Direct detection of plasma dark matter

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CosPA, November 2016

Based on recent work with collaborators, especially J. Clarke; also S.Vagnozzi

Moment please, three possibilities….

The main possibilities for dark matter particles in my view are:

a) DM is cold and (astrophysically) collisionless.

b) DM is warm.

c) DM is cold but collisional.

Possibility a) is simple, gives good explanation for CMB, large scale structure, and also Bullet cluster, but requires baryonic physics to explain the small scale issues and galaxy scaling relations.

Possibilities b) and c) can both explain CMB and large scale structure but also help in resolving the small scale issues, and c) can also explain galaxy scaling relations. However c) could have more difficulty in accounting for Bullet cluster.

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 of a dark electron and dark proton, coupling to a massless dark photon:

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

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

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

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

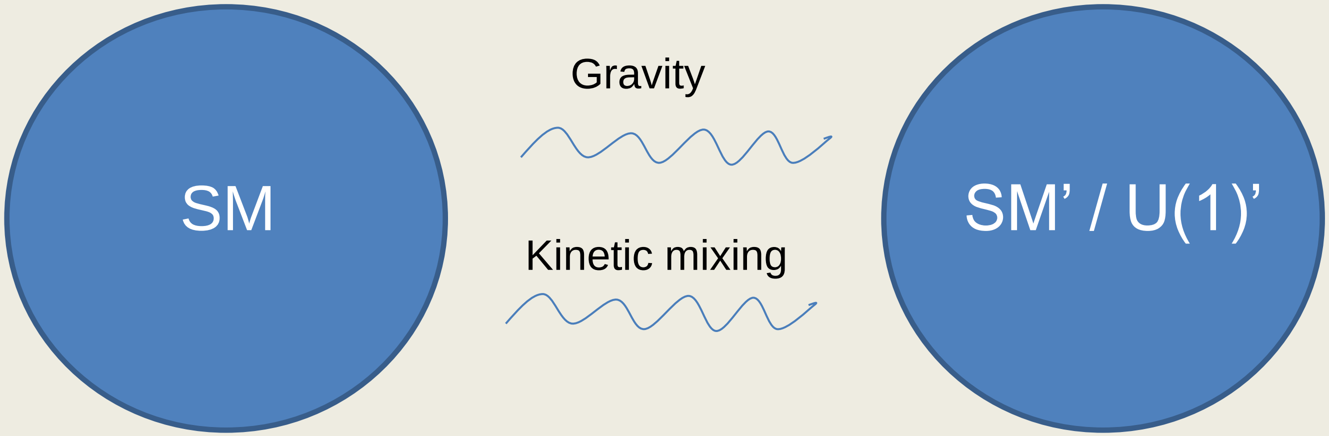
Ref: Foot, Volkas, Vagnozzi, Clarke, and many other people.

Dissipative mirror dark matter

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

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

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



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

Foot, Lew, Volkas, PLB 1991
Foot , IJMP 2014 for detailed bibliography.

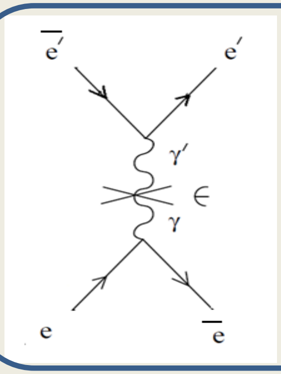
Dissipative halo dynamics – Euler equations

Imagine that dark matter halo around disk galaxies take the form of a roughly spherical plasma composed of dark electrons, dark protons. Their physical properties, density ρ, bulk velocity v and pressure P, are described by Euler's equations of fluid dynamics:

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

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

$$\frac{\partial}{\partial t}\left[\rho\left(\frac{\mathbf{v}^2}{2} + \mathcal{E}\right)\right] + \nabla \cdot \left[\rho\left(\frac{\mathbf{v}^2}{2} + \frac{P}{\rho} + \mathcal{E}\right)\mathbf{v}\right] - \rho \mathbf{v} \cdot \nabla \phi = \frac{d\Gamma_{\rm heat}}{dV} - \frac{d\Gamma_{\rm cool}}{dV}$$



Halo heating supplied by supernova generated γ_D via kinetic mixing mechanism.

Cooling due (assumed to be mainly) bremsstrahlung.

Foot+Volkas, PRD 2004

Disk galaxies today

If the system evolves to a steady-state configuration then the equations reduce to two relatively simple equations (with spherical symmetry assumed):

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

Hydrostatic equilibrium

$$\frac{d\Gamma_{heat}}{dV} = \frac{d\Gamma_{cool}}{dV}$$

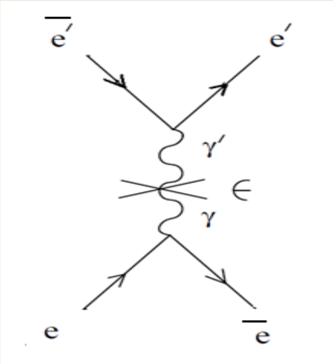
Energy balance equation:
Heating=cooling

That is, two equations for two unknowns, the DM ρ(r), T(r) distributions.

Small-scale structure issues resolved with kinetic mixing

This is a radical picture of small-scale structure.

Can solve cusp-core problem and many other small scale structural issues. It can also solve the missing satellite problem via suppression of the matter power spectrum on small scales due to diffusion damping and dark acoustic oscillations.



In doing so, kinetic mixing interaction plays a critical role:
a) it is the presumed origin of the dark halo heat source via kinetic mixing induced process in supernovae and
b) sets the scale of dark recombination which also sets the diffusion damping and dark oscillation scales.

$$x \equiv \frac{T_{\gamma_D}}{T_\gamma} \simeq 0.31\sqrt{\frac{\epsilon}{10^{-9}}}$$

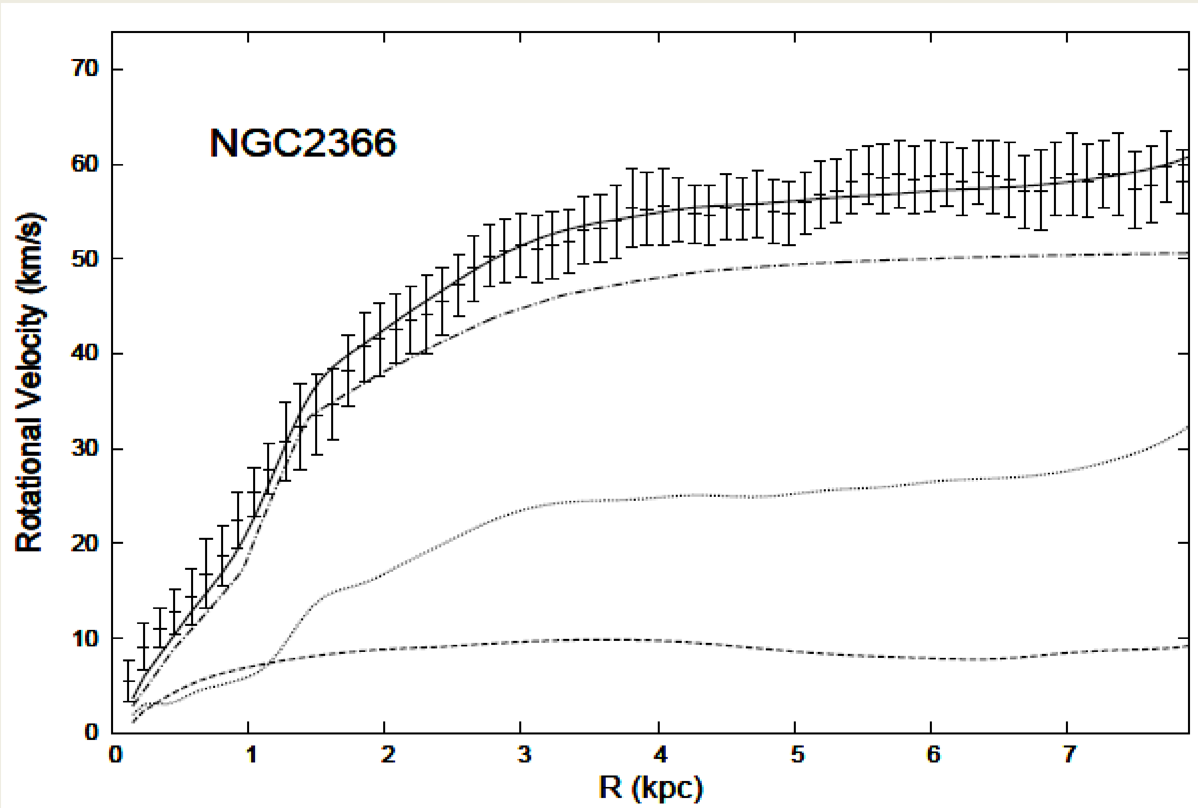
These considerations restrict the kinetic mixing parameter to a reasonably narrow range:

$$10^{-10} \lesssim \epsilon \lesssim 4 \times 10^{-10}$$

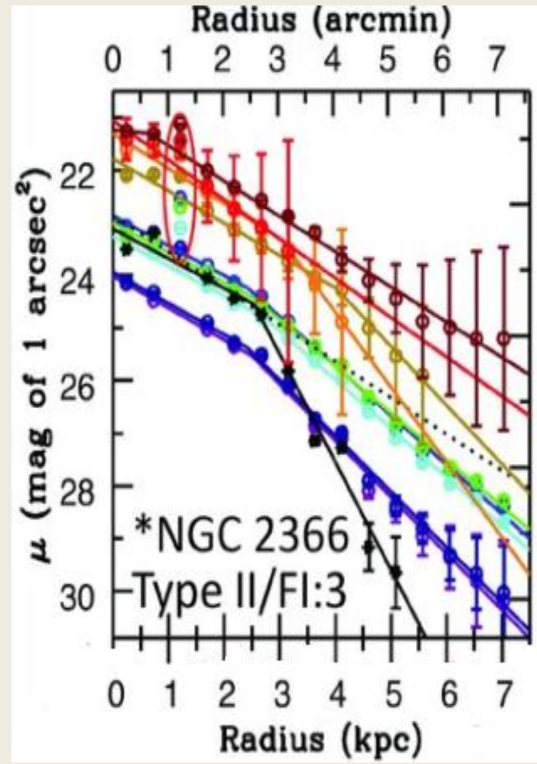
Example of the halo density profile from this dynamics: NGC 2366

Heating = cooling energy balance
a simple form for halo density:

$$\rho(r,\theta,\phi) = \lambda \int d\tilde{\phi} \int d\tilde{r}\, \tilde{r}\, \frac{\Sigma_{SN}(\tilde{r},\tilde{\phi})}{4\pi[r^2+\tilde{r}^2-2r\tilde{r}\sin\theta\cos(\tilde{\phi}-\phi)]}$$



Little things, Oh et al, 2015



Herrmann et al, 2013

Small scale power suppression

Easily calculate halo mass function using extended Press-Schechter formalism.

$$\frac{dn}{d\ln M_{\rm halo}} = \frac{1}{2}\frac{\bar{\rho}}{M} f(\nu) \frac{d\ln\nu}{d\ln M_{\rm halo}}$$

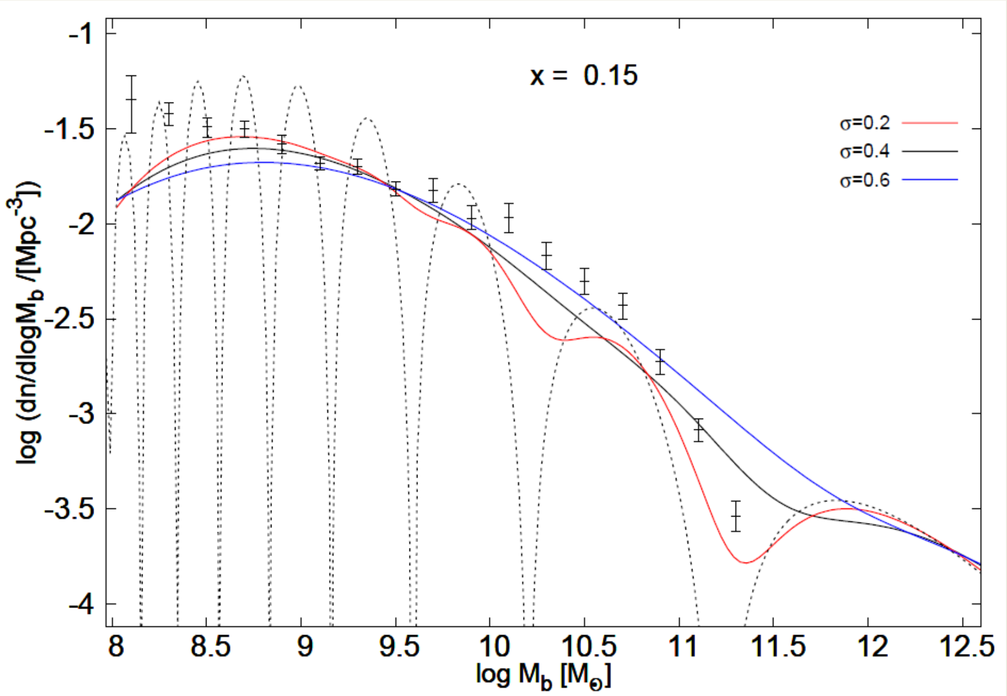
Need to relate M_{halo} to $M_{baryons}$ to connect with observations. Used simplest choice:

$$M_{\rm baryons} \propto M_{\rm halo}$$

Can relate x to ε are related:

$$x \equiv \frac{T_{\gamma_D}}{T_\gamma} \simeq 0.31\sqrt{\frac{\epsilon}{10^{-9}}}$$

Smooth with Gaussian to obtain an estimate of baryonic mass function



$x \approx 0.15 \Rightarrow \epsilon \approx 2 \times 10^{-10}$

S.Vagnozzi, Foot, JCAP 2016

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 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 scales larger than the Debye length $\lambda_D = \sqrt{T/(4\pi\alpha_d n_{e_d})} \sim$ km.

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

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:

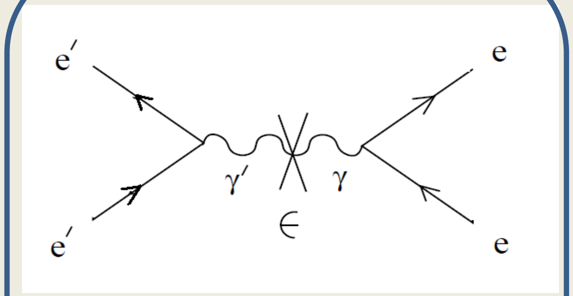
$$\frac{d\sigma_{e'}}{dE_R} = \frac{\lambda}{E_R^2 v^2} \qquad \lambda \equiv 2\pi\epsilon^2\alpha^2/m_e$$

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

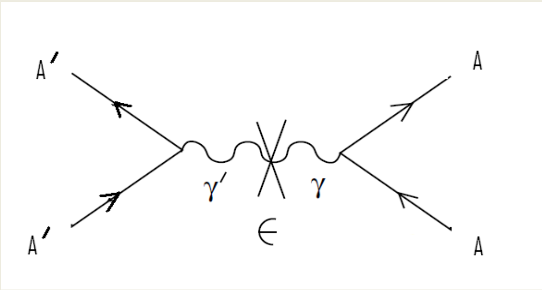
A crude estimate for the interaction rate in a direct detection experiment can be made:

$$\frac{dR_{\rm DM}}{dE_R} = N_T n_{\rm DM} \int_{|\mathbf{v}|>v_{min}} \frac{d\sigma_{\rm DM}}{dE_R} f(\mathbf{v};\mathbf{v}_E)\ |\mathbf{v}|\ d^3v$$

Distribution function unlikely to be Maxwellian, is strongly influenced by halo wind interaction with captured DM within the Earth. Nevertheless, for numerical work a Maxwellian distribution will be assumed: $f(\mathbf{v};\mathbf{v}_E) \propto e^{-(\mathbf{v}_E+\mathbf{v})^2/v_0^2}$

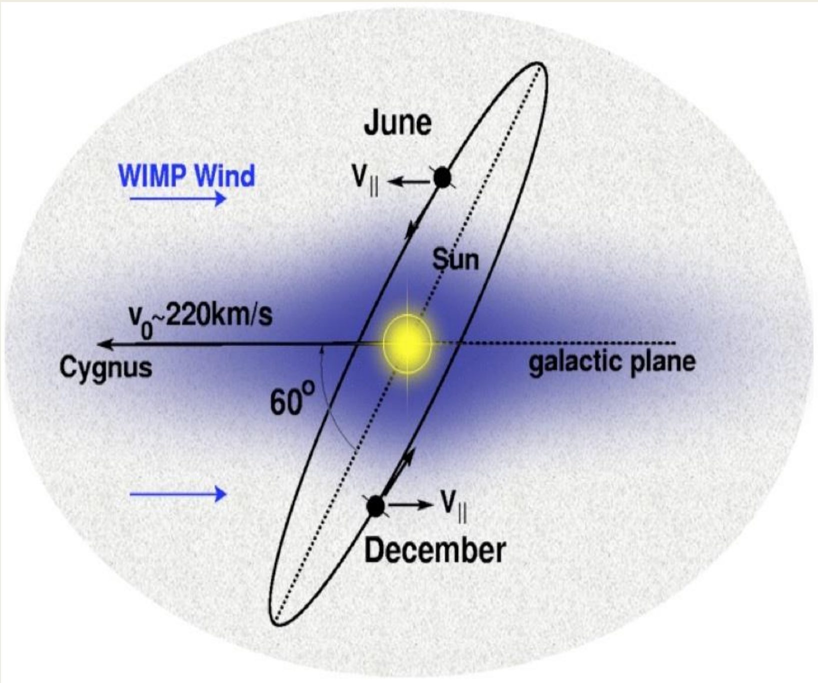


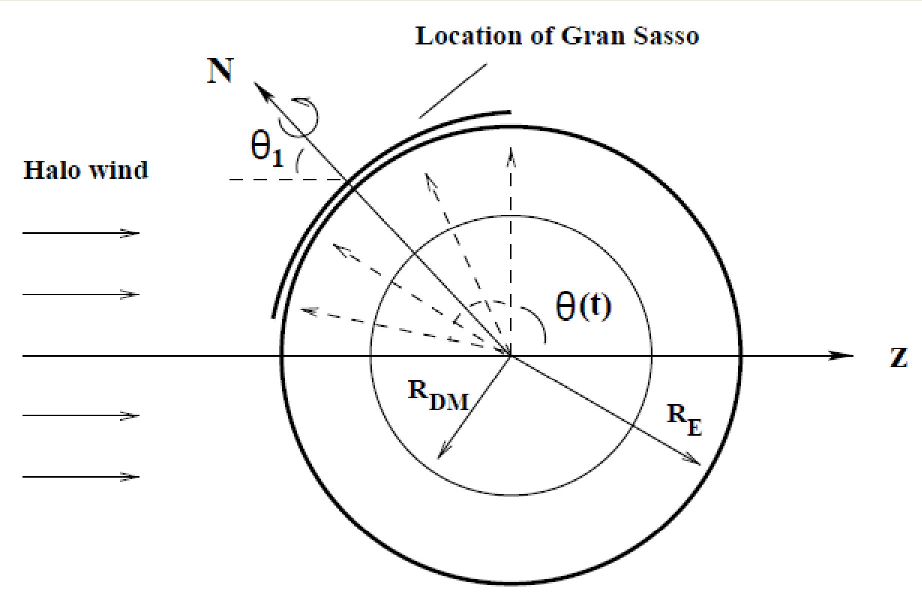
Electron recoils



Nuclear recoils

The detector is in motion…





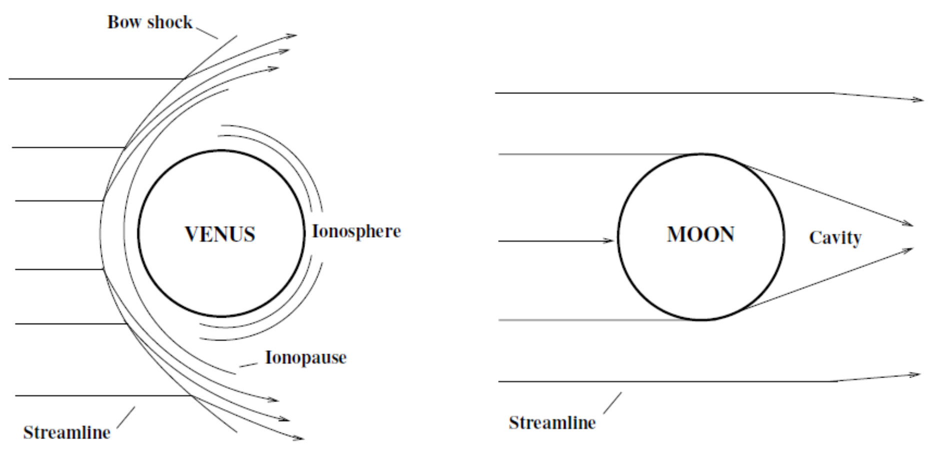
Annual modulation of halo <u>speed</u> (phase t_0 = 152 day), and also an annual modulation of the <u>direction</u> of halo wind (t_0 = 115 day)

Sidereal day modulation of detector location

Halo dark matter wind interaction with dark matter captured in the Earth

Mirror dark matter is complicated because dark matter is captured by the Earth and forms an obstacle to the halo wind

To try to get a handle on the time and spatial variation of the distribution function: Consider an analogy with solar wind. Two quite distinct cases, VENUS-like and MOON-like:



Solve magnetohydrodynamics equations for this system:

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

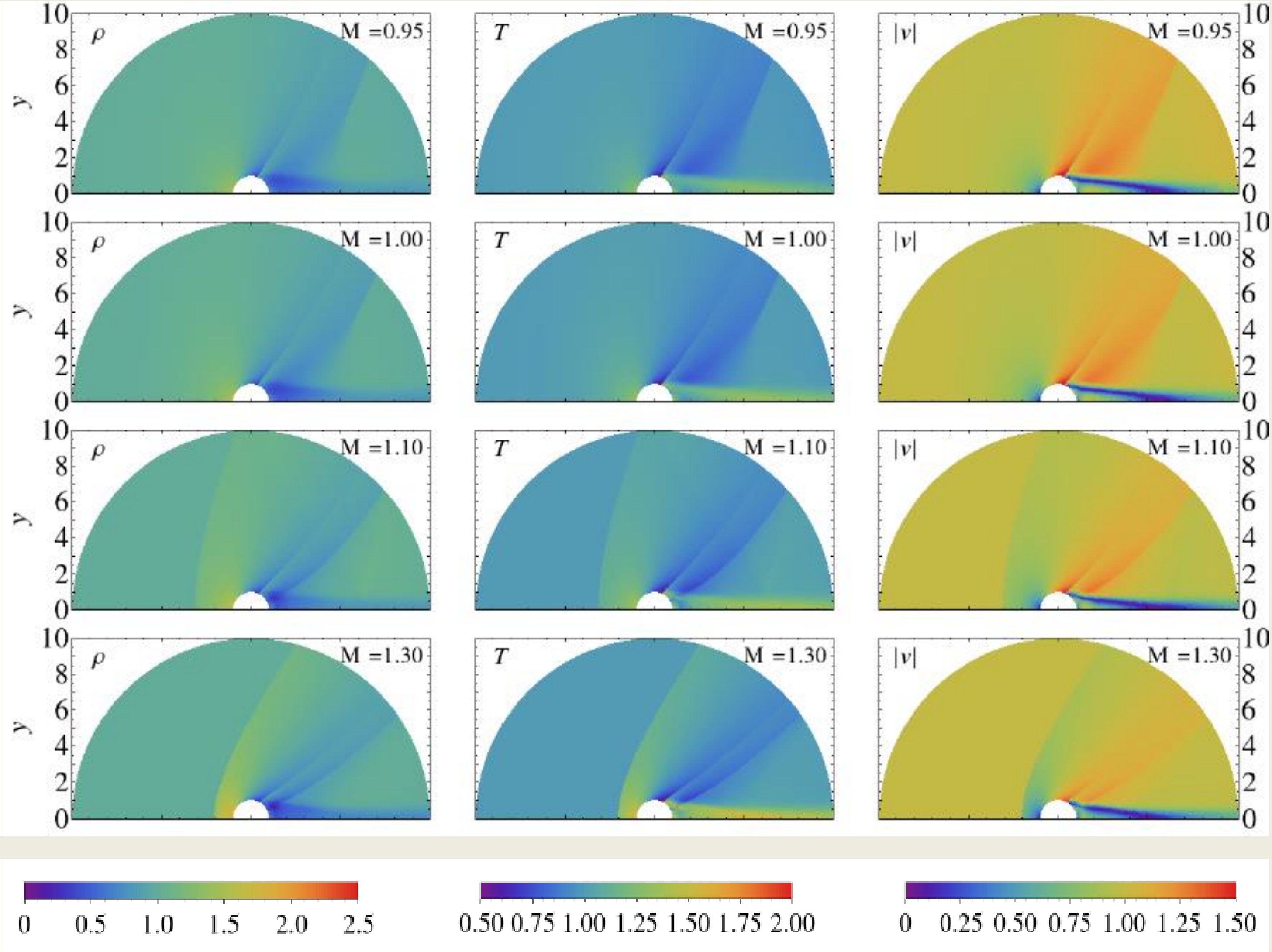
$$\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot \left[\rho \mathbf{v}\mathbf{v} + \mathbf{I}\left(p + \frac{B^2}{2}\right) - \mathbf{B}\mathbf{B}\right] = 0$$

$$\frac{\partial E}{\partial t} + \nabla \cdot \left[\left(E + p + \frac{B^2}{2}\right)\mathbf{v} - \mathbf{B}\left(\mathbf{v} \cdot \mathbf{B}\right)\right] = 0$$

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

$$c_s = \sqrt{\frac{\gamma p}{\rho}} = \sqrt{\frac{\gamma T}{\bar{m}}} \sim \sqrt{\frac{\gamma}{2}} v_{rot}$$

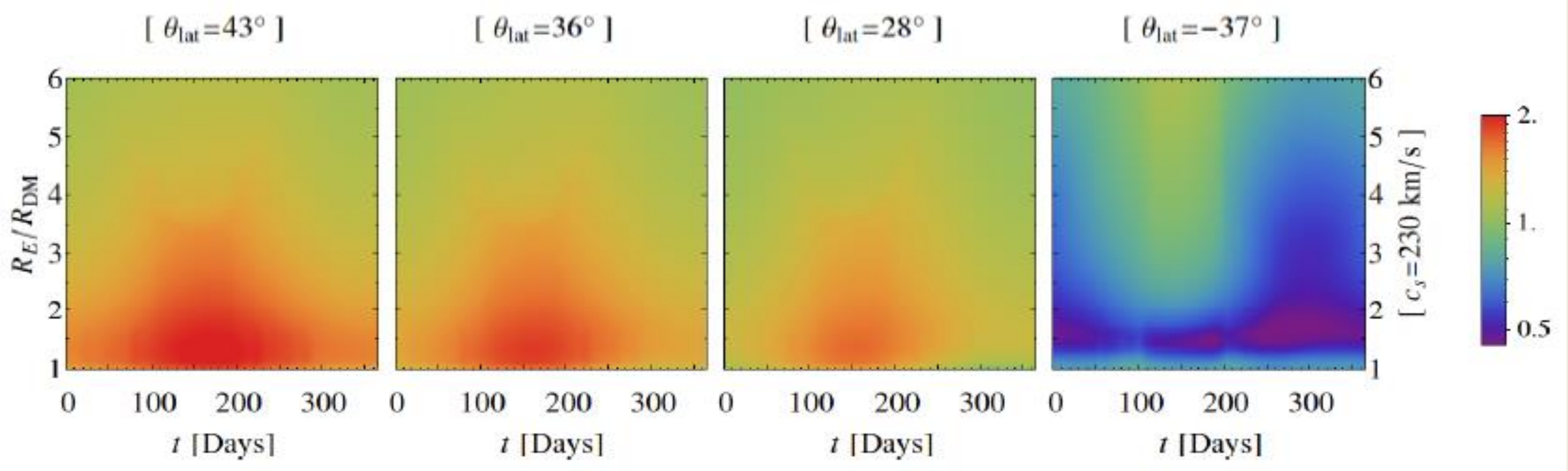
Some examples for venus-like case

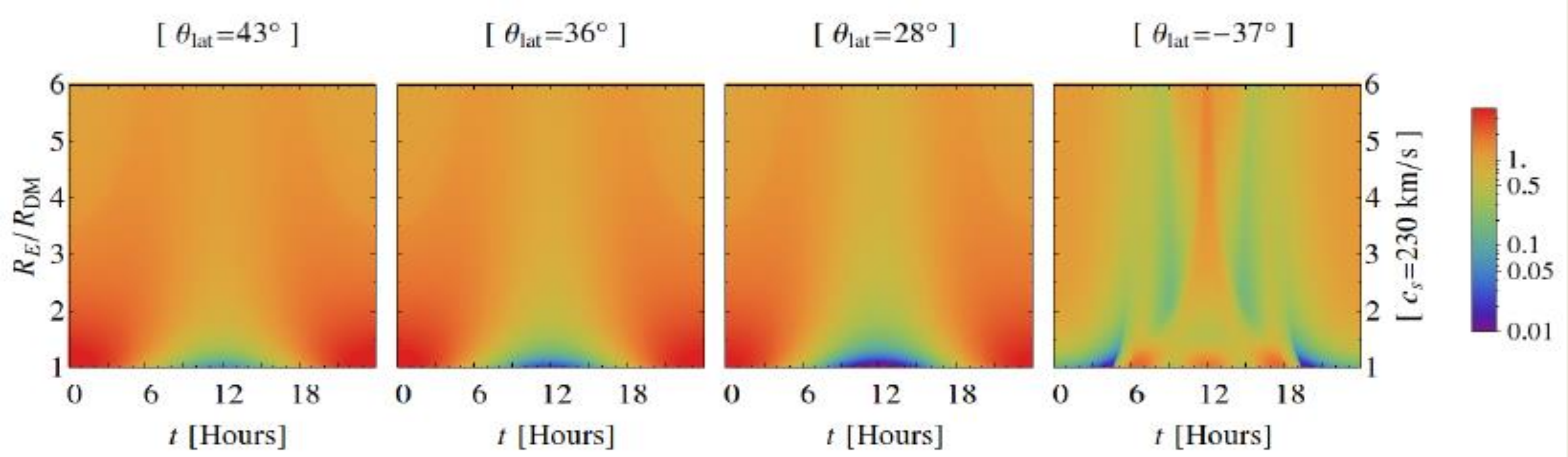


Clarke+ Foot, JCAP 2016

<u>Electron recoil</u> rate above 2 keV

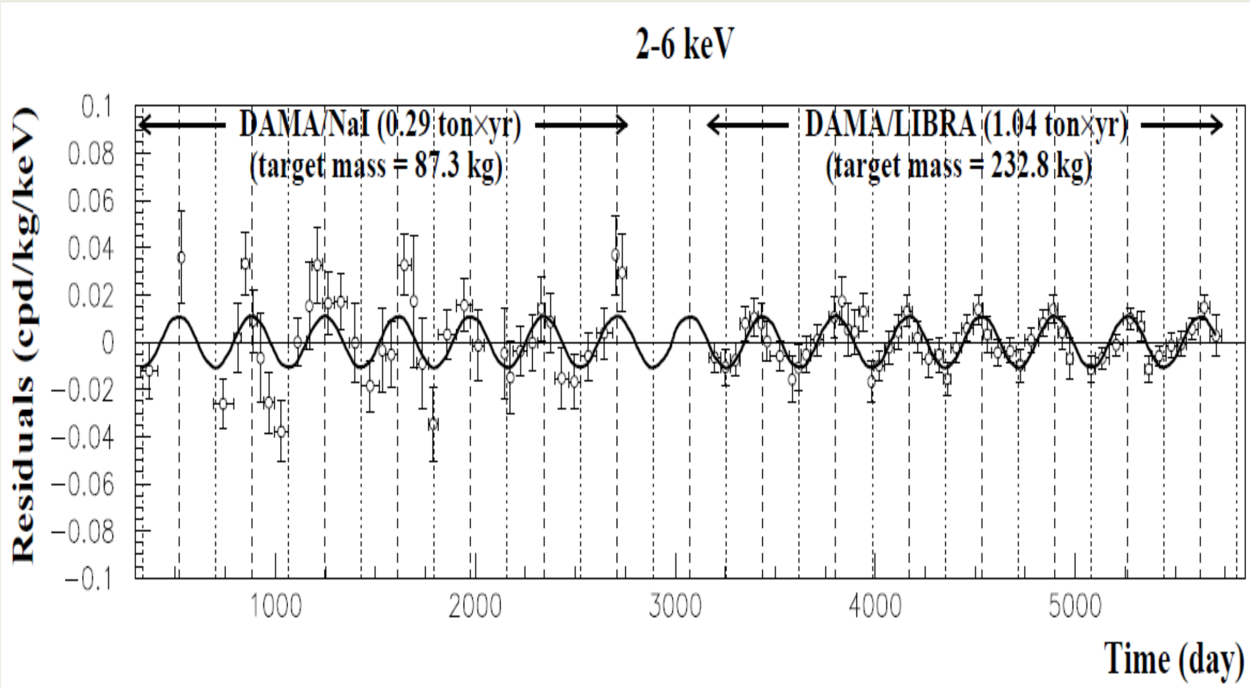
$$R_e = N_T g_T n_{e_d} \lambda \left(\frac{2m_{e_d}}{\pi T} \right)^{\frac{1}{2}} \left(\frac{e^{-\frac{E_t}{T}}}{E_t} - \frac{\Gamma\left[0, \frac{E_t}{T}\right]}{T} \right)$$





Both annual and sidereal day variation expected, and modulation fractions can be large!

Scintillations in DAMA annual modulate:



$A\cos[\omega(t-t_0)]$;
continuous lines: t_0 = 152.5 d, T = 1.00 y

2-4 keV
A=(0.0179±0.0020) cpd/kg/keV
χ^2/dof = 87.1/86 **9.0 σ C.L.**

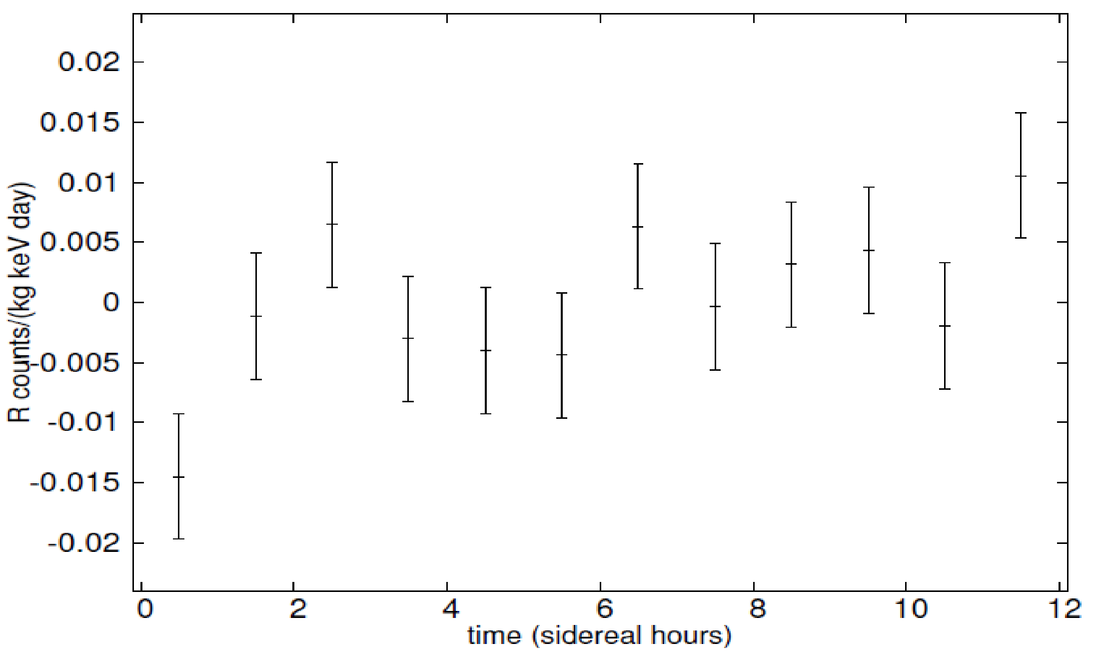
Absence of modulation? No
χ^2/dof=169/87 ⇒ P(A=0) = 3.7×10^{-7}

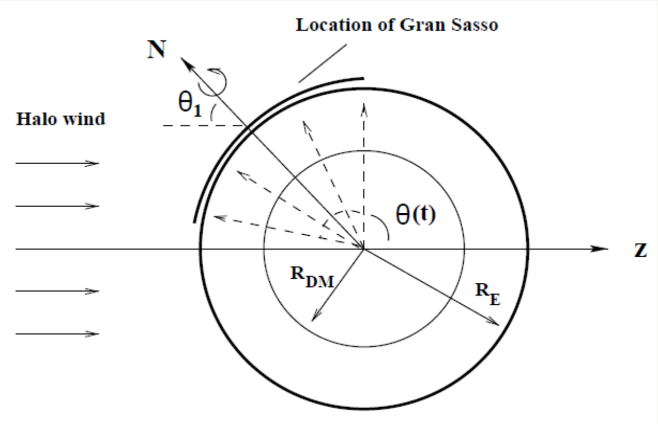
2-5 keV
A=(0.0135±0.0015) cpd/kg/keV
χ^2/dof = 68.2/86 **9.0 σ C.L.**
Absence of modulation? No
χ^2/dof=152/87 ⇒ P(A=0) = 2.2×10^{-5}

2-6 keV
A=(0.0110±0.0012) cpd/kg/keV
χ^2/dof = 70.4/86 **9.2 σ C.L.**
Absence of modulation? No
χ^2/dof=154/87 ⇒ P(A=0) = 1.3×10^{-5}

Bernabei et al, 2013

Hint also of sidereal day modulation in DAMA/Libra:

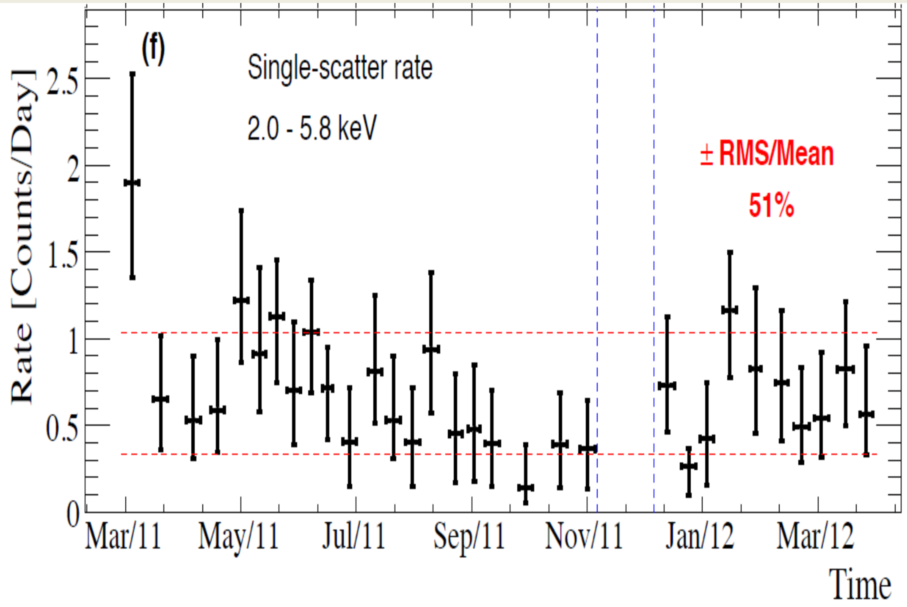


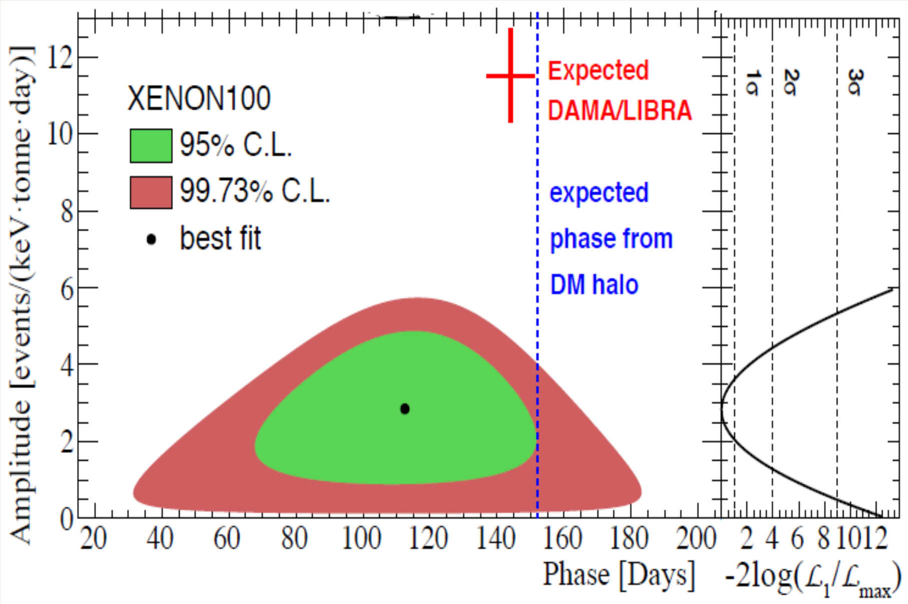


$$\boxed{R_{\mathrm{far/near}} = 1.0072 \pm 0.0031}$$

$$\boxed{2.3\sigma\ \mathrm{C.L.}}$$

XENON100 electron recoil annual modulation search





Aprile et al, PRL 2015

Phase consistent with DAMA, amplitude of modulation ~ 1/3 lower.

Could it be due to larger resolution of DAMA/Libra expt.?

Resolution will be improved with current run!

Average electron recoil rate low in XENON100

⇨ large modulation fraction to be consistent with DAMA/Libra.

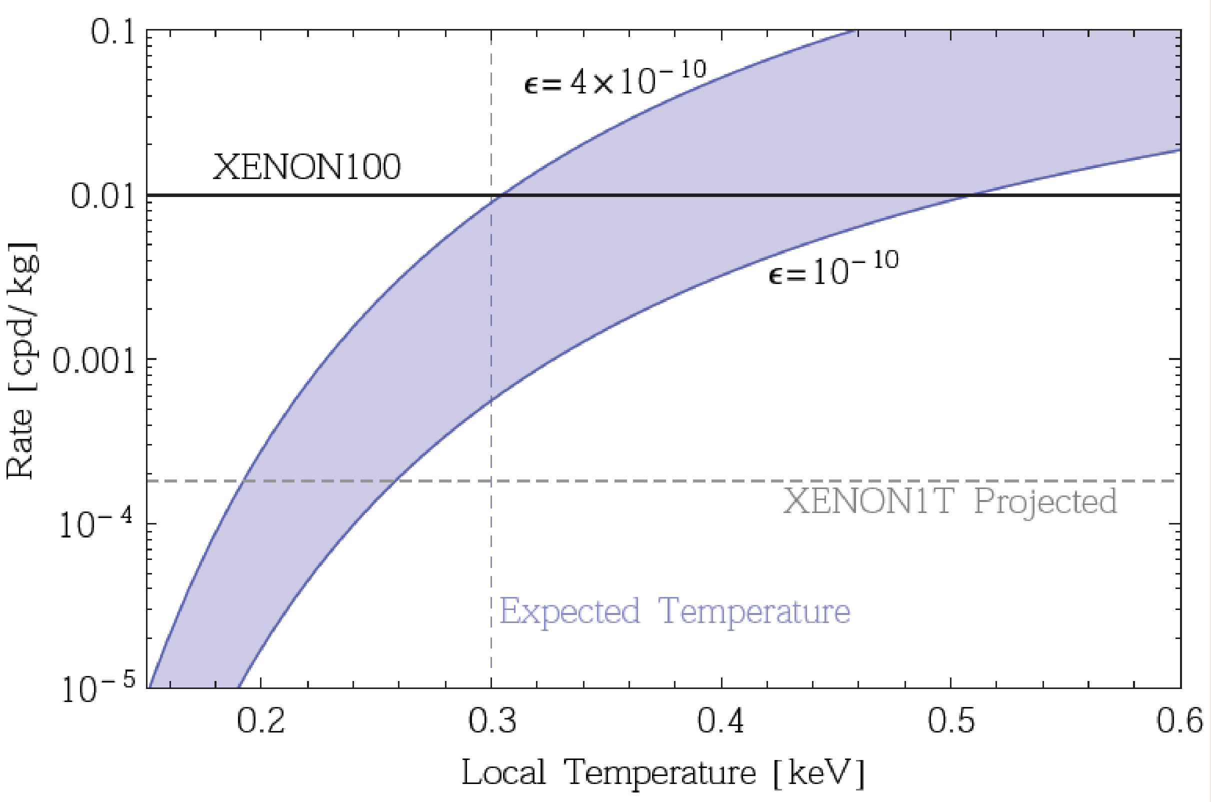
Appears to be possible in this plasma dark matter scenario!

Electron recoils will be probed in more detail be XENON1T

Assuming Maxwellian distribution can calculate electron recoil rate above a threshold:

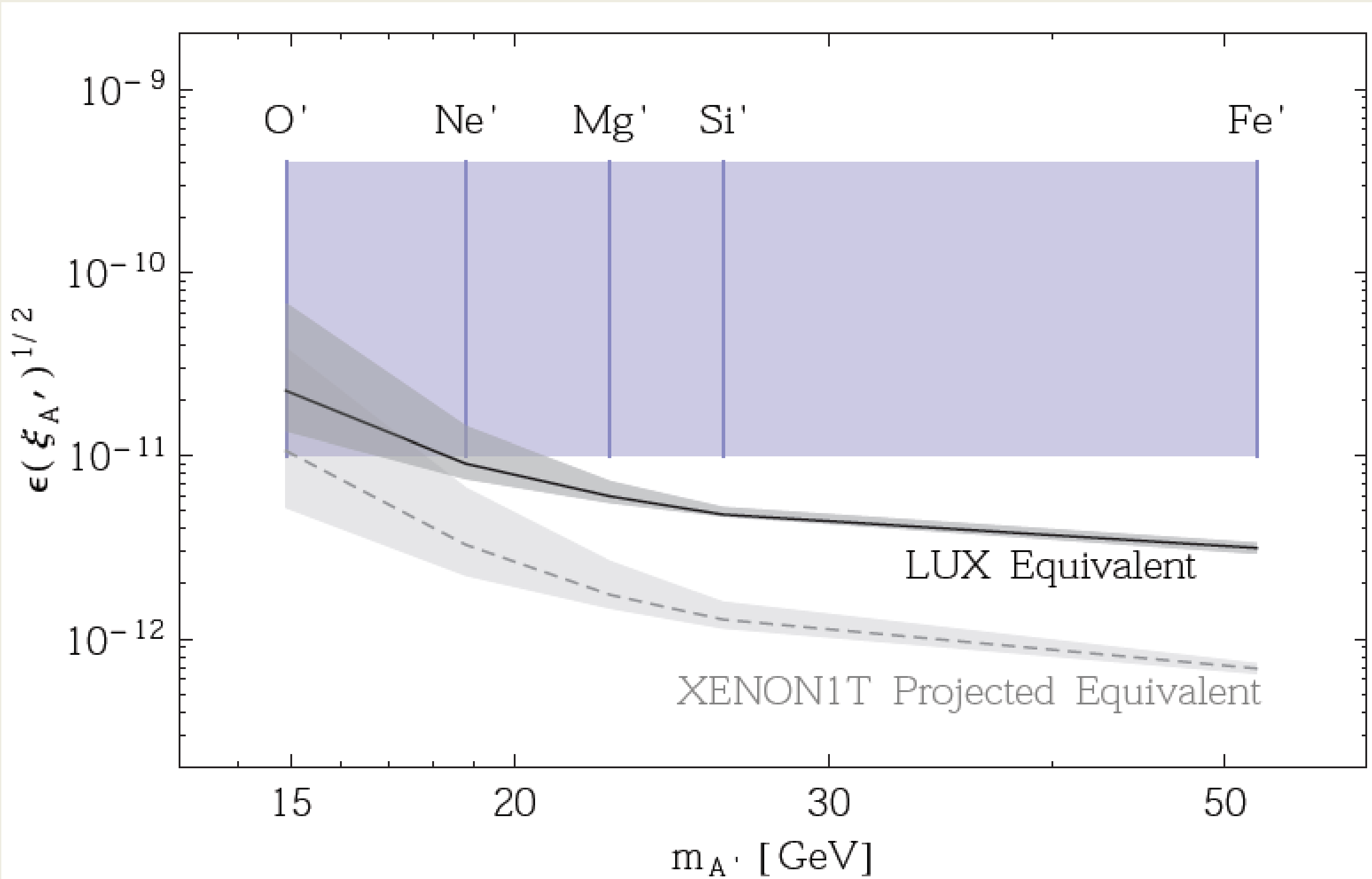
$$R_e = N_T g_T n_{e'} \lambda \left(\frac{2m_e}{\pi T}\right)^{\frac{1}{2}} \left(\frac{e^{-\frac{E_t}{T}}}{E_t} - \frac{\Gamma\left[0, \frac{E_t}{T}\right]}{T}\right)$$

$$T \approx \frac{\bar{m} v_{rot}^2}{2} \sim 0.3 \text{ keV}$$



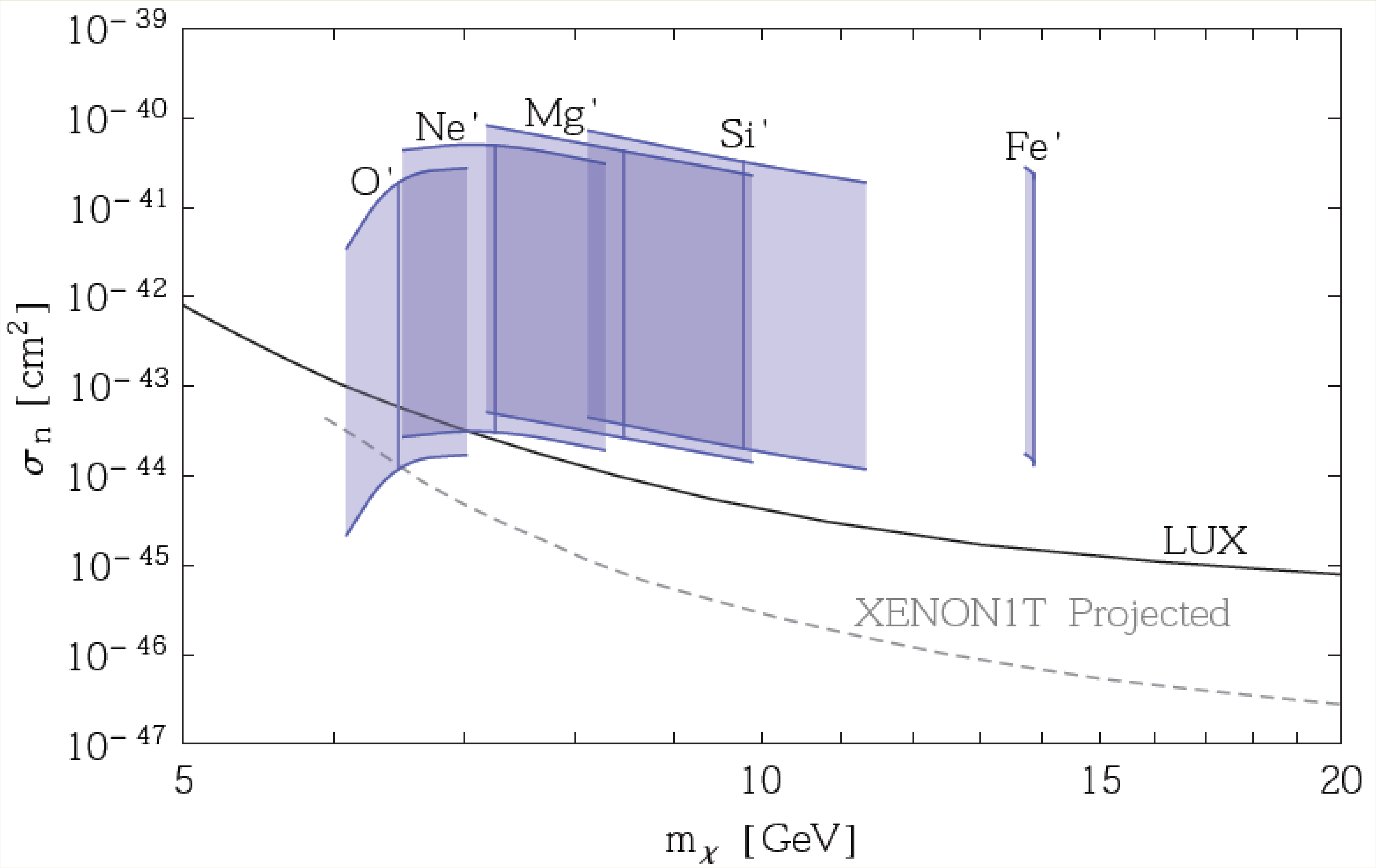
Clarke+Foot, 2016

Nuclear recoils will also be probed very sensitively in LUX, XENON1T, LZ…



$$10^{-11} \lesssim \epsilon\sqrt{\xi_{A'}} \lesssim 4 \times 10^{-10}$$

Nuclear recoils will also be probed very sensitively in LUX, XENON1T, LZ…



Conclusions

Dark matter might be dissipative, e.g. it might arise from a hidden sector with dark electron, dark proton coupling to a massless dark photon, and it can form a plasma around galaxies like Milky Way.

Mirror dark matter provides a theoretically constrained example of such multi-component self-interacting dark matter.

Dissipative dark matter seems to be capable of resolving the small scale structure issues, including core-cusp issue, missing satellite problem, and other small scale issues.

Plasma dark matter has very interesting implications for direct detection experiments: Very different to WIMPs! Light MeV scale components have large velocity dispersions, and can produce keV scale electron recoils.

The scattering rate on electrons is expected to undergo large annual and sidereal day modulations, and can potentially explain DAMA/Libra data consistently with other experiments.