Refs:

Part 1: 0808.3607

and Jungman, Kamionkowski, Griest (PR 267 - 1996)

Part 2: 0811.0399

Part 3: 0807.2250 - why it works
0901.0557 - how it works, numbers

for kinematics: Engel, Vogel - PRD 61 (1999-2000)

Part 4: Halo: astro-ph/0403043
Mirror Photons: astro-ph/0011156
general DAMA: 0804.4518

1. Standard Analysis - ~~[illegible]~~ assumptions

Deposited recoil energy:

$$E_{rec} = \frac{\mu^2 v^2}{M}(1-\cos\theta)$$

μ - reduced nucleus - WIMP mass → contains ~~[illegible]~~ DM mass m
v - speed of WIMP relative to nucleus (more on that later)
M - nucleus mass
θ - scattering angle in CoM frame

~~[illegible]~~

→ 2 assumptions: elastic scattering
scattering on nuclei (even more obvious in cross sections)

central quantity: rate (counts per day, ~~energy~~ per keV and kg detector-mass)

$$\frac{dR}{dE} = \frac{d\sigma}{dE} \underbrace{\frac{\rho v}{m}}_{\text{flux}} \underbrace{\frac{1}{M}}_{\text{nuclei per mass}}$$

ρ - DM density → no free parameter, cross sections normalized to $\rho = 0.3 \frac{GeV}{cm^3}$

→ but $\frac{d\sigma}{dE}$, v

a) Cross section $\frac{d\sigma}{dE}$ usually parameterized as

$$\frac{d\sigma}{dE} = \frac{\sigma(q)}{E_{rec}^{max}} = \frac{\sigma(q)}{2\mu^2 v^2} M$$

For $\sigma(q)$ there are then two main contributions:

$\sigma = \sigma_0 \, |F(q)|^2$ (spin-independent) → 1 free parameter

$\sigma = C \, (a_p^2 \, S_{pp}(q) + a_p a_n \, S_{pn}(q) + a_n^2 \, S_{nn}(q))$ → 2 free parameters a_p, a_n
contains spin J

→ assumptions: WIMP, i.e. interaction via heavy vector bosons
↳ only q dependence in nuclear form factors and structure functions

b) velocity

$$\frac{1}{v} = \eta = \int_{u > v_{min}} \frac{f(\vec{u},t)}{|\vec{u}|} d^3u \qquad \left(v_{min} = \sqrt{\frac{M E_{rec}}{2\mu^2}}\text{, minimal velocity needed to give recoil } E_{rec}\right)$$

~~[illegible]~~

⇒ free parameter, assumptions all in $f(\vec{u},t)$

We don't consider the rel. motion ~~of~~ in the DM halo (giving modulation, t dependence), but only general $f(\vec{u})$, Standard Halo model:
(galactic rest frame)

↳ not assumptions - dep. (very robust)

$$f(\vec{u}) = \begin{cases} N \left(e^{-\frac{v^2}{\bar{v}^2}} - e^{-\frac{v_{esc}^2}{\bar{v}^2}}\right) & v < v_{esc} \\ 0 & v > v_{esc} \end{cases}$$

→ $f(\vec{u}) = f(u)$

→ isotropic, isothermal sphere w/ Maxwellian distribution (assumption!)

$\bar{v} = 220 \, \frac{km}{s}$ (in the SHM → assumption) ~ rotational velocity of solar system in Milky Way

Finally : escape velocity $v_{esc} = 650\ \mathrm{km/s}$, escape velocity of the milky way
(no DM at higher velocities)

That's all the physics, we couple around with ~~[illegible]~~ ~~[illegible]~~.

2. Dropping assumption on nuclear interactions

a.) Why it works ?

→ all direct detection experiments veto on leptonic recoils ... except for DAMA

↳ in a way it's the easiest explanation

b) How it could work

I won't go into the necessary re-analysis of kinematics and all, because the case is so clean cut. Rather, I'll present a model

Leptophilic Dark Matter

→ as always, easy to achieve by a symmetry, surprise, $U(1)_{DS}$ gauge interaction
parity for DM stability

$U(1)_{DS}$ spontaneously broken → gauge boson U

Dark matter is a Dirac fermion χ, with a vector-like mass, charged under $U(1)_{DS}$

To get leptonic interactions we need the SM leptons (at least e^-) to be charged under $U(1)_{DS}$

We don't want this to be some sort of Froggatt-Nielsen, so

charge of $\binom{\nu}{e}$ should be = - charge of e^c

Anomalies ? Take the 2nd gen. to have equal but opposite charges

c) Some numbers. → Parameters g_χ, g_e, M_χ and M_U can be constrained ... and heavily

Is of course actually more popular even for PAMELA / ATIC.
Taking DAMA already tightly constrains parameter space, e.g.

$g_e \sim 10^{-5}$ (rather small coupling to matter)

while $M_U \sim 10\ \mathrm{MeV}$
$M_\chi \sim 700 - 800\ \mathrm{GeV}$
$g_\chi \sim 0.5$

(from Fox, Poppitz, ~~[illegible]~~ arXiv: 0811.0399 v2, which mainly deals with PAMELA / ATIC)

3. Dropping the assumption on elastic scattering

a) ~~[illegible]~~ What this means ?

- There must exist an excited state of DM χ^* with a mass splitting

$$m_{\chi^*} - m_\chi = \delta$$

- Elastic scattering, i.e. $\chi N \to \chi N$ is suppressed compared to inelastic scattering

b) Why it works ?

The recoil energy of the nucleus is now no longer the only kin. erg. lost by the χ

We have: $\frac{1}{2} m v^2 = \frac{1}{2} m v'^2 + E_{rec} + \delta$ (energy, $\delta \ll m$)

$$2ME_{rec} = m^2 |\vec{v} - \vec{v}'|^2 = m^2 (v + v')^2 \quad \text{(momentum, } \delta \ll m \text{, backscattering)}$$

↳ eliminate $v' = \sqrt{2ME_{rec}} \frac{1}{m} - v$ in momentum

↳ insert in Energy, solve for $v = \frac{1}{\sqrt{2ME_{rec}}} \left(\frac{ME_{rec}}{\mu} + \delta \right)$

Is the minimal velocity needed for inelastic scattering with recoil energy E_{rec}

$\Rightarrow$ shifted up by $\frac{\delta}{\sqrt{2ME_{rec}}}$ compared to the inelastic case

- For light targets, this is a substantial shift. Note that

Iodine (DAMA) : A = 127
Germanium (CDMS) : A = 72.6
Xenon (XENON) : A = 131.3

↳ Bonus compared to CDMS

- Modulation is enhanced (imagine extreme case, where only in summer are there fast enough particles)
$\Rightarrow$ DAMA sees more and XENON took its data in winter

- It's also a substantial shift for events with small E_{rec}
↳ Limits obtained from low energy bins in direct detection experiments may not be as stringent

c) How to implement it.

Easiest way: take a complex scalar $\phi = (\phi_r + i\phi_i)\frac{1}{\sqrt{2}}$

This has a regular mass:

$$-M^2|\phi|^2 = -M^2\,(\phi_r^2 + \phi_i^2)\,\frac{1}{2}$$

And a gauge kinetic term coupling it to some neutral gauge boson, which also couples to quarks:

$$|(\partial_\mu + igQZ'_\mu)\phi|^2 = \frac{1}{2}(\partial_\mu\phi_r)^2 + \frac{1}{2}(\partial_\mu\phi_i)^2 - gQZ'_\mu(\phi_i\partial^\mu\phi_r - \phi_r\partial^\mu\phi_i)$$
$$+ \frac{1}{2}g^2Q^2Z'_\mu Z^{\mu\prime}(\phi_r^2 + \phi_i^2)$$

→ has a global $U(1)$ symmetry for rephasing ϕ

→ broken by:

$$-\frac{1}{2}m^2(\phi^2 + (\phi^*)^2) = -\frac{1}{2}m^2\phi_r^2 + \frac{1}{2}m^2\phi_i^2$$

→ two mass eigenstates:

ϕ_r with $\sqrt{M^2+m^2}$ and ϕ_i with $\sqrt{M^2-m^2}$ → δ

↳ coupling to one gauge boson purely off-diagonal → elastic scattering suppressed

→ also works for Fermions (Pseudo/Quasi - Dirac)

c) Some numbers

Mass is still from 100 GeV to 1TeV, the mass splitting should be about 100 keV

4. Mirror Dark Matter / Hidden Sector

a) ~~[illegible]~~ Why it works?

Orthogonal approach to inelastic DM; if $\delta = 0$, we have

$$v_{min} = \sqrt{\frac{ME_{rec}}{2\mu}}$$

~~[illegible]~~

As for the inelastic case, we should compare v_{min} with $\bar{v}$. In this case we get suppression for events with:

- large mass nuclei → luckily DAMA also contains sodium nuclei (Na has $A=23$)
- high energy events → so we would need a detector with low threshold (DAMA), plus an enhancement of low energy events
  ↳ with channeling
  ↳ drop WIMP paradigm of no energy dependence, and take Rutherford scattering $\sigma \propto \frac{1}{E^2}$

- This means more events in DAMA, but still we should see what we expected in the other detectors.
~~- But since we still have standard, elastic kinematics, these should still be visible in other detectors~~

→ important is relation of v_{min} to $\bar{v}$ → also take a lower $\bar{v}$ (non-standard Halo model)
↳ v_{min} for other exp's may be larger than $\bar{v}$

→ Non-Standard Halo Model + Rutherford Scattering

b) How can it be implemented

i) NSHM

→ Halo at rest, allowing for maybe some bulk halo rotation

$$170 \frac{km}{s} \leq \bar{v} \leq 270 \frac{km}{s}$$

How can one get this to be much lower?

In the simplest setup, take two stable particles in the hidden sector, which comprise the majority of Dark Matter. They have masses M_1 and M_2, with $M_1 \ll M_2$.

They interact a lot thru some hidden sector dynamics (at least one unbroken $U(1)'$, which we need later) and are thus in thermodynamic equilibrium.

The mass density of the halo is dominated by the lighter M_1 particles

↳ they have velocity distribution $\propto e^{-v^2/v_{rot}^2}$, $v_{rot} = 220 \frac{km}{s}$, as expected in the regular WIMP setup.

BUT since we have a whole mirror world, or at least some hidden sector, the M_2 component is in thermal equilibrium

$$\hookrightarrow f(v_2) \propto e^{-\frac{M_2 v^2}{M_1 v_{rot}^2}}$$

↳ If these M_2 particles are the DM seen in DAMA, we have

$$\bar{v} = \sqrt{\frac{v_{rot}^2 M_1}{M_2}} = v_{rot} \sqrt{\frac{M_1}{M_2}} \ll v_{rot}$$

→ So two components in thermal equilibrium, easily give low $\bar{v}$ for the heavier component

(In a mirror world M_1 would be mirror He or H, while M_2 would be heavier elements)

ii) Rutherford scattering

We already needed to introduce a massless $U(1)'$ gauge boson in the hidden sector, to ensure thermal equilibrium.

This can also be our scattering transmitter – but why should it couple to nuclei?

→ photon – mirror photon mixing (mirror photon is gauge boson of $U(1)'$)

We need a $U(1)$, because only gauge bosons which are uncharged under their own gauge group can mix. But for two $U(1)$'s, we have that the most general gauge kinetic term is:

→ no impact of $SU(3)' \otimes SU(2)'$ in mirror world

$$\mathcal{L}_{kin} = a F_{\mu\nu} F^{\mu\nu} + b F_{\mu\nu} F'^{\mu\nu} + c F'_{\mu\nu} F'^{\mu\nu}$$

or after normalizing

$$- \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{\varepsilon}{2} F_{\mu\nu} F'^{\mu\nu} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu}$$

(NB: The second term is allowed at tree level if the $U(1)$'s are fundamental, but needs to be generated radiatively – by intermediate world particles – if $U(1)$ is embedded in a GUT)

Now photons and mirror photons are massless, there's no mass eigenstates to diagonalize, nothing.
We can thus define all kinds of linear combos. Here's four of 'em:

$$A_1 = \frac{A + \varepsilon A'}{\sqrt{1+\varepsilon^2}} \qquad A_2 = \frac{A' - \varepsilon A}{\sqrt{1+\varepsilon^2}}$$

physical photon & sterile photon (does NOT couple to ordinary matter)
↳ i.e. in the absence of mirror matter, there's no effect on our world
Do the same for the mirror world.

$$A_1' = \frac{A' + \varepsilon A}{\sqrt{1+\varepsilon^2}} \qquad A_2' = \frac{A - \varepsilon A'}{\sqrt{1+\varepsilon^2}} \quad \text{(doesn't couple to mirror matter)}$$

→ Then Mirror DM emits A_1' and we have

$$A_1' = \frac{1-\varepsilon^2}{1+\varepsilon^2} A_2 + \underbrace{\frac{\varepsilon}{1+\varepsilon^2} A_1}_{\text{admixture of physical photon}}$$

→ effective coupling to matter $\frac{\varepsilon}{1+\varepsilon^2} e \sim \varepsilon e$

→ massless particle responsible for elastic scattering

c) Some numbers: $\varepsilon \sim 10^{-9}$

Masses work well for Mirror world such that

$M_1 \sim 1$ GeV (for mirror H), 4 GeV (for mirror He)

$M_2 \sim 15$–30 GeV (e.g. mirror oxygen)