Astrophysical Uncertainties in Sub-GeV Dark Matter Detection via Single Phonon Excitations

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arXiv:2606.04091 with Xu Xiang Li and Zhengkang (Kevin) Zhang

THE UNIVERSITY OF UTAH

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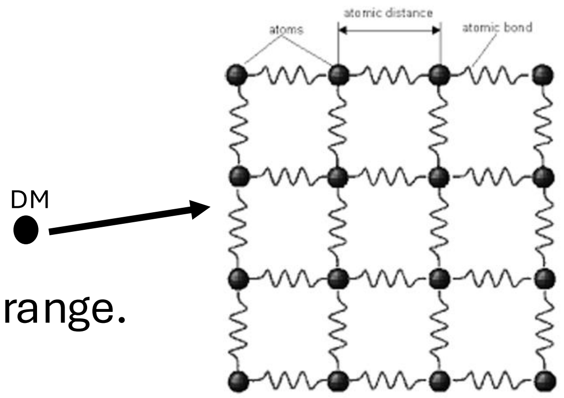
Direct Detection for Sub-GeV Dark Matter

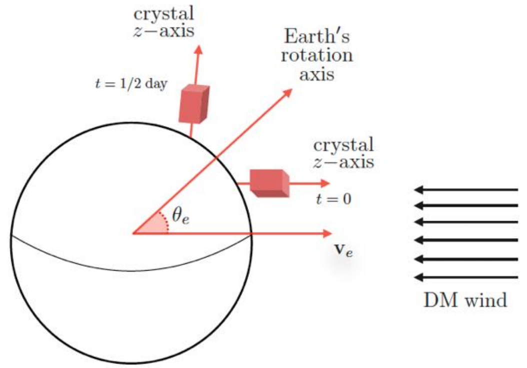
Phonons in crystals - collective oscillation of ions

- Single phonon excitations have meV-scale energies,
  so they can probe dark matter masses down to the keV-MeV range.



Crystal targets

- Anisotropic crystals can also give a daily modulation
  signal as Earth rotates through the dark matter wind.



A. Coskuner, A. Mitridate, A. Olivares, and K. M. Zurek, 2020

Total Rate

For spin-independent dark matter scattering in a crystal,

$$R = \frac{1}{\rho_T}\frac{\rho_\chi}{m_\chi}\frac{\pi}{\mu^2}\int \frac{d^3q}{(2\pi)^3}\underbrace{\bar{\sigma}\mathcal{F}^2_{med}(q)}_{\substack{\text{Particle physics:}\\ \text{cross section and mediator form factor.}}}\sum_\nu \overbrace{S'_\nu(\boldsymbol{q})}^{\substack{\text{Material response:}\\ \text{dynamic structure factor.}}}\;\overbrace{g(\boldsymbol{q},\omega_{\nu,\boldsymbol{k}},t)}^{\substack{\text{Astrophysics: velocity distribution}\\ \text{through the kinematic function } \boldsymbol{g}.}}$$

(equation as of arXiv:2102.09567v2)

$$g(\boldsymbol{q},\omega,t) = \int d^3v f_\chi(v,t) 2\pi\delta(\omega - \omega_q)$$

Kinematic function acts as a filter in q space, and the region it selects depends on the VDF.

Our Question

Previous works:

- Nuclear recoil –1005.0579, 0912.2358, 0711.4895, 1703.10102
- Electron scattering – 2001.09156, 2011.02493, 2011.12896, 2210.15474

How much do uncertainties in the local dark matter velocity distribution change phonon-based direct-detection predictions?

Velocity Distribution Models and Parameters

We compare three Galactic-frame speed distributions:

- Standard Halo Model: truncated Maxwell-Boltzmann.

$$f_{gal,MB}(v) \propto \begin{cases} e^{-v^2/v_0^2}, & v < v_{esc} \\ 0 & v \geq v_{esc} \end{cases}$$

- Tsallis: smoother high-velocity cutoff from non-extensive statistics.
    - $q = 1 - {v_0^2}/{v_{esc}^2}$

$$f_{gal,Tsa}(v) \propto \begin{cases} \left[1 - (1-q)\frac{v^2}{v_0^2}\right]^{1/(1-q)}, & v < v_{esc} \\ 0 & v \geq v_{esc} \end{cases}$$

- Empirical: simulation-motivated exponential core with power-law cutoff (Mao et. al. 2013).
    - $p = 1.5$

$$f_{gal,emp}(v) \propto \begin{cases} e^{-v/v_0}(v_{esc}^2 - v^2)^p, & v < v_{esc} \\ 0 & v \geq v_{esc} \end{cases}$$

Astrophysical parameters varied independently:
(check 2606.04091v1 for aggressive range)

Parameter	Conservative range (km/s)
v_c	220^{+60}_{-20}
v_{esc}	544^{+56}_{-94}
v_e	232 ± 15

A Fair Comparison: rms Matching

The usual choice $v_0 = v_{\mathrm{c}}$ can mix two effects:

- different average kinetic energies;
- different functional shapes of the VDF.

We instead match the rms speed:

$$\langle v^2 \rangle_{\mathrm{SHM}}(v_0 = v_c, v_{esc}) = \langle v^2 \rangle_{\mathrm{Tsa}}(v_{0,Tsa}, v_{esc}) = \langle v^2 \rangle_{\mathrm{Emp}}(v_{0,Emp}, v_{esc})$$

- This puts the three halo models on the same dynamical footing.
- With rms matching, the central halo-model curves are much closer.

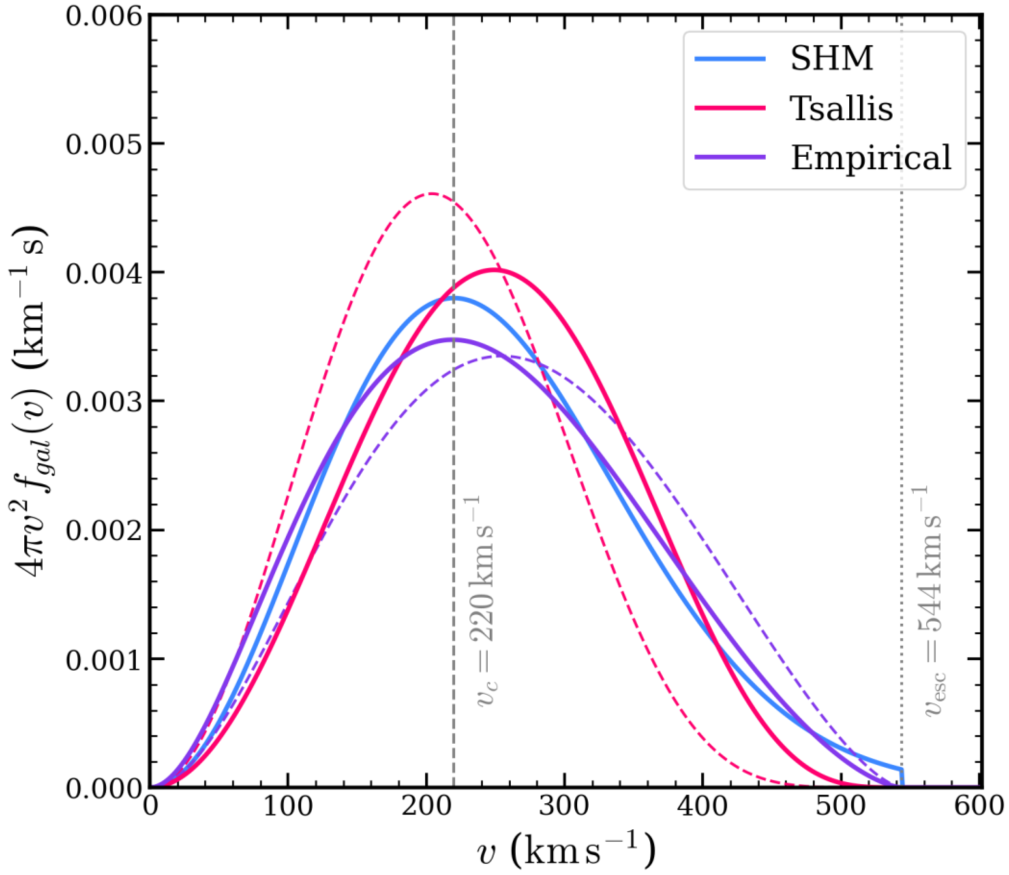
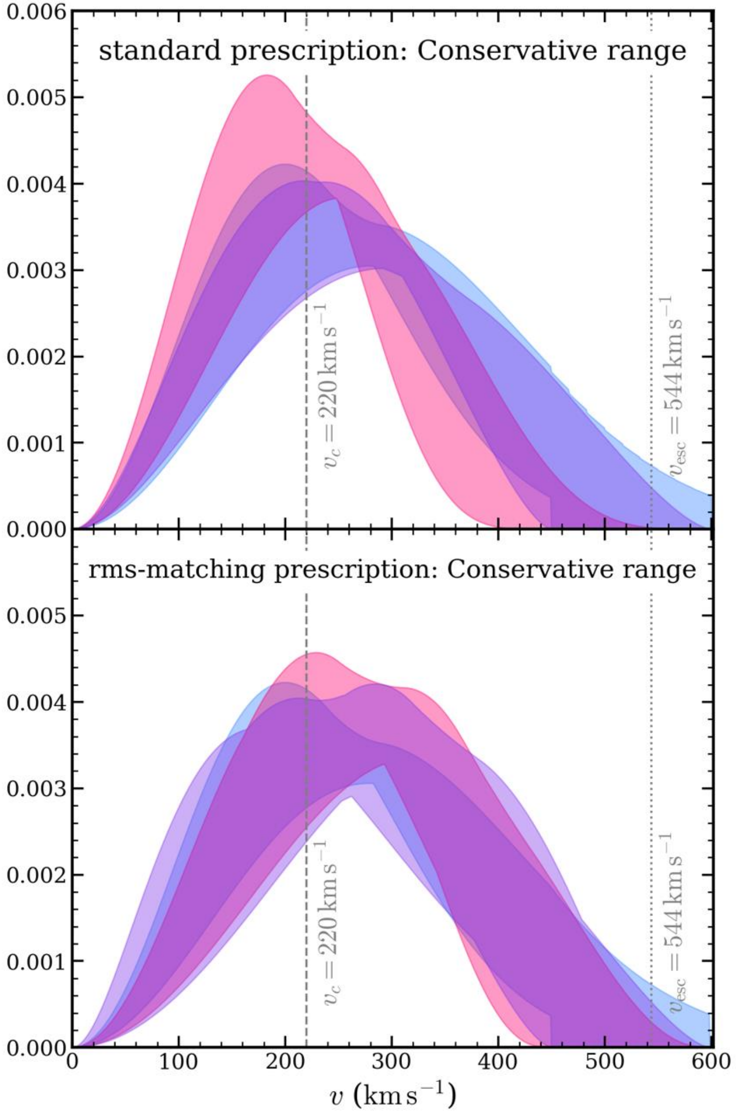


Fig: Speed distribution functions when velocity parameters are set to their central values. Solid (dashed) curves correspond to the rms-matching (standard) prescription.

What rms matching does to the speed distributions

- When parameters are varied, the model bands overlap strongly.
- This already suggests that parameter uncertainty may dominate over model-form uncertainty.



usual choice $v_0 = v_c$

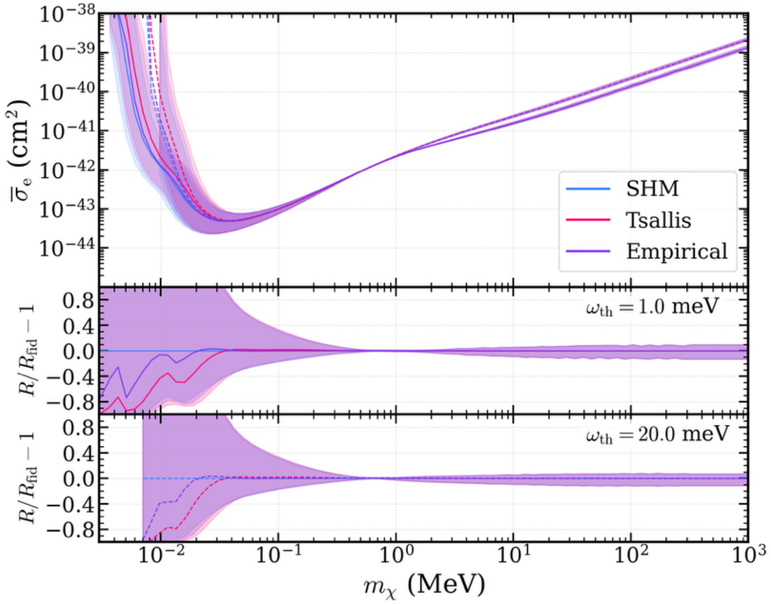
our choice
match the rms speed

Projected reach: main result

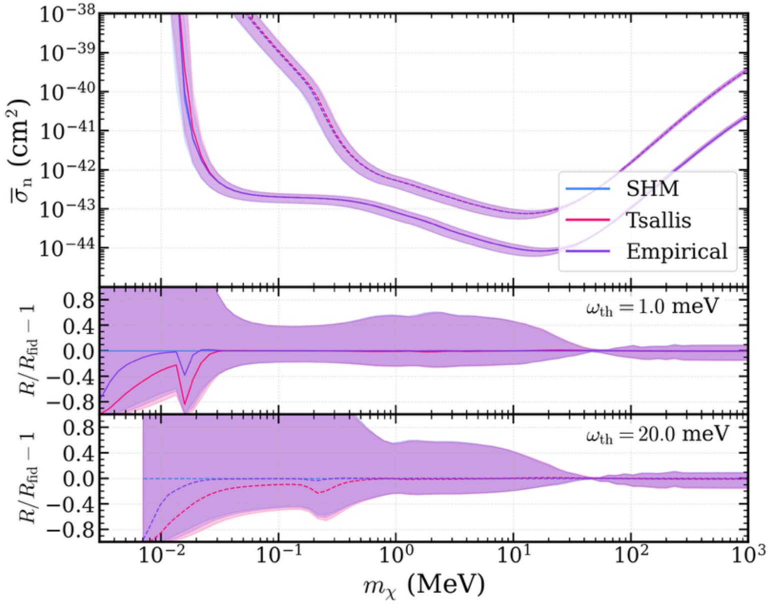
Across targets (GaAs, Al2O_3, SiO_2, $CaWO_4$) and mediator scenarios:

- Under rms matching, SHM, Tsallis, and empirical uncertainty bands nearly overlap.
- Uncertainties are largest near the lowest accessible dark matter masses, $\mathcal{O}(100\%)$.
- At higher masses, the bulk of the VDF contributes, and the uncertainty shrinks, $\mathcal{O}(1\%)$.

$CaWO_4$ – Light dark photon mediator



$CaWO_4$ – Heavy hadrophilic mediator



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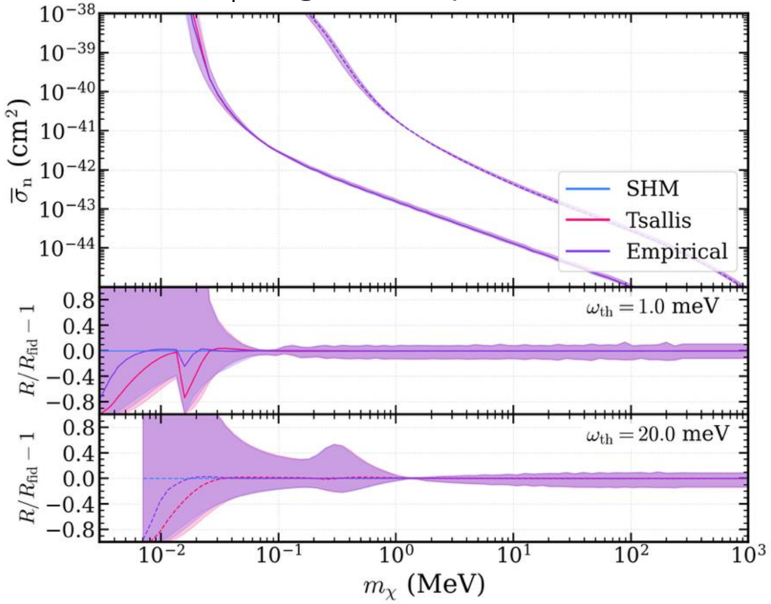


*Exposure criterion: 1 kg target, 3 events/year.

V minimum

The kinematic function integrates over dark matter speeds above a minimum speed:

$$v_{-} = \frac{1}{q}\left|\boldsymbol{q}\cdot\boldsymbol{v_e} + \frac{q^2}{2m_\chi} + \omega\right|$$

v_{-} depends on phonon energy, momentum transfer, dark matter mass, and Earth's velocity.

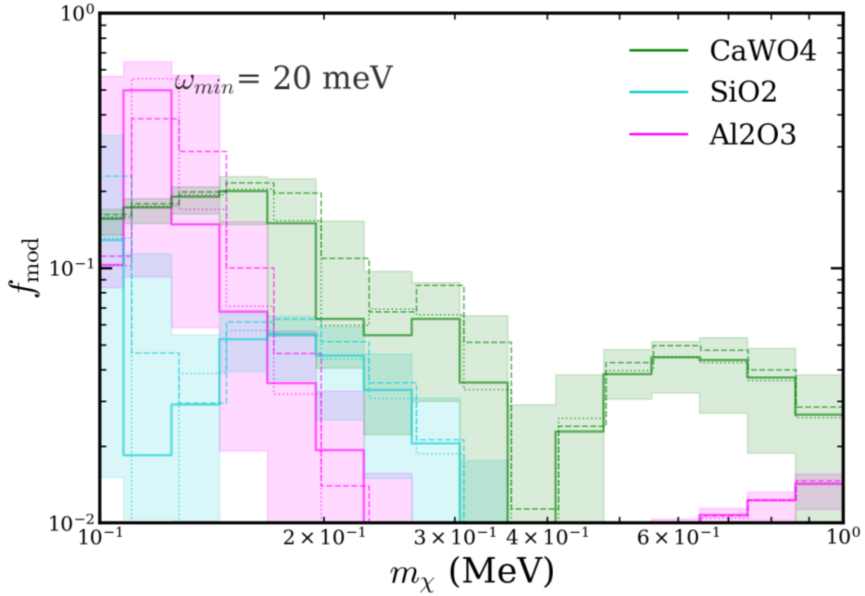
- Low DM mass m_χ or high phonon threshold ω_{min} pushes v_{-} to higher speed.
    - Then the signal depends strongly on the poorly known VDF tail.
- Heavy mediators emphasize larger q, so they keep sensitivity to the tail over a wider mass range.

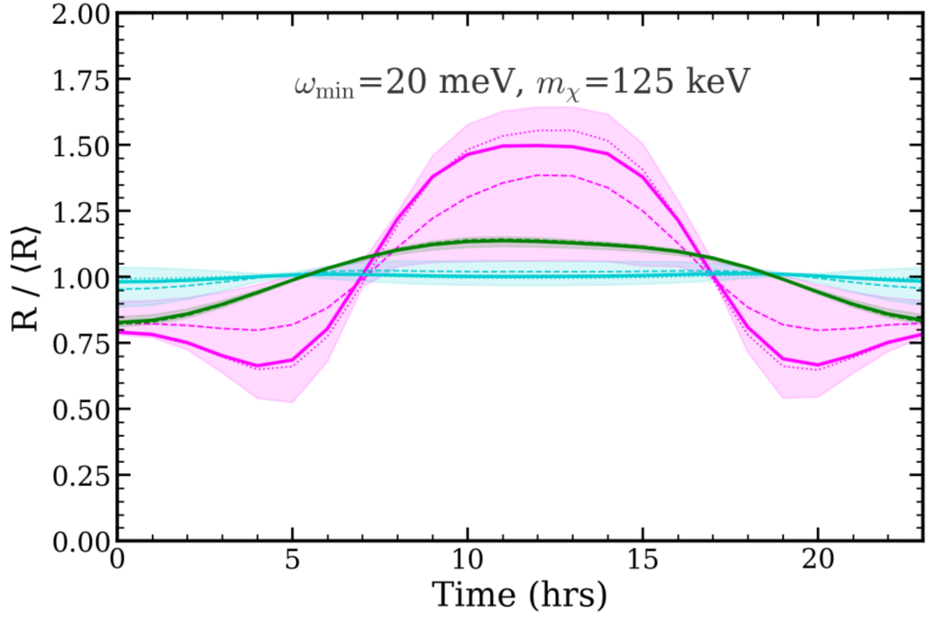
Daily modulation

Across targets ($Al2O_3$, SiO_2, $CaWO_4$) and mediator scenarios:

- Astrophysical parameter variations mostly rescale the modulation amplitude.
- The phase, meaning the times of maxima and minima, is largely stable.

Heavy hadrophilic mediator





Conclusions

- Single-phonon excitations are sensitive to VDF uncertainties, as expected.
- Uncertainties are largest near the lowest accessible dark matter masses.
- Conservative velocity-parameter variations produce $\mathcal{O}(1\%)$ to $\mathcal{O}(100\%)$ rate deviations.
- rms matching makes halo-model shape differences subdominant to parameter variations.
- The daily modulation phase is robust; astrophysical uncertainties mainly change the amplitude.

For these benchmark halo models, carefully varying velocity parameters within the SHM gives a good effective description of astrophysical uncertainty in phonon-based sub-GeV dark matter searches.

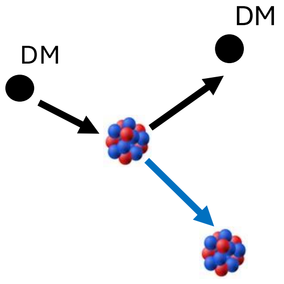
Thankyou!

Backup slides

Direct Detection for Sub-GeV Dark Matter

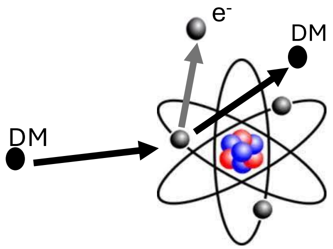
Traditional WIMP searches

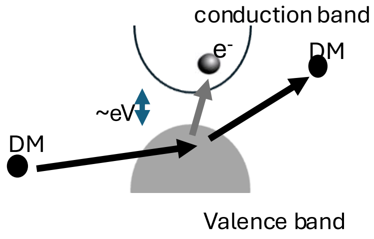
- Based on nuclear recoil
- Lose sensitivity below DM mass ~ GeV



Electron excitation

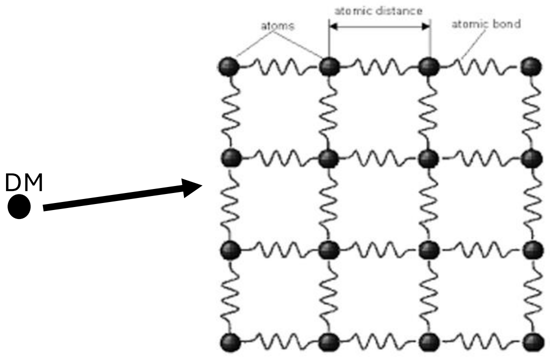
- Atoms (binding energy ~ 10 eV)
- Semiconductors (gap ~ eV)
- Reach down to DM mass ~ MeV





Collective excitation (sub-eV energies)

- Phonons in a crystal (collective oscillation of ions)

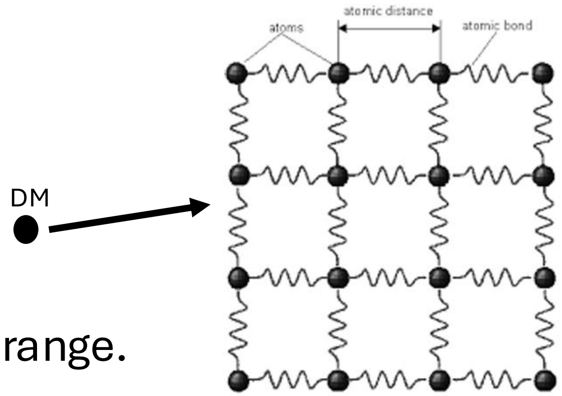


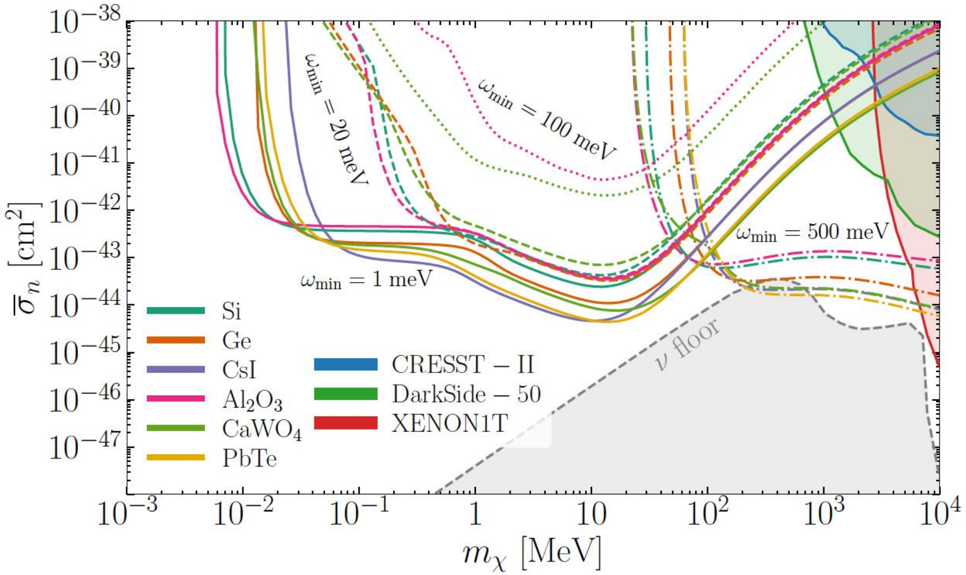
Direct Detection for Sub-GeV Dark Matter

Collective excitation (sub-eV energies) in crystals

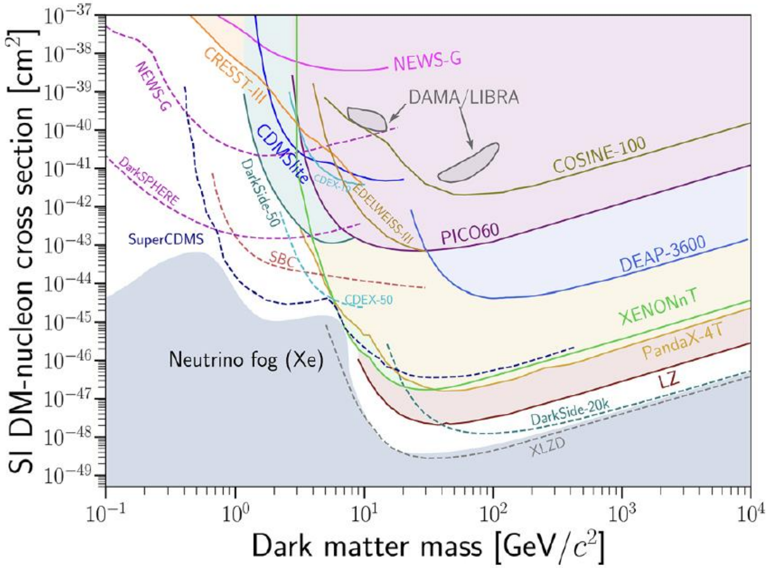
- Phonons: collective oscillation of ions
- Single phonon excitations have meV-scale energies,

  so they can probe dark matter masses down to the keV-MeV range.





S.M. Griffin, K. Inzani, T. Trickle, Z. Zhang, and K.M. Zurek, 2021

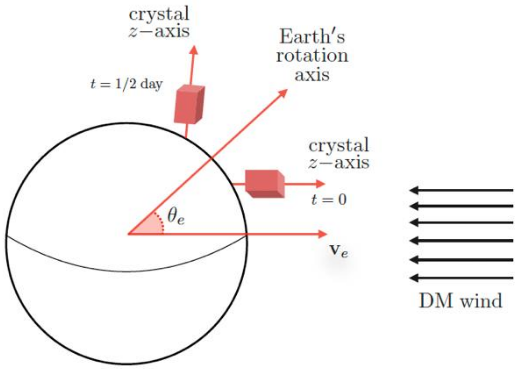


Q. Xia and L. Canonica - https://doi.org/10.1038/s42005-026-02563-1

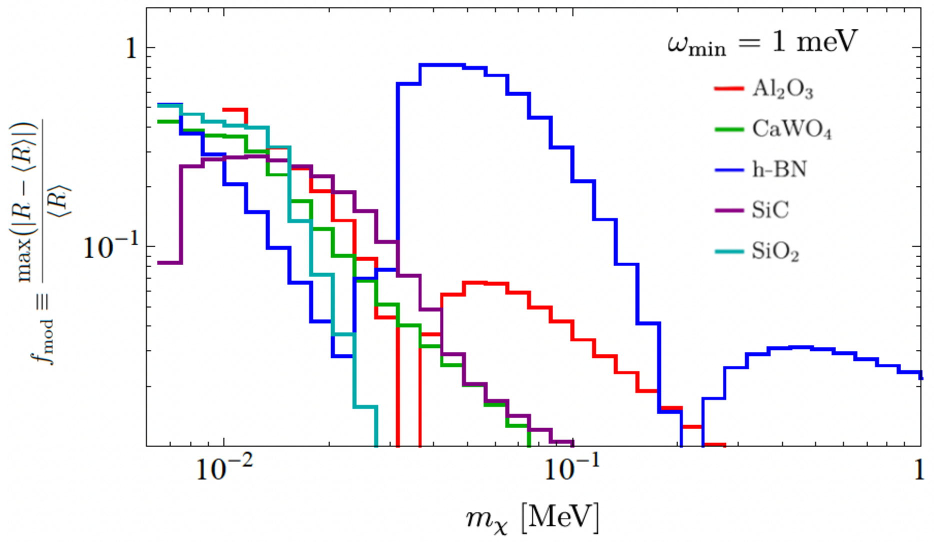
Direct Detection for Sub-GeV Dark Matter

Crystal targets

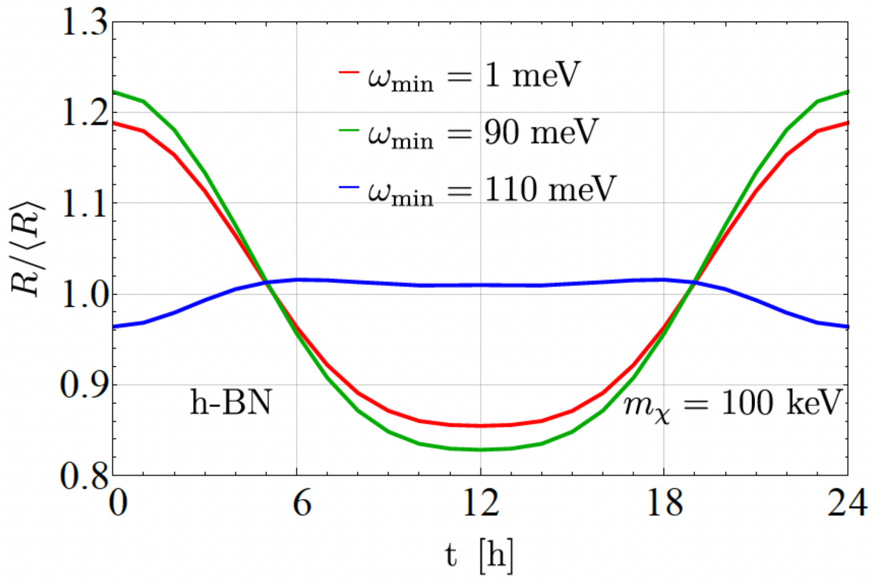
- Anisotropic crystals can also give a daily modulation signal as Earth rotates through the dark matter wind.



A. Coskuner, A. Mitridate, A. Olivares, and K. M. Zurek, 2020



A. Coskuner, T. Trickle, Z. Zhang, and K. M. Zurek, 2022



Halo Models

Standard Halo Model

$$f_{gal,MB}(v) \propto \begin{cases} e^{-v^2/v_0^2}, & v < v_{esc} \\ 0 & v \geq v_{esc} \end{cases}$$

Tsallis Model

Empirical Model

Model assumes isothermal spherical dark matter halo with an inverse-square density distribution

SHM “truncates” or cuts off the Maxwellian distribution at this escape velocity

Model ignores any anisotropy that DM halo might have

Halo Models

Standard Halo Model

Tsallis Model

Empirical Model

$$f_{gal,Tsa}(v) \propto \begin{cases} \left[1-(1-q)\frac{v^2}{v_0^2}\right]^{1/(1-q)}, & v < v_{esc} \\ 0 & v \geq v_{esc} \end{cases}$$

based on Tsallis statistics

$$S_q = -k \sum_i p_i^q \ln_q p_i$$

"q" is the Tsallis parameter, which describes the degree of deviation from a Gaussian distribution

Tsallis model allows for a power-law tail in the VDF

VDF included cut-off at the escape speed

For q<1 $v_{esc}^2 = v_0^2/(1-q).$

Halo Models

Standard Halo Model

Tsallis Model

Empirical Model

$$f_{gal,emp}(v) \propto \begin{cases} e^{-v/v_0}(v_{esc}^2 - v^2)^p, & v < v_{esc} \\ 0 & v \geq v_{esc} \end{cases}$$

based on N-body Cosmological simulations methods, which use simulation codes to describe the dynamics of pure collisionless dark matter

exponential term accounts for the anisotropy in velocity space

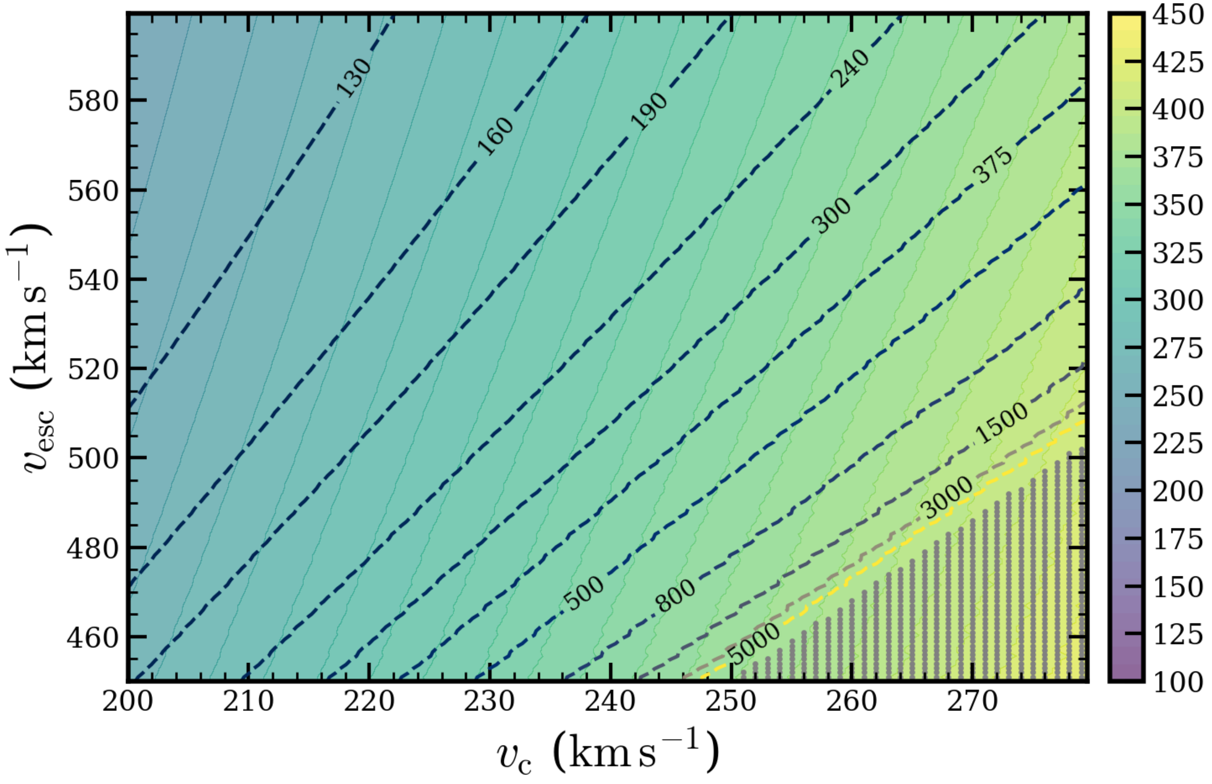
2nd term introduces a cut-off at the escape velocity

VDF exhibits a wider peak and a steeper tail than a Maxwell–Boltzmann distribution

A fair comparison: rms matching

- Tsallis distribution – solutions across the full range of conservative halo parameters.
- Empirical model, certain combinations of (v_c, v_{esc}) admit no finite solution for $v_{0,Emp}$.
- exponential core and power-law cutoff together suppress the high-velocity tail more strongly than the MB form, so matching the SHM's rms velocity requires progressively larger $v_{0,Emp}$.
- In the low-vesc, high-vc region (hatched region), the rms-matching condition cannot be satisfied at any finite $v_{0,Emp}$.

Contours of $v_{0,Tsa}$ and $v_{0,Emp}$ obtained from the rms-matching condition

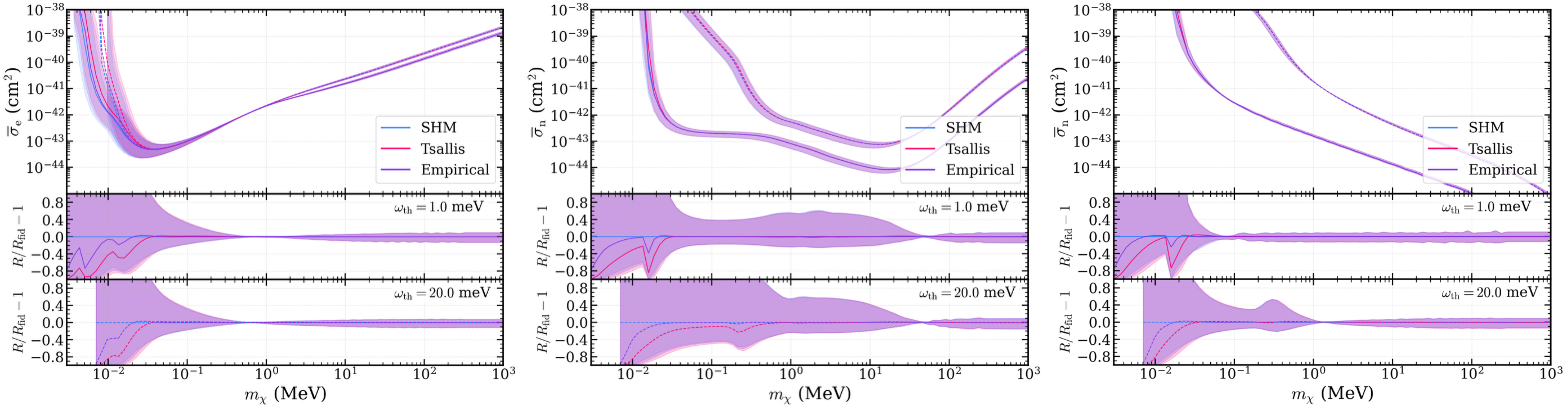


- In such cases, we adopt the limit $v_{0,Emp} \to \infty$, so $f \propto (v_{esc}^2 - v^2)^p$

Results – Projected reach

$CaWO_4$ – rms-matching prescription and conservative velocity range

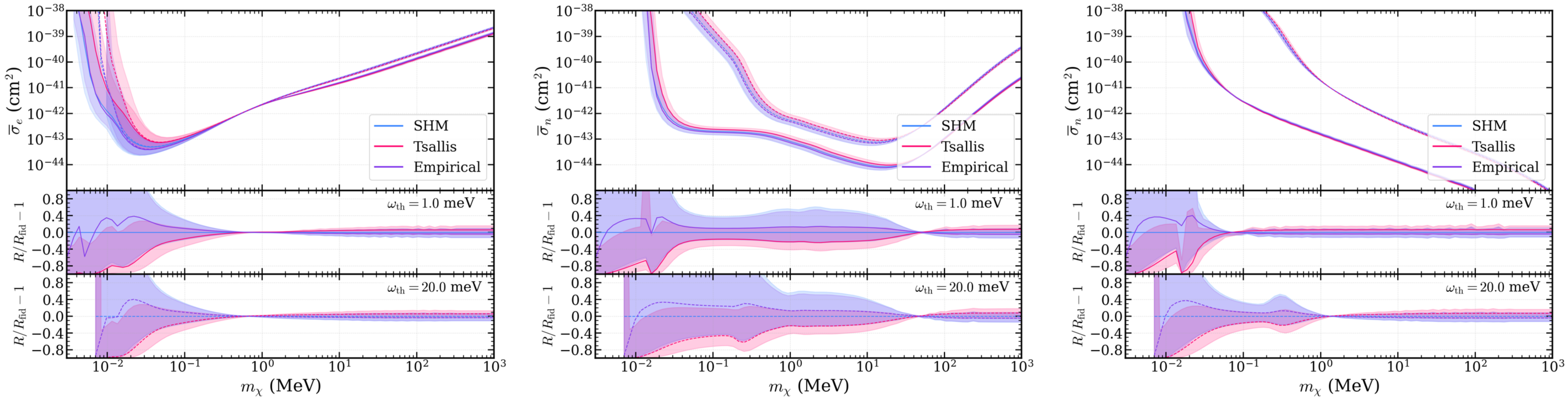
Light dark photon, Heavy hadrophilic and Light hadrophilic mediator



Results – Projected reach

$CaWO_4$ – standard prescription and conservative velocity range

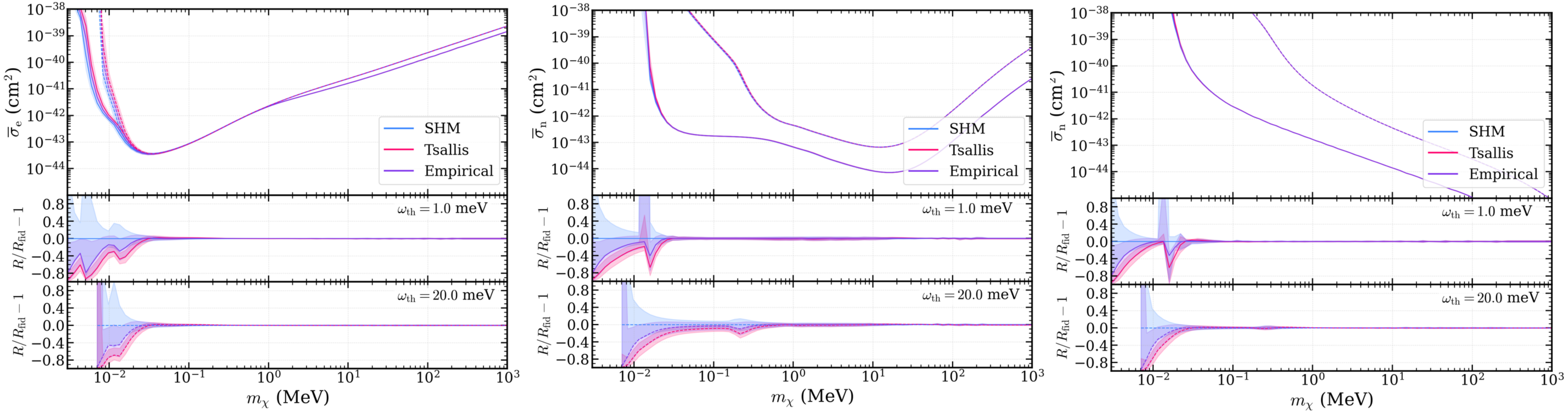
Light dark photon, Heavy hadrophilic and Light hadrophilic mediator



Results – Projected reach

$CaWO_4$ – rms-matching prescription and aggressive velocity range

Light dark photon, Heavy hadrophilic and Light hadrophilic mediator

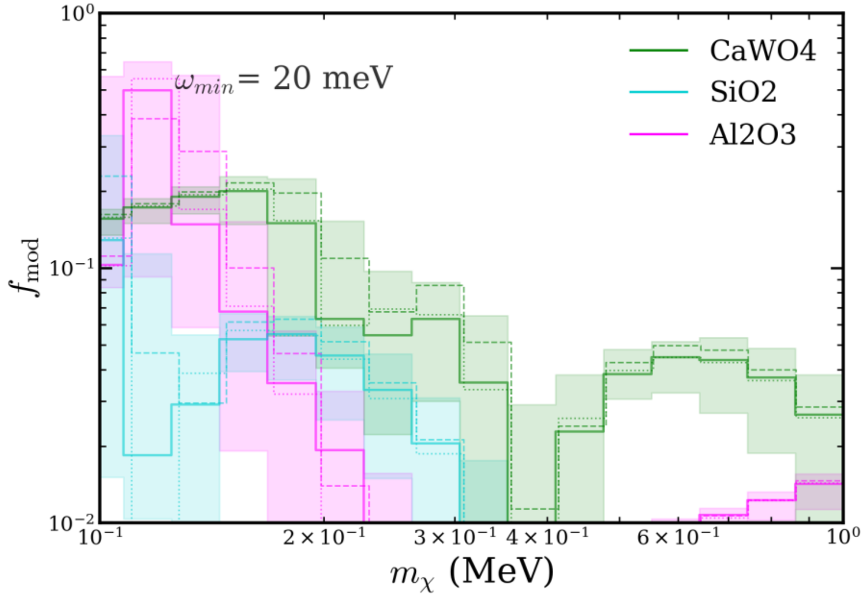


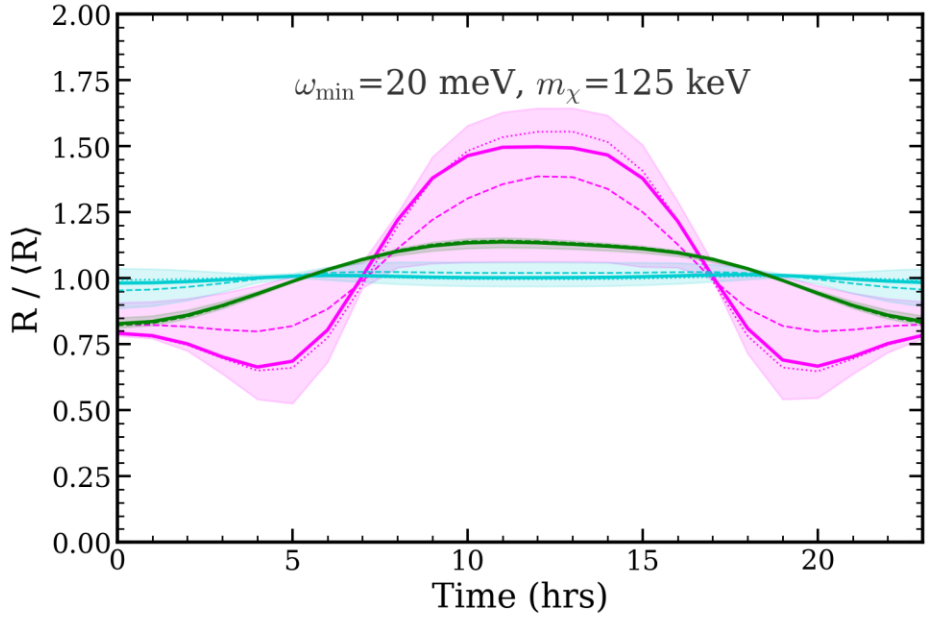
Daily modulation

Across targets ($Al2O_3$, SiO_2, $CaWO_4$) and mediator scenarios:

- Astrophysical parameter variations mostly rescale the modulation amplitude.
- The phase, meaning the times of maxima and minima, is largely stable.

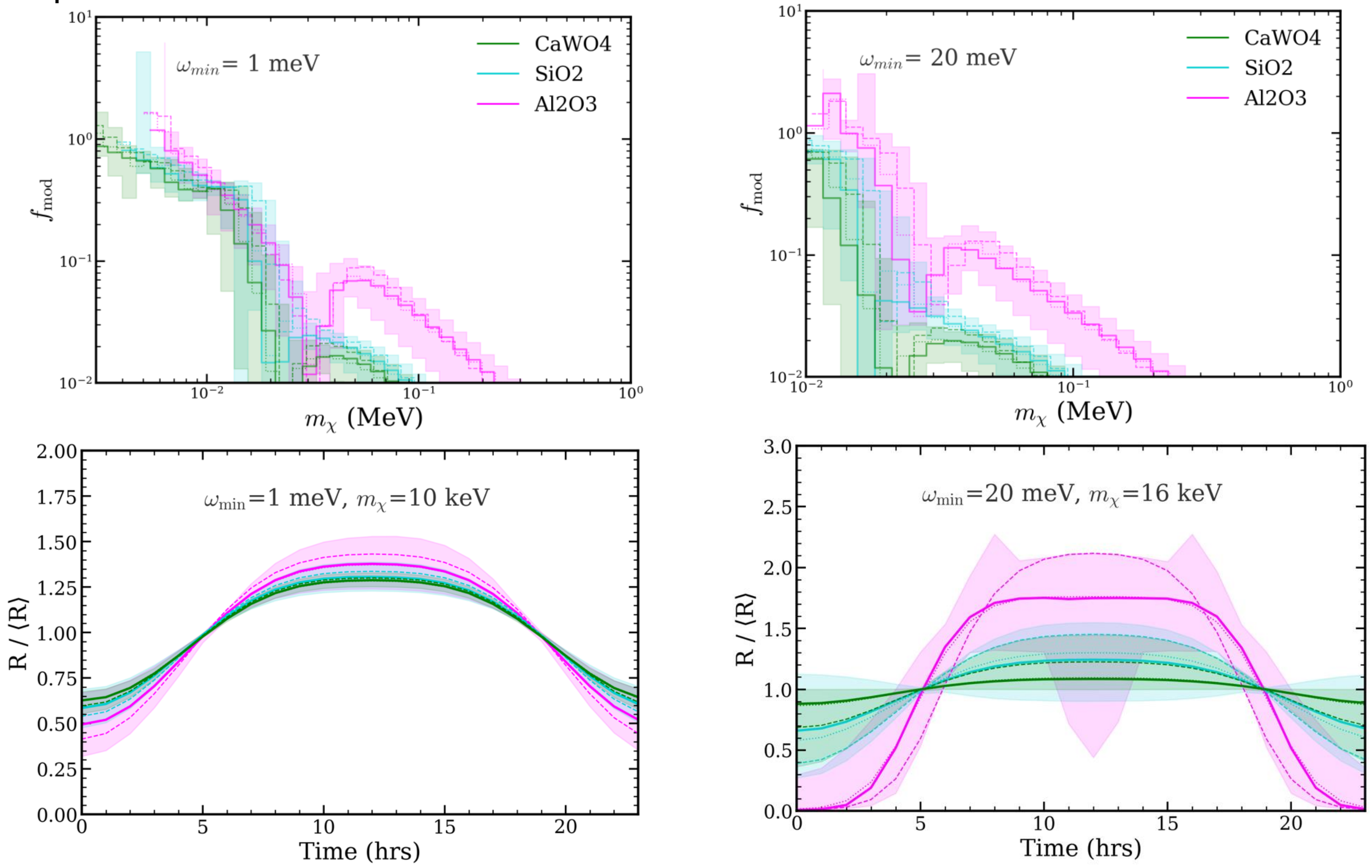
Heavy hadrophilic mediator





Results – Daily modulation

Light dark photon mediator



Which parameter matters most?

Relative difference:

$$\frac{|R_{\max} - R_{\min}|}{R_{\text{fid}}},$$

Standard Halo Model, $\omega_{\min} = 1$ meV

	Target	GaAs			Al_2O_3			SiO_2			$CaWO_4$		
m_χ	Mediator	LDP	LHS	HHS	LDP	LHS	HHS	LDP	LHS	HHS	LDP	LHS	HHS
0.01 MeV	rel.diff (v_c)				1.3192	0.8714	1.0199	1.5491	0.7858	1.1674	2.1114	1.143	1.7987
	rel.diff (v_e)				0.2791	0.1912	0.2665	0.2881	0.2796	0.3181	0.493	0.185	0.2977
	rel.diff (v_{esc})				0.2373	0.2777	0.1817	0.3972	0.0823	0.2122	0.8841	0.201	0.4915

- Rate deviations span roughly $\mathcal{O}(1\%)$ to $\mathcal{O}(100\%)$

Main hierarchy:

- v_c usually gives the largest rate uncertainty.
- v_e and v_{esc} are sub-leading for most masses.
- Near kinematic thresholds, v_{esc} can become more visible because the tail is directly probed.

Why v_c dominates: it controls the bulk velocity scale, so it changes the available flux over much of the relevant phase space.

Projected reach: interpretation

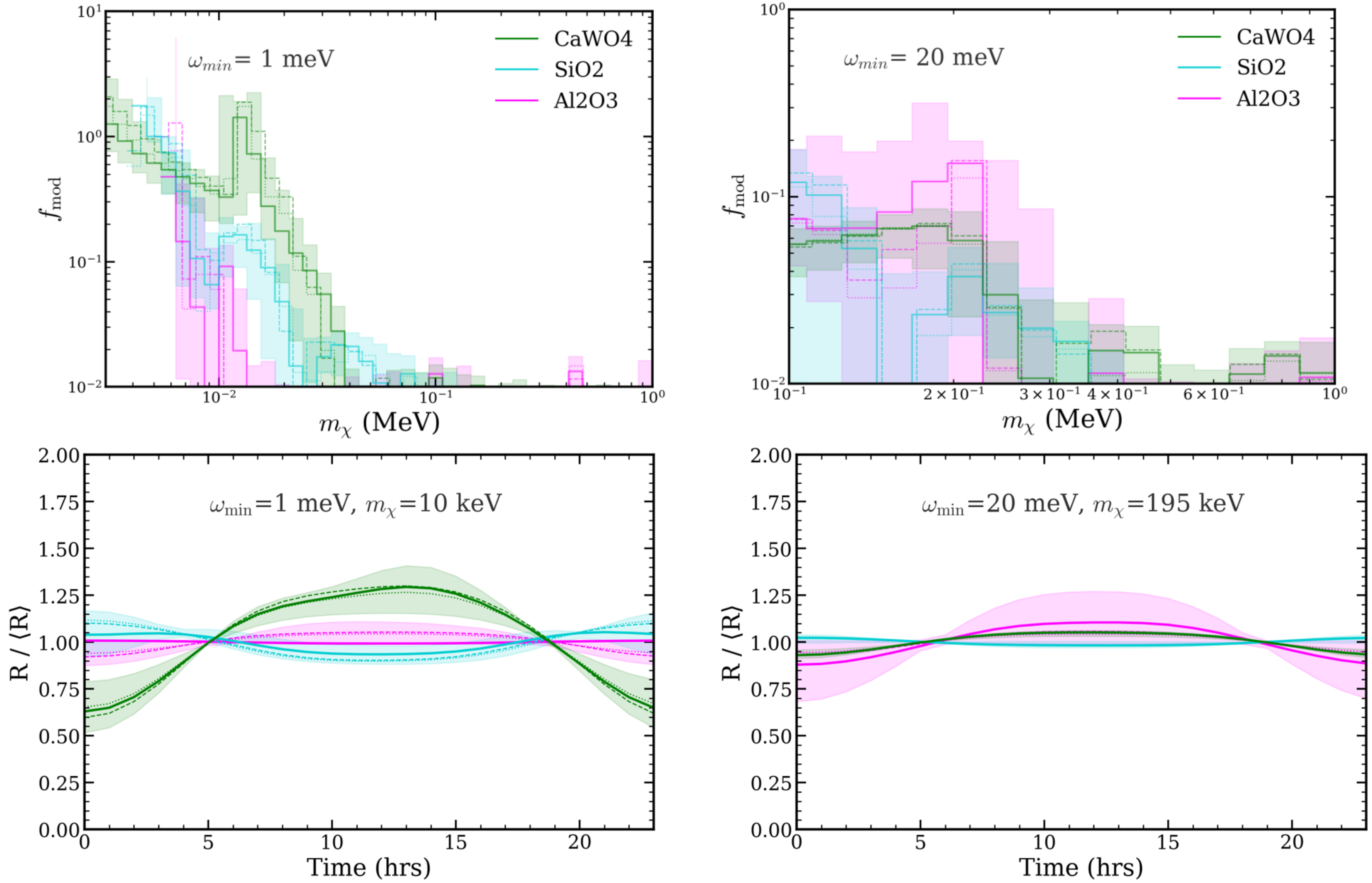
Across targets (GaAs, Al2O_3, SiO_2, $CaWO_4$) and mediator scenarios:

- Rate deviations span roughly $\mathcal{O}(1\%)$ to $\mathcal{O}(100\%)$
- Uncertainties are largest near the lowest accessible dark matter masses.
- At higher masses, more of the VDF contributes and uncertainty shrinks.
- Heavy hadrophilic scalar scattering keeps larger uncertainty to higher masses because it weights larger momentum transfer.
- Under rms matching, SHM, Tsallis, and empirical uncertainty bands nearly overlap.

Practical takeaway: Varying velocity parameters within the SHM captures most of the astrophysical uncertainty for these benchmark VDFs.

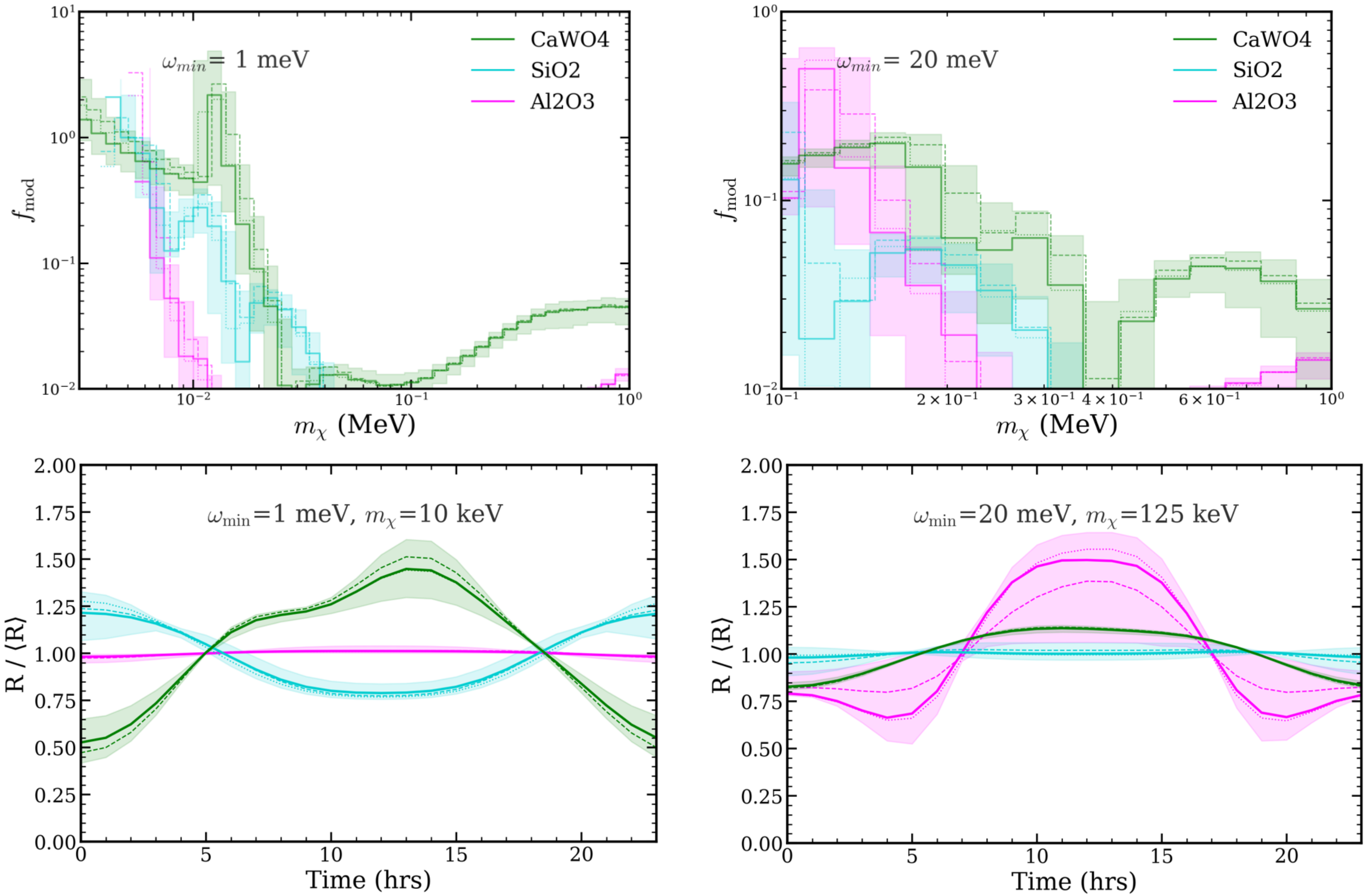
Results – Daily modulation

Heavy hadrophilic mediator



Results – Daily modulation

Light hadrophilic mediator



Daily modulation: robust phase

Main finding:

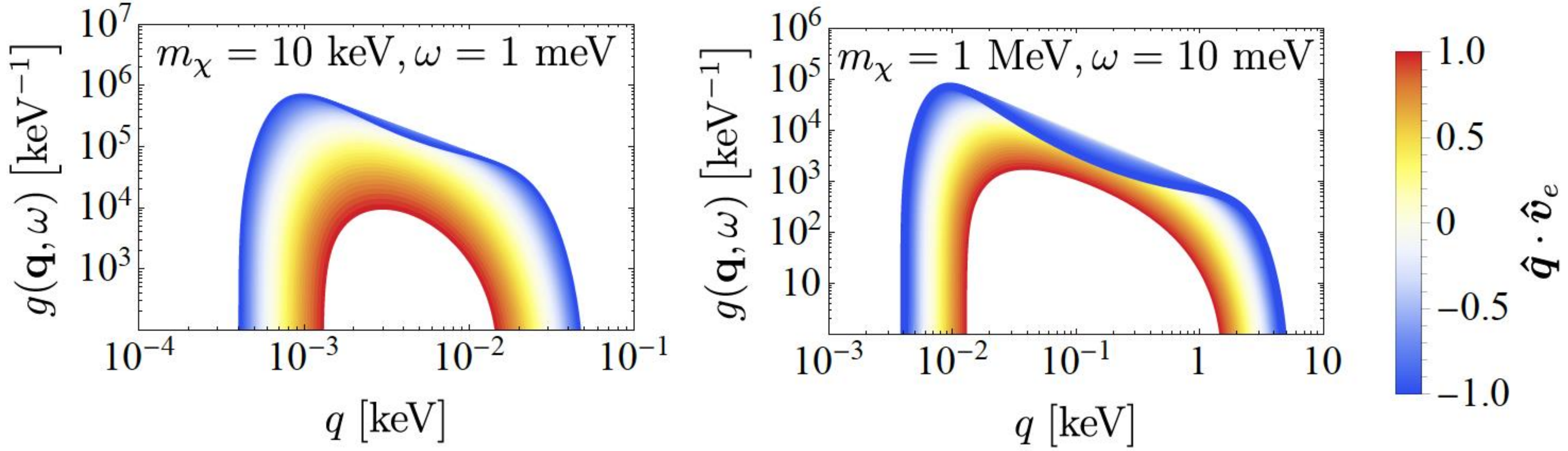
- Astrophysical parameter variations mostly rescale the modulation amplitude.
- The phase, meaning the times of maxima and minima, is largely stable.

Interpretation: The phase is set mostly by crystal orientation relative to Earth's rotating velocity vector, while the VDF controls how strongly each kinematic configuration is weighted.

Daily modulation – Kinematic function

$$g(\boldsymbol{q},\omega) \propto \frac{1}{q}\int_{v_-}^{v_{\rm esc}} v\,dv\,f_{\rm gal}(v)\,,$$

$$v_- = \frac{1}{q}\left|\boldsymbol{q}\cdot\boldsymbol{v_e} + \frac{q^2}{2m_\chi} + \omega\right|$$



arXiv:2102.09567v2