Based on: Phys.Rev.D (108, 123004); arXiv: 2308.10731 [astro-ph.CO]

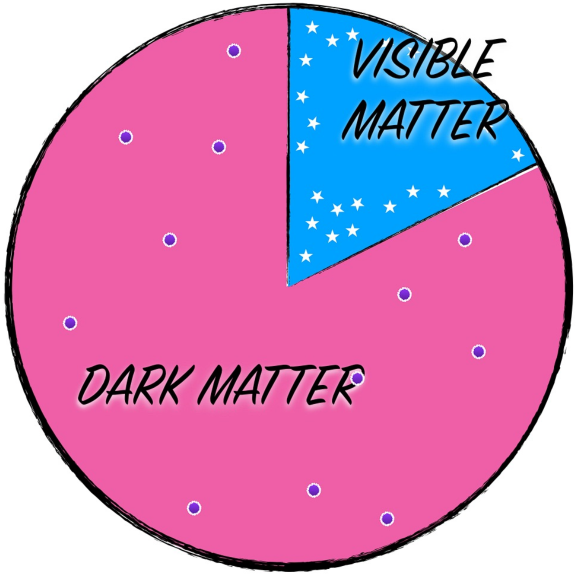
Defying gravity:

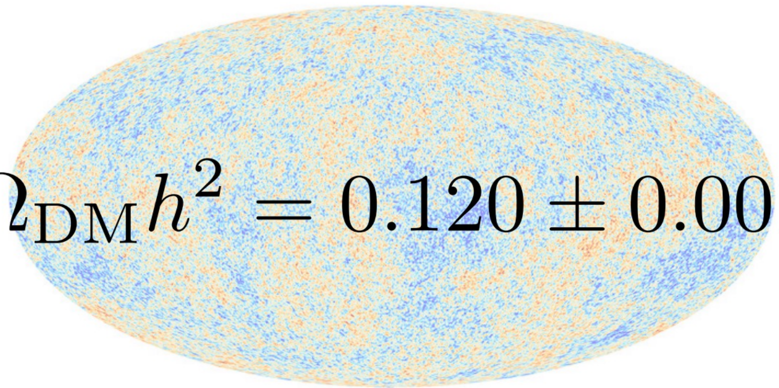
Combating gravity gradient noise in atom interferometer searches for ultra-light dark matter

John Carlton
(with Chris McCabe)
King's College London

How can I find dark matter?

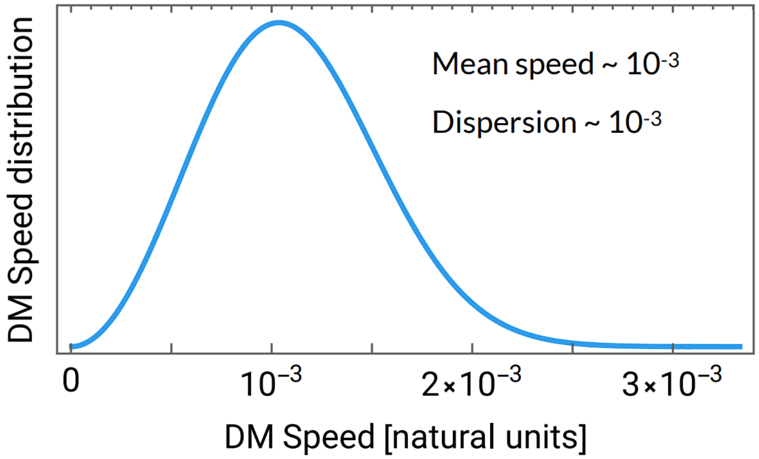
What we know



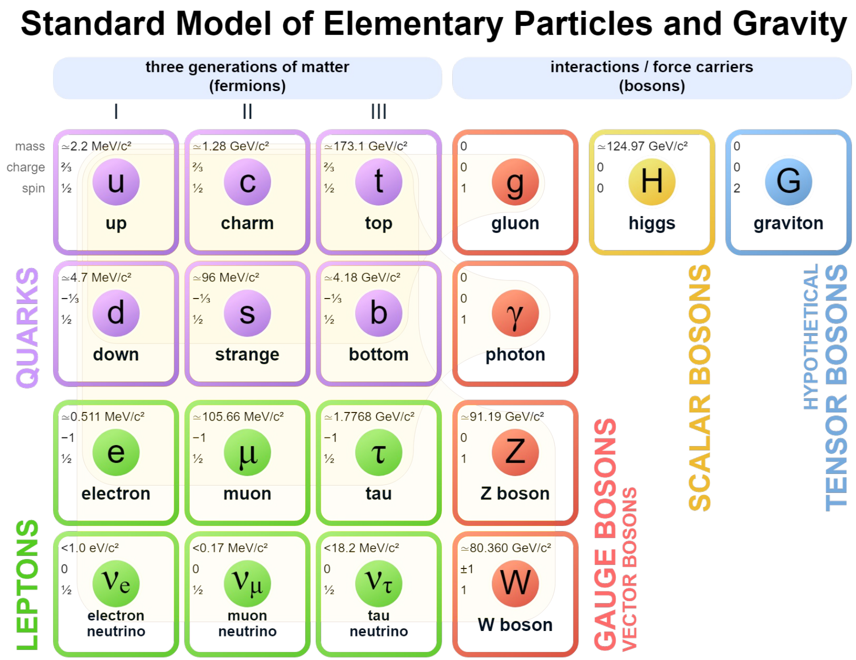


$$\Omega_{\rm DM} h^2 = 0.120 \pm 0.001$$

Relative abundance + speed distribution

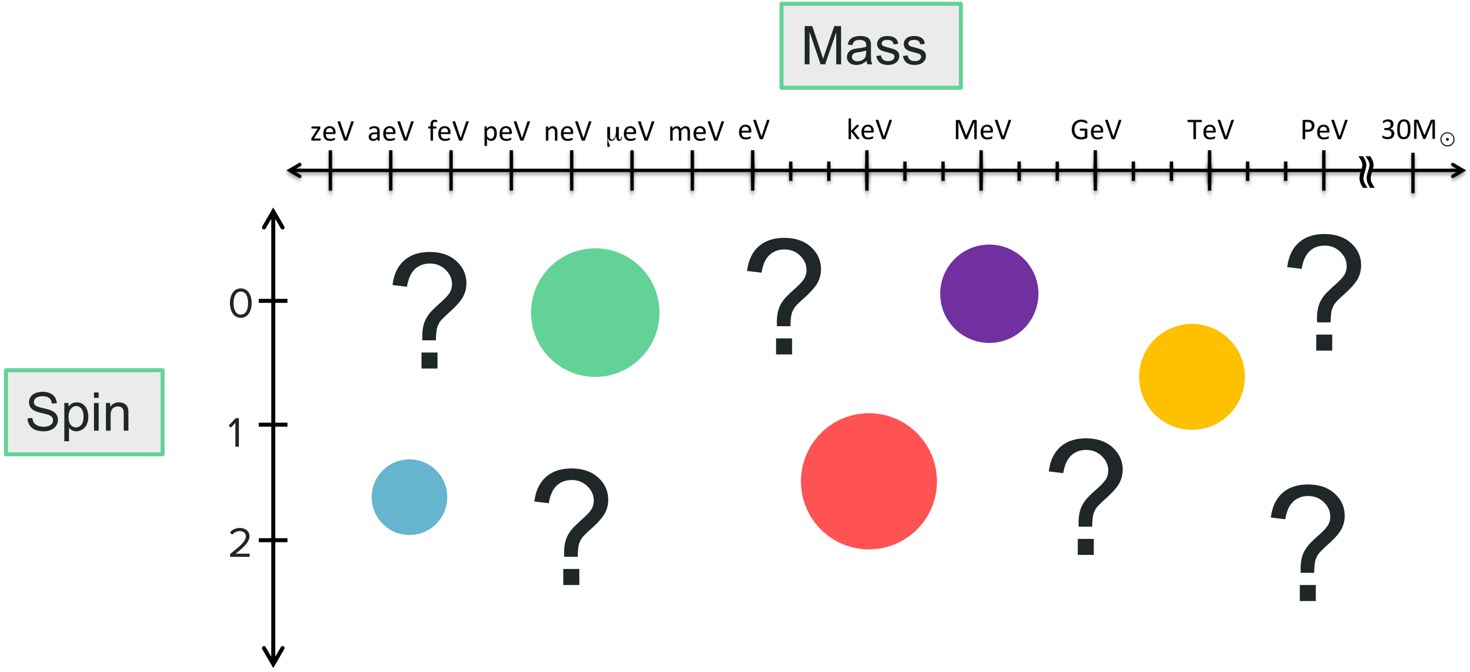


What we don’t

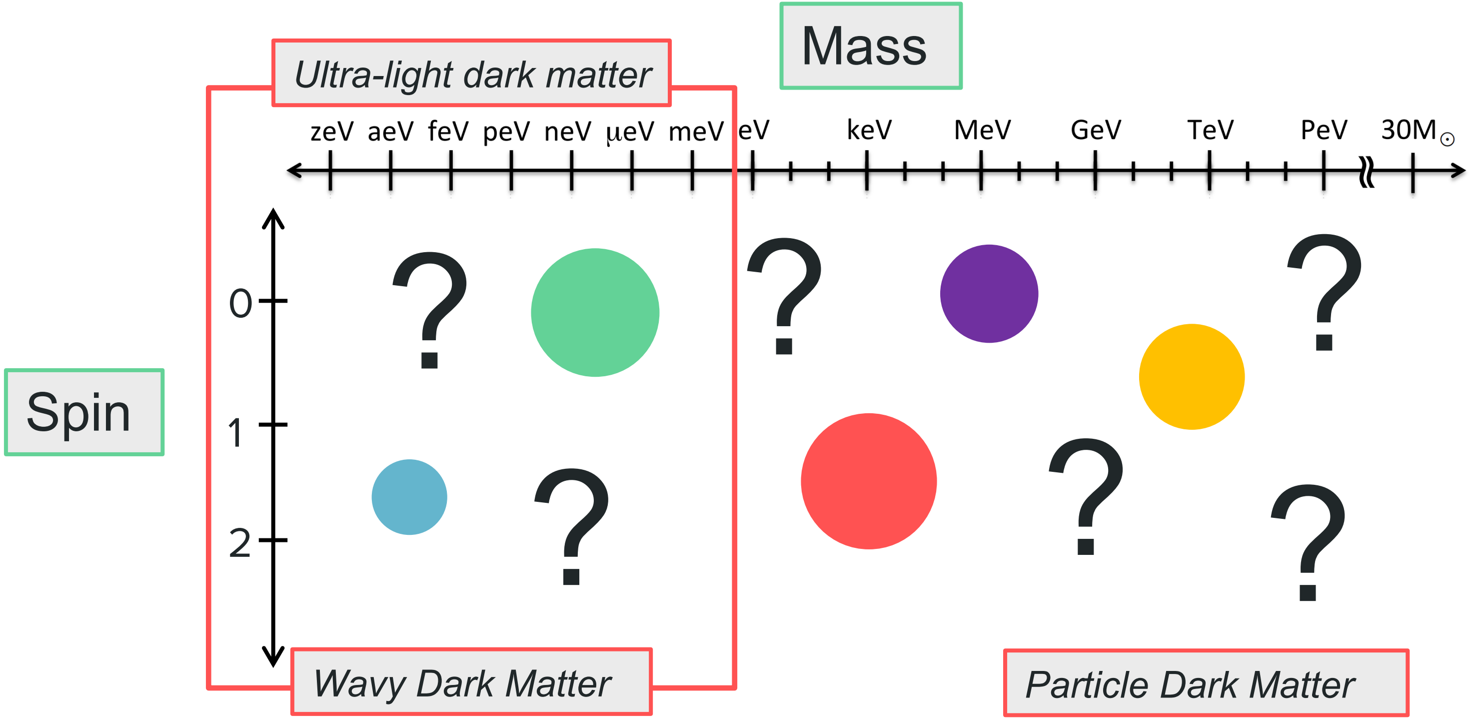


Spin = ?
Mass = ?
Parity = ?
Charge = ?
Interactions with SM = ?
Production mechanism = ?

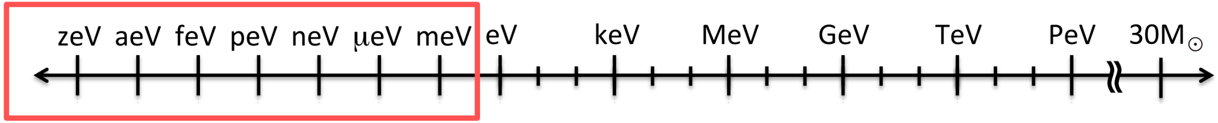
A lot of parameter space!



A lot of parameter space!



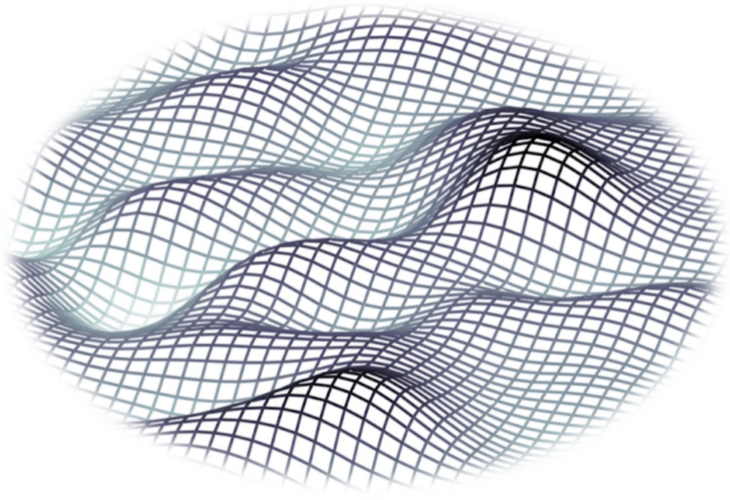
We live in a ULDM bath



Ultralight mass means a high occupation number

Can describe as a classical field

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



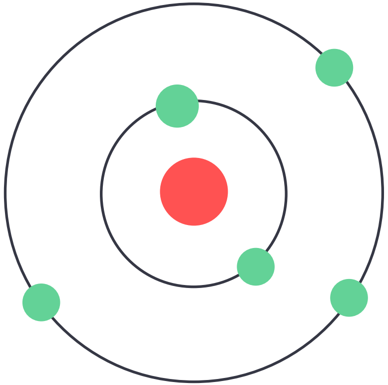
Frequency given by ULDM mass
(with small velocity correction)

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

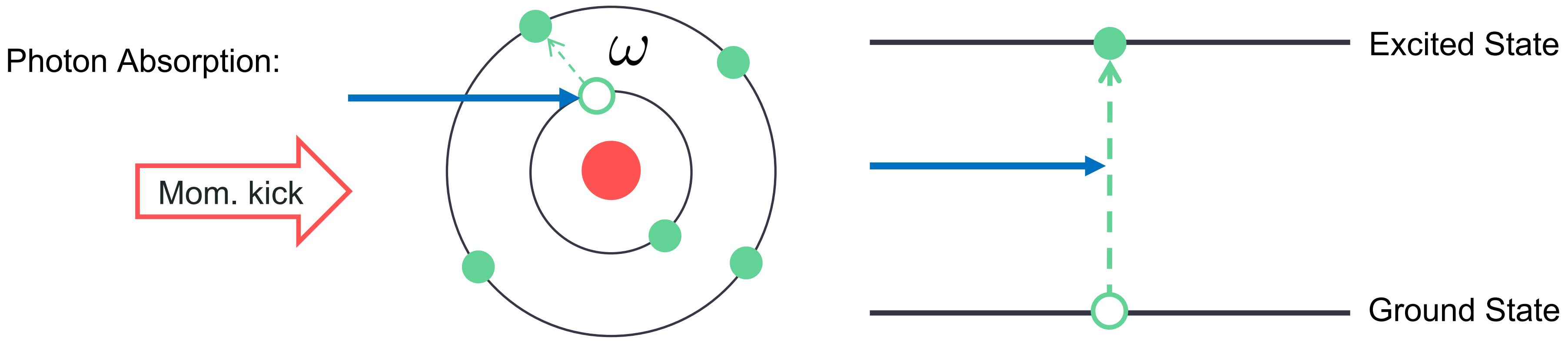
Badurina et al. arxiv: 2109.10965

If I’m bathing in this stuff, surely I can find it?

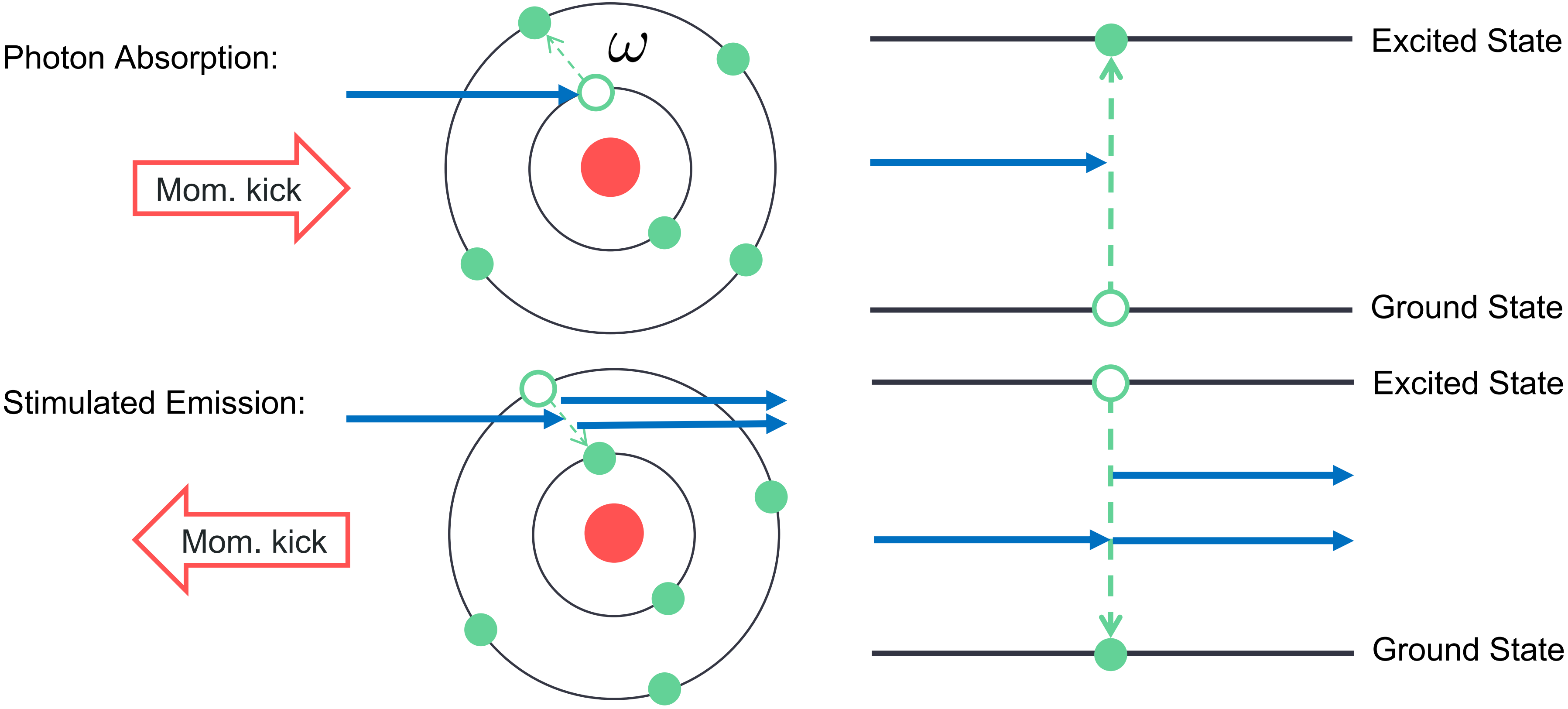
Consider a 2-level atom



Consider a 2-level atom

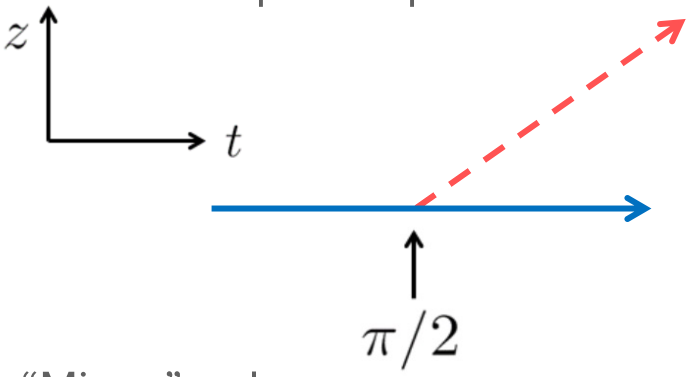


Consider a 2-level atom

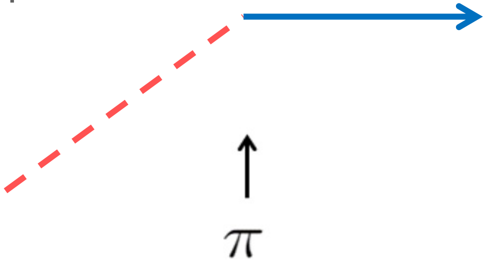


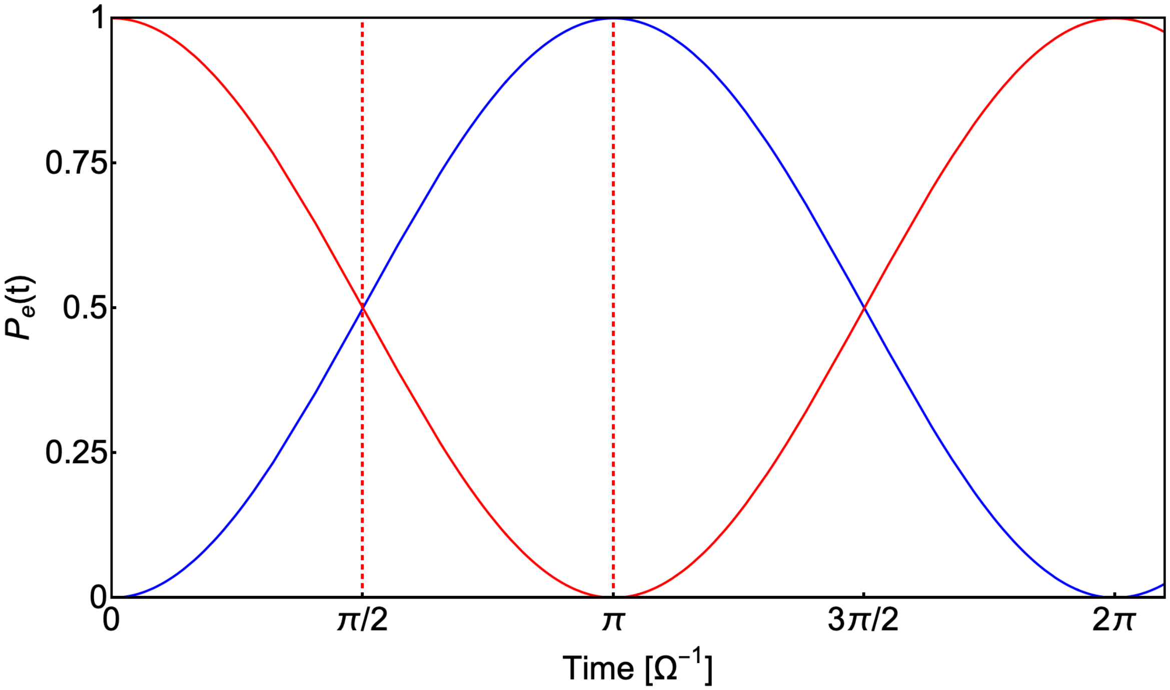
Rabi oscillations

"Beam-splitter" pulse:

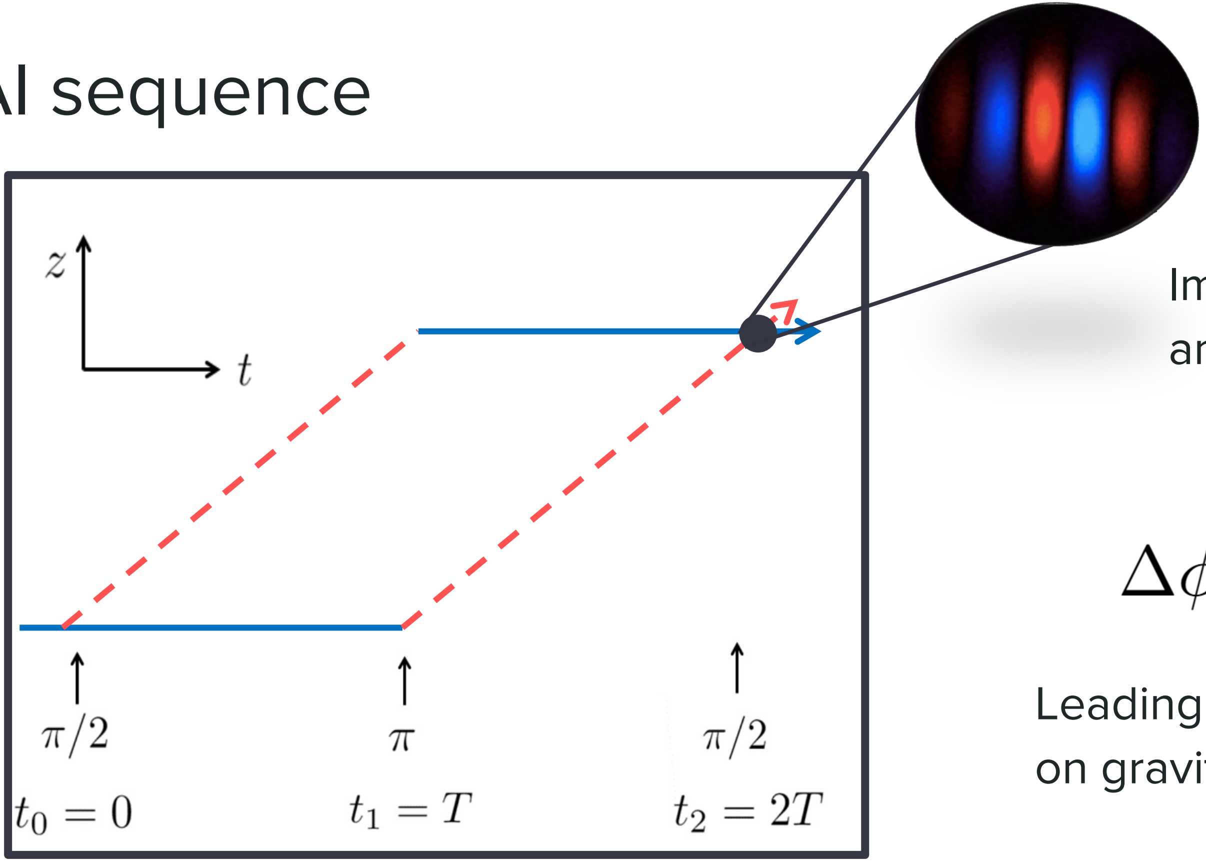


"Mirror" pulse:





AI sequence



Mach-Zehnder interferometer

Image atom fringes and measure phase

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

Leading order phase depends on gravitational acceleration

What can we measure?

$$\phi = kgT^2$$

Atom-light interactions

Gravitational field

Time

Back to the bath:

$$\mathcal{L} \supset \mathcal{L}_{\mathrm{SM}} + \boxed{\mathcal{L}_\phi}$$

photon coupling

electron coupling

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

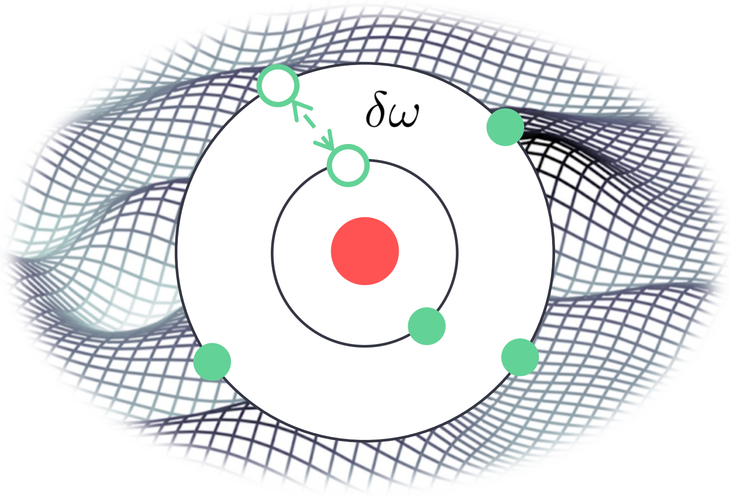
Linear interactions between SM and ULDM

Causes small oscillations in electron mass and fine-structure constant

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

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

Changes atomic transition energy and can be seen in phase measurements!



Badurina et al. arxiv: 2109.10965

Higher-spin ULDM

Spin-1?

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

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

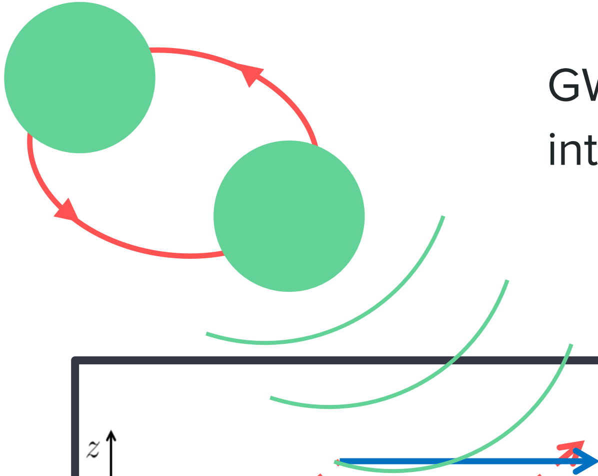
Probe with a dual-species interferometer

Spin-2?

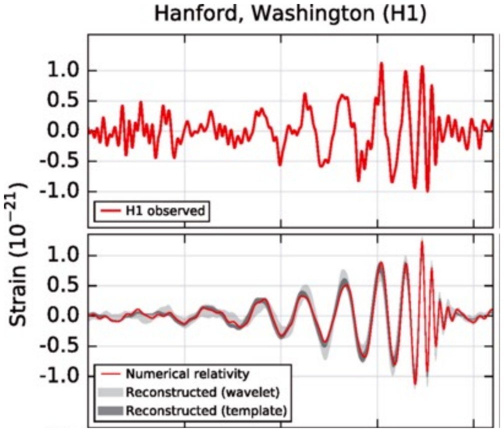
$$\mathcal{L}_\varphi \supset \frac{\alpha}{M_{\rm Pl}} \varphi_{\mu\nu} T^{\mu\nu}_{\rm m}$$

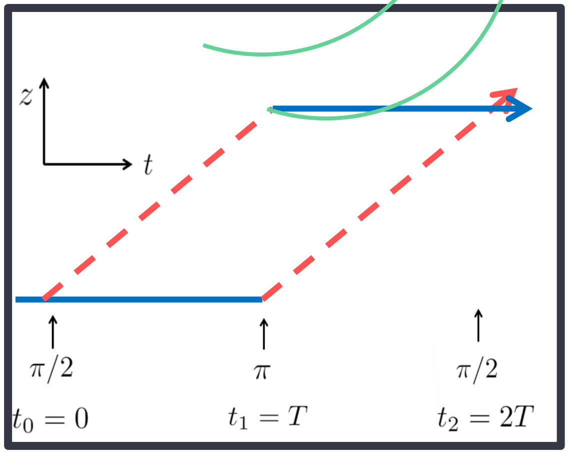
‘Dark graviton’ like particles may interact with Standard Model masses

Gravity just like LIGO

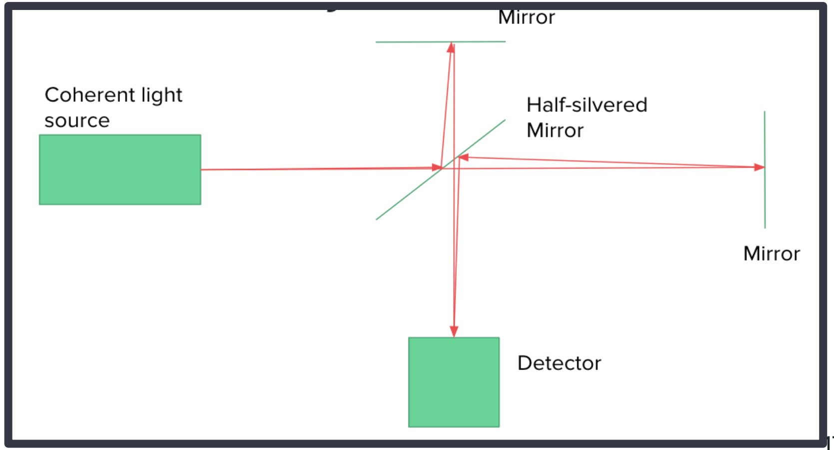


GWs change path length of interfering atoms and lasers!





$$h = \frac{\delta L}{L}$$

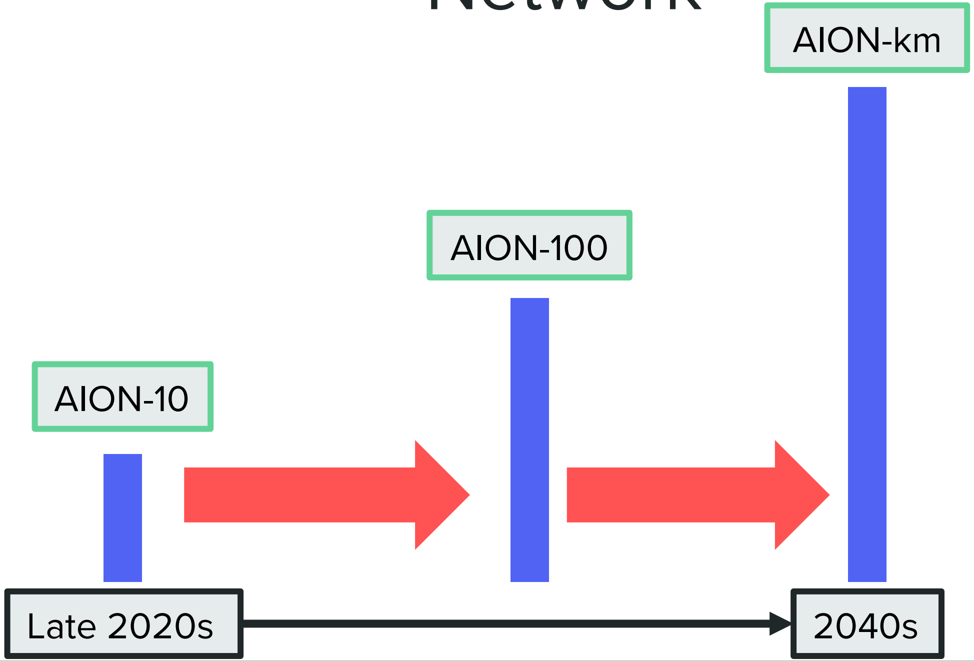


Who’s looking for it?

arXiv: 1911.11755

AION

Atom Interferometer Observatory and Network



The AION-10 Experiment

University of Oxford, Beecroft Building

arXiv: 1911.11755

AION

Atom Interferometer Observatory and Network

arXiv: 1911.11755

AION

Atom Interferometer Observatory and Network

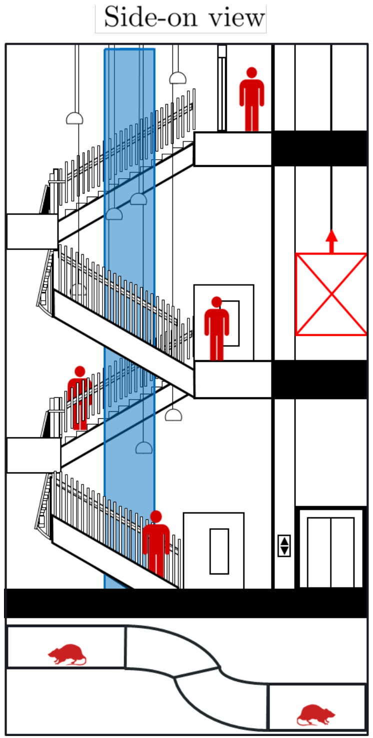
All these people are a problem!

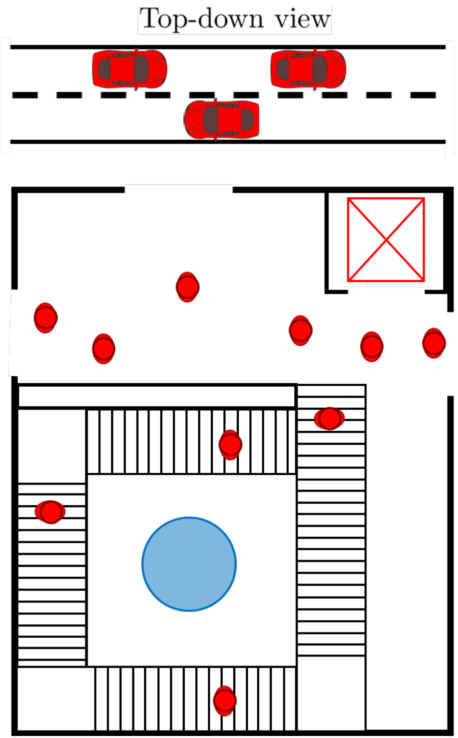
Anthropogenic and synanthropic noise

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)



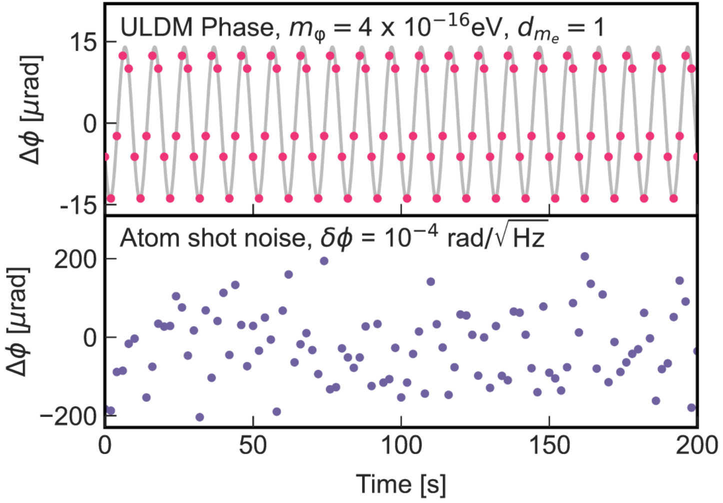


Beecroft building, University of Oxford

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

An ideal ULDM search

Signal and shot noise



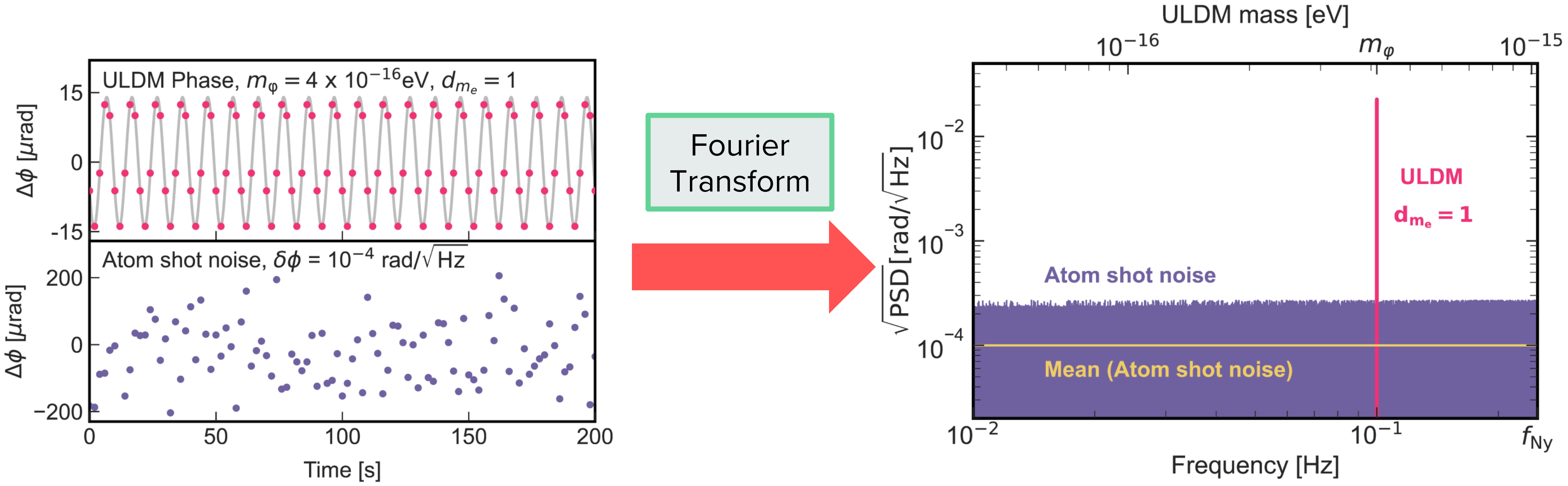
ULDM induces a small oscillating signal.

$$\Delta\phi(t) \sim \varphi(t) \sim \cos(\omega_\varphi t)$$

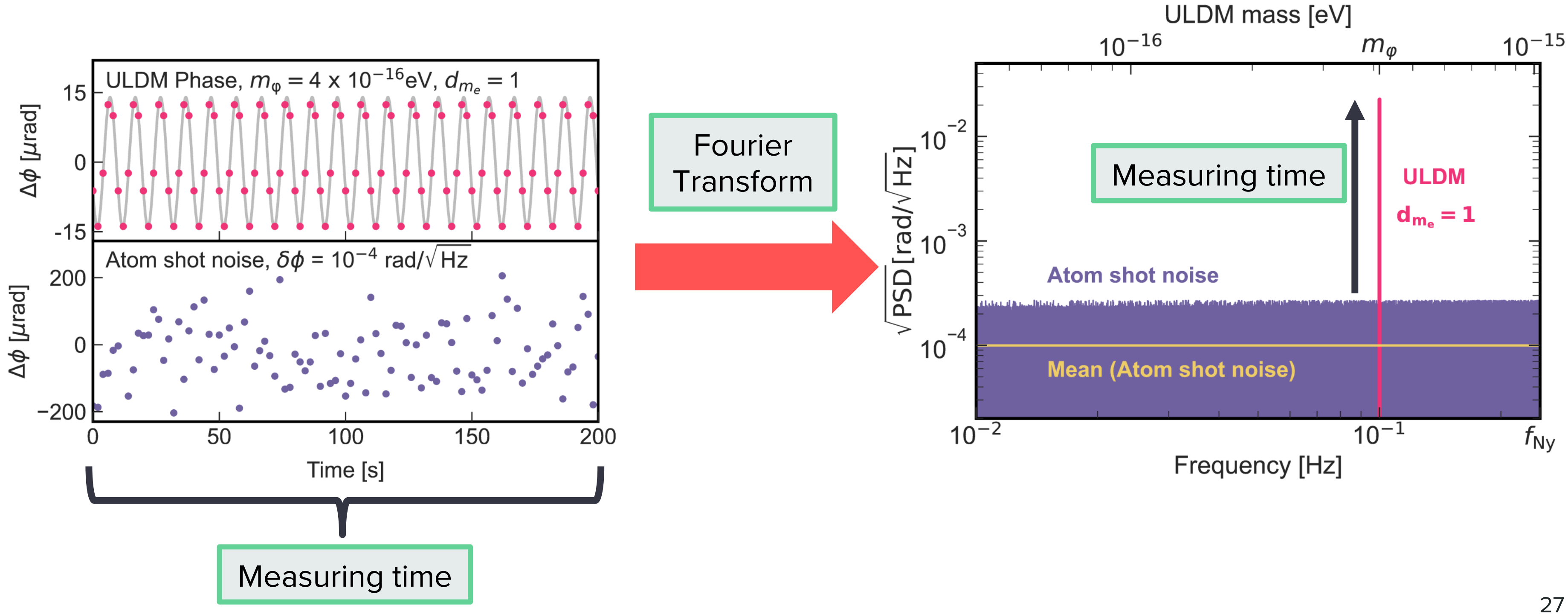
Atom shot noise simulated by sampling a Gaussian distribution.

$$\delta\phi \sim \frac{1}{\sqrt{N_{\text{atom}}}}$$

Features of the PSD

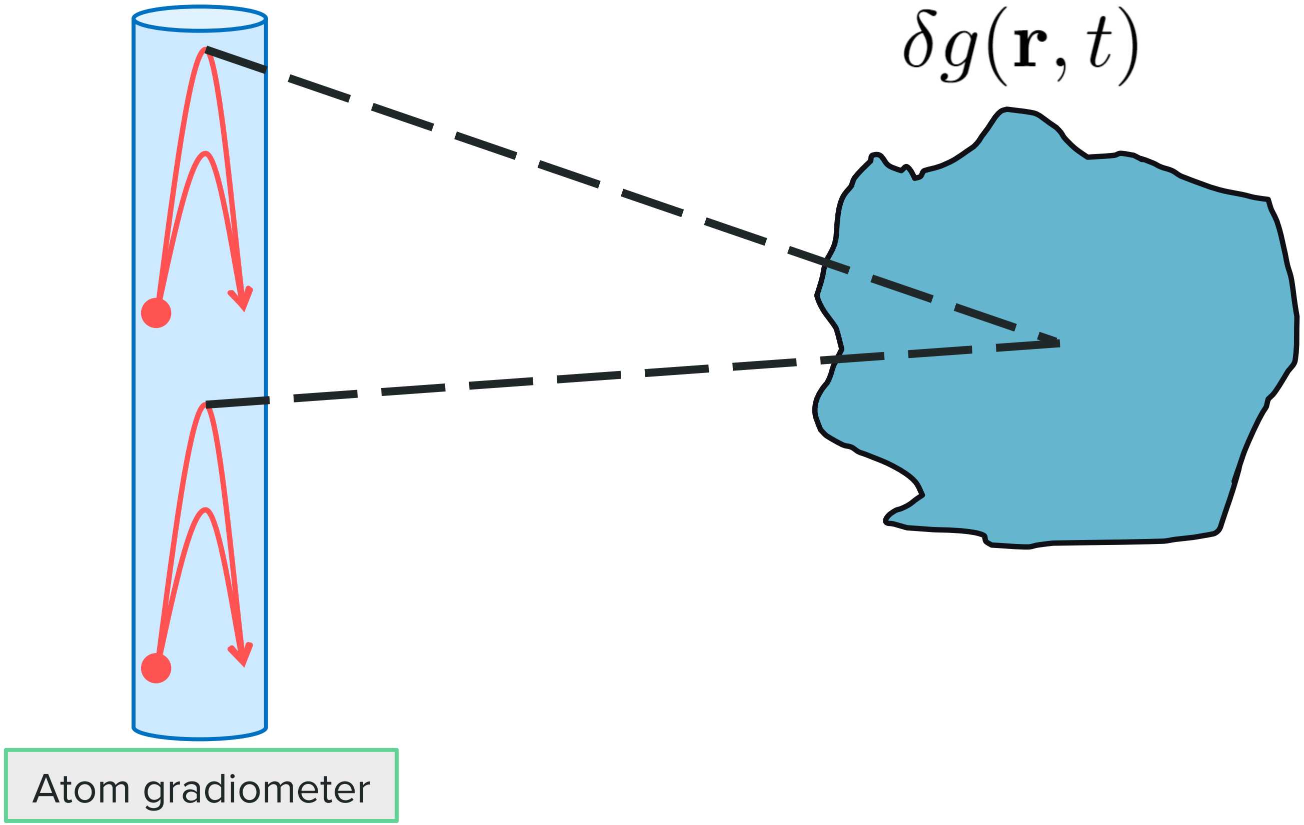


Features of the PSD

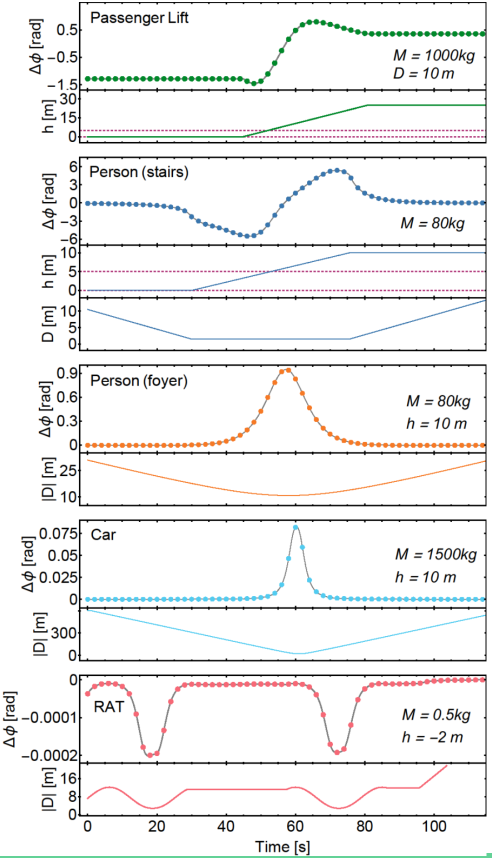


Identifying the enemy

Gravity gradient noise

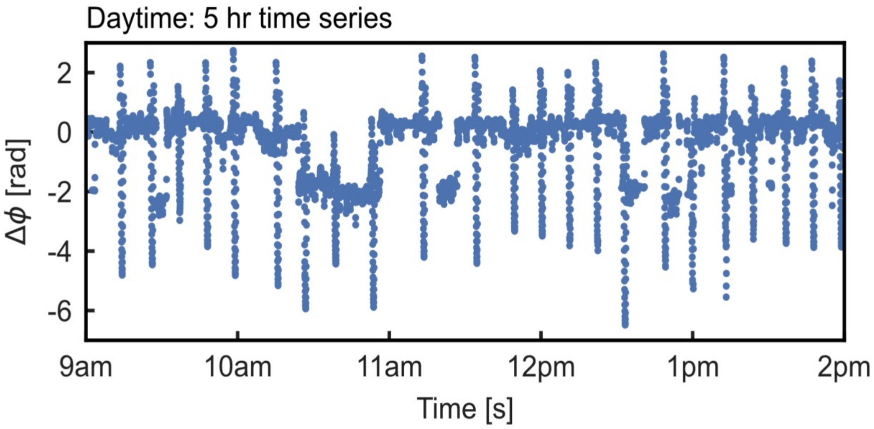


Simulating anthropogenic and synanthropic noise



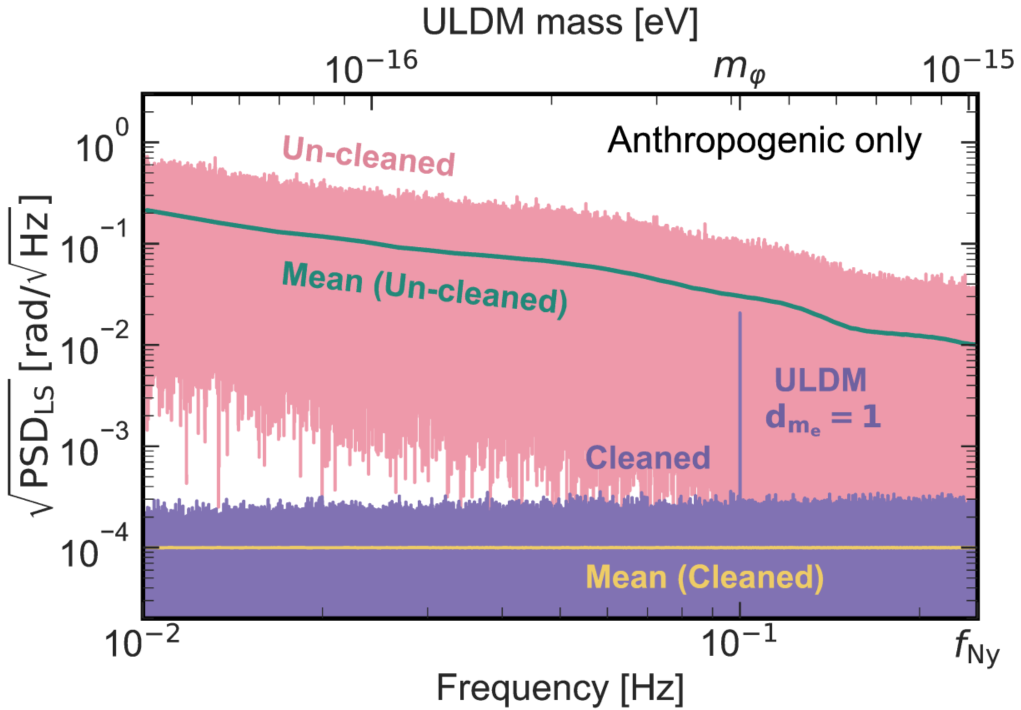
Calculate the phase induced by the presence of these masses.

Then simulate long periods of data taking over 1 year.



The ULDM signal is hidden by all of this noise.

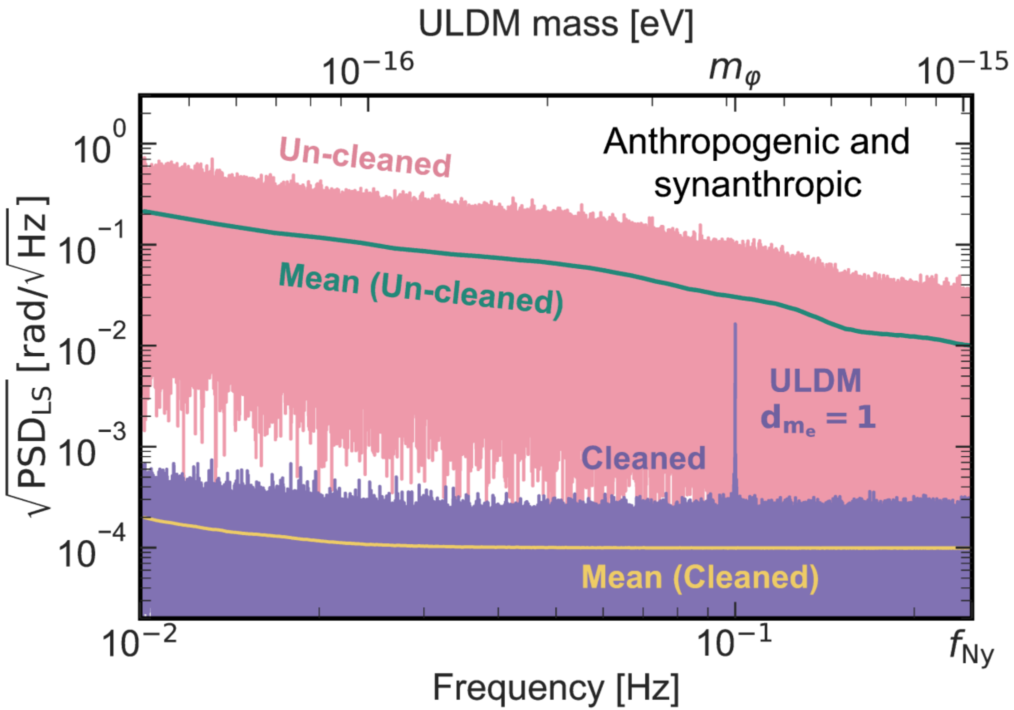
A lot of noise! But can be cleaned...



Unmasked analysis shows the impact from anthropogenic sources.

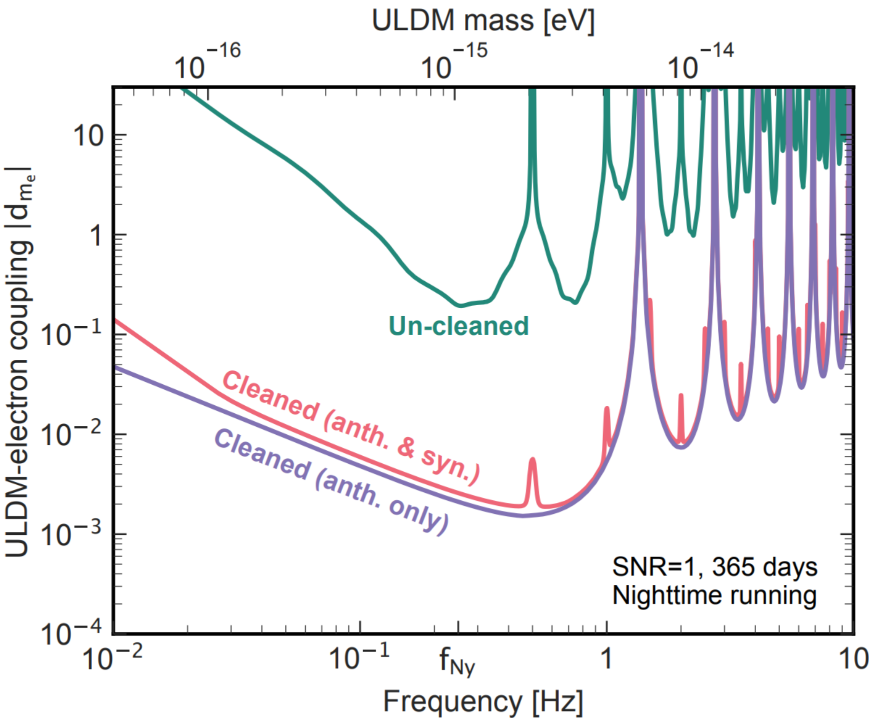
Masked analysis cuts large phase shifts from the time series to recover the shot noise + ULDM spike expected.

The danger of RATs!



Small signals may slip through the cleaning!

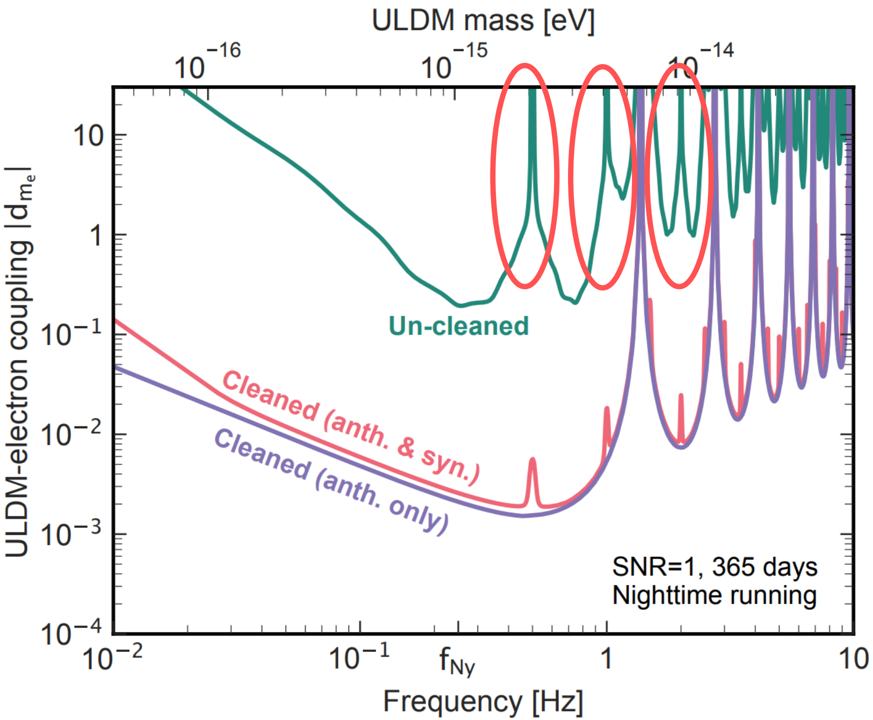
Recovering limits



Take average of many noise simulations to set new limits on detecting ULDM.

The masking method recovers much of the lost parameter space, comparable to the atom shot noise only case.

Recovering limits



Additional peaks arise from aliasing of the noise.

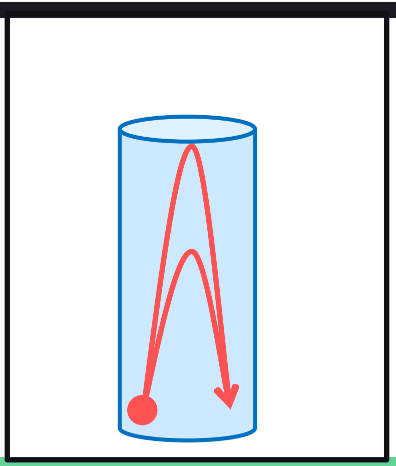
Masking removes these additional losses of sensitivity.

Ongoing and future battles

Pressure waves

$$\delta g(\mathbf{r}, t) \approx G \int dV \; \delta\rho(\mathbf{r}, t) \frac{\mathbf{r}}{|\mathbf{r}|^3}$$

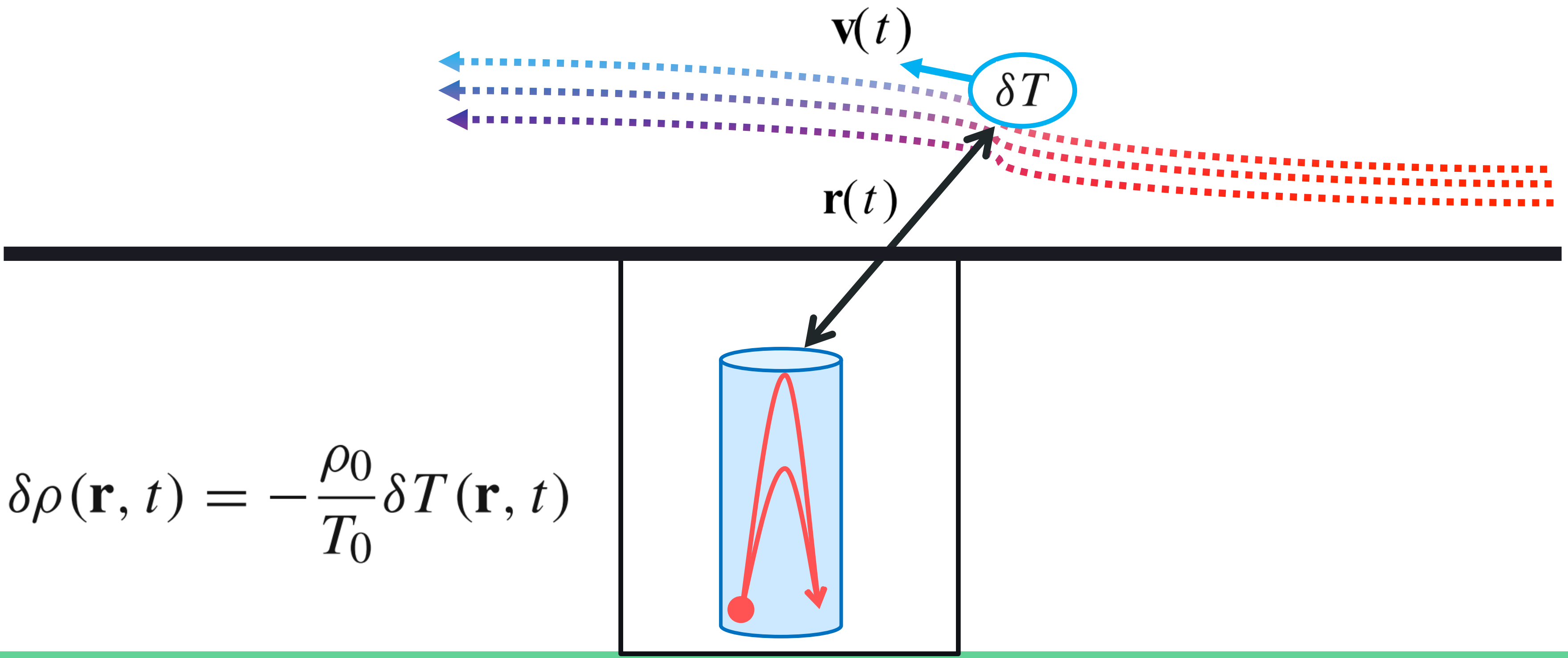
Pressure waves in the air propagating and reflecting off the ground.



Rayleigh seismic waves travelling along boundaries in the ground.

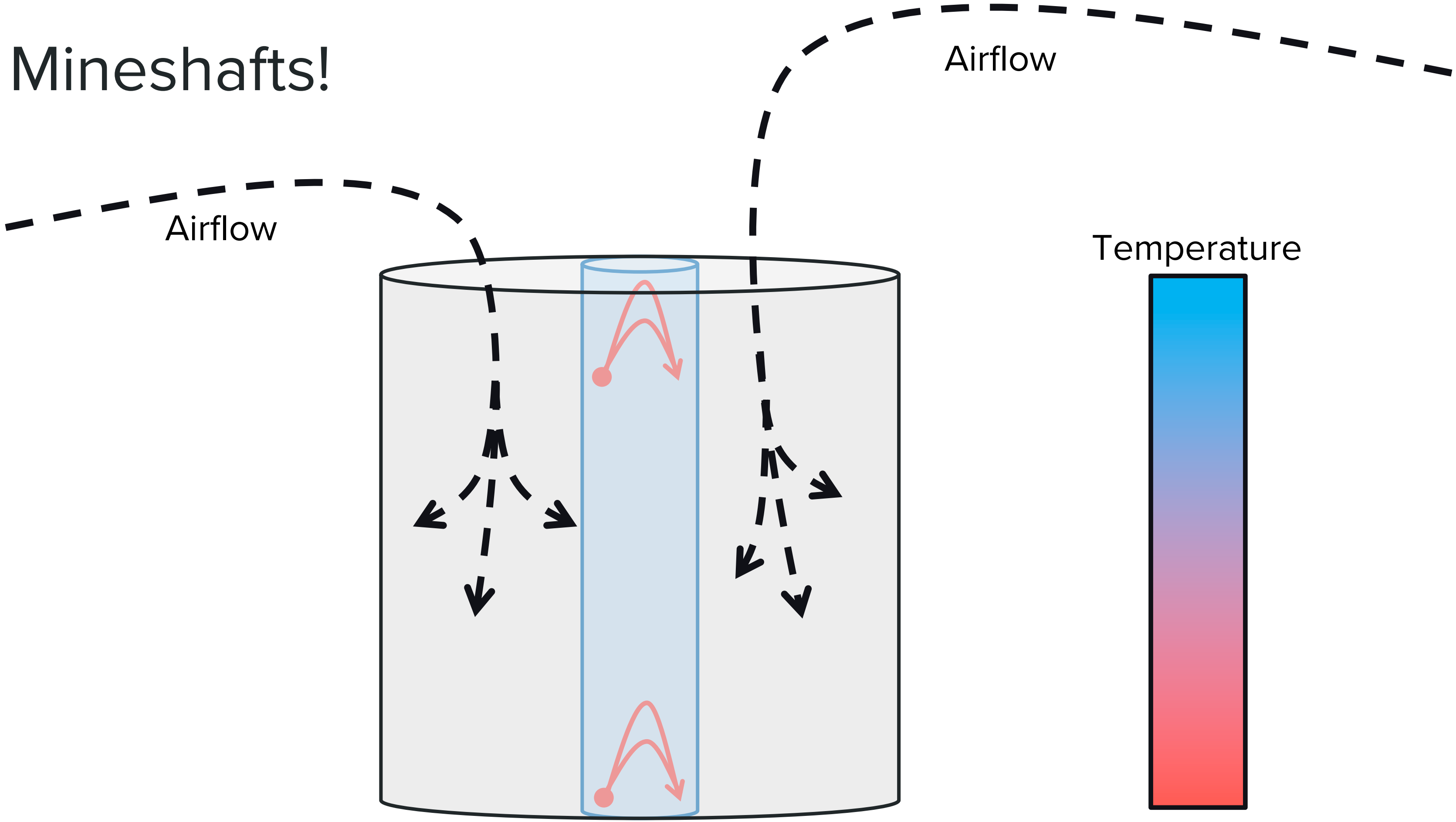
$$\gamma \frac{\delta\rho(\mathbf{r}, t)}{\rho_0} = \frac{\delta p(\mathbf{r}, t)}{p_0}$$

Temperature perturbations



$$\delta\rho(\mathbf{r},t) = -\frac{\rho_0}{T_0}\delta T(\mathbf{r},t)$$

Mineshafts!



Based on: Phys.Rev.D (108, 123004); arXiv: 2308.10731 [astro-ph.CO]

Summary

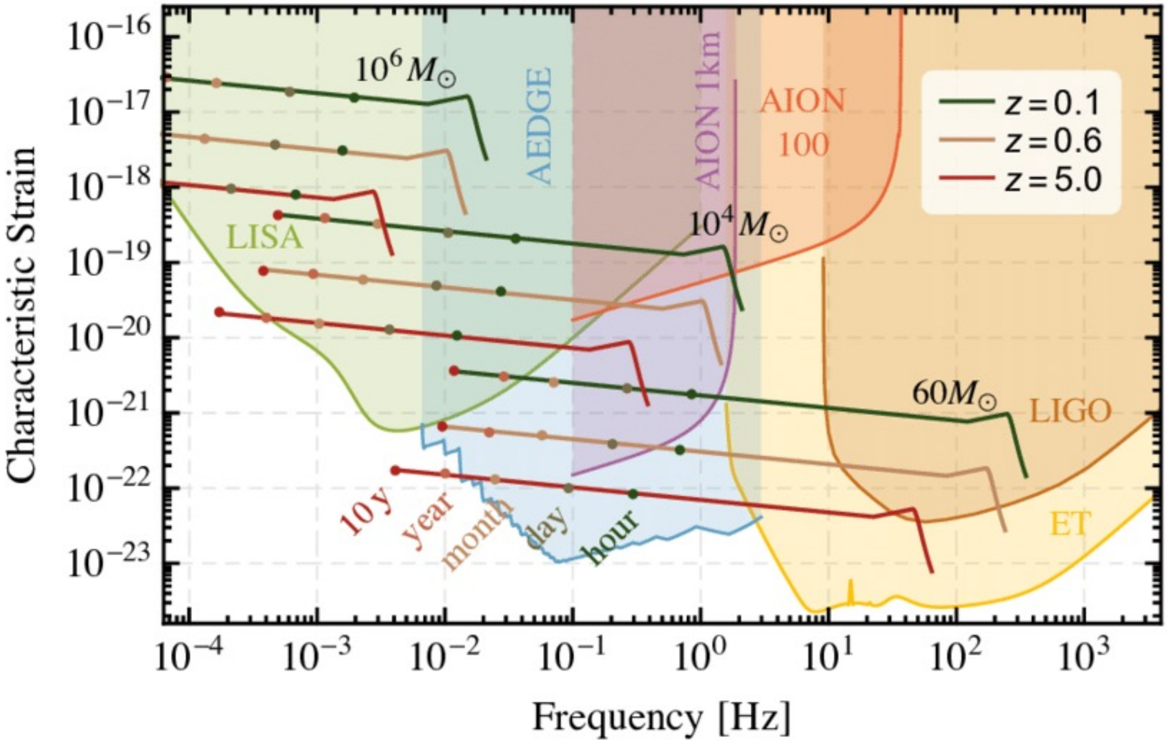
AION is an upcoming atom interferometer experiment, using exquisite quantum sensors for detecting ultralight dark matter and gravitational waves.

Gravity gradient noise from seismic/atmospheric/human/animal sources are a problem to be battled, obscuring potential ULDM signals in frequency space.

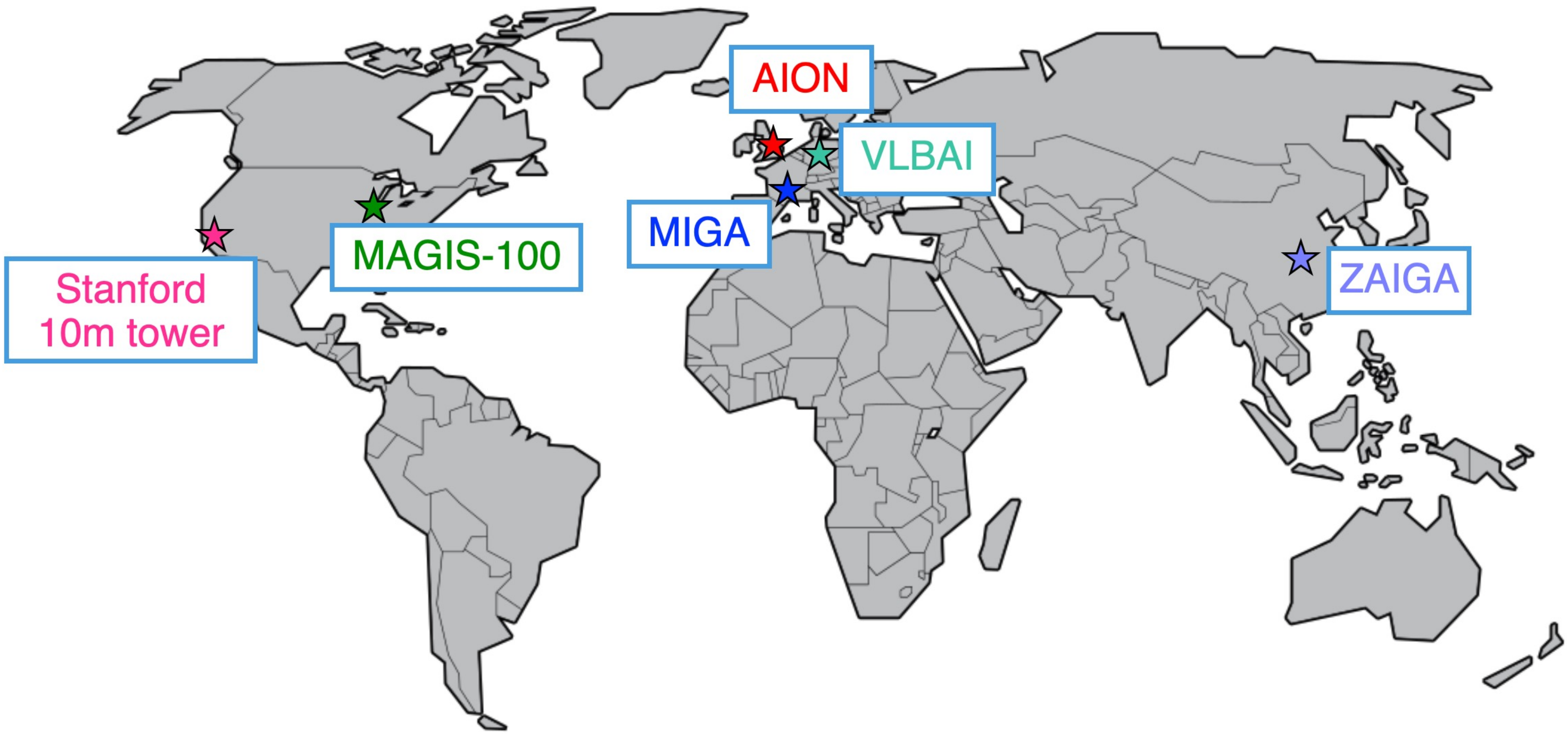
More work to be done on different ULDM models and characterising site-specific noise sources.

Backup

Mid-frequency GWs



New atom interferometers across the world coming online

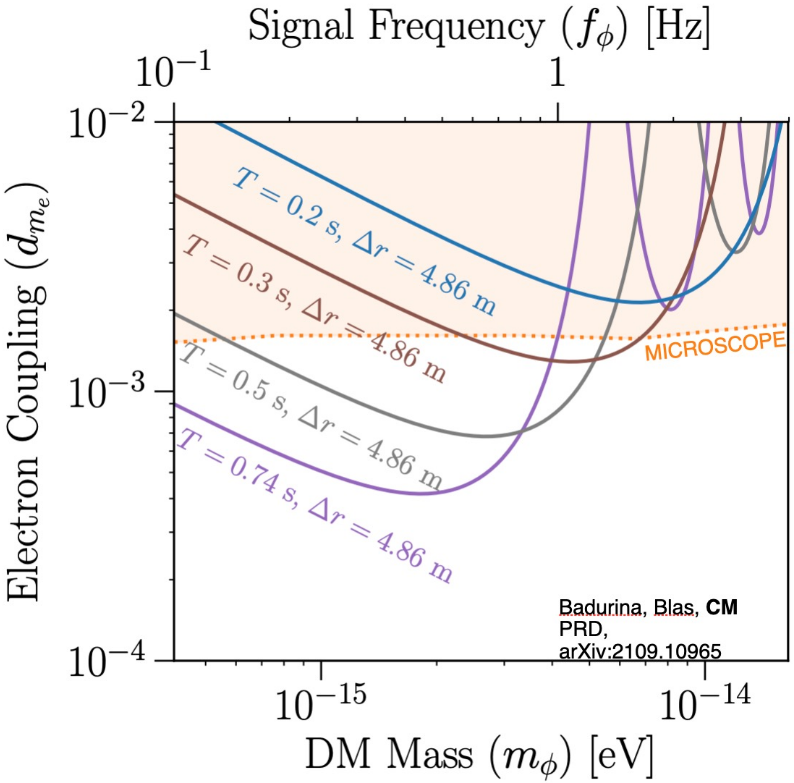


AION-10 sensitivity projections

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

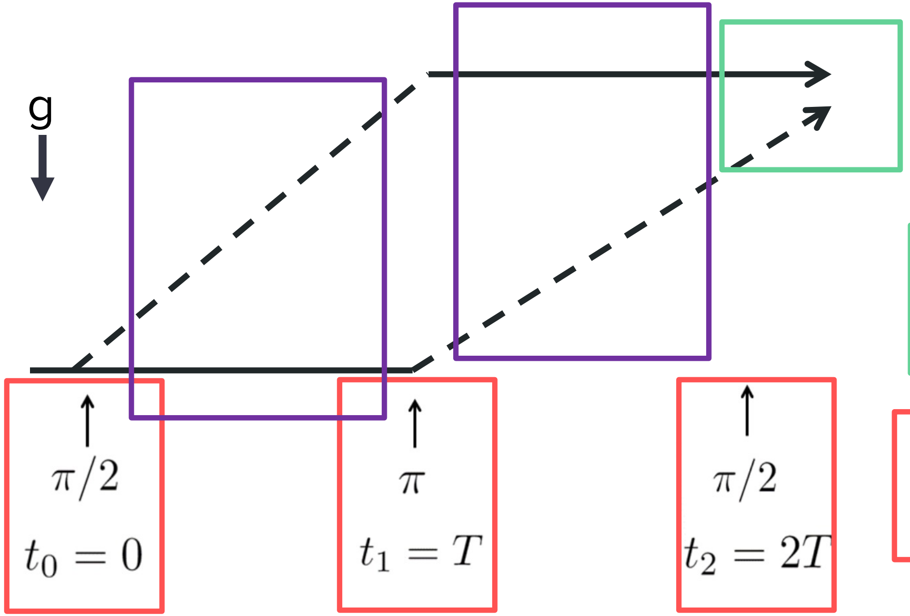
Handles to optimise (in order of priority):

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)



Phase shifts

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



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

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

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

Bi-gravity

So why not two gravitons!

Bi-metric action

Extend GR with two metrics, *g* and *f*

$$S_g = \frac{1}{2\kappa_g^2}\int d^4x\sqrt{-g}R^{(g)} + \frac{1}{2\kappa_f^2}\int d^4x\sqrt{-f}R^{(f)} + \frac{m^2}{\kappa^2}\int d^4x\mathcal{L}_{\rm int}[g_{\mu\nu}, f_{\mu\nu}]\,,$$

g is ordinary massless gravity, and *f* is ULDM a 'fifth force' effect

$$\kappa^2 := \kappa_g^2 + \kappa_f^2$$

Gravitational constants

$$\alpha := \frac{\kappa_g}{\kappa_f} \qquad \alpha \sim \sqrt{G_{\rm N}}$$

Coupling strength of the massive field

Manita et al. arxiv: 2211.15873

Bi-gravity

$$e^{+}_{ij}(\hat{\mathbf{n}}) = \hat{\mathbf{u}}_i\hat{\mathbf{u}}_j - \hat{\mathbf{v}}_i\hat{\mathbf{v}}_j \,, \qquad e^{\times}_{ij}(\hat{\mathbf{n}}) = \hat{\mathbf{u}}_i\hat{\mathbf{v}}_j + \hat{\mathbf{v}}_i\hat{\mathbf{u}}_j \,,$$

Polarisation vector

Model spin-2 field, summing over the polarisations

$$\varphi_{ij} = \sum_\lambda \varphi_{0,\lambda} e^\lambda_{ij} \cos(\omega t - \boldsymbol{k}\cdot\boldsymbol{x} + \delta_\tau(t))$$

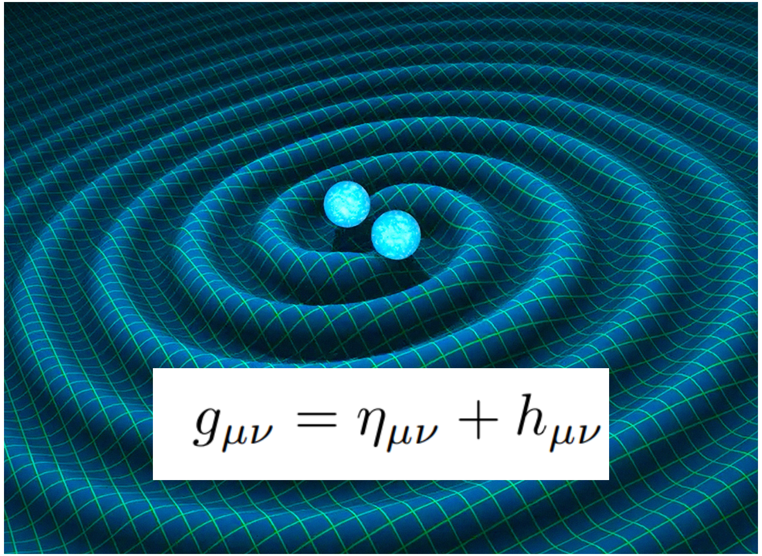
Signal in GW detectors can be found by considering strain induced from fluctuations around the metric

$$g_{\mu\nu} = \eta_{\mu\nu} + \frac{h_{\mu\nu}}{M_{\rm Pl}} + \frac{\varphi_{\mu\nu}}{M_G}$$

$$\langle h^2 \rangle \sim \frac{\alpha^2 f_g \rho_{\rm DM}}{M_{\rm Pl}^2 M^2}$$

We're actually searching for GWs!

Expand Einstein equations around flat space



In the transverse-traceless gauge, treat the GWs with only two polarisations

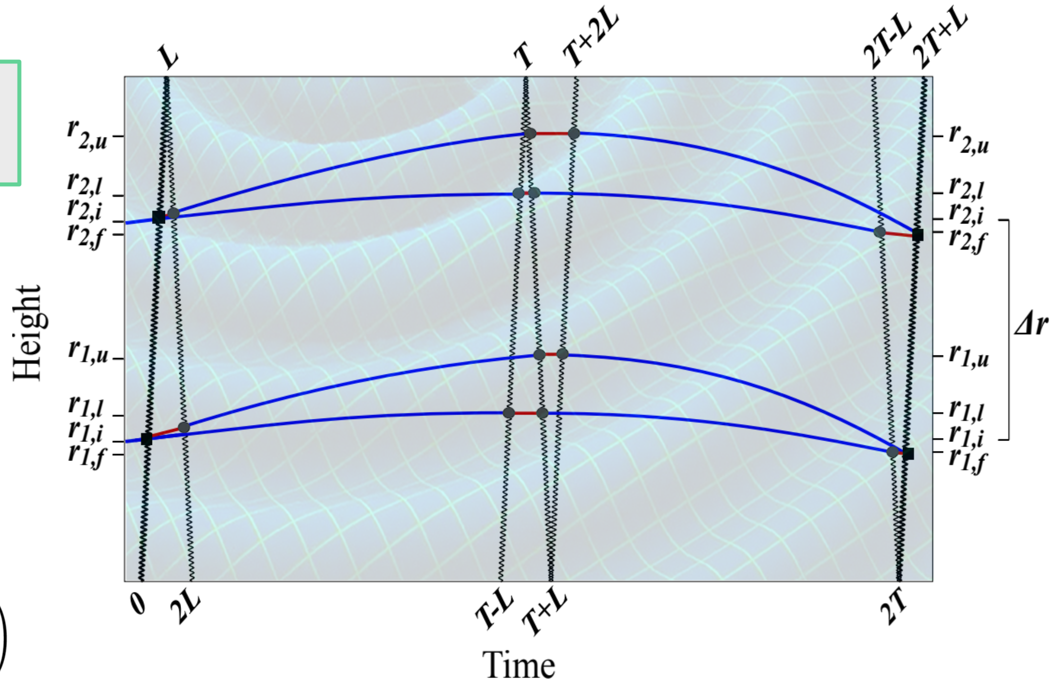
$$h_{ij}^{TT}(t,z) = \begin{pmatrix} h_+ & h_\times \\ h_\times & -h_+ \end{pmatrix}_{ij} \cos[\omega(t - z/c)]$$

Strain in an atom interferometer

Oscillating strain affects laser propagation, imprinting phase on the atoms

$$h \sim \frac{\delta l}{l} \sim \frac{\delta t}{t}$$

$$\Delta\bar{\Phi}_s = nk\Delta r h \frac{\sin(\omega T)}{\cos(\omega T/2)} \operatorname{sinc}\left(\frac{\omega n L}{2c}\right) \times \sin\left(\frac{\omega T}{2} - \frac{\omega(n-1)L}{2c}\right)$$



Detector response

$$h_{ij}^{TT}(t,z) = \begin{pmatrix} h_+ & h_\times \\ h_\times & -h_+ \end{pmatrix}_{ij} \cos[\omega(t - z/c)]$$

$$h(t) = D^{ij} h_{ij}(t)$$

Detector tensor contains information about orientation of GW ‘antennas’

Define detector pattern functions

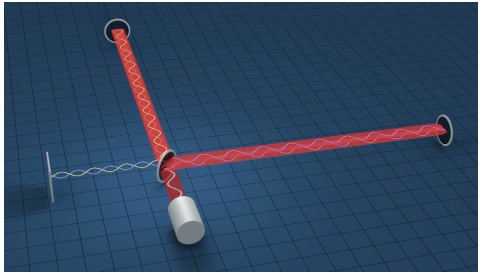
$$F_\lambda(\hat{\boldsymbol{n}}) = D^{ij} e_{ij}^{\lambda}(\hat{\boldsymbol{n}})$$

$$h(t) = h_+(t) F_+(\theta,\phi) + h_\times(t) F_\times(\theta,\phi)$$

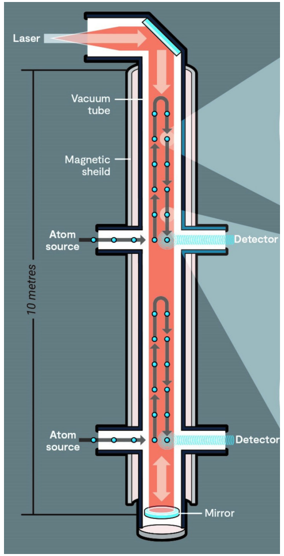
Detector response

$$h(t) = h_+(t)F_+(\theta,\phi) + h_\times(t)F_\times(\theta,\phi)$$

Detector	$F_+(\theta,\phi;\psi=0)$	$F_\times(\theta,\phi;\psi=0)$	F
interferometers	$\frac{1}{2}(1+\cos^2\theta)\cos 2\phi$	$\cos\theta\sin 2\phi$	$2/5$
cylindrical bars	$\sin^2\theta$	0	$8/15$



$$\langle h^2\rangle = \frac{\boxed{2}\alpha^2 f_g \rho_{\rm DM}}{\boxed{5}M_{\rm Pl}^2 M^2}$$



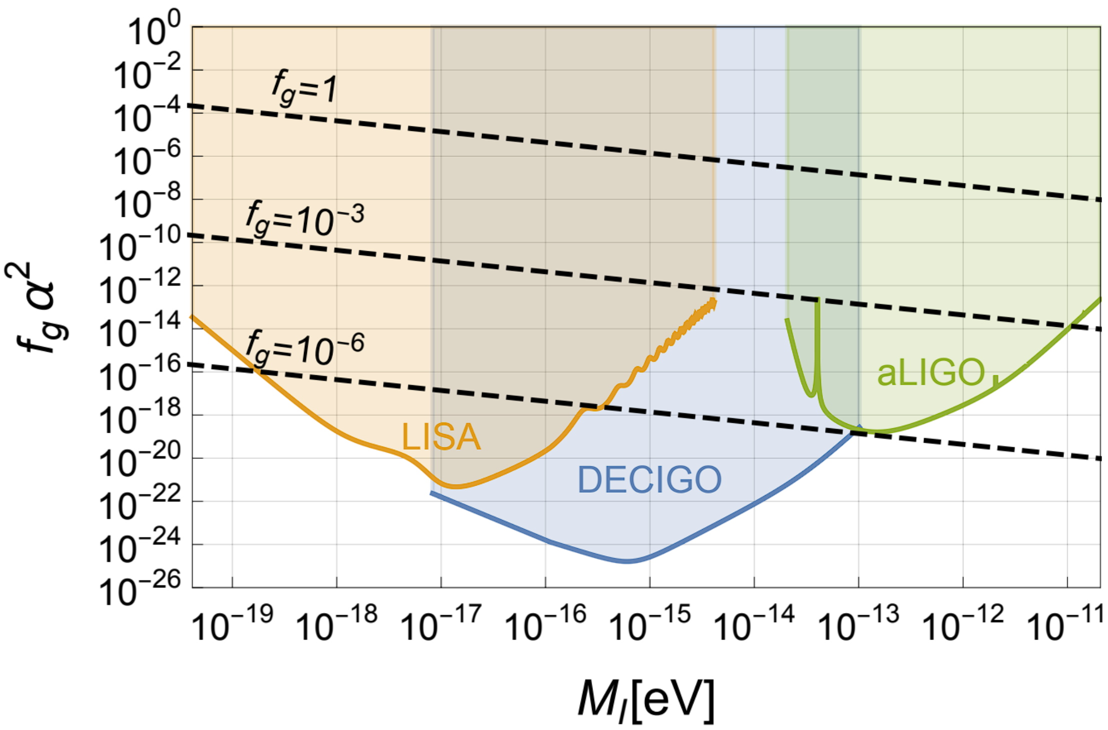
$$\langle h^2\rangle = \boxed{\frac{8}{15}}\frac{\alpha^2 f_g \rho_{\rm DM}}{M_{\rm Pl}^2 M^2}$$

M. Maggiore, *Gravitational Waves. Vol. 1: Theory and Experiments*

Detection limits

Limits have been calculated for laser interferometers

AION-10 may be sensitive to mid-band frequencies.



Manita et al. arxiv: 2211.15873

The power of networking

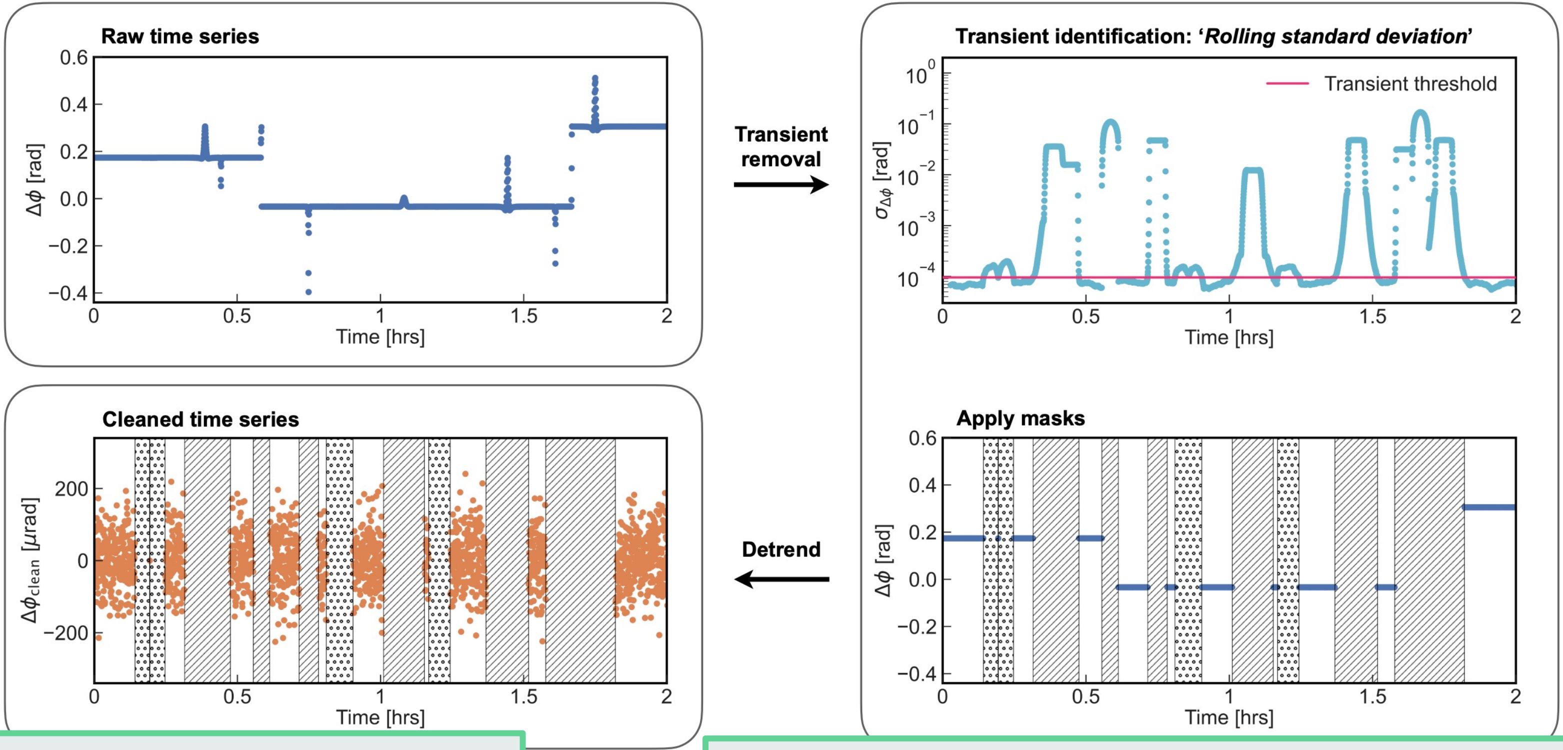
AION and MAGIS-100 are effectively co-located in the spin-2 ULDM field but measuring in different directions

$$\int_0^{2\pi} \frac{d\psi}{2\pi} F_+^2(\hat{\mathbf{n}};\psi) = \int_0^{2\pi} \frac{d\psi}{2\pi} F_\times^2(\hat{\mathbf{n}};\psi)$$

Usually average over angle ψ but with networking we can probe field in multiple directions independently

Data cleaning

Take differences of running average to find large changes in phase.



Cut sections of time series with large changes compared to atom shot noise.

Subtract the mean of uncut sections to recover the expected shot noise + ULDM signal with gaps.