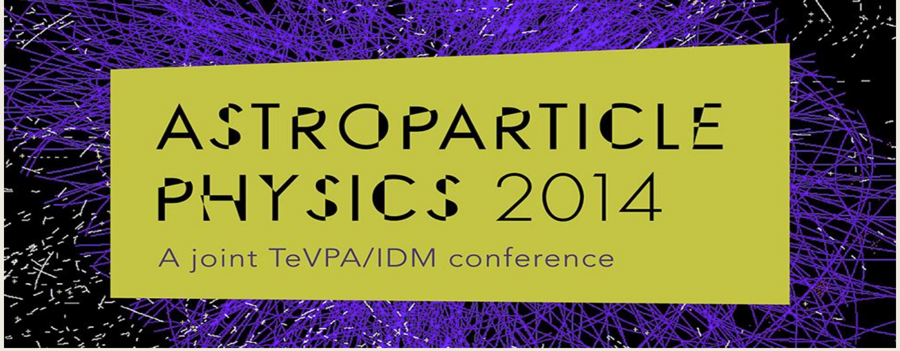

Explaining galactic structure and direct detection experiments with mirror dark matter

Robert Foot, CoEPP, University of Melbourne

June 26 2014

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Mirror dark matter: Cosmology, galaxy structure and direct detection

R. Foot

(Submitted on 16 Jan 2014)

A simple way to accommodate dark matter is to postulate the existence of a hidden sector. That is, a set of new particles and forces interacting with the known particles predominately via gravity. In general this leads to a large set of unknown parameters, however if the hidden sector is an exact copy of the standard model sector, then an enhanced symmetry arises. This symmetry, which can be interpreted as space-time parity, connects each ordinary particle ($e,\ \nu,\ p,\ n,\ \gamma, \dots$) with a mirror partner ($e',\ \nu',\ p',\ n',\ \gamma', \dots$). If this symmetry is completely unbroken, then the mirror particles are degenerate with their ordinary particle counterparts, and would interact amongst themselves with exactly the same dynamics that govern ordinary particle interactions. The only new interaction postulated is photon - mirror photon kinetic mixing, whose strength ϵ, is the sole new fundamental (Lagrangian) parameter relevant for astrophysics and cosmology. It turns out that such a theory, with suitably chosen initial conditions effective in the very early Universe, can provide an adequate description of dark matter phenomena provided that $\epsilon \sim 10^{-9}$. This review focusses on three main developments of this mirror dark matter theory during the last decade: Early universe cosmology, galaxy structure and the application to direct detection experiments.

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Subjects: **Cosmology and Extragalactic Astrophysics (astro-ph.CO)**; High Energy Physics - Phenomenology (hep-ph)
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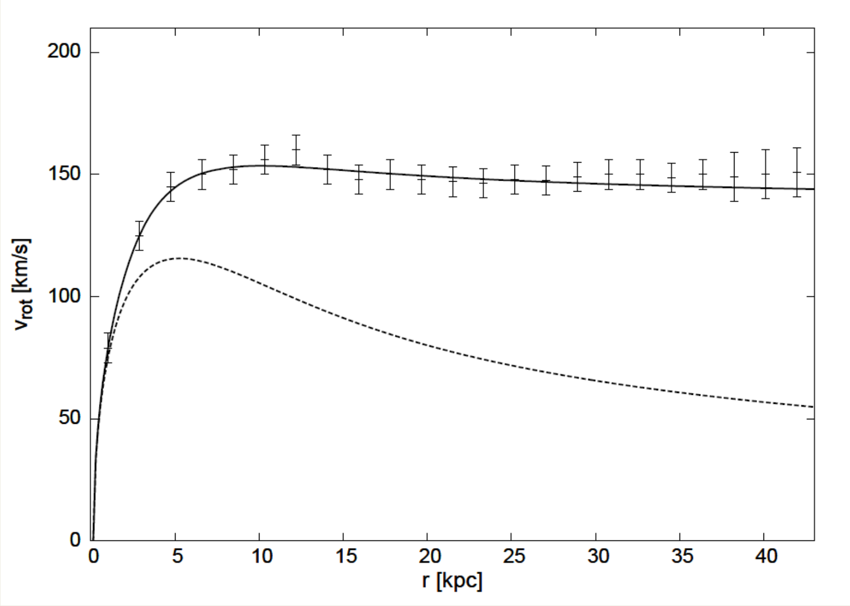
See this review for detailed references to the literature

Link back to: arXiv, form interface, contact.

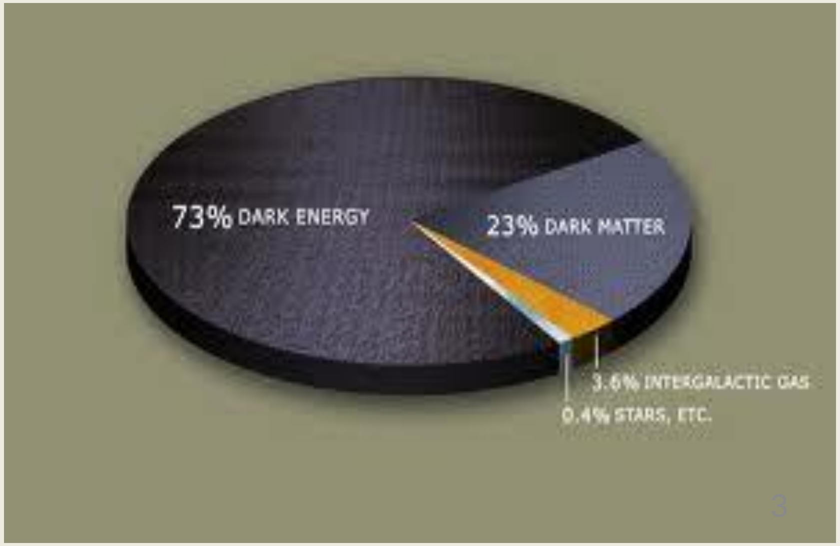
Evidence for non-baryonic dark matter

Rotation curves in spiral galaxies: E.g. NGC3198



Lambda-CDM Model

Suggests 23% of the Universe consists of non-baryonic dark matter



What is dark matter?

Dark matter might arise from a '**hidden sector**':

$$\mathcal{L} = \mathcal{L}_{SM}(e, u, d, \gamma, W, Z, ...) + \mathcal{L}_{dark}(F_1, F_2, G_1, G_2, ...) + \mathcal{L}_{mix}$$

Such a theory generally has accidental U(1) symmetries leading to massive stable fermions. Such a theory is also very poorly constrained by experiments.

An interesting special case is where $\mathcal{L}_{dark}(F_1, F_2, G_1, G_2, ...)$ is 'isomorphic' to the standard model:

$$\mathcal{L} = \mathcal{L}_{SM}(e, u, d, \gamma, W, Z, ...) + \mathcal{L}_{SM}(e', u', d', \gamma', W', Z', ...) + \mathcal{L}_{mix}$$

There is a symmetry swapping each ordinary particle with its mirror partner. If we swap left and right chiral fields then this symmetry can be interpreted as space-time parity:

$$x, y, z, t \to -x, -y, -z, t$$

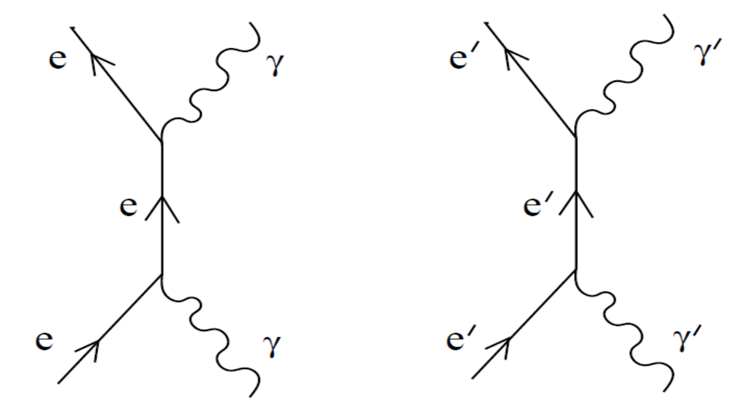
$$G^{\mu} \leftrightarrow G'_{\mu},\ W^{\mu} \leftrightarrow W'_{\mu},\ B^{\mu} \leftrightarrow B'_{\mu},\ \phi \leftrightarrow \phi'$$

$$\ell_{iL} \leftrightarrow \gamma_0 \ell'_{iR},\ e_{iR} \leftrightarrow \gamma_0 e'_{iL},\ q_{iL} \leftrightarrow \gamma_0 q'_{iR},\ u_{iR} \leftrightarrow \gamma_0 u'_{iL},\ d_{iR} \leftrightarrow \gamma_0 d'_{iL}$$

Mirror dark matter with kinetic mixing

Mirror dark matter has a rich structure: it is multi-component, self interacting and dissipative. Importantly there are no free parameters describing masses and self interactions of the mirror particles!

Exact symmetry implies:
$m_{e'} = m_e$, $m_{p'} = m_p$, $m_{\gamma'} = m_\gamma = 0$ etc
and all cross-sections of mirror particle self-interactions the same as for ordinary particles.



Also, ordinary and dark matter almost decoupled from each other. Only gravity and photon-mirror photon kinetic mixing important for dark matter.

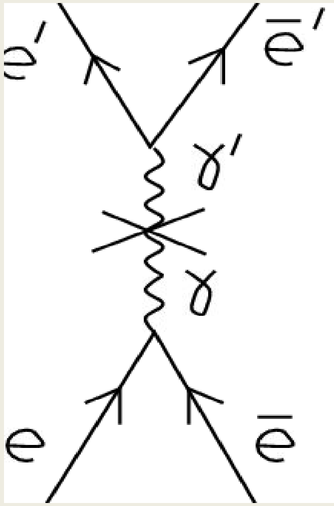
$$\mathcal{L}_{mix} = \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$

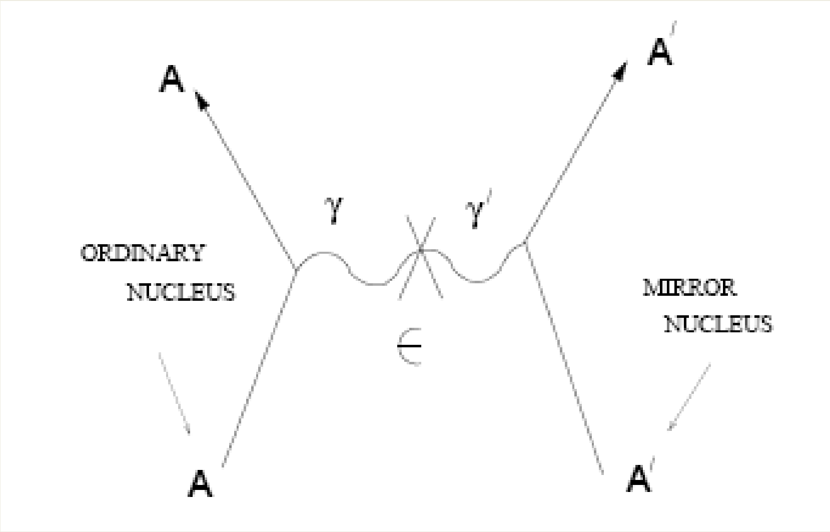
Kinetic mixing is theoretically free parameter, preserves all symmetries of the theory, and is renormalizable.

Kinetic Mixing

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

The physical effect of kinetic mixing is to induce tiny ordinary electric charges for mirror particles. This means that they can couple to ordinary photons:





Important for cosmology, supernova's, Galactic structure, if

$$\epsilon \sim 10^{-9}$$

Important for direct detection experiments, such as DAMA, CoGeNT etc if

$$\epsilon \sim 10^{-9}$$

Early Universe cosmology

Consistent early Universe cosmology requires suitable initial conditions.

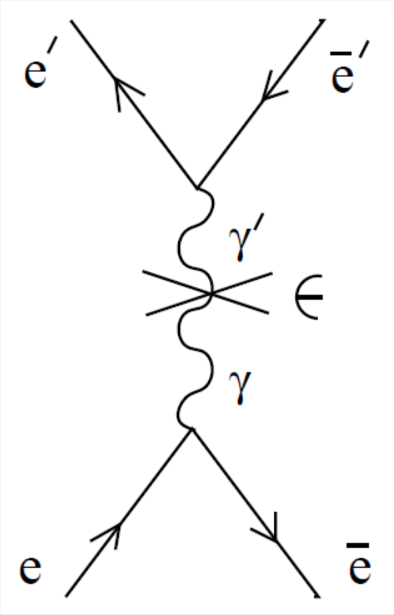
In addition to standard adiabatic (almost) scale invariant density perturbations, need:

(1) $T' \ll T$ BBN/CMB

(2) $\frac{\Omega_b}{\Omega_{cold}} \simeq 0.2 \Rightarrow \frac{n_B}{n_{B'}} \simeq 0.2$ CMB

But kinetic mixing interaction can produce entropy in mirror sector leading to non-negligible T'/T :

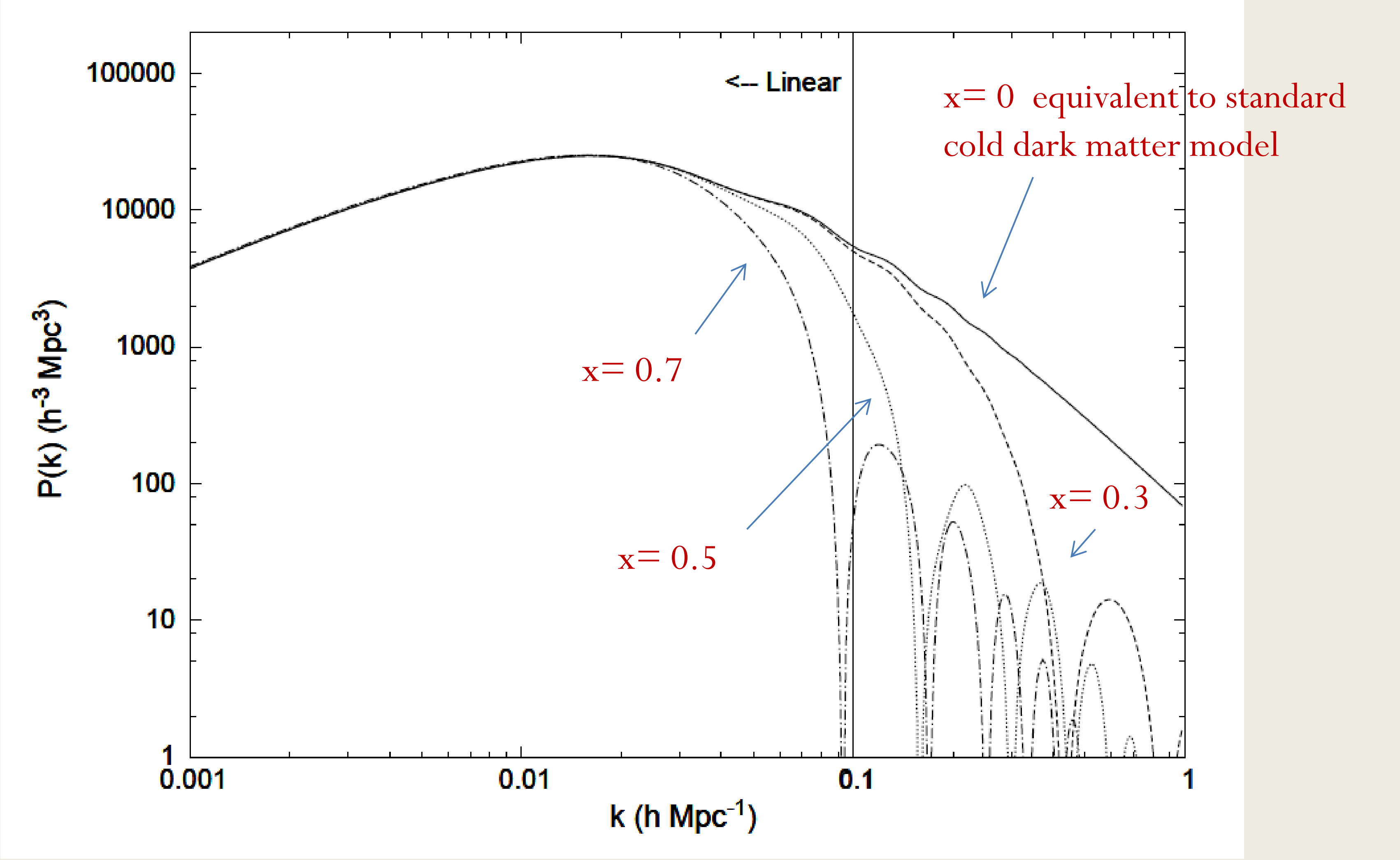
$$\frac{T'_\gamma}{T_\gamma} \simeq 0.31 \left(\frac{\epsilon}{10^{-9}}\right)^{1/2}$$



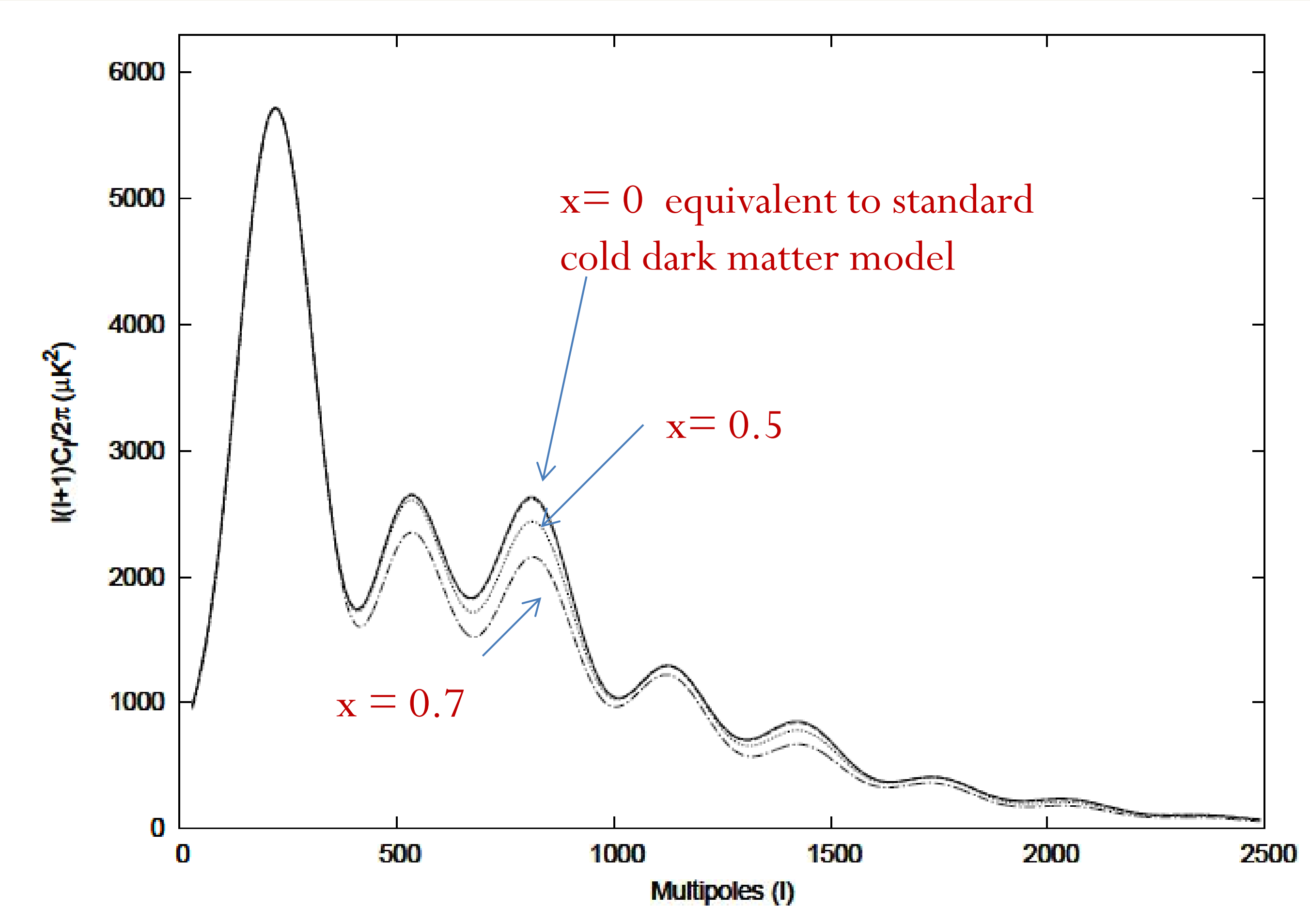
This means that at early times, mirror hydrogen was ionized. Mirror particles undergo <u>acoustic oscillations</u> prior to mirror hydrogen recombination.

Can suppress small scale structure if $\epsilon \sim 10^{-9}$

Implications of kinetic mixing for matter power spectrum



Implications of kinetic mixing for CMB



Current observations limit x = T'/T < 0.3-0.4.

$$\frac{T'_\gamma}{T_\gamma} \simeq 0.31 \left(\frac{\epsilon}{10^{-9}} \right)^{1/2}$$

Galaxy structure

Mirror dark matter is collisional and dissipative.

Mirror particle halos of galaxies are composed of a plasma containing: e', H', He', O', Fe' ….

This plasma can be modelled as a fluid, described by the Euler equations:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} = -\left(\nabla \Phi + \frac{\nabla P}{\rho}\right)$$

$$\frac{\partial}{\partial t}\left[\rho\left(\frac{v^2}{2} + \mathcal{E}\right)\right] + \nabla \cdot \left[\rho\left(\frac{v^2}{2} + \frac{P}{\rho} + \mathcal{E}\right)\mathbf{v}\right] - \rho \mathbf{v} \cdot \nabla \Phi = \mathcal{H} - \mathcal{C}$$

Halo heating supplied by Supernova generated γ'

Cooling due (mainly) to bremsstrahlung.

Spiral galaxies today

If system evolves to a static configuration then v=0 everywhere.

If this happens the equations reduce to two relatively simple equations, if spherical symmetry assumed:

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

Hydrostatic equilibrium

$$\frac{d^2E_{in}}{dtdV} = \frac{d^2E_{out}}{dtdV}$$

Energy balance equation:
Heating=cooling

That is, we have two equations for two unknowns,
the dark matter ρ(r), T(r) distributions.

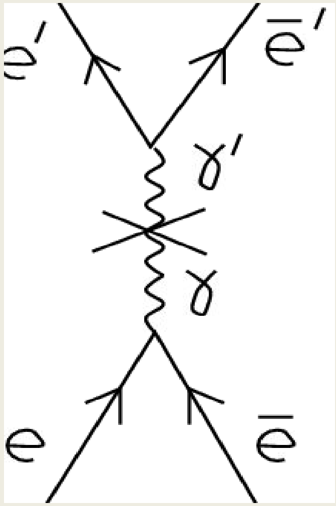
Before we can solve these equations, need to identify the heat source.

Ordinary Supernova can supply required heat for the Halo

Supernova core temperature ~ 30 MeV.

In standard theory, core collapse energy (~310^{53} ergs) is released in neutrinos.

If mirror sector exists with kinetic mixing: $\epsilon \sim 10^{-9}$, then ~1/2 of the core collapse energy will instead be released into light mirror particles: e^{-}', e^{+}', γ'.



In the region around the supernova, this energy is ultimately converted into mirror photons.

Detailed energy spectrum is difficult to predict. If a substantial fraction of these photons (> ~ 10%) have energy less than ~30 keV, then they can provide a substantial heat source ~10^{43} erg/s (for MW galaxy).

Dynamical halo model
Governed by a) heating b) cooling c) hydrostatic equilibrium

$$\frac{d^2E_{in}}{dtdV} = \frac{d^2E_{out}}{dtdV}$$

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

These two equations can be used to work out T(r) and ρ(r), given a known baryonic matter distribution and supernova rate

$$\frac{d^2E_{in}}{dtdV} = \int \frac{dF(r)}{dE_{\gamma'}} \, n_{Fe'}(r) \, \sigma_{PE} \, dE_{\gamma'}$$

$$\frac{dF(r)}{dE_{\gamma'}} = R_{SN} \, E_{\gamma'} \frac{dN_{\gamma'}}{dE_{\gamma'}} \int_0^\infty \int_{-1}^1 \frac{\rho_D}{m_D} \frac{e^{-\tau} \, r'^2}{2\mathrm{d}^2} \, d\cos\theta dr'$$

Supernova rate

$$\frac{d^2E_{out}}{dtdV}$$

Approximate E_{out} with thermal bremsstrahlung rate

$$\frac{d^2W}{dtdV} = \frac{16\alpha^3}{3m_e}\left(\frac{2\pi T}{3m_e}\right)^{1/2} \sum_j \left[Z_j^2 n_j n_{e'} \bar{g}_B\right]$$

Spiral galaxies today

Numerically solve the equations for a `generic' spiral galaxy of stellar mass m_D , disk scale length r_D .

Find that dark matter parameterized via:

$$\rho(r) = \rho_0 \left[\frac{r_0^2}{r^2 + r_0^2} \right]^\beta$$

gives solution to the hydrostatic equilibrium equilibrium and energy balance equation, iff:

$$\begin{aligned} \beta &\simeq 1.0 \\ r_0 &\simeq 1.4 \left(\frac{r_D}{\mathrm{kpc}} \right) \mathrm{kpc} \\ \rho_0 r_0 &\simeq \left[\frac{\xi_{Fe'}}{0.02} \right]^{0.8} \left[\frac{L'^{MW}_{SN}}{10^{45}\ \mathrm{erg/s}} \right]^{0.8} \left[\frac{2}{c_1} \right] 50\ m_\odot/\mathrm{pc}^2 . \end{aligned}$$

Cores of Dark Matter Halos Correlate with Stellar Scale Lengths

Fiorenza Donato [1*], Gianfranco Gentile[2†], and Paolo Salucci[2‡]

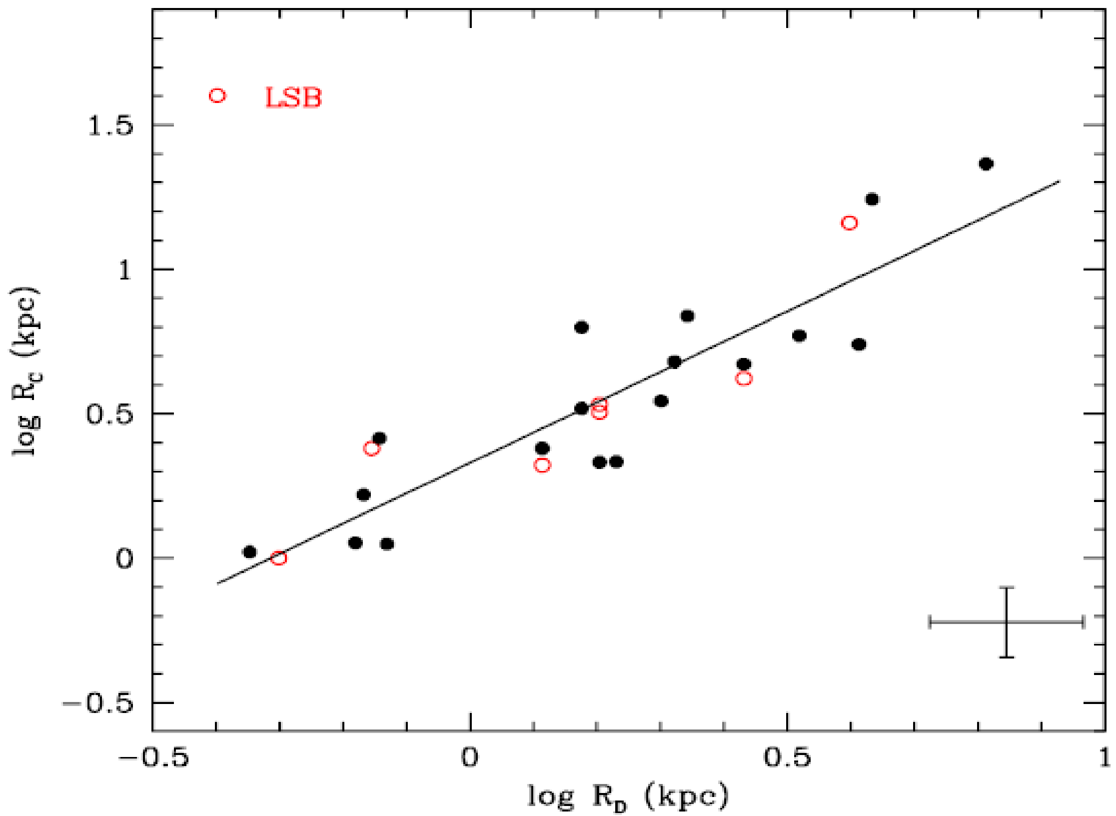


Figure 1. Core radius R_C as a function of the disk scale length R_D. Open and filled circles refer to LSB and HSB galaxies, respectively. The solid line is the least square fit.

Constant halo surface density first discussed by Kormendy and Freeman – 2004 and further studied by Donato et al.

A constant dark matter halo surface density in galaxies

F. Donato[1⋆], G. Gentile[2,3], P. Salucci[4], C. Frigerio Martins[5], M. I. Wilkinson[6], G. Gilmore[7], E. K. Grebel[8], A. Koch[9], R. Wyse[10]

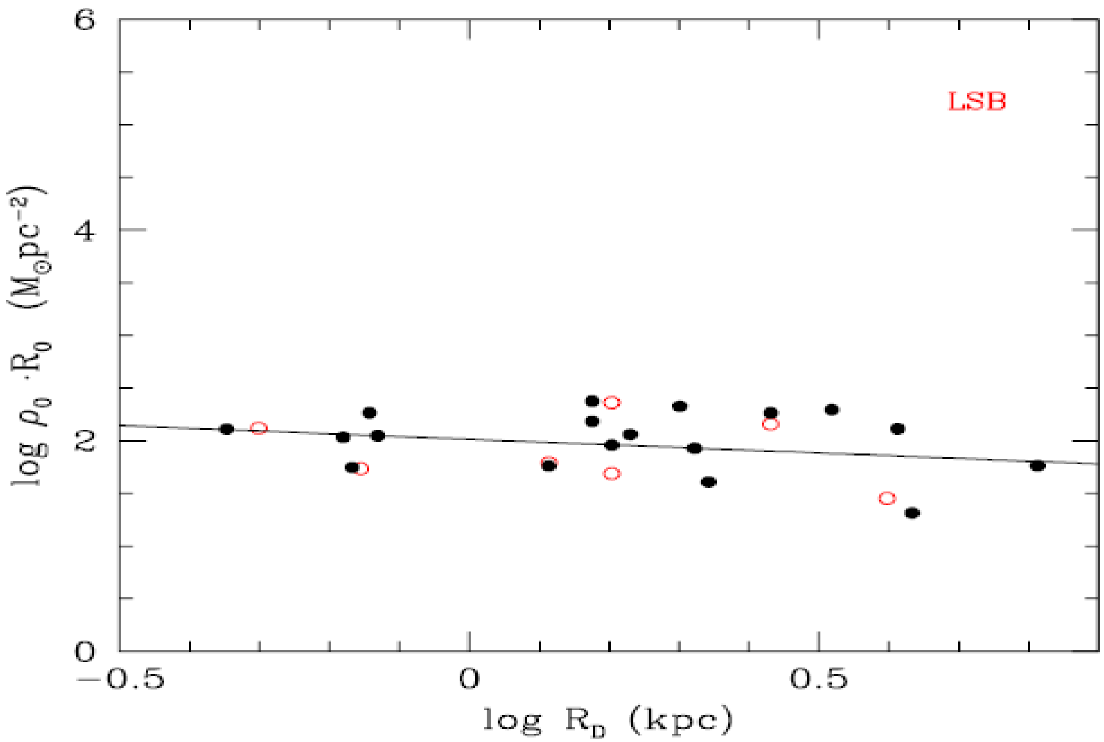


Figure 1. The central halo surface density $\rho_0 r_0$ as a function of disk scale-length R_D for the Donato et al. (2004) sample of galaxies. Open and filled circles refer to LSB and HSB galaxies, respectively. The solid line is our best fit to the data.

Spiral galaxies today – derived temperature profile

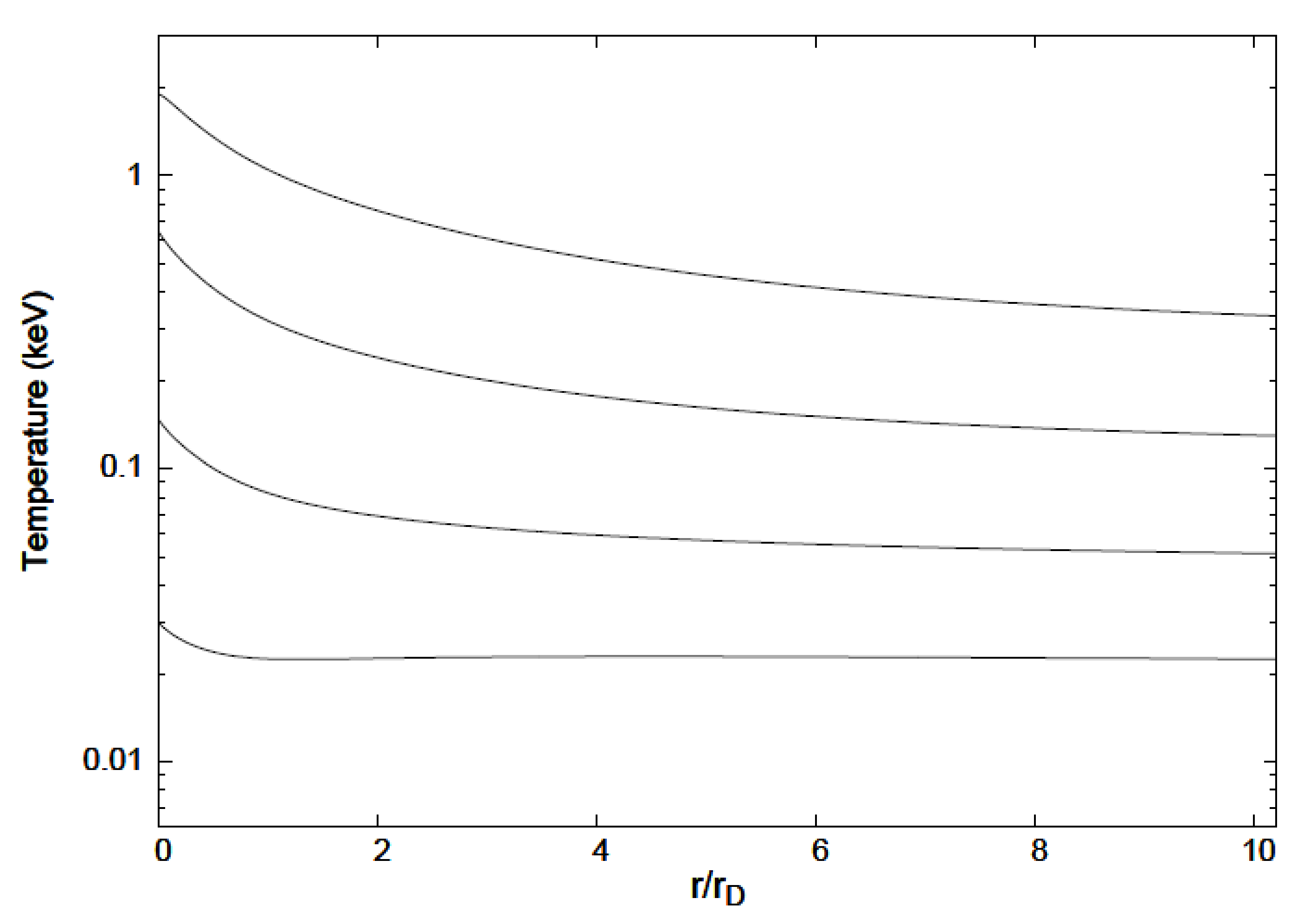


Figure 4.7: Halo mirror plasma temperature versus r/r_D for the examples with (from bottom to top curves): $m_D = 10^9\ m_\odot,\ m_D = 10^{10}\ m_\odot,\ m_D = 10^{11}\ m_\odot,\ m_D = 10^{12}\ m_\odot$.

Spiral galaxies today derived rotation curves

$$v_{rot}(r) = \left[\frac{G_N}{r}\int_0^r \rho_{total}\; dV\right]^{1/2}$$

$\rho_{total} = \rho_{baryons} + \rho_{dark\ matter}$

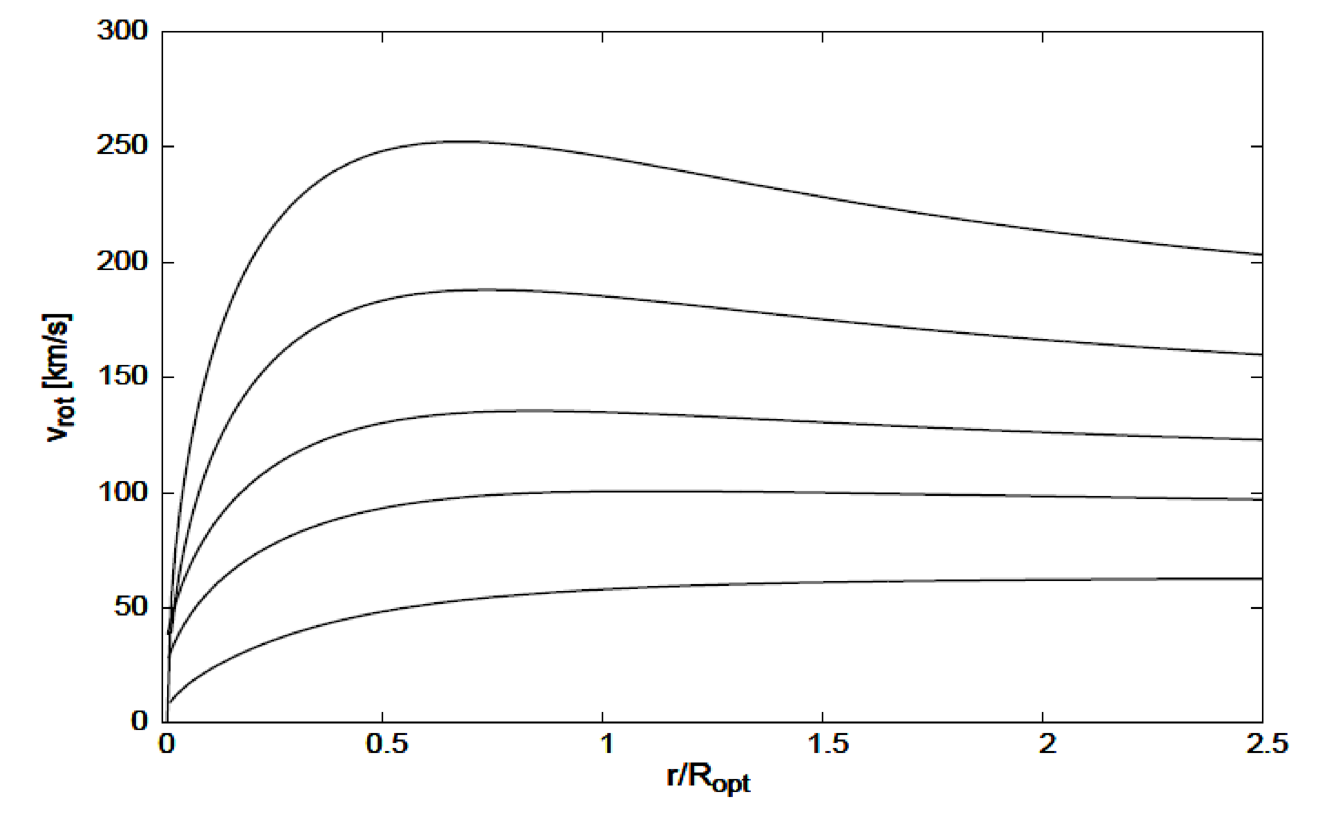
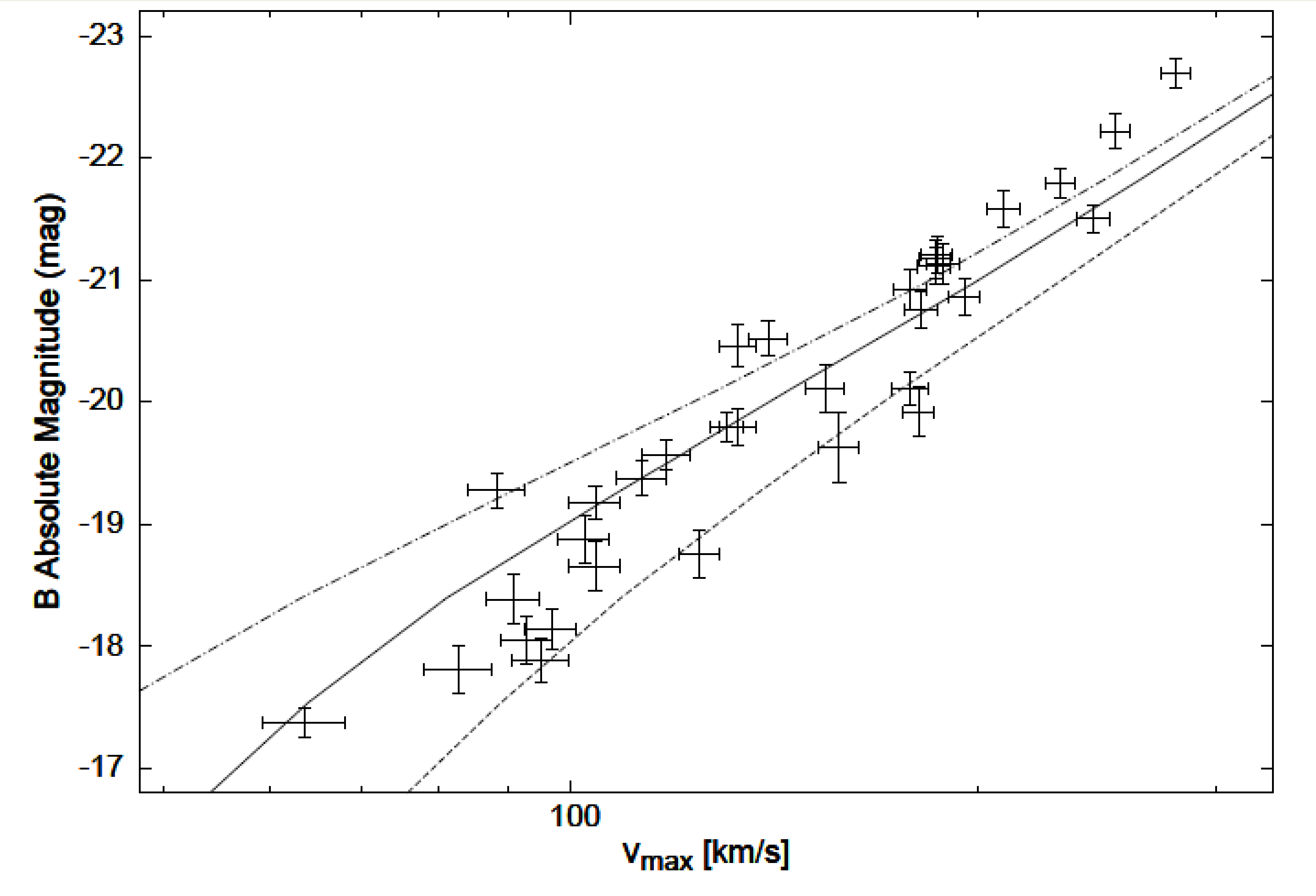


Figure 4.9: Derived rotation curves for examples with (from bottom to top) $m_D = 10^9\ m_\odot$, $m_D = 10^{10}\ m_\odot$, $m_D = 3\times10^{10}\ m_\odot$, $m_D = 10^{11}\ m_\odot$, $m_D = 3\times10^{11}\ m_\odot$. The rotational velocity, v_{rot} [km/s] is plotted against r/R_{opt}, where $R_{opt} = 3.2r_D$.

Spiral galaxies today – Tully Fisher relation



Data: Webster et al, 2008

Spiral galaxies today

Derived mirror dark matter density profile:

$$\rho(r) = \rho_0 \left[\frac{r_0^2}{r^2 + r_0^2} \right]^{\beta}$$

$$\begin{aligned}
\beta &\simeq 1.0 \\
r_0 &\simeq 1.4 \left(\frac{r_D}{\text{kpc}} \right) \text{ kpc} \\
\rho_0 r_0 &\simeq \left[\frac{\xi_{Fe'}}{0.02} \right]^{0.8} \left[\frac{L'^{MW}_{SN}}{10^{45} \text{ erg/s}} \right]^{0.8} \left[\frac{2}{c_1} \right] 50 \; m_\odot/\text{pc}^2 \; .
\end{aligned}$$

Putting in epsilon dependence in last equation:

$$\rho_0 r_0 \sim \left(\frac{\epsilon \sqrt{\xi_{Fe'}}}{4 \times 10^{-10}} \right)^{1.6} 50 \; m_\odot/\text{pc}^2$$

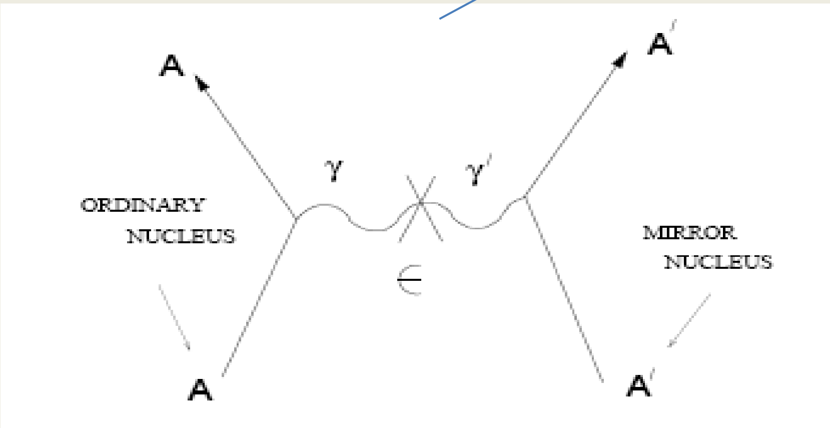
$\Rightarrow$

$$\epsilon \sqrt{\xi_{Fe'}} \sim 10^{-10} - 10^{-9}$$

Mirror dark matter – direct detection

Rate depends on cross-section and halo distribution:

$$\frac{dR}{dE_R} = N_T n_{A'} \int_{|\mathbf{v}|>v_{min}}^{\infty} \frac{d\sigma}{dE_R} \frac{f_{A'}(\mathbf{v},\mathbf{v}_E)}{v_0^3\,\pi^{3/2}} \,|\mathbf{v}|\, d^3\mathbf{v}$$



Halo distribution is Maxwellian with

$$T \approx \frac{1}{2}\bar{m}v_{rot}^2$$

$$\frac{d\sigma}{dE_R} = \frac{\lambda}{E_R^2 v^2}$$

$$\lambda \equiv \frac{2\pi\epsilon^2 Z^2 Z'^2 \alpha^2}{m_A} F_A^2(qr_A) F_{A'}^2(qr_{A'})$$

The bottom line: $Rate \;\propto\; \xi_{Fe'}\; \epsilon^2$

Mirror dark matter – direct detection

Mirror dark matter has 3 key features:

a) It is multi-component and light: H', He', O', Fe',…

b) Interacts via Rutherford scattering.

c) Halo velocity dispersion can be very narrow.

$$T \approx \frac{1}{2}\bar{m}v_{rot}^2 \quad \Rightarrow \quad v_0^2[i] = v_{rot}^2 \frac{\overline{m}}{m_i}$$

Mean mass of particles in halo

$\bar{m} \approx 1.1 \text{ GeV}$

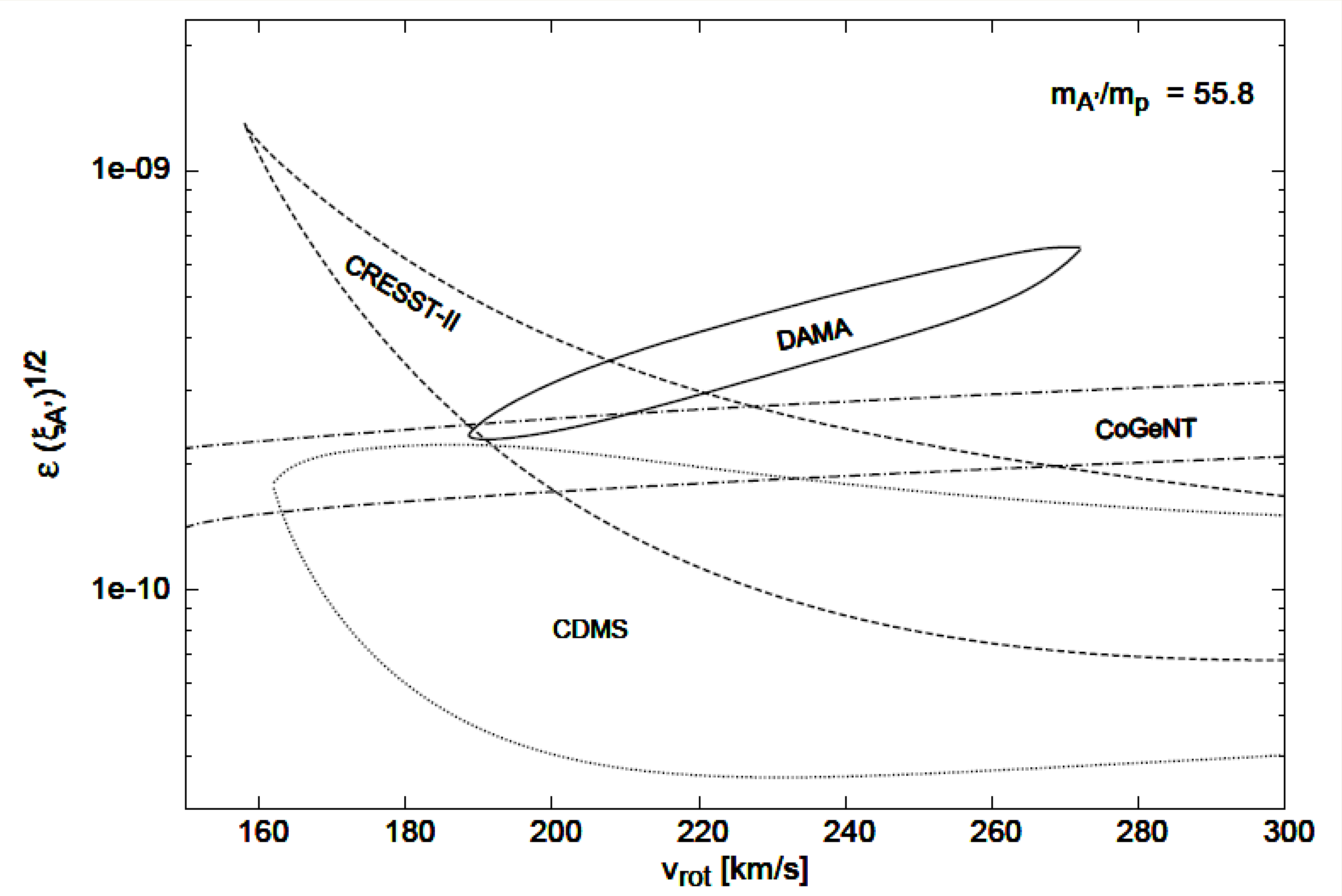
Galactic rotation velocity

$v_{rot} \approx 240 \text{ km/s}$

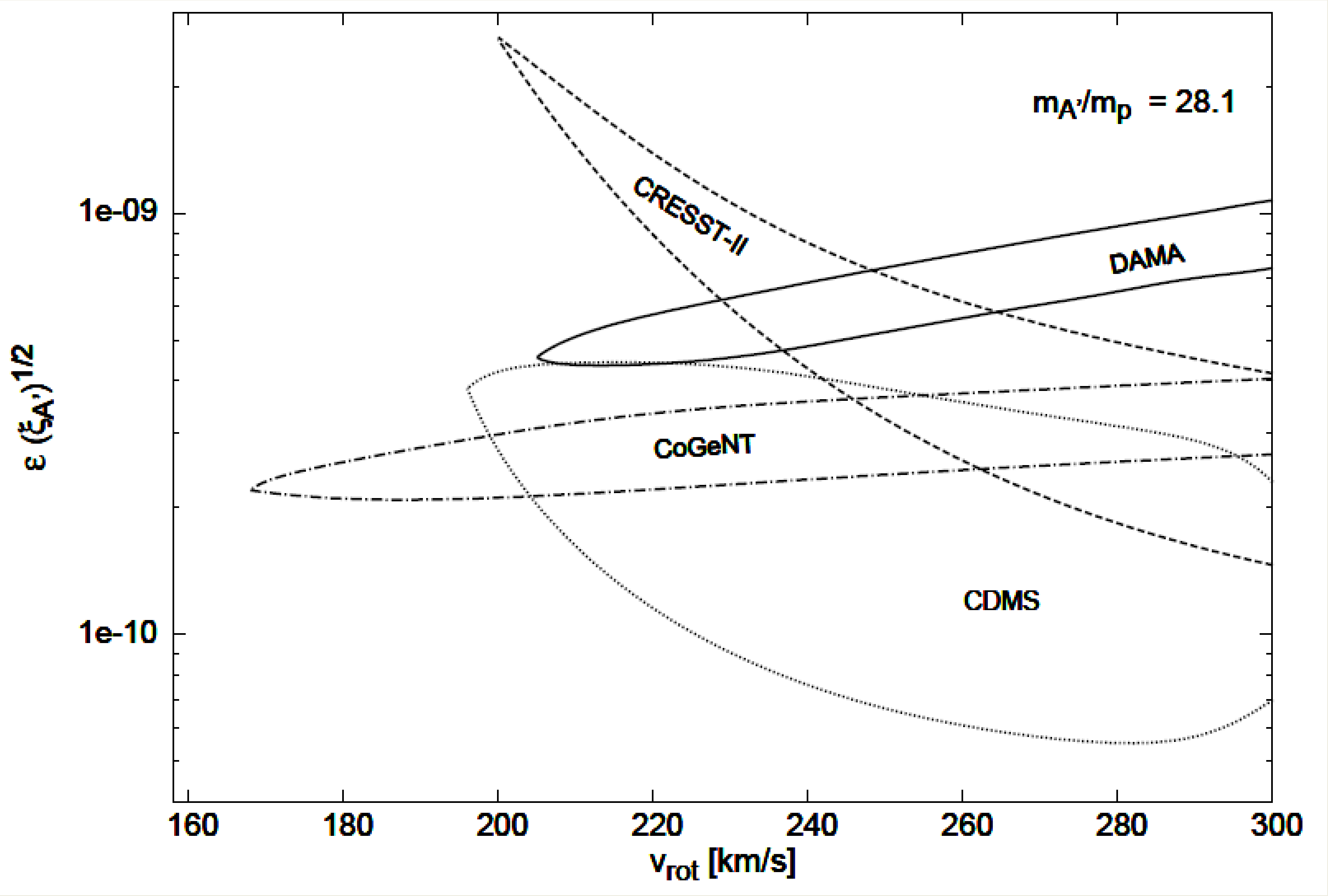
Mirror metal nuclei have masses $m_i \gg \bar{m}$ and thus $v_0^2[i] \ll v_{rot}^2$

This might help explain why higher threshold experiments do not see a signal.

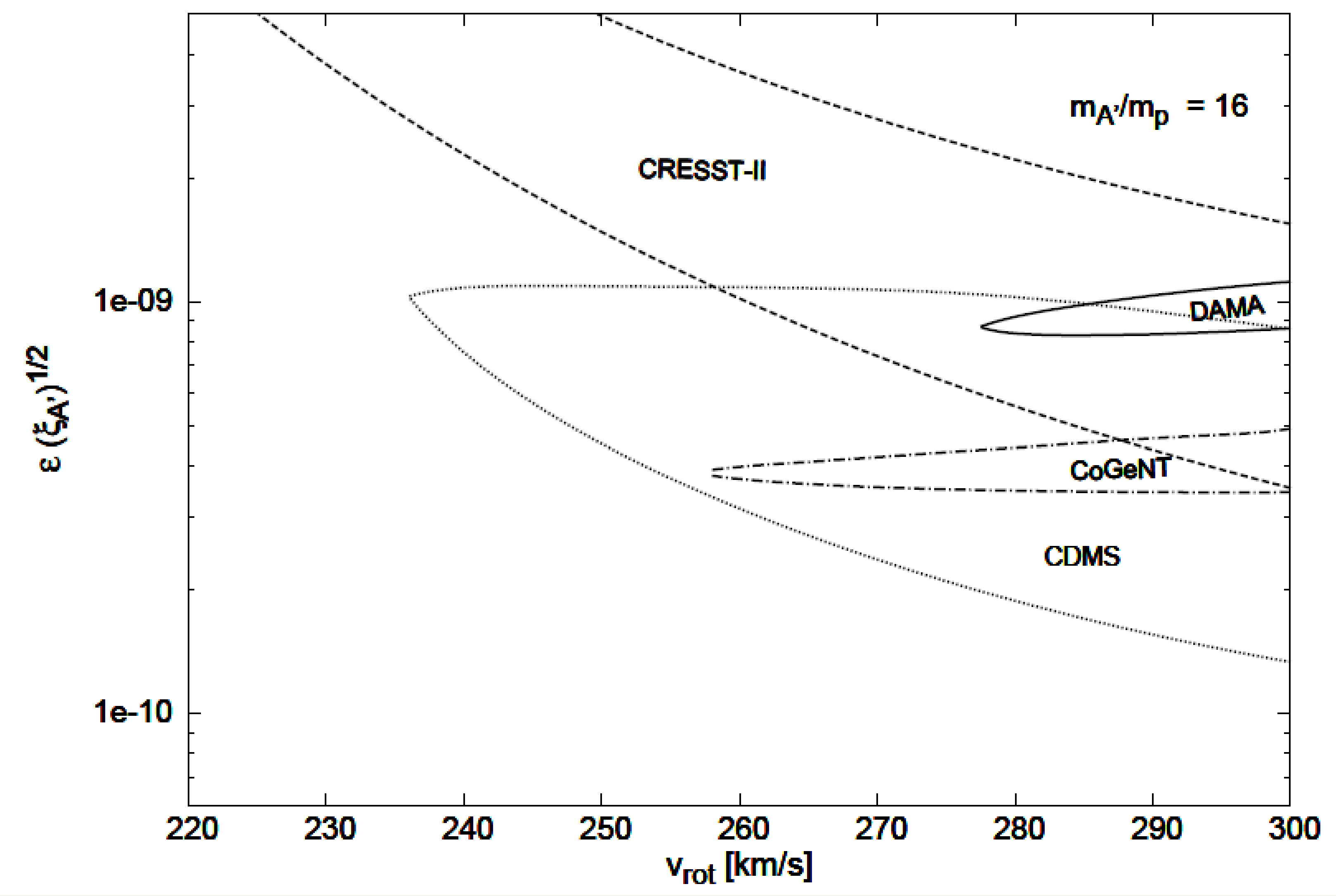
Mirror dark matter – direct detection



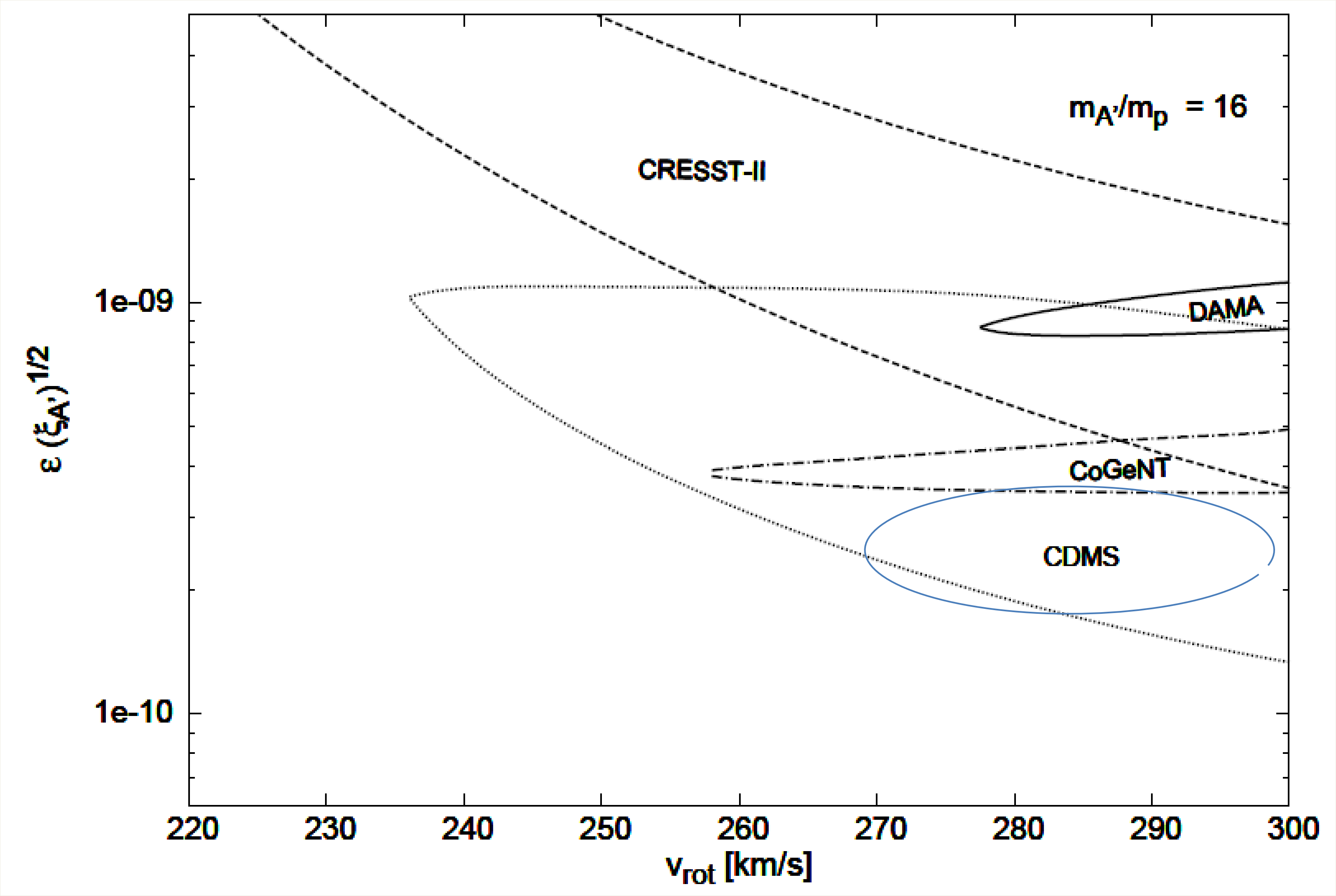
Mirror dark matter – direct detection



Mirror dark matter – direct detection



Mirror dark matter – direct detection



Conclusions

Evidence for non-baryonic dark matter from rotation curves in galaxies, and precision cosmology.

Dissipative dark matter candidates are possible. Mirror dark matter presents as a well motivated predictive example.

Such dark matter can explain the large scale structure of the Universe, and recent work has found that it might also explain small scale structure as well.

The DAMA experiment may have actually detected galactic dark matter! Support from CoGeNT, CRESST-II and CDMS/Si !

Some tension with LUX and the low threshold superCDMS search.