The Effect of Gravitational Focusing on Annual Modulation

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[1307.5323, 1308.1953, in progress]

Direct Detection

Dark matter scatters off of nuclei in detectors

Measure scattering rate in terms of nuclear recoil energy

Lab-frame velocity distribution

Local DM density

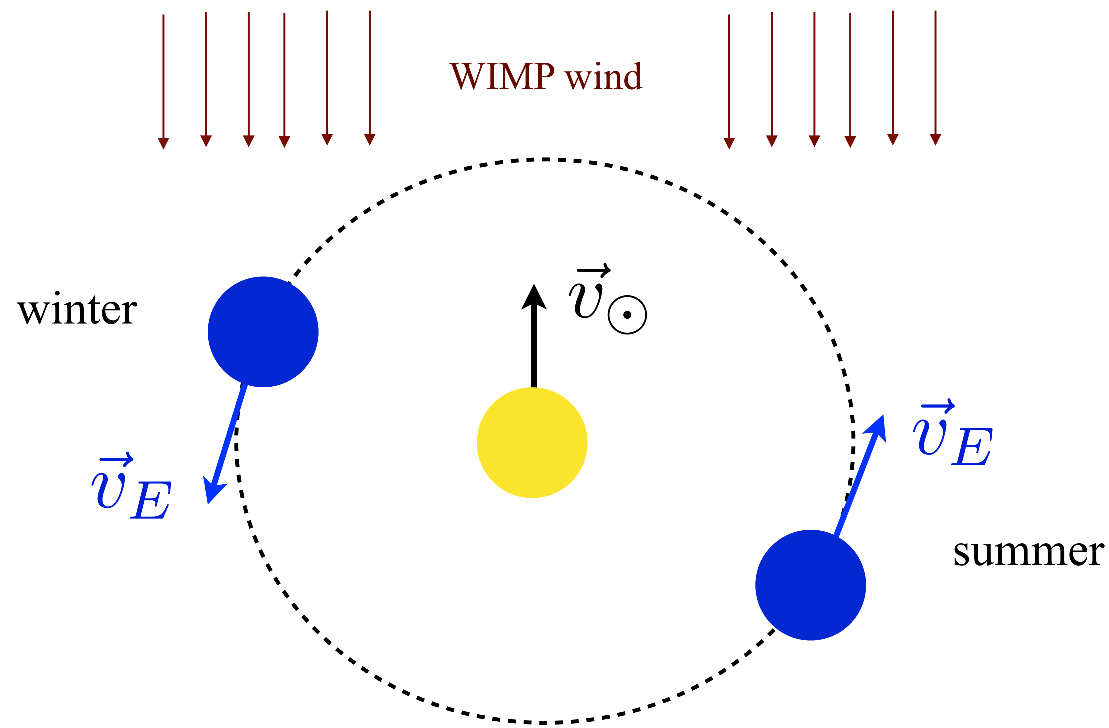
$$\frac{dR}{dE_{\rm nr}} \propto \rho \int_{v_{\rm min}}^{\infty} \frac{f(\mathbf{v}, t)}{v} d^3v$$

Minimum speed to induce
a recoil with energy E_{nr}

(for typical spin-independent and -dependent interactions)

Annual Modulation

Dark matter signal modulates annually due to Earth's orbit about the Sun



$$v \leq v_{\rm esc} + |\vec{v}_E - \vec{v}_\odot| \qquad\qquad v \leq v_{\rm esc} + |\vec{v}_E + \vec{v}_\odot|$$

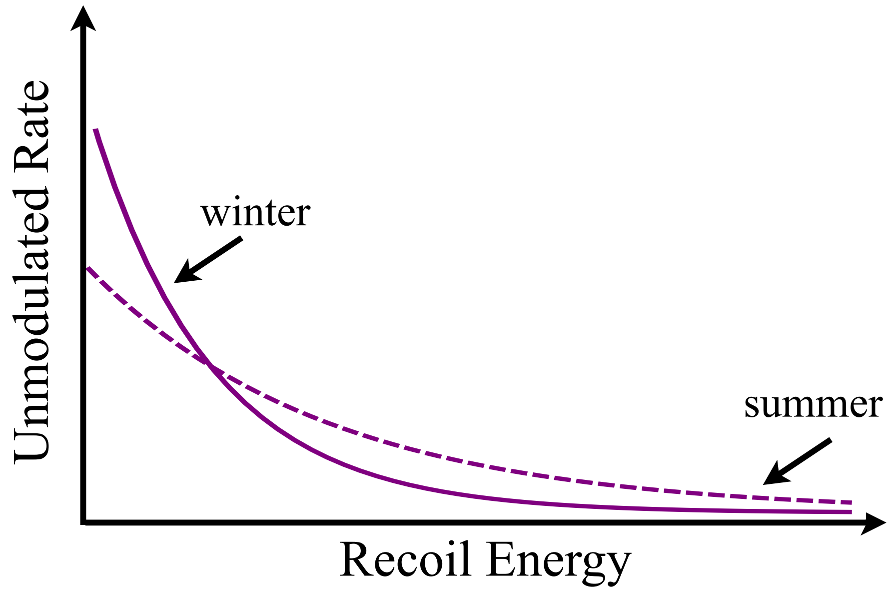
Drukier, Freese, and Spergel [PRD]
Review: Freese, **ML**, Savage [1209.3339]

Annual Modulation

More high-velocity particles in the summer
But, scattering cross section is enhanced for low-velocity particles

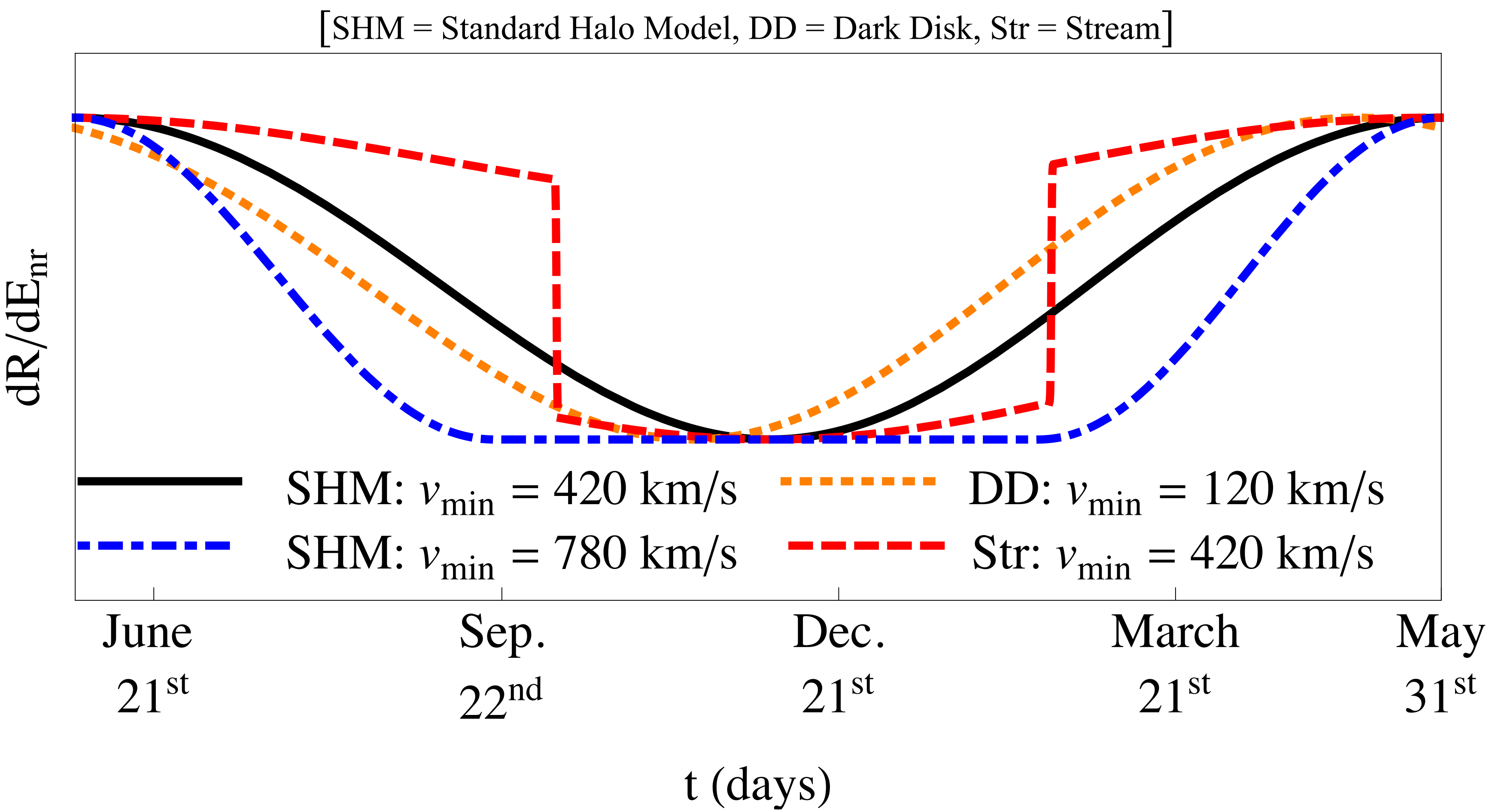
$$\frac{dR}{dE_{\text{nr}}} \propto \rho \int_{v_{\text{min}}}^{\infty} \frac{f(\mathbf{v},t)}{v} d^3v$$

High-energy scattering events have a maximum ~June 1
Low-energy events have a maximum ~Dec 1



Modulation Spectrum

Shape of the modulation spectrum depends on assumptions about the particle and astrophysics properties



Higher Harmonics

Expand differential scattering rate in terms of Fourier components

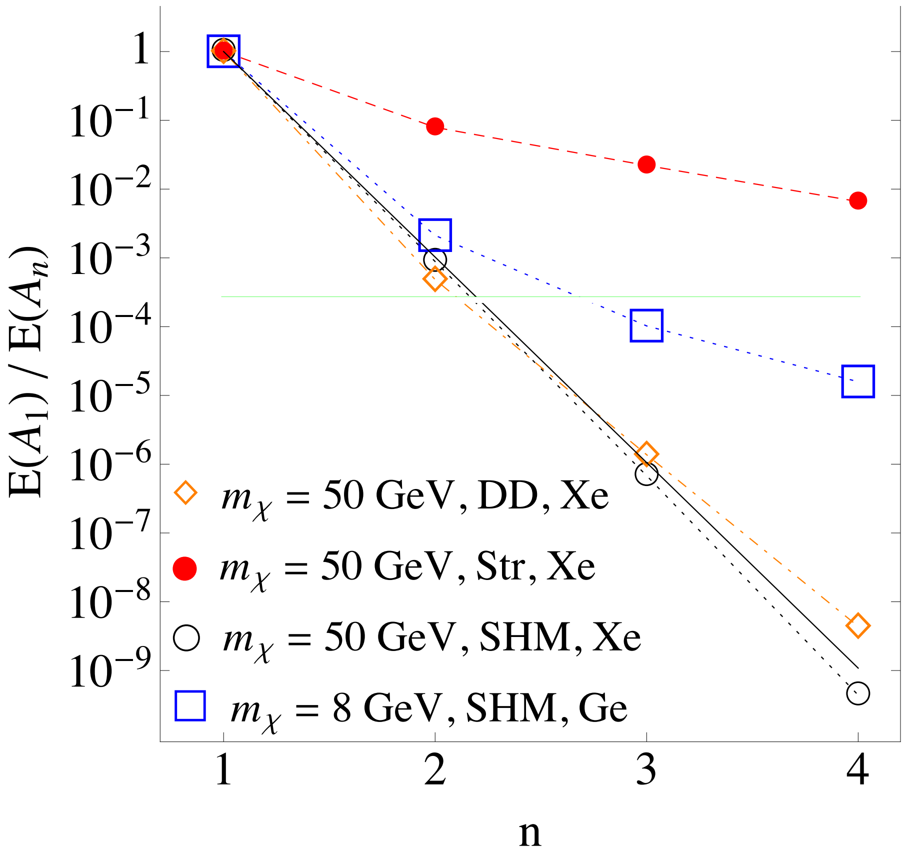
$$\frac{dR}{dE_{\rm nr}} = A_0 + \sum_{n=1}^{\infty} \left[A_n \cos n\omega(t - t_0) + B_n \sin n\omega(t - t_0) \right]$$

Relative strength of higher Fourier modes enhanced for

- high v_{min} scenarios (i.e., light or inelastic DM)
- local DM substructure in the halo

Higher Harmonics

$E(A_1)/E(A_n) =$ Exposure needed to observe A_1 to 95% confidence, relative to that for A_n



[SHM = Standard Halo Model, DD = Dark Disk, Str = Stream]

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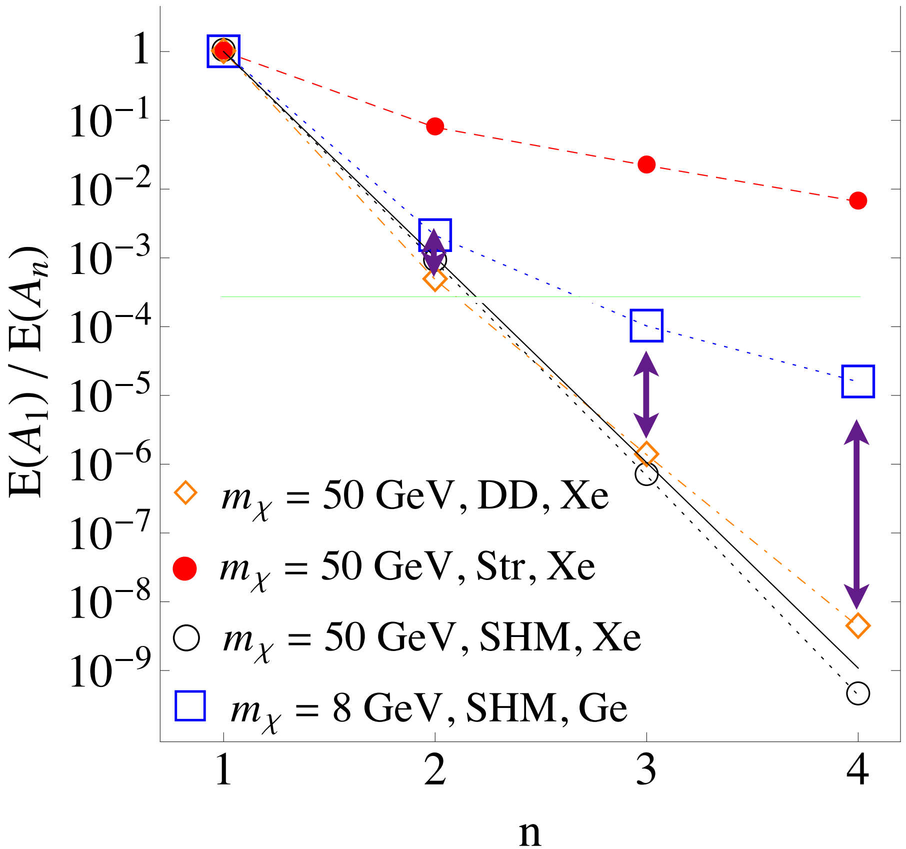

Less exposure needed to observe the higher-frequency modes for light dark matter

[SHM = Standard Halo Model, DD = Dark Disk, Str = Stream]

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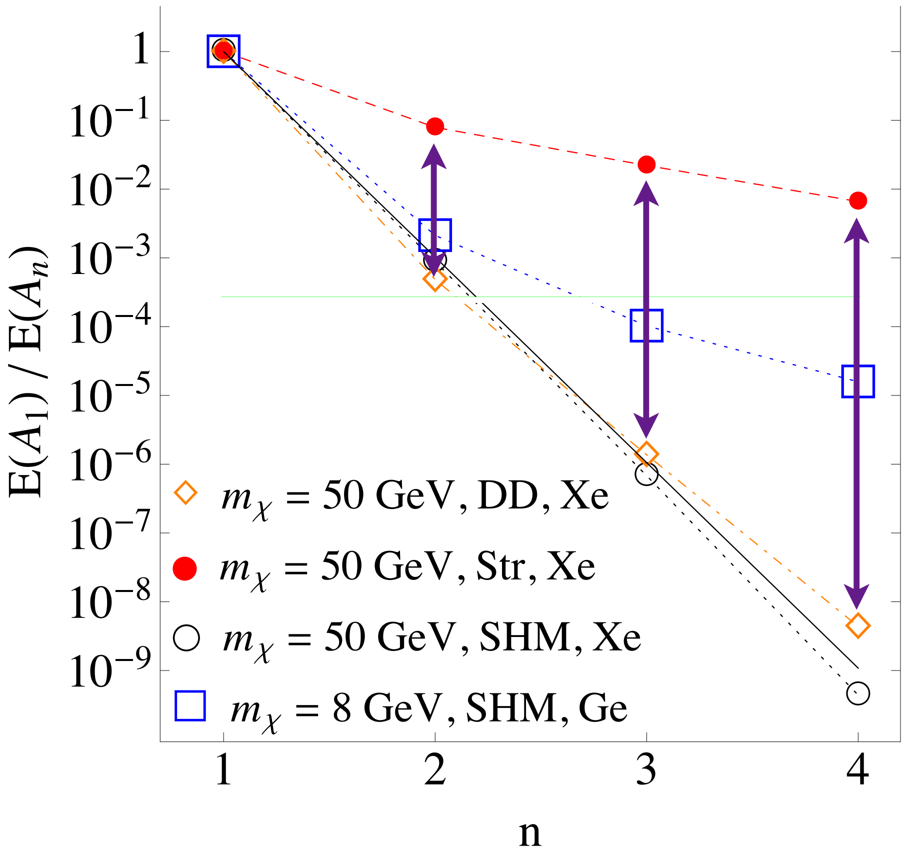


Less exposure needed to observe the higher-frequency modes for light dark matter

High-frequency modes very enhanced for dark matter streams

[SHM = Standard Halo Model, DD = Dark Disk, Str = Stream]

Higher Harmonics

Predicted amount of time to observe higher-harmonic modes for CDMS-Si best-fit point

$$m_\chi = 8.6 \text{ GeV}, \sigma_0 = 1.9 \times 10^{-41}$$

Mode	**XENON1T** E_{thresh}: 4 keV$_{\text{nr}}$	**GEODM DUSEL** 5 keV$_{\text{nr}}$	**GEODM DUSEL** 2 keV$_{\text{nr}}$
A_1	$\leq$ 1 year	$\leq$ 1 year	$\leq$ 1 year
A_2	$\leq$ 1 year	$\leq$ 1 year	$\leq$ 1 year
B_1	-	-	1 - 2 years
B_2	-	-	-
A_d	-	-	2 - 3 years

A particular example:

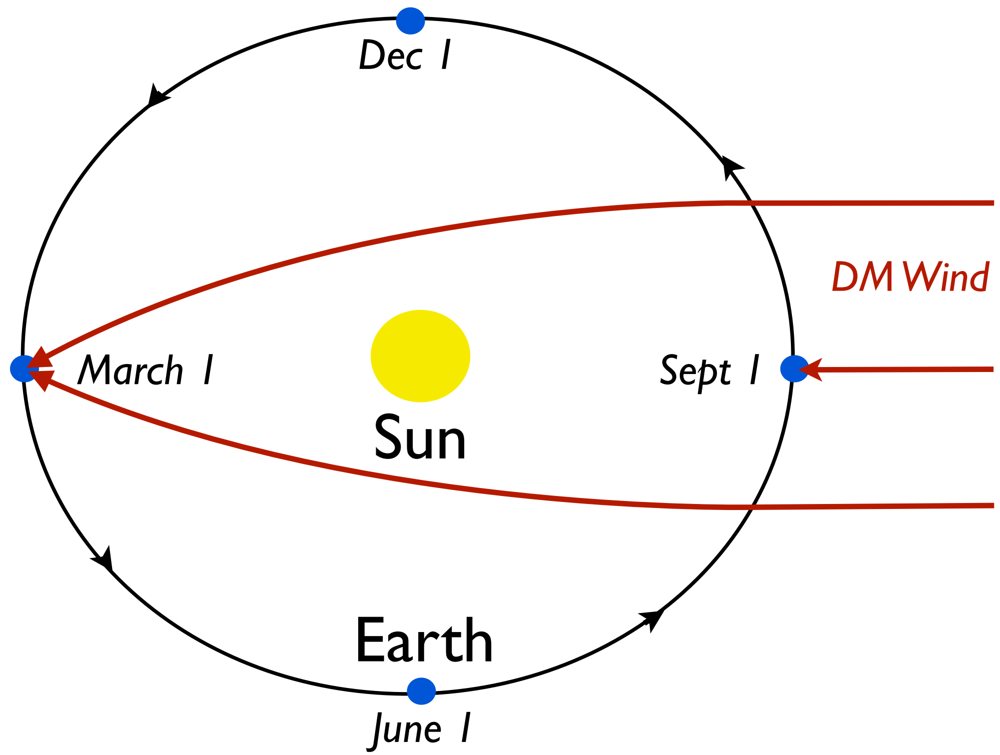
Gravitational focusing of dark matter particles

affects modulation phase (B_1 mode)

Gravitational Focusing

Sun's potential deflects incoming, unbound dark matter particles

Focusing is strongest during the Spring



K. Griest, PRD 1988.
Alenazi and Gondolo [astro-ph/0608390]

Modulation Phase

Earth's orbit causes ~3% modulation that is extremized ~June 1

Focusing causes ~1.5% modulation that is peaked ~March 1

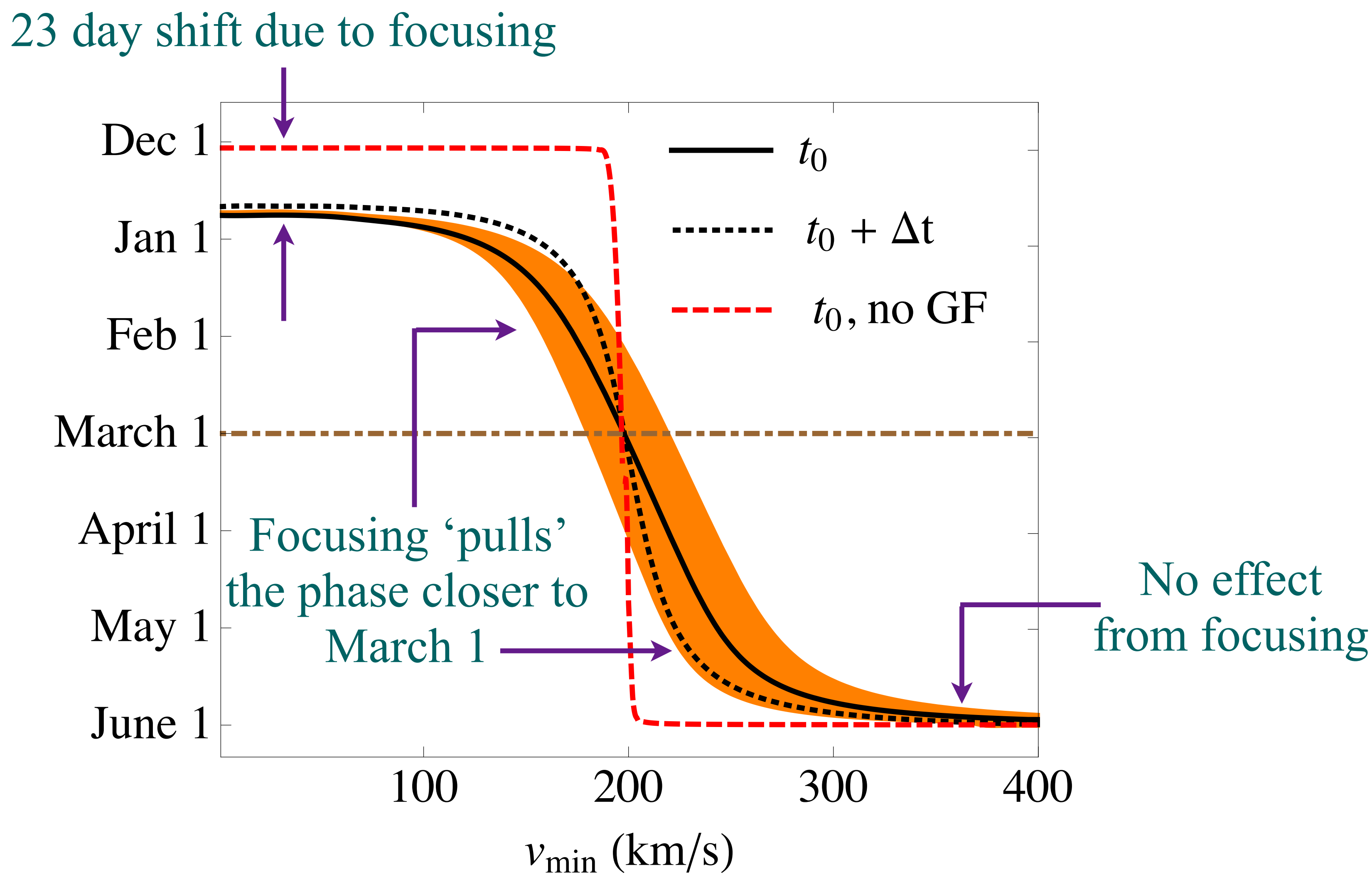
$v_{\rm min} \gtrsim 200\ {\rm km/s}$ Modulation due to Earth's orbit dominates

$v_{\rm min} \sim 200\ {\rm km/s}$ Gravitational focusing starts to become important

$v_{\rm min} \lesssim 200\ {\rm km/s}$ Focusing causes phase to shift towards March 1

Modulation Phase

$$\frac{dR}{dE_{\rm nr}} \approx A_0 + A_1 \cos\omega(t - t_0 - \Delta t)$$



Experimental Implications

Minimum scattering velocity depends on the mass of the dark matter, as well as the target nucleus

Mass of target nucleus

$$v_{\mathrm{min}} = \sqrt{\frac{m_n E_{\mathrm{nr}}}{2\mu^2}}$$

Recoil energy of nucleus

Reduced mass of nucleus and dark matter

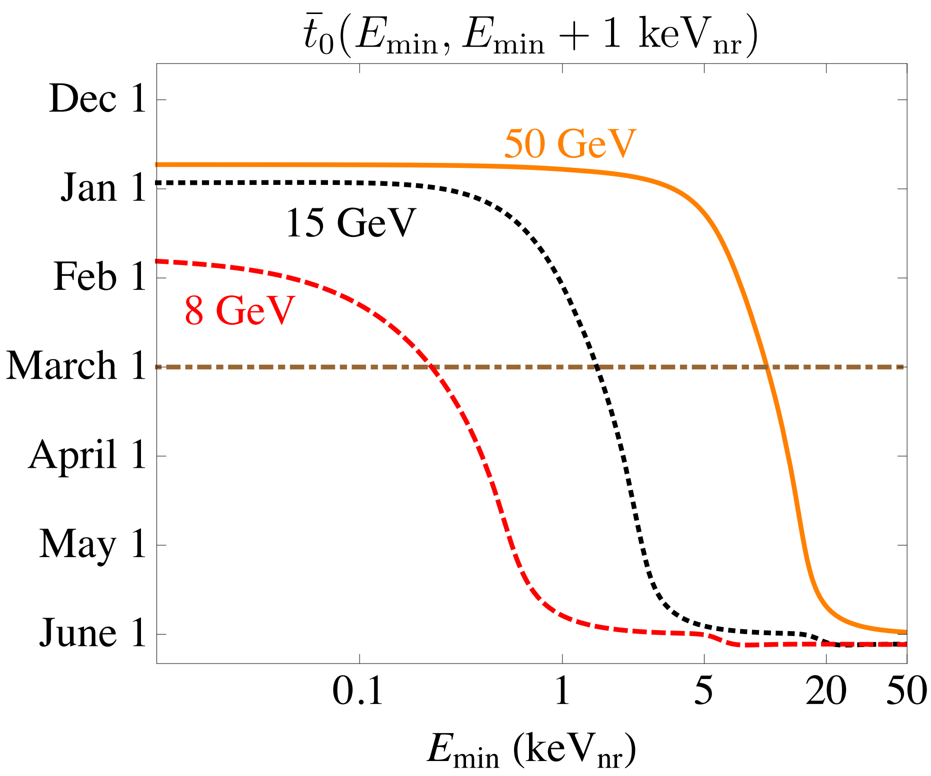
Lower v_{min} for heavier dark matter

Lower v_{min} for lighter dark matter at lower recoil energy

Example: Ge Target

For current thresholds, phase shift particularly significant for masses greater than ~15 GeV

Current advances in low-threshold technology could make shift relevant for ~8 GeV dark matter



Scattering rate in finite energy bin:

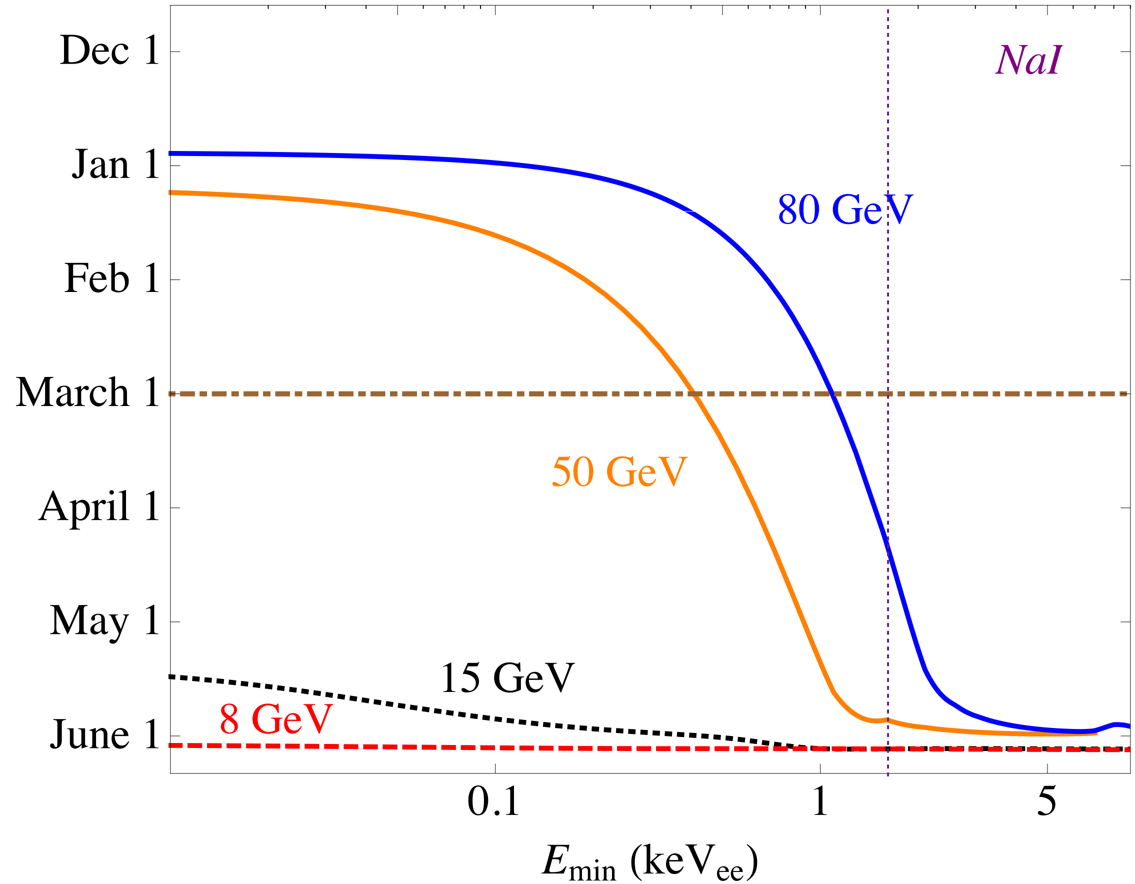
$$\bar{R}(E_{\rm min}, E_{\rm max}) = \int_{E_{\rm min}}^{E_{\rm max}} dE_{\rm nr} \frac{dR}{dE_{\rm nr}}$$

$\bar{t}_0$ is the time of maximal $\bar{R}$

DAMA

NaI(Tl) target, claims 9.3σ modulation

Can correspond to ~10 or 80 GeV dark matter
Both in tension with null results from other experiments



DAMA

80 GeV scenario affected by gravitational focusing

The phase shift can be as much as a ~month in the low-energy bins

	2-2.5 keV_{ee}	**2-3 keV_{ee}**	**2-4 keV_{ee}**	**2-5 keV_{ee}**	**2-6 keV_{ee}**
DAMA, measured	?	?	May 12±7	May 22±7	May 26±7
80 GeV (w/GF)	**April 29**	**May 10**	May 19	May 21	May 22

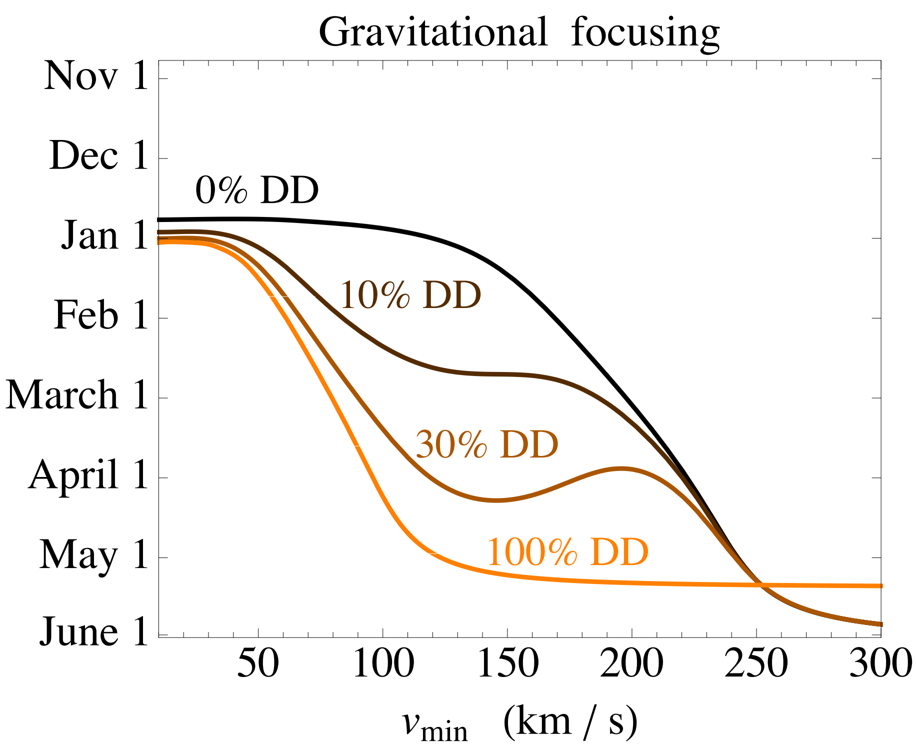
Gravitational focusing results in a dependence of phase on recoil energy bin

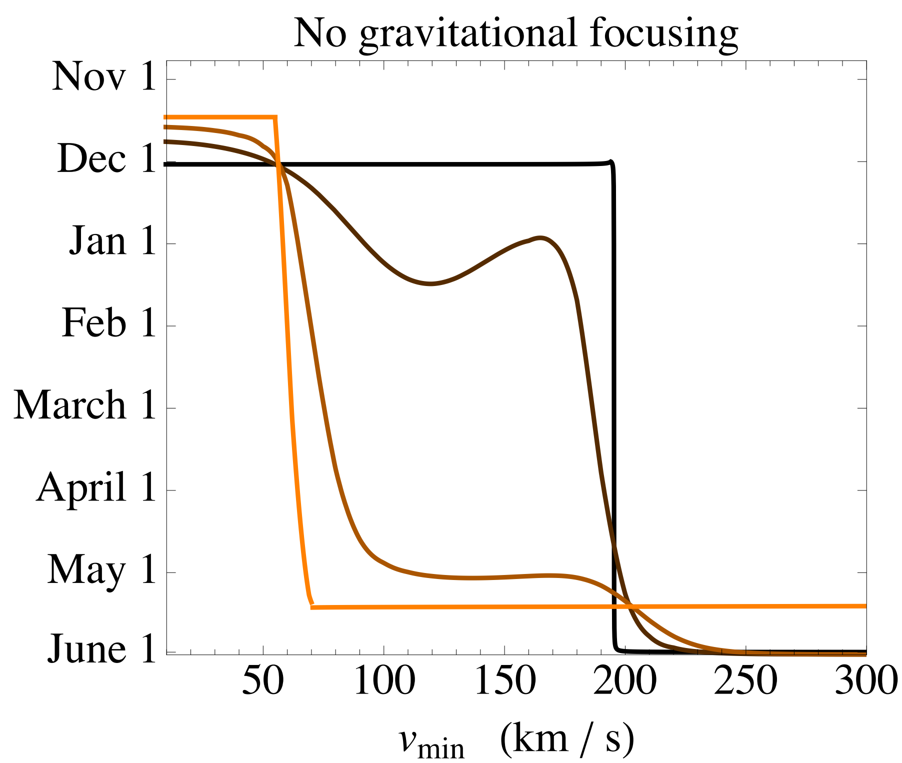
Can be used to distinguish signal from background

Measuring the Dark Disk

Dark disk is thought to rotate in the same direction as the local standard of rest, but with a lag speed ~50 km/s

Significantly affects the modulation phase, even for low dark-disk density





Conclusions

Particle and astrophysics assumptions about dark matter can enhance higher-frequency modes of modulation spectrum

Unbound dark matter particles focused by Sun's gravitational potential, affecting the modulation phase

Phase shift most relevant for low-v_{min} particles

i.e., masses greater than ~15 GeV, or lighter mass particles at low-threshold experiments