Dissipative dark matter

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Based on Master's thesis at the University of Melbourne, published in:

`arXiv:1409.7174` [Phys. Rev. D**91** (2015) 023512, *Editors' Suggestion*],
`arXiv:1412.0762` [Phys. Lett. B**748** (2015), 61-66],
`arXiv:1602.02467` [JCAP **1607** (2016) 07, 013]

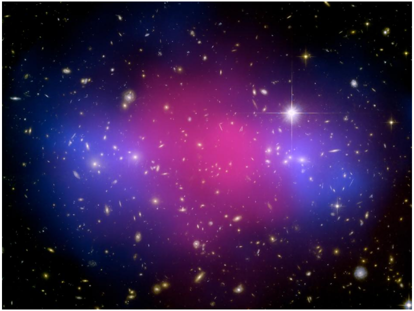
December 13, 2016
OKC Dark Matter Working Group meeting, Stockholm, Sweden

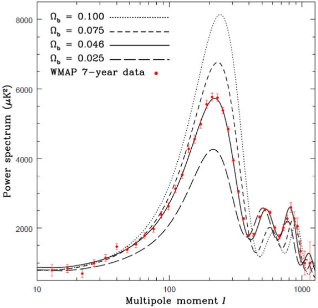
Overview

Evidence for dark matter

- Kinematics of galaxy clusters
- Rotation curves of spiral galaxies
- LSS formation
- Big Bang Nucleosynthesis

- CMB anisotropy power spectra
- BAO in 2pt correlation function
- Galaxy power spectrum
- Gravitational lensing





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 CMB anisotropy spectra

Challenges:

- *Core vs cusp* de Blok 2010
- *Missing satellites* Klypin et al. 1999
- *Too-big-to-fail* Boylan-Kolchin et al. 2011
- *Satellite plane* Ibata et al. 2013
- Several galactic scaling relations hard to explain with collisionless CDM Salucci & De Laurentis 2013

- 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 Spergel & Steinhardt 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? Three possibilities:

- Only a subdominant component of DM is dissipative (see "Double-Disk Dark Matter") Fan et al. 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"

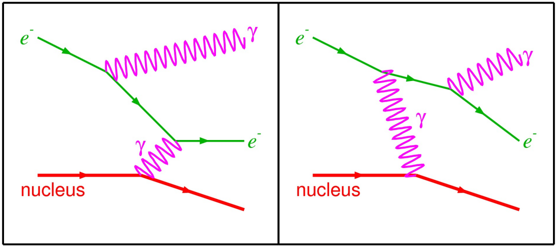
Dissipative dark matter - the prototype

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: $\mathcal{L} \supset \epsilon A'^\mu J_\mu$

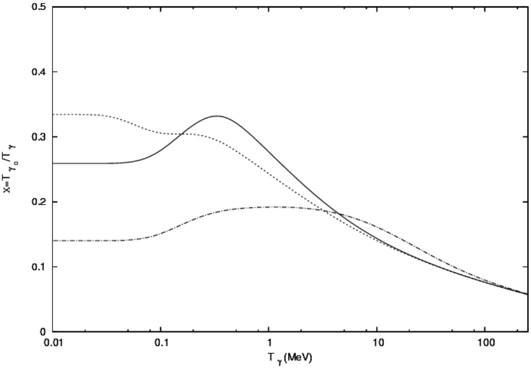
First choice of basis most common one, but in fact the two are equivalent. Dark matter is not that "dark" anymore ($\epsilon \ll 1$).

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 $e\bar{e} \rightarrow e_d \bar{e}_d$

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

$$\begin{aligned}\frac{T_{\text{hid}}}{T_{\text{vis}}} &\rightarrow 0.31\sqrt{\frac{\epsilon}{10^{-9}}}\sqrt[4]{\frac{m_{e_d}}{\mathcal{M}}}\\ \mathcal{M} &\equiv \max(m_e, m_{e_d})\end{aligned}$$



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 et al. 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”

LSS 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:

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

- Resulting bound:

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

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

Heating from ordinary supernovae

- For $\epsilon \sim 10^{-9}$ and $m_{e_d} \lesssim 100\ \mathrm{MeV}$, kinetic mixing induced processes in SNeII can transfer up an important fraction of the core-collapse energy to dark particles: e_d, $\bar{e}_d$, γ_d Raffelt 1996; Davidson et al. 2000; Foot & Silagadze 2005
- Was first proposed for mirror DM Foot & Volkas 2004
- Plasmon decay and pair annihilation: $\gamma \rightarrow e_d \bar{e}_d$, $e\bar{e} \rightarrow e_d \bar{e}_d$

Dynamical halo equations

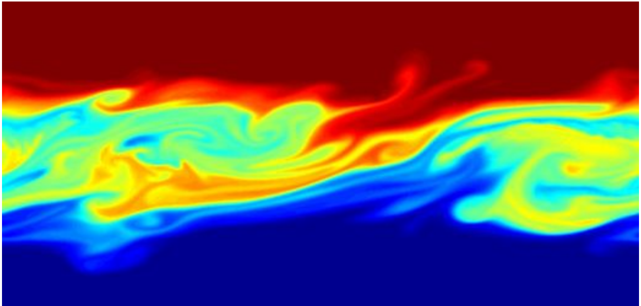
- Local energy balance

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

- Hydrostatic equilibrium:

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

- Equations represent static limit of Euler equations of fluid dynamics



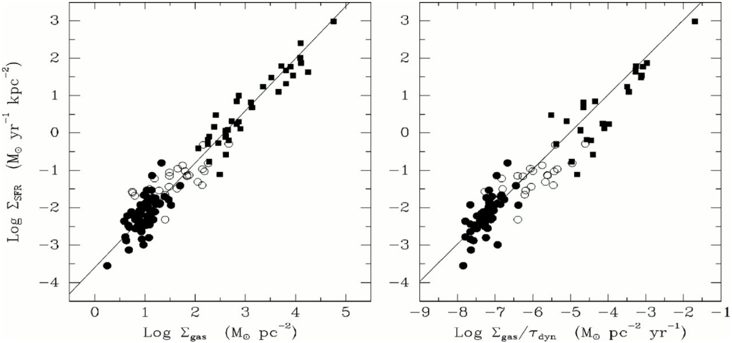
Aside: can the system evolve to a static configuration?

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

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

Schmidt 1959; Kennicutt 1998

- 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



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:

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

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

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

- Energy balance:

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

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 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:

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

- 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 $R_{\mathrm{SN}} \propto v_\infty^3$. Supernovae studies find:

$$R_{\mathrm{SN}} \propto (L_B)^{0.73} \ ,$$

Li et al. 2011

from which we get:

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

The above corresponds to the Tully-Fisher relation: Tully & Fisher 1977

- Ties baryons (L_B) with DM (v_∞)
- Not yet clear whether it can be explained with collisionless CDM
- In the dissipative DM picture, follows from energy balance

Constant surface density

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

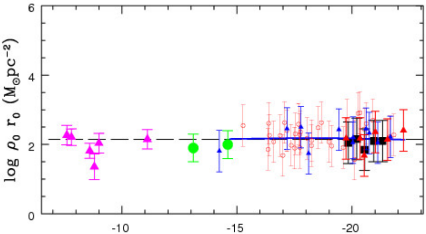
$$m_D \propto (L_B)^{1.3} \,, \quad r_D \propto (m_D)^{0.38}$$

Shankar et al. 2006 Salucci et al. 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 ($\rho_0 r_0 \simeq 100 M_\odot/\mathrm{pc}^2$) over a wide range of masses Kormendy & Freeman 2004; Donato et al. 2009
- Unexplainable with collisionless CDM



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?

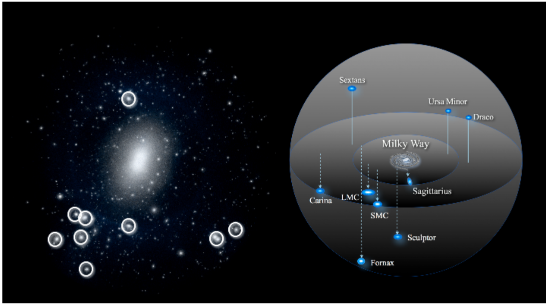
The missing satellites problem

“Where are the missing galactic satellites?” Klypin et al. 1999

- Baryonic physics at play?

  Brooks et al. 2012
- Milky Way is an outlier?
- We have yet to discover most of the satellites?
- ...or dark matter physics is involved? (warm dark matter, dark radiation)

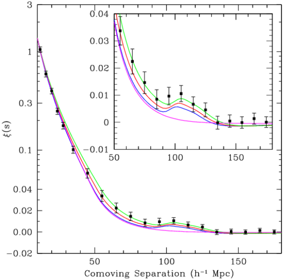
  Vogelsberger et al. 2015

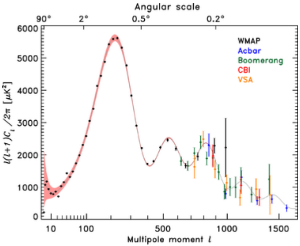


Small-scale power suppression

Two sources of small-scale power suppression:

- Dark acoustic oscillations (DAOs) of the γ_d-e_d-p_d plasma prior to dark recombination: acoustic damping
- Non-zero γ_d mean free path at dark recombination: diffusion (collisional) damping





Boltzmann equations

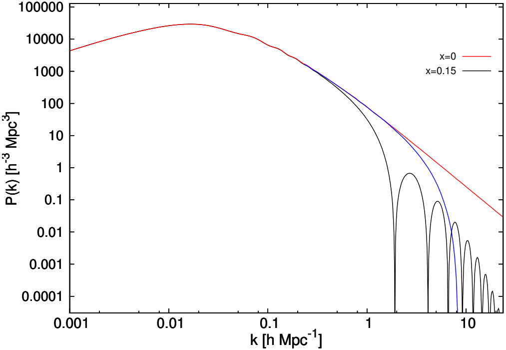
Red terms encode deviations from collisionless CDM

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

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

Power spectrum

Effects of DAOs and diffusion damping easily noticeable in power spectrum



Damping scales

- Acoustic damping scale given by 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:

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

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 use sharp-k filter Schneider 2015
- Halo mass function:

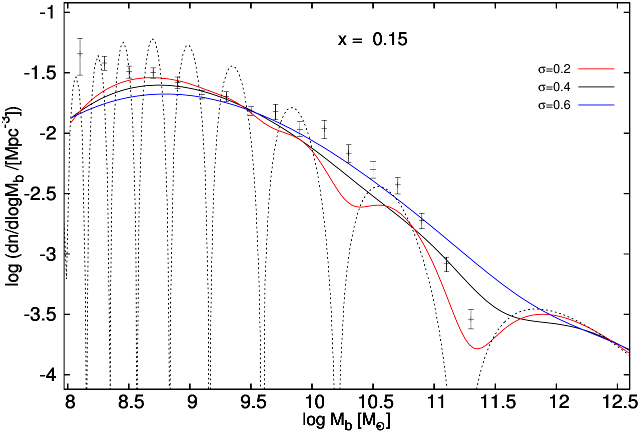
$$\frac{dn}{d\ln M_{\mathrm{halo}}} = \frac{1}{12\pi^2}\frac{\bar{\rho}}{M_{\mathrm{halo}}}\nu f(\nu)\frac{P(1/R)}{\delta_c^2 R^3}$$

From halo mass function to directly observable quantities

- We cannot measure the halo mass function directly because we cannot measure M_{halo}!
- 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 $\alpha' = \alpha$, $m_{e_d} = m_e$, $m_{p_d} = m_p$, $\epsilon \simeq 2.3 \times 10^{-10}$



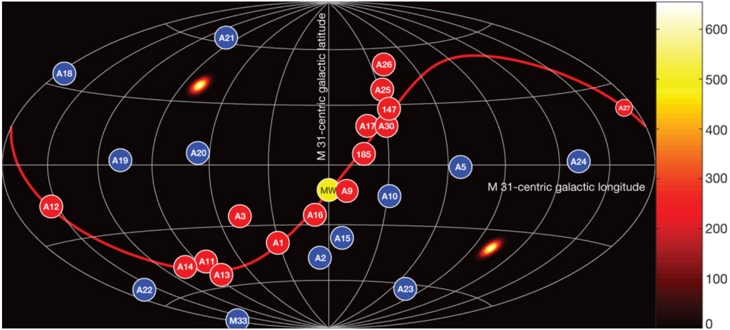
Data: Papastergis et al. 2012

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
- 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 2013



Similar structure around MW Pawlowski et al. 2012

Possibly around other hosts? Ibata et al. 2014

Dissipative dark matter explains satellite plane?

- Initially thought to be tidal dwarf galaxies (TDG) formed as the result of an ancient merger event... Foot & Silagadze 2013; Randall & Scholtz 2015
- ...but TDGs should be baryon dominated... Bournaud et al. 2007; Lelli et al. 2015
- ...whereas these satellites are DM dominated!
- 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

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 address core-cusp and missing satellite problem, and might explain thin disk of co-rotating dwarfs (this requires $\epsilon \approx 2 \times 10^{-10}$)