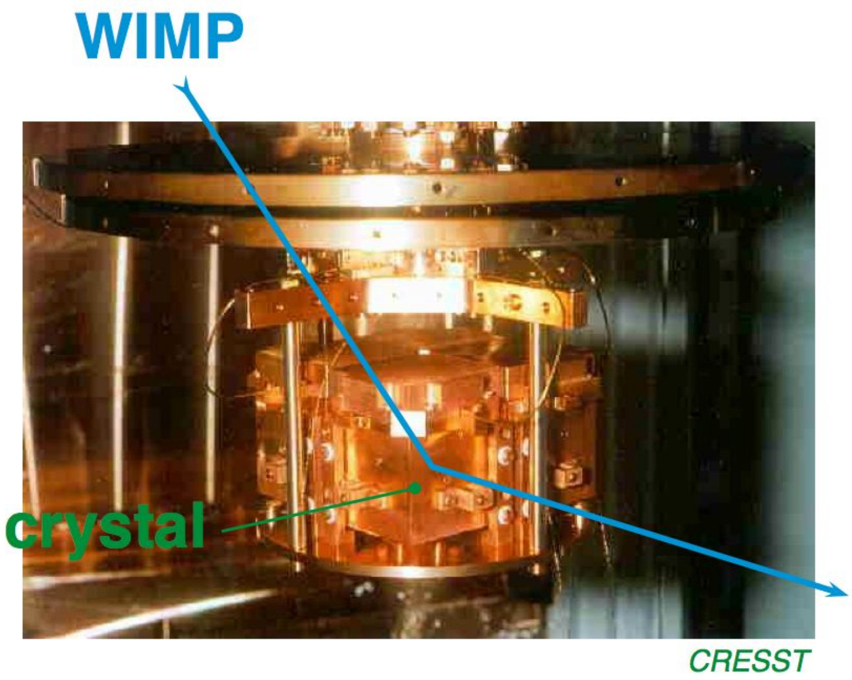
Target dependence of the annual modulation in direct dark matter searches

Graciela Gelmini - UCLA

Stockholm, June 3, 2015

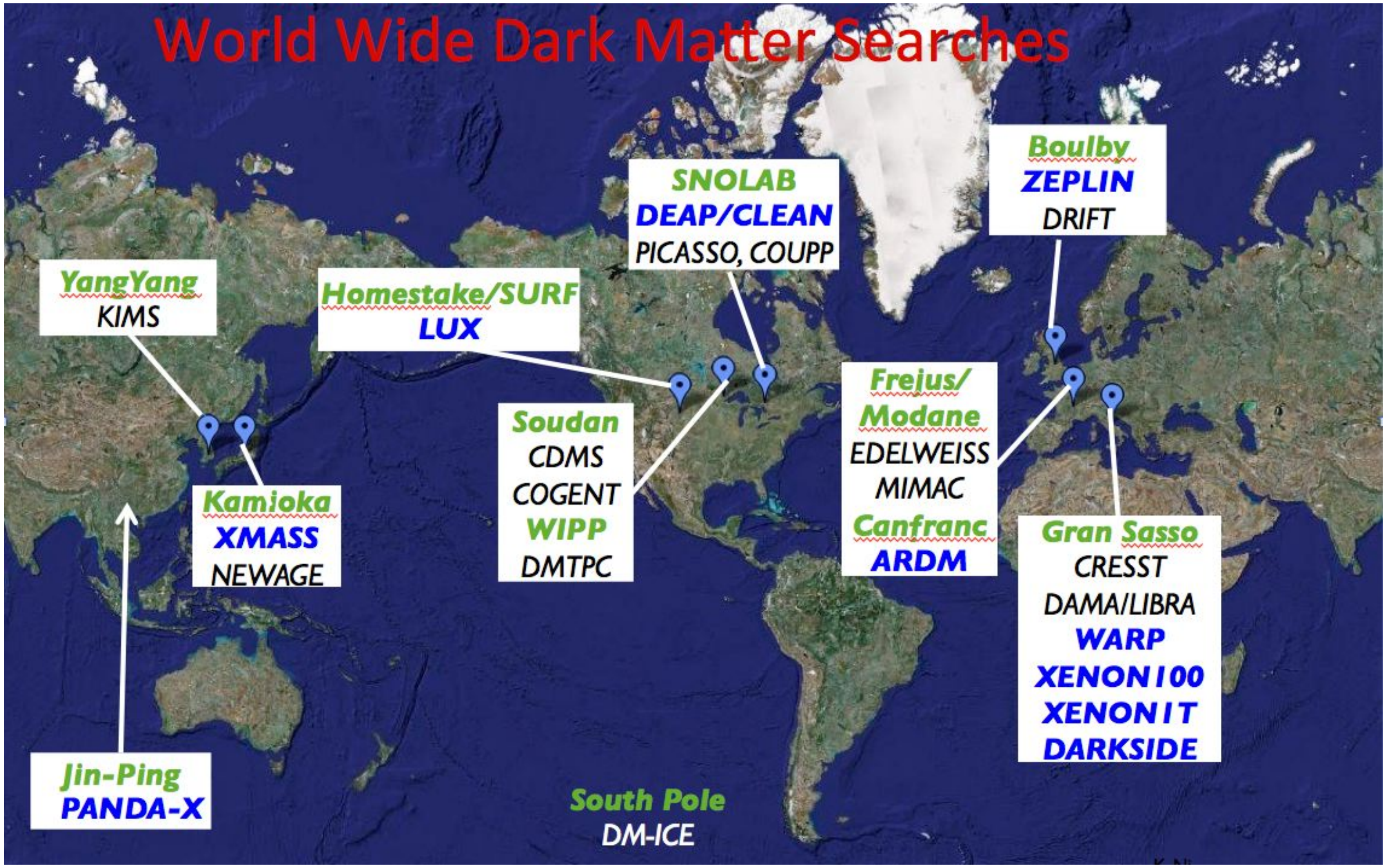
Direct DM Searches:



- Small $E_{Recoil} \leq$ 50keV(m/100 GeV)
- Rate: depends on WIMP mass, cross section, dark halo model, nuclear form factors... typical... $<$ 1 event/ 100 kg/day (need to go underground to shield from cosmic rays)
- Single hits: single scatters, uniform through volume of detector
- Most searches are non-directional (some in development are- try to measure the recoil direction)
- Annual rate modulation (few % effect)

DM signature: same σ and m + compatible annual modulation seen by different experiments with different nuclei (Drukier, Freese, Spergel 1986)

Direct DM Searches: Many experiments, different materials!



- For non-directional direct searches the main DM signature in an annual modulation of the rate with the right characteristics, observed by more than one experiment
- Which are these “right characteristics” of the expected annual modulation?
- Could two experiments observe completely different annual modulations and still be observing the same DM candidate?
- The answer is, yes!

Recall event rate: events/(kg of detector)/(keV of recoil energy)

$$\frac{dR}{dE_R} = \int \frac{N_T}{M_T} \times \frac{d\sigma}{dE_R} \times nvf(\vec{v},t)d^3v$$

- For a WIMP-nucleus differential cross section $d\sigma/dE_R = \sigma(E_R)\ M/2\mu^2v^2$

$$\frac{dR}{dE_R}(t) = \frac{\sigma(E_R)\rho}{2m\mu^2} \int_{v>v_{min}} \frac{f(\vec{v},t)}{v} d^3v = \frac{\sigma(E_R)}{2m\mu^2}\ \rho\eta(v_{min},t)$$

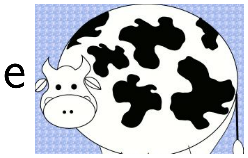
- $\frac{N_T}{M_T}$ = Avogadro's number per mol = Number of atoms per gram; $\mu = mM/(m+M)$
- For elastic scattering: $v_{min} = \sqrt{ME_R/2\mu^2}$ and E_R is the ion recoil energy .
-$\rho = nm$, $f(\vec{v},t)$: local DM density and $\vec{v}$ distribution depend on halo model

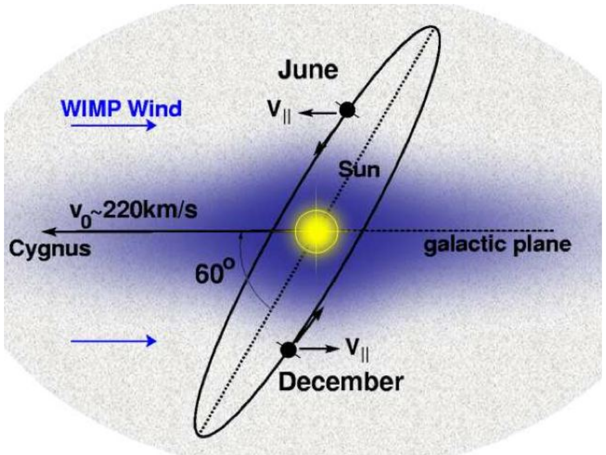
Notice $\rho\eta(v_{min})$ encodes all the dark halo dependence of the rate

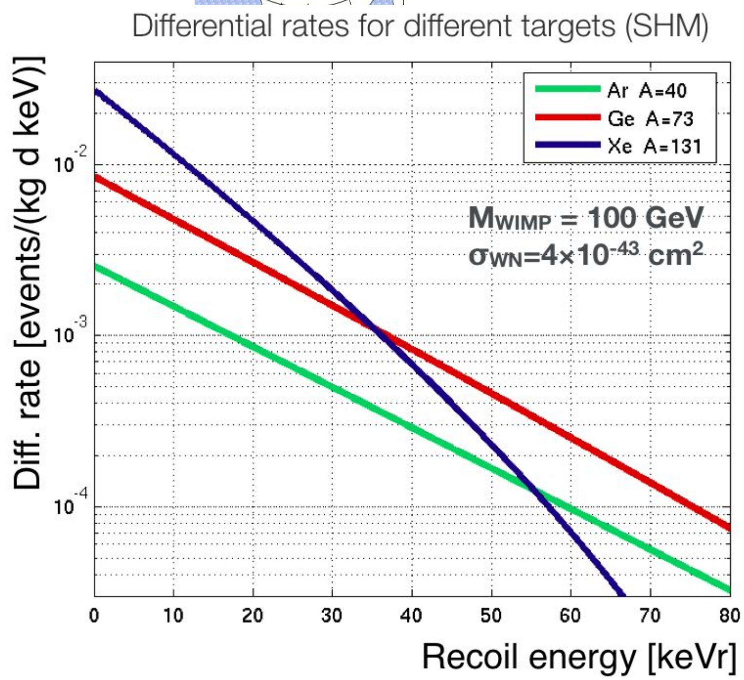
- E.g., for spin-independent (SI) int. $\sigma(E_R) = \sigma_0 F^2(E_R)$ where

$\sigma_0 = \left[Z + (A-Z)(f_n/f_p)\right]^2 (\mu^2/\mu_p^2)\sigma_p = A^2(\mu^2/\mu_p^2)\sigma_p$ for $f_p = f_n$

Thus, given $\eta(v_{min})$ the plots are in the $m, \rho\sigma_p$ plane.

Standard Halo Model (SHM) The  of halo models





- $\rho_{SHM} = 0.3^{+0.2}_{-0.1}$ GeV/cm^3
- $f(v,t)$: Maxwellian $\vec{v}$ distribution at rest with the Galaxy $v_{\odot} \simeq$220km/s (190 to 320km/s), $v_{esc} \simeq$530-650km/s

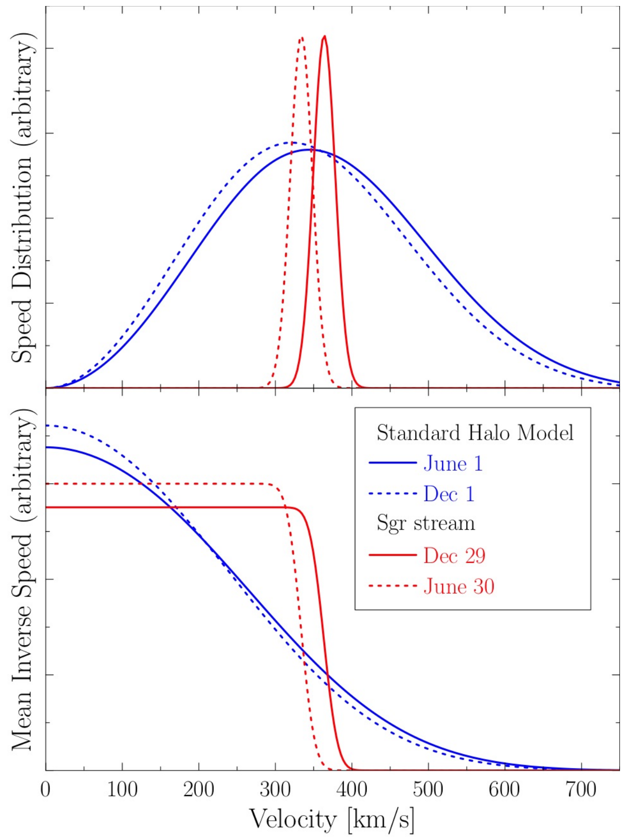
ANNUAL MODULATION: max June 1st, min Dec 1st (Drukier, Freese, Spergel 1986)

Local ρ, v, modulation phase/amplitude could be very different if Earth is within a DM clump or stream or there is a "Dark Disk". Other: anisotropies, velocity tails, debris flows...

SHM + DM in the Sgr. leading trail

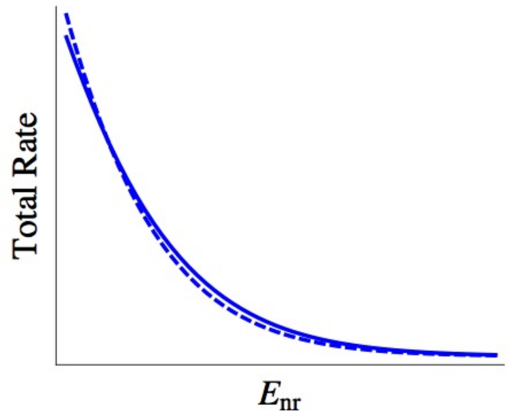
Schematic speed distribution and integral $\eta(v)$ with arbitrary normalization

Freese, Lisanti & Savage 1209.3339



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

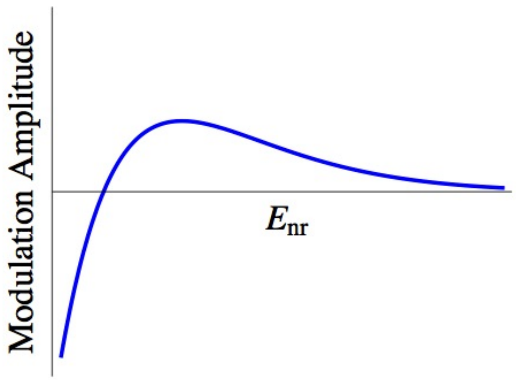
Usually assumed shape of the Annual Modulation



$$\eta(v_{min}, t) = A_0(v_{min}) + A_m(v_{min}) \cos\left(\frac{2\pi}{1 year}(t - t_{max})\right)$$

$$\frac{dR_T}{dE_R}(E_R, t) \sim \eta(v_{min}, t)$$

$$\frac{dR_T}{dE_R}(E_R, t) = S_0(E_R) + S_m(E_R) \cos\left(\frac{2\pi}{1 year}(t - t_{max})\right)$$

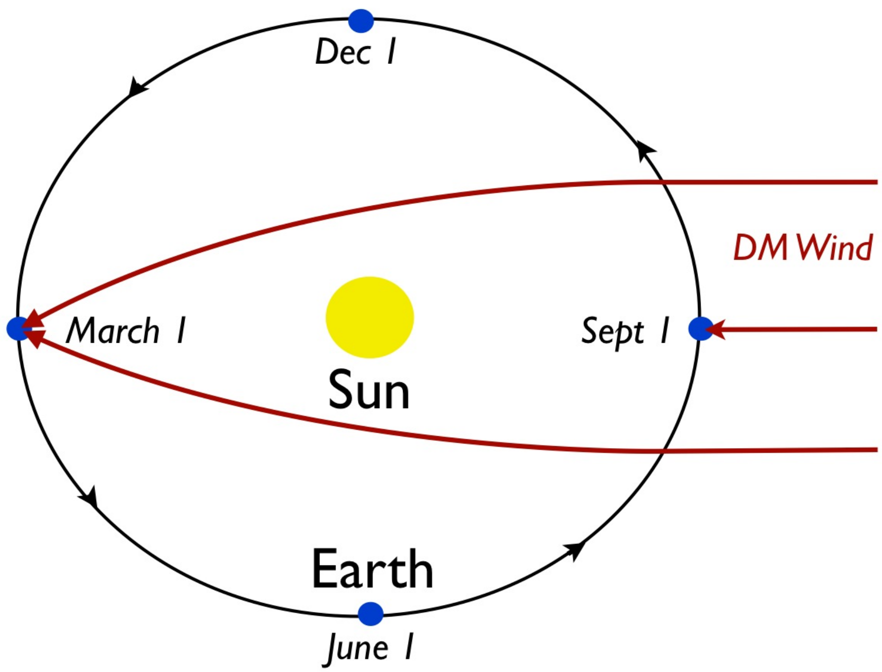


At most the max and min of the rate are exchanged at low energy, which means that with fixed phase at t_{max}, the modulation amplitude S_m becomes negative (below E_R corresponding to $v_{min} \simeq 200$ km/s in the SHM)

This is without considering the GRAVITATIONAL FOCUSING of DM by the Sun

Gravitational Focussing by the Sun affects the Annual Modulation for low velocity WIMPs Lee, Lisanti, Peter & Safdi 1308.1953

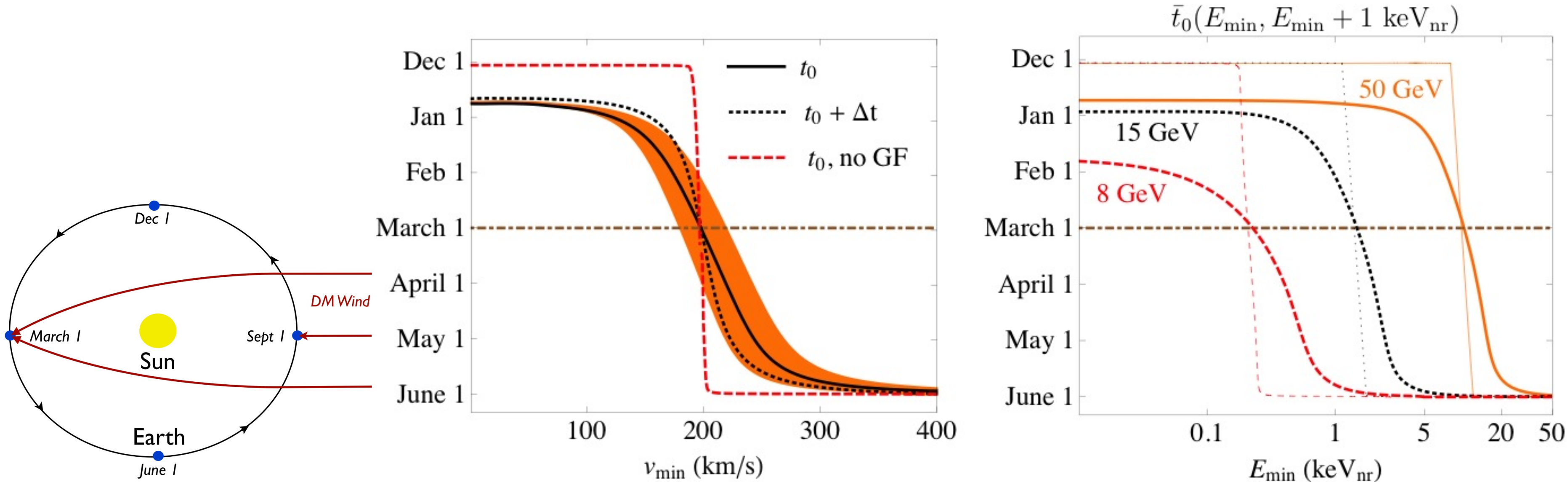
Lee et. al pointed out in 2013 that GF produces a phase change in the annual modulation.



GF affects the Annual Modulation for low velocity WIMPs

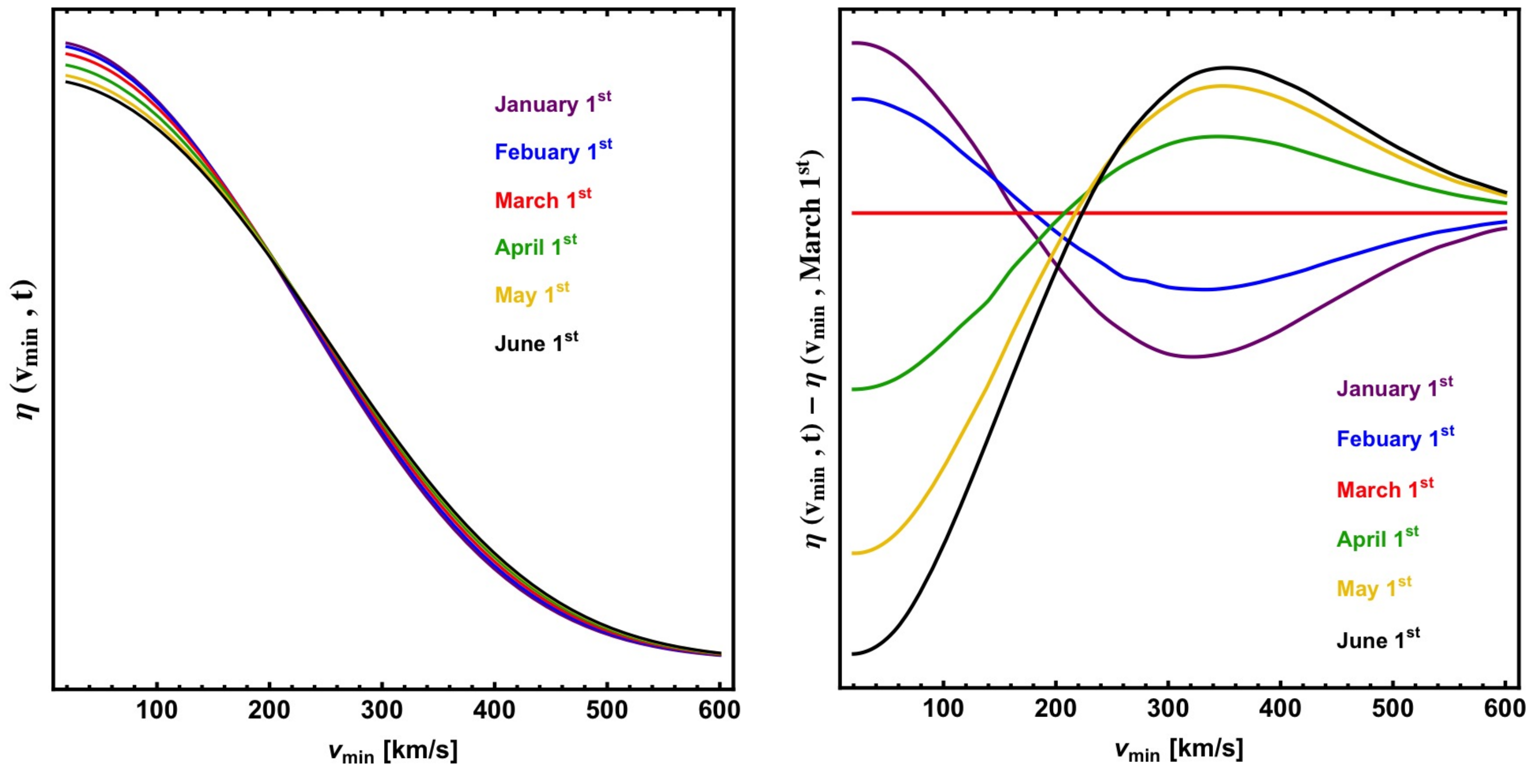
Lee, Lisanti, Peter & Safdi 1308.1953

Lee et. al pointed out in 2013 that GF produces a phase change in the annual modulation



t_0: date of max. of the halo integral $\eta(v_{min}, t)$. Right Plot: Diff rate for elastic scattering in Ge.
Different experiments could observed different regions of v_{min} for the same DM candidate and halo- thus their annual modulation could differ, unless the rate is expressed not in recoil energy but in v_{min}.

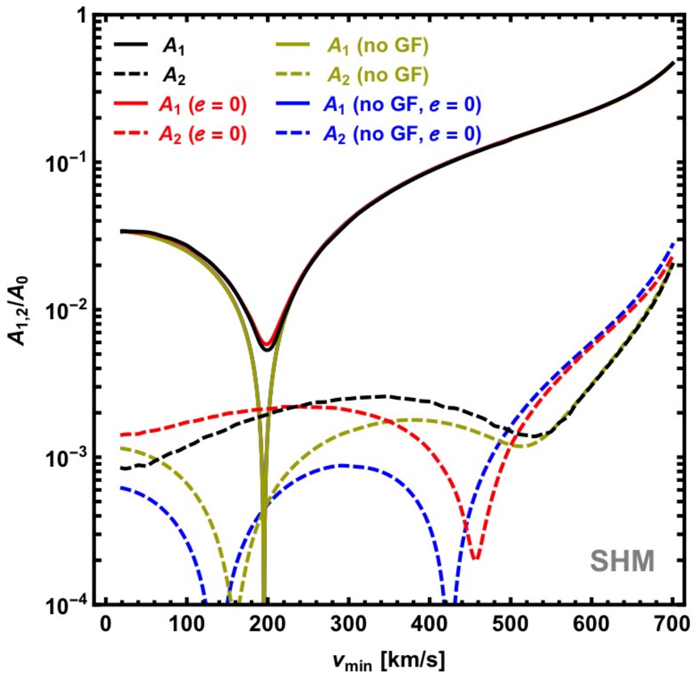
GF affects the Annual Modulation for low velocity WIMPs

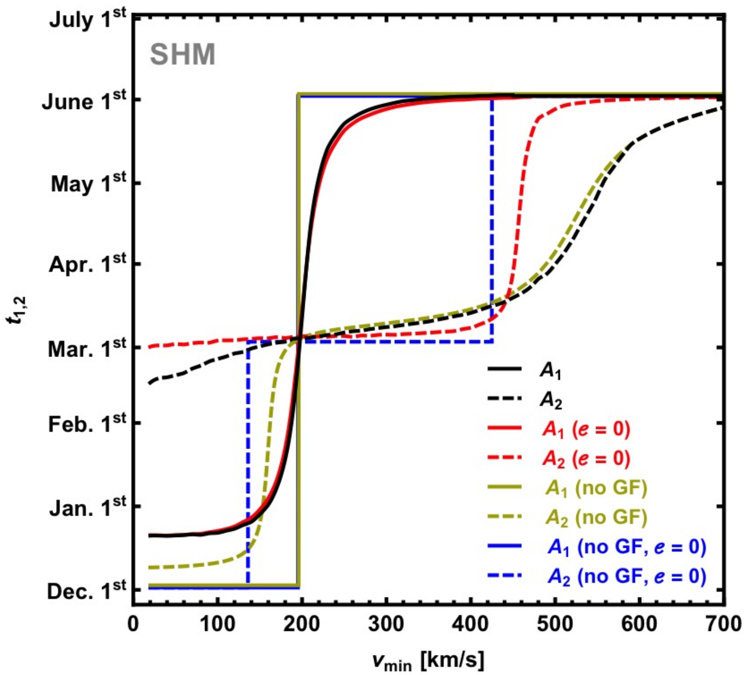


Due to GF maximum moves smoothly between June 1st. and January 1st.

GF affects the Annual Modulation for low v WIMPs

$$\eta(v_{min}, t) = A_0(v_{min}) + \sum_{n=1}^{\infty} A_n(v_{min}) \cos[n\omega(t - t_n(v_{min}))]$$





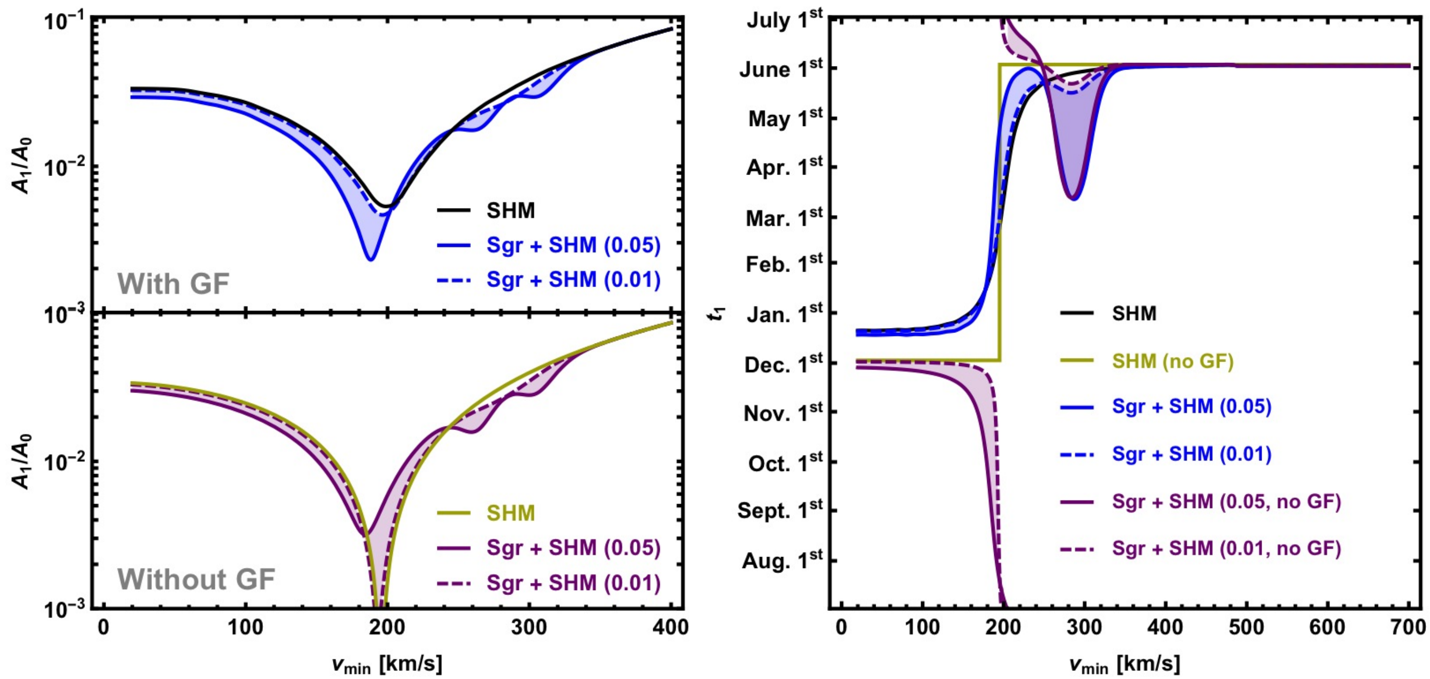
SHM A_1/A_0 solid lines and A_2/A_0 dashed lines- GF+ eccentricity: black,

No-GF +eccentricity: yellow, GF + no-eccentricity, No-GF + no eccentricity of Earth's orbit

Del Nobile, Gelmini, Witte 1505.07538

GF affects the Annual Modulation for low v WIMPs

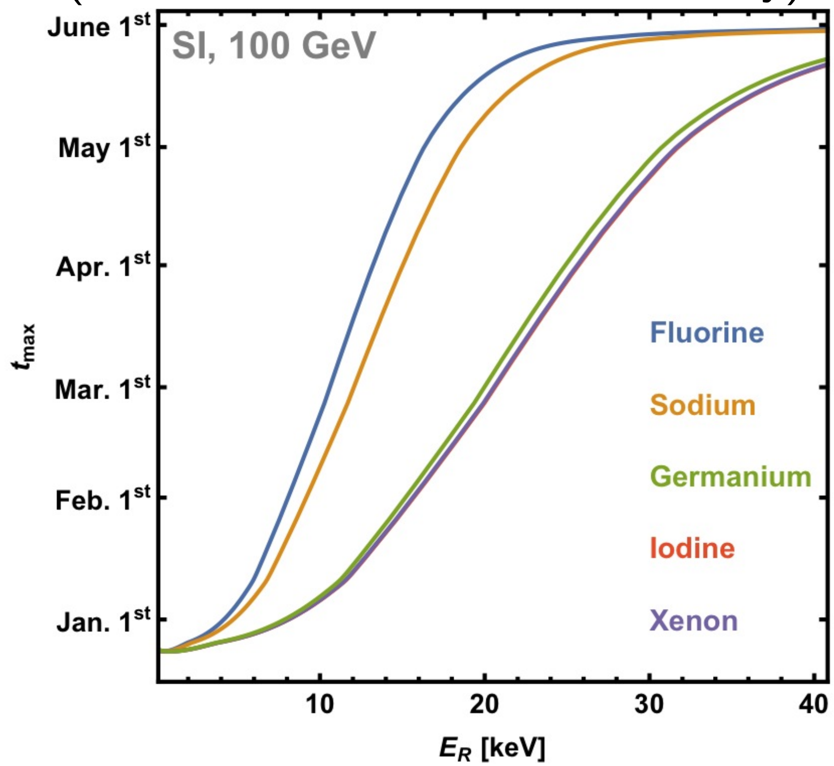
$$\eta(v_{min}, t) = A_0(v_{min}) + \sum_{n=1}^{\infty} A_n(v_{min}) \cos[n\omega(t - t_n(v_{min}))]$$



Sgr. Stream + SHM, A_1/A_0 with GF or without GF Del Nobile, Gelmini and Witte, 1505.0753

These are functions of v_{min}, but experiments measure energy!

GF induces target-material dependent annual modulation in E_R: Even for SI interactions, different elements pick different regions of v_{min} as function of E_R (here elastic collisions- SHM only)



But as function of v_{min} the annual modulation should be the same $R \sim \eta(v_{min}, t)$

The annual modulation in terms of v_{min}

The E_R-v_{min} relation depends on the target and DM particle masses and type of scattering:

Elastic collisions: $v_{min}^{el} = \sqrt{\frac{ME_R}{2\mu^2}}$

If besides the DM state χ with mass m there is a different state χ^* with $m^* - m = \delta << m$ and inelastic scattering $\chi + N \to \chi^* + N$ dominates over elastic. 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 collisions: $v_{min}^{inel} = \left| \sqrt{\frac{ME_R}{2\mu^2}} + \frac{\delta}{\sqrt{2ME_R}} \right|$ ($\delta > 0$ endothermic or $\delta < 0$ exothermic)

Even if different experiments could observed different v_{min} ranges and thus different annual modulations due to GF, expressed in terms of v_{min} with a unique E_R-v_{min} relation, the rate as function of time should be the same for all experiments, only if the velocity dependence factorized in the cross section!

Recall the rate in events/(kg of detector)/(keV of recoil energy)

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

For a WIMP-nucleus differential cross section

$$\frac{d\sigma}{dE_R} = \frac{\sigma(E_R)\ M}{2\mu^2 v^2}$$

we have

$$\frac{dR}{dE_R} = \frac{\sigma(E_R)\rho}{2m\mu^2} \int_{v>v_{min}} \frac{f(\vec{v}, t)}{v} d^3 v = \frac{\sigma(E_R)}{2m\mu^2}\ \rho\ \eta(v_{min}, t)$$

But the v dependence not always factorizes in the cross section... For example, for MDM...

Magnetic Dipole DM (MDM)

Pospelov & Veldhuis 2000, Sigurdson, Doran, Kurylov, Caldwell Kamionkowsky 2004, 2006, Maso, Mohanty, Rao 2009, Fortin, Tait 2012 many more

$$L = -(i/2)\bar{\psi}\sigma_{\mu\nu} d_m \psi F^{\mu\nu} \quad \rightarrow \quad H_{MDM} \sim d_m \vec{\sigma}.\vec{B}$$

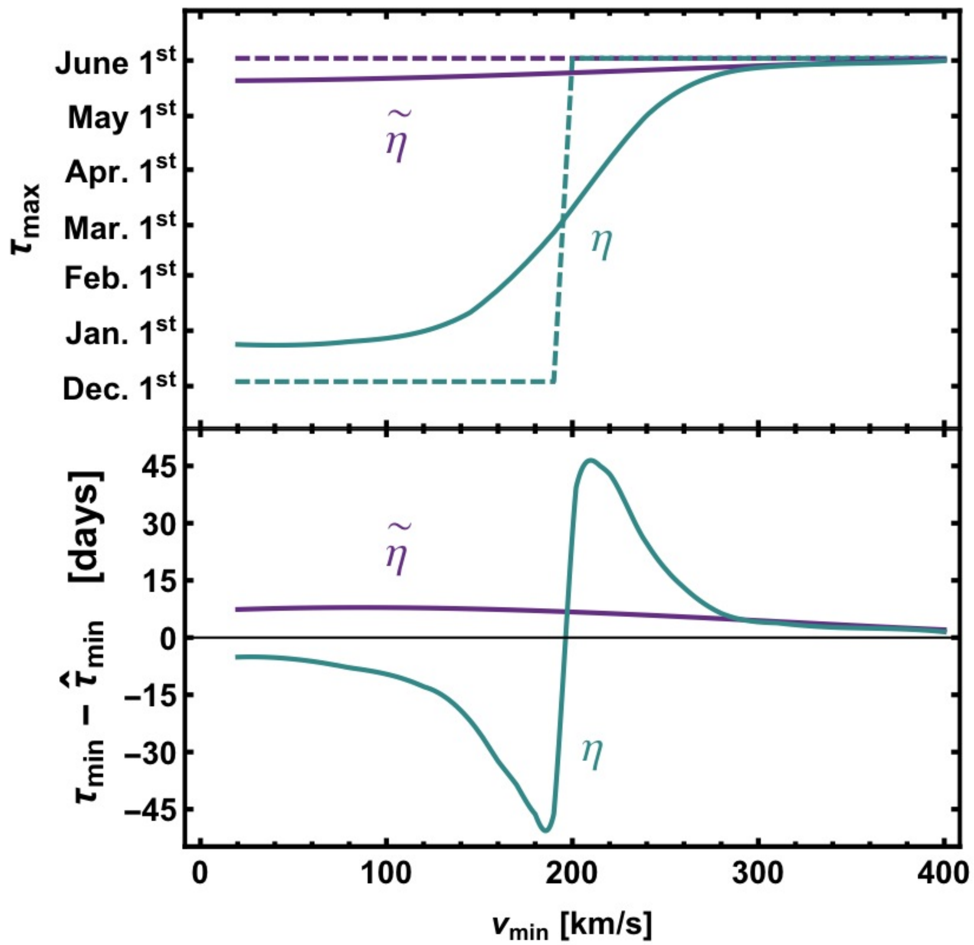
$$\frac{d\sigma_T}{dE_R} = \frac{\alpha d_m^2}{v^2}\left\{ Z_T^2 \frac{M}{2\mu_T^2}\left[\frac{v^2}{v_{min}^2} - \left(1 - \frac{\mu_T^2}{m^2}\right)\right] F_{SI,T}^2(E_R) + \frac{d_{mT}^2}{\mu_N^2}\frac{M}{m_p^2}\left(\frac{S_T+1}{3S_T}\right) F_{M,T}^2(E_R)\right\}$$

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

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

and $dR_T/dE_R = r + \tilde{r}$ with $r \sim \eta(v_{min}, t)$ and $\tilde{r} \sim \tilde{\eta}(v_{min}, t)$.

Velocity integrals
Del Nobile, Gelmini, Witte 1504.06772

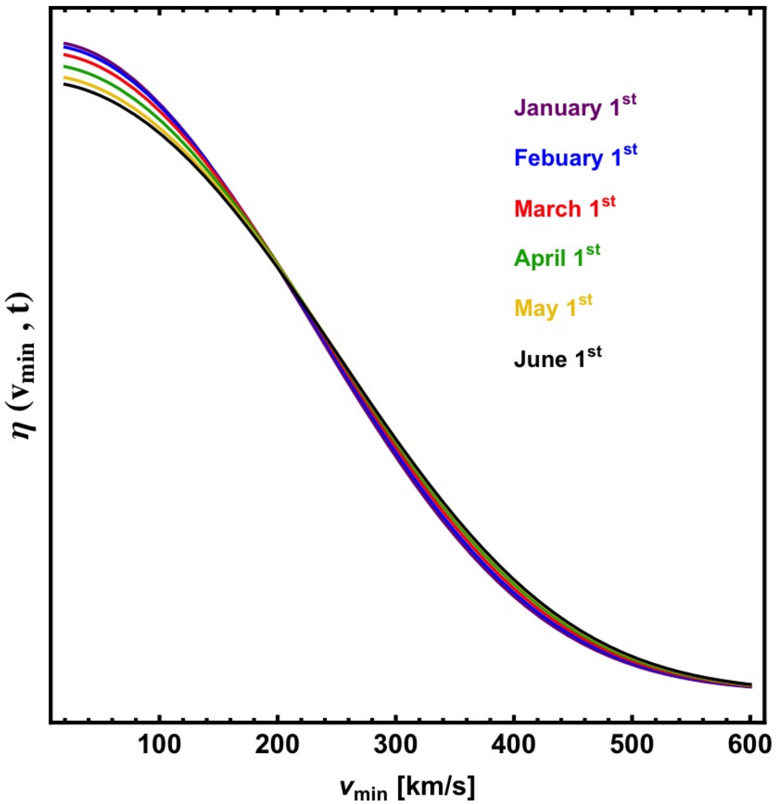


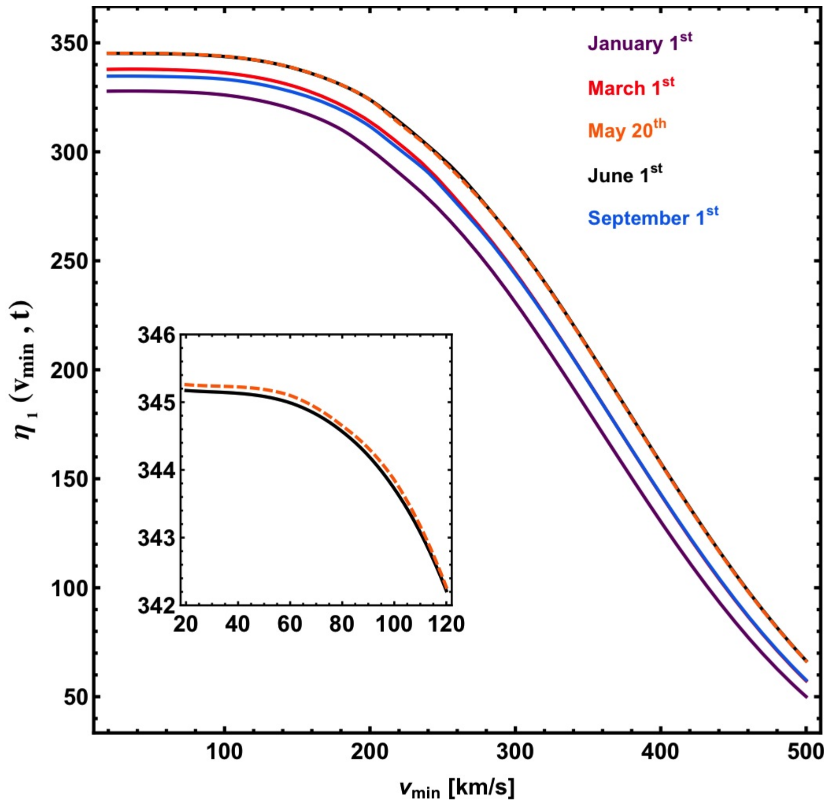
$$\eta(v_{min}, t) \equiv \int_{v \geq v_{min}} \frac{f(\vec{v}, t)}{v} d^3v,$$

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

Time of max. τ_{max} (*top*) and min. [τ_{min} - 1/2 y from max.] (*bottom*) of η and $\tilde{\eta}$ in the SHM, including GF (solid lines) and neglecting GF (dashed lines).

GF affects the Annual Modulation of both integrals

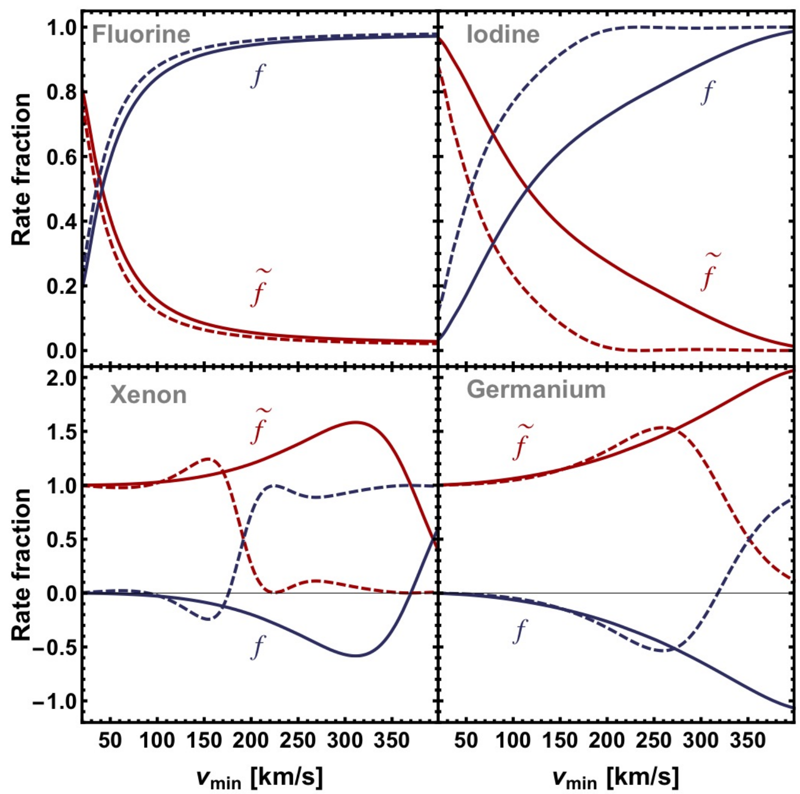




Left: η

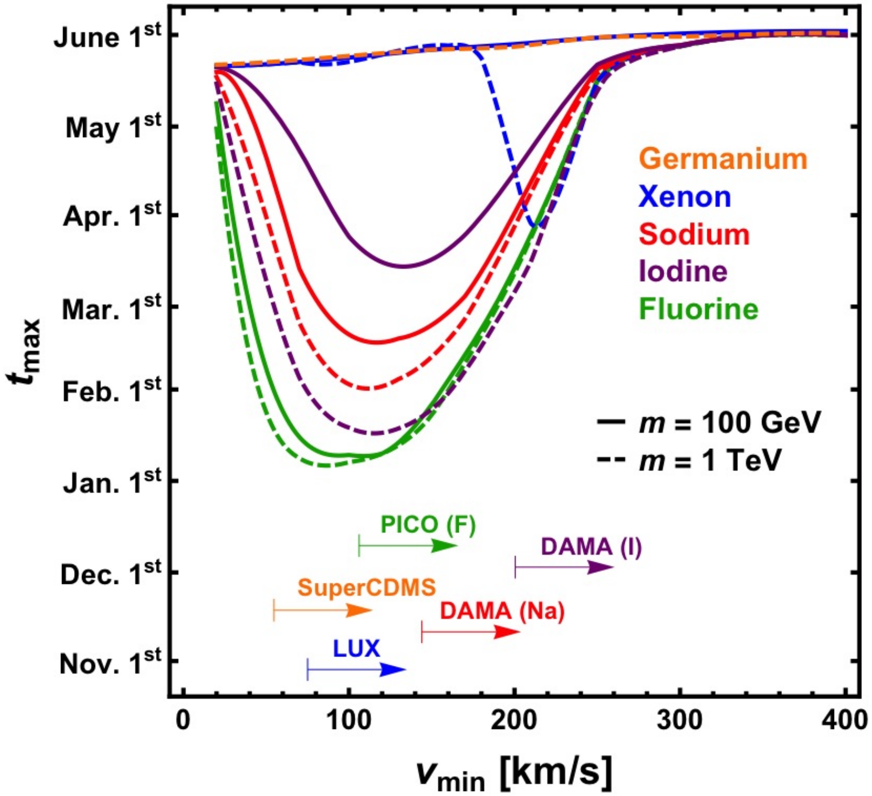
Right: $\tilde{\eta}$

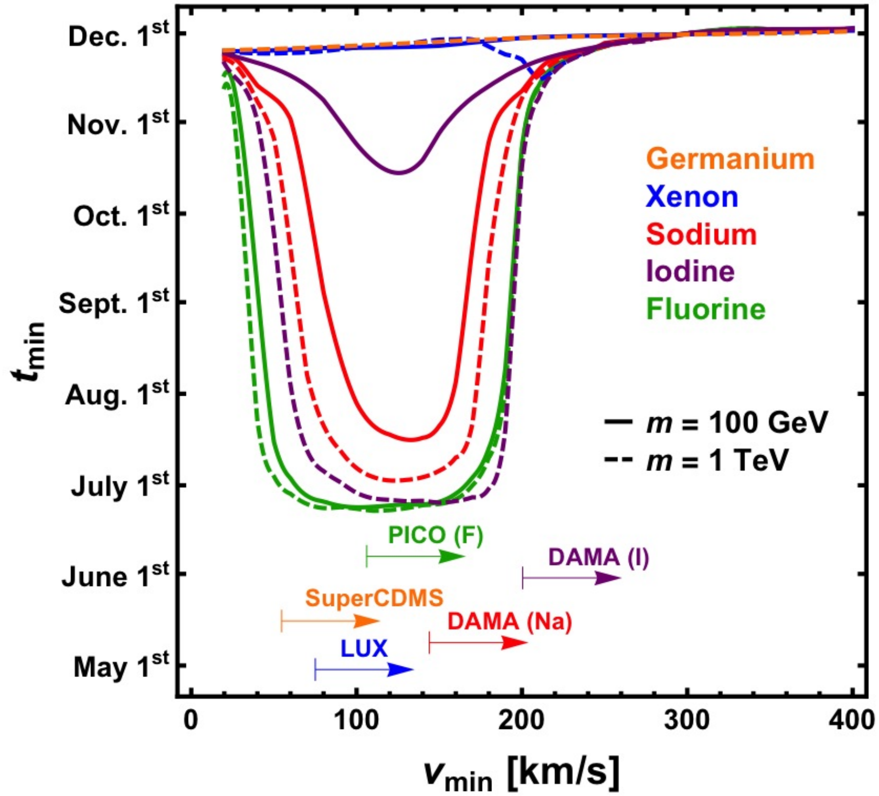
η and $\tilde{\eta}$ fractions for MDM $f \equiv r/(r+\tilde{r})$ and $\widetilde{f} \equiv \tilde{r}/(r+\tilde{r})$ Del Nobile, Gelmini, Witte 1504.06772



Solid (dashed) lines for $m = 100$ GeV (1 TeV). Fractions with their signs

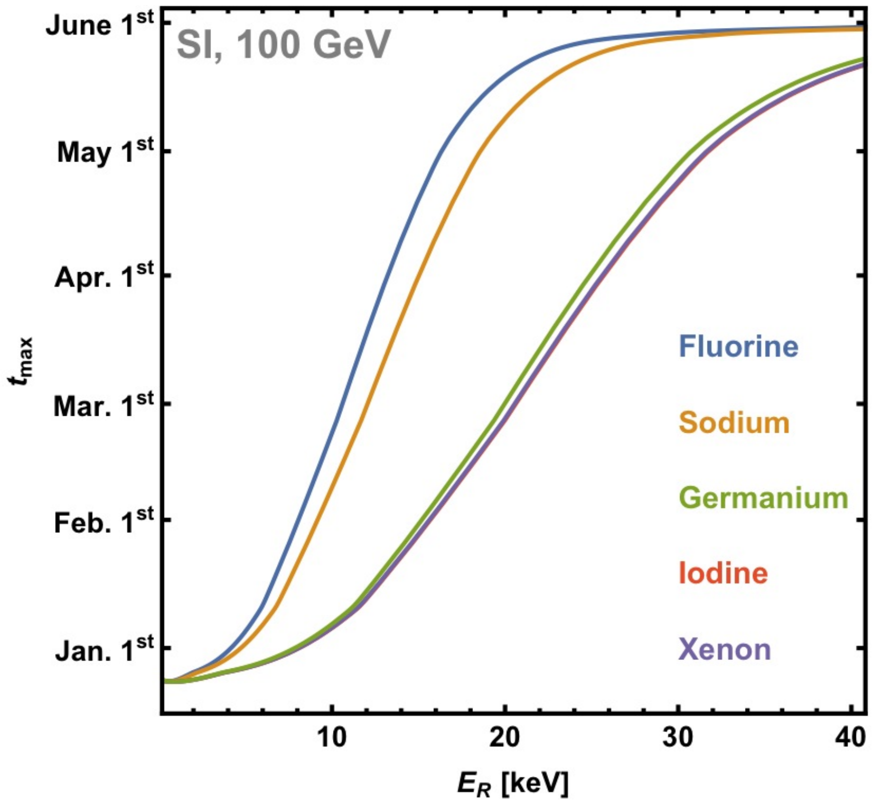
Times of max. and min. of the rate depend on the target material

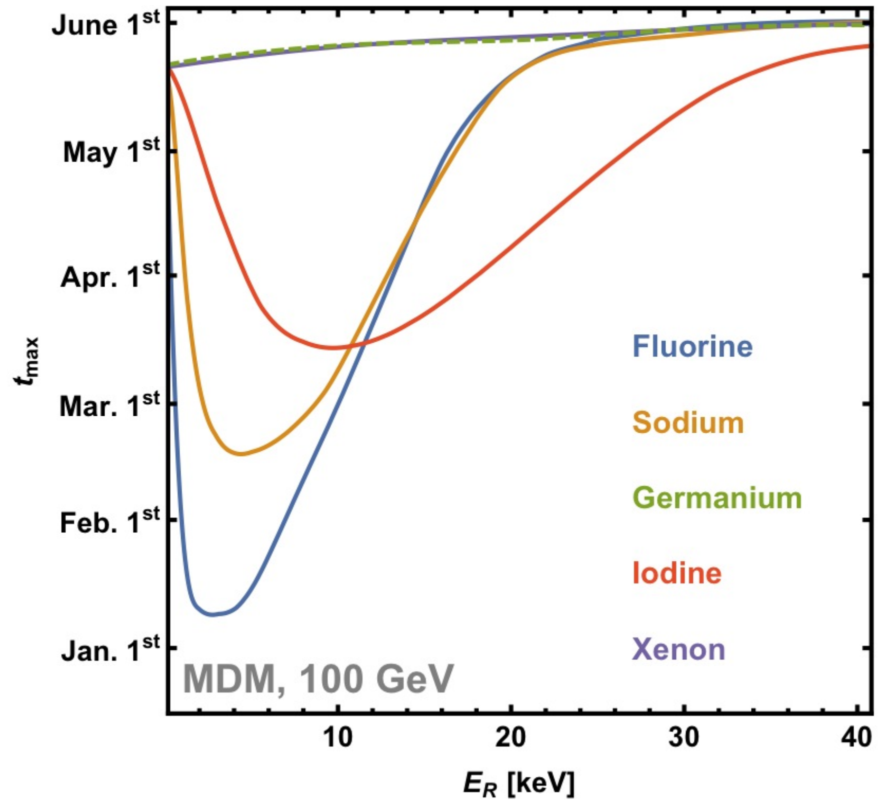




Left: t_{max}, Right: t_{min}- Solid (dashed) lines for $m = 100$ GeV (1 TeV) for magnetic dipole DM scattering elastically. Present thresholds for $m = 100$ GeV and elastic scattering indicated.

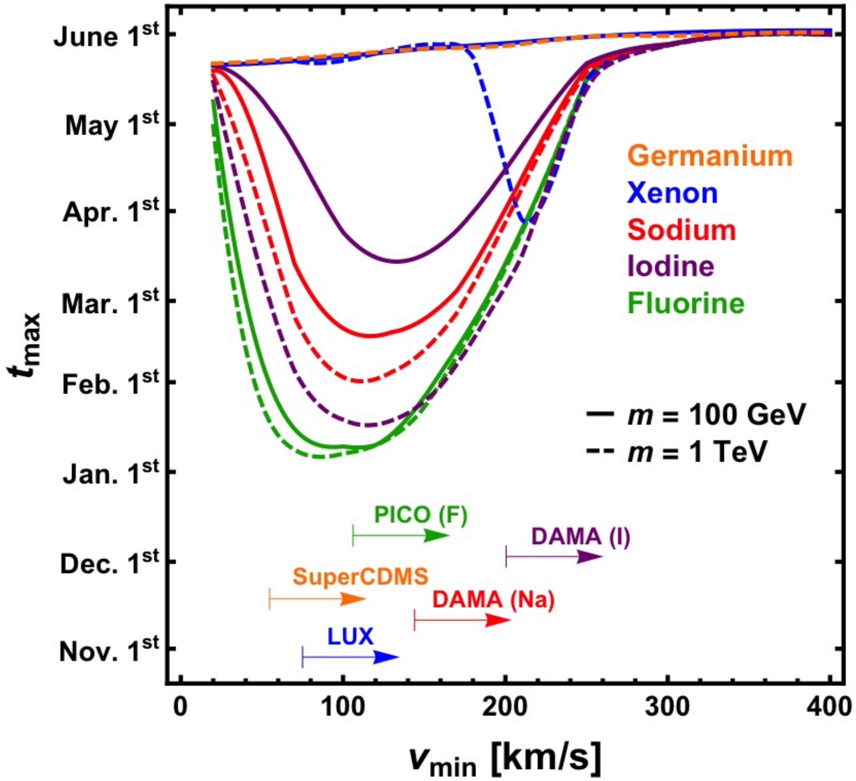
Time of max. and (min.−1/2 year from max.) for SI and MDM

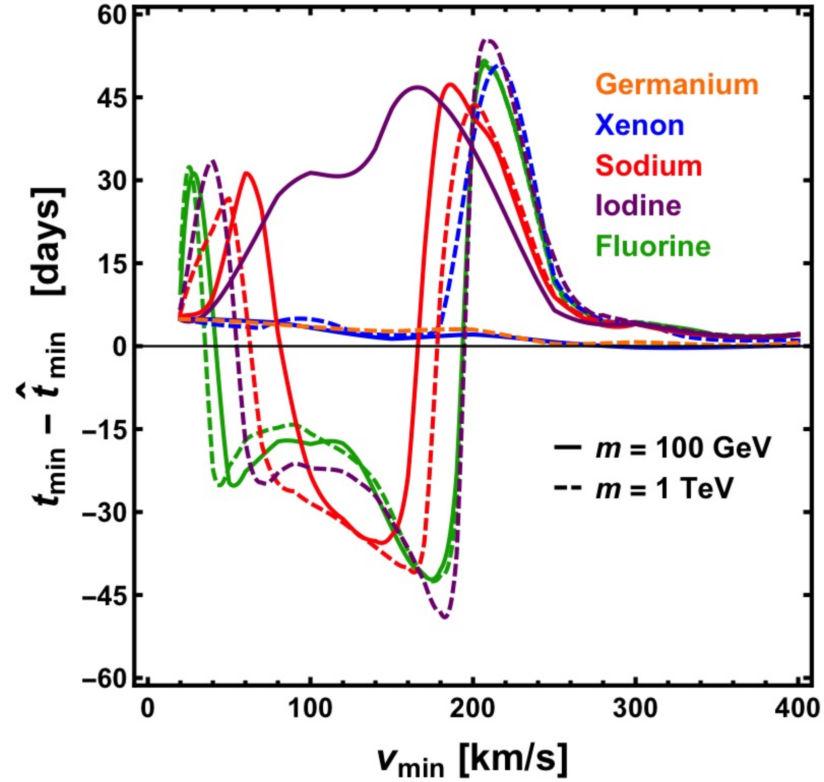




How to test the cross section v dependence: try to find an E_R-v_{min} relation so that the annual mod. as function of v_{min} coincide. If not possible, the cross section may have non-factorizable v dependence.

Time of max. and (min.−1/2 year from max.) of the rate





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

CONCLUSIONS

The annual modulation in direct detection experiments can be detector material dependent. So finding different phases and even different Fourier decompositions of the t-dependence with different target material could still be pointing to the same DM candidate and not an indication of non-compatibility

This is a further argument to do DM direct searches with many different materials