Massive graviton dark matter searches with atom interferometers

John Carlton

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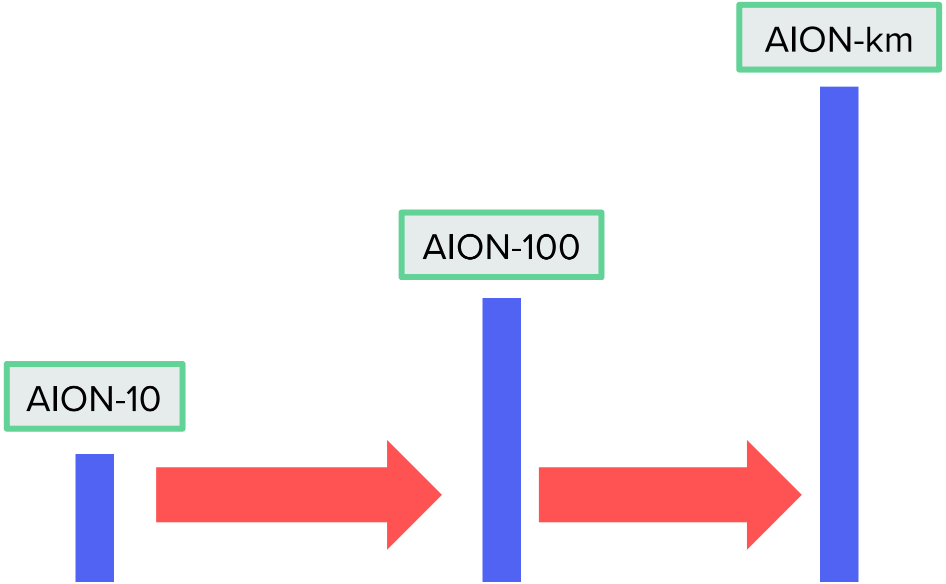
AION

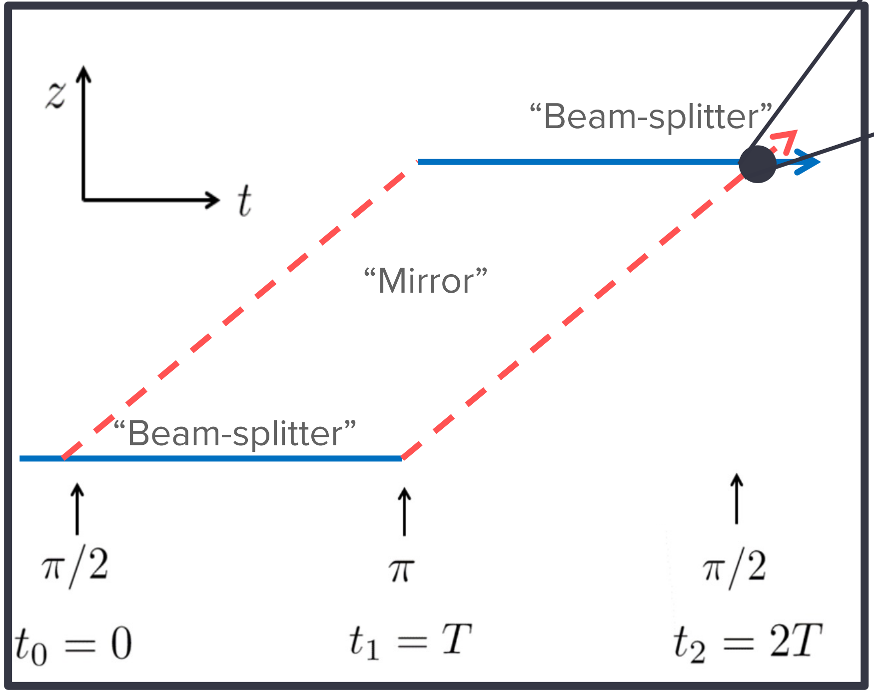
arXiv: 1911.11755

Atom Interferometer Observatory and Network



Atom interferometry

Interferometer sequence



Mach-Zehnder interferometer

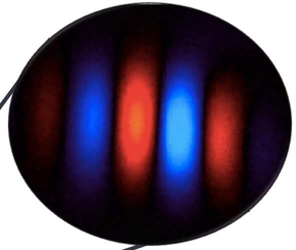


Image atom fringes and measure phase

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

Leading order phase depends on gravitational acceleration

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

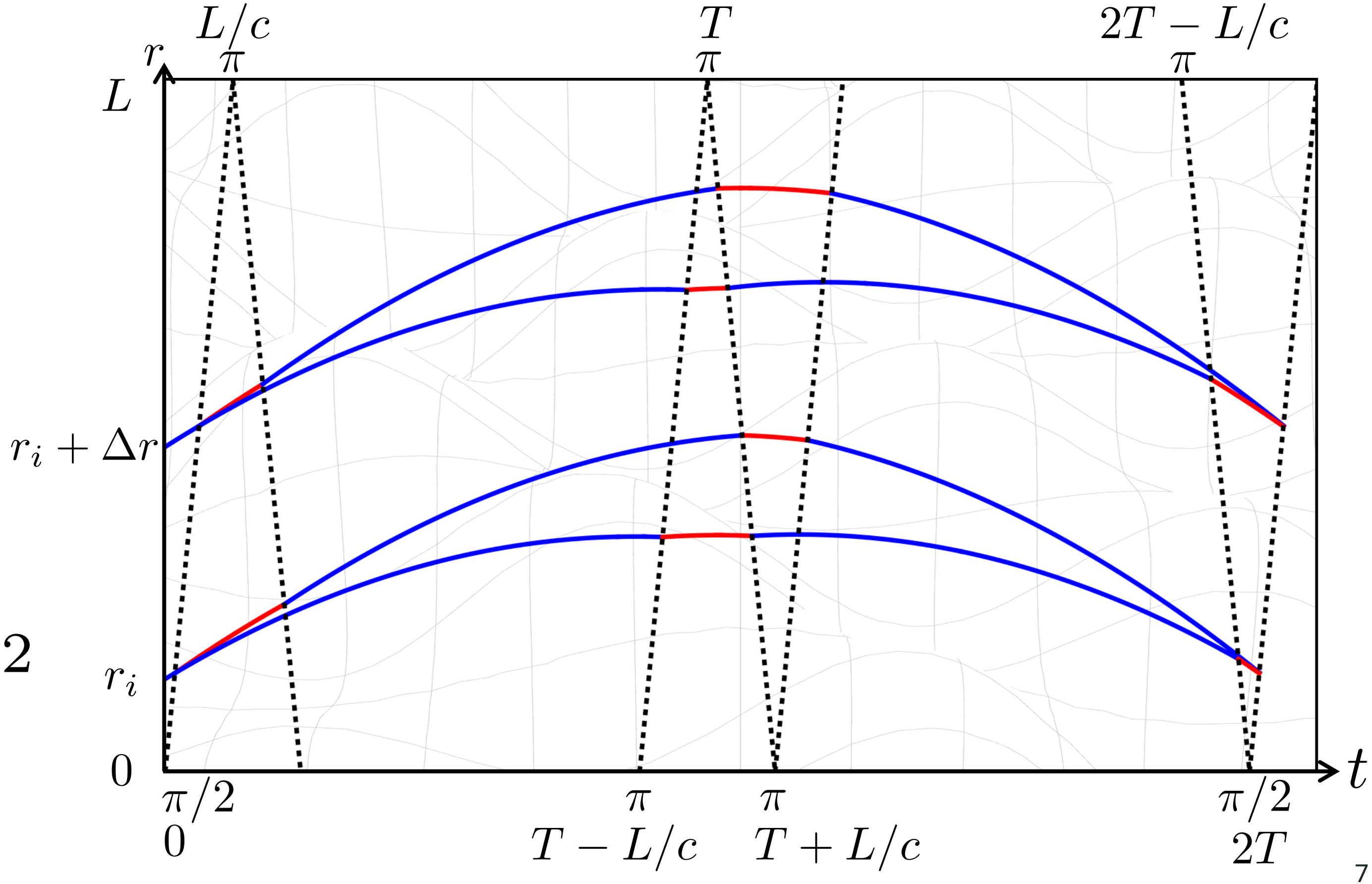
Atom-light interactions

Gravitational field

Time

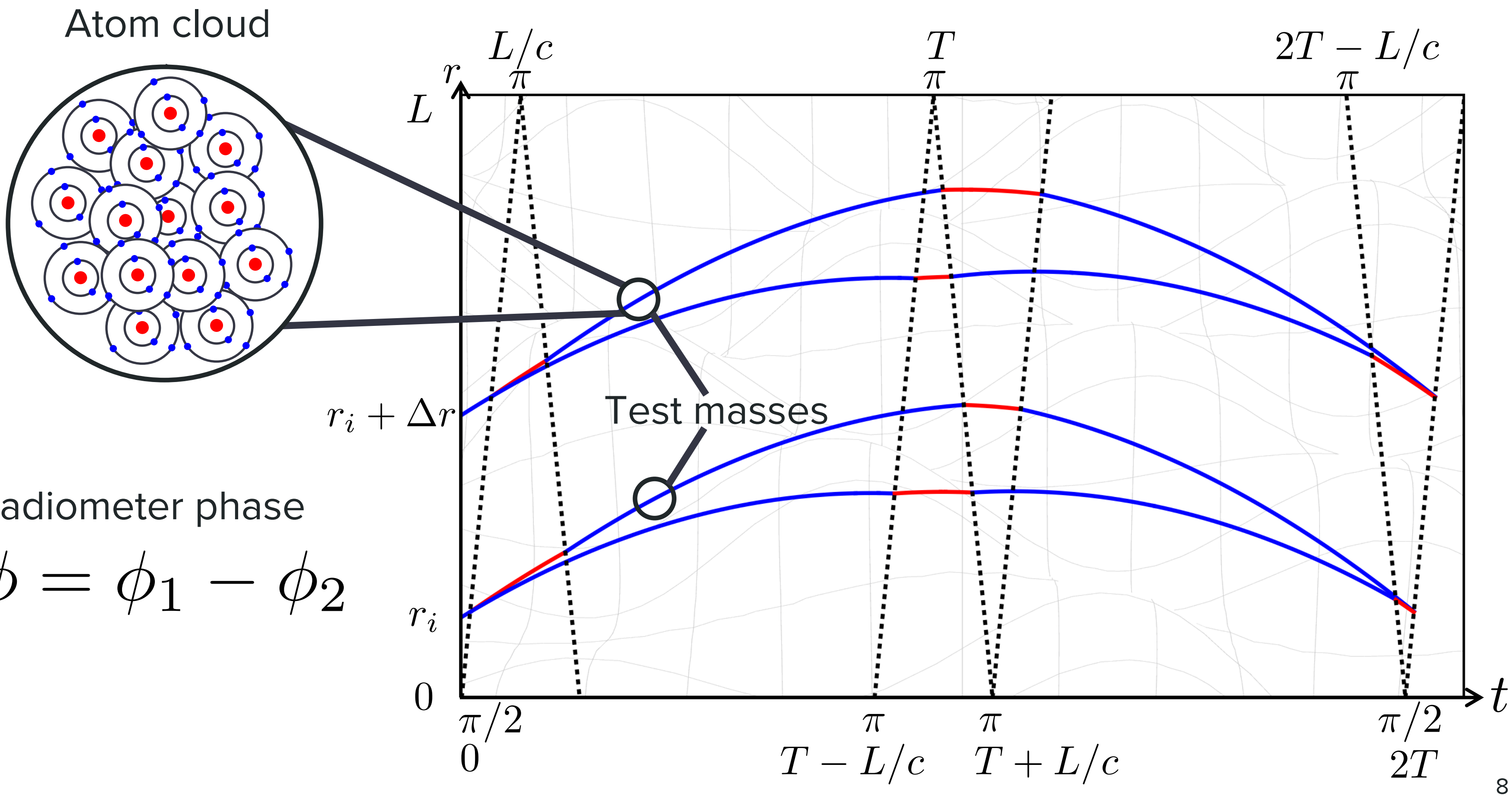
What can we measure?

Atom gradiometer



Gradiometer phase

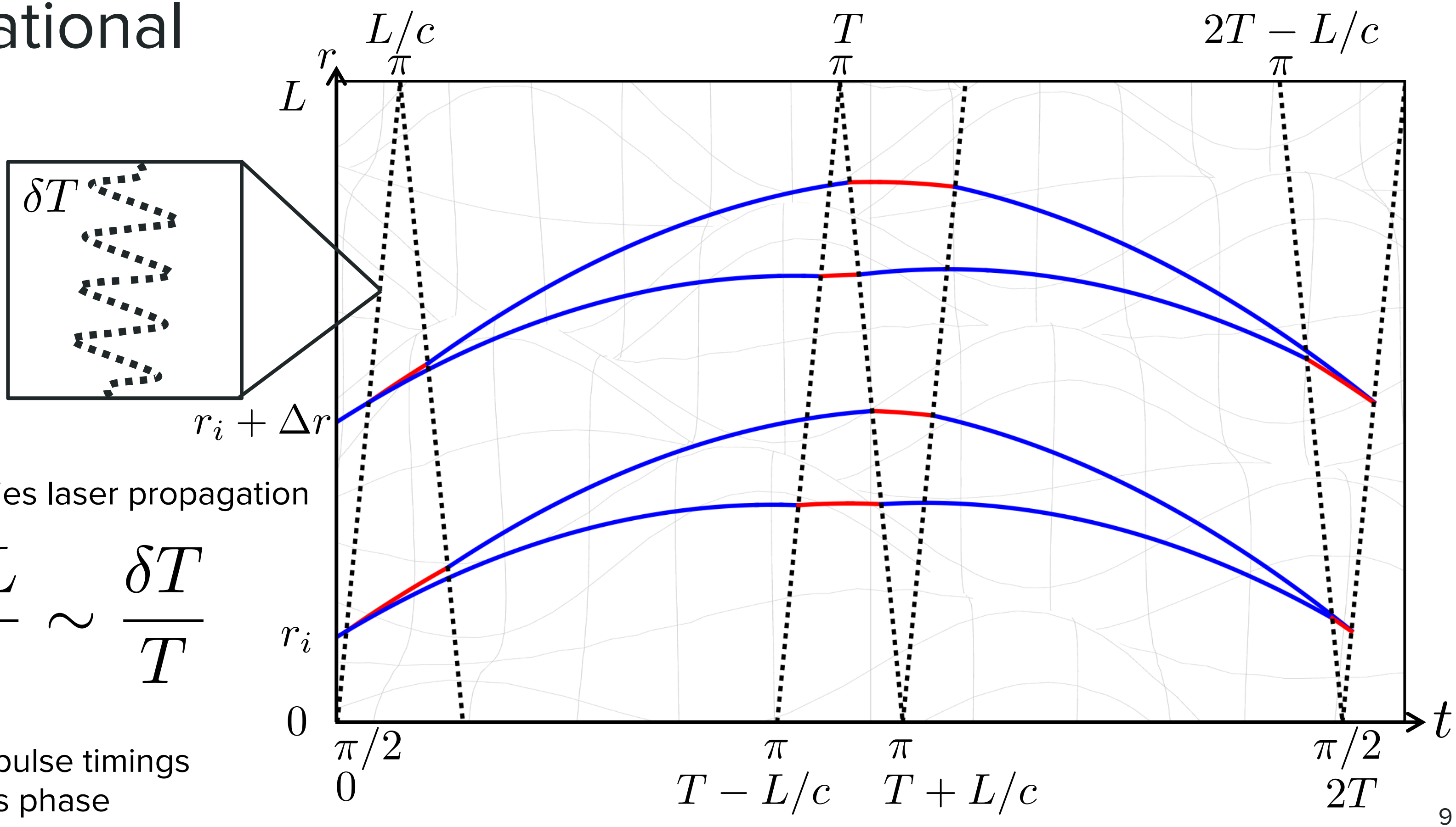
$$\Delta\phi = \phi_1 - \phi_2$$



Gradiometer phase

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

Gravitational waves

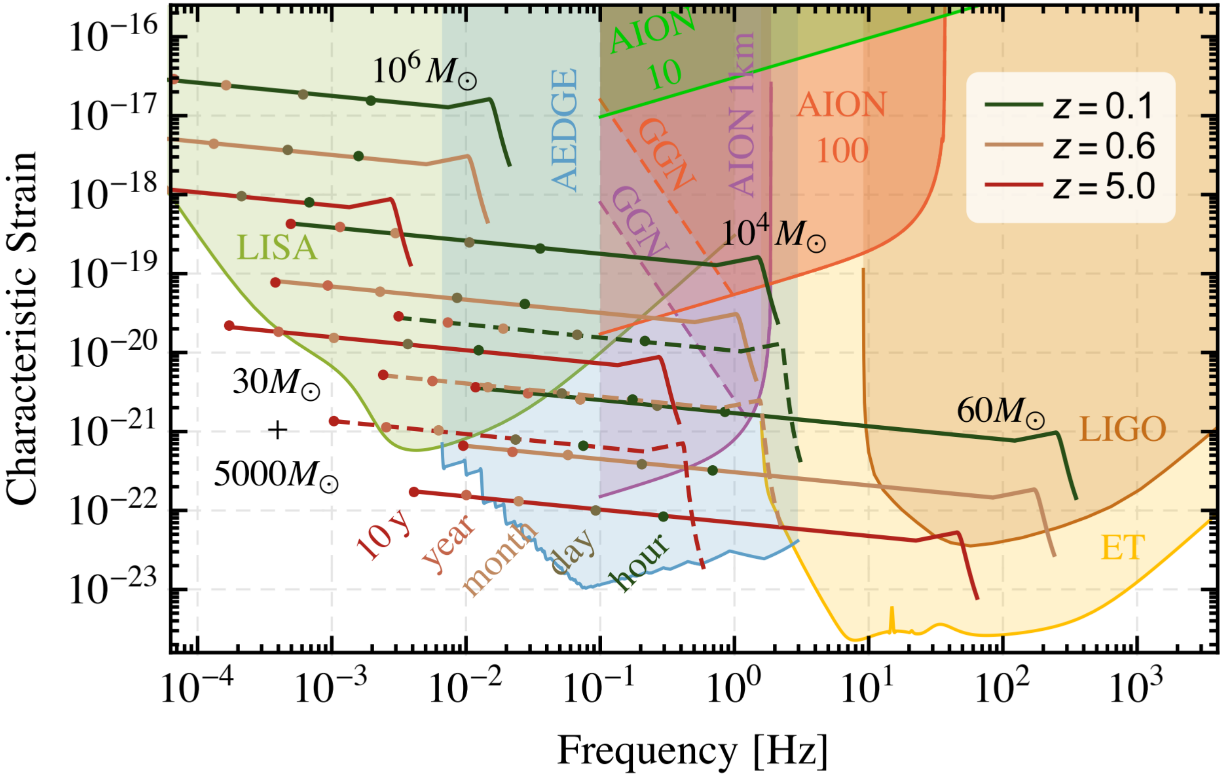


GW strain modifies laser propagation

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

Change in pulse timings affects phase

Gravitational waves

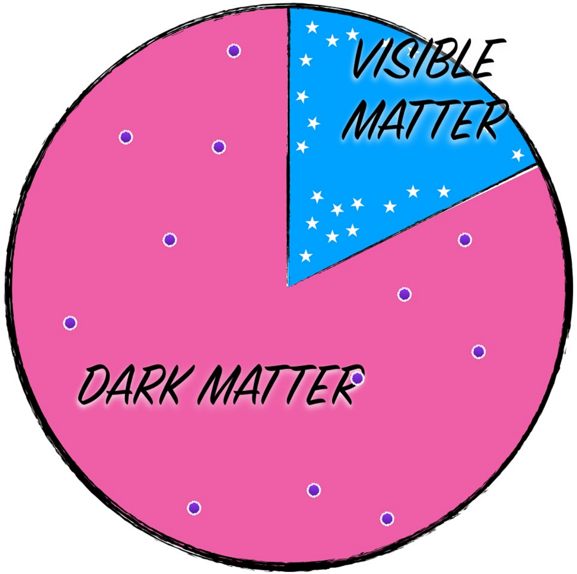


❖ *'Mid-band' sensitivity between LIGO and LISA.*

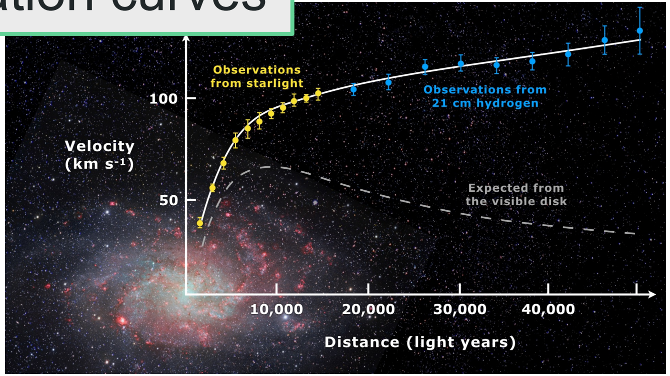
L. Badurina et al. arXiv: 1911.11755

Dark matter

What we know

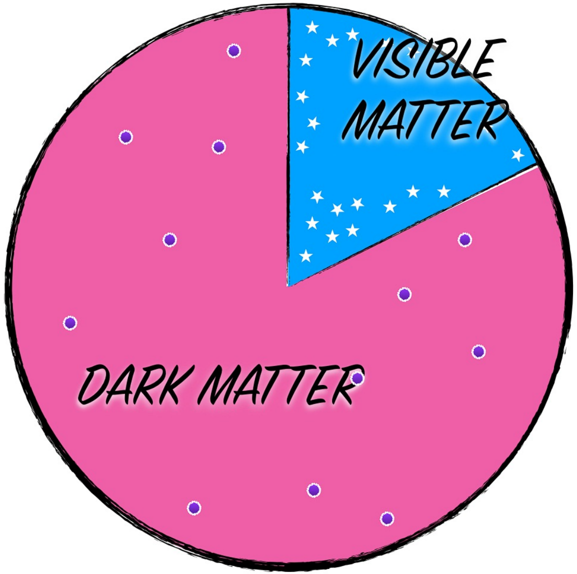


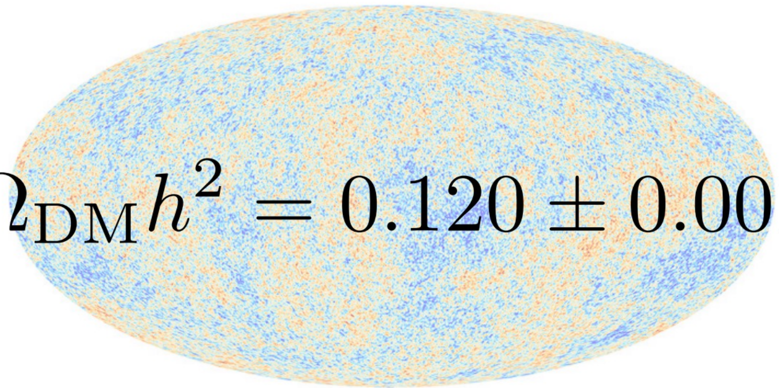
Galaxy rotation curves



Bullet cluster merger

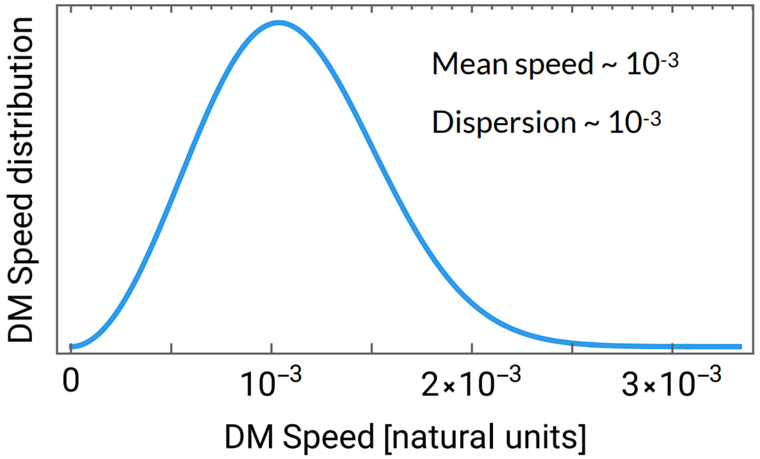
What we know



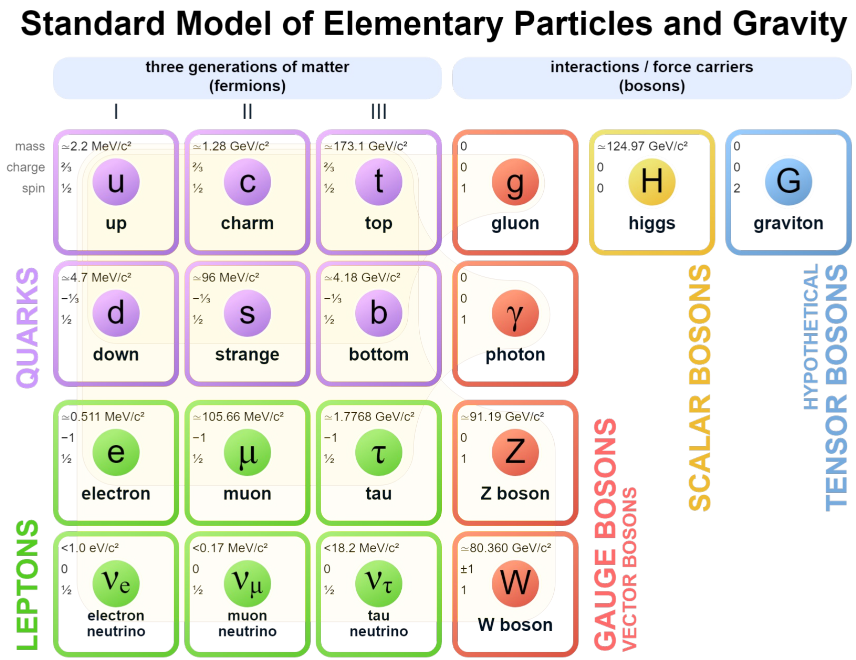


$$\Omega_{\rm DM} h^2 = 0.120 \pm 0.001$$

Relative abundance + speed distribution

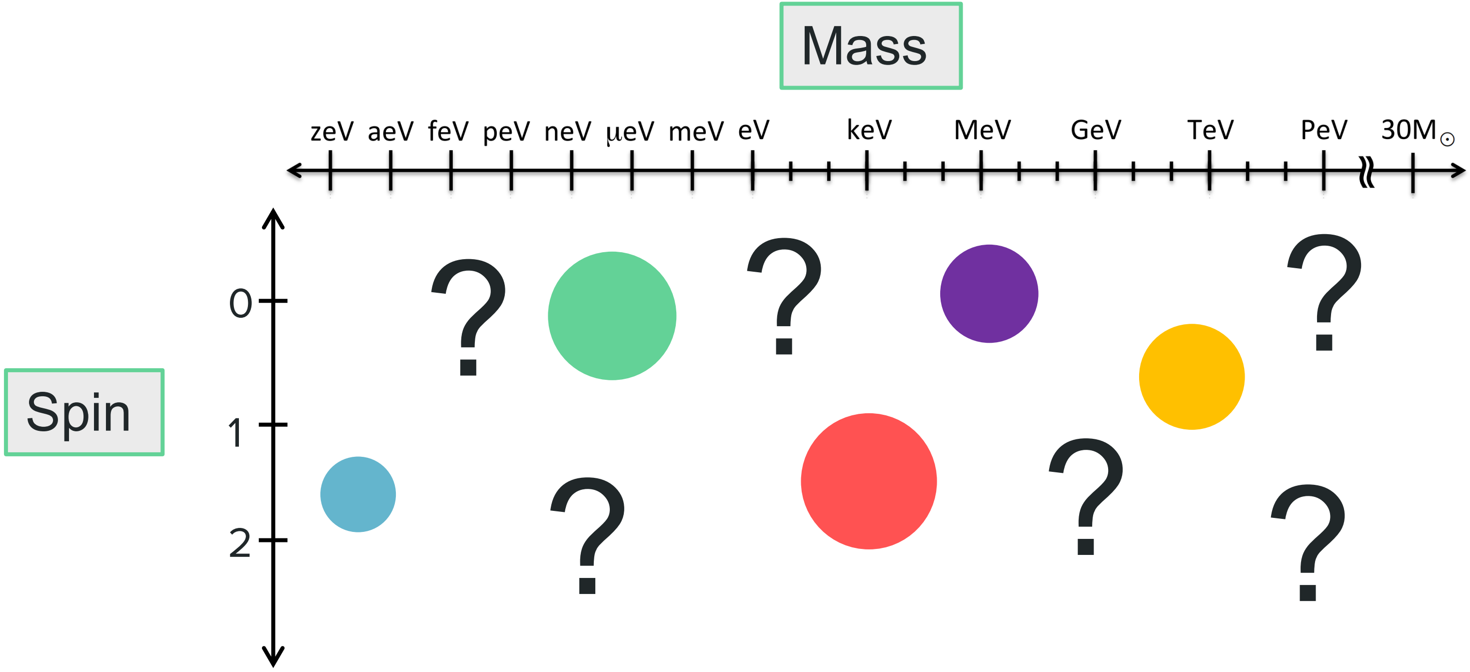


What we don't



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

A lot of parameter space!



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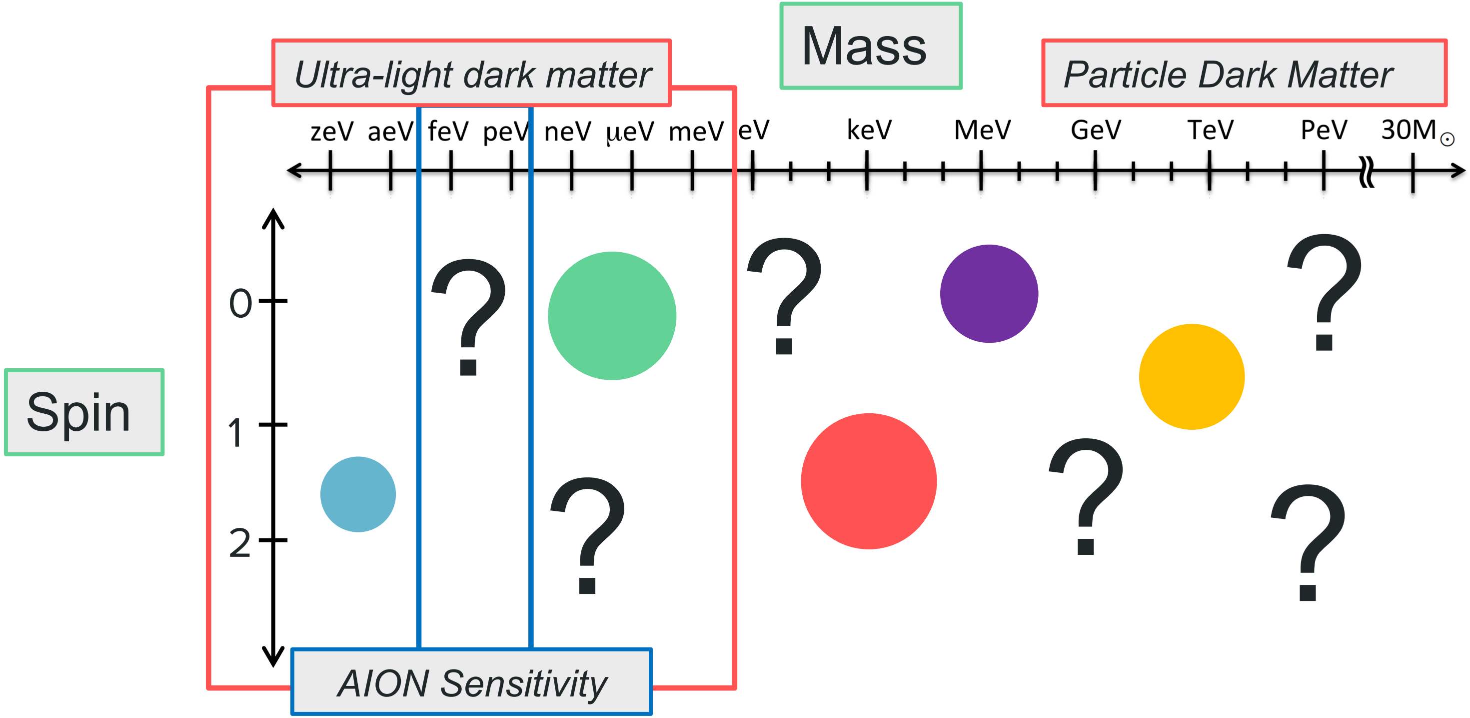
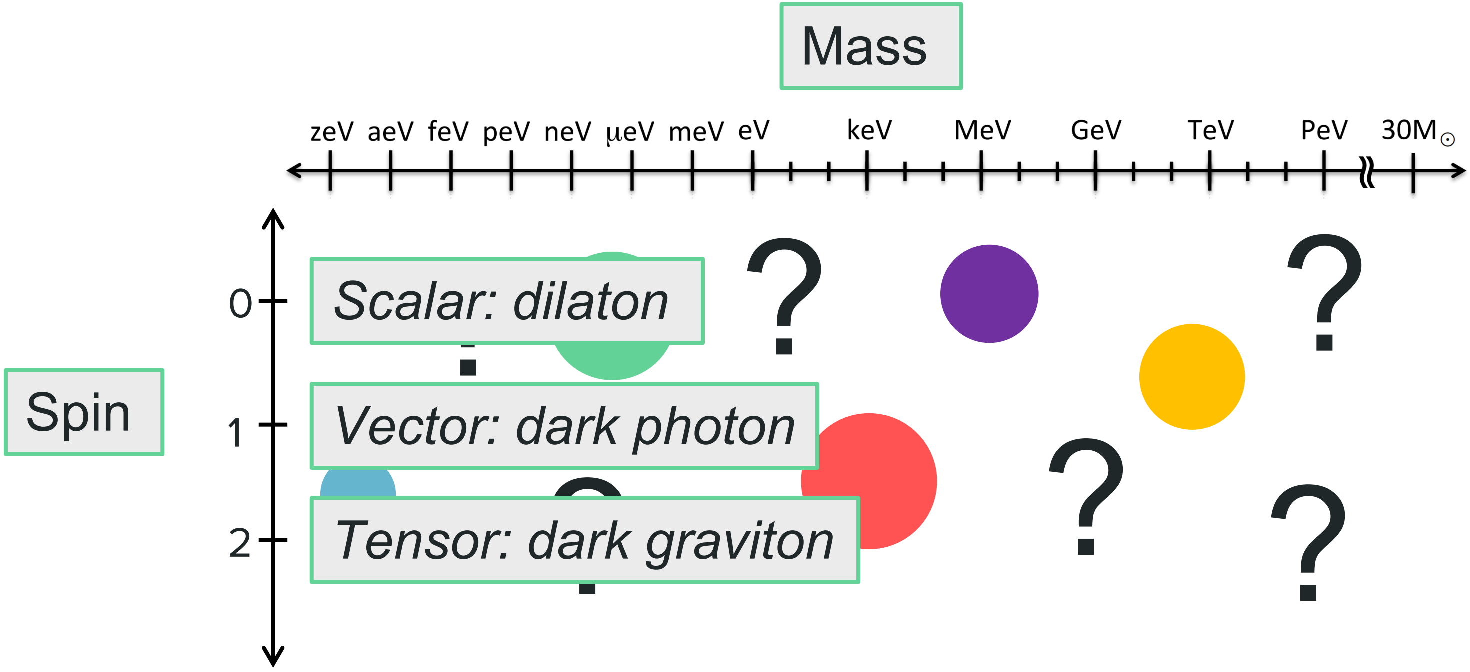
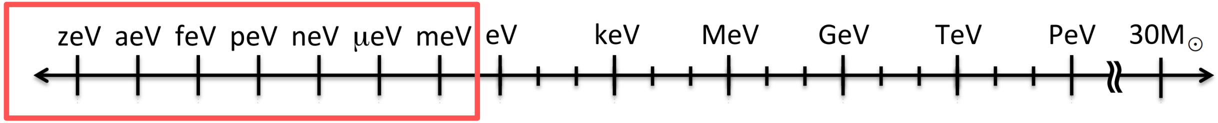


A lot of parameter space!



A classical ULDM field



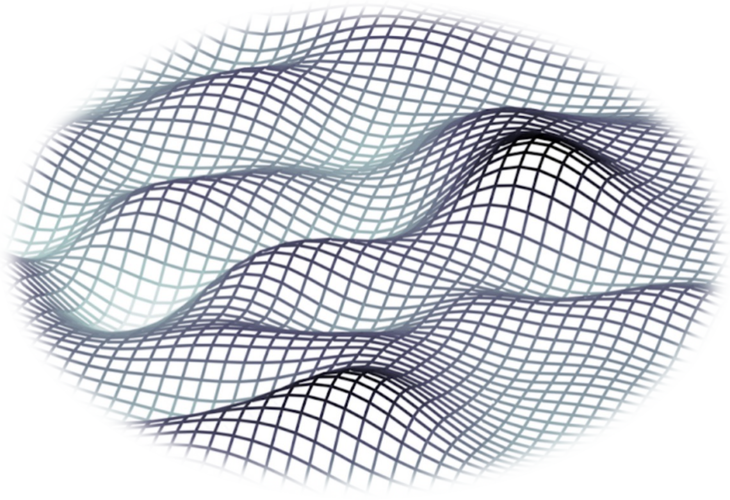
Ultralight mass means a high occupation number

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

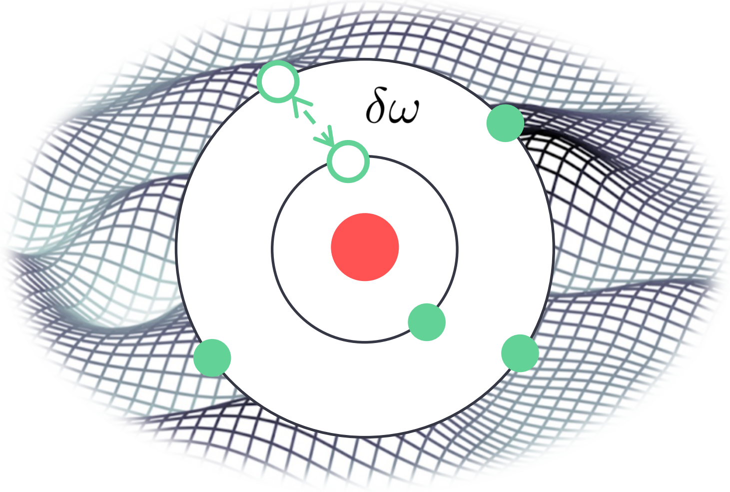
electron coupling

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

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

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

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



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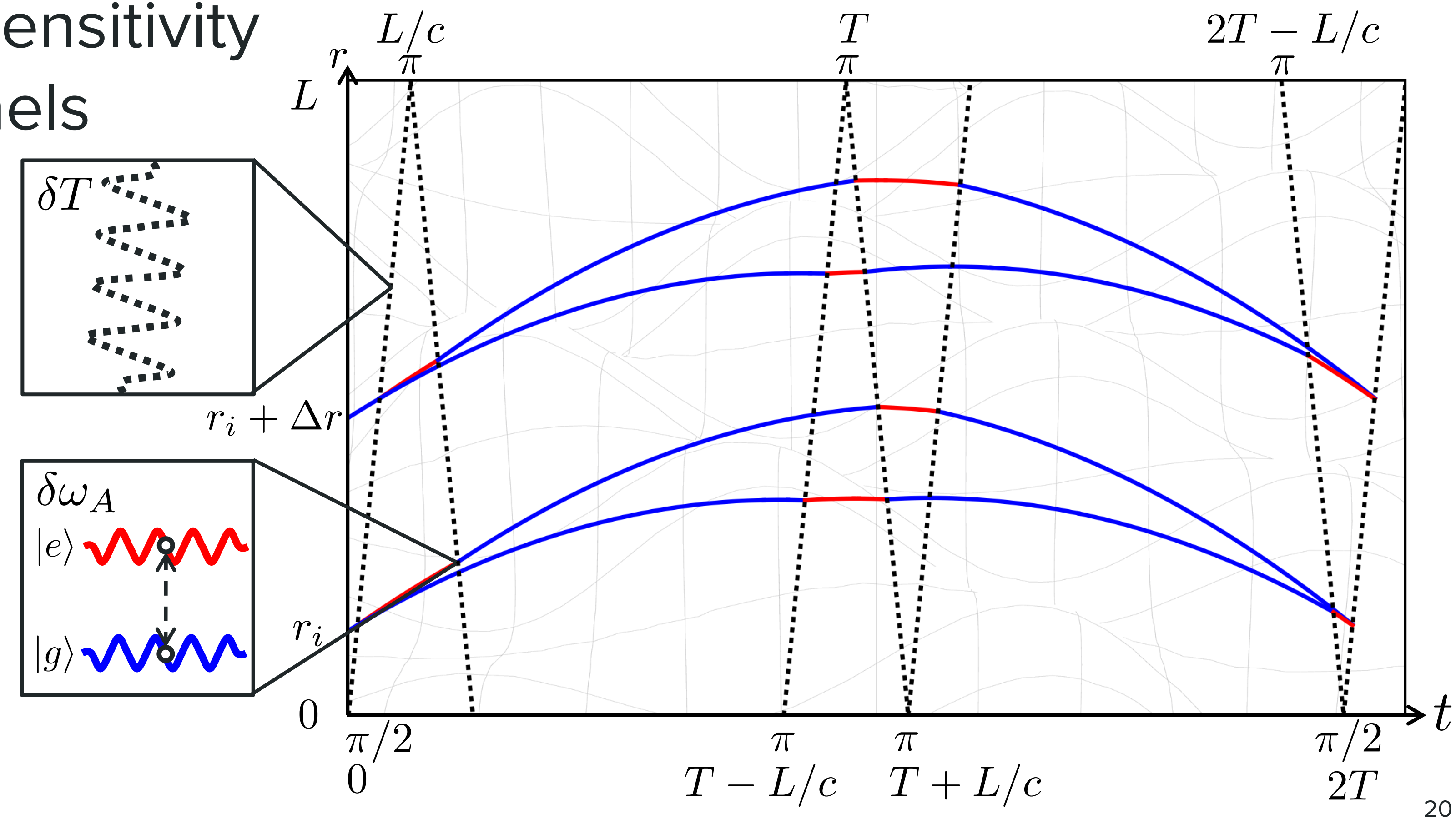
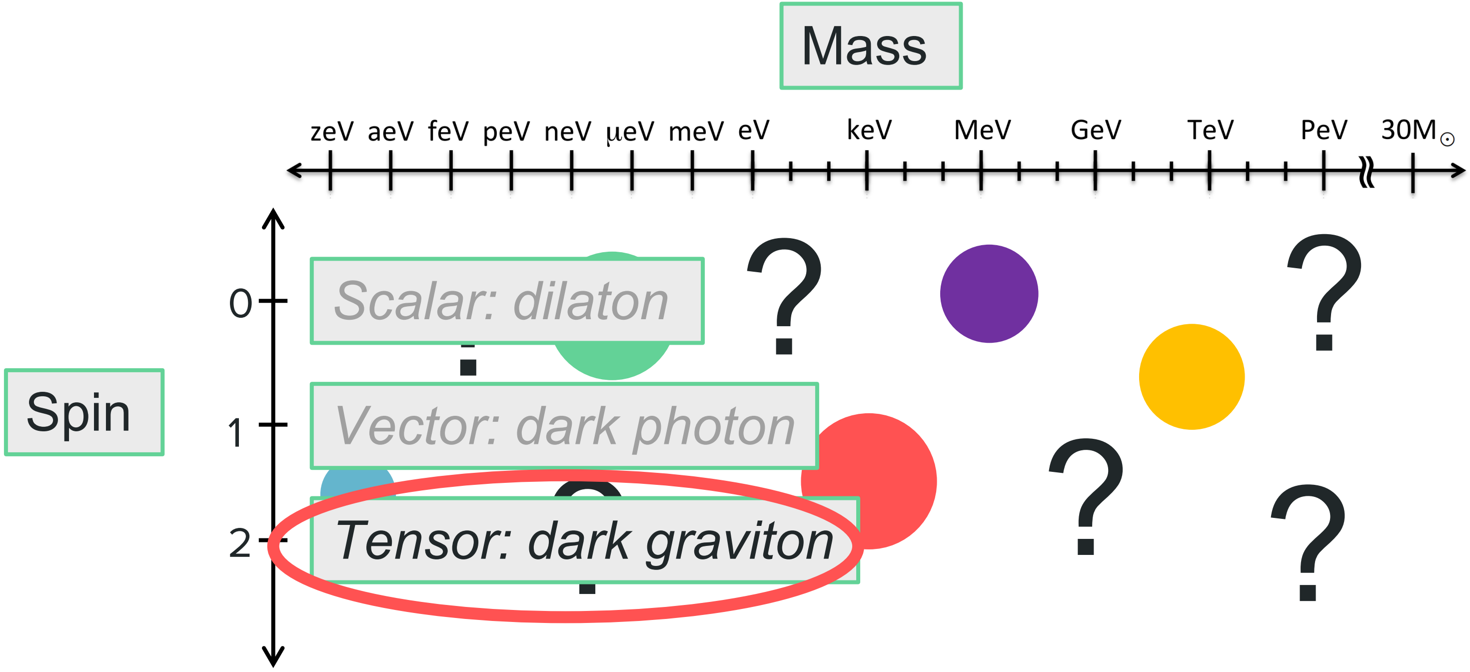
Two sensitivity channels

Interrogation time (GWs)

Atomic transition frequency (Scalar ULDM)



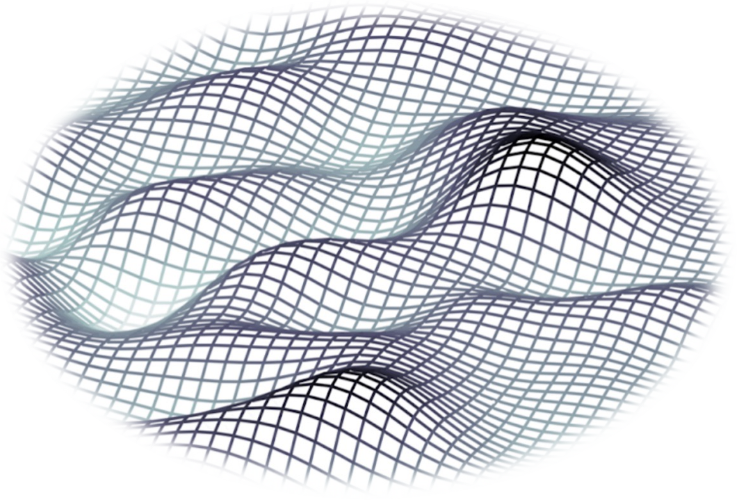
What about spin-2?



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

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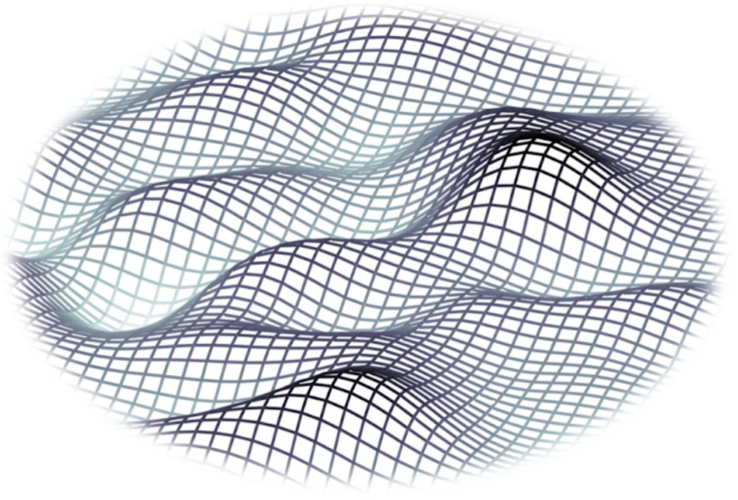
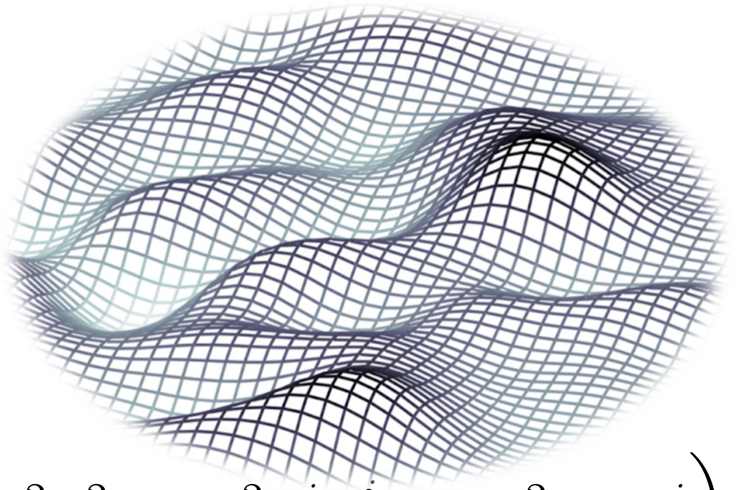


Fierz-Pauli Lagrangian

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

Lorentz invariant massive spin-2 field

Massive gravity field theory

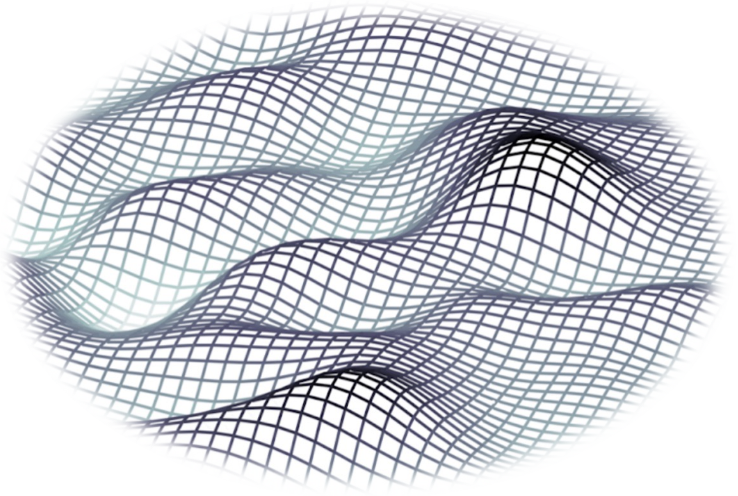


Let's consider a massive spin-2 ultra-light field $\varphi_{\mu\nu}$

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

Lorentz violating massive spin-2 field

Massive gravity field theory



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

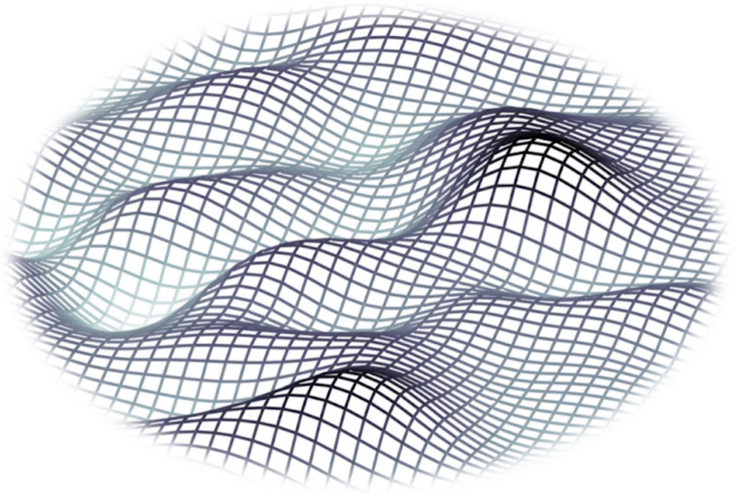
Express as irreducible fields:

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

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

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

Massive gravity field theory



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Tensor

Vector

Scalar

Three normalised fields

Tensor
$$\mathcal{L}_t = \frac{1}{2}\left(\varphi_{ij}^{\mathrm{TT}}\Box\varphi_{ij}^{\mathrm{TT}} - m_t^2\varphi_{ij}^{\mathrm{TT}}\varphi_{ij}^{\mathrm{TT}}\right)$$

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

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

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

Three classical oscillating fields...

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

Sum over polarisations

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

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

$$\varphi_0^{\mathrm{TT}} = \frac{\sqrt{f_t \rho_{\mathrm{DM}}}}{m_t}$$

Vector

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

Scalar

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

… each contributing to the local dark matter

Tensor

$$\varphi_0^{\mathrm{TT}} = \frac{\sqrt{\boxed{f_t}\rho_{\mathrm{DM}}}}{m_t}$$

Vector

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

Fraction of total dark matter

$$f_t + f_v + f_s = 1$$

Scalar

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

Coupling to light and matter

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

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

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

Non-relativistic limit

$$\frac{\alpha}{M_{\rm Pl}}\varphi^{\rm TT}_{ij}T^{ij} \qquad \frac{\beta}{M_{\rm Pl}}\varphi^{\mu}_{\mu}T$$

Tensor modes

coupling const.

Field theory picture:

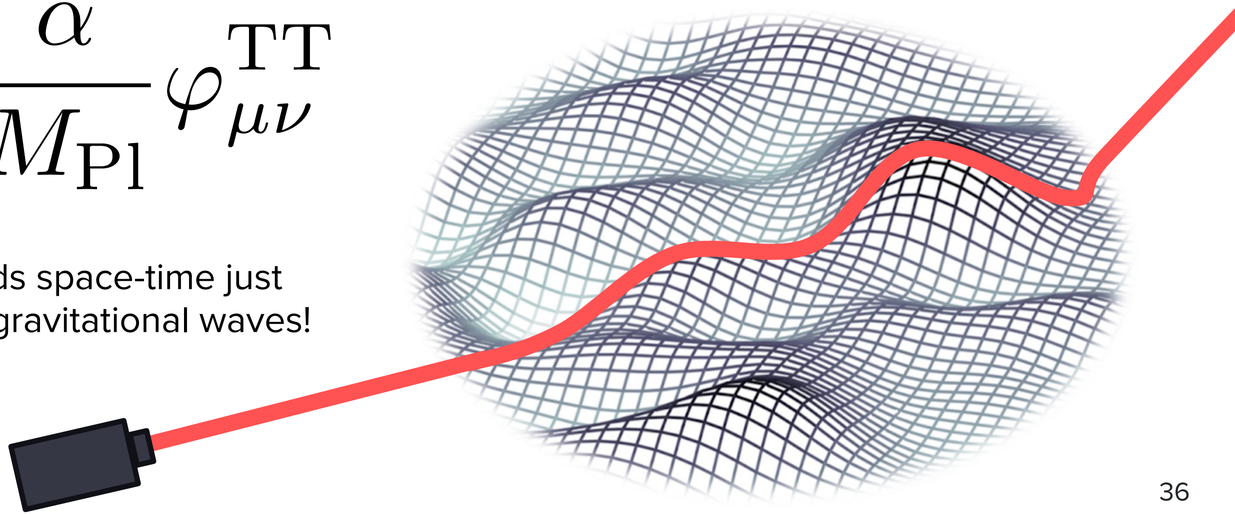
$$\mathcal{L} \supset \mathcal{L}_{\mathrm{SM}} + \boxed{\mathcal{L}_t} \longrightarrow \boxed{\mathcal{L}_t \supset \frac{\alpha}{M_{\mathrm{Pl}}} \varphi_{ij}^{\mathrm{TT}} T^{ij}}$$

stress-energy tensor

Linearised gravity picture:

$$g_{\mu\nu} = \eta_{\mu\nu} + \frac{\alpha}{M_{\mathrm{Pl}}} \varphi_{\mu\nu}^{\mathrm{TT}}$$

Bends space-time just
like gravitational waves!



Scalar mode

Field theory picture:

$$\mathcal{L} \supset \mathcal{L}_{\mathrm{SM}} + \boxed{\mathcal{L}_s} \longrightarrow \boxed{\mathcal{L}_s \supset \frac{\beta}{M_{\mathrm{Pl}}} \varphi^\mu_\mu T} \qquad T \to m_\psi \overline{\psi}\psi$$

coupling const.

trace of stress-energy tensor

But! $\varphi^\mu_\mu = 0$ if $m_2 = m_3 = m_4$

Trace vanishes in Lorentz invariant theory, require Lorentz violation to detect!

Scalar mode

Field theory picture:

$$\mathcal{L} \supset \mathcal{L}_{\mathrm{SM}} + \boxed{\mathcal{L}_s} \rightarrow \boxed{\mathcal{L}_t \supset \frac{\beta}{M_{\mathrm{Pl}}} \varphi^{\mu}_{\mu} T}$$

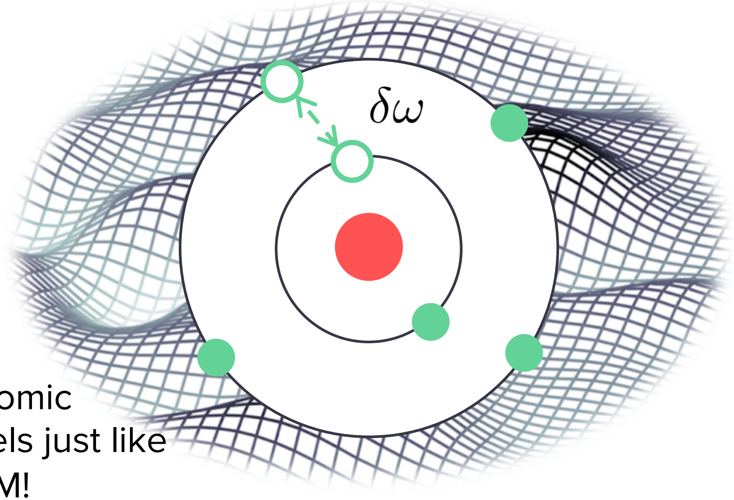
coupling const.

trace of stress-energy tensor

$$T \rightarrow m_\psi \overline{\psi}\psi$$

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

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



Modifies atomic energy levels just like scalar ULDM!

What can we measure?

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

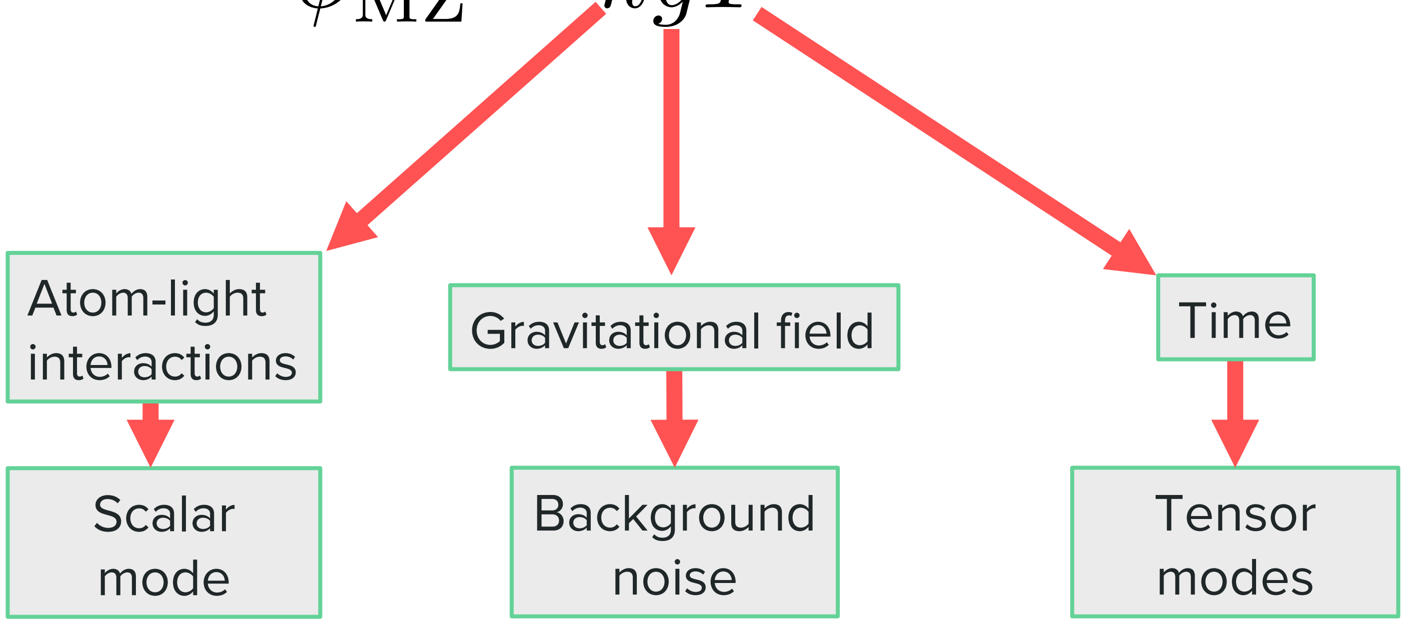
Atom-light interactions

Gravitational field

Time

What can we measure?

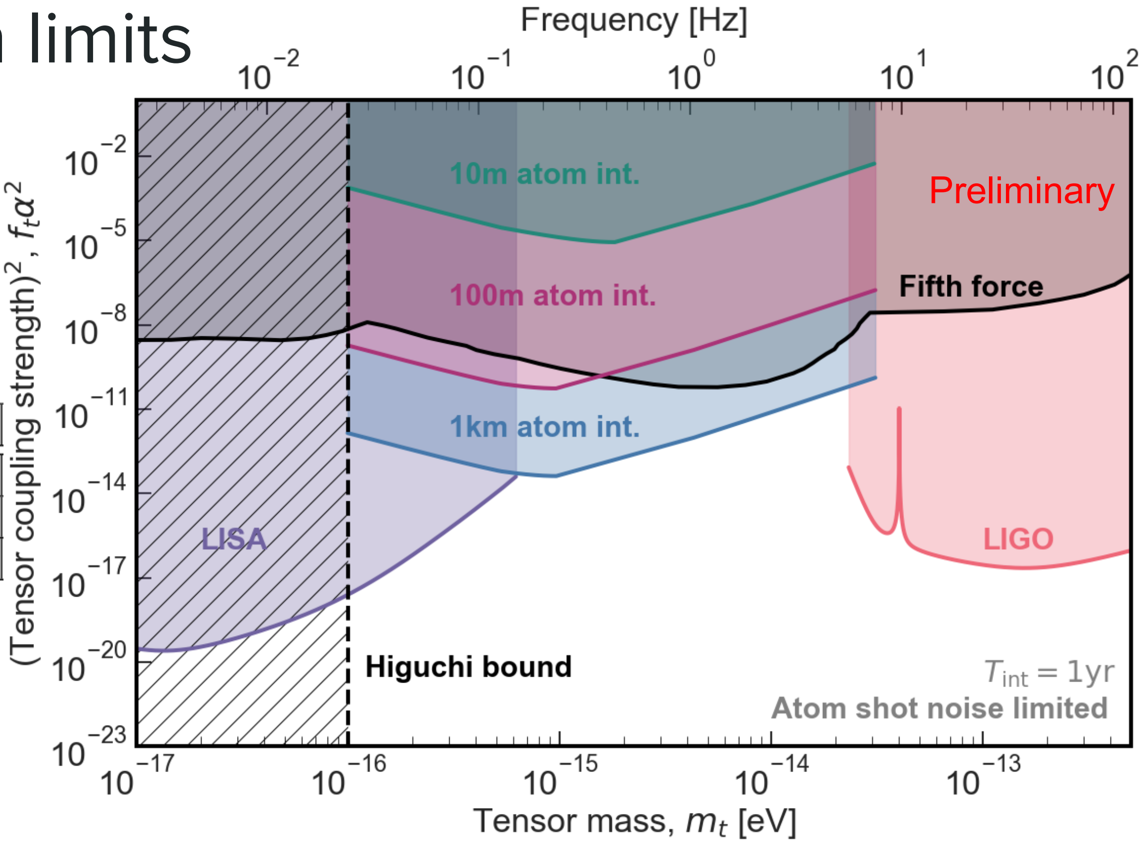
$$\phi_{\mathrm{MZ}} = kgT^2$$



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}



Projected detection limits

10m, 100m and 1km example atom interferometers

Assume Lorentz invariance:

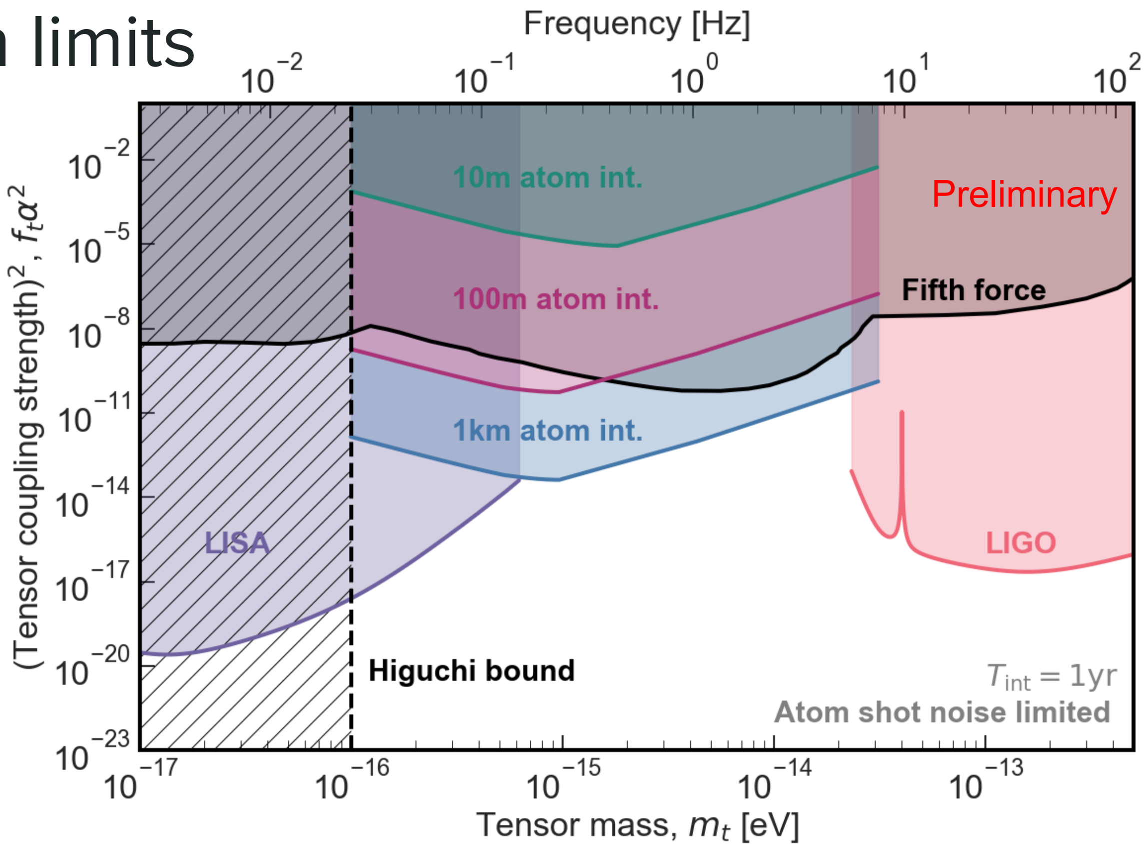
$$m_t = m_v = m_s$$

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

$$f_t = f_v = f_s$$

Only tensor modes contribute.

$$\varphi^\mu_\mu = 0$$

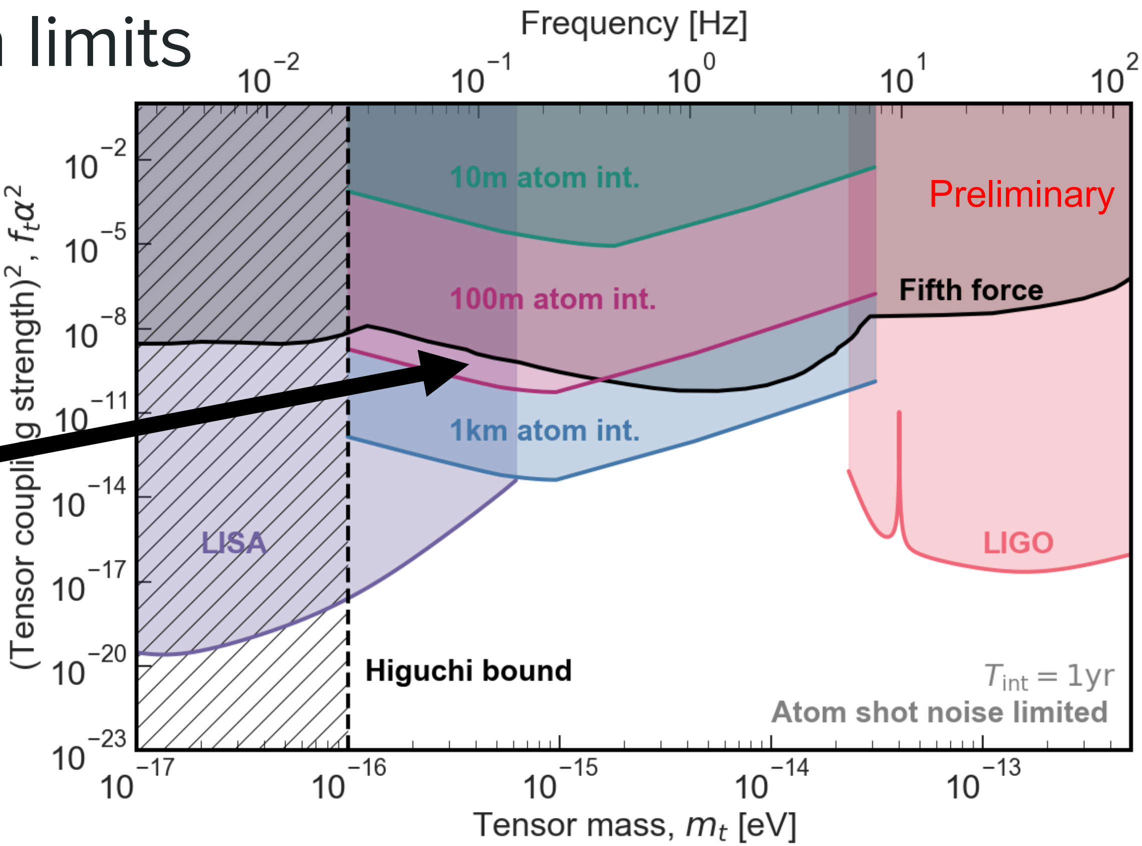


Projected detection limits

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



Projected detection limits

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

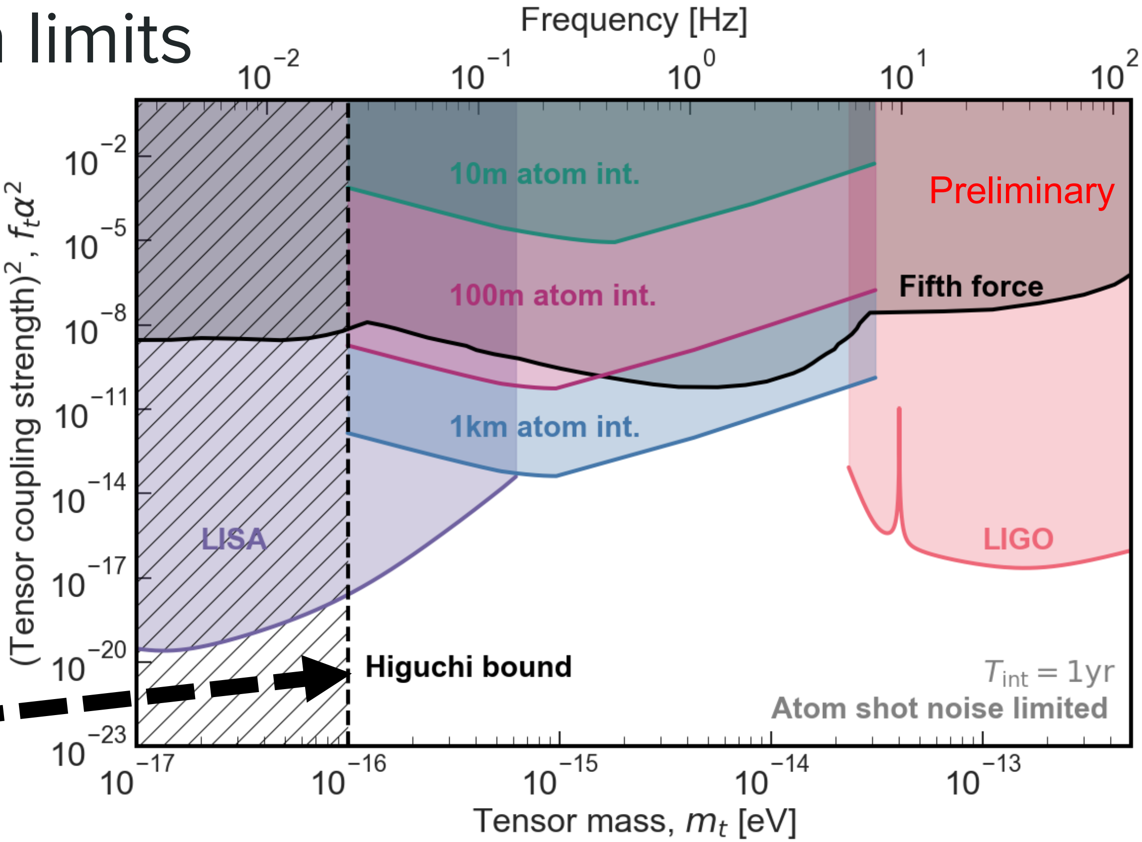
$$\delta V_{\mathrm{Newt}} \propto \alpha^2 e^{-m_{\tilde{\varphi}} r}$$

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

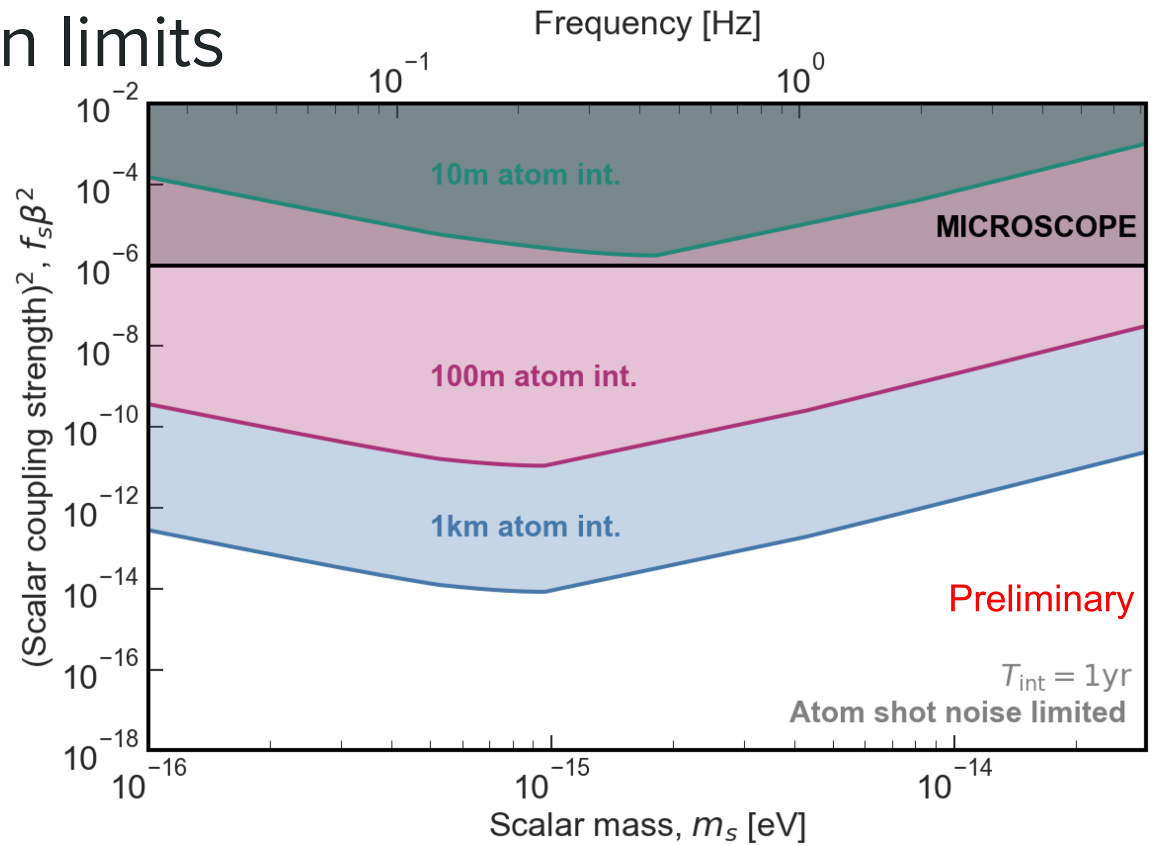


Projected detection limits

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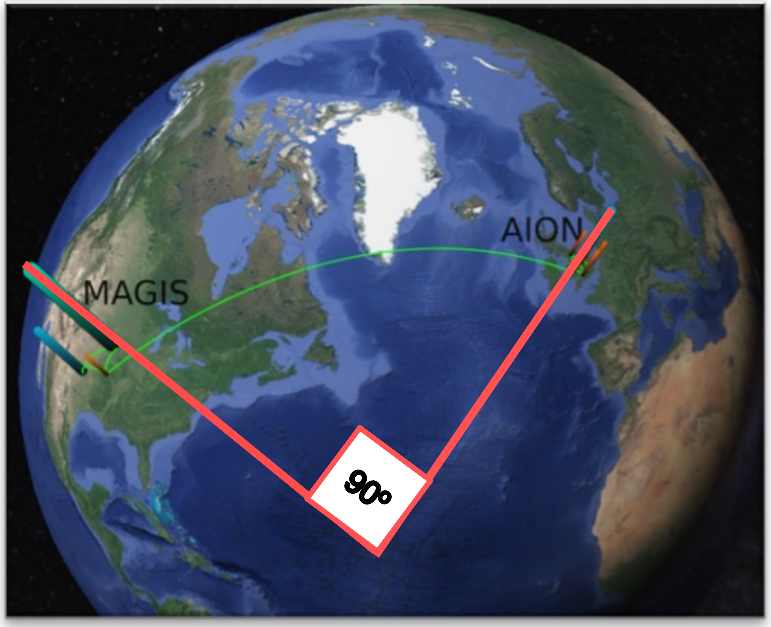
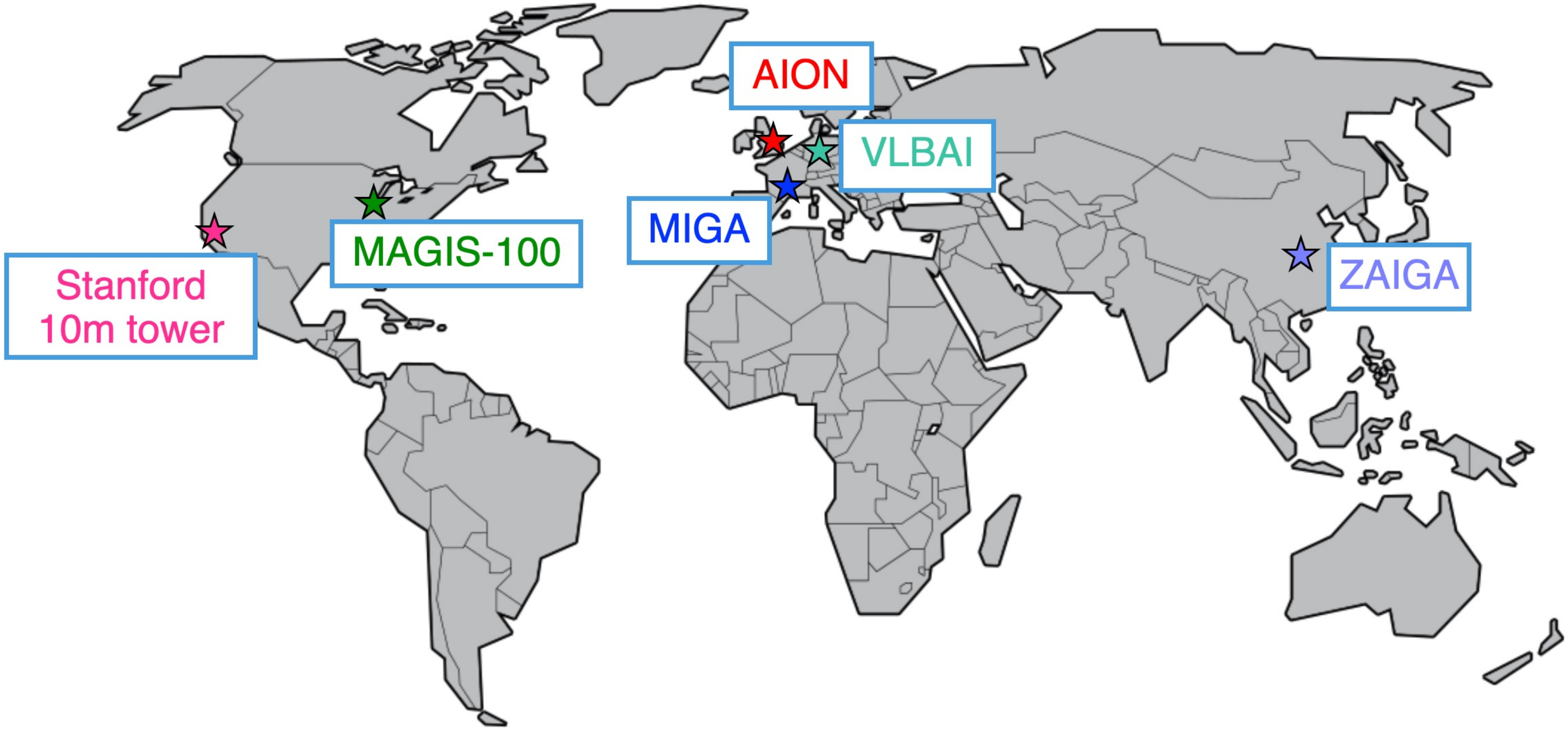
$$\varphi_{ij}^{\mathrm{TT}}(t,\mathbf{x}) = \sum_{\lambda} \varphi_{0,\lambda}^{\mathrm{TT}} \boxed{e_{ij}^{\lambda}}(\mathbf{k}_t)\cos(\omega_t t - \mathbf{k}_t \cdot \mathbf{x})$$

Distinguish dark matter models through directional dependence.



Progress towards a global network!



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

Summary

AION and MAGIS-100 can probe spin-2 ULDM analogously to scalar ULDM and gravitational waves – without changing any of the experimental design!

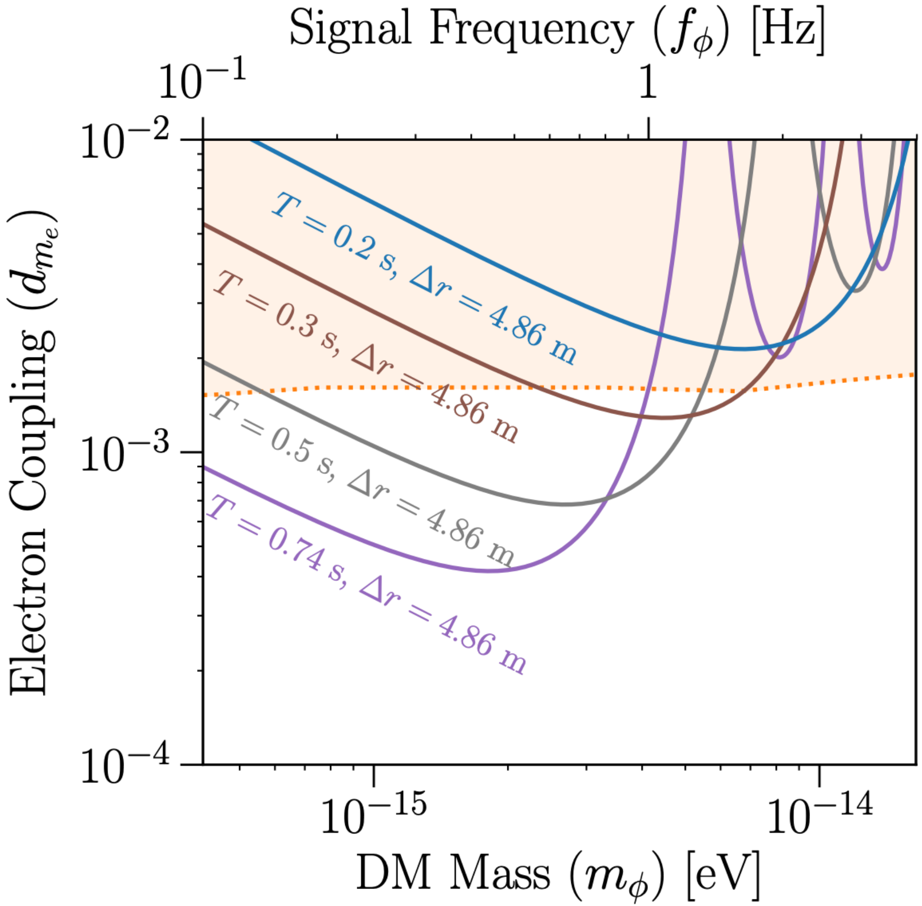
A Lorentz invariant spin-2 field will only have transverse-traceless tensor modes coupling to matter – but Lorentz violating theories have a detectible scalar mode! A scalar ULDM detection may be from a spin-2 field instead!

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

Backup

Scalar ULDM sensitivity

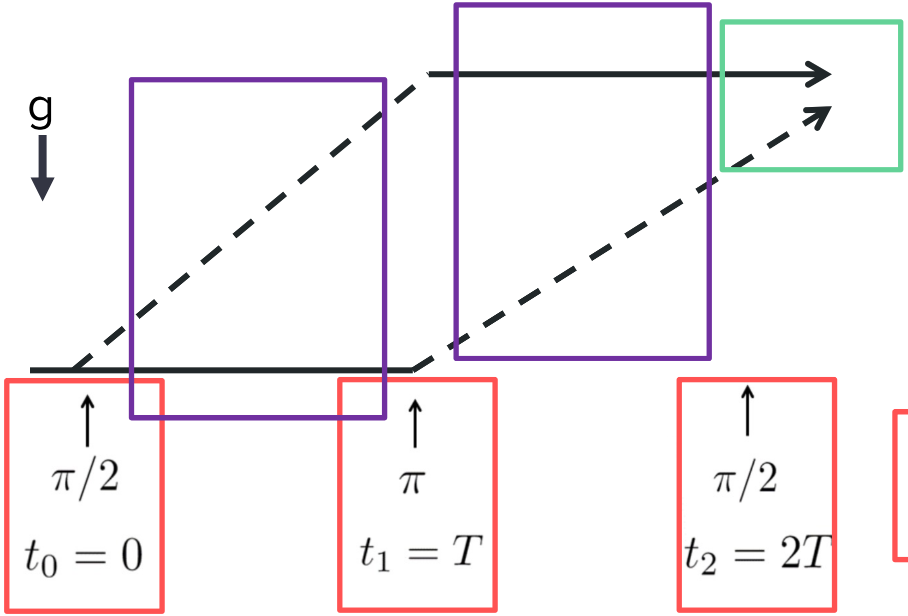
- *ULDM mass/frequency sensitivity depends on T.*



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

Phase shifts

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



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

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

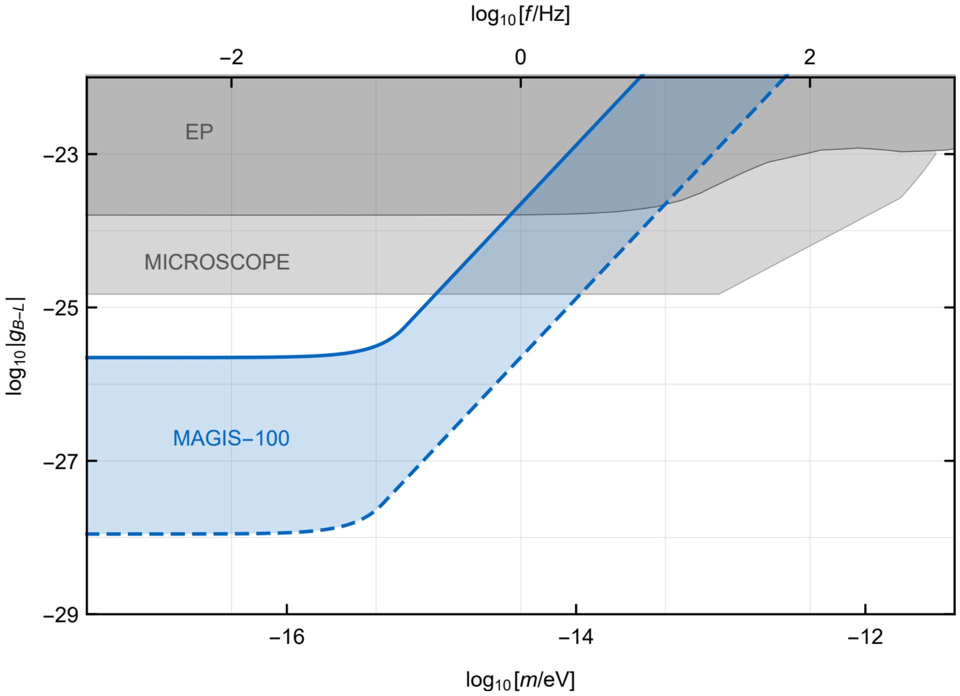
$$\phi_{\text{laser}} = \left(\sum_j \pm\phi_L(t_j, \boldsymbol{z}_u(t_j))\right)_u - \left(\sum_j \pm\phi_L(t_j, \boldsymbol{z}_l(t_j))\right)_l$$

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

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
$T_{\text{int}} \sim 10^7$s (integration time)