Cosmological bounds on dark matter self-interactions

Rainer Stiele

Institute for Theoretical Physics
Heidelberg University

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Outline

Motivation

Problems with collisionless Cold Dark Matter

Simulations of the structure formation with **collisionless** Cold Dark Matter fit to large-scale structure oberservations (galaxy clusters, ...) but 'fail' on subgalactic scales:

- Substructure problem
- Cusp vs. core problem

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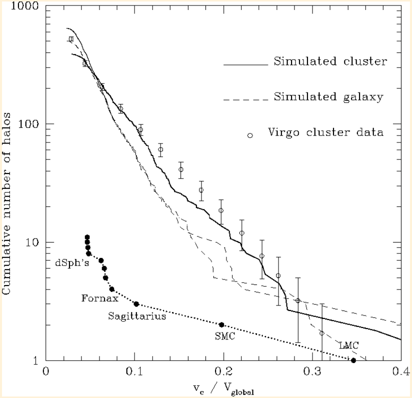
Substructure problem

bottom-up scenario



Moore et al. 1999, ApJ 524

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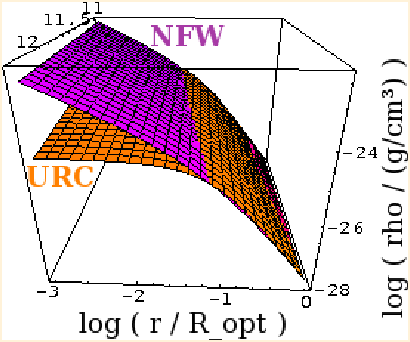
Simulations of the structure formation with collisionless CDM fit to large-scale structure oberservations but 'fail' on subgalactic scales:

- Substructure problem
- Cusp vs. core problem

Cusp vs. Core problem

$$\varrho(r) \propto \frac{1}{\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^2}$$



Salucci et al. 2007, MNRAS 378

Motivation

Problems with collisionless Cold Dark Matter

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- Substructure problem
- Cusp vs. core problem

Self-interacting Cold Dark Matter

Self-interacting CDM: large scattering cross-section

- Colder subhalo in larger halo → heated → spallation or evaporation
- Heat transfer from hotter outer regions to colder center → smoothing from cusp to core

Motivation

Self-interacting Cold Dark Matter

Spergel & Steinhardt 2000, Phys. Rev. Lett. 84

Self-interacting CDM: large scattering cross-section

- Colder subhalo in larger halo → heated
  → **spallation** or evaporation
- Heat transfer from hotter outer regions to colder center
  → smoothing from cusp to **core**

In addition:

- Isotropization of velocity distribution in dense regions
  → **spherical** centers

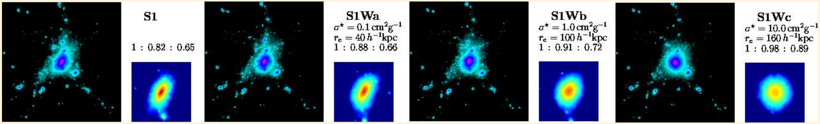
$$0.45\,\mathrm{cm}^2/\mathrm{g} \leq \sigma_{\mathrm{SI}}/m_{\mathrm{DM}} \leq 450\,\mathrm{cm}^2/\mathrm{g}$$

CDM halo cores

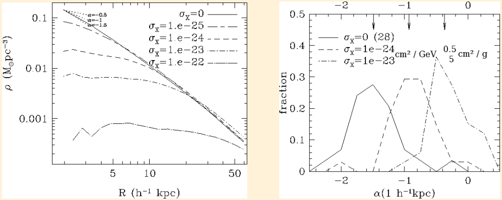
Cold Dark Matter halo core sizes

Heat transfer from hotter outer regions to colder center

$\longrightarrow$ smoothing from cusp to **core**



Yoshida et al. 2000, ApJ 544



Davé et al. 2001, ApJ 547

$$\sigma_{\rm SI}/m_{\rm DM} \lesssim 0.5 - 5\,{\rm cm}^2/{\rm g}$$

Evaporation

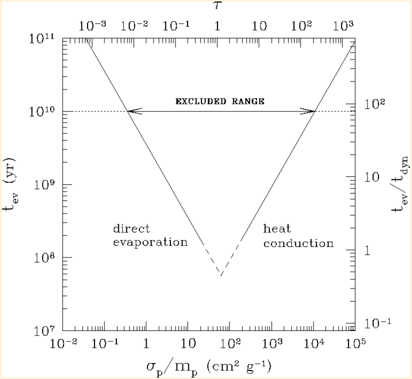
Evaporation of galactic halos

Colder subhalo in larger halo $\rightarrow$ heated
$\rightarrow$ spallation or **evaporation**

Galactic halos have to survive heating from hot cluster halos at least for a Hubble time:

$$\sigma_{\mathrm{SI}}/m_{\mathrm{DM}} \lesssim 0.3\,\mathrm{cm}^2/\mathrm{g}$$

Gnedin & Ostriker 2001, ApJ 561



Ellipticity

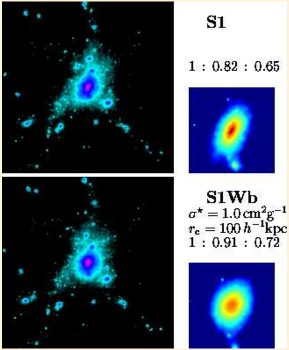
Cluster halo ellipticity

Isotropization of velocity distribution in dense regions
$\rightarrow$ **spherical** centers

Ellipticity of cluster halos at radii $\sim 100\,\mathrm{kpc}$

$$\sigma_{\mathrm{SI}}/m_{\mathrm{DM}} \lesssim 0.02\,\mathrm{cm}^2/\mathrm{g}$$

Miralda-Escudé 2002, ApJ 564



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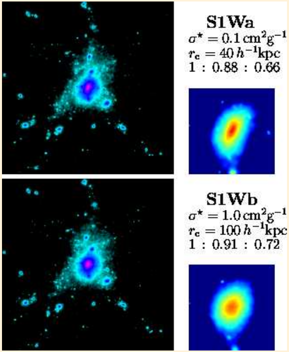


Yoshida et al. 2000, ApJ 544

Galaxy clusters collision

Bullet cluster

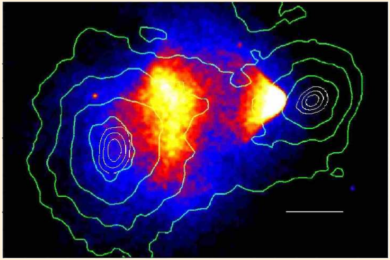
No offset between galaxies and mass peaks:

$$\sigma_{\mathrm{SI}}/m_{\mathrm{DM}} < 1.25\,\mathrm{cm}^2/\mathrm{g}$$

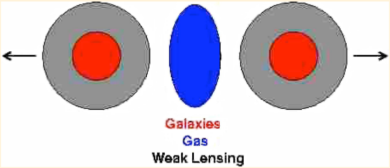
Unchanged subcluster mass-to-light ratio:

$$\sigma_{\mathrm{SI}}/m_{\mathrm{DM}} < 0.7\,\mathrm{cm}^2/\mathrm{g}$$

Randall et al. 2008, ApJ 679



Clowe et al. 2006, ApJ 648



Clowe 2007, Paris Cosmol. Colloq. 2007

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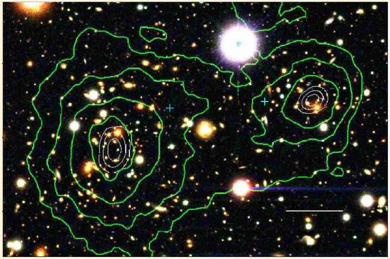

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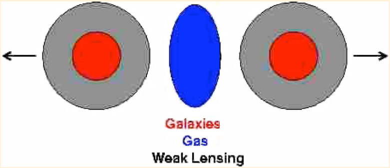

Clowe 2007, Paris Cosmol. Colloq. 2007

Outline

RS, T. Boeckel, J. Schaffner-Bielich
arXiv:1003.2304 [astro-ph.CO]
accepted for publication in Phys. Rev. D

Self-interaction energy density

Self-interaction energy density

$$\mathcal{L} = \bar{\psi}\left(i\not{D} - m_\psi\right)\psi - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_{\mathrm{v}}^2 V_\mu V^\mu$$

$$\mathcal{D}_\mu = \partial_\mu + i g_{\mathrm{v}\psi} V_\mu \; ; \qquad V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$$

$$\Rightarrow \quad \varrho_{\mathrm{SI}} = \frac{\alpha_{\mathrm{SI}}}{m_{\mathrm{SI}}^2}\, n_{\mathrm{SIDM}}^2 = p_{\mathrm{SI}}$$

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$$\varrho_\psi = \bar{\psi}\gamma^0\left(i\partial_0 - g_{\mathrm{v}\psi}V_0\right)\psi + \frac{1}{2}m_{\mathrm{v}}^2 V_0^2 = \varrho_\psi^{\mathrm{free}} + \frac{g_{\mathrm{v}\psi}^2}{2m_{\mathrm{v}}^2}\, n_\psi^2$$

$$p_\psi = \frac{1}{3}\bar{\psi}\left[\gamma^0\left(i\partial_0 - g_{\mathrm{v}\psi}V_0\right) - m_\psi\right]\psi + \frac{1}{2}m_{\mathrm{v}}^2 V_0^2 = p_\psi^{\mathrm{free}} + \frac{g_{\mathrm{v}\psi}^2}{2m_{\mathrm{v}}^2}\, n_\psi^2$$

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Self-interaction energy density

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$$\mathcal{L} = \bar{\psi}\left(i\not{D} - m_\psi\right)\psi - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_{\mathrm{v}}^2 V_\mu V^\mu$$

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$$m_{\mathrm{SIDM}} \equiv m_{\psi(\phi)}, \quad m_{\mathrm{SI}} \equiv m_{\mathrm{v}}; \qquad \alpha_{\mathrm{SI}} \equiv g_{\mathrm{v}\psi}^2/2$$

$$\Rightarrow \quad \varrho_{\mathrm{SI}} = \frac{\alpha_{\mathrm{SI}}}{m_{\mathrm{SI}}^2}\, n_{\mathrm{SIDM}}^2 = p_{\mathrm{SI}}$$

Self-interaction energy density

Self-interaction energy density

- $\varrho_{\rm SI} = \frac{\alpha_{\rm SI}}{m_{\rm SI}^2} n_{\rm SIDM}^2$

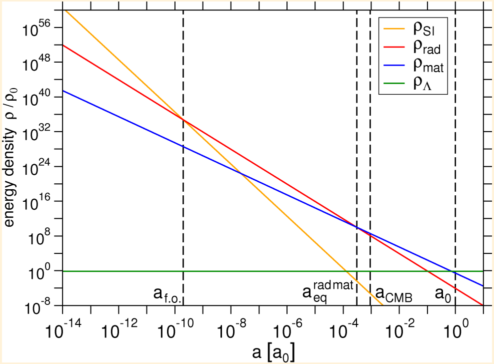
  For comparison:

  $\frac{m_{\rm weak}}{\sqrt{\alpha_{\rm weak}}} \sim 300\,{\rm GeV},$

  $\frac{m_{\rm strong}}{\sqrt{\alpha_{\rm strong}}} \sim 100\,{\rm MeV}$

- $p_{\rm SI} = \varrho_{\rm SI} \quad \Rightarrow$

  $\varrho_{\rm SI} \propto a^{-6}$



⇒ Epoch of self-interaction domination prior to radiation-dominated era.

Self-interaction energy density

Scaling arguments

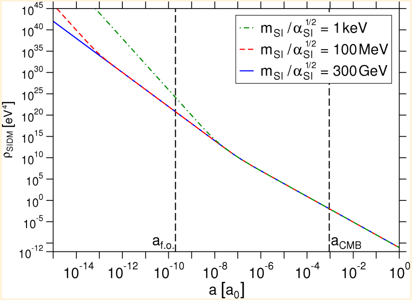
$\varrho_{\rm SI} \propto n_{\rm SIDM}^2; \quad \varrho_{\rm SI} \propto a^{-6} \quad \Rightarrow \quad n_{\rm SIDM} \propto a^{-3}$

$\Rightarrow$ **Warm** self-interacting dark matter

Energy density evolution

WSIDM particle parameters:

- $n_{\rm WDM} = \frac{g_{\rm WDM}}{\pi^2} T_{\rm WDM}^3 \exp\left(\frac{\mu_{\rm WDM}}{T_{\rm WDM}}\right)$
- $T_{\rm WDM}(a) = \left(\frac{g_{\rm th\,eq}(a)}{g_{\rm th\,eq}^{\rm Wdec}}\right)^{1/3} T(a)$
- $\varrho_{\rm WDM}^0 = m_{\rm WDM}\, n_{\rm WDM}^0$
- $F_{\rm WDM}^0 = \Omega_{\rm WDM}^0 / \Omega_{\rm DM}^0$



$m_{\rm WDM} = 1\,{\rm keV},\ g_{\rm WDM} = 2,\ \mu_{\rm WDM}/T_{\rm WDM} = 0,\ F_{\rm WDM}^0 = 1$

Self-interaction energy density

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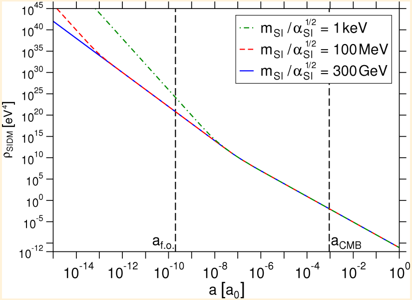
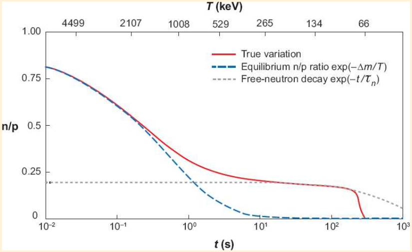


$m_{\rm WDM} = 1\,{\rm keV},\ g_{\rm WDM} = 2,\ \mu_{\rm WDM}/T_{\rm WDM} = 0,\ F_{\rm WDM}^0 = 1$

$\Rightarrow$ Only very strong interactions would have an impact on the very early Universe. $\rightarrow$ BBN perfect test!

Self-interaction energy density

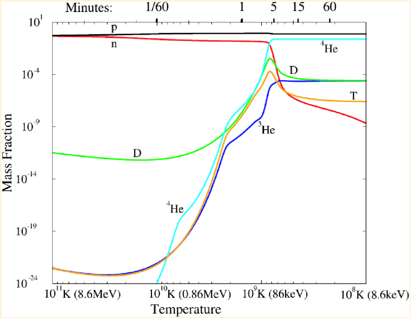
BBN constraint



Steigman 2007, Ann. Rev. of Nucl. and Part. Sci. 57

- Kick-off of BBN freeze-out of n/p: $\Gamma_{\rm np} < H$
- $H \propto \varrho^{1/2}$
- Nearly all n's captured in ^{4}He

$$\varrho_{\rm SI} \propto a^{-6} \Rightarrow \text{n/p} \longrightarrow Y_{\rm P}$$



Mukhanov 2004, Intern. Journal of Theor. Physics 43

Self-interaction energy density

Allowed energy density at n/p freeze-out

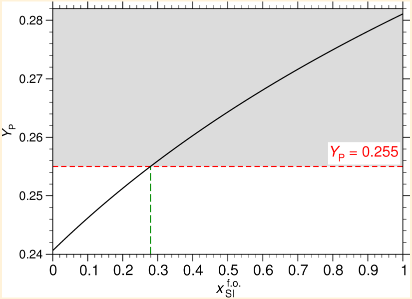
$\varrho_{\rm SI} \propto a^{-6} \quad \Rightarrow \quad$ n/p $\quad \longrightarrow \quad Y_{\rm P}$

$$\varrho_{\rm tot}^{\rm f.o.} = \varrho_{\rm SI}^{\rm f.o.} + \varrho_{\rm rad}^{\rm f.o.} \equiv \left(1 + x_{\rm SI}^{\rm f.o.}\right) \varrho_{\rm rad}^{\rm f.o.}, \qquad 0 \leq x_{\rm SI}^{\rm f.o.} < 1$$

$\varrho_{\rm SI}$ increases $({\rm n/p})_{\rm f.o.} \longrightarrow$ increases ${}^4{\rm He}$ abundance $Y_{\rm P}$

$$Y_{\rm P} < 0.255$$ (*Steigman 2007, Annu. Rev. Nucl. Part. Sci. 57*)

$$\Rightarrow \quad \varrho_{\rm SI}^{\rm f.o.} < 0.279\, \varrho_{\rm rad}^{\rm f.o.}$$



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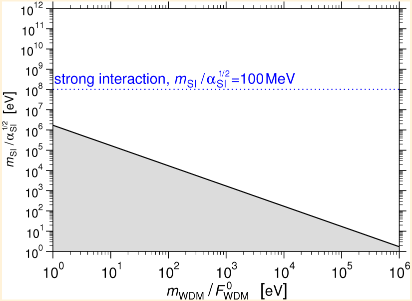
$\Leftrightarrow$

$$\frac{m_{\rm SI}}{\sqrt{\alpha_{\rm SI}}} \gtrsim 1.70 \cdot 10^6\, {\rm eV}^2 \times \frac{F^0_{\rm WDM}}{m_{\rm WDM}}$$

$\Rightarrow$ Dark Matter particles can interact with the strength of the strong interaction

. . . and even stronger!



Self-interaction energy density

Comparison

$$\sigma_{\mathrm{SI}} \approx s\,\frac{\alpha_{\mathrm{SI}}^2}{m_{\mathrm{SI}}^4}$$

$$s = 4E_{\mathrm{SIDM}}^2, \qquad E_{\mathrm{SIDM}} \sim T_{\mathrm{SIDM}} \;\; (\sim m_{\mathrm{SIDM}})$$

$$\frac{\sigma_{\mathrm{SI}}}{m_{\mathrm{SIDM}}} \approx 4\left(\frac{\sqrt{\alpha_{\mathrm{SI}}}}{m_{\mathrm{SI}}}\right)^4 m_{\mathrm{SIDM}}$$

Spergel & Steinhardt 2000, Phys. Rev. Lett. 84:
$\sigma_{\mathrm{SI}}/m_{\mathrm{SIDM}} = 0.45 - 450\,\mathrm{cm}^2/\mathrm{g}$

Randall et al. 2008, ApJ 679:
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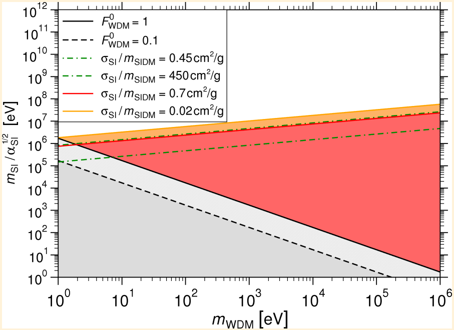
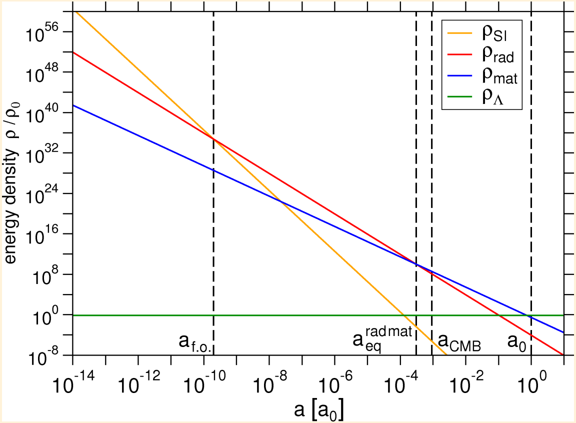


Self-interaction energy density

Consequences



$\longrightarrow$ **DM decoupling during self-interaction domination**

Self-interaction energy density

Warm self-interacting dark matter decoupling

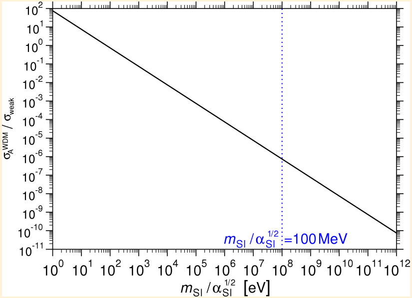
Decoupling: $\Gamma_A = H \qquad \Gamma_A = n_{DM} \langle \sigma_A v \rangle \qquad H \propto \varrho^{1/2}$

WDM: $\Gamma_A = n_{WDM}\, \sigma_A^{WDM}$

$$H \propto \varrho_{SI}^{1/2} = \frac{\sqrt{\alpha_{SI}}}{m_{SI}}\, n_{WDM}$$

$$\Rightarrow \sigma_A^{WDM} = (8\pi/3)^{1/2}\, m_{Pl}^{-1}\, \frac{\sqrt{\alpha_{SI}}}{m_{SI}}$$

$$\approx 7.45 \times 10^{-7}\, \frac{100\ \mathrm{MeV}}{m_{SI}/\sqrt{\alpha_{SI}}}\, \sigma_{weak}$$



$$\sigma_{weak} \equiv \frac{T_0^3}{m_{Pl}^3\, H_0^2} \approx 3.18 \cdot 10^{-12}\ \mathrm{GeV}^{-2} \approx 1.24 \cdot 10^{-39}\ \mathrm{cm}^2$$

"the elastic scattering cross section cannot be arbitrarily small given a nonvanishing inelastic cross section" (*Hui 2001, Phys. Rev. Lett. 86*)

Self-interaction energy density

Collisionless cold dark matter decoupling $(F^0_{\mathrm{WDM}} \neq 1)$

Decoupling: $\Gamma_{\mathrm{A}} = H \qquad \Gamma_{\mathrm{A}} = n_{\mathrm{CDM}} \langle \sigma_{\mathrm{A}} \mathrm{v} \rangle \qquad H \propto \varrho^{1/2}$

$$\langle \sigma_{\mathrm{A}} \mathrm{v} \rangle \propto \sigma^{\mathrm{CDM}}_{\mathrm{A}} \left(\frac{T}{m_{\mathrm{CDM}}} \right)^{1/2} \qquad H \propto \varrho^{1/2}_{\mathrm{SI}} = \frac{\sqrt{\alpha_{\mathrm{SI}}}}{m_{\mathrm{SI}}} n_{\mathrm{WDM}}$$

$$\Rightarrow \quad n^{\mathrm{Cdec}}_{\mathrm{CDM}} \, \sigma^{\mathrm{CDM}}_{\mathrm{A}} \left(\frac{m_{\mathrm{CDM}}}{T_{\mathrm{Cdec}}} \right)^{-1/2} \propto n^{\mathrm{Cdec}}_{\mathrm{WDM}} \frac{\sqrt{\alpha_{\mathrm{SI}}}}{m_{\mathrm{SI}}}$$

conditional equations for decoupling:

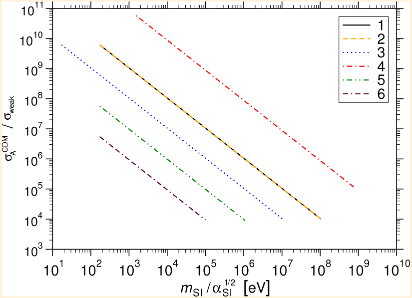
$$\frac{m_{\mathrm{CDM}}}{T_{\mathrm{Cdec}}} \approx 20.8 + \ln \left[\frac{g_{\mathrm{CDM}}}{g^{\mathrm{Cdec}}_{\mathrm{th\,eq}}} F^0_{\mathrm{WDM}} \frac{m_{\mathrm{WDM}}}{1\,\mathrm{keV}} \frac{\sqrt{m_{\mathrm{SI}}/\alpha_{\mathrm{SI}}}}{100\,\mathrm{MeV}} \frac{\sigma^{\mathrm{CDM}}_{\mathrm{A}}}{\sigma_{\mathrm{weak}}} \right] + \ln \left(\frac{m_{\mathrm{CDM}}}{T_{\mathrm{Cdec}}} \right)$$

$$\frac{\sigma^{\mathrm{CDM}}_{\mathrm{A}}}{\sigma_{\mathrm{weak}}} \propto \left(\frac{m_{\mathrm{CDM}}}{T_{\mathrm{Cdec}}} \right)^{1/2} \frac{F^0_{\mathrm{WDM}}}{1-F^0_{\mathrm{WDM}}} \frac{m_{\mathrm{CDM}}}{m_{\mathrm{WDM}}} \frac{\sqrt{\alpha_{\mathrm{SI}}}}{m_{\mathrm{SI}}}$$

Self-interaction energy density

Collisionless cold dark matter decoupling

$$\sigma_A^{\rm CDM} \propto \frac{F_{\rm WDM}^0}{1-F_{\rm WDM}^0}\,\frac{1}{m_{\rm WDM}}\,m_{\rm CDM}\,\frac{\sqrt{\alpha_{\rm SI}}}{m_{\rm SI}}\,\sigma_{\rm weak}$$



set	$m_{\rm CDM}$ [TeV]	$g_{\rm CDM}$	$m_{\rm WDM}$ [keV]	$F_{\rm WDM}^0$
1	10	2	1	0.1
2	10	3	1	0.1
3	10	2	10	0.1
4	10	2	1	0.9
5	0.1	2	1	0.1
6	0.01	2	1	0.1

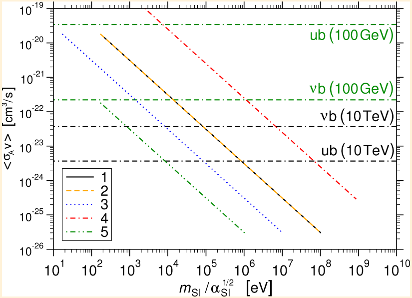
no $Z \rightarrow \chi\,\chi$ $\Rightarrow$ $m_{\rm CDM} \lesssim m_Z/2 \approx 45.6\,\mathrm{GeV}$ ruled out

for $\sigma_A^{\rm CDM} \geq \sigma_{\rm weak}$

Self-interaction energy density

Collisionless cold dark matter decoupling

$$\langle\sigma_A v\rangle \approx 2.77\cdot 10^{-23}\,\mathrm{cm^3\,s^{-1}} \times \frac{m_{CDM}/10\,\mathrm{TeV}}{m_{WDM}/1\,\mathrm{keV}}\;\frac{1\,\mathrm{MeV}}{m_{SI}/\sqrt{\alpha_{SI}}}\;\frac{F^0_{WDM}}{1-F^0_{WDM}}$$



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3	10	2	10	0.1
4	10	2	1	0.9
5	0.1	2	1	0.1

radiation domination:

$$\langle\sigma_A v\rangle \sim 3\times 10^{-26}\,\mathrm{cm^3\,s^{-1}}/(1-F^0_{WDM})$$

ub: unitary bound $\langle\sigma_A v\rangle \leq \frac{4\pi}{m^2_{CDM}\,v}$

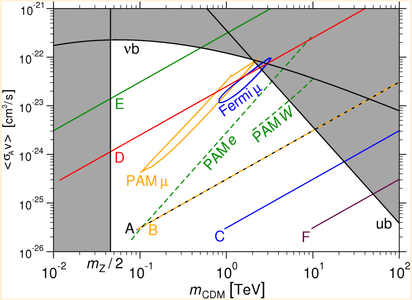
νb: neutrino constraint; *Yüksel et al. 2007, Phys. Rev. D 76*

Self-interaction energy density

Collisionless cold dark matter decoupling

Fermi-LAT: cosmic-ray electron-plus-positron spectrum

PAMELA: excess in the positron fraction



set	$\frac{m_{SI}}{\sqrt{\alpha_{SI}}}$ [MeV]	g_{CDM}	m_{WDM} [keV]	F^0_{WDM}
A	1	2	1	0.1
B	1	3	1	0.1
C	1	2	10	0.1
D	1	2	1	0.9
E	10^{-3}	2	1	0.1
F	100	2	1	0.1

νb: *Yüksel et al. 2007, Phys. Rev. D 76*

PAM μ, Fermi μ: *Bergström et al. 2009, Phys. Rev. Lett. 103*

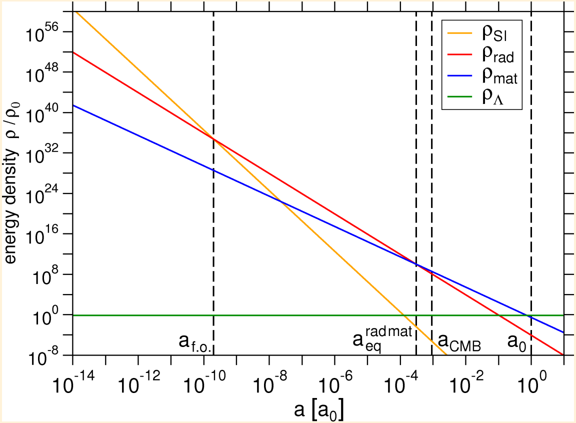
PAM e, PAM W: *Catena et al. 2009, arXiv:0912.4421 [astro-ph.CO]*

radiation domination:

$$\langle \sigma_A v \rangle \sim 3 \times 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}/(1 - F^0_{WDM})$$

Self-interaction energy density

Consequences



$\longrightarrow$ **Structure formation in self-interaction dominated era**

Self-interaction energy density

Structure formation

$$\delta_i' = \frac{3\left(w_i - c_{si}^2\right)}{a}\delta_i + \frac{k}{a\mathcal{H}}\hat{\psi}_i - \frac{3(1+w_i)}{a}\alpha$$
$$\hat{\psi}_i' = \frac{3w_i - 1}{a}\hat{\psi}_i - c_{si}^2\frac{k}{a\mathcal{H}}\delta_i - \frac{(1+w_i)k}{a\mathcal{H}}\alpha$$
$$\alpha = -\frac{\frac{3}{2}\left(1+3c_s^2\right)}{\left(\frac{k}{\mathcal{H}}\right)^2 + \frac{9}{2}(1+w)}\delta$$

single fluid $w = 1$, subhorizon ($k_{ph}/H \gg 1$):

$$\delta_{SIDM}(a) \propto a \cdot \left(A\cos(a^2 - 3\pi/4) + B\sin(a^2 - 3\pi/4)\right)$$

Hwang 1993, ApJ 415

damping scales:

$$l_{sd}^2 \approx \int_0^{t_{sdec}} \frac{v_{WDM}^2(t)\,dt}{\Gamma_{SI}(t)\,a^2(t)}$$ self-damping

Boehm et al. 2005, A&A 483

$$l_{fs} \approx \int_{t_{sdec}}^{t_{collapse}} \frac{v_{WDM}(t)\,dt}{a(t)}$$ free-streaming

Self-interaction energy density

Structure formation $(F^0_{\mathrm{WDM}} \neq 1)$

subdominant CDM:

$$w_{\mathrm{CDM}} = c^2_{\mathrm{s\,CDM}} = 0, \; w \approx w_{\mathrm{SI}} = 1, \; c^2_{\mathrm{s}} \approx c^2_{\mathrm{s\,SI}} = 1$$

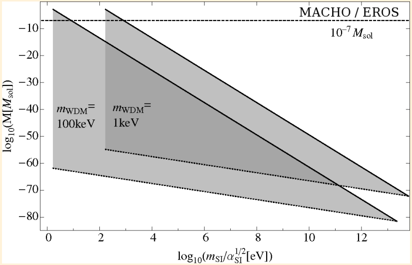
$$\delta_{\mathrm{CDM}} = a \cdot \left(C / a_k^{\mathrm{in}\,2} \right) + D$$

Transfer function $T(k)$:

$$T(k) = A^{\mathrm{eq}}(k) / A^{\mathrm{in}}(k)$$

$$T(k) = \sqrt{\frac{k}{\mathcal{H}^{\mathrm{eq}}}}, \quad k^{\mathrm{eq}}_{\mathrm{sd}} > k > \mathcal{H}^{\mathrm{eq}}$$

$$M \lesssim 10^{-3} M_\odot$$



$\mu_{\mathrm{WDM}} / T_{\mathrm{WDM}} = 0, \; F^0_{\mathrm{WDM}} = 0.1$

MACHO / EROS sensitivity limit: $\sim 10^{-7} M_\odot$

Alcock et al. 1998, ApJ 499; Afonso et al. 2003, A&A 400

Summary

Bounds on Cold Dark Matter self-scattering cross-section

	$\sigma_{\rm SI}/m_{\rm DM}$ $[{\rm cm}^2/{\rm g}]$
Halo cores	$\lesssim 0.5 - 5$
Galactic evaporation	$\lesssim 0.3$
Cluster ellipticity	$\lesssim 0.02$
Bullet cluster	$< 0.7 - 1.25$

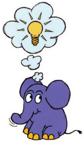
Self-interaction energy density

- Additional energy density contribution dominating in the early universe
- Restrict self-interaction strength by Big Bang Nucleosynthesis
- DM decoupling during self-interaction domination
- Structure formation during self-interaction domination

Summary

Self-interaction energy density

- Additional energy density contribution dominating in the early universe: $\varrho_{\mathrm{SI}} = \frac{\alpha_{\mathrm{SI}}}{m_{\mathrm{SI}}^2} n_{\mathrm{SIDM}}^2 \propto a^{-6}$
- Restrict particle parameters by today's Dark Matter energy density:
  $\frac{g_{\mathrm{WDM}}\, m_{\mathrm{WDM}}}{g_{\mathrm{th\ eq}}^{\mathrm{Wdec}}\, F_{\mathrm{WDM}}^0} \exp\left(\frac{\mu_{\mathrm{WDM}}}{T_{\mathrm{WDM}}}\right) \propto \Omega_{\mathrm{DM}}^0 h_0^2$
- Restrict self-interaction strength by Big Bang Nucleosynthesis:
  $\frac{m_{\mathrm{SI}}}{\sqrt{\alpha_{\mathrm{SI}}}} \gtrsim \propto \frac{F_{\mathrm{WDM}}^0}{m_{\mathrm{WDM}}} \quad \Rightarrow \quad m_{\mathrm{SI}}/\sqrt{\alpha_{\mathrm{SI}}} \sim \mathrm{MeV}$ allowed
- WSIDM decoupling in SI dominated universe: $\sigma_{\mathrm{A}}^{\mathrm{WDM}} \ll \sigma_{\mathrm{weak}}$
- Collisionless CDM decoupling in SI dominated universe:
  $\sigma_{\mathrm{A}}^{\mathrm{CDM}} \propto m_{\mathrm{CDM}} \frac{\sqrt{\alpha_{\mathrm{SI}}}}{m_{\mathrm{SI}}}; \qquad \langle \sigma_{\mathrm{A}} \mathrm{v} \rangle > 3 \times 10^{-26}\, \mathrm{cm}^3\, \mathrm{s}^{-1}$
- Structure formation in SI dominated universe:
  $\delta_{\mathrm{SIWDM}} \propto a\,; \qquad \delta_{\mathrm{CDM}} \propto a, \quad M \lesssim 10^{-3} M_{\odot}$



Thank You for Your attention!

Self-interaction energy density

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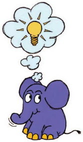


Thank You for Your attention!

Self-interacting Dark Matter, thanks to whom?

VOLUME 84, NUMBER 17 PHYSICAL REVIEW LETTERS 24 APRIL 2000

Observational Evidence for Self-Interacting Cold Dark Matter

David N. Spergel and Paul J. Steinhardt
Princeton University, Princeton, New Jersey 08544
(Received 20 September 1999)

Cosmological models with cold dark matter composed of weakly interacting particles predict overly dense cores in the centers of galaxies and clusters and an overly large number of halos within the Local Group compared to actual observations. We propose that the conflict can be resolved if the cold dark matter particles are self-interacting with a large scattering cross section but negligible annihilation or dissipation. In this scenario, astronomical observations may enable us to study dark matter properties that are inaccessible in the laboratory.

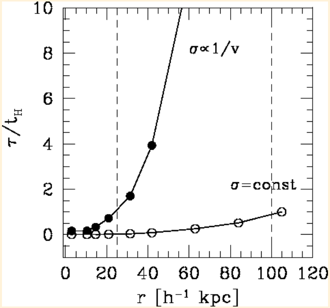
We thank R. Dave, J. Dalcanton, G. Dvali, J. Goodman, E. Kolb, J. March-Russell, J. Miralda-Escude, J. Ostriker, J. Peebles, J. Silk, S. Tremaine, M. Turner, and N. Turok for discussions. We are grateful to the West Anglia Great Northern Railway whose train delay provided the opportunity for initial discussions. This work was initiated at the Newton Institute for Mathematical Sciences. D.N.S. acknowledges the NASA Theory program and the NASA MAP Satellite program for support, and P.J.S. was supported by the U.S. Department of Energy Grant No. DE-FG02-91ER40671.

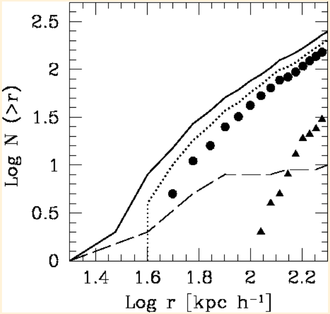
backup

Galactic satellite population

Disruption of satellite halos

Colder subhalo in larger halo → heated
→ spallation or evaporation





D'Onghia & Burkert 2003, ApJ 568

Galactic satellite population

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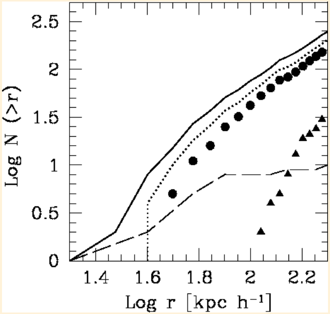
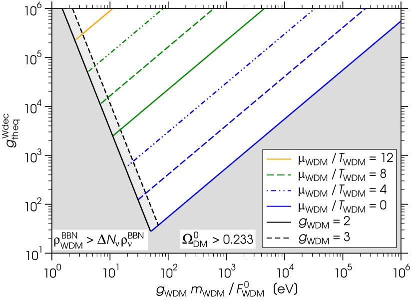


FIG. 3.—*Solid line*: Abundance of dark satellite halos predicted by SCDM *N*-body simulations at different distances from the center of the Milky Way halo (courtesy B. Moore 2002, private communication). *Dashed line*: Cumulative number of dwarf galaxies observed in the Local Group at different Galactocentric distances (Grebel 2000). *Dotted line*: Abundance of dark satellite halos, predicted for a cross section dependent on the halo velocity dispersion: $\sigma \propto 1/v$, when tidal stripping is not taken into account. *Filled circles*: Cumulative number of subhalos that survive tidal stripping and collisions in a self-interacting scenario with $\sigma \propto 1/v$. *Triangles*: These show that if the cross section is assumed to be independent of the relative velocity, the overabundance is unsolved at larger radii.

D'Onghia & Burkert 2003, ApJ 568

WSIDM particle parameters

$$\frac{g_{\rm WDM}\, m_{\rm WDM}}{g_{\rm th\,eq}^{\rm Wdec}\, F_{\rm WDM}^0}\ \exp\left(\frac{\mu_{\rm WDM}}{T_{\rm WDM}}\right) \approx 1.80\,{\rm eV} \times \frac{\Omega_{\rm DM}^0 h_0^2}{0.1143}$$



$$\varrho_{\rm WDM}^{\rm BBN} \leq \Delta N_\nu\, \varrho_\nu^{\rm BBN}$$

$$\frac{m_{\rm WDM}}{F_{\rm WDM}^0} \gtrsim 22.6\,{\rm eV} \times \frac{\Omega_{\rm DM}^0 h_0^2}{0.1143}\, \frac{g_{\rm th\,eq}^{\rm Wdec\ -1/3}}{\Delta N_\nu}; \qquad \Delta N_\nu \leq 0.3$$

Self-interacting Dark Matter – Structure formation

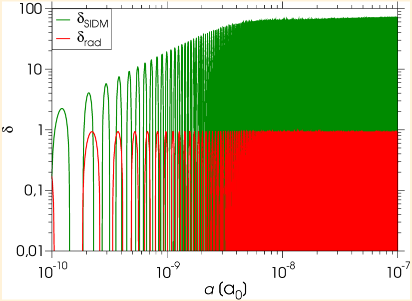
Structure formation of Self-interacting Dark Matter

Analyse relativistic structure formation of linear perturbations:

$$\varrho = \varrho_0 + \delta\varrho; \qquad \delta = \delta\varrho/\varrho_0$$

- **self-interaction domination**:
  $\delta \propto a$
- relativistic:
  $\delta = \text{const.}$
- nonrelativistic:

$$\delta \propto \begin{cases} \ln a & \text{during radiation domination} \\ a & \text{when matter dominated} \end{cases}$$



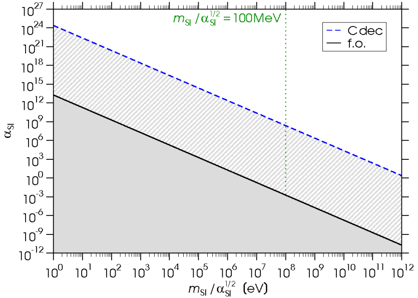
$\frac{m_{SI}}{\sqrt{\alpha_{SI}}} = 1\,\text{keV},\ m_{DM} = 5\,\text{keV},\ g_{DM} = 2,\ \frac{\mu_{DM}}{T_{DM}} = 0,\ g^{\text{dec}}_{\text{th eq}} = 10^4$

All modes inside Hubble horizon during self-interaction domination grow already. Concerns only very small, non-cosmological scales ($M \lesssim 10^{-3} M_\odot$). $\rightarrow$ Washed-out due to free-streaming?

Coupling constant

$$\varrho_{\mathrm{SI}} = \frac{\alpha_{\mathrm{SI}}}{m_{\mathrm{SI}}^2}\, n_{\mathrm{SIDM}}^2 \quad \text{only for} \quad m_{\mathrm{SI}} > 5\, T_{\mathrm{SIDM}}$$

$$\Rightarrow \quad \alpha_{\mathrm{SI}} > 25\, \frac{\alpha_{\mathrm{SI}}}{m_{\mathrm{SI}}^2}\, T_{\mathrm{SIDM}}^2$$



BBN ($T_{\mathrm{WDM}}^{\mathrm{f.o.}} = T_{\mathrm{f.o.}}$): $\alpha_{\mathrm{strong}} > 1.93 \times 10^{-3}$

Cdec ($T_{\mathrm{WDM}}^{\mathrm{Cdec}} = m_{\mathrm{CDM}} / \left(m_{\mathrm{CDM}} / T_{\mathrm{Cdec}} \right)$): $\alpha_{\mathrm{strong}} > 2.47 \times 10^{8}$