Mirror dark matter, galaxy structure, and the DAMA annual modulation signal

Robert Foot, COEPP, University of Sydney and University of Melbourne

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This talk based on papers: arXiv: 1804.11018, 1806.xxx, 1512.06471

Collisional dark matter: A plethora of possibilities

One can envisage the possibility that dark matter has some properties similar to ordinary matter, e.g. charged under an unbroken U(1)’ gauge interaction (dark electromagnetism). E.g. consider a “hidden sector” comprising a dark electron and dark proton, coupling to a massless dark photon:

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

where $D_\mu = \partial_\mu + ig'Q'A'_\mu$ is the covariant derivative.

The term: $\mathcal{L}_{\mathrm{mix}} = \frac{\epsilon'}{2} F^{\mu\nu}F'_{\mu\nu}$ represents kinetic mixing interaction.

Provides a mechanism for ordinary matter to interact with dark matter on galactic scales.

E.g. Vagnozzi+Foot, 2016.

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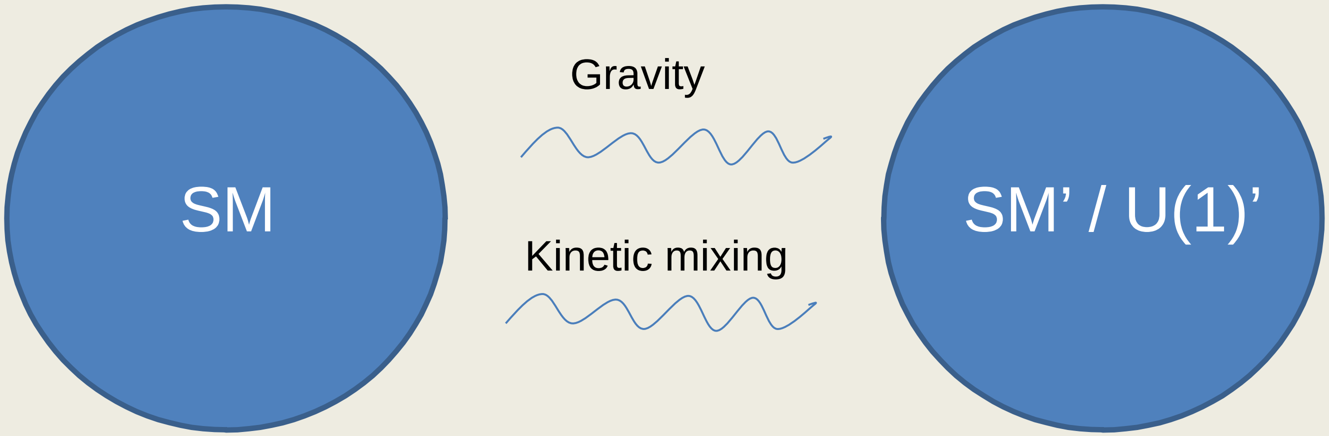
Dissipative mirror dark matter

Mirror dark matter is a theoretically constrained possibility, where dark matter arises from a hidden sector exactly duplicating the SM:

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

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



The two systems can evolve semi-independently, being only relatively weakly coupled together via gravity and kinetic mixing interaction.

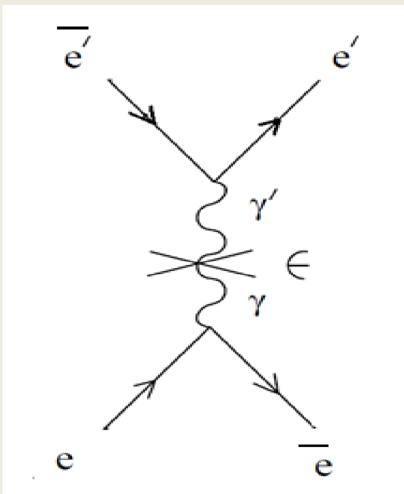
Foot, Lew, Volkas, PLB 1991
Concept first discussed by Lee and Yang, 1956.
Foot 2014 for detailed bibliography.

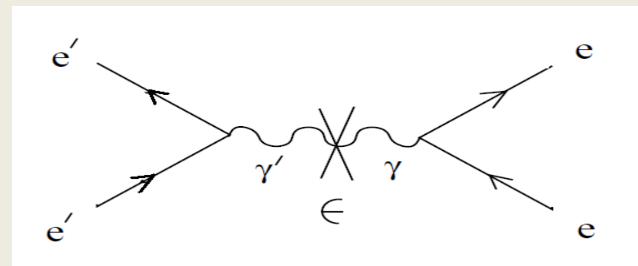
Dissipative dark matter with kinetic mixing

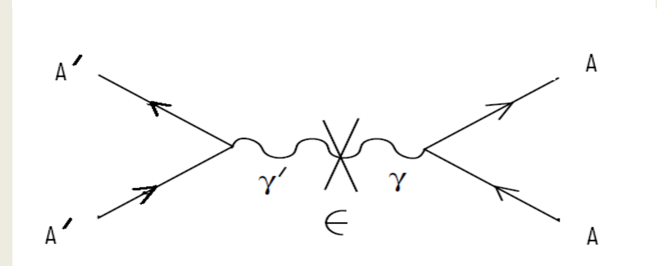
Kinetic mixing is a renormalizable interaction, described by a dimensionless parameter, ε.

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

The physical effect is to induce tiny ordinary electric charges for mirror particles, Q = εe. This means that they can couple to ordinary photons:







Important for small scale structure, supernova's, if

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

Important for direct detection experiments, such as DAMA, XENON, LUX etc if

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

Implications of plasma dark matter for direct detection experiments

If energy equipartition is approx. valid, then mean energy of light mirror electrons is equal to the heavy mirror nuclei. Indeed, halo temperature for MW can be estimated from hydrostatic equilibrium condition:

$$T \approx \frac{\bar{m} v_{rot}^2}{2} \sim 0.3 \text{ keV} \qquad \bar{m} \equiv \sum n_i m_i / \sum n_i$$

This implies a velocity dispersion for mirror electrons:

$$v_0 = \sqrt{2T/m_{e'}} = \sqrt{\bar{m}/m_{e'}}\, v_{rot} \sim 10{,}000 \text{ km/s}$$

Collective effects keep the plasma neutral over macroscopic scales.

➡ Mirror electrons cannot escape the galaxy despite $v_0(e') \gg v_{esc}$

Both mirror nuclei – nuclei scattering and mirror electron – electron scattering can give keV energy recoils.

Clarke+ Foot, JCAP 2016

The cross section – Rutherford scattering

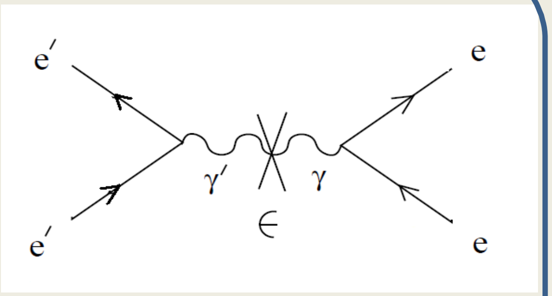
Kinetic mixing interaction induces tiny electric charges for mirror electron, and mirror nuclei, and thus permits Rutherford-type scattering to occur:

$$\frac{d\sigma_{e'}}{dE_R} = \frac{\lambda}{E_R^2 v^2} \qquad \lambda \equiv 2\pi\epsilon^2\alpha^2/m_e$$

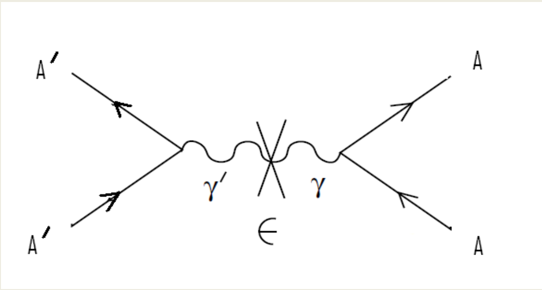
$$\frac{d\sigma_{A'}}{dE_R} = \frac{2\pi\epsilon^2 Z^2 Z'^2 \alpha^2 F_A^2 F_{A'}^2}{m_A E_R^2 v^2}$$

Electron recoils can be important for experiments such as DAMA, which do not descriminate between electron recoils and nuclear recoils. For electron recoils,

$$\begin{aligned} \frac{dR_e}{dE_R} &= g_T N_T n_{e'} \int \frac{d\sigma}{dE_R} f(\mathbf{v};\mathbf{v}_E;\theta)\ |\mathbf{v}|\ d^3v \\ &= g_T N_T n_{e'} \frac{\lambda}{E_R^2} I(\mathbf{v}_E,\theta) \end{aligned}$$



Electron recoils



Nuclear recoils

That is, the rate is proportional to the velocity integral:

$$I(\mathbf{v}_E, \theta) \equiv \int_{|\mathbf{v}|>v_{min}(E_R)}^{\infty} \frac{f(\mathbf{v}; \mathbf{v}_E; \theta)}{|\mathbf{v}|} \, d^3v$$

$$v_{\min} = \sqrt{2E_R/m_e}$$

What is f? The distribution might be Mawellian far from the Earth, but mirror dark matter accumulates in the Earth, thermalizes with ordinary matter and forms an obstacle to the halo wind.

For low recoil energies, $\langle|\mathbf{v}|\rangle \gg v_{\min}$, $I(\mathbf{v}_E, \theta)$ becomes independent of E_R

This might arise due to e.g. a low velocity cutoff due to collisional shielding, or shielding from induced dark electromagnetic interactions in a 'dark ionosphere'.

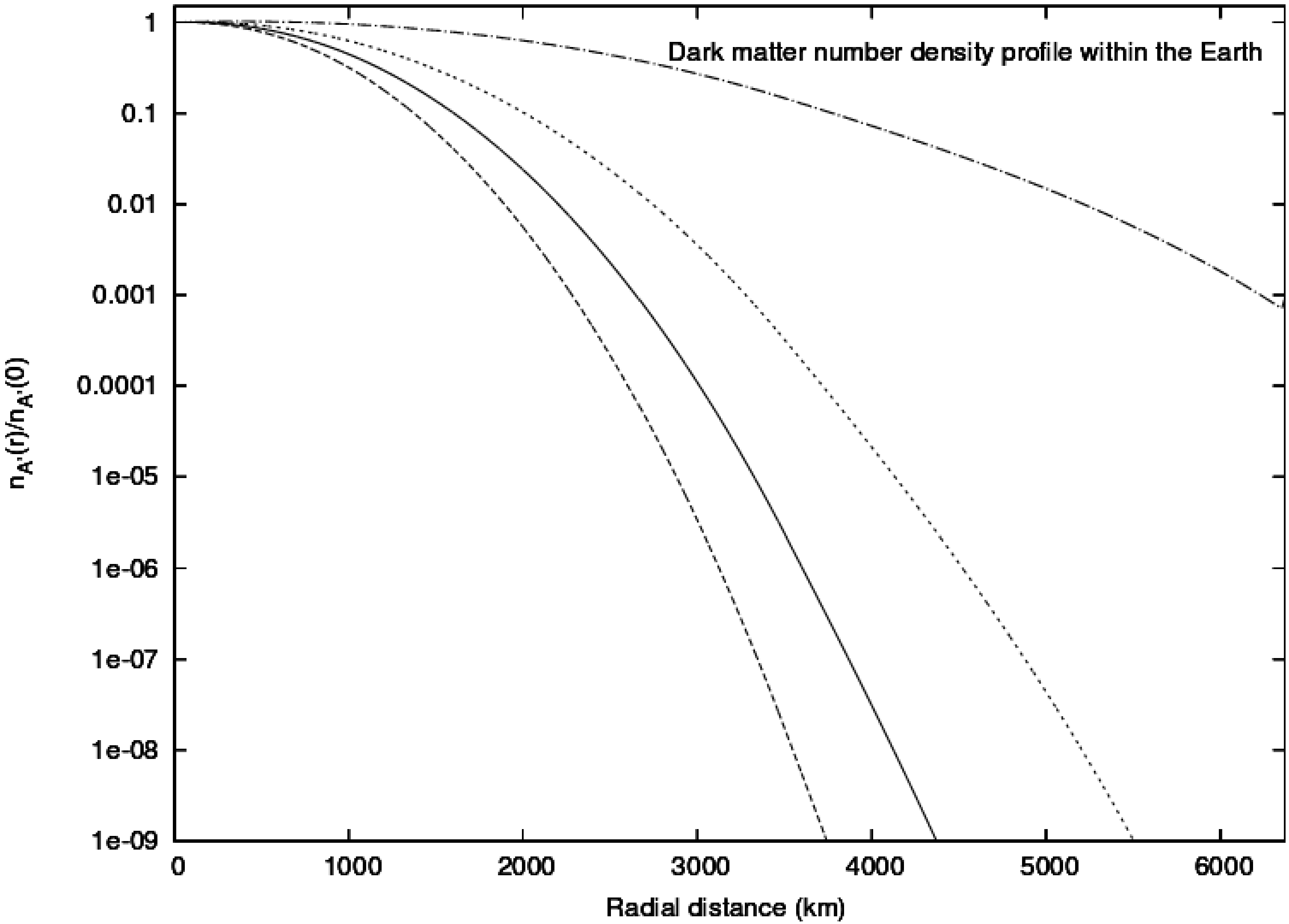
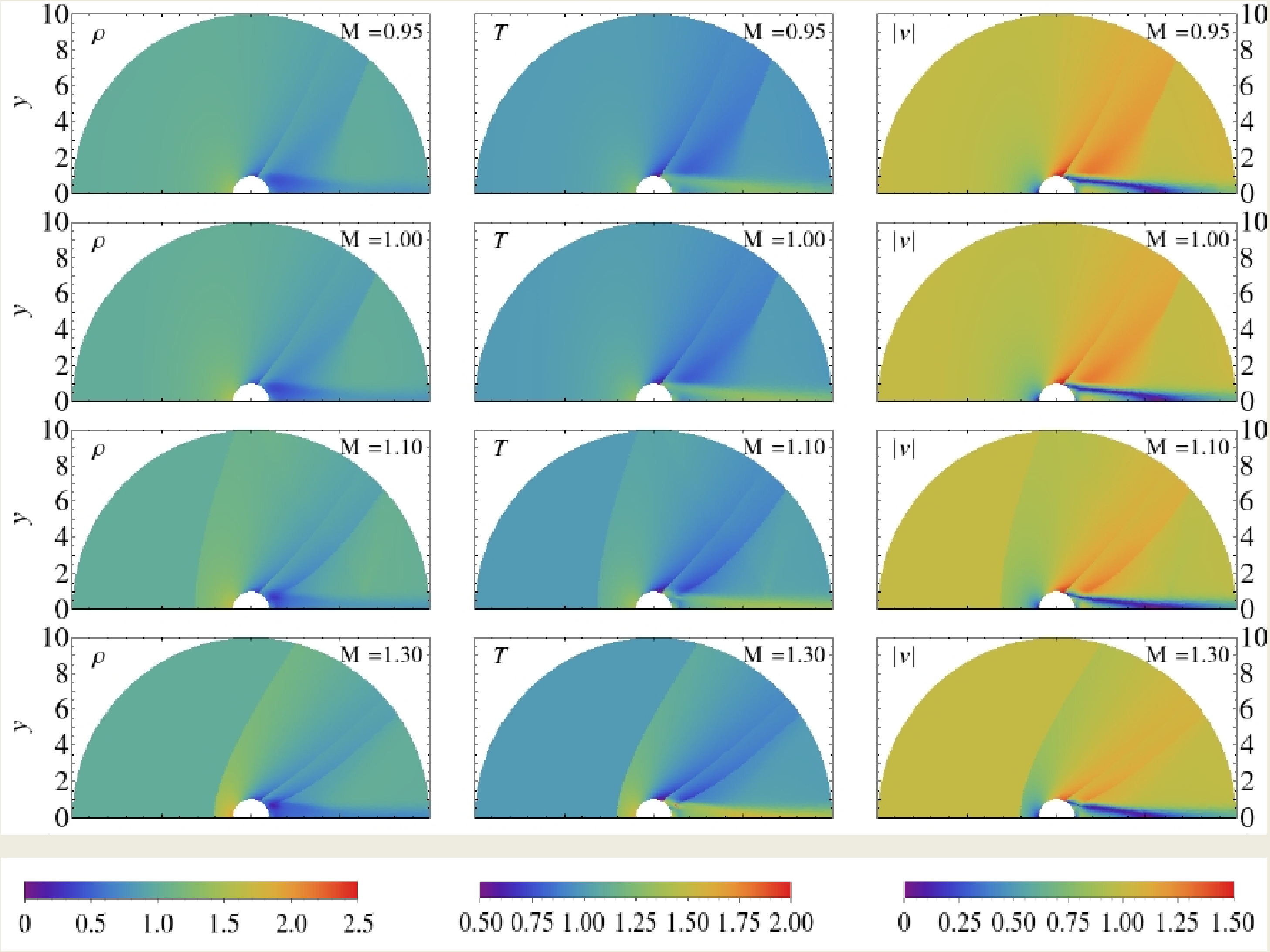


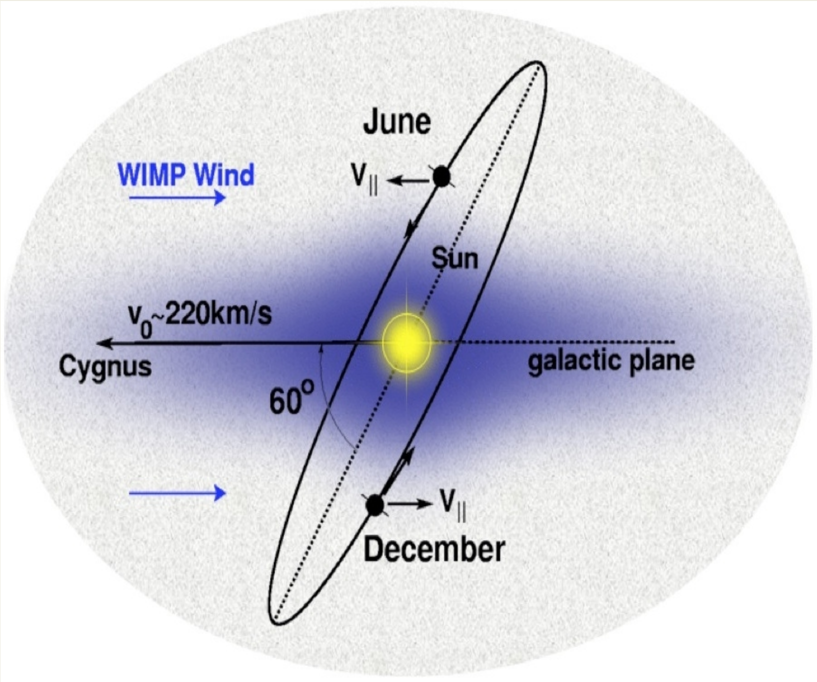
Figure 2: The distribution within the Earth, $n_{A'}(r)/n_{A'}(0)$, of captured mirror particles of mass $m_{A'} = 22m_p$ (solid line), $m_{A'} = 30m_p$ (dashed line), $m_{A'} = 14m_p$ (dotted line) and $m_{A'} = 4m_p$ (dashed-dotted line).

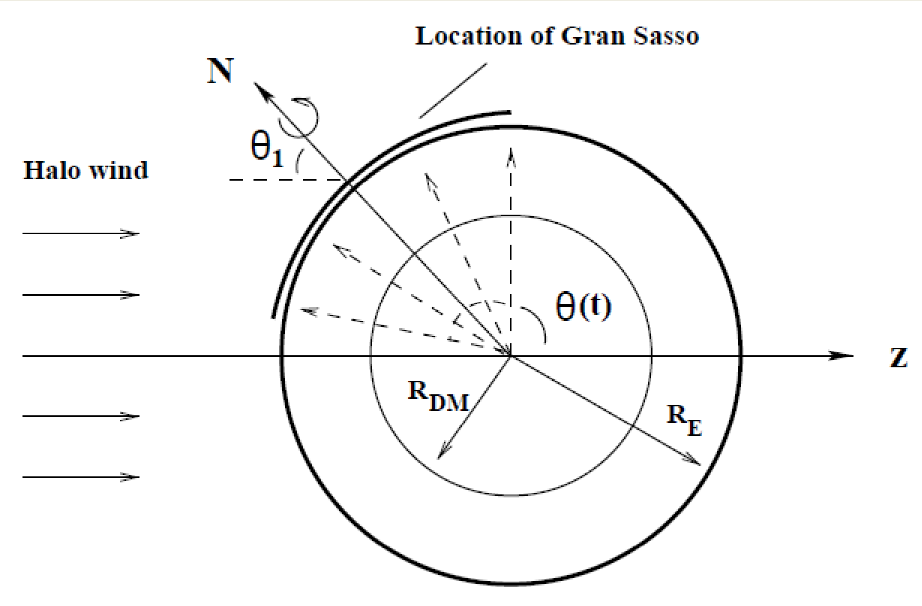
Some examples for venus-like case (Dark ionosphere)



Clarke+ Foot, JCAP 2016

The detector is in motion…





Annual modulation of halo <u>speed</u> (phase t_0 = 152 day), and also an annual modulation of the <u>direction</u> of halo wind (t_0 = 115 day)

Sidereal day modulation of detector location

Expand velocity integral in a Taylor series, assuming $\langle|\mathbf{v}|\rangle \gg v_{\min}$

$$I(\mathbf{v}_E, \theta) = I_0 + \frac{\partial I}{\partial v_E}\Delta v_E \cos\omega(t - t_0) + \frac{\partial I}{\partial \theta}(\theta - \bar{\theta}) + \ldots$$

Gives a simple phenomenological model for the electron scattering rate

$$\frac{dR_e}{dE_R} = g_T N_T n^0_{e'} \frac{\lambda}{v^0_c E^2_R}\left[1 + A_v \cos\omega(t - t_0) + A_\theta(\theta - \bar{\theta})\right]$$

$\mathrm{E_R} < \mathrm{E_R^T}$

where $\langle n_{e'} I\rangle \equiv n^0_{e'}/v^0_c$ and recall $\lambda \equiv 2\pi\epsilon^2\alpha^2/m_e$

To compare with actual experiments, need to take into account resolution and detection efficiency

$$\frac{dR_e}{dE^m_R} = \int \mathcal{G}(E^m_R, E_R)\frac{dR_e}{dE_R}\epsilon_F(E_R)\, dE_R$$

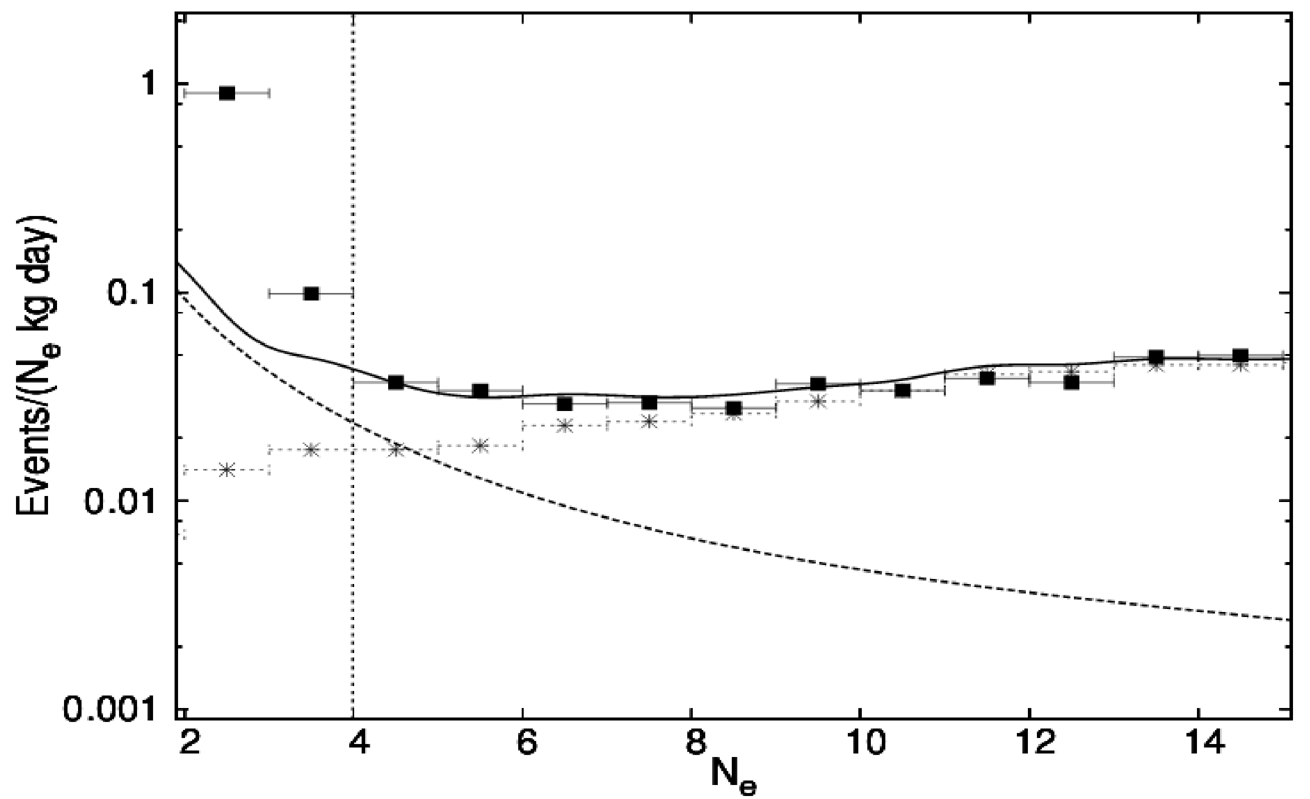
$$\frac{dR_e}{dE_R} = g_T N_T n^0_{e'} \frac{\lambda}{v^0_c E^2_R} \left[1 + A_v \cos\omega(t - t_0) + A_\theta(\theta - \bar{\theta})\right]$$

DarkSide-50

ArXiv:1802.06998

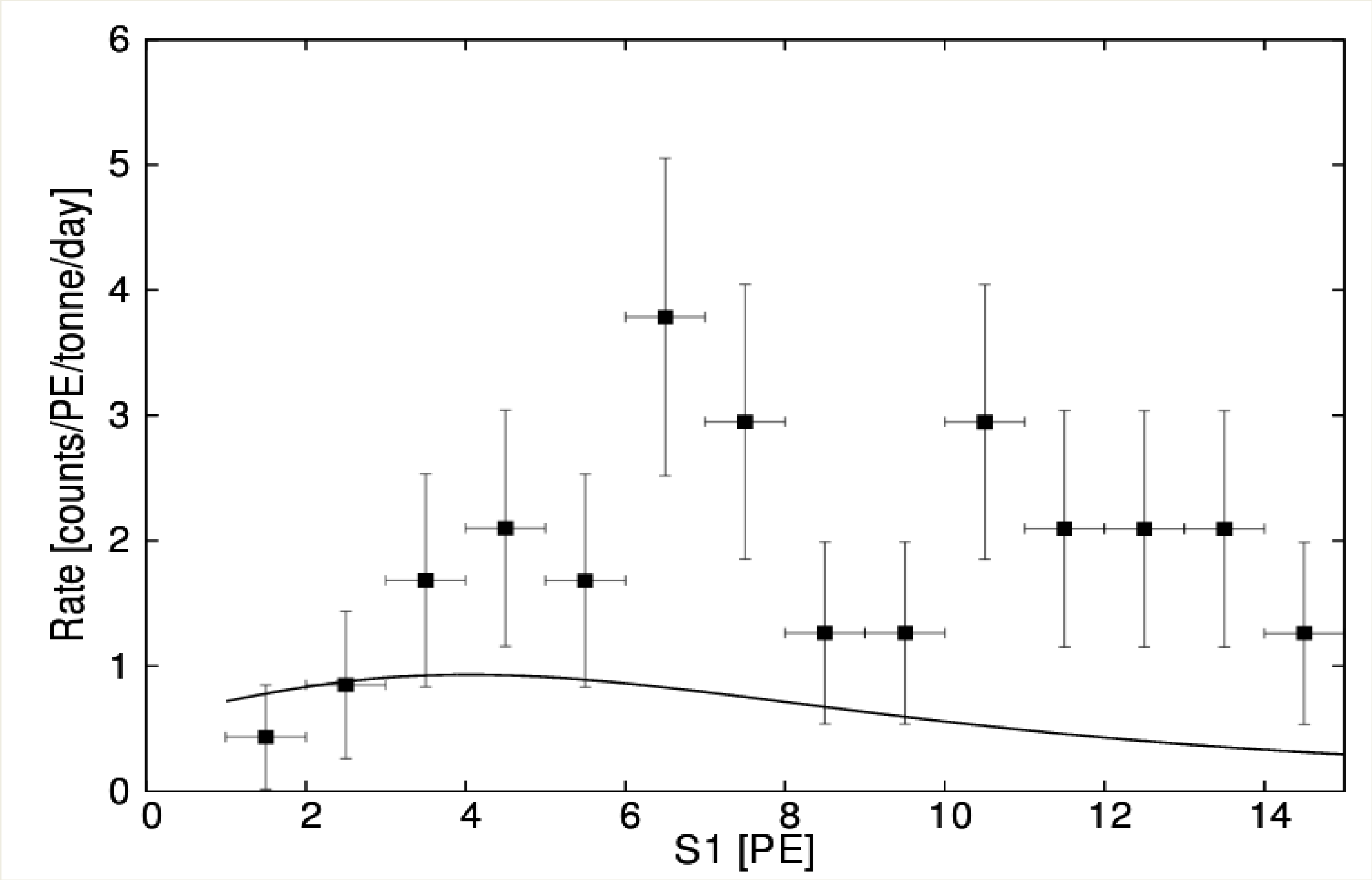
0.1 keV

0.4 keV



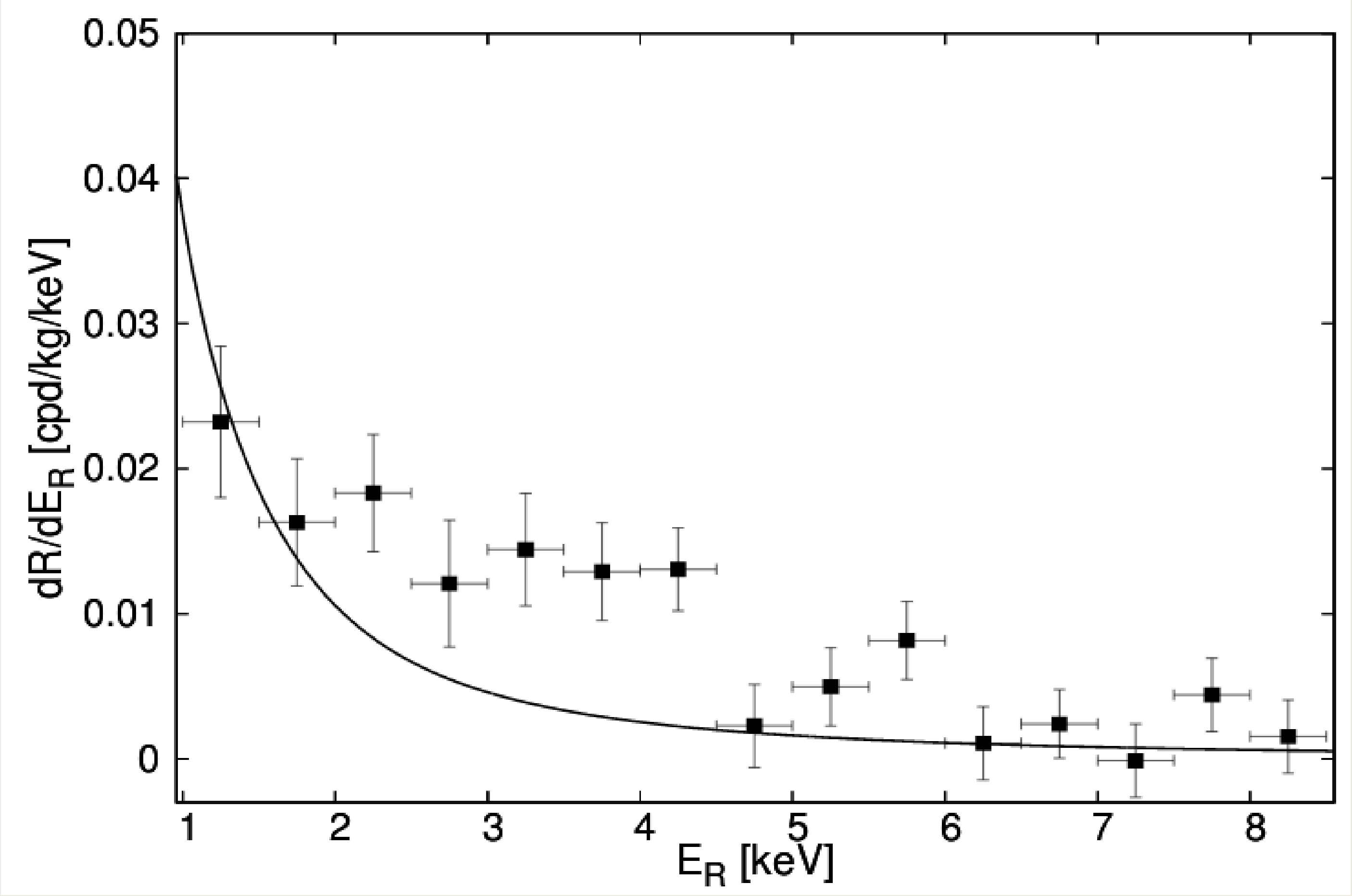
$$\epsilon\sqrt{\frac{n_{e'}}{0.2\ \mathrm{cm}^{-3}}} \approx 1.5 \times 10^{-11}\sqrt{\frac{v^0_c}{50000\ \mathrm{km/s}}}$$

$$\frac{dR_e}{dE_R} = g_T N_T n^0_{e'} \frac{\lambda}{v^0_c E^2_R} \left[1 + A_v \cos\omega(t - t_0) + A_\theta(\theta - \bar{\theta})\right]$$



Xenon100
Science, 2015

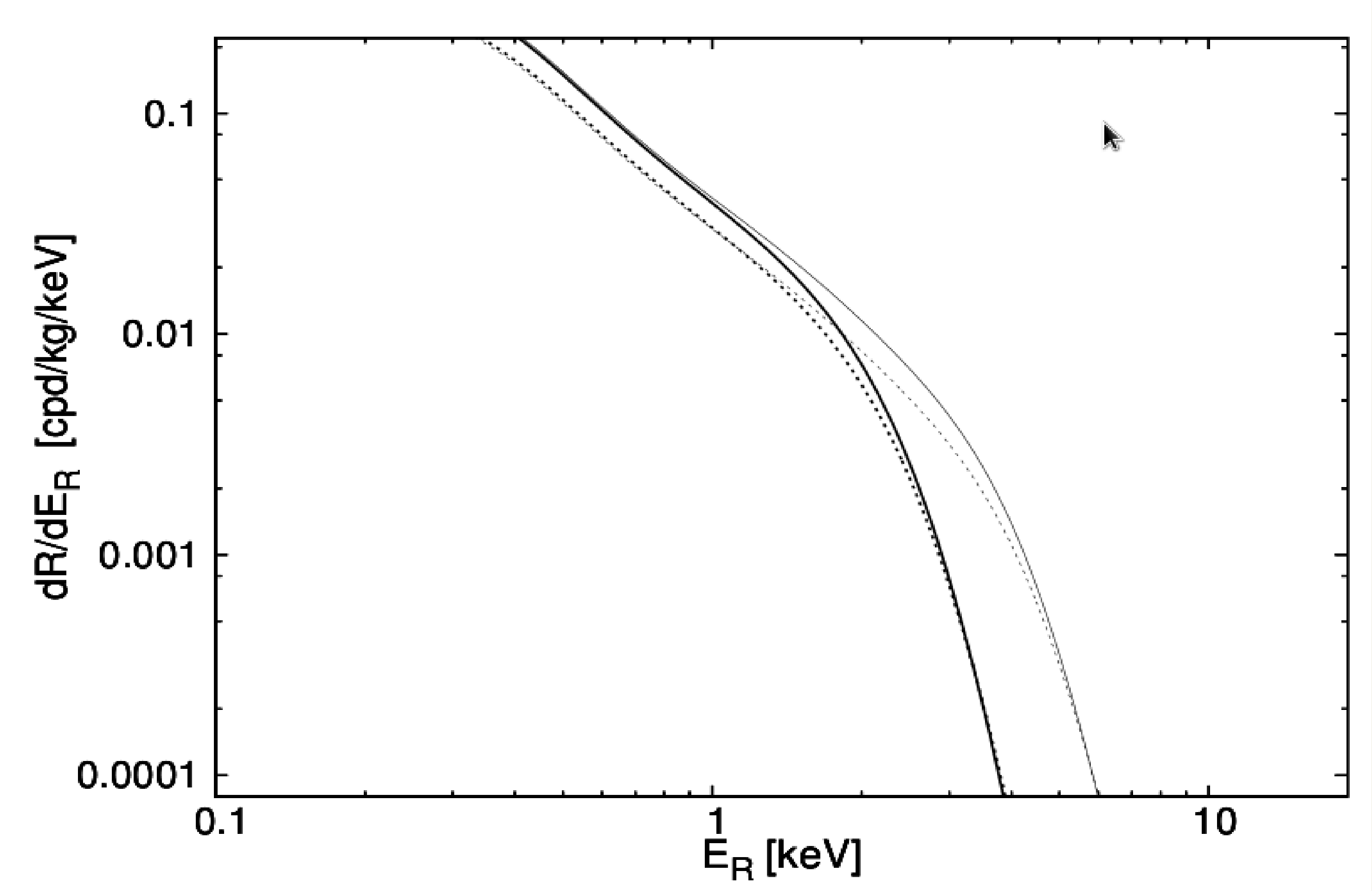
$$\frac{dR_e}{dE_R} = g_T N_T n^0_{e'} \frac{\lambda}{v^0_c E^2_R} \left[1 + A_v \cos\omega(t - t_0) + A_\theta(\theta - \bar{\theta})\right]$$



DAMA
ArXiv: 1805.10486

$$\frac{dR_e}{dE_R} = g_T N_T n^0_{e'} \frac{\lambda}{v^0_c E^2_R} \left[1 + A_v \cos\omega(t - t_0) + A_\theta(\theta - \bar{\theta})\right]$$

Rate for DAMA, modelling shielding effects, assuming $\epsilon \approx 2 \times 10^{-10}$
Find rate suppressed at a threshold: $E^T_R = 2 - 3 \text{ keV}$



Conclusion

DAMA annual modulation can be explained consistently with results of other experiments in the framework of plasma dark matter models. In these kinds of models the DAMA signal is due to electron recoils.

The annual modulation is constrained to be near maximal, with rate

$$dR_e/dE_R \propto 1/E_R^2 \quad \text{for} \quad \mathrm{E_R < E_R^T}$$

Mirror dark matter case studied in most detail.

Modelling the shielding of halo mirror dark matter via the Earth-bound mirror dark matter, I have found that the DAMA signal is consistent with the kinetic mixing parameter inferred from halo dynamics: $\epsilon \approx 2 \times 10^{-10}$

Also find sharp suppression of electron scattering rate above 2-3 keV.

DAMA experiment should be conclusively tested by SABRE experiment.