Warm Dark Matter & Sterile Neutrinos

The XXIX International Conference on Neutrino Physics and Astrophysics

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June 24, 2020

Is an extra neutrino the dark matter?

Sterile Neutrino Dark Matter

keV Sterile Neutrinos as Dark Matter: History

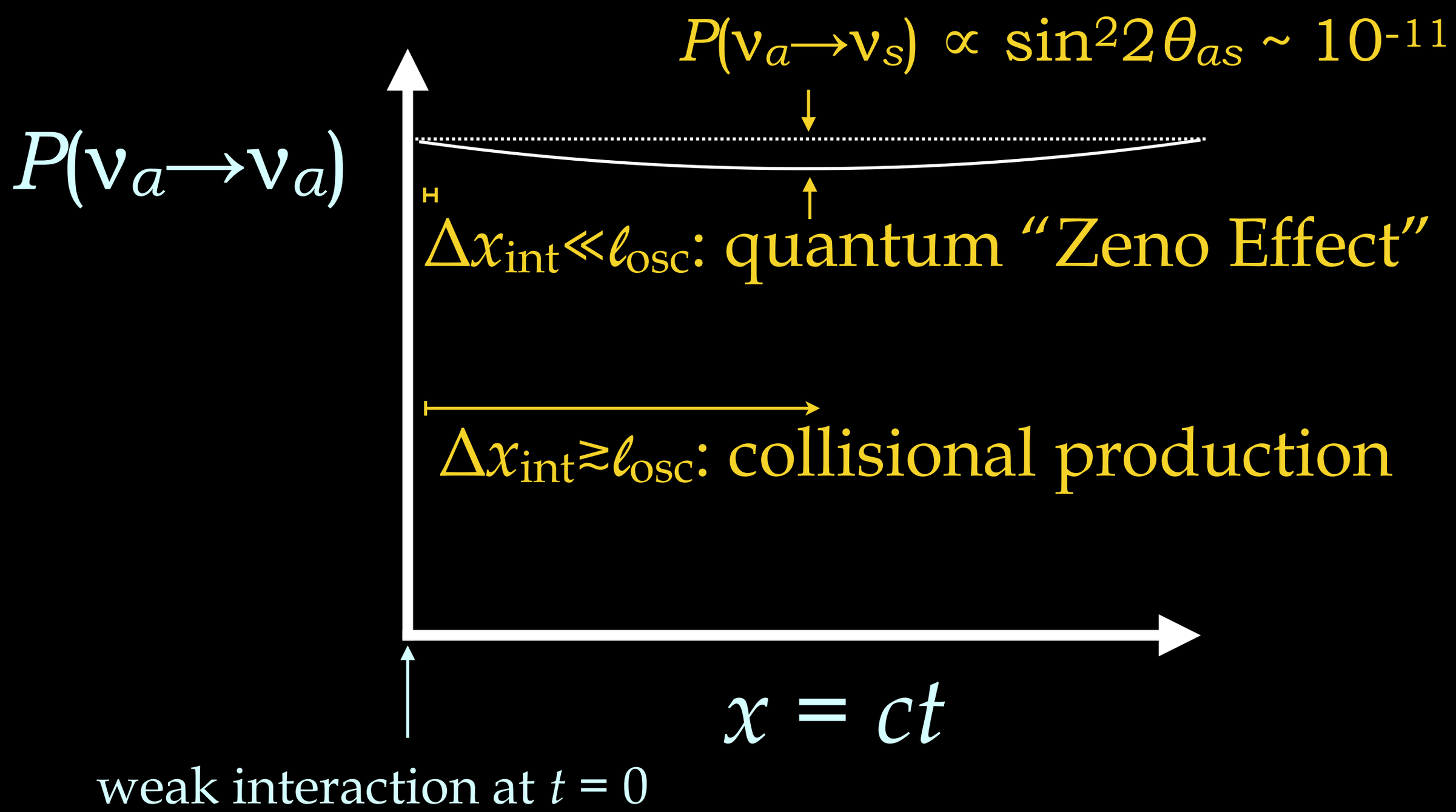
- "Super-weak" neutrinos ($G < G_F$) [Olive & Turner, 1982]: Earlier Decoupling, abundance set by standard dark matter production mechanism of decoupling temperature and degrees of freedom disappearance

- "Sterile" neutrinos [Dodelson & Widrow, 1993]: No SM interactions beyond mass terms, inclusion of finite-temperature modifications to self-energy, lack of thermalization. **keV scale**: WDM.

- "Resonant" sterile neutrinos [Shi & Fuller, 1999]: Finite temperature production with non-zero lepton number resonant enhanced production. WDM to CDM. "Cool" Dark Matter.

- "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.

A Simplified View of Oscillation-Based Sterile Neutrino Dark Matter Production



Beyond Oscillation Production:
Several mechanisms, with varied effects on structure

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

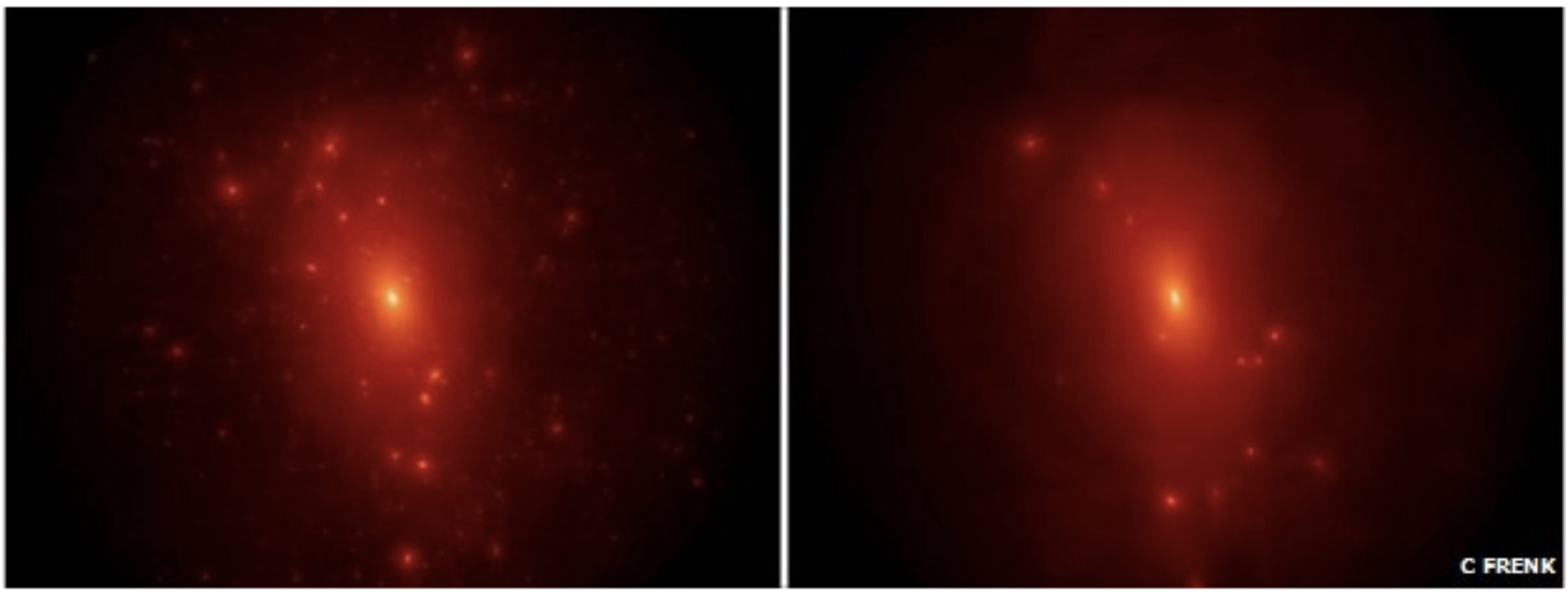
- **Split See-Saw Out of Equilibrium Production:**
  Kusenko, Takahashi, & Yanagida 2010

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

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

Cosmological Structure Formation & Sterile Neutrinos

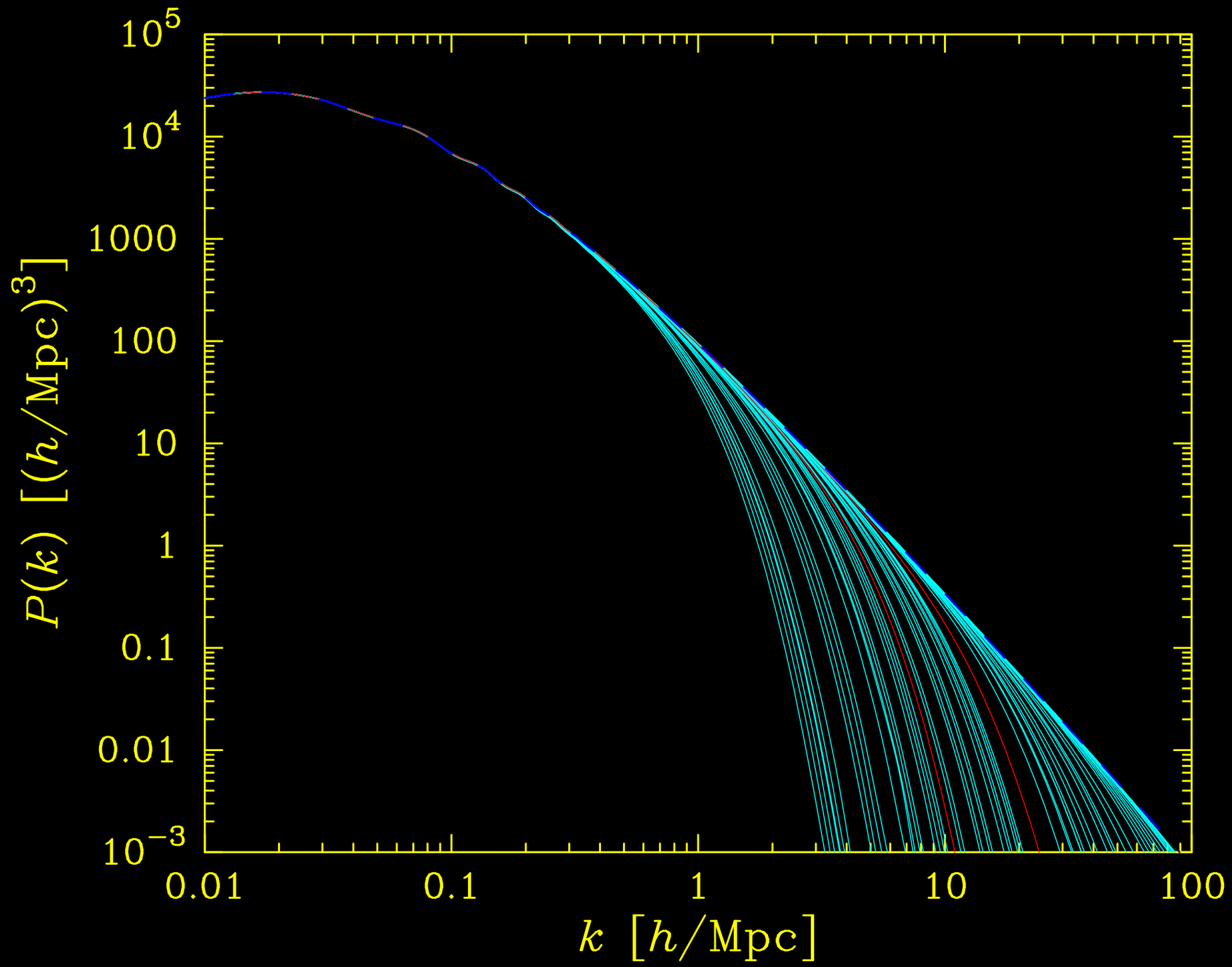
How much small scale structure is there?



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

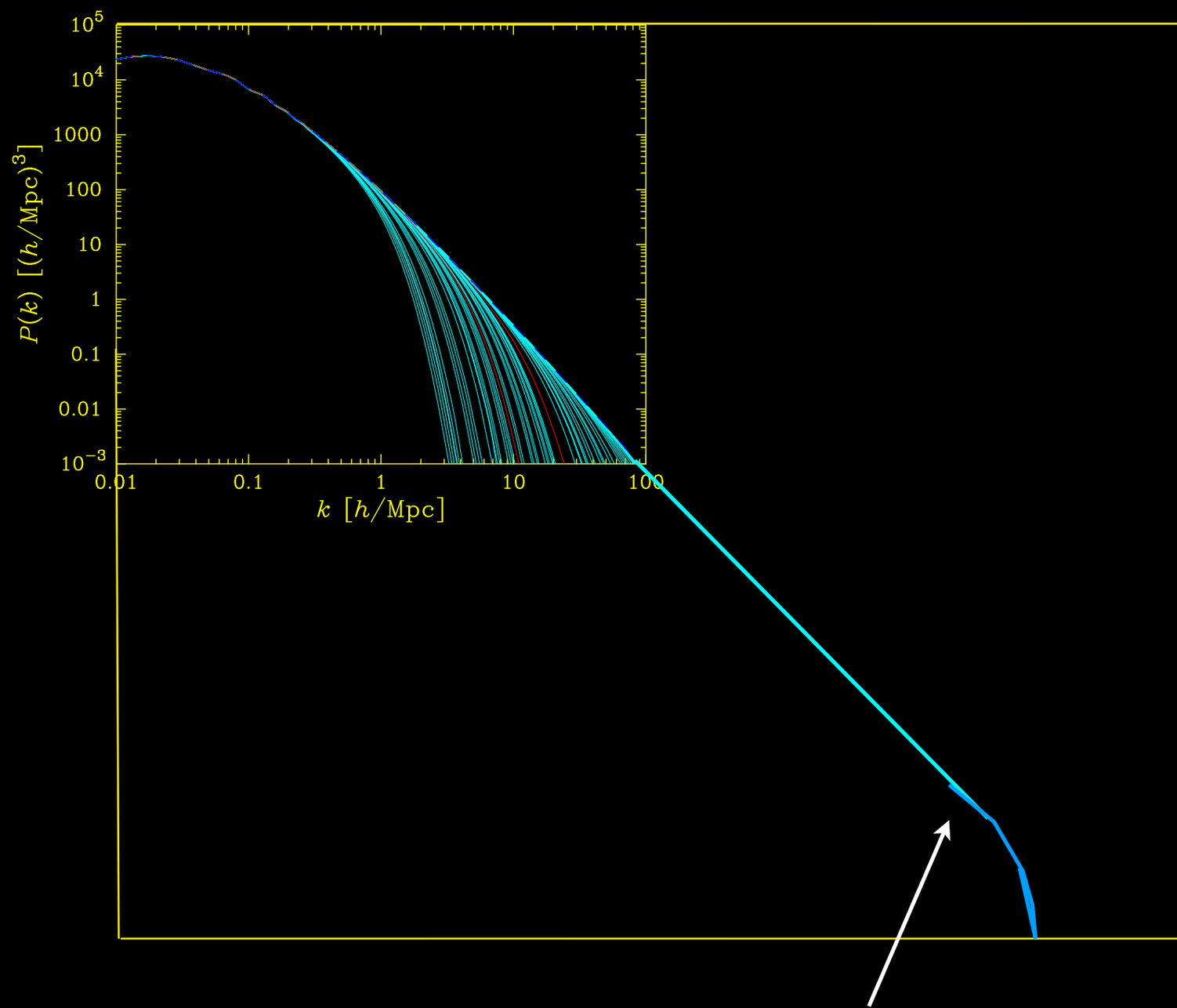
Perturbation Evolution

Is there evidence for a small-scale cutoff, and *how warm is too warm?*



Abazajian astro-ph/0511630

Canonical “Cold” Dark Matter...

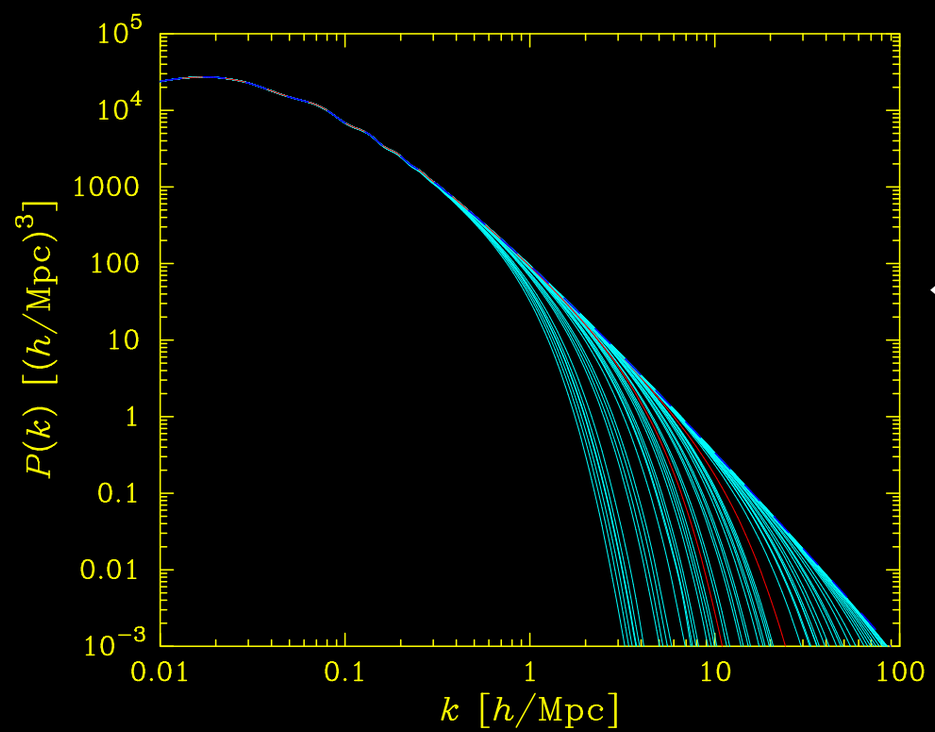


WIMP CDM

$k_c \sim 10^6\ h/\mathrm{Mpc}$

(Zaldarriaga & Loeb 2006)

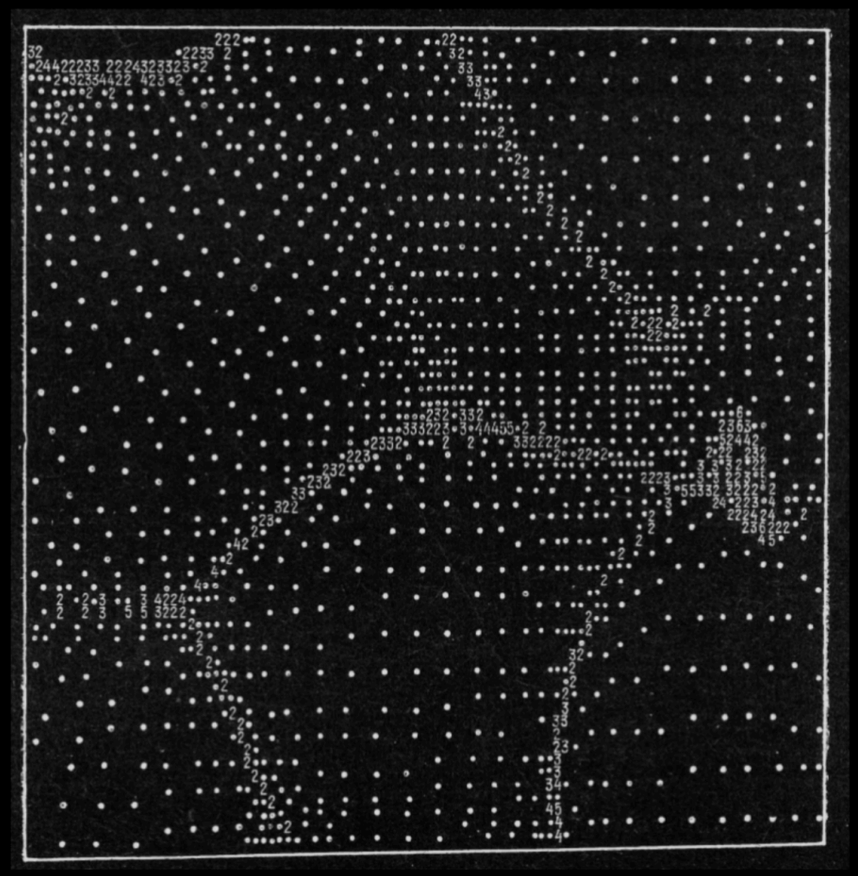
Simulating the Universe's Structure



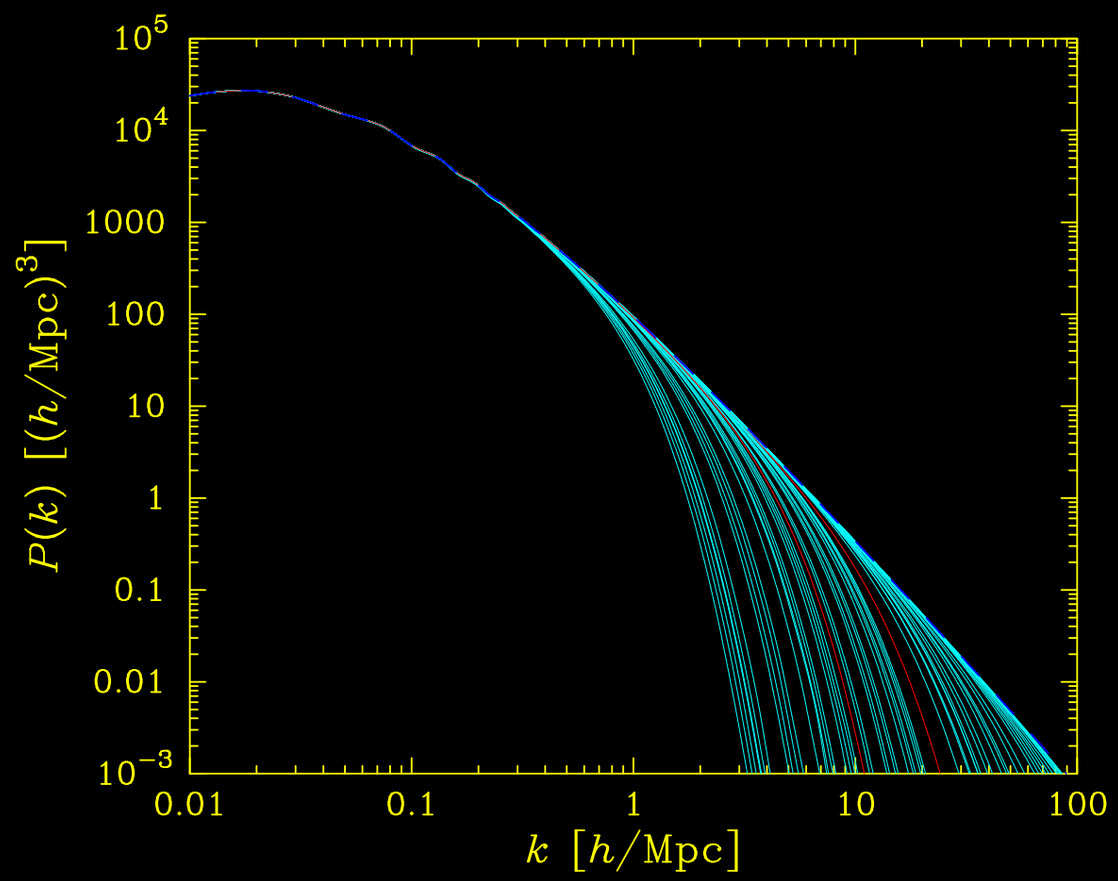
This is a description of the statistical distribution of the density fluctuations in the *linear regime*...

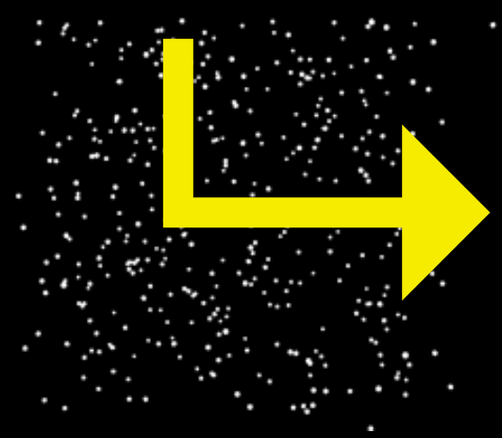
It is realized by giving a "push" to a grid of particles with that statistical distribution...

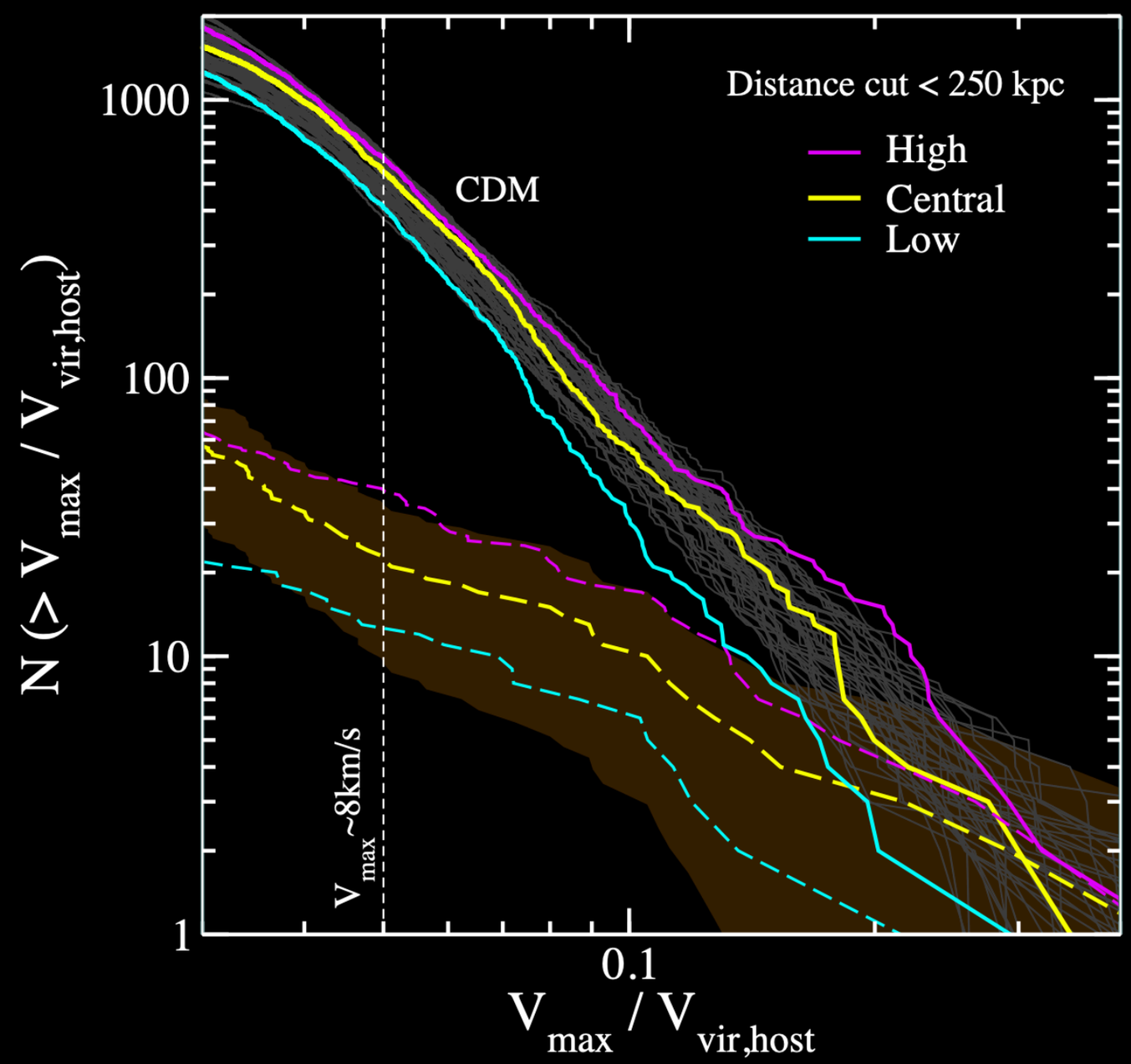
...and then gravity is allowed to do its duty.



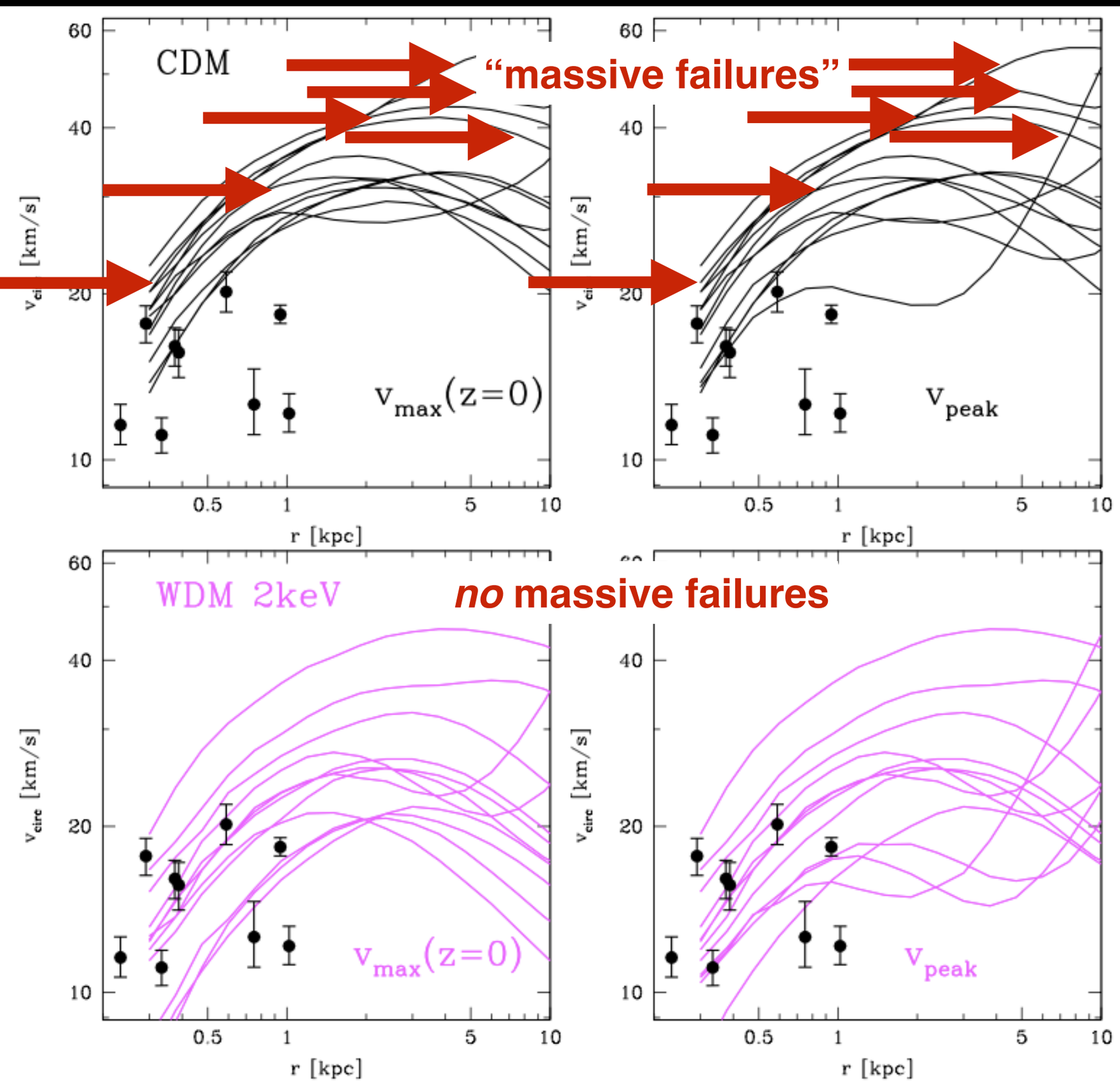
Suppression of small scale power
⇒ Suppression of Small Halos







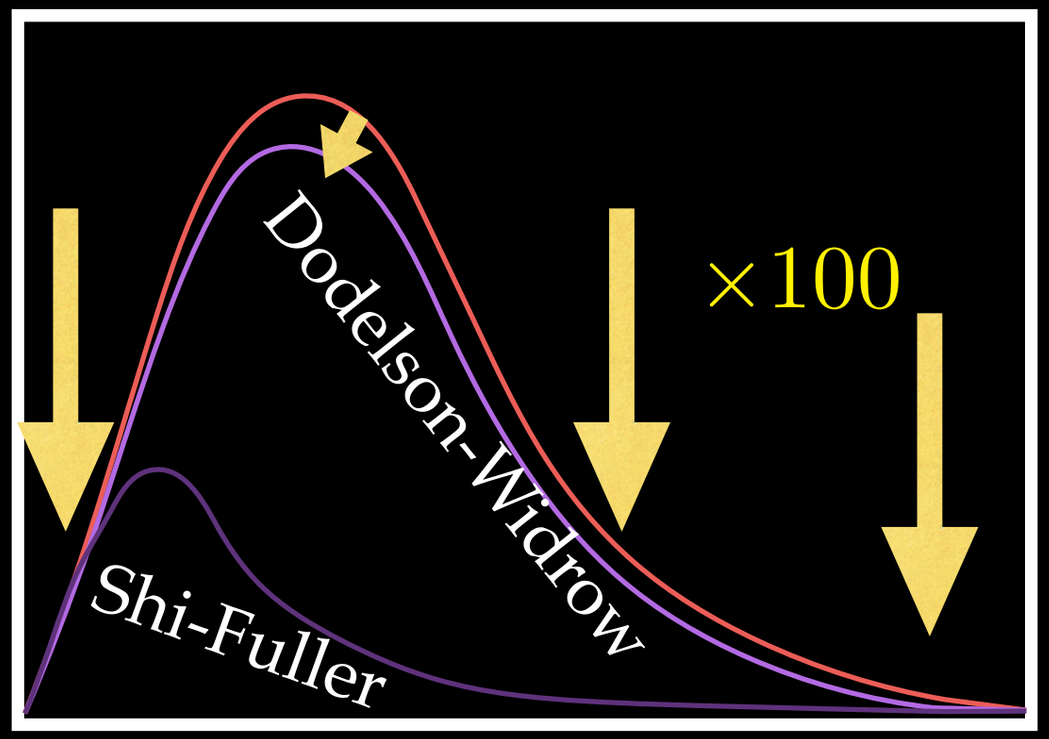
WDM Solution to Local Group Galaxy Properties?

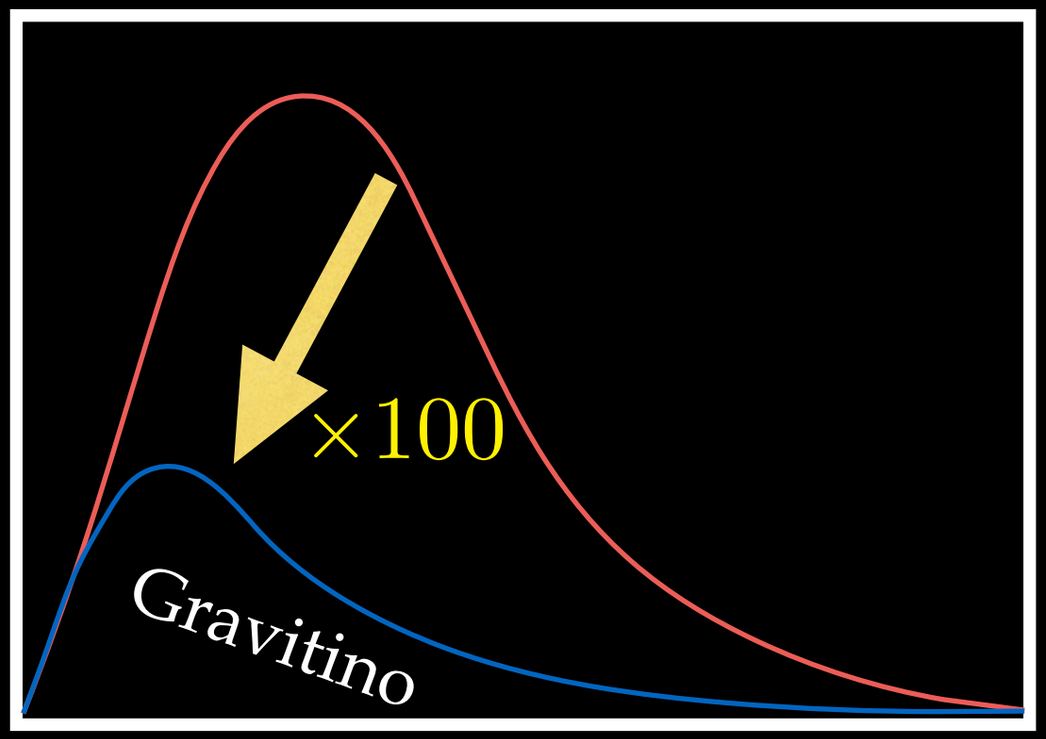


Lovell+
arXiv:1104.2929.
Anderhalden+
arXiv:1212.2967:
"It seems that only the pure WDM model with a 2 keV [thermal] particle is able to match the all observations" of the Milky Way Satellites: "the total satellite abundance, their radial distribution and their mass profile" (or TBTF)

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

Sterile WDM vs. Thermal WDM





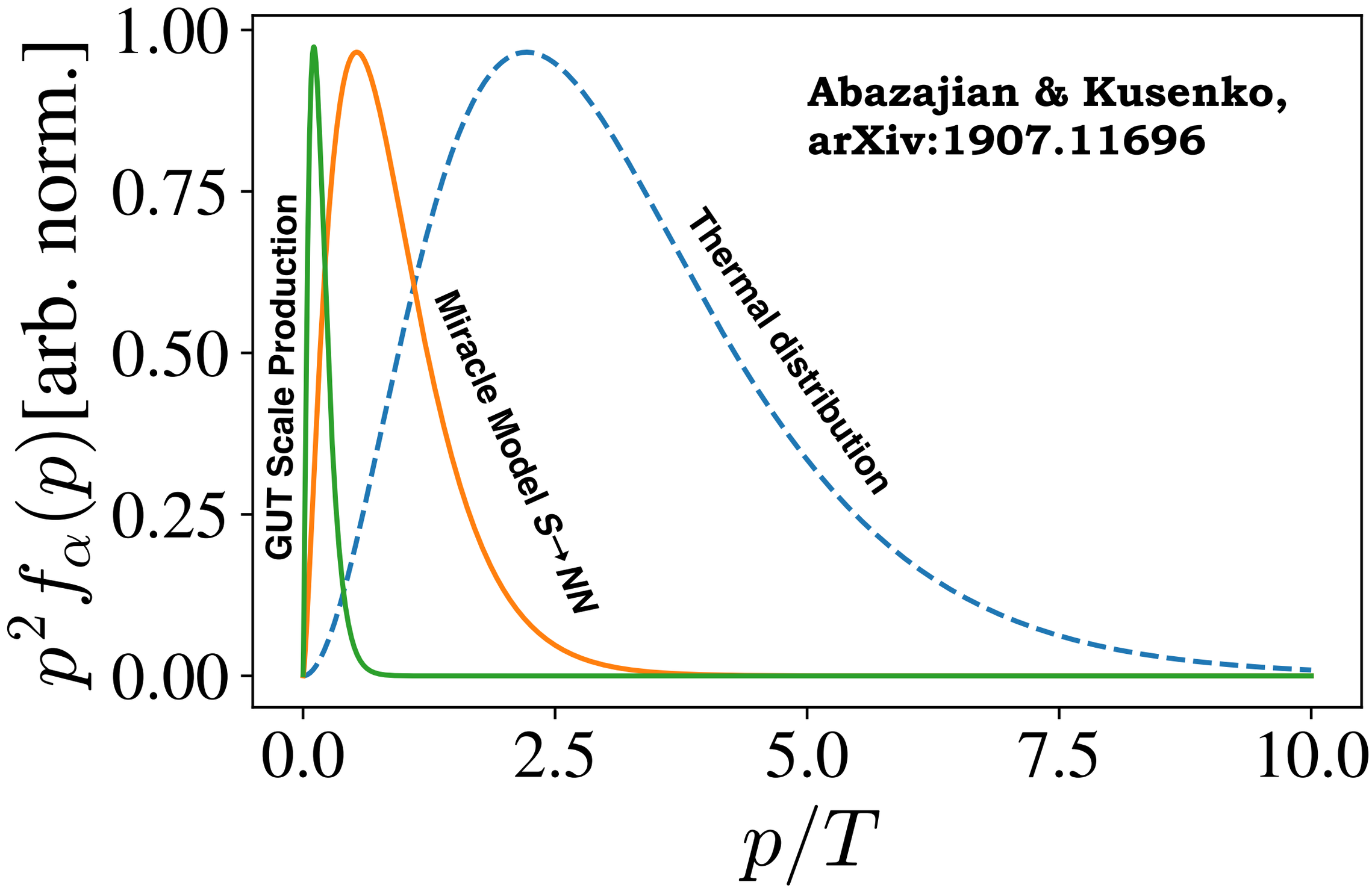
$$m_s\big|_{\text{Dodelson-Widrow,ideal}} \approx 4.46\,\text{keV}\left(\frac{m_{\text{thermal}}}{1\,\text{keV}}\right)^{4/3}$$

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

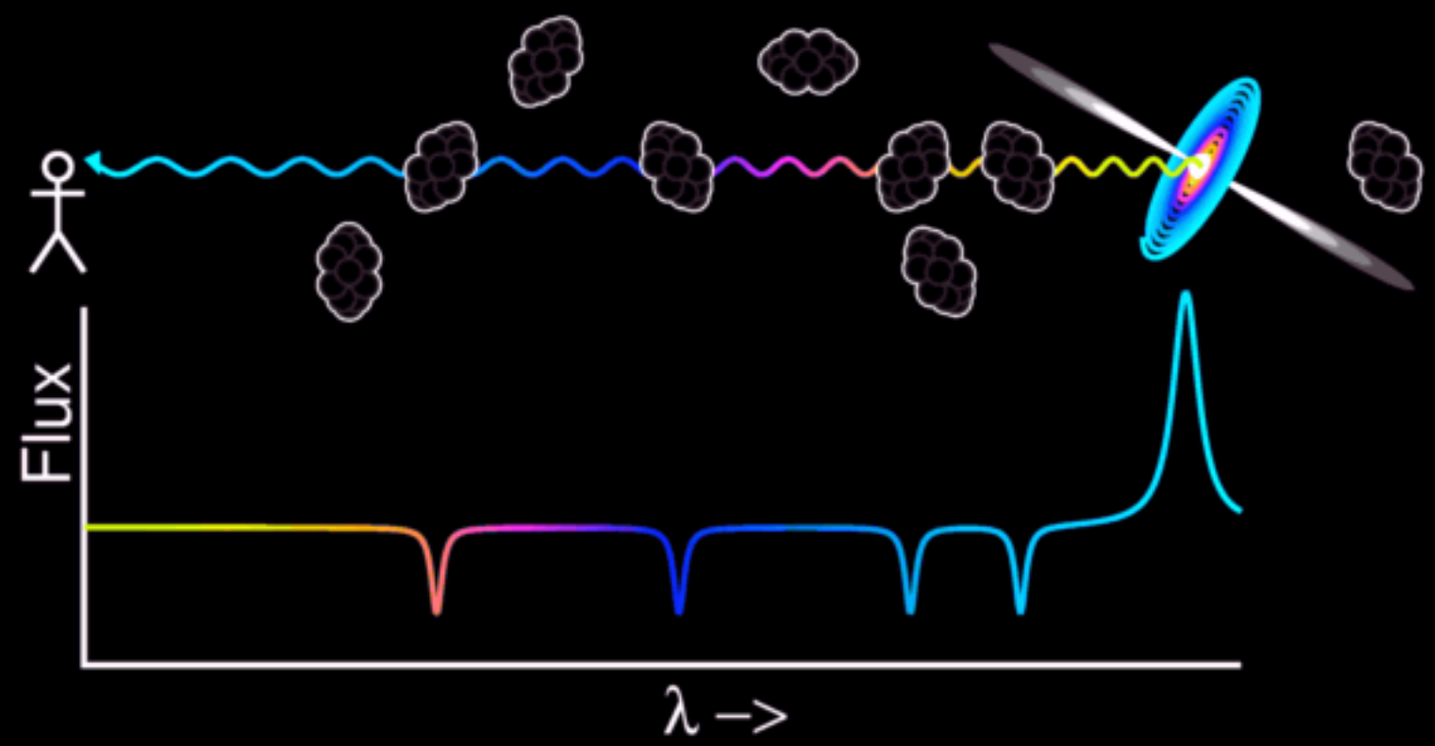
$$m_{\text{thermal}} = 2\,\text{keV} \Rightarrow m_s\big|_{\text{DW,ideal}} \approx 11\,\text{keV} \Rightarrow m_s\big|_{\text{Shi-Fuller}} \approx 7\,\text{keV}$$

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

Varied Momenta Distributions for Different Production Mechanisms



Lyman-α Forest Constraints on WDM



Lyman-α forest:

m_{th} > 3 keV (WDM) (95% CL)

$m_{s,DW}$ > **16 keV**

(Baur et al. 2015)

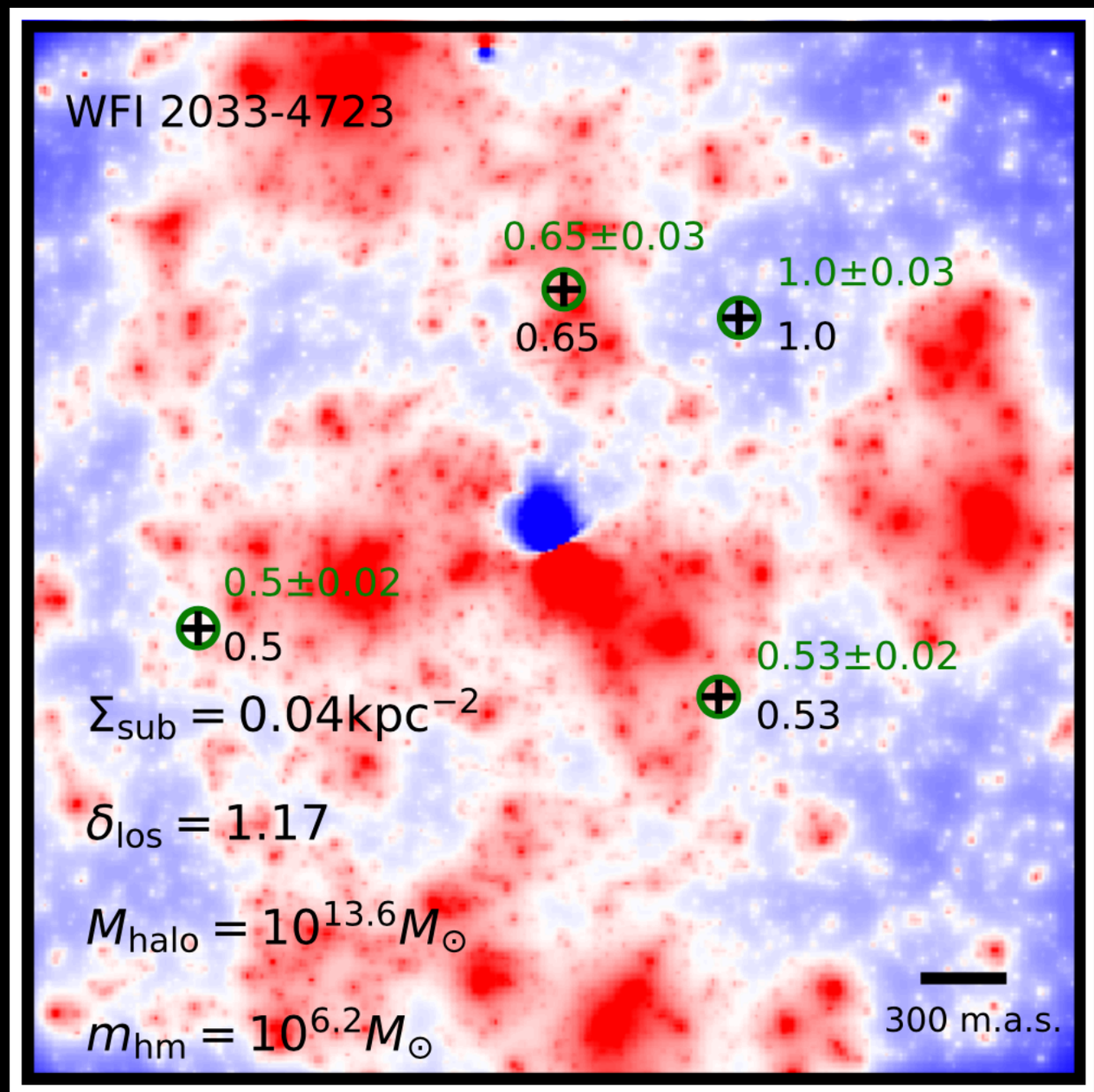
Milky Way galaxy counts:

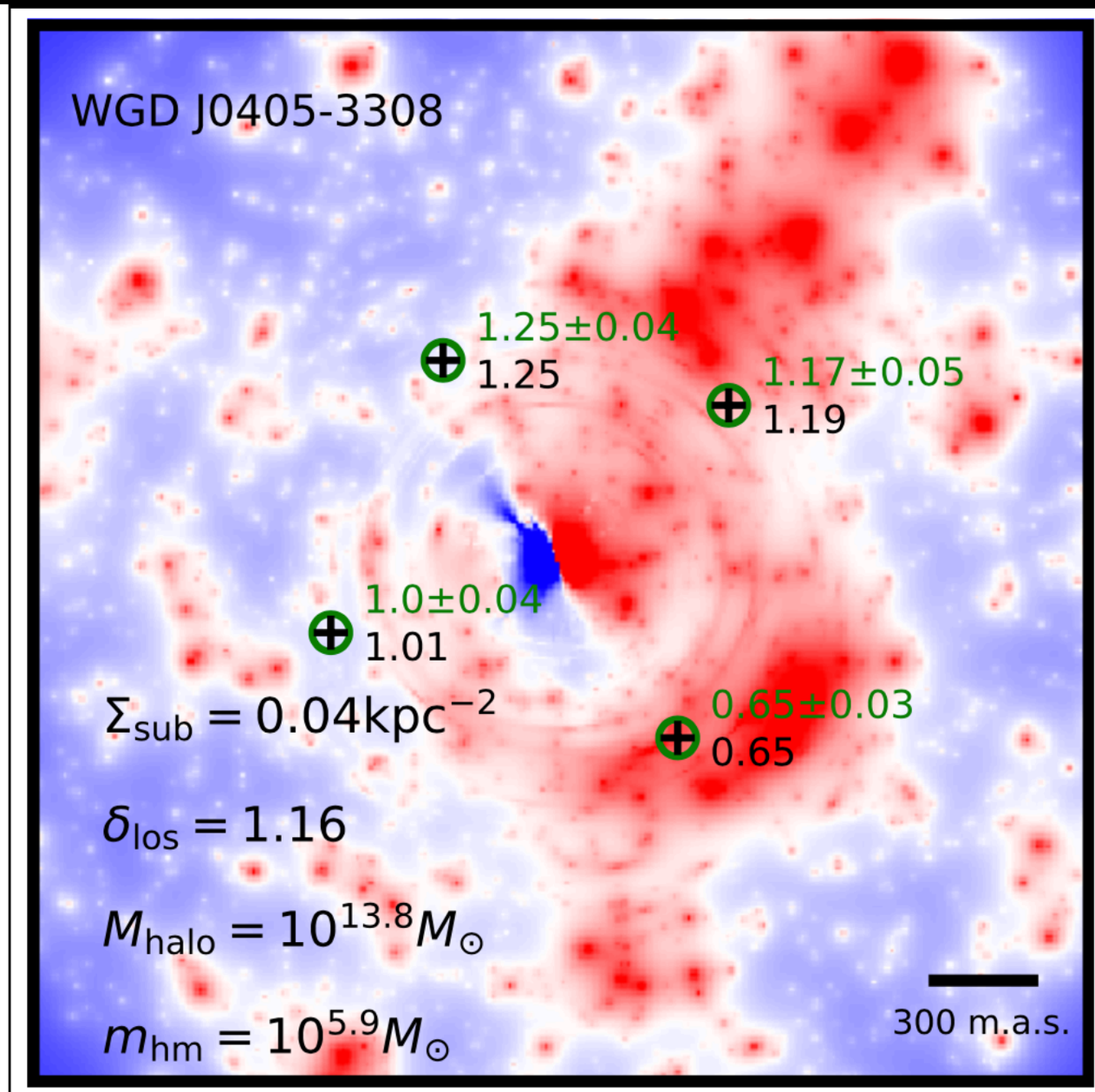
m_{th} > 3 keV (WDM)

(Horiuchi+ 2013, Cherry & Horiuchi 2017, Nadler+ 2019)

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

Lensing Constraints on WDM



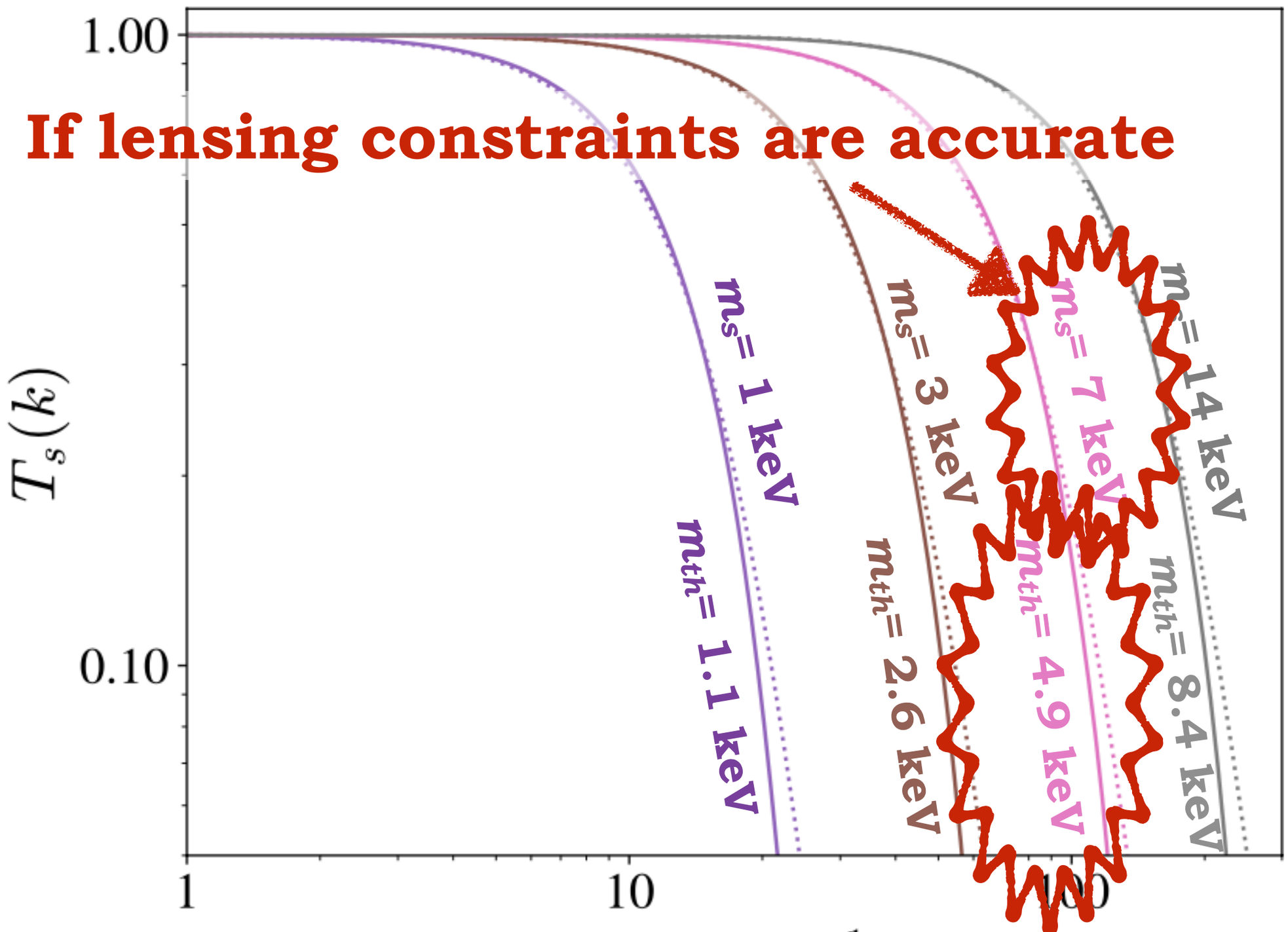


Lensing substructure constraints push:

m_{th} > 5.3 keV ($m_{s,DW}$ > 41 keV)

(Gilman+ 2019)

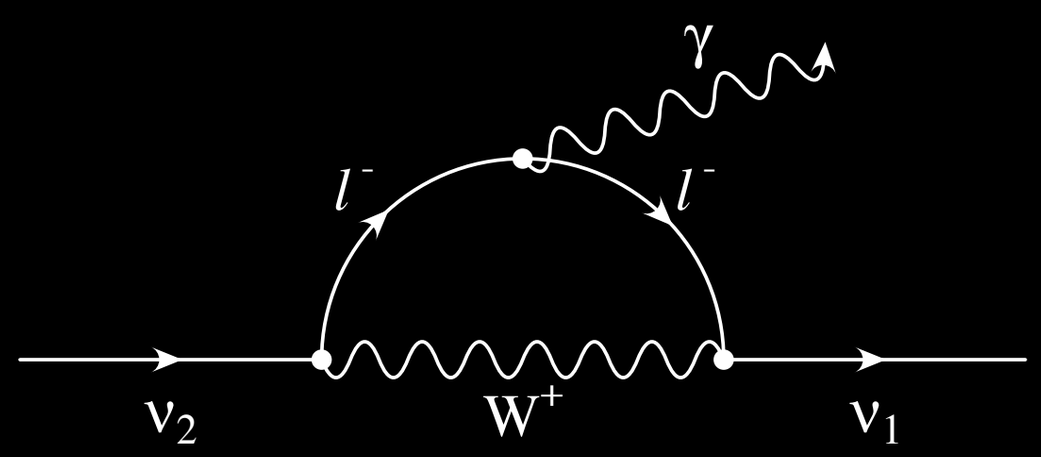
GUT-scale Split-Seesaw Model (High-T Phase Transition)



Abazajian & Kusenko, arXiv:1907.11696

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

Sterile Neutrino WDM Radiative Decay in the X-ray



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

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

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

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

Detections in 2014:

- Stacked clusters with *XMM-Newton* MOS and PN (Bulbul+ 2014)
- in Andromeda (M31) with *XMM-Newton* (Boyarsky+ 2014)

3.55 keV line consistent with DM in field of view seen

- **Stacked clusters with *XMM-Newton* MOS and PN (Bulbul+ 2014)**
- **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

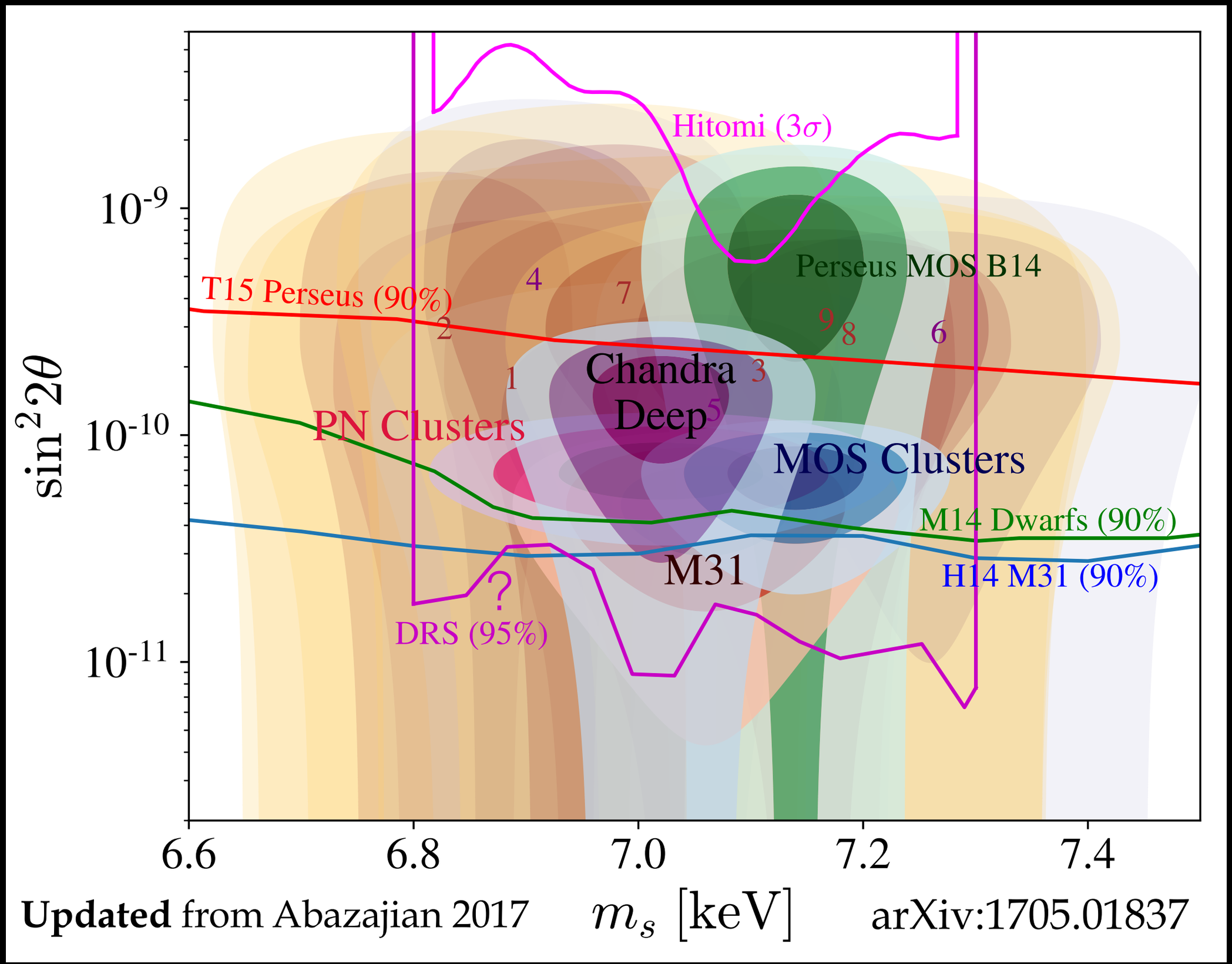
3 places it may have been expected

- **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."*** Ruchayskiy+ arXiv:1512.07217

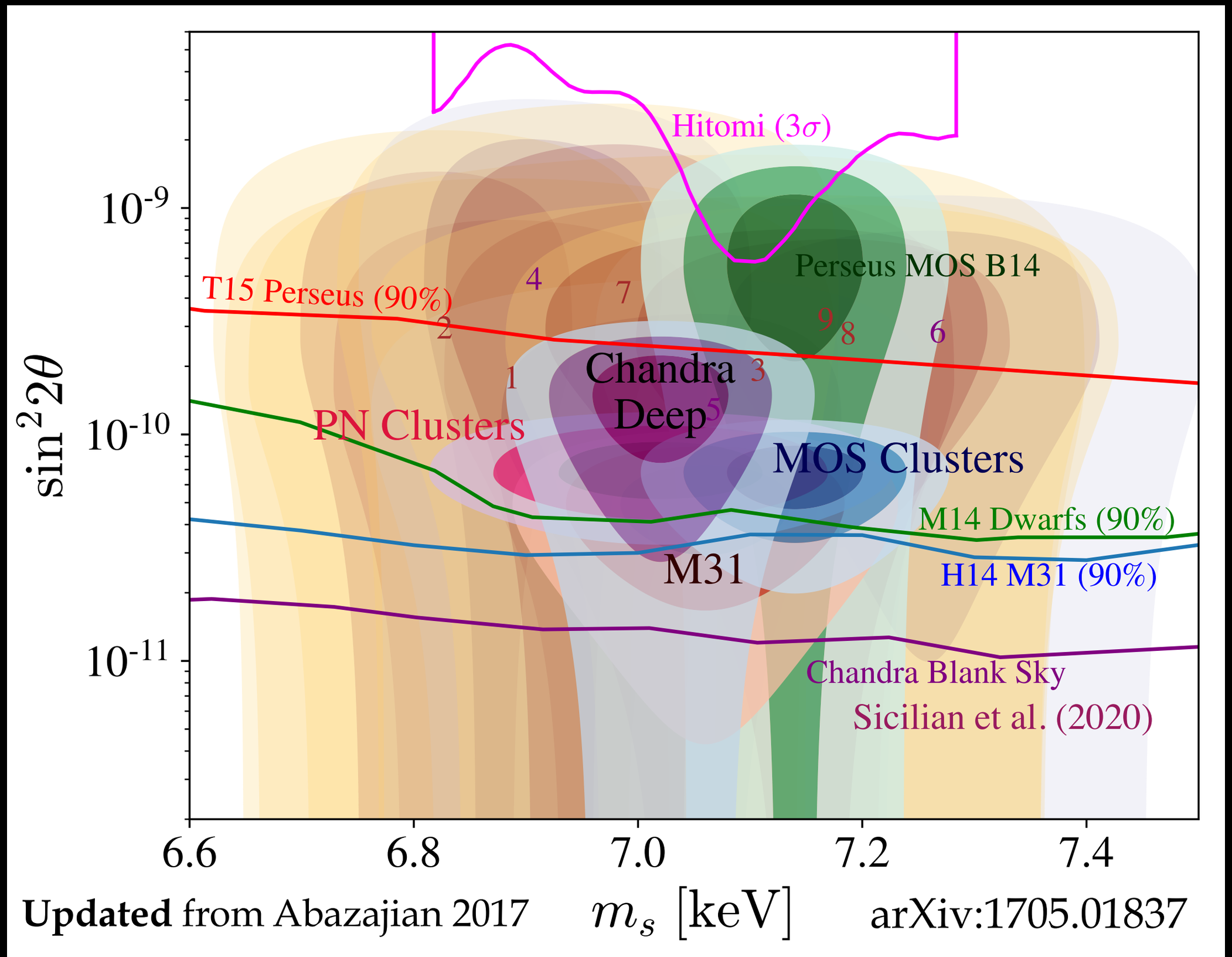
- **Stacked galaxies:** 81 with Chandra and 89 with *XMM-Newton*, using outskirts of the galaxies:
  Anderson, Churazov & Bregman arXiv:1408.4115.
  ➥***Systematic continuum errors are of order the uncertainties on detected $\sin^2 2\theta$***

- **Stacked blank sky:** 30 Ms *XMM-Newton* data, 0.5 keV energy window analysis.
  Dessert, Rodd & Safdi arXiv:1812.06976 (journal *Science*, 2020)

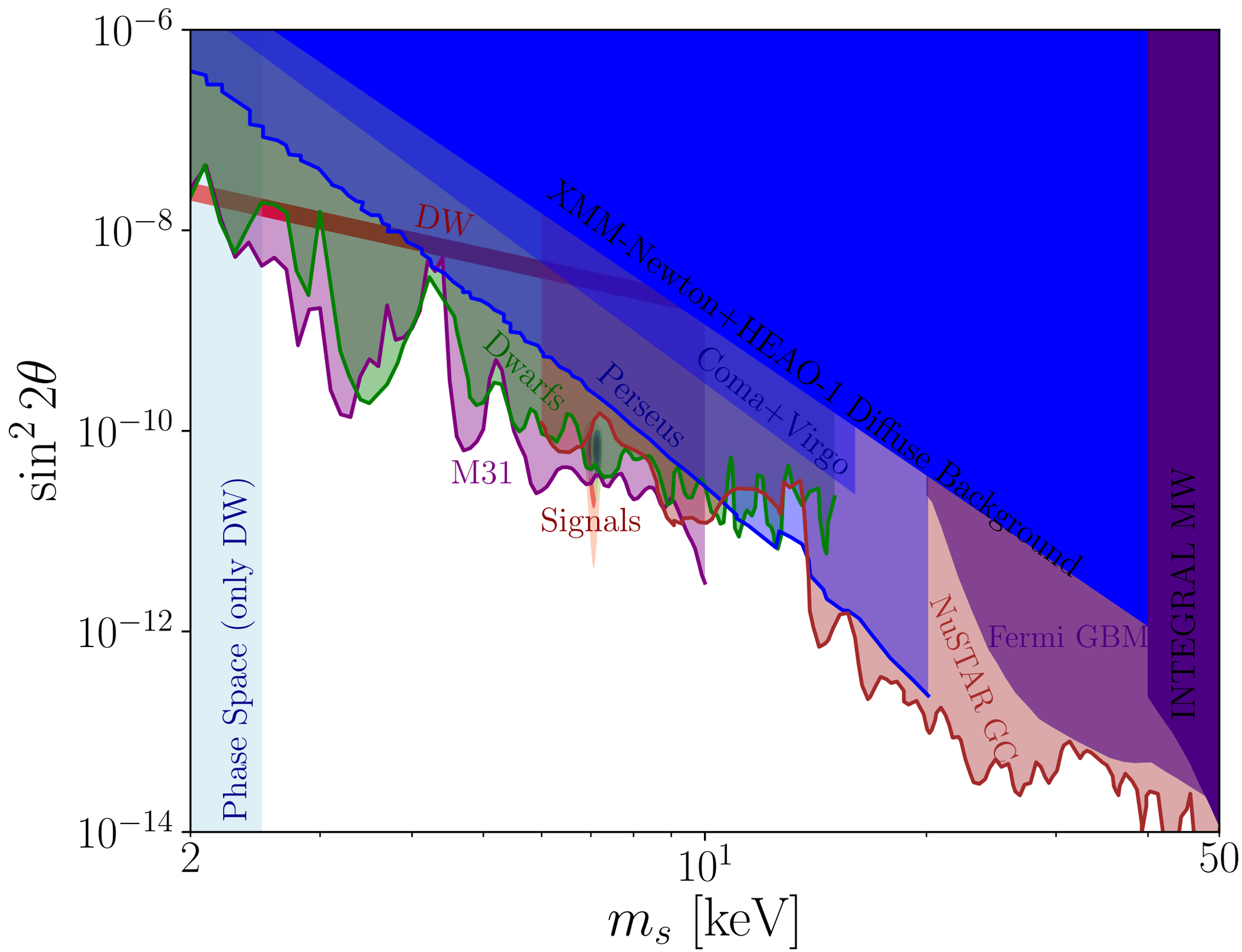
The 7 keV Region Today



The 7 keV Region Today



Sterile Neutrino Dark Matter: Parameter Space Summary



Updated from Abazajian *Phys. Rep.* arXiv:1705.01837

A Fraction of Dark Matter as Sterile Neutrinos

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

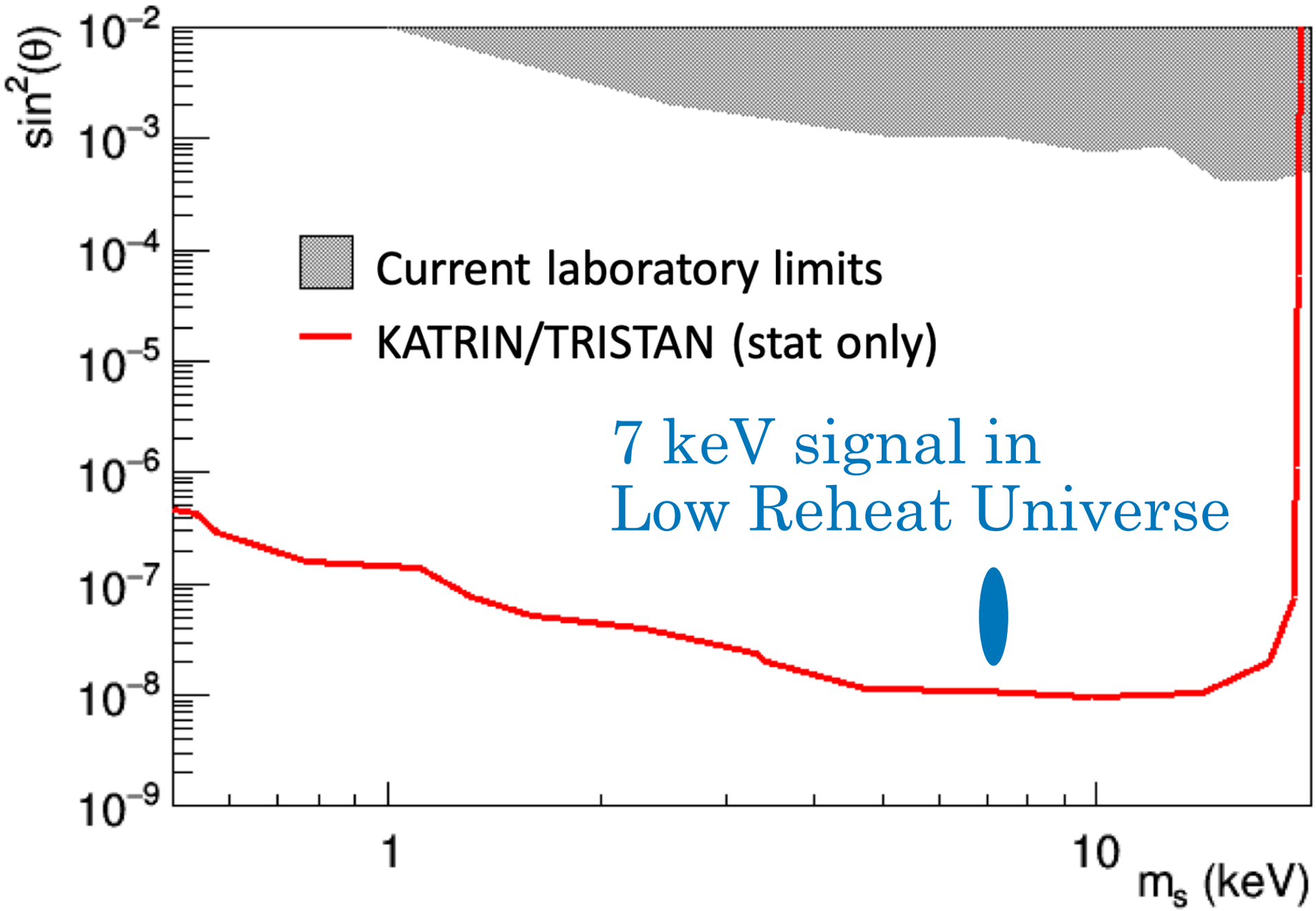
$$\text{Flux} \propto f_{\rm DM} \sin^2 2\theta \qquad \text{but: } f_{\rm DM} \propto \left(\sin^2 2\theta\right)^{1.23} \quad \text{(Abazajian 2005)}$$

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)

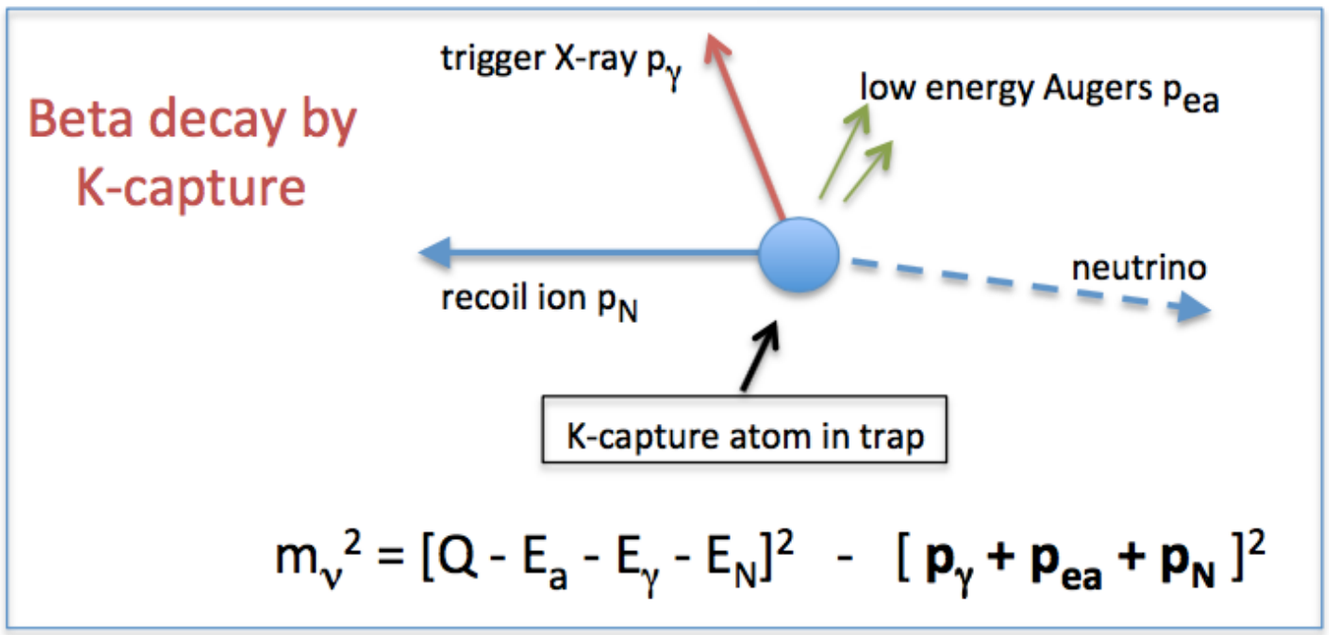
⇒ Low-reheating temperature universe can produce 3.5 signal with **7×10^{-4} of DM** as sterile neutrinos

Confirmation? kinematic searches in nuclear β-decay: TRISTAN at KATRIN



Mertens et al. JCAP 1502 (2015)
Mertens et al. J. Phys. G46 (2019)

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

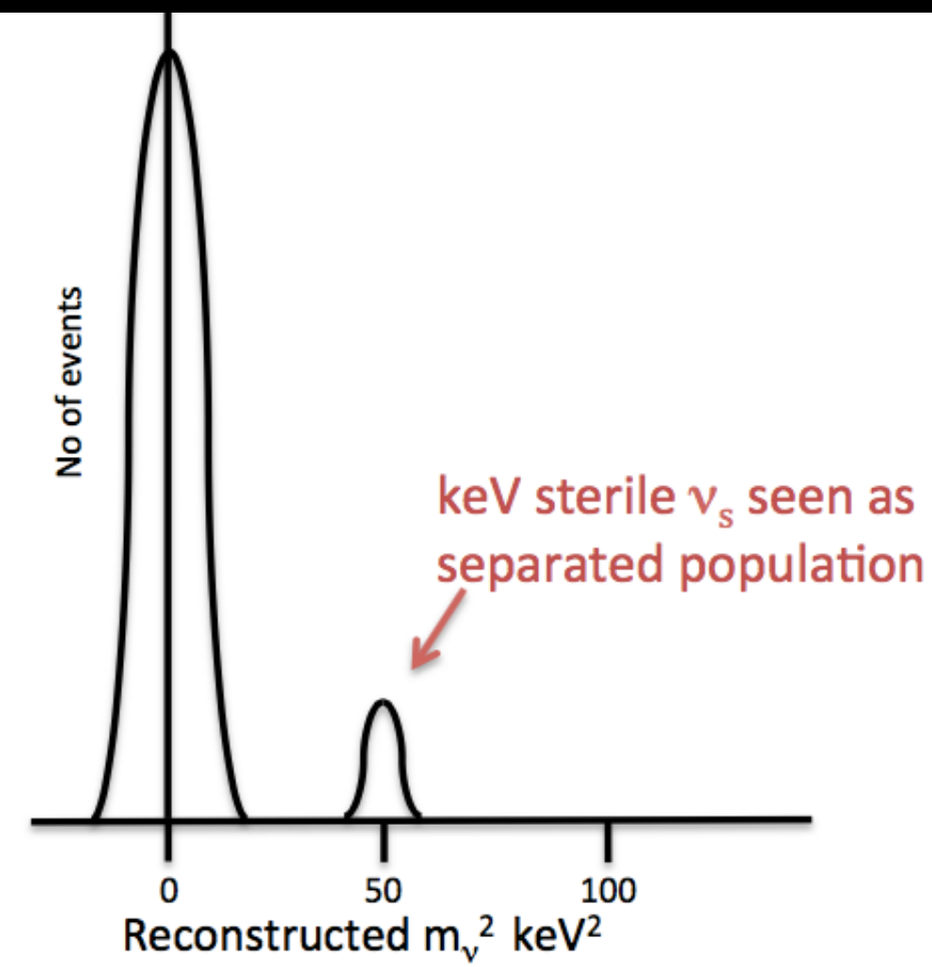


$$m_\nu^2 = [Q - E_a - E_\gamma - E_N]^2 - [\mathbf{p}_\gamma + \mathbf{p}_{ea} + \mathbf{p}_N]^2$$

Original studies: Finocchiaro & Shrock 1992

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

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



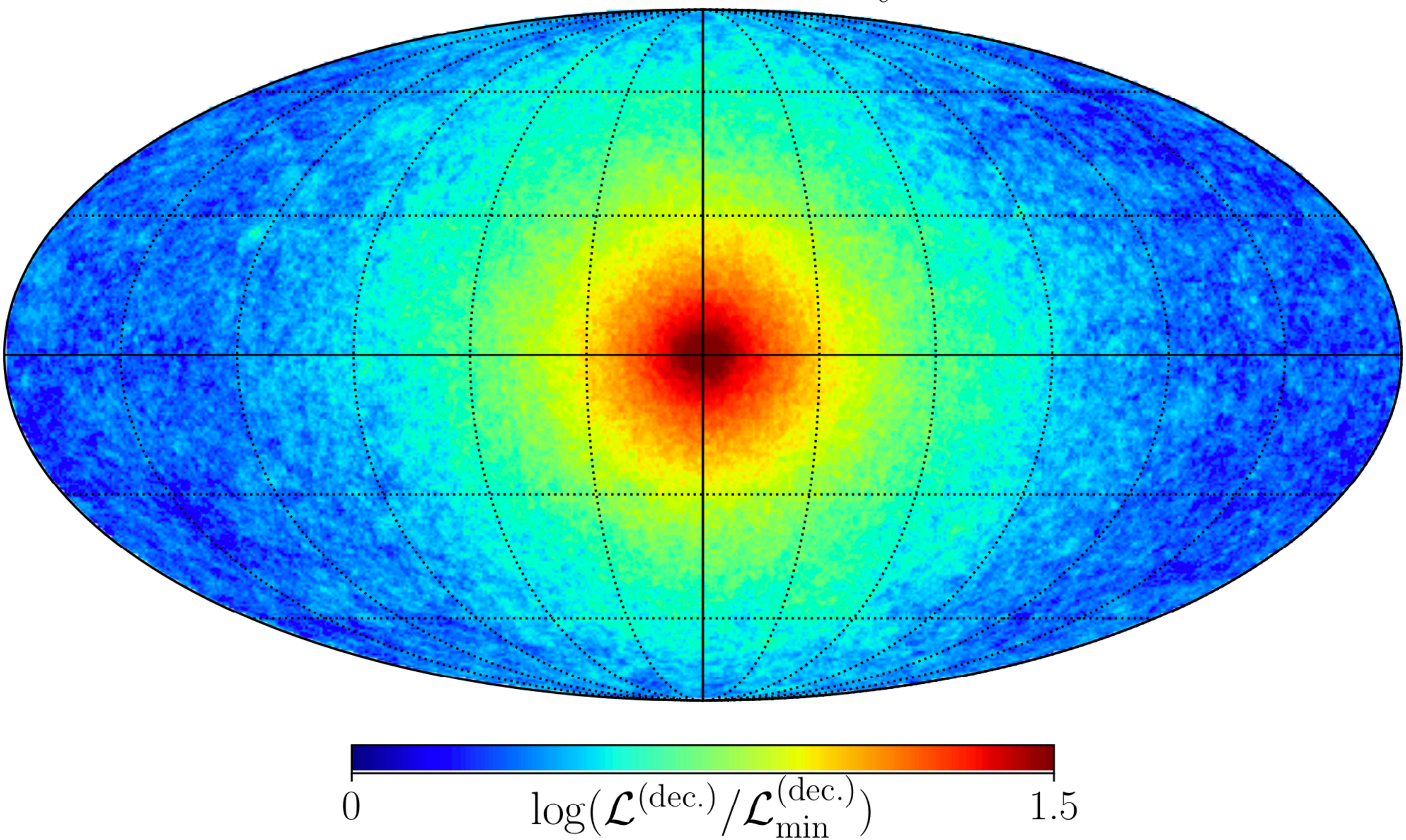
High precision time of flight measurements needed to achieve 6σ separation from zero mass peak

Recent studies show this may now be feasible

What if we do really see dark matter emission on the sky?

The Era of Dark Matter Astronomy?

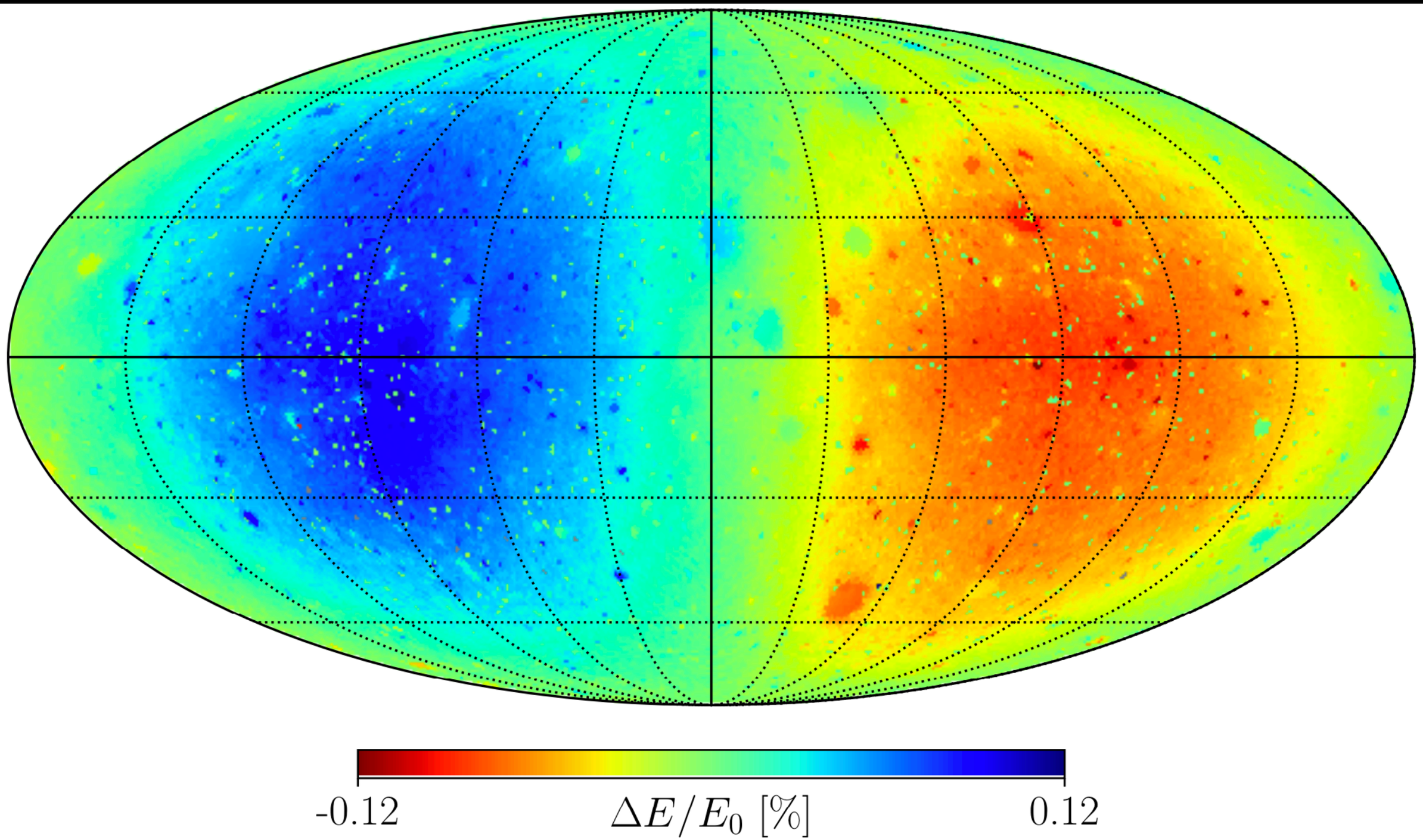
Dark Matter Decay Flux Map



Zhong, Valli, Abazajian 2003.00148

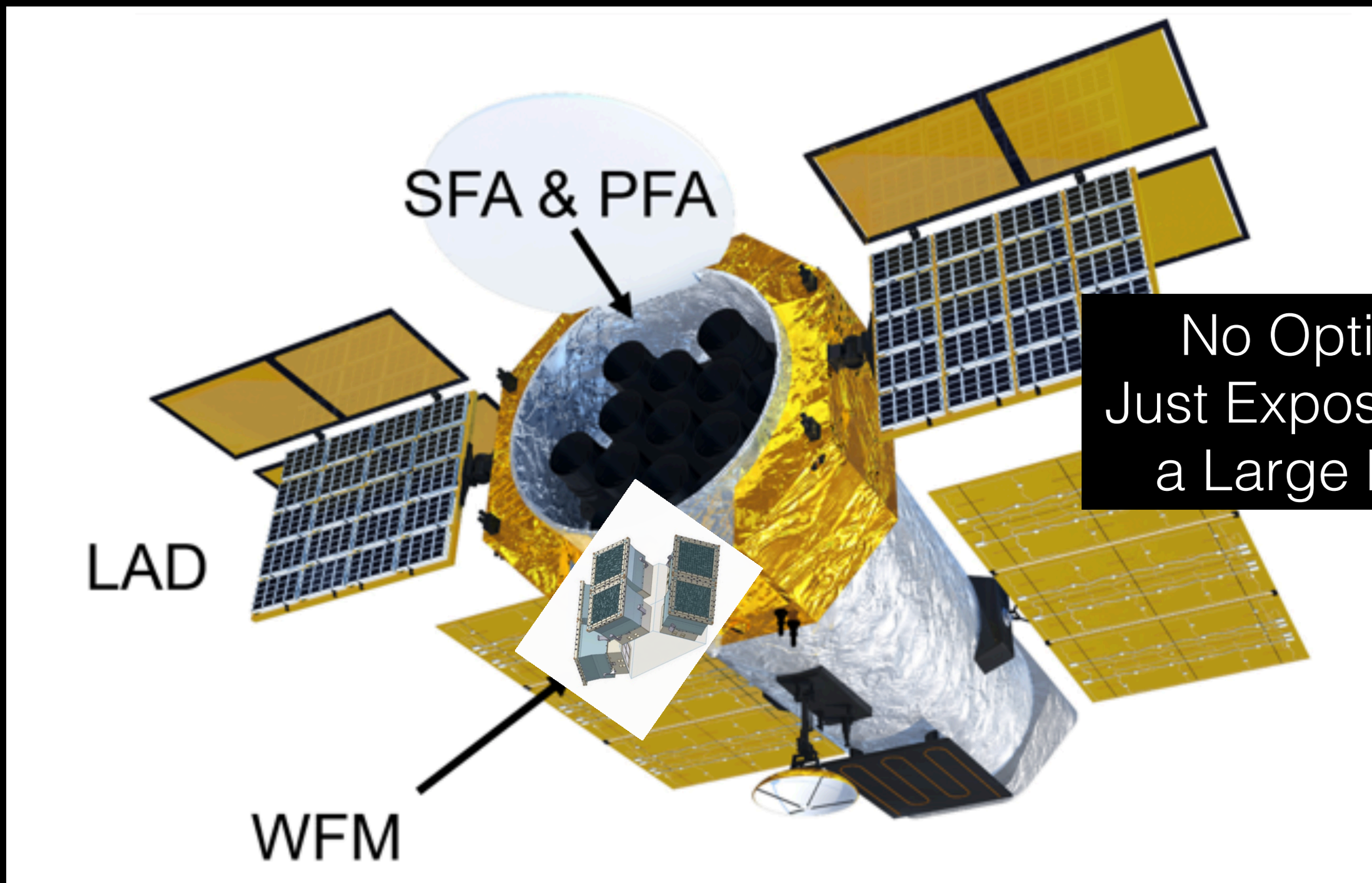
Dark Matter Doppler Energy Shift: *Velocity Spectroscopy*

Speckhard+ 1507.04744



Zhong, Valli, Abazajian 2003.00148

The Power of Pure Counts: The Wide Field Monitor aboard the Enhanced X-ray Timing Explorer



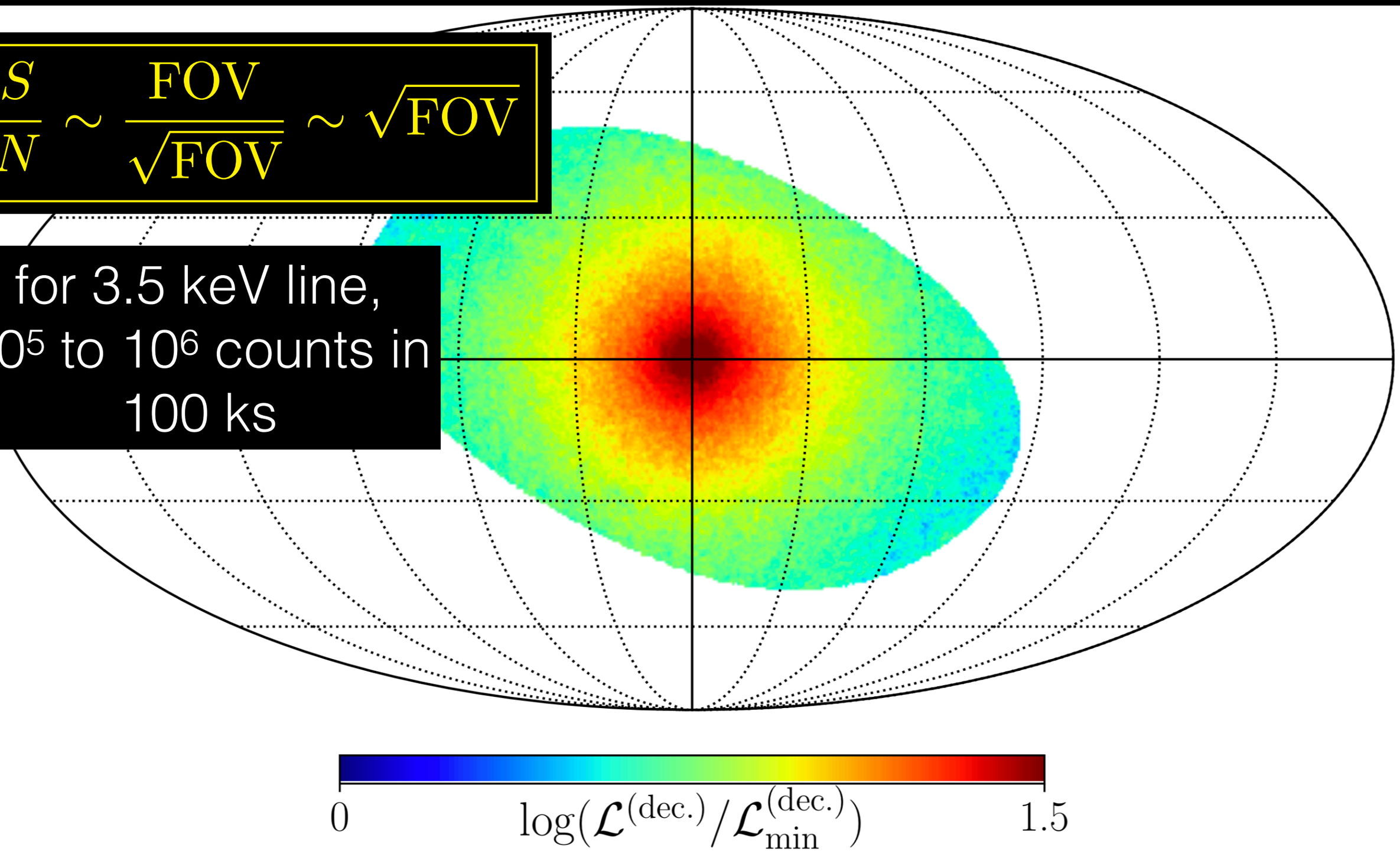
No Optics, Just Exposure to a Large FOV

Zhong, Valli, Abazajian 2003.00148

The Power of Pure Counts: WFM Field of View

$$\frac{S}{N} \sim \frac{\mathrm{FOV}}{\sqrt{\mathrm{FOV}}} \sim \sqrt{\mathrm{FOV}}$$

for 3.5 keV line, 10^5 to 10^6 counts in 100 ks



Zhong, Valli, Abazajian 2003.00148
Malyshev+ 2001.07014v2

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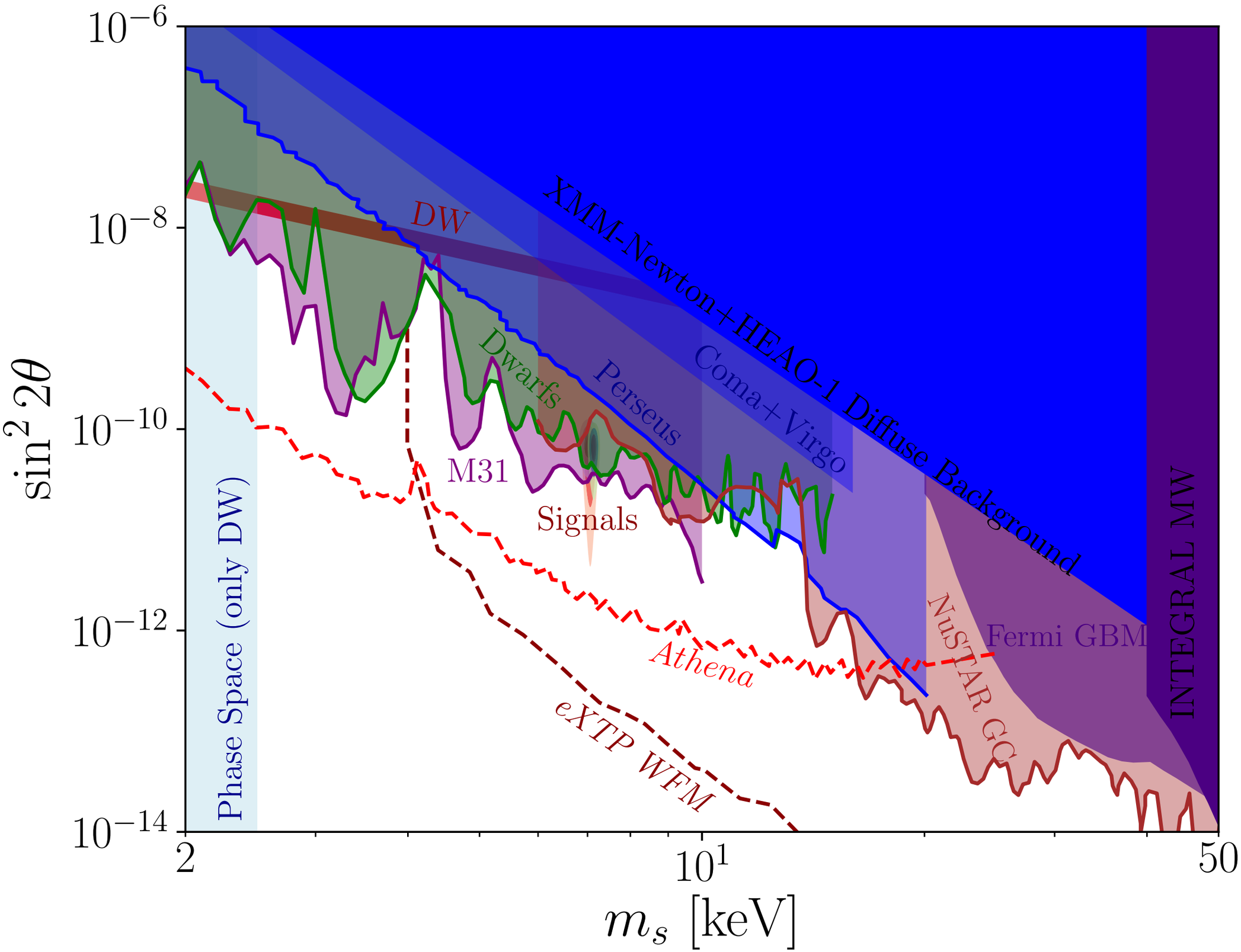


Updated from Abazajian *Phys. Rep.* arXiv:1705.01837

Summary

- **Sterile neutrino dark matter** crosses a transition from "cold" dark matter to "warm" dark matter, at a cutoff scale of great interest in galaxy formation.
- **Warm Dark Matter** is on the ropes. New recent limits from lensing place the free streaming scale at sub-dwarf-galaxy scales
- **Varied production** mechanisms can produce different relations between mass scale and effects on small scale structure. Sterile neutrino dark matter may be of the colder variety.
- **3.5 keV signal?** Many signals, but some deep dark sky searches do not see signature line. Future Follow up observations:
  - 2020: *eROSITA*
  - 2021: *Micro-X, XQC,* X-ray CubeSAT
  - 2022: *XRISM*
  - 2027: *eXTP*
  - 2030+: *ATHENA, Lynx*
- **Laboratory searches**: TRISTAN at KATRIN, HUNTER, Project 8

Backup

A Word About Dessert+ & the Journal *Science*…

- **Dessert, Safdi & Rodd concluding sentence:**
  - "Our analysis rules out the decaying DM interpretation of the previously observed 3.5-keV UXL because our results exclude the required decay rate by more than an order of magnitude."

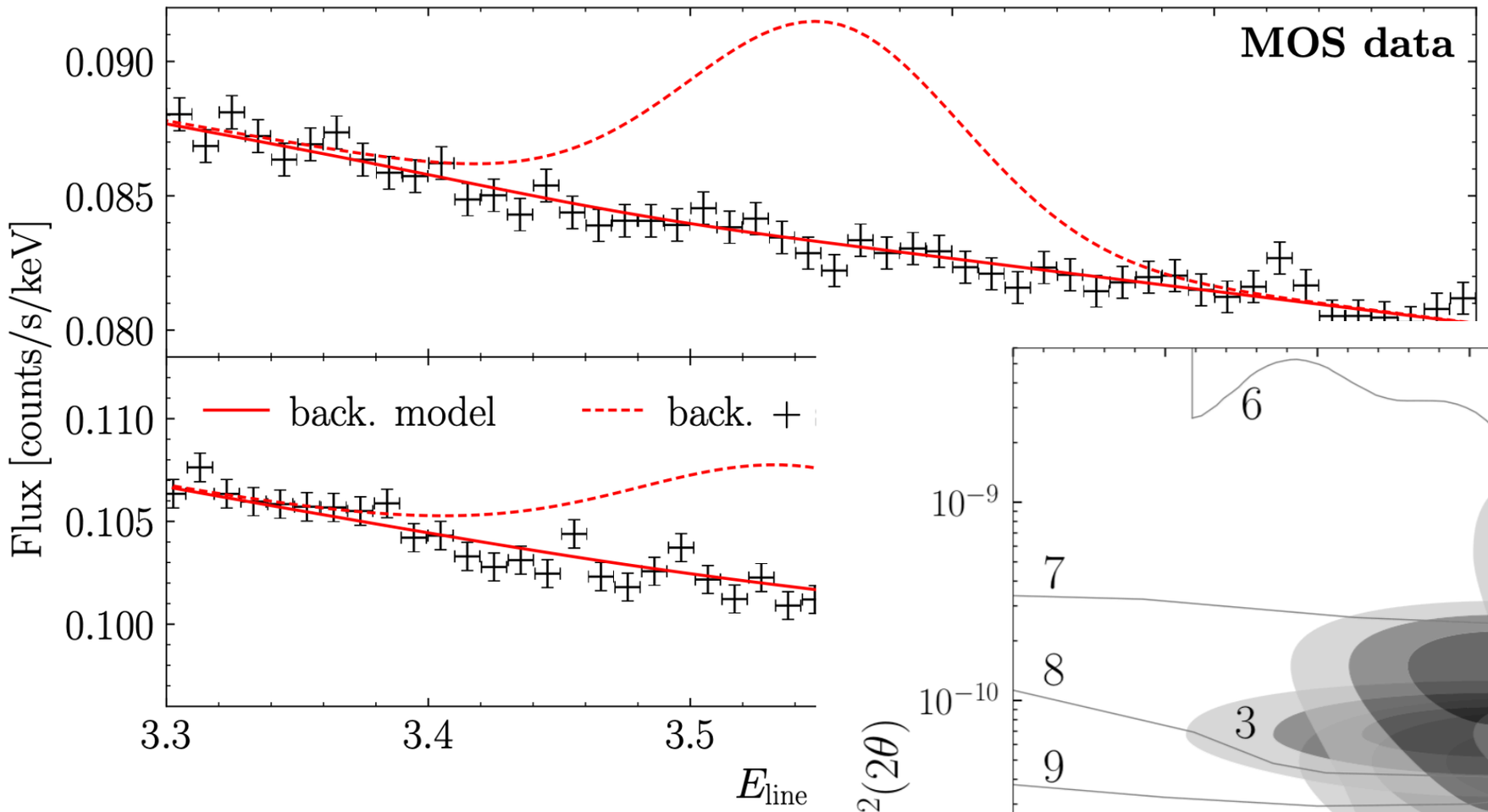
- **Comment on their paper (Abazajian 2004.06170):**
  - known dark matter uncertainties are not included. This relaxes limits by a factor of ~3. Some of those uncertainties were not included in Safdi+.
  - including known lines at 3.3 & 3.7 keV finds evidence for them, and relaxes constraint on 3.5 keV line by a factor of 8 to 9 (MOS & PN).
  - combining both model dependencies, the limit is a factor of 3×8 ~ 20 weaker than that plotted and quoted.

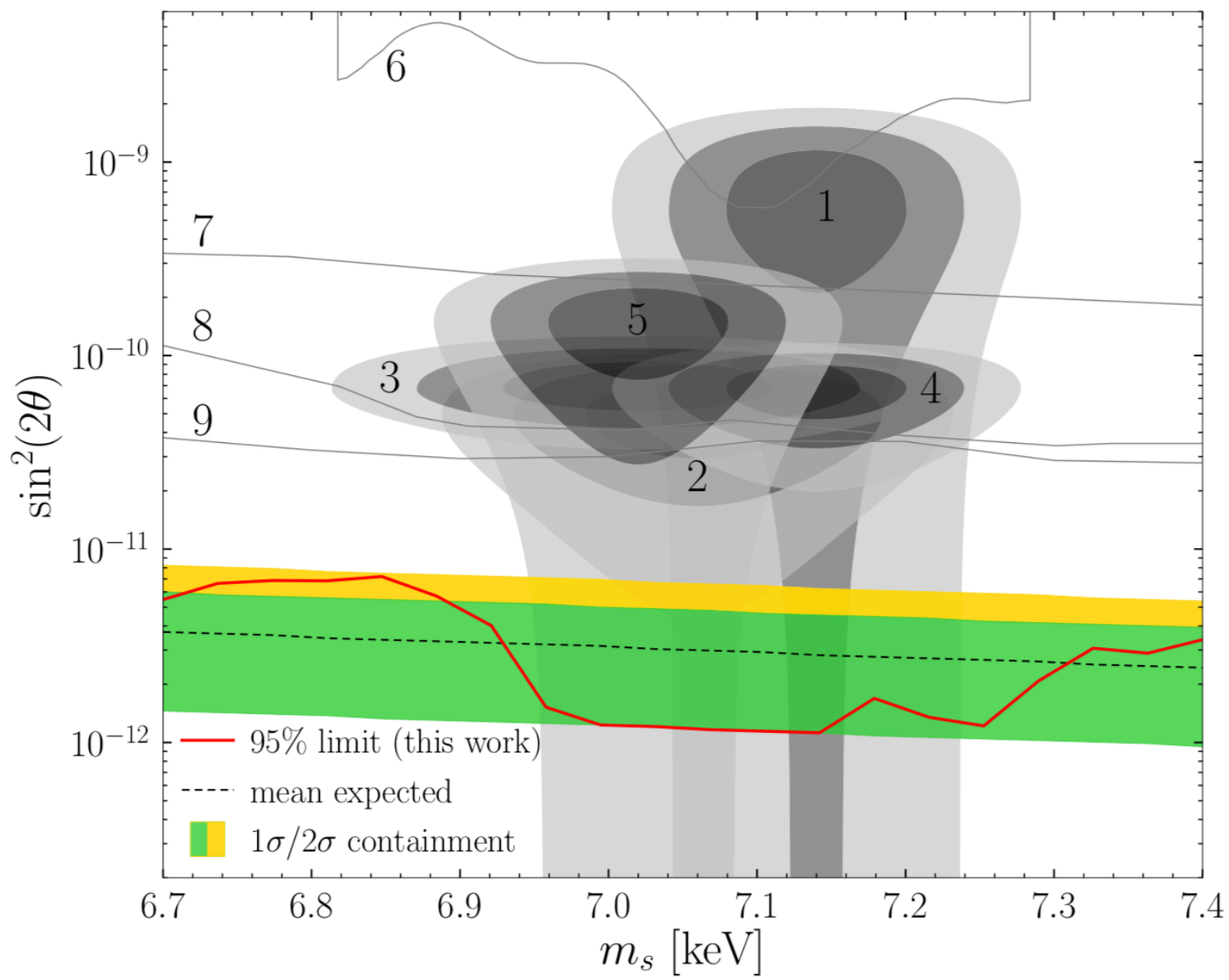
- **Safdi & Rodd email response:**
  - "We do not believe that you are correct in that fitting the stacked data and adding in these extra lines at 3.3 and 3.7 keV leads to the improvement that you quote… Fig. 2 is correct."

- ***Science* Editor Keith Smith on my comment:**
  - "the [Dessert+] paper already discussed and tested those issues… we are therefore rejecting [your comment]"

- ***Science* and *the authors* admit that the claim is a factor of ~20 weaker, but do not correct the record in their own journal/paper. Correction is certainly warranted.**

Joint Multi-Pointing observations…

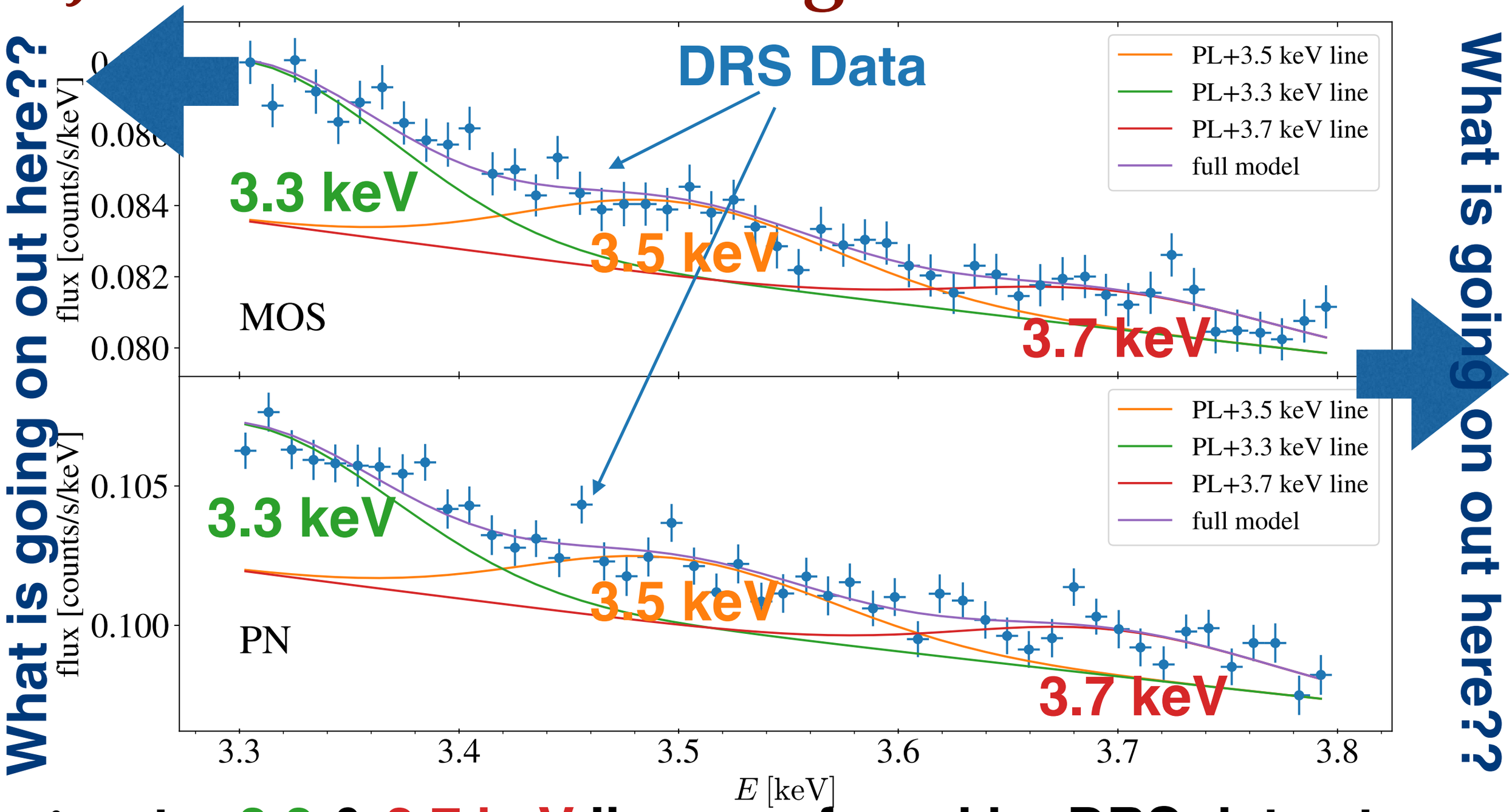




"Our analysis rules out the decaying DM interpretation of the previously observed 3.5-keV UXL because our results exclude the required decay rate by **more than an order of magnitude**."

Dessert, Rodd & Safdi
arXiv:1812.06976

Joint Multi-Pointing observations…



➜ extra 3.3 & 3.7 keV lines preferred by DRS data at 4.3(3.5)σ & 2.8(1.6)σ, for the PN (MOS) cases

➜ room left for 3.5 keV line (shown at 95% upper limit)