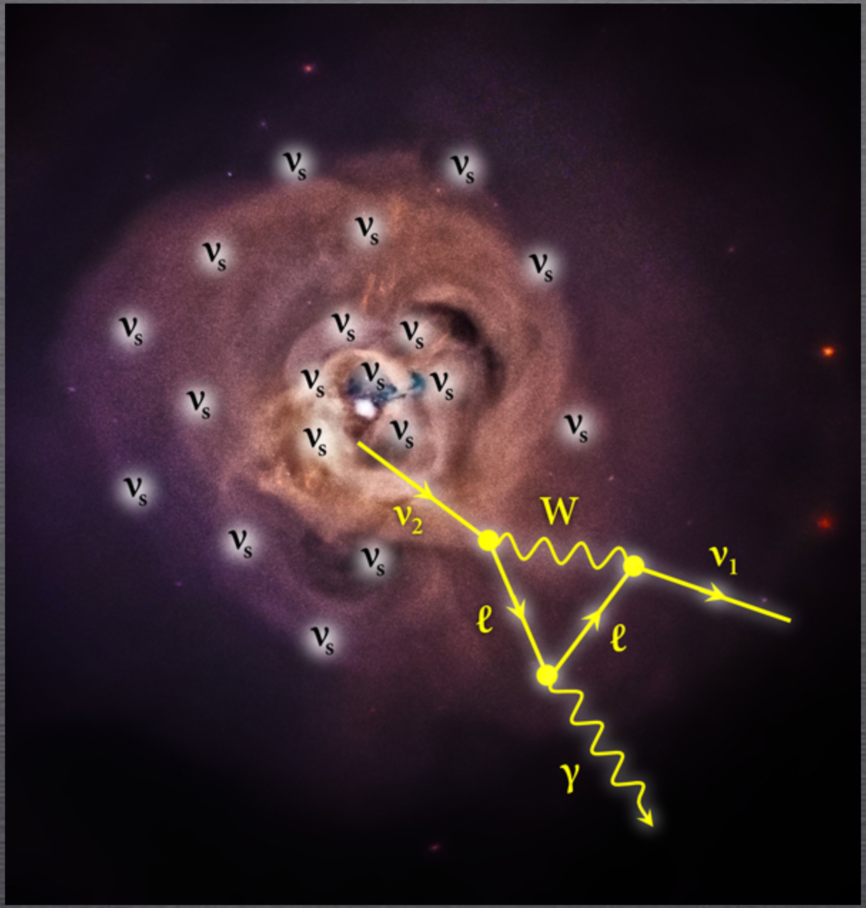
Evidence the 3.5 keV line is not from Dark Matter Decay



Nick Rodd

1812.06976 (under review Science)

w/ Chris Dessert and Ben Safdi

TeVPA, 3 December 2019

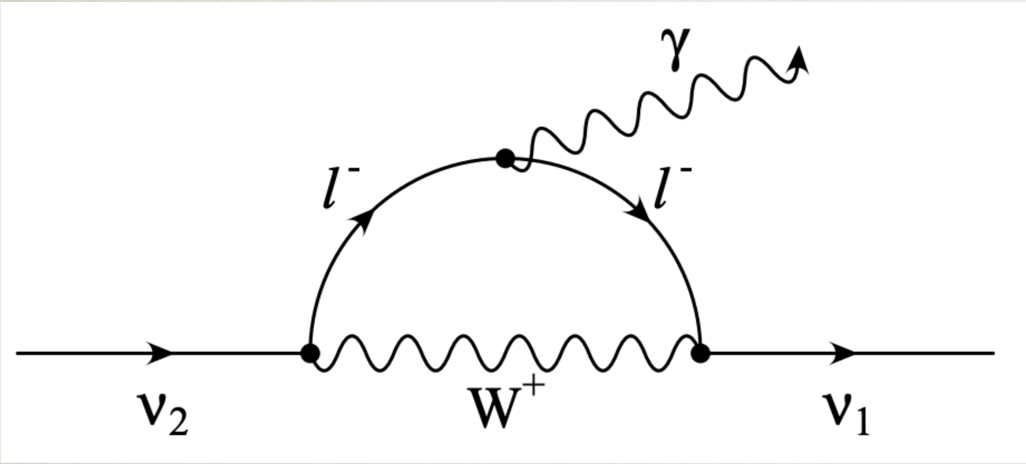
Image Courtesy of NASA/ CXC/SAO/E.Bulbul et al., Overlay: APS/Alan Stonebraker

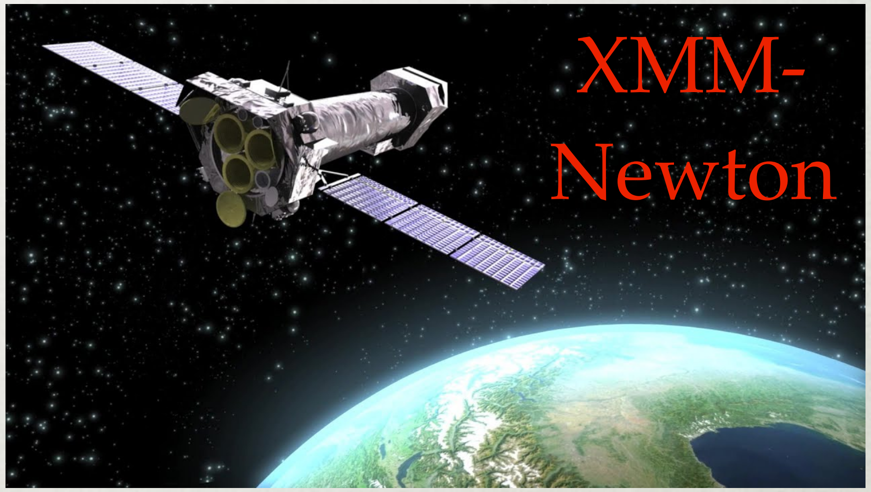
Sterile ν Dark Matter

- **ν_s: a detectable dark matter candidate**

  [Abazajian+ astro-ph/0101524, astro-ph/0106002]

$$\nu_s \to \nu_a + \gamma \qquad m_s \sim \text{keV} \Rightarrow E_\gamma \sim \text{X-ray}$$





- Decay leads to a finite ν_s lifetime [Pal+Wolfenstein]

$$\tau = 4.37 \times 10^{28}\ \text{s} \left(\frac{10^{-11}}{\sin^2(2\theta)}\right)\left(\frac{7\ \text{keV}}{m_s}\right)^5$$

The Discovery of Dark Matter

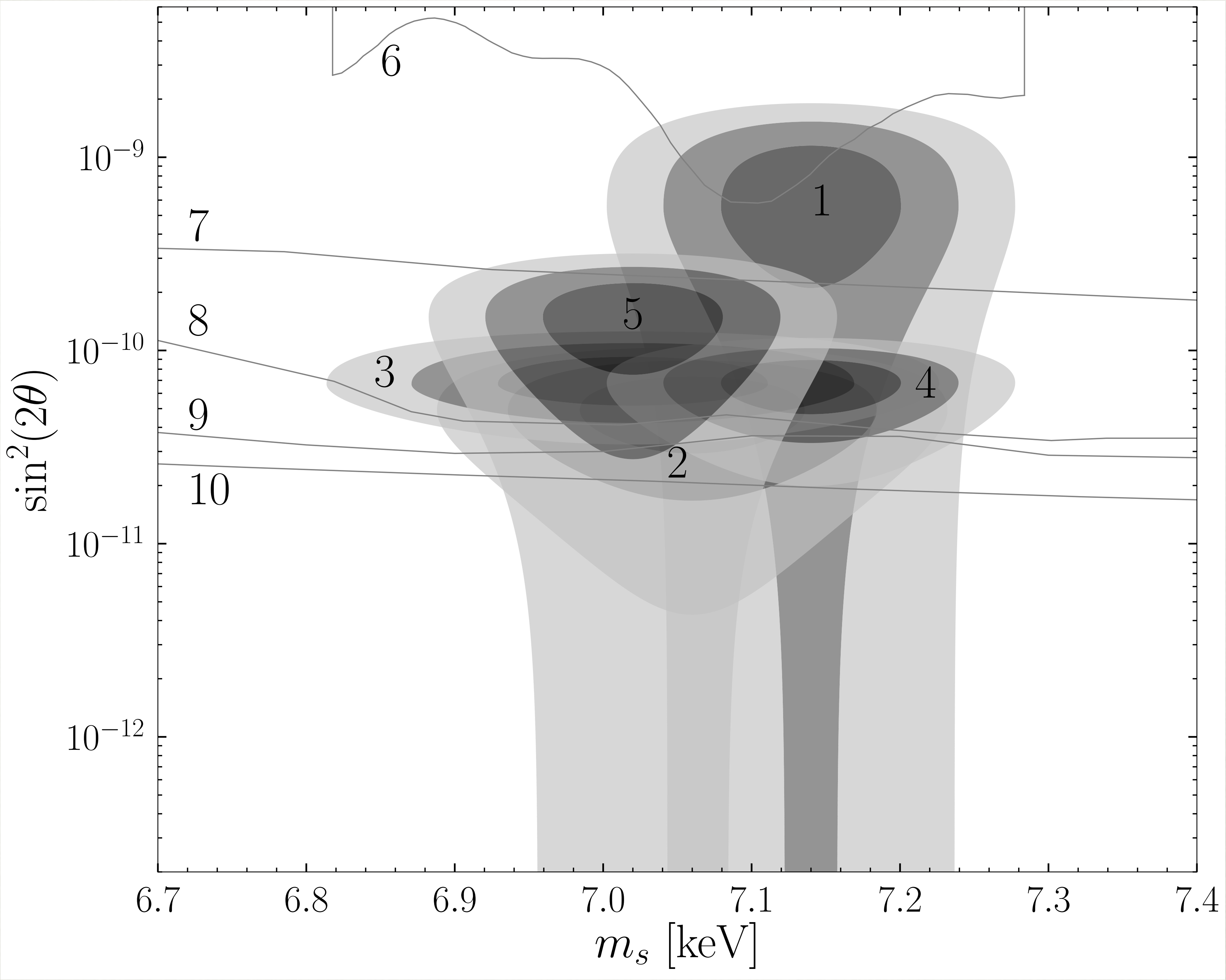
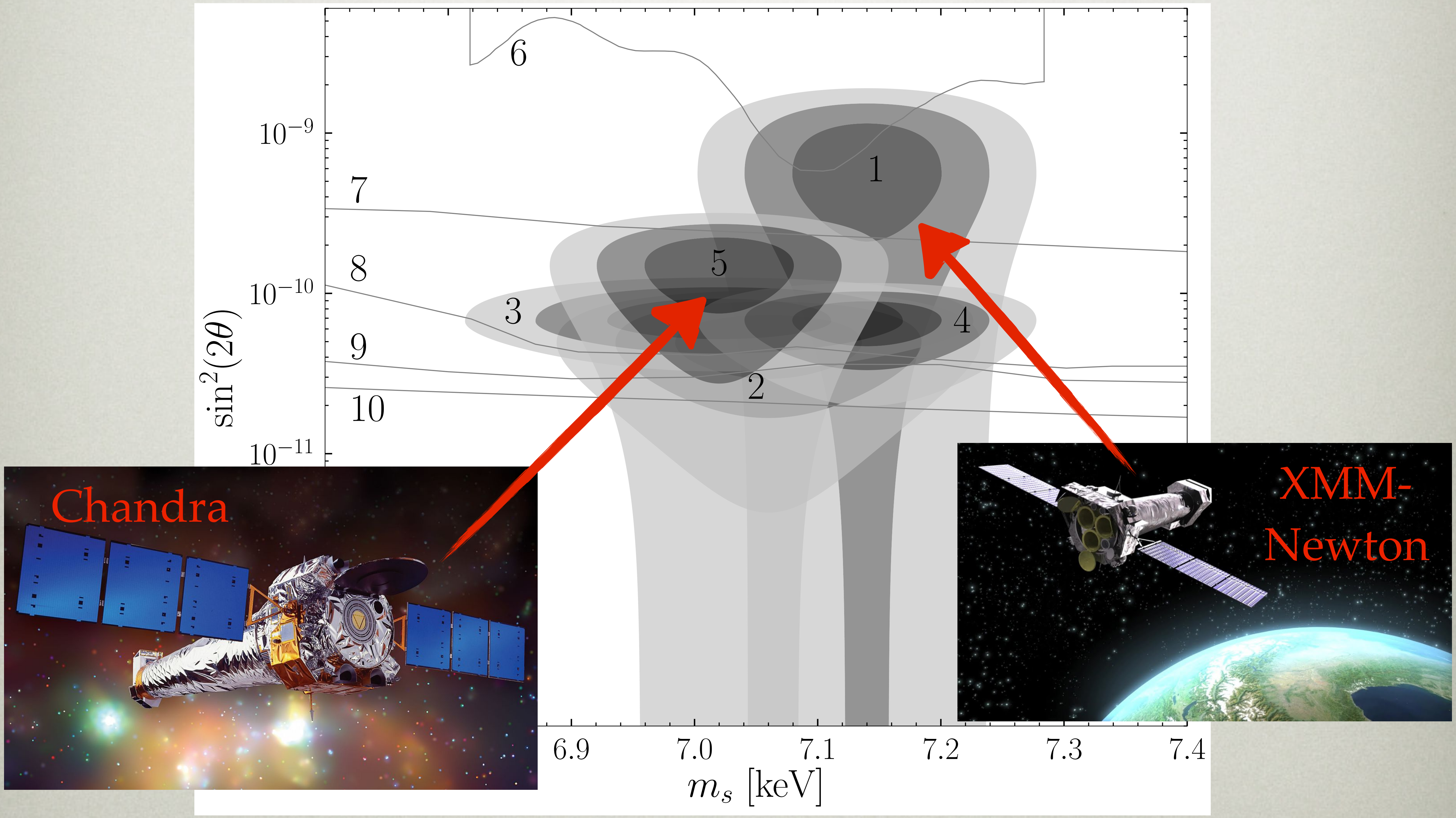
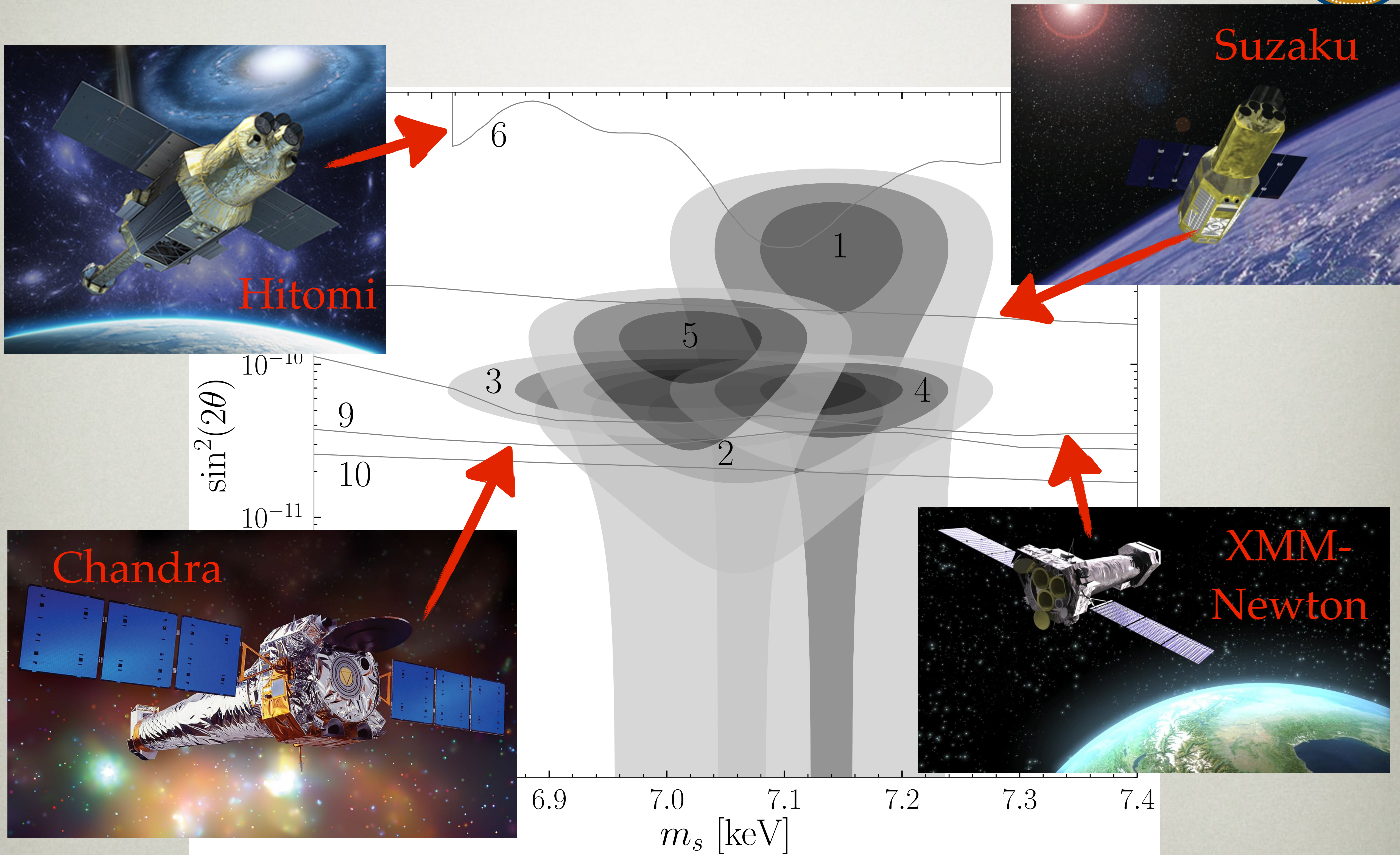


Figure reproduced from [Abazajian 1705.01837]

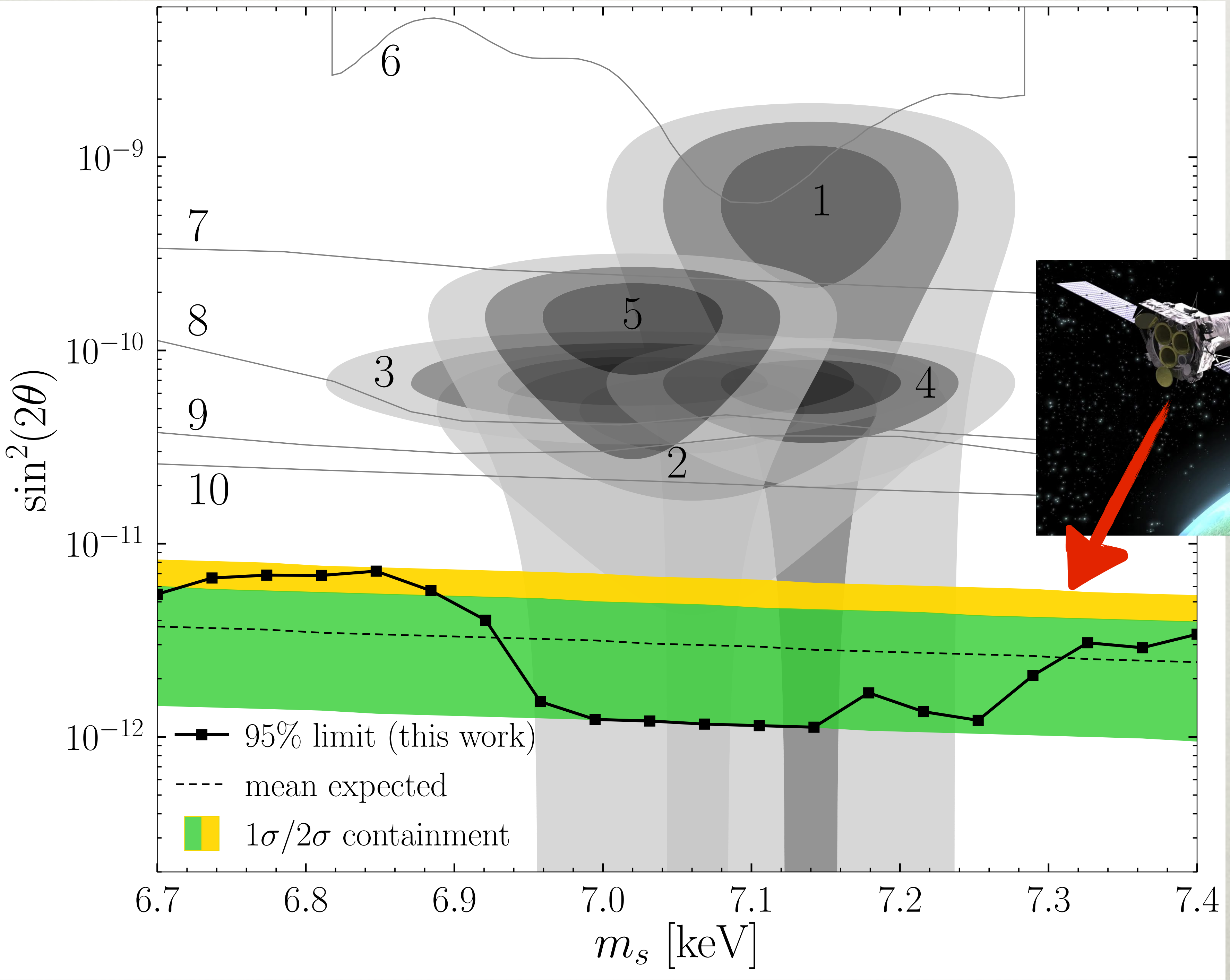
The Discovery of Dark Matter



The Discovery of Dark Matter?



Towards a Definitive Statement



[NLR+ 1812.06976]

Original Claim

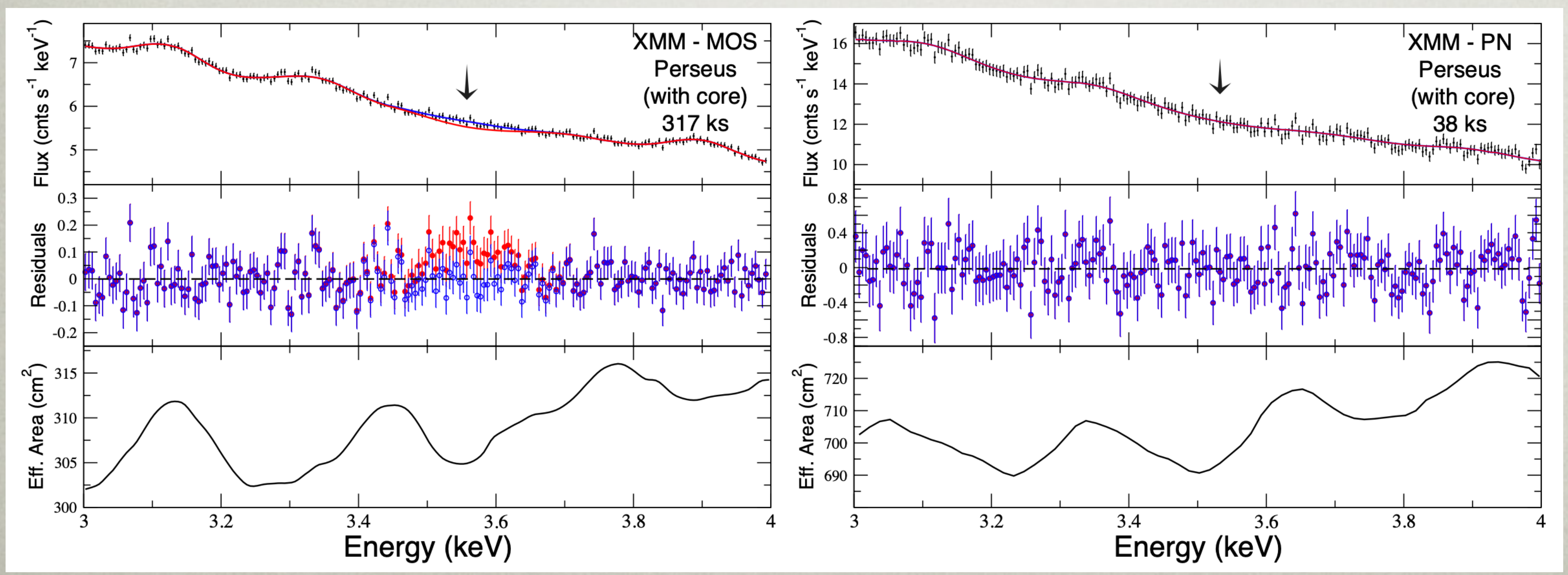
DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS

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, USA
[2] CRESST and X-ray Astrophysics Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA
[3] NASA Goddard Space Flight Center, Greenbelt, MD, USA
[4] Department of Astronomy, University of Maryland, College Park, MD, USA

[1402.2301]

- 3.55 keV line detected in stacked sample of 73 galaxy clusters
  - Redshifts correctly $z \in [0.01, 0.35]$
  - Seen in MOS and PN XMM-Newton cameras
  - Seen in Perseus cluster individually, also with Chandra
  - Confirmed by [Boyarsky+ 1402.4119]



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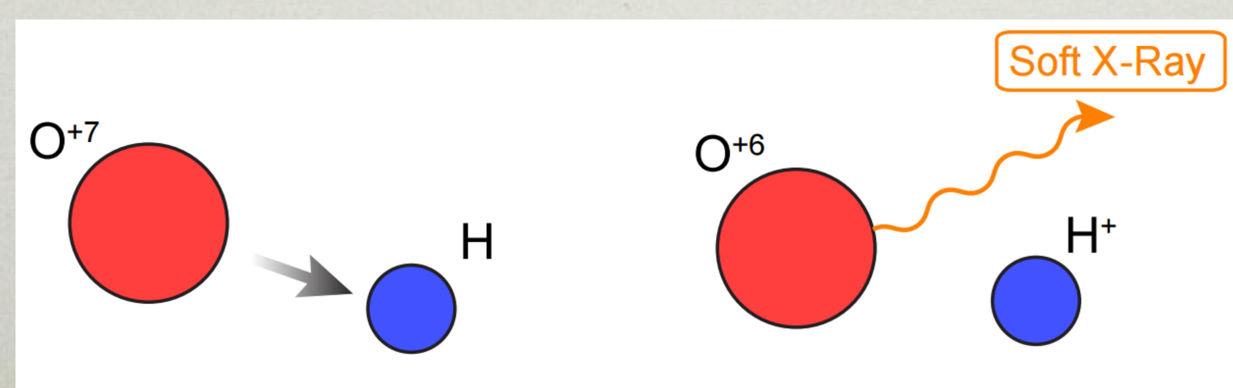
[1402.2301]

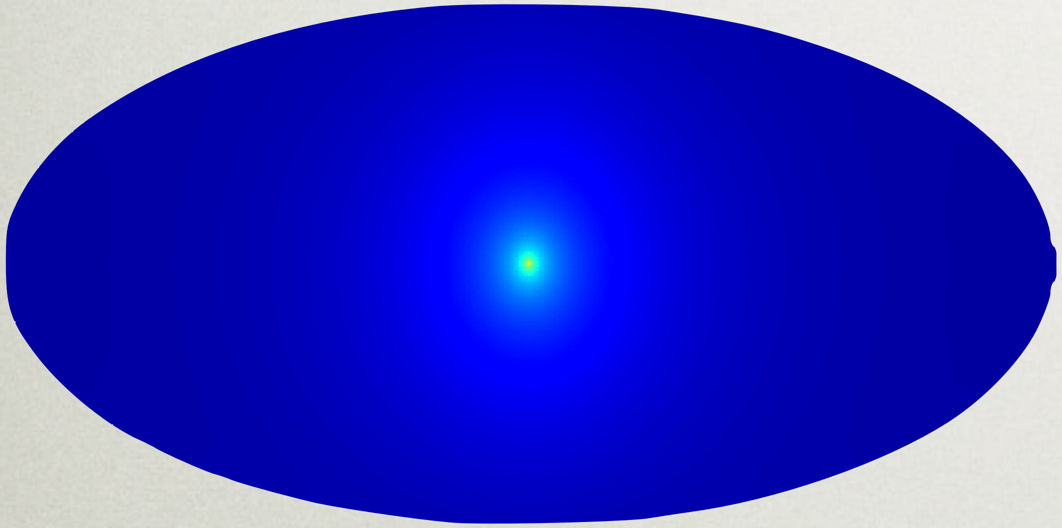
- Is the line consistent with dark matter?
  - ~scale with cluster mass (see [Lovell+ 1810.05168])
  - No known significant lines nearby, but cluster emission is complex - model 31 known emission lines
- A real line we missed?
  - K XVIII lines at 3.48 and 3.52 keV [Jeltema+Profumo 1408.1699]
  - S XVI charge exchange at 3.5 keV [Gu+ 1511.06557]



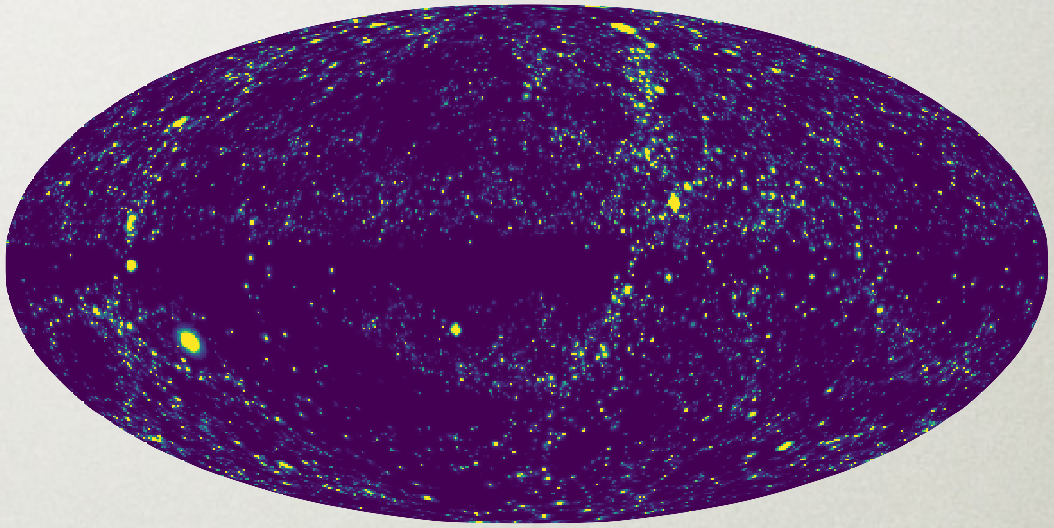
Canonical Strategy

- X-ray telescopes have small field of view ~5x10^{-5} sr
- Use observations of highest expected DM decay flux (GC+clusters)

Decays in the Milky Way



Extragalactic Decays



- Bulbul+ used ~6 Ms of data (~70 days)
- XMM-Newton has operated for 19 years (~600 Ms), can we use this?

New Strategy

- Expected DM flux

$$\frac{d\Phi}{dE} = \frac{1}{4\pi\, m_s\, \tau}\delta(E - m_s/2) \times \frac{\int_{\rm LoS} ds\ \int_{\rm FoV} d\Omega\, \rho_{\rm DM}(s,\Omega)}{\int_{\rm FoV} d\Omega}$$

New Strategy

- Expected DM flux

$$\frac{d\Phi}{dE} = \frac{1}{4\pi\, m_s\, \tau}\delta(E - m_s/2) \times \frac{\int_{\rm LoS} ds\ \int_{\rm FoV} d\Omega\, \rho_{\rm DM}(s,\Omega)}{\int_{\rm FoV} d\Omega}$$

- Perseus flux

$$D_{\rm Pers} \approx \frac{1}{\Omega_{\rm XMM}} \frac{M_{\rm Pers}}{d_{\rm Pers}^2} \approx \frac{1}{(10^{-4}\ {\rm sr})} \frac{(10^{15}\ M_\odot)}{(100\ {\rm Mpc})^2} \sim 10^{29}\ {\rm keV/cm}^2$$

- Perseus halo > XMM Field of View, reduces flux by factor of ~3

New Strategy

- Expected DM flux

$$\frac{d\Phi}{dE} = \frac{1}{4\pi\, m_s\, \tau}\delta(E - m_s/2) \times \frac{\int_{\rm LoS} ds\ \int_{\rm FoV} d\Omega\, \rho_{\rm DM}(s,\Omega)}{\int_{\rm FoV} d\Omega}$$

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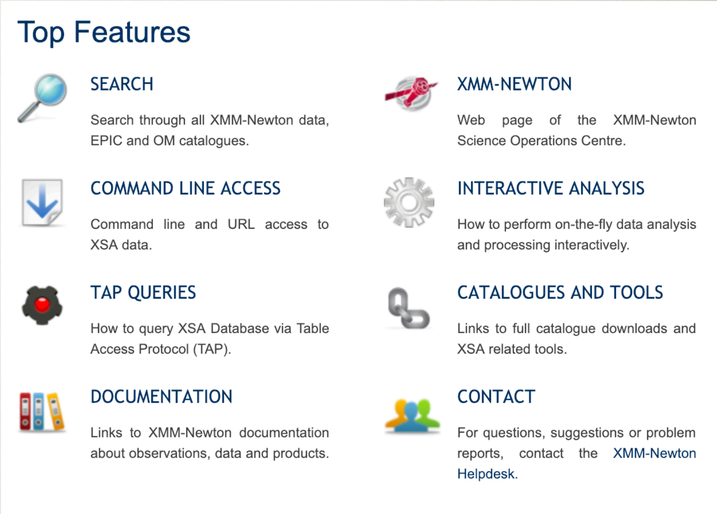
- Perseus halo > XMM Field of View, reduces flux by factor of ~3
- What about for the Milky Way?

$$D_{\rm MW} \approx \int ds\, \rho_{\rm DM}(s,\Omega) \approx (0.4\ {\rm GeV/cm}^3) \times (20\ {\rm kpc}) \approx 2 \times 10^{28}\ {\rm keV/cm}^2$$

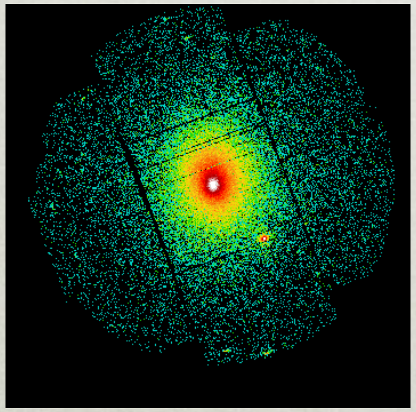
- **Number comparable! Yet more MW we can see than Perseus clusters**

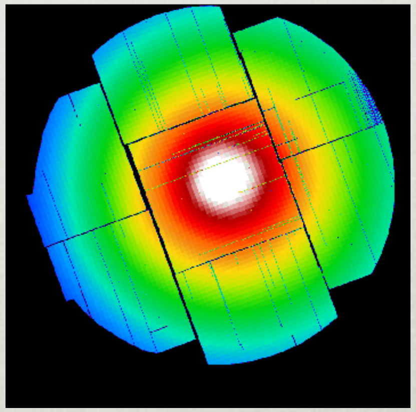
New Strategy

- Strategy motivates using all ~12,000 observations
  - Developed automating tools:
    github.com/nickrodd/XMM-DM
  - Processed all 6,350 obs with
- So much data, can be picky
  - Exclude the galactic centre
  - Restrict to low background observations



http://nxsa.esac.esa.int

Data: 

Exposure: 

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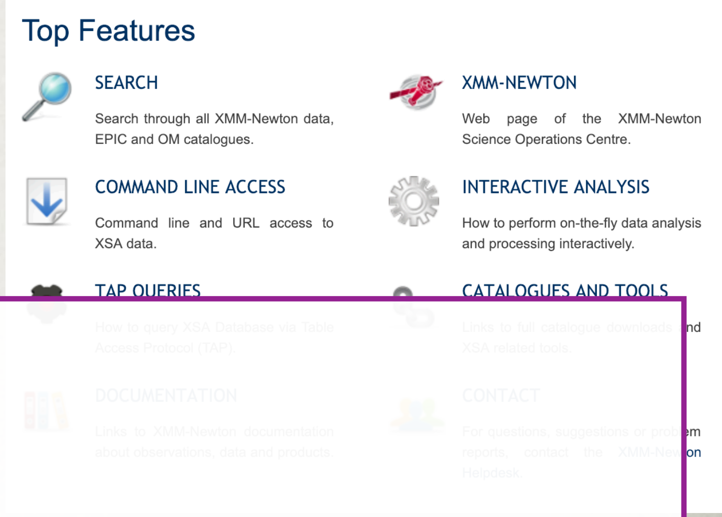
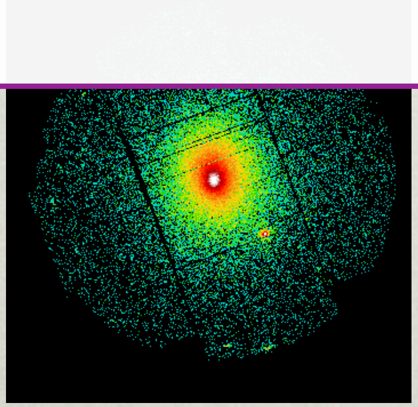
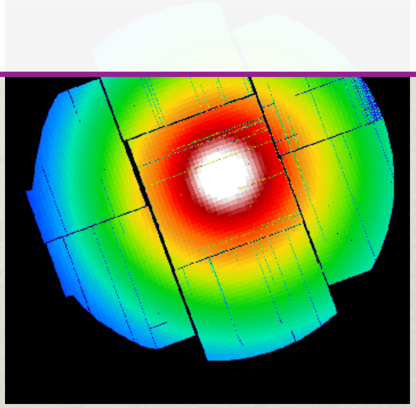


http://nxsa.esac.esa.int

In Short

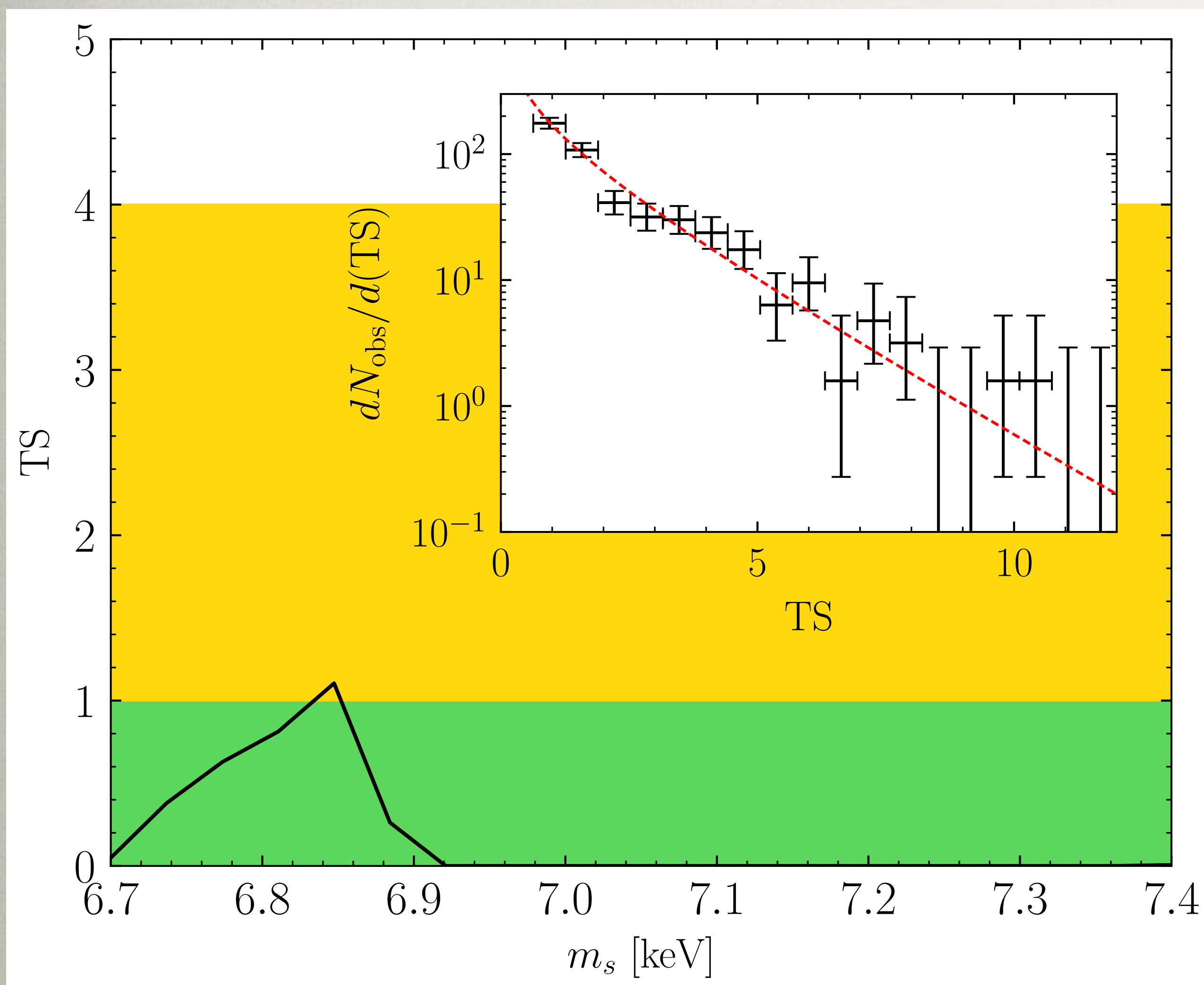
- ***More data***
- ***Larger signal***
- ***Lower background***
- If the line is from dark matter: **see it at over 100σ**

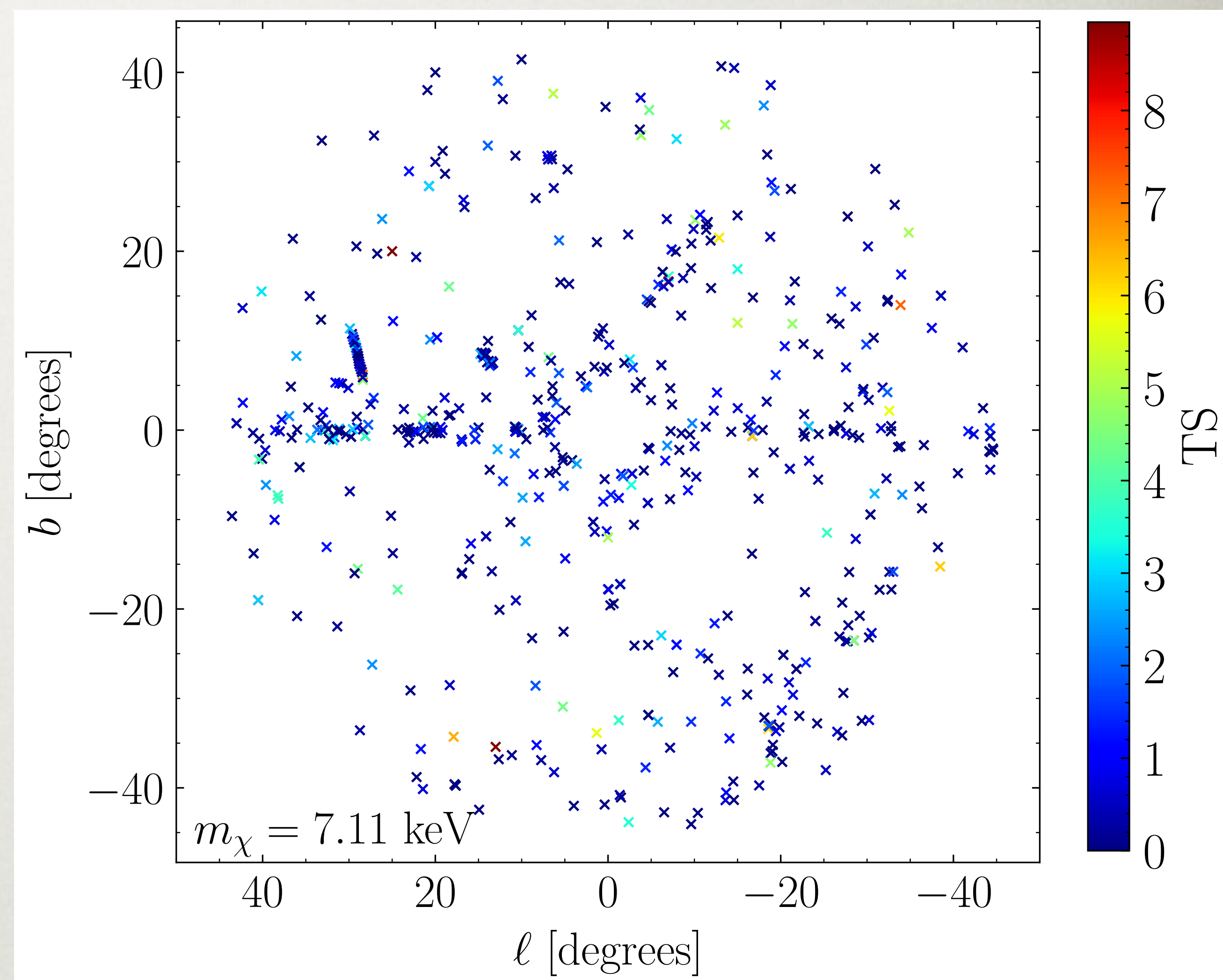
Data: 

Exposure: 

Results

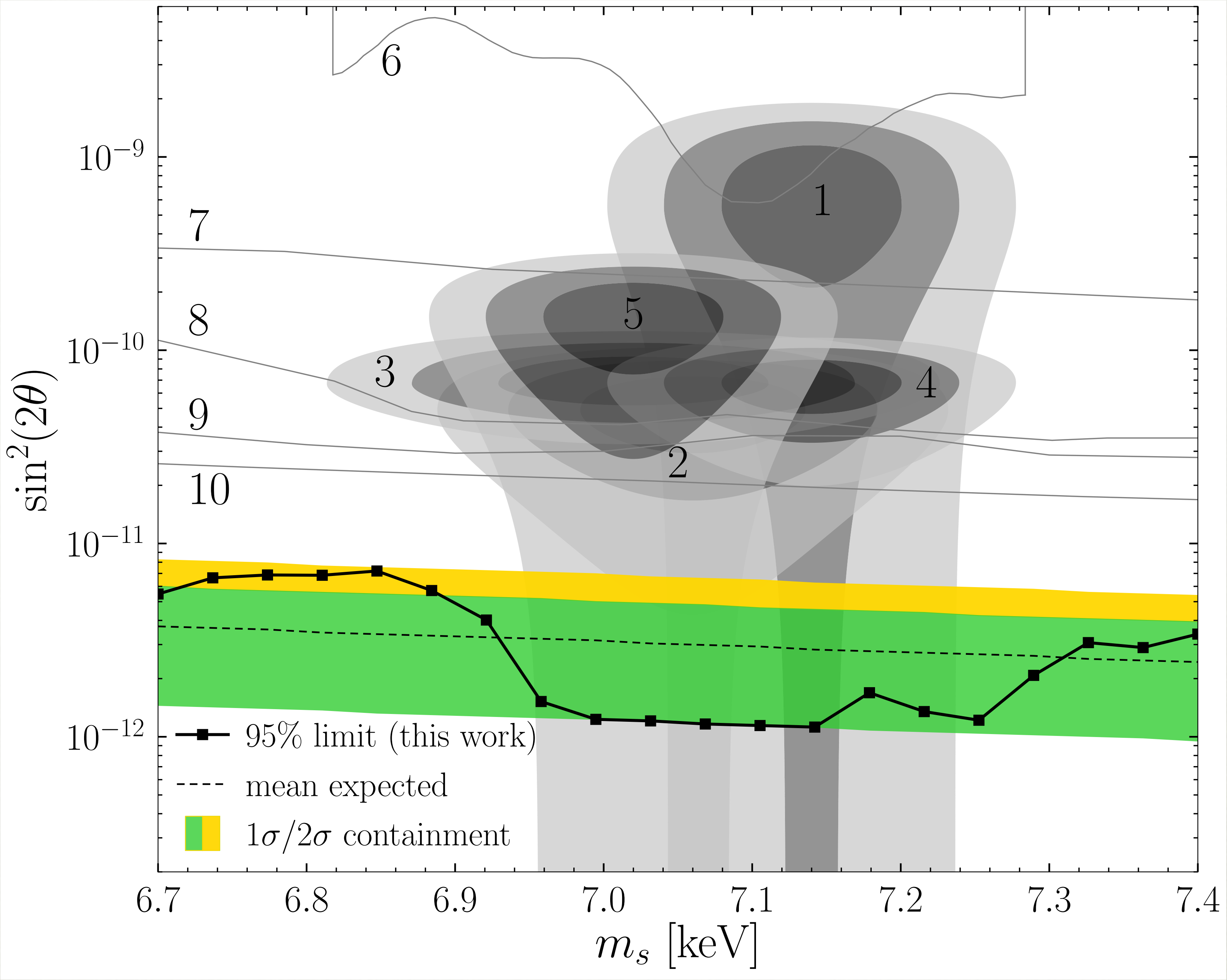
- Calculate the TS for the DM line from the joint profiled likelihood





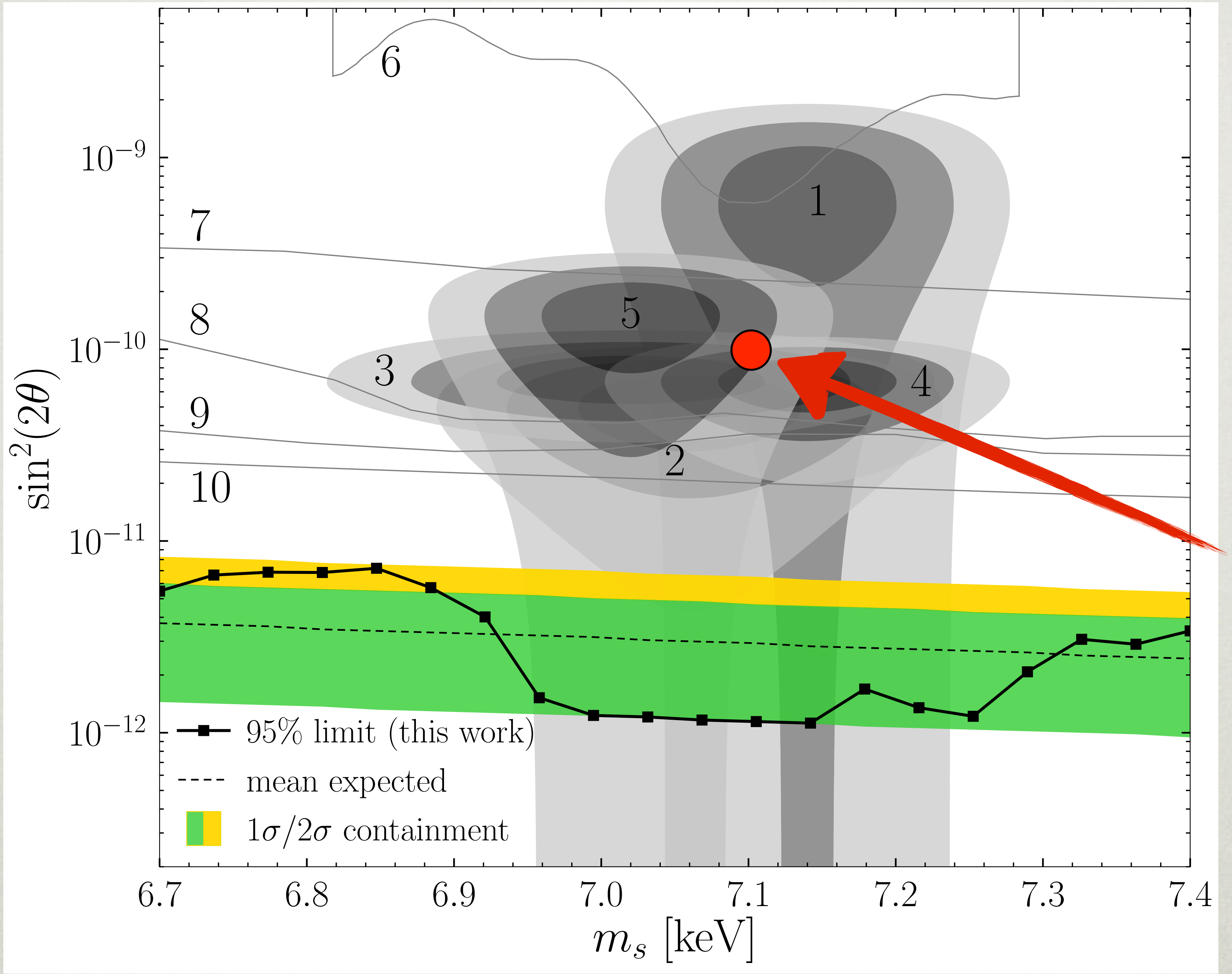
- **No evidence for a DM decay line**
- Left inset shows the distribution of individual exposures versus a χ^2 distribution under the null, provides a good fit to the data

Results



- Expectations from Asimov dataset [Cowan+ 1007.1727]
- Limits are power constrained [Cowan+ 1105.3166]

Results

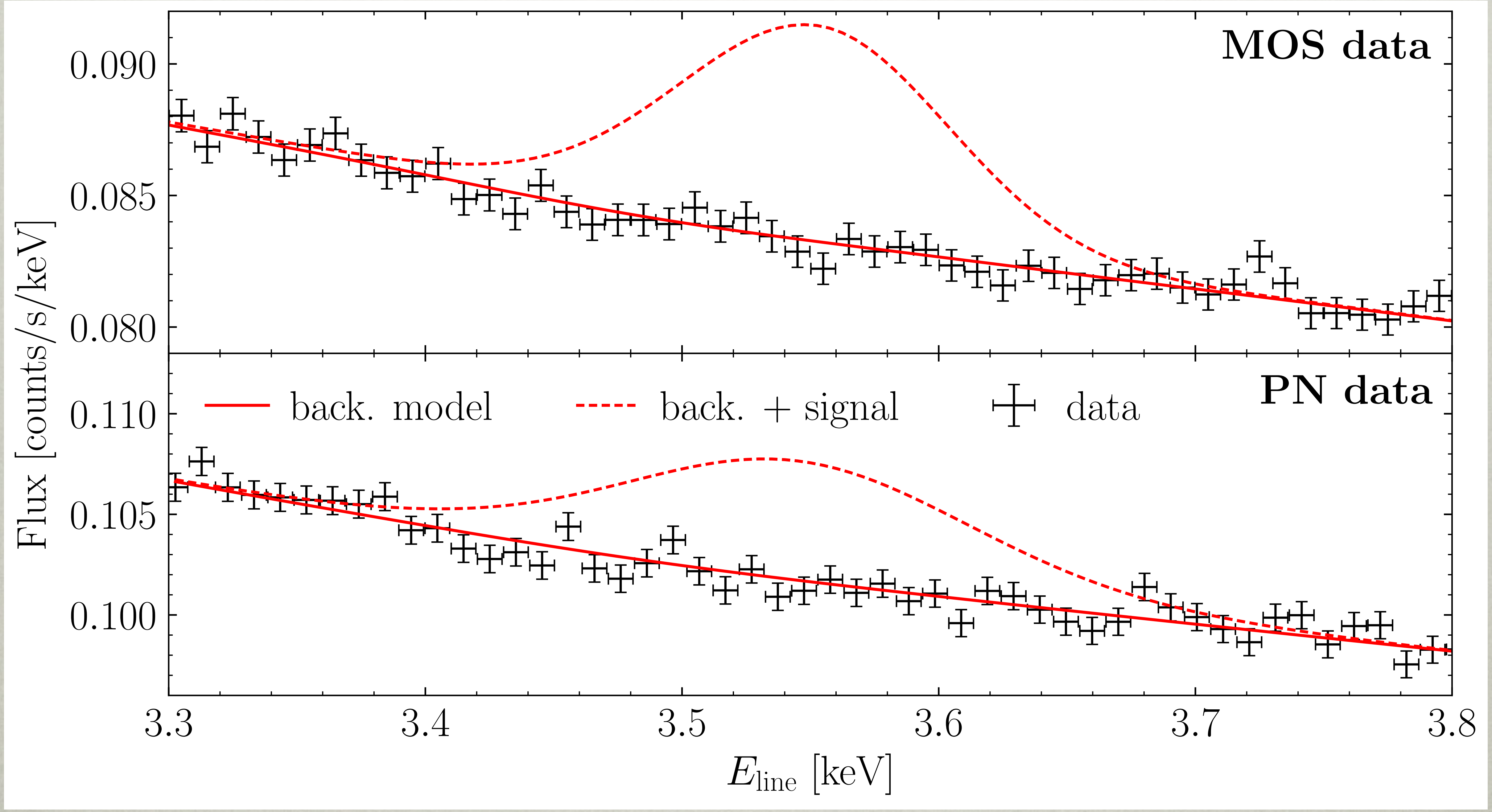


What would this point look like in our data?

- Expectations from Asimov dataset [Cowan+ 1007.1727]
- Limits are power constrained [Cowan+ 1105.3166]

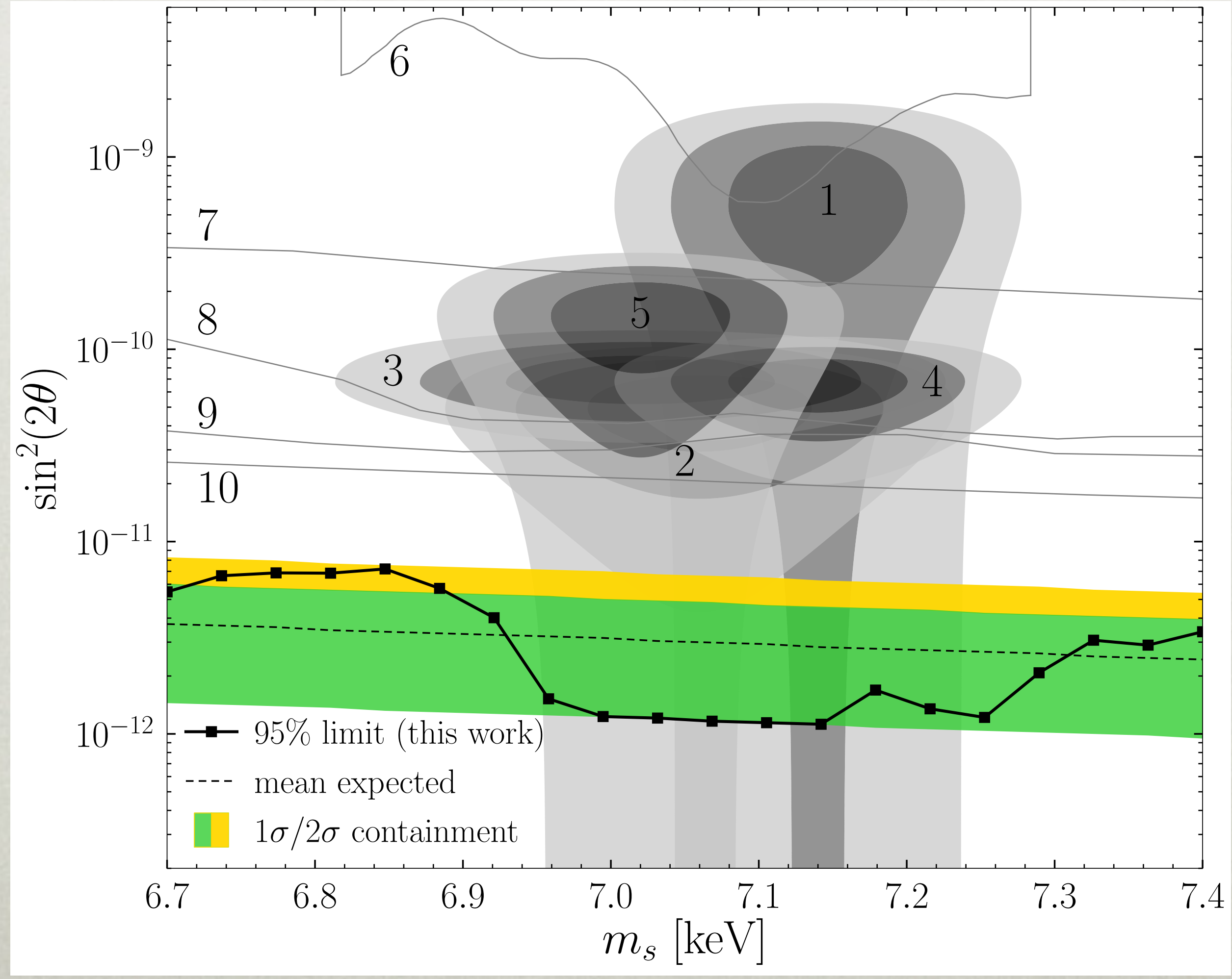
Results

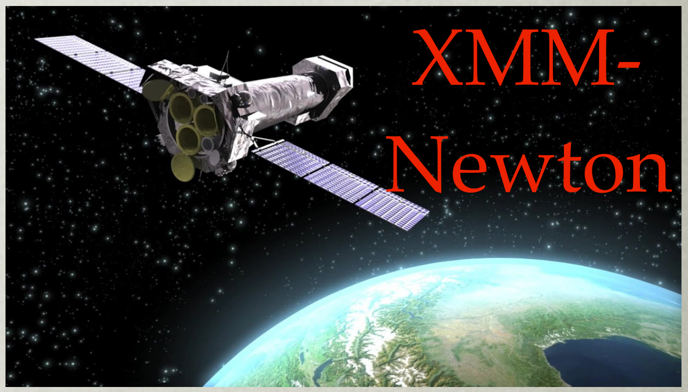
- Stack data and best fit models, overlay expected signal
  - NB: we don't stack in our analysis, but this makes a compelling plot!



Conclusion

- Milky Way halo is a bright source of dark matter decay
- Allows us to use almost all XMM-Newton data
- Our results provide very strong evidence the line is not from dark matter decay

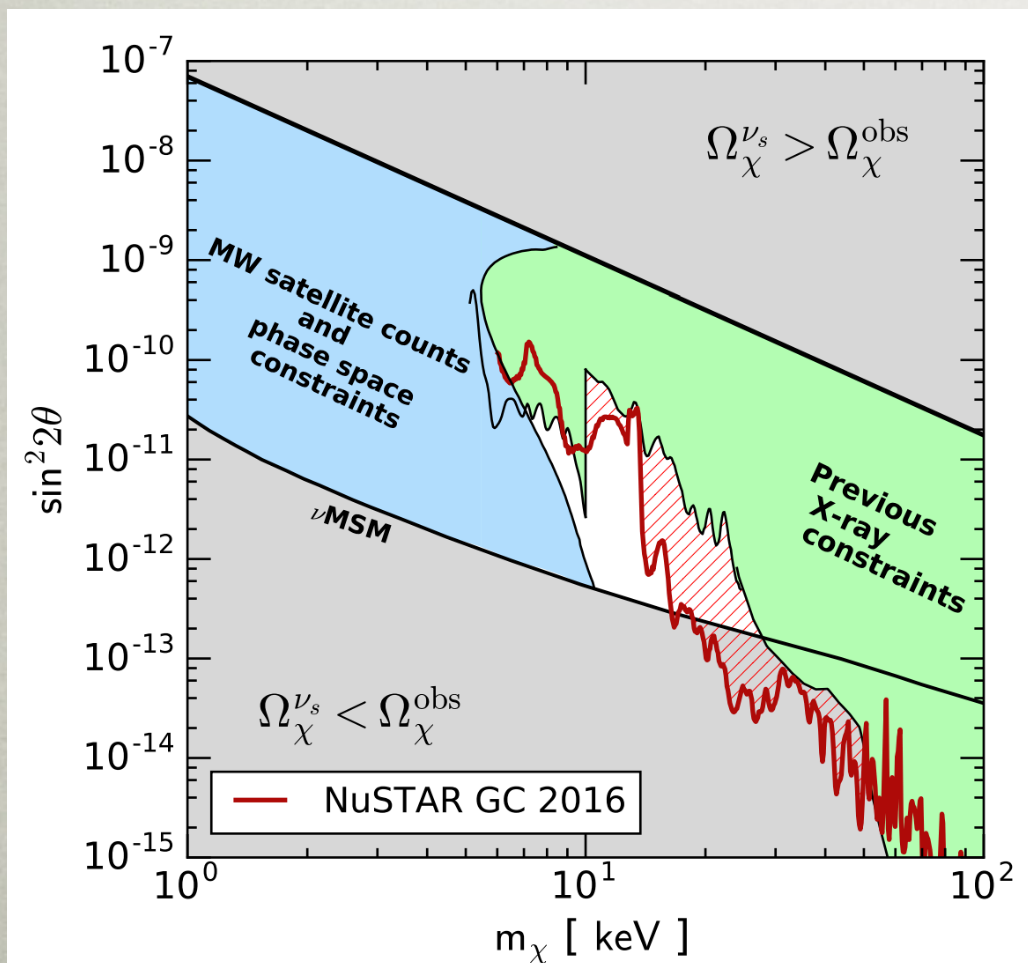




Backup Slides

Sterile ν Dark Matter

- **ν_s: a compelling dark matter candidate**
  - Early universe production: conversion of active ν [Dodelson+Widrow; Shi+Fuller]
  - Can be realised with seesaw or baryogenesis [e.g Canetti+ 1208.4607]



- If ν_α and ν_β mix with angle θ

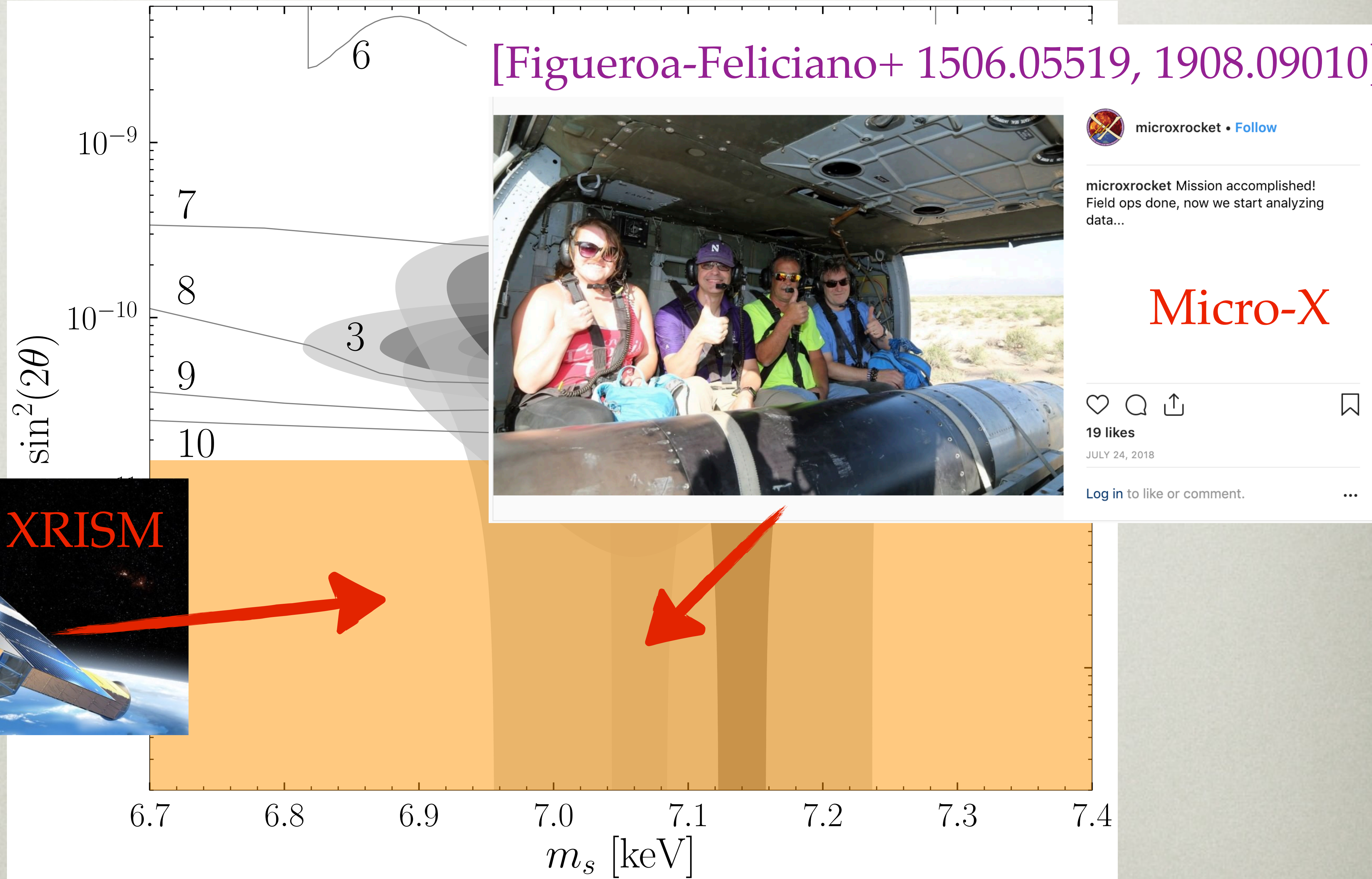
$$P_{\alpha\to\beta} \propto \sin^2(2\theta)$$

[Perez+ 1609.00667, see also Ng+ 1901.01262]

Towards a Definitive Statement

1. New experiments

[Figueroa-Feliciano+ 1506.05519, 1908.09010]



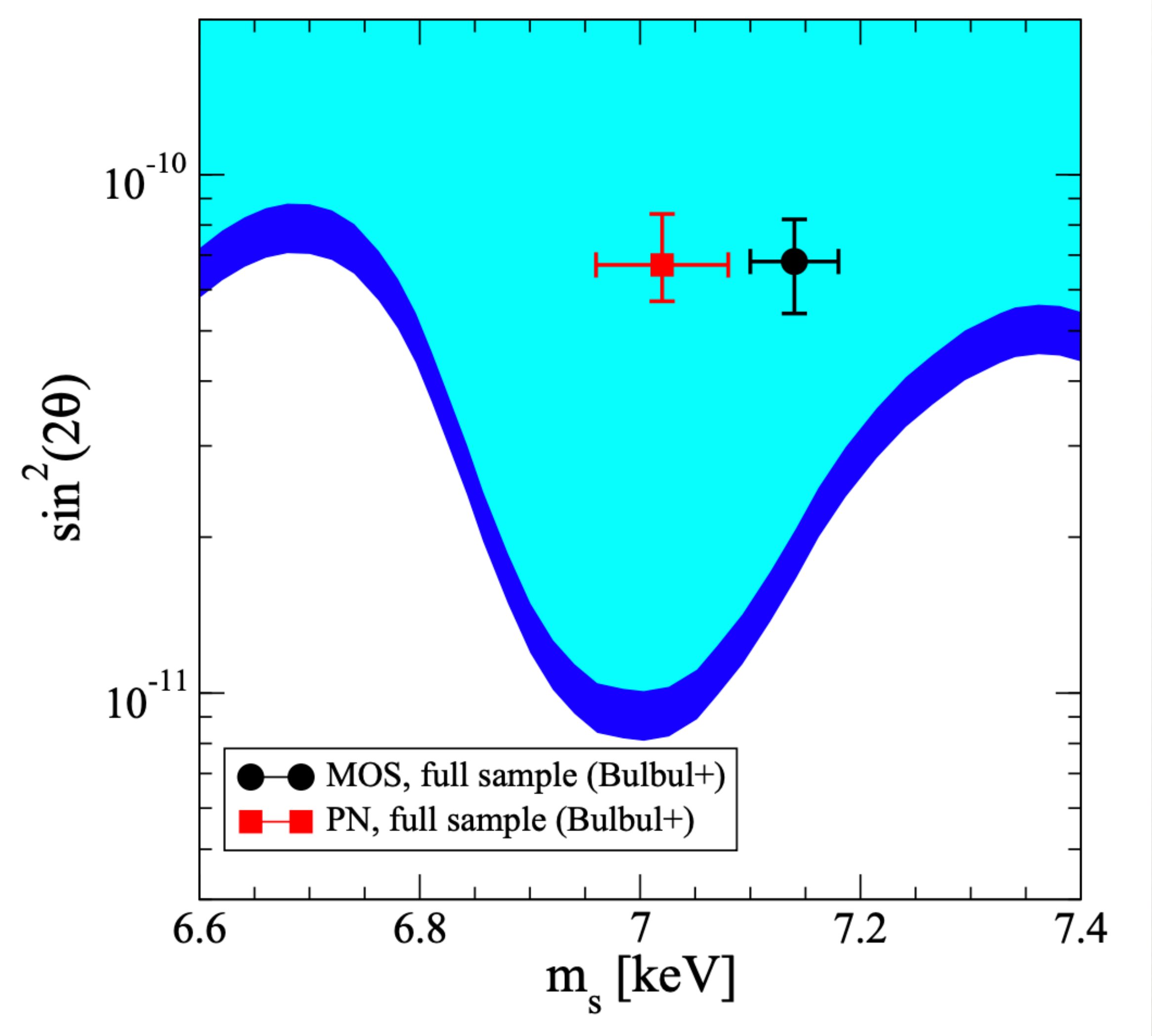
Towards a Definitive Statement

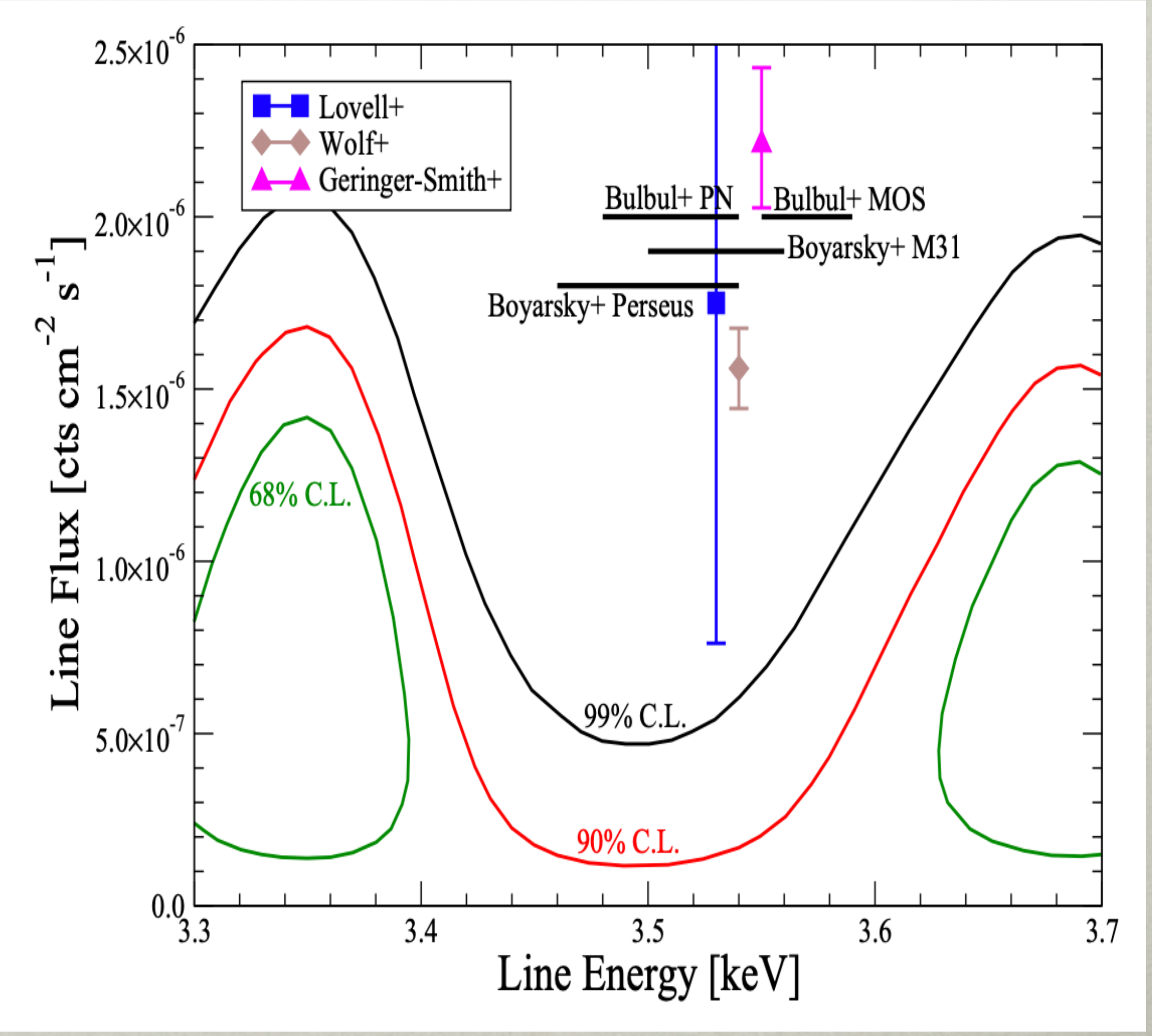
2. Deep observation of dark matter bright object

Deep XMM Observations of Draco rule out at the 99% Confidence Level a Dark Matter Decay Origin for the 3.5 keV Line

Tesla Jeltema[1*] and Stefano Profumo[1†]
[1] *Department of Physics and Santa Cruz Institute for Particle Physics University of California, Santa Cruz, CA 95064, USA*

[1512.01239]





Towards a Definitive Statement

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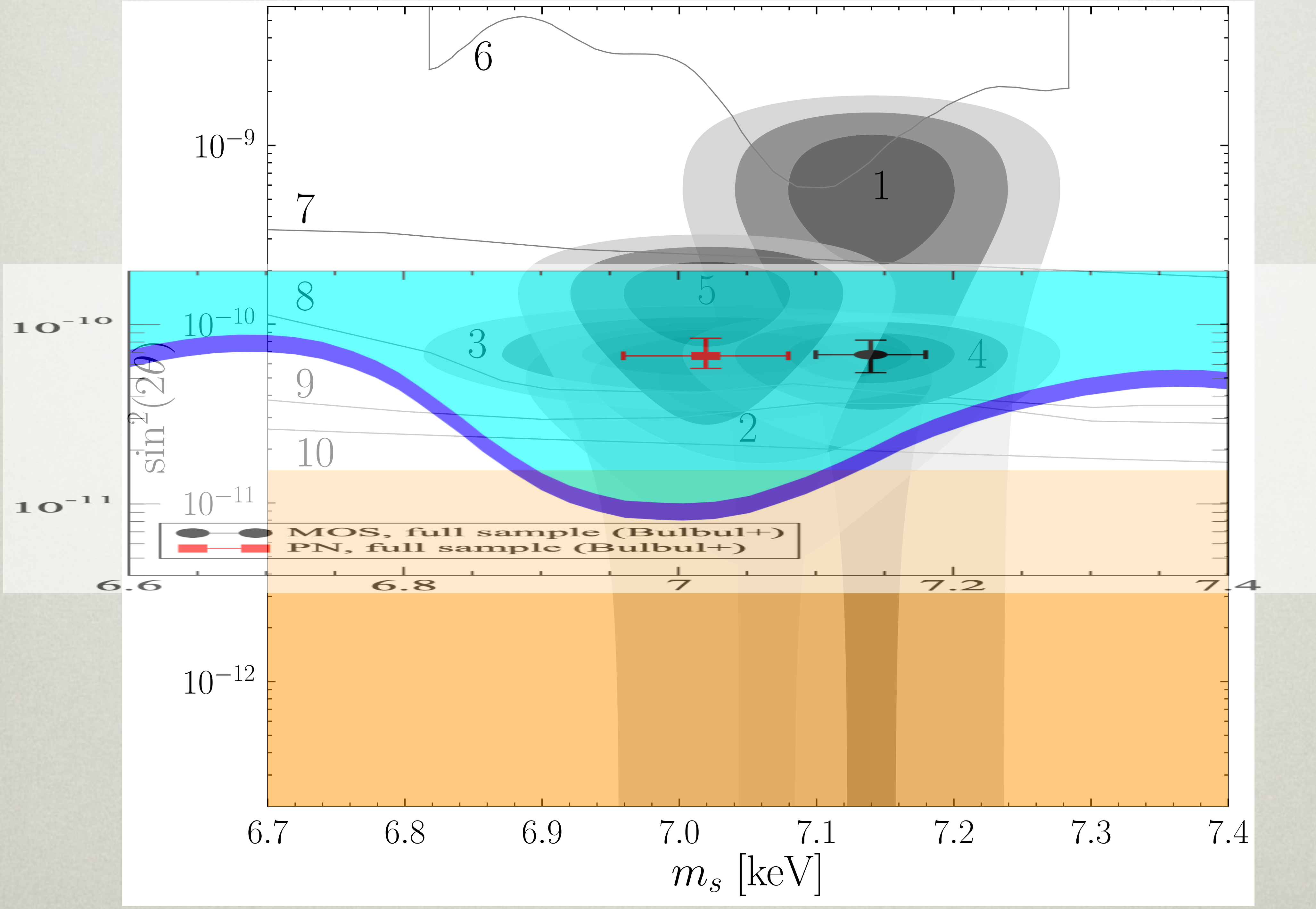


[1512.01239]

Towards a Definitive Statement

2. Deep observation of dark matter bright object

Searching for decaying dark matter in deep *XMM-Newton* observation of the Draco dwarf spheroidal

[1512.07217]

Oleg Ruchayskiy,[1,2⋆] Alexey Boyarsky,[3] Dmytro Iakubovskyi,[2,4]
Esra Bulbul,[5] Dominique Eckert,[6] Jeroen Franse,[3,7] Denys Malyshev,[6]
Maxim Markevitch,[8] Andrii Neronov[6]

X-ray bright objects, such as galaxies and galaxy clusters. We do not detect a statistically significant emission line from Draco; this constrains the lifetime of a decaying dark matter particle to $\tau > (7-9) \times 10^{27}$ s at 95% CL (combining all three *XMM-Newton* cameras; the interval corresponds to the uncertainty of the dark matter column density in the direction of Draco). The PN camera, which has the highest sensitivity of the three, does show a positive spectral residual (above the carefully modeled continuum) at $E = 3.54 \pm 0.06$ keV with a 2.3σ significance. The two MOS cameras show less-significant or no positive deviations, consistently within 1σ with PN. Our Draco limit on τ is consistent with previous detections in the stacked galaxy clusters, M31 and the Galactic Center within their $1-2\sigma$ uncertainties, but is inconsistent with the high signal from the core of the Perseus cluster (which has itself been inconsistent with the rest of the detections). We conclude that this Draco observation does not exclude the dark matter interpretation of the 3.5 keV line in those objects.

New Strategy

- **Key observation:** Milky Way halo is bright even away from GC

$$\frac{d\Phi}{dE} = \frac{1}{4\pi\, m_s\, \tau}\delta(E - m_s/2) \times \underbrace{\int ds\, \rho_{\rm DM}(s,\Omega)}_{\text{“D-factor”}}$$

$\psi_{\rm Pers} = 148^\circ$

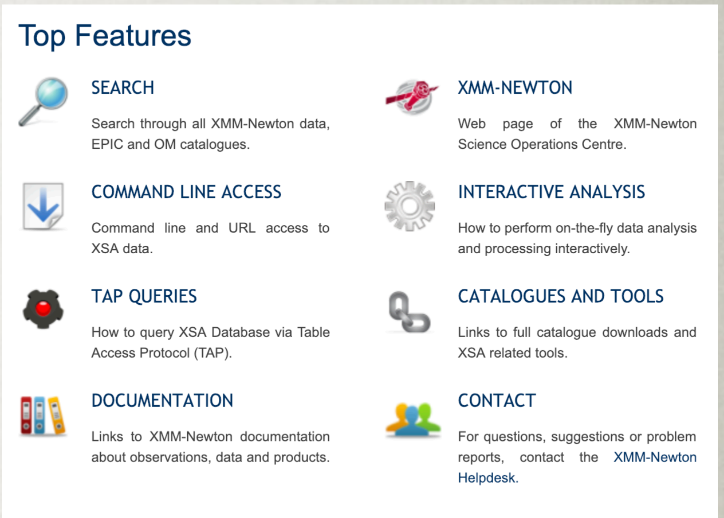
- Average emission over the XMM-Newton FoV

$$D_{\rm Pers} \sim 3 \times 10^{28}\ {\rm keV/cm^2}$$
$$D_{\rm MW}(\psi = 148^\circ) \sim 1 \times 10^{28}\ {\rm keV/cm^2}$$
$$D_{\rm MW}(\psi = 45^\circ) \sim 3 \times 10^{28}\ {\rm keV/cm^2}$$

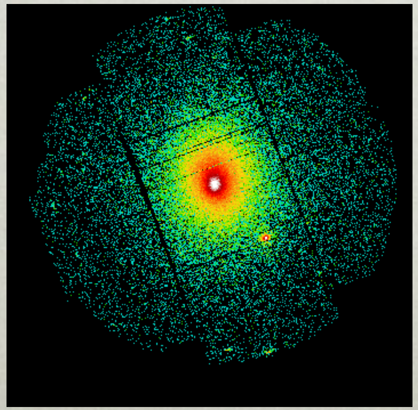
- MW flux is comparable to clusters: the line is present in every observation XMM has ever made!
- Same observation exploited in γ-rays [NLR+ 1612.05638]

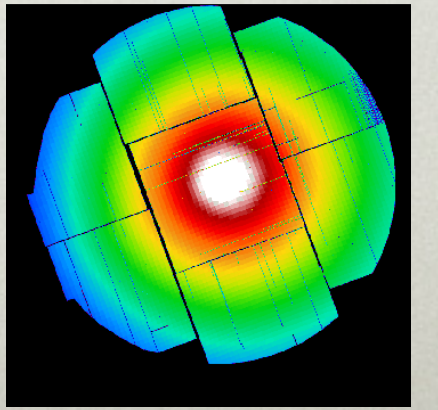
New Strategy

- Strategy motivates using all ~12,000 observations
  - Developed automating tools: github.com/nickrodd/XMM-DM
  - Processed all 6,350 obs with $\psi < 90^\circ$
- Apply cuts to restrict this to the best datasets
  - $5^\circ < \psi < 45^\circ$
  - $I_{2-10} < 5 \times I_{2-10}^{\rm CXRB}$
  - Lowest 68% of instrumental background
  - Remove $t_{\rm obs} < 1$ ks
- **1,397 exposures, 752 observations, 30.6 Ms**



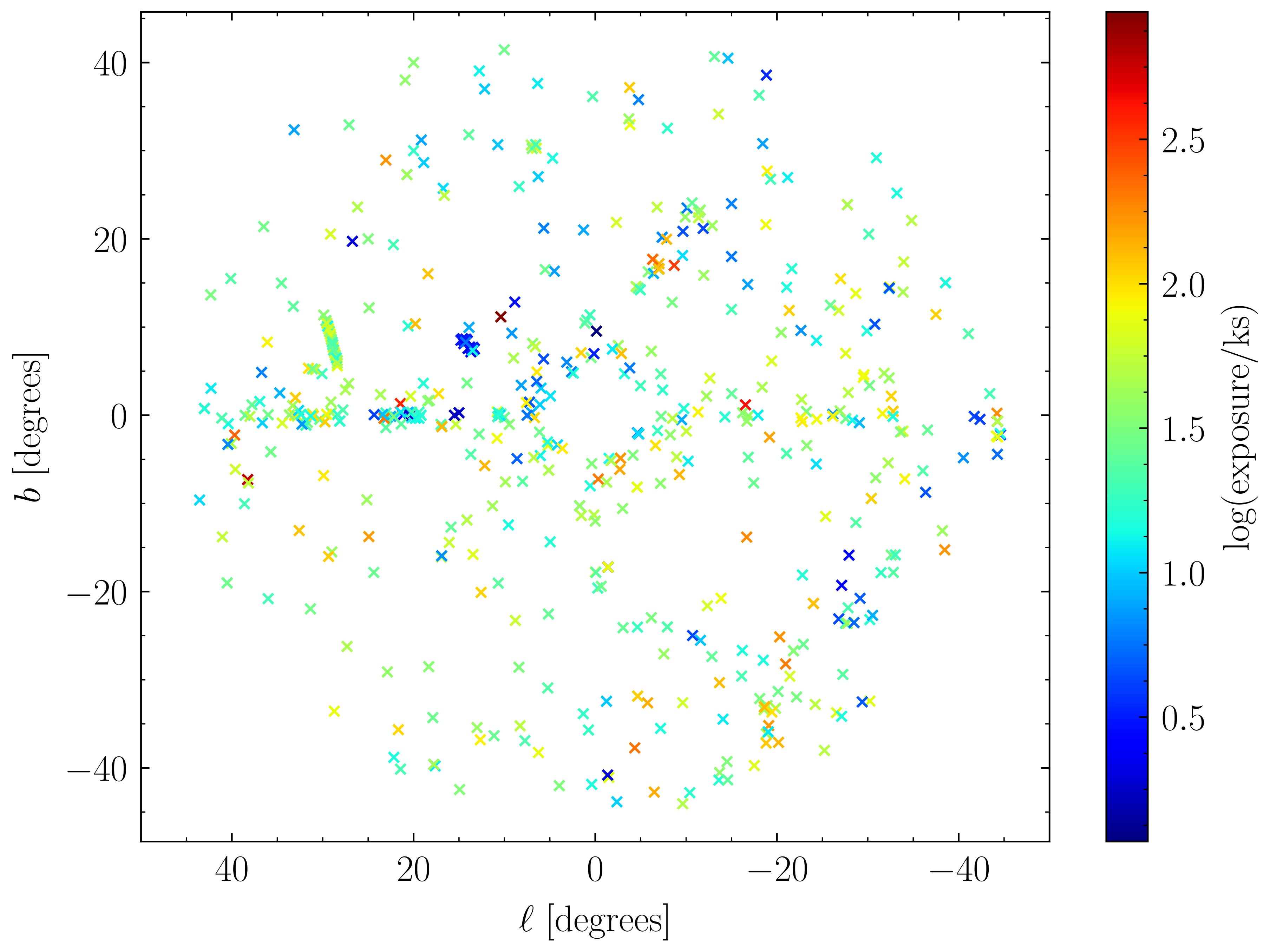
http://nxsa.esac.esa.int

Data: 

Exposure: 

New Strategy

- Exposures well distributed over the region



Estimated Sensitivity

- What reach should we expect? In the large count limit

$$\mathrm{TS} = 2[\ln \mathcal{L}_S - \ln \mathcal{L}_B] \sim \sigma^2 \sim S^2/B = \Phi_S^2/\Phi_B \times t$$

- Bulbul+ detected line with $\mathrm{TS} \sim 16$ and $t_{\mathrm{Pers}} \sim 320$ ks

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- Bulbul+ detected line with $\mathrm{TS} \sim 16$ and $t_{\mathrm{Pers}} \sim 320\ \mathrm{ks}$
- Blank sky observations (BSO) much lower background than Perseus, by selection:

$$\Phi_B^{\mathrm{BSO}}/\Phi_B^{\mathrm{Pers}} \sim 0.02$$

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- As the signal is at least as bright starting at 45$^{\text{o}}$, we could reach the same significance using only

$$t_{\text{BSO}} \approx t_{\text{Pers}} \times (\Phi_B^{\text{BSO}}/\Phi_B^{\text{Pers}}) \approx 6 \text{ ks}$$

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- Blank sky observations (BSO) much lower background than Perseus, by selection:

$$\Phi_B^\text{BSO}/\Phi_B^\text{Pers} \sim 0.02$$

- As the signal is at least as bright starting at 45º, we could reach the same significance using only

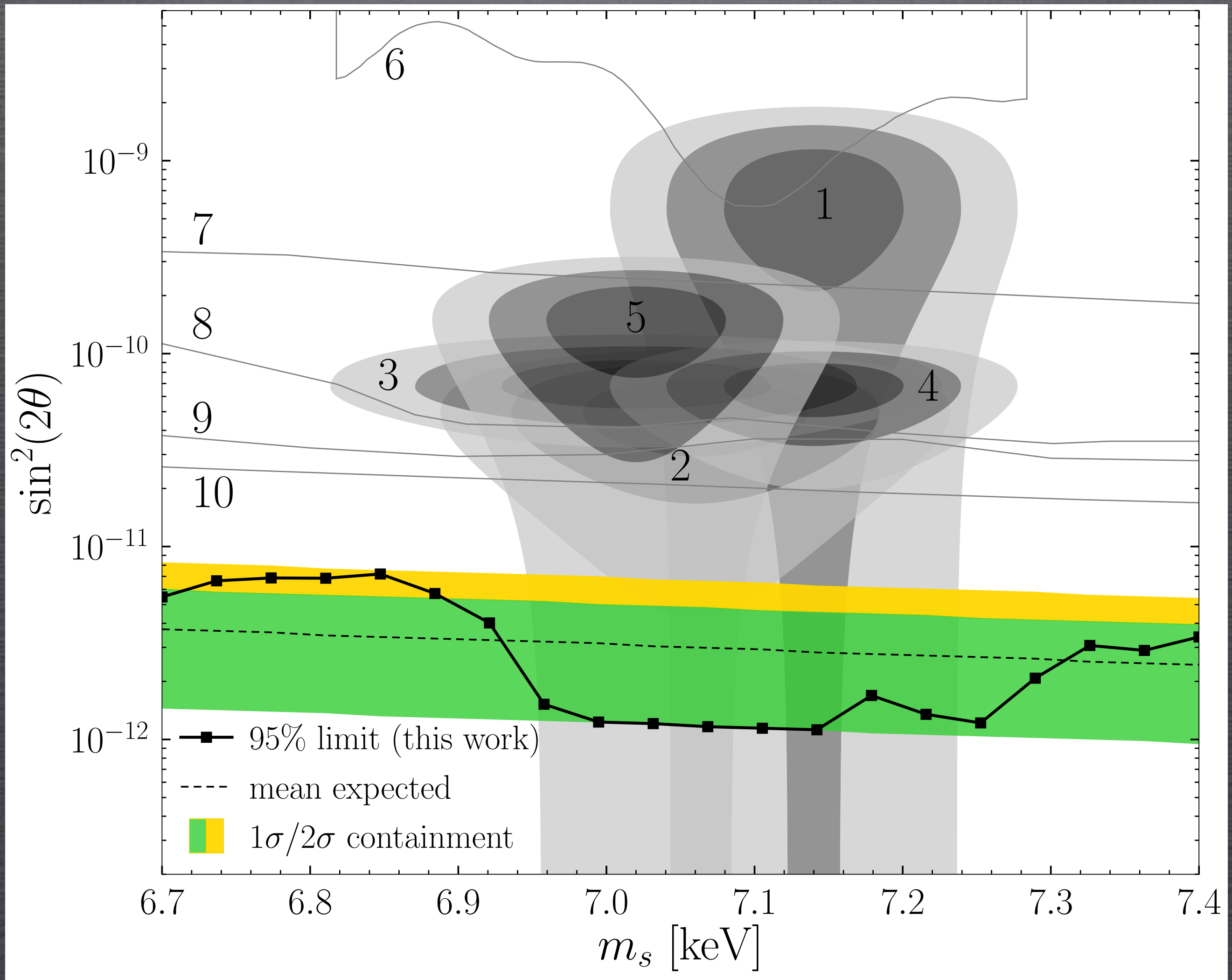
$$t_\text{BSO} \approx t_\text{Pers} \times (\Phi_B^\text{BSO}/\Phi_B^\text{Pers}) \approx 6 \text{ ks}$$

- With the full ~30 Ms dataset expect

$$\text{TS}_\text{BSO} \approx 16 \times (30 \text{ Ms}/6 \text{ ks}) \approx 75,000$$

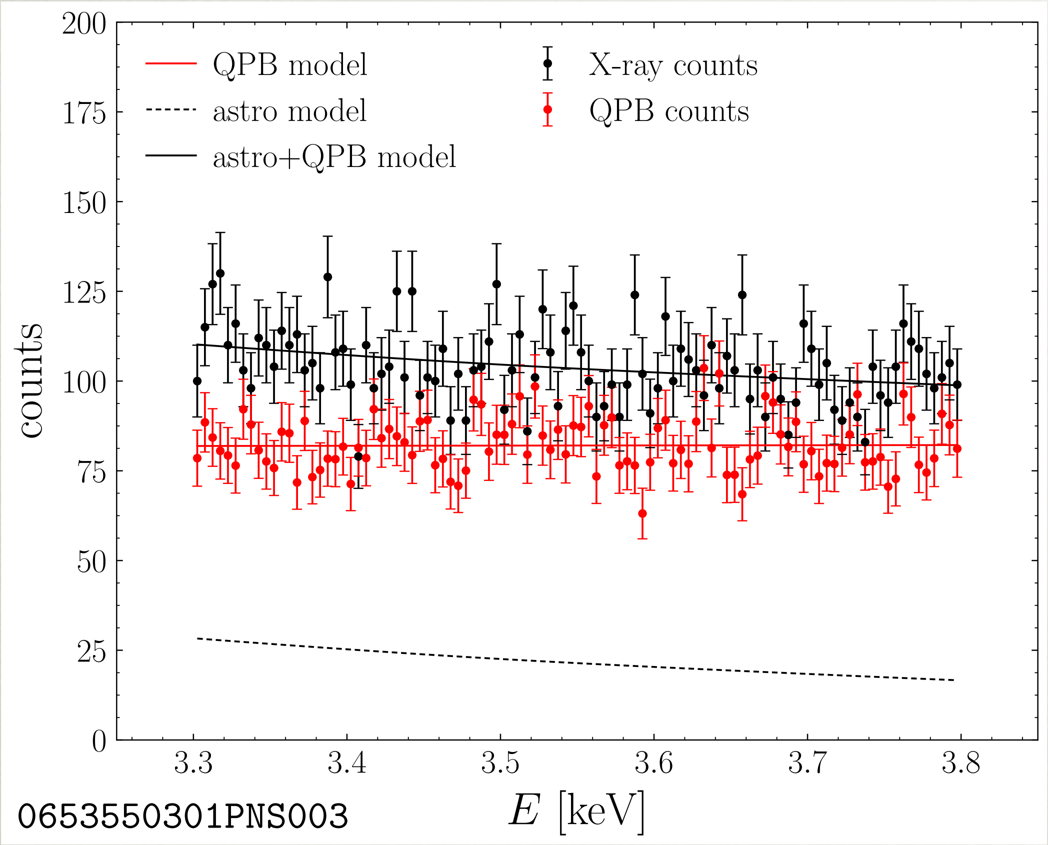
- **This analysis could detect particle dark matter at over 100σ**

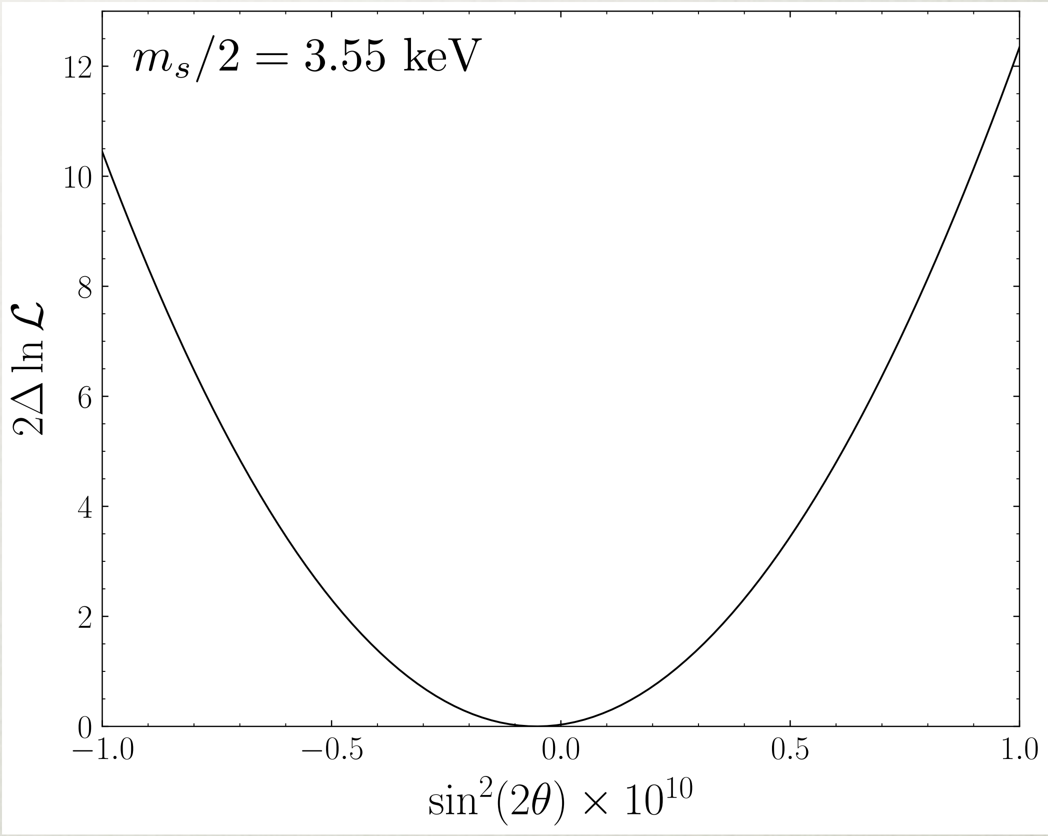
Analysis and Results



Profile Likelihood Analysis

- Analyse each exposure using **profile likelihood**
  - Likelihoods are then joined, we do not stack the datasets
  - Use narrow energy window: $m_s/2 \pm 0.25$ keV ($\Delta E_{\rm XMM} \approx 0.1$ keV)
  - Model: astrophysical power-law, instrumental power-law, DM

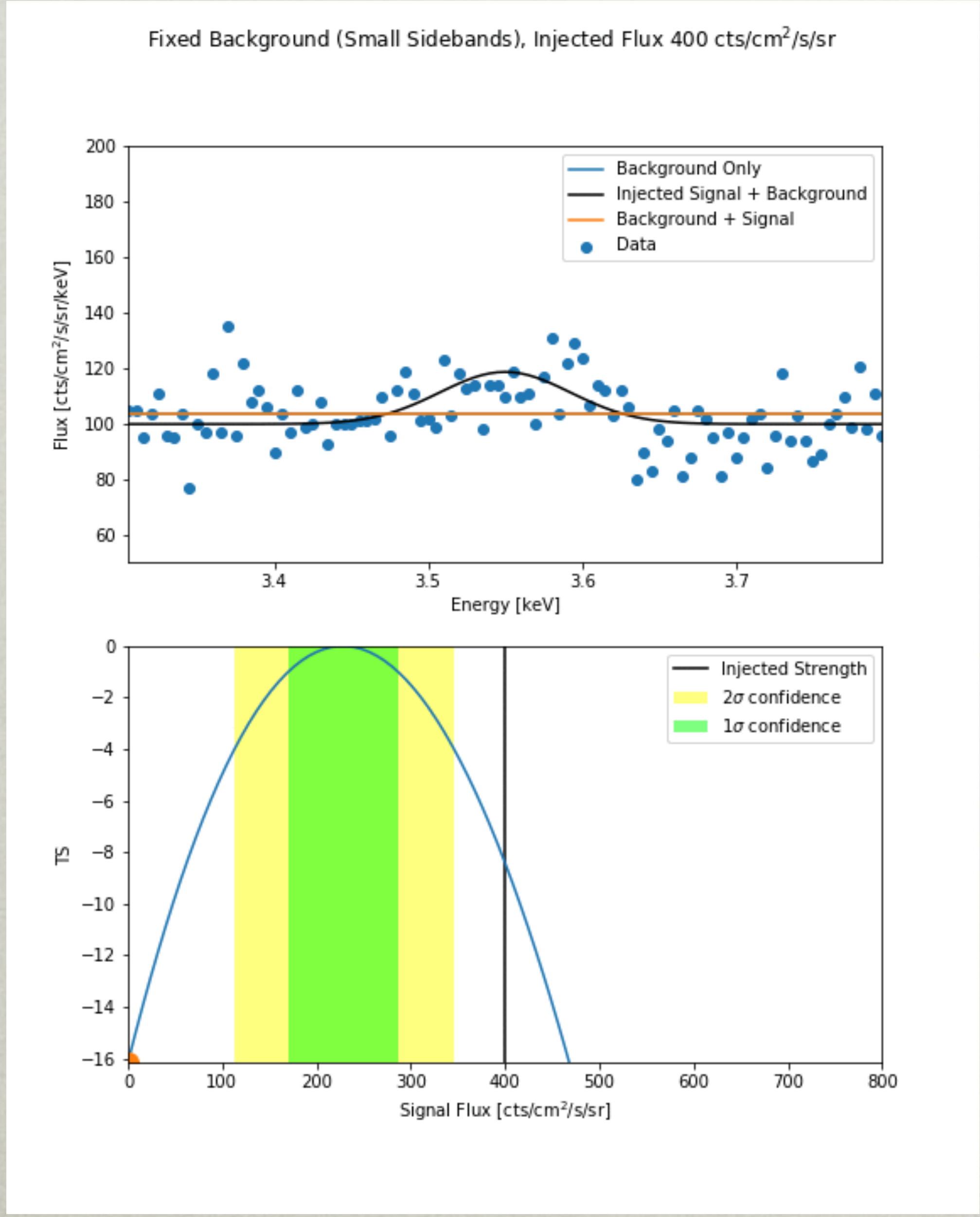


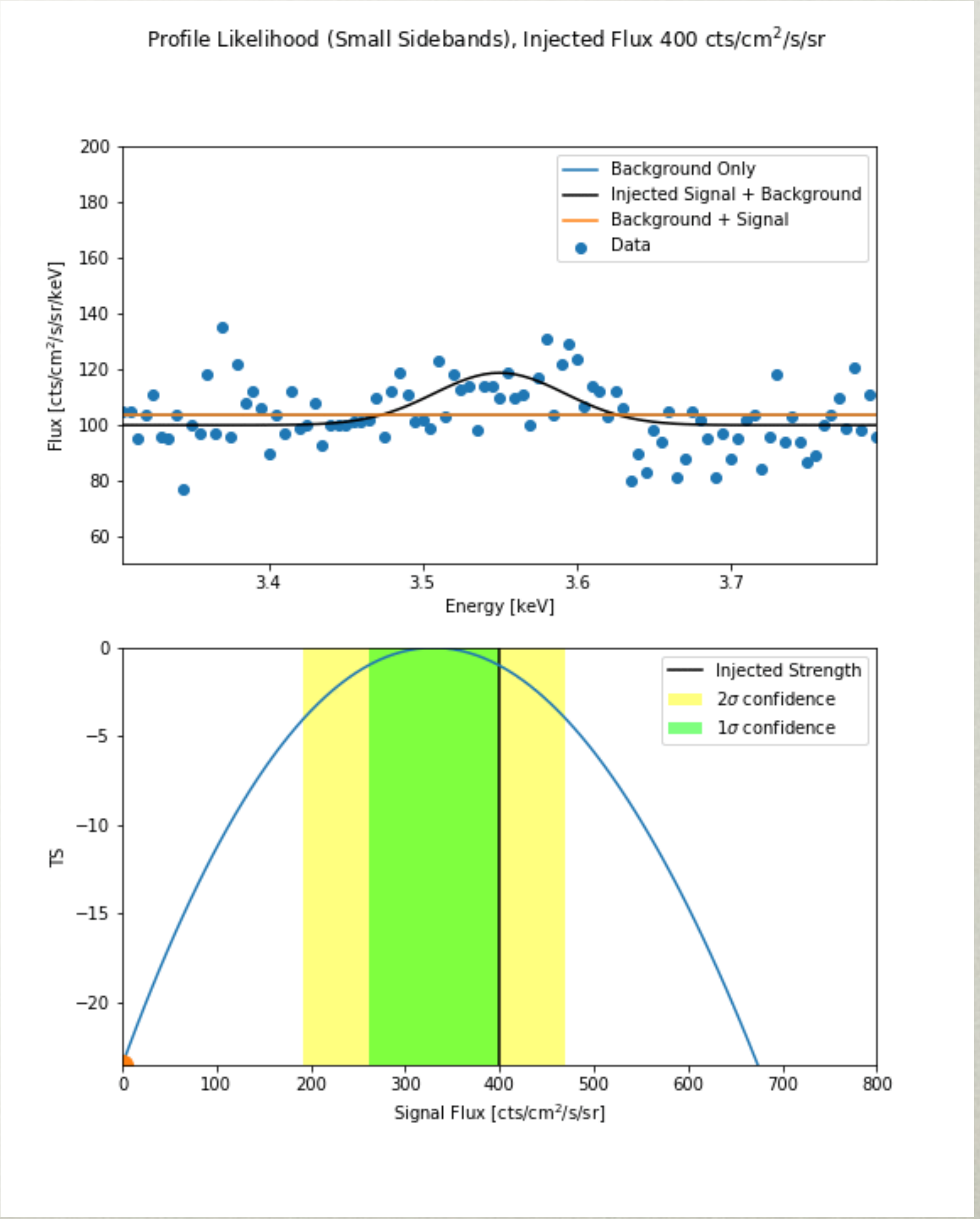


- In detail use Poisson likelihood for counts + Gaussian likelihood for QPB estimates. Instrument response folded into the model prediction

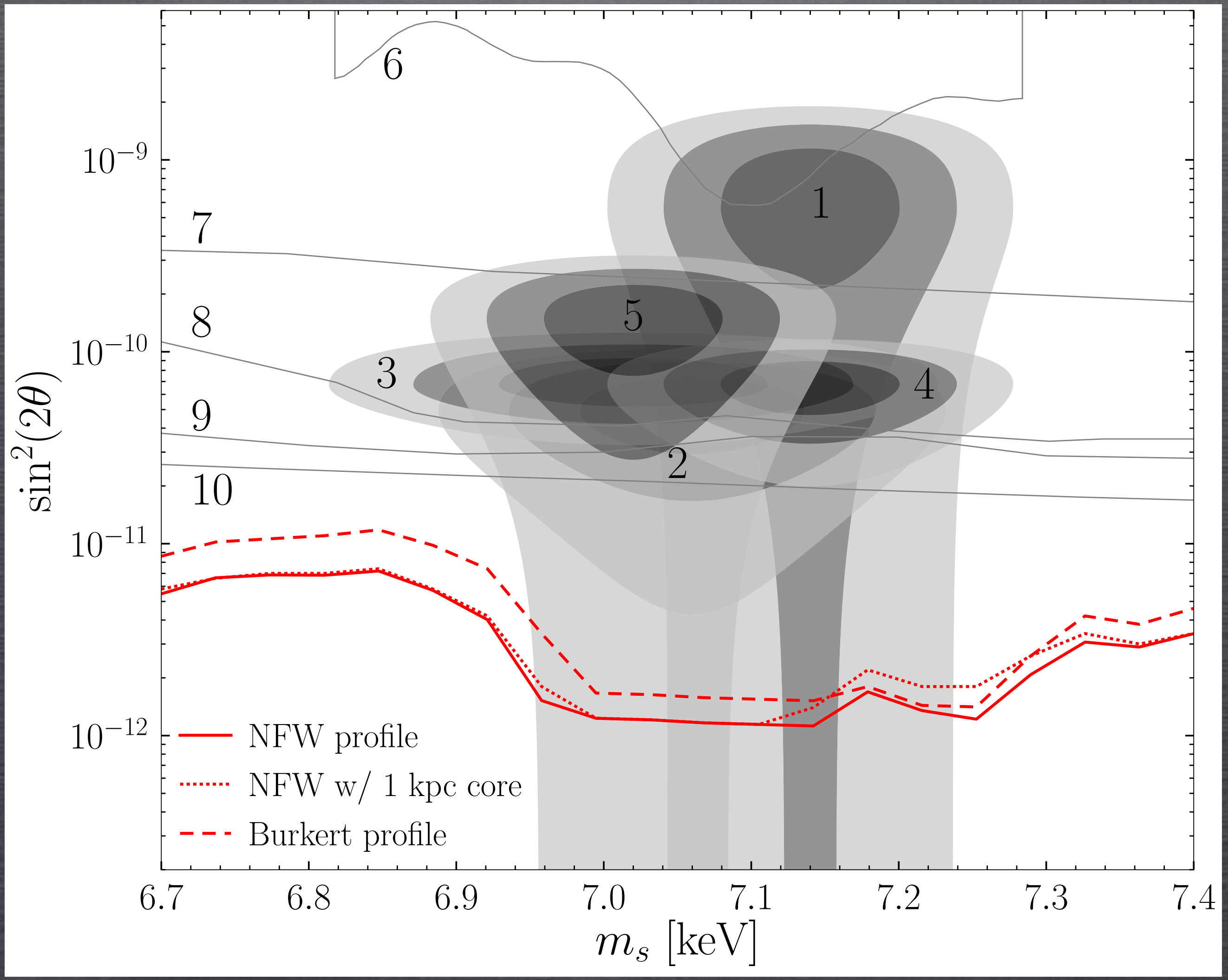
Profile Likelihood Analysis

- Nuisance parameters removed using the profile likelihood
- *The background is refit for every value of the signal*



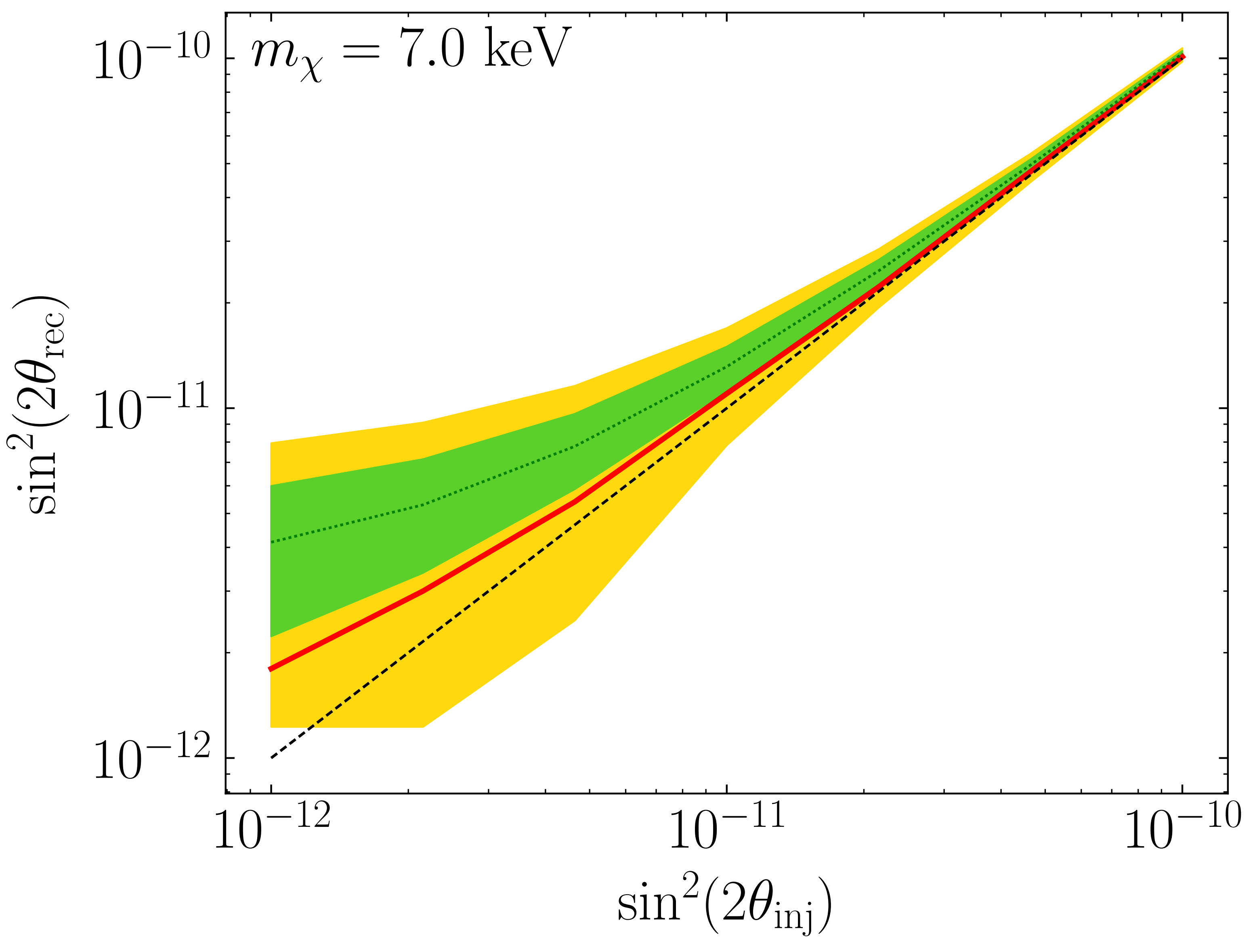


Systematic Checks



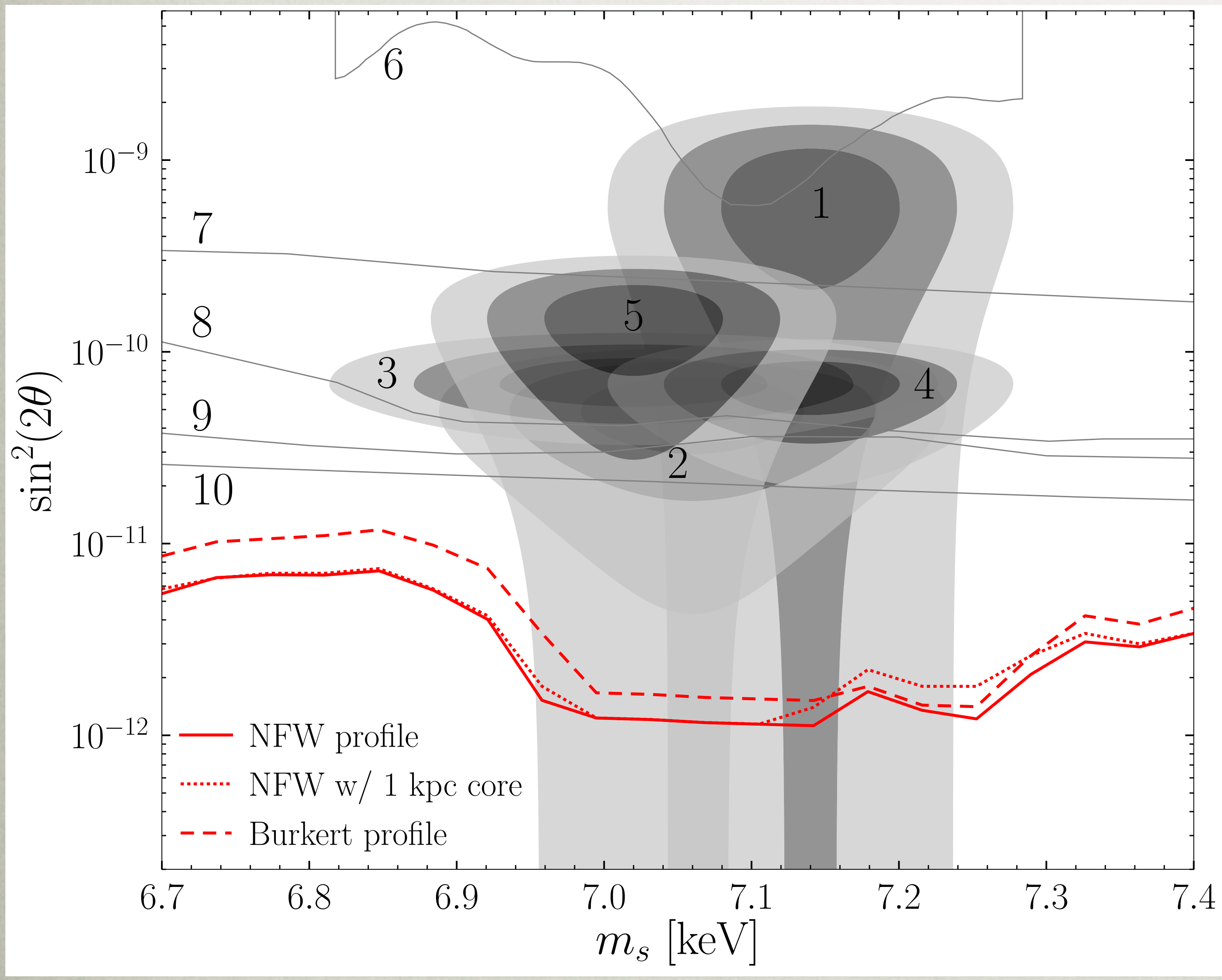
SYSTEMATIC CROSS CHECKS

- The result is controversial, so we have cross checked extensively
- If there was a real signal in the data, would we have excluded it?
- Check by injecting a real signal into the data



SYSTEMATIC CROSS CHECKS

- How dependent are these results on the assumed halo profile?



$$\rho_{\rm local} = 0.4\ {\rm GeV/cm^3}$$

$$r_\odot = 8.127\ {\rm kpc}$$

$$\rho_{\rm NFW}(r) = \frac{\rho_0}{r/r_s\ (1+r/r_s)^2}$$

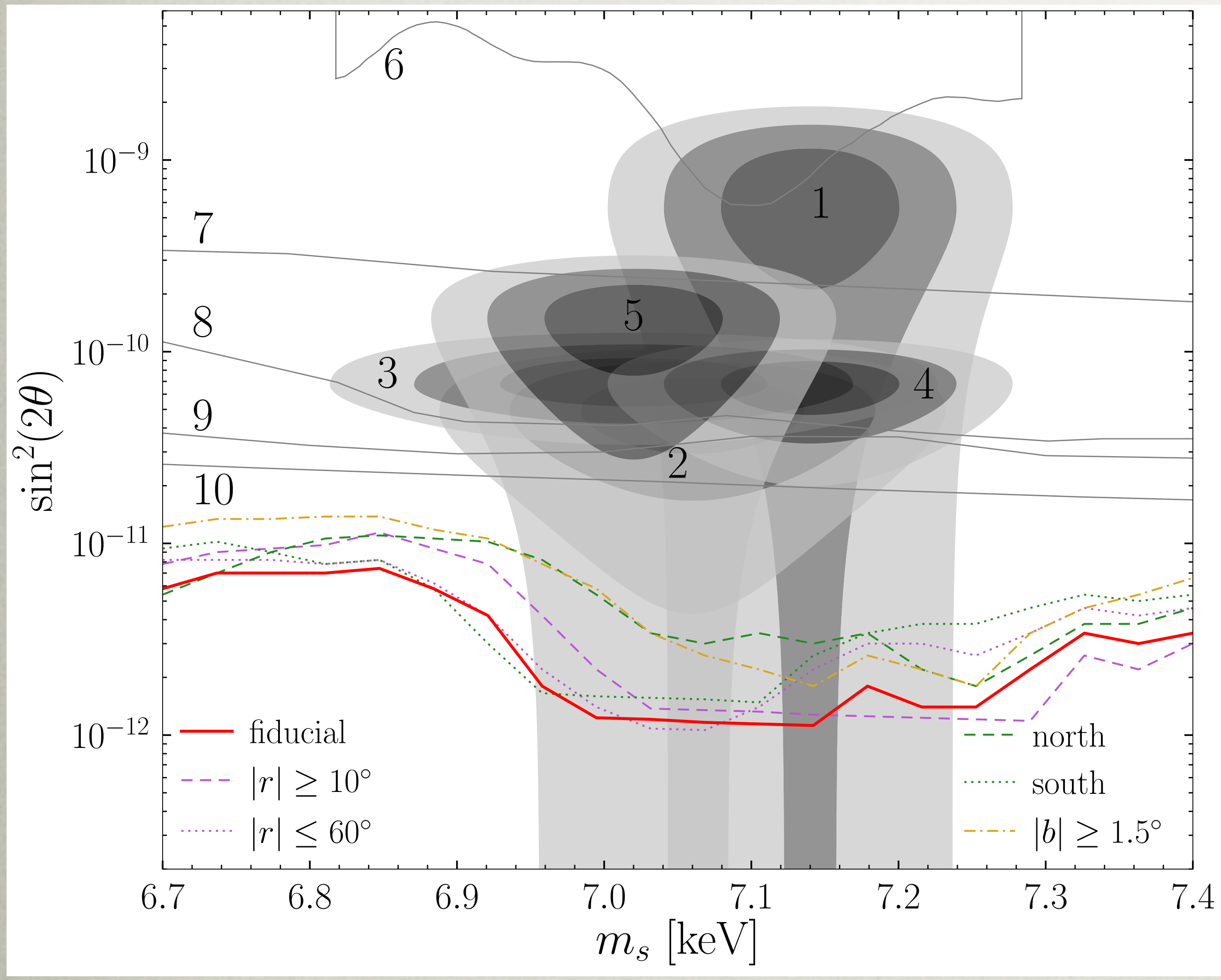
$$r_s = 20\ {\rm kpc}$$

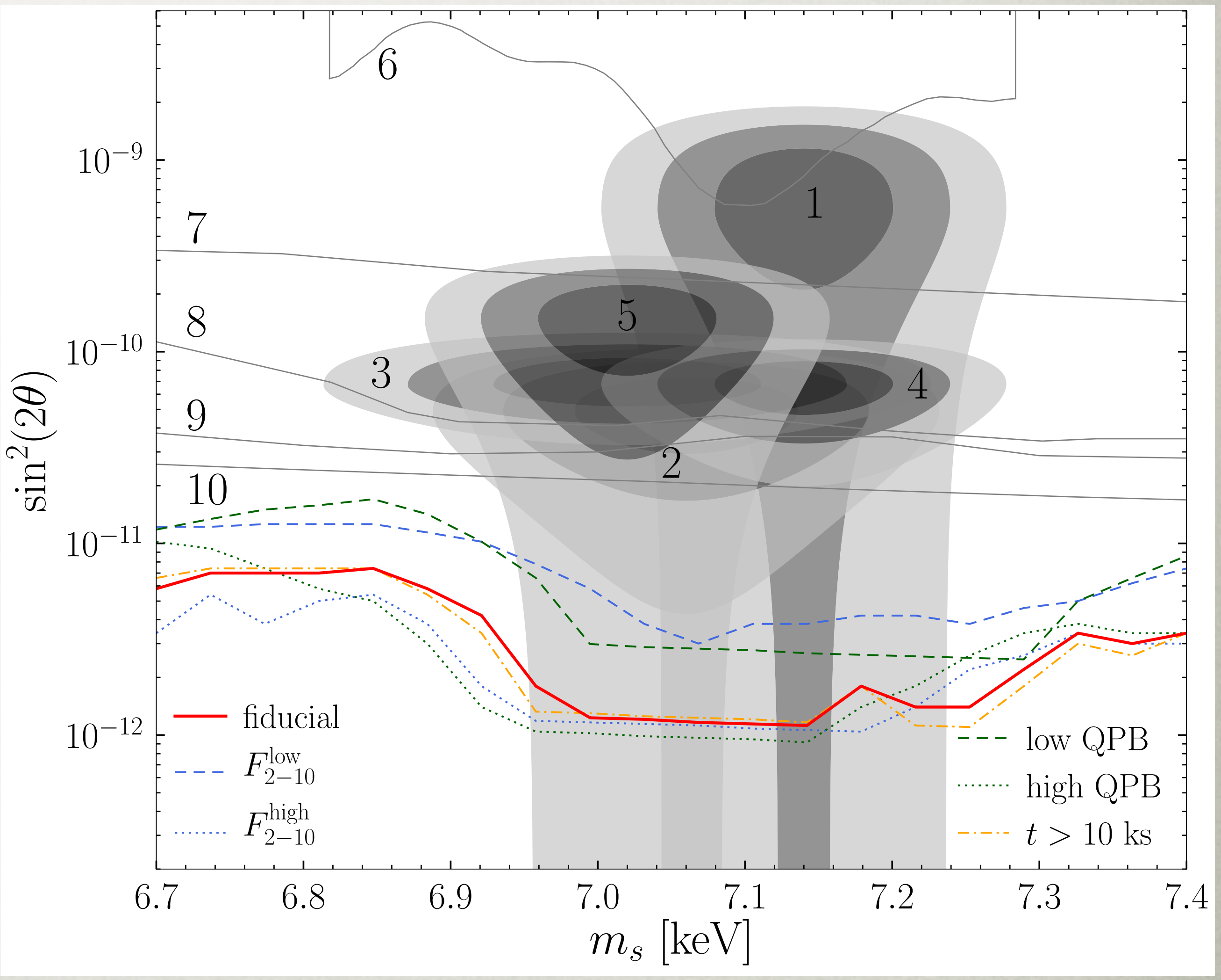
$$\rho_{\rm Burk}(r) = \frac{\rho_0}{(1+r/r_c)(1+(r/r_c)^2)}$$

$$r_c = 9\ {\rm kpc}$$

SYSTEMATIC CROSS CHECKS

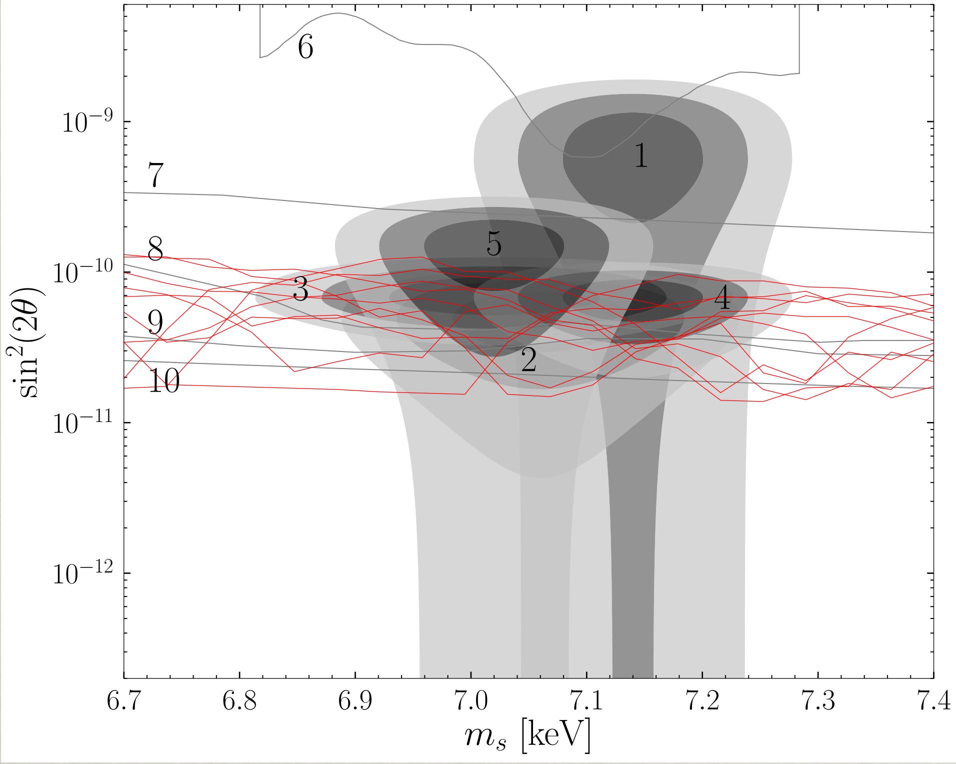
- Is the result strongly dependent upon our cuts?

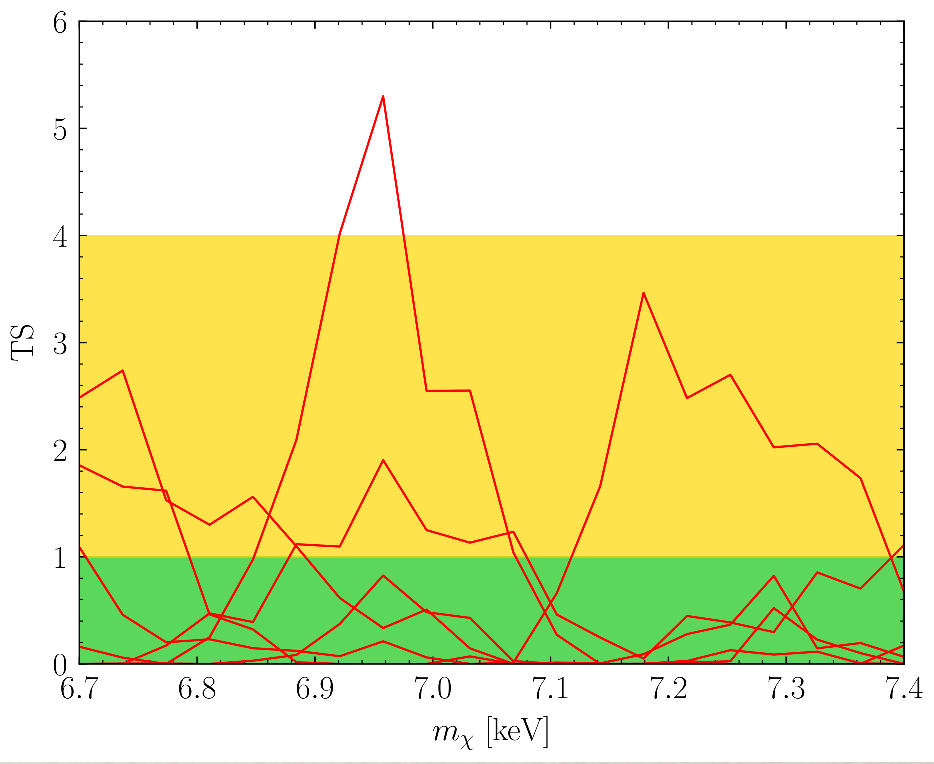




Top 10 Individual Exposures

Observation ID	Camera	Identifier	Exposure [ks]	l [deg]	b [deg]	Target Type
0653550301	PN	S003	63.2	5.1	-6.2	Quiescent Novae
0203750101	PN	S003	33.7	-2.8	-4.9	LMXRB Black Hole
0152750101	PN	S001	30.1	1.6	7.1	Dark Cloud
0203750101	MOS2	S002	43.4	-2.8	-4.9	LMXRB Black Hole
0781760101	PN	S003	46.0	-2.7	-6.1	LMXRB Burster
0761090301	PN	S003	95.2	-8.7	17.0	B2III Star
0206610101	PN	S003	35.4	-2.9	7.0	Dark Cloud
0412601501	MOS2	S002	90.2	-1.4	-17.2	Neutron Star
0727760301	MOS2	S003	67.9	-1.4	-17.2	Neutron Star
0761090301	MOS2	S002	107.4	-8.7	17.0	B2III Star





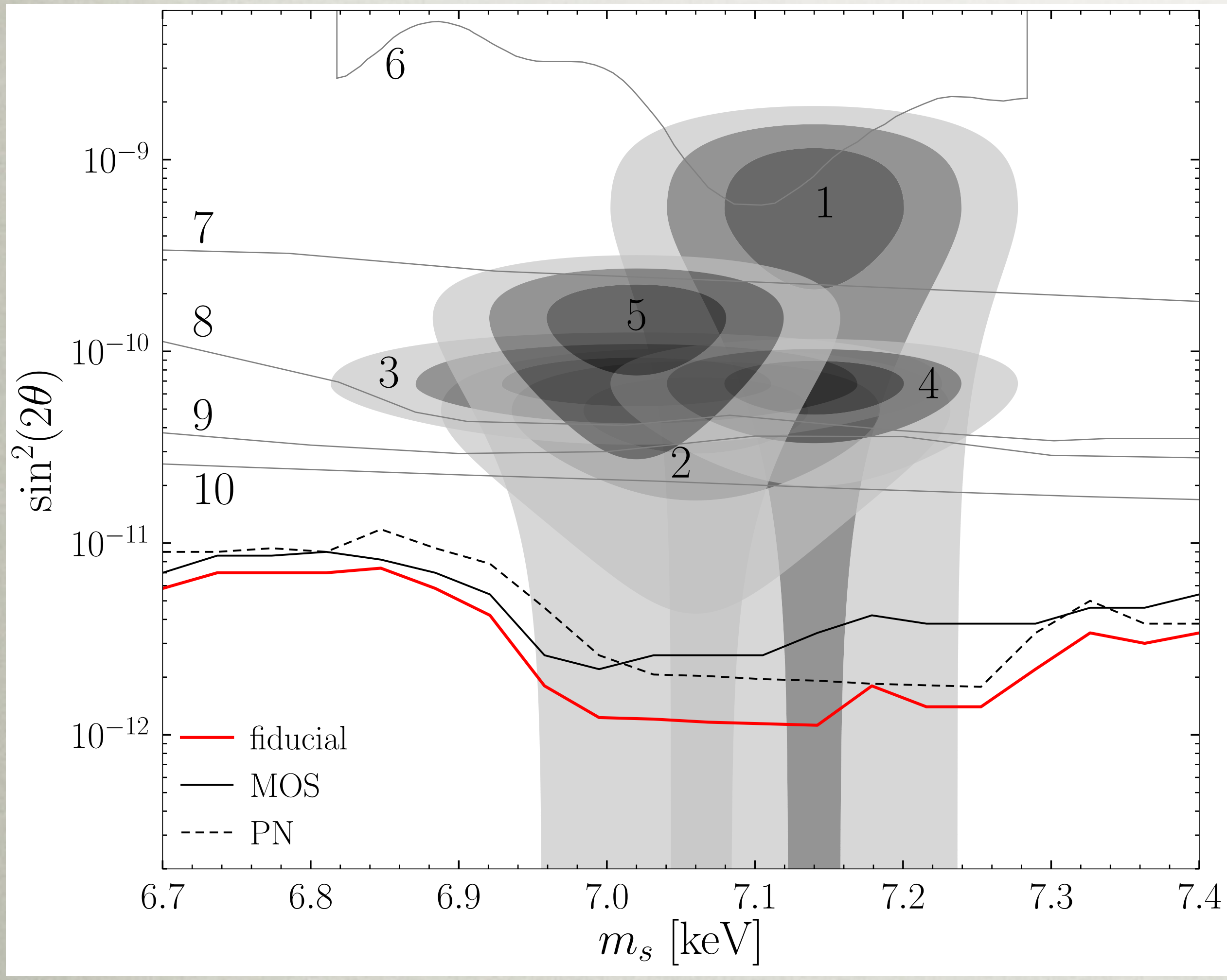
SYSTEMATIC CROSS CHECKS

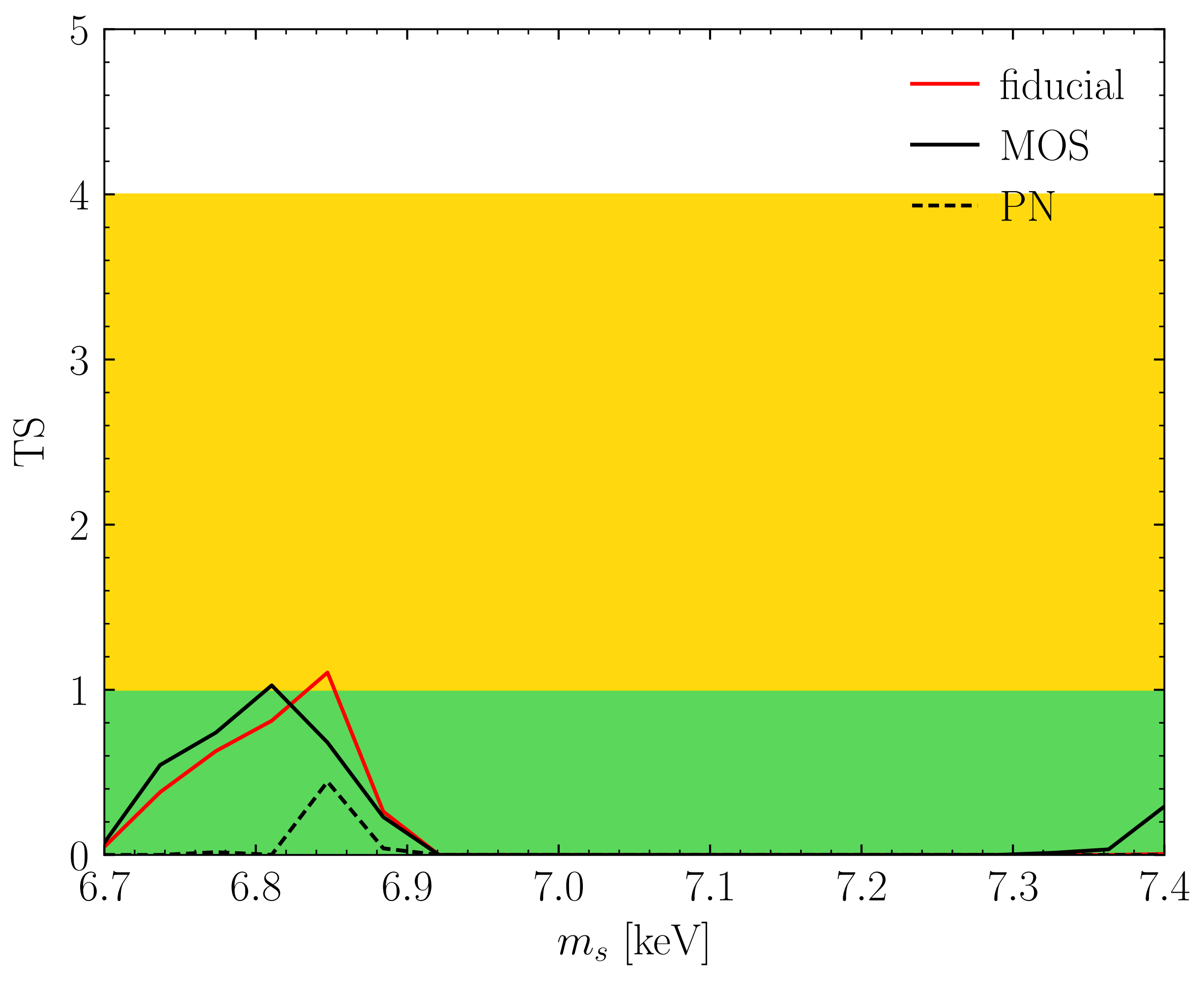
- Parameters of systematic checks

	$r_{\rm min}$ [deg]	$r_{\rm max}$ [deg]	$\lvert b\rvert_{\rm min}$ [deg]	$I_{2-10}^{\rm max}$ [erg/cm^2/s/deg^2]	$F_{\rm QPB}^{\rm max}$ [%]	Exposure [Ms]	other
fiducial	5	45	0	10^{-10}	68	30.6	-
$r \geq 10^\circ$	10	45	0	10^{-10}	68	27.9	-
$r \leq 60^\circ$	5	60	0	10^{-10}	68	56.9	-
$b \geq 1.5^\circ$	5	45	1.5	10^{-10}	68	24.8	-
north	5	45	0	10^{-10}	68	12.5	mask $b < 0^\circ$
south	5	45	0	10^{-10}	68	18.1	mask $b > 0^\circ$
$F_{2-10}^{\rm low}$	5	45	0	5×10^{-11}	68	18.8	-
$F_{2-10}^{\rm high}$	5	45	0	5×10^{-10}	68	35.7	-
low QPB	5	45	0	10^{-10}	16	6.3	-
high QPB	5	45	0	10^{-10}	95	45.6	-
$t > 10$ ks	5	45	0	10^{-10}	68	28.2	require $t^e > 10$ ks

SYSTEMATIC CROSS CHECKS

- Results for the MOS or PN detectors individually

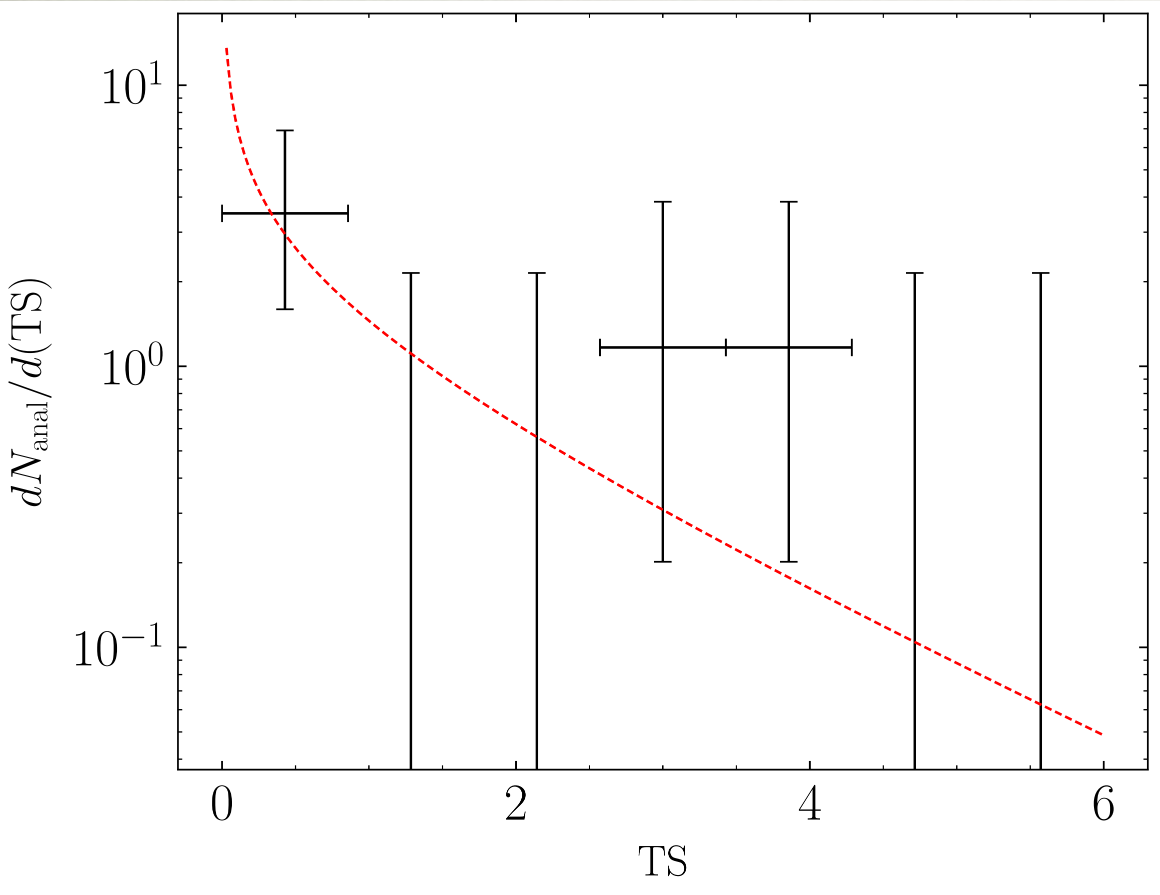


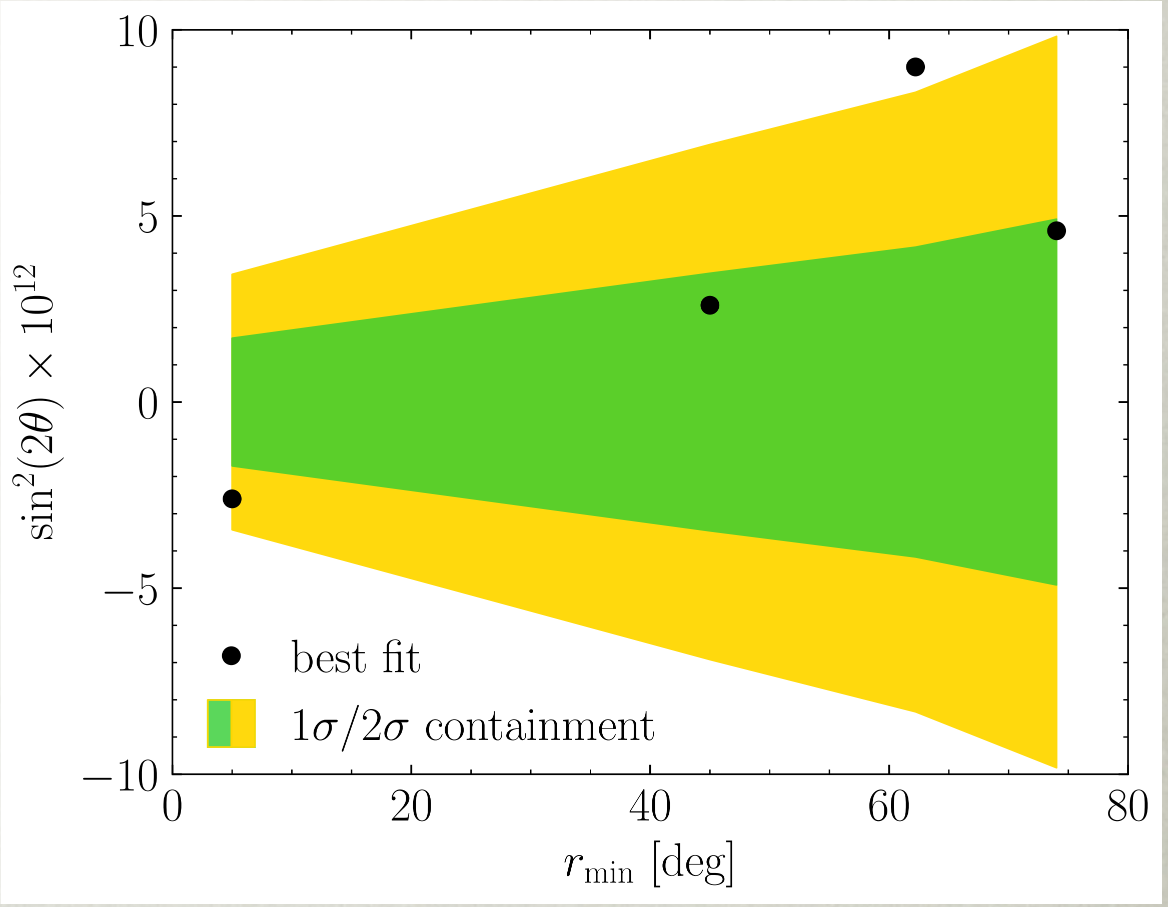


SYSTEMATIC CROSS CHECKS

- Repeat the analysis in 4 equal exposure regions

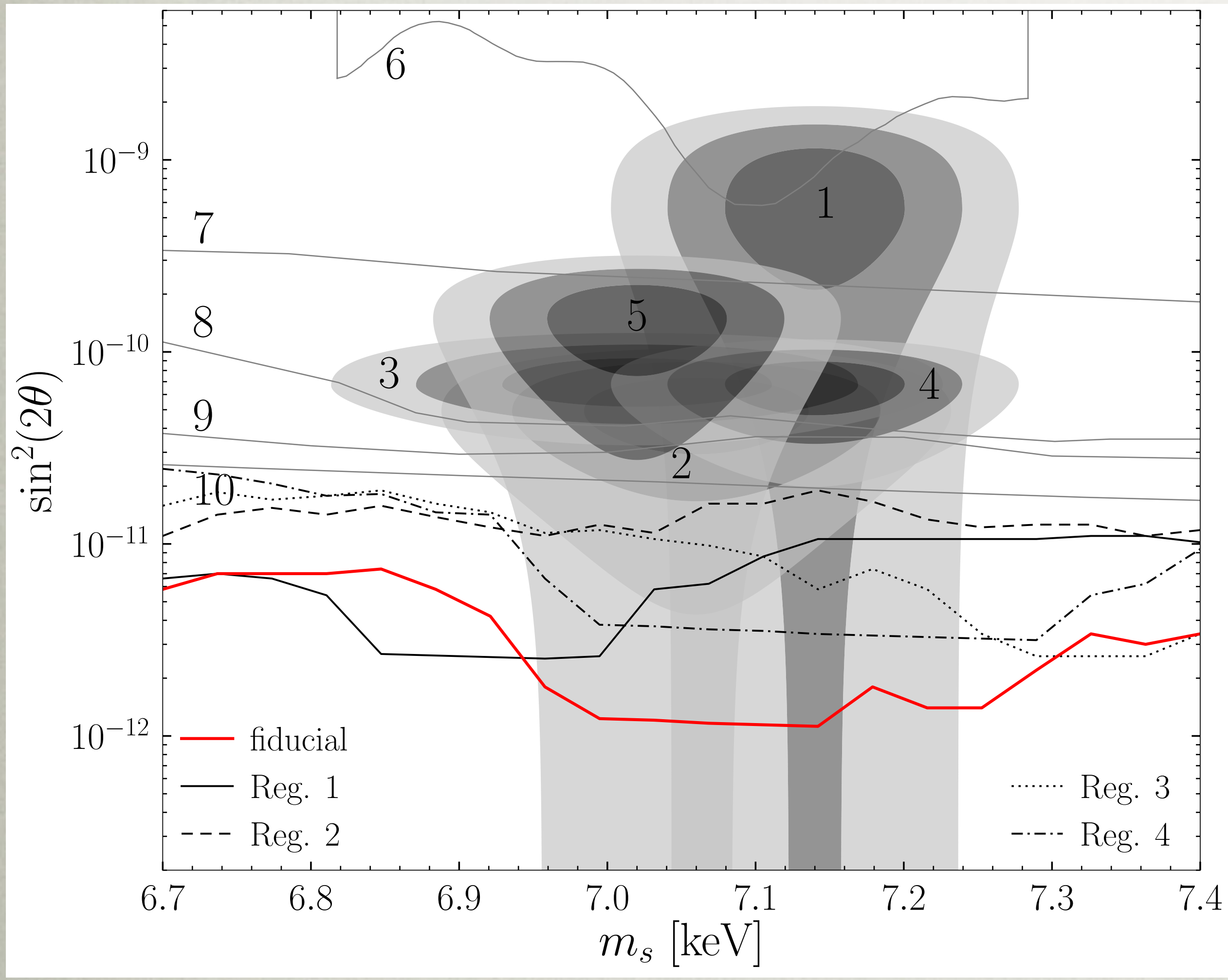
$$5^\circ < \psi < 45^\circ;\ 45^\circ < \psi < 62.2^\circ;\ 62.2^\circ < \psi < 74^\circ;\ 74^\circ < \psi < 83.4^\circ$$

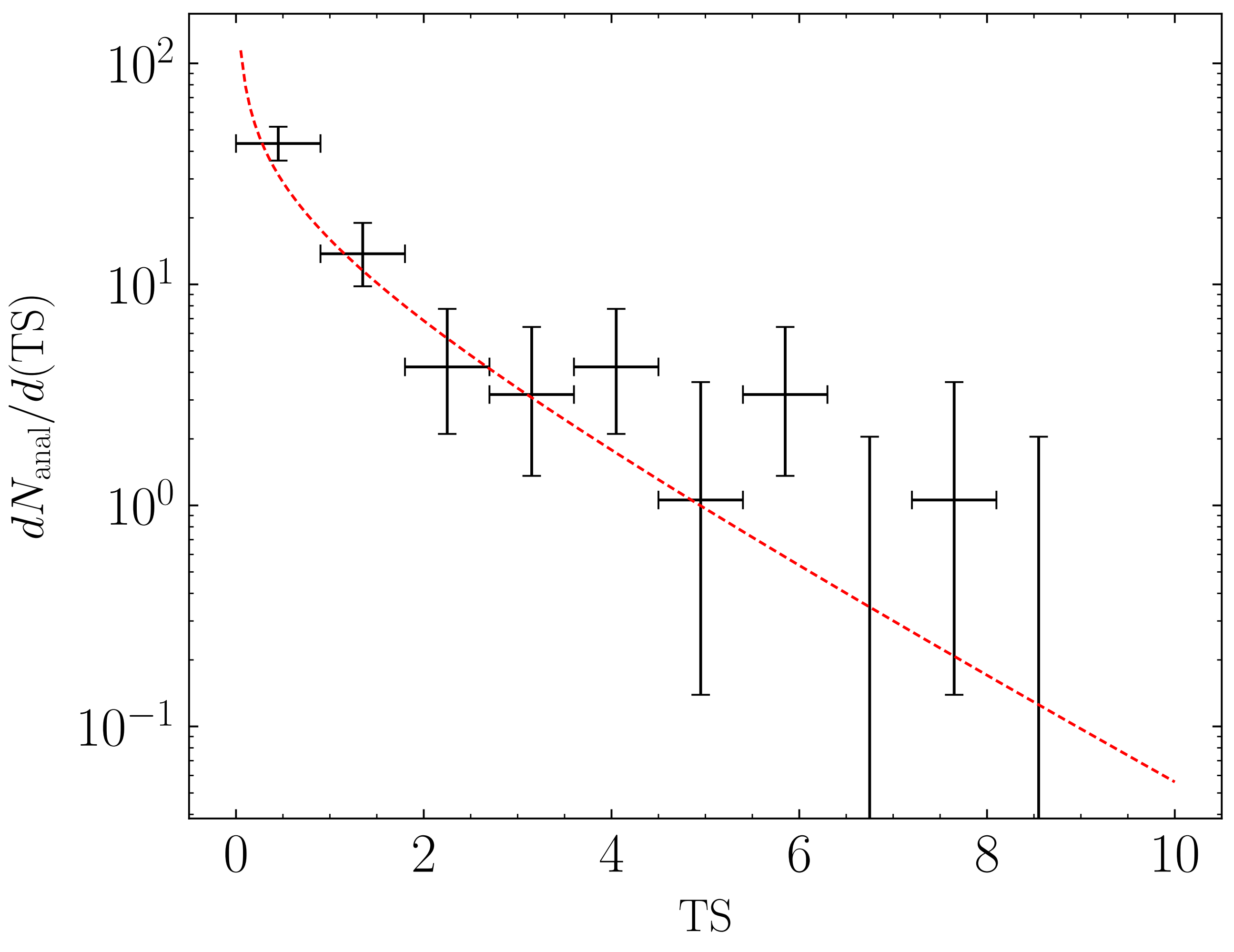




SYSTEMATIC CROSS CHECKS

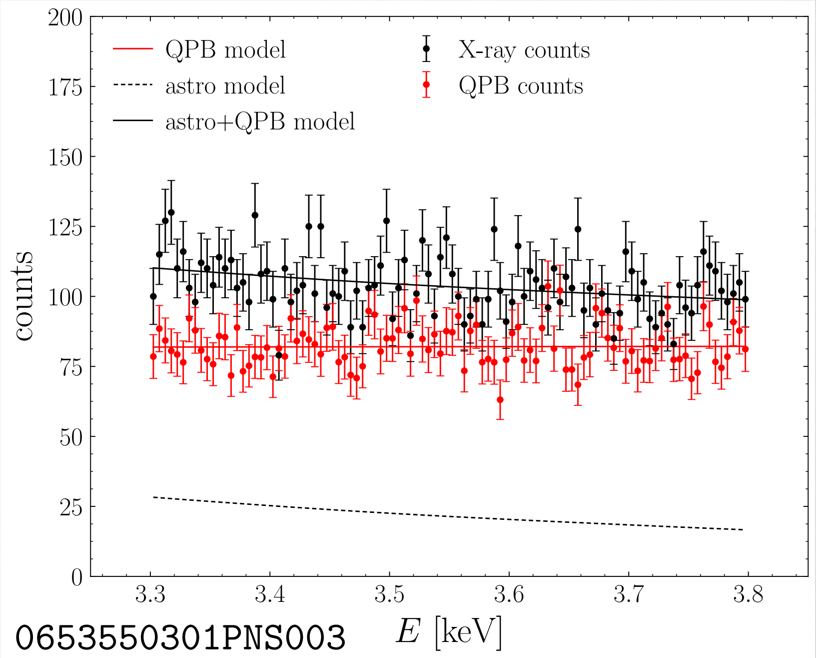
- Repeat the analysis in 45 equal exposure regions from 5º to 90º

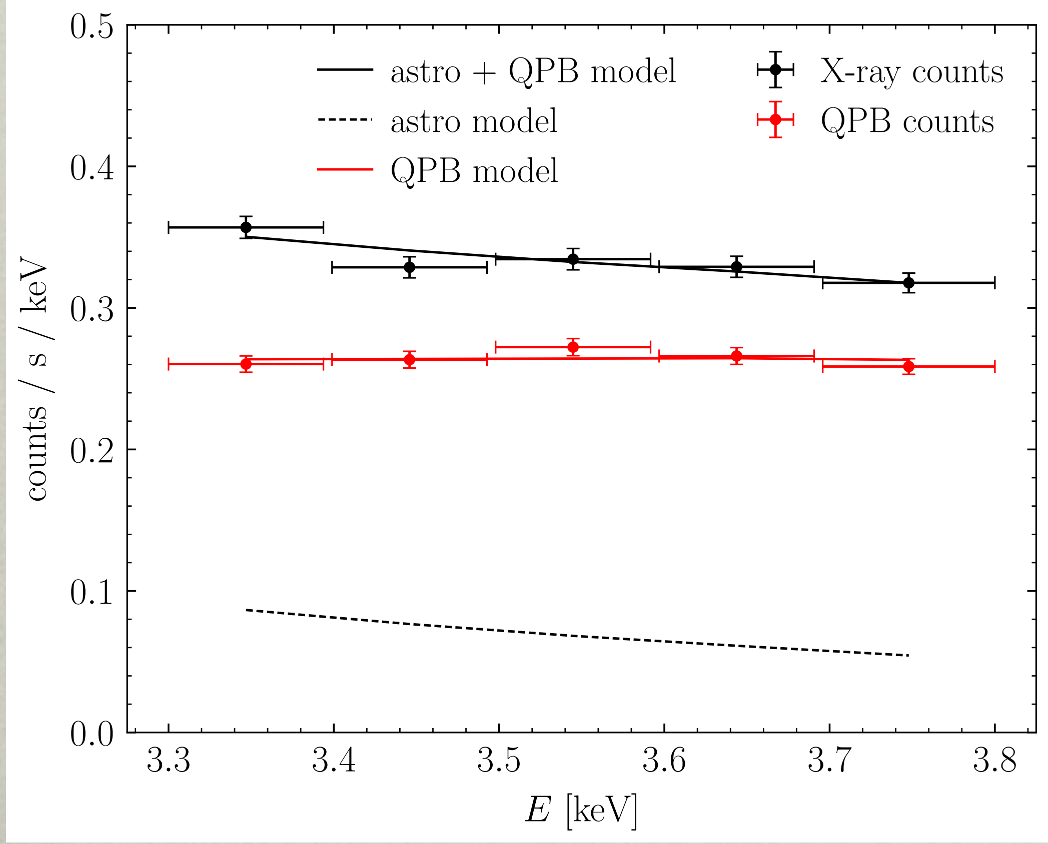


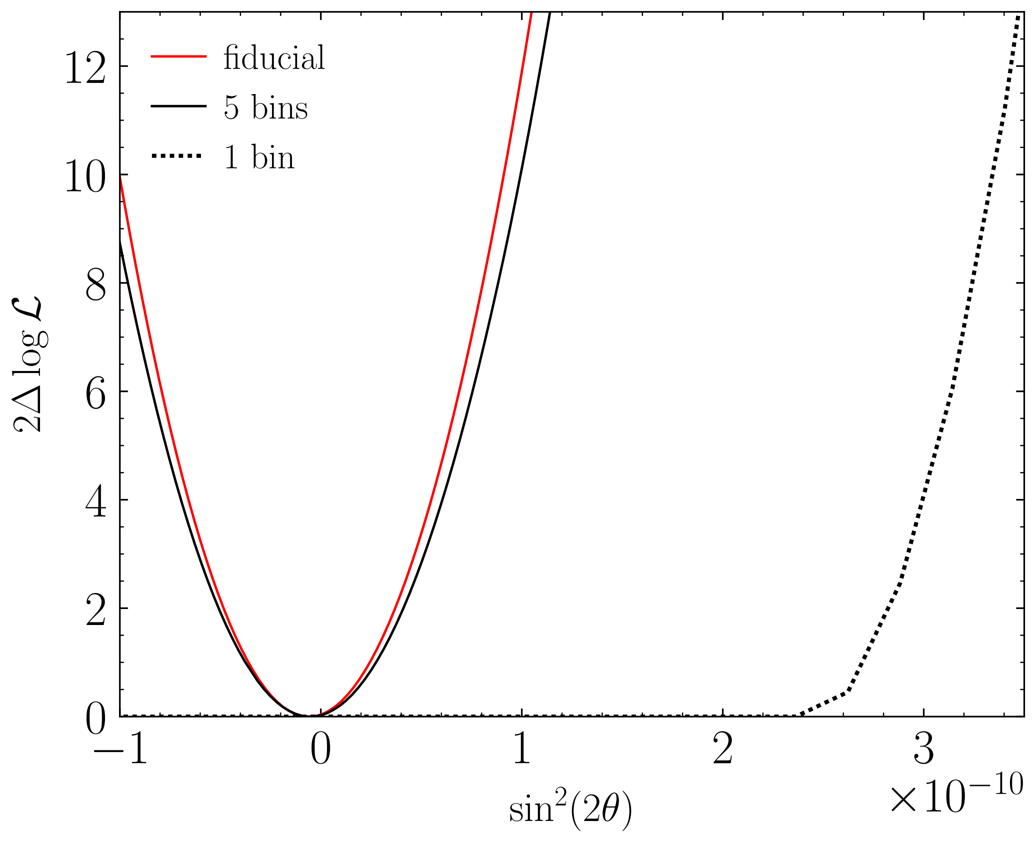


SYSTEMATIC CROSS CHECKS

- Modifying the binning







The Debate Continues?

Surface brightness profile of the 3.5 keV line in the Milky Way halo

A. Boyarsky,[1] D. Iakubovskyi,[2,3] O. Ruchayskiy,[2] and D. Savchenko[3]

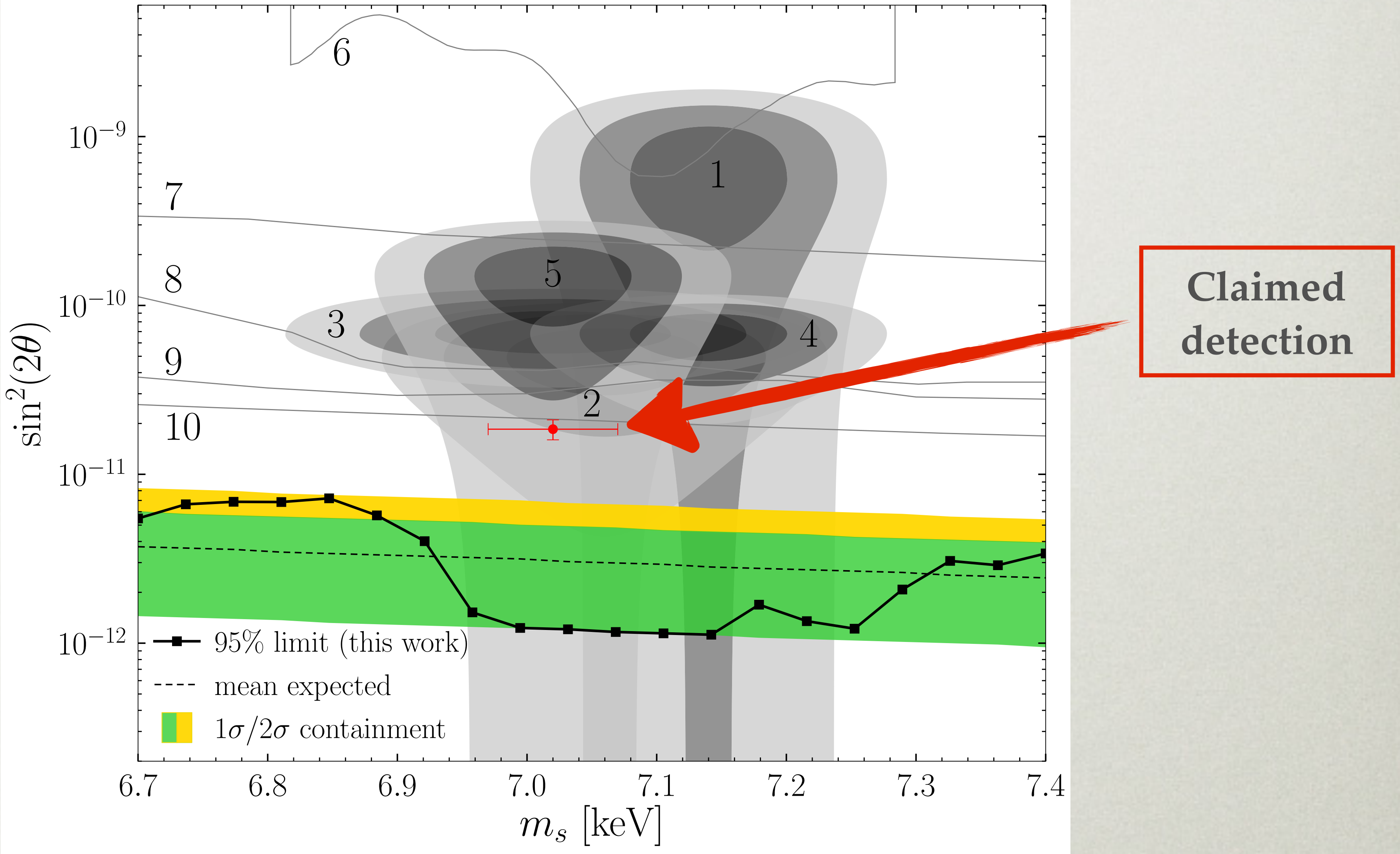
[1]*Lorentz Institute, Leiden University, Niels Bohrweg 2, Leiden, NL-2333 CA, The Netherlands*
[2]*Discovery Center, Niels Bohr Institute, Blegdamsvej 17, Copenhagen, Denmark*
[3]*Bogolyubov Institute of Theoretical Physics, Metrologichna Str. 14-b, 03143, Kyiv, Ukraine*

We report a detection of 3.5 keV line in the Milky Way in 5 regions offset from the Galactic Center by distances from 10' to 35 degrees. We build an angular profile of this line and compare it with profiles of several astrophysical lines detected in the same observations. We compare our results with other detections and bounds previously obtained using observations of the Milky Way.

[1812.10488]

THE DEBATE CONTINUES?

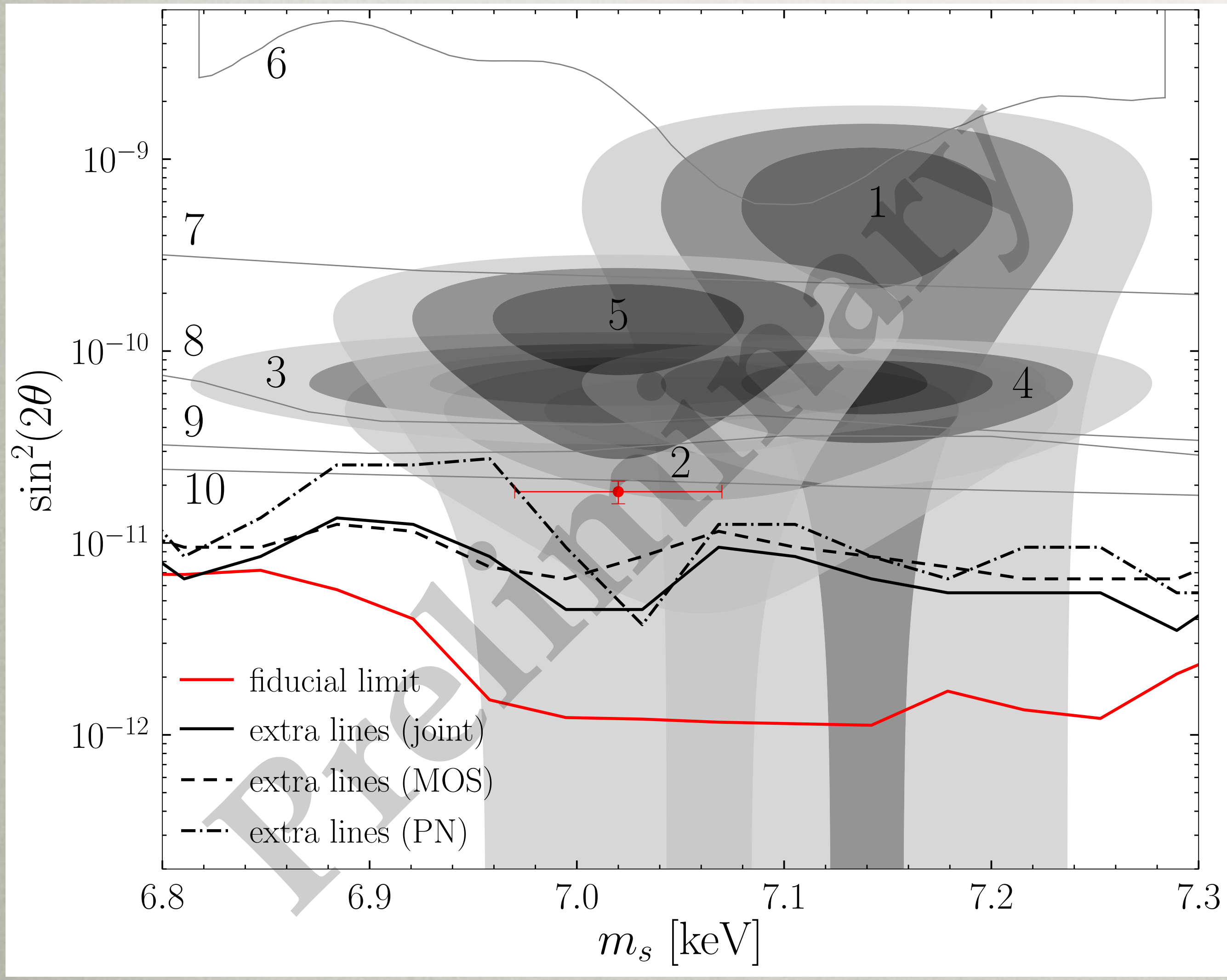
- 9 days after our paper [Boyarsky+ 1812.10488] appeared, claiming discovery of a "consistent" line from the Milky Way ambient halo

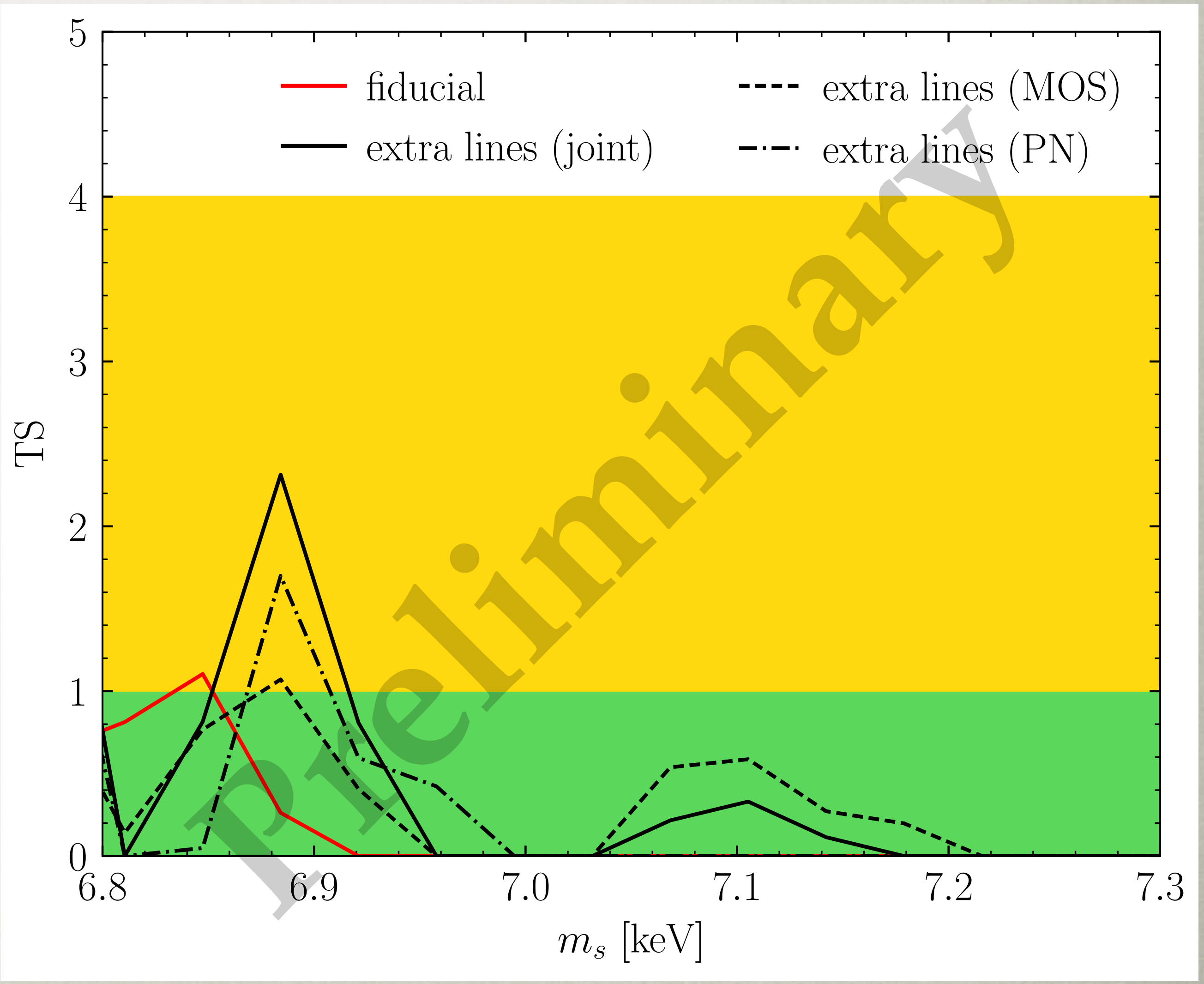


- This is using some of the same data as our analysis
- Working with these authors to sort out exact disagreement

THE DEBATE CONTINUES?

- [Boyarsky+] model two additional instrumental lines:
  - 3.31 and 3.69 keV
- These weaken our limit due to degeneracy with the signal
- But even this does not significantly change our story





THE DEBATE CONTINUES?

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