Bringing Dark Matter into Focus

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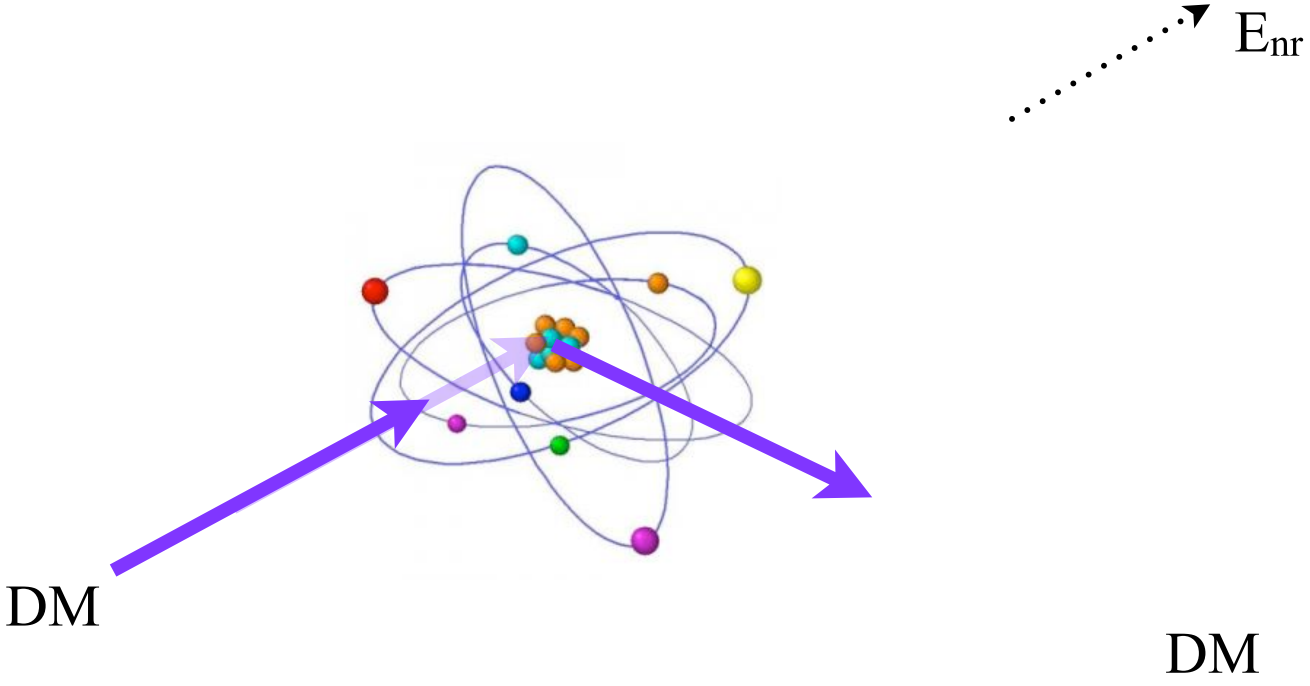
Princeton University

with Joseph Formaggio, Samuel Lee, Annika Peter, Benjamin Safdi,
Siddharth Sharma, and Joshua Spitz

Direct Detection

Dark matter scatters off of nuclei in detectors

Measure recoil energy of nuclei



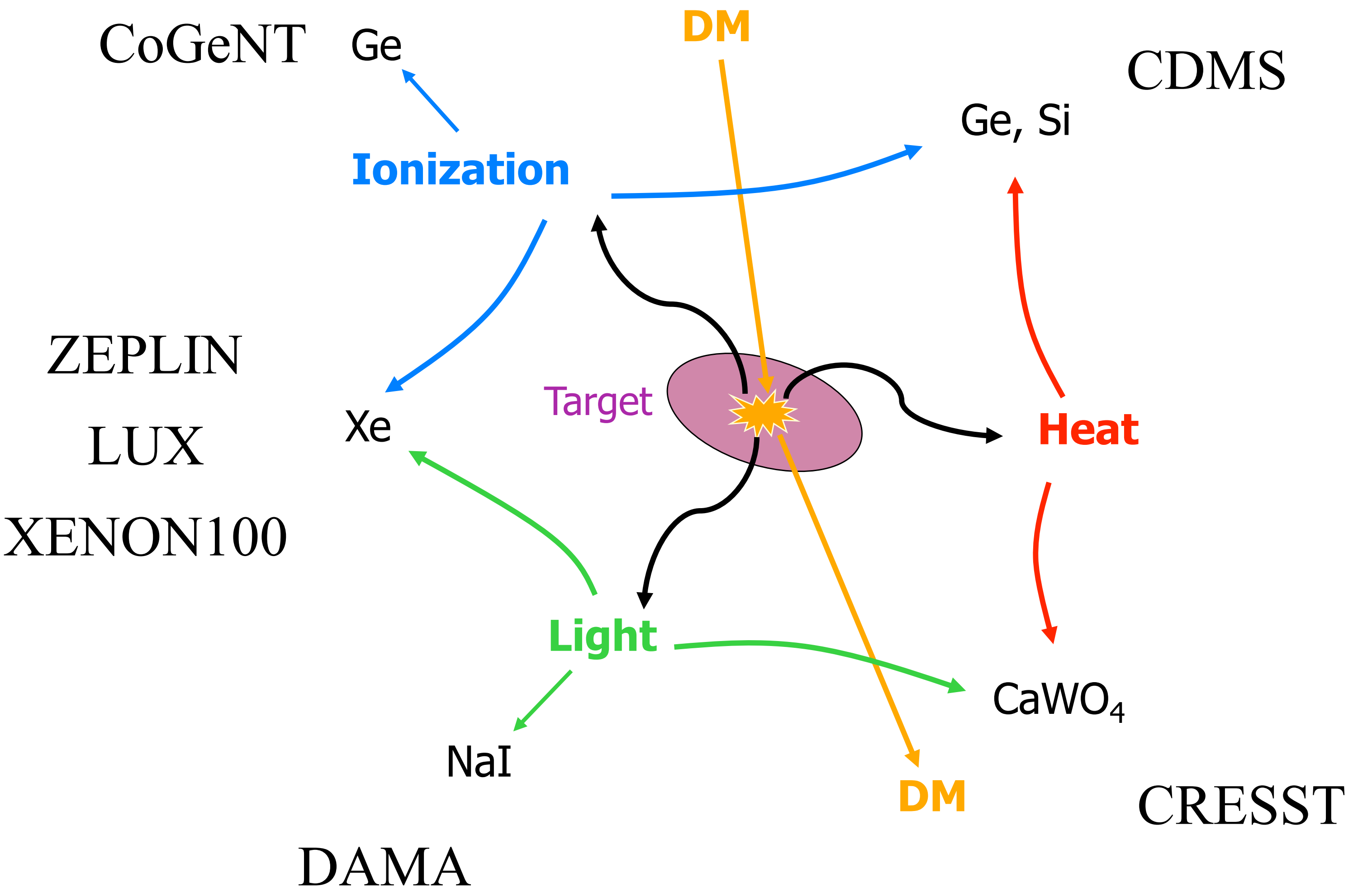
E_{nr}

DM

DM

Direct Detection

Several different strategies for detecting recoil energy

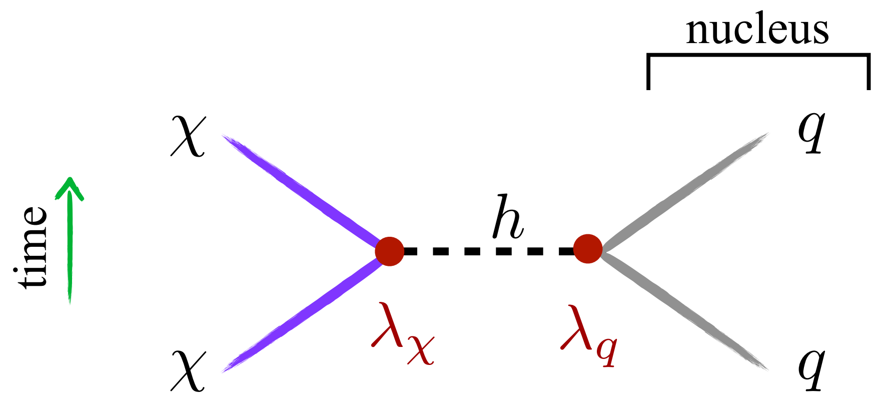


CoGeNT
Ge
DM
CDMS
Ge, Si
Ionization
ZEPLIN
LUX
XENON100
Xe
Target
Heat
Light
$CaWO_4$
NaI
DM
CRESST
DAMA

From: Véronique Sanglard (La Thuille 2005)

Scattering Cross Section

Example: spin-independent interaction due to Higgs exchange

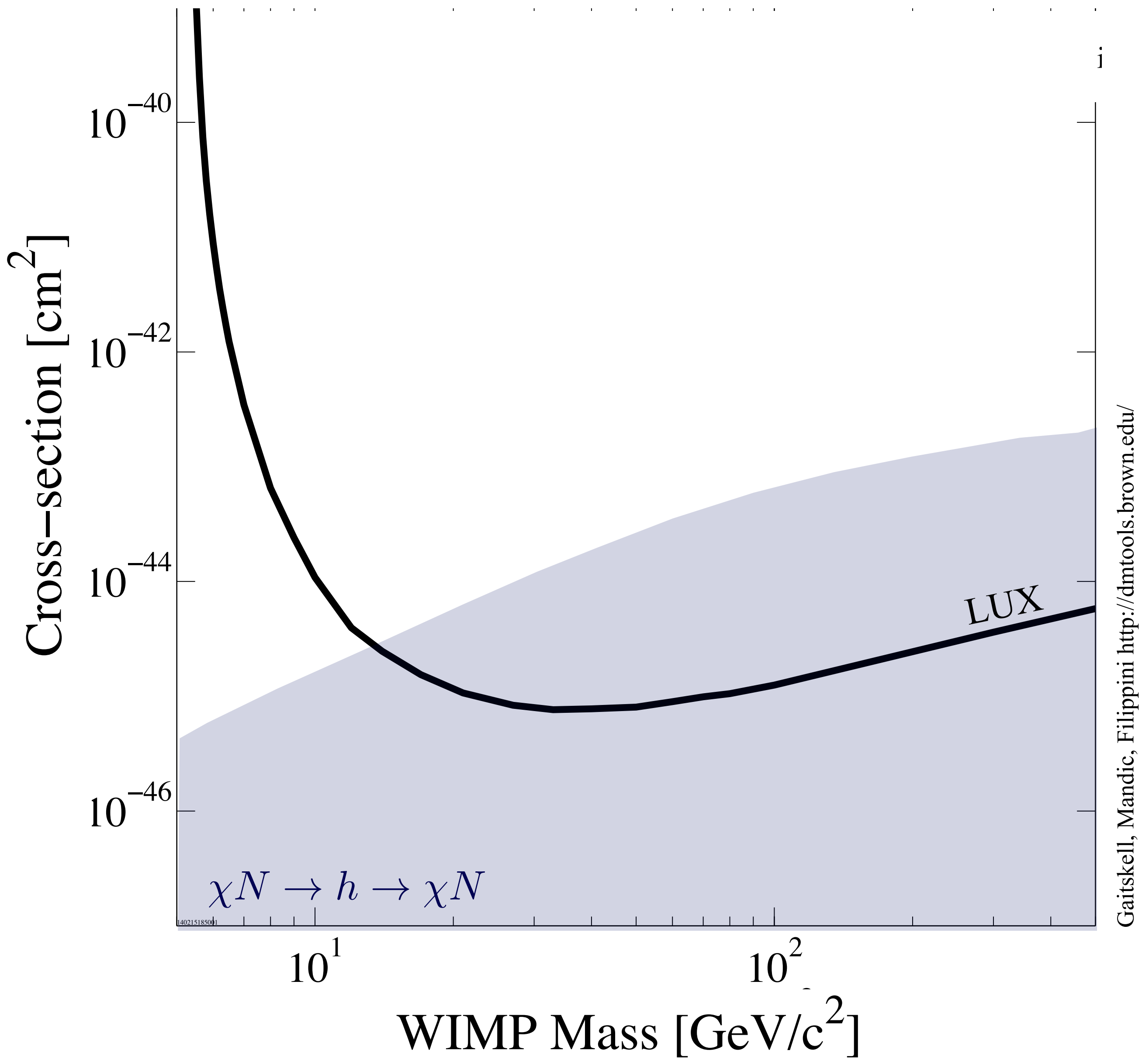


$$\sigma_{\chi N \to \chi N} \simeq \frac{\lambda_\chi^2 \lambda_q^2}{4 m_h^4} \cdot \mu_{\chi N}^2$$

$$\sim (7 \times 10^{-44} \text{ cm}^2) \cdot \lambda_\chi^2$$

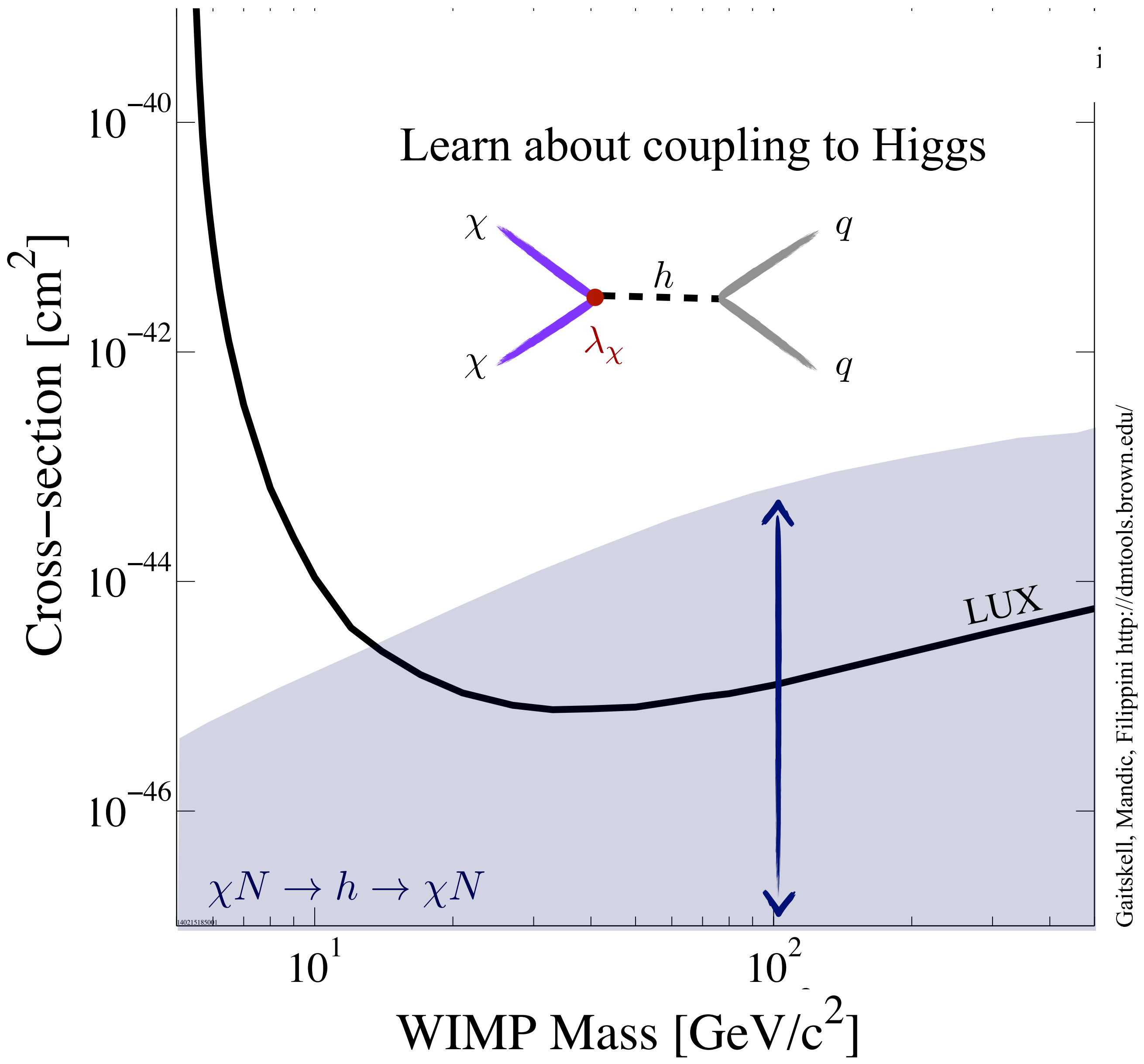
for Xe target, 125 GeV Higgs,
100 GeV DM

Spin-Independent Limit



LUX Collaboration [1310.8214]

Spin-Independent Limit



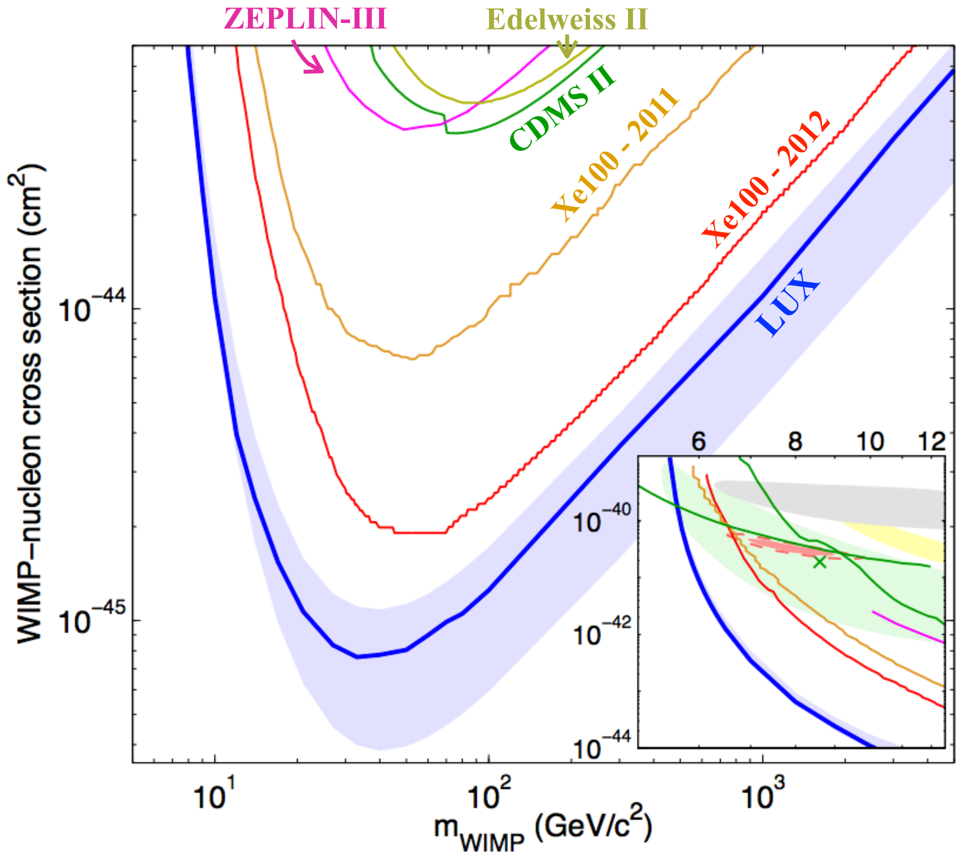
Learn about coupling to Higgs

Gaitskell, Mandic, Filippini http://dmtools.brown.edu/

LUX Collaboration [1310.8214]

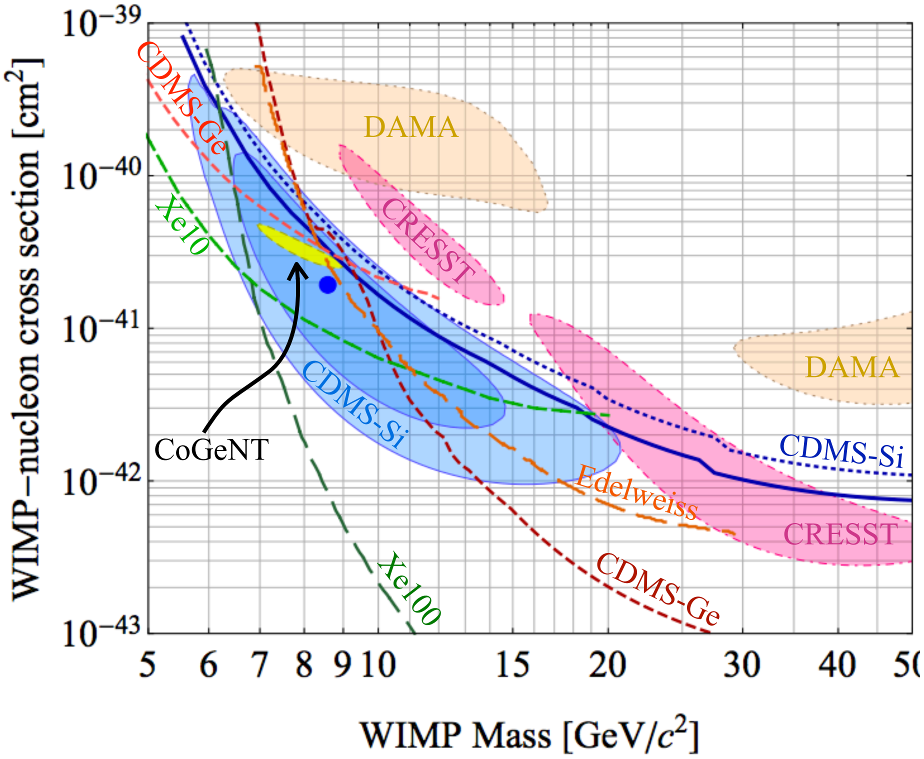
Experimental Status

Probing the Higgs-Exchange Region



LUX Collaboration [1310.8214]

Low-Mass Anomalies



CDMS Collaboration [1304.4279]

Direct Detection Signals

Total Rate

Annual Modulation

Gravitational Focusing

Scattering Rate

For typical spin-independent and -dependent interactions,
the differential scattering rate is given by

Lab-frame velocity distribution

Local DM density

$$\frac{dR}{dE_R} = n_{\rm dm}\left\langle v\frac{d\sigma}{dE_R}\right\rangle \propto \rho\int_{v_{\rm min}}^{\infty}\frac{f(\mathbf{v},t)}{v}d^3v$$

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

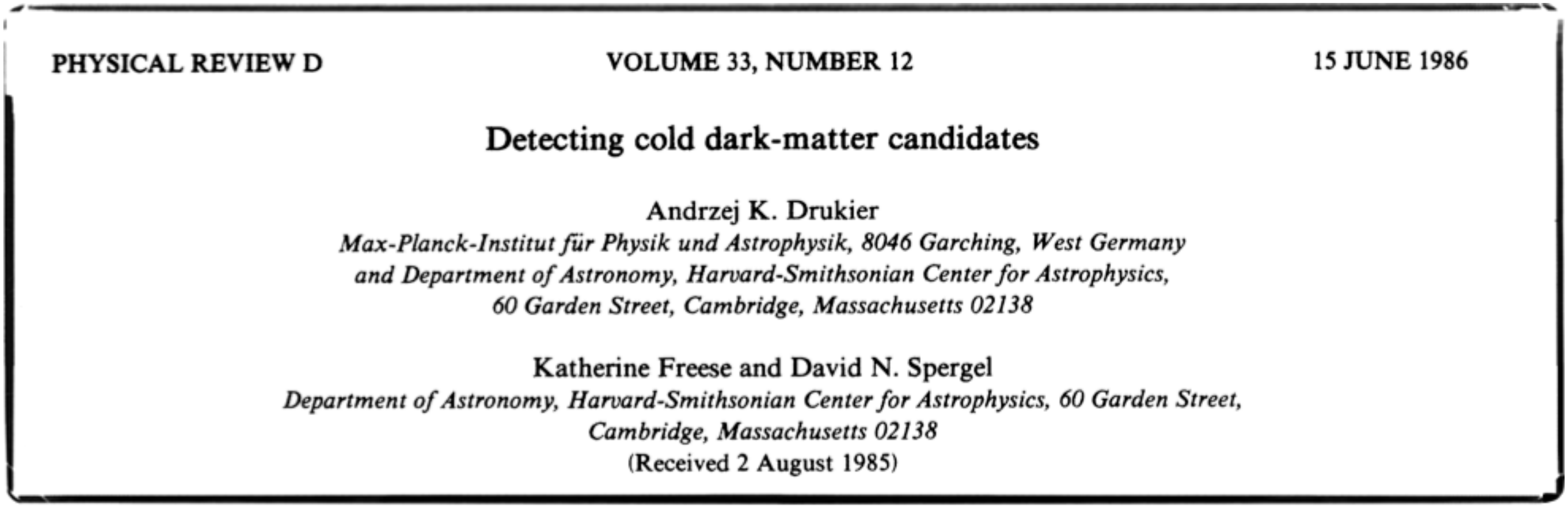
A Spectrum of Possibilities

Smooth Halo

Streams

Fully Virialized ↔ Not Virialized

Smooth Halo



PHYSICAL REVIEW D VOLUME 33, NUMBER 12 15 JUNE 1986

Detecting cold dark-matter candidates

Andrzej K. Drukier
*Max-Planck-Institut für Physik und Astrophysik, 8046 Garching, West Germany
and Department of Astronomy, Harvard-Smithsonian Center for Astrophysics,
60 Garden Street, Cambridge, Massachusetts 02138*

Katherine Freese and David N. Spergel
*Department of Astronomy, Harvard-Smithsonian Center for Astrophysics, 60 Garden Street,
Cambridge, Massachusetts 02138*

(Received 2 August 1985)

Proposed a model for the velocity distribution of dark matter

Flat rotation curves imply that density falls off as $1/r^2$

Isotropy + Equilibrium + $\rho \sim r^{-2}$ = Maxwell-Boltzmann

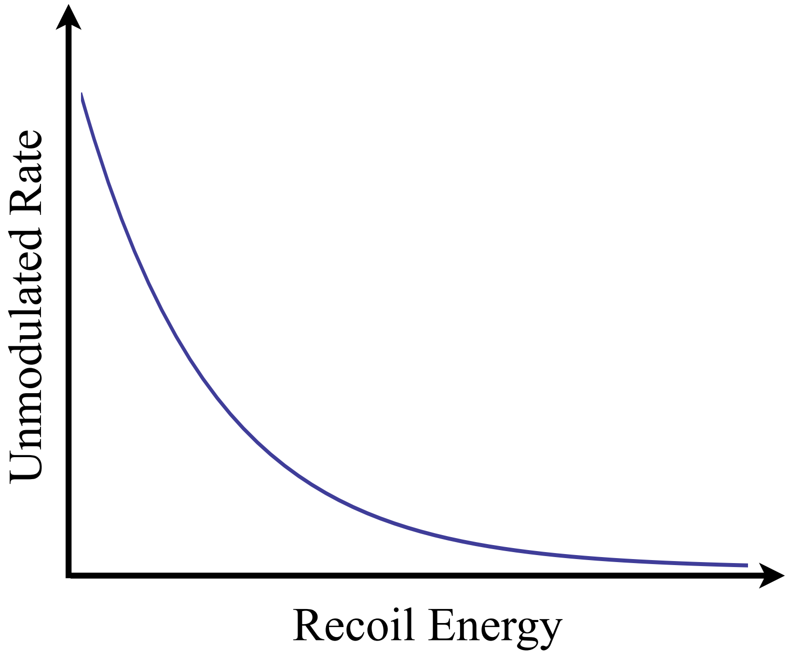
Recoil Spectrum

Average over all possible DM velocities in the galactic halo

$$\frac{dR}{dE_R} \propto \int_{\underbrace{v_{\min}}_{\sqrt{\frac{m_N E_R}{2\mu^2}}}}^{v_{\text{esc}}} d^3v \, \frac{d\sigma}{dE_R} \, v \, \underbrace{e^{-v^2/v_0^2}}_{\text{Maxwell-Boltzmann}} \sim e^{-E_R/E_0}$$

For standard assumptions,
recoil spectrum is exponential

Signal dominates at low recoil energy

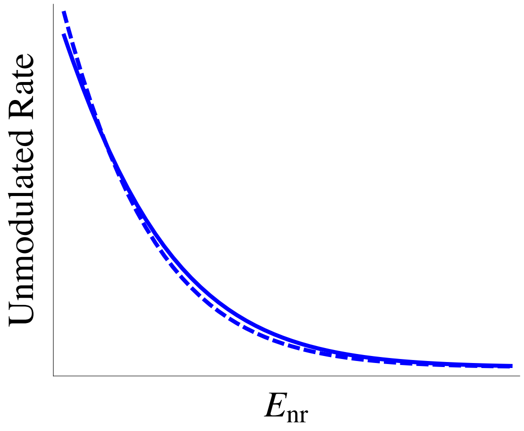


A Spectrum of Possibilities

Smooth Halo

Streams

$$f(\vec{v}) \sim e^{-v^2/v_0^2}$$



Fully Virialized ⟷ Not Virialized

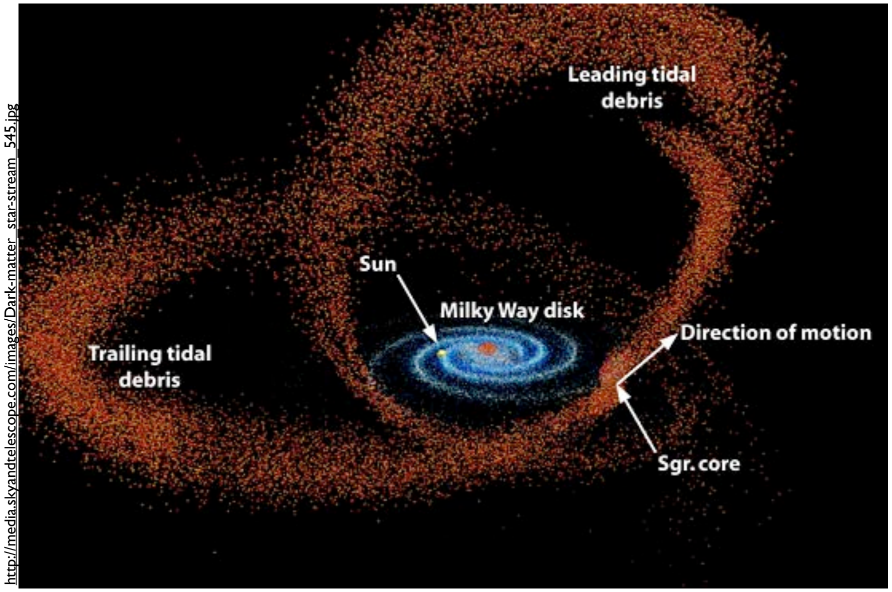
Streams

Trailing tidal debris of infalling subhalos results in ‘streams’ of dark matter

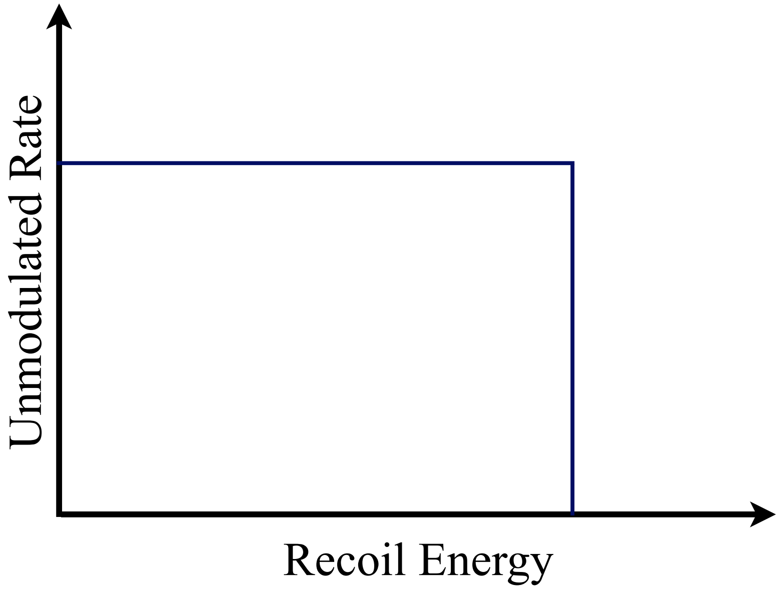
Streams are dynamically cold, have 1D morphology

$$\frac{dR}{dE_R} \propto \int_{v_{\rm min}}^{v_{\rm esc}} d^3v \; \frac{d\sigma}{dE_R} \; v \; \boxed{\delta(\vec{v} - \vec{v}_{\rm stream})}$$

Coherent velocities



http://media.skyandtelescope.com/images/Dark-matter_star-stream_545.jpg



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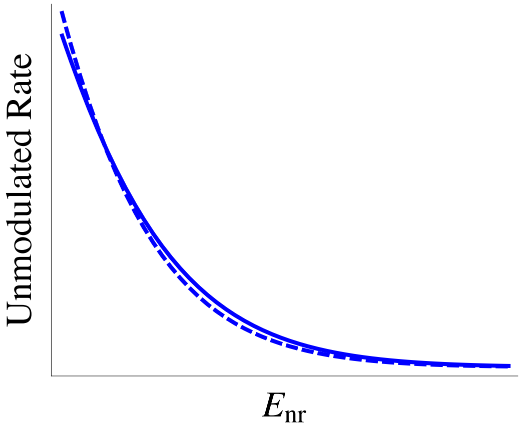
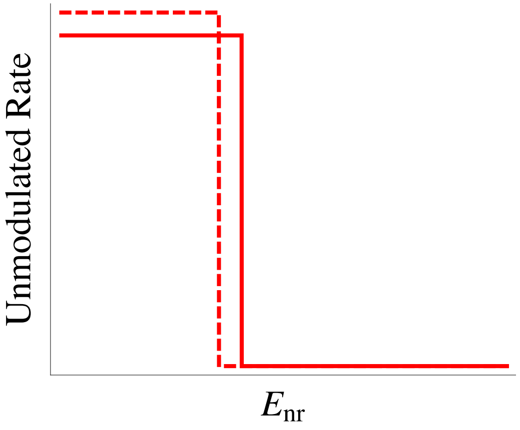


Streams

$$f(\vec{v}) = \delta(\vec{v} - \vec{v}_{\rm stream})$$



Fully Virialized ↔ Not Virialized

Direct Detection Signals

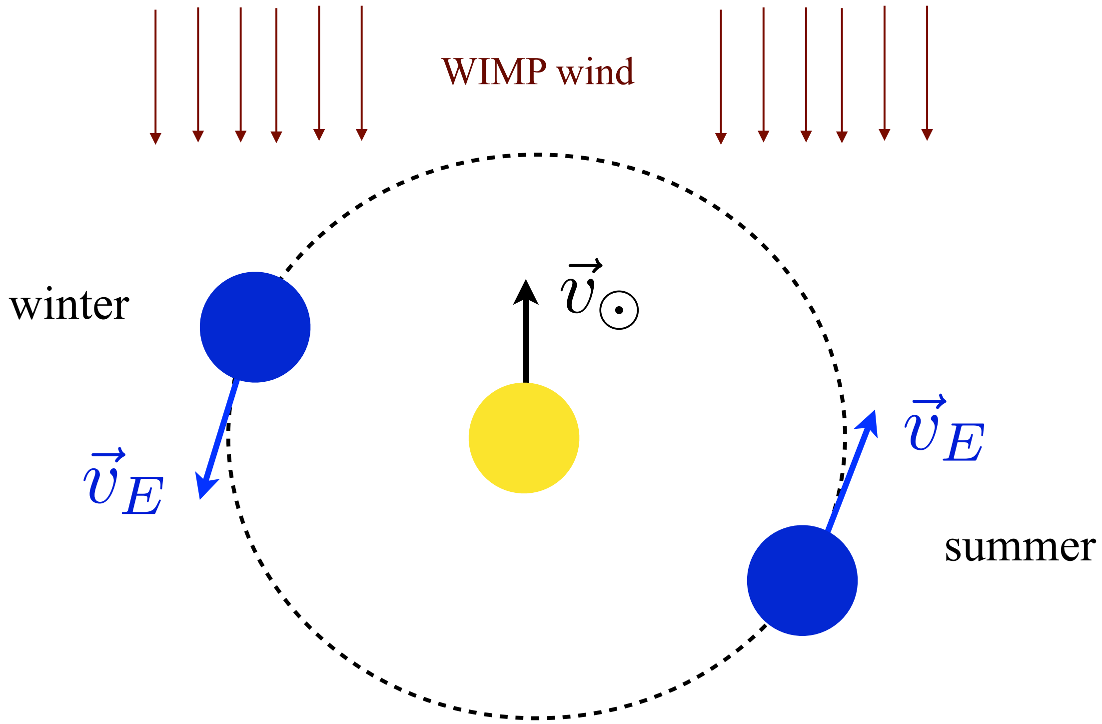
Total Rate

Annual Modulation

Gravitational Focusing

Annual Modulation

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



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

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

Annual Modulation

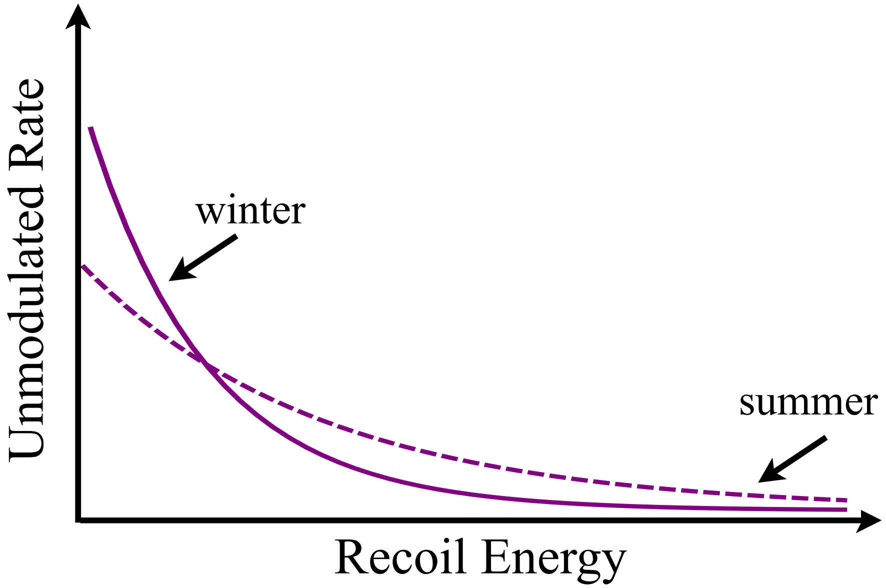
More high-velocity particles in the summer

But, scattering cross section is enhanced for low-velocity particles

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

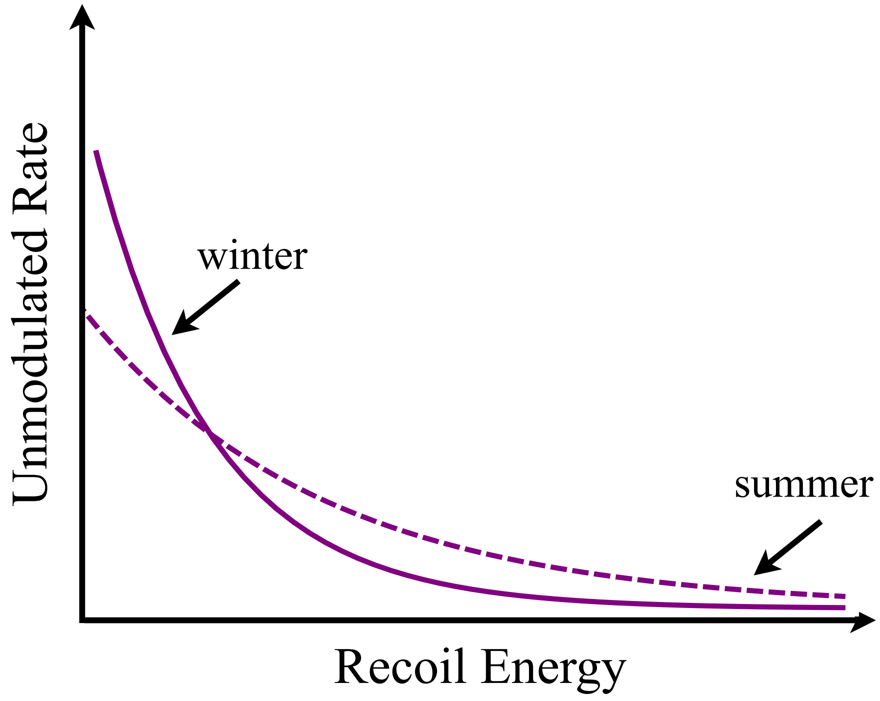
High-energy scattering events have a maximum ~June 1

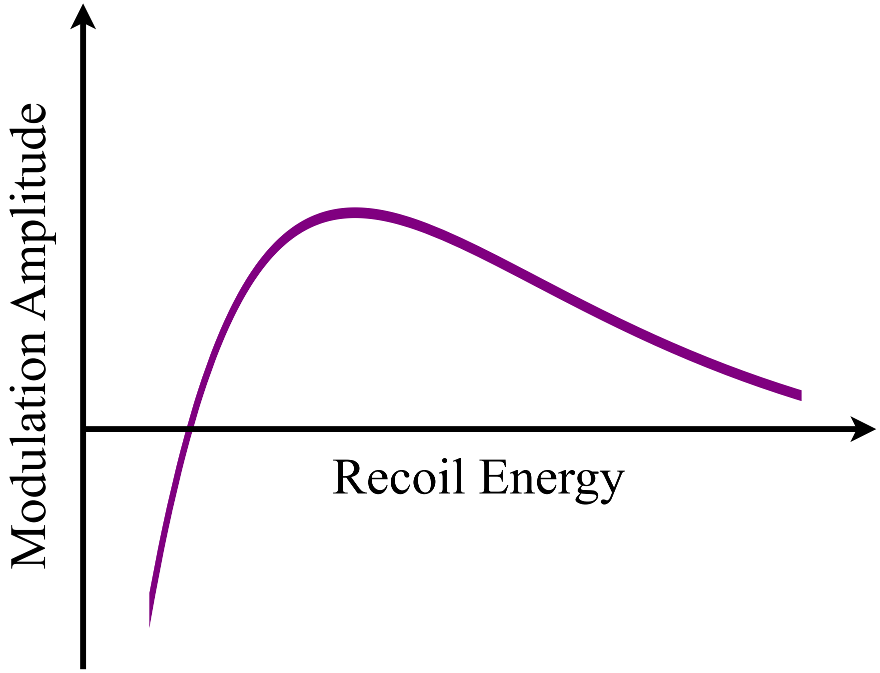
Low-energy events have a maximum ~Dec 1



Modulation Amplitude

$$\text{Amplitude} = \frac{1}{2}(R_{\text{summer}} - R_{\text{winter}})$$





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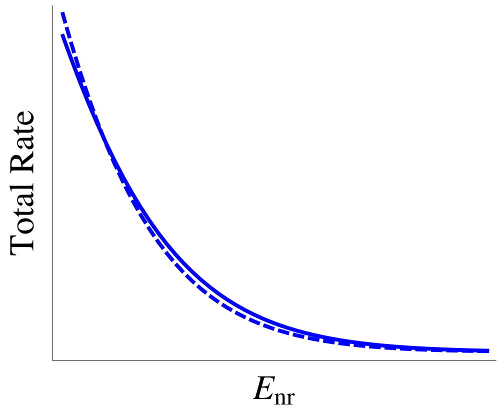
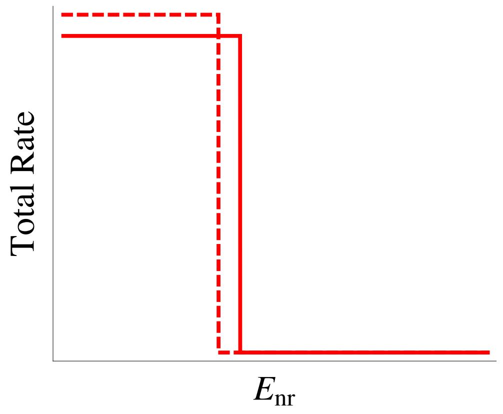


Streams

$$f(\vec{v}) = \delta(\vec{v} - \vec{v}_{\mathrm{stream}})$$



Fully Virialized ↔ Not Virialized

Modulation Spectrum

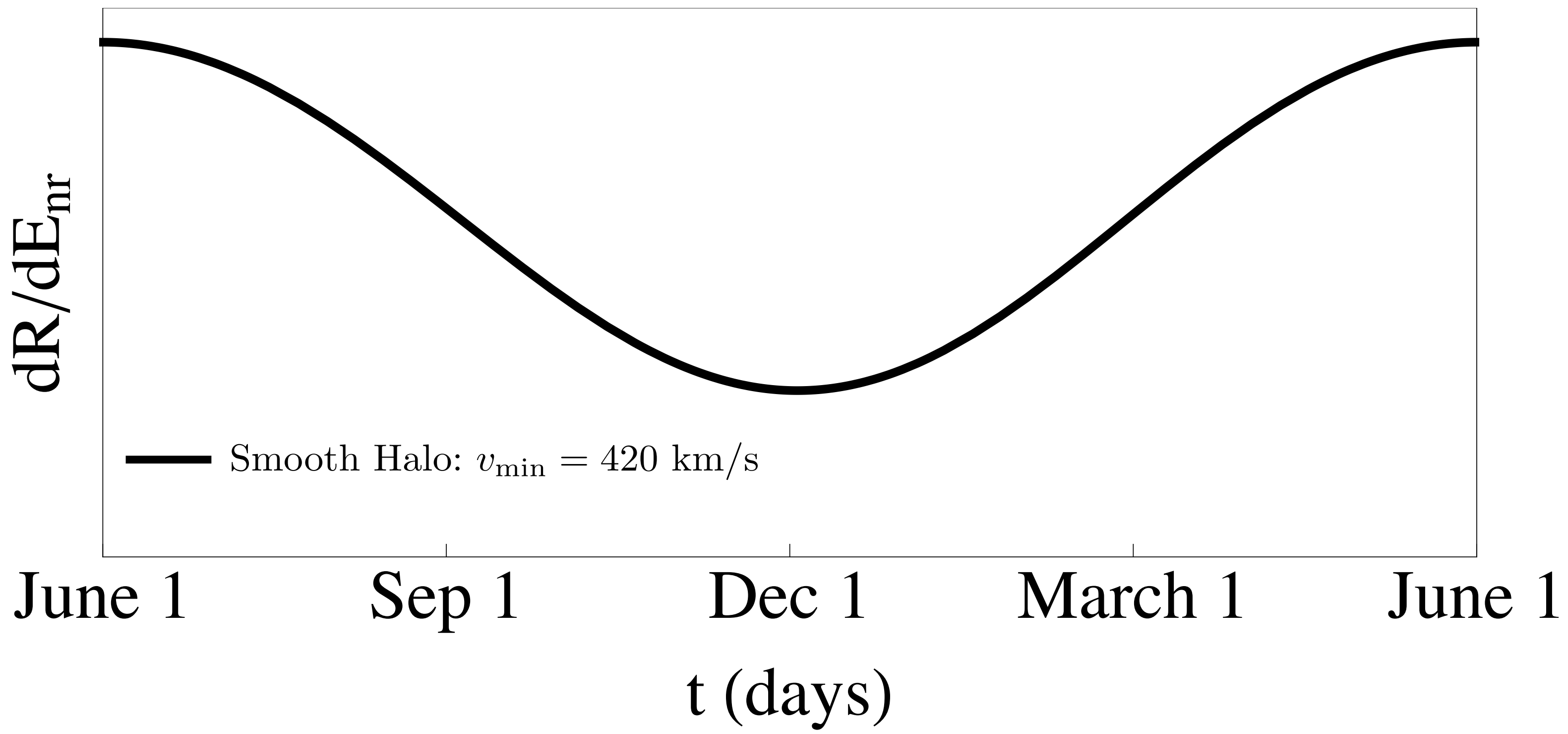
Shape of the modulation also depends on particle properties

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

$m_{\rm DM} \sim 20$ GeV $\quad v_{\rm min} \sim 780$ km/s

$m_{\rm DM} \sim 40$ GeV $\quad v_{\rm min} \sim 420$ km/s

$(E_{\rm nr} = 30 \text{ keV},\ m_n = m_{\rm Xe})$



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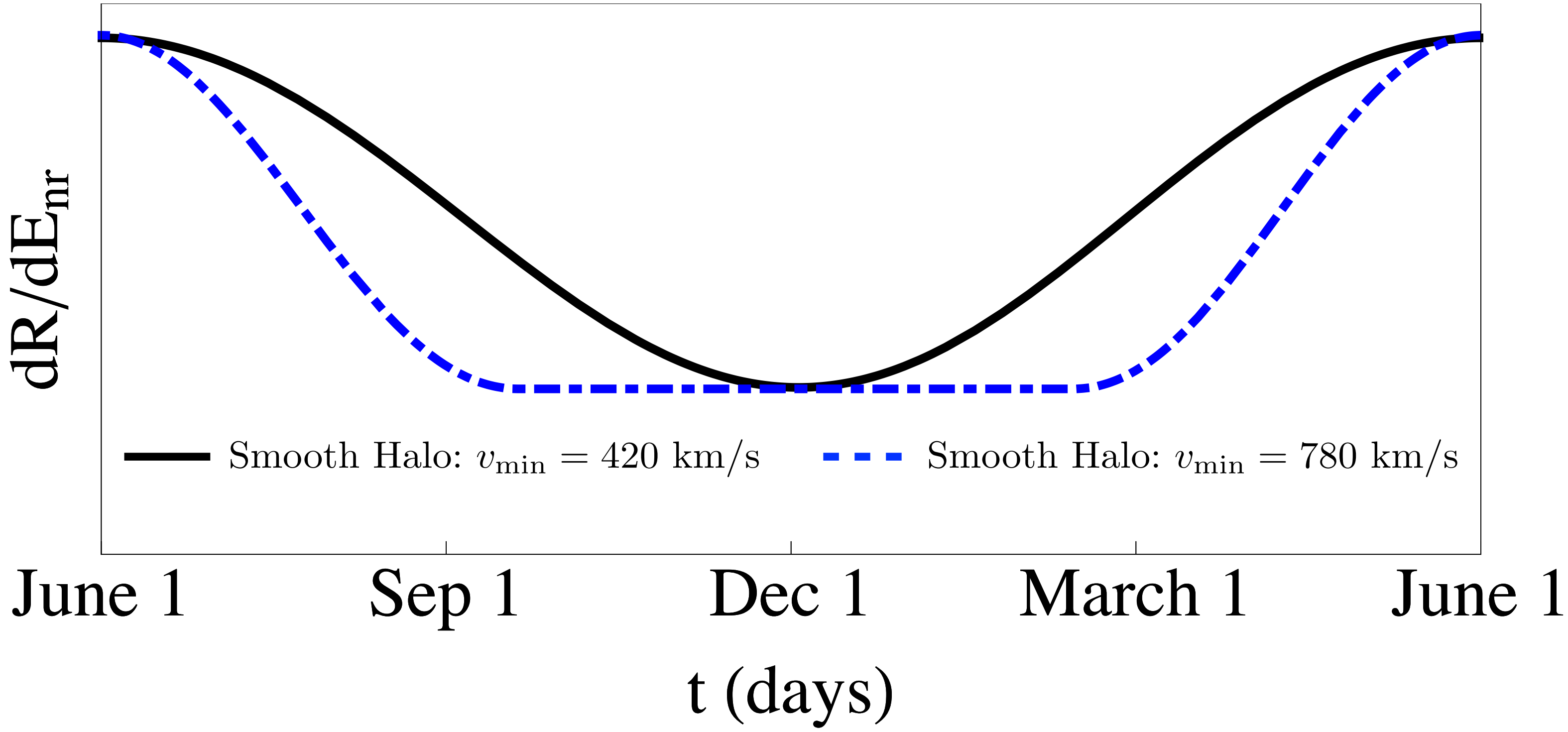

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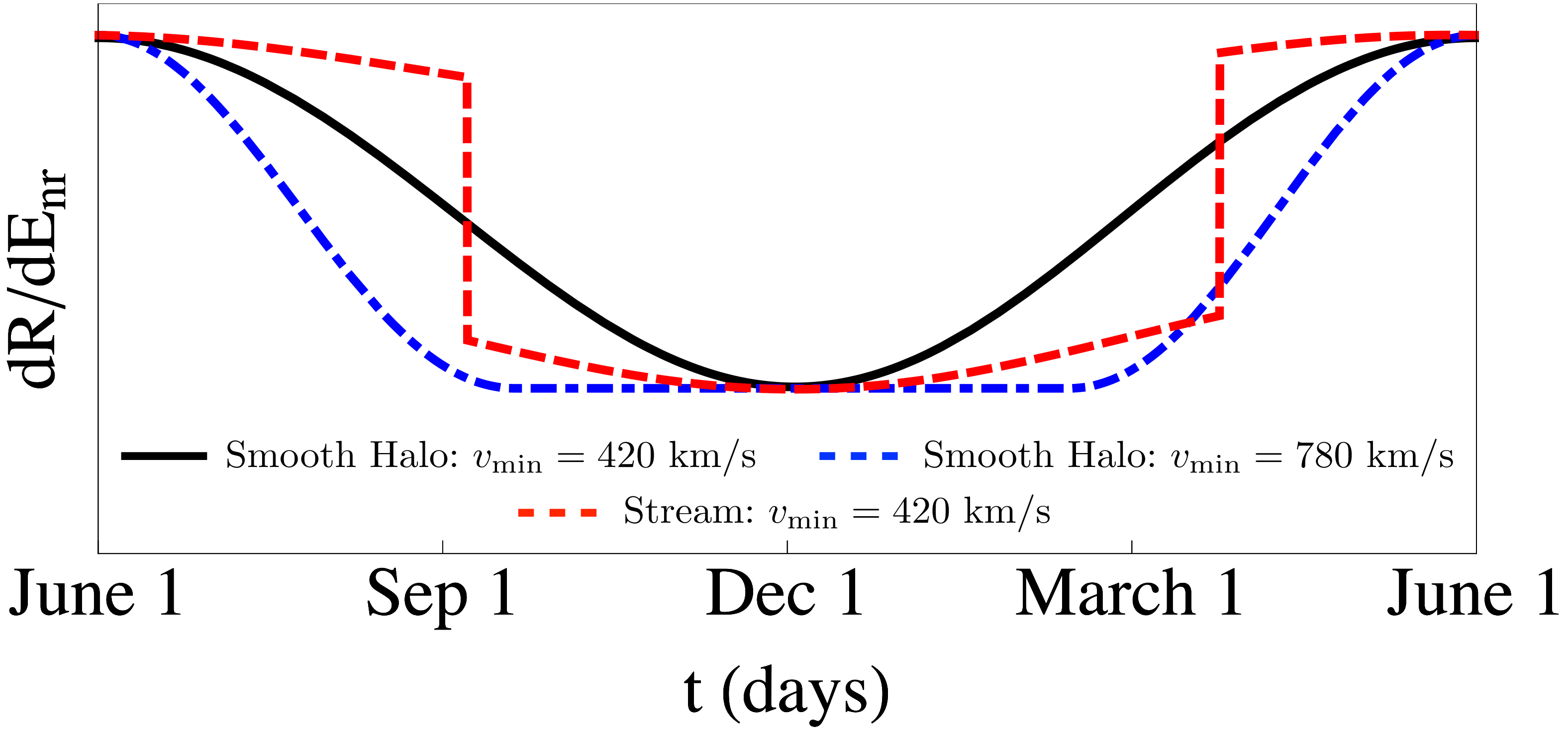


Higher Harmonics

Lee, **ML**, and Safdi [1307.5323]

Expand differential scattering rate in terms of Fourier components

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

Higher Fourier modes are enhanced for

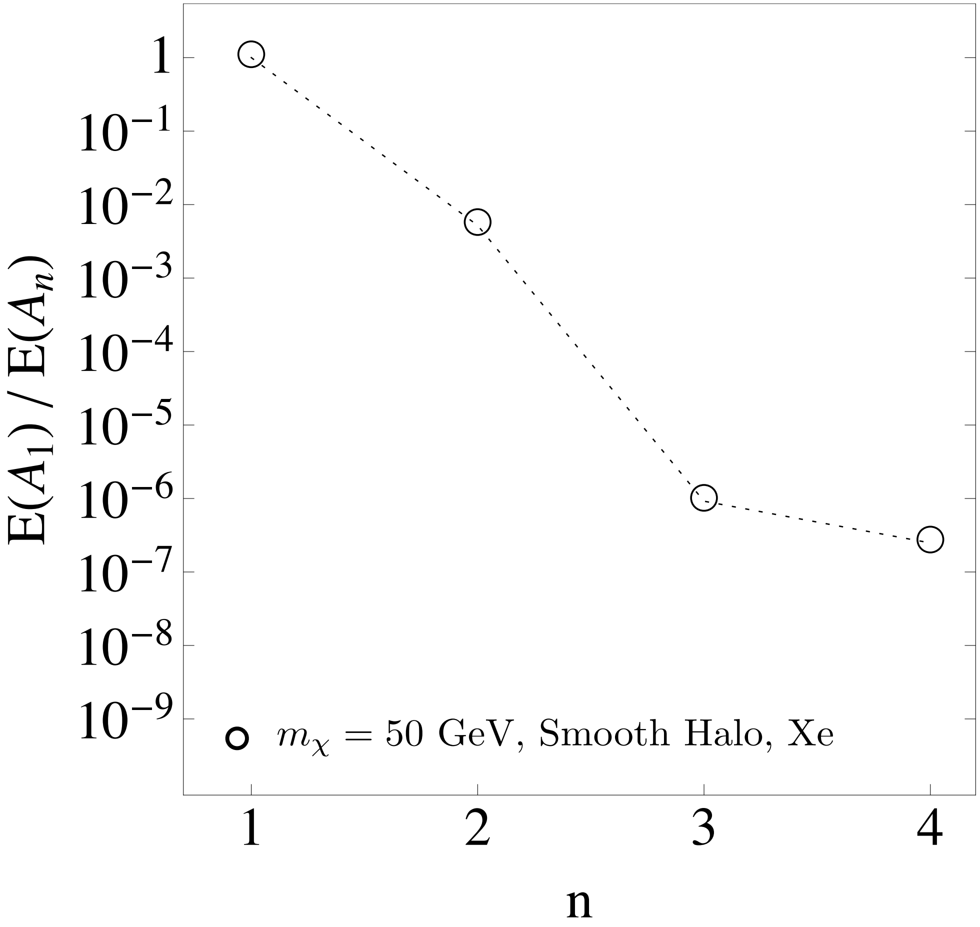
high $v_{\rm min}$ scenarios
(*i.e.*, light DM)

local DM substructure in the halo
(*i.e.*, streams)

Higher Harmonics

Lee, **ML**, and Safdi [1307.5323]

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



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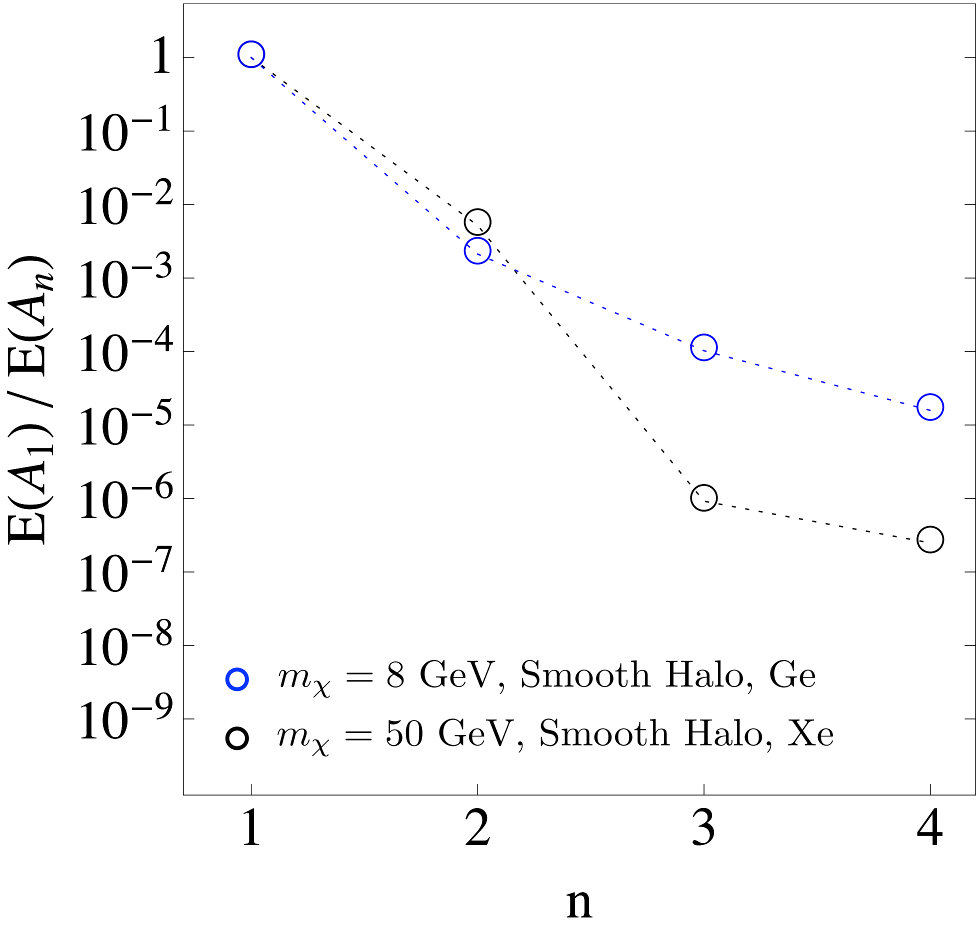

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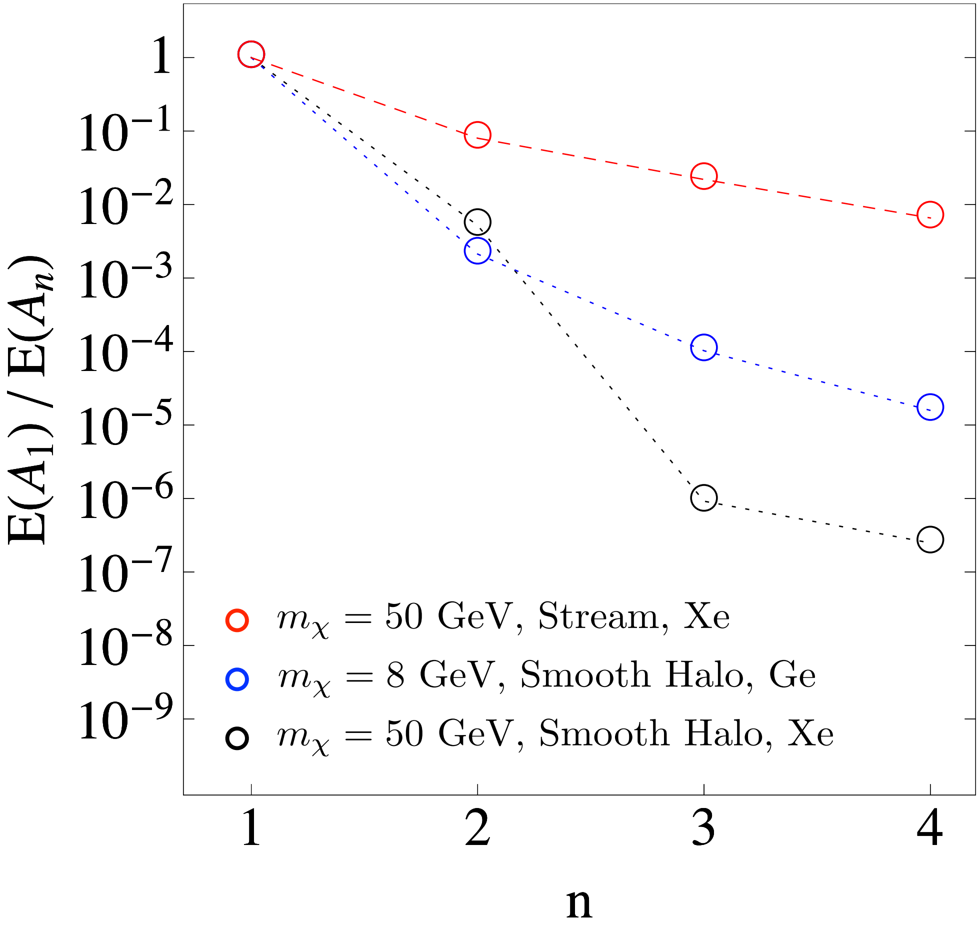
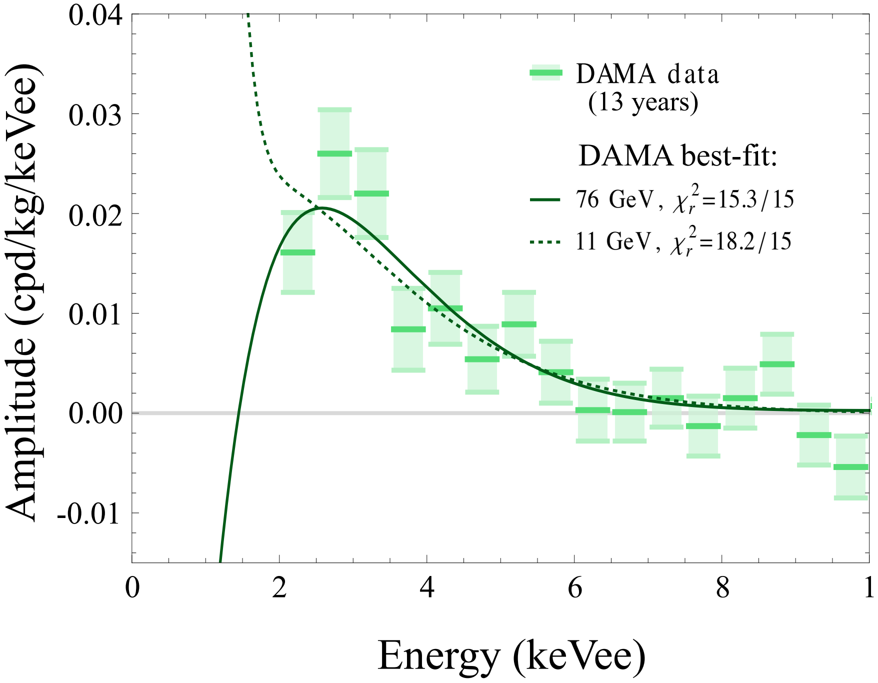


Modulation Anomalies

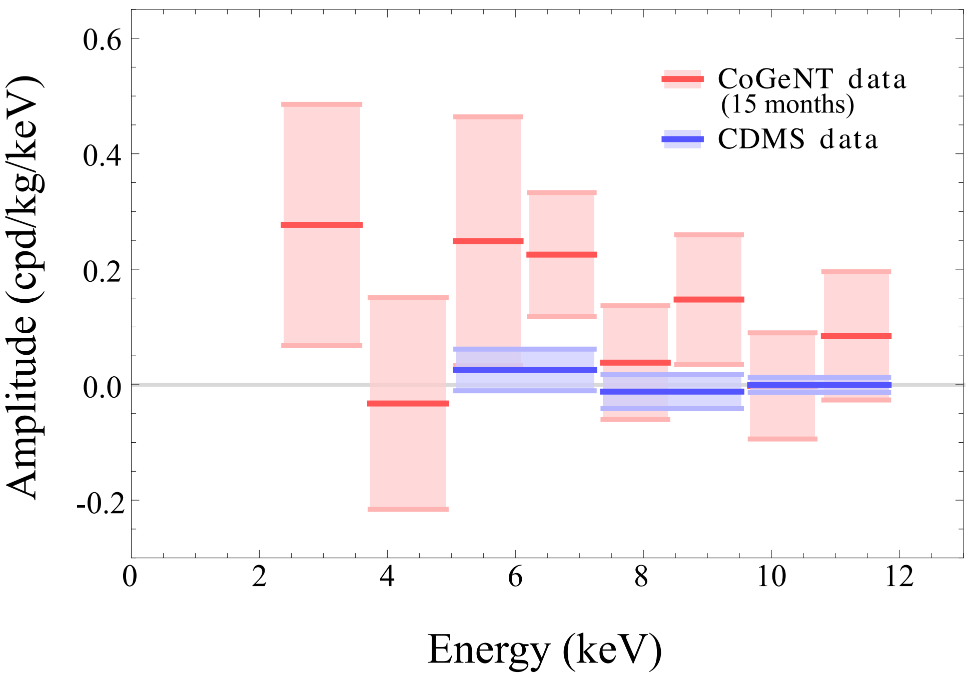
DAMA, 9.3σ

NaI(Tl) target, 14 years of data



CoGeNT, 2.2σ

Ge target, 3.4 years of data



DAMA [astro-ph/0307403, 1002.1028, 1308.5109]; CoGeNT [1106.0650, 1401.3295]; CDMS [1203.1309]

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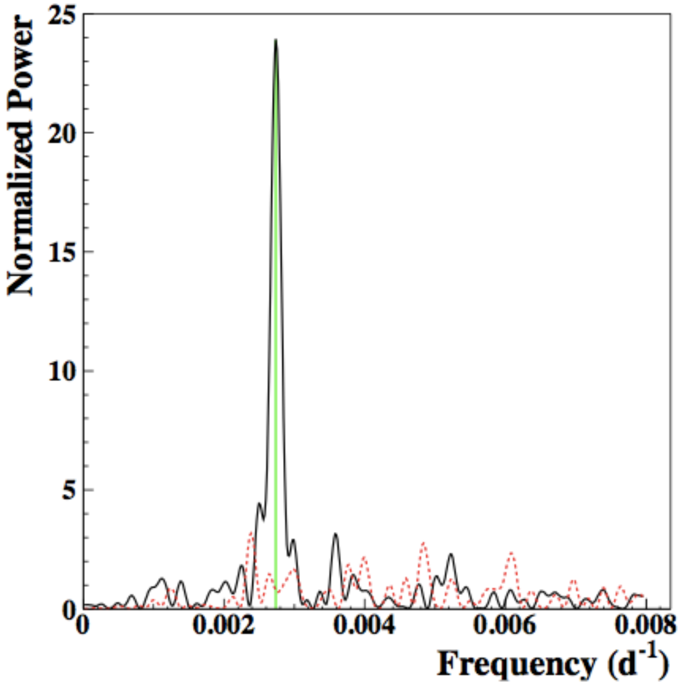

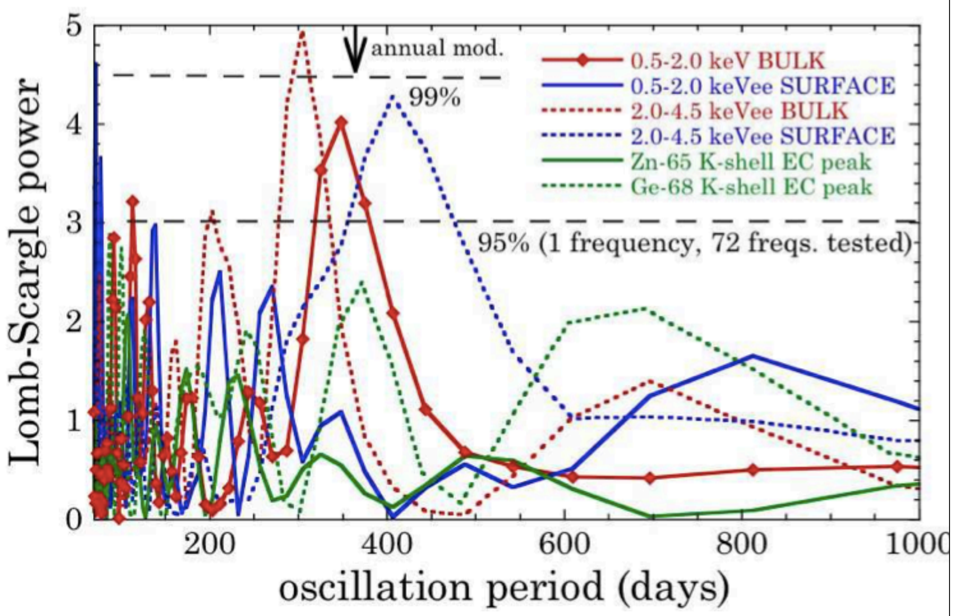

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Direct Detection Signals

Total Rate

Annual Modulation

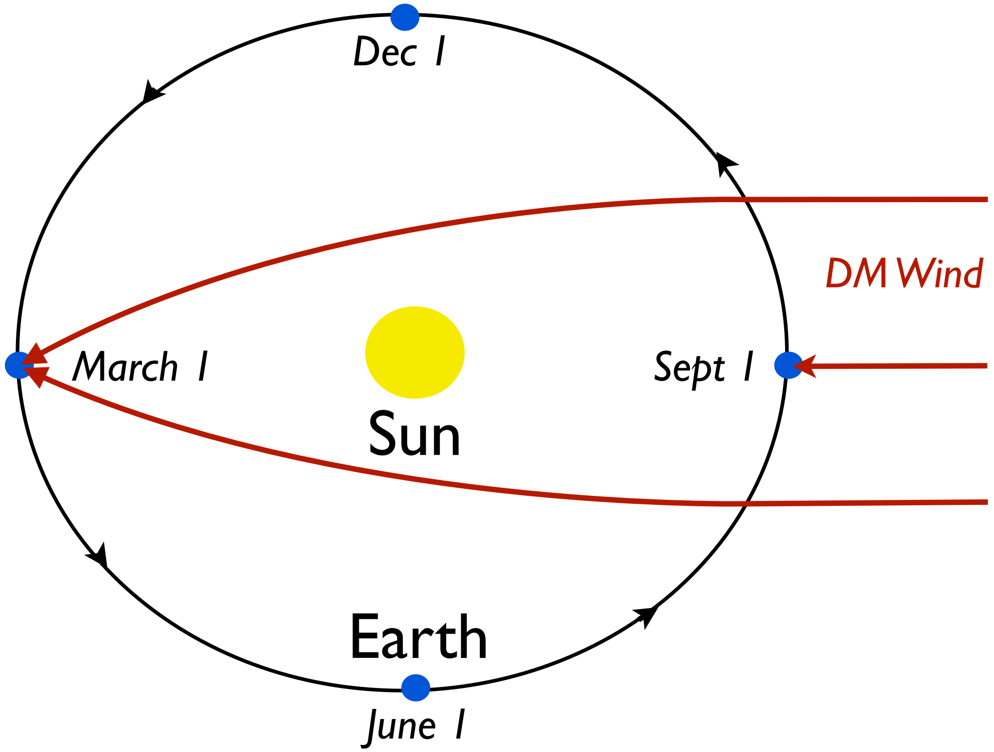
Gravitational Focusing

Gravitational Focusing

Lee, **ML**, Peter, and Safdi [1308.1953]

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

Lee, **ML**, Peter, and Safdi [1308.1953]

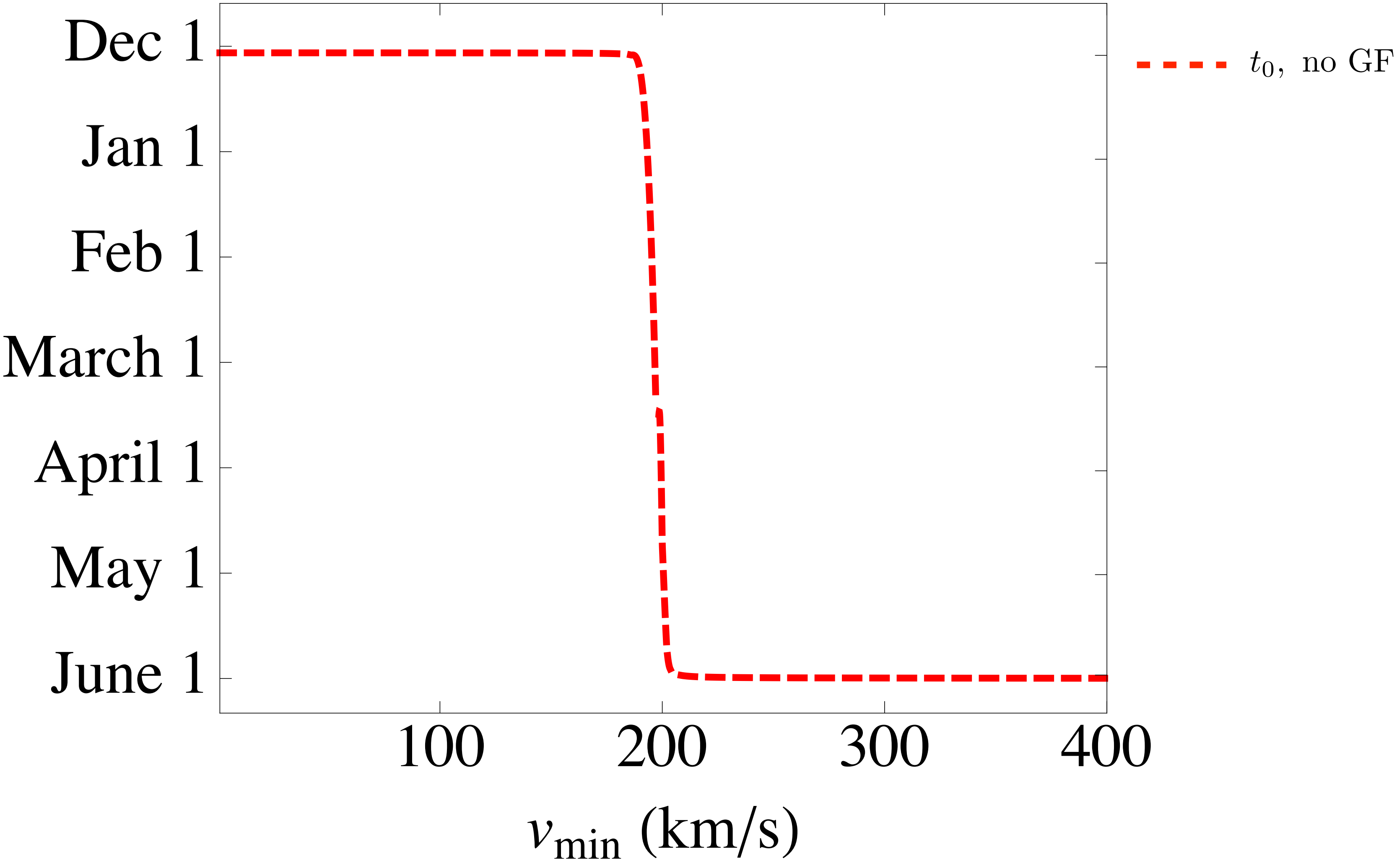
Earth's orbit causes ~3% modulation that is extremized ~June 1

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

A competition between two different modulation effects

Modulation Phase

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



Lee, **ML**, Peter, and Safdi [1308.1953]

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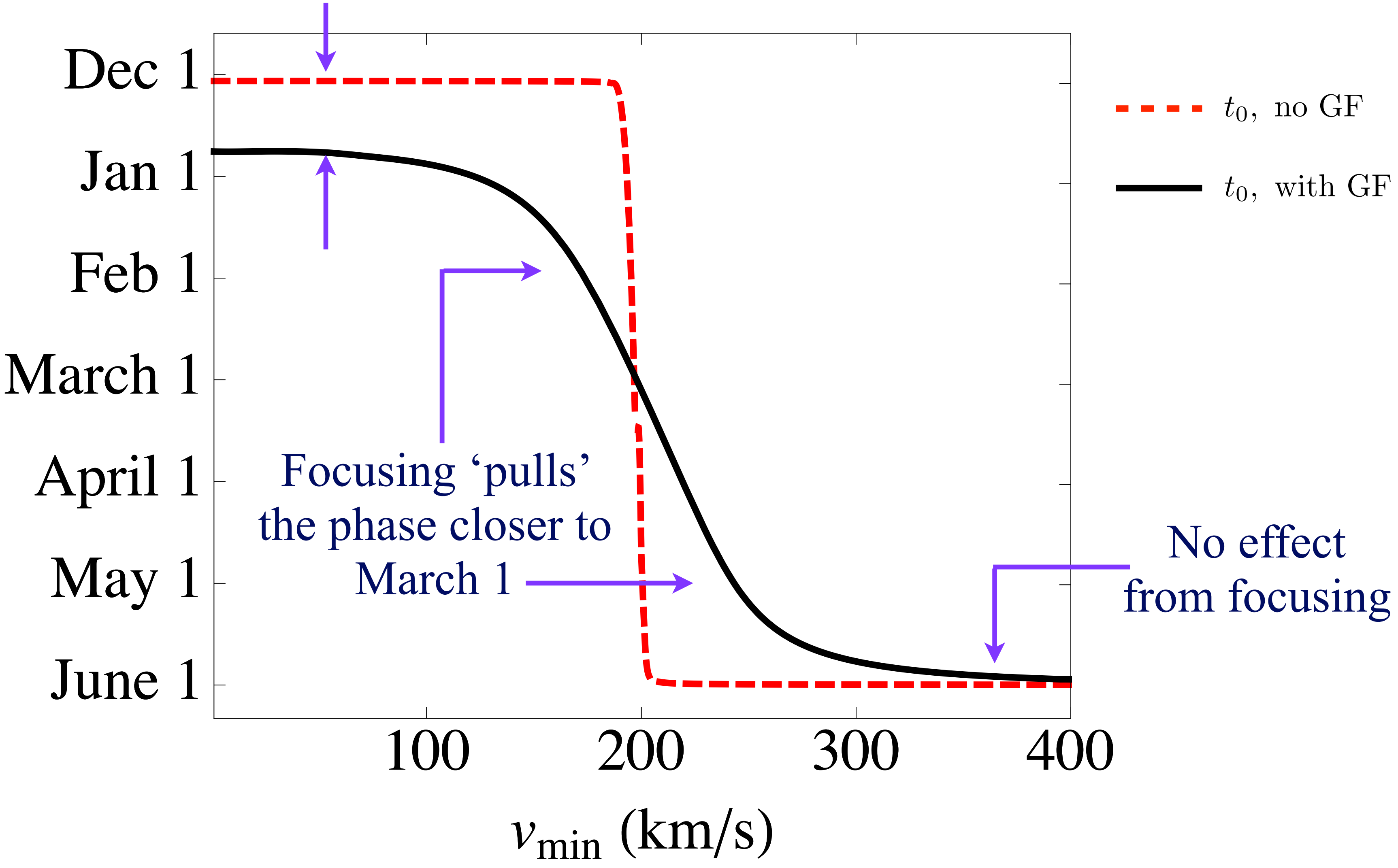

23 day shift due to focusing

Focusing 'pulls' the phase closer to March 1

No effect from focusing

Lee, **ML**, Peter, and Safdi [1308.1953]

Modulation Phase

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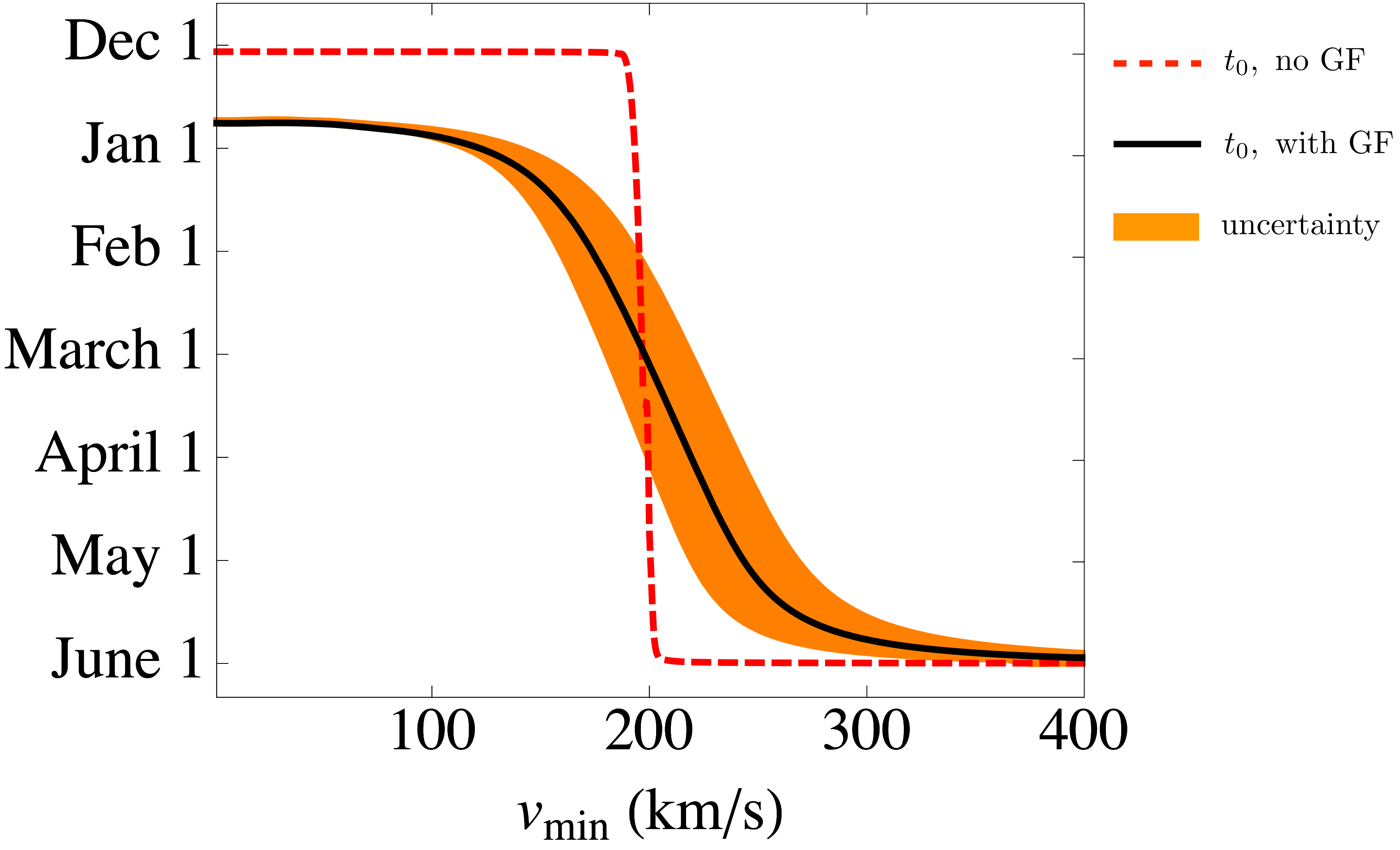

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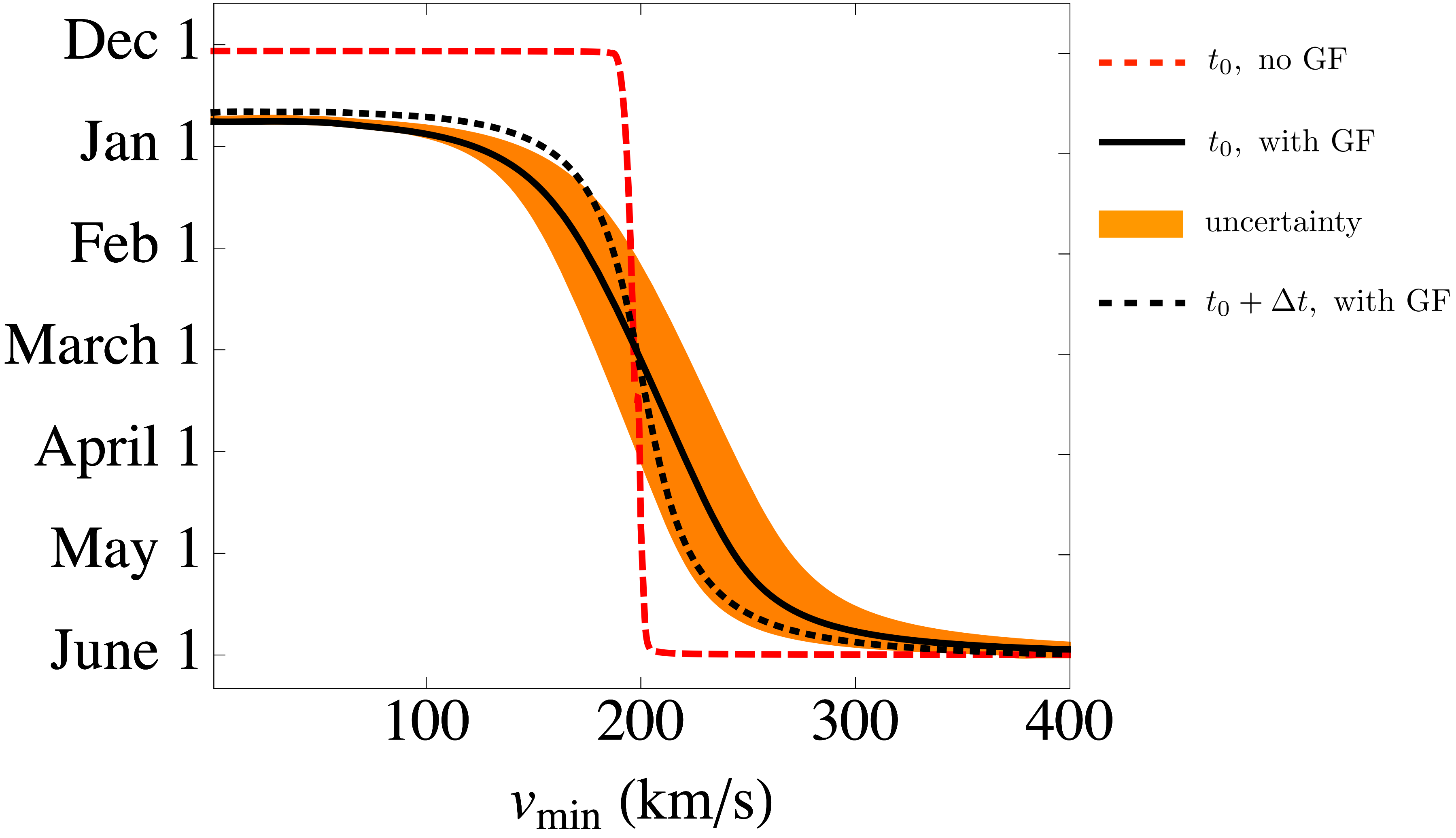


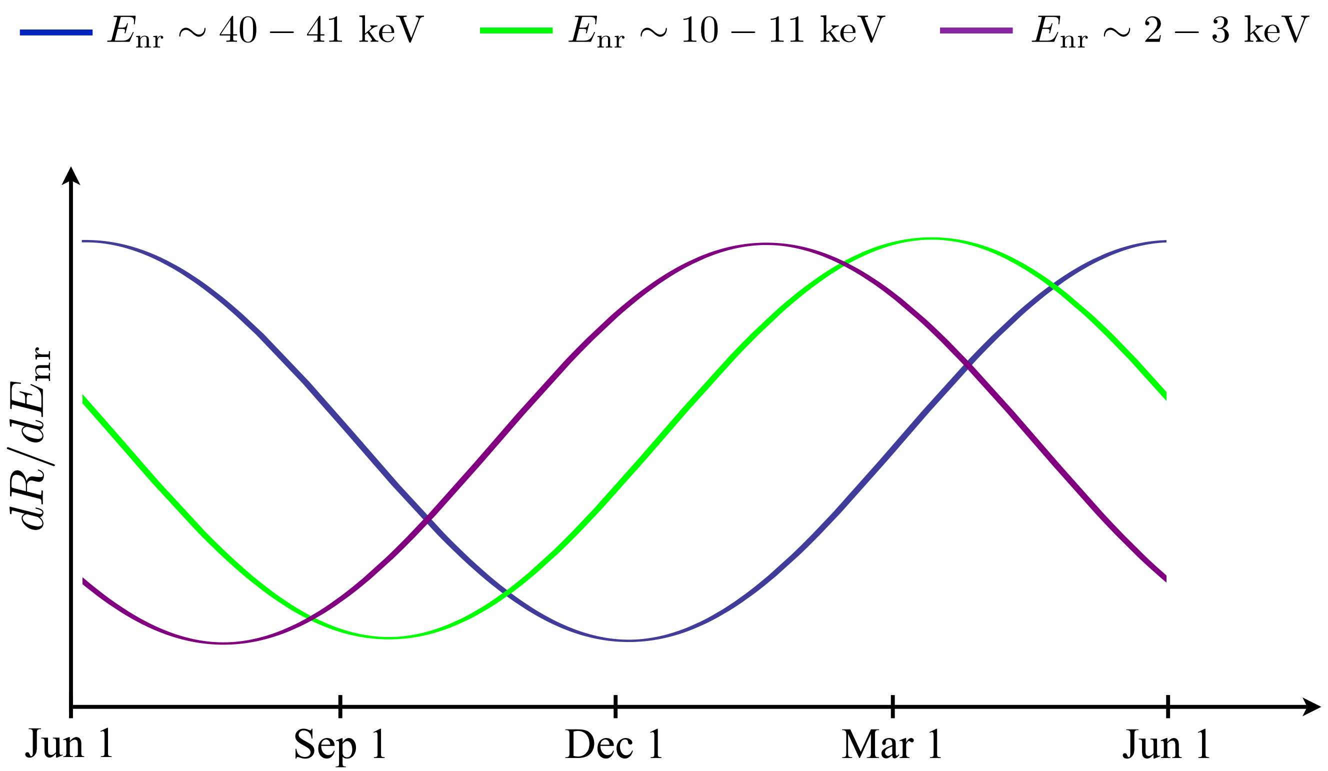
Lee, **ML**, Peter, and Safdi [1308.1953]

Experimental Implications

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

Powerful way to distinguish signal from background

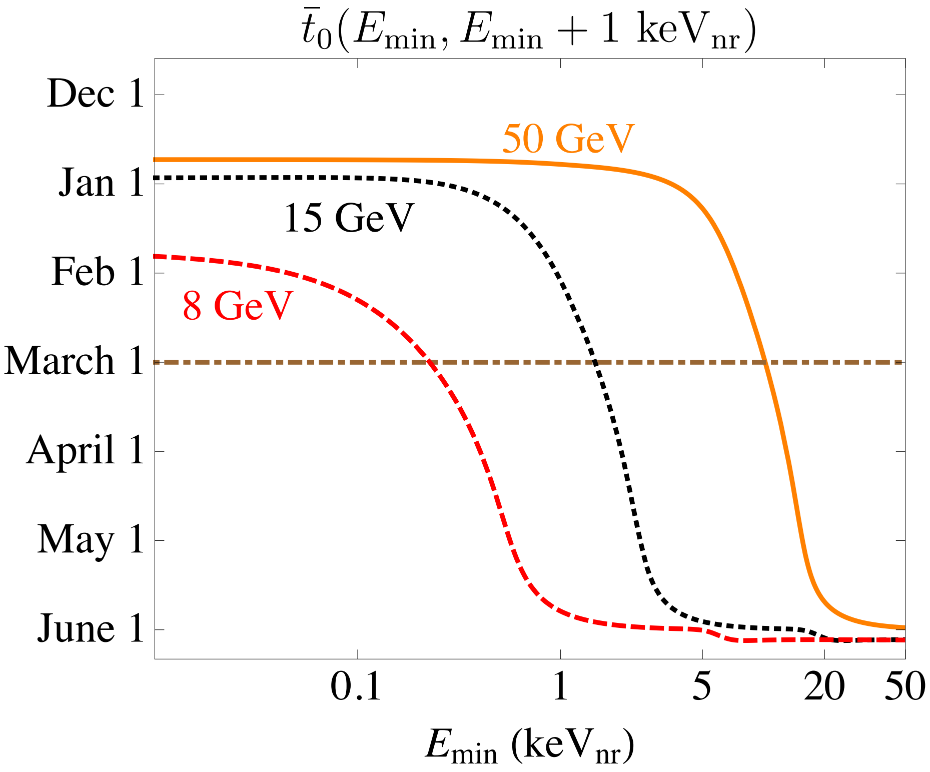
Example: 50 GeV DM, Ge target



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:

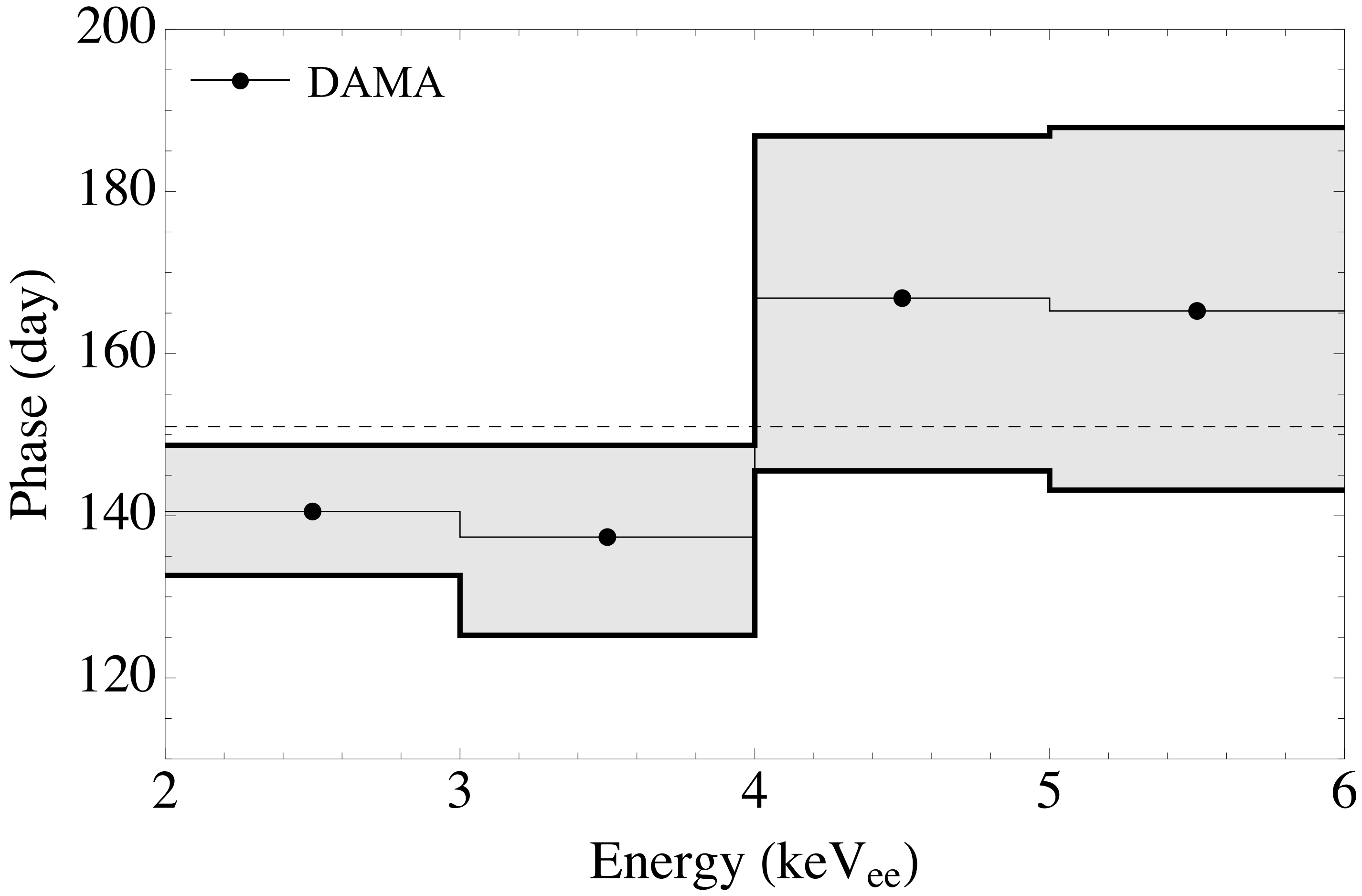
$$\bar{R}(E_{\min}, E_{\max}) = \int_{E_{\min}}^{E_{\max}} dE_{\mathrm{nr}} \frac{dR}{dE_{\mathrm{nr}}}$$

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

DAMA Revisited

DAMA signal can correspond to ~11 or 76 GeV dark matter

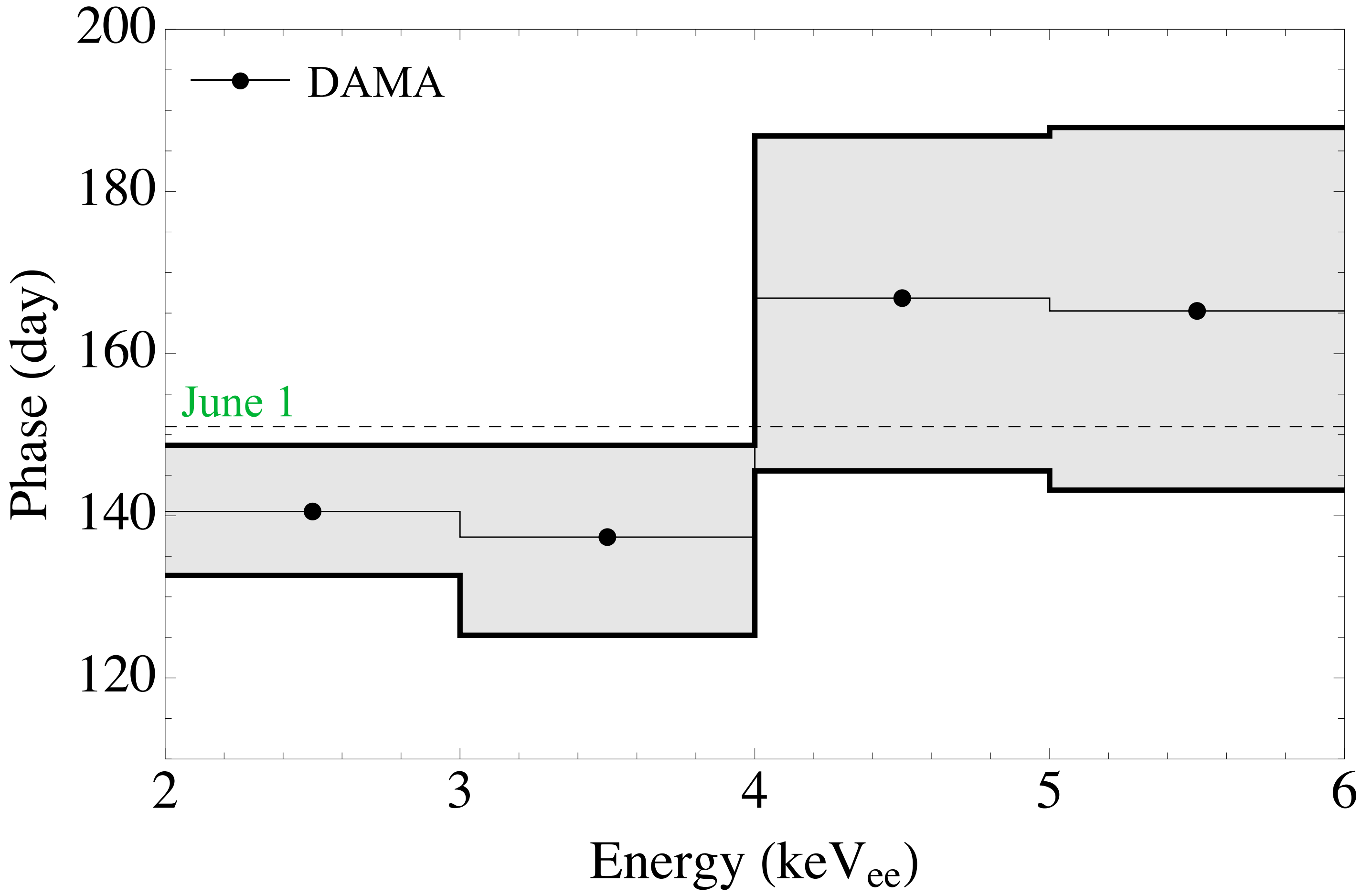
Both masses are in tension with null results from other experiments



DAMA Revisited

11 GeV scenario should still peak ~June 1 in each bin

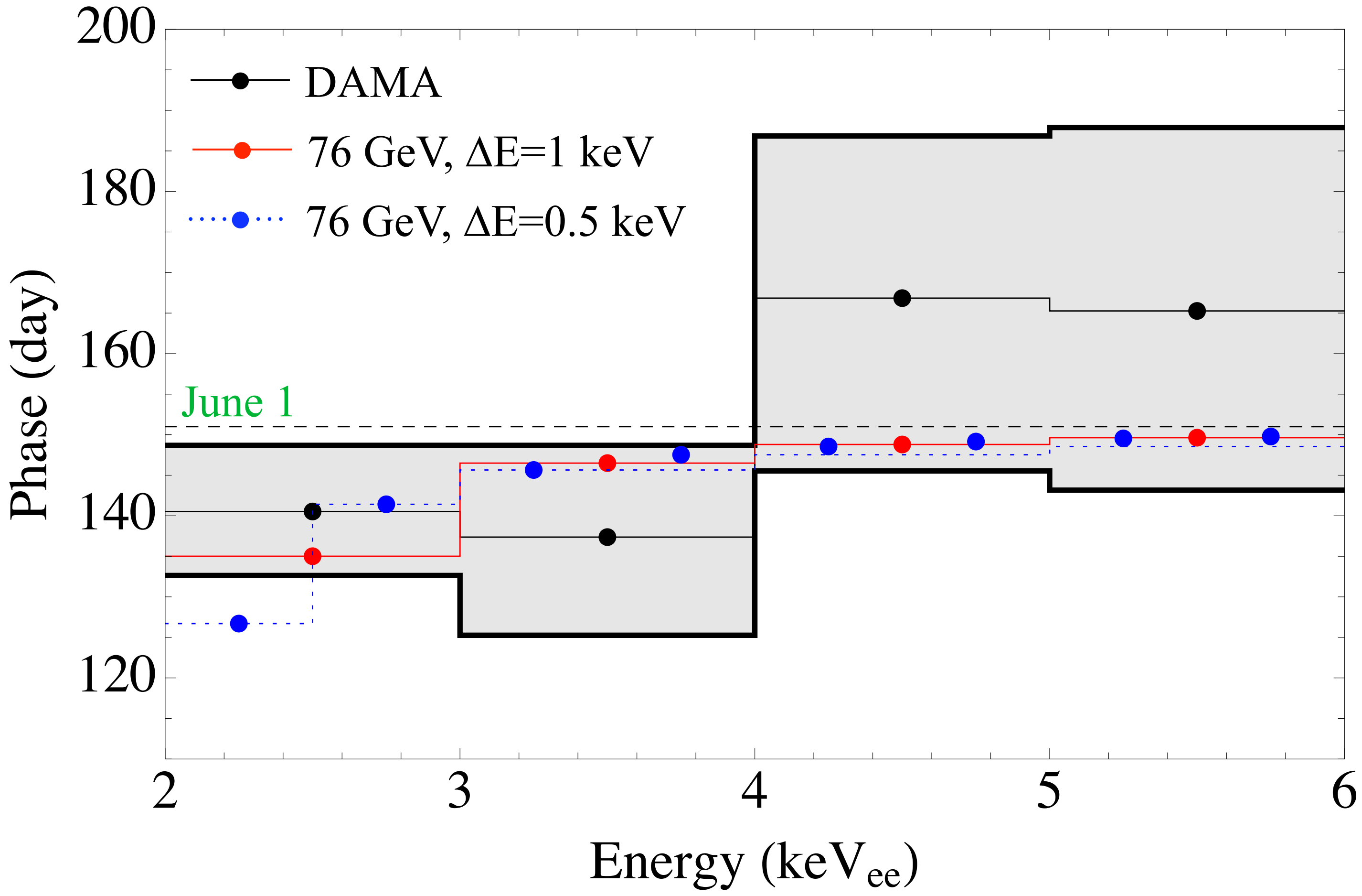
Future NaI experiments (*i.e.,* SABRE) might push the threshold lower to where a phase shift would be measurable



DAMA Revisited

76 GeV scenario is affected by gravitational focusing

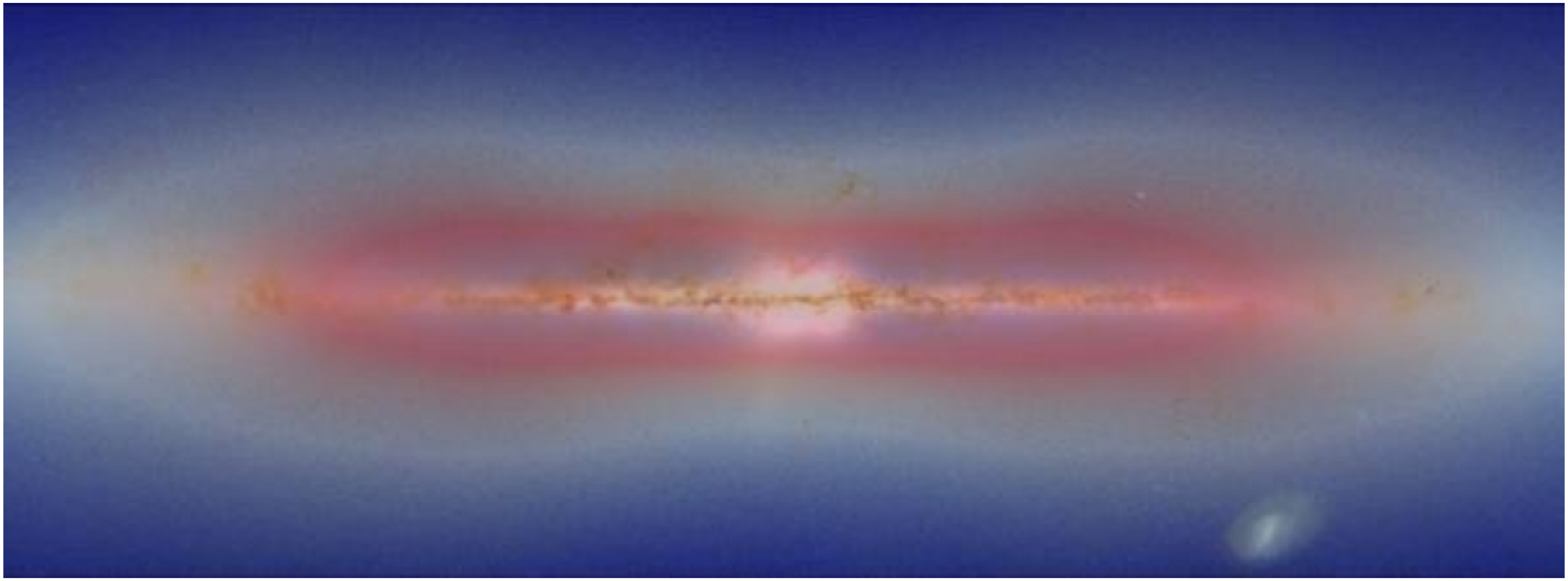
The phase shift can be as much as a ~month in the low-energy bins



Dark Matter Disk

May form from the merger of subhalos that are dragged into the baryonic disk and disrupted

Corotates with the Galactic disk, but with a lag speed ~50 km/s



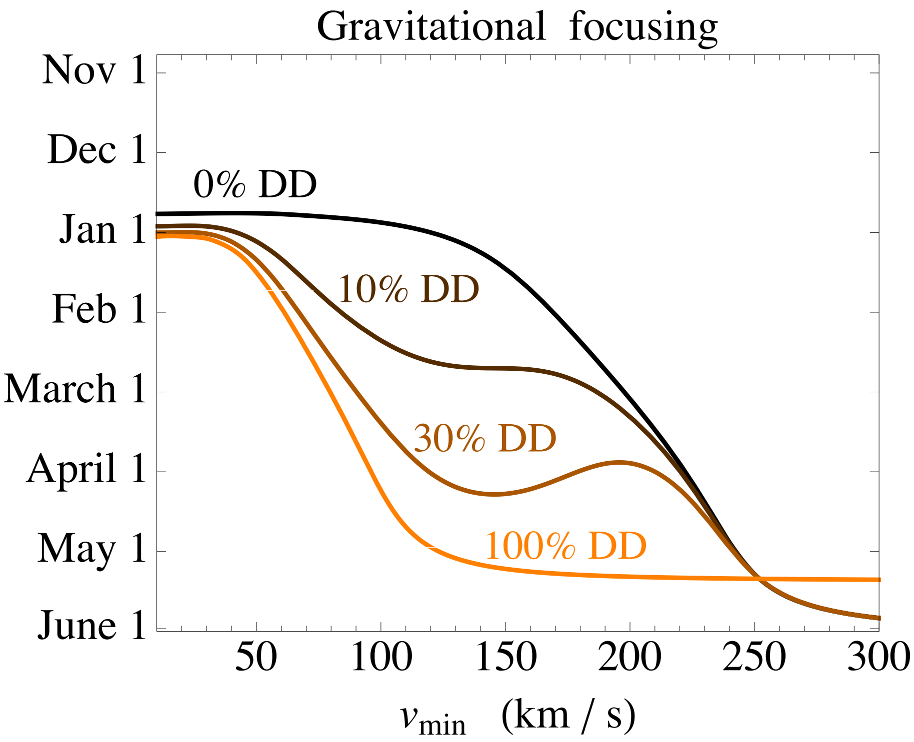
http://www.sciencedaily.com/releases/2008/09/080915210506.htm

Measuring the Dark Disk

Lee, **ML**, Safdi and Sharma [in progress]

Particles in the dark disk have low velocities in the lab frame

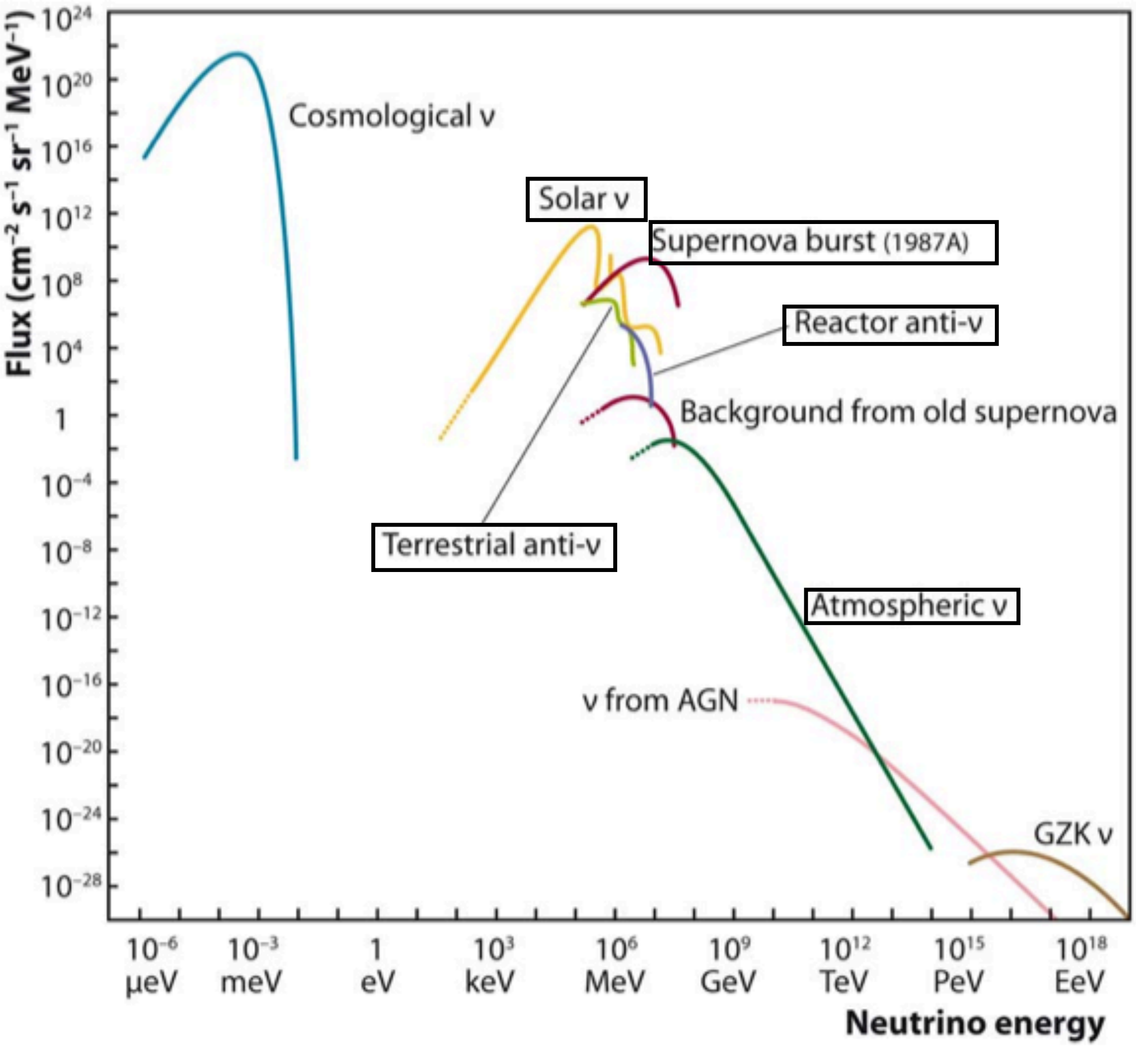
Therefore, significantly affected by gravitational focusing



Teaser

Relic Neutrinos

The “holy grail” of neutrino physics



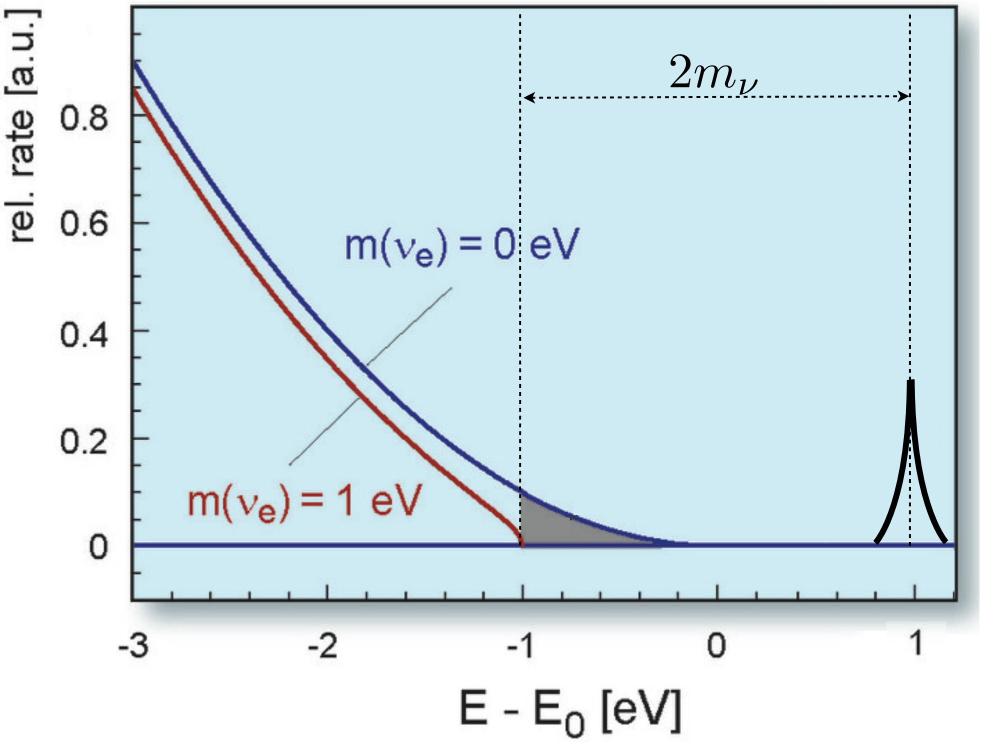
http://www.aspera-eu.org/images/stories/files/Roadmap.pdf

Neutrino Capture

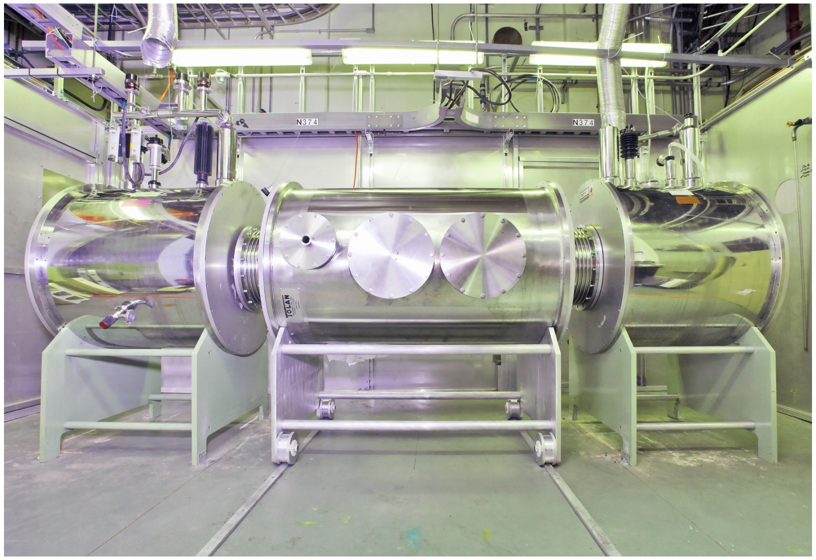
Neutrino capture on β-decaying nuclei provides a clear path forward

$$\nu_e + {}^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^-$$

No threshold on incoming neutrino energy



PTOLEMY Prototype



Beta *et al.*, arXiv: 1307/4738.
Weinberg, Phys. Rev **128**, 1457 (1962).

The Case for Neutrinos

The neutrino capture rate on a single nucleus is given by

$$\lambda_\nu \propto \rho \int \sigma_{\rm NCB}\, v_\nu\, f_\oplus(\mathbf{v}, t)\, d^3v$$

$\sigma_{\rm NCB} v_\nu$ is velocity-independent to high accuracy at low neutrino energy

$$\lambda_\nu \propto \rho\, (\sigma_{\rm NCB}\, v_\nu) \boxed{\int f_\oplus(\mathbf{v}, t)\, d^3v}$$

Integrates to unity!

However, the density still modulates due to gravitational focusing!

Relic Neutrino Modulation

Safdi, **ML**, Spitz, and Formaggio [1404.0680]

Gravitational focusing is the *only* source of modulation for relic neutrinos

Modulation fractions ~0.1-1% depending on ν mass and velocity distribution

Requires a 10 kg-sized tritium target, which is feasible with PTOLEMY

Summary

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-speed particles

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