Beyond standard dark matter phenomenology with quantum sensors

John Carlton

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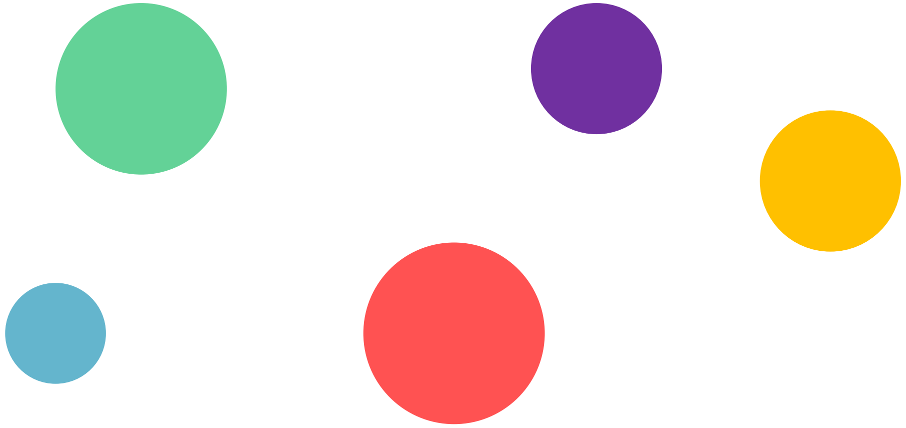
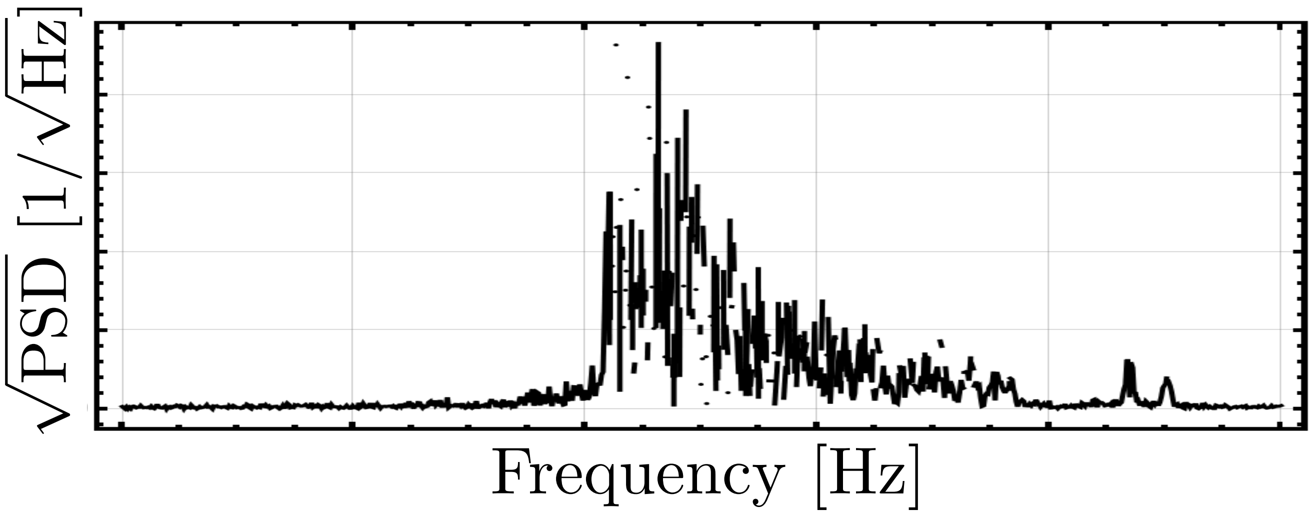
Let’s maximise quantum sensor phenomenology

New couplings



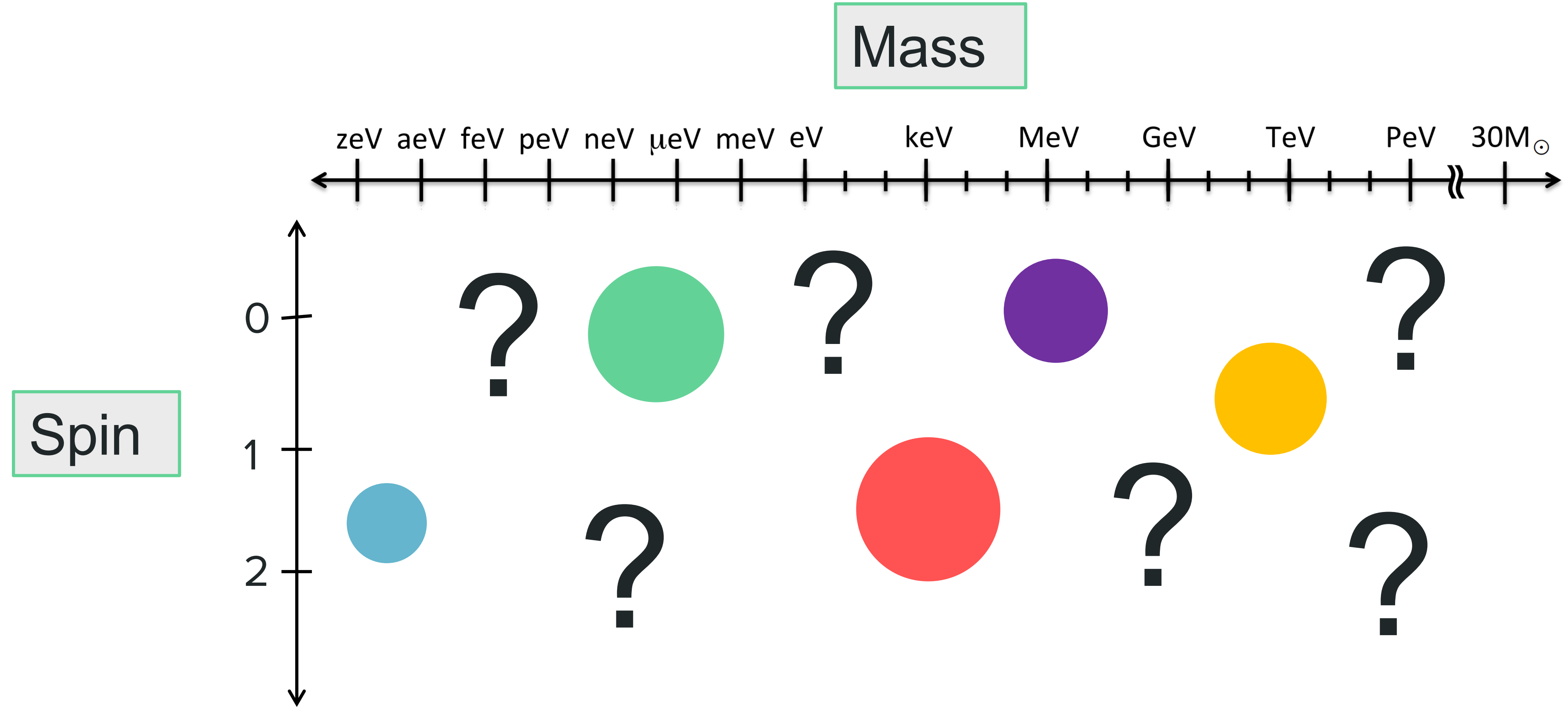
New signatures



Massive graviton dark matter

Based on D. Blas, J. Carlton, C. McCabe. arXiv: 2412.14282

A lot of parameter space!



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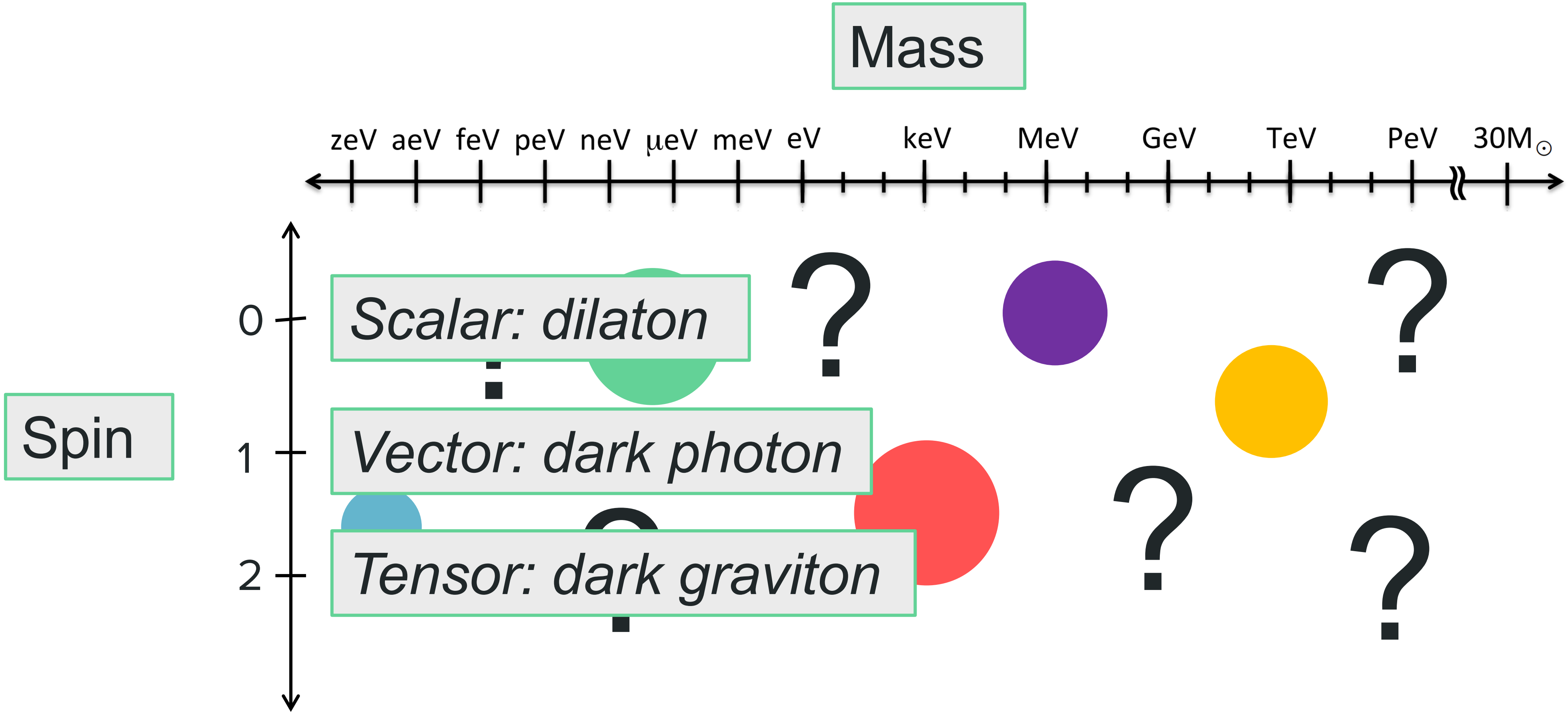
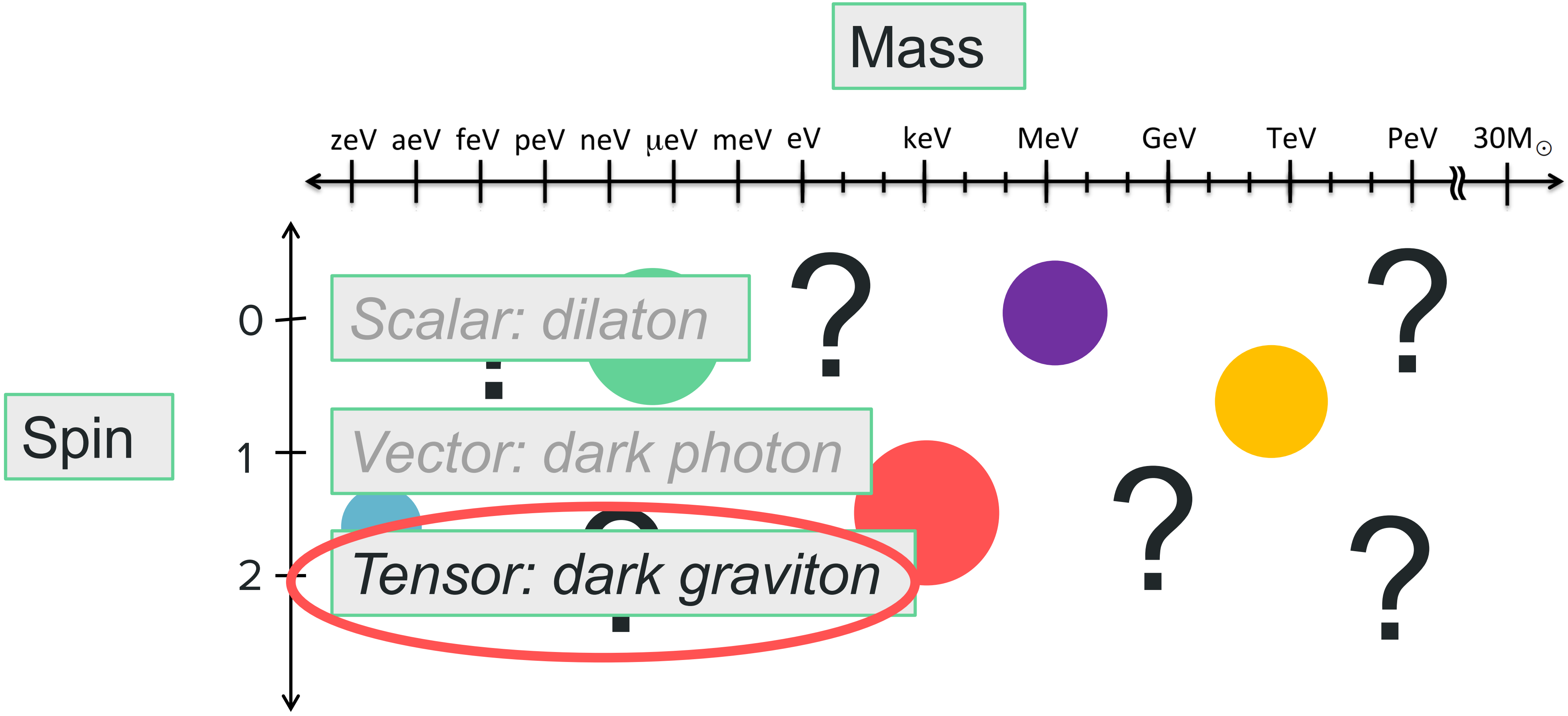
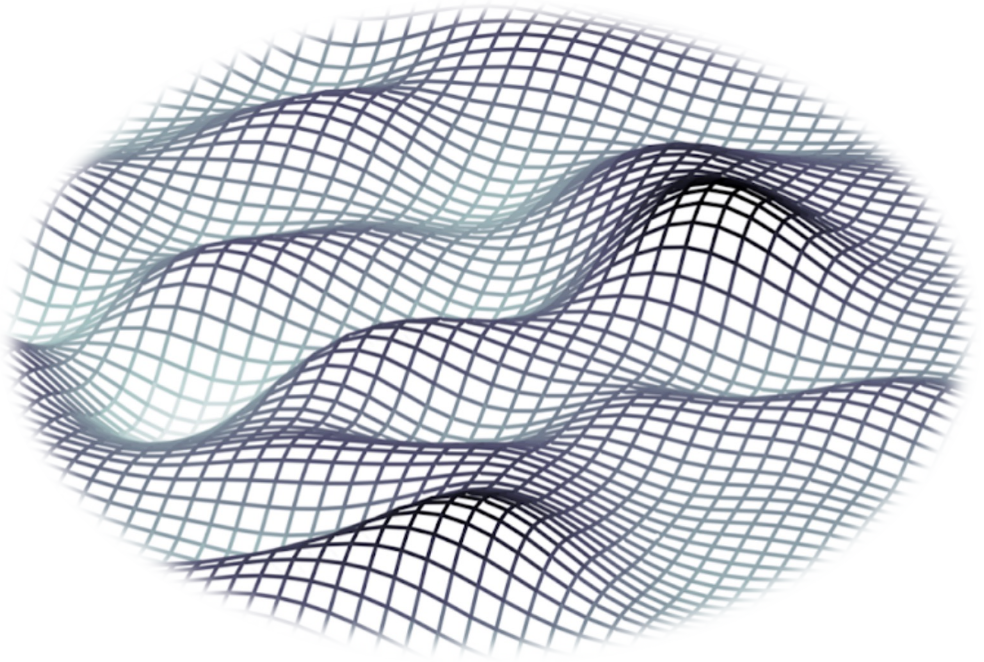


What about spin-2?



Massive gravity field theory



Let's consider a massive spin-2 ultra-light field $\varphi_{\mu\nu}$

Lorentz *invariant* massive spin-2 field

$$\mathcal{L}_{\mathrm{FP}} = \mathcal{L}_{\mathrm{EH}} - \frac{1}{4} m^2 \left(\varphi_{\mu\nu}\varphi^{\mu\nu} - \varphi^2\right)$$

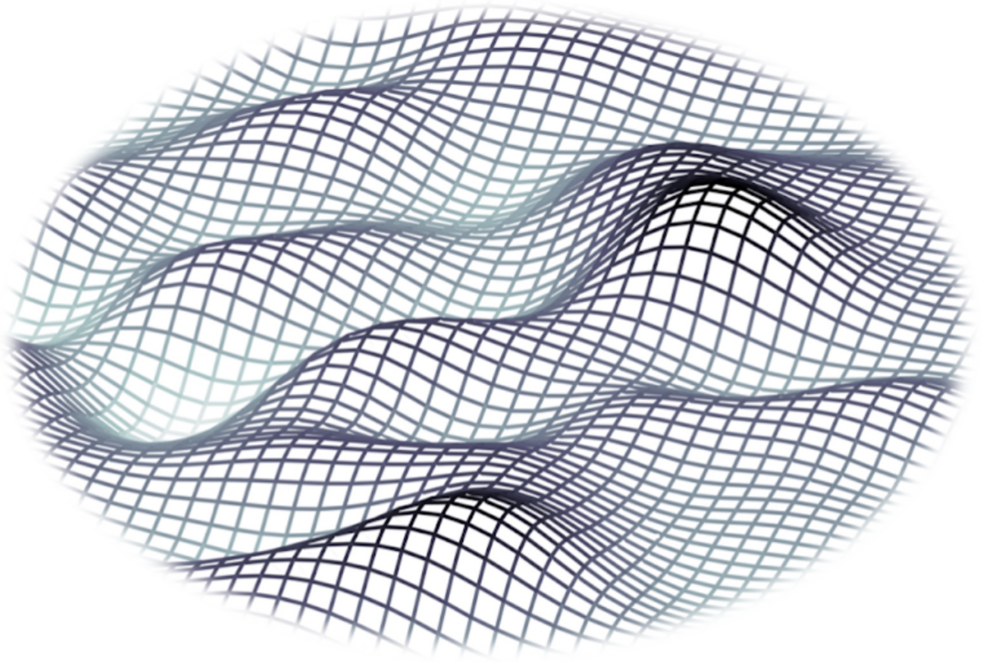
Fierz-Pauli Lagrangian

Lorentz *violating* massive spin-2 field

$$\mathcal{L} = \mathcal{L}_{\mathrm{EH}} - \frac{1}{4}\left(m_0^2\varphi_{00}^2 + 2m_1^2\varphi_{0i}^2 - m_2^2\varphi_{ij}^2 + m_3^2\varphi_i^i\varphi_j^j - 2m_4^2\varphi_{00}\varphi_i^i\right)$$

Massive gravity field theory

Let's consider a massive spin-2 ultra-light field $\varphi_{\mu\nu}$



Express as irreducible fields:

Tensor

Vector

Scalar

$$\varphi_{00} = \Psi$$

$$\varphi_{0i} = u_i + \partial_i v$$

$$\varphi_{ij} = \varphi_{ij}^{\mathrm{TT}} + 2\partial_{(i}A_{j)} + \partial_i\partial_j\sigma + \delta_{ij}\pi$$

Coupling to light and matter

Tensor | Vector | Scalar

$$\mathcal{L}_{\text{int}} = \kappa^{\phi}\varphi^{\mu\nu}\mathcal{O}_{\mu\nu} \longrightarrow \kappa_t\varphi^{ij}\mathcal{O}^t_{ij} + \kappa_v\varphi^{0i}\mathcal{O}^v_{0i} + \kappa_s\varphi^{00}\mathcal{O}^s$$

Non-relativistic limit

$$\frac{\beta^{(2)}}{\Lambda}\varphi^{\text{TT}}_{ij}F^{i\sigma}F^{j}_{\sigma} \qquad \left(\frac{\beta^{(0)}}{\Lambda}F^2 + m_\psi\frac{\alpha^{(0)}}{\Lambda}\overline{\psi}\psi\right)\widetilde{\pi}$$

In all theories

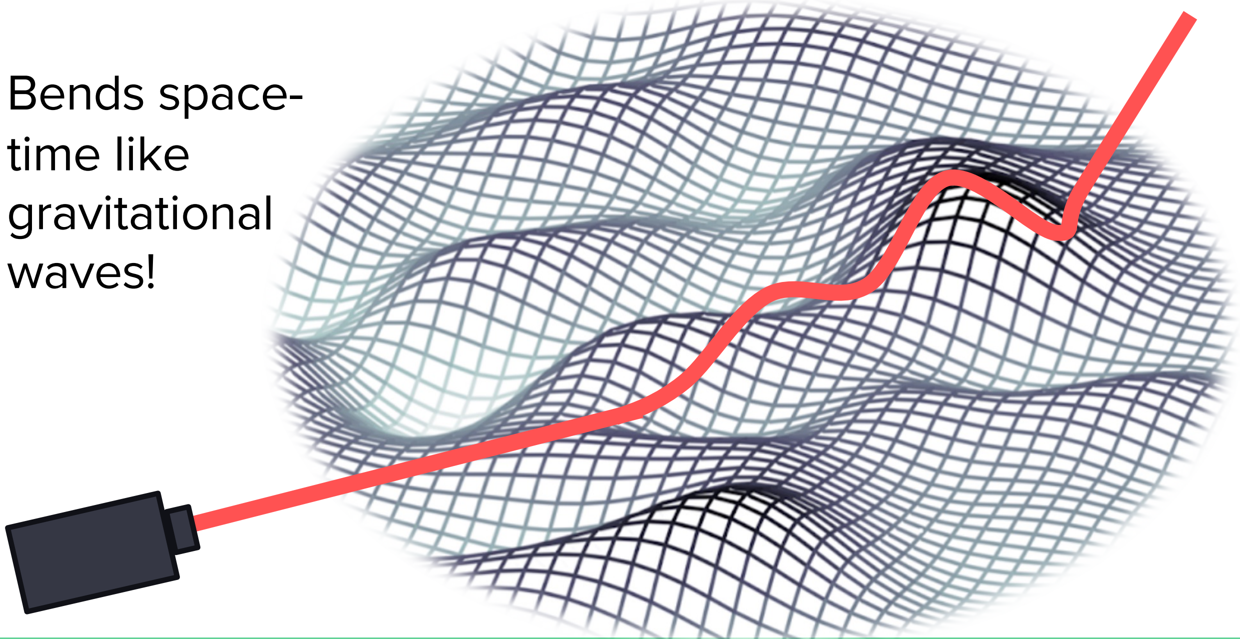
Only in Lorentz violating theories!

Coupling to light and matter

Tensor modes

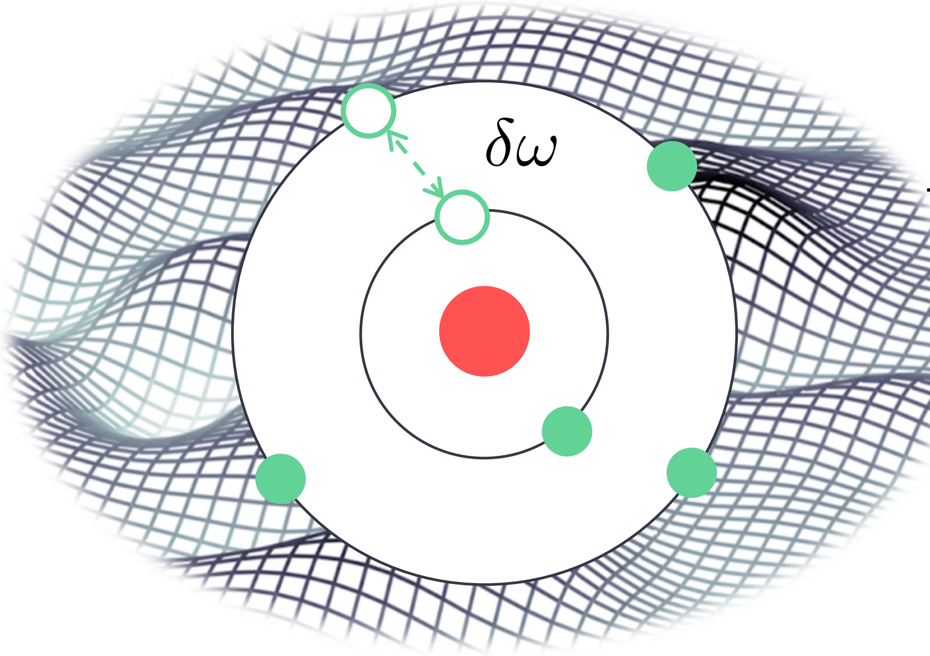
$$\frac{\beta^{(2)}}{\Lambda}\varphi_{ij}^{\mathrm{TT}} F^{i\sigma} F_{\sigma}^{j}$$

Bends space-time like gravitational waves!



Scalar modes

$$\left(\frac{\beta^{(0)}}{\Lambda}F^2 + m_\psi \frac{\alpha^{(0)}}{\Lambda}\overline{\psi}\psi\right)\widetilde{\pi}$$



Modifies atomic energy levels just like scalar ULDM!

All the possible couplings

Matter couplings

$$\mathcal{H} = \sqrt{\rho_{\mathrm{DM}}}\left(\frac{\alpha^{(0)}}{\Lambda}X(t) + \frac{\alpha^{(1)}}{\Lambda}v_A^i V_i(t) + \frac{\alpha^{(2)}}{\Lambda}v_A^i v_A^j M_{ij}(t)\right) m_A \delta^{(3)}(\vec{x} - \vec{x}_A(t))$$
$$+ \sqrt{\rho_{\mathrm{DM}}}\left(\frac{\beta^{(0)}}{\Lambda}(F^2 Y_1(t) + F_{0i}F^{0i}Y_2(t)) + \frac{\beta^{(1)}}{\Lambda}F_{\sigma 0}F^{i\sigma}W_i(t) + \frac{\beta^{(2)}}{\Lambda}F^{i\sigma}F_\sigma^j N_{ij}(t)\right)$$

Light couplings

D. Blas, J. Carlton, C. McCabe. arXiv: 2412.14282

All the possible couplings

Matter couplings

Electron mass variation

Atom propagation delay

$$\mathcal{H} = \sqrt{\rho_{\mathrm{DM}}} \left(\frac{\alpha^{(0)}}{\Lambda} X(t) + \frac{\alpha^{(1)}}{\Lambda} v_A^i V_i(t) + \frac{\alpha^{(2)}}{\Lambda} v_A^i v_A^j M_{ij}(t) \right) m_A \delta^{(3)}(\vec{x} - \vec{x}_A(t))$$

$$+ \sqrt{\rho_{\mathrm{DM}}} \left(\frac{\beta^{(0)}}{\Lambda} (F^2 Y_1(t) + F_{0i} F^{0i} Y_2(t)) + \frac{\beta^{(1)}}{\Lambda} F_{\sigma 0} F^{i\sigma} W_i(t) + \frac{\beta^{(2)}}{\Lambda} F^{i\sigma} F_{\sigma}^{j} N_{ij}(t) \right)$$

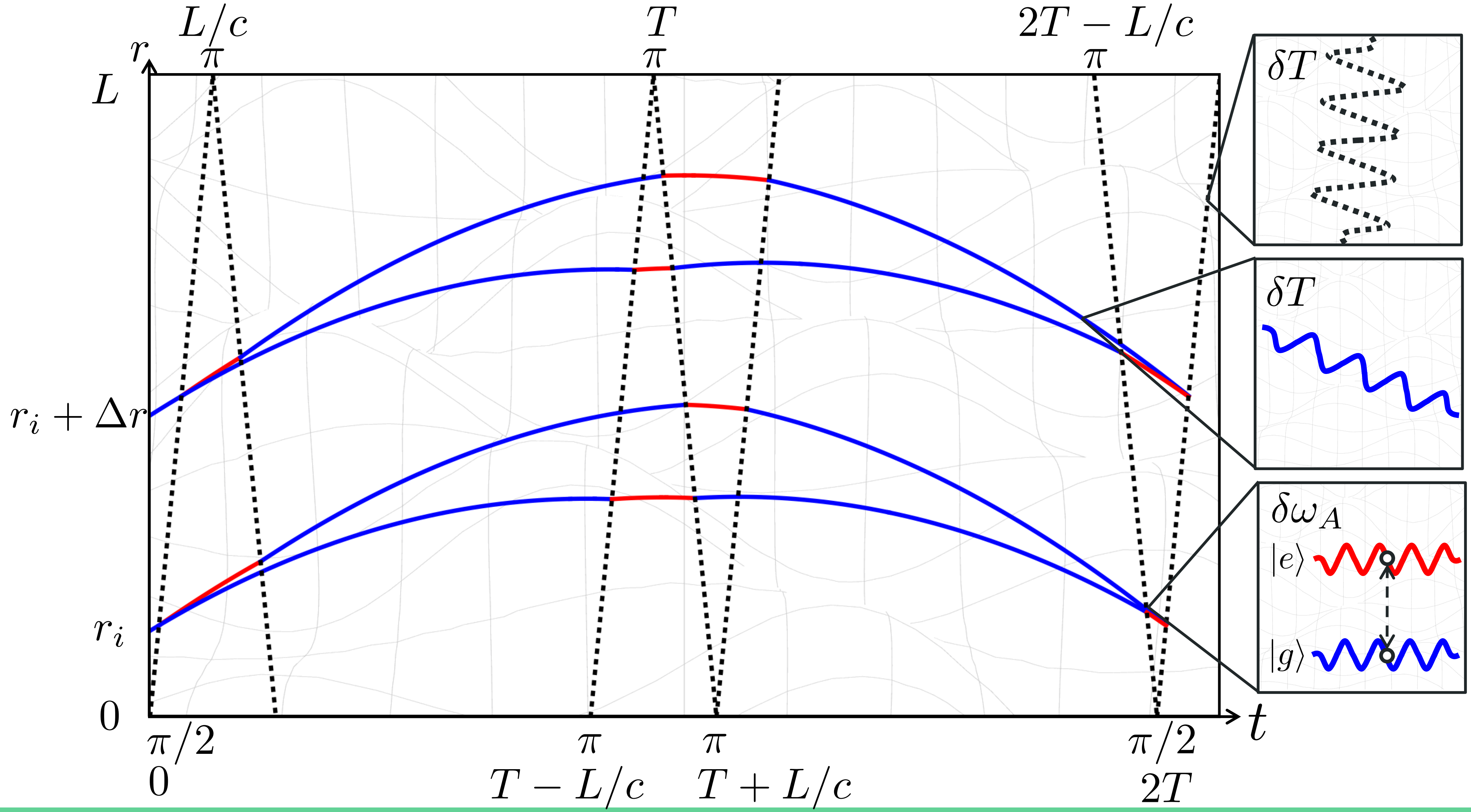
Fine structure variation

Light couplings

Laser propagation delay

D. Blas, J. Carlton, C. McCabe. arXiv: 2412.14282

Three sensitivity channels in atom interferometers!



Laser propagation delay (tensor)

Atom propagation delay (vector)

Electron energy level modification (scalar)

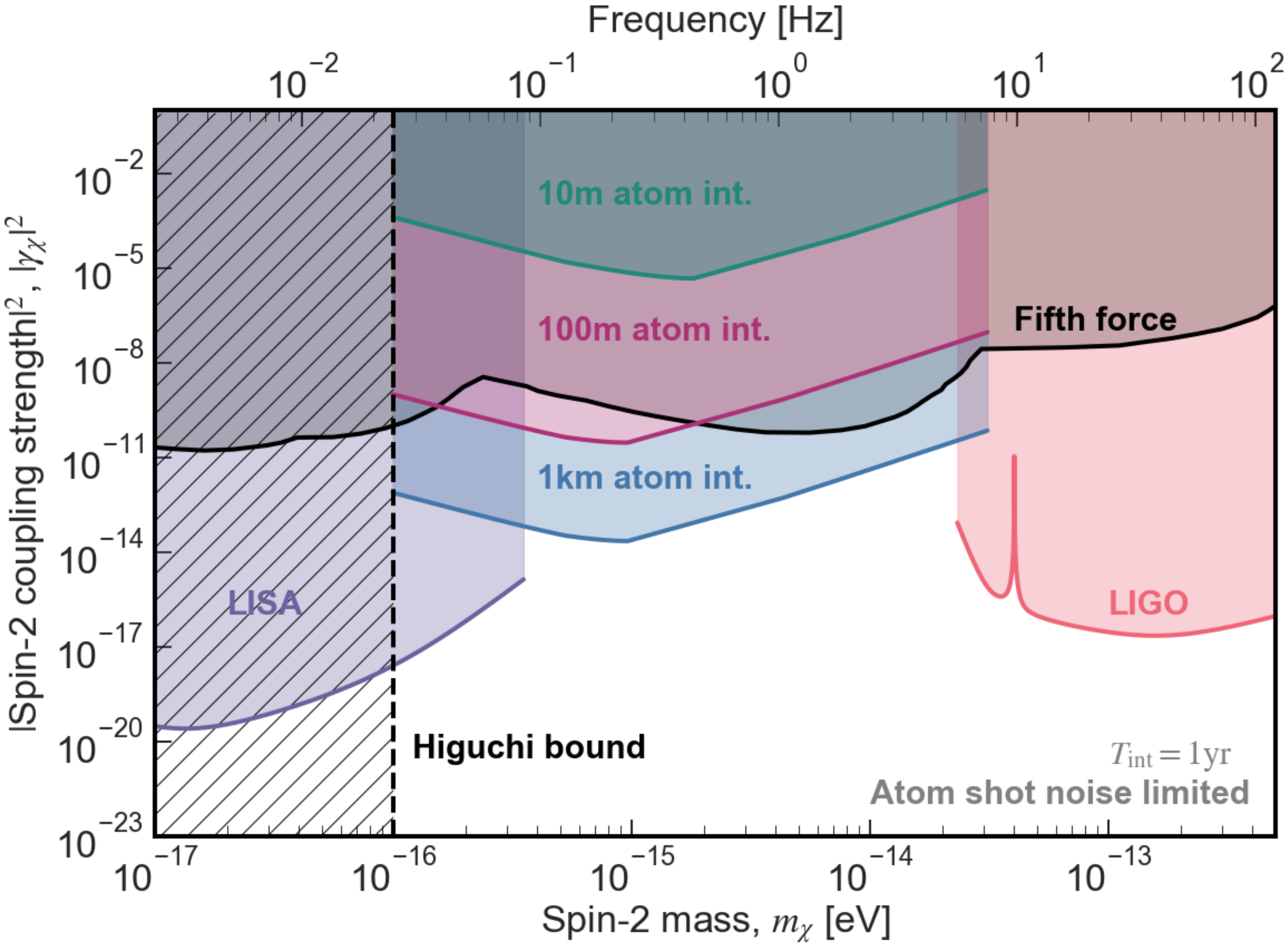
Projected detection limits

Leading constraints on scalar mode come from 'fifth force' experiments

$$\delta V_{\rm Newt} \propto (\alpha^{(0)})^2 e^{-m_s r}$$

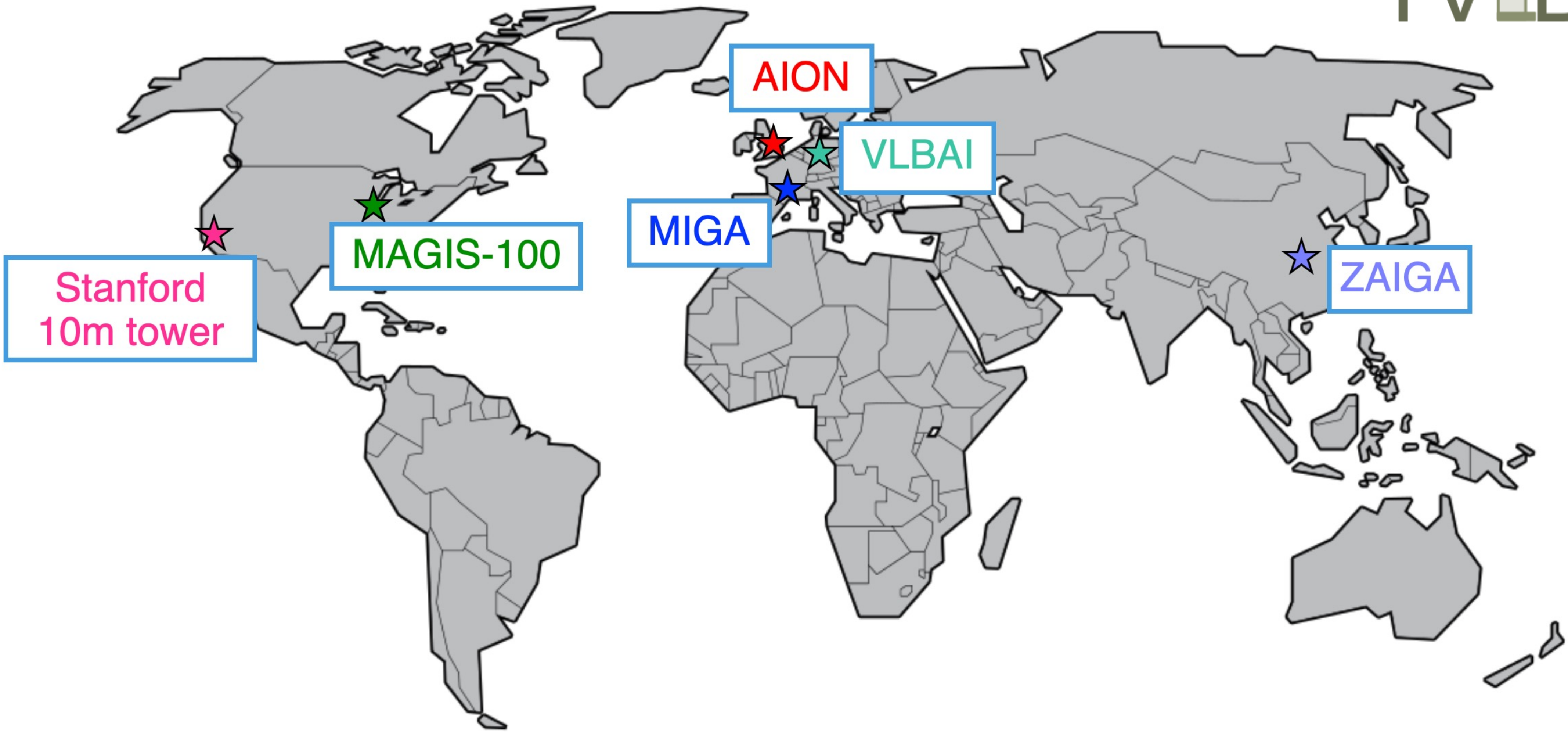
In this range, from lunar laser ranging

In absence of scalar mode, no constraints on vector and tensor modes!



D. Blas, J. Carlton, C. McCabe. arXiv: 2412.14282

Part of a global network!



Terrestrial very-long baseline atom interferometry workshop summary: arXiv: 2310.08183

Dark matter in the solar system

Based on J. Carlton, S. Gardner. (In progress)

Kim et al. (2112.05718), Budker et al. (2306.12477)
Widrow et al. (Astrophys.J.Lett. 416 1993)

Gravitational focusing of wave dark matter

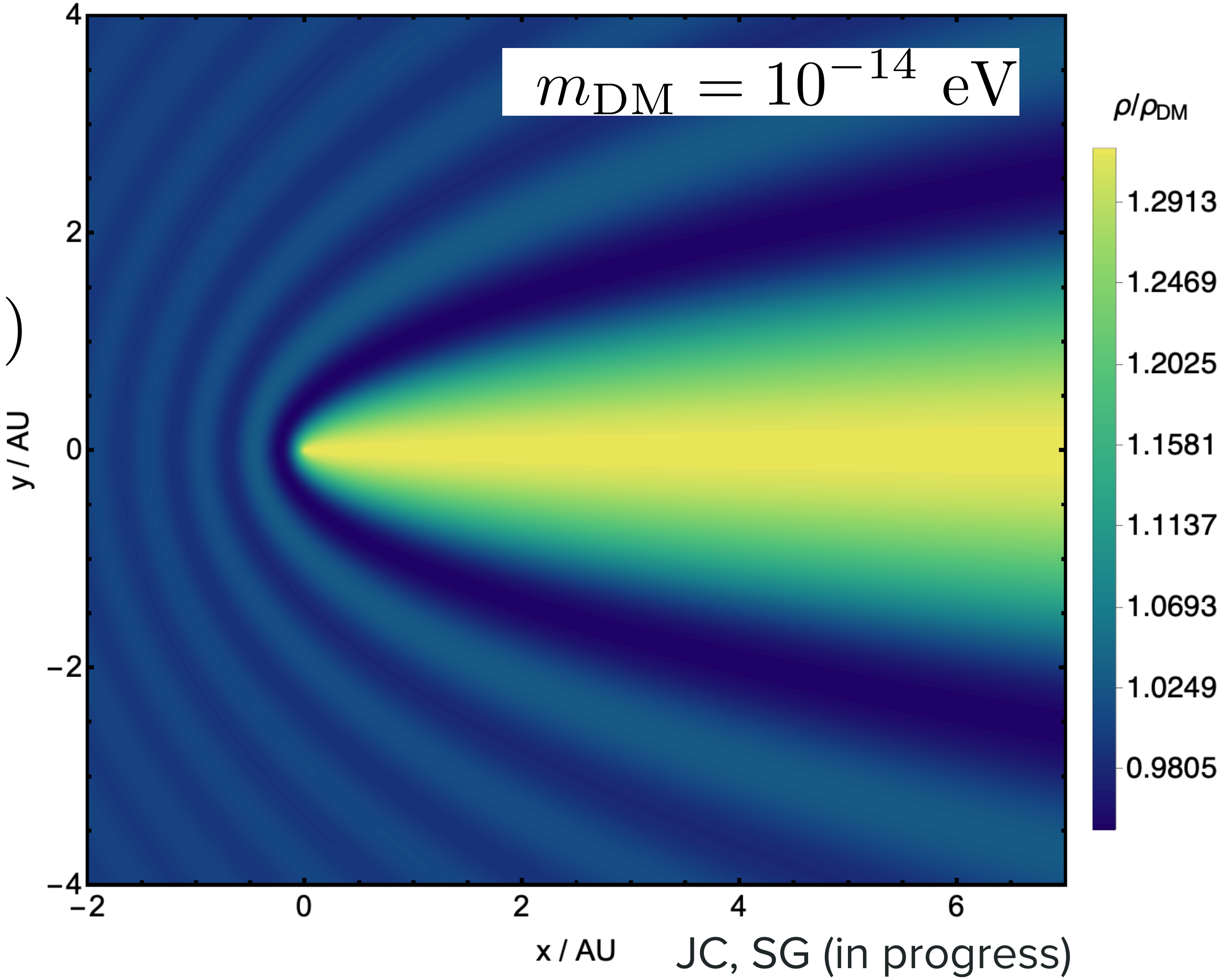
Under Schrödinger-Poisson formalism find analytic solutions to wave dark matter scattering analogous to Coulomb scattering

$$\psi(r,k) \propto {}_1F_1(i\xi_{\rm foc}/2\pi, 1, ikr(1-\hat{\mathbf{k}}\cdot\hat{\mathbf{r}}))$$

Controlled by focusing parameter

$$\xi_{\rm foc} = \frac{\lambda_{\rm dB}}{R_*} = \frac{\lambda_{\rm dB}}{1/GM_\odot m_{\rm DM}^2} = \frac{2\pi G M_\odot m_{\rm DM}}{v_{\rm DM}}$$

$\xi_{\rm foc} \ll 1$	$\xi_{\rm foc} \gg 1$	$\xi_{\rm foc} \sim 1$
No focusing	Too focused	Just right



JC, SG (in progress)

ULDM focused by the Sun

Sub-halo formation around celestial bodies

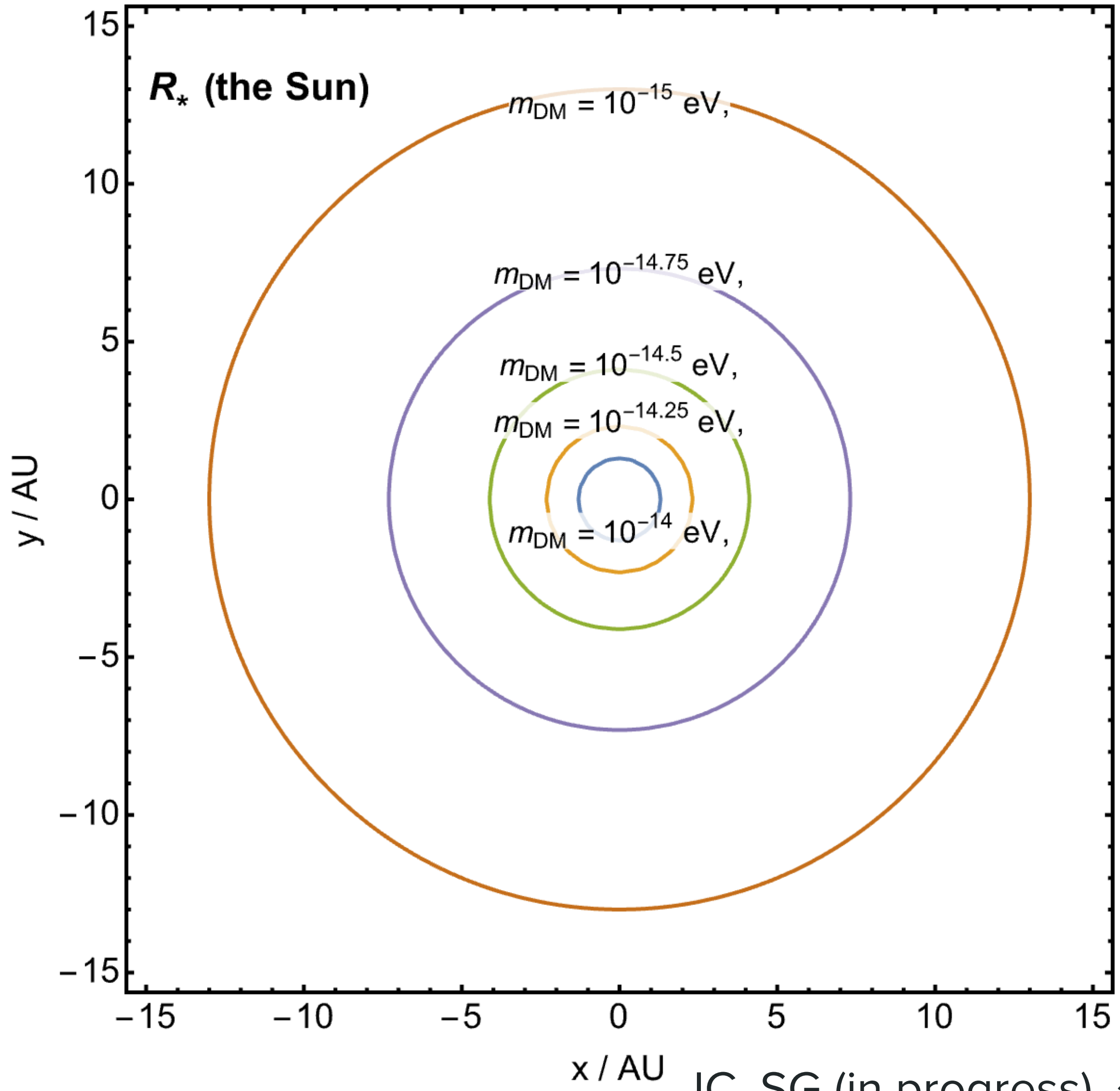
DM self-interactions can cause focused DM to slow down and become captured by celestial objects

Assume quartic self-interactions $V \supset \frac{\lambda}{4!}\varphi^4$

Where: $\lambda \equiv -m_{\mathrm{DM}}^2/f_a^2$

Relaxation time tracks sub-halo capture and growth process

$$\tau_{\mathrm{rel}} \equiv \frac{64 m_{\mathrm{DM}}^7 v_{\mathrm{DM}}^2}{\lambda^2 \rho_{\mathrm{DM}}^2}$$



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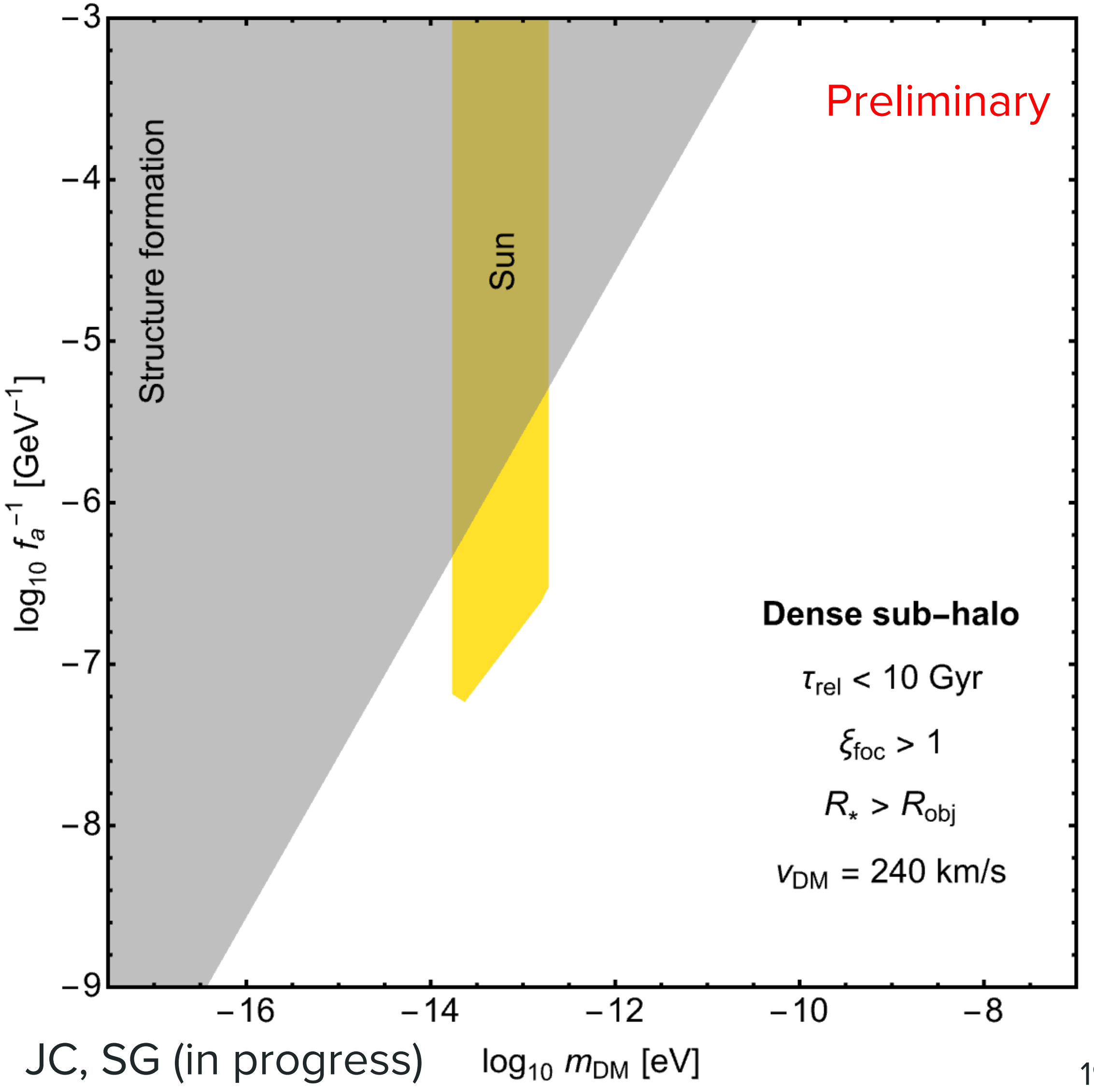

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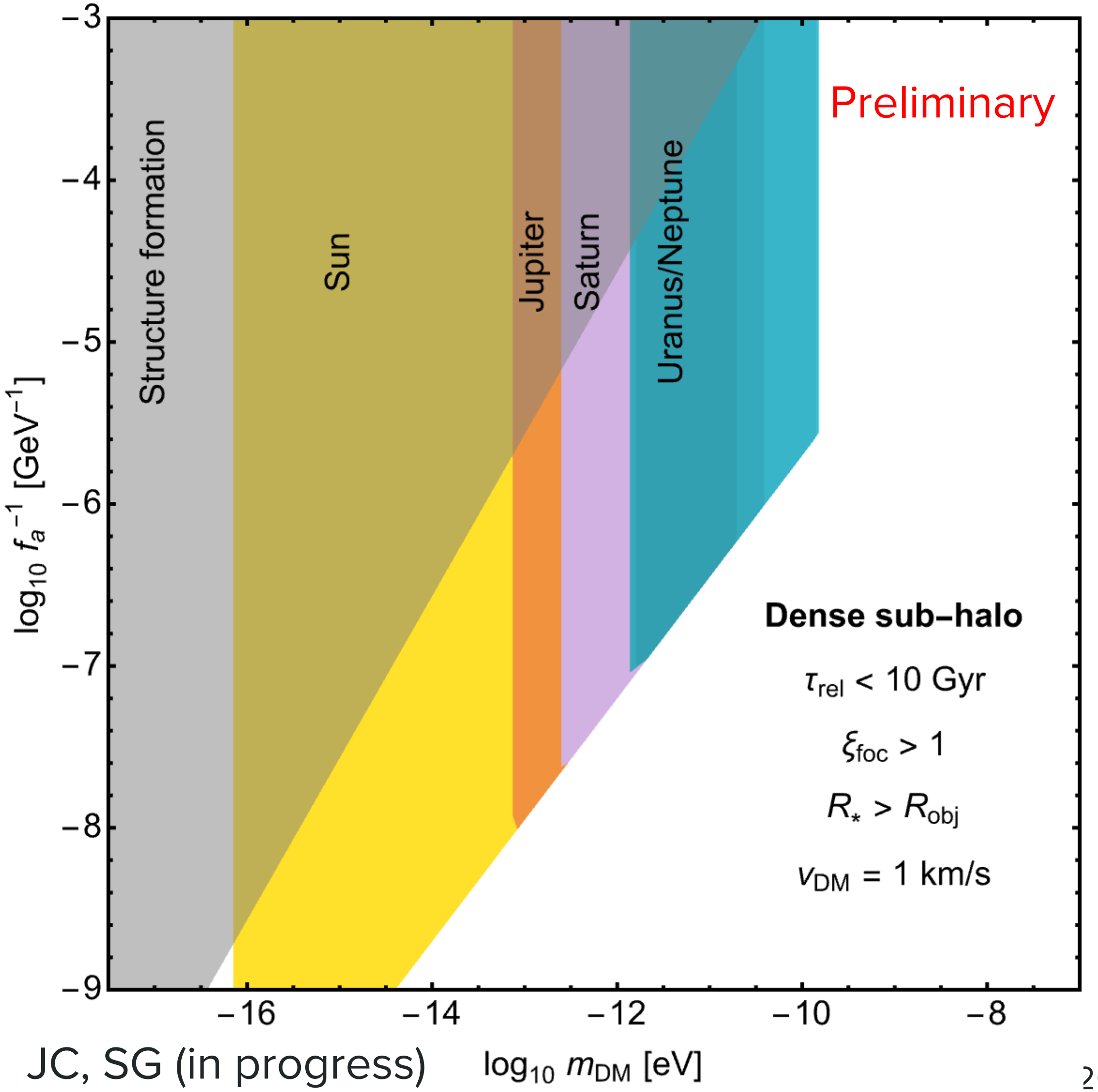
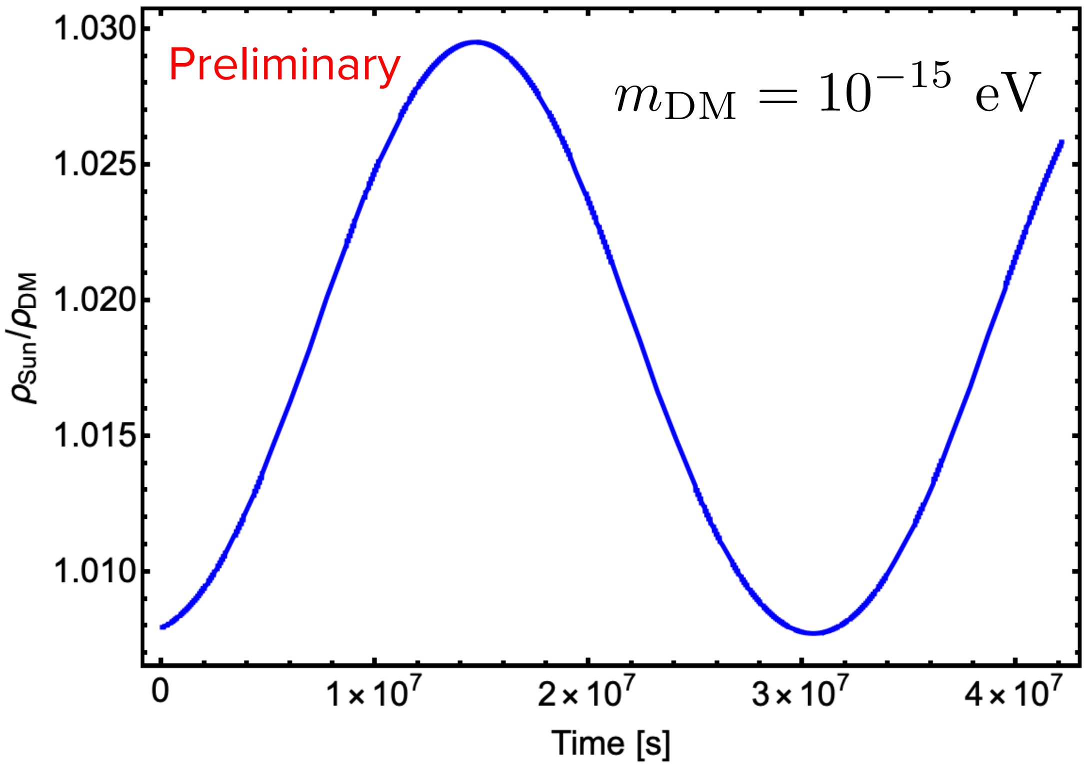


JC, SG (in progress)

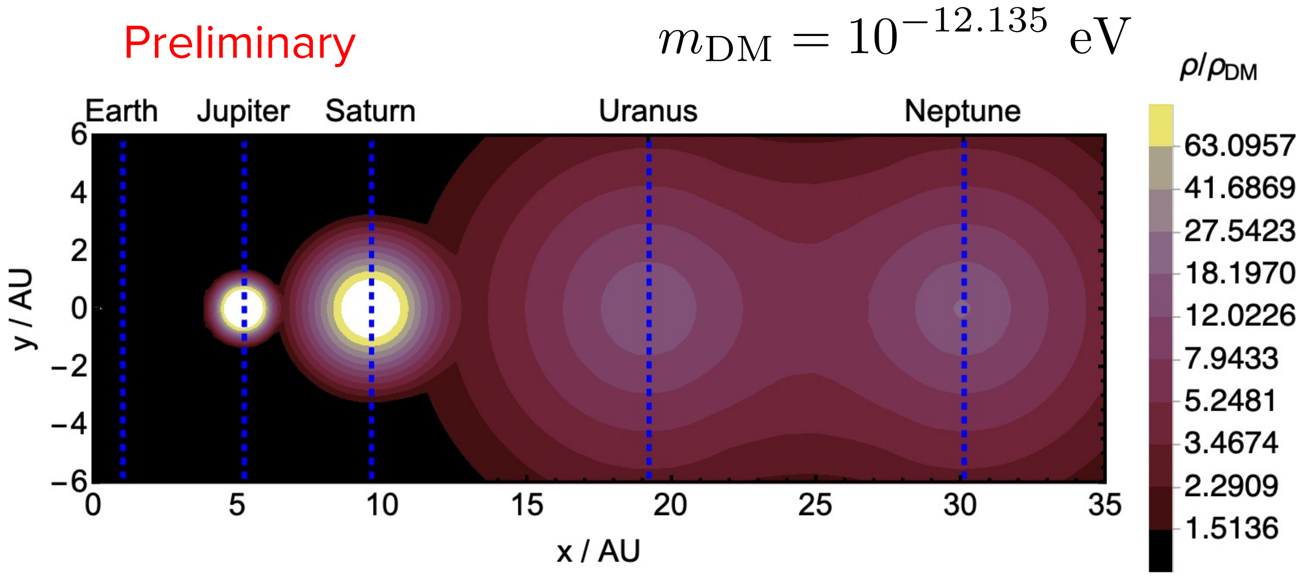
Experimental signatures – over-densities

Unbound (gravitational focusing)



Oscillating lighthouse effect of solar-focused dark matter density on Earth

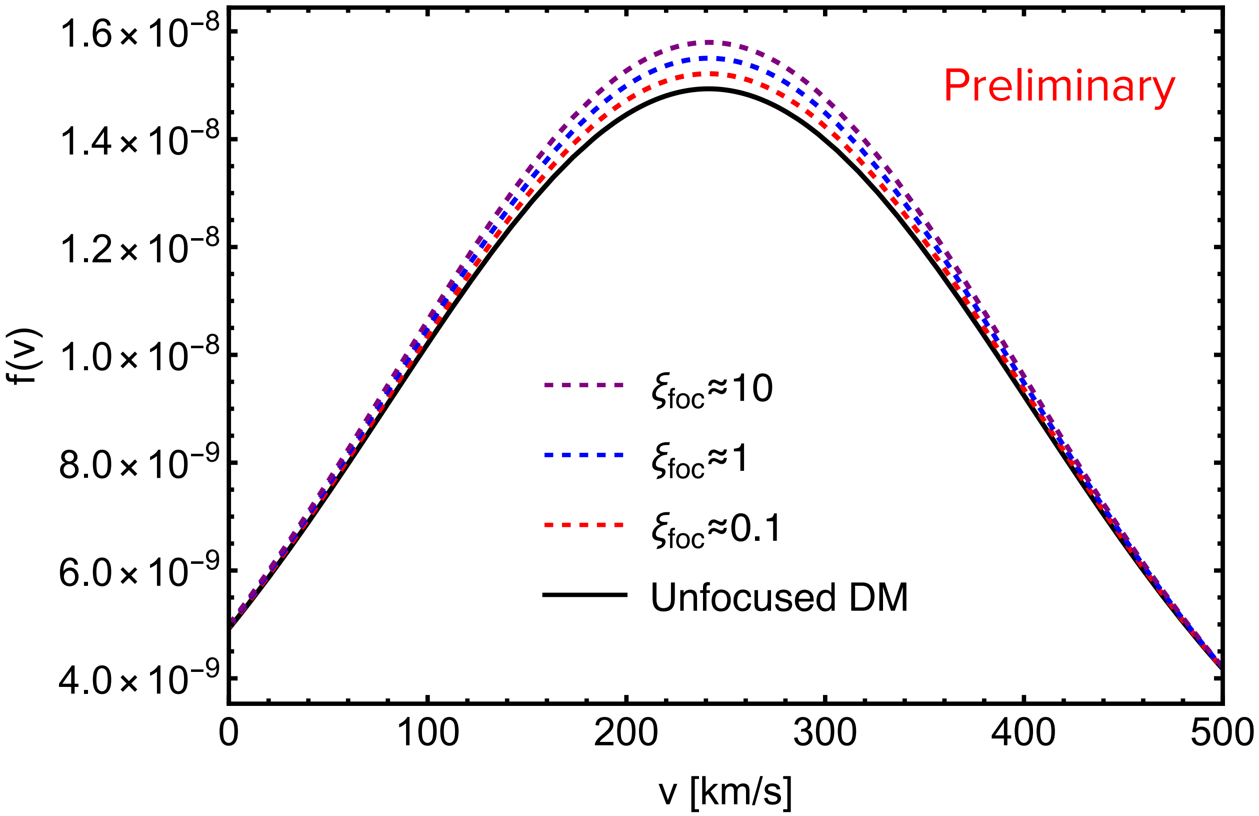
Bound (gravitational atoms)



Over-dense sub-halos form around the Sun and planets potentially overlapping

Experimental signatures – coherence time

Unbound (gravitational focusing)



Velocity dispersion narrows, coherence time increases

Bound (gravitational atoms)

In bound states, velocity becomes

$$v_b = \sqrt{\frac{GM_\odot}{R_*}}$$

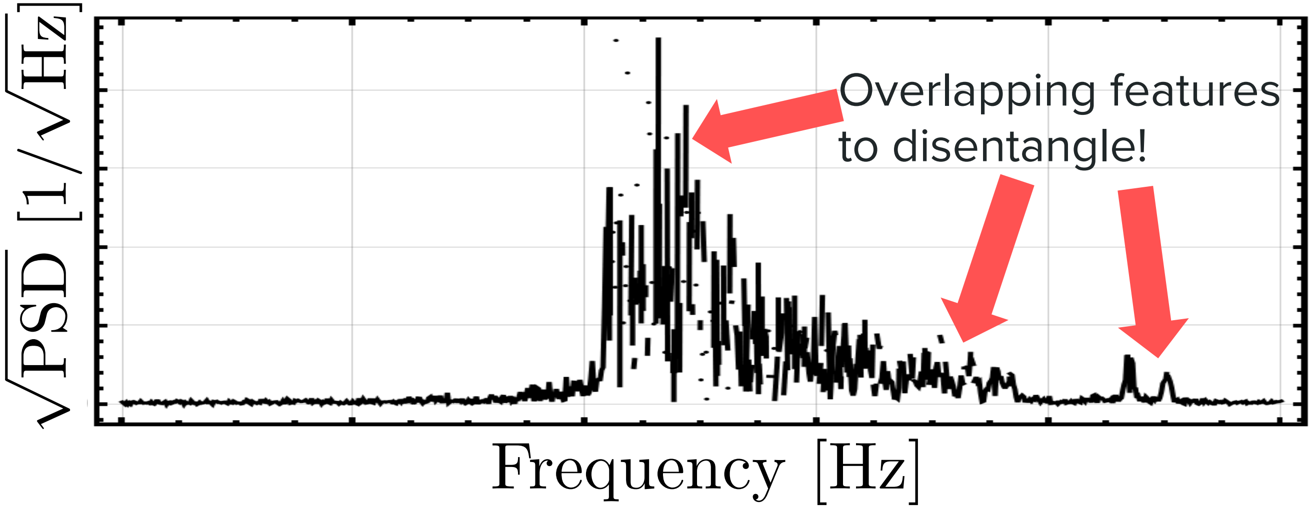
Dispersion tends to zero, coherence time tends to infinity

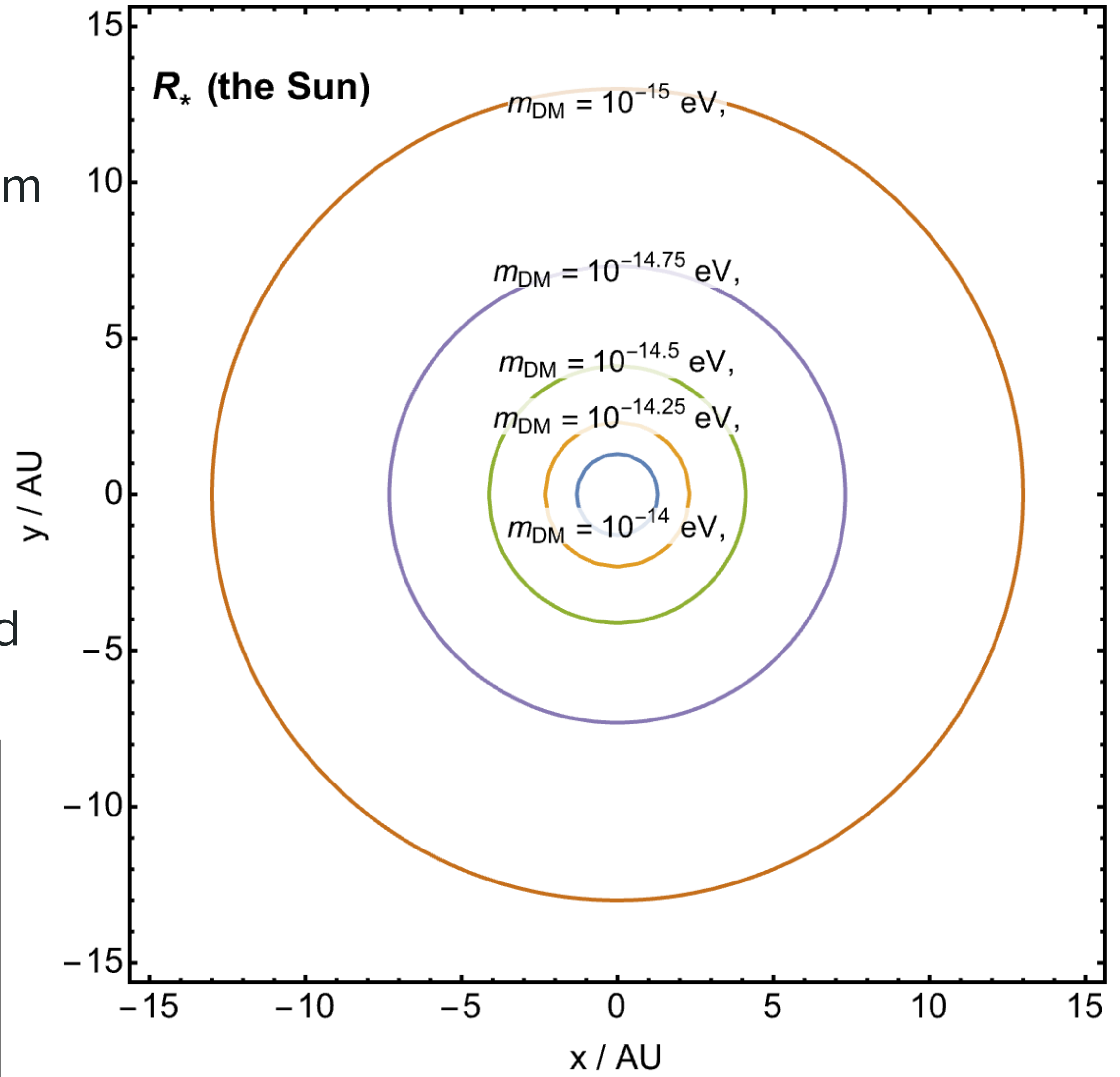
Multi-axion halos and focusing

The **string axiverse** and other theories predict a spectrum of axion masses that could make up dark matter

$$\rho_{\rm DM} = \sum_i \rho_i = \sum_i \frac{1}{2} m_i^2 f_i^2 \theta_i^2$$

Each of these are a small subcomponent of the total dark matter, relaxing constraints on self-interactions and allowing many overlapping dense sub-halos to form!

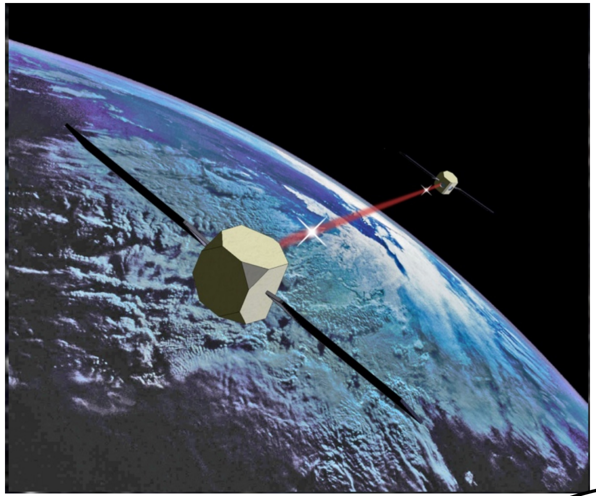


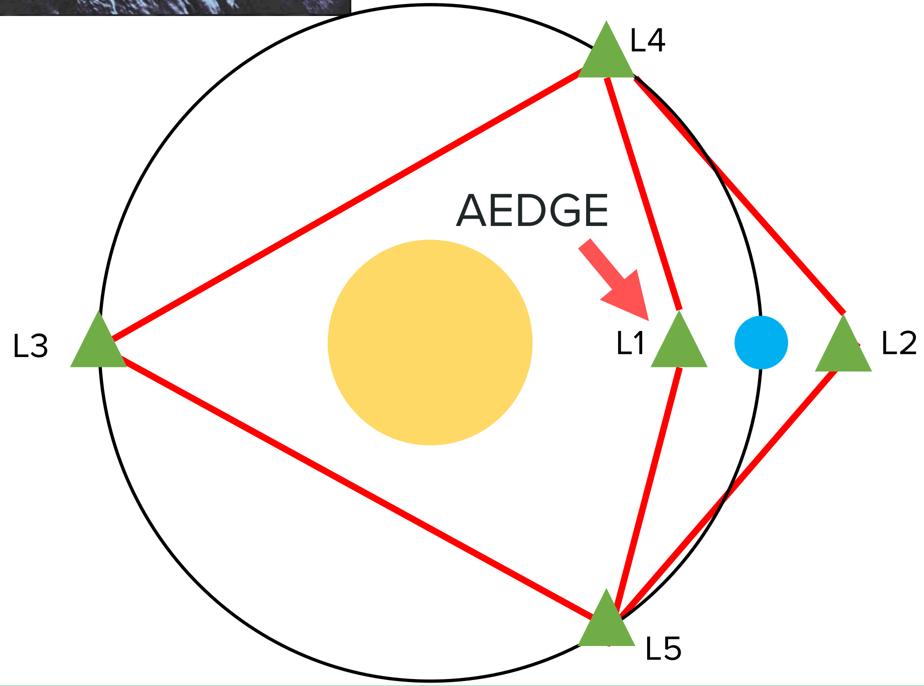


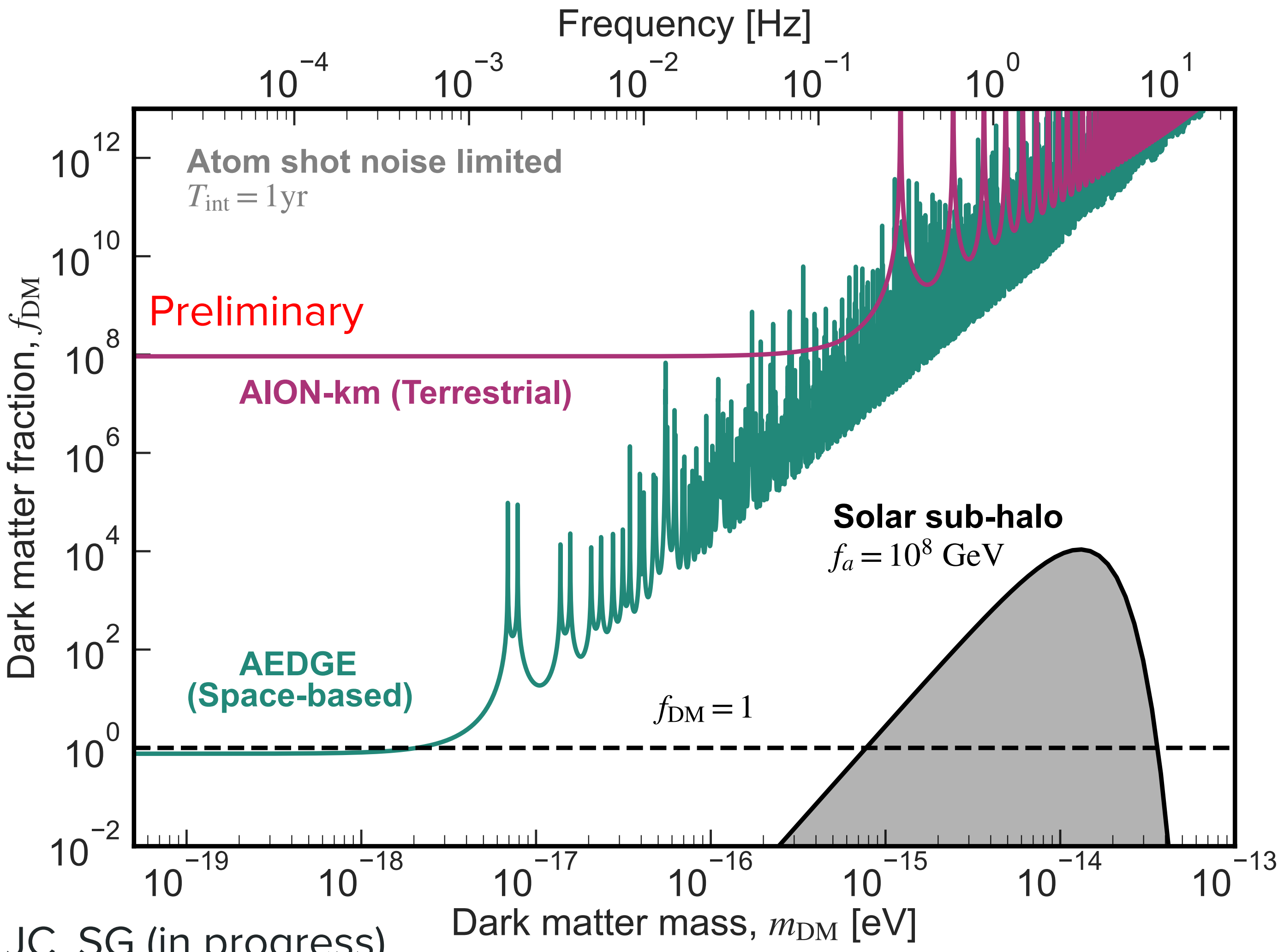
Solar onion with many overlapping halos

Badurina et al. (2505.00781)

Detection scenarios in space



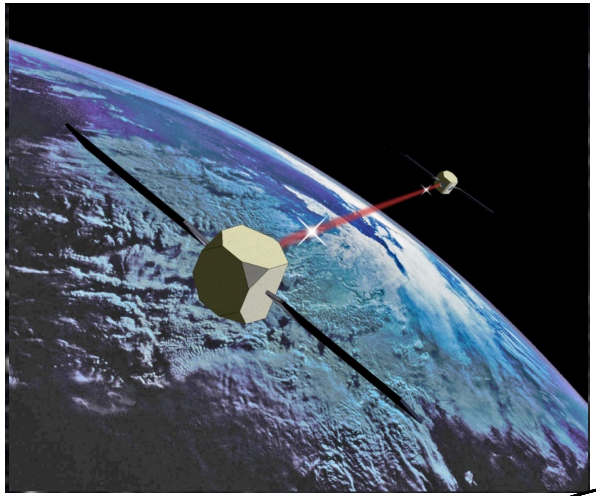


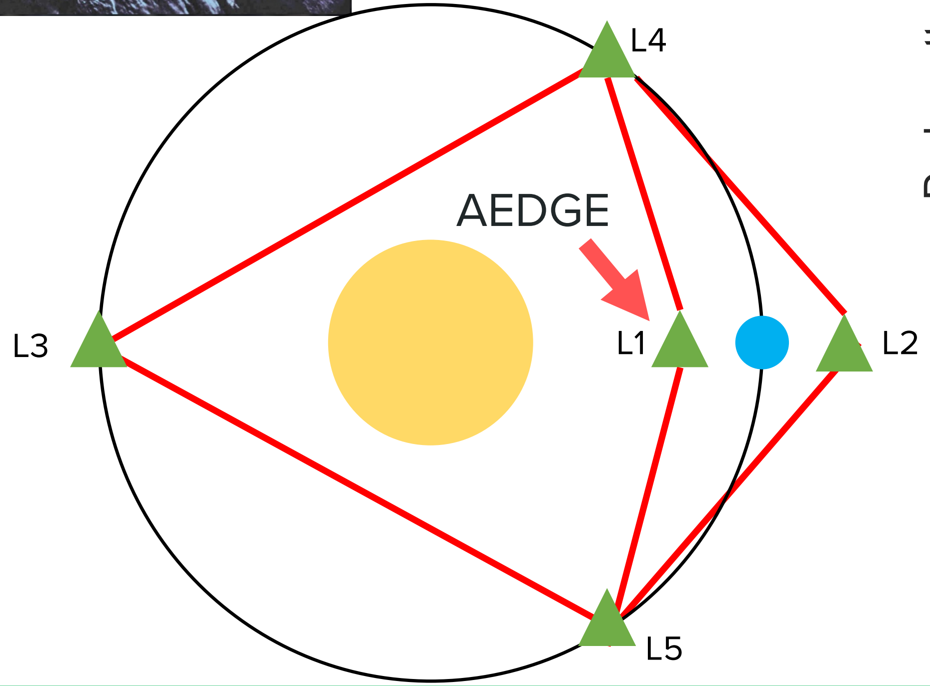


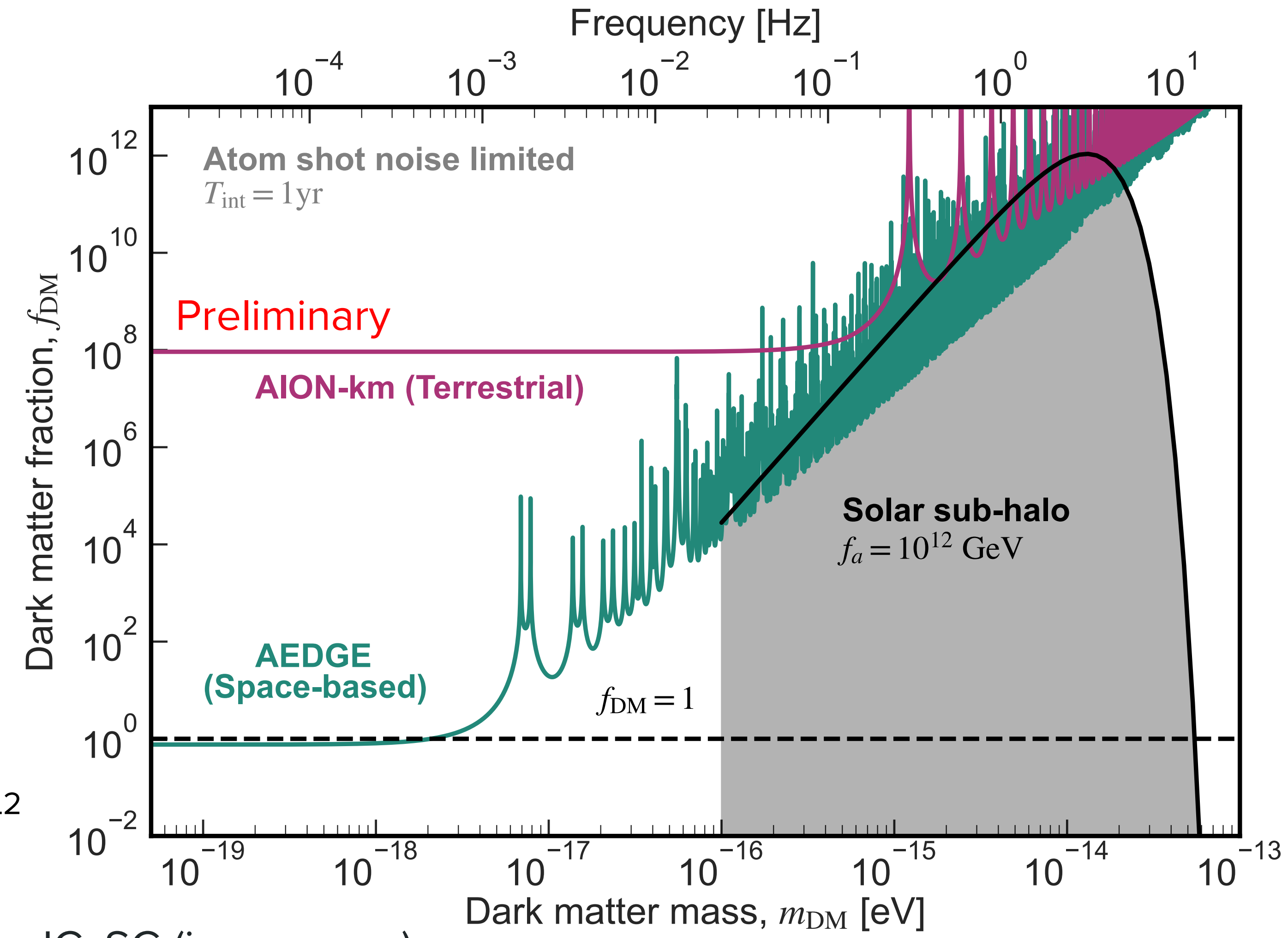
JC, SG (in progress)

Optimistic atom interferometry bounds

Detection scenarios in space







JC, SG (in progress)

Optimistic atom interferometry bounds

Summary

Upcoming quantum sensor experiments have an increasingly rich phenomenology of candidates and signatures to explore!

Spin-2 ULDM is naturally probed by atom interferometers through several different channels! Other GW/ULDM experiments may also detect other couplings not probed by atom interferometers.

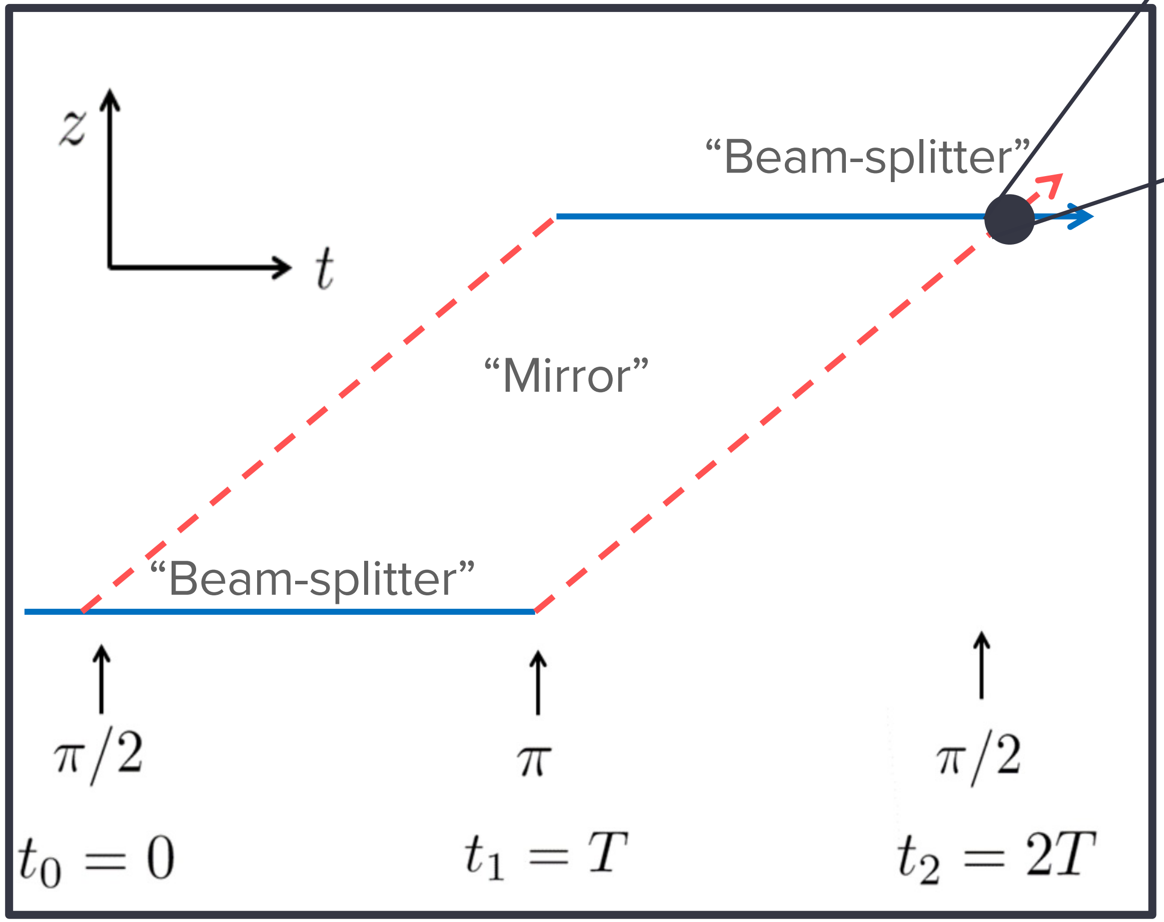
Generic features of ULDM in the solar system may lead to new search strategies and motivate space-based quantum sensors. Results are even more promising in multi-DM scenarios!

D. Blas, J. Carlton, C. McCabe. arXiv: 2412.14282

J. Carlton, S. Gardner. (In progress)

Back up

Interferometer sequence



Mach-Zehnder
interferometer

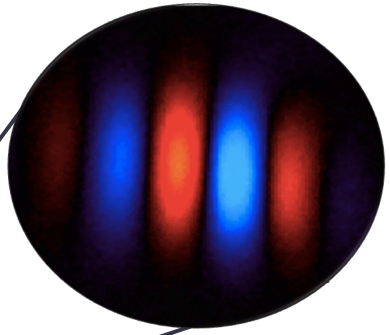
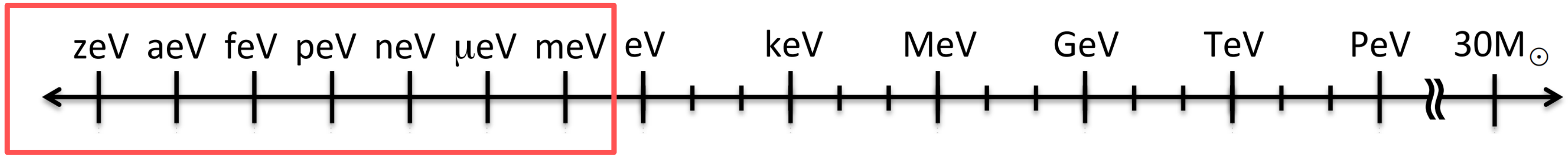


Image atom fringes
and measure phase

$$\phi_{\mathrm{MZ}} = kgT^2$$

Leading order phase depends
on gravitational acceleration

A classical ULDM field



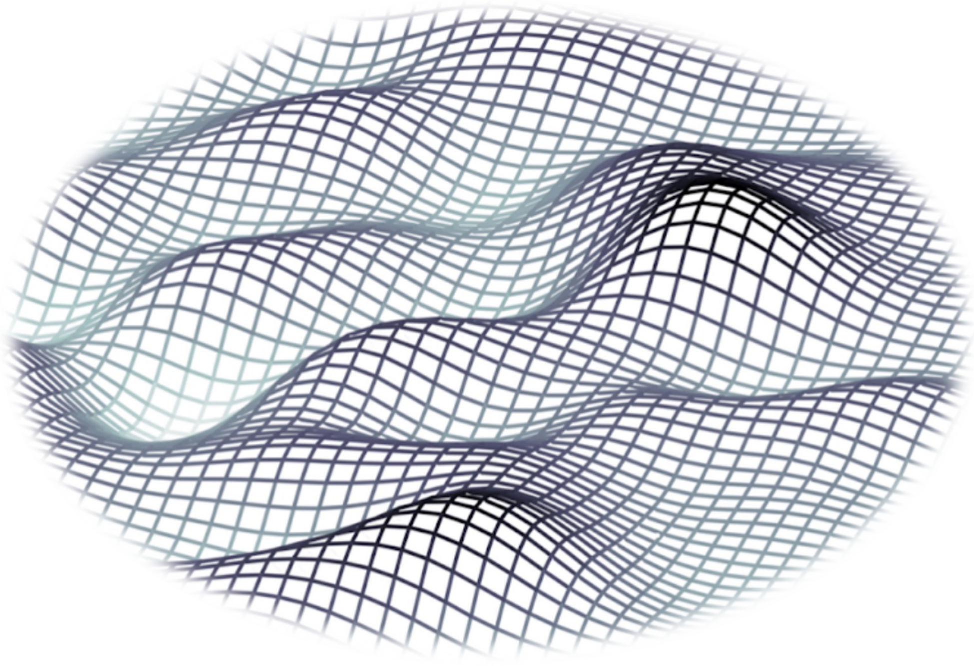
Ultralight mass means a high occupation number

Can describe as a classical field

$$\varphi(t, \mathbf{x}) \sim \cos(\omega_\varphi t - \mathbf{k}_\varphi \cdot \mathbf{x})$$

Frequency given by ULDM mass
(with small velocity correction)

$$\omega_\varphi \simeq m_\varphi \left(1 + \frac{v^2}{2}\right)$$



Badurina et al. arxiv: 2109.10965

Atoms in a scalar ULDM field

photon coupling

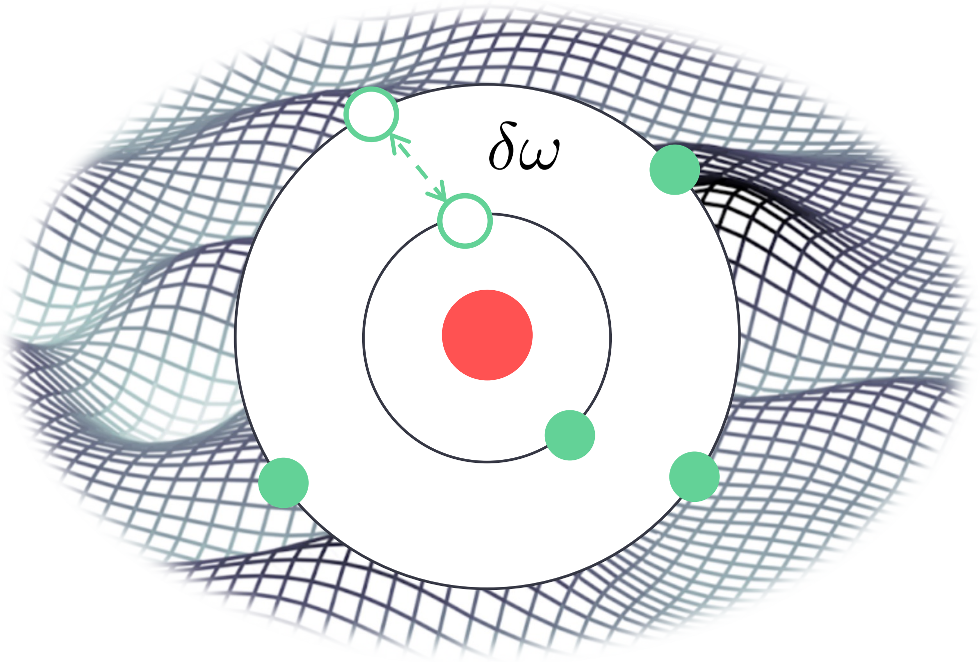
electron coupling

$$\mathcal{L} \supset \mathcal{L}_{\rm SM} + \boxed{\mathcal{L}_\varphi} \longrightarrow \boxed{\mathcal{L}_\varphi \supset \varphi(t,\boldsymbol{x})\sqrt{4\pi G_{\rm N}}\left[\frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu} - d_{m_e} m_e \bar{\psi}_e \psi_e\right]}$$

$$\alpha(t,\boldsymbol{x}) \approx \alpha\left[1 + d_e\sqrt{4\pi G_{\rm N}}\,\varphi(t,\boldsymbol{x})\right],$$

$$m_e(t,\boldsymbol{x}) = m_e\left[1 + d_{m_e}\sqrt{4\pi G_{\rm N}}\,\varphi(t,\boldsymbol{x})\right]$$

$$\delta\phi \sim \delta\omega \sim \varphi(t,\boldsymbol{x})$$



Badurina et al. arxiv: 2109.10965

Two sensitivity channels

Interrogation time (GWs)

Atomic transition frequency (Scalar ULDM)