Direct Detection and Collider Searches of Dark Matter Lecture 3

Graciela Gelmini - UCLA

Dark Matter School, Lund, Sept. 26-30, 2016

Content of Lecture 3

- The Standard Halo Model (SHM)
- Uncertainties in the local dark matter distribution and the expected annual modulation of the rate.
- Halo-Independent direct detection data comparison.
- Past hints of dark matter in direct detection experiments.
- Can potential signals and upper limits be compatible?

Subject is very vast, so idiosyncratic choice of subjects + citations disclaimer

Event rate: usually in events/kg of detector/keV of recoil energy/day

$$\frac{dR}{dE_R} = \sum_T \int_{v>v_{min}} \frac{C_T}{M_T} \times \frac{d\sigma_T}{dE_R} \times n v f(\vec{v}, t) d^3 v$$

-E_R: nuclear recoil energy- T: each target nuclide (elements and isotopes)
- $\frac{C_T}{M_T}$= mass fraction of nuclide T× Number of nuclides T per kg=Number of nuclides T per kg in the detector
- v_{min} min WIMP speed to impart E_R to the target T - $\mu_T = mM_T/(m + M_T)$

- For a WIMP-nucleus contact differential cross section (for momentum transfer and velocity-independent interaction operators)

$$\frac{d\sigma_T}{dE_R} = \frac{\sigma_T(E_R)\ M_T}{2\mu_T^2 v^2} \qquad \sigma_T(E_R) \sim \sigma_{ref}$$

$$\frac{dR}{dE_R} = \sum_T \frac{\sigma_T(E_R)}{2m\mu_T^2}\ \rho\eta(v_{min}) \qquad where \qquad \eta(v_{min}) = \int_{v>v_{min}} \frac{f(\vec{v}, t)}{v} d^3 v$$

-$\rho = nm$, $f(\vec{v}, t)$: local DM density and $\vec{v}$ distribution depend on halo model.

Thus, given $\rho\eta(v_{min})$ and the particle model, the plots are in the m, σ_{ref} plane ("Halo-Dependent" analysis)

The recoil spectrum dR_T/dE_R is not directly accessible to experiments

because of energy dependent energy resolution and efficiencies and because they often observe only a fraction $E^{'}$ for the recoil energy E_R.

Observed event rate:

$$\frac{dR}{dE^{'}} = \epsilon(E^{'}) \int_0^\infty dE_R \sum_T C_T\, G_T(E_R, E^{'})\, \frac{dR_T}{dE_R}$$

- $E^{'}$: detected energy (in keVee or number of PE), C_T: mass fraction in target nuclide T;
- $\epsilon(E^{'})$: counting efficiency or cut acceptance; $G_T(E_R, E^{'})$: energy response function

$$\frac{dR_T}{dE_R} = \int \frac{1}{M_T} \frac{d\sigma_T}{dE_R} \times \frac{\rho}{m} v f(\vec{v}, t) d^3 v$$

[Event Rate] = [Detector Response] X [Cross Section] X [Halo Model]

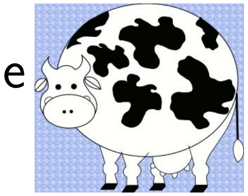
Elements of the Event Rate

[Event Rate] = [Detector Response] x [Cross Section] x [Halo Model]

How many dark matter particles are passing through the detector and with which velocity distribution?

.

The Standard Halo Model

Standard Halo Model (SHM) The  of halo models

The Dark Halo is modeled as an Isothermal Sphere

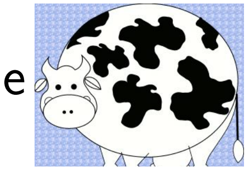
- Assumes hydrostatic equilibrium: pressure balances gravitational potential.

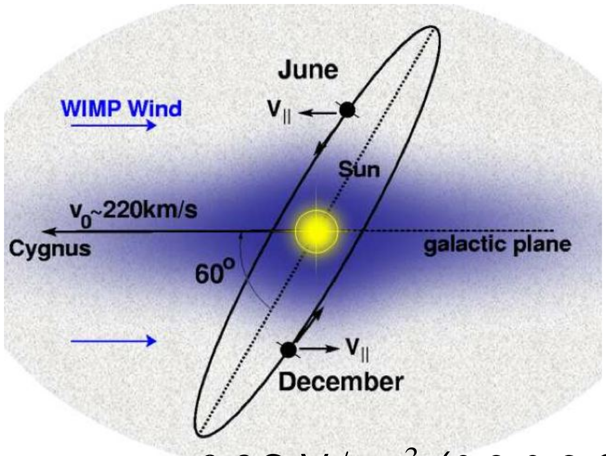
The rapidly changing gravitational potential of the forming Galaxy may have lead the DM particles to thermal equilibrium (Lynden-Bell's model of "Violent relaxation").

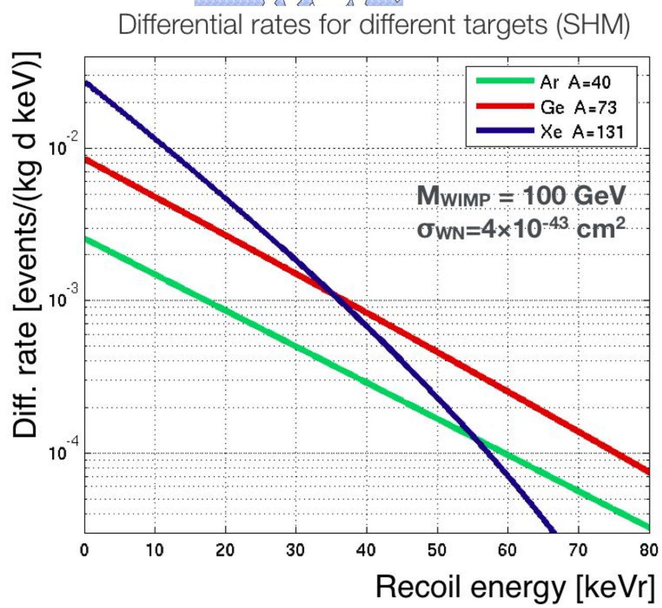
- Resulting density profile $\rho(r) \sim r^{-2}$ and gravitational potential $\Phi(r) \sim \ln(r^2)$

- Produces flat rotation curves

- The local dark matter density in $\rho \simeq 0.3 GeV/cm^3$

Standard Halo Model (SHM) The  of halo models



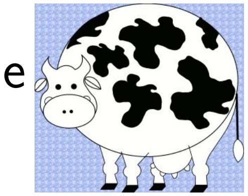


- ρ_{SHM} = 0.3GeV/cm^3 (0.2-0.6 GeV/cm^3)
- $f(v,t)$: Maxwellian $\vec{v}$ distribution

at rest with the Galaxy $v_\odot$ ≃220km/s (190 to 320 km/s), v_{esc} ≃530-650km/s

WIMP wind v max in June 1, min in Dec 1. lead to annual modulation of the rate (rate maximum or minimum at June 1)(Drukier, Freese, Spergel 1986)

Local ρ, $\vec{v}$ distribution, modulation phase/amplitude could be very different if Earth is within a DM clump or stream, if there is a "Dark Disk", anisotropy, triaxiality, debris flows...

Standard Halo Model (SHM) The  of halo models

Maxwellian distribution truncated at the local Galactic escape speed v_{esc}

$$f_h(\vec{v},t) = \begin{cases} \frac{1}{N_h(2\pi\sigma_h^2)^{3/2}} e^{-|\vec{v}+\vec{v}_\odot+\vec{v}_\oplus(t)|^2/2\sigma_h^2} & \text{if } |\vec{v}+\vec{v}_\odot+\vec{v}_\oplus(t)| < v_{esc} = 650 \text{ km/s}, \\ 0 & \text{otherwise.} \end{cases}$$

The velocity of a WIMP relative to the Galaxy is $\vec{v}+\vec{v}_\oplus+\vec{v}_\odot$

$\vec{v}$: WIMP velocity relative to the Earth

$\vec{v}_\oplus(t)$: velocity of the Earth relative to the Sun (29.8 km/s tangent to orbit)

$\vec{v}_\odot$: velocity of the Sun relative to the Galactic Rest Frame (in which halo WIMPs assumed to be stationary)= 232 km/s in direction $\lambda_\odot = 340^\circ$, $\beta_\odot = 60^\circ$ ecliptic coordinates;

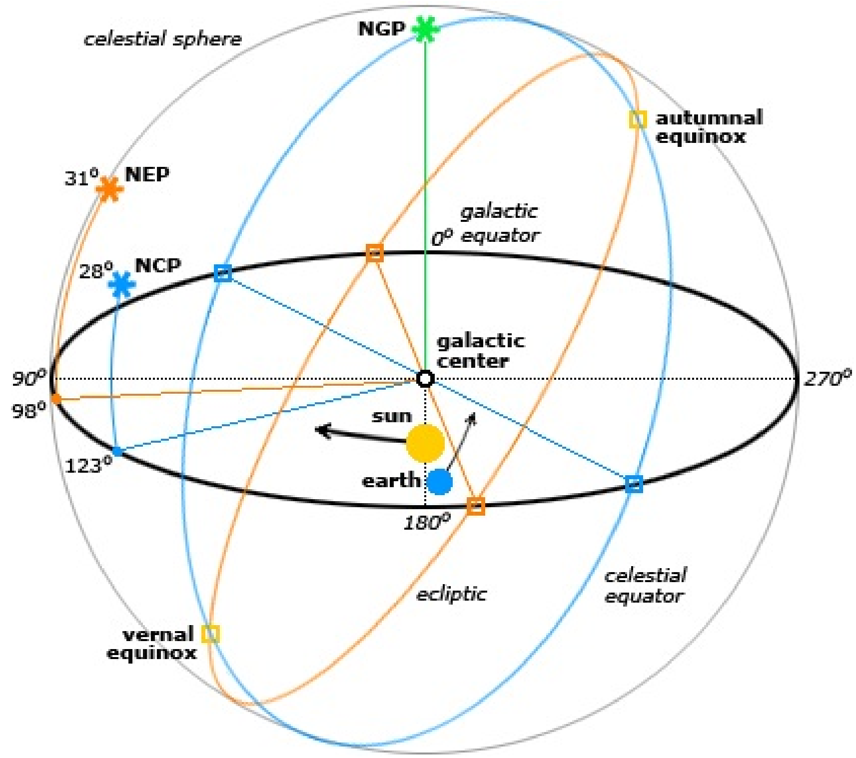
σ_h: velocity dispersion of WIMPs = $(220/\sqrt{2})$ km/s in isothermal model,

$N_h = erf(z/\sqrt{2}) - (2/\pi)^{1/2} z e^{-z^2/2}$, with $z = v_{esc}/\sigma_h$: normalization factor.

With this model: maximum possible heliocentric WIMP velocity is $v_{esc} + v_\odot = 882$ km/s.

Annual Modulation of the Rate

$|\vec{v}_\odot + \vec{v}_\oplus|$ is maximum at the end of May or beginning of June (uncertainty in velocities mostly due to the galactic rotation velocity $v_{Gal\,Rot}$ = 180 - 232 km/s). $\vec{v}_\odot$ and $\vec{v}_\oplus$ are at 60^o, so $\simeq v_\oplus$ cos 60^o sums or subtructs from $v_\odot$.



Annual Modulation of the Rate in the SHM

Schematic speed distribution $F(v,t)$ and integral $\eta(v)$ with arbitrary normalization, where

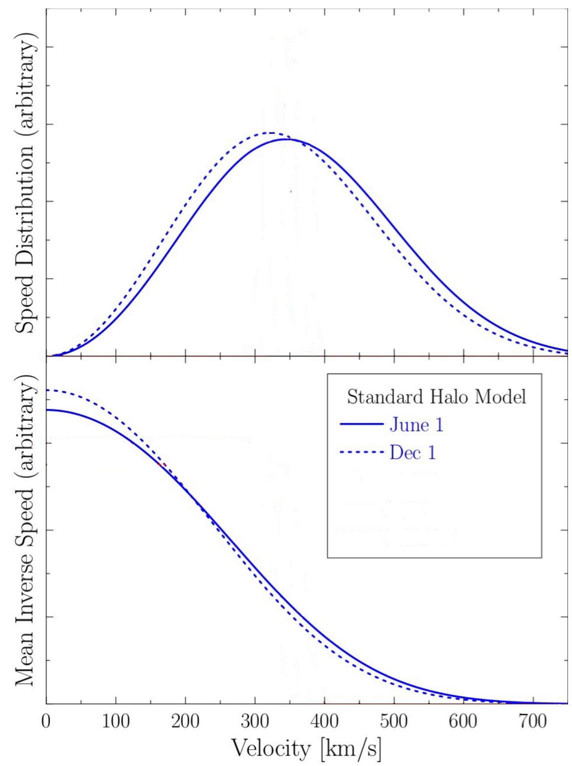
$$\eta(v_{min},t) = \int_{v>v_{min}} \frac{f(\vec{v},t)}{v} d^3v = \int_{v>v_{min}} \frac{F(v,t)}{v} dv \qquad (^*)$$

(*) You will compute the SHM η function

Notice that the maximum of η changes from June 1 to Dec. 1 at $v_{min} < 200$km/s. Annual modulation is due only to $\vec{v}_\oplus$, so

$\eta(v_{min},t) \simeq \eta(v_{min}, v_\oplus = 0) + \vec{v}_\oplus \cdot \frac{\partial\eta}{\partial \vec{v}_\odot}\Big|_{v_\oplus=0}$

Thus the annual modulation amplitude is linear in Earth's orbital speed $v_\oplus$



(fig. from Freese, Lisanti & Savage 1209.3339)

Annual Modulation of the Rate in the SHM

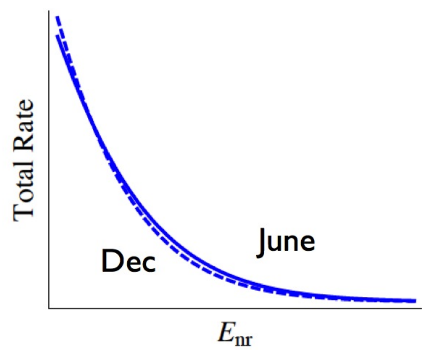
The rate can be well approximated by the 1st term of a harmonic expansion

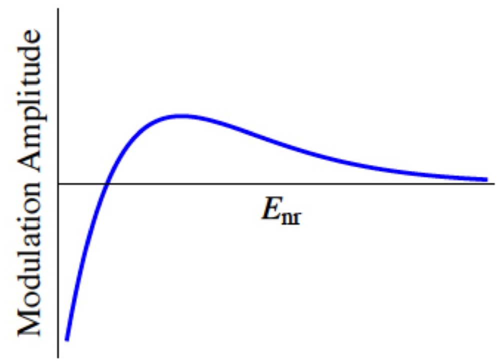
$$\frac{dR}{dE_r}(E_R,t) \simeq S_0(E_R) + S_m(E_R)\ cos[\omega(t-t_0)]$$

t_0 is the phase, $\omega = 2\pi/$ year. Written in this way, the annual modulation amplitude

$$S_m(E_R) = \frac{1}{2}\left[\frac{dR(June1)}{dE_R} - \frac{dR(Dec1)}{dE_R}\right]$$

changes sign at low recoil energies. $S_m/S_0 \simeq$ 1- 10% for most v_{min} values ($\sim v_{\oplus}/v_{\odot} \simeq$ 10%)

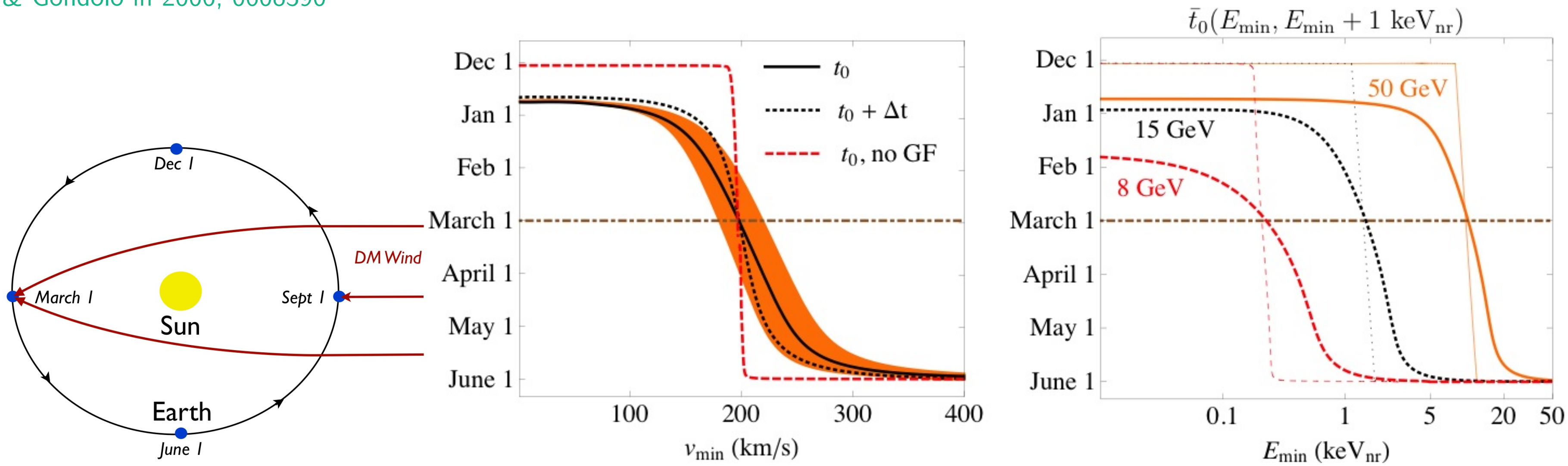




Recall $E_R = 2\mu v_{min}^2/M$, and is change at E_R corresponding to $v_{min} = 200$km/s

Gravitational Focussing by the Sun affects the Annual Modulation for low v_{min}

Lee, Lisanti, Peter & Safdi 1308.1953 for theGF effect, see e.g. Alenazi & Gondolo in 2006, 0608390



t_0: date of max. of the halo integral $\eta(v_{min}, t)$. Δt : change in annual modulation phase of if higher-frequency harmonic terms are included. Orange band: uncertainty due to $v_\odot$.
Right Plot: for elastic scattering in Ge for DM mass 8, 15 and 50 GeV

For v_{min} <200 km/s the maximum of $\eta(v_{min}, t)$ shifts to 21 days later

Target dependence of the Annual Modulation

The annual modulation could be different in different experiments even as function of v_{min}, if the speed dependence of the cross section does not factorize.

Usual cross section $\sigma \sim 1/v^2$ imply the rate in any experiment as function of v_{min} has the same time dependence: $dR_T/dE_R \sim \rho\eta(v_{min}, t)$ for any target T

In some cross sections the v dependence does not factorize, e.g. Magnetic Dipole DM

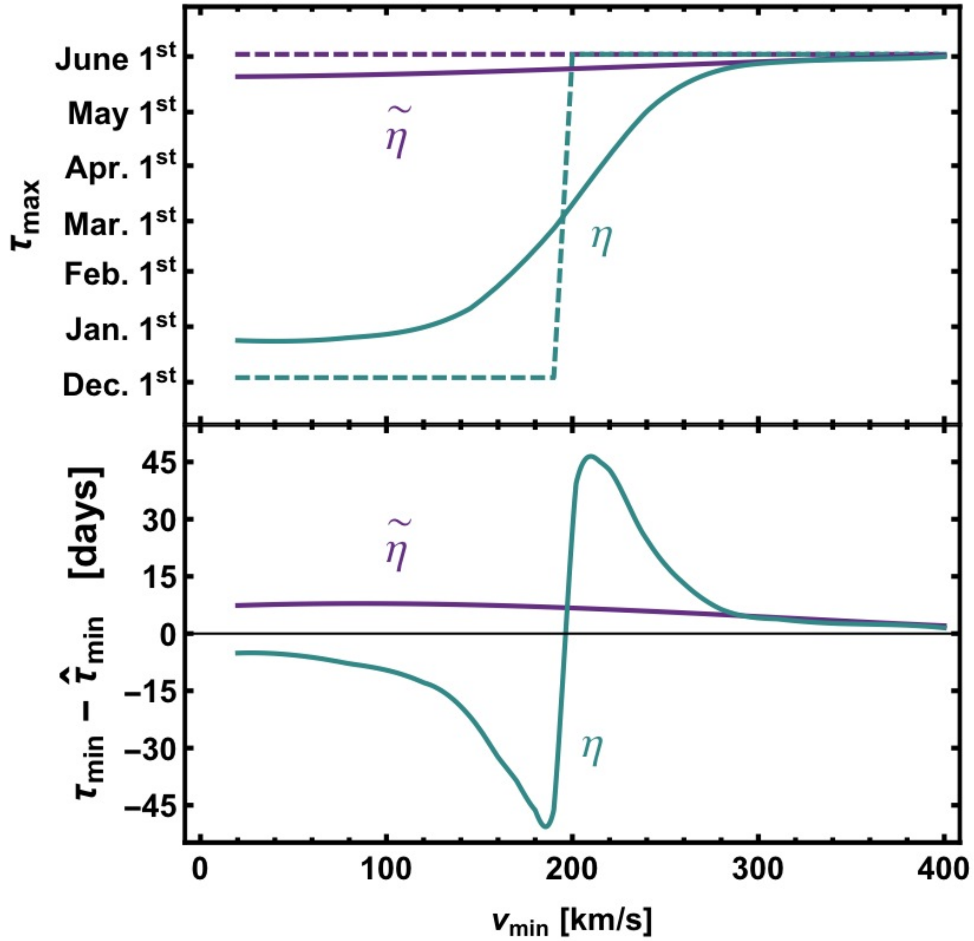
$$\frac{d\sigma_T}{dE_R} = \frac{\alpha d_m^2}{v^2}\left\{ Z_T^2 \frac{M}{2\mu_T^2}\left[\frac{v^2}{v_{min}^2} - \left(1 - \frac{\mu_T^2}{m^2}\right)\right] F_{SI,T}^2(E_R) + \frac{d_{mT}^2}{\mu_N^2}\frac{M}{m_p^2}\left(\frac{S_T+1}{3S_T}\right) F_{M,T}^2(E_R)\right\}$$

one term $\sim v^{-2}$ another $\sim v^0$ so just integrating over v yields two different functions of v_{min}, with different detector dependent coefficients

$$\eta(v_{min}, t) \equiv \int_{v \geq v_{min}} \frac{f(\vec{v}, t)}{v} d^3v, \qquad \tilde{\eta}(v_{min}, t) \equiv \int_{v \geq v_{min}} v f(\vec{v}, t) d^3v$$

In the rate, the combination of these is target dependent:
$dR_T/dE_R = C_1^T \eta(v_{min}, t) + C_2^T \tilde{\eta}(v_{min}, t)$ with C_1^T, C_2^T target nucleus T dependent coefficients.Thus, the annual modulation is target material dependent!

Times of max and (min – 1/2 y from max) of η and $\tilde{\eta}$



Del Nobile, Gelmini, Witte 1504.06772

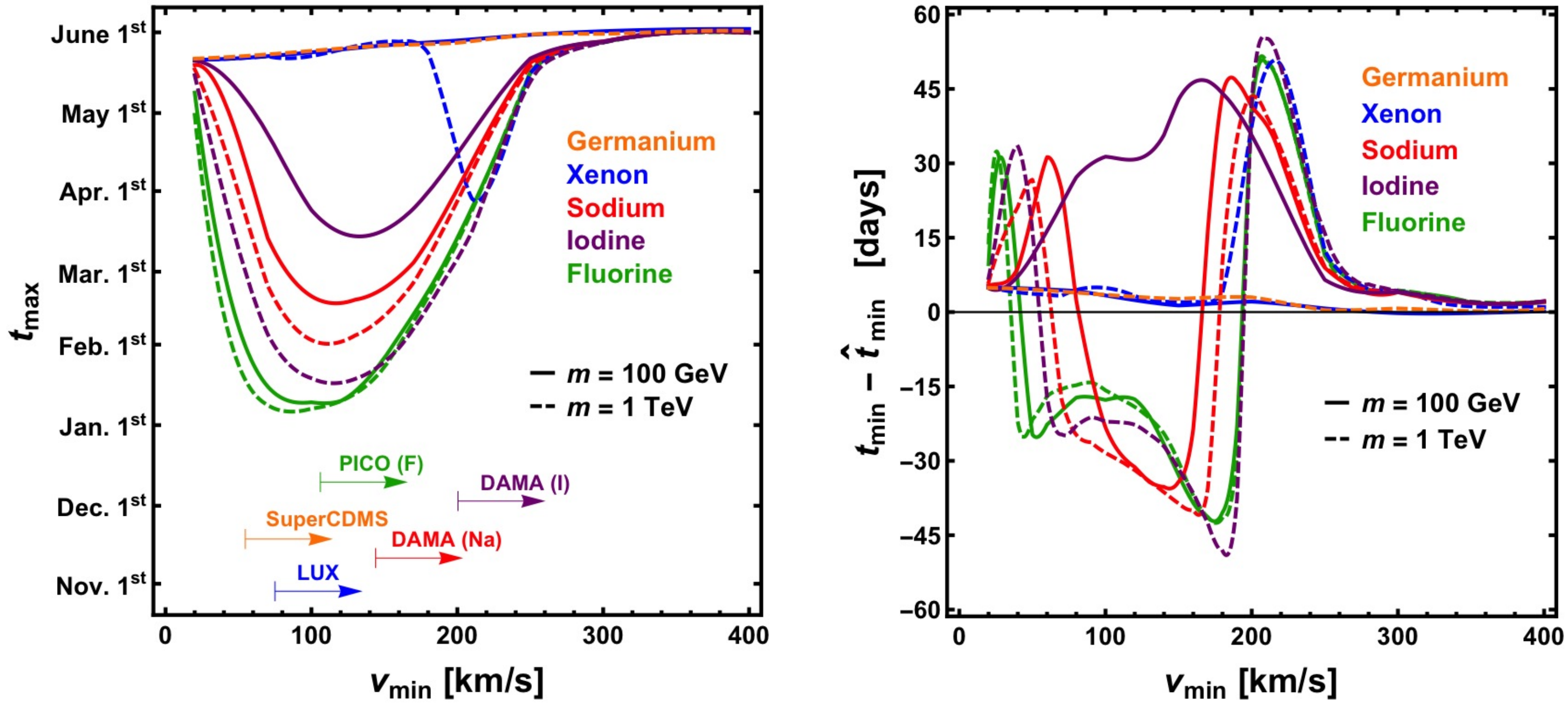
- τ_{max}: time of maximum of η or $\tilde{\eta}$
- $\widehat{\tau_{min}}$: 1/2 year apart from τ_{max}
- τ_{min}: time of minimum of η or $\tilde{\eta}$

$$\eta(v_{min}, t) \equiv \int_{v \geq v_{min}} \frac{f(\vec{v}, t)}{v} d^3 v,$$

$$\tilde{\eta}(v_{min}, t) \equiv \int_{v \geq v_{min}} v f(\vec{v}, t) d^3 v$$

Times of max and (min – 1/2 y from max) of the rate

Del Nobile, Gelmini, Witte 1504.06772 and 1512.03961



Solid (dashed) lines for $m = 100$ GeV (1 TeV) for magnetic dipole DM scattering elastically E.g.
-t_{max} in Xe&F close to the present LUX&PICO thresholds could differ by 4 months
-and modulation in Xe better described by a sinusoidal t-dependence than in F

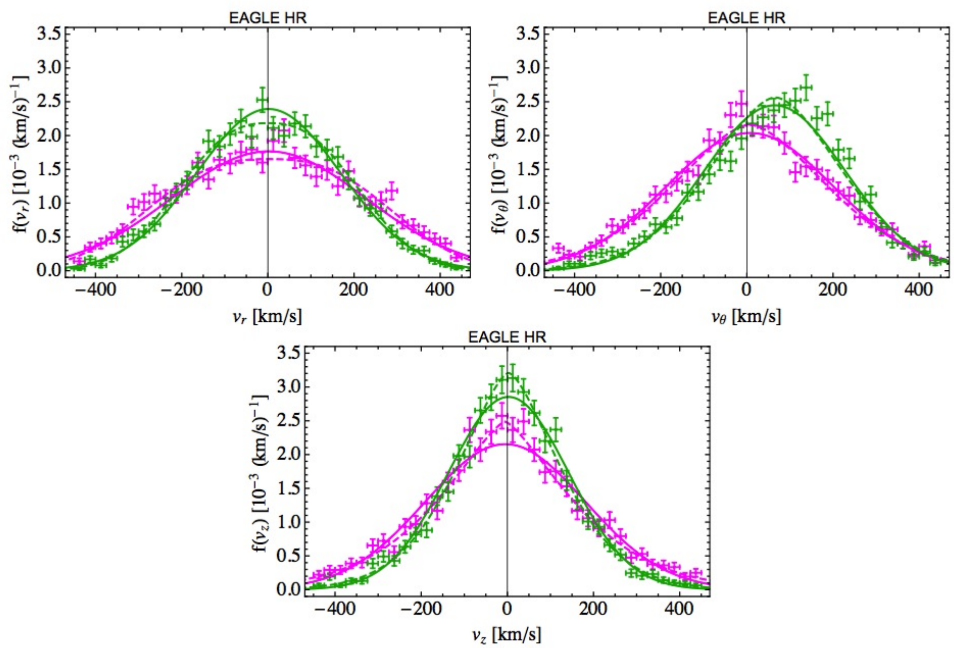
.

Uncertainties in the local DM distribution and the annual modulation of the rate

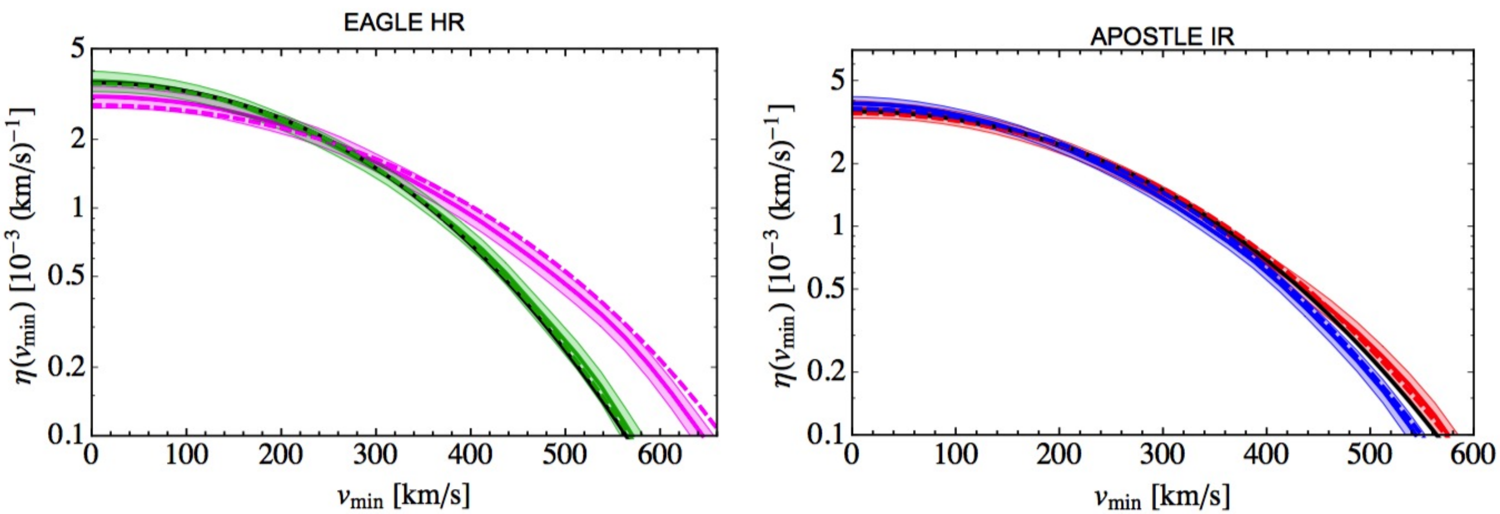
Is a Maxwellian distribution a good approximation?

Numerical simulations of MilkyWay-like galaxy formation predict DM velocity distributions which deviate from a Maxwellian- e.g.EAGLE and APOSTLE hydrodynamic simulations (DM + baryons): MW total mass, good fit to observed MW rotation curve, stellar mass in the 3σ observed MW stellar mass range. Bozorgnia et al 1601.04707

Distributions of radial, azimuthal, and vertical velocity components:



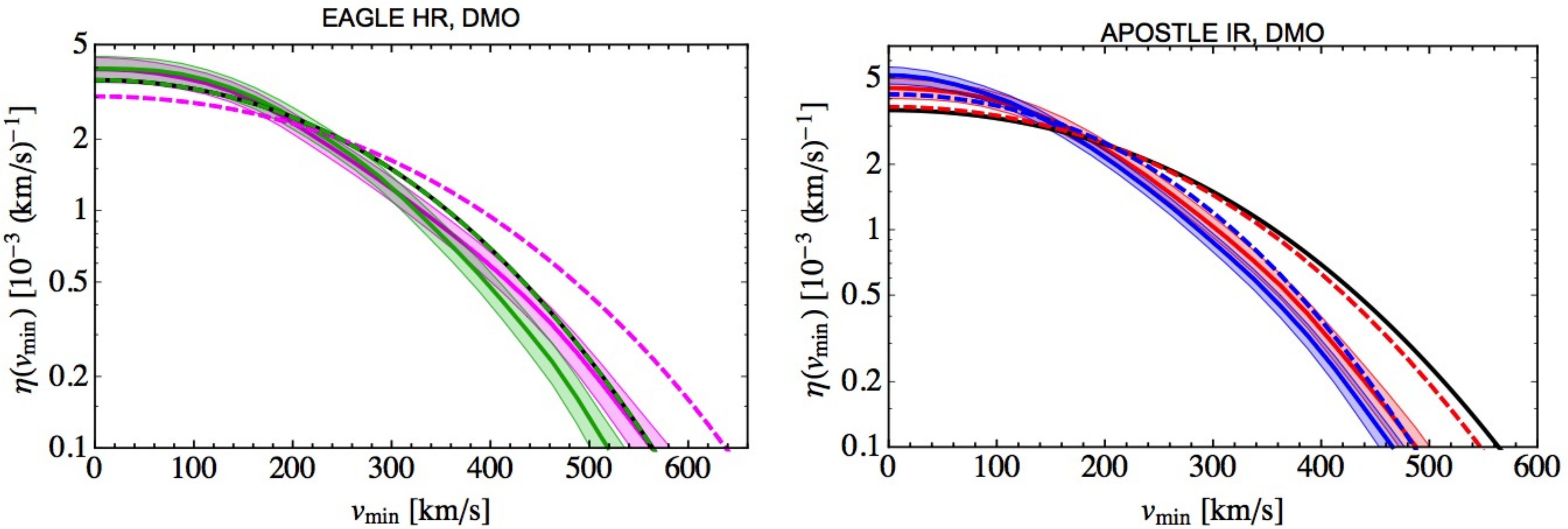
Maxwellian distribution is OK to obtain η for CDM + baryons EAGLE and APOSTLE hydrodynamic numerical simulations (CDM + baryons) of MilkyWay-like galaxy formation derived $\eta(v_{min})$ Bozorgnia etal. 1601.04707



- Significant halo-to-halo differences in η functions
- The η function for the best fit Maxwellian velocity distribution (peak speed 223 - 289 km/s) fall within the 1σ uncertainty band of the halo integrals of the simulated haloes.
- Local DM density ρ =0.41 - 0.73 GeV/ cm^3 (in a torus aligned with the stellar disc with 7 kpc $< R <$ 9 kpc, and -1 kpc $< z <$ 1 kpc)

Instead Maxwellian distribution not OK with DM only

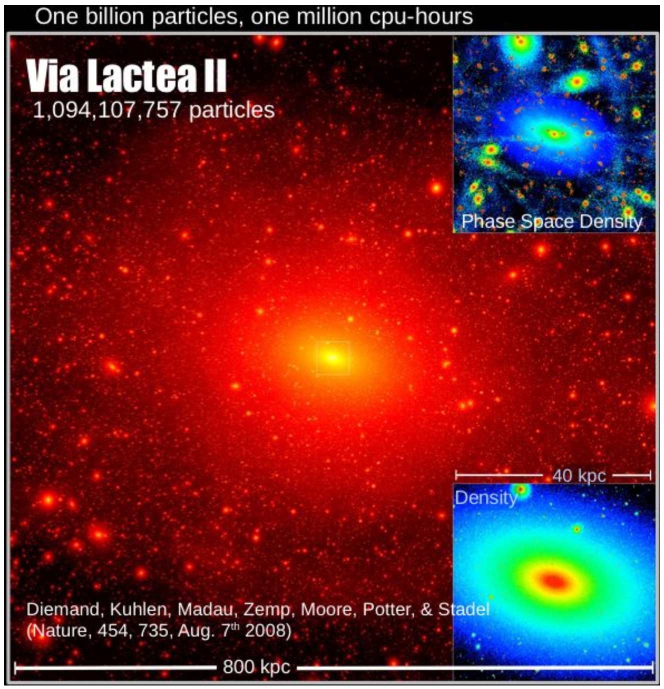
EAGLE and APOSTLE hydrodynamic simulations (CDM only) of MilkyWay-like galaxy formation derived $\eta(v_{min})$ Bozorgnia etal. 1601.04707

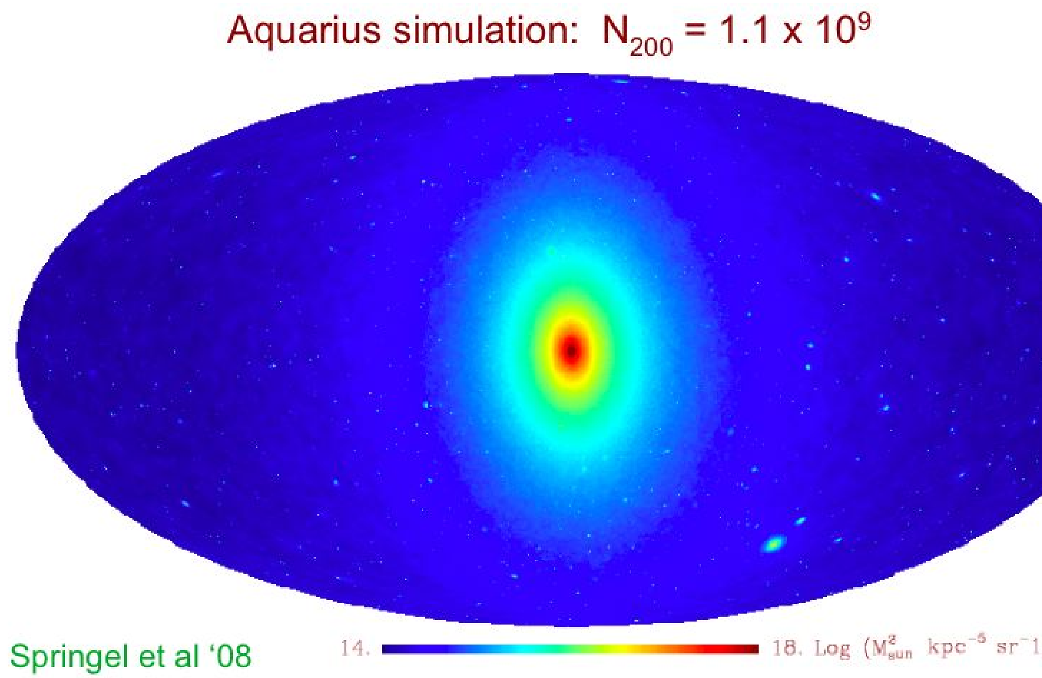


- With CDM only (DMO) η functions quite different from best fit Maxwellian halo integrals.
- Speed distributions of DMO haloes not well fit by a Maxwellian: large deficits at the peak, and an excess at low and very high velocities compared to the best fit Maxwellian.

Simulations of Dark Haloes No baryons included (so no disk)!

Left: 800 kpc cube. Lower inset: density in inner 40 kpc- Sun at 8kpc from the center.



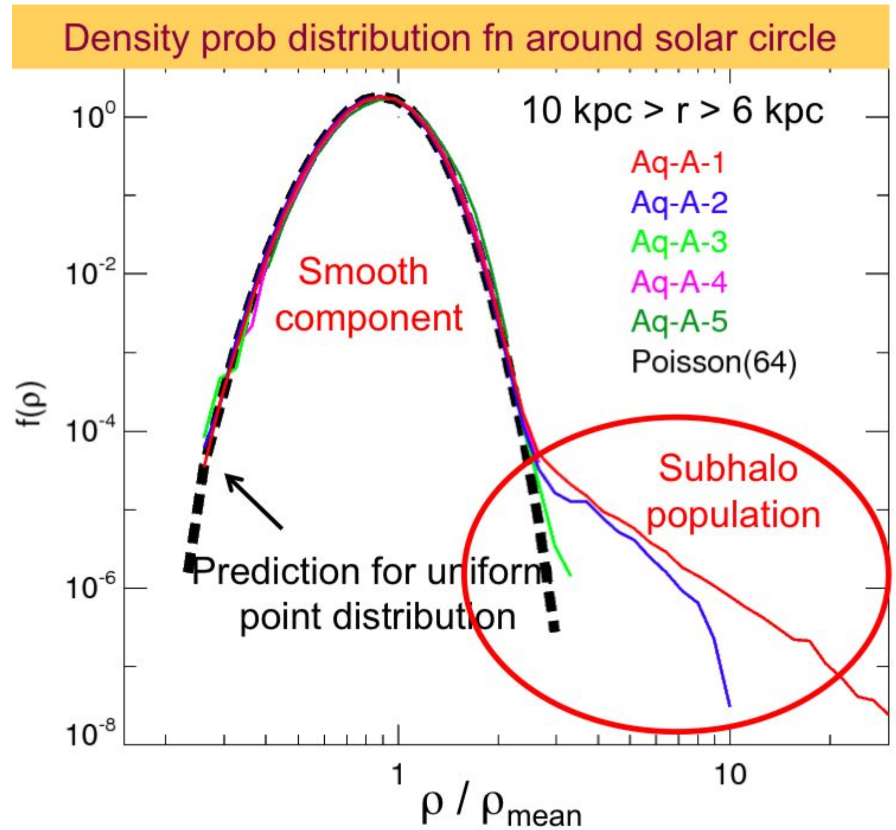


Lots of subhalos and tidal streams at large distances from the galactic center

Dark halo substructure: VIRGO Collaboration-Aquarius Programme

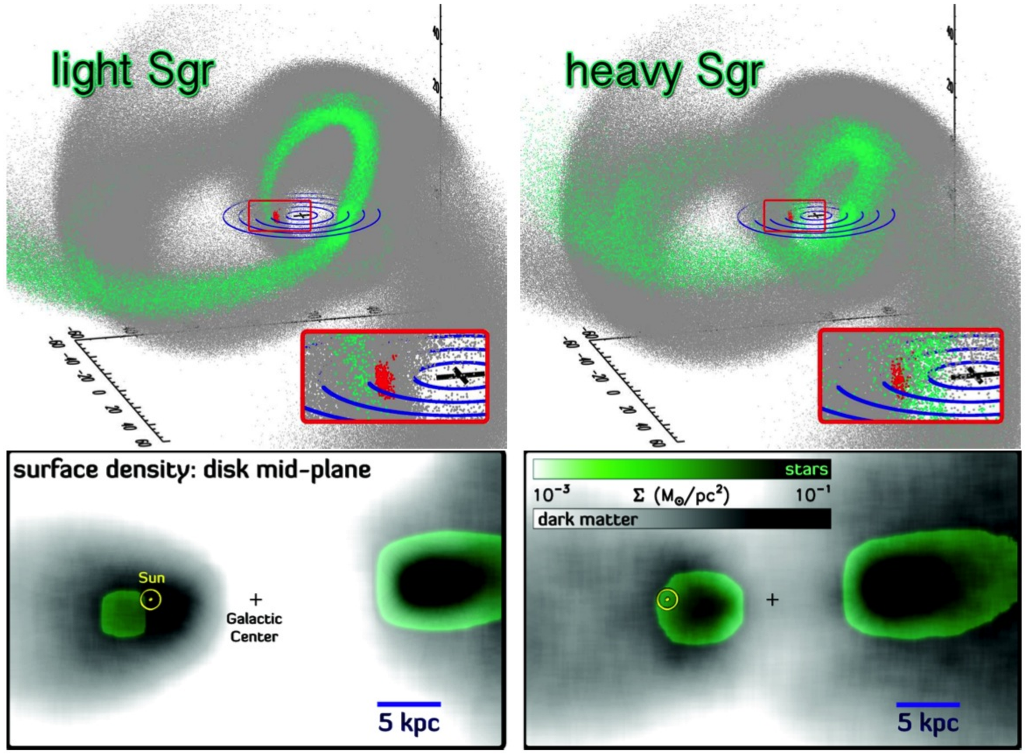
Most subhaloes are at large distances from the galactic center, far from the Sun. Subhaloes are more effectively destroyed near the center

The chance of a random point close to the Sun lying in a substructure is $< 10^{-4}$, but the SGR leading trail could and "debris flows" do pass by the solar system



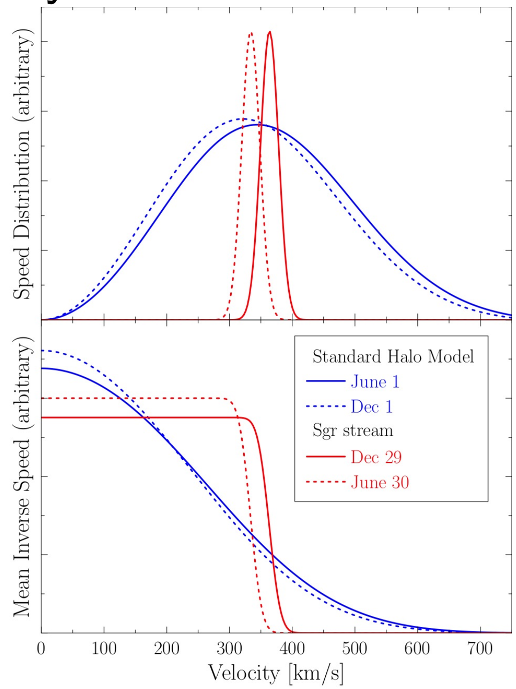
Vogelsberger et al. 0812.0362 [astro-ph]

Sgr. leading trail DM passing through the Solar System



Large uncertainties in local stream density, $\rho_{Sgr} < 5\%\ \rho_{SHM}$ and velocity $v \simeq 250 - 400$ km/s with respect to the Sun Purcell, Zentner, Wang 1203.6617

SHM + DM in the Sgr. leading trail Schematic speed distribution and integral $\eta(v)$ with arbitrary normalization Freese, Lisanti & Savage 1209.3339

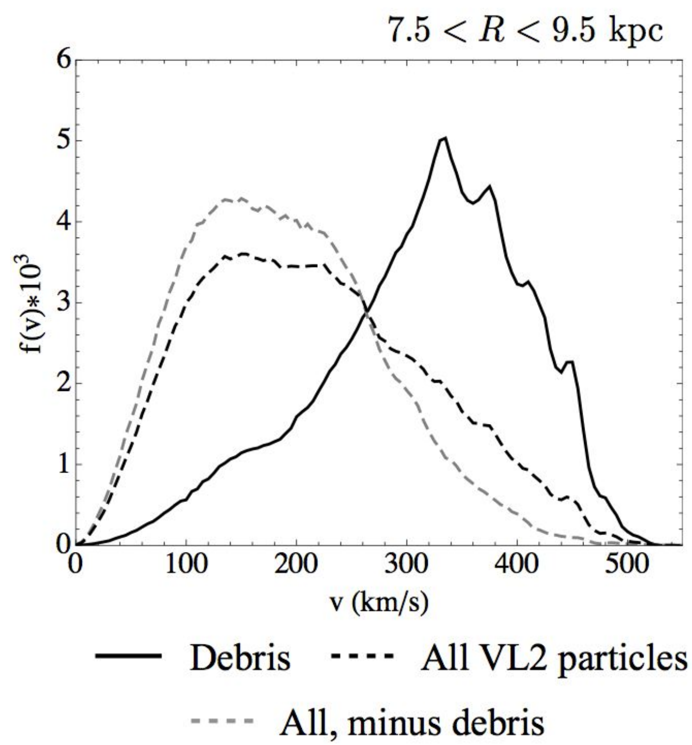


For $m_\chi < 20$ GeV, Sgr DM stream could enhance Direct DM detection rate by 20% to 45%, reduce the annual modulation amplitude by as much as 50% and change its phase by 20 days (but large uncertainties) Purcell, Zentner, Wang 1203.6617

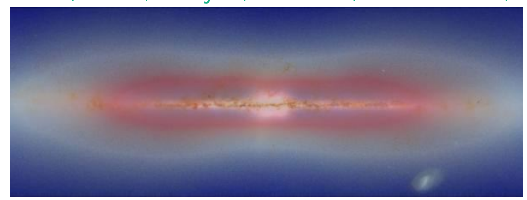
(* You will compute η for the SHM and for a stream in an exercise)

"Debris Flows" Lisanti & Spergel 2011, Khulen, Lisanti & Spergel 2012

Spatially homogeneous, structures in velocity



Dark Disk: Read, Lake, Agertz, Debattista MNRA 389, 8/2008;Read, Mayer, Brooks, Governato, Lake 0902.0009



"A stellar/gas disc, already in place at high redshift, causes merging satellites to be dragged preferentially towards the disc plane where they are torn apart by tides."

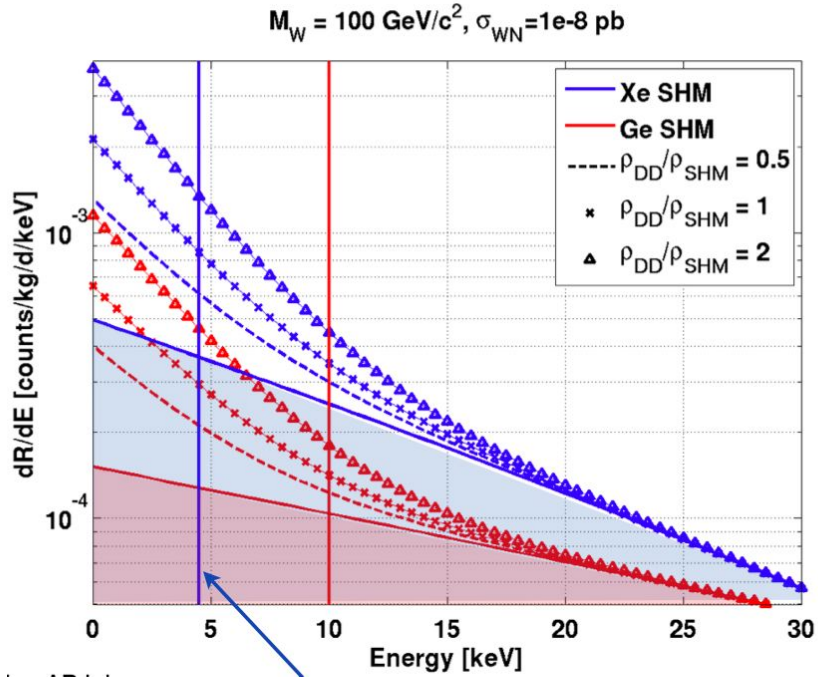
Dark Disk: equilibrium structure

$\rho_D \leq 2 \times \rho_{SHM}$

$v_{lag} \simeq 50$ km/s with respect to Sun

$v_{disp} \simeq 50$ km/s

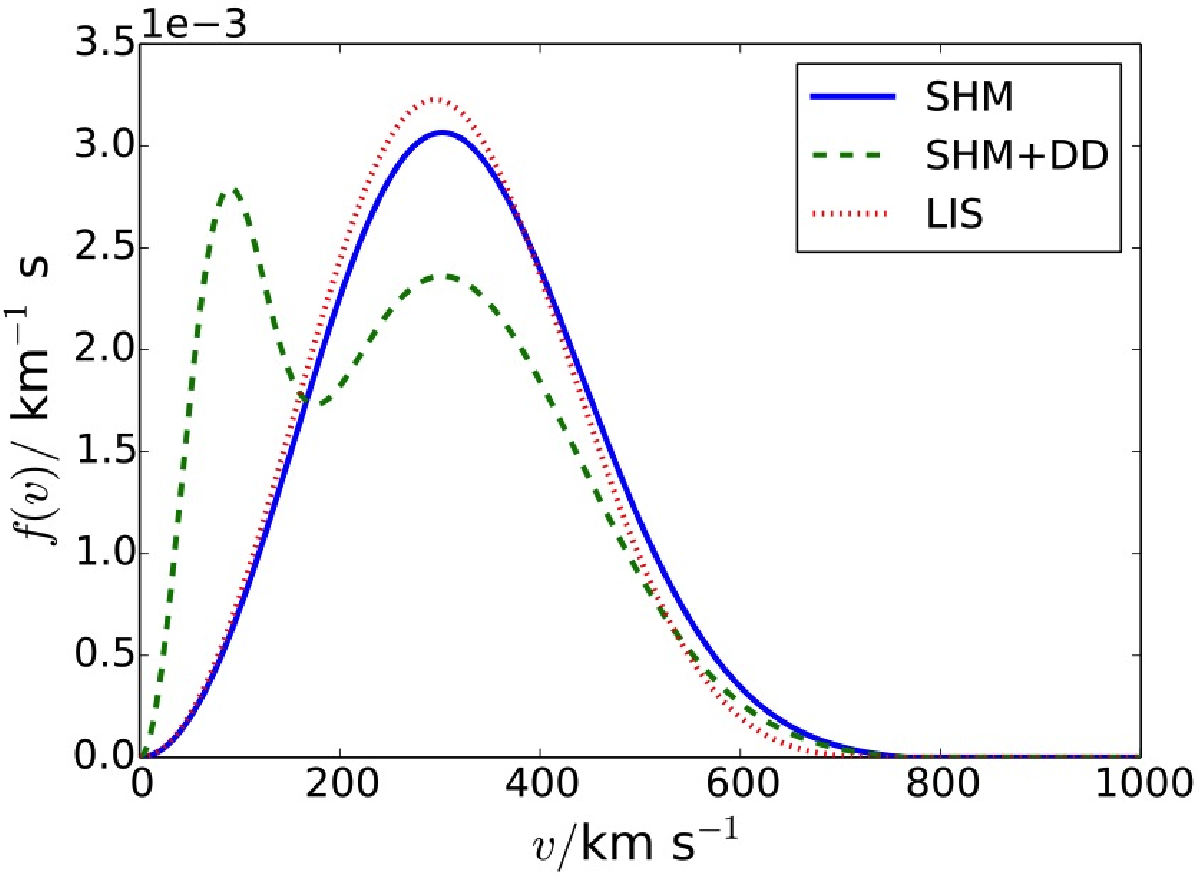
Rare feature with simple CDM (pervasive if part of the DM is dissipative, as in DDDM) Fan, Katz, Randall & Reece 1303.1521-1303.3271



Threshold of XENON 10

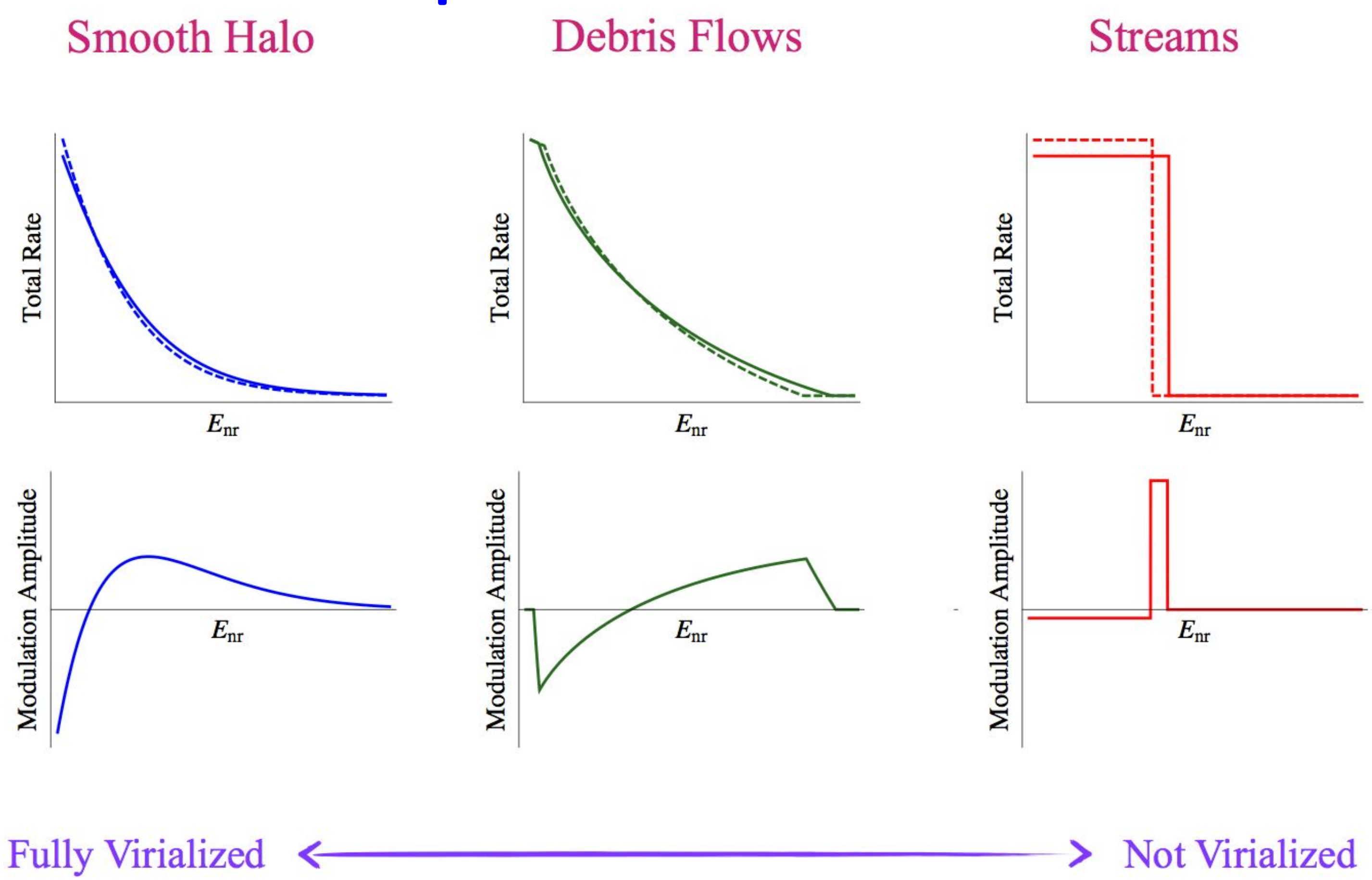
Bruch, Read, Baudis, Lake Ap.J.696:920-923,2009 and arXiv:0811.4172

Dark Disk enhanced population at very low speeds



Peter, Gluscevic, Green, Kavanah & Lee 1310.7039

Rate modulation depends on the Dark Halo



Freese, Lisanti & Savage 1209.3339

The expected rate depends on the Dark Halo

Usually assumed Standard Halo Model is a good first approximation but not expected to be correct. Uncertainty in measurements of key parameters, and Earth could be within a DM clump, or stream, and maybe a Dark Disk and there are debris flows ....

Given all these uncertainties, could we avoid using a halo model when comparing Direct DM detection data?

.

Halo-Independent direct detection data comparison

Halo-Independent direct DM detection data comparison

Event rate: events/(unit mass of detector)/(keV of recoil energy)/day

$$\frac{dR}{dE_R} = \sum_T \int \frac{C_T}{M_T} \times \frac{d\sigma_T}{dE_R} \times n v f(\vec{v}, t) d^3 v$$

$$\frac{d\sigma_T}{dE_R} = \frac{\sigma_T(E_R)\ M_T}{2\mu_T^2 v^2} \qquad \sigma_T(E_R) \sim \sigma_{ref}$$

$$\frac{dR}{dE_R} = \sum_T \frac{\sigma_T(E_R)}{2m\mu_T^2} \rho\eta(v_{min}, t) \quad where \qquad \eta(v_{min}, t) = \int_{v>v_{min}} \frac{f(\vec{v}, t)}{v} d^3 v$$

-$\rho = nm$, $f(\vec{v}, t)$: local DM density and $\vec{v}$ distribution depend on halo model.
Given $\rho\eta(v_{min})$ the plots are in the m, σ_{ref} plane: usual "Halo-Dependent"

NOTICE: $\tilde{\eta}(v_{min}) = \sigma_{ref}\rho\eta(v_{min})/m$ contains all the dependence of the rate on the halo and is common to all experiments! Fox, Liu, Weiner 1011.1915

Given m the plots are in the $v_{min}, \tilde{\eta}(v_{min})$ plane: "Halo-Independent"

Halo-Independent direct DM detection data comparison

Early versions of the method used the recoil spectrum dR/dE_R which is not directly accessible to experiments, and SI interactions Fox, Liu, Weiner 1011.1915; Frandsen et al 1111.0292

Halo Independent analysis for ANY interaction

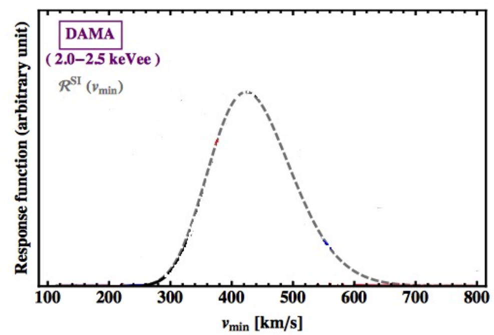
Gondolo-Gelmini 1202.6359; Del Nobile, Gelmini, Gondolo and Huh, 1306.5273

Using instead experimentally accessible quantities, including isotopic composition and energy resolution and efficiency with arbitrary energy dependence, we write the expected rate over a detected energy interval $[E'_1, E'_2]$ for any cross section as

$$R_{[E'_1,E'_2]} = \int_0^\infty dv_{min}\ \mathscr{R}_{[E'_1,E'_2]}(v_{min})\,\tilde{\eta}(v_{min})$$

$\mathscr{R}_{[E'_1,E'_2]}$: EXPERIMENT AND INTERACTION DEPENDENT response function non zero only in an interval in v_{min} given an interval $[E'_1, E'_2]$

Every experiment is sensitive to a "window in velocity space"

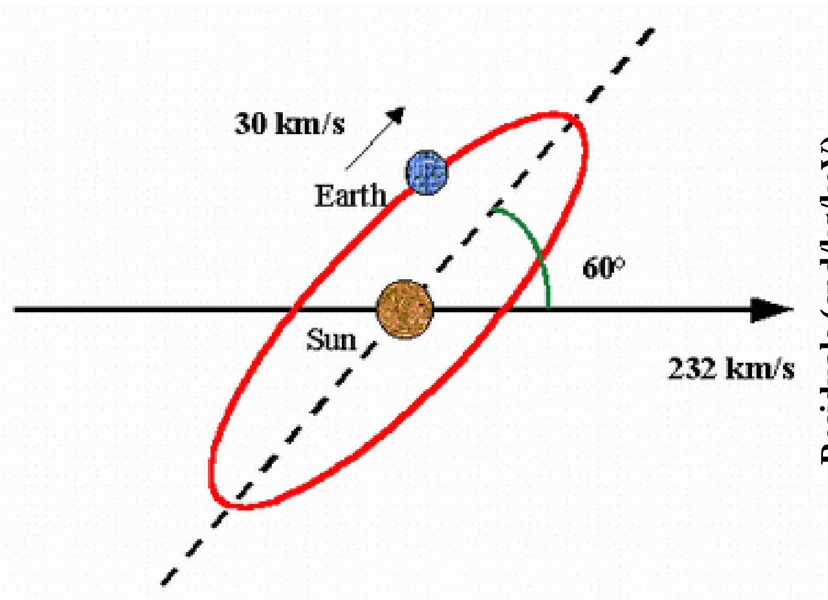


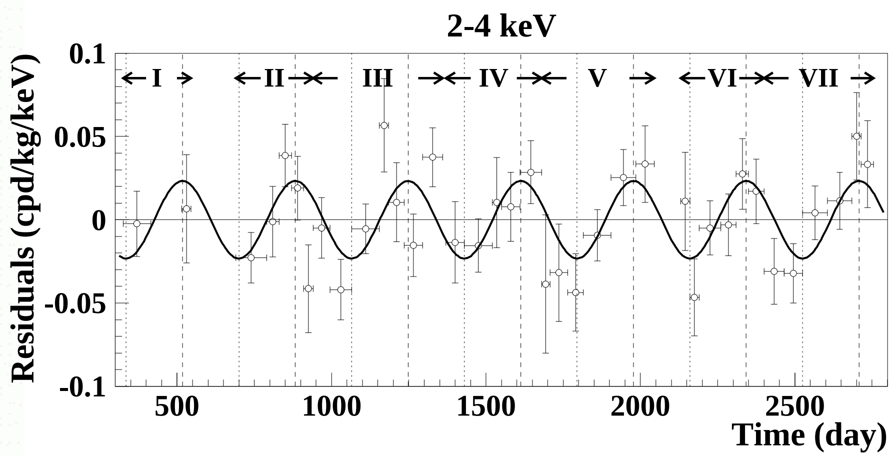
.

Hints of dark matter in direct detection experiments

DM hints in four direct detection experiments

Oldest DM hint: DAMA/NaI annual modulation

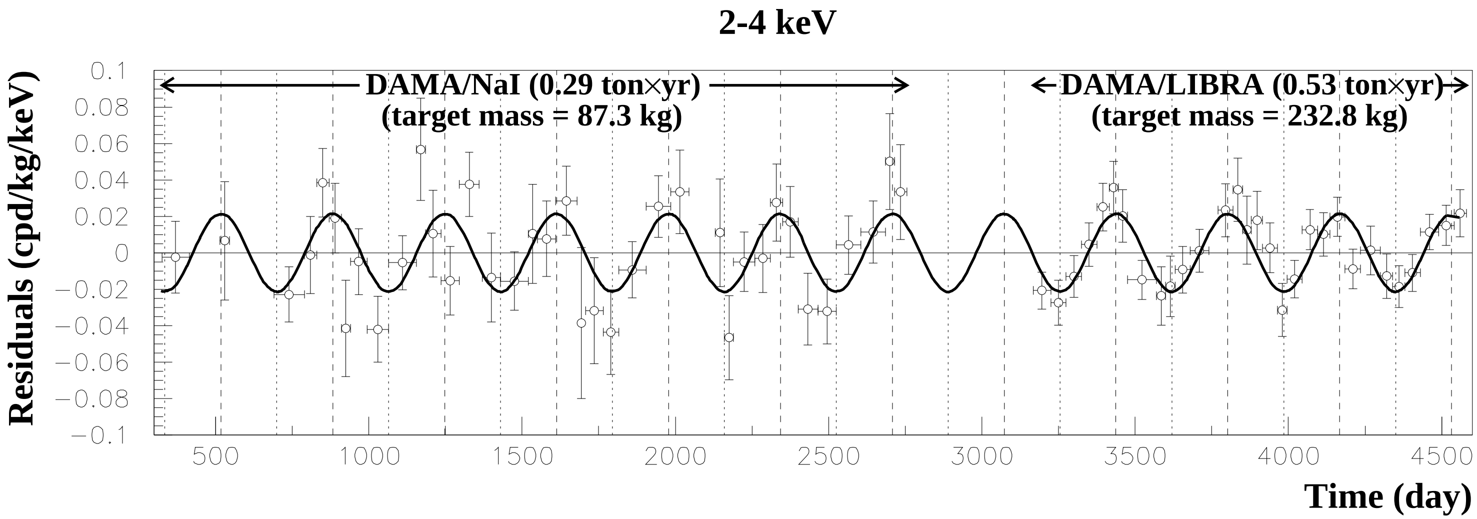




By 2002: 7 years of DAMA/NaI showed a 6σ modulation signal compatible with the Standard Halo Model.

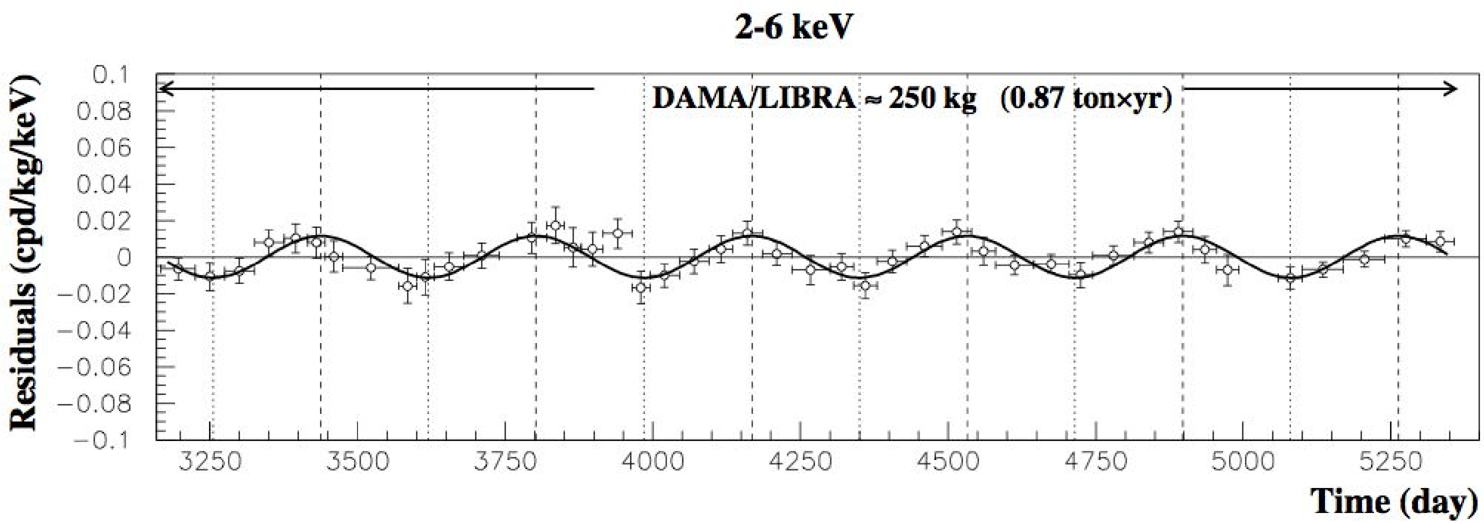
DAMA/LIBRA 25 NaI (Tl) crystal of 9.5 kg each. At present 12y in LIBRA (19 years total), 1.33 ton × year, 9.3σ modulation signal.

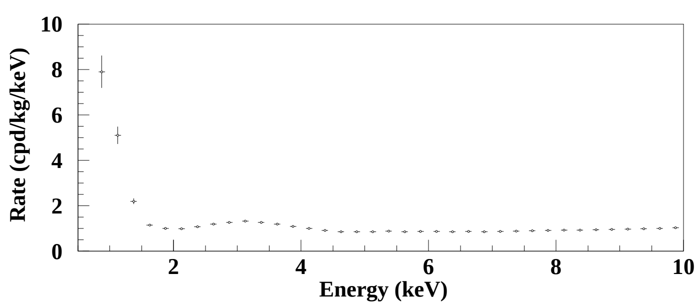
Modulation data from 2008 (in the 2-4 keVee bin)



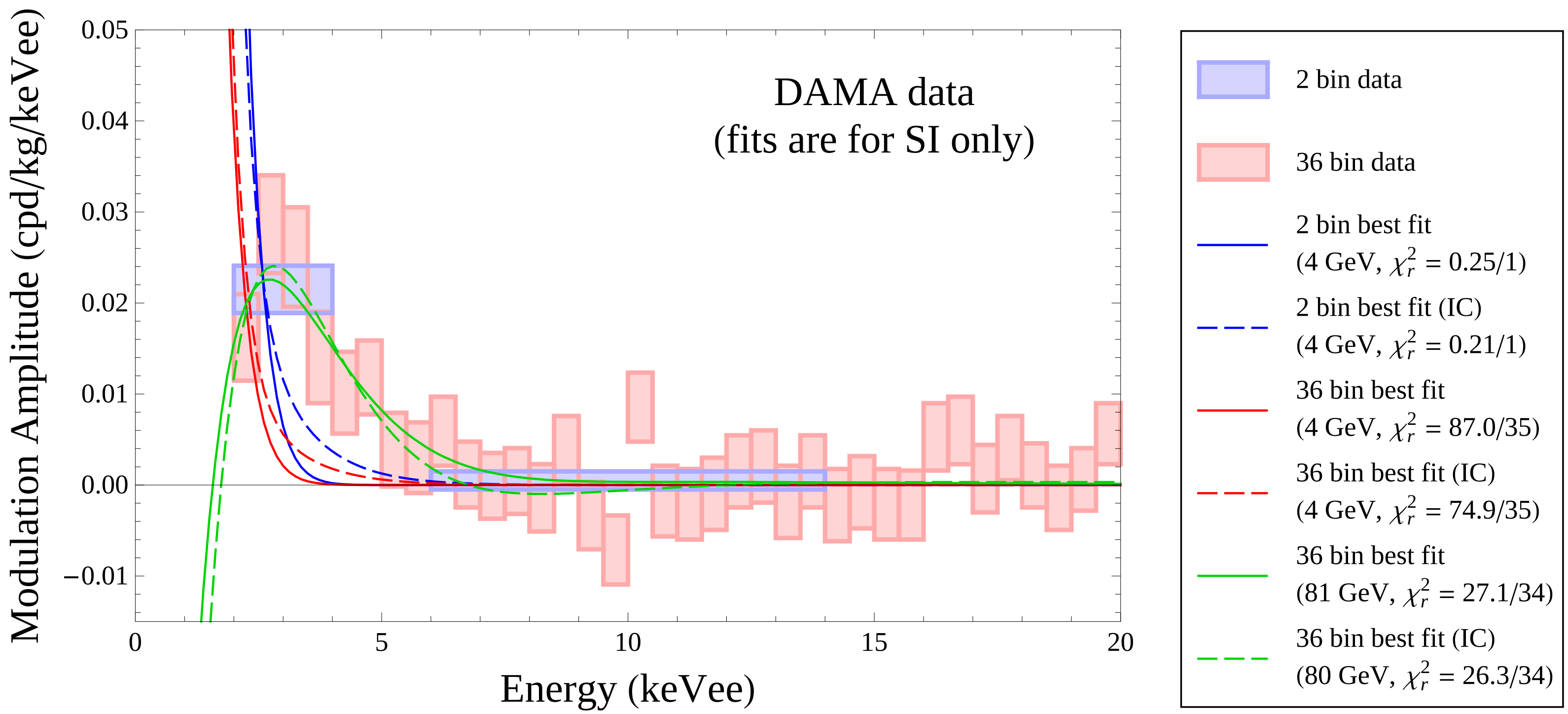
Compatible with the modulation expected from the SHM!

DAMA/LIBRA 25 NaI (Tl) crystal of 9.5 kg each. At present 12y in LIBRA (19 years total), 1.33 ton $\times$ year, 9.3σ modulation signal.
Figures from 2010- Modulation in the 2-4 keVee bin (Bernabei et al 1002.1028)



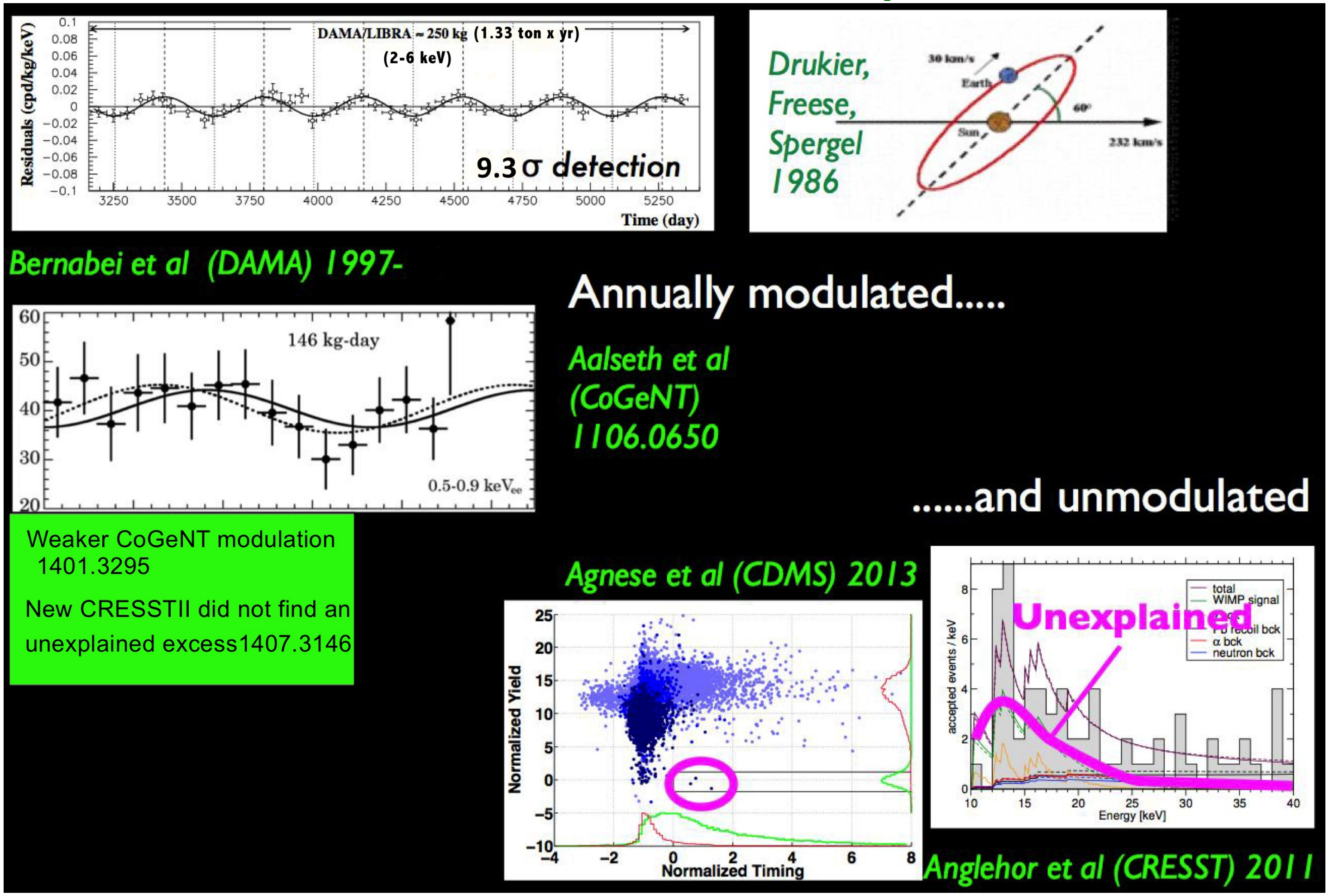


DAMA/LIBRA modulation amplitude Savage,Gelmini, Gondolo and Freese 0808.3607



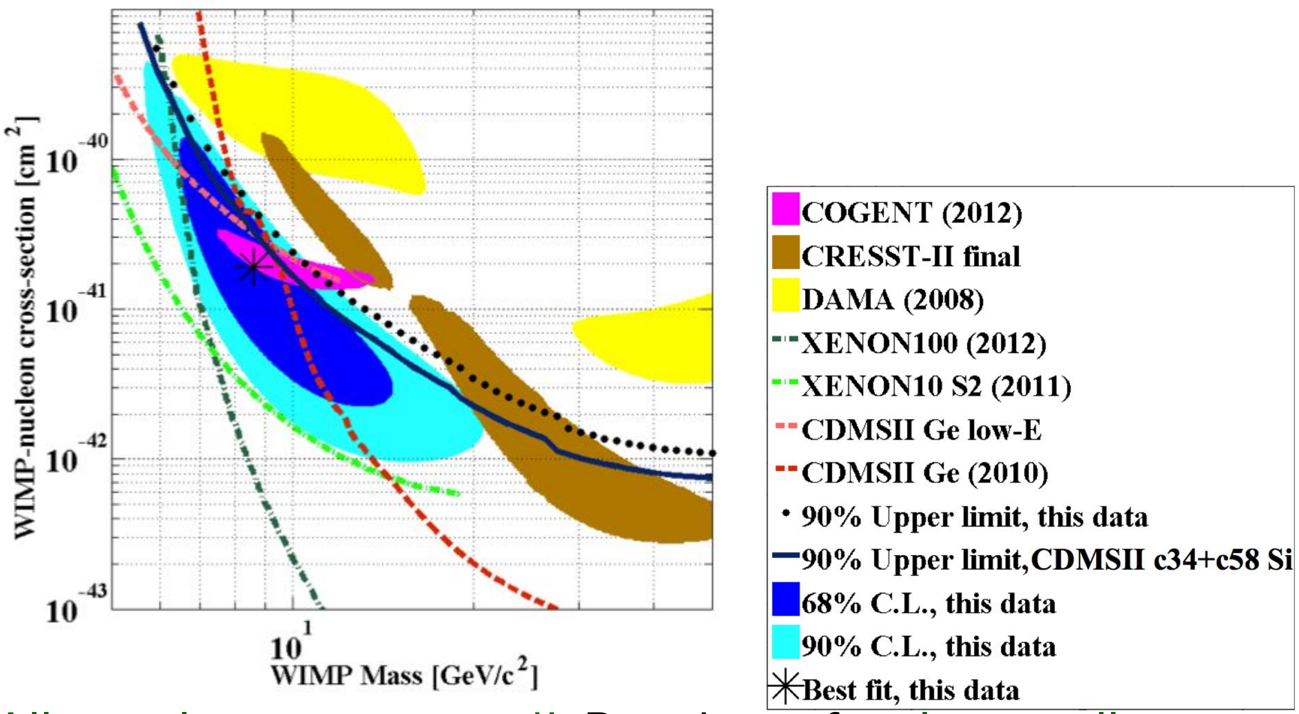
Modulation data are well fitted with HEAVY WIMPs (e.g. m =81 GeV) or LIGHT WIMPs (e.g. m =4GeV) but lower limits of negative searches are much more constraining for heavy WIMPs

DM hints in four direct detection experiments (Fig. from P. Gondolo)



All point to “Light WIMP’s” with mass of few to 10 GeV

As of 2013-



All signal regions rejected! But this is for elastic collisions and Spin Independent WIMP nucleus coupling with equal coupling to neutron and proton $f_n = f_p$ and assuming the Standard Halo Model

Uncertainties in regions and bounds

- Backgrounds: part, or all of the "DM signals" may be actually due to backgrounds?
- Detector response model: e.g. energy resolution, efficiency, fraction of energy deposited which is detectable, has large uncertainties at low E.
- **Type of DM interaction:** spin-indep. or dep.? With different couplings with p and n (i.e isospin violating-IV)? Magnetic moment interaction (MDM)? Milli-charged DM? anapole DM? resonant DM? Form factor DM? inelastic endothermic (iDM)? inelastic exothermic (ieDM)?
- **Characteristics of the Dark Halo:** Xe is heavy, thus only sensitive to high v WIMP tail, which may be missing: make a **"halo independent analysis"**

.

Can potential signals and and upper limits be compatible?

All point to "Light WIMP's" with mass of few to 10 GeV?

However:

- some data were not confirmed by the further data of the same collaboration (CRESST)

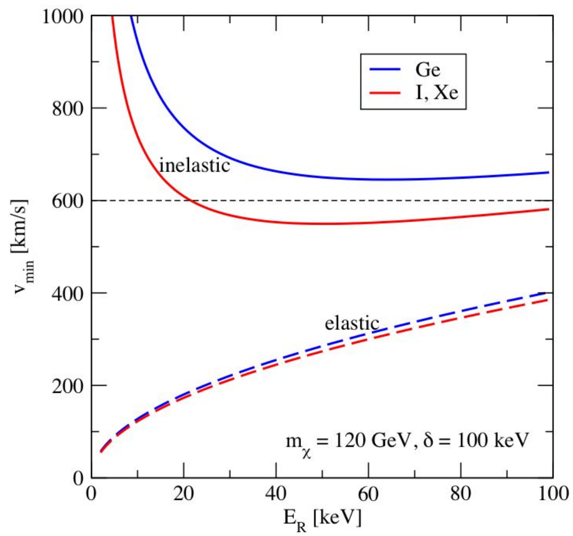
- some lost significance with more data (CoGeNT)

- no particle candidate of many tried seems to make compatible any two hints with all upper limits of direct searches with negative results. One can make either DAMA or CDMS-II-Si potential signals compatible with all negative results, not both, and this is not enough.

Extraordinary claims require extraordinary evidence! So several experiments must find the same DM candidate to believe it is there.

DAMA compatible with all limits?

Inelastic DM (IDM) scatters to another state with with mass $m_{final} = m_{initial} + \delta$



(fig from T. Schwetz)

$$v_{min}^{inel} = \left| \sqrt{\frac{ME_R}{2\mu^2}} + \frac{\delta}{\sqrt{2ME_R}} \right| \qquad v_{min}^{el} = \sqrt{\frac{ME_R}{2\mu^2}}$$

Only high v DM particles have enough energy to up-scatter, and v_{min}^{inel} decreases with increasing target mass M_T, thus targets with high mass are favored (better I than Ge...).

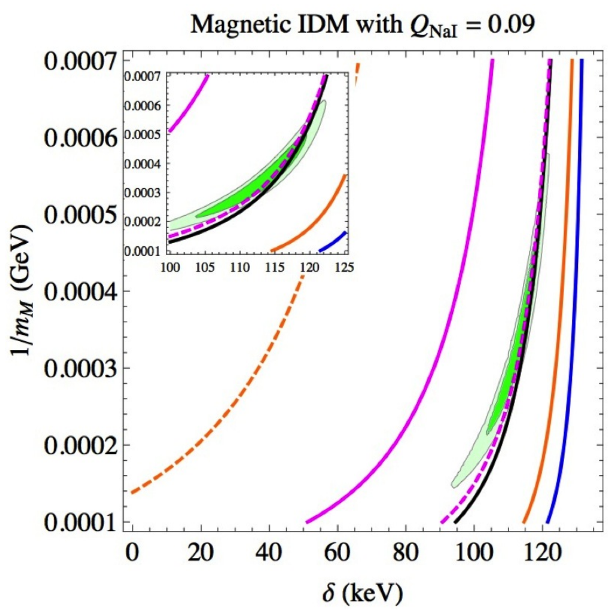
This was OK for DAMA (NaI) vs CDMS (Ge) and Simple,PICASSO, COUPP (F)- But Xe is heavier so XENON and LUX reject SI- IDM- But could work for Magnetic Inelastic DM (MIDM) -I has a large magnetic moment Chang, Weiner, Yavin 1007.4200, Barello, Chang, Newby 1409.0536 or DM with spin dependent coupling to only protons

Barello, Chang, Newby 1409.0536; Del Nobile, Georgescu, Gelmini, Hu 1502.07682v2

DAMA compatible with all limits?

Inelastic DM (IDM) scatters to another state with mass $m_{final} = m_{initial} + \delta$

Magnetic IDM $m_{initial} = 58\text{GeV}$, $1/m_M = e\mu$ Barello, Chang, Newby 1409.0536



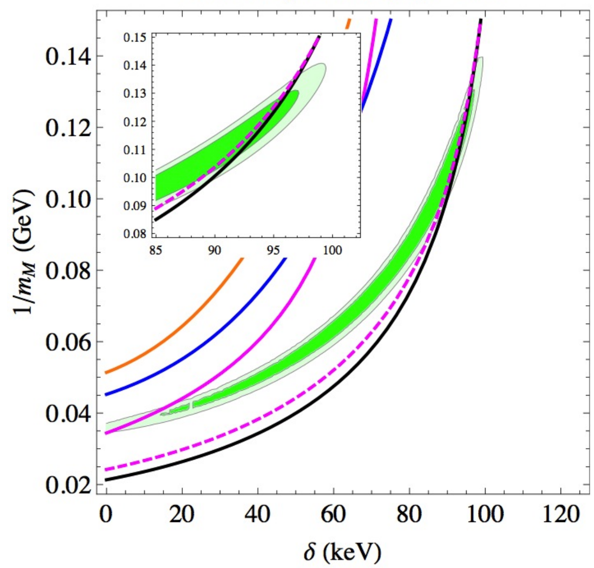
Best limits: LUX (blue), Xenon100 (solid orange), KIMS (magenta, solid $Q_I = 0.05$ and dashed 0.10), COUPP (black).

DAMA compatible with all limits?

Inelastic DM (IDM) scatters to another state with mass $m_{final} = m_{initial} + \delta$

Spin coupling to p only Here just one operator $\sim \overrightarrow{S_N} \cdot \vec{q}$ (but no complete model!), dimensionful coupling is $1/m_M^2$ (m_M is mediator mass) and $m_\chi = 44.2$ GeV (best fit value)

Fermion Op. 2 with $Q_{NaI} = 0.09$



Best limits LUX (blue), Xenon100 (solid orange), KIMS (magenta, solid $Q_I = 0.05$ and dashed 0.10), COUPP (black). But Cs in KIMS not included (lack of form factor), has also unpaired p and would make bounds stronger.

For CDMS-Si: Inelastic Exothermic (ieDM)

In iDM in addition to the DM state χ with mass m_χ there is an excited state χ^* with mass m_{χ^*}

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

and inelastic scattering $\chi + N \to \chi^* + N$ dominates over elastic. Thus

$$v_{min}^{inel} = \left| \sqrt{\frac{ME_R}{2\mu^2}} + \frac{\delta}{\sqrt{2ME_R}} \right| \qquad \text{instead of } v_{min}^{el} = \sqrt{\frac{ME_R}{2\mu^2}}$$

Inelastic Endothermic DM (iDM) i.e. Inelastic with $\delta > 0$ was the initial idea.

Tucker-Smith, Weiner 01 and 04; Chang, Kribs, Tucker-Smith, Weiner 08; March-Russel, McCabe, McCullough 08; Cui, Morrisey, Poland, Randall 09, many more. . .

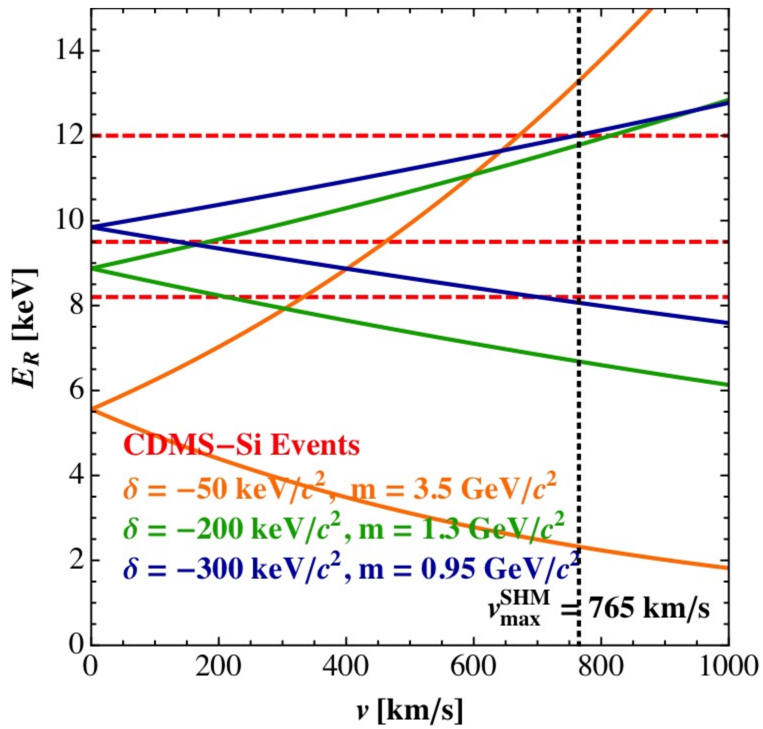
Inelastic Exothermic DM (ieDM) i.e. Inelastic with $\delta < 0$

Favors light materials (Si in CDMS over Xe in LUX and XENON) and reduces the annual modulation amplitude Graham, Harnik, Rajendran, Saraswat 1004.0937

Problem: make the excited state sufficiently long lived to be still present!

Inelastic Exothermic Scattering

GG, Georgescu, Huh 1404.7484

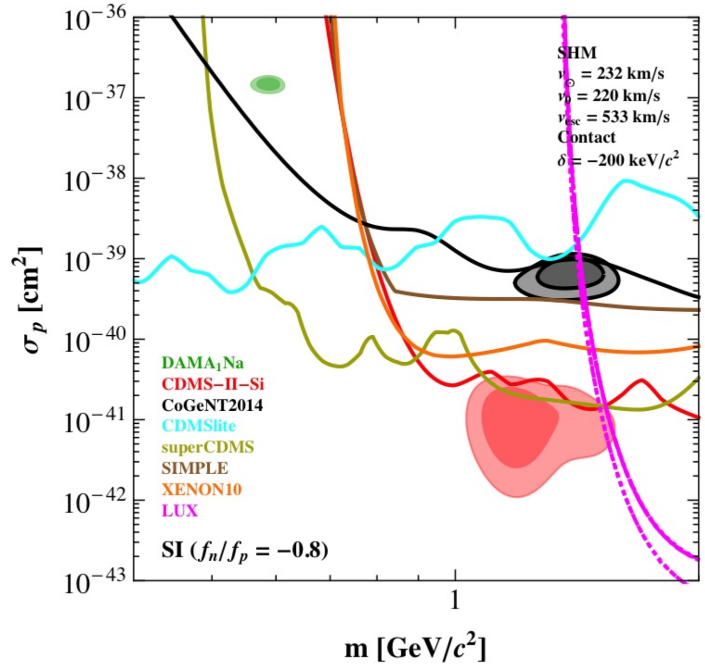


Characteristic recoil energy is $E_\delta = \mu_\chi \delta / M \simeq m_\chi \delta / M$ for $m_\chi << m_T$, which is larger for smaller M (for larger M it may be below threshold).

CDMS-Si compatible with all limits?

Exothermic Inelastic DM with $m_{final} - m_{initial} = \delta < 0$

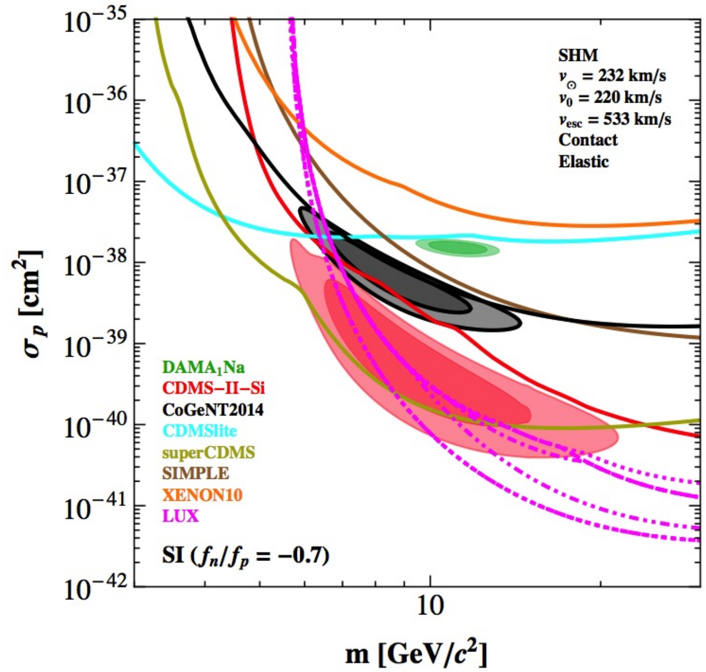
Here $\delta = -200$keV Spin-Independent DM with $f_n/f_p = -0.8$ GG, Georgescu, Huh 1404.7484



68% and 90%CL CDMS-II-Si (red) regions scape all 90%CL limits- but not compatible with DAMA (green) or CoGeNT (gray)

CDMS-Si compatible with all limits? Gelmini, Georgescu, Huh 1404.7484

Also marginally compatible for SI elastic interactions with $f_n/f_p = -0.7$



A sliver of the 90%CL CDMS-II-Si (red) region scape all 90%CL limits- but not compatible with DAMA (green) or CoGeNT (gray)

Direct detection DM hints compatible with all limits?

The CoGeNT signal has become weaker with time (its continuation C4 may clarify what they observed) and CRESST with better data does not find any unexplained excess in their rate.

By choosing kinematical and dynamical ways to suppress the best limits due to searches with negative results it might be still possible to find DM candidates which make either the DAMA/LIBRA region or the CDMS-Si region compatible with all bounds while assuming they are due to DM, but not simultaneously compatible also with each other (or with CoGeNT).

For DAMA:use the large p spin component of I and Na or the large magnetic moment of I (and Na) to disfavor Xe and Ge (have unpaired n) upper limits. But this would still keep the F limits (SIMPLE, PICASSO, COUPP), since F also has unpaired p. So add endothermic inelasticity to disfavor light nuclei (like F and Ge) with respect to I

For CDMS-Si:use Isospin Violation to disfavor SI coupling of Xe and Ge and exothermic inelasticity to disfavor nuclei heavier than Si (Xe and Ge again). The SI coupling disfavors light nuclei (F) because it is proportional to A^2.

Main issue is: Can one believe that Nature has chosen precisely the type of DM-nucleus coupling which weaken the present strongest upper limits?!

So far we have assumed the SHM.
One more thing we have not yet tried: Halo-Independent data comparison (next lecture)