Self-interacting dark matter

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in collaboration with

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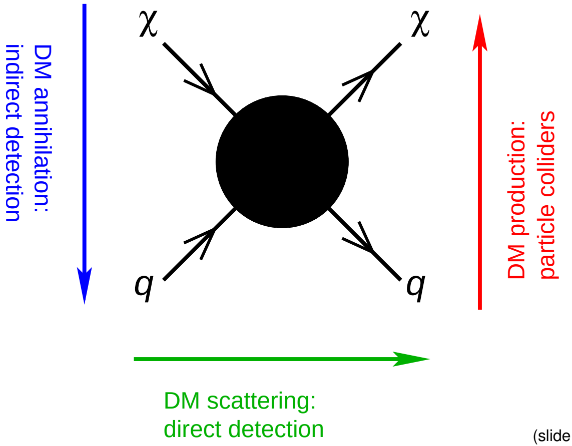
Searching for dark matter (DM)

correct relic density → DM annihilation in the Early Universe



(slide concept Feng)

Outline

1. Standard WIMPS
   - Chemical decoupling
   - Kinetic decoupling
   - Smallest protohalos
2. Self-interacting WIMPS
   - Sommerfeld effect
   - Small-scale problems
   - A solution to *all* ΛCDM problems
3. Cosmological simulations

Outline

The WIMP “miracle”

- “freeze-out”: annihilation rate drops below expansion rate H
  $\rightarrow$ number density of Weakly Interacting Massive Particles:

$$\frac{\mathrm{d}n_\chi}{\mathrm{d}t} + 3Hn_\chi = -\langle\sigma v\rangle \left(n_\chi^2 - n_{\chi,\mathrm{eq}}^2\right), \quad \langle\sigma v\rangle : \chi\chi \rightarrow \text{ SM SM}$$

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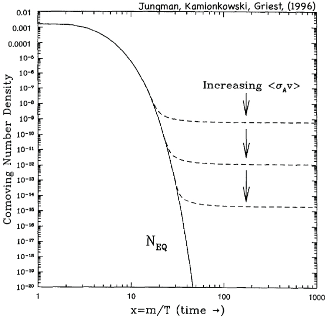

- assuming a particle χ, initially in thermal equilibrium, with a relic density

$$\Omega_\chi \sim \frac{1}{m_{\mathrm{Pl}}\, T_0\, \langle\sigma v\rangle} \sim \frac{m_\chi^2}{m_{\mathrm{Pl}}\, T_0\, g_\chi^4},$$

$$\left.\begin{array}{l} m_\chi \sim m_{\mathrm{weak}} \sim 100\ \mathrm{GeV} \\ g_\chi \sim g_{\mathrm{weak}} \sim 0.6 \end{array}\right\} \Omega_\chi \sim 0.1$$

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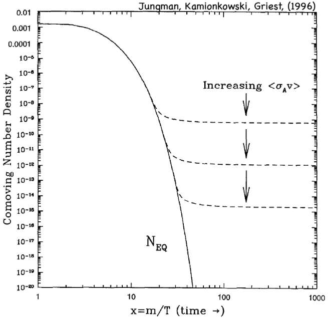

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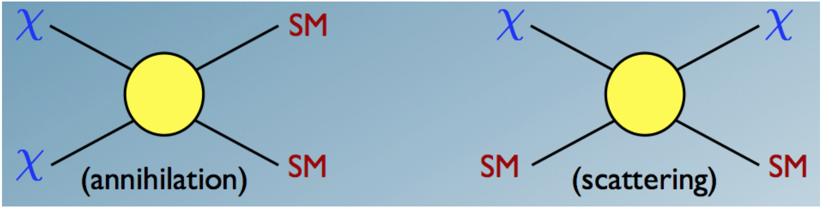
- remarkable coincidence: particle physics independently predicts particles with the right density to be dark matter

Freeze-out $\neq$ decoupling!

- WIMP interactions with heat bath of SM particles:



- Boltzmann suppression of n_χ:
  - scattering process more frequent
  - continue even after chemical decoupling ("freeze-out") at $T_{\rm cd} \sim m_\chi/25$
- kinetic decoupling much later: $\tau(T_{\rm kd}) \equiv N_{\rm coll}/\Gamma_{\rm el} \sim H^{-1}(T_{\rm kd})$
  random walk in momentum space: $N_{\rm coll} \sim m_\chi/T$ (Schmid+ 1999, Green+ 2005)

Kinetic decoupling

- evolution of phase space density f_χ given by the full Boltzmann equation in FRW space time:

$$E\left(\partial_t - H\boldsymbol{p}\cdot\nabla_{\boldsymbol{p}}\right) f_\chi = C\left[f_\chi\right]$$

- 1^{st} moment ($\int \mathrm{d}^3 p$) recovers the familiar continuity equation:

$$\frac{\mathrm{d}n_\chi}{\mathrm{d}t} + 3Hn_\chi = -\left\langle\sigma\upsilon\right\rangle\left(n_\chi^2 - n_{\chi,\mathrm{eq}}^2\right)$$

- consider the 2^{nd} moment ($\int \mathrm{d}^3 p\, \boldsymbol{p}^2$) and introduce

$$T_\chi n_\chi \equiv \int \frac{\mathrm{d}^3 p}{(2\pi)^3}\frac{\boldsymbol{p}^2}{3m_\chi} f_\chi(\boldsymbol{p})$$

$\rightarrow$ analytic treatment possible without assumptions about $f_\chi(\boldsymbol{p})$

Bertschinger (2006), Bringmann & Hofmann (2007), Bringmann (2009)

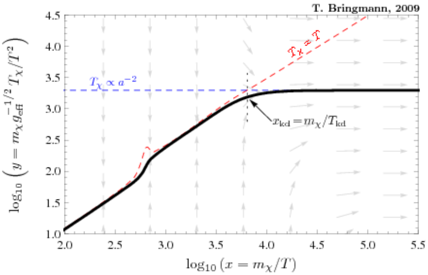
Thermal history of WIMPs

- resulting ODE for T_χ

$$\frac{dy}{dx} = 2\frac{m_\chi c(T)}{H\tilde{g}^{-1/2}}\left(1 - \frac{T_\chi}{T}\right)$$

example:

$m_\chi = 100$ GeV
$|\mathcal{M}|^2 \sim g_Y^4 (E_\chi/m_\chi)^2$



- fast transition allows definition of $T_{\rm kd}$:

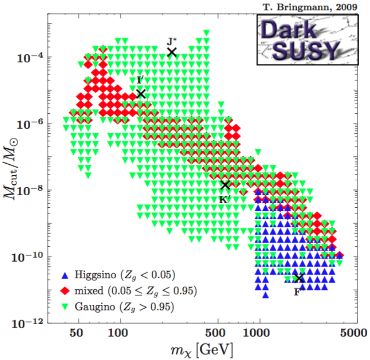
$$T_\chi = \begin{cases} T & \text{for } T \gtrsim T_{\rm kd}, \\ T_{\rm kd}(a_{\rm kd}/a)^2 & \text{for } T \lesssim T_{\rm kd} \end{cases}$$

Bringmann & Hofmann (2007), Bringmann (2009)

The smallest protohalos

- free streaming of WIMPS after $t_{\rm kd}$ at the thermal speed of decoupling erases small-scale fluctuations (Green+ 2005)
- initial coupling between WIMPS and the radiation field $\rightarrow$ acoustic oscillations in the power-spectrum at the horizon scale of kinematic decoupling

(Loeb & Zaldarriaga 2005, Bertschinger 2006)



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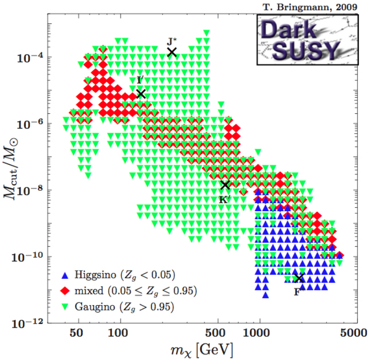


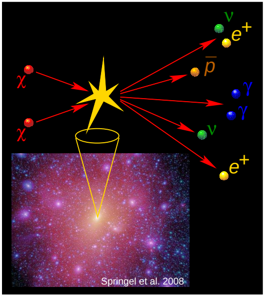
- cutoff in the power spectrum corresponds to smallest gravitationally bound objects in the universe
- strong dependence on particle physics properties, no "typical" value of $M_{\mathrm{cut}} \sim 10^{-6}\,\mathrm{M}_\odot$ (Profumo+ 2006)

Consequences

- indirect detection experiments through WIMP annihilation:

$$\Phi_{\mathrm{SM}} \propto \langle \rho_\chi^2 \rangle = (1 + \mathrm{BF}) \langle \rho_\chi \rangle^2,$$
$$\mathrm{BF} \propto \log(M_{\mathrm{halo}} / M_{\mathrm{min}})$$

(Pinzke+ 2011, Gao+ 2012, Ludlow+ 2014)



- flux depends on astrophysics, particle physics, detector properties:

$$N_\gamma = \left[\int_{\mathrm{LOS}} \rho_\chi^2 \, \mathrm{d}l_\chi \right] \frac{\langle \sigma v \rangle}{2 M_\chi^2} \left[\int_{E_{\mathrm{th}}}^{M_\chi} \left(\frac{\mathrm{d}N_\gamma}{\mathrm{d}E} \right)_{\mathrm{SUSY}} A_{\mathrm{eff}}(E) \, \mathrm{d}E \right] \frac{\Delta\Omega}{4\pi} \tau_{\mathrm{exp}}$$

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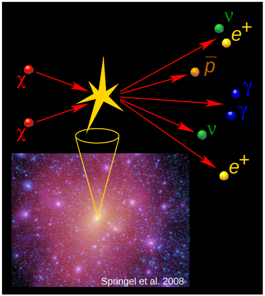

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- fluctuations in the event rate of direct detection experiments
- gravitational lensing of substructures $\rightarrow$ flux anomalies
- Lyman-α forest ...

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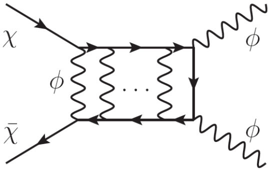
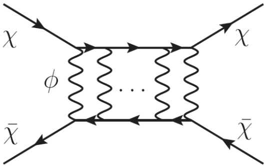
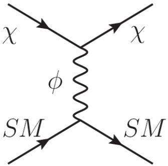
WIMPS with long-range forces



annihilation

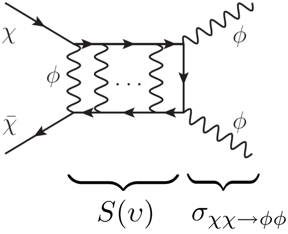


self-scattering



scattering

Sommerfeld effect



Arkani-Hamed+ (2009)

- kinematics: non-relativistic DM particle χ interacts with light force carrier ϕ ($m_\phi \ll m_\chi$)
- repeated exchange of ϕ: each "rung" of ladder contributes at $\mathcal{O}(\alpha/v)$ $\rightarrow$ resummation necessary
- long range interaction: potential distorts wave function
- short-range interaction: standard QFT result

$$\left(-\frac{\nabla^2}{m_\chi} + V\right)\psi(r) = m_\chi v^2 \psi(r)$$

$$\sigma_{\chi\chi\to\phi\phi}$$

$$\Rightarrow \sigma = S(v)\sigma_{\chi\chi\to\phi\phi}, \quad \text{with } S(v) = |\psi(0)|^2$$

HITS

Enhancement factor

- Coulomb potential: analytic solution

$$S(v) = \frac{\pi\alpha/v}{1 - \exp(-\pi\alpha/v)} \quad \xrightarrow{v\to 0} \quad \frac{\pi\alpha}{v}$$

- Yukawa potential: numerical solution
  $\rightarrow$ appearance of resonances near bound states

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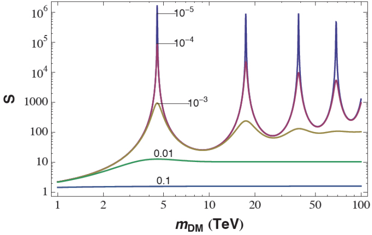

Lattanzi, Silk (2009)

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  - off resonance: $S \propto v^{-1}$
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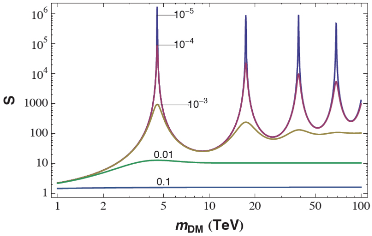
- for $m_\phi \lesssim 100$ MeV, ϕ can only decay into leptons (e, μ)

  $\rightarrow$ leptophilic DM



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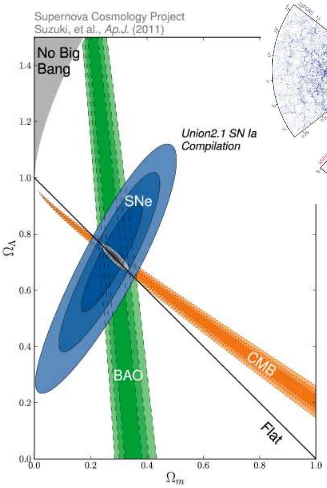
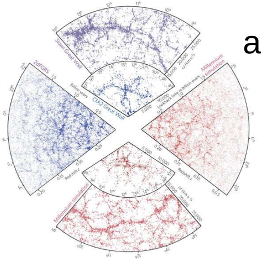
ΛCDM cosmology

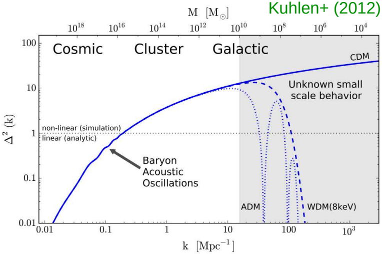




Springel+ (2006)

a great success story on large scales

Kuhlen+ (2012)



ΛCDM small-scale problems

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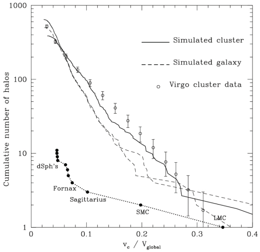

Moore+ (1999)

→ many more satellites in simulations of MW-sized galaxies than observed

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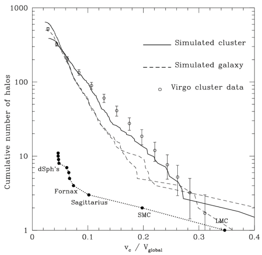

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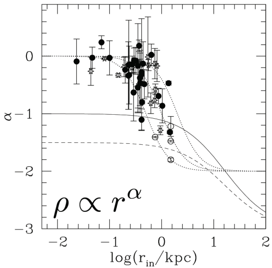

Blok+ (2001)

→ cuspy inner density profiles predicted by simulations not found in observations

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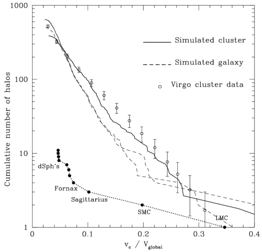

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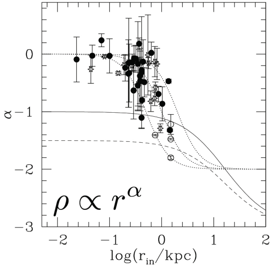

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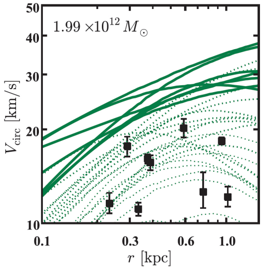
3. Too big to fail?

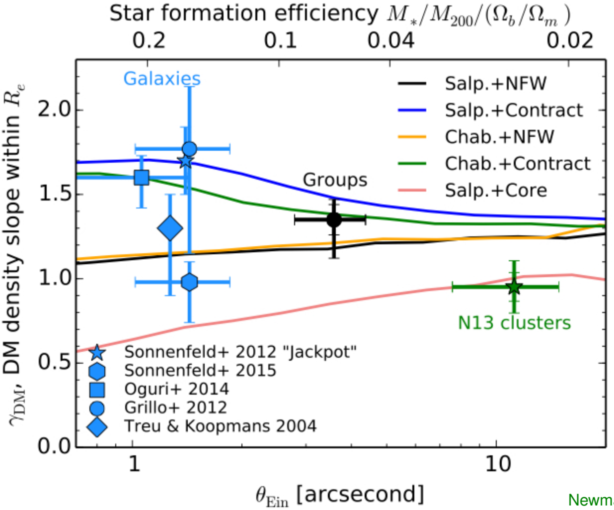


Boylan-Kolchin+ (2011)

→ most massive sub-halos in simulations too dense to host observed brightest dwarf satellites

HITS

Inner DM profile in galaxy groups and clusters



Newman+ (2015)

Solutions?

many possibilities, no consensus reached yet:

- astrophysical solutions:
  increased gas entropy, suppress cooling efficiency, SN feedback, large velocity anisotropy, other baryonic feedback, increased stochasticity of galaxy formation, small MW mass,. . .
- dark matter solutions:
  warm DM, interacting DM, DM from late decays, large annihilation rates, condensates, . . .
- all have shortcomings and/or solve at most 2 problems at the time!

Solutions?

velocity-dependent self-interacting dark matter:

- scattering cross-section for Yukawa potential Khrapak+ (2003)
  $\sigma_{\chi\bar{\chi}} =$ const. unnatural from particle physics viewpoint!
- elastic DM self-scattering is completely analogous to screened Coulomb scattering in a plasma

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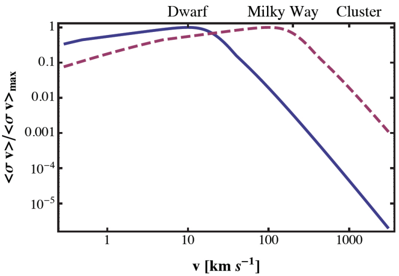
- elastic DM self-scattering is completely analogous to screened Coulomb scattering in a plasma
- cored profiles possible without violating astrophysical constraints
  Feng+ (2010), Loeb & Weiner (2011)
- N-body simulations: "too big to fail" problem avoided
  Vogelsberger+ (2012)
- what about missing satellites?



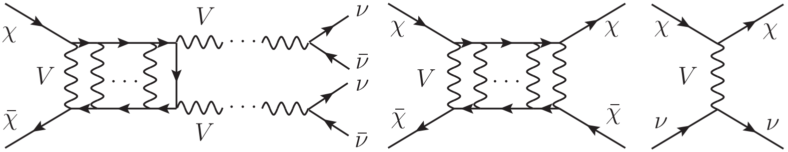
Loeb & Weiner (2011)

Our model

van den Aarssen, Bringmann, C.P. (2012)

- assume light vector mediator coupling to dark matter and neutrinos:

$$\mathcal{L}_{\rm int} \supset -g_\chi \bar\chi \not{V} \chi - g_\nu \bar\nu \not{V} \nu$$



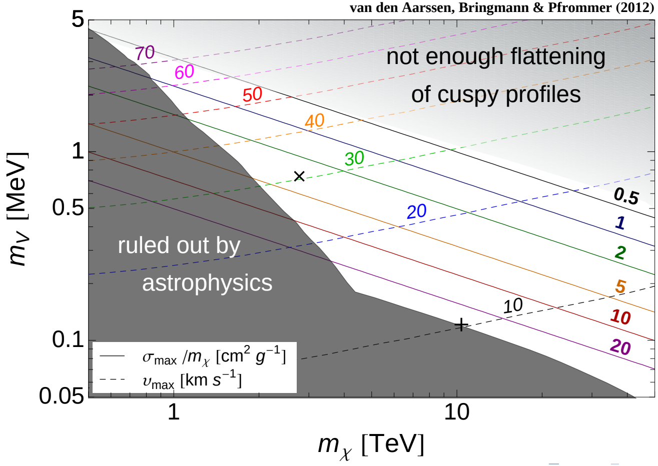
annihilation
→ relic density
→ indirect 4ν detection signal from galactic center(?)

self-scattering
→ changes inner density and velocity profiles of dwarf galaxies

scattering
→ large $M_{\rm min}$

"Cusp vs. core" and "too big to fail" problems

- demand correct relic density
  → unique relation between $(\upsilon_{\max}, \sigma_{\max})$ and (m_χ, m_V)



DM scattering off standard model particles

- free-streaming of WIMPs after kinetic decoupling creates cutoff in power spectrum
- acoustic oscillations leads to similar cutoff
- cutoff scale is set by size of horizon at KD: late KD $\rightarrow$ high $M_{\rm min}$
- $M_{\rm min} = \max(M_{\rm fs}, M_{\rm ao})$: only objects with $M \geq M_{\rm min}$ form

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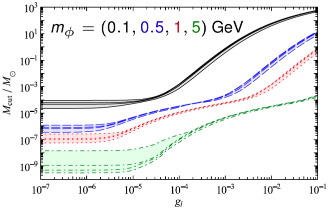
- scalar mediator:
  - scatters off ϕ, $\mu^{\pm}$, $e^{\pm}$
  - saturation at $M_{\mathrm{min}} \sim 10^3\,\mathrm{M}_{\odot}$
  - ν's negligible: $|\mathcal{M}_{\phi l \to \phi l}|^2 \propto m_l^2$
- vector mediator:
  - ν's contribute: $|\mathcal{M}_{V\nu \to V\nu}|^2 \propto E_\nu^2$
  - M_{min} increases to $\mathcal{O}(10^{11}\mathrm{M}_{\odot})$

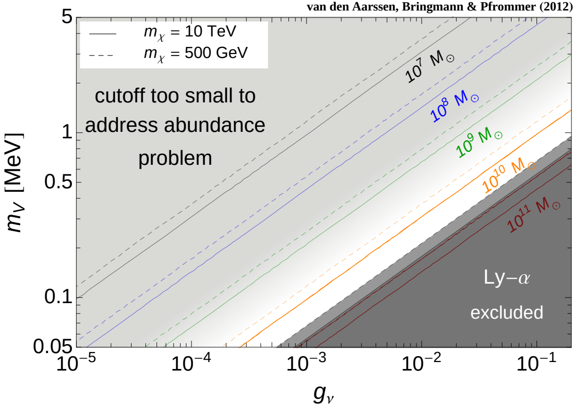


van den Aarssen+ (2012)

HITS

"Missing satellites" problem

- now compute $M_{\rm min}$ from kinetic decoupling temperature ...



- in this simple phenomenological model, it is possible to simultaneously solve all small-scale problems of ΛCDM!

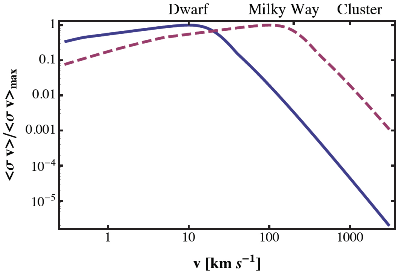
Cored central density profiles of clusters

- velocity-dependent DM self-scattering cores out central density slopes in clusters with rate

$$\Gamma \sim \frac{\rho}{m_\chi} \langle \sigma_{\chi\bar{\chi}} v \rangle \sim H$$

- ellipticals/clusters, $f_s = 10 - 100$:

$$\Gamma \sim \frac{f_s \rho}{m_\chi} \frac{\langle \sigma_{\chi\bar{\chi}} v \rangle|_{\max}}{f_s}$$



Loeb & Weiner (2011)

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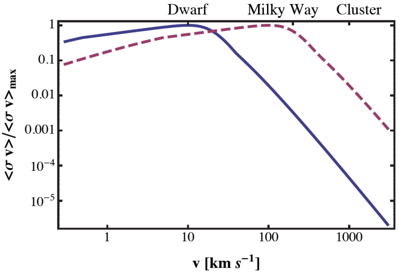

Loeb & Weiner (2011)

- using $\rho \sim 1/r$ for $r \ll r_s$:

$$\left.\frac{r_\mathrm{core}}{r_{200}}\right|_\mathrm{cluster} \sim \frac{1}{f_s} \left.\frac{r_\mathrm{core}}{r_{200}}\right|_\mathrm{dwarf} \sim \frac{1}{f_s 10} \quad \Rightarrow \quad r_\mathrm{core}(10^{15} \mathrm{M}_\odot) \sim \mathcal{O}(1-10\,\mathrm{kpc})$$

- need simulations to understand interplay of hierarchical evolution and determination of cluster-r_core: merging history → scatter

Conclusions on small-scale problems of ΛCDM

small-scale problems of ΛCDM can be solved by a DM model with:

- velocity-dependent self-interactions mediated by (sub-)MeV vector:
  → transforms cusps to cores and solves "too big to fail" problem
- much later kinetic decoupling than in standard case follows naturally for vector mediator coupling to neutrinos:
  → potentially solves "missing satellites" problem
- predicts cores in clusters on scales $\mathcal{O}(1-10\text{ kpc})$

→ need further model building and simulations to confirm

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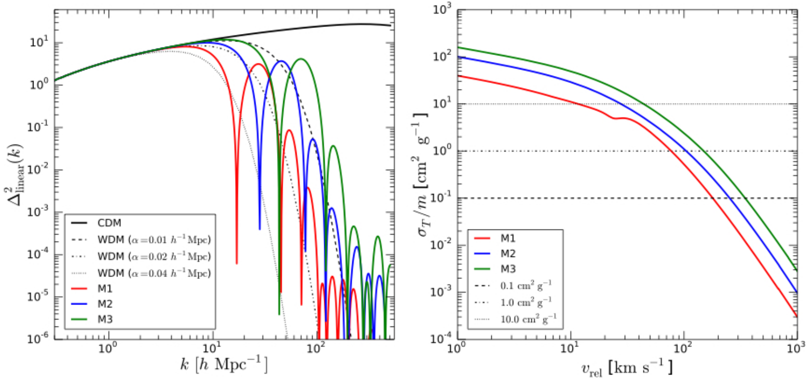
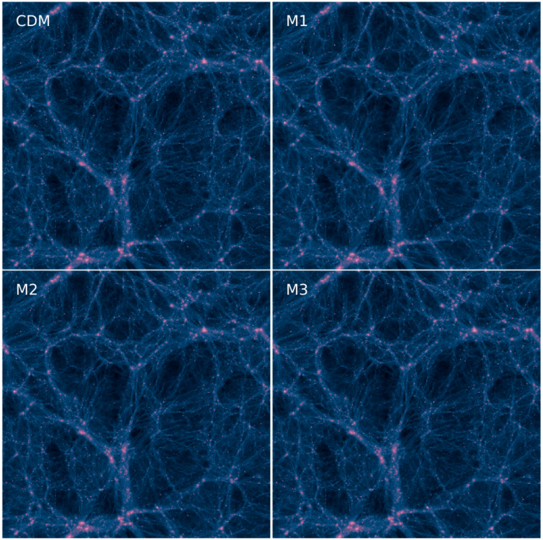
3. Cosmological simulations

SIDM simulations: models



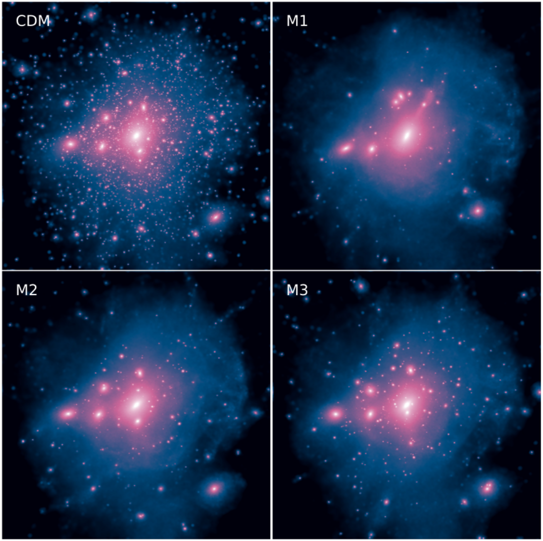
Vogelsberger, Zavala, Cyr-Racine, Pfrommer, Bringmann, Sigurdson, in prep.

SIDM simulations: large-scale structure



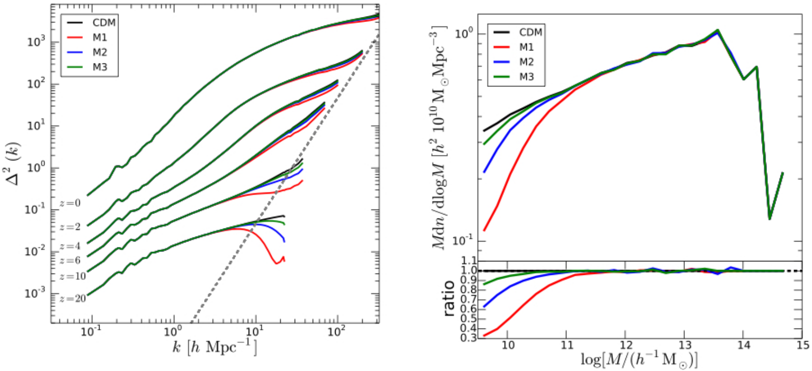
Vogelsberger, Zavala, Cyr-Racine, Pfrommer, Bringmann, Sigurdson, in prep.

SIDM simulations: Milky Way-sized halos



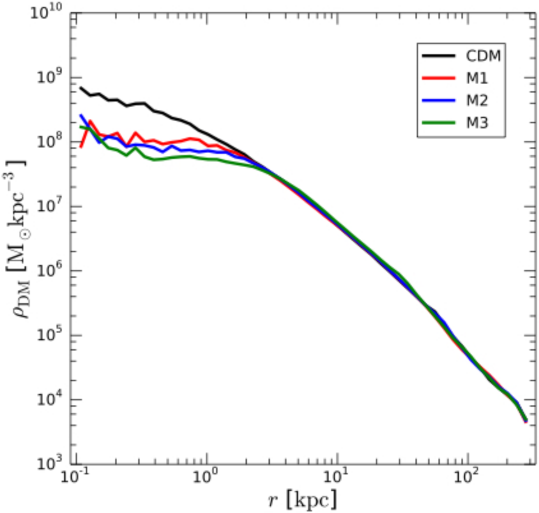
Vogelsberger, Zavala, Cyr-Racine, Pfrommer, Bringmann, Sigurdson, in prep.

SIDM simulations: power spectrum and mass function



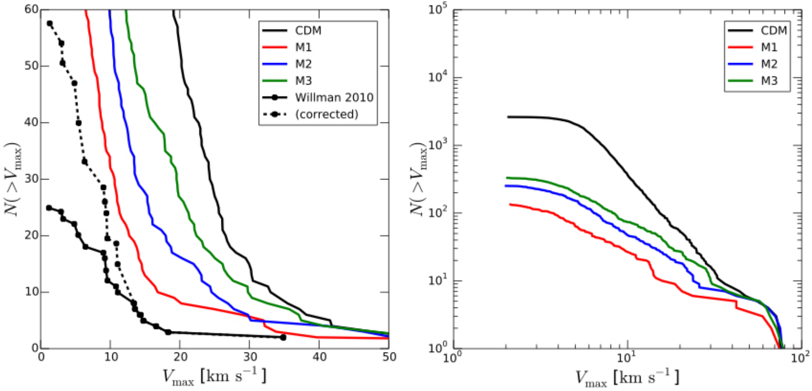
Vogelsberger, Zavala, Cyr-Racine, Pfrommer, Bringmann, Sigurdson, in prep.

SIDM simulations: density profile of MW-sized halo



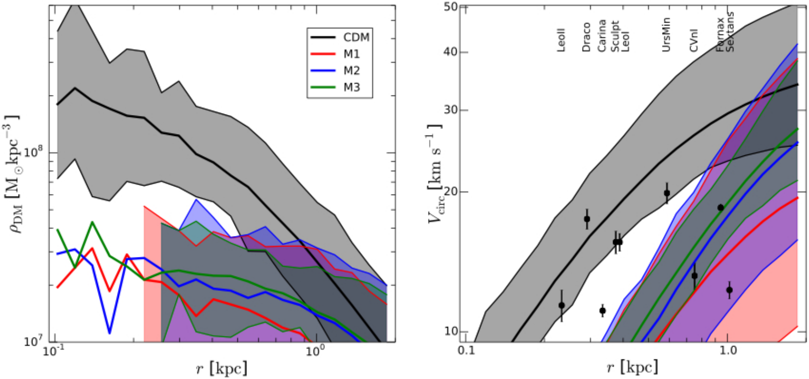
Vogelsberger, Zavala, Cyr-Racine, Pfrommer, Bringmann, Sigurdson, in prep.

SIDM simulations: subhalo abundances



Vogelsberger, Zavala, Cyr-Racine, Pfrommer, Bringmann, Sigurdson, in prep.

SIDM simulations: internal subhalo structure



Vogelsberger, Zavala, Cyr-Racine, Pfrommer, Bringmann, Sigurdson, in prep.

Conclusions

If DM searches (production, indirect, and direct experiments) continue to deliver null results, we need to search for alternative windows:

- small-scale features of ΛCDM cosmology: abundances, density profiles, . . . in the most DM-dominated objects (dwarfs, clusters)
- particle physics model building that addresses anomalies (beam dump experiments, . . .)
- develop effective theory for structure formation that connects particle physics properties to effective parameters of structure formation