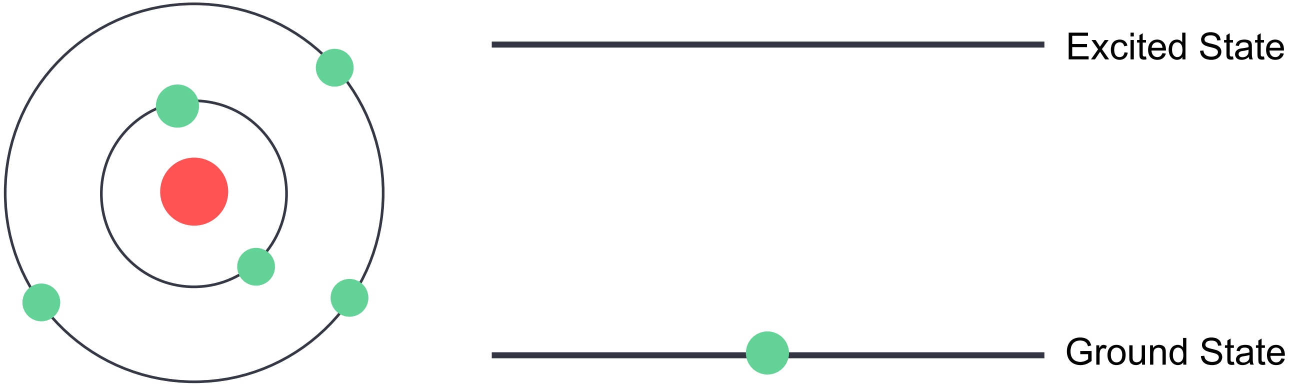
Consider a 2-level atom



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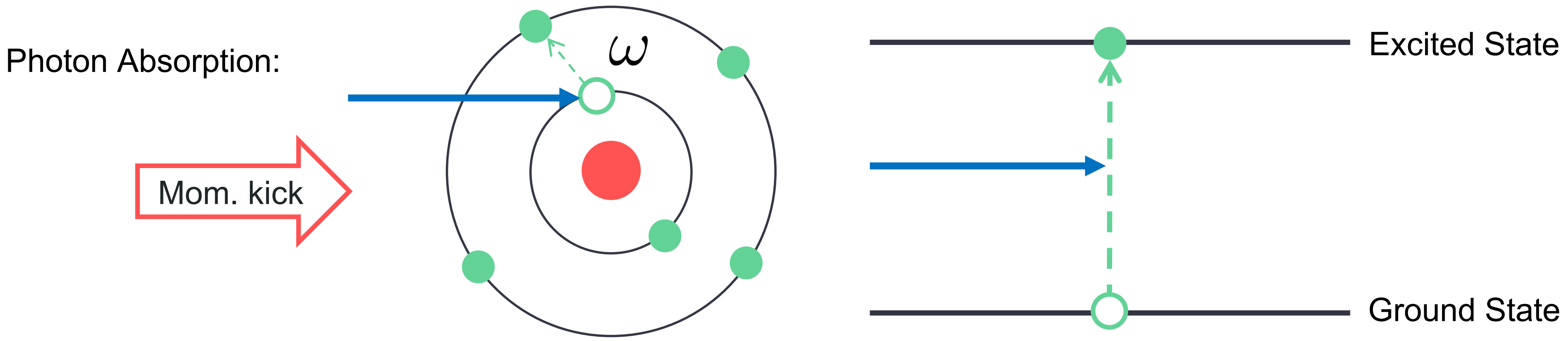

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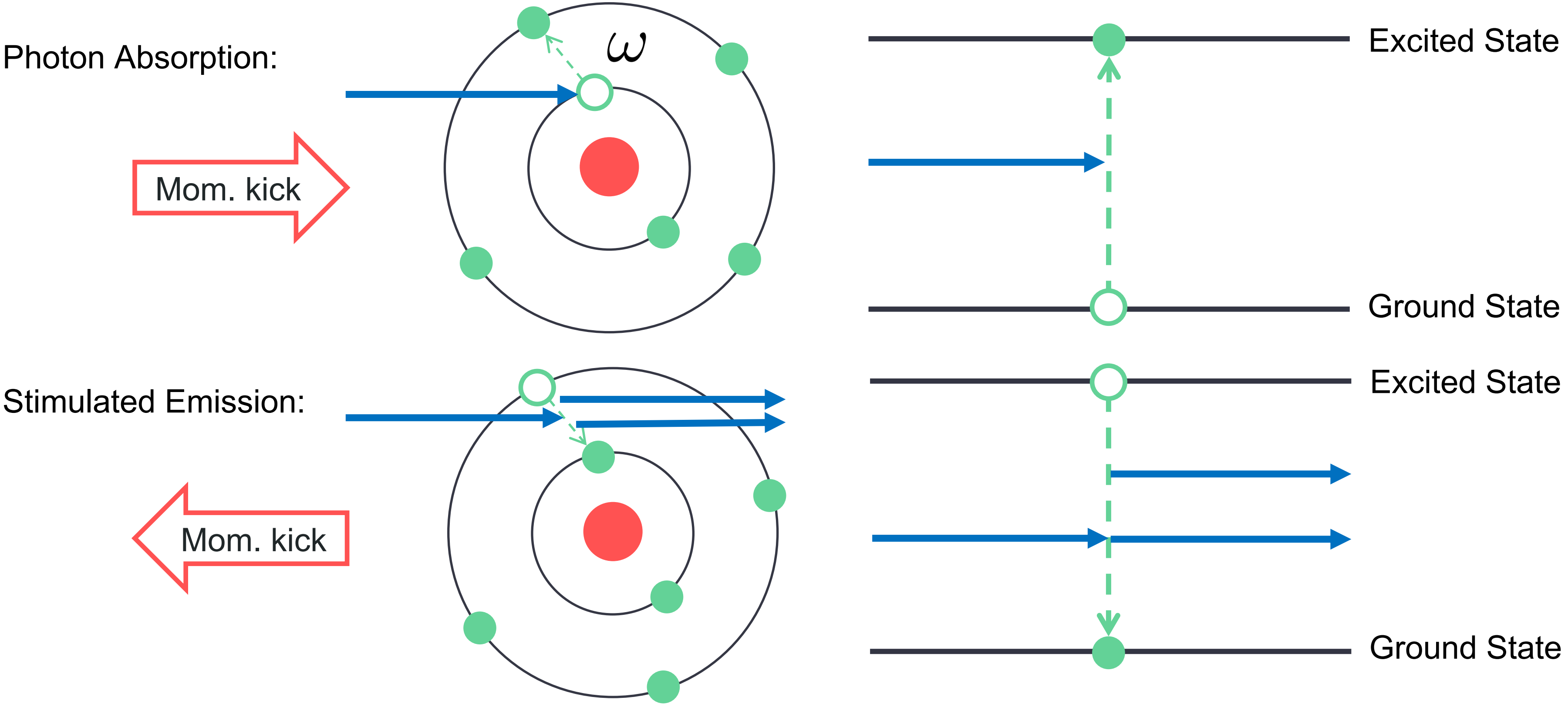
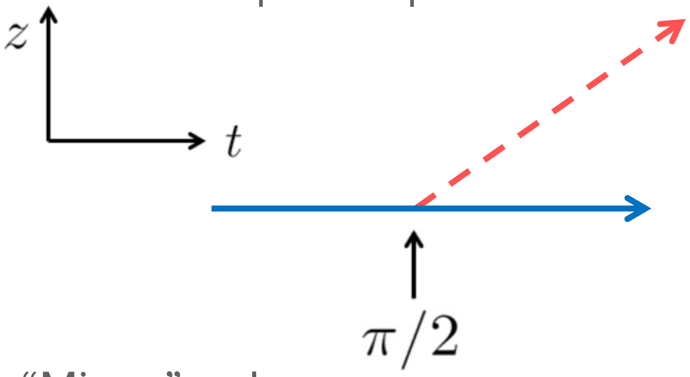
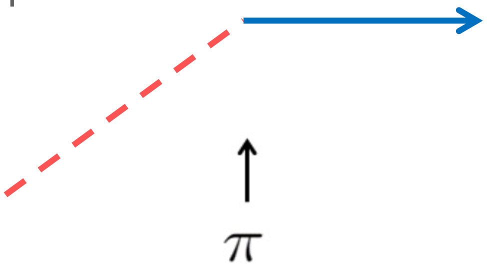


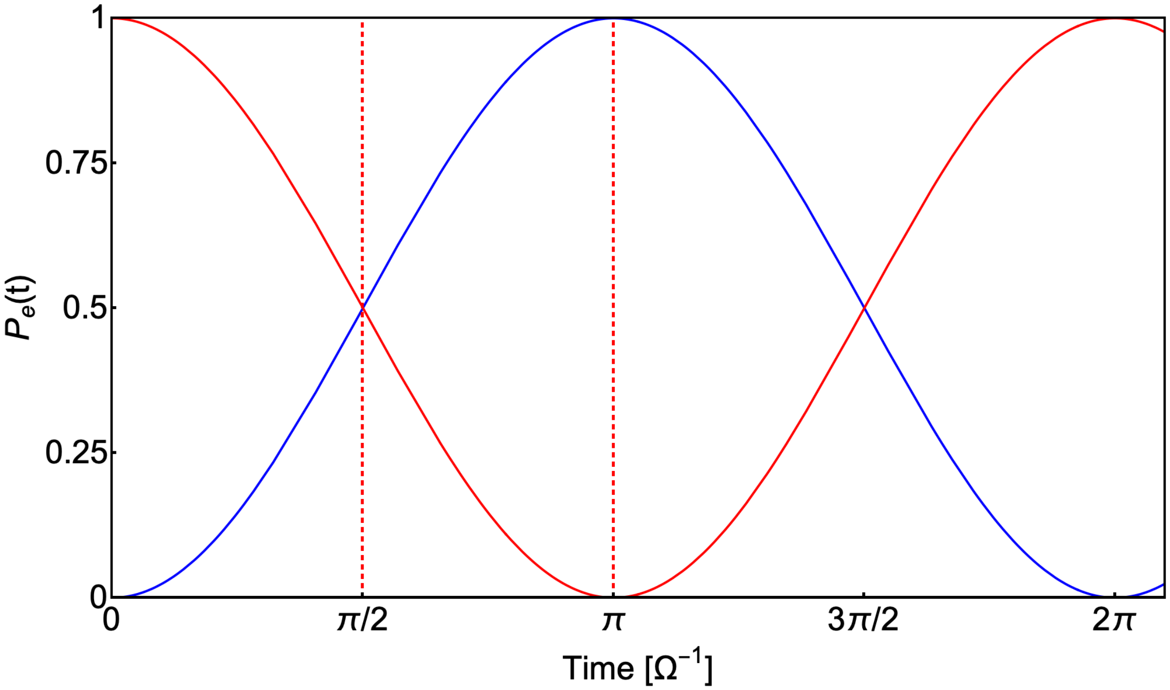
Rabi oscillations

"Beam-splitter" pulse:

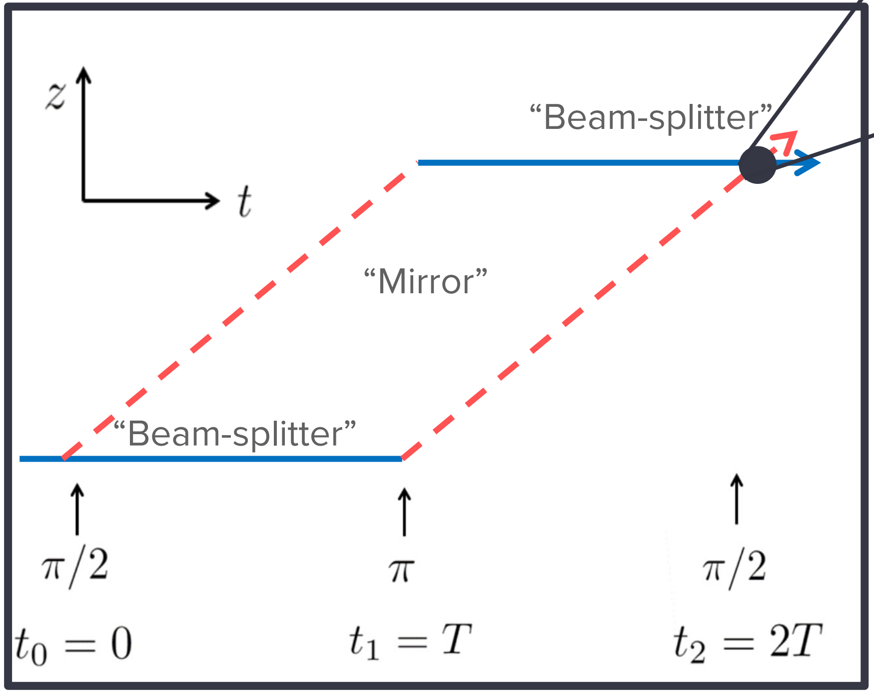


"Mirror" pulse:





Interferometer sequence



Mach-Zehnder interferometer

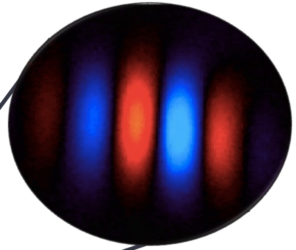


Image atom fringes and measure phase

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

Leading order phase depends on gravitational acceleration

On massive gravitons, atmospheric turbulence and RATs in atom interferometry

John Carlton

john.carlton@desy.de

Hallo!

Top 3 research interests:

- Dark matter
- Quantum sensors
- Gravitational waves

2017-2021

MSci
University of Birmingham

2021-2025

PhD
King's College London

2025-2025

(Very short) Postdoc
University of Kentucky

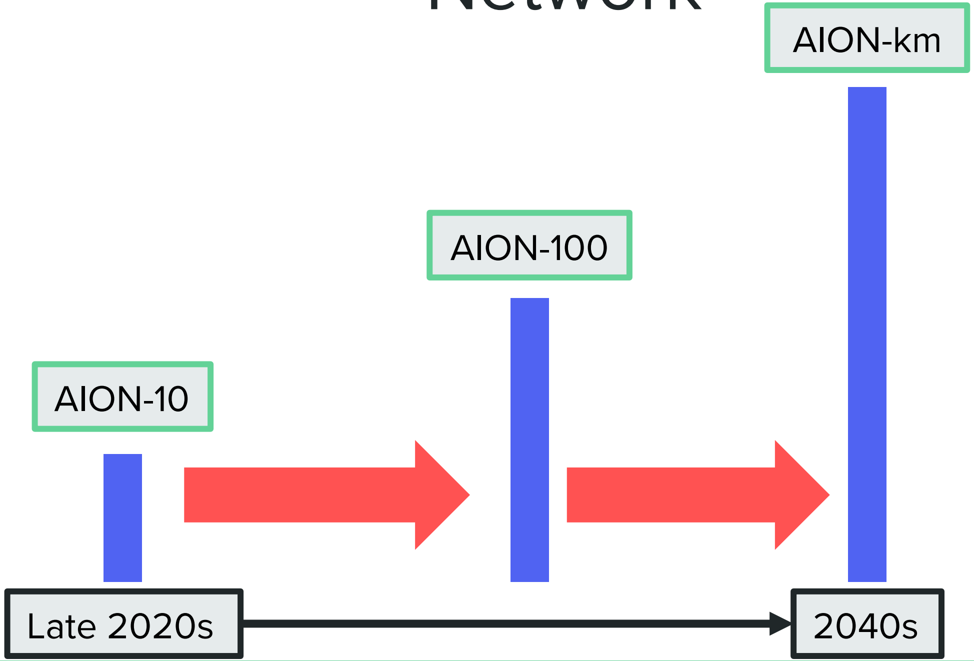
2026

(Hopefully much longer) Postdoc
DESY

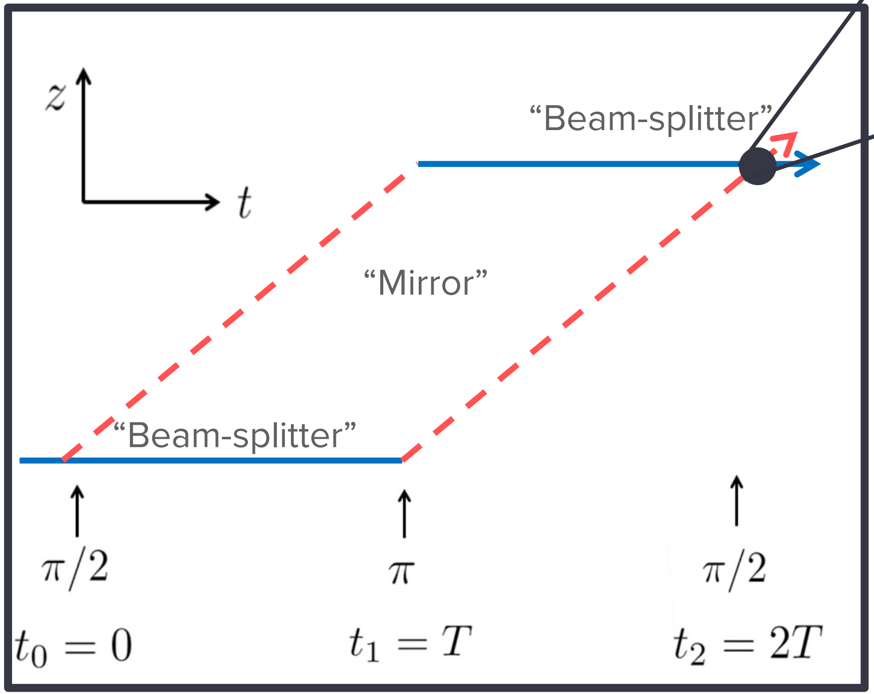
AION

arXiv: 1911.11755

Atom Interferometer Observatory and Network



Interferometer sequence



Mach-Zehnder interferometer

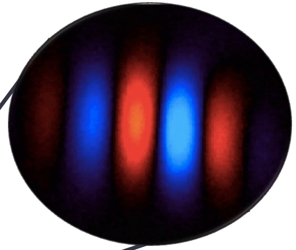


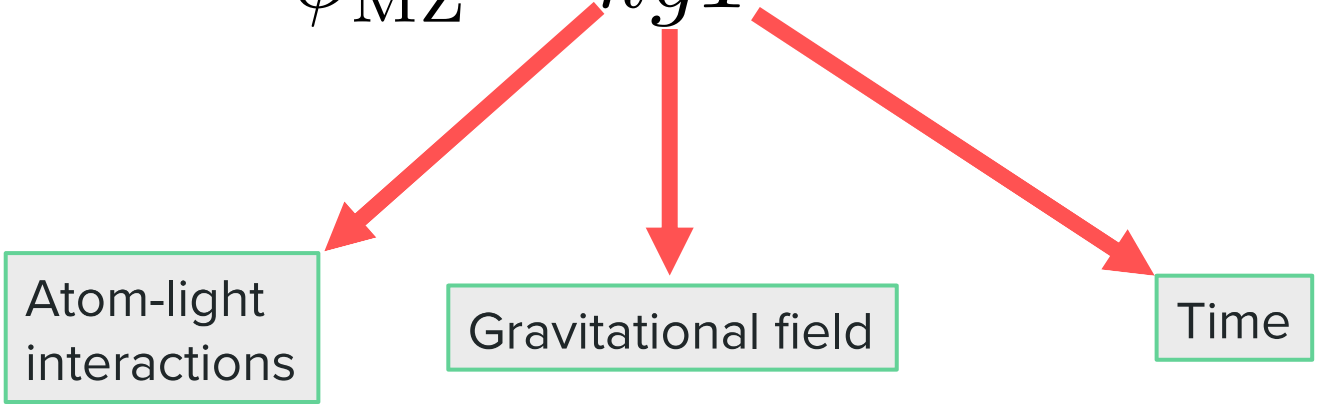
Image atom fringes and measure phase

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

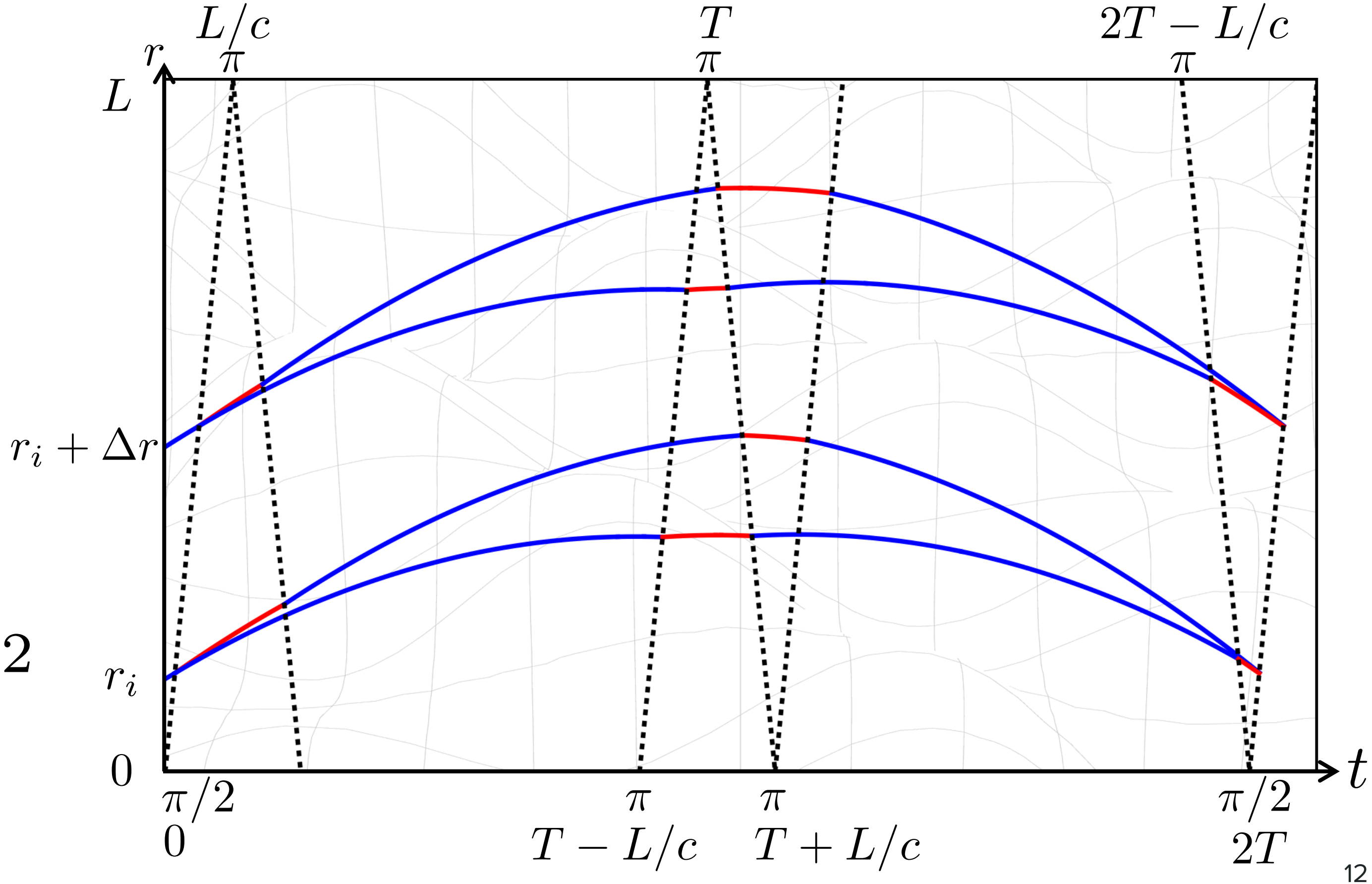
Leading order phase depends on gravitational acceleration

What can we measure?

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

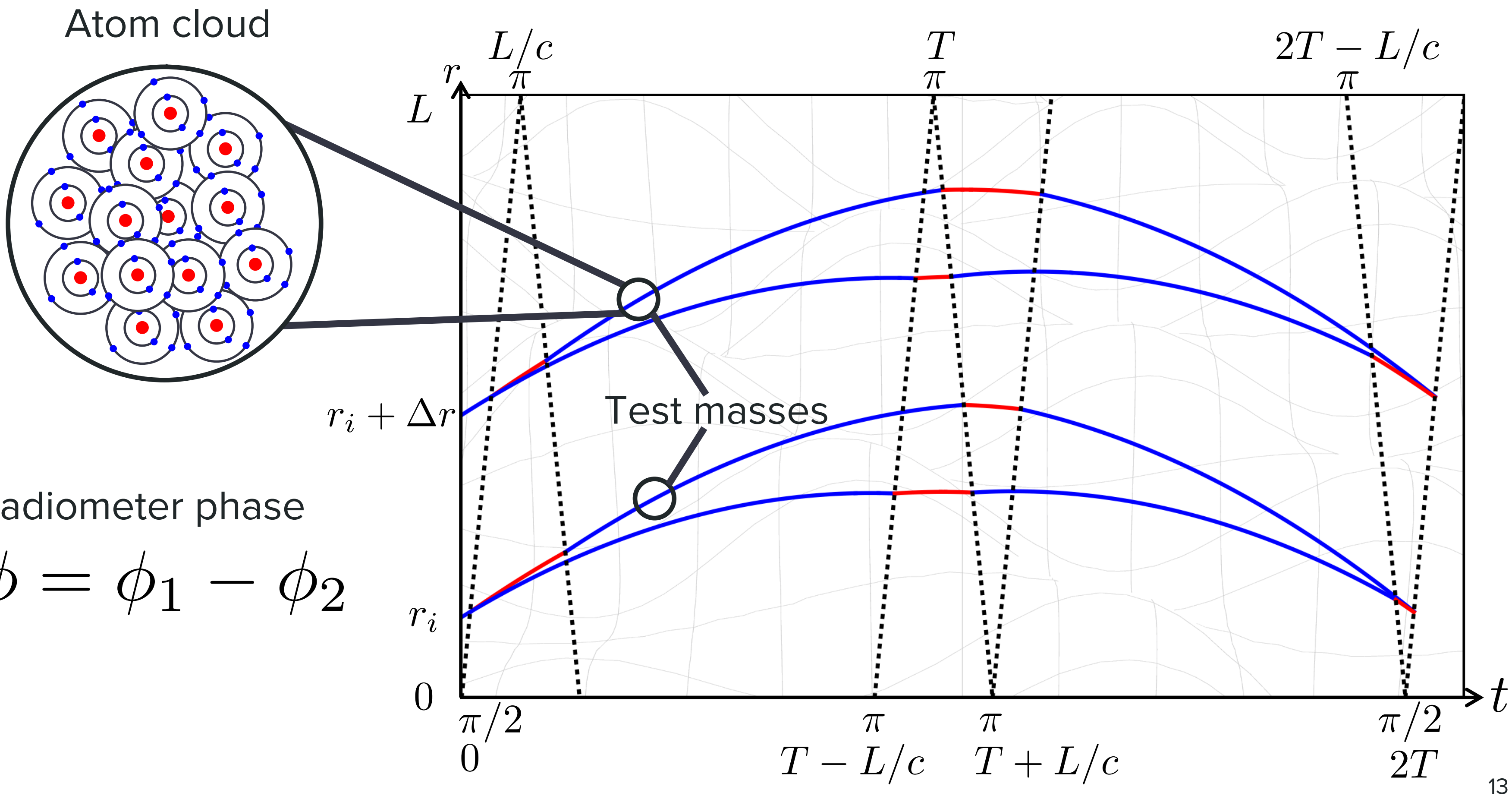


Atom gradiometer



Gradiometer phase

$$\Delta\phi = \phi_1 - \phi_2$$



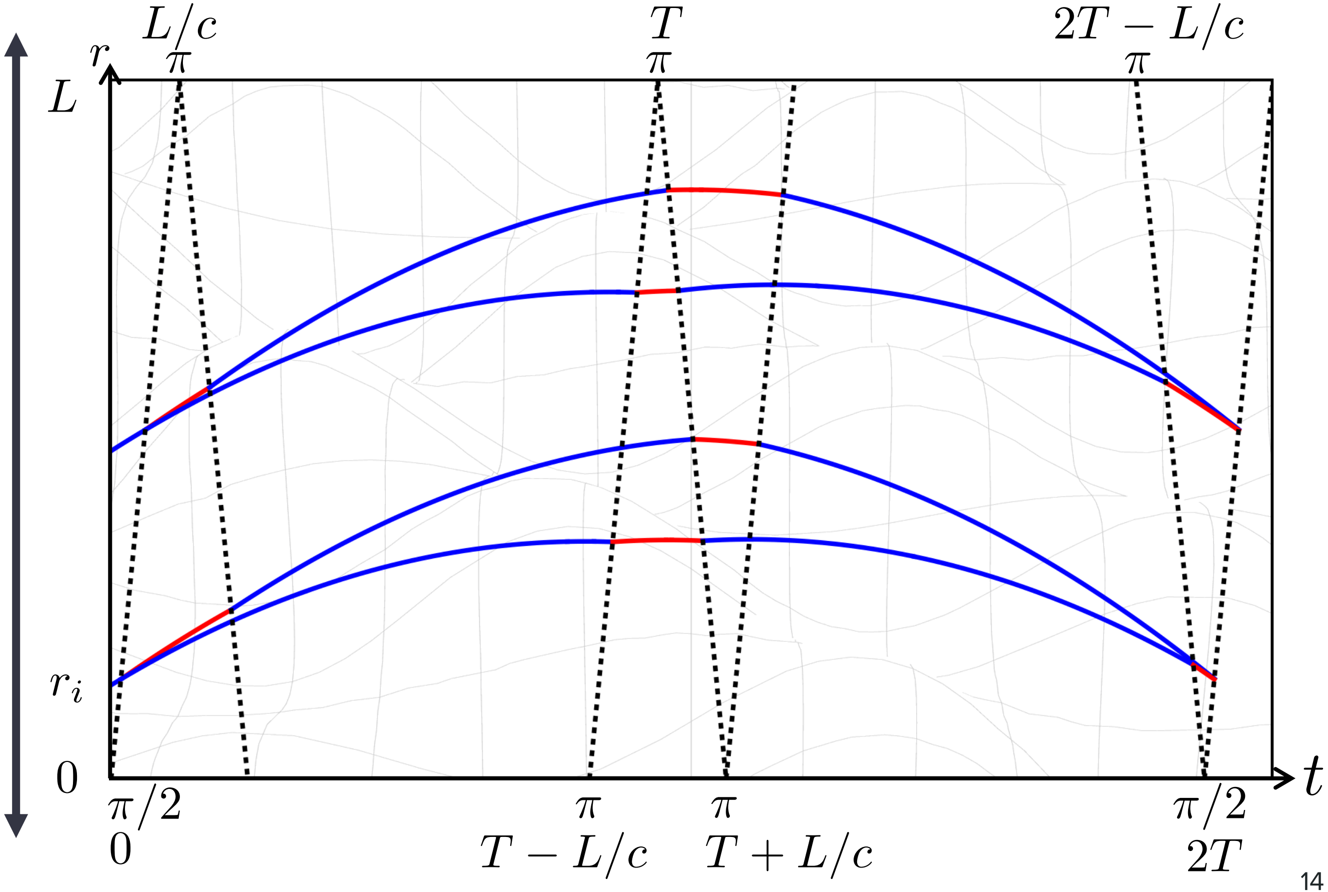
Gradiometer phase

$$\Delta\phi = \phi_1 - \phi_2$$

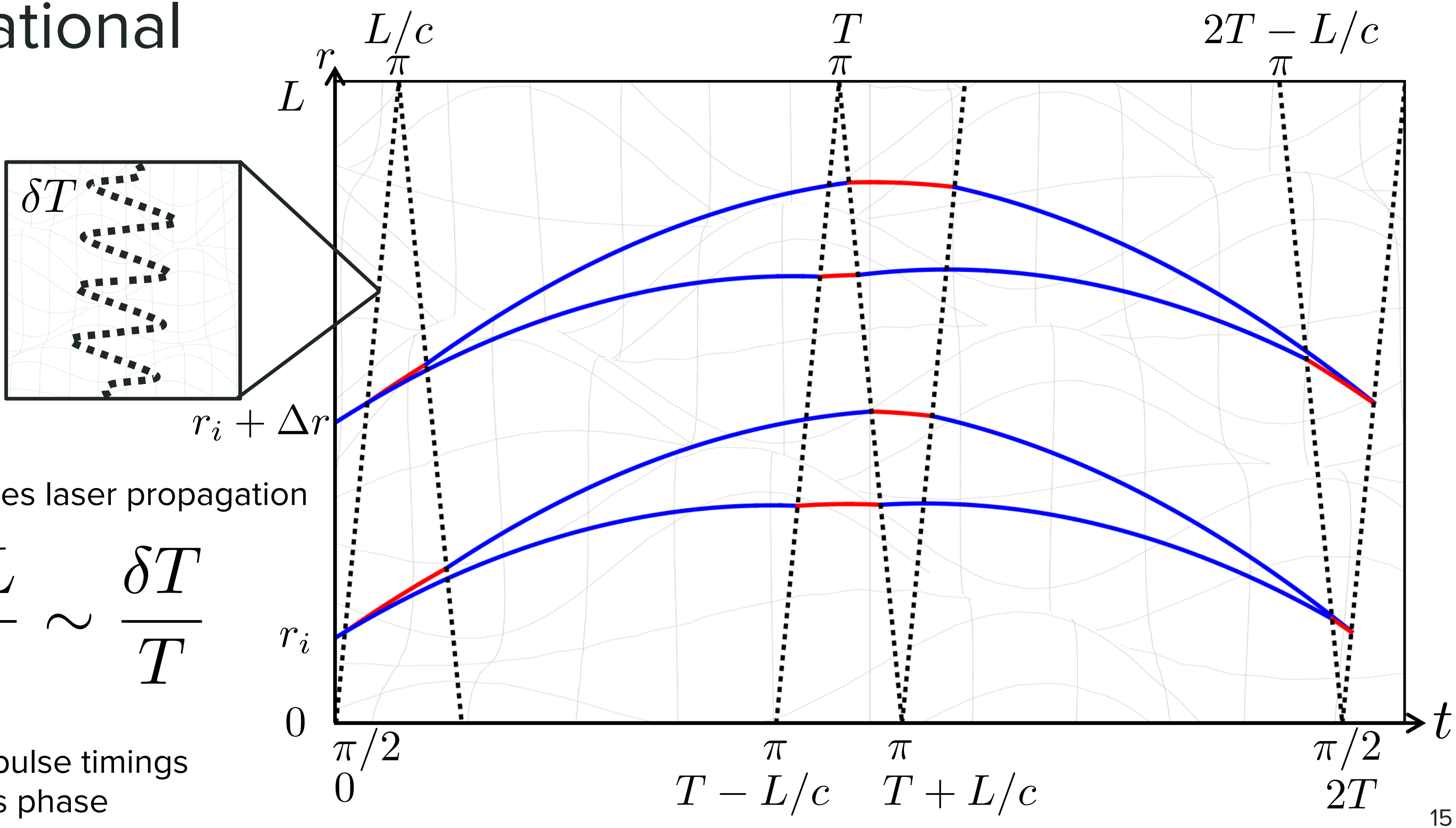
Longer baseline L

Longer time of flight T

More sensitivity $\Delta\phi$



Gravitational waves



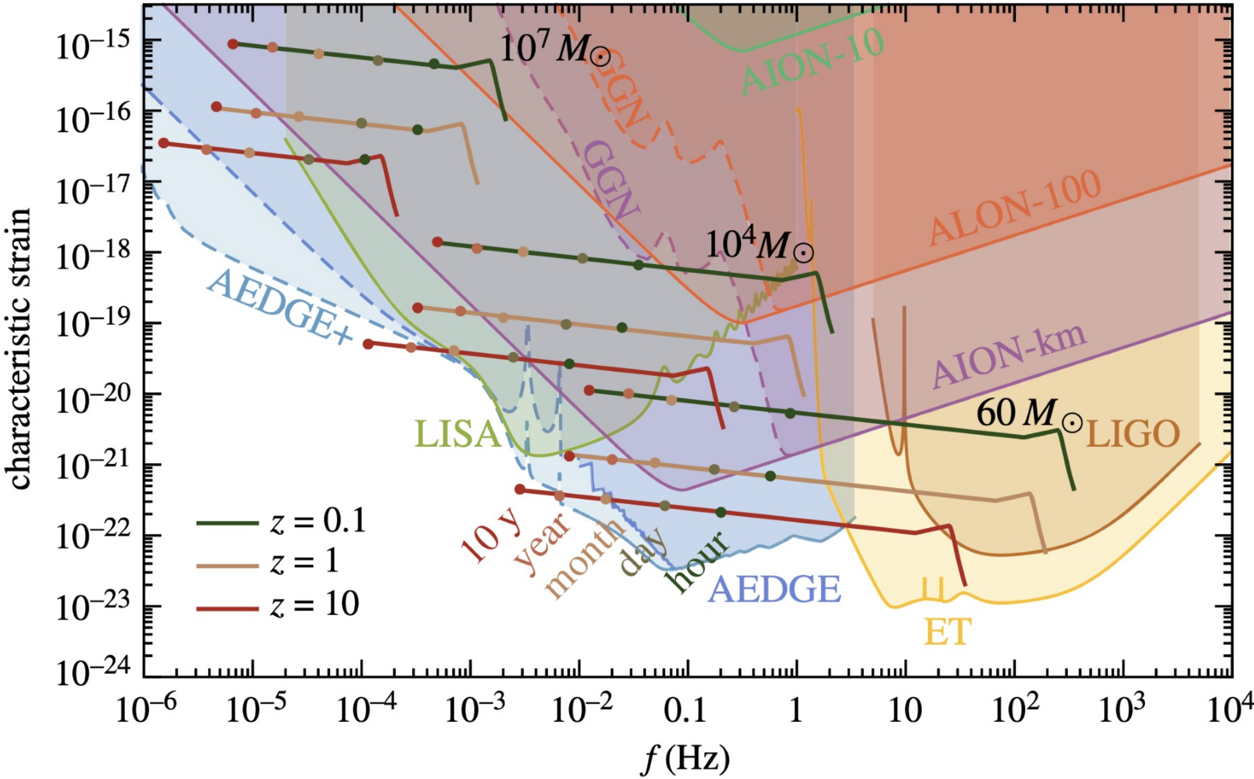
GW strain modifies laser propagation

$$h \sim \frac{\delta L}{L} \sim \frac{\delta T}{T}$$

Change in pulse timings affects phase

Gravitational waves

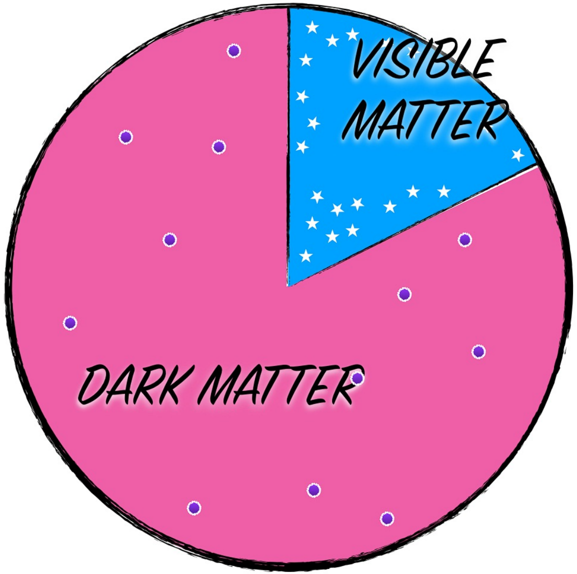
❖ *'Mid-band' sensitivity between LIGO and LISA.*

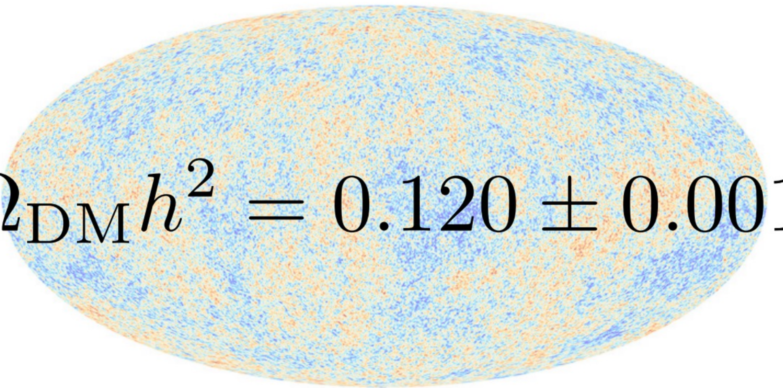


L. Badurina et al. arXiv: 2108.02468

Dark matter

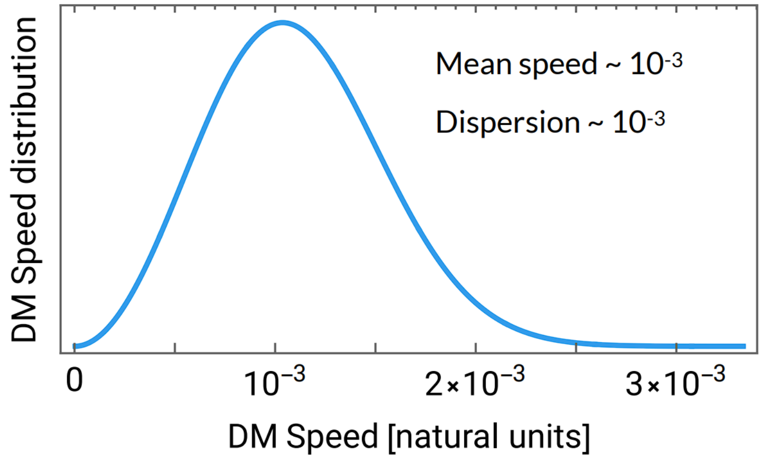
What we know



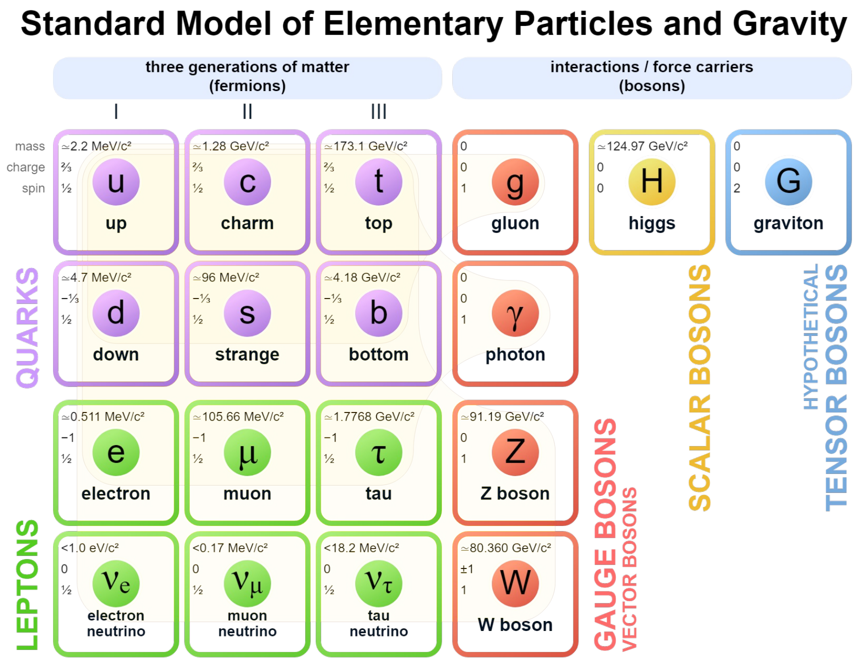


$$\Omega_{\rm DM}h^2 = 0.120 \pm 0.001$$

Relative abundance + speed distribution

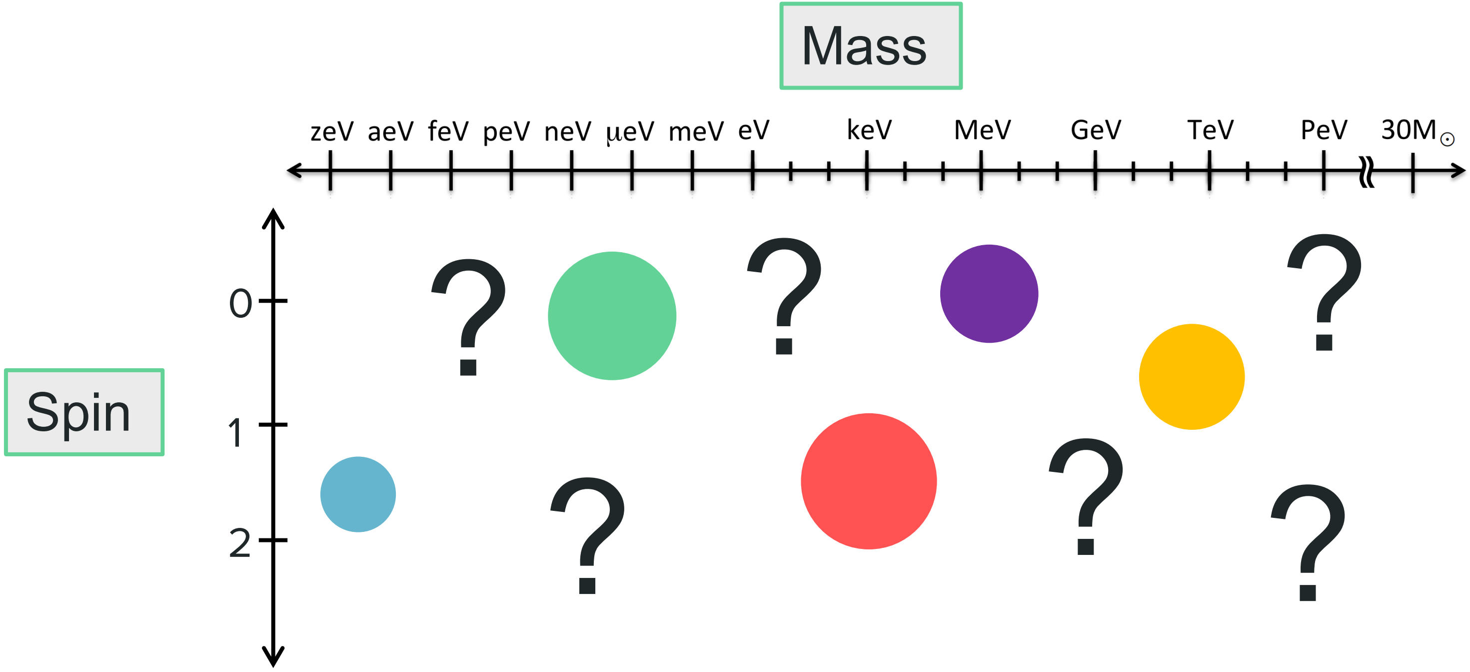


What we don’t



Spin = ?
Mass = ?
Parity = ?
Charge = ?
Interactions with SM = ?
Production mechanism = ?

A lot of parameter space!



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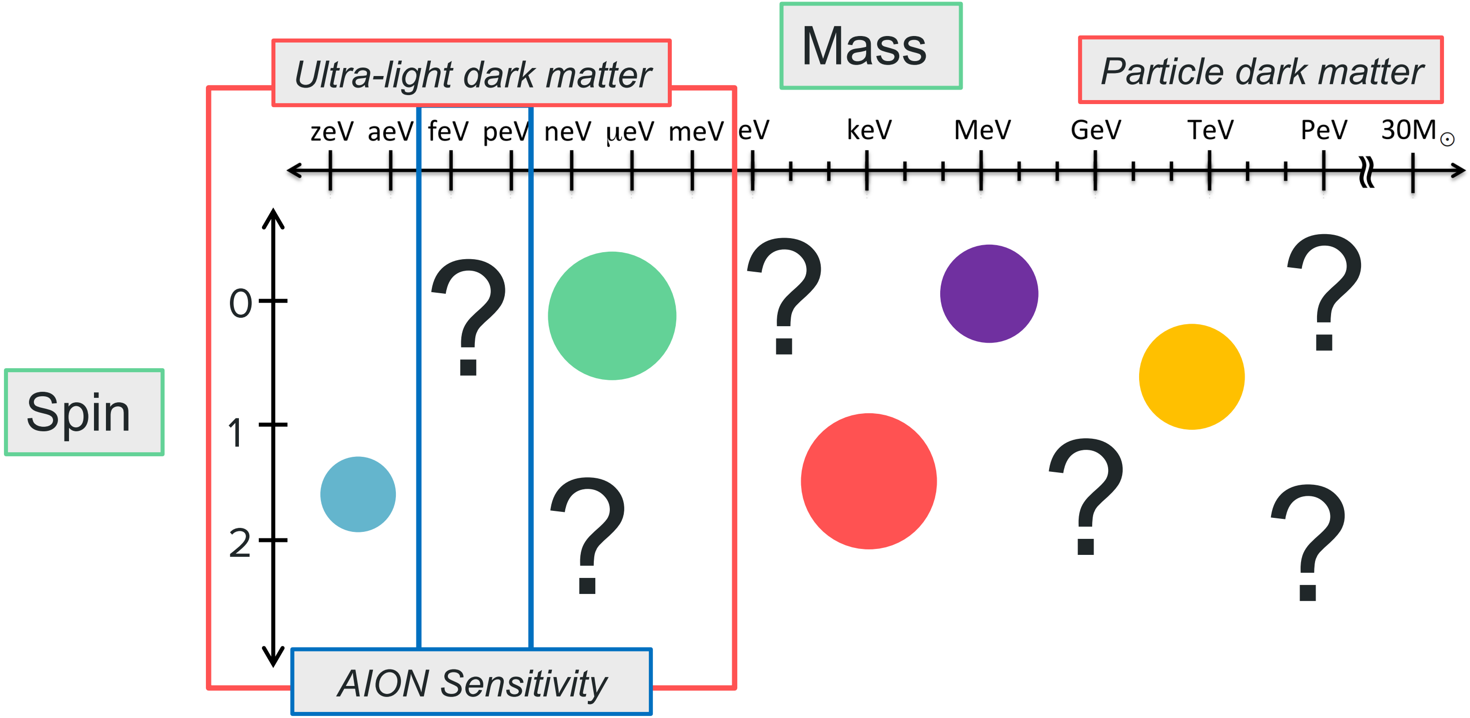

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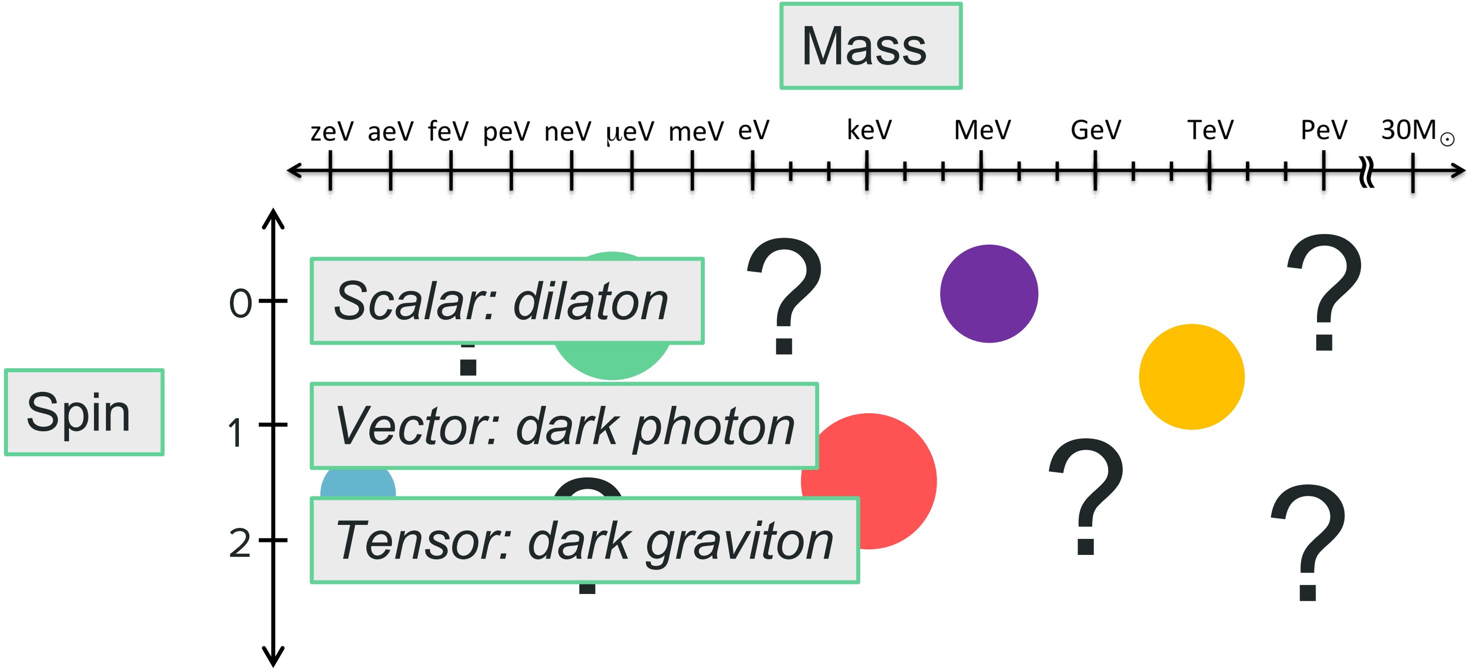
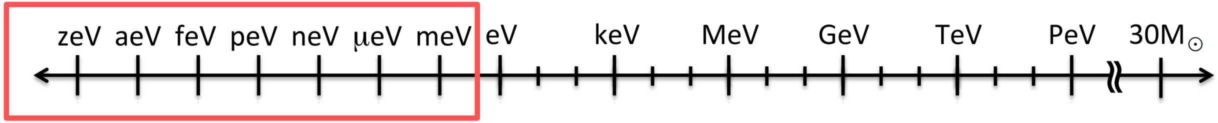


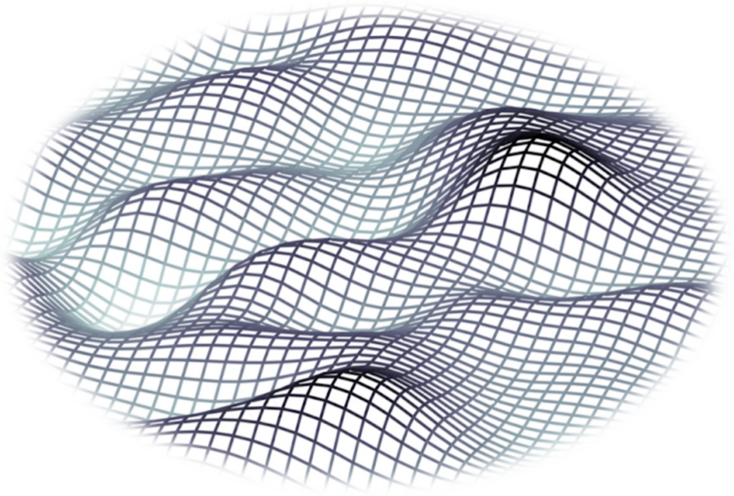
A classical ULDM field



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)

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

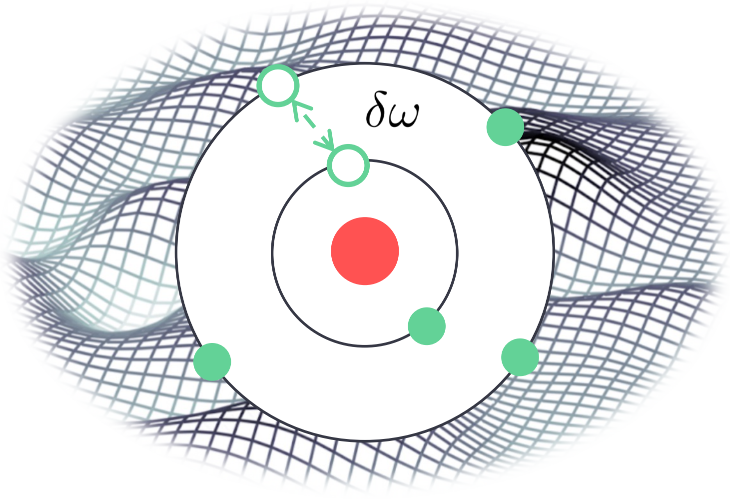
Badurina et al. arxiv: 2109.10965

Atoms in a scalar ULDM field

photon coupling

electron coupling

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



Badurina et al. arxiv: 2109.10965

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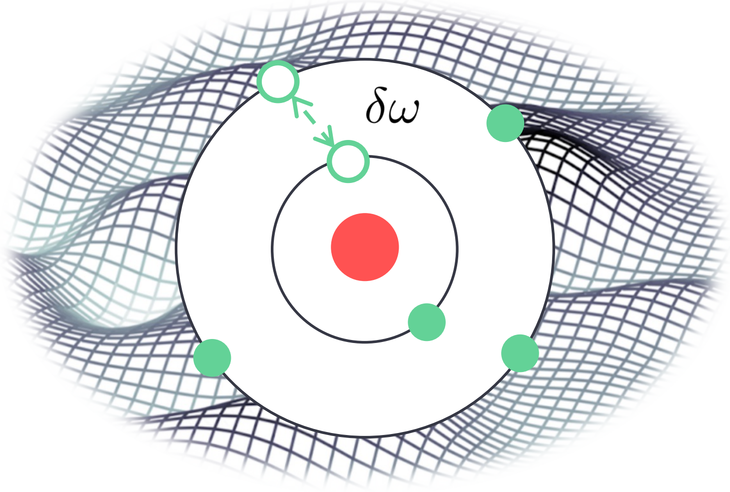
$$\mathcal{L} \supset \mathcal{L}_{\rm SM} + \mathcal{L}_\varphi \quad \longrightarrow \quad \mathcal{L}_\varphi \supset \varphi(t,\boldsymbol{x})\sqrt{4\pi G_{\rm N}}\left[\frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu} - d_{m_e} m_e \bar{\psi}_e \psi_e\right]$$

photon coupling (d_e) — electron coupling (d_{m_e})

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

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

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

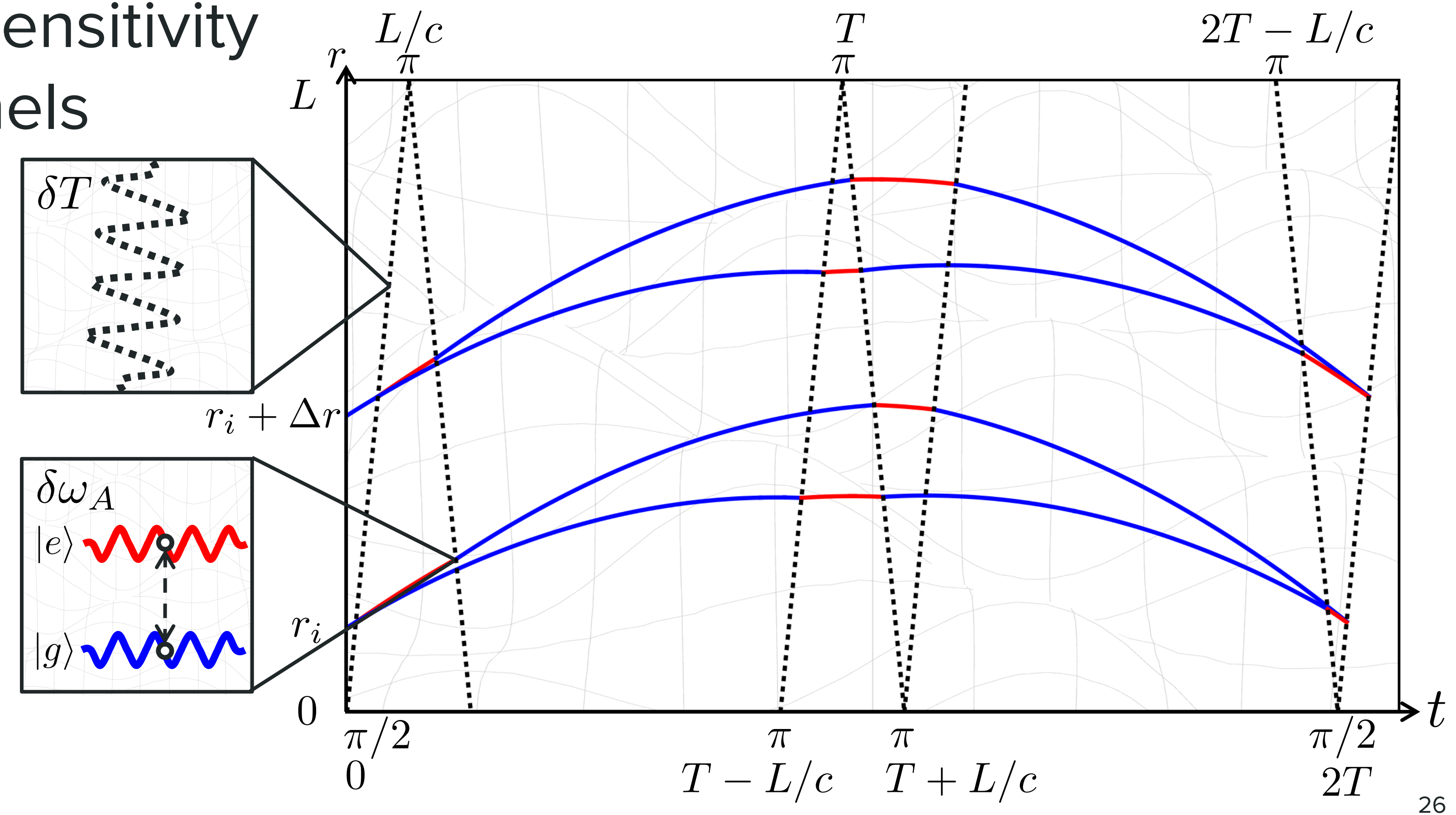


Badurina et al. arxiv: 2109.10965

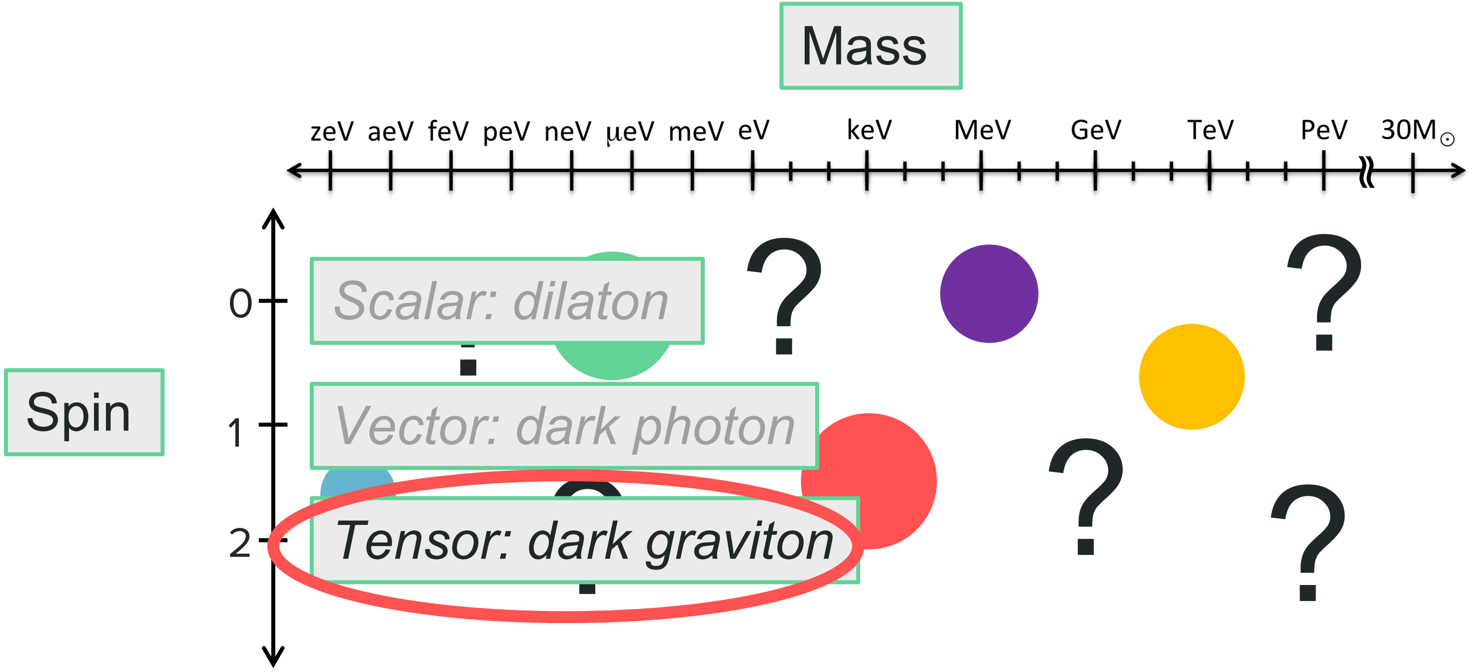
Two sensitivity channels

Interrogation time (GWs)

Atomic transition frequency (Scalar ULDM)



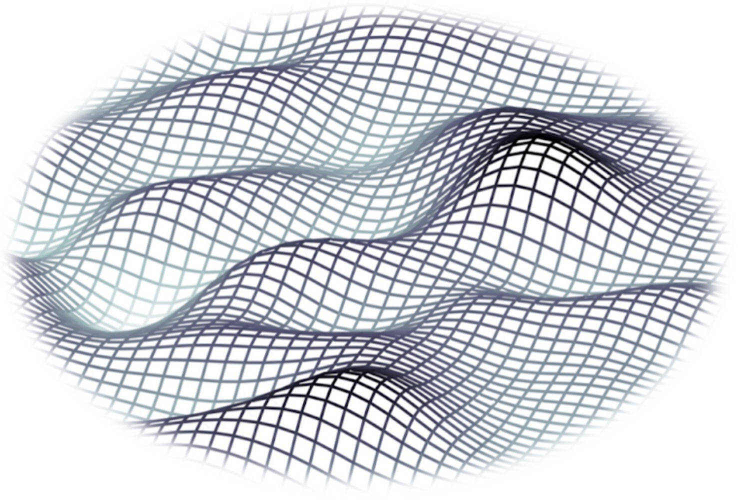
What about spin-2?



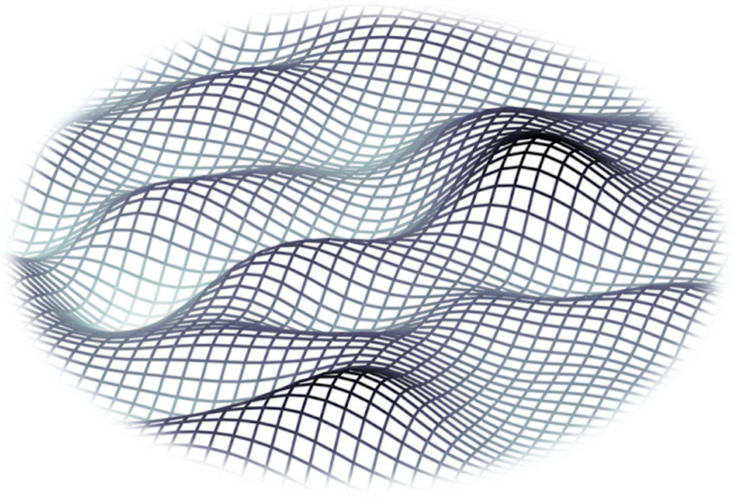
Massive graviton dark matter

Massive gravity field theory

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



Massive gravity field theory



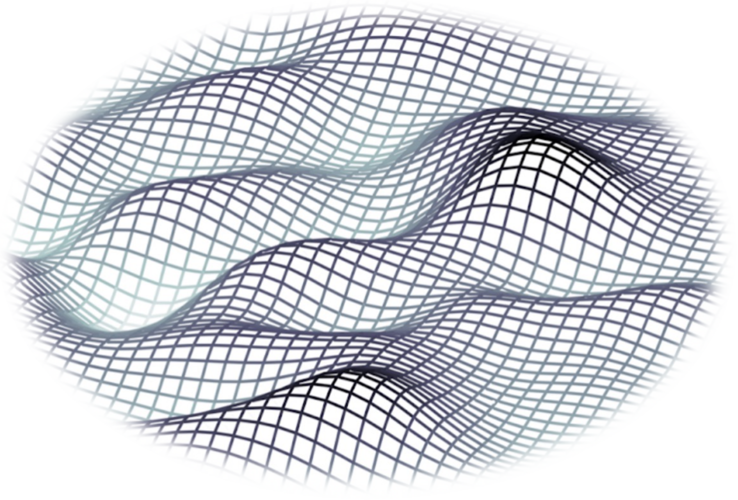
Let's consider a massive spin-2 ultra-light field $\varphi_{\mu\nu}$

Fierz-Pauli Lagrangian

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

Lorentz *invariant* massive spin-2 field

Massive gravity field theory



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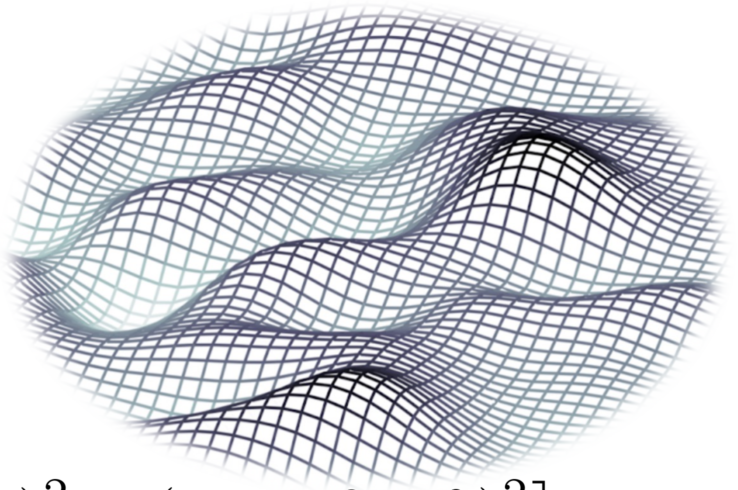
Lorentz *invariant* massive spin-2 field

Need to recover usual gauge transformations of GR $\varphi_{\mu\nu} \to \varphi_{\mu\nu} + \partial_\mu \xi_\nu + \partial_\nu \xi_\mu$

Massive gravity field theory



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

Fierz-Pauli Lagrangian

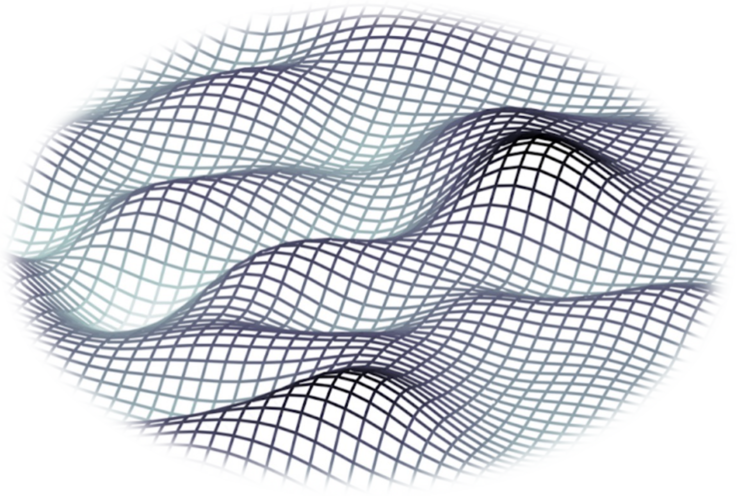
$$\mathcal{L}_{\rm FP} = \mathcal{L}_{\rm EH} - \frac{1}{4}m^2\left[(\varphi_{\mu\nu} + 2\partial_{(\mu}\chi_{\nu)})^2 - (\varphi + 2\partial_\alpha\chi^\alpha)^2\right]$$

Stückelberg fields

Lorentz *invariant* massive spin-2 field

Need to recover usual gauge transformations of GR $\varphi_{\mu\nu} \to \varphi_{\mu\nu} + \partial_\mu\xi_\nu + \partial_\nu\xi_\mu$

Massive gravity field theory



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

Express as irreducible fields:

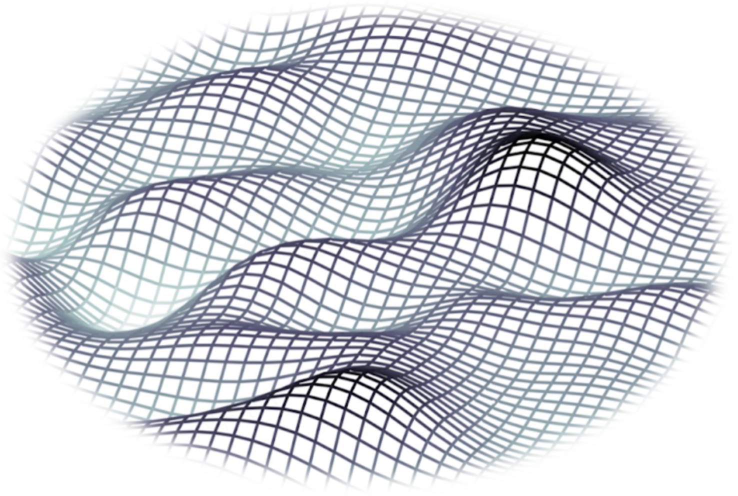
$$\varphi_{00} = \Psi$$

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

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

Massive gravity field theory

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



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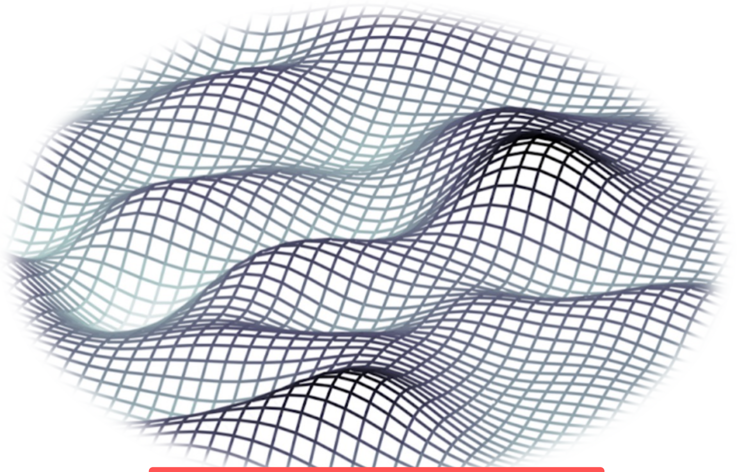
Tensor

Vector

Scalar

Massive gravity field theory

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



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Tensor

Vector

Scalar

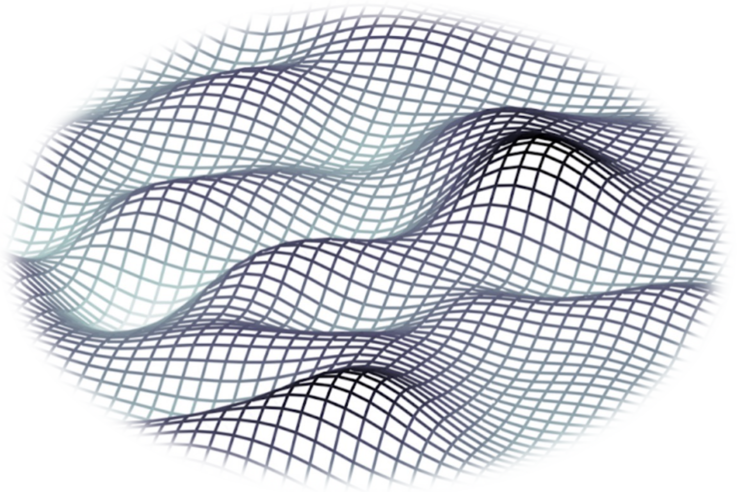
$$u_i \to u_i + \partial_0 \xi_i^T$$

$$\Psi \to \Psi + 2\partial_0\xi_0$$

$\pi \to \pi$ etc.

Massive gravity field theory

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



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

Lorentz *violating* massive spin-2 field

Phases of massive gravity

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

General LV Lagrangian has 6
propagating DOF with a *ghost*

Phases of massive gravity

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

$$\mathbf{FP}: \; m_0^2 = 0, \, m_1^2 = m_2^2 = m_3^2 = m_4^2 = m^2$$

Recover Fierz-Pauli case

Phases of massive gravity

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

$$\mathbf{LV1}:\ m_1 = 0,\ m_0 \neq 0 \qquad \mathbf{LV2}:\ m_1 = 0,\ m_0 = 0$$

Phases of massive gravity

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

$$\mathbf{LV1}:\ m_1 = 0,\ m_0 \neq 0 \qquad \mathbf{LV2}:\ m_1 = 0,\ m_0 = 0$$

$$x^i \to x^i + \xi^i(t) \qquad t \to f(t)$$

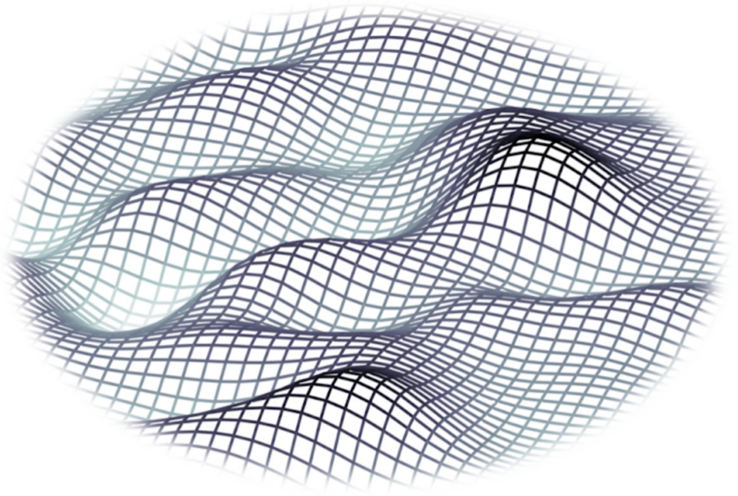
Protected by residual symmetries

Only tensor modes propagate

Tensor, vector, and scalar modes propagate!

Massive gravity field theory

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



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Tensor

Vector

Scalar

Three normalised fields

Tensor $$\mathcal{L}_t = \frac{1}{2}\left(\widetilde{\varphi}_{ij}\Box\widetilde{\varphi}_{ij} - m_t^2\widetilde{\varphi}_{ij}\widetilde{\varphi}_{ij}\right)$$

Vector $$\mathcal{L}_v = \frac{1}{2}\left(\widetilde{A}_i\Box\widetilde{A}_i - m_v^2\widetilde{A}_i\widetilde{A}_i\right)$$

Scalar $$\mathcal{L}_s = \frac{1}{2}\left(\widetilde{\pi}\Box\widetilde{\pi} - m_s^2\widetilde{\pi}^2\right)$$

Three classical oscillating fields...

Tensor $$\widetilde{\varphi}_{ij}(t,\mathbf{x}) = \sum_{\lambda} \widetilde{\varphi}_{0,\lambda} e^{\lambda}_{ij}(\mathbf{k}_t) \cos(\omega_t t - \mathbf{k}_t \cdot \mathbf{x})$$

Vector $$\widetilde{A}_i(t,\mathbf{x}) = \sum_{\lambda} \widetilde{A}_{0,\lambda} e^{\lambda}_{i}(\mathbf{k}_v) \cos(\omega_v t - \mathbf{k}_v \cdot \mathbf{x})$$

Scalar $$\widetilde{\pi}(t,\mathbf{x}) = \widetilde{\pi}_0 \cos(\omega_s t - \mathbf{k}_s \cdot \mathbf{x})$$

Three classical oscillating fields...

Tensor $$\widetilde{\varphi}_{ij}(t,\mathbf{x}) = \sum_\lambda \widetilde{\varphi}_{0,\lambda} e^\lambda_{ij}(\mathbf{k}_t) \cos(\omega_t t - \mathbf{k}_t \cdot \mathbf{x})$$

Sum over polarisations

Vector $$\widetilde{A}_i(t,\mathbf{x}) = \sum_\lambda \widetilde{A}_{0,\lambda} e^\lambda_i(\mathbf{k}_v) \cos(\omega_v t - \mathbf{k}_v \cdot \mathbf{x})$$

Scalar $$\widetilde{\pi}(t,\mathbf{x}) = \widetilde{\pi}_0 \cos(\omega_s t - \mathbf{k}_s \cdot \mathbf{x})$$

… each contributing to the local dark matter

Tensor

$$\widetilde{\varphi}_0 = \frac{\sqrt{2 f_t \rho_{\mathrm{DM}}}}{m_t}$$

Vector

$$\widetilde{A}_0 = \frac{\sqrt{2 f_v \rho_{\mathrm{DM}}}}{m_v}$$

Scalar

$$\widetilde{\pi}_0 = \frac{\sqrt{2 f_s \rho_{\mathrm{DM}}}}{m_s}$$

… each contributing to the local dark matter

Tensor

$$\widetilde{\varphi}_0 = \frac{\sqrt{2 f_t \rho_{\mathrm{DM}}}}{m_t}$$

Vector

$$\widetilde{A}_0 = \frac{\sqrt{2 f_v \rho_{\mathrm{DM}}}}{m_v}$$

Scalar

$$\widetilde{\pi}_0 = \frac{\sqrt{2 f_s \rho_{\mathrm{DM}}}}{m_s}$$

Fraction of total dark matter

$$f_t + f_v + f_s = 1$$

Coupling to light and matter

$$\mathcal{L}_{\rm int} = \kappa^{\phi}\varphi^{\mu\nu}\mathcal{O}_{\mu\nu}$$

↑

Symmetric Standard Model operator

Coupling to light and matter

Tensor — Vector — Scalar

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

Coupling to light and matter

Tensor Vector Scalar

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

Matter $$\varphi^{\mu\nu}\mathcal{O}^{\text{at}}_{\mu\nu} = \frac{\alpha^{(0)}}{\Lambda}\varphi^{\mu}_{\mu}m_A + \frac{\alpha^{(2)}}{\Lambda}\varphi^{\mu\nu}\frac{p_{A\,\mu}p_{A\,\nu}}{m_A}$$

Light $$\varphi^{\mu\nu}\mathcal{O}^{l}_{\mu\nu} = \frac{\beta^{(0)}}{\Lambda}\varphi^{\mu}_{\mu}F^2 + \frac{\beta^{(2)}}{\Lambda}\varphi^{\mu\nu}F_{\mu\alpha}F^{\alpha}_{\nu}$$

Coupling to light and matter

Tensor | Vector | Scalar

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

Matter

$$\varphi^{\mu\nu}\mathcal{O}^{\text{at}}_{\mu\nu} = \frac{\alpha^{(0)}}{\Lambda}\cancel{\varphi^{\mu}_{\mu}}m_A + \frac{\alpha^{(2)}}{\Lambda}\varphi^{\mu\nu}\frac{p_{A\,\mu}p_{A\,\nu}}{m_A}$$

$\varphi^{\mu}_{\mu} = 0$ in **FP** case

Light

$$\varphi^{\mu\nu}\mathcal{O}^{l}_{\mu\nu} = \frac{\beta^{(0)}}{\Lambda}\cancel{\varphi^{\mu}_{\mu}}F^2 + \frac{\beta^{(2)}}{\Lambda}\varphi^{\mu\nu}F_{\mu\alpha}F^{\alpha}_{\nu}$$

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

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

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

$$\frac{\beta^{(2)}}{\Lambda} \varphi^{\text{TT}}_{ij} F^{i\sigma} F^{j}_{\sigma}$$

In all theories

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

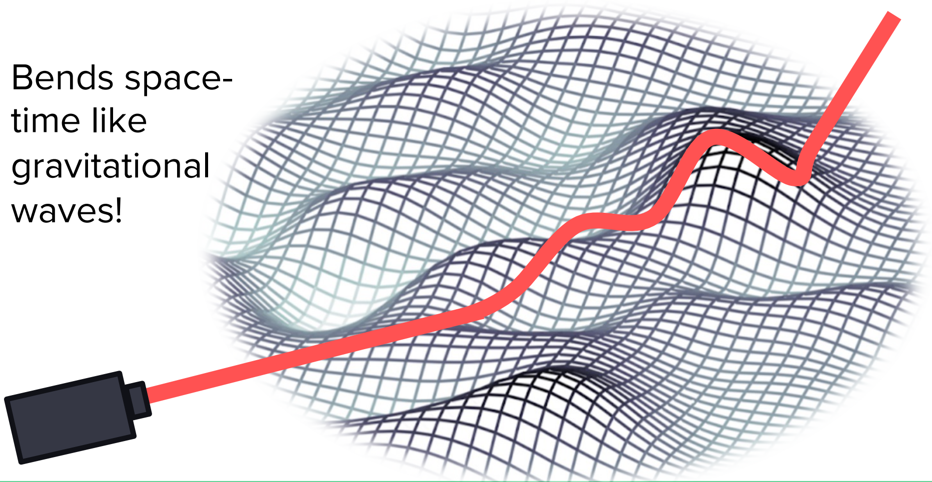
Only in Lorentz violating theories!

Coupling to light and matter

Tensor modes

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

Bends space-time like gravitational waves!



Coupling to light and matter

Tensor modes

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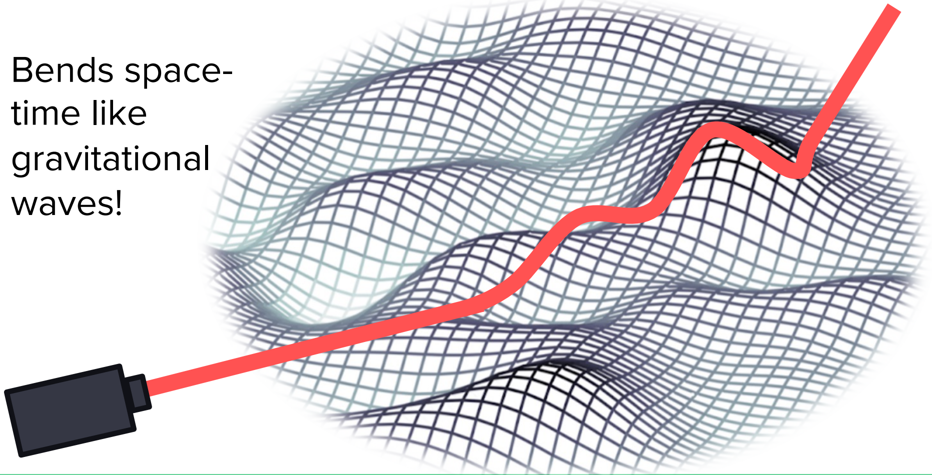
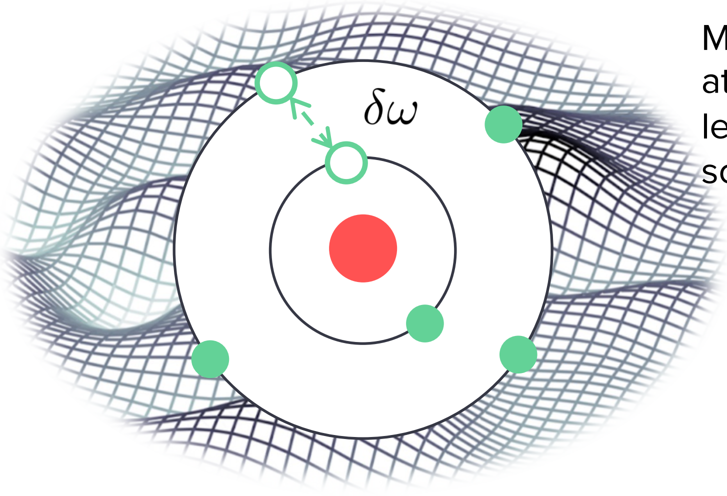


Scalar modes

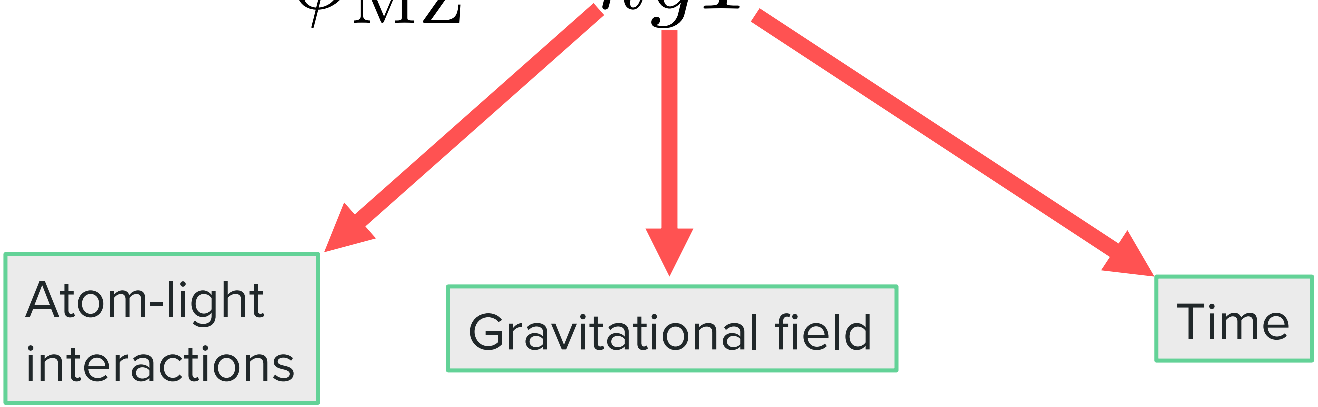
$$\left(\frac{\beta^{(0)}}{\Lambda}F^2 + m_\psi \frac{\alpha^{(0)}}{\Lambda}\overline{\psi}\psi\right)\widetilde{\pi}$$



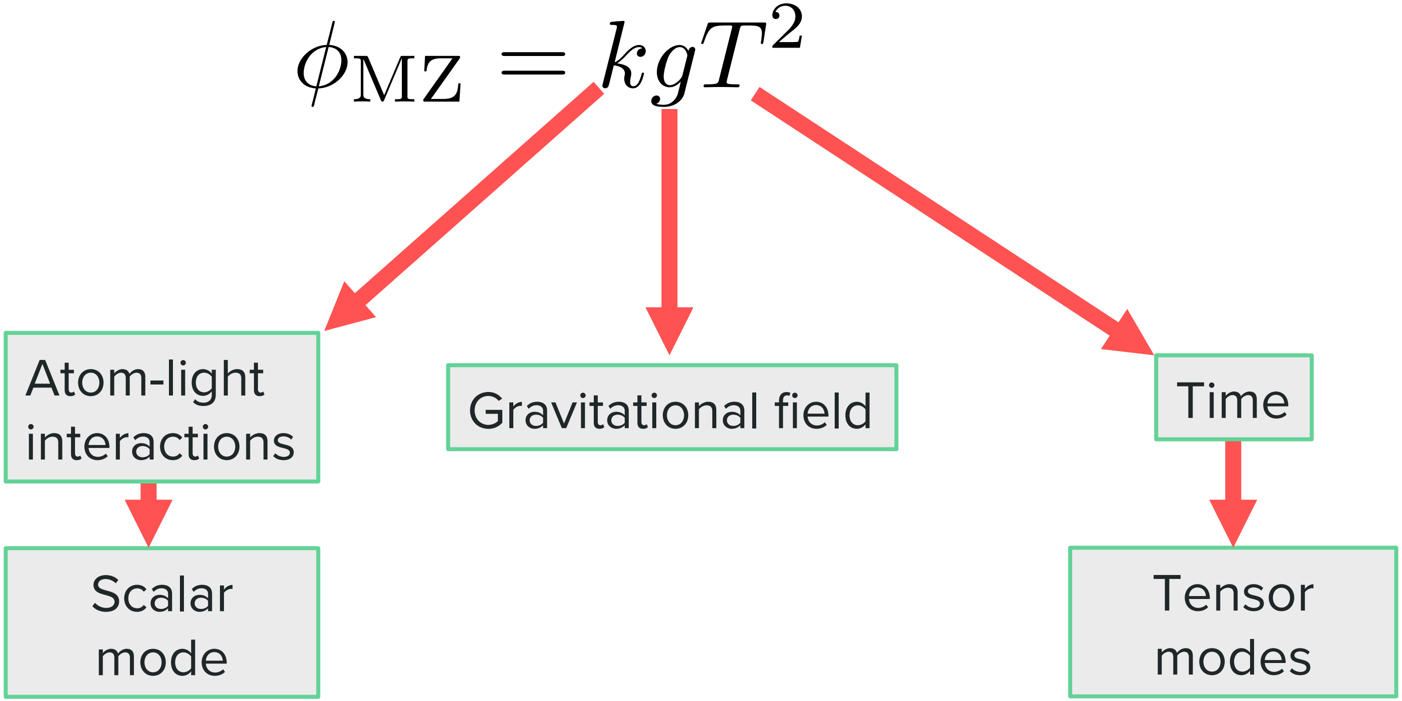
Modifies atomic energy levels just like scalar ULDM!

What can we measure?

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



What can we measure?



Other couplings

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

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

Matter couplings

	FP	LV1	LV2
$\alpha^{(0)}X(t)$	$-\alpha^{(2)}_{\rm FP} v^2_{\rm DM} \frac{\sqrt{\frac{8}{3}f_s}}{m} \cos(\phi_s(t))$	0	$\alpha^{(0)}_{\rm LV} \frac{\sqrt{\frac{8}{3}f_s}}{m_s} \left(\alpha^{-1} + \lambda_{\rm at}\right) \cos(\phi_s(t))$
$\alpha^{(1)}V_i(t)$	$-2\frac{\alpha^{(2)}_{\rm FP}}{m}\left[v_{{\rm DM},\,i}\sqrt{\frac{8f_s}{3}}\cos(\phi_s(t)) + v_{\rm DM}\sqrt{\frac{f_v}{2}}\sum_\lambda e_i^\lambda \cos(\phi_v(t))\right]$	0	$\alpha^{(1)}_{\rm LV} \frac{\sqrt{\frac{2}{3}f_s}}{m_s} \frac{\hat{v}_{{\rm DM},i}}{v_{\rm DM}} \frac{1+\lambda}{\lambda+\beta} \cos(\phi_s(t))$
$\alpha^{(2)}M_{ij}(t)$	0	$\frac{\alpha^{(2)}_{\rm LV}}{m_t} v_A \sum_\lambda e^\lambda_{ij}\sqrt{f_t}\cos(\phi_t(t))$	0

Light couplings

	FP	LV1	LV2
$\beta^{(0)}Y_1(t)$	0	0	$\beta^{(0)}_{\rm LV} \frac{\sqrt{\frac{8}{3}f_s}}{m_s} \left(-\alpha^{-1} + \lambda_{l1}\right) \cos(\phi_s(t))$
$\beta^{(0)}Y_2(t)$	$\beta^{(2)}_{\rm FP} \frac{v^2_{\rm DM}}{m} \sqrt{\frac{8}{3}f_s} \cos(\phi_s(t))$	0	$\beta^{(0)}_{\rm LV} \frac{\sqrt{\frac{8}{3}f_s}}{m_s} \left(4\alpha^{-1} + \lambda_{l2}\right) \cos(\phi_s(t))$
$\beta^{(1)}W_i(t)$	0	0	$\beta^{(1)}_{\rm LV} \frac{\sqrt{\frac{2}{3}f_s}}{m_s} \frac{\hat{v}_{{\rm DM},i}}{v_{\rm DM}} \frac{1+\lambda}{\lambda+\beta} \cos(\phi_s(t))$
$\beta^{(2)}N_{ij}(t)$	$\frac{\beta^{(2)}_{\rm FP}}{m}\Big((\delta_{ij} - 3\hat{v}_{{\rm DM}\,i}\hat{v}_{{\rm DM}\,j})\sqrt{\frac{2}{3}f_s}\cos(\phi_s(t)) - \hat{v}_{{\rm DM}\,i}\sum_\lambda e_j^\lambda\sqrt{2f_v}\cos(\phi_v(t)) + \sum_\lambda e^\lambda_{ij}\sqrt{f_t}\cos(\phi_t(t))\Big)$	$\frac{\beta^{(2)}_{\rm LV}}{m_t}\sum_\lambda e^\lambda_{ij}\sqrt{f_t}\cos(\phi_t(t))$	$\beta^{(2)}_{\rm LV}\left[\sum_\lambda e^\lambda_{ij}\frac{\sqrt{f_t}}{m_t}\cos(\phi_s(t)) + (\delta_{ij} - \hat{v}_i\hat{v}_j)\frac{\sqrt{2/3 f_s}}{m_s}\cos(\phi_t(t))\right]$

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

Other couplings

Matter couplings

Electron mass variation

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

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

Fine structure variation

Light couplings

Laser propagation delay

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

Other couplings

Matter couplings

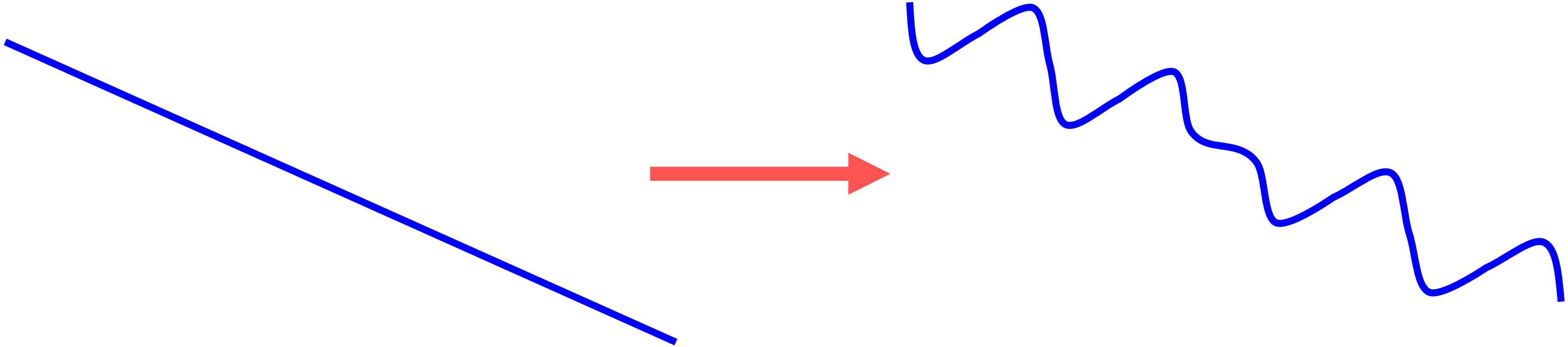
$$\mathcal{H} = \sqrt{\rho_{\rm DM}}\left(\frac{\alpha^{(0)}}{\Lambda}X(t) + \frac{\alpha^{(1)}}{\Lambda}v_A^i V_i(t) + \frac{\alpha^{(2)}}{\Lambda}v_A^i v_A^j M_{ij}(t)\right) m_A \delta^{(3)}(\vec{x} - \vec{x}_A(t))$$

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

Light couplings

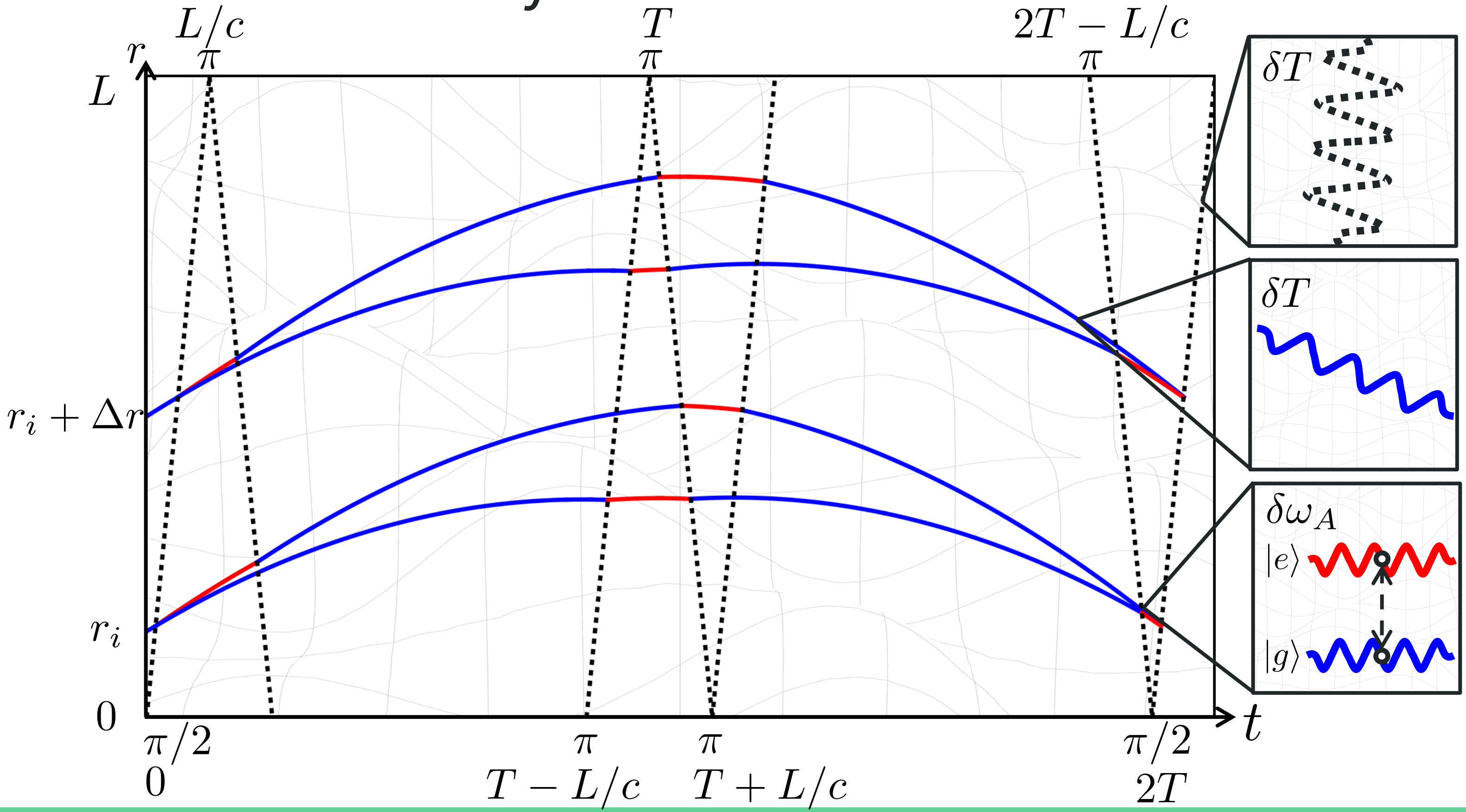
D. Blas, J. Carlton, C. McCabe. arXiv: 2412.14282

Atom propagation delay



$$\frac{\alpha^{(1)}}{\Lambda} v_A^i m_A V_i(t) \delta^{(3)}(\vec{x} - \vec{x}_A(t))$$

Three sensitivity channels!



Laser propagation delay (tensor)

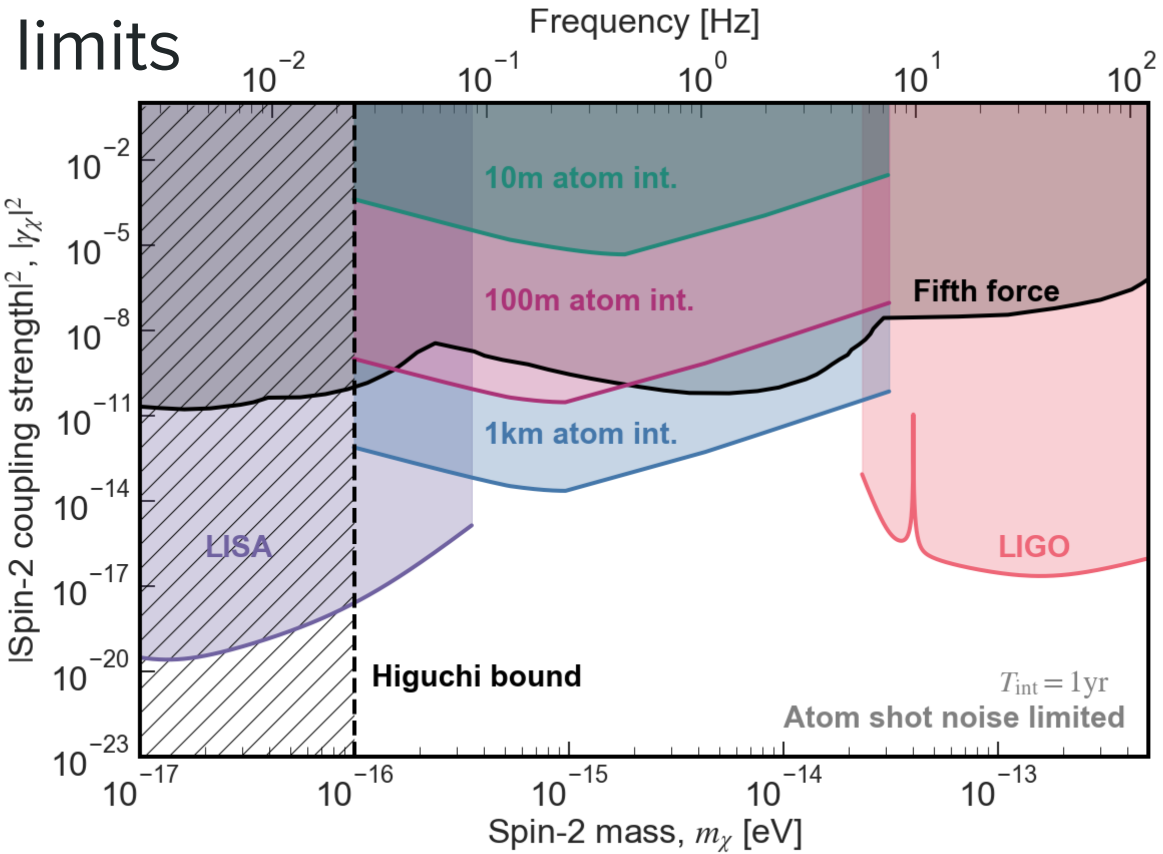
Atom propagation delay (vector)

Electron energy level modification (scalar)

Projected detection limits

10m, 100m and 1km example atom interferometers

Isotope	L [m]	T [s]	n	Δr [m]	S_n [Hz^{-1}]
^{87}Sr	10	0.74	1000	5	10^{-8}
^{87}Sr	100	1.4	1000	90	10^{-10}
^{87}Sr	1000	1.4	1000	980	0.09×10^{-10}



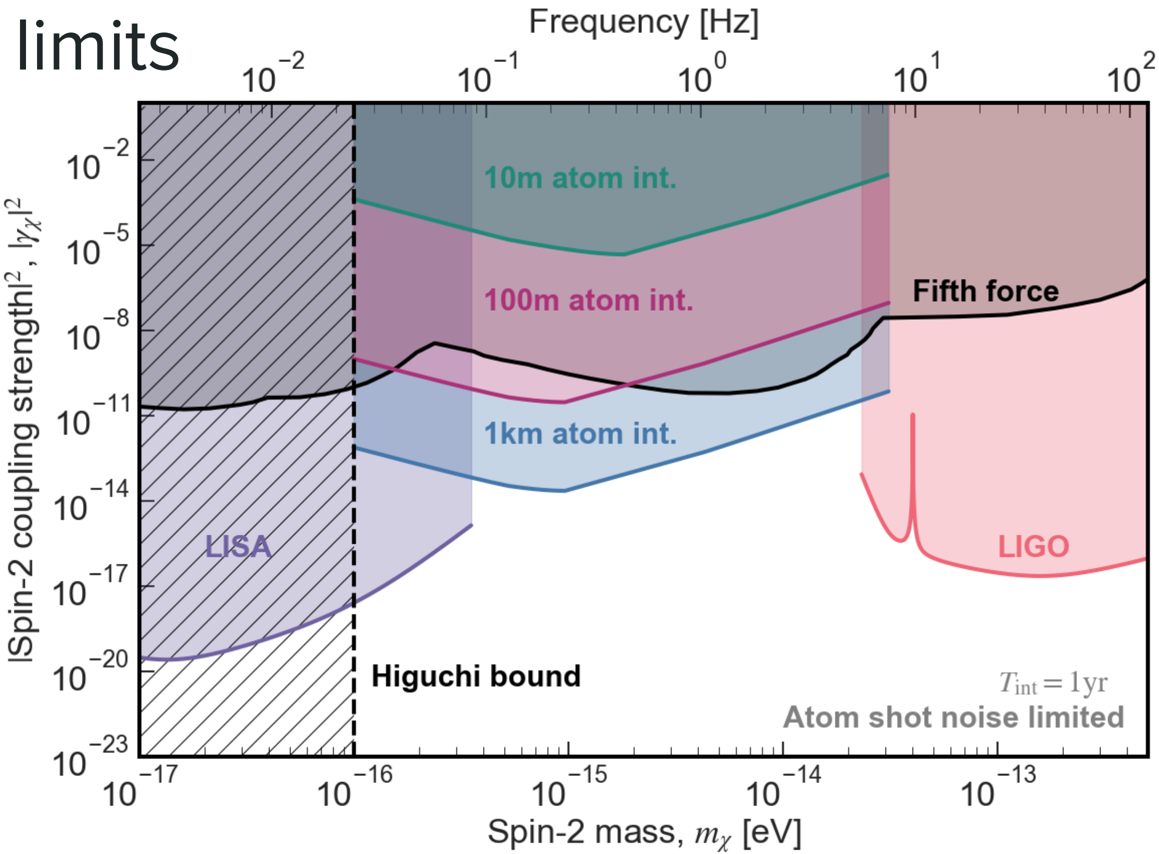
D. Blas, J. Carlton, C. McCabe. arXiv: 2412.14282

Projected detection limits

10m, 100m and 1km example atom interferometers

Generic coupling gamma

$$\gamma_\chi = \alpha^{(i)}, \beta^{(j)} \quad \text{for all } i, j$$



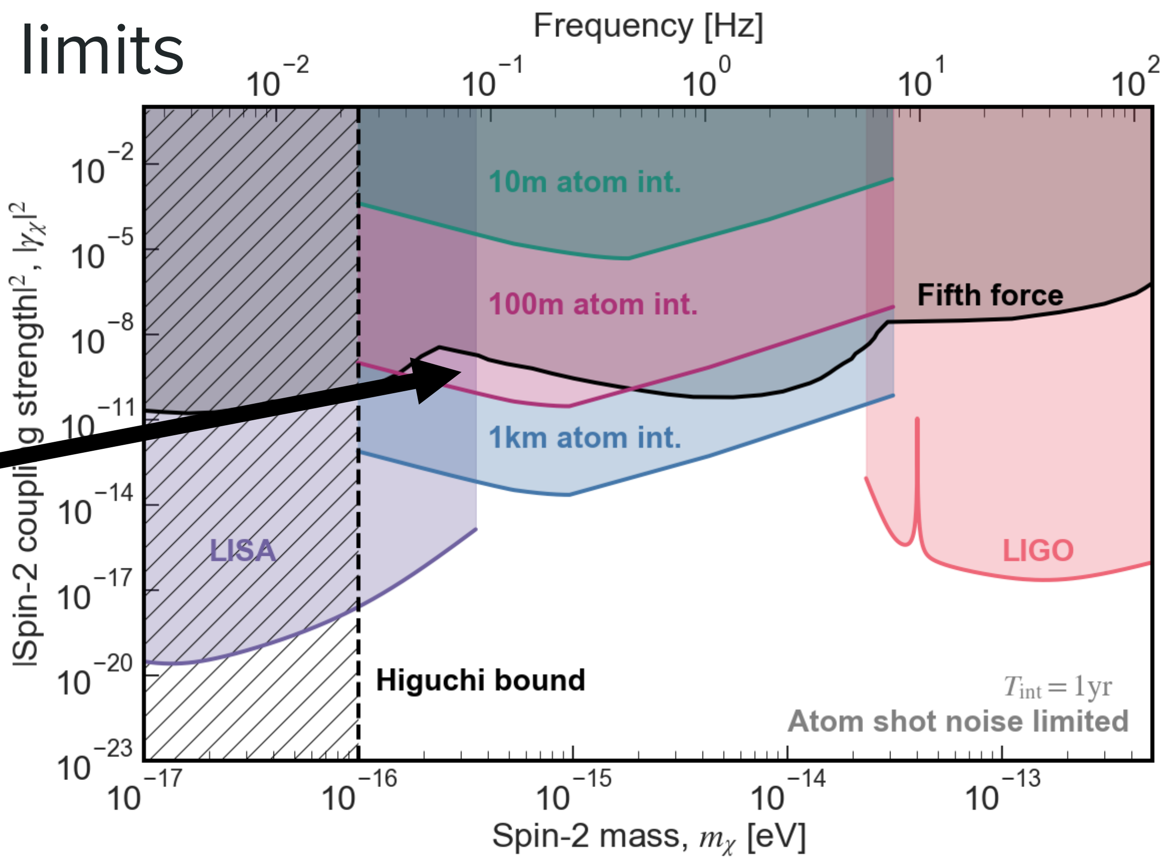
D. Blas, J. Carlton, C. McCabe. arXiv: 2412.14282

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



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Projected detection limits

Leading constraints on scalar mode come from ‘fifth force’ experiments

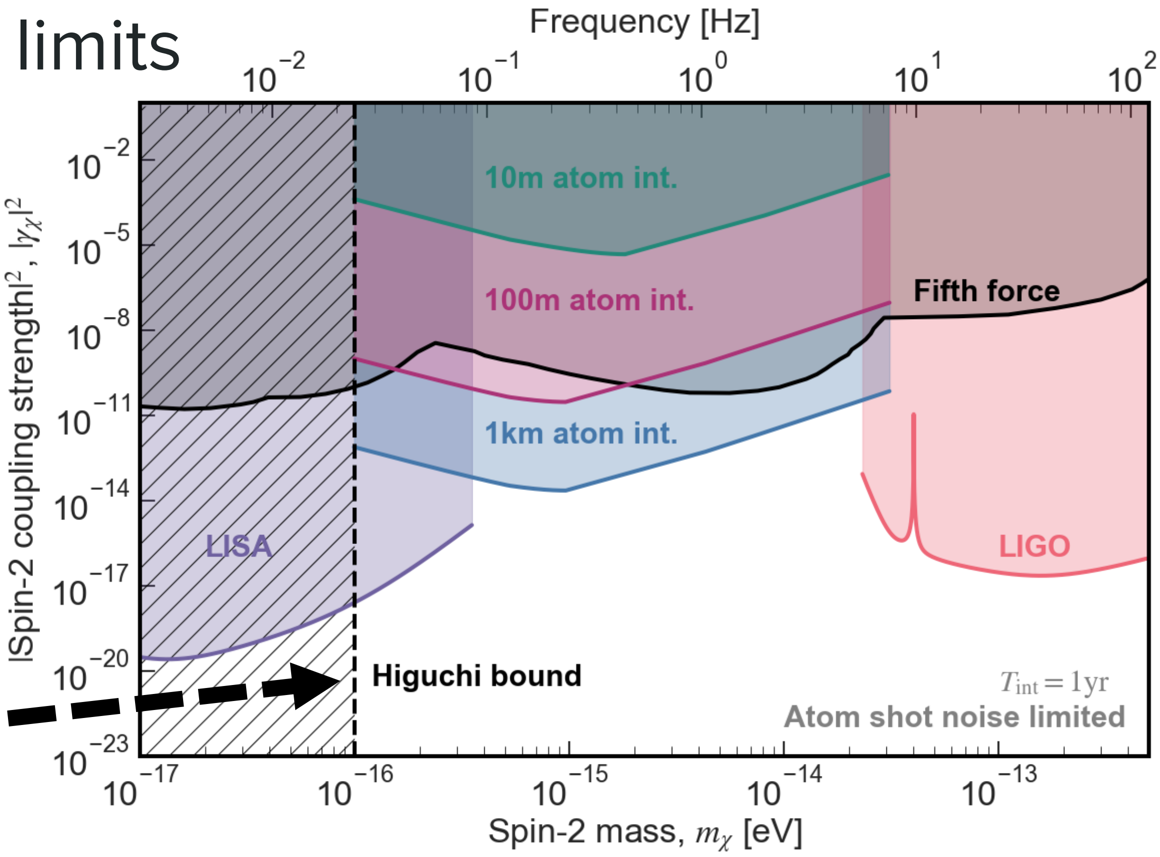
$$\delta V_{\mathrm{Newt}} \propto (\alpha^{(0)})^2 e^{-m_s r}$$

In this range, from lunar laser ranging

Higuchi bound sets a lower bound for mass of spin-2 field

$$m^2 \geq 2H_{inf}^2$$

Least stringent bound from BBN



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Advantages of networking!

AION plans to network with MAGIS-100 to enhance sensitivity in ULDM/GW searches.

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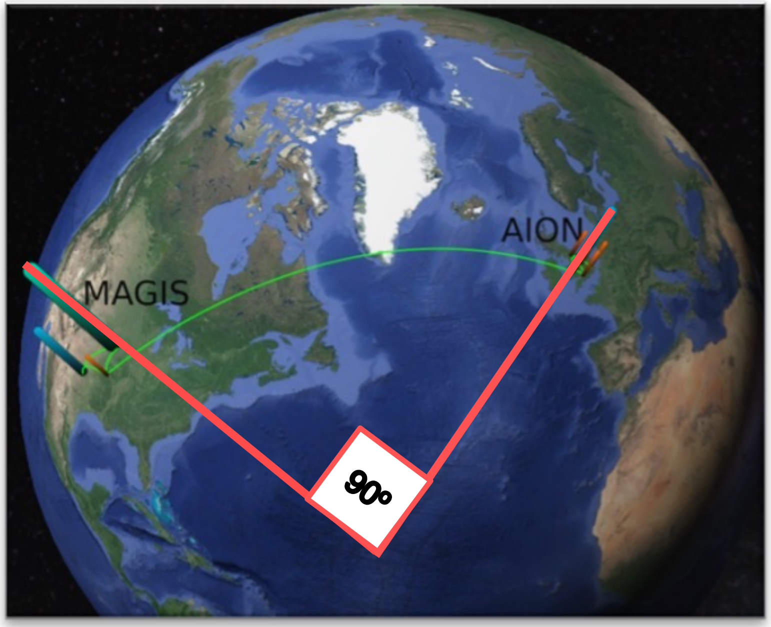
AION plans to network with MAGIS-100 to enhance sensitivity in ULDM/GW searches.

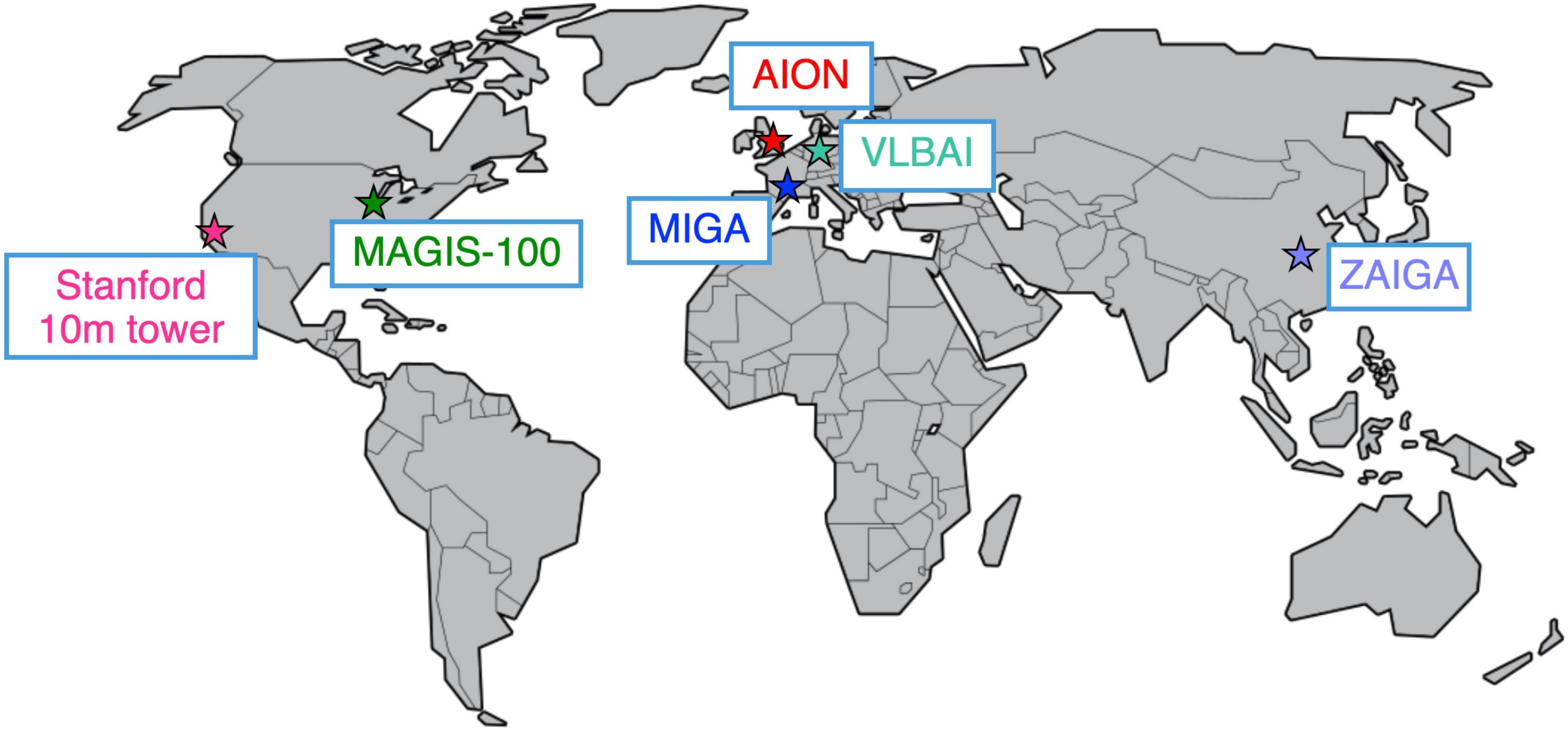
$$\varphi_{ij}^{\mathrm{TT}}(t,\mathbf{x}) = \sum_{\lambda} \varphi_{0,\lambda}^{\mathrm{TT}} e_{ij}^{\lambda}(\mathbf{k}_t) \cos(\omega_t t - \mathbf{k}_t \cdot \mathbf{x})$$

Distinguish dark matter models through directional dependence.

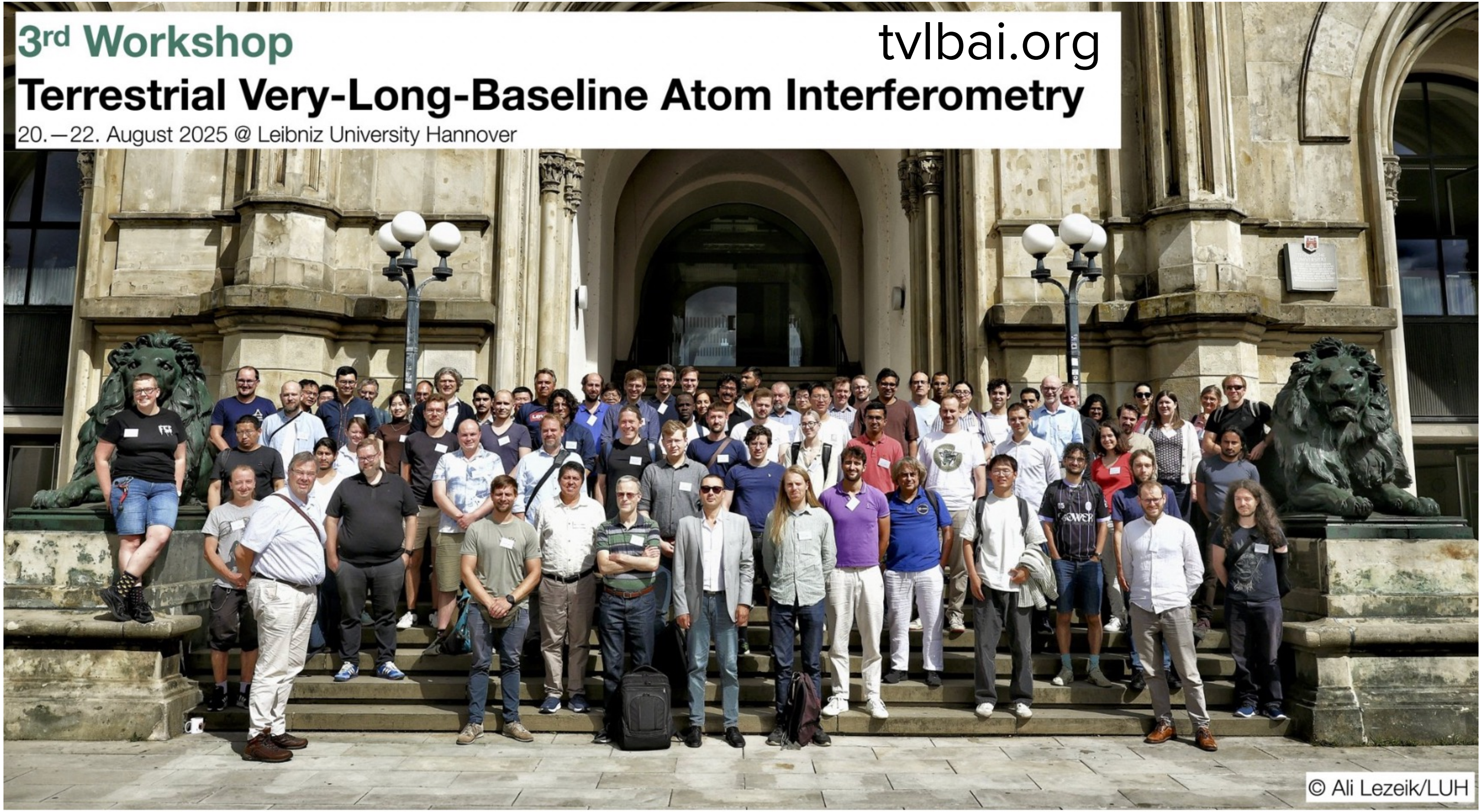


Progress towards a global network!

tvlbai.org



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



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Challenges

What can we measure?

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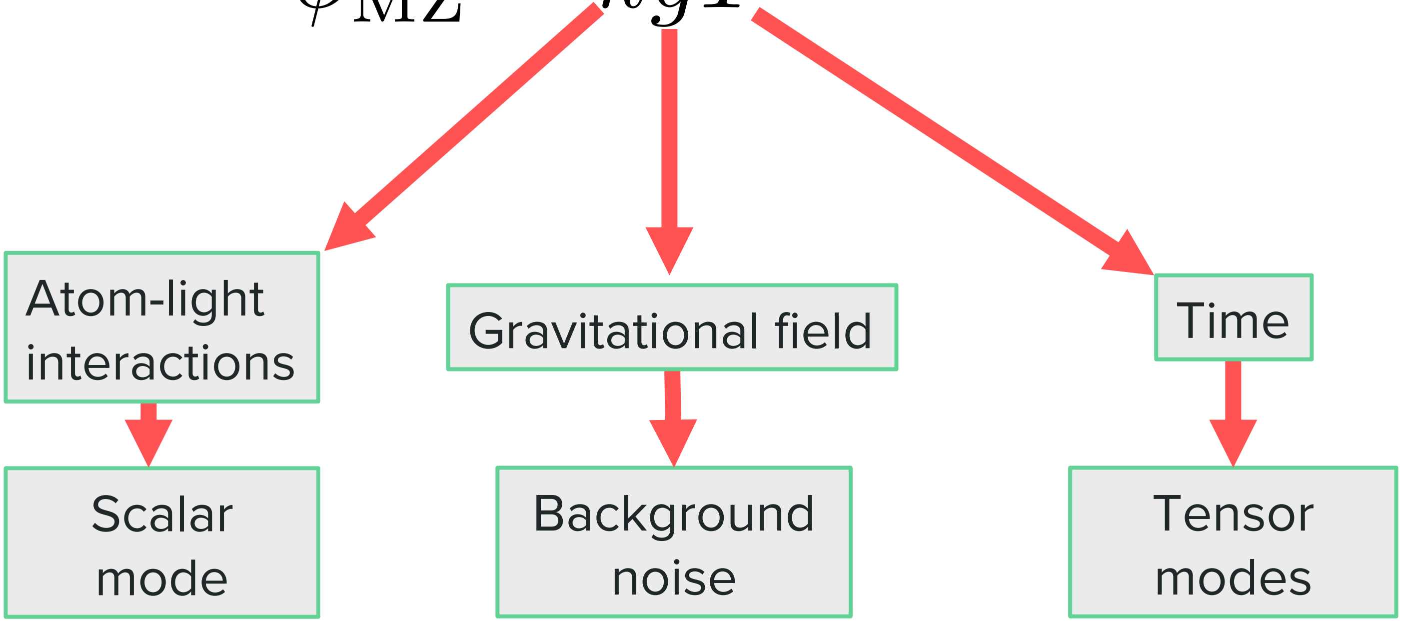
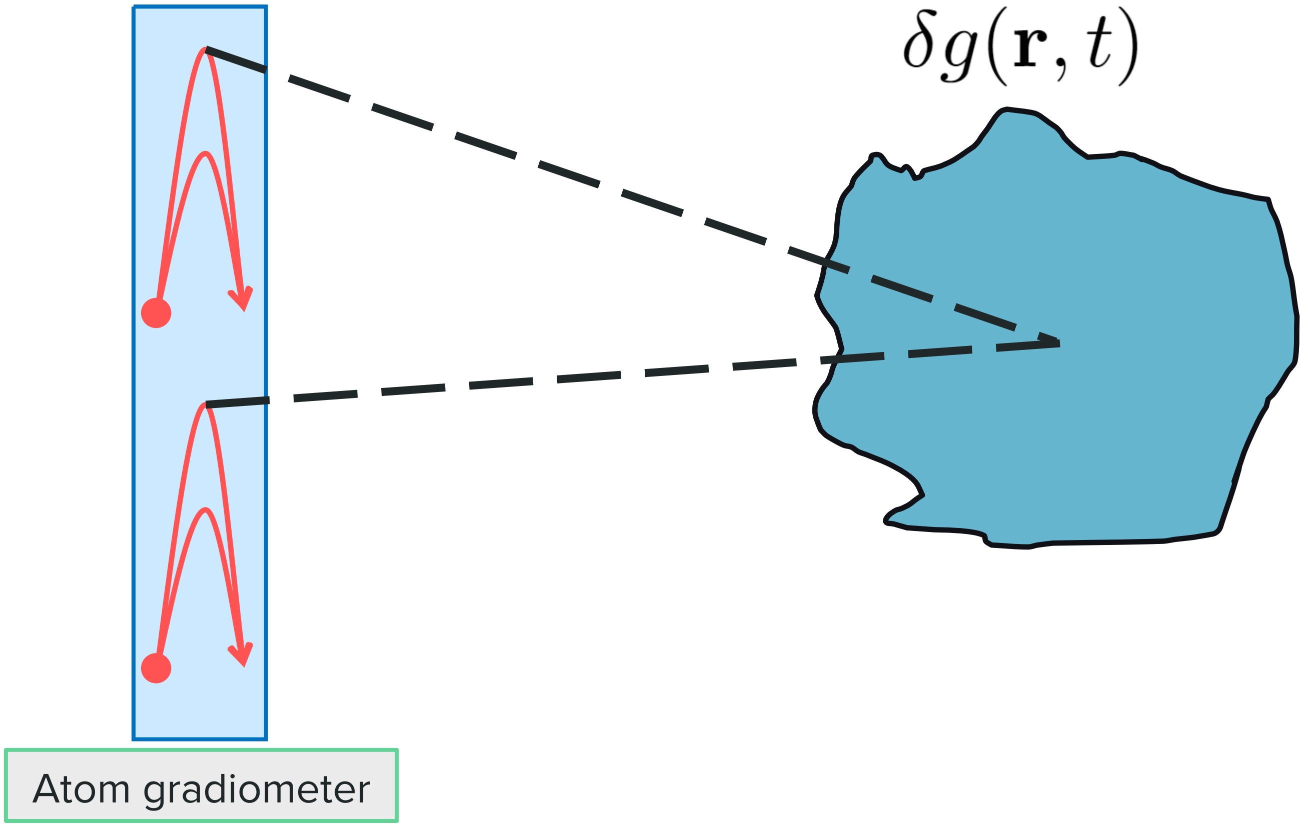


Gravity Gradient Noise (GGN)



The AION-10 Experiment

University of Oxford, Beecroft Building

The AION-10 Experiment

The AION-10 Experiment

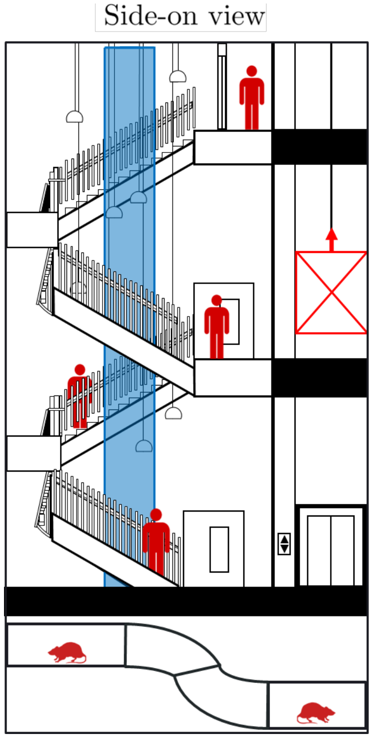
All these people are a problem!

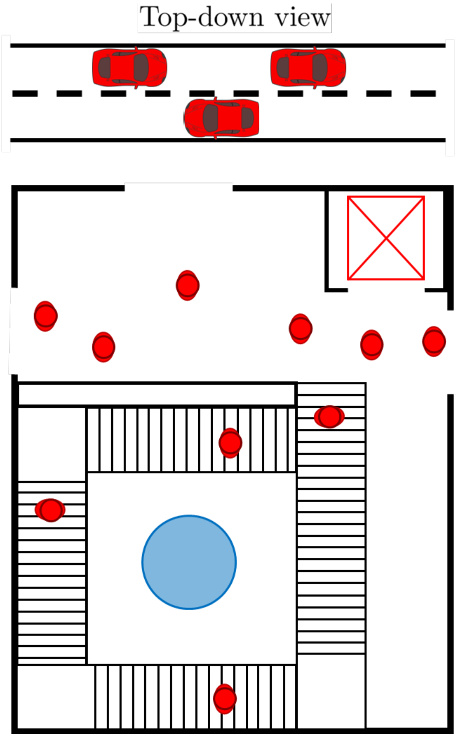
Anthropogenic and synanthropic noise

Many potential sources of noise surround the detector:

Large anthropogenic sources
People walking on the stairs/in the foyer
Traffic on the road outside
Lift moving next to the tower

Small synanthropic sources
Random animal transients (RATs)





Beecroft building, University of Oxford

J. Carlton, C. McCabe
Phys.Rev.D (108, 123004); arXiv: 2308.10731 [astro-ph.CO]

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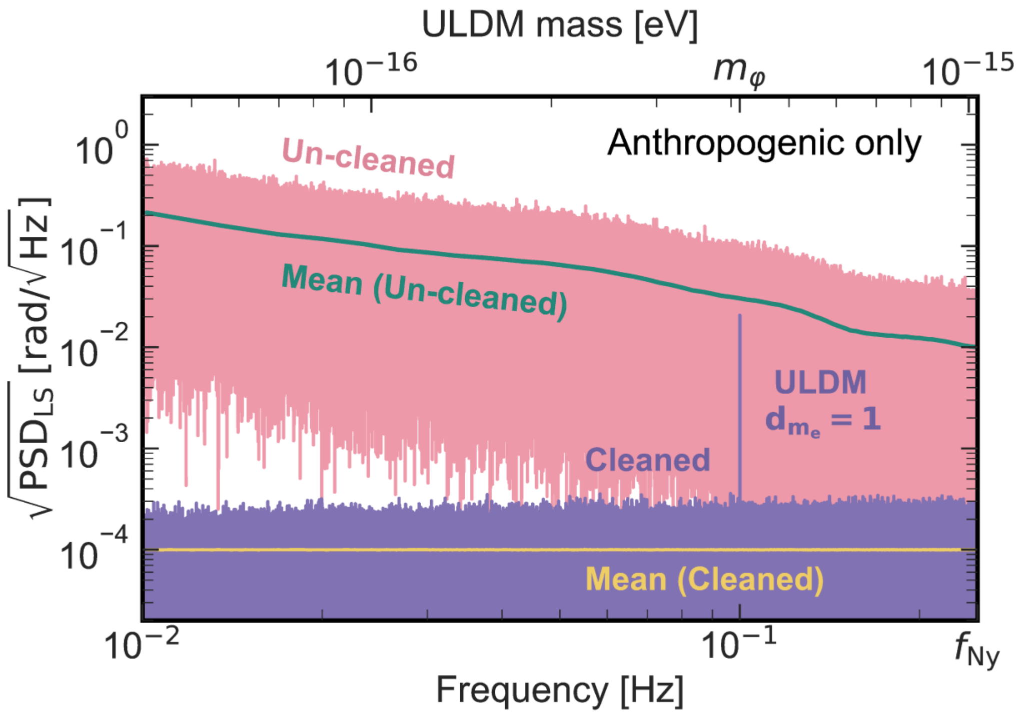

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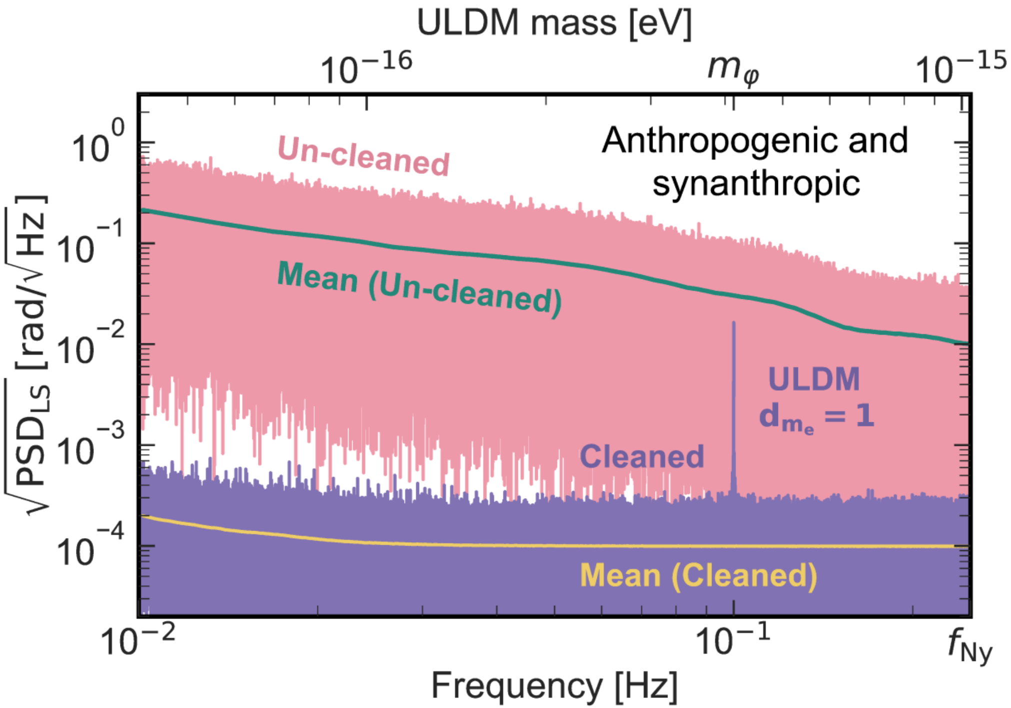

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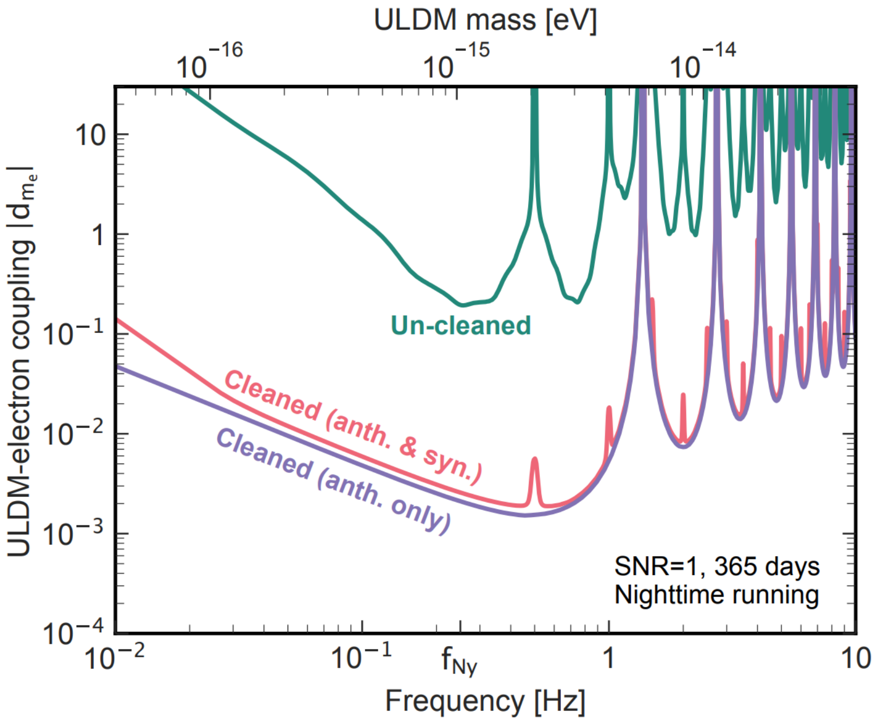

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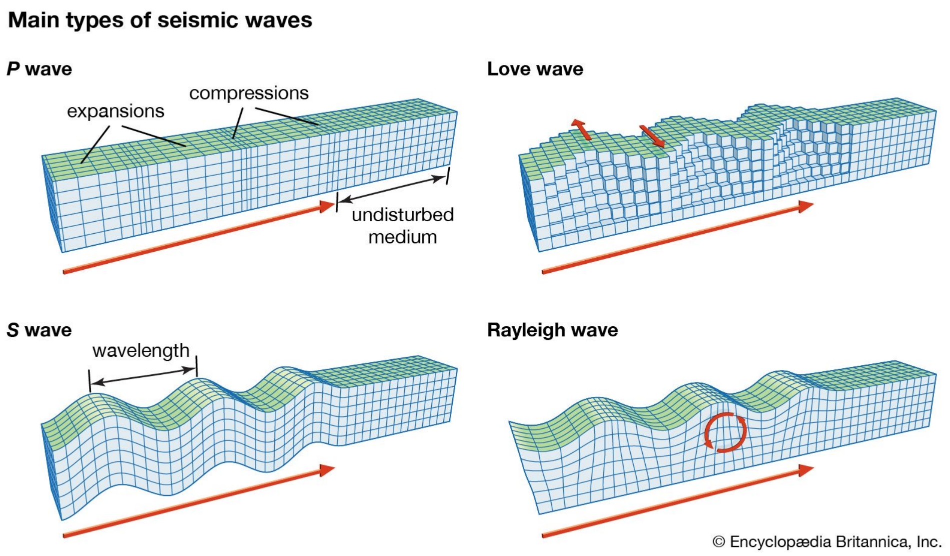
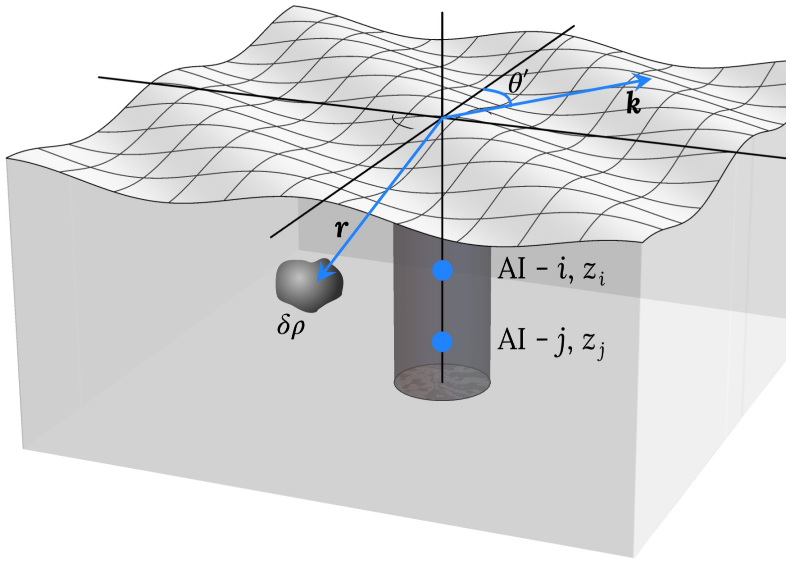
Gravity perturbations from nature?
Seismic GGN



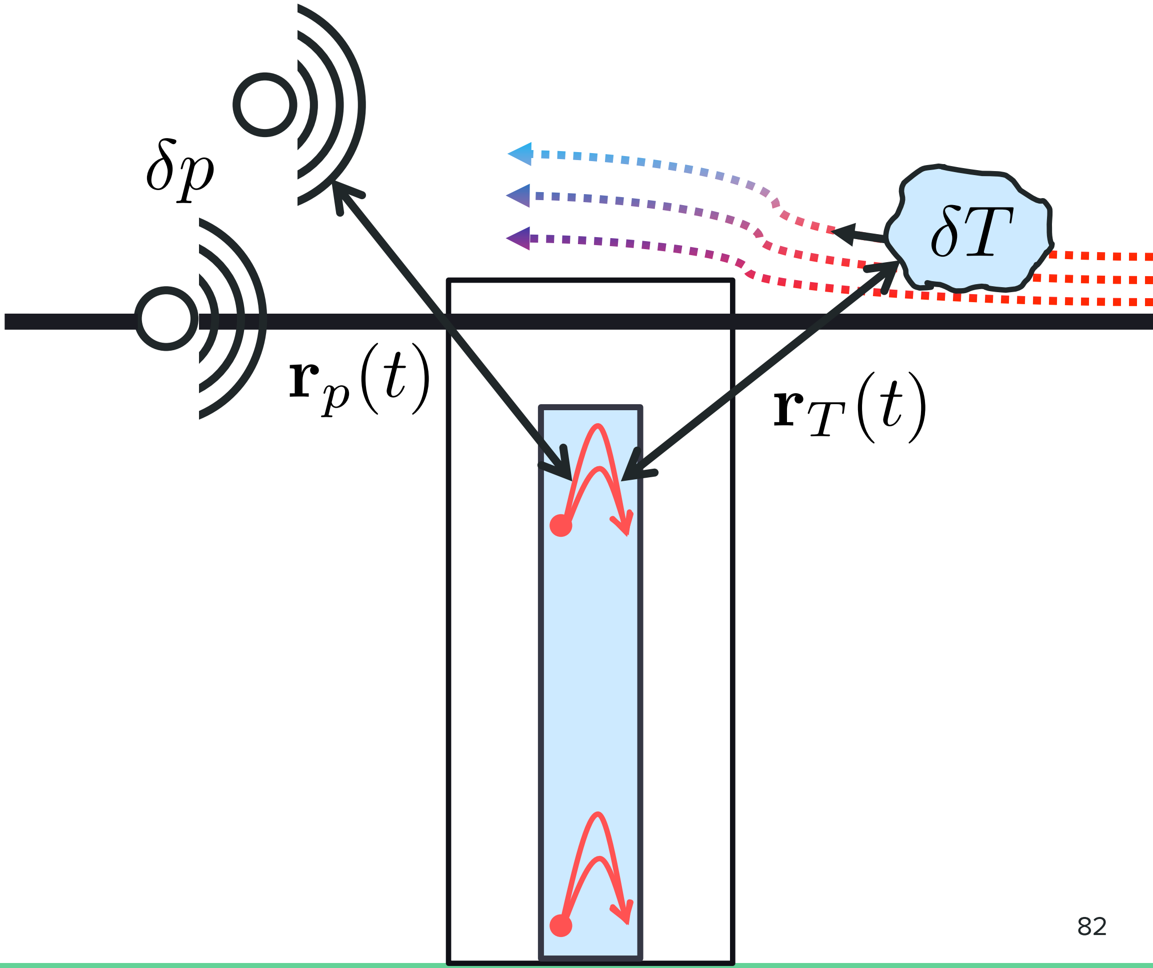


L. Badurina et al. arXiv: 2211.01854

Gravity perturbations from nature? Atmospheric GGN

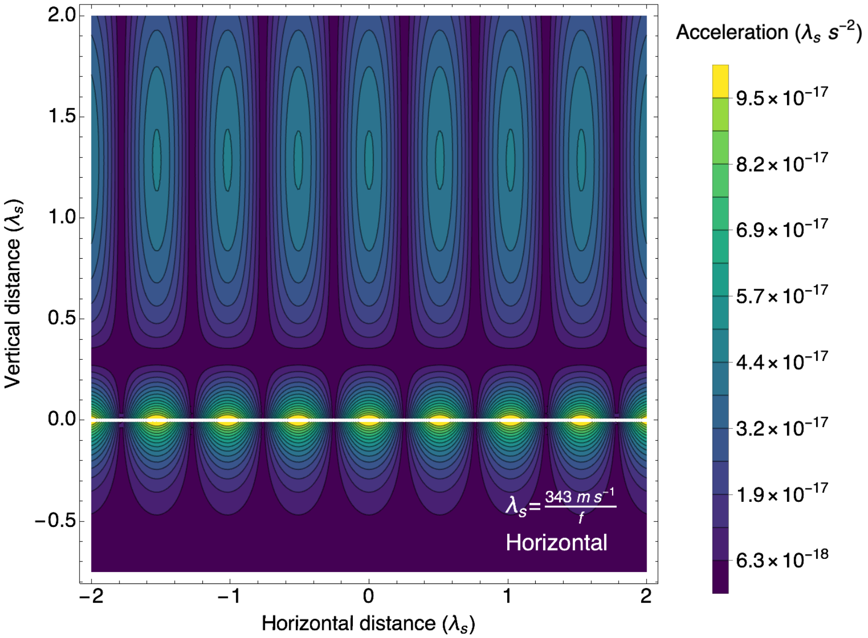
$$\frac{\delta\rho}{\rho_0} = \frac{\delta p}{\gamma p_0}$$

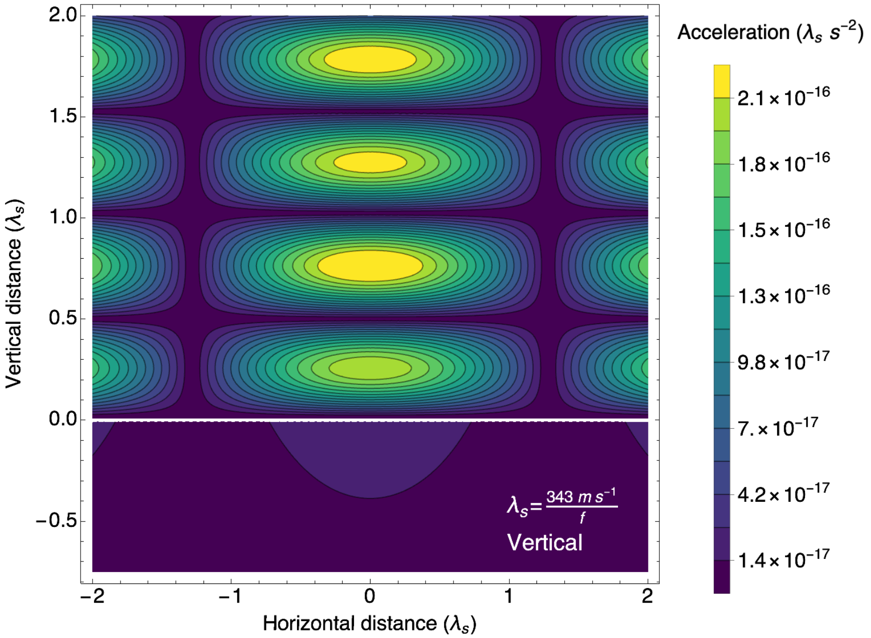
$$\frac{\delta\rho}{\rho_0} = \frac{\delta T}{T_0}$$



J. Carlton et al. arXiv: 2412.05379

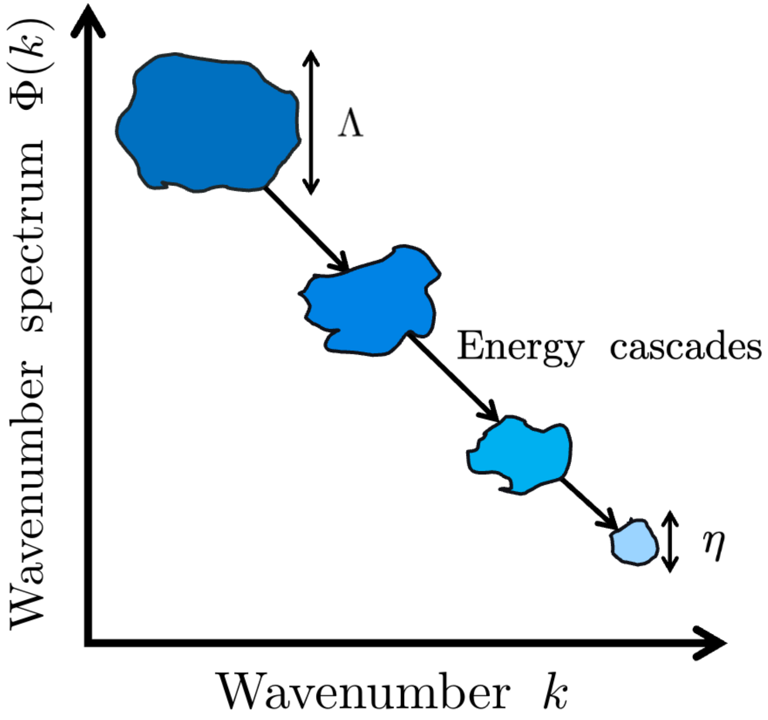
Why pressure matters?

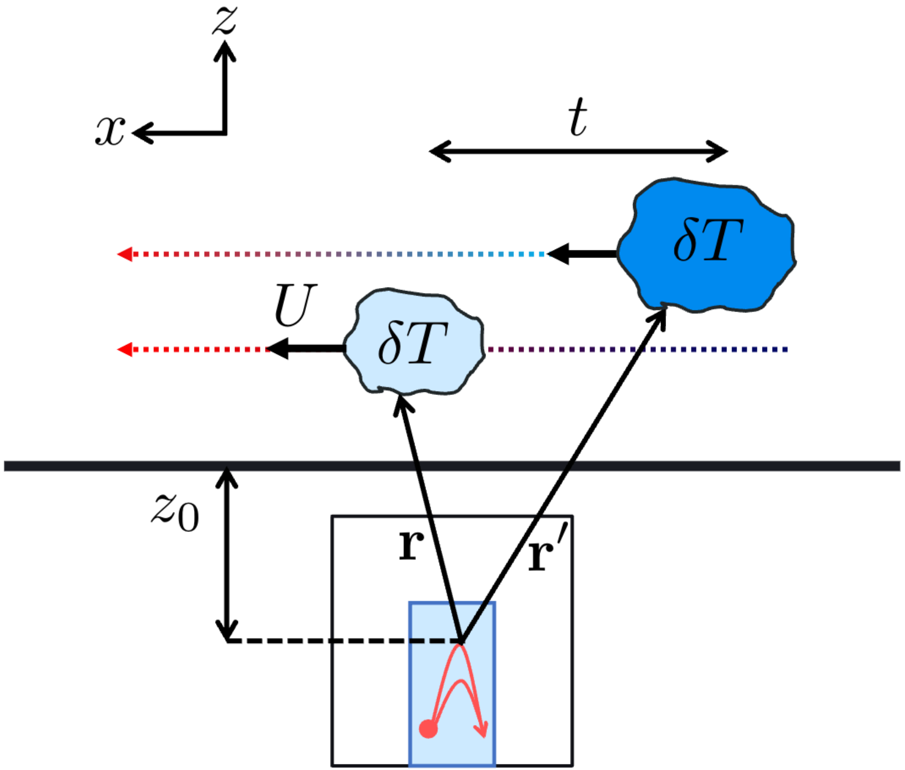




J. Carlton et al. arXiv: 2412.05379

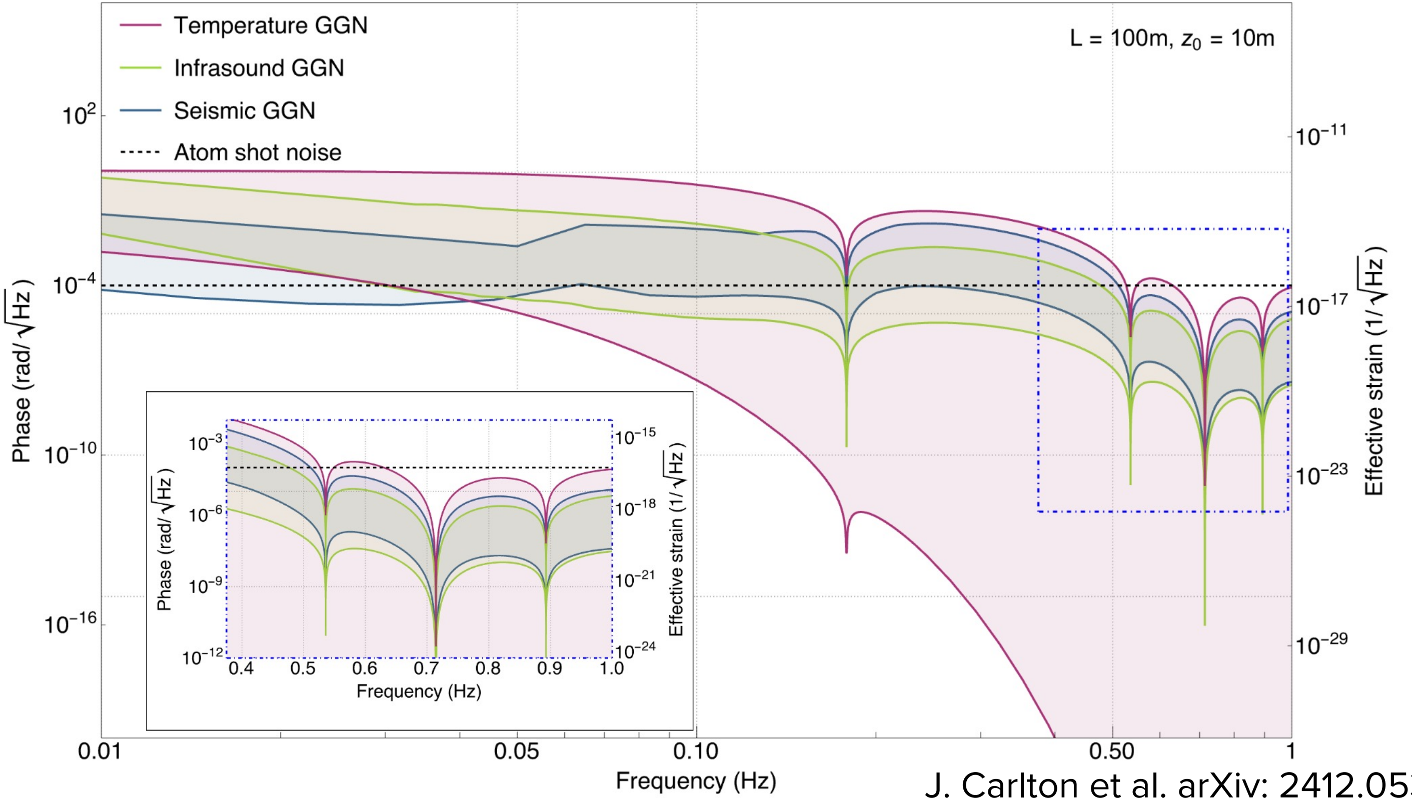
Why temperature matters?





J. Carlton et al. arXiv: 2412.05379

GGN limits sensitivity

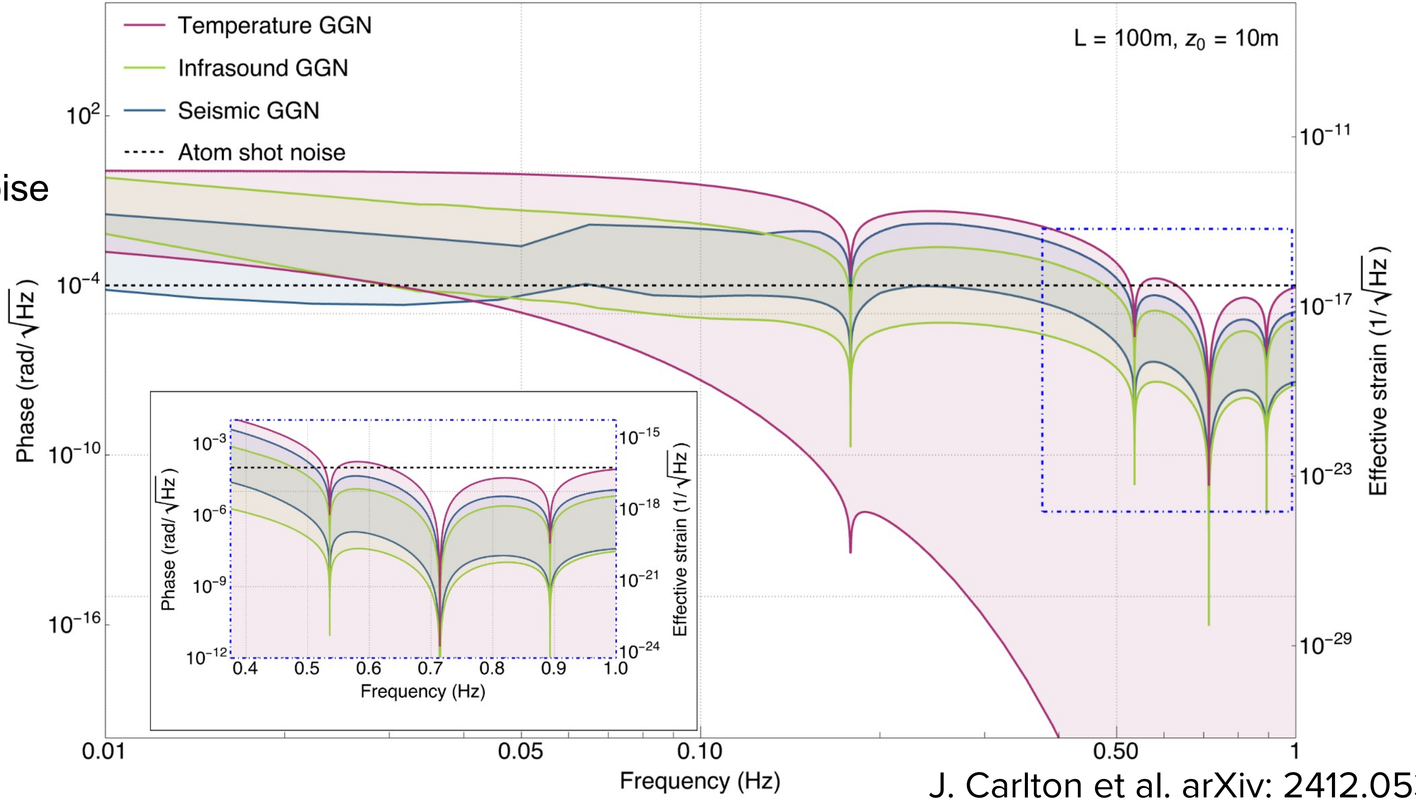


J. Carlton et al. arXiv: 2412.05379

GGN limits sensitivity

Atmospheric noise dominates

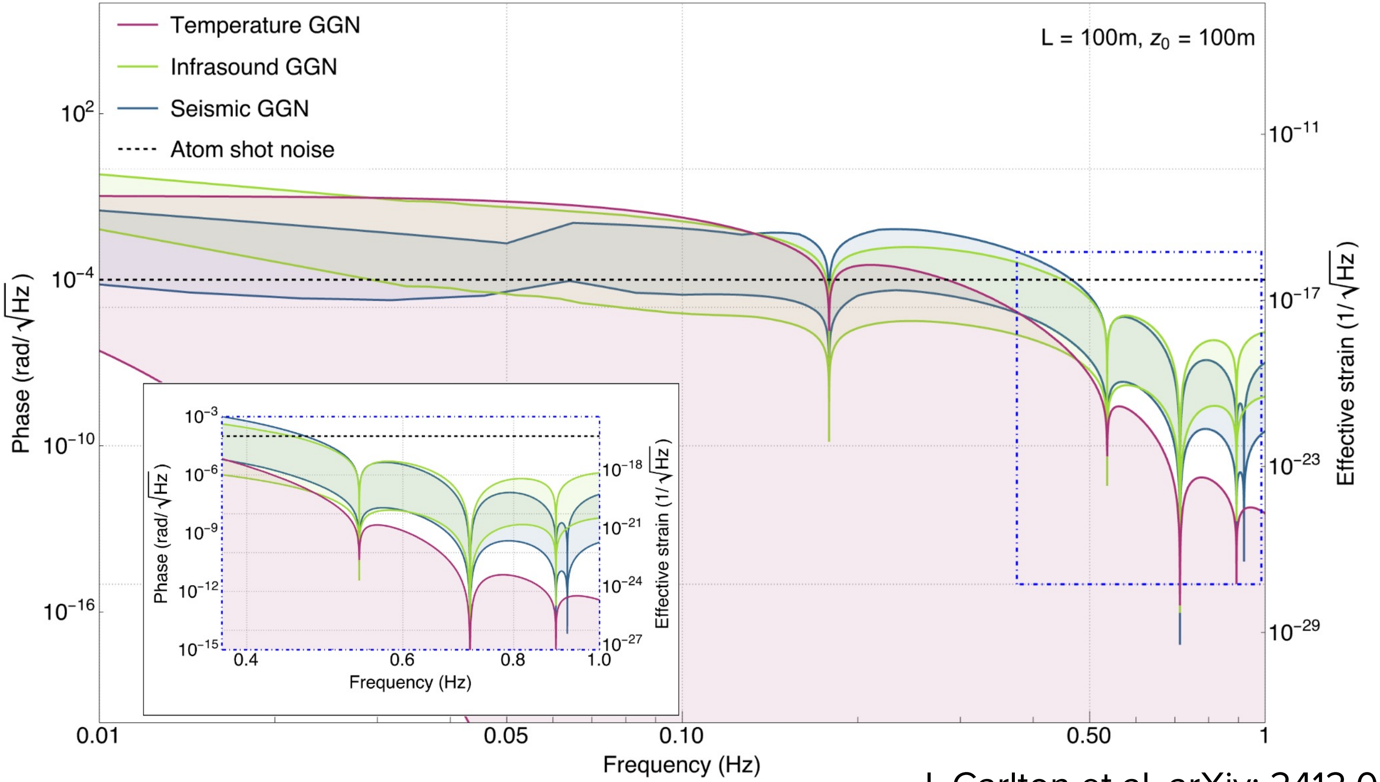
Atom shot noise dominates



J. Carlton et al. arXiv: 2412.05379

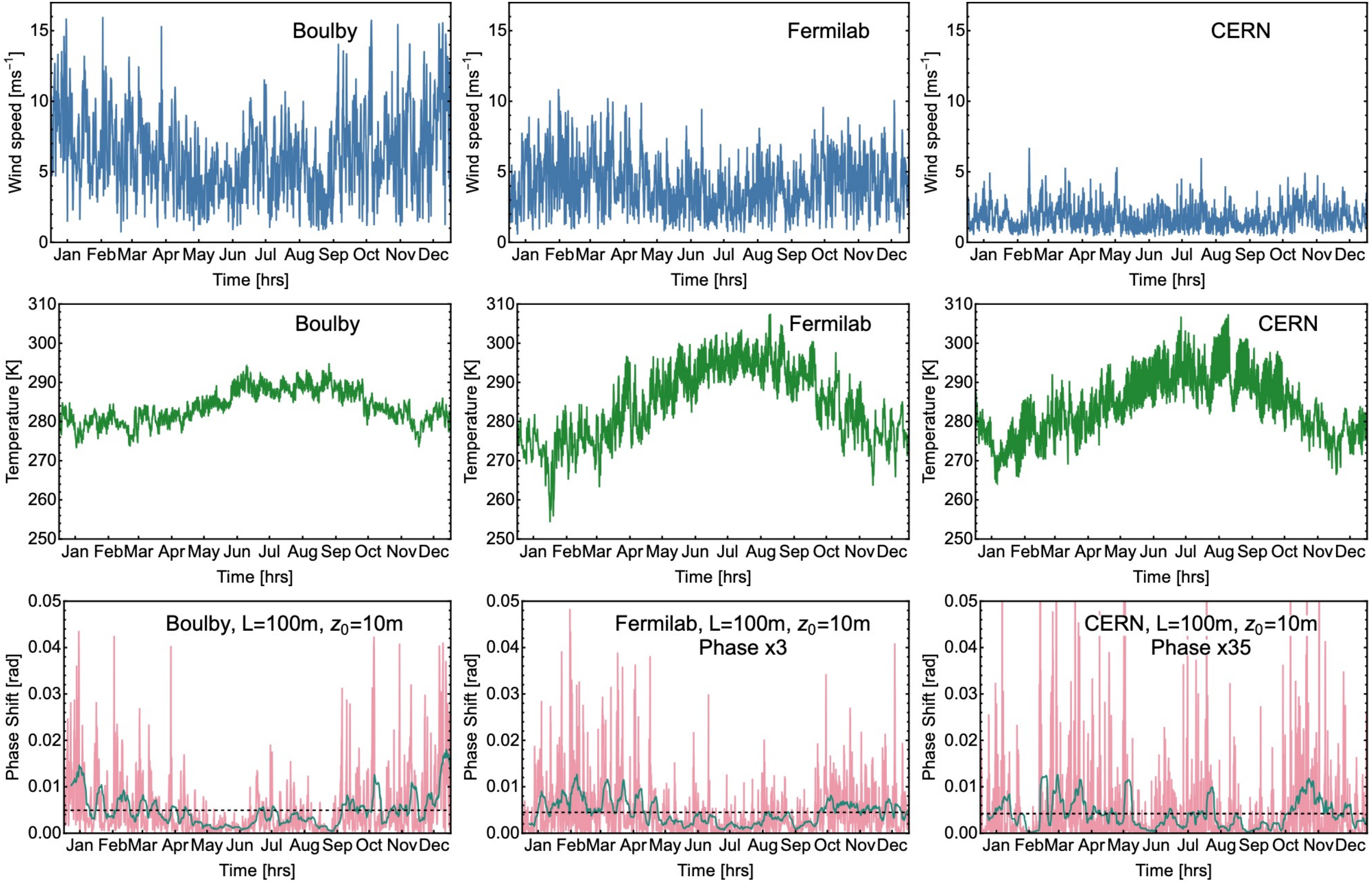
Depth helps!

But we need continuous active noise monitoring!

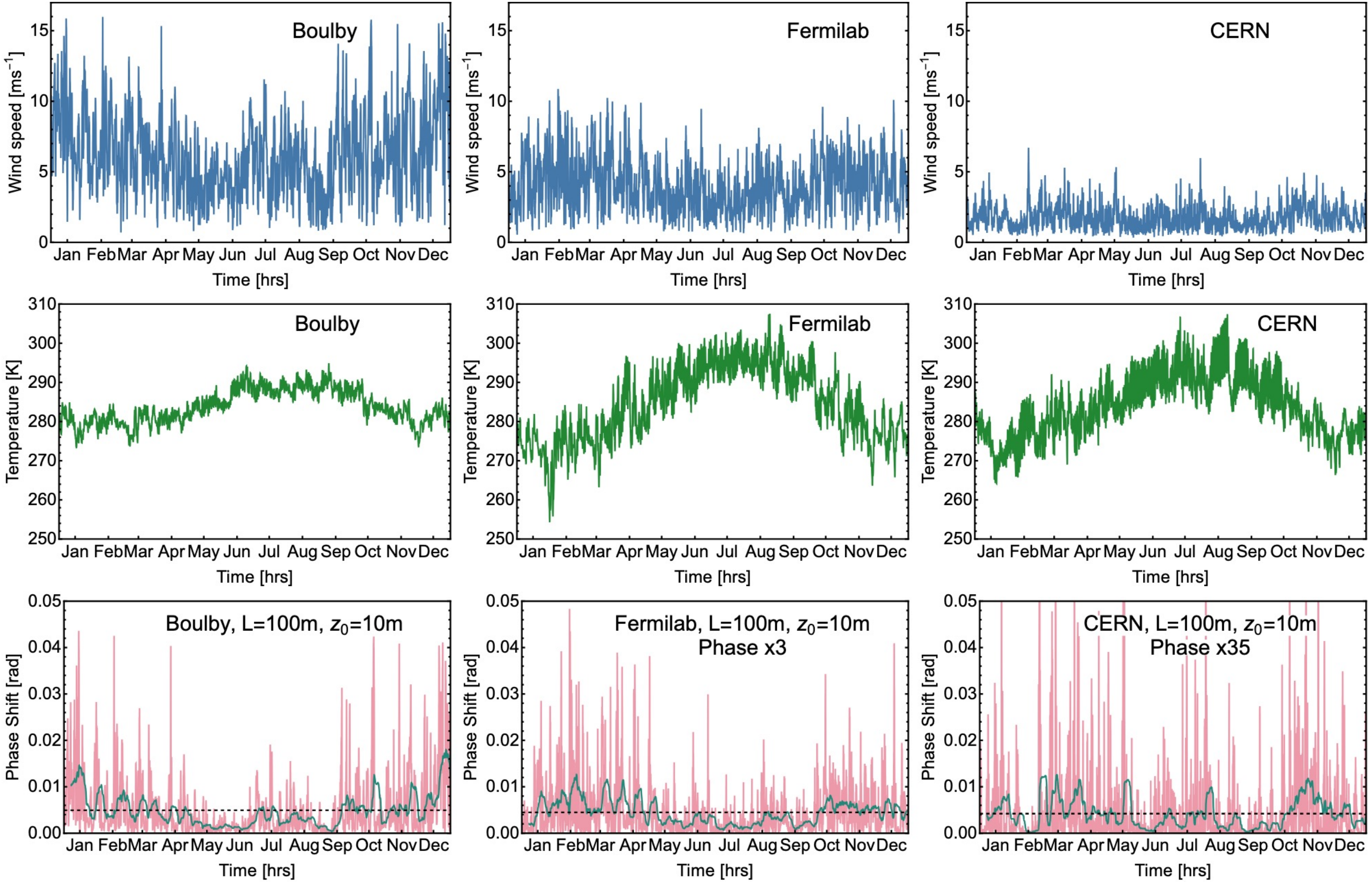


J. Carlton et al. arXiv: 2412.05379

Site selection

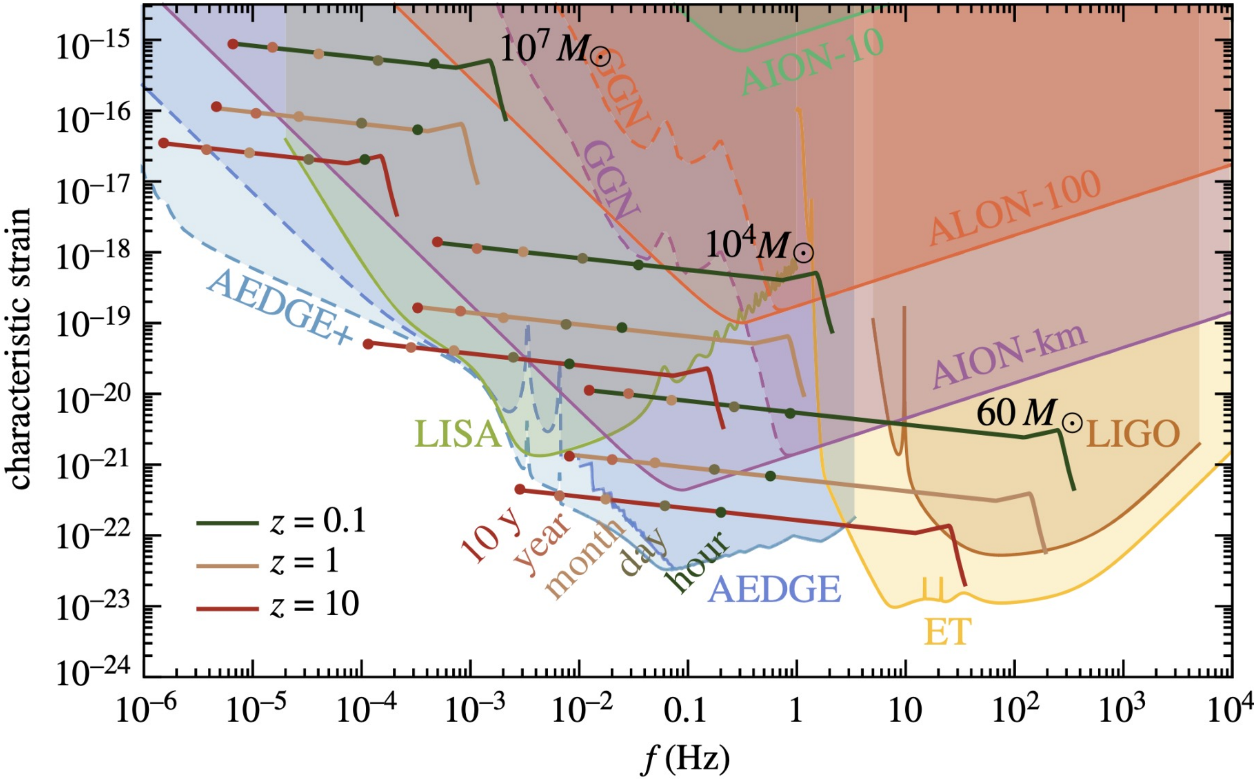


Site selection



Boulby is windy!

Gravitational waves



❖ *'Mid-band' sensitivity between LIGO and LISA.*

L. Badurina et al. arXiv: 2108.02468

Summary

AION is an upcoming atom interferometer experiment, using quantum sensors for detecting ultralight dark matter and gravitational waves – in the ‘mid-band’ between LISA and LIGO.

Spin-2 ULDM can be probed by gravitational wave detectors – however, atom interferometers can detect it through several different channels without altering any of the experimental design! Other GW/ULDM experiments may also detect other couplings not probed by atom interferometers.

Near term intermediate scale atom interferometers will provide leading bounds on screened fifth force searches such as the chameleon and symmetron.

GGN is a leading challenge in terrestrial long-baseline searches.

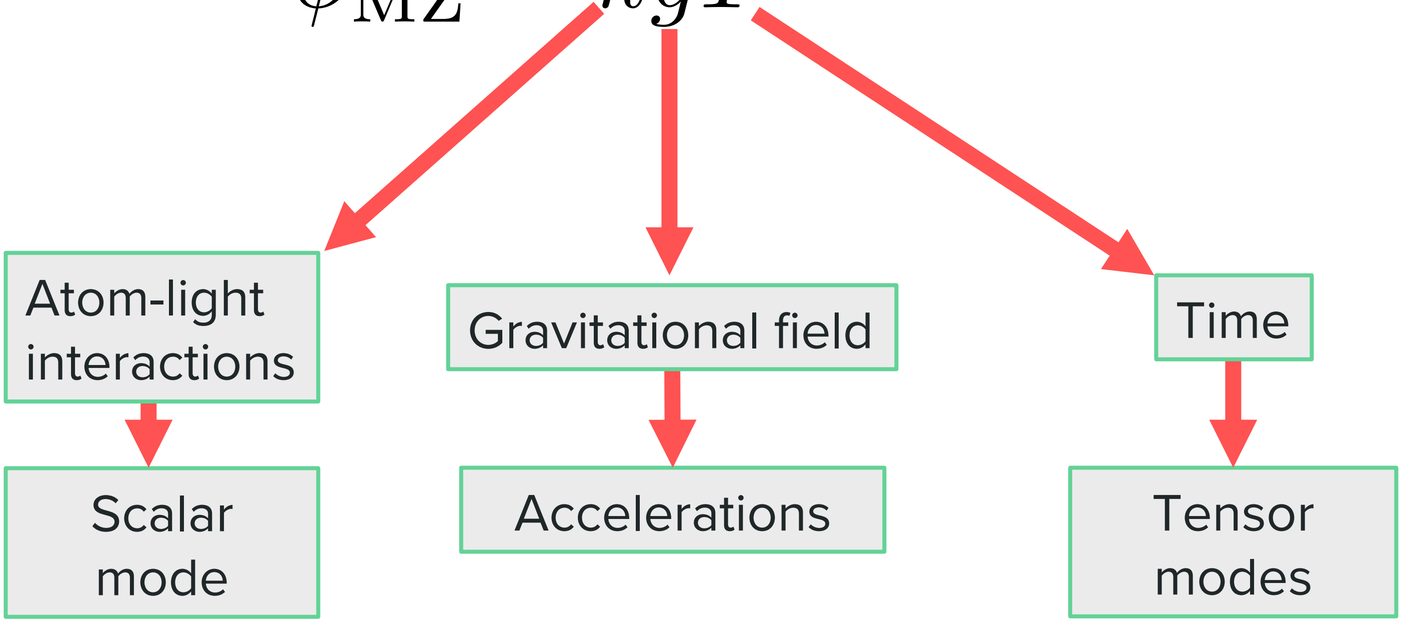
D. Blas, J. Carlton, C. McCabe. arXiv: 2412.14282

Backup

Dark forces

What can we measure?

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



Screened fifth forces

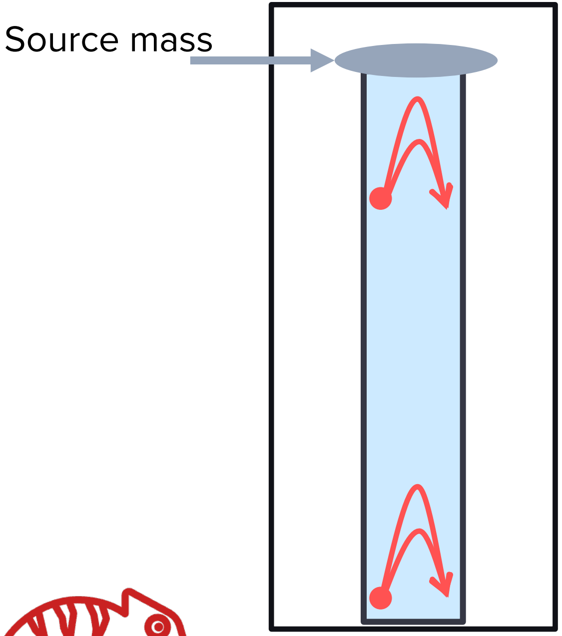
$$S_\varphi = \int \mathrm{d}^4x \sqrt{-g}\left(-\frac{1}{2}(\partial\varphi)^2 - V(\varphi) - A(\varphi)\rho_{\mathrm{m}}\right)$$

Matter coupling

Real scalar field

Self-interaction potential

Atom interferometers are
very good gravimeters/accelerometers



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Atom interferometers are
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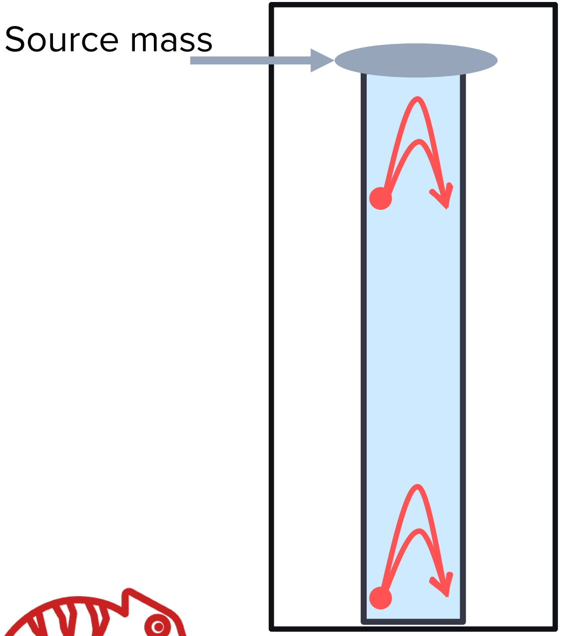

$$V_{ch}(\varphi) = \frac{\Lambda^5}{\varphi}\,, \quad A_{ch}(\varphi) = \frac{\varphi}{M}$$

Chameleon

$$V_{sym}(\varphi) = -\frac{1}{2}\mu^2\varphi^2 + \frac{\lambda}{4}\varphi^4\,, \quad A_{sym}(\varphi) = \frac{\varphi^2}{2M^2}$$

Symmetron

Screened fifth forces

$$S_\varphi = \int \mathrm{d}^4x\,\sqrt{-g}\left(-\frac{1}{2}(\partial\varphi)^2 - V(\varphi) - A(\varphi)\rho_\mathrm{m}\right)$$

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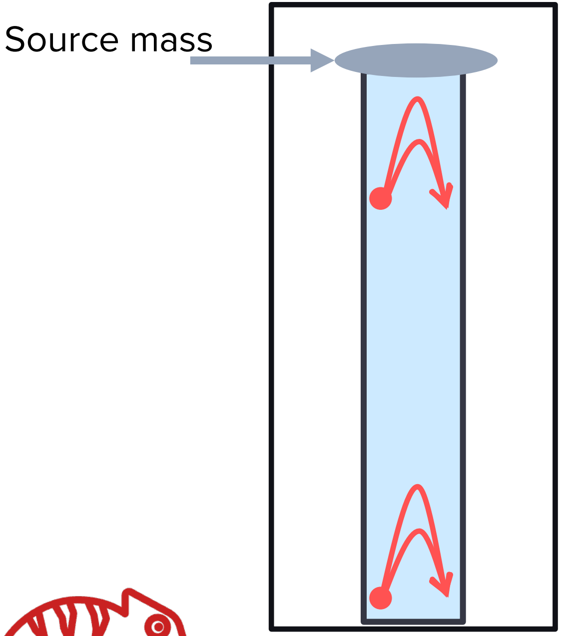
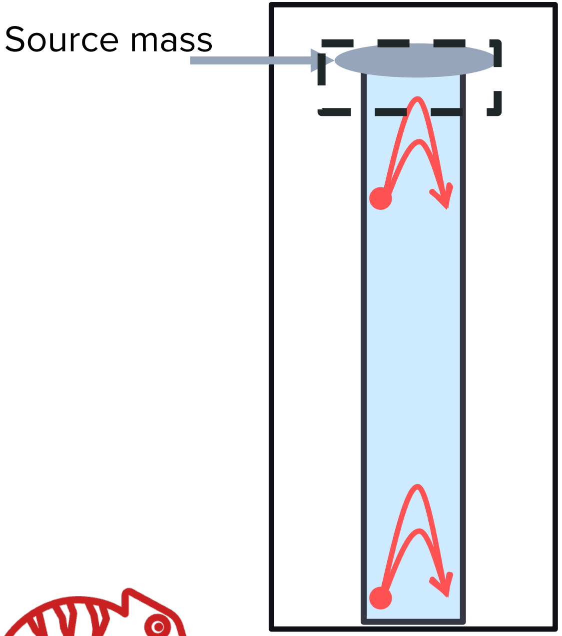


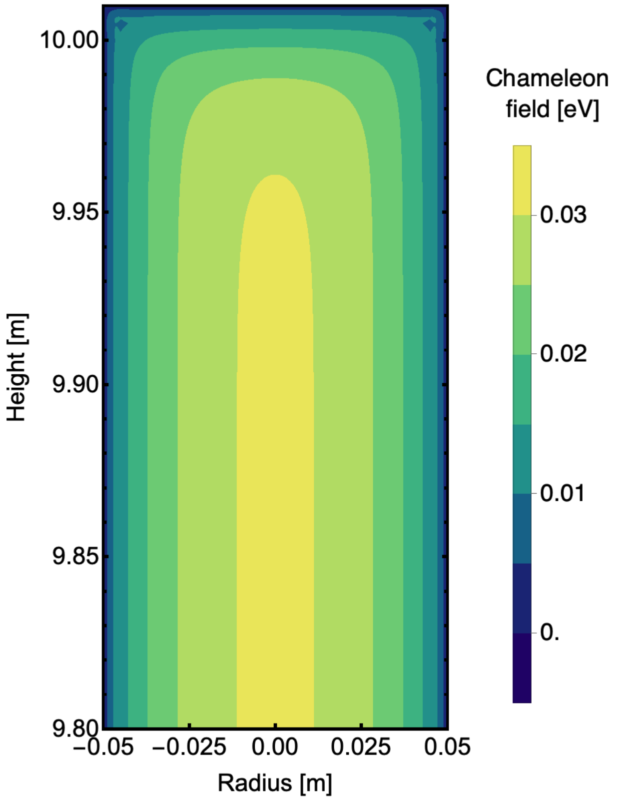
Real scalar field

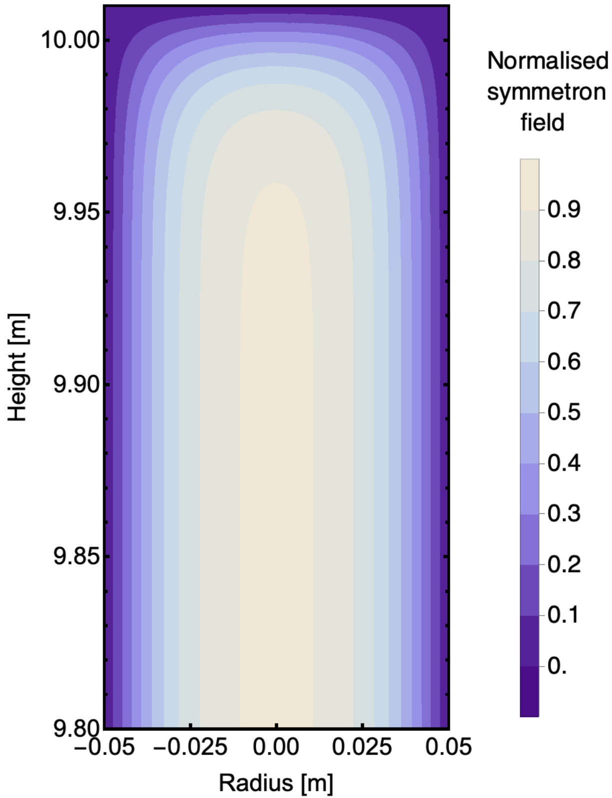
$$\vec{a}_\varphi = -\lambda_a \frac{\mathrm{d}A}{\mathrm{d}\varphi}\vec{\nabla}\varphi(\vec{x})$$

Acceleration
with screening factor

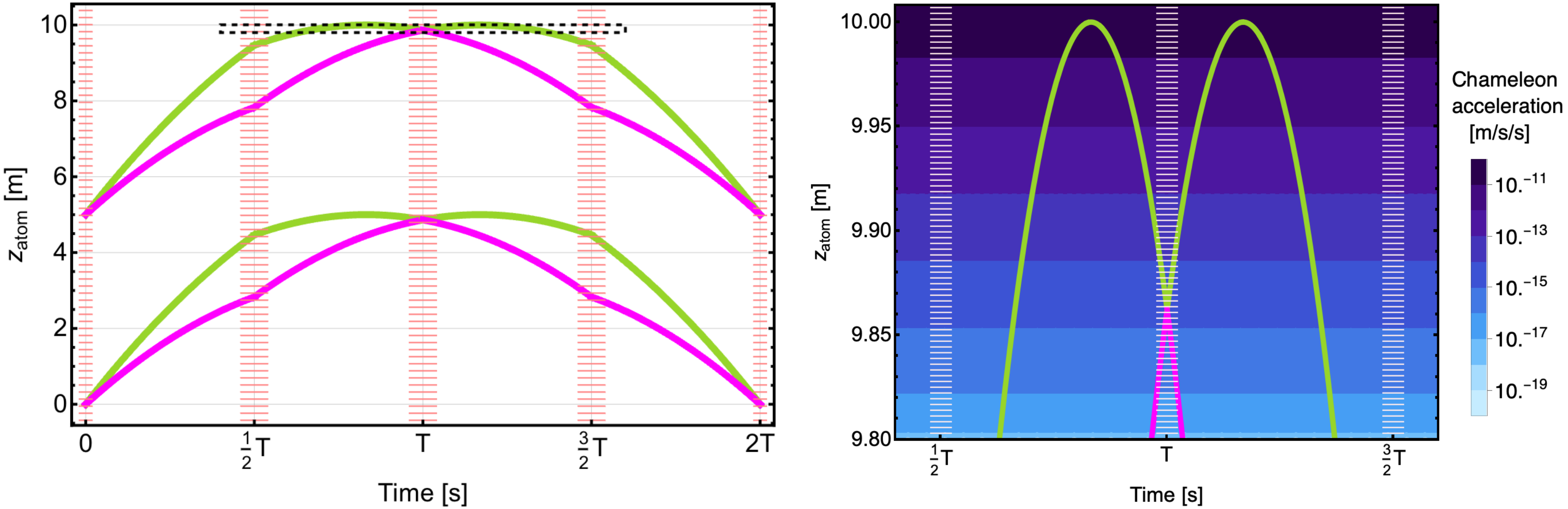
Numerically modelling the fields





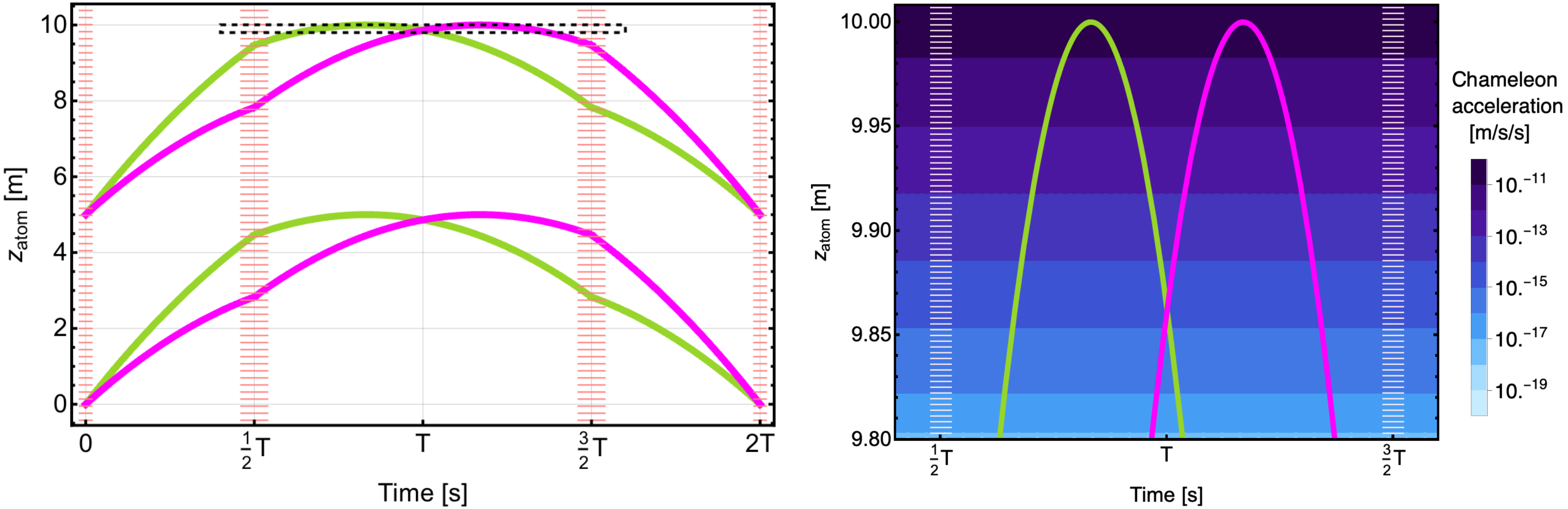


Boosting sensitivity



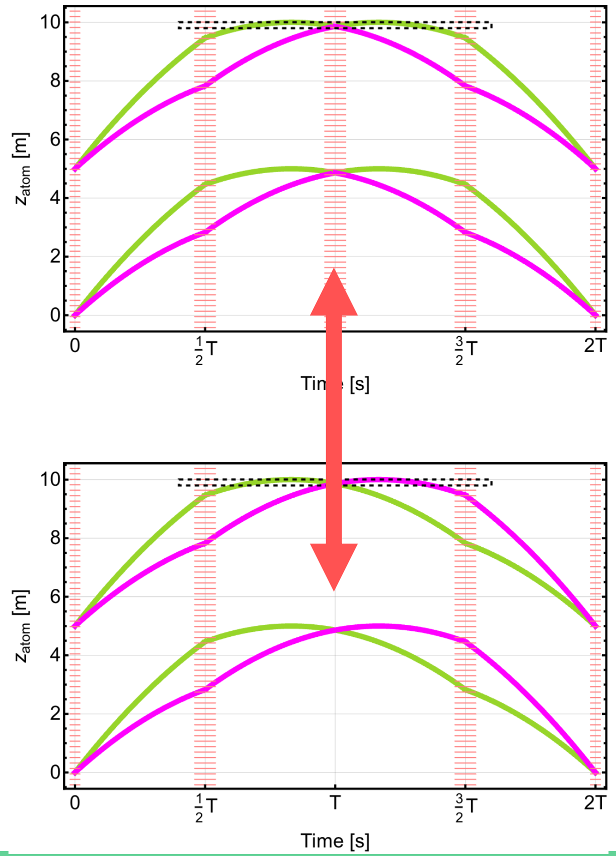
Q=2 resonant sequence
(sensitive)

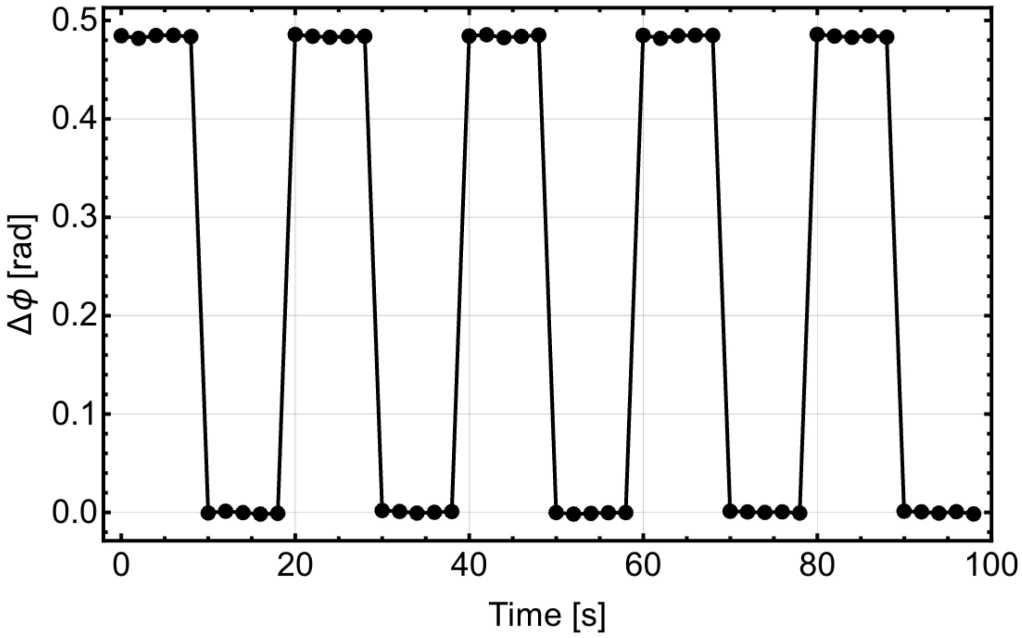
Boosting sensitivity



Butterfly sequence
(insensitive)

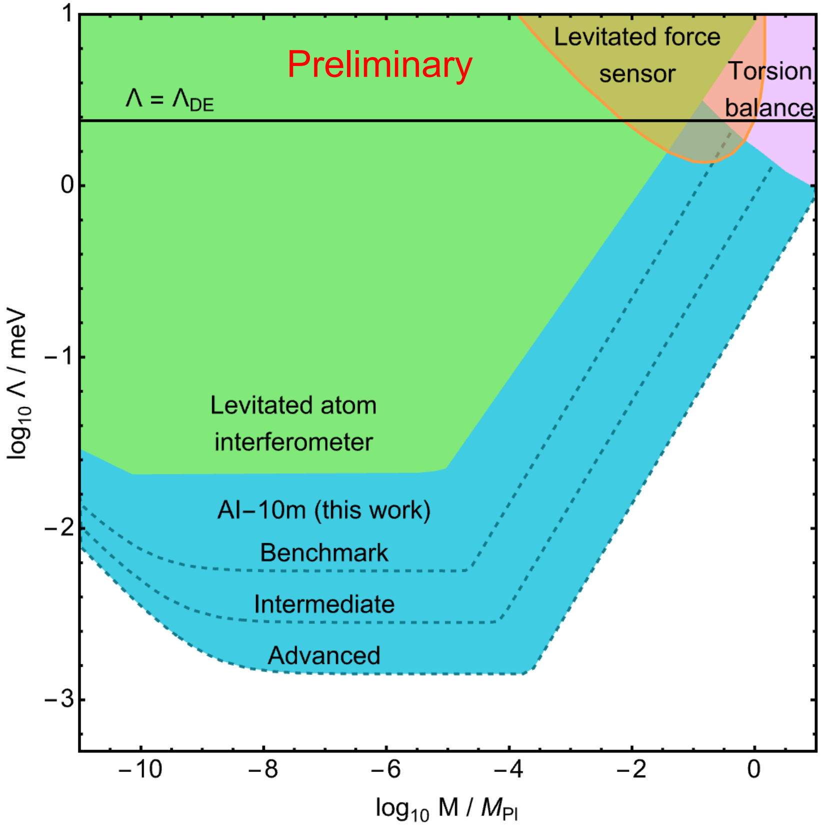
Create a ‘moving’ source mass



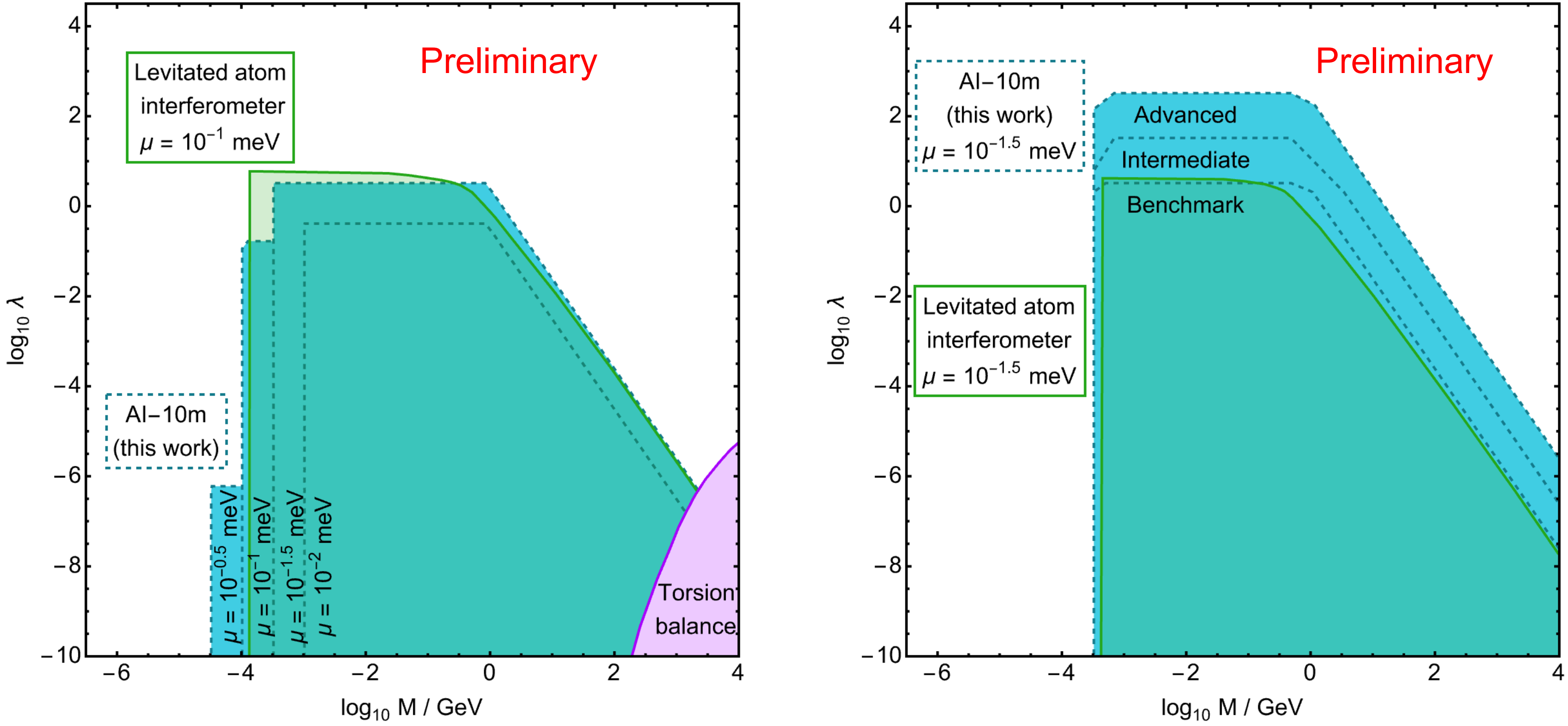


Much improved chameleon sensitivity!

AI-10m	T_{int}	$\delta\phi_{\text{int}}$ [rad/$\sqrt{\text{Hz}}$]
Benchmark	~ 2 s	10^{-3}
Intermediate	~ 400 s	10^{-4}
Advanced	~ 11 hrs	10^{-5}

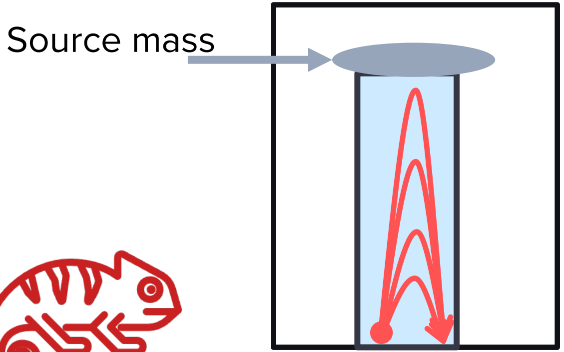


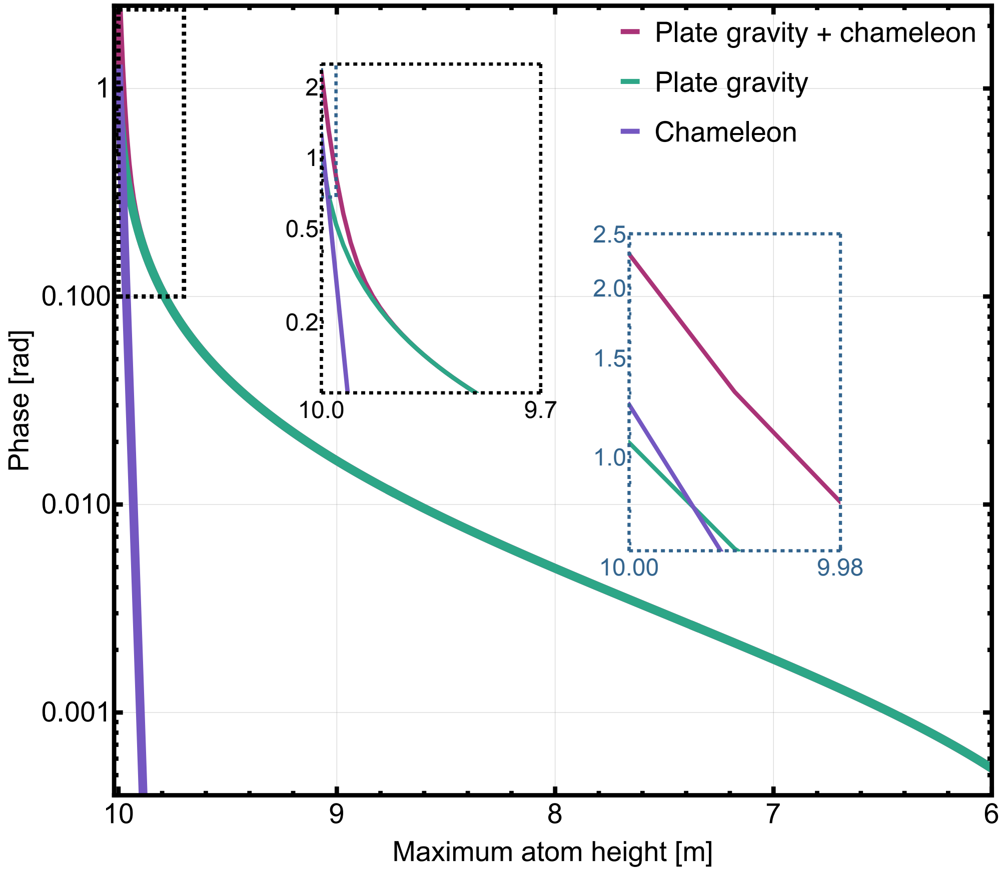
Competitive symmetron limits!



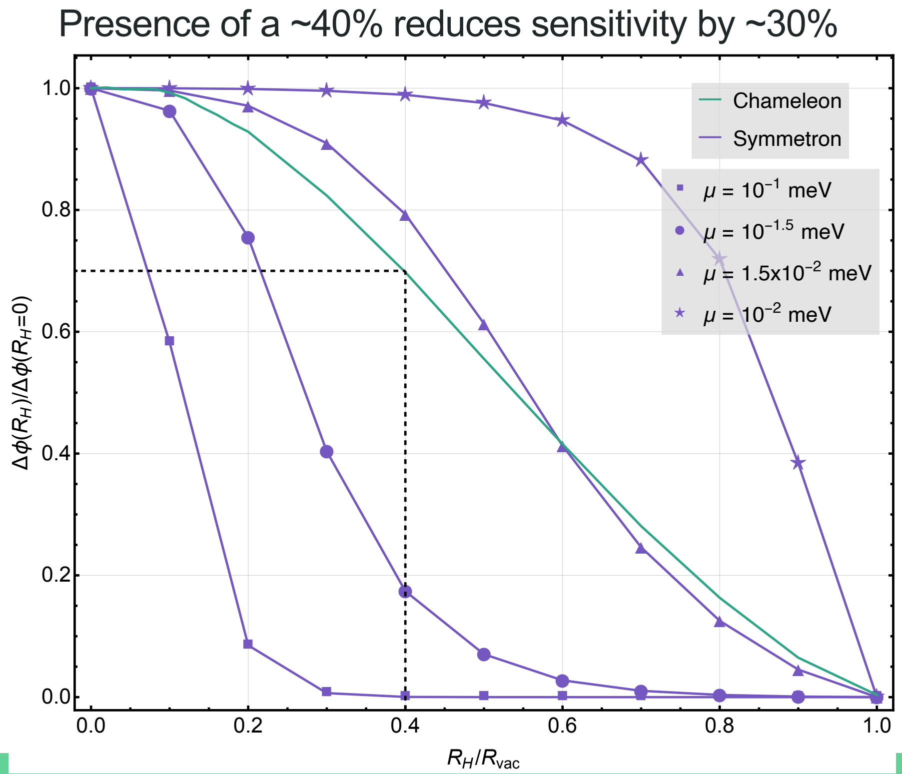
Systematics

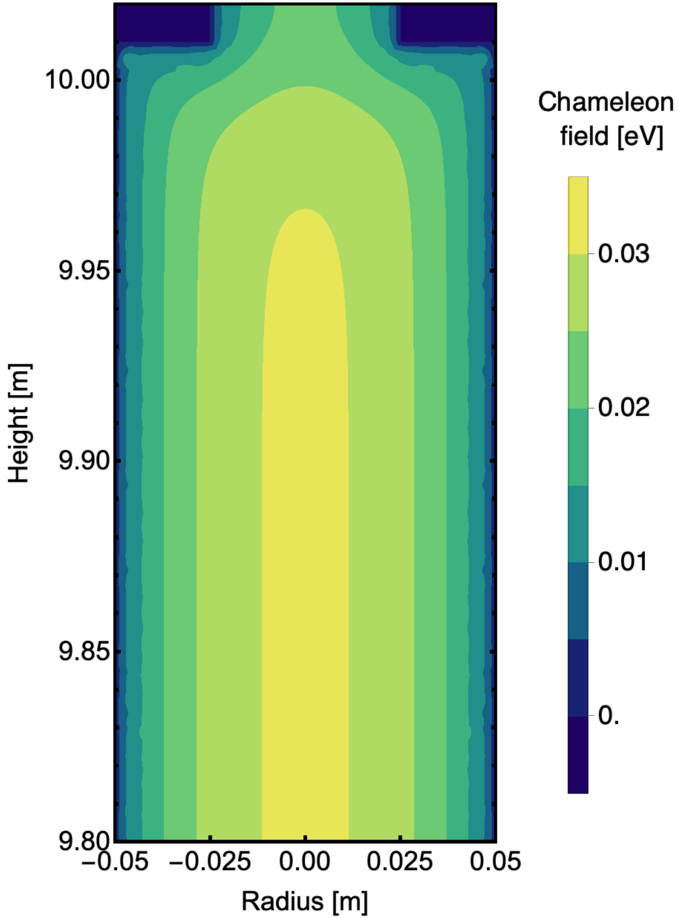
- Plate gravity
- Patch potentials
- Black body radiation





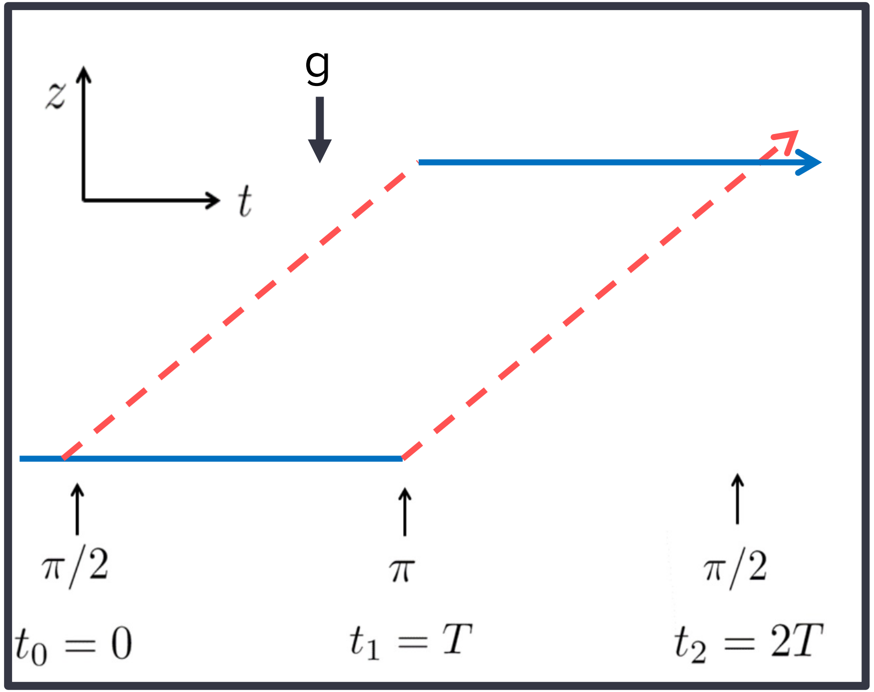
Do we need a hole in the plate?





Phase shifts

$$\phi = \phi_{\text{prop}} + \phi_{\text{sep}} + \phi_{\text{laser}}$$



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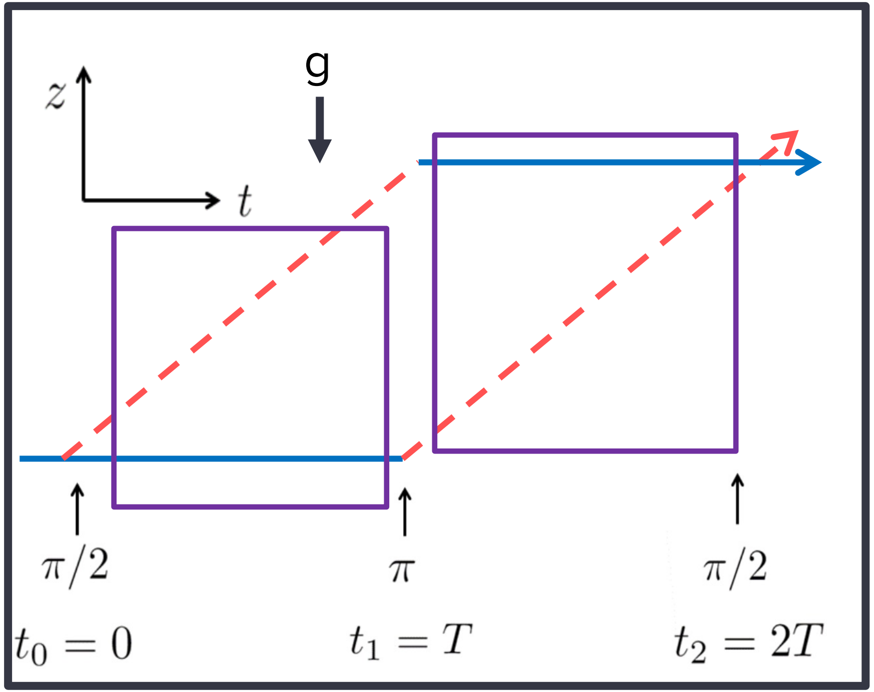

$$\phi_{\text{prop}} = \frac{1}{\hbar}\left[\sum_u \left(\int_{ti}^{tf} (L_c - E_i)\mathrm{d}t\right) - \sum_l \left(\int_{ti}^{tf} (L_c - E_i)\mathrm{d}t\right)\right]$$

Phase shifts

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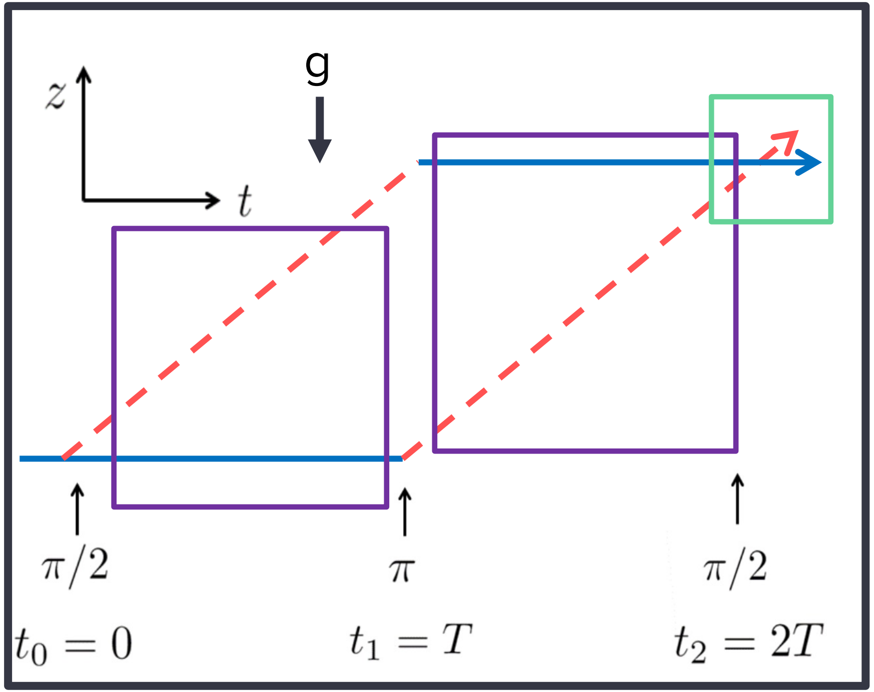

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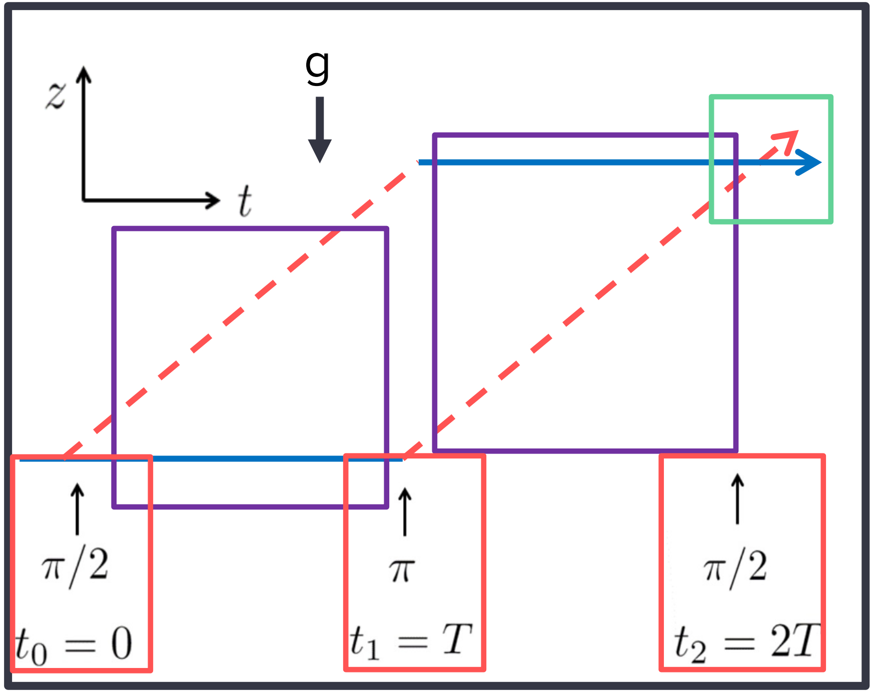
$$\phi_{\text{sep}} = \frac{1}{\hbar}\bar{\boldsymbol{p}} \cdot \Delta \boldsymbol{z}$$

Phase shifts

$$\phi = \phi_{\text{prop}} + \phi_{\text{sep}} + \phi_{\text{laser}}$$



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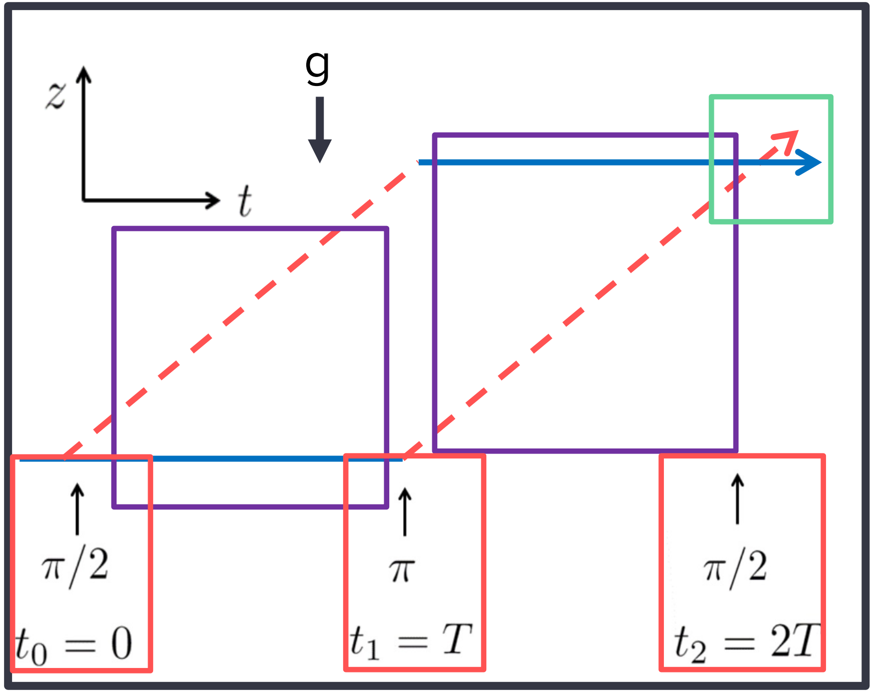
$$\phi_{\text{sep}} = \frac{1}{\hbar}\bar{\boldsymbol{p}} \cdot \Delta \boldsymbol{z}$$

$$\phi_{\text{laser}} = \left(\sum_j \pm\phi_L(t_j, \boldsymbol{z}_u(t_j))\right)_u - \left(\sum_j \pm\phi_L(t_j, \boldsymbol{z}_l(t_j))\right)_l$$

Phase shifts

$$\phi = \phi_{\text{prop}} + \phi_{\text{sep}} + \phi_{\text{laser}} = kgT^2$$



$$\phi_{\text{prop}} = \frac{1}{\hbar}\left[\sum_u \left(\int_{ti}^{tf} (L_c - E_i)\mathrm{d}t\right) - \sum_l \left(\int_{ti}^{tf} (L_c - E_i)\mathrm{d}t\right)\right]$$

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Spin-2 sensitivity

$$\Delta\Phi = \sum_\chi \Delta\Phi_\chi = \sum_\chi 4\gamma_\chi \frac{\omega_{A,0}}{\Lambda}\frac{\sqrt{\rho_{\rm DM}}}{m_\chi^2}\frac{\Delta r}{L}\sin\left[\frac{m_\chi n L}{2}\right]\sin\left[\frac{m_\chi T}{2}\right]\sin\left[\frac{m_\chi(T-(n-1)L)}{2}\right]\cos\left[m_\chi\frac{2T+L}{2}+\phi_\chi\right]$$

γ_χ	**FP**	**LV1**	**LV2**
$\alpha^{(0)}$	$-\alpha^{(0)} v_{\rm DM}^2 \frac{8\sqrt{2f_s}}{\sqrt{3}}$	0	$\alpha^{(0)} \frac{8\sqrt{2f_s}}{\sqrt{3}}(\alpha^{-1}+\lambda_{\rm at})$
$\beta^{(0)}$	$\beta^{(0)} v_{\rm DM}^2 \frac{8\sqrt{2f_s}}{\sqrt{3}}$	0	$\beta^{(0)} \frac{8\sqrt{2f_s}}{\sqrt{3}}(3\alpha^{-1}+\lambda_{l1}+\lambda_{l2})(2+\xi_A)$
$\alpha^{(1)}$	$-2\alpha^{(1)} v_{\rm DM} D^i\left[\hat{v}_{{\rm DM},\,i}\sqrt{\frac{8f_s}{3}}+\sqrt{\frac{f_v}{2}}\sum_\lambda e_i^\lambda\right]$	0	$\alpha^{(1)} \frac{2\sqrt{f_s}}{\sqrt{3}} D^i \frac{\hat{v}_{{\rm DM},i}}{v_{\rm DM}}\frac{1+\lambda}{\lambda+\beta}$
$\beta^{(1)}$	0	0	0
$\alpha^{(2)}$	0	0	0
$\beta^{(2)}$	$\beta^{(2)} D^{ij}\Big[(\delta_{ij}-3\hat{v}_{{\rm DM},i}\hat{v}_{{\rm DM},j})\sqrt{f_s} + \sqrt{f_t}\sum_\lambda e_{ij}^\lambda - \sqrt{f_v}\hat{v}_{{\rm DM},i}\sum_\lambda e_j^\lambda\Big]$	$\beta^{(2)}\sqrt{f_t}\sum_\lambda D^{ij} e_{ij}^\lambda$	$\beta^{(2)} D^{ij}\Big[\sqrt{f_t}\sum_\lambda e_{ij}^\lambda + \frac{2\sqrt{f_s}}{\sqrt{3}}(\delta_{ij}-\hat{v}_{{\rm DM},i}\hat{v}_{{\rm DM},j})\Big]$

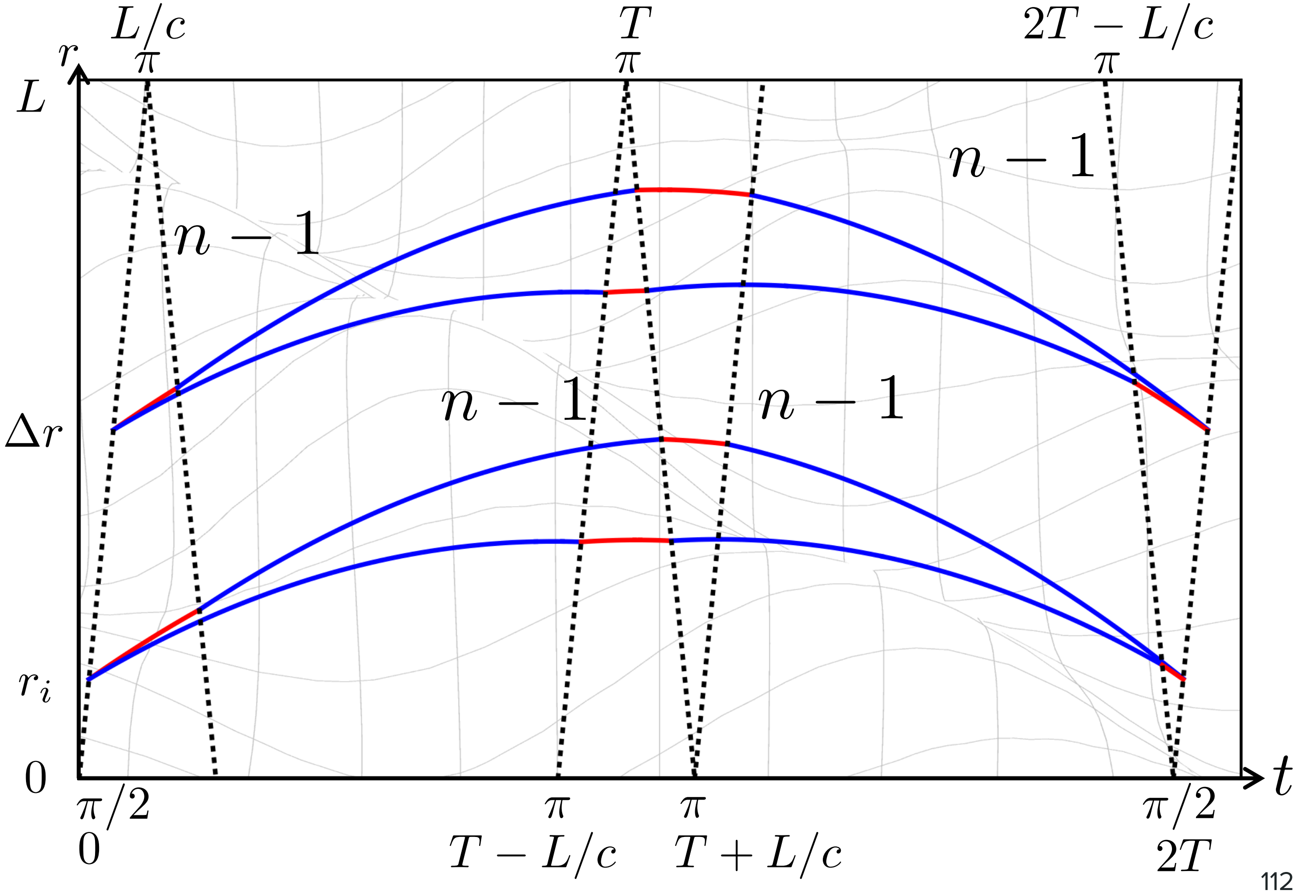
LMT pulses

Additional pulses
enhance sensitivity

$$n = 2$$

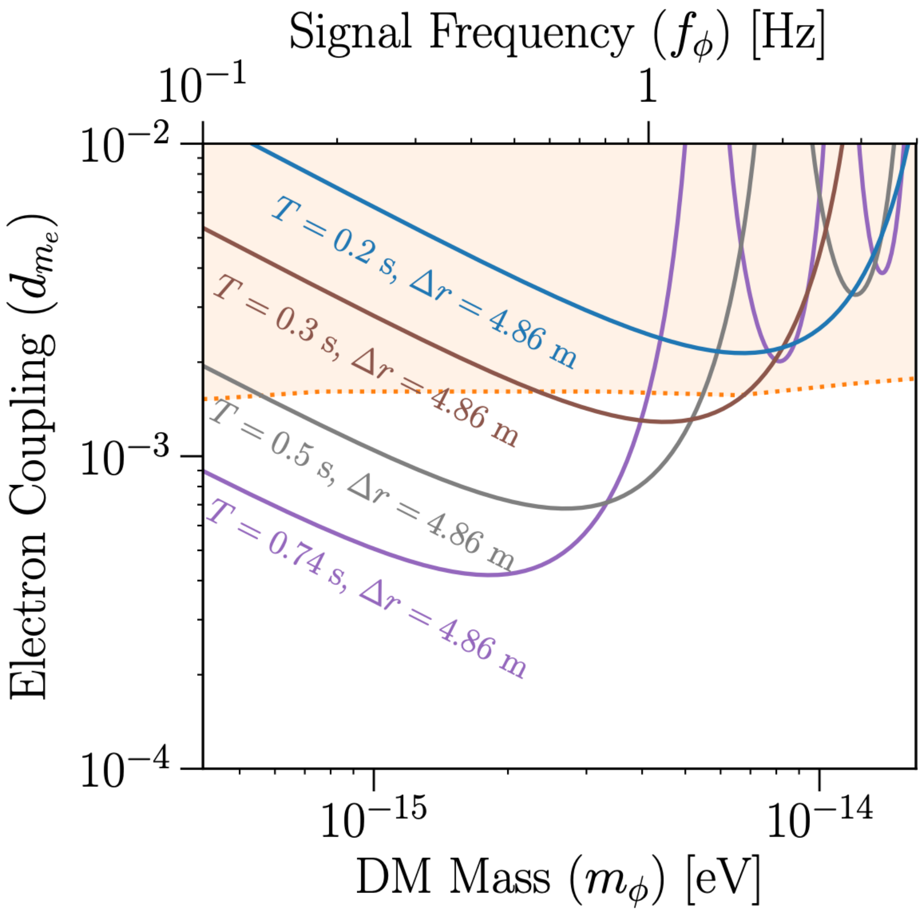
Atom gradiometer

$$\Delta\phi = \phi_1 - \phi_2$$



Scalar ULDM sensitivity

- *ULDM mass/frequency sensitivity depends on T.*



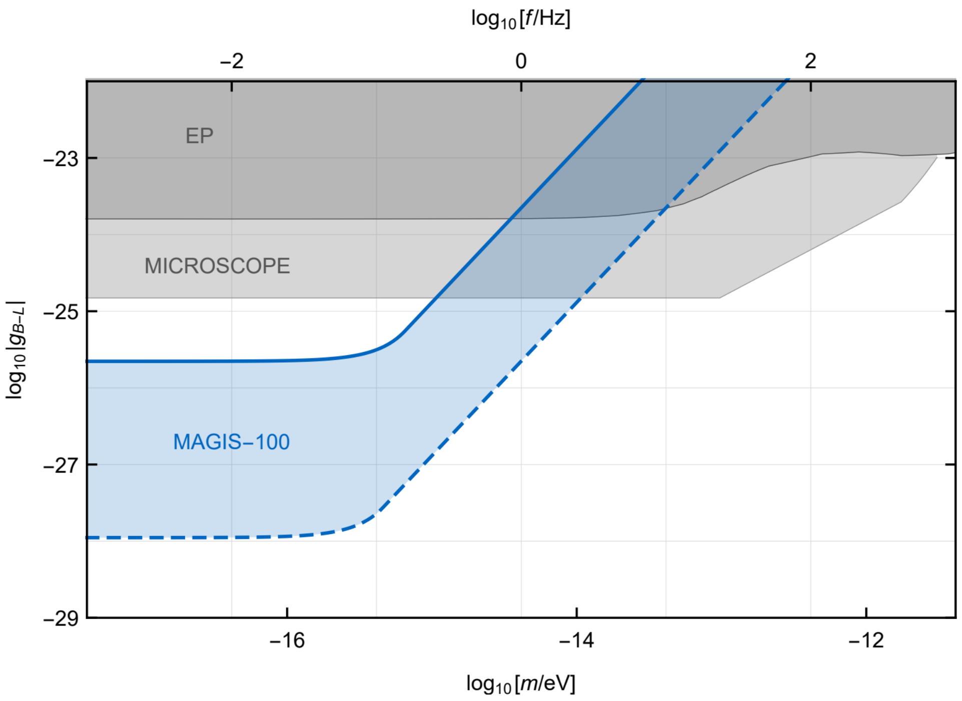
L. Badurina, D. Blas, C. McCabe. arXiv: 2109.10965

Spin-1 dark matter

B-L coupling, which generates a ‘dark’ electric field

$$\Delta F_{B-L} \sim g_{B-L} \left(\frac{Z_1}{A_1} - \frac{Z_2}{A_2} \right) E_{B-L}$$

Probe with a dual-species interferometer



M. Abe et al. arXiv: 2104.02835

Other couplings

Matter couplings

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

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

Light couplings

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

Axion-like coupling/other quantum sensors

$$\frac{\beta^{(1)}}{\Lambda} F_{\sigma 0} F^{i\sigma} W_i(t)$$

$$\downarrow$$

$$\epsilon^{ijk} E_j B_k$$

E cross B term probed by axion cavity experiments?

AION-10 sensitivity projections

$$d_{m_e}^{\text{best}} \sim \left(\frac{1}{T}\right)^{5/4} \frac{1}{C\, n \Delta r} \left(\frac{\Delta t}{N_a}\right)^{1/2} \left(\frac{1}{T_{\text{int}}}\right)^{1/4}$$

Handles to optimise (in order of priority):

T ~ 1s (interrogation time)
C ~ 0.1 - 1 (constrast)
n ~ 1000 (LMT)
Δr ~ AI separation
Δt ~ sampling time
$N_a \sim$ atoms in cloud
$T_{\text{int}} \sim 10^7\text{s}$ (integration time)