Small-Scale Crisis in Cosmology
Sterile Neutrinos to the Rescue?

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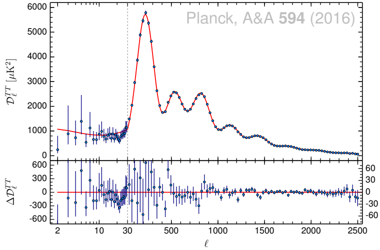
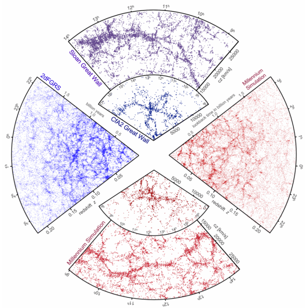
UNIVERSITY OF BERGEN

Outline

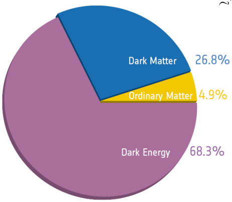
1. Tensions in ΛCDM Cosmology
2. Dark Matter Interacting with Sterile Neutrinos
3. Challenges

ΛCDM Cosmology Works Great

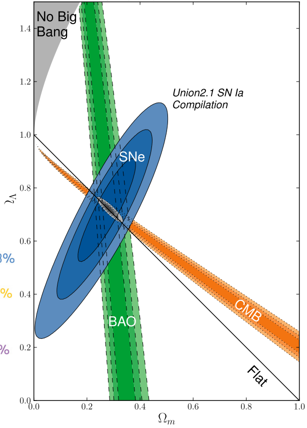




Springel, Frenk, White, Nature **440** (2006)



Supernova Cosmology Project
Suzuki, et al., *Ap.J.* (2011)



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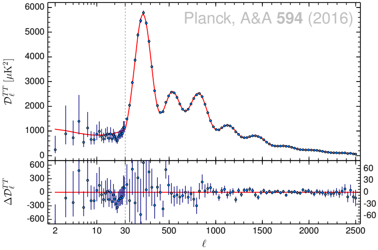

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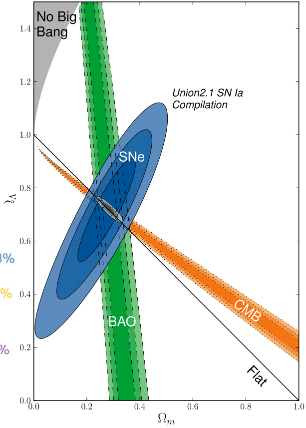

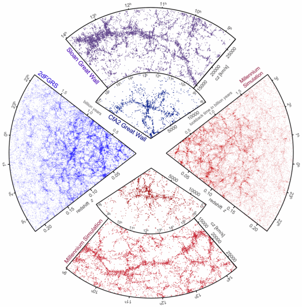

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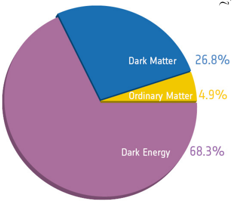
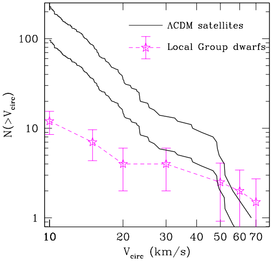


. . . on large scales

Small-Scale Problems of Structure Formation

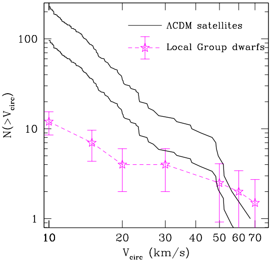
Missing satellites



Kravtsov, Adv. Astron. (2010)
Klypin et al., ApJ **522** (1999)

More galactic satellites predicted than observed

Missing satellites



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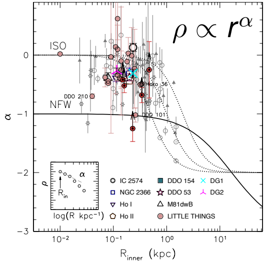
More galactic satellites predicted than observed

Cusp-core



Oh et al., Astron. J. **149** (2015)
De Blok et al., ApJ **552** (2001)

More cuspy density profiles predicted than observed

Small-Scale Problems of Structure Formation

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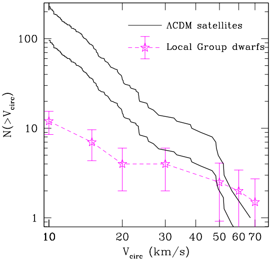

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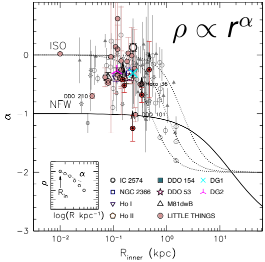

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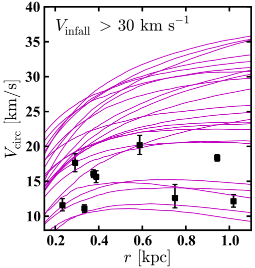
More cuspy density profiles predicted than observed

Too big to fail

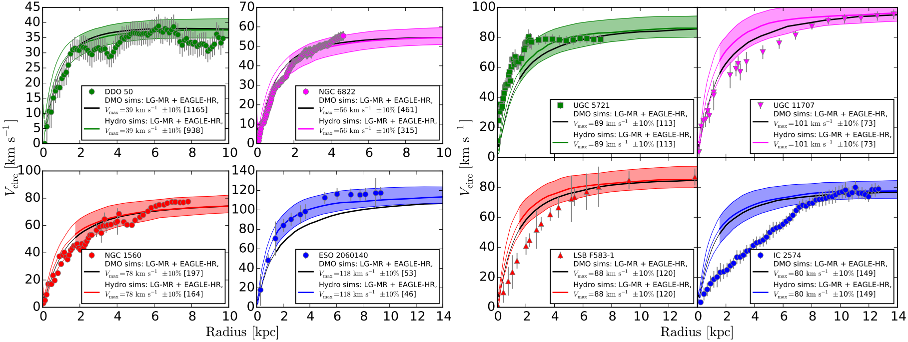


Boylan-Kolchin et al., MNRAS **422** (2011)

Most massive satellites predicted denser than observed

Small-Scale Problems of Structure Formation

Diversity of dwarf rotation curves



Oman et al., MNRAS **452** (2015)

Some observations agree with simulations including baryons

Others don't

Small-Scale Problems of Structure Formation

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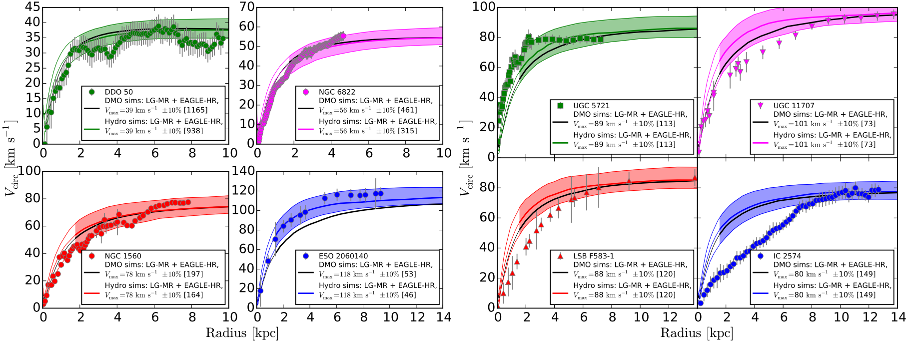


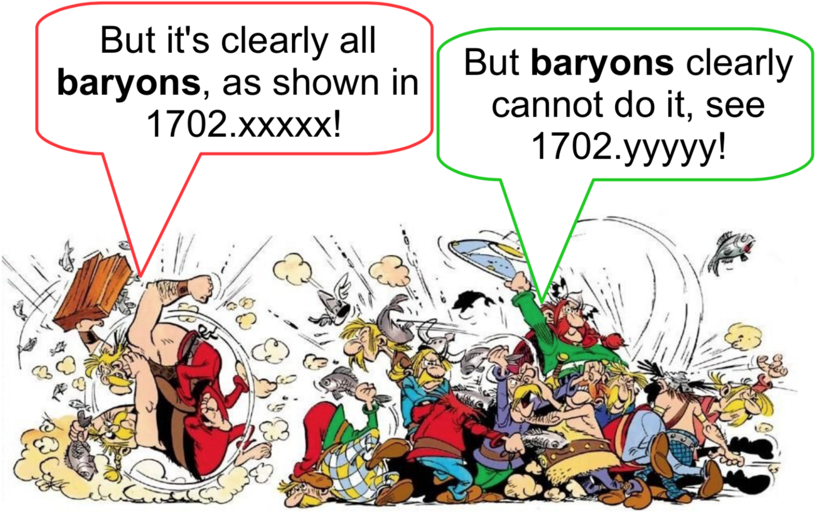
Oman et al., MNRAS **452** (2015)

Some observations agree with simulations including baryons

Others don't

+ a few additional anomalies Bullock & Boylan-Kolchin, Ann. Rev. A&A **55** (2017)

Astrophysics Solutions or New Particle Physics?

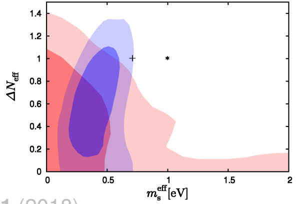


Summary by Kai Schmidt-Hoberg

CMB-Local Tension

- $3\,\sigma$ tension: CMB ($z > 1000$) vs. low-redshift ($z < 10$) observations
- Expansion rate
  - Planck: $H_0 = (67.4 \pm 0.5) \frac{\text{km}}{\text{s Mpc}}$ arXiv:1807.06209
  - Hubble: $H_0 = (73.45 \pm 1.66) \frac{\text{km}}{\text{s Mpc}}$ Riess et al., ApJ **855** (2018)
  - H0LiCOW: $H_0 = (72.5^{+2.1}_{-2.3}) \frac{\text{km}}{\text{s Mpc}}$ Birrer et al., arXiv:1809.01274
- Magnitude of matter density fluctuations (σ_8)
- Resolved by dark radiation (additional relativistic particles)?

Hamann, Hasenkamp, JCAP **10** (2013)
Gariazzo, Giunti, Laveder, JHEP **11** (2013)
Wyman, Rudd, Vanderveld, Hu, PRL **112** (2014)
Battye, Moss, PRL **112** (2014)
Feng, Zhang, Zhang, EPJC **77** (2017)
Nunes, Bonilla, MNRAS **473** (2018)
Pan, Kaplinghat, Knox, PRD **97** (2018)
Choudhury, Choubey, arXiv:1807.10294
Buen-Abad, Schmaltz, Lesgourgues, Brinckmann, JCAP **01** (2018)



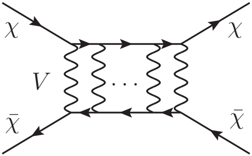
Self-Interacting Dark Matter

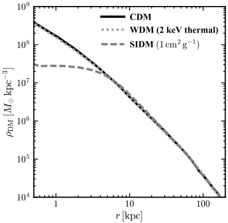
- Dark matter χ interacts with dark sector
- E.g., $U(1)_X$ with light gauge boson V, $m_V \sim$ MeV (dark photon)

⇝ Long-range, velocity-dependent interaction

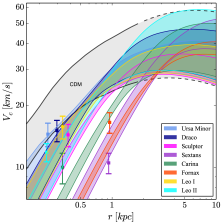
⇝ Cusp-core, too big to fail, and diversity solved

Feng, Kaplinghat, Yu, PRL **104** (2010)
Loeb, Weiner, PRL **106** (2011)
Vogelsberger, Zavala, Loeb, MNRAS **423** (2012)
Valli, Yu, Nature Astronomy (2018)
Kamada, Kaplinghat, Pace, Yu, PRL **119** (2017)





Bullock & Boylan-Kolchin, Ann. Rev. A&A **55** (2017)



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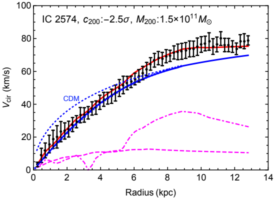
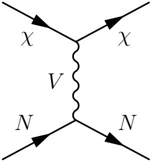


Kamada et al., PRL **119** (2017)

Suppressing Dwarfs by Late Kinetic Decoupling

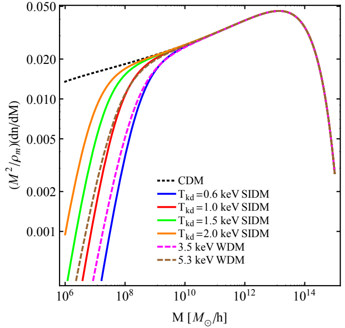
- Additional light particle N (dark radiation) charged under $U(1)_X$
- Efficient Dark matter – dark radiation scattering



⇝ Late kinetic decoupling

⇝ Structure formation suppressed at small scales

Boehm, Fayet, Schaeffer, PLB **518** (2001)
Green, Hofmann, Schwarz, JCAP **08** (2005)
Loeb & Zaldarriaga, PRD **71** (2005)



Huo, Kaplinghat, Pan, Yu, PLB **783** (2018)

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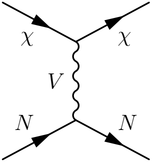

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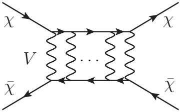
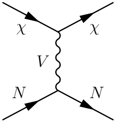
⇝ Minimal galaxy mass Vogelsberger et al., MNRAS **460** (2016)

$$M_{\text{cut}} = 5 \cdot 10^{10} \left(\frac{100\text{ eV}}{T_{\text{kd}}}\right)^3 h^{-1}\, M_\odot$$

⇝ Missing satellite problem solved for $T_{\text{kd}} \lesssim 1$ keV ($M_{\text{cut}} \simeq 10^{10}\, M_\odot$)
Boehm, Fayet, Schaeffer, PLB **518** (2001)
Van den Aarssen, Bringmann, Pfrommer, PRL **109** (2012)

One Model to Solve Them All





- Dark matter χ
- Dark radiation N, $m_N \lesssim$ eV
- Dark photon V couples to both, $m_V \sim$ MeV
- Some ingredients for anomaly cancellation etc.

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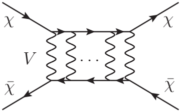

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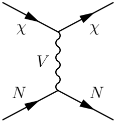

$\rightsquigarrow$ All small-scale problems of structure formation solved

$\rightsquigarrow$ Oscillation anomalies and CMB-local tension solved if $N = \nu_{\text{sterile}}$?

Bringmann, Hasenkamp, JK, JCAP **07** (2014)
Dasgupta, Kopp, PRL **112** (2014)

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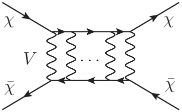

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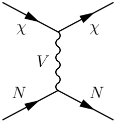

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Dasgupta, Kopp, PRL **112** (2014)

- Related models (different particle spins, more sterile neutrinos, . . .)

  Ko, Tang, PLB **739** (2014), PLB **768** (2017)
  Archidiacono, Hannestad, Hansen, Tram, PRD **91** (2015)
  Chu, Dasgupta, PRL **113** (2014)
  Cherry, Friedland, Shoemaker, `arXiv:1411.1071`
  Kouvaris, Shoemaker, Tuominen, PRD **91** (2015)
  Binder et al., JCAP **11** (2016)
  Tang, PLB **757** (2016)

- Classification of minimal possibilities

  Bringmann, Ihle, JK, Walia, PRD **94** (2016)

Dark Matter Production

- High temperatures: $U(1)_X$ sector thermalized via Higgs portal

$$\mathcal{L}_{\text{Higgs}} \supset \kappa |H|^2 |\Theta|^2$$

- $\langle \Theta \rangle \sim$ MeV breaks $U(1)_X$

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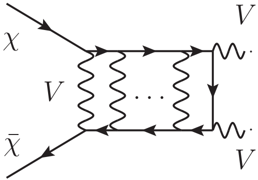
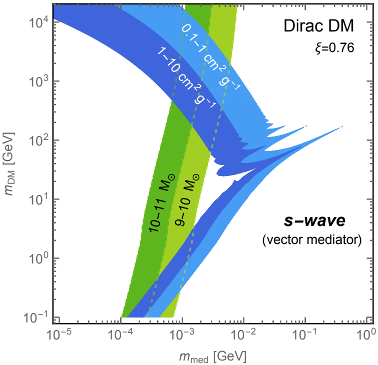
- $\langle \Theta \rangle \sim$ MeV breaks $U(1)_X$
- $T_\chi \sim m_\chi/25$: freeze-out (chemical decoupling) of dark matter

$$\Omega_{\text{CDM}} h^2 \sim 0.11 \left(\frac{0.67}{g_X}\right)^4 \left(\frac{m_\chi}{\text{TeV}}\right)^2$$

(neglecting bound state formation)



Cold Dark Matter Parameter Space



Bringmann (today)

- Calculated by `DarkSUSY 6.1`
  Bringmann Edsjö, Gondolo, Ullio, Bergström, JCAP **07** (2018)
- DM mass $\sim$ TeV or $\lesssim$ GeV
- Light DM region favored by cluster observations?
  Huo, Kaplinghat, Pan, Yu, PLB **783** (2018)

Big Bang Nucleosynthesis

- $T\downarrow \rightsquigarrow$ Higgs portal no longer effective
  $\rightsquigarrow U(1)_X$ sector decouples at T_x^{dpl} (depending on κ)
- SM particles becoming non-relativistic afterwards heat SM bath, not $U(1)_X$ bath $\rightsquigarrow T_N < T_\nu$ (depending on number of d.o.f. g_*)

$$\Delta N_{\text{eff}}\big|_{\text{BBN}} \simeq \left(\frac{46}{g_{*,\nu}(T_x^{\text{dpl}})}\right)^{\frac{4}{3}} \gtrsim 0.33$$

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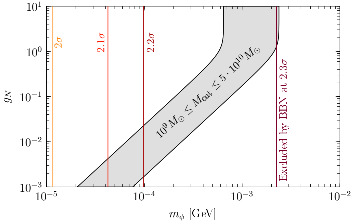
$\rightsquigarrow$ Correct order of magnitude for CMB-local tension
$\rightsquigarrow$ Tension with BBN bounds

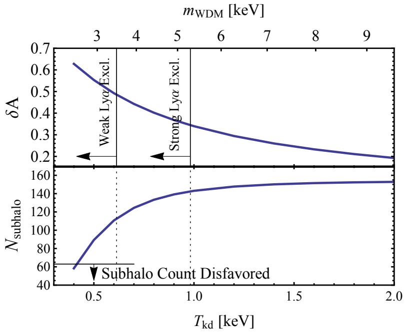


Hufnagel, Schmidt-Hoberg, Wild, JCAP **02** (2018)

Lyman-α Forest

- Constrains suppression of matter power spectrum by late KD
- Analogous to bounds on warm DM

⇝ Number of satellites reduced by only 30%



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- Systematic effects? Recasting of warm DM bounds ok?

Sterile Neutrino Production by Oscillations

- Standard scenario: mixing between active and sterile neutrinos $\rightsquigarrow$ oscillations $\rightsquigarrow$ $\Delta N_{\text{eff}} \simeq 1$ $\rightsquigarrow$ ruled out by Planck and BBN
- $U(1)_X$ interactions $\rightsquigarrow$ effective matter potential suppresses mixing $\rightsquigarrow$ no production by oscillations for $T \gtrsim$ MeV

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- $T <$ MeV: mixing unsuppressed

  $\rightsquigarrow$ sterile neutrinos from oscillations + $U(1)_X$-mediated scatterings

  Bringmann, Hasenkamp, JK, JCAP **07** (2014)
  Mirizzi, Mangano, Pisanti, Saviano, PRD **91** (2015)
  Tang, PLB **750** (2015)
  Chu, Dasgupta, Kopp, JCAP **10** (2015)
  Cherry, Friedland, Shoemaker, `arXiv:1605.06506`
  Forastieri et al., JCAP **07** (2017)
  Chu, Dasgupta, Dentler, Kopp, Saviano, `arXiv:1806.10629`

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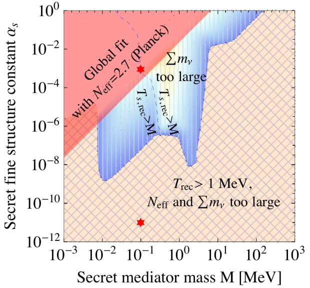
  - $\rightsquigarrow$ $\sum m_\nu$ bound violated or too little free-streaming
  - $\rightsquigarrow$ Ruled out for $m_N \sim$ eV and $\mathcal{O}(0.1)$ mixing



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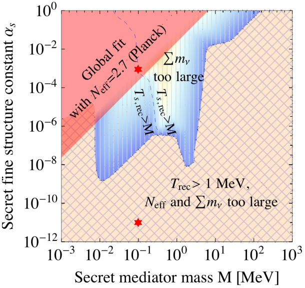
  - $\rightsquigarrow$ Ruled out for $m_N \sim$ eV and $\mathcal{O}(0.1)$ mixing
  - $\rightsquigarrow$ More complicated dark sector?

    Chu et al., arXiv:1806.10629



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Conclusions

Particle physics solution for tensions in ΛCDM cosmology

- Dark matter with mass $\sim$ TeV or $\lesssim$ GeV
- Dark radiation with mass $\lesssim$ eV
- Dark photon with mass $\sim$ MeV $\rightsquigarrow$ secret interactions

$\rightsquigarrow$ Late kinetic decoupling solves missing satellites problem

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- Dark radiation probably not able to address oscillation anomalies
- Data from astrophysics and cosmology probe DM properties

Dark Radiation

- Dark radiation: relativistic particles $\neq \gamma, \nu^{\text{SM}}$
- Parameterized via radiation energy density

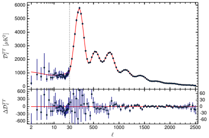
$$\rho_{\text{rad}} \equiv \left[1 + N_{\text{eff}} \frac{7}{8} \left(\frac{T_\nu}{T}\right)^4\right] \rho_\gamma$$

- $T \equiv T_\gamma$
- N_{eff}: effective number of neutrino species
- Standard Model: $N_{\text{eff}} = 3.046$
- Existence of dark radiation $\Leftrightarrow$ $\Delta N_{\text{eff}} \equiv N_{\text{eff}} - 3.046 > 0$
- Measurements of Cosmic Microwave Background (CMB):

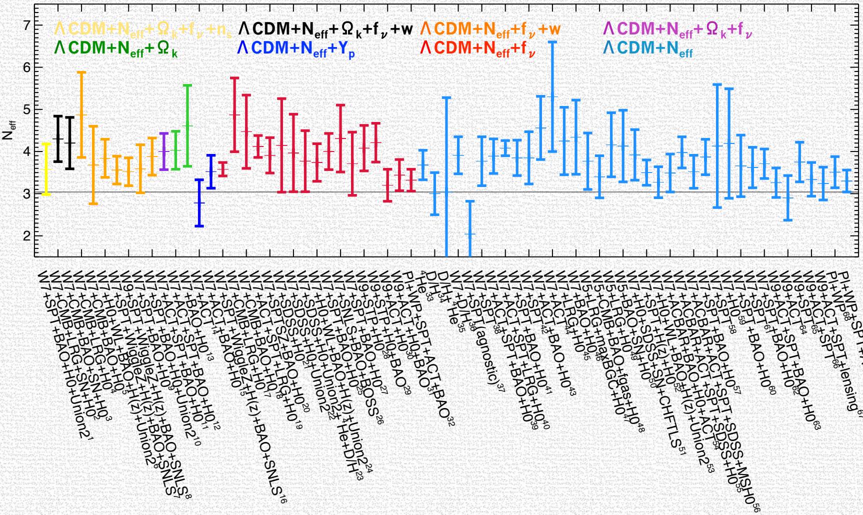
$\Delta N_{\text{eff}} = 1.51 \pm 0.75$ ACT, ApJ **739** (2011)

$\Delta N_{\text{eff}} = 0.81 \pm 0.42$ SPT, ApJ **743** (2011)

$\Delta N_{\text{eff}} = 0.10 \pm 0.23$ Planck, A&A **594** (2016)



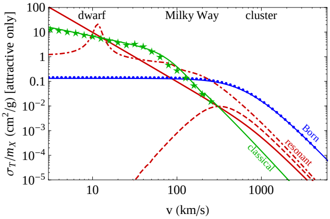
Measurements



Modified from Riemer-Sørensen et al. (2013 review) arXiv:1301.7102

Velocity-Dependent Self-Interactions

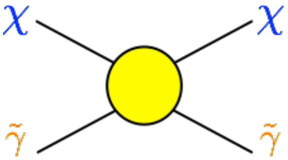
- Described by Yukawa potential $V(r) = \pm \frac{\alpha_X}{r} e^{-m_V r}$
- Desired scattering cross section σ_T:
  - Large in dwarf galaxies
  - Small on larger scales to satisfy experimental limits
- Very different behavior depending on model parameters



Tulin, Yu, Zurek, PRL **110**, PRD **87** (2013)

Here: classical regime $\rightsquigarrow$ analytical approximations exist

Particle Physics Models with Late Kinetic Decoupling

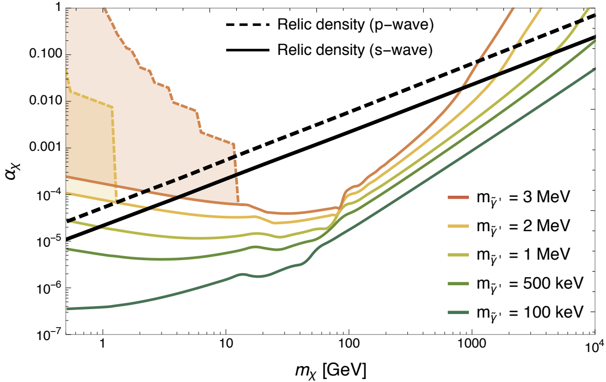


- Need scattering partner $\tilde{\gamma}$ with large abundance until $T_{\rm kd} \lesssim 1$ keV
  $\rightsquigarrow$ photon, (SM) neutrino, dark radiation
- Here: classification of all minimal possibilities
  Bringmann, Ihle, JK, Walia, PRD **94** (2016)
- Scattering amplitude close to kinetic decoupling:

$$|\mathcal{M}|^2 \simeq c_n \left(E_{\tilde{\gamma}}/m_\chi\right)^n$$

- $M_{\rm cut} \simeq 10^{10}\, M_\odot$ needs large coefficients c_n and/or light dark matter

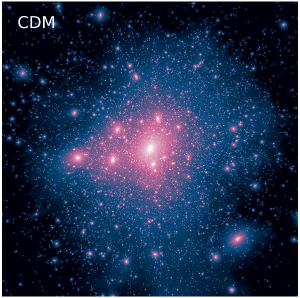
Desired Self-Interactions with t-Channel Mediator

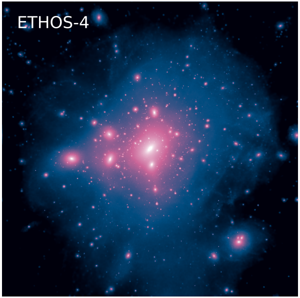


$\rightsquigarrow$ Both $m_\chi \sim$ GeV and $m_\chi \sim$ TeV work

Simulating Self-Interacting Dark Matter

N-body simulation of structure formation with DM-DM and DM-*N* interactions

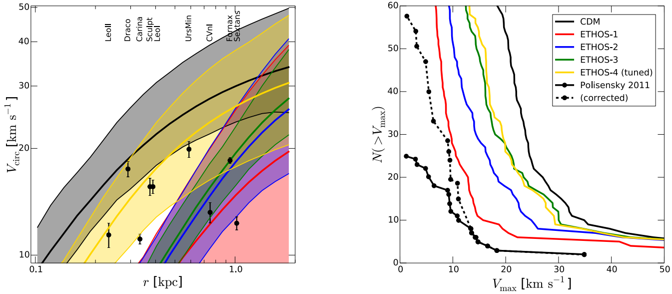




Vogelsberger et al., MNRAS **460** (2016)

Simulating Self-Interacting Dark Matter

N-body simulation of structure formation with DM-DM and DM-*N* interactions



Vogelsberger et al., MNRAS **460** (2016)

- Confirms solution (alleviation) of too big to fail, missing satellites
- Cusp-core and rotation curve diversity unclear

Timeline

t

- $\gtrsim m_\chi \sim$ TeV: thermalization of $U(1)_X$ sector via Higgs portal
- $T_\chi^{\rm fo} \sim m_\chi/25$: CDM freeze-out
- $T_x^{\rm dpl} \gtrsim 10$ GeV: $U(1)_X$ sector decoupling
- SM particles heat SM bath
- matter effects prevent N_1 overproduction
- BBN — $T_\nu^{\rm dpl} \sim$ MeV: active neutrino decoupling
- $U(1)_X$ particles heat N_1
- $T_\chi^{\rm kd} \sim 100$ eV: CDM kinetic decoupling
- $T_{N_1}^{\rm kd}$: N_1 kinetic decoupling from itself
- CMB — $T_{\rm eq} \sim 1$ eV: matter-radiation equality
- $T_\gamma^{\rm dpl} \sim 0.2$ eV: photon decoupling; N_1 becomes non-relativistic
- CDM-CDM scattering via Yukawa potential
- $T_0 \sim 0.2$ meV: today

T