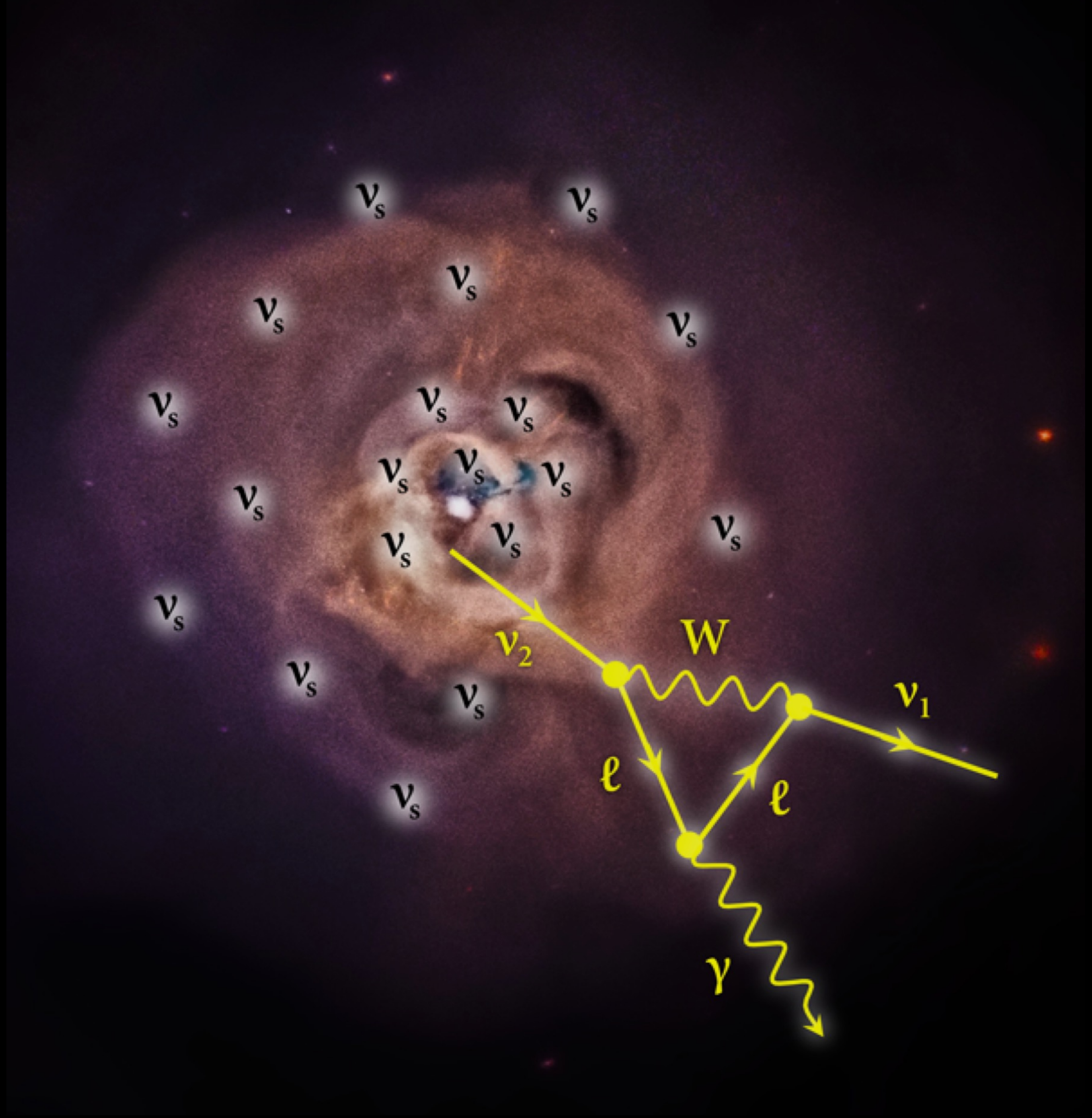
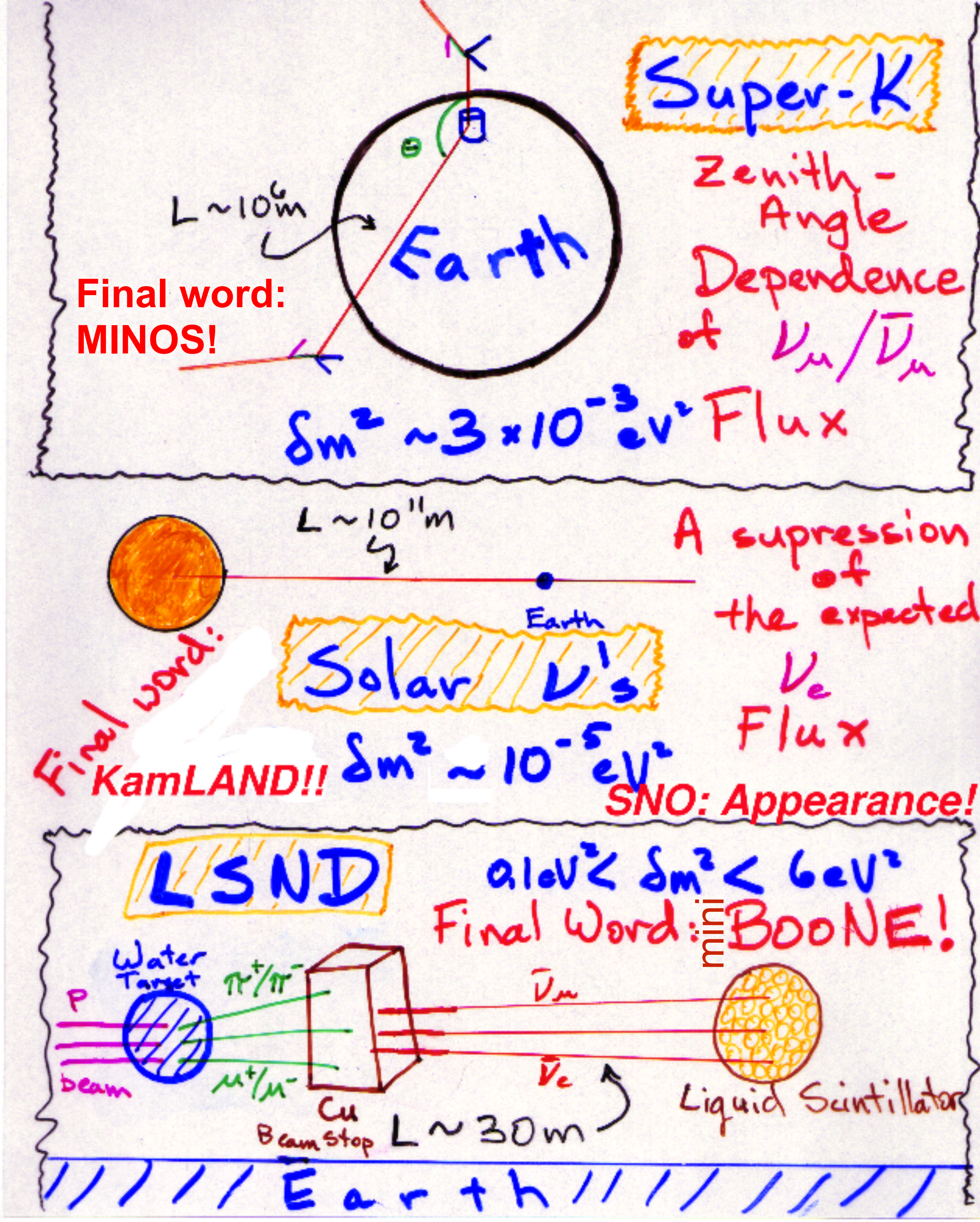


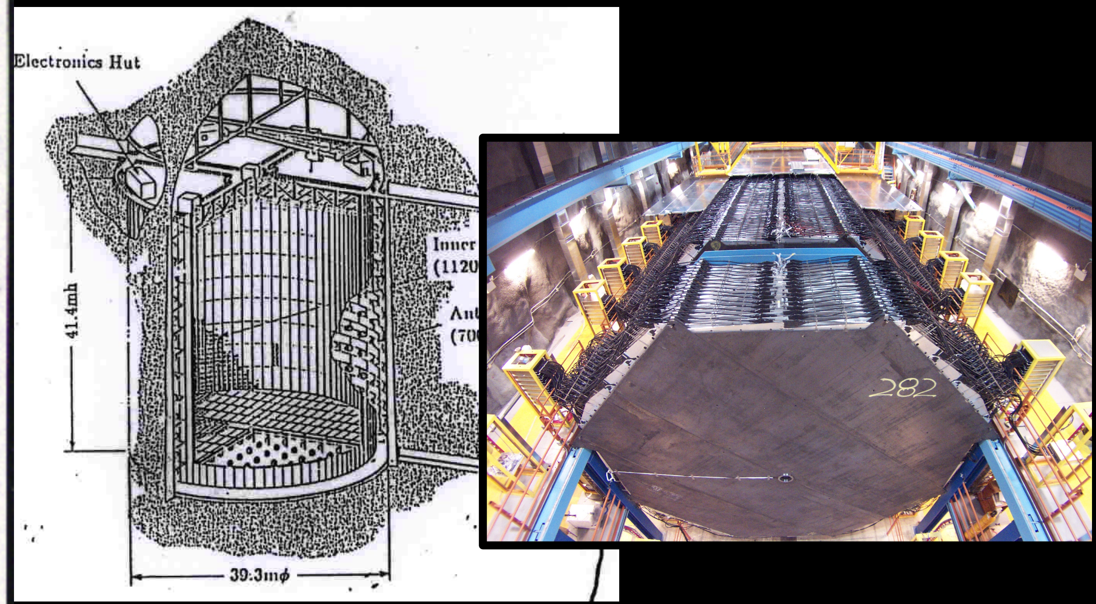
Neutrino Dark Matter and the 3.5 keV Line

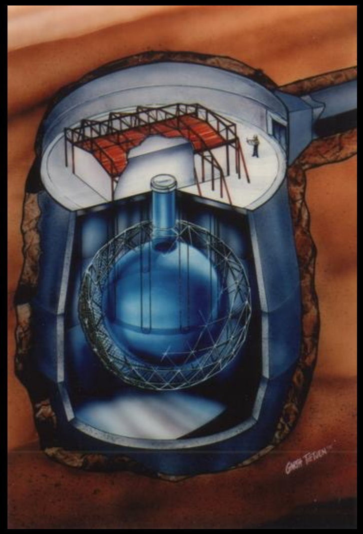
Kev Abazajian
University of California, Irvine

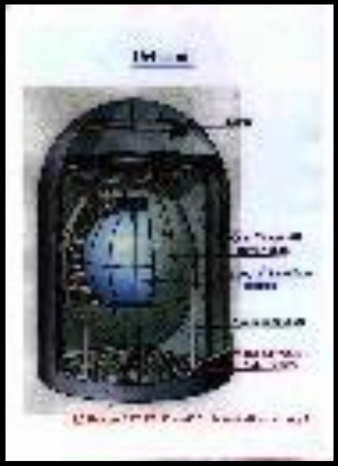
August 30, 2017

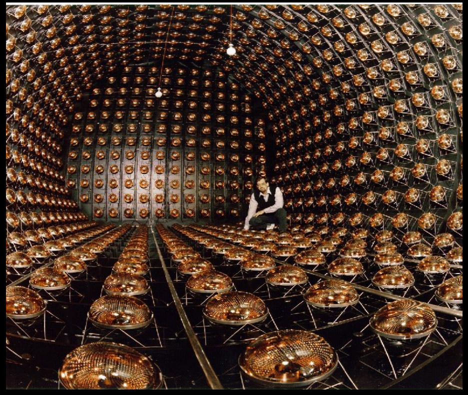
Dark Matter in Southern California - DaMaSC IV
Carnegie Science - UCI Center for Cosmology - Keck Institute for Space Science

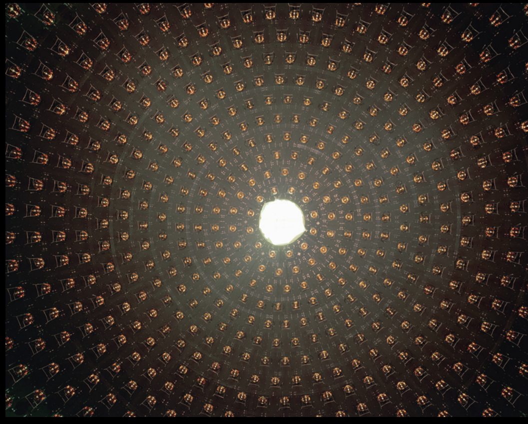

Super-K
Zenith-Angle Dependence of $\nu_\mu/\bar{\nu}_\mu$ Flux
$L \sim 10^6$ m
Earth
Final word: MINOS!
$\delta m^2 \sim 3\times10^{-3}$ eV^2
$L \sim 10^{11}$ m
Earth
A supression of the expected ν_e Flux
Solar ν's
$\delta m^2 \sim 10^{-5}$ eV^2
Final word: KamLAND!!
SNO: Appearance!
LSND
0.1 eV$^2 < \delta m^2 < 6$ eV^2
Final Word: miniBOONE!
Water Target
P beam
π^+/π^-
μ^+/μ^-
Cu Beam Stop
$\bar{\nu}_\mu$
$\bar{\nu}_e$
$L \sim 30$ m
Liquid Scintillator
Earth


Electronics Hut
41.4m
39.3m









Note:

eV $\neq$ keV

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short baseline $\nu \neq$ dark matter ν

Neutrino Mass & Sterile Neutrinos

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- 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)

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

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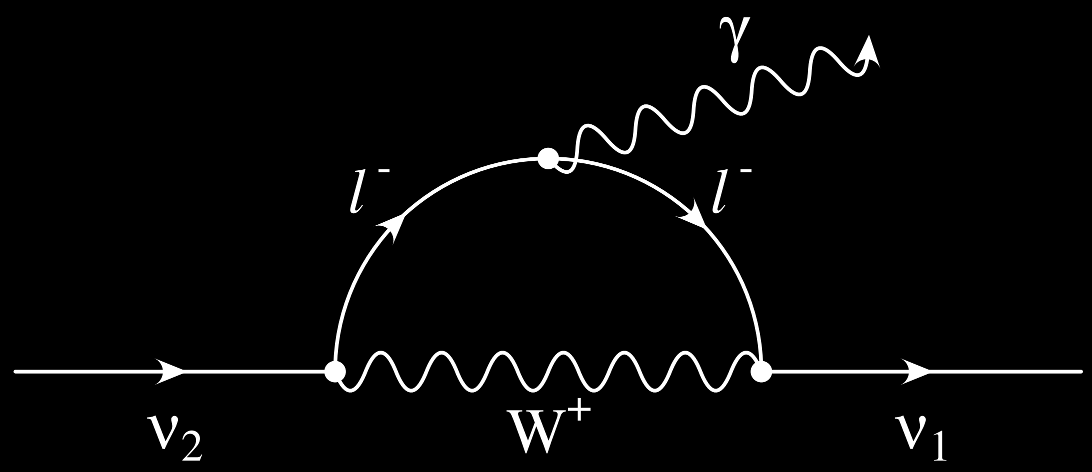
- "Precision" Sterile Neutrino Dark Matter & **Proposal for X-ray Detection** [Abazajian, Fuller & Patel 2001; KA 2005]: Full momentum-space production description with QCD transition corrections, resonant to non-resonant solutions as a continuum in lepton number.

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

Sterile ν WDM Radiative Decay in the X-ray



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

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

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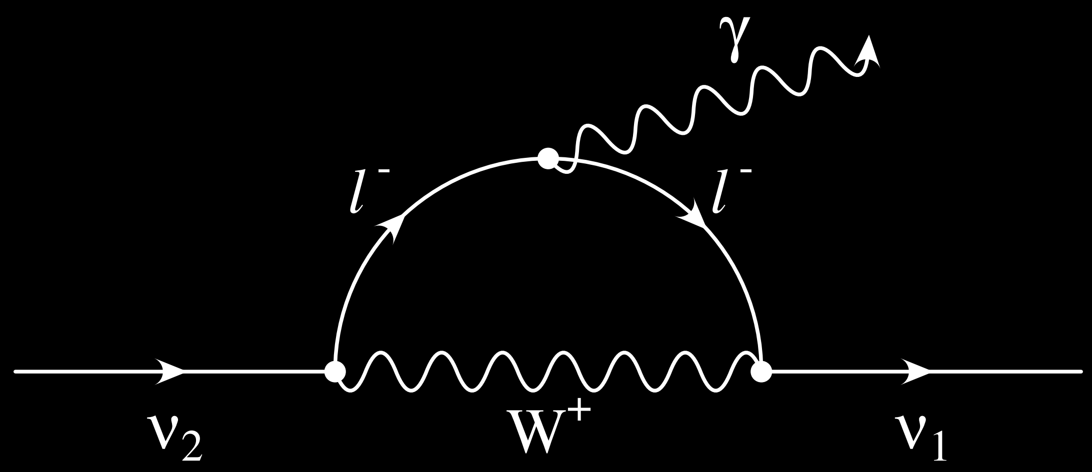

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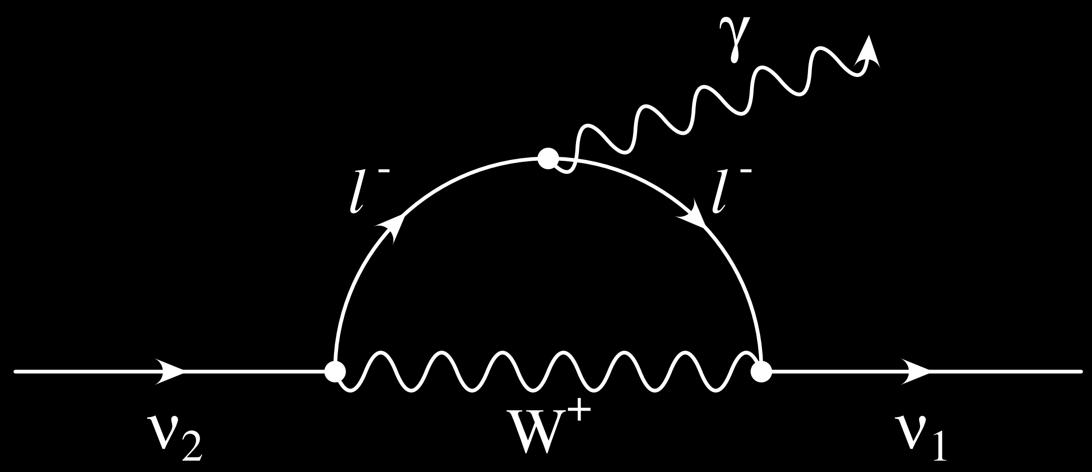

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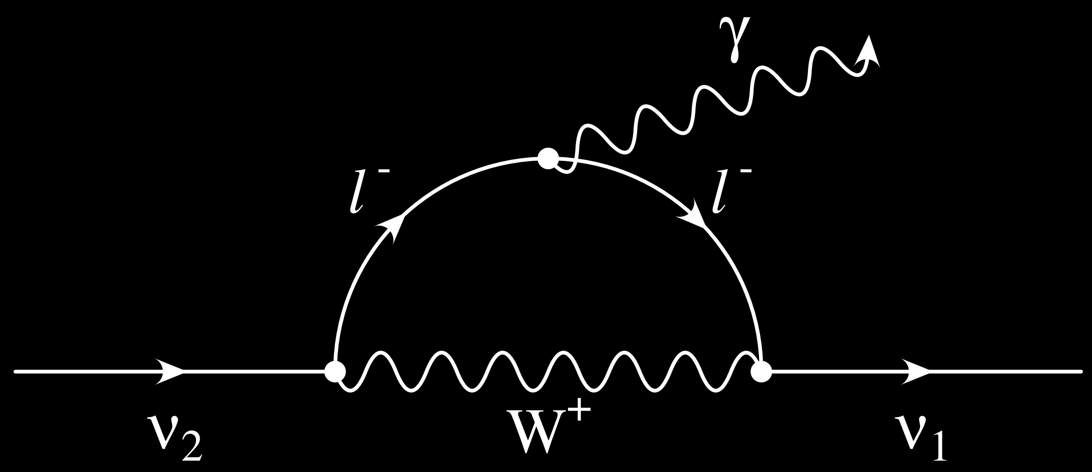

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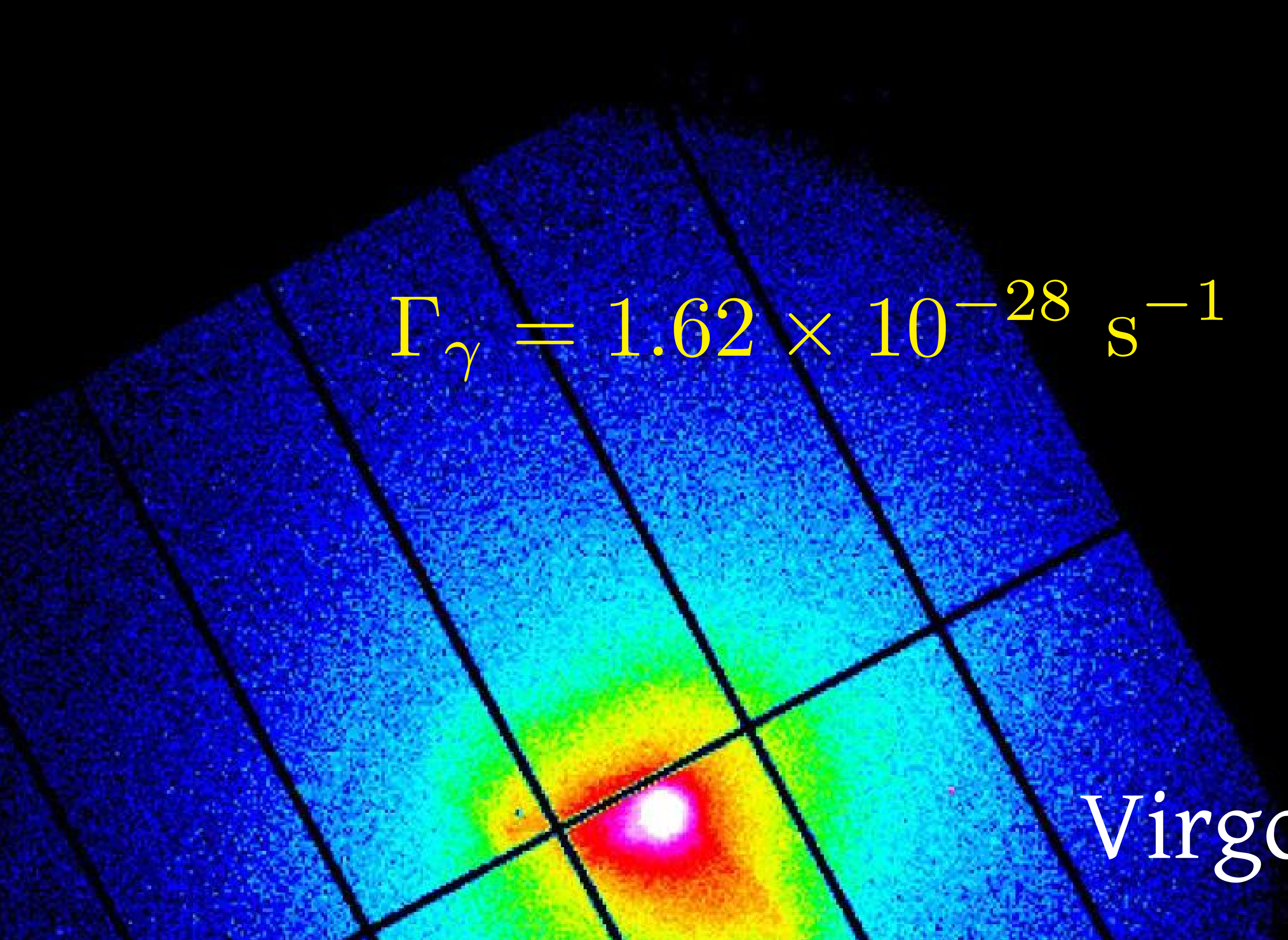
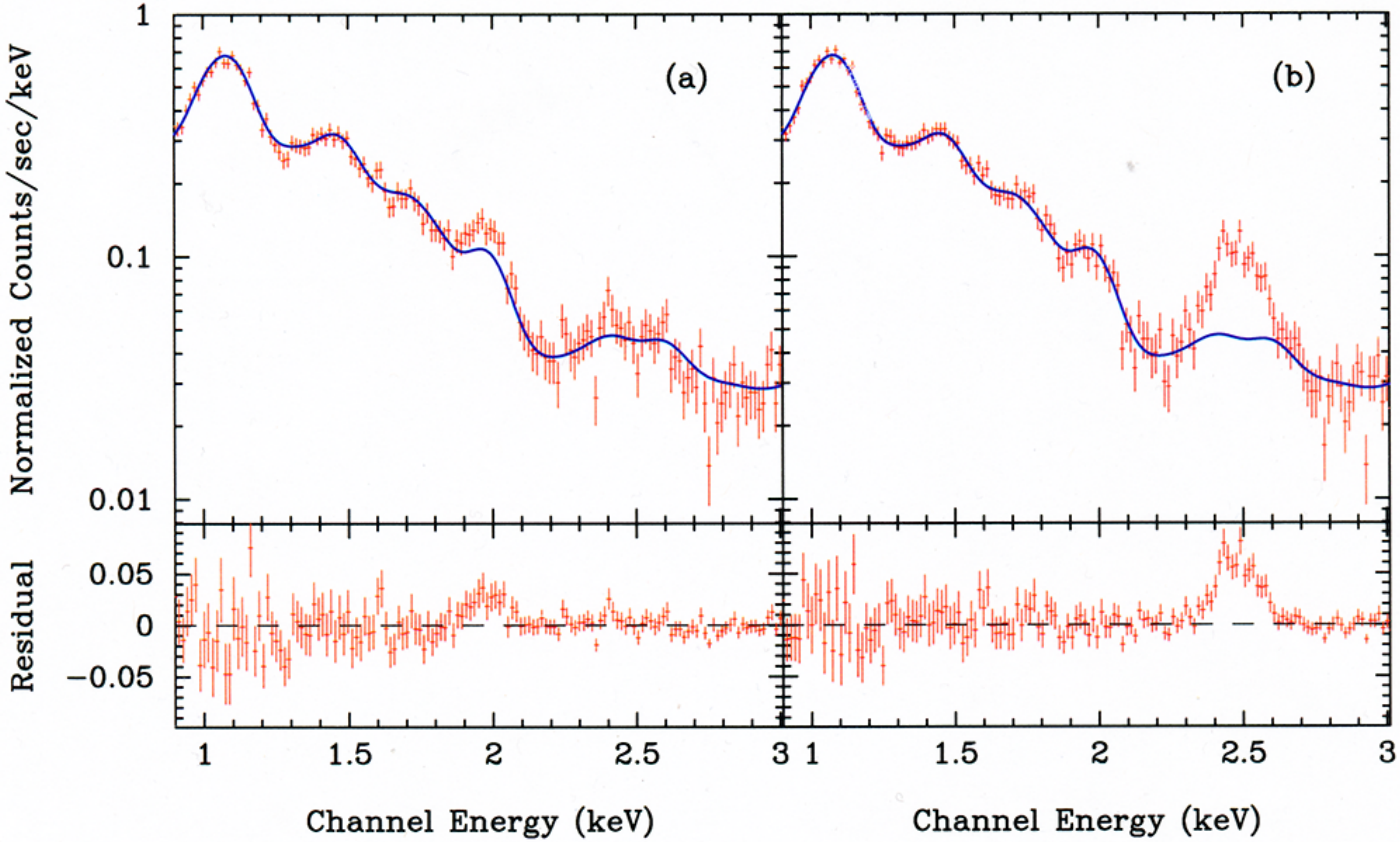


Virgo Cluster: 10^{78} DM particles

Slide from 2001: Virgo Cluster

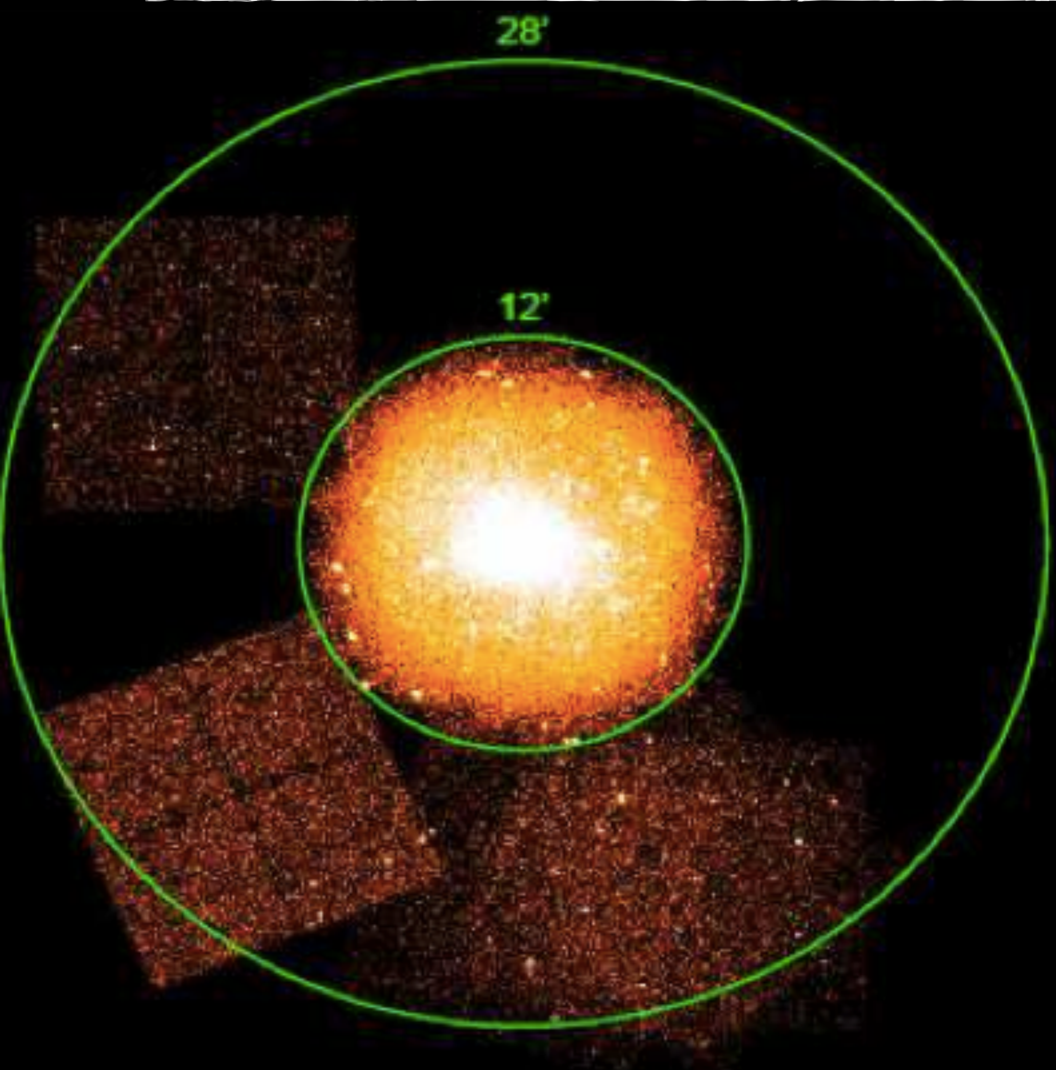


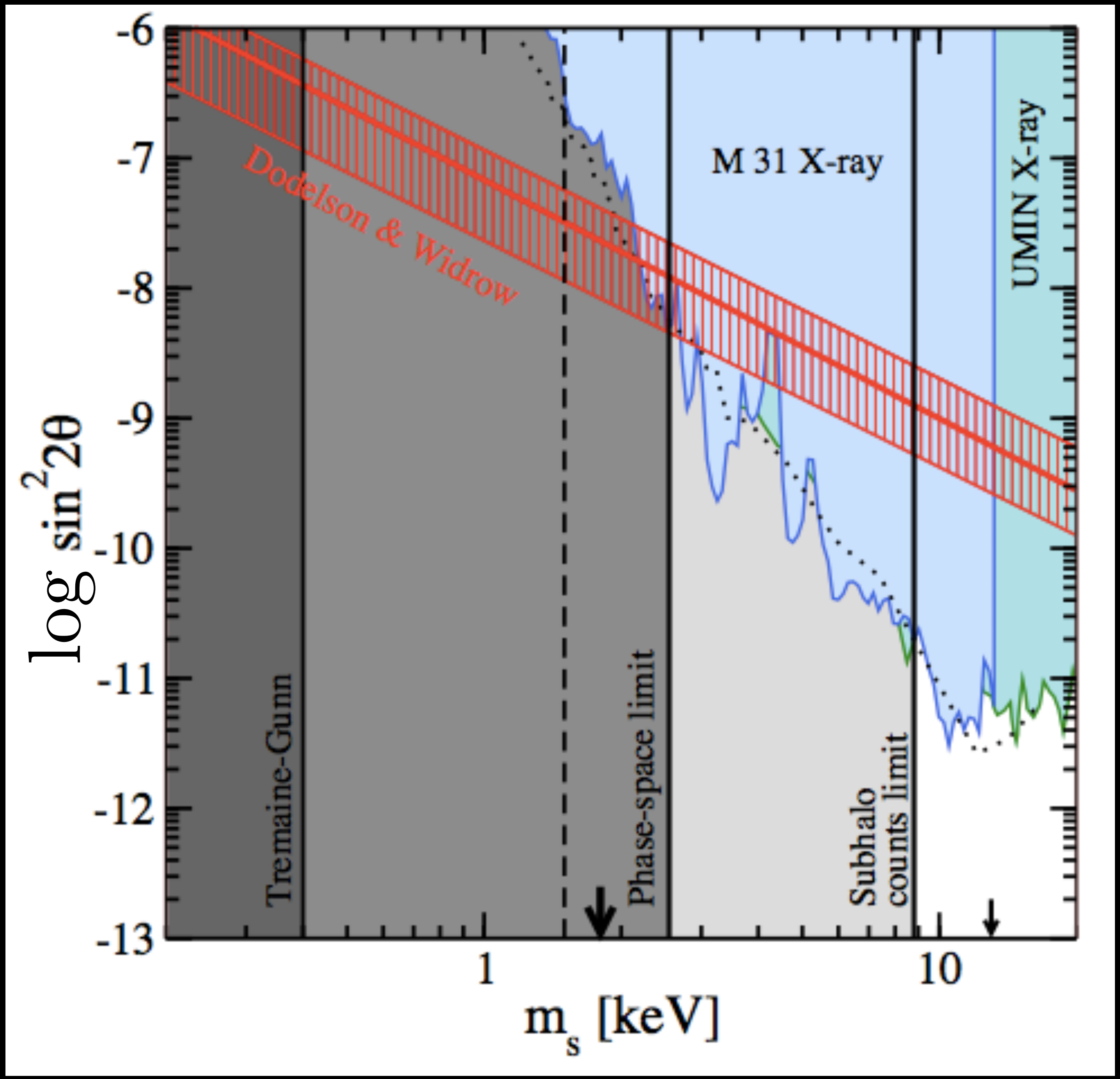
Current Limits

+

Future Detection?

Best constraints are from Horiuchi+ 2013



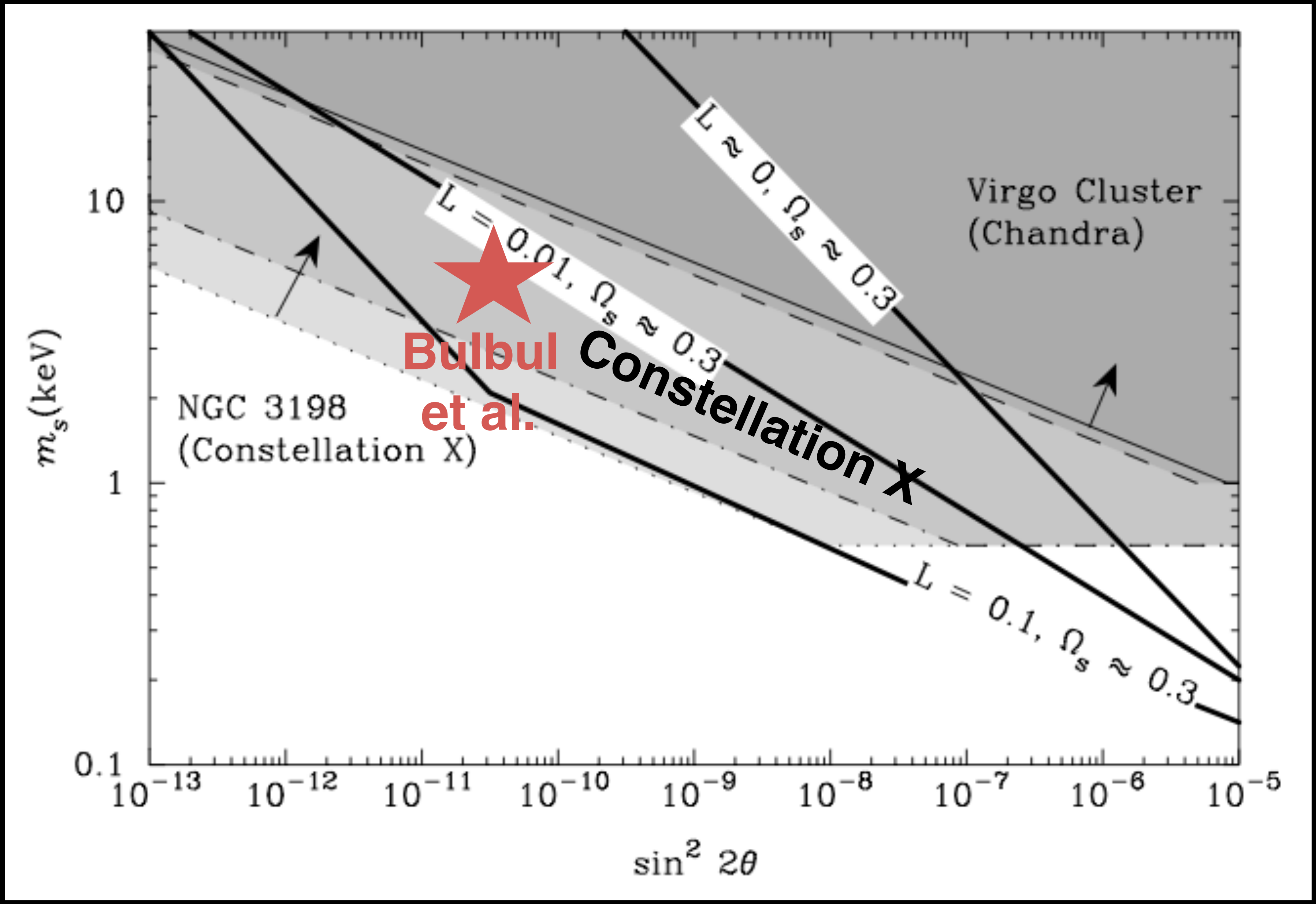


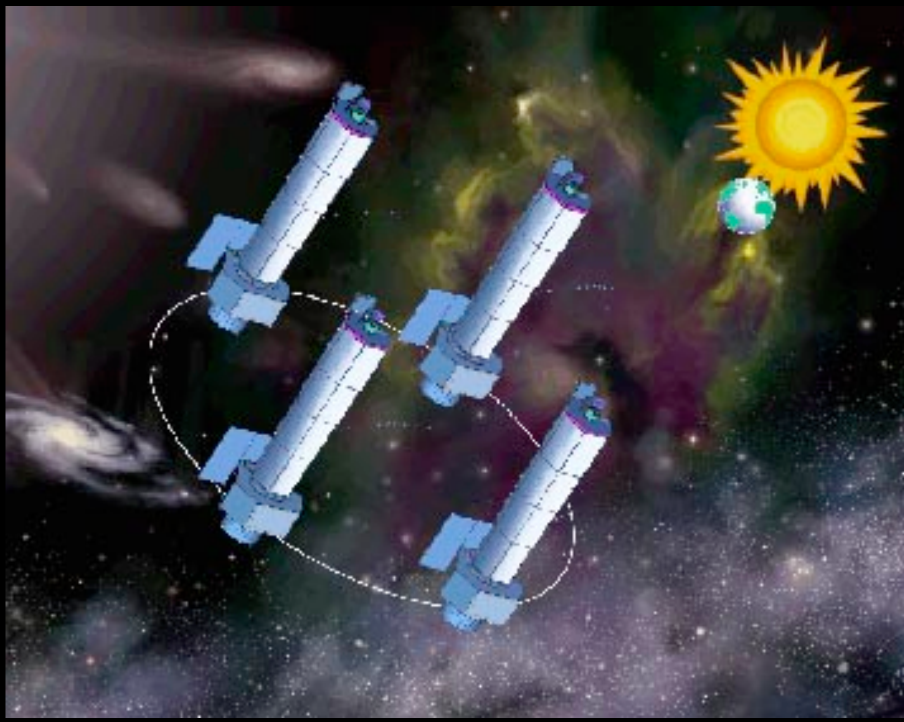
Combined subhalo and X-ray constraints: exclude standard DW dark matter ν_s

Horiuchi, Humphrey, Abazajian & Kaplinghat, PRD arXiv:1311.0282

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

Abazajian, Fuller & Tucker 2001





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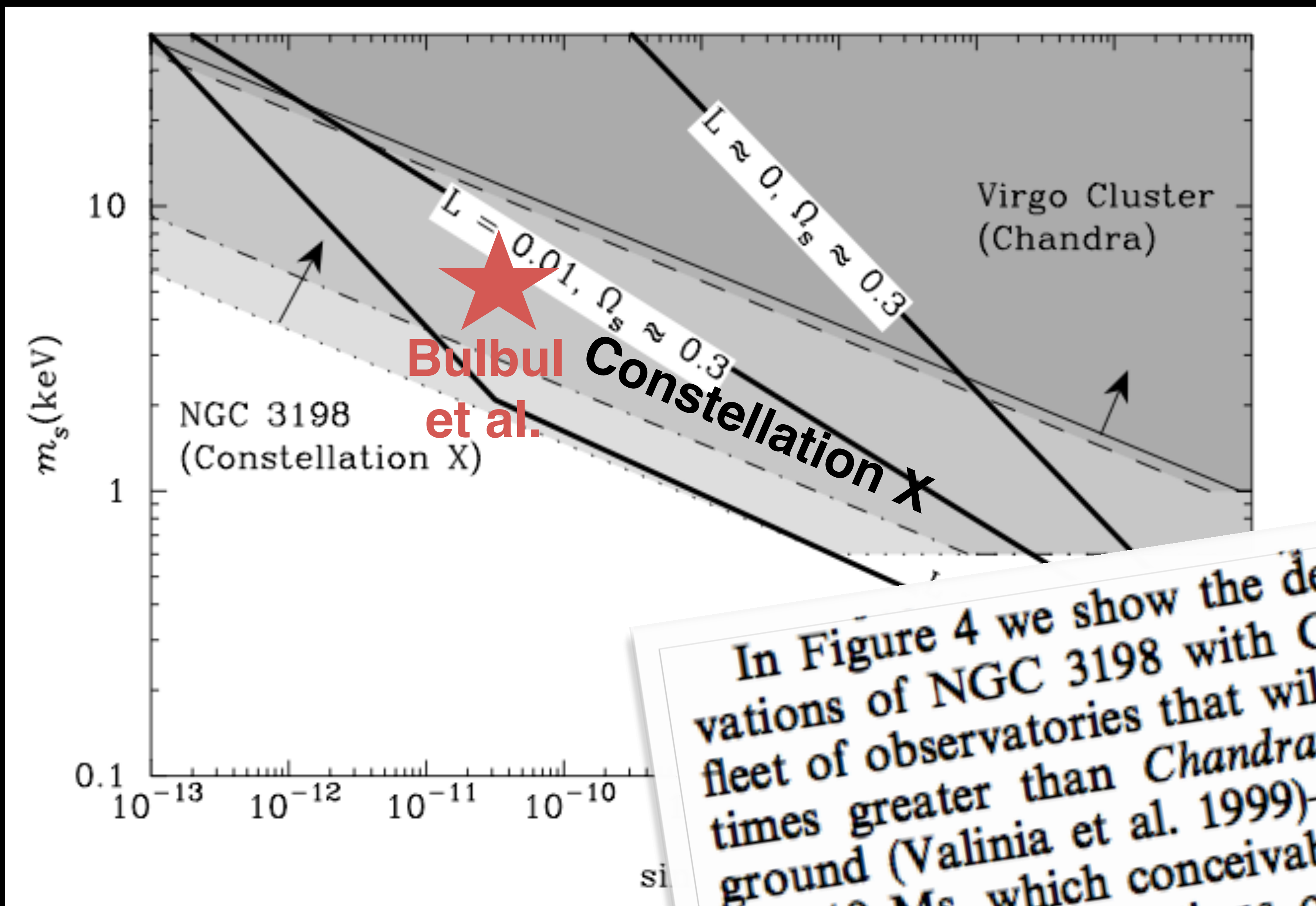
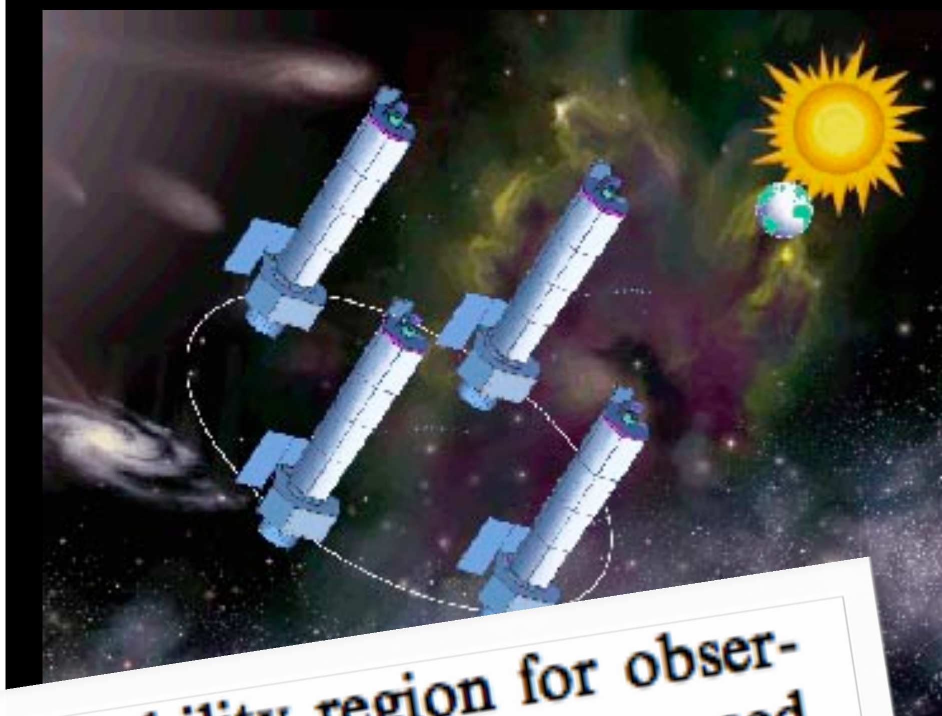
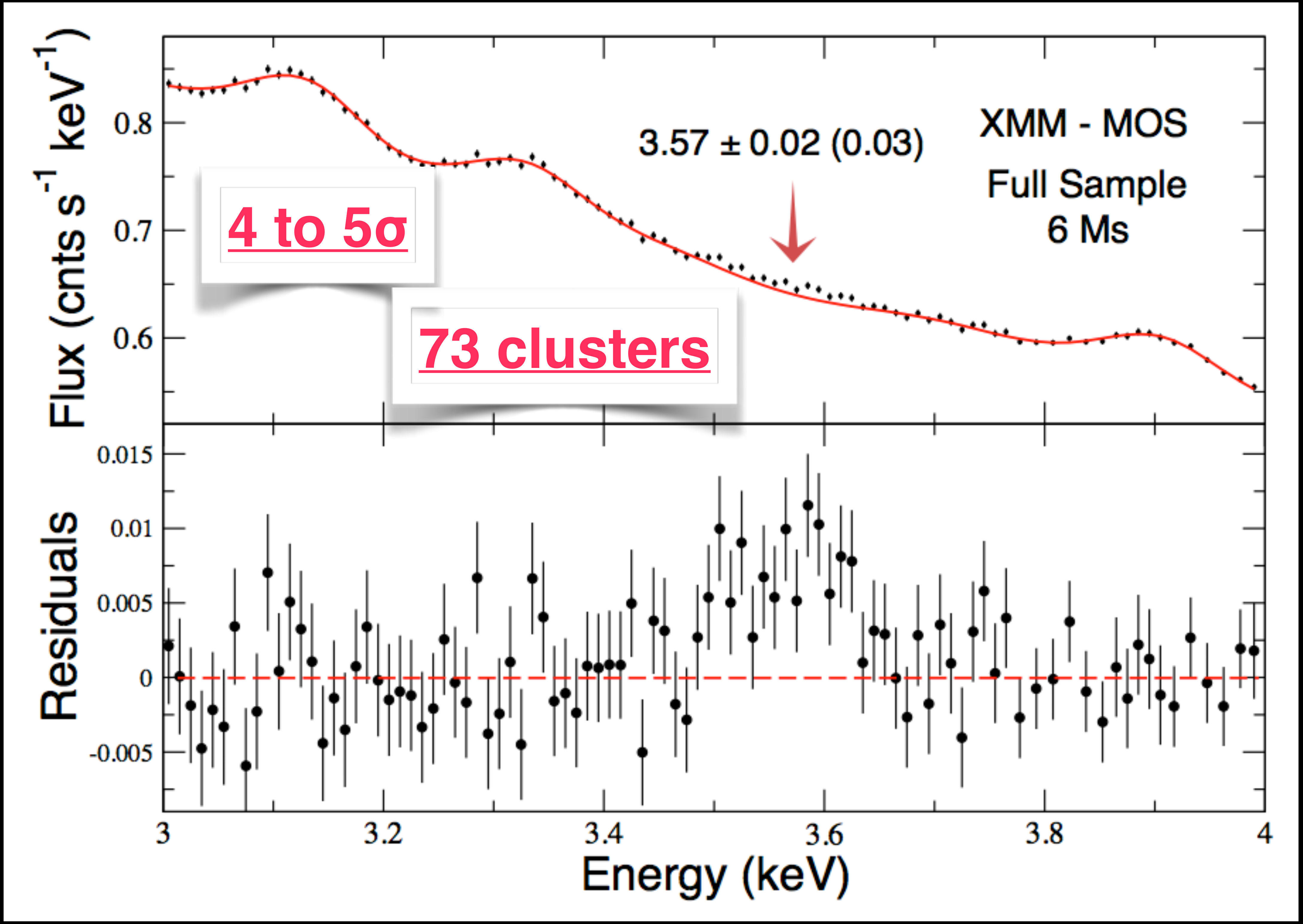




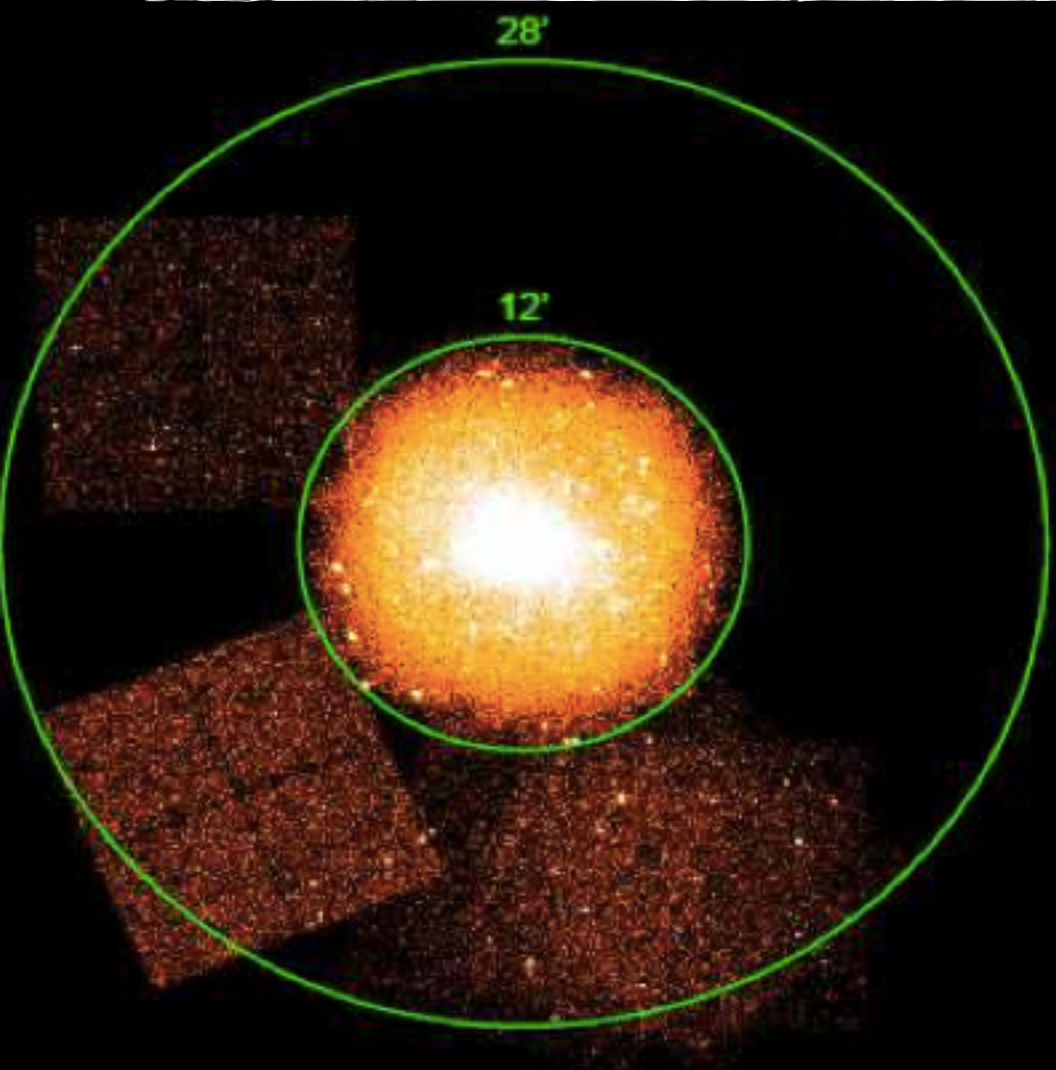
In Figure 4 we show the detectability region for observations of NGC 3198 with Constellation X—a proposed fleet of observatories that will have an effective area ~10 times greater than *Chandra* and no instrumental background (Valinia et al. 1999)—for two integration times, 1 and 10 Ms, which conceivably 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 arXiv:1402.2301

Chandra X-ray M31 plus substructure constraints



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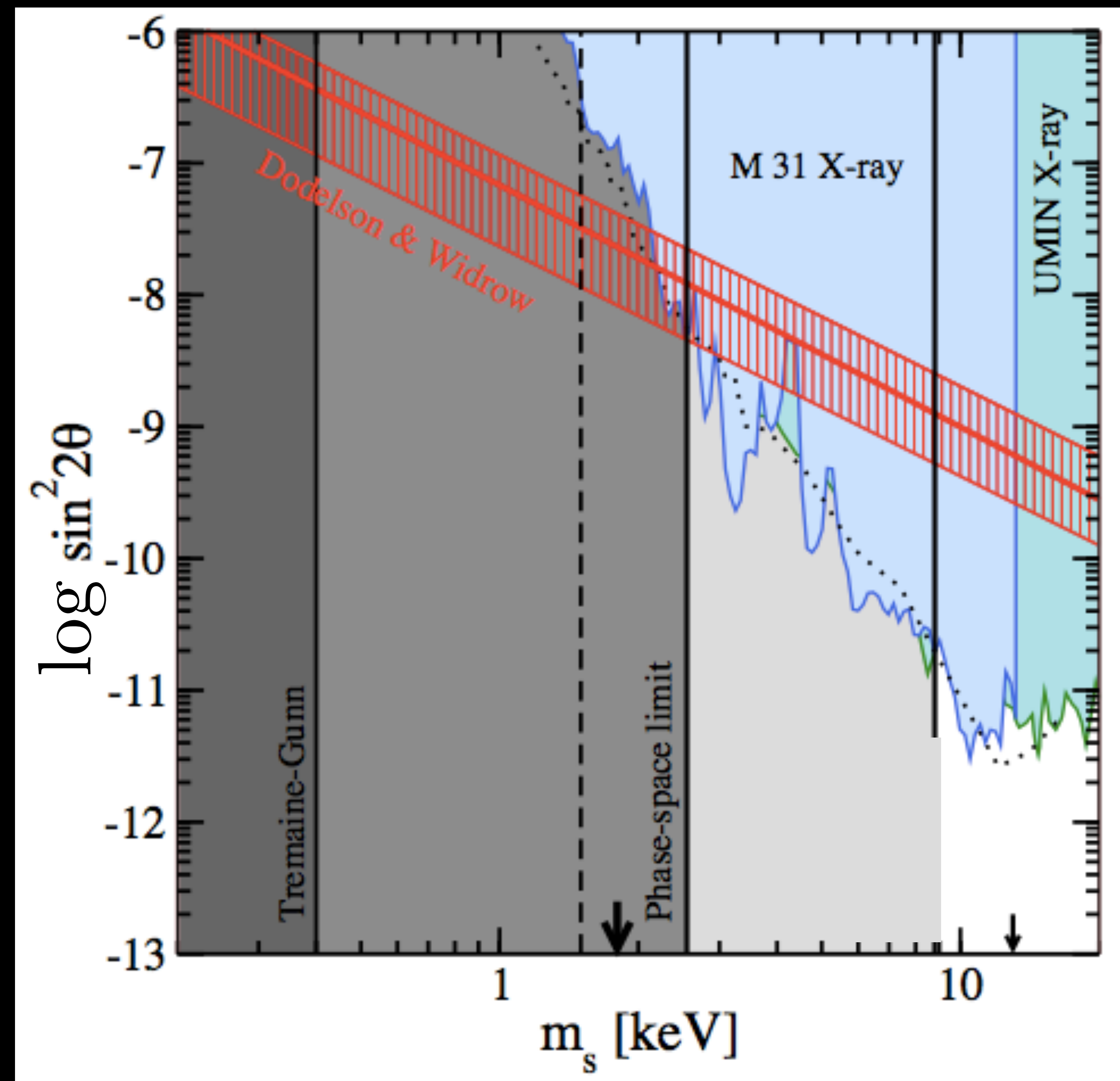

Horiuchi, Humphrey, Abazajian & Kaplinghat, PRD 2013

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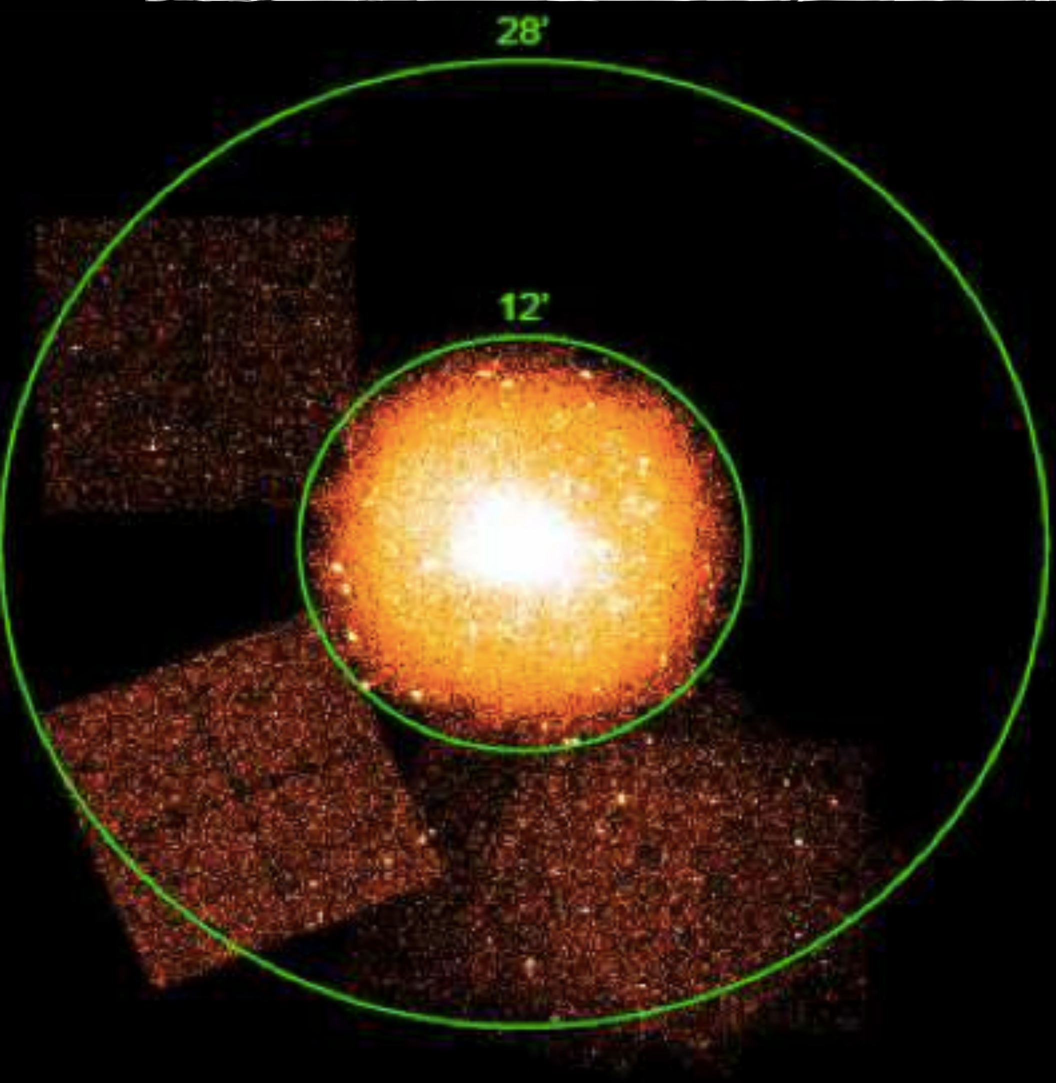

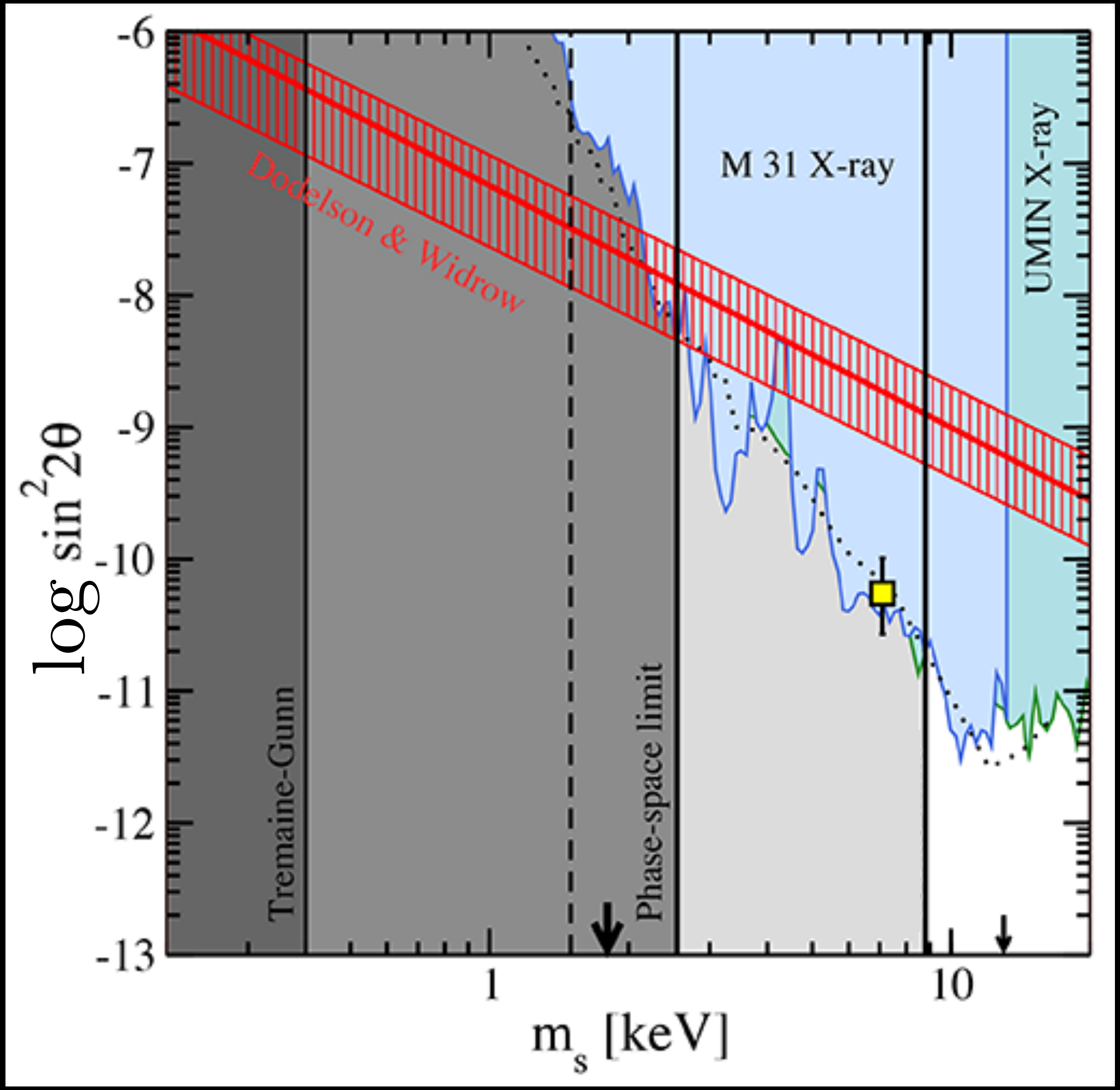

Combined subhalo and X-ray constraints: exclude standard ν_s

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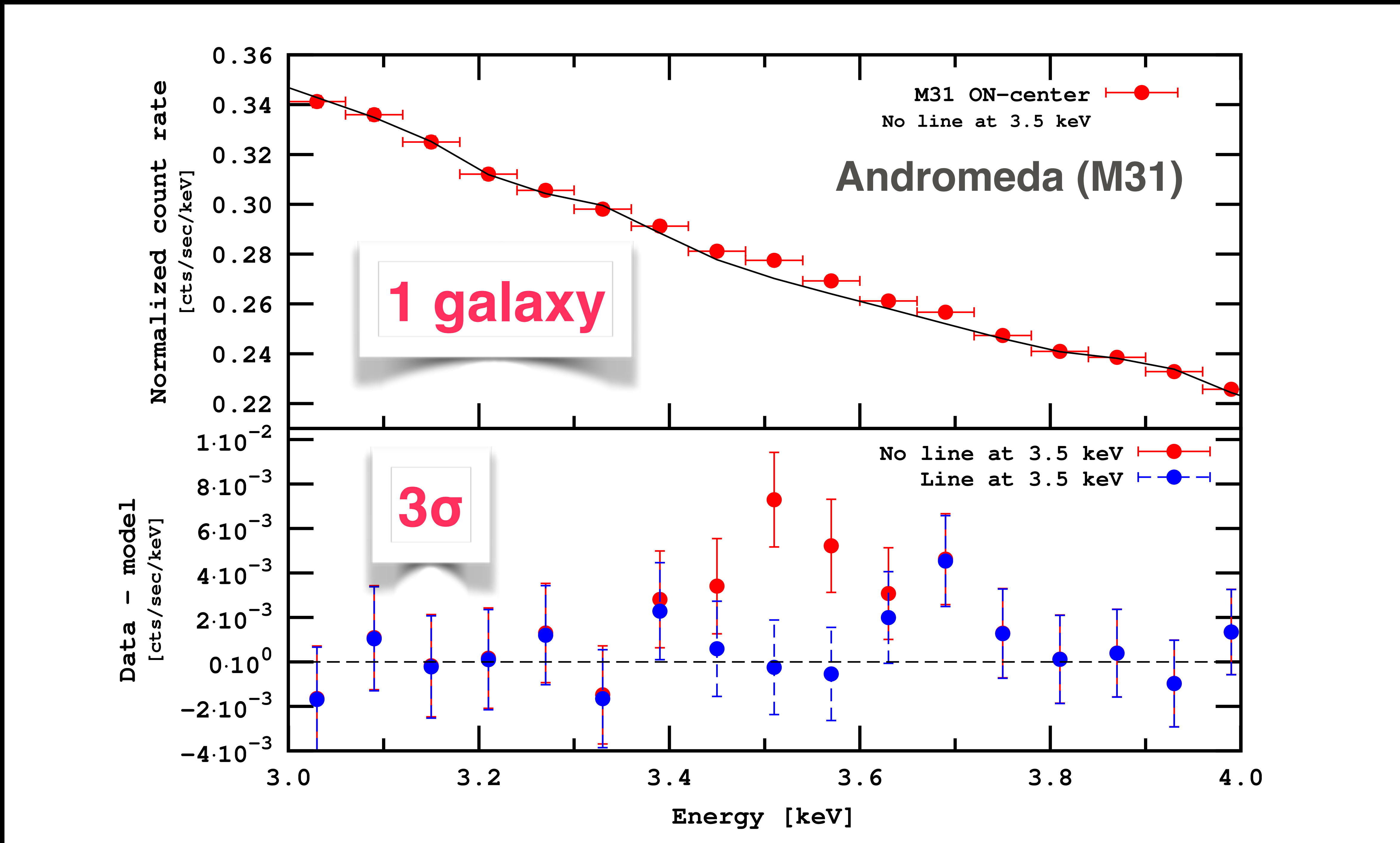
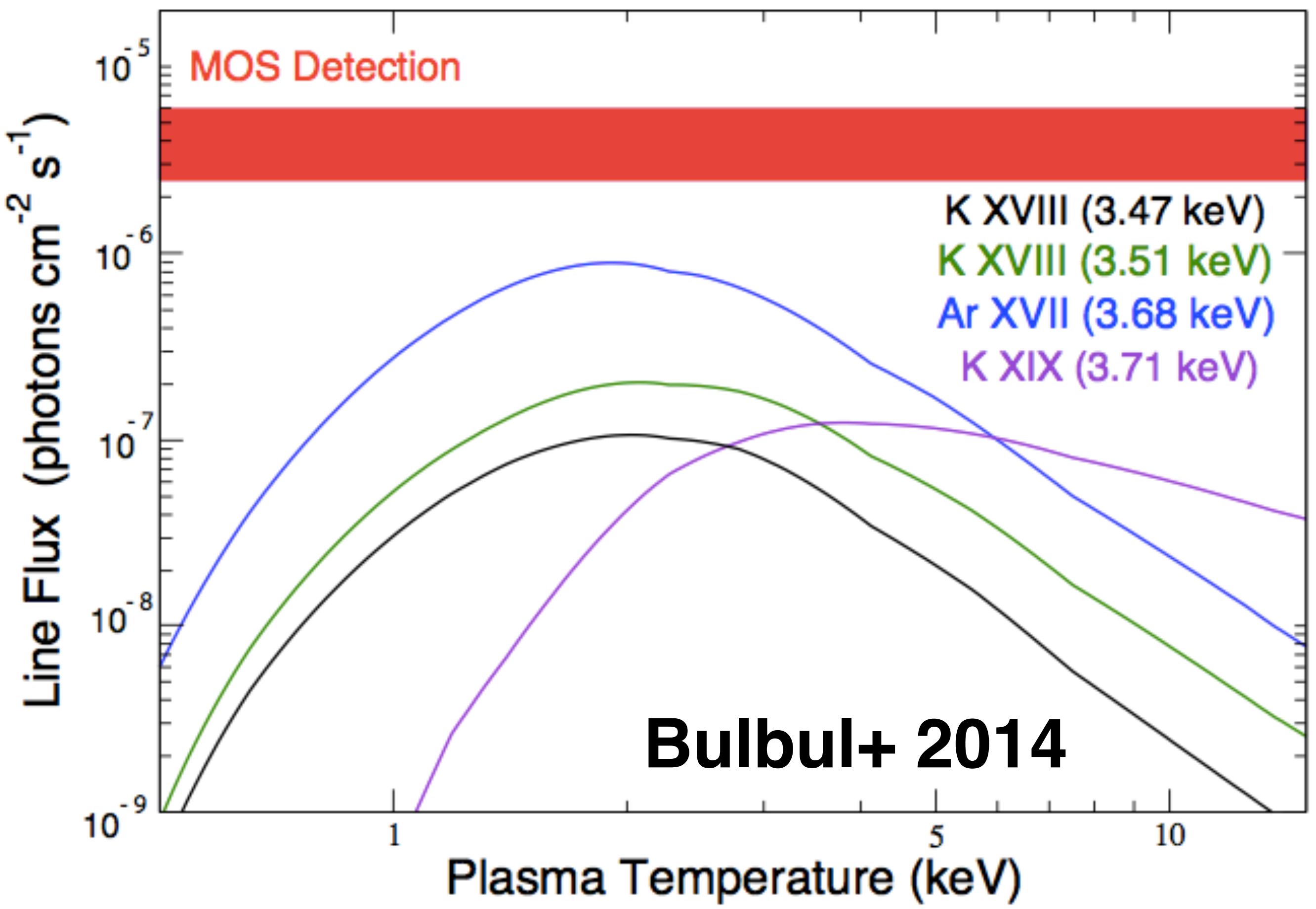
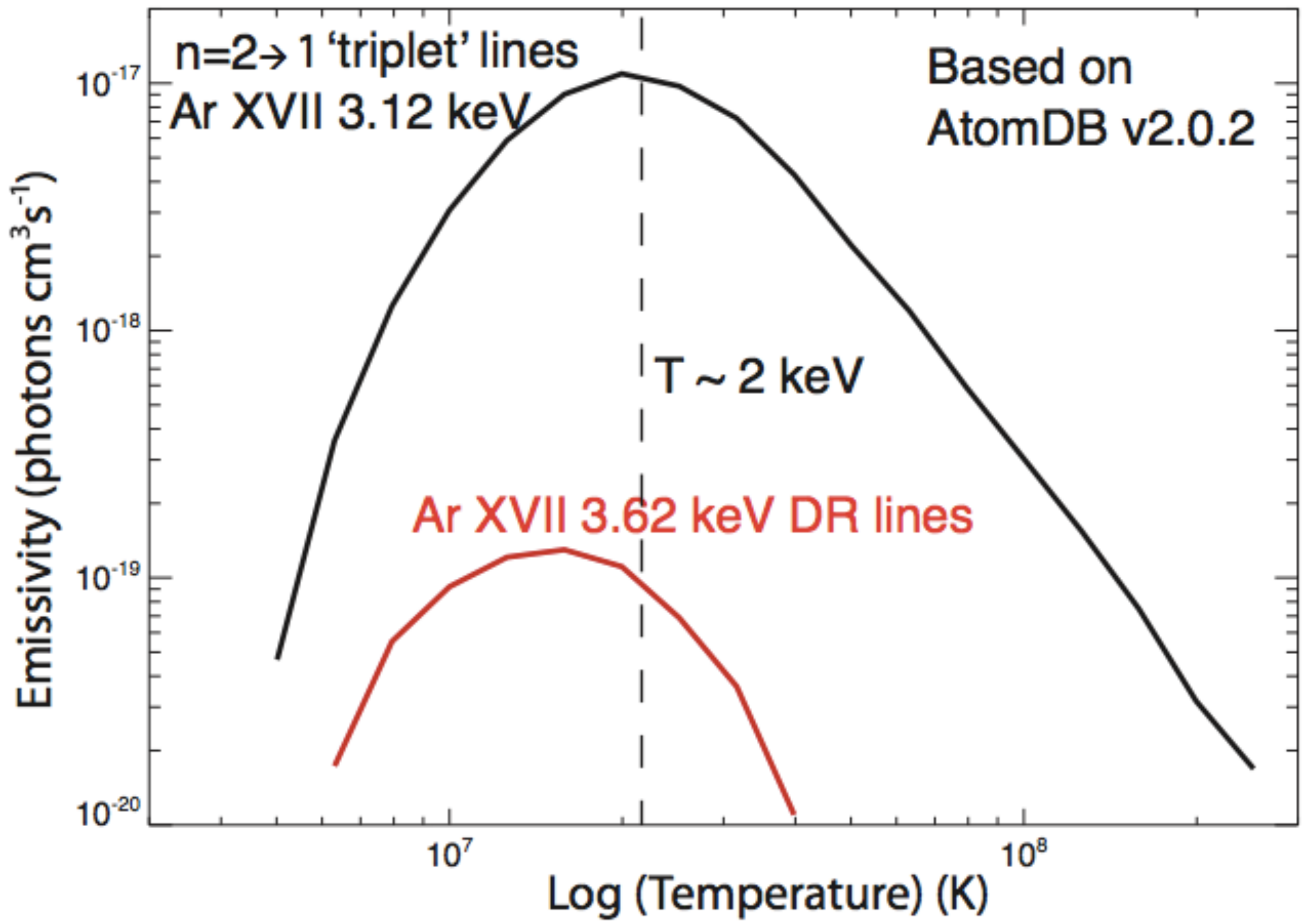
The Detection of an Unidentified Line II



Boyarsky et al. PRL arXiv:1402.4119

Metal Lines in Clusters at 3.5 keV? *unlikely*





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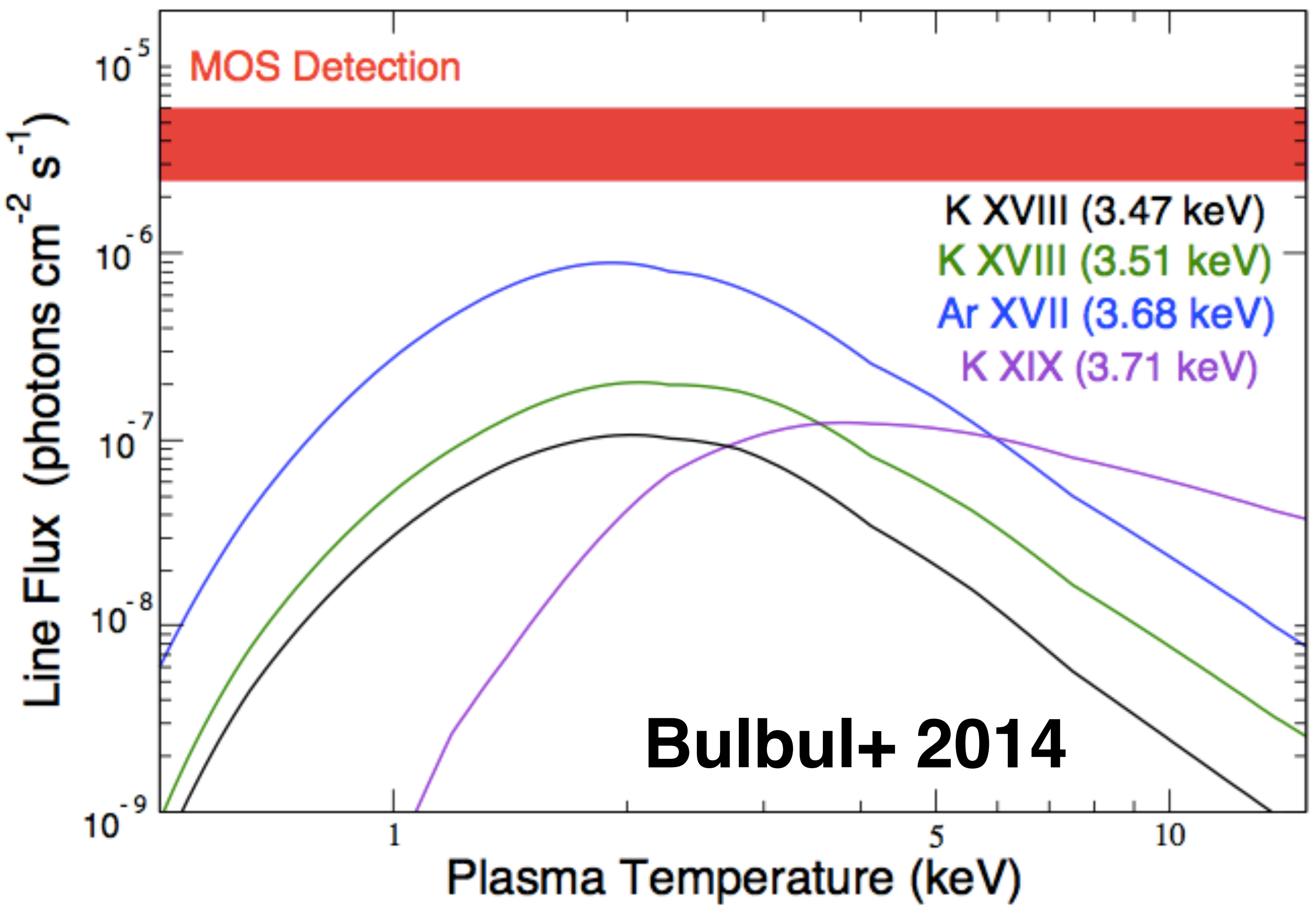

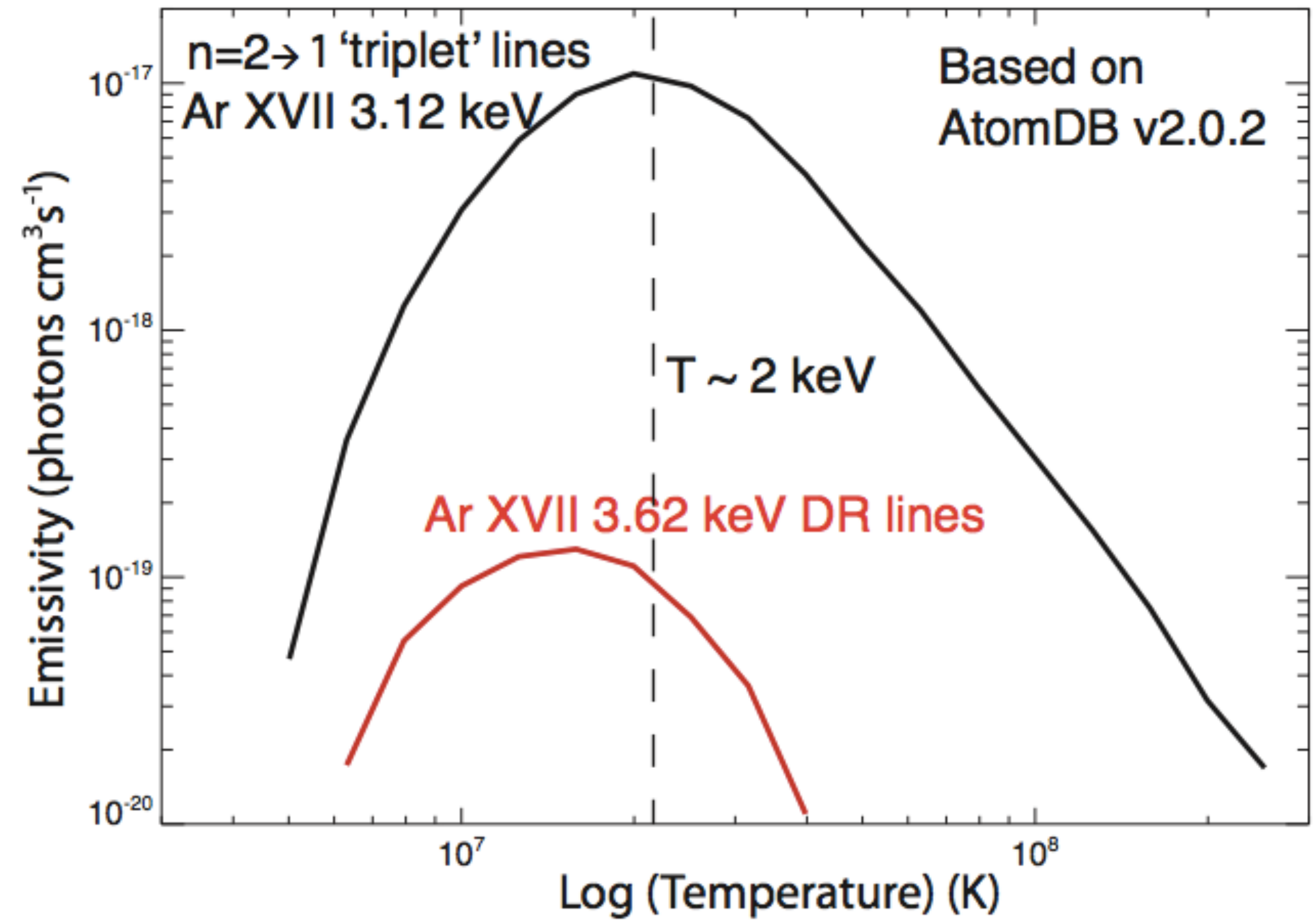

- Most lines at this energy are too low in flux for the typical plasma temperatures

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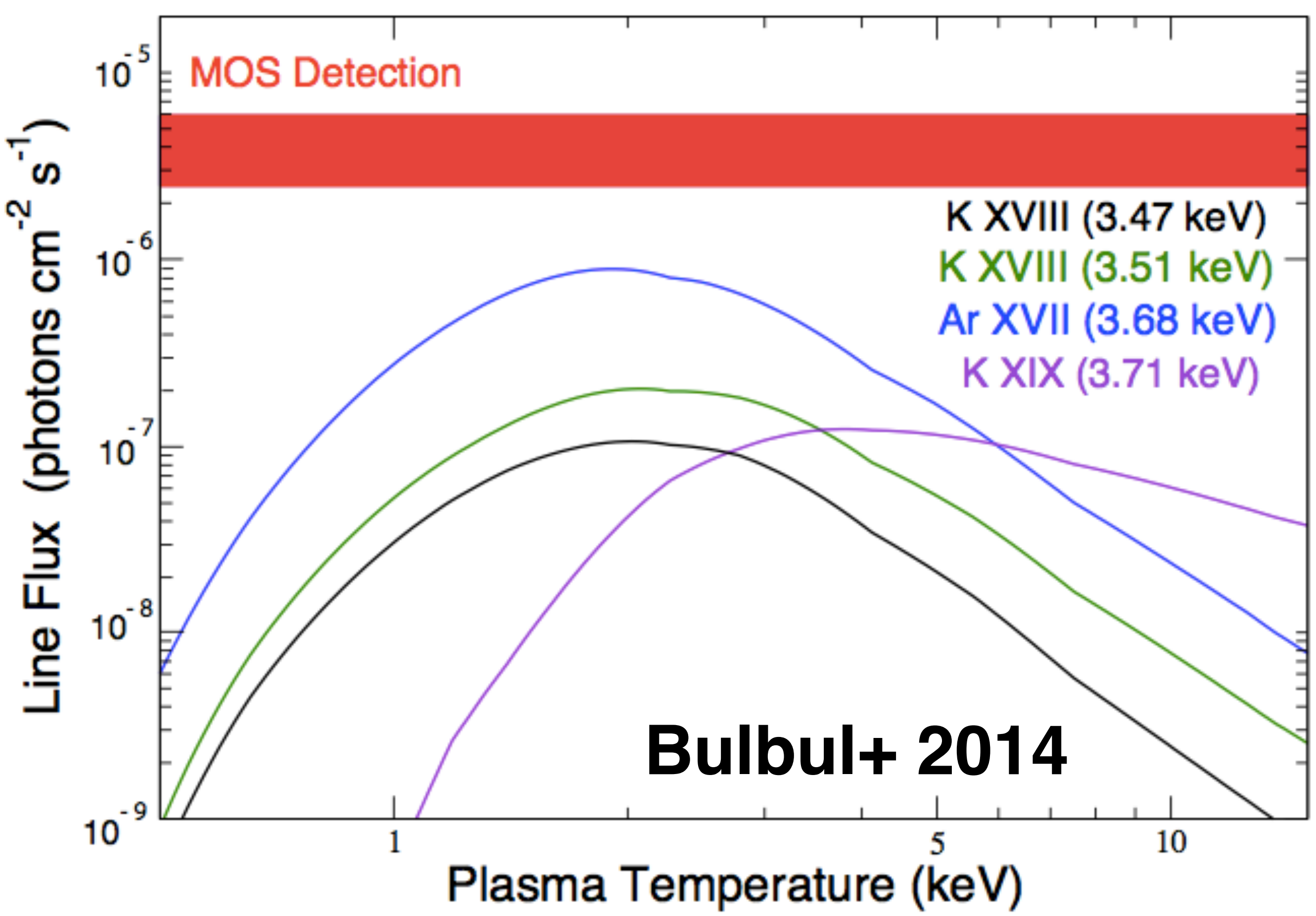

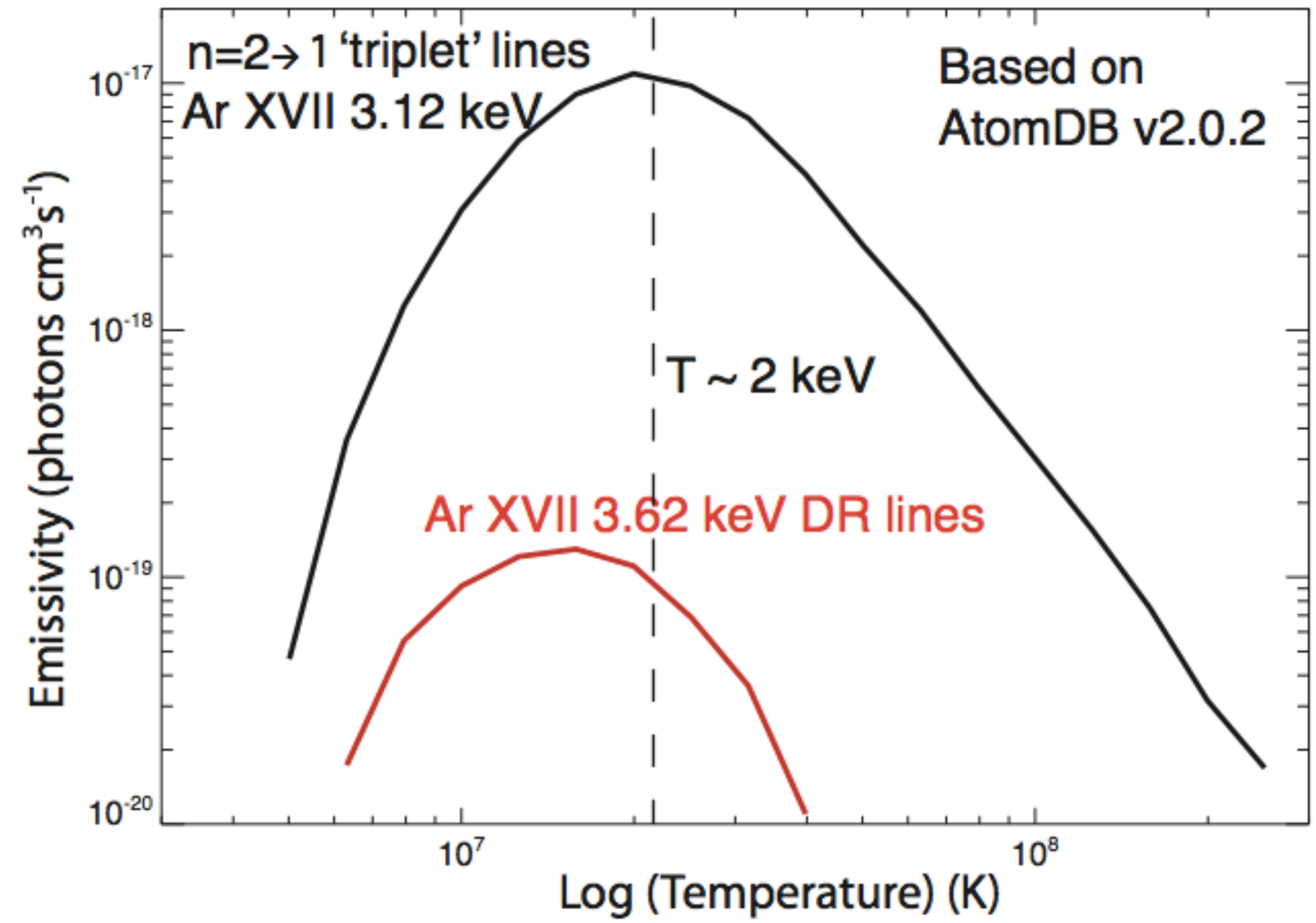

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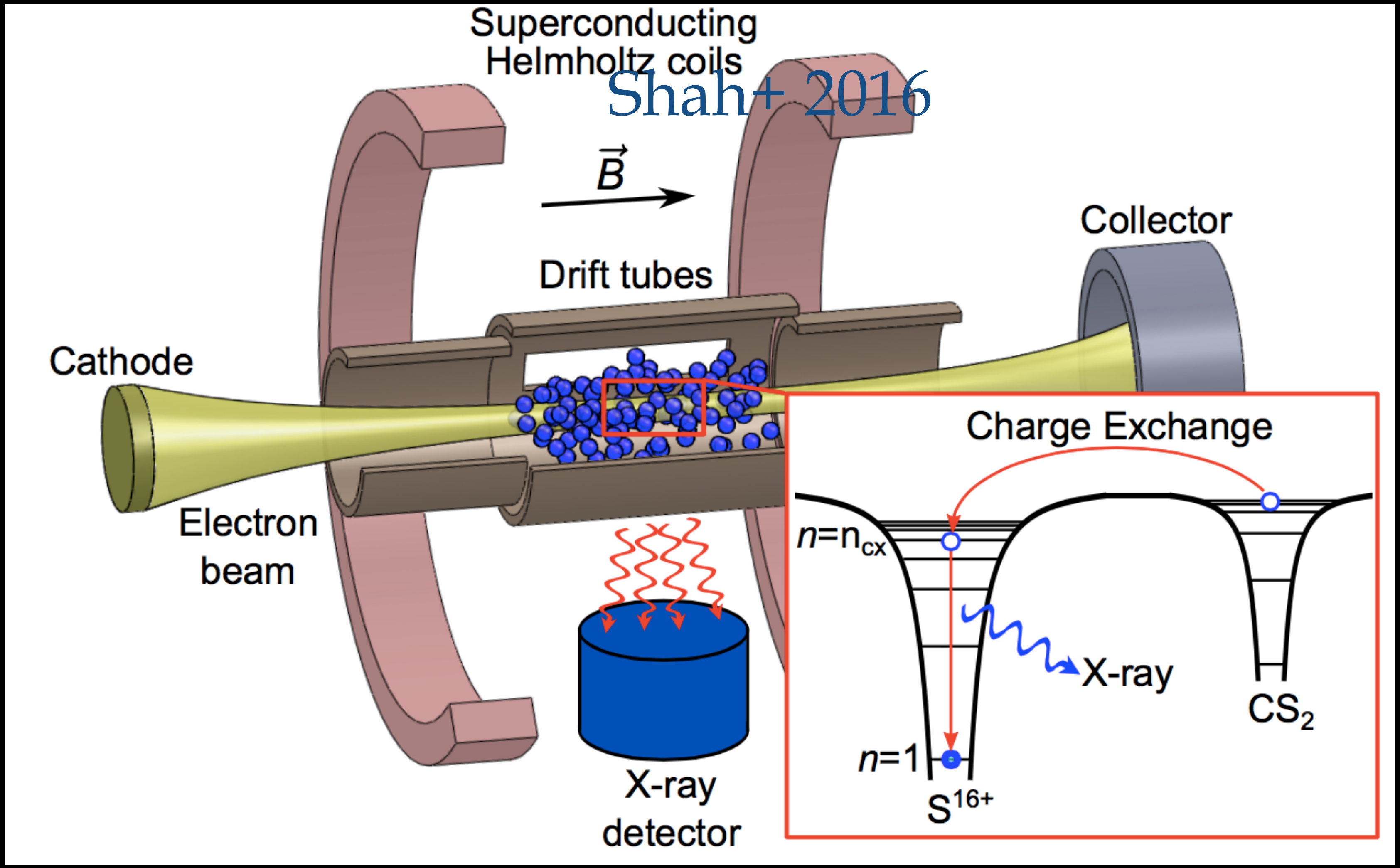
- Those that could be close, Ar XVII DR, would have accompanying lines that make its flux a factor of 30 too low

CX lines at ~3.5 keV?



Betancourt-Martinez+ 2014; Gu+ 2015; Shah+ arXiv:1608.04751

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
Loss of satellite March 26

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UK X-RAY ASTRO

RAS X-ray 2017 @UKXrayastro

Following

Richard Kelley: #Hitomi X-ray Astronomy Recovery Mission (#XARM) approved in Japan and USA! Launch ~03/2021. Remarkably quick turnround.

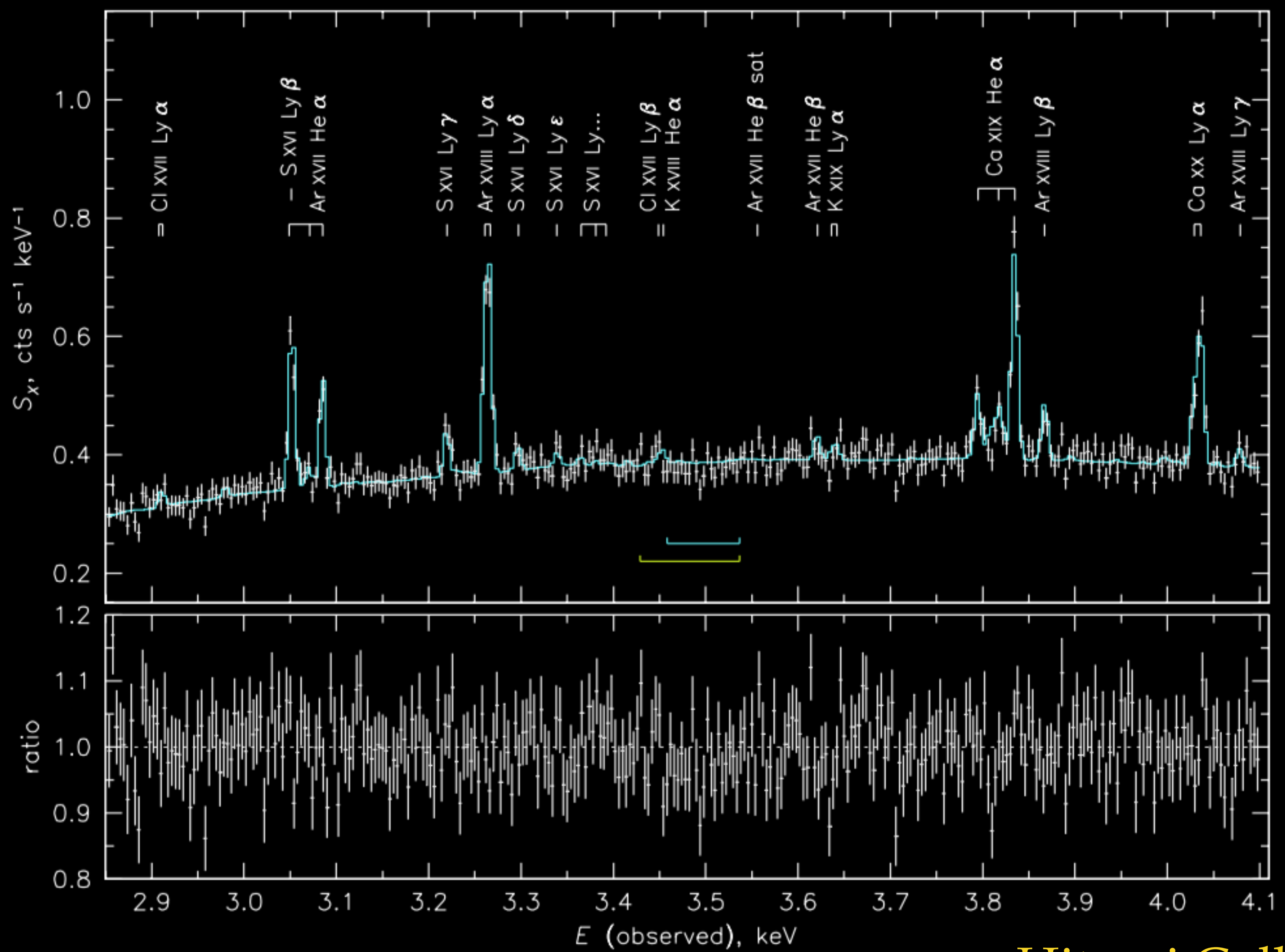
RETWEETS 7 LIKES 7

7:41 AM - 10 Feb 2017

1 7 7

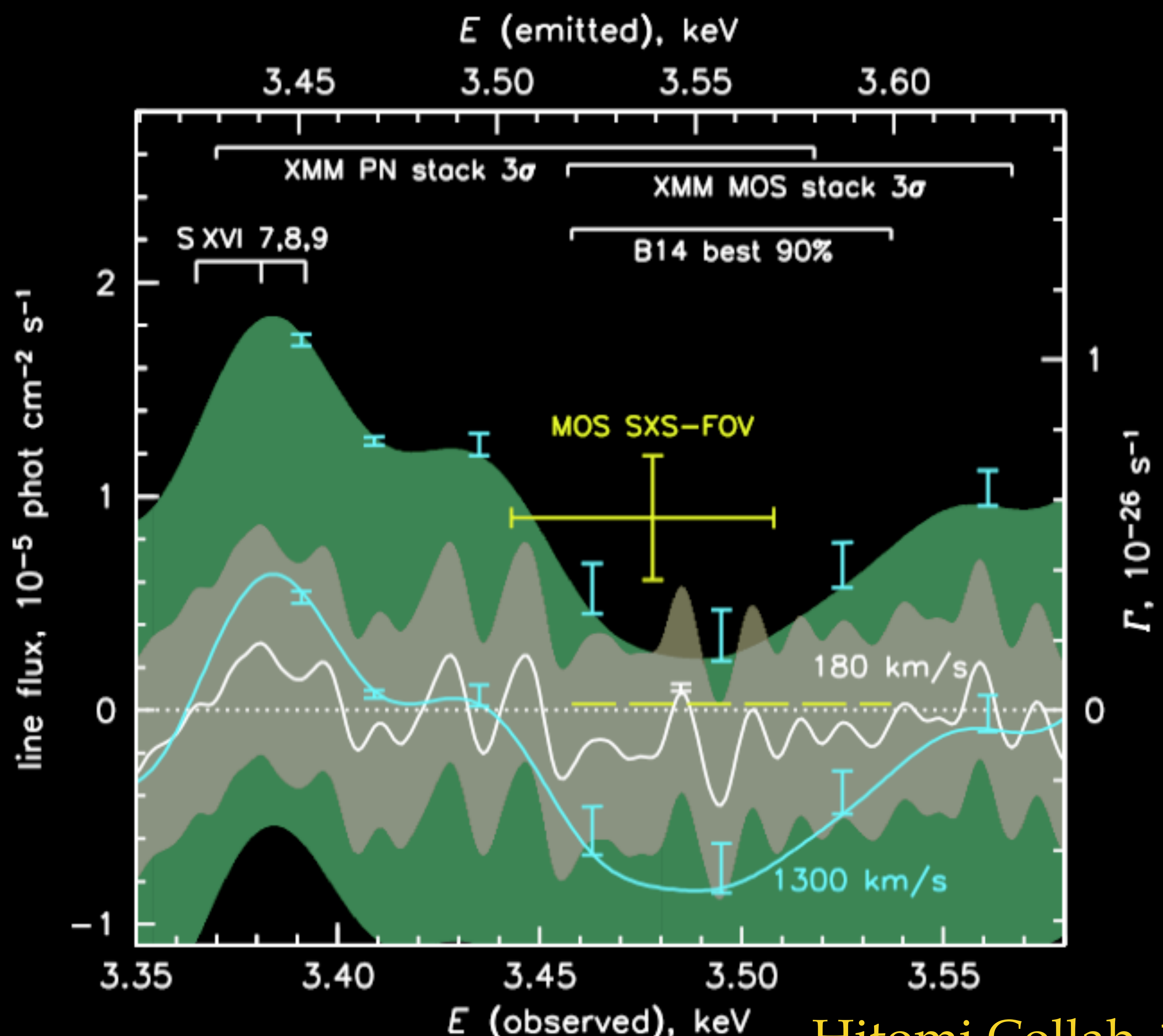
Hitomi X-ray Telescope: Few Days of Data

Unprecedented energy resolution: factor ~50 higher



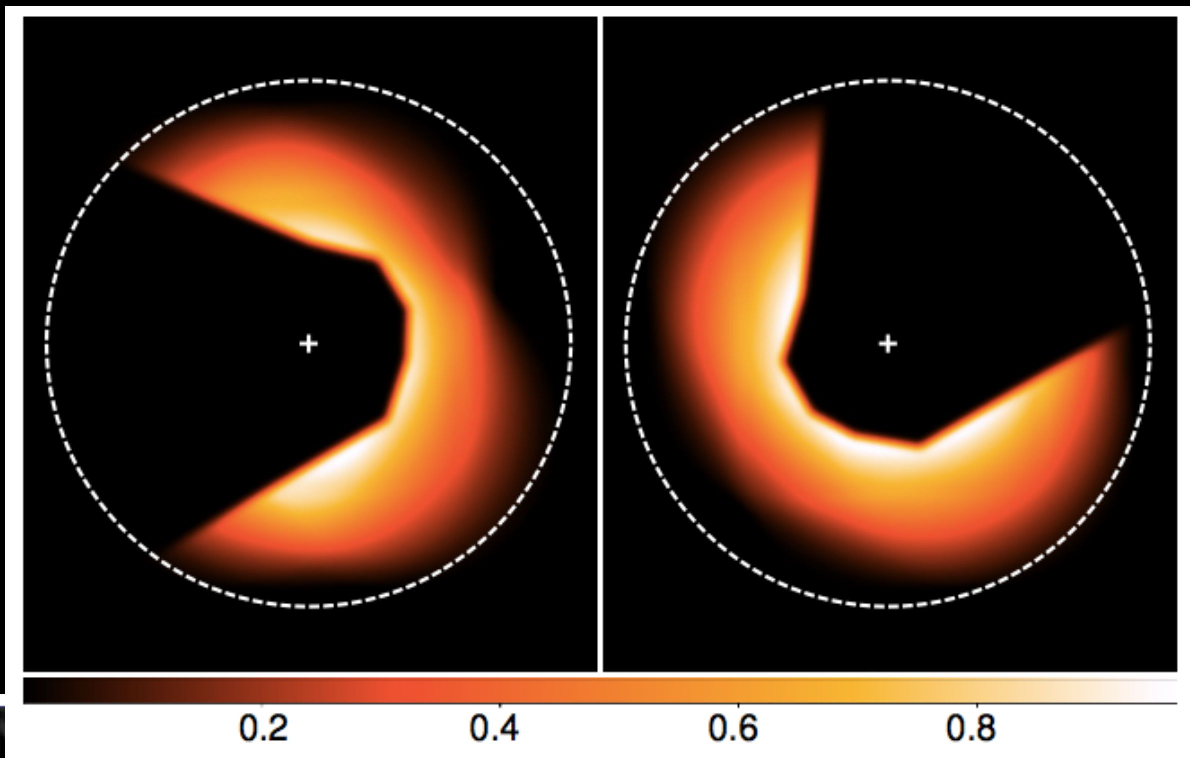
Hitomi Collab. 1607.07420

Hitomi X-ray Telescope: Expected line or not?



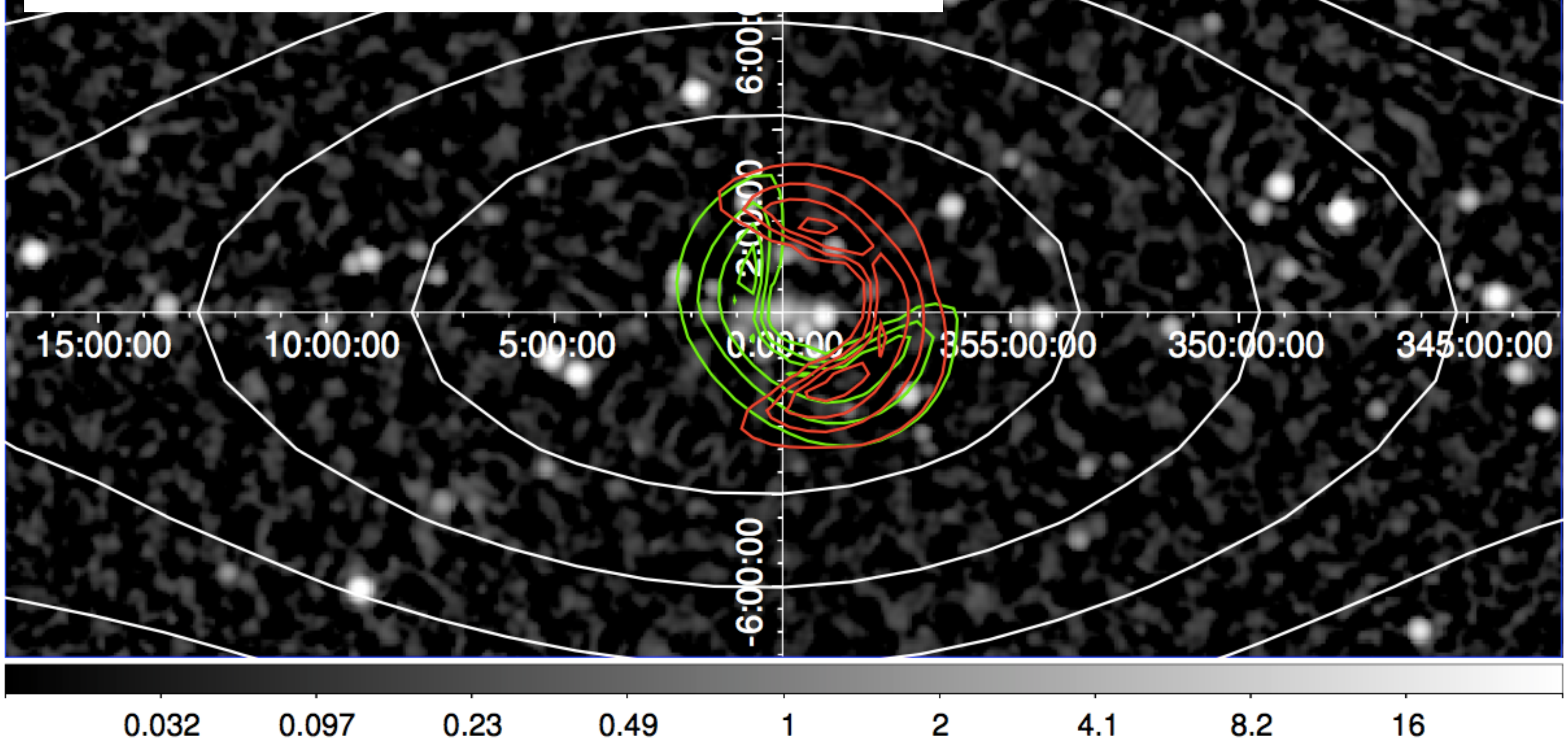
Hitomi Collab. 1607.07420

NuSTAR: **11σ** detection!!??

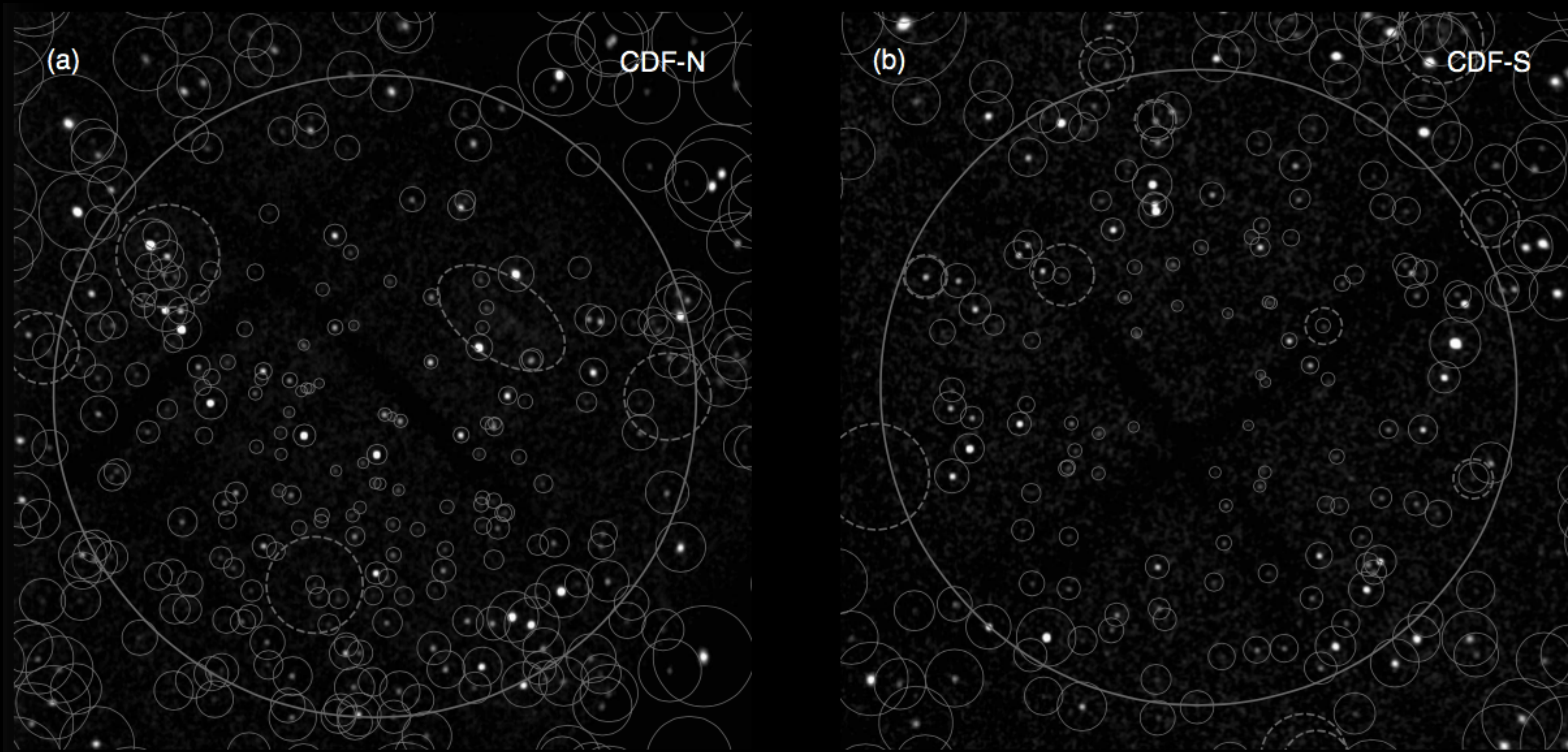


Shielding gap in telescope lets in 0 bounce photons. 37 deg^2 aperture!

Perez+: **limits** (1609.00667)
Neronov+: **Deep field sees 11.1σ 3.5 keV line consistent with DM decay** (1607.07328)

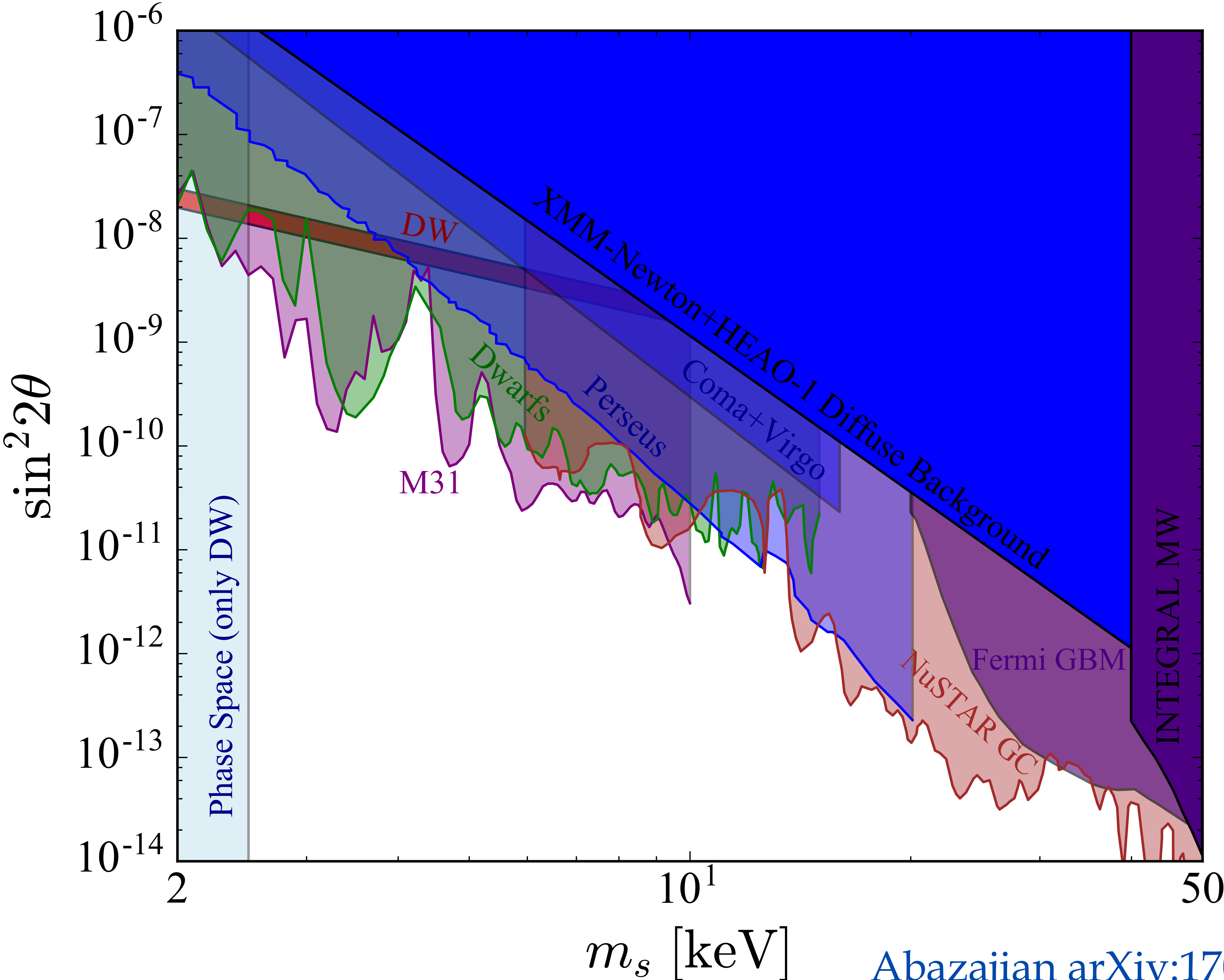


Chandra Deep Fields: 10 Ms of data



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 arXiv:1705.01837

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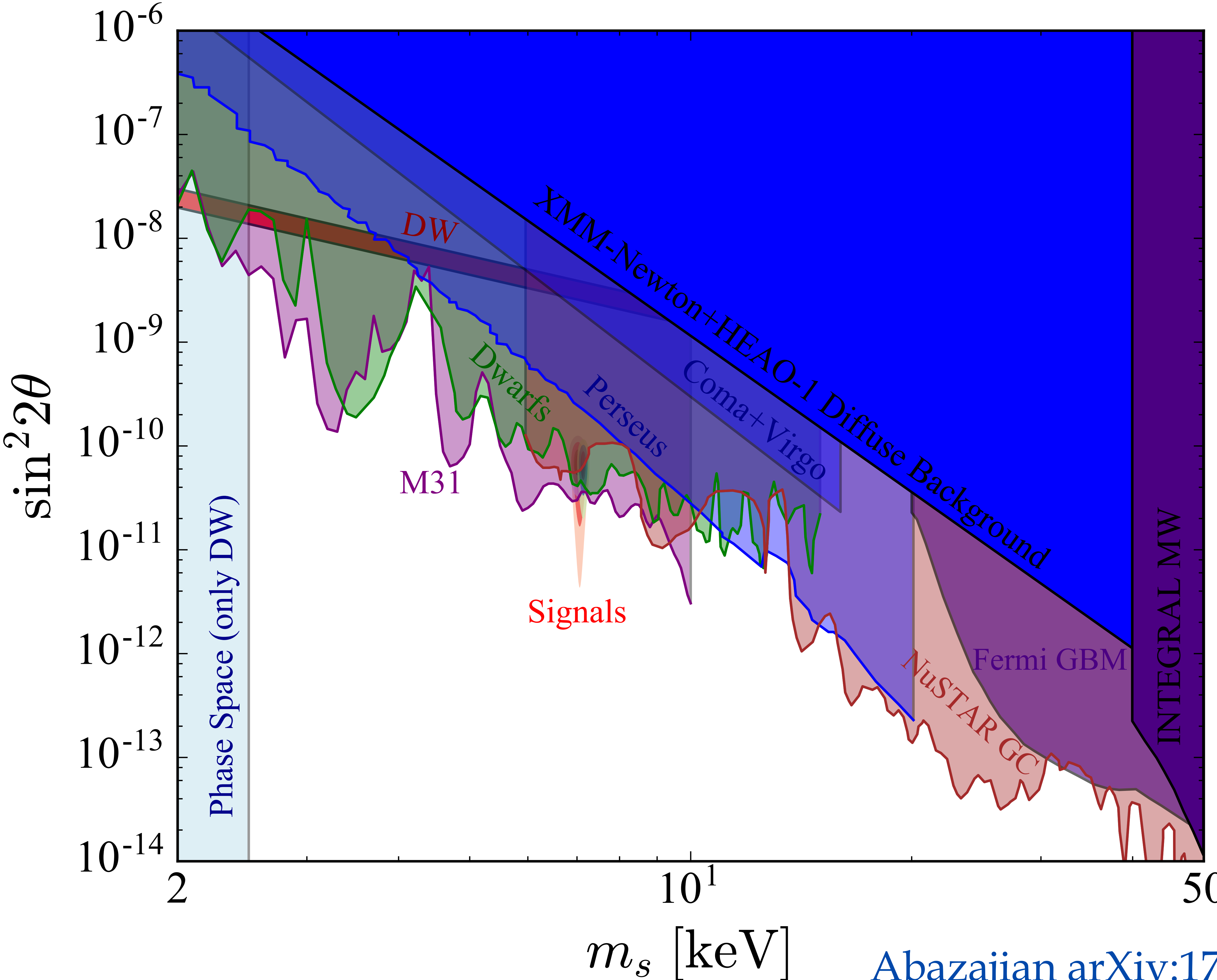

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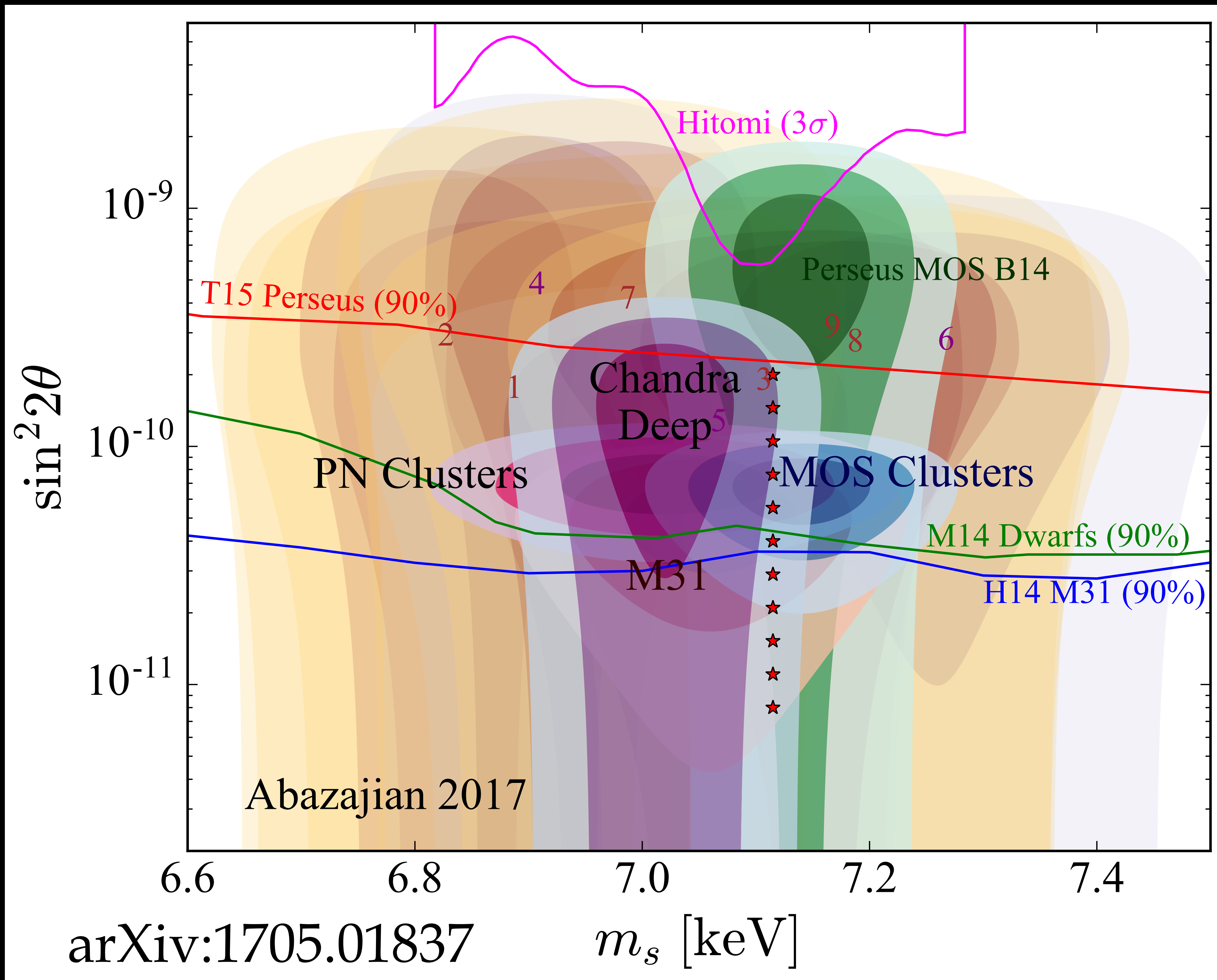
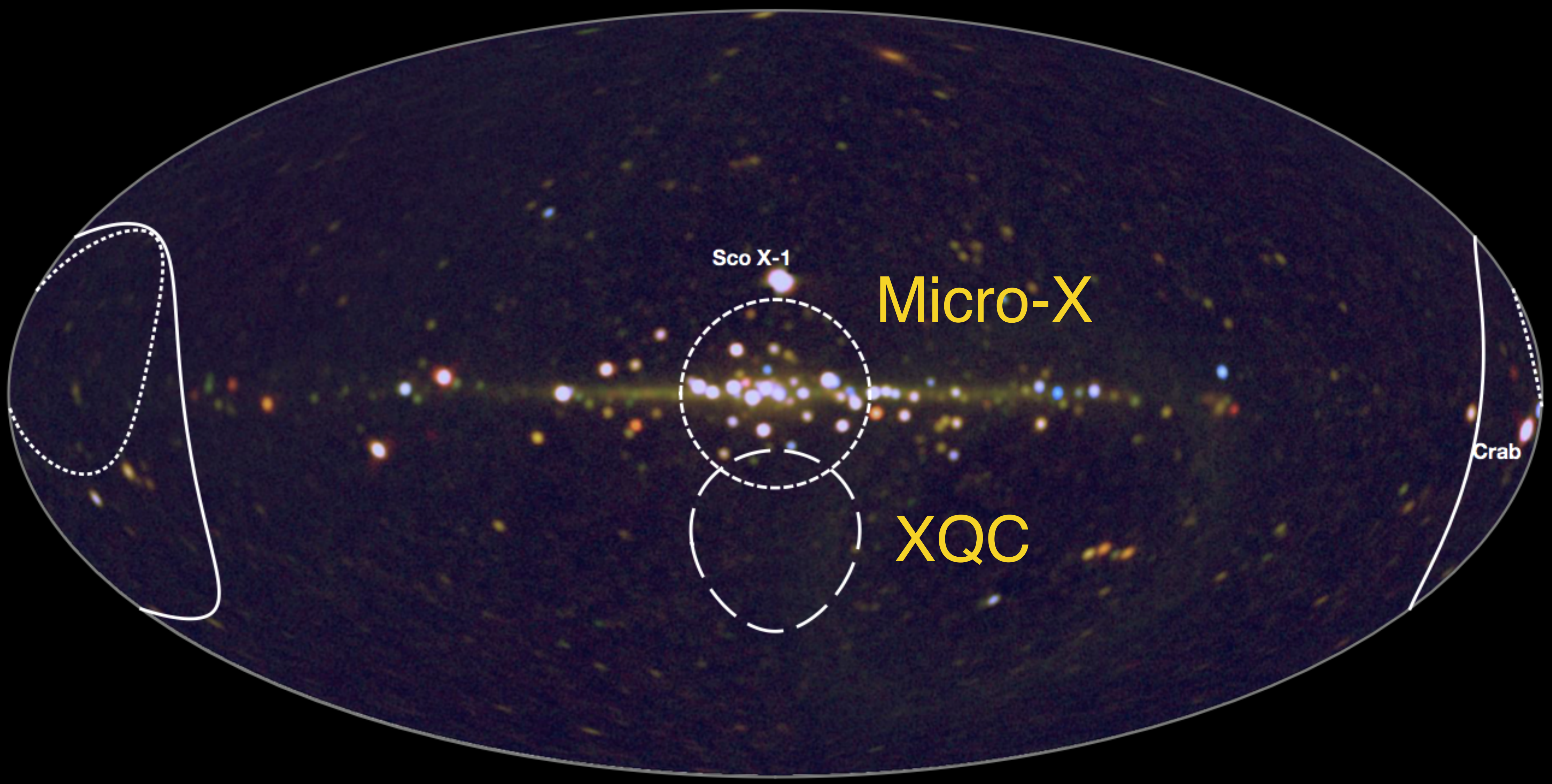
The 7 keV Region Today



Cluster search: Iakubovskyi+ 1508.05186

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



Figueroa-Feliciano+ 1506.05519

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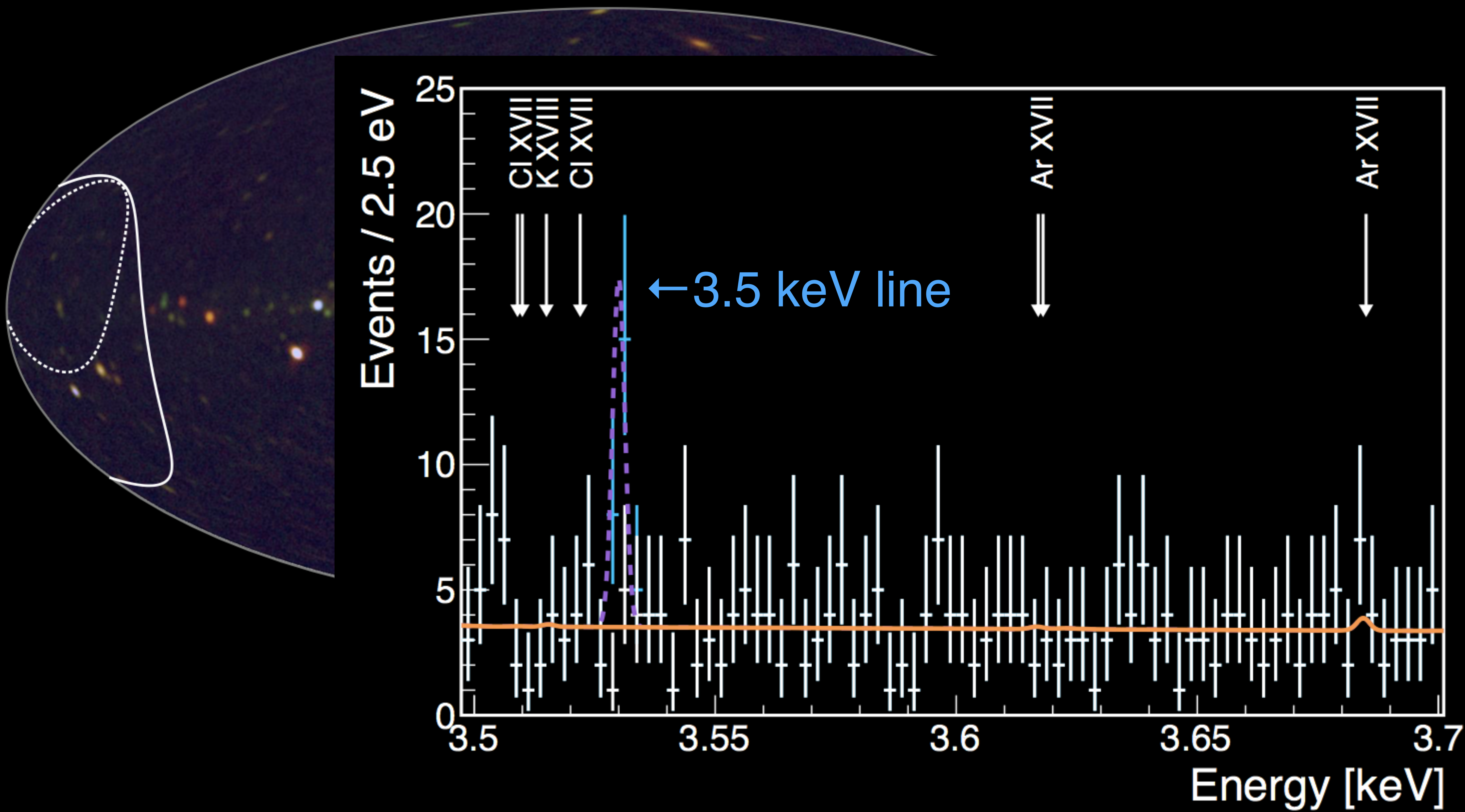
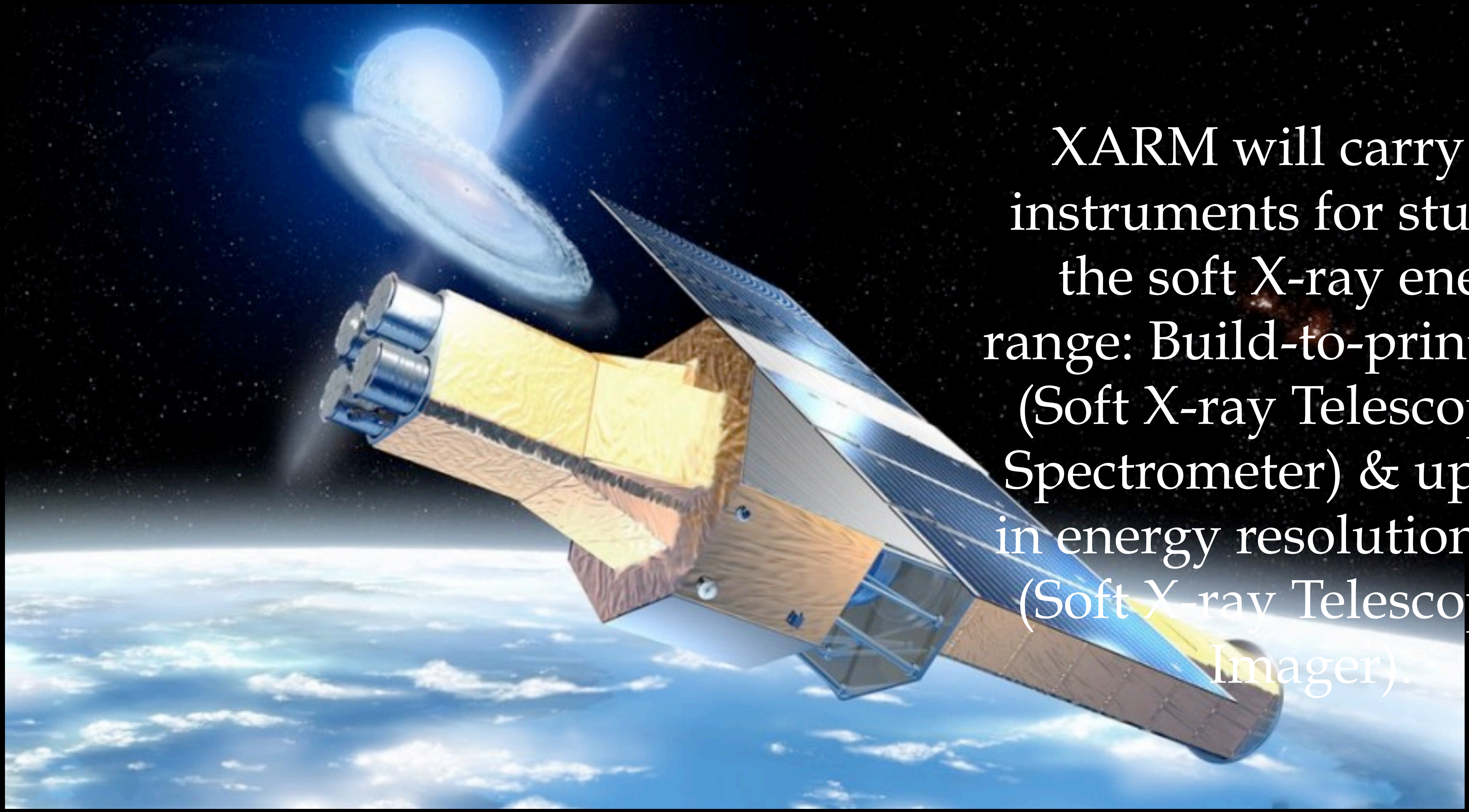


Figueroa-Feliciano+ 1506.05519

Next Space Mission in X-ray Astronomy

X-ray Astronomy Recovery Mission (XARM) ~2021



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).

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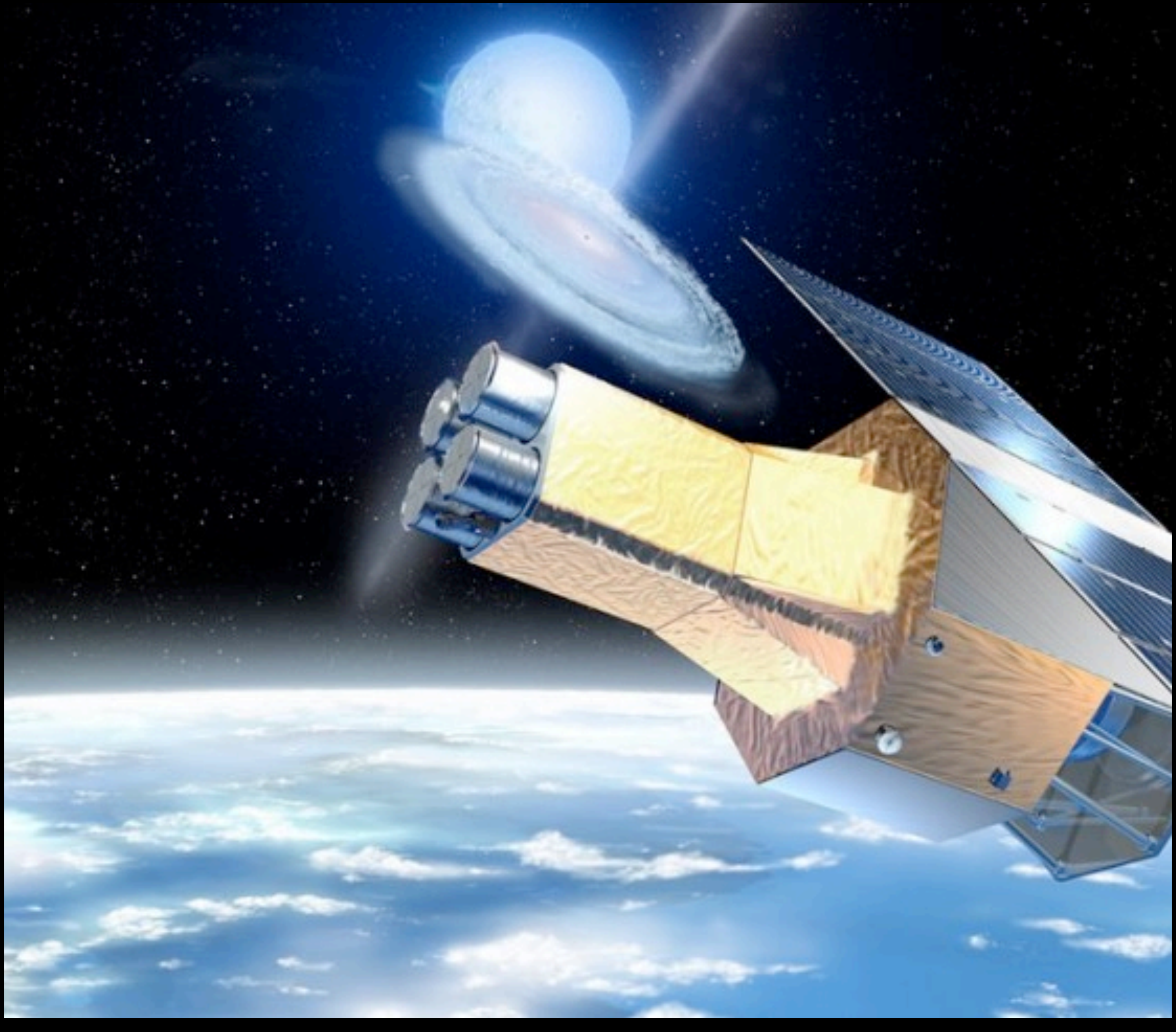
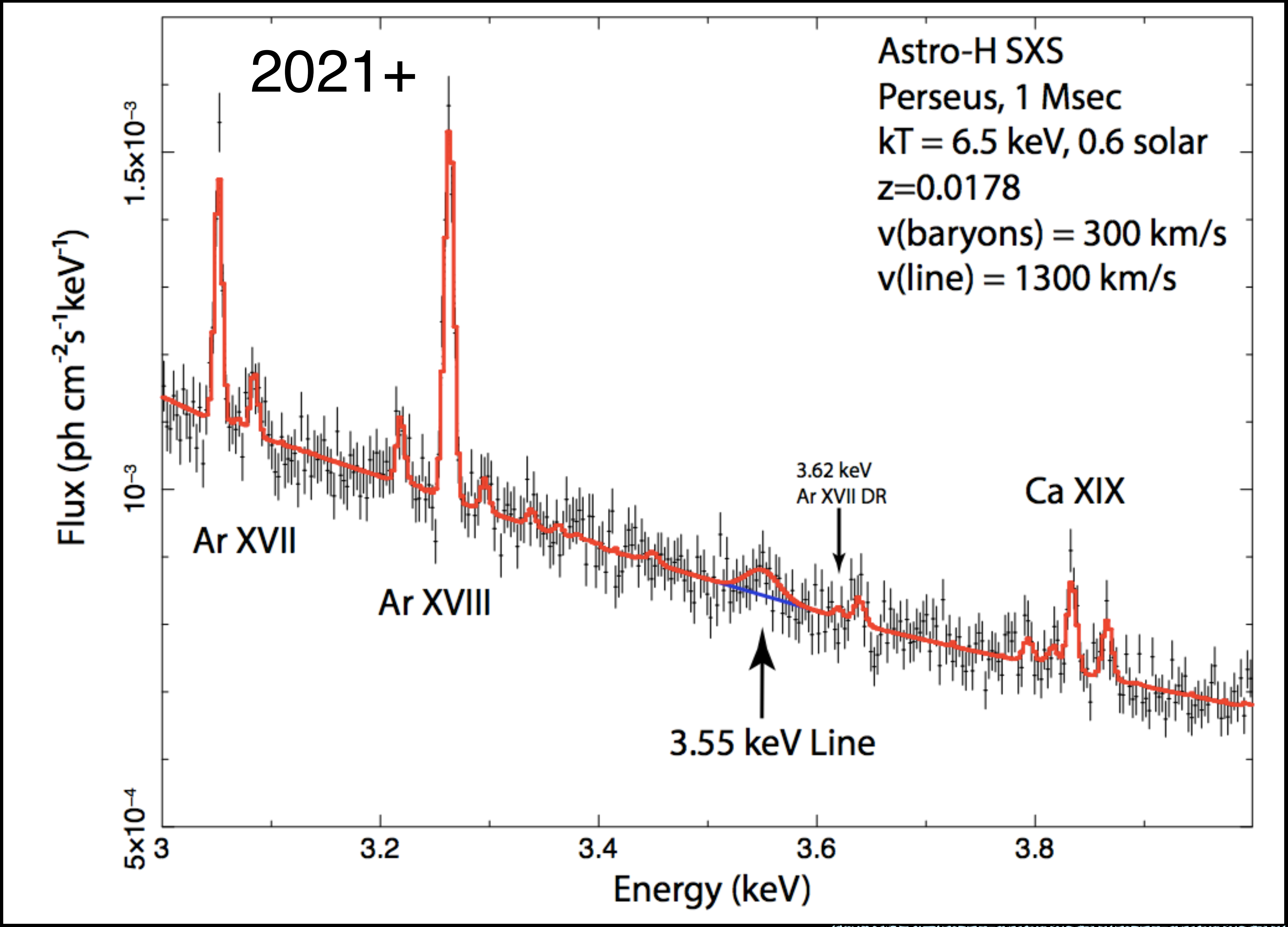


XARM will carry two instruments for studying the soft X-ray energy range: Build-to-print SXT-S (Soft X-ray Telescope for Spectrometer) & updated in energy resolution SXT-I (Soft X-ray Telescope for Imager).

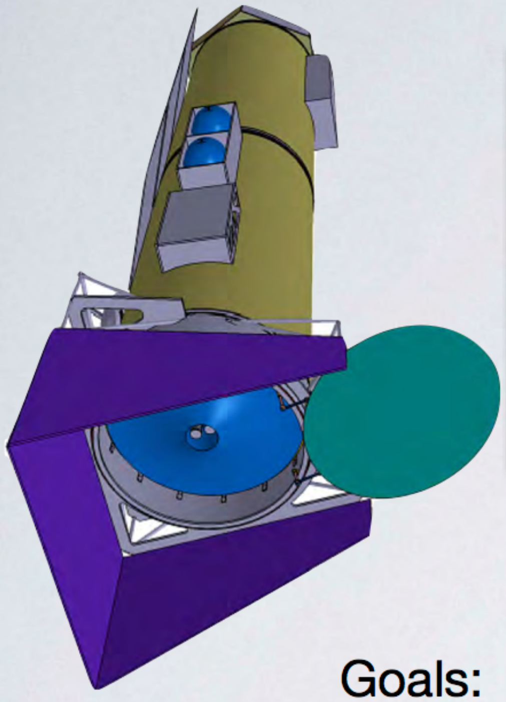
Confirmation? XARM

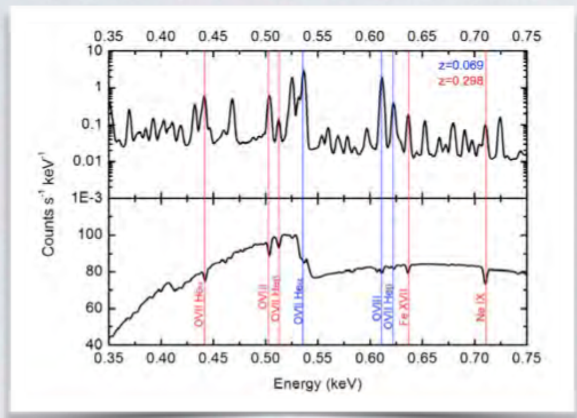


Bulbul et al. ApJ arXiv:1402.2301

Future Space X-ray Astronomy

Athena





about 2028

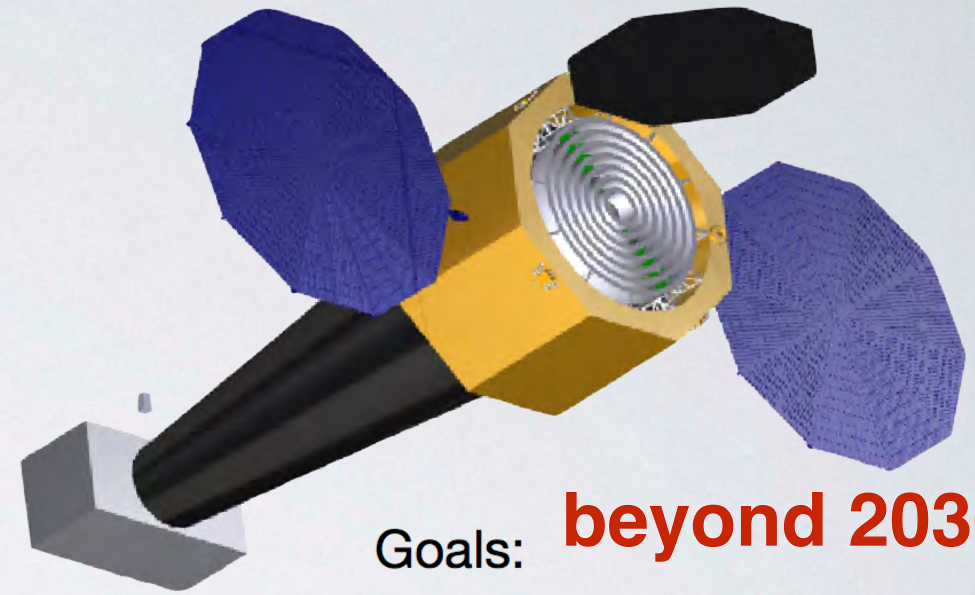
Goals:

- Microcalorimeter spectroscopy (R≈1000)
- Wide, medium-sensitivity surveys

$$\left(R = \frac{\lambda}{\Delta\lambda} \right)$$

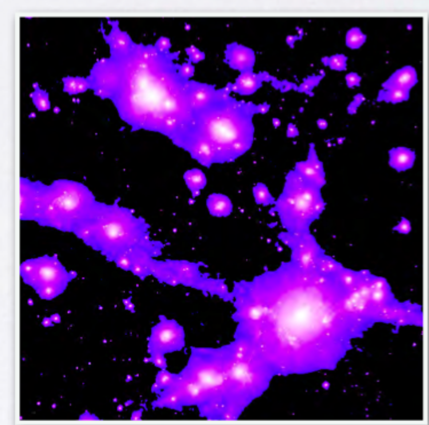
Area is built up at the expense of coarser angular resolution (10×) & sensitivity (5×)

Lynx X-ray Surveyor



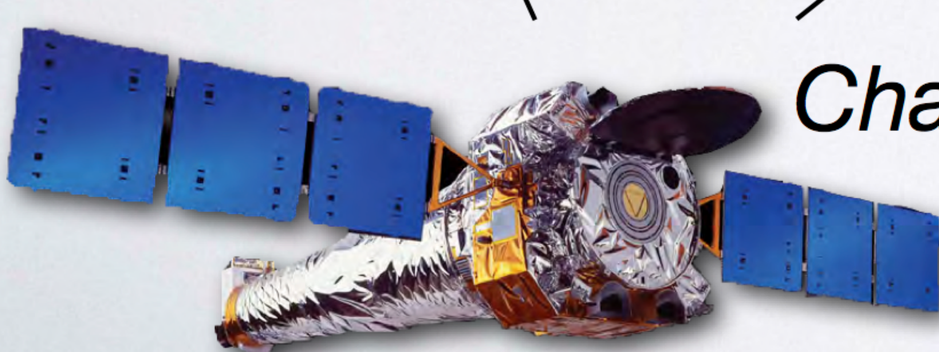
Goals: **beyond 2030**

- 50× sensitivity
- *R*≈1000 spectroscopy on 1″ scales adds 3rd dimension to the data
- *R*≈5000 spectroscopy for point sources



✓ Area is built up while preserving *Chandra* angular resolution (0.5″)

✓ 10× field of view with fine imaging



Chandra

[Courtesy Alexey Vikhlinin]

Confirmation? kinematic searches in nuclear β-decay

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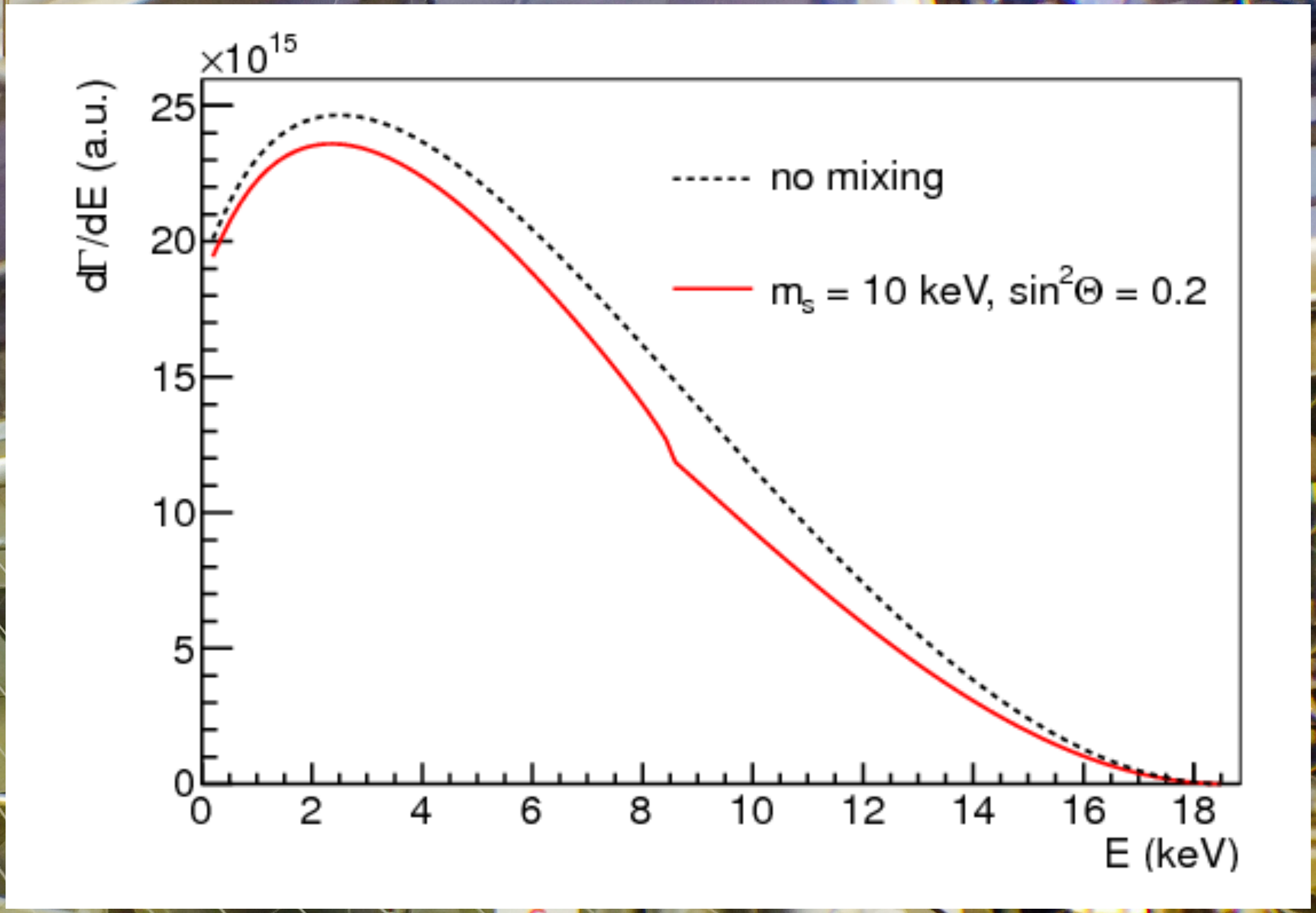

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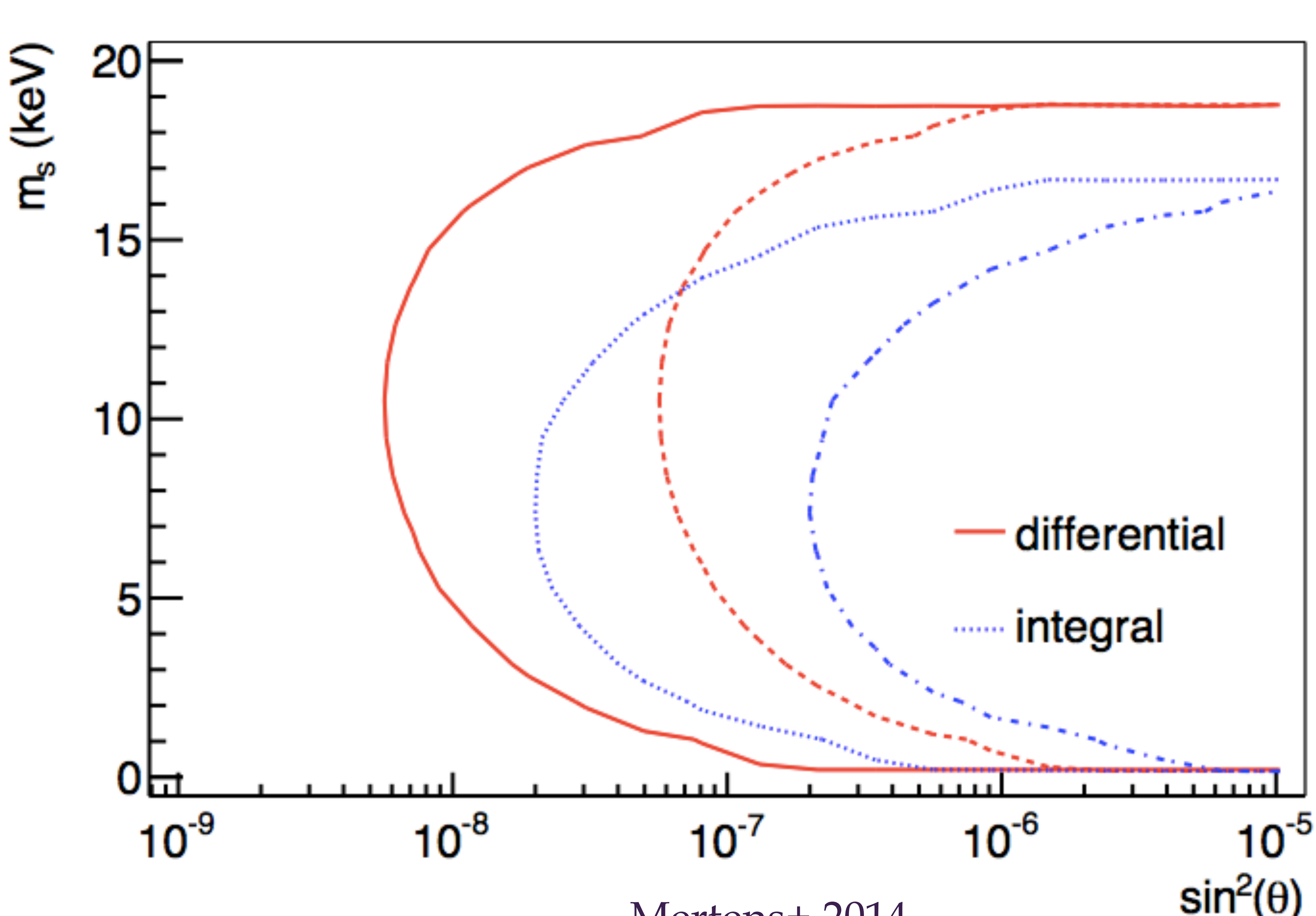

Mertens+ 2014

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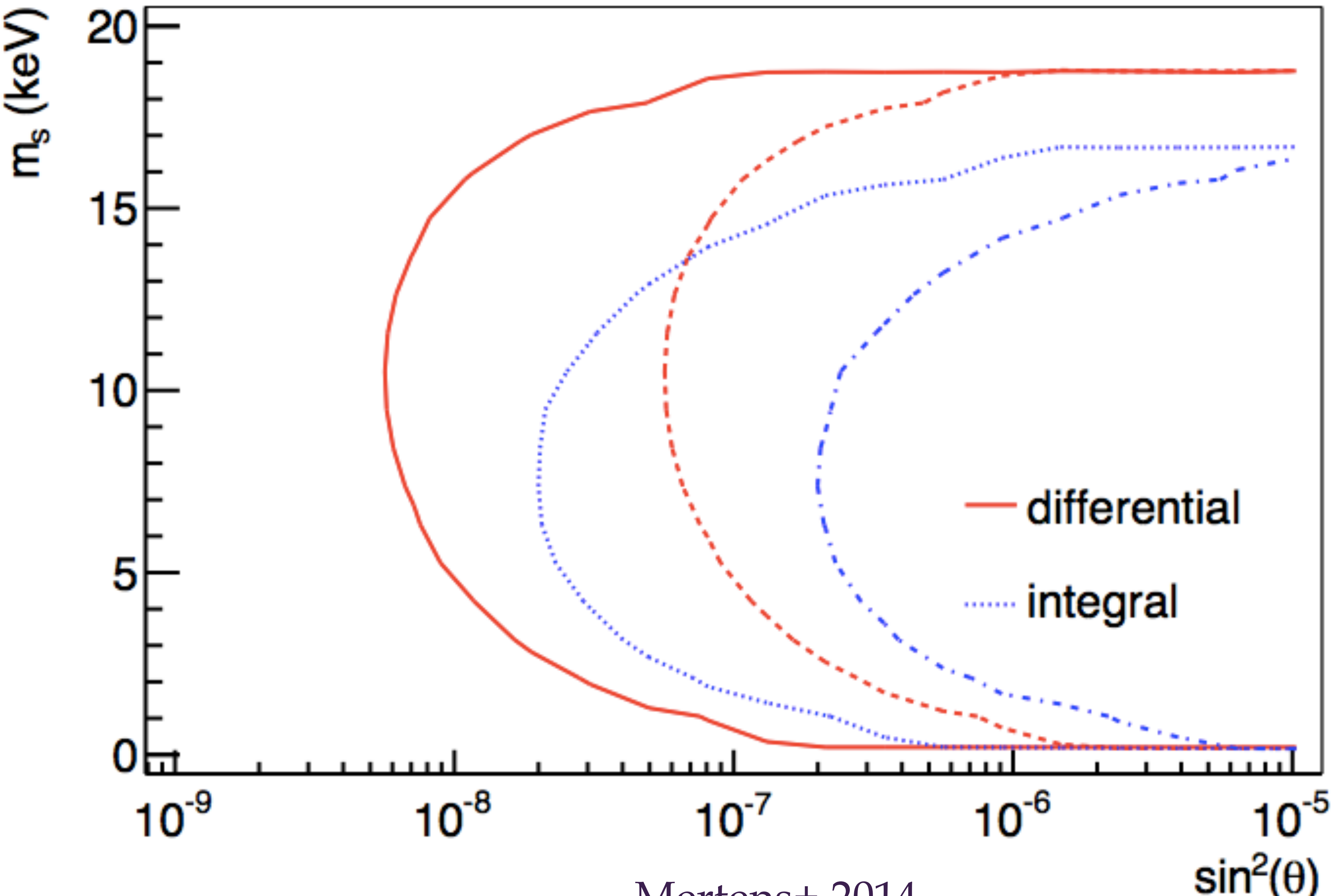
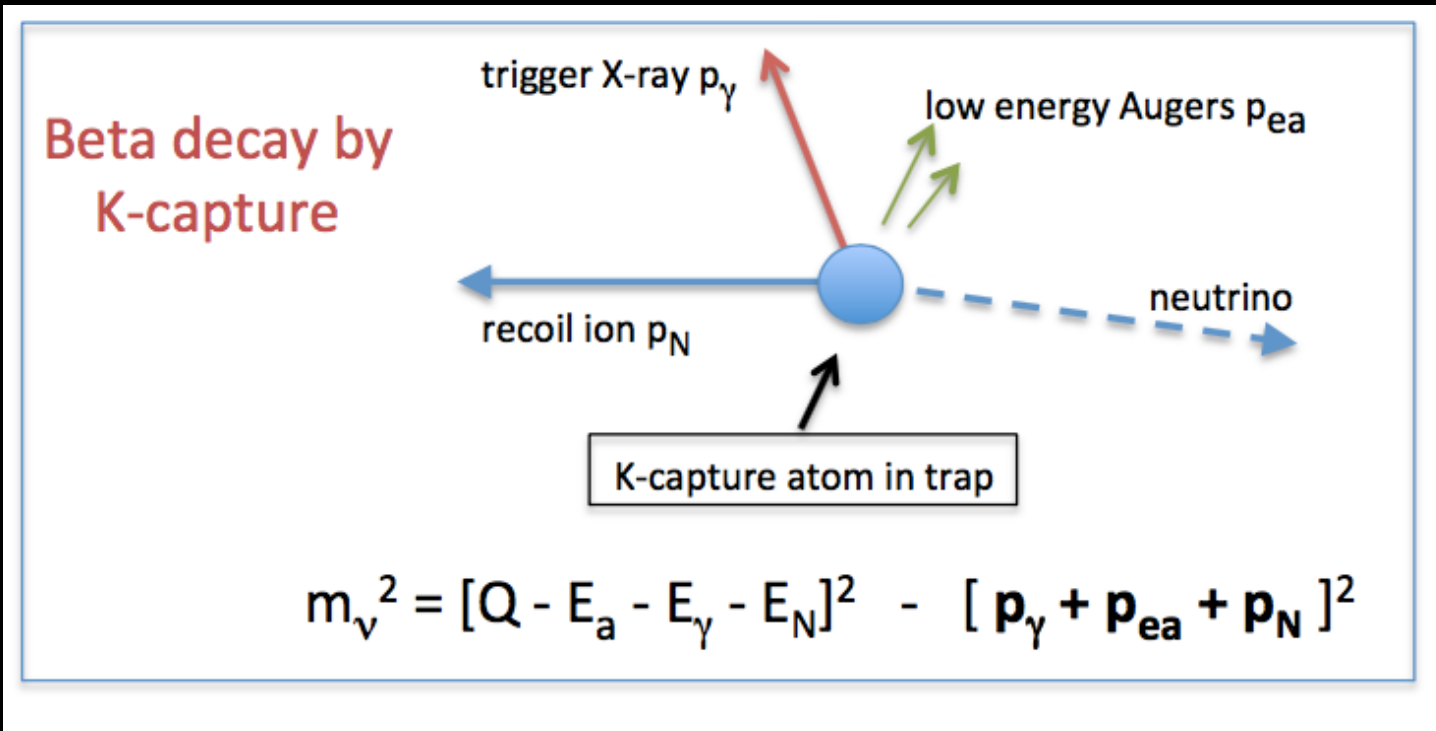


Mertens+ 2014

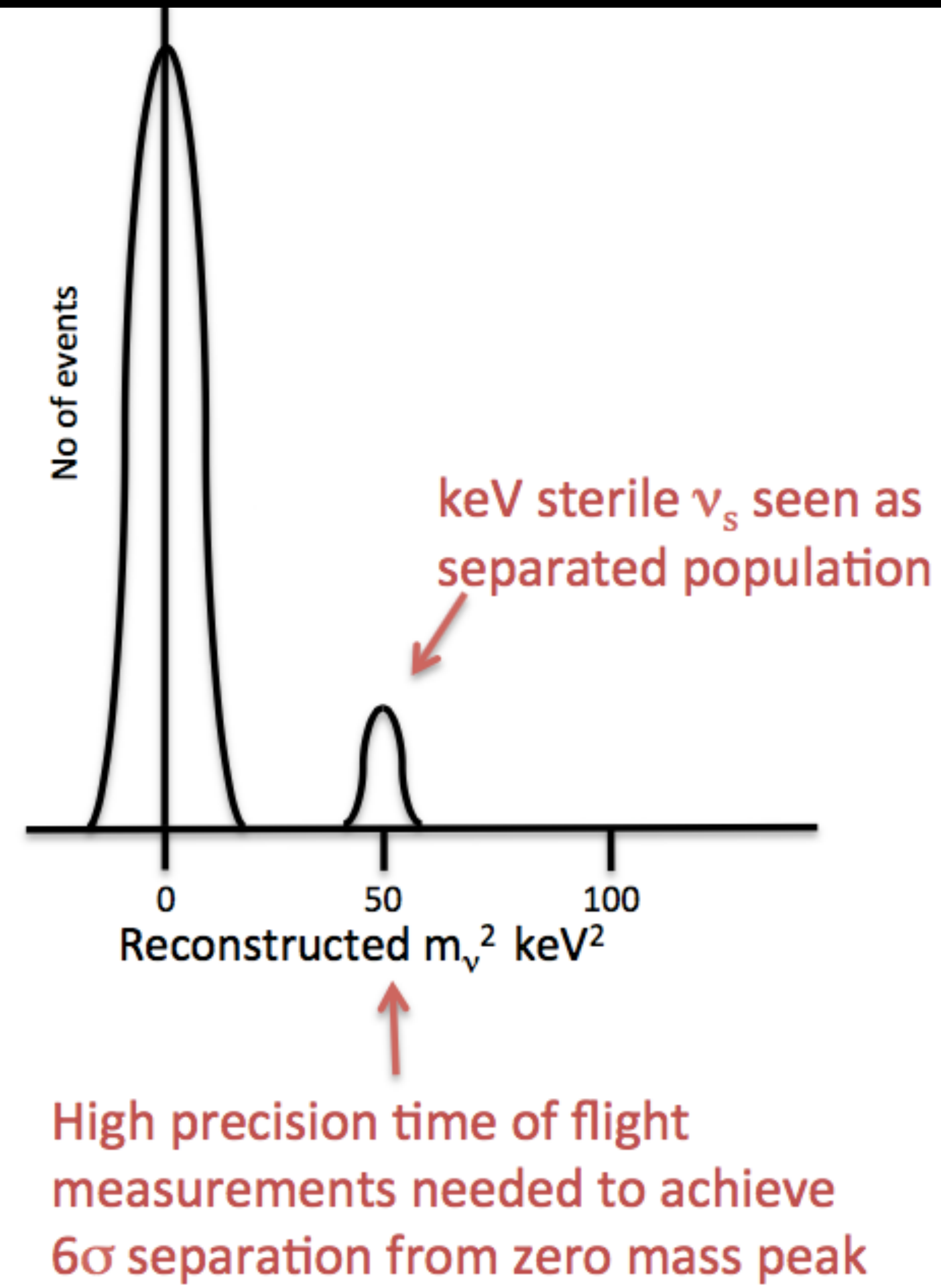
Confirmation Method #4: full kinematic reconstruction of K-capture nuclear decay



Original studies: Finocchiaro & Schrock 1992

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

^{131}Cs Ion trap proposal:
Peter Smith at UCLA Dark Matter Conference, Feb. 2016
[Martoff, Napolitano, Hudson, Wang, Smith, Renshaw, Fuller, Grohs]



Recent studies show this may now be feasible

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- **No consistent astrophysical interpretation exists.**

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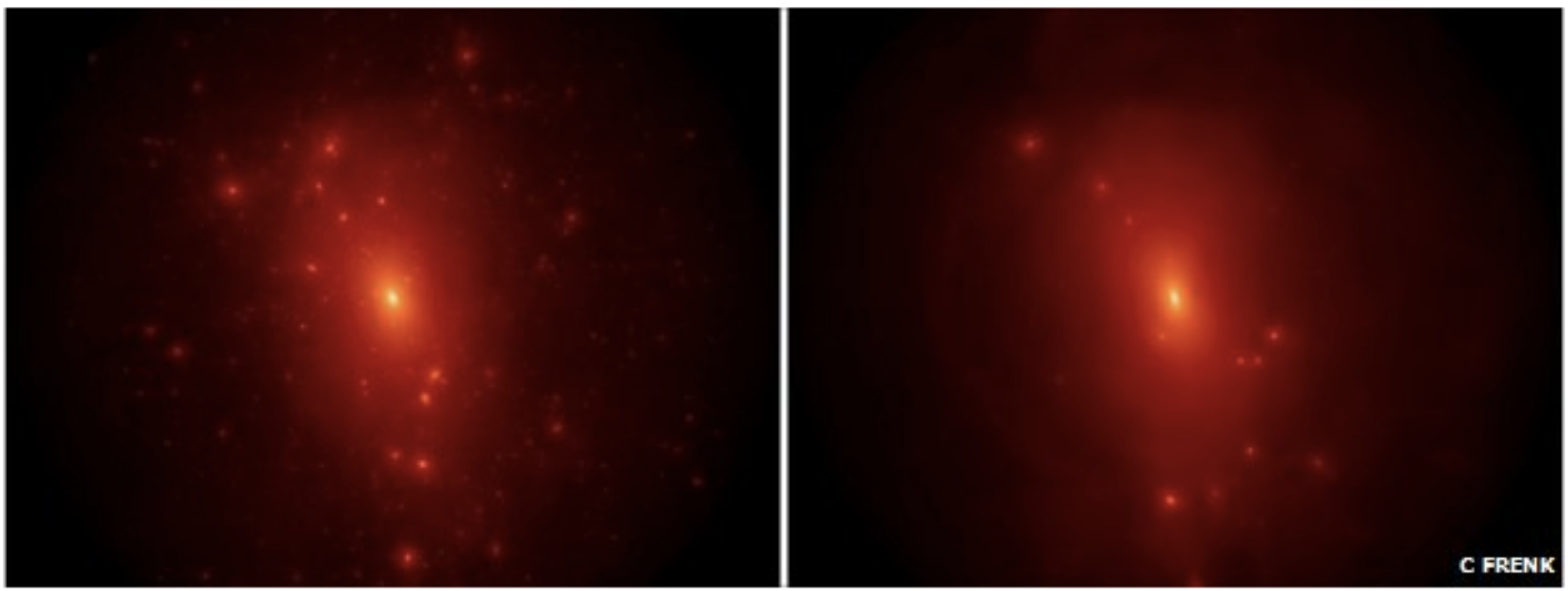
- “Space will not be conquered by missiles… but by the impregnation of all of space with human sensibility.”
  — Yves Klein (1962)

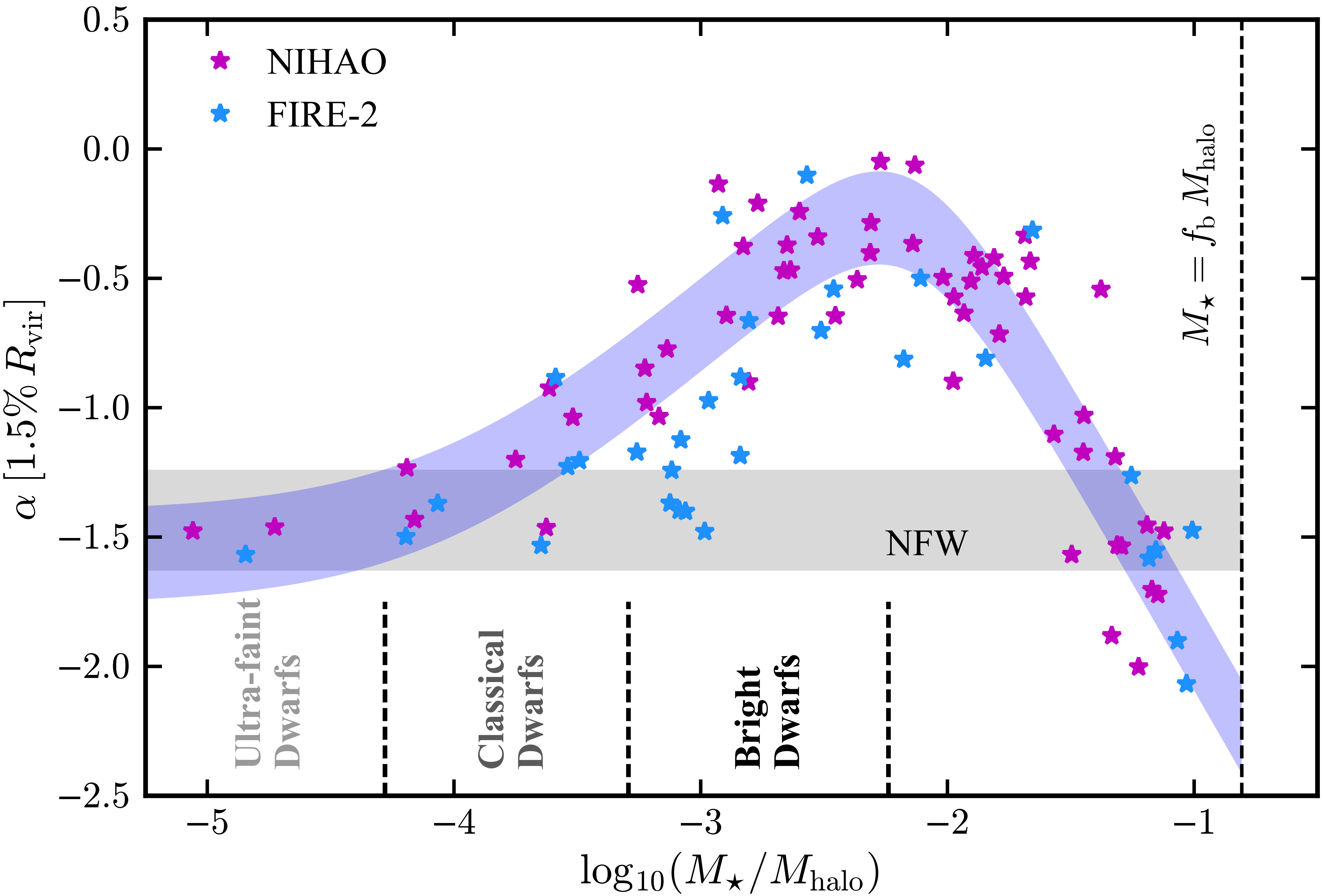
Issues in Cosmological Small-scale Structure?

And is Warm Dark Matter a Solution?



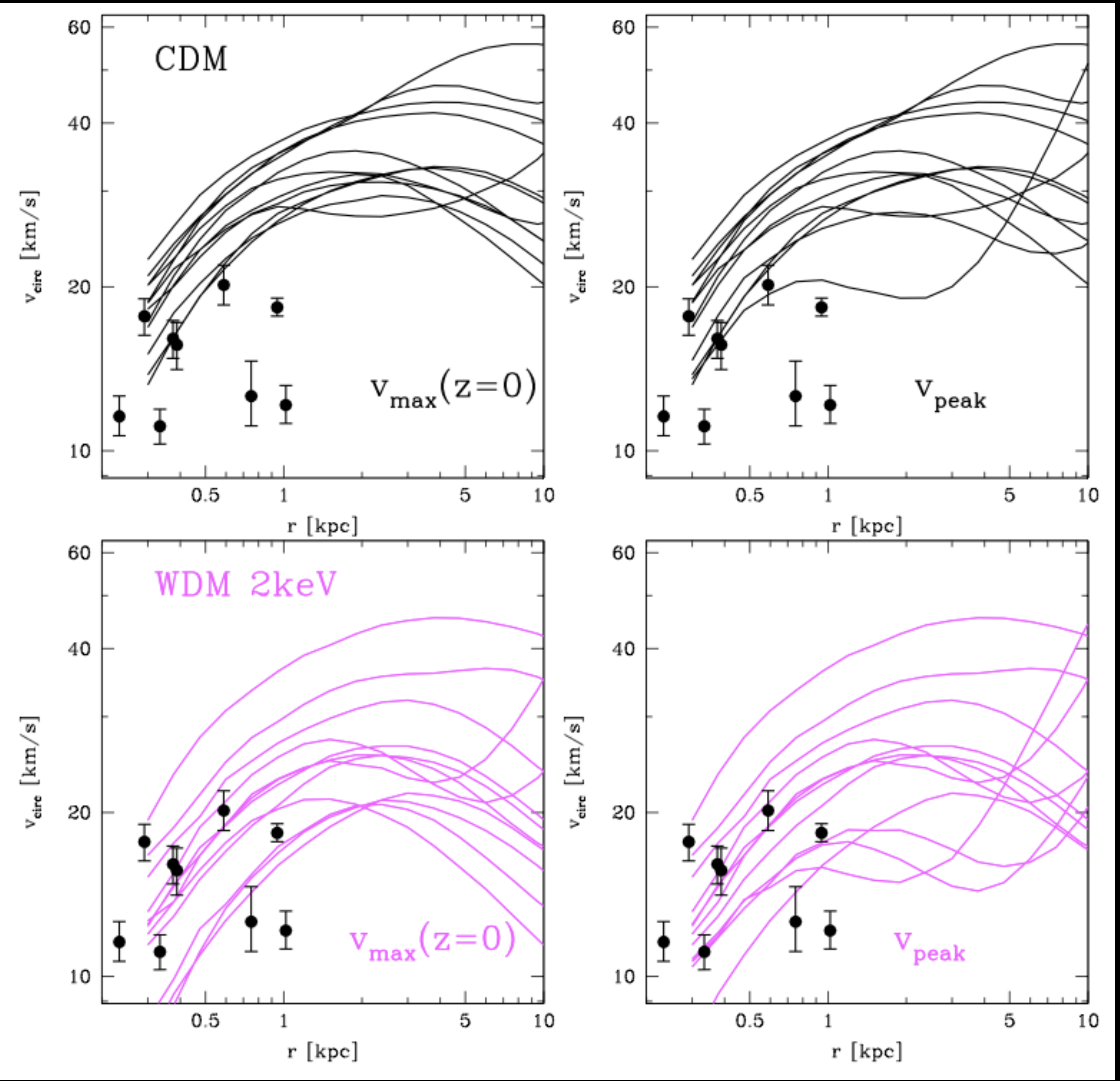
Dwarf galaxies around the Milky Way are less dense than they should be if they held cold dark matter

Too Big Too Fail: ***Feedback does not work at all scales***



Bullock & Boylan-Kolchin, Ann Rev A&A (2017)

WDM Solution to All Local Group Galaxy Properties?



Anderhalden et al. arXiv:1212.2967

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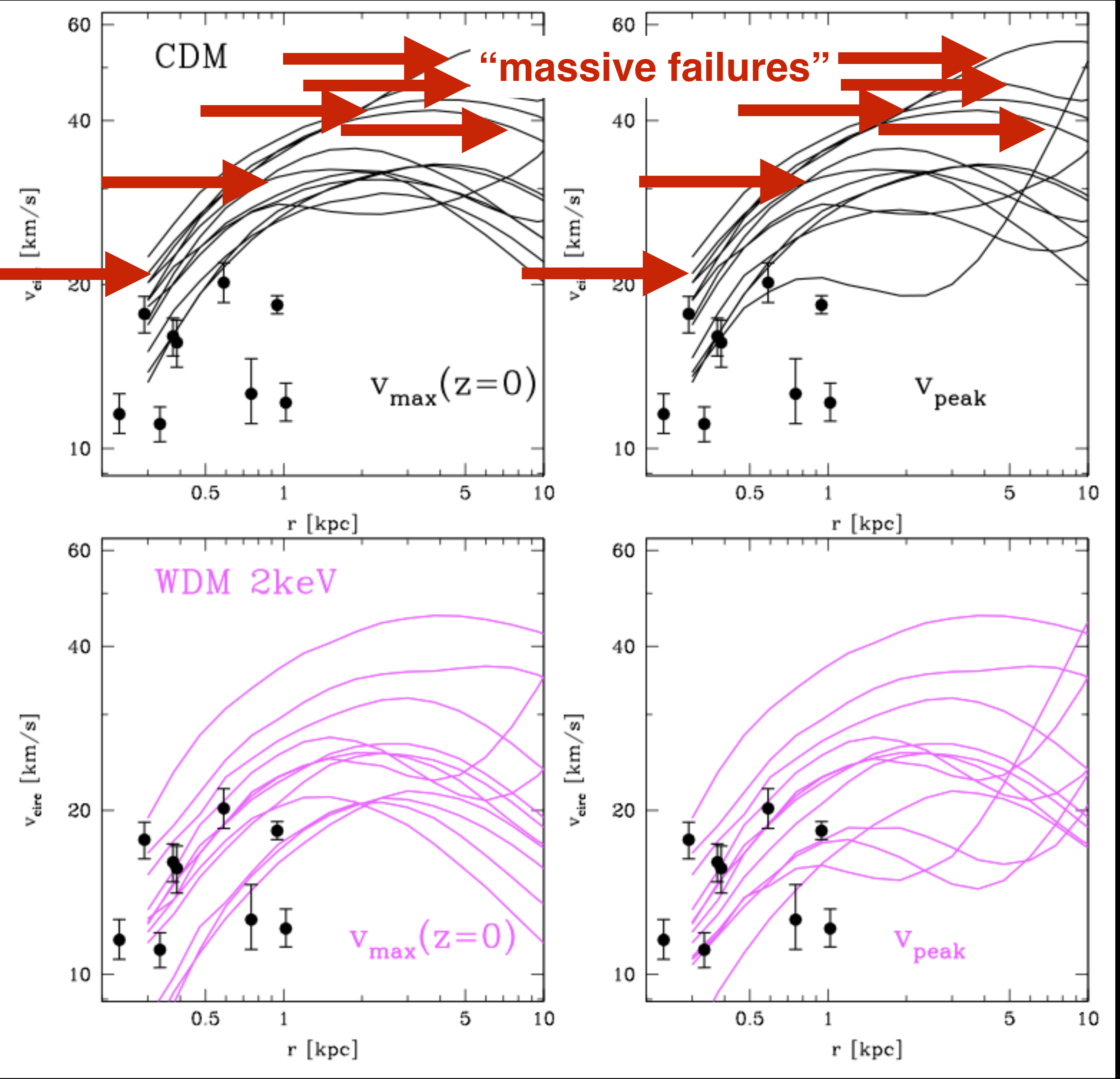

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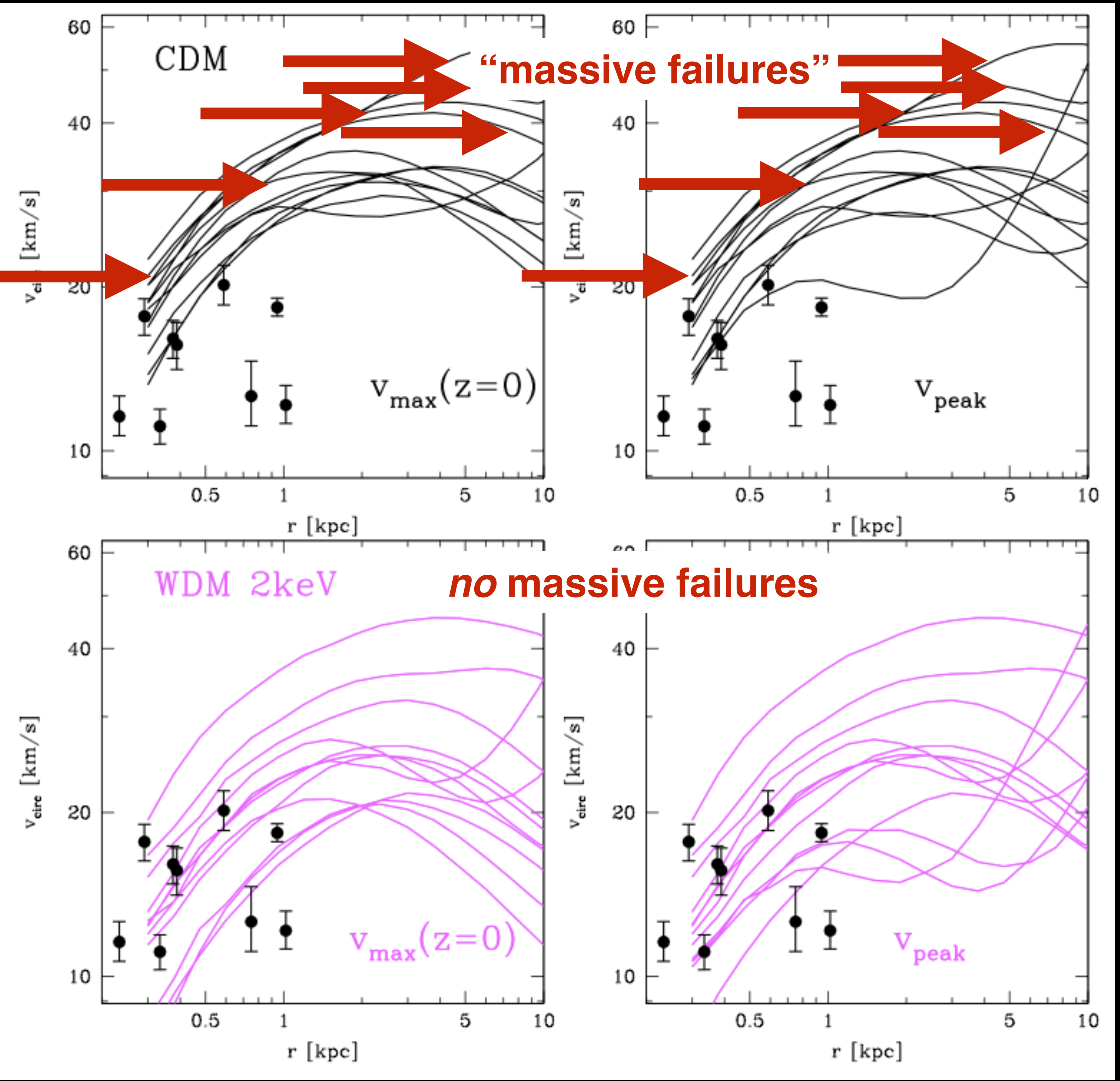

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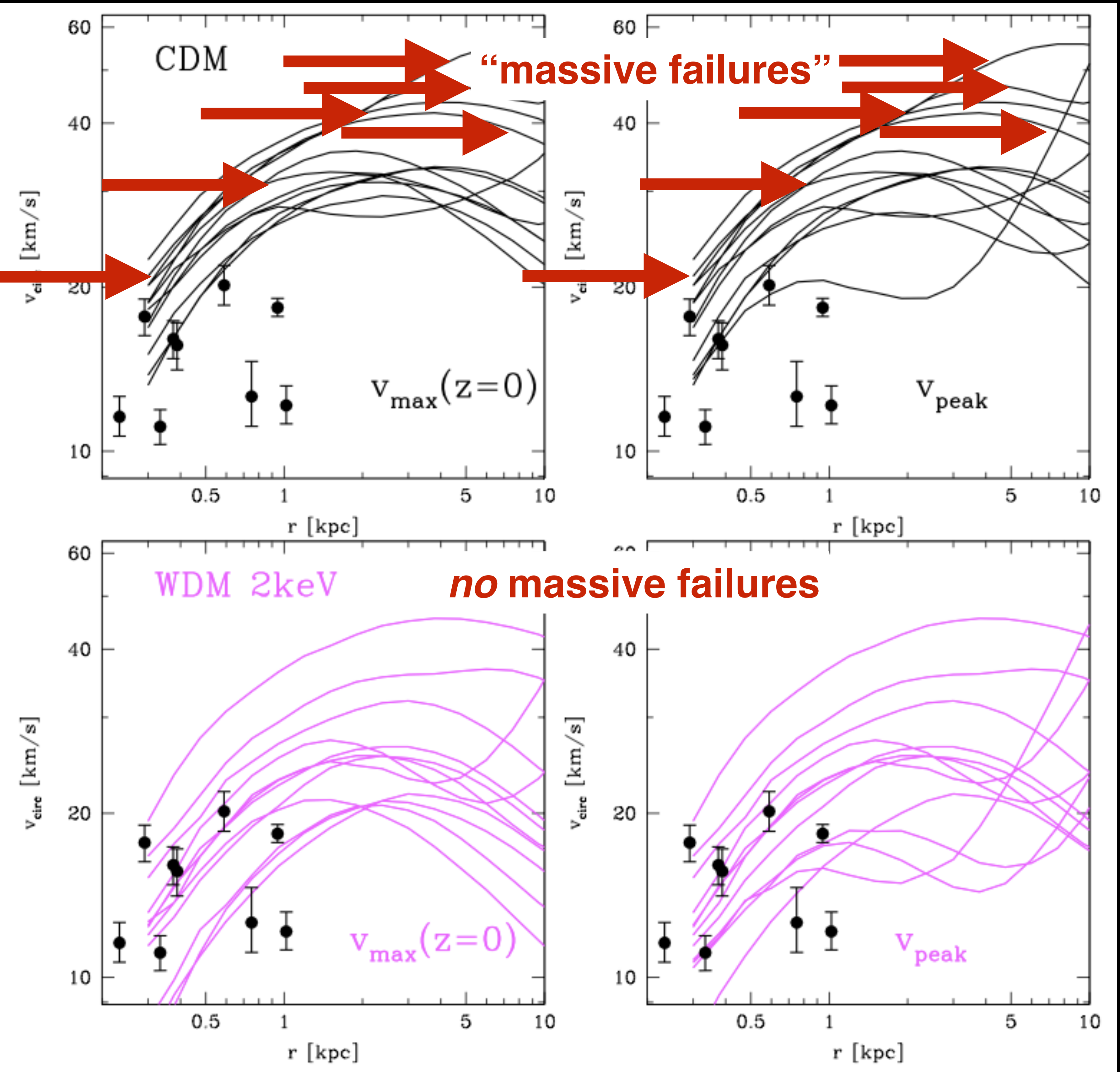

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$$\text{Cowsik-McClelland/Gershtein-Zeldovich bound: } \Omega = \frac{M}{94.1h^2\,{\rm eV}} < 1$$

Thermal WDM

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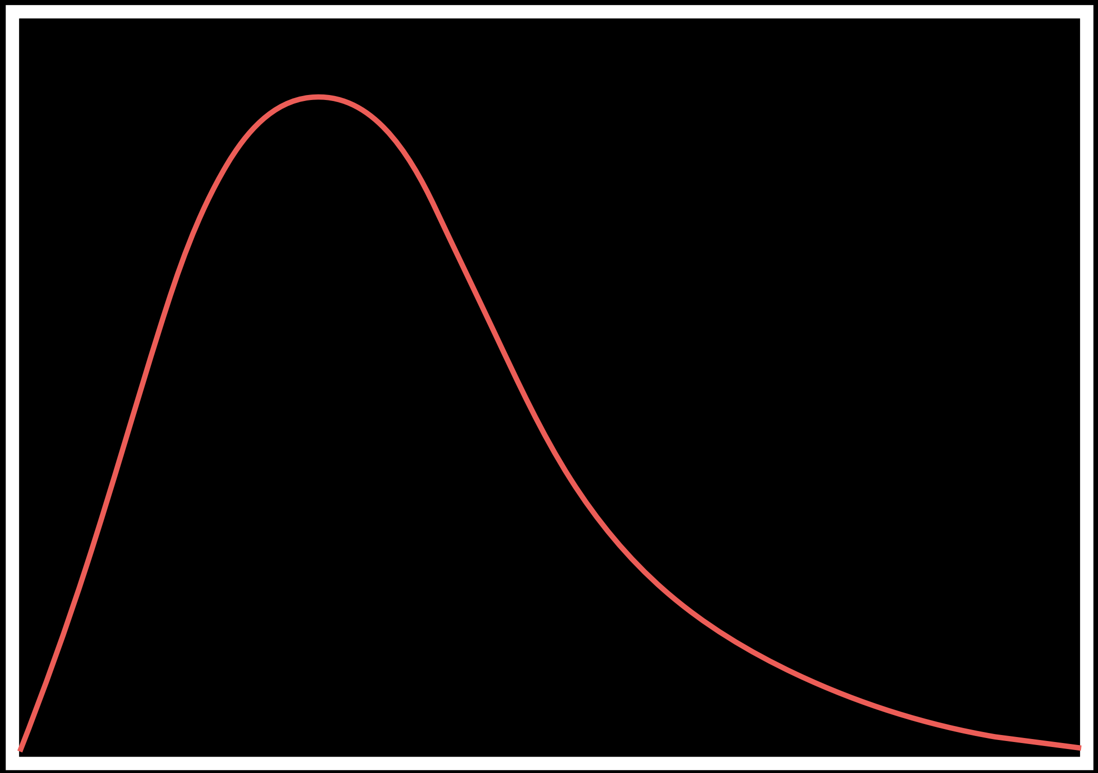

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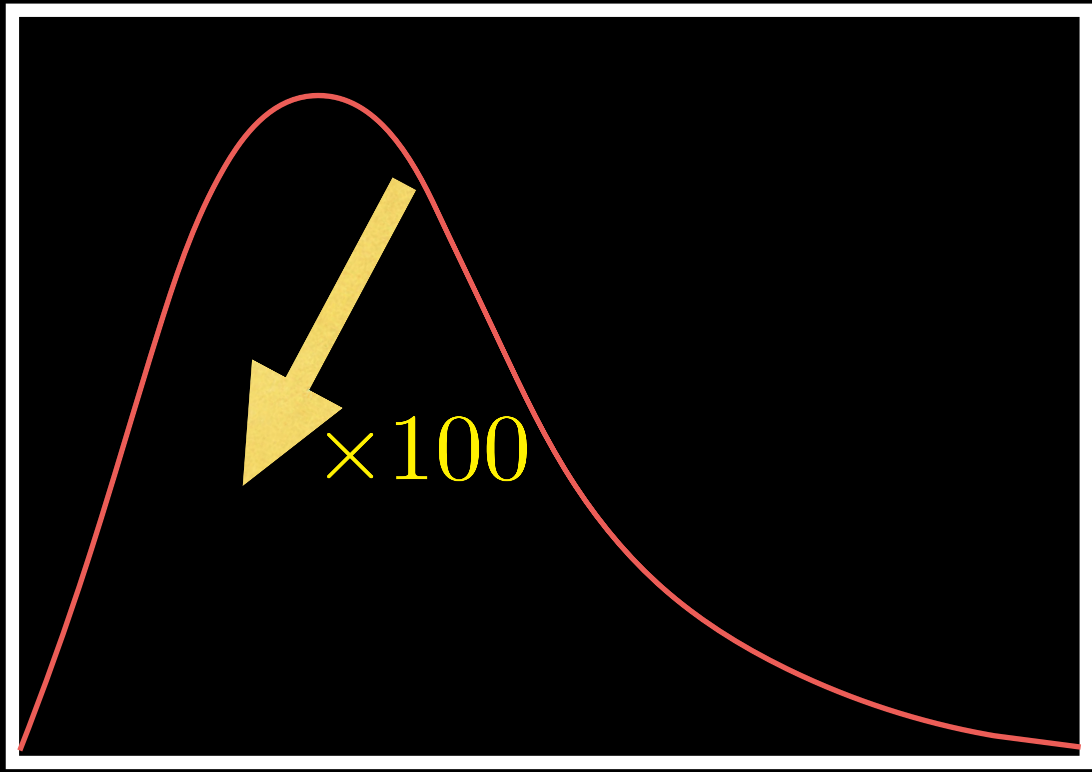

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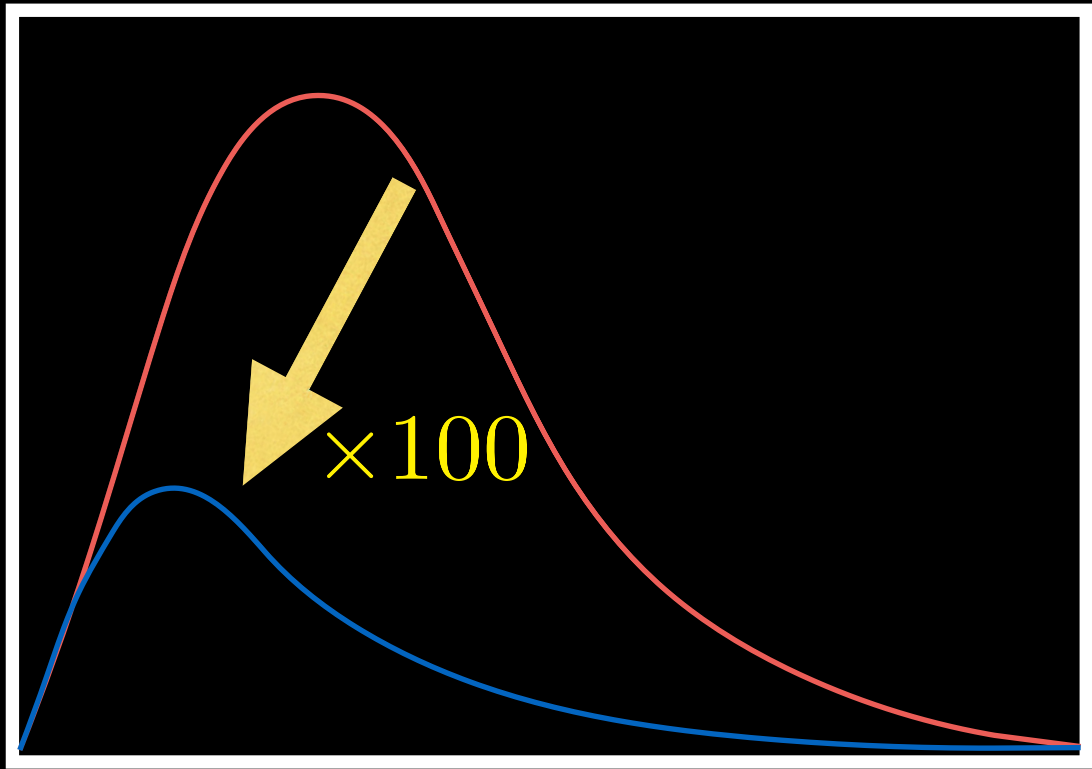

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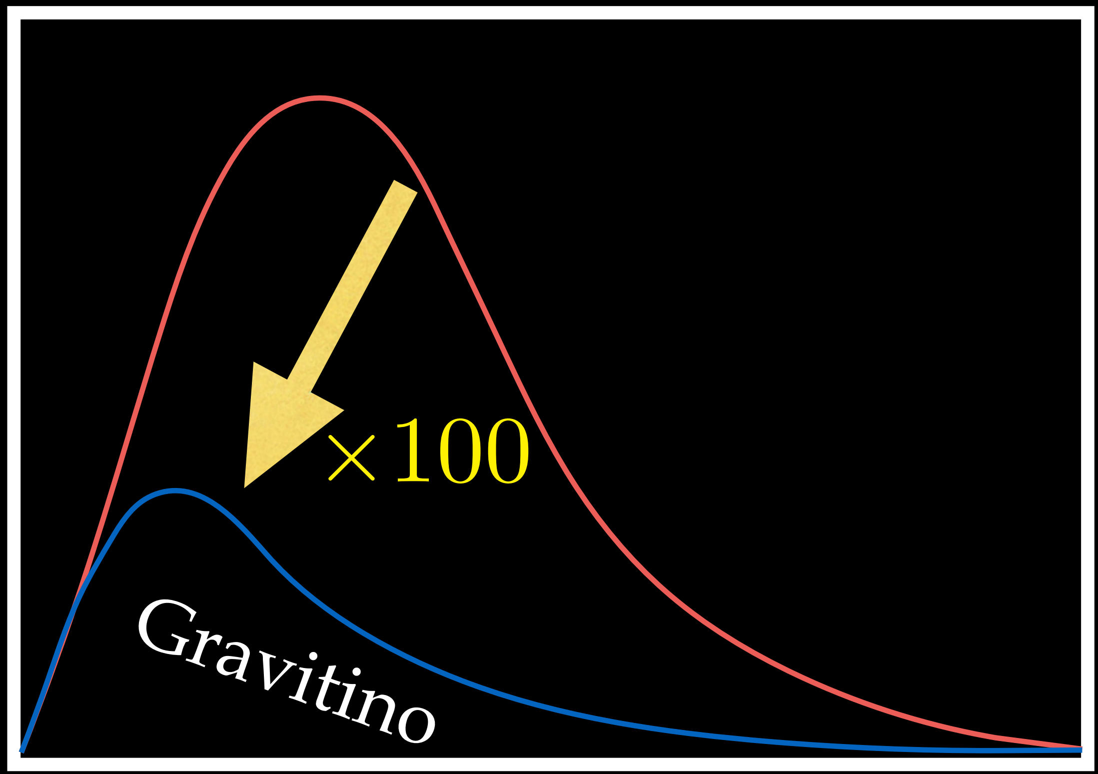

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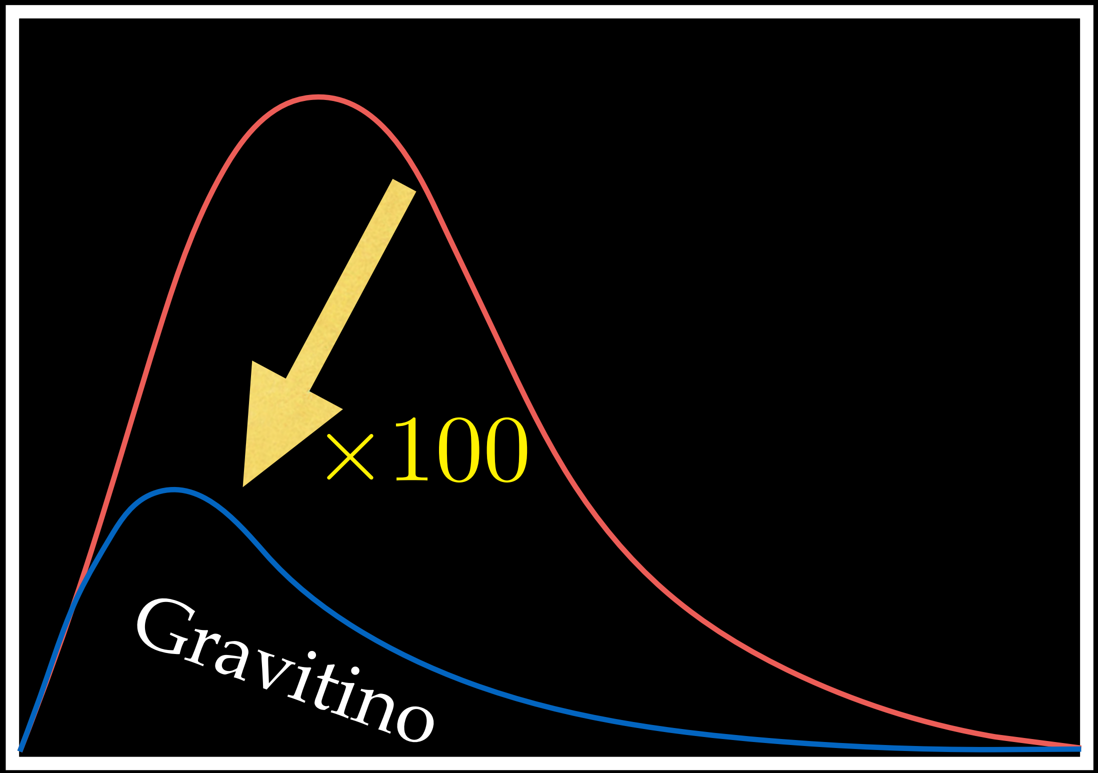

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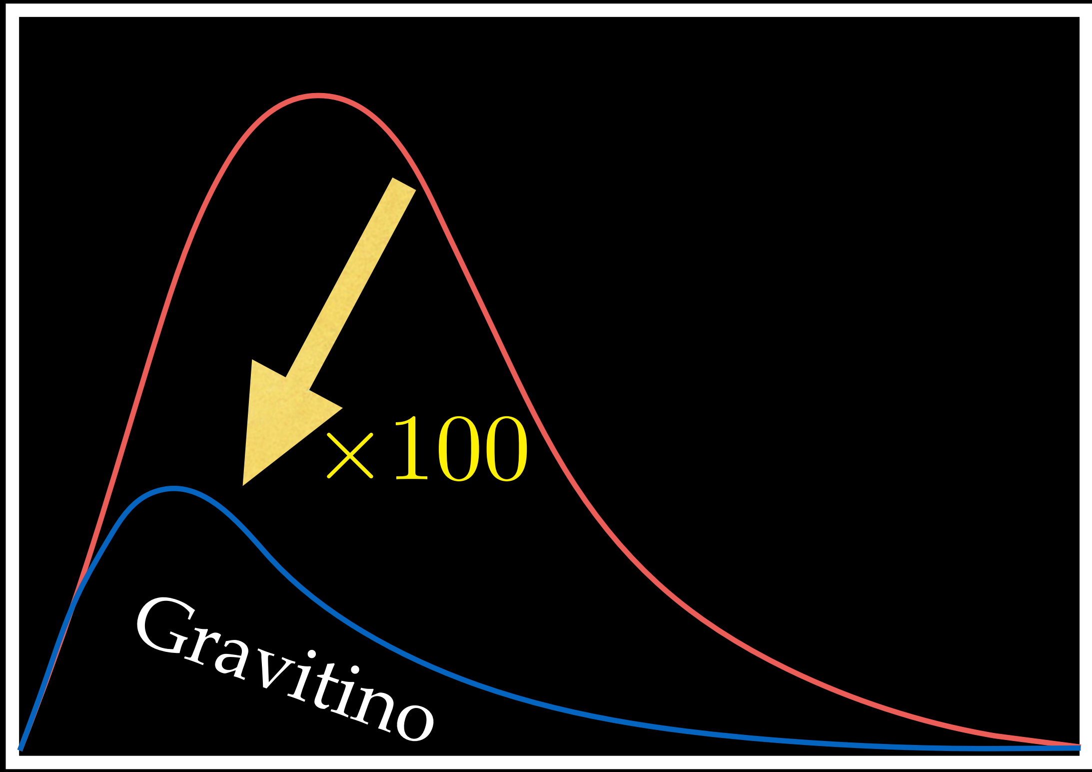

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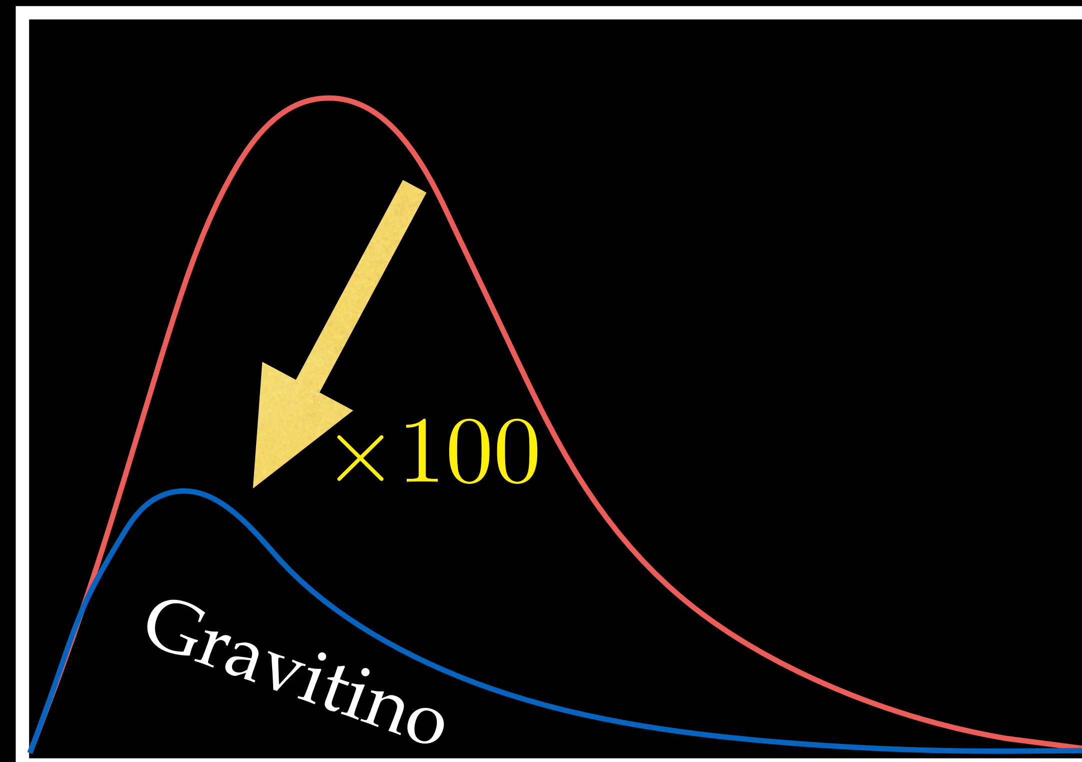

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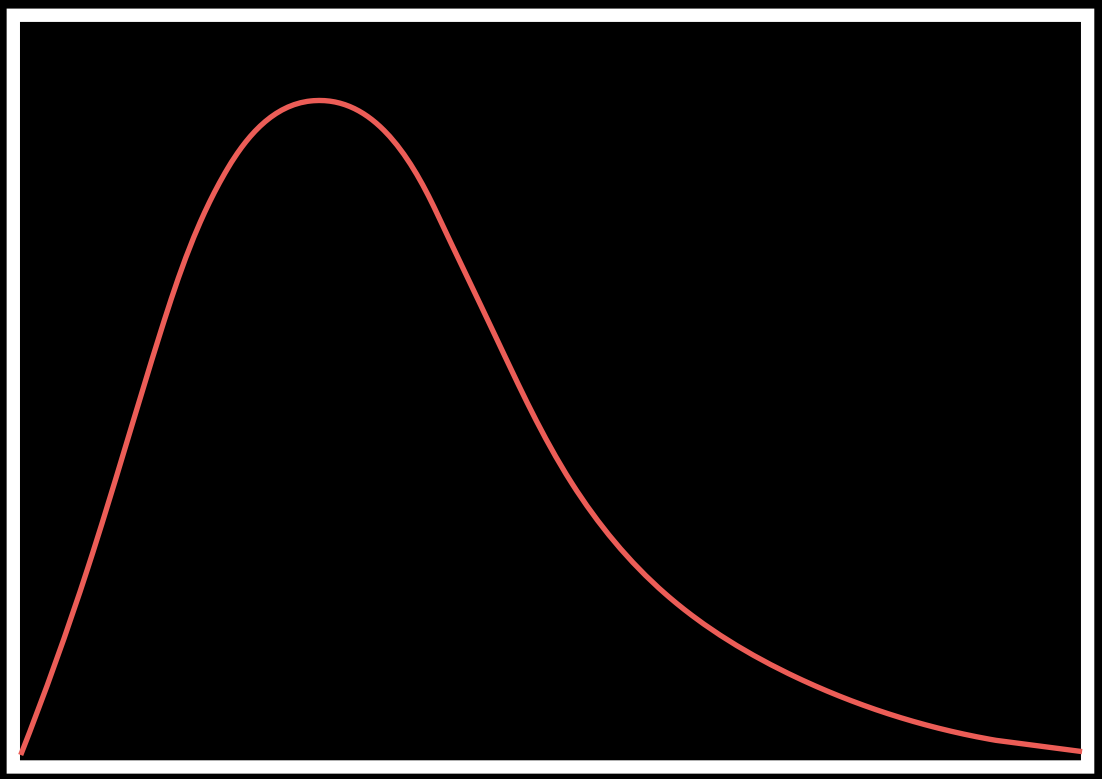

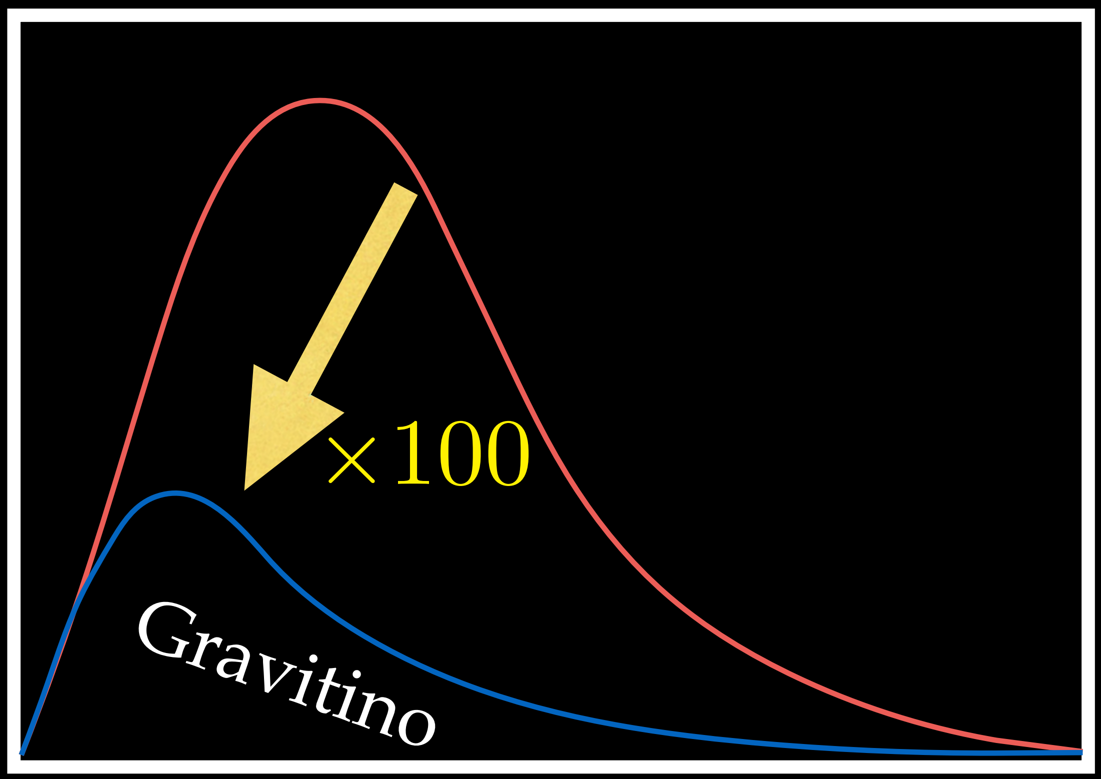

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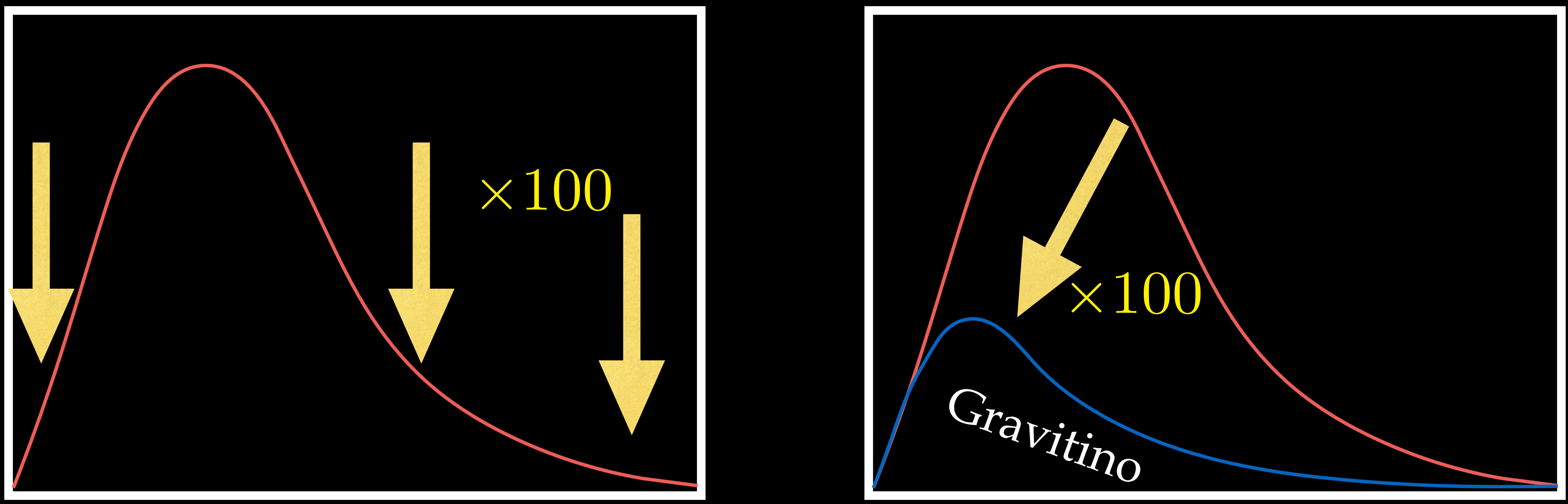

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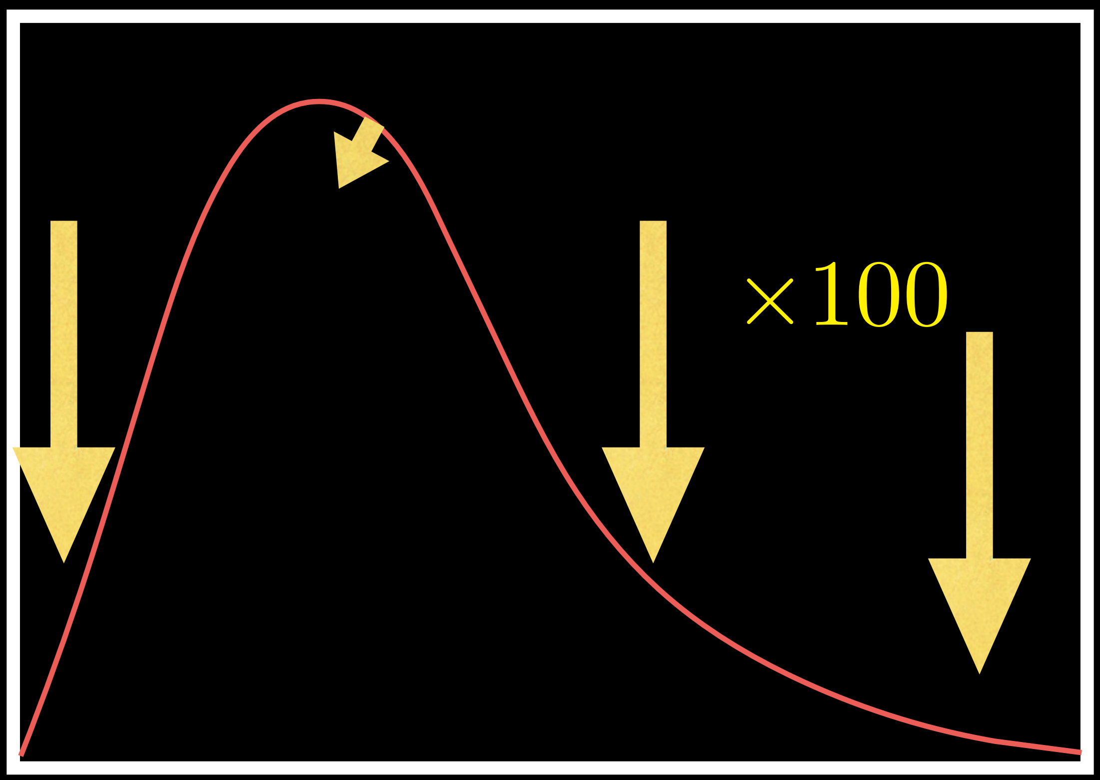

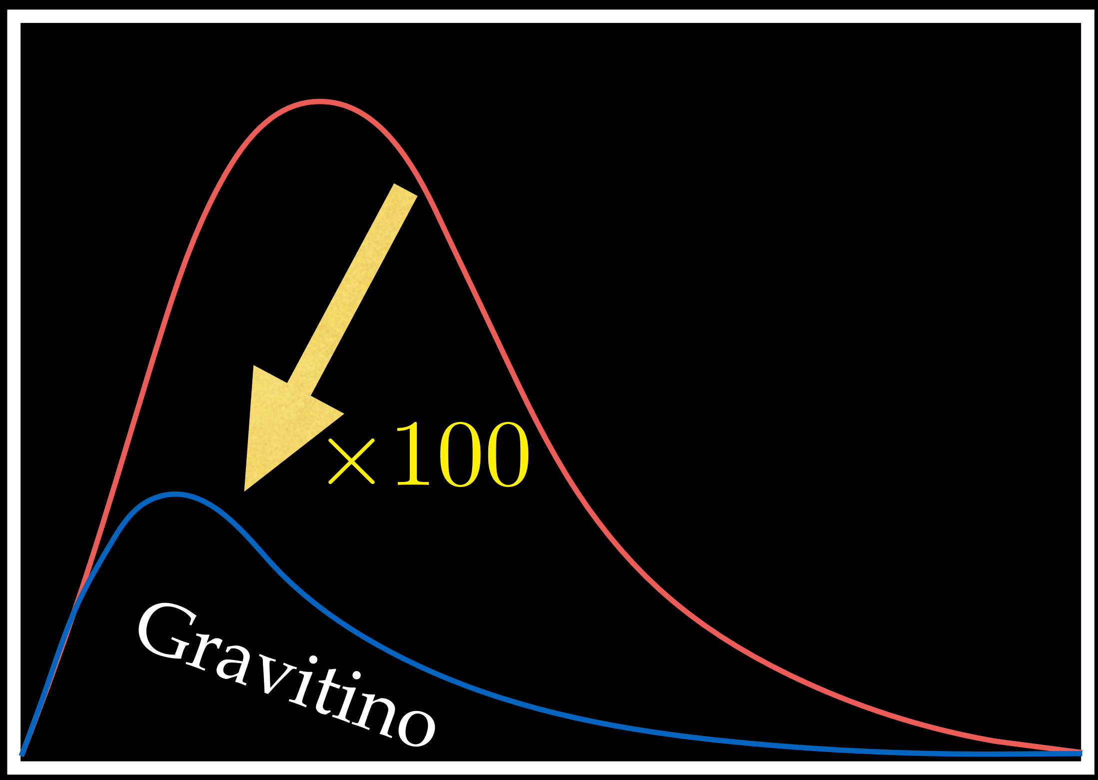

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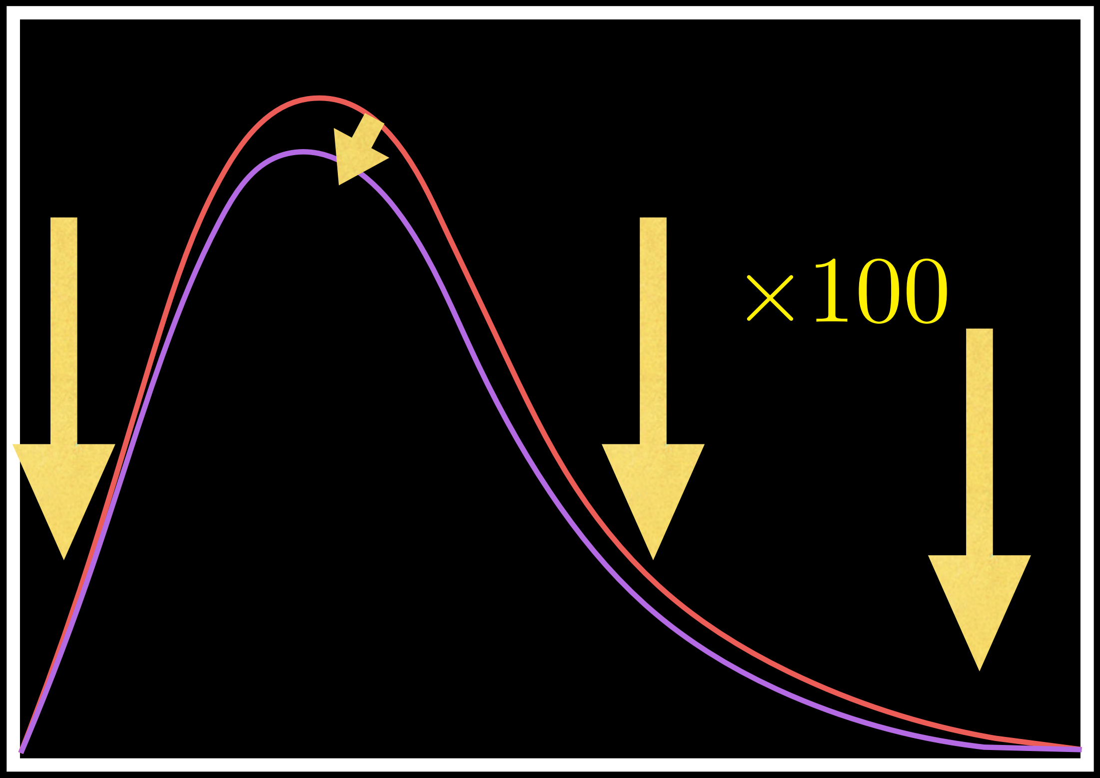

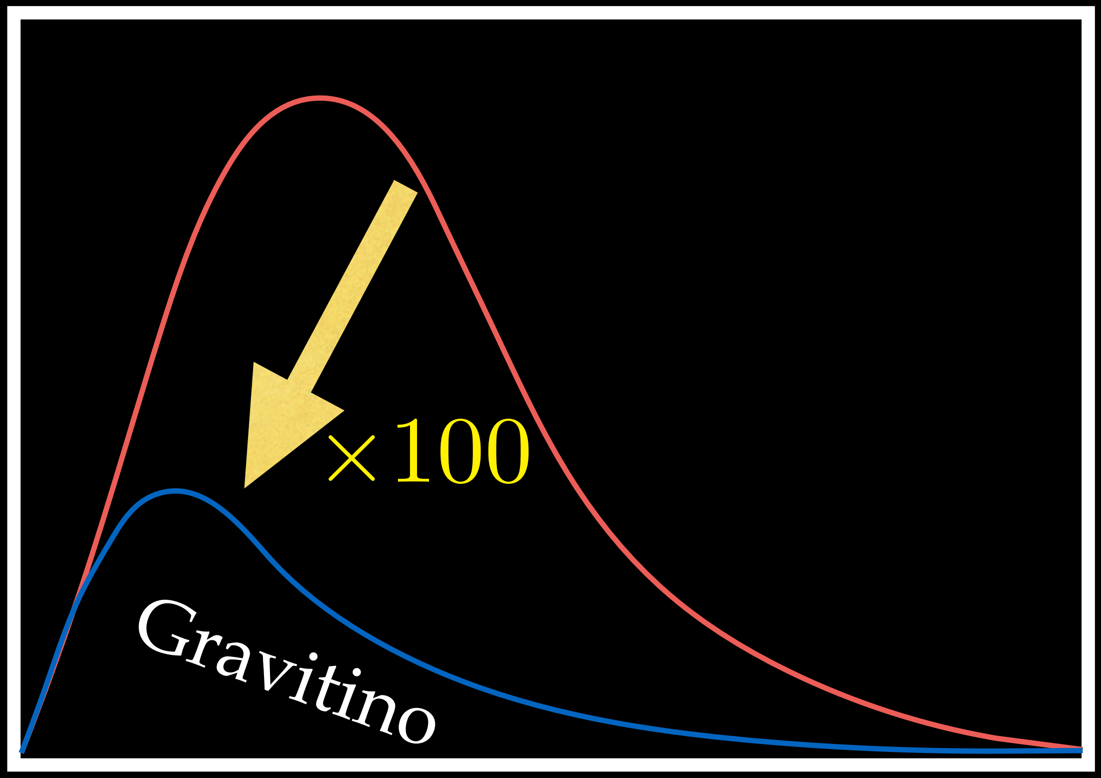

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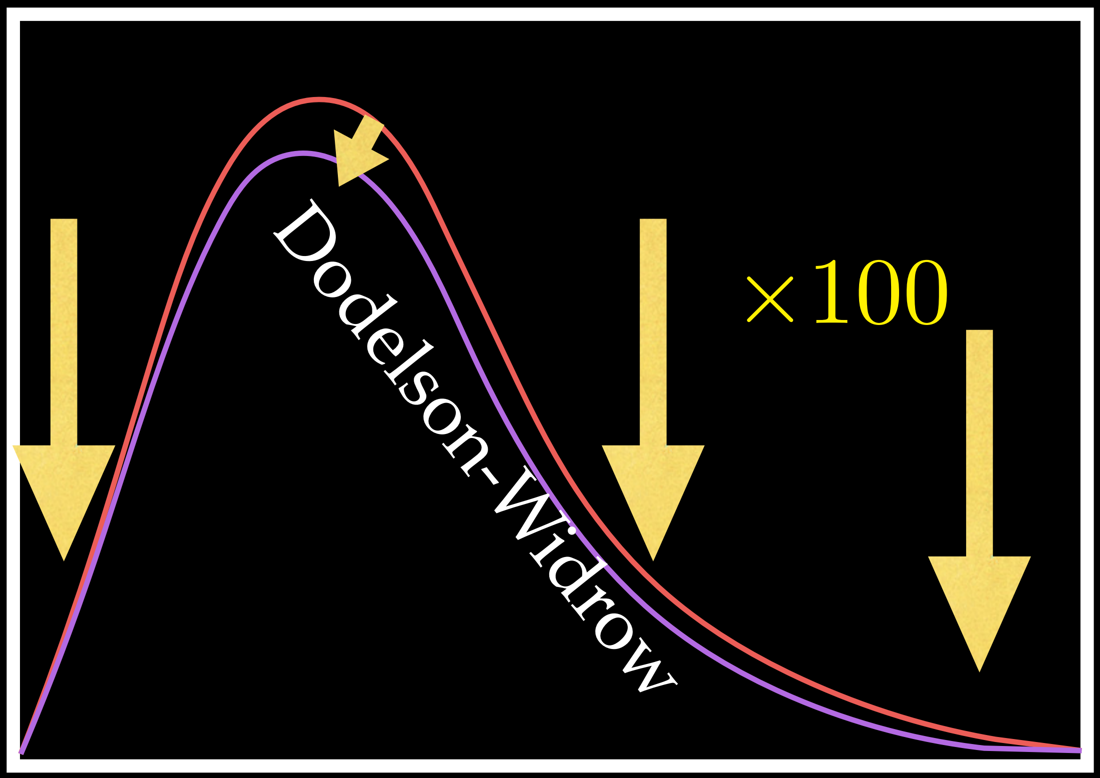

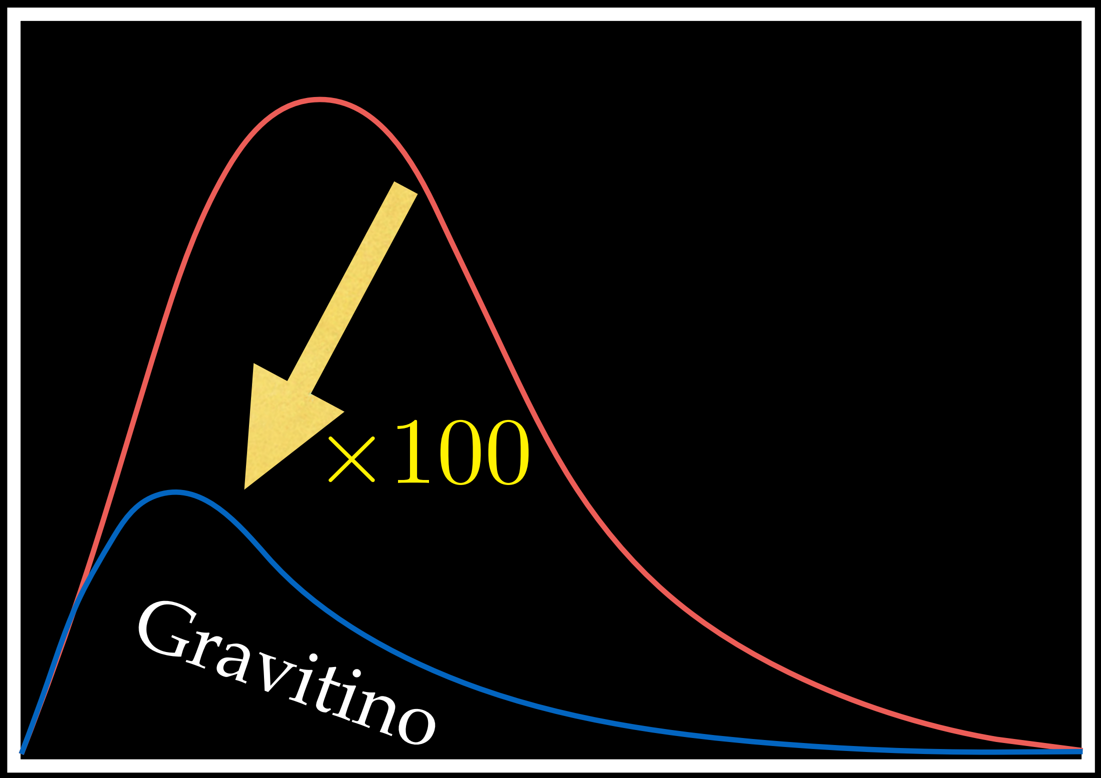

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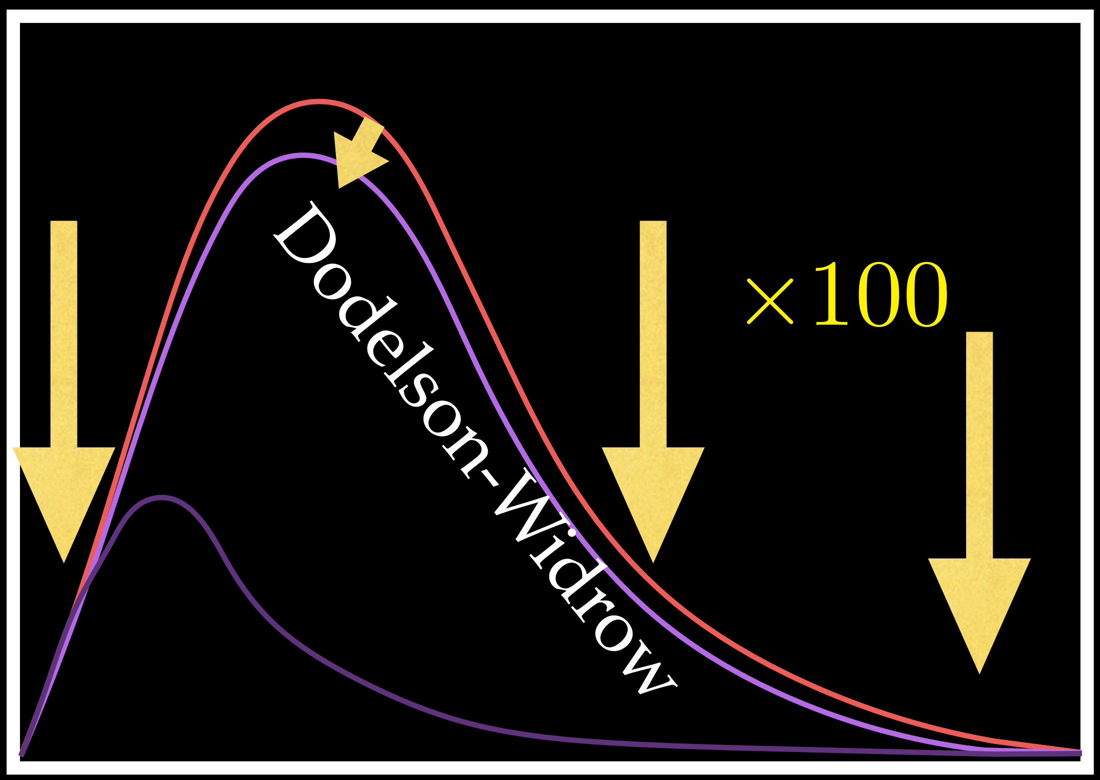

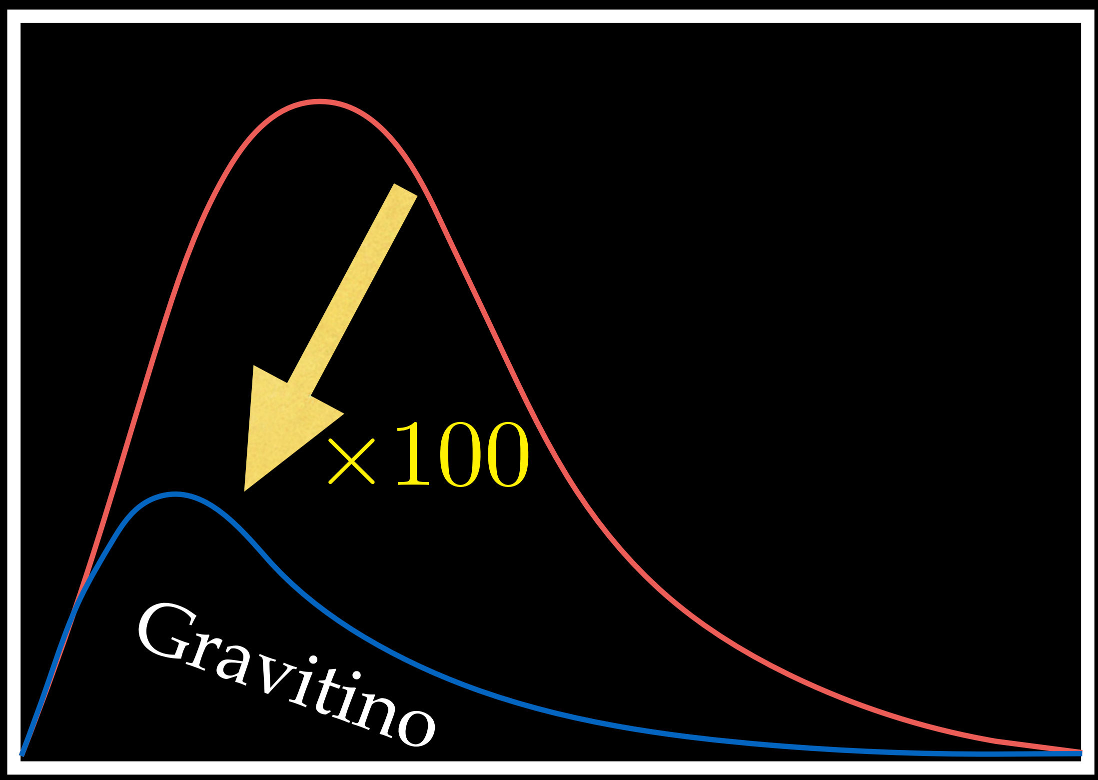

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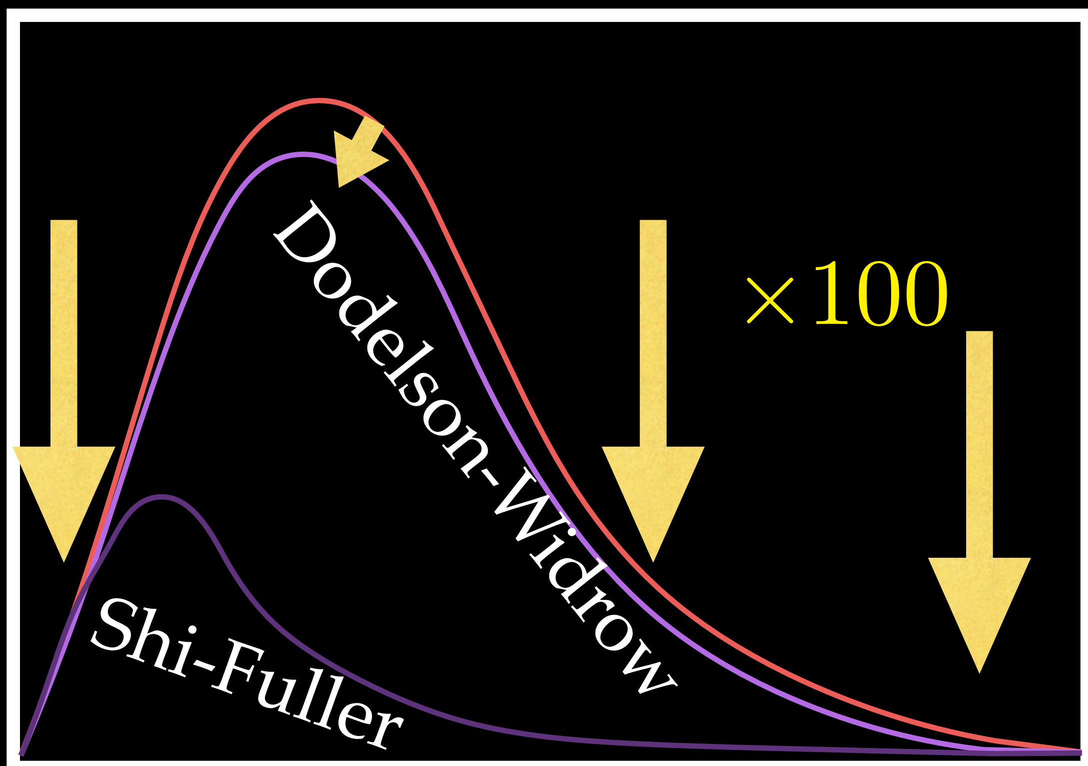

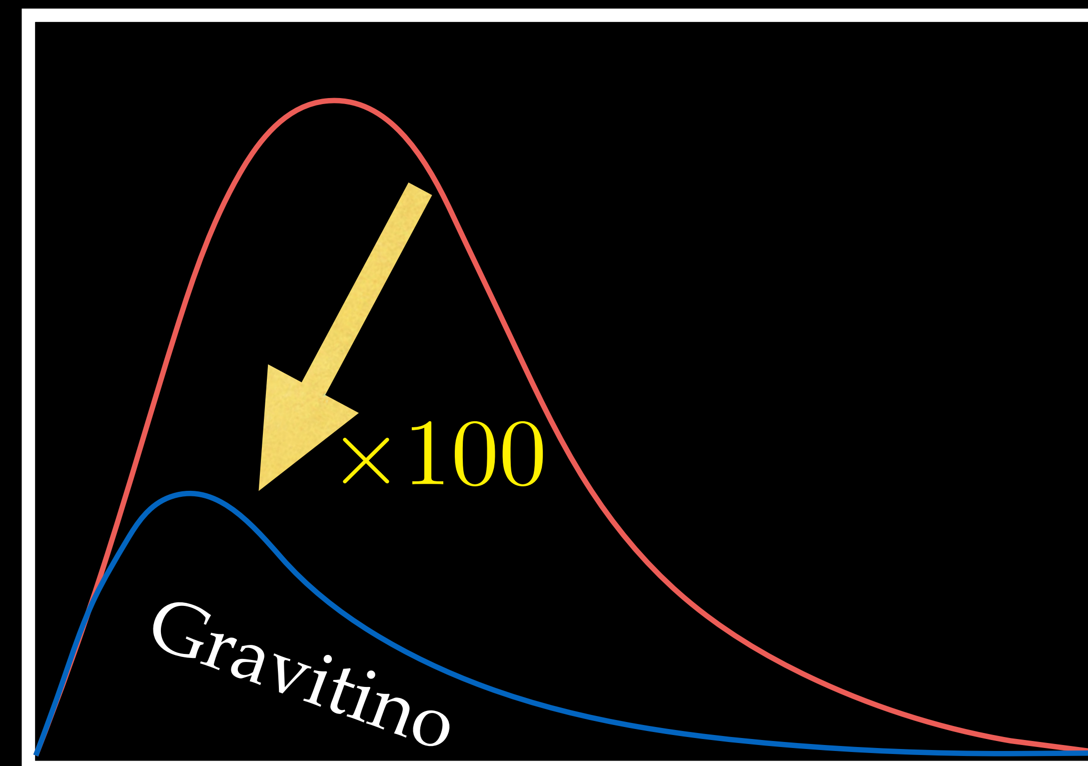

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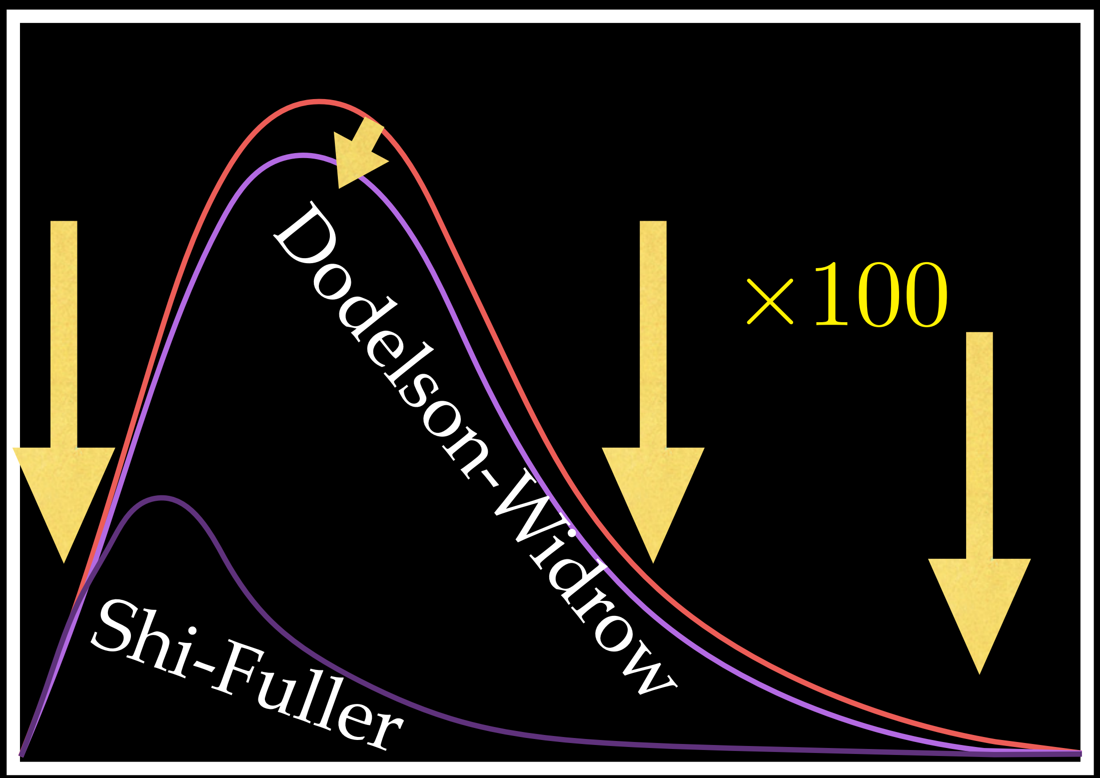

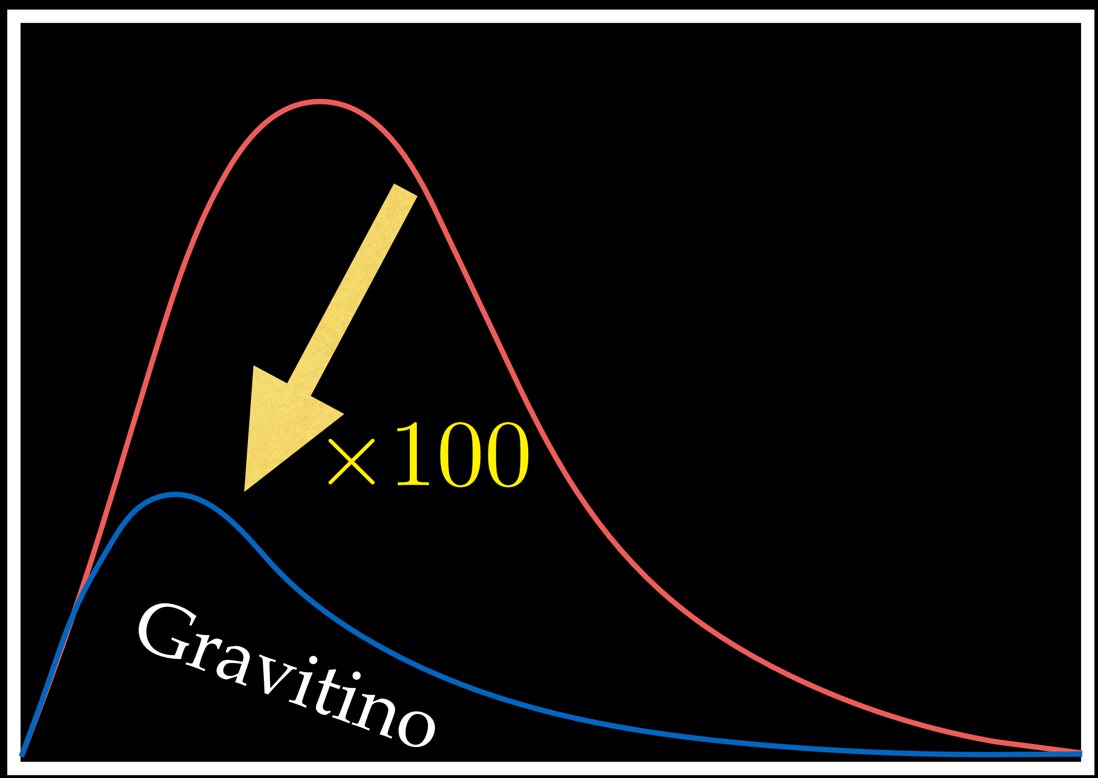

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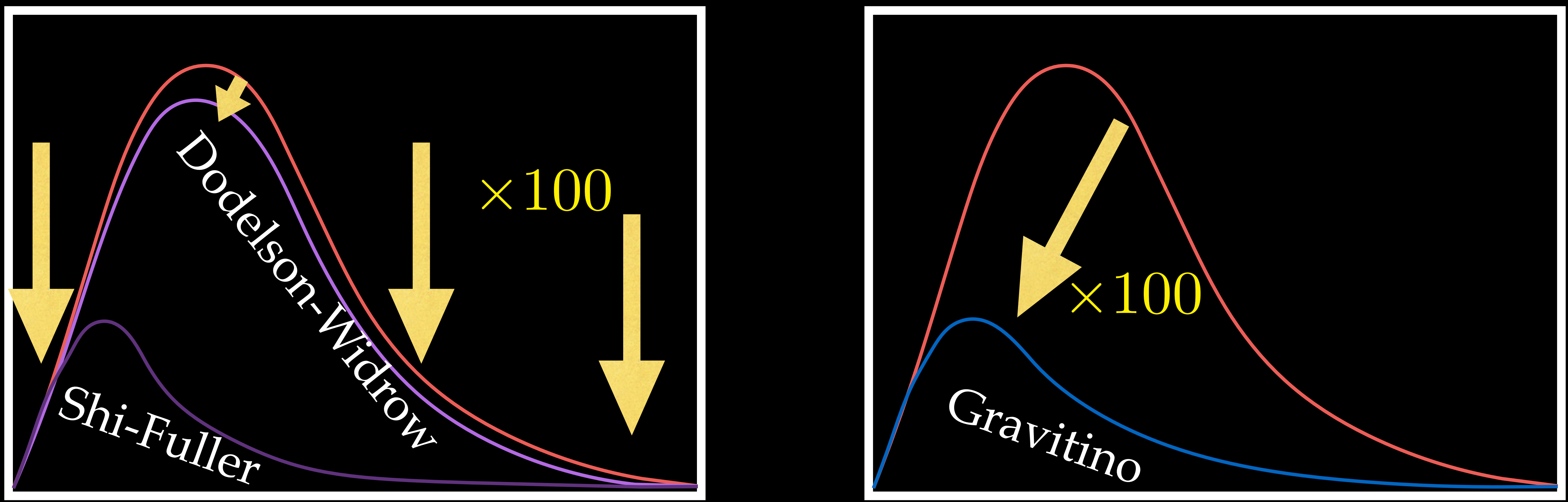

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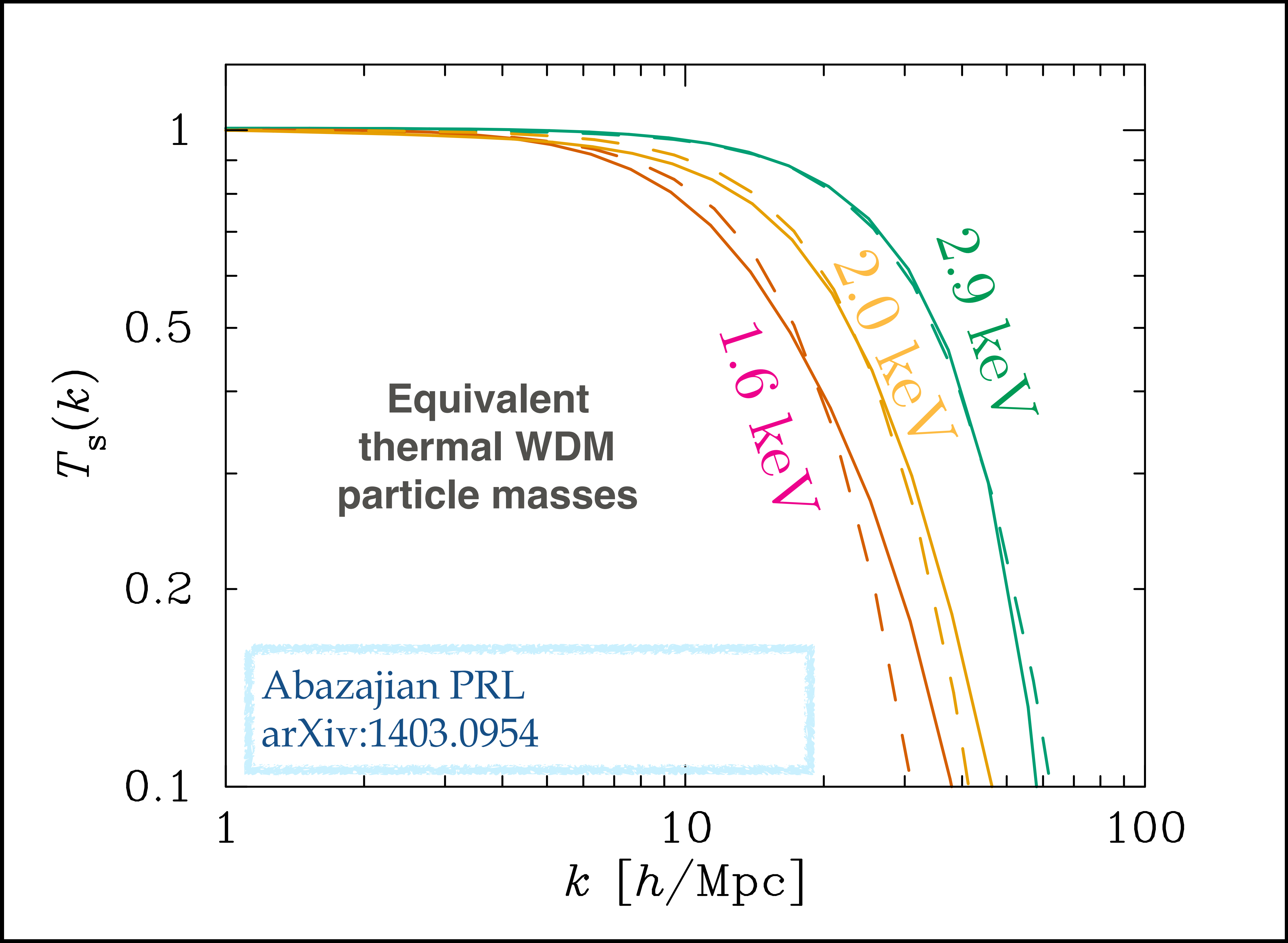
Colombi, Dodelson & Widrow astro-ph/9505029;
Abazajian astro-ph/0511630, astro-ph/0512631, arXiv:1705.01837

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



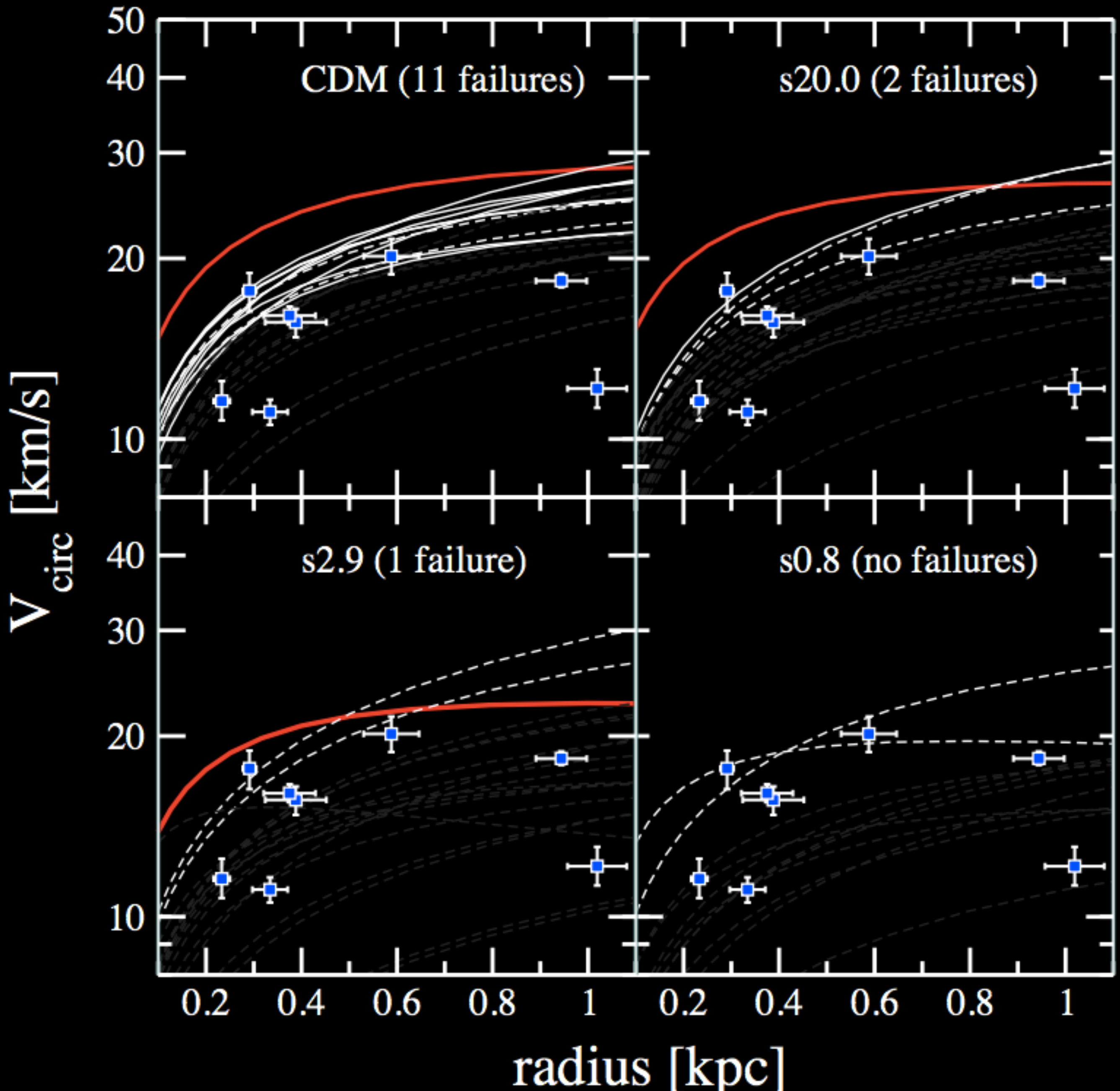
Most recent detailed production calculations: A tale of weak interactions in the strong coupling epoch

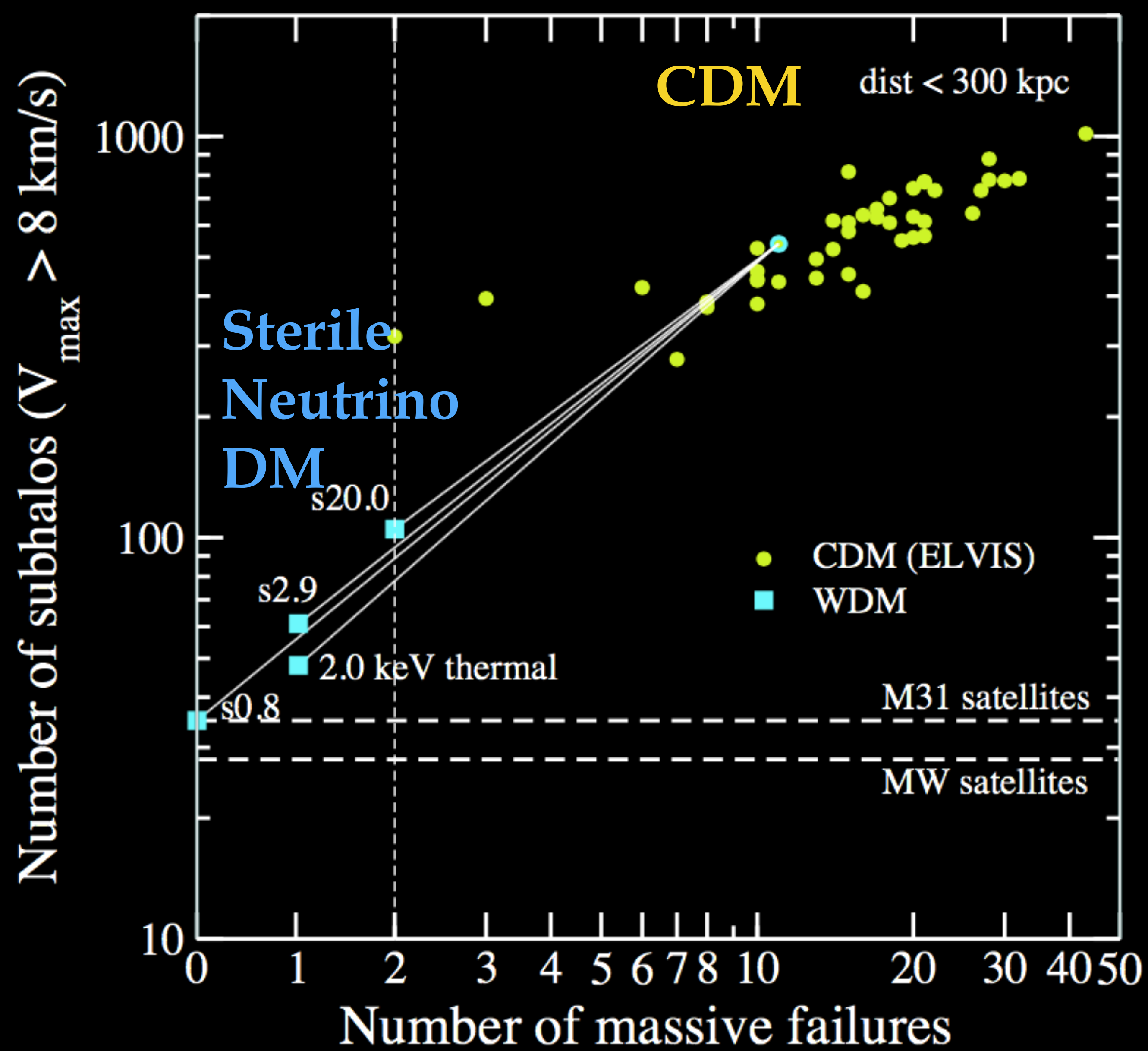
Latest production calculations include

1. Redistribution of lepton asymmetry in collisional processes
2. More accurate inclusion of neutrino scattering on leptons, hadrons, quarks
3. Updated time-temperature evolution of the plasma, and more robust numerics

Venumadhav, Cyr-Racine, Abazajian & Hirata (2016) arXiv:1507.06655

7 keV Alleviation of Too Big To Fail…





Horiuchi, Bozek, Abazajian, Boylan-Kolchin, Bullock, Garrison-Kimmel, Oñorbe MNRAS 2015

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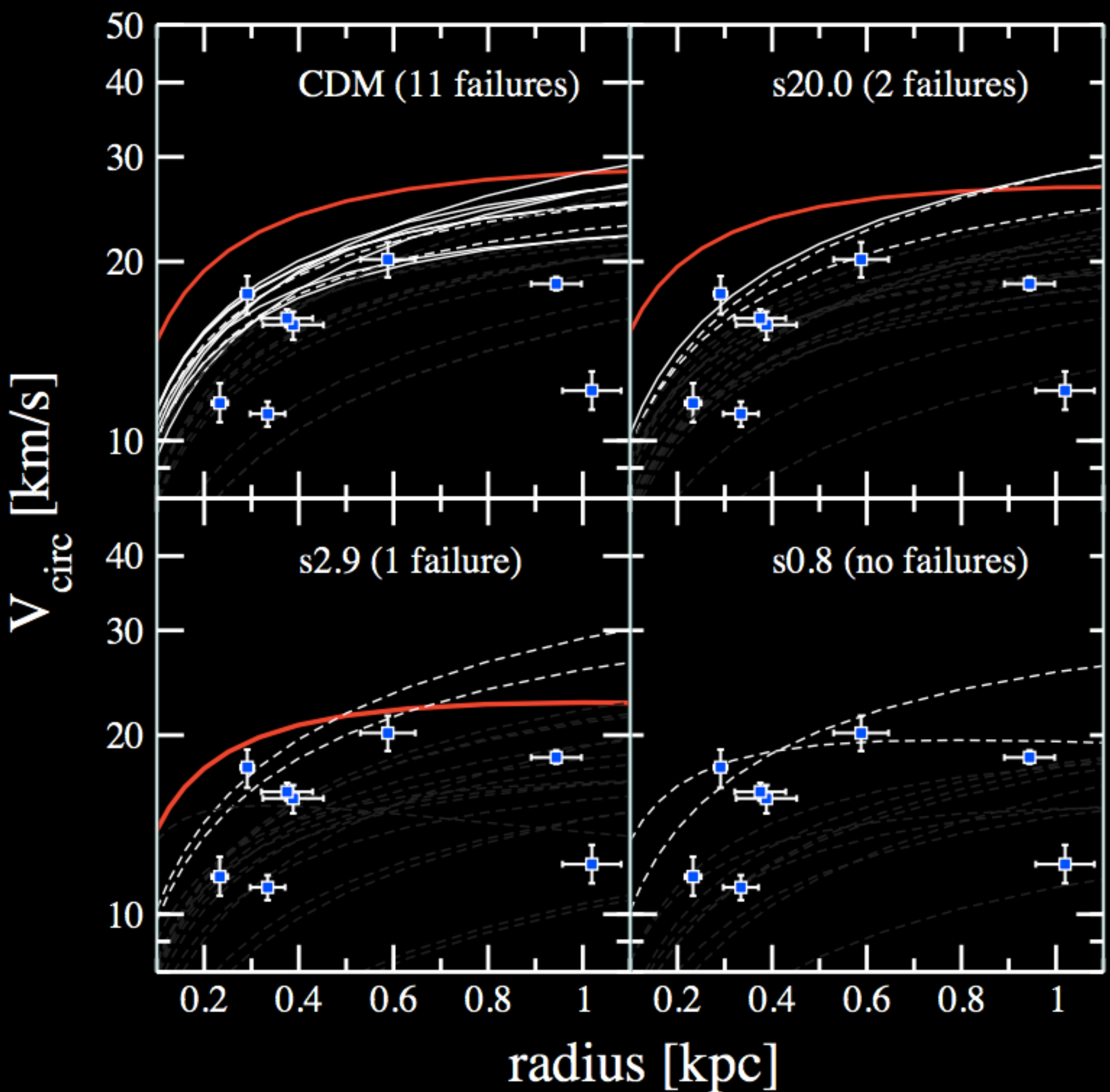

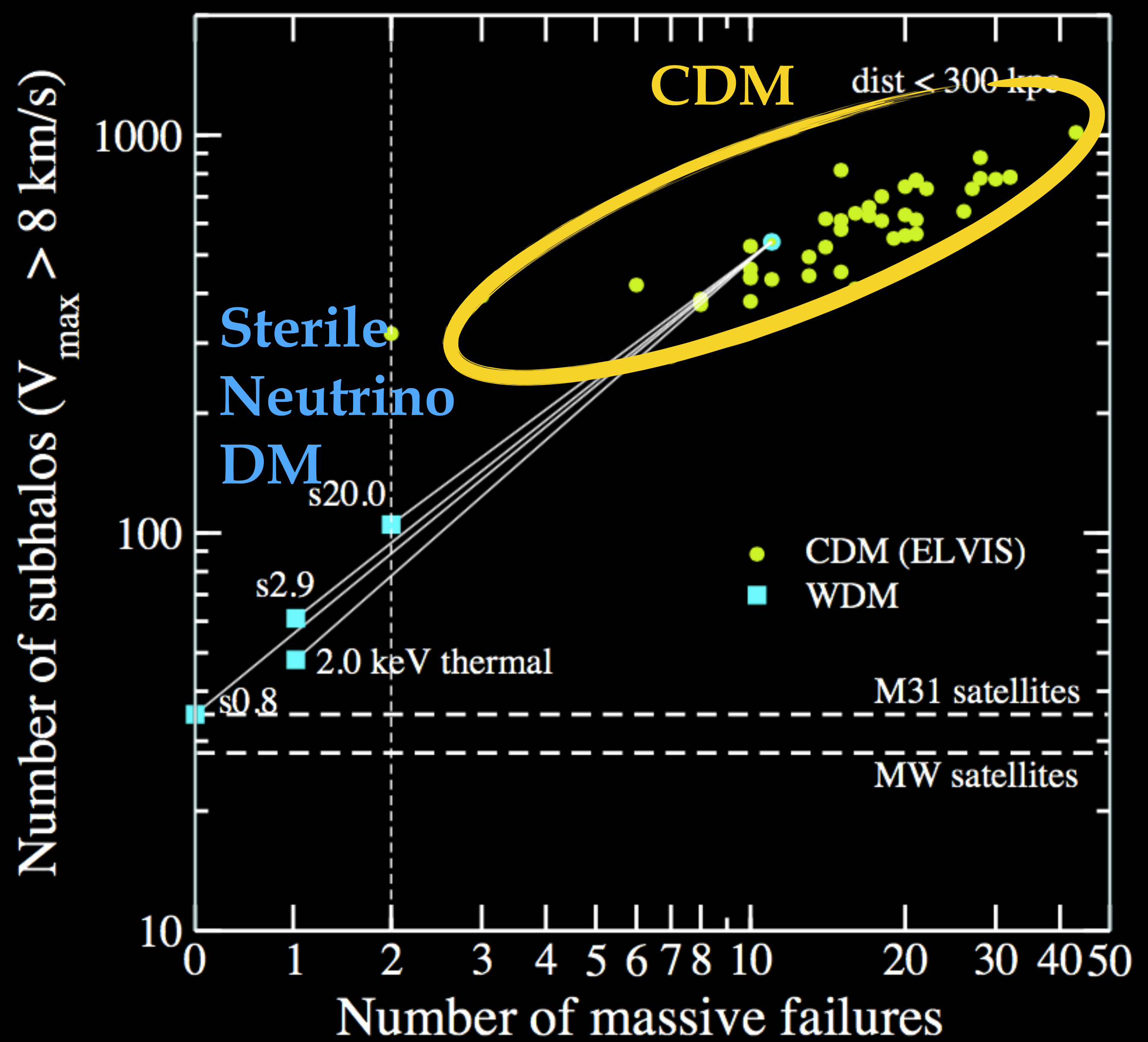

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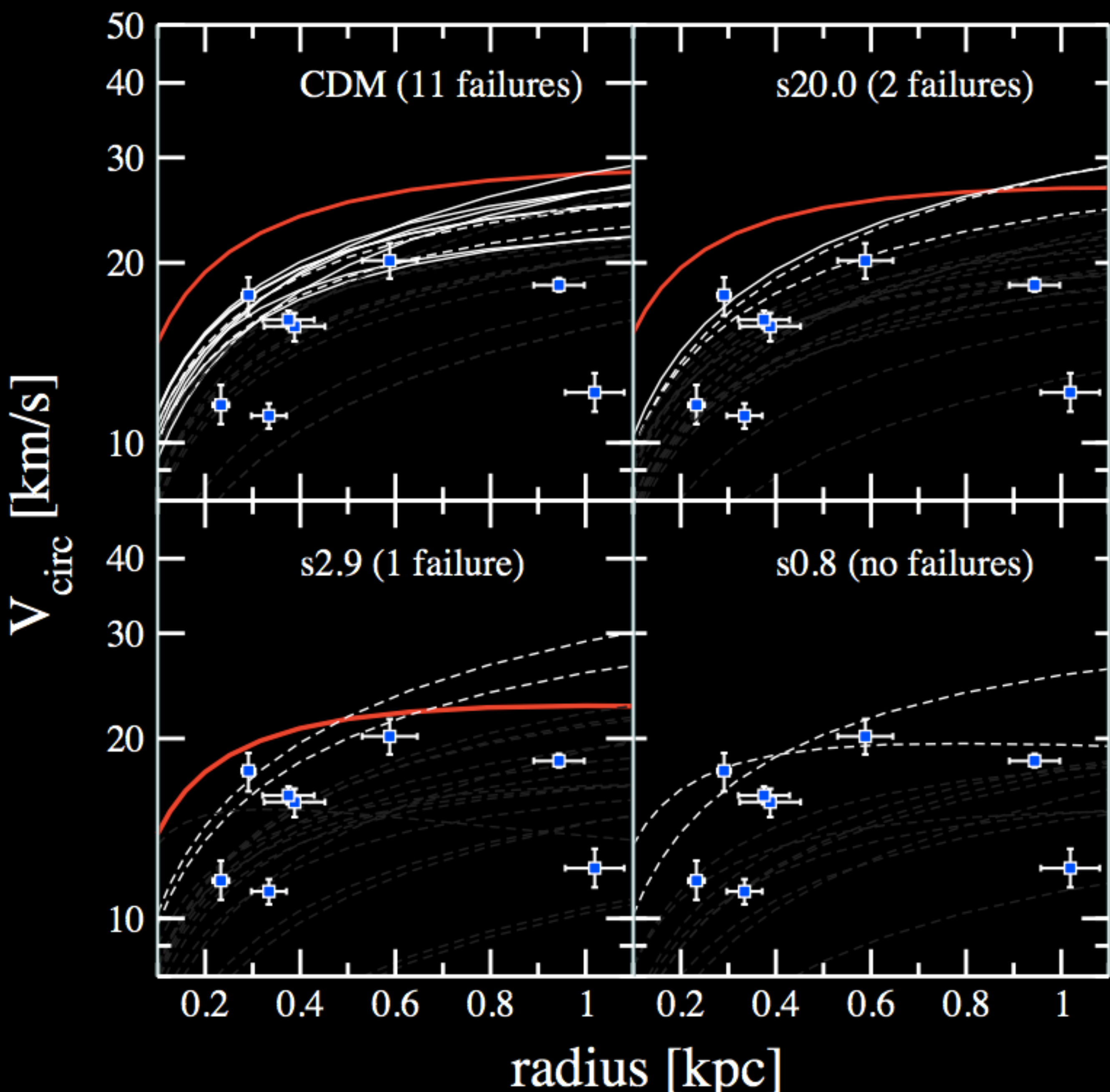

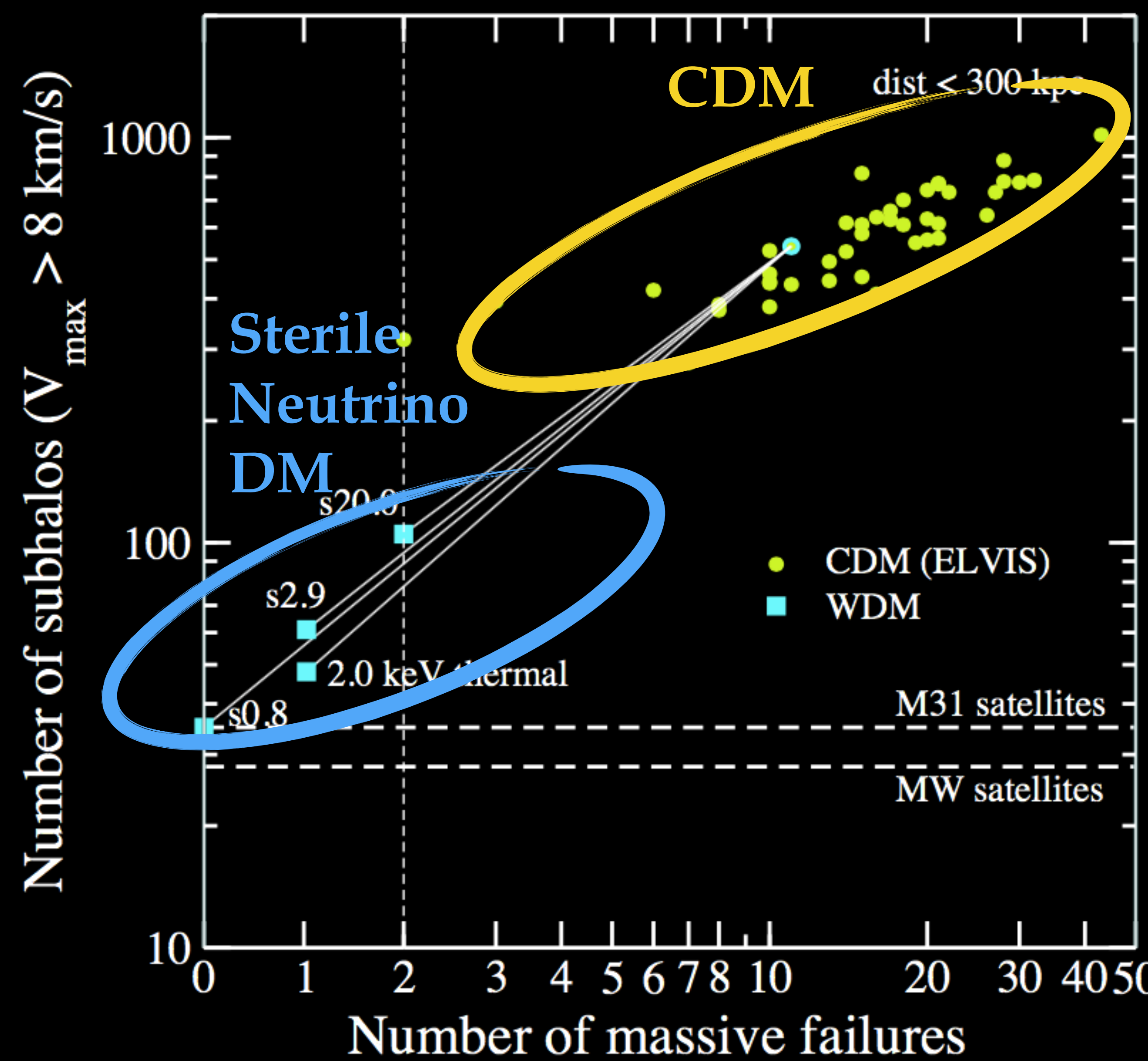

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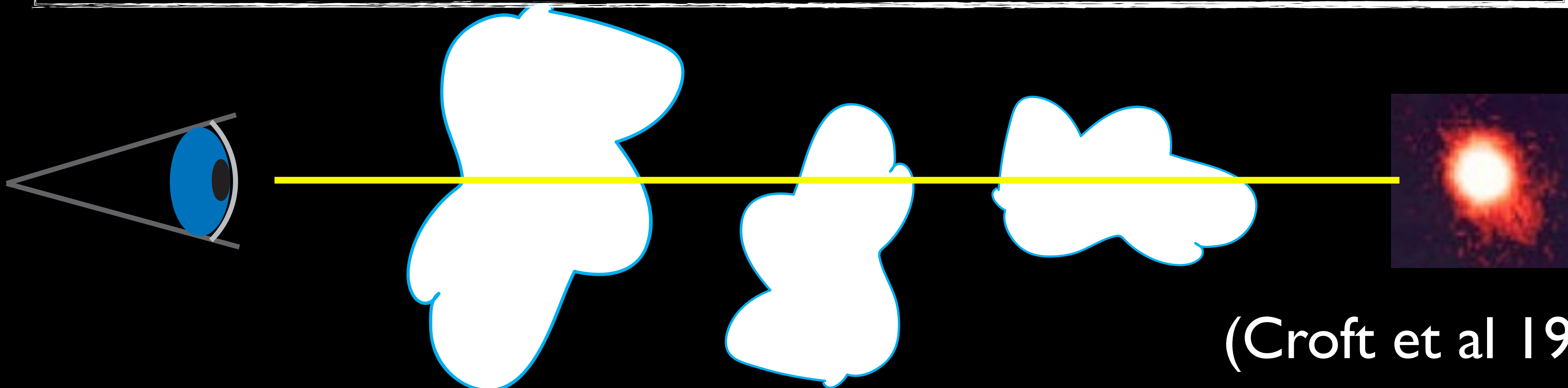
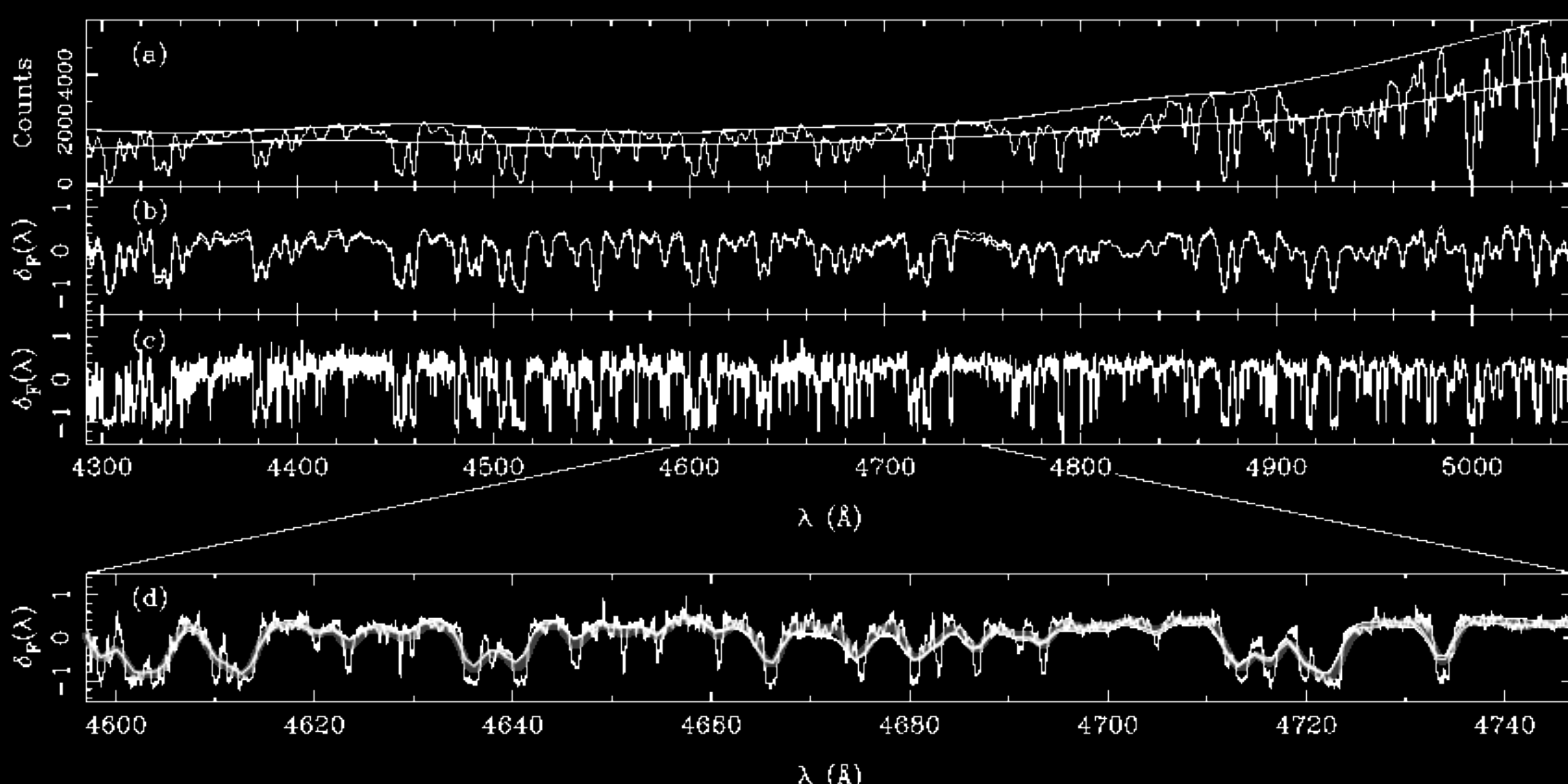
The Lyman-α Forest: Powerful & Challenging



(Croft et al 1999)



Iršič 1702.01764:

$m_{\mathrm{thermal}} > 5.3$ keV

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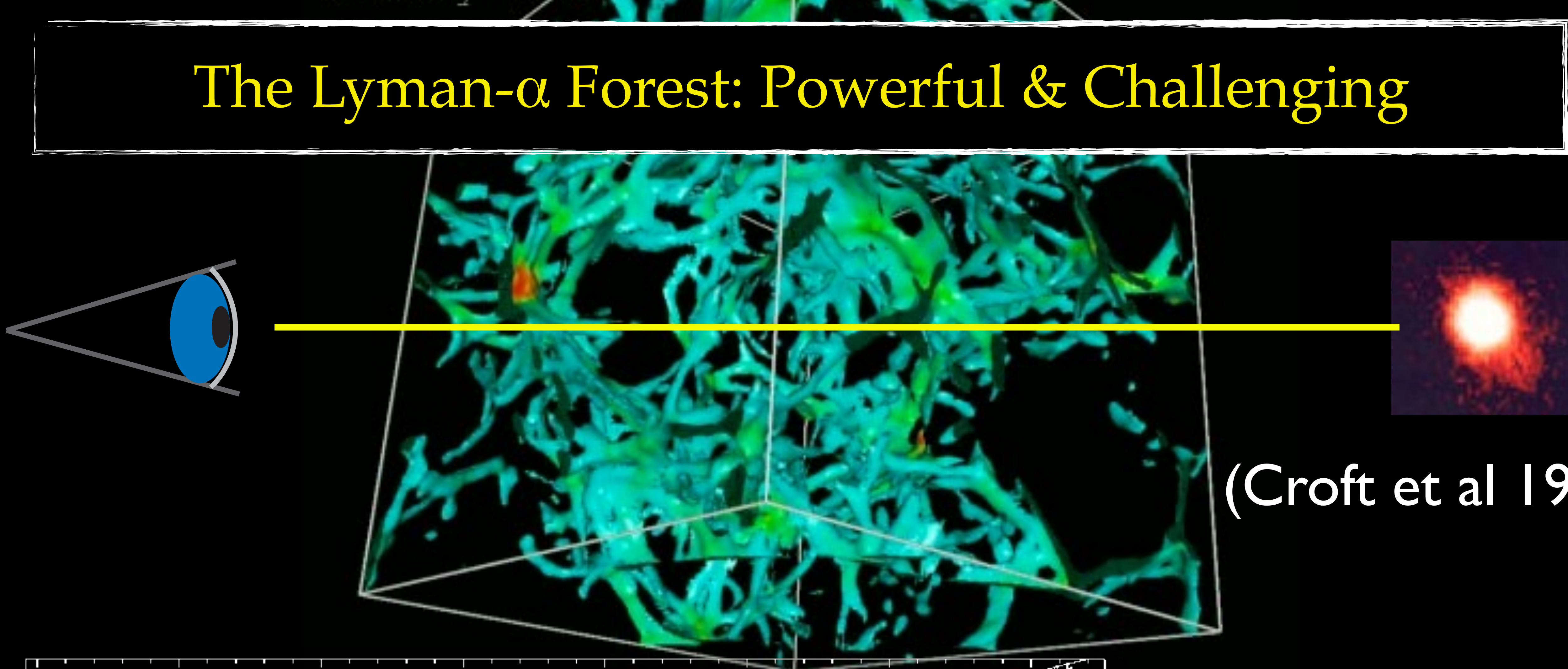

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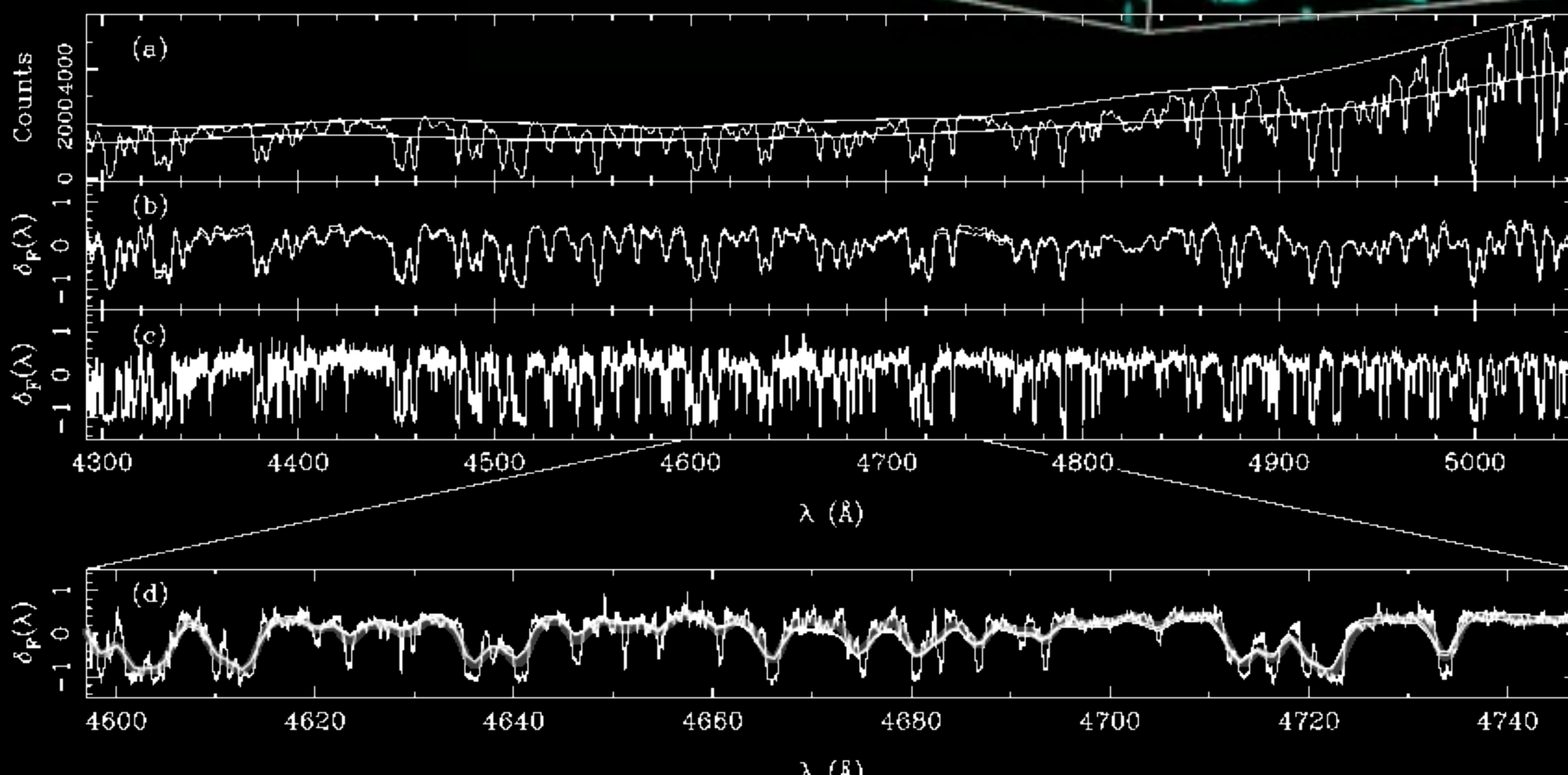

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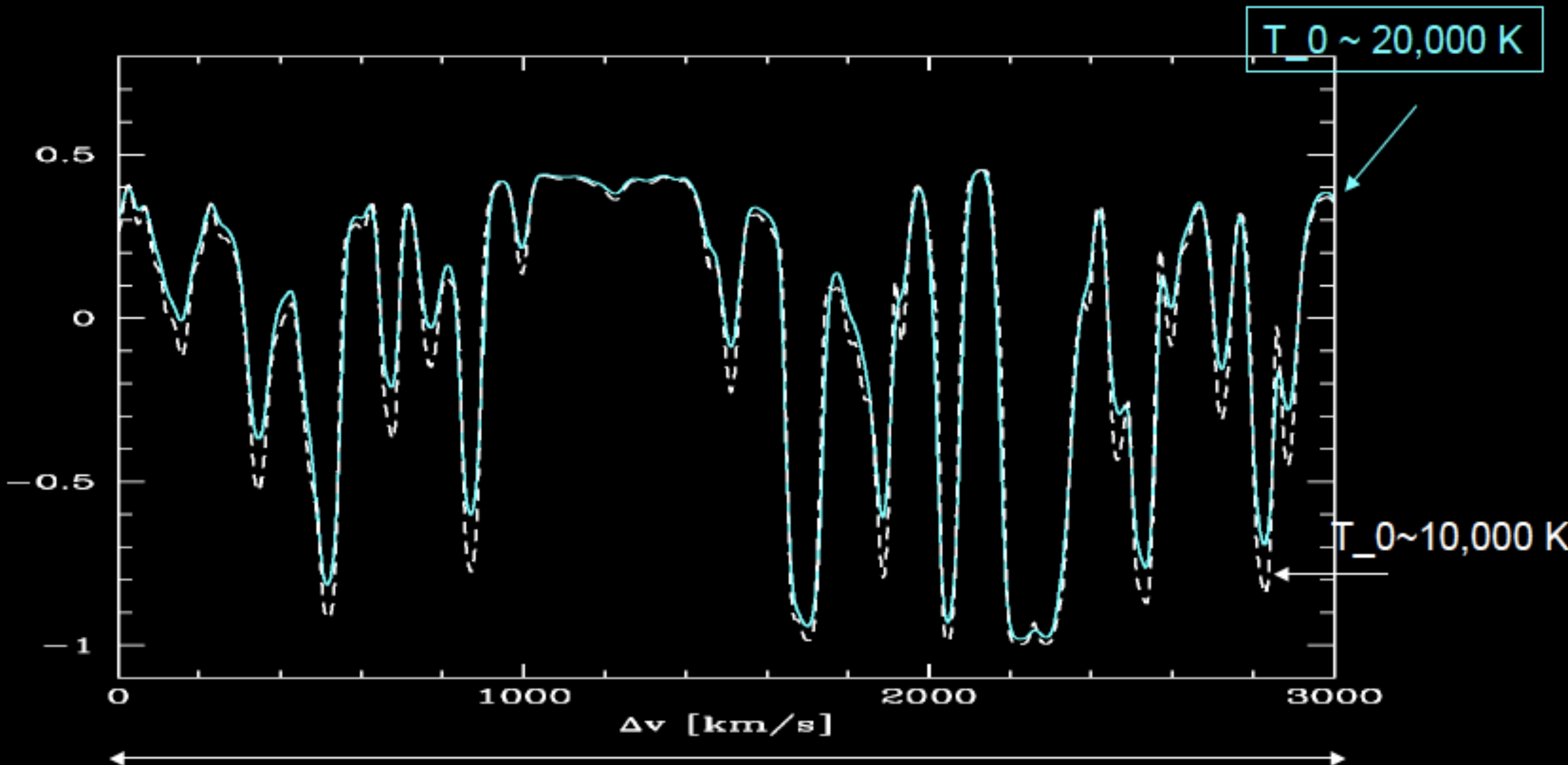
T impacts structure of H I Ly-a Forest

Doppler broadening and Jeans-smoothing….



~ 30 mpc/h co-moving

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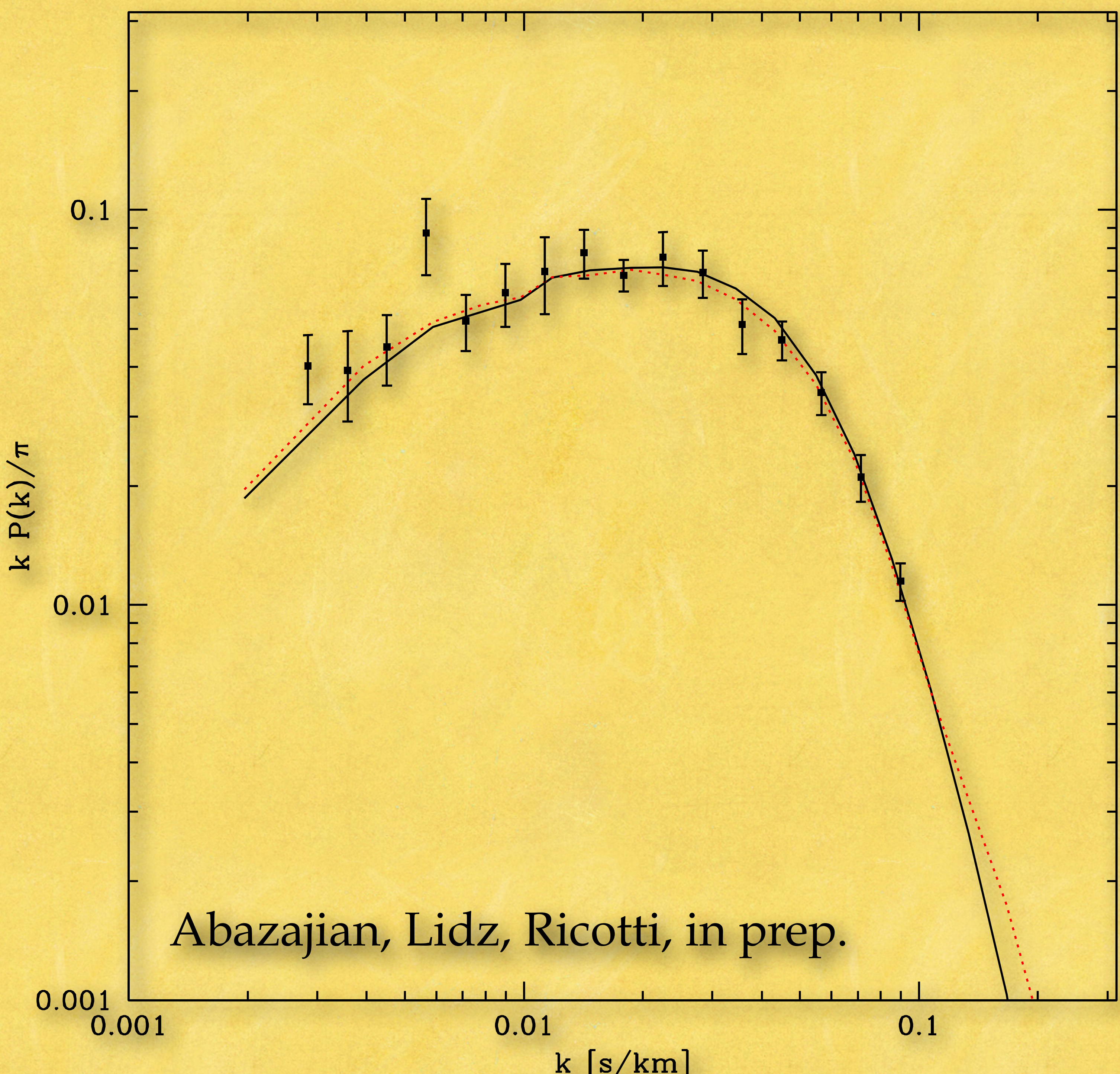

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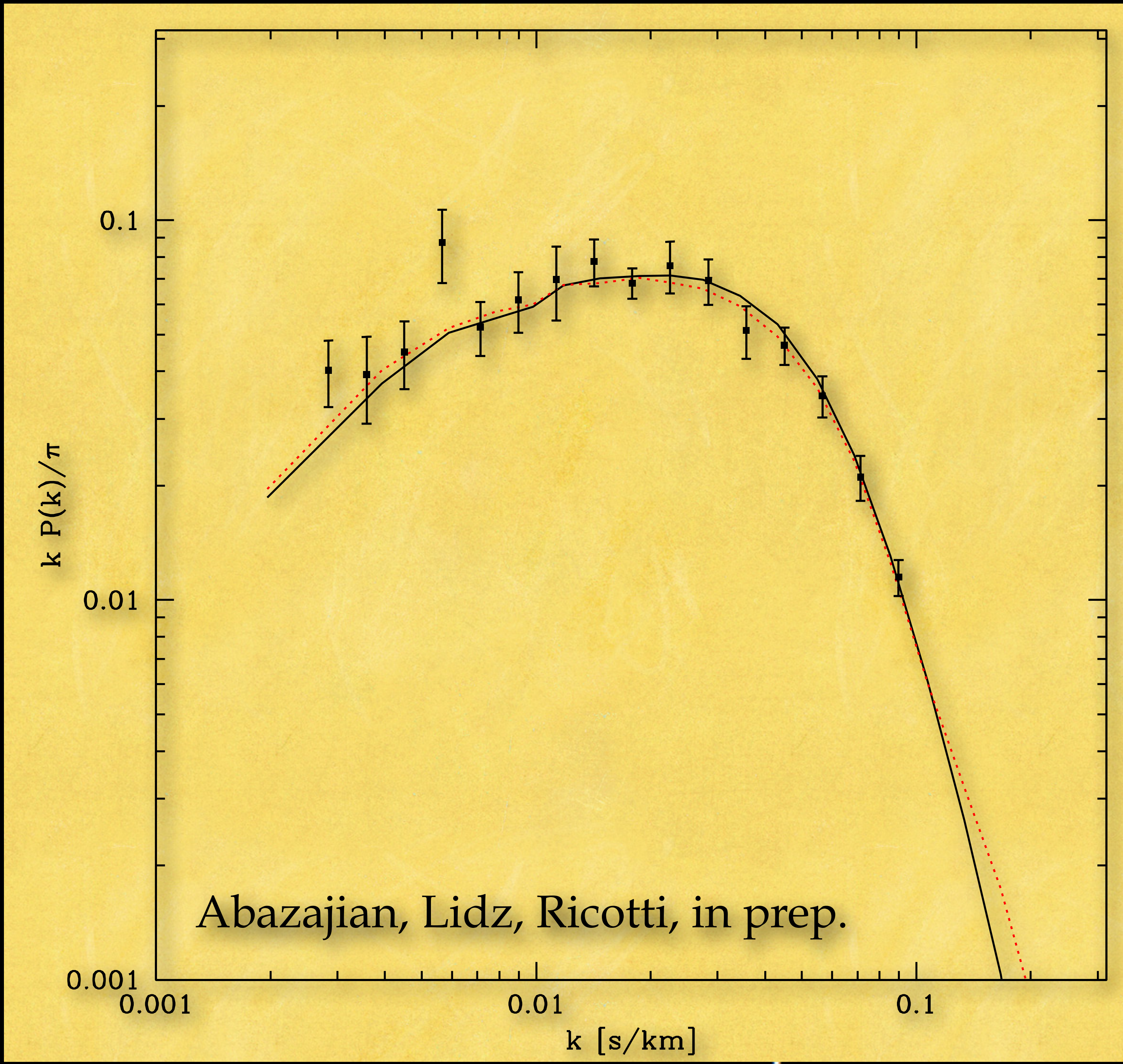
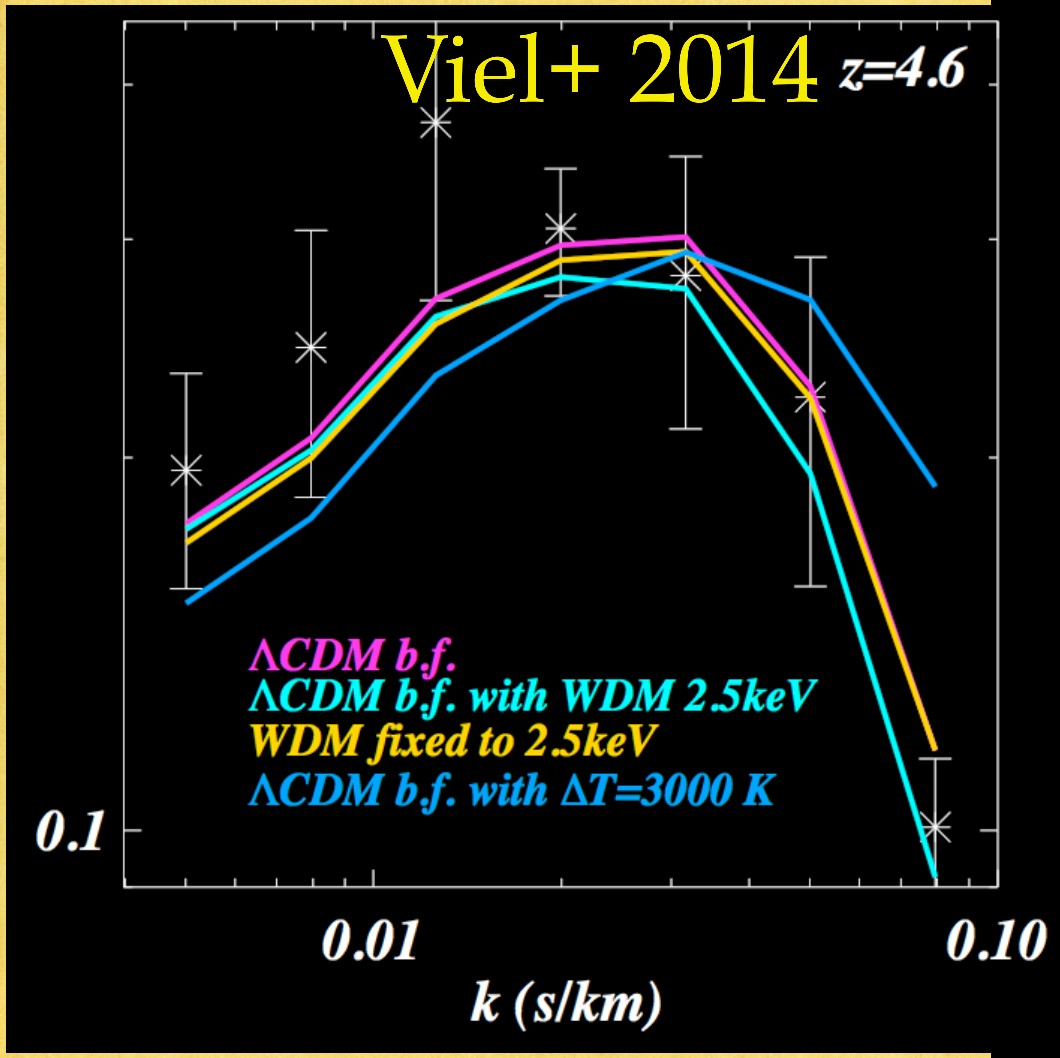




The Lyman-α Forest: Powerful & Challenging

The Astrophysical Journal, 812:30 (15pp), 2015 October 10 Kulkarni et al.

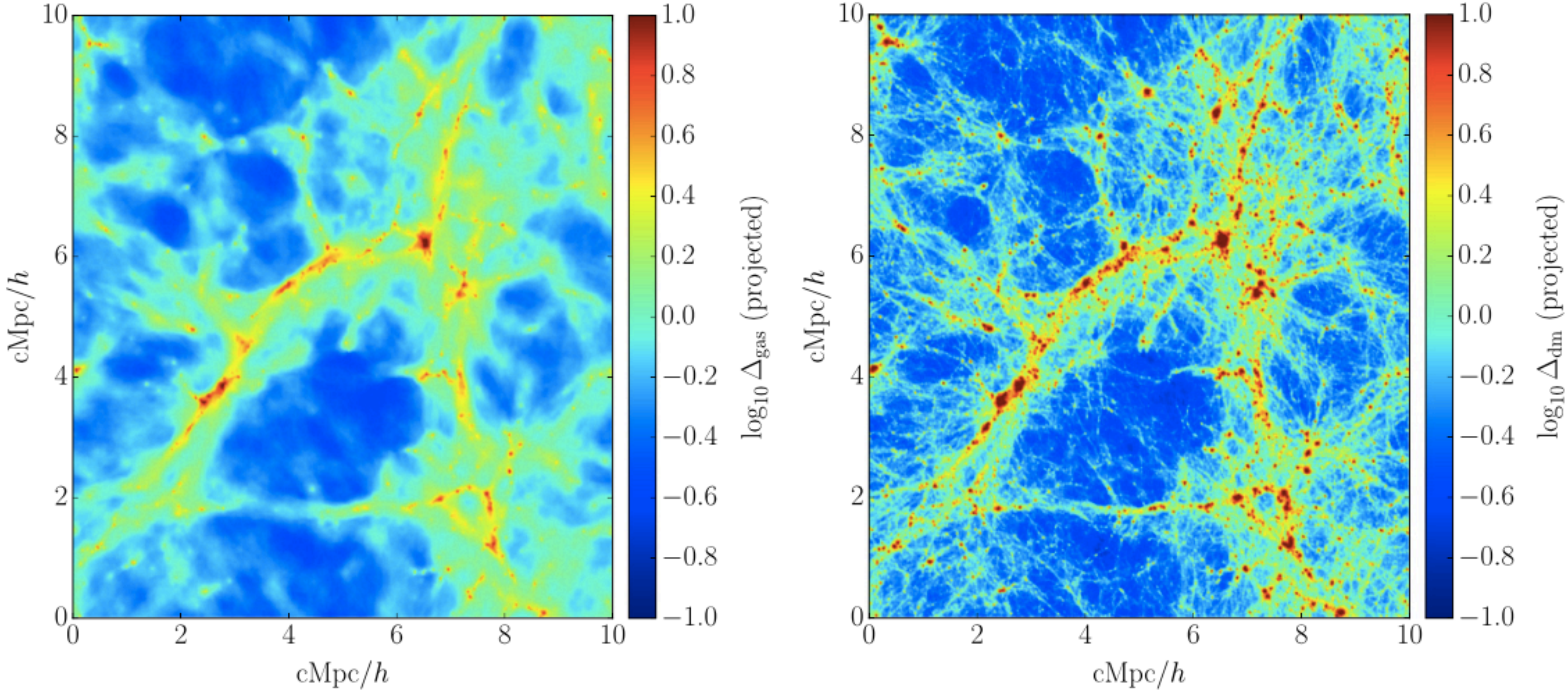
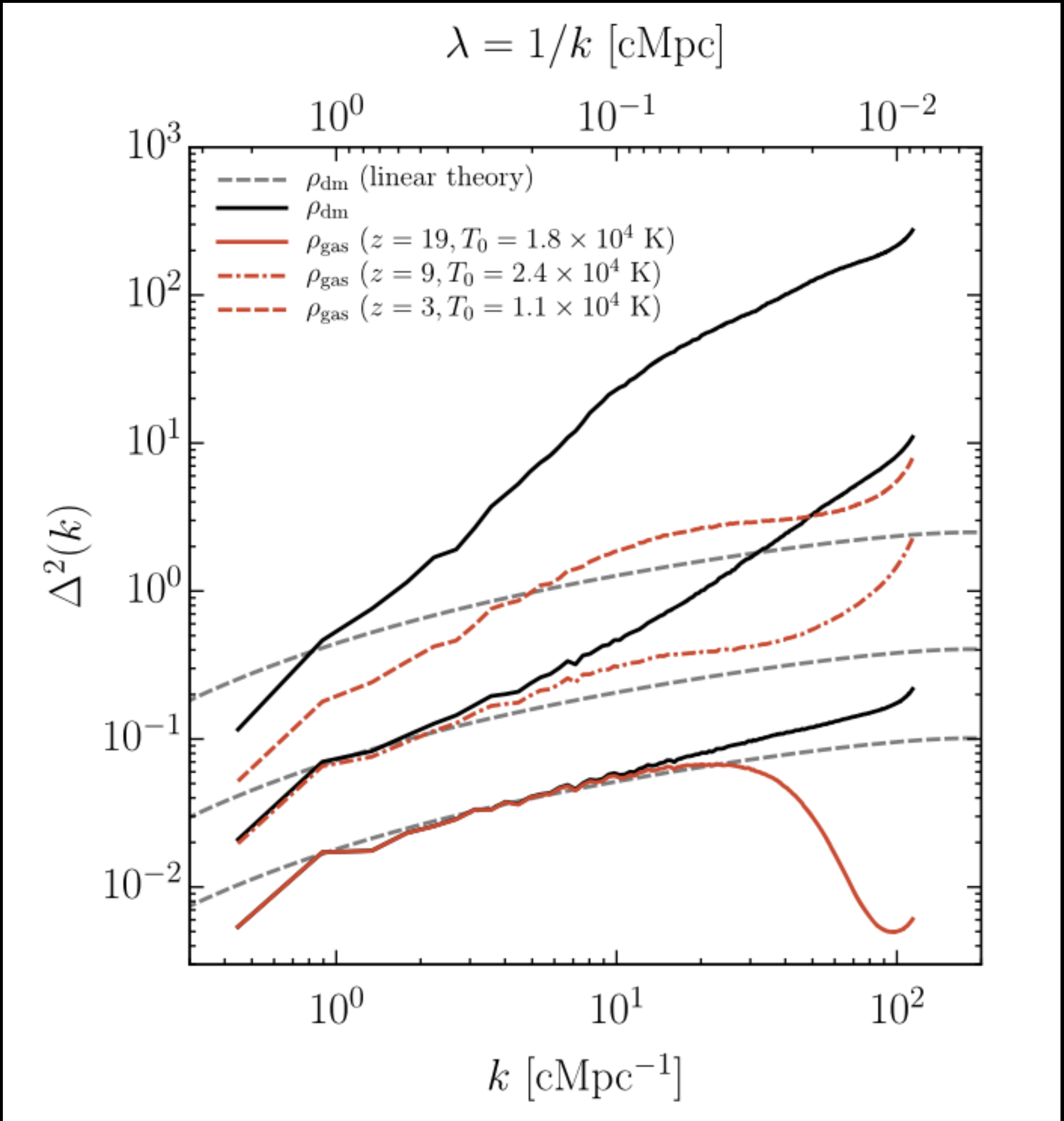


Figure 1. Projected density distributions of gas (left) and dark matter (right) at $z = 3$ in our fiducial simulation, showing pressure smoothing of gas relative to dark matter. The density at each point is an average for a column approximately 5 Mpc/h long.

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)

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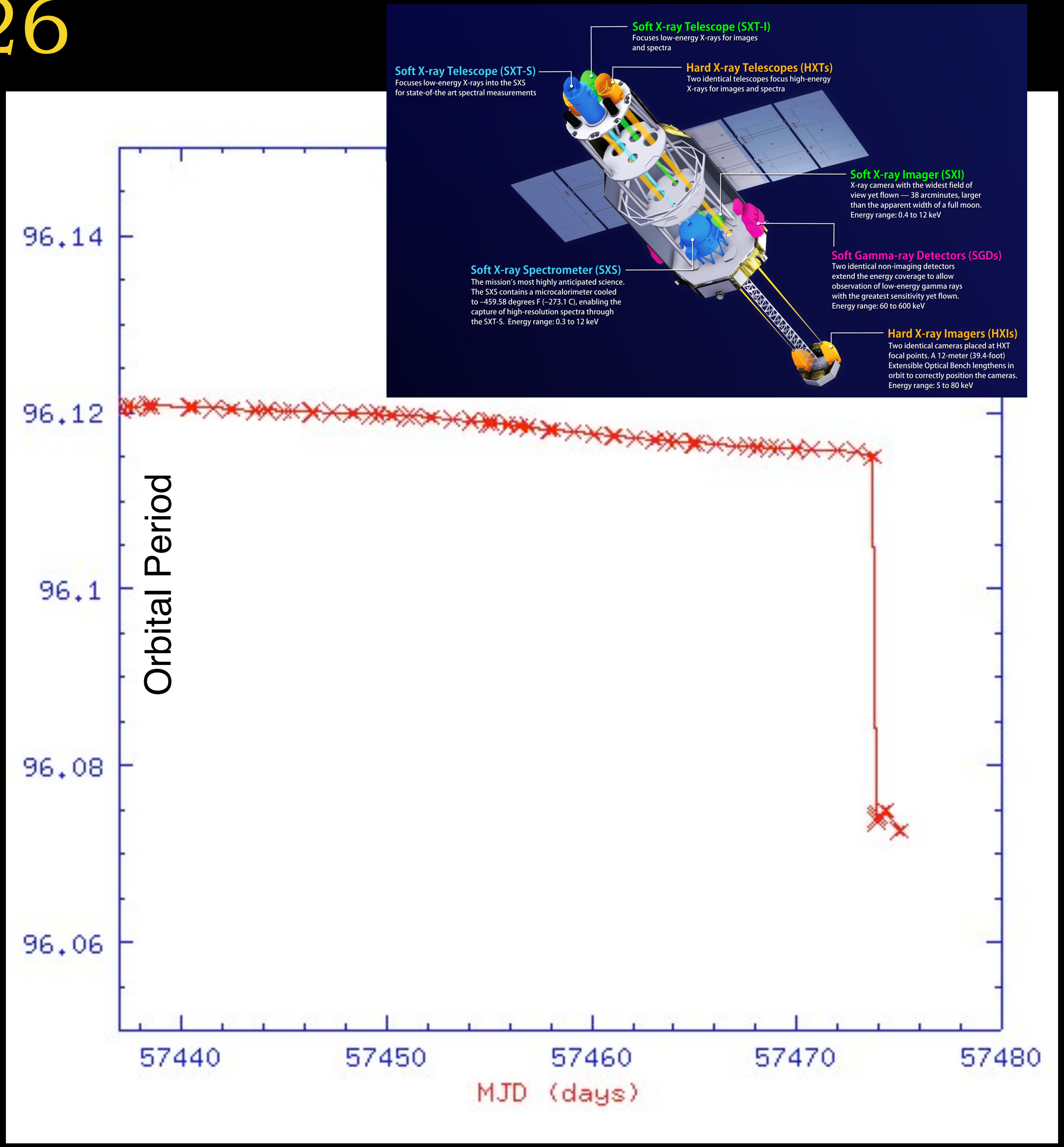
  - » The Bulbul+ team showed that JP use over-simplified single-temperature model arguments with incorrect line ratios in their X-ray cluster modeling [arXiv:1409.0920].

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

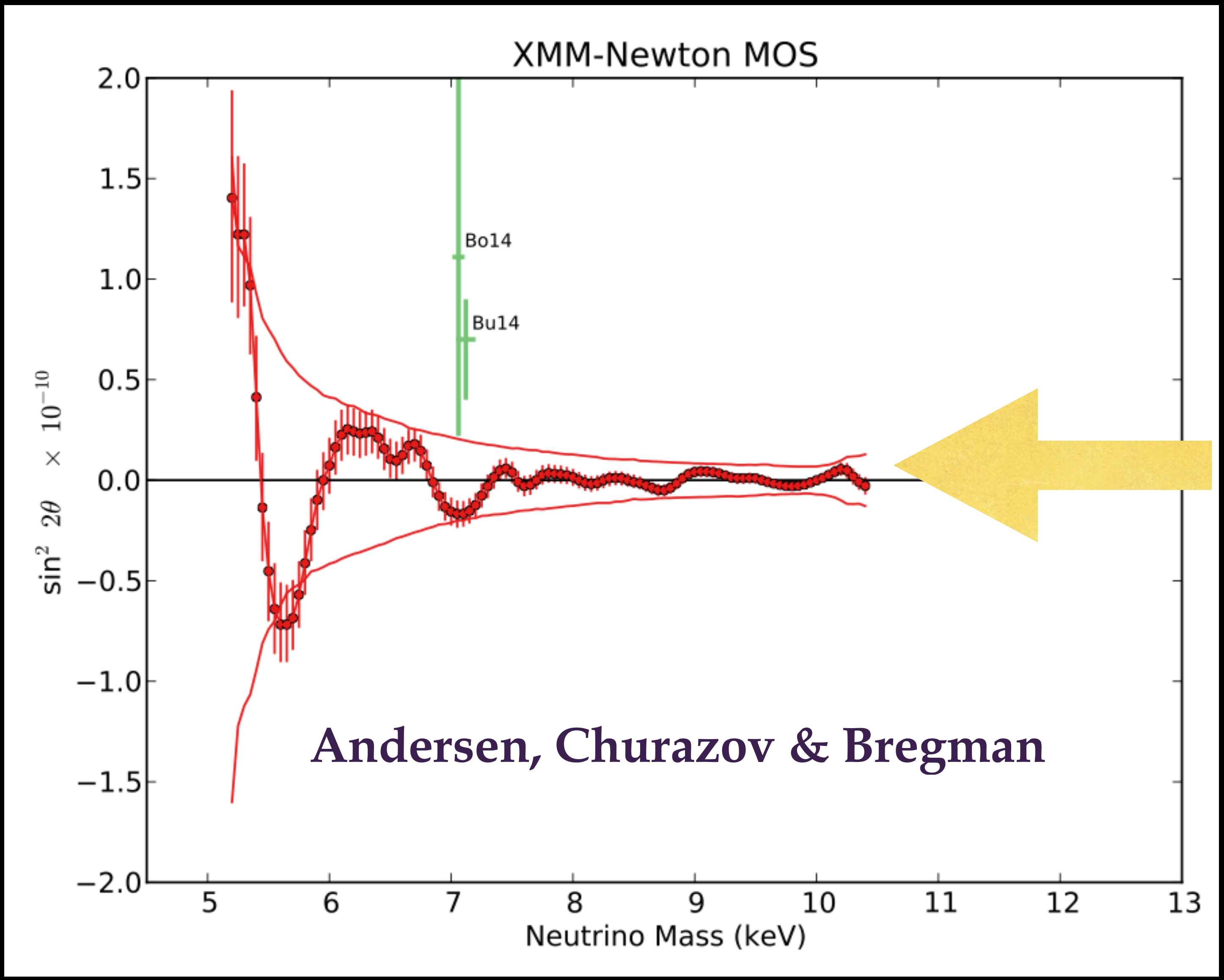


JAXA Press Releases:

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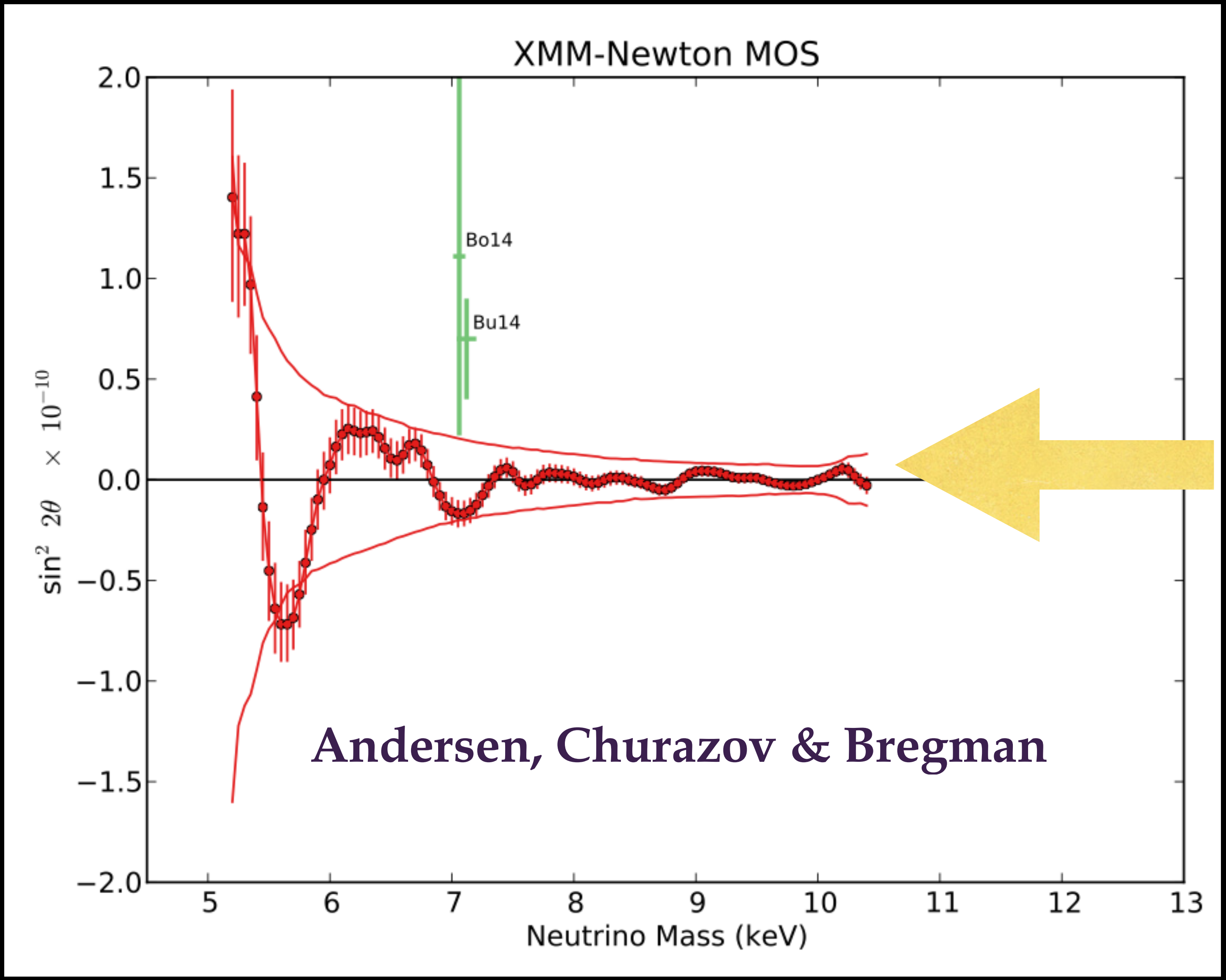
Sample of 81 galaxies observed with Chandra and a sample of 89 galaxies observed with XMM-Newton, using outskirts of the galaxies (Andersen, Churazov & Bregman 2014)



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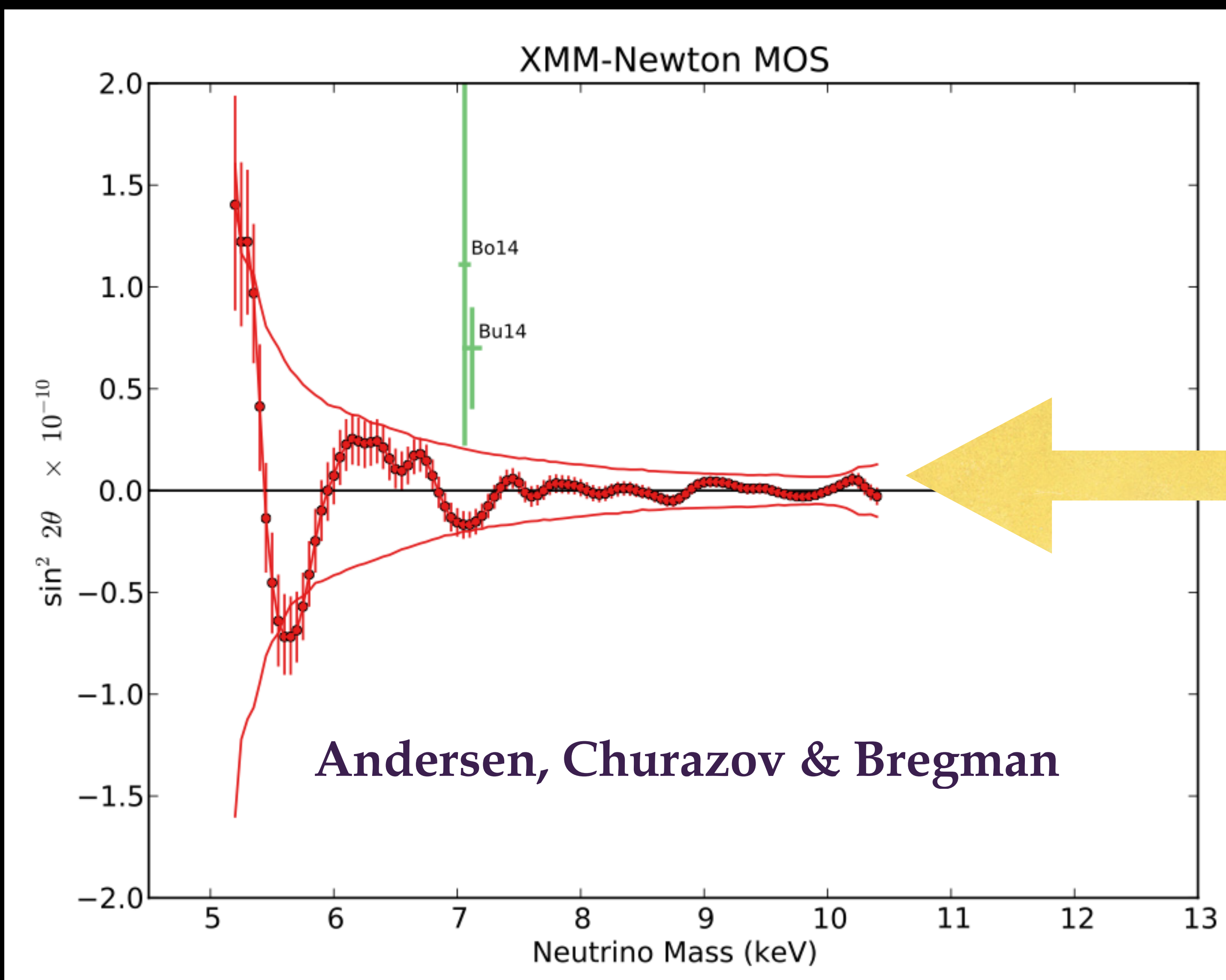

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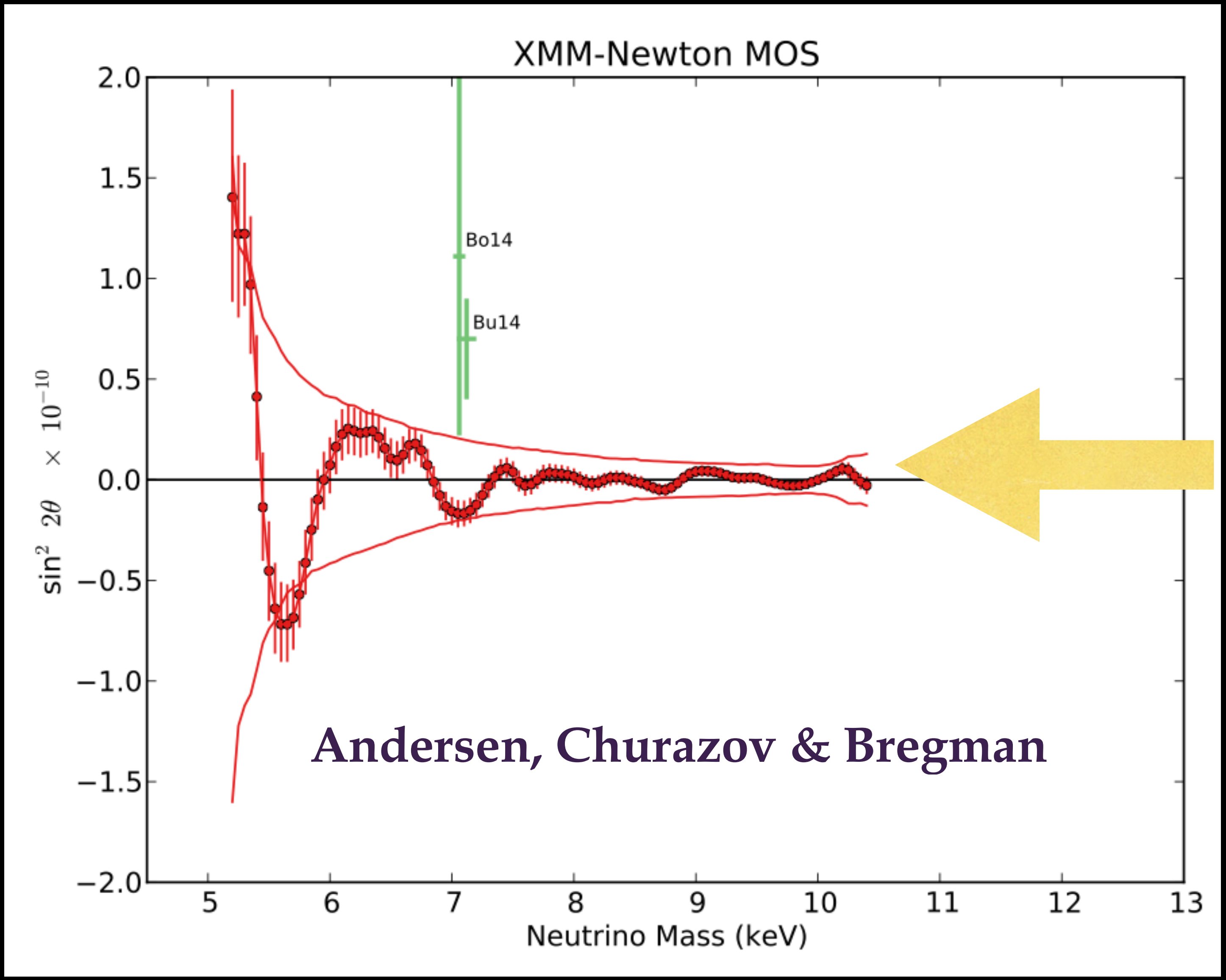

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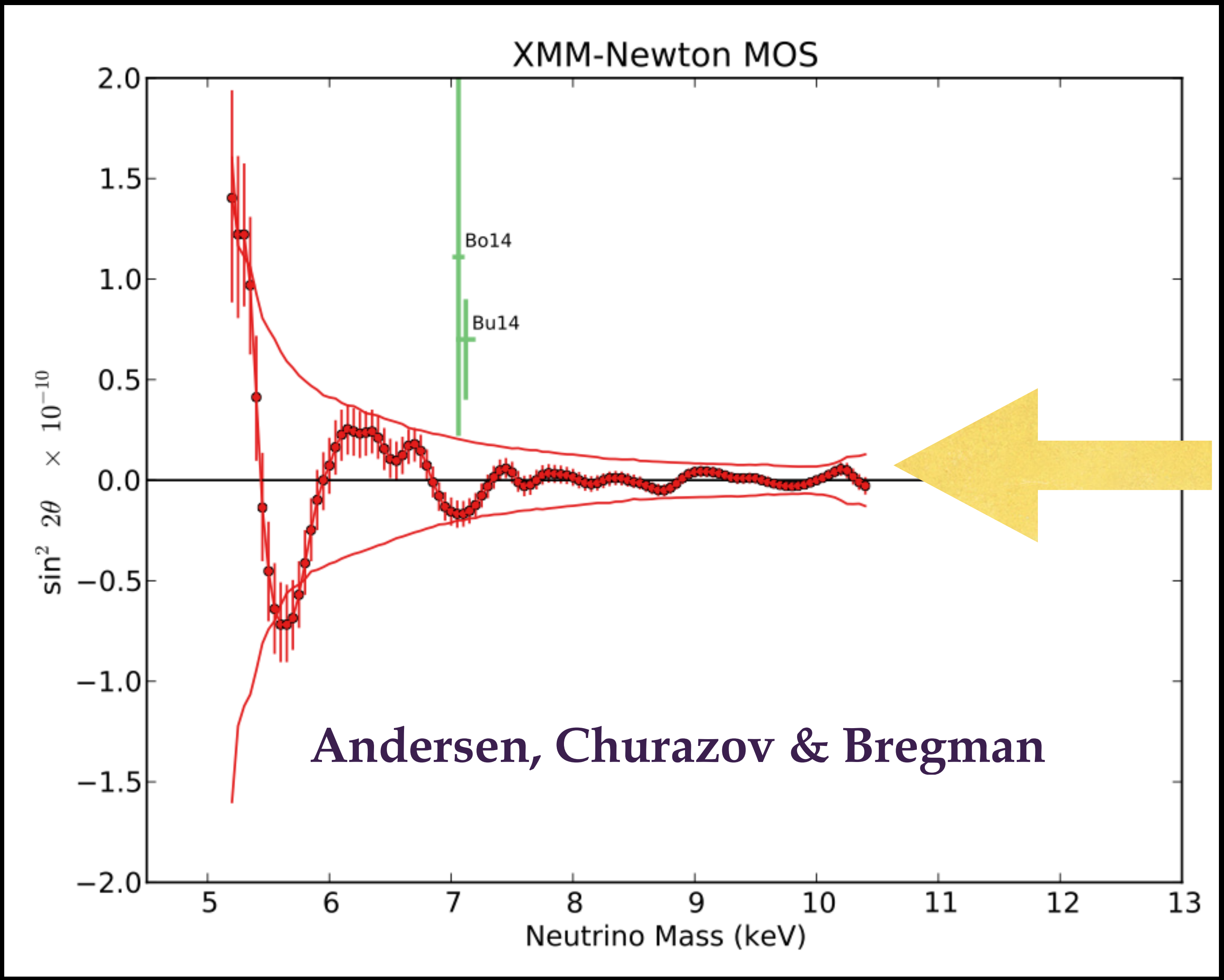

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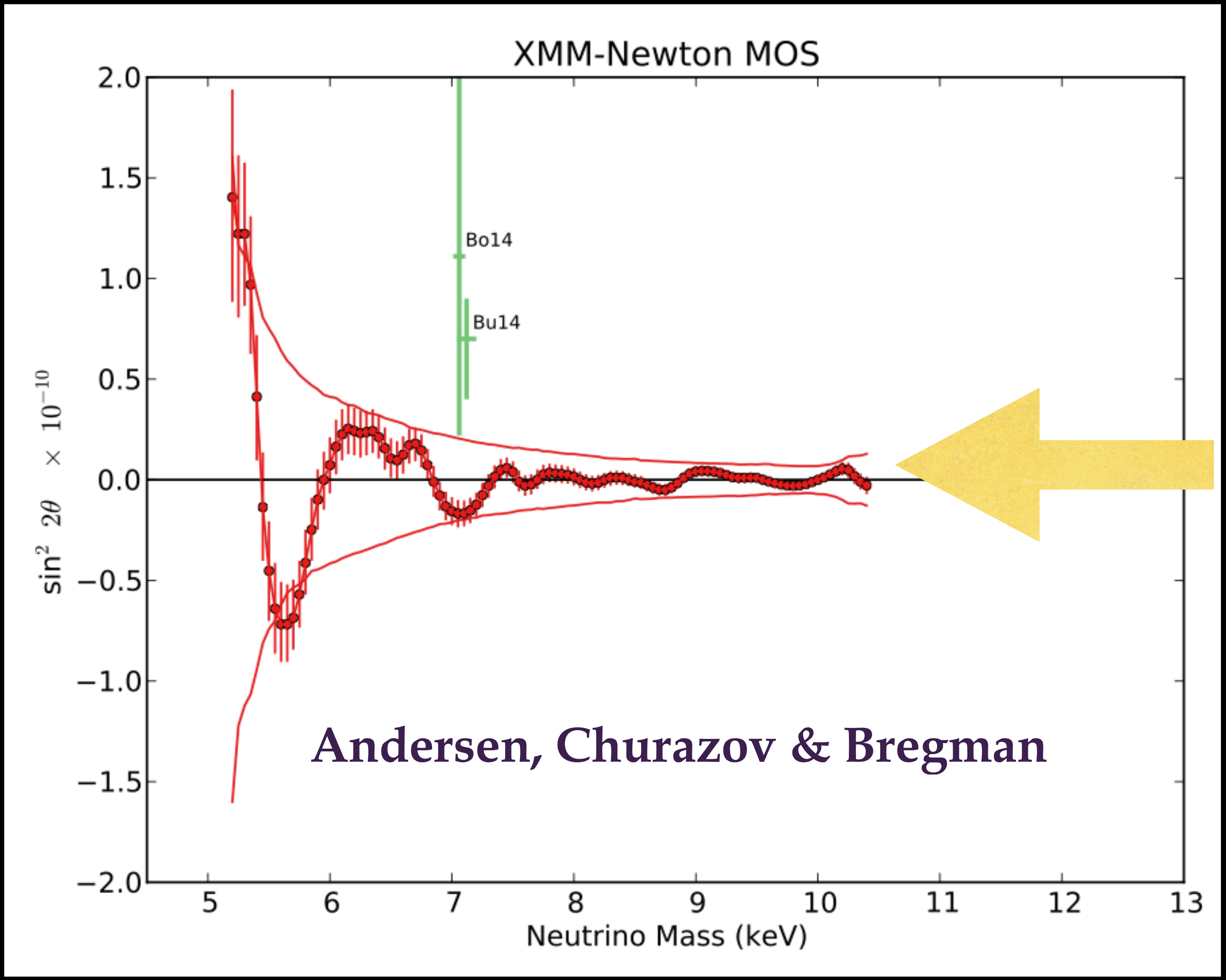

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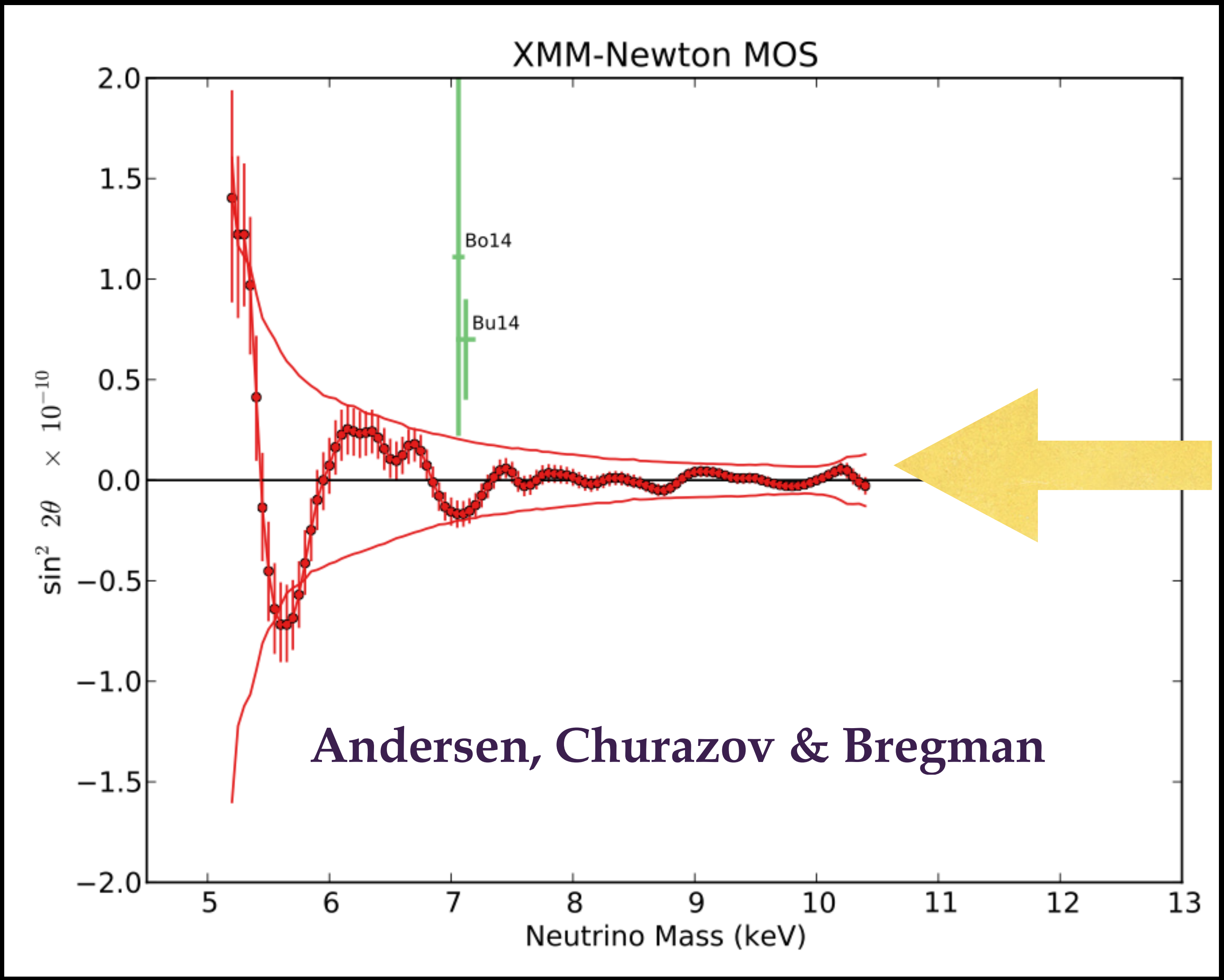

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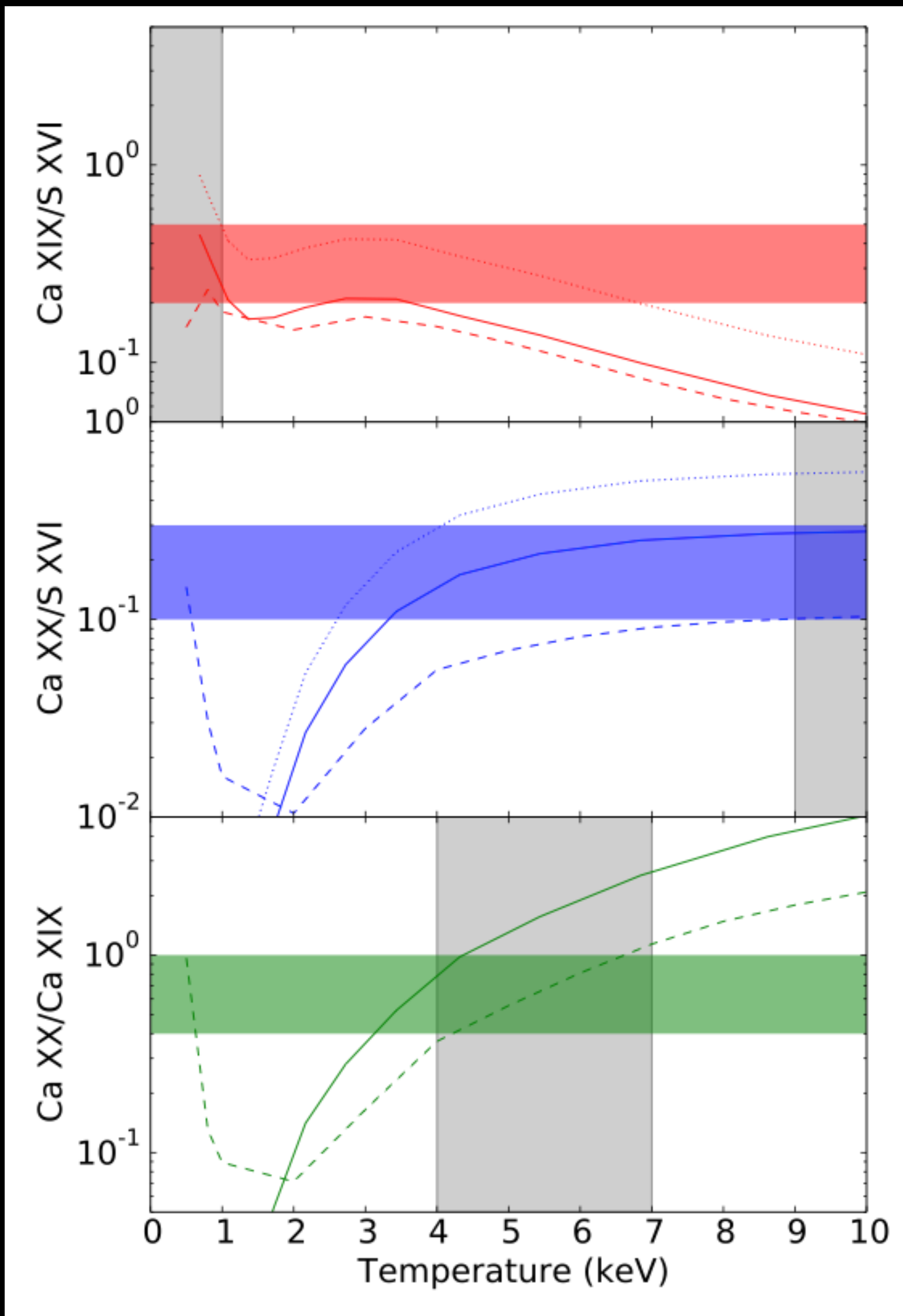
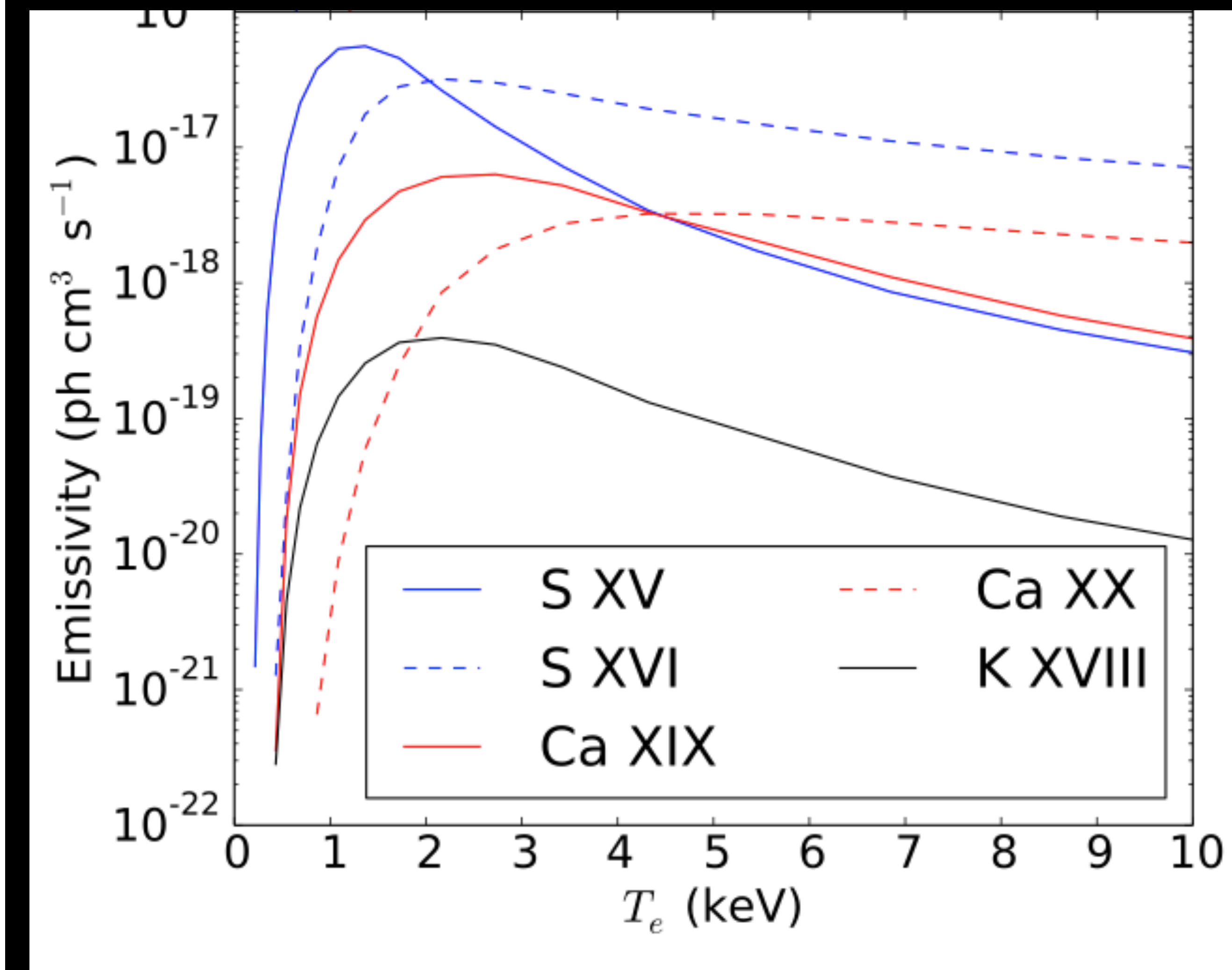
Proper methodology would find a more robust, less systematics dominated method & not quote irrelevant statistical evidence which reach an invalid conclusion.

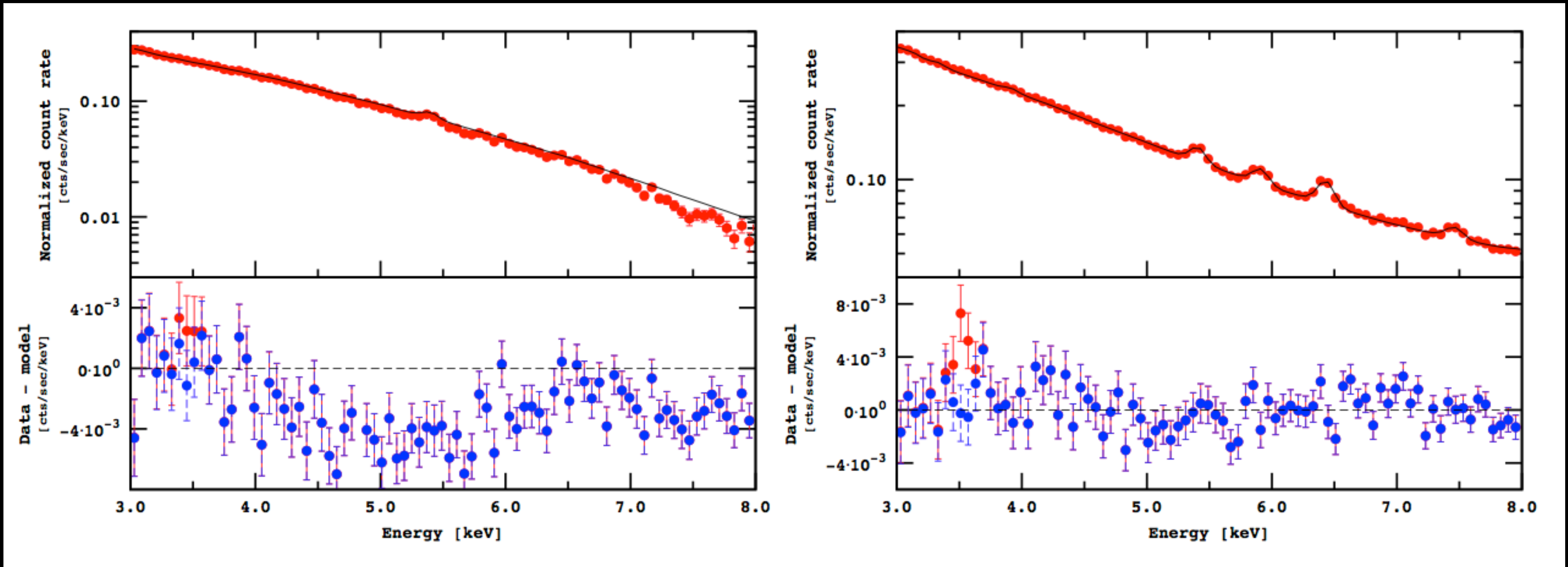
Inconsistent T? Potassium Line? (JP)





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."

A Morphological Template Analysis

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"Where do the 3.5 keV photons come from?" Carlson, Jeltema & Profumo claim not finding DM template morphology when including templates from continuum and line residuals [arXiv:1411.1758], and claim to"robustly exclude dark matter origin"

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- ν_s CJP make the same mistake for their mixing angle constraints, regardless of their spatial analysis — the conversion between the observed and emitted line flux is incorrect by factor up to 3.

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Now, if the continuum model is incorrect by, say, 5% (which is very optimistic), and the line is 1% of the continuum, then their residual signal would be 5/6 continuum and only 1/6 the line. Since all their continuum templates are astrophysical, their residual map will have the astrophysical spatial distribution. Given that it's very unlikely that their continuum is <1% accurate, their signal is strongly biased against a DM-like spatial distribution. **To me this makes this whole analysis worthless.**

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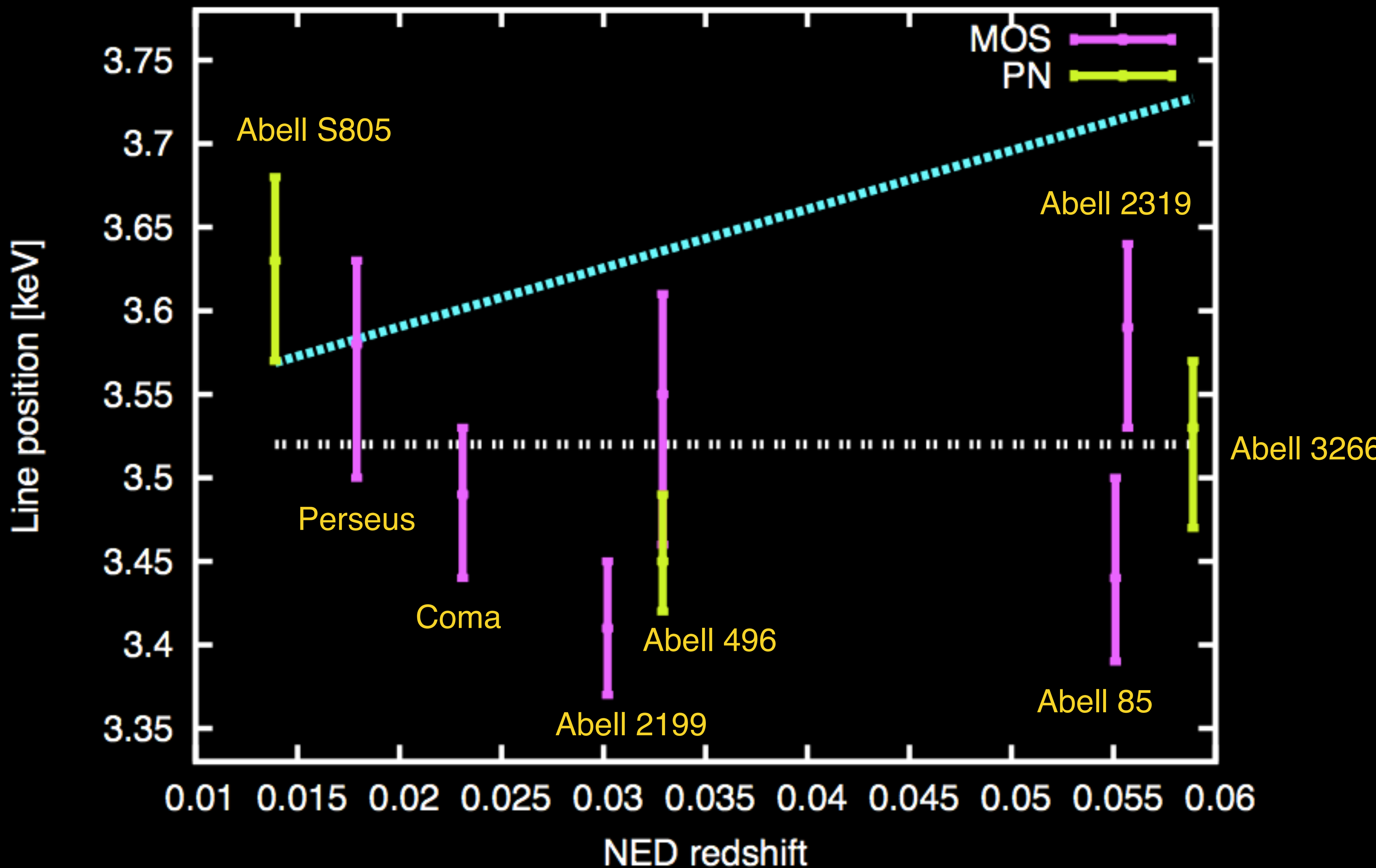
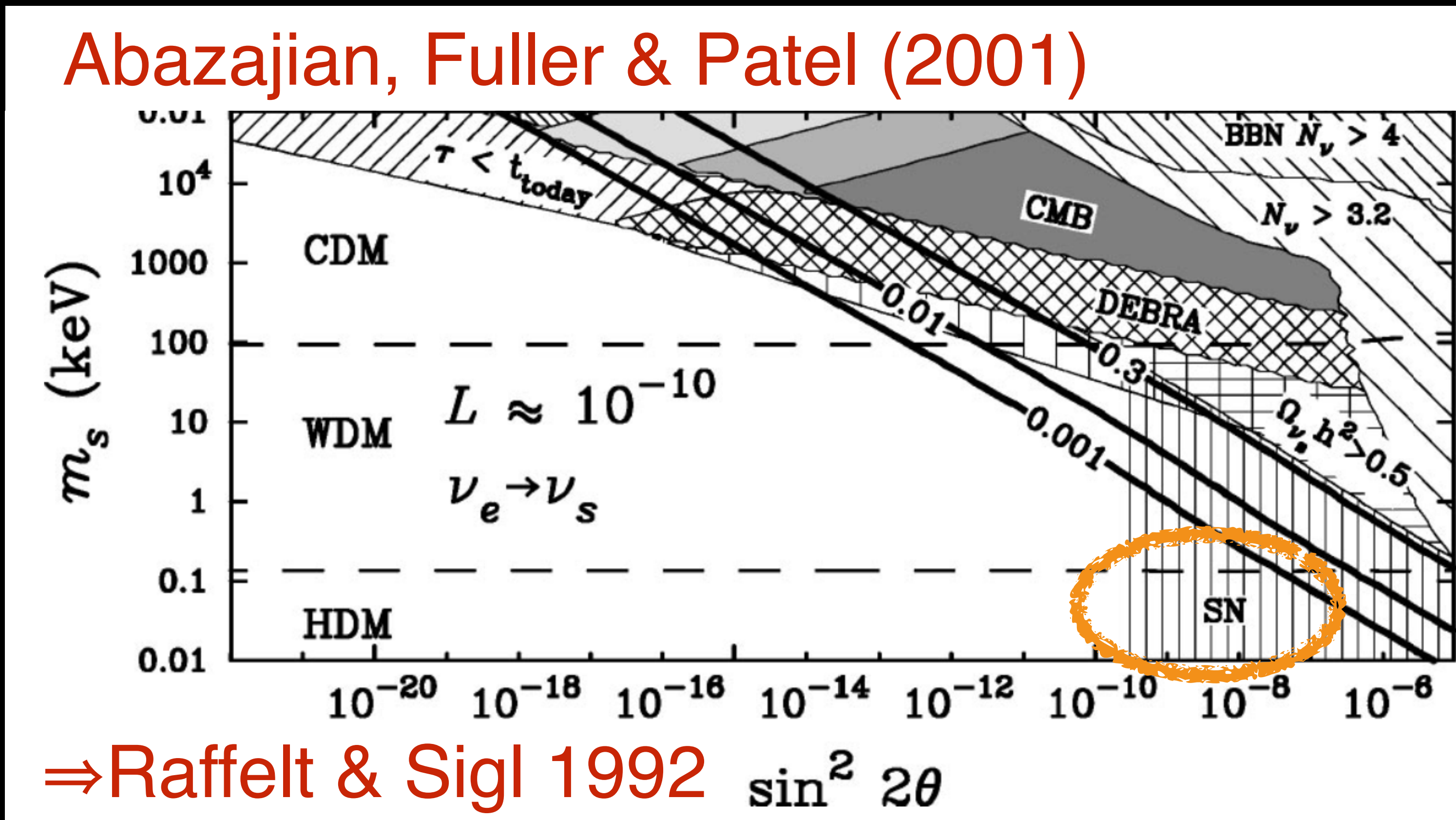
- ν_s [The discussion] about "clumped nature of these hot spots" in Perseus residuals that's "difficult toreconcile with the much smoother distribution" of DM, they are seriously discussing a clumped distribution of photons that are detected at 3.4 sigma from the whole cluster. **Those clumps are, of course, the direct analog of canals on Mars.**

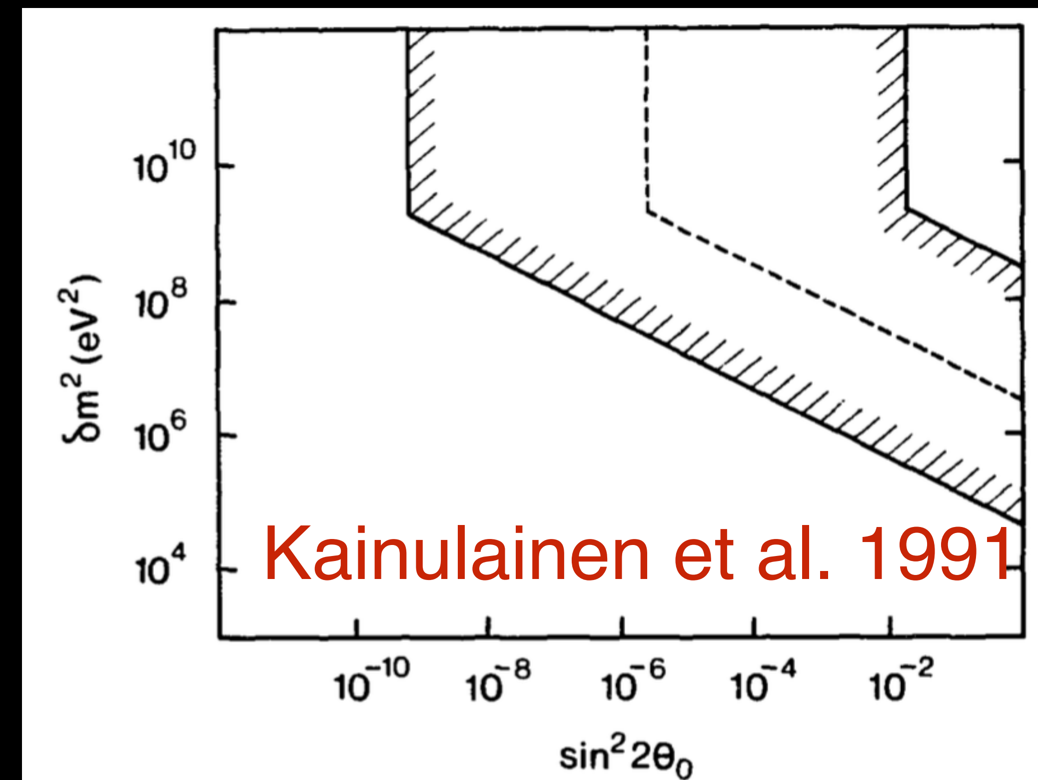
8 New Cluster Detections at >2σ Reported in August



Iakubovskyi+ 1508.05186

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.