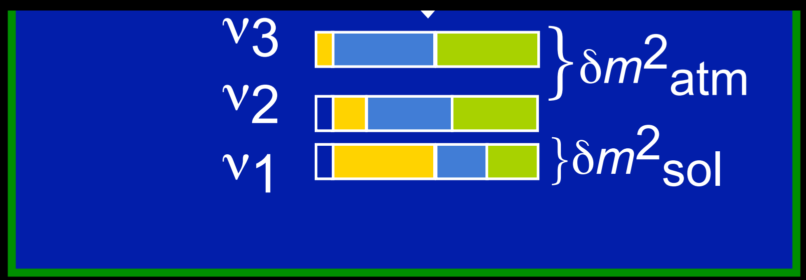

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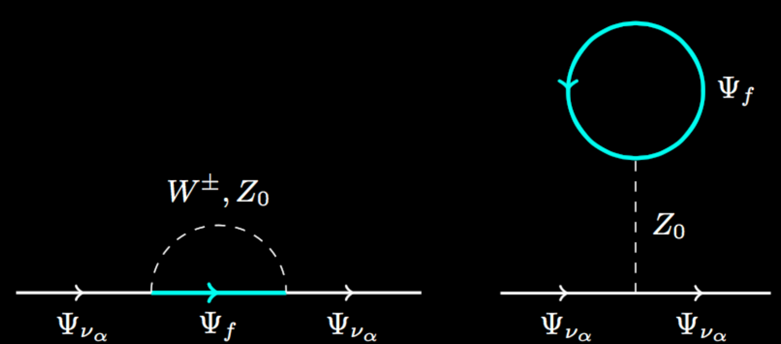

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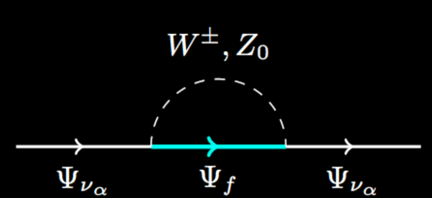

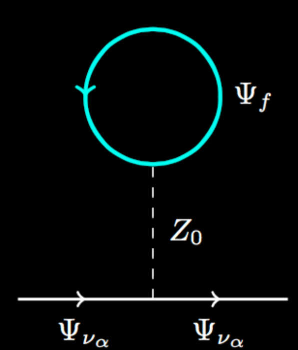

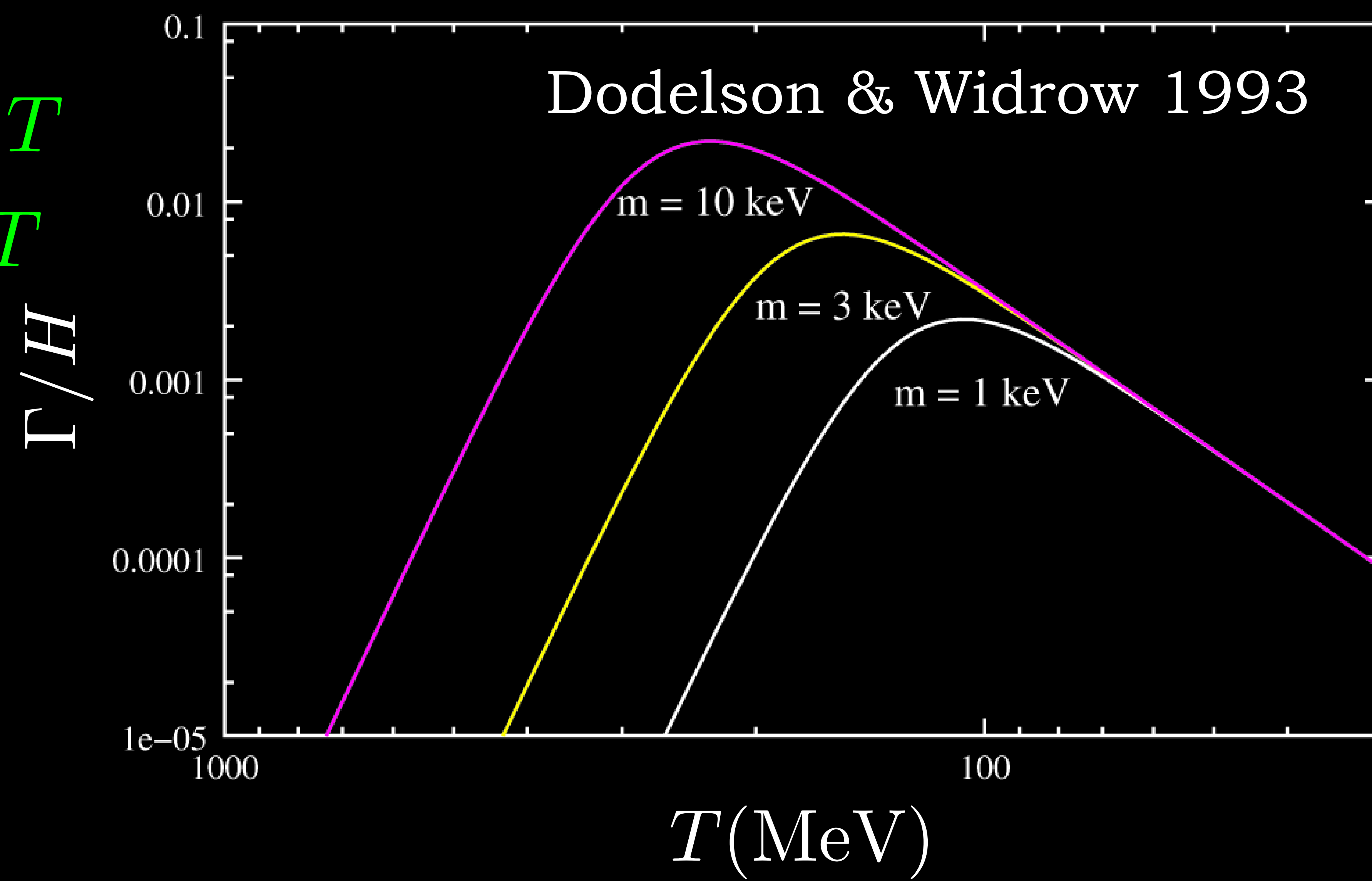

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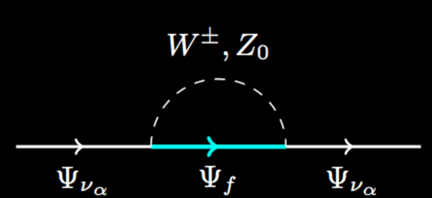
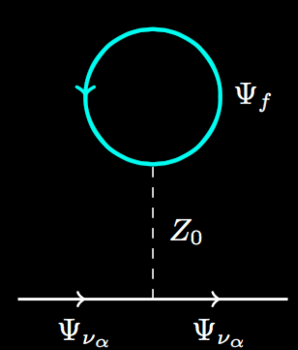
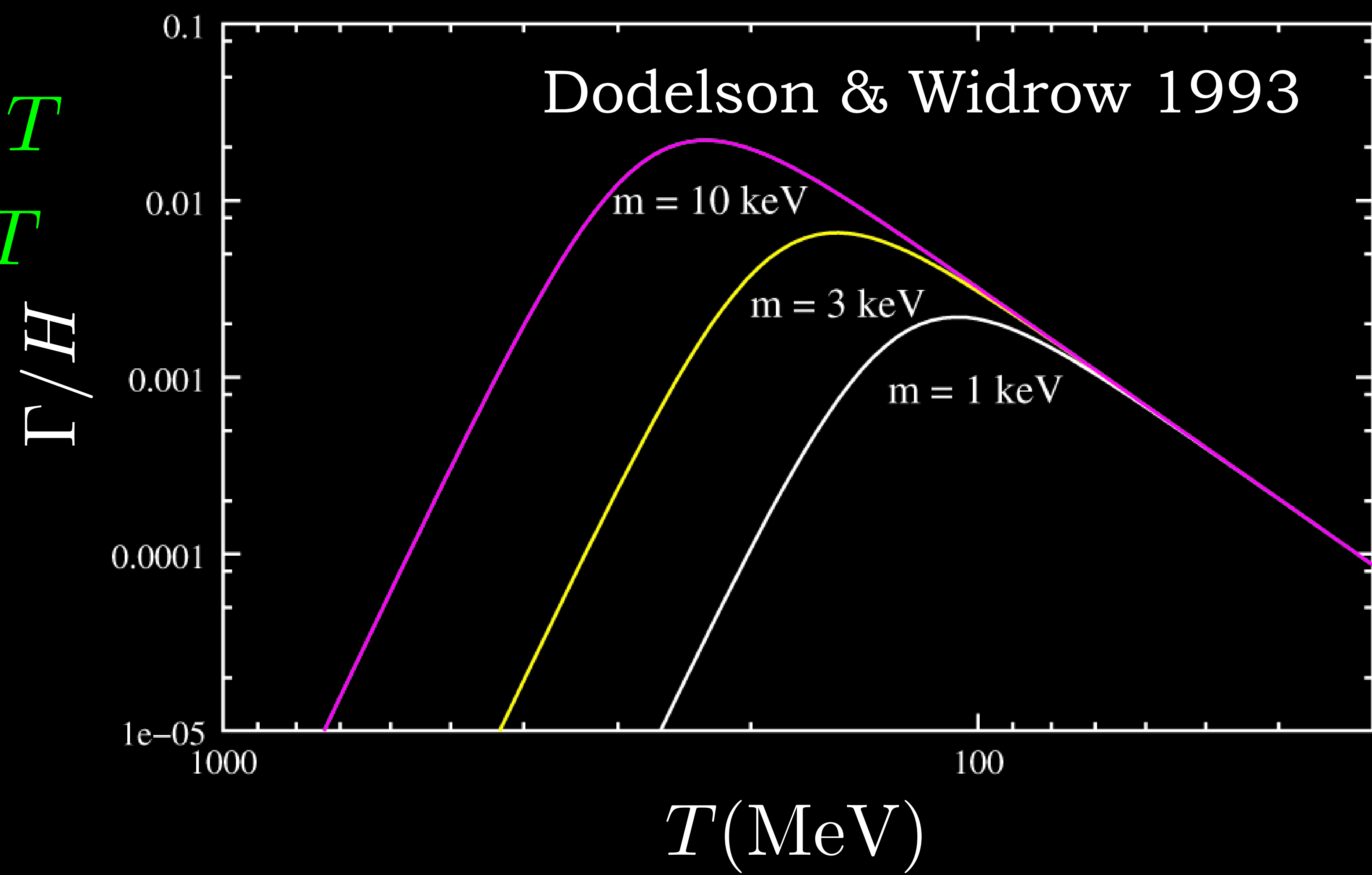




Resonance: Shi & Fuller 1998



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

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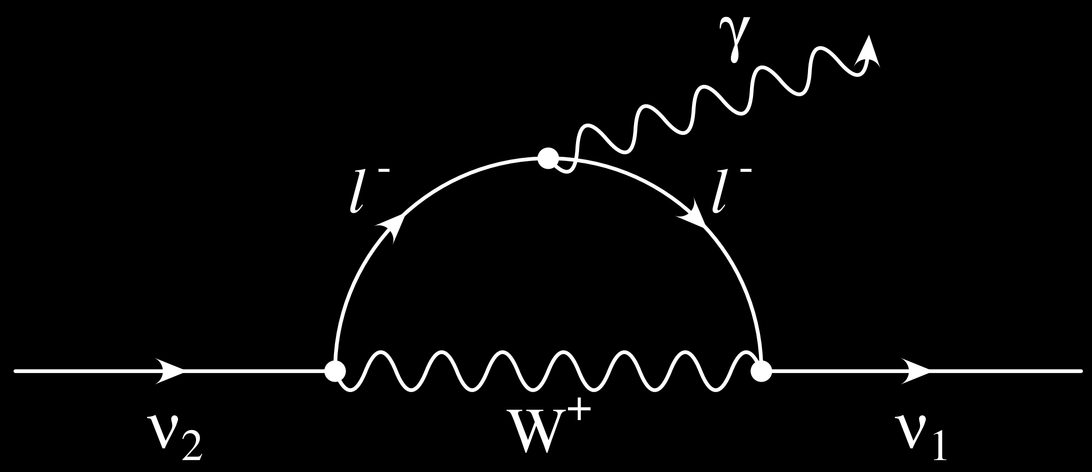
Dark Fermion WDM Radiative Decay in the X-ray



Decay: Shrock 1974; Pal & Wolfenstein 1981; Barger, Philips & Sarkar 1995
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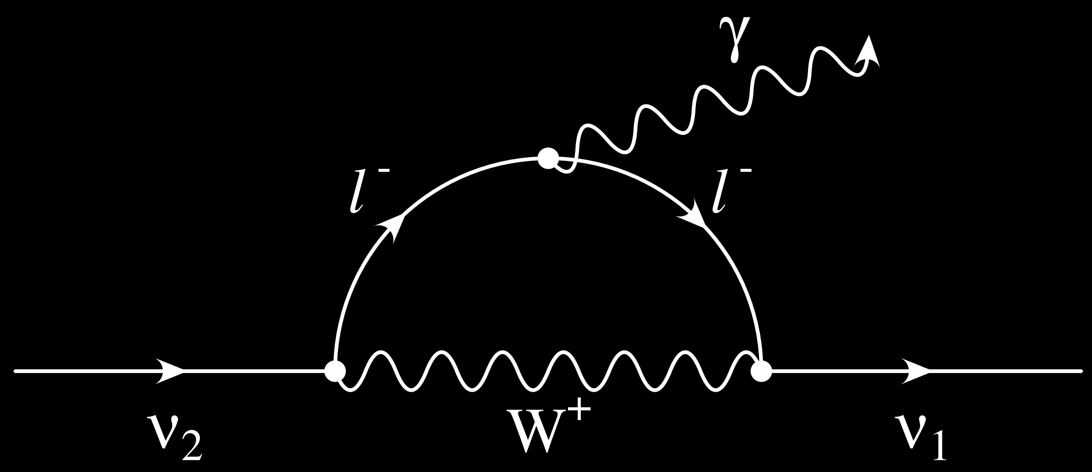

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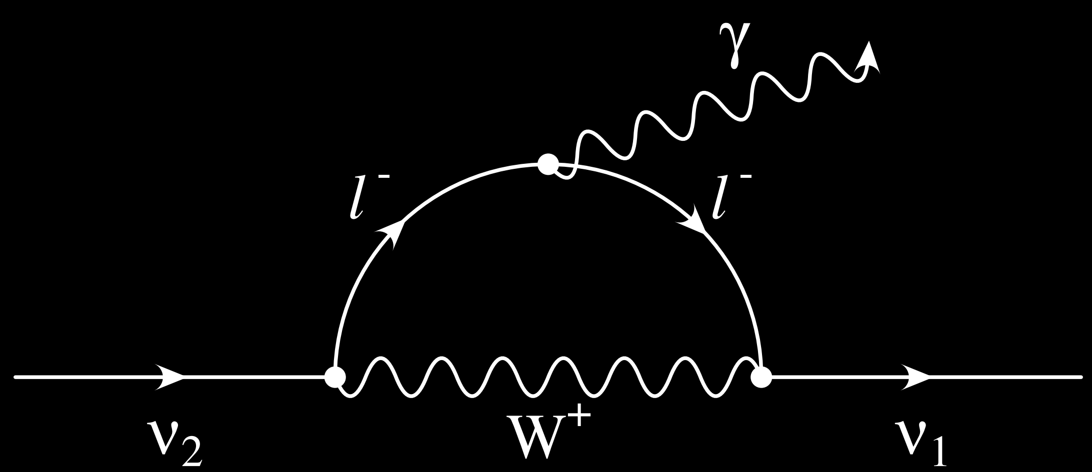

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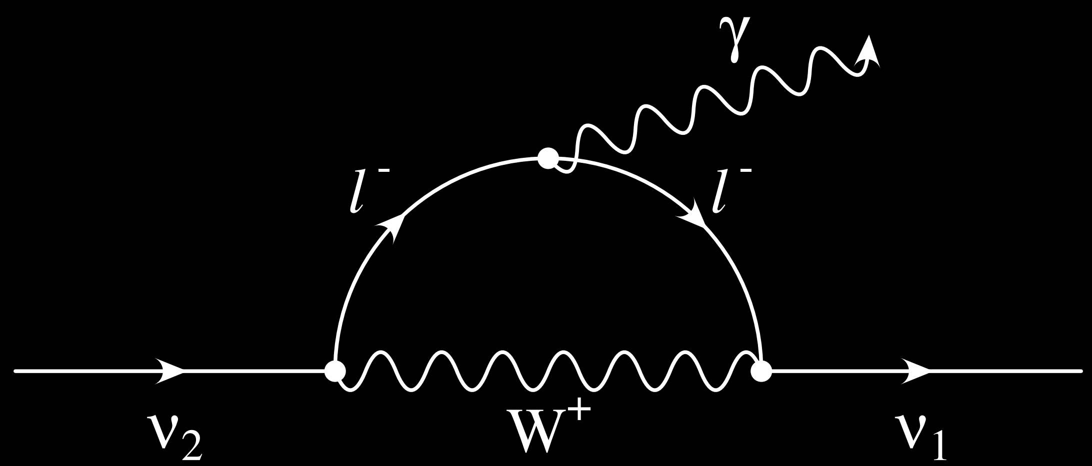

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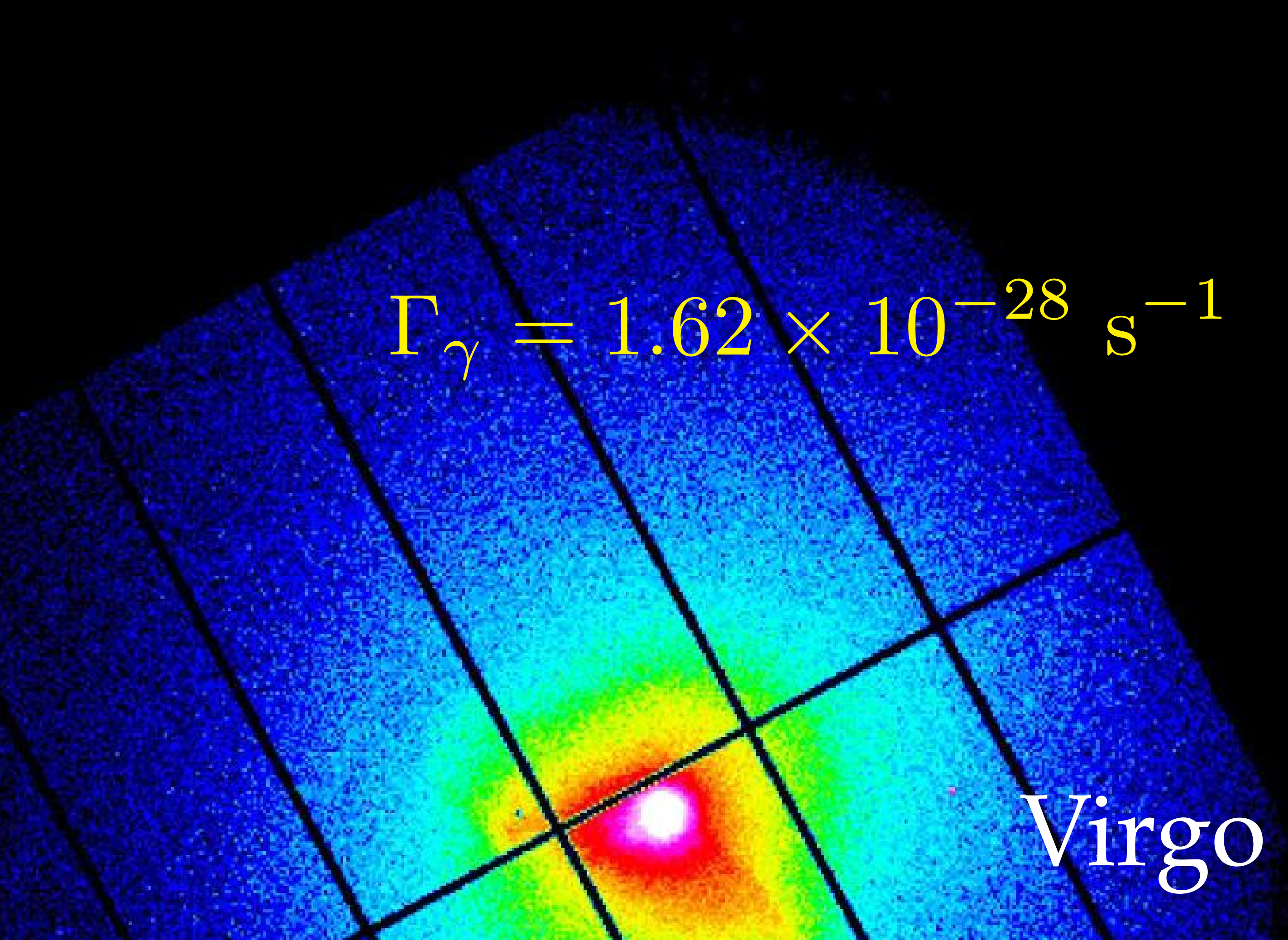
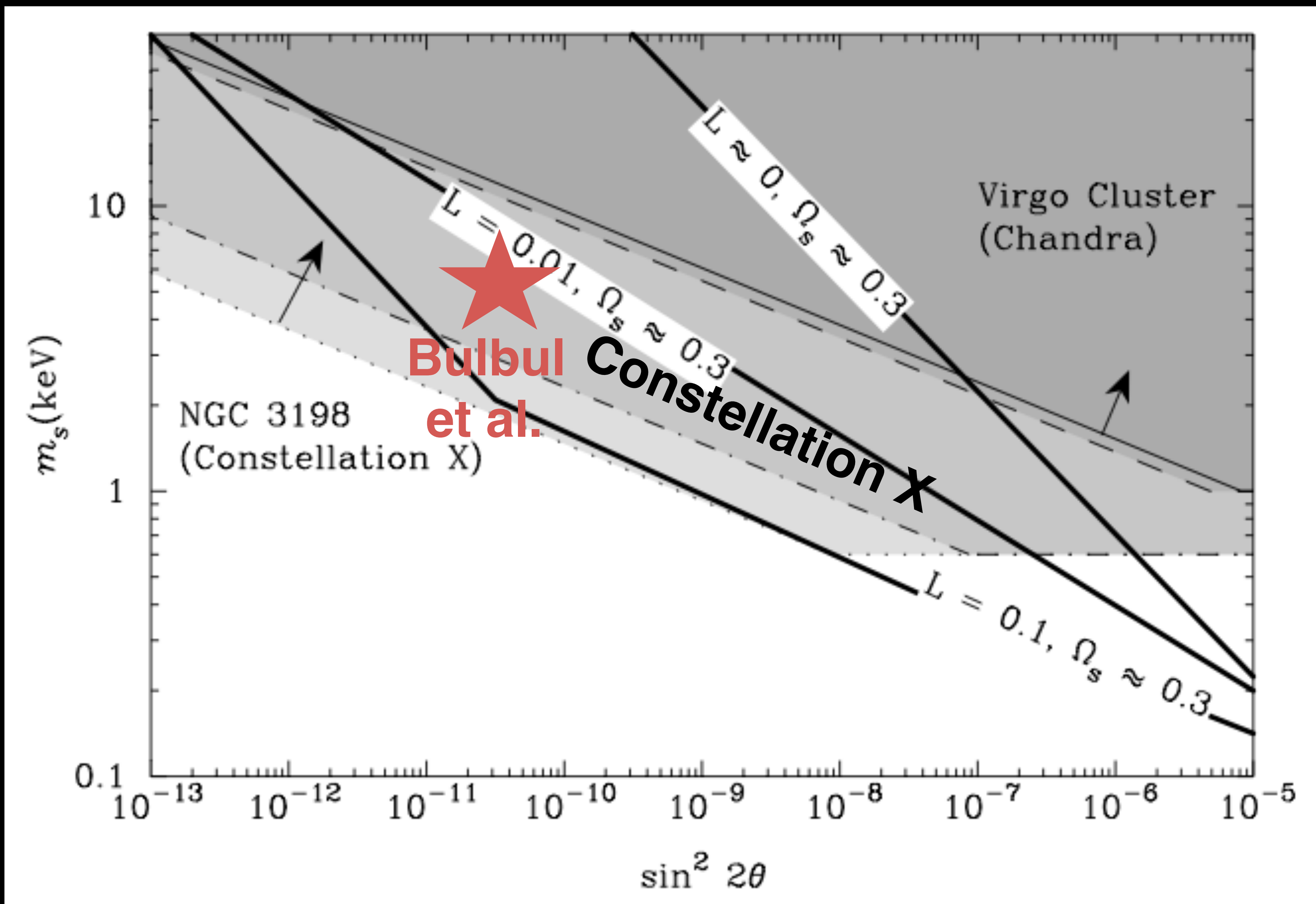
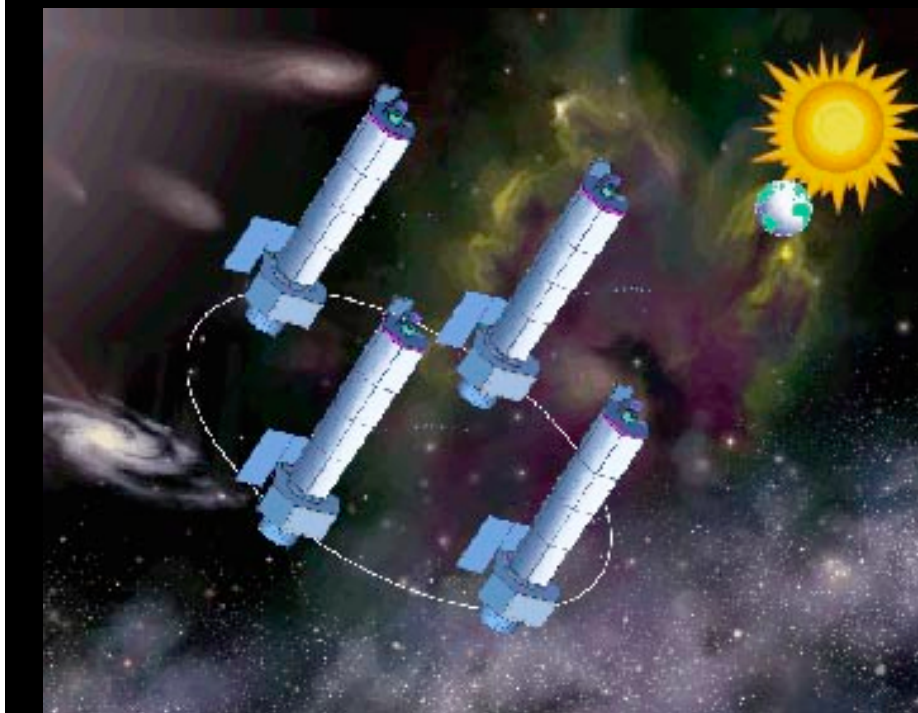


Virgo Cluster: 10^{78} DM particles

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

Abazajian, Fuller & Tucker 2001





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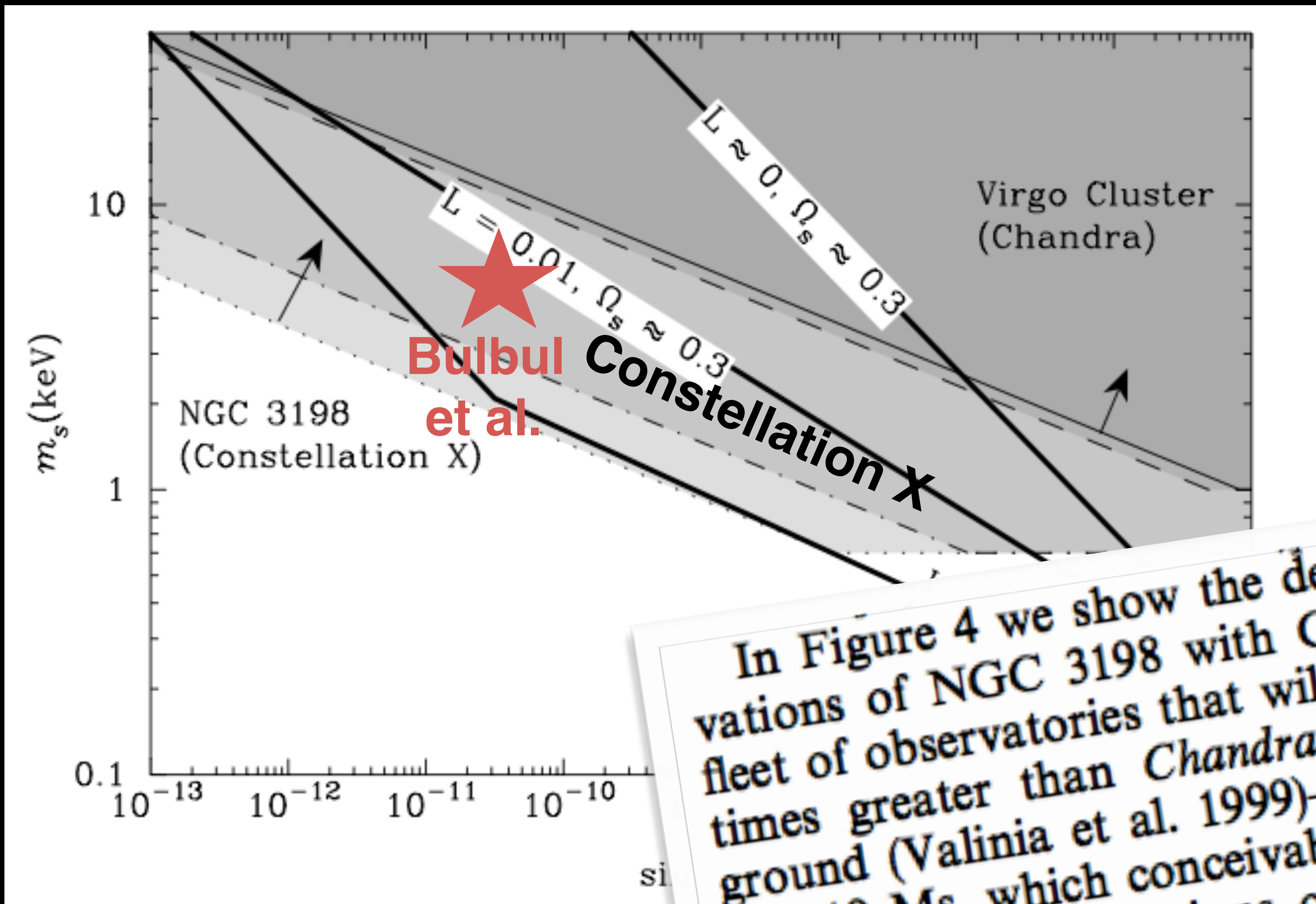
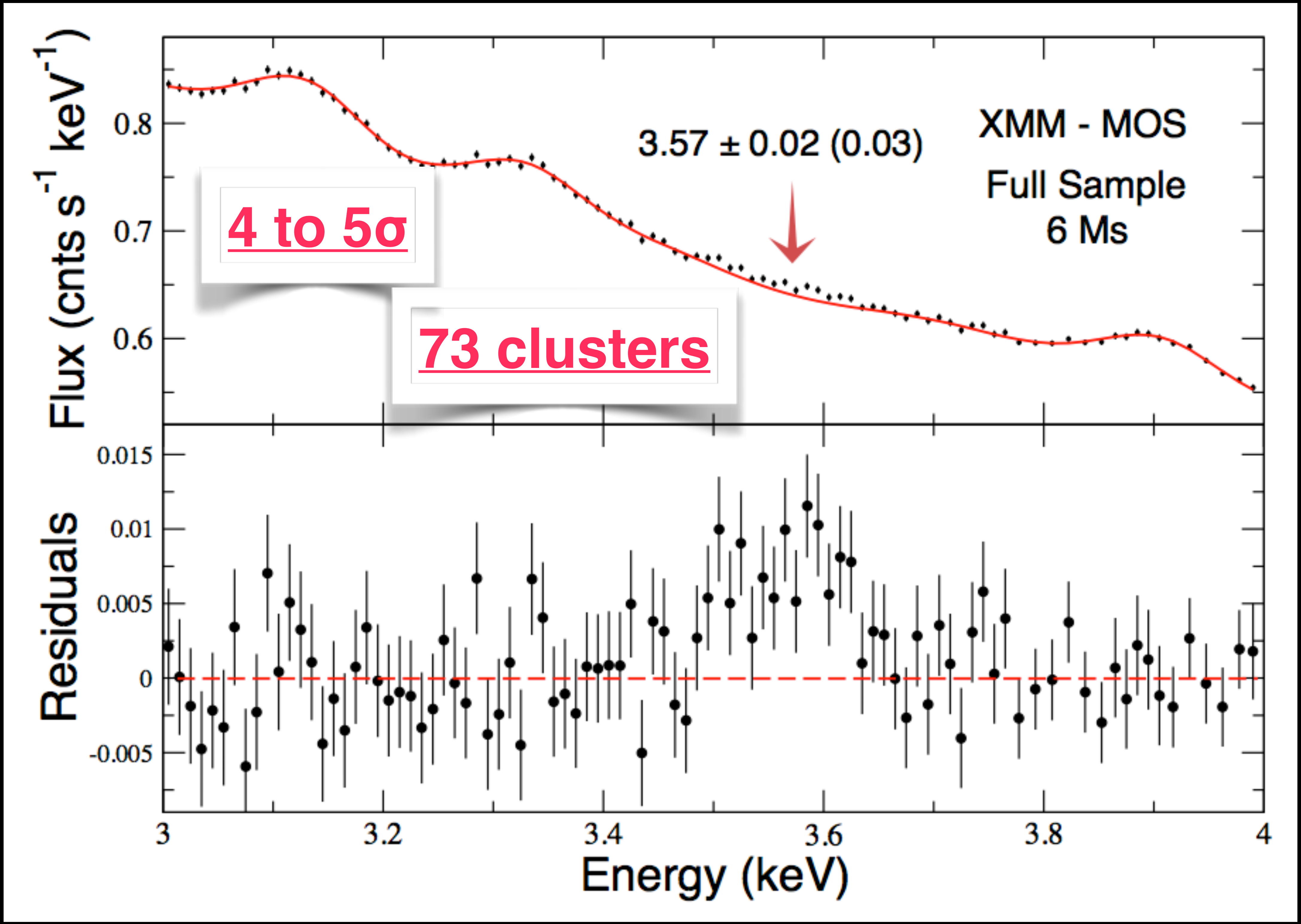


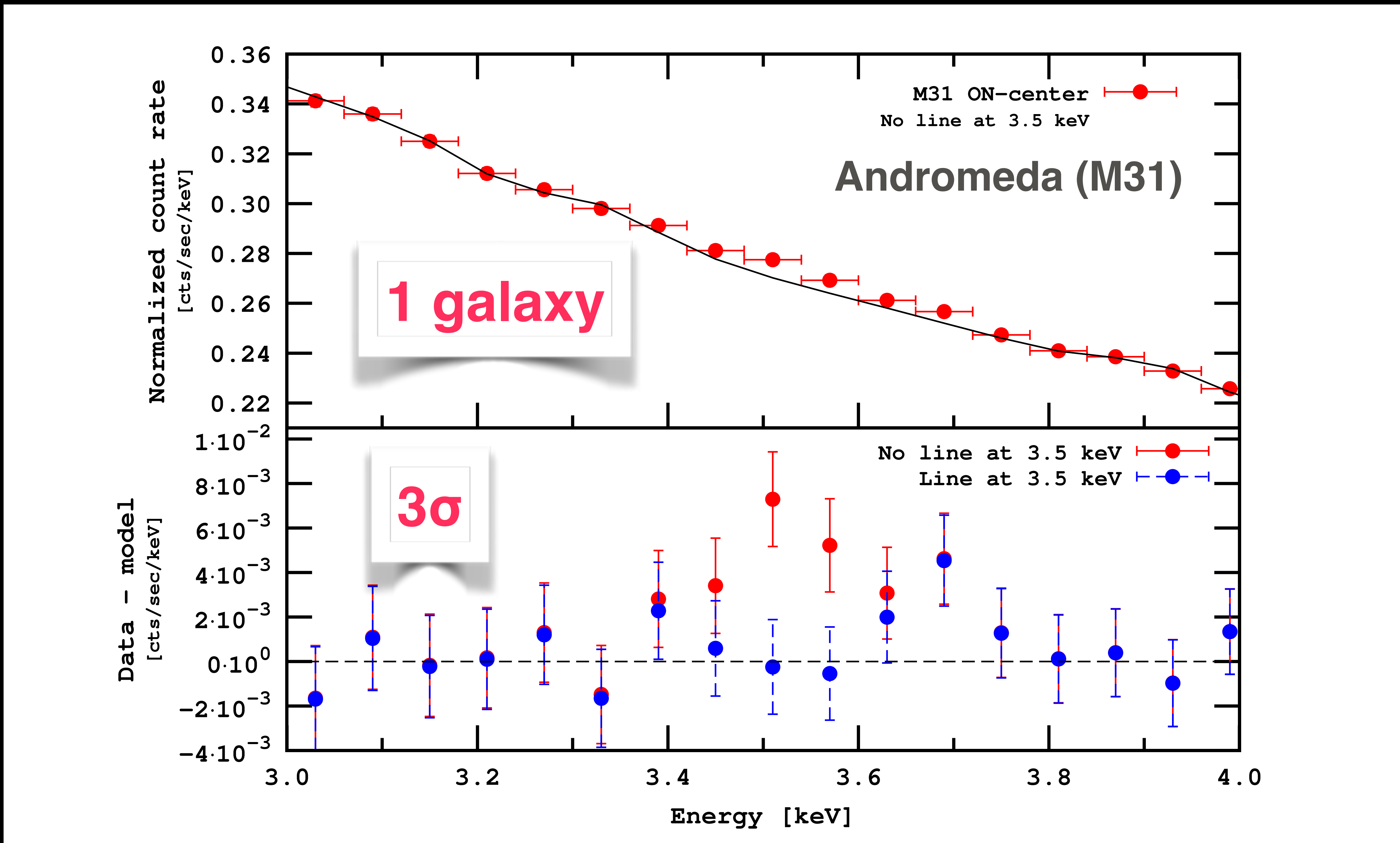
In Figure 4 we show the detectability region for observations of NGC 3198 with Constellation X—a proposed fleet of observatories that will have an effective area ~10 times greater than *Chandra* and no instrumental background (Valinia et al. 1999)—for two integration times, 1 and 10 Ms, which conceivably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



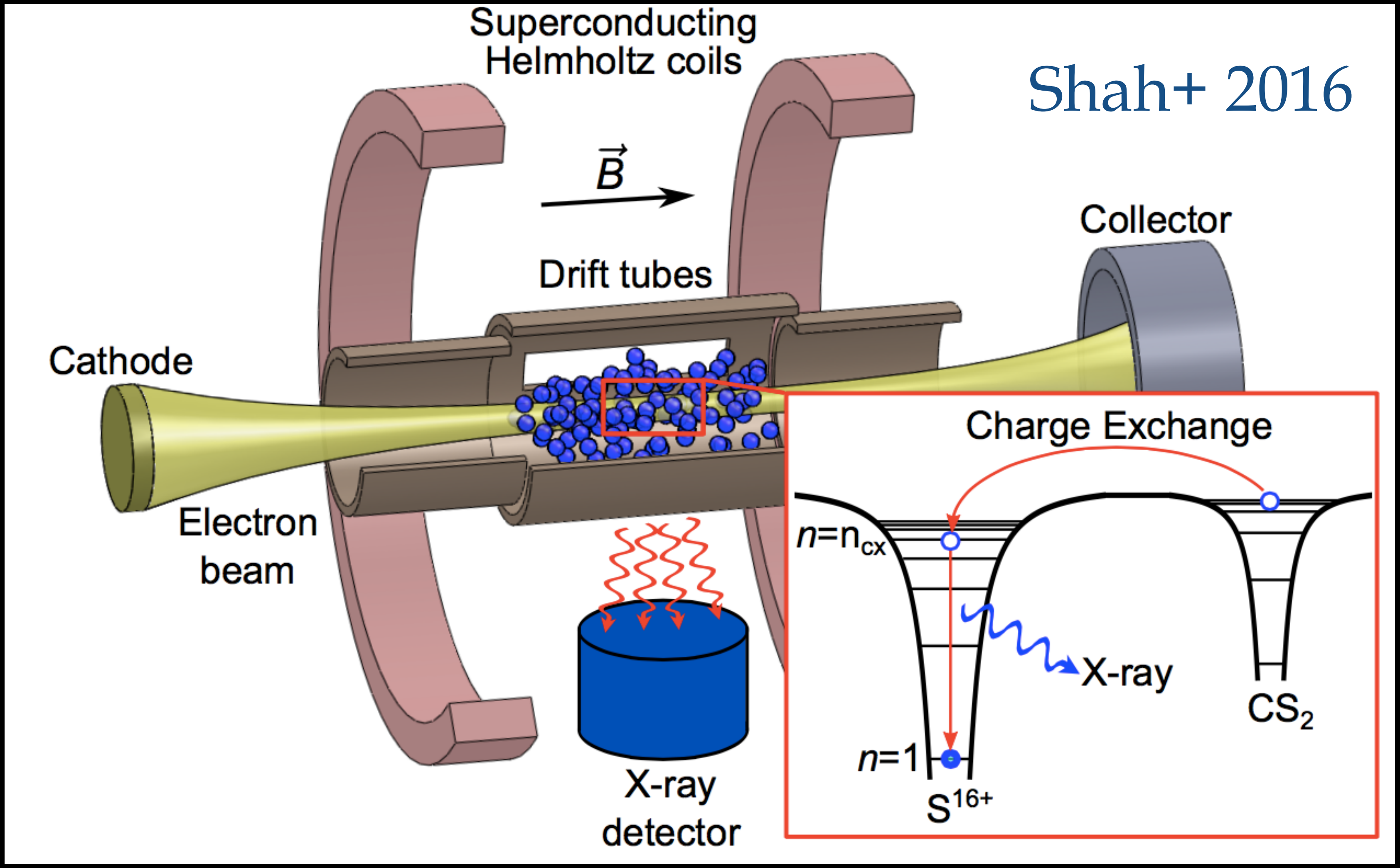
Bulbul et al. ApJ 2014

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

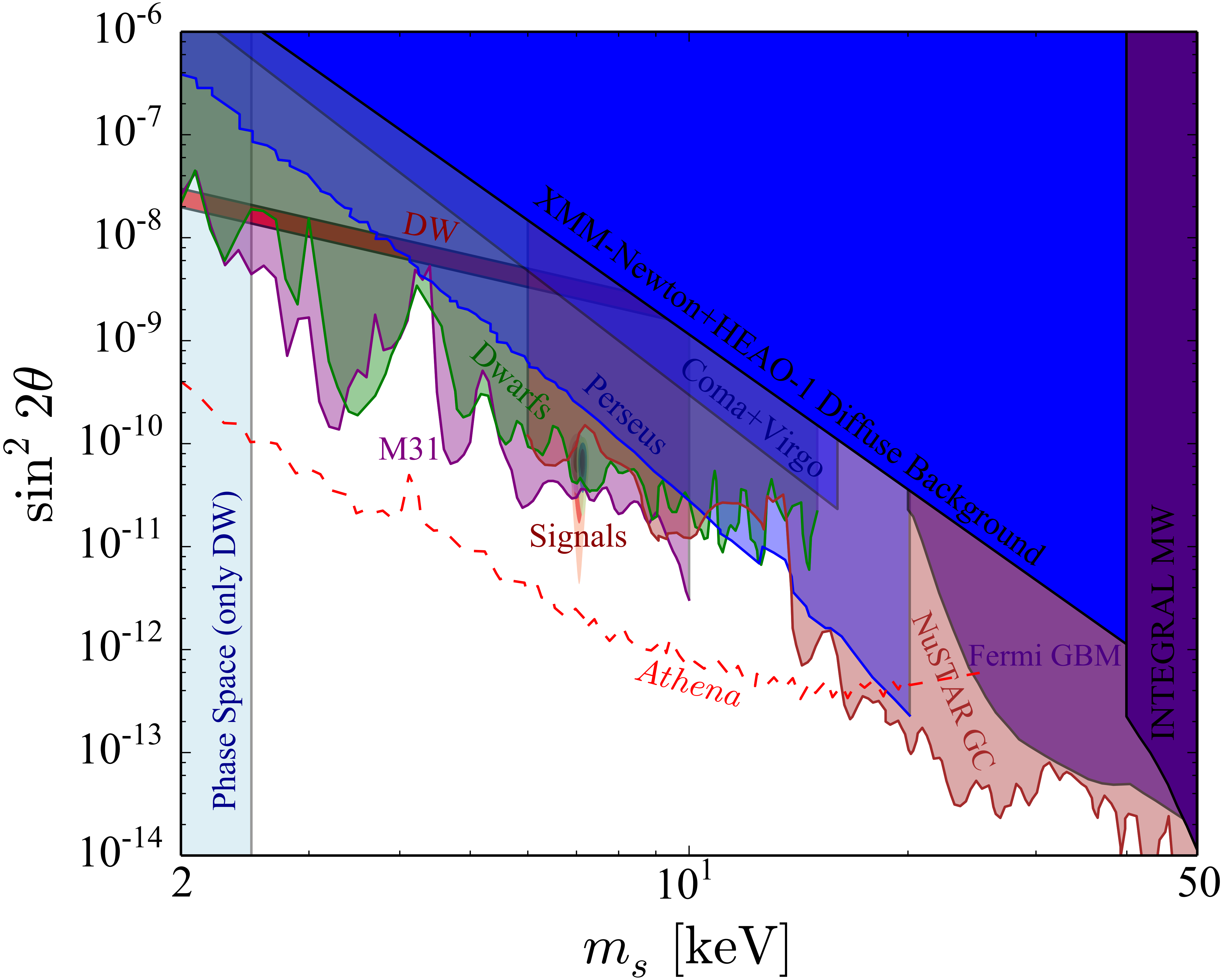
3 places it may have been expected

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

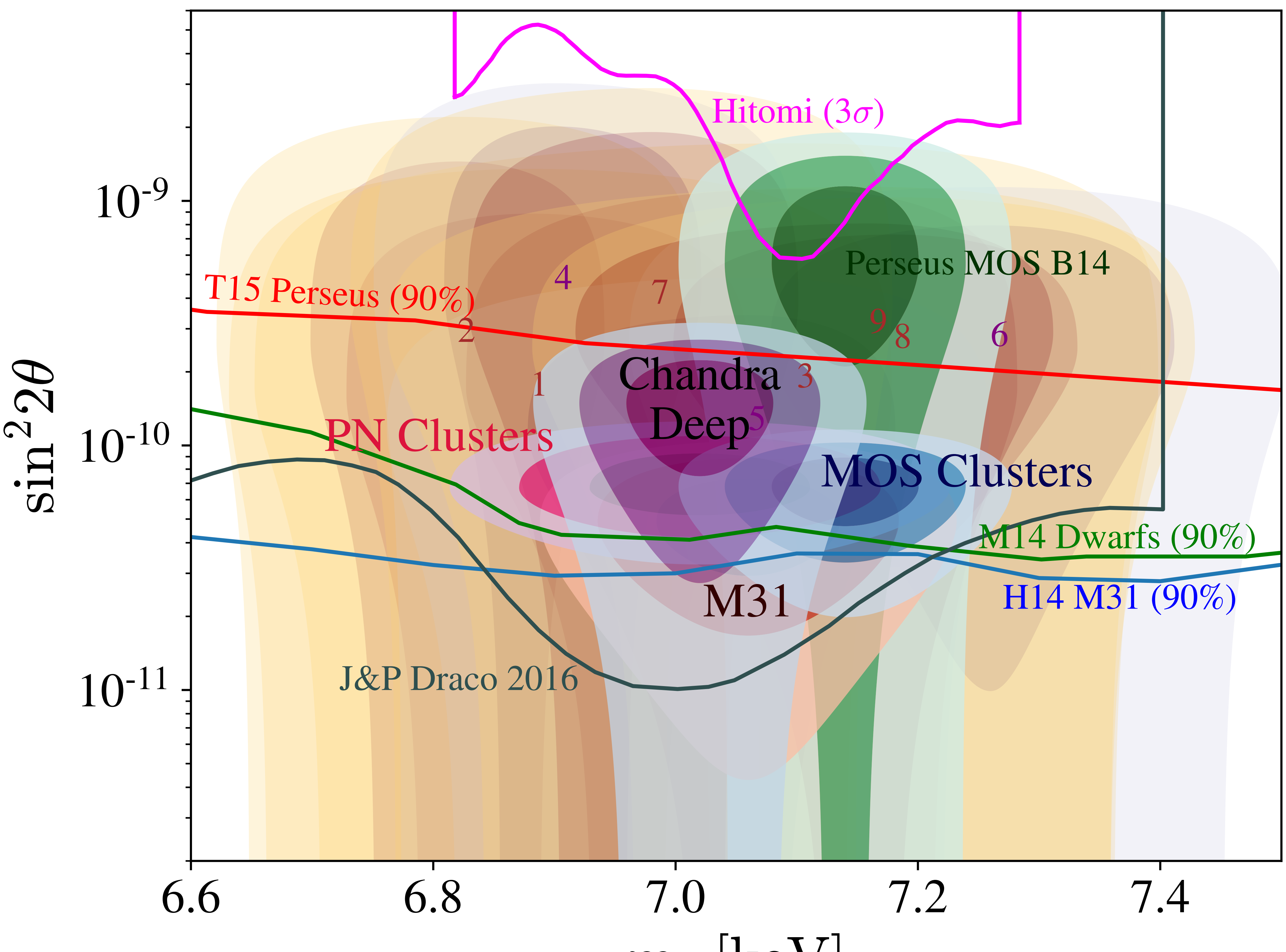
- **Stacked blank sky:** 30 Ms *XMM-Newton* data, 0.5 keV energy window analysis. Dessert, Rodd & Safdi arXiv:1812.06976

Sterile Neutrino Dark Matter: Parameter Space Summary



Abazajian *Physics Reports* arXiv:1705.01837

The 7 keV Region Today



Updated from Abazajian 2017

arXiv:1705.01837

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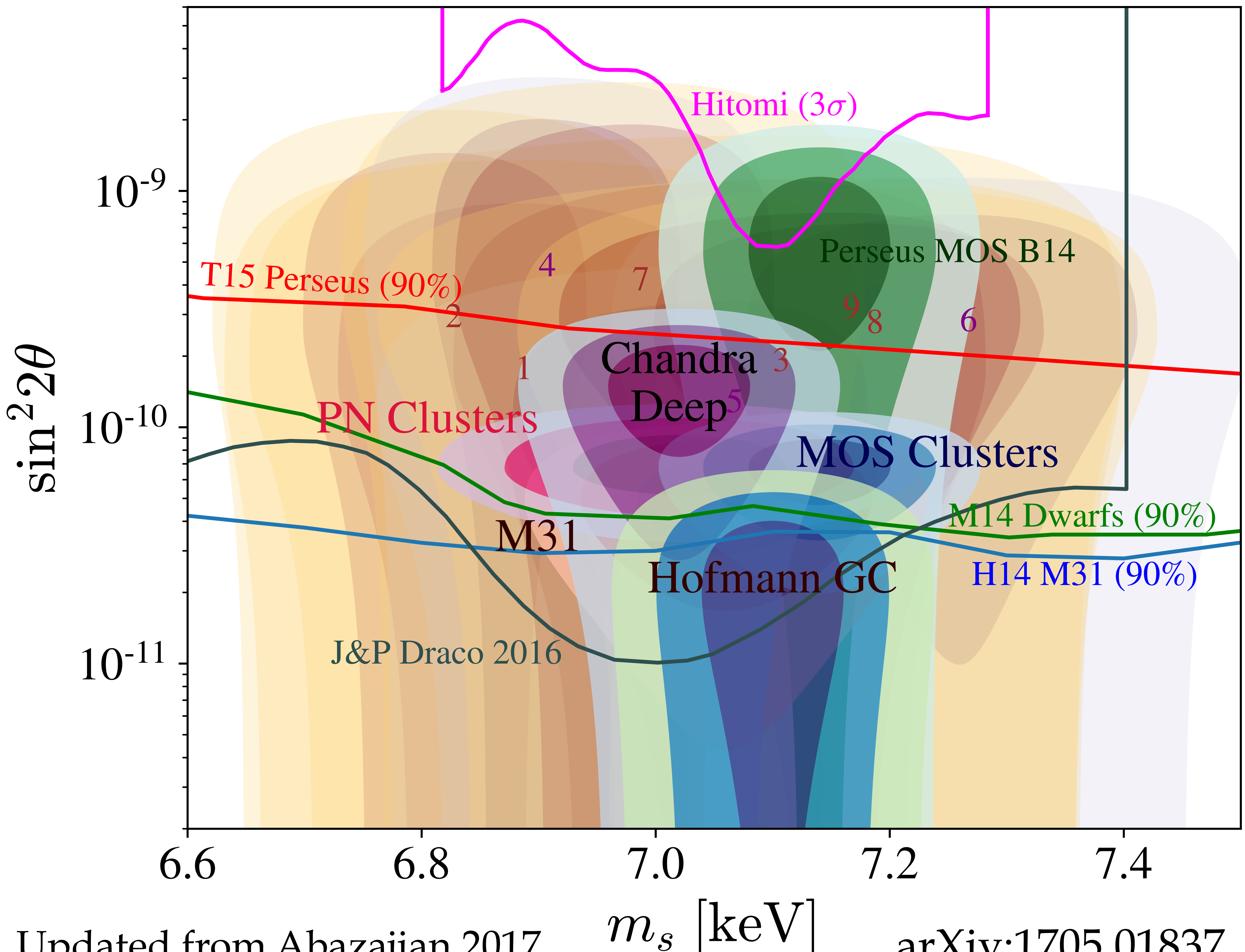

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Visibility of Dark Fermions

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

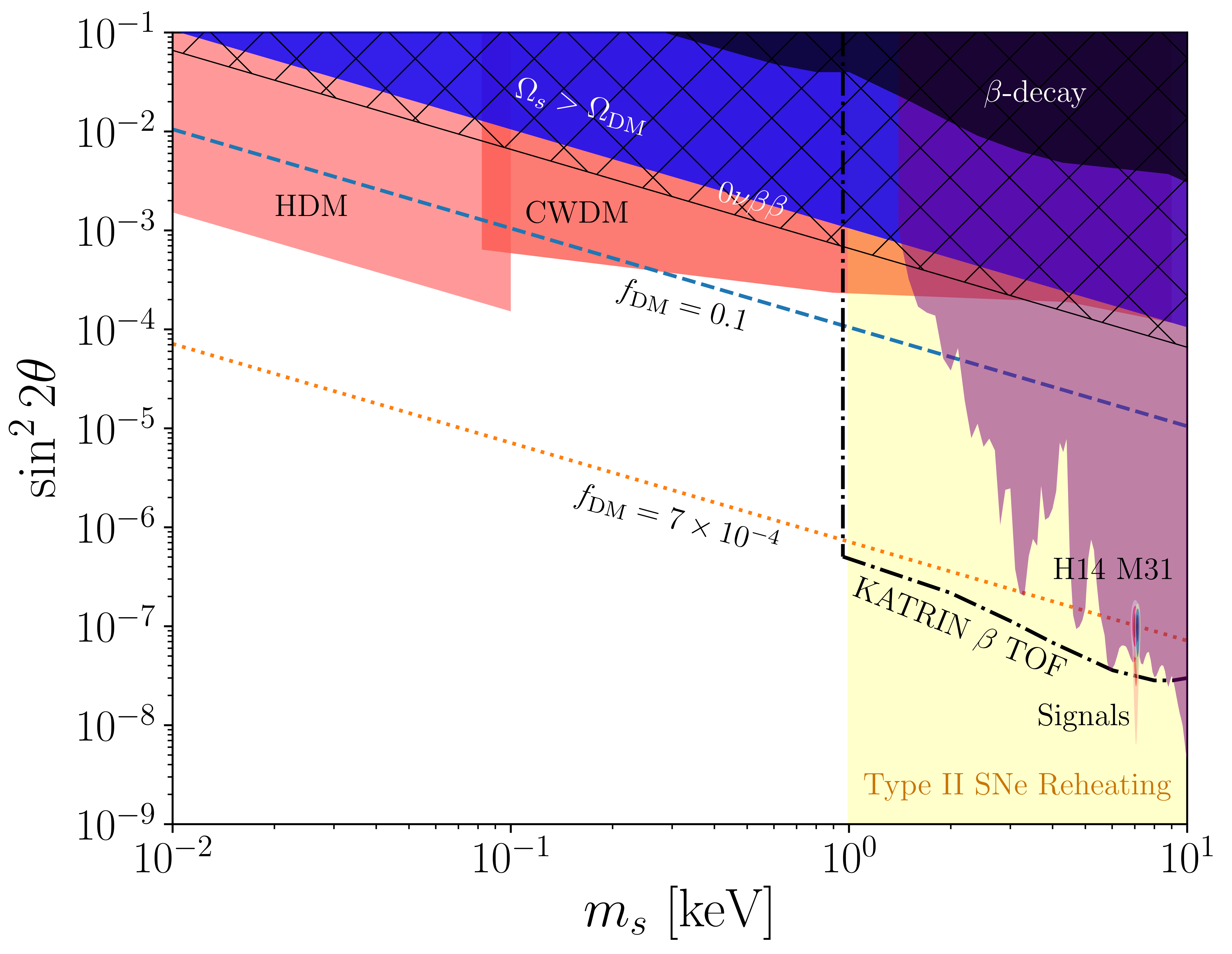
$$\mathrm{Flux} \propto f_{\mathrm{DM}} \sin^2 2\theta \qquad \text{but: } f_{\mathrm{DM}} \propto \left(\sin^2 2\theta\right)^{1.23} \ \text{(Abazajian 2005)}$$

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

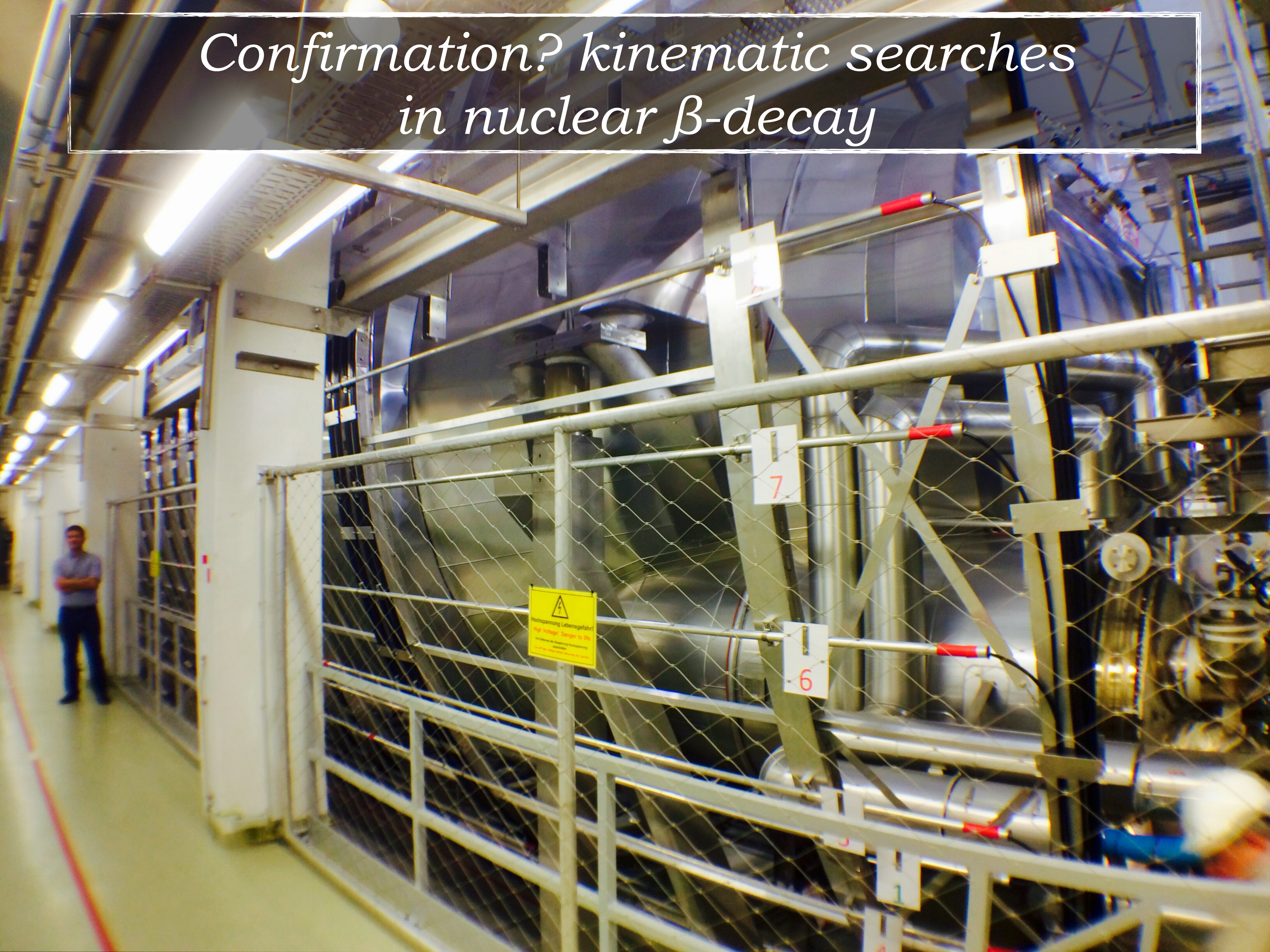
⇒Can achieve even larger mixing angles in low-reheating temperature universes (Gelmini, Palomares-Ruis & Pascoli 2004)

⇒ 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



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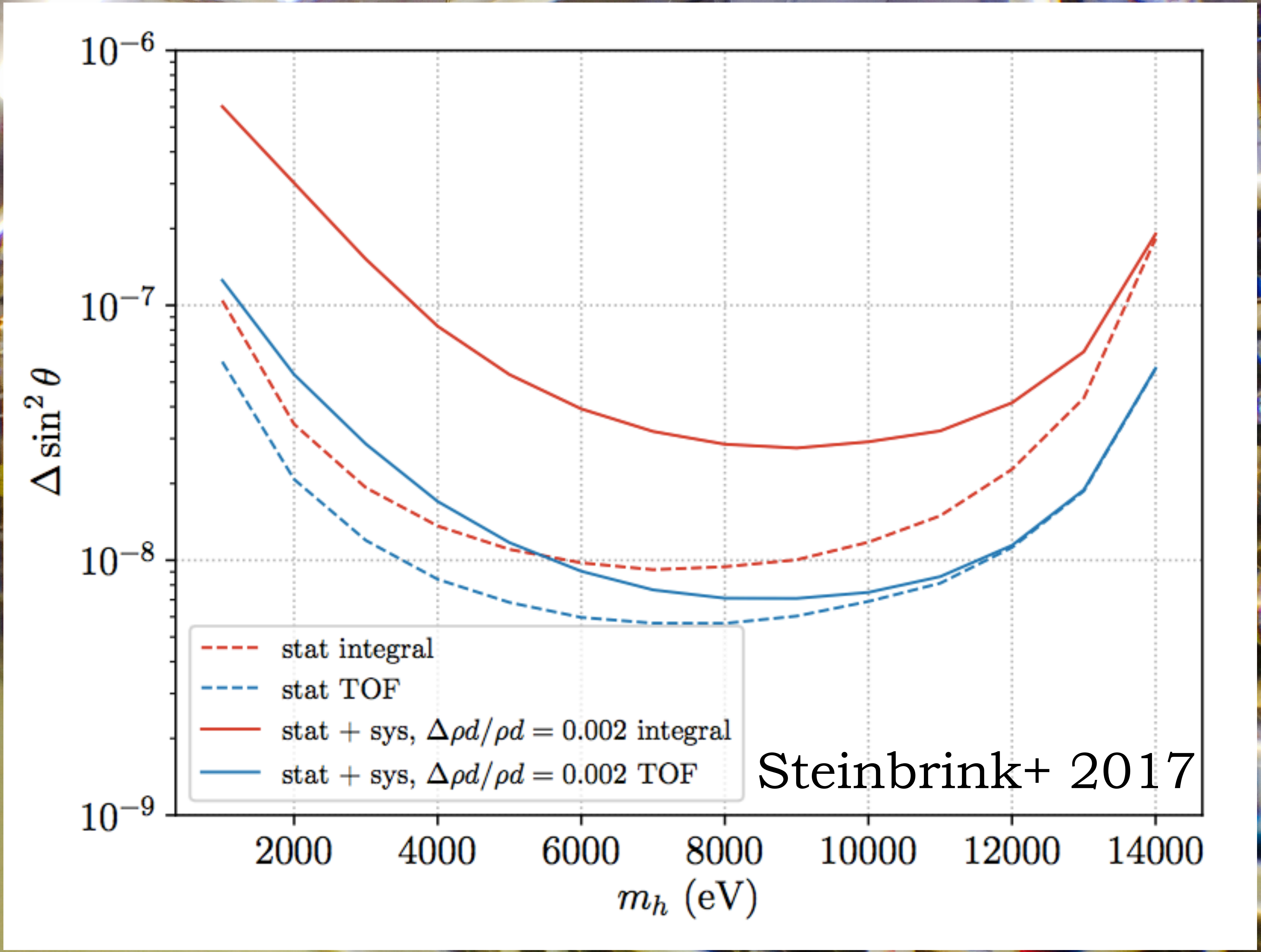
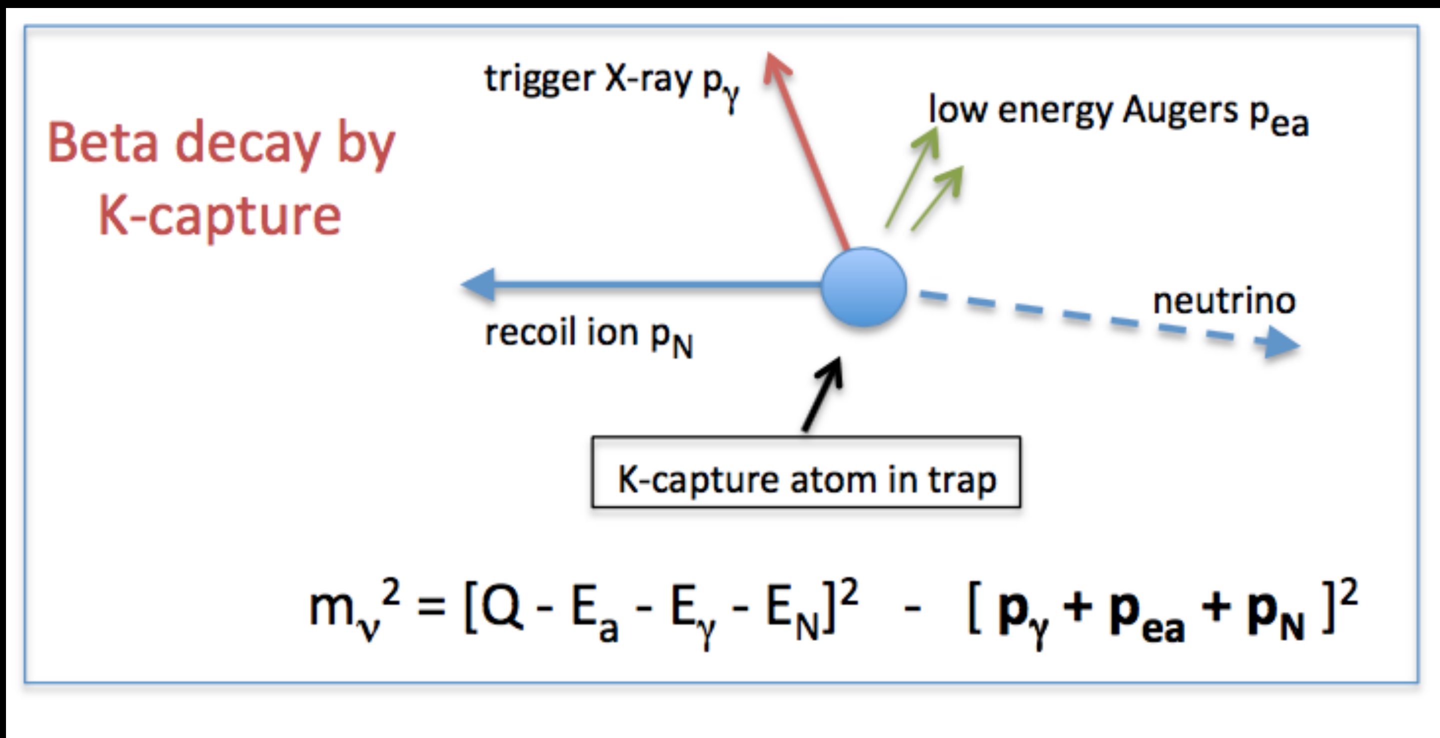


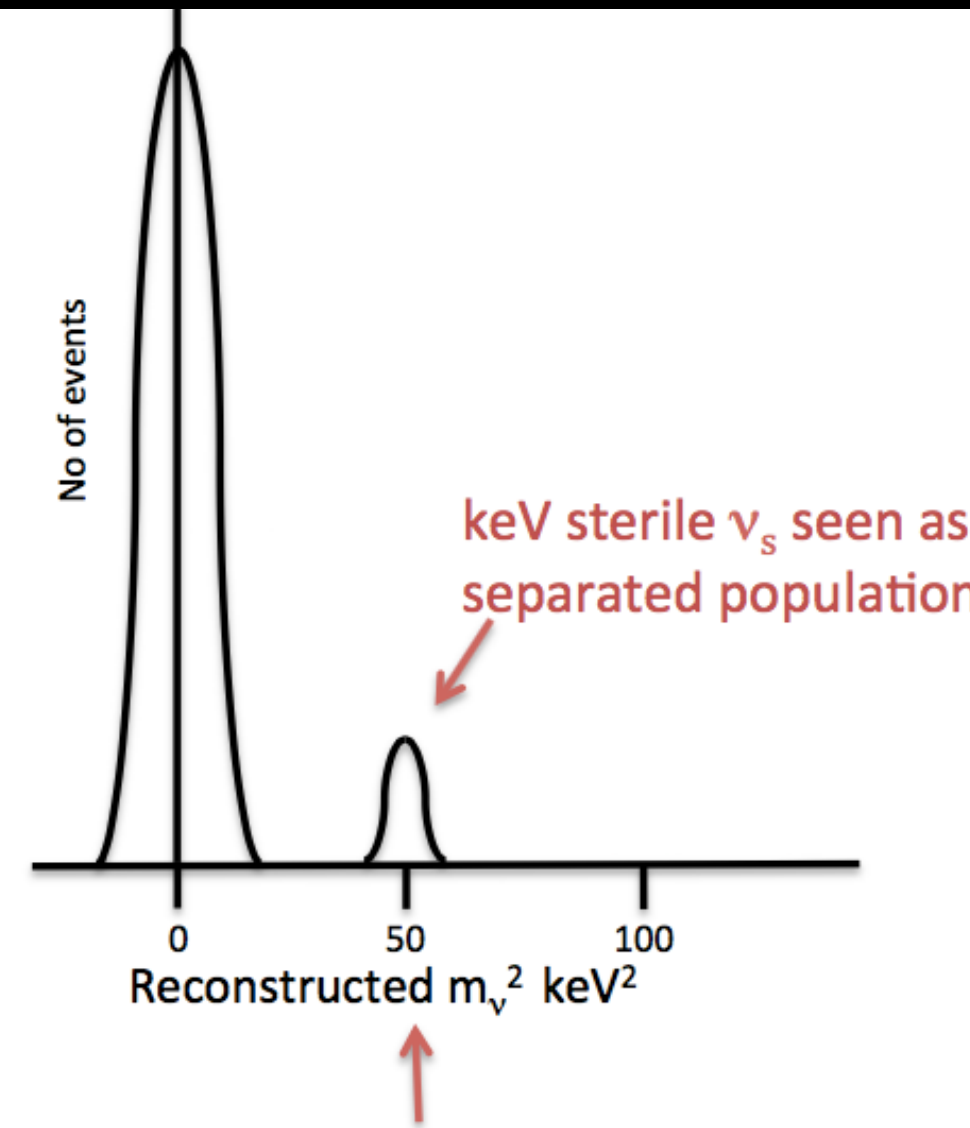
Laboratory Method: full kinematic reconstruction of K-capture nuclear decay



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

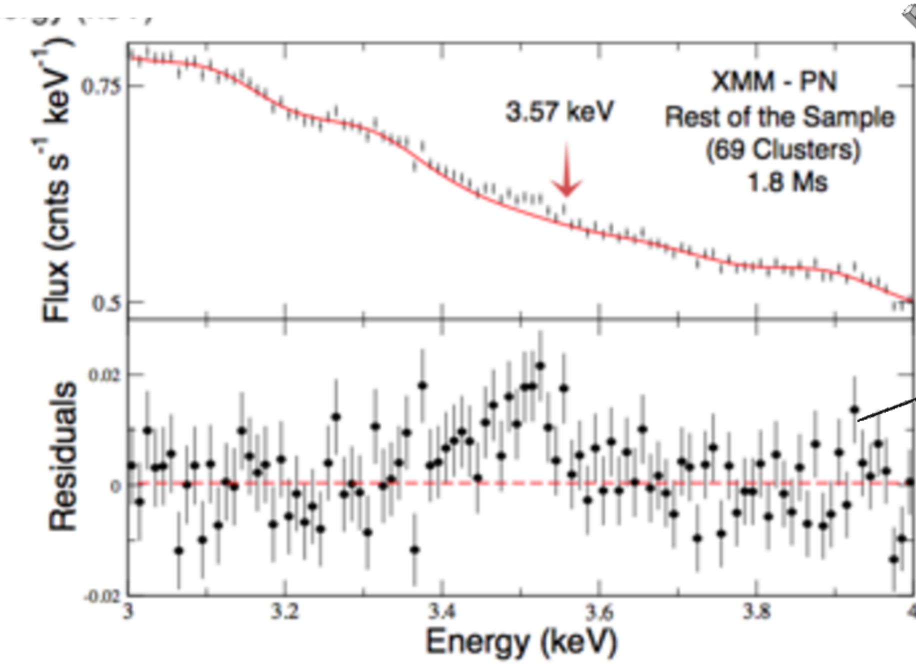


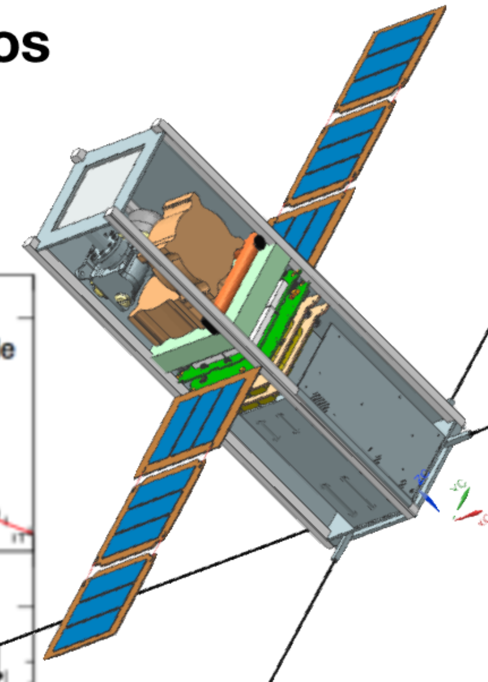
High precision time of flight measurements needed to achieve 6σ separation from zero mass peak

Recent studies show this may now be feasible

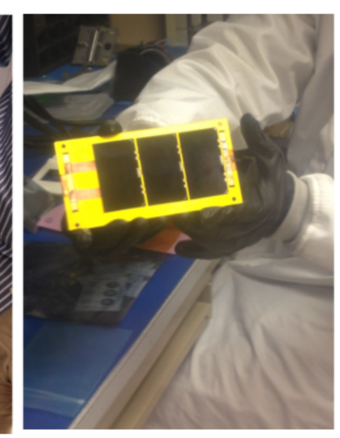
New Technology: New CCDs plus CubeSats

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

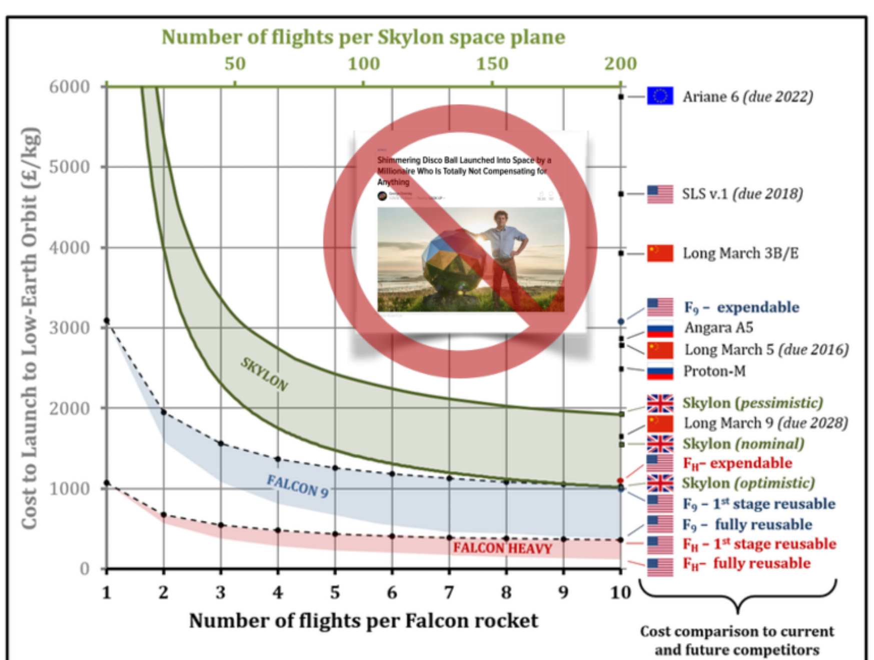




A cubeSat with a large CCD detector (DESI size) with good energy resolution (maybe skipper) in low earth orbit could go after this signal in our own galaxy. Others (Tali et al) are planning to do this with a “CDMS” detector in a rocket. A couple of summer students work on a conceptual design.



partnership with UIUC (aerospace)



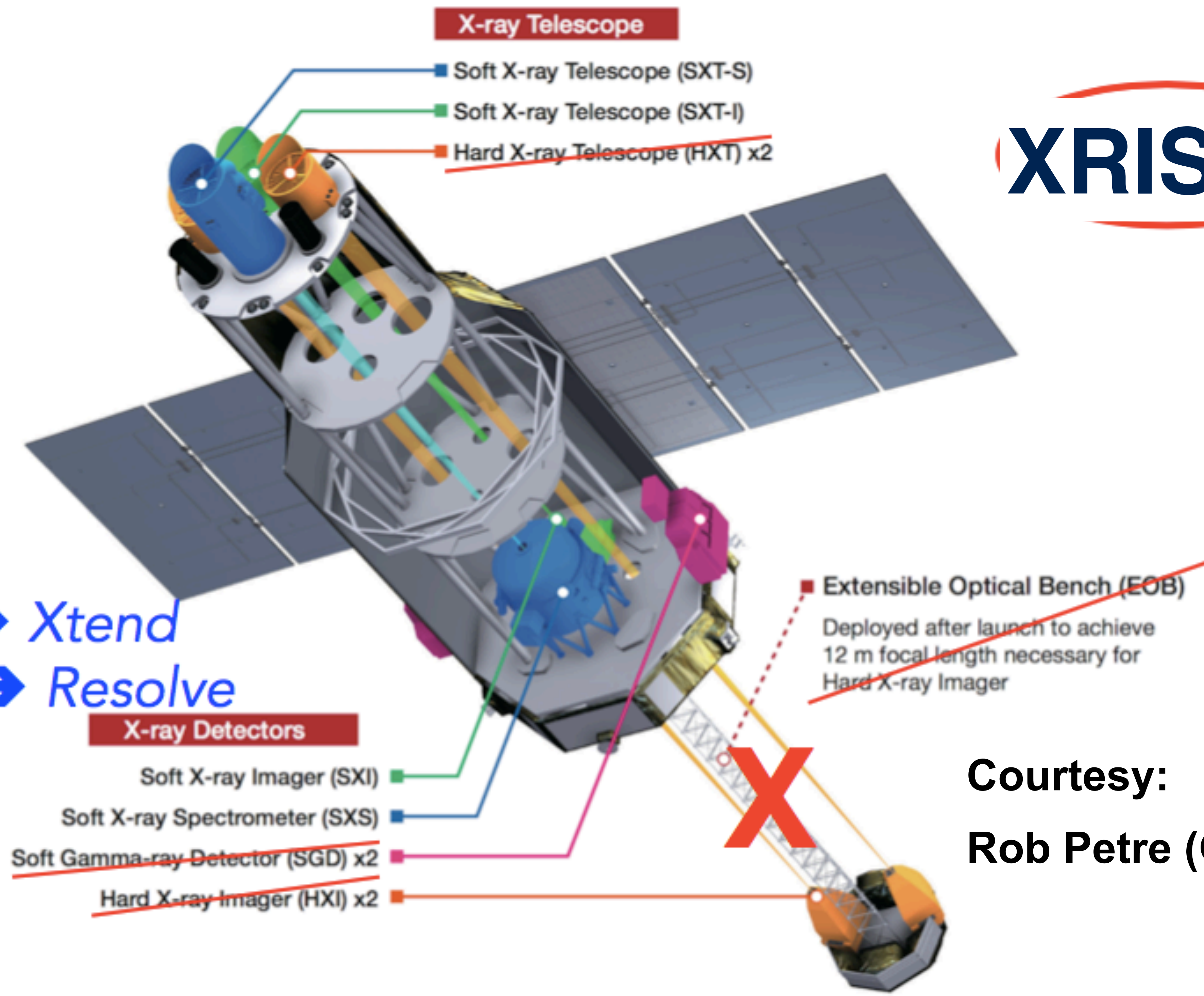
LDRD proposal by S. Timpone

opportunity:

- look for 3.5 signal
- train our engineers in space applications
- new partnerships
- **<u>get in better shape to take advantage of “cheap space”</u>**

Next Space Mission in X-ray Astronomy

X-ray Imaging and Spectroscopy Mission **XRISM**



SXI+SXT → *Xtend*

SXS+SXT → *Resolve*

Courtesy:

Rob Petre (GSFC)

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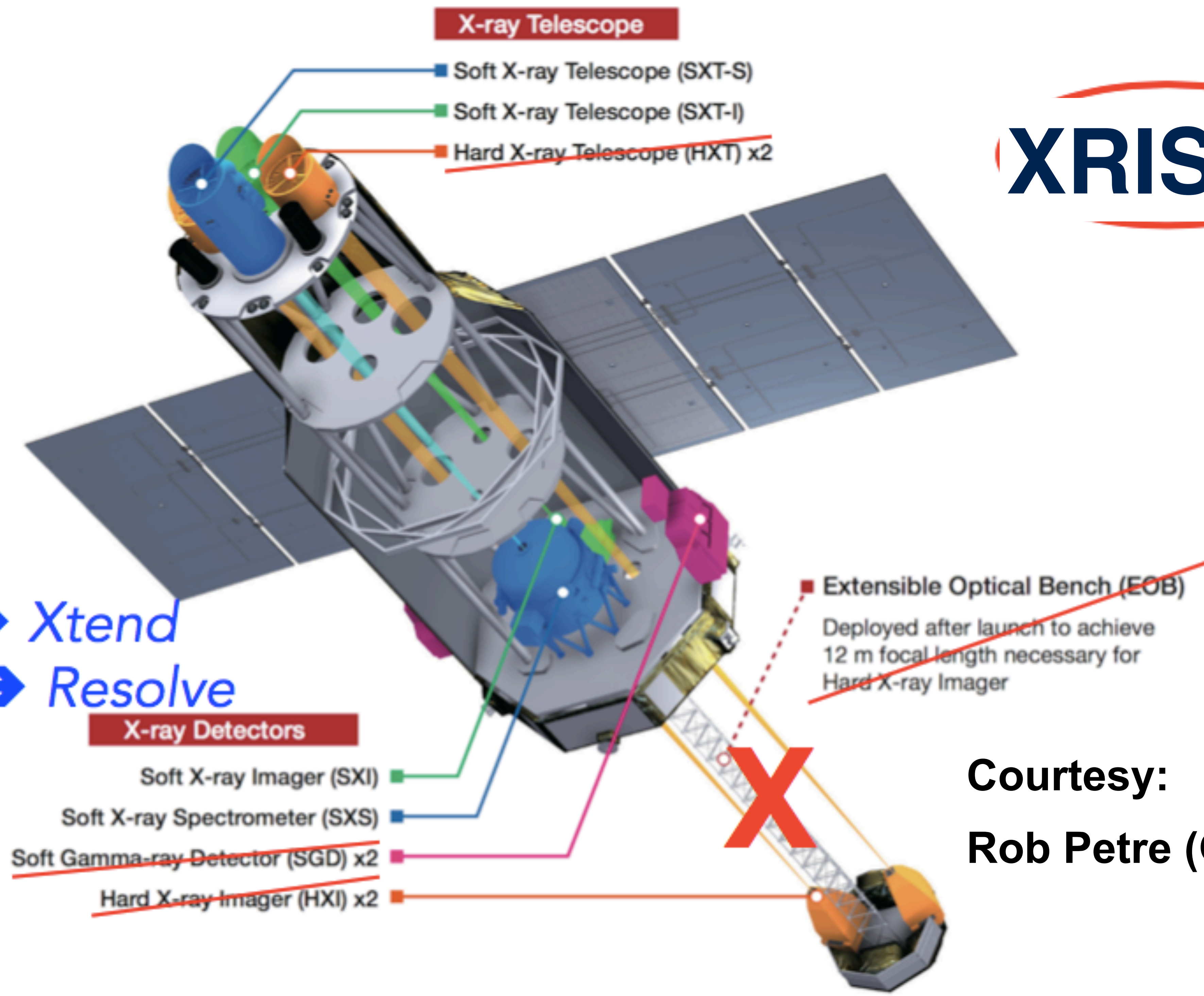

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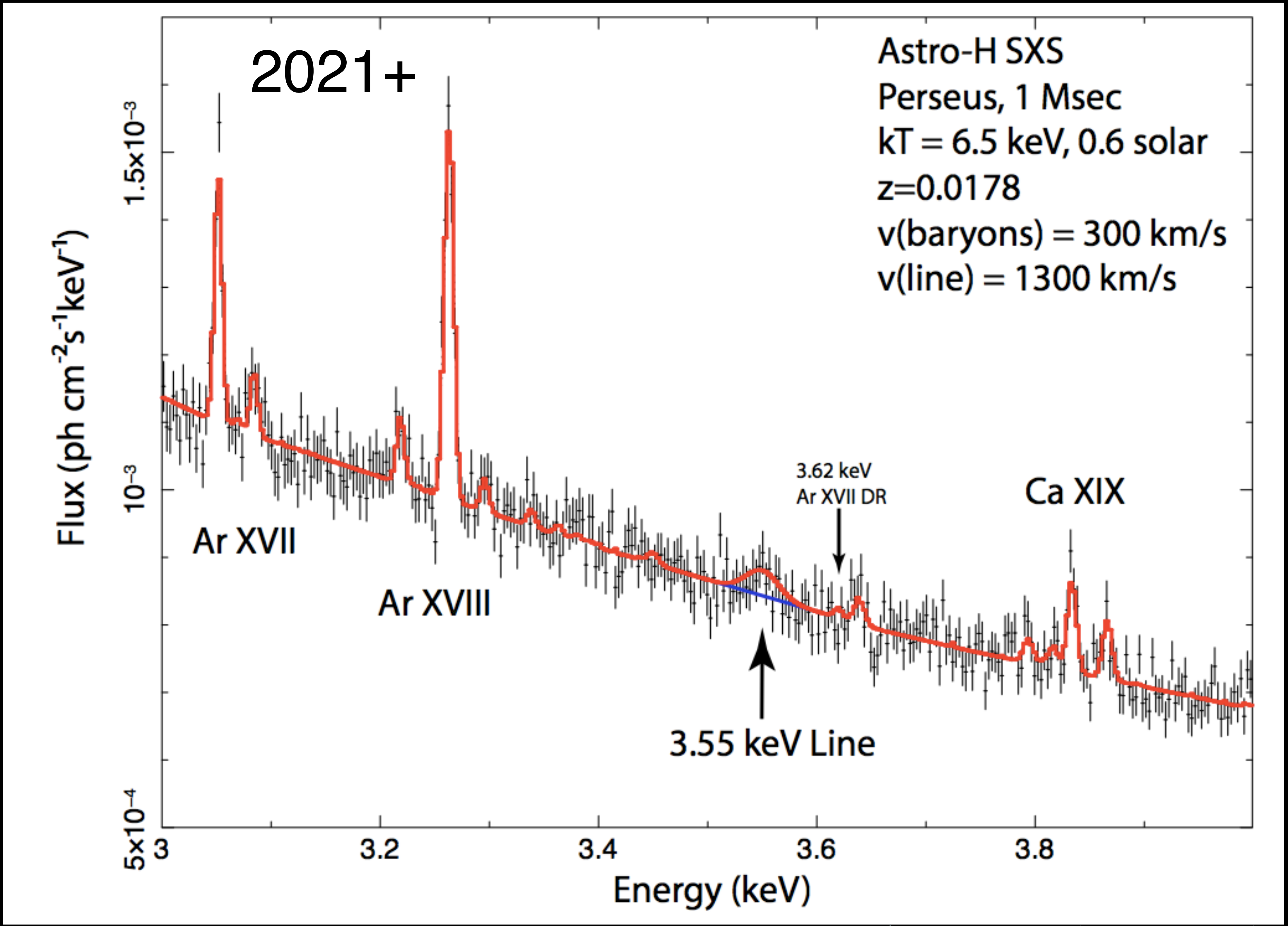
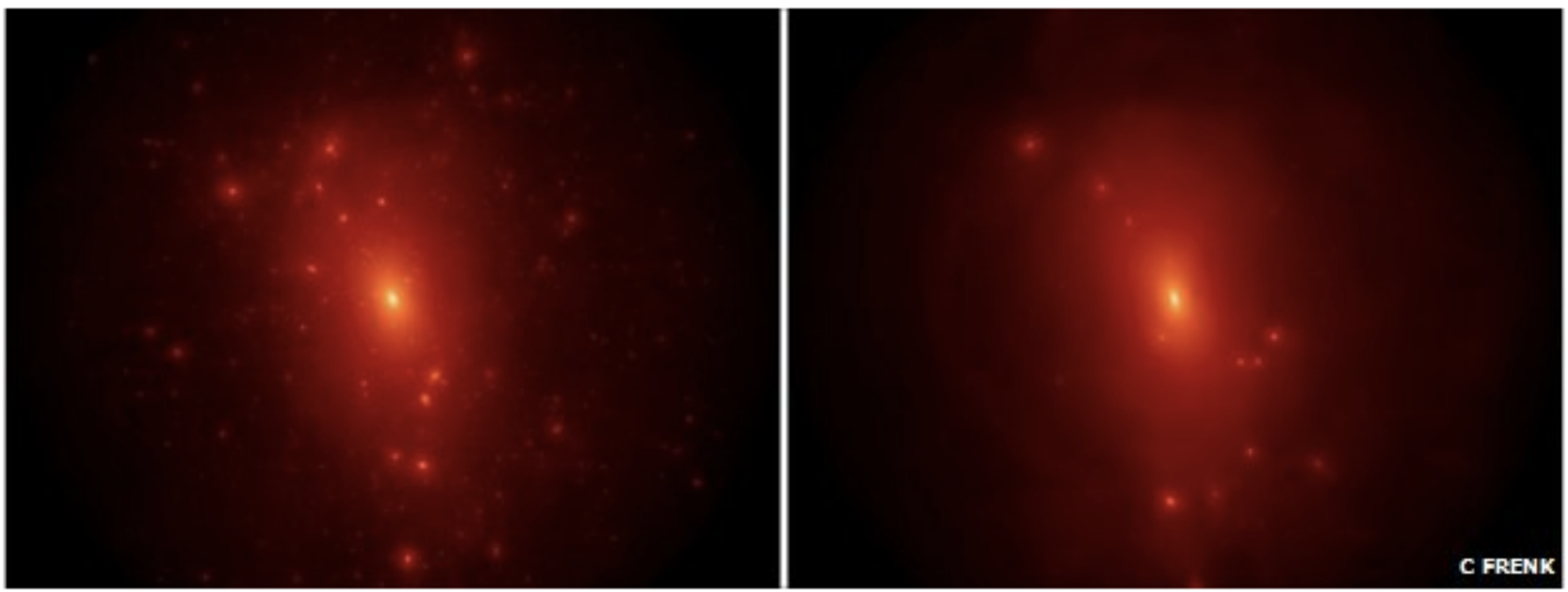
Confirmation: XARM Space Telescope



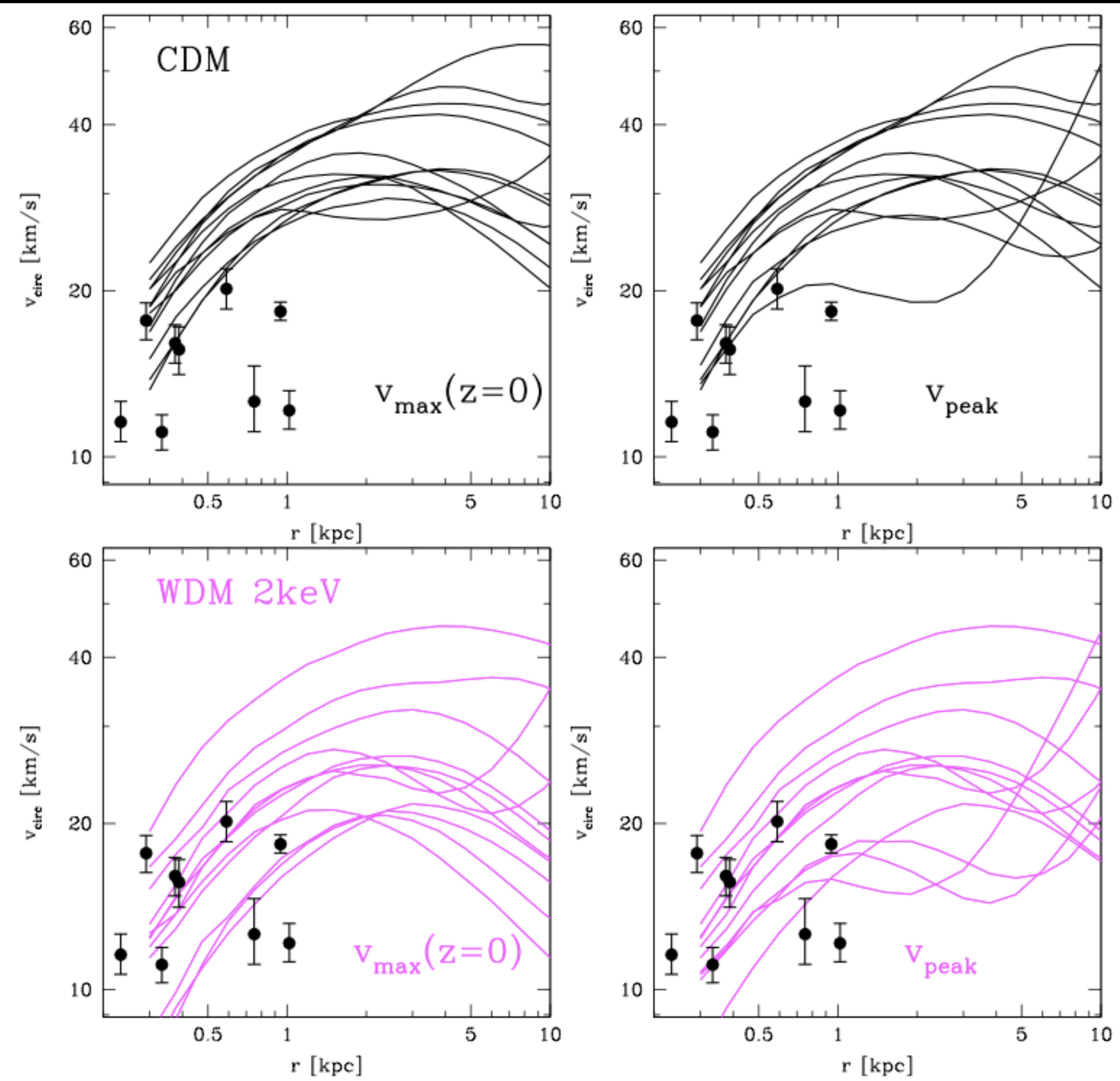
Bulbul et al. ApJ arXiv:1402.2301

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:
"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:
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arXiv:1512.04548
Bozek+
arXiv:1512.04544

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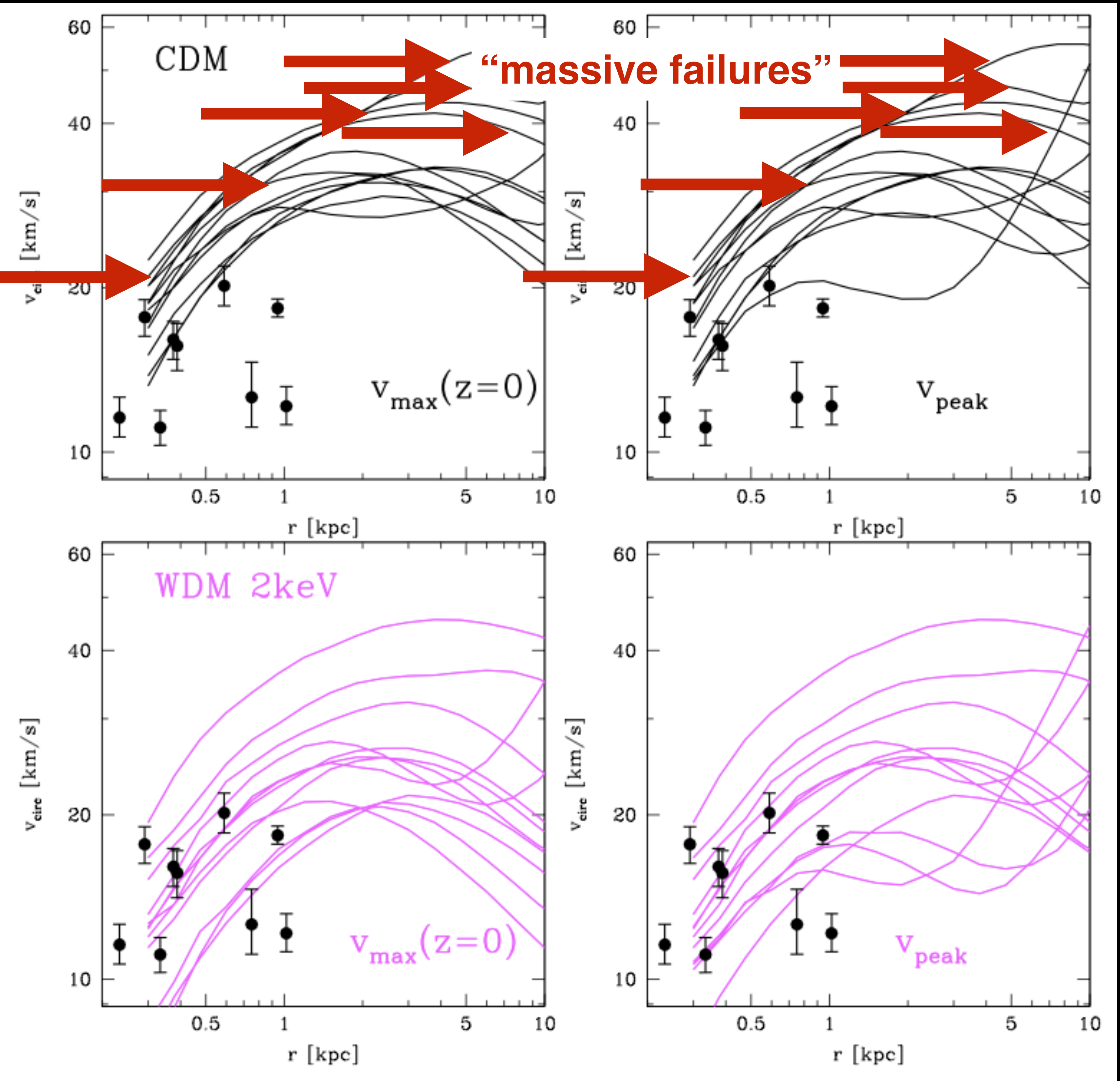

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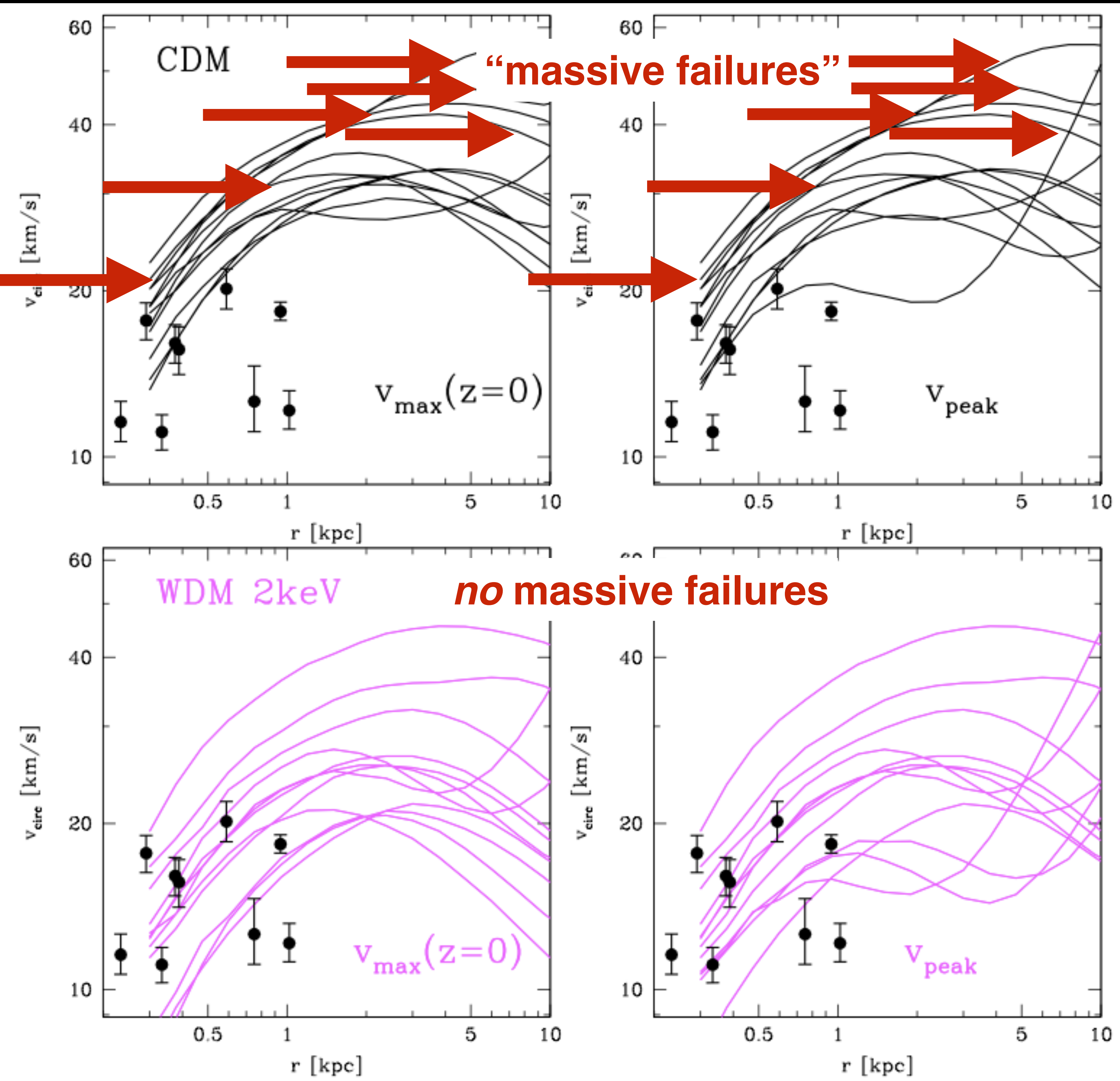

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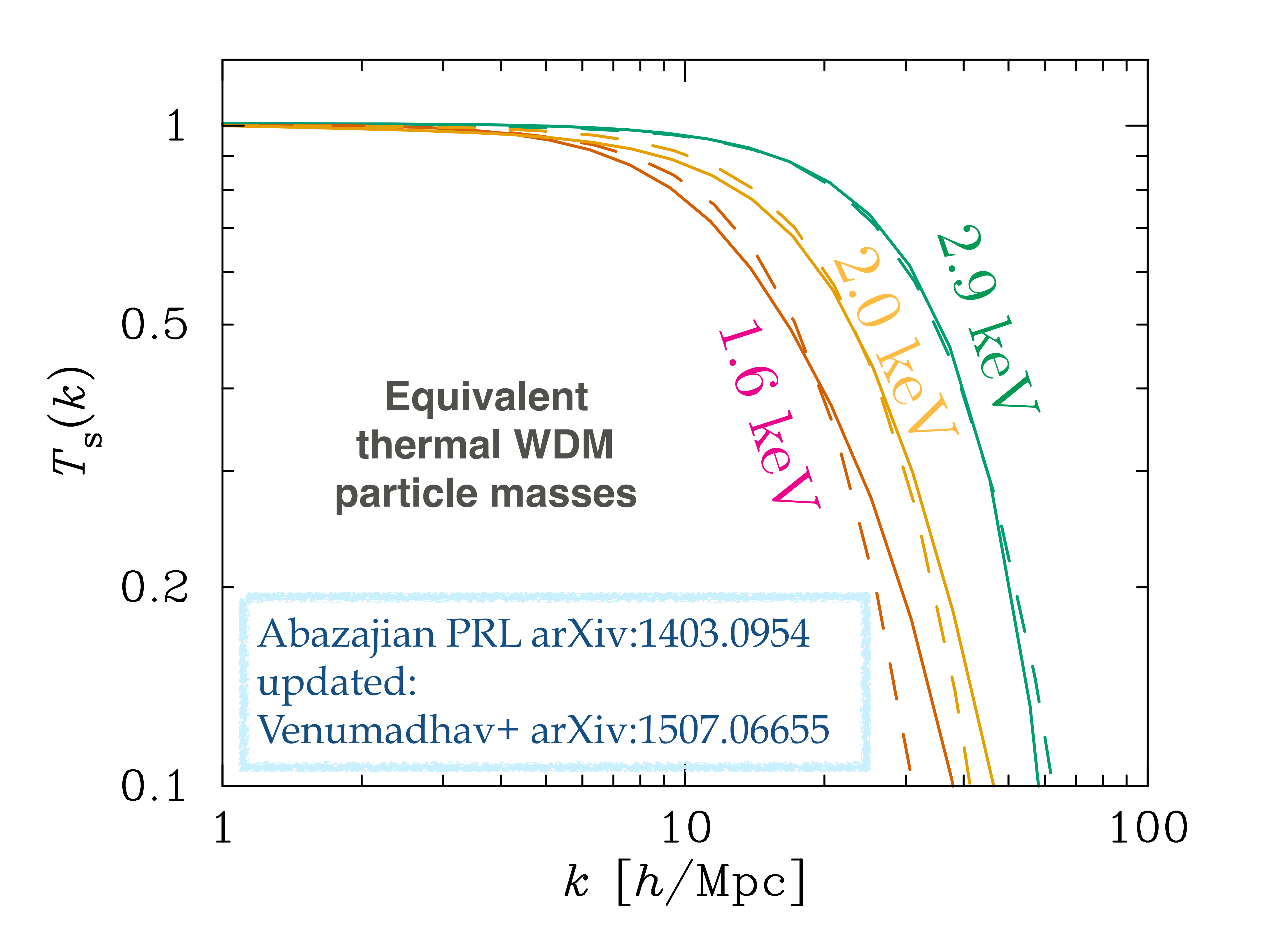
7 keV Resonant Sterile Neutrino: Free streaming cutoff is very different, even for the same particle mass



What is the relationship between particle mass and warm dark matter effects?

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$$\lambda_{\rm FS} = \int_0^{\rm EQ} \frac{v(t)dt}{a(t)} \approx 40\,{\rm Mpc}\left(\frac{30\,{\rm eV}}{m_\nu}\right)\left(\frac{\langle p/T\rangle}{3.15}\right)$$

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Cowsik-McClelland/Gershtein-Zeldovich bound: $\Omega = \dfrac{M}{94.1h^2\,\mathrm{eV}} < 1$

Thermal WDM

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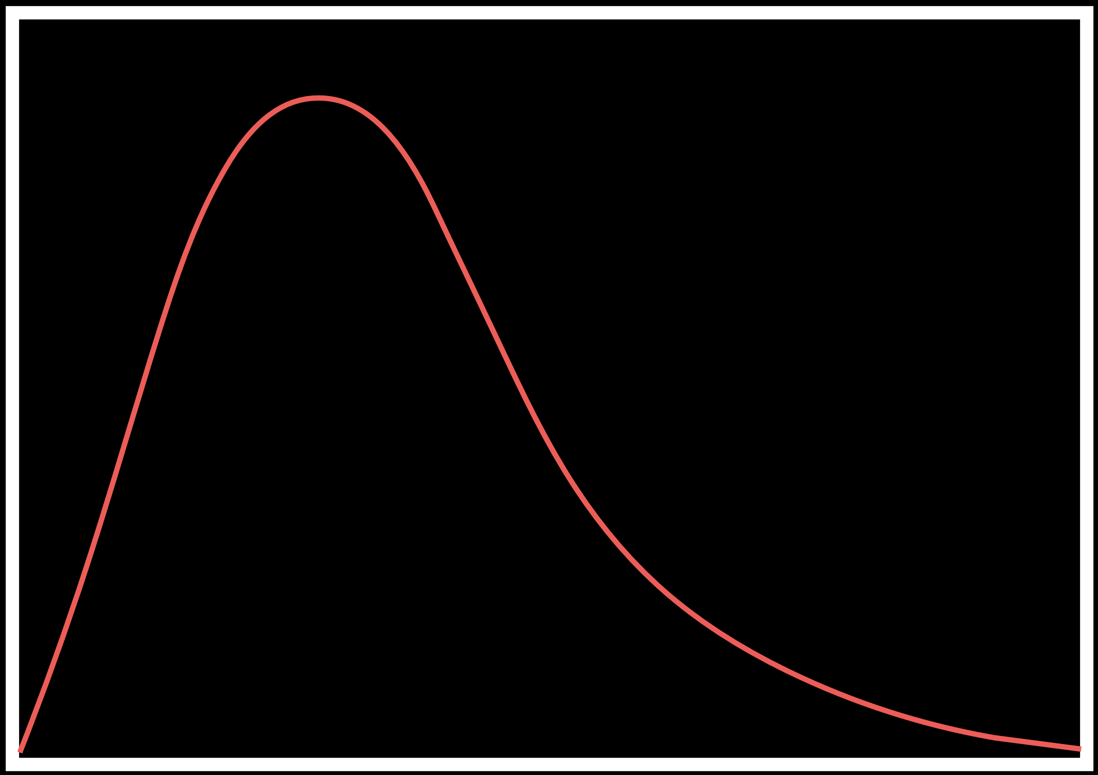

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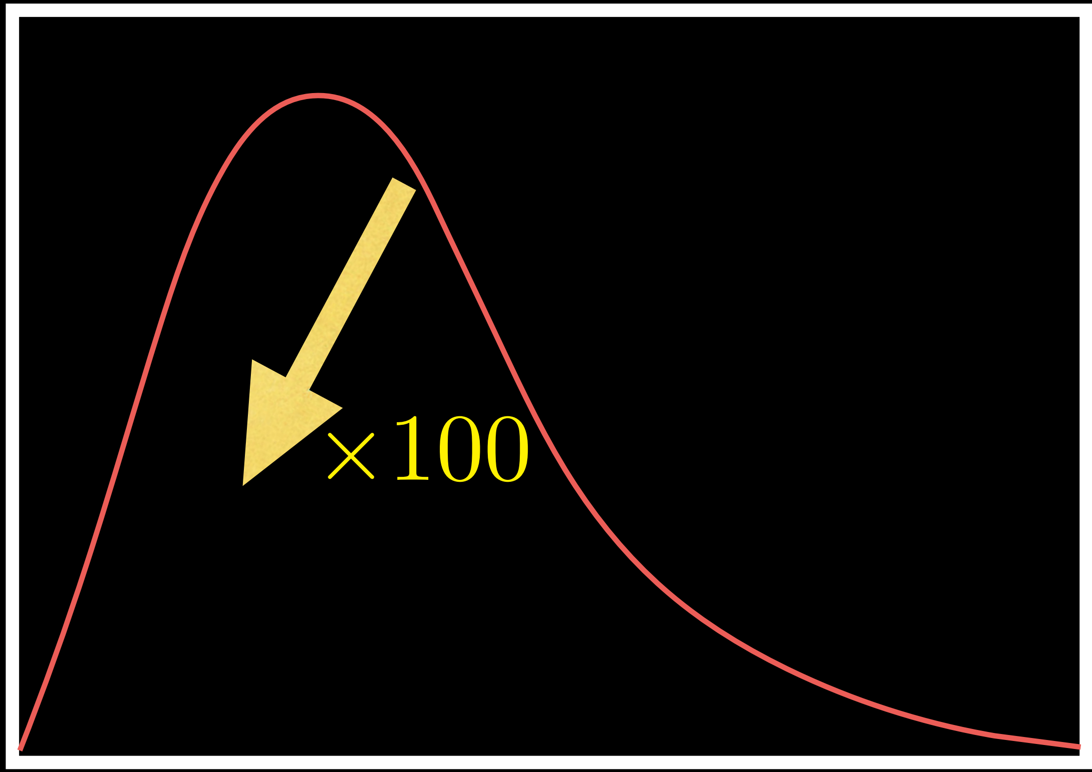

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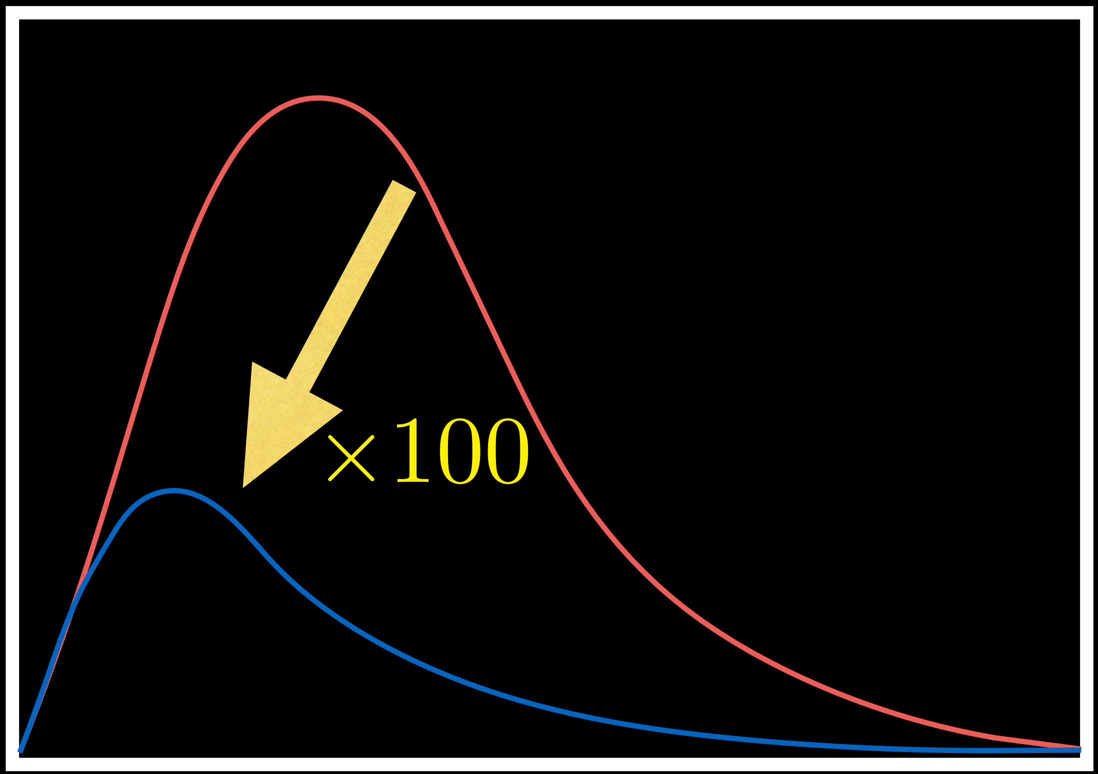

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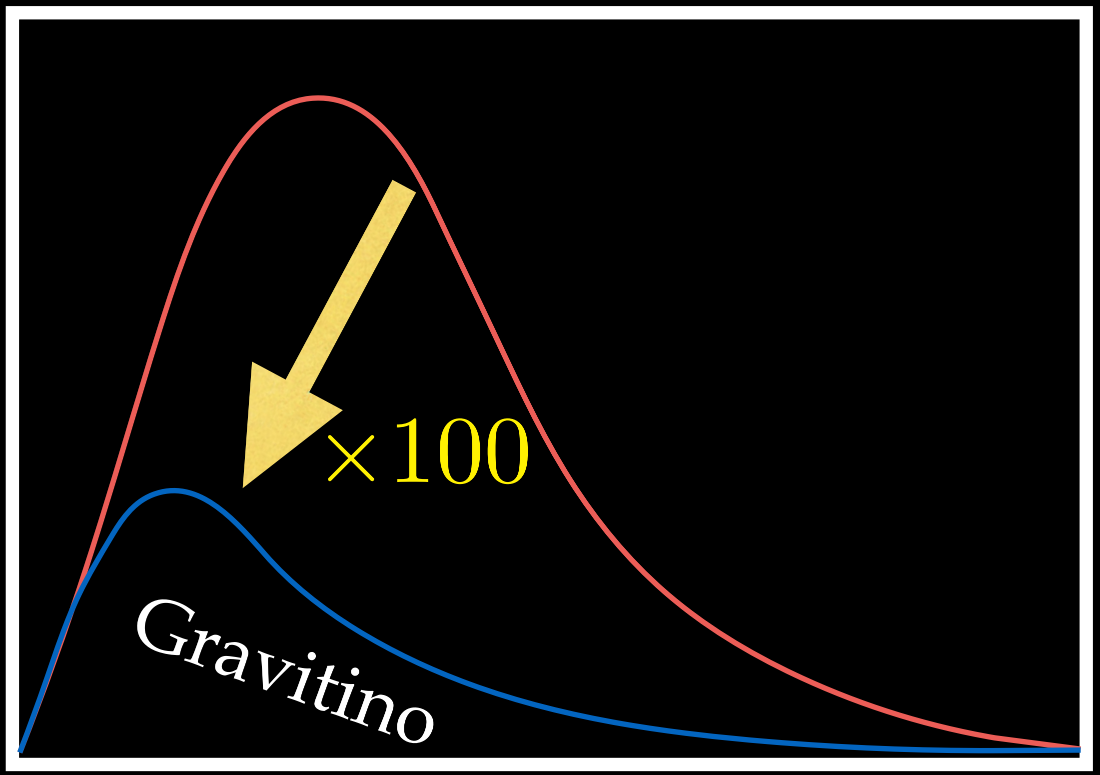
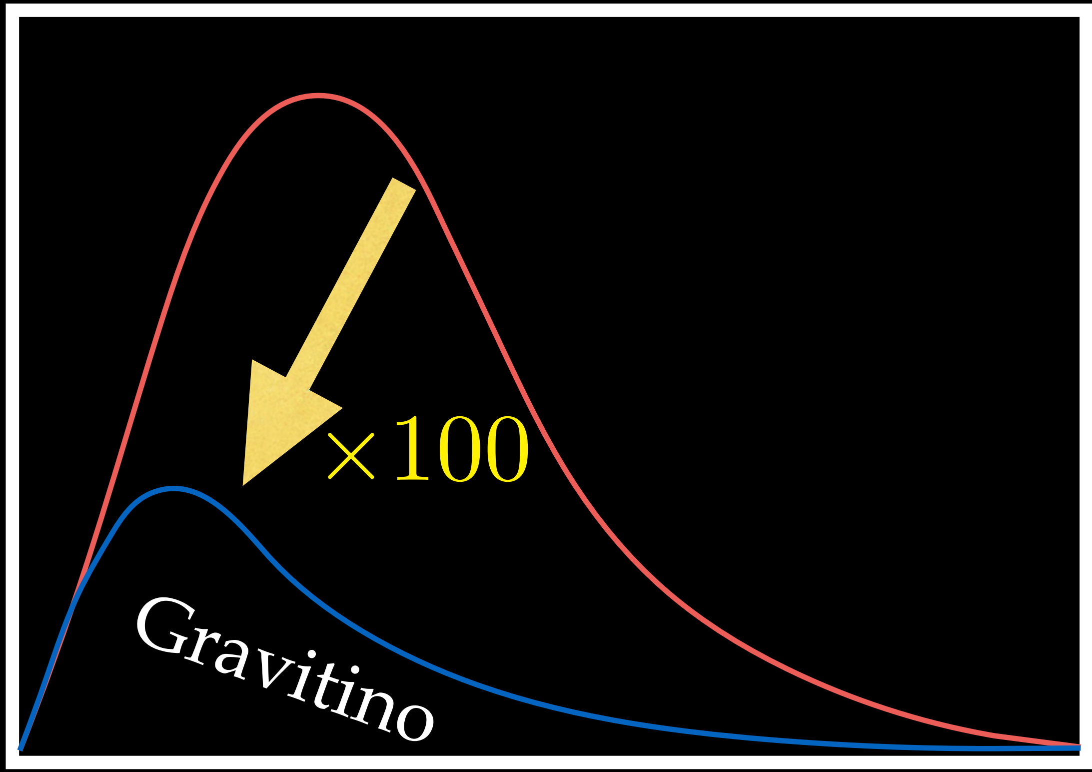
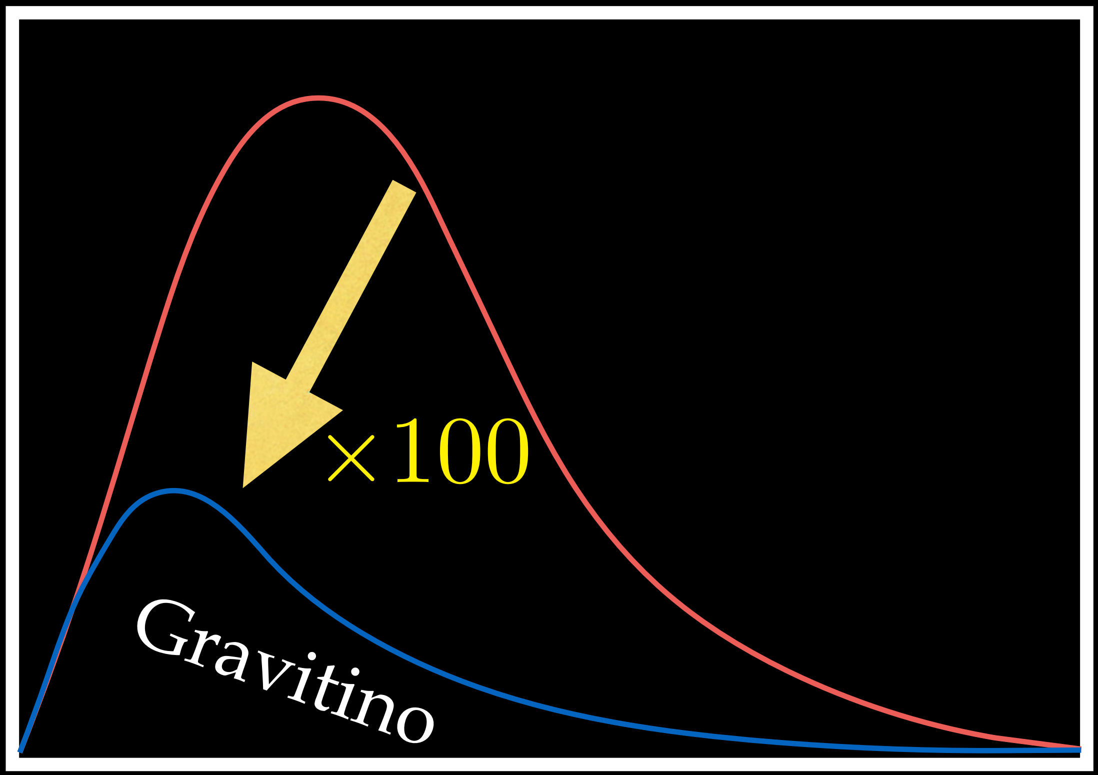


Sterile WDM

Thermal WDM



Sterile WDM vs. Thermal WDM



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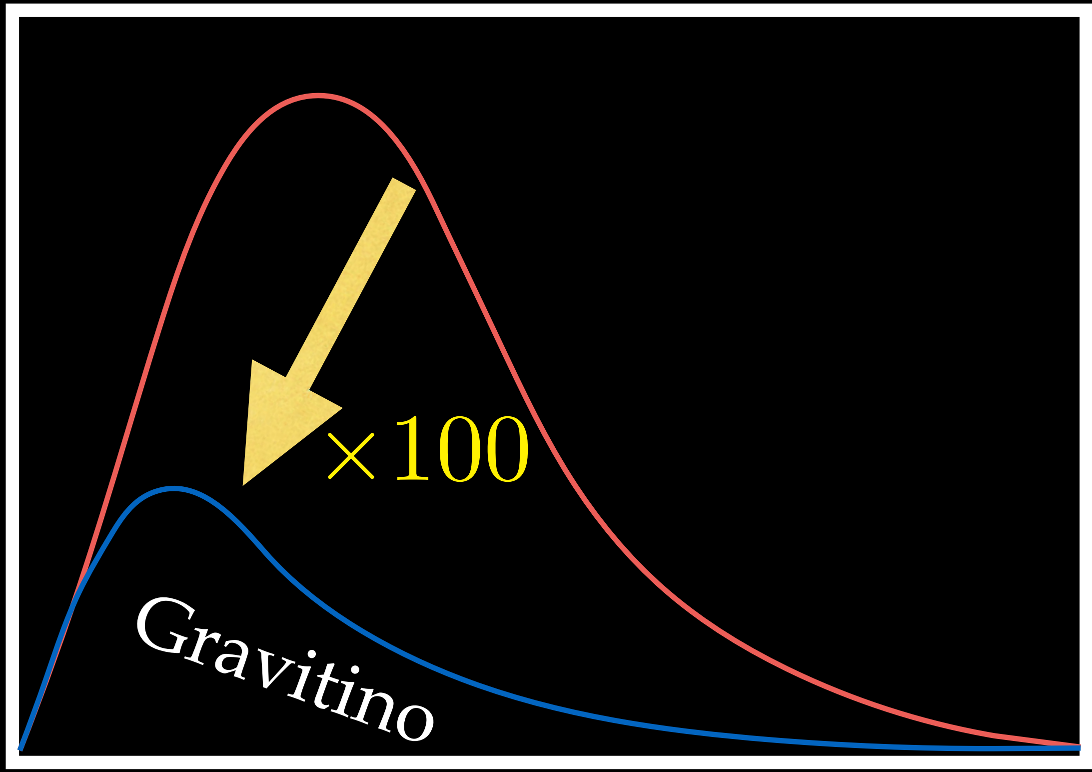

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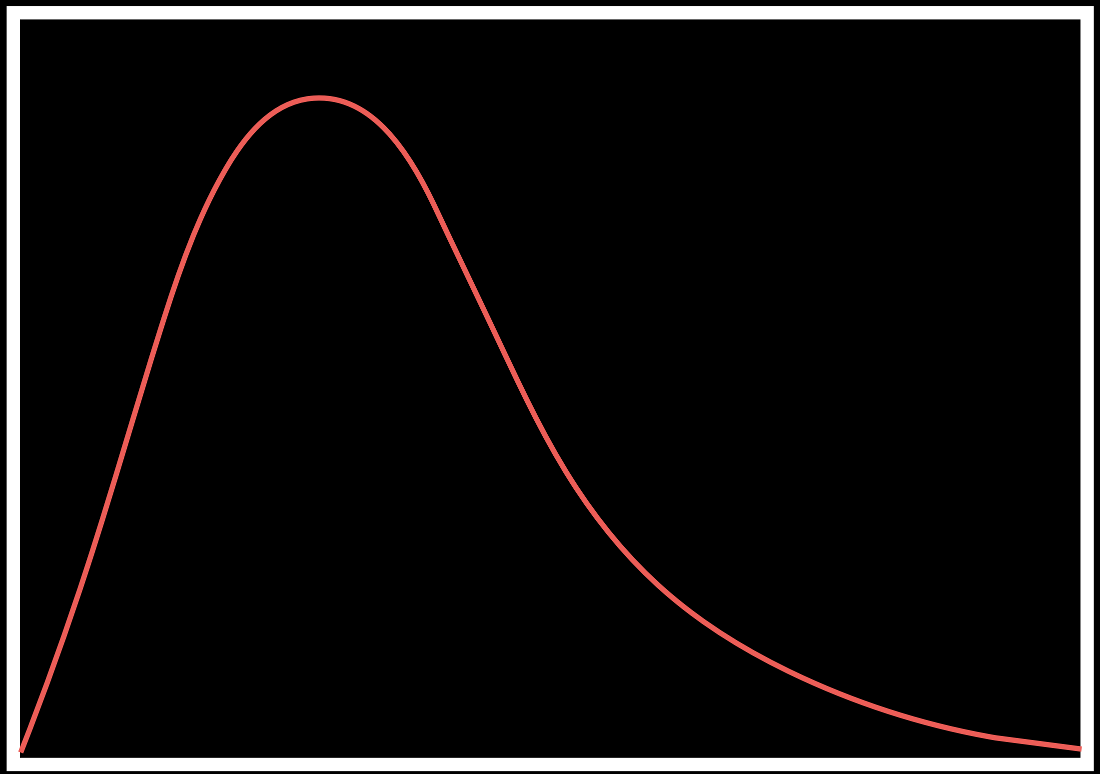

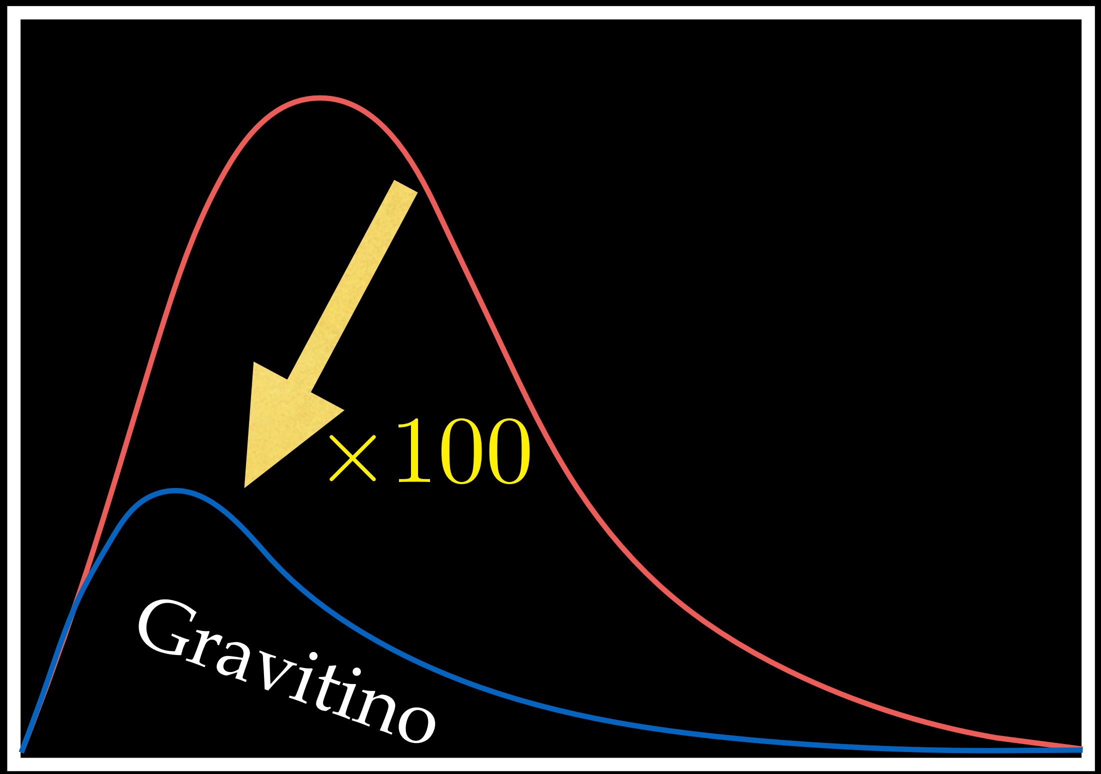

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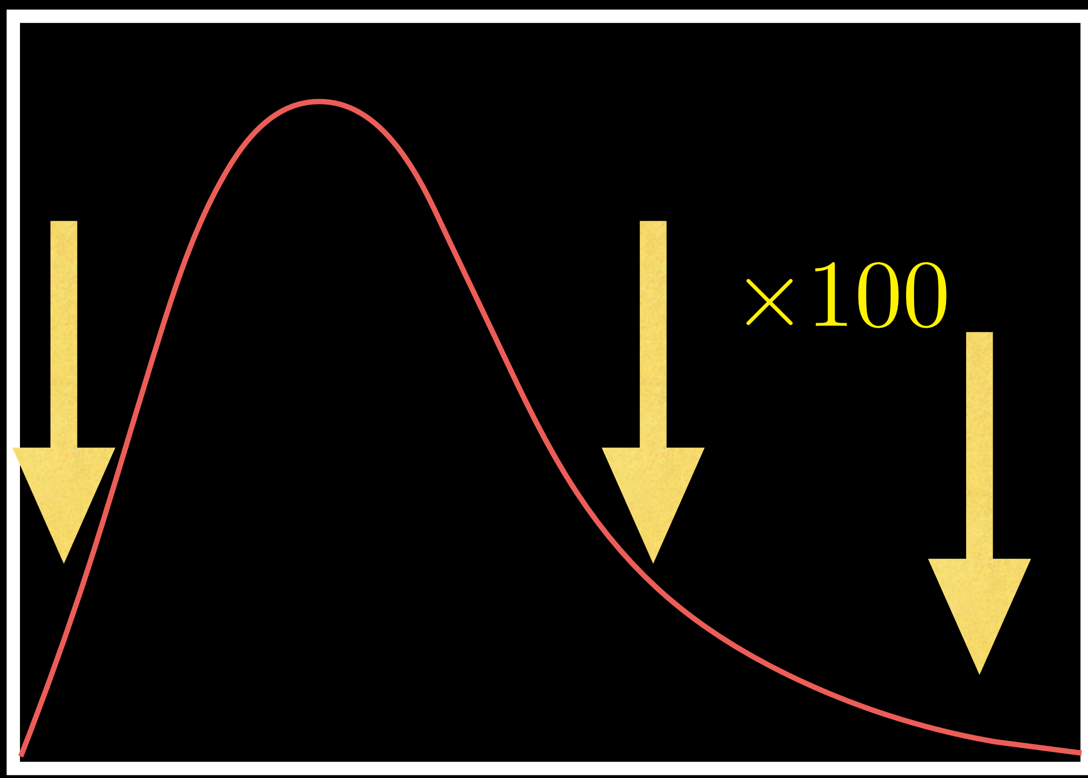

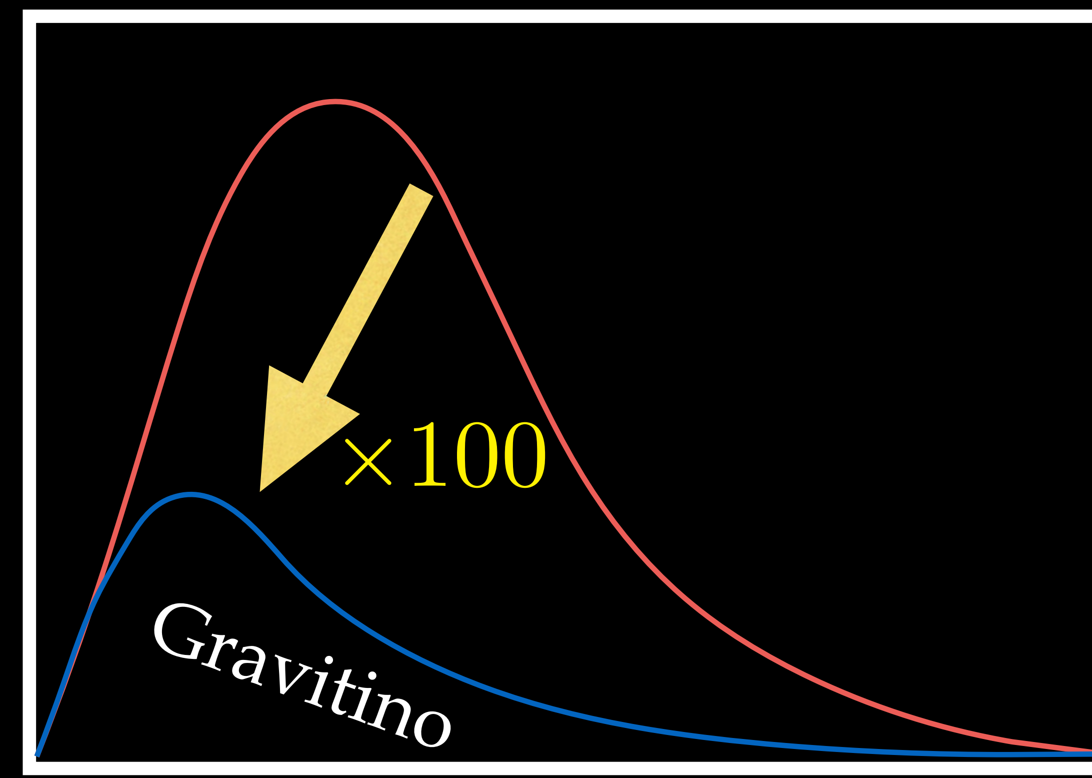

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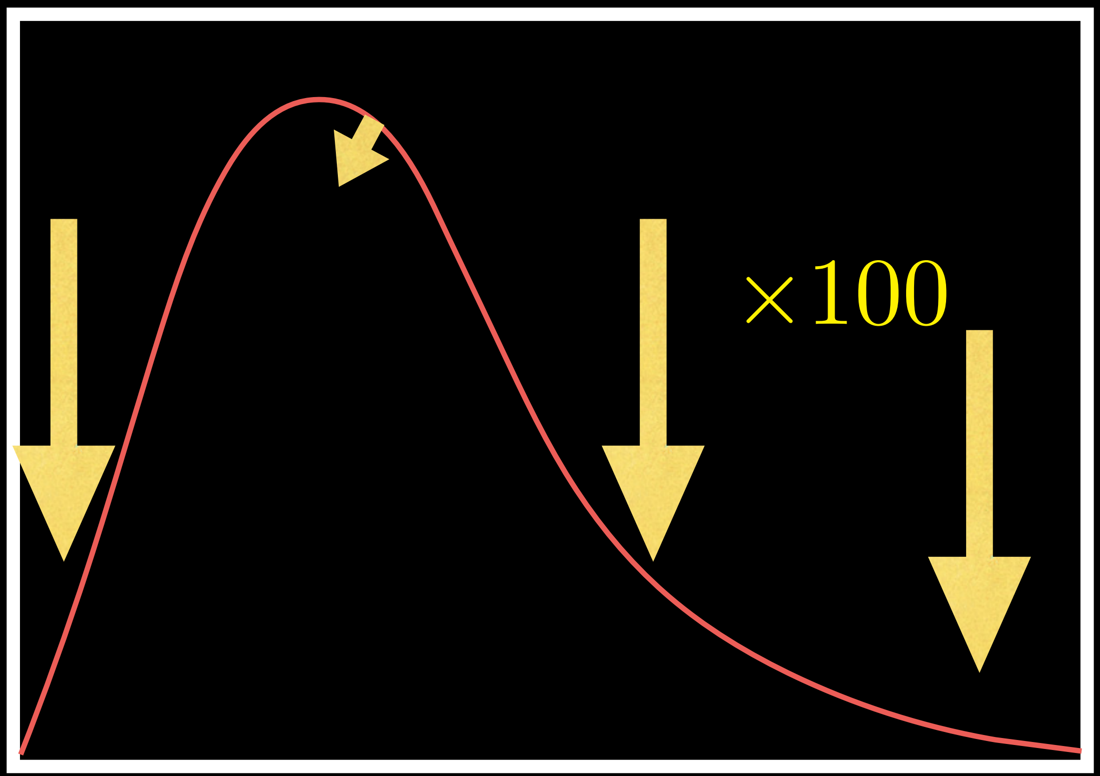

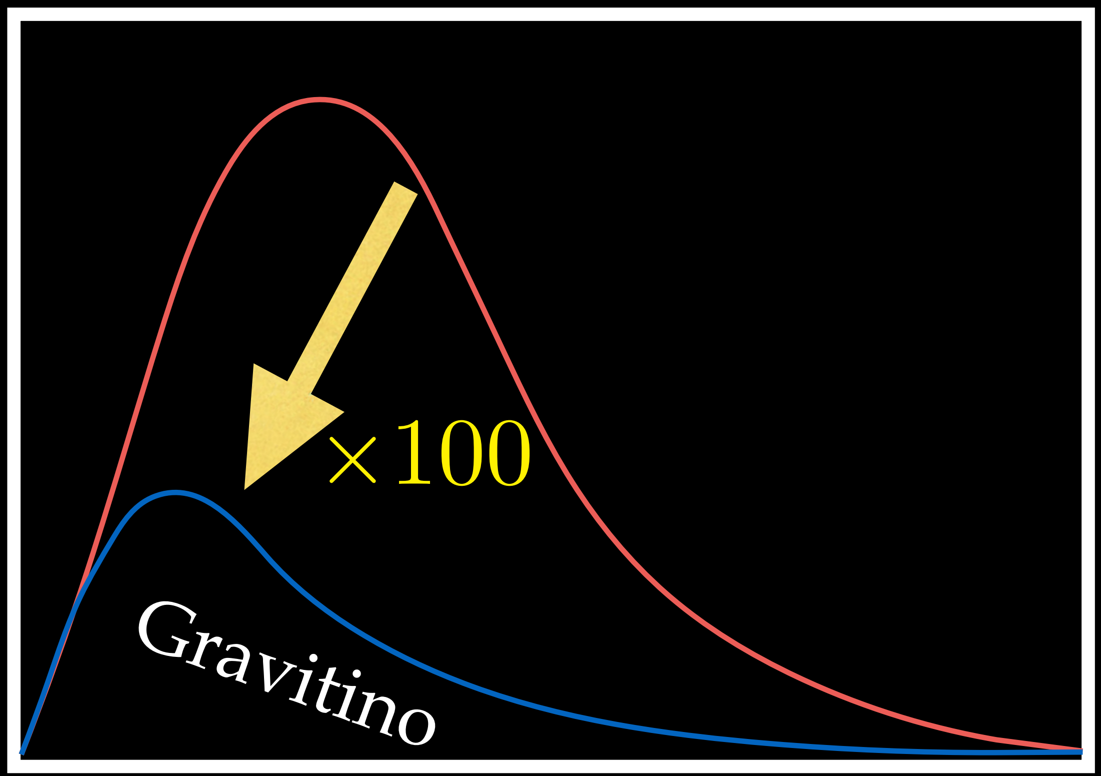

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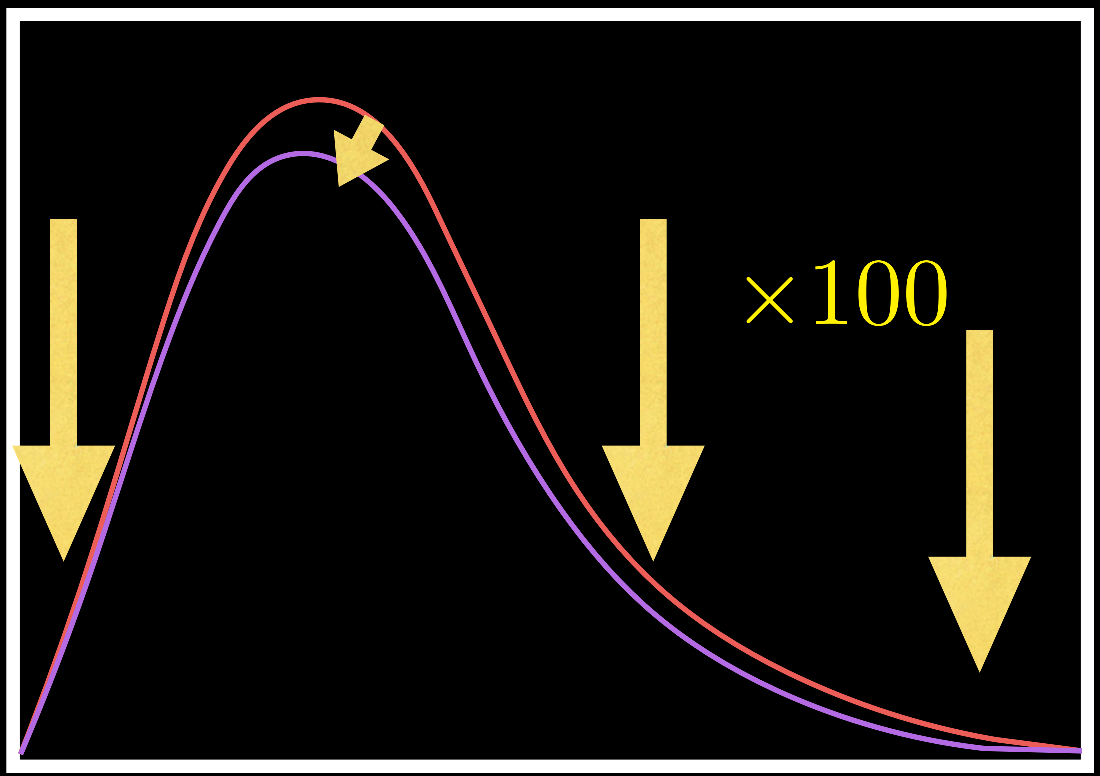

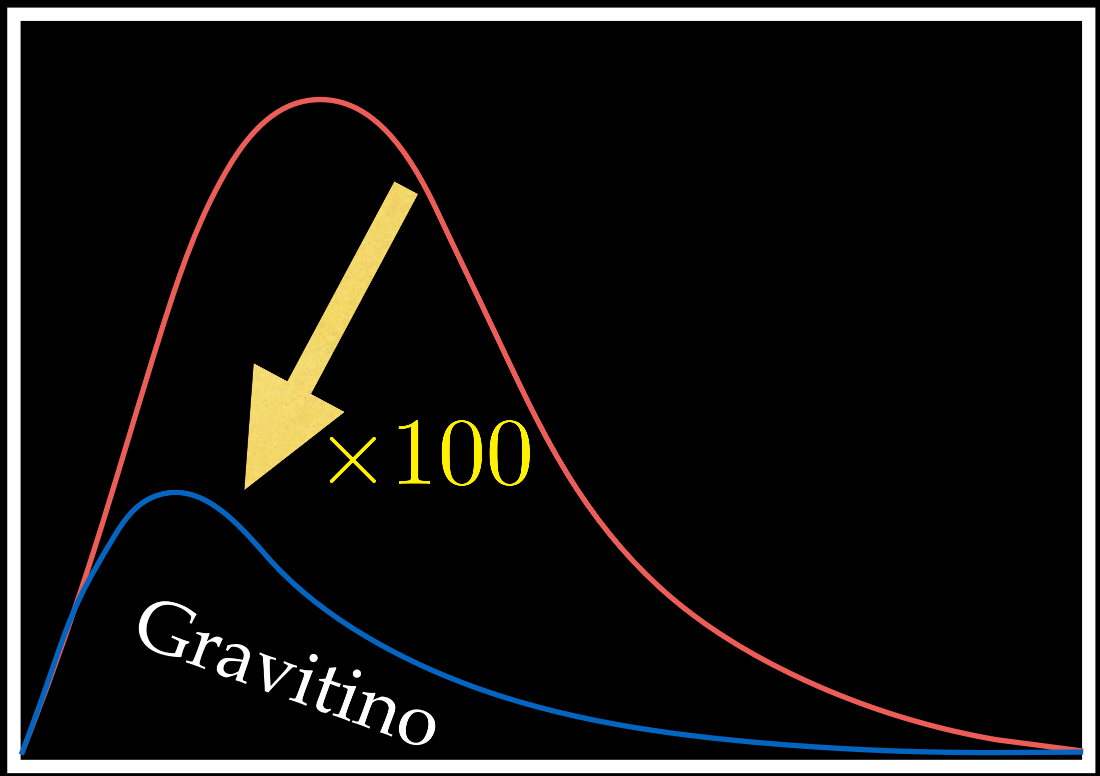

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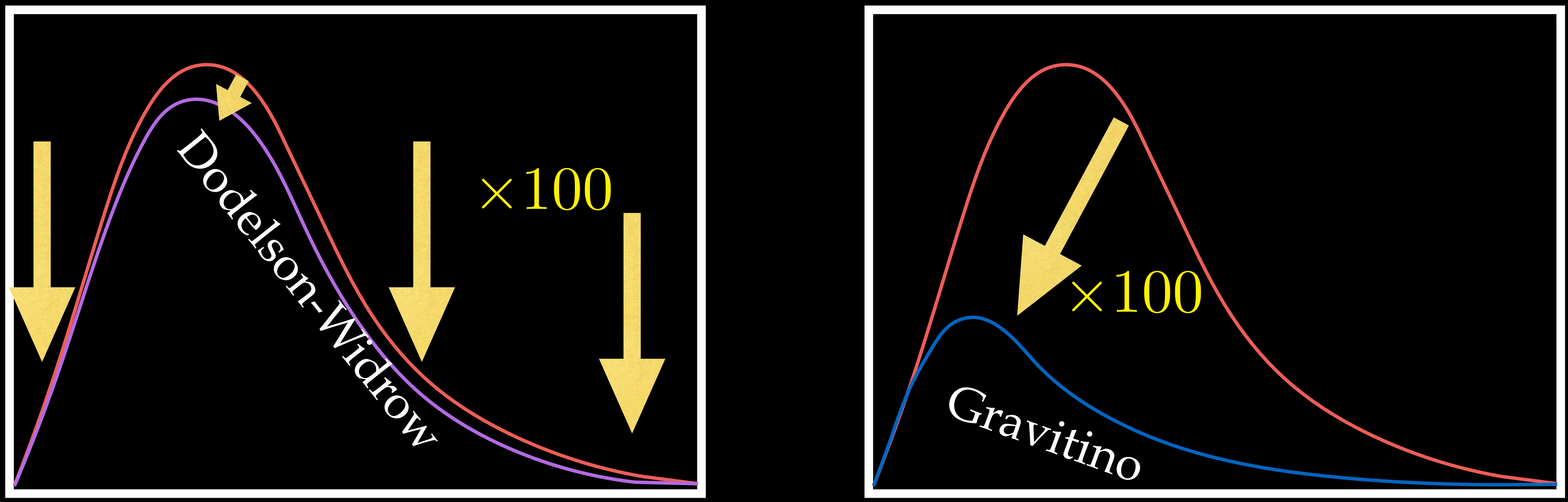

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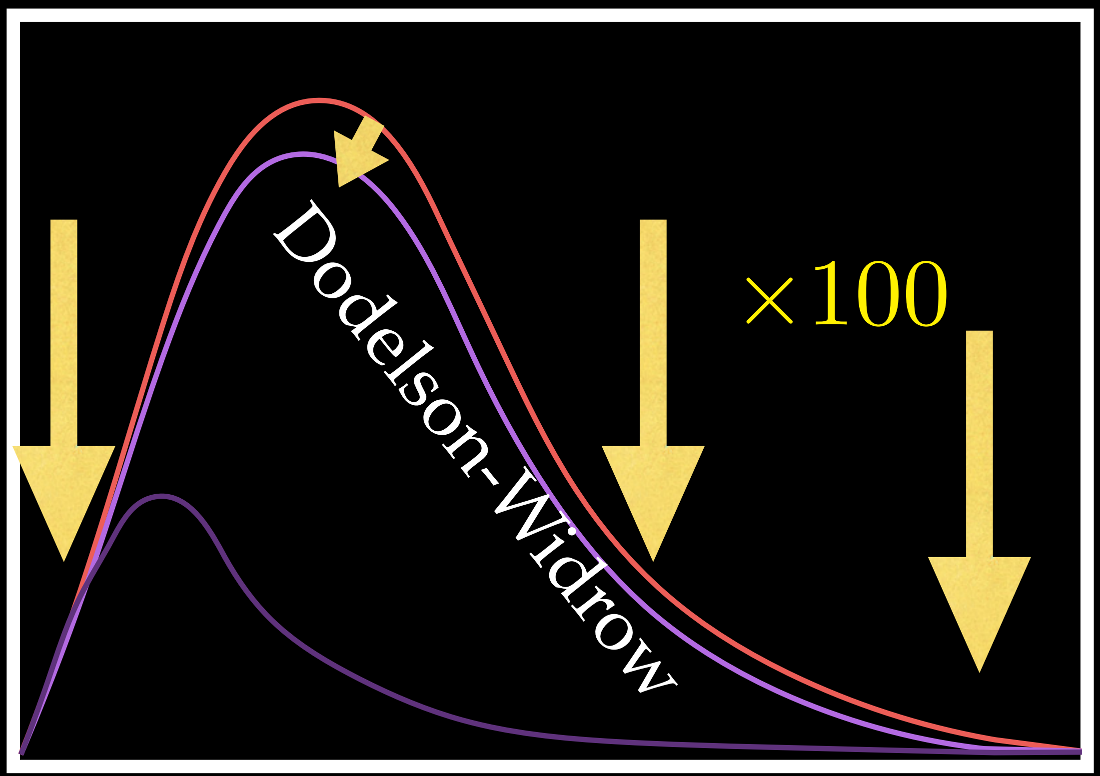

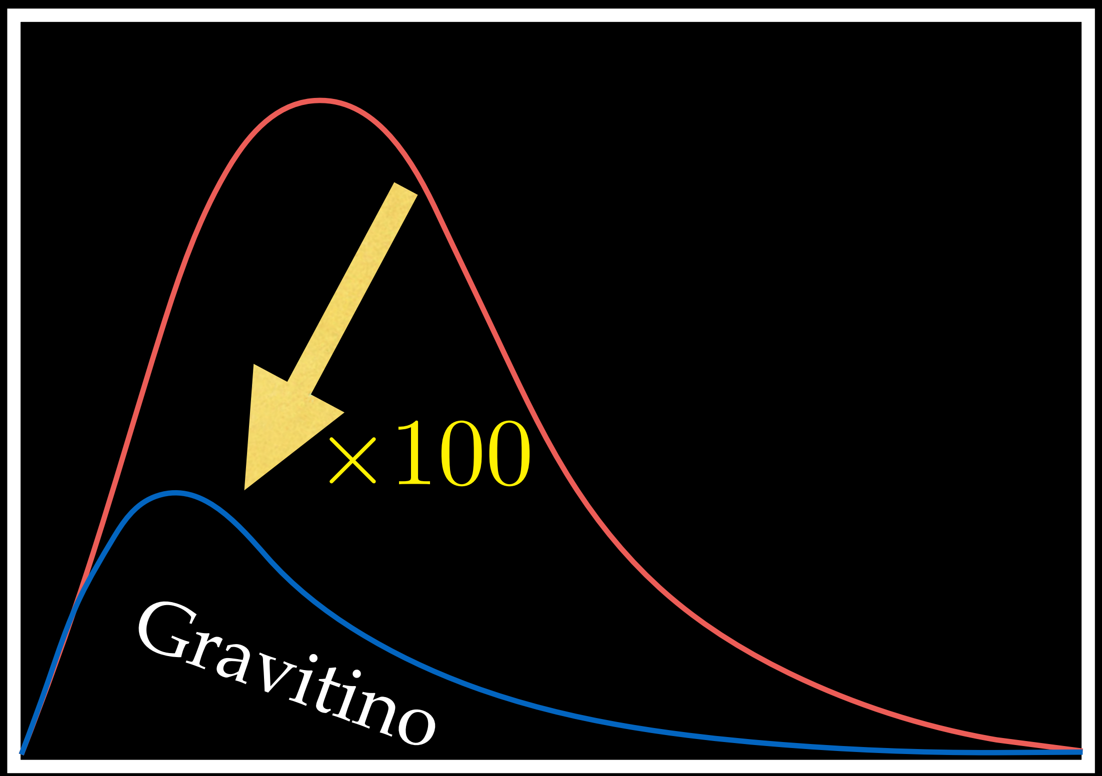

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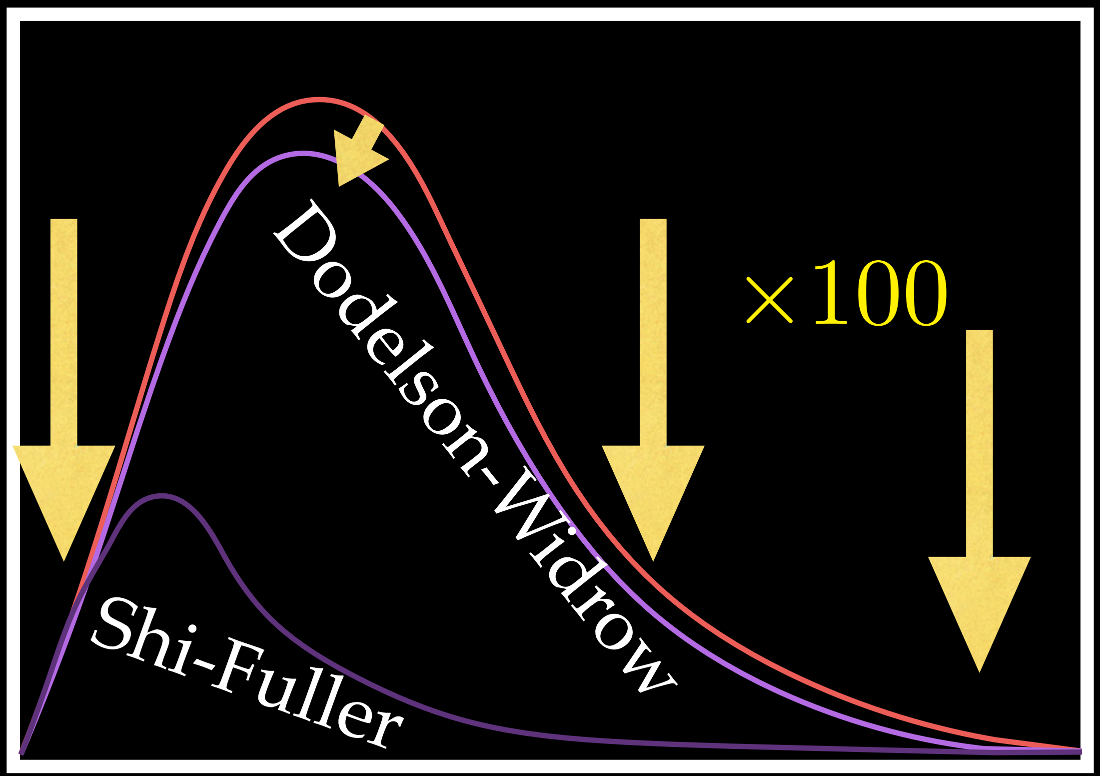

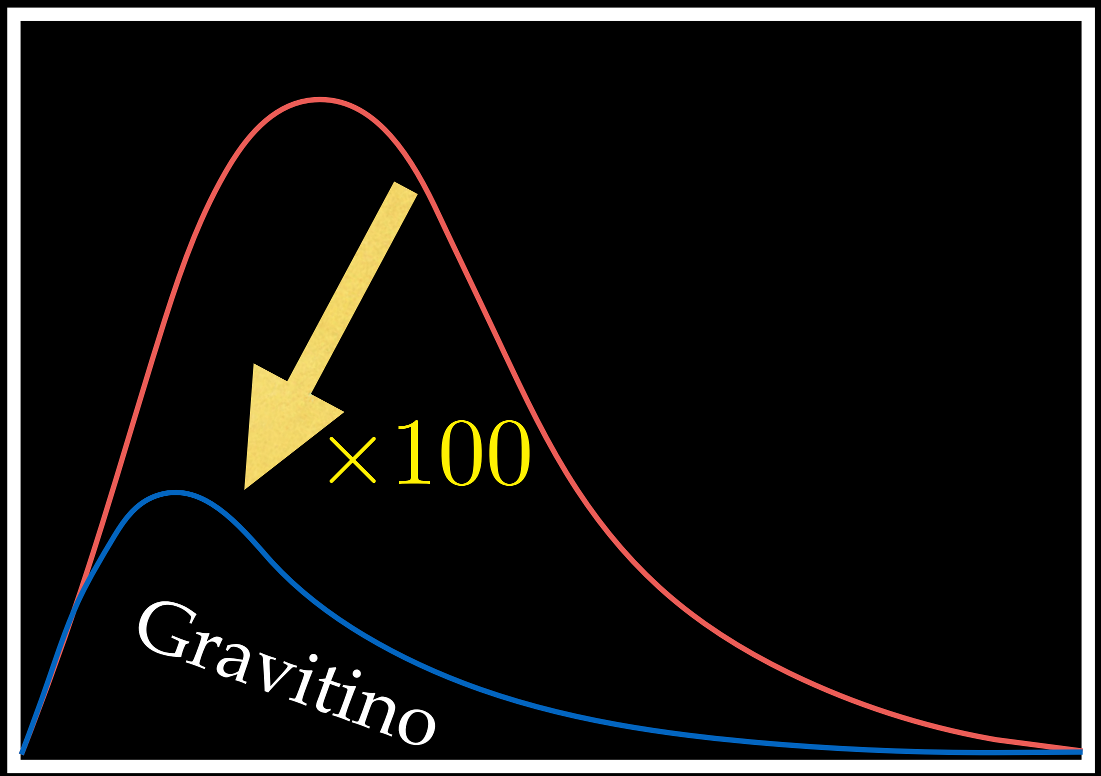

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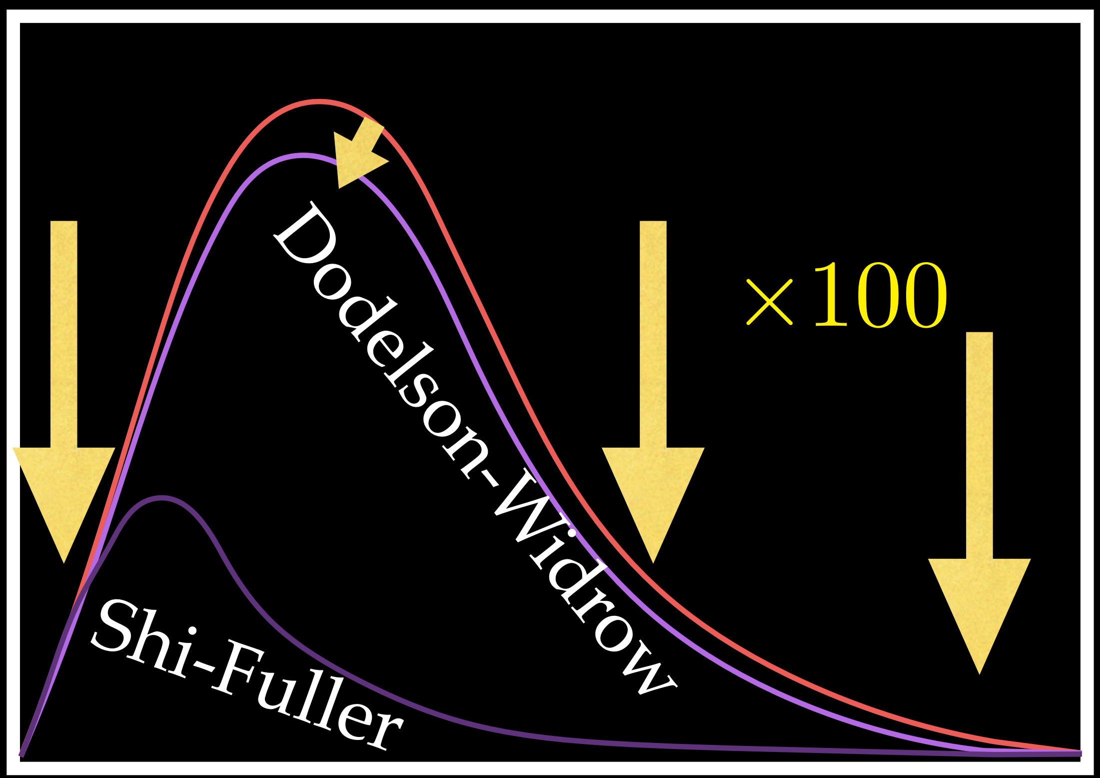

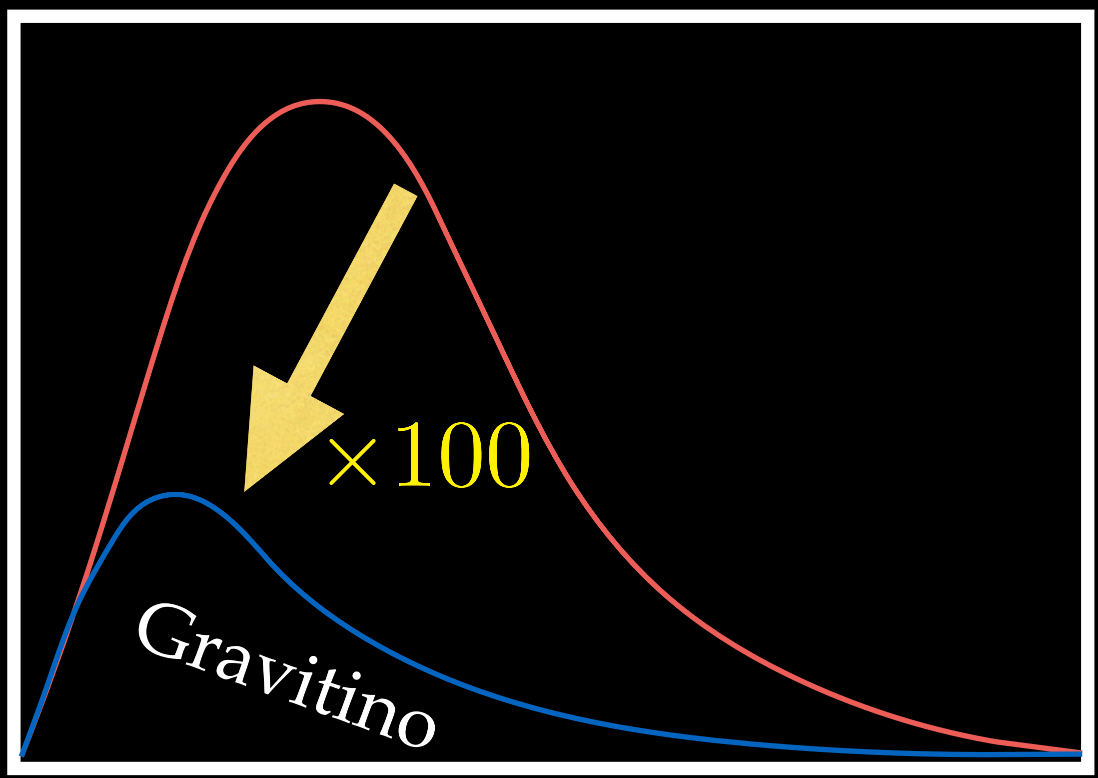

$$m_s\big|_{\text{Dodelson-Widrow,ideal}} \approx 4.46\,\text{keV}\,\left(\frac{m_{\text{thermal}}}{1\,\text{keV}}\right)^{4/3}$$

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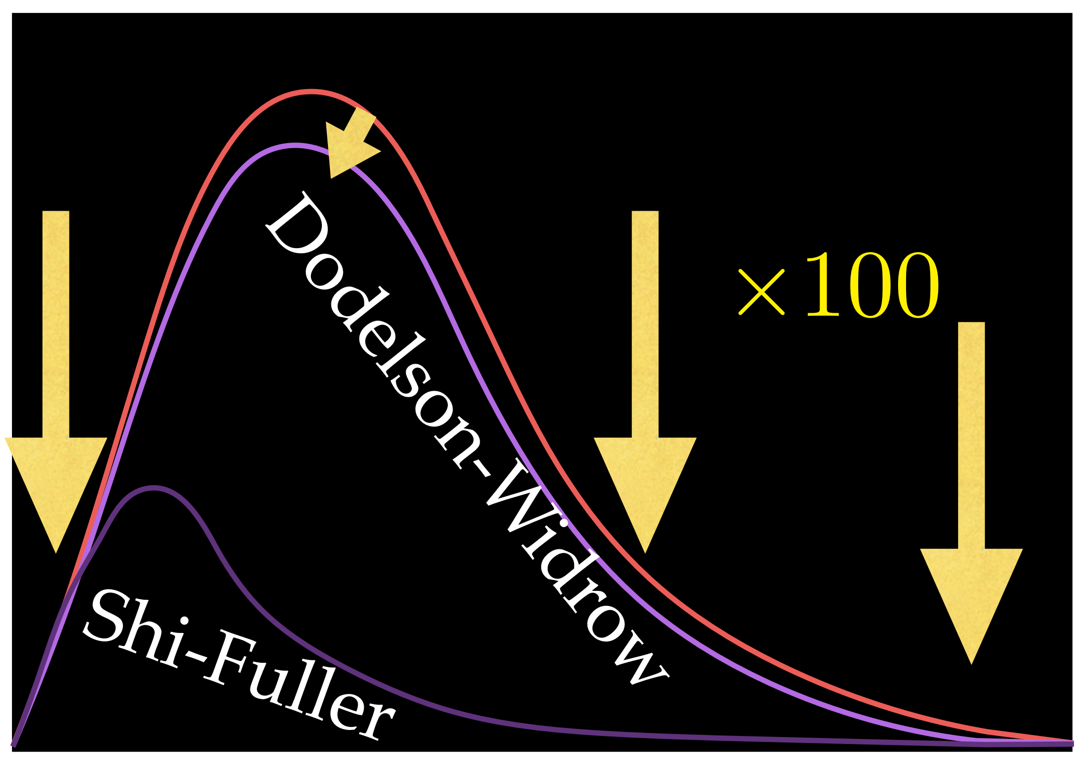

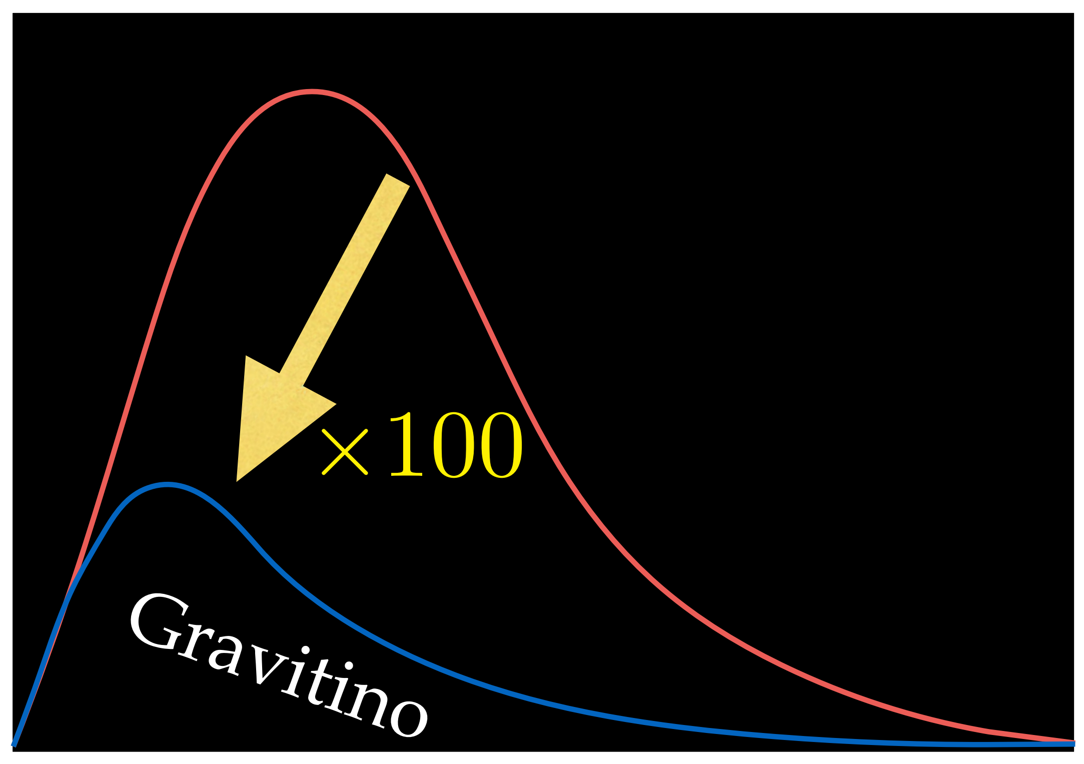

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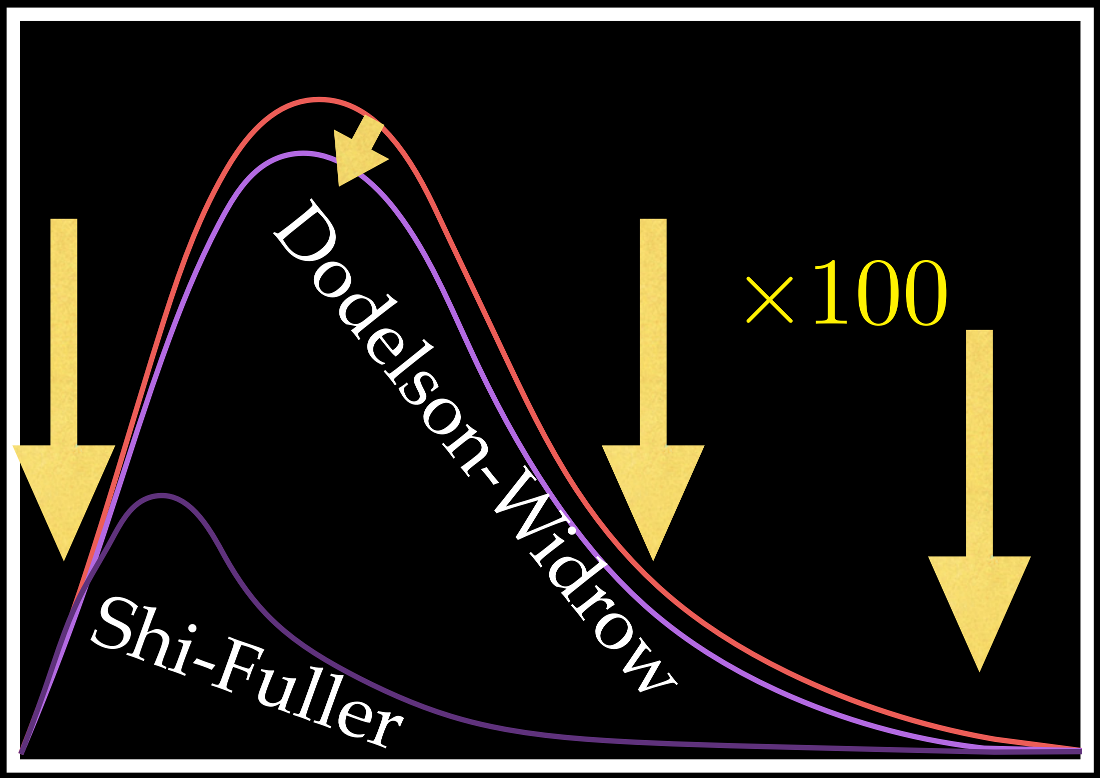

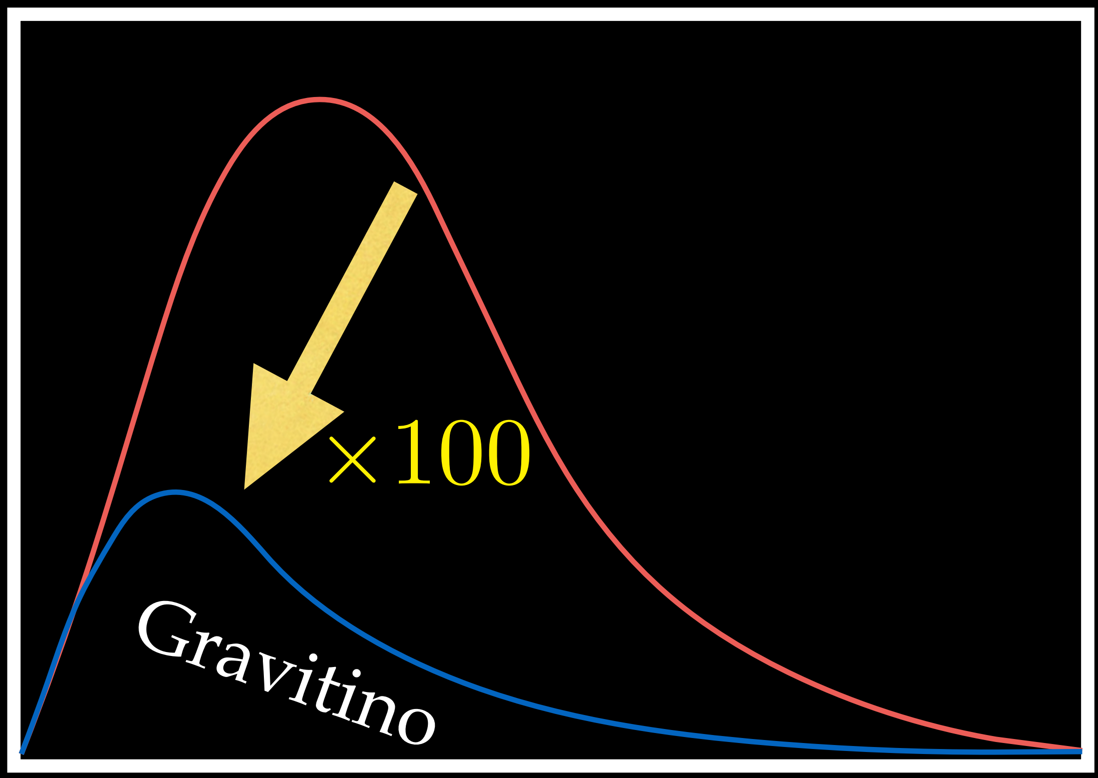

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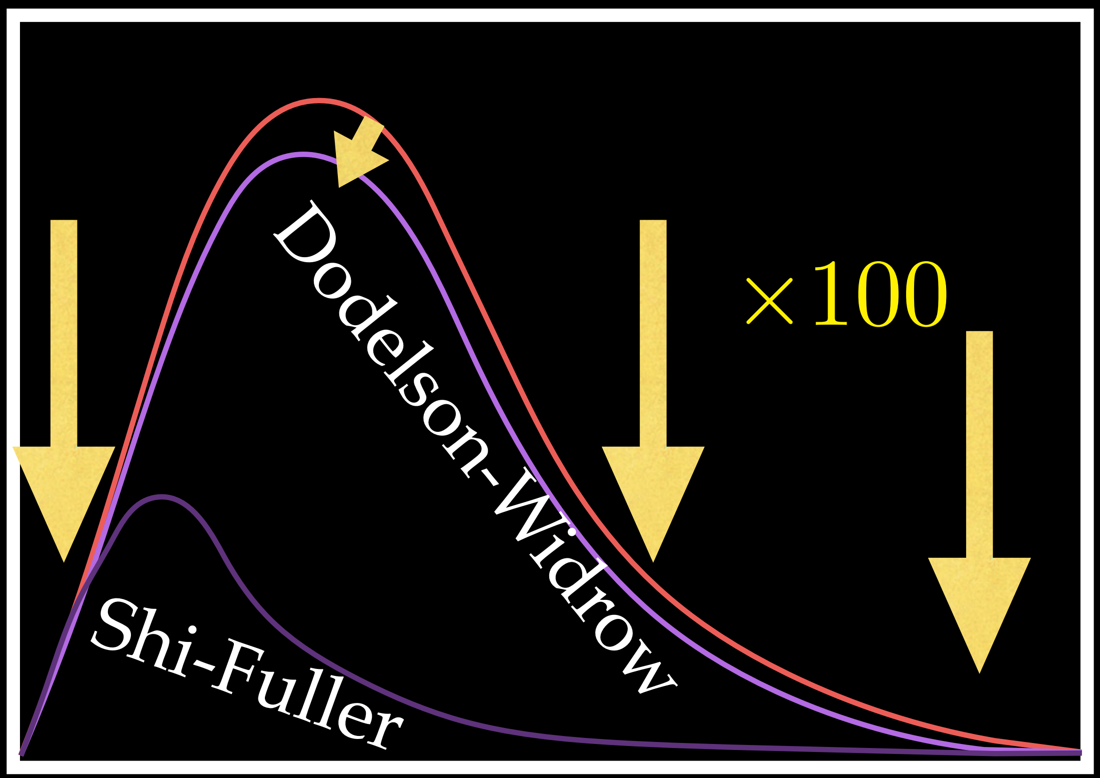

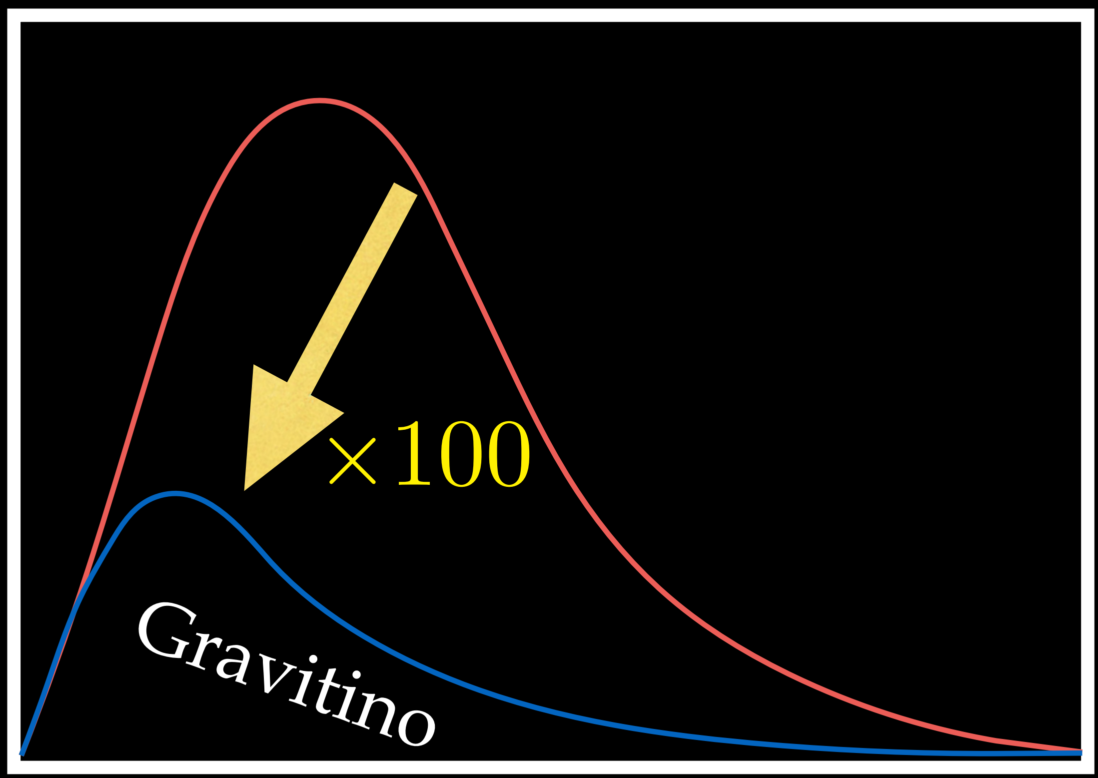

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Colombi, Dodelson & Widrow astro-ph/9505029;
Abazajian 2005; arXiv:1705.01837; Venumadhav+ 2016

Other mechanisms of production, and effects on structure

- **Singlet Higgs Decay Production:**
  Kusenko 2006; Petraki & Kusenko 2007

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

- **Production by Generic Scalar Decay**
  (Adhikari+ 2017)

- **Vector Decay** (Schuve+ 2014)

keV Miracle Higgs Decay

$$V(H,S) = \mu_H^2 |H|^2 + m_2^2 S^2 + \lambda_3 S^3 + \lambda_{HS} |H|^2 S^2 + \lambda_S S^4 + \lambda_H |H|^4,$$

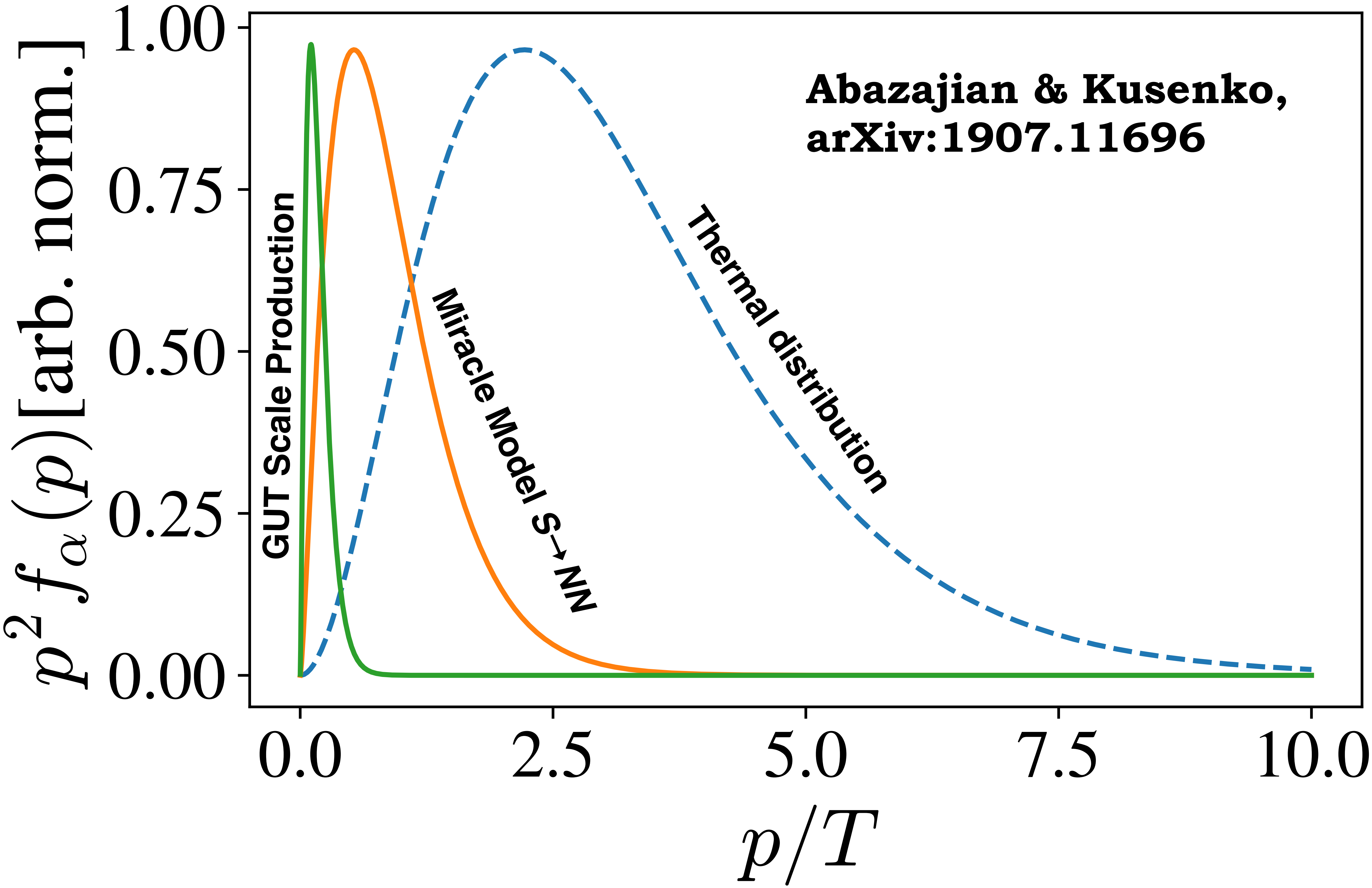
$$\left(\frac{n_s}{T^3}\right)\Big|_{T\sim m_S} \sim \Gamma \frac{M_0}{T^2}\Big|_{T\sim m_S} \sim \frac{f^2}{16\pi}\frac{M_0}{m_S}$$

$$\left(\frac{\rho_s}{T^3}\right)\Big|_{T\sim m_S} \sim \frac{f^3}{16\pi}\frac{M_0\langle S\rangle}{m_S}$$

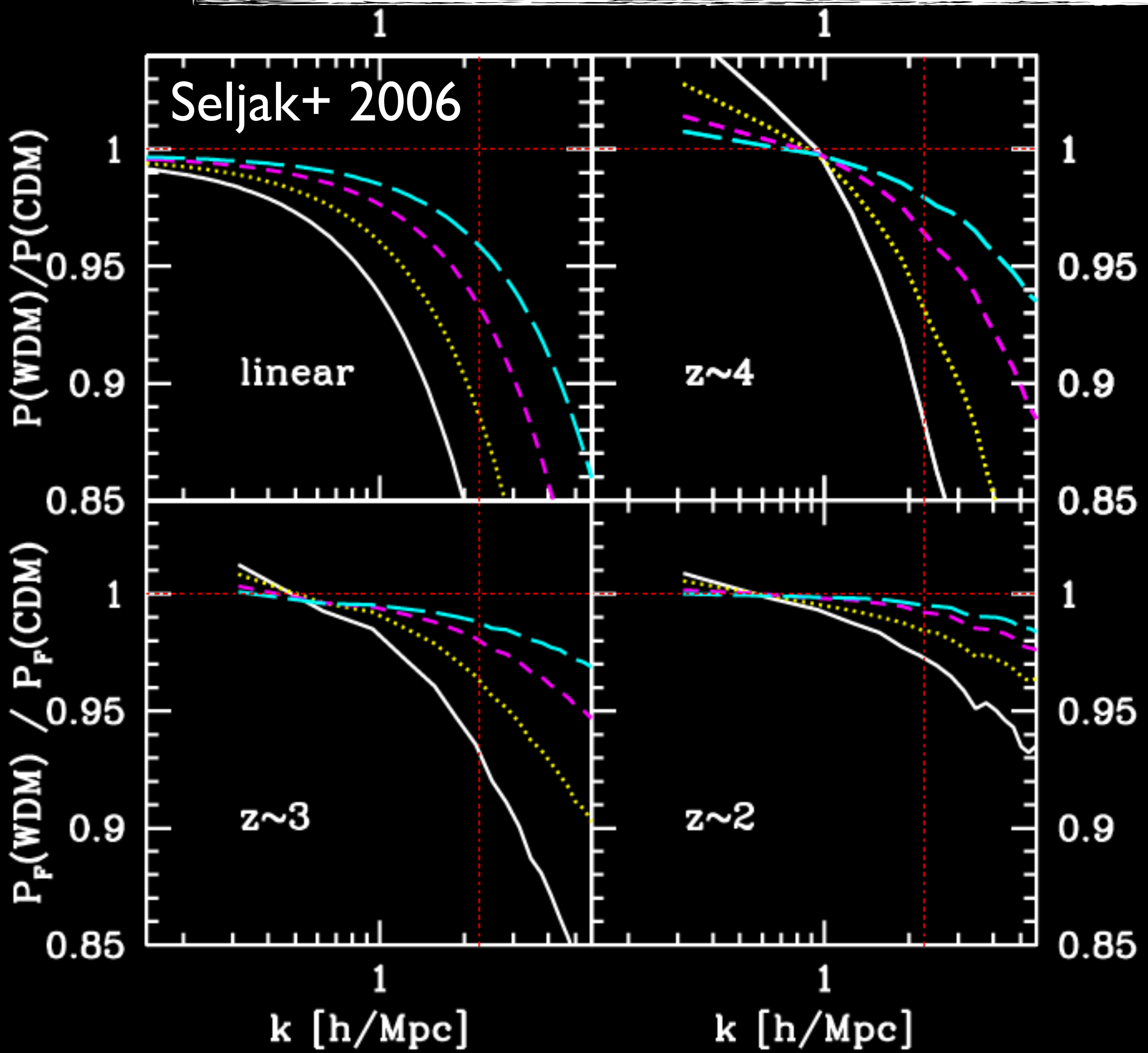
$$\left(\frac{\rho_s}{T^3}\right)\Big|_{T<\mathrm{MeV}} \sim \frac{1}{\xi}\frac{f^3}{16\pi}\frac{M_0\langle S\rangle}{m_S} = \frac{m_1^3 M_0}{16\pi\xi m_S\langle S\rangle^2} \sim \mathrm{eV}$$

Kusenko 2006
Abazajian & Kusenko 2019

Varied Momenta Distributions for Different Production Mechanisms



Lyman-α Forest Constraints on WDM



m > 3 keV (WDM) (95% CL) [$m_{s,DW}$ > 16 keV] (Baur et al. 2015)
Similar limits from galaxy counts (Cherry & Horiuchi 2017, Nadler+ 2019)
Lensing substructure constraints push m > 5.3 keV (Gilman+ 2019)

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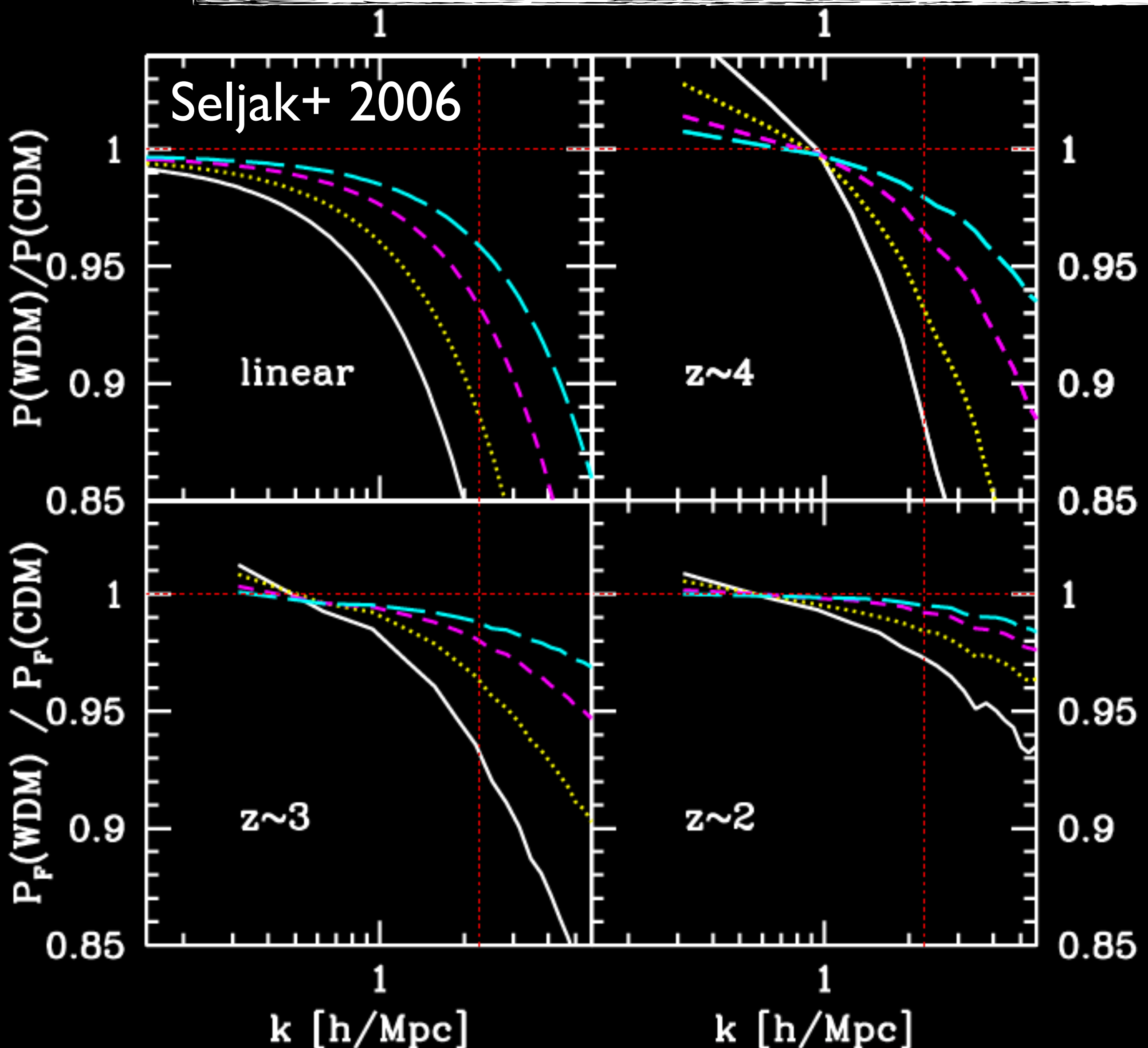

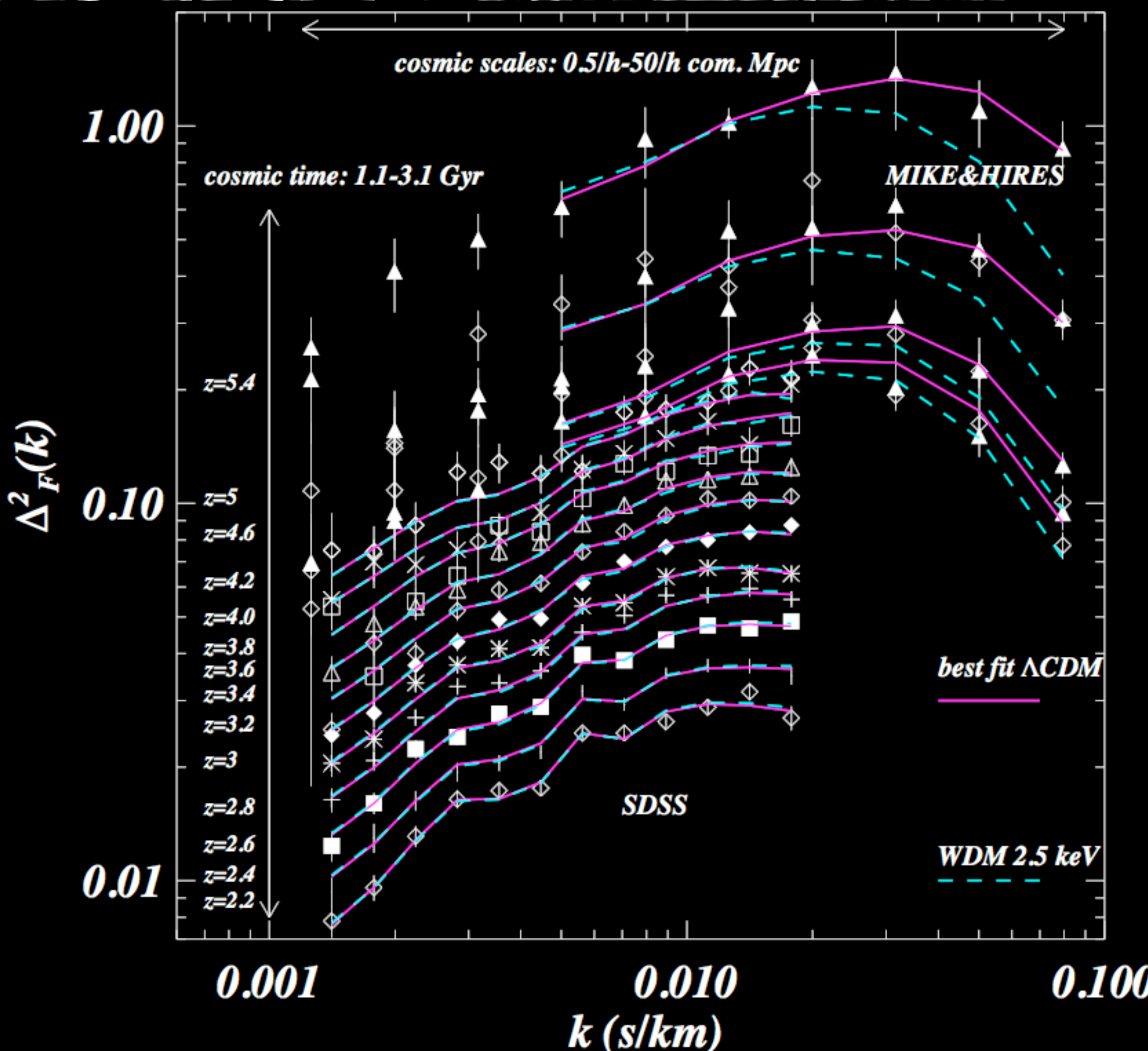

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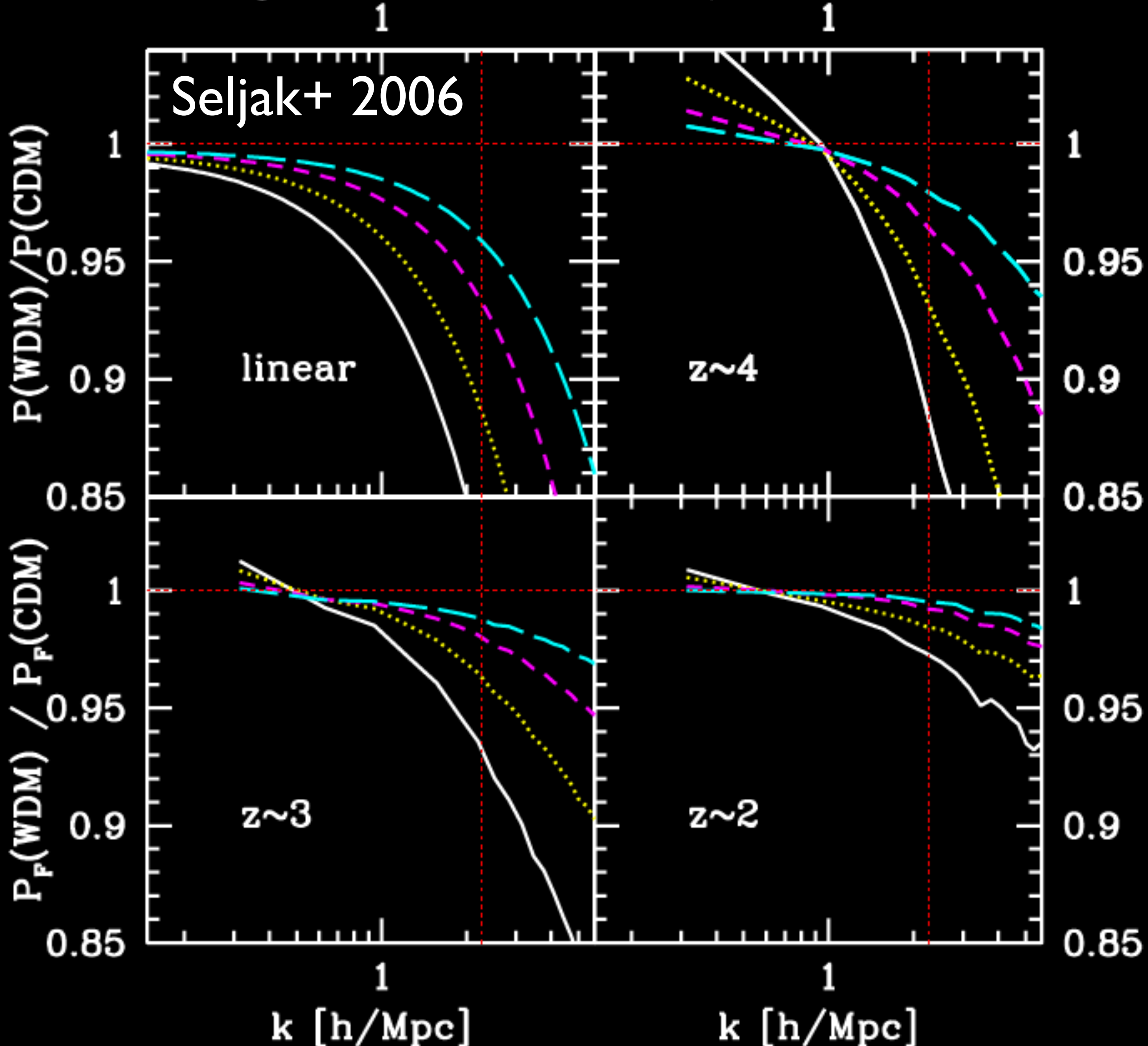
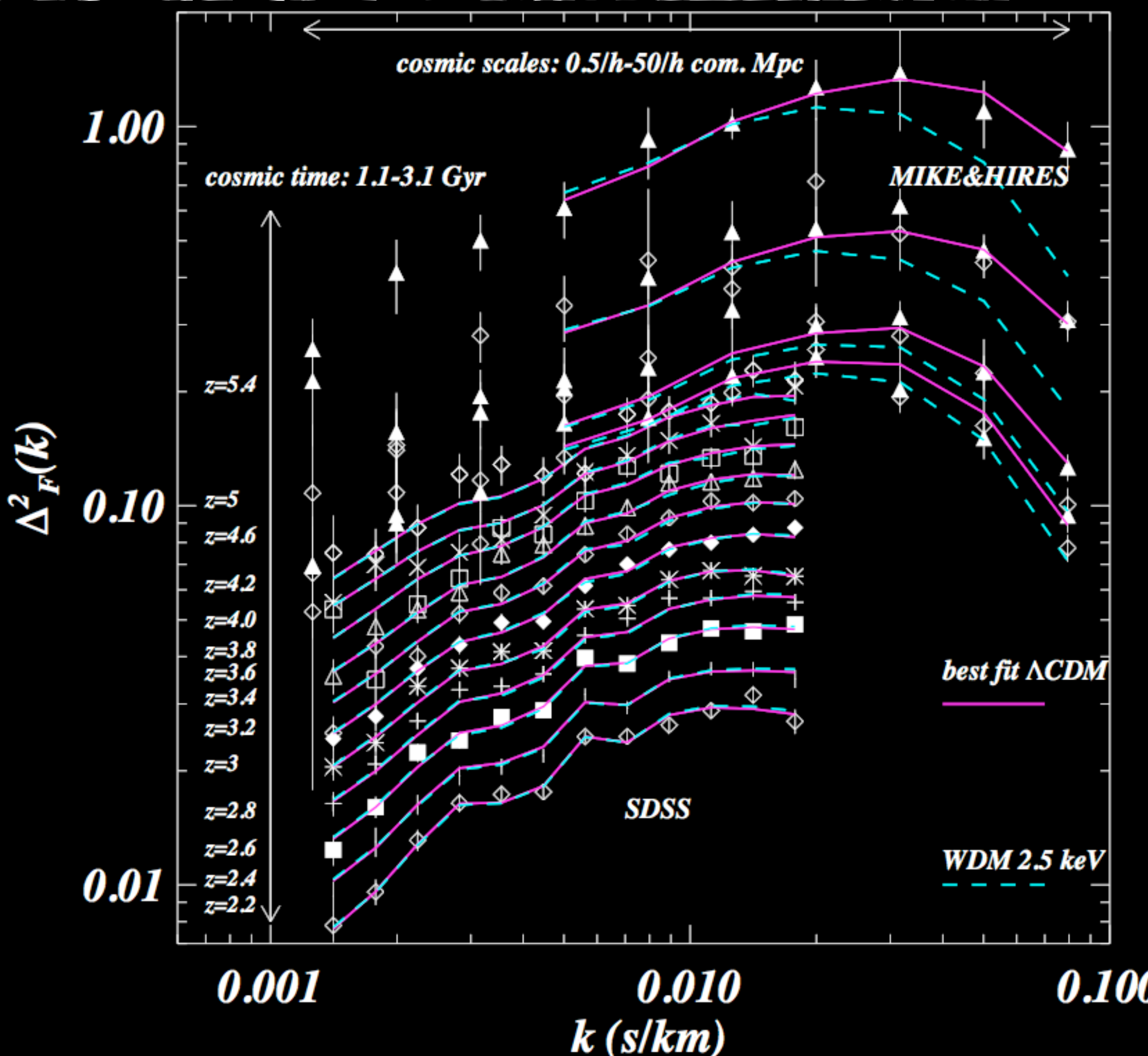
Lyman-α Forest Constraints on WDM





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

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