Dissipative dark matter

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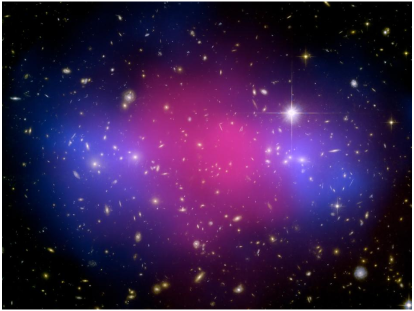
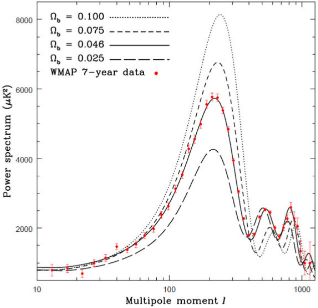
Overview

Evidence for dark matter

- Kinematics of galaxy clusters
- Rotation curves of spiral galaxies
- Gravitational lensing
- Large-scale structure formation
- Big Bang Nucleosynthesis

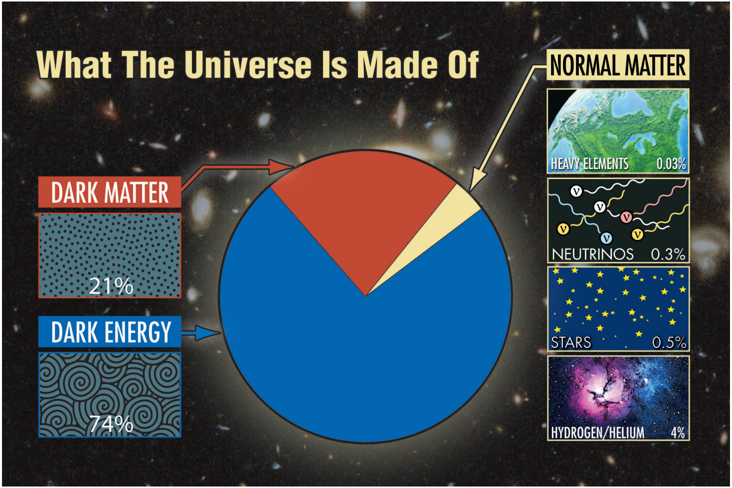
- CMB angular power spectrum
- BAO in 2pt correlation function
- RSDs in redshift surveys
- SNe1a distance measurements
- Ly-α flux power spectrum





The concordance ΛCDM model

6 fundamental parameters: $\Omega_b h^2$, $\Omega_{\rm dm} h^2$, θ_s, A_s, n_s, $\tau_{\rm reion}$
($+\ \Omega_k$, $\sum m_\nu$, n_t, $f_{\rm NL}$, $g_{\rm NL}$, $w_{\rm de}$, r, $dn_s/d\ln k$, $N_{\rm eff}$,...)



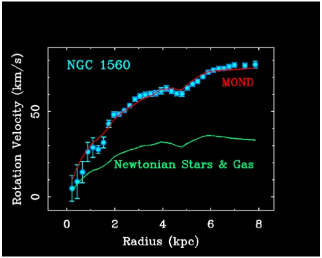
Dark matter candidates

Particle/matter candidates:

- WIMPs (e.g. SUSY neutralino)
- Axions
- Sterile neutrinos
- Mirror dark matter
- WIMPless dark matter
- MACHOs
- Primordial BHs
- Exotics: WIMPzillas, CHAMPs, cryptons, LKP, UEDs
- Ad hoc models for experimental anomalies: MDM, xDM, iDM

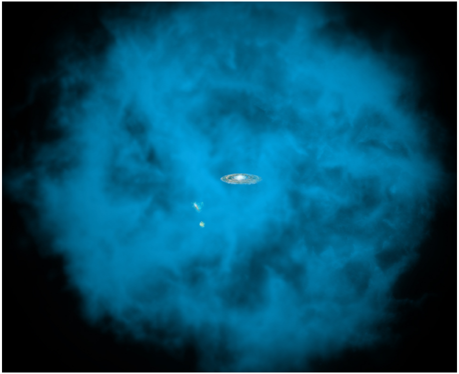
Modifications of gravity:

- MOND
- Mimetic gravity
- Non-Riemannian volume forms
- Horava-Lifshitz gravity
- Conformal Weyl gravity
- $f(R)$ gravity



The collisionless CDM paradigm

Dark matter is composed of collisionless, cold, dissipationless, non- or weakly-interacting massive particles. Around (spiral) galaxies it is distributed in the form of a roughly spherical collapsed structures ("halos"), extended well beyond the edge of the visible matter.



The collisionless CDM paradigm

Successes:

- Explains structure formation on scales of galaxy clusters or larger
- Correctly predicts BAO feature
- Predicts statistics of WGL
- Correctly predicts the CMB TT, TE, EE spectra

Challenges:

- *Core vs cusp* de Blok, Adv. Astron. (2010)
- *Missing satellites* Klypin, Kravtsov, Valenzuela, Prada, ApJ 522, 82-89 (1999)
- *Too-big-to-fail* Boylan-Kolchin, Bullock, Kaplinghat, MNRAS 415:L40 (2011)
- *Satellite plane problem* Ibata et al., Nature 493, 62-65 (2013)
- Several galactic scaling relations unexplainable with conventional CDM Salucci & De Laurentis, 1302.2268

- Solution lies in baryonic physics?
- ...or these challenges suggest shift from collisionless CDM paradigm?

Shifting from CDM

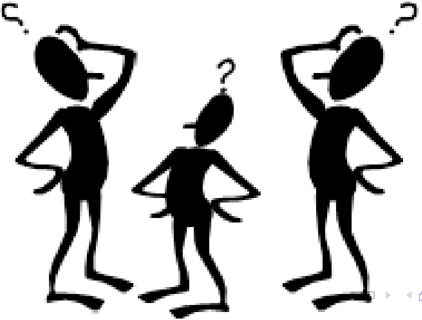
Must dark matter be:

- **Collisionless**? No, in fact $\sigma/m \simeq 0.1 - 1\ \mathrm{cm}^2/\mathrm{g}$ could alleviate some of the small-scale problems Steinhardt & Spergel, PRL 84, 3760-3763 (2000)
- **Cold**? It definitely can't be hot, could be warm or a bit "chilled"
- **Dark**? Basically yes, else coupling to photons (e.g. millicharges or magnetic moments) must be appropriately suppressed
- **Matter**? Not necessarily, but modifying gravity and explaining DM within constraints from CMB, LSS and Solar System tests is hard!
- **Dissipationless**? Most would say "yes", but...

Dissipative dark matter

Can dark matter dissipate on a time-scale $\tau \lesssim H_0^{-1}$ and still result in spheroidal halos?

- Only a subdominant component of DM is dissipative (see "Double-Disk Dark Matter") Fan, Katz, Randall, Reece, Phys. Dark Univ. 2, 139-156 (2013)
- Part could collapse to a dark disk, remaining part could condense into compact MACHO-like objects, roughly spherically distributed
- Energy lost to dissipation could be replaced by a heat source, which would prevent halo from collapsing and keep it "puffy"



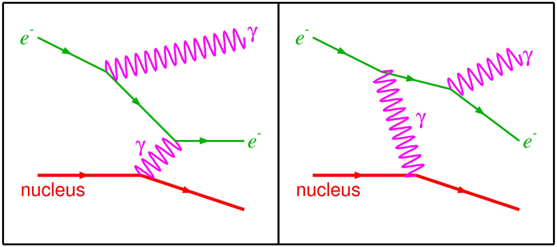
Dissipative dark matter - the prototype

Try to mimic $U(1)_{\text{em}}$ sector of Standard Model: a "dark electron a "dark proton" with interactions mediated by a "dark photon"

$$\mathcal{L} = -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \bar{e}_d(i\gamma^\mu D_\mu - m_{e_d})e_d + \bar{p}_d(i\gamma^\mu D_\mu - m_{p_d})p_d$$

$U(1)'$ unbroken $\implies$ $m_{\gamma_d} = 0$ $\implies$ mediates dissipative interactions

Bremsstrahlung



$U(1)'$-$U(1)_Y$ kinetic mixing

$$\mathcal{L}_{\text{mix}} = \frac{\epsilon}{2} B^{\mu\nu} F'_{\mu\nu}$$

Leads to γ_d-γ mixing. To remove kinetic mixing, perform non-orthogonal transformation, then canonically normalize kinetic terms. Then:

- γ couples to $U(1)'$ current with strength proportional to ϵ: $\mathcal{L} \supset \epsilon A^\mu J'_\mu$ (*millicharged* dark matter), *or*:
- γ_d couples to $U(1)_{\text{em}}$ current in same way: $\mathcal{L} \supset \epsilon A'^\mu J_\mu$

First choice of basis most common one, but in fact the two are equivalent. Dark matter is not that "dark" anymore ($\epsilon \ll 1$).

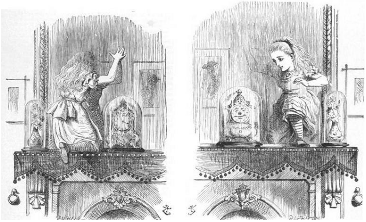
Mirror dark matter

Mirror DM is a special theoretically constrained example of dissipative dark matter

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}'_{\rm SM} + \mathcal{L}_{\rm mix}\,, \quad \mathcal{L}_{\rm mix} = \frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu} + \lambda \phi^\dagger \phi \phi'^\dagger \phi'$$

More general dissipative DM model described previously can be seen as a toy model generalization of mirror DM: dark electron e_d represents mirror electron, and dark proton p_d represents mirror nuclei

Many works on mirror DM! Foot, Lew & Volkas, PLB 272, 67-70 (1991); Berezhiani, Dolgov & Mohapatra, PLB 375, 26-36 (1996); Berezhiani, Comelli & Villante, PLB 503, 362-275 (2001); Berezhiani, hep-ph/0508233; Foot, Int. J. Mod. Phys. A 29, 1430013 (2014)



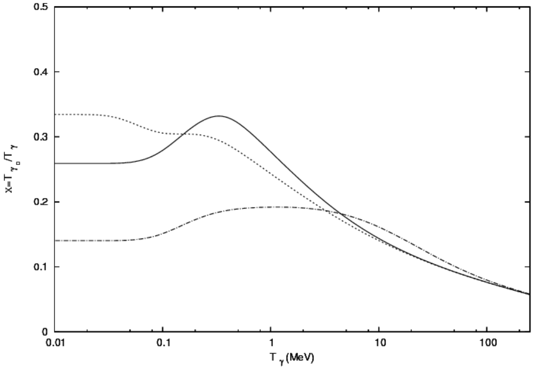
Early Universe cosmology

- Hidden sector should be colder and not thermalize with visible sector. Assume initial condition $T_{\text{hid}}/T_{\text{vis}} \simeq 0$ (from asymmetric reheating?)
- Can populate hidden sector through kinetic mixing-induced processes such as $e\bar{e} \to e_d \bar{e}_d$

For $0.01 \lesssim m_{e_d}/\mathrm{MeV} \lesssim 100$:

$$\frac{T_{\text{hid}}}{T_{\text{vis}}} \to 0.31\sqrt{\frac{\epsilon}{10^{-9}}}\sqrt[4]{\frac{m_{e_d}}{\mathcal{M}}}$$

$$\mathcal{M} \equiv \max(m_e, m_{e_d})$$



Early Universe cosmology bounds

Relativistic DOFs at recombination and BBN parametrized by N_{eff}:

$$\delta N_{\text{eff}}[\text{CMB}] = \frac{8}{7}\left(\frac{T_{\gamma_D}(\epsilon)}{T_\nu(\epsilon=0)}\right)^4 + 3\left(\left[\frac{T_\nu(\epsilon)}{T_\nu(\epsilon=0)}\right]^4 - 1\right)$$

$$\delta N_{\text{eff}}[\text{CMB}] \lesssim 0.33 \text{ @95\%CL}$$

Planck 2015 TT,TE,EE+lensing+BAO+JLA+H_0

$$\delta N_{\text{eff}}[\text{BBN}] = \frac{Y_p(\epsilon) - Y_p(\epsilon=0)}{0.013}$$

$$\delta N_{\text{eff}}[\text{BBN}] \lesssim 1 \text{ @95\%CL}$$

Aver, Olive & Skillman, JCAP 1005, 003 (2010)

$$\epsilon \lesssim 3.5 \times 10^{-9}\left(\frac{\mathcal{M}}{m_e}\right)^{\frac{1}{2}}$$

$\implies T_{\text{hid}} \ll T_{\text{vis}} \implies$ dark matter is “cold”

Large-Scale Structure bounds

- Prior to dark recombination, dark acoustic oscillations occur in the hidden sector (analogous to BAOs)
- Strong radiation pressure prevents growth of structure for modes which enter the horizon before dark recombination
- Require dark recombination to occur prior to matter-radiation equality, else structure formation does not proceed correctly:

$$z_{\rm dr} \gtrsim z_{\rm eq} \simeq 3200$$

- Resulting bound:

$$\epsilon \lesssim 10^{-8} \left(\frac{\alpha_d}{\alpha}\right)^4 \left(\frac{m_{e_d}}{\rm MeV}\right)^2 \left(\frac{\mathcal{M}}{m_e}\right)^{\frac{1}{2}}$$

- Ensures DM is "collisionless" on scales relevant for structure formation: reproduce successes of collisionless CDM on large scales!

Recap

What have we got so far:

- Constructed kinetically mixed dissipative DM model
- Bounds from extra energy density at recombination and BBN ensure DM is cold
- Bounds from LSS formation ensure DM is collisionless on cosmological scales

What we still need:

- Heat source to replace energy dissipated
- Tie DM and baryons, try to explain galactic scaling relations
- Address the small-scale problems of collisionless cold DM

Heating from ordinary supernovae

- For $\epsilon \sim 10^{-9}$, kinetic mixing induced processes in SNeII can transfer up to 1/2 the core-collapse energy to dark particles: e_d, $\bar{e}_d$, γ_d Raffelt 1996; Davidson, Hannestad & Raffelt, JHEP 0005, 003 (2000); Foot & Silagadze, Int. J. Mod. Phys. D 14, 143 (2005)
- Was first proposed for mirror DM Foot & Volkas, PRD 70, 123508 (2004)
- Plasmon decay and pair annihilation: $\gamma \to e_d \bar{e}_d$, $e\bar{e} \to e_d \bar{e}_d$
- Another option: part of DM collapses to a disk (and is what we detect in direct detection experiments), the rest of the halo is populated by "dark stars"

Dynamical halo equations

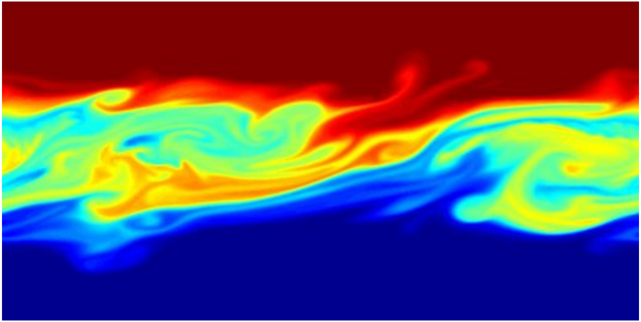
- Local energy balance

$$\frac{d\Gamma_{\text{heat}}(r)}{dV} = \frac{d\Gamma_{\text{cool}}(r)}{dV}$$

- Hydrostatic equilibrium:

$$\frac{dP(r)}{dr} = -\rho(r)g(r)$$

- Equations represent static limit of Euler equations of fluid dynamics

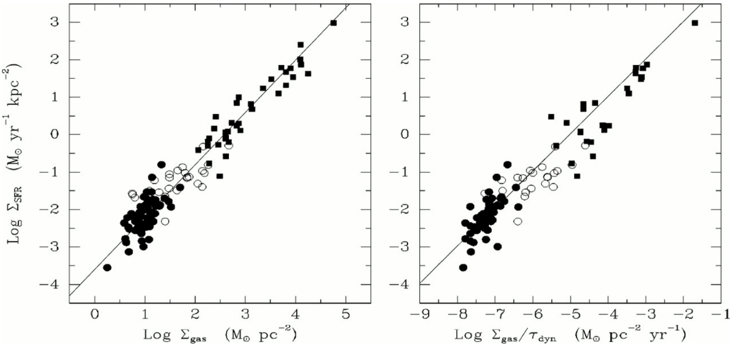


Aside: can the system evolve to a static configuration?

Needs to be checked eventually numerically or by simulations, but seems plausible. Exploit Schmidt-Kennicutt law:

$$\dot{\Sigma}_\star \propto n_{\rm gas}^N , \quad N \sim 1 - 2$$

- If halo contracts too much, $\Sigma_\star$ and thus $\Gamma_{\rm heat}$ increase
- If halo expands too much, $\Sigma_\star$ and thus $\Gamma_{\rm heat}$ decrease



Let's get some insight...

Assume isothermal halo and approximate total energy density being given by dark matter energy density (both can be reasonable in the outer regions of the galaxy), solve hydrostatic equilibrium equation

$$\frac{dP(r)}{dr} = -\rho(r)g(r)\,, \quad g(r) = \frac{v_{\rm rot}^2}{r} = \frac{G}{r^2}\int_0^r dr'\ 4\pi r'^2 \rho_T(r')\,, \quad P(r) = \frac{\rho(r)T(r)}{\overline{m}}$$

$$\Longrightarrow \frac{d\rho}{dr} = -\frac{\overline{m}\rho(r)G}{Tr^2}\int_0^r dr'\ 4\pi r'^2 \rho(r')$$

Solution:

$$\rho(r) = \frac{T}{2\pi G\overline{m}r^2}$$

$$v_{\rm rot}^2 = \frac{G}{r}\int_0^r dr'\ 4\pi r'^2 \frac{T}{2\pi G\overline{m}r'^2} = \frac{2T}{\overline{m}} \Longrightarrow T = \frac{1}{2}\overline{m}v_{\rm rot}^2 \equiv \frac{1}{2}\overline{m}v_\infty^2$$

Solution to halo equations - toy model

- Cooling mechanism: bremsstrahlung of e_d off p_d ($e_d p_d \to \gamma_d e_d p_d$)

$$d\Gamma_{\text{cool}} = \Lambda(T) n_{e_d} n_{p_d} dV$$

- Heating mechanism: photoionization of p_d-e_ds bound states, assume supernovae act as point source at $r = 0$

$$d\Gamma_{\text{heat}} = \frac{L_{\text{SN}} e^{-\tau}}{4\pi r^2} \sigma n_{p_d} dV$$

- Energy balance:

$$d\Gamma_{\text{cool}} = d\Gamma_{\text{heat}} \implies \rho(r) \propto n_{e_d}(r) = \frac{L_{\text{SN}} e^{-\tau}}{\Lambda(T) 4\pi r^2} \sigma$$

- Solution:

$$\rho(r) \propto \frac{1}{r^2} \implies \implies v_{\text{rot}} \equiv v_\infty \simeq \text{const}$$

Solution to halo equations - more realistic model

- Previous model unphysical at $r = 0$, smear supernovae on scale r_D:

$$\Sigma(\tilde{r}) = \frac{m_D}{2\pi r_D^2} e^{-\frac{\tilde{r}}{r_D}}$$

- Dark photon flux at point $P = (r_1, 0, z_1)$ [cylindrical coordinates]:

$$f(r, \cos\phi) = \frac{L_{\rm SN}}{4\pi m_D} \int d\tilde{\theta} \int d\tilde{r}\, \tilde{r} \frac{\Sigma(\tilde{r})}{\tilde{r}^2 - 2\tilde{r} r_1 \cos\tilde{\theta} + r_1^2 + z_1^2} \propto \begin{cases} \text{const}, & r \ll r_D\ , \\ \log r, & r \lesssim r_D\ , \\ \frac{1}{r^2}, & r \gg r_D\ . \end{cases}$$

- Energy balance:

$$d\Gamma_{\rm heat} = f\sigma n_{p_d} dV\ , \quad d\Gamma_{\rm cool} = \Lambda(T) n_{e_d} n_{p_d} dV\ , \quad \Longrightarrow \rho(r) \propto n_{e_d}(r) = \frac{f\sigma}{\Lambda(T)}$$

Solution to core-cusp problem

- Cuspy halo solution obtained by having supernovae act as a point heat source gets smeared to a cored halo when considering that supernovae are distributed on a finite length scale
- Density well approximated by a quasi-isothermal profile:

$$\rho(r) \simeq \frac{\rho_0 r_0^2}{r^2 + r_0^2}$$

- $r_0 \sim r_D$ since this is the only physical scale present
- Observations of high resolution rotation curves infer:

$$\log r_0 = (1.05 \pm 0.11) \log r_D + (0.33 \pm 0.04)$$

Donato & Salucci, MNRAS 353, L17 (2004)

- Scaling relation unexplained by collisionless CDM: ties DM (r_0) to baryons (r_D) [gravity is not sufficient to explain it]

More scaling relations...

- Heating rate (for an optically thin halo):

$$\Gamma_{\text{heat}} \propto \tau R_{\text{SN}} \propto \rho_0 r_0 R_{\text{SN}}$$

- Cooling rate dominated by bremsstrahlung:

$$\Gamma_{\text{cool}} \propto \Lambda(T)\rho_0^2 r_0^3 \propto \sqrt{T}\rho_0^2 r_0^3 \propto v_\infty \rho_0^2 r_0^3$$

- For a quasi-isothermal halo, rotational velocity:

$$v_{\text{rot}}^2 = \frac{G}{r}\int_0^r dr'\ 4\pi r'^2 \frac{\rho_0 r_0^2}{r'^2 + r_0^2} = 4\pi G \rho_0 r_0^2 \left[1 - \frac{r_0}{r}\tan^{-1}\left(\frac{r}{r_0}\right)\right] \implies v_\infty \propto \sqrt{\rho_0 r_0^2}$$

Combine the above, get:

$$\Gamma_{\text{heat}} \propto \rho_0 r_0 R_{\text{SN}} = \Gamma_{\text{cool}} \propto \rho_0^{\frac{5}{2}} r_0^4 \implies R_{\text{SN}} \propto v_\infty^3$$

...looks familiar? Not yet!

Tully-Fisher relation

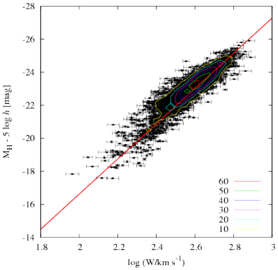
Let's massage the previous $R_{\text{SN}} \propto v_\infty^3$. Supernovae studies find:

$$R_{\text{SN}} \propto (L_B)^{0.73} \quad \text{Li et al., MNRAS 412, 1473 (2011)} ,$$

from which we get:

$$L_B \propto v_\infty^4$$

The above corresponds to the Tully-Fisher relation! Tully & Fisher, A&A 54, 661 (1977)
Ties baryons (L_B) with DM (v_∞), hard to explain with collisionless CDM.
In the dissipative DM picture, follows from energy balance



Let's start from $R_{\rm SN} \propto v_\infty^3$ again. Other observational studies find:

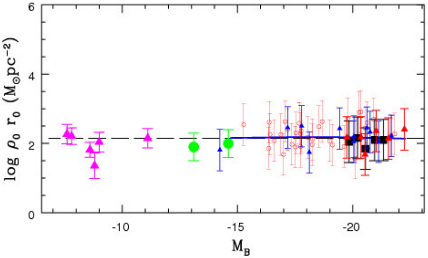
$$m_D \propto (L_B)^{1.3} \;, \quad r_D \propto (m_D)^{0.38}$$

Shankar et al., ApJ 643, 14 (2006) Salucci et al., MNRAS 378, 41 (2007)

Combining with our previously found $r_0 \propto r_D$, $L_B \propto v_\infty^4 \propto \rho_0^2 r_0^4$:

$$\rho_0 r_0 \simeq \mathrm{const}$$

Observed to hold in spiral galaxies ($\rho_0 r_0 \simeq 100 M_\odot/\mathrm{pc}^2$), unexplained using collisionless CDM Kormendy & Freeman, astro-ph/0407321; Donato et al., MNRAS 397, 1169 (2009)



Elliptical galaxies (very speculative)

- Elliptical galaxies are devoid of baryonic matter and have little star formation $\implies$ cannot use SNeII heating mechanism
- Perhaps ellipticals might be the final evolutionary stage of spirals, after they exhaust baryonic gas and can no longer heat
- If $t_{\text{cool}} \ll t_{\text{ff}}$, halo can cool and fragment into compact "dark stars"
- Since $t_{\text{cool}} \ll t_{\text{ff}}$, structural properties preserved (e.g. $\rho_0 r_0 \simeq \text{const}$)
- Dark stars could produce dark supernovae, producing lots of ionizing $\gamma \implies \gamma$s heat the baryonic gas explaining a) why only little gas left and b) why the gas left is spherically distributed

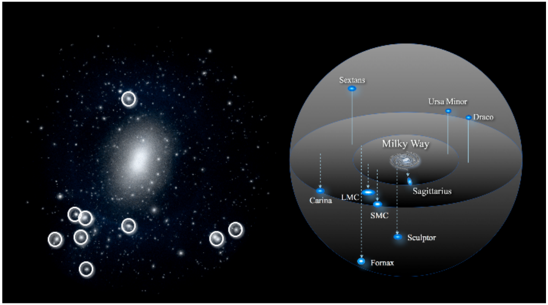
Some numbers

- For heating mechanism to work + bounds from white dwarfs: $0.01\ \mathrm{MeV} \lesssim m_{e_d} \lesssim 100\ \mathrm{MeV}$
- For cooling rate not to exceed Hubble time and ionization state of halo to be consistent with energy balance: $1\ \mathrm{GeV} \lesssim m_{p_d} \lesssim 1\mathrm{TeV}$
- For supernovae heating to replace energy dissipated: $\epsilon \gtrsim 10^{-10}$
- Bounds from LSS formation and perturbativity: $10^{-4} \lesssim \alpha_d \lesssim 10^{-1}$
- Mass range of dark electron and dark proton interesting for direct detection: could recoil on electrons and nuclei respectively? Foot, PRD 90, 121302 (2015); Foot, 1508.07402; Clarke & Foot, JCAP 1601 01, 029 (2016)

The missing satellites problem

"Where are the missing galactic satellites?" Klypin, Kravtsov, Valenzuela & Prada 522, 82-92 (1999)

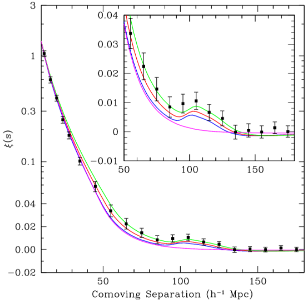
- Baryonic physics at play? (supernovae feedback, photoionization)
- Milky Way is not typical?
- We have yet to discover most of the satellites?
- ...or dark matter physics is involved? (warm dark matter, dark radiation)



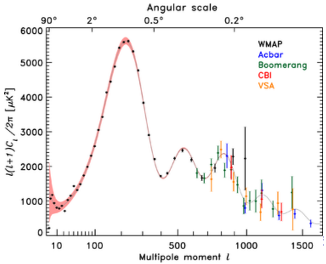
Small-scale power suppression

In our model we have two sources of power suppression:

- Acoustic damping due to dark acoustic oscillations (DAOs) of the γ_d-e_d-p_d plasma prior to dark recombination



- Diffusion (Silk) damping due to nonzero γ_d mean free path at dark recombination



Boltzmann equations

Red terms encode deviations from collisionless CDM

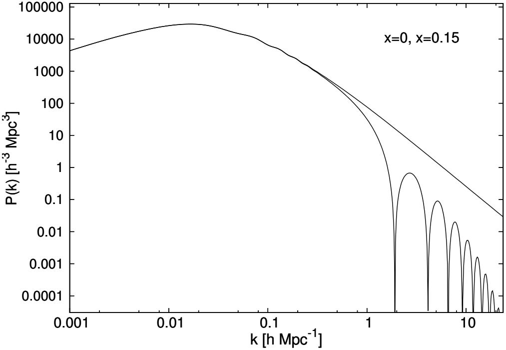
$$\begin{aligned}
\dot{\Theta}_0 + k\Theta_1 &= -\dot{\Phi} \\
\dot{\Theta}_1 - \frac{k}{3}\Theta_0 + \frac{2k}{3}\Theta_2 &= \frac{k}{3}\Psi + \dot{\tau}\left[\Theta_1 - i\frac{v_b}{3}\right] \\
\dot{\Theta}_l - \frac{kl}{2l+1}\Theta_{l-1} + \frac{k(l+1)}{2l+1}\Theta_{l+1} &= \dot{\tau}\left[\Theta_l - \delta_{l2}\frac{\Pi}{10}\right], \quad l \geq 2 \\
\dot{\delta}_b + ikv_b &= -3\dot{\Phi} \\
\dot{v}_b + \frac{\dot{a}}{a}v_b &= -ik\Psi + \frac{\dot{\tau}}{R}\left[v_b + 3i\Theta_1\right], \quad R \equiv \frac{3\rho_b}{4\rho_\gamma}
\end{aligned}$$

...etc., similarly for photon & neutrino perturbations, polarization field, dark matter + Poisson equation

Note these are in conformal Newtonian gauge, unlike CAMB which is written in synchronous gauge

Power spectrum

Effects of DAOs and diffusion damping easily noticeable in power spectrum
Take special case of mirror dark matter



First studied (to my knowledge) by groups in L'Aquila and Ferrara Berezhiani, Ciarcelluti, Comelli & Villante, Int. J. Mod. Phys. D 14, 107-120 (2005)

Damping scales

- Acoustic damping scale is sound horizon at dark recombination:

$$L_{\rm DAO} \simeq \int_0^{\eta_{\rm dr}} d\eta\; c_D(\eta) \approx 8.6 \left(\frac{\epsilon}{10^{-9}}\right)^{5/4} \left(\frac{\alpha}{\alpha_d}\right) \left(\frac{m_e}{\mathcal{M}}\right)^{5/8} \left(\frac{m_e}{m_{e_d}}\right)^{1/2} \; h^{-1}\ \mathrm{Mpc}$$

- Diffusion damping scale determined by imaginary part of dispersion relation

$$\begin{aligned} L_{\rm DSD} &\approx \pi \left[\int_0^{\eta_{\rm dr}} d\eta' \; \frac{1}{6(1+\Delta) n_{e_d} \sigma_{T_d} a(\eta')} \left(\frac{\Delta^2}{1+\Delta} + \frac{8}{9}\right)\right]^{\frac{1}{2}} \\ &\approx 0.7 \left(\frac{\epsilon}{10^{-9}}\right)^{3/4} \left(\frac{\alpha}{\alpha_d}\right)^{4} \left(\frac{m_e}{\mathcal{M}}\right)^{3/8} \left(\frac{m_e}{m_{e_d}}\right)^{1/2} \left(\frac{m_{p_d}}{m_p}\right)^{\frac{1}{2}} \; h^{-1}\ \mathrm{Mpc} \end{aligned}$$

- Associated wavenumber and mass scales:

$$k \simeq \frac{2\pi}{L}\,, \quad M \simeq \frac{\pi}{6}\rho_{\rm crit}\Omega_m L^3\,, \quad M(k) \approx 3\times 10^{12} \left(\frac{k}{\mathrm{Mpc}^{-1}}\right)^{-3} M_\odot$$

For mirror DM $L_{\rm DAO} > L_{\rm DSD}$, but for the more general model the reverse can be true

Structure formation and clustering

- Use extended Press-Schechter formalism to go from power spectrum $P(k)$ to halo mass function $dn/d\ln M$
- For cosmologies with suppressed power have to use a sharp-k filter

Schneider, MNRAS 451 3, 3117-3130 (2015)

- Halo mass function:

$$\frac{dn}{d\ln M_{\rm halo}} = \frac{1}{12\pi^2}\frac{\bar{\rho}}{M_{\rm halo}}\nu f(\nu)\frac{P(1/R)}{\delta_c^2 R^3}$$

where

$$\nu \equiv \frac{\delta_c^2}{\sigma}\,, \quad \delta_c \simeq 1.69\,, \quad \sigma(R) \equiv \frac{1}{2\pi^2}\int dk\; k^2 P(k)|W(k;R)|^2\,, \quad M_{\rm halo} \simeq \frac{4\pi}{3}(2.5R)^3\,,$$

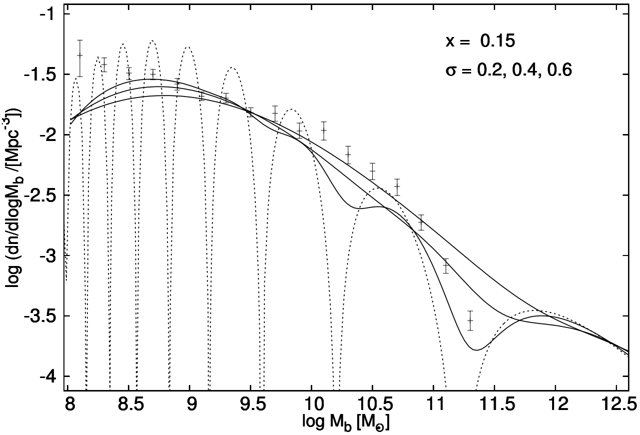
$$f(\nu) = A\sqrt{\frac{2q\nu}{\pi}}\left[1+(q\nu)^{-p}\right]e^{-\frac{q\nu}{2}}\,, \quad A \simeq 0.3222\,, \quad p = 0.3\,, \quad q = 1$$

From halo mass function to directly observable quantities

- We cannot measure the halo mass function directly because we cannot measure M_{halo} reliably!
- Relate M_{halo} to directly measurable quantities, e.g. M_b, $M_\star$, L, v_∞
- To zeroth order, try setting $M_b \propto M_{\text{halo}}$, with proportionality constant given by cosmic value
- Relate M_b to v_∞ with baryonic Tully-Fisher relation
- In the process of going from M_{halo} to M_b to v_∞, and due to finite resolution of our observations, possible effects of DAOs get smoothed out $\implies$ we model this by convolving with a Gaussian

Baryonic mass function

Take mirror DM and $\epsilon \simeq 2.3 \times 10^{-10}$



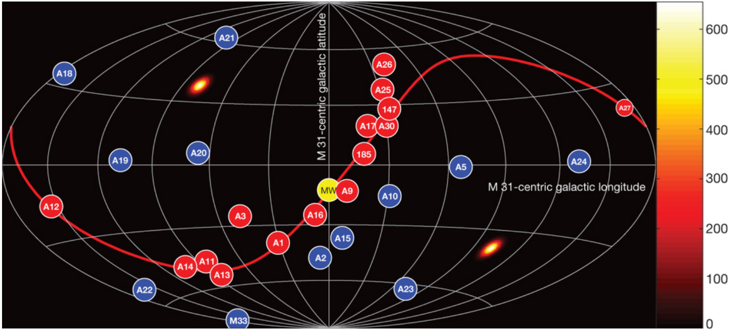
Data: Papastergis et al., ApJ 759, 138 (2012)

Mass function with dissipative dark matter

- Moderate suppression in mass function due to DAOs on galactic scales
- Strong suppression due to diffusion damping for $M \lesssim 10^9 M_\odot$
- Mass function does not match observations for $M \gtrsim 10^{12} M_\odot$, but this occurs also with collisionless cold DM $\implies$ feedback effects from SMBH energy injection can prevent structure formation
- Halo cooling timescale for large halos is slower, can slow or prevent formation of very large galaxies
- Or (especially in the case of mirror DM) halo can undergo an ionization state transition such that heating via photoionization becomes inefficient, dynamically determining a limiting galaxy scale
- For $\epsilon \approx 2 \times 10^{-10}$, power suppression on galactic and subgalactic scales yields baryonic mass function agreeing with observations

Satellite plane problem

Thin disk of co-rotating dwarfs around M31 Ibata et al., Nature 493, 62 (2013)



Similar structure around MW Pawlowski, Pflamm-Altenburg & Kroupa, MNRAS 423, 1109 (2012)

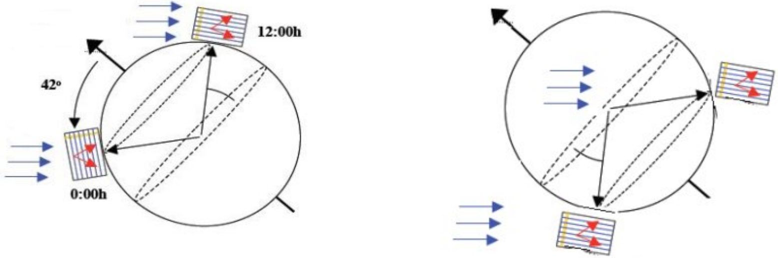
Possibly around other hosts? N. Ibata, R. Ibata, Famaey & Lewis, Nature 511, 563 (2014)

Dissipative dark matter to the rescue?

- Initially thought to be tidal dwarf galaxies (TDG) formed as the result of an ancient merger event... Foot & Silagadze, Phys. Dark Univ. 2, 163-165 (2013); Randall & Scholtz, JCAP 1509 09, 057 (2015)
- ...but TDGs should be baryon dominated, whereas these satellites are DM dominated! Lelli et al., A&A 584, A113 (2015)
- In dissipative DM scenario can have dissipative collapse followed by violent fragmentation in sufficiently overdense regions $\implies$ results in small DM dominated objects: dwarf satellites?
- Structures are naturally formed along a thin disk
- (Very speculative!) Pressure gradient would tend to align thin disk perpendicular to host galaxy $\implies$ can explain polar structure of thin disk?

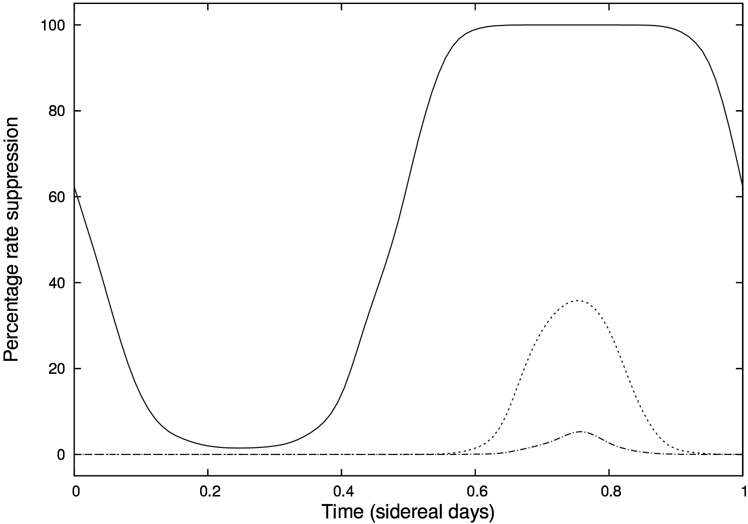
A curious experimental signal

Dark matter can be captured within the Earth and possibly shield detectors



For a detector in the Southern hemisphere, the suppression can be null at a certain point of the day, and total 12 hours after

Diurnal modulation signal

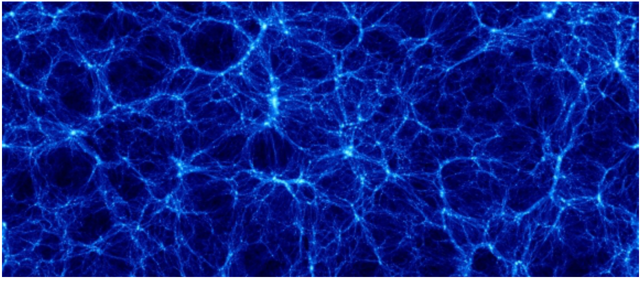


Foot & Vagnozzi, PLB 748, 61-66 (2015)

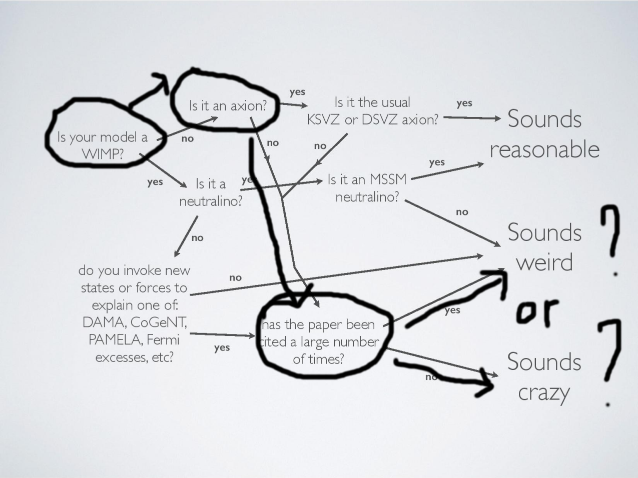
An experiment starting in Australia!

Conclusions

- Dissipative dark matter is an interesting and viable DM model which can address the shortcomings of collisionless CDM
- Cooling via bremsstrahlung compensated by heating through kinetic mixing induced processes in core-collapse supernovae
- Energy balance ties baryons and DM in a non-trivial way, explains several observed galactic scaling relations
- Can solve core-cusp and missing satellite problem (if $\epsilon \approx 2 \times 10^{-10}$)
- Can explain thin disk of co-rotating dwarfs via violent fragmentation
- Testable by direct detection (perhaps could explain DAMA?)



The end!



Courtesy: Neal Weiner

THANK YOU FOR YOUR ATTENTION!