ICHEP 2016, Chicago, Aug 4th 2016

Sterile neutrino dark matter and the 3.5 keV line

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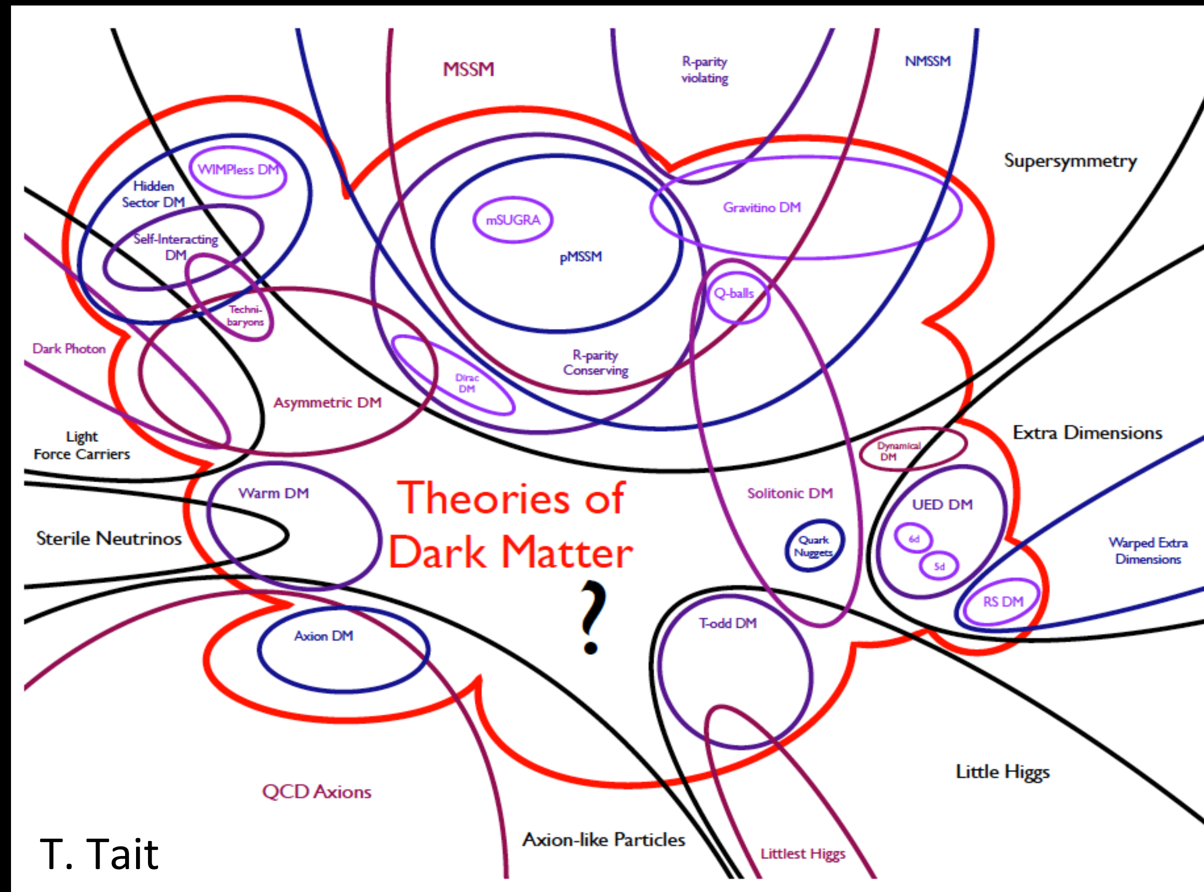
Beyond CDM

Particle dark matter:
We are very far from knowing the particle nature of dark matter: lots of ideas.



Small-scale issues:
There are numerous small-scale issues have been pointed out in CDM

- Missing satellites
- Too big to fail
- Core/cusp
- Plane of satellites
- Galaxies in voids
- ...and others

→ Go beyond CDM

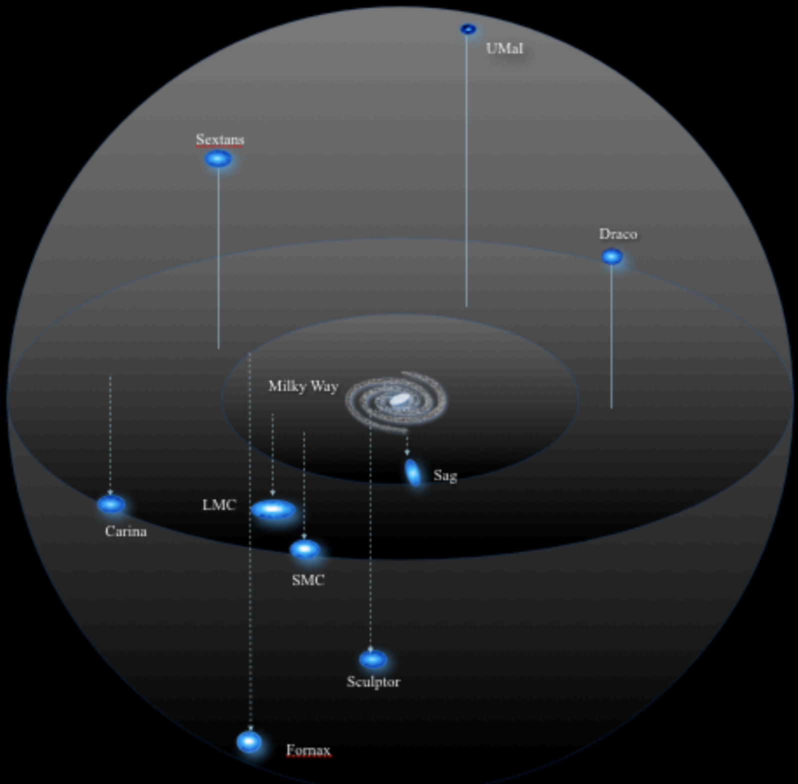
Baryonic solutions has not been able to explain everything.

Cold dark matter challenged

CDM is challenged by observations probing small scales

1. <u>Missing satellites problem:</u> expect > 100 satellites but see ~10

Theory N > 100



Observed $N_{lum} \sim 10$ [$L \sim$ 1e5-7 L_{sun}]

Klypin et al. (1999), Moore et al. (1999), Kauffmann et al. (1993)

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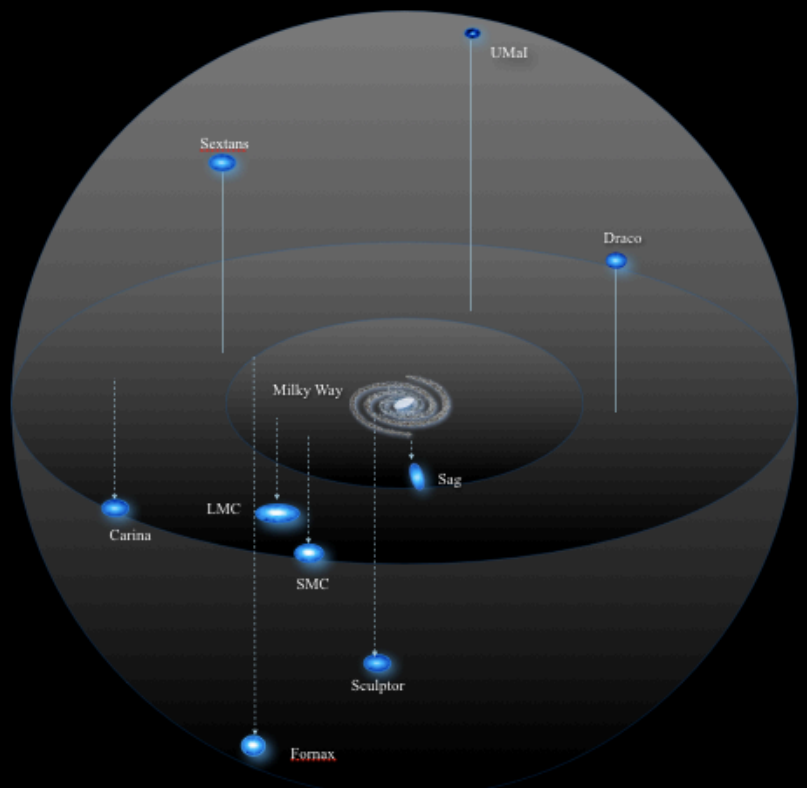

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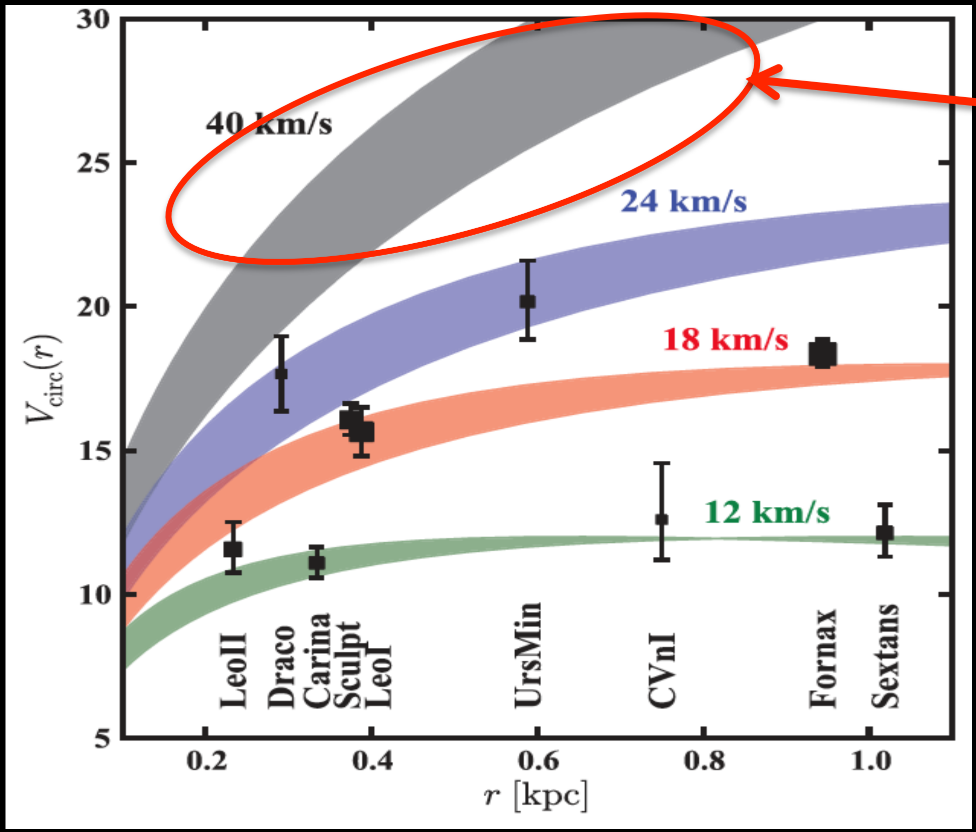
Cold dark matter challenged

CDM is challenged by observations probing small scales

1. Missing satellites problem: expect > 100 satellites but see ~10
2. Too big to fail problem: massive subhalos are too dense to match data



Boylan-kolchin et al (2011, 2012), Aquarius sims

"Massive failures"
Subhalos with V_{max} > 25 km/s that do not find observational counterparts: why do these not "light" up?

Between 5 – 40 (median ~20) "*massive failures*" based on 48 realizations of the Milky Way Halo

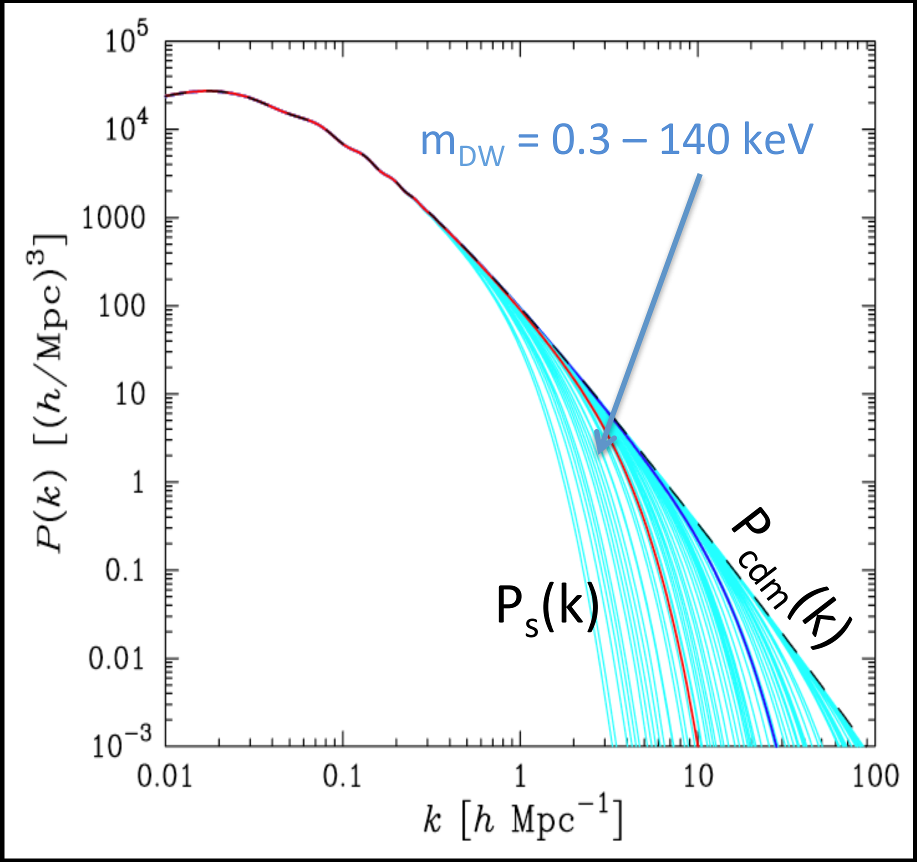
Garrison-Kimmel et al (2014)

Sterile neutrino as warm dark matter

Production:

Sterile neutrino can be **WARM** or **COLD** depending on how they're produced.

1. Oscillation based production: Dodelson-Widrow mechanism – WARM
   Abundance set by mixing angle, warmness set by mass. *Dodelson & Widrow (1994)*



Transfer function: the ratio to CDM

$$T_s^2(k) = \frac{P_s(k)}{P_{\rm cdm}(k)}$$

There is a 1-to-1 correspondence between sterile neutrino mass and cutoff scale:

$$T_s(k) = [1 + (\alpha k)^\nu]^{-\mu}$$

$$\alpha = a\left(\frac{m_s}{1\ \mathrm{keV}}\right)^b \left(\frac{\Omega_{\rm DM}}{0.26}\right)^c \left(\frac{h}{0.7}\right)^d h^{-1}\ \mathrm{Mpc}$$

Abazajian (2006)

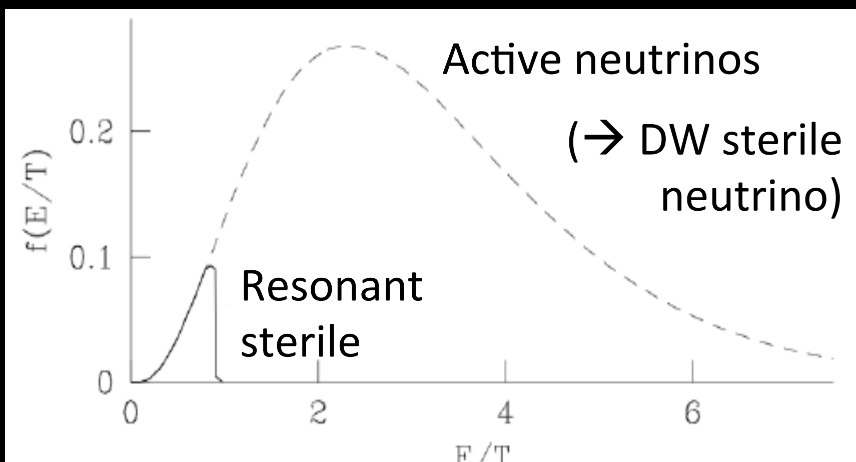
Sterile neutrino as warm dark matter

Production:

Sterile neutrino can be **WARM** or **COLD** depending on how they're produced.

2. Non-zero lepton number "resonant" production – WARM, but less
   Properties set by mass, angle, lepton asymmetry *Shi & Fuller ('99)*

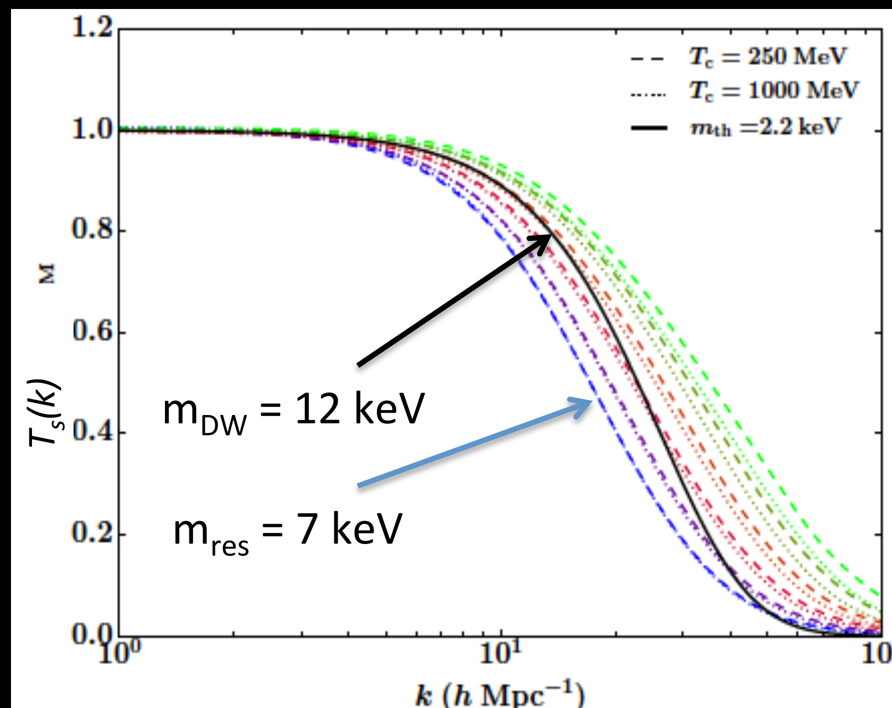
Active → sterile oscillation occurs from low momenta states:



Resonance condition:

$$V_\nu \approx M_{N_1}^2 \cos 2\theta / 2E$$

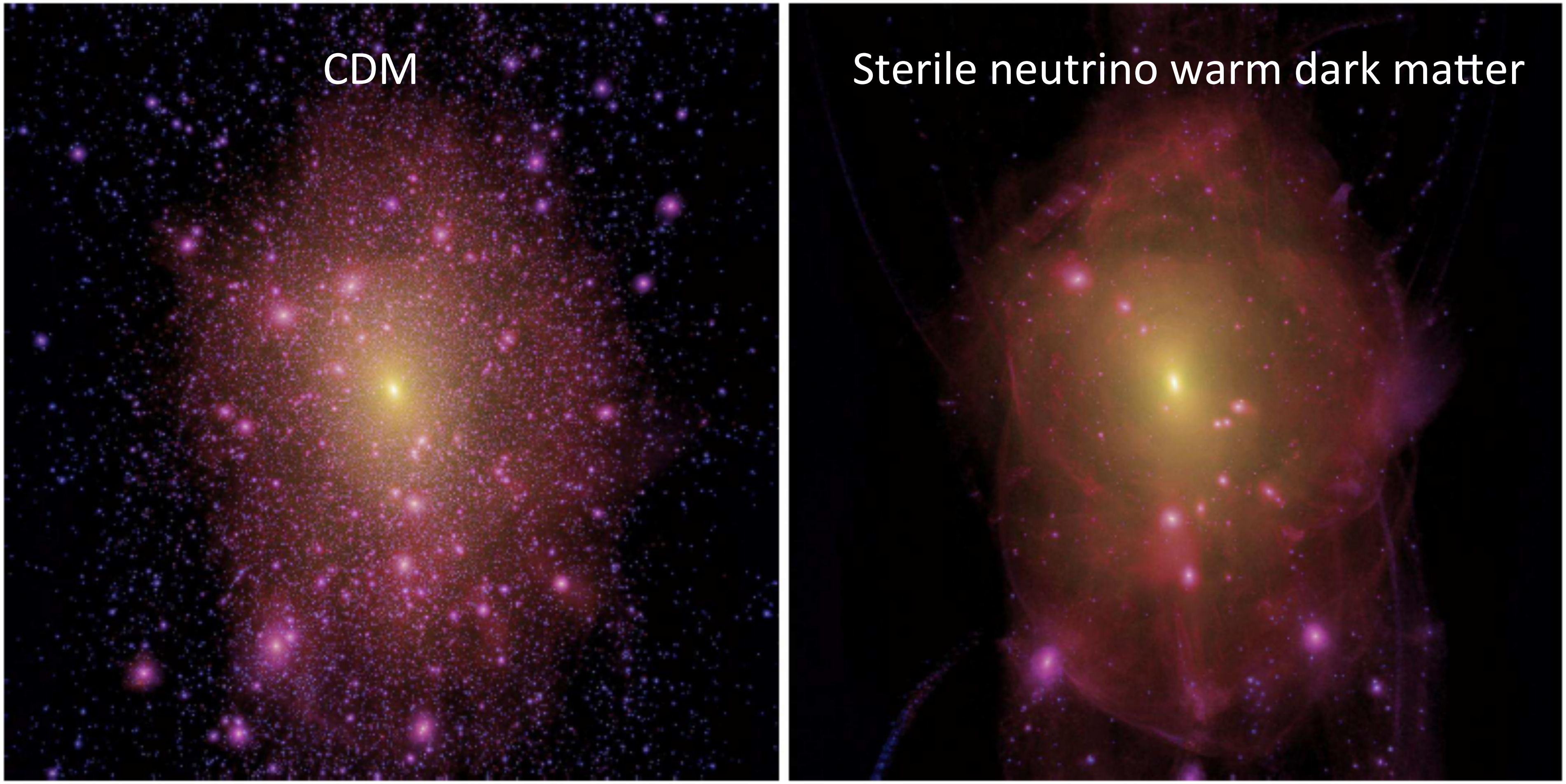
Similar cutoff occurs at lower mass than Dodelson-Widrow (DW):



3. "Decay" sterile neutrinos – **COLD**

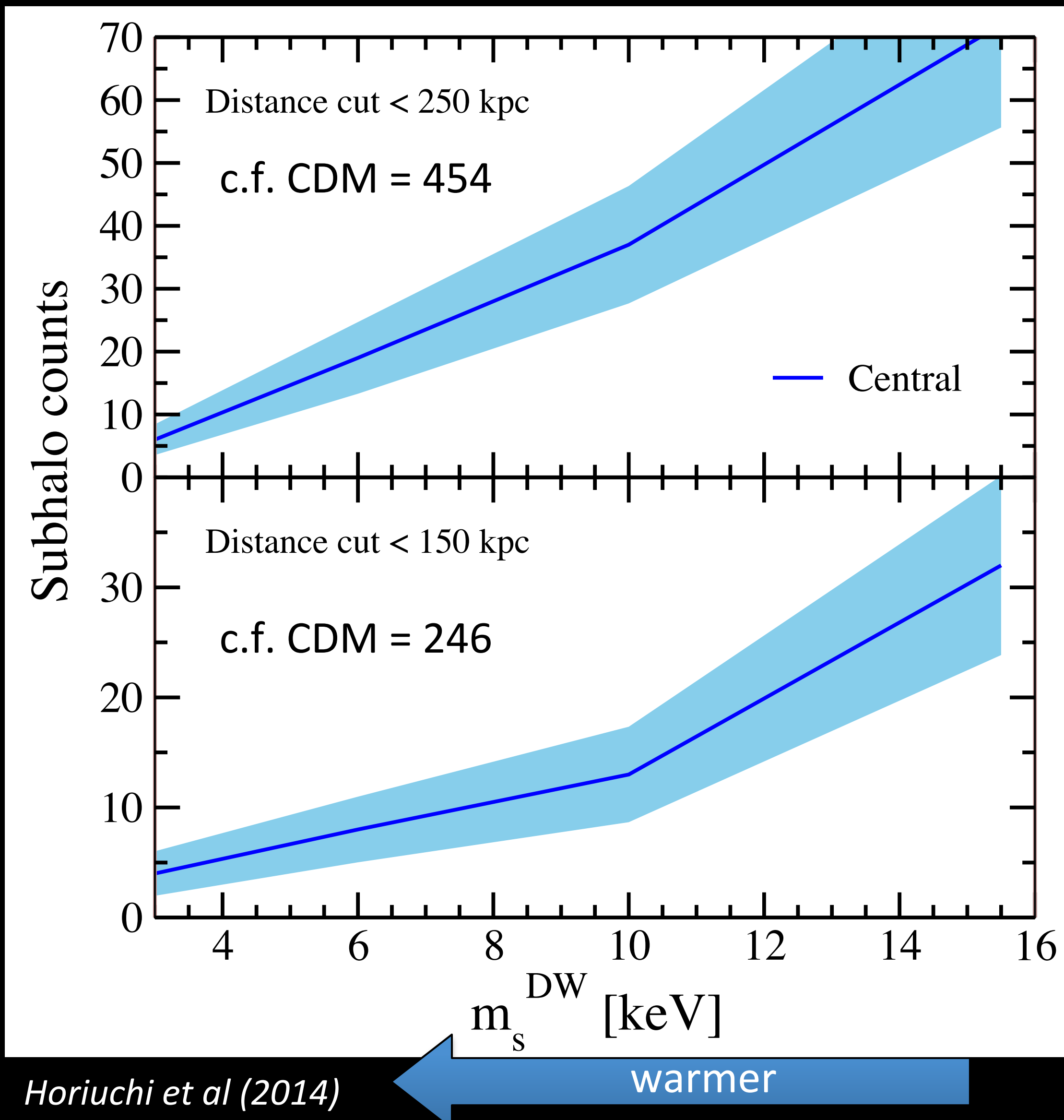
Venumadhav et al (2015)

Structures in sterile neutrino cosmology



Lovell et al (2012)
Based on a resonant sterile neutrino models in Boyarsky et al (2009)

Reduced, but sufficient, structure



Horiuchi et al (2014)

Simulations:

Smaller Dodelson-Widrow (DW) sterile neutrino mass results in less subhalos.

To estimate uncertainty use 44 Milky Way analogues in CDM

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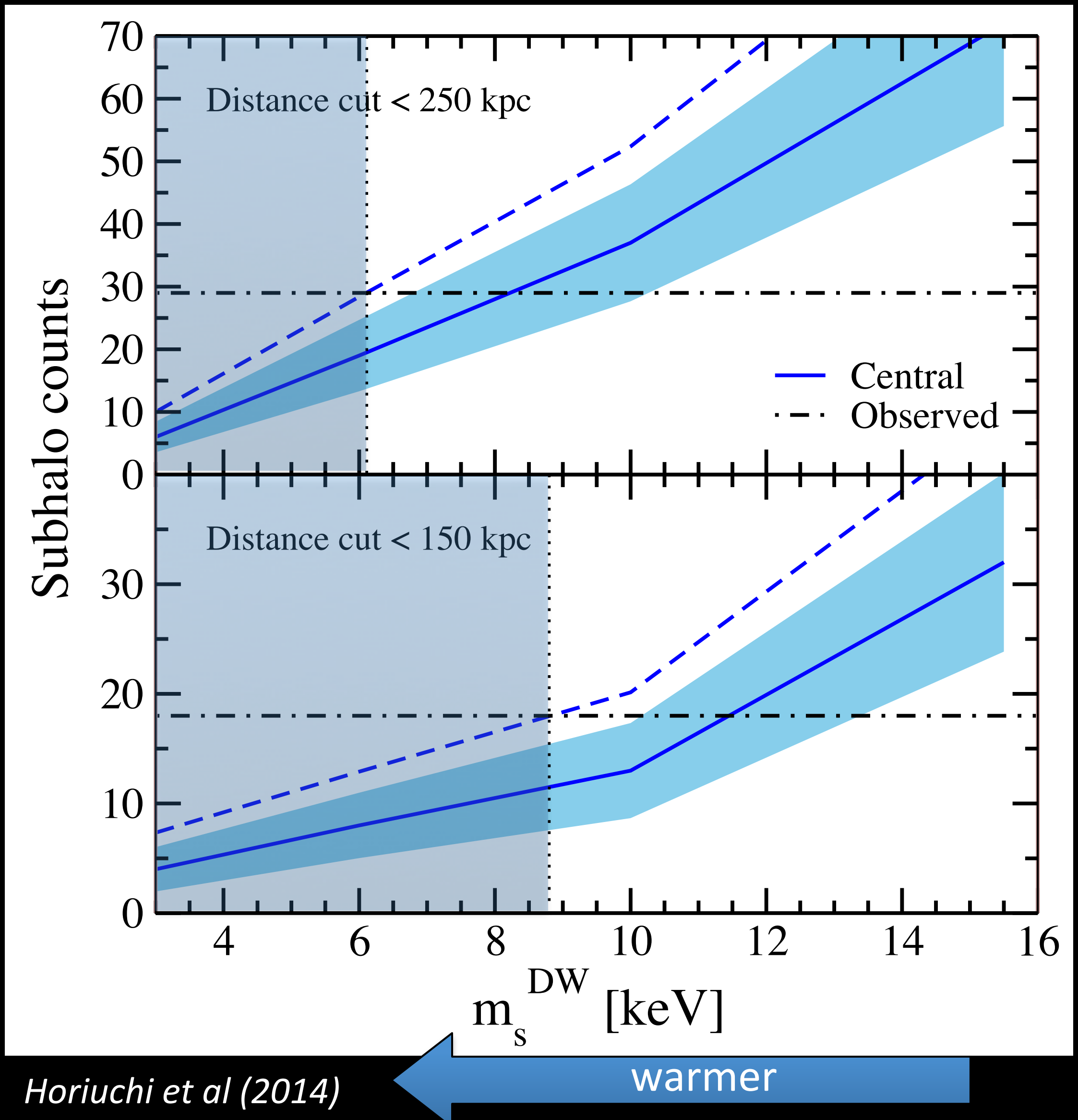

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Observation:

Panchromatic study of M31 reveals 18 (29) within 150 (250) kpc (and growing).

Richardson et al (2011)

Comparison yields limits of:

m_{DW} > 8.8 keV (95%CL)

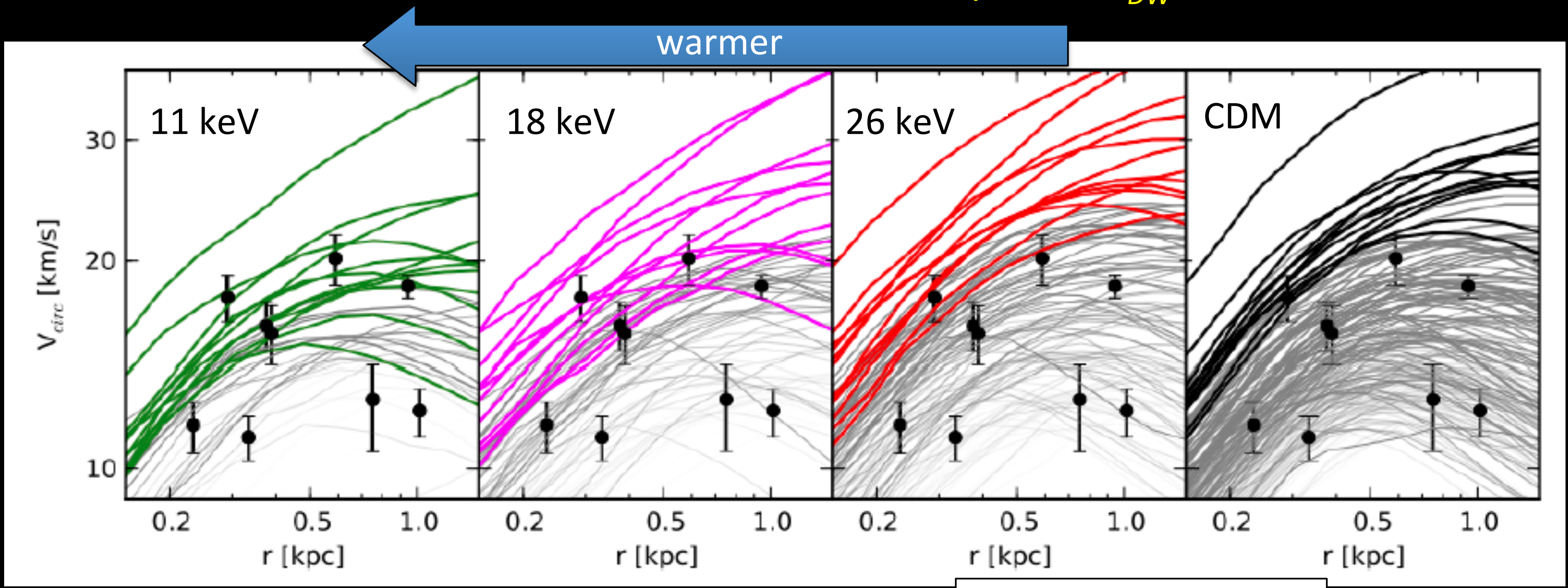
See also Polisensky & Ricotti 2011

Addressing the density problem

Sterile neutrino solution:

Delayed structure formation → less concentrated halos, effective by ~11 keV

→ Combined with satellite counts, *there is a sweet spot at m_{DW} ~ 10 keV*



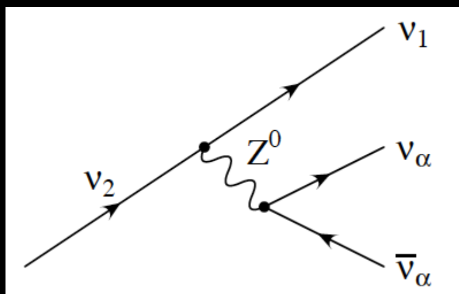
Schneider et al (2013); See also Lovell et al (2012)

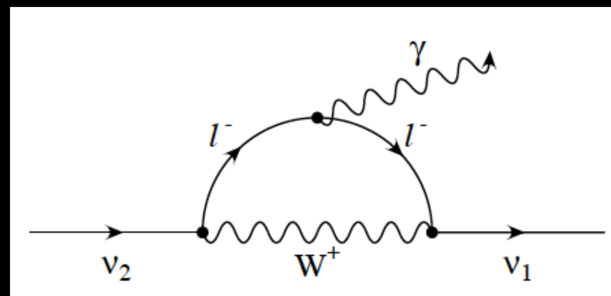
(~11 keV DW sterile)

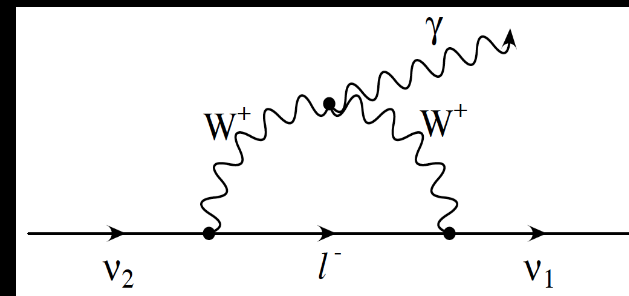
It seems that only the pure WDM model with a 2 keV [thermal] particle is able to match the all observations of the Milky Way Satellites: the total satellite abundance, their radial distribution and their mass profile [Too Big to Fail]. *Anderhalden et al (2013)*

X-ray considerations

Sterile neutrino decays:







radiative decay to active neutrino + photon

"ν_s" → "ν_a" + γ $\quad E_\gamma = m_s/2$

$$\Gamma_\gamma \approx 7 \times 10^{-33}\,\mathrm{sec}^{-1} \left(\frac{\sin^2 2\theta}{10^{-10}}\right) \left(\frac{m_s}{1\,\mathrm{keV}}\right)^5$$

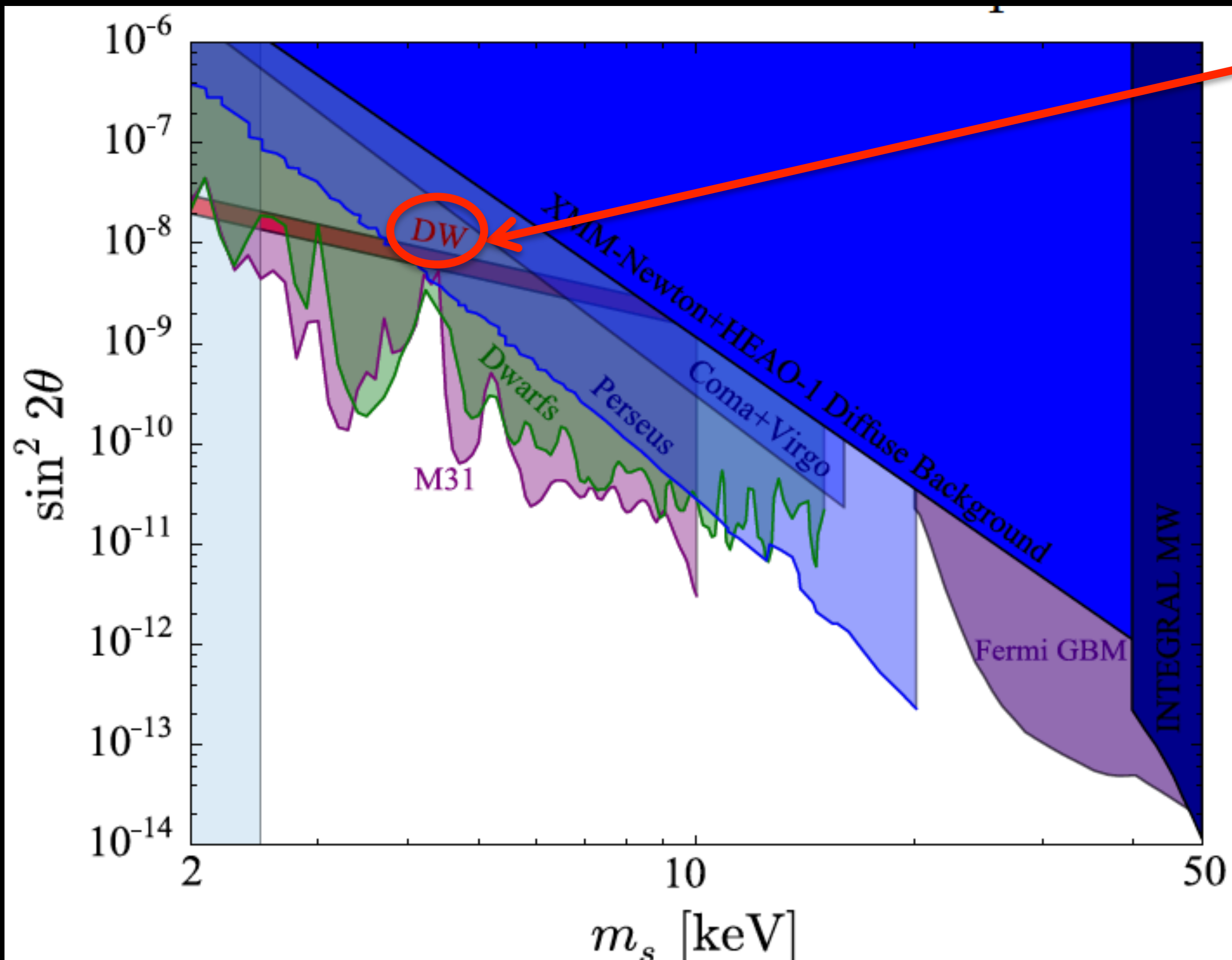
Abazajian et al (2001), and many others

Searches:

Many dark matter targets considered for x-ray telescopes.

Source	Pros	Cons
clusters	Photon statistics	ICM background
M31	proximity	Large ROI
MW	proximity	Rich background
dwarfs	Low backgrounds	Weak signal

Sterile neutrino parameter space



Abazajian, from IDM 2016

Dodelson & Widrow (DW): Combining limits, the DW parameter space is ruled out (>99%C.L.)

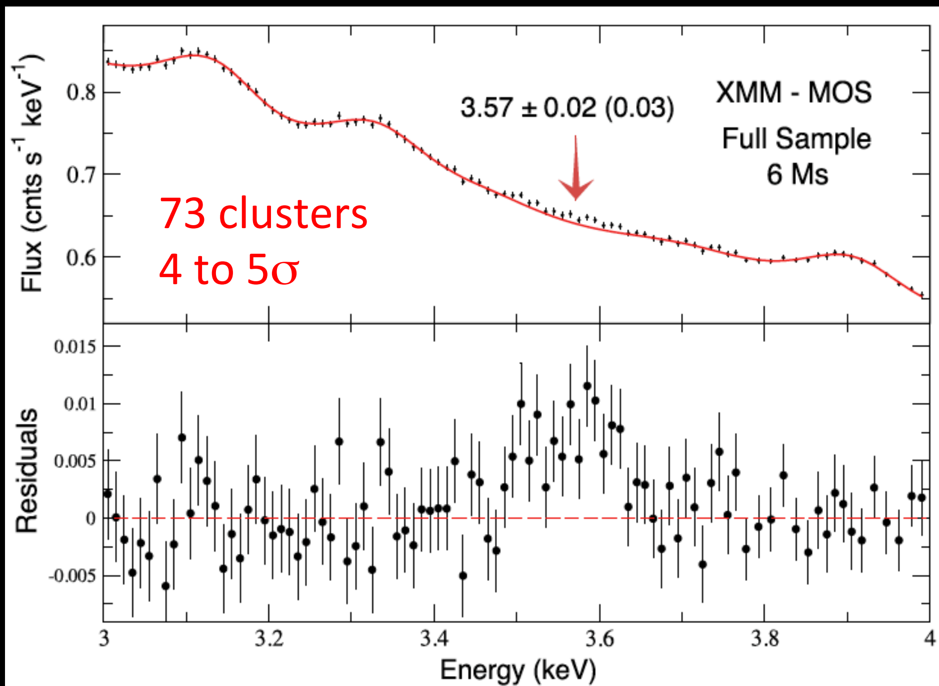
→ Sterile neutrino must be resonantly produced

Horiuchi et al (2014)

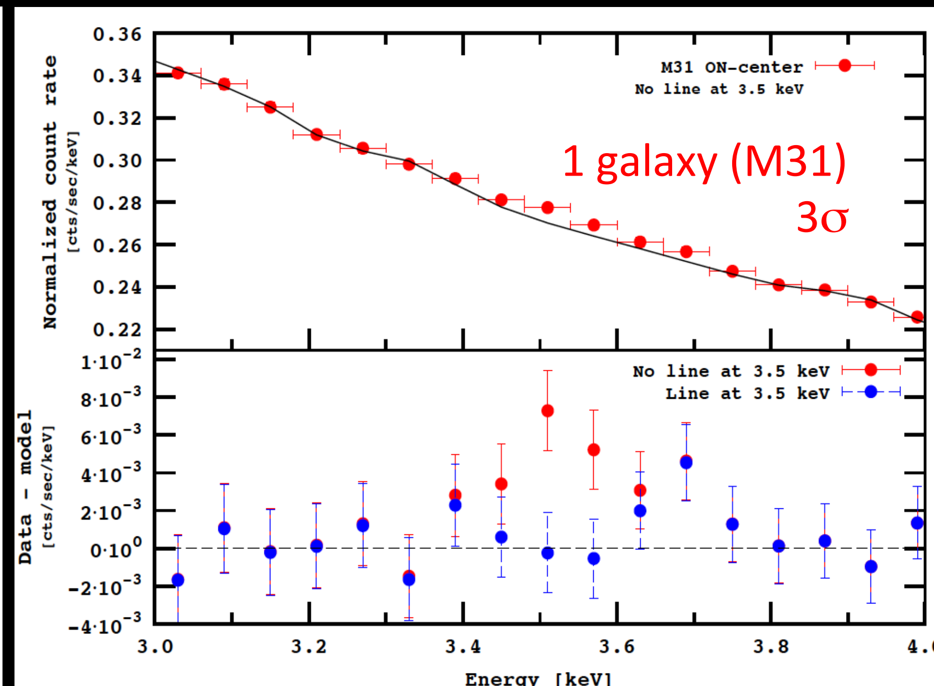
Anomalous X-ray line detections

Claims of anomalous X-ray lines from nearby dark matter concentrations

Bulbul et al (2014)



Boyarsky et al (2014)

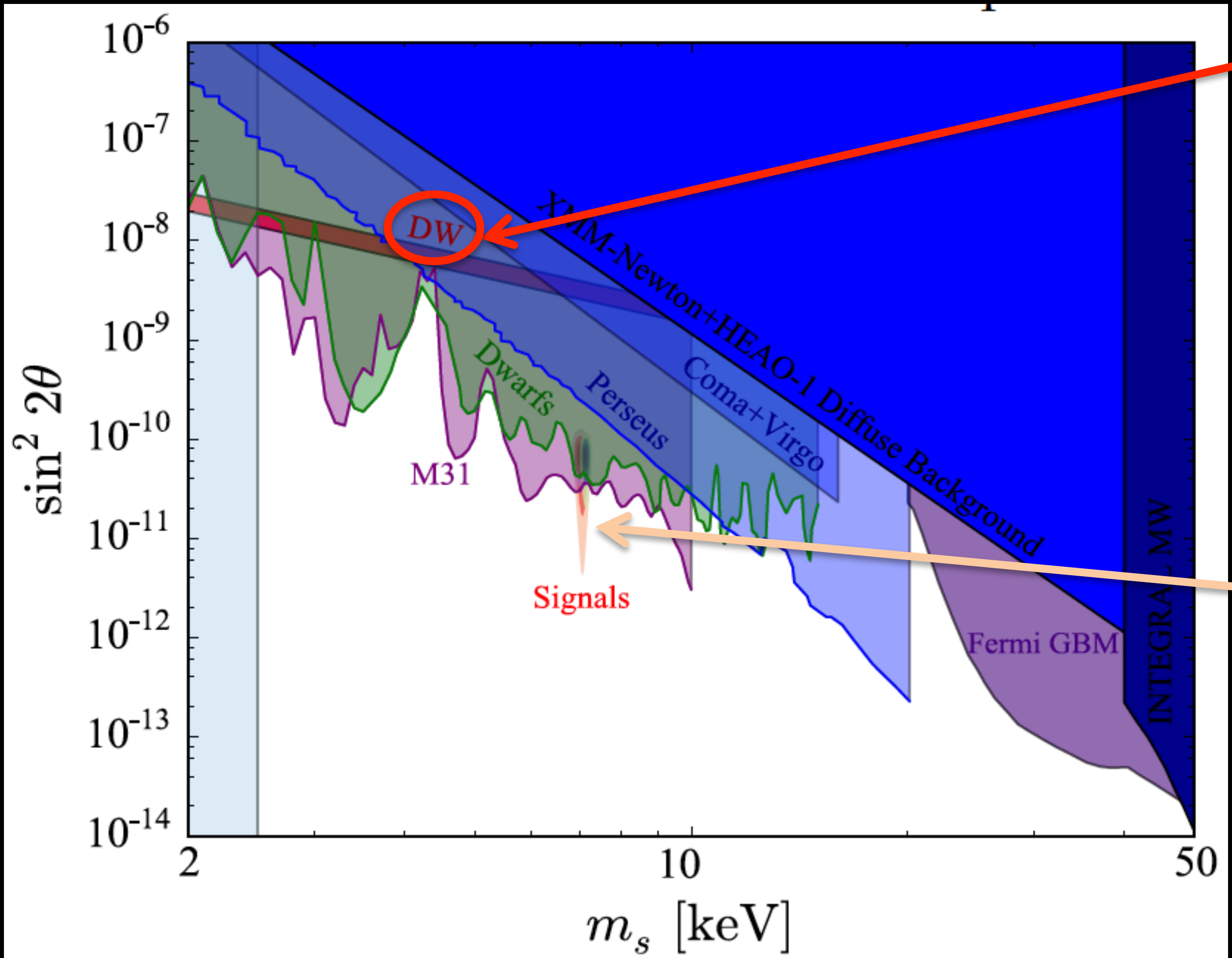


- **73 galaxy clusters stacked**
- Range z = 0.01 to 0.35
- 4 to 5σ detection with XMM-MOS
- Also see in XMM PN
- Also seen in **Perseus** with Chandra at 2.2σ

- **Perseus** indication at 2.3σ with XMM
- **M31** indication at 3σ with XMM
- Combined 4.4σ

+Milky Way, *Boyarsky et al (2015)*
+8 clusters, *Iakubovskyi et al (2015)*

Sterile neutrino parameter space



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Claimed signal:
Anomalous 3.5 keV line

Bulbul et al (2014)
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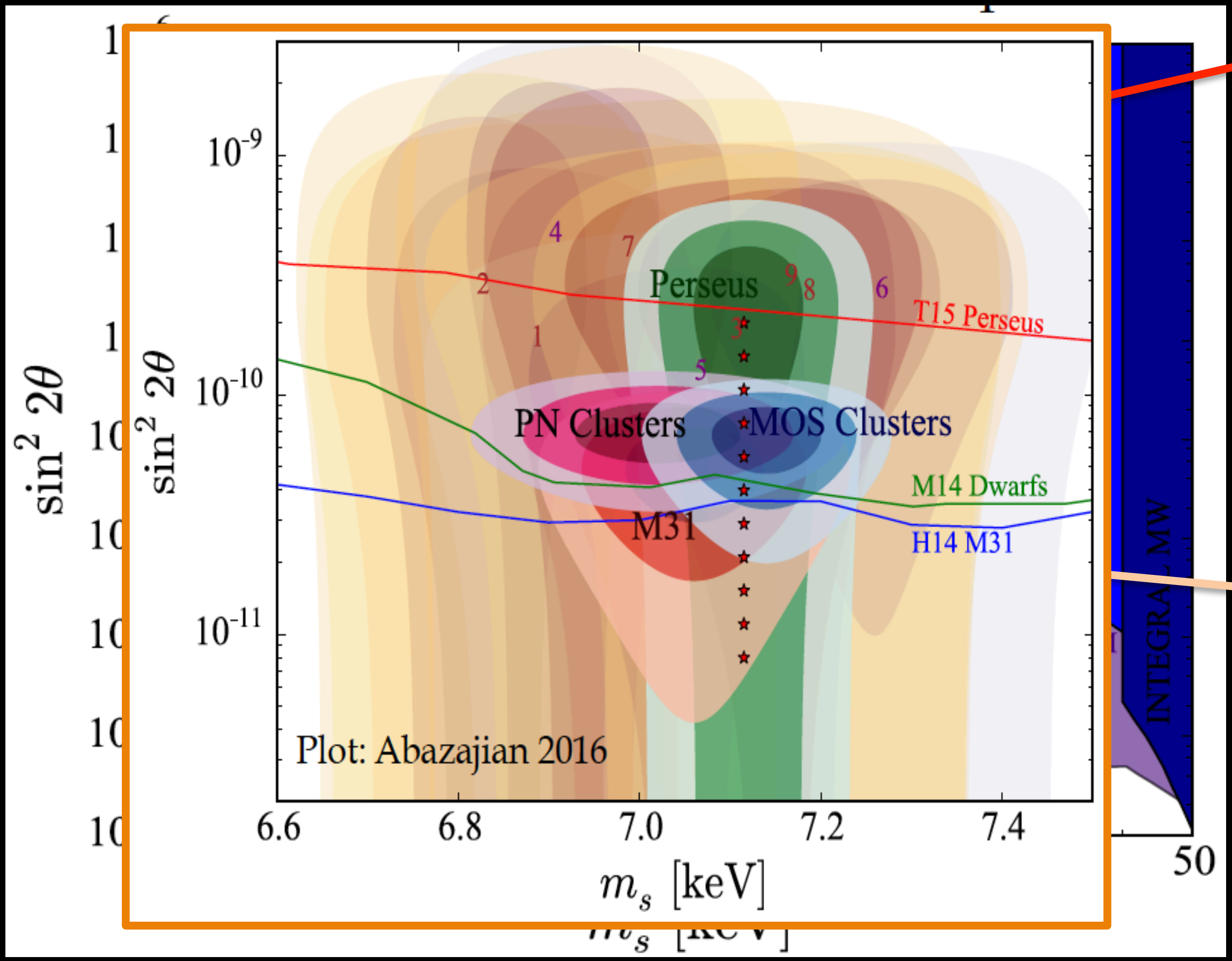
→ Consistent with decay of 7.1 keV resonantly produced sterile neutrino

Abazajian (2014)

Sterile neutrino parameter space



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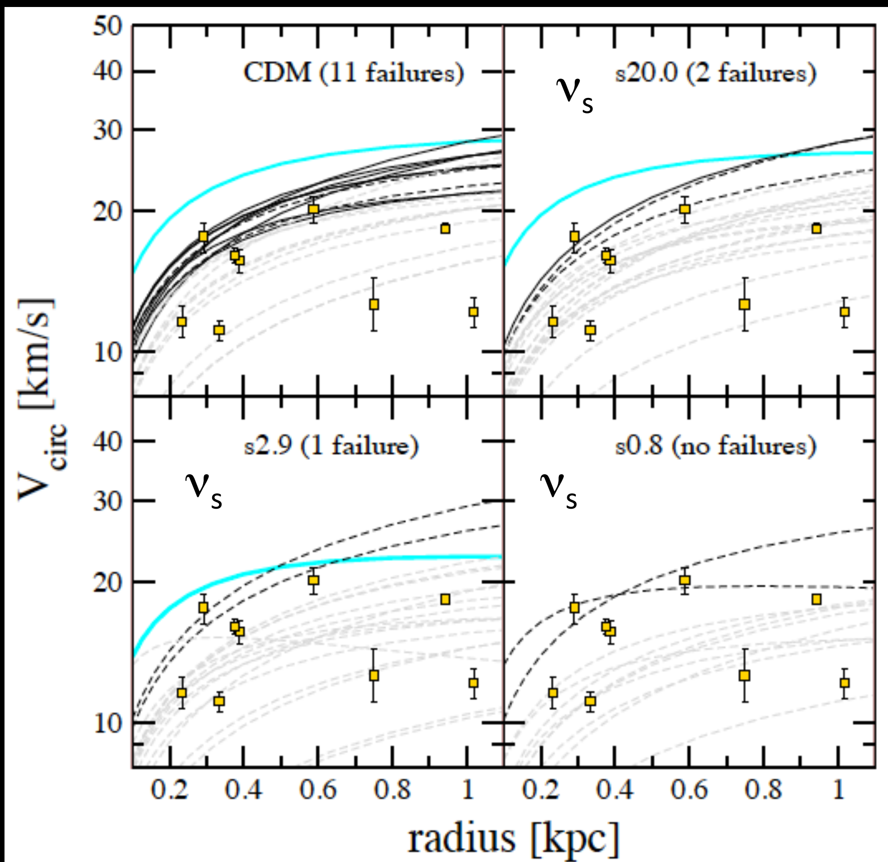
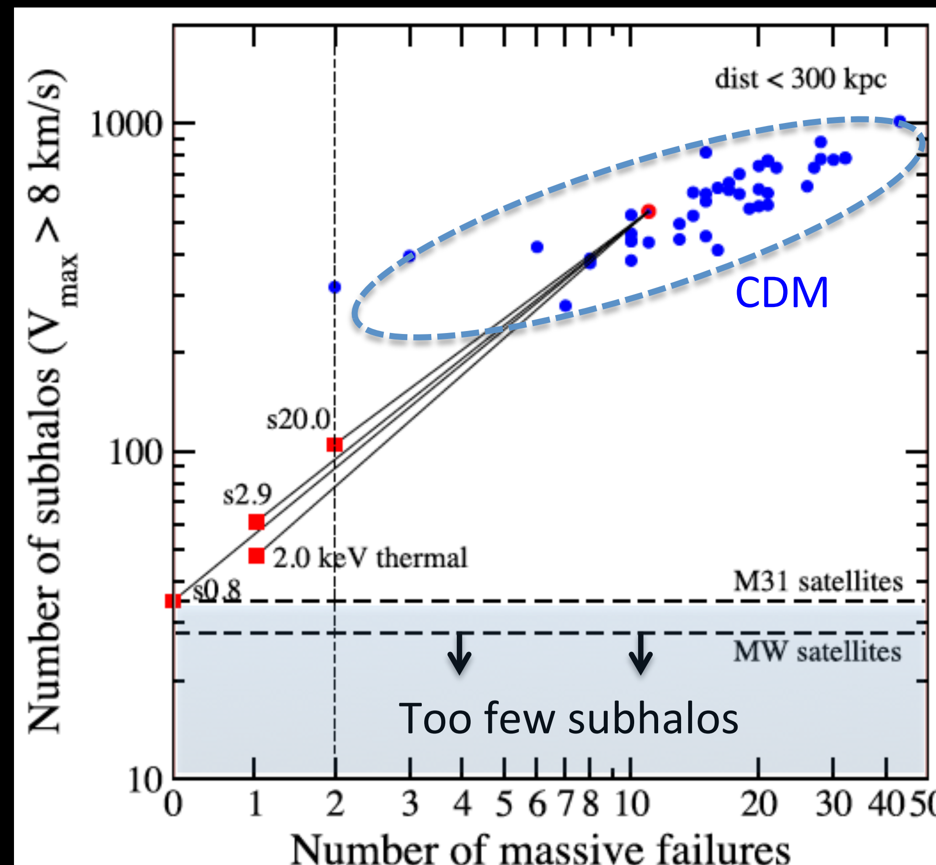
7.1 keV sterile neutrino cosmology

Inner structure:
Later halo formation times → reduced central density → better match to data



Horiuchi et al (2016)

Subhalo counts:
Suppressed small-scale power → reduced counts → better match to data



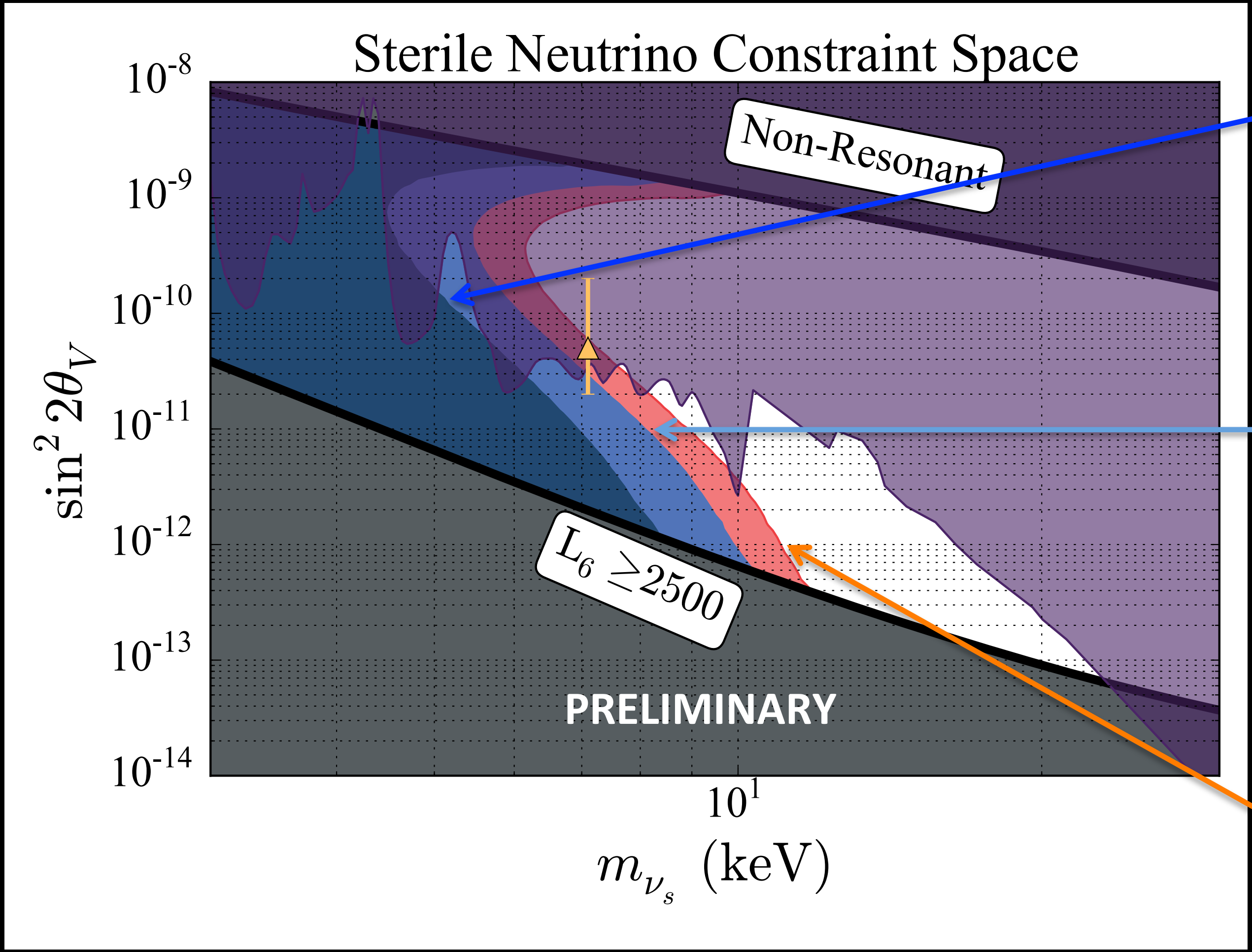
*Using updated production & matter power spectrum

Venumadhav et al (2015)

7.1 keV sterile neutrino in perspective

X-ray and satellite count limits:

The line is at the boarder of both limits



Conservative limit:
Only observed satellites, no sky coverage correction

Current limits:
From 11 classical dwarfs and 15 SDSS discovered dwarfs (correcting for 29% sky coverage)

Projected limits:
Using DES forecasts

Cherry & Horiuchi (in prep); see also Schneider (2016)

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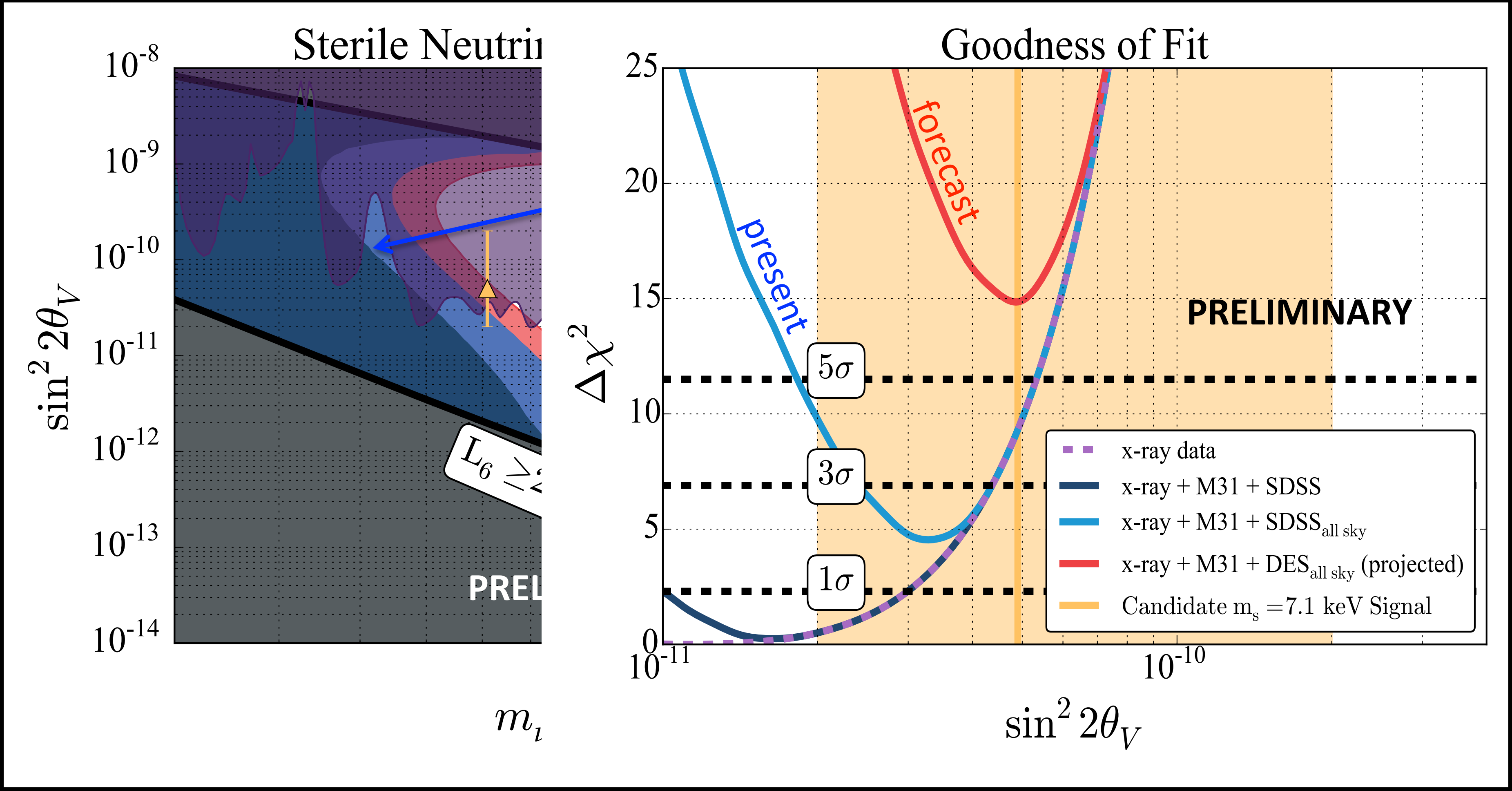

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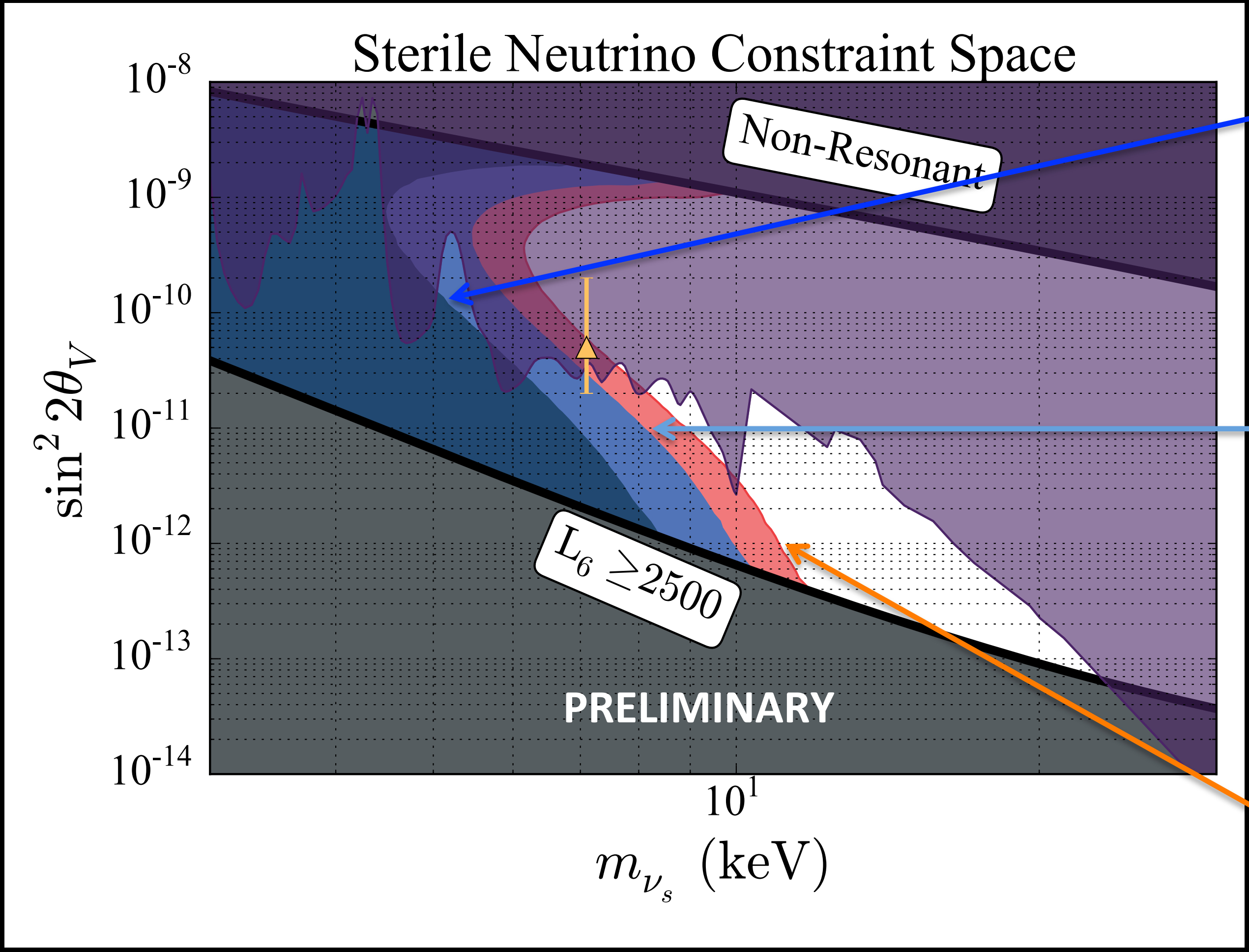

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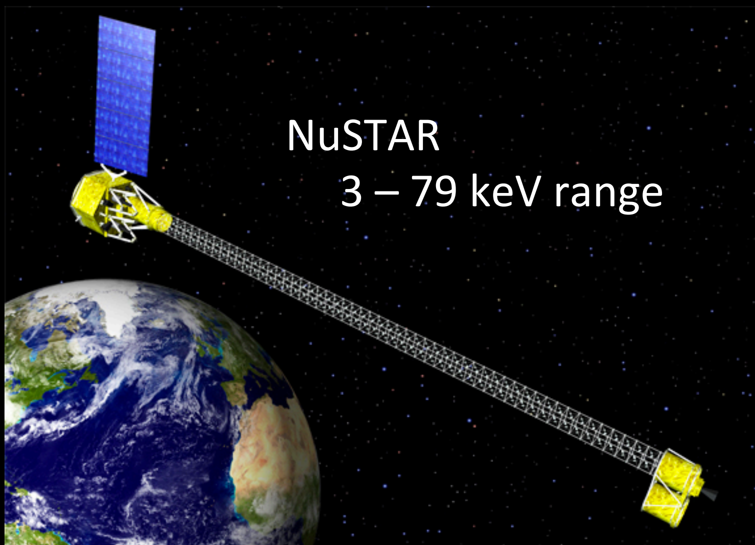
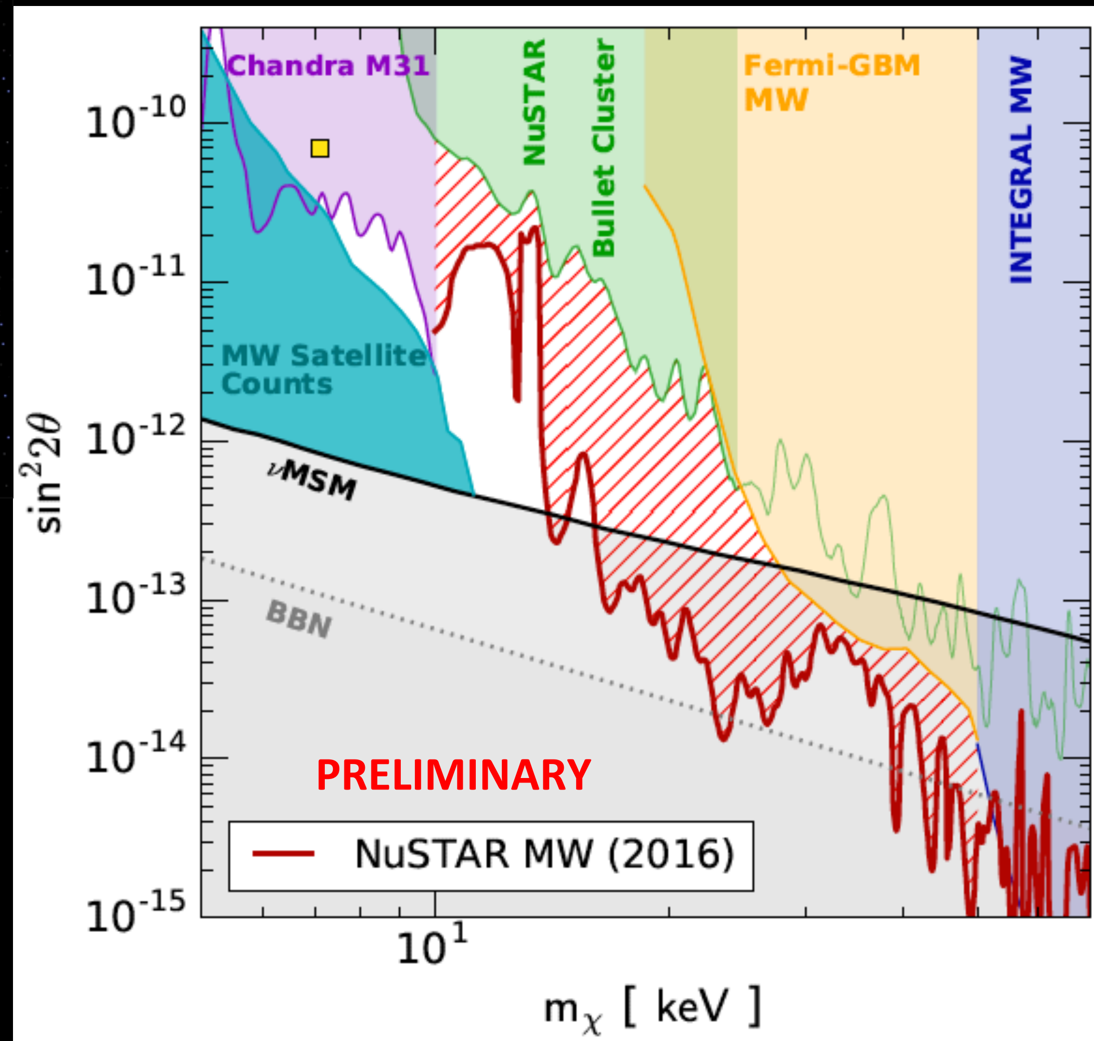
Closing the resonant production space



New GC analysis:
Using ~2 Ms observation of the inner 1.4° x 0.6° region

Improved sensitivity to >10 keV mass → rapidly closing in on remaining parameter space



With Beacom, Ng, Perez, Roman

Summary & take away messages

Sterile neutrino as dark matter candidate

- Sterile neutrino dark matter helps relax small-scale issues faced by CDM, but it must be in the sweet spot; otherwise, either the effect is too weak or there is insufficient small-scale power
- Sterile neutrino dark matter must be resonantly produced
- The parameter space is <u>closing from all</u> sides

3.5 keV line

- Claims of anomalous X-ray line can be interpreted as decays of sterile neutrino dark matter produced via Shi-Fuller resonantly enhanced oscillation
  - This sterile neutrino happens to be in the sweet spot to help solve small-scale issues in CDM
  - This is a <u>testable</u> scenario: by Milky Way (and M31) satellite galaxy searches

Interesting hints; on-going searches will provide great tests…stay tuned!

BACKUP SLIDES

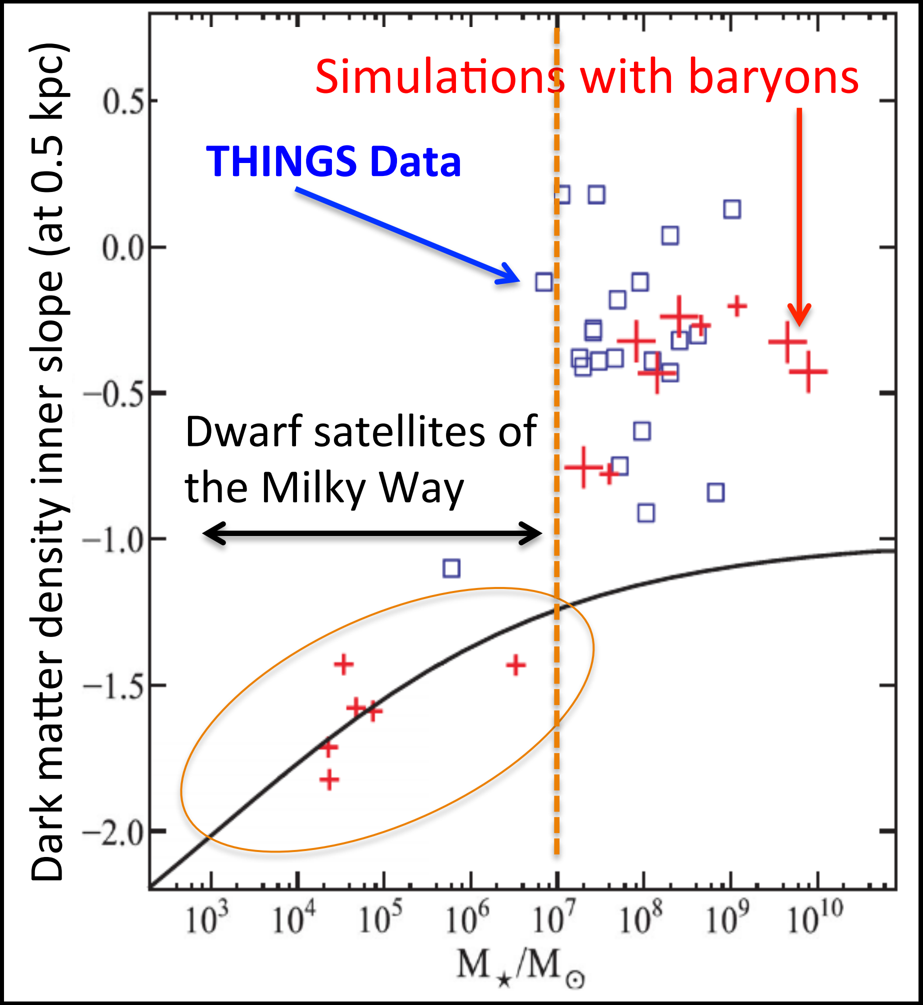
Baryon solution

Feedback is important: stars & supernovae blow baryons to outer radii, creating a less concentrated dark matter distribution *Navarro et al (1996), Madau et al (2014)*

But for many dSph galaxies:
No effect on the DM distribution, either due to lack of baryons & supernovae, or treatment of stellar feedback

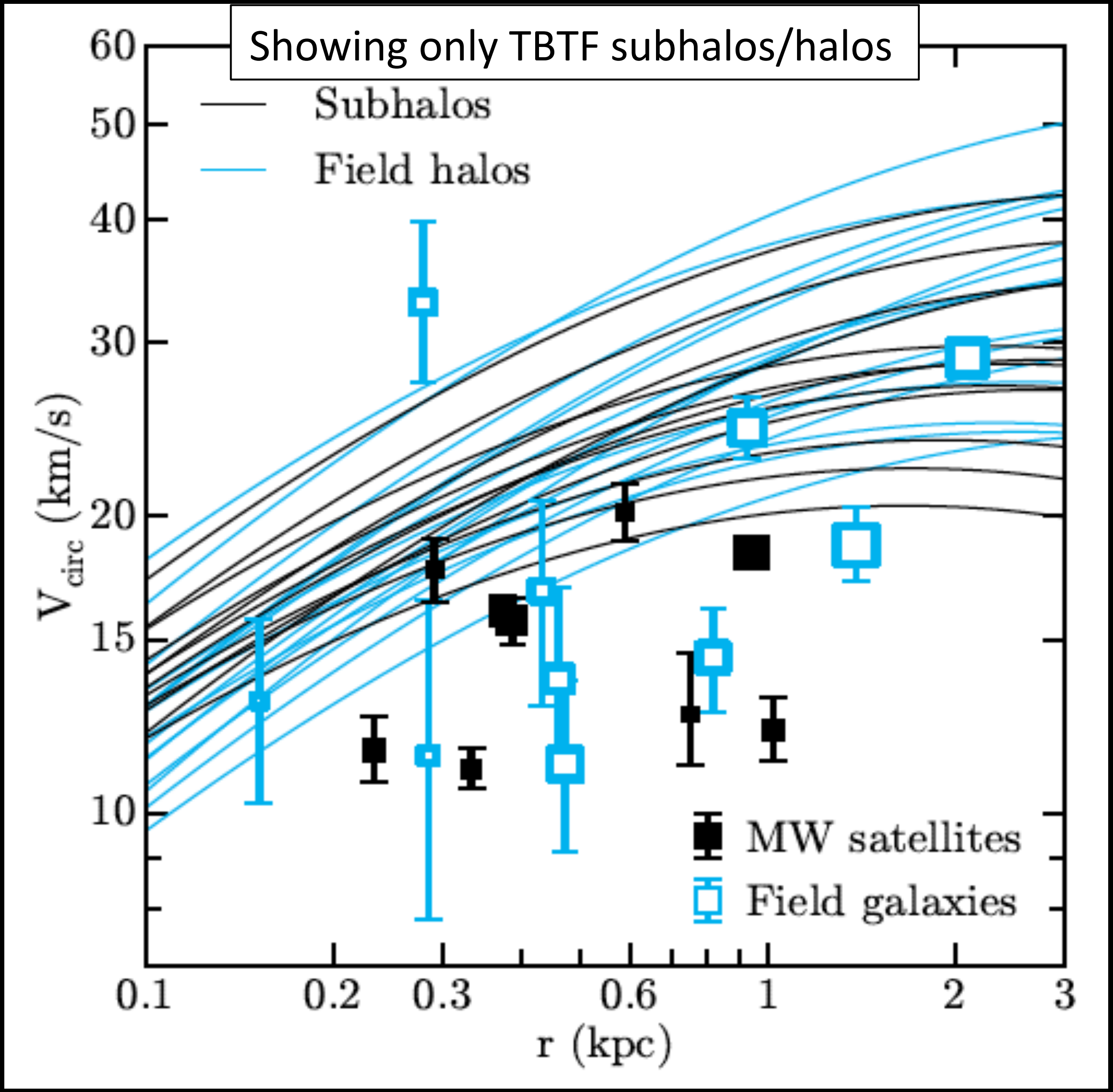
Peñarrubia et al (2012)
Zolotov et al (2012)
Garrison-Kimmel et al (2013)
Di Cintio et al (2014)
Vogelsberger et al (2014)
Onorbe et al (2015)

These galaxies are in the range of the "problematic" satellite galaxies of the Milky Way and M31.



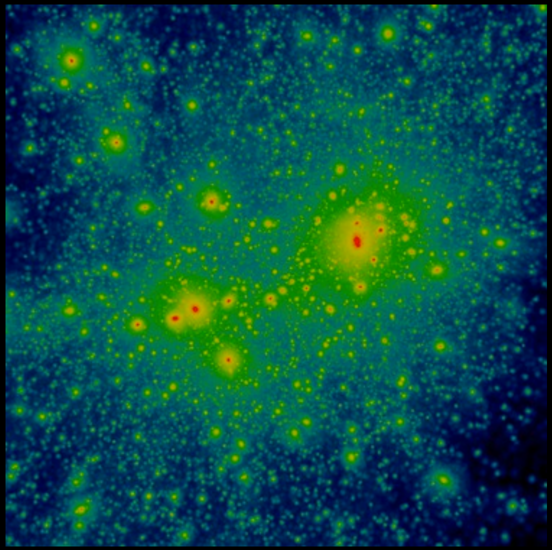
Governato et al (2012)

Too-big-to-fail in local field dwarfs



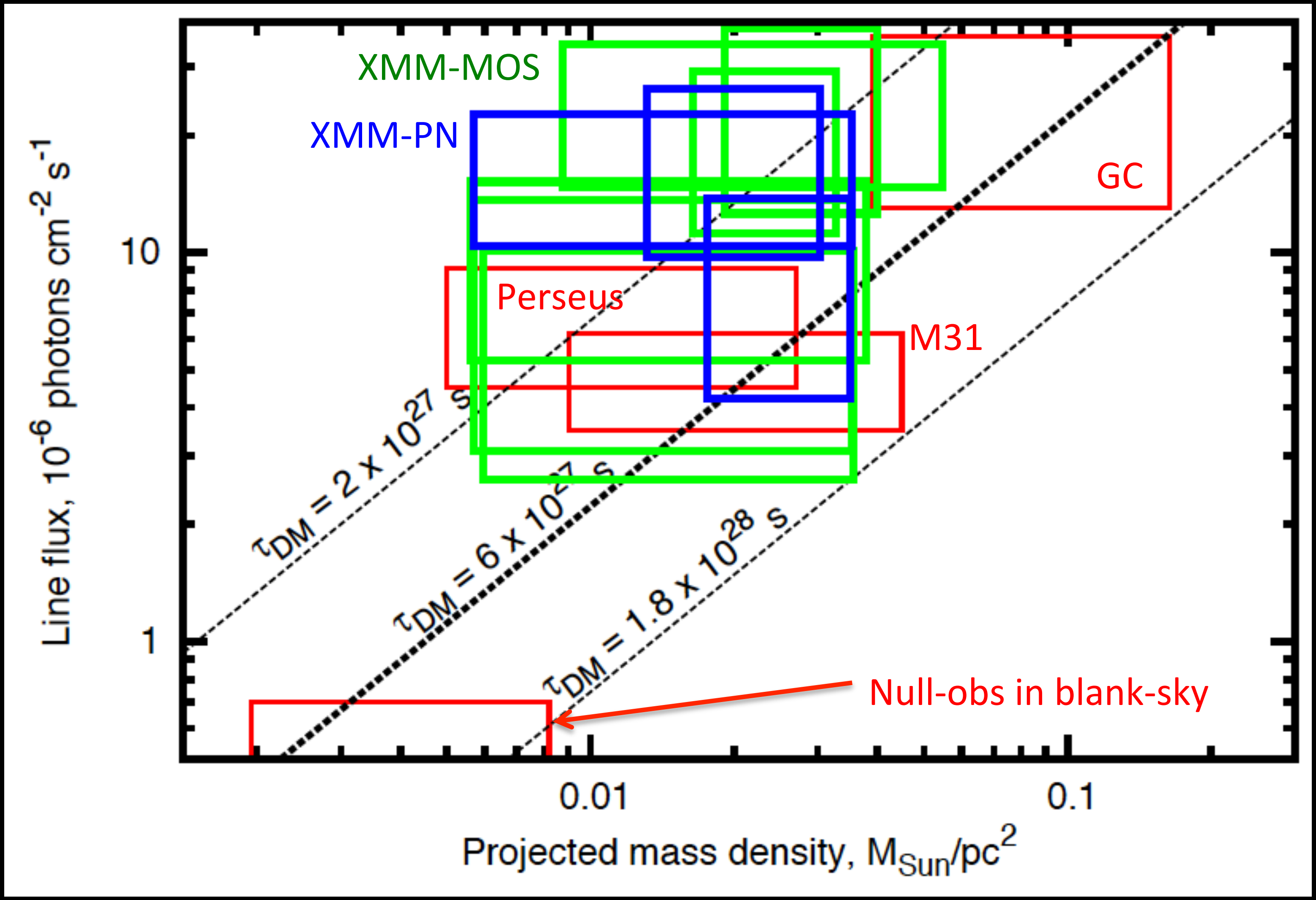
Garrison-Kimmel et al (2014)

The problem persists in the local field galaxies:
Many (>15) missing massive halos beyond the virial radii of the Milky Way and M31.
→ hard to appeal to environmental solutions.



See also, e.g., Ferrero et al (2012), Brook & Di Cintio (2015)

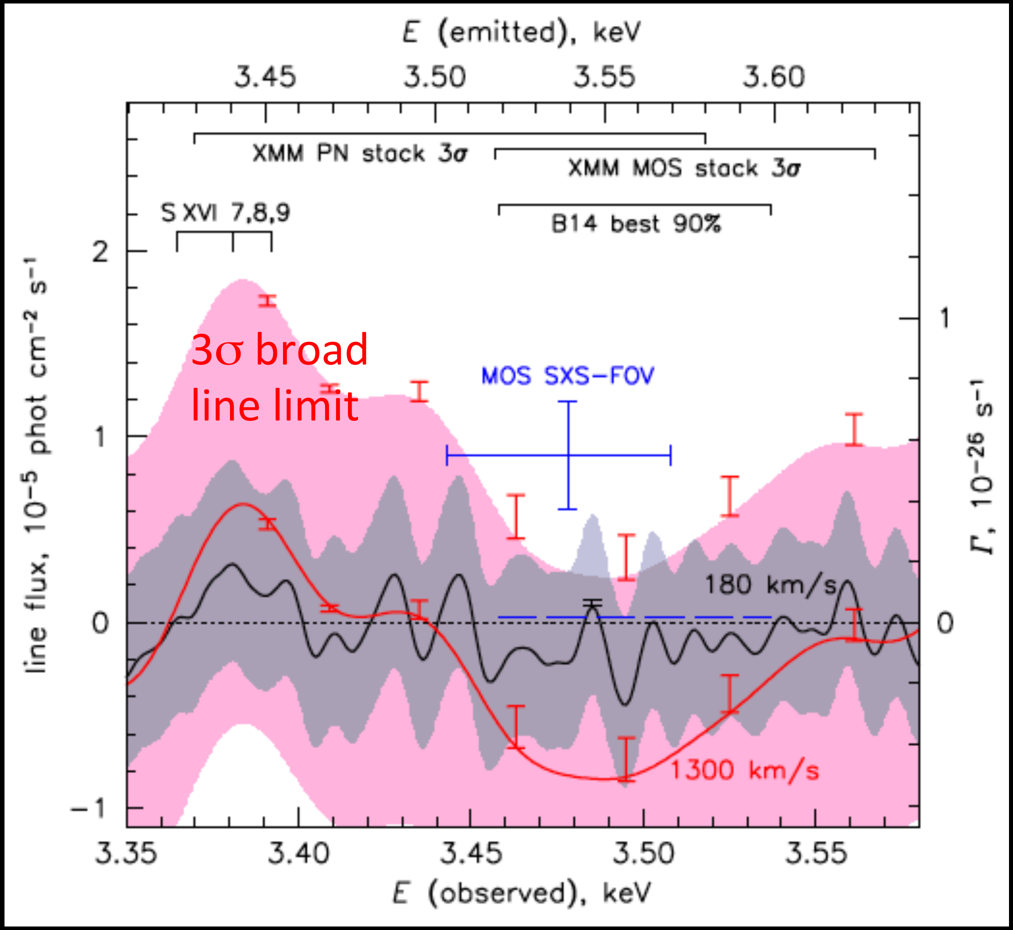
Decaying dark matter interpretation



Iakubovskyi et al (2015); see also Boyarsky et al 2014

Hitomi satellite

- Consistent with no 3.5 keV excess line
- Inconsistent with past Perseus line (99%CL)
- Consistent with mean line flux



March 26th: "*…anomaly in attitude control system…. JAXA ceased efforts to recover the satellite and turned to investigating the cause of the anomaly.*" – JAXA

But there was ~70 ks of Perseus data

Hitomi (2016)