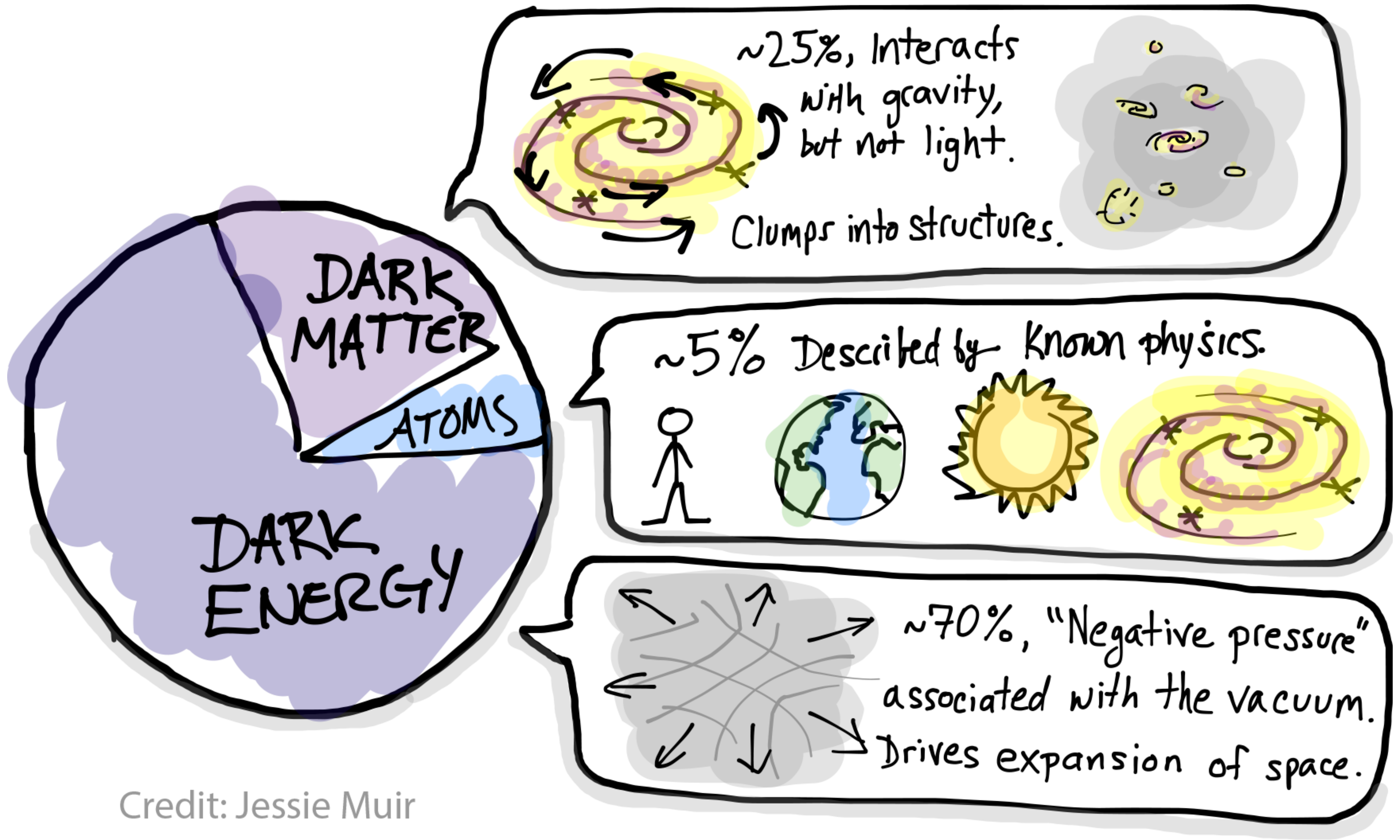
Sterile Neutrino Searches, Dark Matter and Cosmology

Vladislav Barinov
(INR RAS)

22 May 2024, Quarks-2024

Universe Content



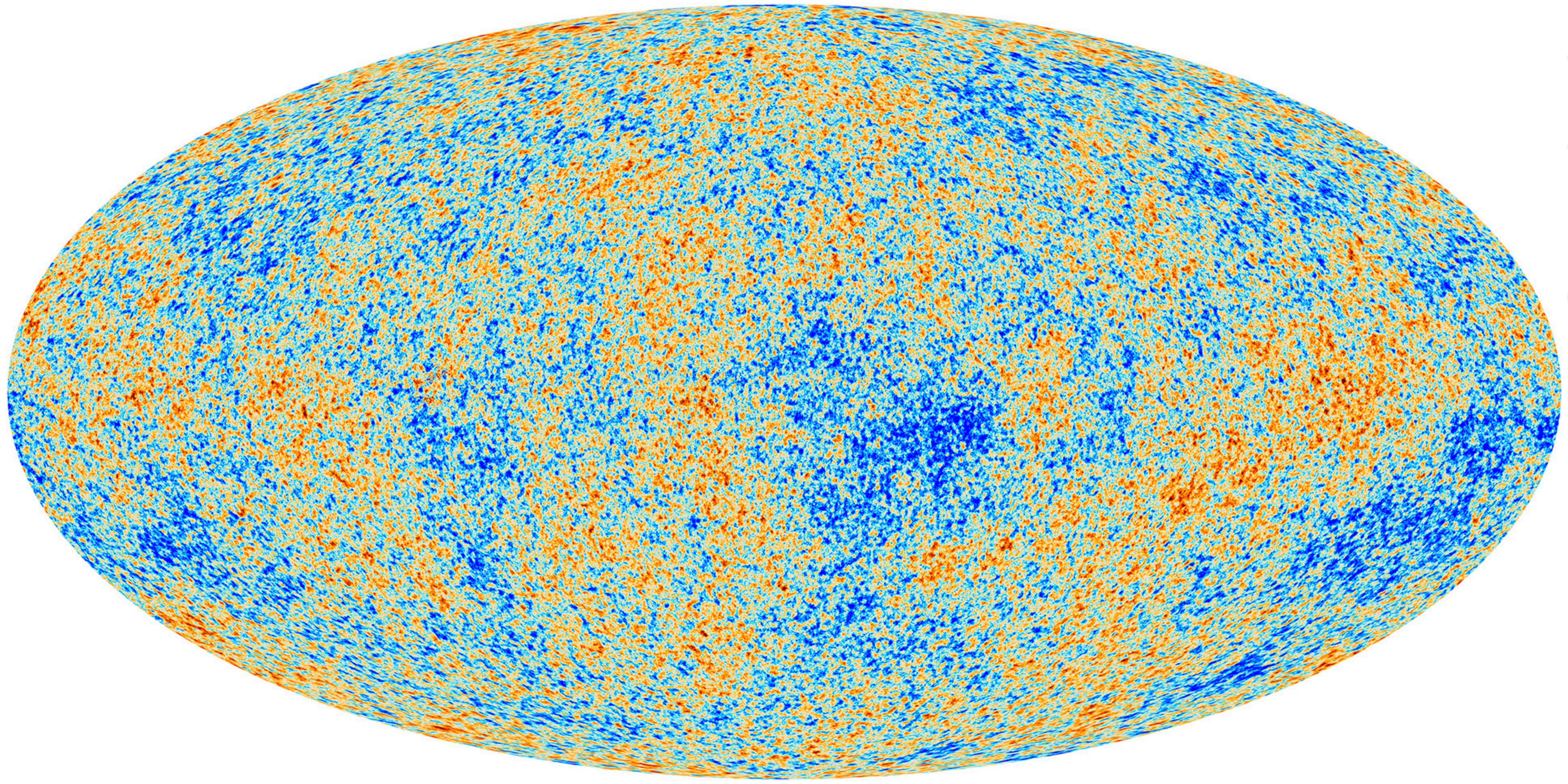
Credit: Jessie Muir

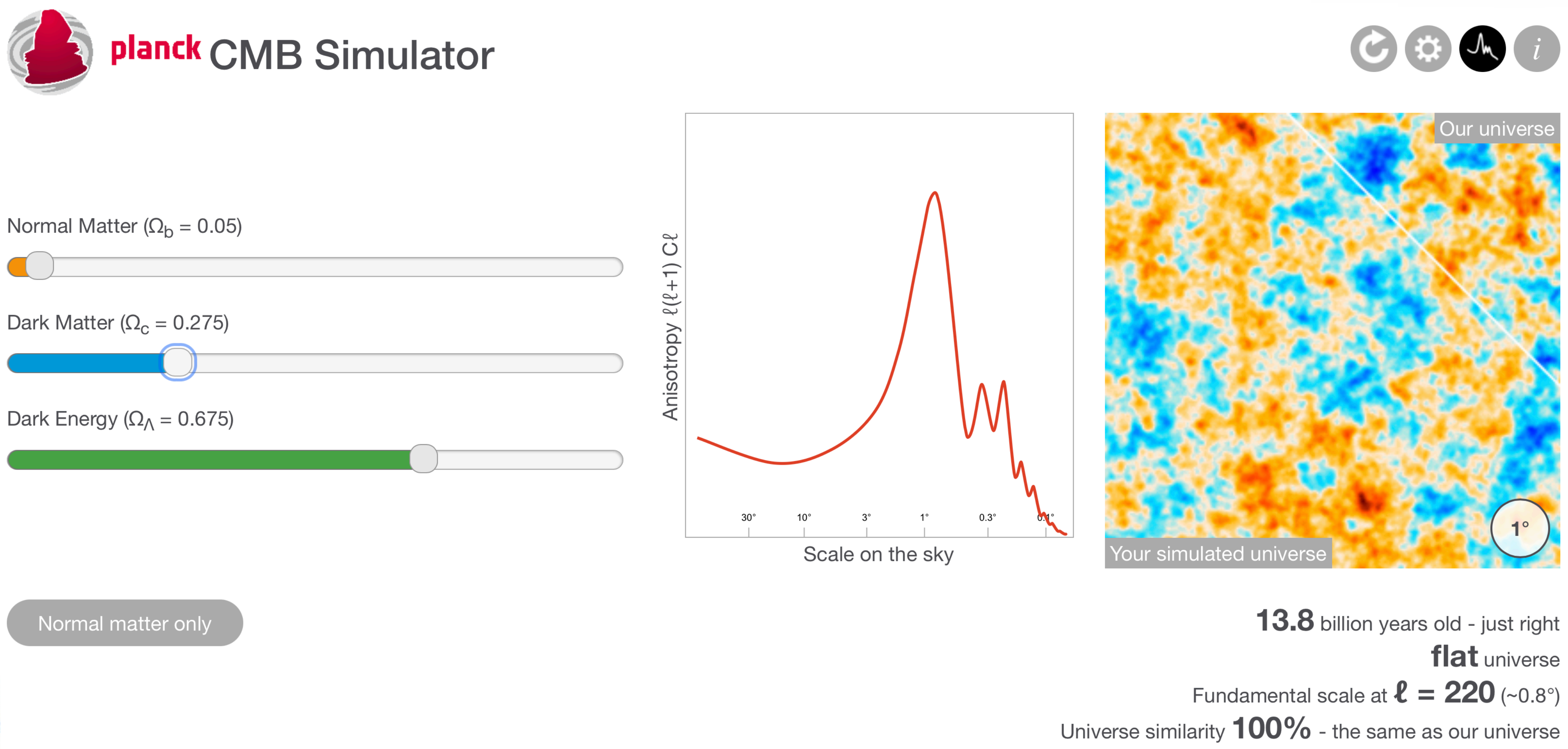
- - - *Planck* 2018 6-parameter fit to flat ΛCDM cosmology -

baryon density of the Universe	$\Omega_b = \rho_b/\rho_{crit}$	$^\ddagger\,0.02237(15)\,h^{-2} = {}^\dagger\,0.0493(6)$
cold dark matter density of the Universe	$\Omega_c = \rho_c/\rho_{crit}$	$^\ddagger\,0.1200(12)\,h^{-2} = {}^\dagger\,0.265(7)$
100 × approximation to r_*/D_A	$100 \times \theta_{MC}$	$^\ddagger\,1.04092(31)$
reionization optical depth	τ	$^\ddagger\,0.054(7)$
ln(power prim. curv. pert.) ($k_0 = 0.05\,\mathrm{Mpc}^{-1}$)	$\ln(10^{10}\Delta^2_{\mathcal{R}})$	$^\ddagger\,3.044(14)$
scalar spectral index	n_s	$^\ddagger\,0.965(4)$
pressureless matter density parameter	$\Omega_m = \Omega_c + \Omega_b$	$^\dagger\,0.315(7)$
dark energy density parameter	Ω_Λ	$^\dagger\,0.685(7)$
energy density of dark energy	ρ_Λ	$^\dagger\,5.83(16) \times 10^{-30}\,\mathrm{g\,cm^{-3}}$
cosmological constant	Λ	$^\dagger\,1.088(30) \times 10^{-56}\,\mathrm{cm^{-2}}$
fluctuation amplitude at $8\,h^{-1}$ Mpc scale	σ_8	$^\dagger\,0.811(6)$

Particle Data Group

Universe Content



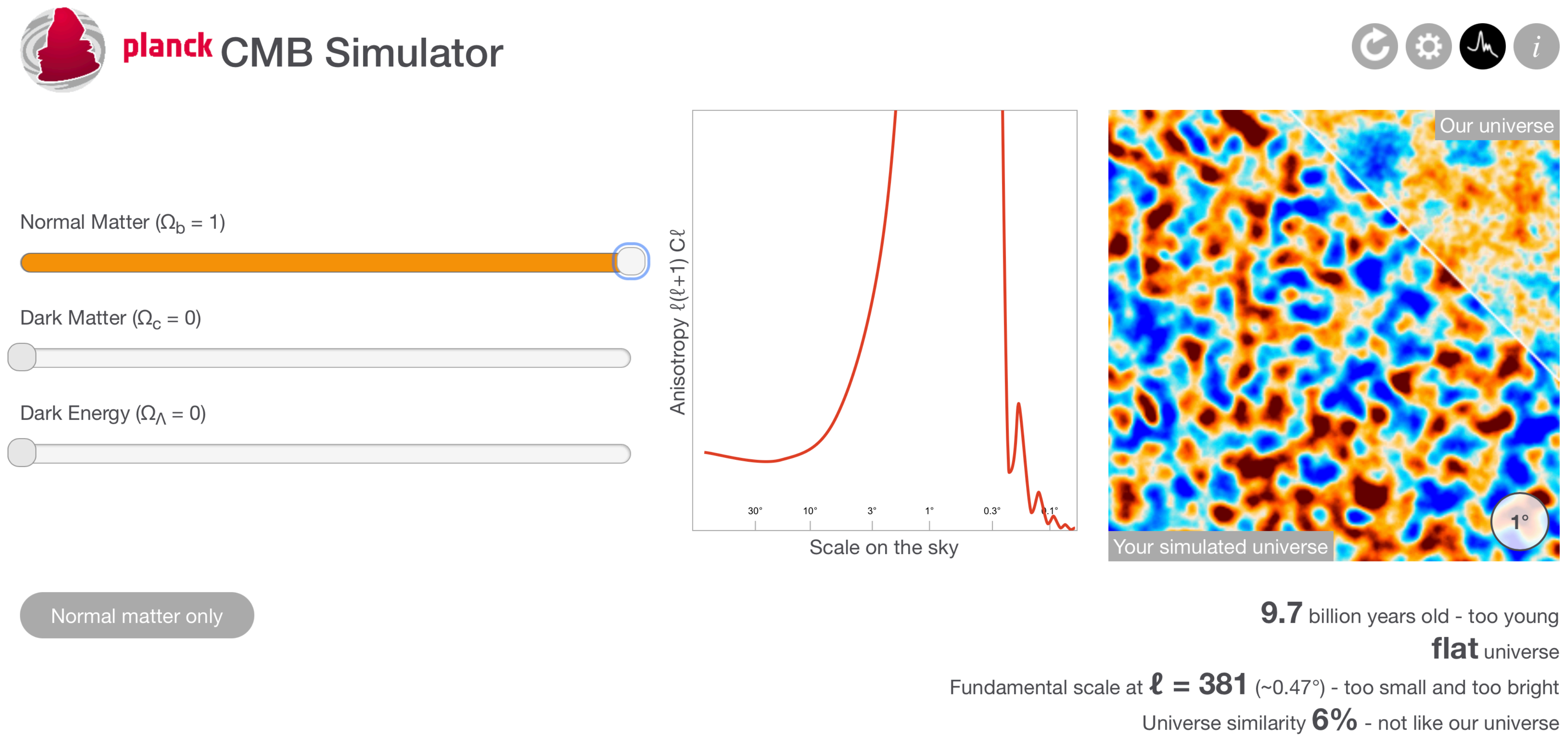


Normal Matter ($\Omega_b = 0.05$)

Dark Matter ($\Omega_c = 0.275$)

Dark Energy ($\Omega_\Lambda = 0.675$)

13.8 billion years old - just right
flat universe
Fundamental scale at **ℓ = 220** (~0.8°)
Universe similarity **100%** - the same as our universe



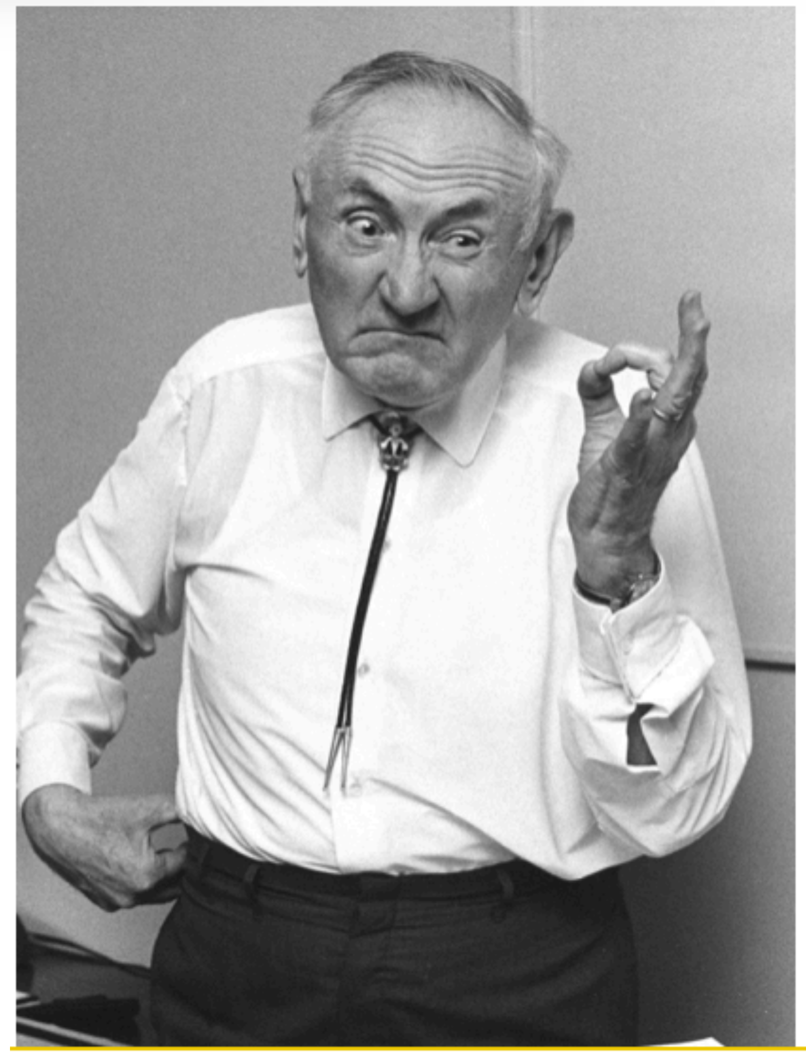
Normal Matter ($\Omega_b = 1$)

Dark Matter ($\Omega_c = 0$)

Dark Energy ($\Omega_\Lambda = 0$)

9.7 billion years old - too young
flat universe
Fundamental scale at **ℓ = 381** (~0.47°) - too small and too bright
Universe similarity **6%** - not like our universe

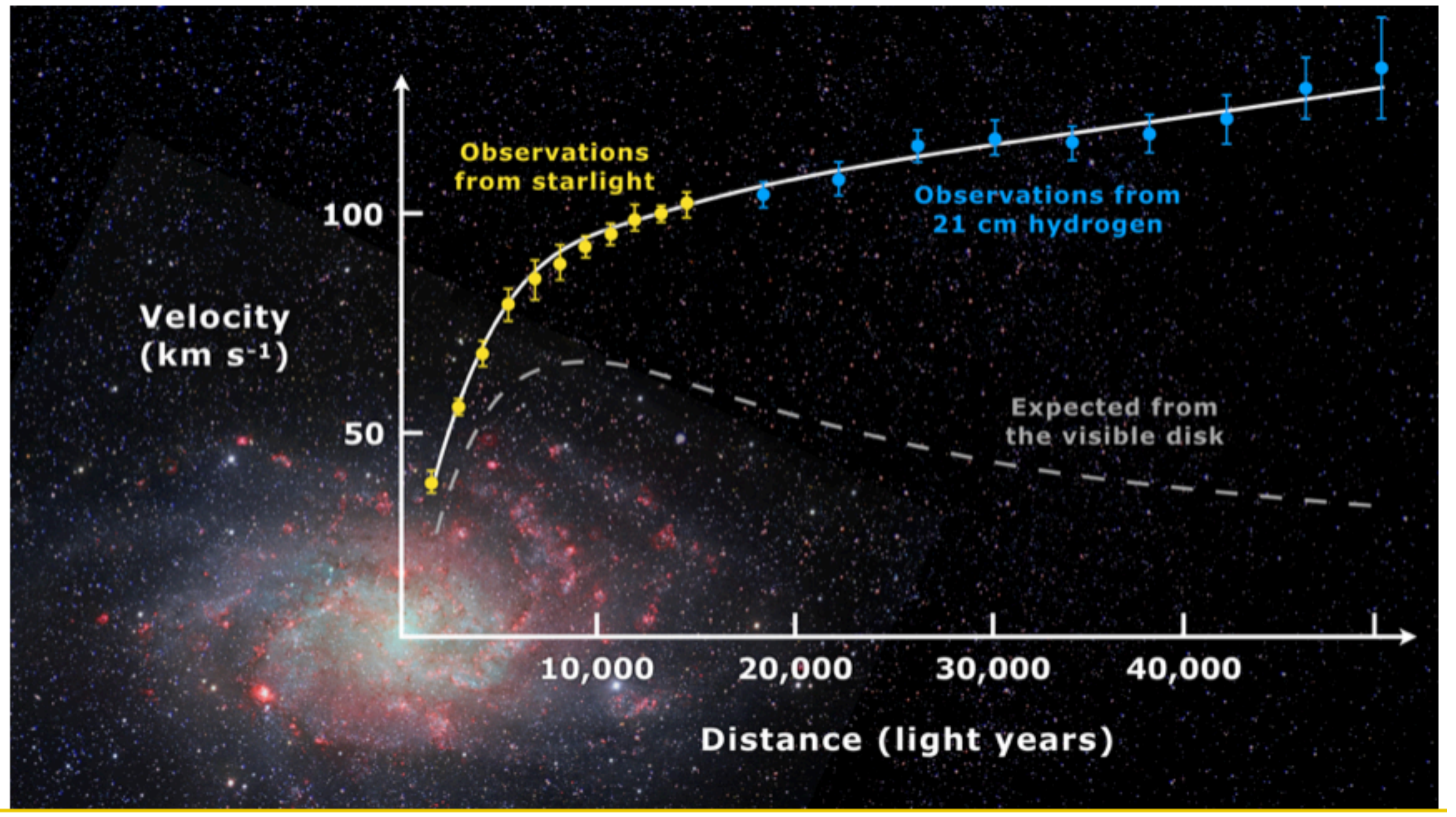
Dark Matter: *What is dark matter? How was it generated?*



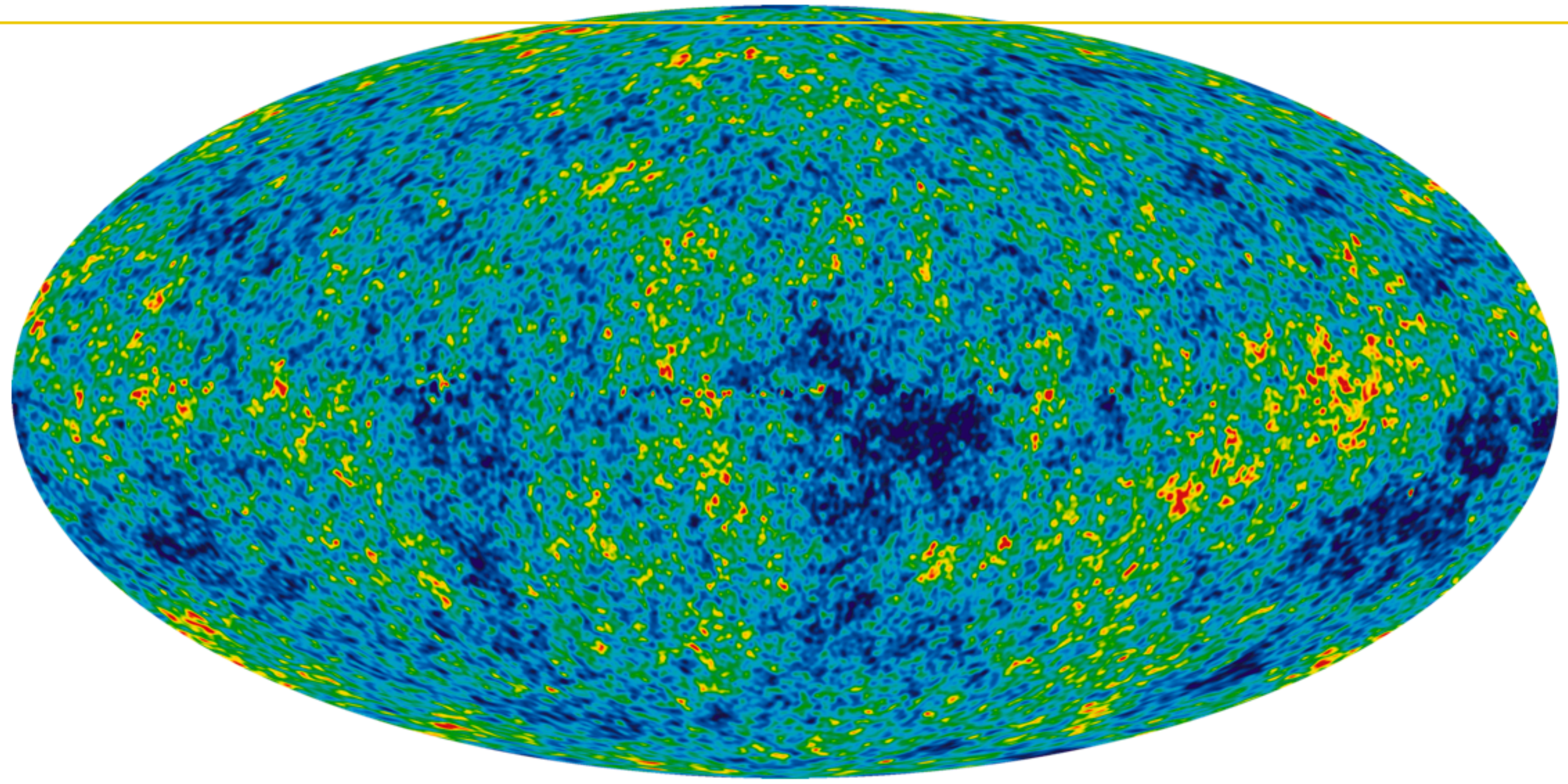
Fritz Zwicky 1933

Virial Mass of the Coma Cluster

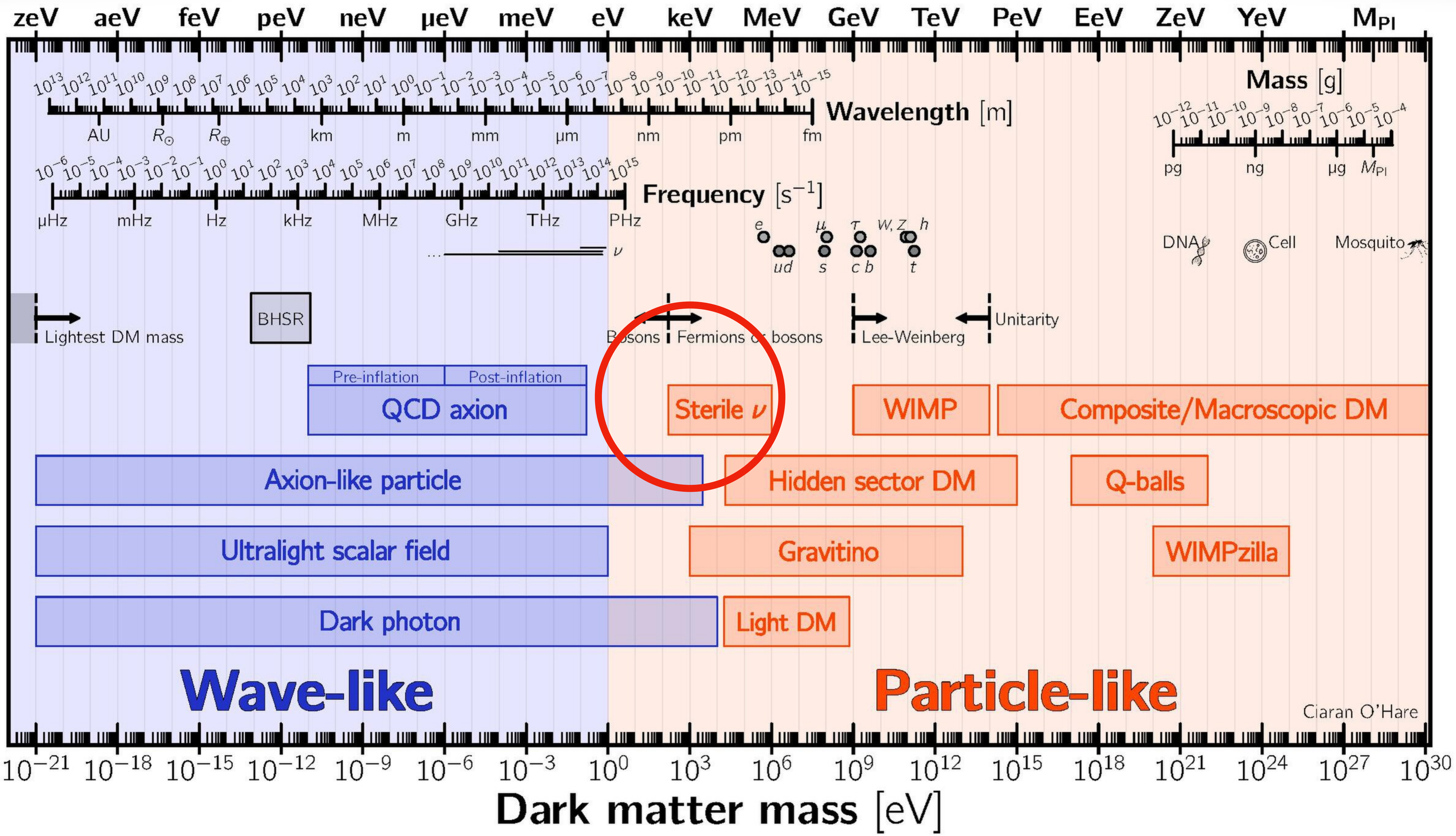
Rotation Curves



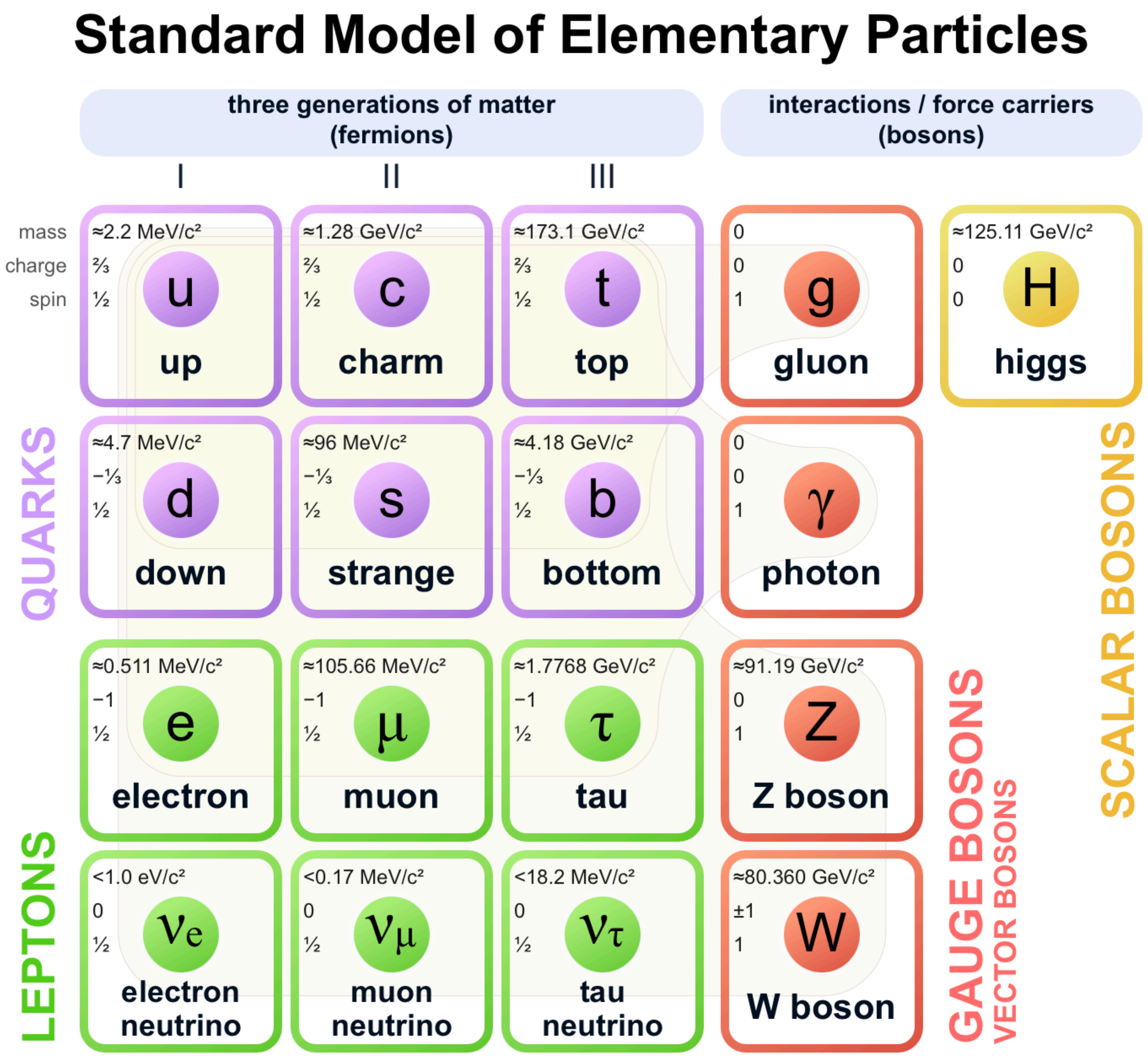
Gravitational Lensing



Dark Matter Candidates



What’s Wrong with Neutrino?



i. Solar neutrino problem
ii. Neutrino Oscillations -> Non zero mass
iii. Reactor Anomaly?
iv. Gallium Anomaly?

It all started with the fact that the expected neutrino flux from the Sun turned out to be about ~3 times less than what was predicted by the standard model of the Sun.

The solution to the problem has been found: ***NEUTRINOS HAVE MASS AND OSCILLATE****. We have received evidence that* ***the standard model of particle physics is incomplete.***

However, in a series of measurements of neutrino fluxes from artificial sources in a series of 4 experiments (SAGE and GALLEX), a neutrino deficit was recorded at a level of about 3 sigma ***(Gallium Anomaly)****. -- What is this?* ***THERE IS POSSIBLE PRESENCE OF A NEW TYPE OF NEUTRINO (Sterile Neutrino).***

BEST Impact on Sterile Neutrino Hypothesis

Result of the BEST

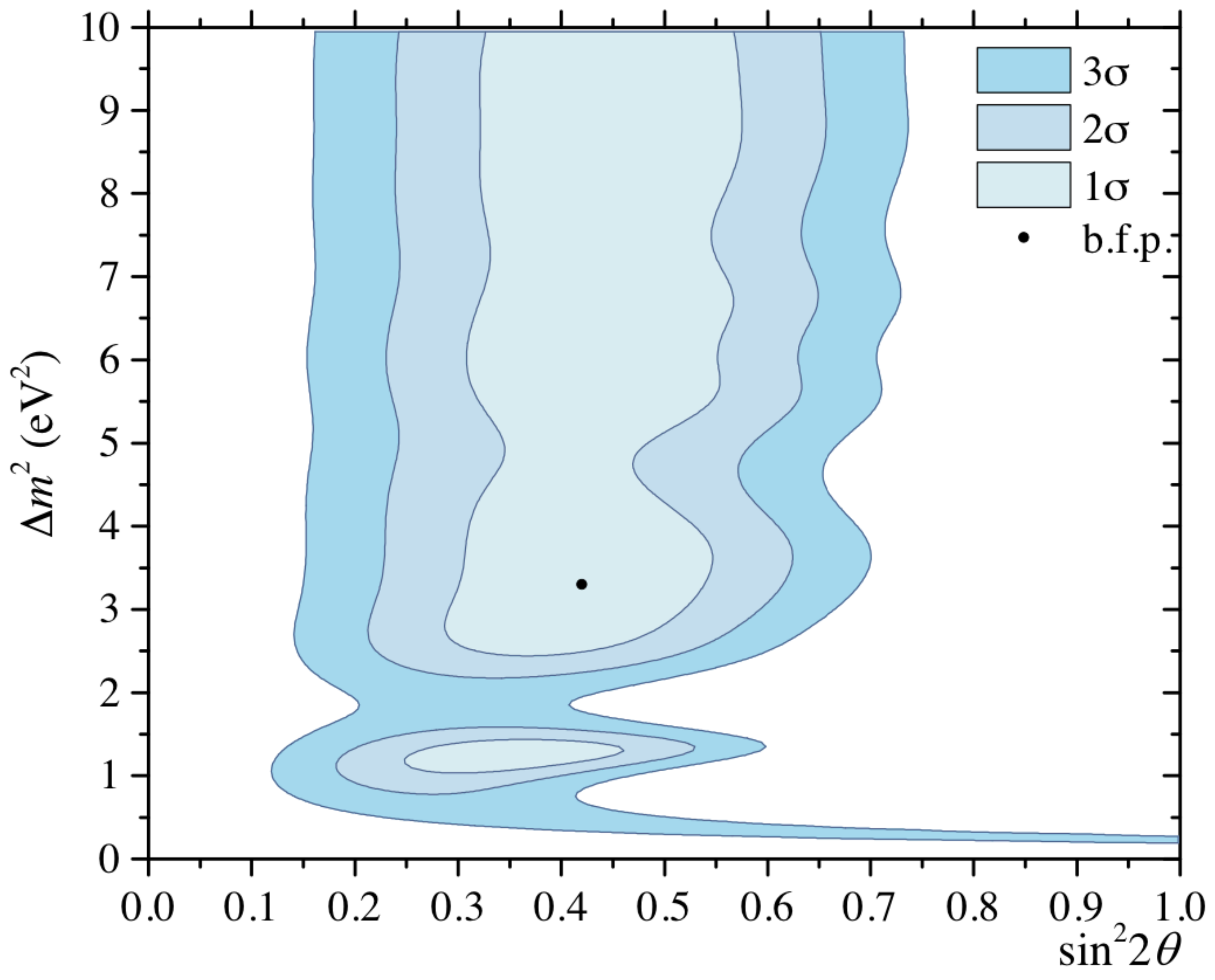


FIG. 10. Allowed regions for two BEST results. The best-fit point is $\sin^2 2\theta = 0.42^{+0.15}_{-0.17}$, $\Delta m^2 = 3.3^{+\infty}_{-2.3}$ eV^2 and is indicated by a point.

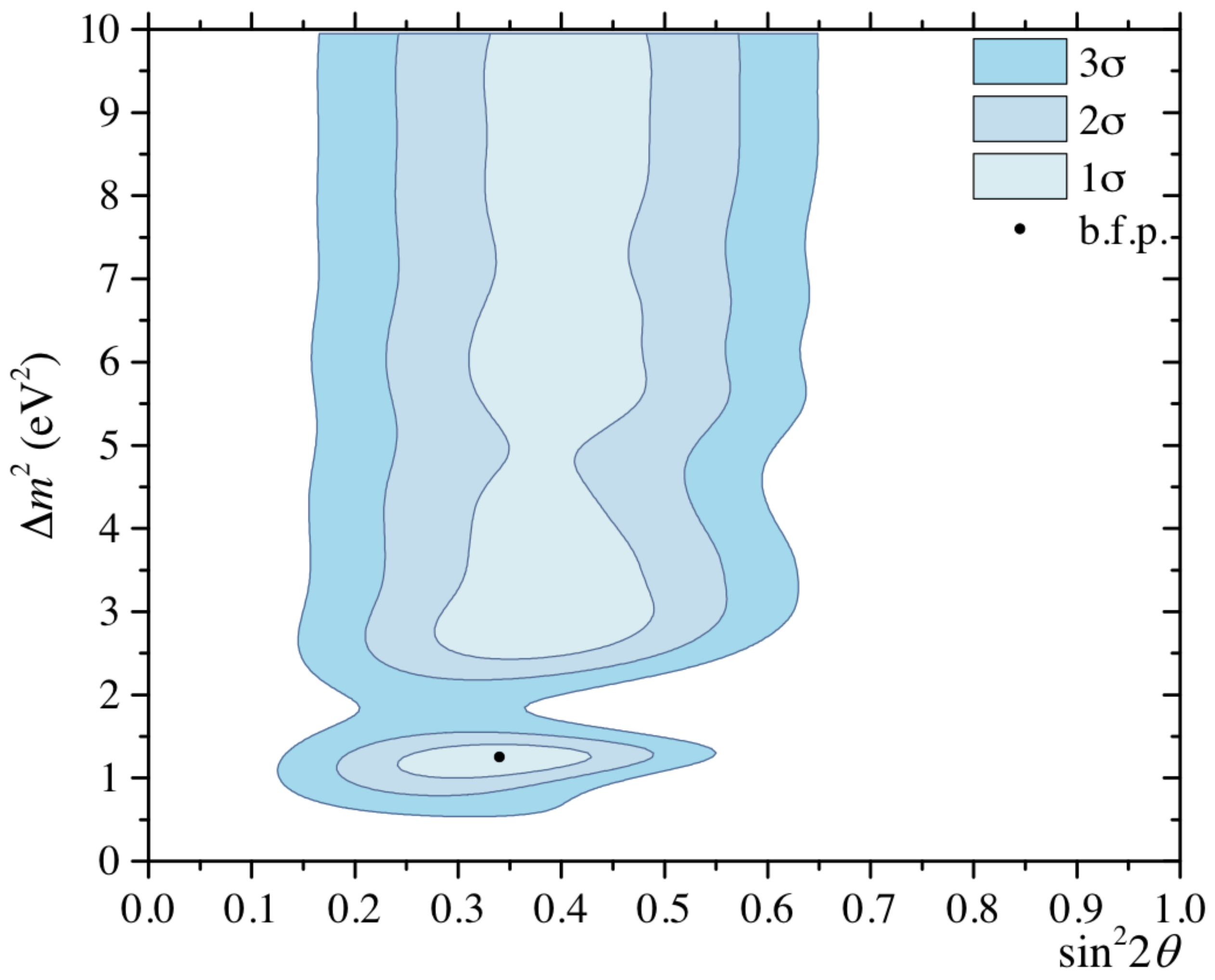


FIG. 11. Allowed regions for two GALLEX, two SAGE and two BEST results. The best-fit point is $\sin^2 2\theta = 0.34^{+0.14}_{-0.09}$, $\Delta m^2 = 1.25^{+\infty}_{-0.25}$ eV^2 and is indicated by a point.

Measured/Expected Rate for the Inner Zone and Outer Zone

$$R_{\rm In} = \frac{54.9^{+3.0}_{-2.9}}{69.4^{+2.5}_{-2.0}} = 0.79^{+0.05}_{-0.05}$$

$$R_{\rm Out} = \frac{55.6^{+3.1}_{-3.1}}{72.6^{+2.6}_{-2.1}} = 0.77^{+0.05}_{-0.05}$$

Barinov et al., Phys.Rev.C 105 (2022)

Barinov et al., Phys.Rev.Lett. 128 (2022)

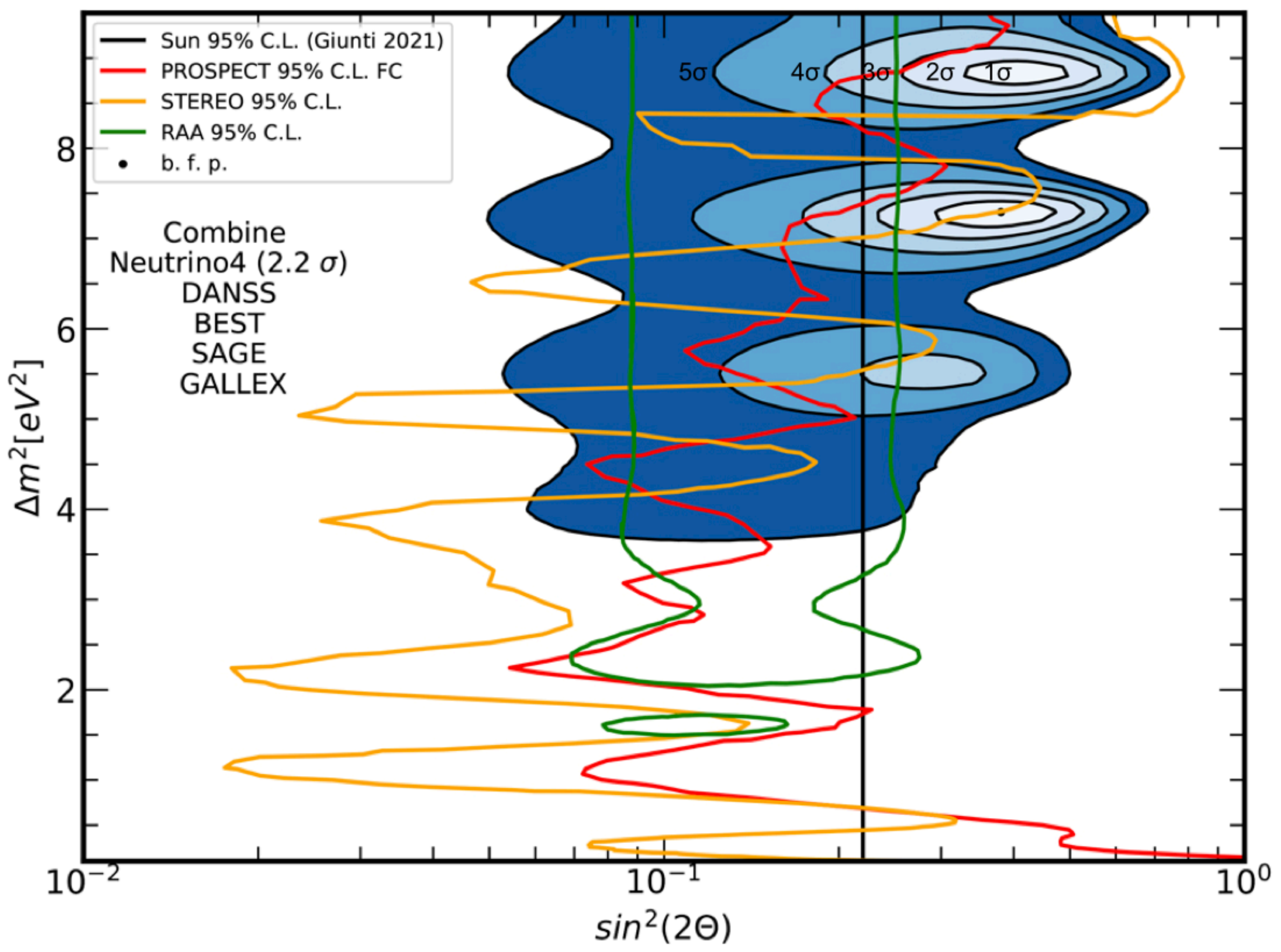


FIG. 3. The regions (in shades of blue) *favored* by the joint analysis of the gallium experiments, DANSS [32] and NEUTRINO-4 [29]. There are also regions *excluded* at 95% C.L. from sterile neutrino searches at reactor antineutrino experiments STEREO [30], PROSPECT [31]. The regions outlined by the green line is *favored* at 95% C.L. by the reactor antineutrino anomaly (RAA) [16]. The region to the right of the black vertical line is *excluded* at 95% C.L. from observations of solar neutrinos [34].

Vladislav Barinov and Dmitry Gorbunov., Phys. Rev. D **105**, L051703 (2022)

Constraints on the Parameters of Sterile Neutrinos from Astrophysical Observations

KeV Sterile Neutrinos

In this and the next chapter, we focus on specific candidates for dark matter particles, namely, sterile neutrinos, which can decay into an active neutrino (electron, muon, or tau neutrino) and a photon due to mixing with active neutrinos

$$\nu_{\mathrm{s}} \to \nu_{\mathrm{e},\mu,\tau} + \gamma .$$

The decay width of the sterile neutrino in this process is defined by the following expression

$$\Gamma_{\nu_{\mathrm{s}}} = \frac{9}{1024}\frac{\alpha}{\pi^4}\mathrm{G}_{\mathrm{F}}^2 \mathrm{m}_{\nu_{\mathrm{s}}}^5 \sin^2 2\theta = 1.36 \times 10^{-22} \left(\frac{\mathrm{m}_{\nu_{\mathrm{s}}}}{1\mathrm{keV}}\right)^5 \sin^2 2\theta \quad \mathrm{s}^{-1}$$

where $\mathrm{m}_{\nu_{\mathrm{s}}}$ is the mass of the sterile neutrino, θ is the mixing angle between active and sterile neutrinos.

In this two-particle decay, the energy of the outgoing photon is $\mathrm{E}_\gamma = \mathrm{m}_{\nu_{\mathrm{s}}}/2$, and the sterile neutrinos, which form the galactic dark matter, produce a monochromatic photon spectrum of the order of the speed of dark matter particles in the galaxy, i.e. $\mathrm{v} \sim 10^{-4} - 10^{-3}$.

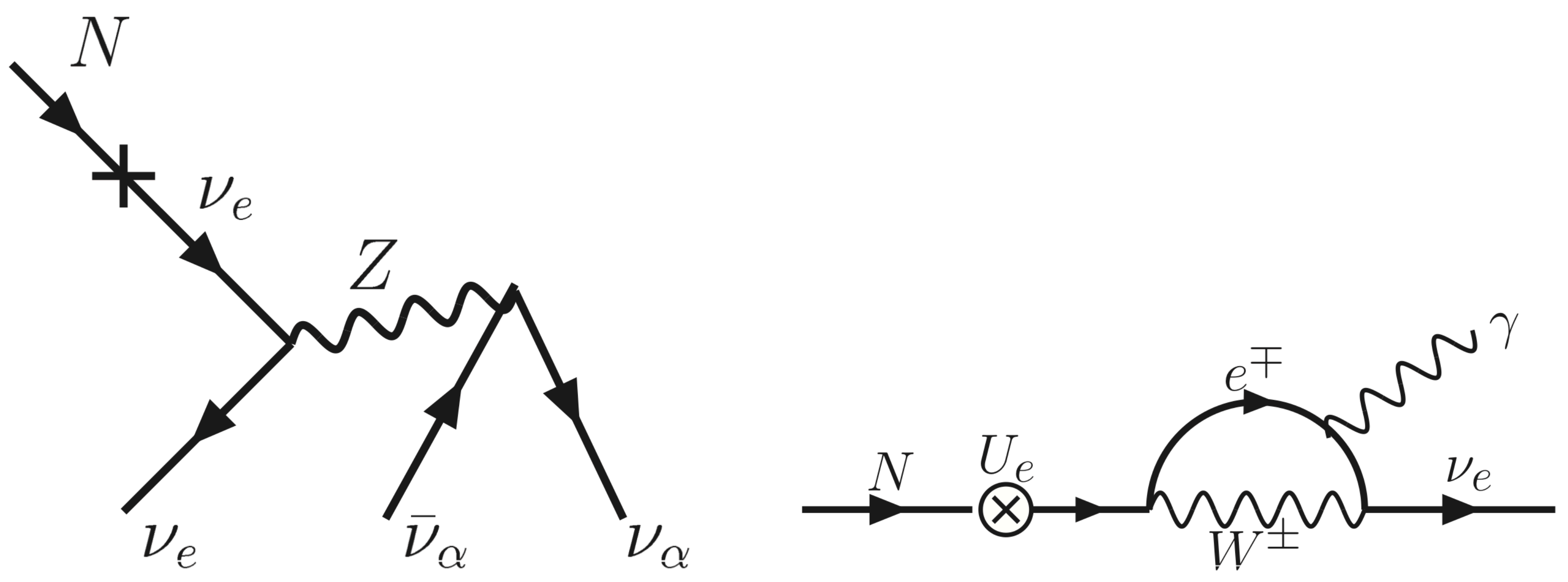
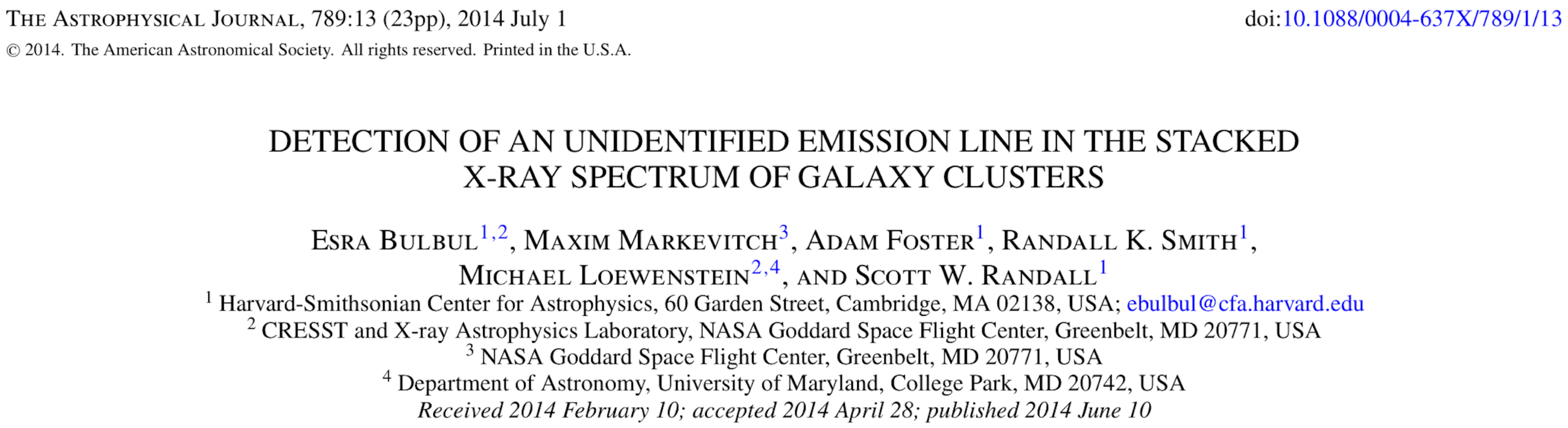


Figure 18. Decay channels of the sterile neutrino N with the mass below twice the electron mass. Left panel: dominant decay channel to three (anti)neutrinos. Right panel shows radiative decay channel that allows to look for the signal of sterile neutrino DM in the spectra of DM dominated objects.

R. Adhikari et al JCAP01(2017)025

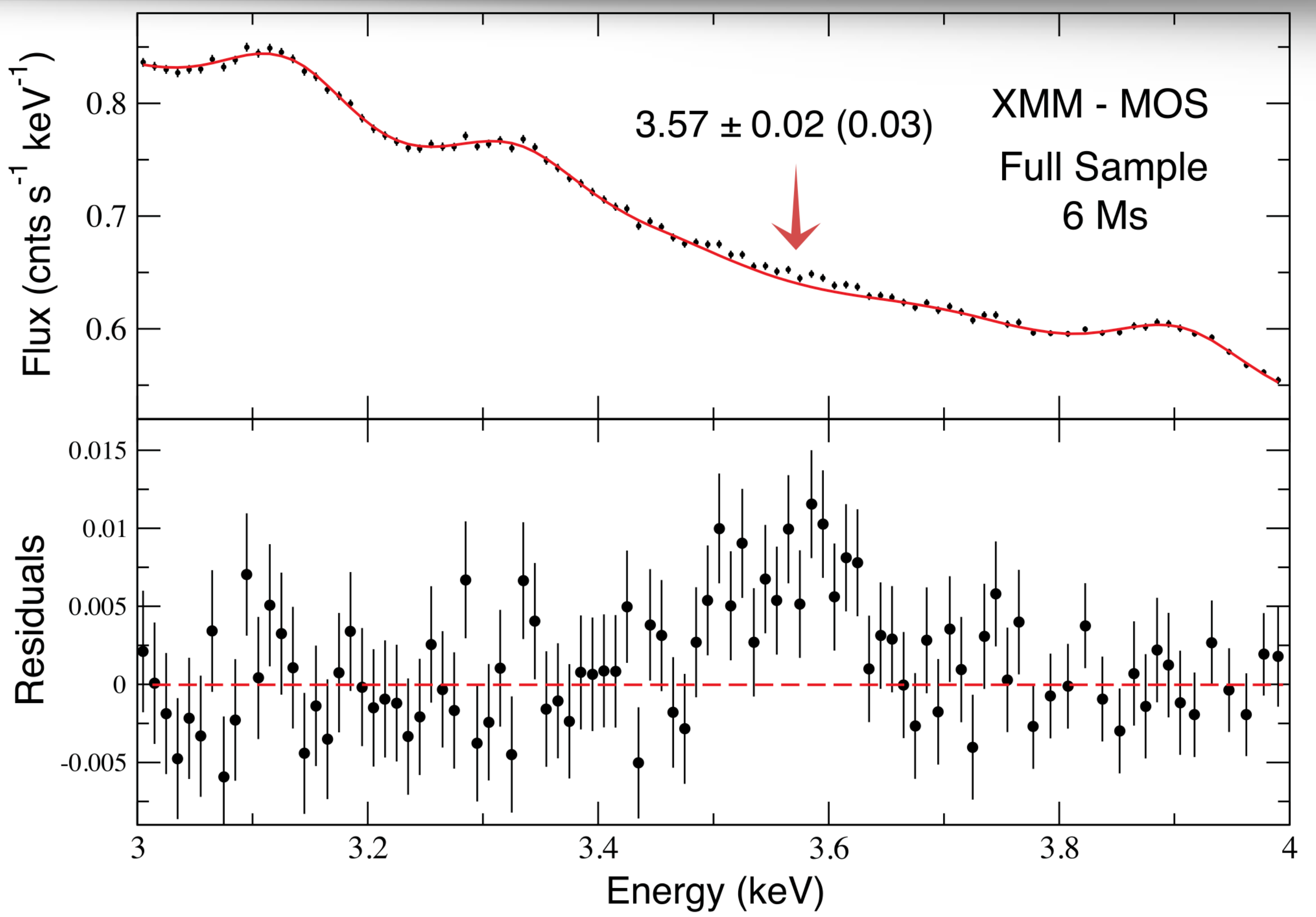
Undefined Line in X-Ray Spectra

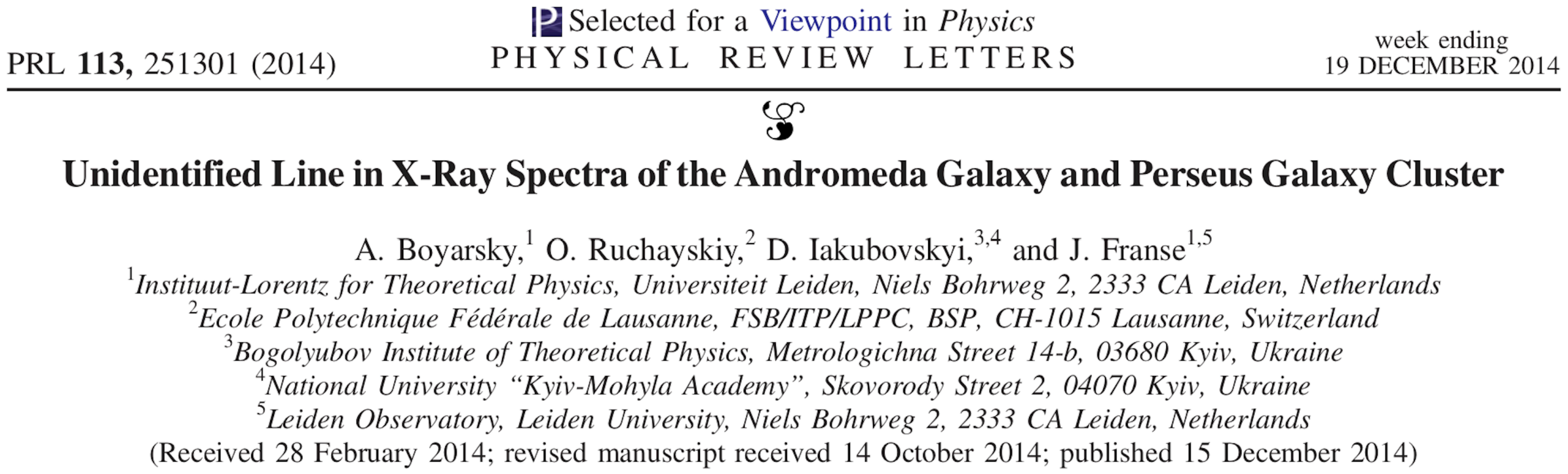


The Astrophysical Journal, 789:13 (23pp), 2014 July 1 doi:10.1088/0004-637X/789/1/13
© 2014. The American Astronomical Society. All rights reserved. Printed in the U.S.A.

DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED
X-RAY SPECTRUM OF GALAXY CLUSTERS

Esra Bulbul[1,2], Maxim Markevitch[3], Adam Foster[1], Randall K. Smith[1],
Michael Loewenstein[2,4], and Scott W. Randall[1]
[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA; ebulbul@cfa.harvard.edu
[2] CRESST and X-ray Astrophysics Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
[3] NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
[4] Department of Astronomy, University of Maryland, College Park, MD 20742, USA
Received 2014 February 10; accepted 2014 April 28; published 2014 June 10

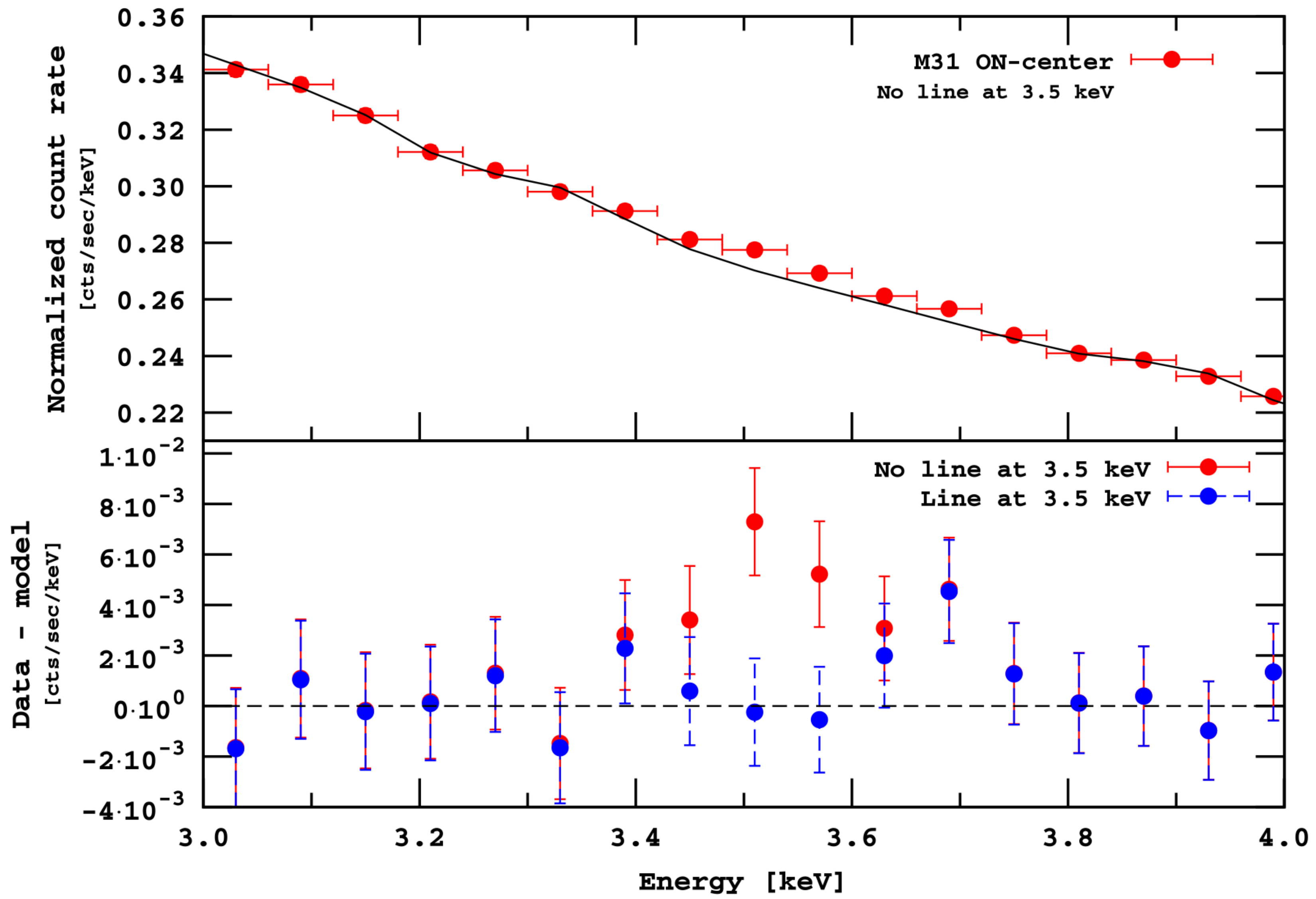




Selected for a Viewpoint in *Physics*
PRL **113,** 251301 (2014) PHYSICAL REVIEW LETTERS week ending 19 DECEMBER 2014

Unidentified Line in X-Ray Spectra of the Andromeda Galaxy and Perseus Galaxy Cluster

A. Boyarsky,[1] O. Ruchayskiy,[2] D. Iakubovskyi,[3,4] and J. Franse[1,5]
[1]*Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, 2333 CA Leiden, Netherlands*
[2]*Ecole Polytechnique Fédérale de Lausanne, FSB/ITP/LPPC, BSP, CH-1015 Lausanne, Switzerland*
[3]*Bogolyubov Institute of Theoretical Physics, Metrologichna Street 14-b, 03680 Kyiv, Ukraine*
[4]*National University "Kyiv-Mohyla Academy", Skovorody Street 2, 04070 Kyiv, Ukraine*
[5]*Leiden Observatory, Leiden University, Niels Bohrweg 2, 2333 CA Leiden, Netherlands*
(Received 28 February 2014; revised manuscript received 14 October 2014; published 15 December 2014)



Search Strategy / Expected Signal & Observation Scheme

Intensity from Sterile Neutrino Decays

$$I_\gamma \equiv \frac{d^2F_\gamma}{dE_\gamma d\Omega}\left[\frac{\text{cts}}{\text{cm}^2\text{skeVSr}}\right]$$

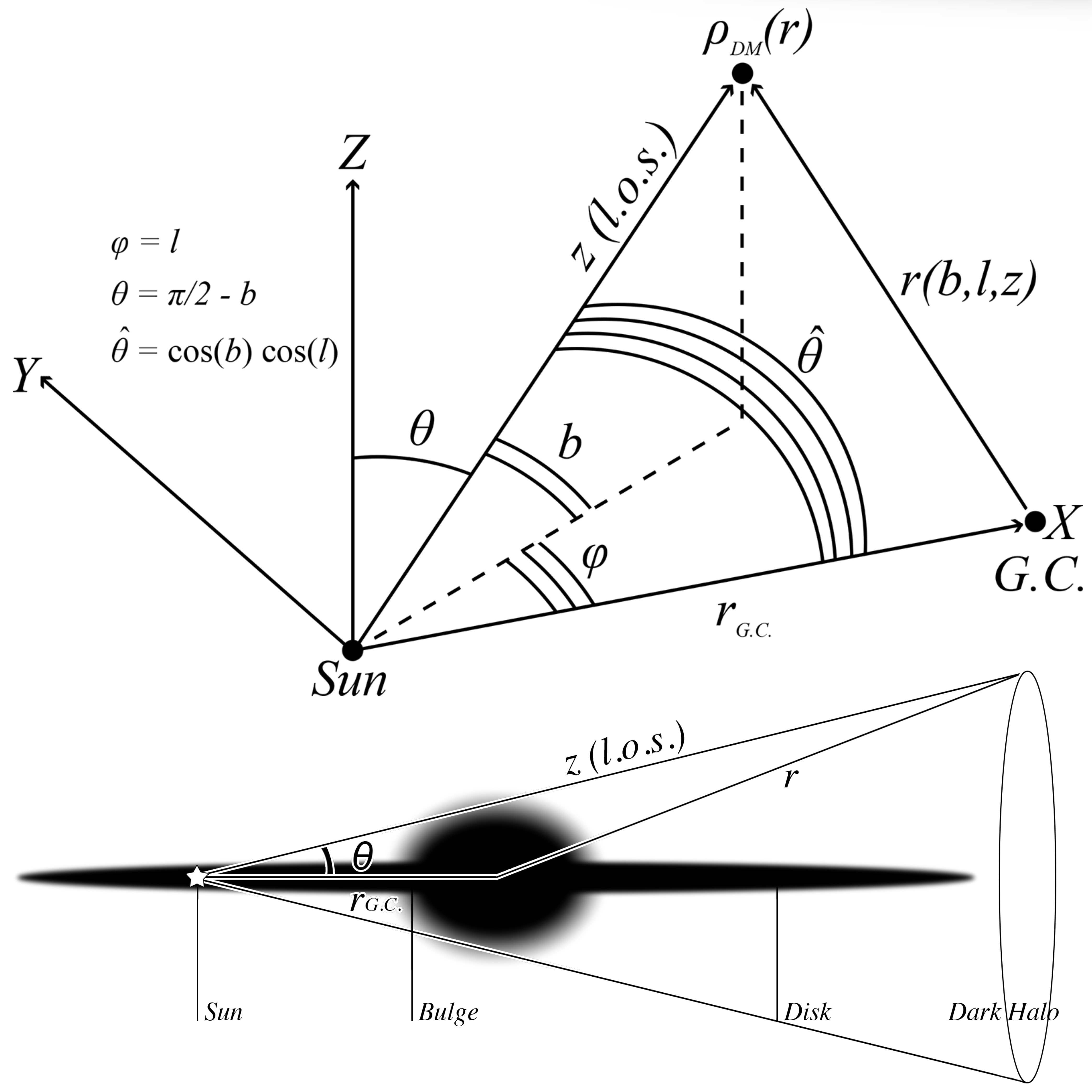
Dark Matter Flux and Column Density in given FOV

$$F_\gamma = \frac{1}{4\pi}\frac{\Gamma_{\nu_s}}{m_{\nu_s}}\iint \frac{dN}{dE_\gamma}\frac{d\mathscr{D}_{DM}}{d\Omega}dE_\gamma d\Omega$$

$$\mathscr{D}_{DM} = \int_{f.o.v.}\int_{l.o.s.}\frac{\rho_{DM}(r)}{z^2}z^2\,\mathrm{d}z\,\mathrm{d}\Omega$$

Stacked Intensity

$$\langle I_\gamma\rangle = \frac{1}{4\pi}\frac{\Gamma_{\nu_s}}{m_{\nu_s}}\frac{dN}{dE_\gamma}\left[\frac{1}{\mathrm{T_{tot}}}\sum_i \mathrm{T}_i\frac{\mathrm{d}\mathscr{D}_{DM,i}}{\mathrm{d}\Omega}\right] = \frac{1}{4\pi}\frac{\Gamma_{\nu_s}}{m_{\nu_s}}\frac{dN}{dE_\gamma}\left\langle\frac{\mathrm{d}\mathscr{D}_{DM}}{\mathrm{d}\Omega}\right\rangle$$

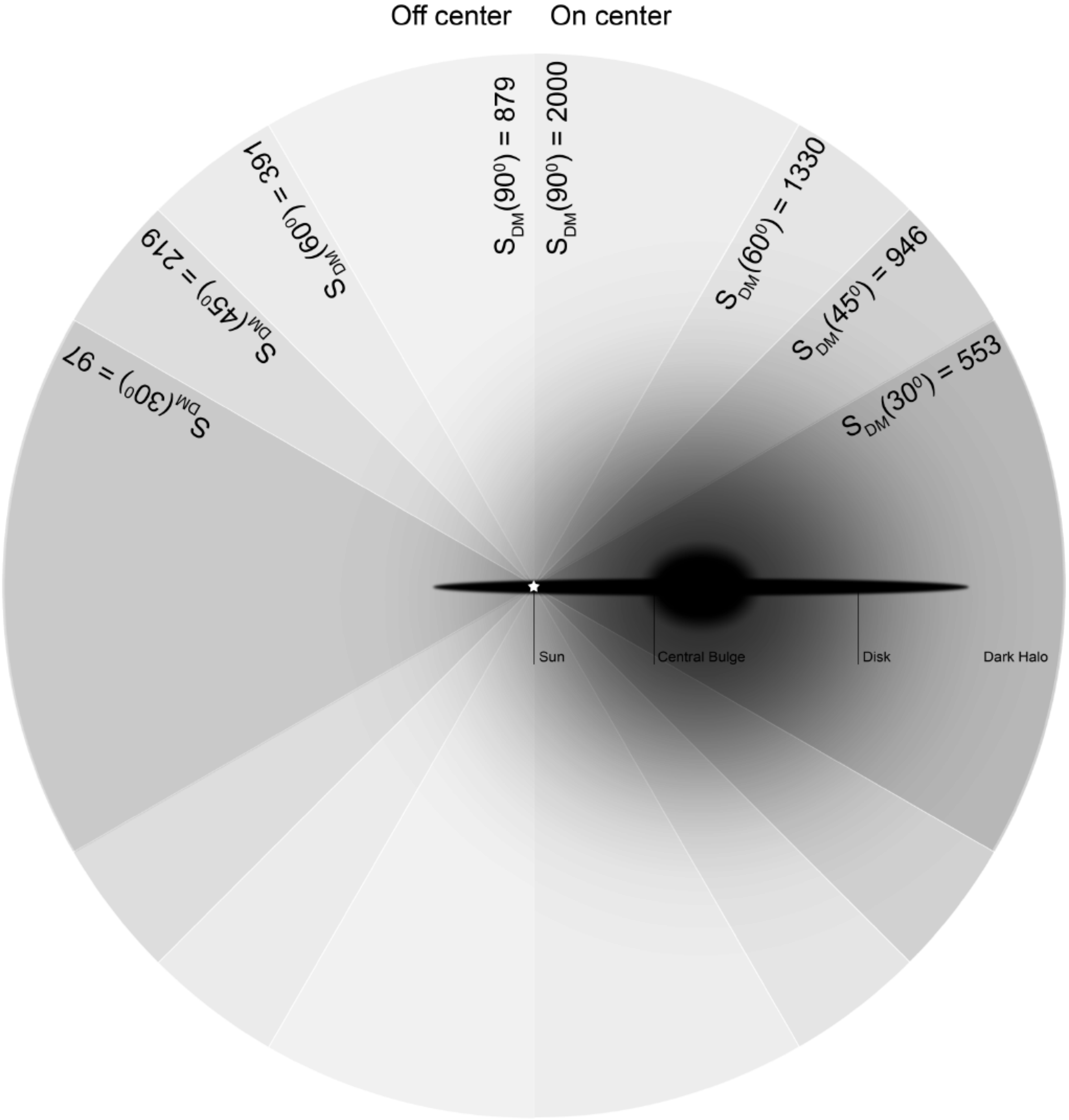


Dark Matter Profiles

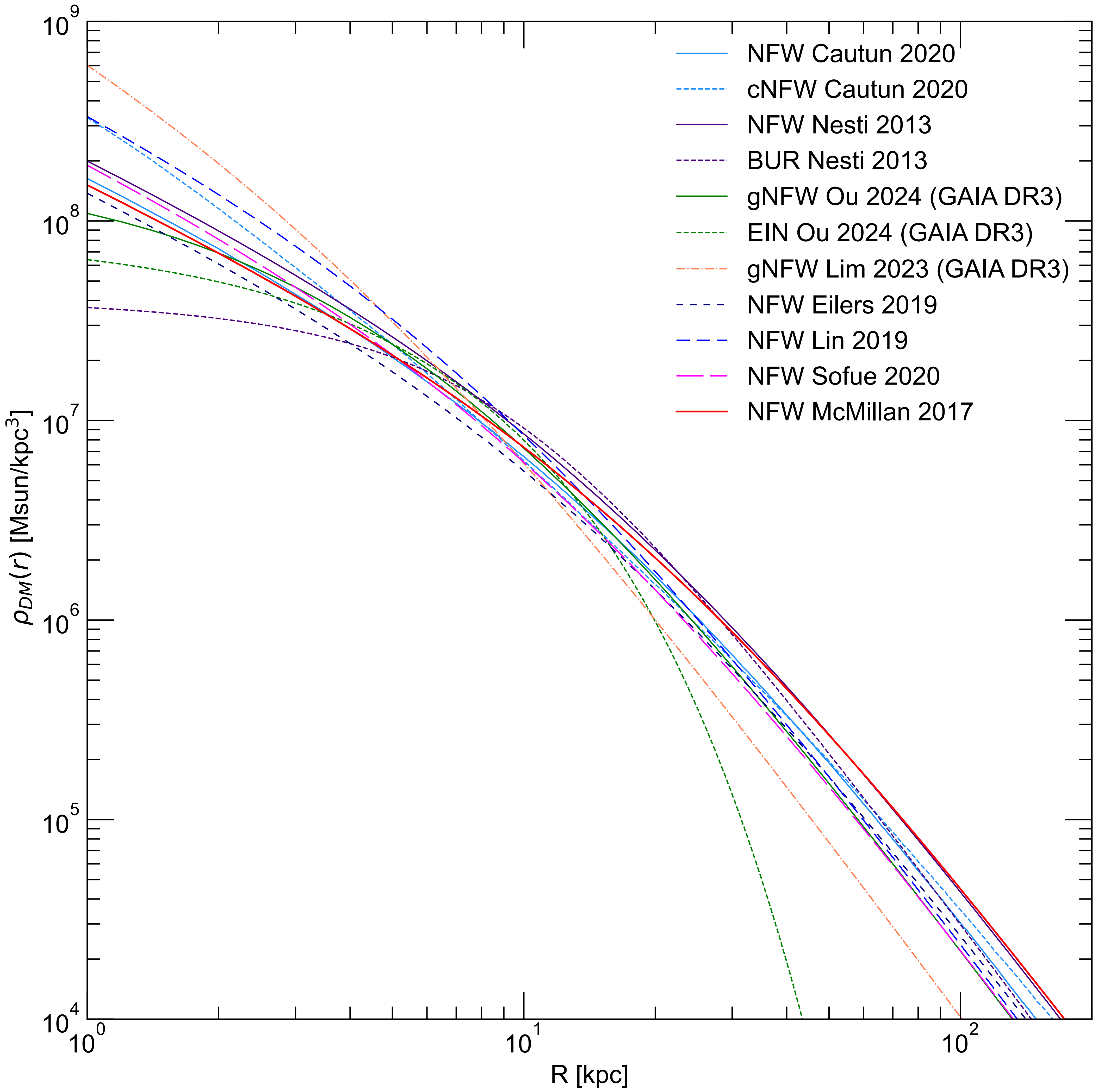
To describe the dark matter density distribution in the Milky Way galaxy, we use the standard NFW profile

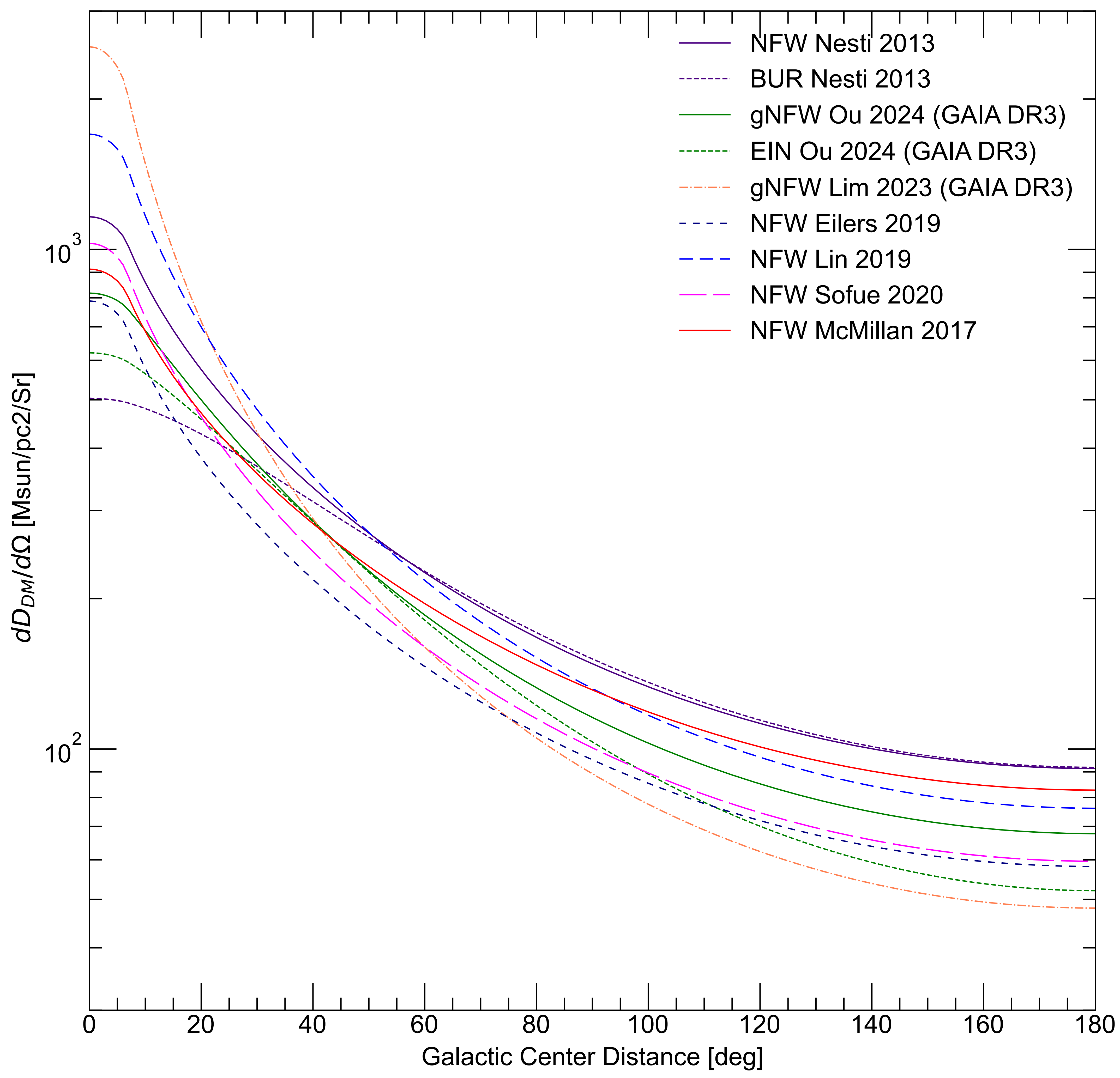
$$\rho(\mathrm{r}) = \frac{\rho_{\mathrm{s}}}{(\mathrm{r}/\mathrm{r}_{\mathrm{s}})\,(1+\mathrm{r}/\mathrm{r}_{\mathrm{s}})^2}$$

Right: Diagram of the dark matter density distribution $\mathcal{S}_{\mathrm{DM}}$ for different directions and viewing angles of the Milky Way. The values of $\mathcal{S}_{\mathrm{DM}}$ are presented in the $\mathrm{M}_{\odot}\mathrm{nk}^{-2}$.

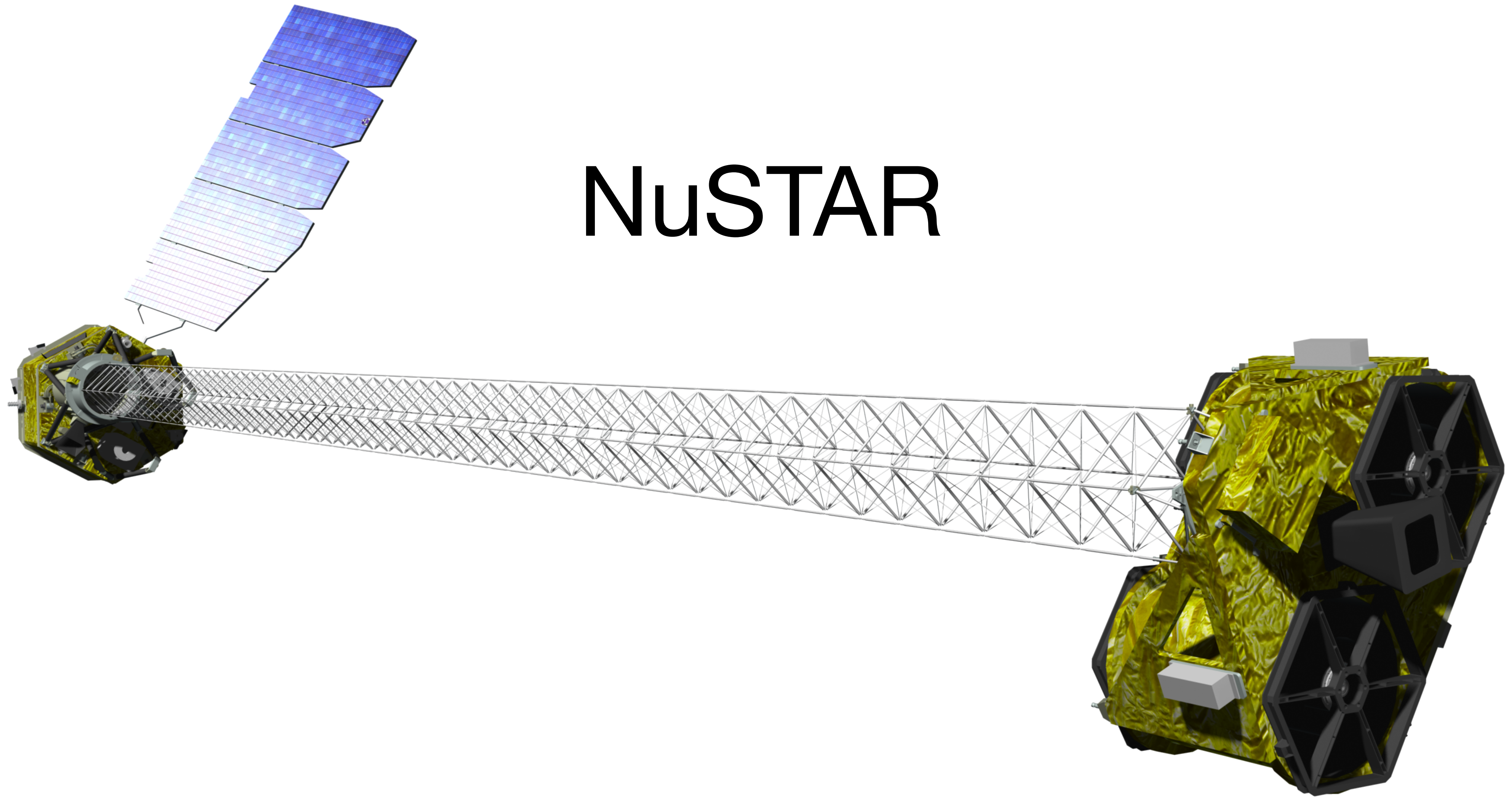


Dark Matter Profiles / Uncertainty

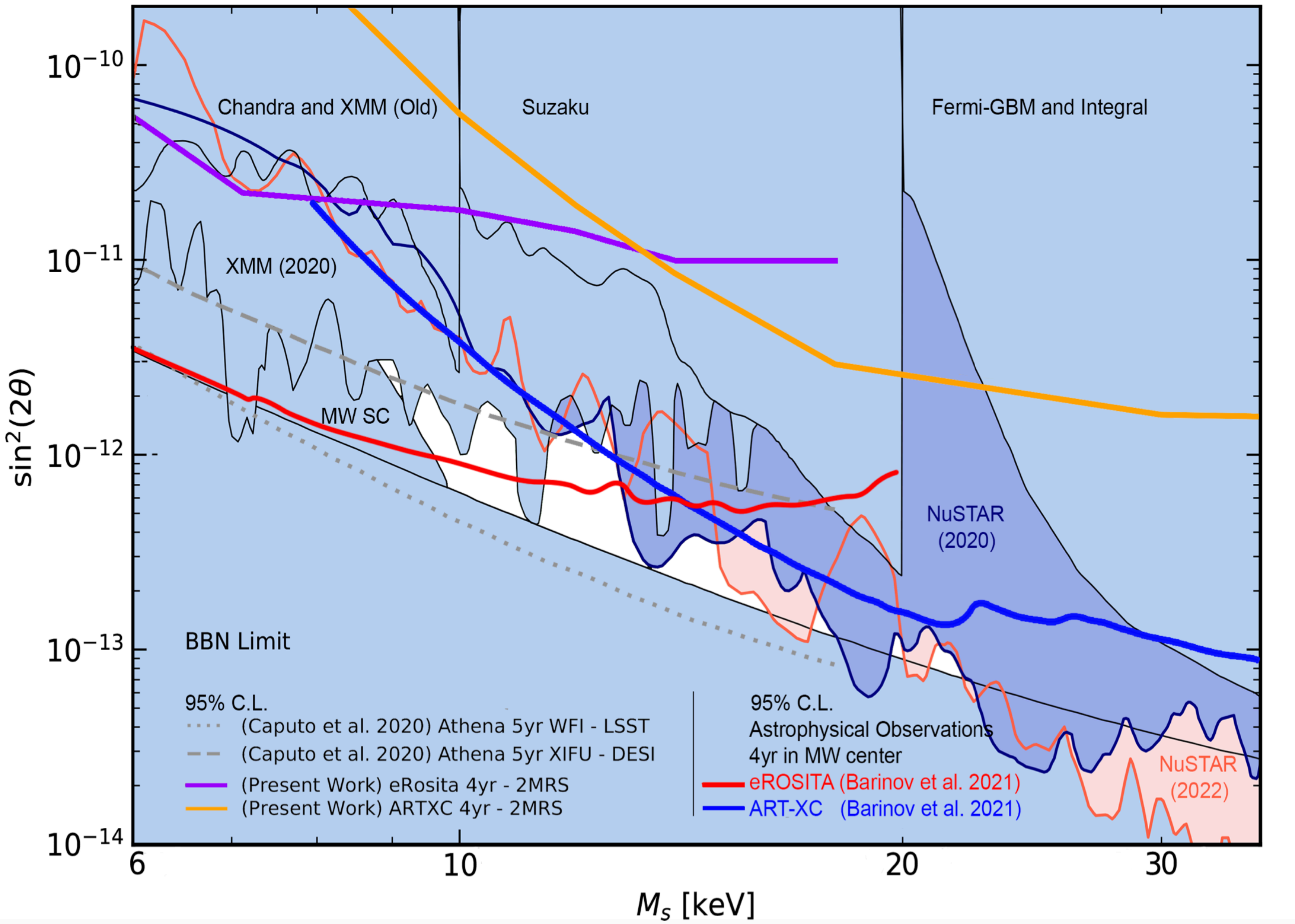


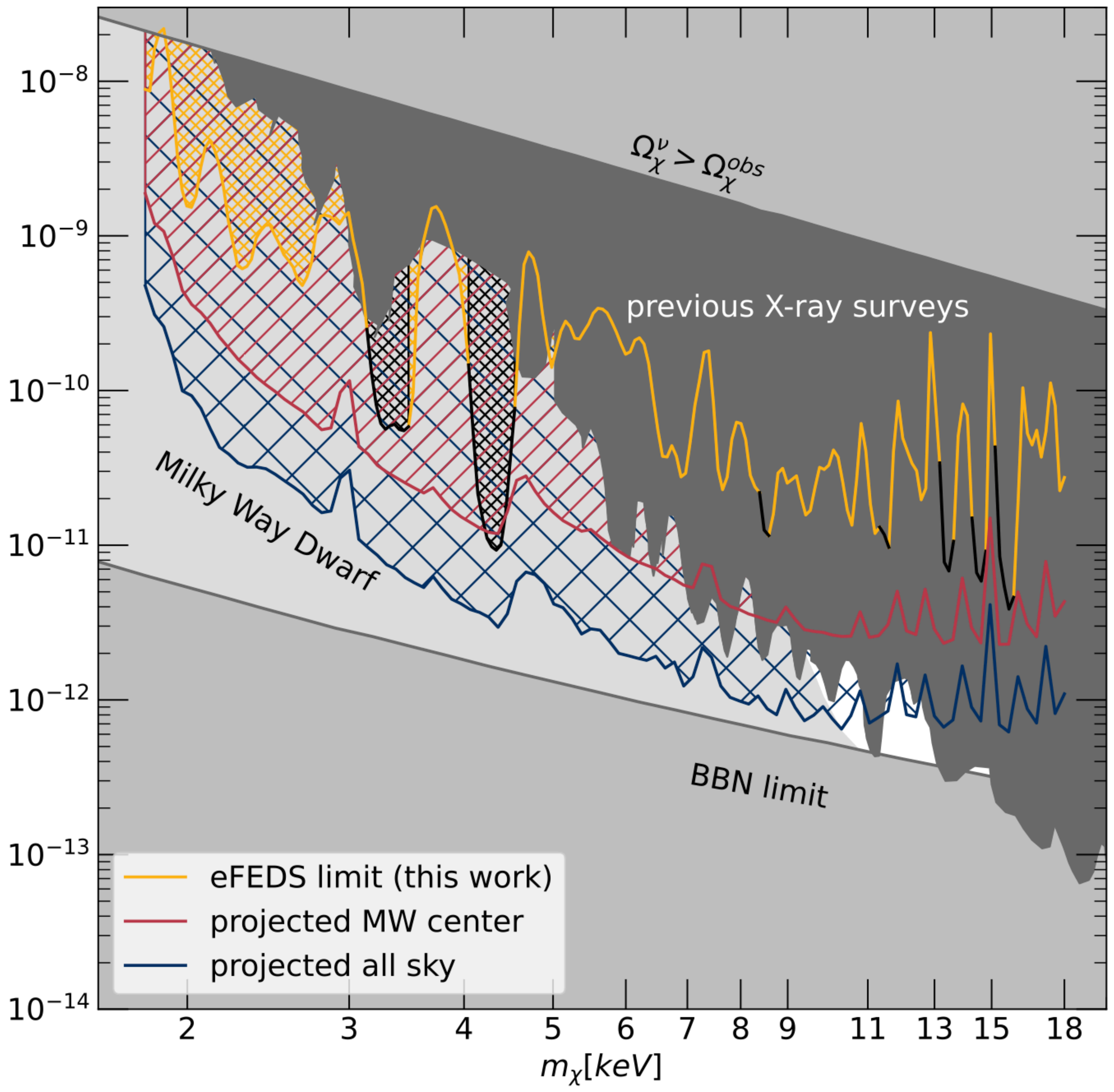


X-Ray Instruments



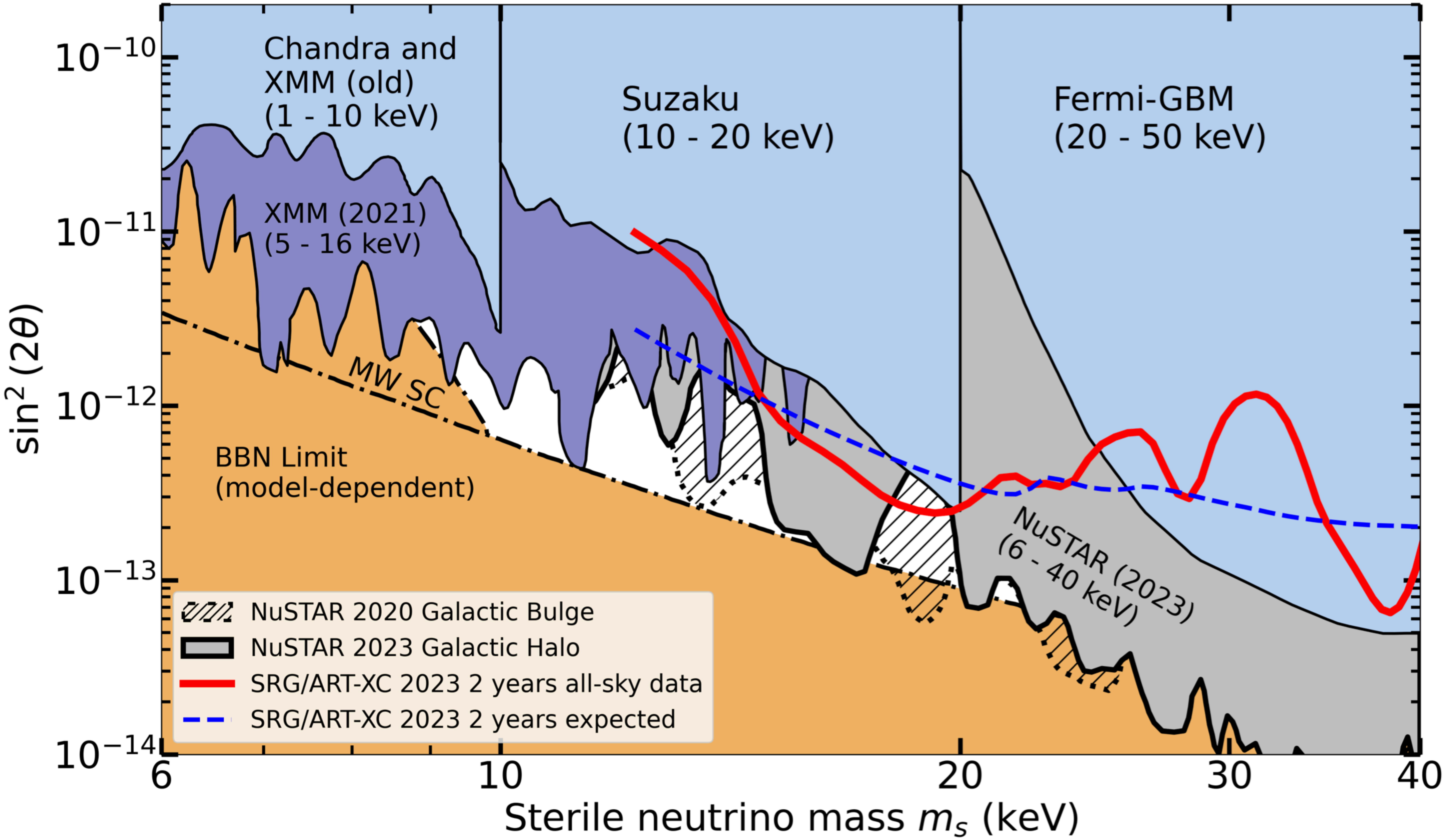
Current Constraints: Our Expectation /eROSITA Early Data





Searching for Particle Dark Matter with eROSITA Early Data [arXiv:2401.16747v2]

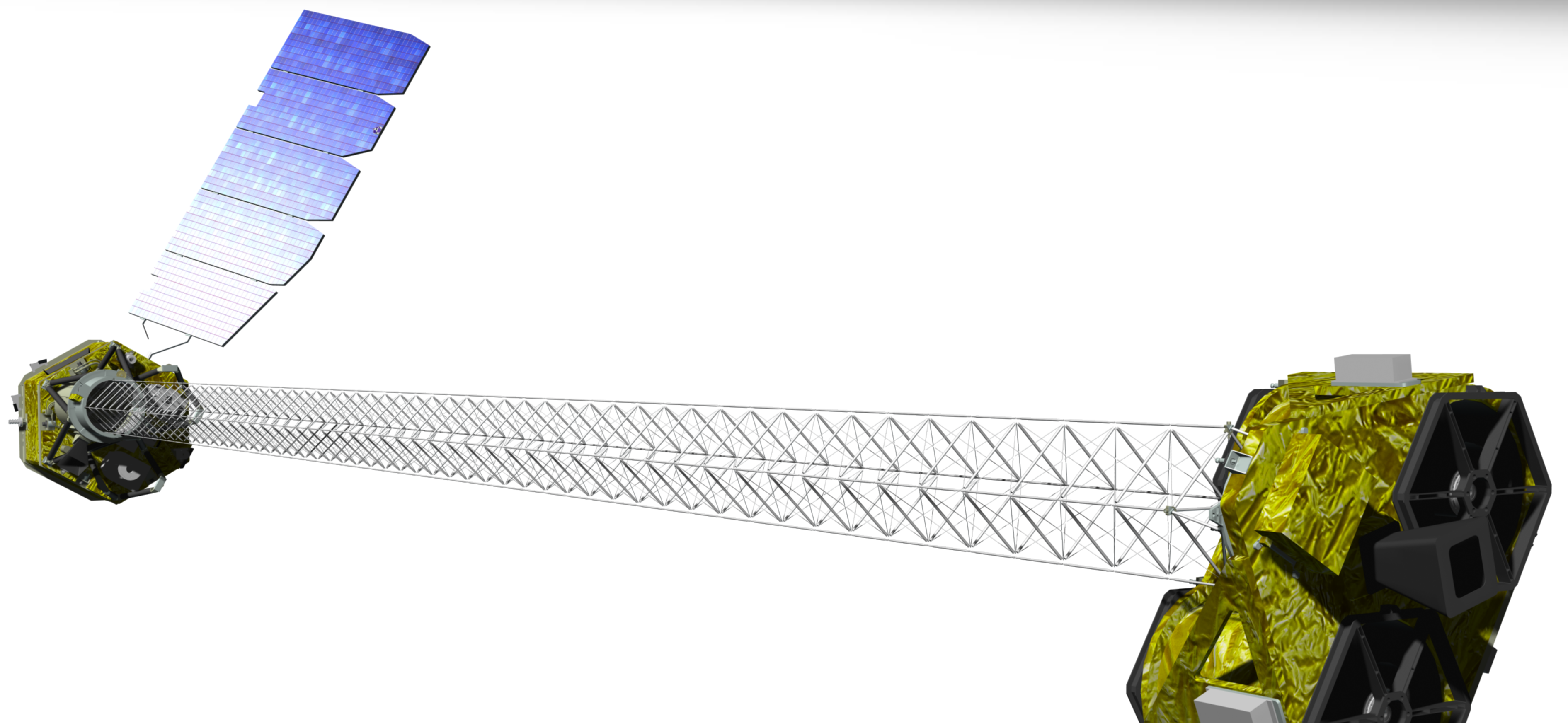
ART-XC Constraints after 2 years of operations



E.I. Zakharov et al., Phys. Rev. D 109, L021301 (2024)

NuSTAR Sterile Neutrino Constraints

- 11 years of Observations
- Exposure ~ 234Ms
- Combined A + B Modules
- Stacked Spectra ~ 3917 Observations



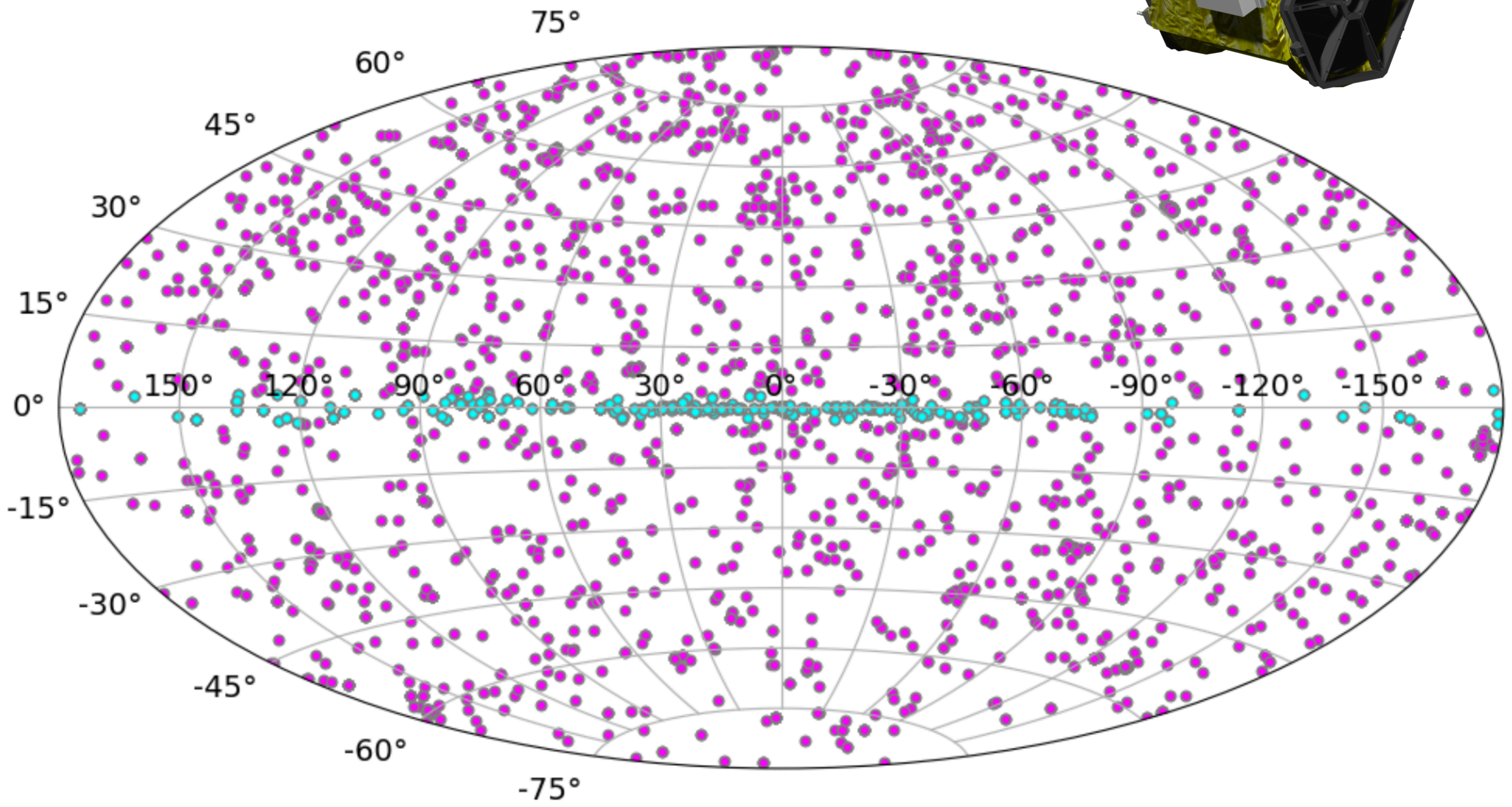


FIG. 4. The distribution of 3248 (FPMA) and 3139 (FPMB) *NuSTAR* observations on the sky in Galactic coordinates. Cyan and magenta points show *NuSTAR* observations at $|b| < 3^\circ$ and $|b| > 3^\circ$, respectively.

Spectral Model and Data Analysis / DM Line

First, we fit original spectrum without DM Line

`XSPEC` Base Model: **`powerlaw + cflux(highecut*powerlaw)`**

Solar component: $I_{\text{sol}} = N_{\text{sol}} \left(\frac{E_\gamma}{1\text{keV}} \right)^{-\Gamma_{\text{sol}}}$

CXB (Gruber Model): $I_{\text{CXB}} = N_{\text{CXB}} \left(\frac{E_\gamma}{1\text{keV}} \right)^{-\Gamma_{\text{CXB}}} \exp \left(\frac{E_{\text{cut}} - E_\gamma}{E_{\text{fold}}} \right)$

Our Best Fit Model

Model	Parameter	Value	Frozen
`powerlaw`	Γ_{sol}	4.00000	True
`powerlaw`	N_{sol}	9.80293×10^{-3}	False
`cflux`	E_{min}	3.00000	True
`cflux`	E_{max}	20.0000	True
`cflux`	lg10Flux	-10.5196	False
`powerlaw`	Γ_{CXB}	1.29000	True
`powerlaw`	N_{CXB}	2.39933×10^{-3}	True
`highecut`	E_{cut}	1.00000×10^{-4}	True
`highecut`	E_{fold}	34.8765	False
Test statistic: $\chi^2/\text{dof} = 1.38,\ \text{p} = 8.27 \times 10^{-3}$			

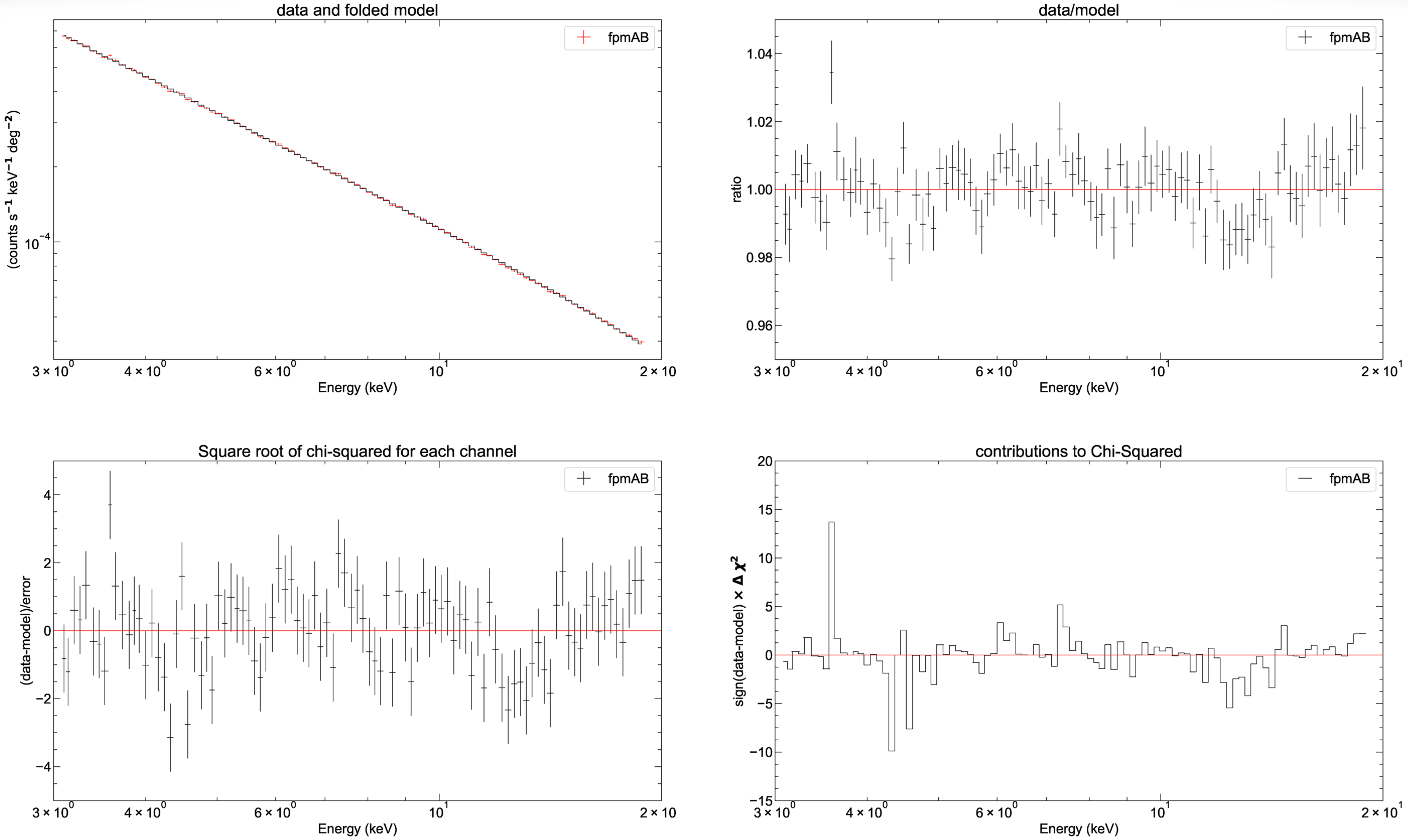
Next, we add **DM Line**: **`powerlaw + cflux(highecut*powerlaw)+ gauss`**

We perform scan for the each energy in **(3, 20) keV** range

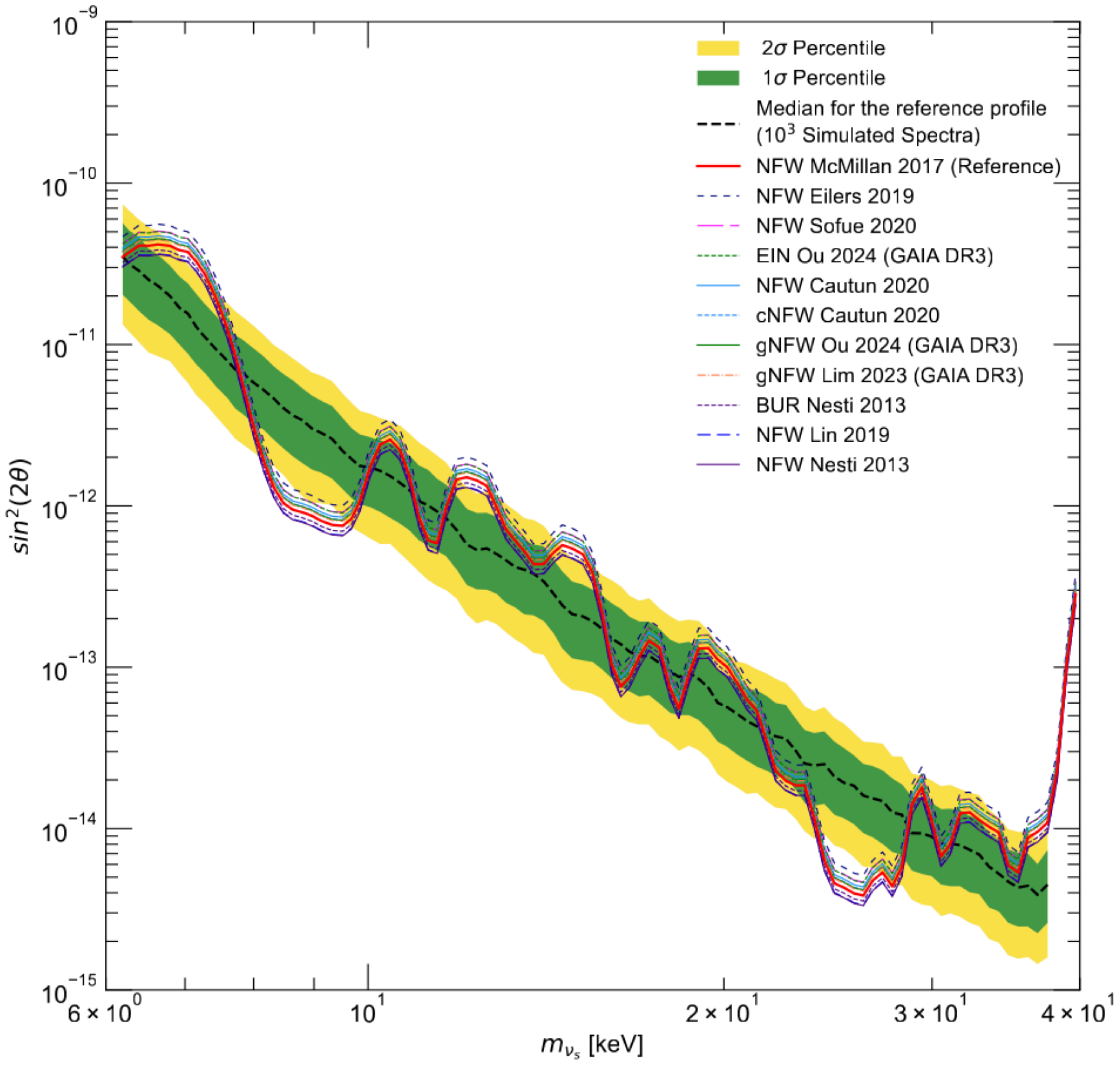
$\Delta\chi^2(sin^2(2\theta)) = 2.71$,for 95% upper limit with one degree of freedom

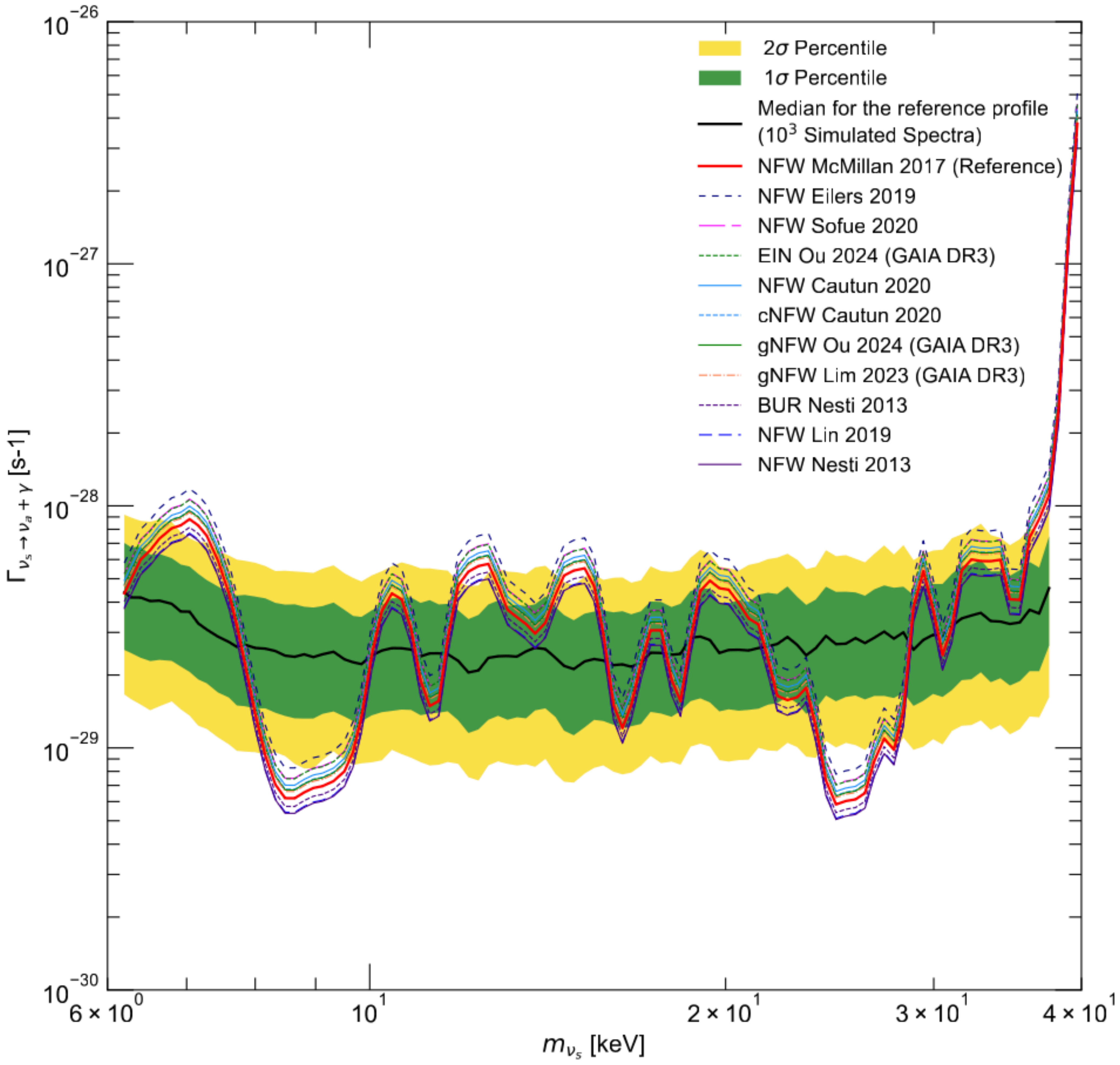
Finally, we generate 1000 fakeit spectra based on original spectrum

Spectral Model and Data Analysis / Spectrum



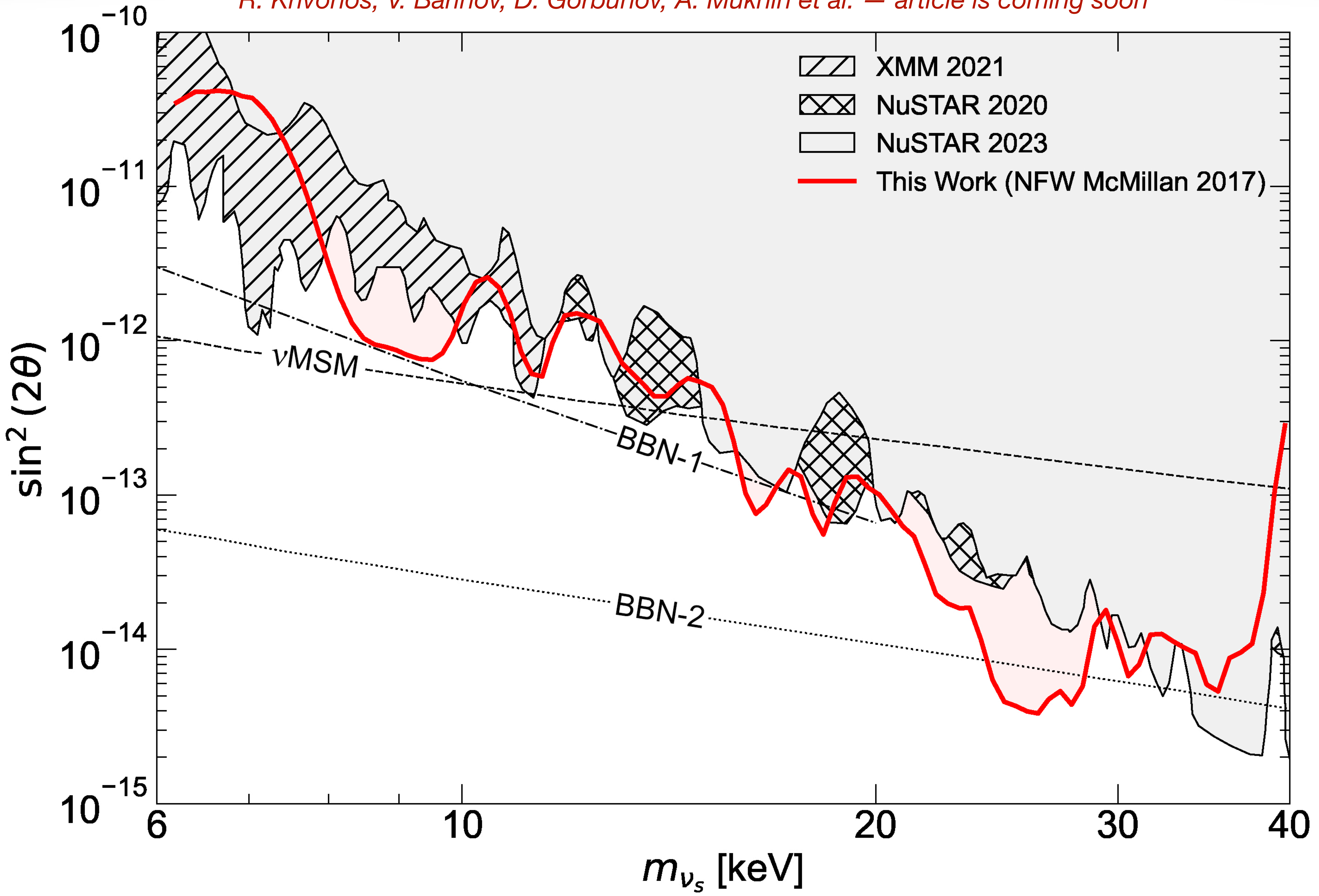
NuSTAR 234 Ms Constraints



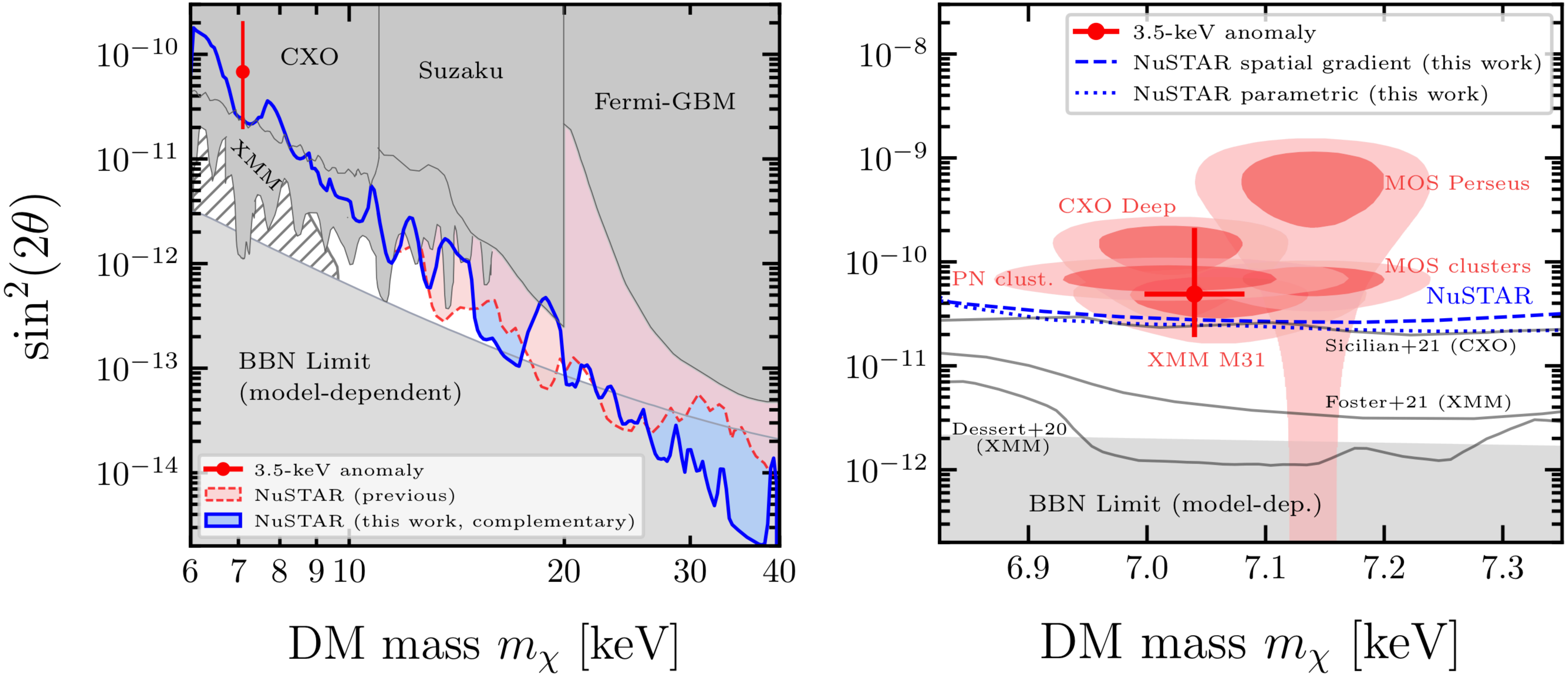


New NuSTAR 234 Ms Constraints

R. Krivonos, V. Barinov, D. Gorbunov, A. Mukhin et al. — article is coming soon



NuSTAR Previous Constraints



Long-Exposure NuSTAR Constraints on Decaying Dark Matter in the Galactic Halo
[arXiv:2207.04572v4]

A few words about cosmology…

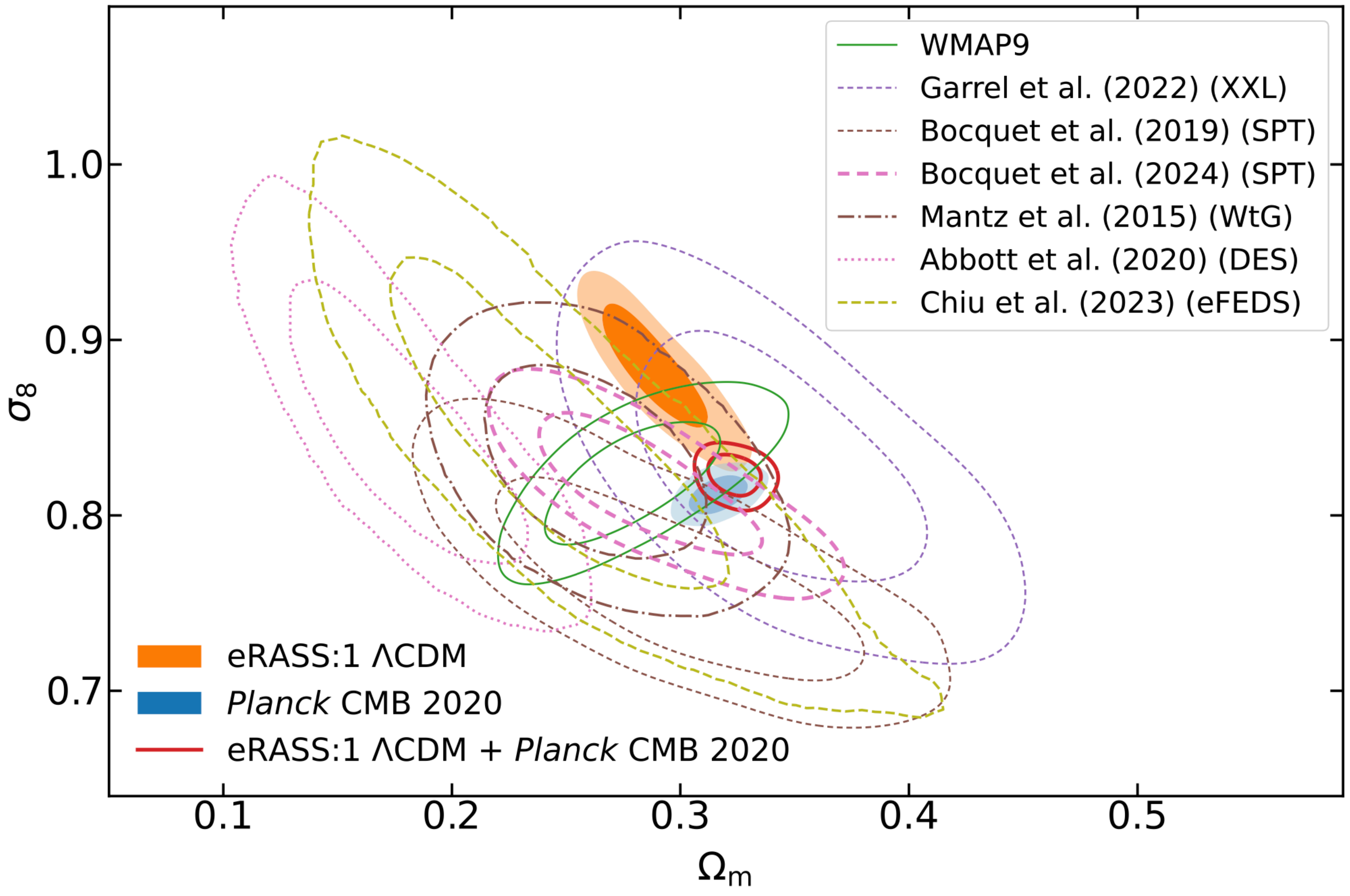
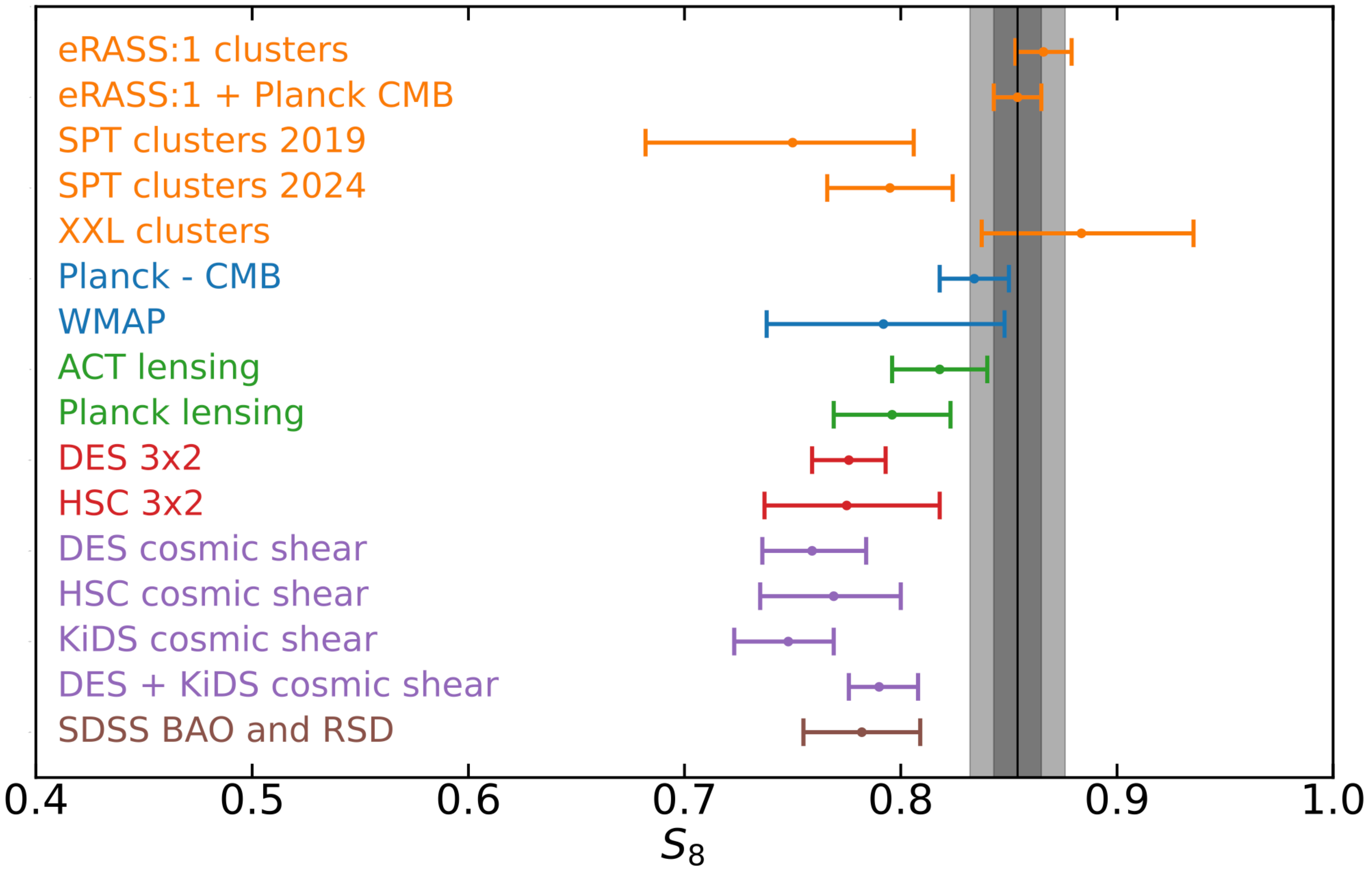


Fig. 8: Posterior distributions on the parameters Ω_m and σ_8 from the ΛCDM fit on eRASS1 data shown in orange. In blue, we show the *Planck* CMB 2020 constraints without combination with BAO and SNe Ia Planck Collaboration et al. (2020a). In red, we show the combination of eRASS1 with *Planck* CMB. As a comparison, we also present previous results from similar cluster surveys that employ weak lensing shear data in their mass calibration, e.g., WtG (Mantz et al. 2015), DES (Dark Energy Survey Collaboration et al. 2020), SPT-SZ (Bocquet et al. 2019), eFEDS (Chiu et al. 2023), XXL (Garrel et al. 2022), and SPT (Bocquet et al. 2024) surveys.



The SRG/eROSITA All-Sky Survey

Cosmology Constraints from Cluster Abundances in the Western Galactic Hemisphere

arXiv:2402.08458v1 [astro-ph.CO] 13 Feb 2024,

The Future…

Gallium Anomaly —> The question remains open

(It may be Look elsewhere effect, Statistical Fluctuation or New type of neutrino)

These light sterile neutrinos are bad for cosmology!

KeV Sterile Neutrino —> New data may help *rule out* or *find something interesting*!

(Stacked Spectra, Milky Way Observations, Galaxy Clusters…)

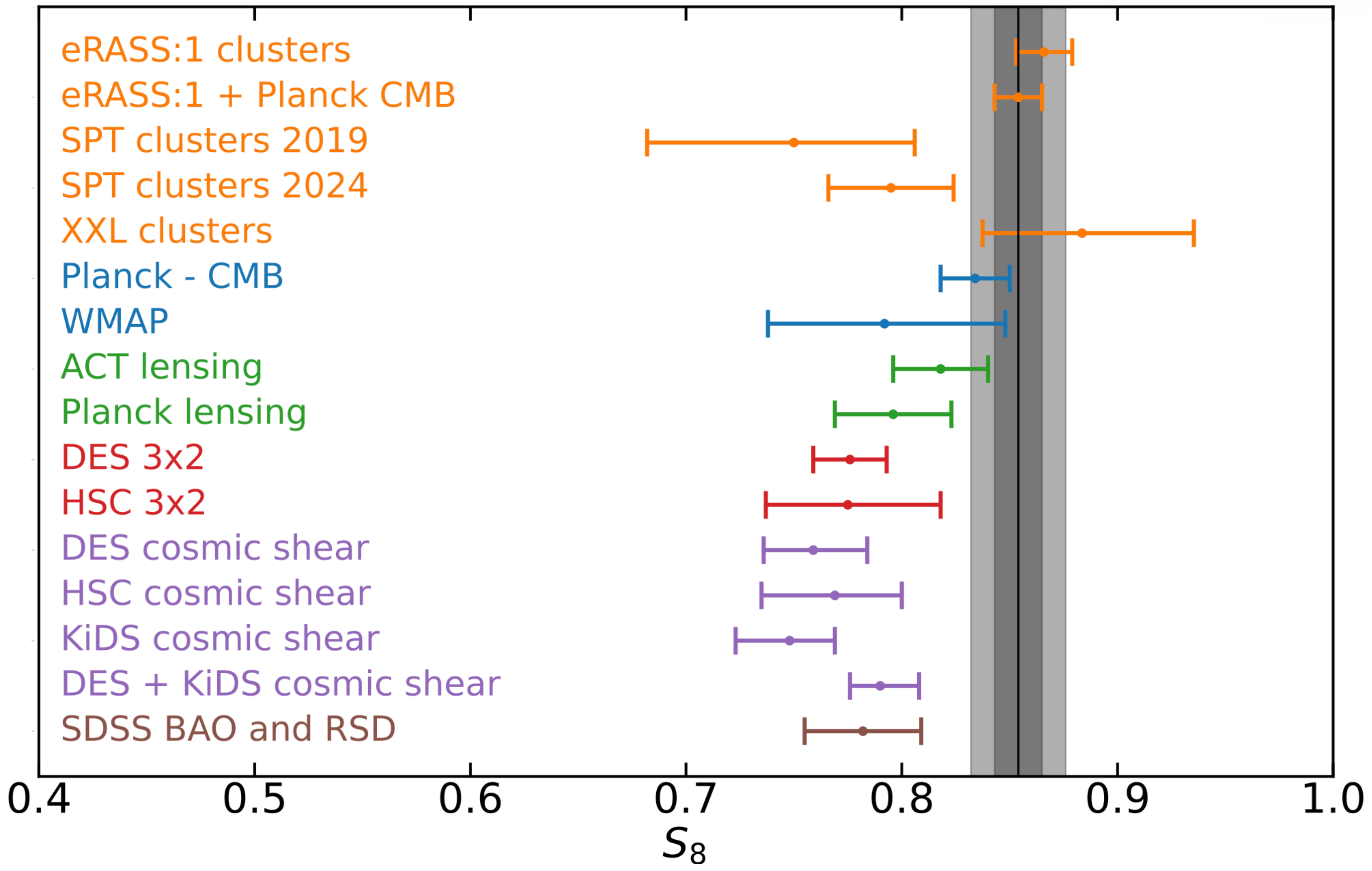
Recent News:

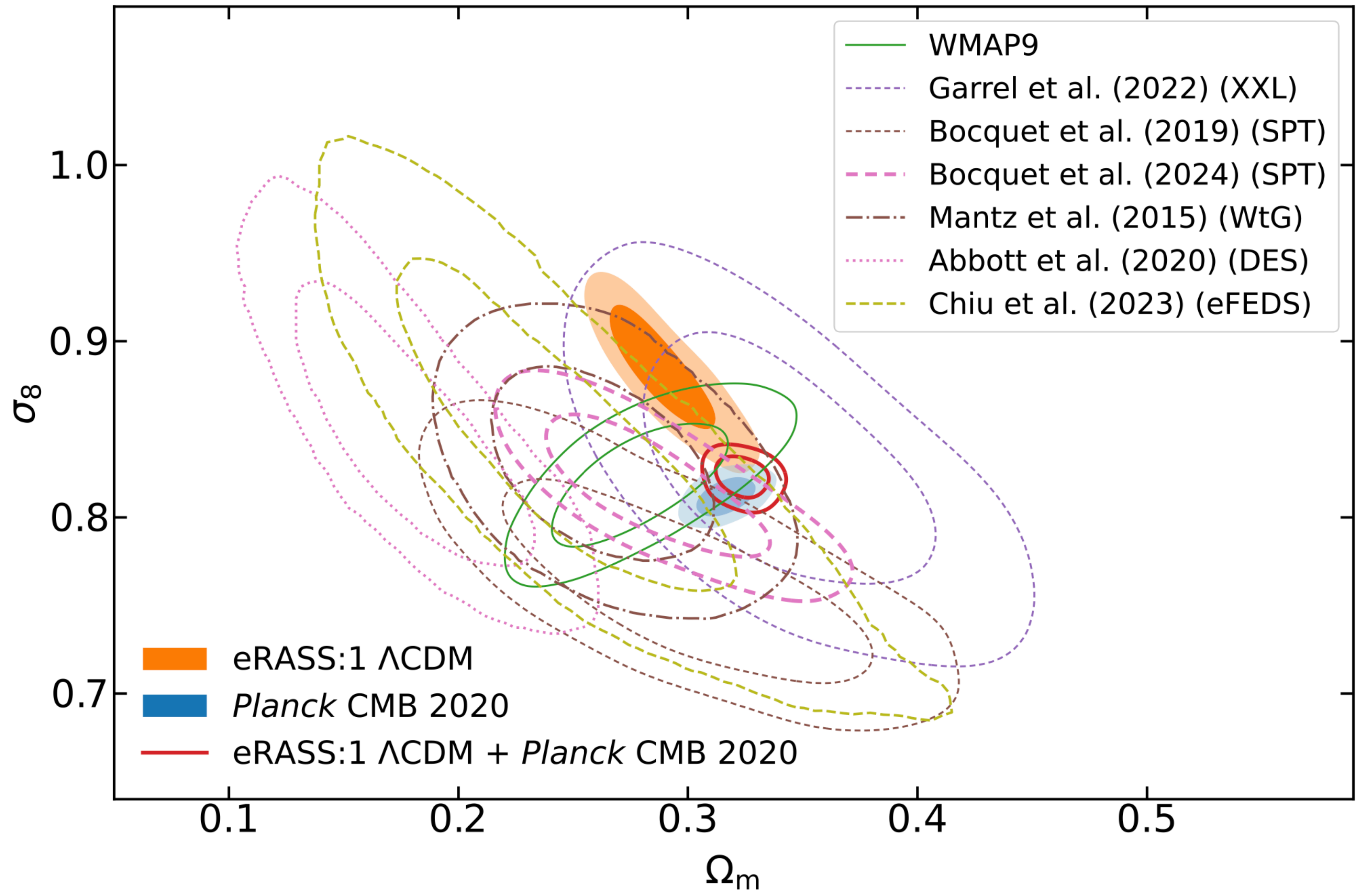
Further research in Galaxy Clusters is the powerful tool

to testing dark matter models and cosmological studies!

For Example: SRG: eROSITA/ART-XC, Athena, Lynx

Galaxy Clusters! —> Large Scale Structure, Cosmology, Neutrino, …





Thank you for your attention!

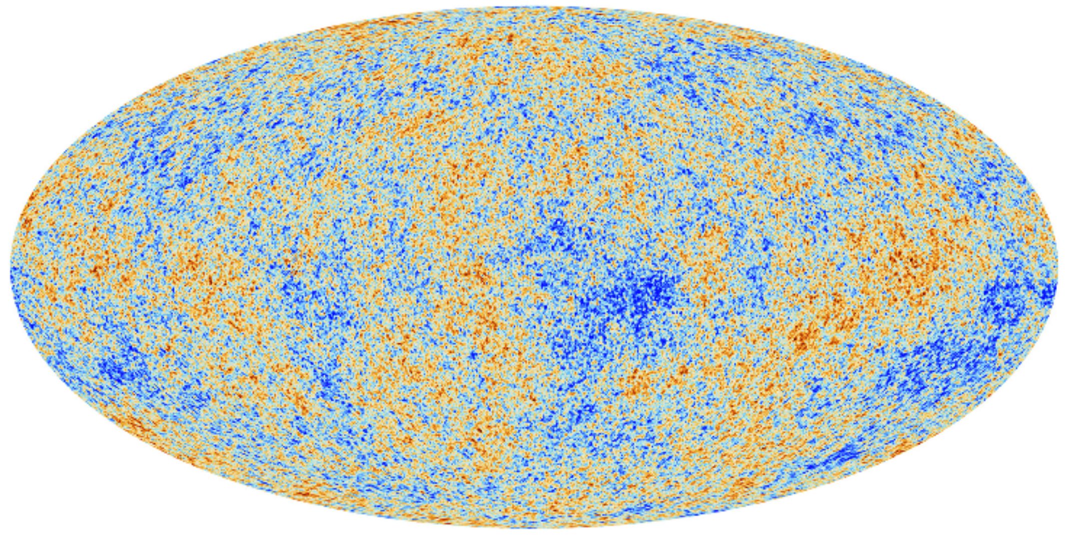
The work is supported by the RSF Grant 22-12-00271

Expected Constraints on the Parameters of Sterile Neutrinos from the Correlation Analysis of Structures within the the SRG Mission

Basic Concept

- Since dark matter particles are concentrated inside galaxies and galaxy clusters, each photon from dark matter decay must point to a specific object (structure) where the decay occurs.
- If photons were not deflected, they point to a part of this structure in the sky. Including the spatial distribution of that structure due to redshift.
- Even if an object cannot be recognized by an observer so far (unresolved sources), the connection between a photon and its source exists and can be traced statistically, by a joint analysis of the distribution of all registered photons in the direction of arrival, energy and distribution map of cosmic structures.

Like CMB ΔT



This approach is based on the study of the auto and cross-correlation angular power spectrum of dark matter and galaxies.

As part of the correlation analysis for each pair of signatures (dark matter - dark matter, galaxies - galaxies, dark matter - galaxies) a nonlinear power spectrum is calculated, and then a cross-correlation function is constructed for all pairs of studied signatures.

The correlation function of intensity fluctuations of different signatures i, j is defined as

$$\langle \delta \mathrm{I_i}(\vec{\mathrm{n_1}}) \delta \mathrm{I_j}(\vec{\mathrm{n_2}}) \rangle = \sum_{\mathrm{l}} \frac{2\mathrm{l}+1}{4\pi} \mathrm{C_l^{ij}} \mathrm{P_l}(\cos\theta),$$

$\mathrm{C_l^{ij}}$ - the angular power correlation spectrum between the fluctuations of the i and j signatures

$$\delta \mathrm{I_i}(\vec{\mathrm{n}}) = \mathrm{I_i}(\vec{\mathrm{n}}) - \langle \mathrm{I_i} \rangle$$

Intensity fluctuations of different signatures, where $\langle \mathrm{I_i} \rangle$ is the average intensity across the sky.

Correlation Angular Power Spectrum

The angular correlation power spectrum is a Fourier image of the two-point correlation function for the given signatures. It determines the magnitude and properties of the anisotropy of the signatures (signatures) and is given by the following expression

$$C_l^{ij} = \frac{2}{\pi} \int_0^\infty \mathrm{d}\chi \int_0^\infty \mathrm{d}\chi' \int_0^\infty k^2 \mathrm{d}k \, \overline{W}_i(\chi) \, \overline{W}_j(\chi') \, P_{ij}\left(k, \chi, \chi'\right) \; j_l(k\chi) j_l(k\chi')$$

In Limber Approximation we have

$$C_l^{ij} = \int_0^\infty \frac{\mathrm{d}\chi}{\chi^2(z)} \, \overline{W}_i(\chi) \overline{W}_j(\chi) \; P_{ij}\left(k \approx \frac{l}{\chi}, z\right), \, l \gg 1, \, l \approx kr = k\chi$$

$$\overline{W}_i(z) = \int_{E_{min}}^{E_{max}} \mathrm{d}E W_i(E, z)$$

$$W_g(z) = \frac{\mathrm{d}z}{\mathrm{d}\chi} \left[\frac{1}{N_{\mathrm{2MRS}}} \frac{\mathrm{d}N_{\mathrm{2MRS}}}{\mathrm{d}z} \right]$$

$$W_{\mathrm{dm}}(E, z) = \frac{\Omega_{\mathrm{CDM}} \rho_{crit}}{(1+z)} \frac{\Gamma_{\nu_s}}{4\pi m_{\nu_s}} \frac{1}{\sqrt{2\pi\sigma_E^2}} \exp\left[- \frac{\left(E - \frac{m_{\nu_s}}{2(1+z)}\right)^2}{2\sigma_E^2} \right]$$

$$P_{ij}\left(k, \chi, \chi'\right) = \sqrt{P_{ij}\left(k, \chi\right) P_{ij}\left(k, \chi'\right)}$$

Expected Constraints

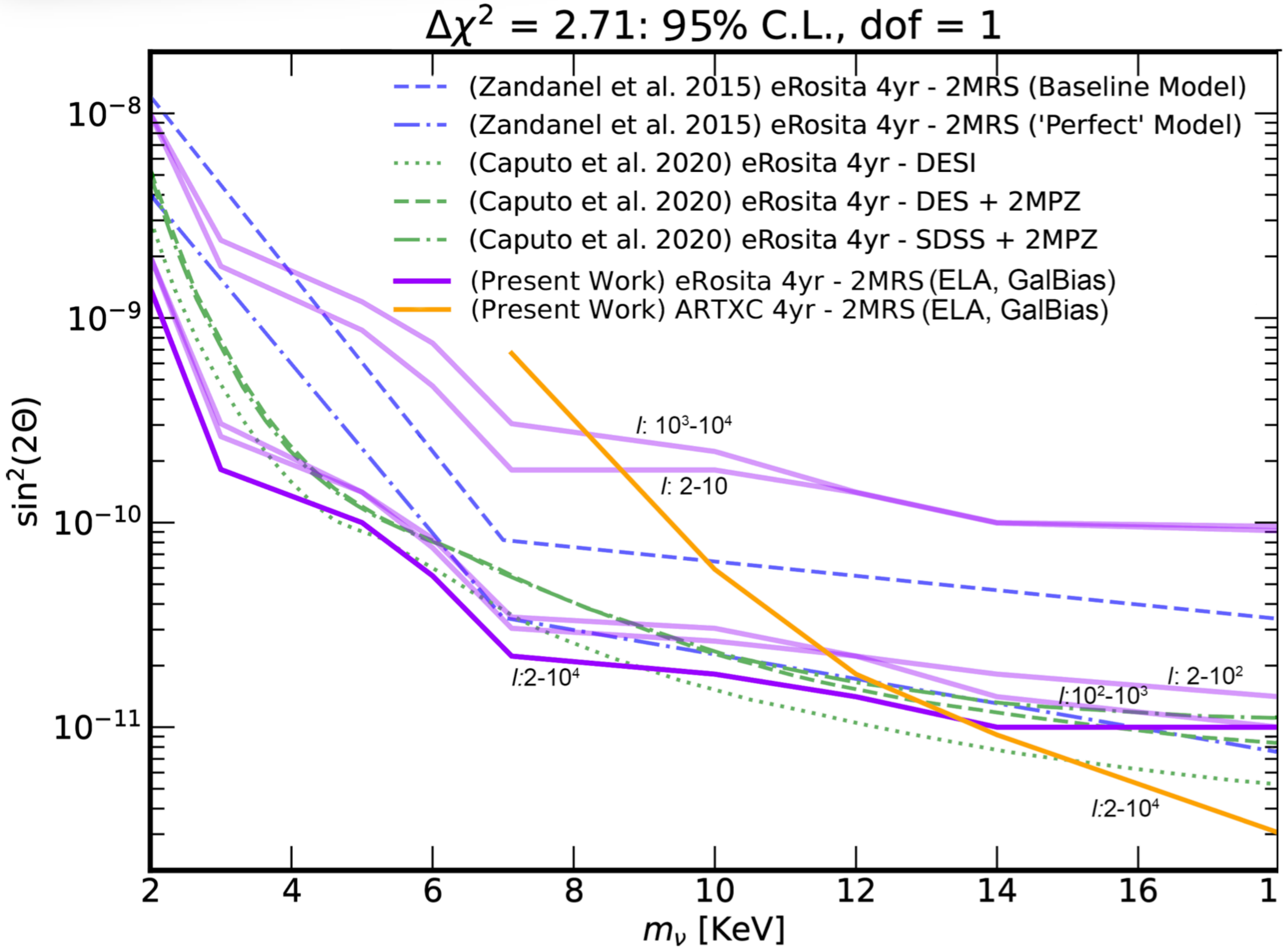


Figure 2. Expected constraints on the parameters of sterile neutrinos obtained in the framework our analysis for various ranges of multipoles. The purple line corresponds to the constraints for th eROSITA telescope (the translucent purple lines show the contributions to the constraints for differen ranges of multipoles). The yellow line corresponds to the ART-XC telescope. For comparison, th constraints from the works [27, 28] are presented. The observation time is 4 years in the full sk survey mode.

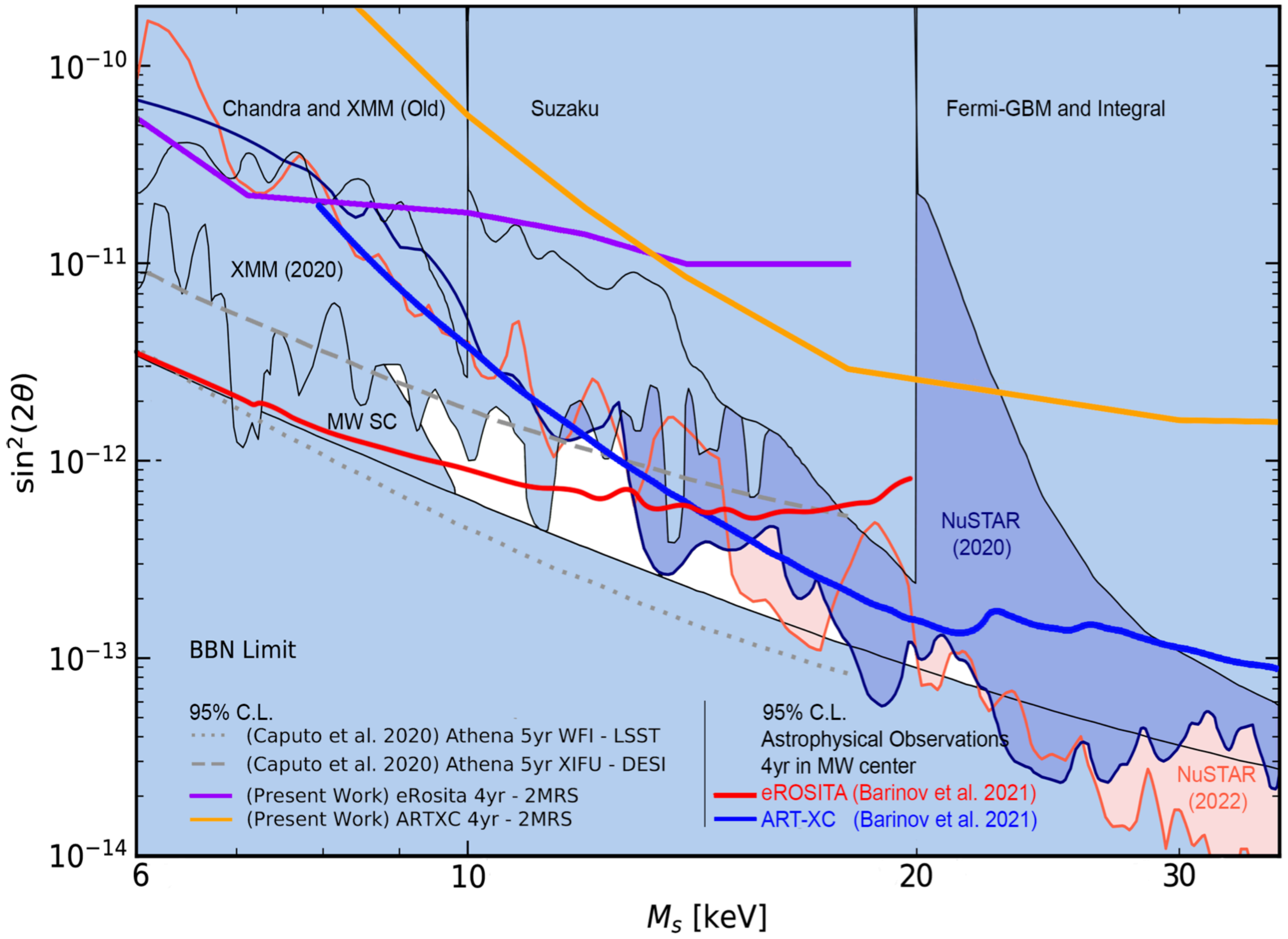


Figure 3. Expected Constraints on the parameters of sterile neutrinos obtained in our analysis (same as Figure 2) in comparison with the constraints that can be obtained in the framework of the astrophysical observations of the center of the Milky Way in a cone with an opening angle of 60 degrees [45] (the red line corresponds to the constraints for the eROSITA telescope, the blue line corresponds to the ART-XC telescope). Background Corrected means that the background has been additionally normalized taking into account additional features for the ART-XC telescope [43] compared to the previous work [45]. Additionally, we present the constraints that can be obtained for the Athena telescope [28].

V.V. Barinov., JCAP02(2023)055 (2023)