Dark Matter Signals at keV & GeV

CETUP 2023

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Discovery of New Physics: Massive Neutrinos

Neutrino Mass Generation: An Original Hidden Sector Theory

- Simplest models of neutrino mass introduce sterile neutrinos that generate small active neutrino mass scales from very massive sterile neutrinos (Seesaw models)

- Phenomenological Insertion of Majorana & Dirac Mass Terms:

$$\mathcal{L} \supset -y_{\alpha i} L_\alpha N_i H - \frac{1}{2} M_{ij} N_i N_j + H.c.$$

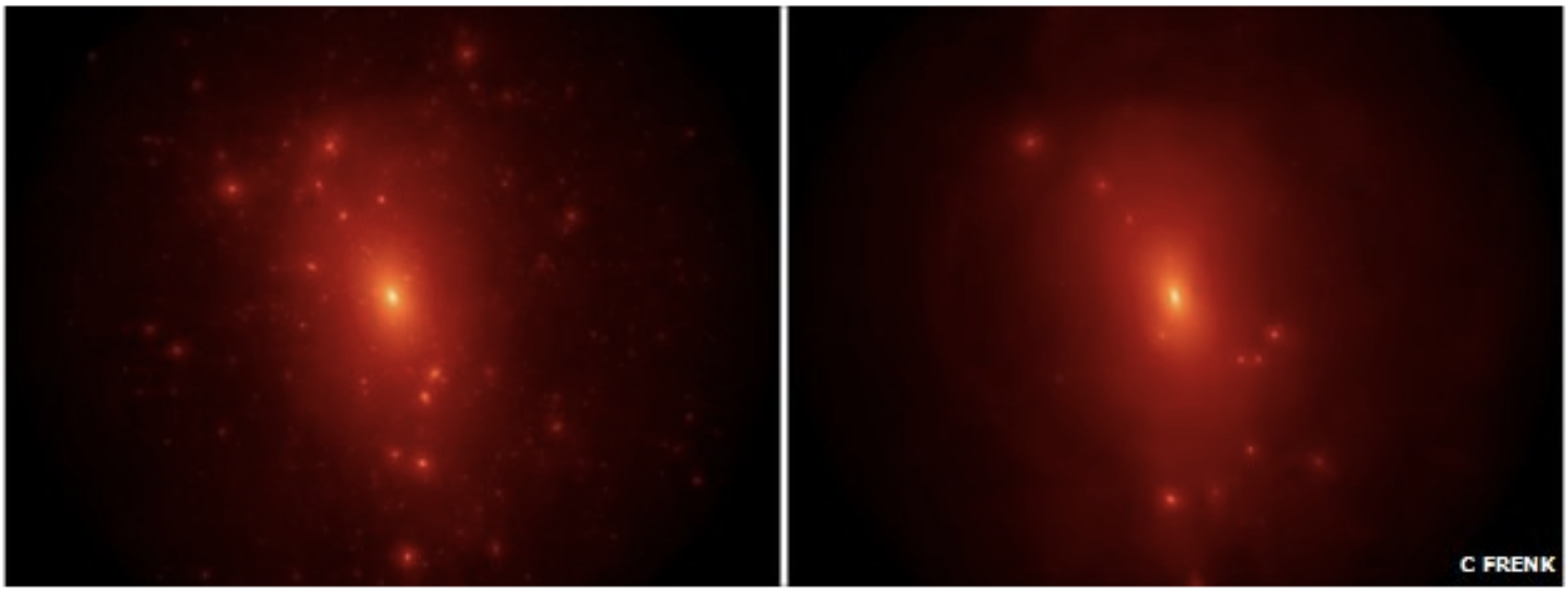
(e.g. νSM de Gouvêa 2005; νMSM Asaka et al 2005; L_e-L_μ-L_τ Lindner+ 2010)

- Two massive (≳100 GeV) sterile neutrinos are required by atmospheric and solar neutrino mass scales. *Only hidden sector model with evidence for its existence!*

- 3rd sterile neutrino has complete freedom. In simplest formulations, since lowest mass light ν is unbounded from below, so is the mixing of the lightest sterile neutrinos with the active ν.

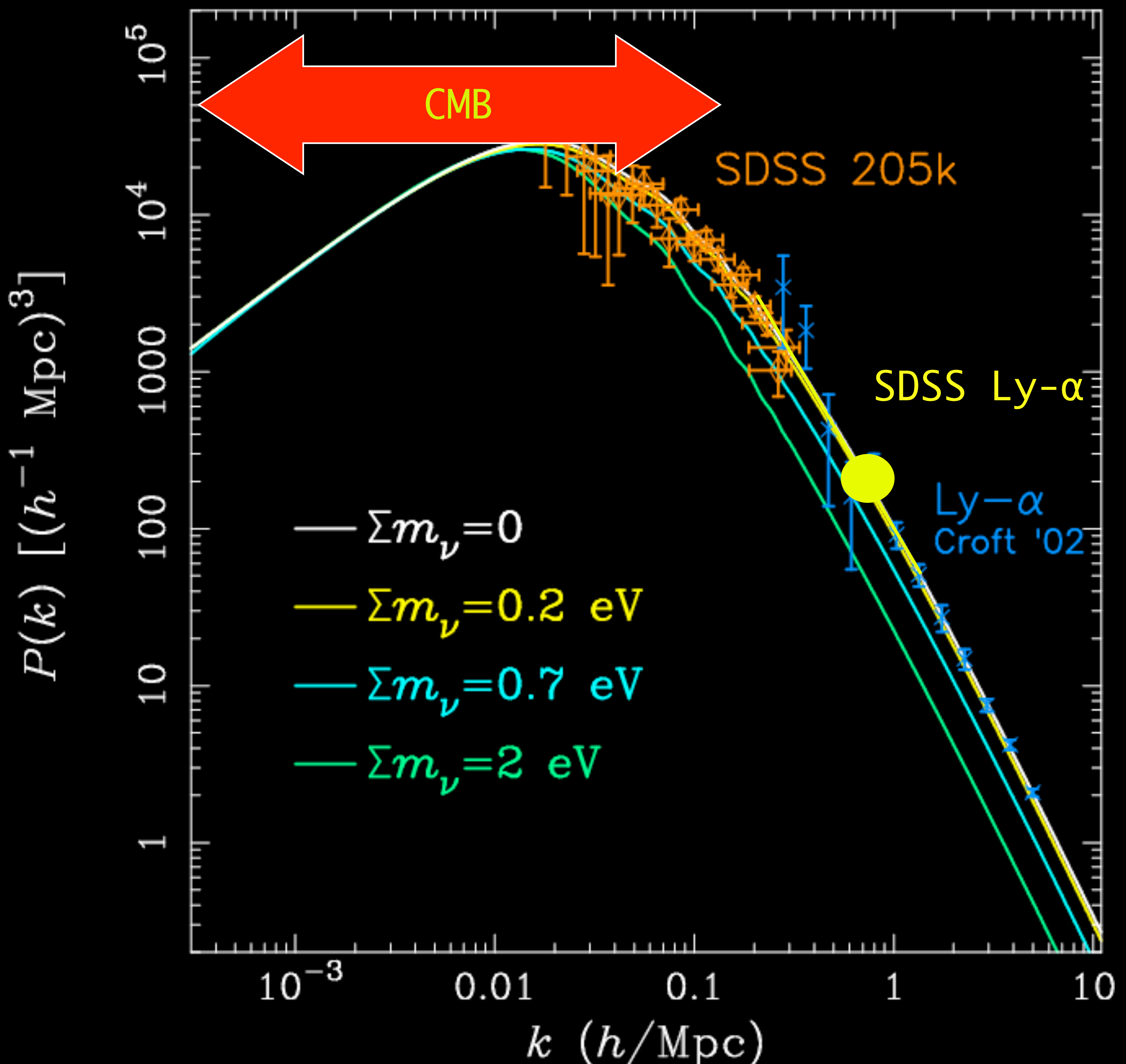
$$\theta \sim \sqrt{\frac{m_\alpha}{M}}$$

How much small scale structure is there?



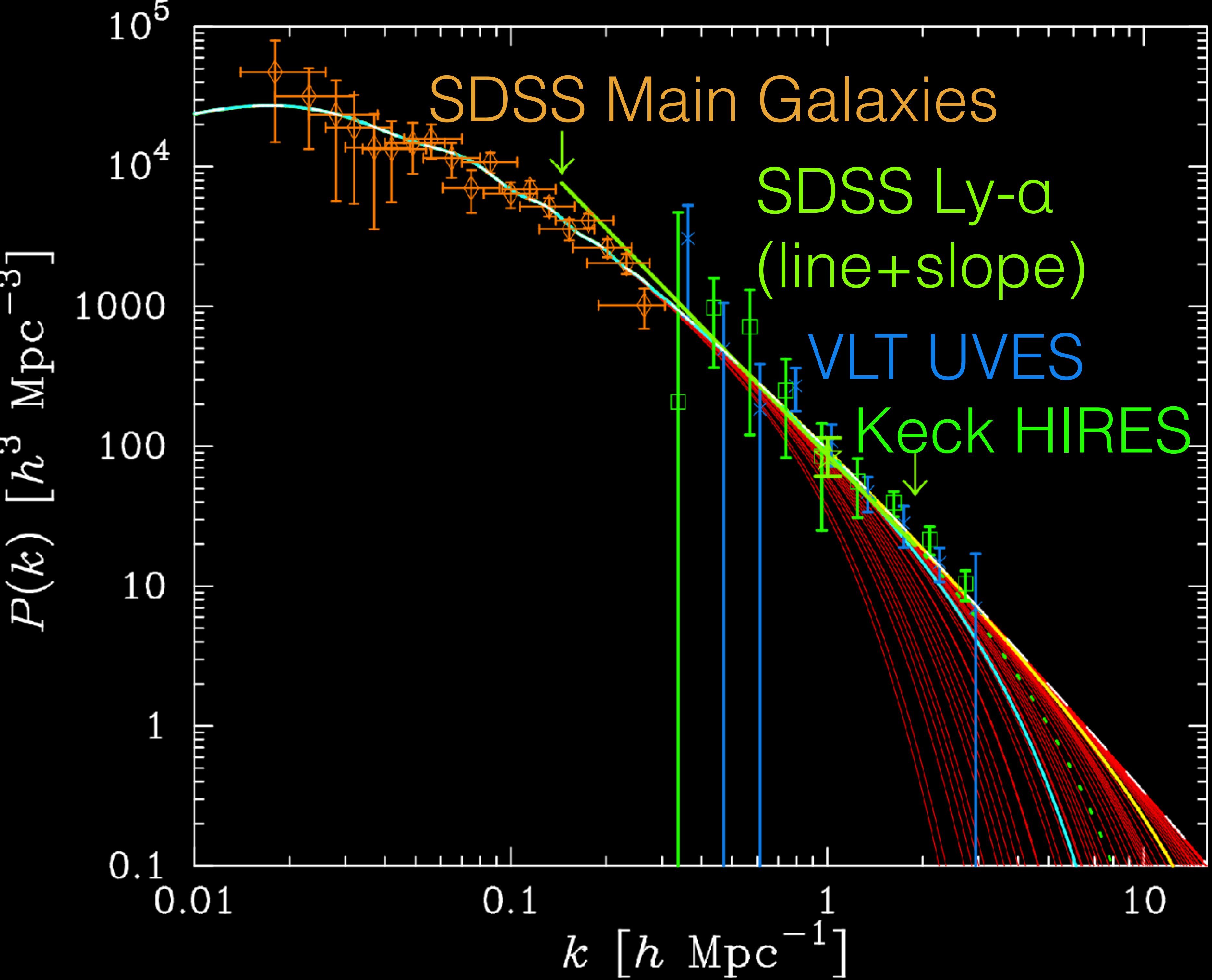
Dwarf galaxies around the Milky Way are less dense than they should be if they held cold dark matter

Measuring Large Scale Structure $P(k)$



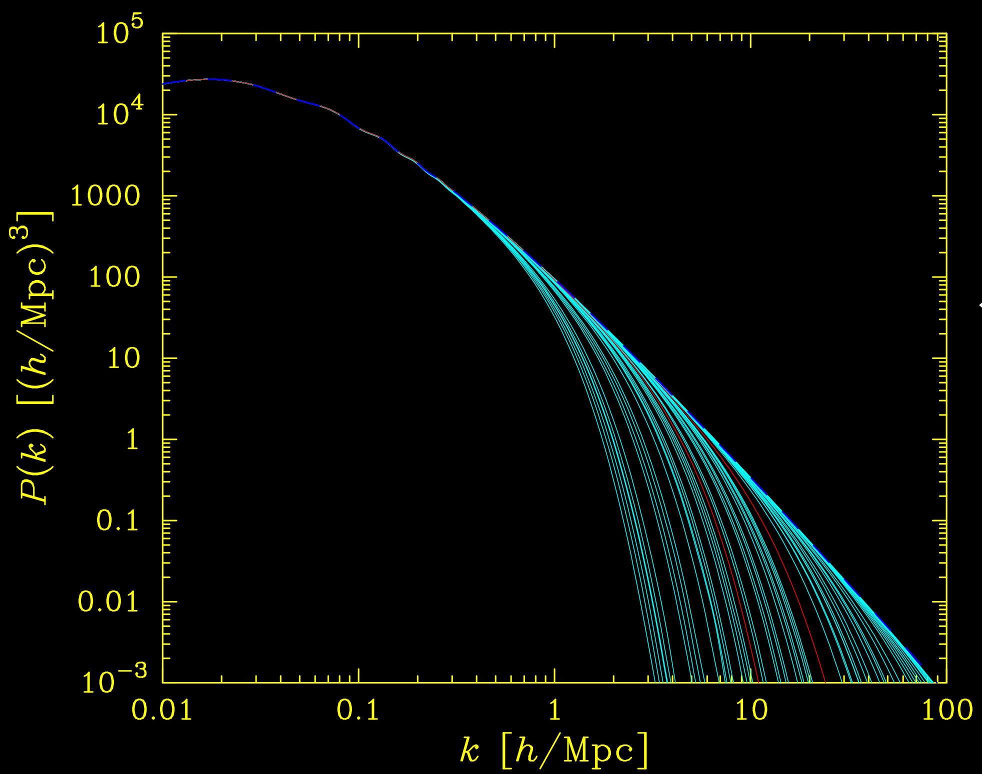
Perturbation Evolution

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



Abazajian astro-ph/0511630

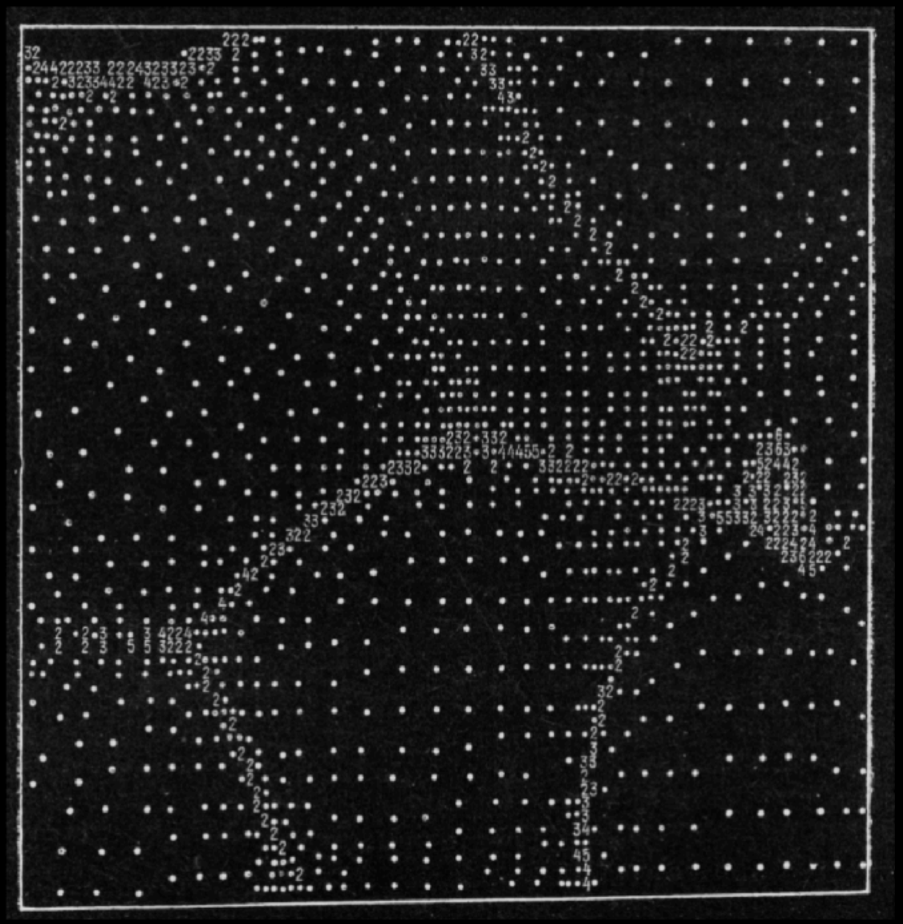
Simulating the Universe's Structure



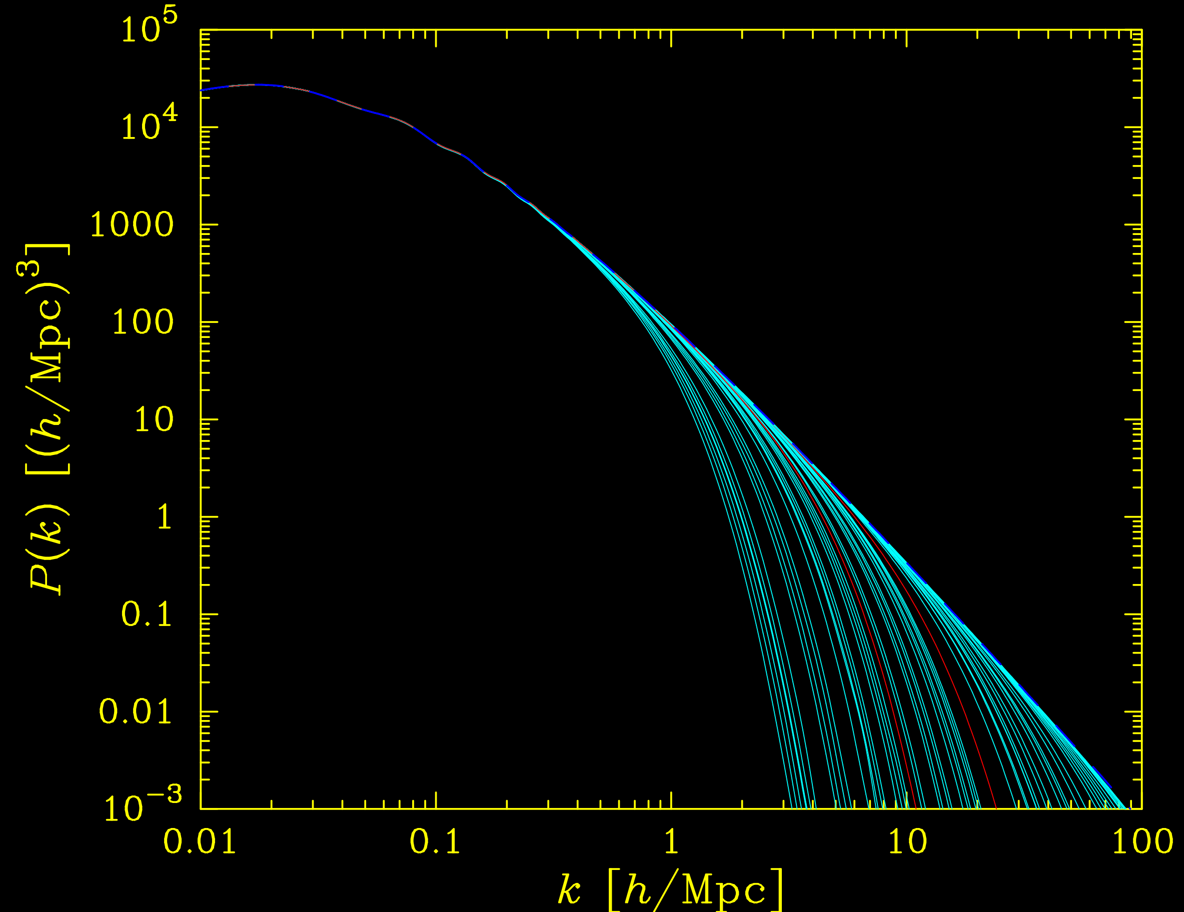
This is a description of the statistical distribution of the density fluctuations in the *linear regime*…

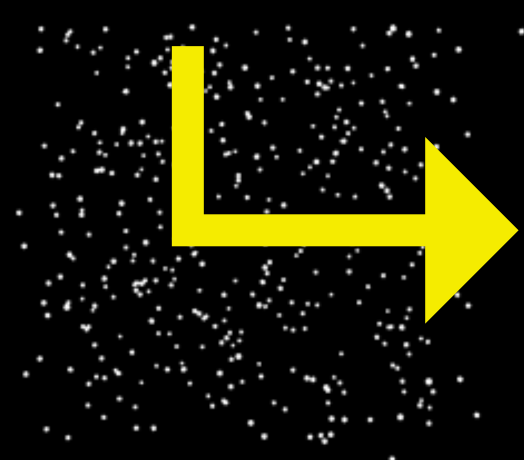
It is realized by giving a "push" to a grid of particles with that statistical distribution…

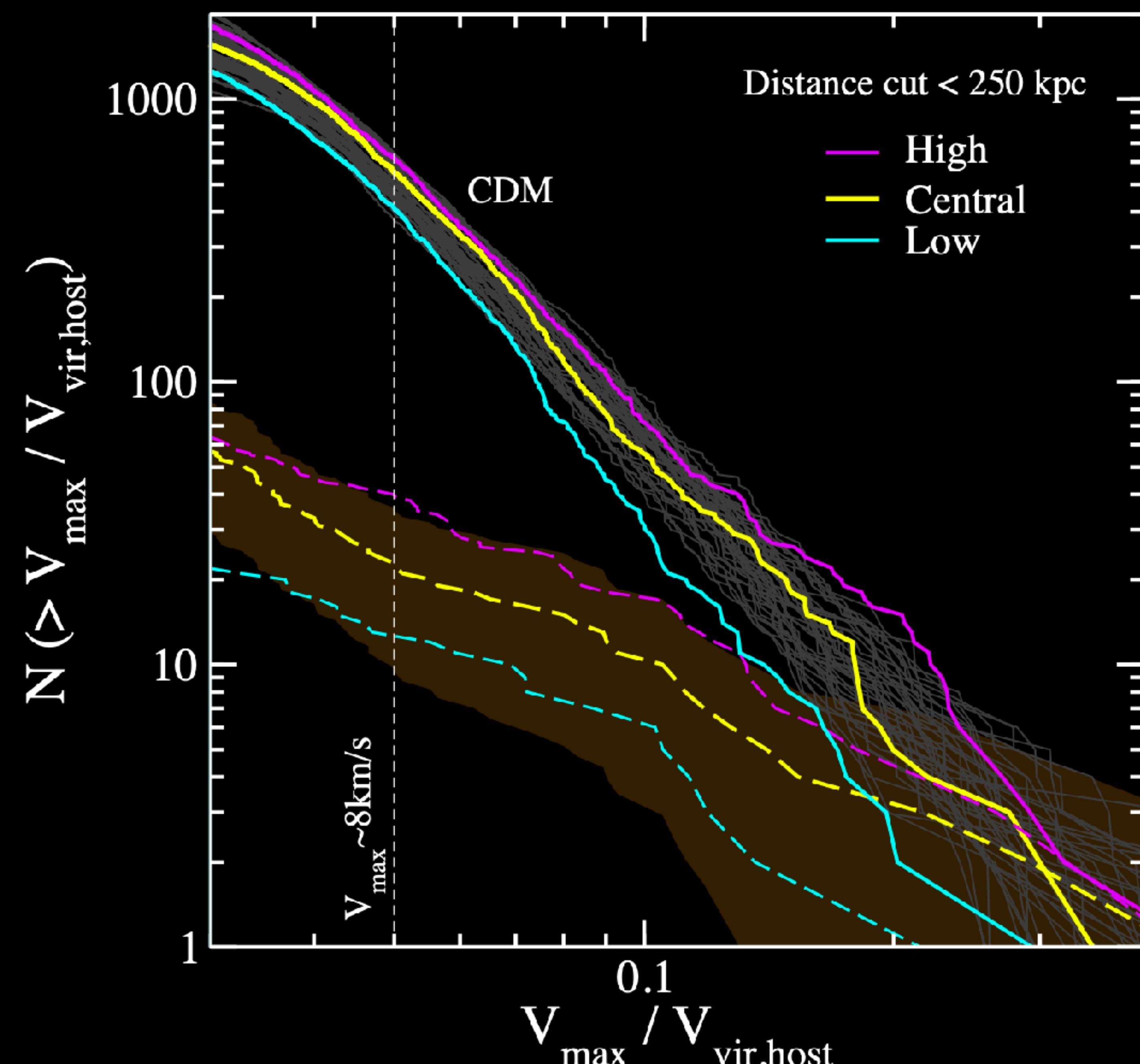
…and then gravity is allowed to do its duty.



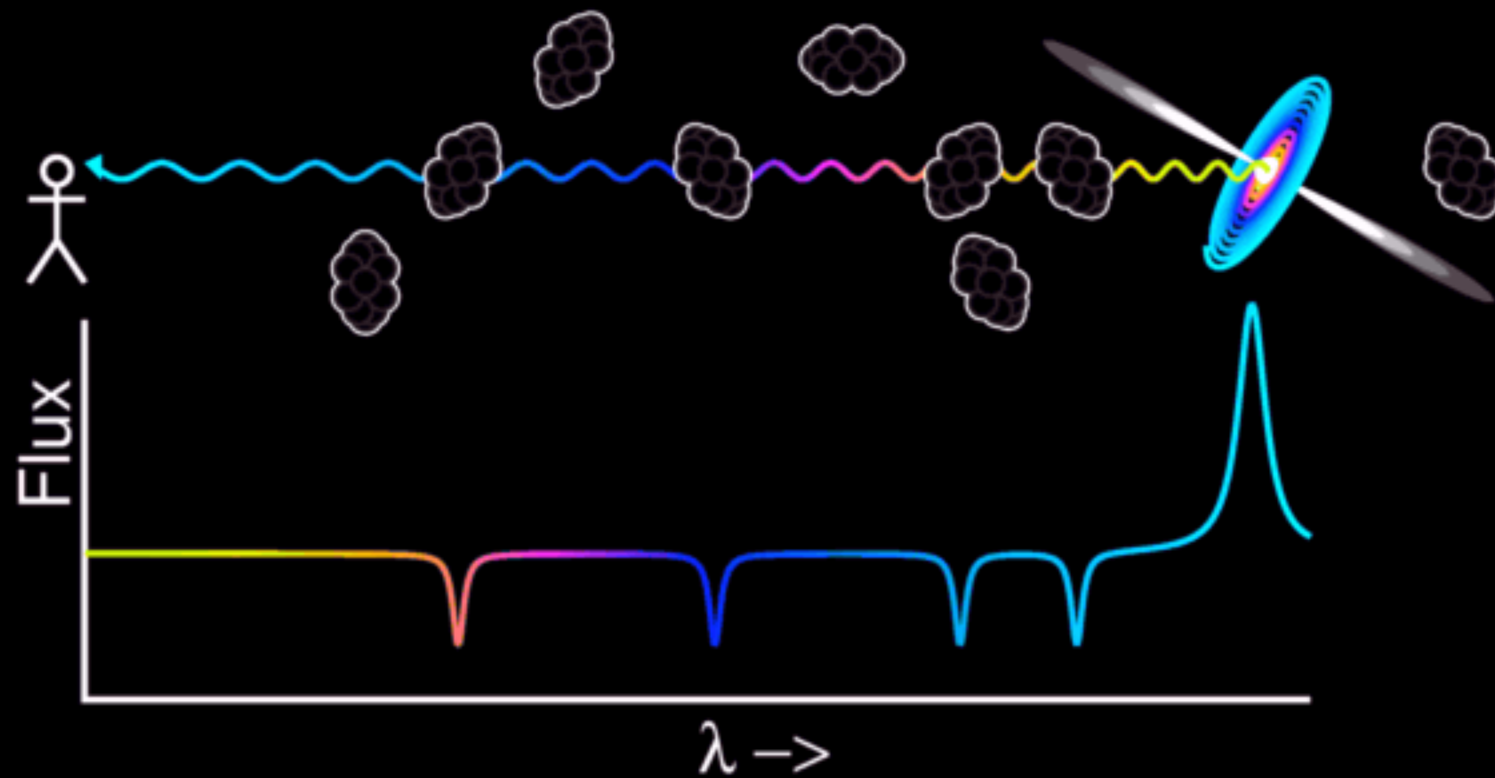
Suppression of small scale power
⇒ Suppression of Small Halos







Lyman-α Forest Constraints on WDM

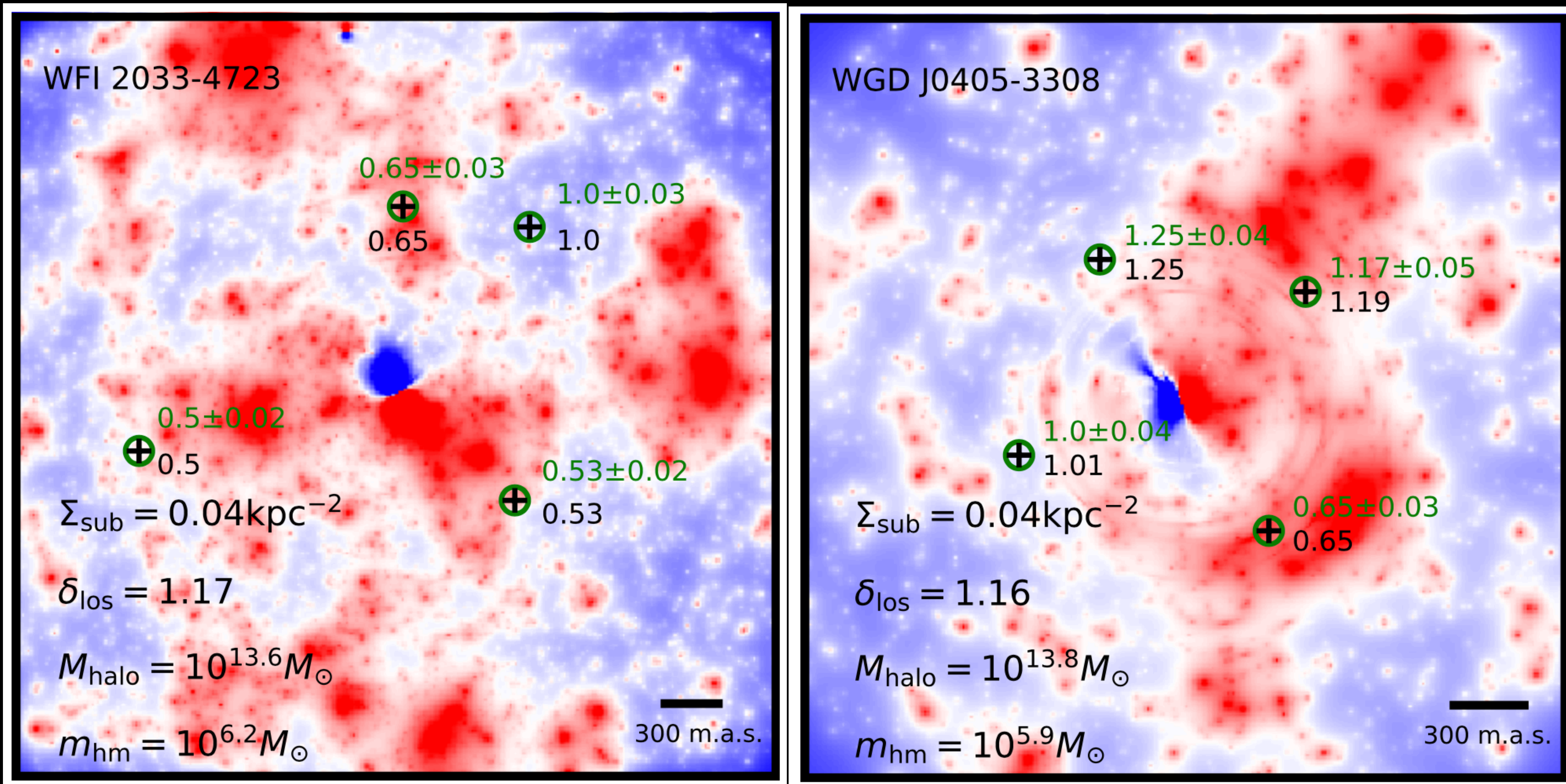


Lyman-α forest:
m_{th} **> 3 keV (WDM)** (95% CL)
$m_{s,DW}$ **> 16 keV**
(Baur et al. 2015)

Milky Way galaxy counts:
m_{th} **> 3 keV (WDM)**
(Horiuchi+ 2013, Cherry & Horiuchi 2017, Nadler+ 2019)

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

Lensing Constraints on WDM



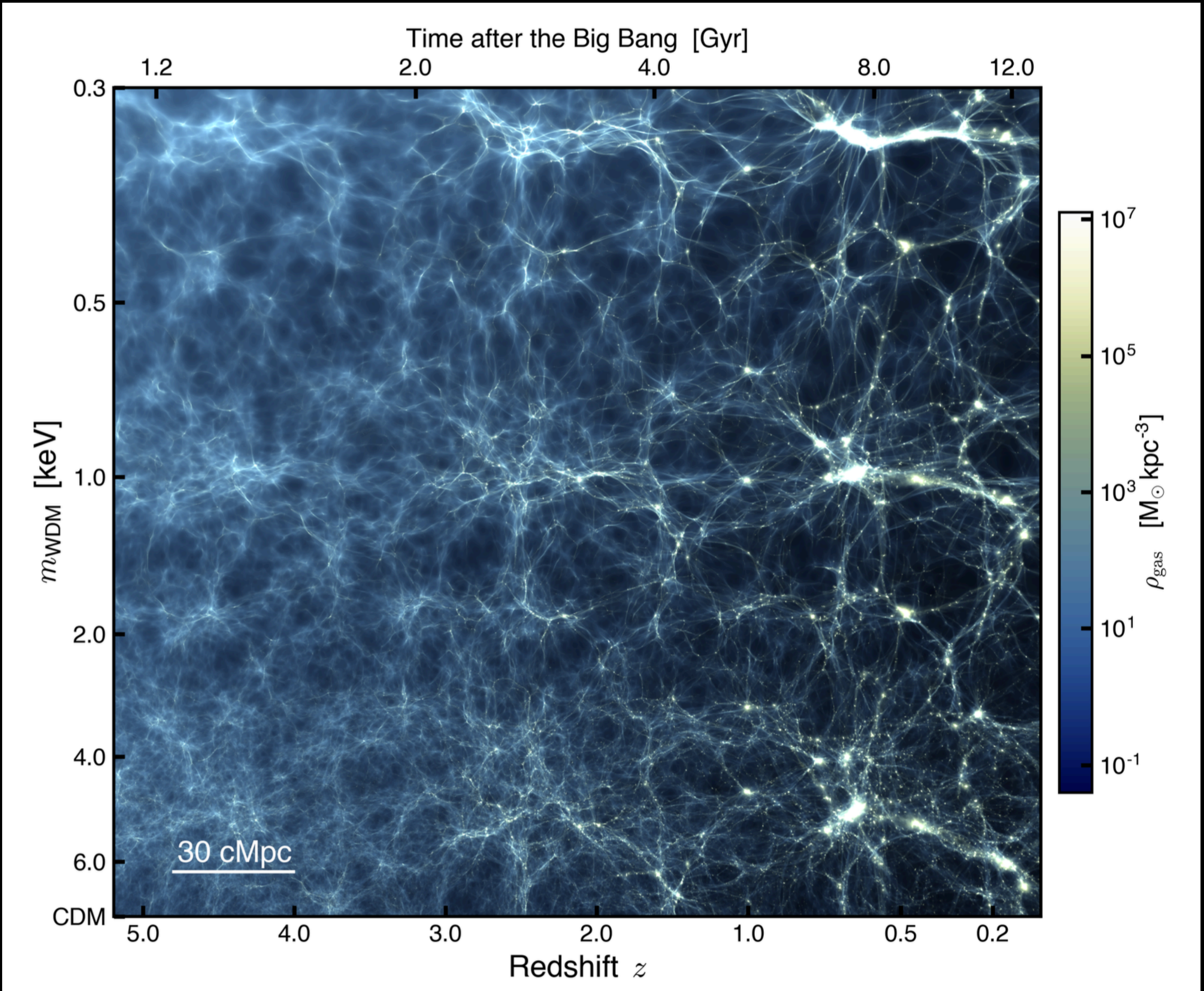
Lensing substructure constraints push:

m_{th} > 5.3 keV ($m_{s,DW}$ > 41 keV) (Gilman+ 2019)

combined with galaxy counts: **m_{th} > 9.7 keV** (Nadler+ 2021)

Simulation Resolution to Match Ly-α Observations

Villasenor+ 2209.14220



Simulation Resolution to Match Ly-α Observations

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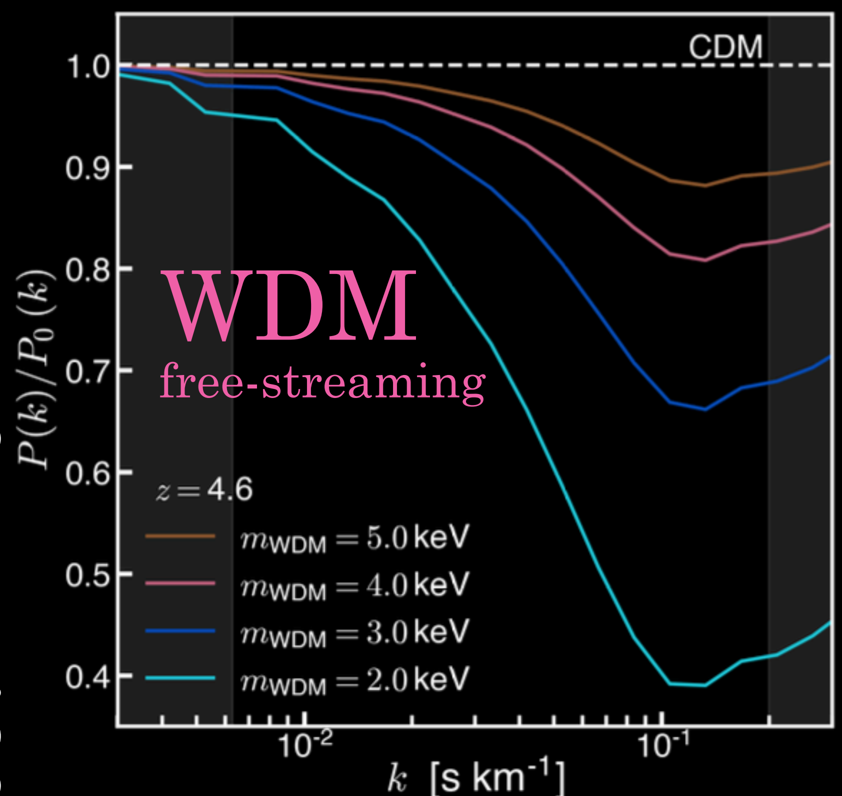
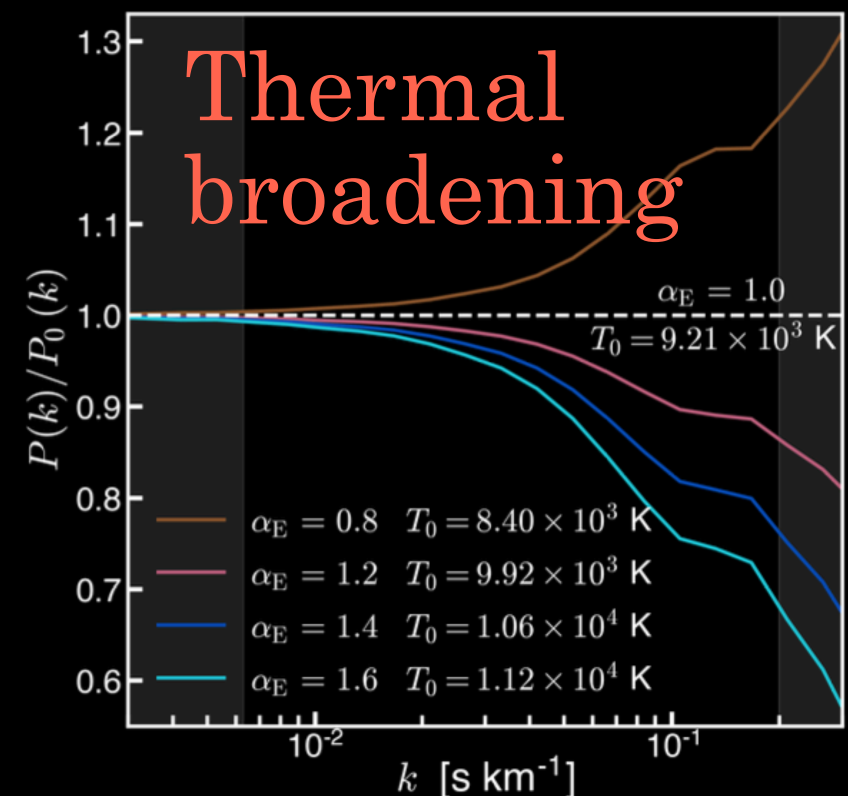
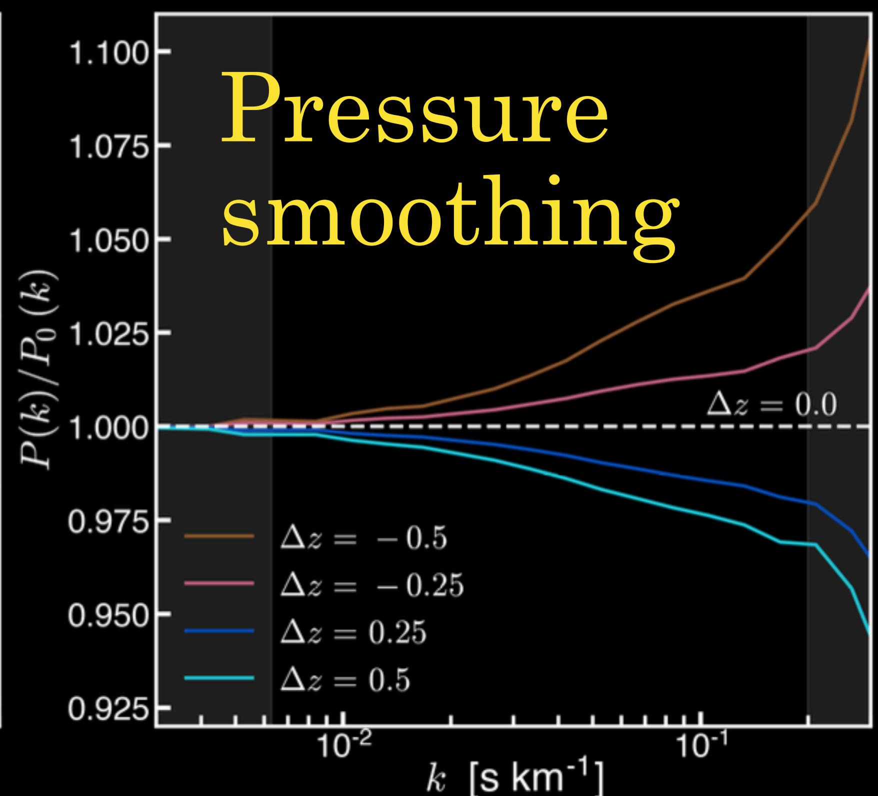






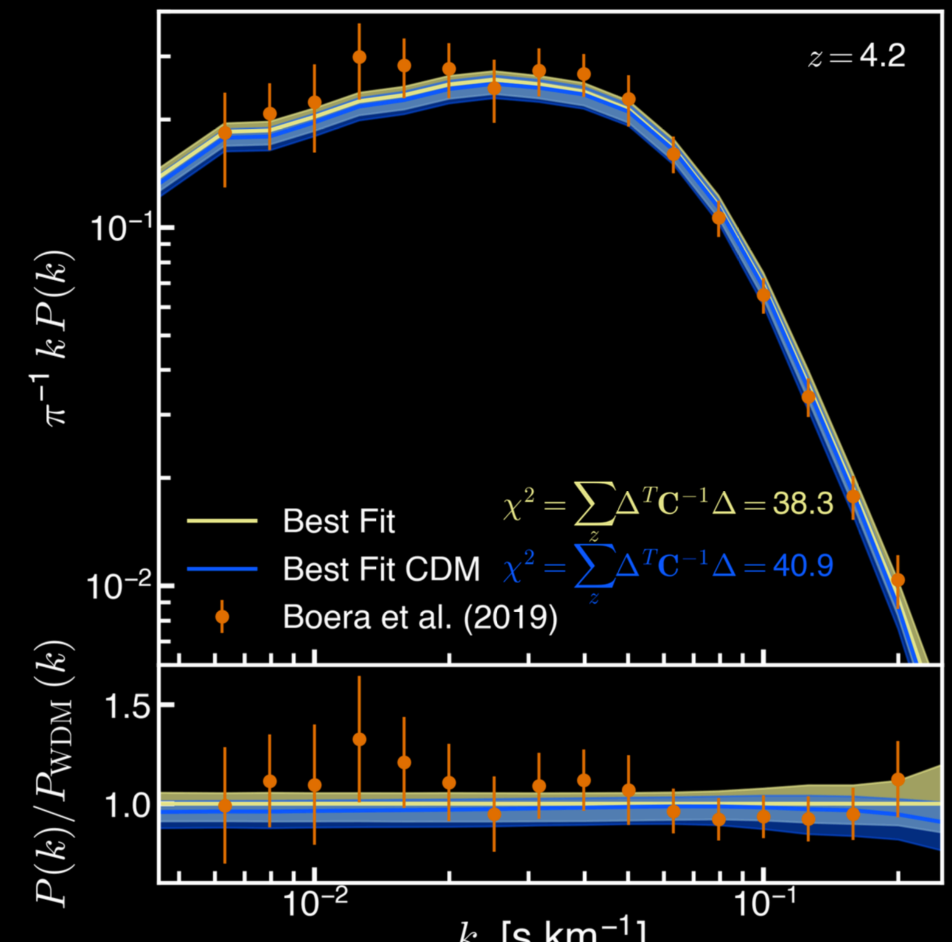
1080 2×1024³ particle sims

"We find a weak (3σ) preference for WDM over ΛCDM"

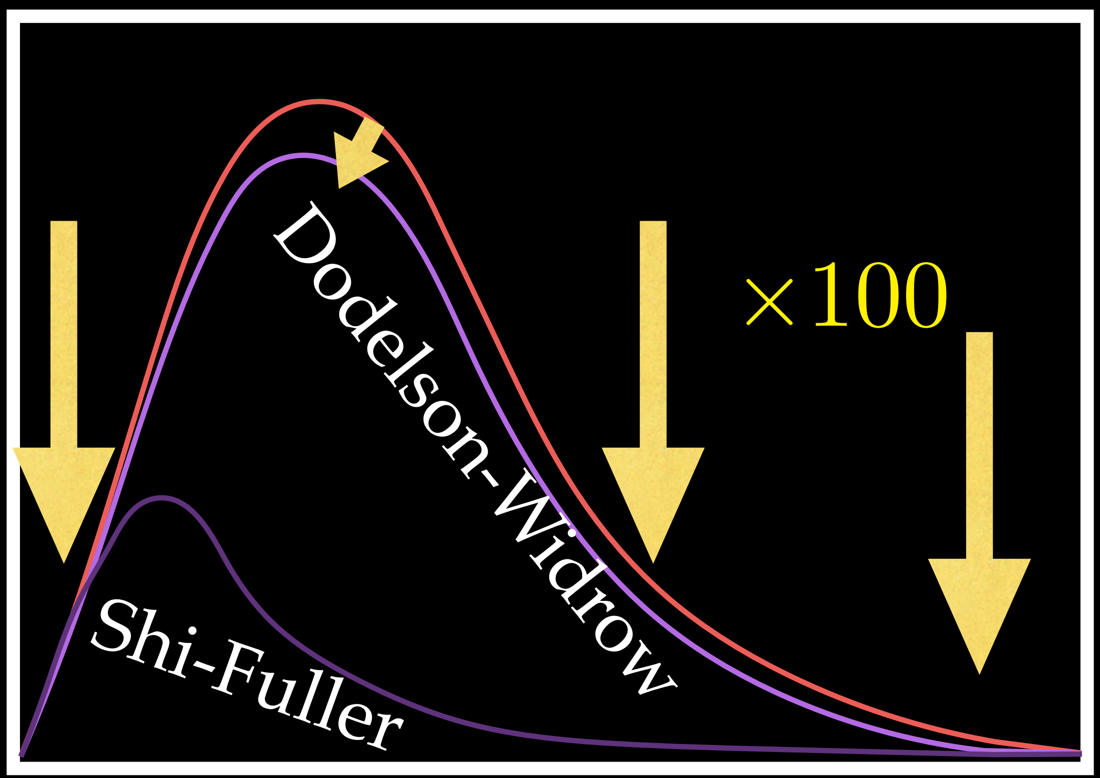
$$m_{\mathrm{th,WDM}} = 4.5^{+45}_{-1.4}\ \mathrm{keV}$$

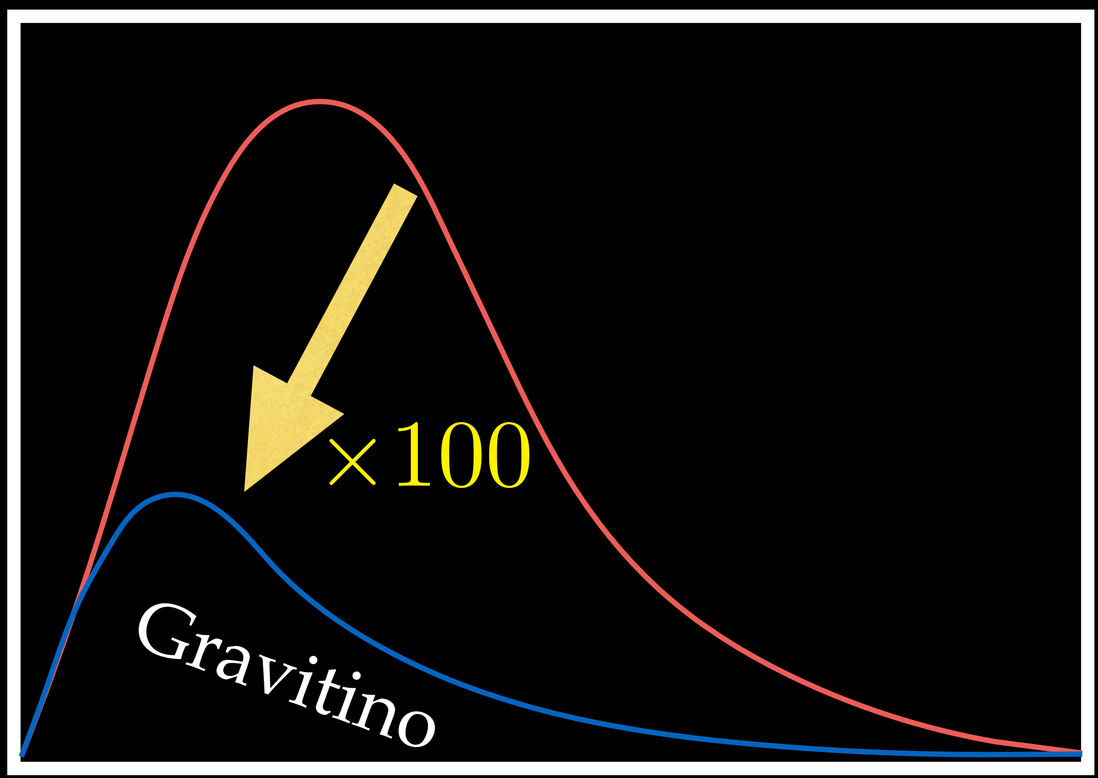
DESI, EUCLID, LSST, WEAVE forecast (1/4 covariance)

$$m_{\mathrm{th,WDM}} = 4.5^{+1.9}_{-1.0}\ \mathrm{keV}$$



Sterile WDM vs. Thermal WDM





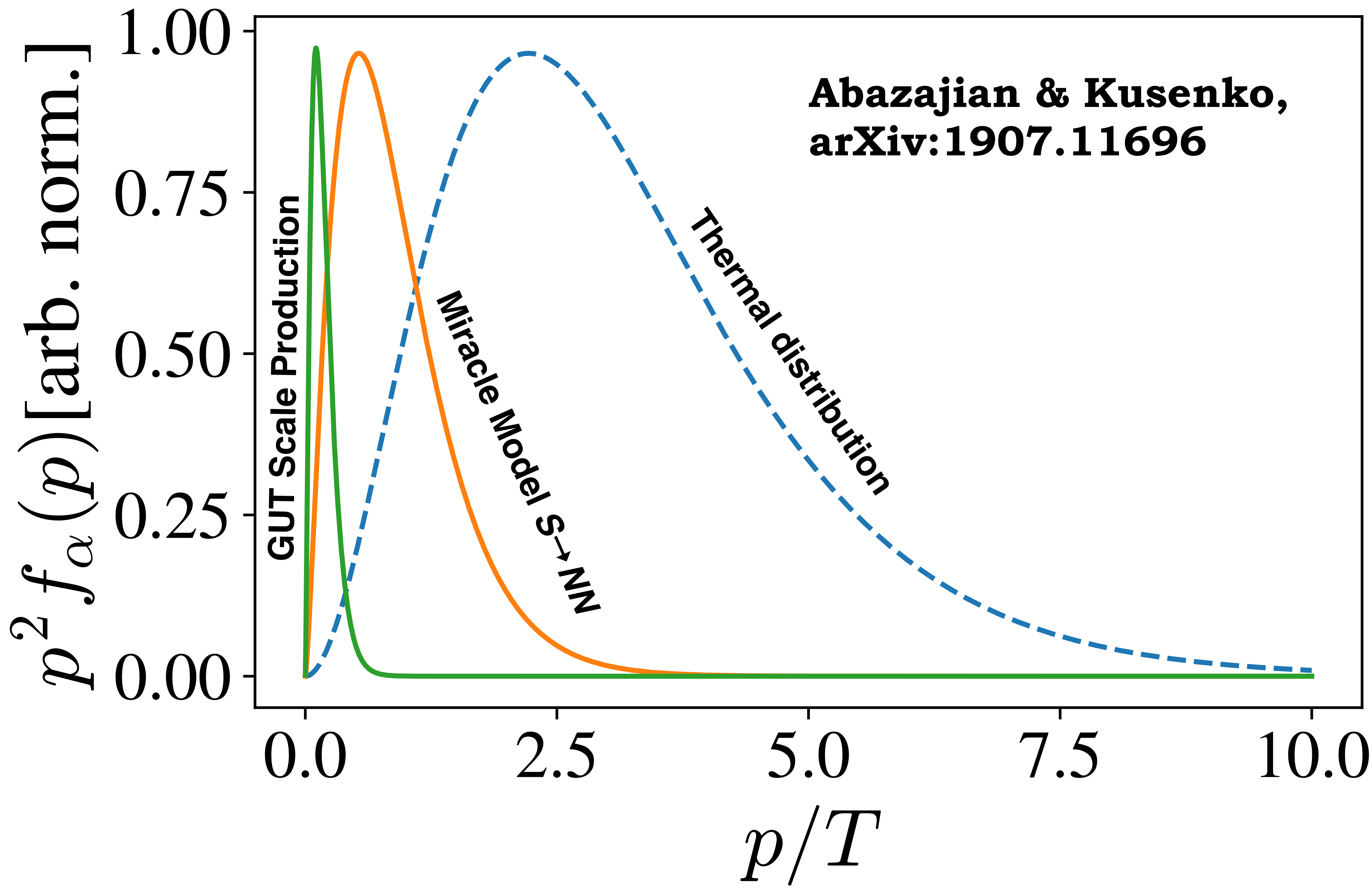
$$m_s\big|_{\text{Dodelson-Widrow,ideal}} \approx 4.46\,\text{keV}\left(\frac{m_{\text{thermal}}}{1\,\text{keV}}\right)^{4/3}$$

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

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

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

Varied Momenta Distributions for Different Production Mechanisms

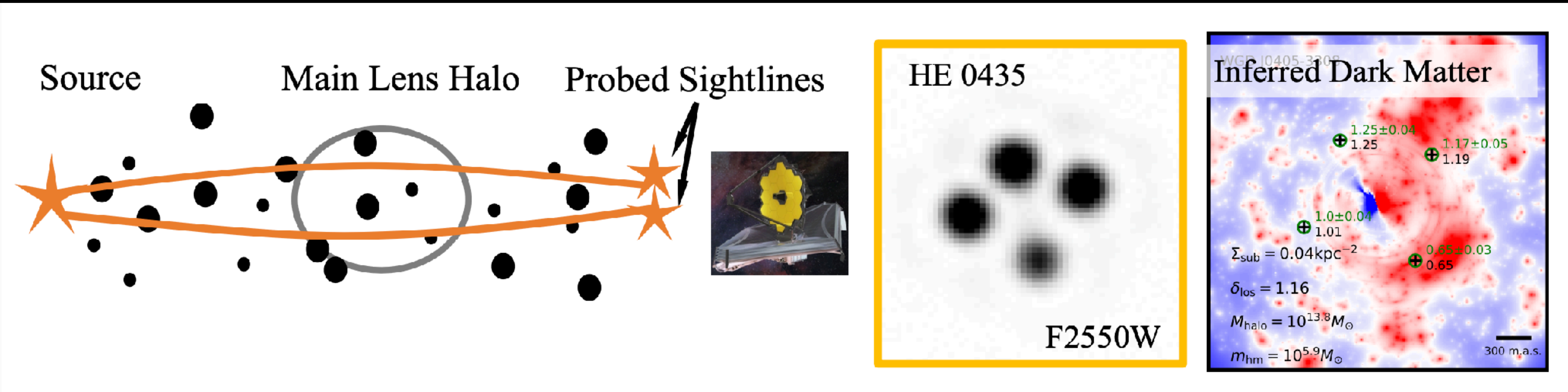


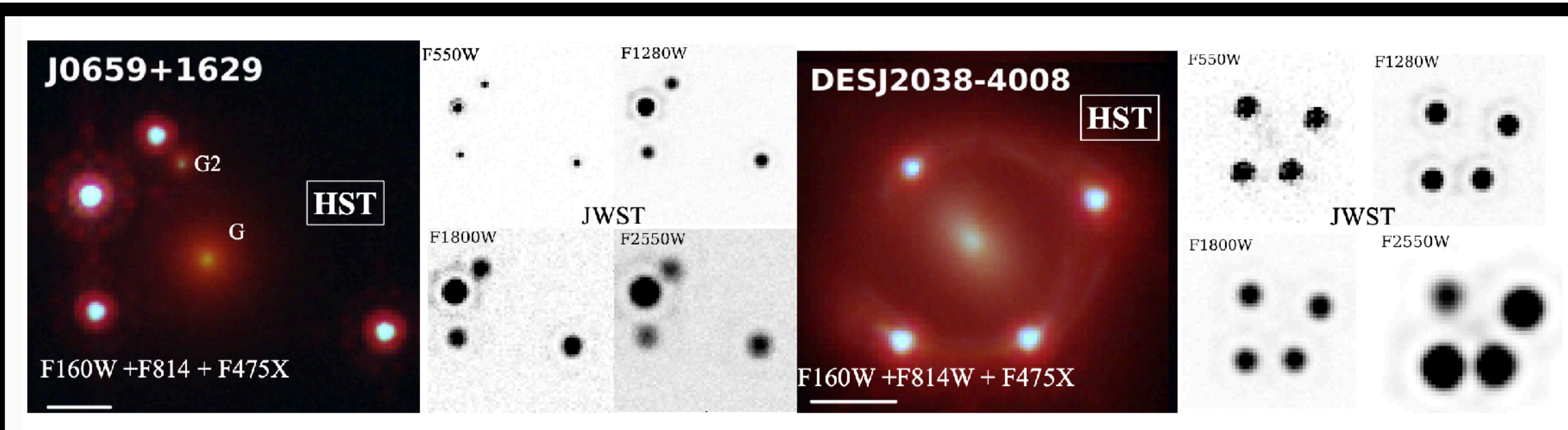
Lensing Test of Sterile Neutrino DM Models

	Strong Lensing [keV]	Strong Lensing & Galaxy Counts [keV]	Lyman-α [keV]	Lyman-α & Thermo. [keV]
PK	I: 10 II: 9.6	I: 26 II: 24	6.9	12
KTY	I: 2.1 II: 1.9	I: 5.2 II: 4.8	1.3	2.4
νMSM	7.0	16	I: 5.0 II: 5.0	I: 9.0 II: 10
DW	I: 34 II: 31	I: 92 II: 84	21	40
thermal	4.6	9.8	3.3	5.3

(Zelko et al., *PRL*, arXiv:2205.09777)

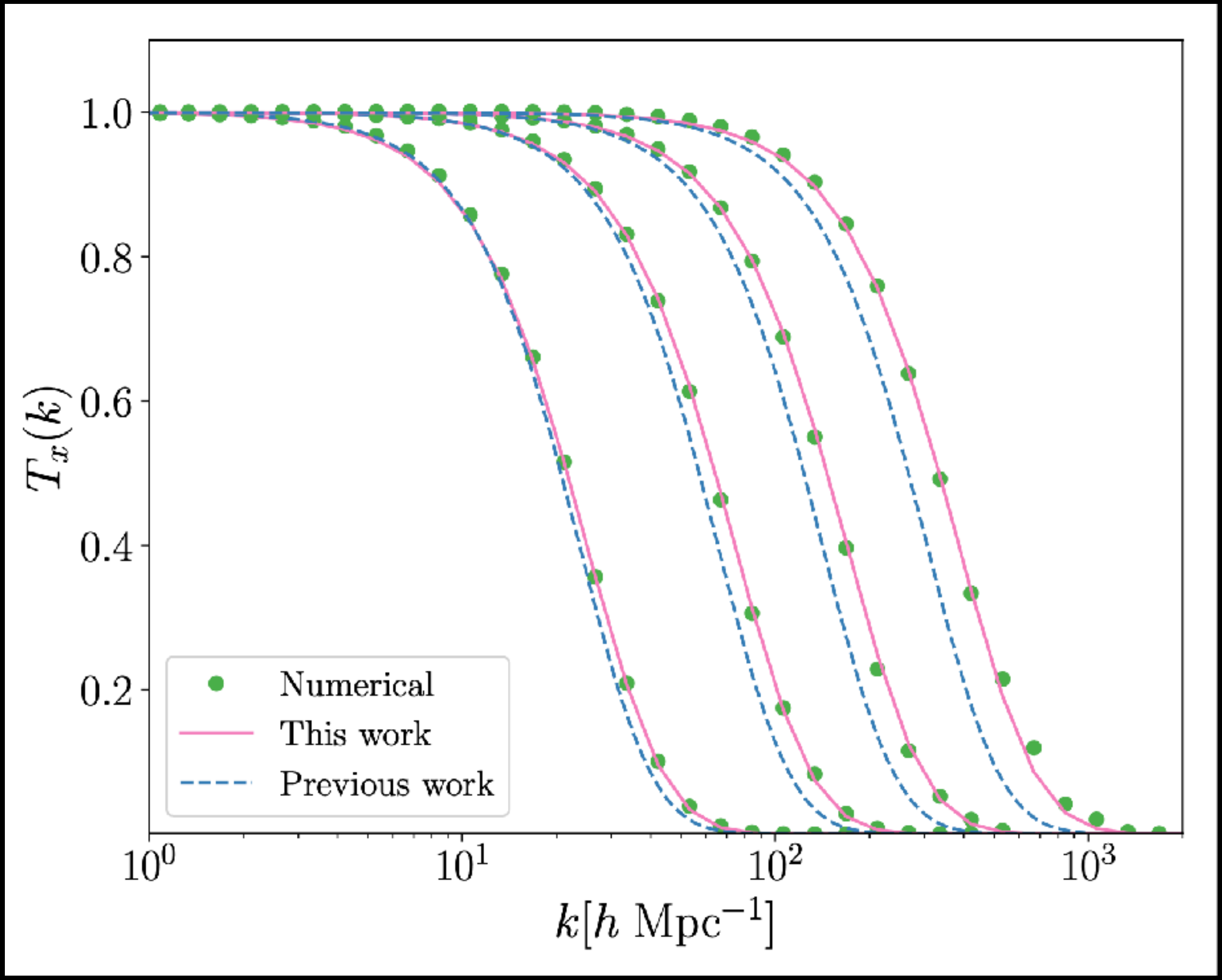
Strong Lensing Tests of WDM: Quadruply-Lensed Systems

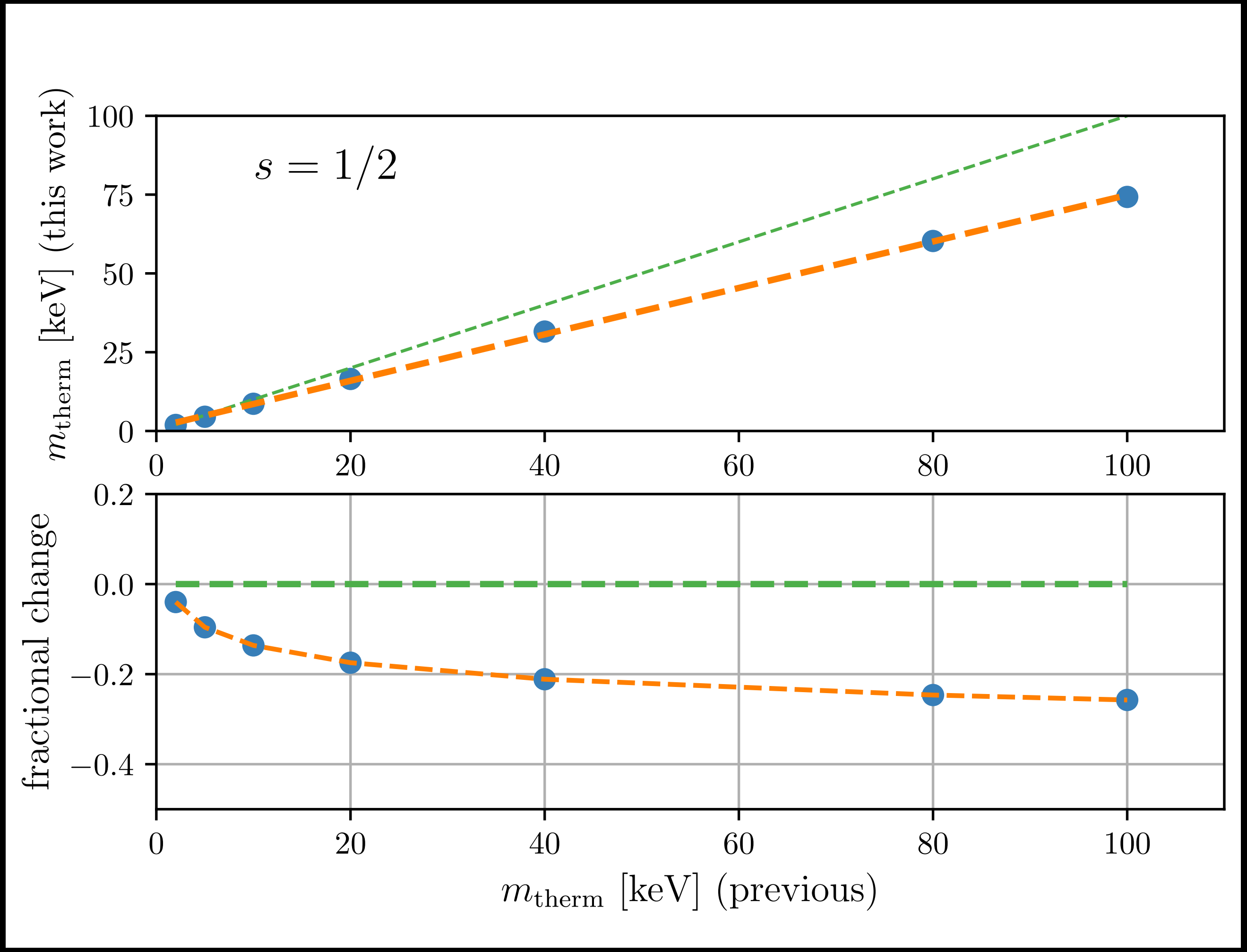




JWST Cycle ONE Proposal 2022 (PI Nierenberg): ***m_{th} > 10 keV***

Pushing beyond m_{th} > 10 keV: Accurate Calculations of Standard *Thermal* WDM

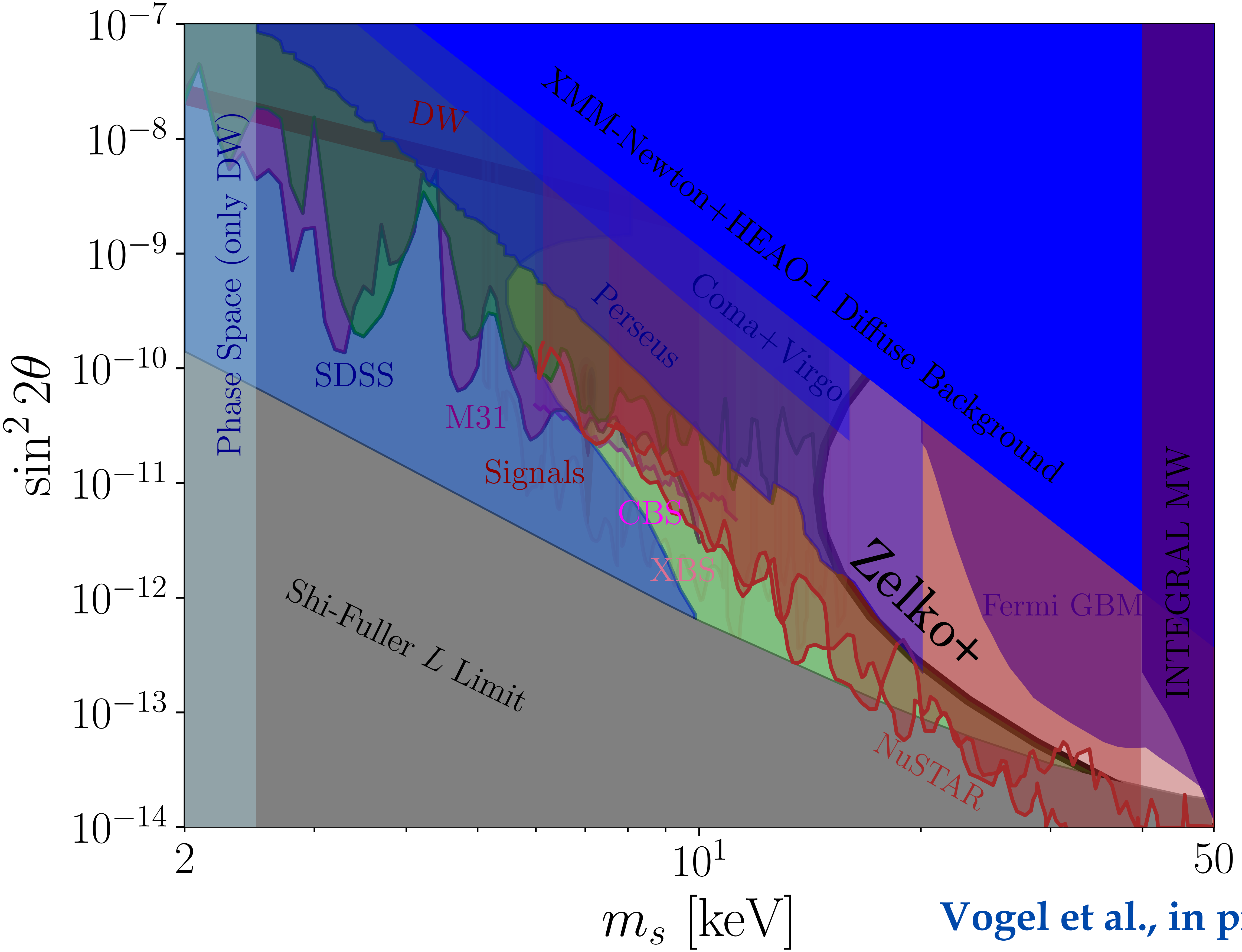




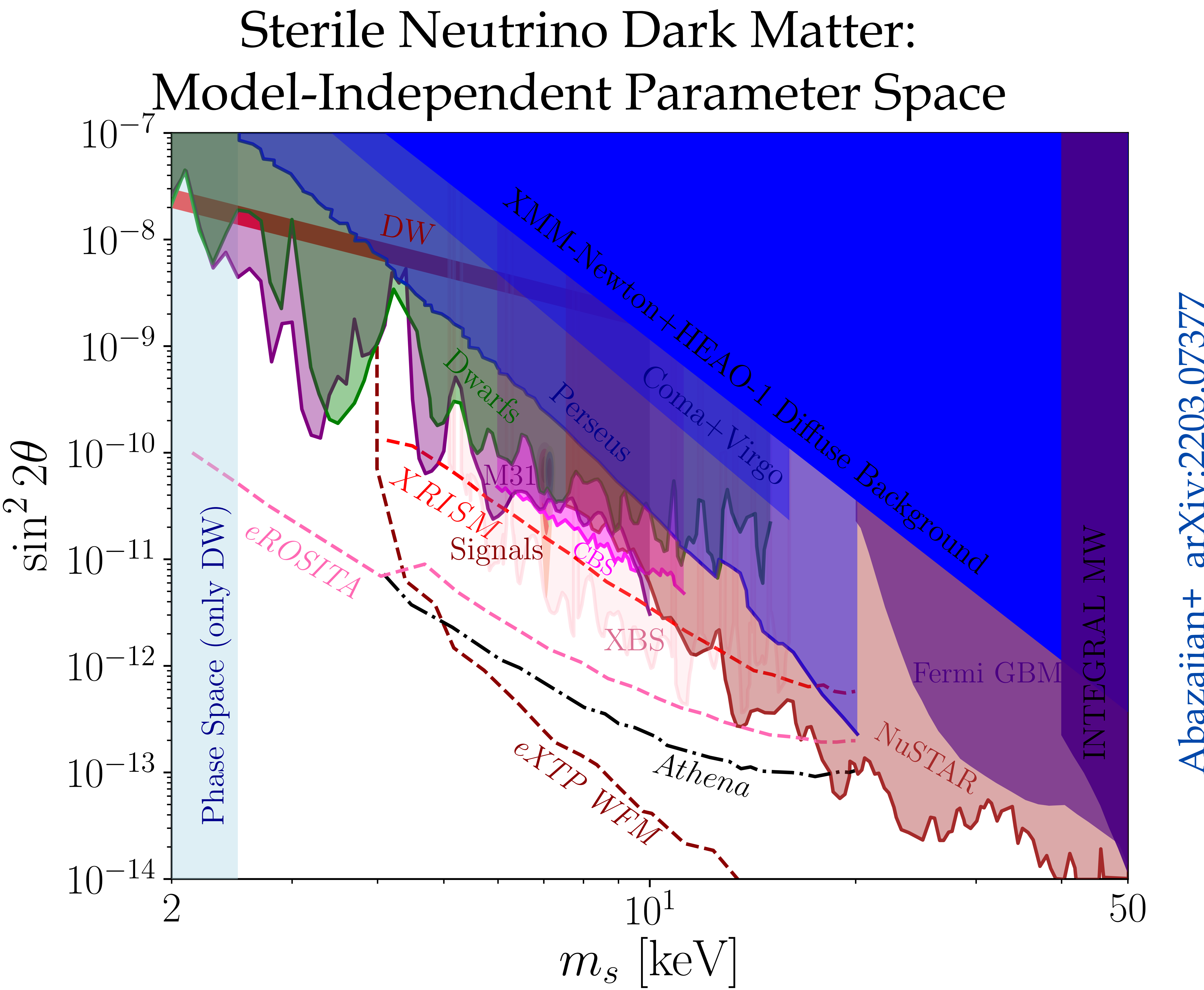
Given exact temperature via dilution, and training on 1 keV < m_{th} < 100 keV, we corrected the particle mass inferred from a given cutoff scale by 20% to 40% from previous WDM fits (e.g. Viel et al. 2005)

Vogel & Abazajian 2210.10753

Sterile Neutrino Dark Matter: Shi-Fuller Mechanism Excluded



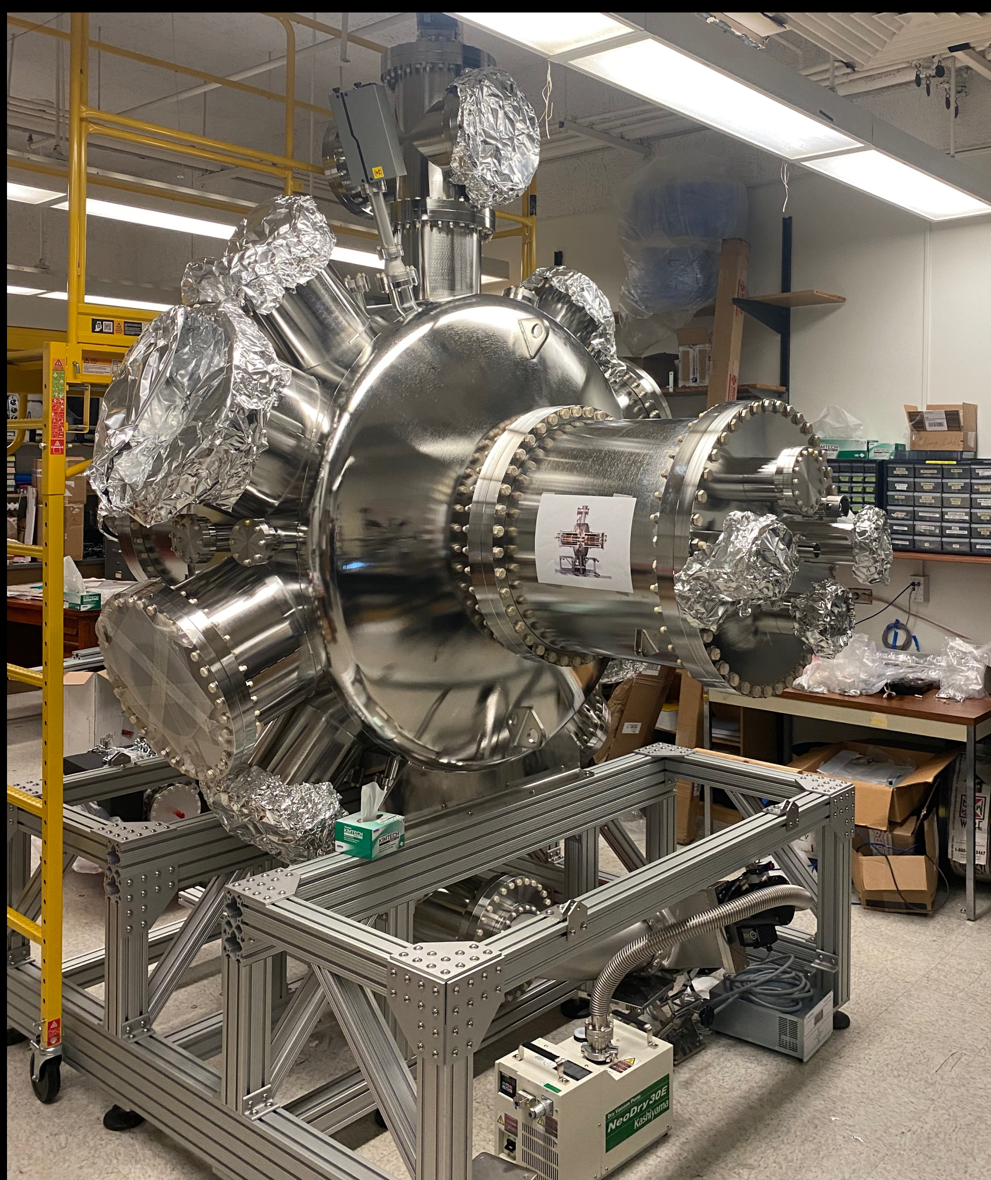
Vogel et al., in prep.



Sterile Neutrino Dark Matter:
Model-Independent Parameter Space
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
$\sin^2 2\theta$
2
10^1
50
m_s [keV]
DW
XMM-Newton+HEAO-1 Diffuse Background
Dwarfs
Perseus
Coma+Virgo
M31
XRISM
Signals
CBS
eROSITA
XBS
Fermi GBM
INTEGRAL MW
NuSTAR
Athena
eXTP WFM
Phase Space (only DW)
Abazajian+ arXiv:2203.07377

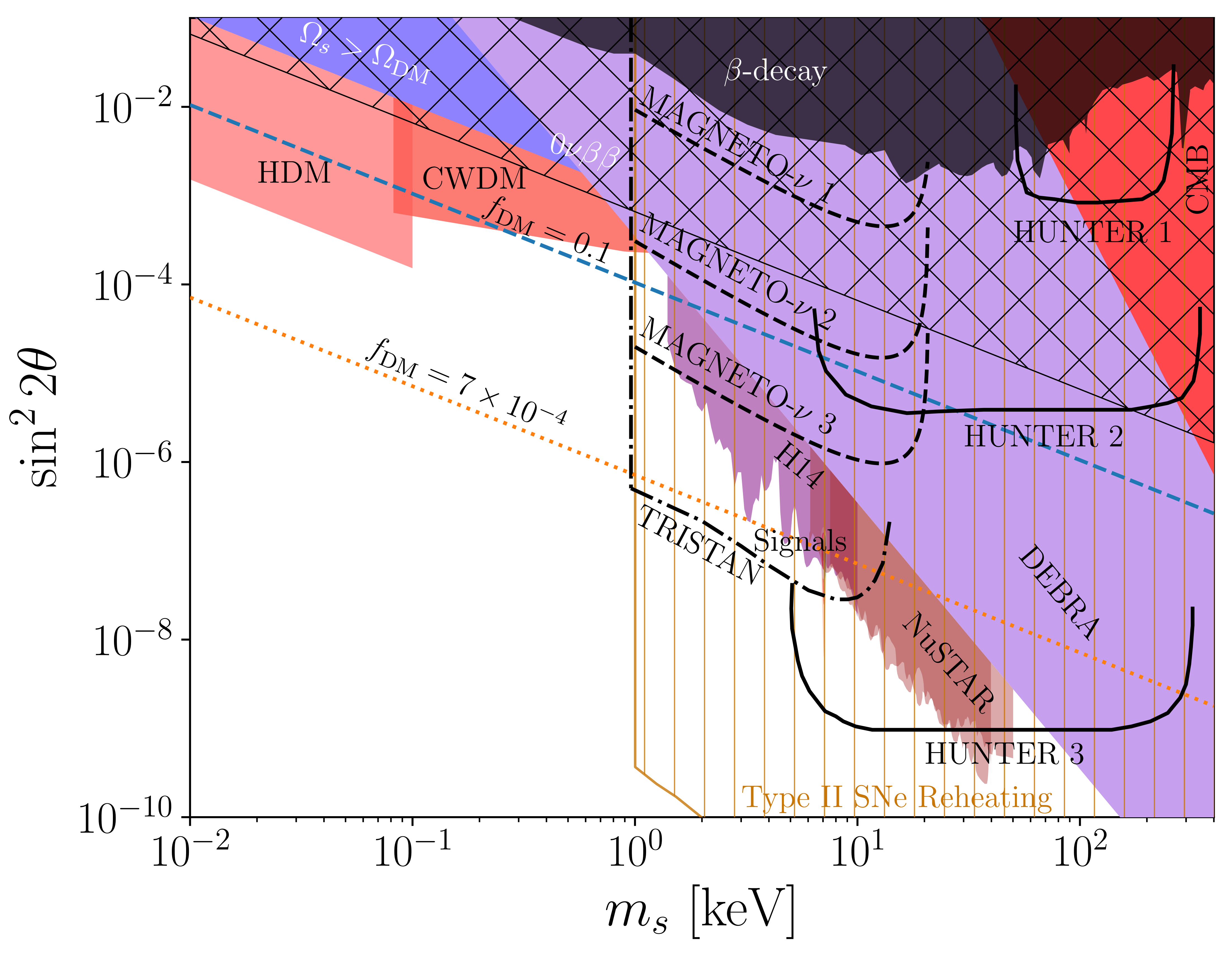
Sterile Neutrino kinematic searches in nuclear β-decay: KATRIN/TRISTAN, HUNTER, MAGNETO-ν

HUNTER



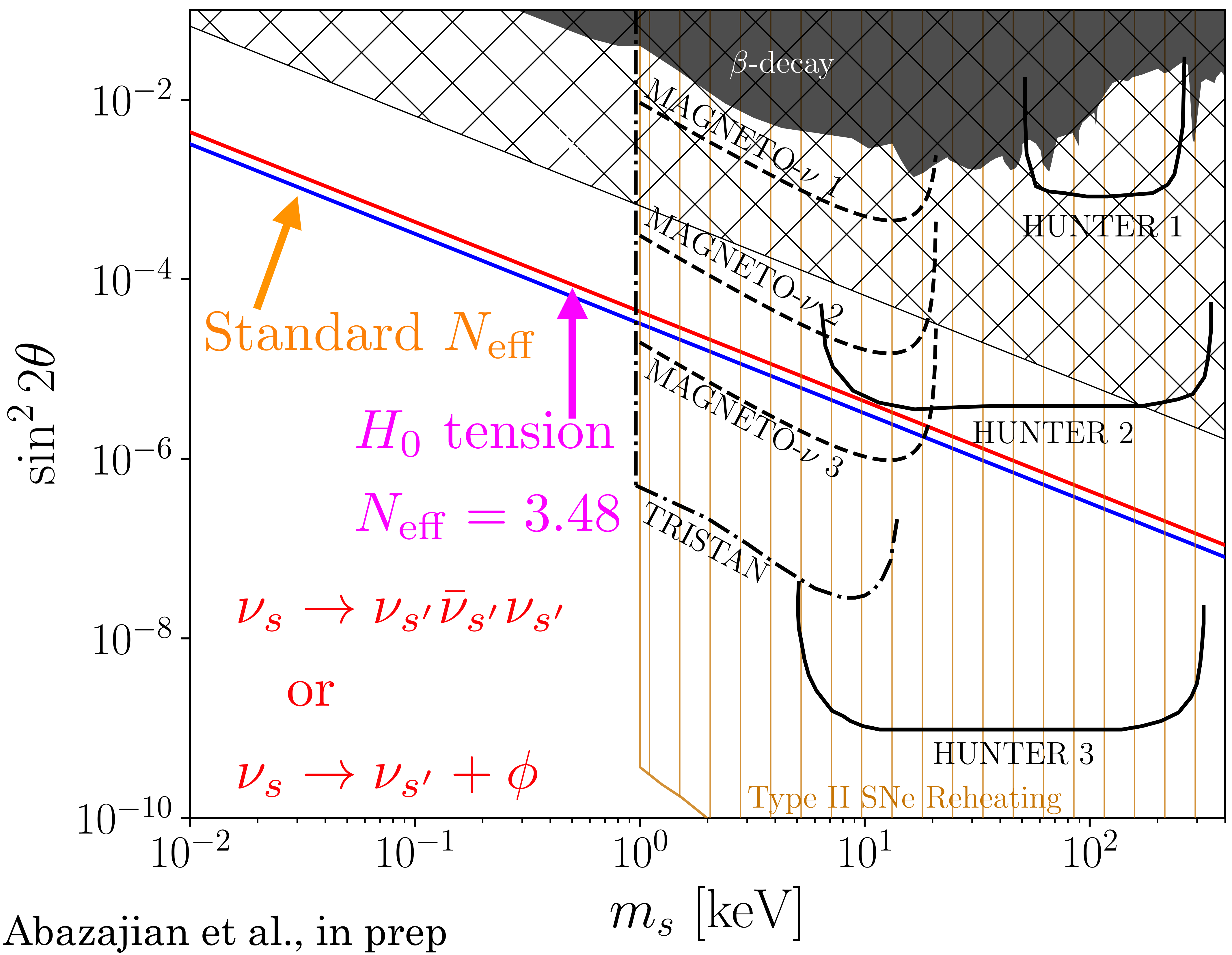
KATRIN/TRISTAN

Visible Sterile ν in the Low-Reheat Universe: Cosmological Constraints & Laboratory Constraints



updated from
Abazajian+ arXiv:2203.07377

Visible Sterile ν in the Low-Reheat Universe: Cosmological Signals & Laboratory Constraints



Abazajian et al., in prep

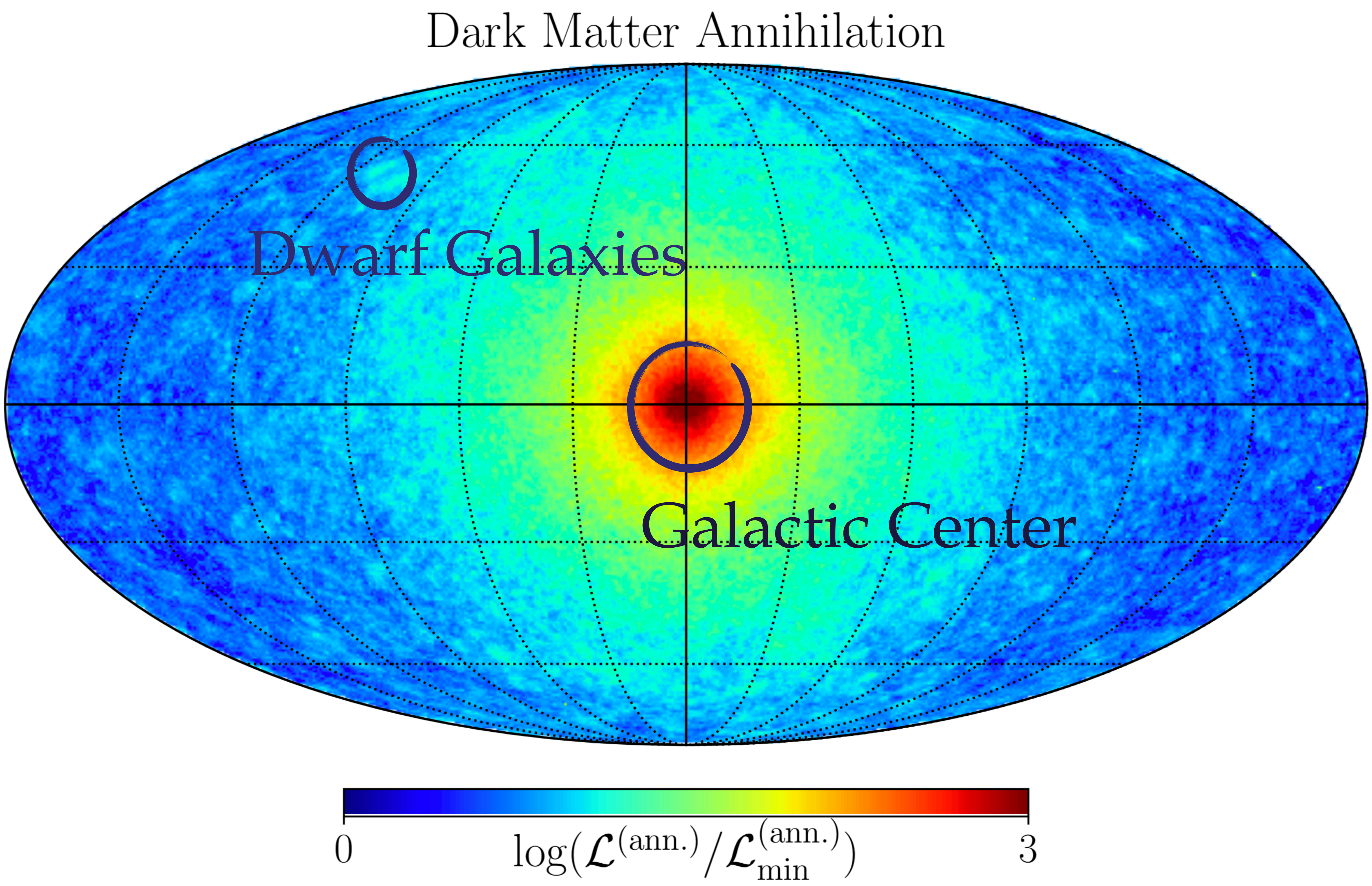
keV ➤ GeV

neutrinos ➤ WIMPs

Small Scale Structure: for WIMPS, all of this should be annihilating today…

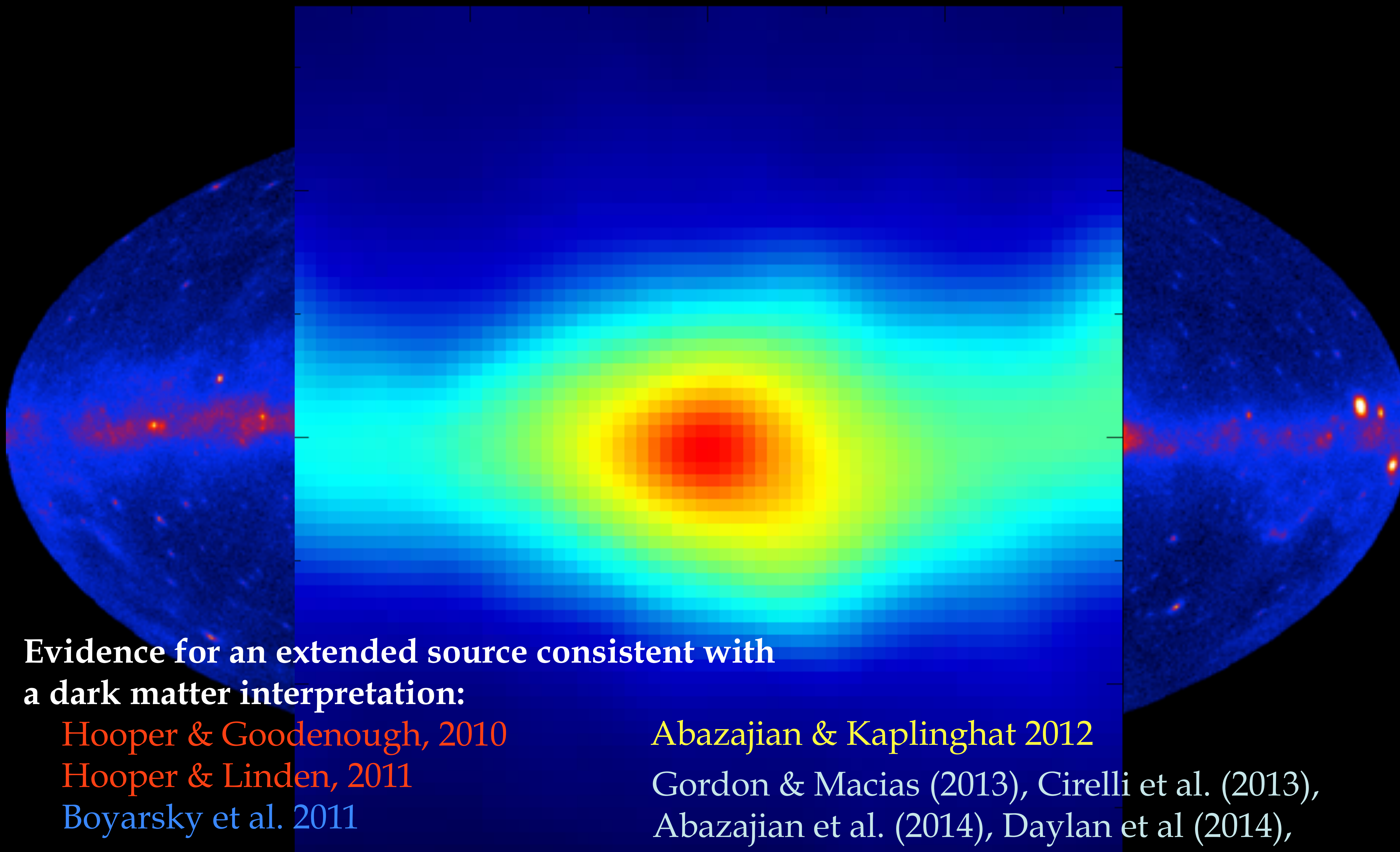
Need a line-of-sight integral through the dark matter…

The Signal Projected in Galactic Coordinates



Zhong, Valli & Abazajian arXiv:2003.00148

Let's just go ahead and look…



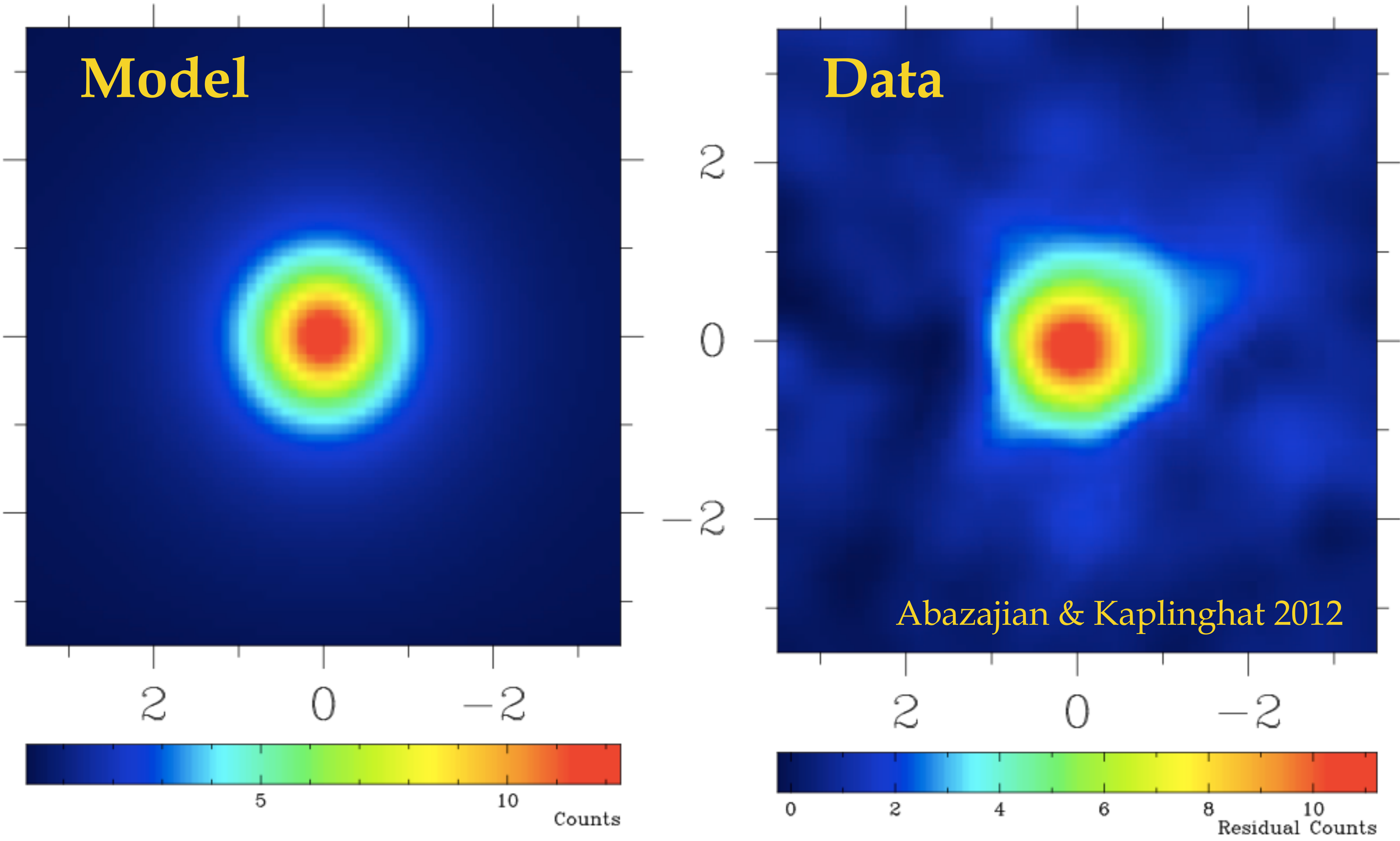
Evidence for an extended source consistent with a dark matter interpretation:

Hooper & Goodenough, 2010
Hooper & Linden, 2011
Boyarsky et al. 2011

Abazajian & Kaplinghat 2012

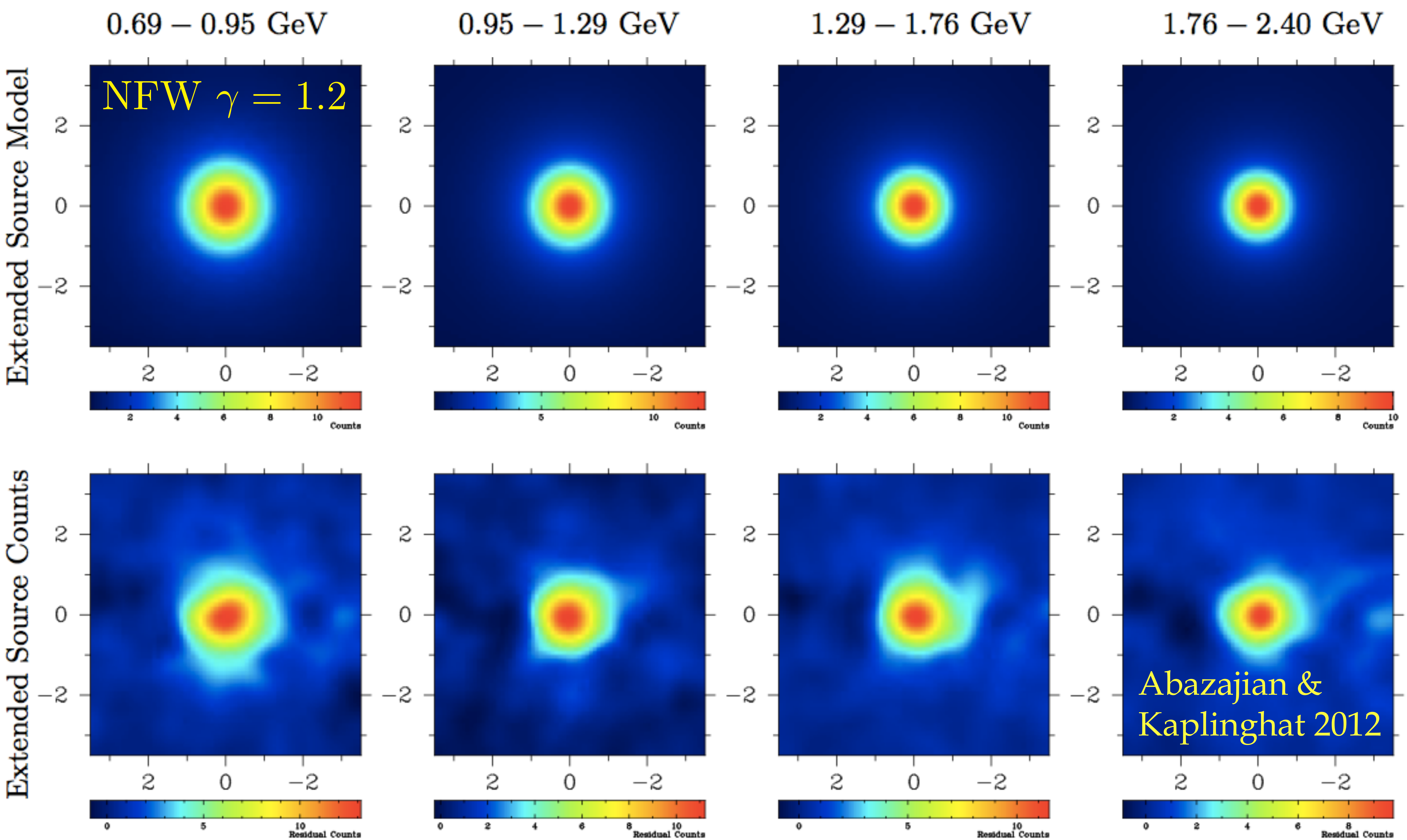
Gordon & Macias (2013), Cirelli et al. (2013), Abazajian et al. (2014), Daylan et al (2014), Calore et al. (2014), Abazajian et al (2015), Ackermann et al (2015)

Looks *so much* like dark matter…

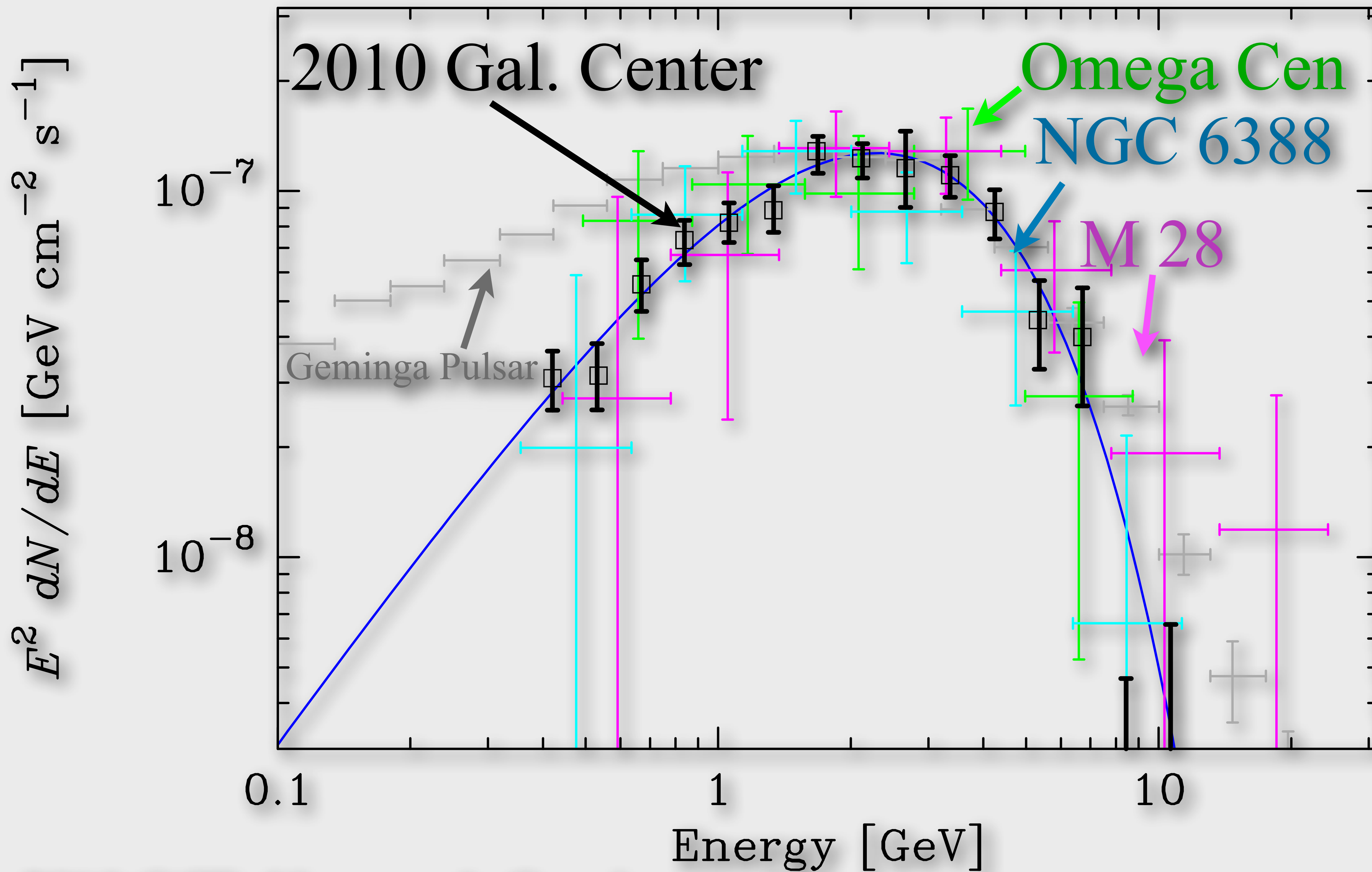


WIMP Dark Matter in the Galactic Center?!

$m_\chi = 30$ GeV $\text{TS}_{\text{true}} = 2\Delta \ln \mathcal{L} = 824, \ 28.7\sigma, \ p = 4 \times 10^{-181}$



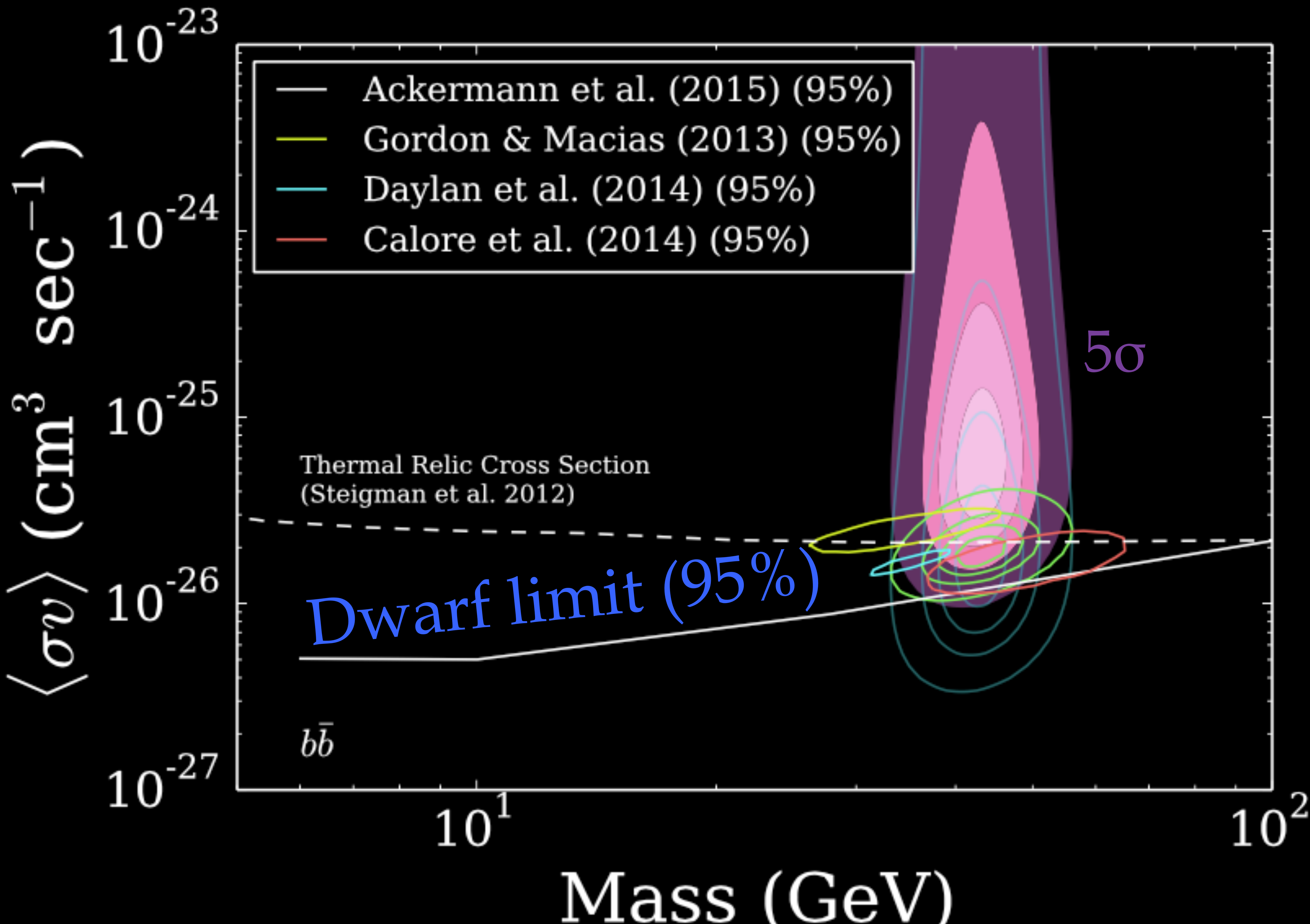
GCE as MSPs: Spectral Comparison



2010 GCE: Hooper & Goodenough

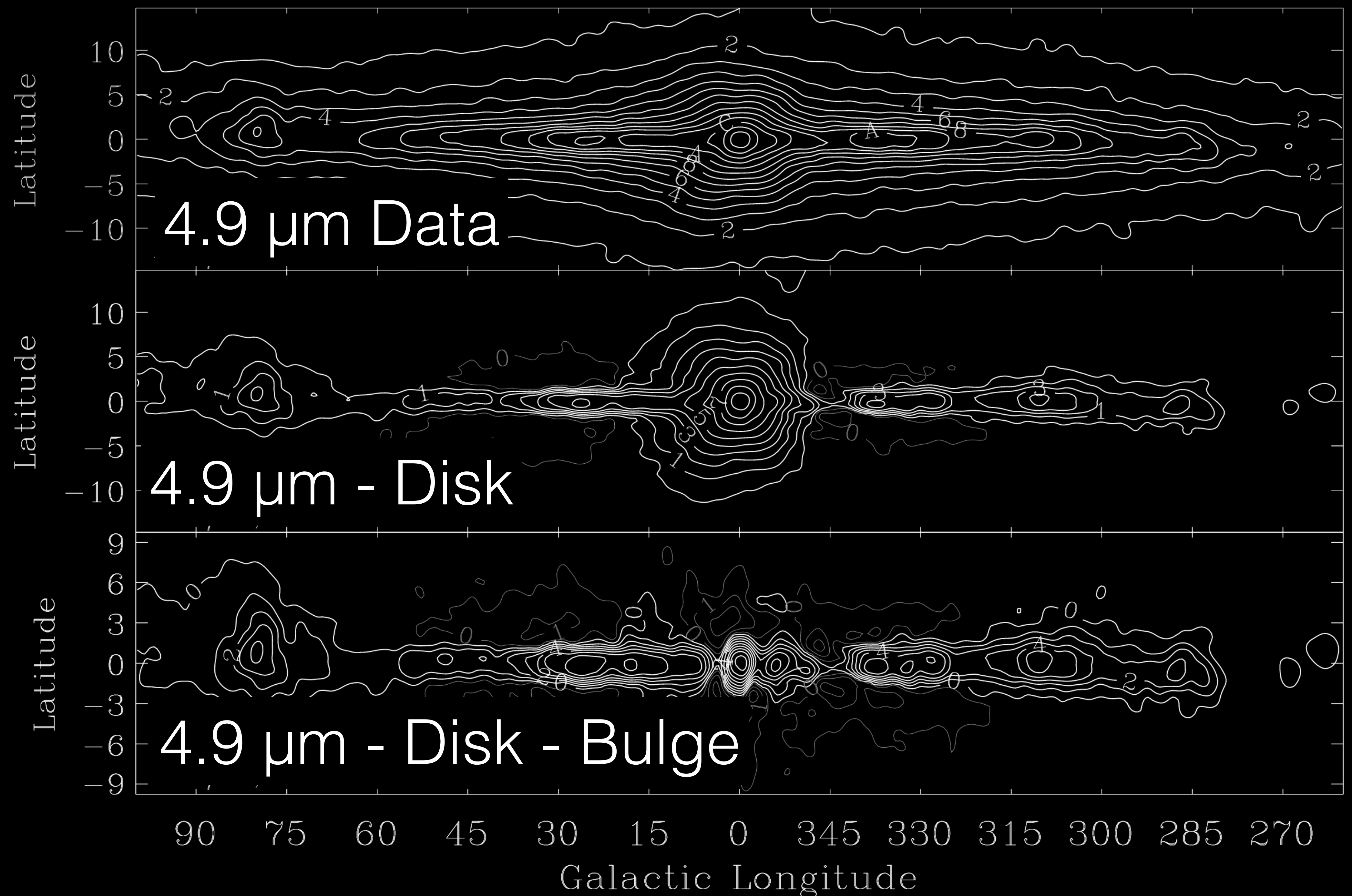
GCE-MSP Spectral Equivalence: Abazajian *2010*

Bright GCE, Dim Dwarfs: *Strong Tension!*



Abazajian & **Ryan Keeley** arXiv:1510.06424

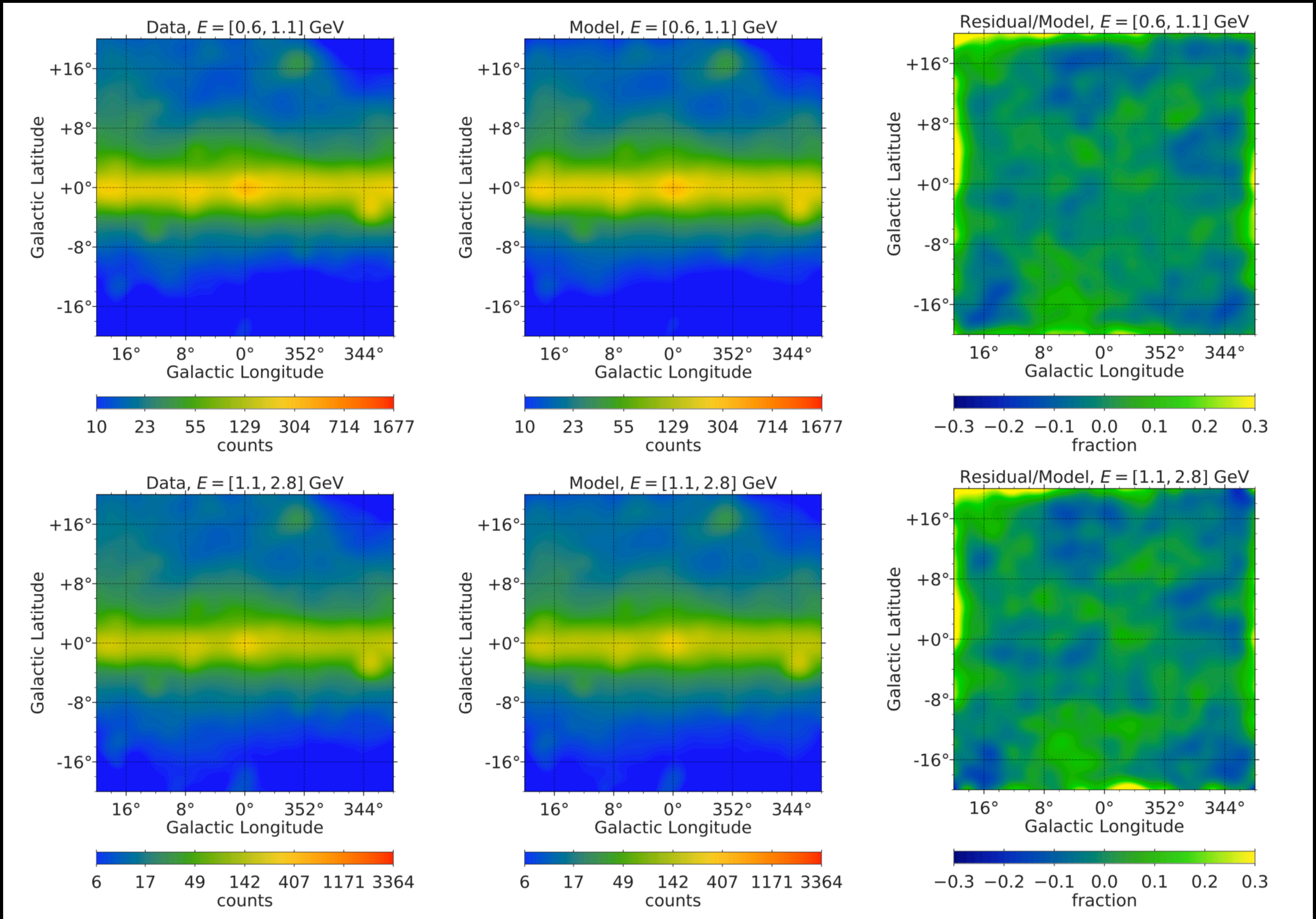
End of GCE and start of Stellar Bulge Gamma-rays?



GCE match with WISE IR X-map & even better with COBE/DIRBE Boxy Bulge Map: Macias+ arXiv:1611.06644, Luminosity function consistency: Ploeg+ arXiv:1705.00806

How much better are stellar maps than DM?

Bulge Maps are ***> 10σ Better Fit:*** Macias+ 1901.03822

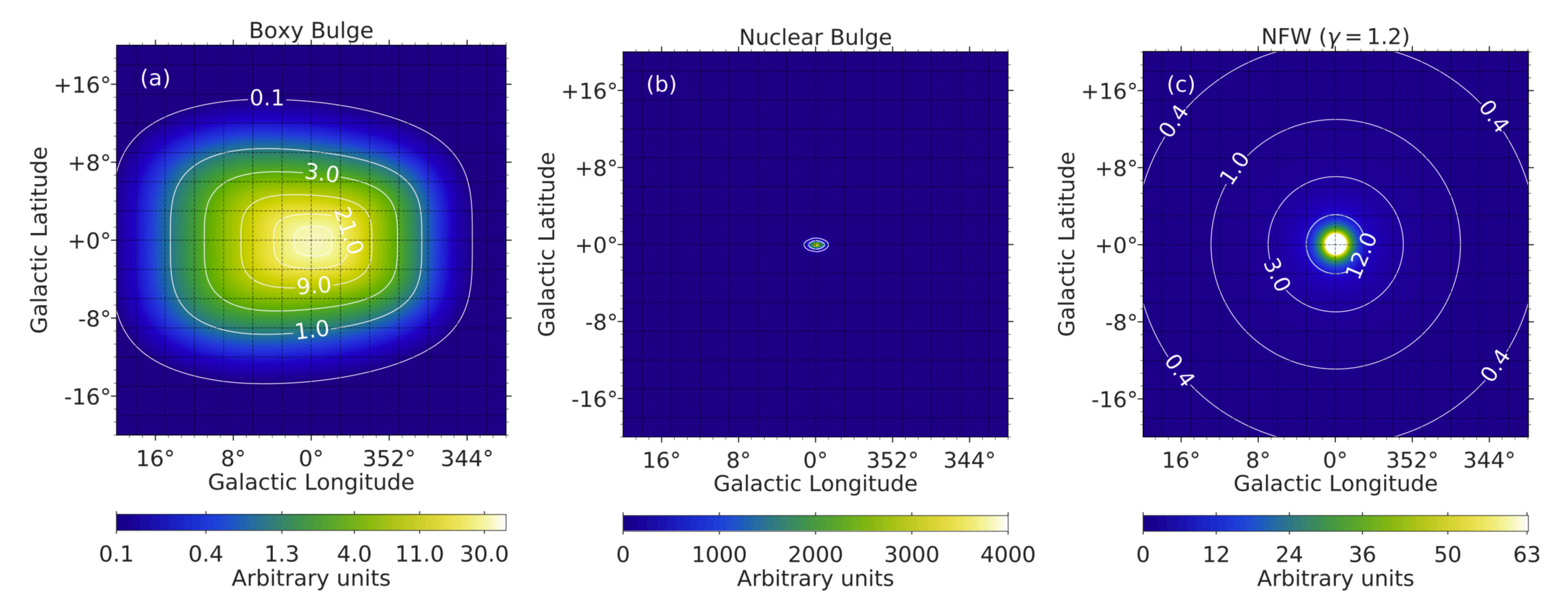


Oscar Macias Visits Irvine: April 18, 2017

How much room can be left for dark matter?

Not much!

Abazajian, Horiuchi, Kaplinghat, **Keeley,** Macias 2003.10416



New Claims that DM is better than Stellar Distributions

- Di Mauro (2021)
  - claimed that dark-matter templates were preferred for all the diffuse emission models considered, but only 2 of 7 of those considered did that
  - of those, the Di Mauro (2021) did not use ring subdivision binning that is the standard (Fermi Collab. & beyond) for analyses of the GC (Pohl et al. 2022)

- Cholis et al (2022)
  - Cholis et al (2022) claimed better fits for DM than Bulge models for masked data from the GC, using their diffuse models
  - They claimed their diffuse models were better fits than Macias et al (2017), and was the reason for their DM preference, but did not explicitly test this claim
  - Didn’t specify their bulge model source

New Claims that DM is better than Stellar Distributions

- McDermott et al (2022) [follow on to Cholis et al (2022)]
  - shared the models by github
  - used same ring-based diffuse models as Pohl et al (2022)
  - Our analysis found that:
    - McDermott+ had an artificial upper limit in their fits on some ring normalizations that was maximized so that the diffuse model did not fit properly
    - their bulge model (same as Cholis+) was not centered on GC
  - these both combined to lead to conclusion that DM fit better than the stellar nuclear bulge (NB) and extended bulge (BB)

Stellar-Associated Sources Remain Strongly Preferred Over Dark Matter

- Song et al (2023) [in prep.]
  - used data provided by McDermott+ to test previously mentioned problems
  - uses previous work's diffuse models to show that Pohl et al (2022) provide much better fits to GC diffuse emission than used in McDermott+ by a level of $-2\Delta \ln \mathcal{L} = 3510$ (driven by upper-limit issue)
  - Bulge Models—3 different ones — are preferred over DM by $-2\Delta \ln \mathcal{L} \approx 200$ to $-2\Delta \ln \mathcal{L} \approx 500$ *using the Cholis+ diffuse models*

Baseline model	Additional source	ΔTS	Significance
Base	BB	77.5	7.3 σ
Base	DM	80.7	7.5 σ
Base	NB	299.7	16.2 σ
Base+NB	DM	21.0	2.8 σ
Base+NB	BB	90.9	8.1 σ
Base+NB+BB	DM	3.5	0.3 σ

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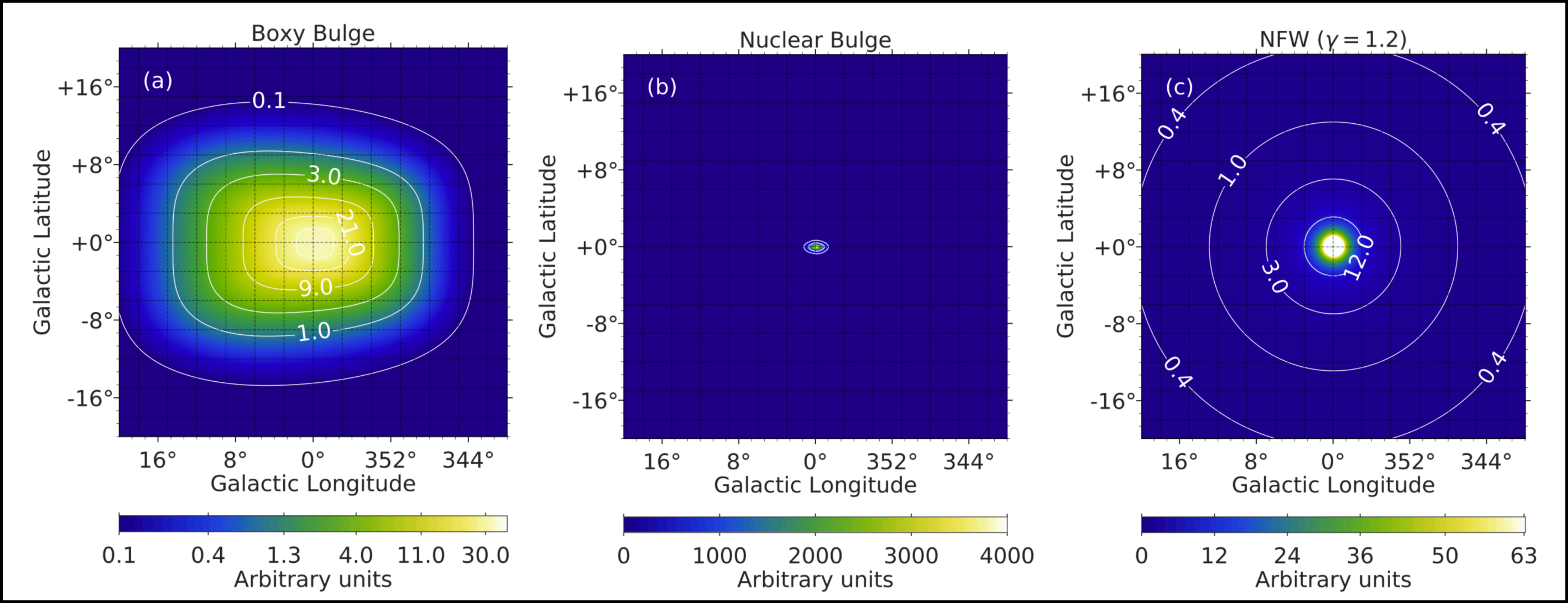

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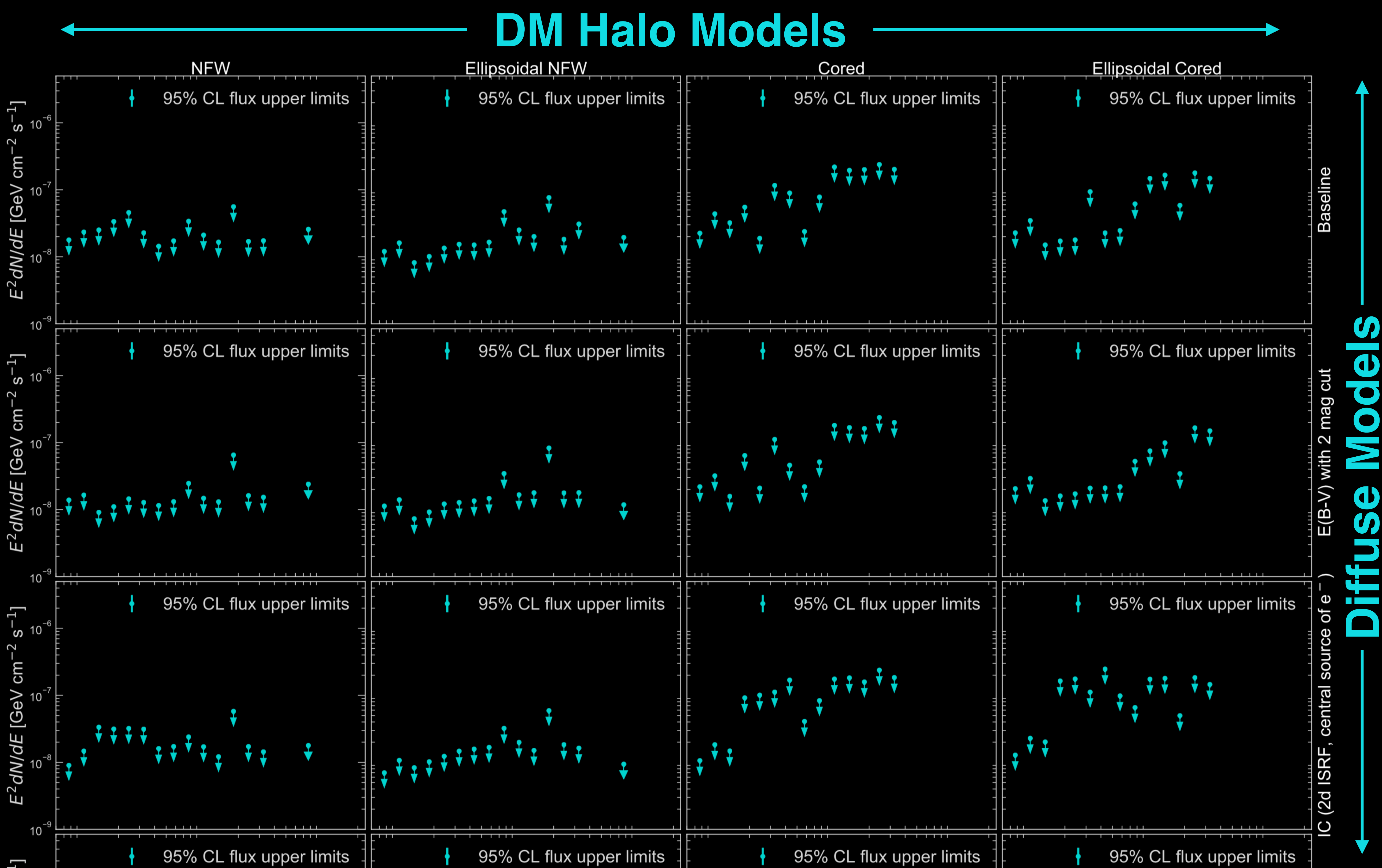

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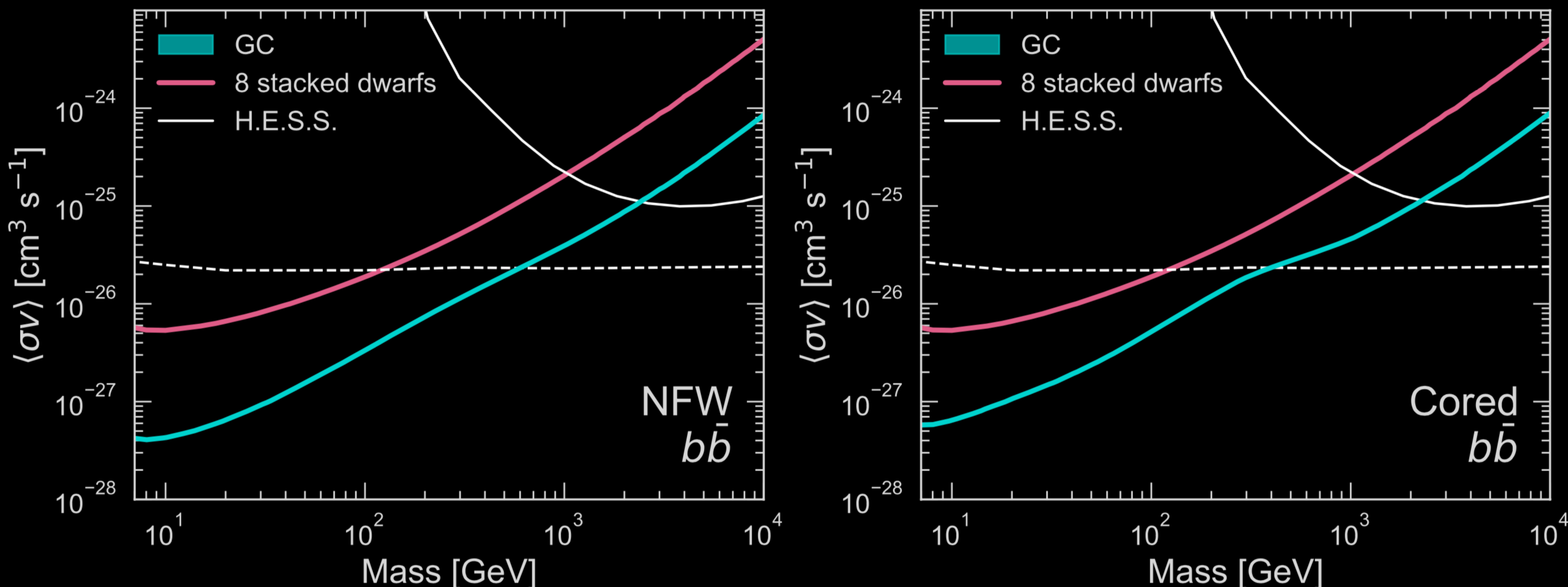
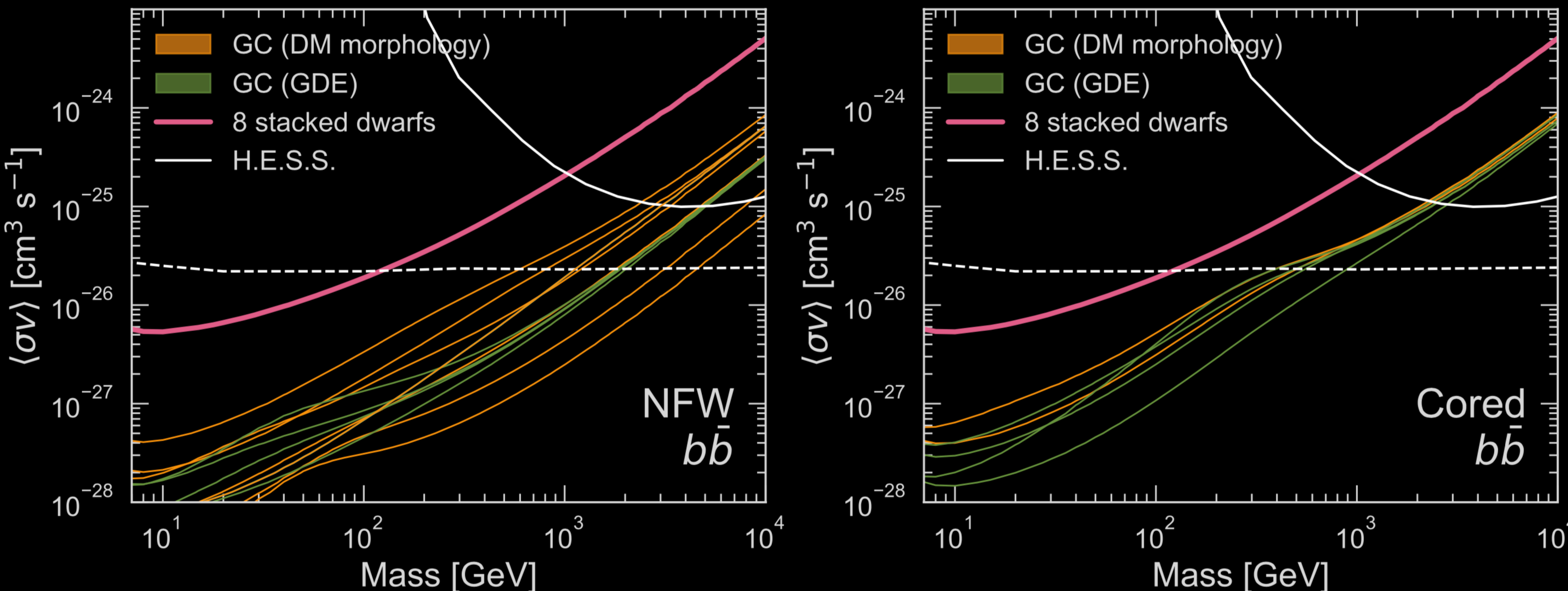


➜We use the most conservative local density determinations, marginalize over them, as well as the most physical, conservative DM profiles

Limits are close to that expected from GC by Fermi-LAT Collaboration (Charles+ arXiv:1605.02016)

But what about Diffuse Model Uncertainties??



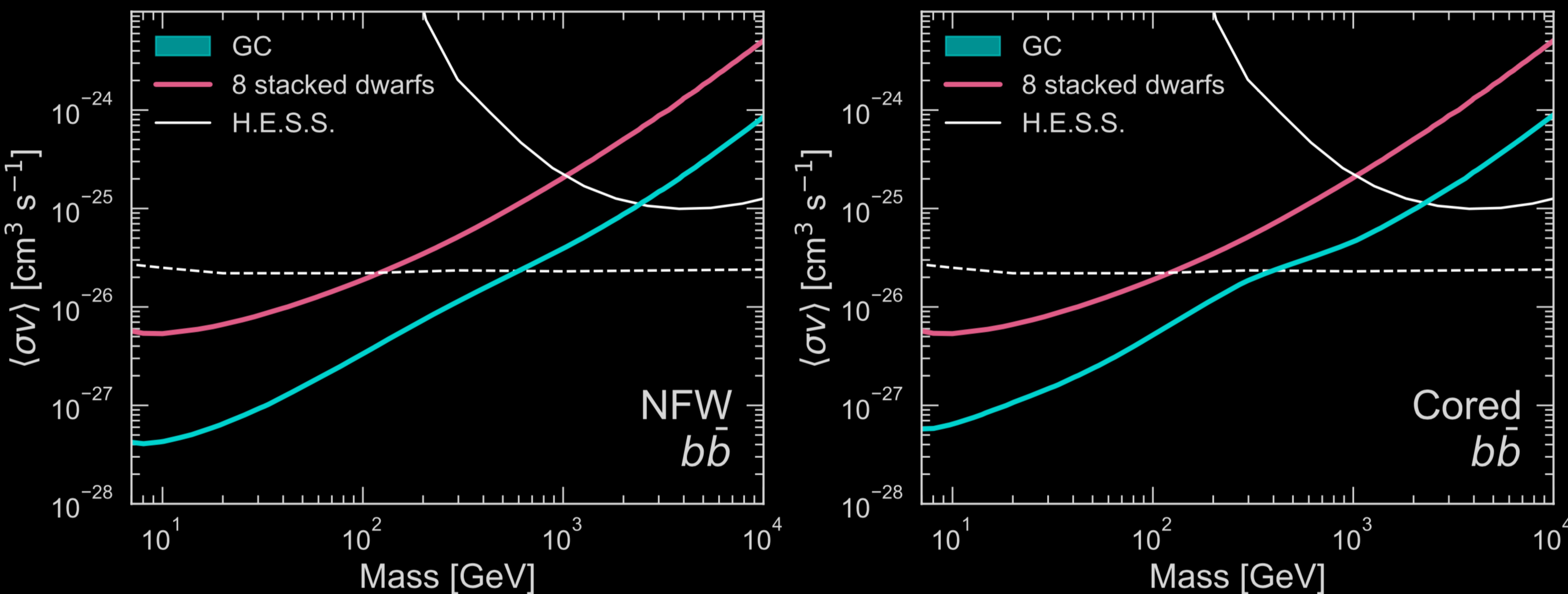
We took all diffuse models used in GCE analyses into account…

some much better fits than others…

still report ***most conservative*** limit

Abazajian, Horiuchi, Kaplinghat, **Keeley, Macias** 2003.10416

The *Most Stringent,* Robust Constraint on WIMP Annihilation from Fermi-LAT



Abazajian, Horiuchi, Kaplinghat, **Keeley,** Macias 2003.10416

Conclusions

- Warm Dark Matter has a 3σ preference over CDM in a recent high-resolution Ly-α WDM analysis (Villasenor et al. 2022)
- Sterile neutrino dark matter remains of interest: varied impact on structure formation for a given mass (Zelko et al. 2021)
- We have updated the thermal WDM transfer functions to improve accuracy by 20% to 40% (Vogel & Abazajian 2022)
- Sterile neutrino laboratory probes underway, with significant cosmological implications (Abazajian et al. in prep)
- The GCE in gamma rays is due to stellar remnants, likely MSPs (Song et al. in prep)
- Given this, the GC places the most stringent indirect detection limits on WIMP DM (Macias et al 2020)
- *But the GC in gamma rays remains very interesting* (e.g. 2σ evidence for higgsino WIMP DM in GC data analyzed by Dessert+ 2023)