Massive graviton dark matter searches with atom interferometers

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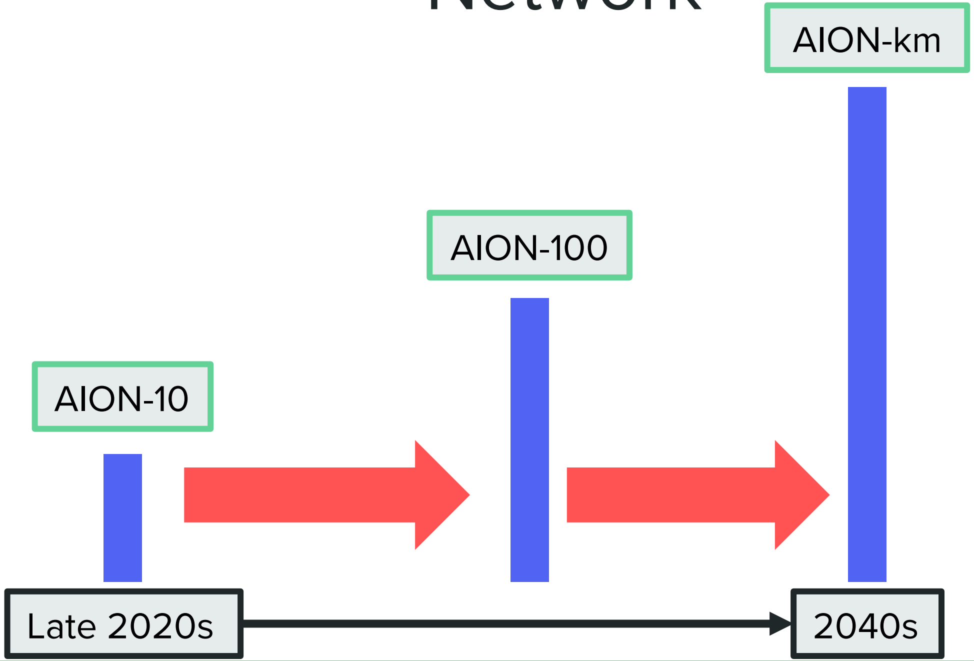
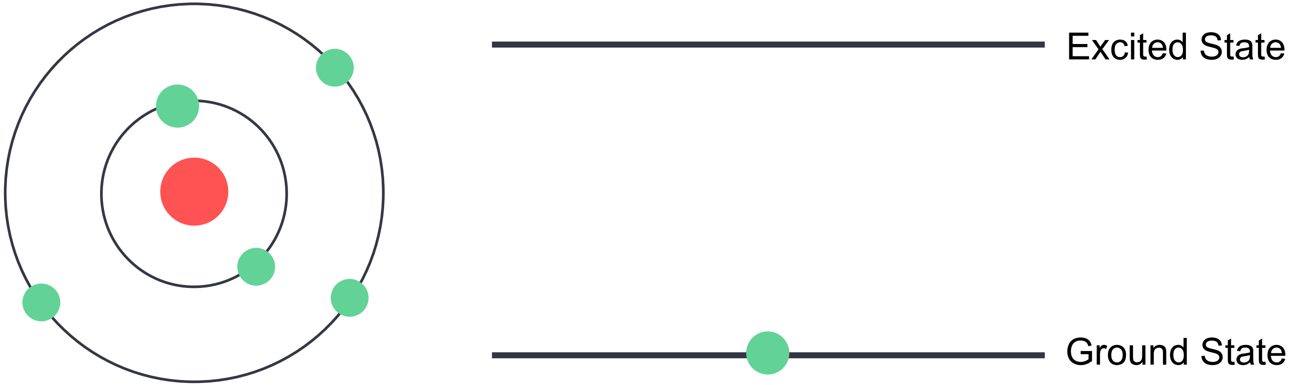
arXiv: 1911.11755

Atom Interferometer Observatory and Network



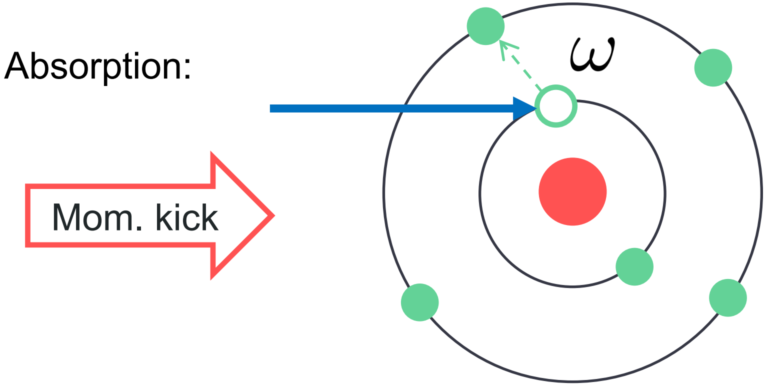
Atom interferometry

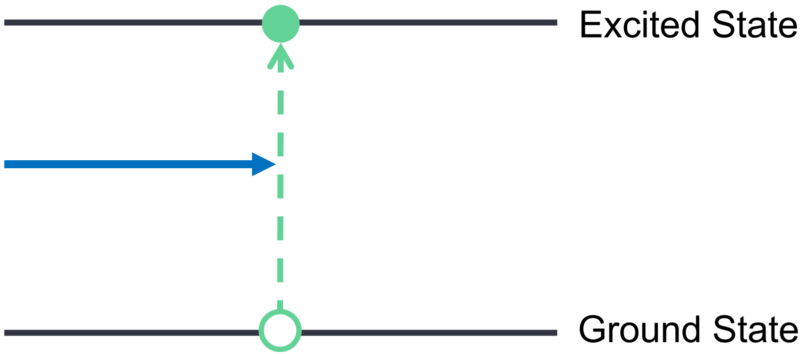
Consider a 2-level atom



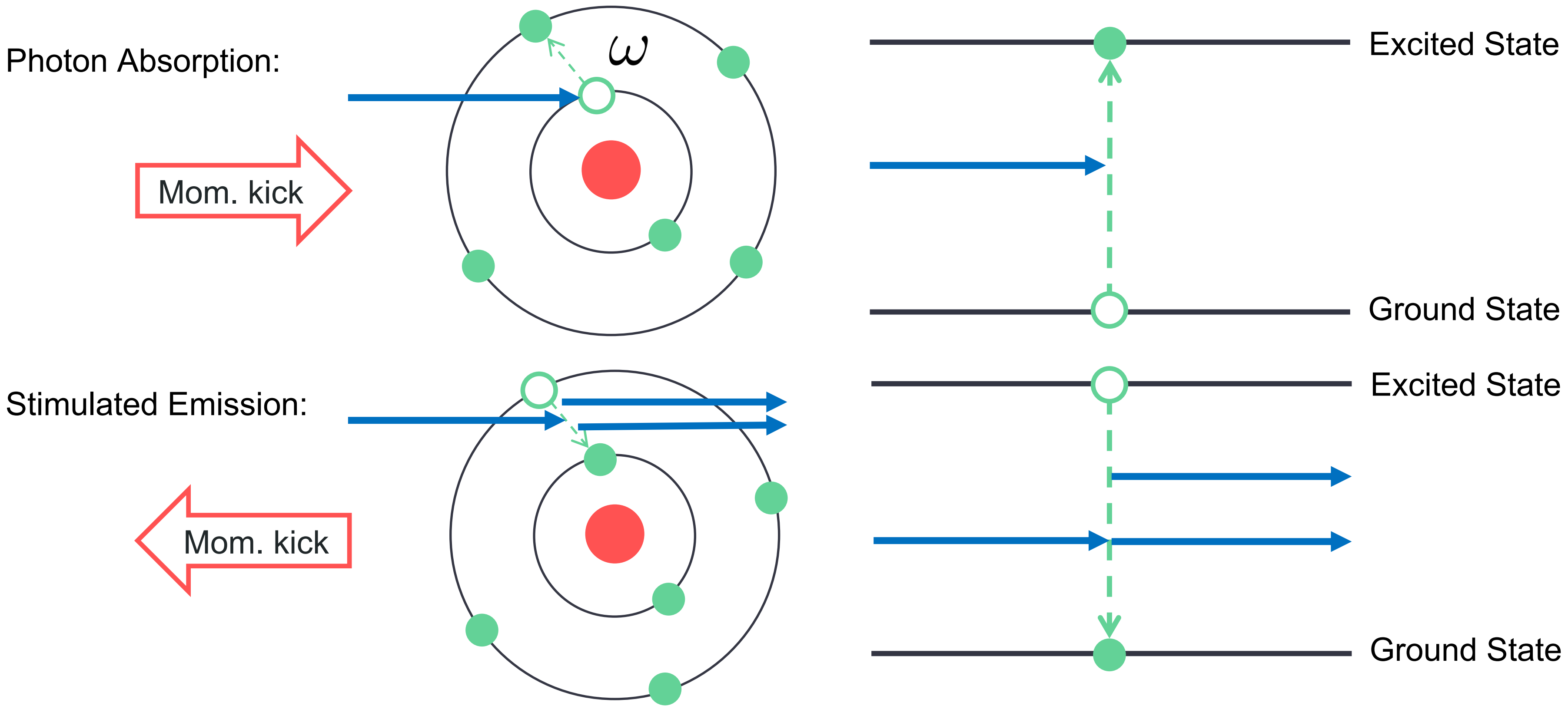
Consider a 2-level atom

Photon Absorption:



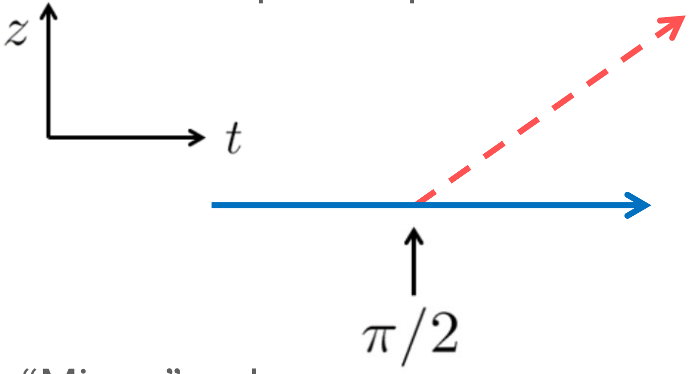


Consider a 2-level atom

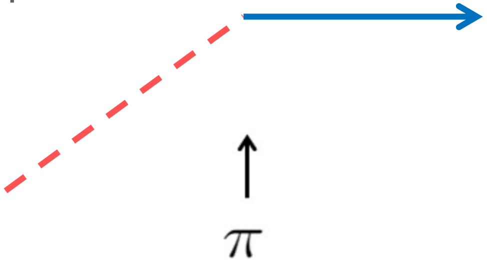


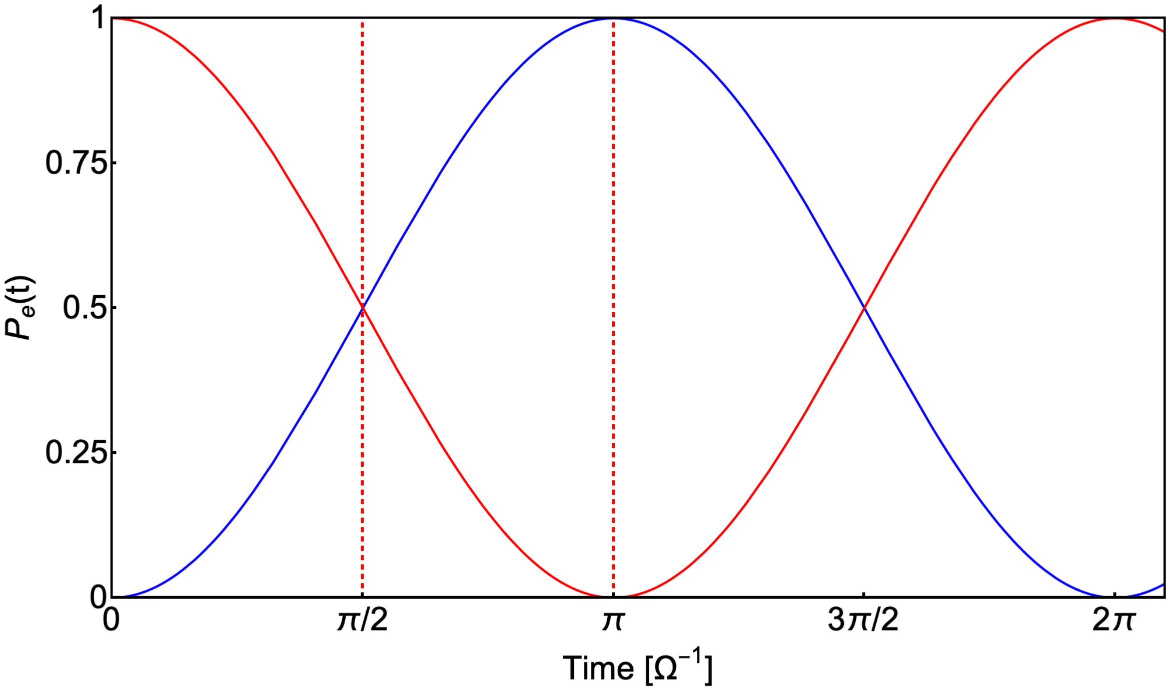
Rabi oscillations

"Beam-splitter" pulse:

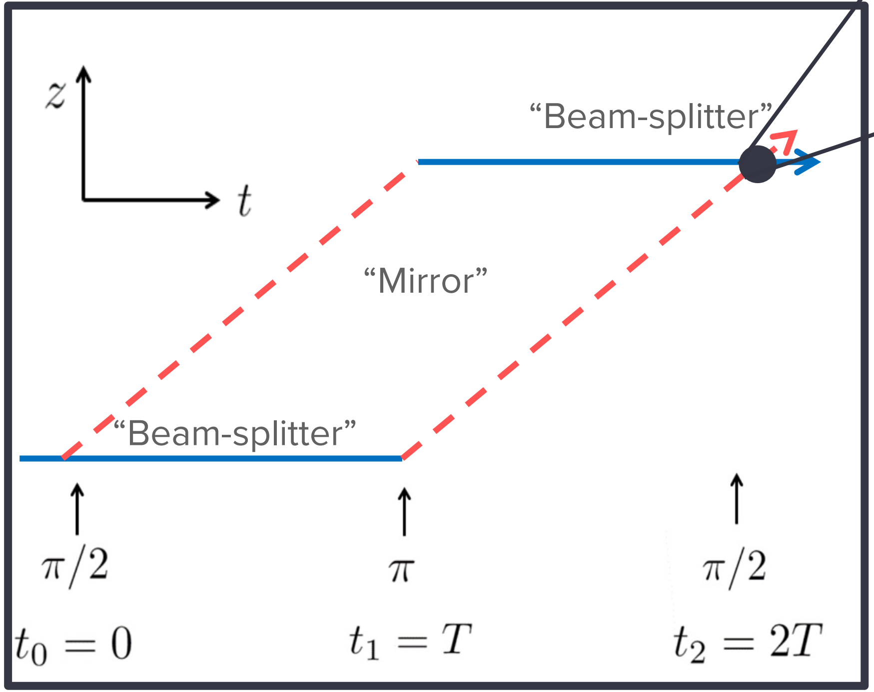


"Mirror" pulse:





Interferometer sequence



Mach-Zehnder
interferometer

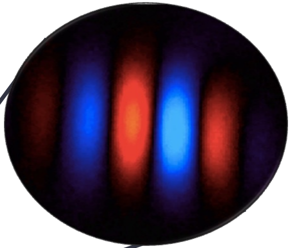


Image atom fringes
and measure phase

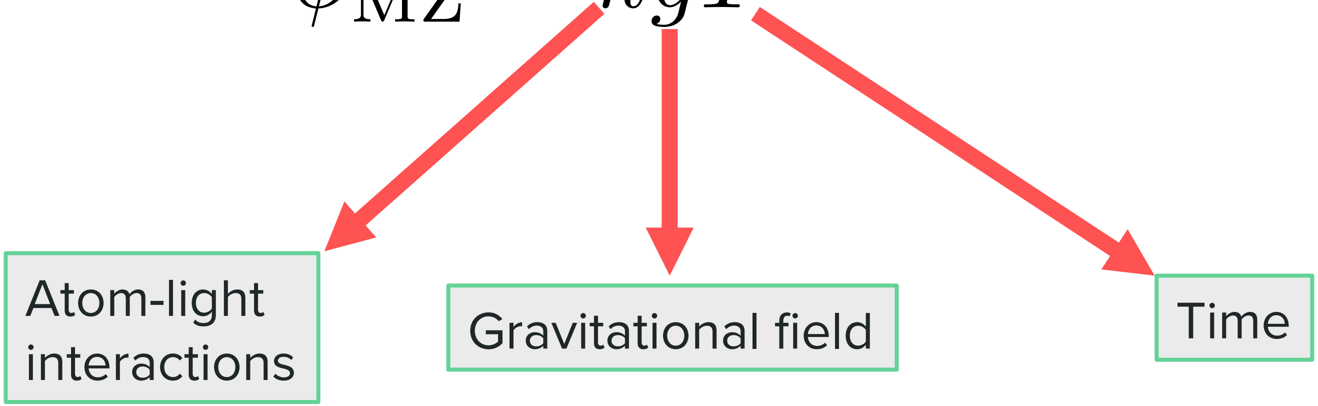
$$\phi_{\mathrm{MZ}} = kgT^2$$

Leading order phase depends
on gravitational acceleration

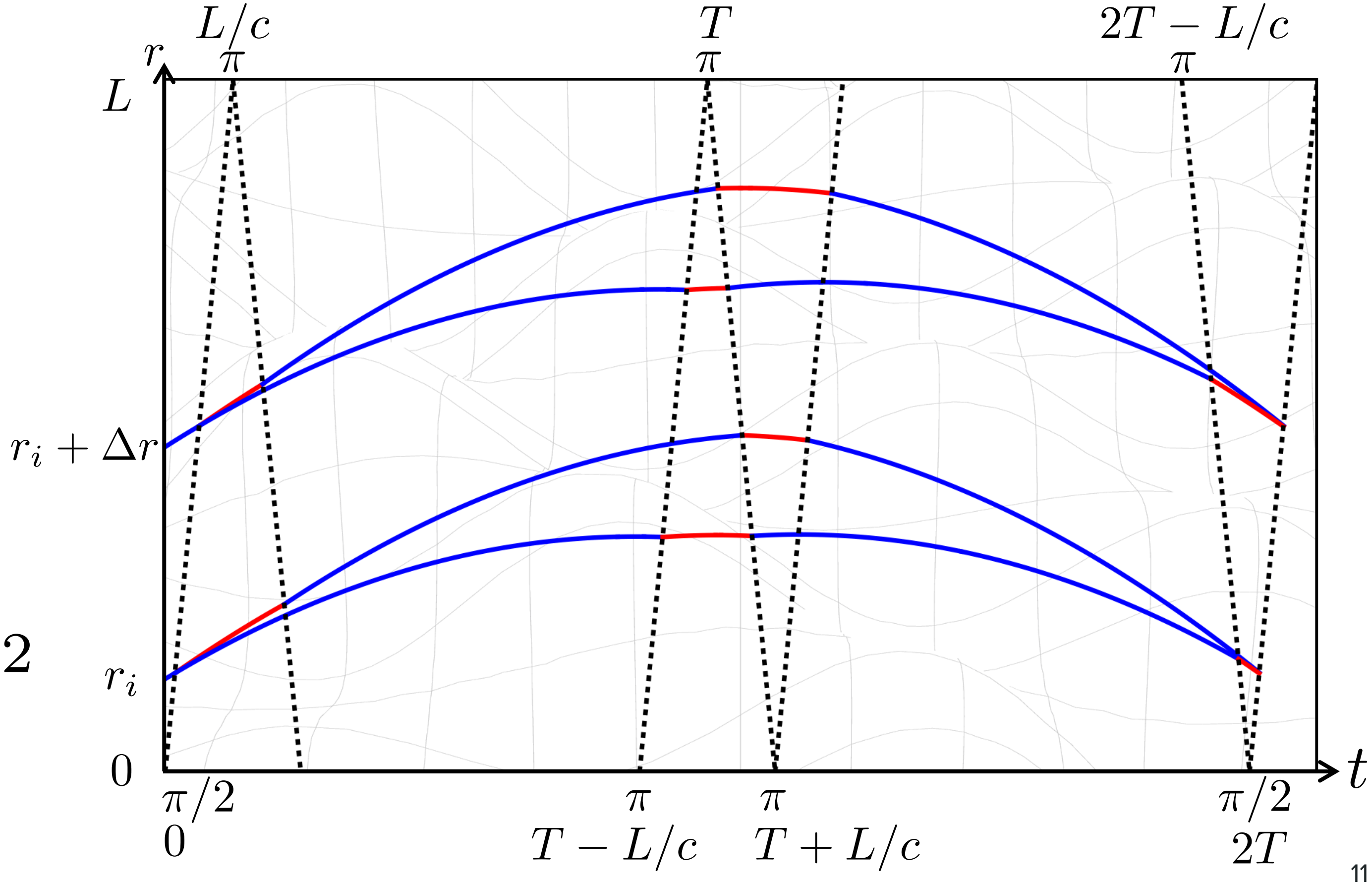
What are we sensitive to?

What can we measure?

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



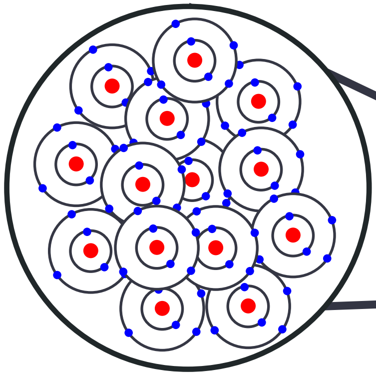
Atom gradiometer

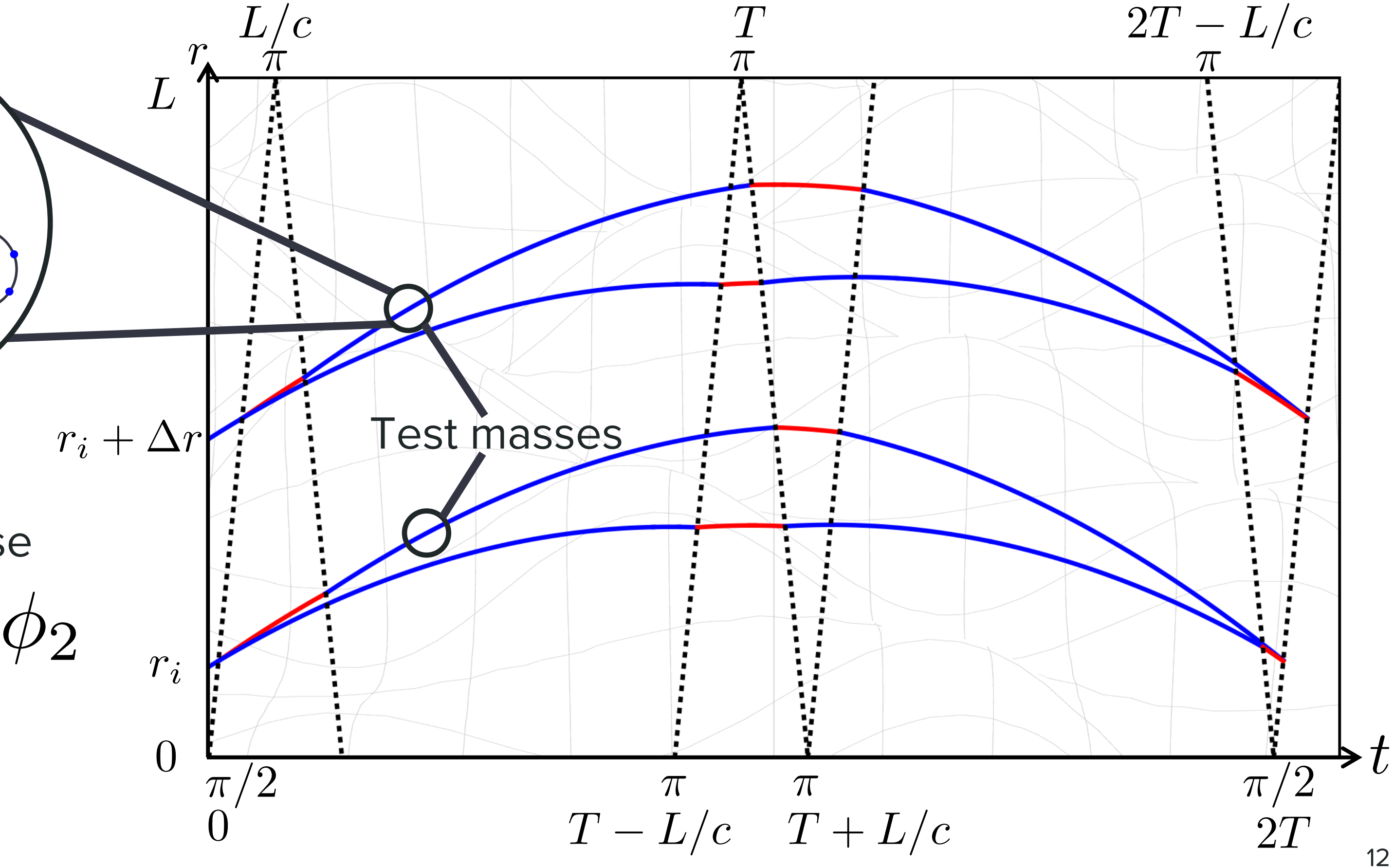


Gradiometer phase

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

Atom cloud





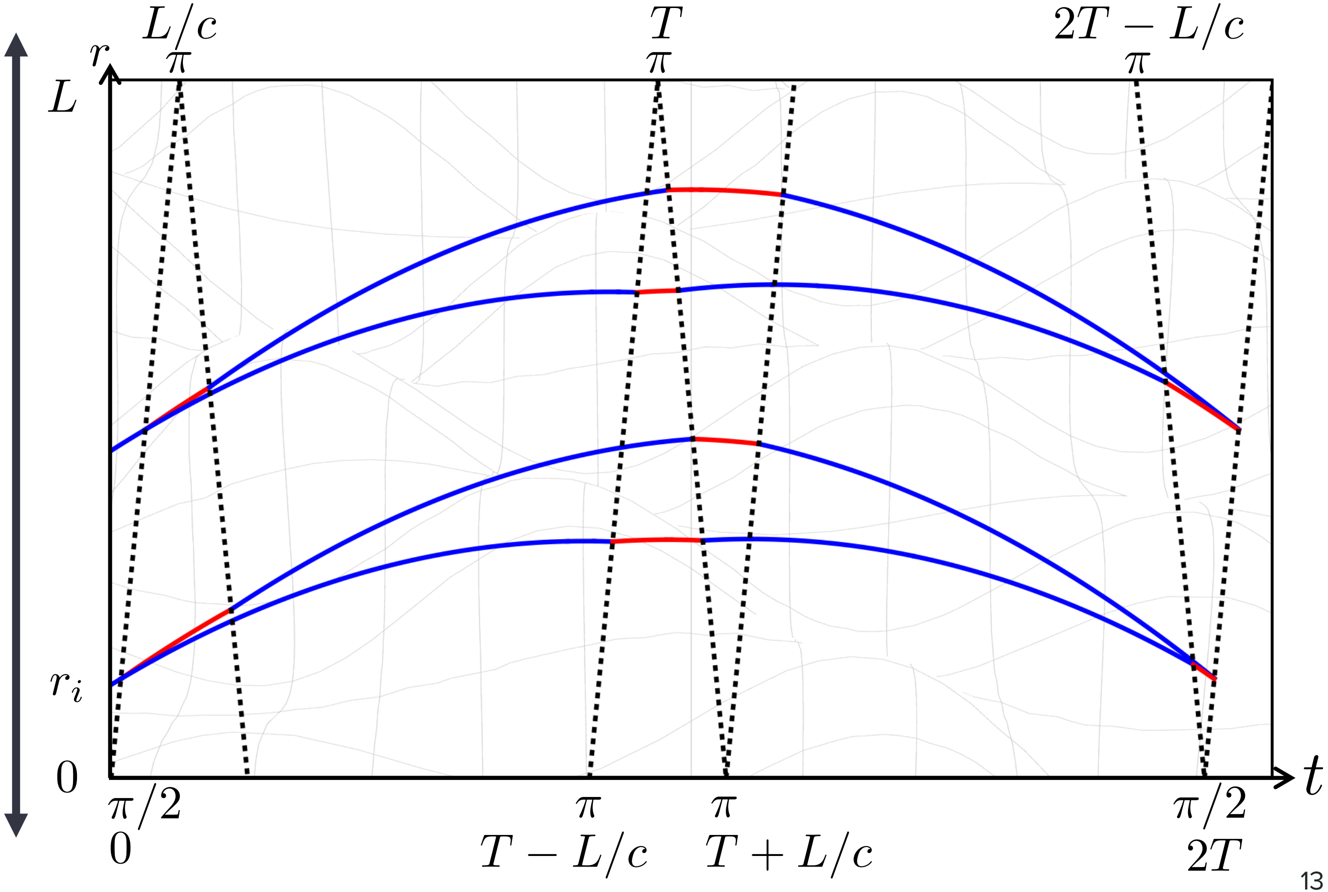
Gradiometer phase

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

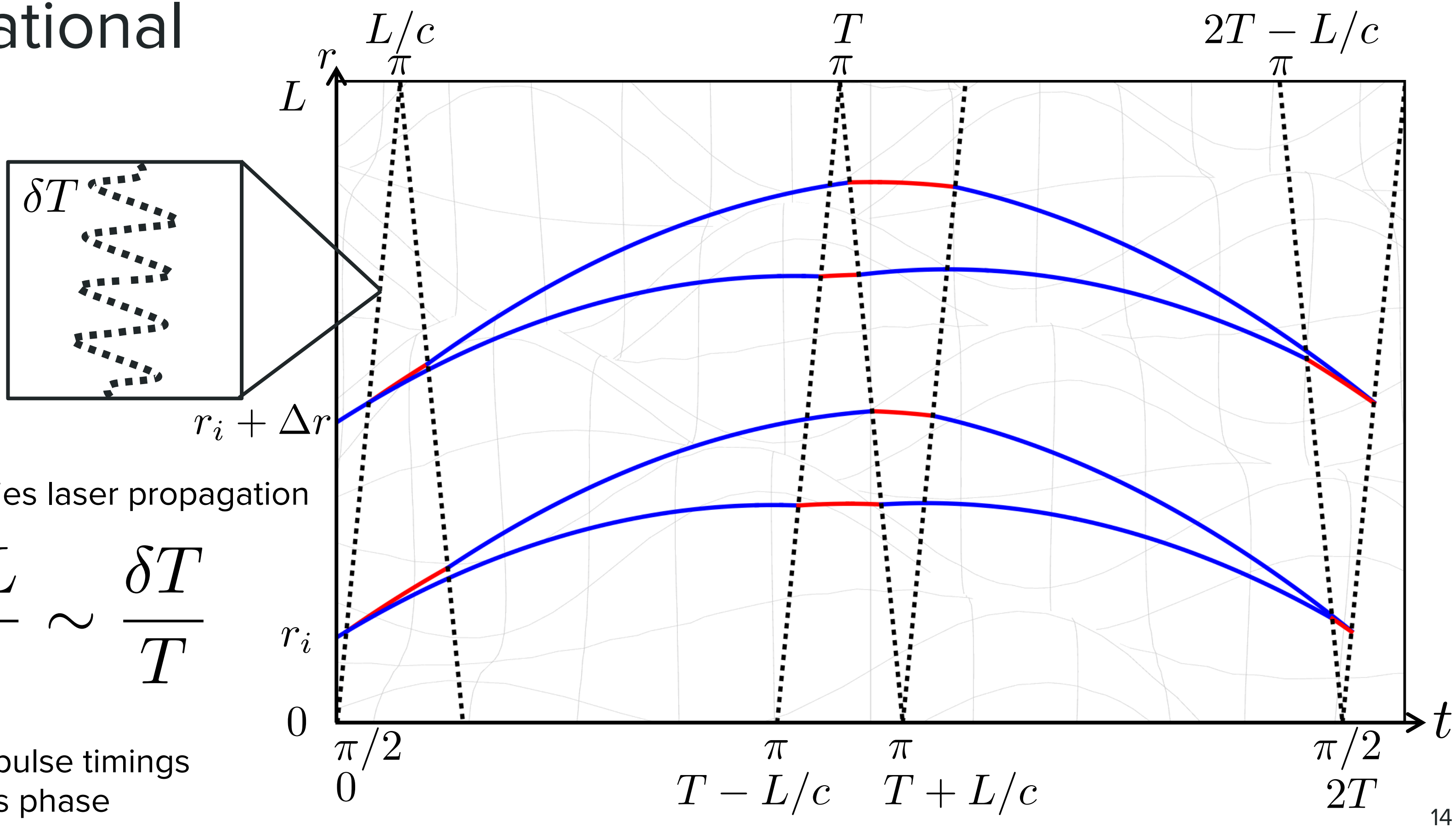
Longer baseline L

Longer time of flight T

More sensitivity $\Delta\phi$



Gravitational waves



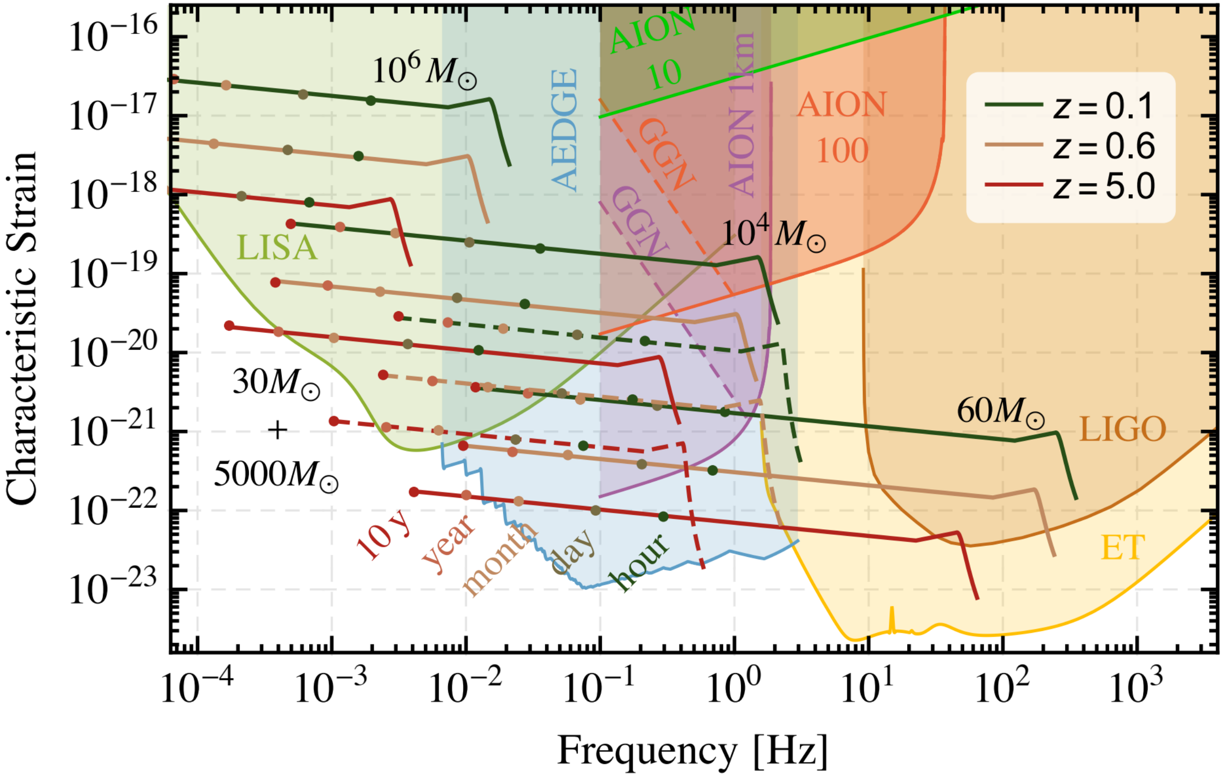
GW strain modifies laser propagation

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

Change in pulse timings affects phase

Gravitational waves

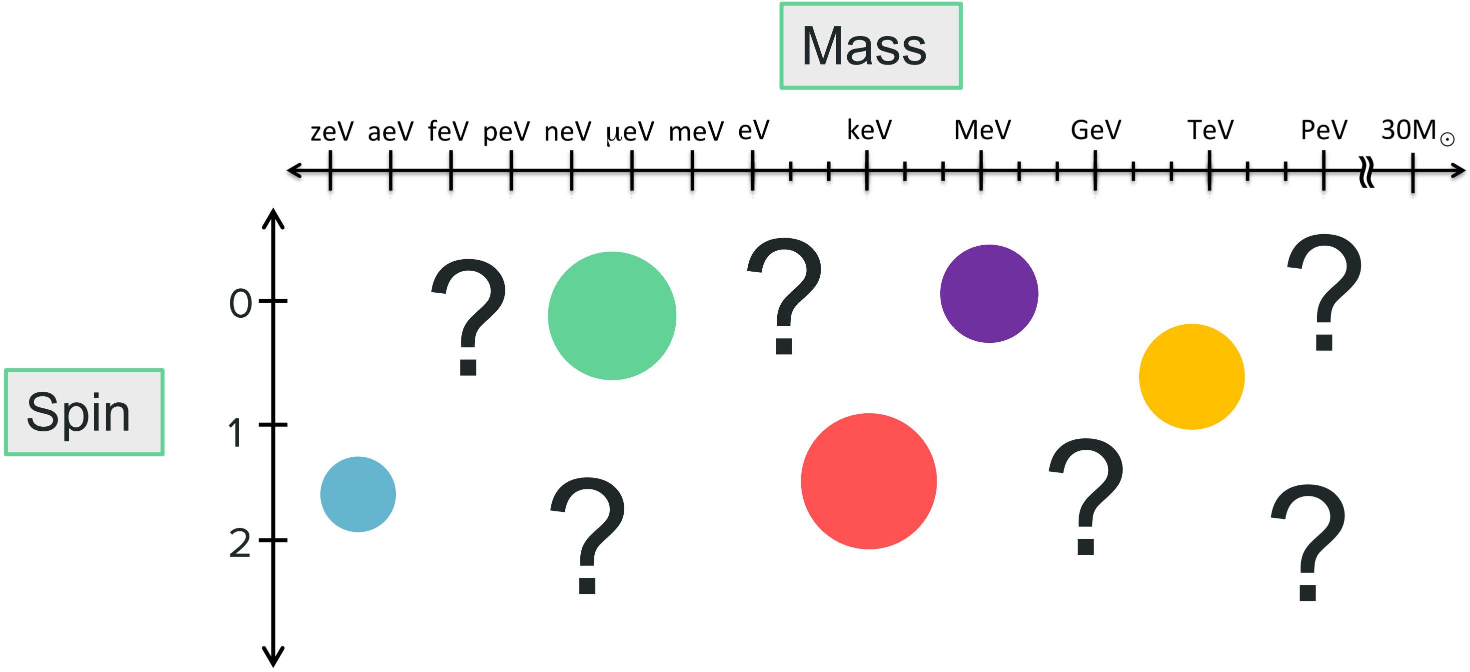
❖ *'Mid-band' sensitivity between LIGO and LISA.*



L. Badurina et al. arXiv: 1911.11755

Dark matter

A lot of parameter space!



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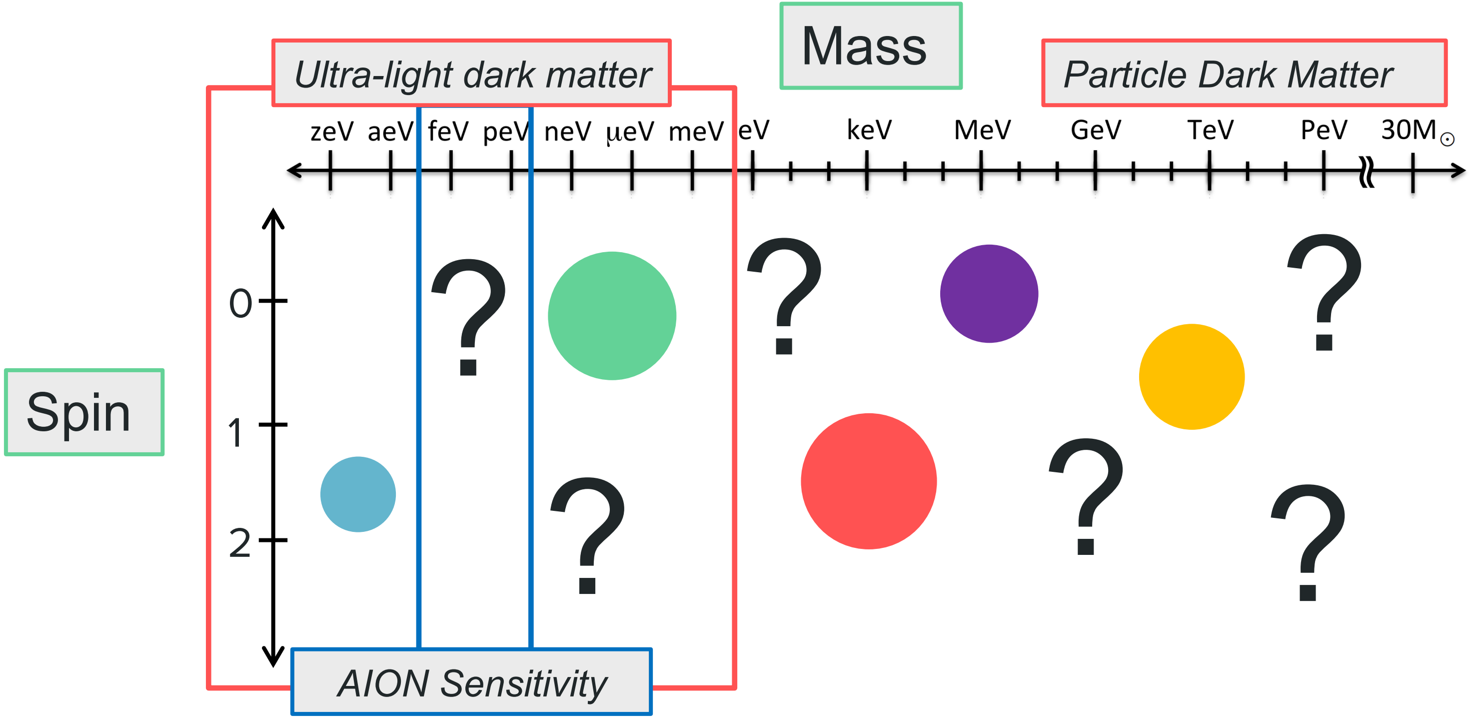

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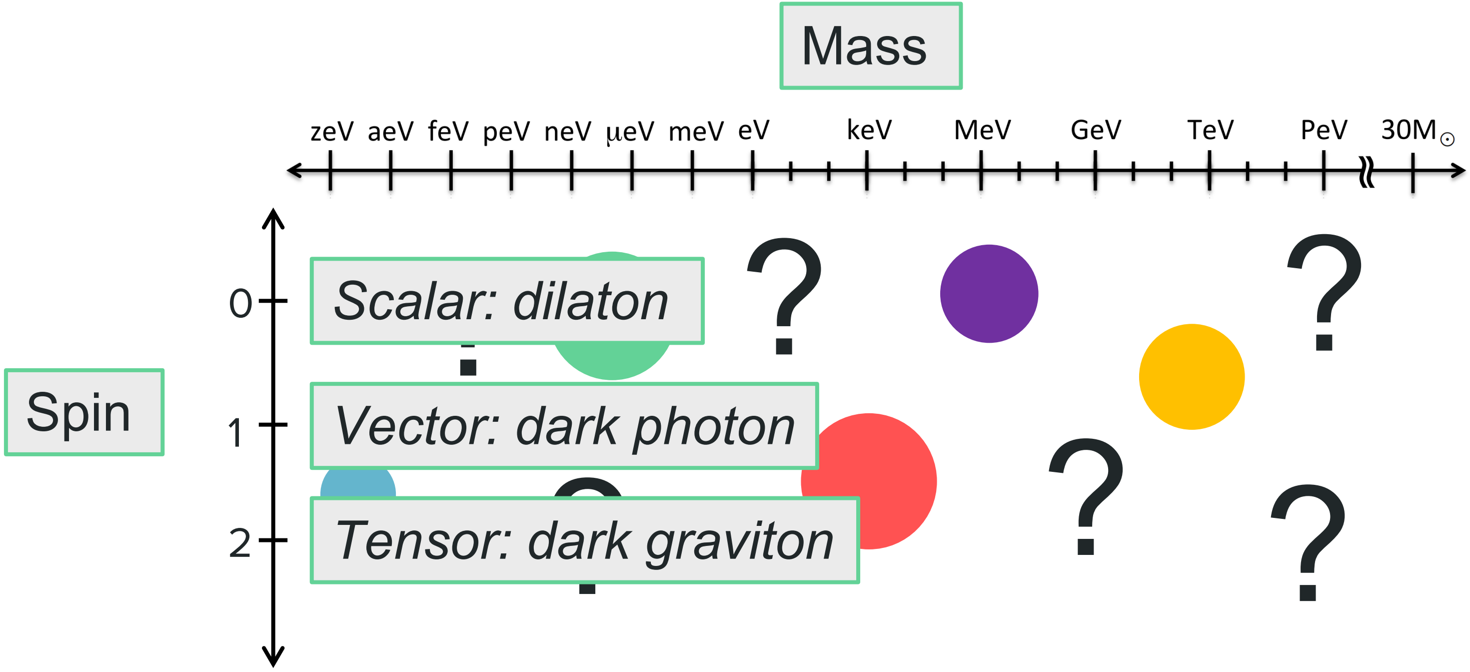
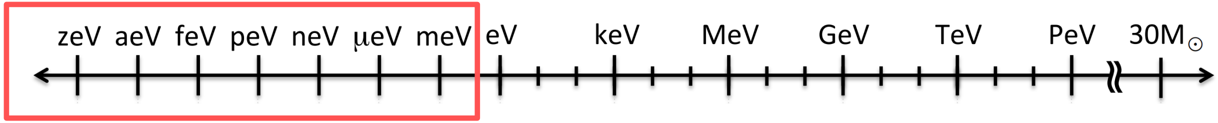


A classical ULDM field



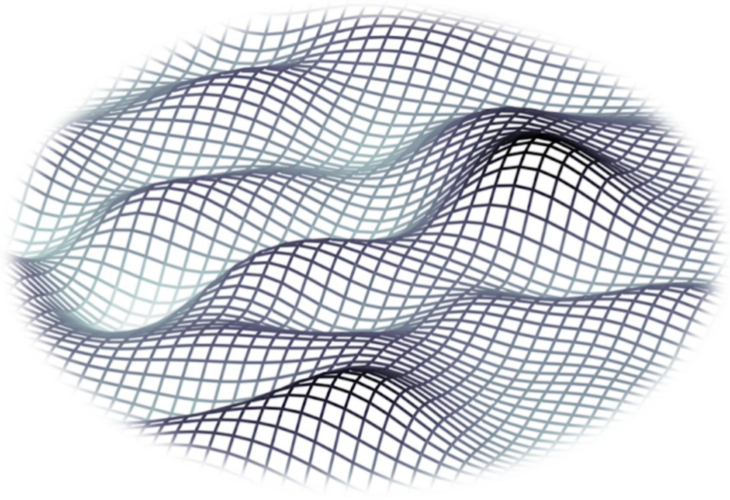
Ultralight mass means a high occupation number

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

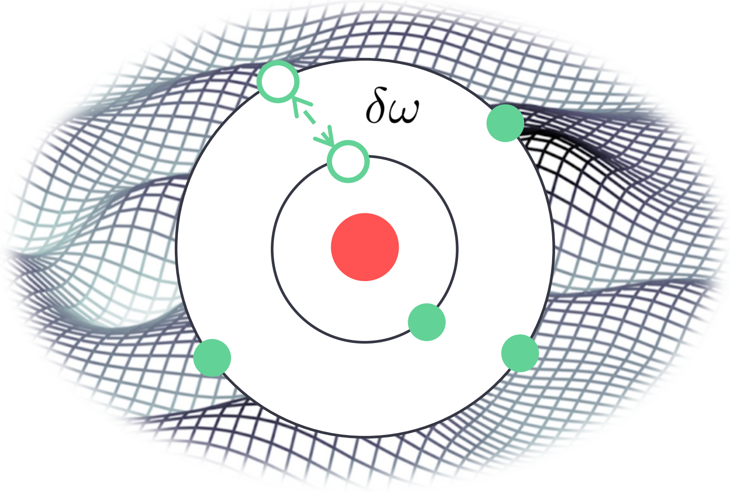
electron coupling

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

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

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

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



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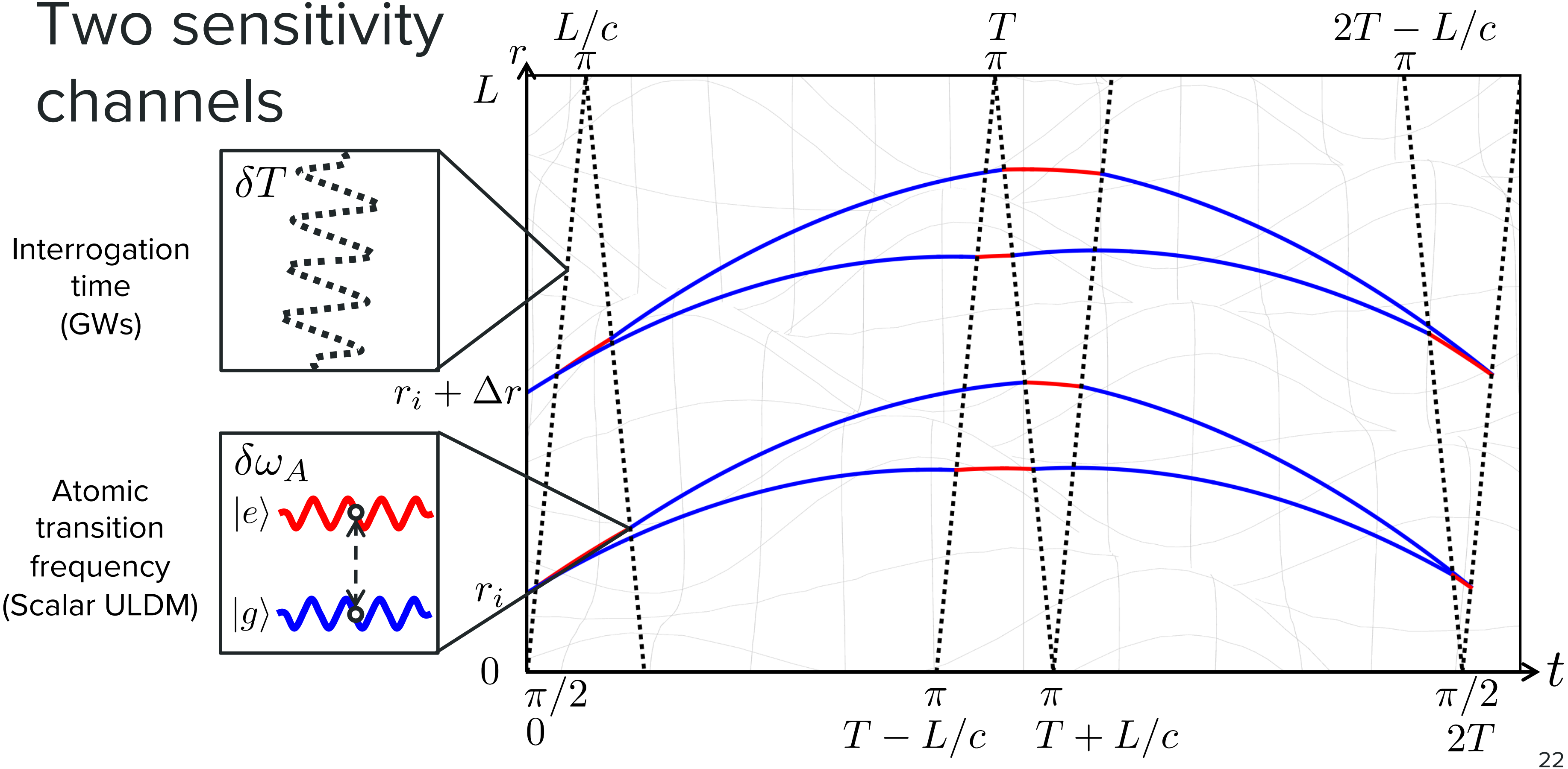
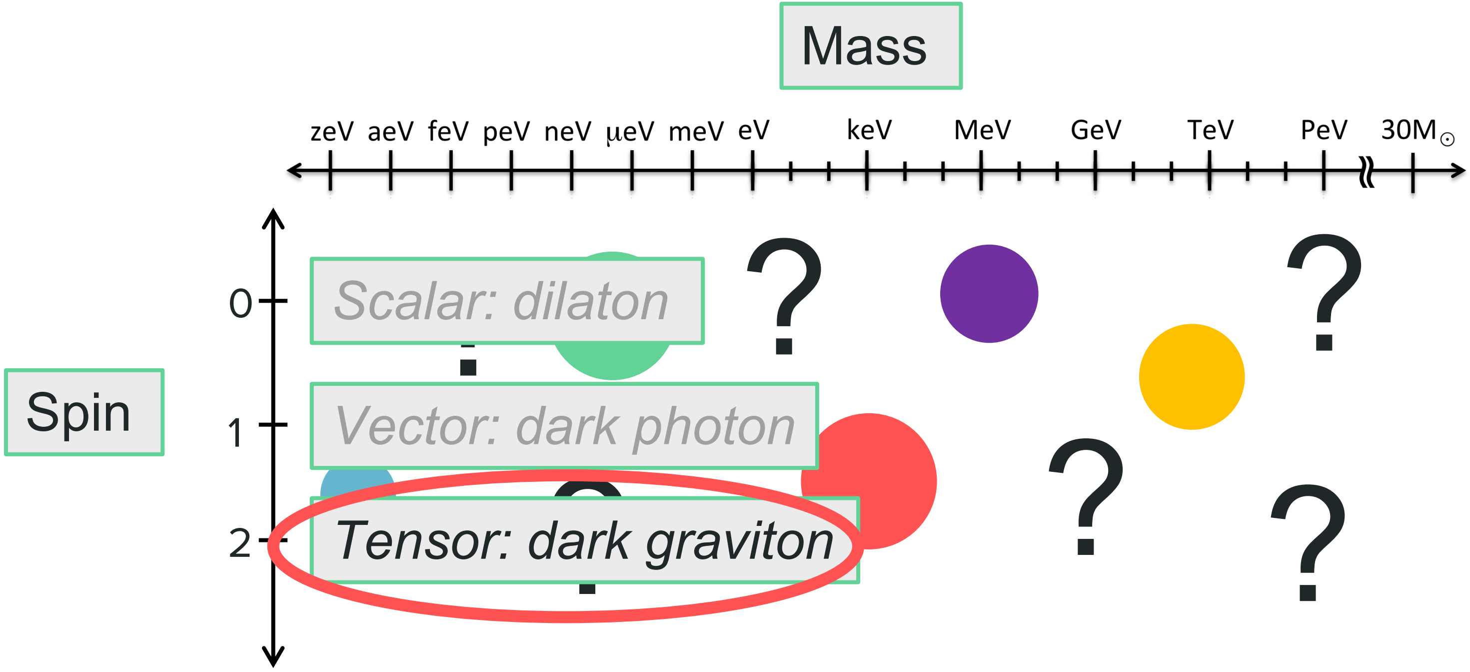
Two sensitivity channels

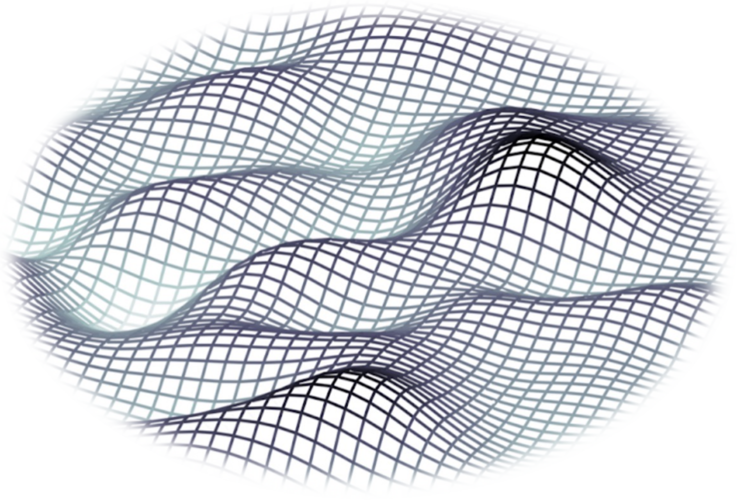


What about spin-2?



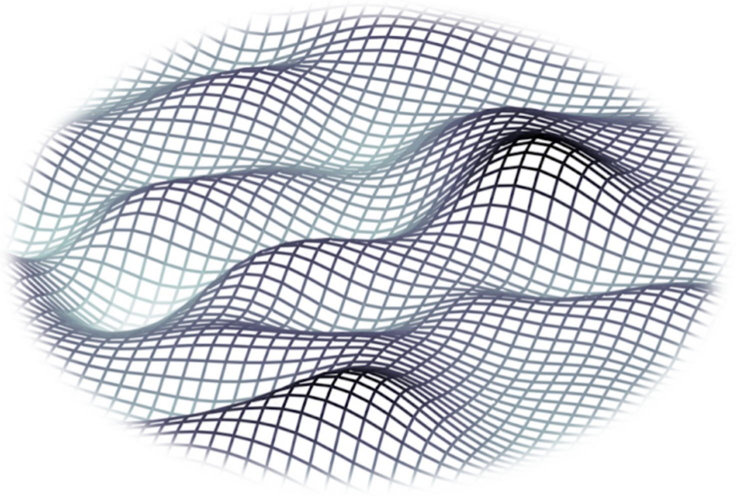
Massive graviton dark matter

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 $\varphi_{\mu\nu}$

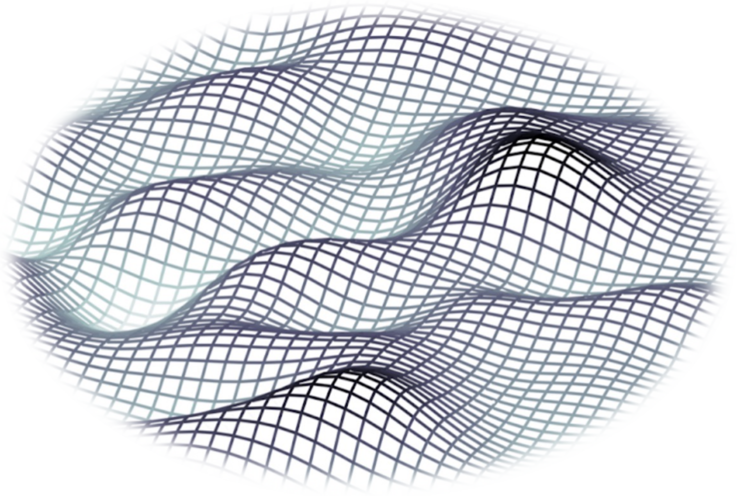
Express as irreducible fields:

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

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

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

Massive gravity field theory



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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

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

Vector

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

Scalar

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

... each contributing to the local dark matter

Tensor

$$\tilde{\varphi}_0 = \frac{\sqrt{2 f_t \rho_{\rm DM}}}{m_t}$$

Vector

$$\tilde{A}_0 = \frac{\sqrt{2 f_v \rho_{\rm DM}}}{m_v}$$

Scalar

$$\tilde{\pi}_0 = \frac{\sqrt{2 f_s \rho_{\rm DM}}}{m_s}$$

Fraction of total dark matter

$$f_t + f_v + f_s = 1$$

Coupling to matter

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

↑

Symmetric Standard Model operator

Coupling to matter

Tensor — Vector — Scalar

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

Coupling to matter

Tensor · Vector · Scalar

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

Non-relativistic limit

$$\frac{\alpha}{M_{\rm Pl}}\widetilde{\varphi}^{ij}T_{ij} \qquad \frac{\beta}{M_{\rm Pl}}\widetilde{\pi}T$$

Tensor modes

Field theory picture:

$$\mathcal{L} \supset \mathcal{L}_{\rm SM} + \mathcal{L}_{\widetilde{\varphi}} \rightarrow \mathcal{L}_{\widetilde{\varphi}} \supset \frac{\alpha}{M_{\rm Pl}} \widetilde{\varphi}^{ij} T_{ij}$$

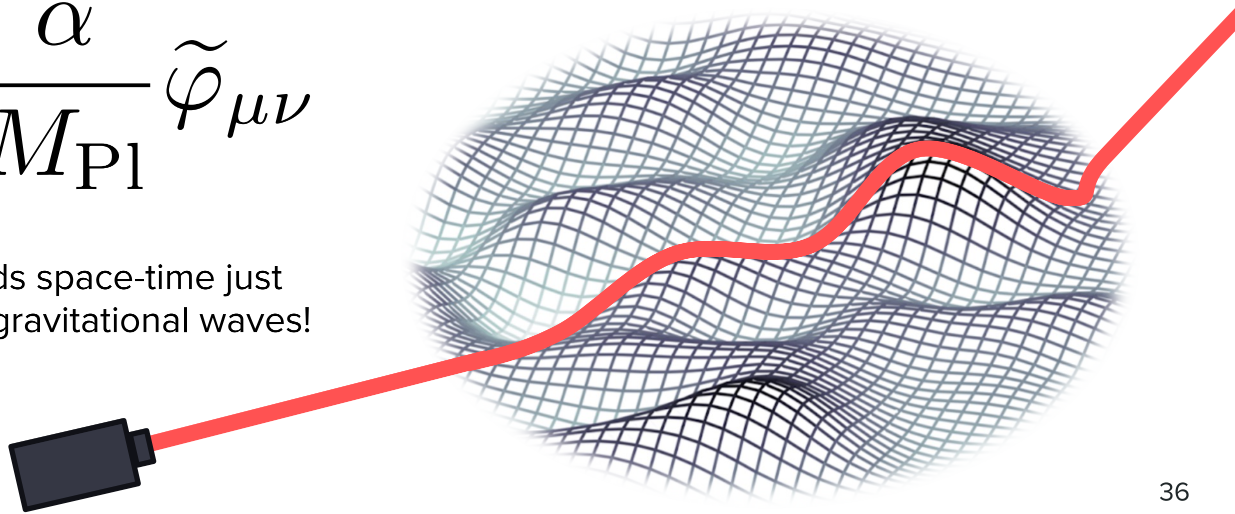
coupling const.

stress-energy tensor

Linearised gravity picture:

$$g_{\mu\nu} = \eta_{\mu\nu} + \frac{\alpha}{M_{\rm Pl}} \widetilde{\varphi}_{\mu\nu}$$

Bends space-time just
like gravitational waves!



Scalar mode

Field theory picture:

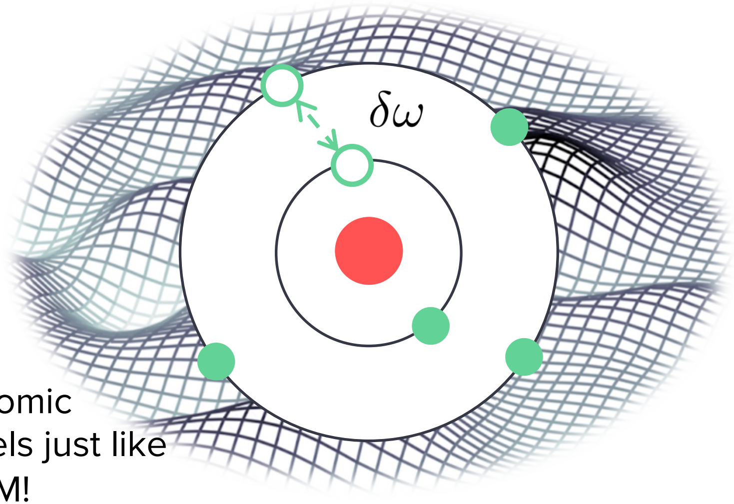
$$\mathcal{L} \supset \mathcal{L}_{\rm SM} + \mathcal{L}_{\tilde{\pi}} \rightarrow \mathcal{L}_{\tilde{\pi}} \supset \frac{\beta}{M_{\rm Pl}}\tilde{\pi}T \qquad T \to m_\psi \overline{\psi}\psi$$

coupling const. (β)

trace of stress-energy tensor (T)

$$m_e(t) = m_{e,0}\left[1 - \frac{\beta}{M_{\rm Pl}}\tilde{\pi}(t)\right]$$

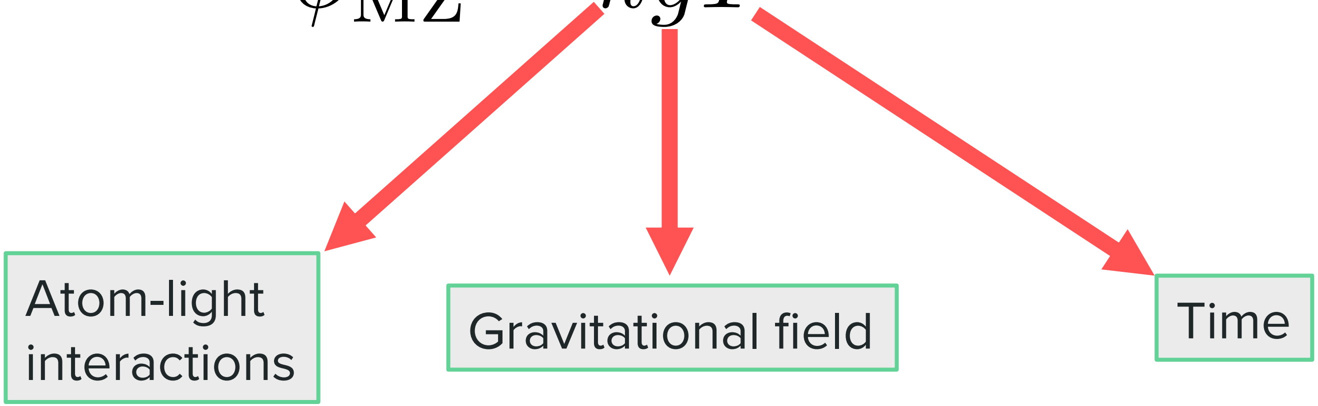
$$\delta\phi \sim \delta\omega \sim \varphi(t, \boldsymbol{x})$$



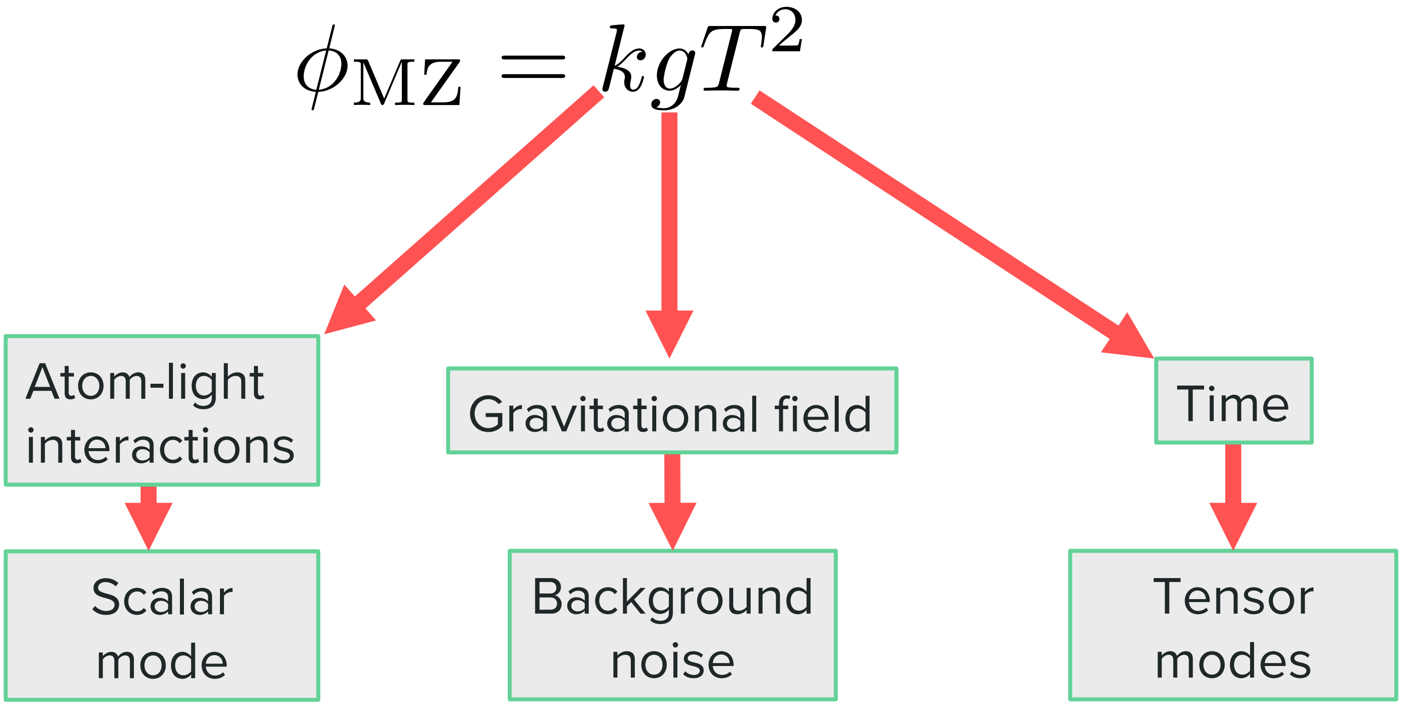
Modifies atomic energy levels just like scalar ULDM!

What can we measure?

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



What can we measure?



Projected detection limits

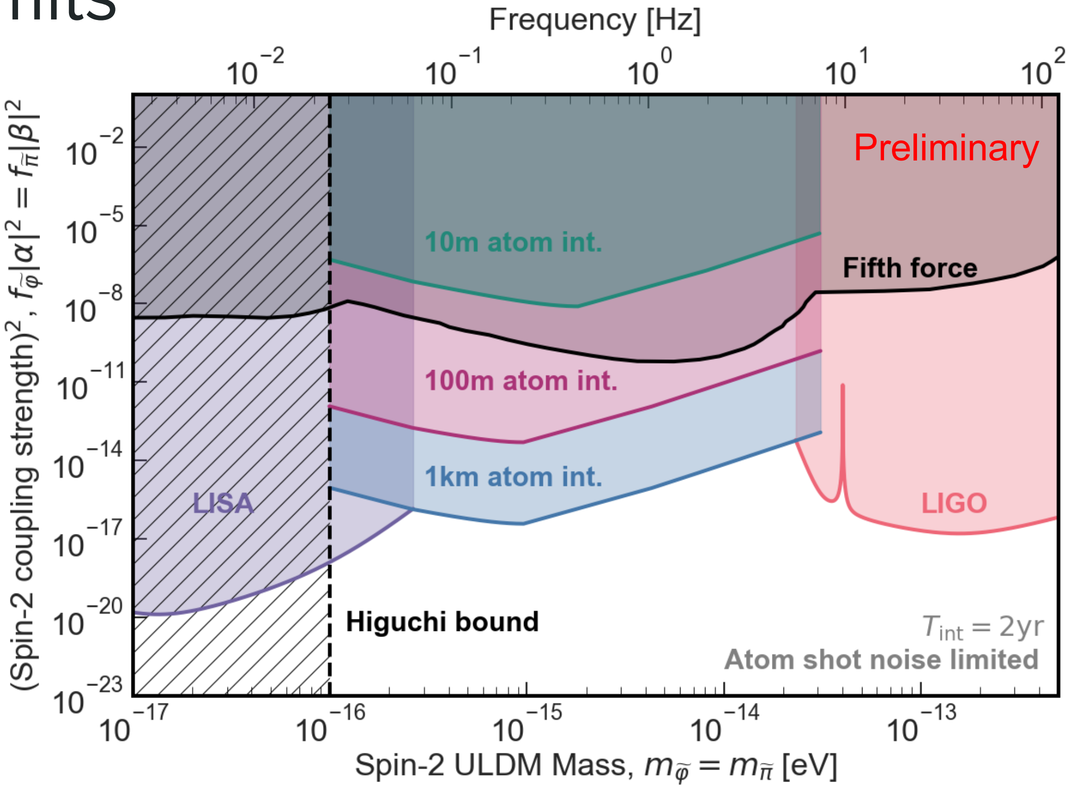
10m, 100m and 1km example atom interferometers

Assume Lorentz invariance:

$$m_t = m_v = m_s$$

$$\kappa_t = \kappa_v = \kappa_s$$

$$f_t = f_v = f_s$$

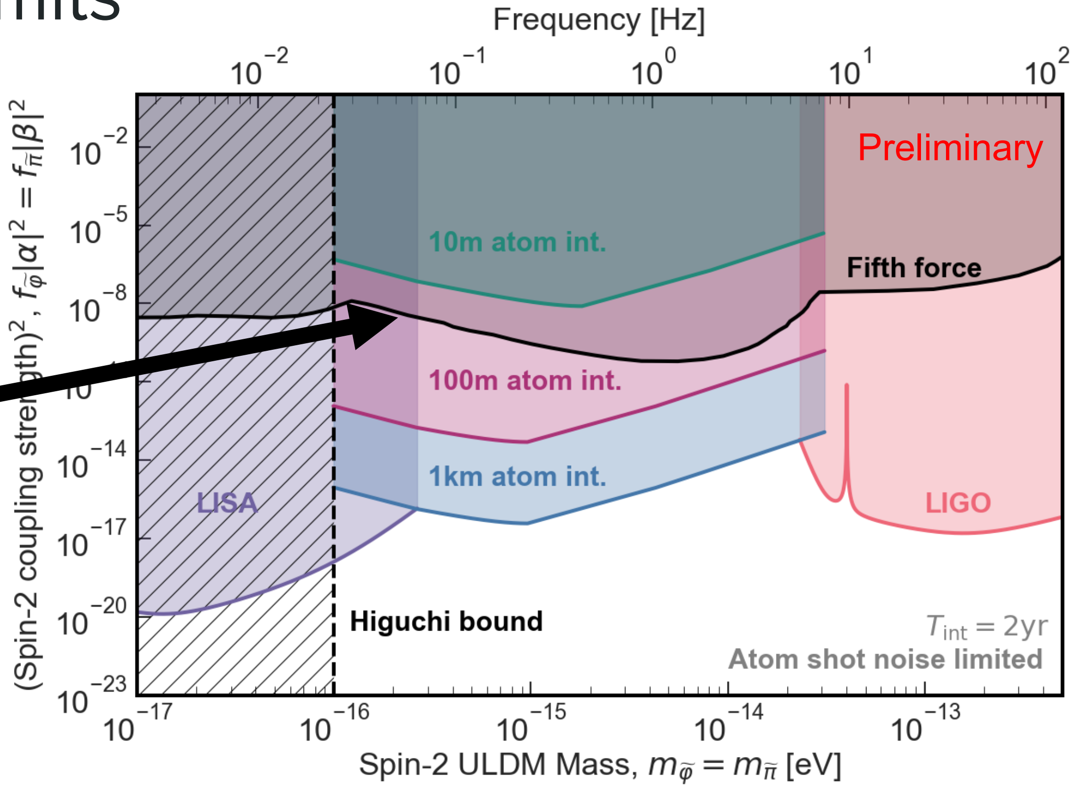


Projected detection limits

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

$$\delta V_{\rm Newt} \propto \alpha^2 e^{-m_{\tilde{\varphi}} r}$$

In this range, from lunar laser ranging



Projected detection limits

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

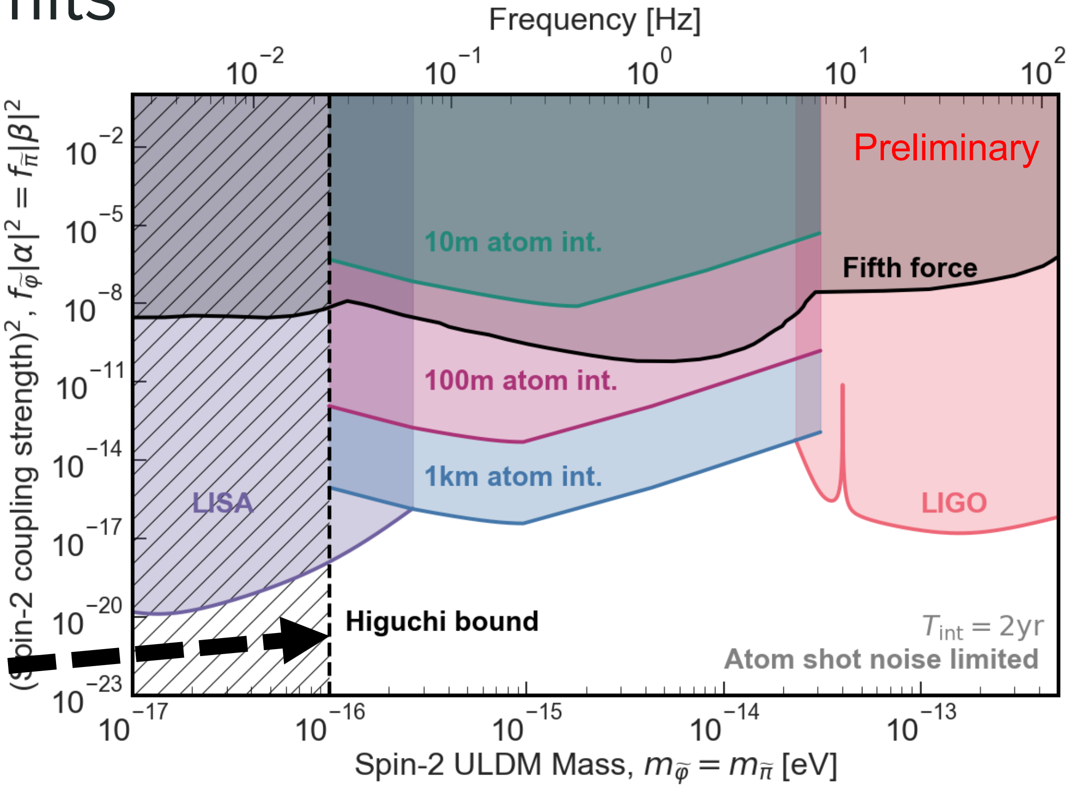
$$\delta V_{\mathrm{Newt}} \propto \alpha^2 e^{-m_{\tilde{\varphi}} r}$$

In this range, from lunar laser ranging

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

$$m^2 \geq 2H^2$$

Least stringent bound from BBN



Projected detection limits

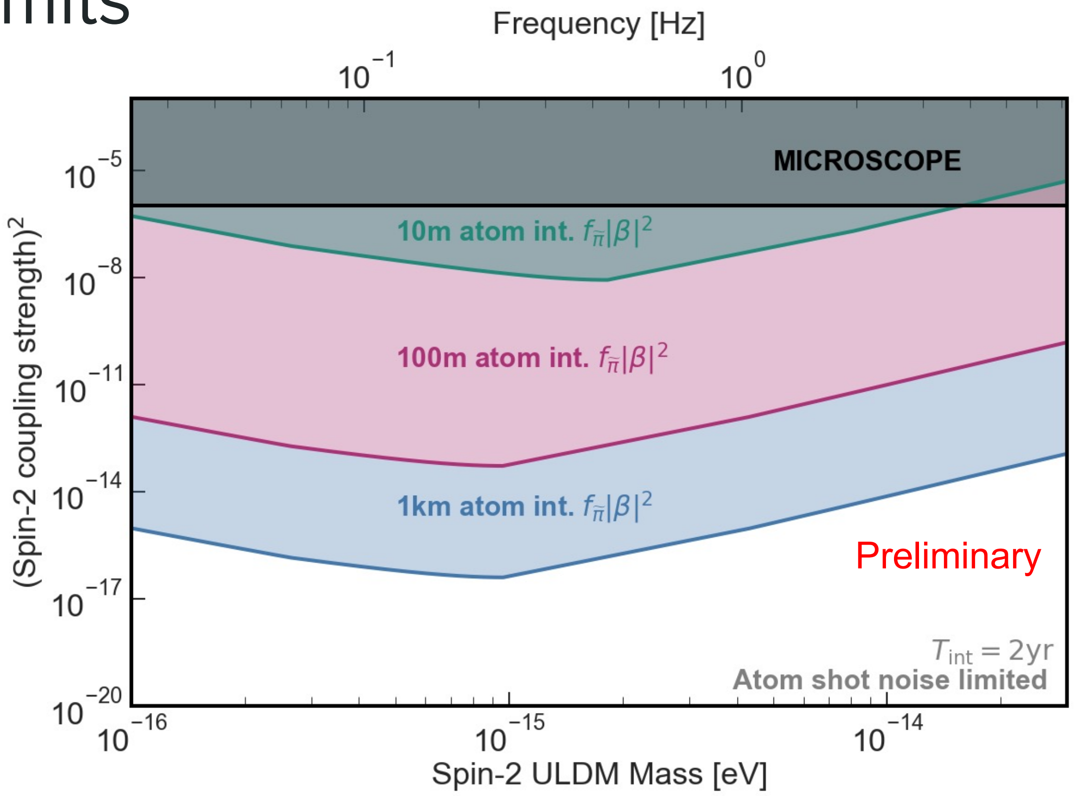
Consider the tensor and scalar couplings independently in the Lorentz violating case.

$$m_t \neq m_s$$

$$\alpha \neq \beta$$

$$f_t \neq f_s$$

Scalar mode constrained by tests of equivalence principle



Advantages of networking!

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

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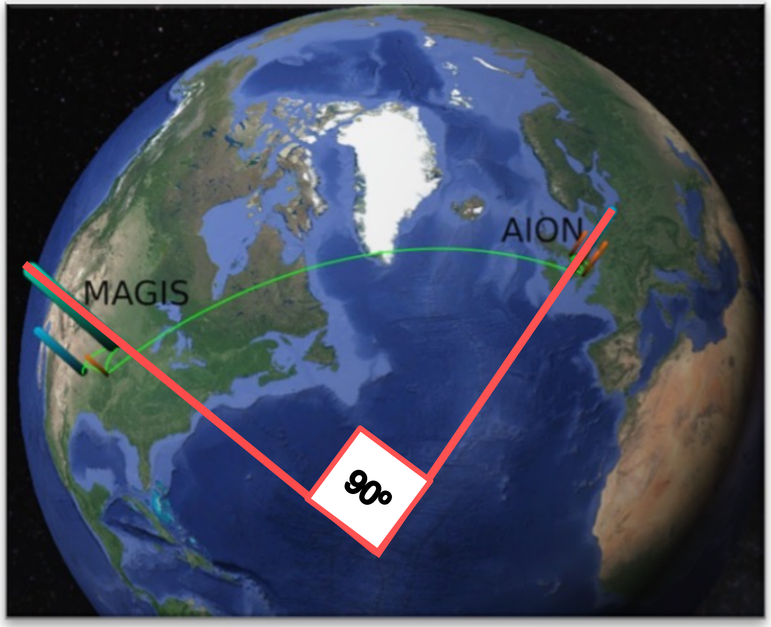
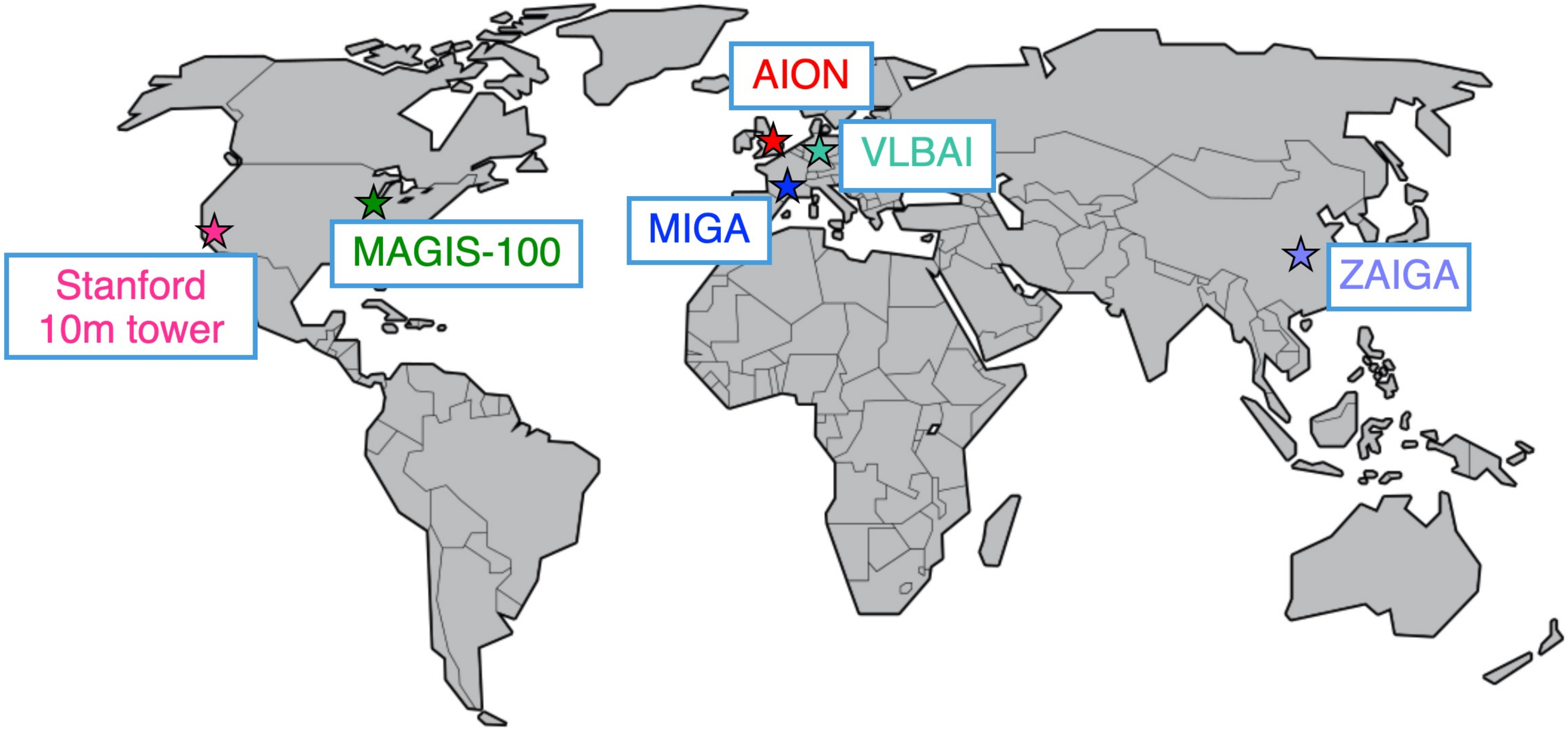
$$\widetilde{\varphi}_{ij}(t,\mathbf{x}) = \sum_{\lambda} \widetilde{\varphi}_{0,\lambda} e^{\lambda}_{ij}(\mathbf{k}_t) \cos(\omega_t t - \mathbf{k}_t \cdot \mathbf{x})$$

Distinguish dark matter models through directional dependence.



Progress towards a global network!



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

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.

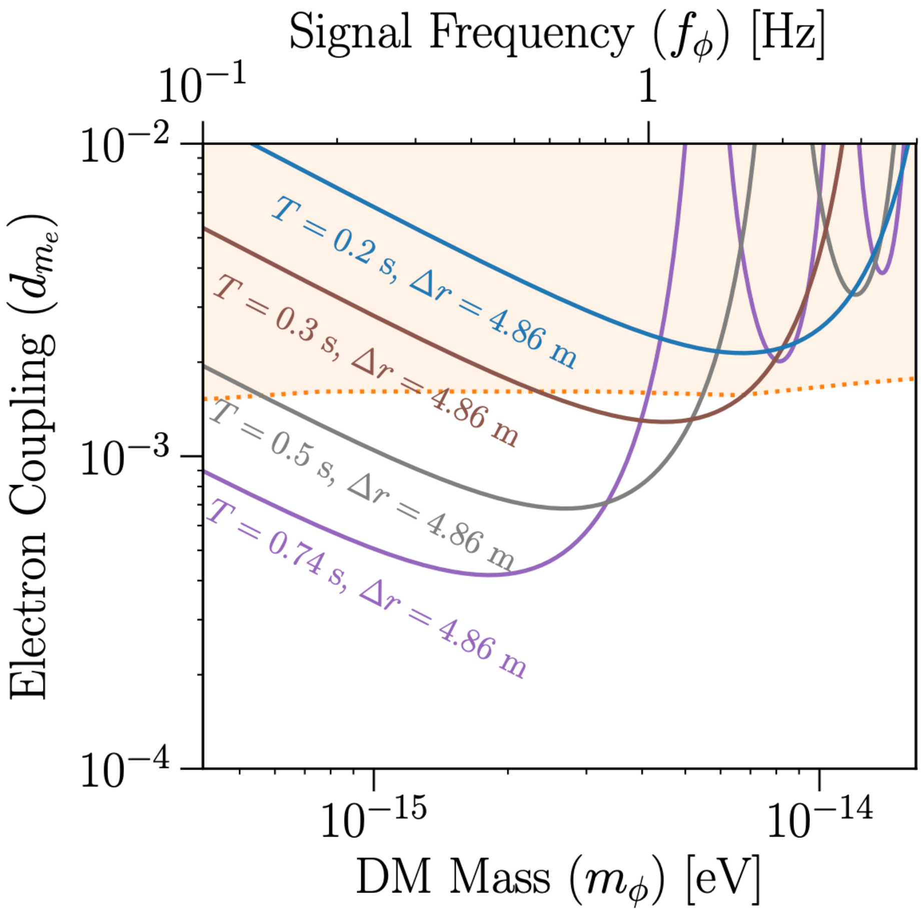
Spin-2 ULDM can be probed by gravitational wave detectors – however, atom interferometers can detect it through two different channels without altering any of the experimental design!

A global network of atom interferometers will enhance these searches further, probing the directional dependence of the field.

Backup

Scalar ULDM sensitivity

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



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

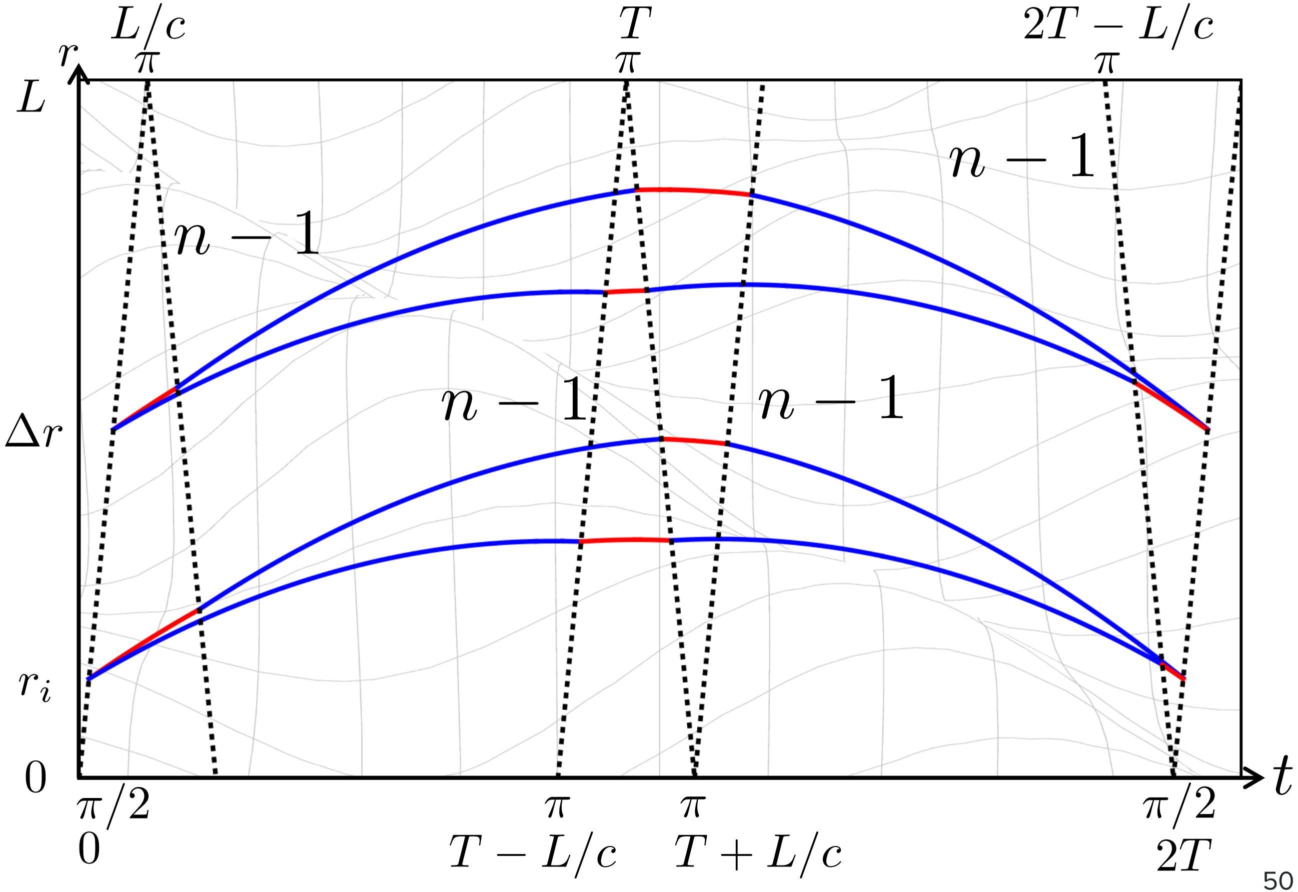
LMT pulses

Additional pulses enhance sensitivity

$$n = 2$$

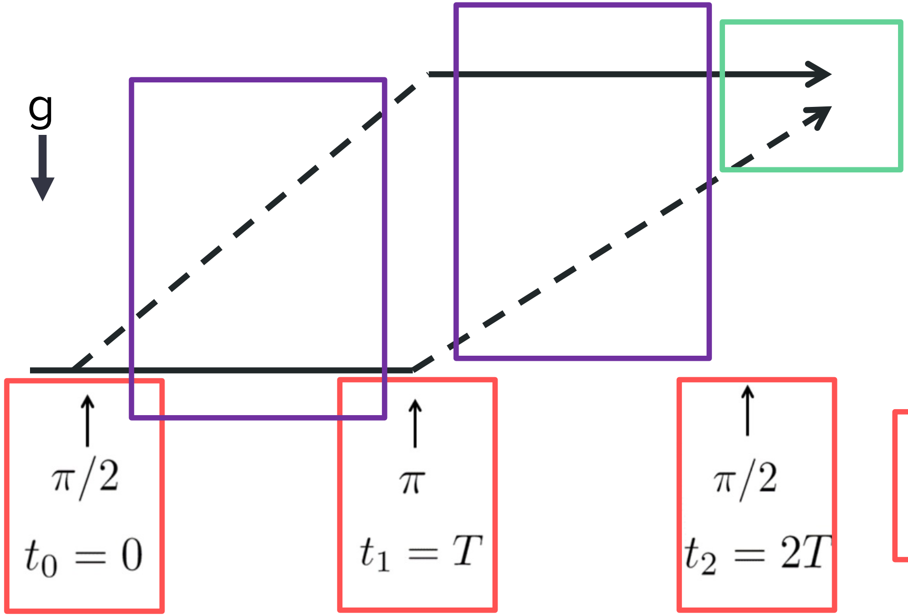
Atom gradiometer

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



Phase shifts

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



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

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

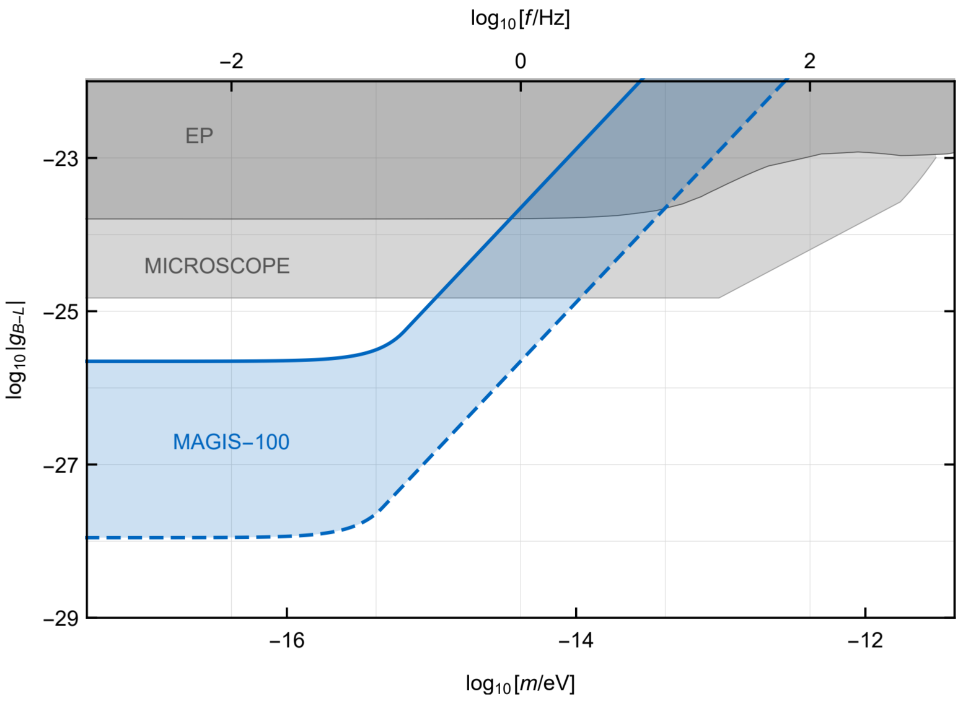
$$\phi_{\text{laser}} = \left(\sum_j \pm\phi_L(t_j, \boldsymbol{z}_u(t_j))\right)_u - \left(\sum_j \pm\phi_L(t_j, \boldsymbol{z}_l(t_j))\right)_l$$

Spin-1 dark matter

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

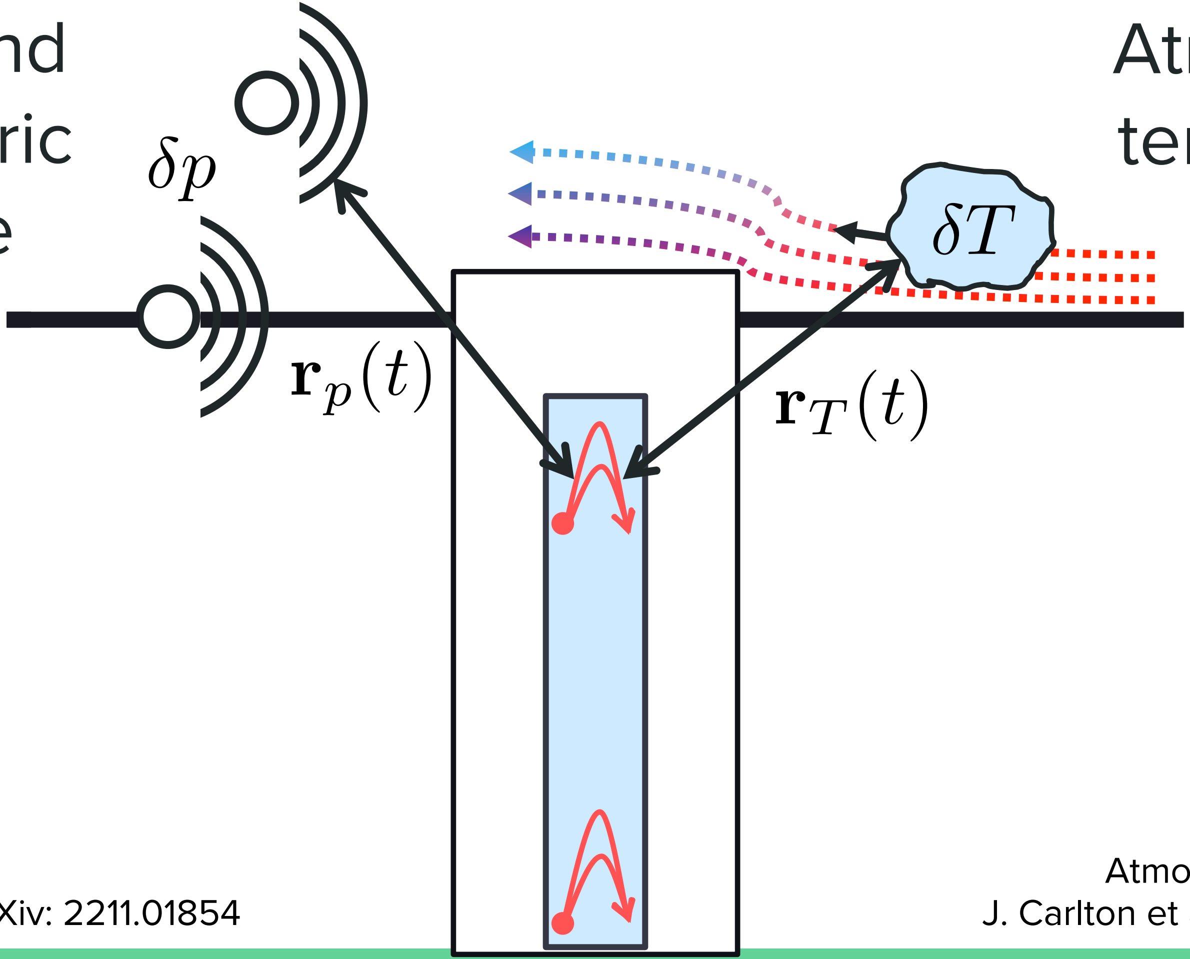
$$\Delta F_{B-L} \sim g_{B-L} \left(\frac{Z_1}{A_1} - \frac{Z_2}{A_2} \right) E_{B-L}$$

Probe with a dual-species interferometer



M. Abe et al. arXiv: 2104.02835

Seismic and atmospheric pressure

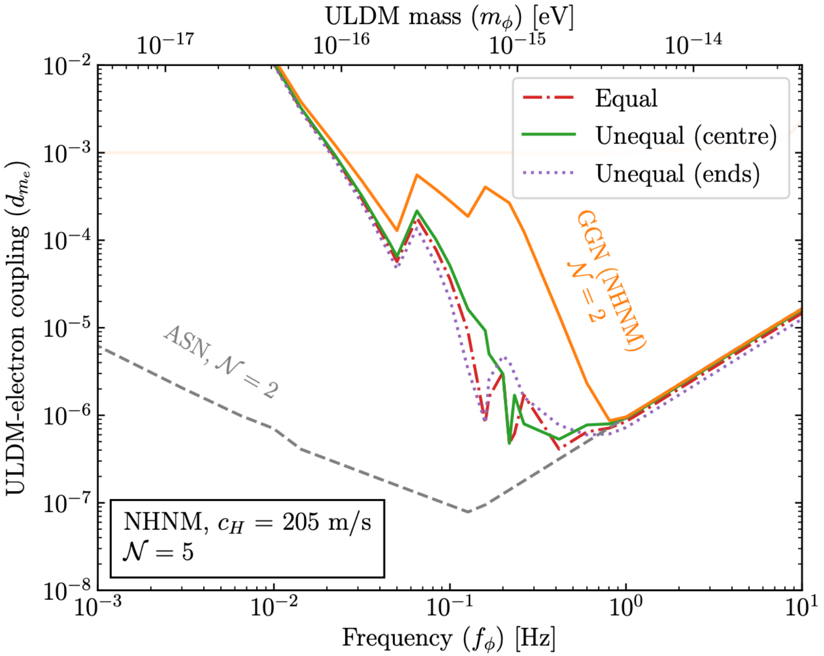


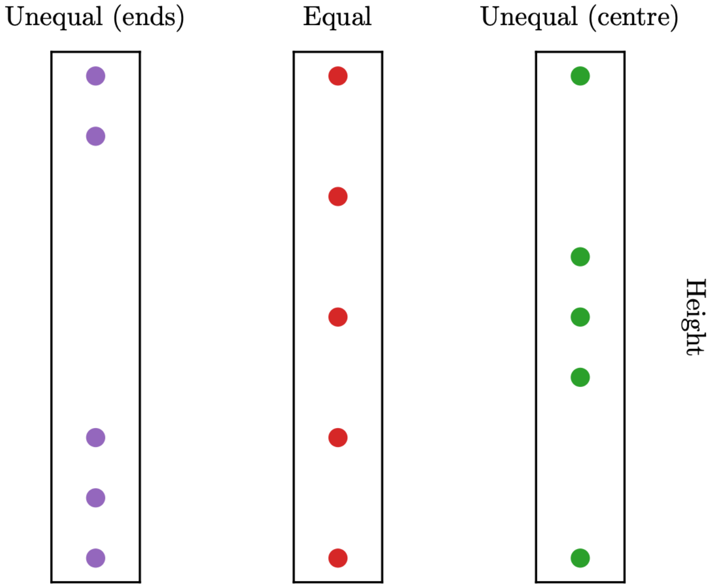
Atmospheric temperature

Seismic noise:
L. Badurina et al. arXiv: 2211.01854

Atmospheric noise:
J. Carlton et al. *In progress*

GGN vs Multi-gradiometry





L. Badurina et al. arXiv: 2211.01854

The AION-10 Experiment

University of Oxford, Beecroft Building

The AION-10 Experiment

The AION-10 Experiment

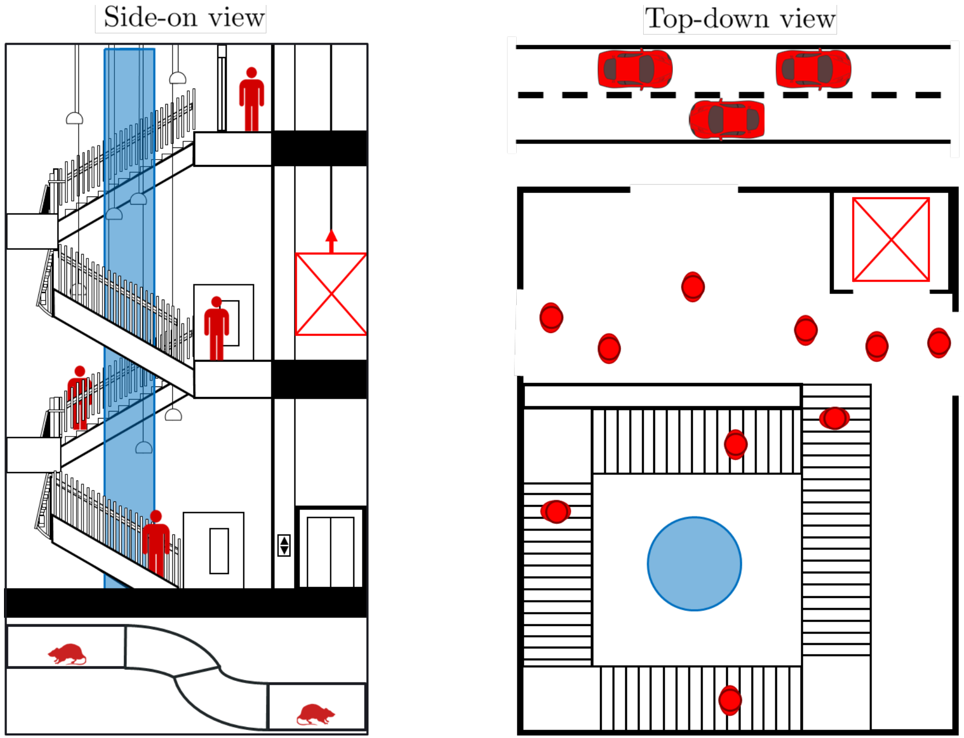
All these people are a problem!

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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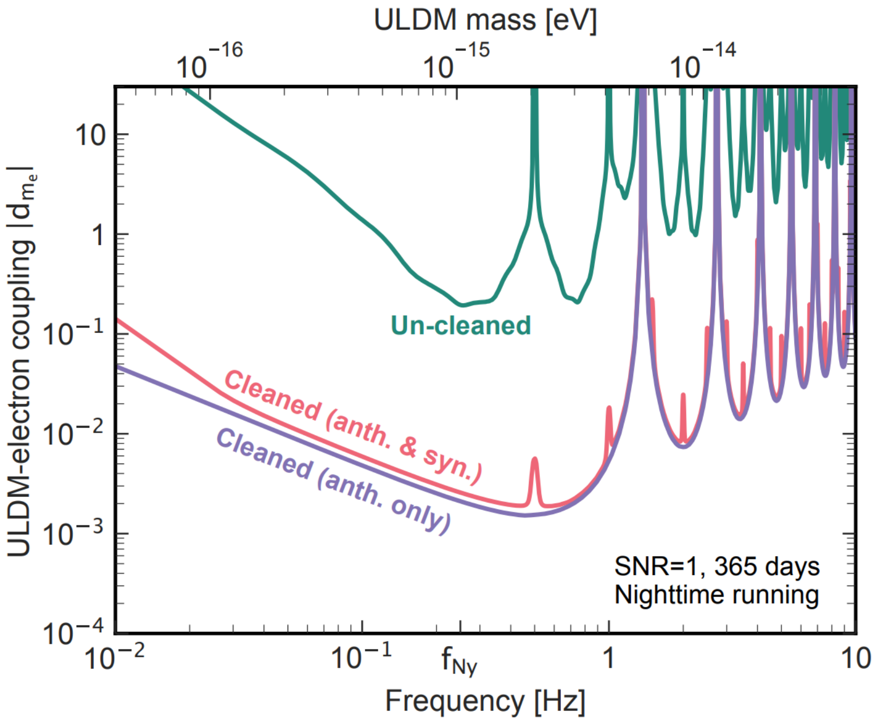

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AION-10 sensitivity projections

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

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)