Confining Dark Matter and Self-Interactions

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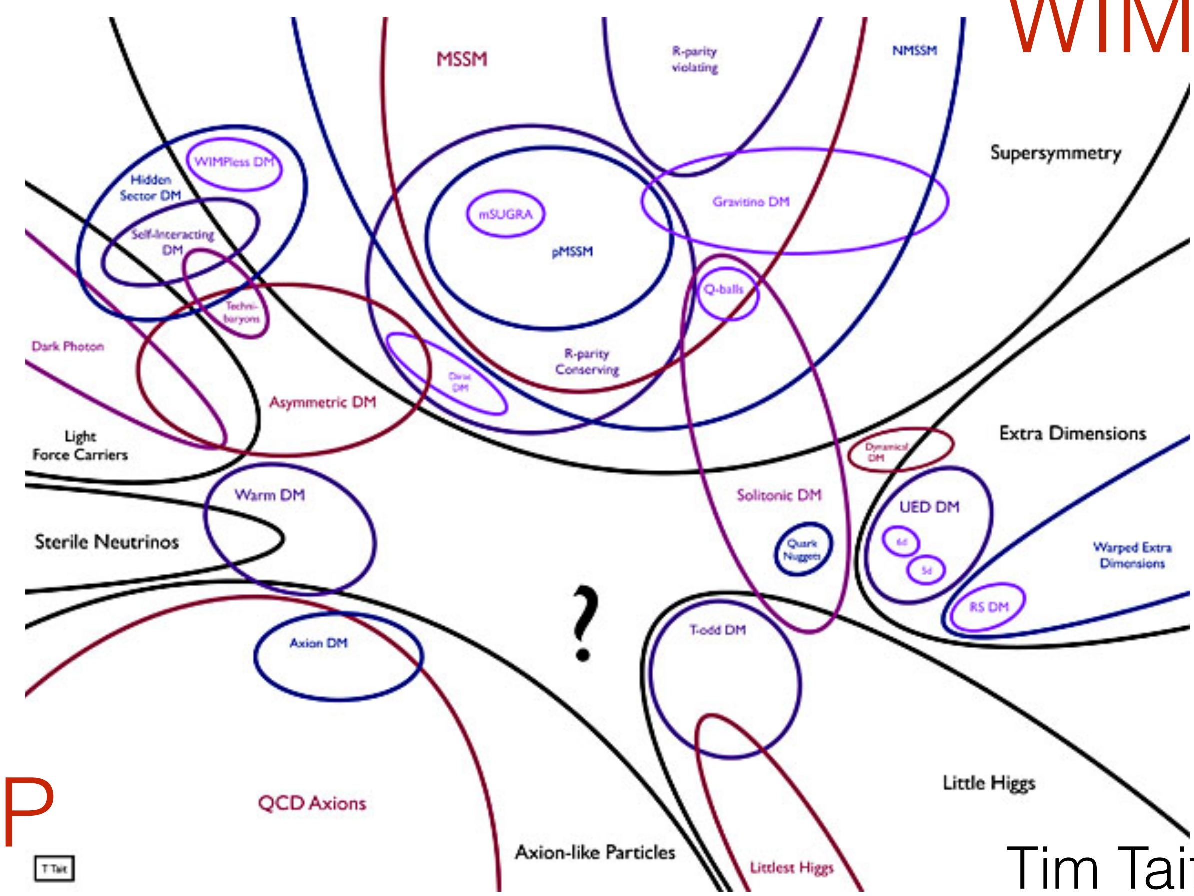
Theories for Dark Matter

- Our knowledge of dark matter most in terms of what it isn't
  - No (unsuppressed) QCD or electromagnetic charges
  - Upper limits on annihilation/scattering cross sections
    - Not the neutral component of an EW doublet
  - Non-relativistic early in the Universe's history

Theories for Dark Matter

- But we know it *exists*, and existed in the early Universe.
- So what is it?
    - Lot's of theoretical options.
    - Common to consider models that are related to other problems.

WIMPs ↔ EWSB, Naturalness



Axions ↔ Strong CP

Tim Tait

Confining Dark Matter

- Most visible energy density from a confining gauge force.
  - Reasonable to ask if dark matter is like this too.

- Well motivated from a number of theoretical angles:
  - Asymmetric dark matter
  - Technicolor dark matter
  - Theories of “scale-less” Standard Model+dark matter
  - Provides explicit examples with interesting phenomenology in dark matter experiments

Confining Thermal Relics

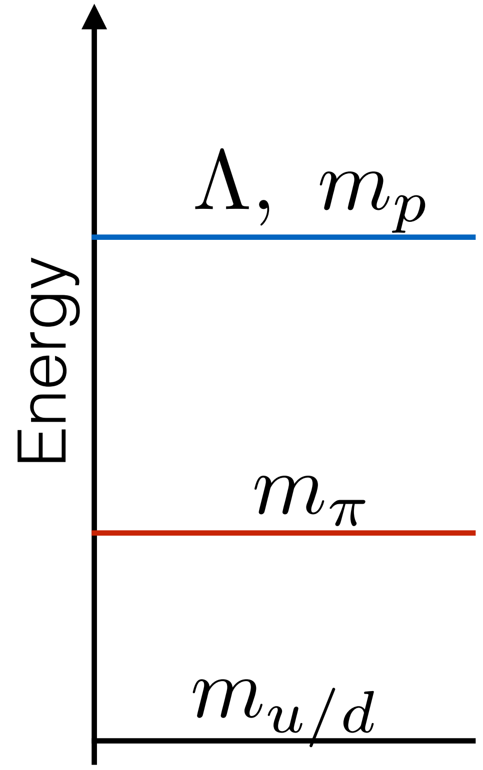
- Assume dark matter is a thermal relic.
  - Requires freeze-out annihilation cross-section

$$\langle \sigma v \rangle \sim 1 \text{ pb} \sim 3 \times 10^{-9} \text{ GeV}^{-2}$$

- For dark confining sector similar to Standard Model QCD, dark matter would be stable baryon.
  - Confining scale Λ will set both $m_\chi \sim \Lambda$ and $\langle \sigma v \rangle \sim \Lambda^{-2}$
  - Thermal relic abundance when $\Lambda \sim 20 \text{ TeV}$
  - Similar to unitarity limit on thermal dark matter.

Confining Thermal Relics

- Dark sector is not the visible sector
- No reason to expect gauge groups, number of flavors, ratios of m_q/Λ to be as in the Standard Model.
- Can we separate m_χ and Λ?
    - From QCD:

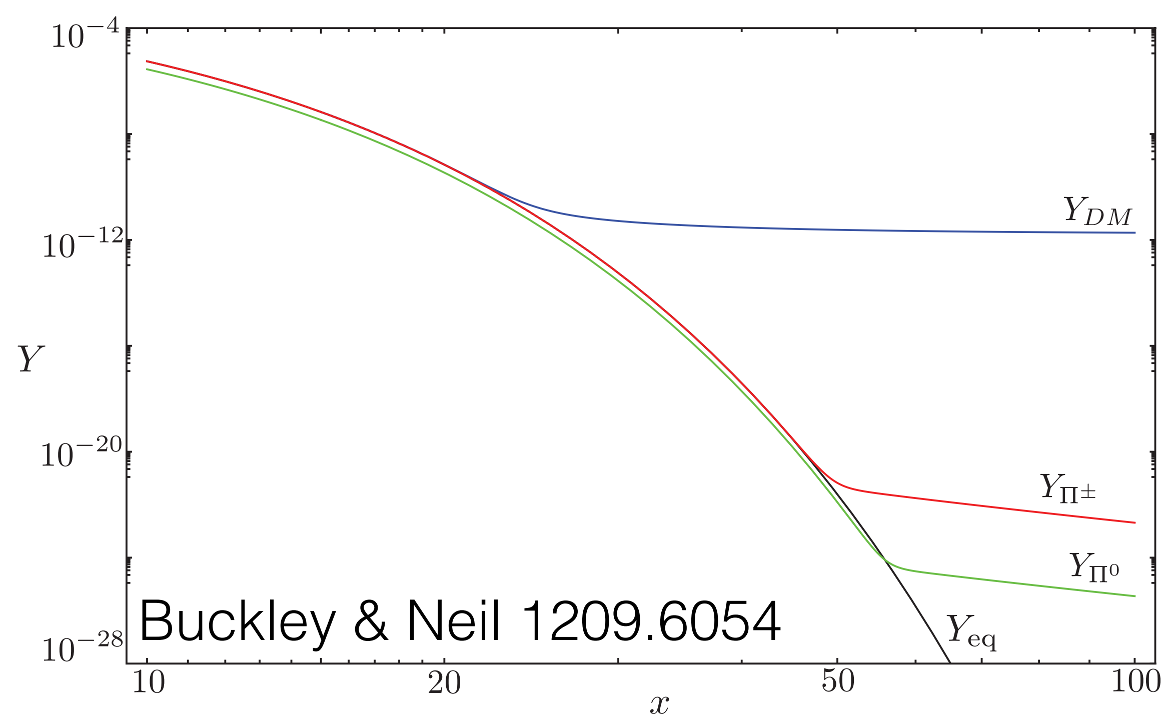


Confining Thermal Relics

- Pions can be significantly lighter than Λ
  - Can be made stable if quarks are real or pseudoreal reps of confining gauge group. *e.g.* doublets of $SU(2)$
  - Now dark matter depends on multiple parameters

$$F_\Pi^2 M_\Pi^2 = m_q\langle\bar{Q}Q\rangle \sim m_Q\Lambda^3$$

- Still have to have connections to Standard Model:



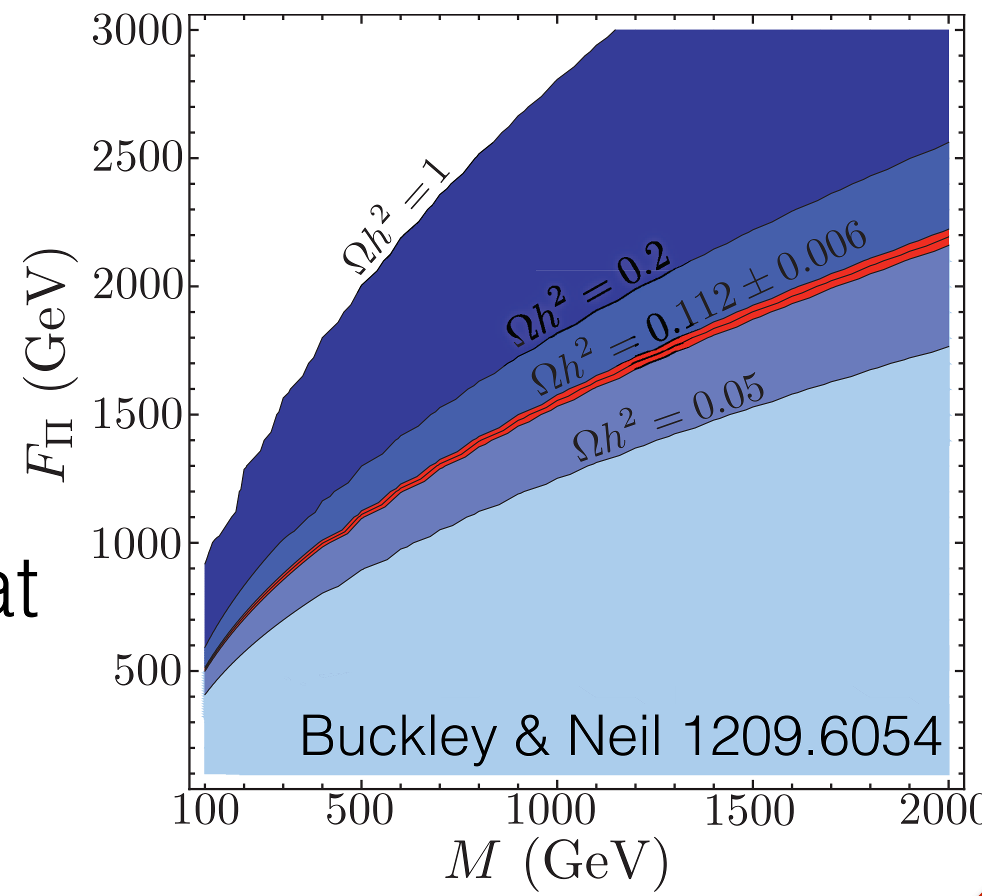
Buckley & Neil 1209.6054

Confining Thermal Relics

- Wide range of parameters that give relic abundance.
- Annihilation cross section goes as $\langle \sigma v \rangle \propto v$
  - Expected from nuclear scattering, somewhat unique in "standard lore" of dark matter phenomenology.
- Direct detection through charge radius and polarizability.
  - Vanish at leading order for

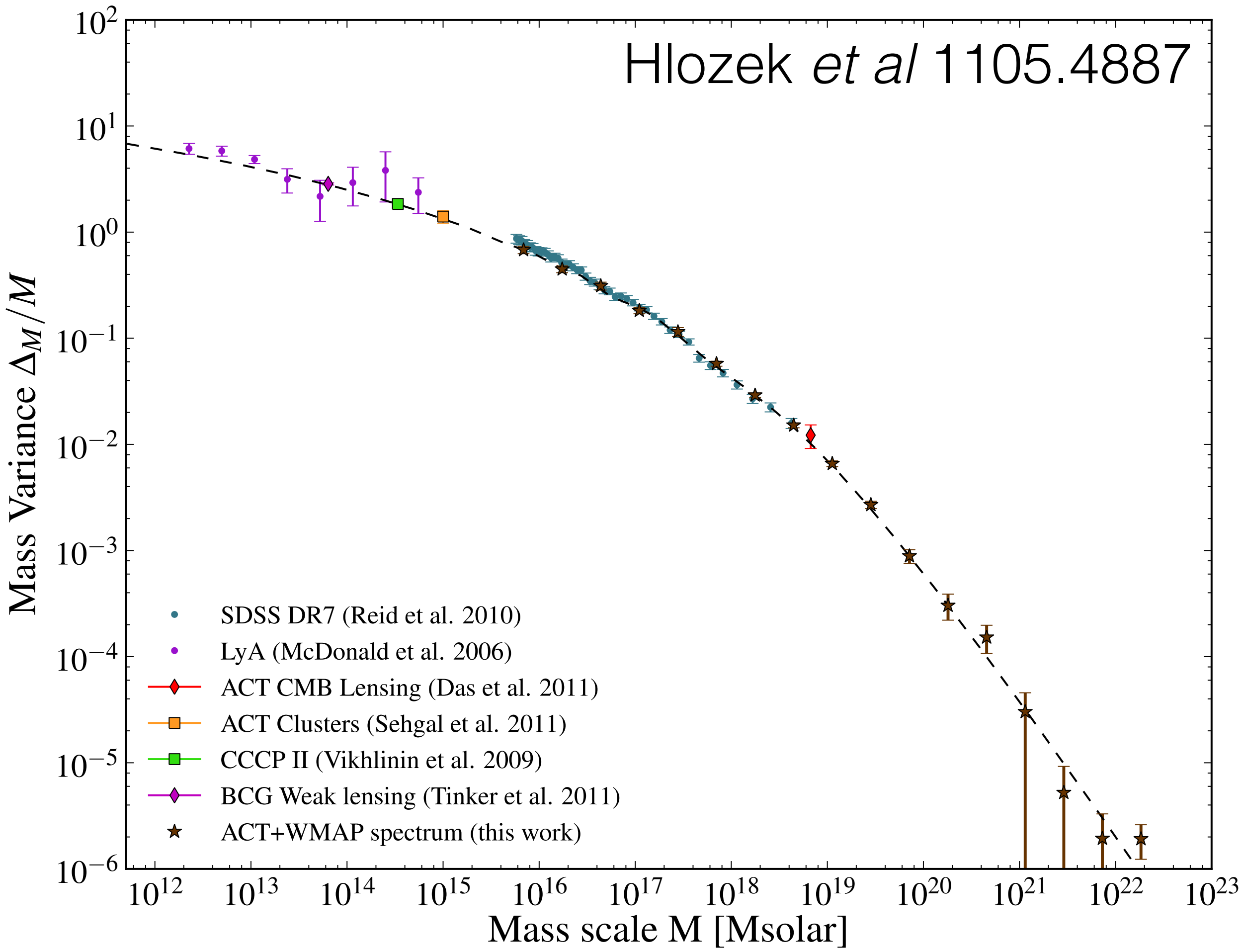
$$m_u - m_d \to 0$$

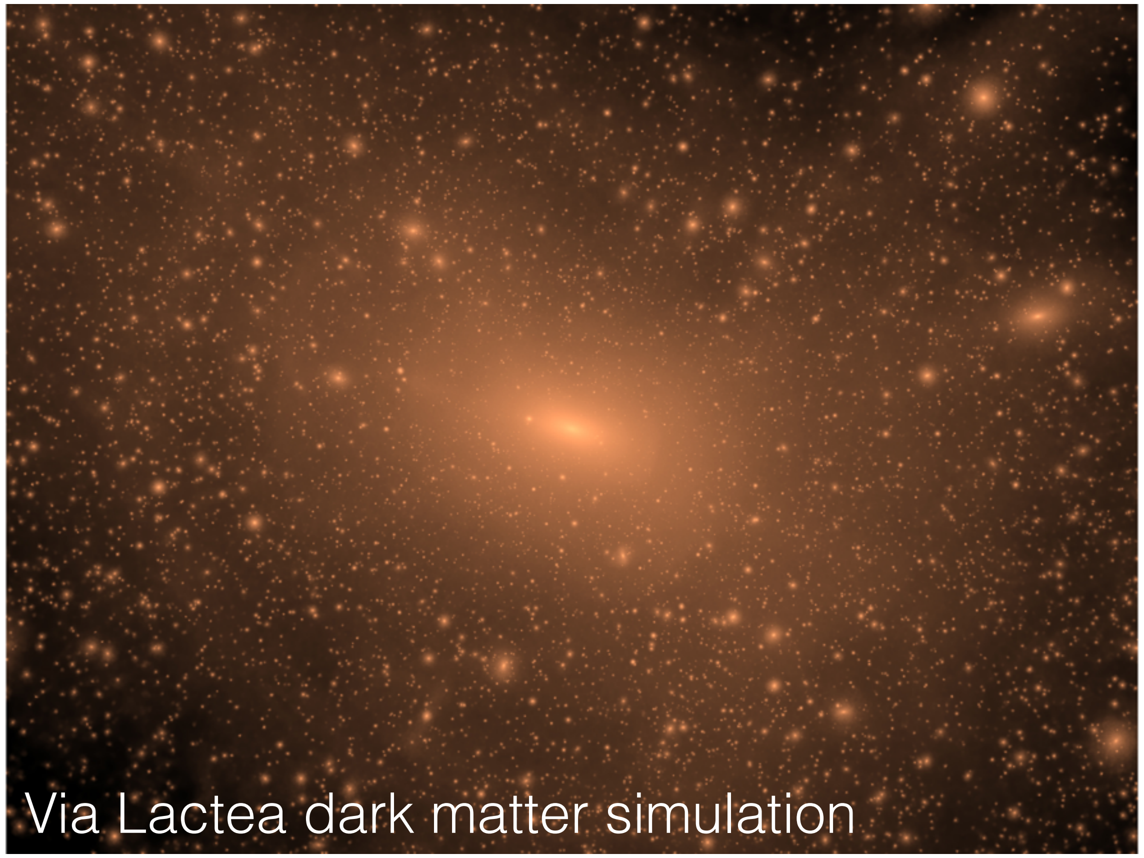
- Charged states more accessible at LHC, but limits still weak.



Unsolved Problems

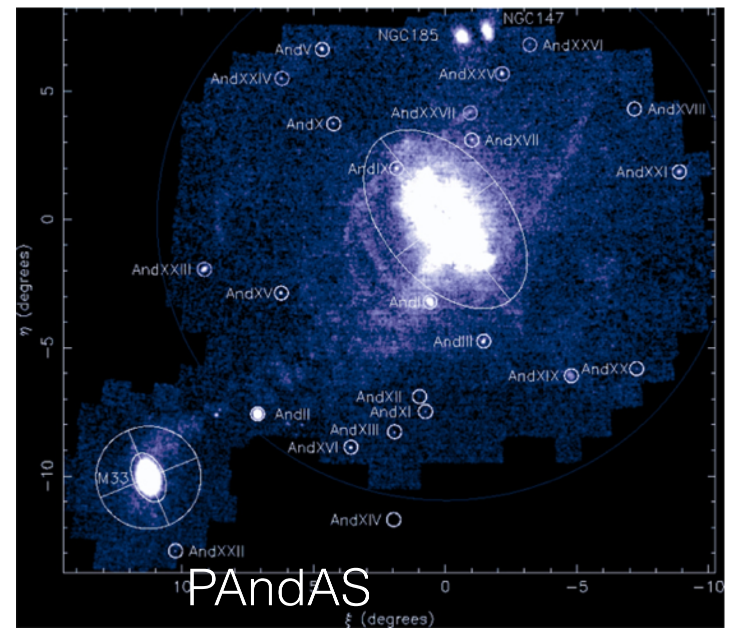
- A problem with dark matter theory is that there are too many good ideas. Which to pursue?
- Always nice to have an experimental push.
  - Consider the “Crisis in small scale structure”



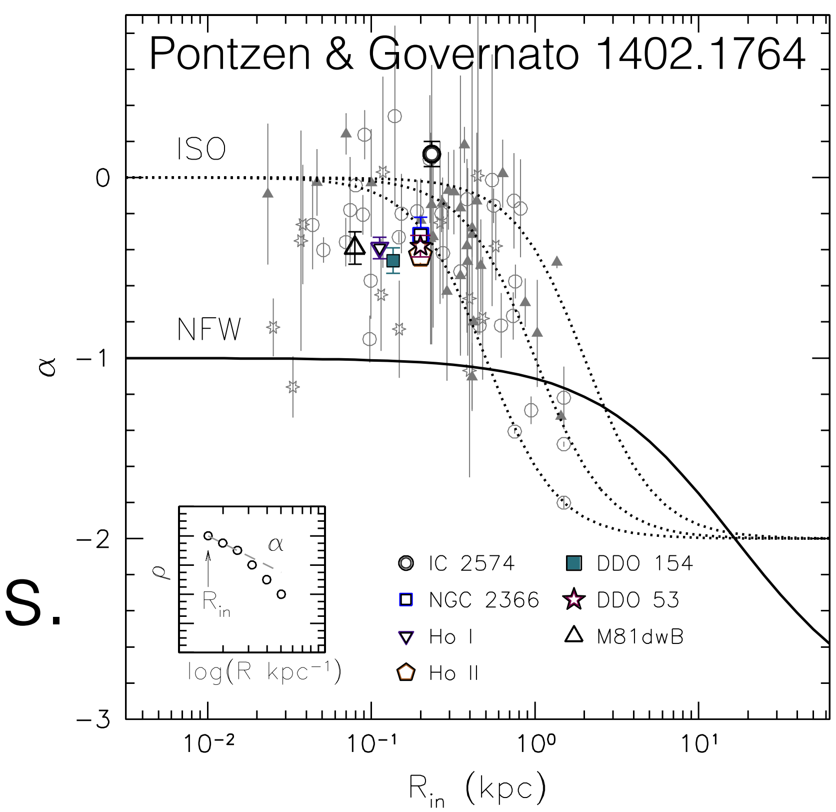


A Small Crisis

- Number of dwarf galaxies inconsistent with predictions from dark matter simulations.

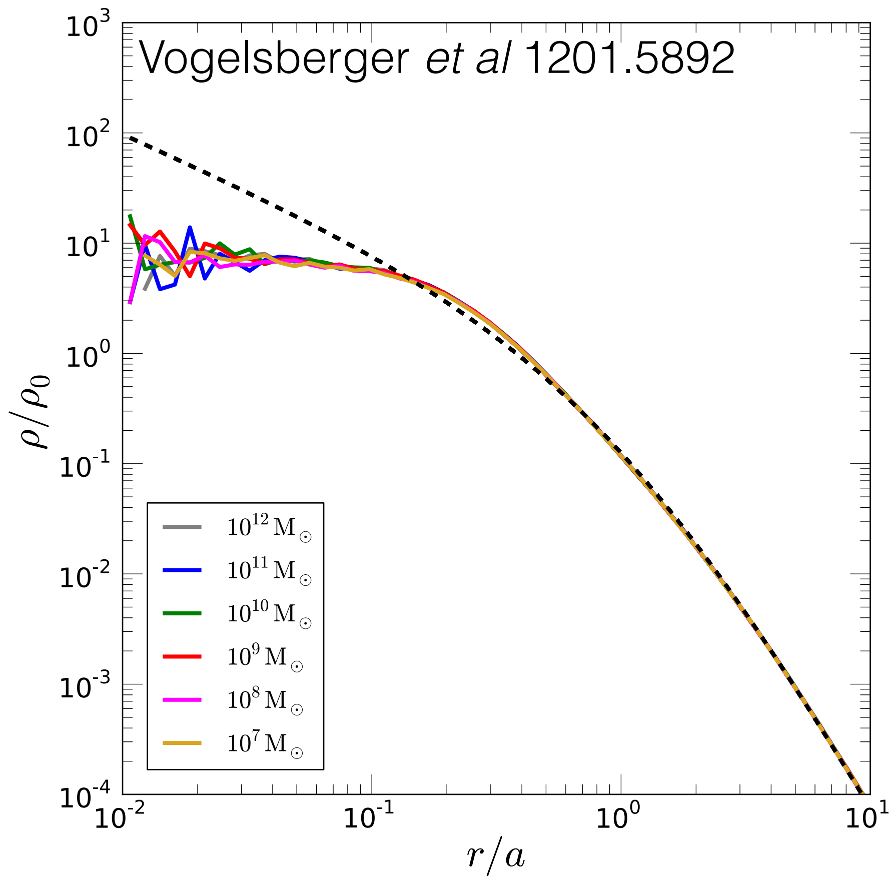


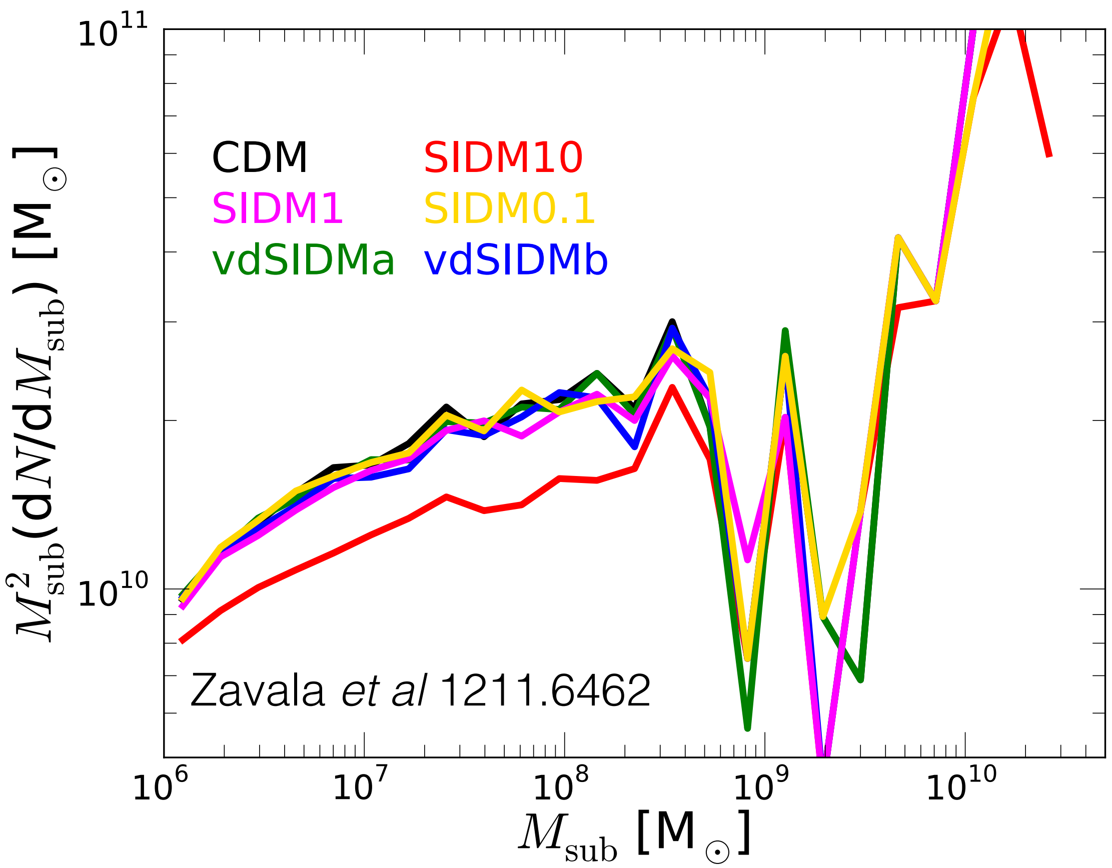
- Predicted dwarf galaxies too dense
  - "Too Big to Fail"
- Profiles of dwarf galaxies more cored than simulations.



Self-Interacting Dark Matter

- Some of these problems may be “fixed” by self-scattering in dark matter
  - Allows fast DM to transfer energy to slow-moving DM

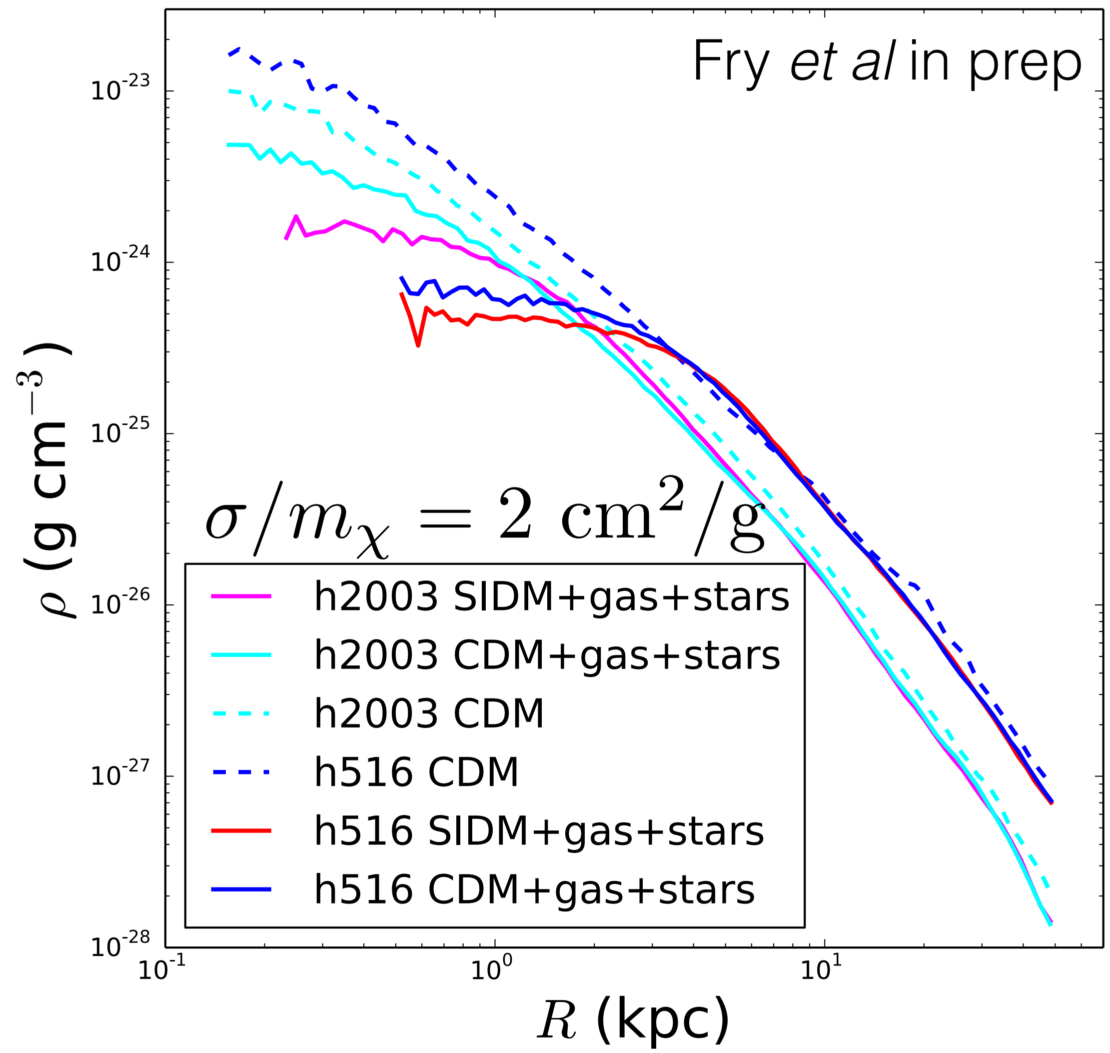




Self-Interacting Dark Matter

- Might also be fixed by baryonic feedback, now being included in simulations.

- Until recently, no one had included both baryons and SIDM
- Baryons might solve small-scale crisis, but still room for SIDM



Confining SIDM

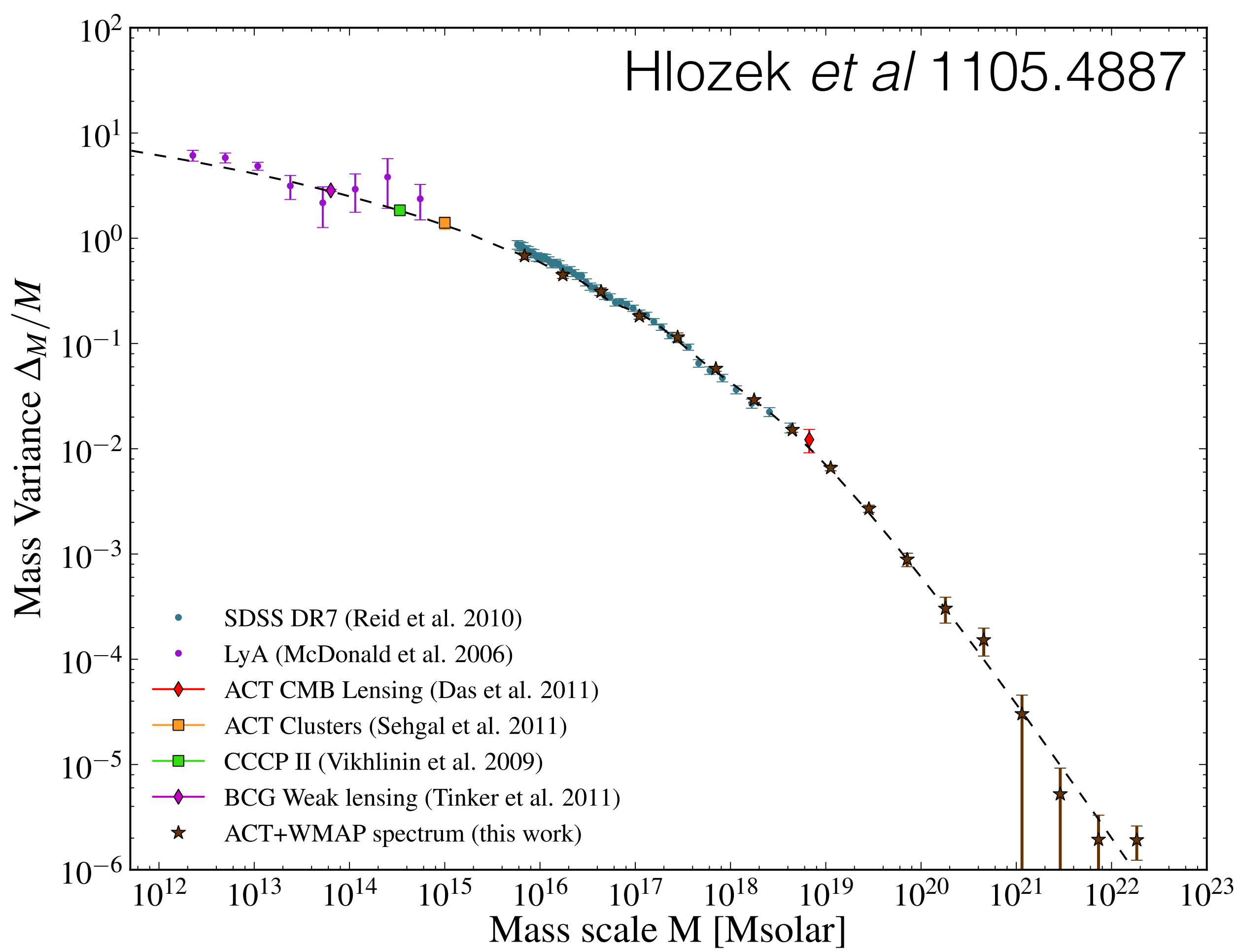
- Necessary SIDM scattering cross section is *big*

$$\sigma/m_\chi \sim 0.1 - 1\ \mathrm{cm}^2/\mathrm{g} \sim 500 - 5000\ \mathrm{GeV}^{-3} \sim 7 - 70\ \mathrm{barn}/\mathrm{GeV}$$

- Demands large couplings, or light mediators, or both.
  - Perfect playground for confining dark sectors
  - Not *necessary* for confining dark matter, but a possibility that can be realized depending on parameters.
- Note that "atomic" dark matter also attractive.
  - Why should dark matter be boring?

SIDM in the Early Universe

- Simulations of dark matter with or without self-interactions need a set of initial conditions for the Universe.
  - Typical to start with the power-spectrum of cold DM

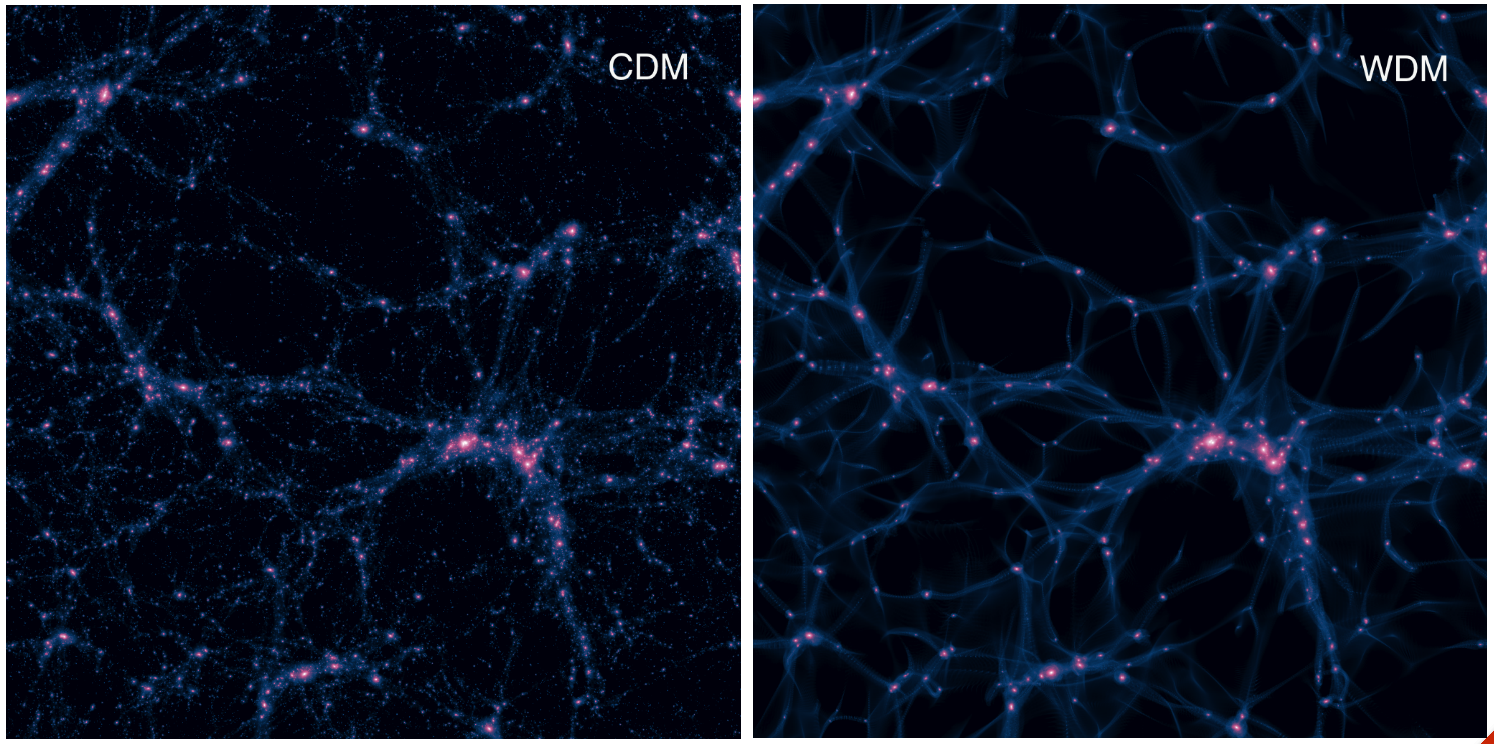


SIDM in the Early Universe

- SIDM σ keeps dark matter in kinetic equilibrium, until

$$n_\chi(T)\langle\sigma v\rangle v_\chi^2 \sim H(T)^{-1}$$

  - This can be until very late times ($T \lesssim \mathrm{keV}$)
- Might expect this to alter the initial power-spectrum of dark matter in SIDM, in addition to altering the evolution of small-scale structure
- *e.g.* "warm" DM



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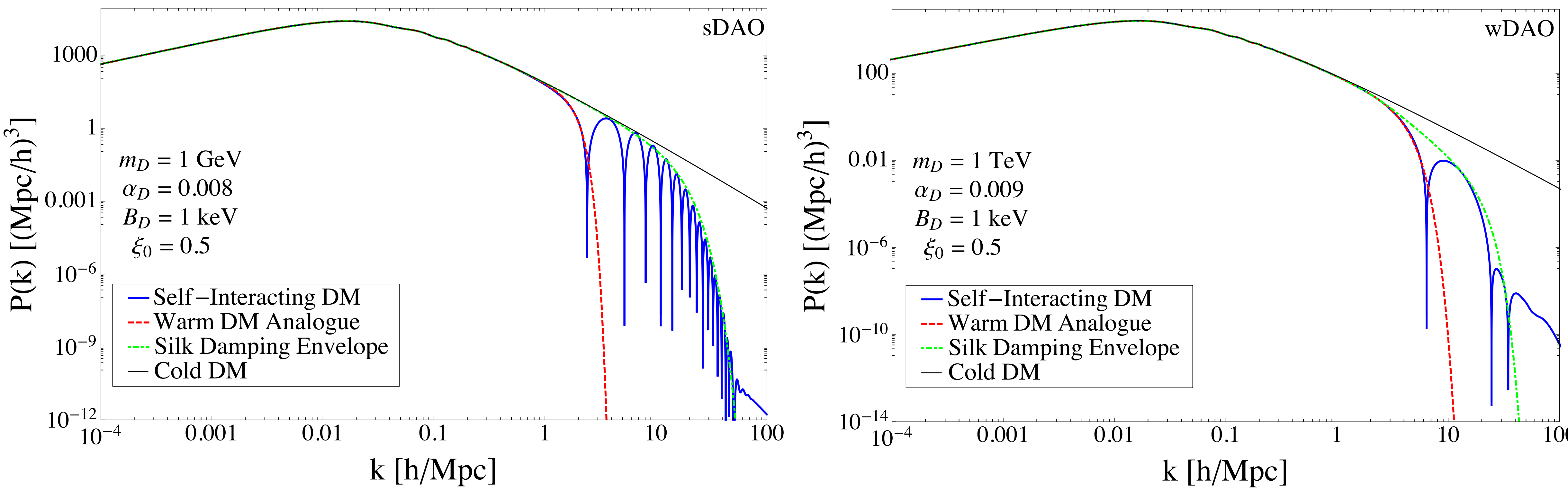
SIDM in the Early Universe

- If SIDM given by "black disk" scattering, then energy can't propagate very far. $v_{\rm sound} \ll c$
- But add a light force carrier, $v_{\rm sound} \sim c$ until $T < m_{\rm med}$.
  - This will allow energy to free-stream in early Universe



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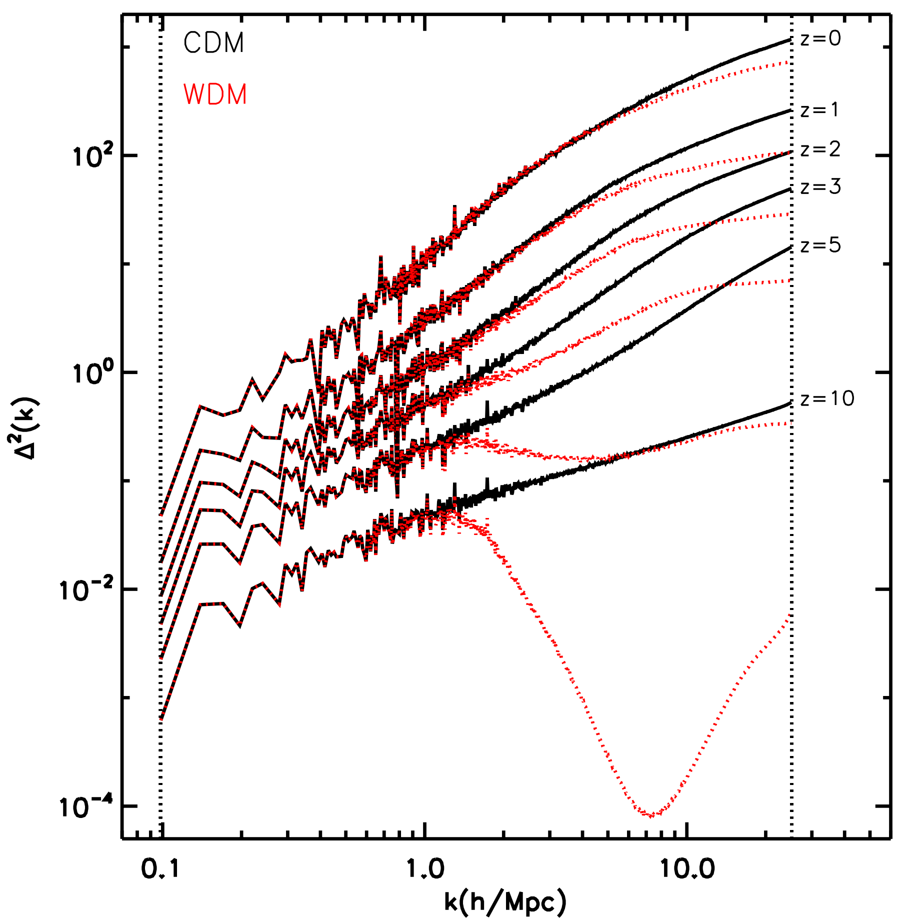
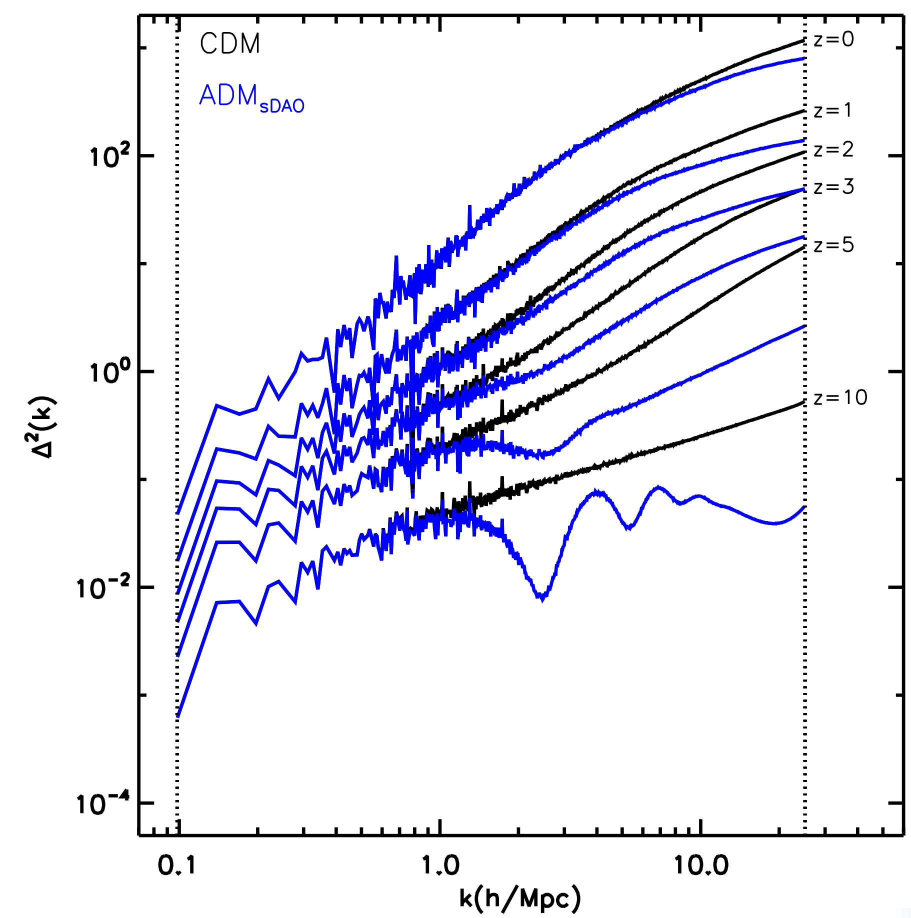
Multiple Effects from SIDM

- If your model has such a long-range force, get two sets of effects on formation of structure:
  - "Regular" effects of SIDM (small-scale crisis related)
  - Initial suppression of small halos, like warm dark matter





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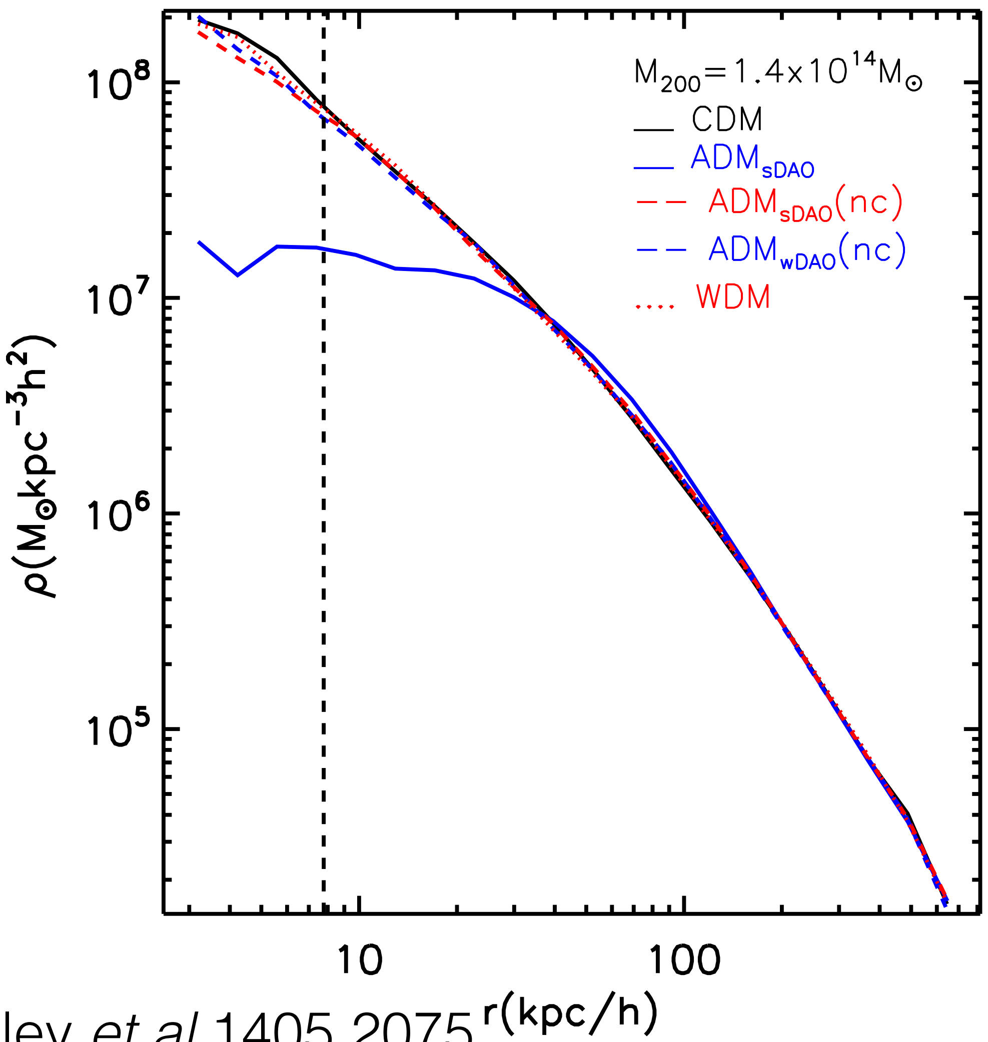
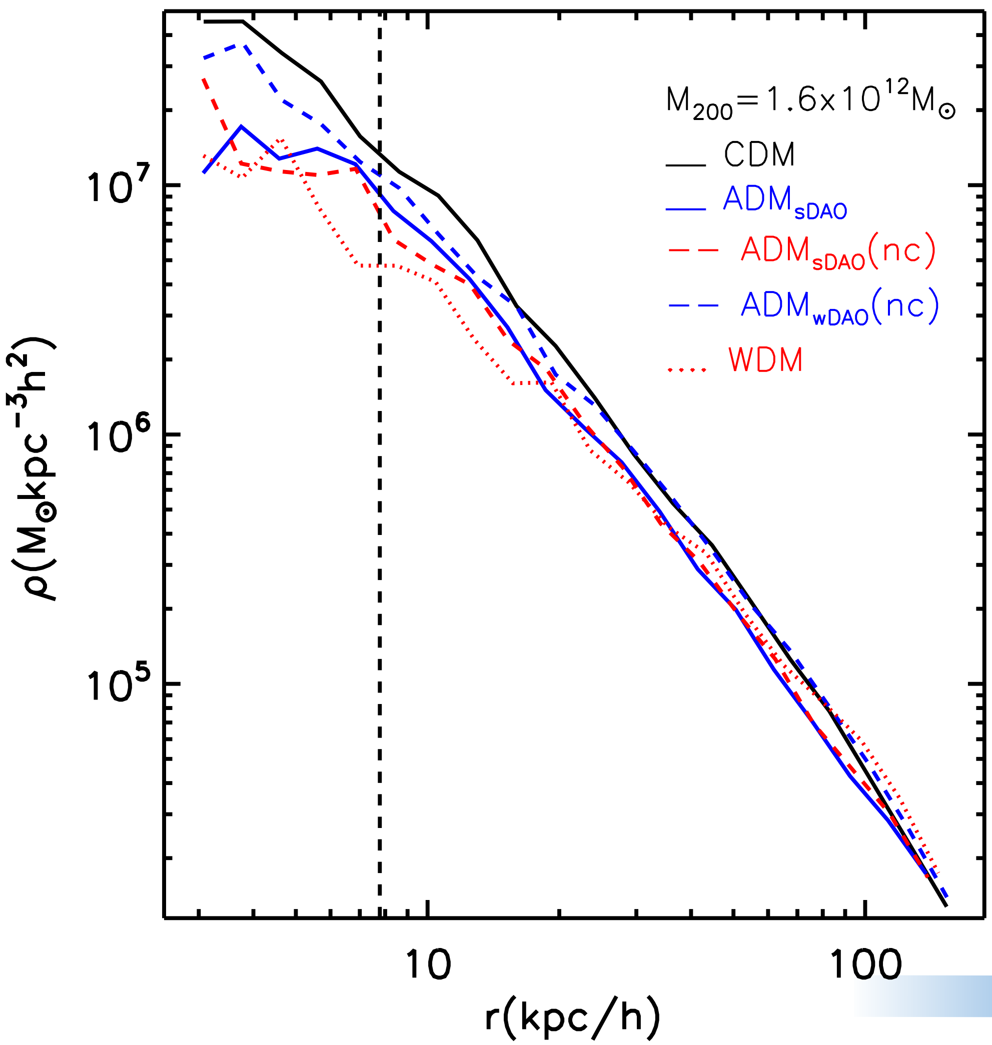
Multiple Effects from SIDM

- Reduction of the central density of small halos
  - Small halos form later, when Universe less dense
  - Independent of SIDM scattering





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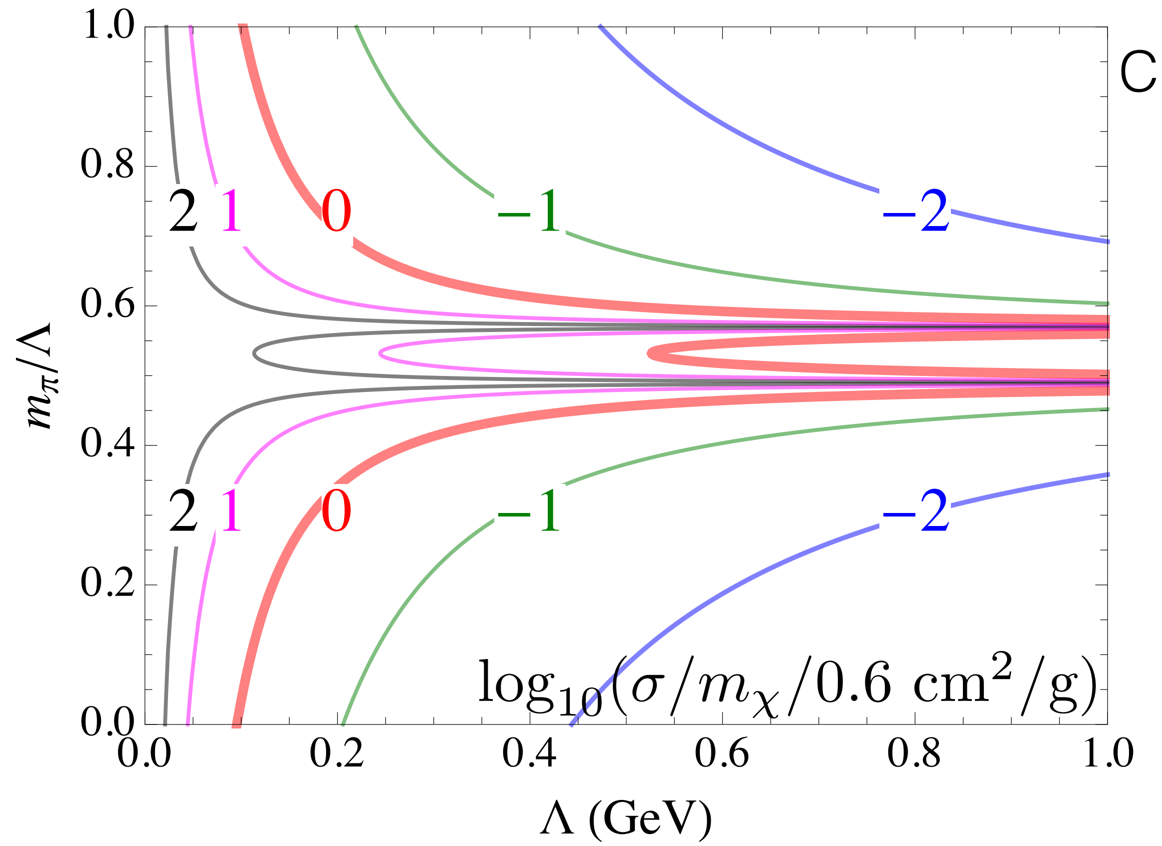
Return to Confining DM

- These effects only realized when there exists a relativistic force carrier. Can we do this with confining DM models?
  - Yes. Assuming similar parameters to QCD
    - Scattering gets boost from deuterium bound state
  - Not guaranteed to get thermal relic abundance

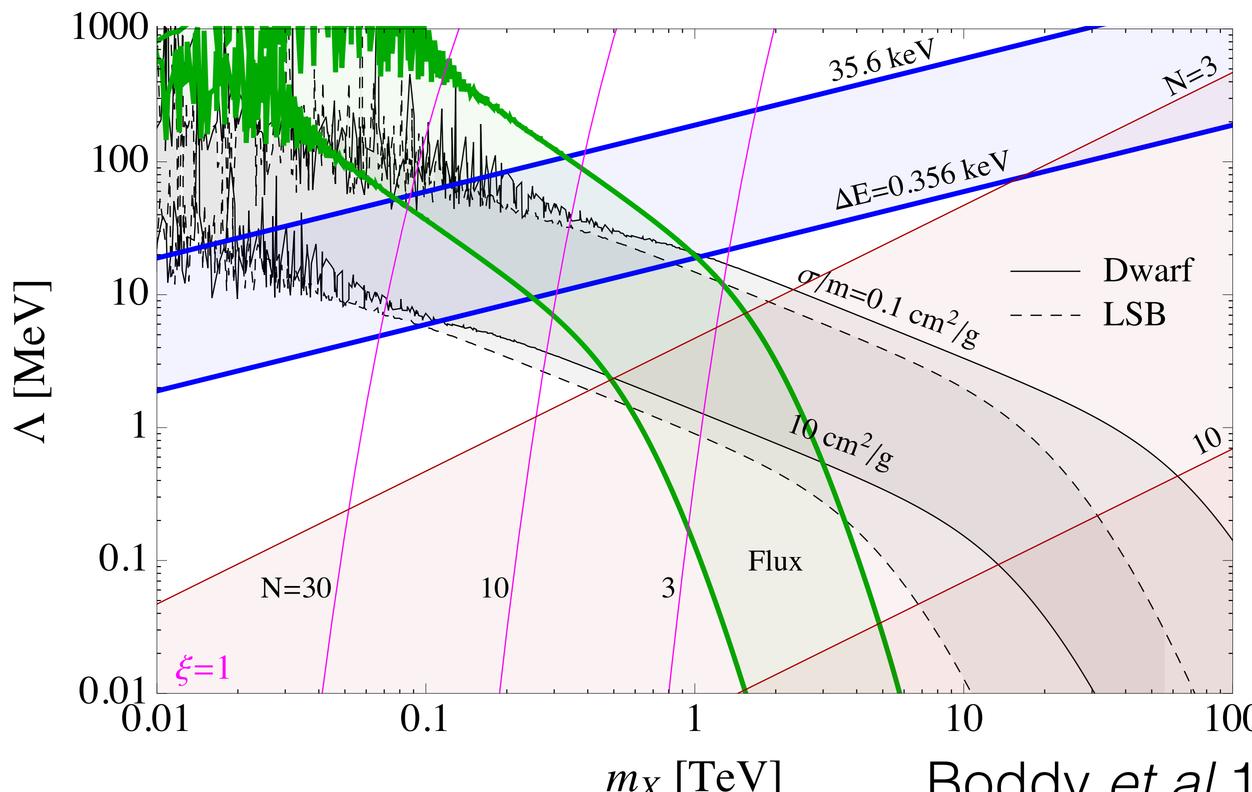


Cline *et al* 1312.3325

Return to Confining DM

- Split DM mass and scale Λ via heavy DM constituents
- "Quirks" with electroweak-mass "quarks" and $\Lambda \lesssim 1\ \mathrm{GeV}$
- Add in supersymmetry, can get heavy gluino (glueballino) dark matter with light glueball mediators.

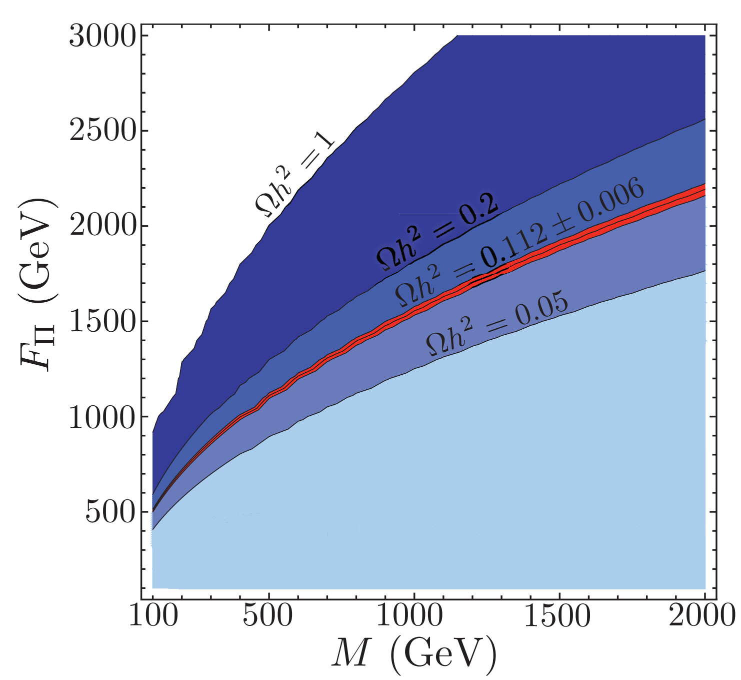
$$m_{\text{glueball}} \sim \Lambda \ll m_{\text{glueballino}} \sim m_{\tilde{g}}$$

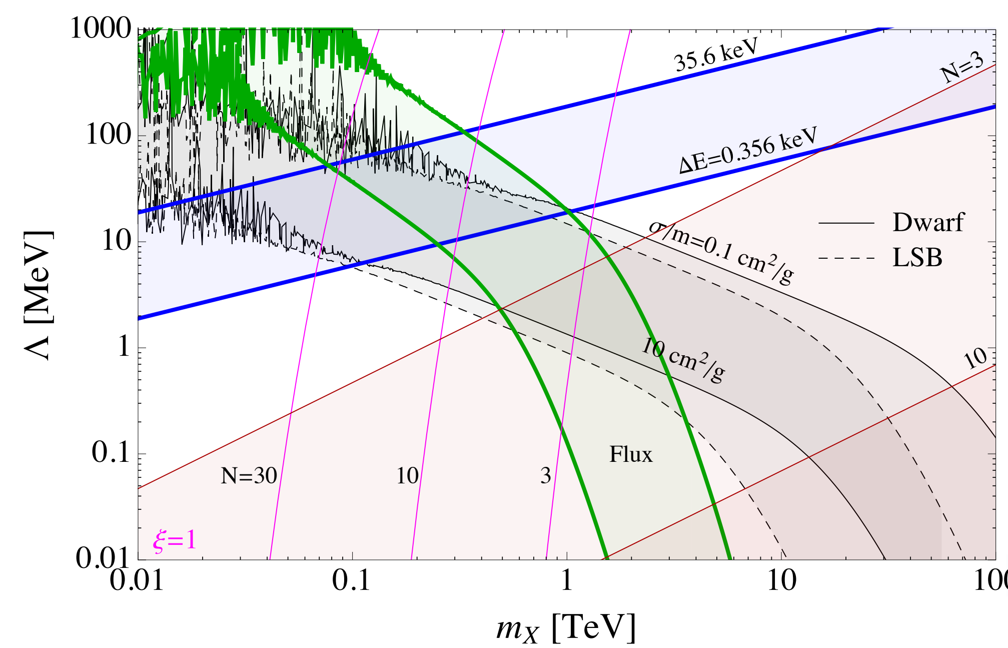


Boddy *et al* 1408.6532

Conclusions

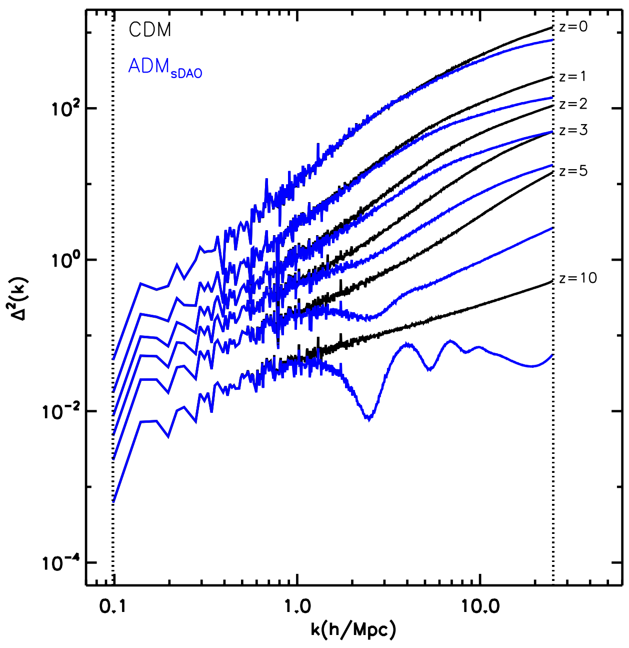
- Adding in confining gauge sectors to dark matter has some attractive theoretical properties.
- Most of the efforts from particle theorists so far involve naïve scaling assumptions, based on QCD
    - Lots of room for improvement,
    - Lots of room for models that differ greatly from Standard Model, or the $m_\chi \sim 20\ \mathrm{TeV}$ assumptions

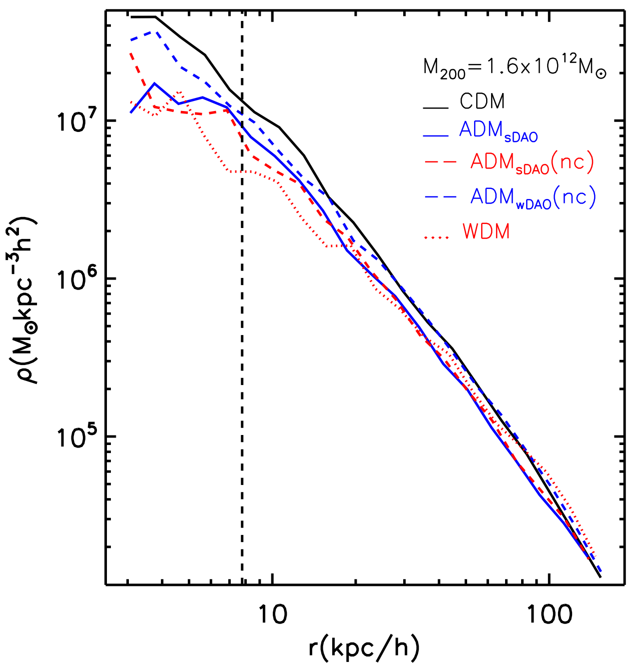




Conclusions II

- Experimental anomalies are a good way to see where you can push your theories.
  - There are a number of anomalies with cold dark matter at small scales.
- Light mediators may resolve these, and give interesting deviations from predications that we will be probing soon.





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