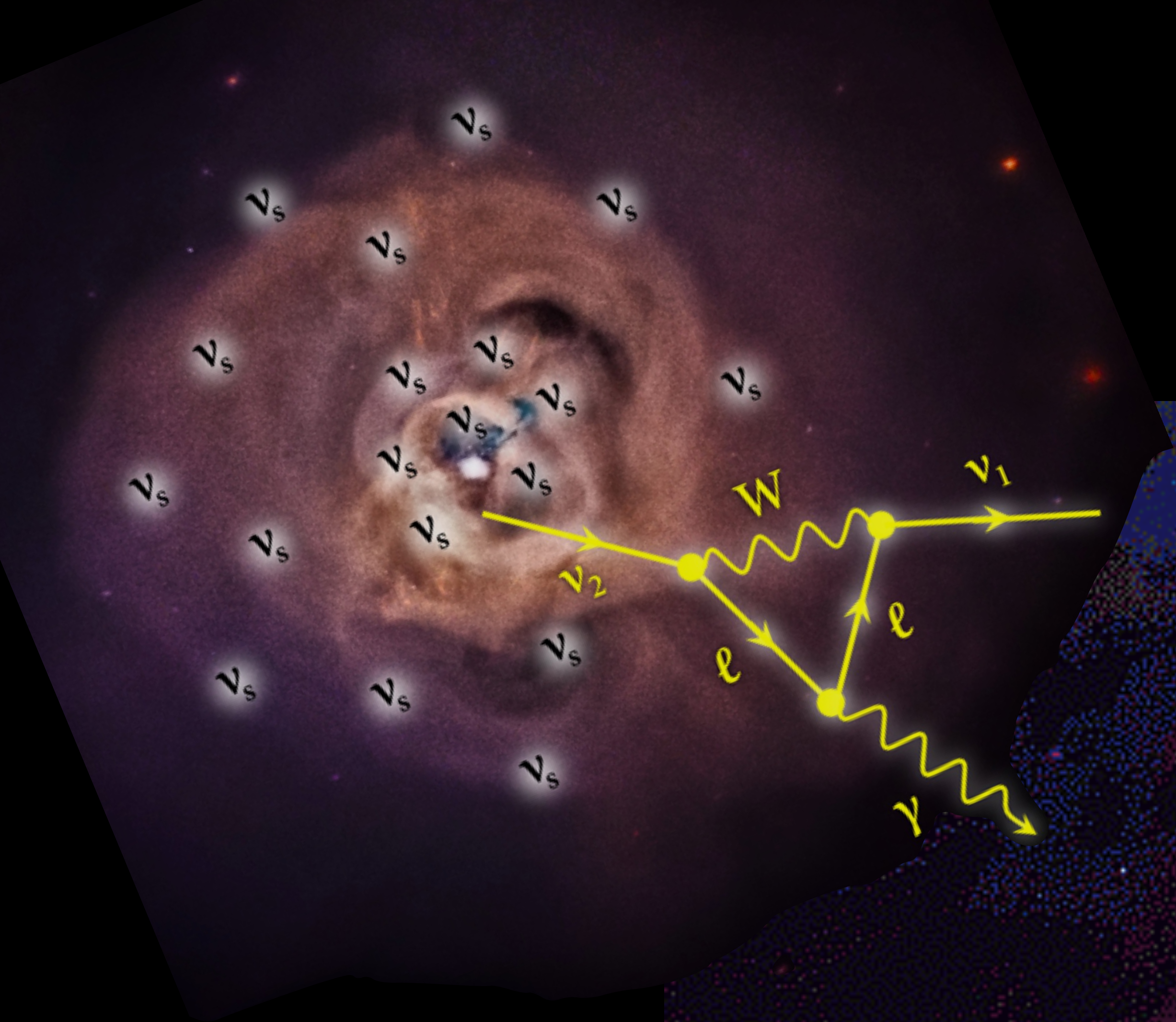
Dark Matter Sterile Neutrinos



Kevork Abazajian

University of California, Irvine

February 21

UCLA Dark Matter 2018

Number of Neutrinos

with Weak Interactions

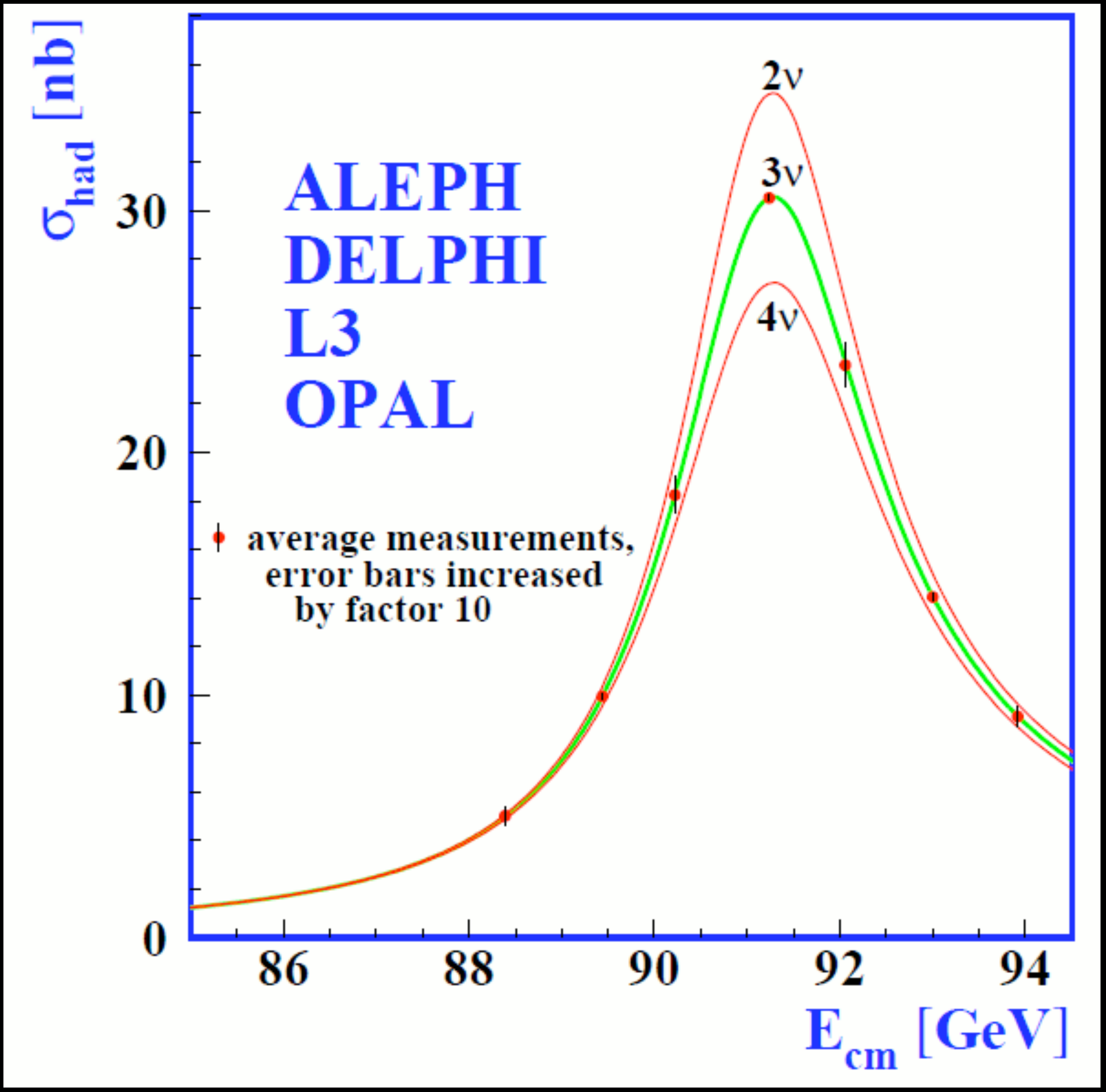
Invisible decays of Z boson observed by LEP

⇒Number of neutrinos

$N_\nu = 3.00 \pm 0.08$

with weak interactions

any extra ν must be sterile



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


NEUTRINO

Sterile Neutrino Dark Matter Production

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

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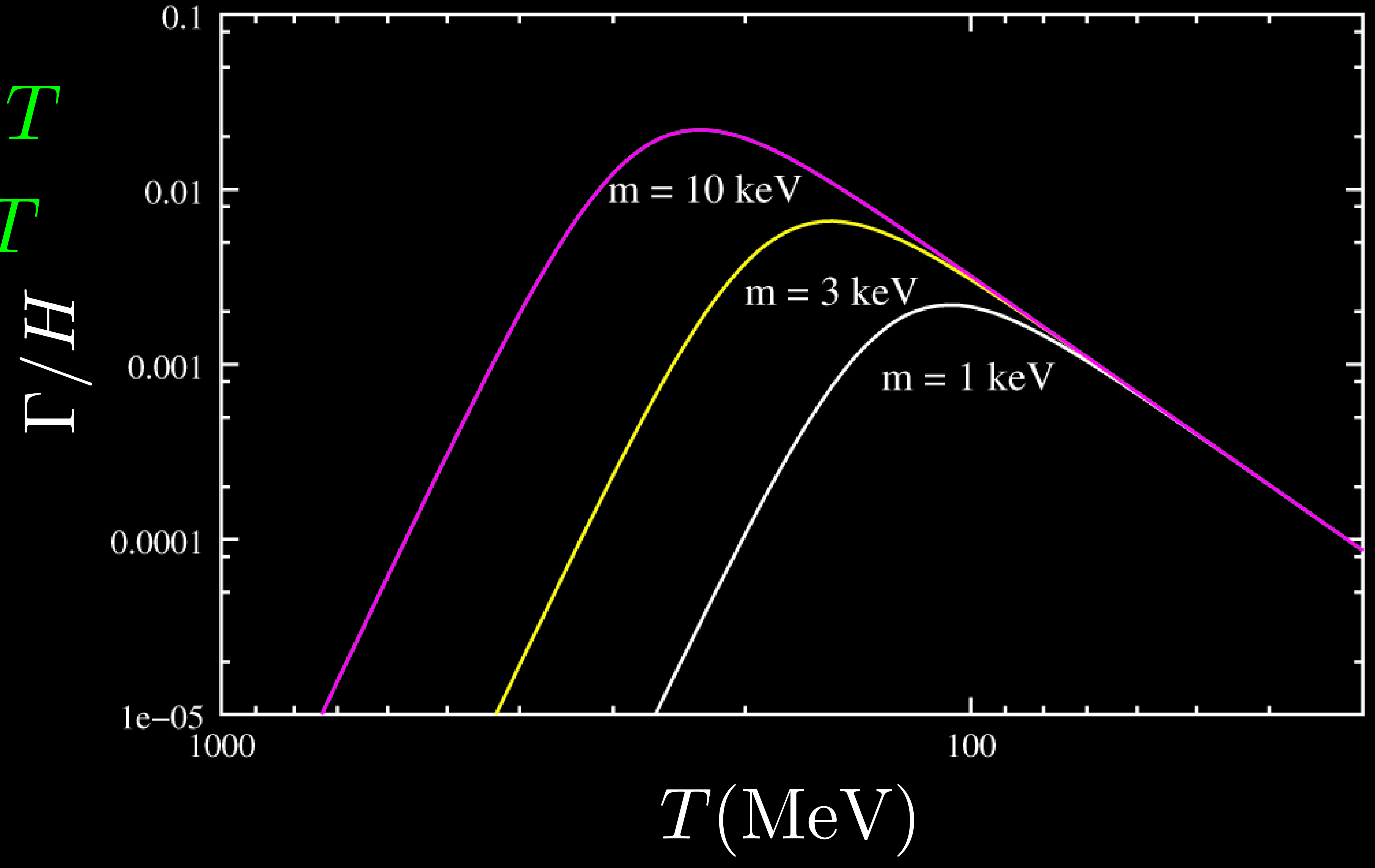

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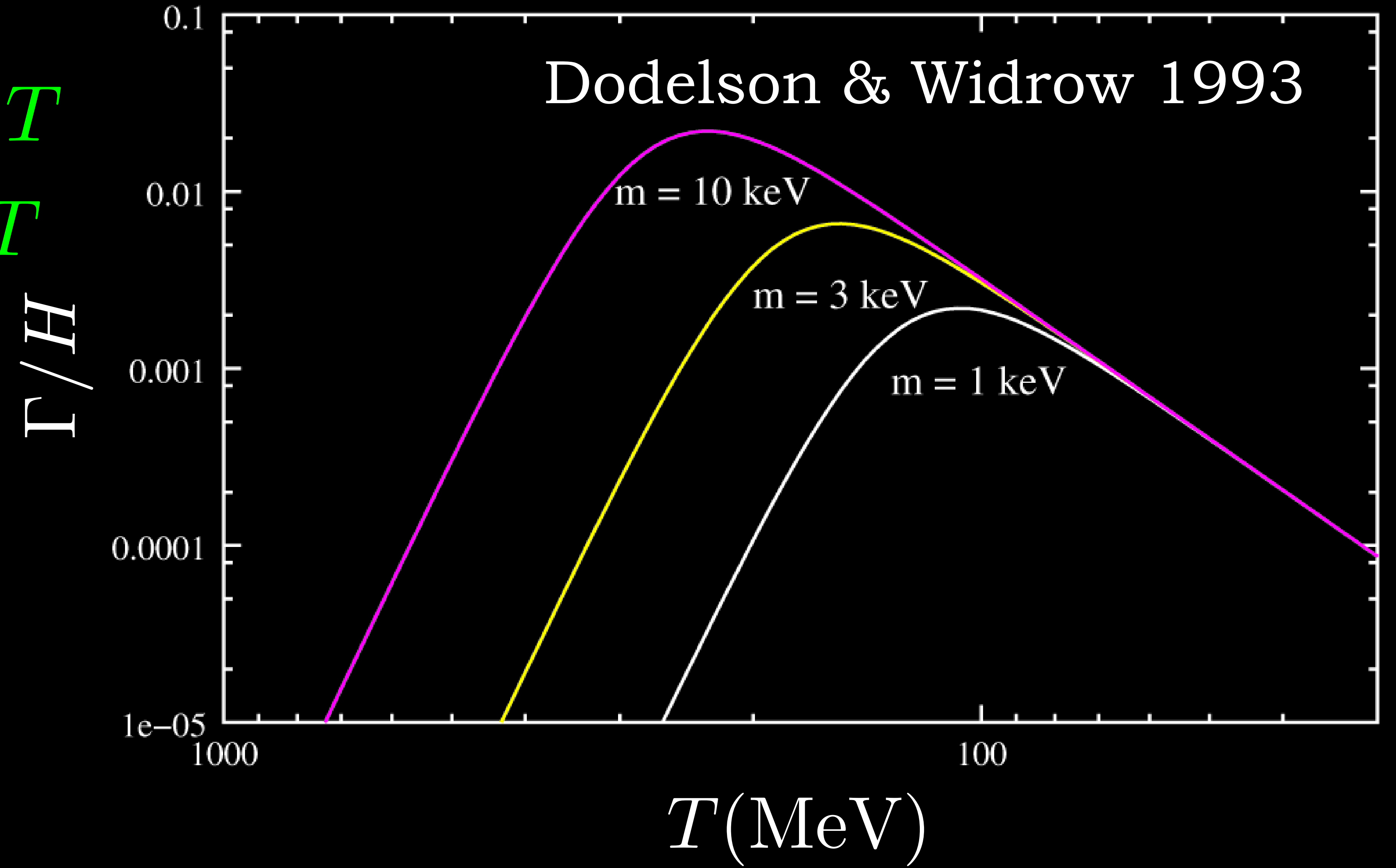

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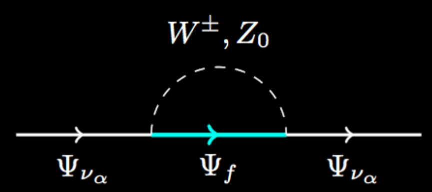

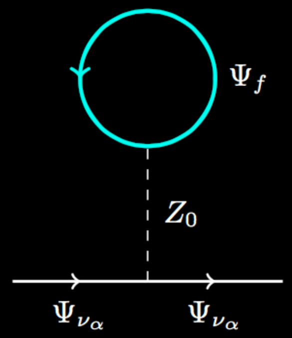

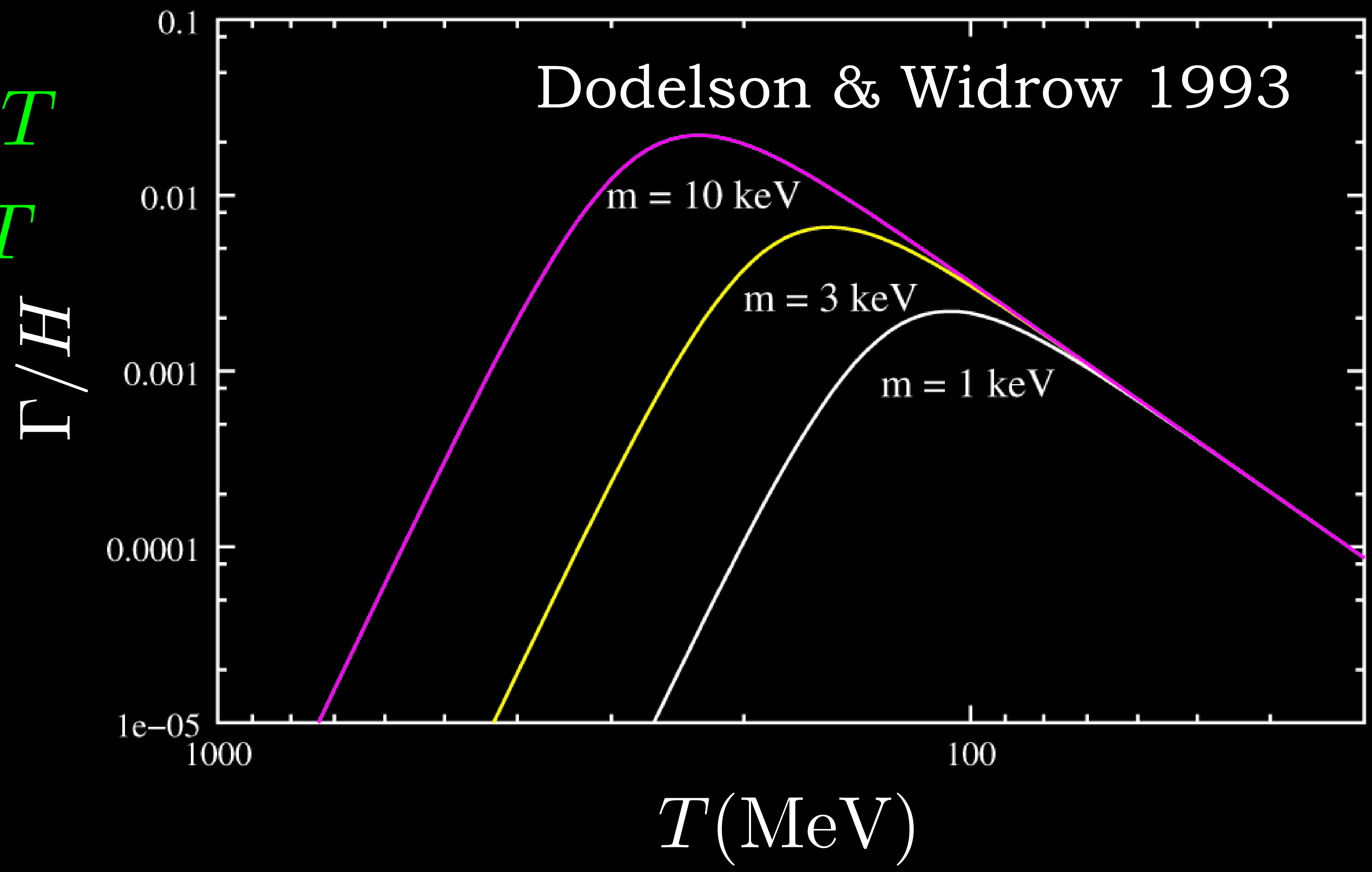

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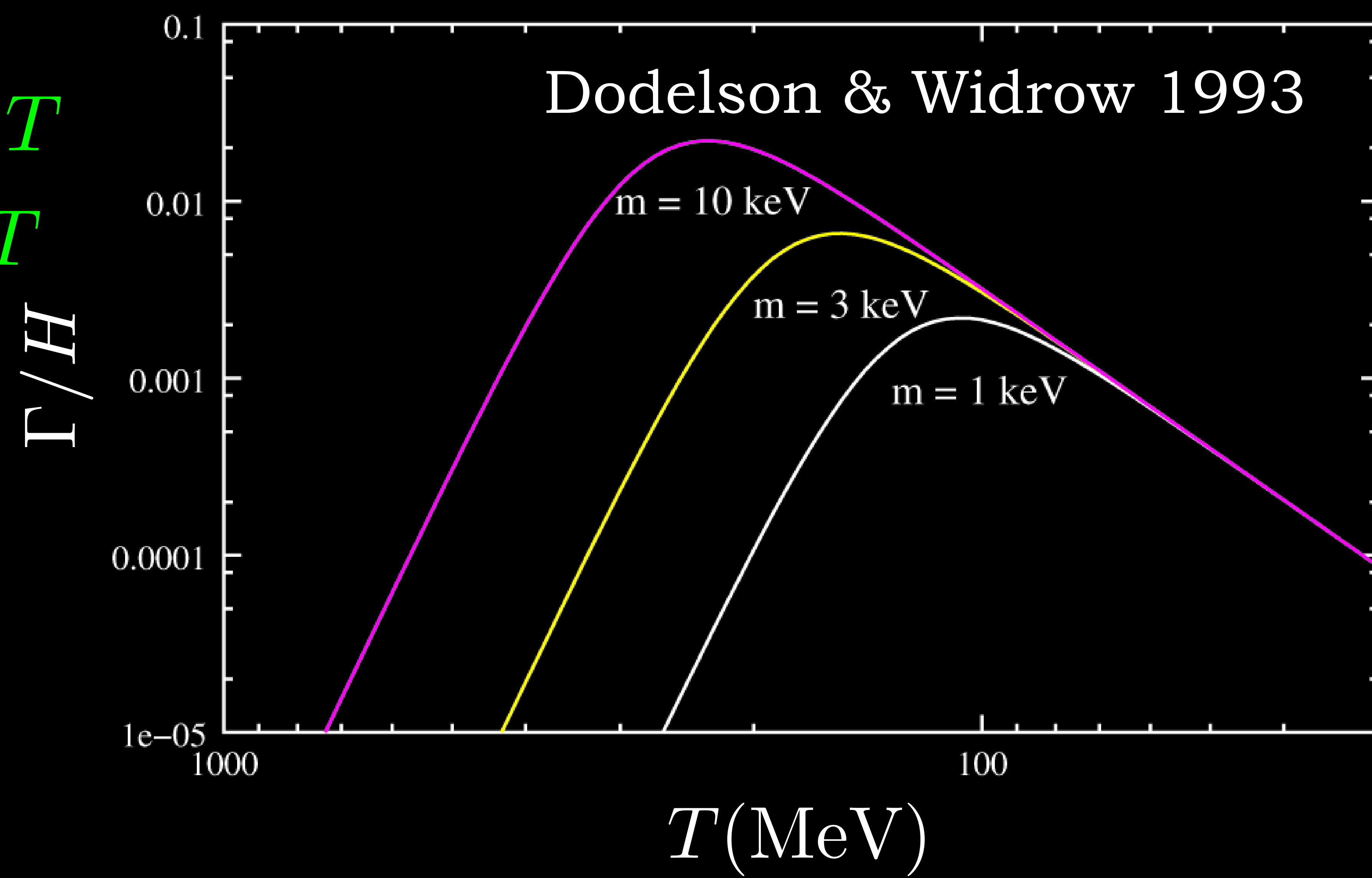

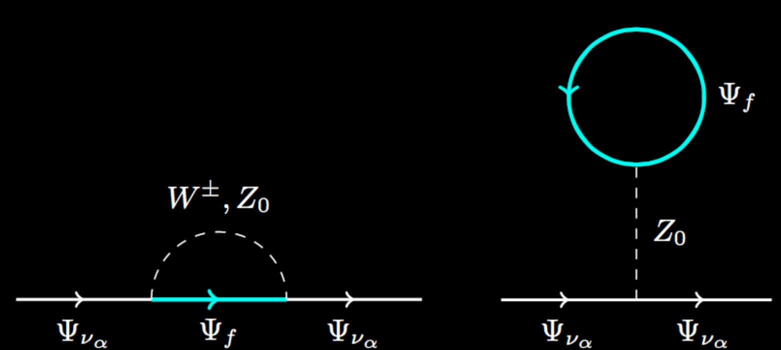

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Resonance: Shi & Fuller 1998

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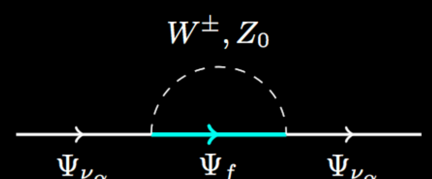

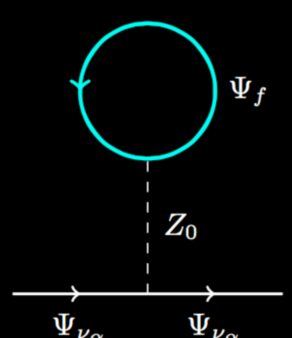

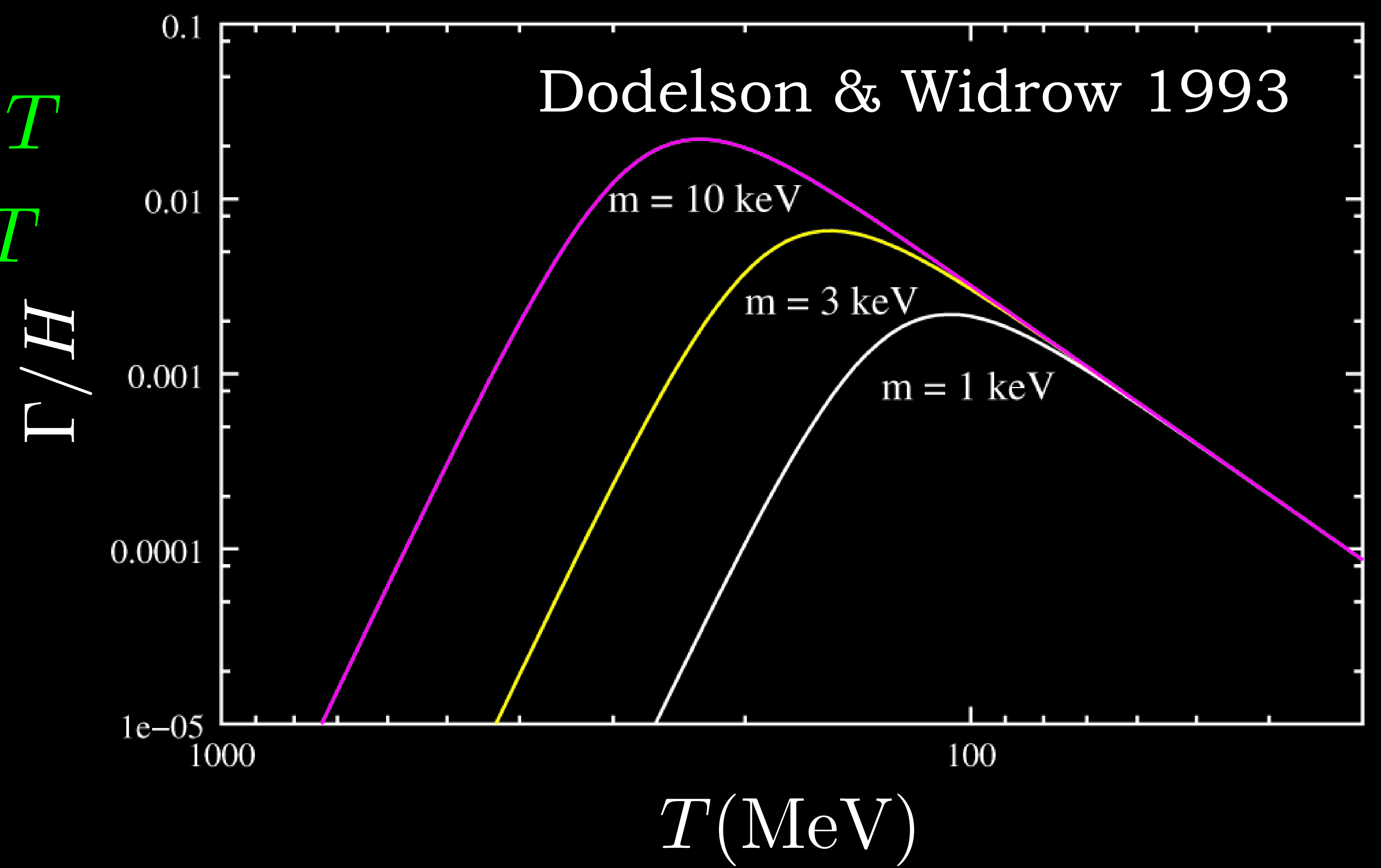

Observing the Sterile Neutrino in the X-ray:
Chandra & XMM-Newton X-ray Space Telescopes

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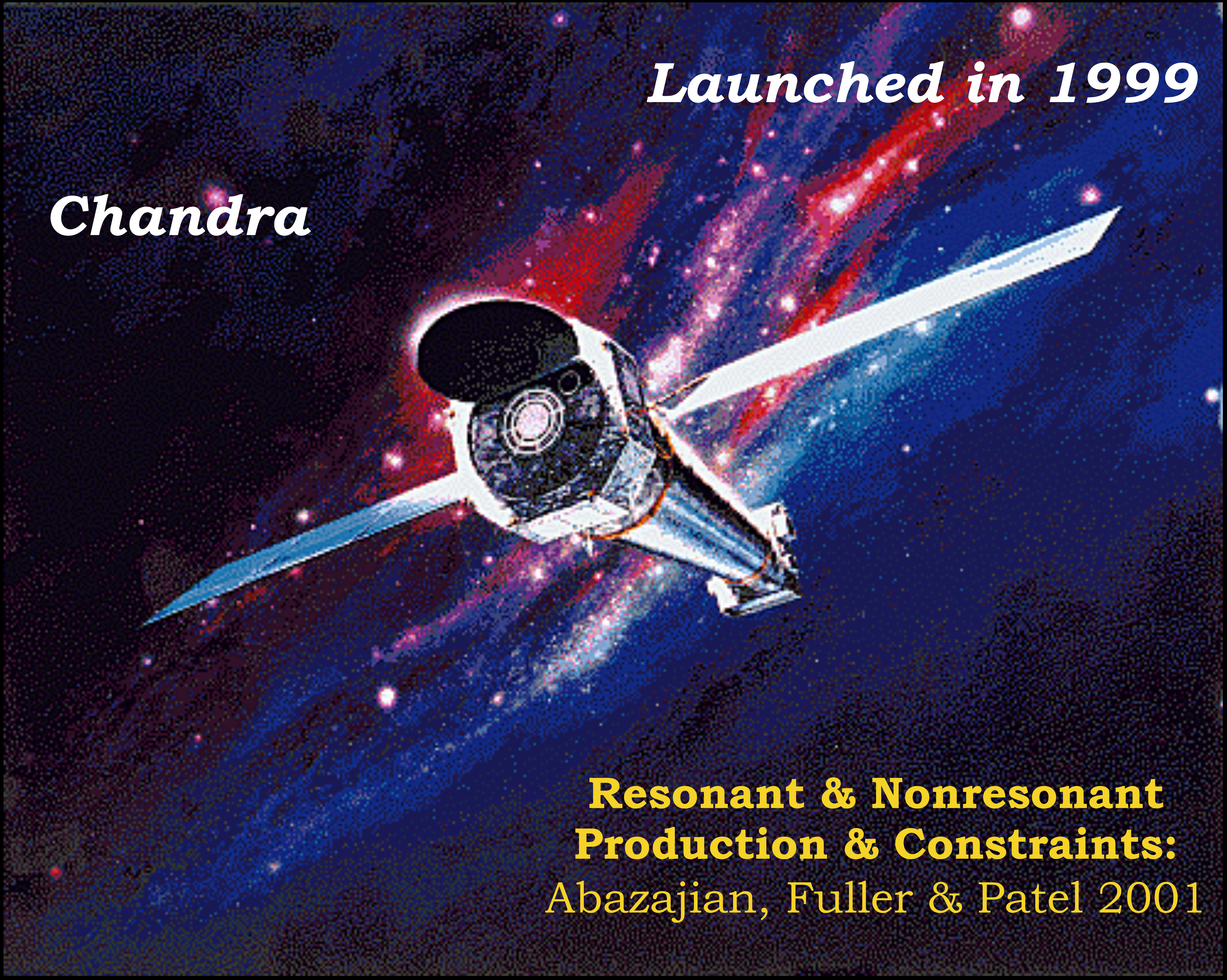
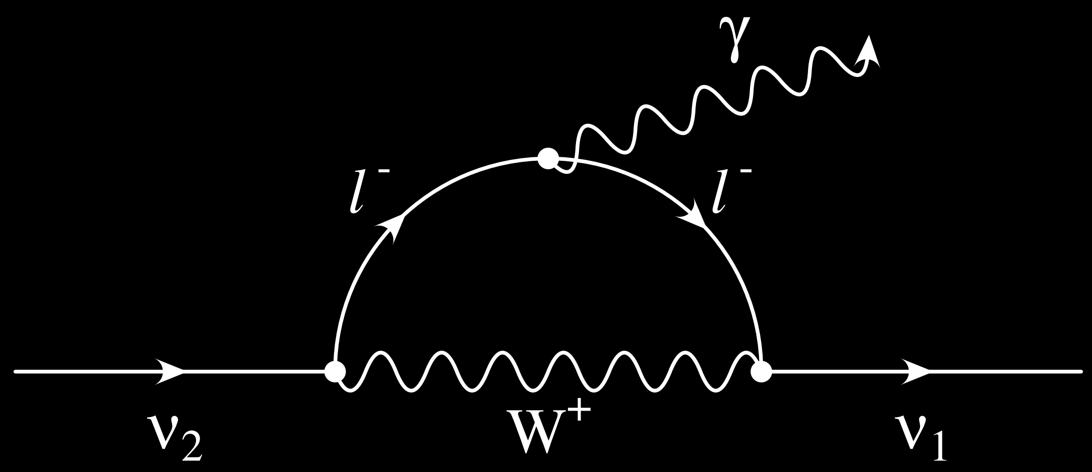


Sterile ν WDM Radiative Decay in the X-ray



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

$$``\nu_s" \rightarrow ``\nu_\alpha" + \gamma$$

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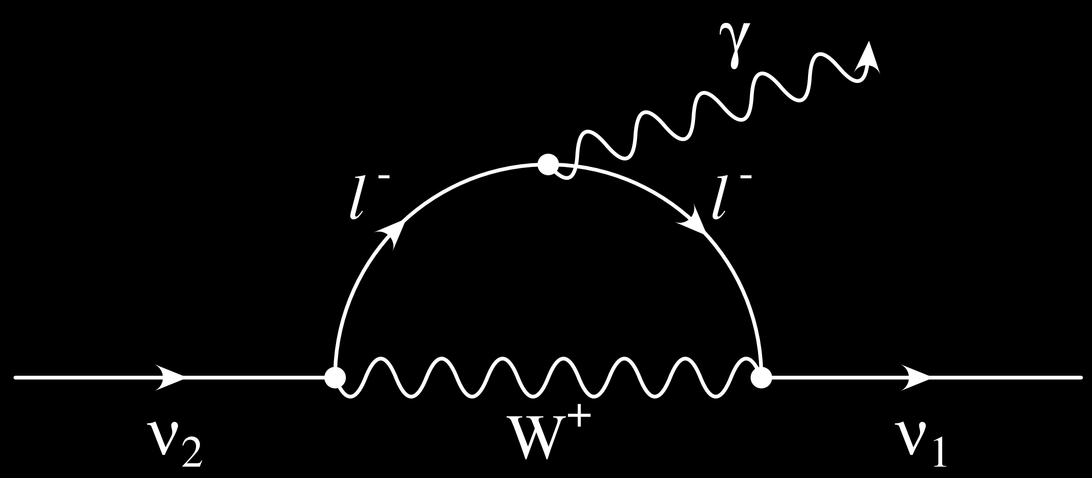

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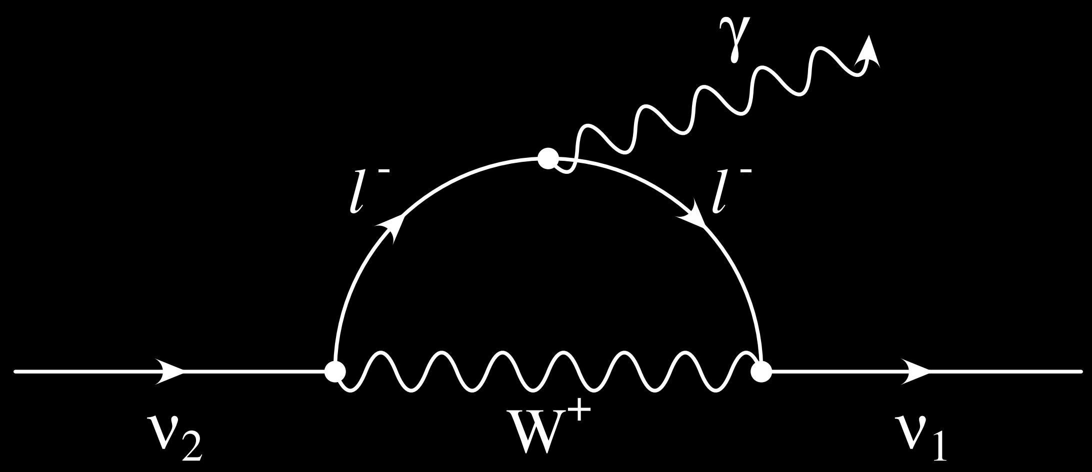

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$$\Gamma_\gamma = 1.62 \times 10^{-28}\ \text{s}^{-1} \left(\frac{\sin^2 2\theta}{7 \times 10^{-11}}\right) \left(\frac{m_s}{7\ \text{keV}}\right)^5$$

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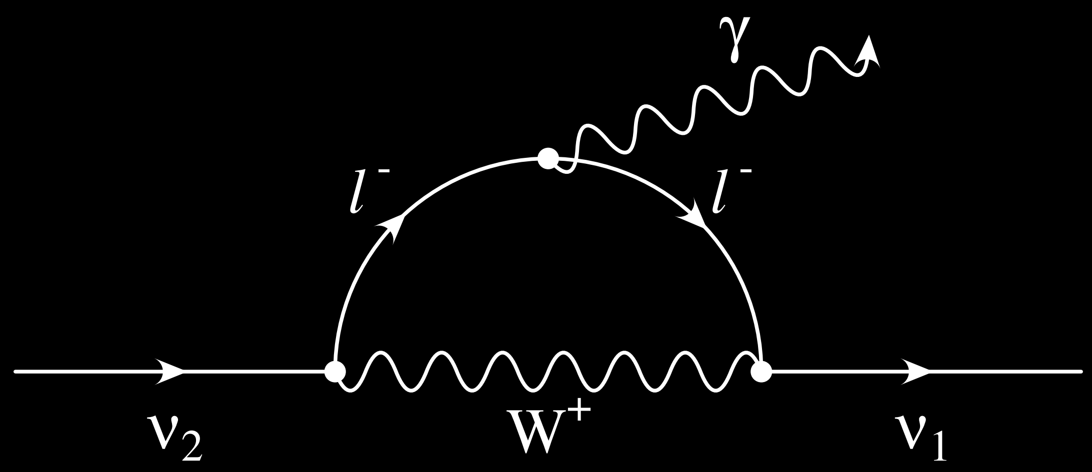

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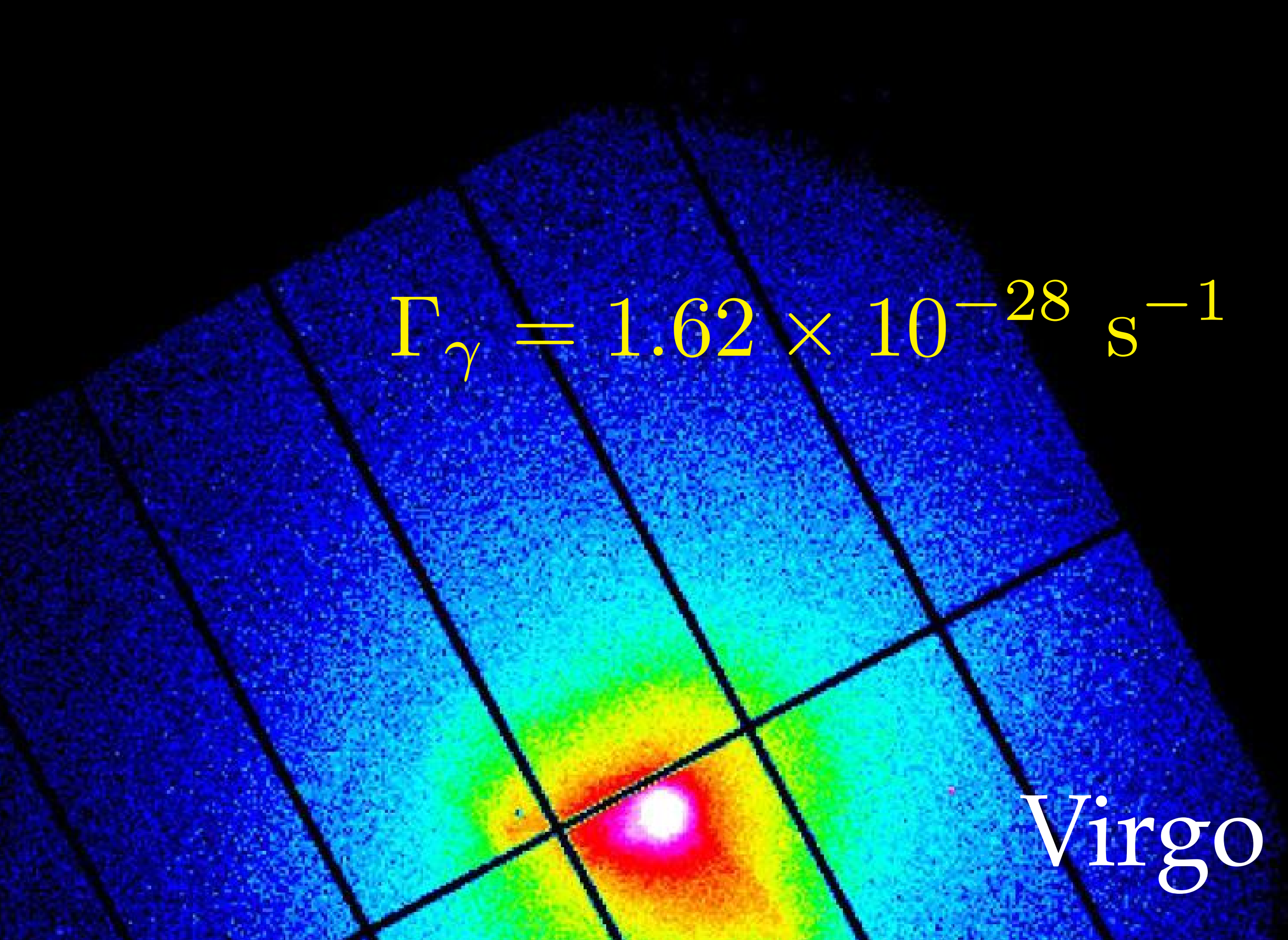

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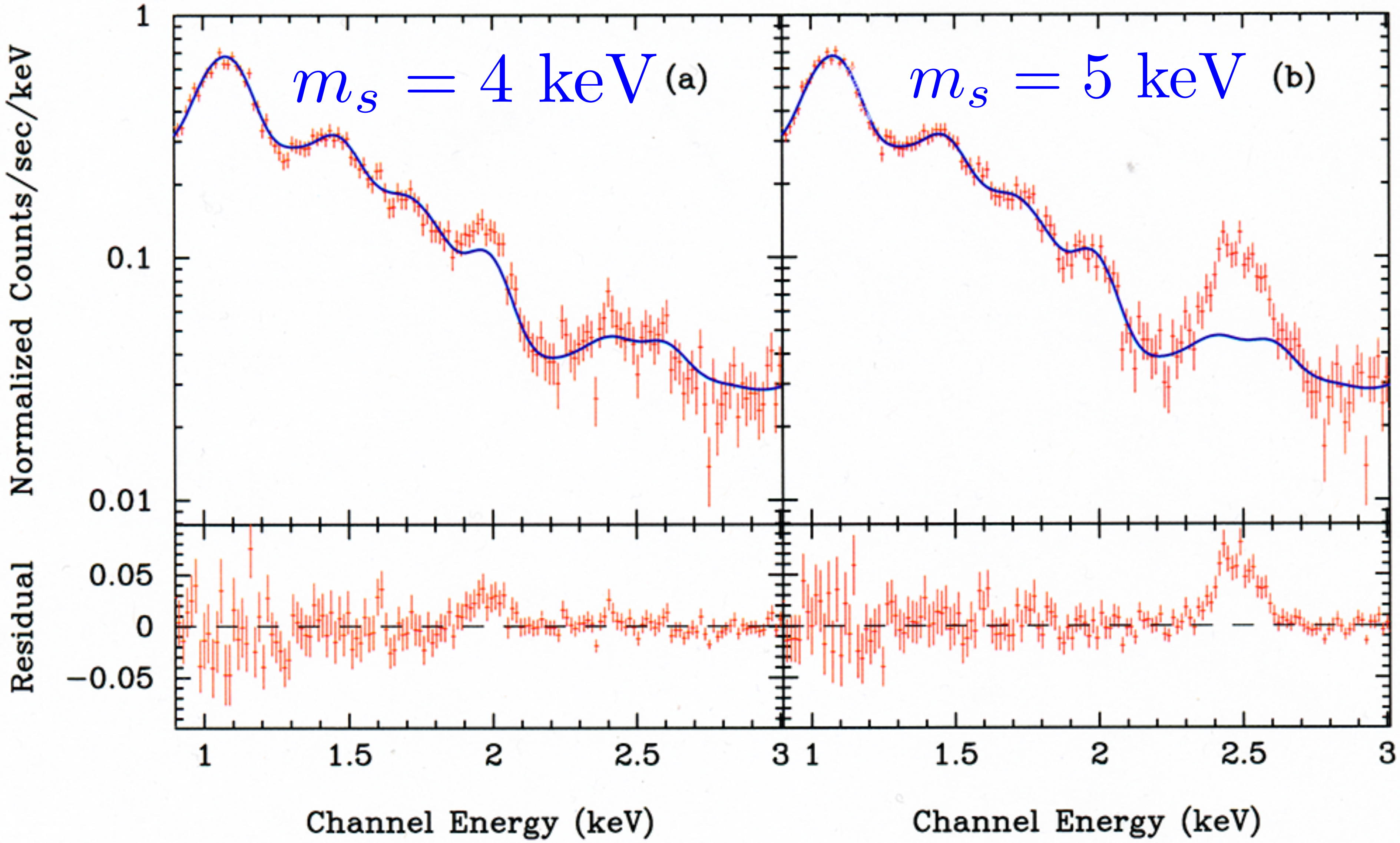
Virgo Cluster: 10^{78} DM particles

Slide from 2001



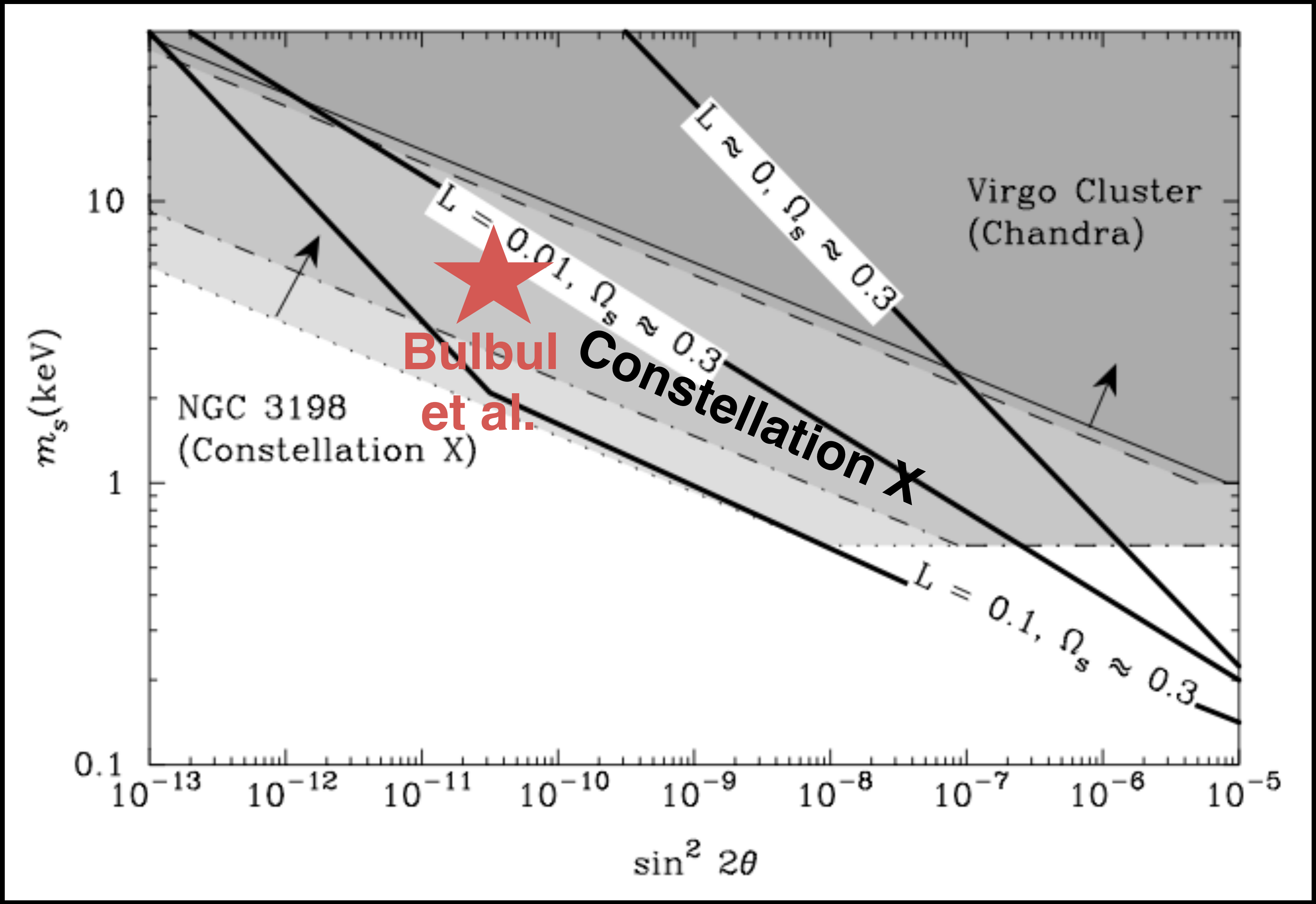
Current Limits

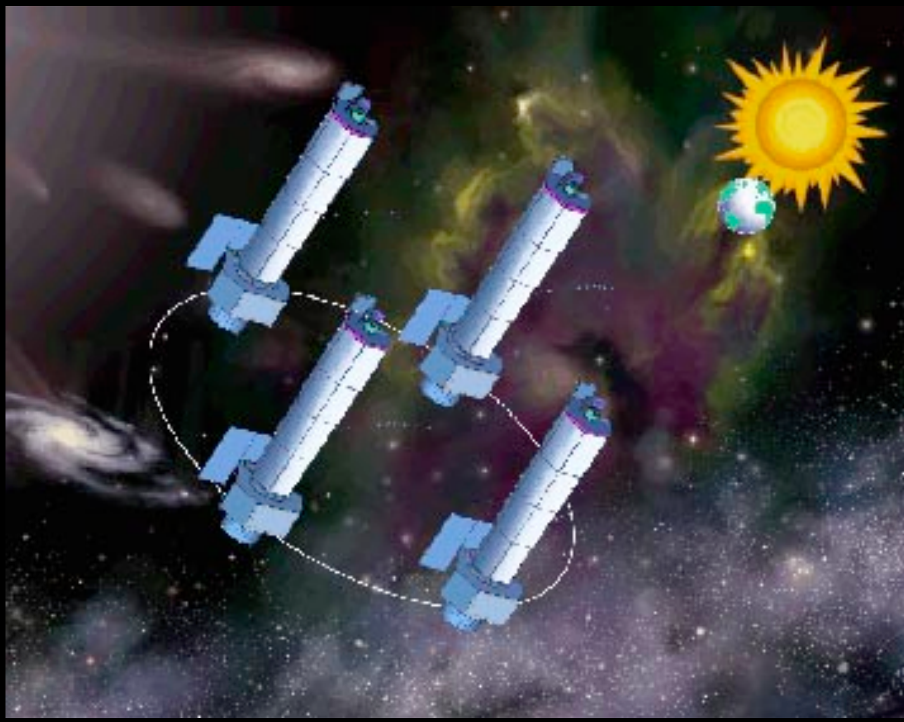
+

Future Detection?

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

Abazajian, Fuller & Tucker 2001





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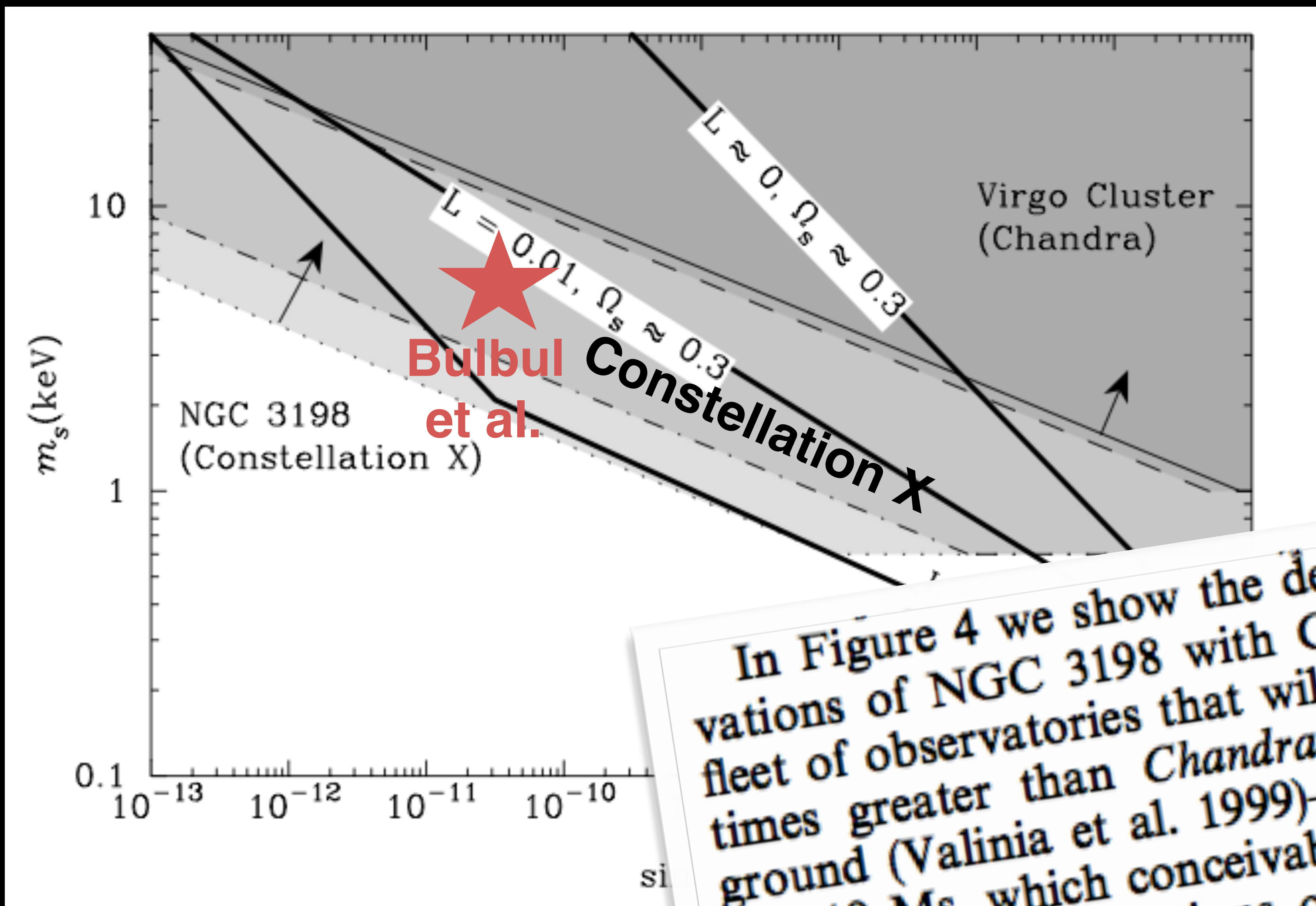
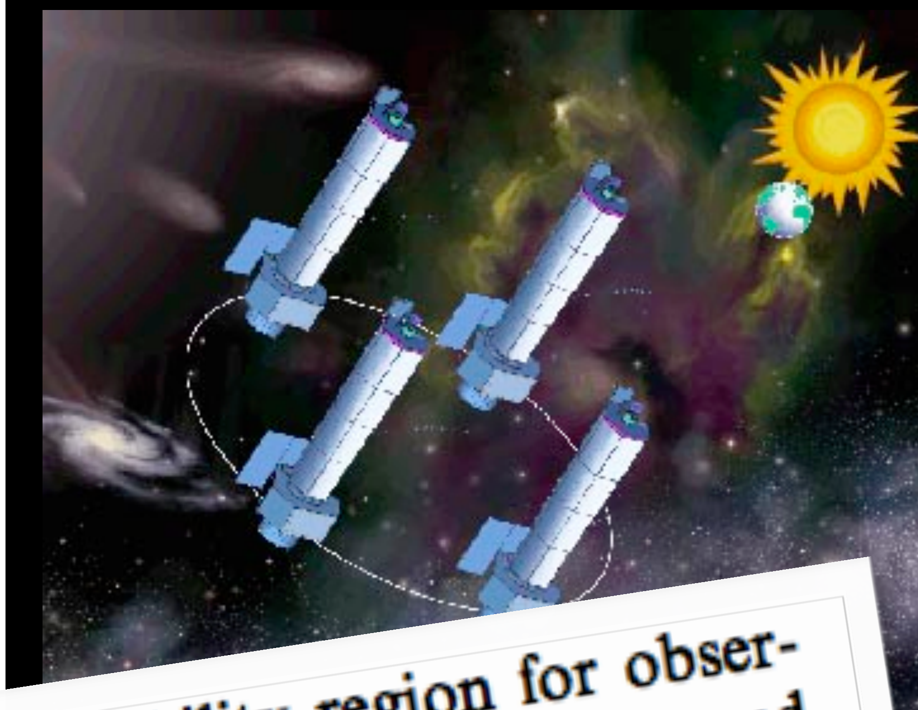
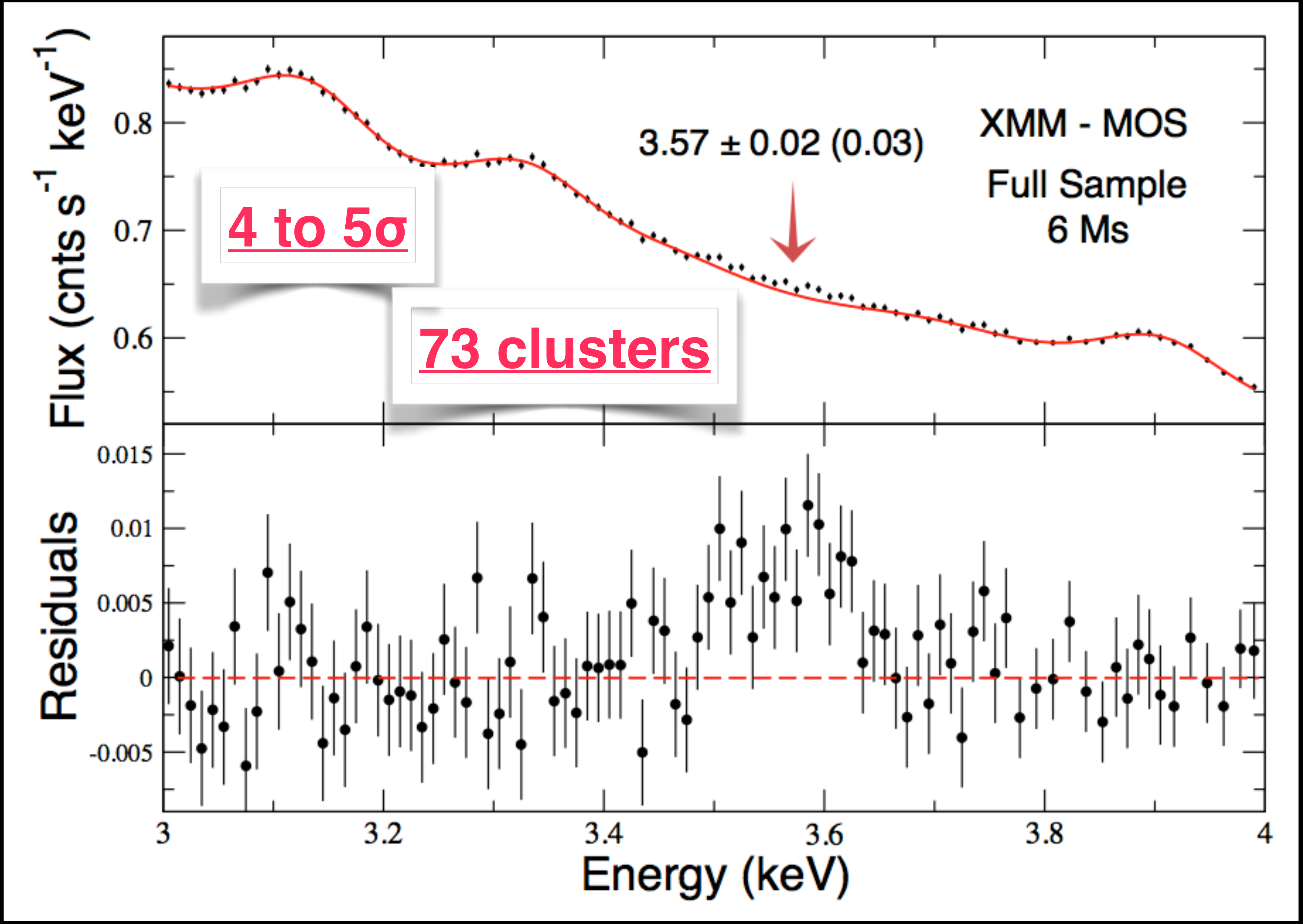




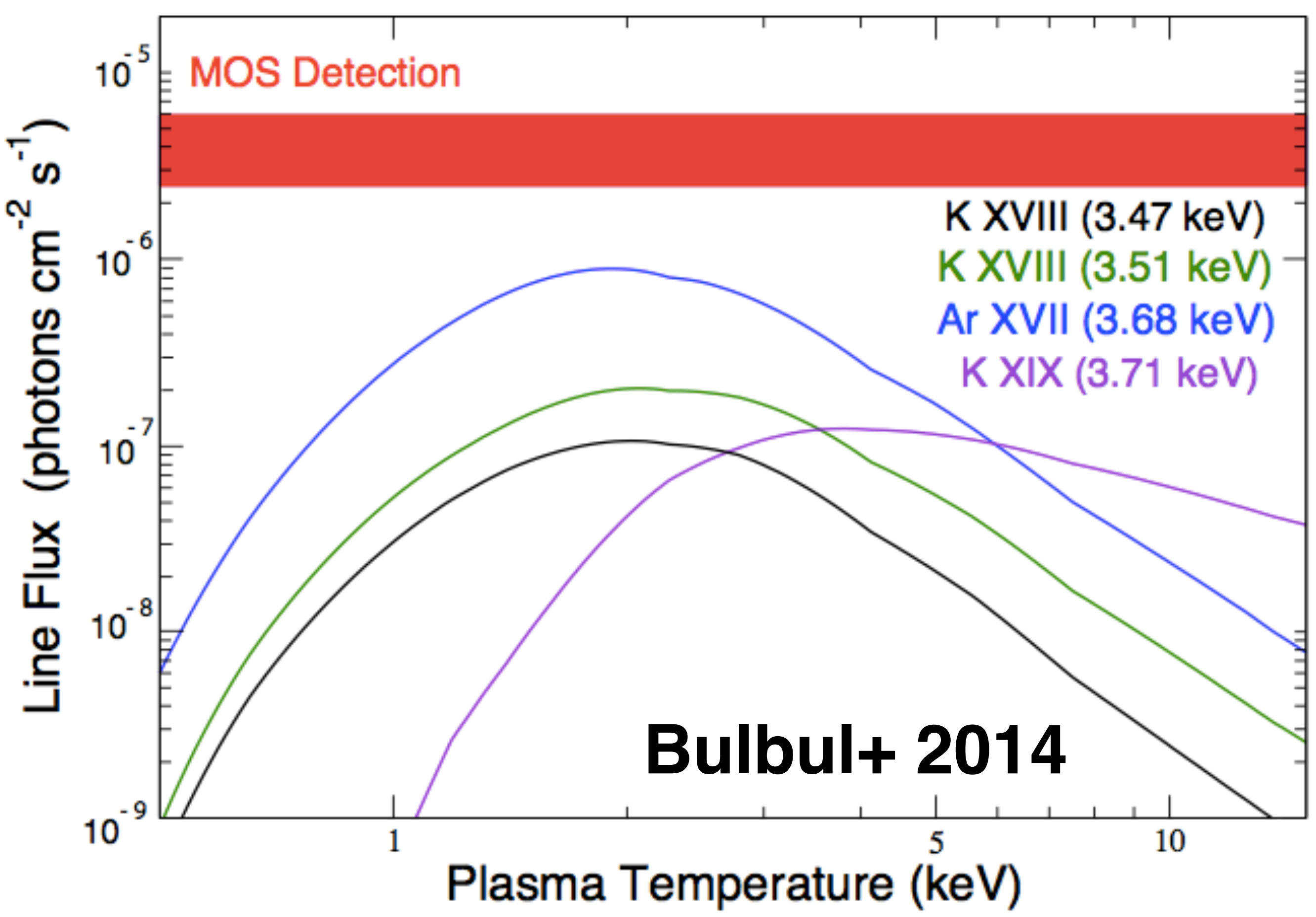
In Figure 4 we show the detectability region for observations of NGC 3198 with Constellation X—a proposed fleet of observatories that will have an effective area ~10 times greater than *Chandra* and no instrumental background (Valinia et al. 1999)—for two integration times, 1 and 10 Ms, which conceivably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

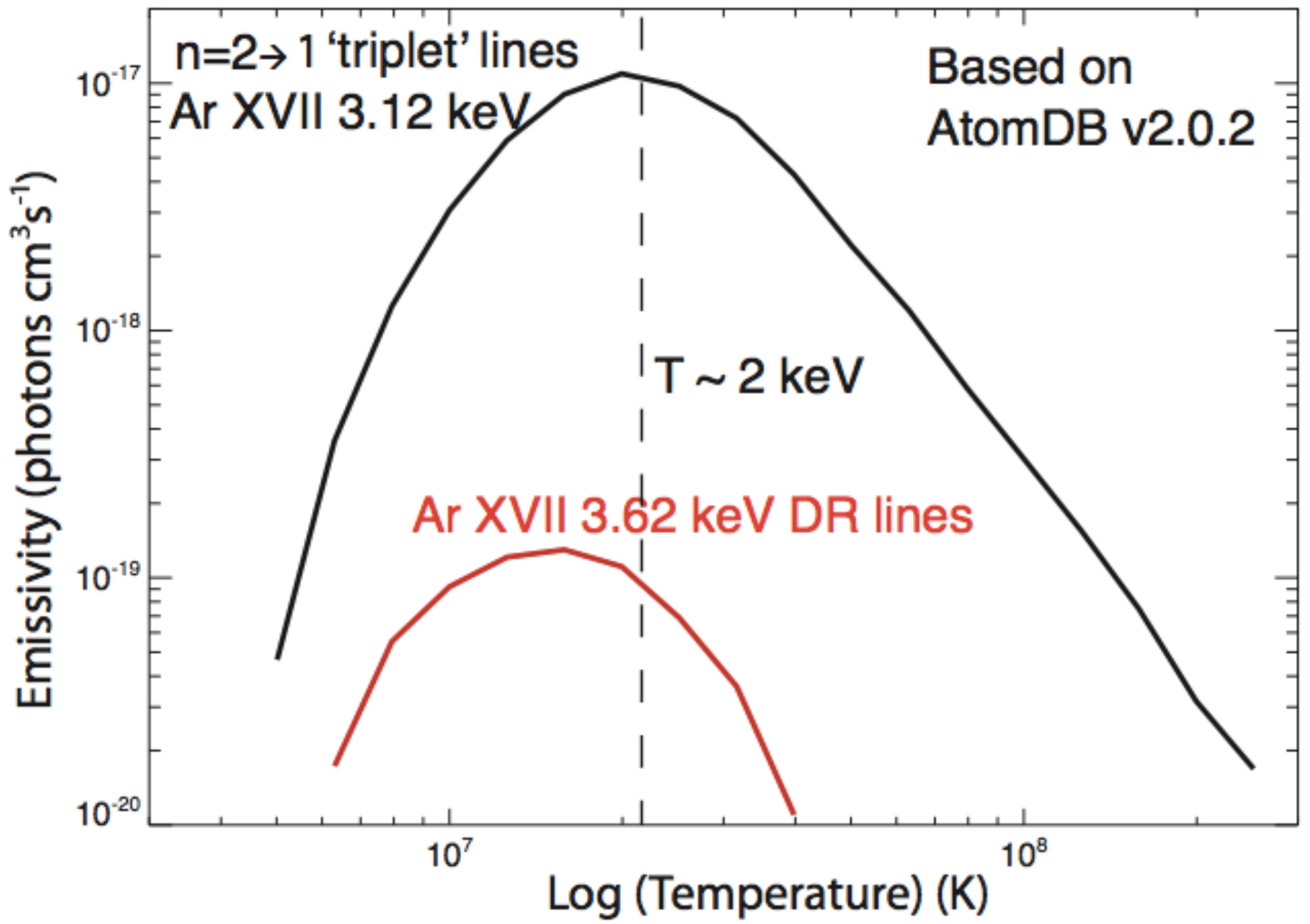
The Detection of an Unidentified Line



Bulbul et al. ApJ 2014

Metal Lines in Clusters at 3.5 keV? *unlikely*





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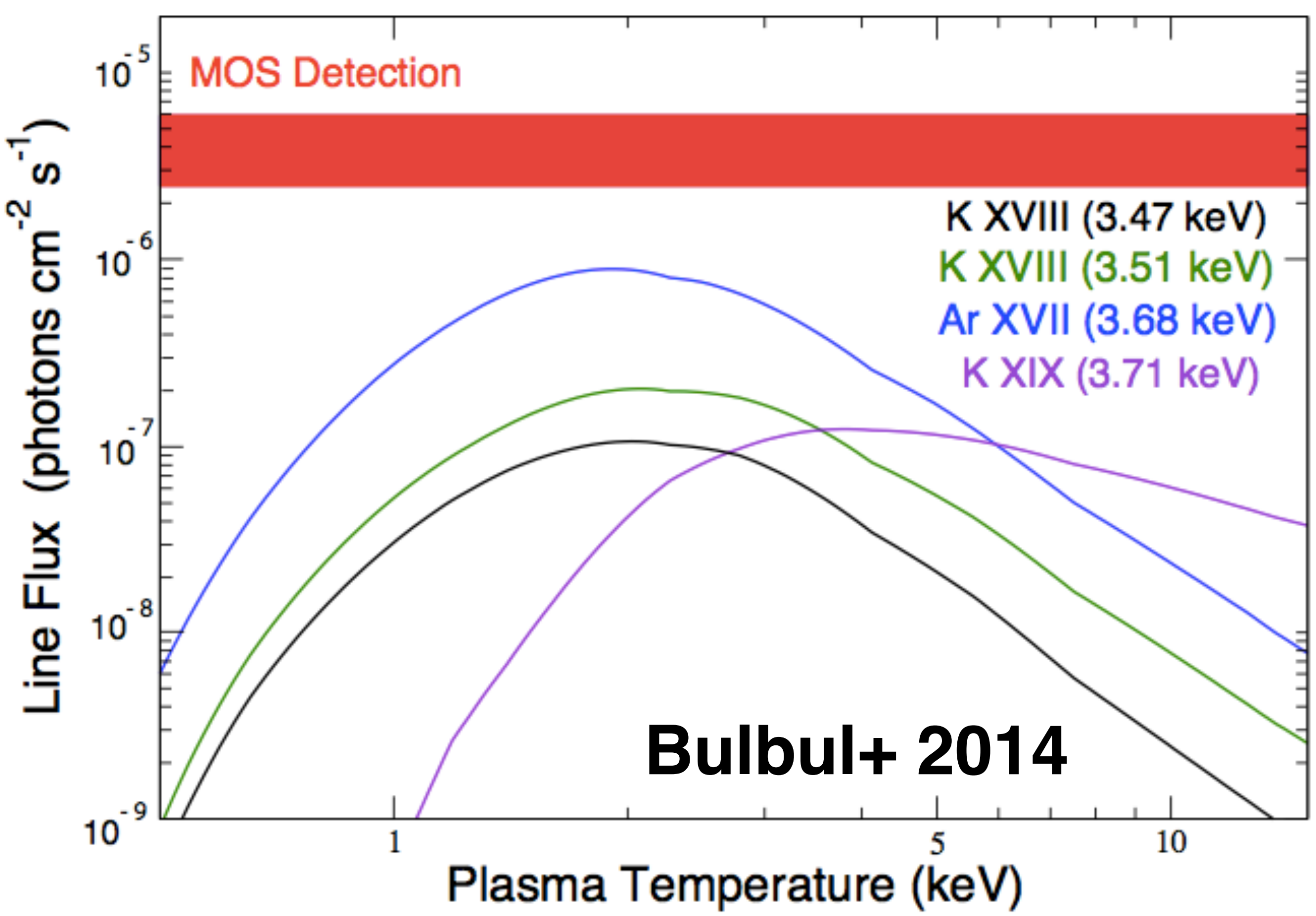

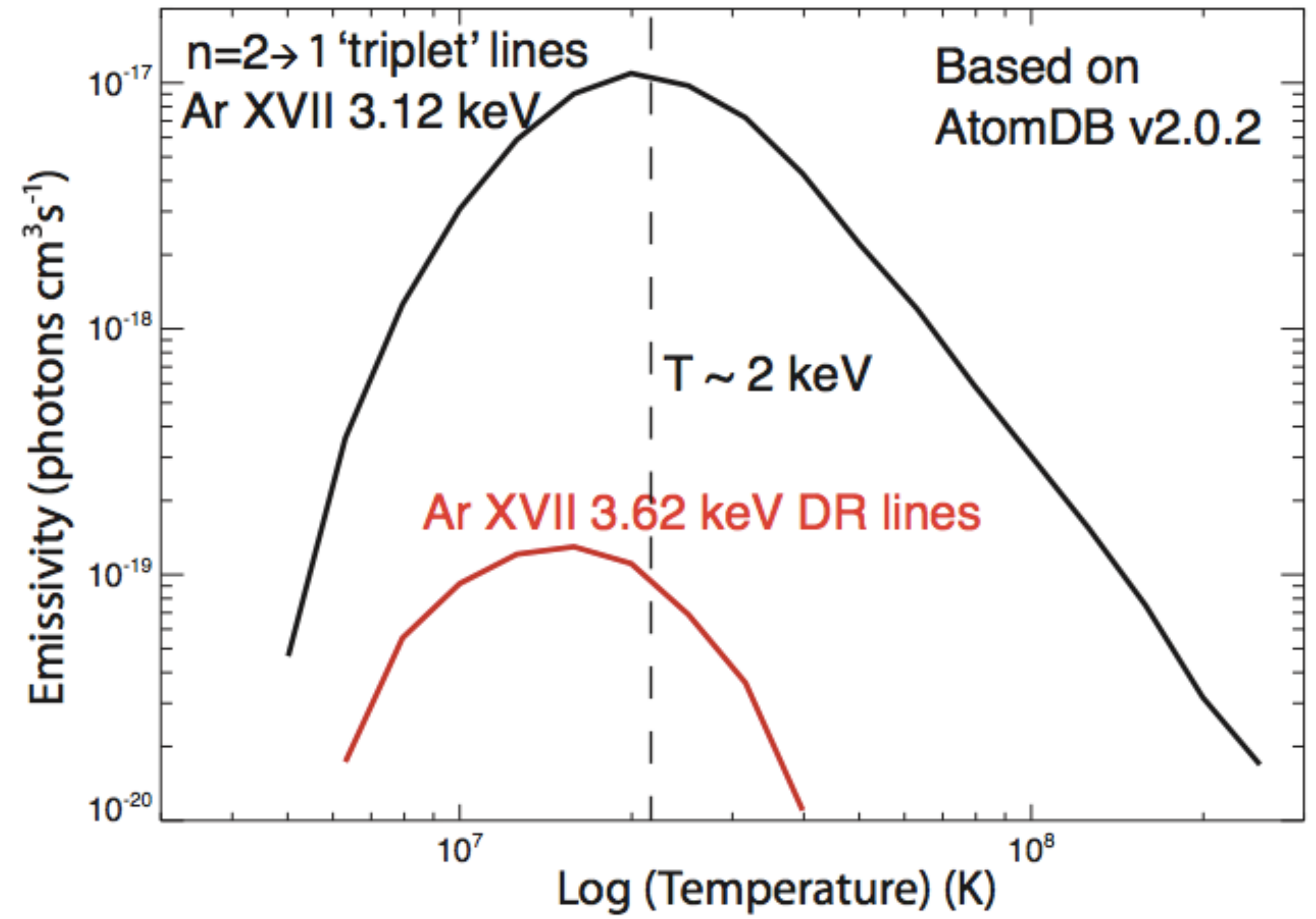

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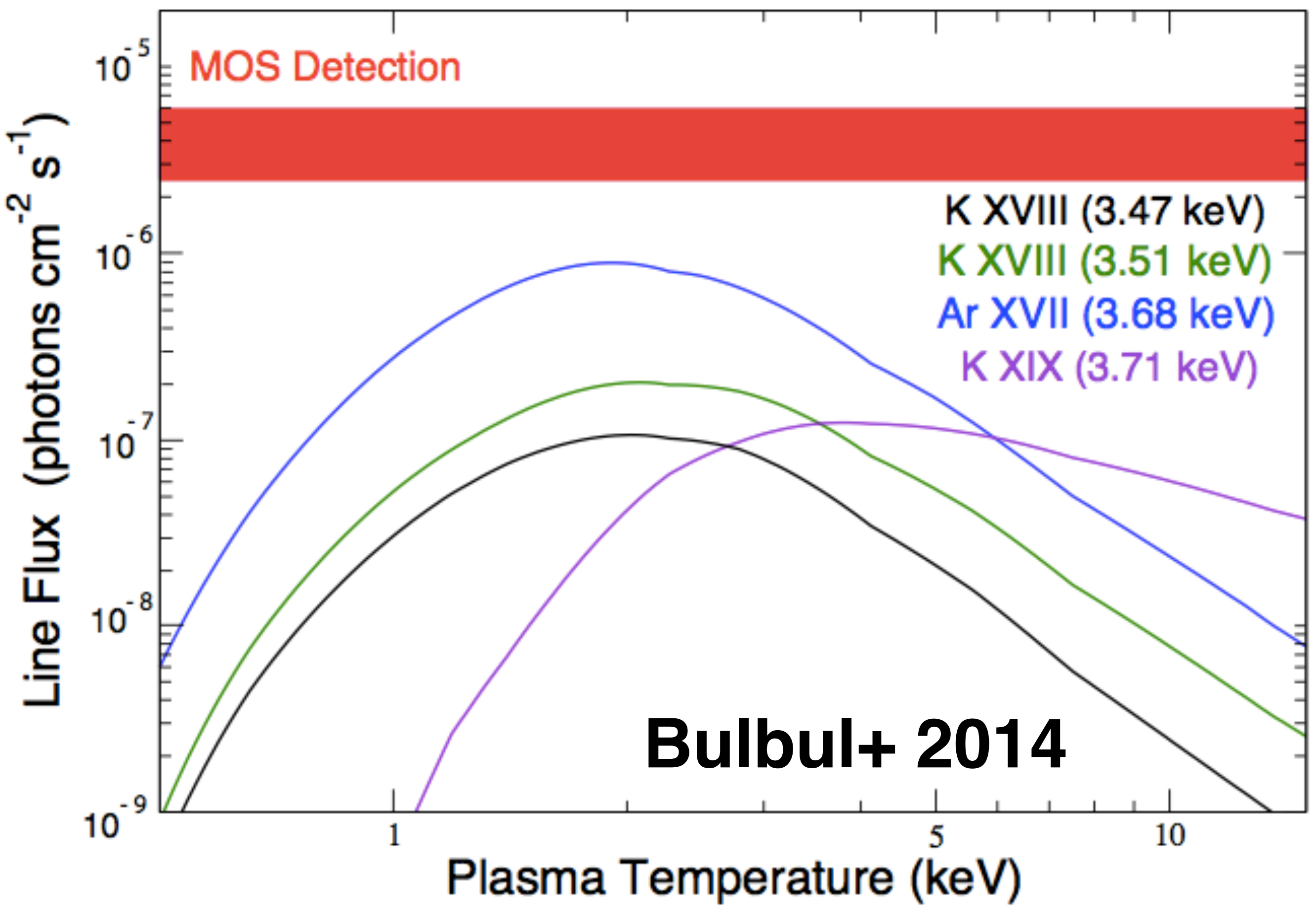
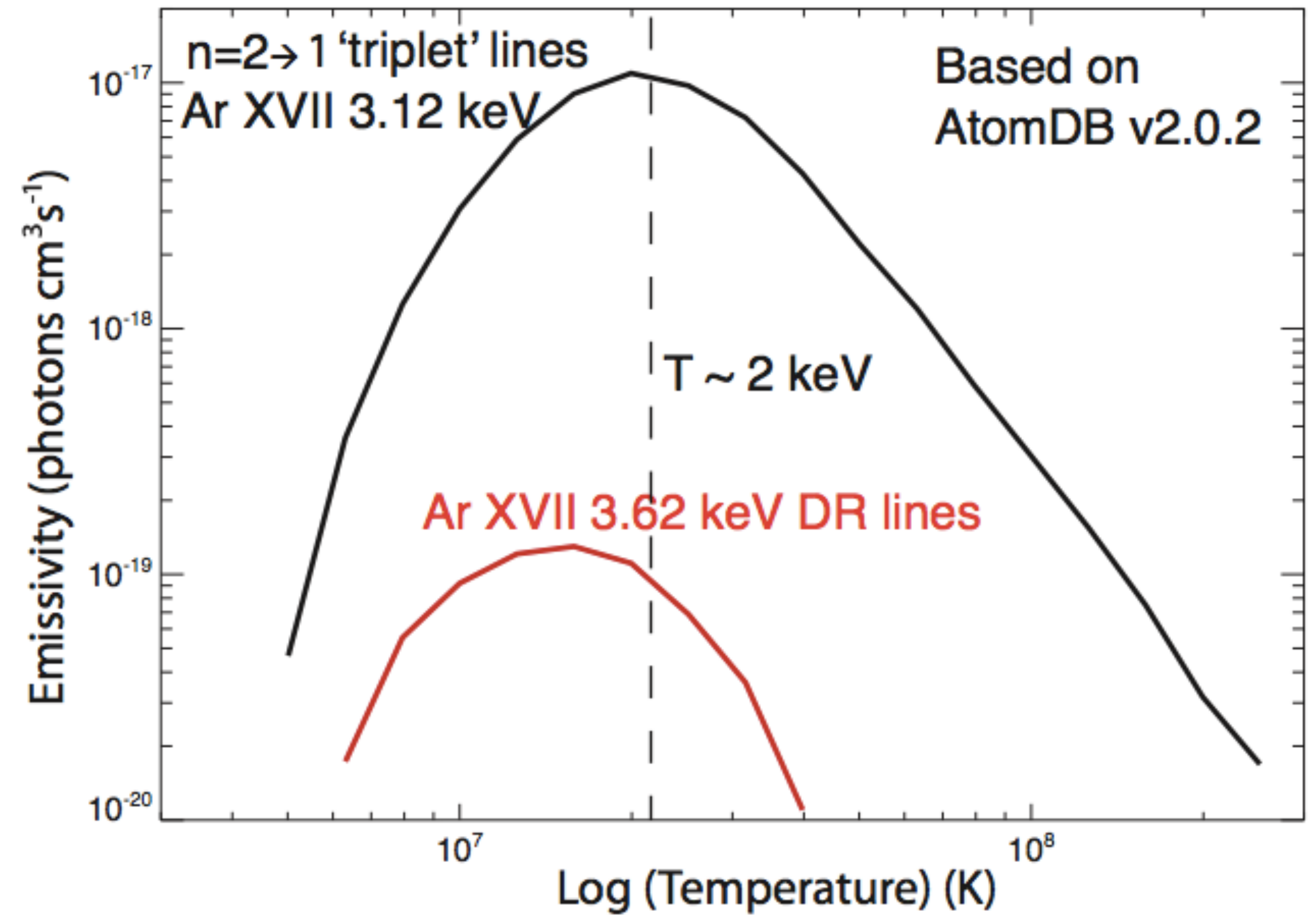
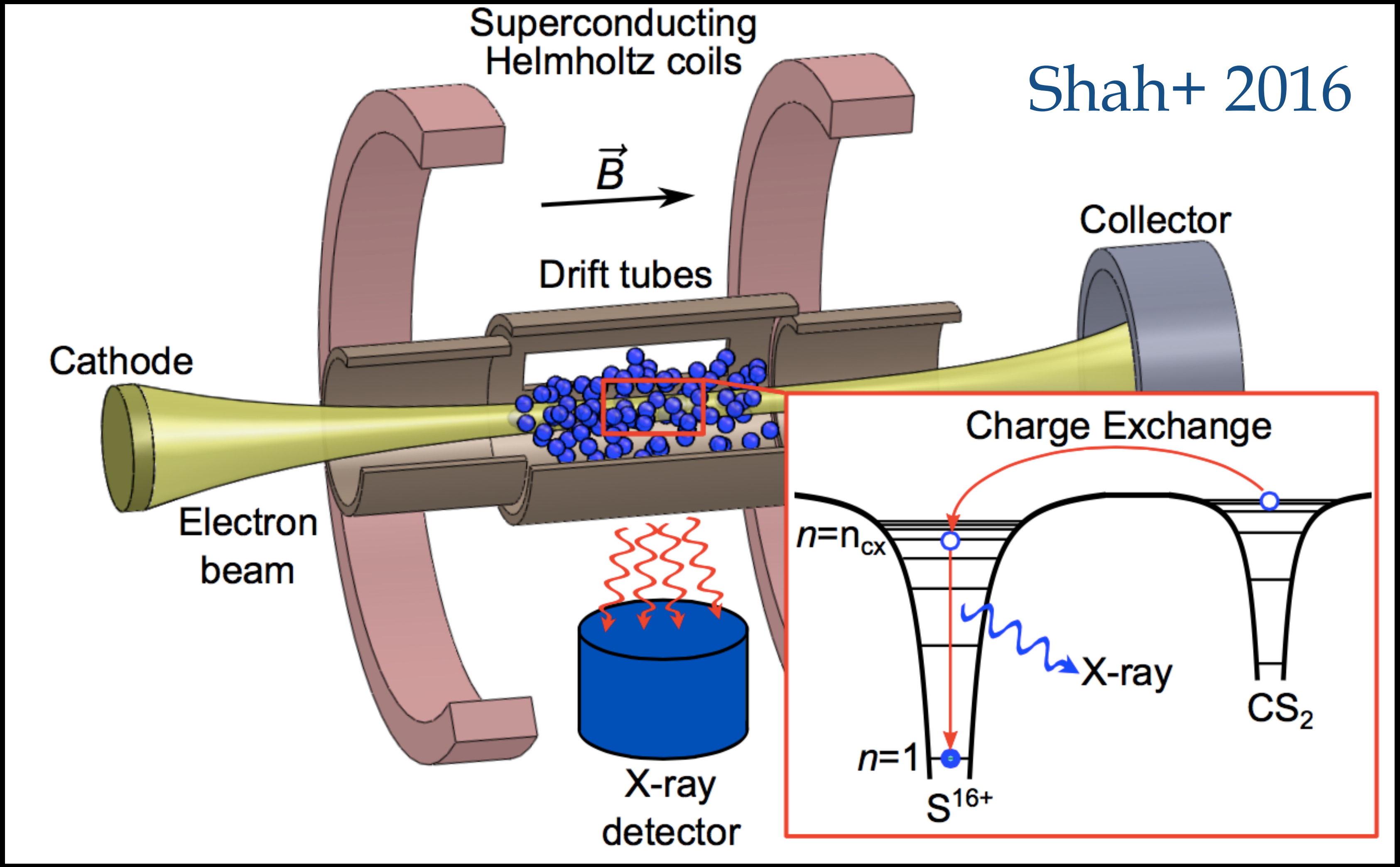




- Most lines at this energy are too low in flux for the typical plasma temperatures
- Those that could be close, Ar XVII DR, would have accompanying lines that make its flux a factor of 30 too low

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

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Successful launch Feb. 17, 2016

Loss of satellite March 26, 2016

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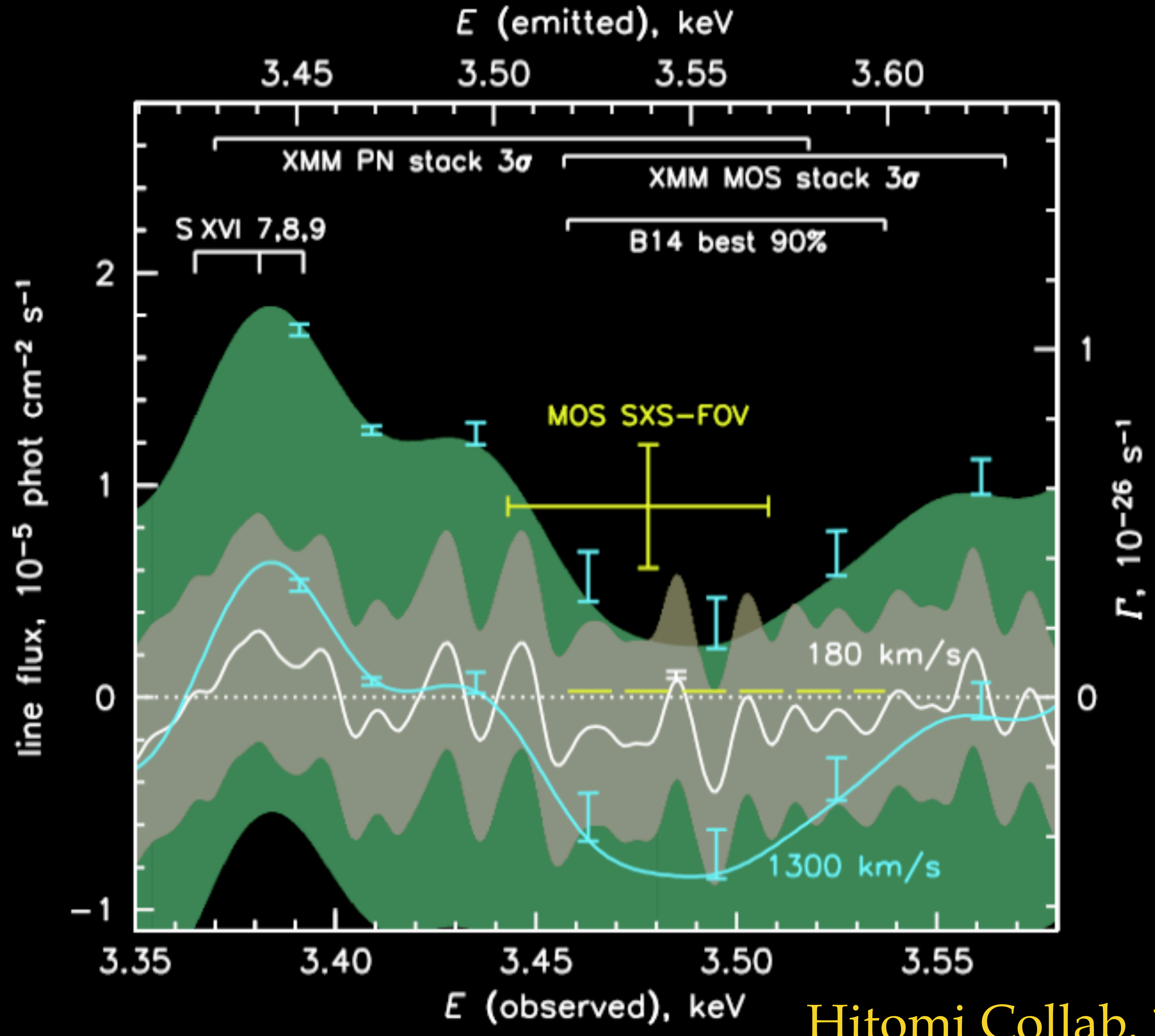
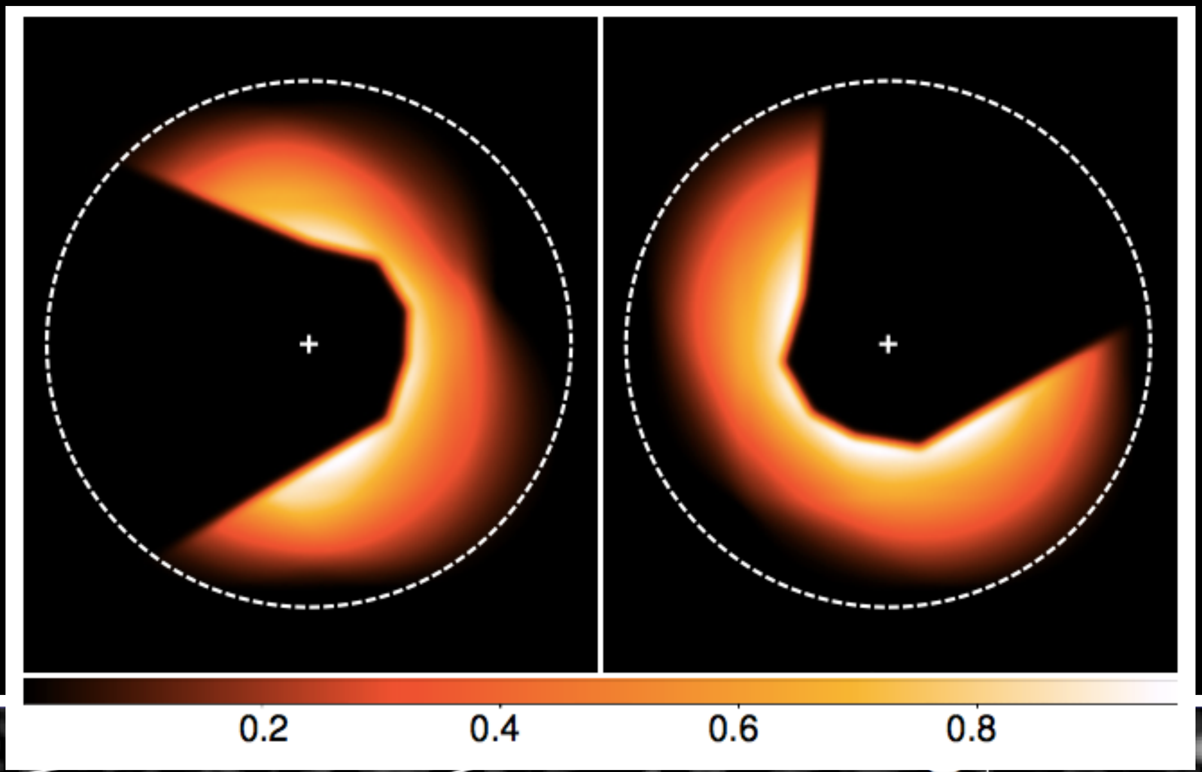
NASA Build-to-print SXS for the
X-Ray Astronomy Recovery Mission
launch March 2021

Hitomi X-ray Telescope: Expected line or not?



Hitomi Collab. 1607.07420

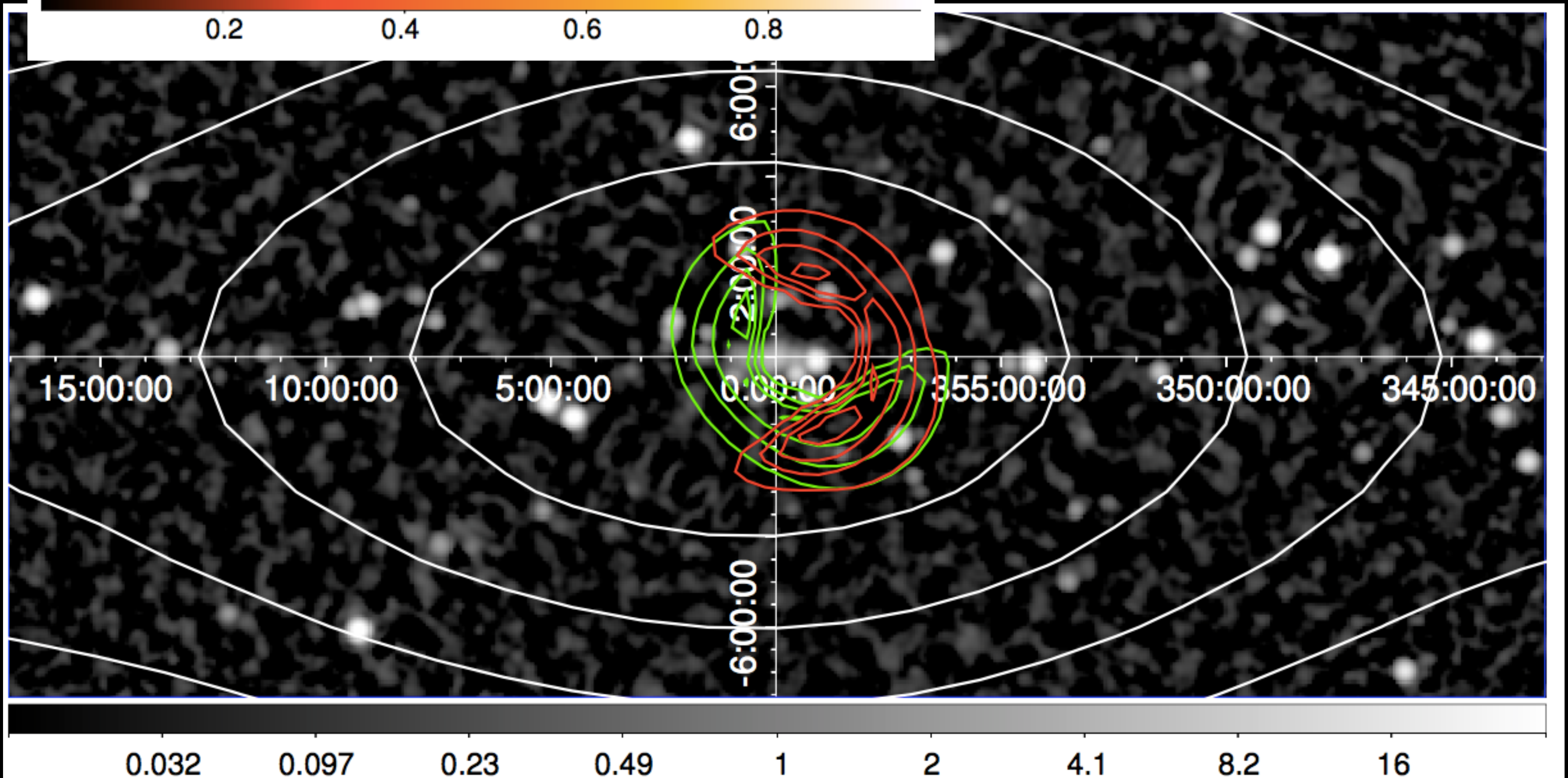
NuSTAR: the best current telescope?



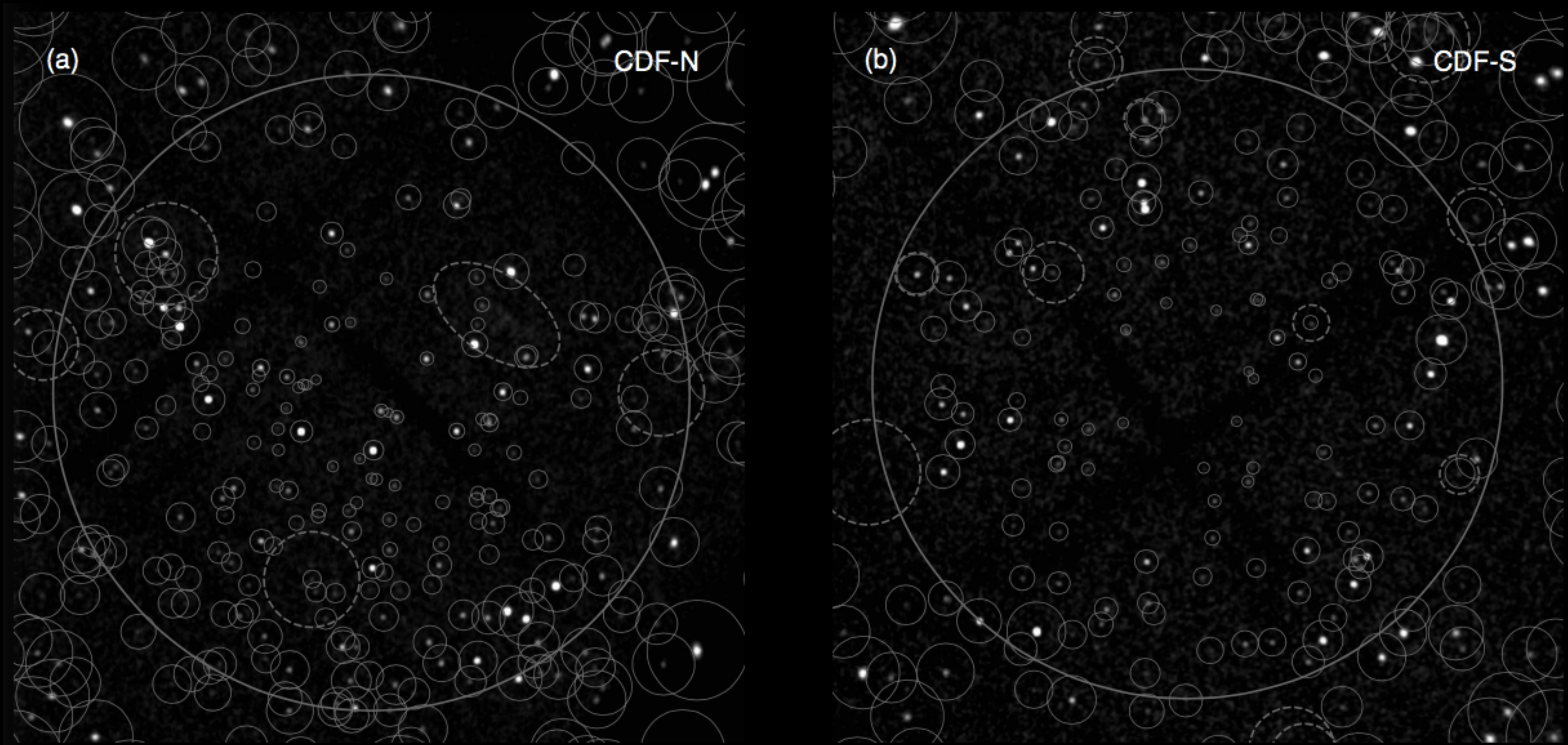
Shielding gap in telescope lets in 0 bounce photons. 37 deg² aperture!

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

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



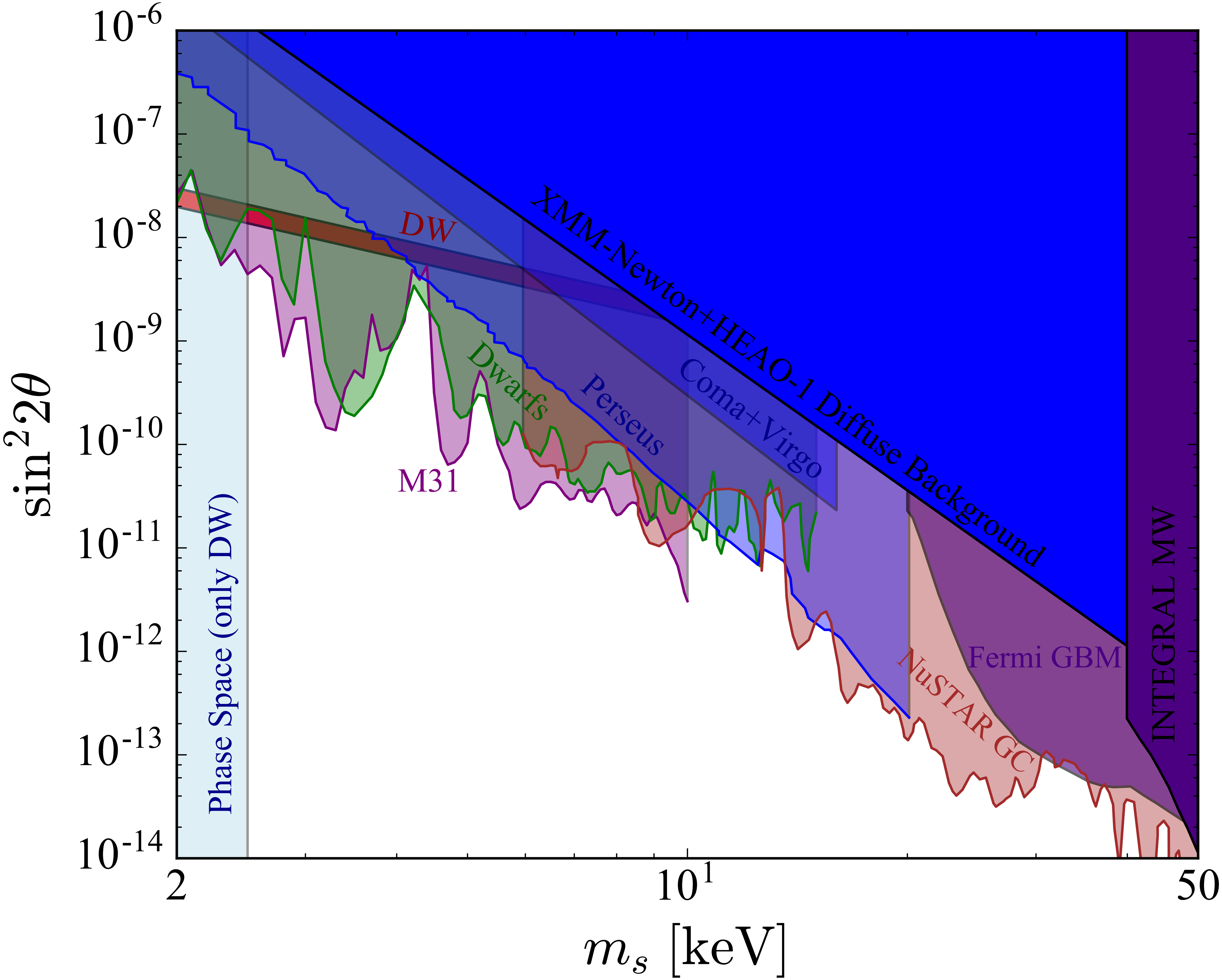
Chandra Deep Fields: 10 Ms of data



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

Sterile Neutrino Dark Matter: Parameter Space Summary



Abazajian *Physics Reports* arXiv:1705.01837

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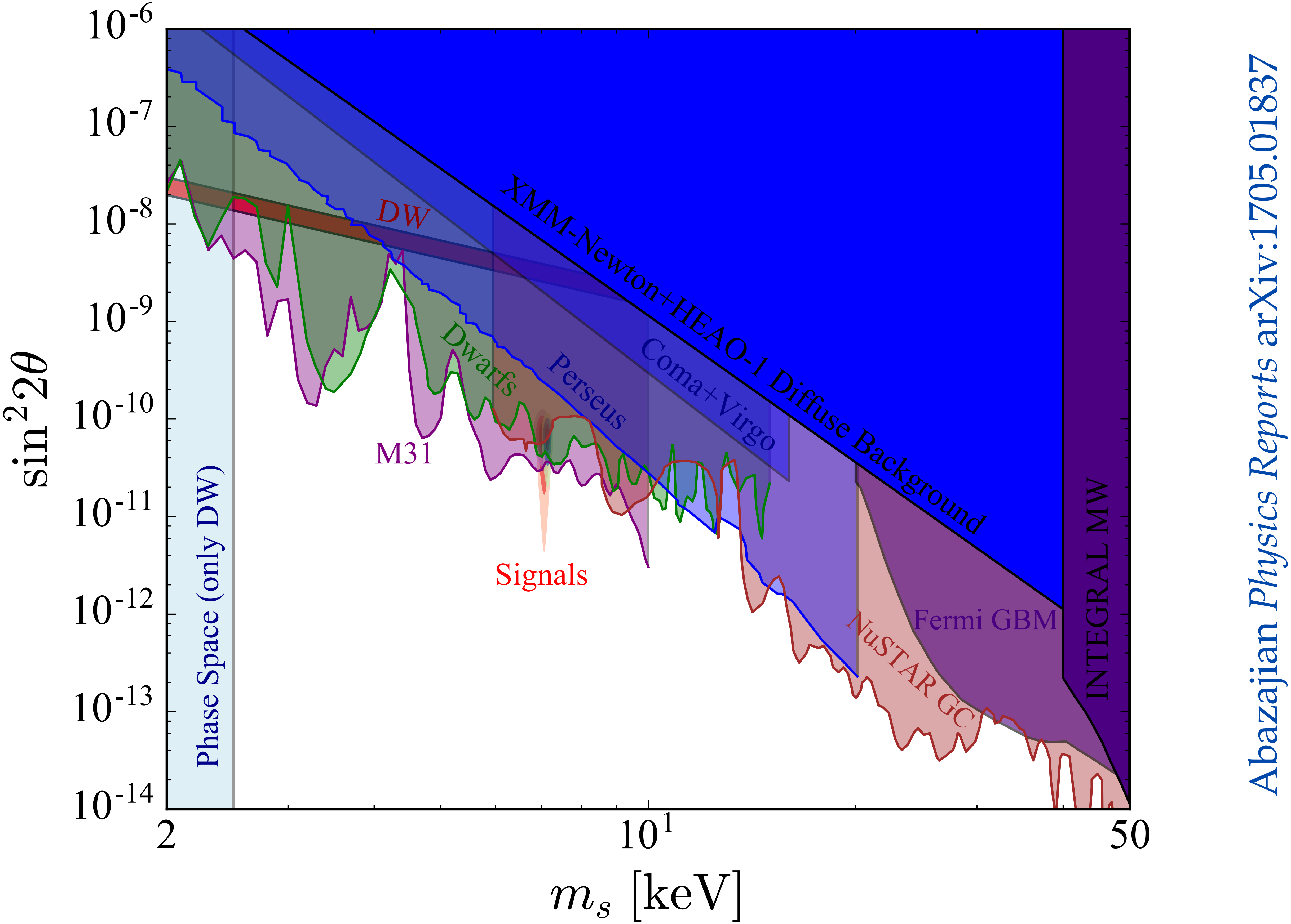
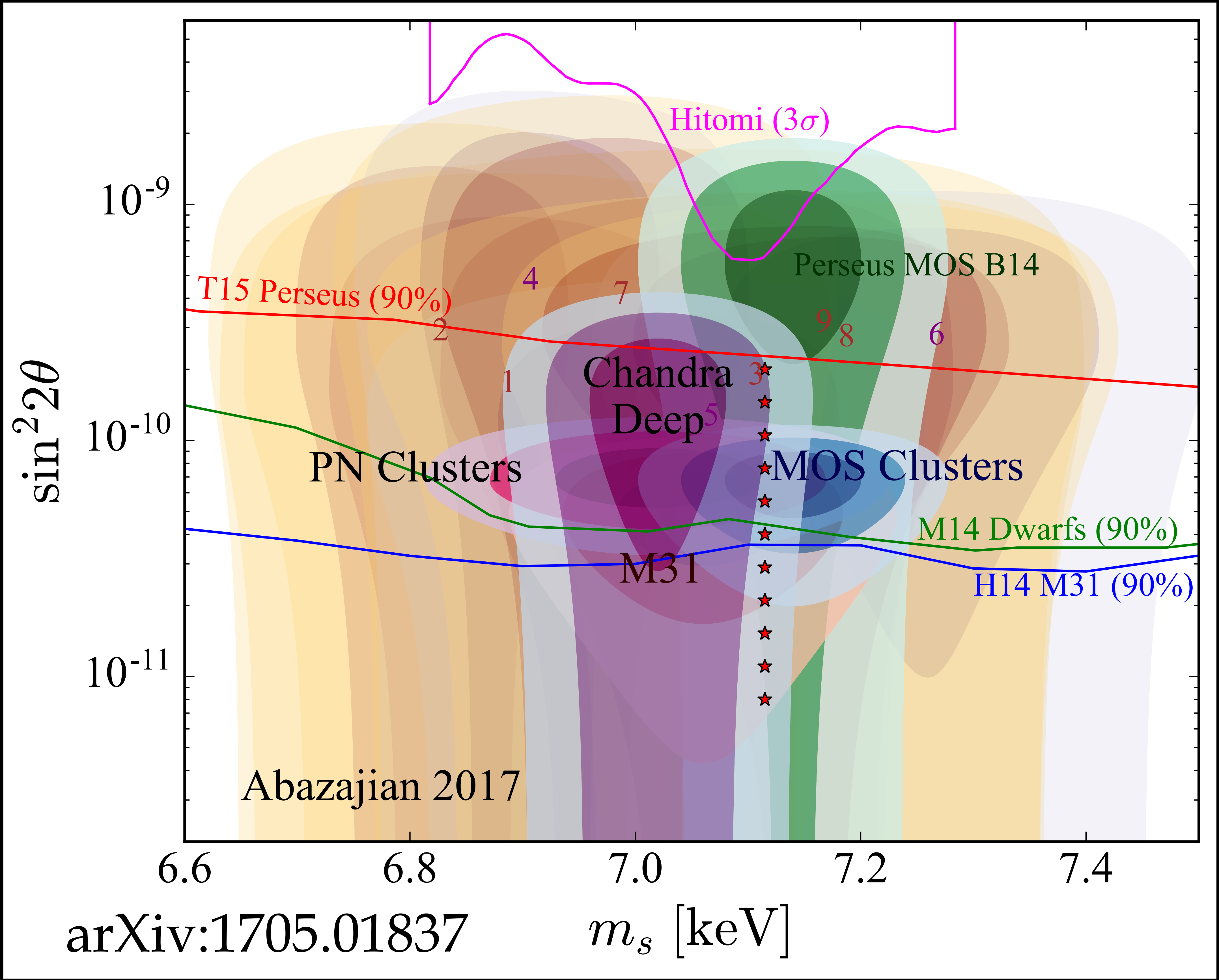
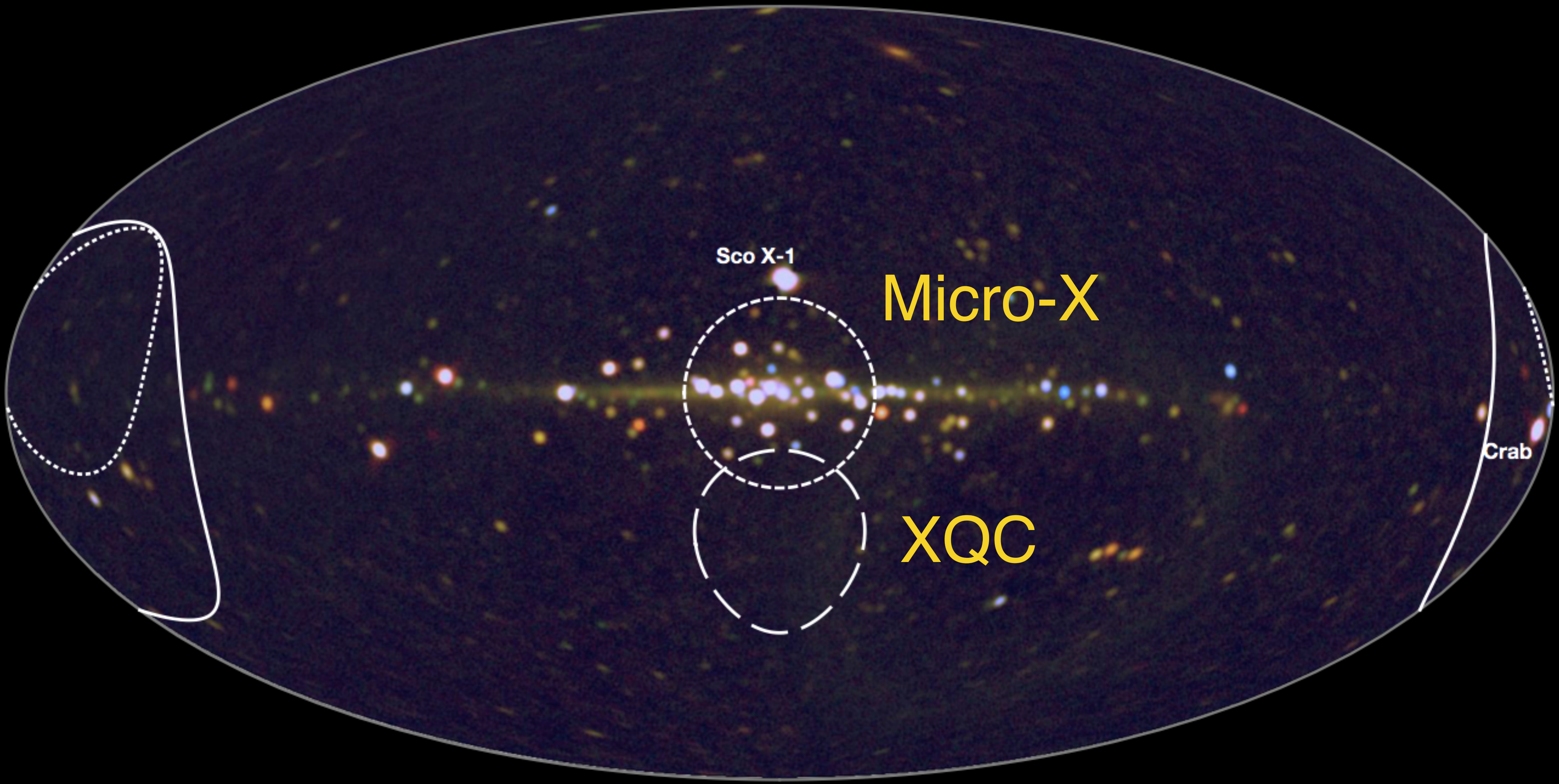


The 7 keV Region Today



Cluster search: Iakubovskyi+ 1508.05186

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



Figueroa-Feliciano+ 1506.05519

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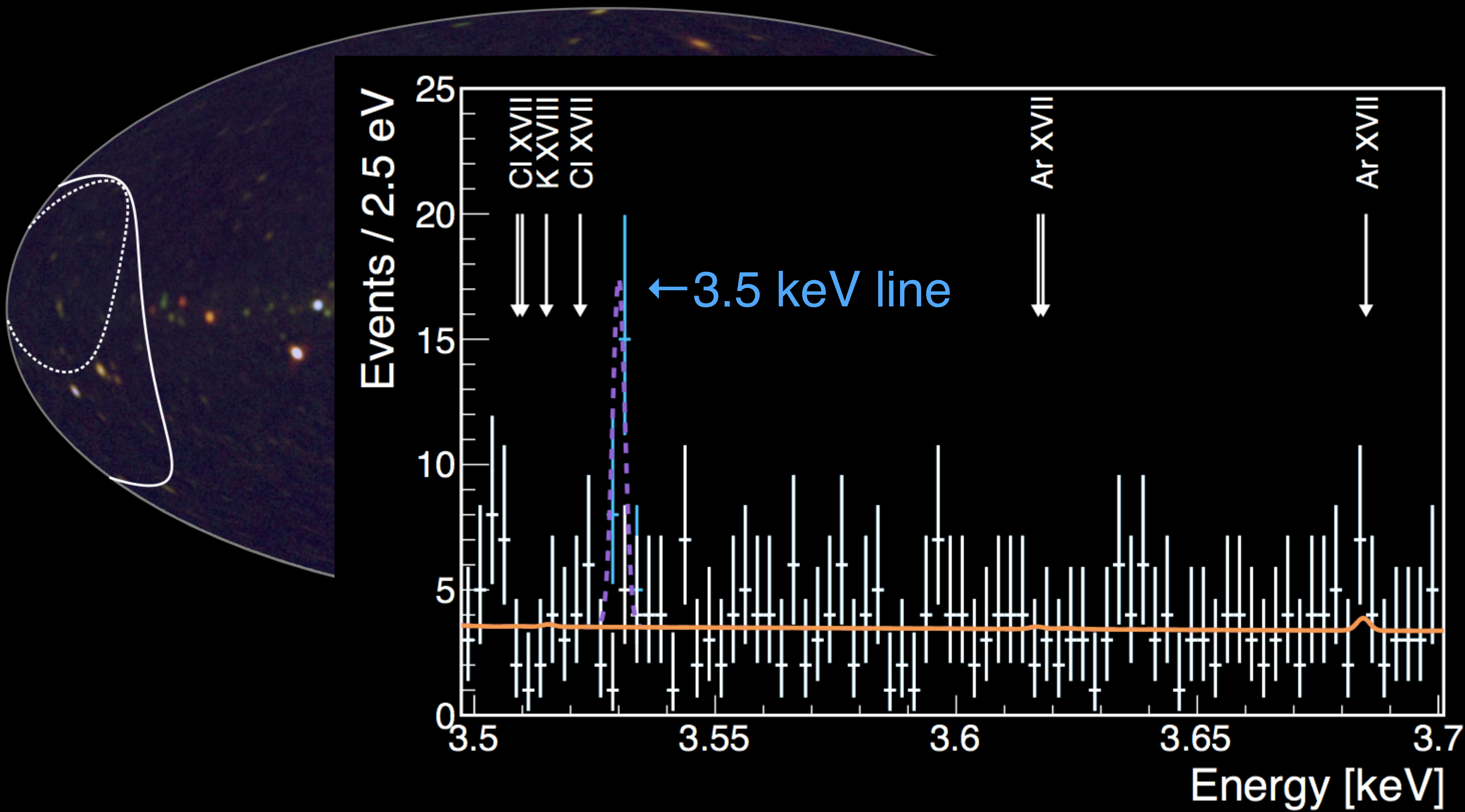

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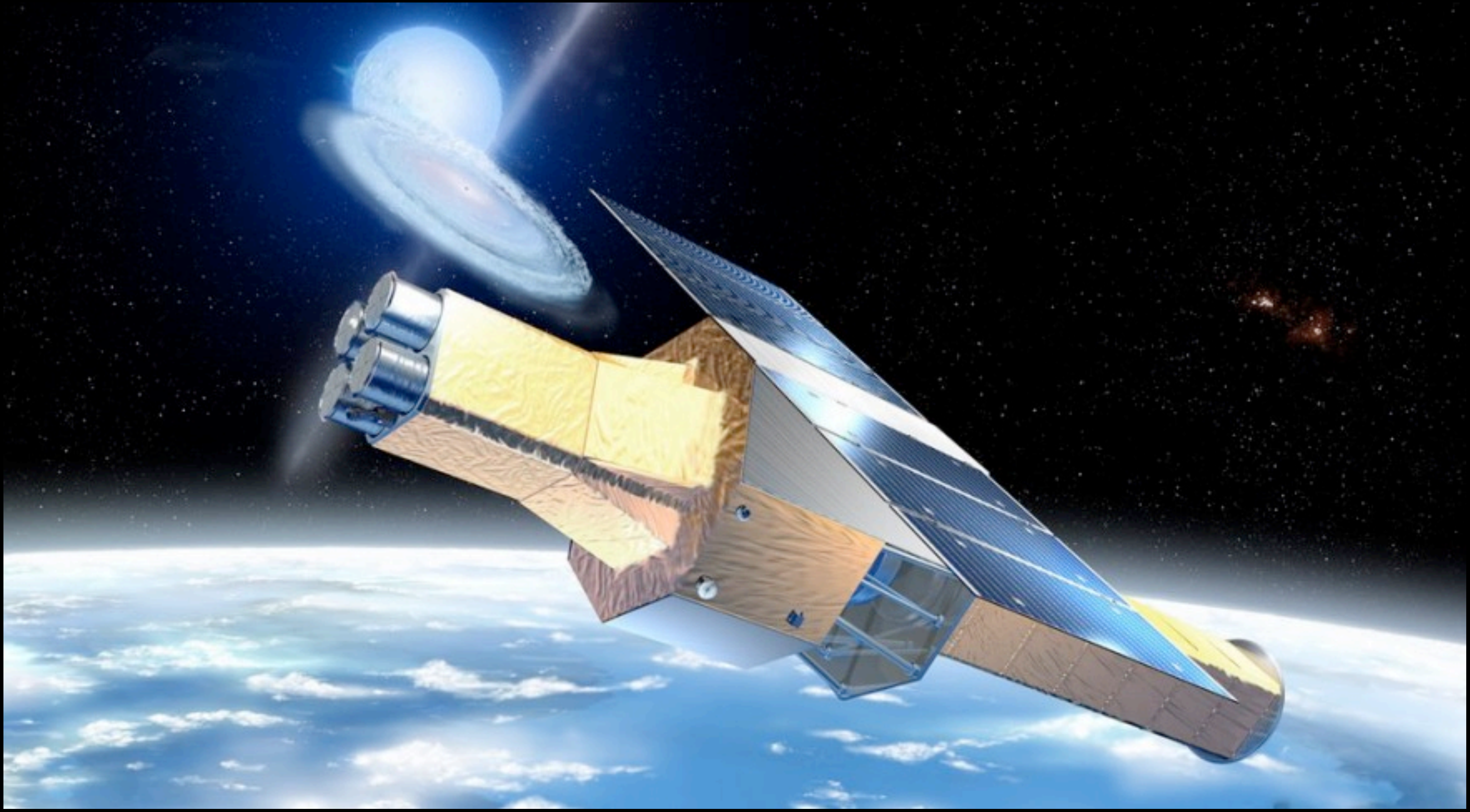
Next Space Mission in X-ray Astronomy

X-ray Astronomy Recovery Mission (XARM) ~2021



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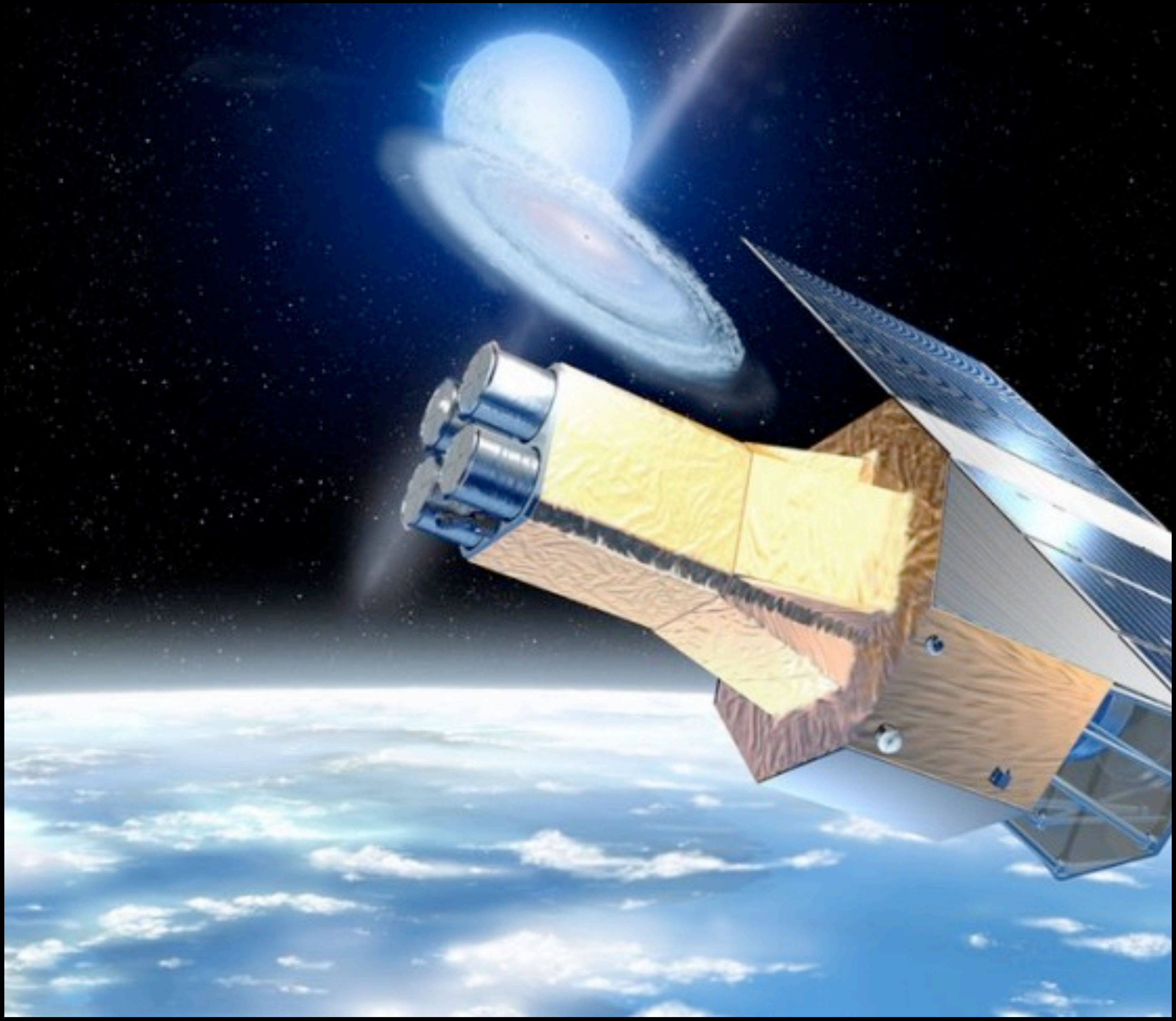

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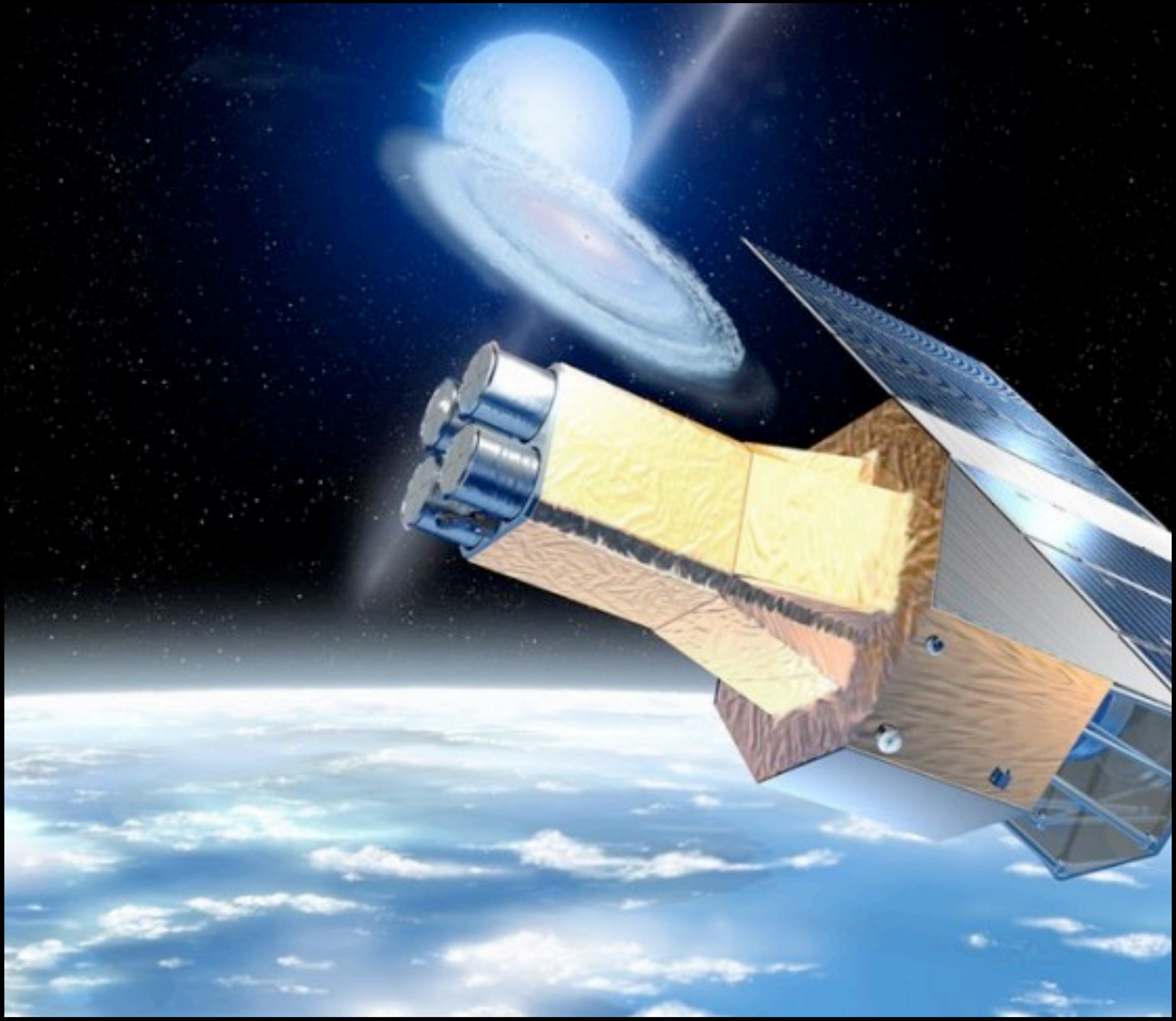
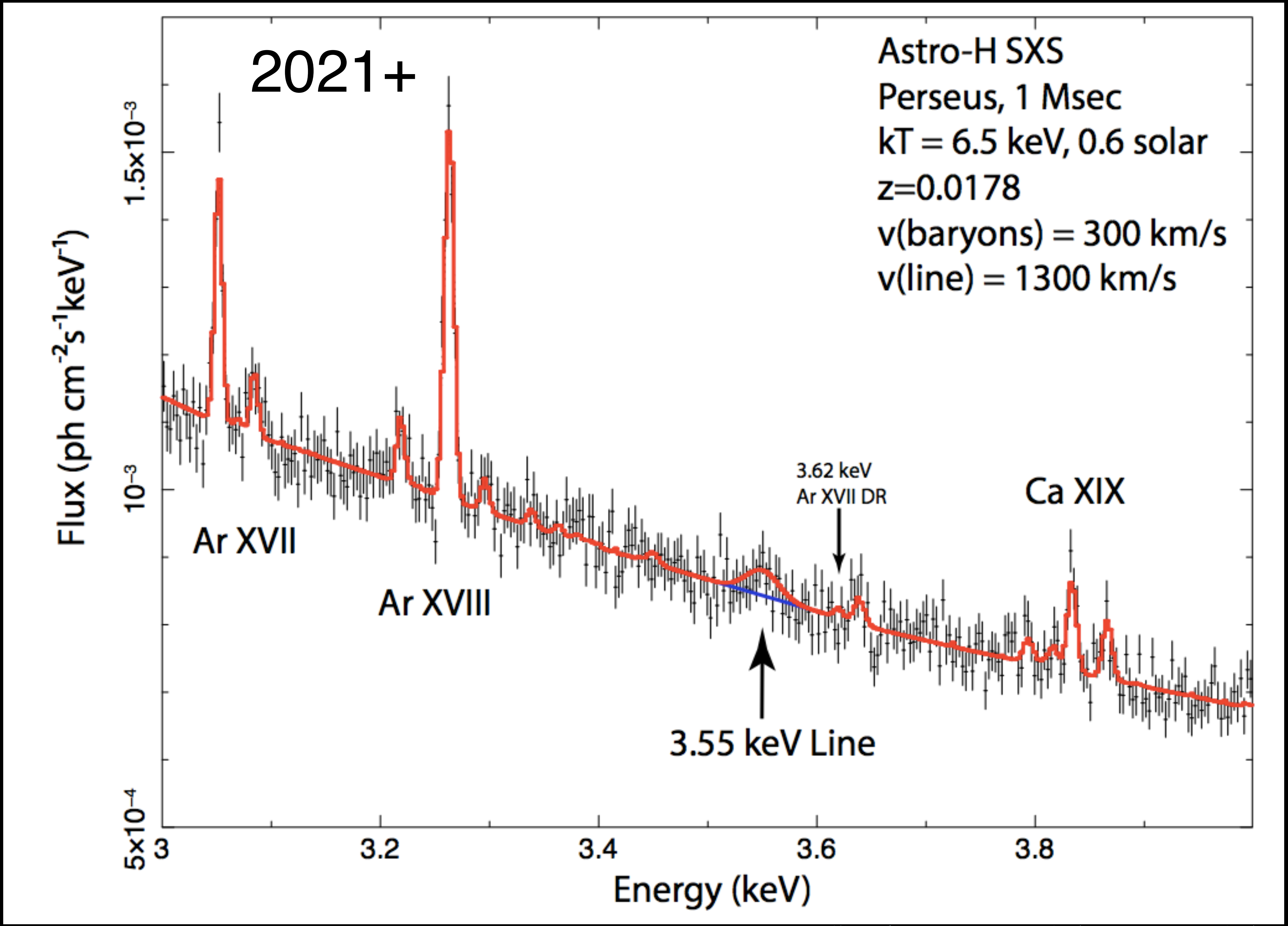


XARM will carry two instruments for studying the soft X-ray energy range: Build-to-print SXT-S (Soft X-ray Telescope for Spectrometer) & updated in energy resolution SXT-I (Soft X-ray Telescope for Imager).

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

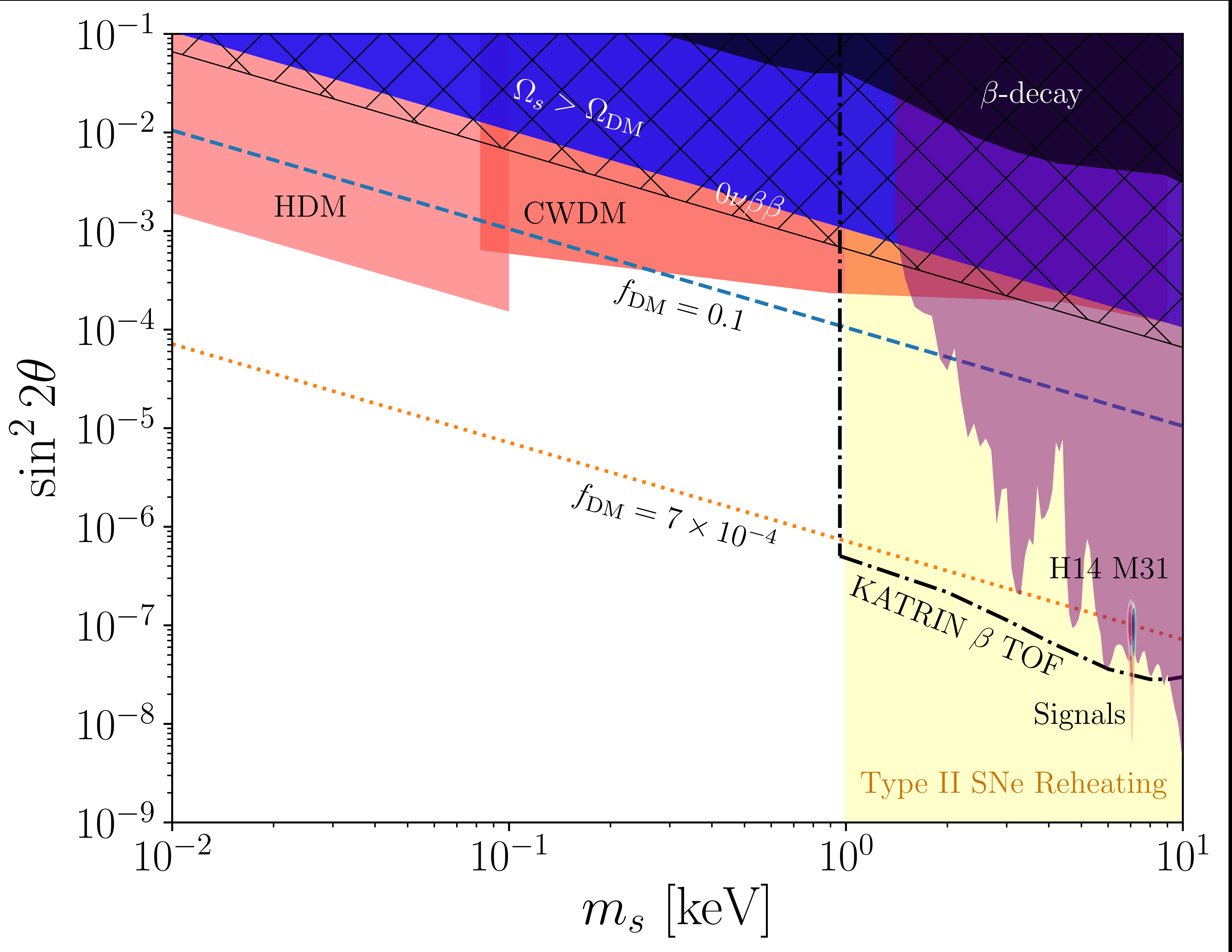
$$\mathrm{Flux} \propto f_{\mathrm{DM}} \sin^2 2\theta \qquad \text{but: } f_{\mathrm{DM}} \propto \left(\sin^2 2\theta\right)^{1.23} \ \text{(Abazajian 2005)}$$

Nonresonant production (DW) can provide signal with ~13% of dark matter as 7.1 keV 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



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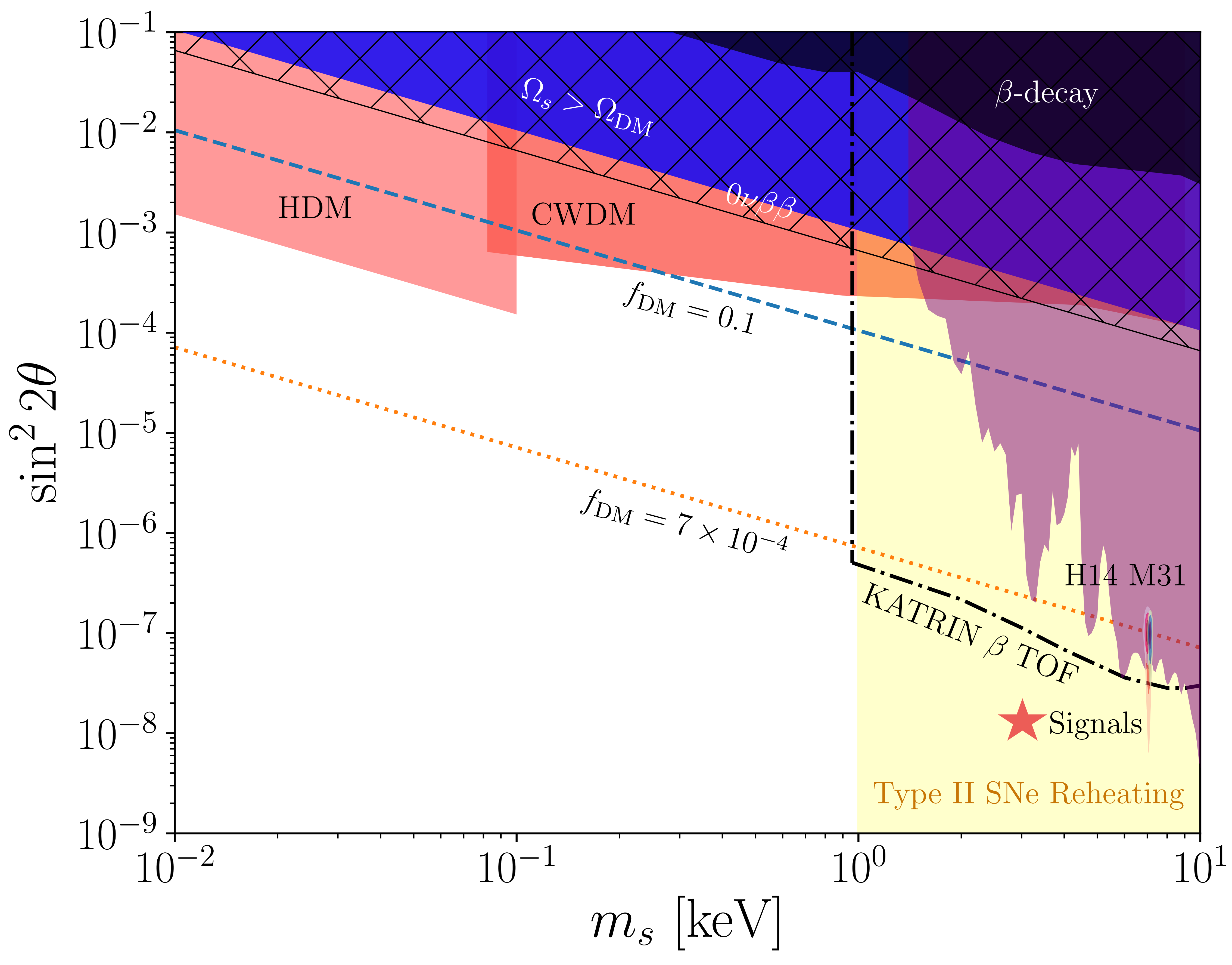
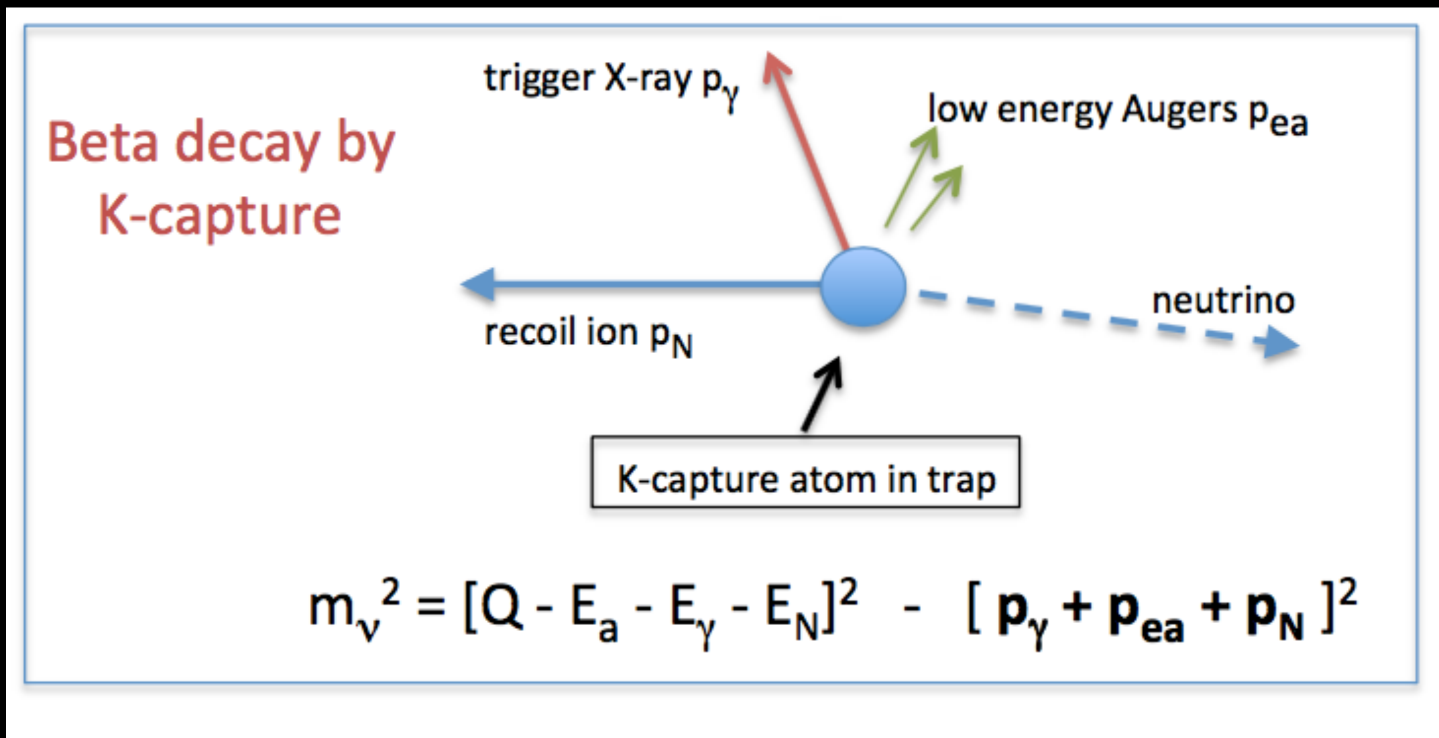


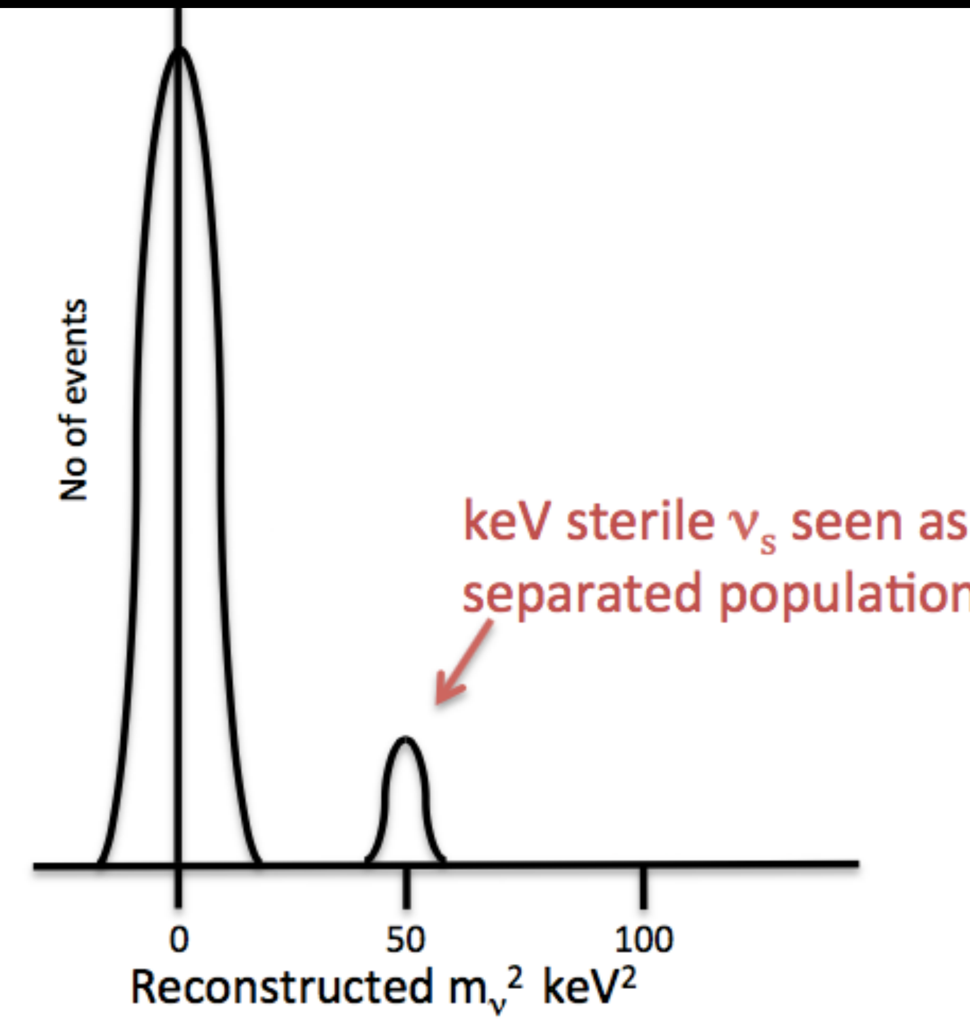
Laboratory Method: full kinematic reconstruction of K-capture nuclear decay



Original studies: Finocchiaro & Shrock 1992

CACHE (Cesium Atomic-electron Capture with Heavy neutrino Emission)

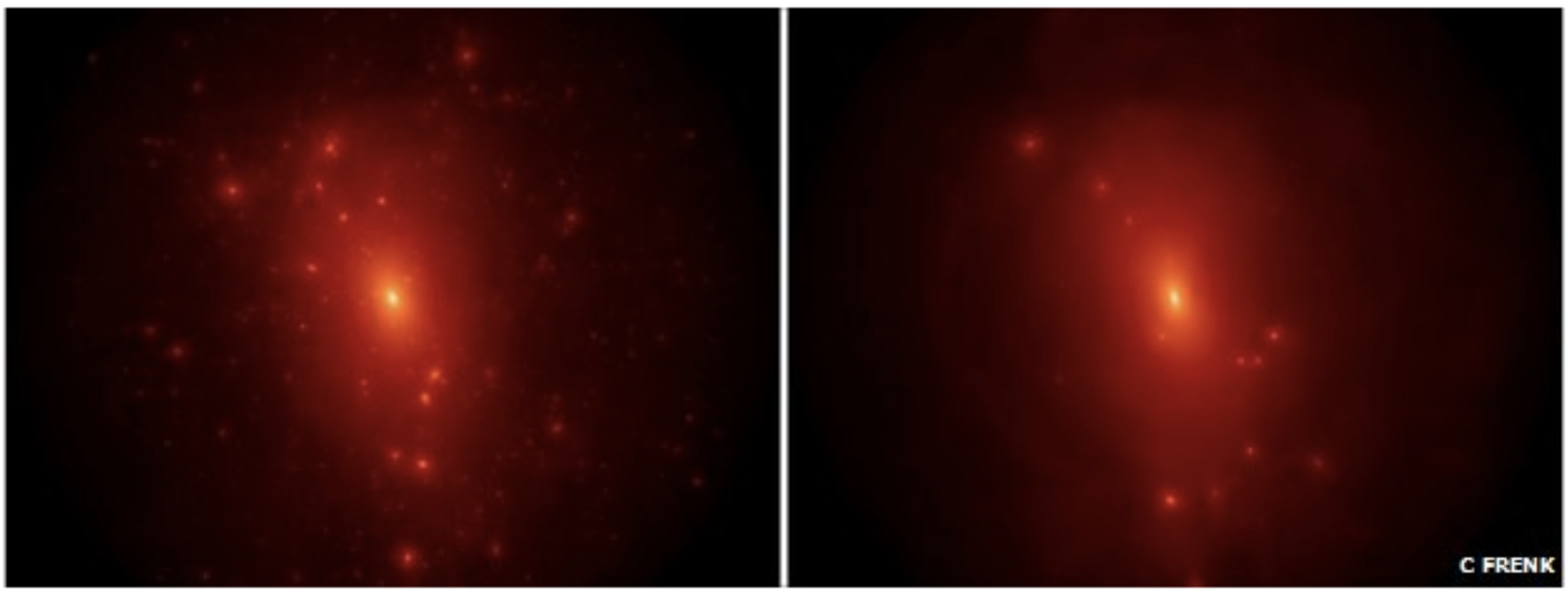
^{131}Cs Ion trap proposal:
Peter Smith+ arXiv:1705.06876



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

Recent studies show this may now be feasible

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

Thermal WDM

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

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

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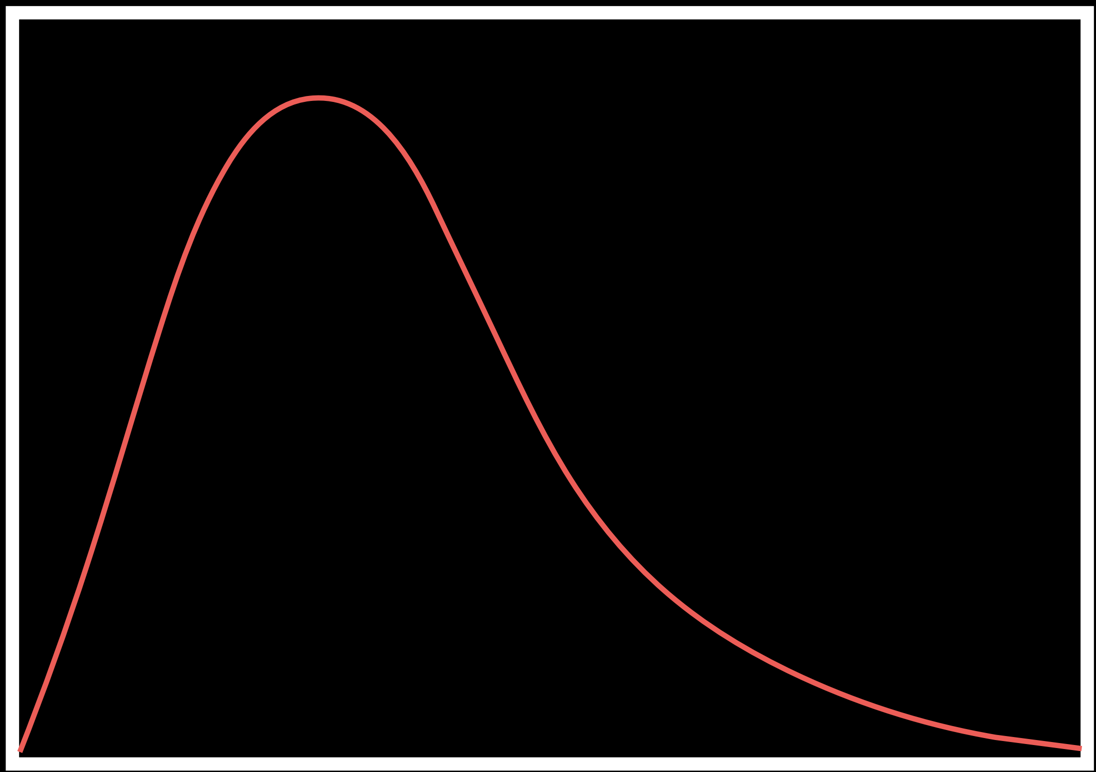

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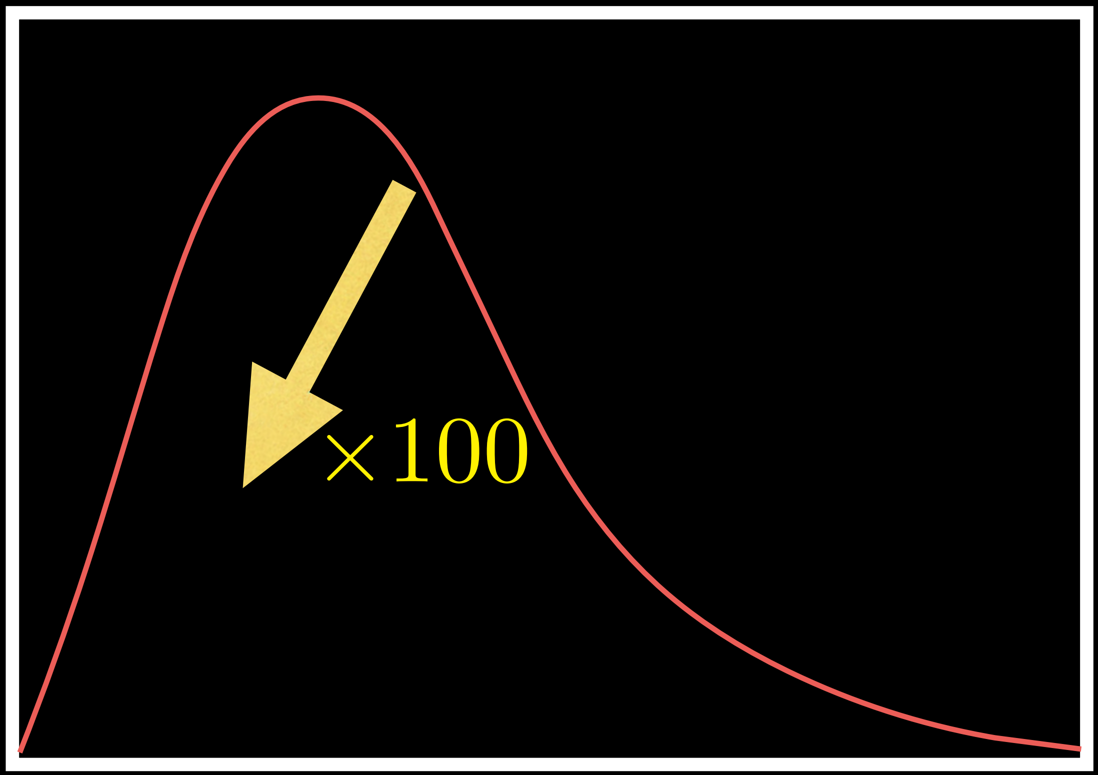

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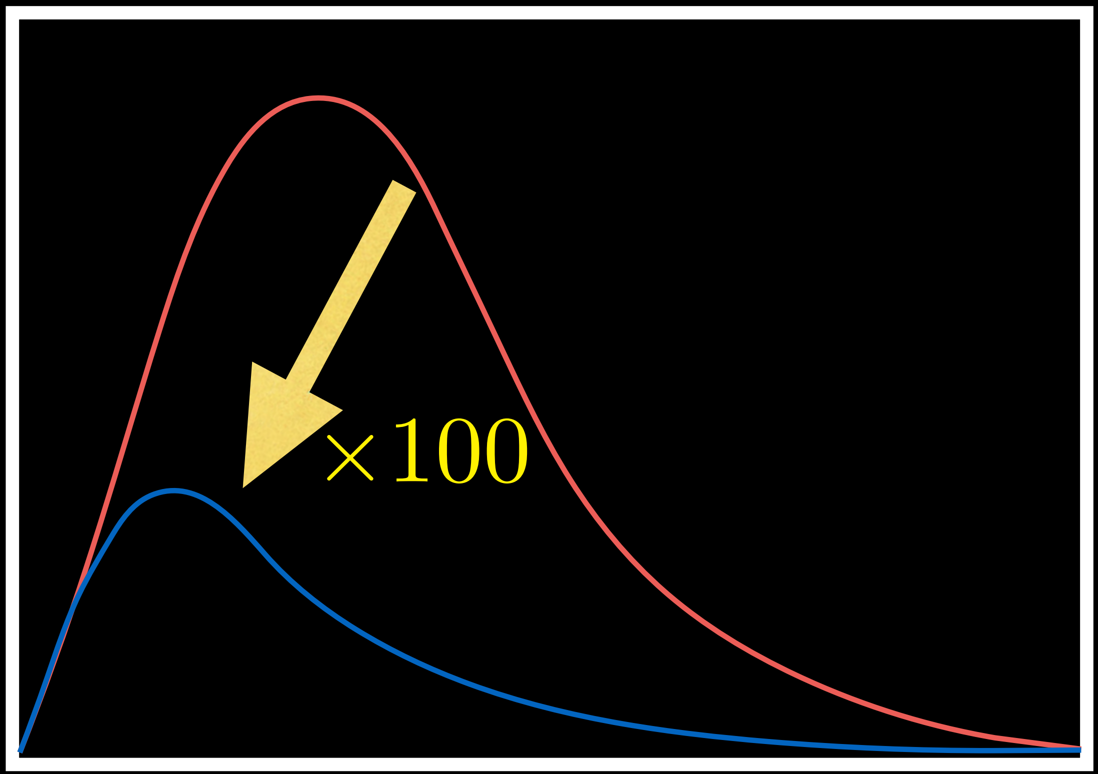

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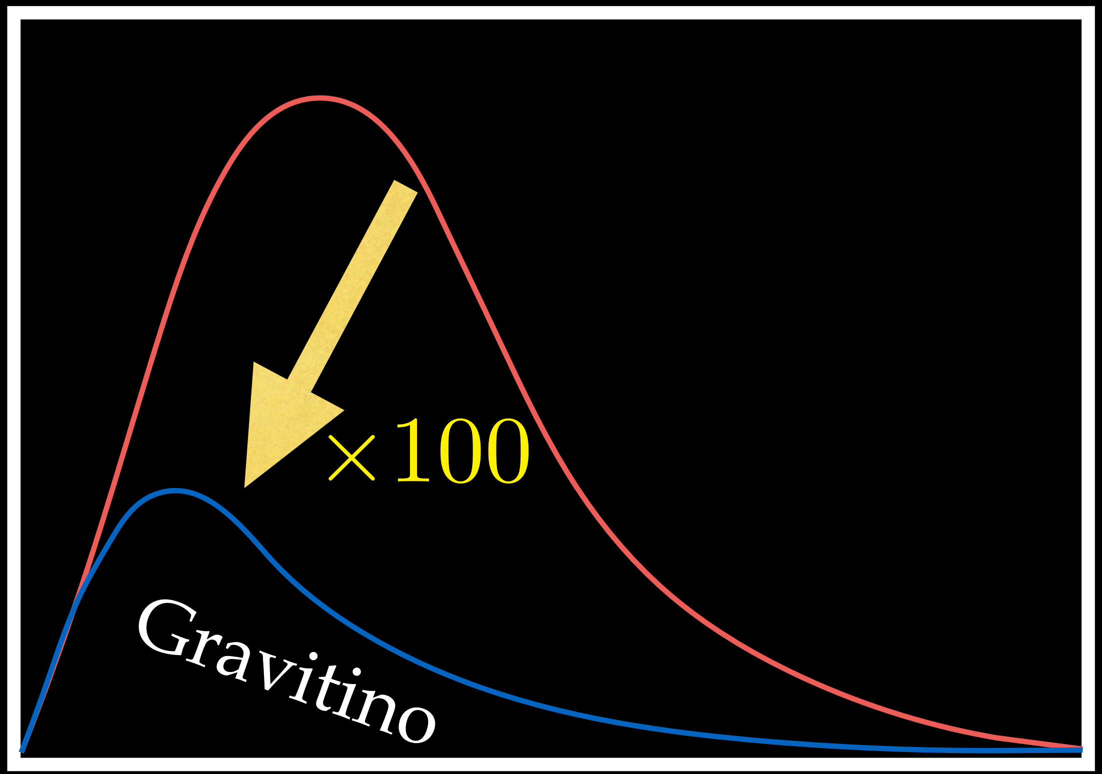

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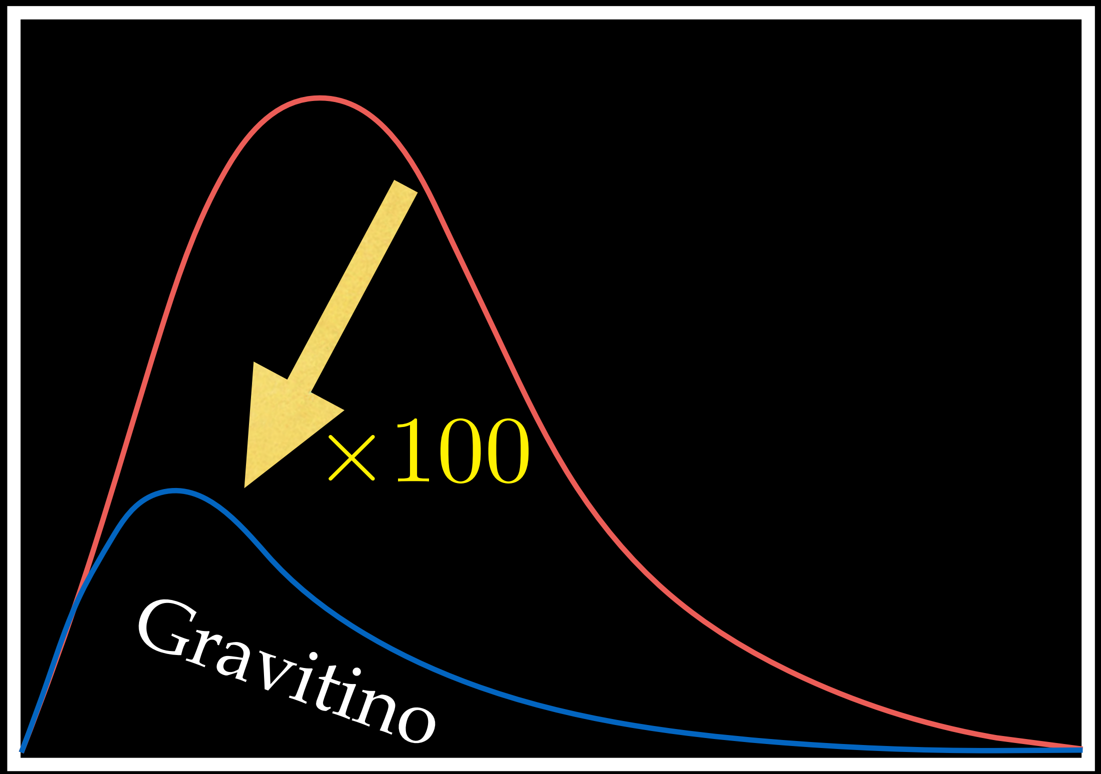

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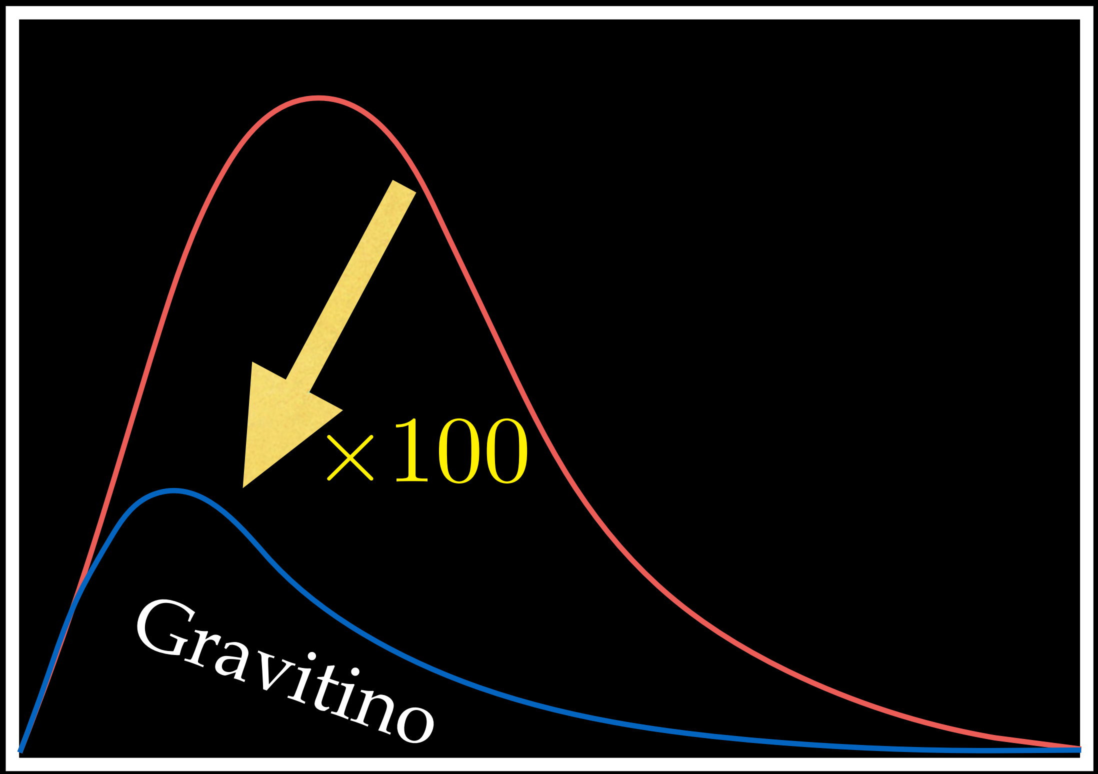

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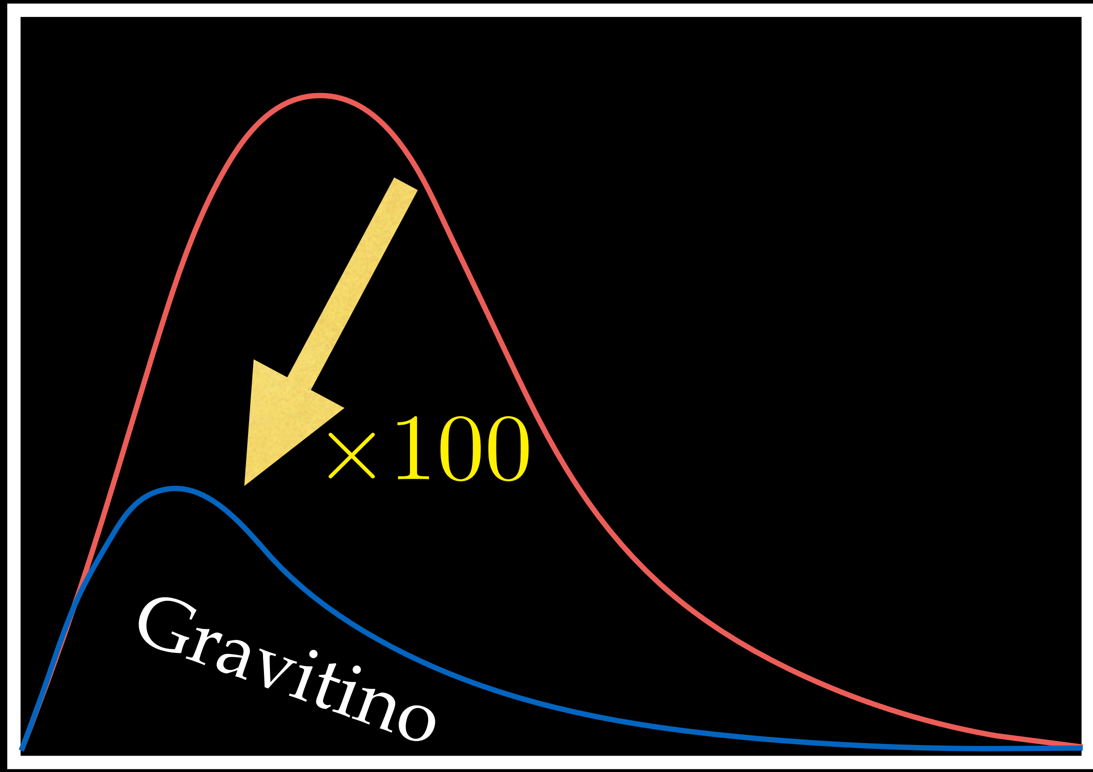

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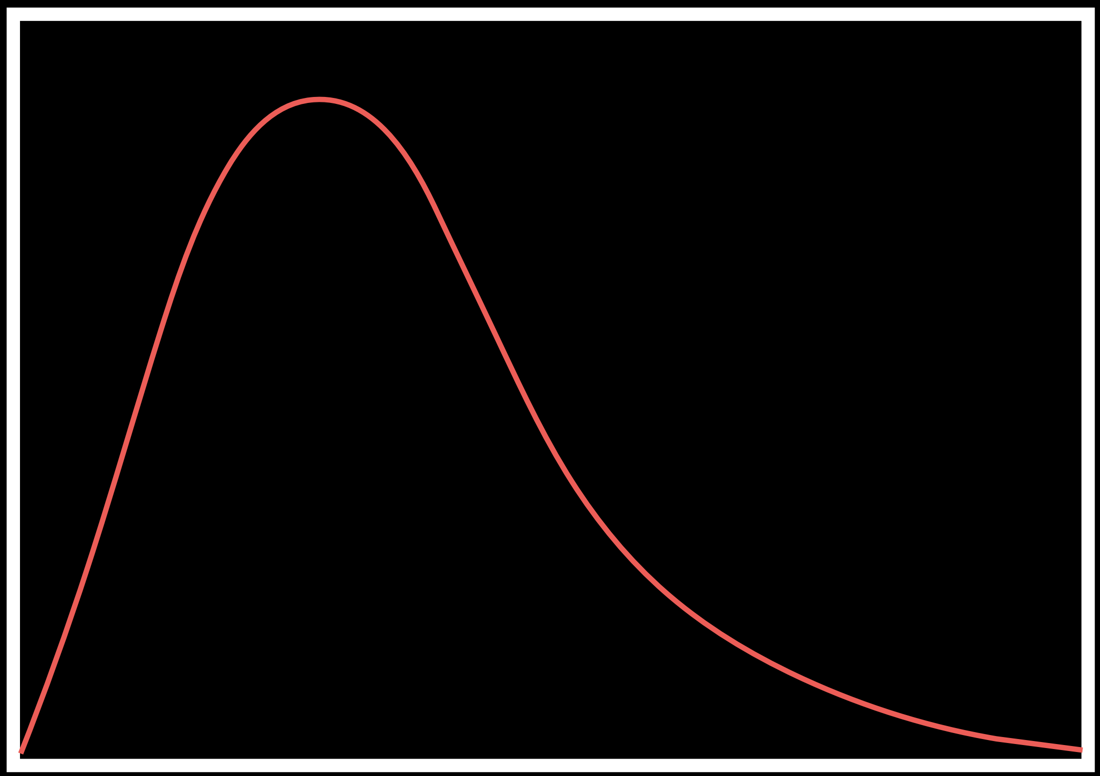

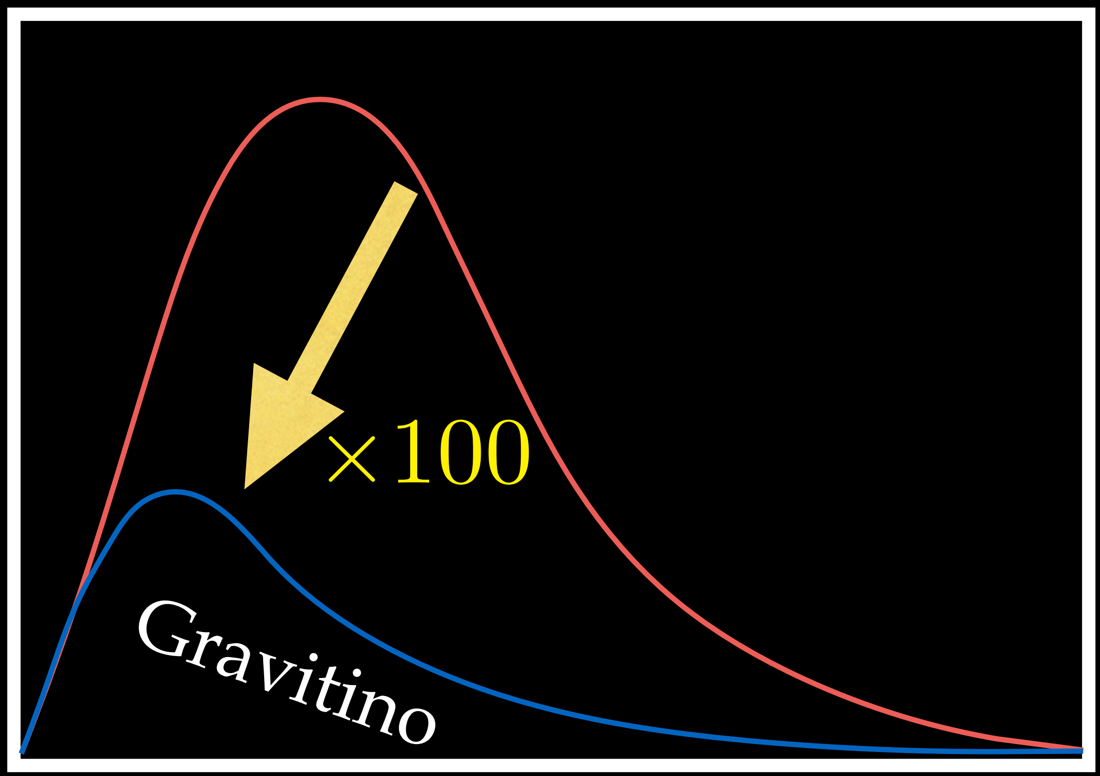

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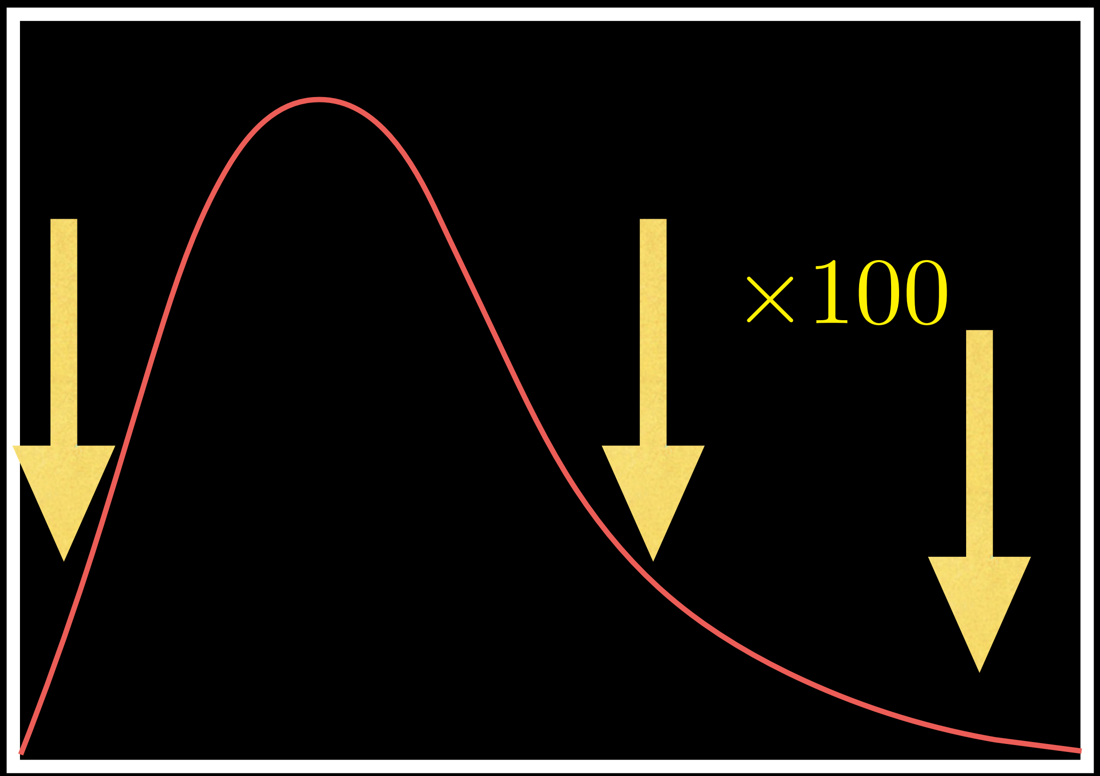

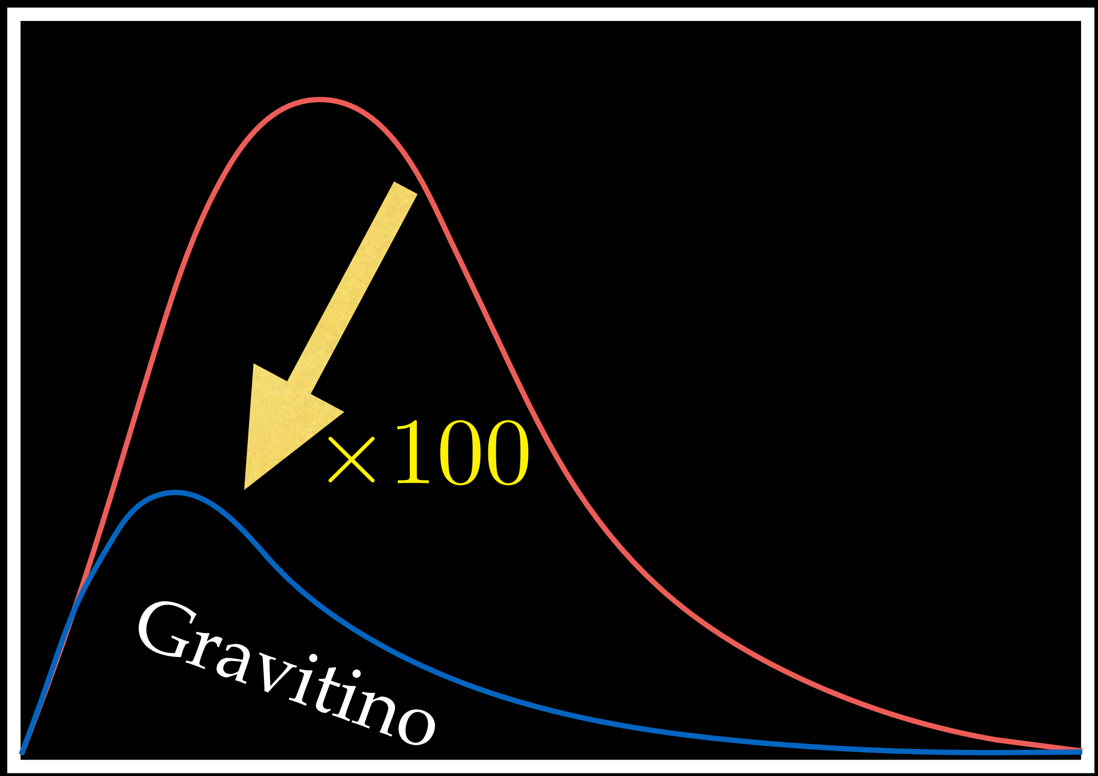

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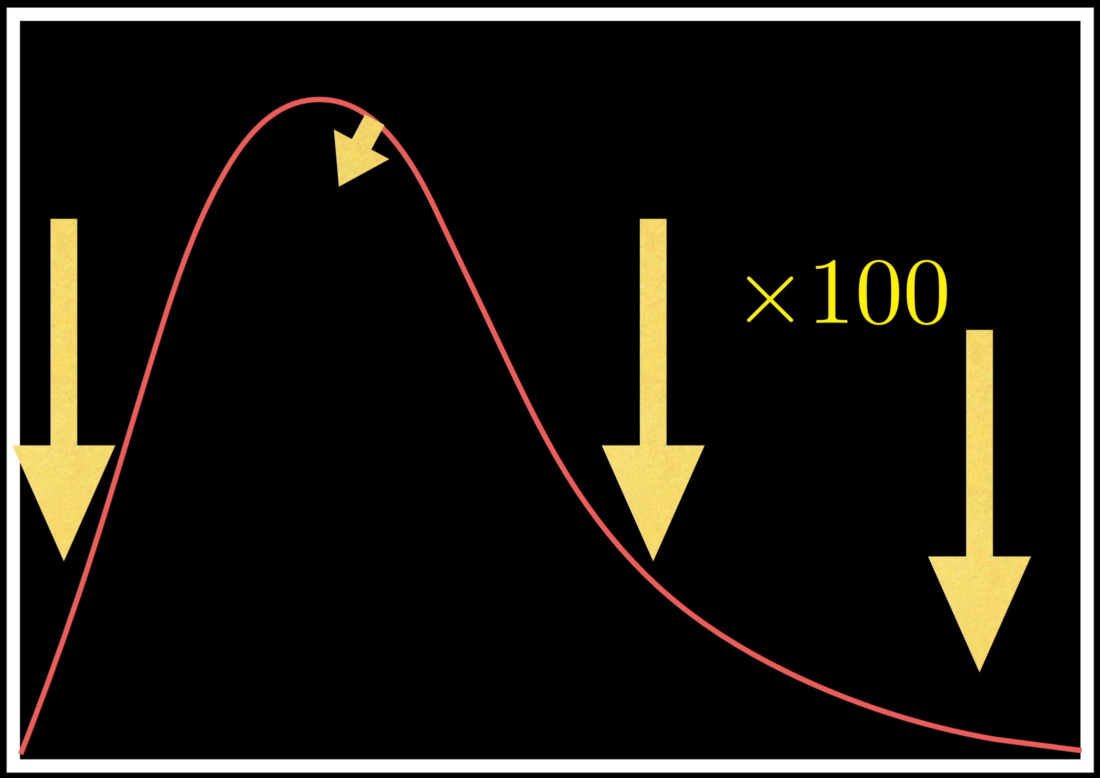

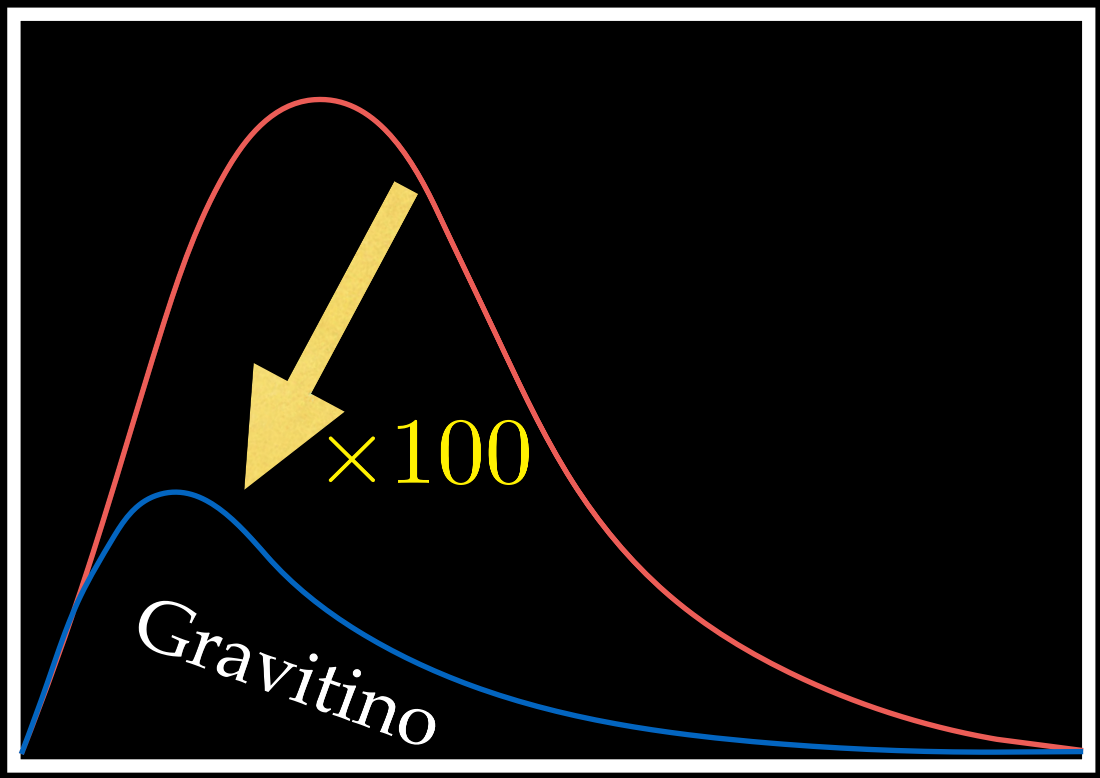

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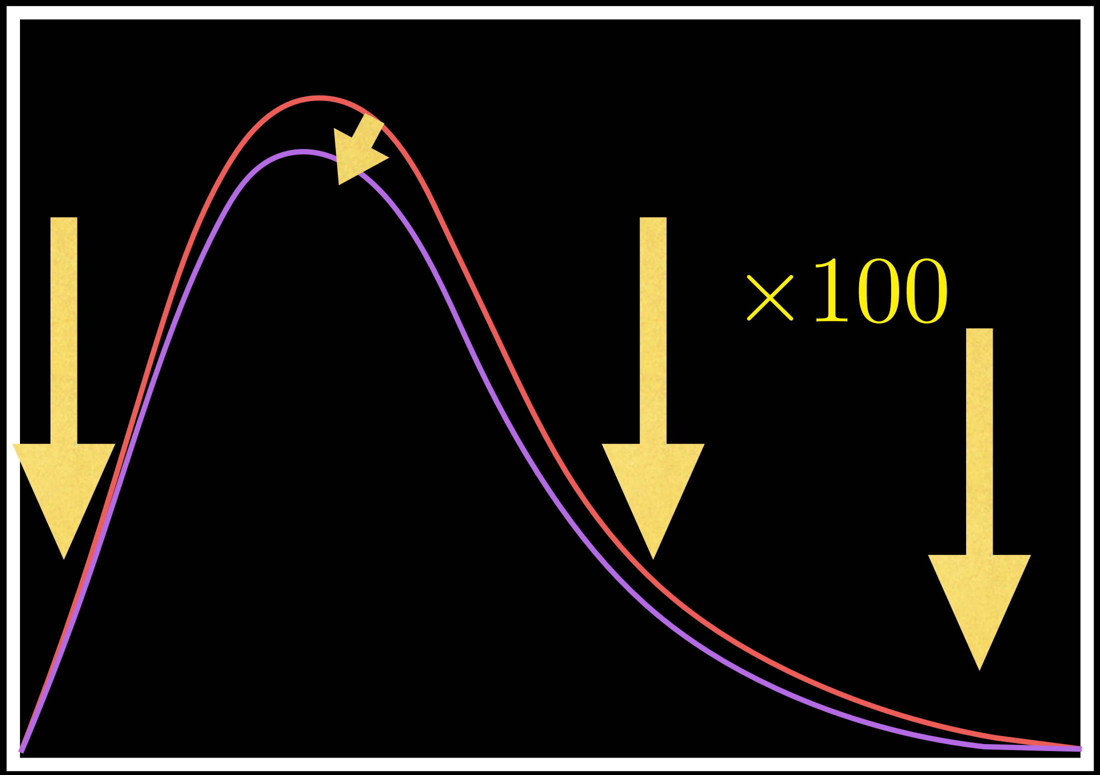

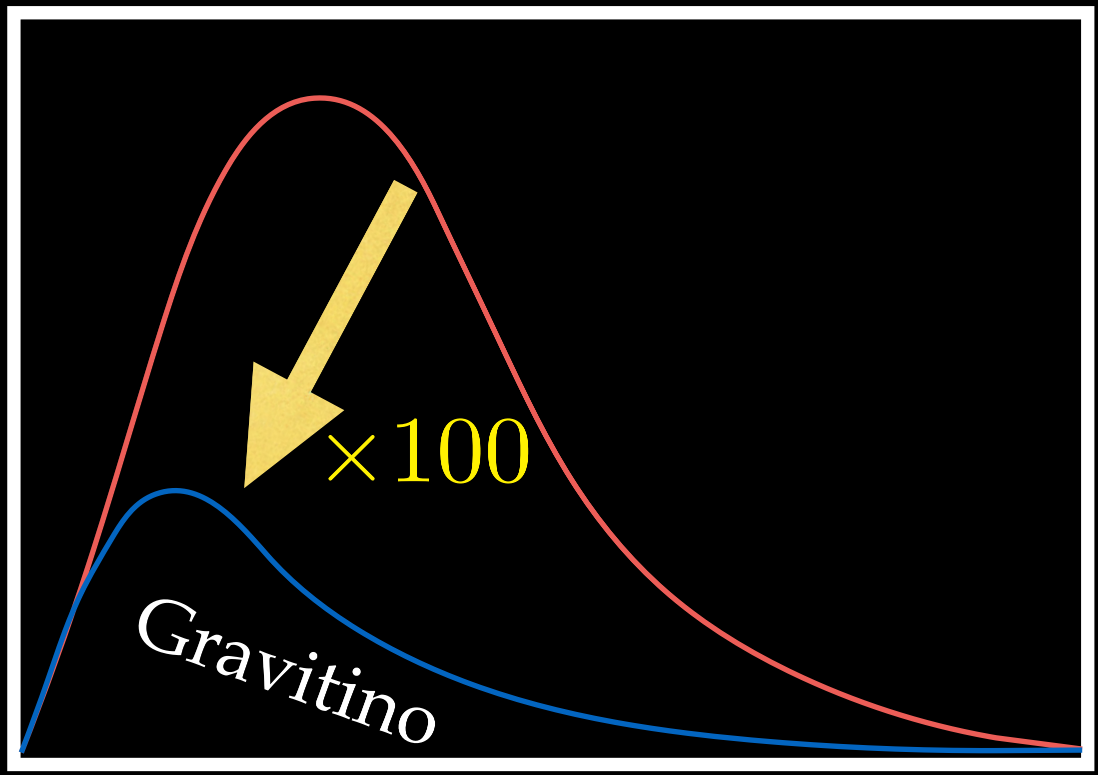

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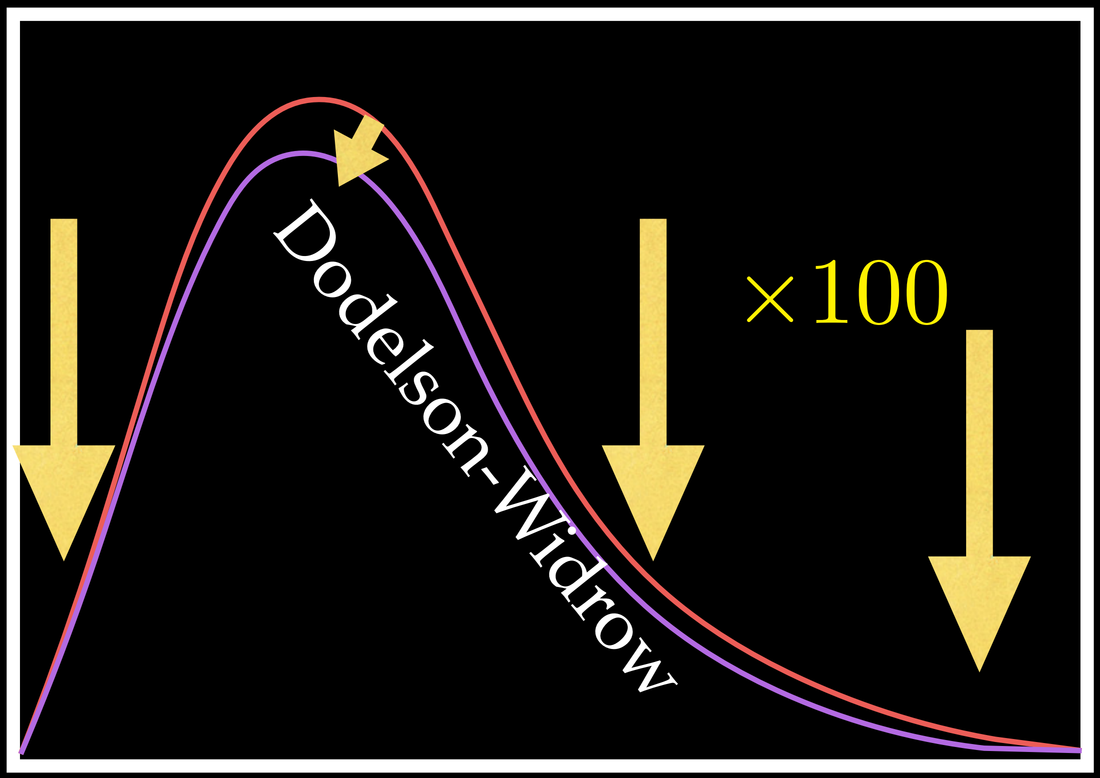

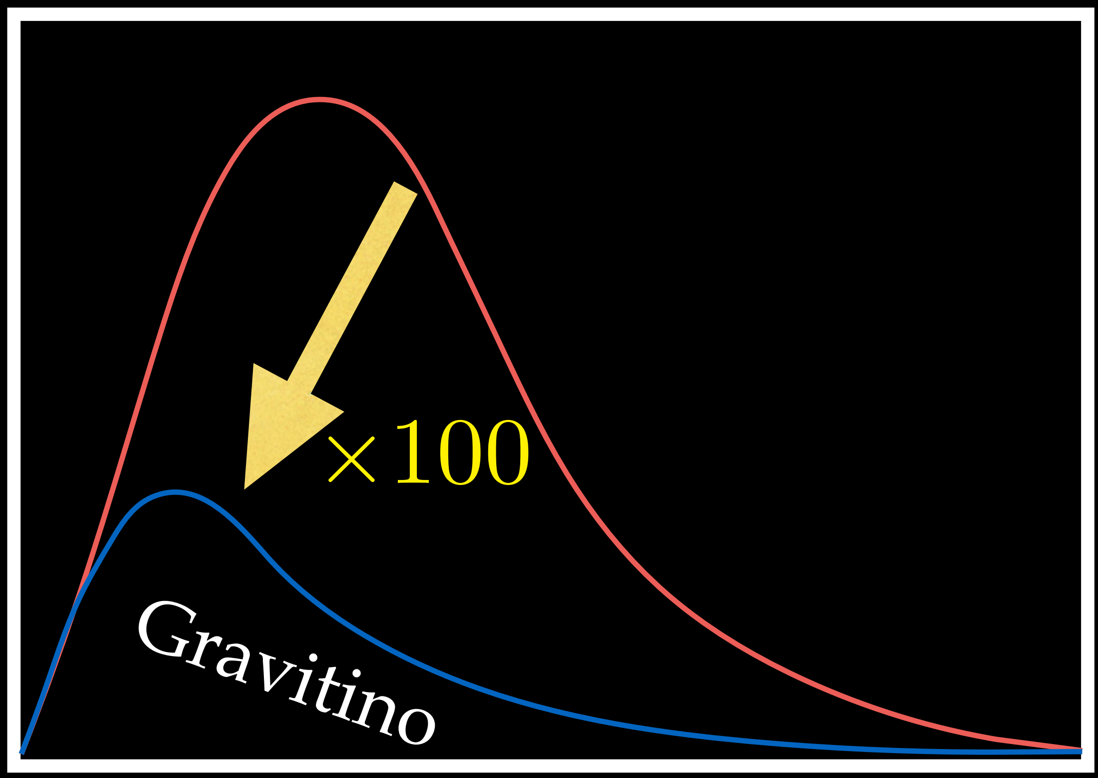

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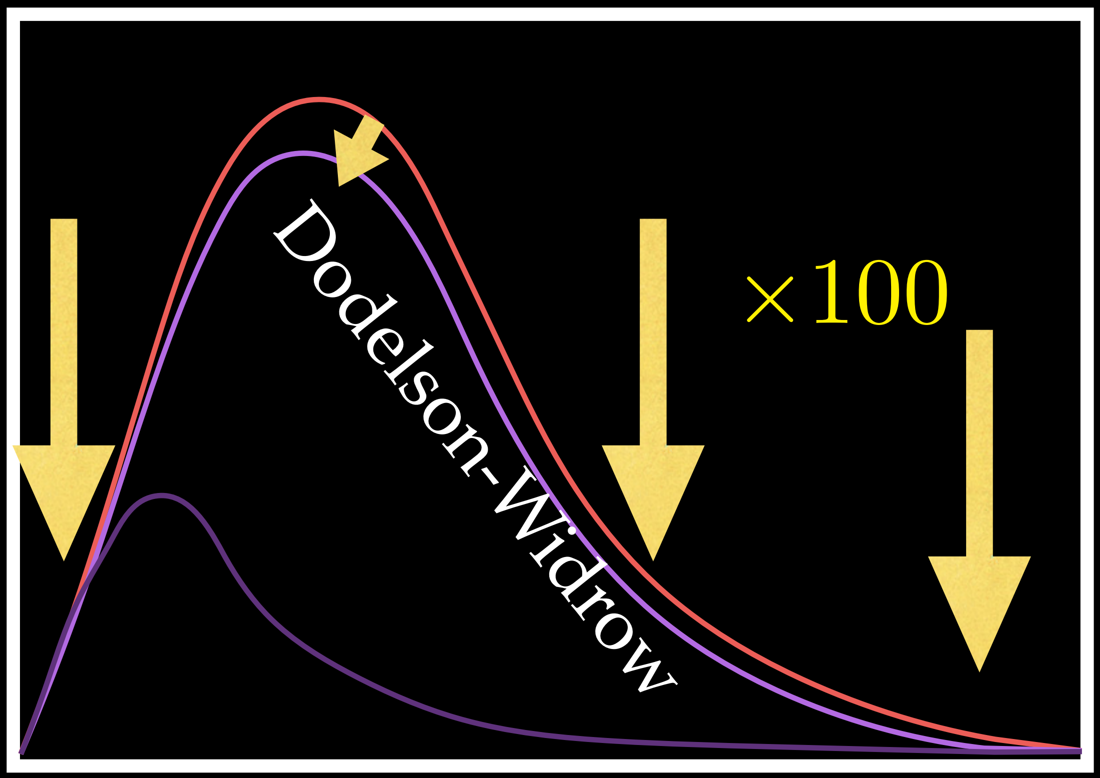

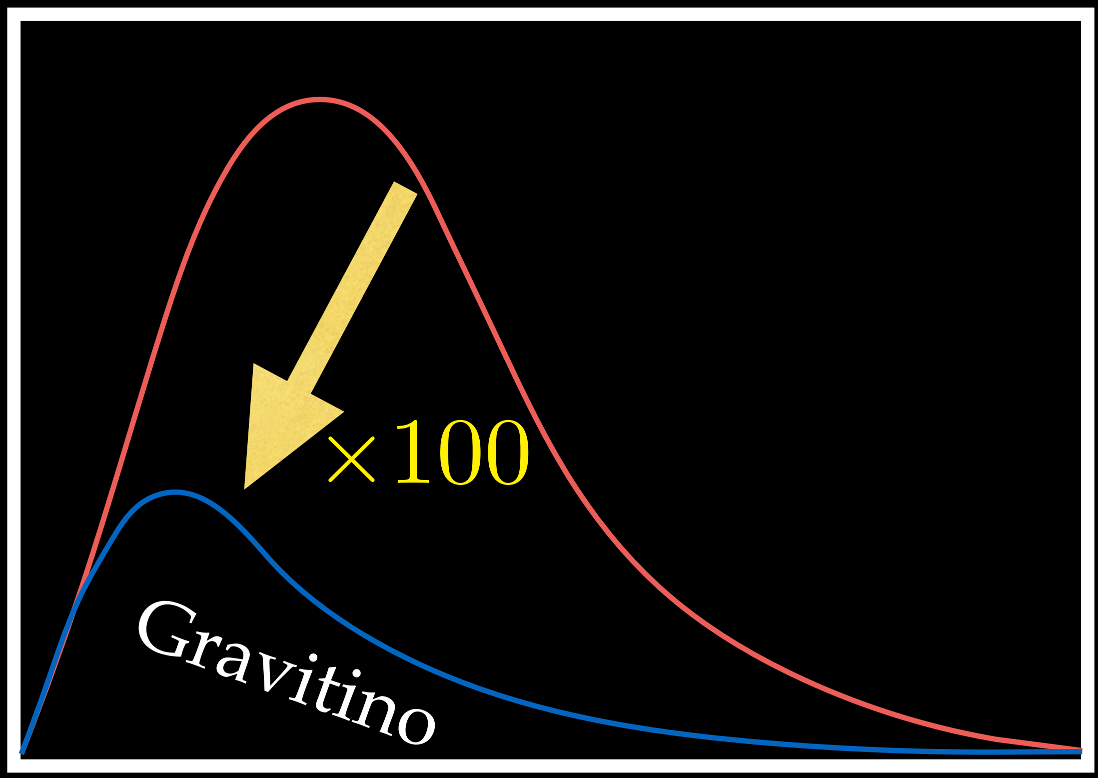

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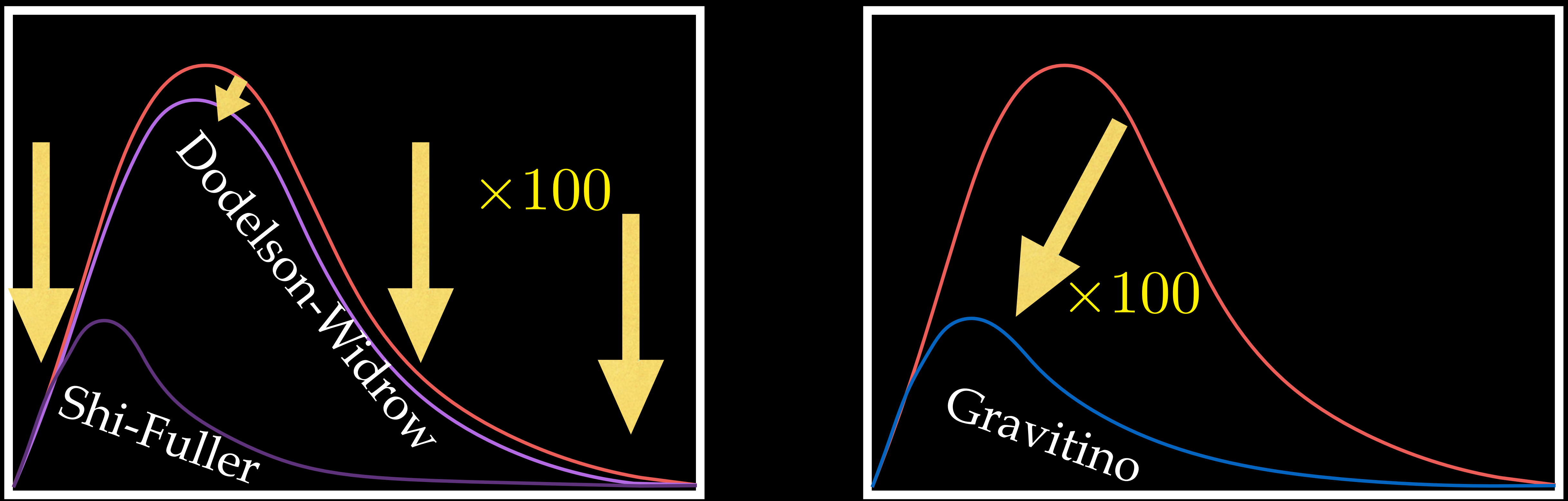

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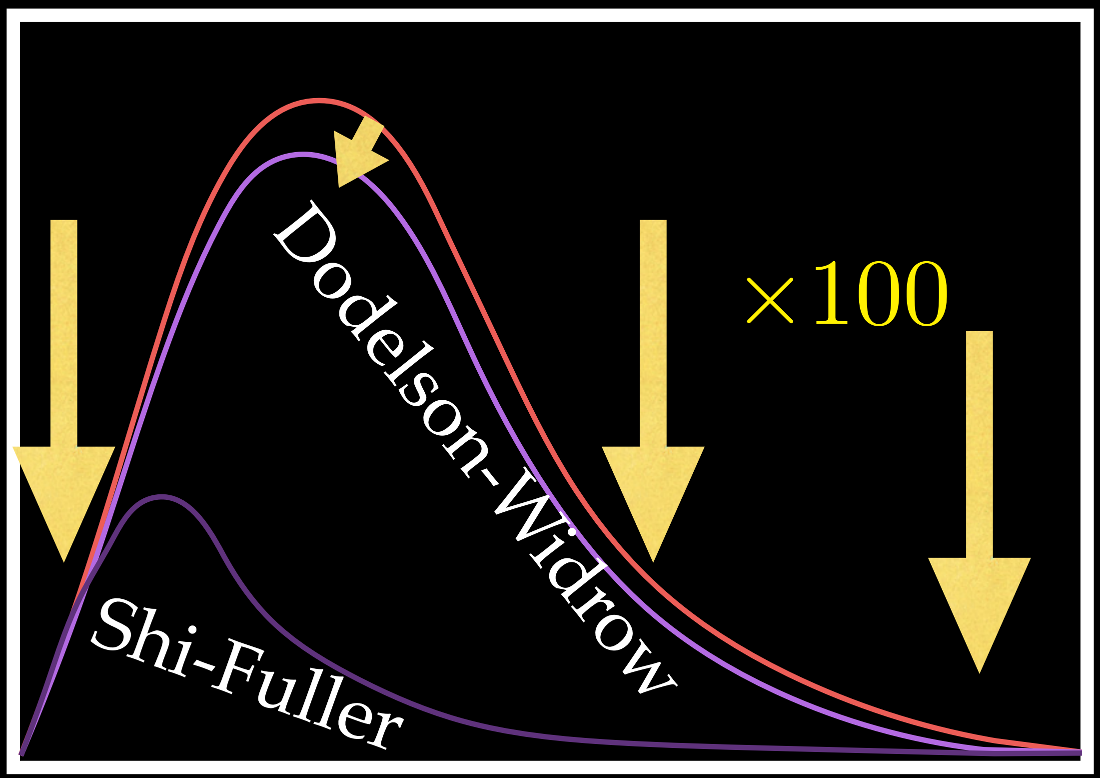

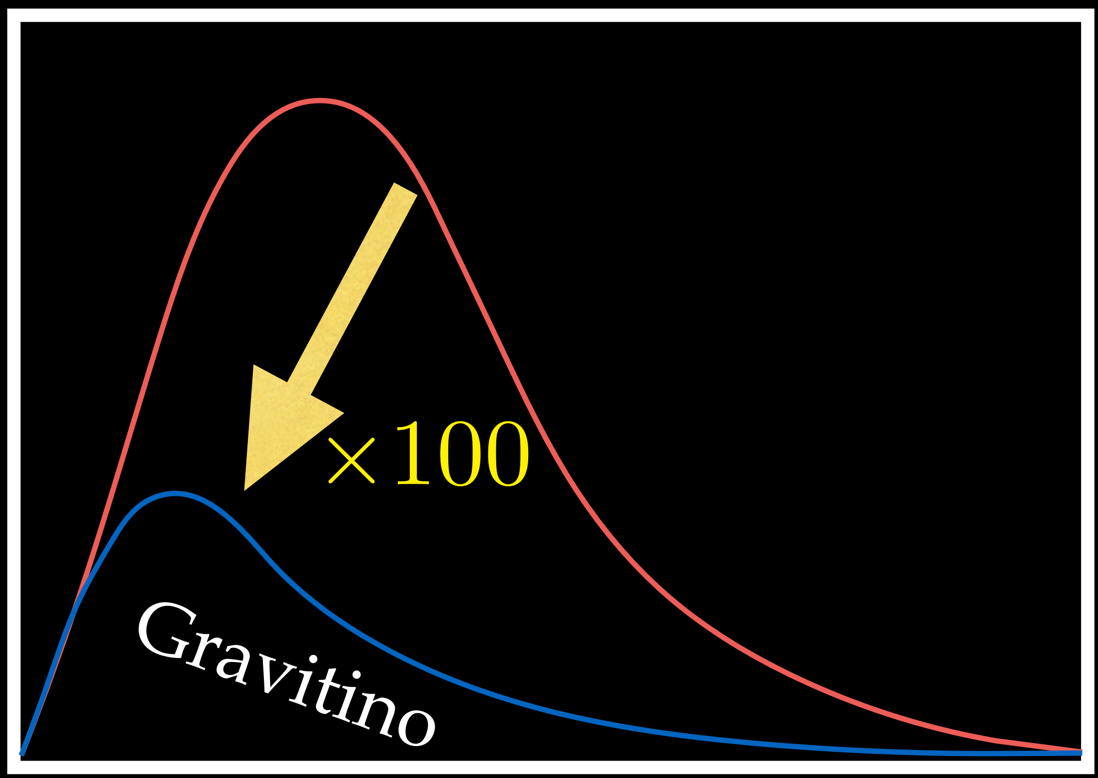

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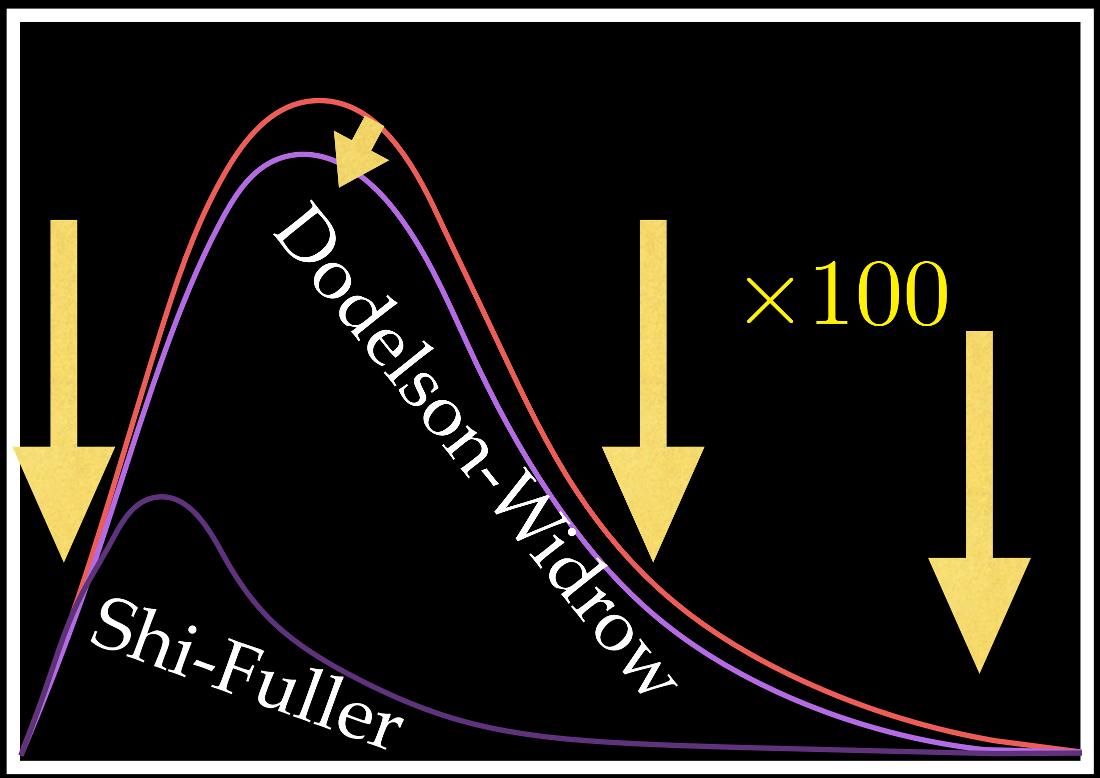

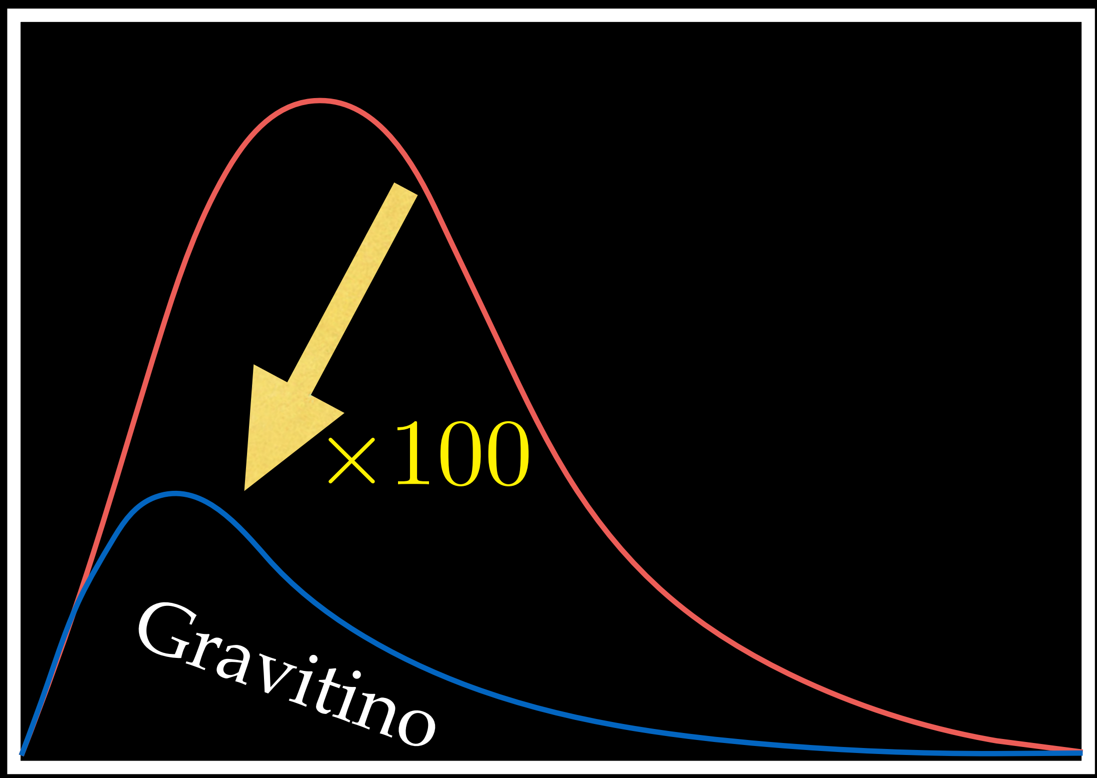

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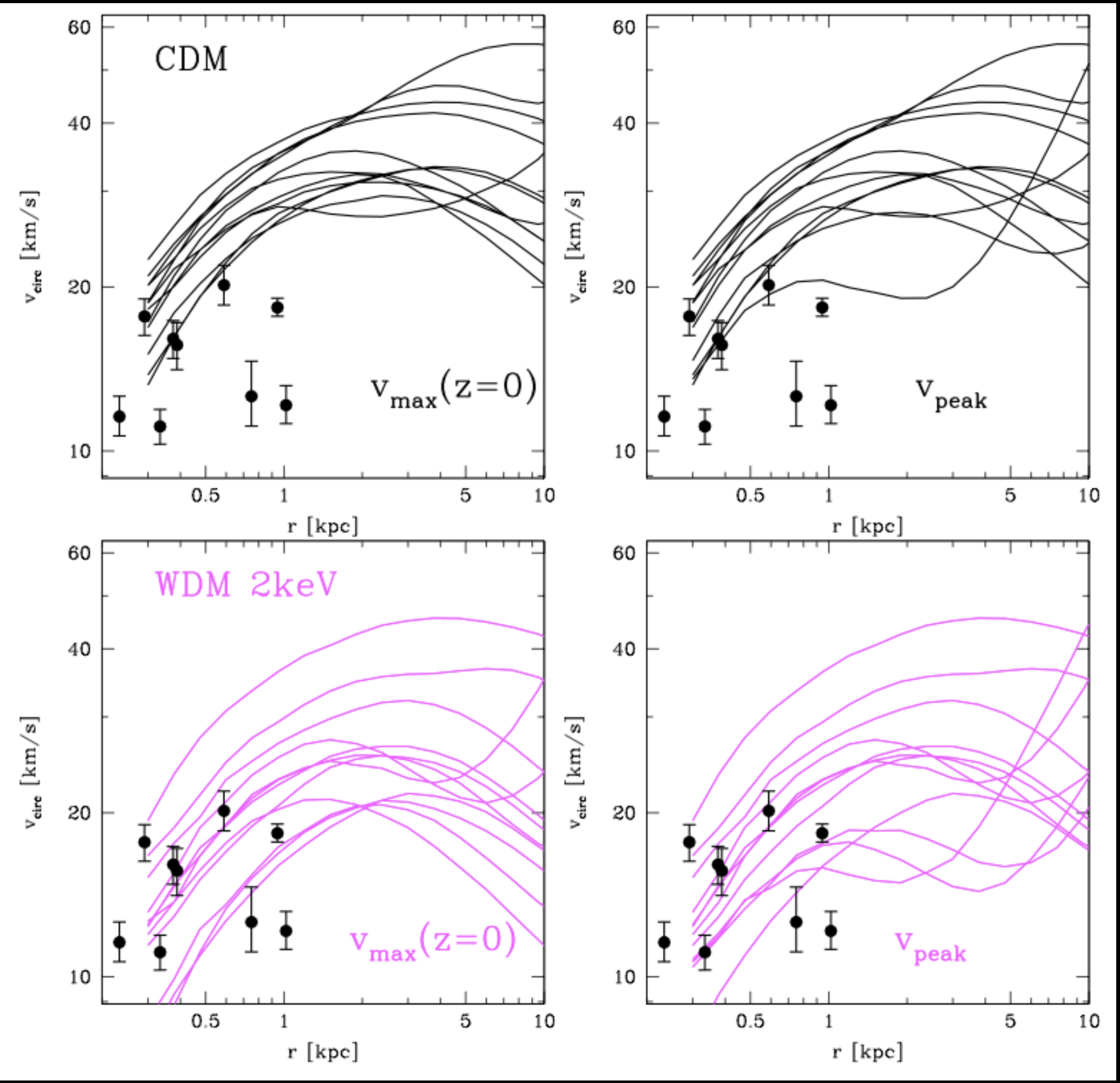
Colombi, Dodelson & Widrow astro-ph/9505029;
Abazajian 2005; arXiv:1705.01837; Venumadhav+ 2016

WDM Solution to All Local Group Galaxy Properties?



Anderhalden+
arXiv:1212.2967

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

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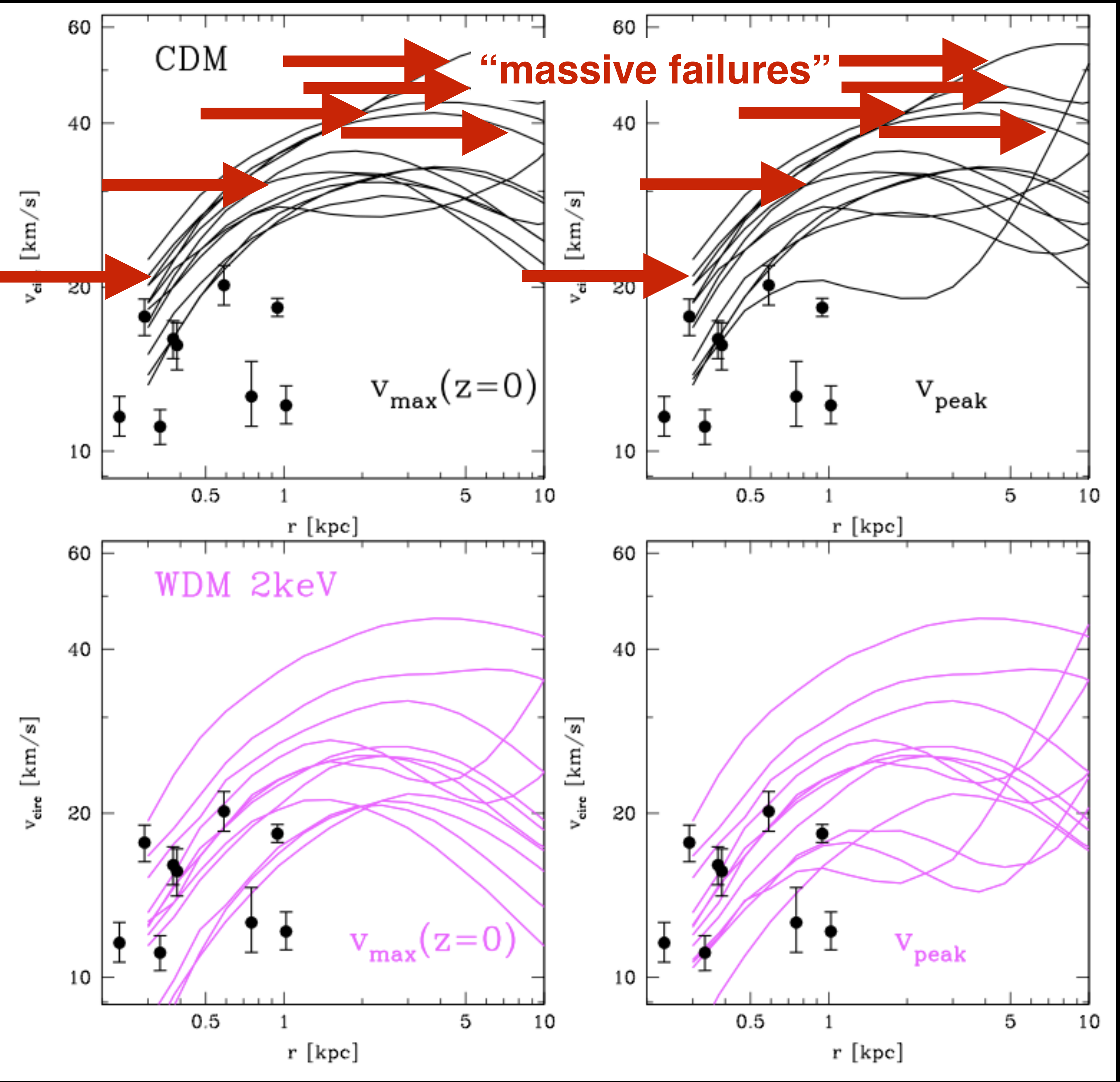

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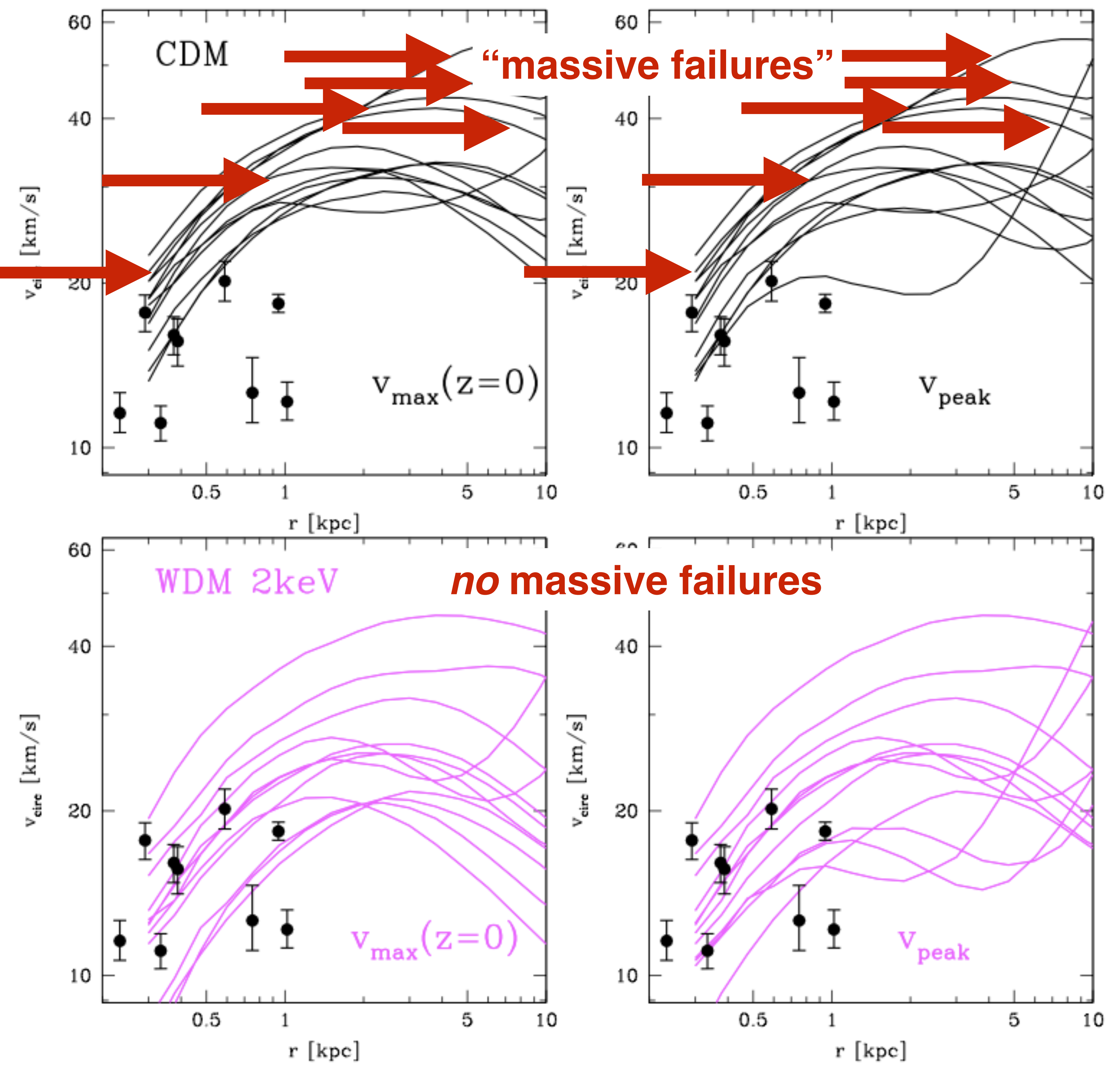

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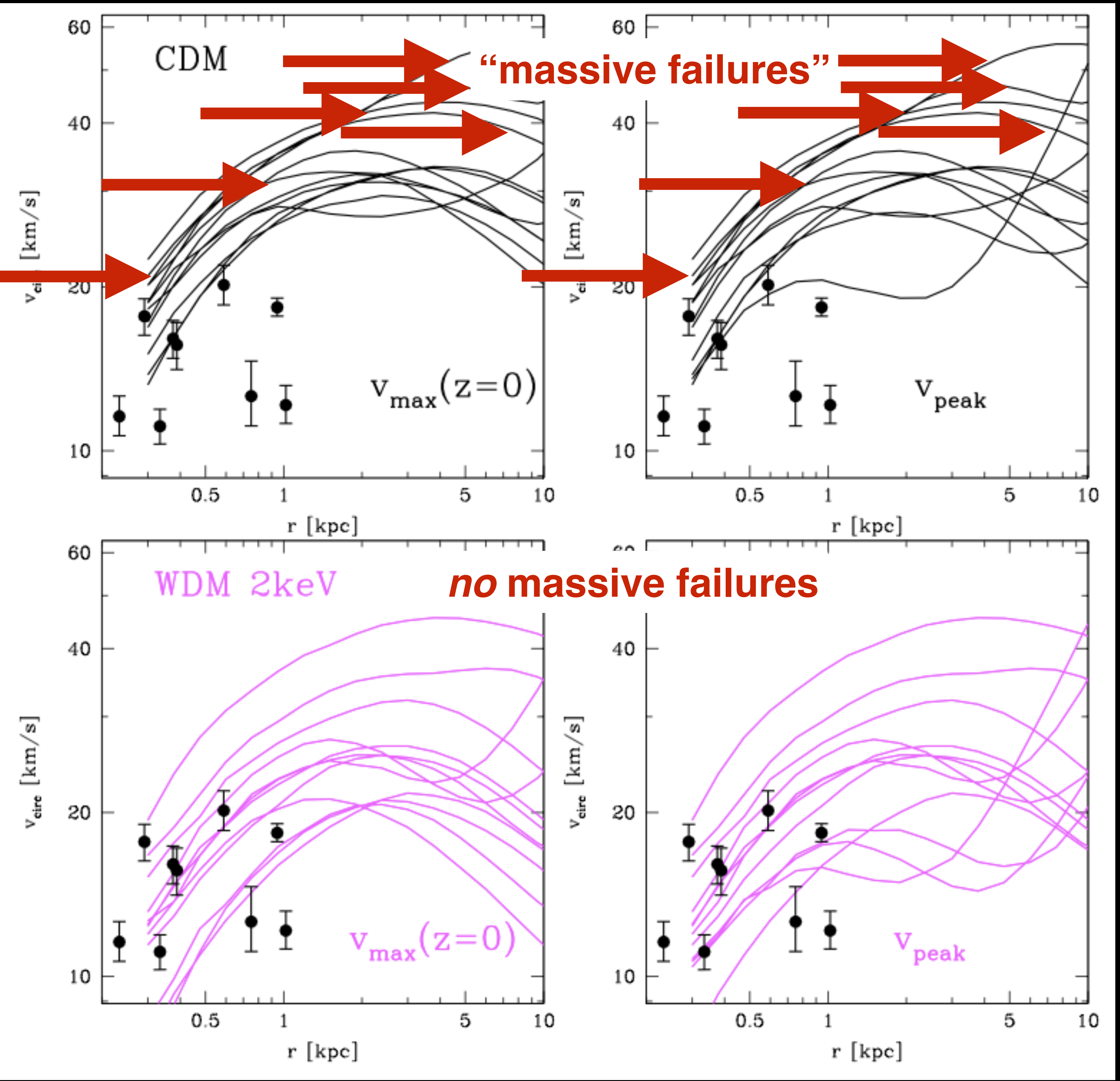

Anderhalden+
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"It seems that only the pure WDM model with a 2 keV [thermal] particle is able to match the all observations" of the Milky Way Satellites: "the total satellite abundance, their radial distribution and their mass profile" (or TBTF)

Sterile Neutrino DM:
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Summary

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- 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).

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- Also seen:

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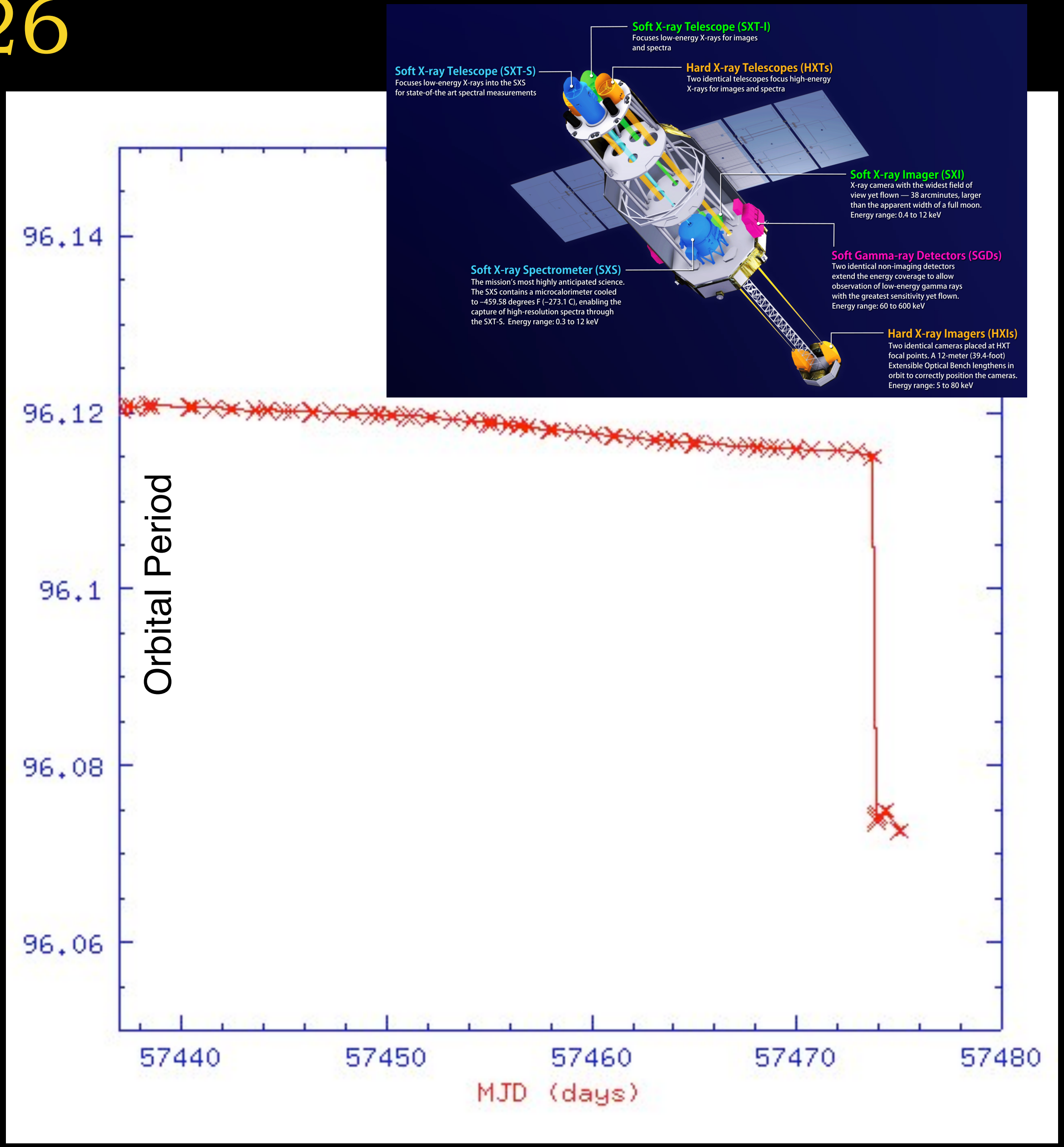
Communication anomaly of X-ray Astronomy Satellite "Hitomi" (ASTRO-H) - March 26

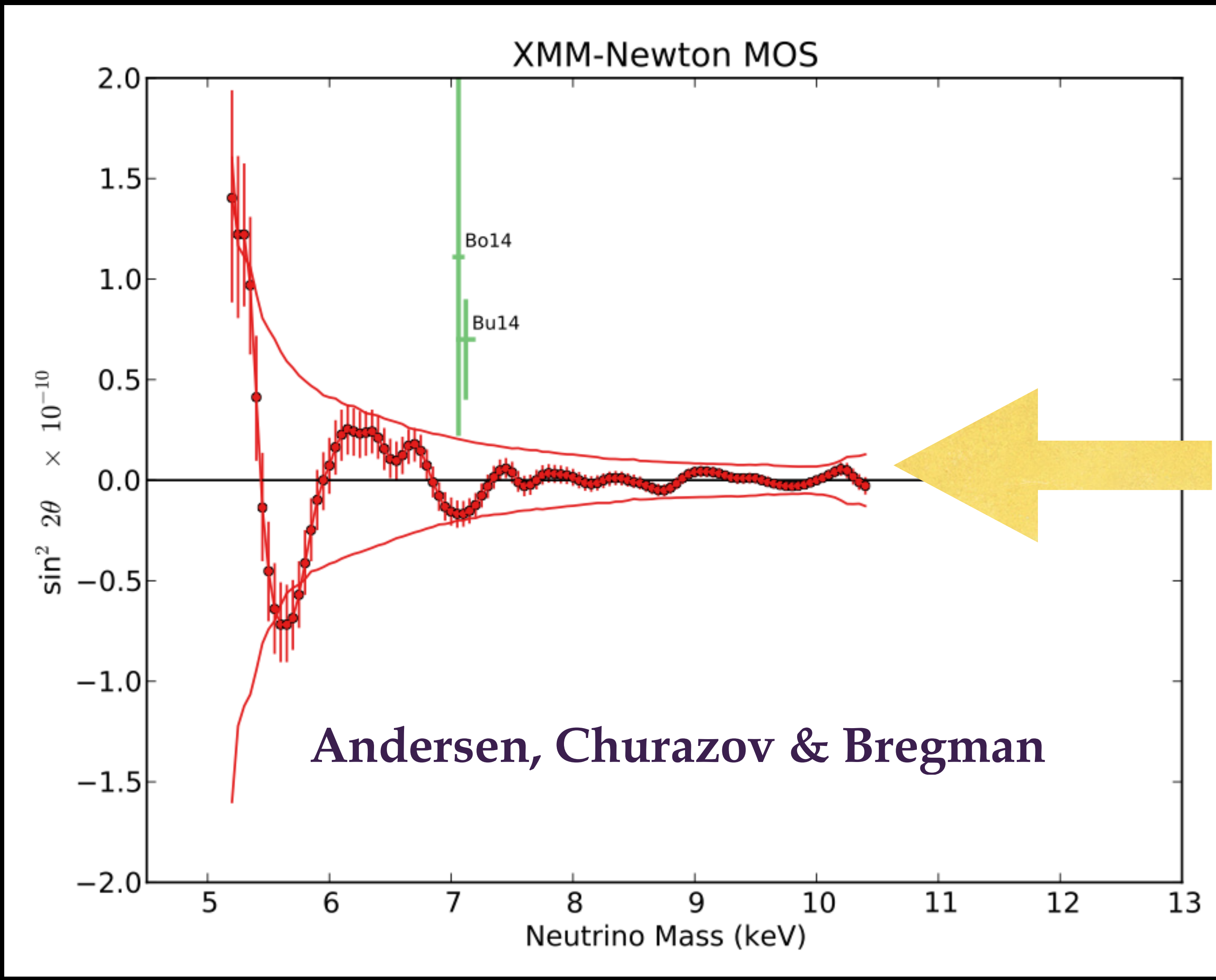
JAXA Press Releases:

- 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



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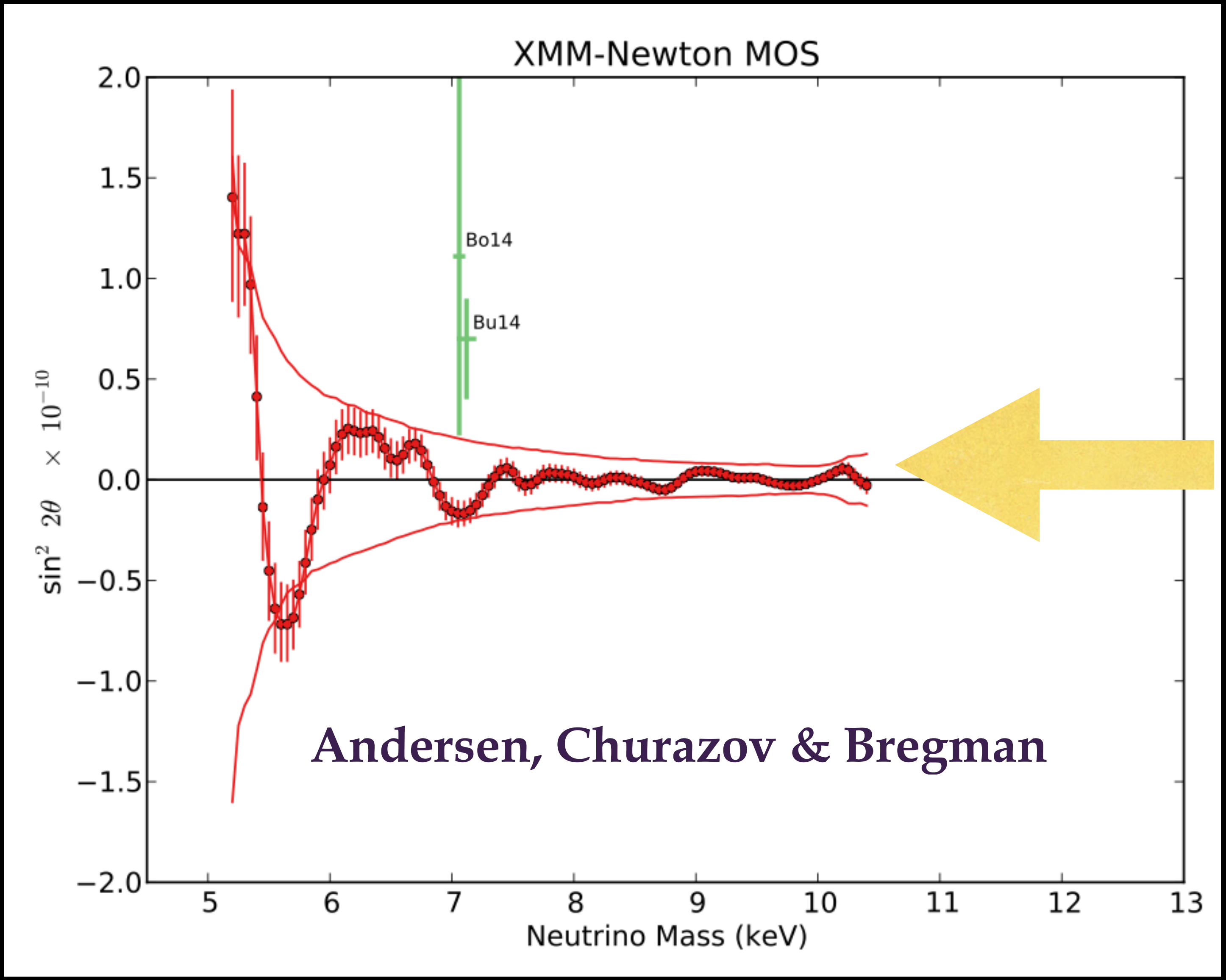
Sample of 81 galaxies observed with Chandra and a sample of 89 galaxies observed with XMM-Newton, using outskirts of the galaxies (Andersen, Churazov & Bregman 2014)



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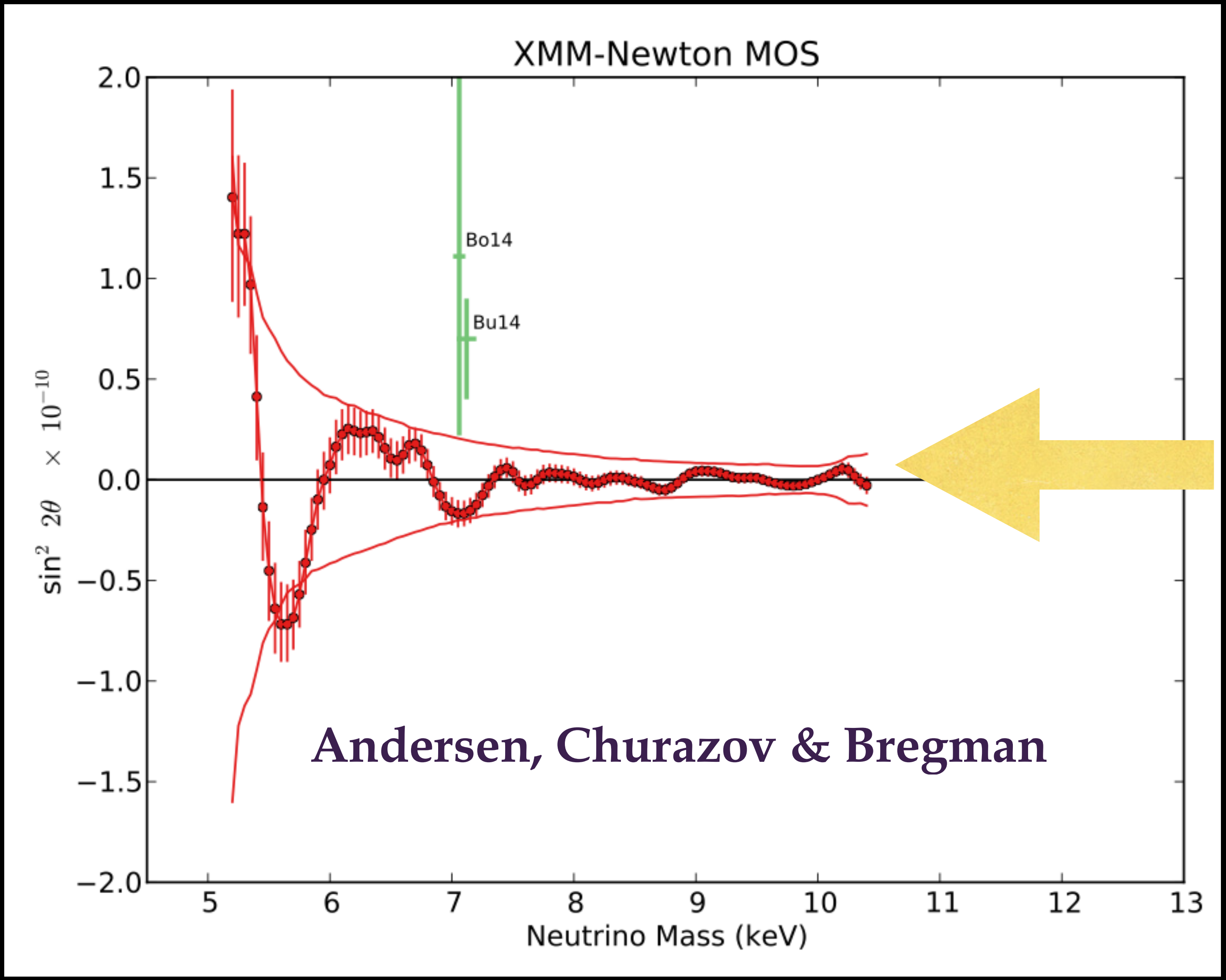

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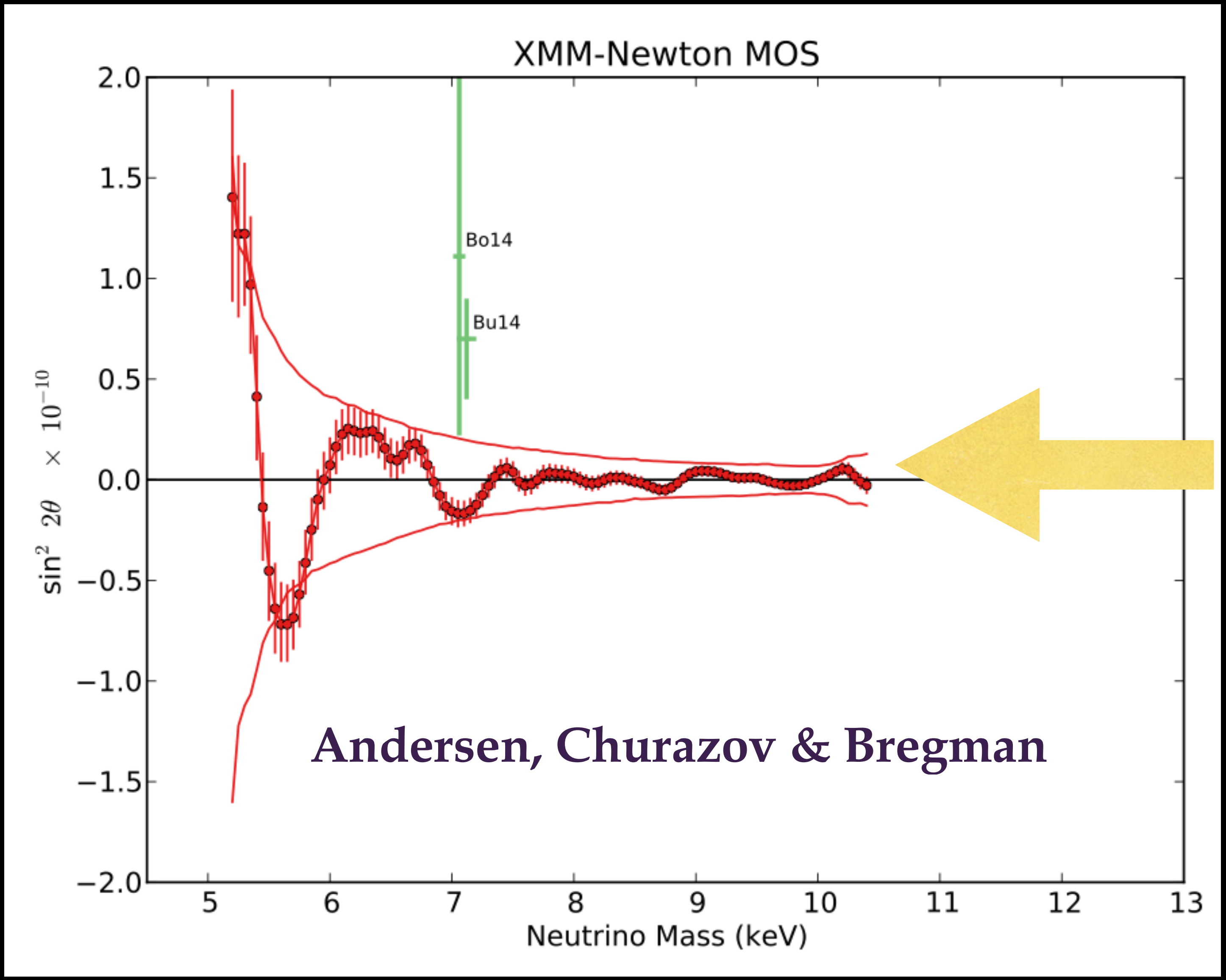

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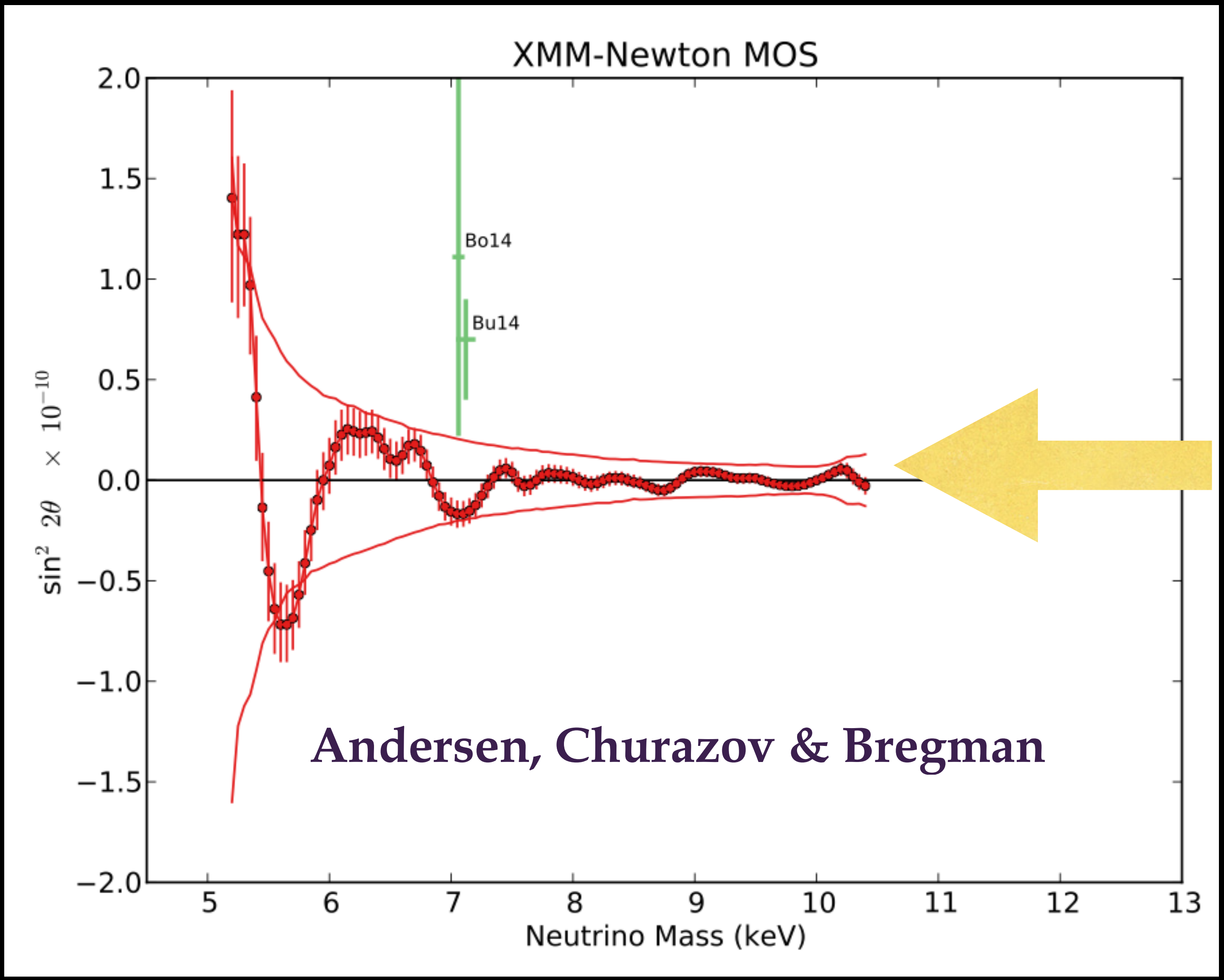

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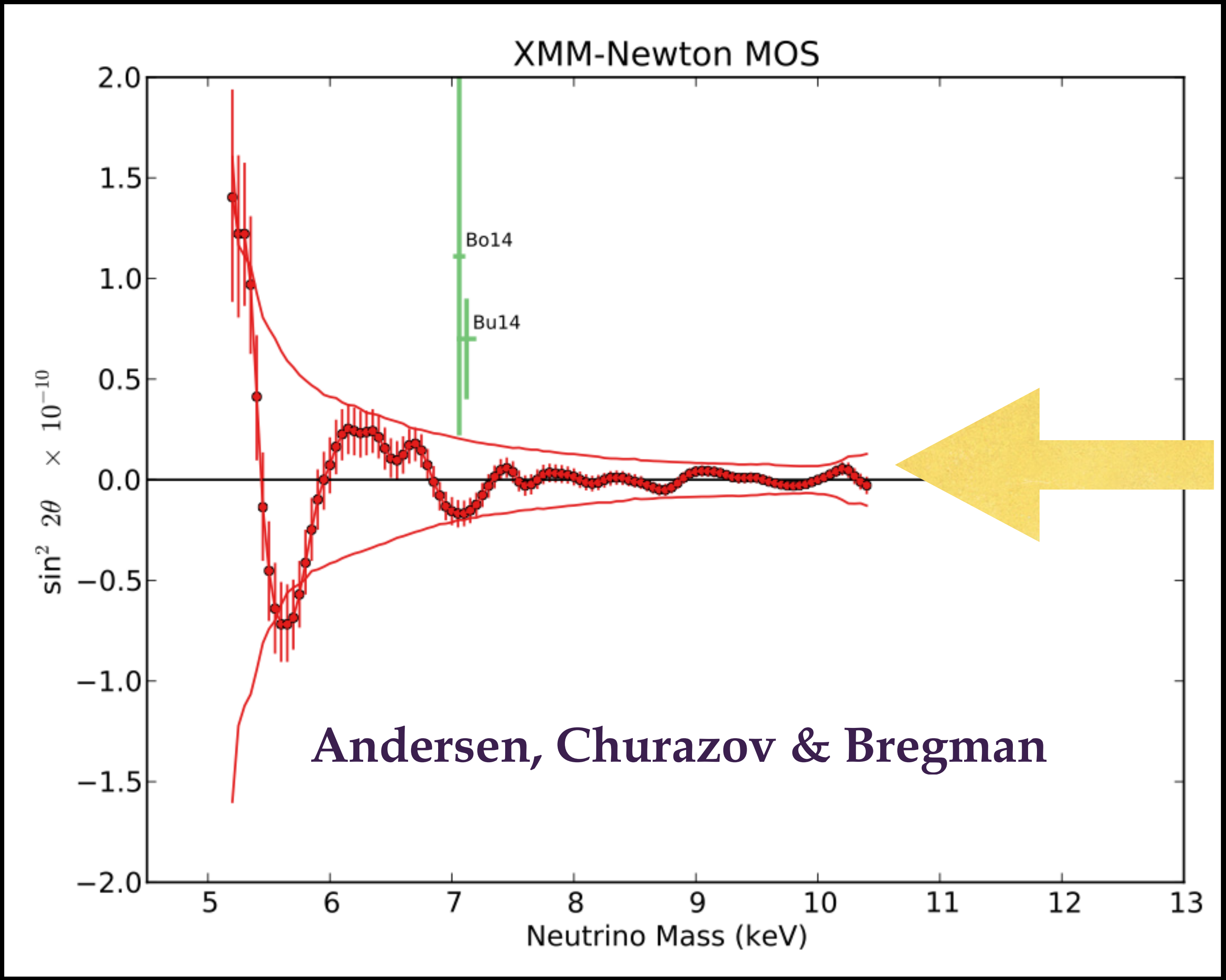

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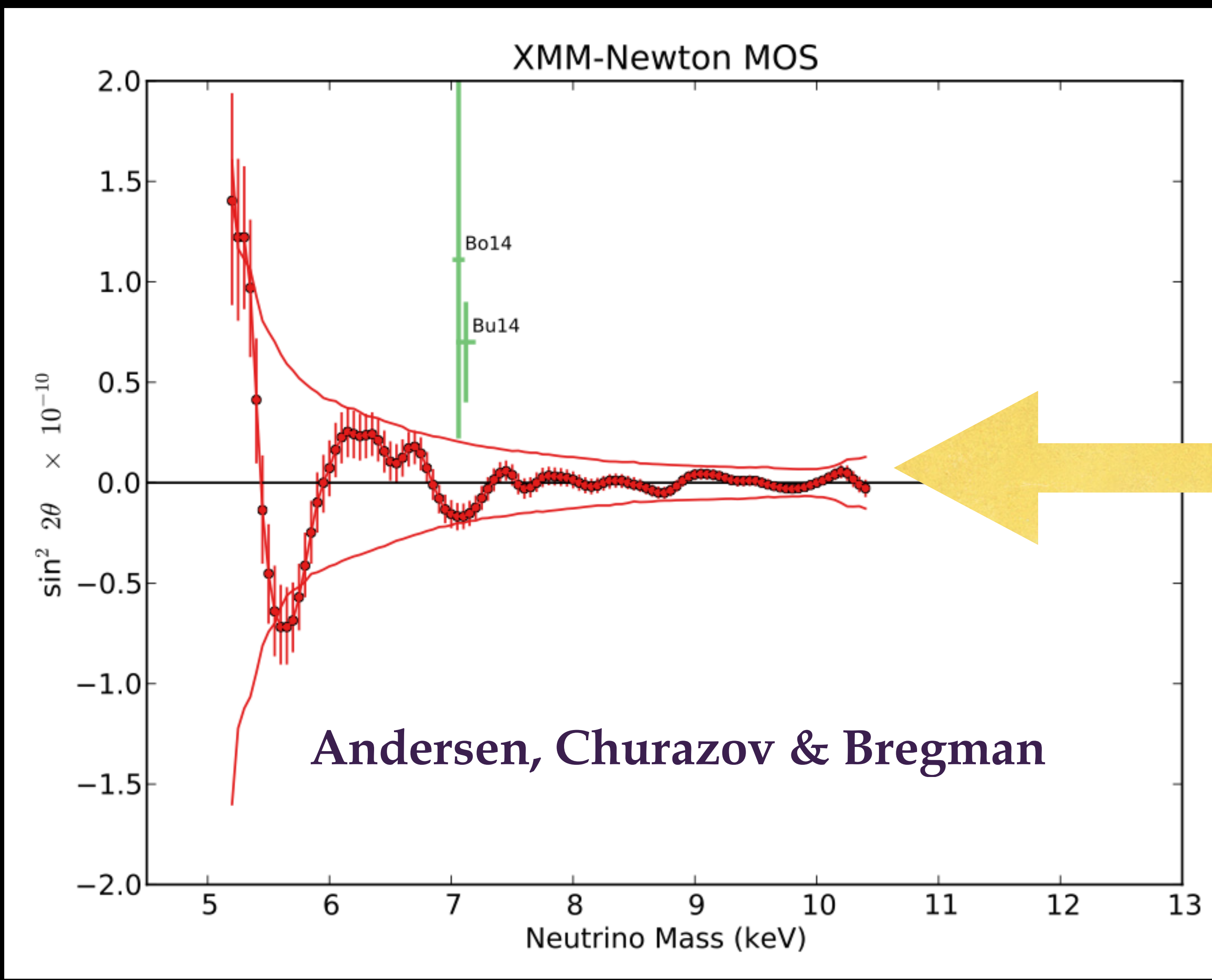

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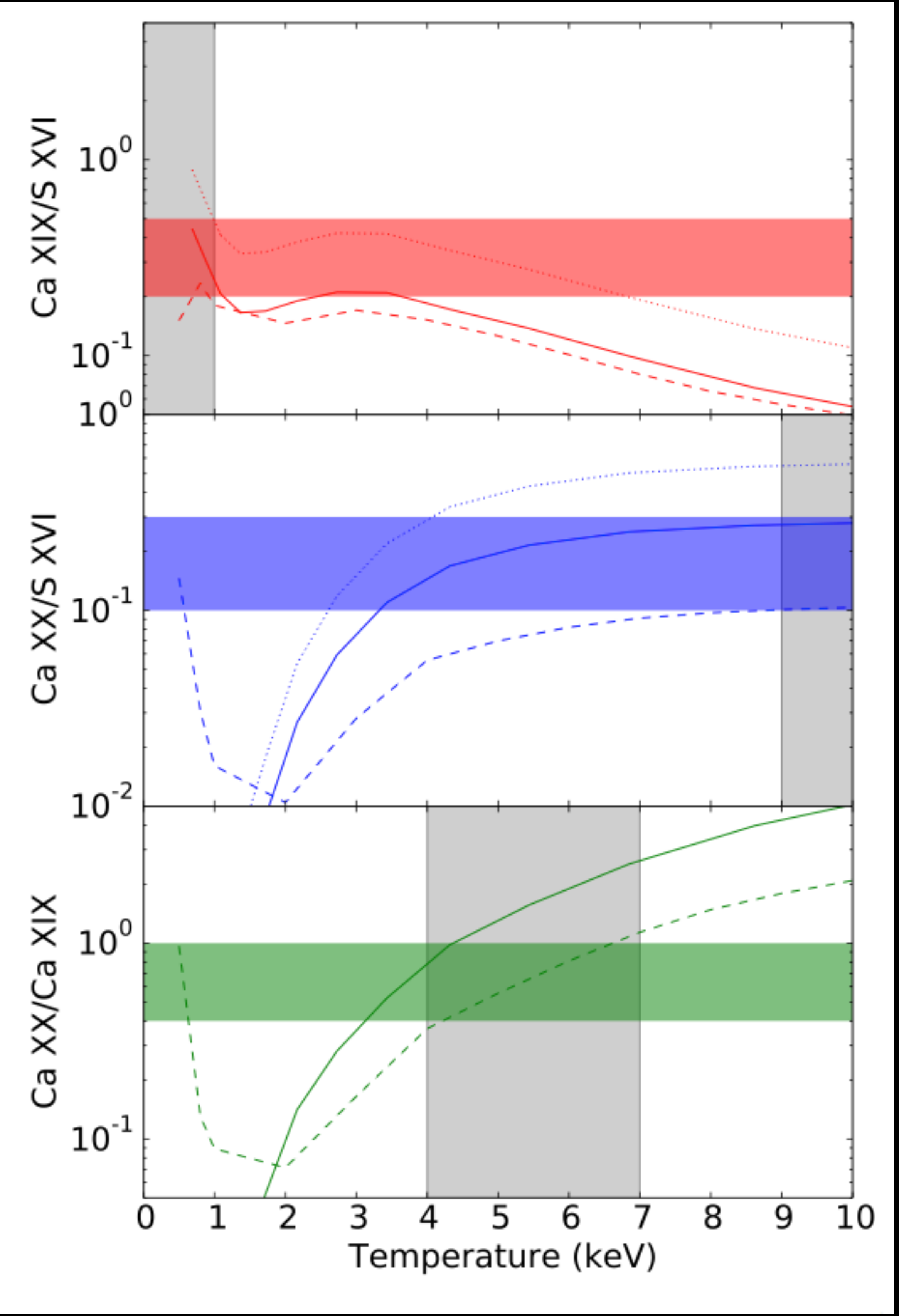
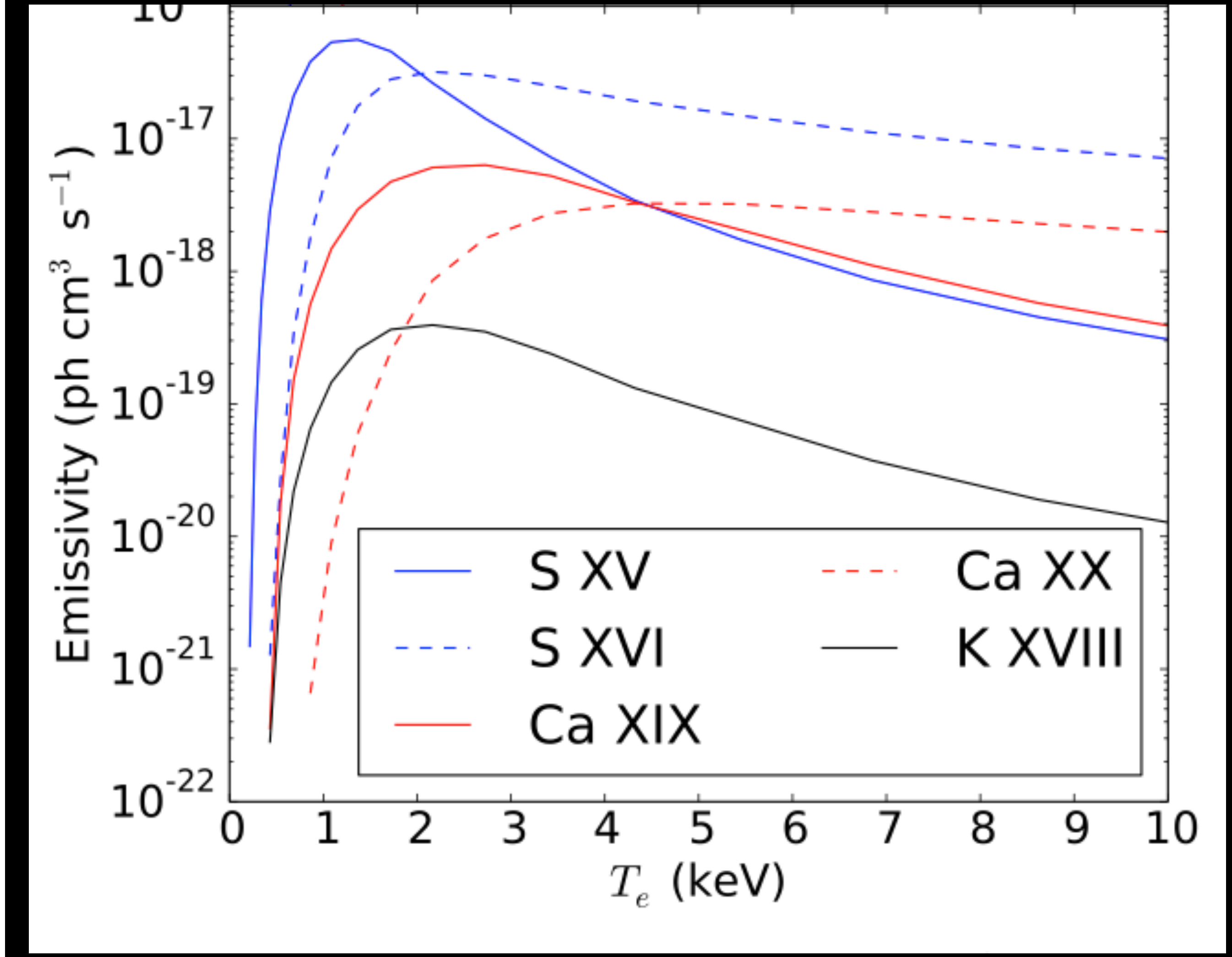
Proper methodology would find a more robust, less systematics dominated method & not quote irrelevant statistical evidence which reach an invalid conclusion.

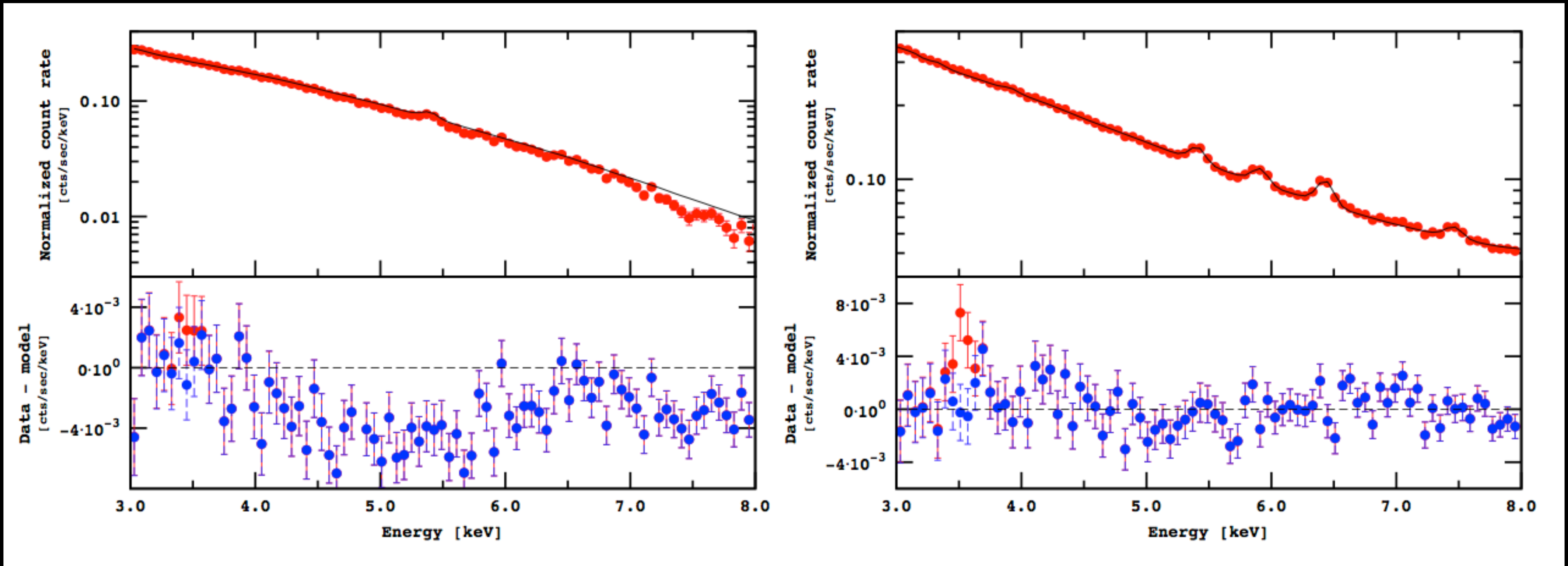
Inconsistent T? Potassium Line? (JP)





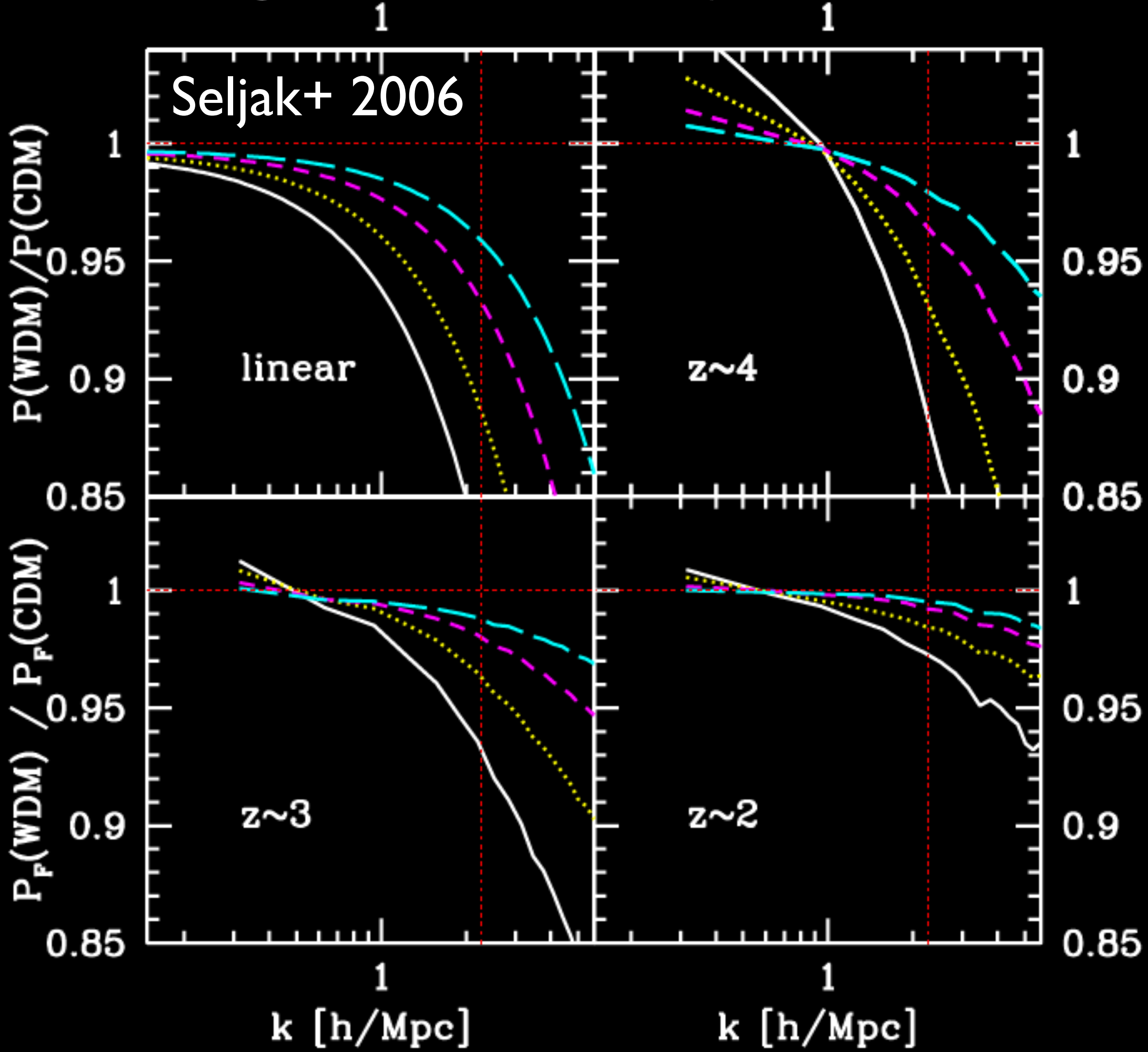
Bulbul+: “An independent consideration is the observed absolute line fluxes. Because the Ca XX, Ca XIX and S XVI emissivities drop steeply at low temperatures (lower panel in Fig. 3), any cool component would have to have a very high abundance of those elements to contribute significantly to the observed 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).”

No detection in M31? Consistent with K? (JP)



Boyarsky+ 2014: “The observation of the line at 3.53 keV in the center of M31 is in stark contradiction with its interpretation as a K XVIII atomic transition – it would require an extremely super-solar abundance of K XVIII and a super-solar ratio of abundance of K XVIII relative to AR XVII and CA XIX. The presence of this line in different types of objects – galaxy clusters, M31, and the Galactic Center – makes it challenging to explain all these signals together by emission from K XVIII, even if this interpretation is hard to exclude from the GC data only.”

Lyman-α Forest Constraints on WDM



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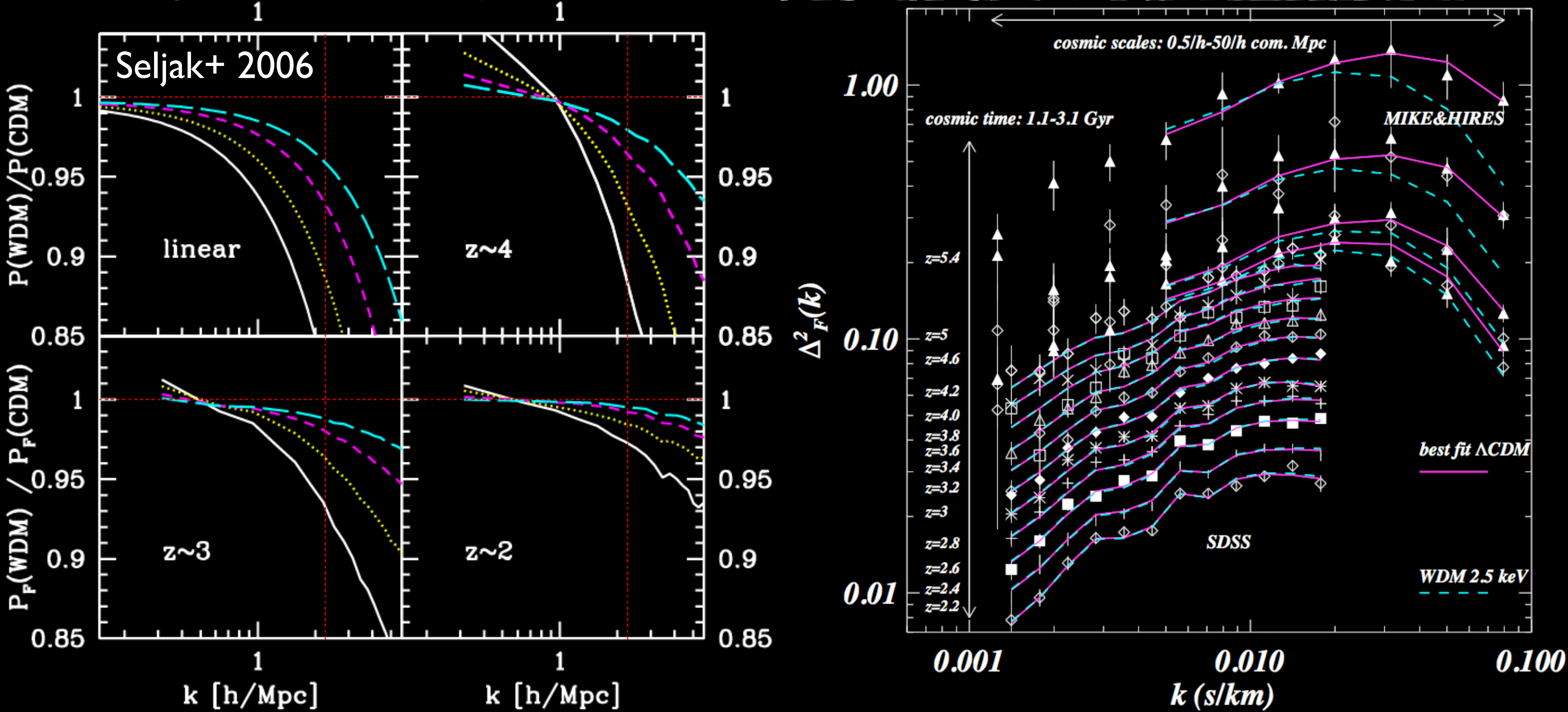

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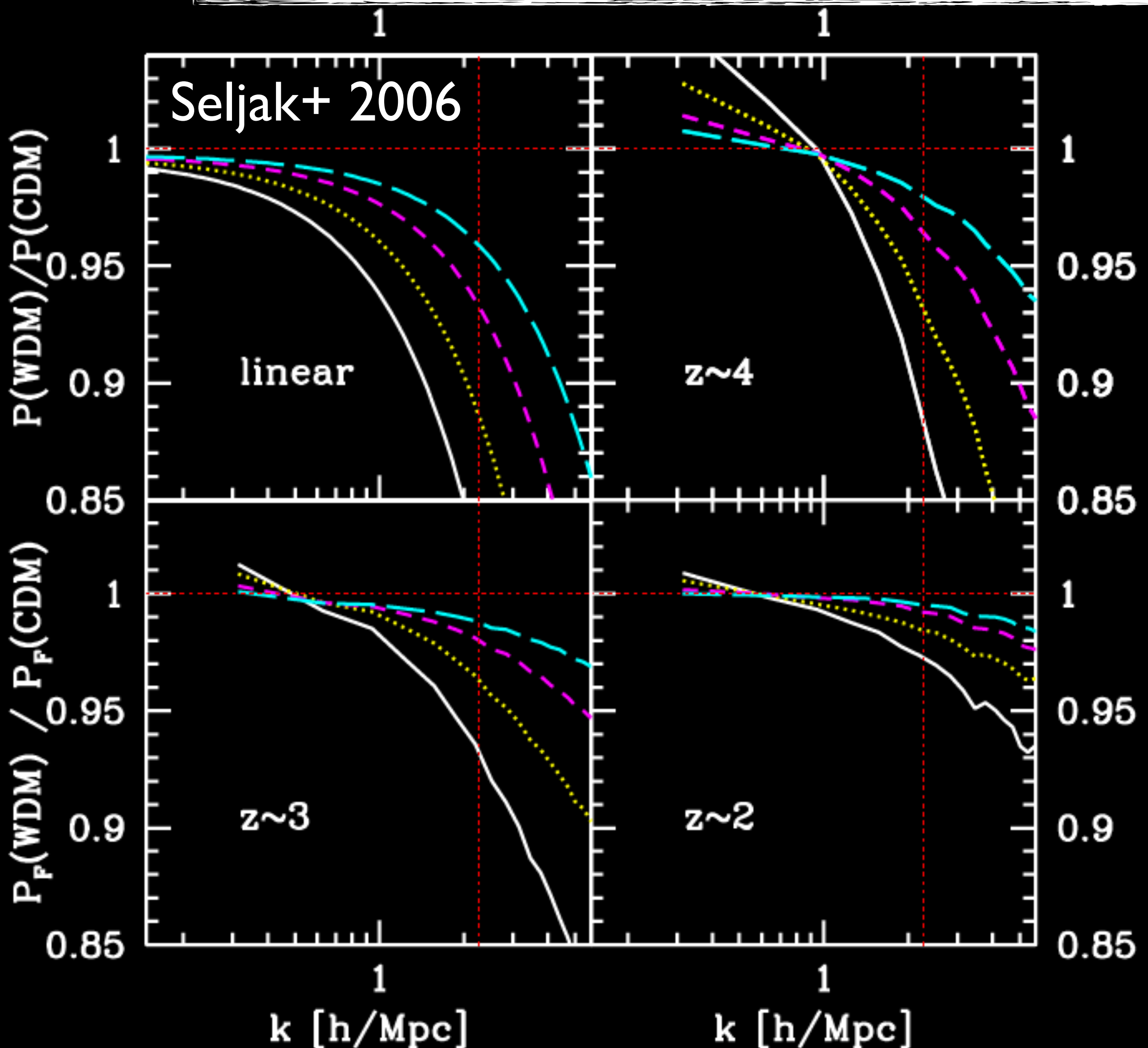

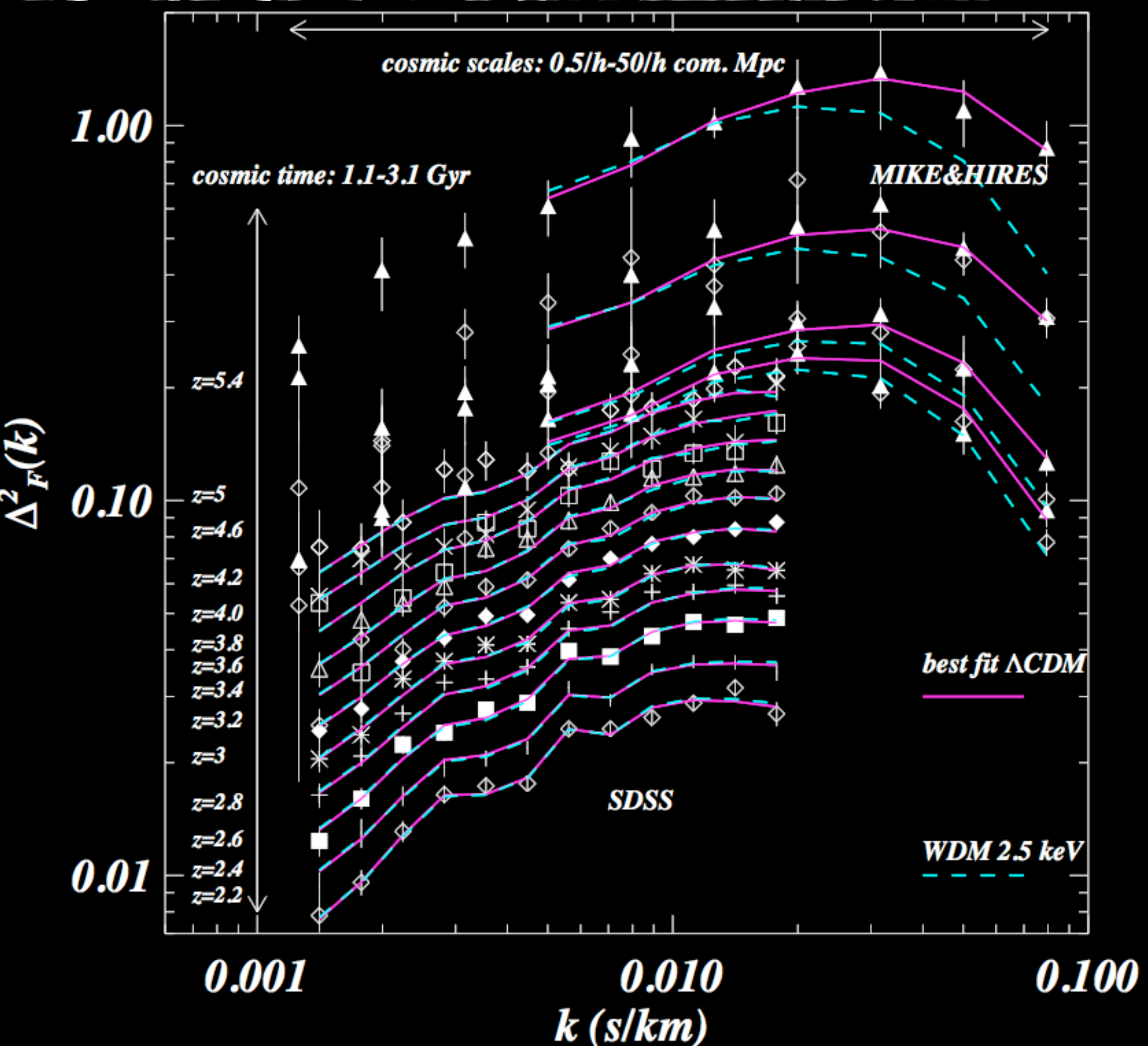

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Viel et al. 2013: Magellan MIKE + Keck HIRES

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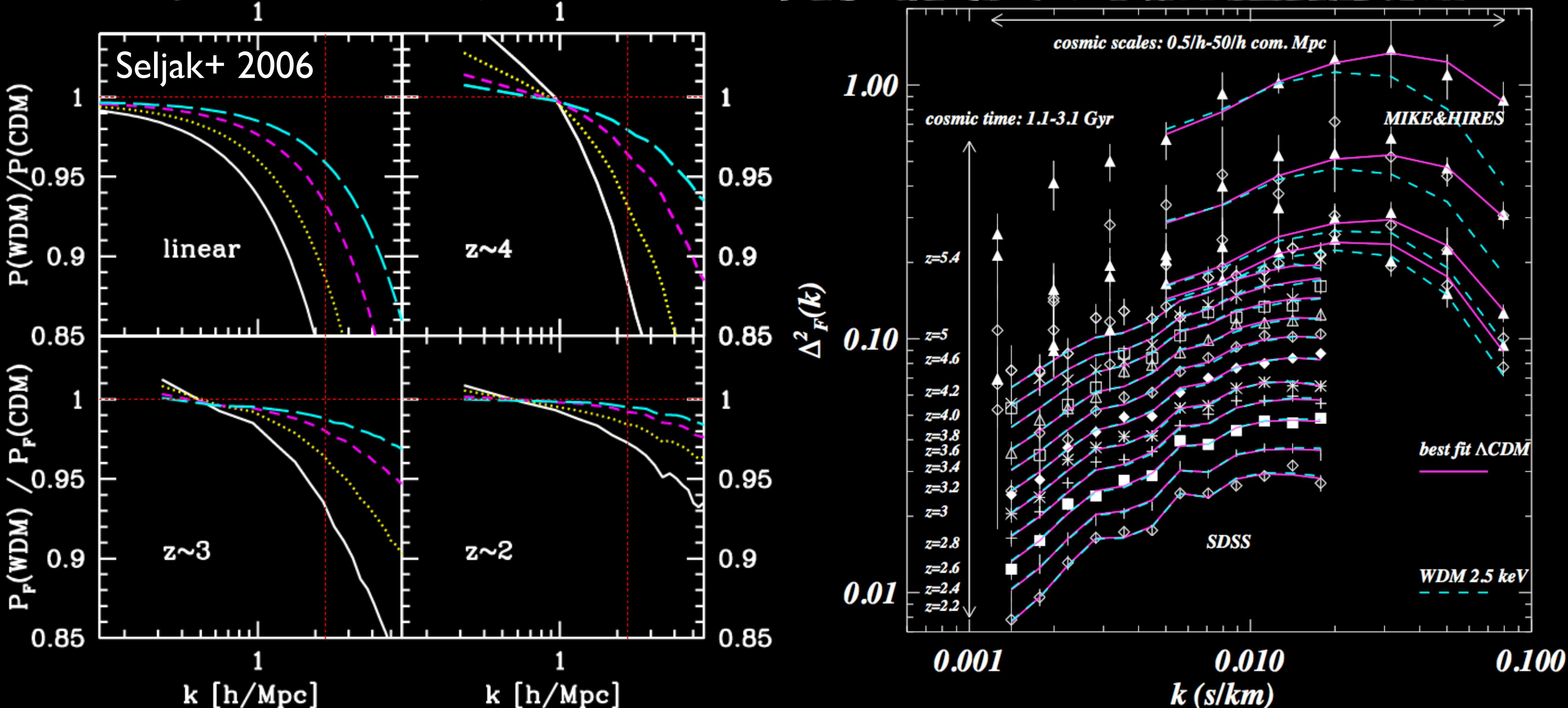

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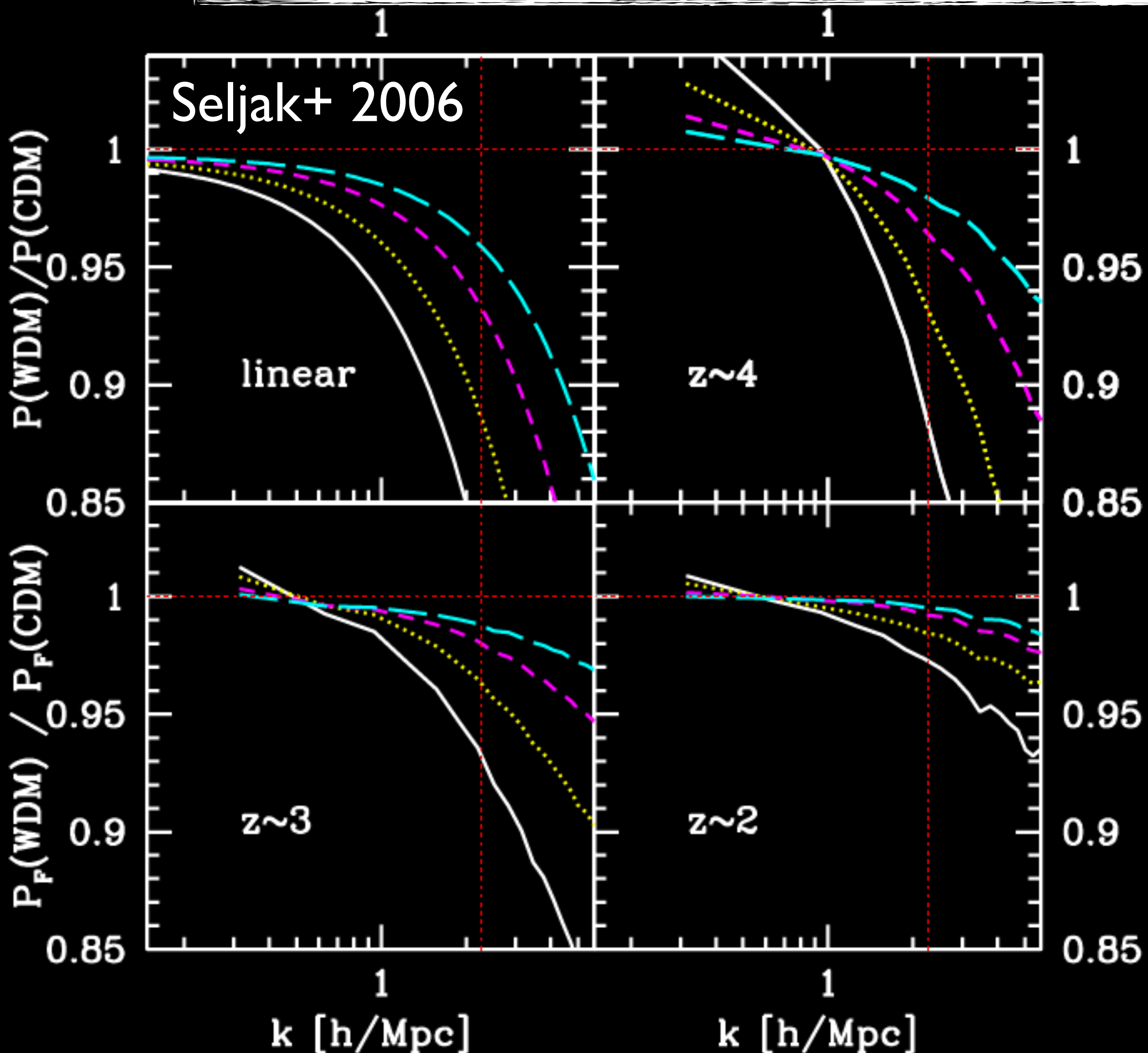

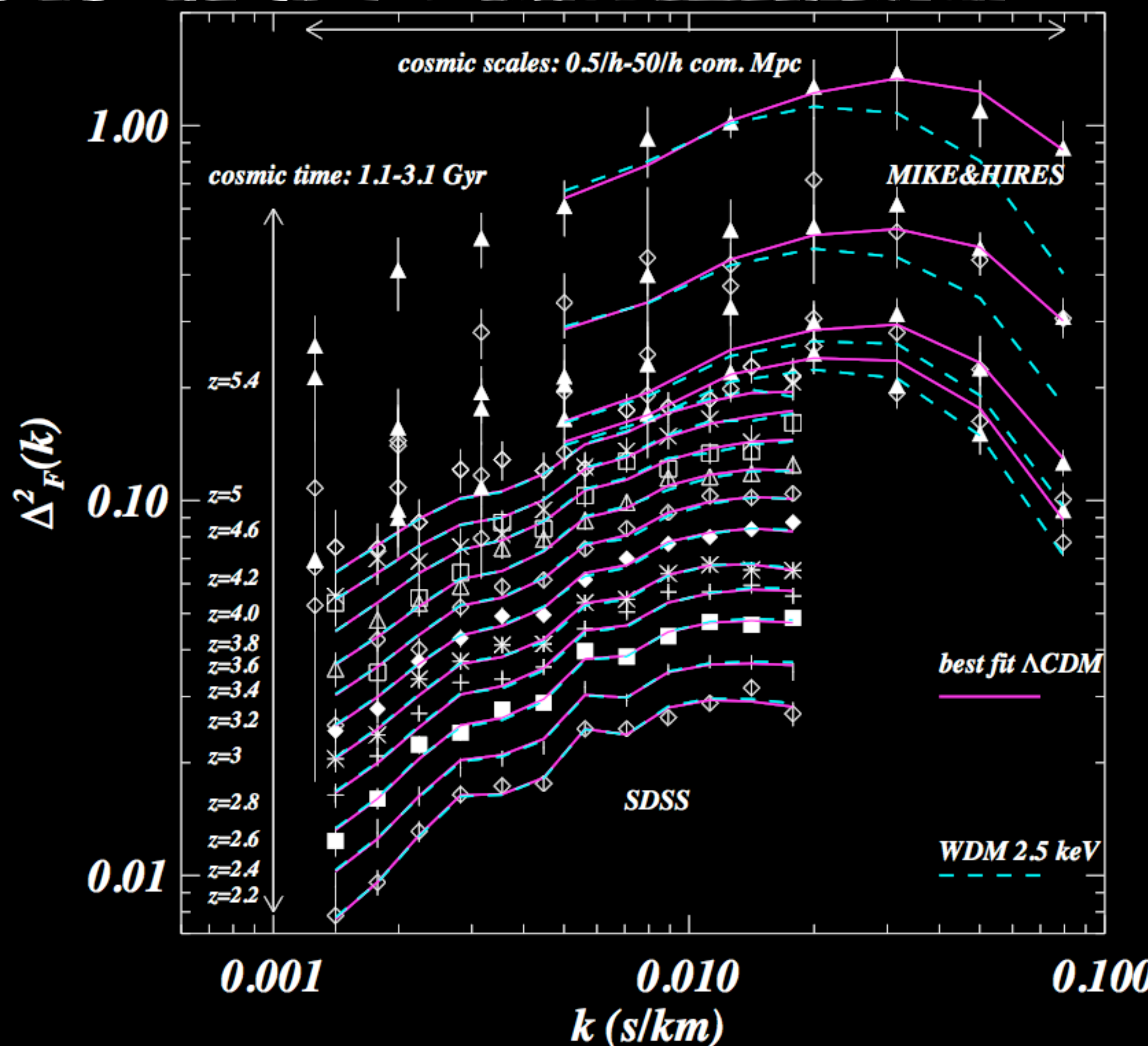

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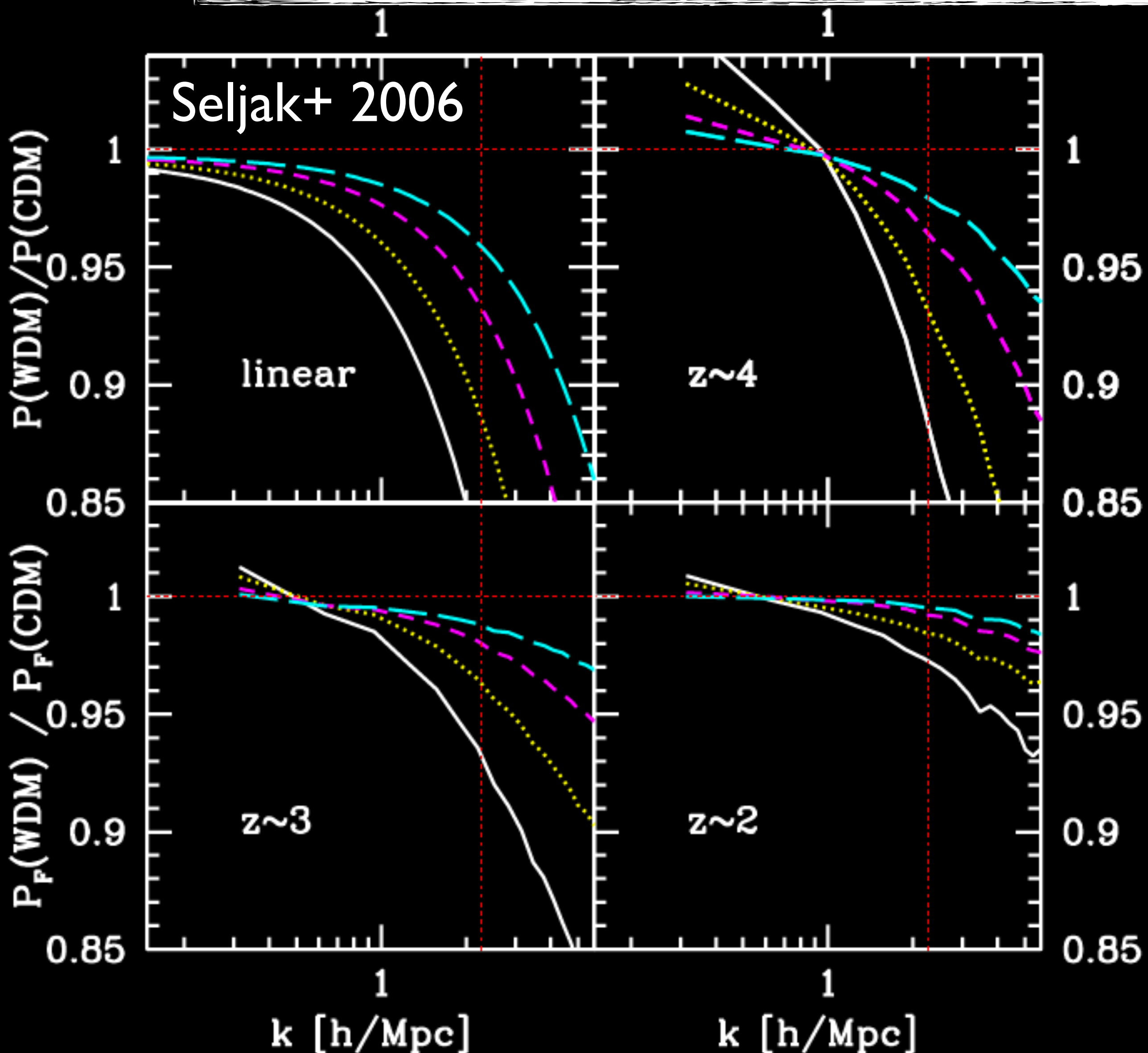

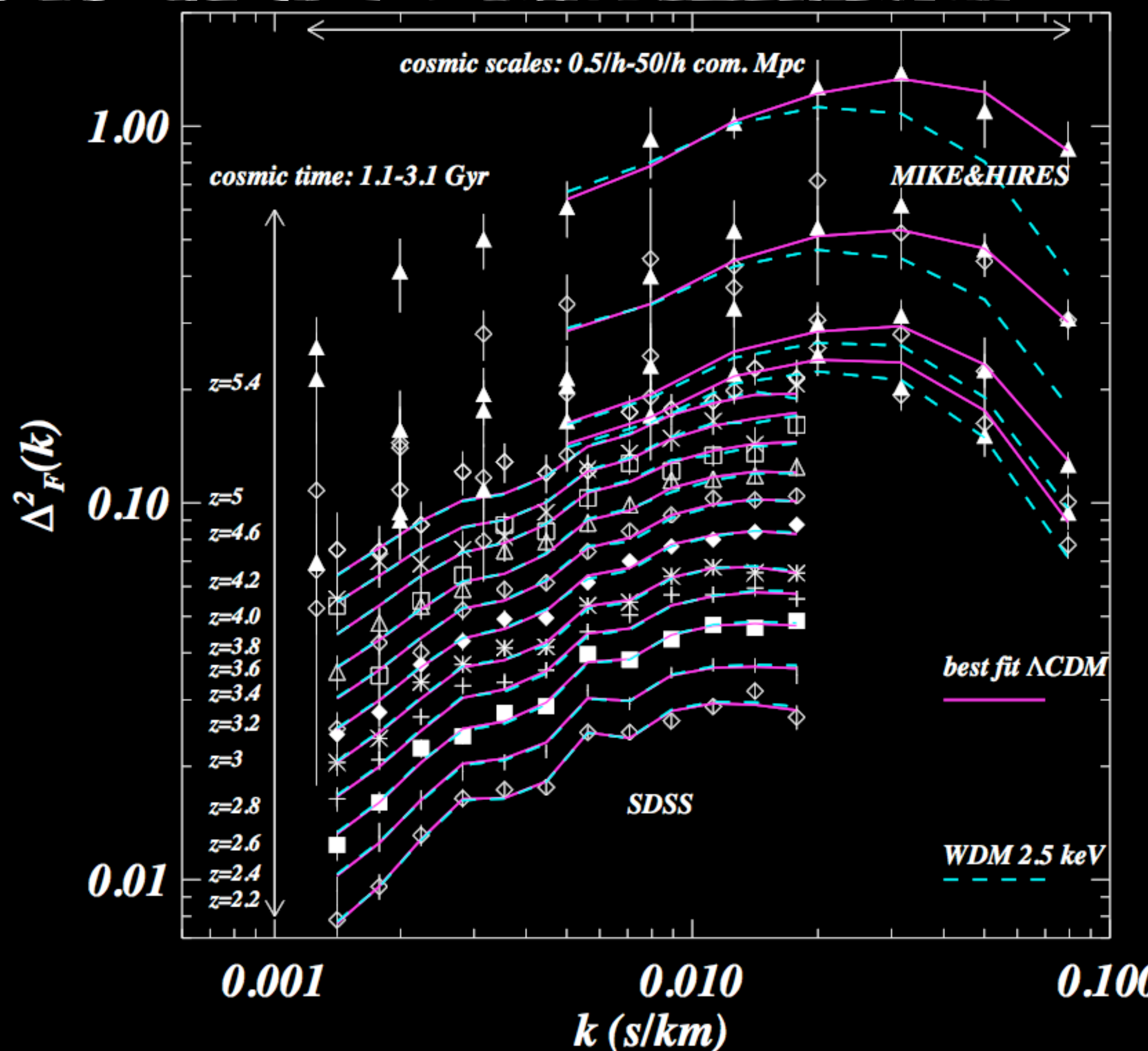

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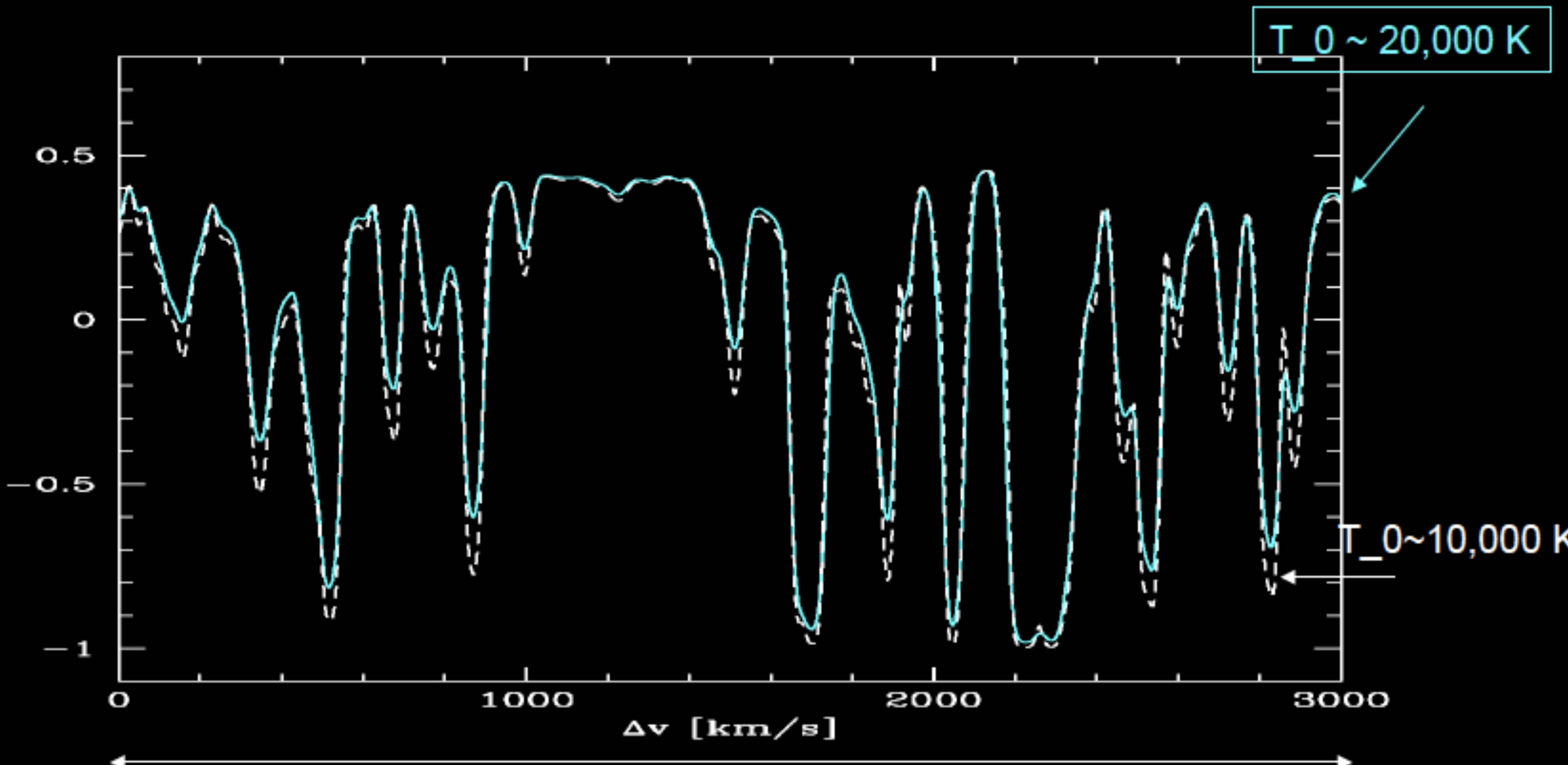
$m_s > 2\ \mathrm{keV}\ (99\%\mathrm{CL})$ "Cool DM"

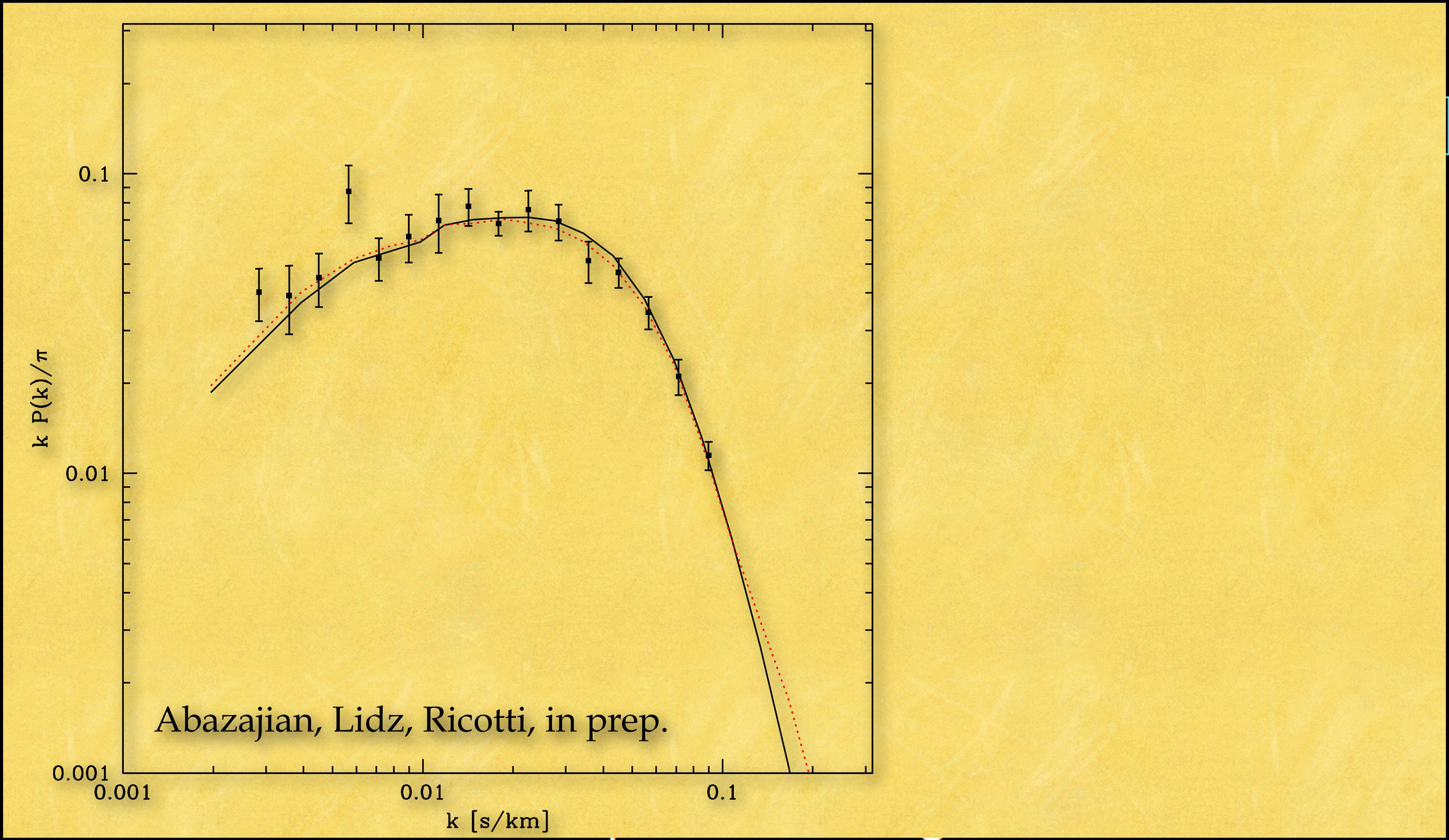
T impacts structure of H I Ly-a Forest

Doppler broadening and Jeans-smoothing….



~ 30 mpc/h co-moving

T impacts structure of HI Ly-a Forest



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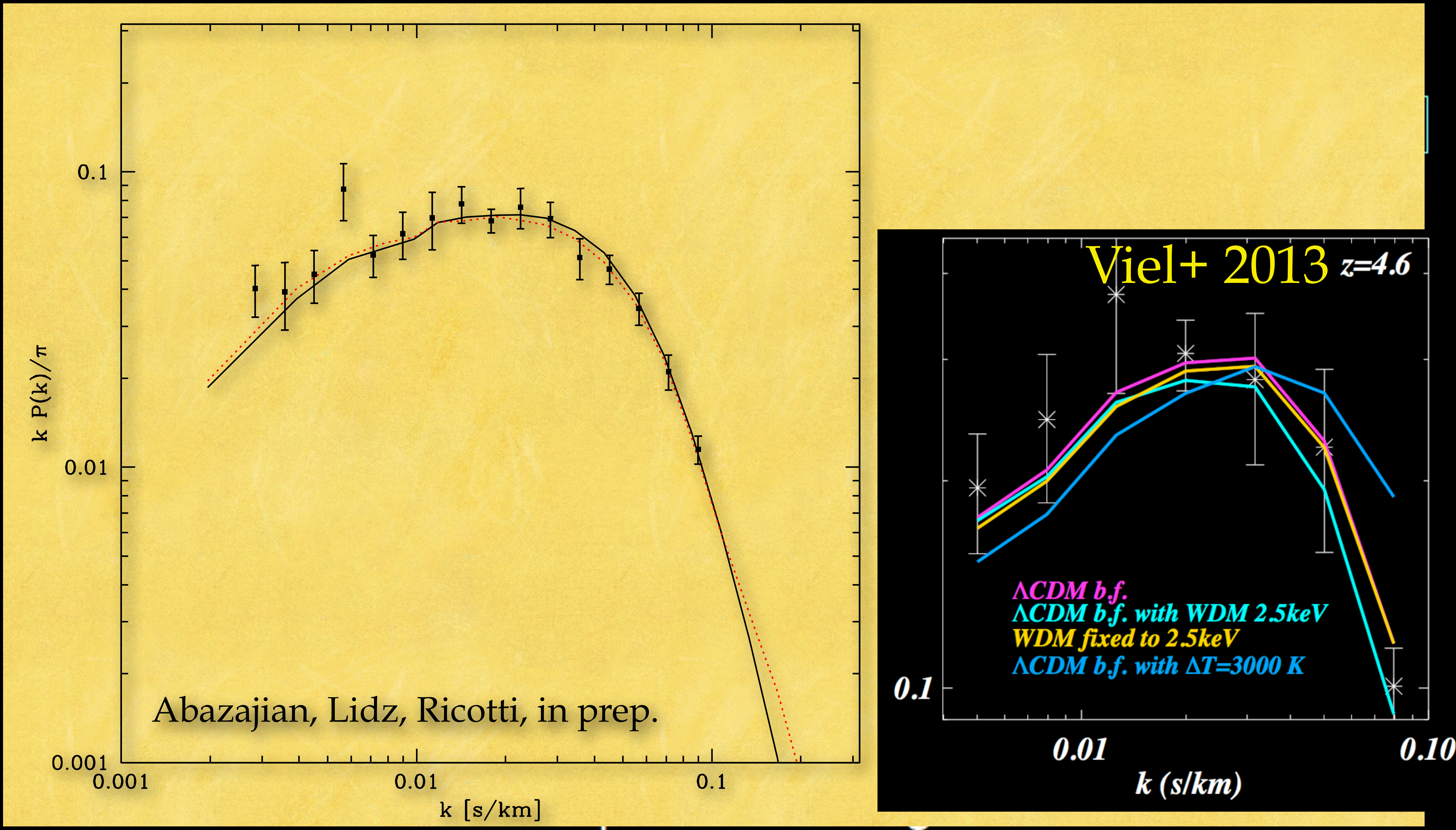


The Lyman-α Forest: Powerful & Challenging

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

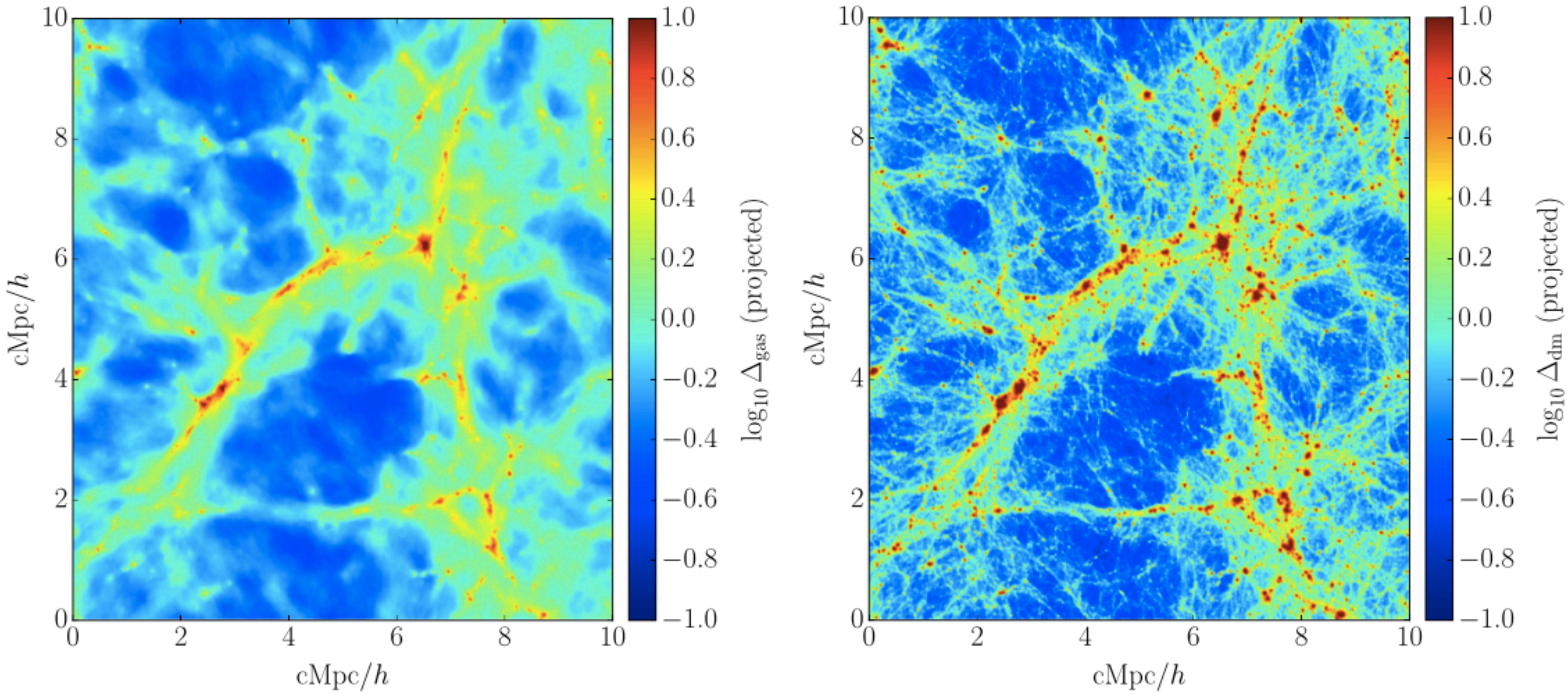
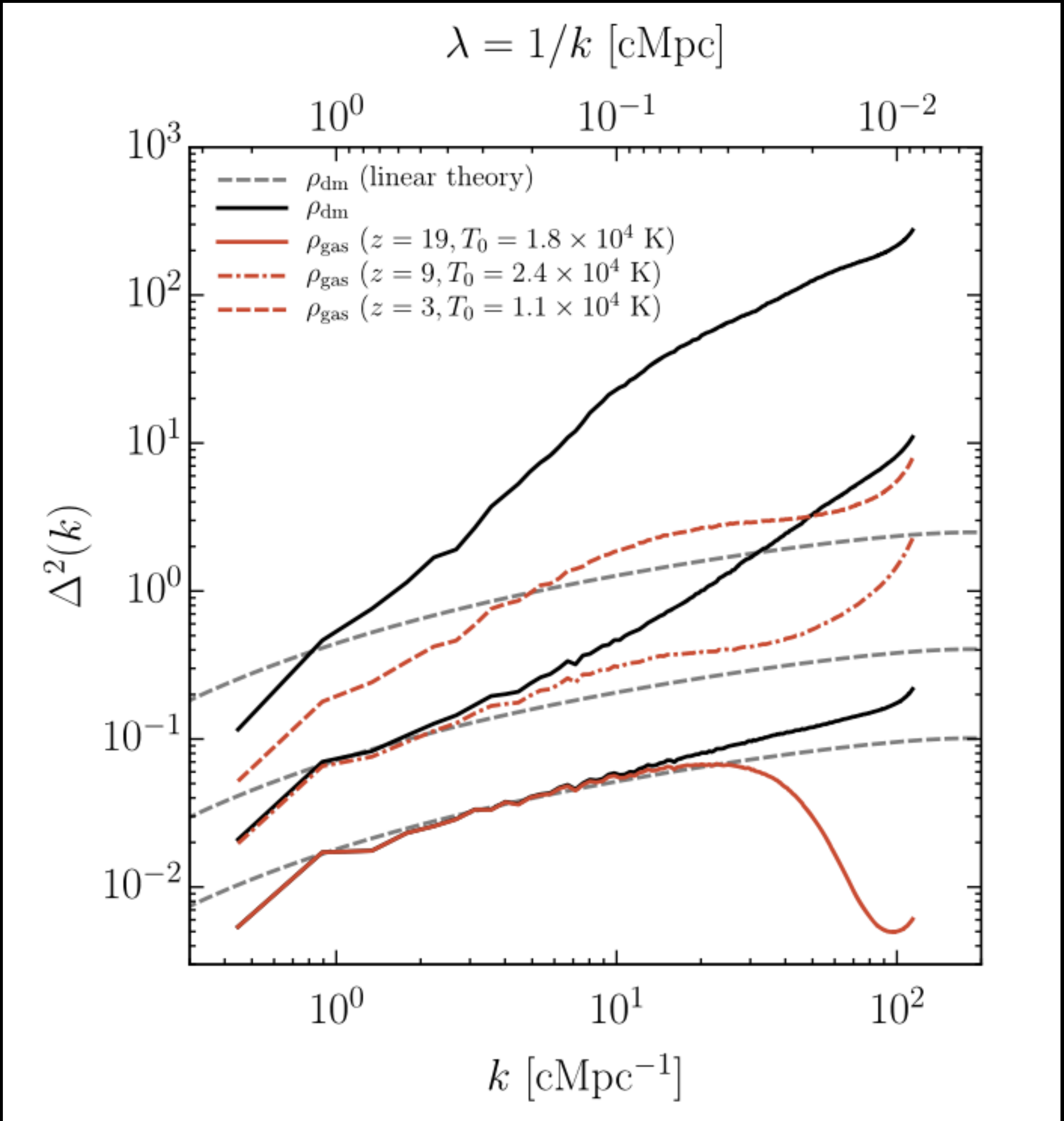


Figure 1. Projected density distributions of gas (left) and dark matter (right) at $z = 3$ in our fiducial simulation, showing pressure smoothing of gas relative to dark matter. The density at each point is an average for a column approximately 5 Mpc/h long.

Kulkarni et al. arXiv:1504.00366:

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

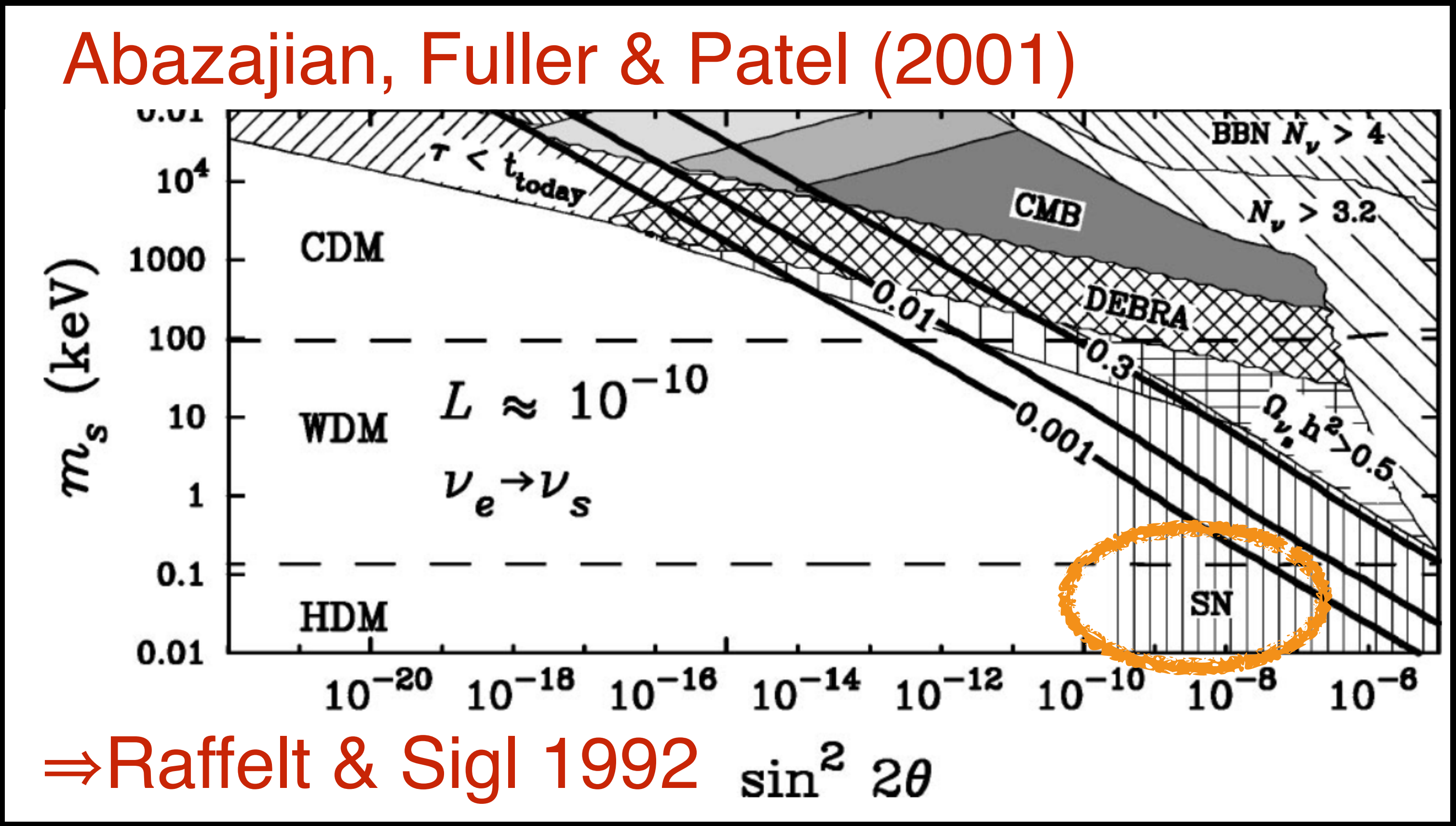
The Lyman-α Forest: Powerful & Challenging

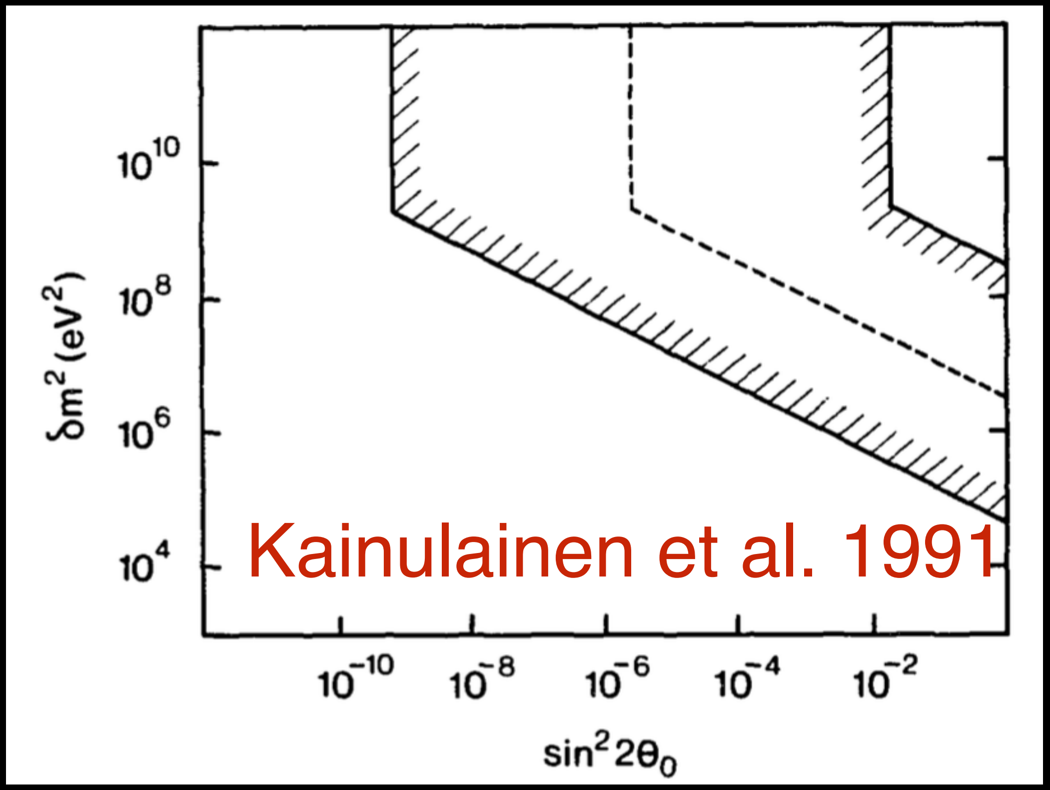


Kulkarni+: "The structure of the IGM in hydrodynamical simulations is very different from linear theory expectations at redshifts probed by the Lyα forest."… "the temperature–density relation should be augmented with a third pressure smoothing scale parameter λ_F"

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

Constraints from Energy Loss in Supernovae





Hidaka & Fuller (2006): Active-sterile conversion on collapse alters the electron fraction profile, temperature, etc. Cases were found with double resonances, re-converting steriles produced deep into active neutrinos and below the neutrino sphere, so the steriles never even exit the core

Argüelles, Brdar & Kopp (2016) arrive at stronger limits from energy loss, but do not address issues raised in previous work, both during collapse and later in the core energy loss: degeneracy pressure, rapid timescale evolution of ρ, multiple resonances.