# Beyond Annual Modulation at WIMP Direct-Detection Experiments

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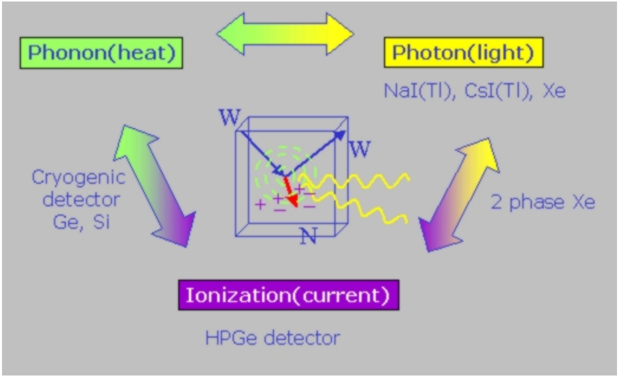
# Overview

- Basics of WIMP direct detection & annual modulation
- CoGeNT and DAMA modulation signals
- A more detailed treatment of modulation?
  - Gravitational focusing of WIMPs (and cosmic neutrinos)
  - Higher-harmonic modes

# Direct Detection 101




Direct detection of WIMP-induced nuclear recoils
via phonons, scintillation, ionization, etc.

# Direct Detection 101

Event rate given by

$$\frac{dR}{dE}(t) = \underbrace{\frac{\sigma_0 F^2(E)}{2m_\chi \mu_{\chi N}^2}}_{\text{PARTICLE}} \times \underbrace{\rho_0 \int_{v_{\min}}^{\infty} d^3v \, \frac{f(\mathbf{v}, t)}{v}}_{\text{ASTRO}}$$

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Minimum lab-frame WIMP speed required to induce nuclear recoil with energy $E$

$$v_{\min} = \sqrt{\frac{m_N E}{2\mu_{\chi N}^2}}$$

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Event rate depends on lab-frame WIMP velocity distribution

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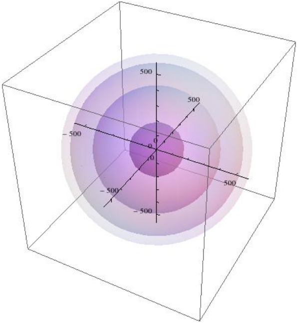
Standard Halo Model (truncated Maxwellian) generally assumed for galactic-frame velocity distribution

$$g(\mathbf{v}) \propto e^{-v^2/v_0^2}\,\theta(v_{\text{esc}} - v)$$

$$v_0 = 220 \text{ km/s}, \quad v_{\text{esc}} \approx 550 \text{ km/s}$$



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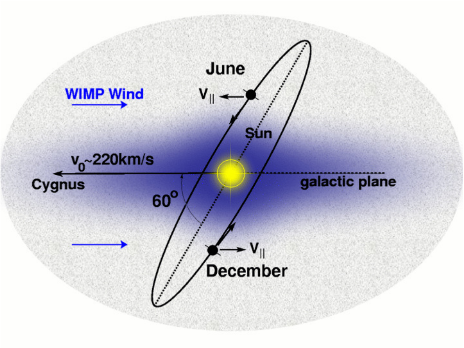
Event rate can be written as

$$\frac{dR}{dE} \propto \int_{v_{\min}(E)}^{\infty} d^3v\,\frac{f\,(\mathbf{v})}{v} \approx A_0(E)$$

For SHM, and typical WIMP and experiments,

$$A_0(E) \propto e^{-E/E_0}, \quad E_0 \approx 10\text{ keV}$$

# Modulation 101



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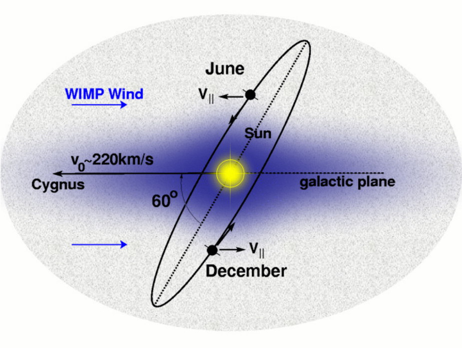


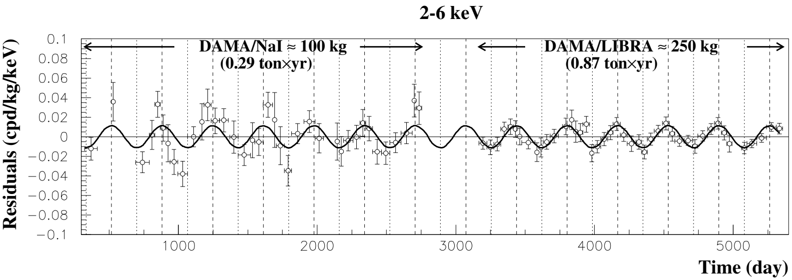

Modulation of event rate can be written as

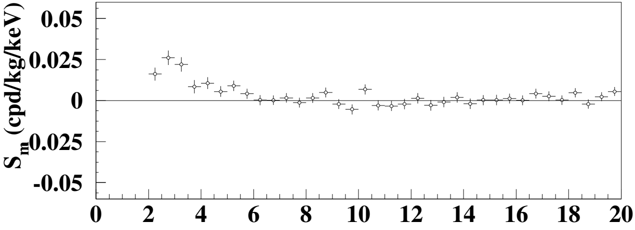
$$\frac{dR}{dE}(t) \propto \int_{v_{\min}(E)}^{\infty} d^3v \, \frac{f(\mathbf{v}, t)}{v} \approx A_0(E) + A_1(E)\cos[\omega(t - t_{\max})]$$

For SHM, and typical WIMP and experiments,

$$A_0(E) \propto e^{-E/E_0}, \quad E_0 \approx 10\,\text{keV}, \quad \bar{A}_1/\bar{A}_0 \approx \text{few}\%, \quad t_{\max} \approx \text{June 1}$$

# Modulation at DAMA: Signal



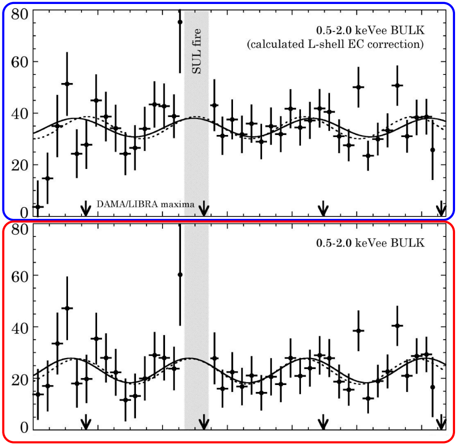

$$T = 0.999 \pm 0.002 \text{ year}, \quad t_{\text{max}} = \text{May } 25 \pm 7 \text{ days}$$

# Modulation at DAMA: Summary

- Exposure of $\sim$ton-year at NaI target
- $\sim 9\sigma$ annual modulation of single-hit residuals at 2–6 keVee
- Assuming SHM, 10 GeV and 80 GeV ROIs allowed
- Phase compatible, fractional amplitude not measured

# Modulation at CoGeNT: Signal

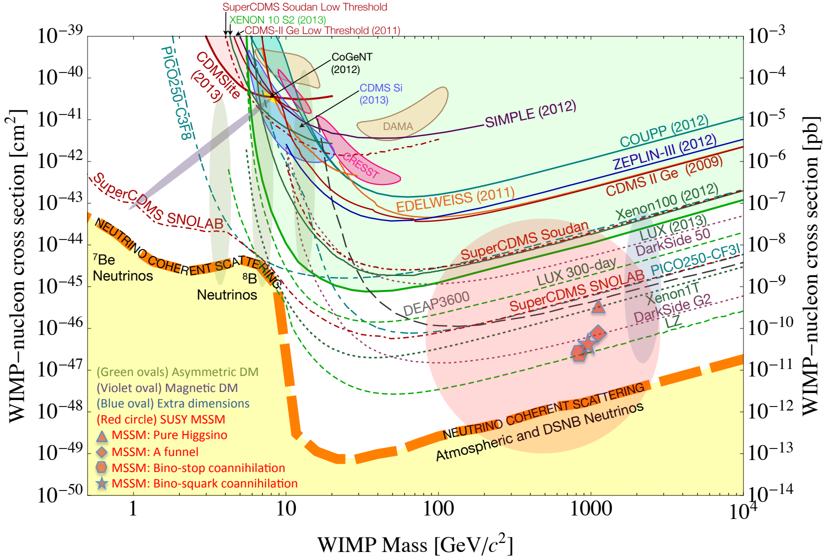
- Calculating EC BG:
  - $T = 336 \pm 24$ days
  - $S = 12.4 \pm 5\%$
    $\rightarrow \bar{A}_1/\bar{A}_0 \approx 35\%$
- Fitting EC BG:
  - $T = 350 \pm 20$ days
  - $S = 21.7 \pm 15\%$
    $\rightarrow \bar{A}_1/\bar{A}_0 \approx 62\%$
- Fixing $T = 1$ year:
  $t_{\rm max} =$ April $13 \pm 47$ days



# Modulation at CoGeNT: Summary

- Exposure of 1,129 live days at Ge target
- Events in low-energy (0.5–2.0 keVee) and high-energy (2.0–4.5 keVee) bins
- Improved bulk/surface discrimination via rise-time cuts
- $\sim 2.2\sigma$ annual modulation in low-energy, bulk events (decrease from $\sim 2.8\sigma$)
- For SHM, best fit by $\sim 8$ GeV & $2 \times 10^{-41}$ cm$^2$
- Phase compatible, but fractional amplitude ∼4-7x larger

# Exclusion at Other Experiments?




Billard et al. 2013 (and others...)

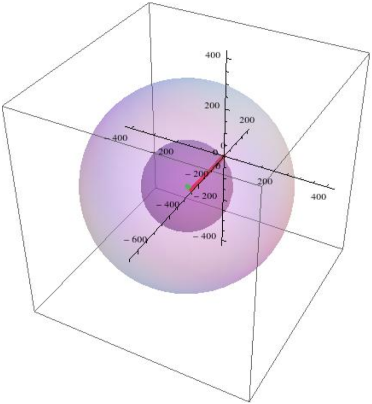
# Modulation in More Detail: Motivation

- Making modulation a better smoking gun?
- Moving towards a holistic understanding of dark-matter particle physics and astrophysics
- Sensitivity to velocity substructures (disk, streams, etc.)
- May extend reach below neutrino floor (if necessary...)

# Modulation 102

Galilean transformation relates lab and galactic frame

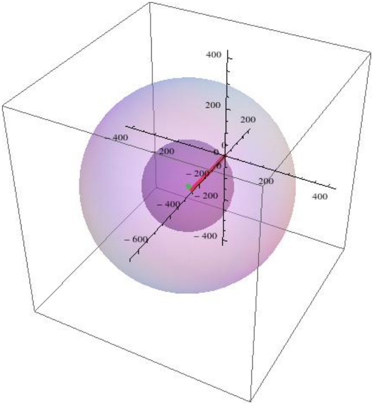
$$
\begin{aligned}
f(\mathbf{v}, t) &= g(\mathbf{v} + \mathbf{v}_{\text{lab}}(t)) \\
&= g(\mathbf{v} + \mathbf{v}_{\odot} + \mathbf{v}_{\oplus}(t))
\end{aligned}
$$



# Modulation 102

Event rate $\frac{dR}{dE}(t)$ proportional to integral of

$$\frac{f(\mathbf{v},t)}{v}$$



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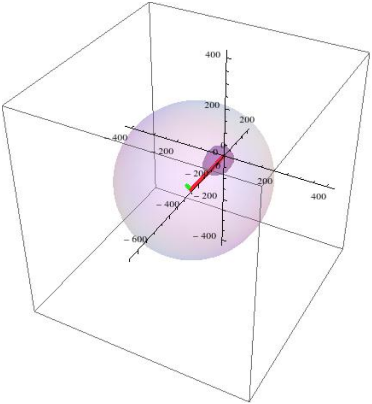
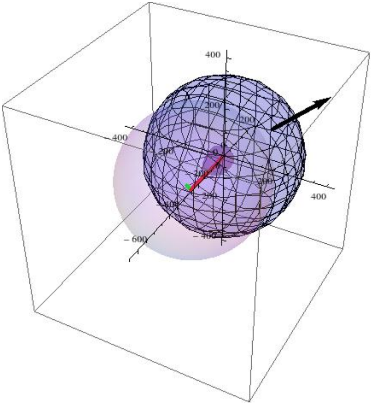


# Modulation 102

Event rate $\frac{dR}{dE}(t)$ proportional to integral of

$$\frac{f(\mathbf{v},t)}{v}$$

integrated over $v \geq v_{\text{min}}(E)$



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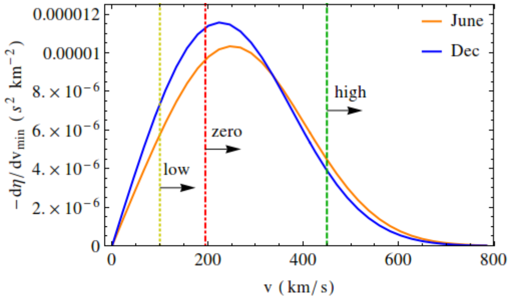

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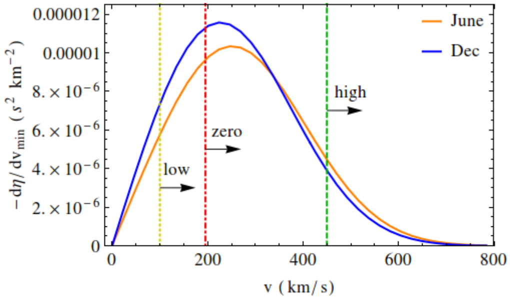


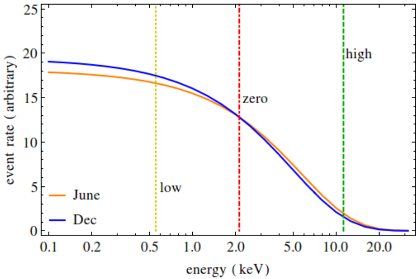

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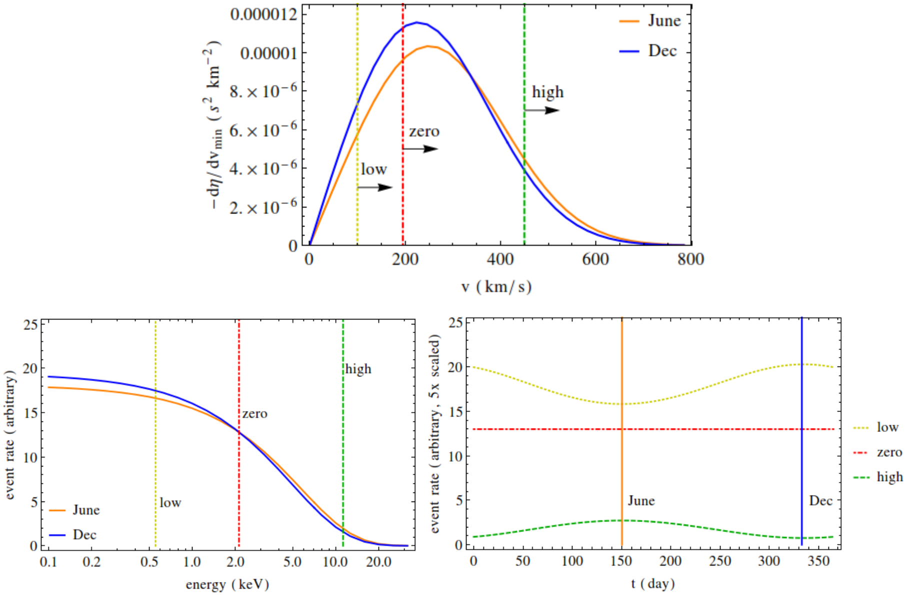
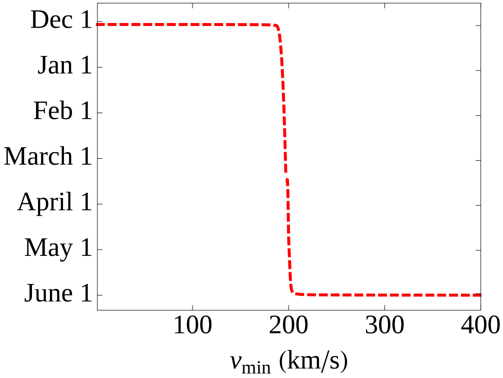
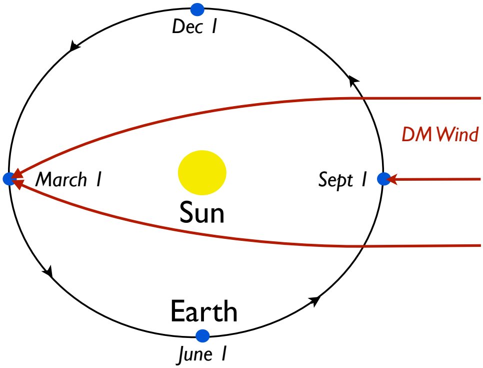


Phase of the modulation flips: maximum of event rate in December (June) at low (high) $v_{\min}$



Sun's gravitational potential induces comparable modulation (for slowly moving WIMPs)

$$\bar{A}_1/\bar{A}_0 \sim \epsilon \sim \frac{v_\oplus}{v_\odot} \sim \frac{\sqrt{GM_\odot/R_\oplus}}{v_0}$$

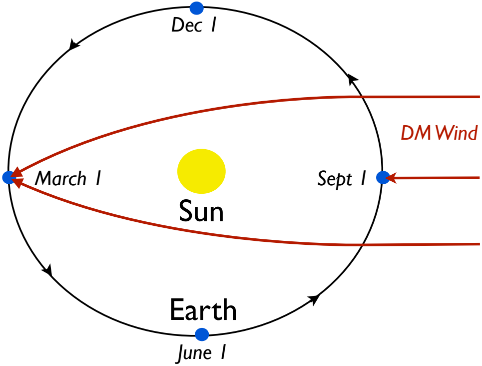



SKL, Mariangela Lisanti, Annika Peter, Ben Safdi 2013

# Modulation 201: Gravitational Focusing

**joepoppa** January 6, 2014, 2:35 PM

At long last, we know something definite about dark matter: it hibernates, during the winter. That, alone, should yield a wealth of clues. I think the reason dark matter is most noticeable, come March, is that long hibernation has made it VERY hungry. What they should now do is launch a thorough investigation into bear hibernation, and that might afford more clues into dark matter hibernation.




SKL, Mariangela Lisanti, Annika Peter, Ben Safdi 2013

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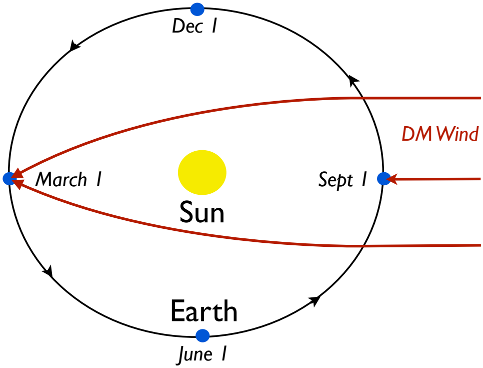
Non-Galilean transformation relates lab and galactic frames

$$f(\mathbf{v}, t) = g(\mathbf{v}_\infty[\mathbf{v} + \mathbf{v}_\oplus(t), t] + \mathbf{v}_\odot)$$

$$\mathbf{v}_\infty[\mathbf{v_s}, t] = \frac{v_\infty^2 \mathbf{v_s} + v_\infty (G\,M_\odot / r_s)\hat{\mathbf{r}}_\mathbf{s} - v_\infty \mathbf{v_s}(\mathbf{v_s} \cdot \hat{\mathbf{r}}_\mathbf{s})}{v_\infty^2 + G\,M_\odot / r_s - v_\infty(\mathbf{v_s} \cdot \hat{\mathbf{r}}_\mathbf{s})}$$




Alenazi and Gondolo 2006

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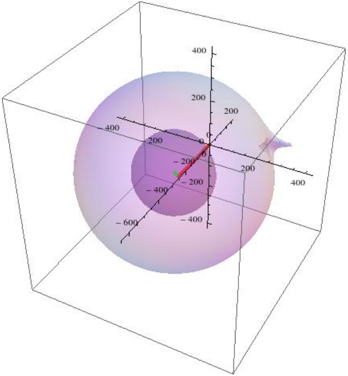

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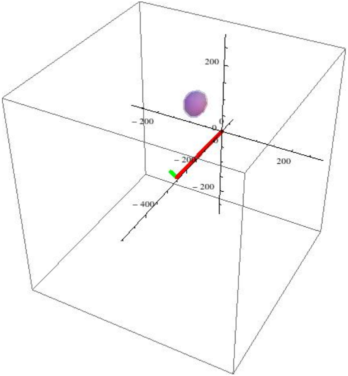
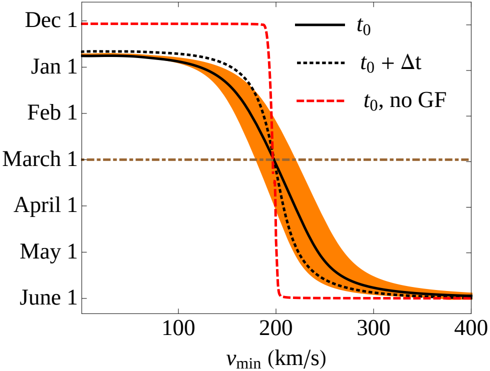


Gravitational focusing results in an
ENERGY-DEPENDENT MODULATION PHASE



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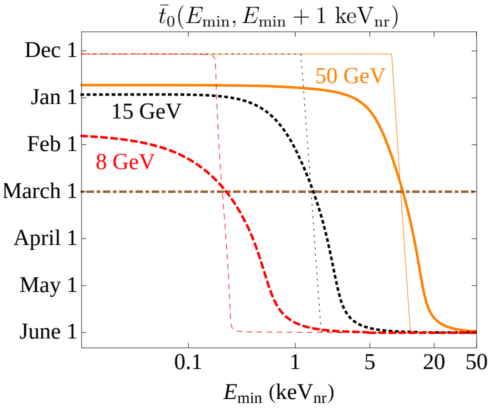


Smoking gun 2.0 – but low energy thresholds required!

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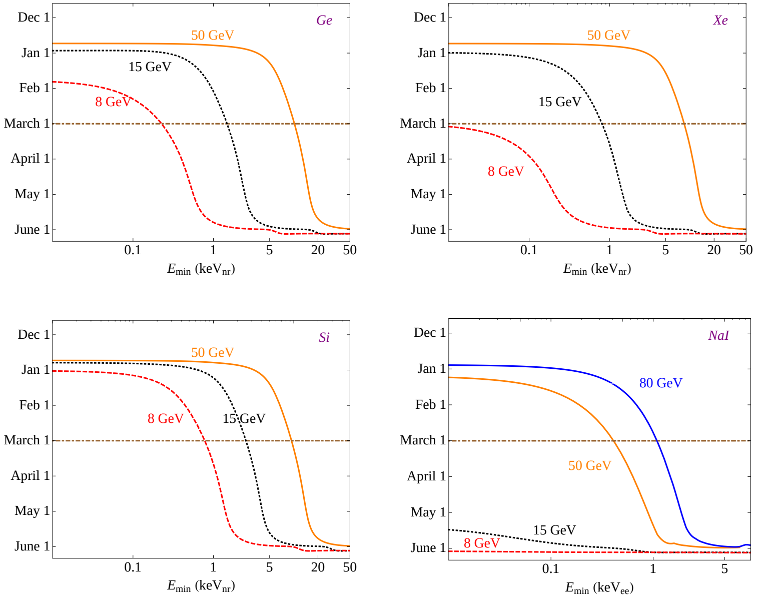
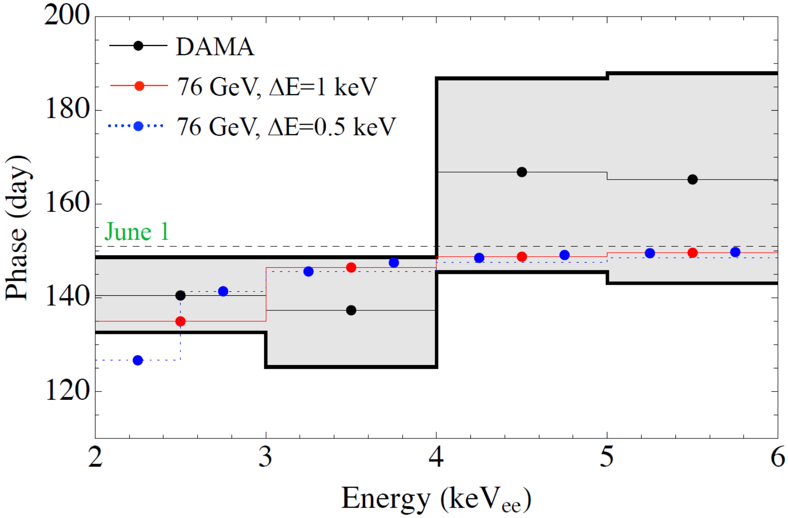
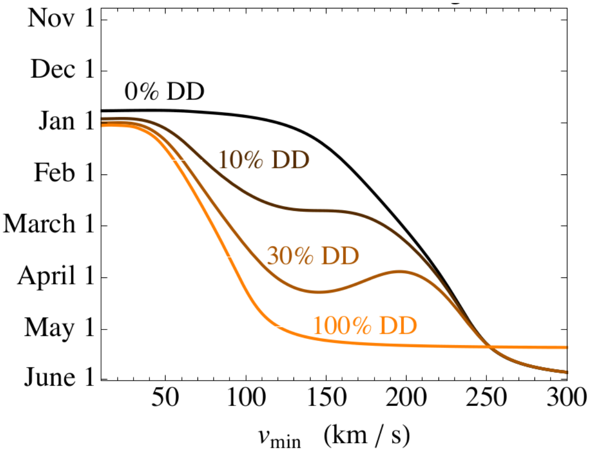


GF may already be important for 80 GeV DAMA ROI



# Modulation 201: GF and Dark Disk

Co-rotating dark-disk scenarios with slowly moving WIMPs will be especially sensitive to GF

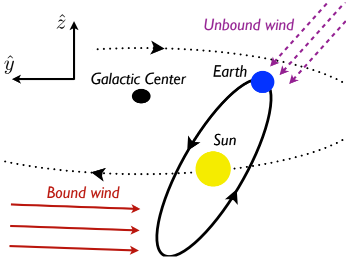


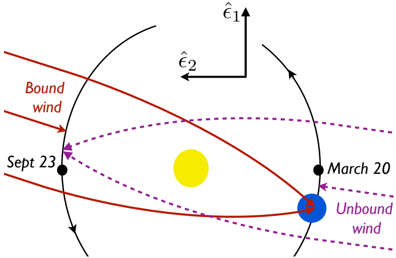

SKL, Lisanti, Peter, Safdi in prep

# Modulation 201: GF and Cosmic Neutrinos

GF is solely responsible for modulation of cosmic neutrinos, which may be detected via velocity-independent capture

$$\nu_e + N \to N' + e$$




Safdi, Lisanti, Spitz, Formaggio 2014

# Modulation 201: Higher Harmonics

Higher modes are generically present, but suppressed by $\epsilon = \frac{v_\oplus}{4v_\odot}$
Circular orbit usually assumed, leading to cosine expansion

$$\frac{dR}{dE}(t) = A_0(E) + \sum_n A_n(E)\cos[n\omega(t - t_{\max})]$$

with $A_n/A_0 \sim \epsilon^n$ and $MT(A_n)/MT(A_0) \sim \epsilon^{-2n}$

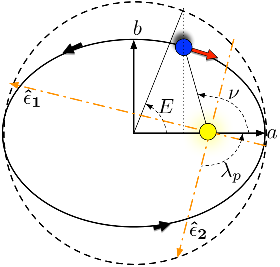
SKL, Lisanti, Safdi 2013

# Modulation 201: Higher Harmonics

Consistent expansion should include eccentricity $e = 0.017 \sim \epsilon$
Elliptical orbit (correcting Lewin and Smith 1996) leads to

$$\frac{dR}{dE}(t) = A_0(E) + \sum_n A_n(E)\cos[n\omega(t - t_{\max})] + \sum_n B_n(E)\sin[n\omega(t - t_{\max})]$$

with $B_n/A_0 \sim \epsilon^n$ and $MT(B_n)/MT(B_0) \sim \epsilon^{-2n}$ (except $n = 1$)



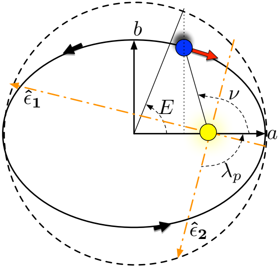

SKL, Lisanti, Safdi 2013

# Modulation 201: Higher Harmonics

Harmonic structure is typically related to orbital parameters

$$\frac{B_1(E)}{A_1(E)} \approx 2e\sin(\lambda_p - w\phi) \approx \frac{1}{59}$$

$$\frac{B_2(E)}{B_1(E)} \approx \frac{1}{2}$$




SKL, Lisanti, Safdi 2013

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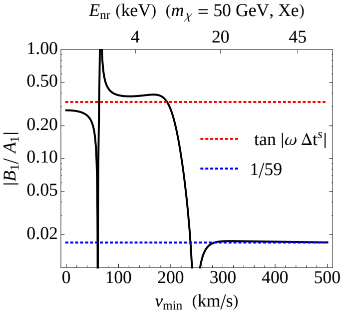
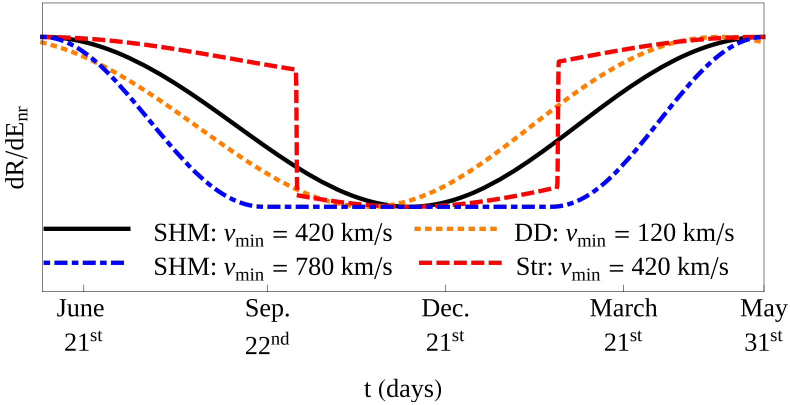
Relations can be used to test presence of velocity substructure




SKL, Lisanti, Safdi 2013

# Modulation 201: Higher Harmonics

Higher harmonics can be enhanced in various scenarios



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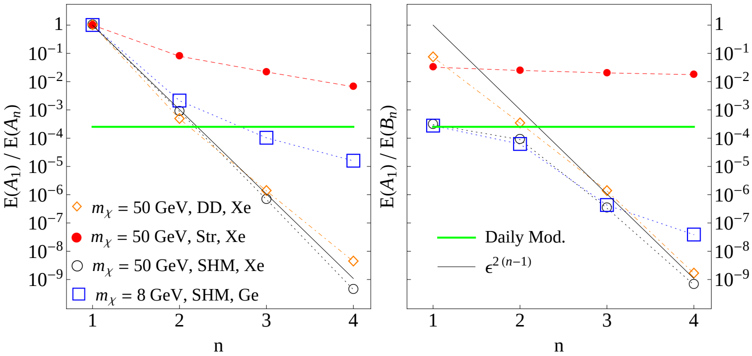

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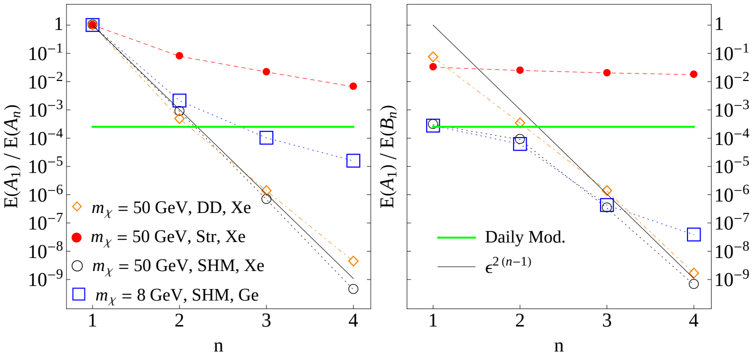


Orbit of the earth and DM velocity distribution both leave UNIQUE IMPRINT ON HARMONIC STRUCTURE

# Conclusion

- Confusion surrounding hints of signals motivates a more detailed consideration of modulation
- Higher-order effects can be powerful and informative discriminators
  - Gravitational focusing by sun $\rightarrow$ energy-dependent phase
  - Details of earth's orbit $\rightarrow$ structure of higher harmonics
- Low thresholds (GF) or large exposures (harmonics)
- Time dependence provides a key axis (along with directional and material signals) for DM detection and characterization!