Present and Future Neutrino Physics, Dec 12th 2014

Sterile neutrino cosmology

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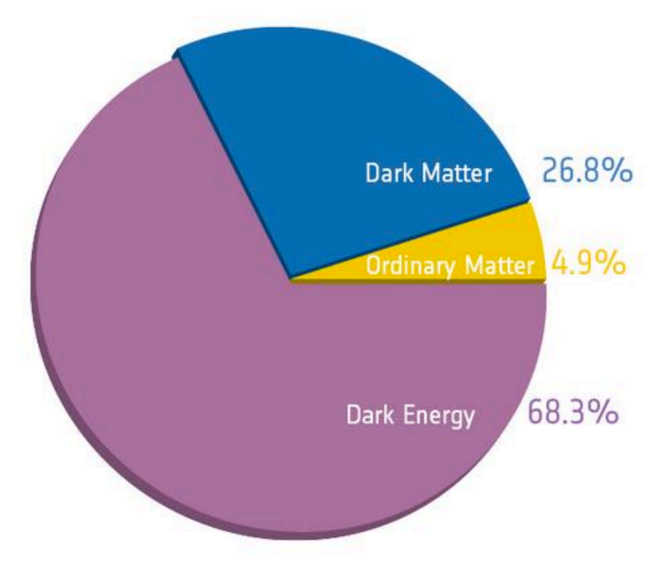
Lambda CDM: very successful

- DM-only simulations have had great success in explaining the observed large-scale structure of the universe. Recent inclusions of baryons again have great success

  e.g., Springel et al (2004), Vogelsberger et al (2014)

- Numerous small-scale issues have been pointed out:
  - Missing satellites
  - Too big to fail
  - Core/cusp
  - Plane of satellites
  - Number of galaxies in voids
  - Existence of bulgeless disk galaxies



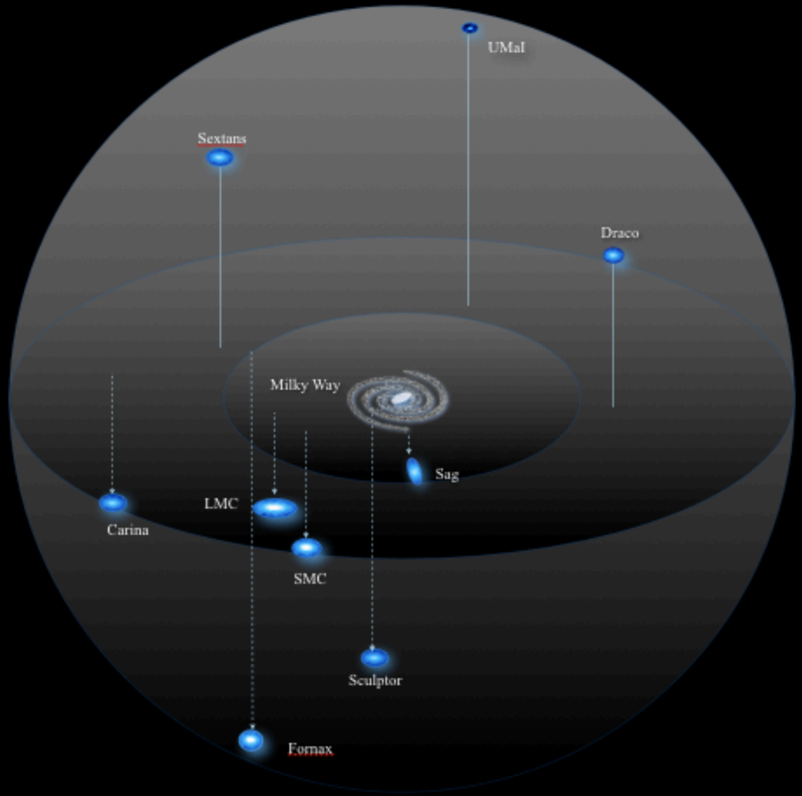
- Some important assumptions:
  - Baryons are not included
  - CDM has a very specific meaning in cosmological simulations

Cold dark matter challenged

CDM is challenged by observations probing small scales

1. Missing satellites problem: expect $O(100)$ satellites but see $\sim$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)

Cold dark matter challenged

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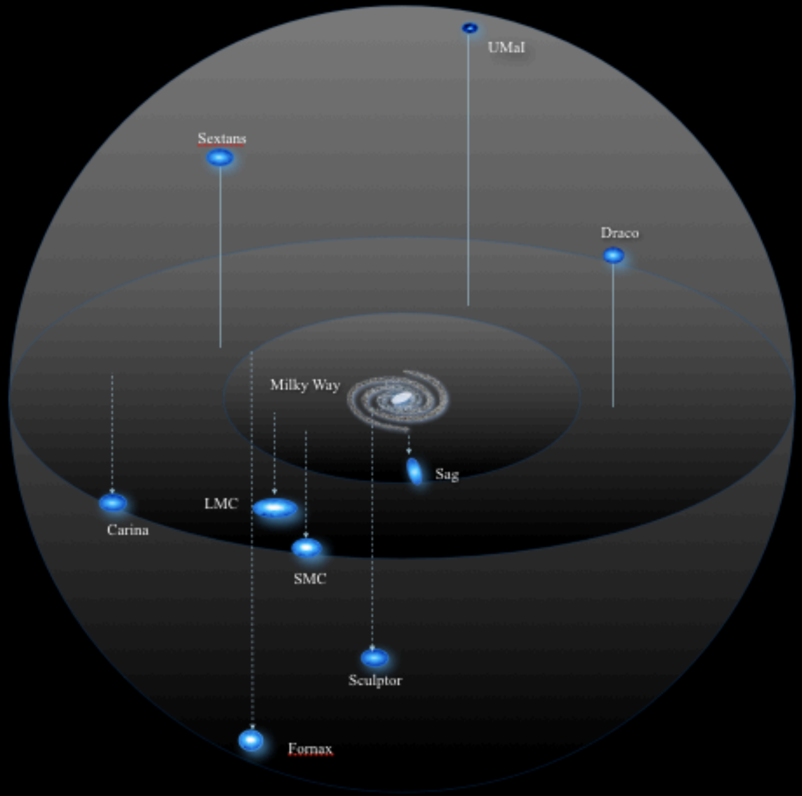

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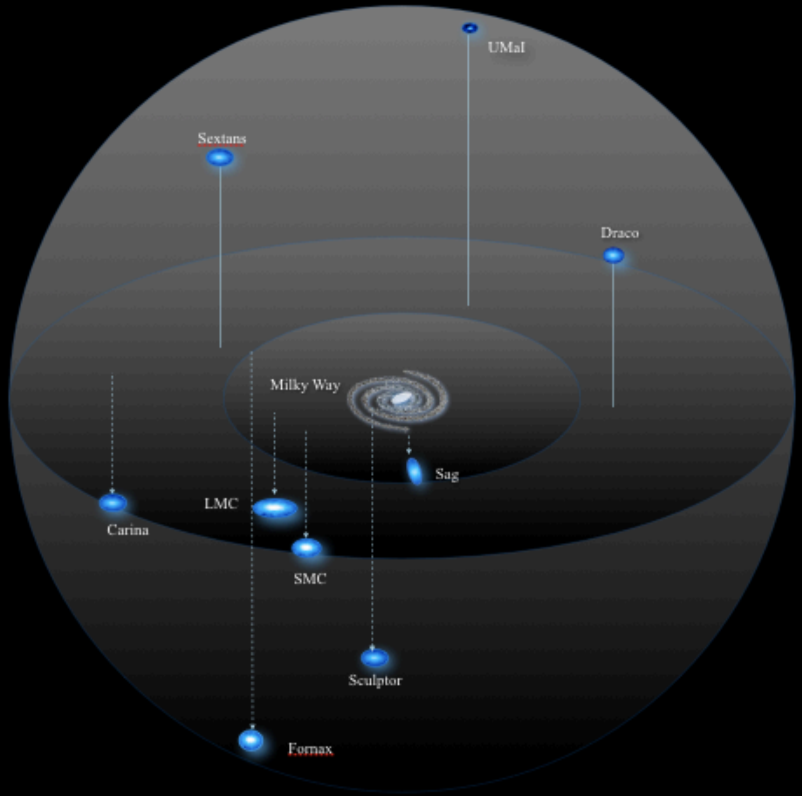

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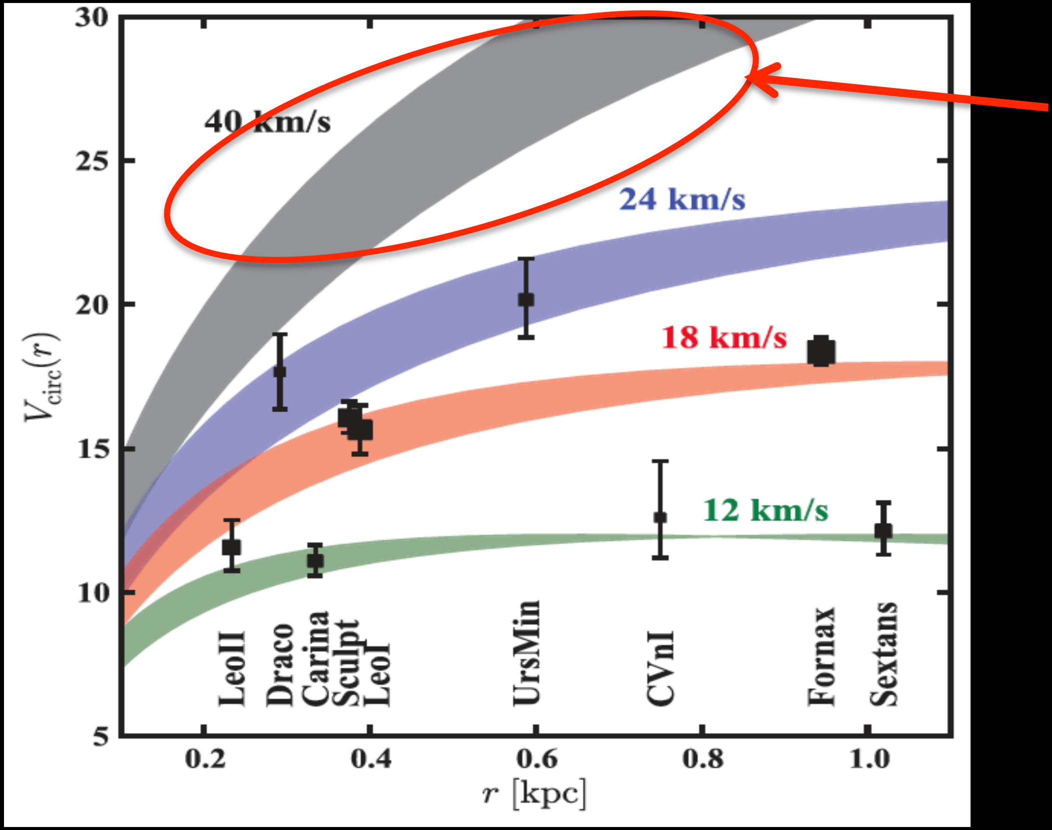


Boylan-kolchin et al, MNRAS (2011, 2012)

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

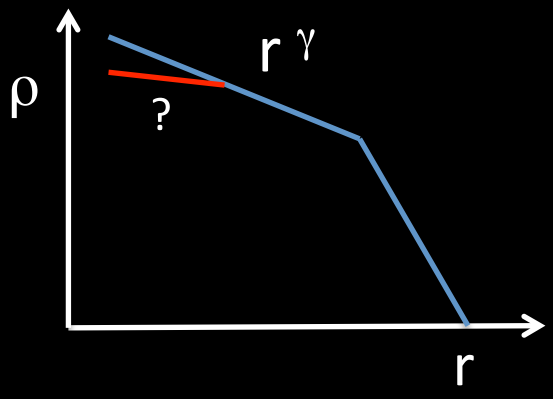
Between 5 – 40 massive failures (median 25) based on 48 realizations of the Milky Way Halo

Garrison-Kimmel et al MNRAS (2014)

Cold dark matter challenged

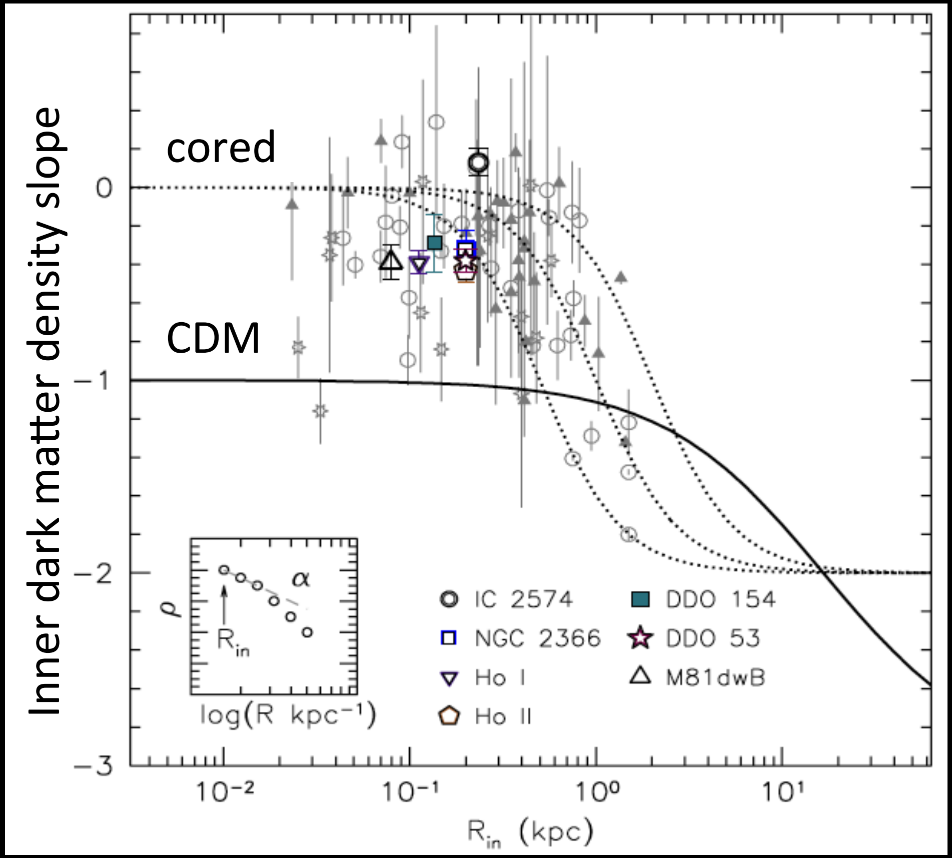
CDM is challenged by observations probing small scales

1. <u>Missing satellites problem:</u> expect *O*(100) satellites but see ~10
2. <u>Too big to fail problem</u>: massive subhalos are too dense to match data
3. <u>Core/cusp problem:</u> inner density profile steeper than data



The DM density profiles in Milky Way satellites is currently under debate.

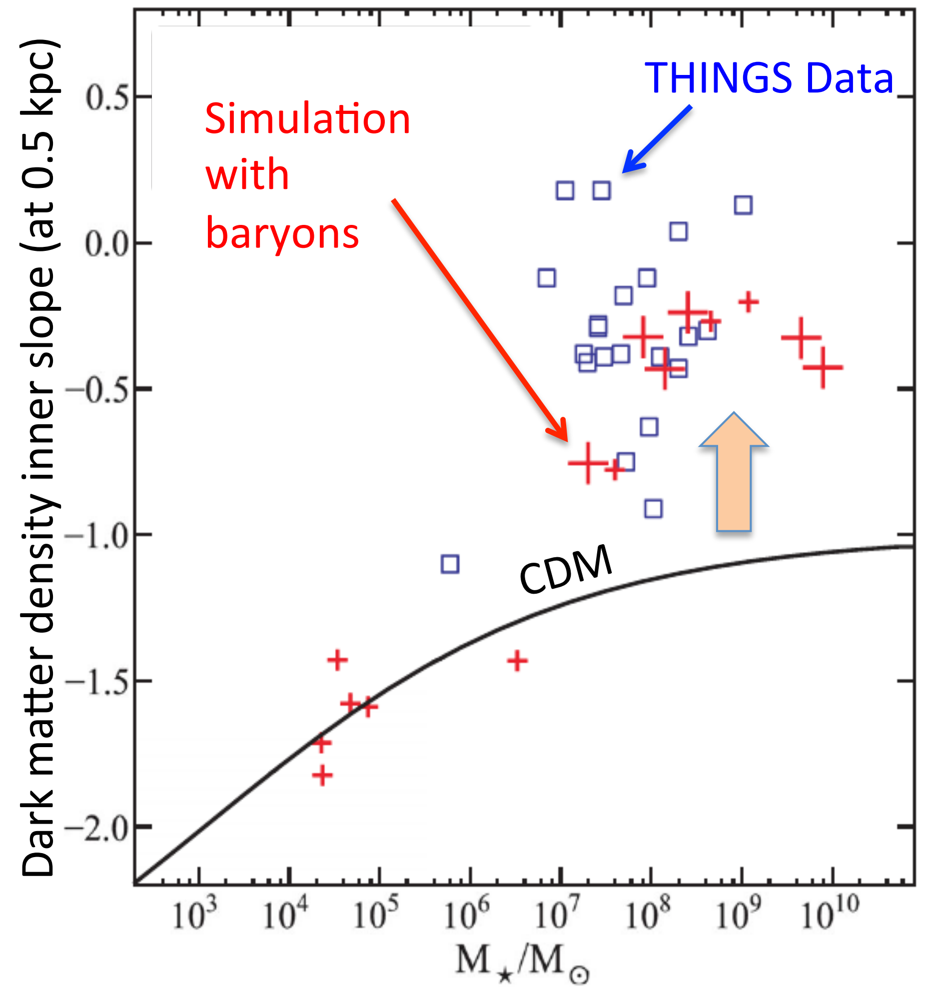
→: low surface brightness galaxies in the ~4 Mpc volume

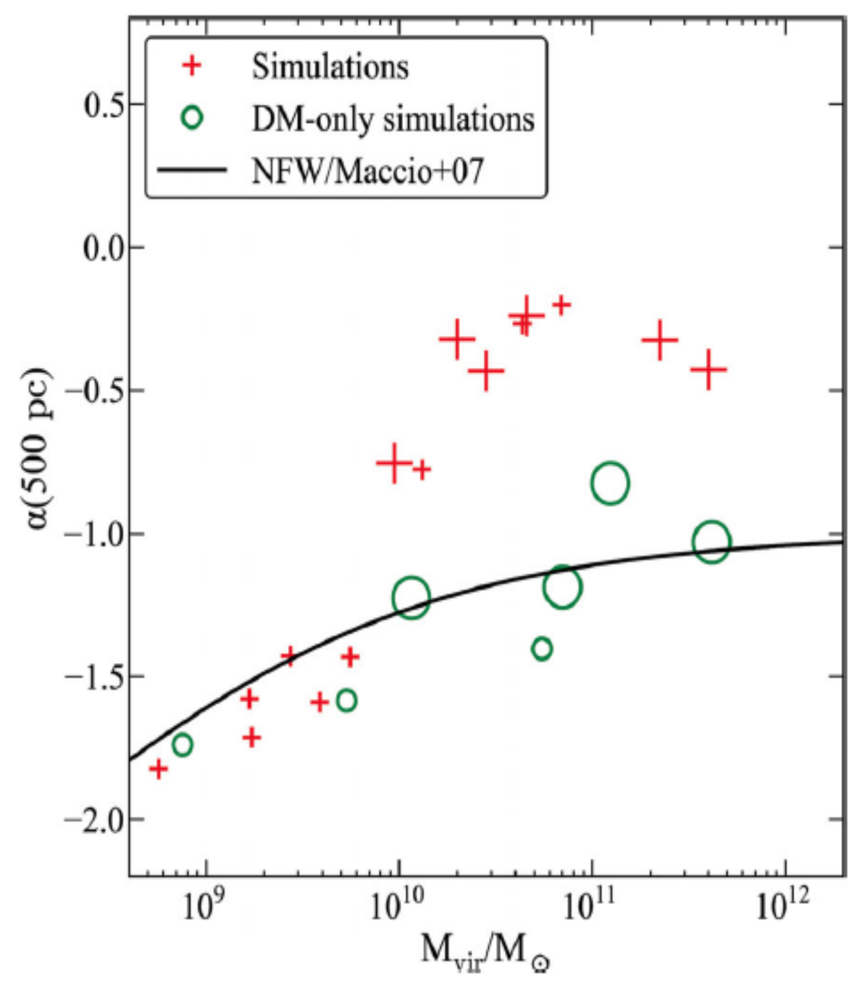


Oh et al (2011) [THINGS]

Baryon solution

Feedback is important: Supernova blows baryons to outer radii, leaving a less concentrated dark matter distribution *Navarro et al MNRAS (1996), Teyssier et al, MNRAS (2012),* etc





Governato et al, MNRAS (2012)

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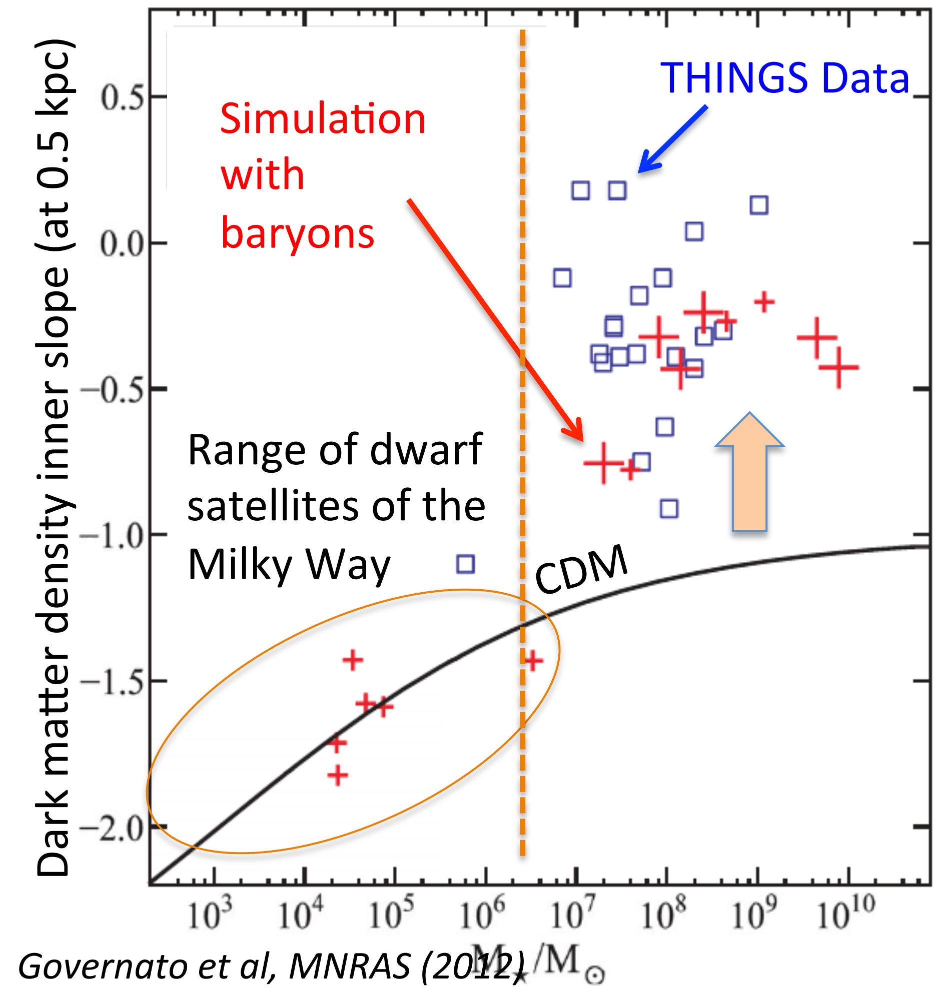


Governato et al, MNRAS (2012)

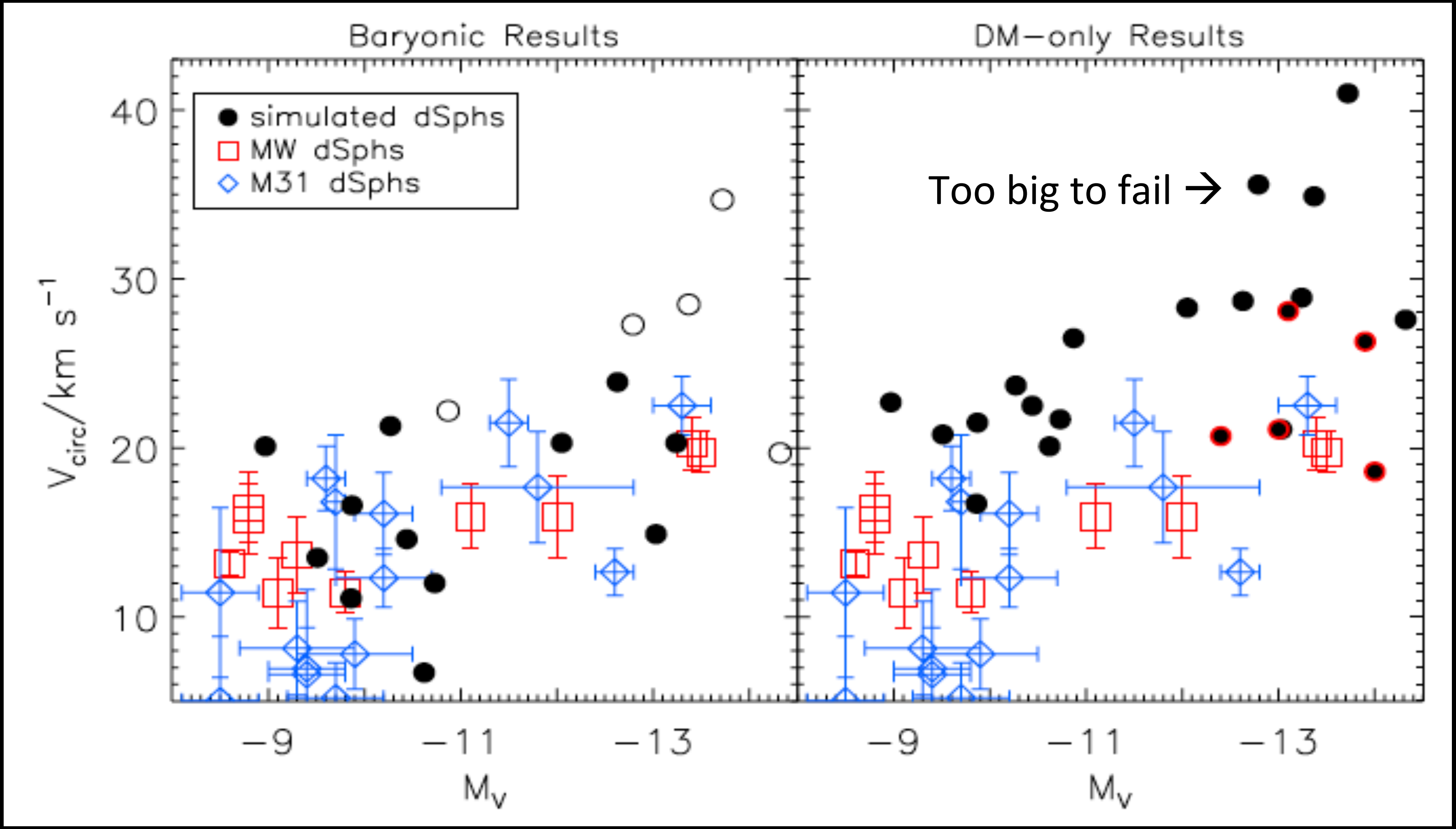
Insufficient supernova:
The observed star does not allow enough supernova feedback to have substantially affected the DM distribution

Pen̄arrubia et al, ApJL (2012)
Zolotov et al, ApJ (2012)
Garrison-Kimmel et al, MNRAS (2013)

This is the range where most of the “problematic” satellite galaxies of the Milky Way are (and also for M31).

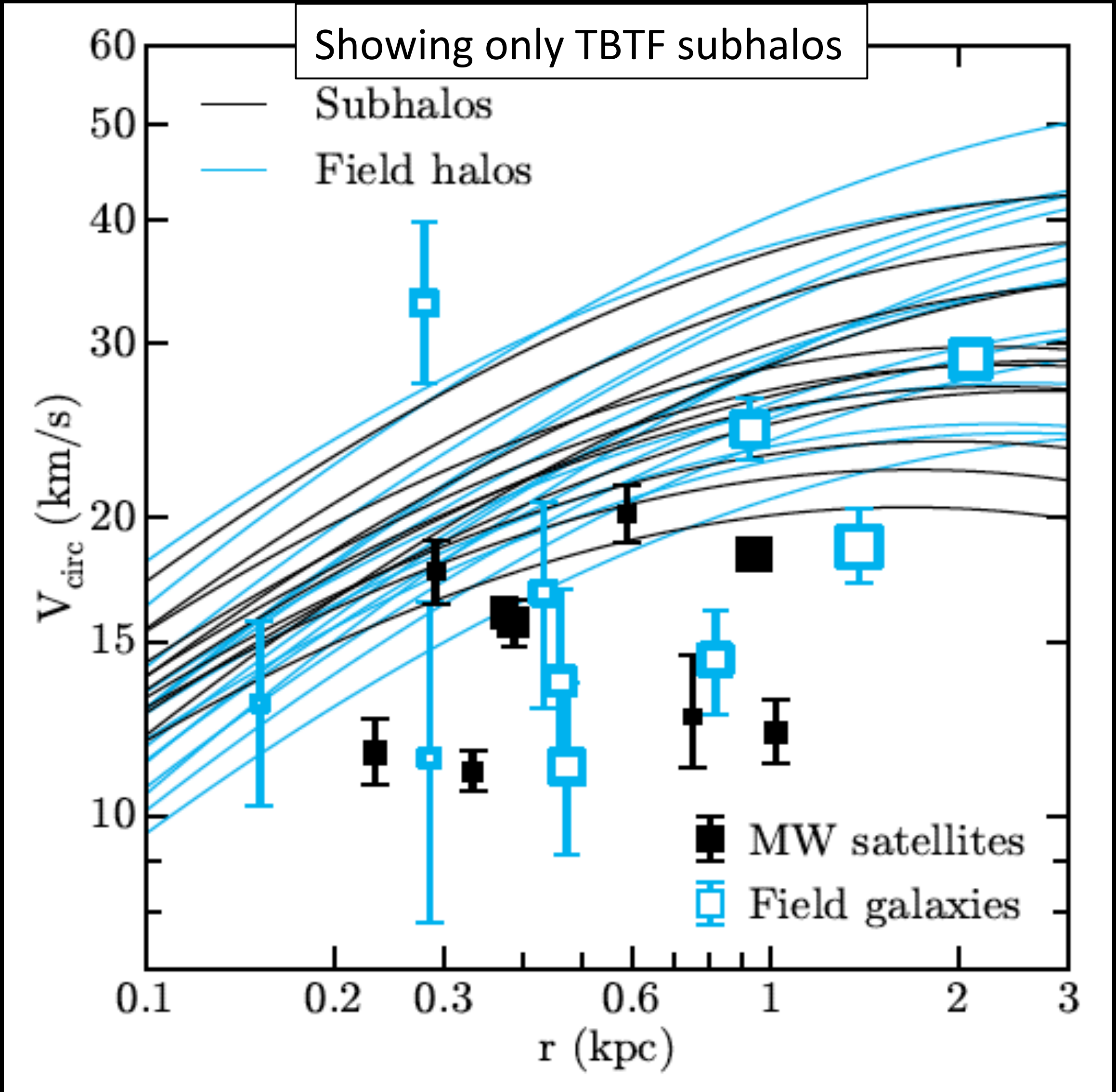
Baryon physics is rich

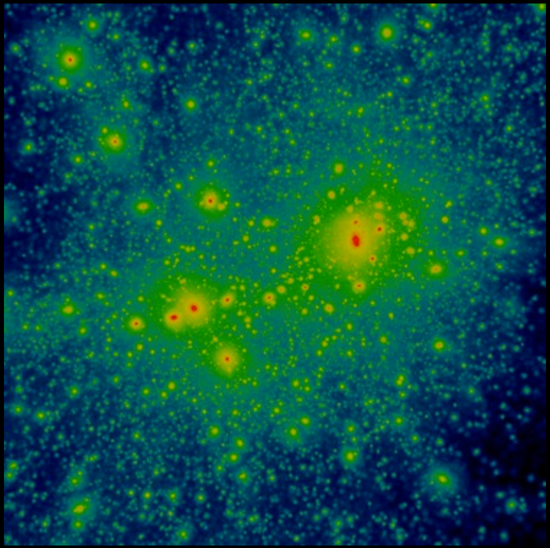
Tidal stripping due to the host disk: reduces inner mas. Two regimes identified, the "cored regime" for high stellar mass dwarfs (where SN feedback is important), and the regime that requires small pericenter orbits



Brooks & Zolotov ApJ (2014)

Too-big-to-fail in local field dwarfs





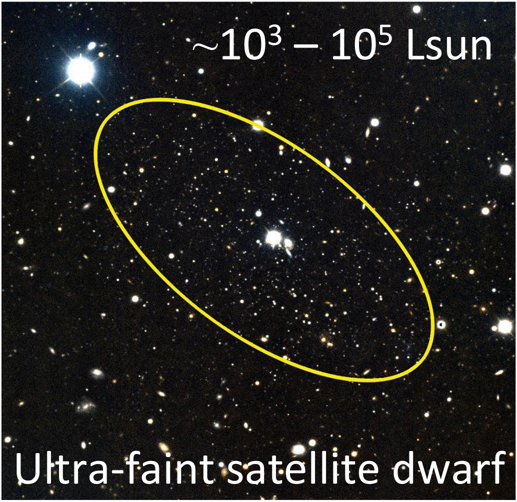
Garrison-Kimmel et al (2014)

The problem persists in the Local Volume:
A lot (> 15) of missing massive halos beyond the virial radii of the Milky Way and M31.
→ hard to appeal to environmental solutions.

See also Ferrero et al, MNRAS (2012)

Dwarf galaxies: dark matter laboratories

Our satellite dwarf galaxies are excellent laboratories for testing dark matter



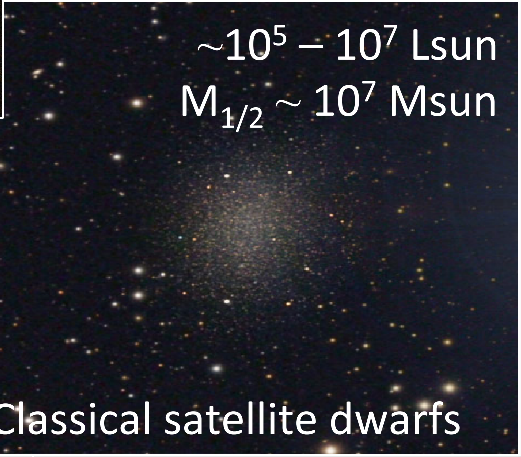
$\sim 10^3 - 10^5$ Lsun

Ultra-faint satellite dwarf

$R_{*1/2} \sim 500$ pc

$M_{1/2} \sim 10^7$ Msun

Mass-to-light ratio ~ 100 – 5000



$\sim 10^5 - 10^7$ Lsun

$M_{1/2} \sim 10^7$ Msun

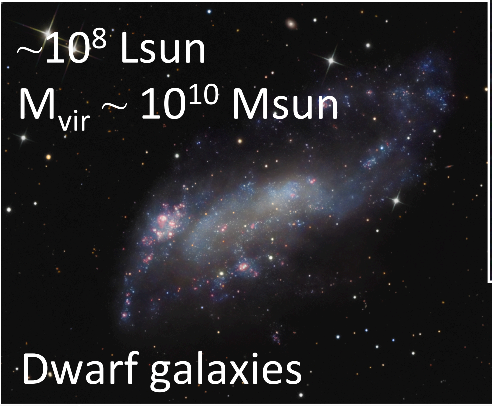
Classical satellite dwarfs

Mass-to-light ratio ~ 5

$\sim 10^{10}$ Lsun

$M_{vir} \sim 10^{12}$ Msun

Things like Milky Way



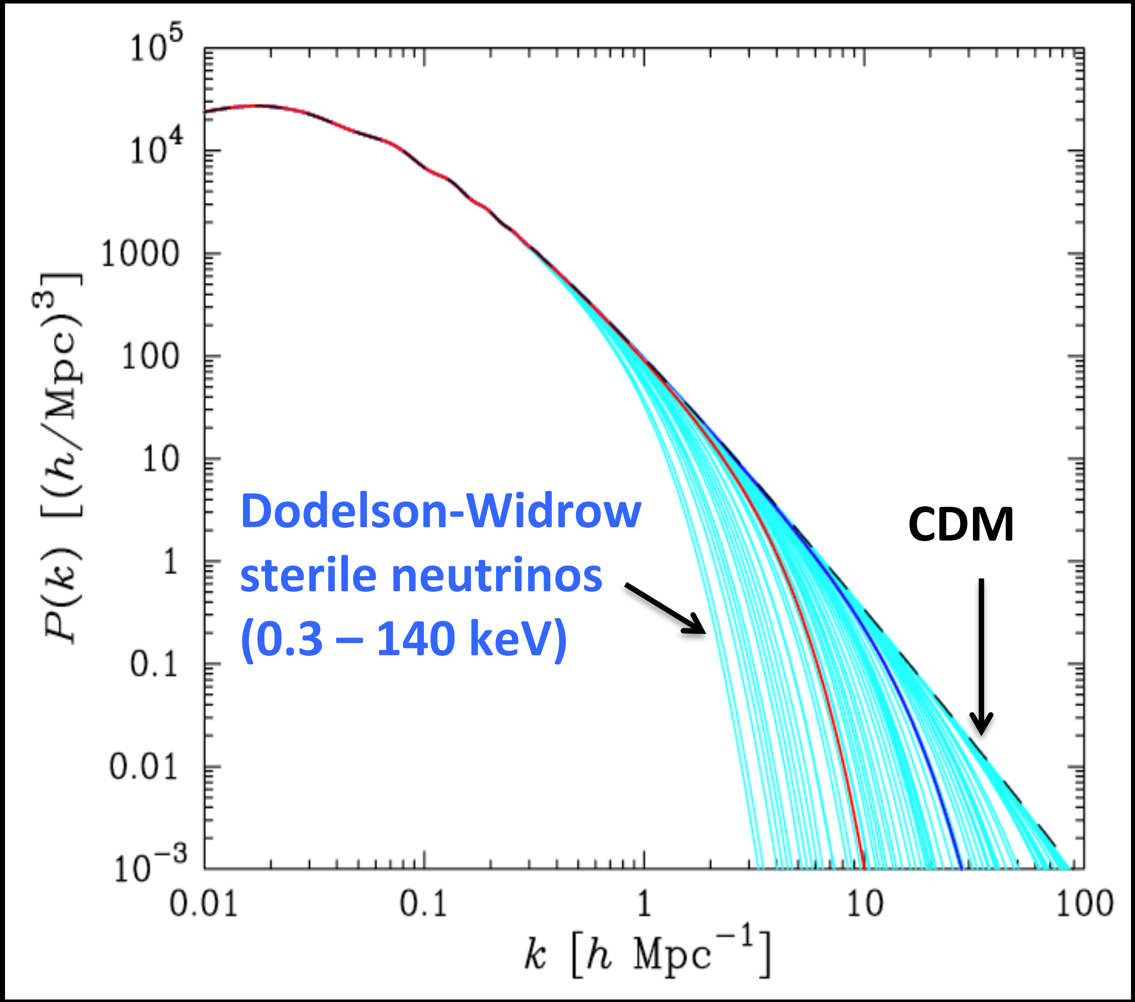
$\sim 10^8$ Lsun

$M_{vir} \sim 10^{10}$ Msun

Dwarf galaxies

Sterile neutrino dark matter

Suppression of power on small scales



Abazajian, PRD (2006)

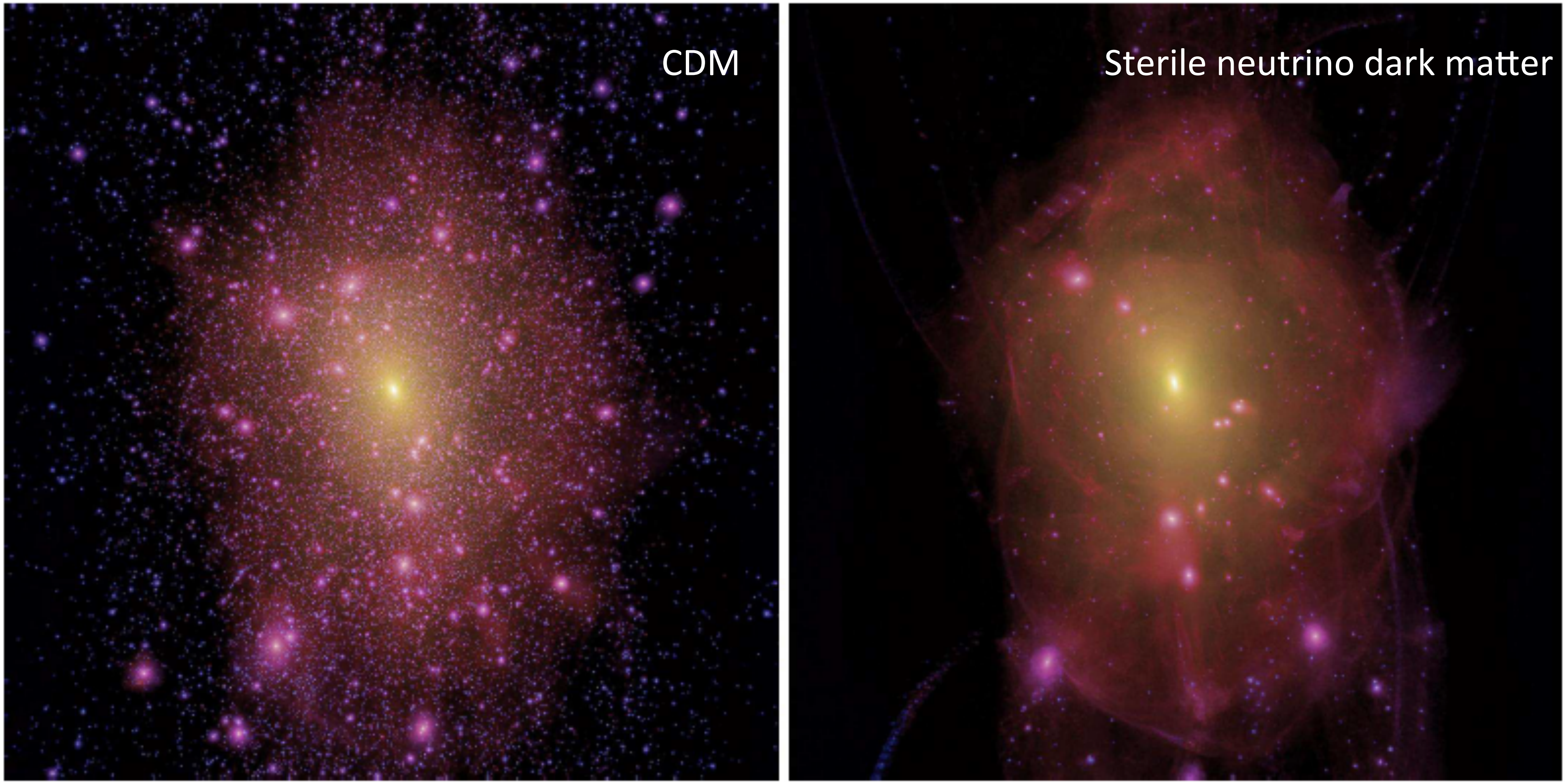
In the Dodelson-Widrow production mechanism, the cutoff scales as the mass:

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

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

This is not so in most other production mechanisms, e.g., resonantly-enhanced Shi-Fuller mechanism. (Tends to be colder than DW for a given sterile neutrino mass).

Warm dark matter structures



Lovell et al, MNRAS (2012)

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

Subhalo counting

When is sterile neutrino too warm?

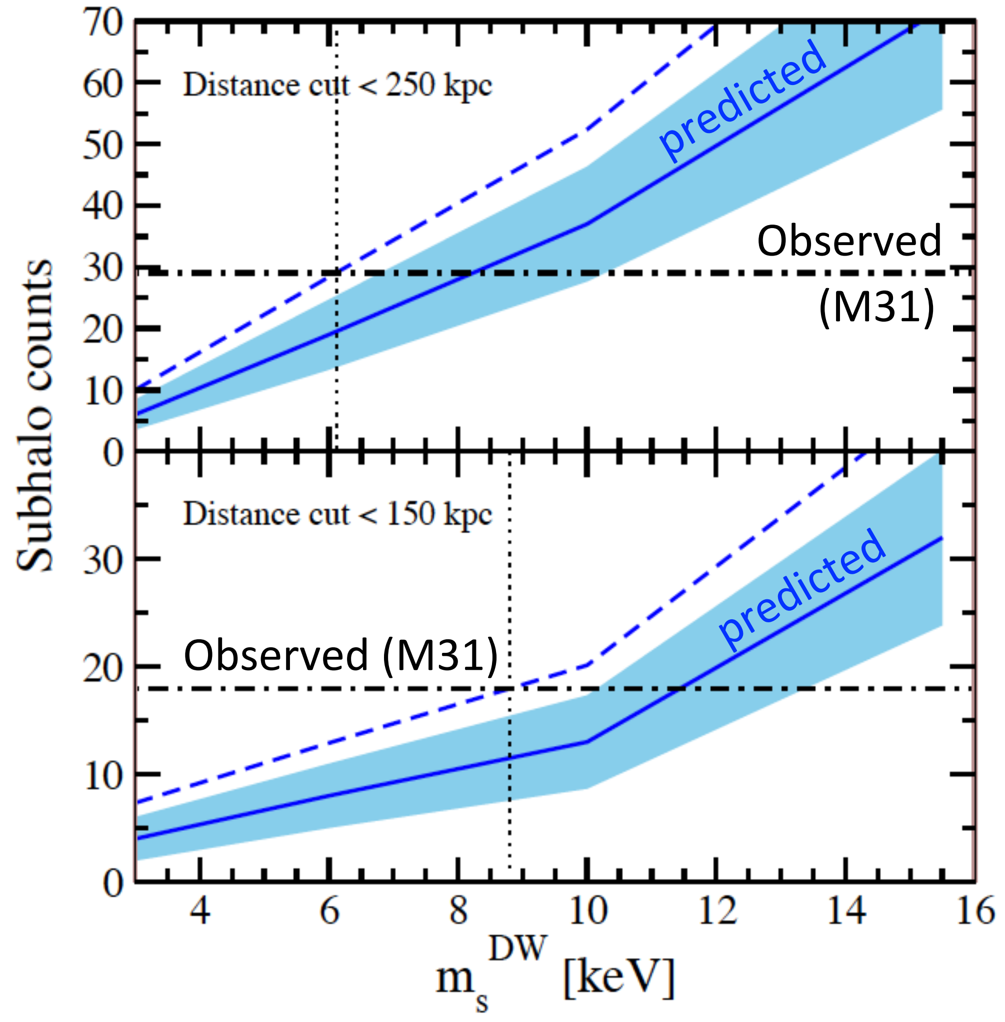
Require that sterile neutrino dark matter does not over erase small-scale structure (=subhalo counts)

Polisensky & Ricotti, PRD (2011)
Horiuchi et al, PRD (2014)

Include systematics, e.g., host halo mass uncertainty and incompleteness corrections.

Obtain robust limits of:

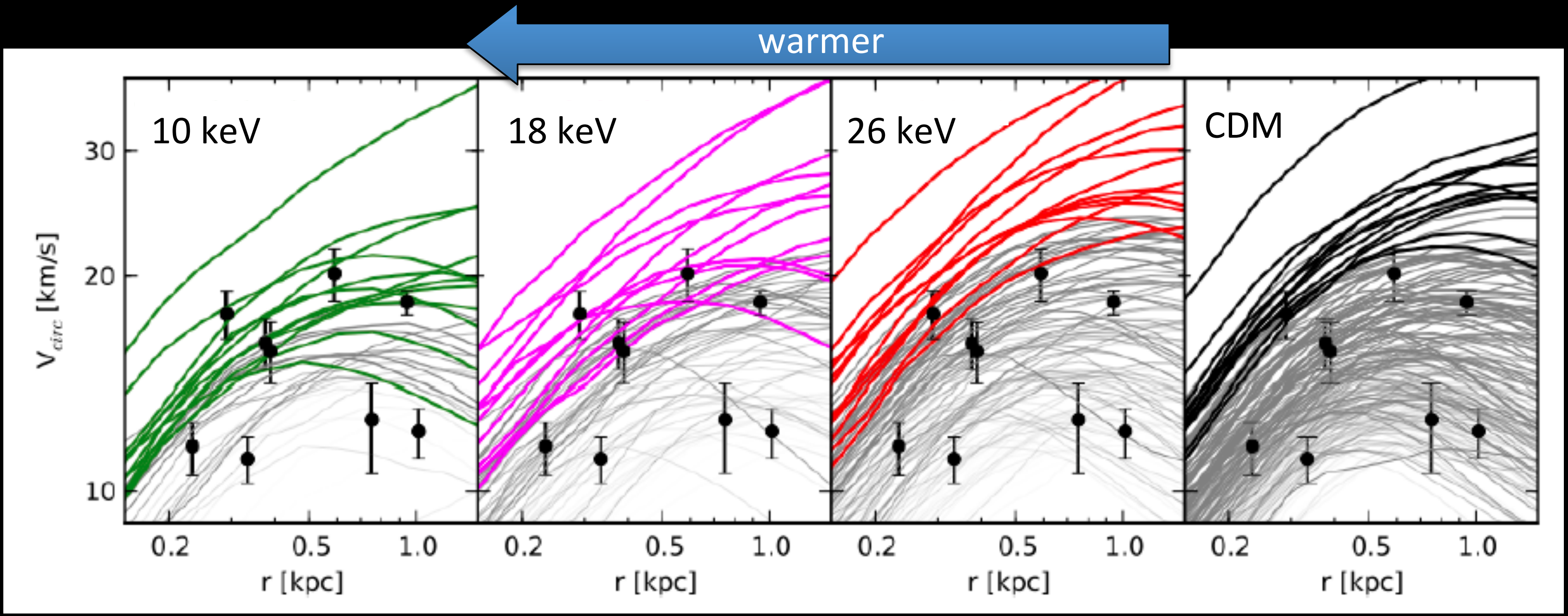
$m_{DW} > 8.8$ keV (95%CL)



Horiuchi et al, PRD (2014)

Addressing the density problem

- Delayed structure formation results in less concentrated halos
- the warmer the dark matter, the larger the effect
- Too-big-to-fail is reduced considerably by $m_{DW} \sim 10$ keV



- Typically, total removal of TBTF under-predicts subhalo counts

Schneider et al, MNRAS (2013)
See also*:*
Lovell et al, MNRAS (2012)
Anderhalden et al, MNRAS (2012)

Sterile neutrino dark matter limits

X-ray limits

Targeting radiative decays of sterile neutrino (ν_s):

$$\nu_s \rightarrow \nu_a + \gamma$$

Phase-space limits

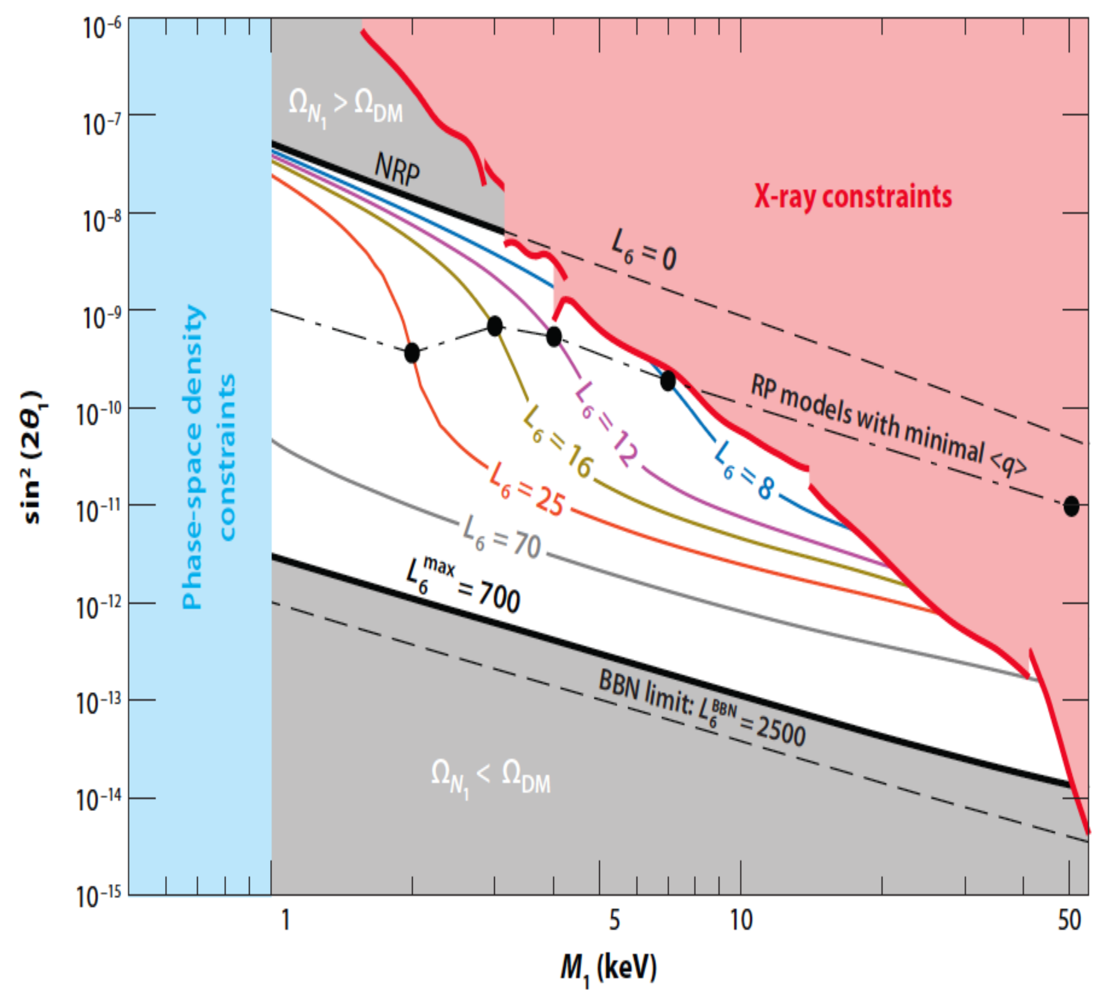
Limited phase-space packing gives a lower mass limit (c.f. Pauli exclusion principle)

BBN limits

Lepton asymmetry cannot be too large, disrupts ^{4}He

Limits not shown:

- Subhalo counting
- Lyman-α probes of small scale power

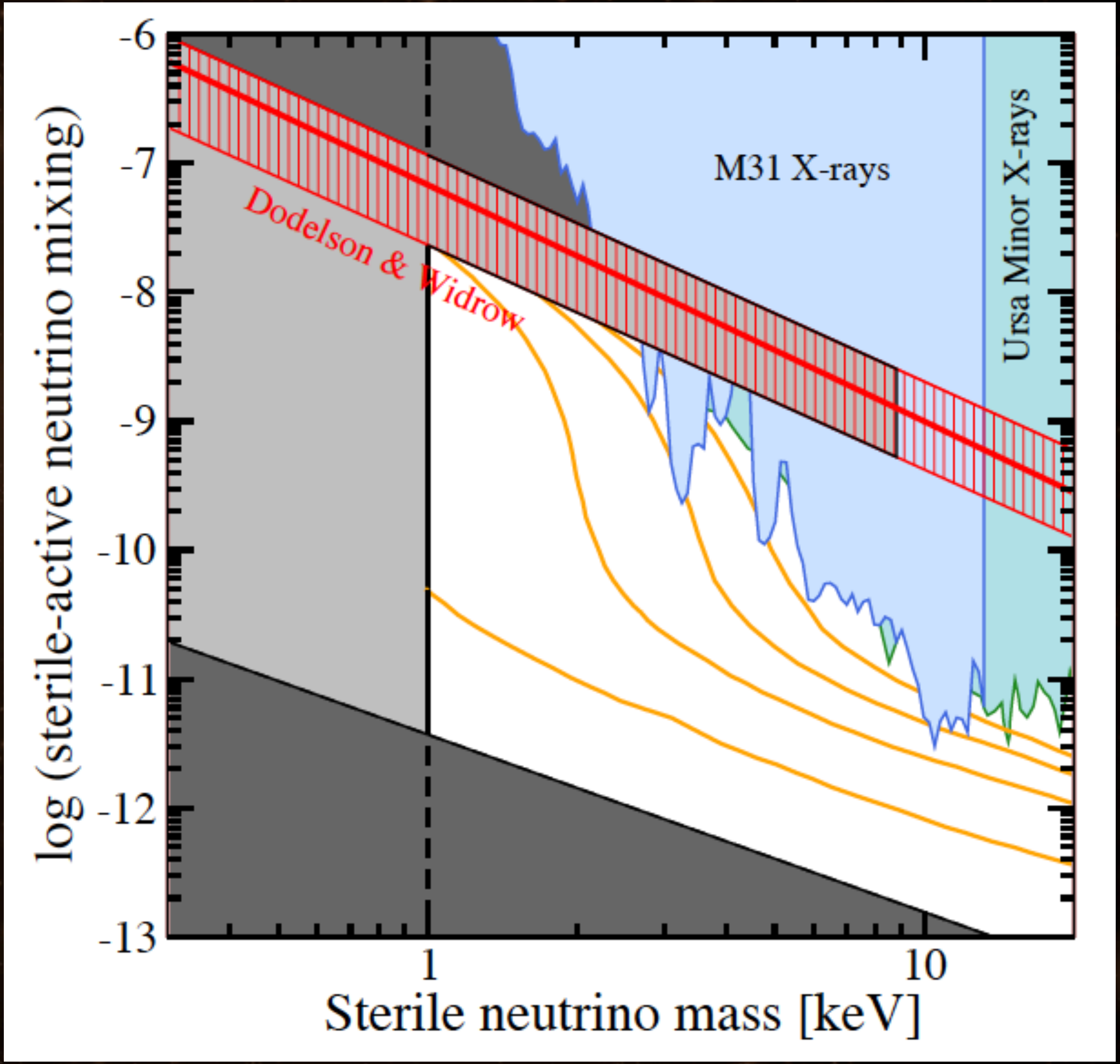


Boyarsky et al (2009)
See also e.g., Kusenko 2009

Joint limits on Dodelson-Widrow model

Combining x-ray limits with structure limits, the Dodelson-Widrow mechanism is ruled out (for producing 100% the dark matter abundance)

Leaves resonant production parameter space for viable DM



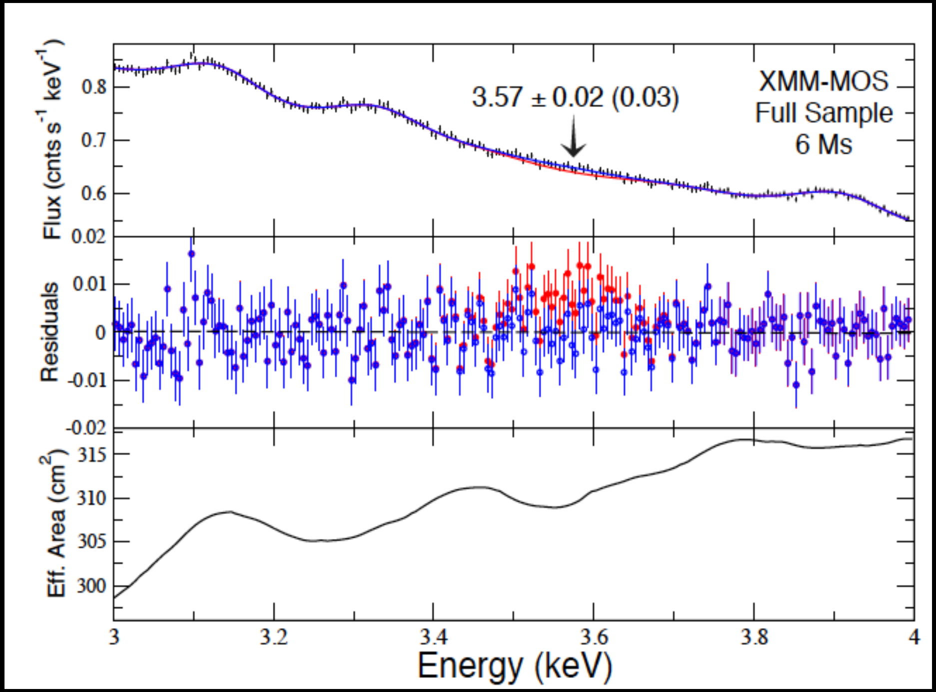
Horiuchi et al, PRD (2014)

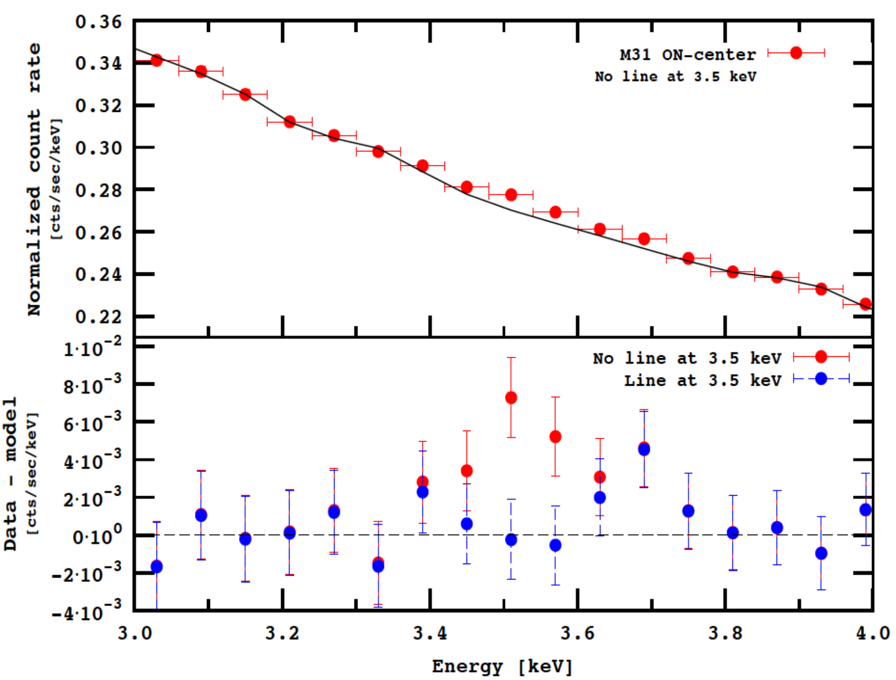
Anomalous X-ray line detections

Recent claims for anomalous X-ray lines detected from nearby DM densities

Bulbul et al (2014)

Boyarsky et al (2014)



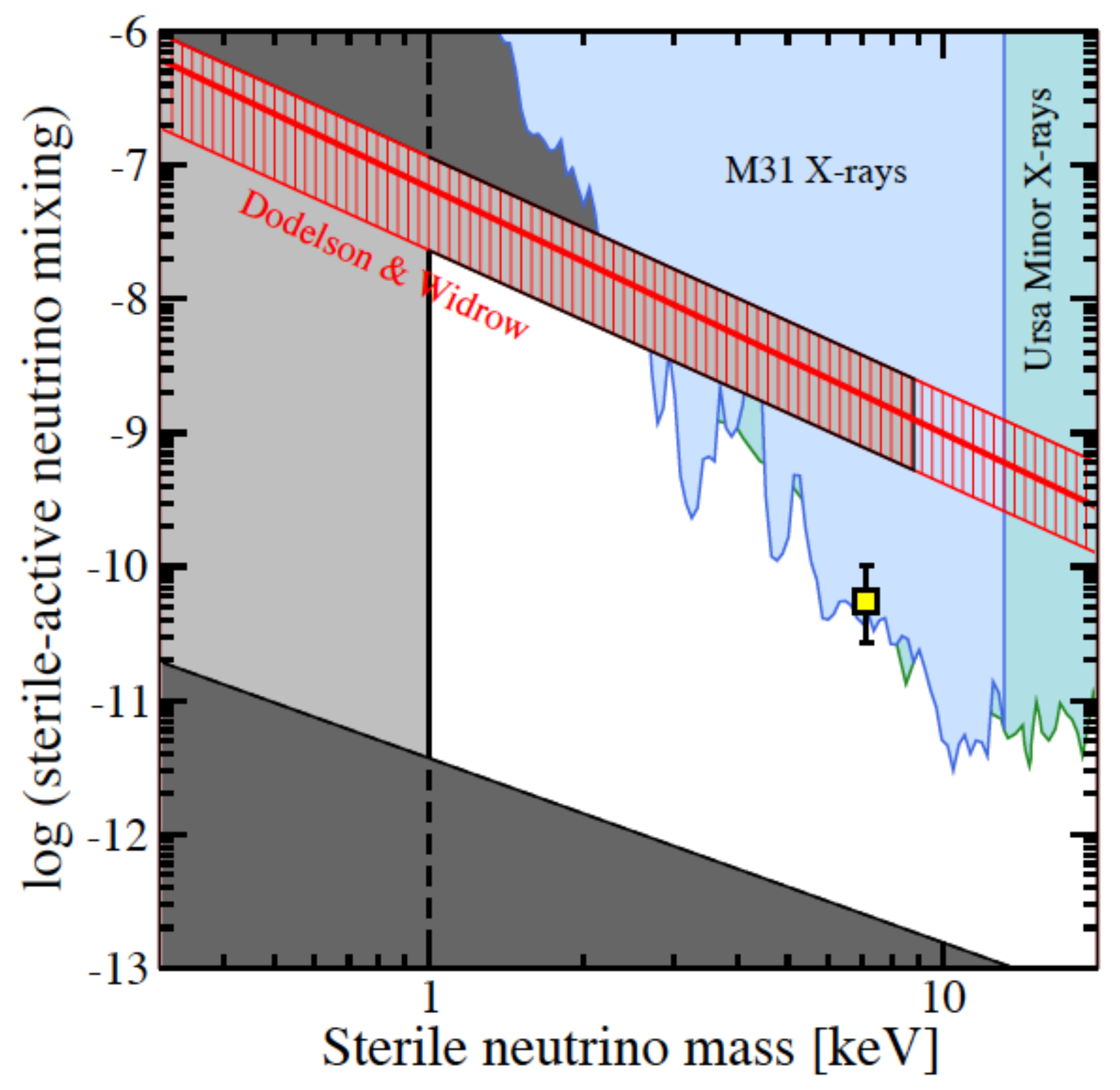


- 73 galaxy clusters stacked
- Range z = 0.01 to 0.35
- 4 to 5σ detection with XMM-Newton MOS
- Also see in XMM PN CCDs
- Also seen in Perseus with Chandra at 2.2σ

- Perseus indication at 2.3σ with XMM
- M31 indication at 3σ with XMM
- Combined detection ~4σ

Signals are consistent with each other

Sterile neutrino interpretation



(data point: Bulbul et al 2014)

Horiuchi et al, PRD (2014)

Sterile neutrino interpretation

Lepton number

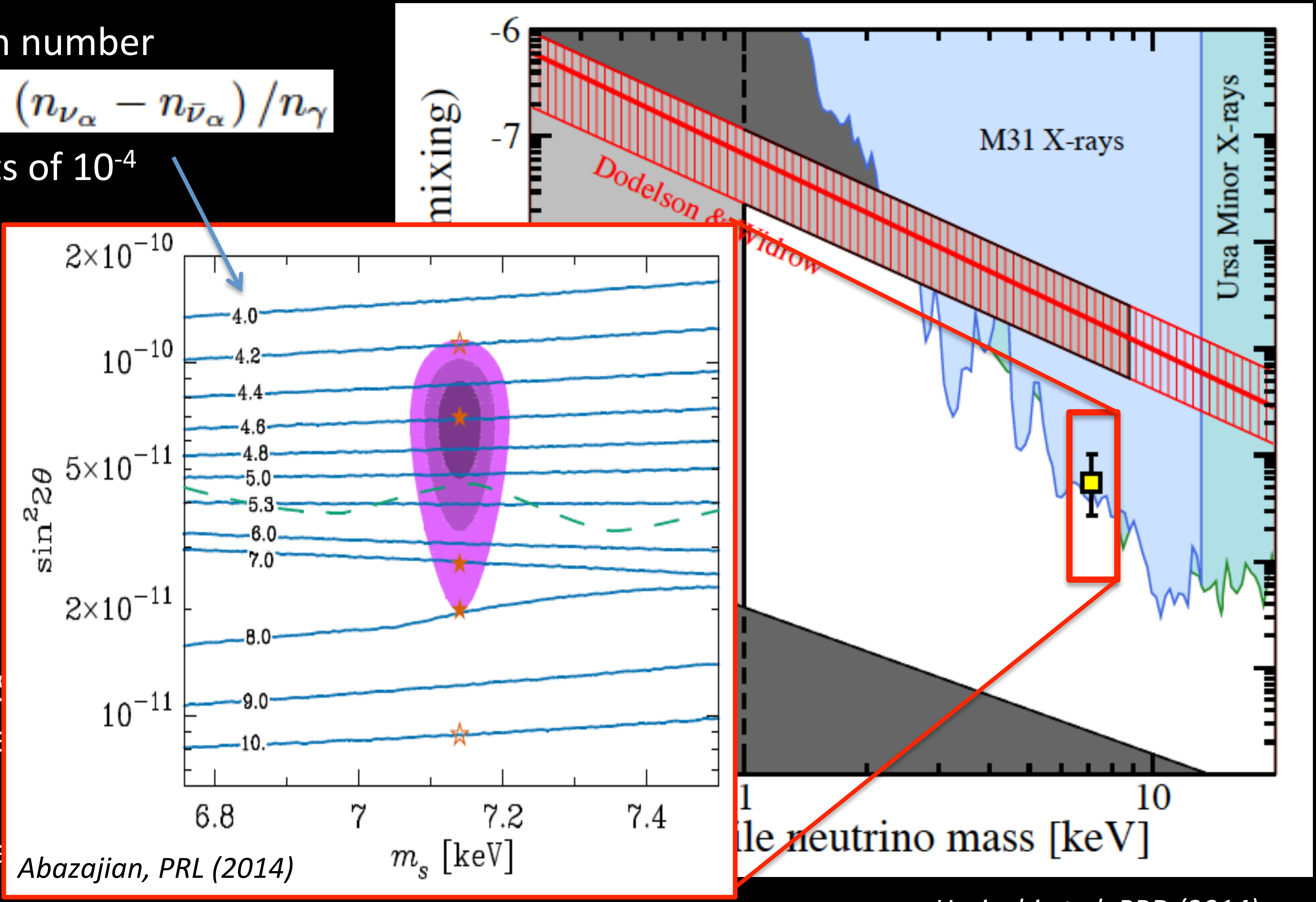
$$L \equiv \left(n_{\nu_\alpha} - n_{\bar{\nu}_\alpha}\right)/n_\gamma$$

In units of 10^{-4}

→ S

alre

(data



Abazajian, PRL (2014)

Horiuchi et al, PRD (2014)

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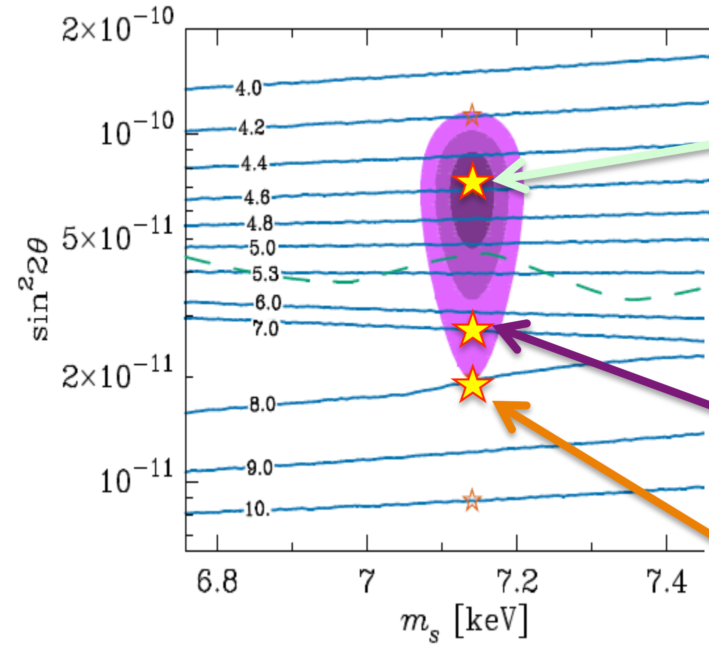
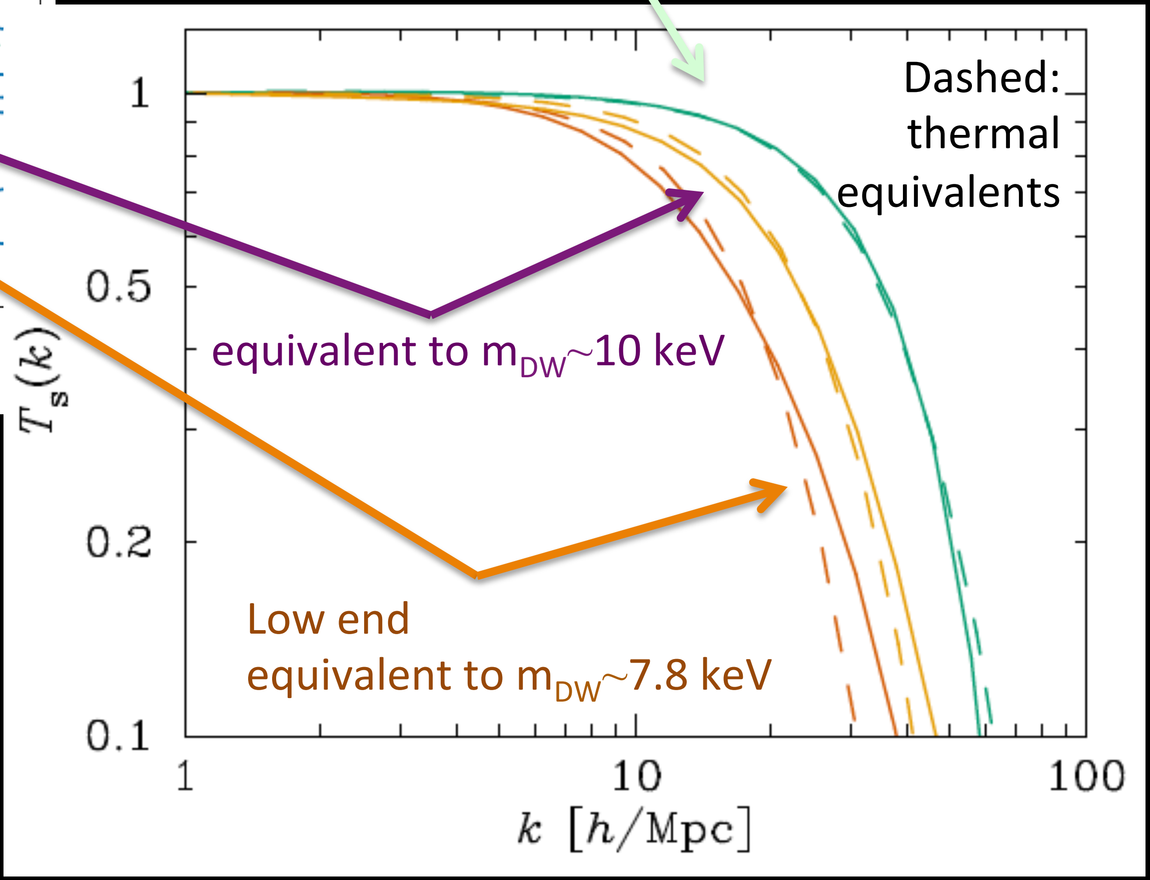




Central sterile neutrino (equivalent to m_{DW}~17 keV)

Dashed: thermal equivalents

equivalent to m_{DW}~10 keV

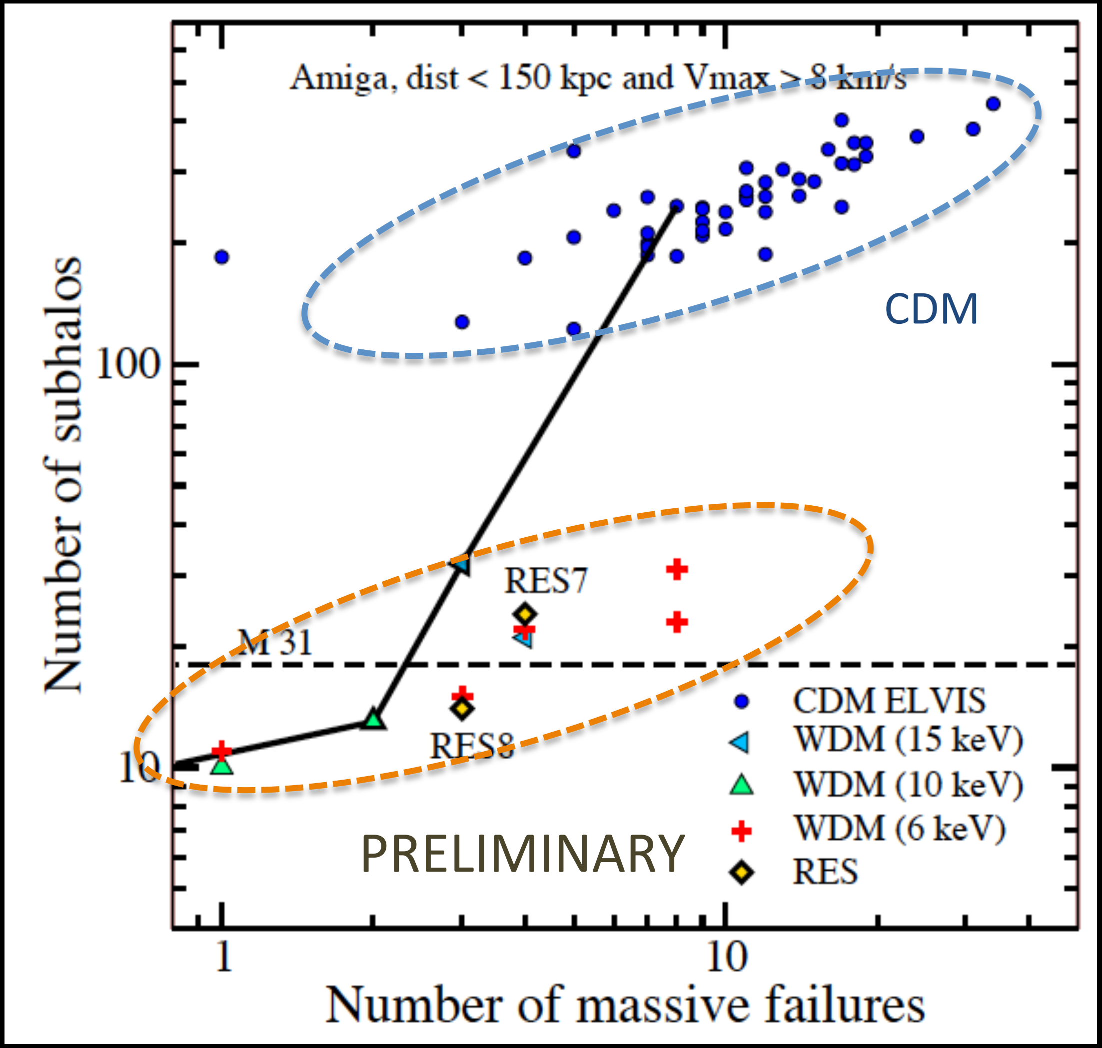
Low end
equivalent to m_{DW}~7.8 keV

Resonant interpretation implies a wide range of “warmness”, including ranges that work best for helping remove small-scale issues

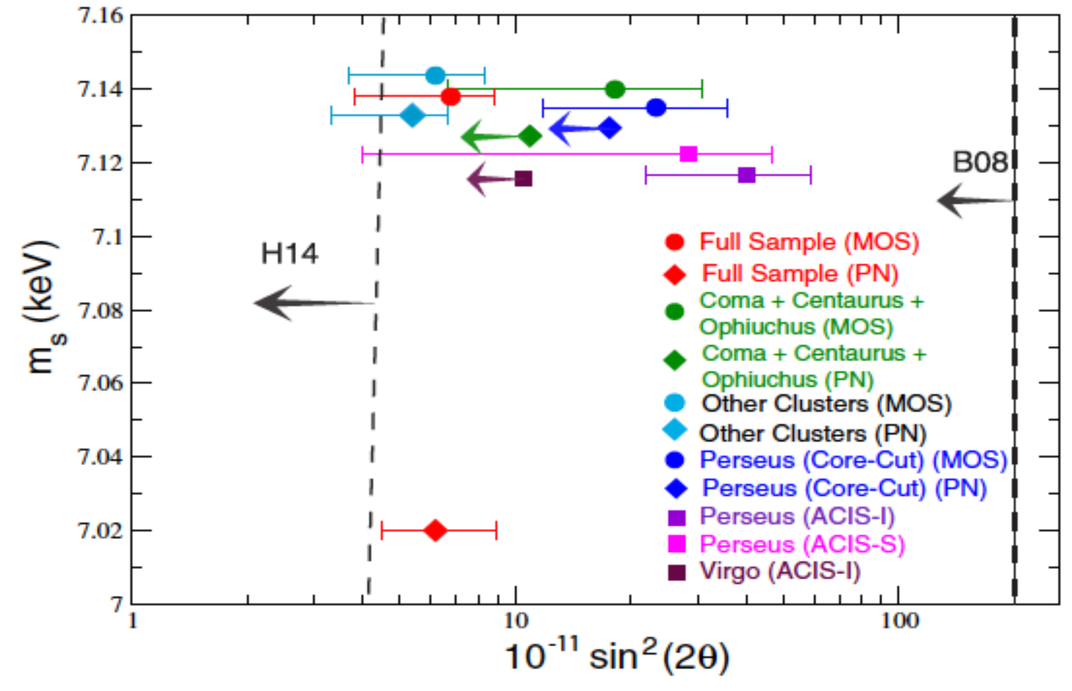
Abazajian, PRL (2014)

Consistent with satellite counts and Too-big-to-Fail

- Simulations confirm the expected behavior:
  - The "lower" res7 and res8 cases, which are not excluded by other x-ray studies, live in the space that helps too-big-to-fail without under-predicting subhalo counts.



More x-ray observations



← Bulbul et al 2014:

- ✓ 73 galaxy cluster stack [XMM]
- ✓ Perseus [XMM]
- ✓ Perseus [Chandra]
- × Coma+Cen+Ophiuchus [XMM]
- × Virgo [Chandra]

Boyarsky et al 2014:

- ✓ Perseus [XMM]
- ✓ M31 [XMM]

- × Riemer-Sorensen 2014: Milky Way [Chandra] – via modeling
- × Jeltema & Profumo 2014: Milky Way [XMM] – via modeling
- ✓ Boyarsky et al 2014b: Milky Way [XMM]
- × Anderson et al 2014: 81 galaxies [Chandra], 89 galaxies [XMM]
- × Malyshev et al 2014: 8 satellite dwarfs [XMM]
- × Tamura et al 2014: Perseus [Suzaku]
- ✓ Urban et al 2014: Perseus [Suzaku]
- × Urban et al 2014: Coma, Virgo, Ophiuchus [Suzaku]

← Contested in:
Bulbul et al 2014b
Boyarsky et al 2014c

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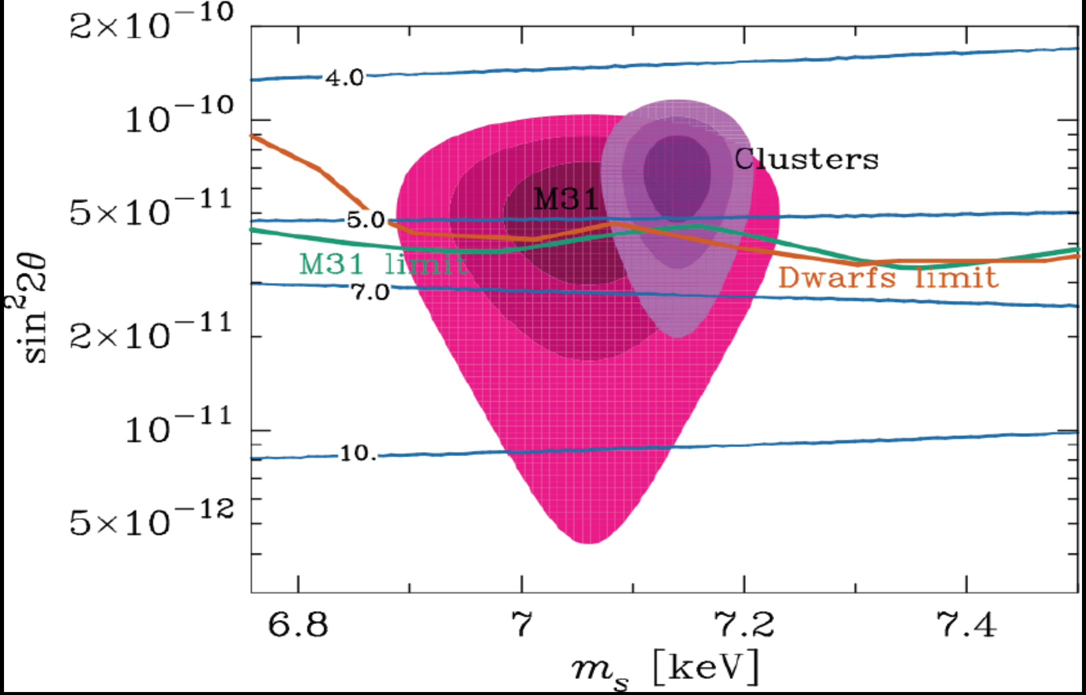

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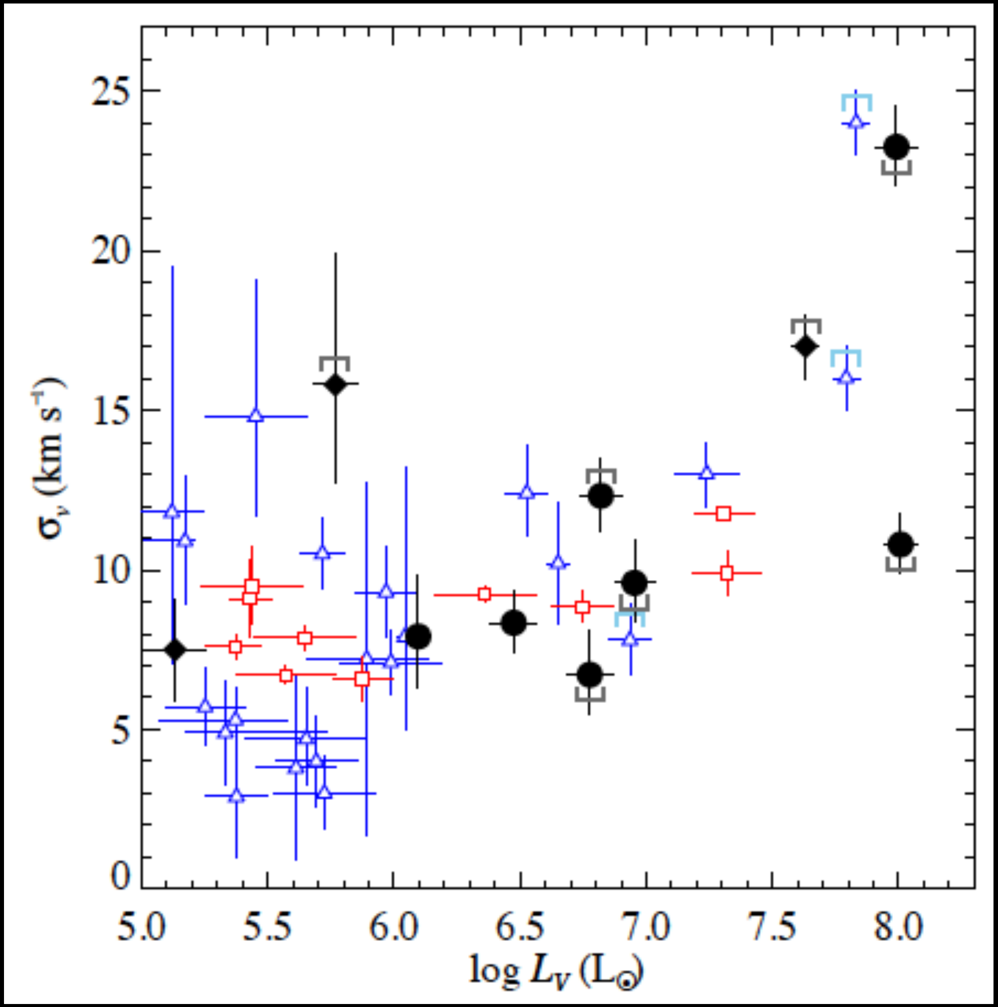
Conclusions

- Cold dark matter (CDM) :
  - Continues to be challenged by small-scale issues driven by new data and high-resolution simulations. Effect of baryons may solve most?
- Warm dark matter (WDM) solutions:
  - WDM helps relax the missing satellites and TBTF issues
- Status of constraints on sterile neutrino models:
  - the combination of structure and X-ray considerations rules out the simplest oscillation-based (Dodelson-Widrow) sterile neutrino
  - Resonant and non-oscillation production are still viable. Sterile neutrino dark matter can be WARM or COLD
- X-ray line detections:
  - Recent claims of anomalous X-ray lines can be interpreted as a resonant sterile neutrino
  - This sterile neutrino is in the sweet spot required to help solve the missing satellites & the too bog to fail issues.

Thank you!

BACKUP

Field dwarfs: closer look

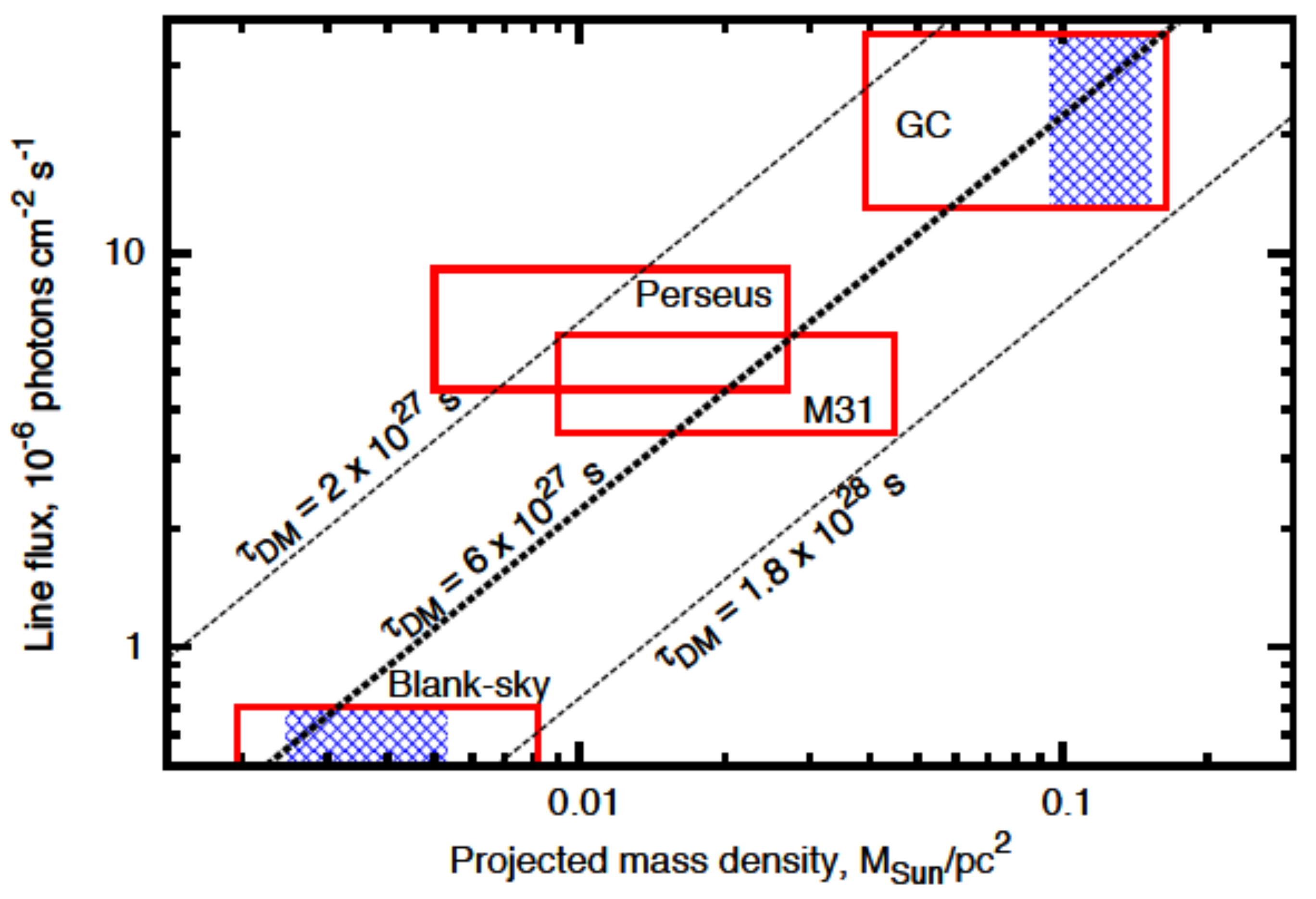


Kirby et al 2014

Stellar luminosities are higher than satellite dwarfs but many are just as small

→ supernova feedback alone will not solve the density issue

Are measurements are consistent?

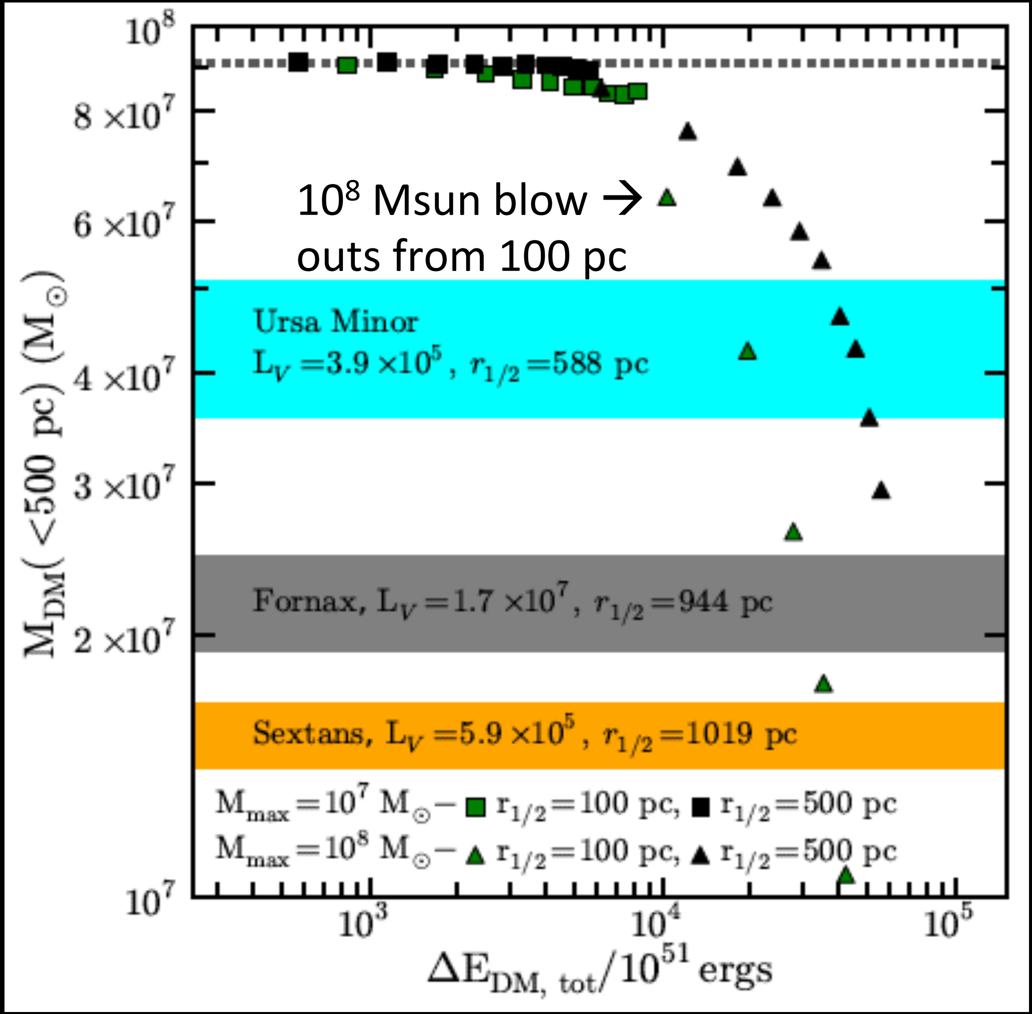


Boyarsky et al 2014a

Baryon solutions on dwarf scales

- Problem: ~10^6 Msun of stars must remove ~10^9 Msun of dark matter from the galaxy (not necessarily from the halo).
- This translates to ~$10^{4\text{-}5}$ SNe, which exceeds the total # of SN expected from the observed baryons

→ Unlikely for supernova feedback alone to solve too-big-to-fail



10^8 Msun blow → outs from 100 pc

Garrison-Kimmel et al (2013) [see, also, Navarro et al 1996, Arraki et al 2012, Zolotov et al 2012]

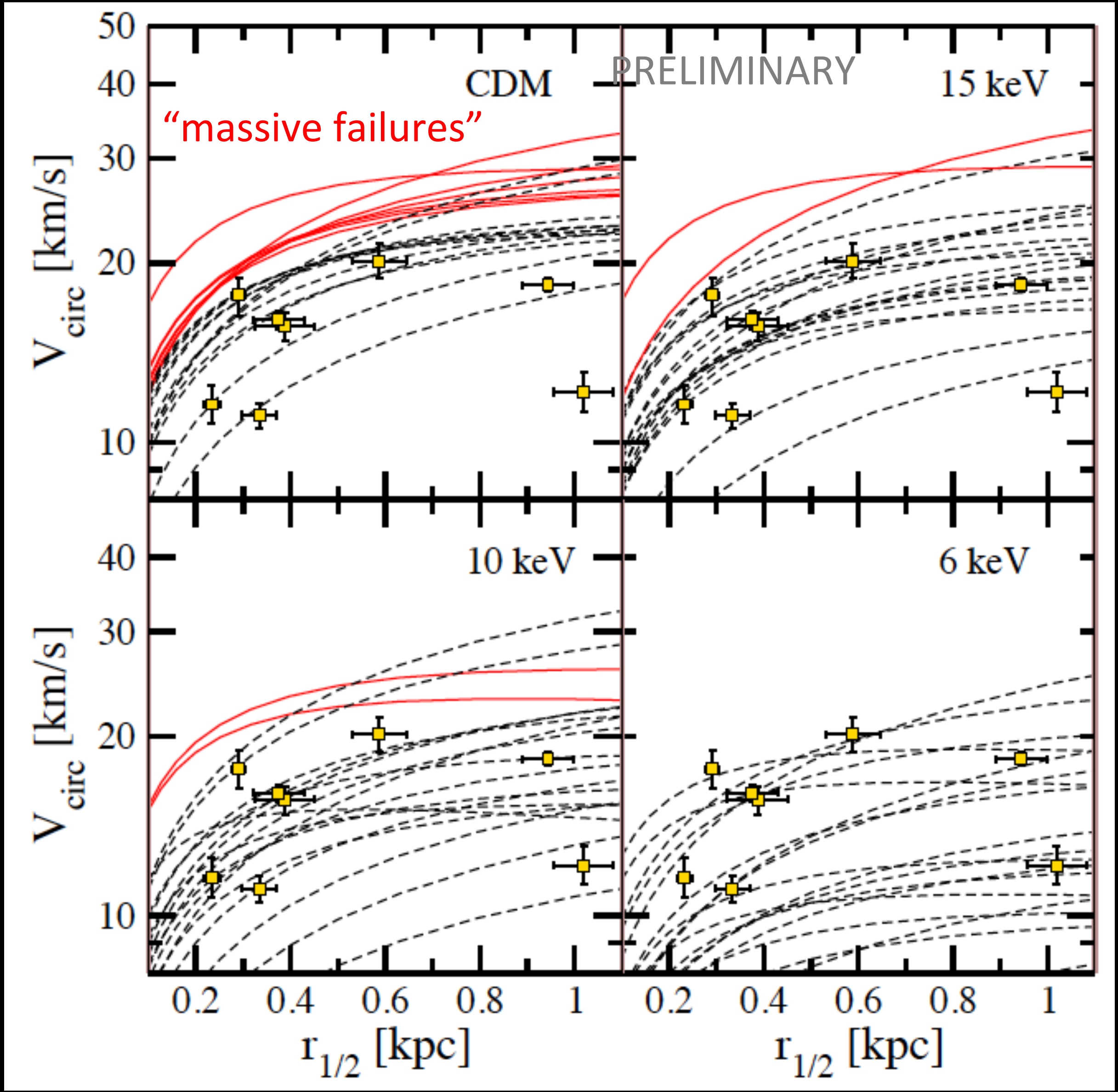
The density problem

Run identical zoom simulations with different initial power spectra corresponding to WDM of mass m_s.

Reduced small-scale power → reduced merger history → desired effect of bloating the density profile

See, also:

Lovell et al, MNRAS (2012)
Anderhalden et al, MNRAS (2012)
Schneider et al, MNRAS (2013)



Sterile neutrino production

- Production via oscillations of active (left) <--> sterile (right) neutrinos
  - Dictated by mixing angle, θ_M and the usual probability

$$\sin^2 2\theta_M \sin^2 vt/L$$

where

$$L = 4E/(M^2 - \mu^2)$$

  - Collision time >> oscillation time, so $\sin^2 vt/L \sim ½$
- The mixing angle and collision rates are

$$\sin^2(2\theta_M) = \frac{\mu^2}{\mu^2 + [(c\Gamma E/M) + (M/2)]^2}$$

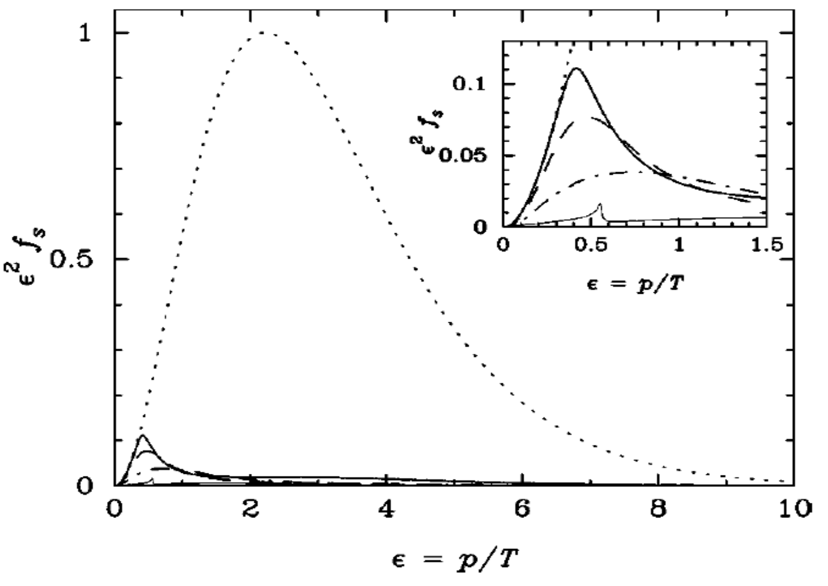
$$\Gamma \simeq \frac{7\pi}{24} G^2_{\text{Fermi}} T^4 E$$

- In resonant production, MSW resonance occurs when the potential $\sim m^2/2E \cos 2\theta_M$

$$V_\nu \approx 2\sqrt{2} G_{\rm F}(N_\nu - N_{\bar{\nu}}) - \frac{7\pi}{90\alpha} \sin^2(2\theta_{\rm W}) G_{\rm F}^2 T^4 E_\nu$$

$$\sin^2(2\theta_{\text{m},\alpha 1}) = \frac{\sin^2(2\theta_{\alpha 1})}{\sin^2(2\theta_{\alpha 1}) + \left(\cos 2\theta_{\alpha 1} - \frac{2V_{\nu,\alpha}E}{M^2_{N_1}}\right)^2}$$

Shi & Fuller 1999



- The spectrum is typically colder

Constraints from small-scale structure

Lyman-α forest:

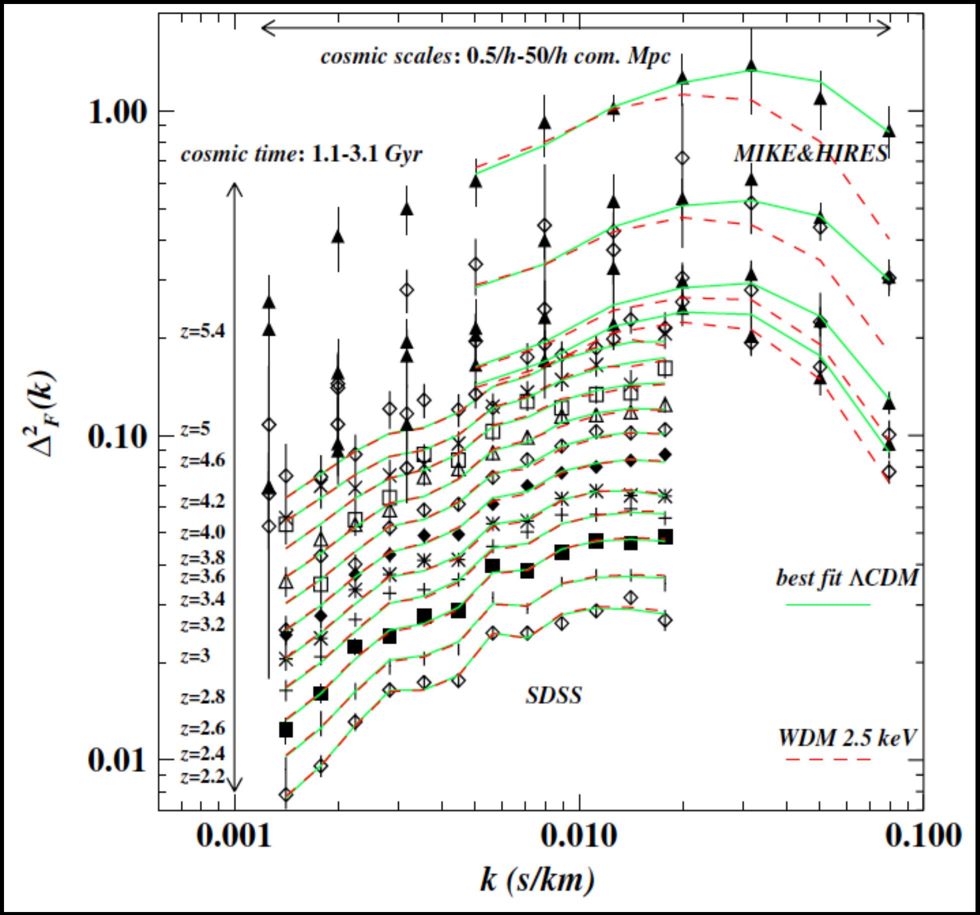
powerful but challenging. Use QSO absorption spectra, but the IGM temperature impacts similarly the structure of the Ly-α forest.

e.g., Seljak et al, PRL (2006)
Abazajian et al, PRD (2006)

with Magellan MIKE + Keck HIRES:

$m_{DW} > 20$ keV

Viel et al, PRD (2013)



Viel et al, PRD (2013)

Phase-space arguments:

Phase-space packing limitations yields robust lower mass limit of:

$m_{DW} > 2.5$ keV

Gorbunov et al, AstroPart (2008)
Boyarsky et al, AstroPart (2008)
Horiuchi et al, PRD (2014)

Lyman-a forest constraints on WDM

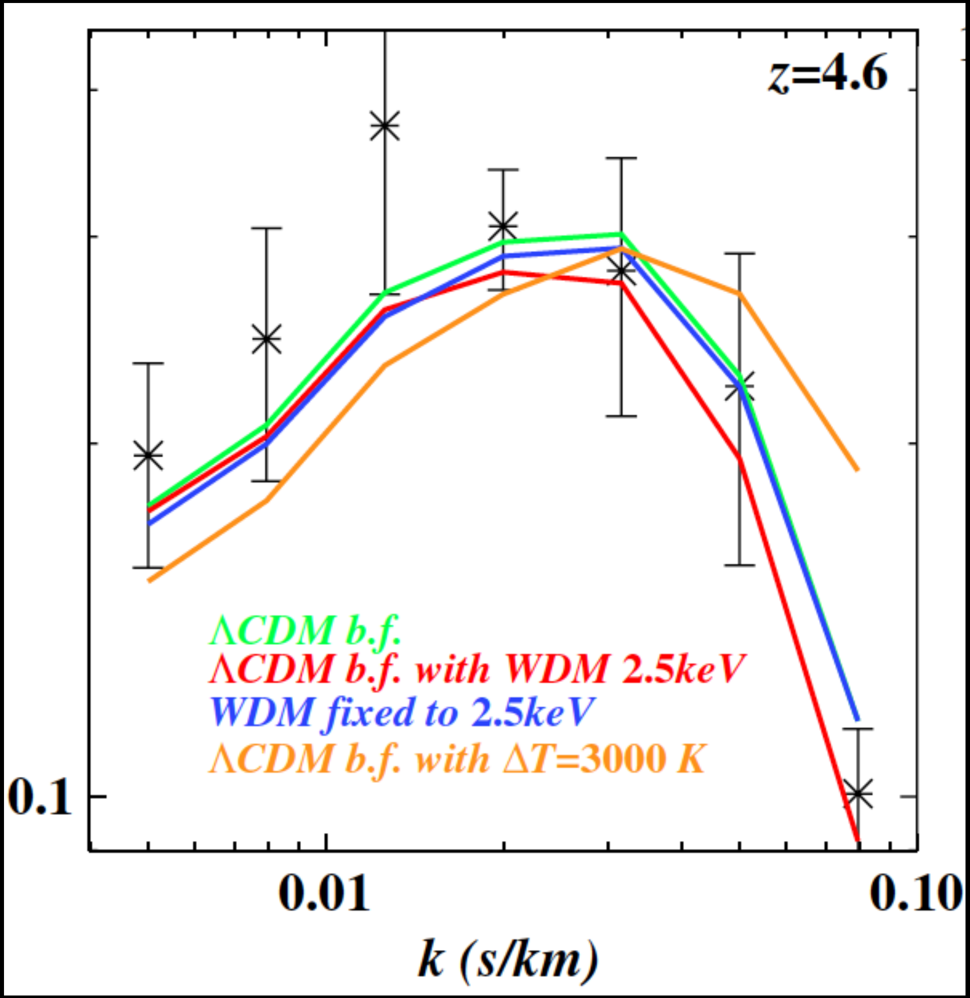
- QSO absorption spectra as test of small-scale power

Seljak et al, PRL (2006)

- Hydro simulations links DM power → gas → HI gas distribution.

- Limits of m_{DW} > 20 keV [Magellan MIKE + Keck HIRES]
- But large uncertainty due to the weakly constrained thermal state of the IGM
- CDM with a different IGM temperature can mimic a WDM signature

Viel et al, PRD (2013)

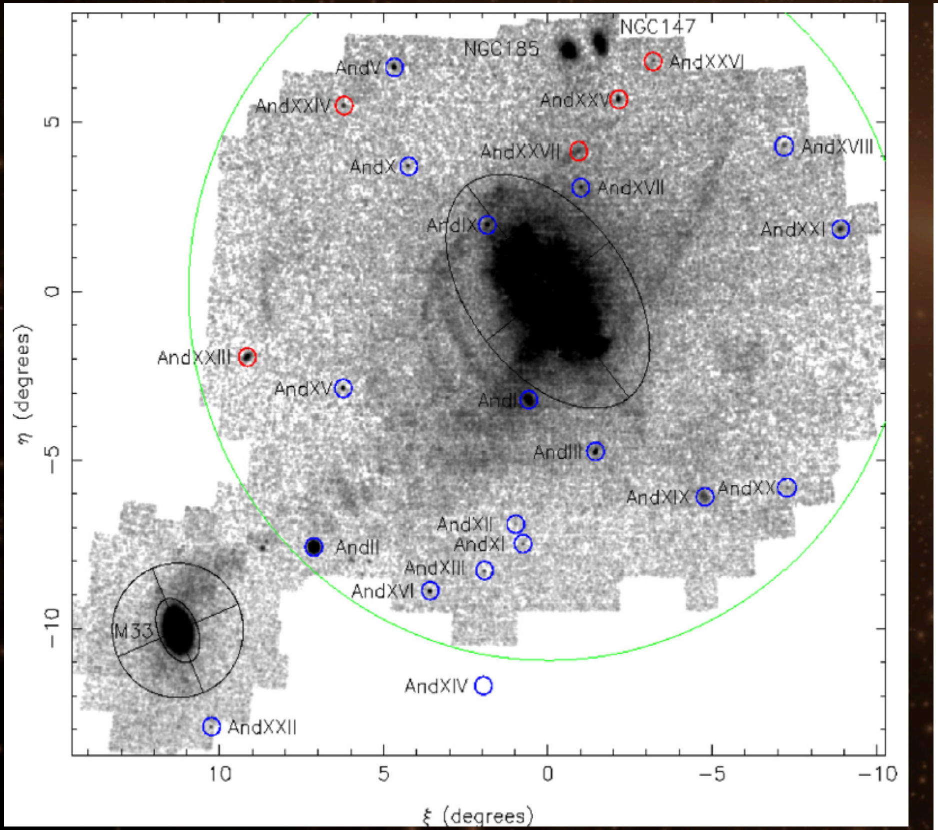


Viel et al 2013

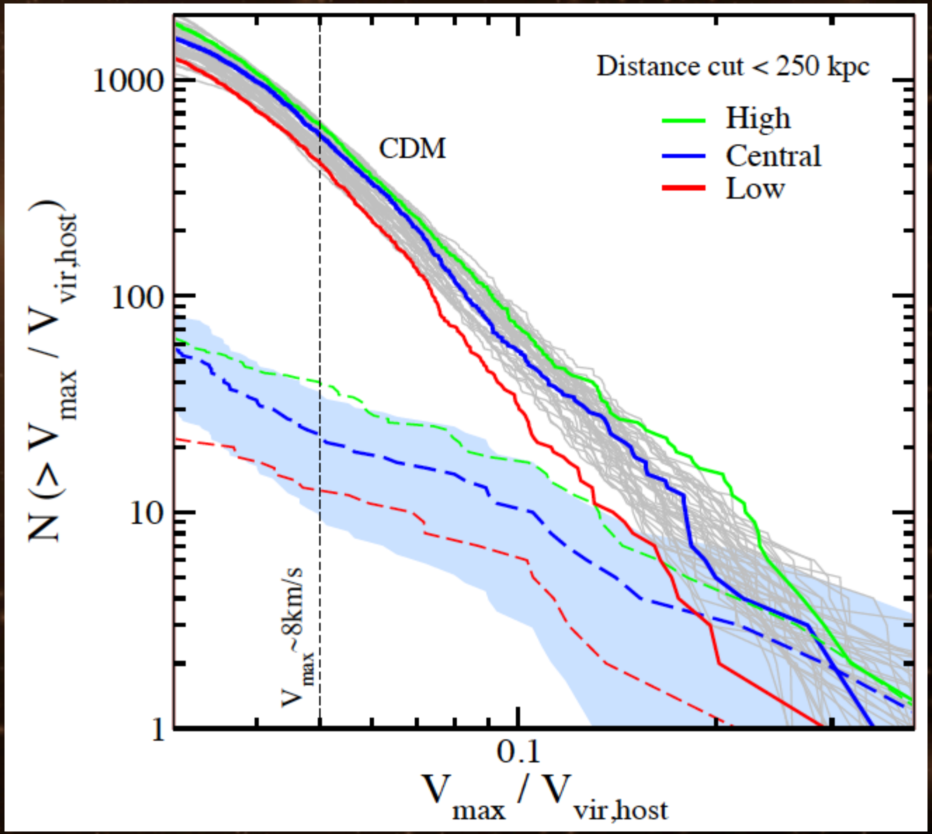
M31 count limits

Pan-Andromeda Archaeological Survey: Complete out to ~150 kpc of the M31 center and down to ~10^5 *Lsun* in luminosity.

V_{max} cumulative distribution based on 44 CDM simulations of MW-analogues. WDM (m_{DW} = 6 keV) for comparison



Richardson et al, ApJ (2011)

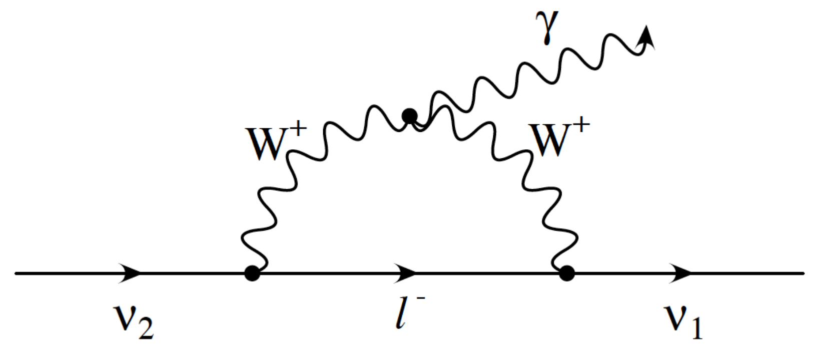


HORIUCHI et al, PRD (2014)

X-ray considerations

Signal: heavy sterile neutrinos radiatively decay to active neutrinos + photon

$$``\nu_s" \rightarrow ``\nu_a" + \gamma \qquad E_\gamma = m_s/2$$



Decay rate:

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

	Chandra	XMM-N	Suzaku	Astro-H
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"

Strategy: nearby dark matter densities are excellent targets for X-ray telescopes

Abazajian et al (2001)

Source	Pros	Cons
clusters	Photon statistics	ICM background
M31	proximity	Large ROI
MW	promixity	Very large ROI
dwarfs	Weak astro bkgs	Weak signal

X-ray searches and limits

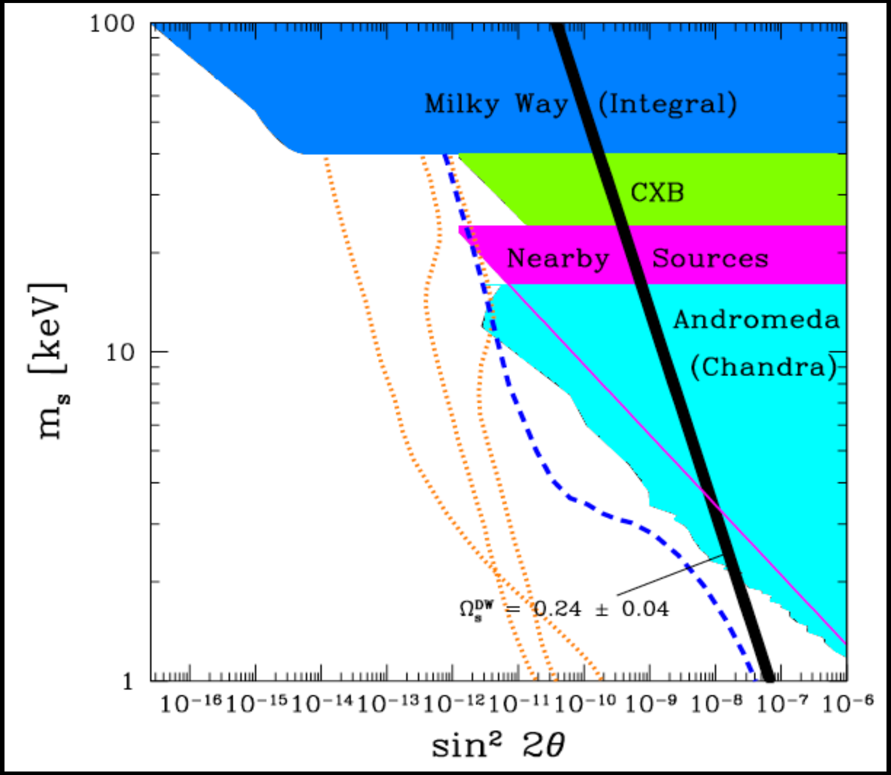
A variety of strong model independent limits:

X-ray telescope limits from M31

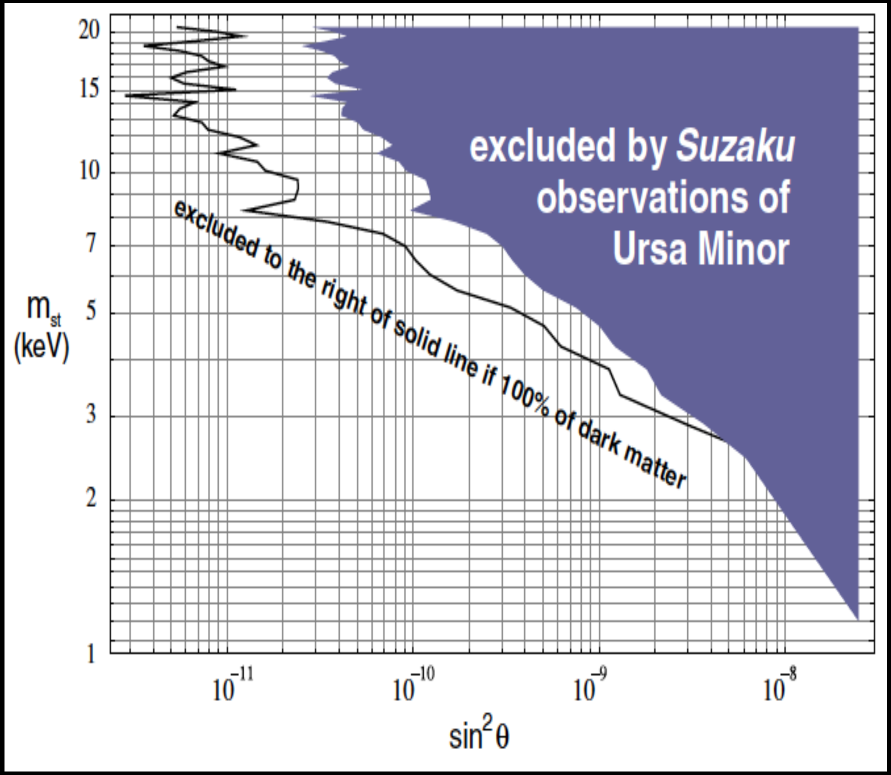
- M31 provides the optimum "dark matter within FoV" situation

Limits from dwarf galaxies

- Advantage of lower astrophysical backgrounds



Watson et al, JCAP (2012)



Loewenstein et al, ApJ (2009)