# Dark Matter

**ASTR 333/433**
**Spring 2026**
**TR 11:30am-12:45pm**
**Sears 552**

http://astroweb.case.edu/ssm/ASTR333/


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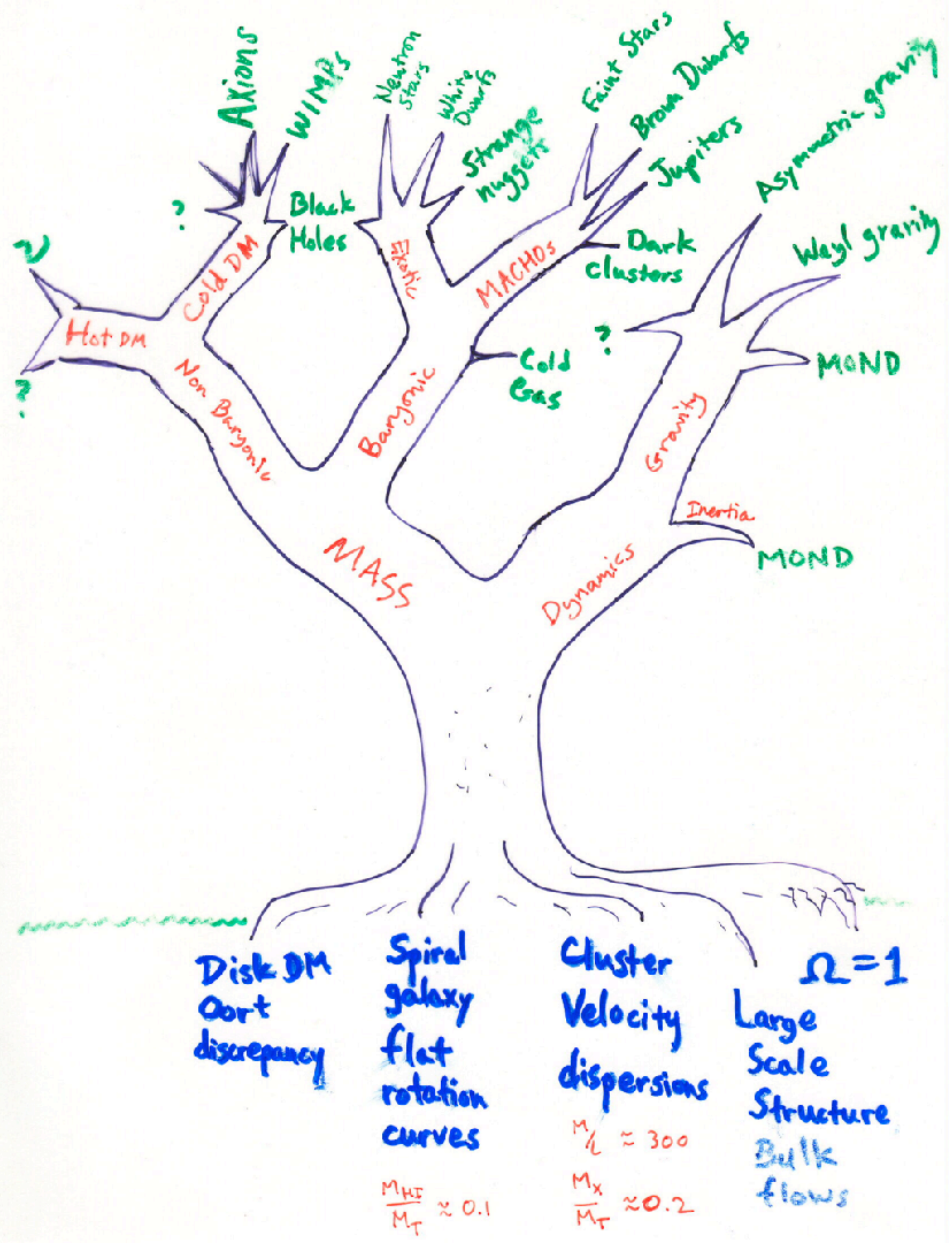
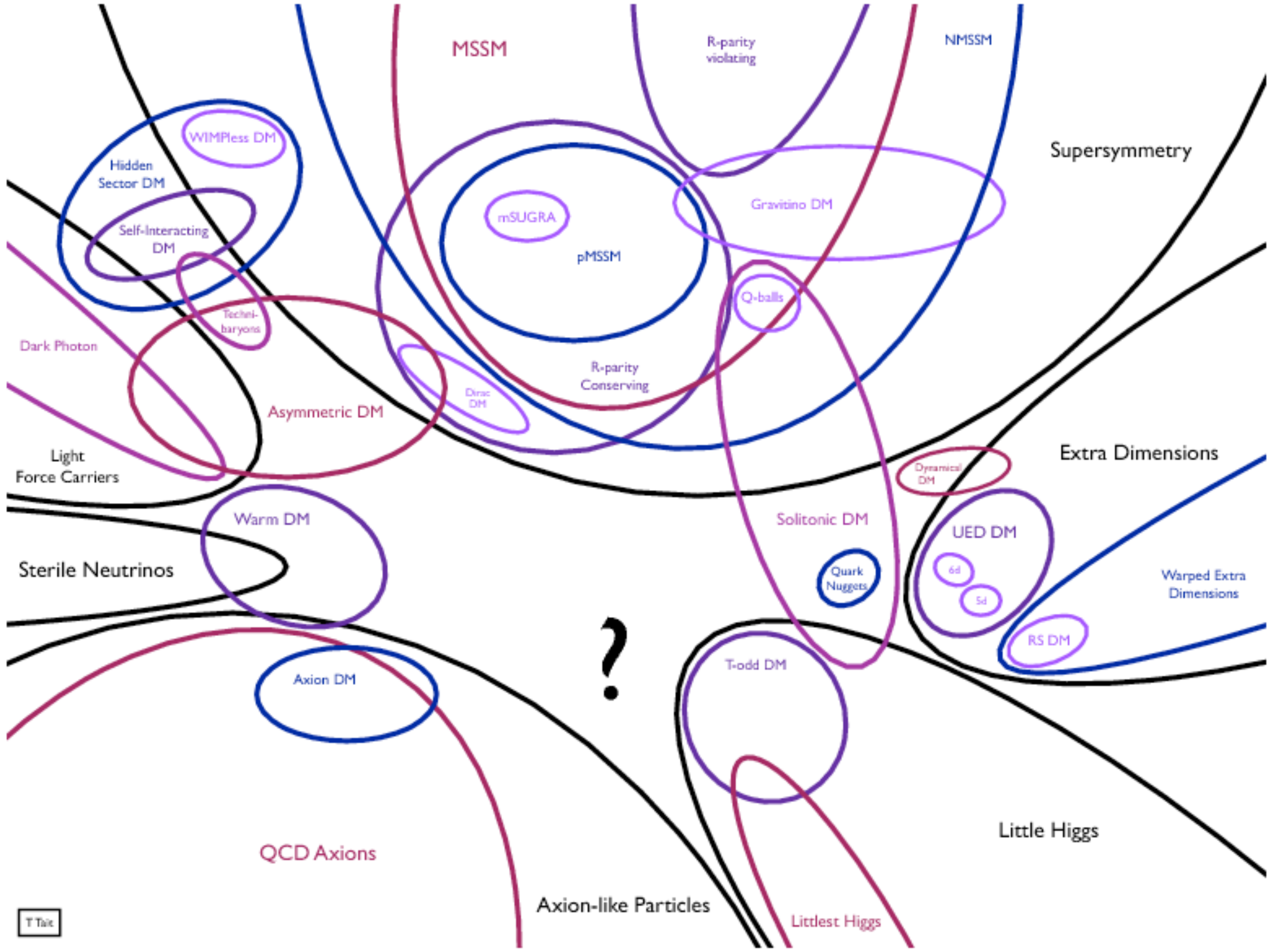





Lots of particle candidates for CDM:

WIMPs
Axions
Light dark matter
wimpzillas
etc.

Can imagine other candidates as well:

Warm DM
Self-interacting DM
Fuzzy DM
Superfluid DM
etc.

## Structure formation with dark matter that is

Free streaming scale:

$$M_{FS} = (4 \times 10^{15}\ \mathrm{M}_{\odot}) \left(\frac{m_x}{30\ \mathrm{eV}}\right)^{-2}$$

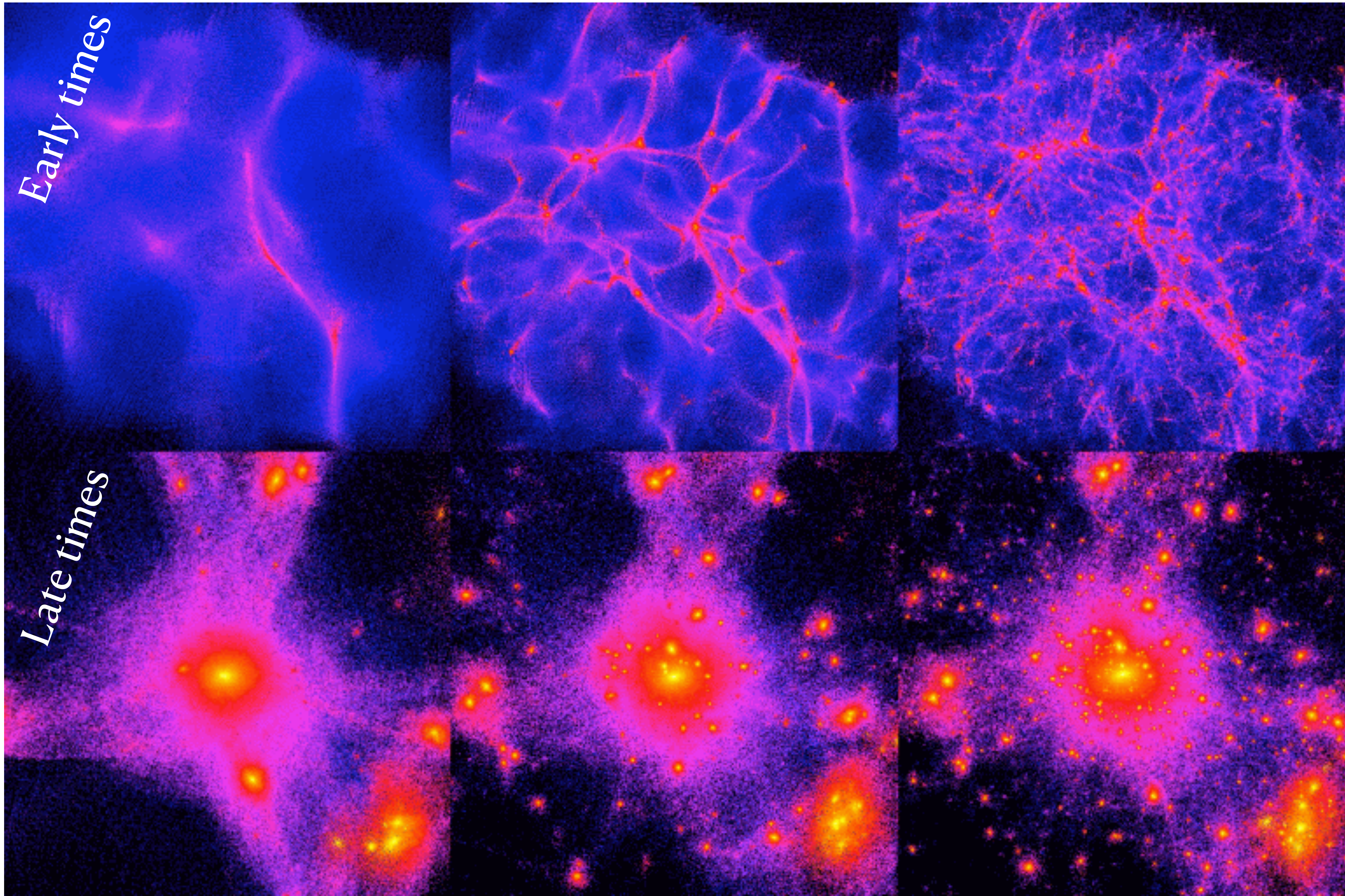
So only structures larger than the largest clusters of galaxies form with hot dark matter of mass $m_X < 30$ eV.

Neutrinos of mass $m_\nu > 0.06$ eV have some effect even in a CDM universe, ergo the structure formation limit $m_\nu < 0.12$ eV.

$$M_{FS} \approx 4 \times 10^{-4}\ \mathrm{M}_{\odot}$$

For cold dark matter with $m_X \approx 100$ GeV.

Hot DM | Warm DM | Cold DM



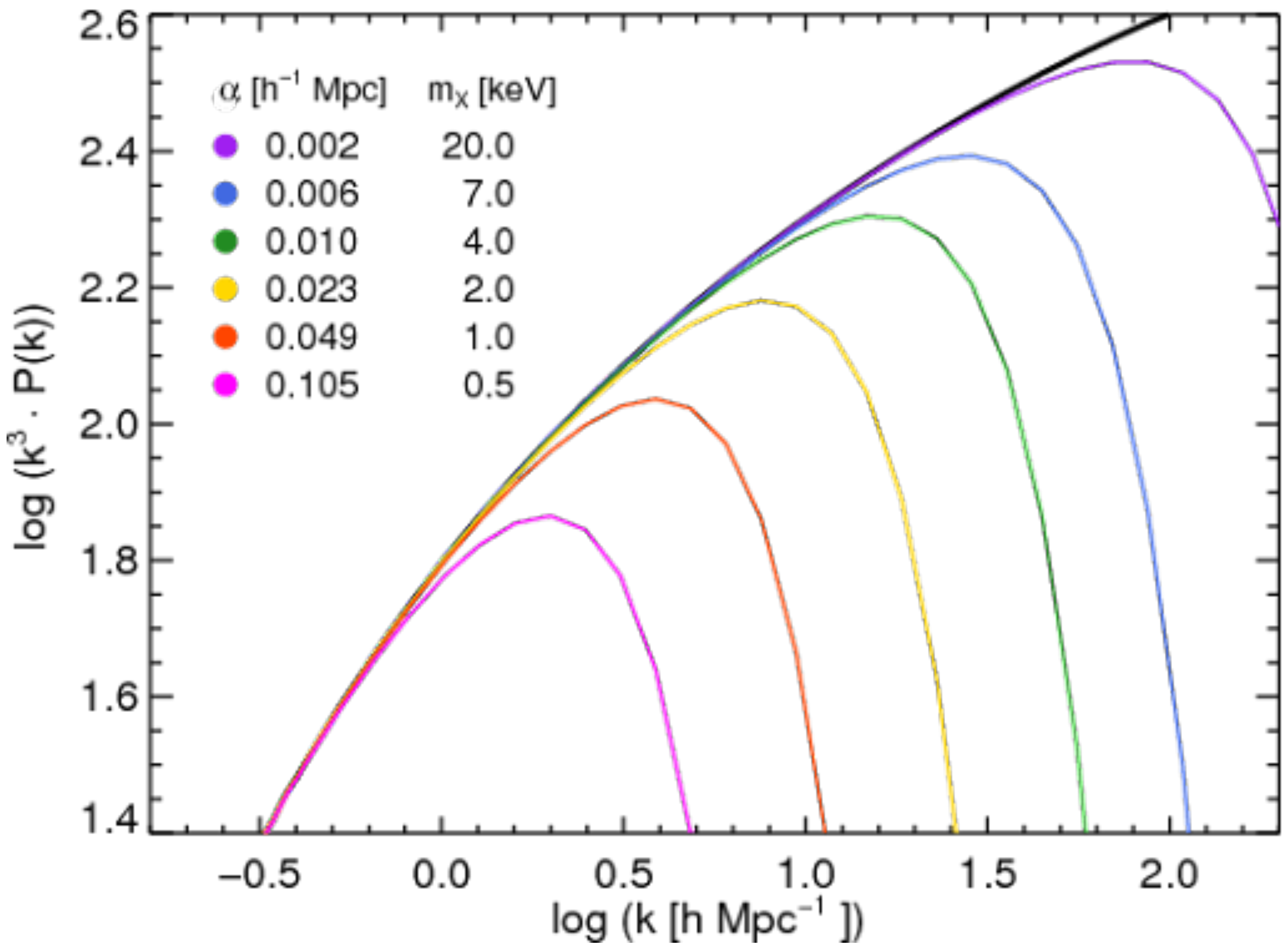
# Warm Dark Matter
# (WDM)

Warm dark matter is a Goldilocks solution that tries to find an intermediate mass that is "just right".

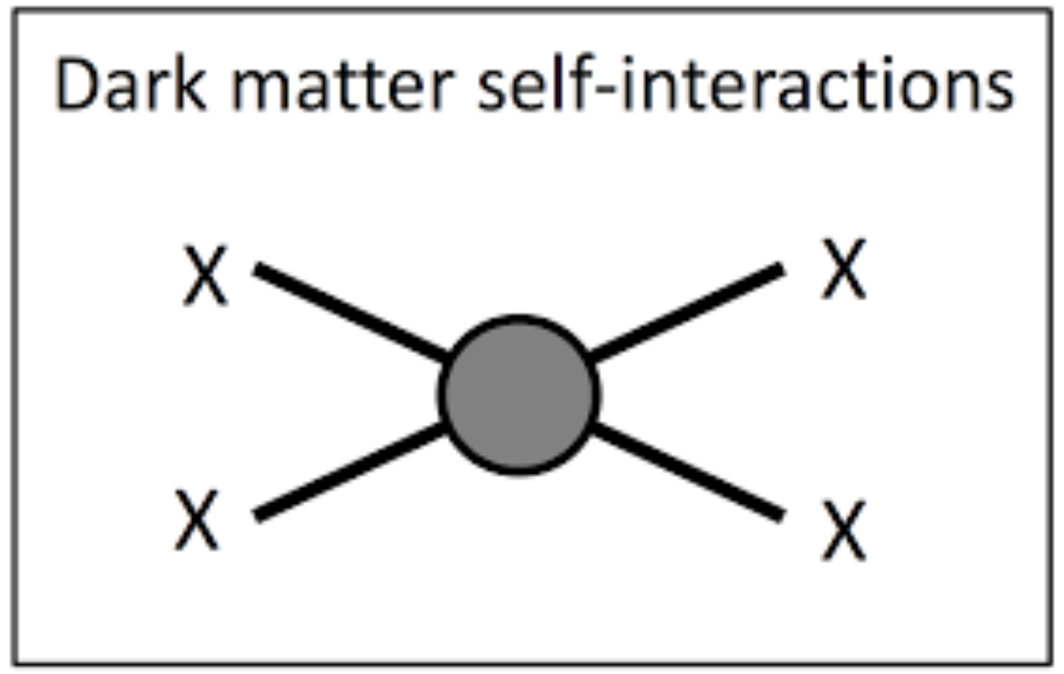
Just right for what?

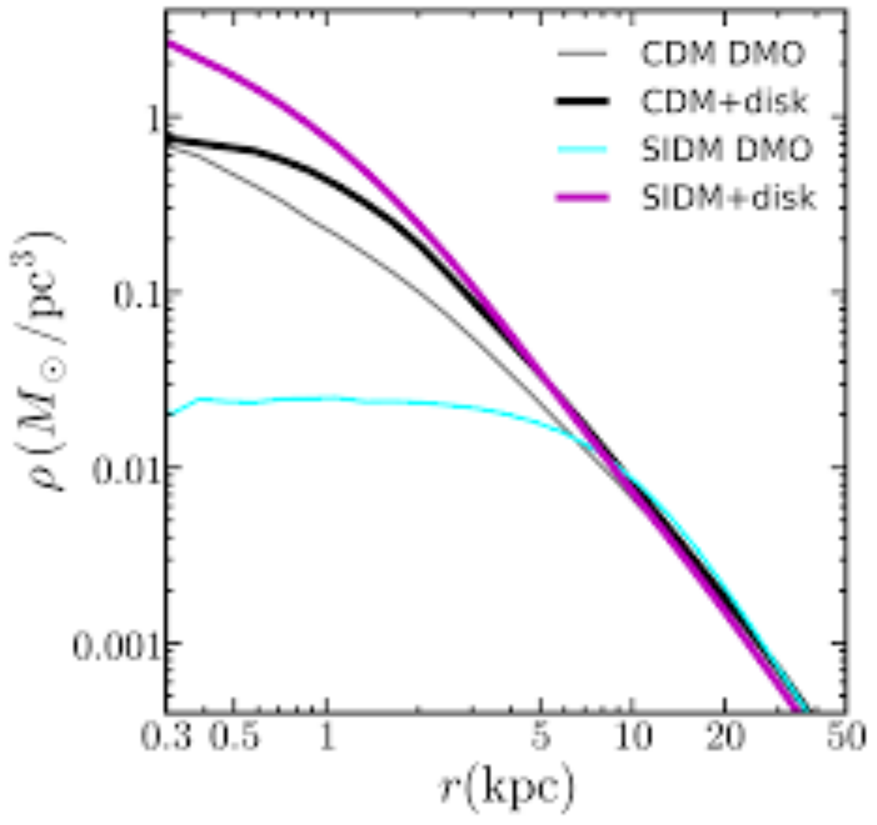
Free streaming suppresses small scale structure, so reduces the number of small dark matter halos to address the missing satellite problem. Might also soften the cusps of dark matter halos into cores more like those found observationally.

Free streaming scale imprints a small-scale cut-off on the power spectrum:



# Self-Interacting Dark Matter (SIDM)



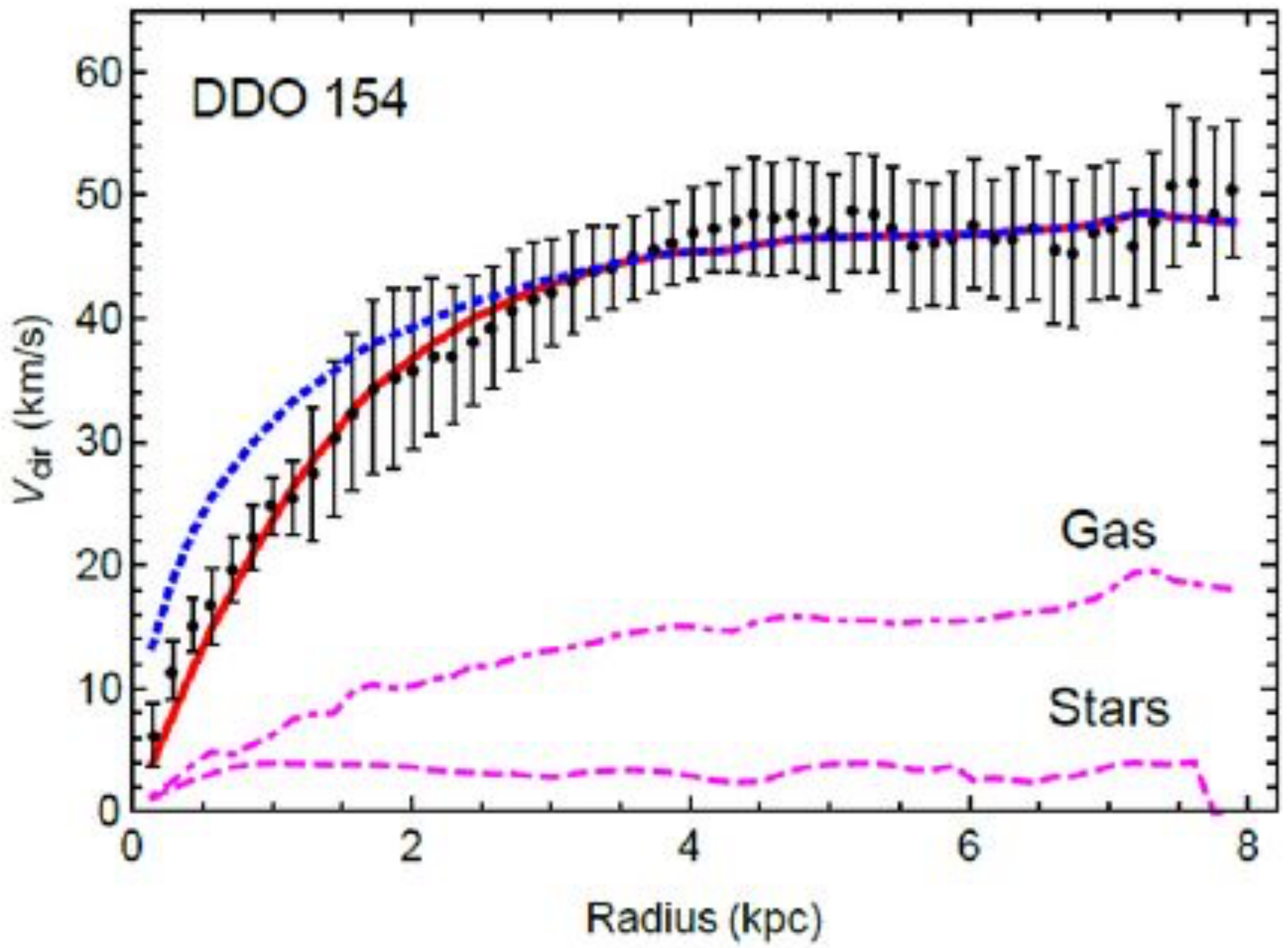

What if dark matter interacts with itself?

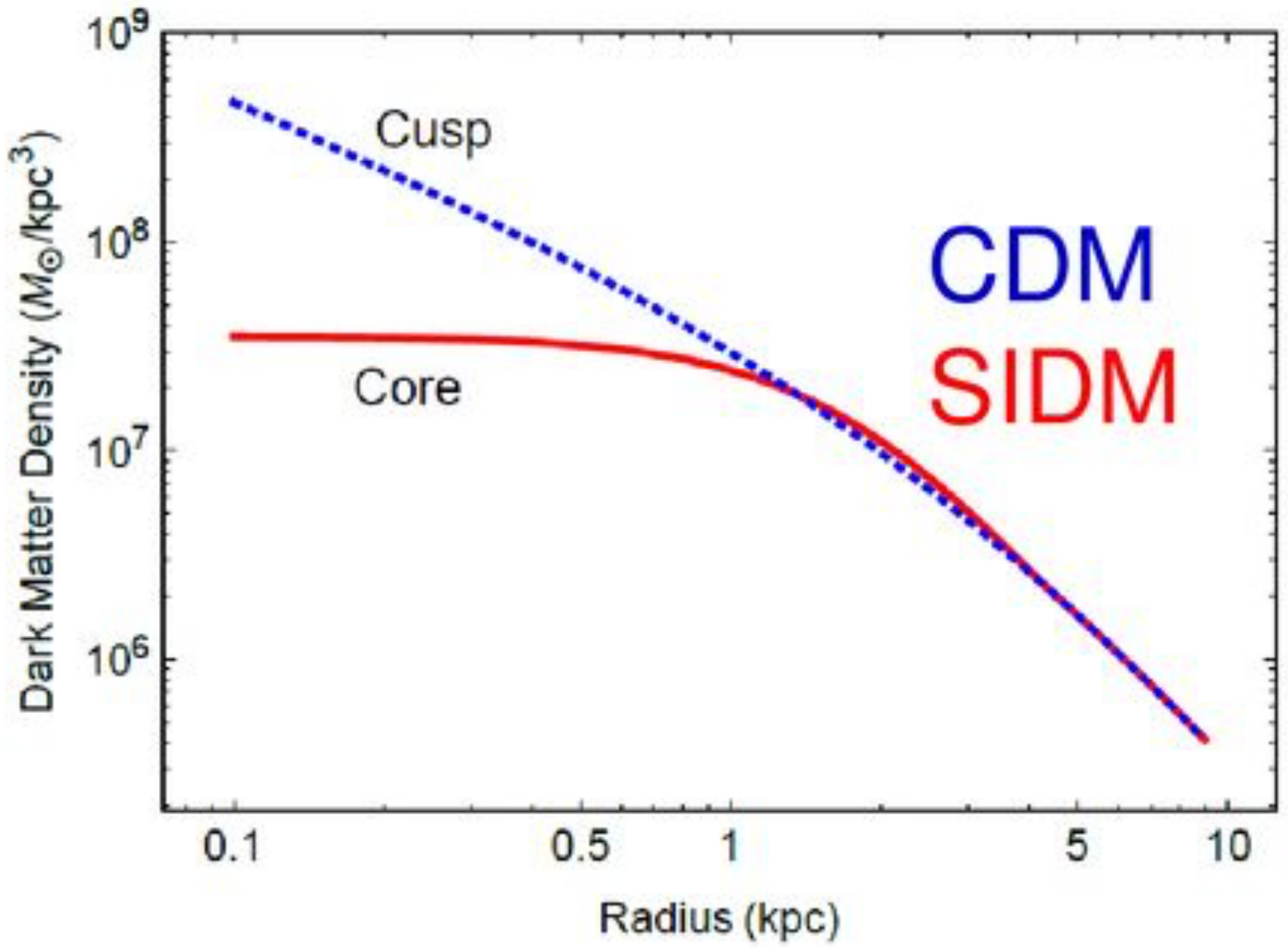
Simulations with SIDM suggest it might create cores rather than cusps

In order for dark matter to self-interact, there needs to be a new force that is only active in the dark sector (mediated, e.g., by dark photons). The interaction cross section needs to be a function of velocity in order to make cores in galaxies but not huge ones in clusters of galaxies.


# Self-interacting dark matter

*Phys.Rept. 730 (2018) 1-57*




- Collisionless CDM-only simulations predict “cuspy” DM density profiles, while observation prefer “core”.
- Others: Missing satellites problem, Rotation curve diversity problem, Too-big-to-Fail problem.
- SIDM is leading candidate to solve these issues.

SIDM with a constant self-interaction cross-section does not work simultaneously for both galaxies and clusters, so a velocity-dependent cross-section is often considered.

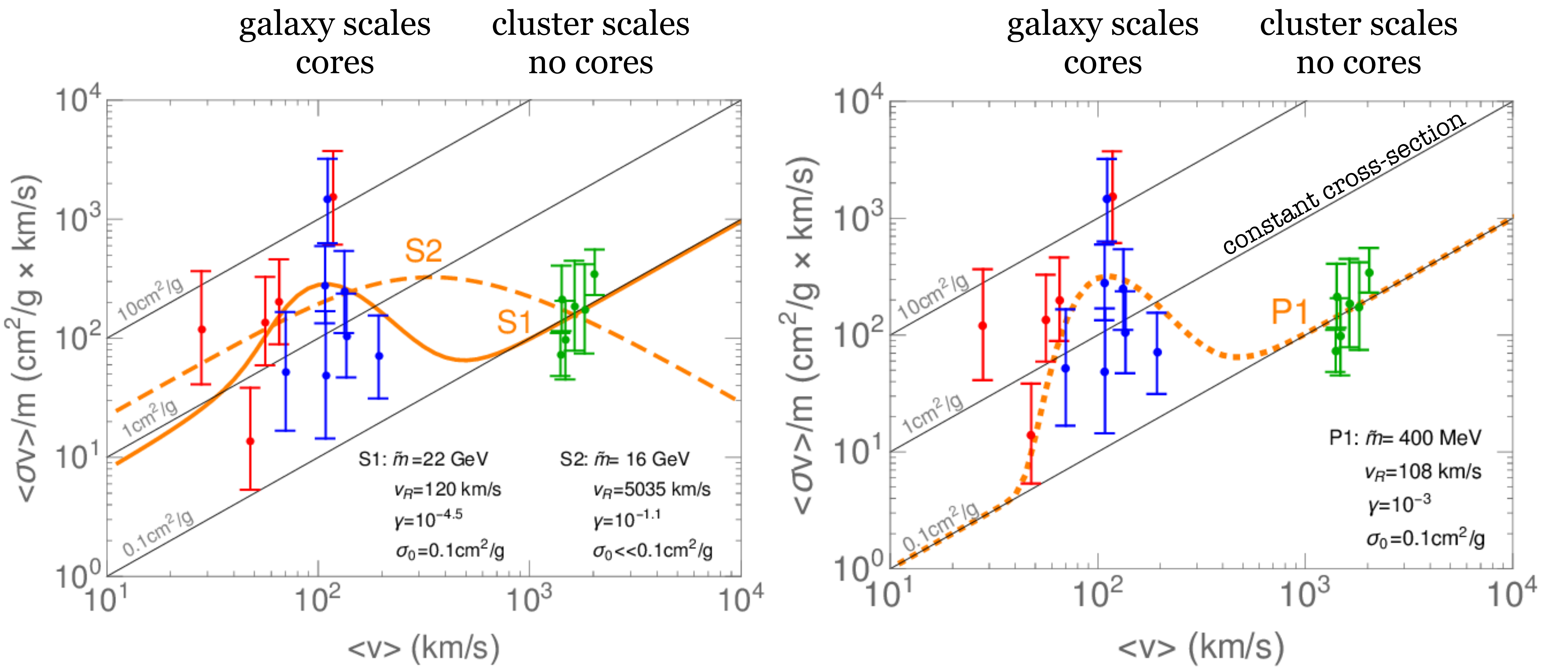



Figure 1: RSIDM cross section per unit of mass as a function of the velocity. Best-fit curves to data [15] for S-wave (left) and P -wave scatterings (right). The latter is also the best-fit curve for $L > 1$ after rescaling the mass with Eq. (8). Here $\tilde{m} = mS^{-1/3}$ .

X. Chu, C. Garcia-Cely, H. Murayama (2019, PRL)

# Fuzzy Dark Matter (FDM)

Fuzzy DM[1] consist of extremely light scalar particles with masses on the order of $10^{-22}$ eV. At this extraordinarily low mass, particles have a Compton wavelength on the order of a pc, manifesting in quantum wave behavior on astrophysical scales. The wave behavior leads to interference patterns, causing spherical soliton cores in dark matter halos,[2] and cylindrical soliton-like cores in dark matter cosmic web filaments.[3]

**Good:** The soliton core has a constant density, hence addressing the cusp-core problem.
**Bad:** This creates a new problem, as the absolute density of the soliton is far too large to fit the data for real galaxies.


1. Hu, Wayne; Barkana, Rennan; Gruzinov, Andrei (2000). "Cold and Fuzzy Dark Matter". *Physical Review Letters*. **85** (6): 1158–61. arXiv:astro-ph/0003365. Bibcode:2000PhRvL..85.1158H. doi:10.1103/PhysRevLett.85.1158. PMID 10991501. S2CID 118938504.
2. Schive, Hsi-Yu; Chiueh, Tzihong; Broadhurst, Tom (2014). "Cosmic structure as the quantum interference of a coherent dark wave". *Nature Physics*. **10** (7): 496–499. arXiv:1406.6586. Bibcode:2014NatPh..10..496S. doi:10.1038/nphys2996. S2CID 118725080.
3. Mocz, Philip; Fialkov, Anastasia; Vogelsberger, Mark; Becerra, Fernando; Amin, Mustafa A.; Bose, Sownak; Boylan-Kolchin, Michael; Chavanis, Pierre-Henri; Hernquist, Lars; Lancaster, Lachlan; Marinacci, Federico; Robles, Victor H.; Zavala, Jesús (2019). "First Star-Forming Structures in Fuzzy Cosmic Filaments". *Physical Review Letters*. **123** (14): 141301. arXiv:1910.01653. Bibcode:2019PhRvL.123n1301M. doi:10.1103/PhysRevLett.123.141301. ISSN 0031-9007. PMID 31702225. S2CID 203734641.

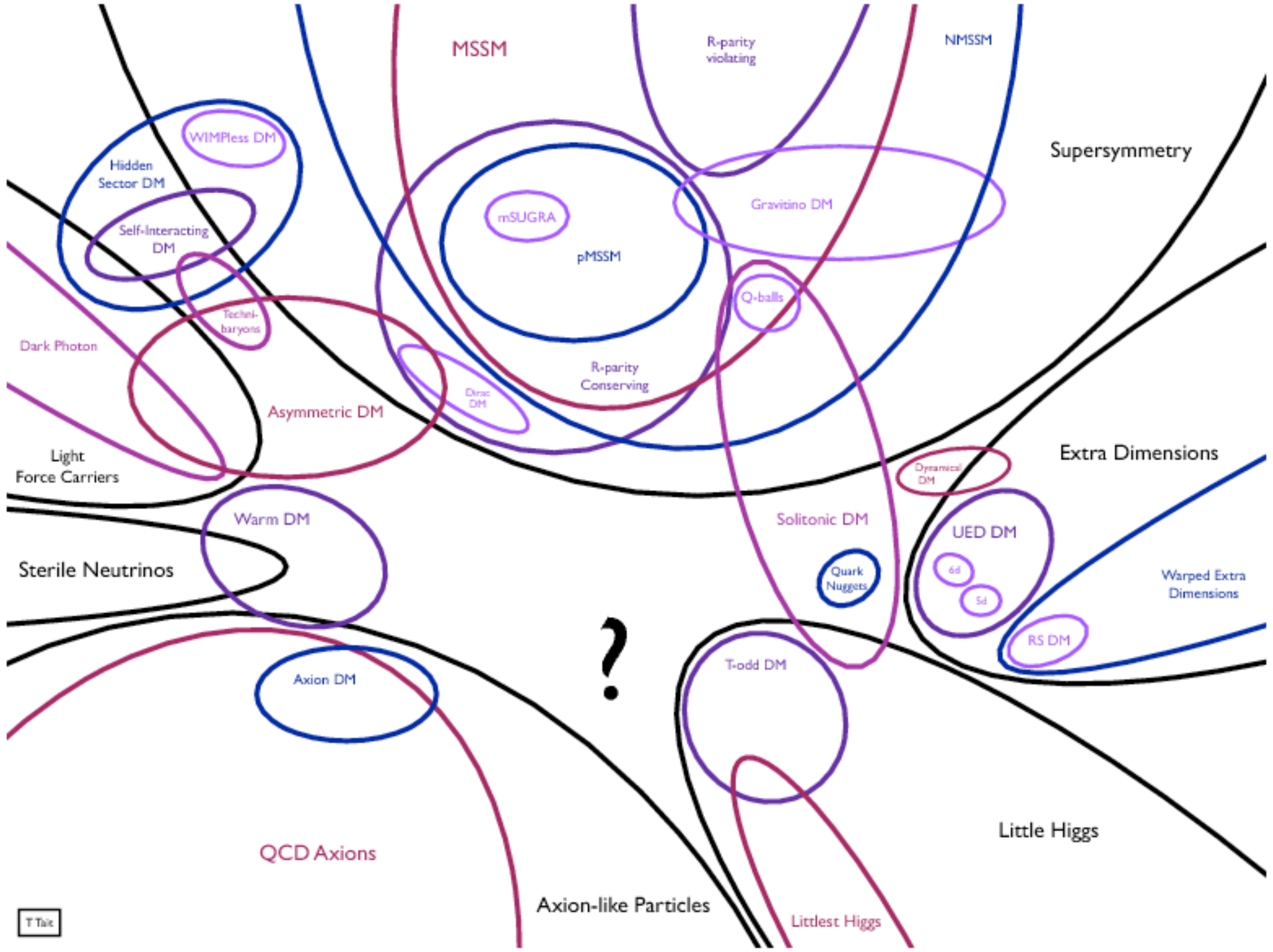
# Superfluid Dark Matter (SFDM)

A type of DM particle that can form a Bose-Einstein condensate. This results in dark matter halos with a superfluid core but which behave like CDM on larger scales. The idea is to obtain MOND-like behavior on galaxy scales while retaining the successes of CDM on larger scales.

Khoury 2021 (2109.10928)

Particles must be of mass $m_x \lesssim (\rho/v^3)^{1/4} \approx 3$ eV with a critical condensate temperature $T_c \approx 0.2$ mK.

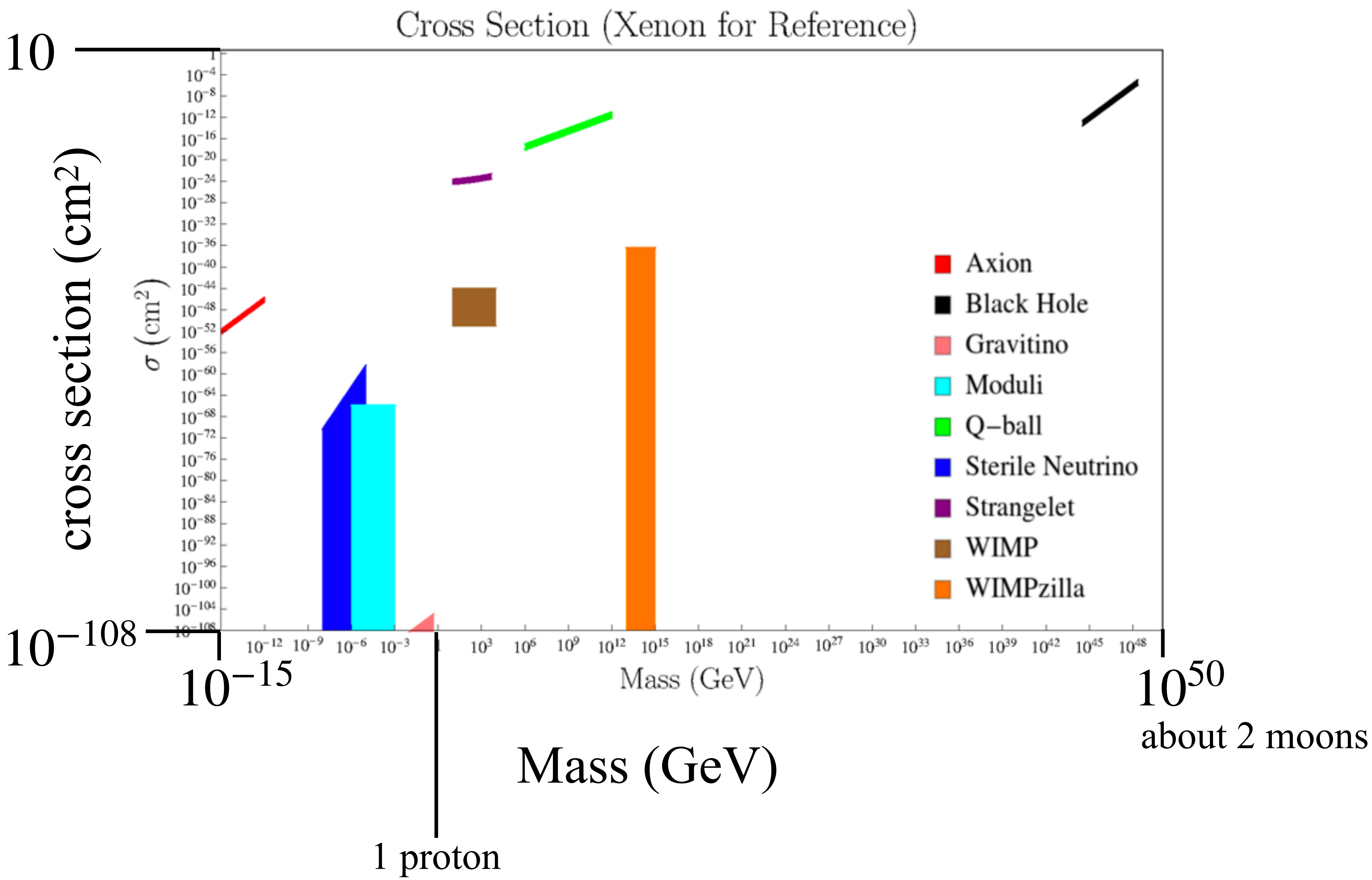
# Etc.



MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
mSUGRA
pMSSM
Gravitino DM
Q-balls
R-parity Conserving
Dirac DM
Dark Photon
Asymmetric DM
Light Force Carriers
Extra Dimensions
Dynamical DM
Warm DM
Solitonic DM
UED DM
6d
5d
Sterile Neutrinos
Quark Nuggets
Warped Extra Dimensions
RS DM
?
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs

Snowmass-2013 Cosmic Frontier 3 (CF3) Working Group Summary: Non-WIMP dark matter

arXiv:1310.8642



arXiv:1310.8642

Axion limits

# Axions

An **axion** is a hypothetical particle originally postulated by the Peccei–Quinn theory in 1977 to resolve the strong CP problem in quantum chromodynamics (QCD). If axions exist and have low mass within a specific range, they are of interest as a possible component of CDM.

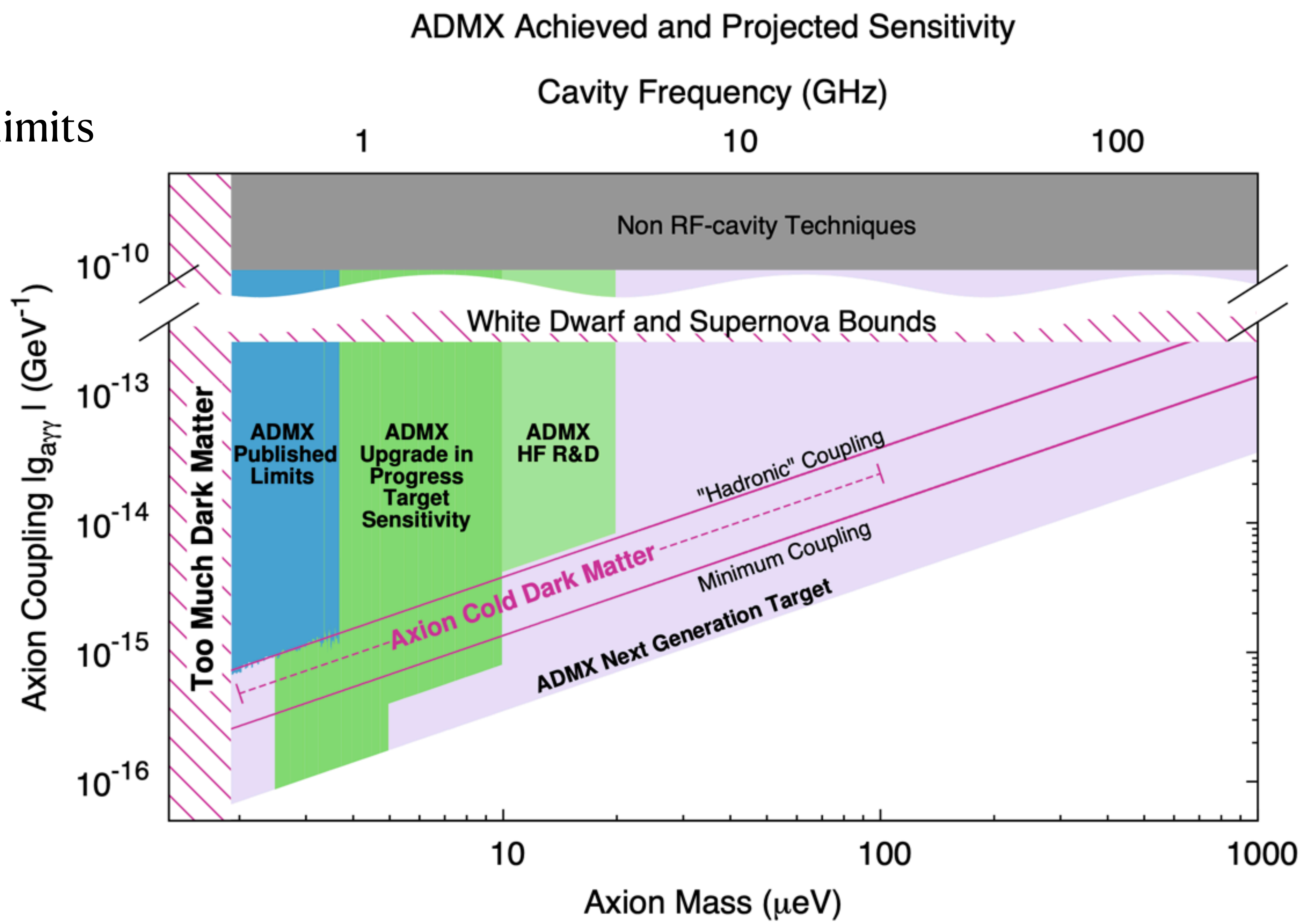



**Figure 2.** *The search reach of the ADMX RF-cavity experiments over the next 3 years. The first decade of allowed axion mass will be explored at "definitive" sensitivity to QCD axions over the next year. The middle decade will be explored at over the following two years. These two decades are expected to encompass the mass of the dark matter axion.*

2015

Snowmass-2013 Cosmic Frontier 3 (CF3) Working Group Summary: Non-WIMP dark matter

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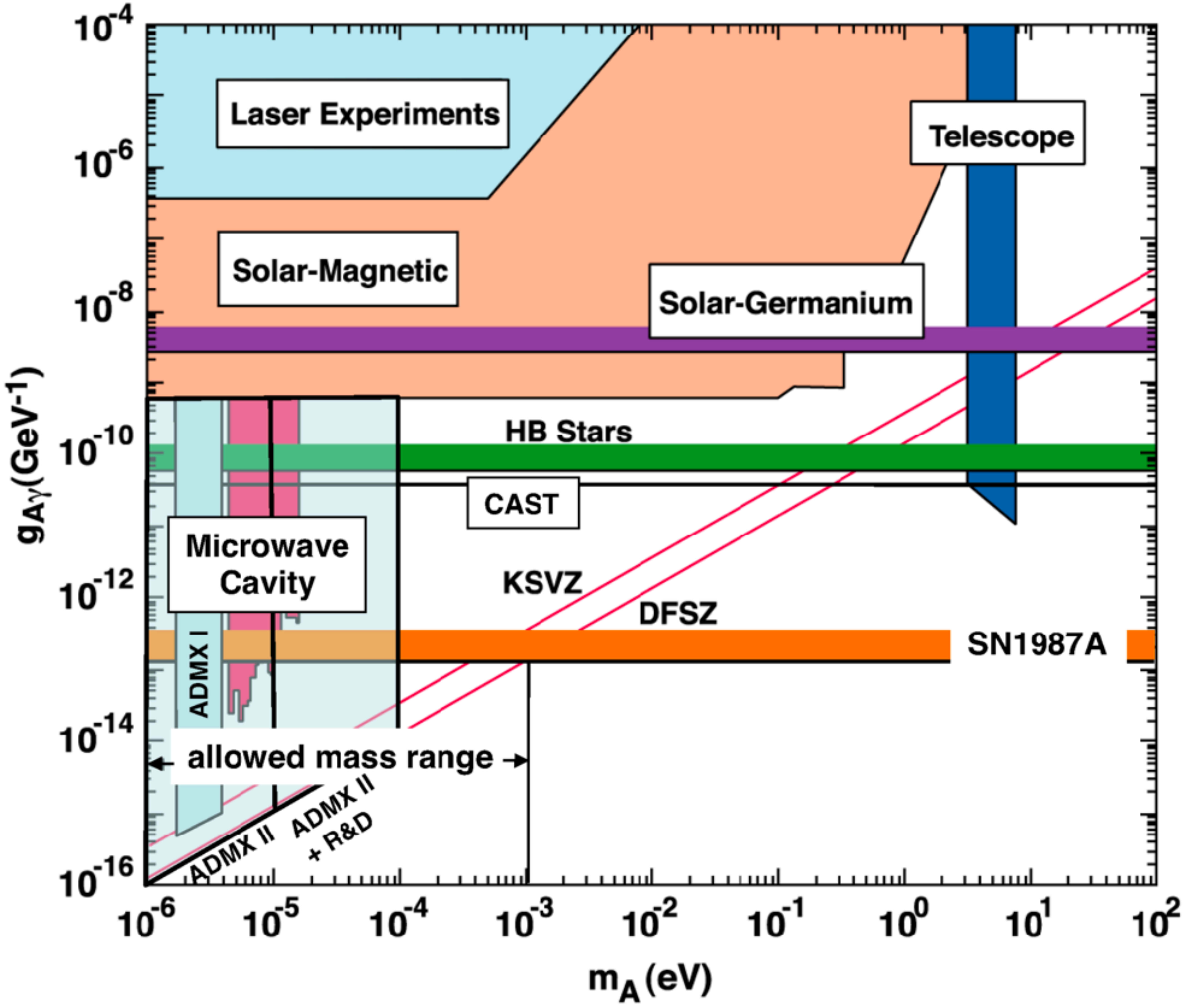



**Figure 3.** *The landscape of axion searches. The vertical axis is the axion's coupling to two photons. The horizontal axis is the axion's mass. The diagonal lines are the expected range in coupling for the QCD axion. The allowed QCD axion window is approximately between 1 μeV and 1 meV. Dark matter QCD axions are in the approximate mass range 1 μeV to 100 μeV, with the bounds having considerable uncertainties. Also shown are upper limits from SN1987A (also white dwarfs) and HB stars (the red giant bound). Sensitivities of various technologies are also shown ("Laser", etc.). The QCD (PQ) dark-matter axions will be explored with high sensitivity in the next decade by RF-cavity experiments. The solar experiments (CAST and IAXO) have sensitivity a a large part of the non-PQ search space and the upper end of the QCD axion window. Of course, there could be surprises in both mass and couplings.*

arXiv:1310.8642

# Sterile Neutrinos

**Sterile neutrinos** (or **inert neutrinos**) are hypothetical particles (neutral leptons – neutrinos) that interact only via gravity and not via any of the other fundamental interactions of the Standard Model.[1] The term *sterile neutrino* is used to distinguish them from the known, ordinary *active neutrinos* in the Standard Model, which engage in the weak interaction. The term typically refers to neutrinos with right-handed chirality that may be inserted into the Standard Model.

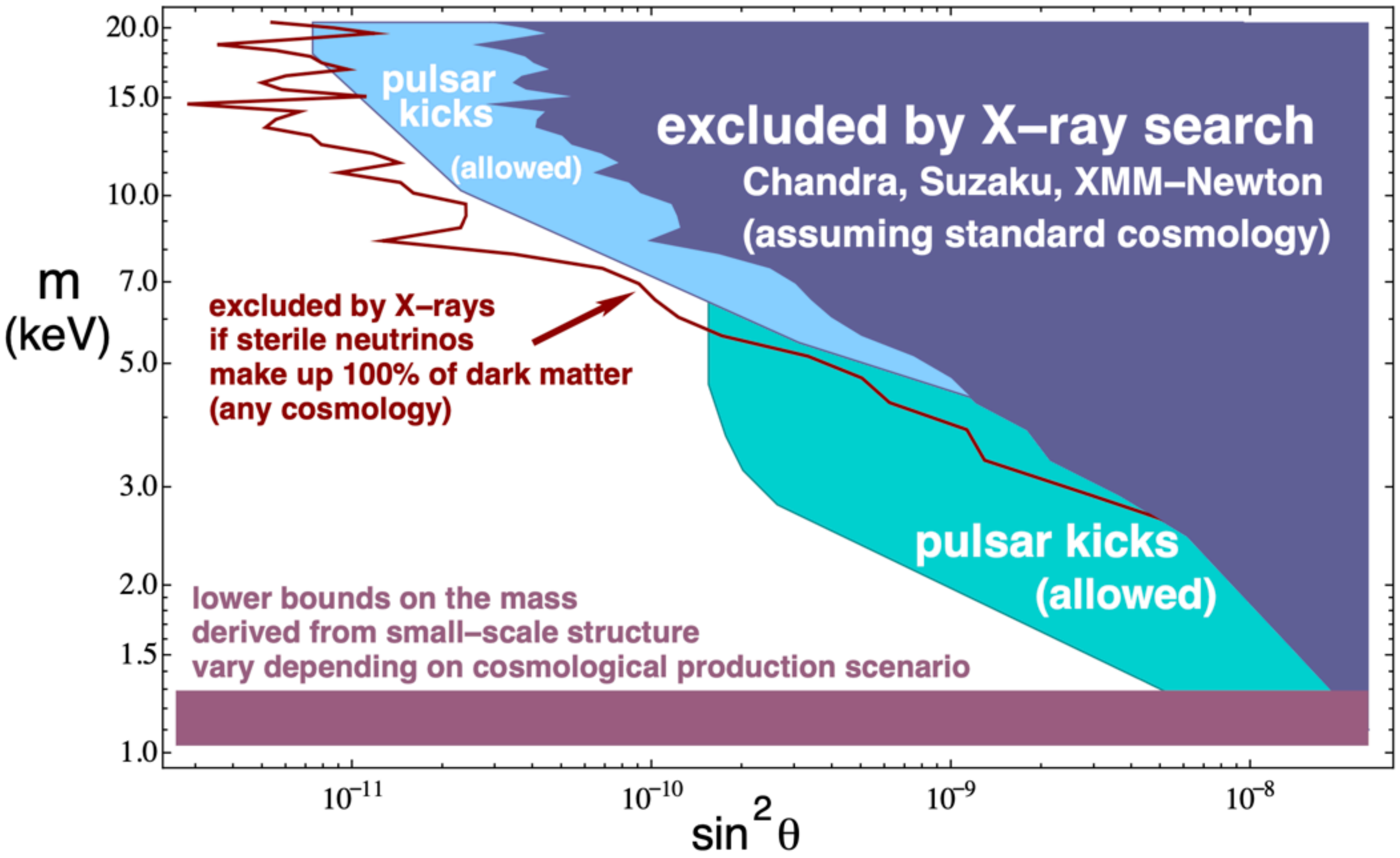



**Figure 4.** *Sterile neutrino parameters to the right of the solid red curve are excluded by the X-ray observations, if the sterile neutrinos make up all of dark matter. If the sterile neutrino abundance is determined by neutrino oscillations and no other mechanism contributes, then the excluded region is smaller (shaded area). Lower bounds from structure formation depend on the production mechanism, because they constrain the primordial velocity distribution whose connection to mass and mixing is model dependent. Also shown is the range in which the pulsar velocities can be explain by anisotropic emission of sterile neutrinos from a supernova.*

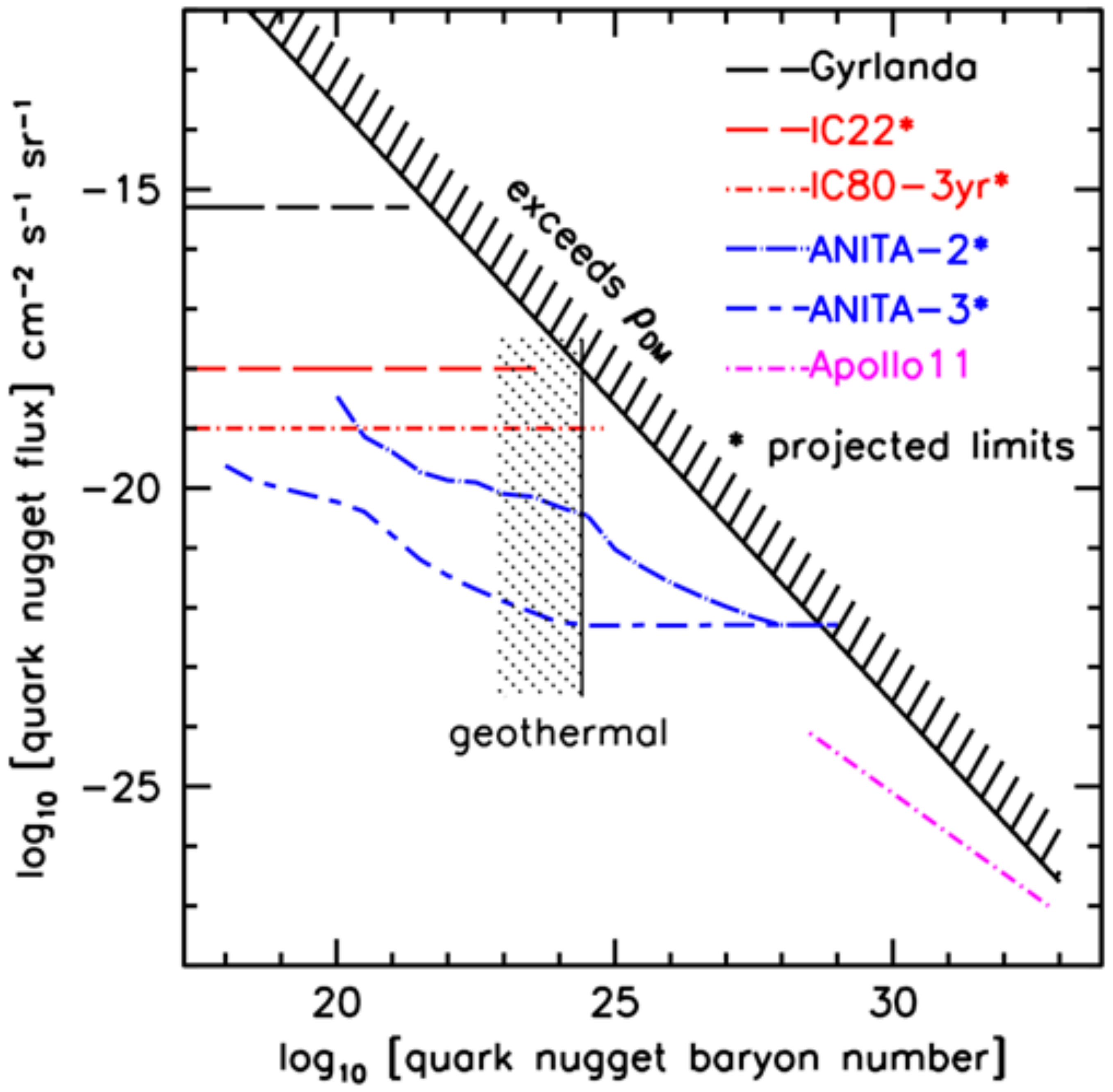
arXiv:1310.8642

# Strange Nuggets

aka macros

aka quark nuggets

i.e., a dark matter candidate composed of nuclear density matter, like a neutron star.




*Current and projected limits on quark nuggets. See Refs. [333, 334] for discussion.*

P. W. Gorham, "Antiquark nuggets as dark matter: New constraints and detection prospects," Phys. Rev. D86 (2012) 123005, arXiv:1208.3697.

K. Lawson and A. R. Zhitnitsky, "Quark (Anti) Nugget Dark Matter," arXiv:1305.6318.

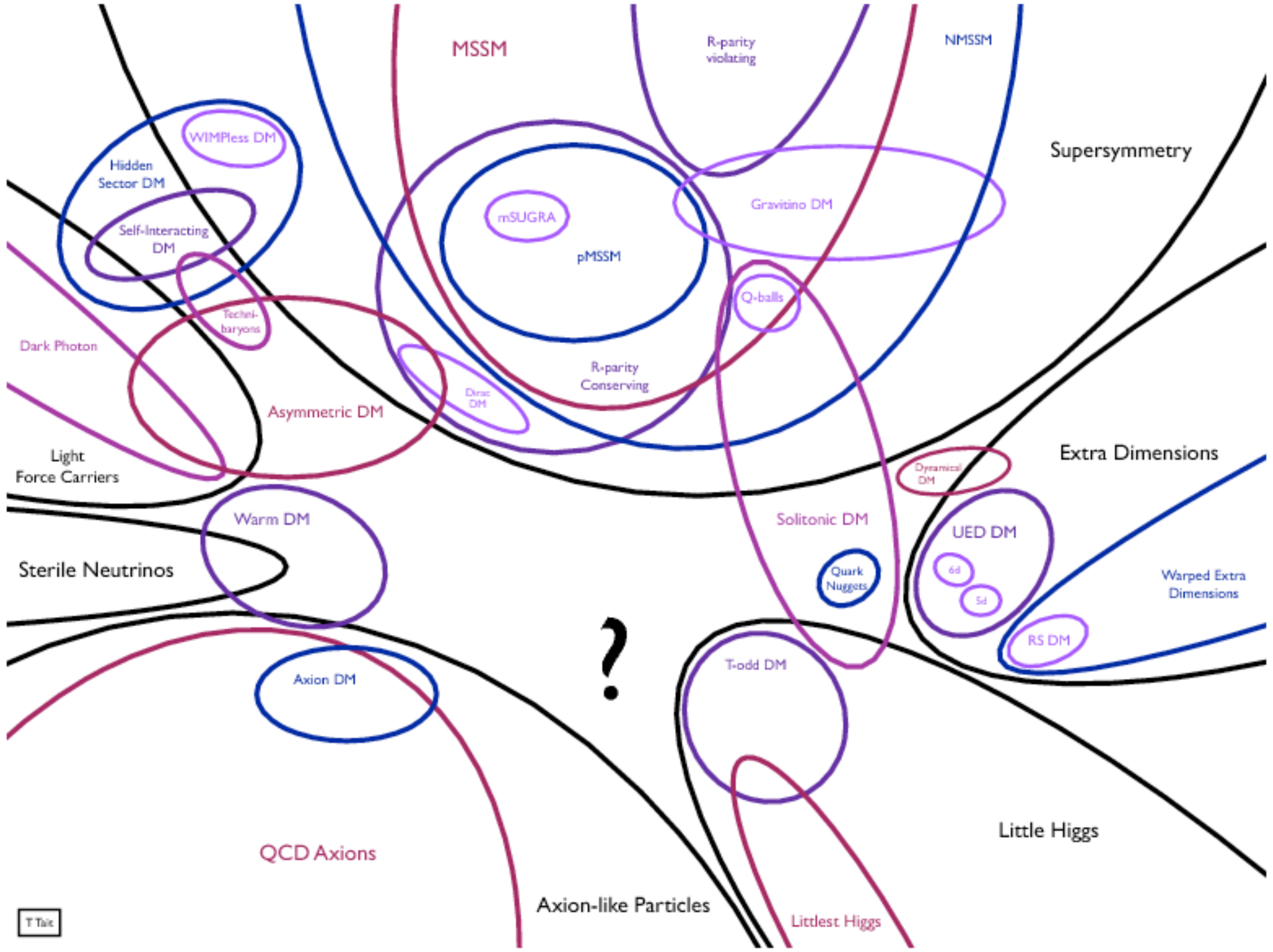
# DM types

## Motivation

- Apparent dynamical mass exceeds visible baryonic mass
- Need to grow structure by $10^5$

- Third peak of CMB power spectrum
    - this is an important corroborative afterthought rather than a motivation.

## Etc.



# Lots of particle dark matter candidates:

WIMPs — Traditionally preferred candidate for CDM

Axions — Hypothesized for a perceived problem with CP symmetry; not obvious it is related to DM problem

Light dark matter — A low mass WIMP-like entity that violates the Lee-Weinberg limit ($m_X > 2$ GeV)

wimpzillas — A very high mass WIMP-like entity approaching the unitarity limit (1000s of GeV)

etc. — There are limits that exclude many possibilities, yet no limit to stuff we can make up

# Can imagine other candidates as well:

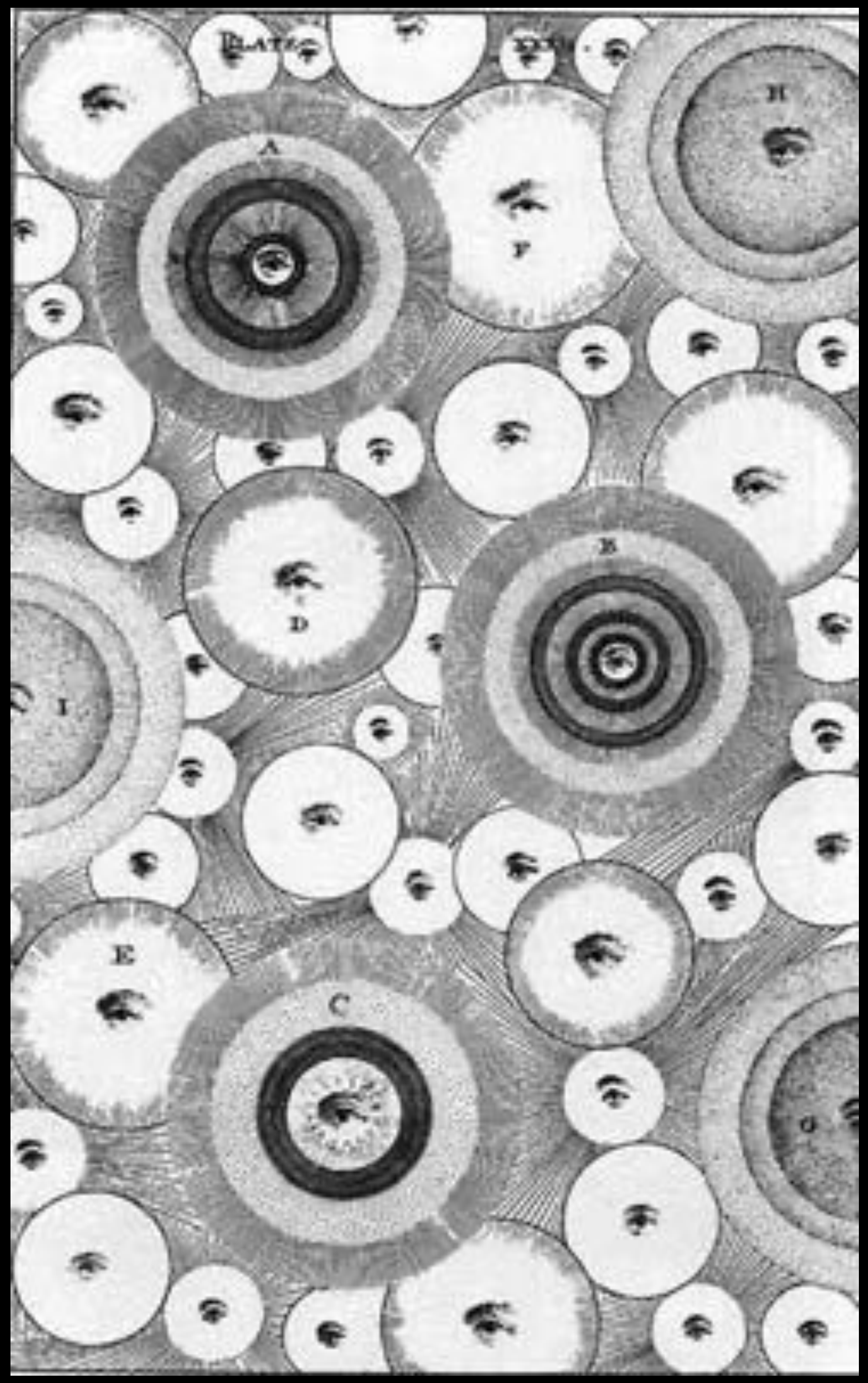
Warm DM — Low mass (typically keV scale) so not dynamically cold, but not too hot either

Self-interacting DM — These DM particles interact with themselves via some new force that is only active in the dark sector, mediated by dark photons

etc.

***All of these ideas require a new "dark sector" beyond the known physics of the Standard Model. Some require complex dark sectors, with new forces as well as new particles (i.e., new forces of nature that only interact in the dark sector, e.g., dark E&M mediated by dark photons.)***

*slide from second class*



"No competent thinker, with the whole of the available evidence before him, can now, it is safe to say, maintain any single nebula to be a star system of coordinate rank with the Milky Way. A practical certainty has been attained that the entire contents, stellar and nebular, of the sphere belong to one mighty aggregation" [i.e., the Milky Way]

- Agnes Mary Clerke (1890)

*Popular History of Astronomy during the Nineteenth Century*

*There is never a result in cosmology that it so secure that it cannot turn out to be completely wrong*