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Dark matter with mirror model

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arXiv.org > astro-ph > arXiv:1401.3965

Astrophysics > Cosmology and Extragalactic Astrophysics

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. Th
a large set of unknown parameters, however if the hidden sector is an exact copy of the stan
connects each ordinary particle $(e,\ \nu,\ p,\ n,\ \gamma, \ldots)$ with a mirror partner $(e',\ \nu',\ p',$
counterparts, and would interact amongst themselves with exactly the same dynamics that go
strength ϵ, is the sole new fundamental (Lagrangian) parameter relevant for astrophysics an
provide an adequate description of dark matter phenomena provided that $\epsilon \sim 10^{-9}$. This r
cosmology, galaxy structure and the application to direct detection experiments.

Comments: 129 pages
Subjects: **Cosmology and Extragalactic Astrophysics (astro-ph.CO)**; High Energy Physics - Phen
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High Energy Physics - Phenomenology

Can dark matter - electron scattering explain the DAMA annual modulation signal?

R. Foot

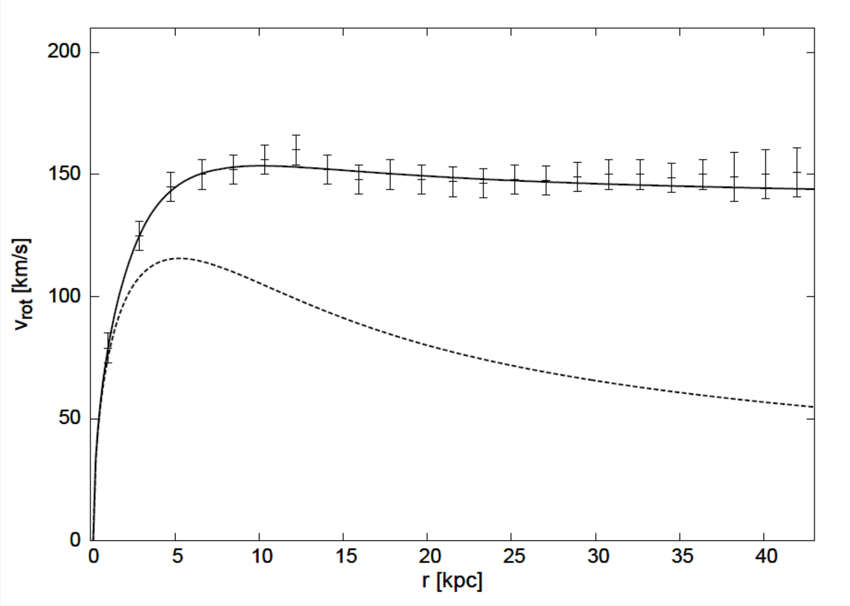
(Submitted on 16 Jul 2014 (v1), last revised 25 Aug 2014 (this version, v2))

The annually modulating $\sim$ keV scintillations observed in the DAMA/NaI and DAMA/Libra experiments might be due to dark matter - electron scattering. Such an explanation is now favoured given the stringent constraints on nuclear recoil rates obtained by LUX, SuperCDMS and other experiments. We suggest that multi-component dark matter models featuring light dark matter particles of mass $\sim$ MeV can potentially explain the data. A specific example, kinetically mixed mirror dark matter, is shown to have the right broad properties to consistently explain the experiments via dark matter - electron scattering. If this is the explanation of the annual modulation signal found in the DAMA experiments then a sidereal diurnal modulation signal is also anticipated. We point out that the data from the DAMA experiments show a diurnal variation at around 2.3σ C.L. with phase consistent with that expected. This electron scattering interpretation of the DAMA experiments can potentially be probed in large xenon experiments (LUX, XENON1T,...), as well as in low threshold experiments (CoGeNT, CDEX, C4, ...) by searching for annually and diurnally modulated electron recoils.

Comments: About 10 pages, extended discussion
Subjects: **High Energy Physics - Phenomenology (hep-ph)**; Astrophysics of Galaxies (astro-ph.GA)
Cite as: arXiv:1407.4213 [hep-ph]
(or arXiv:1407.4213v2 [hep-ph] for this version)

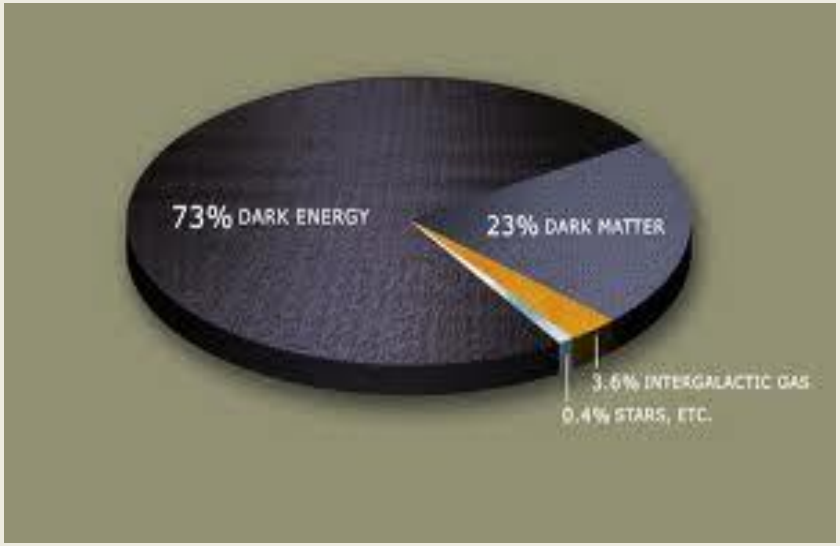
Evidence for non-baryonic dark matter

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:

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

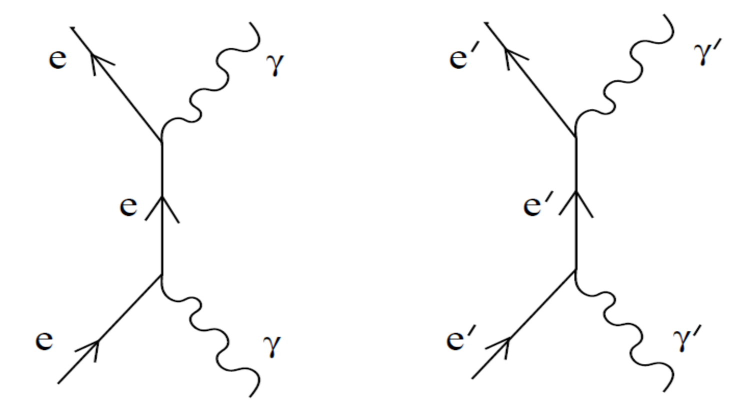
$$G^{\mu} \leftrightarrow G'_{\mu},\ W^{\mu} \leftrightarrow W'_{\mu},\ B^{\mu} \leftrightarrow B'_{\mu},\ \phi \leftrightarrow \phi'$$

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

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.

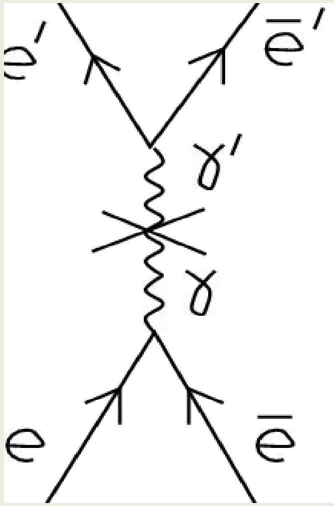
$$\mathcal{L}_{mix} = \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$

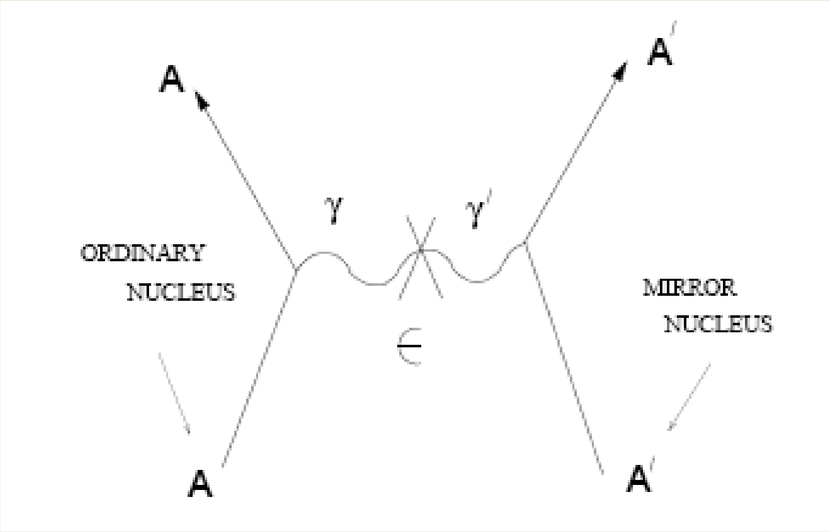
Kinetic mixing is theoretically free parameter, preserves all symmetries of the theory, and is renormalizable.

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

The physics of the very early Universe (t << 1 second) depends on initial conditions. In addition to standard adiabatic (almost) scale invariant density perturbations, we need to assume:

BBN/CMB ⇨ $T' \ll T$

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

Berezhinai, Comelli and Villante, PLB 01,
Ignatiev and Volkas, PRD 03.

With such initial conditions the theory exactly mimics standard cold dark matter on large scales, i.e. successful LSS and CMB.

Why? Because with $T' \ll T$ mirror hydrogen recombination occurs much earlier than recombination era for ordinary sector. After recombination mirror atoms decouple from the mirror photons and are free to collapse into gravitational wells.

Prior to mirror recombination mirror particles form a fluid which undergoes acoustic oscillations.

Acoustic oscillations suppress power on small scales…

Structure in the Universe – the emerging picture

Stage 1: Dark matter structure forms first as a consequence of initial conditions – after photon decoupling baryons can start accumulating in these DM structures.

Stage 2: Mirror stars and Mirror supernovae form as the mirror particles cool within galaxy scale systems. Kinetic mixing induced processes in core of mirror supernova produce ordinary photons ionizing ordinary matter.

Stage 3: Since ordinary matter is still primordial, i.e. low metal fraction, ordinary matter eventually cools and ordinary stars, SN form…

Stage 4: By this time (~few billion years), mirror photon flux from ordinary SN (again due to kinetic mixing) heats mirror matter (which by now has significant mirror metal component), and expands this matter into a roughly spherical halo.

End result: Dark matter halo is a mirror particle plasma governed by Euler equations of fluid dynamics. If such a system evolves to a static configuration, then this leads to two equations: Hydrostatic equilibrium equation and energy balance. These two equations can be used to solve for $\rho(r)$, $T(r)$.

Spiral galaxies today

If system evolves to a static configuration have two equations (assuming spherical symmetry) governing dark matter galactic halo:

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

Hydrostatic equilibrium

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

Energy balance equation:
Heating=cooling

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

Importantly we do not need to know the details of the history of the galaxy!

This dynamics can explain rotation curves, cored dark matter profile, galactic scaling relations etc.

Spiral galaxies today

Do the energetics work out? For Milky Way galaxy find:

Cooling (Bremsstrahlung) ➡

$$\mathcal{E}_{out} \approx \left(\frac{\Lambda(T)}{10^{-23}\ \mathrm{erg\ cm^3/s}}\right)\left(\frac{\rho_0 r_0}{50\ M_\odot/\mathrm{pc}^2}\right)^2\left(\frac{r_0}{5\ \mathrm{kpc}}\right)\ 3\times10^{43}\ \mathrm{erg/s}$$

Heating from ordinary supernova ➡

$$\begin{aligned}\mathcal{E}_{in} &= f_{SN}\langle E_{SN}\rangle R_{SN}\\ &\simeq \left(\frac{f_{SN}}{0.1}\right)\left(\frac{\langle E_{SN}\rangle}{3\times10^{53}\ \mathrm{erg}}\right)\left(\frac{R_{SN}}{0.03\ \mathrm{yr}^{-1}}\right)\ 3\times10^{43}\ \mathrm{erg/s}\end{aligned}$$

Energies match, $\mathcal{E}_{in} \simeq \mathcal{E}_{out}$, if halo able to absorb around 10% of total supernova energy. Suggests kinetic mixing of strength: $\epsilon \sim 10^{-9}$

For energies to match for every spiral suggests a scaling relation: (equivalent to Tully-Fisher)

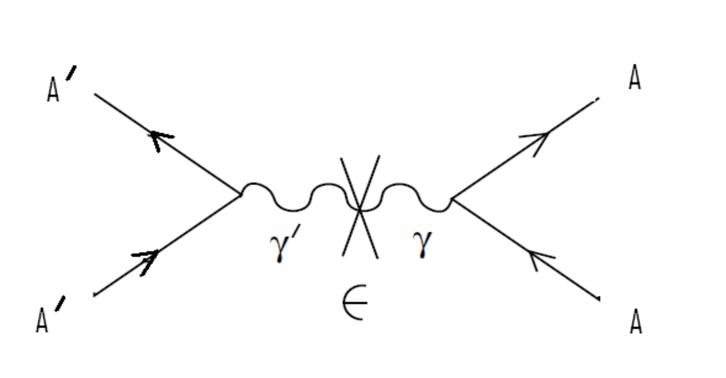
$$R_{SN} \propto \Lambda(T)\rho_0 r_0^2$$

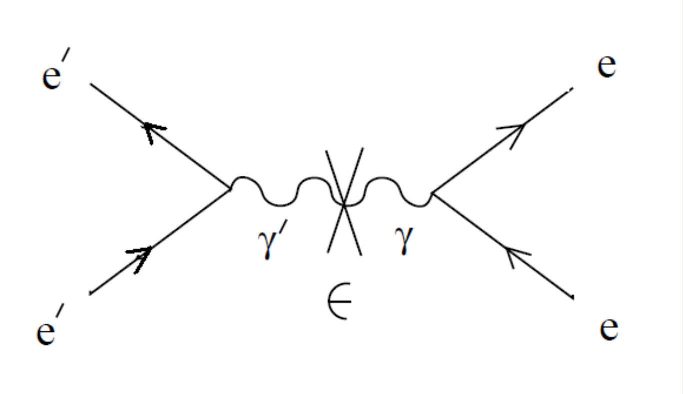
Kinetic Mixing

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

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.

For direct detection experiments two interesting possibilities: dark matter nuclei interactions and also dark matter electron interactions:





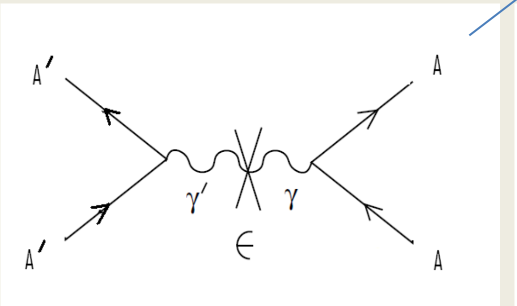
Important for direct detection experiments, such as DAMA, CoGeNT etc if

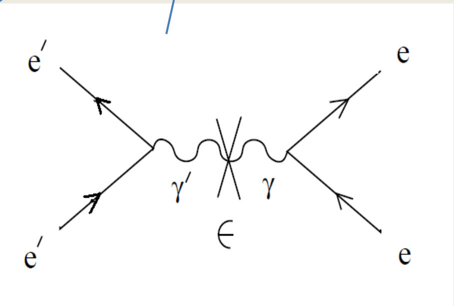
$$\epsilon \sim 10^{-9}$$

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

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

Cross-section: Rutherford Scattering:

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

For nuclear recoils:

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

For electron recoils:

$$\lambda \equiv \frac{2\pi\epsilon^2\alpha^2}{m_e}$$

Halo distribution of mirror electrons (e') and mirror ions (He', O', Fe',..)

The electron and nuclear recoil rates depend on the halo distribution of mirror electrons (e') and mirror ions (He', O', Fe',…) respectively.

Mirror dark matter is self interacting. Milky Way halo is a multi-component plasma with a common local temperature, T.

Hydrostatic equilibrium implies: $T \simeq \frac{1}{2}\bar{m}v_{rot}^2$

Distribution will be Maxwellian: $f_i = e^{-E/T} = e^{-|\mathbf{u}|^2/v_0^2}$

That is, a mass dependent velocity dispersion results:

$$v_0(i) = \sqrt{\frac{2T}{m_i}} \simeq v_{rot}\sqrt{\frac{\bar{m}}{m_i}} \ .$$

Halo distribution of mirror electrons (e') and mirror helium (He')

$$f_i = e^{-E/T} = e^{-|\mathbf{u}|^2/v_0^2}$$

That is, a mass dependent velocity dispersion results:

$$v_0(i) = \sqrt{\frac{2T}{m_i}} \simeq v_{rot}\sqrt{\frac{\bar{m}}{m_i}} \, .$$

Early Universe cosmology suggests mirror world is helium dominated, giving:

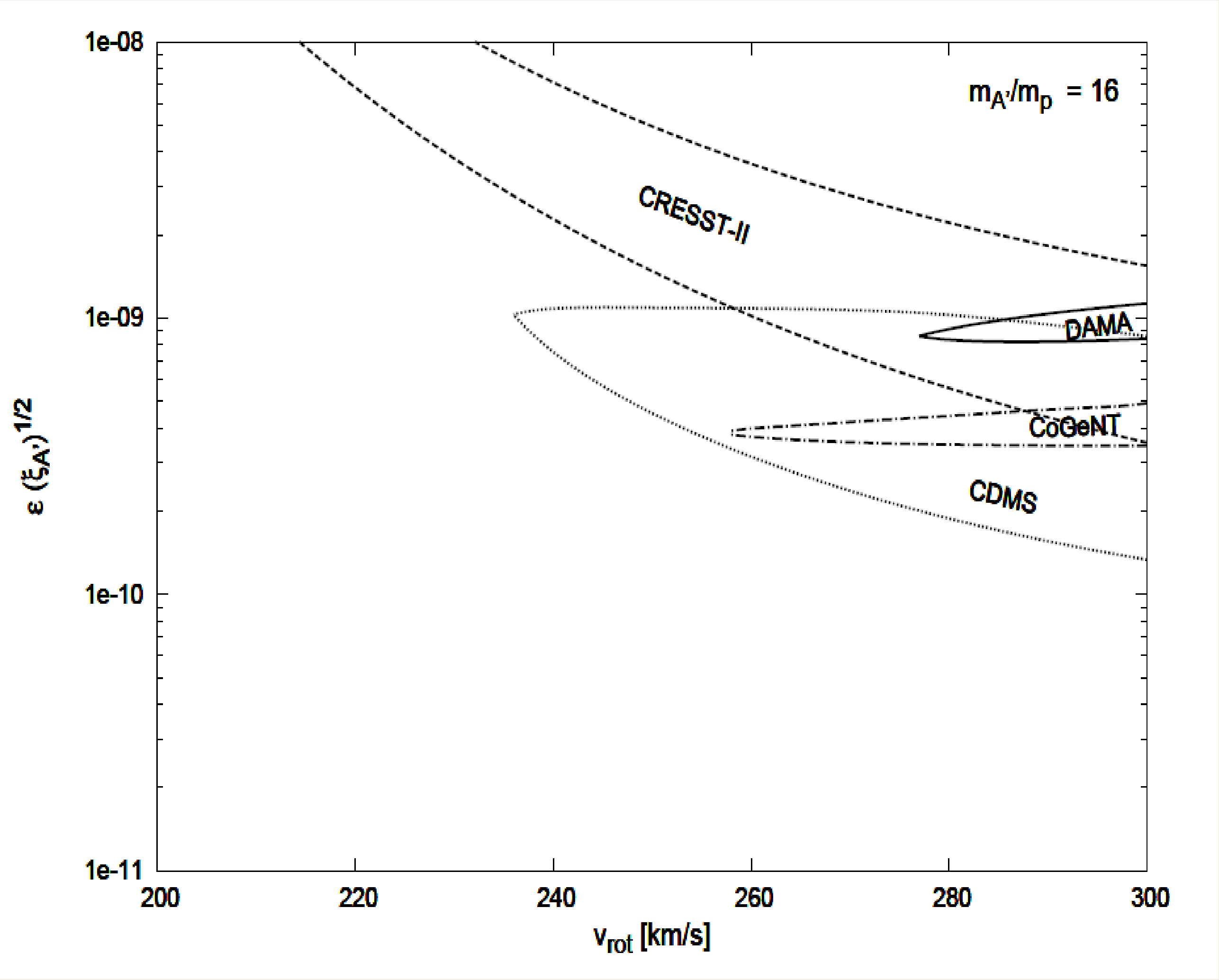
$$\bar{m} \approx 1.1 \ \mathrm{GeV}$$

Thus, can estimate the velocity dispersions for e', He' to be:

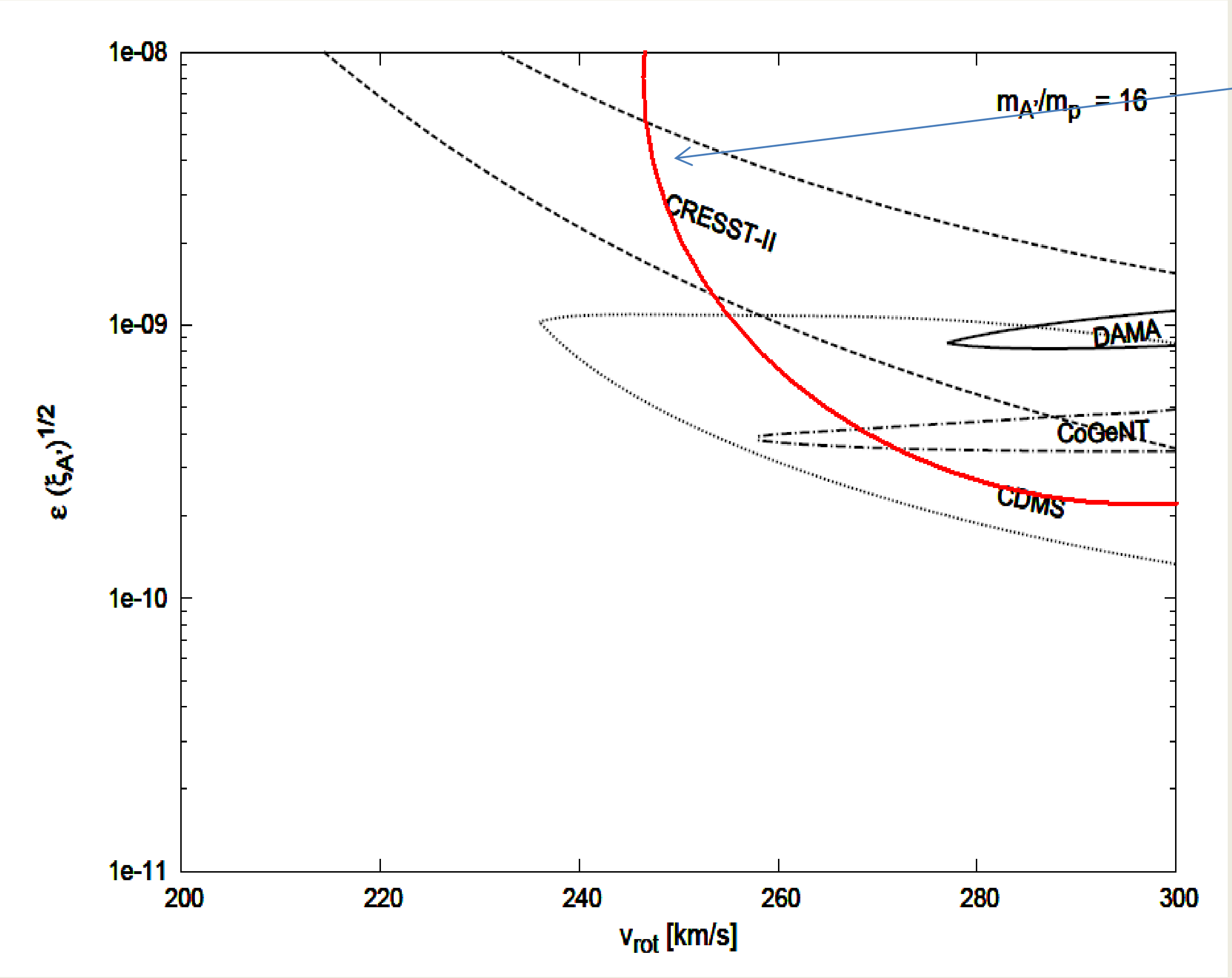
$$v_0(e') \approx 10,000 \ \mathrm{km/s} \qquad v_0(He') \approx 100 \ \mathrm{km/s}.$$

Cf. rotation velocity: $v_{rot} \sim 240 \ \mathrm{km/s}$

A year ago, nuclear recoils could potentially explain DAMA and some other possible dark matter detections…

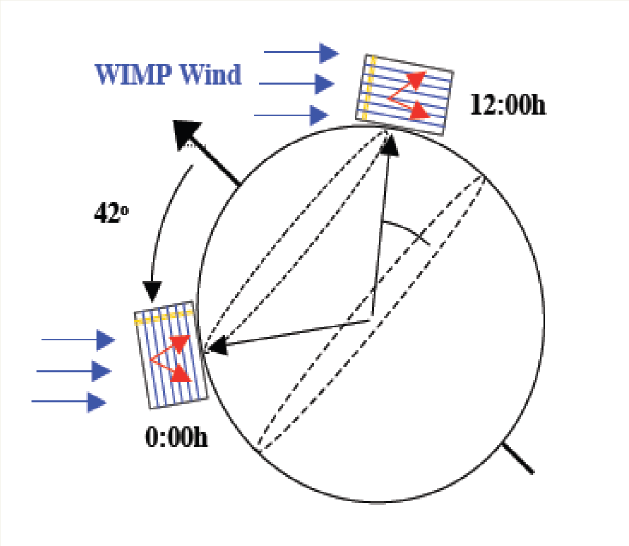


Nuclear recoils now disfavoured, but need to keep looking. In these types of dark matter models nuclear recoils should be observable in near future.



SuperCDMS, CRESST-II, LUX, CDEX ….

Trying to understand electron recoils

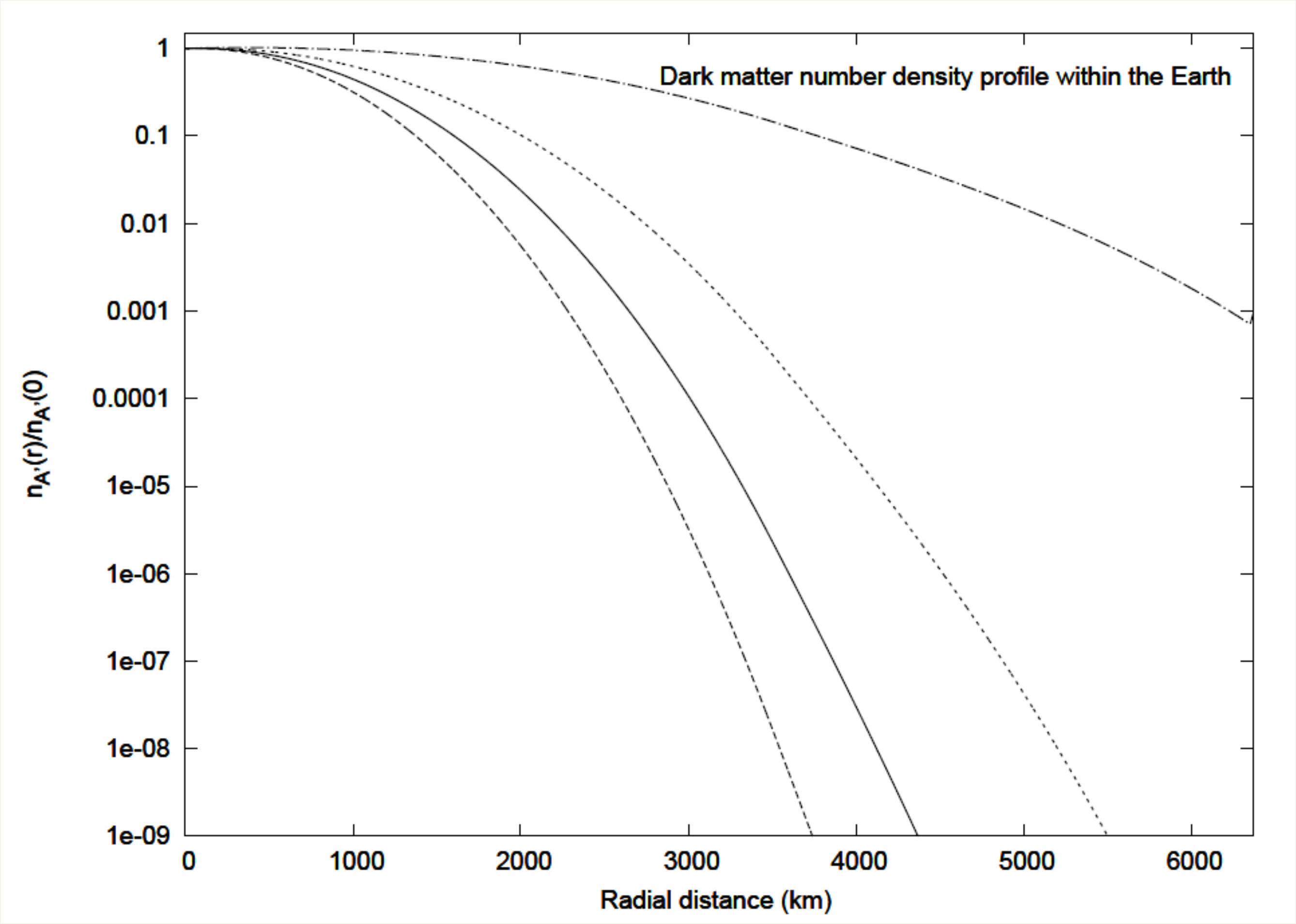


$$R_{He'} \approx \pi R_E^2 n_{He'} \langle v_E \rangle$$

$$\begin{aligned} R_{e'} &= 4\pi R_E^2 n_{e'} \langle |v_{e'}^z| \rangle / 2 \\ &\approx 2\sqrt{\pi} R_E^2 n_{e'} v_0(e') \quad \text{for} \quad \mathbf{E}' = \mathbf{B}' = 0 \end{aligned}$$

$$\frac{R_{e'}}{R_{He'}} \approx \frac{4 v_0(e')}{\sqrt{\pi} v_{rot}} \approx \frac{4}{\sqrt{\pi}} \sqrt{\frac{\bar{m}}{m_e}} \approx 100$$

Mirror dark matter accumulates within the Earth. Initially by hard scattering between dark matter particles and nuclei, and then by dark matter – dark matter self interactions.



Mirror electromagnetic fields must be generated within the Earth

E' and B' fields have to be generated within the Earth, so that the mirror electron (light dm) flux equalizes with the (heavy) mirror ion flux.

E.g. more mirror electrons getting captured in the Earth, lead to a net negative mirror electromagnetic charge, until the Coulomb repulsion is large enough so that flux of negative and positive halo particles are equalized at Earth's surface.

If flux is equalized, the annual modulation of the heavy mirror ion component, implies that the light mirror electron component will also annually modulate.

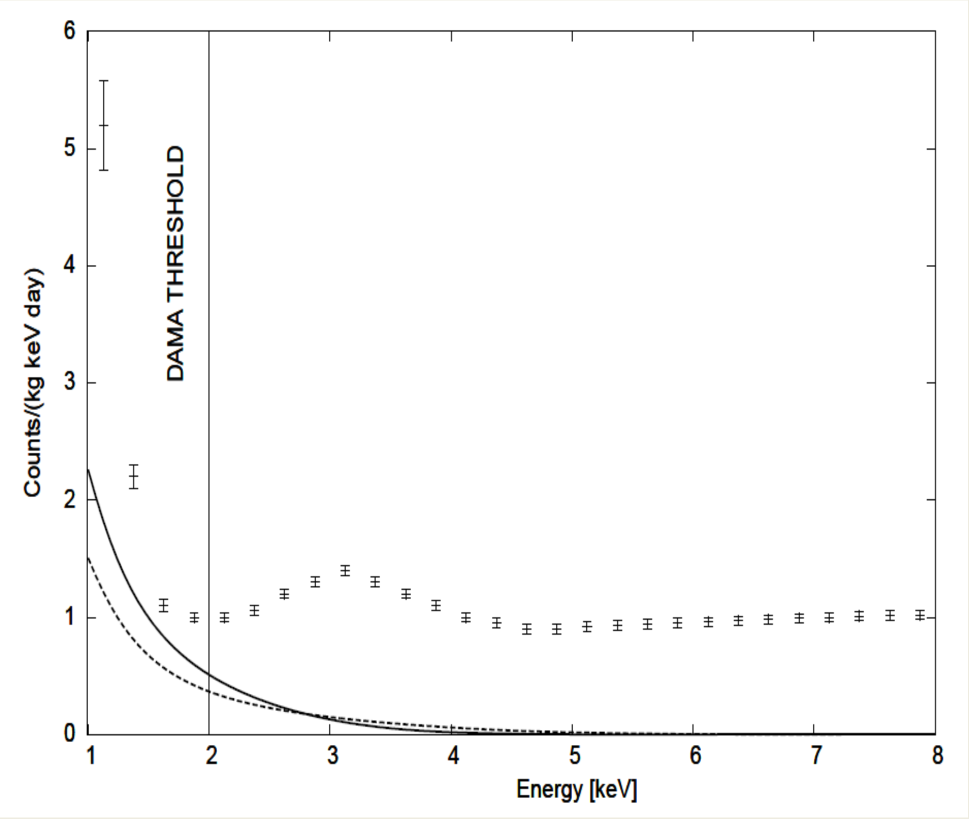
If we make the simplistic assumption that effect of E' and B' fields is to prevent the slowest halo mirror electrons from reaching the Earth, then can model their distribution with a cut-off:

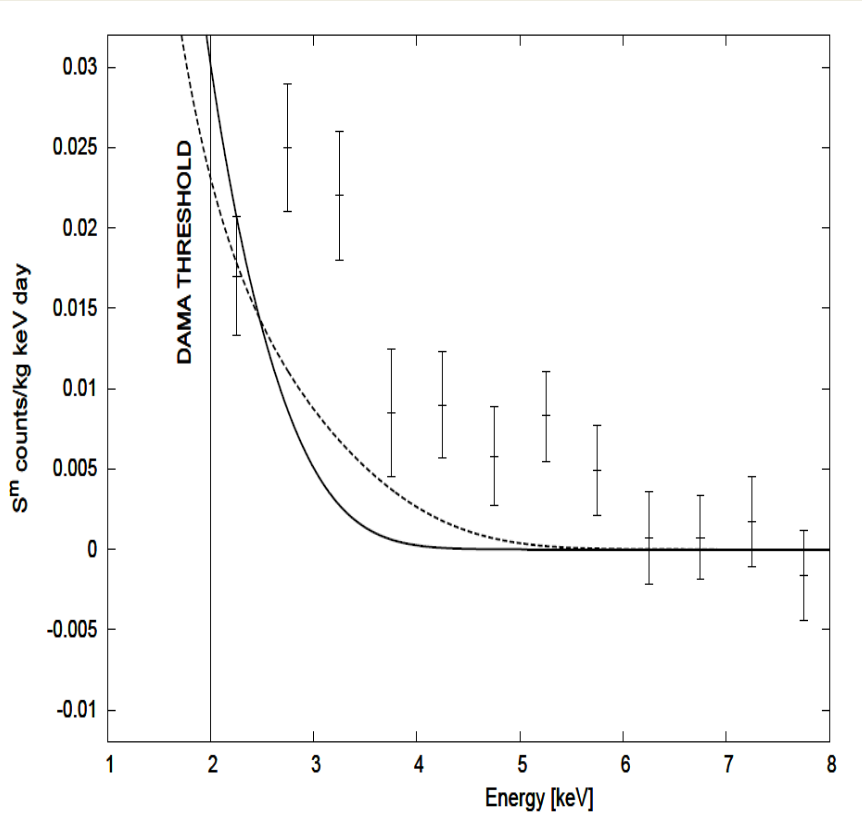
$$
\begin{aligned}
f_{e'} &= e^{-|\mathbf{v}|^2/v_0^2} \quad \text{for} \quad |\mathbf{v}| > v_c \\
f_{e'} &= 0 \quad \text{for} \quad |\mathbf{v}| < v_c \ .
\end{aligned}
$$

Can now estimate the rates for DAMA experiment: average rate and annual modulated component

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

For kinetic mixing induced mirror electron – electron recoils, with $\epsilon = 10^{-9}$



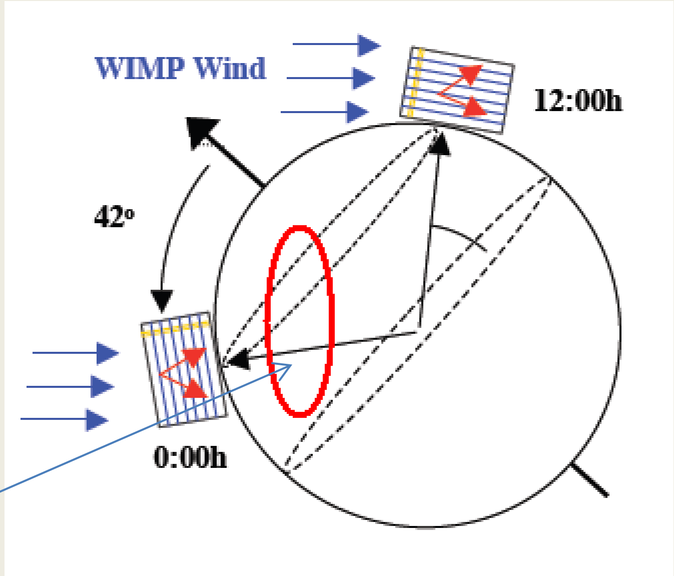


What about diurnal variation in electron recoils?

Mirror electron flux at Earth's surface equalizes with mirror ion flux due to induced E', B' fields generated within the Earth.

These fields are <u>not</u> spherically symmetric.

Therefore, as the Earth rotates, expect different electron scattering rate!



Mirror ions accumulate on one side of the Earth

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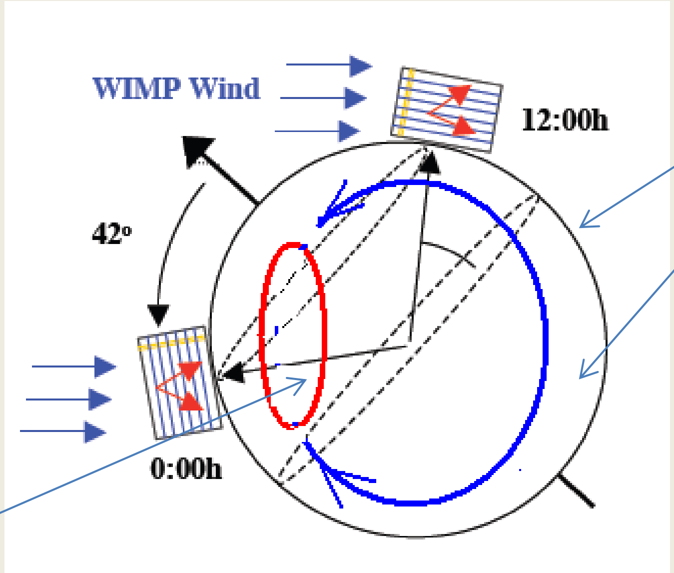
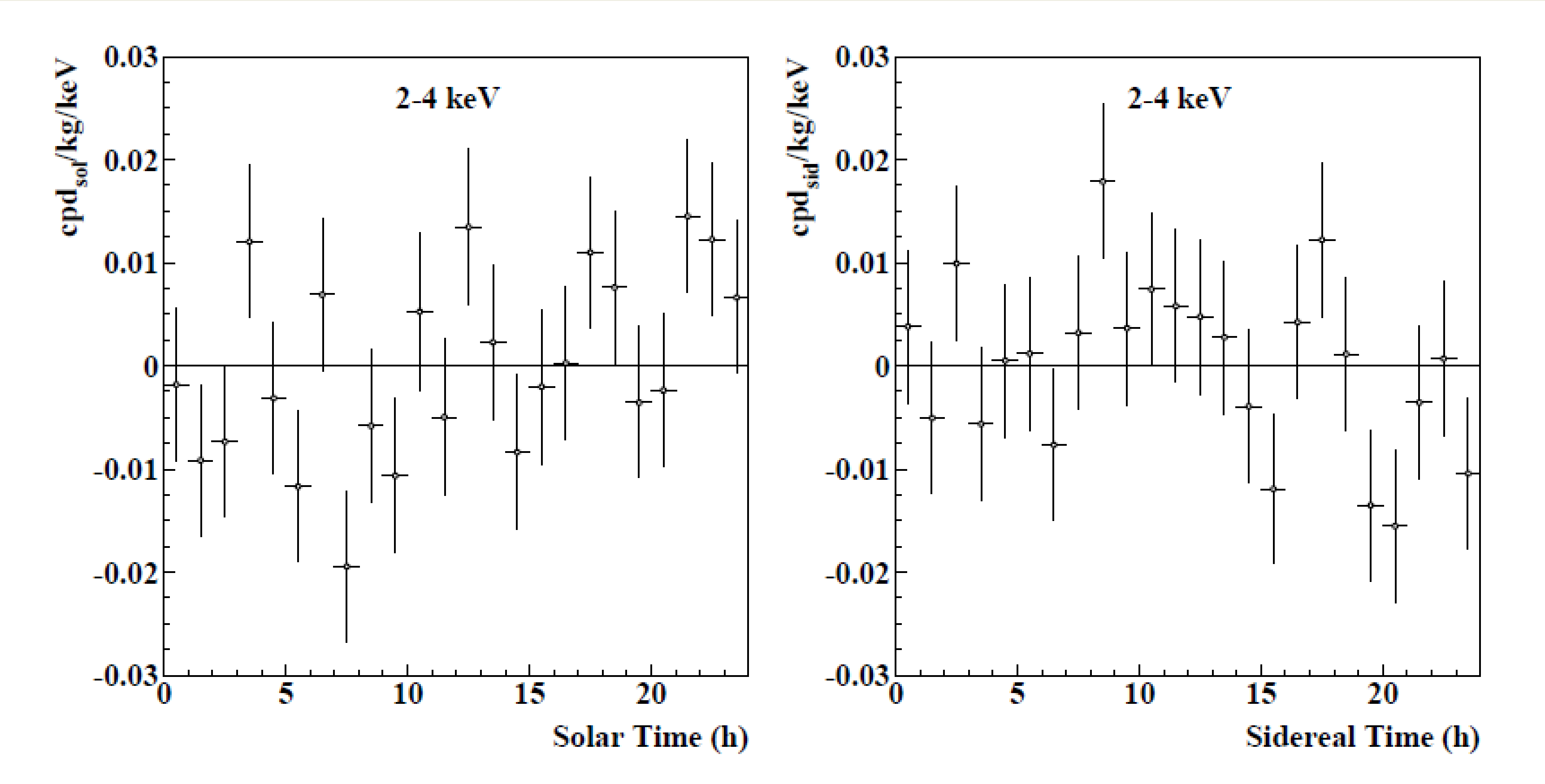


Mirror electrons travel towards the deposited positive charge

Mirror ions accumulate on one side of the Earth

DAMA diurnal rate measurement

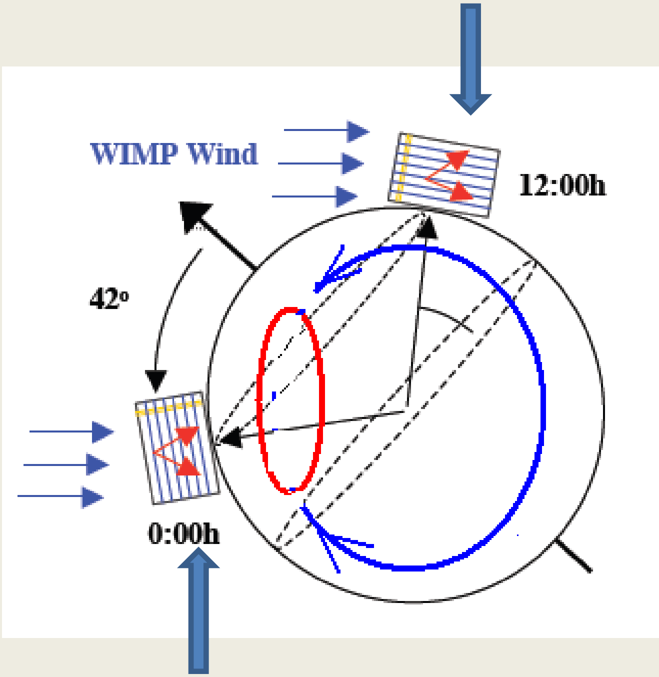


R = Rate(T=8 $\pm$ 6 hours)/Rate(T=20 $\pm$ 6 hours)

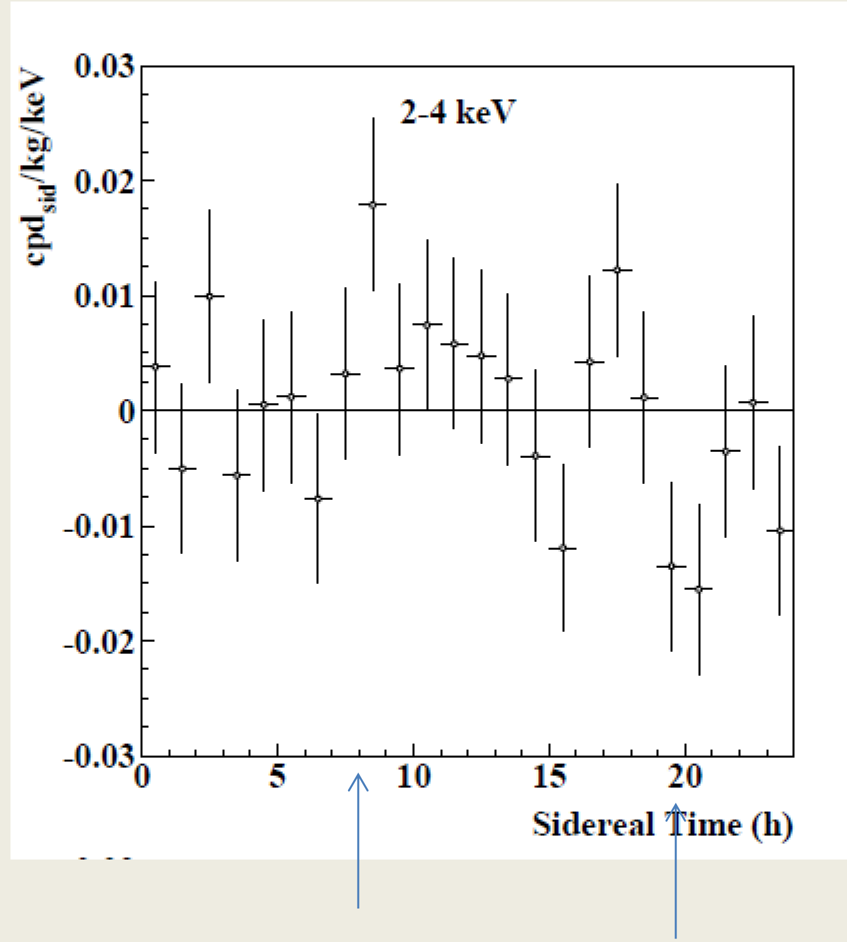
$$R(measured) = 1.0072 \pm 0.0031.$$

2.3σ diurnal signal !

T = 8h



T = 20h



R = Rate(T=8 ± 6 hours)/Rate(T=20 ± 6 hours)

$$R(measured) = 1.0072 \pm 0.0031.$$

2.3σ diurnal signal !

Final remarks

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 models feature nontrivial galaxy dynamics, enabling them to explain both large and small scale structure. Requires kinetic mixing of around:

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

Mirror dark matter, as well as more generic dissipative dark matter candidates can be tested in direct detection experiments, with experiments located in the southern hemisphere particularly sensitive!

Can potentially explain the DAMA (and CoGeNT) annual modulation signals via electron recoils, and predicts diurnal modulation.