Neutrinos: the quest for a new physics scale, March 27-31st 2017

The status of sterile neutrino dark matter

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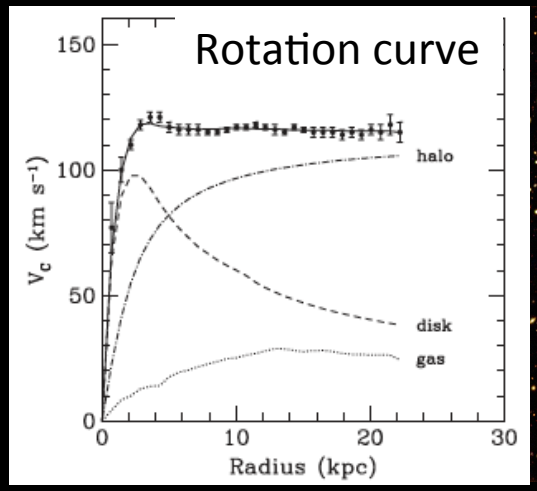
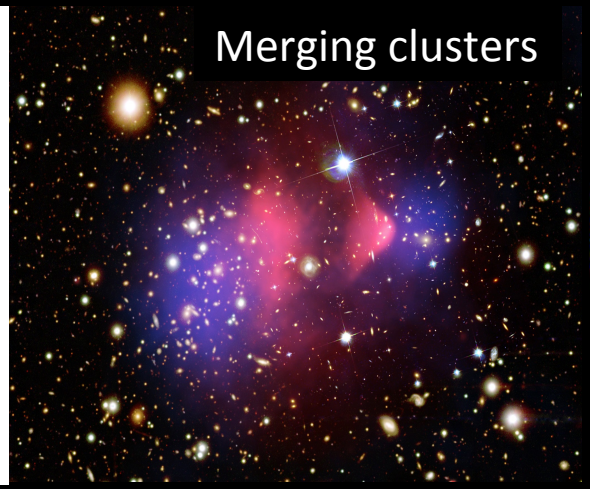
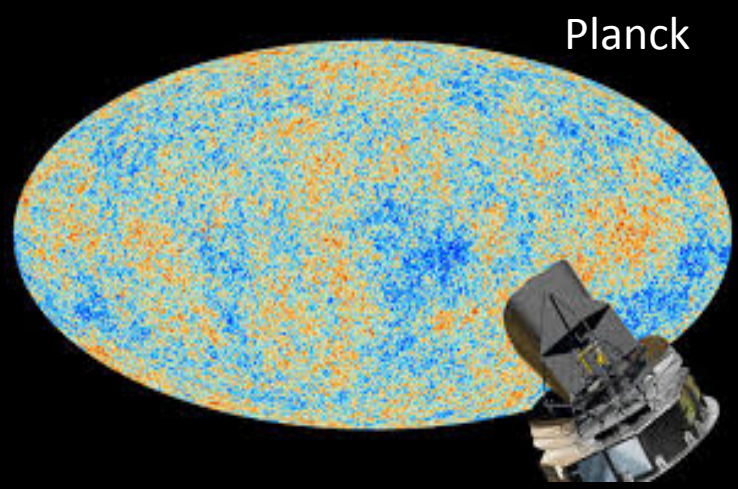
Rich evidence for dark matter

Multiple evidence

Data on various scales point to the presence of dark matter







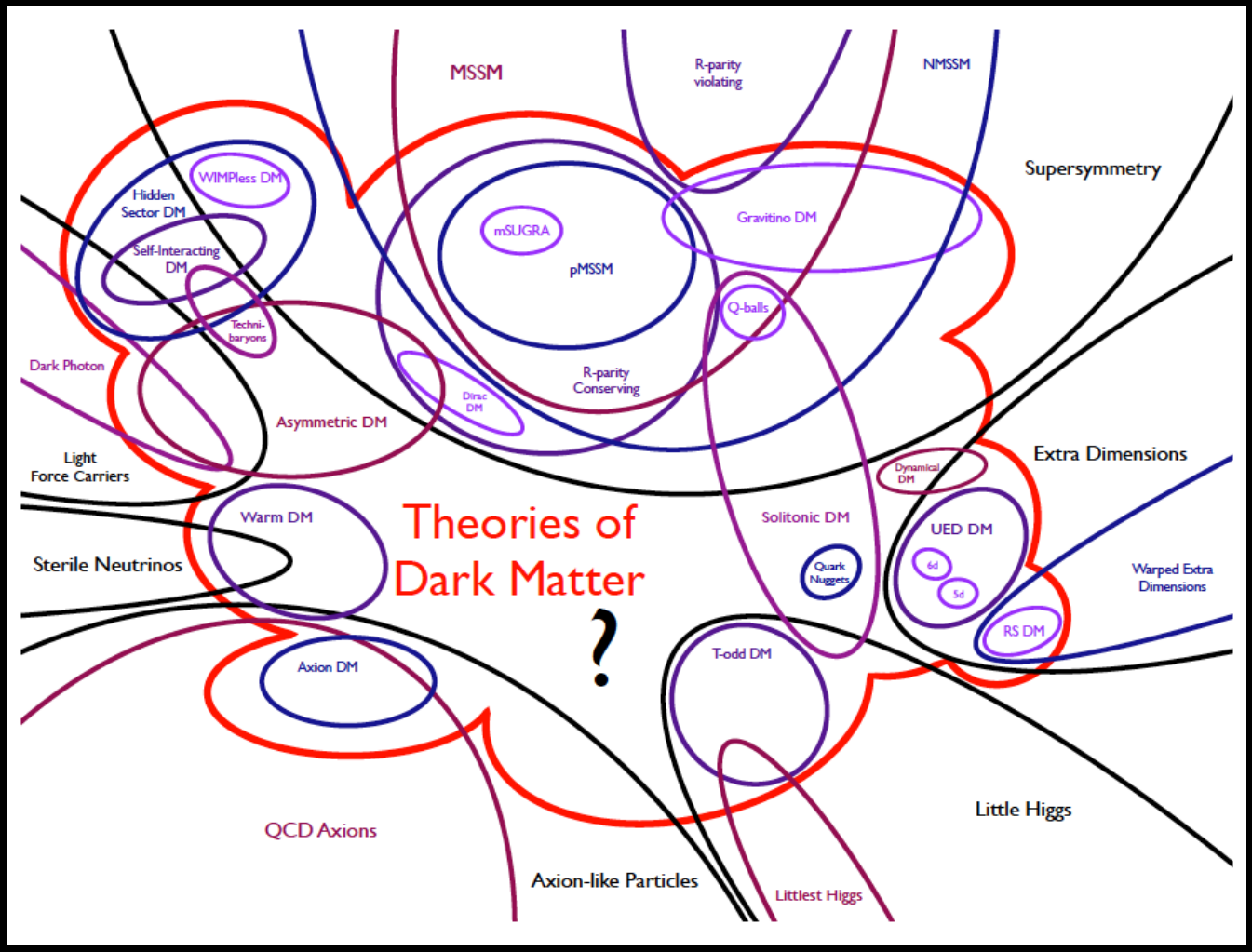
Cosmological simulations with *collisionless cold dark matter (CDM)* match the observed large-scale structure very well

➔ **Motivate massive, stable particles with gravity + weak or no other interactions**

Active neutrinos? Too light, hot dark matter

Dark matter needs new physics

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



Snowmass; Kusenko et al arXiv:1310.8642

Sterile neutrino dark matter

Sterile neutrino

Right-handed 'sterile' neutrinos, can be dark matter in some range of parameters.
Additional interaction necessary to produce them as dark matter.

Production

Sterile neutrino dark matter can be **COLD** or **WARM** or highly non-thermal depending on their production mechanism:

1. Mix with active neutrinos?

$$|\nu_e\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$

$$|\nu_s\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle$$

   → Active-sterile mixing: warm to cold, non-thermal
2. Yukawa coupling to new scalar field?
   → New scalar decays: cold
3. Charged under some gauge group?
   → Thermal produced, then diluted: cold

Non-thermal production

mass > ~400 eV

- Smaller masses violate phase-space packing constraints (Pauli principle)

$$\frac{\rho}{m_s} F_s \leq \frac{g_s}{(2\pi)^3}$$

Observed macroscopic coarse-grained packing

Maximum allowed packing

Tremaine & Gunn (1979)

Active-sterile mixing angle small

- Equilibrium will overproduce dark matter

$$m_\nu n_\nu \approx (0.5\,\mathrm{keV})(112\,\mathrm{cm}^{-3}) \gg \rho_{\mathrm{crit}}$$

- Produce sterile neutrinos out of equilibrium
  - Departure from Fermi-Dirac

Oscillation based production

1. Dodelson-Widrow (non-resonant) mechanism – **WARM**

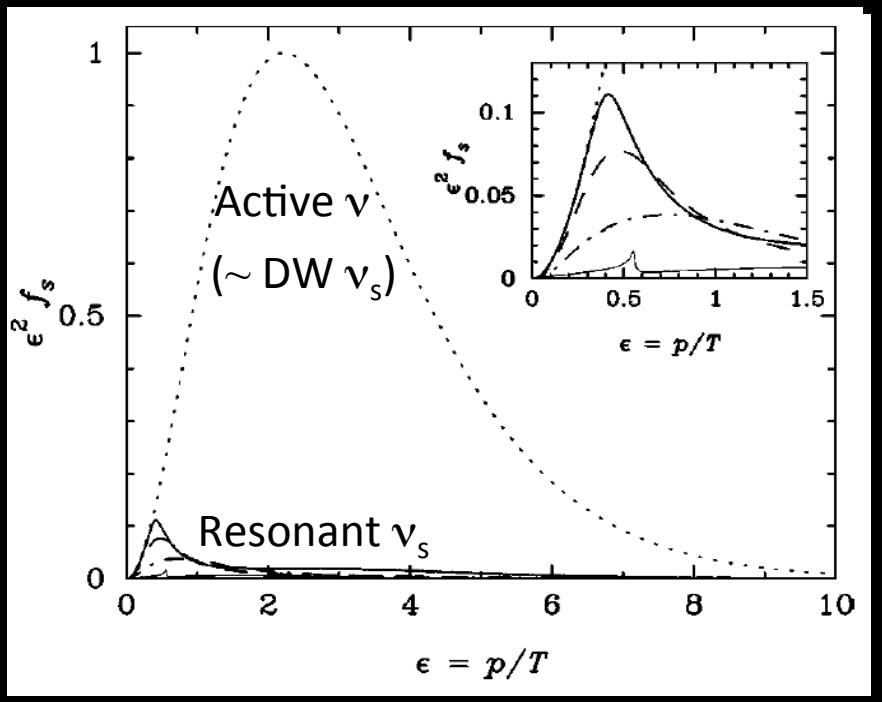
Dodelson & Widrow (1994)
Dolgov & Hansen (2002)

Scattering induced de-coherence builds up a density of sterile neutrinos – always on, peaks *O*(100) MeV

To within ~20% a thermal shape with:

$$f_{\rm NRP}(p) = \frac{g\chi}{e^{p/T_\nu}+1}$$

Asaka et al (2006)
Boyarsky et al (2009)



2. Lepton number enhanced resonant mechanism – **LESS WARM**

Shi & Fuller (1999)

Mass-level crossing in L asym ~ 10^{-5}

→ Allows smaller mixing angles & lower mass than DW scenario

Lepton asymmetry can be made by other sterile neutrinos: νMSM

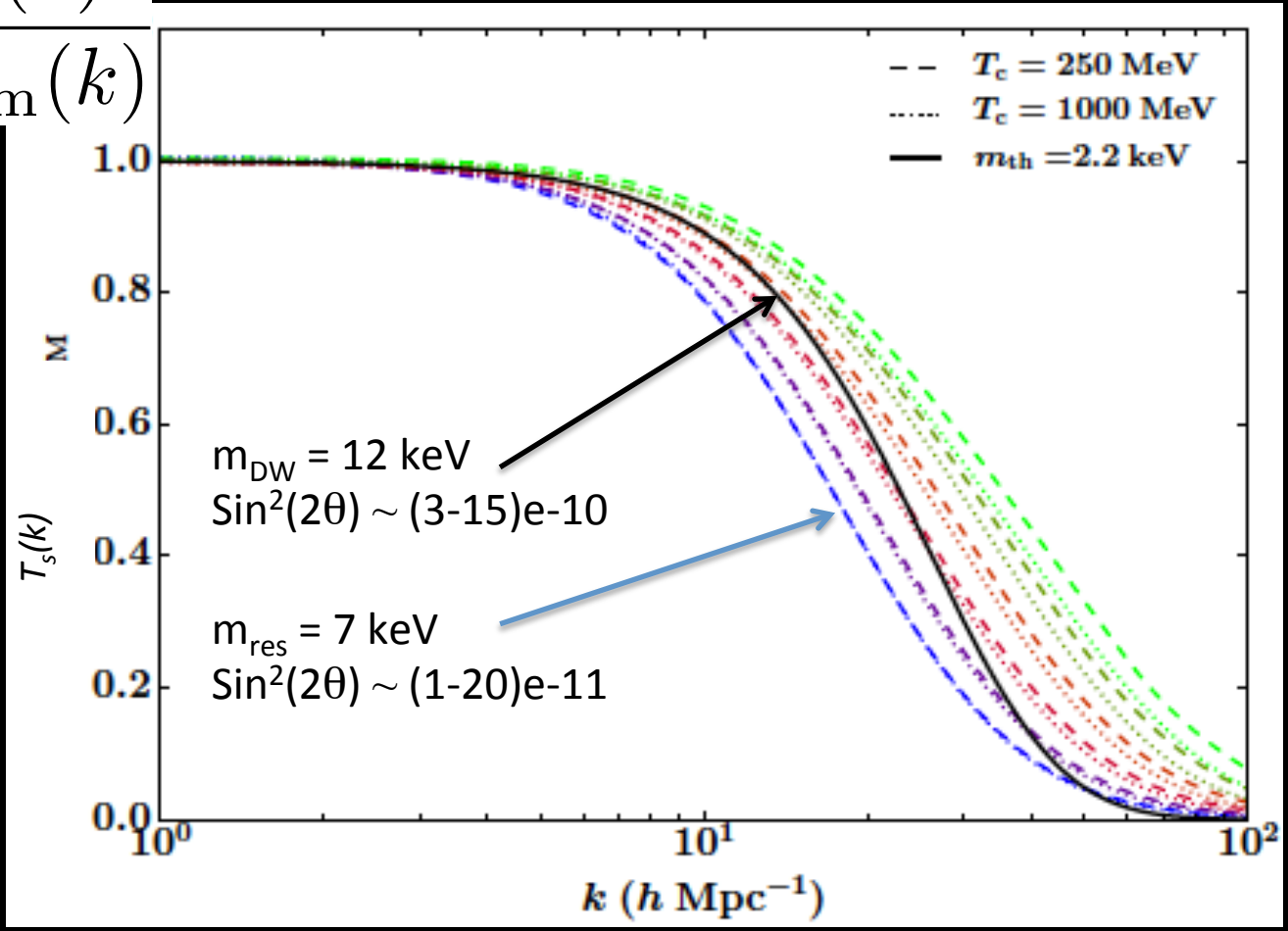
Asaka & Shaposhnikov (2005)

Non-resonant & resonant production

Transfer function:

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

Resonant production allows smaller mixing angles & lower mass for equivalent DW production



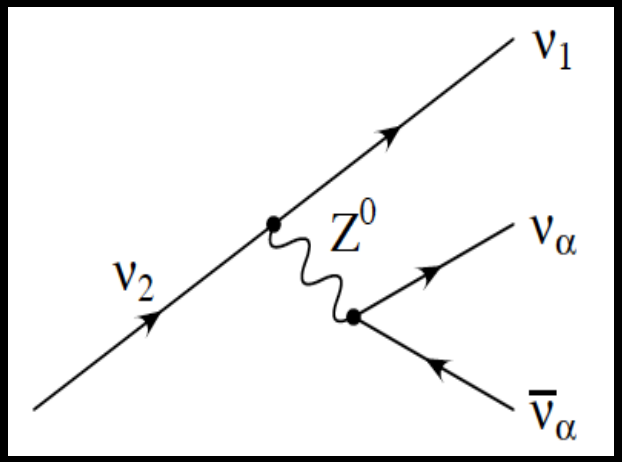
Venumadhav et al (2015); see also Ghiglieri & Laine (2015)

Sterile neutrino decay

Sterile neutrino decays

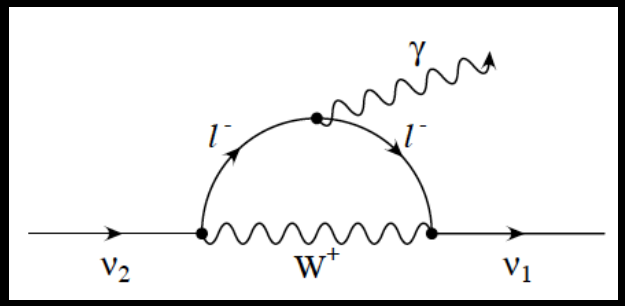
Applicable with mixing, regardless of production mechanism.

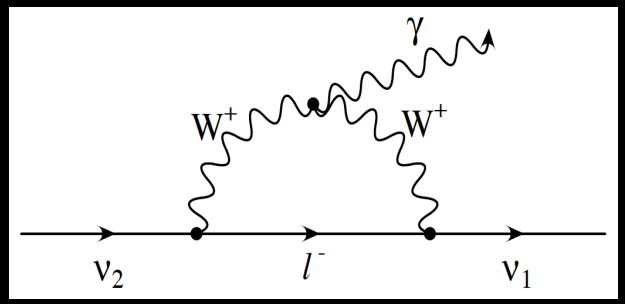
Small mixing angle ensures long lifetime



Responsible for setting lifetime

Good detection prospects: radiative decay to active neutrino + photon





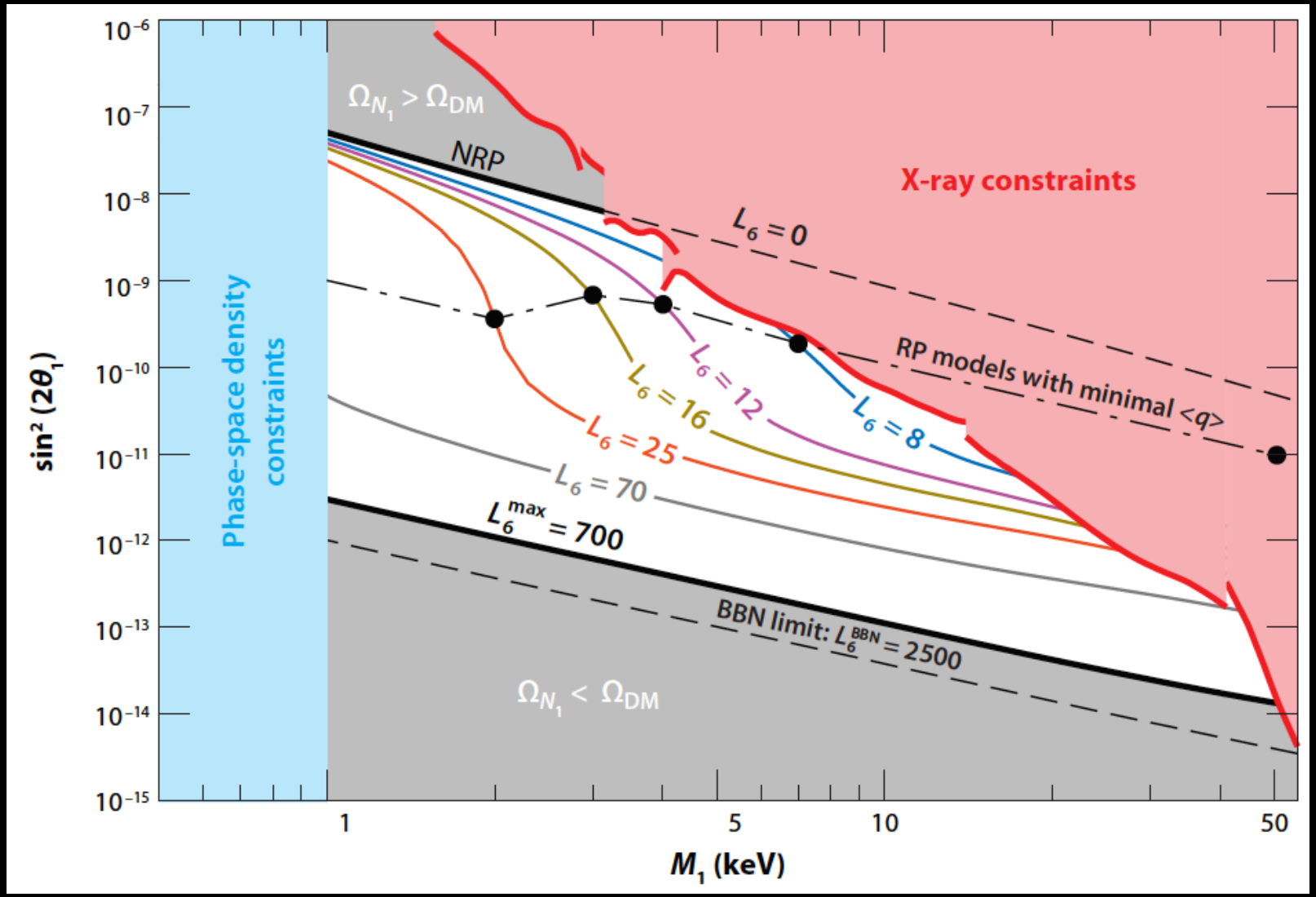
"ν_s" → "ν_a" + γ

$$E_\gamma = m_s/2$$

$$\Gamma \sim 10^{-32}\,\mathrm{s}^{-1}\left(\frac{\sin^2 2\theta}{10^{-10}}\right)\left(\frac{m_s}{1\,\mathrm{keV}}\right)^5$$

Abazajian et al (2001), and many others

Probes coming from all sides



Boyarsky et al (2009)

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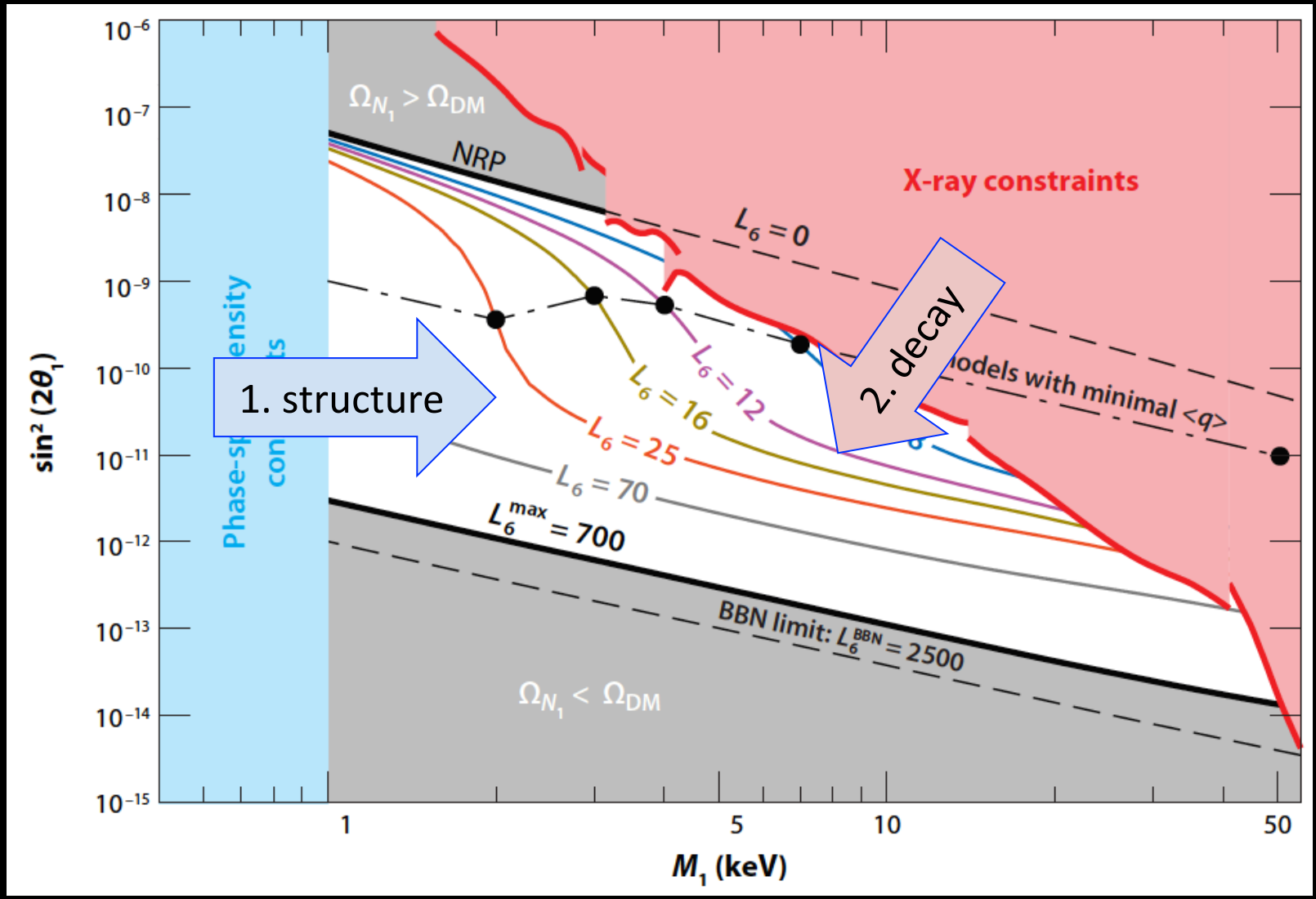

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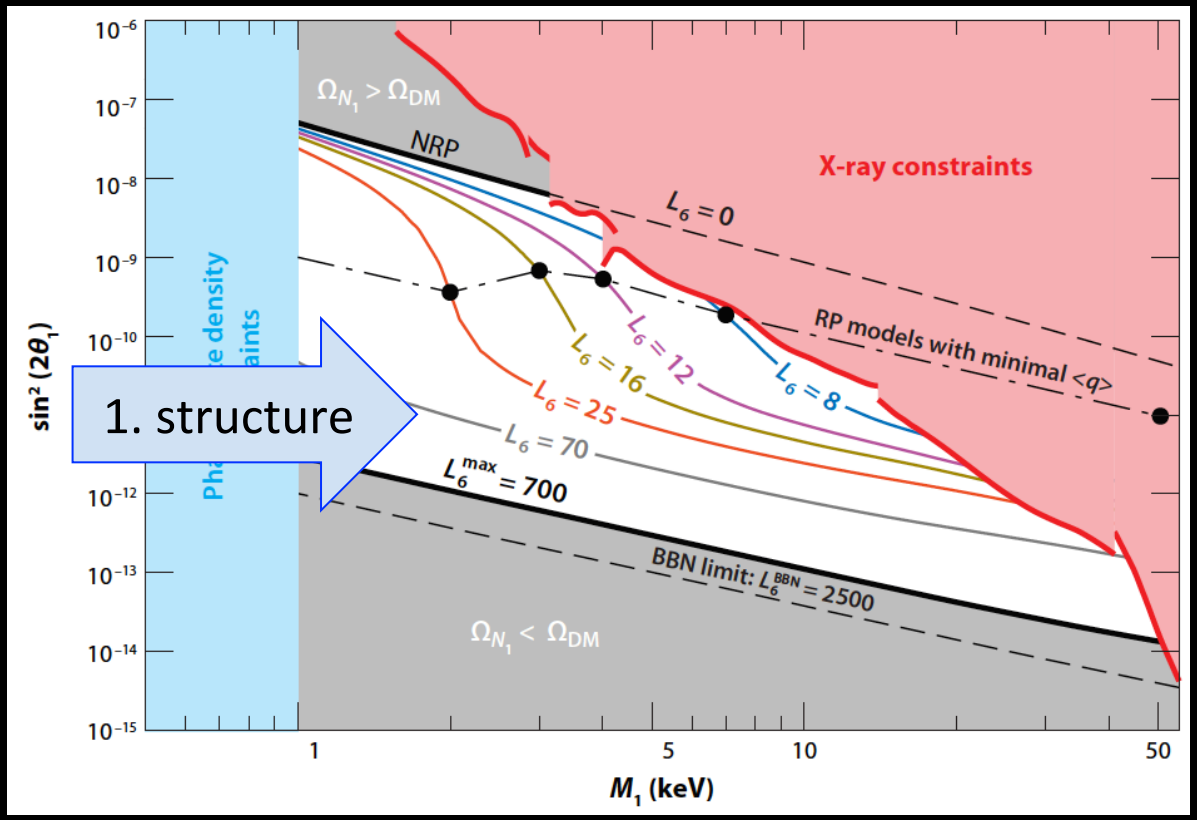


PREDICTION 1: STRUCTURE FORMATION

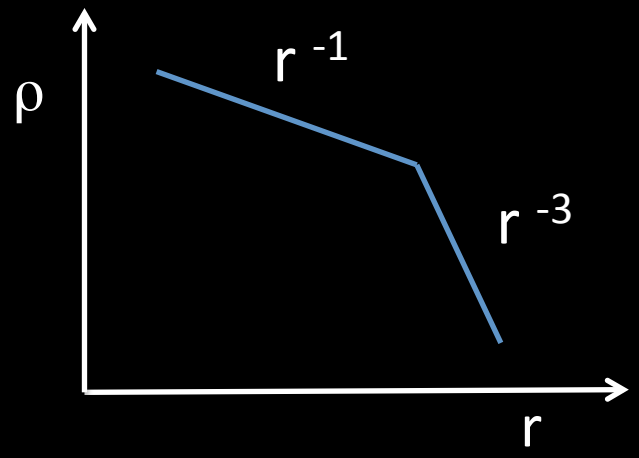
Structure formation in CDM

Mass function

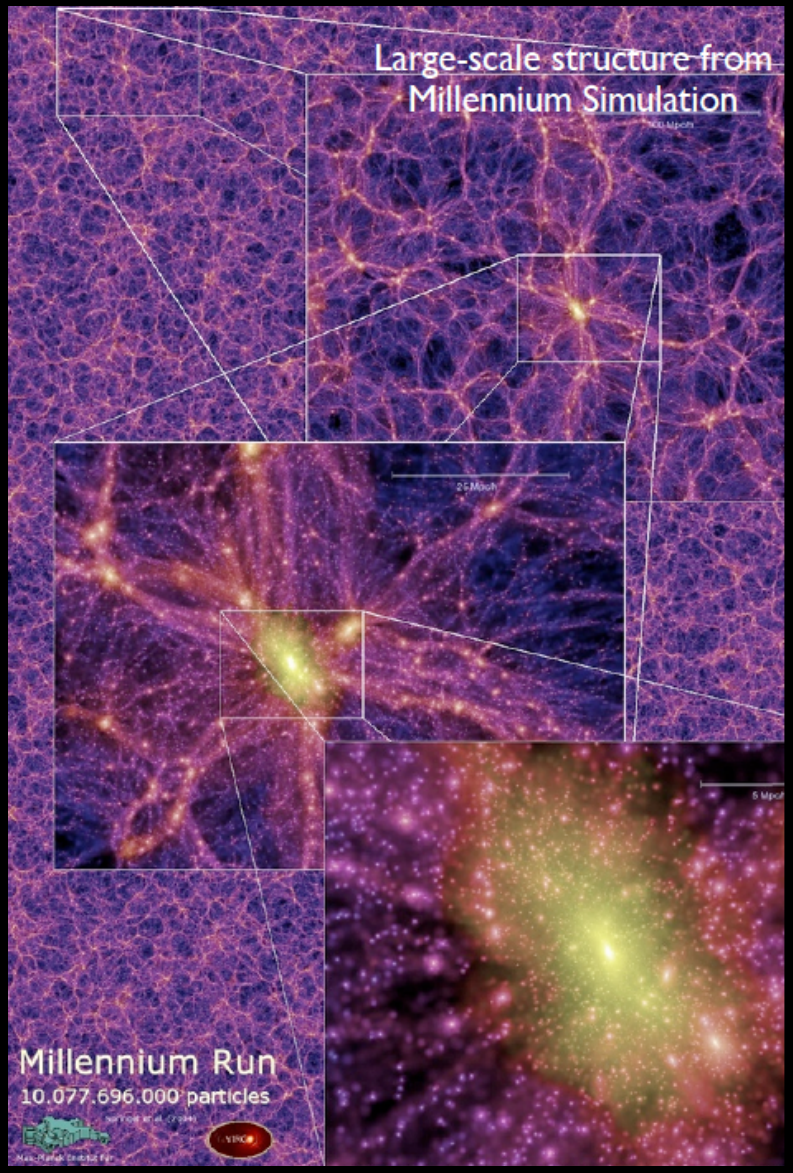
Scale-invariant matter power spectrum extending down to simulation resolution

Density profile

The density per halo follows a centrally peaked universal profile



Navarro et al, ApJ (1997)
many other fitting formulae

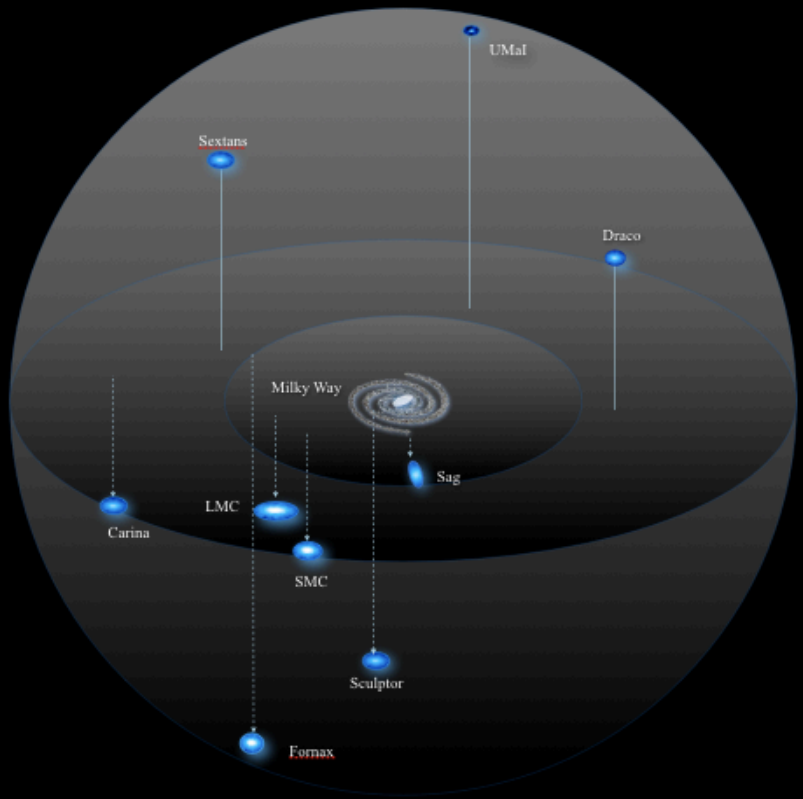


CDM and small-scale issues

CDM is challenged by observations probing small scales

1. Missing satellites problem: expect > few x100 satellites but see O(10)

Theory N > 100



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

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

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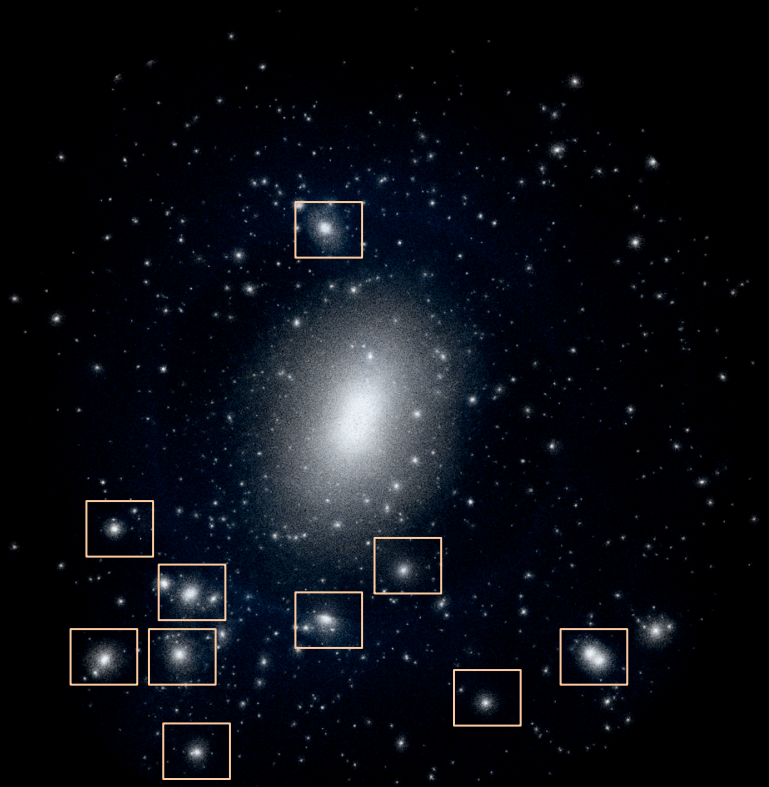

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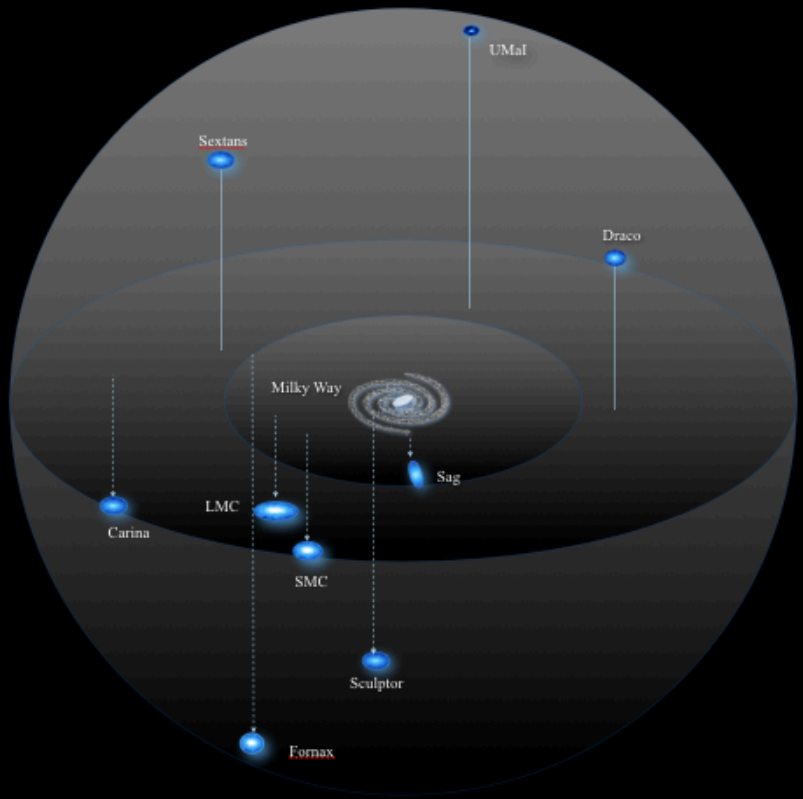


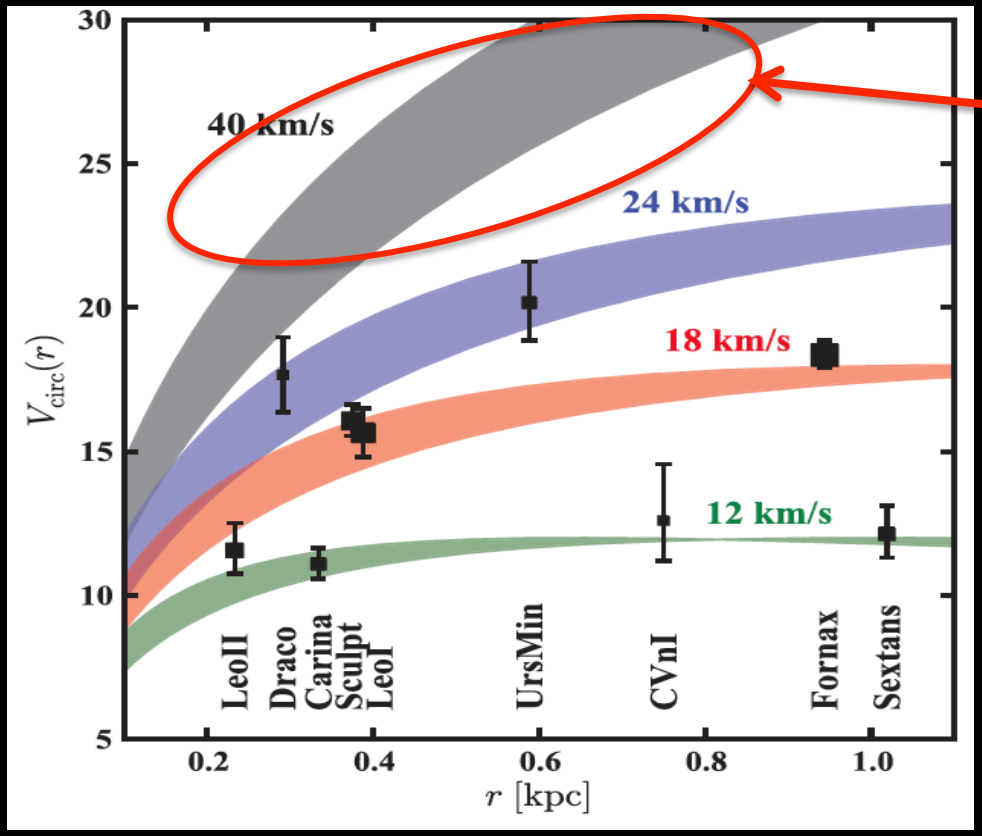
Observed N_{lum} ~ O(10) [L ~ 1e5-7 L_{sun}]

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

CDM and small-scale issues

CDM is challenged by observations probing small scales

1. Missing satellites problem: expect > few x100 satellites but see O(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?

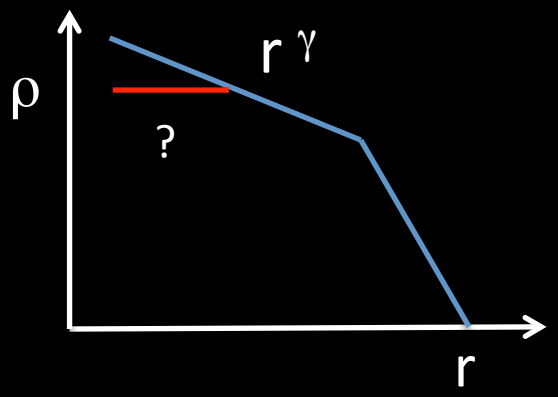
Between 5 – 40 (median ~20) "*massive failures*" based on 48 realizations of the Milky Way Halo

Garrison-Kimmel et al (2014)

CDM and small-scale issues

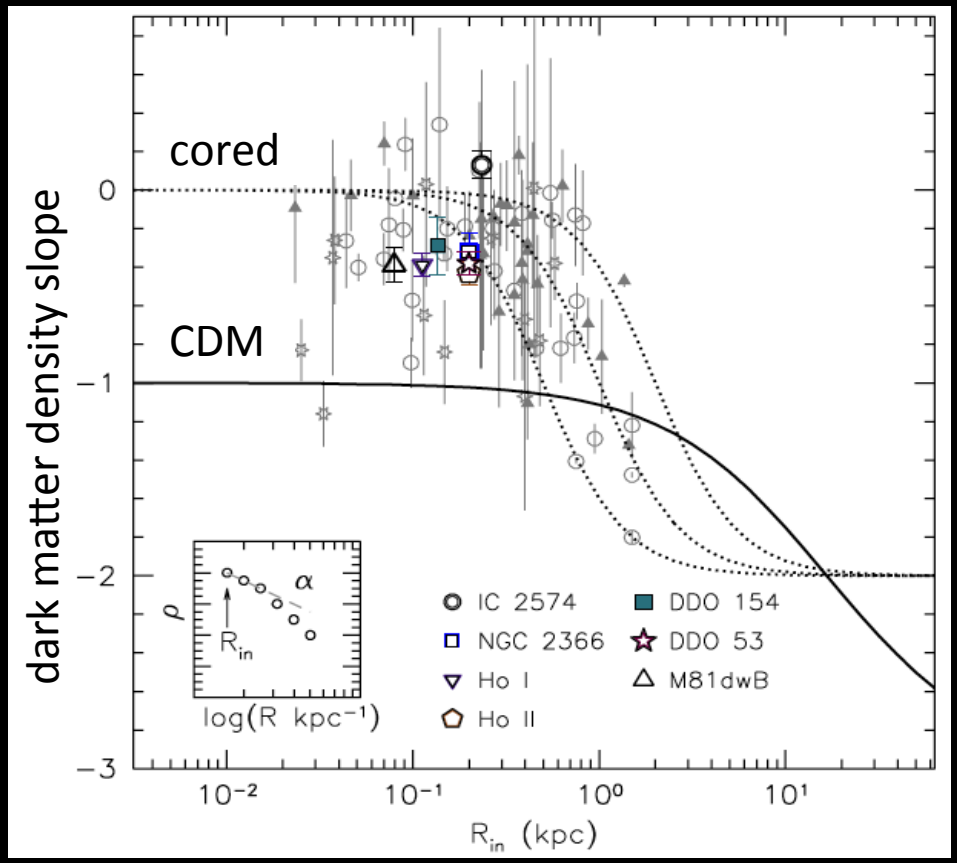
CDM is challenged by observations probing small scales

1. Missing satellites problem: expect > few x100 satellites but see O(10)
2. Too big to fail problem: massive subhalos are too dense to match data
3. Core/cusp problem: inner density profile steeper than data



→: low surface brightness galaxies in the ~4 Mpc volume

DM density profiles in Milky Way satellites are under debate.



Flores & Primack (1994), Simon et al (2005), Oh et al (2011) *Oh et al (2011) [THINGS]*

Possible interpretations

Possibilities for what is the underlying cause:

1. Missing dark matter physics?
2. Missing baryon physics: gas dissipation, star formation, and tidal effects?

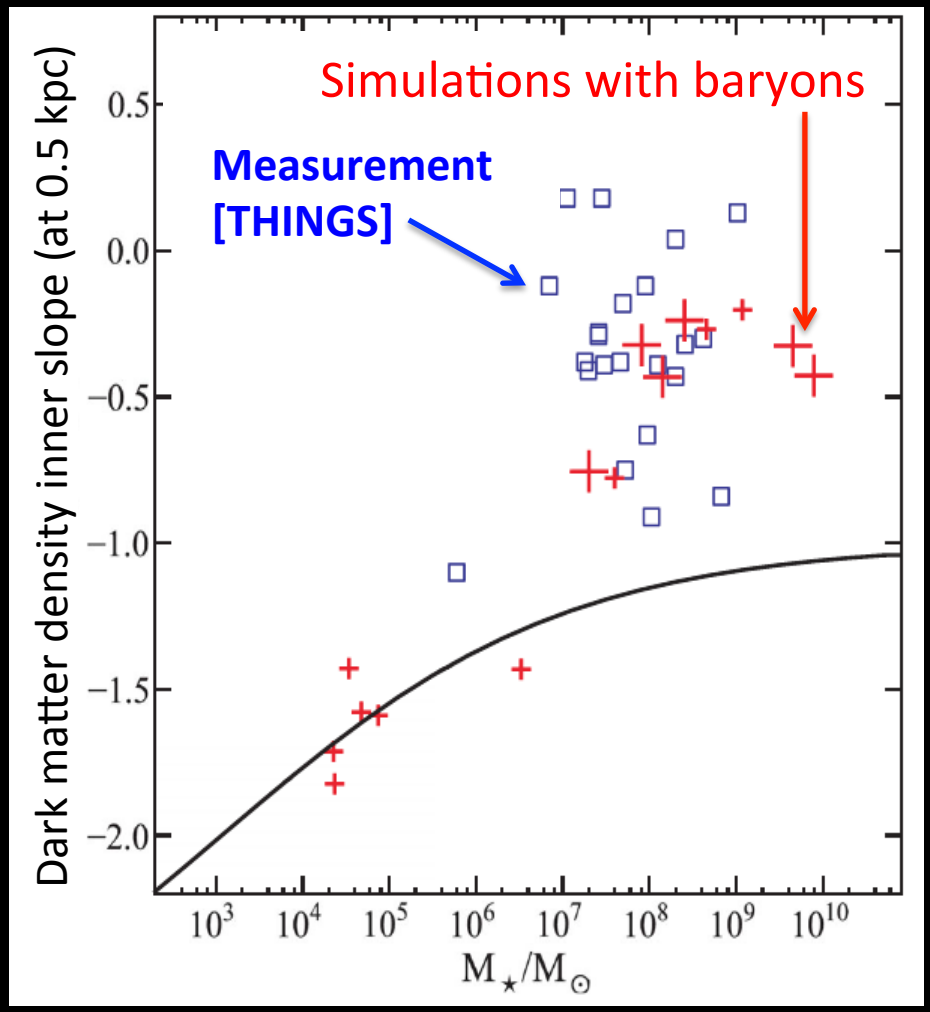
3. Uncertainty in cosmological parameters?
4. Milky Way is an odd ball?
5. Dwarf galaxy incompleteness?
6. Unexpected difficulty in kinematics?
7. Others…?

The importance of baryon physics

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), Wetzel et al (2016), …



Governato et al (2012)

The importance of baryon physics

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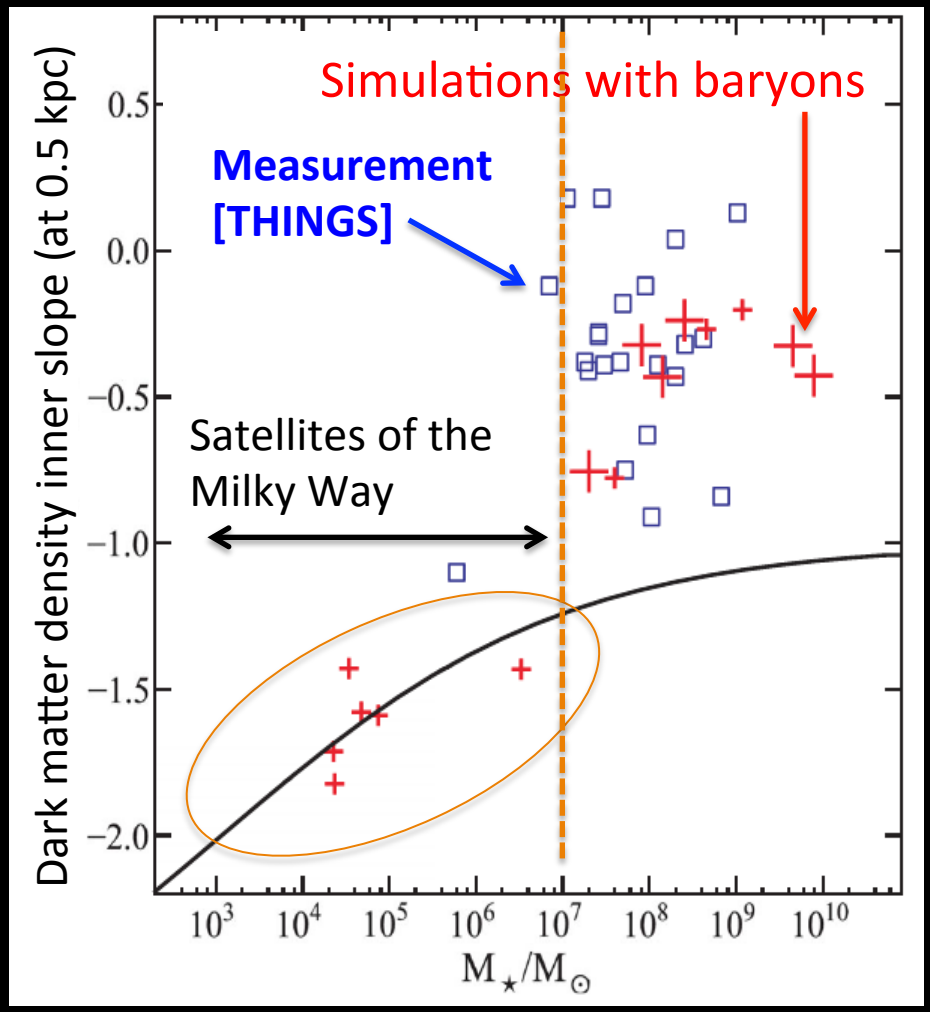
Navarro et al (1996), Madau et al (2014), Wetzel et al (2016), …

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)

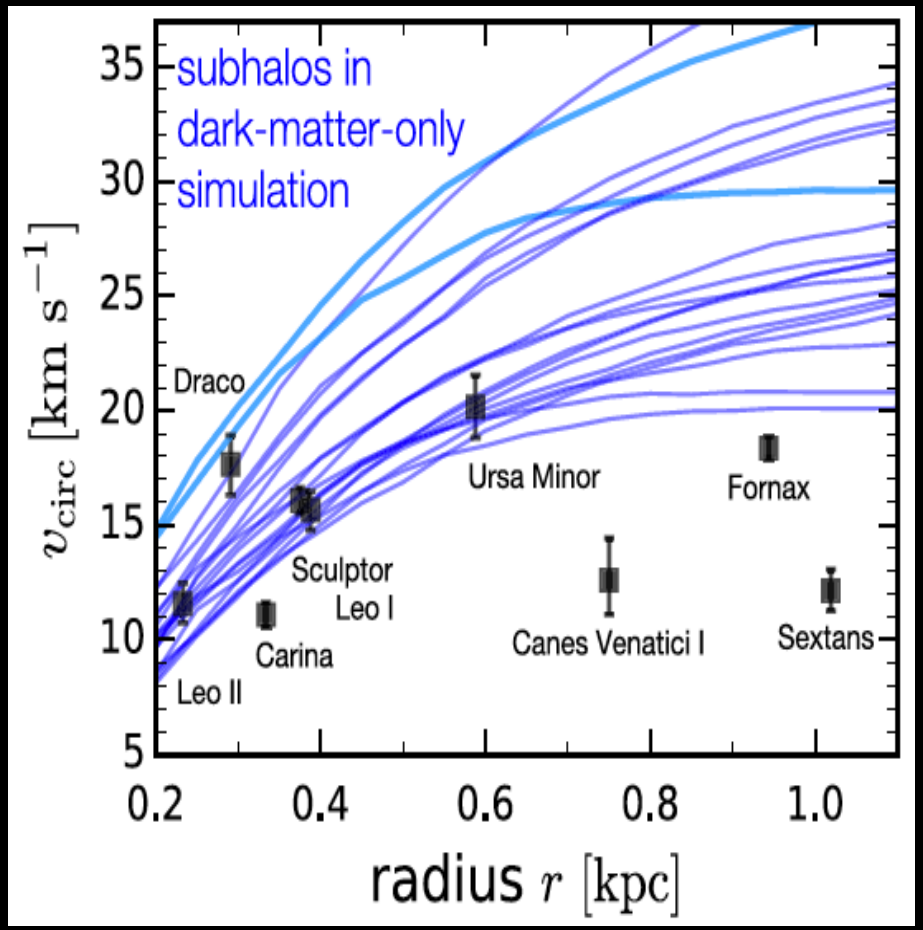
These galaxies are in the range of the "problematic" satellite galaxies of the Milky Way and M31.

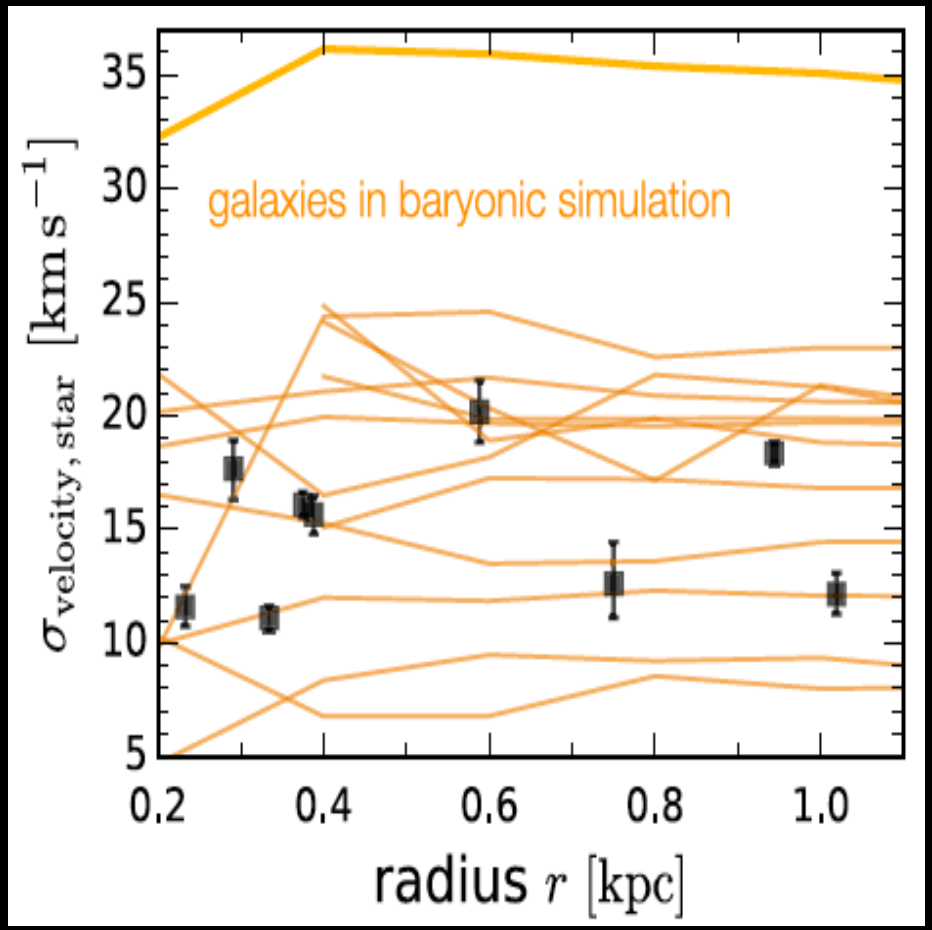


Governato et al (2012)

Baryon physics is rich

Tidal stripping due to the host disk:
Reduces subhalo inner mass density

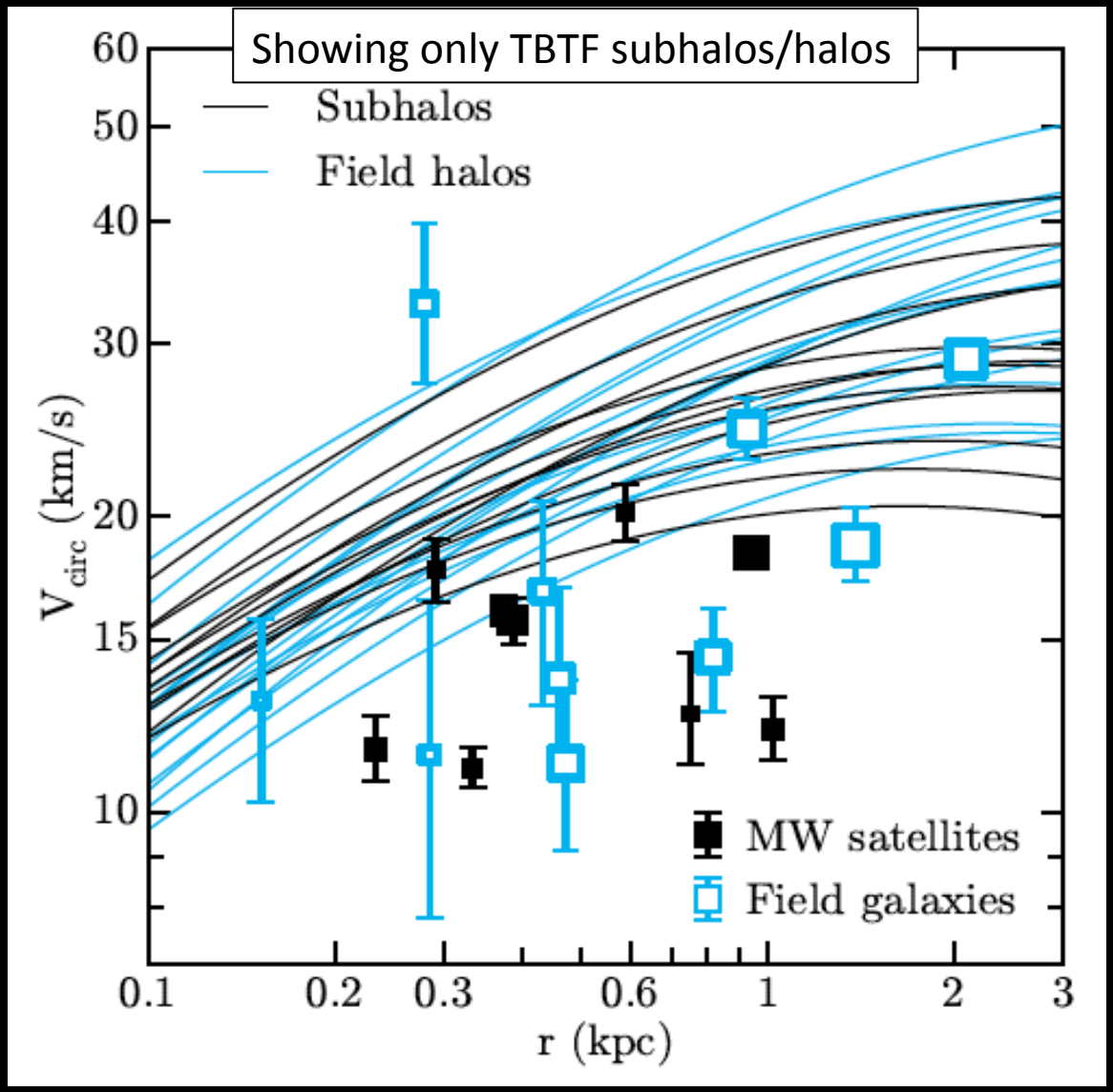




Wetzel et al (2016)

See also, Zolotov et al (2012), Brook & Di Cintio (2015), Garrison-Kimmel et al (2017)

Too-big-to-fail in local field dwarfs

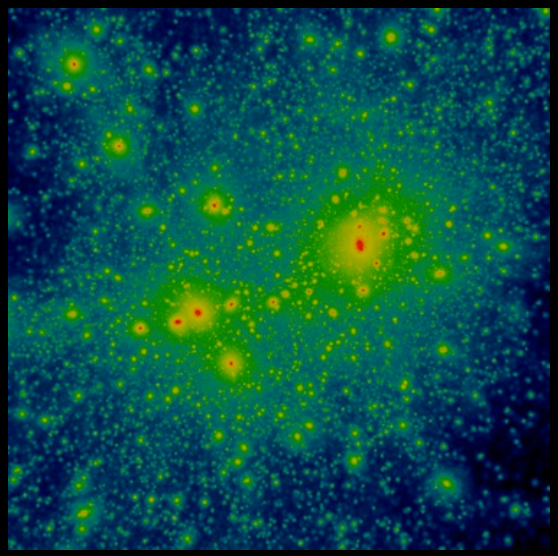


Garrison-Kimmel et al (2014)

The problem persists in the local field galaxies:

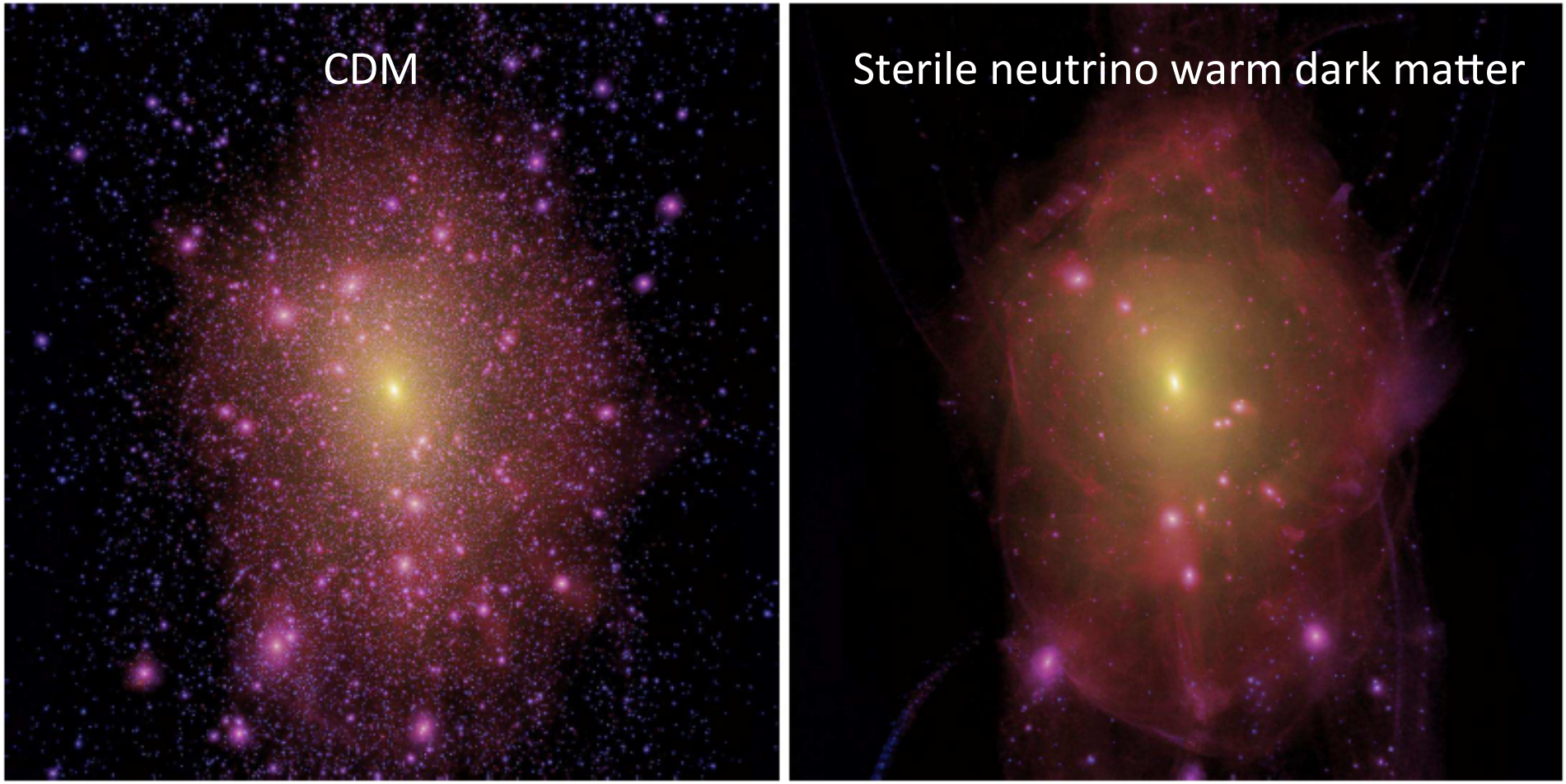
Many (>15) missing massive halos beyond the virial radii of the Milky Way and M31.

→ hard to appeal to environmental solutions.



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

Structures in sterile neutrino cosmology



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

How many satellite galaxies? Updates

Classical satellites

11 known (maybe 12), with luminosities > ~10^5 Lsun

SDSS-era satellites

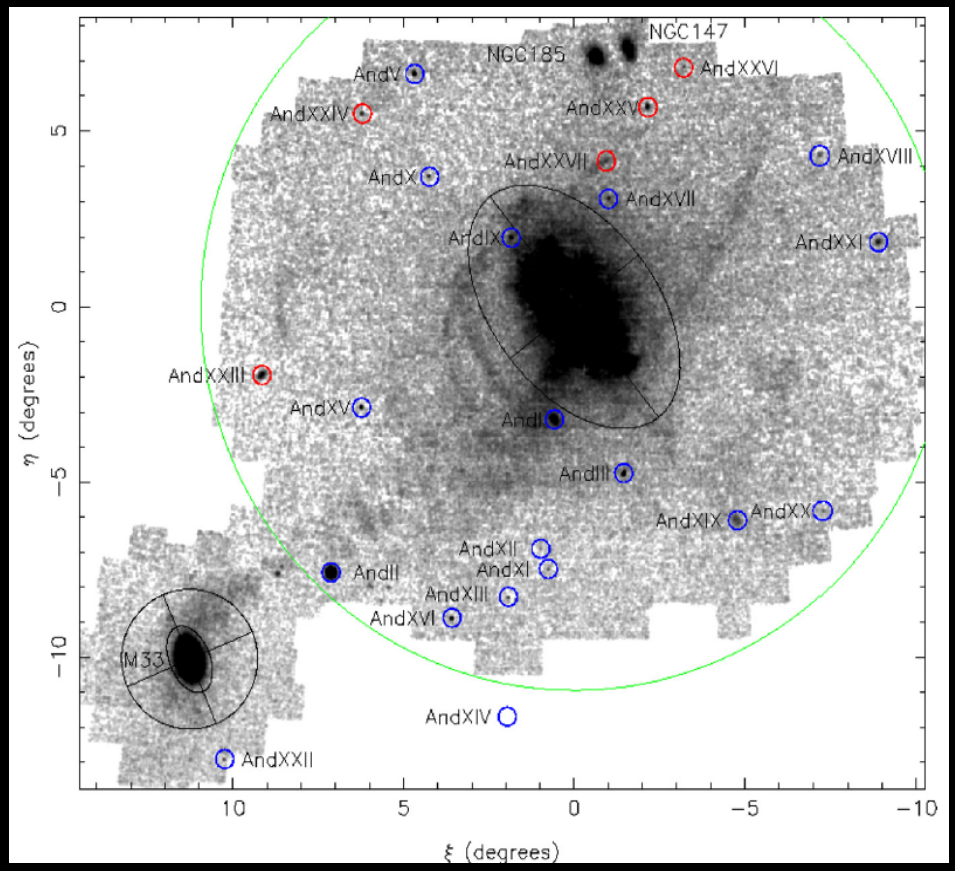
Expect complete out to 200 kpc and down to ~10^5 *Lsun*, but SDSS sky coverage is ~29%: 15 (maybe 16) additional

➔ Total 26 raw (~63 assuming isotropic distribution)

Pan-Andromeda Archaeological Survey:

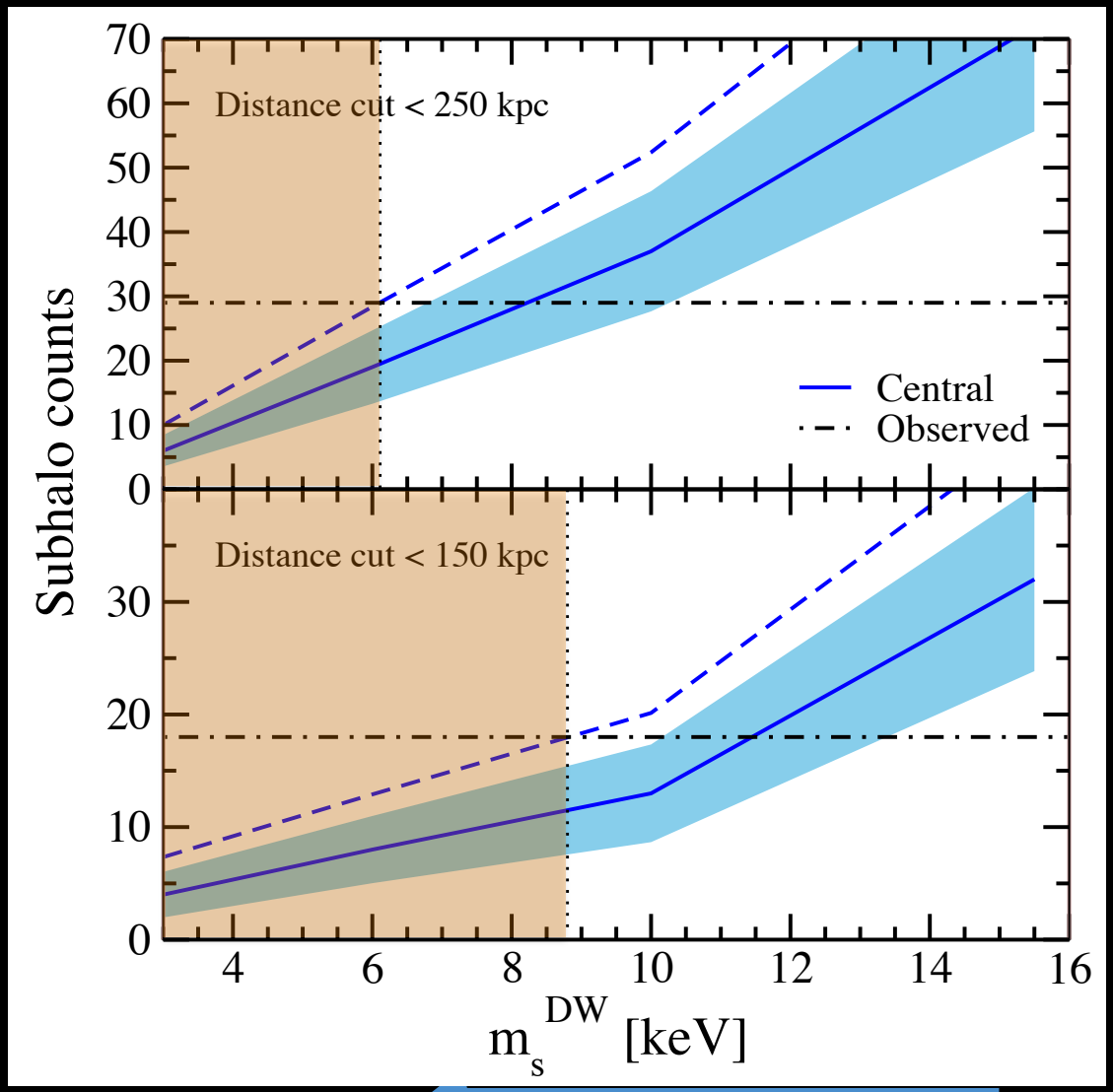
Complete out to ~150 kpc of the M31 center and down to ~10^5 *Lsun* in luminosity: 29 (26, 18) within 250 (200, 150) kpc

McConnachie (2012)



Richardson et al (2011)

Reduced, but sufficient, structure



Horiuchi et al (2014)

Simulations:

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

- Halo-to-halo scatter: use 44 Milky Way analogues
- Cosmology uncertainty smaller

See also Polisensky & Ricotti 2013

➔ Comparison yields limit of:

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

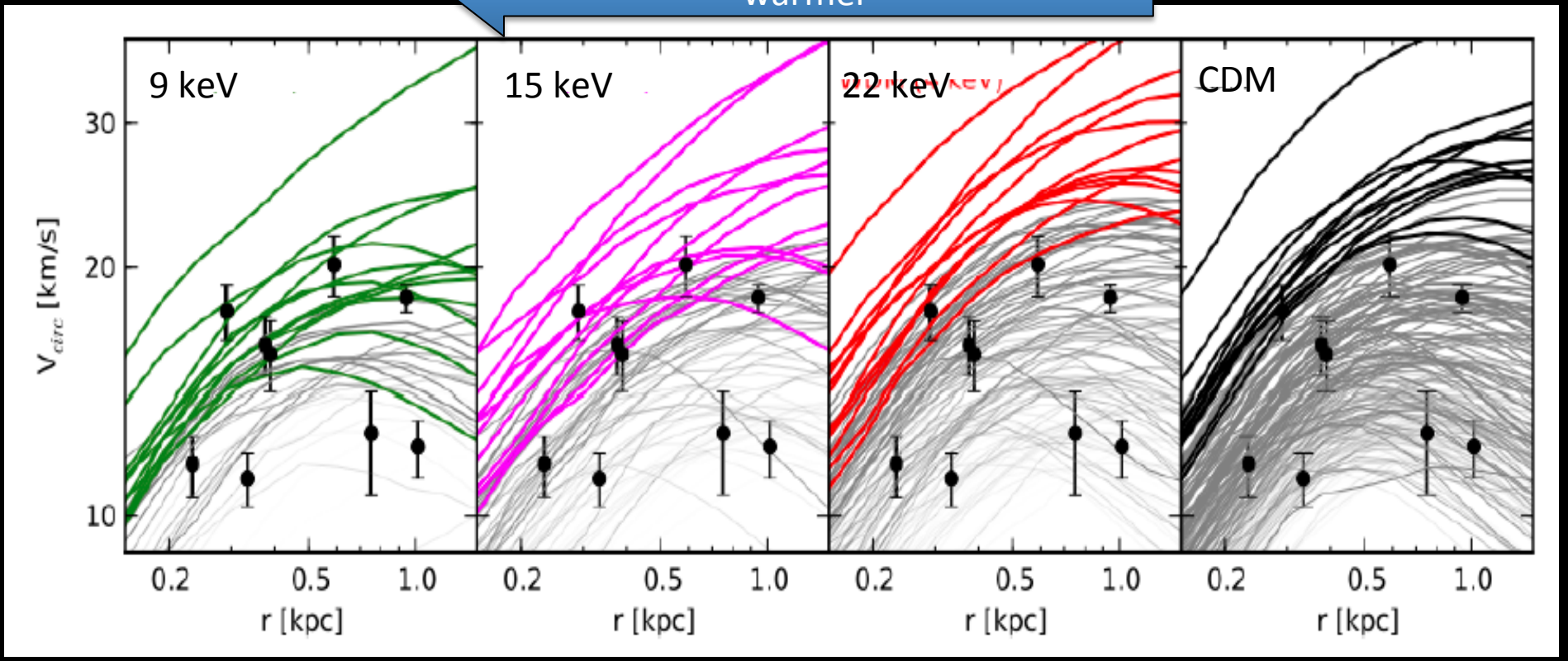
See also Polisensky & Ricotti 2011

Predictions of density

Sterile neutrino solution:

Delayed structure formation → less concentrated halos

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



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

Anderhalden et al (2013)

Lyman-alpha probes

Small-scale probe

Absorption by HI in QSO spectra probes small-scale power to high-z

Hydro simulation links DM power → HI gas power → obs. spectra

e.g., Narayanan et al (2000)
Viel et al (2006),, Seljak et al (2006)

Sterile neutrino limits

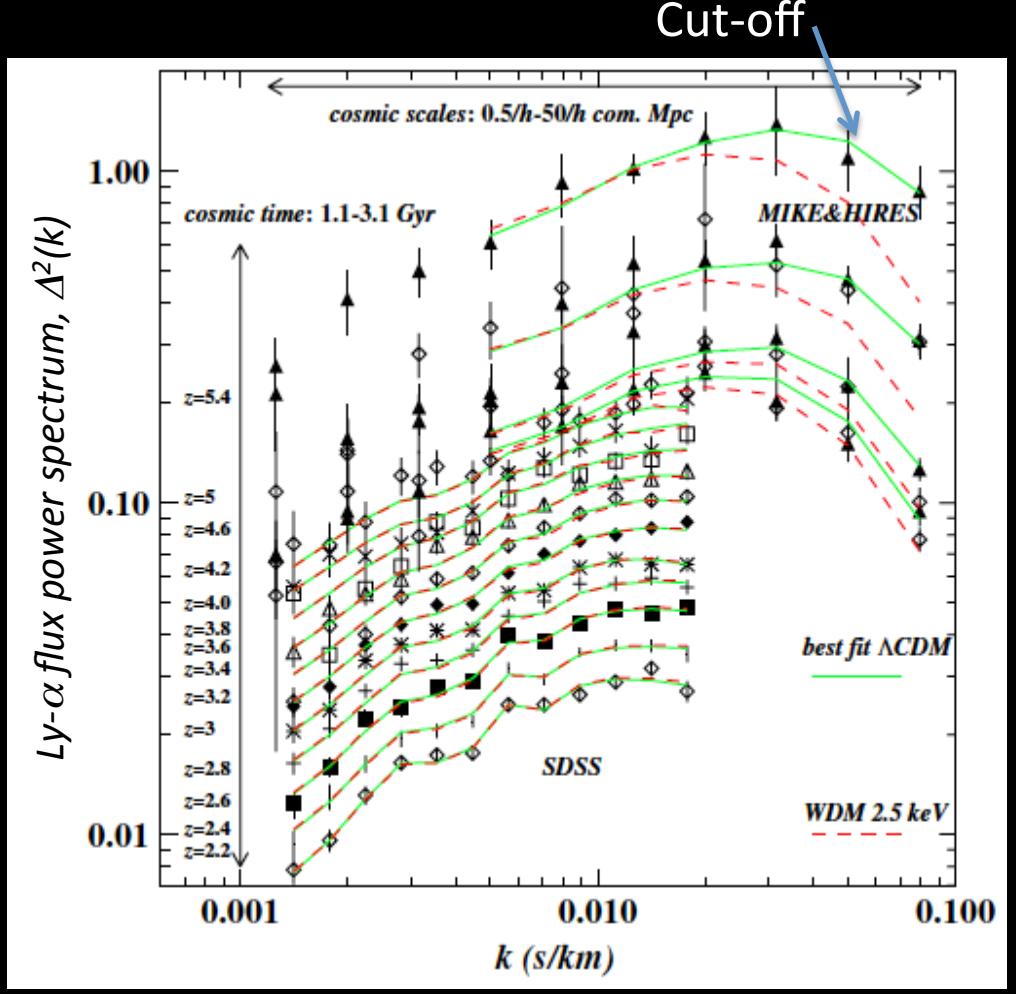
Using Magellan + Keck HIRES spectra

m_{DW} > 17 keV, 26.3 keV (95%CL)

Viel et al (2013), Baur et al (2016)

Caveats

IGM thermal & pressure smoothing reduces power, i.e., degenerate with WDM feature → weakens limits to **m_{DW} ~ 11 keV**

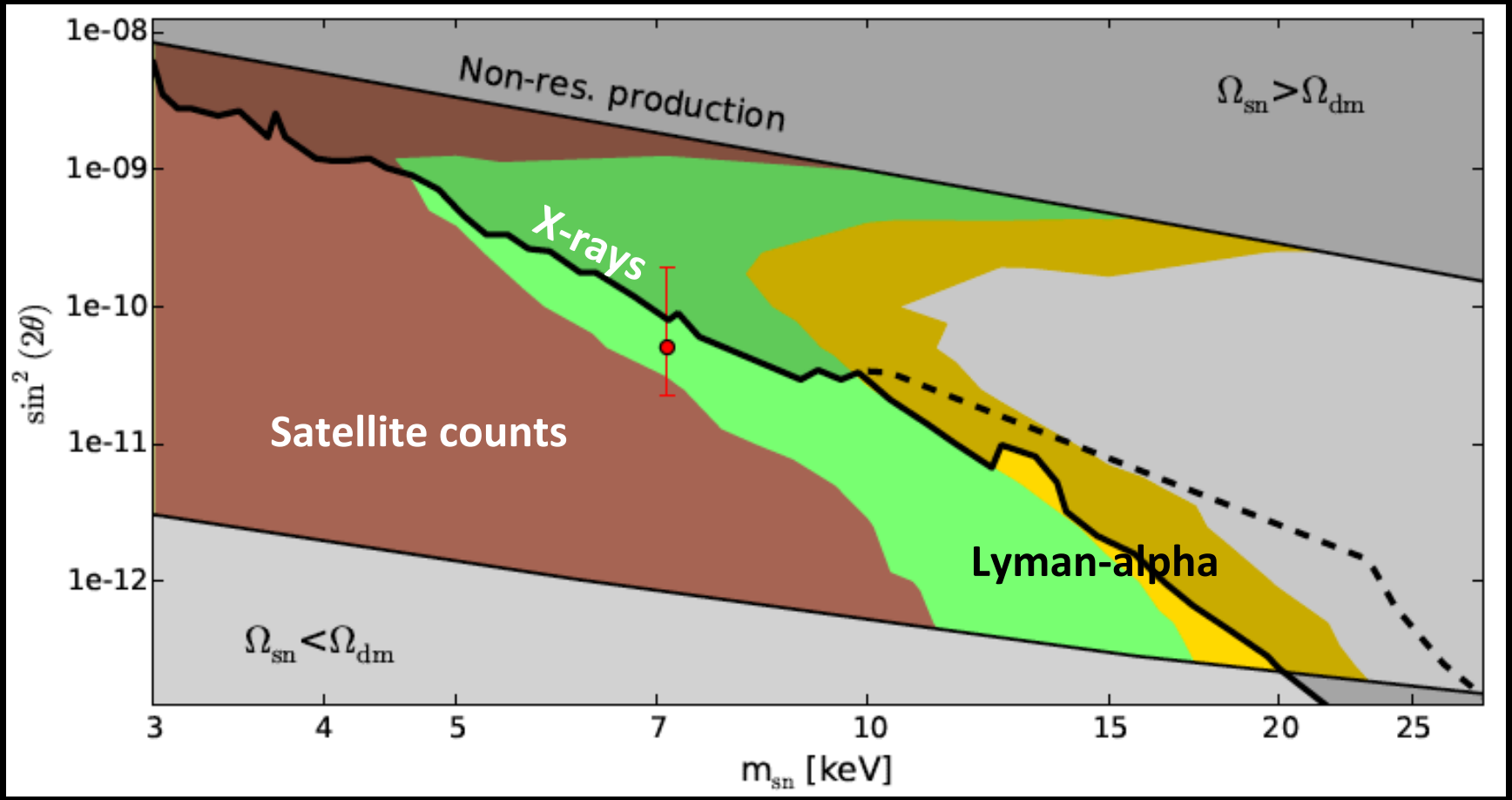


Viel et al (2013)

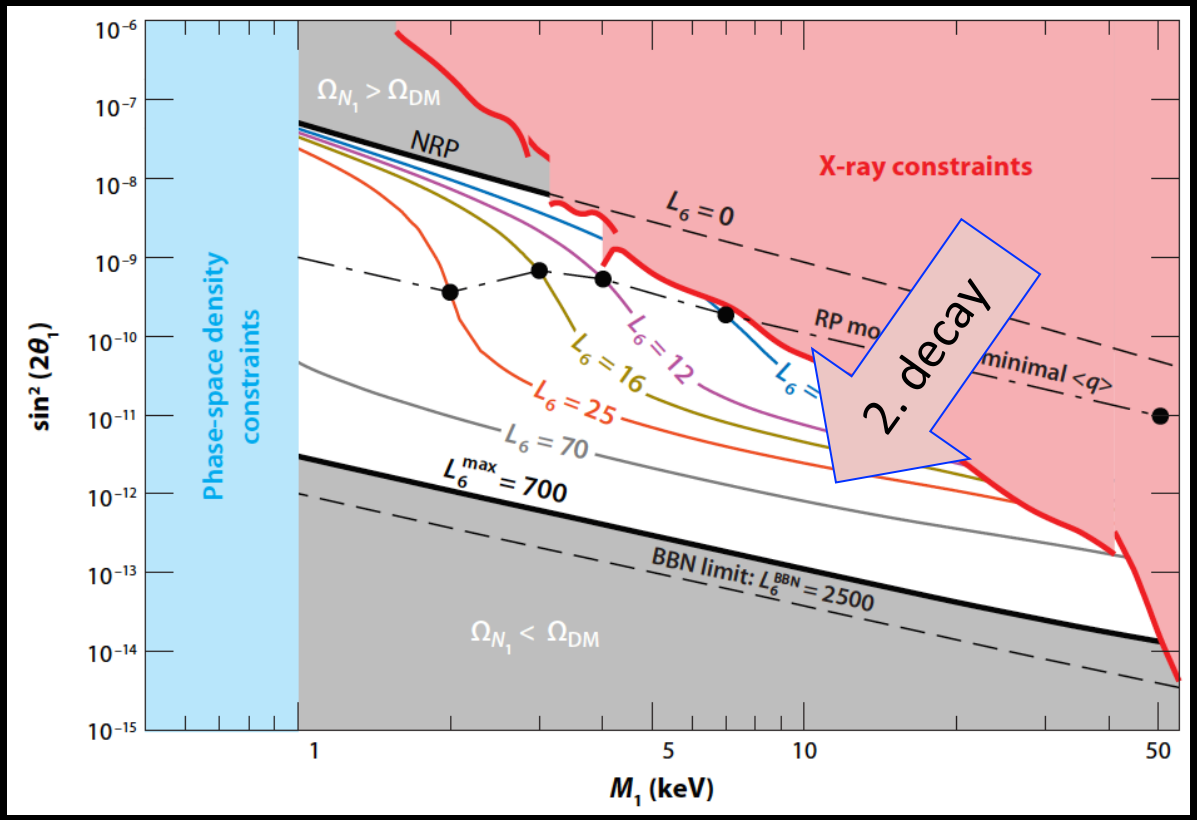
e.g., Viel et al (2013), Garzilli et al (2015), Kulkarni et al (2015)

Application to the resonant regime

1. Based on analytic estimate of subhalo counts
2. Based on full power of Lyman-alpha limits
   - Approximate by considering deviations of the *matter power spectrum*



Schneider (2016); see also Cherry & Horiuchi (2017)



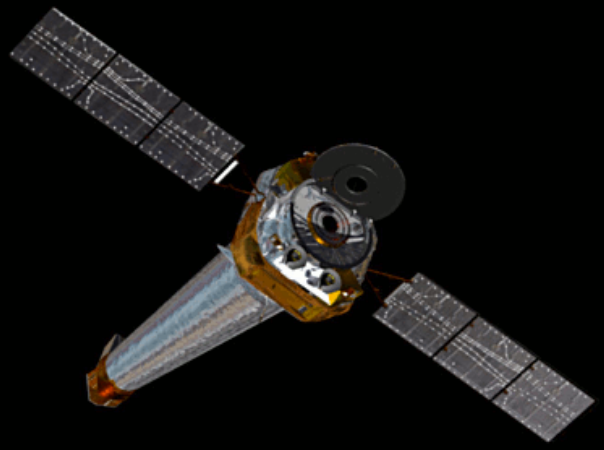
PREDICTION 2: DECAYS

X-ray considerations

Strategies

Many satellites and dark matter targets considered for X-ray studies

	Chandra	XMM	Suzaku	Hitomi
FoV	17’ x 17’	30’ x 30’	18’ x 18’	3’ x 3’
range [keV]	0.4–8	0.2–12	0.3–12	0.3–12
E res (E/dE)	~50	~50	~50	~1000
Ang res	1”	6”	90”	60”

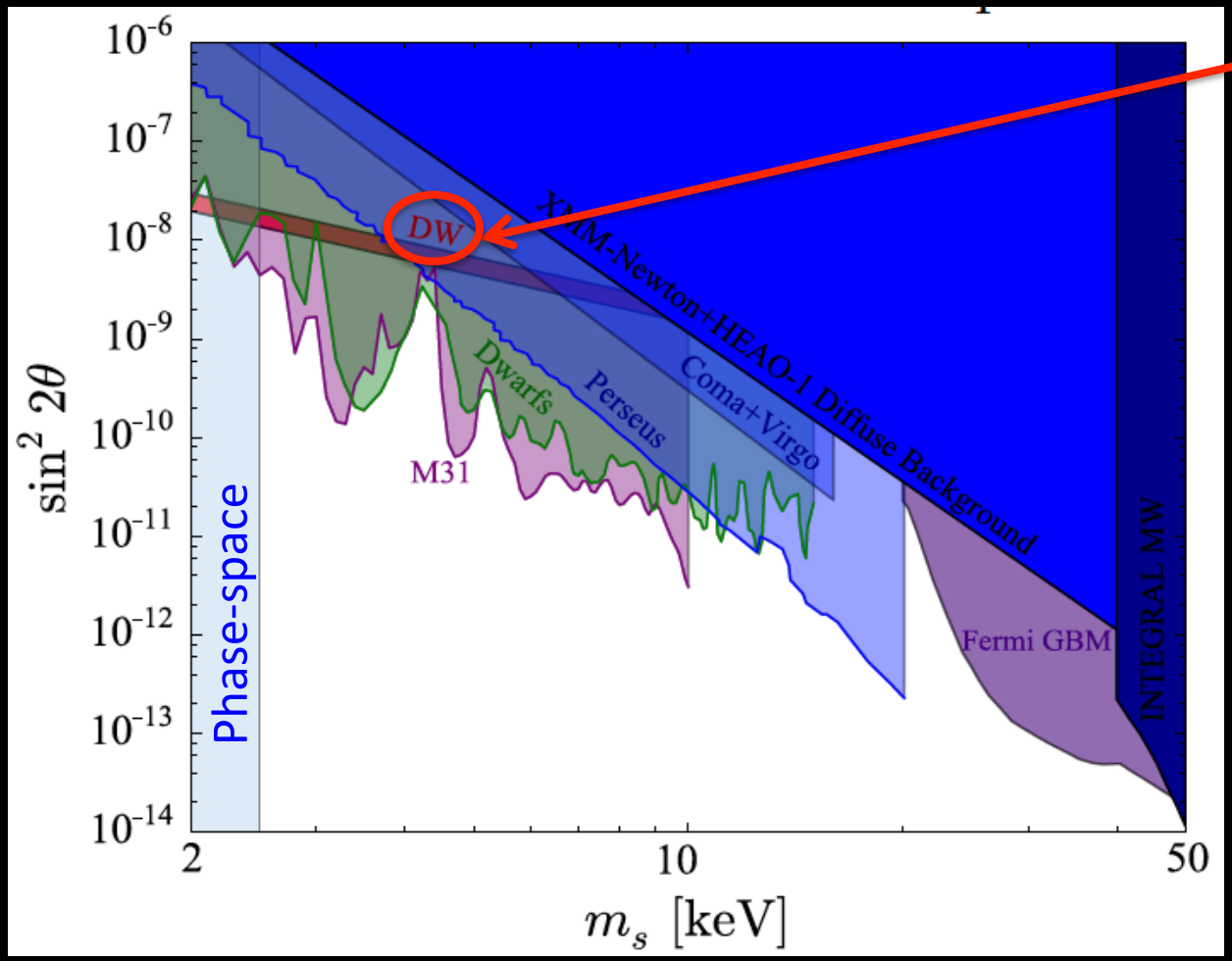


Source	Pros	Cons
clusters	Photon statistics	ICM background
M31	proximity	Large ROI
MW	proximity	Very large ROI
MW-GC	proximity	Rich background
dwarfs	Low backgrounds	Weak signal

Gamma-ray telescopes

Probes higher mass steriles (>20 keV): *INTEGRAL*, *Fermi-GBM*

Sterile neutrino parameter space

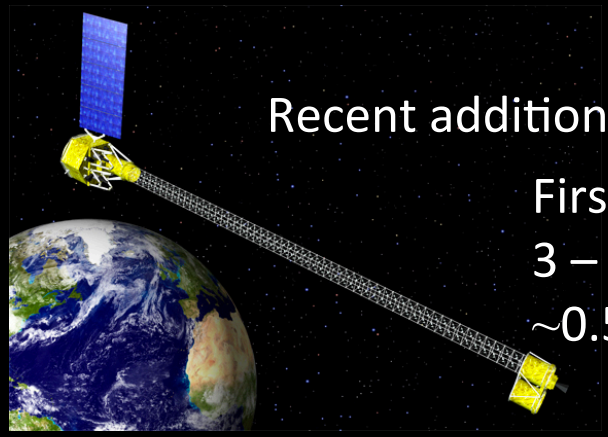


Abazajian, from IDM 2016

Dodelson & Widrow (DW): Combining limits, the DW parameter space is ruled out

→ Sterile neutrino must be resonantly produced

NuSTAR



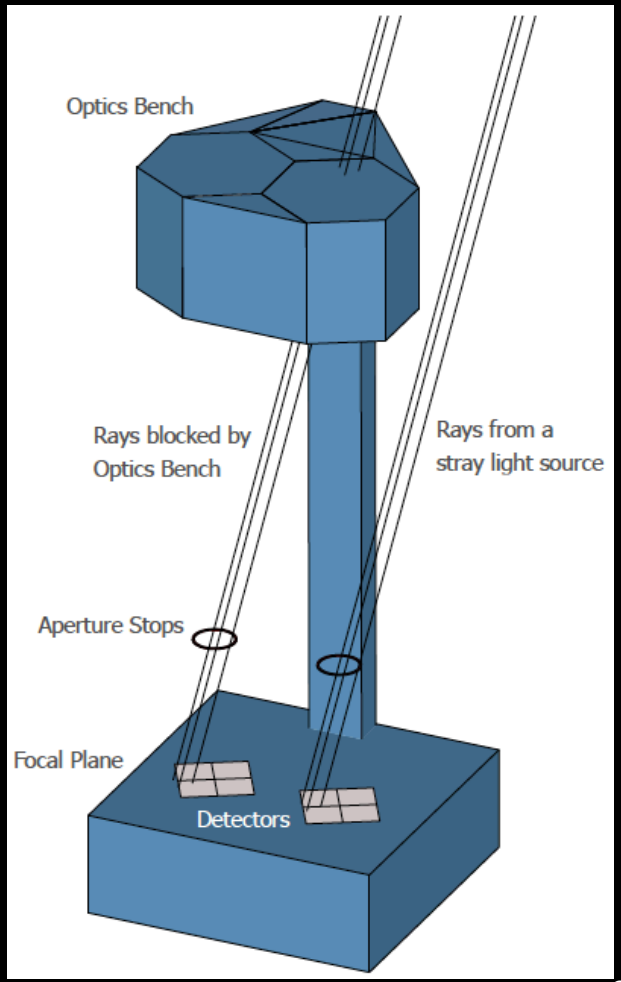
Recent addition to X-ray obs (06/2012~)

First *focusing* X-ray telescope

3 – 79 keV range

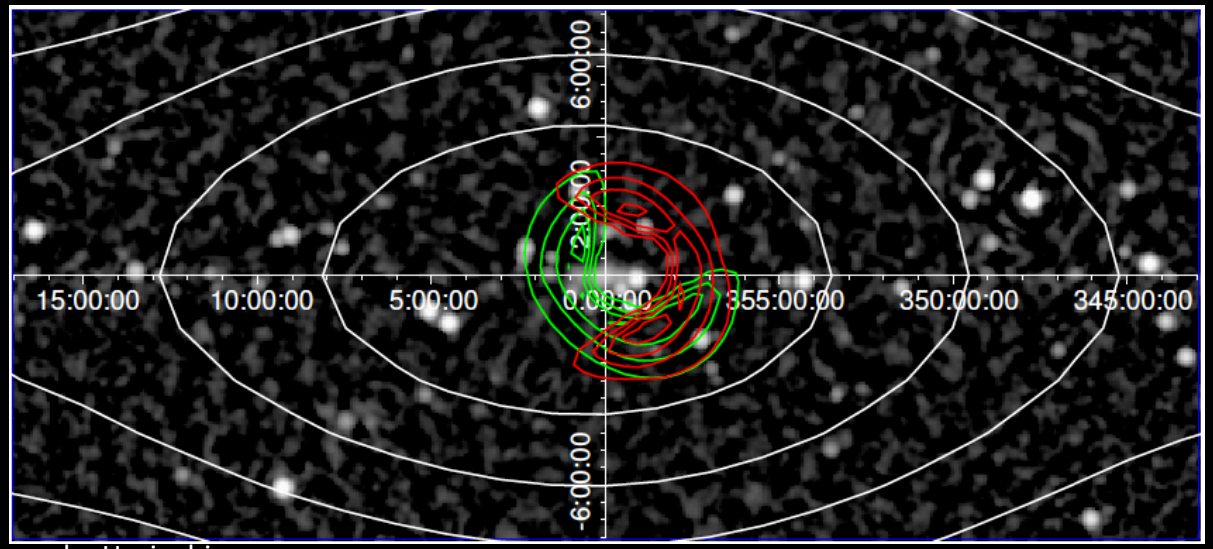
~0.5 keV energy resolution

Increased FOV using 0-bounce photons



Galactic Center analysis

Using ~2 Ms observation of the inner 1.4° x 0.6° region: combined pac-man ROIs



Limits on resonant production space

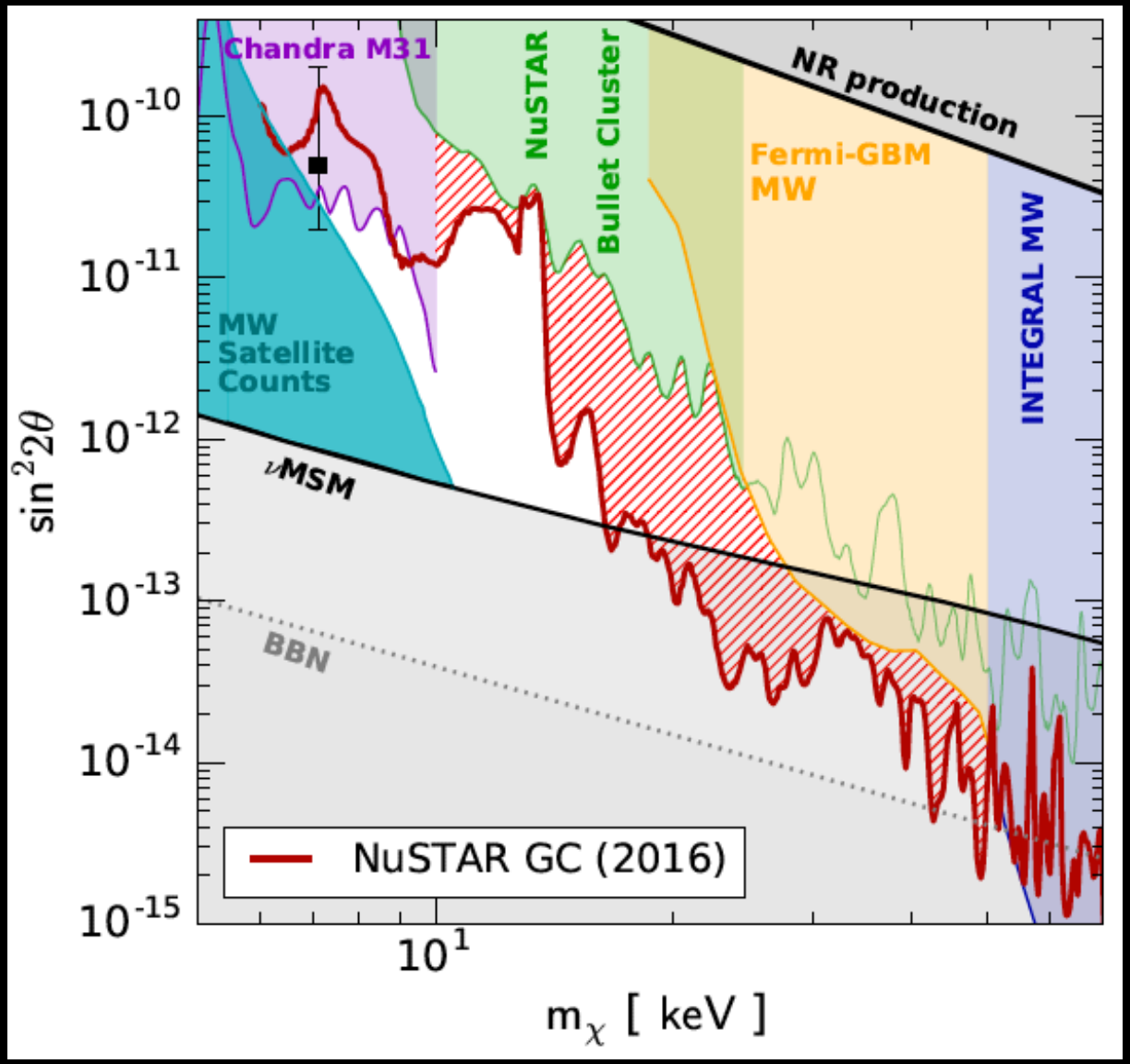
Limits

Improved sensitivity to >10 keV mass

→ rapidly closing in on remaining parameter space

NuSTAR data of CXB also used, with similar constraints on sterile neutrino parameters

Nerenov et al (2016)

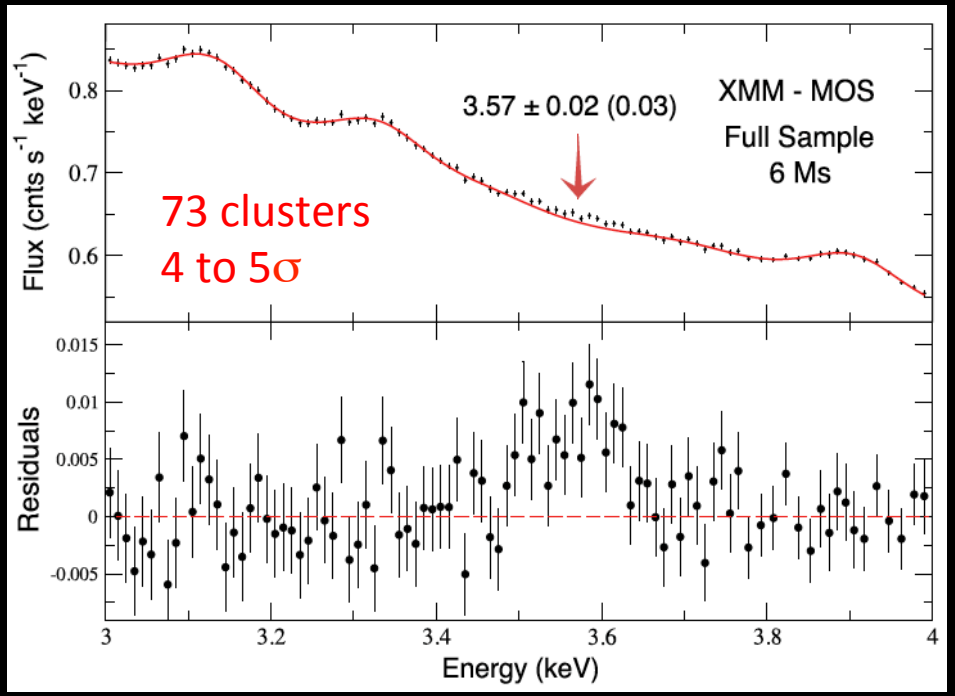


Perez et al (2016)

Anomalous X-ray line detections

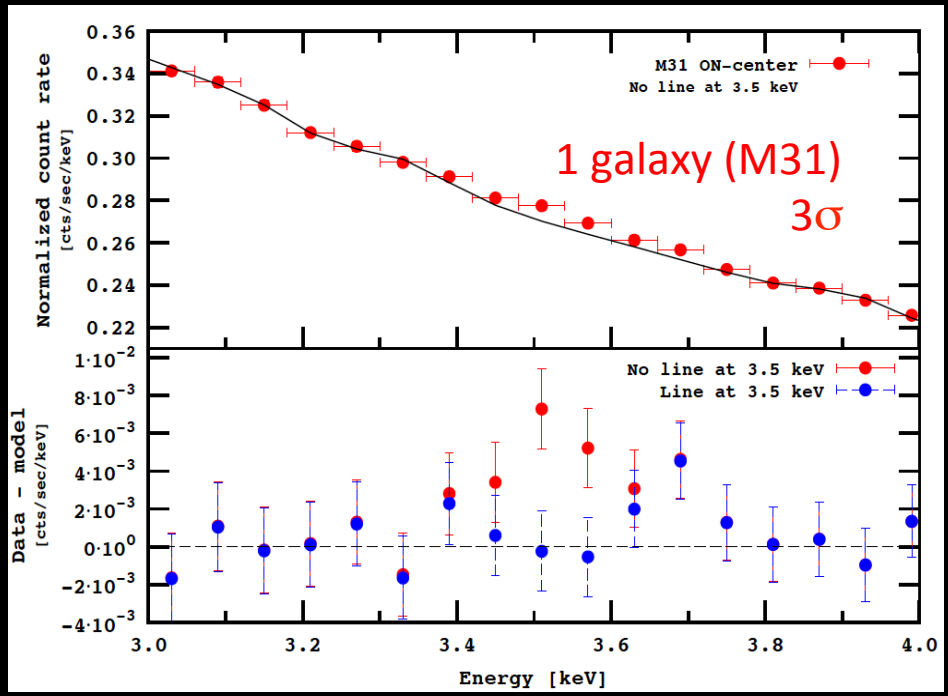
Claims of anomalous X-ray lines from nearby dark matter concentrations

Bulbul 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

Boyarsky et al (2014)



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

+ many follow ups

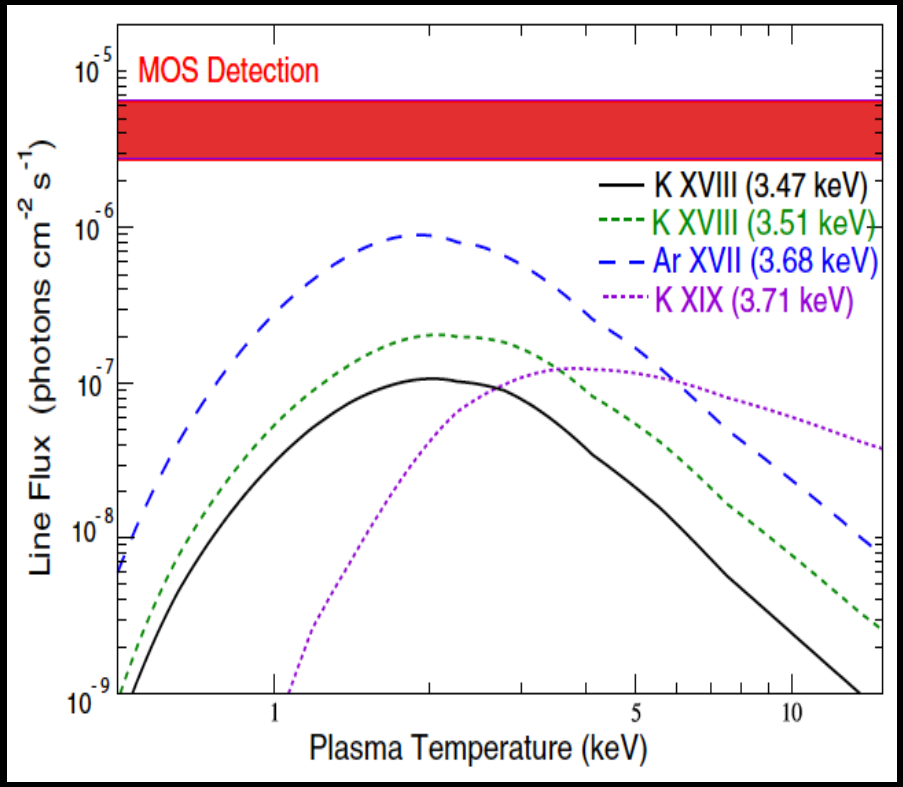
Standard Model explanations?

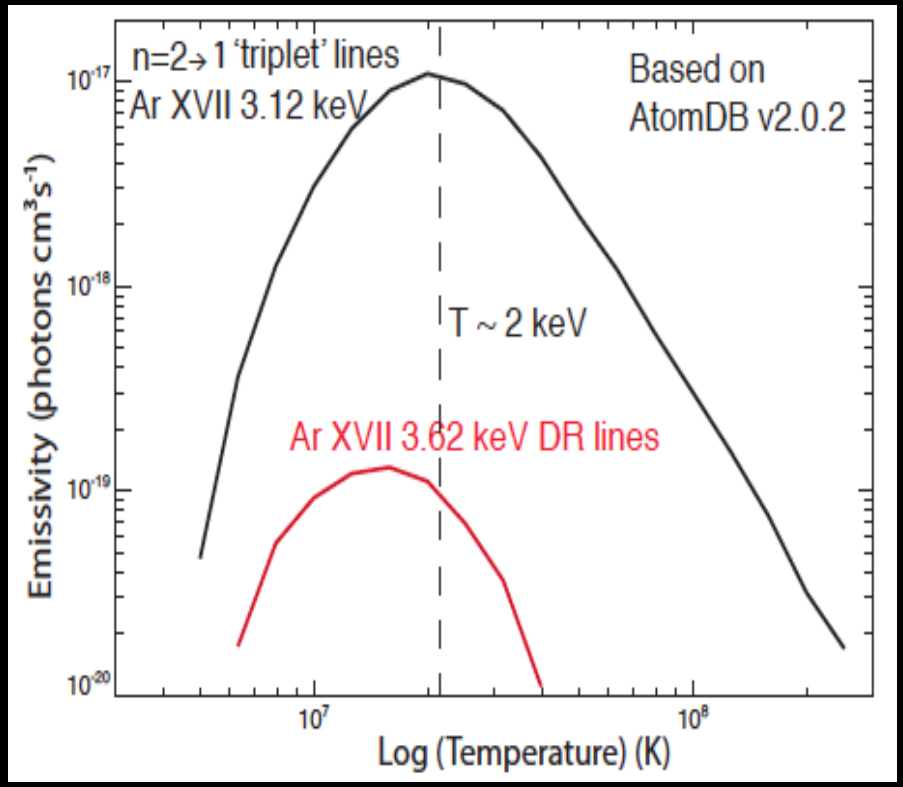
Weak lines

There are nuclei with lines near 3.54 keV, e.g., Ar XVII, K XVIII, but line flux is typically low (assuming solar abundance ratio of S, Ca, Ar, K)

Free abundance

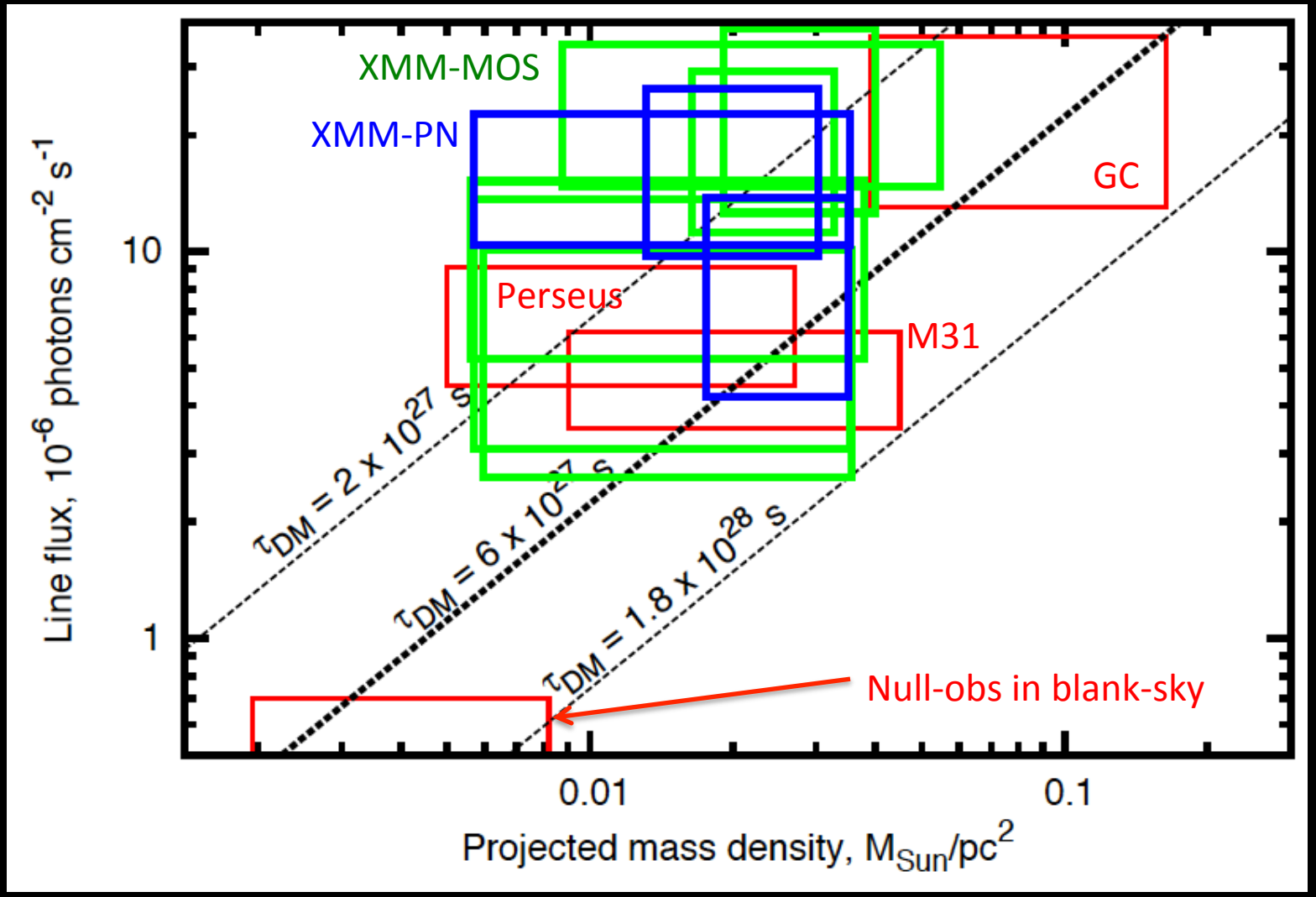
Even if we have an open mind about the abundance, nuclei have accompanying lines that cause a problem. Similar story for charge-X.





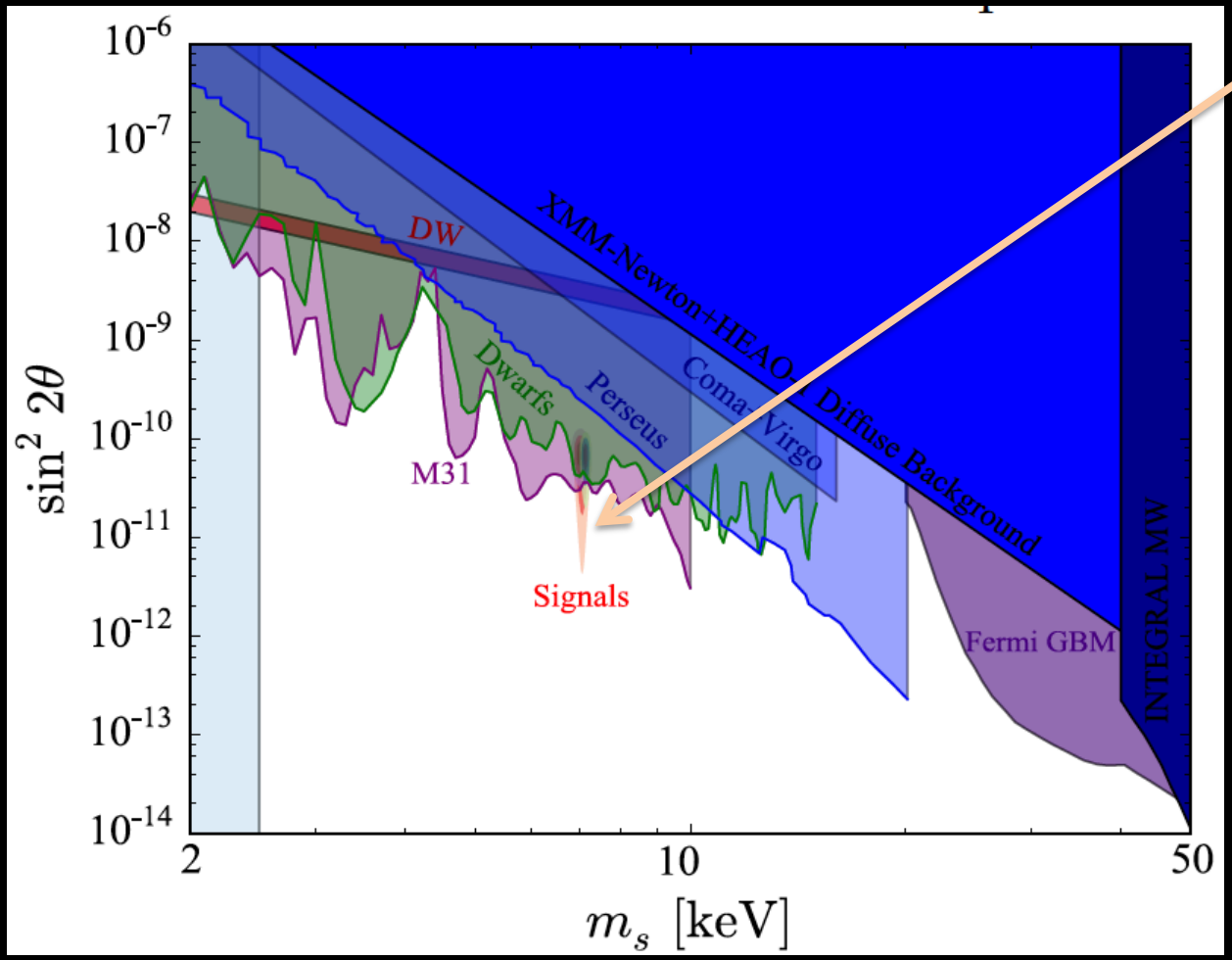
Bulbul et al (2014)

Decaying dark matter interpretation



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

Sterile neutrino parameter space



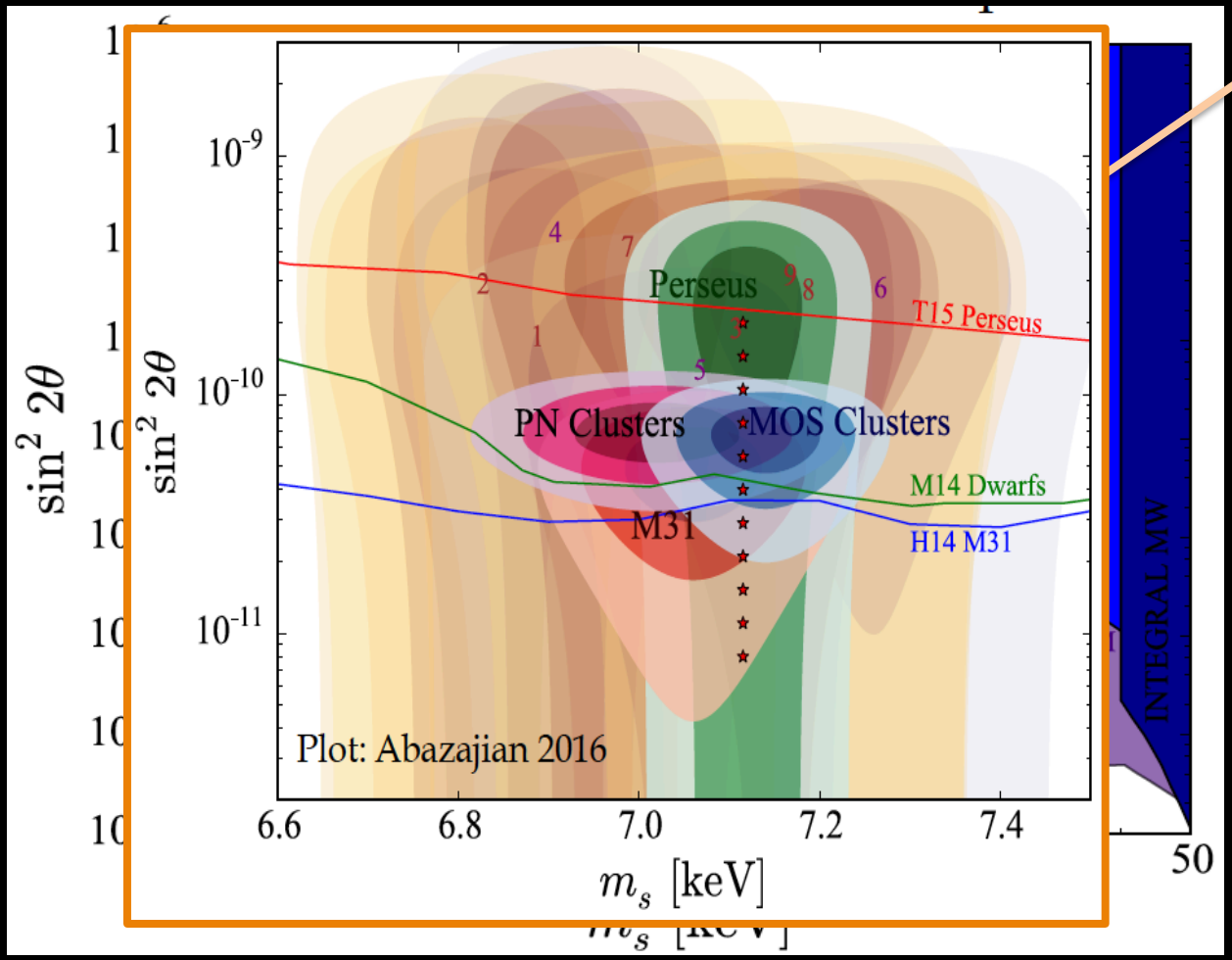
Abazajian, from IDM 2016

Claimed signal:
Anomalous 3.55 keV line

Bulbul et al (2014)
Boyarsky et al (2014)

→ Consistent with decay of 7.1 keV resonantly produced sterile neutrino

Sterile neutrino parameter space



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Boyarsky et al (2014)

→ Consistent with decay of 7.1 keV resonantly produced sterile neutrino

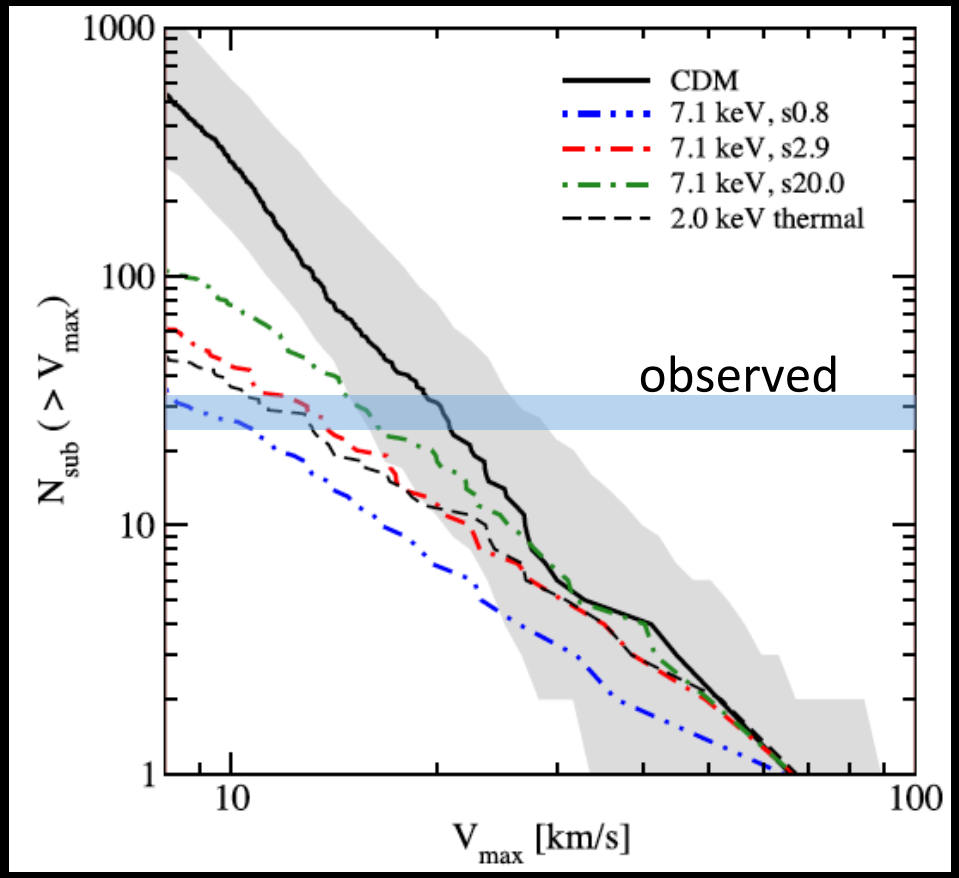
7.1 keV sterile neutrino cosmology

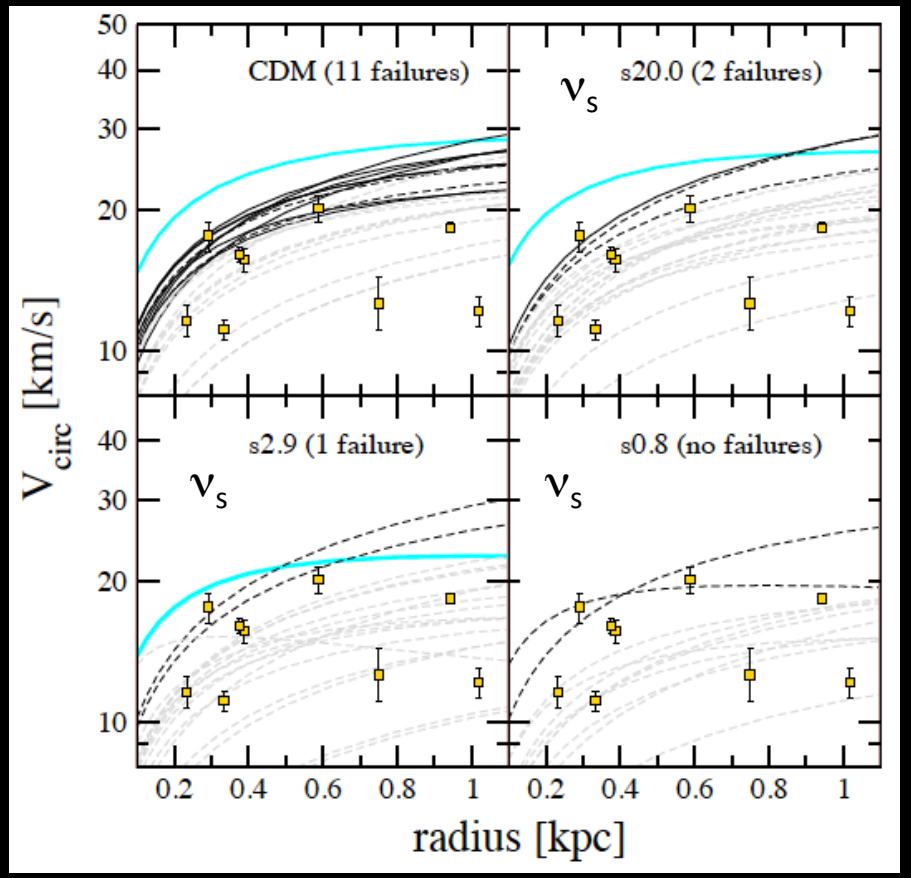
Subhalo counts

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

Density issue

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





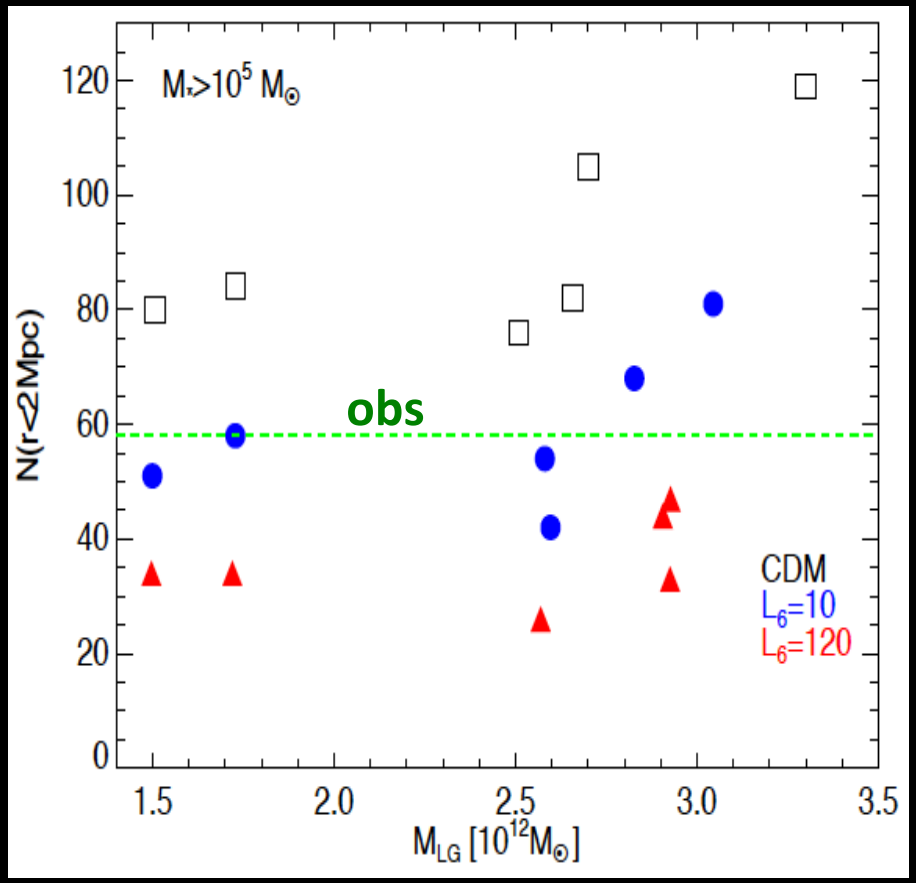
Horiuchi et al (2016)

*Using production & matter power spectrum of *Venumadhav et al (2015)*

Sterile neutrino + baryon simulations

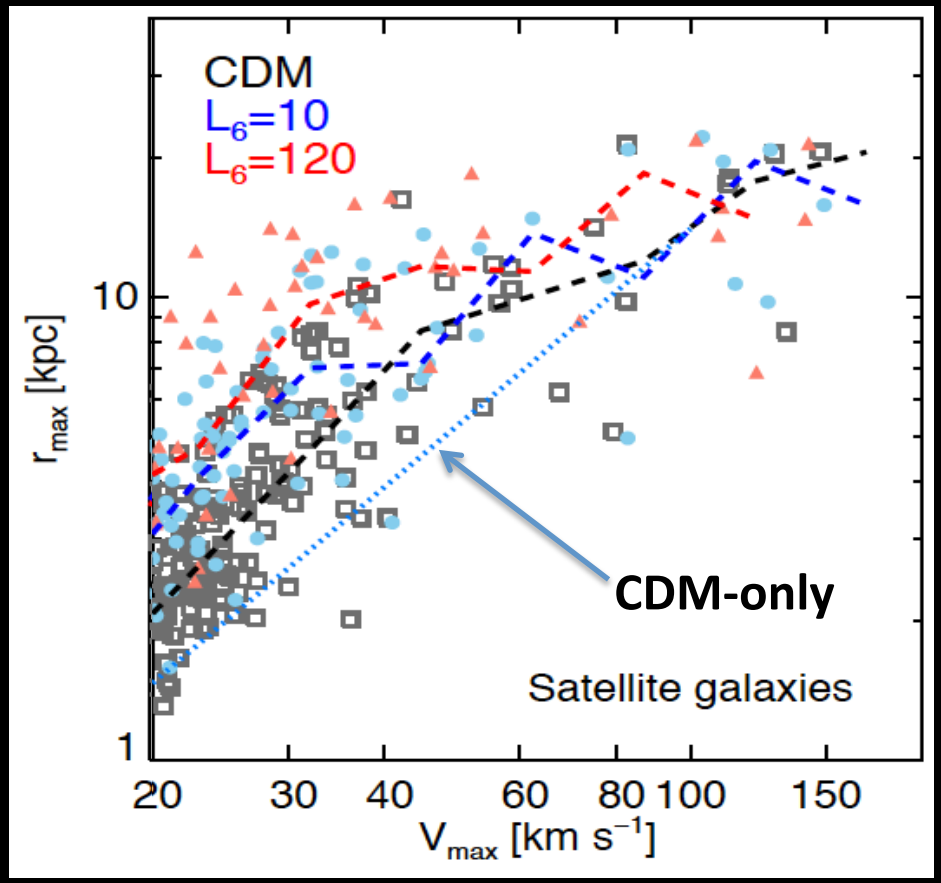
Galaxy counts

WDM has systematically lower counts, but so is CDM. **The 7.0 keV sterile does a good job with local dwarf galaxies**



Density issue

WDM has lower concentration than CDM, but **the 7.0 keV sterile scenario is essentially indistinguishable from CDM**



Lovell et al (2016)

Many follow-up searches

Many detections and null detections

- Bulbul et al, arXiv:1402.2301
  - 73 clusters: 4–5σ with XMM
- Boyarsky et al, arXiv: 1402.4119
  - Andromeda & Perseus: ~4.4σ with XMM
- Boyarsky et al, arXiv: 1408.2503
  - Milky Way: 5.7σ with XMM
- Urban et al, arXiv:1411.0050
  - Perseus: 7.4σ with Suzaku
- Iakubovski et al, arXiv:1508.05168
  - 8 clusters: all >2σ with XMM and Chandra
- Ruchayskiy et al, arXiv:1512.07217
  - Draco: 2.3σ with XMM-PN (but not MOS)
- Franse et al, arXiv:1604.01759
  - Perseus: with Suzaku
- Neronov et al, arXiv:1607.07328
  - CXB, 11σ with NuSTAR
- Cappelluti et al, arXiv:1702.01660
  - CXB: 3σ with Chandra
- Riemer-Sorensen, arXiv:1405.7943
  - Milky Way: null at 95%CL with Chandra
- Jeltema & Profumo, arXiv:1408.1699
  - Milky Way: null with XMM
- Anderson et al, arXiv:1408.4115
  - 80–90 galaxies: null with XMM and Chandra
- Malyshev et al, arXiv:1408.3531
  - Dwarfs: null with XMM
- Tamura et al, arXiv:1412.1869
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  - Diffuse background: null with Suzaku
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  - Draco: null with XMM
- Bulbul et al, arXiv:1605.02034
  - Stacked clusters: 2σ with Suzaku
- Hofmann et al, arXiv:1606.04091
  - 33 clusters: null with Chandra
- Hitomi, arXiv:1607.07420
  - Perseus: null at >99%

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- ✓ Detection by multiple satellites and detectors
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- ✓ Not detected in 'blank sky'
- x Same data can give different results

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Is it dark matter?

- ✓ All observed line fluxes scale with the dark matter content
- ✓ Surface brightness profiles trace dark matter

Is it astrophysics?

- ✓ Surface brightness profiles trace plasma
- ✓ Possibilities have been pointed out (K XVIII, charge exchange)
- x No astrophysical explanation for all positive measurements

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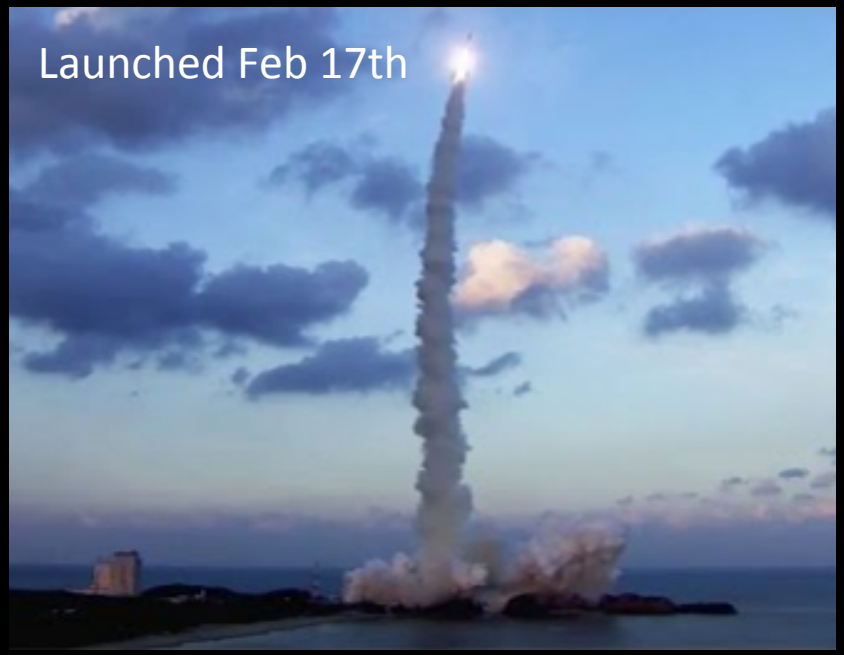
- x No astrophysical explanation for all positive measurements

Debate continues

- Does the surface brightness profile trace the dark matter or plasma?
- Is there a line detection from dwarf galaxies? ← smoking gun!

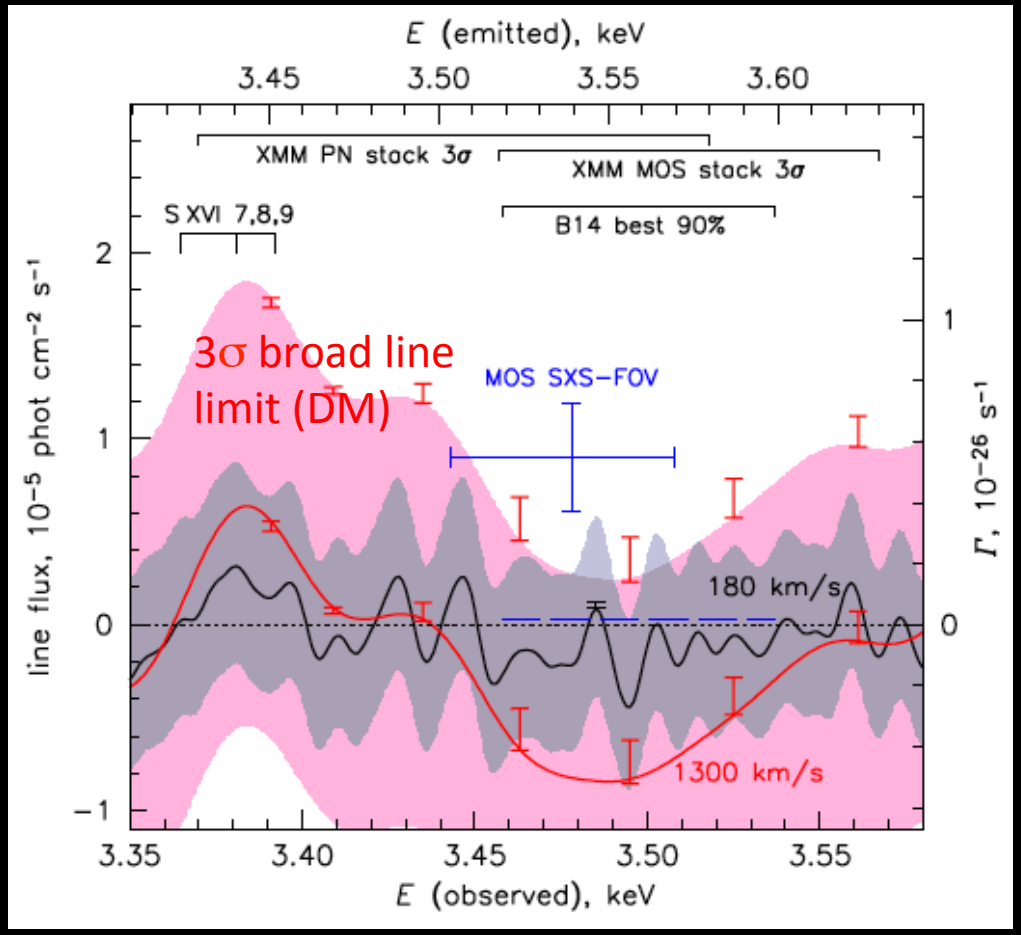
Hitomi satellite



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

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

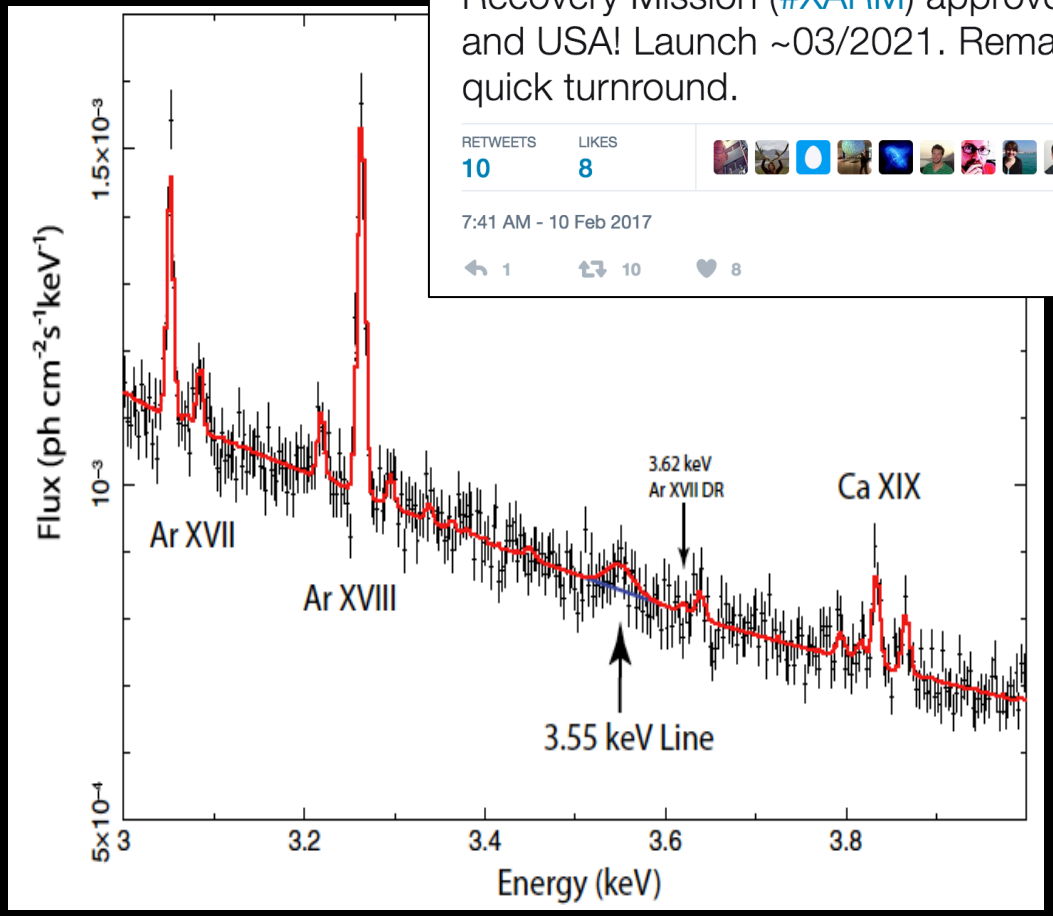


Hitomi (2016)

FUTURE PROBES

Future tests – direct

1. More data & analyses comparisons – many on-going & proposed
   - More observations, e.g., dwarfs
   - Revive spectrometer
   - Rockets
2. Signal in dwarfs?
3. Spectral width
4. Spatial morphology
5. Velocity spectroscopy



Bulbul et al (2014)

3.5 keV in NuSTAR?

There is a line at 3.5 keV in the NuSTAR background model, but its origin is not yet well understood.

Background modeling

3.5 keV (and 4.5 keV) assigned to `solar model' due to variation *Wik et al (2014)*

→ detailed study going on

CXB analysis

Identified 3.5 keV and 4.5 keV lines, but did not see variations with on/off Sun.

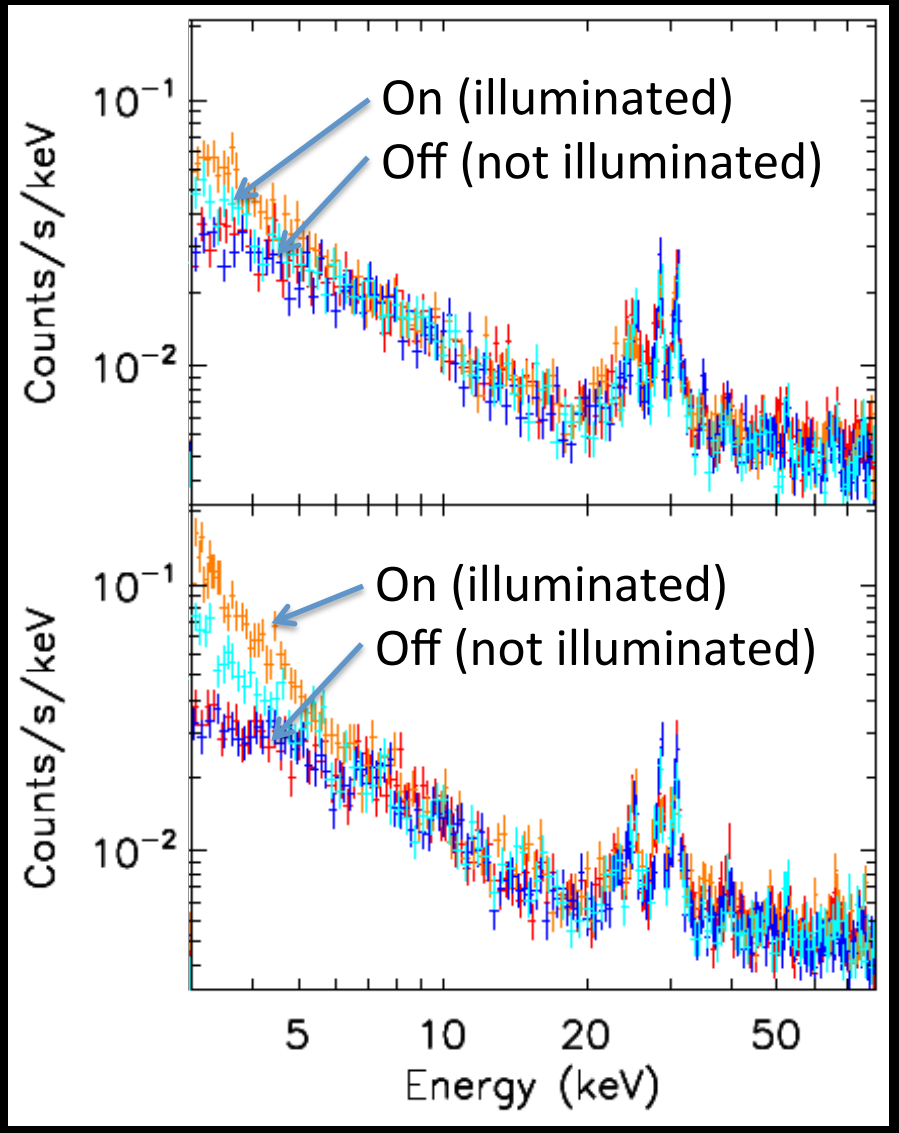
Neronov et al (2016)

GC analysis

3.5 keV seen in the GC dataset, but also in the occulted data set, with consistent line strengths

→ Conservatively assigned `background'

Perez et al (2016)



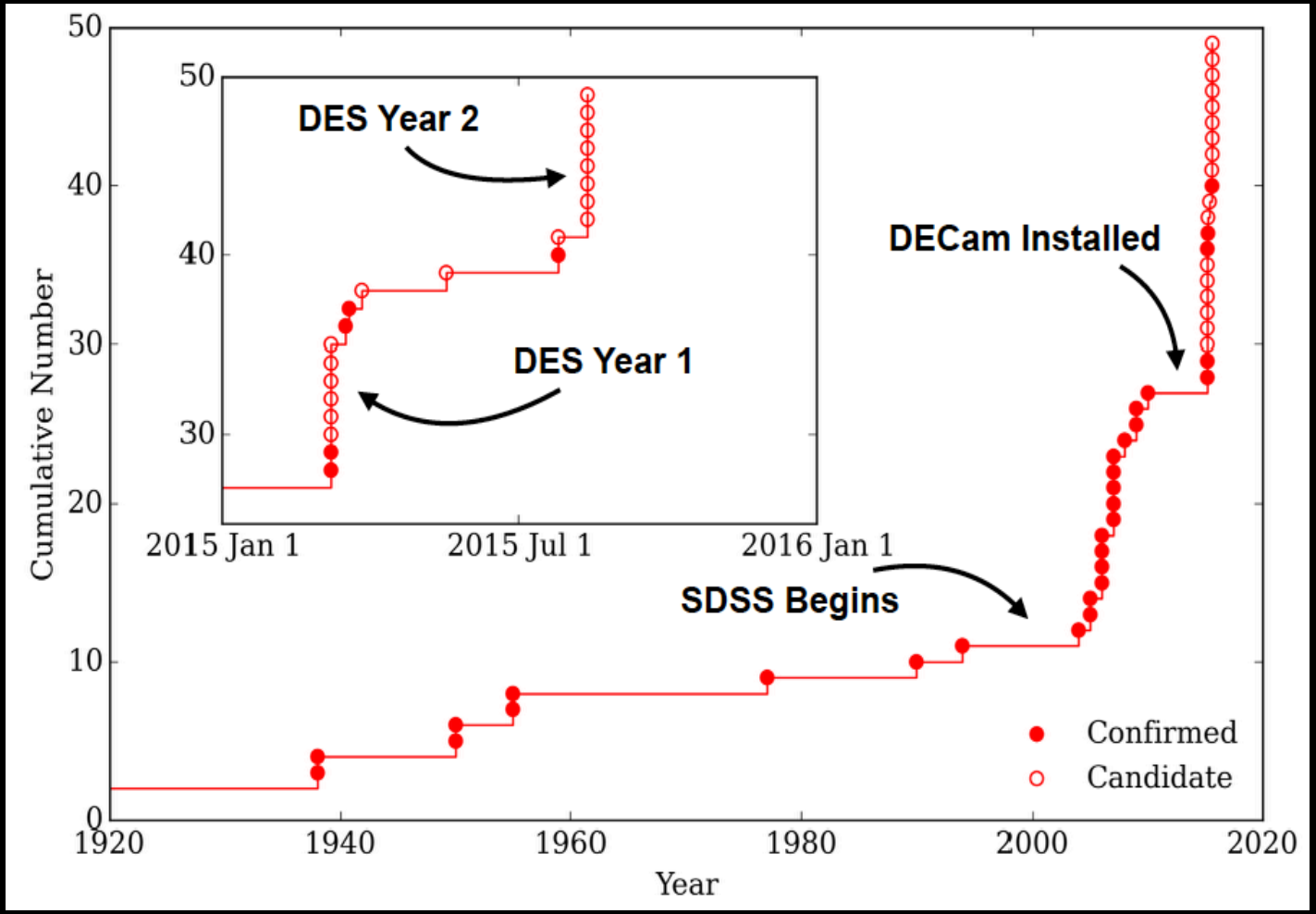
Wik et al (2014)

On-going satellite galaxy searches

Discoveries
DES finding new satellites in new surveys of the Southern sky

Many await spectroscopic confirmation, but size & luminosity already strongly indicative most are dwarf galaxies

DES (2016)



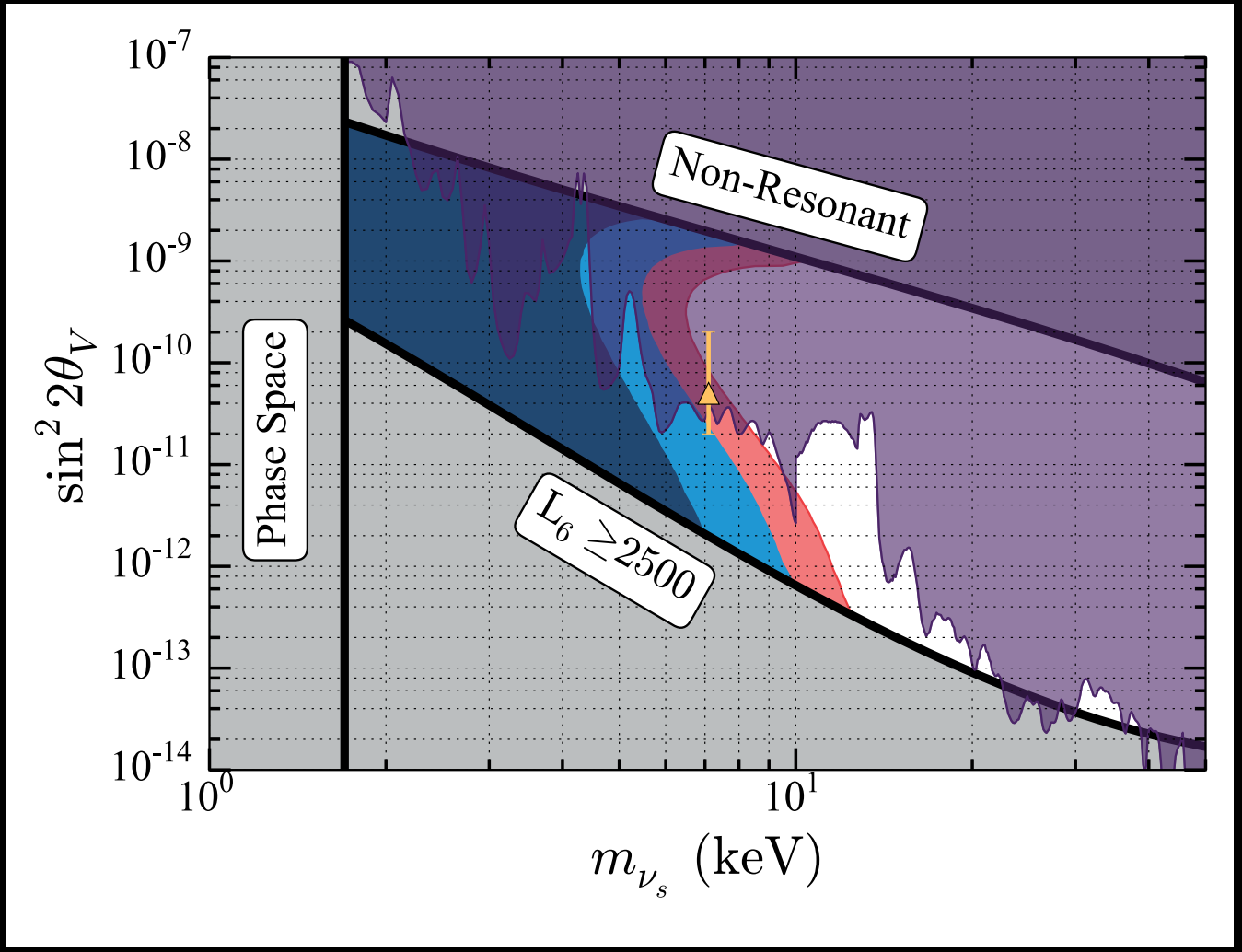
Final counts expected (after correcting for coverage, flux bias, etc): ~100 dwarfs

- Future: LSST

Drlica-Wagner et al (2015)

Implication for 7.1 keV sterile neutrino

3.5 keV line origin:
The 7.1 keV sterile neutrino decay interpretation can be strongly tested by DES satellite galaxy searches



Cherry & Horiuchi (2017)

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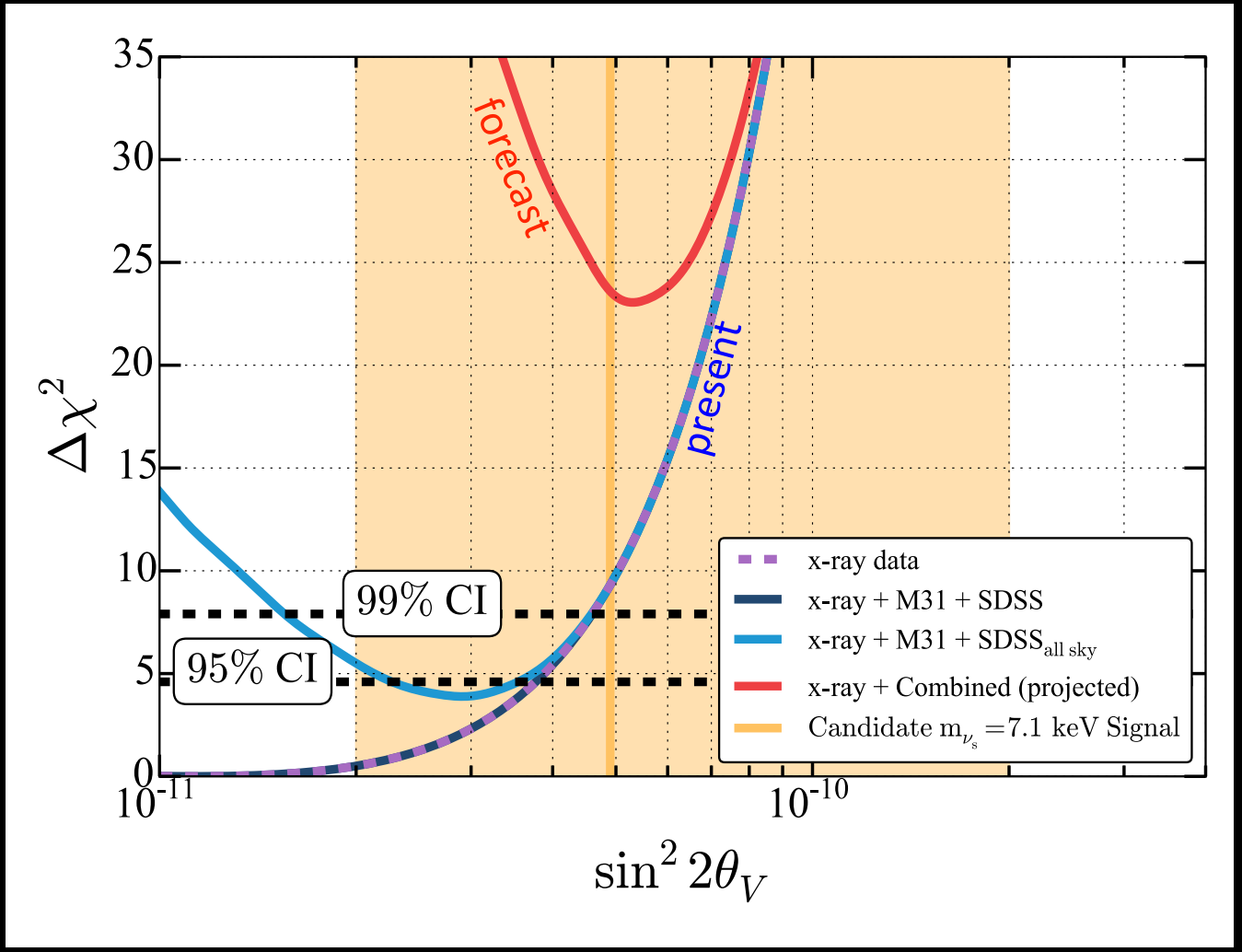


Cherry & Horiuchi (2017)

Summary & take away messages

Sterile neutrino as dark matter

- Compelling candidate
- Oscillation-produced caseis being tested from all sides
  - Warm dark matter: from satellite counts, Lyman-alpha
  - Decays: from X-ray searches
- Many other implications, e.g., pulsar kicks, supernovae, lepton asymmetry
- Note: small-scale issues are becoming less critical with baryonic physics

3.5 keV line

- Anomalous X-ray line can be interpreted as dark matter decay
  - Is consistent with resonantly produced ν_s
  - Is in the sweet spot to help solve small-scale issues in CDM
  - Is a testable scenario: future X rays, satellite galaxy searches

Connected to many areas; interesting hints; on-going searches will provide tests

Review: A white paper on keV sterile neutrino dark matter, 1602.04816

Charge exchange

Charge exchange

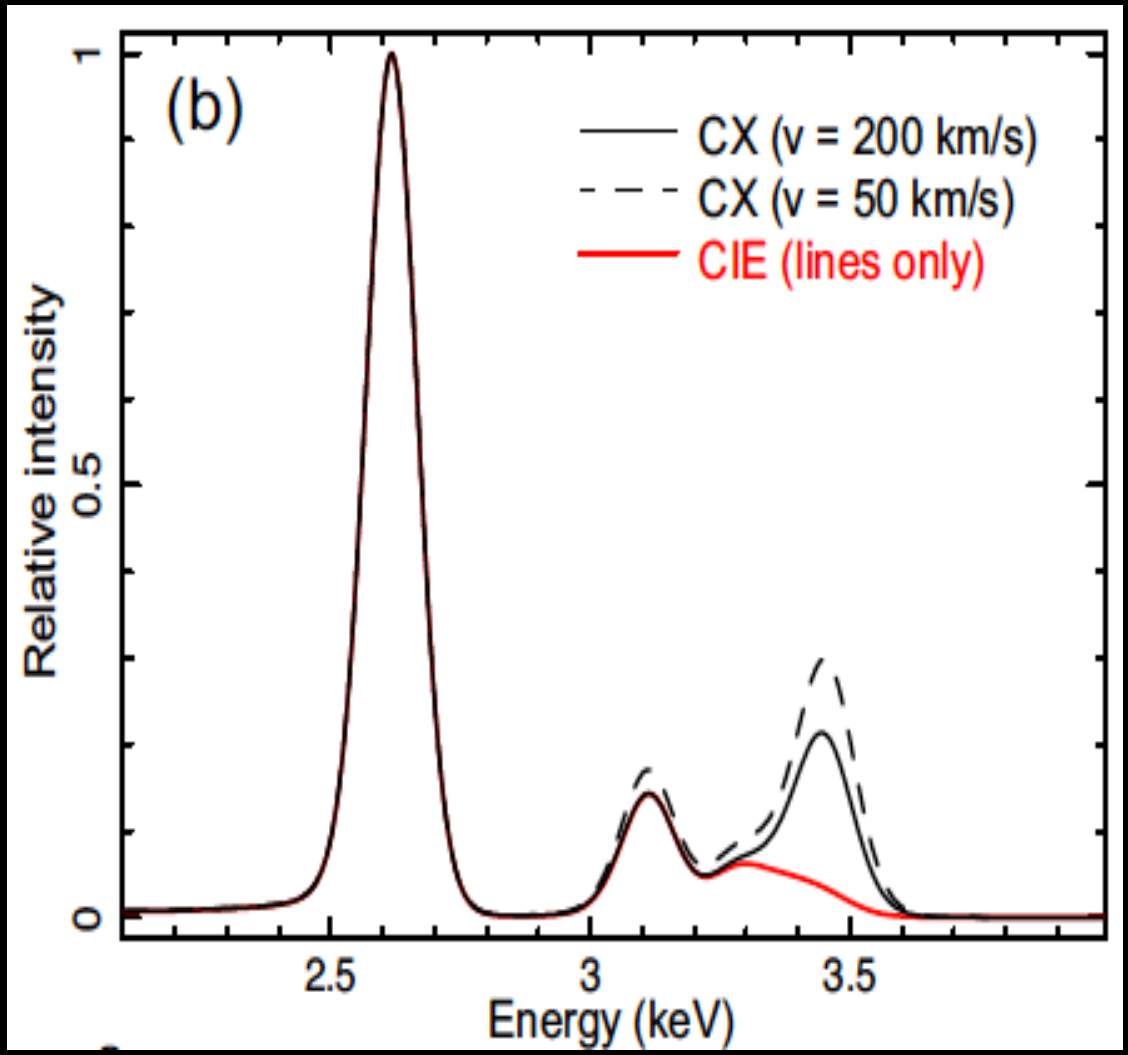
S XVI generates a line at ~3.44 keV (*n*≥9 to GS), induced by charge exchange between H2 and bare S.

Gu et al (2015)
Shah et al (2015)

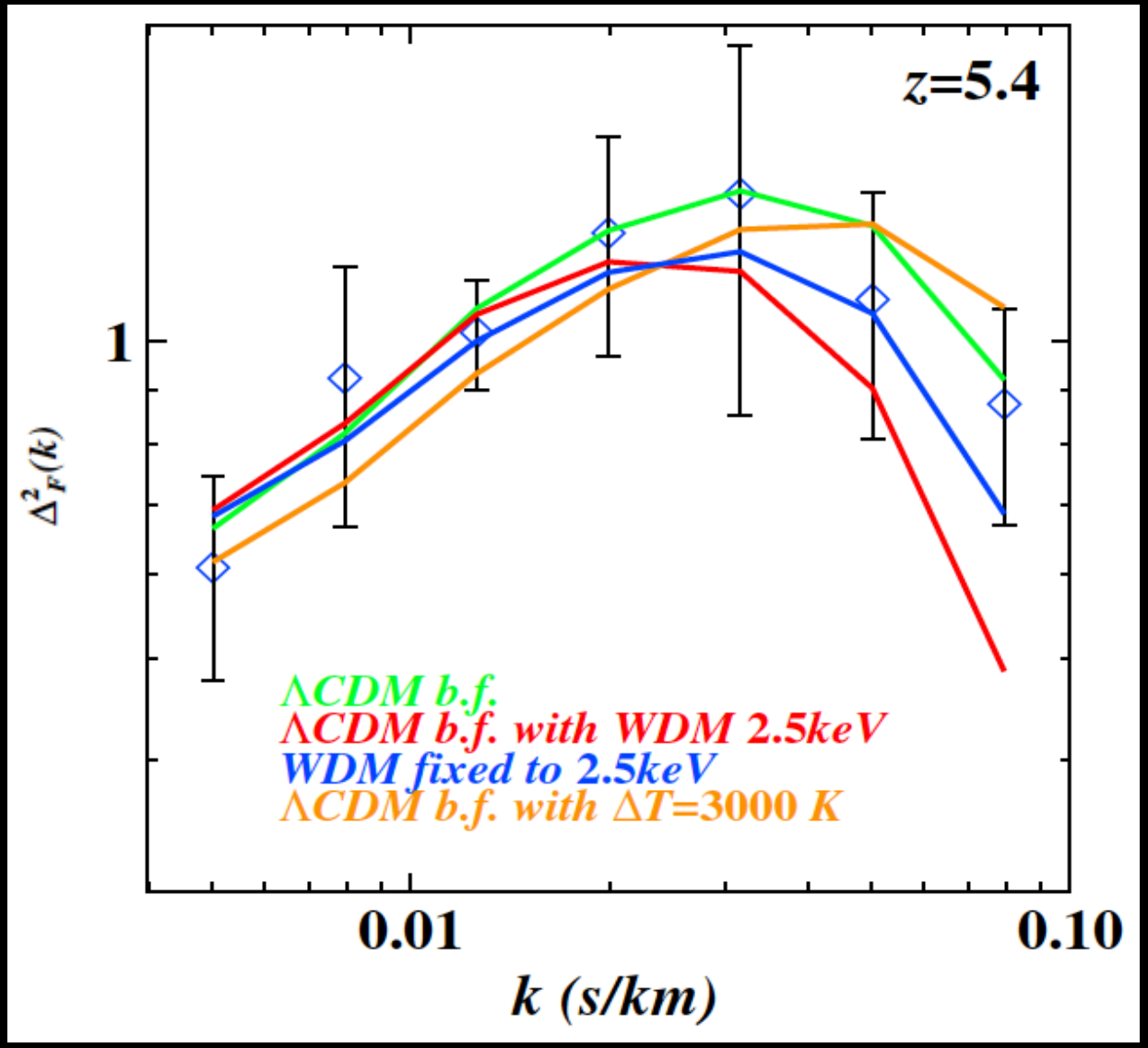
But these initiate a range of lines, including a strong Lyman-alpha at 2.62 keV, which is not seen. Upper limits exclude this scenario at > 3σ

Cappelluti et al (2017)

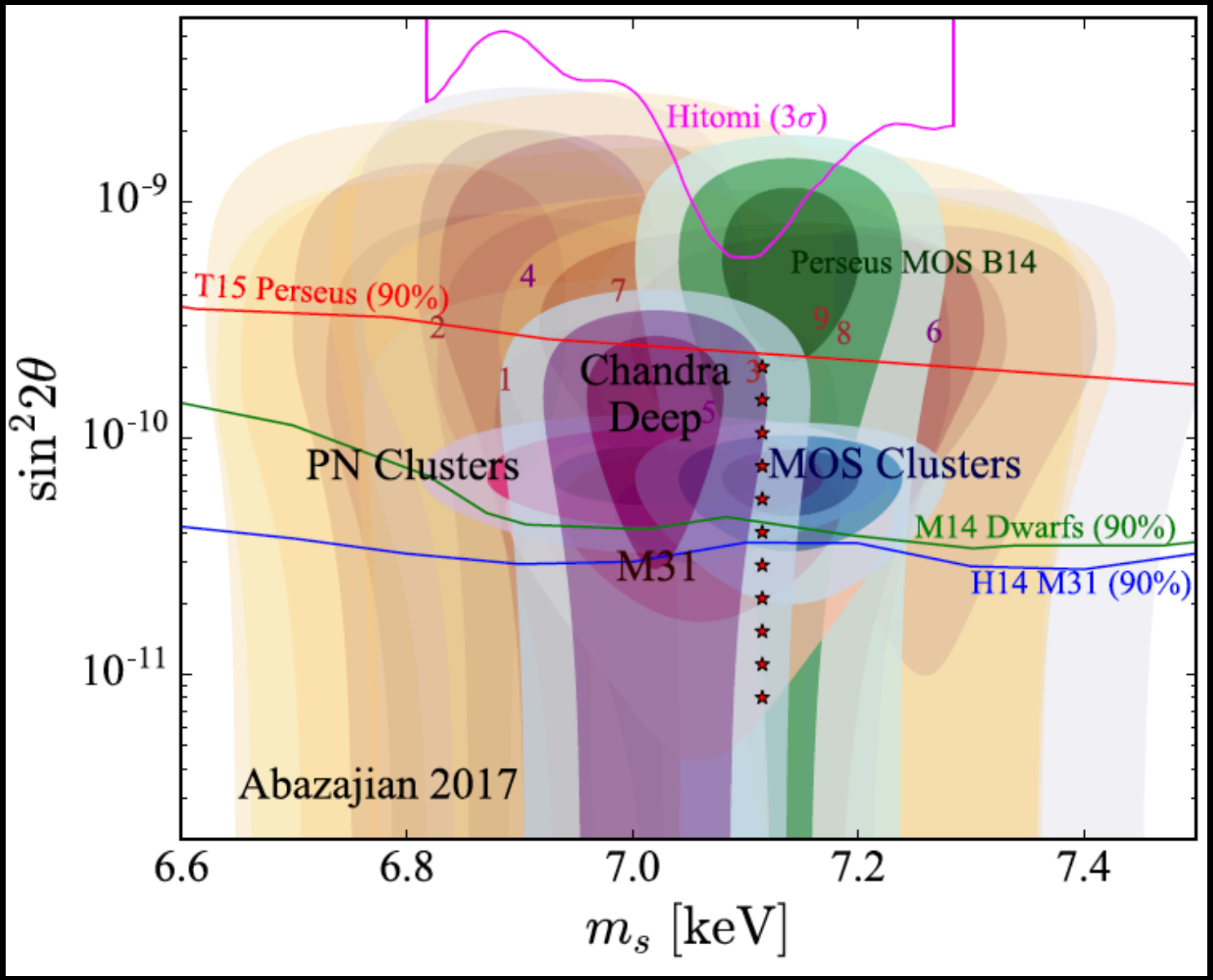
The line energy is also too low (by several sigma)



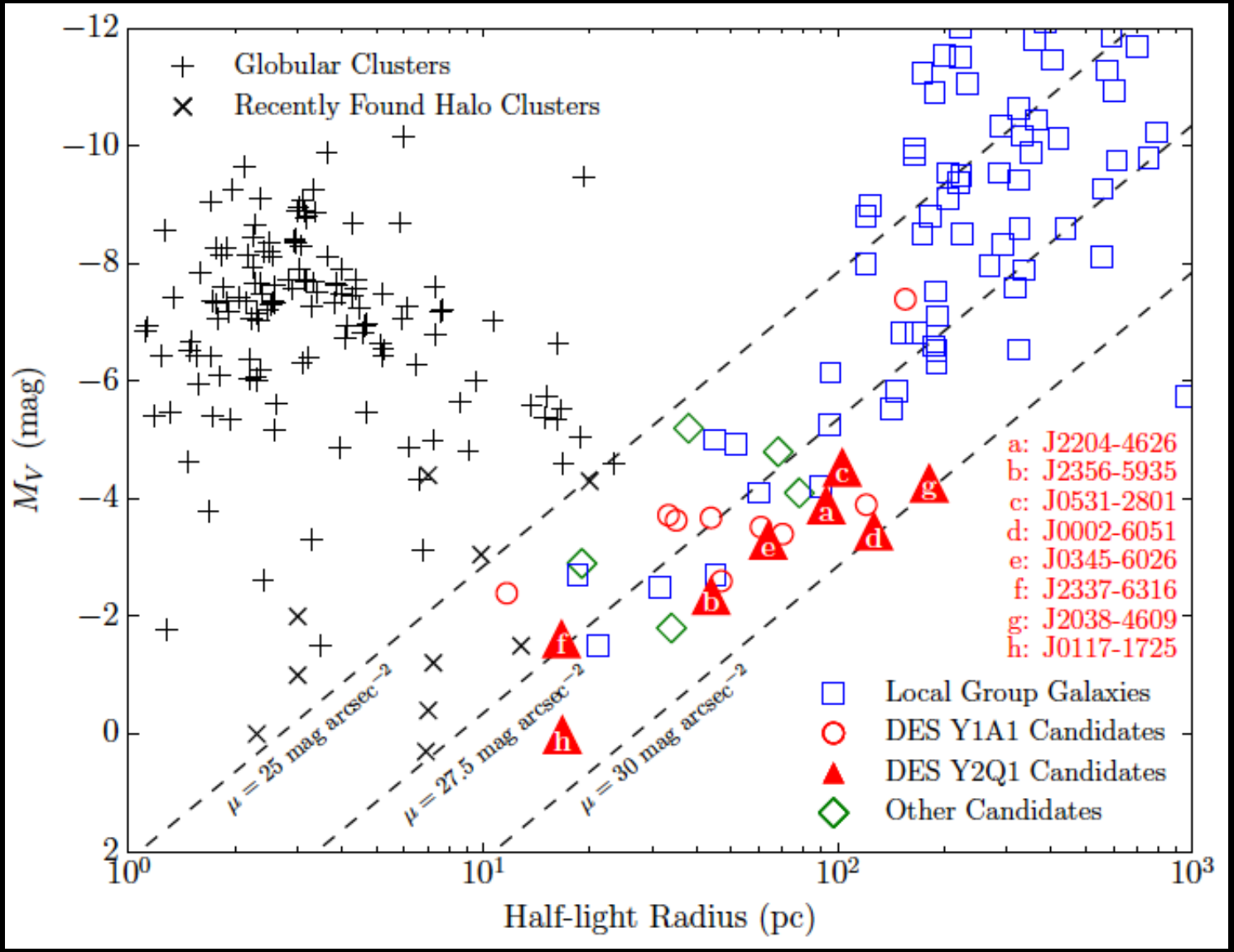
Gu et al (2015)


z=5.4
1
$\Delta^2_F(k)$
ΛCDM b.f.
ΛCDM b.f. with WDM 2.5keV
WDM fixed to 2.5keV
ΛCDM b.f. with ΔT=3000 K
0.01
0.10
k (s/km)

Updates


Hitomi (3σ)
Perseus MOS B14
T15 Perseus (90%)
Chandra Deep
PN Clusters
MOS Clusters
M14 Dwarfs (90%)
M31
H14 M31 (90%)
Abazajian 2017
10^{-9}
10^{-10}
10^{-11}
$\sin^2 2\theta$
6.6
6.8
7.0
7.2
7.4
m_s [keV]

DES: dwarf galaxy or stellar cluster?



DES (2015)

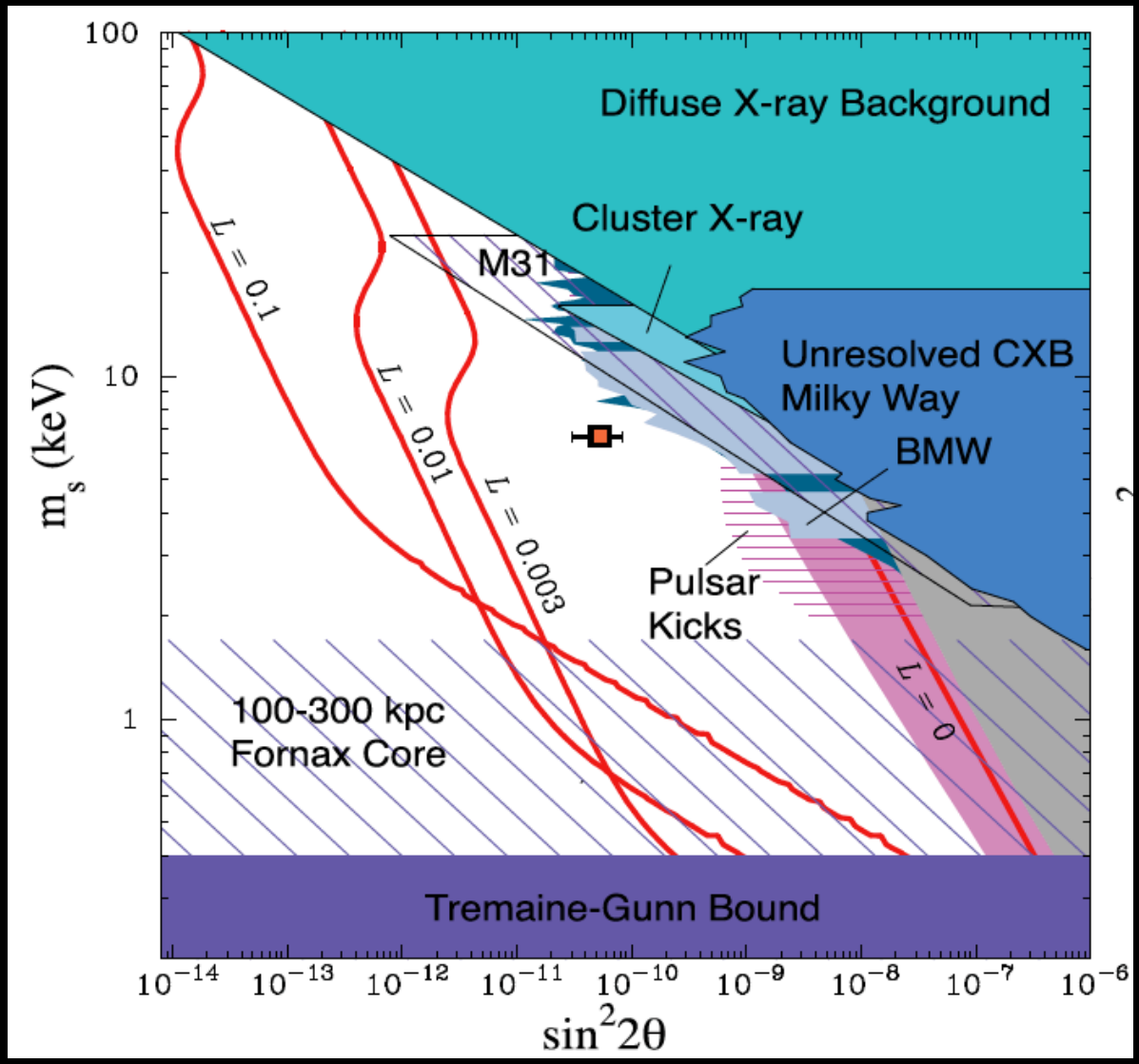
Pulsar kicks

Pulsar velocity

Outliers with ~1500 km/s velocities: how are they kicked so fast?

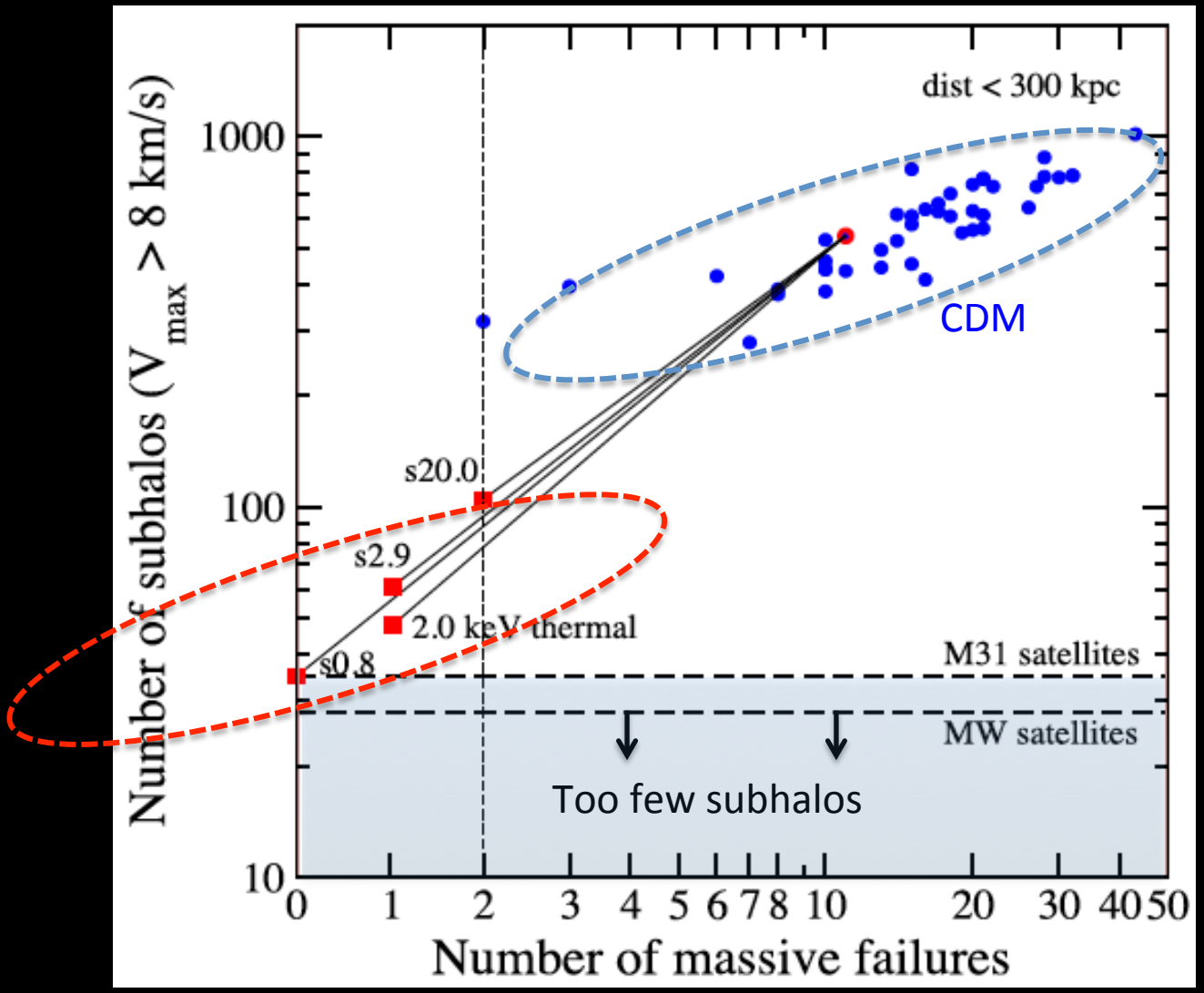
Sterile neutrino

Asymmetric emission of sterile neutrinos (a few percent of active neutrino emission is enough; cannot be too efficient, otherwise violates neutrino burst detection)

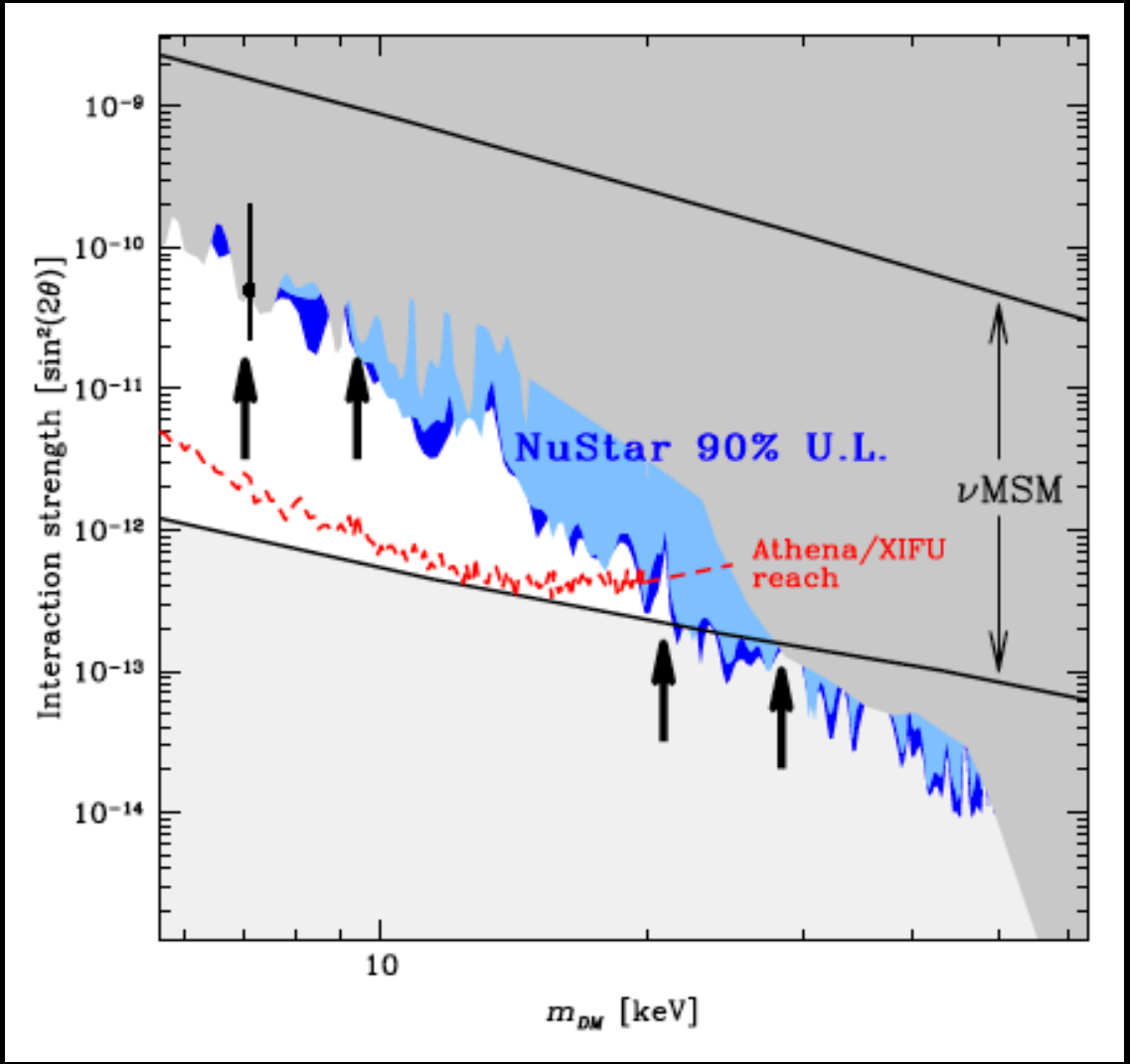
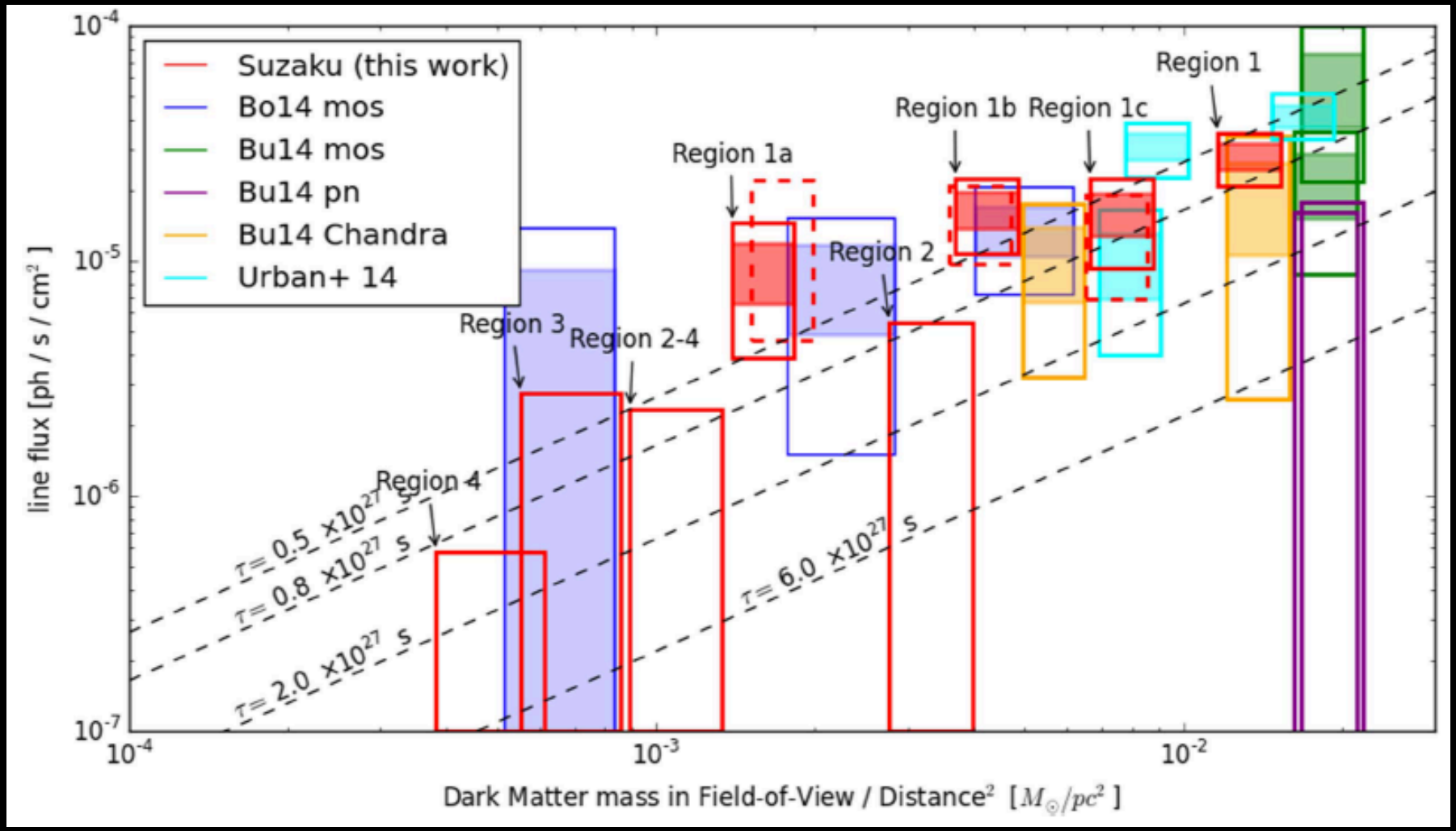


Adapted from Abazajian (2009)

Halo-to-halo scatter & systematics



NuSTAR: CXB limits



Decaying dark matter interpretation