Probing ultralight scalar field dark matter with GW interferometers

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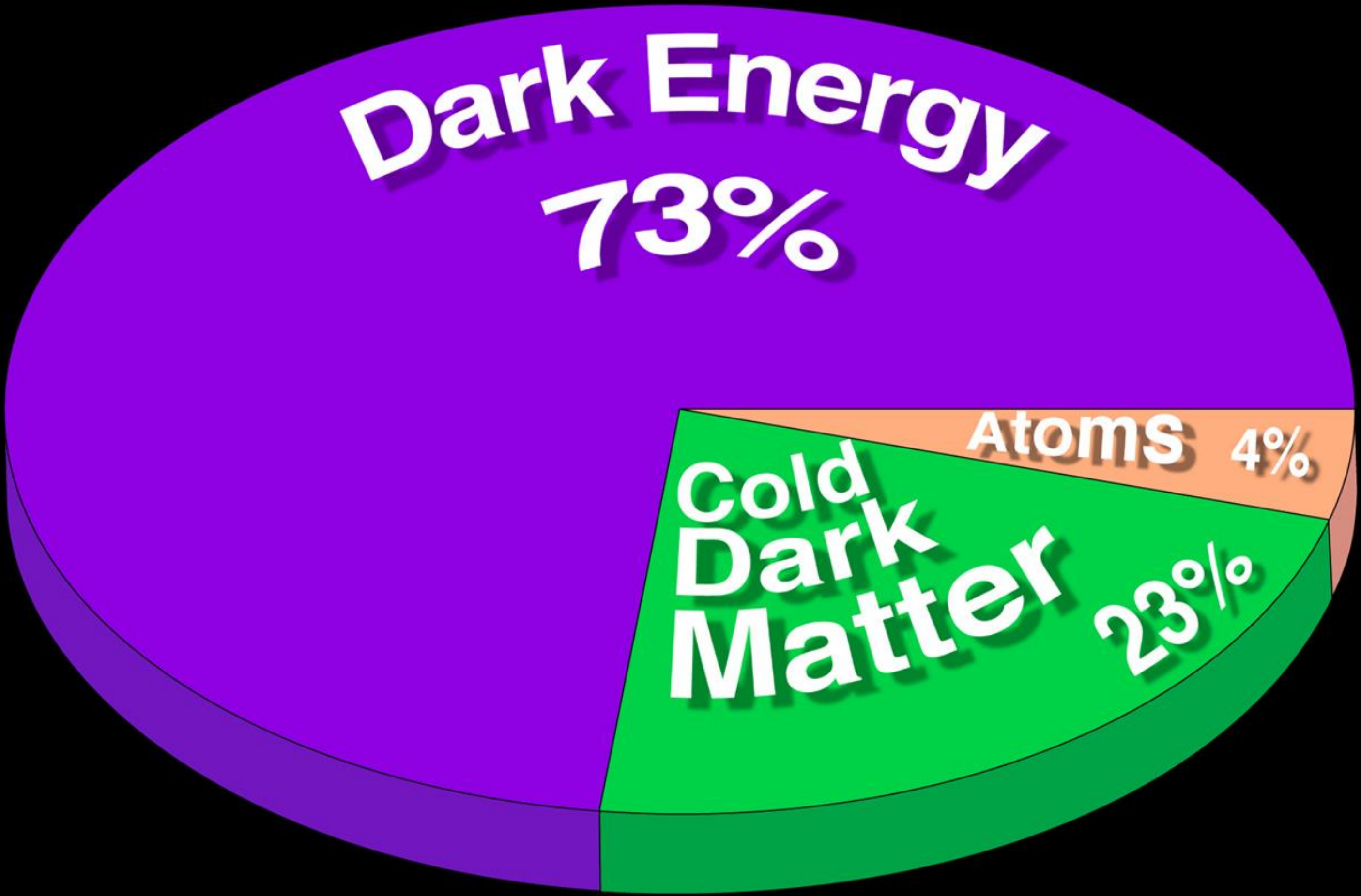
$\hbar = c = 1$



What is the nature of dark matter?

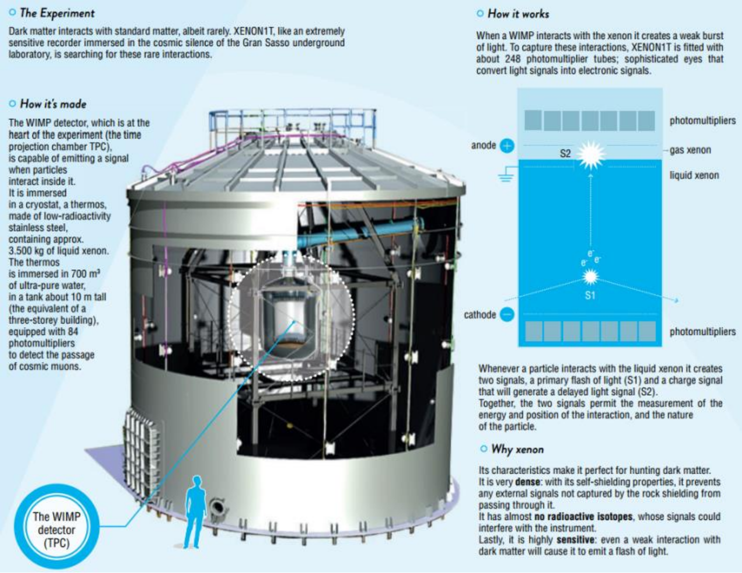
DM candidates

- Weakly interacting massive particles (WIMPs)
- Axion
- Strongly interacting particles
- Hidden photons
- Fuzzy dark matter
- Dilaton (light scalar field)
- Primordial black holes

etc.

Each has different properties.

Different experiments have different target.



The Experiment

Dark matter interacts with standard matter, albeit rarely. XENON1T, like an extremely sensitive recorder immersed in the cosmic silence of the Gran Sasso underground laboratory, is searching for these rare interactions.

How it's made

The WIMP detector, which is at the heart of the experiment (the time projection chamber TPC), is capable of emitting a signal when particles interact inside it. It is immersed in a cryostat, a thermos, made of low-radioactivity stainless steel, containing approx. 3.500 kg of liquid xenon. The thermos is immersed in 700 m³ of ultra-pure water, in a tank about 10 m tall (the equivalent of a three-storey building), equipped with 84 photomultipliers to detect the passage of cosmic muons.

How it works

When a WIMP interacts with the xenon it creates a weak burst of light. To capture these interactions, XENON1T is fitted with about 248 photomultiplier tubes; sophisticated eyes that convert light signals into electronic signals.

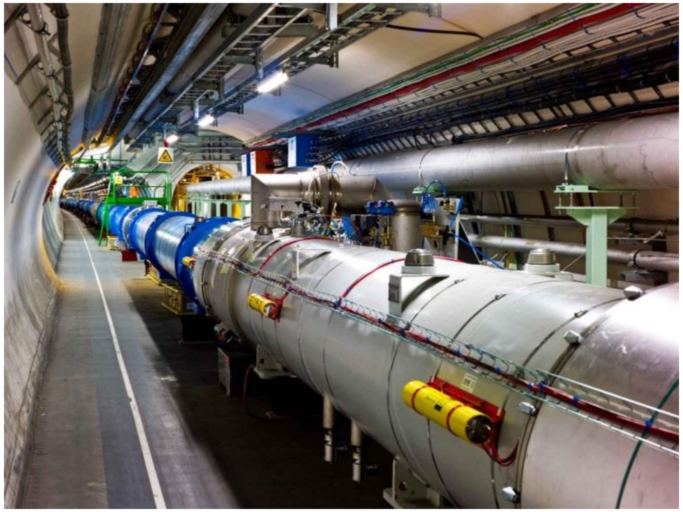
Whenever a particle interacts with the liquid xenon it creates two signals, a primary flash of light (S1) and a charge signal that will generate a delayed light signal (S2).
Together, the two signals permit the measurement of the energy and position of the interaction, and the nature of the particle.

Why xenon

Its characteristics make it perfect for hunting dark matter.
It is very **dense**: with its self-shielding properties, it prevents any external signals not captured by the rock shielding from passing through it.
It has almost **no radioactive isotopes**, whose signals could interfere with the instrument.
Lastly, it is highly **sensitive**: even a weak interaction with dark matter will cause it to emit a flash of light.

Xenon 1T

CAST



LHC

We have to consider various possibilities and propose many ideas.

Dawn of GW astronomy

We have gained a new tool to probe dark sector!!

Can we use GW interferometers to search dark matter?

YES!!

GW interferometers are useful to test weakly interacting light scalar field as dark matter.

Arvanitaki, Huang, Tilburg ‘15

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Searching for dilaton dark matter with atomic clocks

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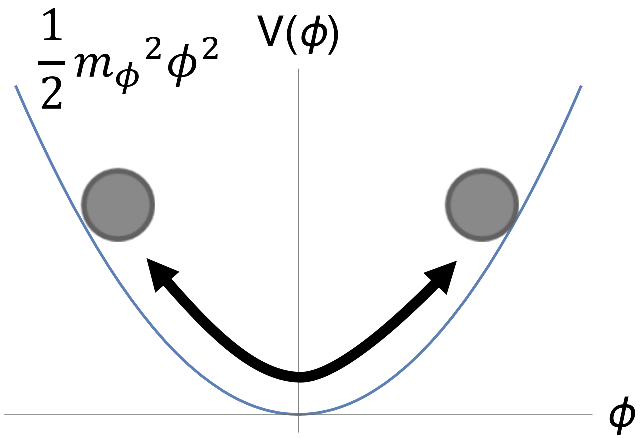
We propose an experiment to search for ultralight scalar dark matter (DM) with dilatonic interactions. Such couplings can arise for the dilaton as well as for moduli and axion-like particles in the presence of *CP* violation. Ultralight dilaton DM acts as a background field that can cause tiny but coherent oscillations in

- Motion of detectors
- More systematic calculation

Cosmic evolution of light scalar field

$$\ddot{\phi} + 3H\dot{\phi} + {m_\phi}^2\phi = 0$$ （m_ϕ: mass of the field）



Initially, $\phi \neq 0$.

After $m_\phi = H$, the field oscillates with its frequency given by.

$$\nu = \frac{m_\phi}{2\pi} \simeq 100\mathrm{Hz}\left(\frac{m_\phi}{4\times 10^{-13}\mathrm{eV}}\right)$$

After ϕ starts oscillations,

$$\rho = \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}{m_\phi}^2\phi^2$$

$$P = \frac{1}{2}\dot{\phi}^2 - \frac{1}{2}{m_\phi}^2\phi^2 \approx 0 \longrightarrow$$ Behaves as dust.

The scalar field ϕ is not exactly uniform and inhomogeneities grow by the structure formation.

Inside the dark matter halos, ϕ is virialized.

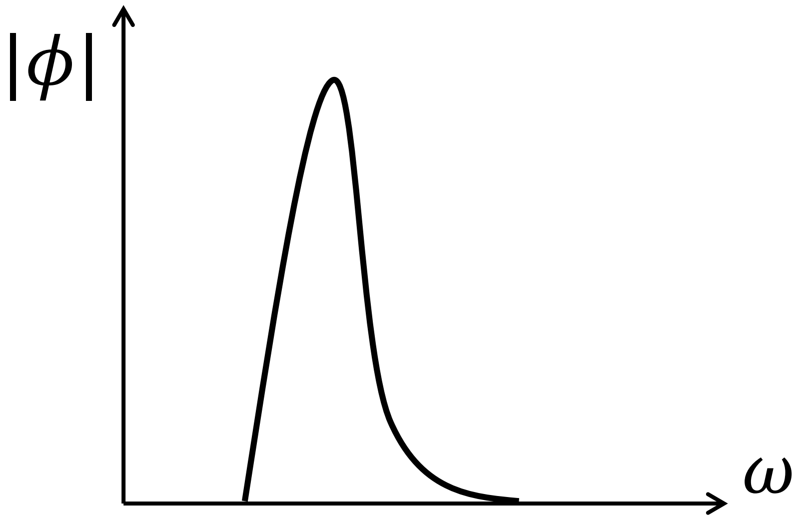
$$\phi(t,\vec{x}) = \int d^3k\ \phi_k e^{i\vec{k}\vec{x}-i\omega_k t}$$

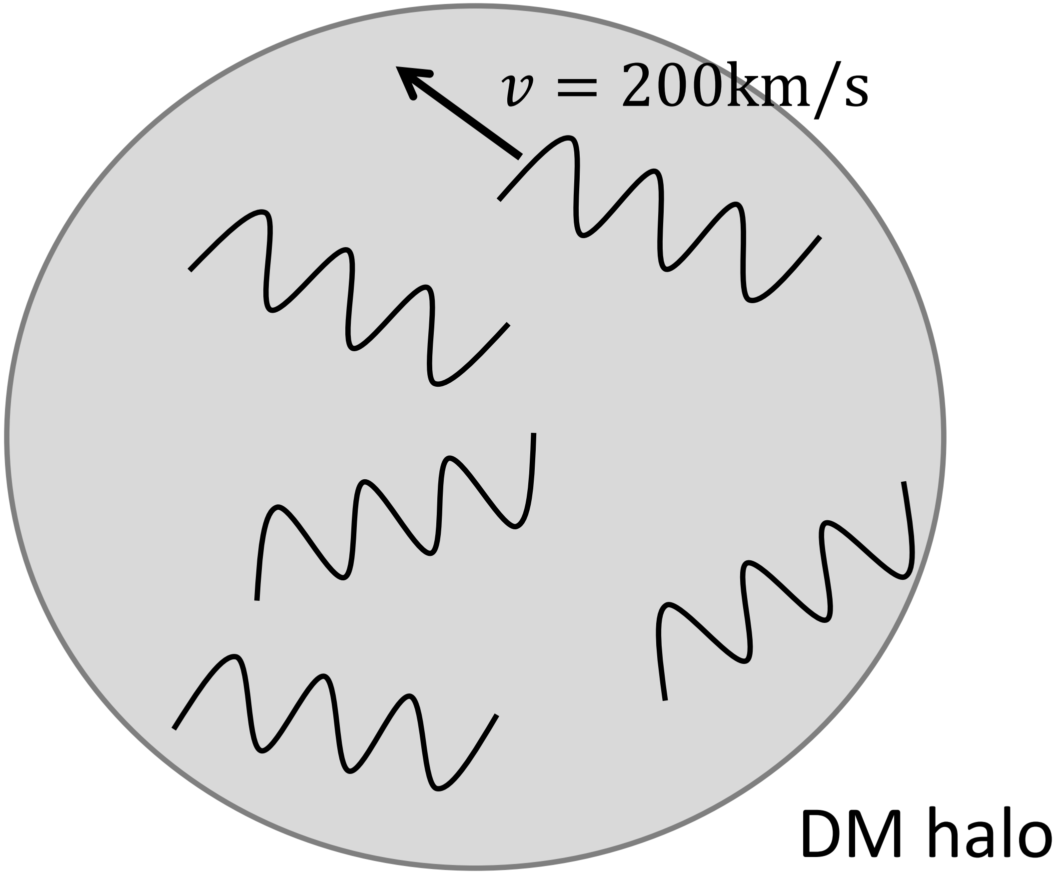
ϕ_k: random variables

$$\omega_k = \sqrt{k^2 + {m_\phi}^2} \approx m_\phi + \frac{k^2}{2m_\phi}$$

$$k = m_\phi v$$

$$v \simeq 200\mathrm{km/s}$$





$$\lambda_\phi \simeq \frac{1}{m_\phi v_{DM}} \backsimeq 3\times10^{11} cm \left(\frac{m_\phi}{4\times10^{-13} eV}\right)^{-1}\left(\frac{v_{DM}}{10^{-3}}\right)^{-1}$$

For scales > λ_ϕ, ϕ behaves as CDM.

Phenomenological Model

Damour, Donoghue, ‘10

We consider the following interaction between ϕ and SM particles.

$$\mathcal{L}_{\phi-\mathrm{SM}} = \kappa\phi\left[\frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu} - \frac{d_g\beta_3}{2g_3}G^A_{\mu\nu}G^{A\mu\nu} - \sum_{i=e,u,d}(d_{m_i} + \gamma_{m_i}d_g)m_i\bar{\psi}_i\psi_i\right]$$

1/(Planck mass)

EM field

Gluon field

Quark field

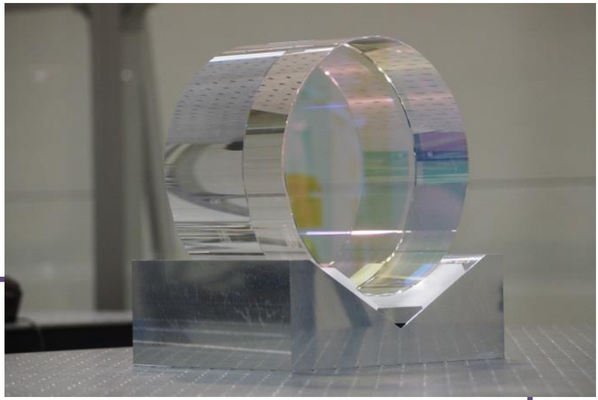
d_e, d_g, d_{mi}: dimensionless coupling constants we want to probe

GW detectors are primarily sensitive to d_g

Change of ϕ produces change of the QCD scale and thus the change of the nucleon mass.

Nucleon mass becomes a function of ϕ

Effect of the scalar field on a mirror



Action of a mirror

$$S = \int \underline{m(\phi)}\sqrt{-\eta_{\mu\nu}dx^{\mu}dx^{\mu}}$$

$m(\phi)$: Mirror mass

Equation of motion of the mirror

$$\frac{d^2x^i}{dt^2} \simeq -\kappa\alpha(\phi)\partial_i\phi$$

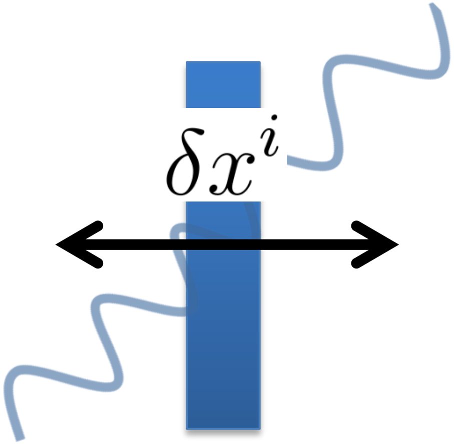
$$\alpha(\phi) \simeq d_g^* \simeq d_g + 0.093(d_{\hat{m}} - d_g)$$

→ Spatial variation of ϕ exerts force on the mirror

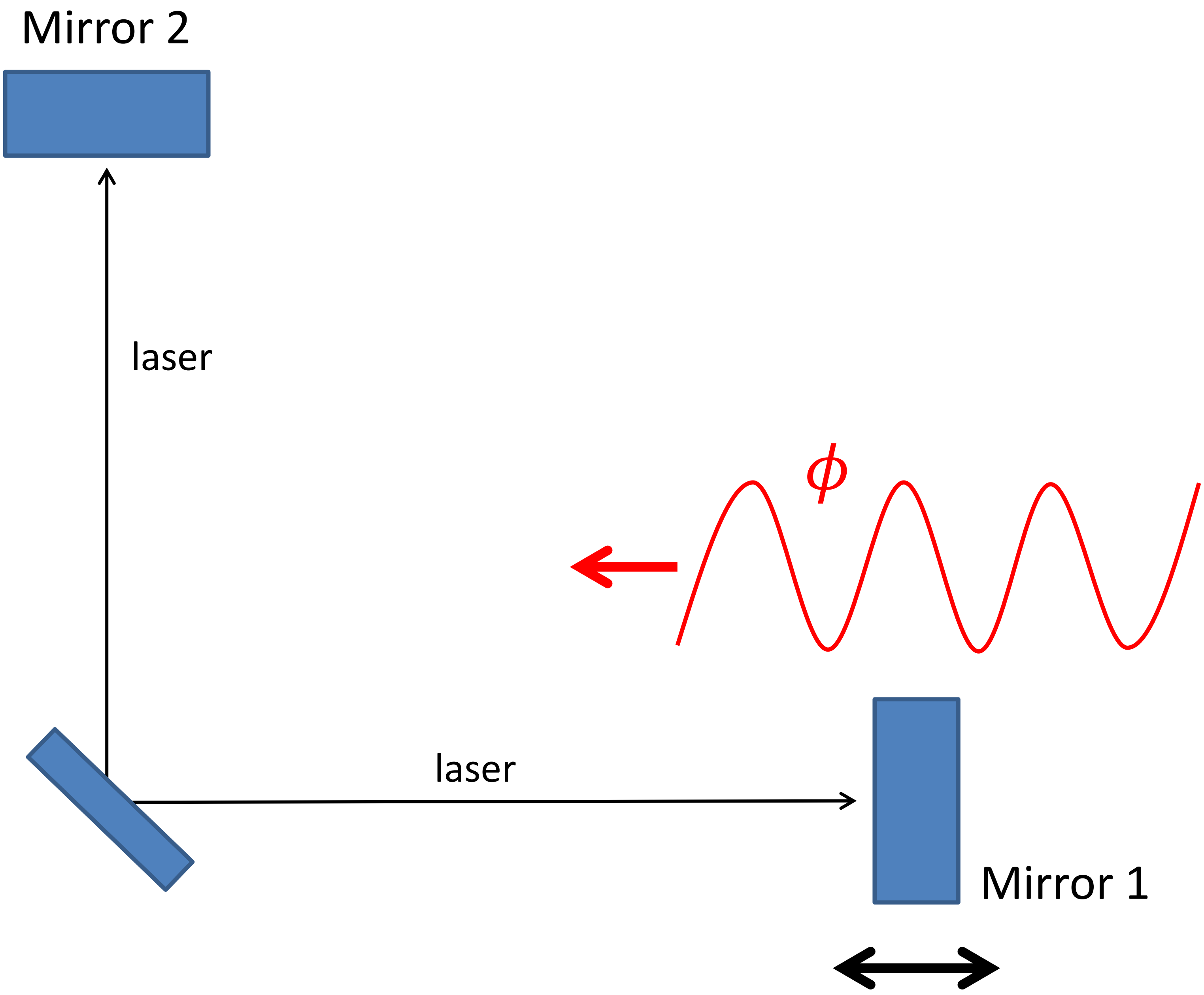
Effect of the scalar field on a mirror

$$\phi = \phi_{\vec{k}} \cos(\omega_k t - \vec{k}\cdot\vec{x} + \theta_{\vec{k}}).$$

$$\delta x^i \simeq \underline{d_g} \kappa \phi_{\vec{k}} \frac{\underline{k^i}}{m_\phi^2} \sin(\omega_k t - \vec{k}\cdot\vec{x} + \theta_{\vec{k}})$$



- Mirror motion // propagation direction of ϕ
- Oscillation frequency of the mirror = frequency of ϕ


Mirror 2
laser
ϕ
laser
Mirror 1

Detection of the scalar field by GW interferometers

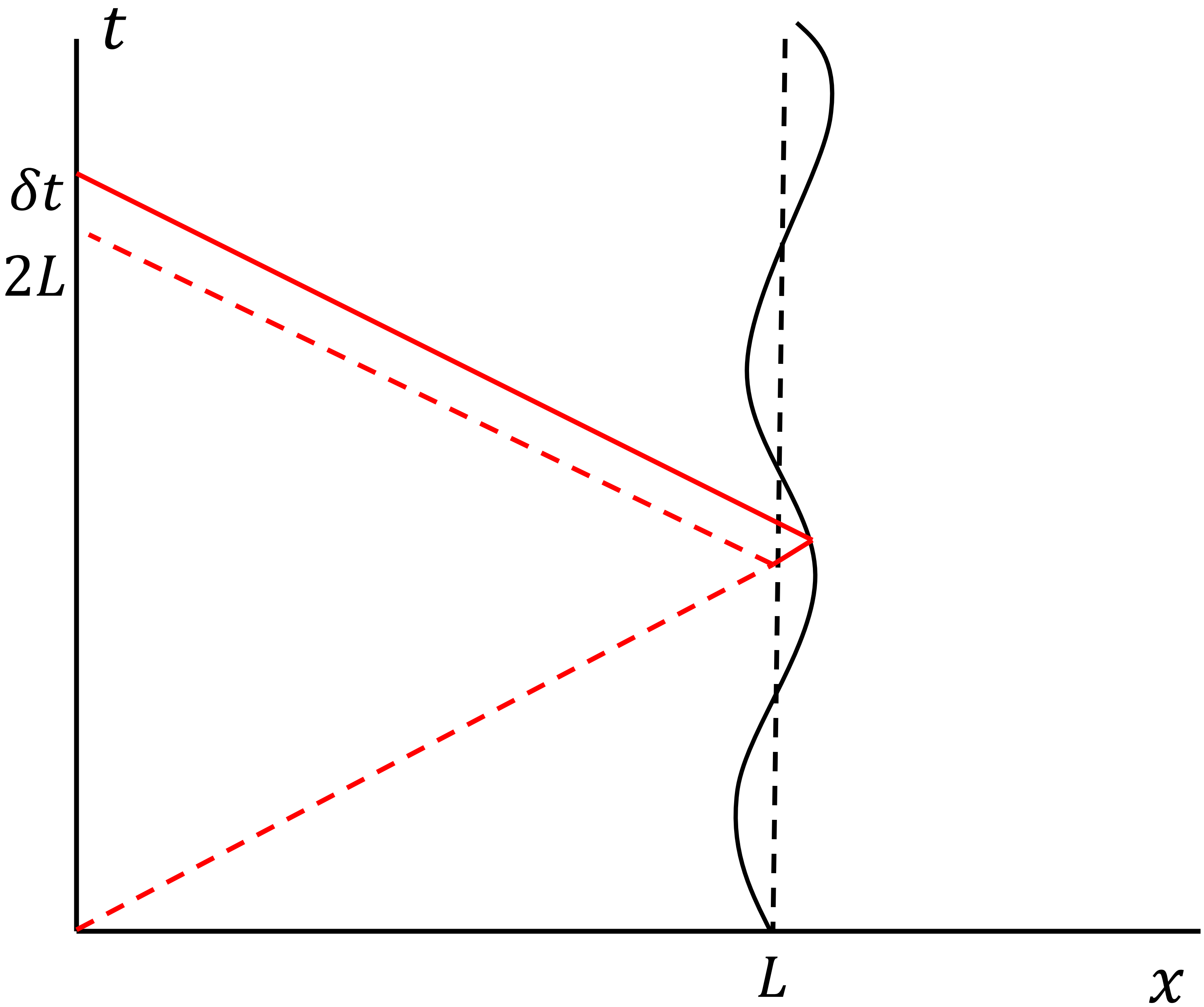
GW interferometers can probe the scalar field for

$m_\phi \in$ frequency band of the detectors

Arvanitaki, Huang, Tilburg ‘15

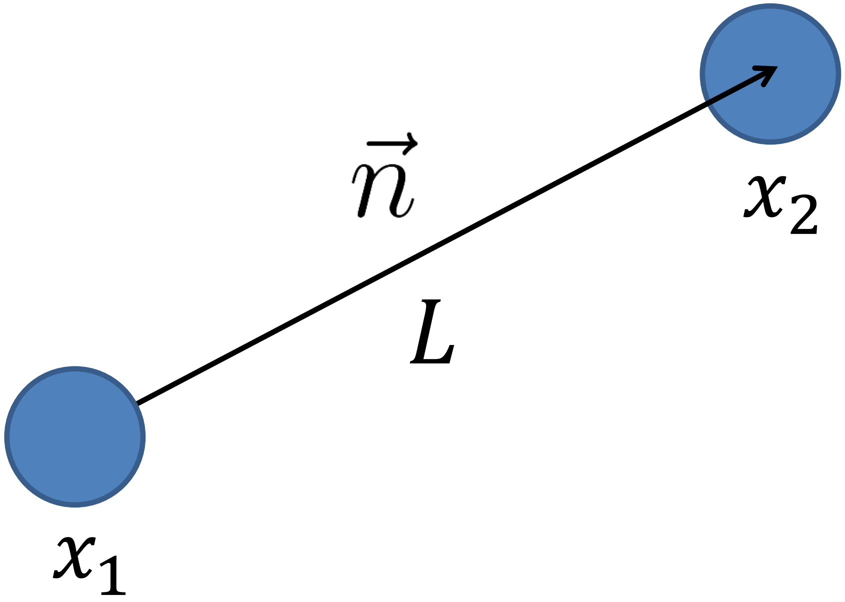
For LIGO-like detectors, $4 \times 10^{-13}\ \mathrm{eV} \simeq 100\ \mathrm{Hz}$

- What type of signal?
- What type of data analysis?
- How strong are the constraints?


t
δt
2L
L
x

Signal

$$x_1^i(t) = x^i + \delta x^i(t, \vec{x}),$$
$$x_2^i(t) = x^i + Ln^i + \delta x^i(t, \vec{x} + L\vec{n})$$



$$\delta t(t; L, \vec{n}) \simeq n_i(-\delta x^i(t, \vec{x}) + 2\delta x^i(t - L, \vec{x} + L\vec{n}) - \delta x^i(t - 2L, \vec{x}))$$

Signal

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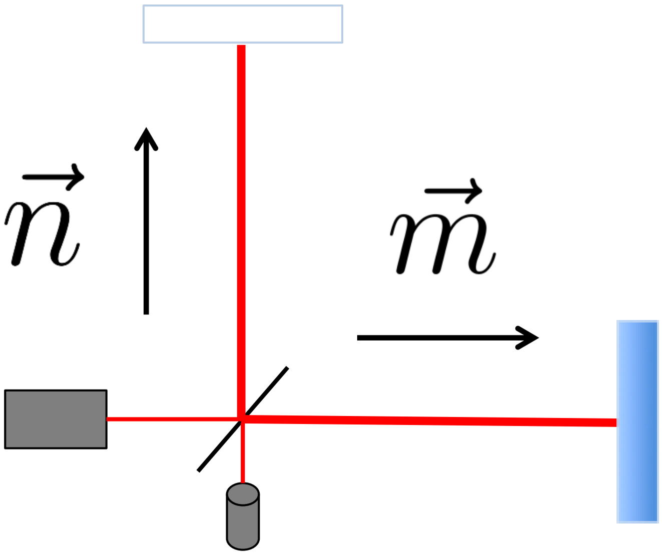
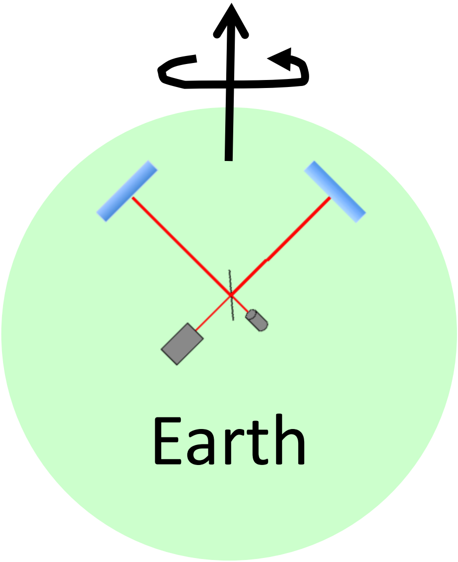
$$h(t) = \boxed{d_g} \kappa \left(\boxed{2 \frac{\sin^2\left(\frac{m_\phi L}{2}\right)}{m_\phi^2 L} (n^i - m^i) \partial_i \phi(t, \vec{x})} + \frac{n^i n^j - m^i m^j}{m_\phi^2} \partial_i \partial_j \phi(t, \vec{x}) \right).$$

New term

Proportional to d_g



$$
\begin{aligned}
h(t) =& d_g \kappa \Bigg(2 \frac{\sin^2\left(\frac{m_\phi L}{2}\right)}{m_\phi^2 L} (n^i(t) - m^i(t)) \partial_i \phi(t, \vec{x}) \\
&+ \frac{n^i(t) n^j(t) - m^i(t) m^j(t)}{m_\phi^2} \partial_i \partial_j \phi(t, \vec{x}) \Bigg).
\end{aligned}
$$

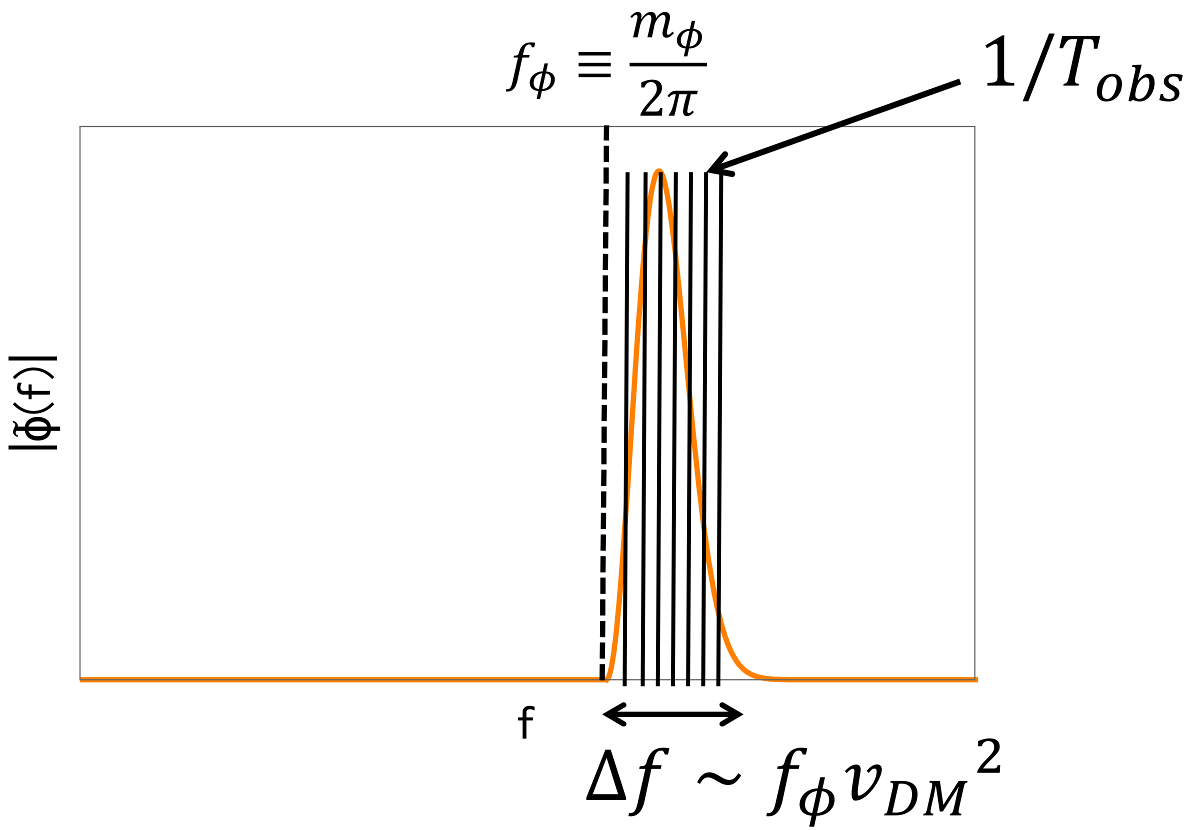


The signal is modulated over the timescale given by

$$
f_{\rm d} = \begin{cases} 1\ \text{day}^{-1} & (\text{LIGO},\ \text{ET},\ \text{CE}) \\ 1\ \text{year}^{-1} & (\text{DECIGO},\ \text{LISA}) \end{cases}
$$

Upper limit on h

$$\tilde{s}(f_k) = \int_0^{T_{\rm obs}} s(t)\mathrm{e}^{-2\pi i f_k t} dt, \qquad f_k = \frac{k}{T_{\rm obs}}$$

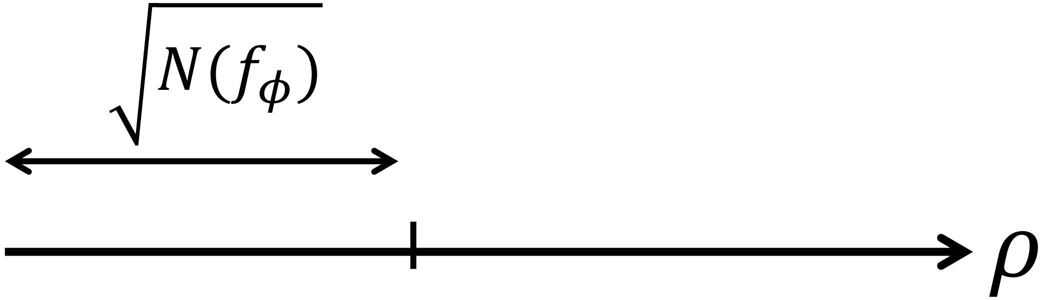


$$\rho(f_\phi) = \frac{1}{T_{\rm obs}} \sum_{k=-\infty}^{\infty} \tilde{s}_1^*(f_k)\tilde{s}_2(f_k)\tilde{Q}(f_k; f_\phi)$$

Upper limit on h

$$E\left[\left(\rho(f_\phi) - E[\rho(f_\phi)]\right)^2\right] = 2N(f_\phi)$$

Case of noise only

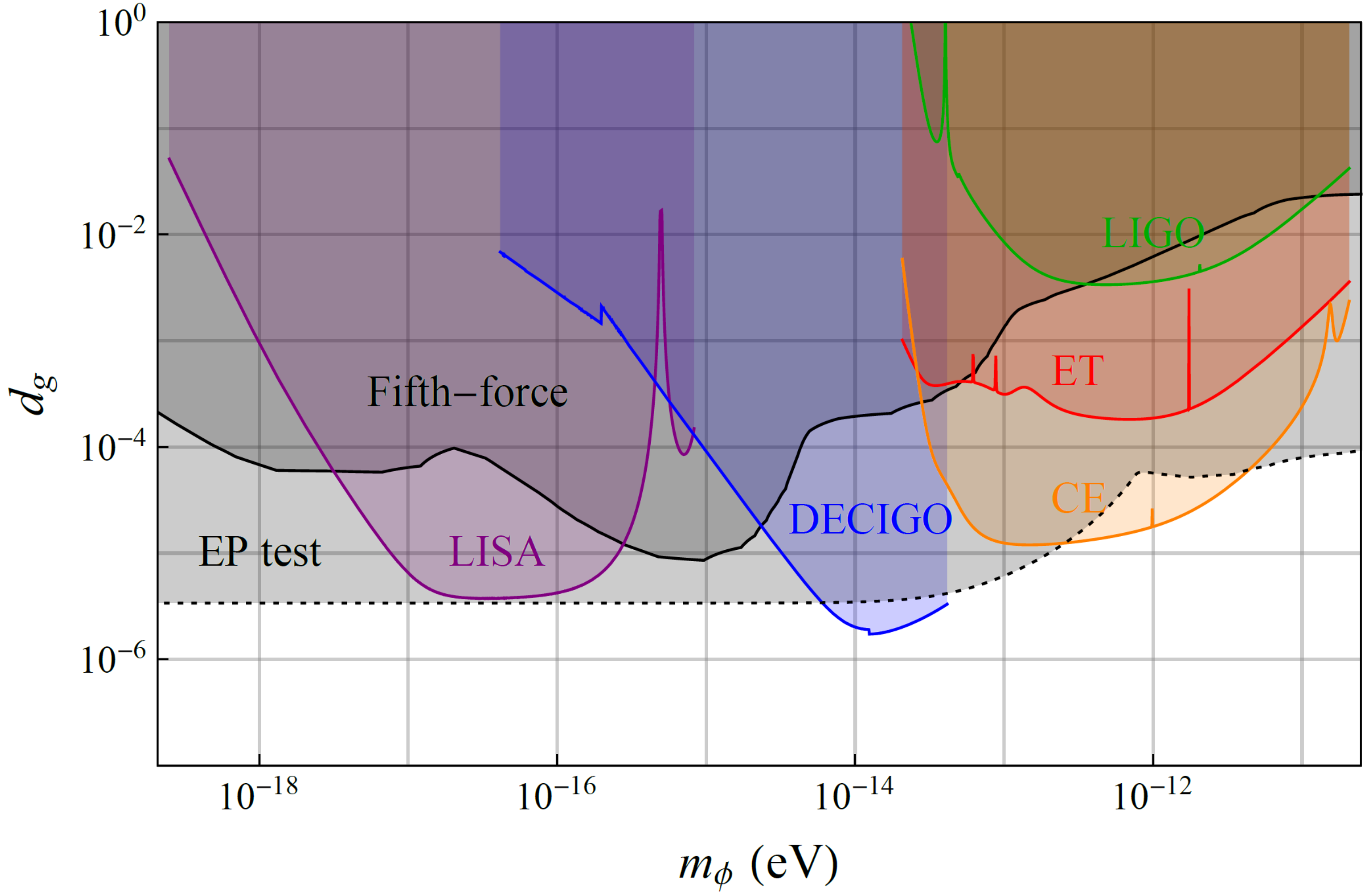


$$E[\rho(f_\phi)]_{s(t)=h(t)+n(t)} - E[\rho(f_\phi)]_{s(t)=n(t)} \simeq \frac{T_{\rm obs}}{S(f_\phi)}\overline{h^2},$$

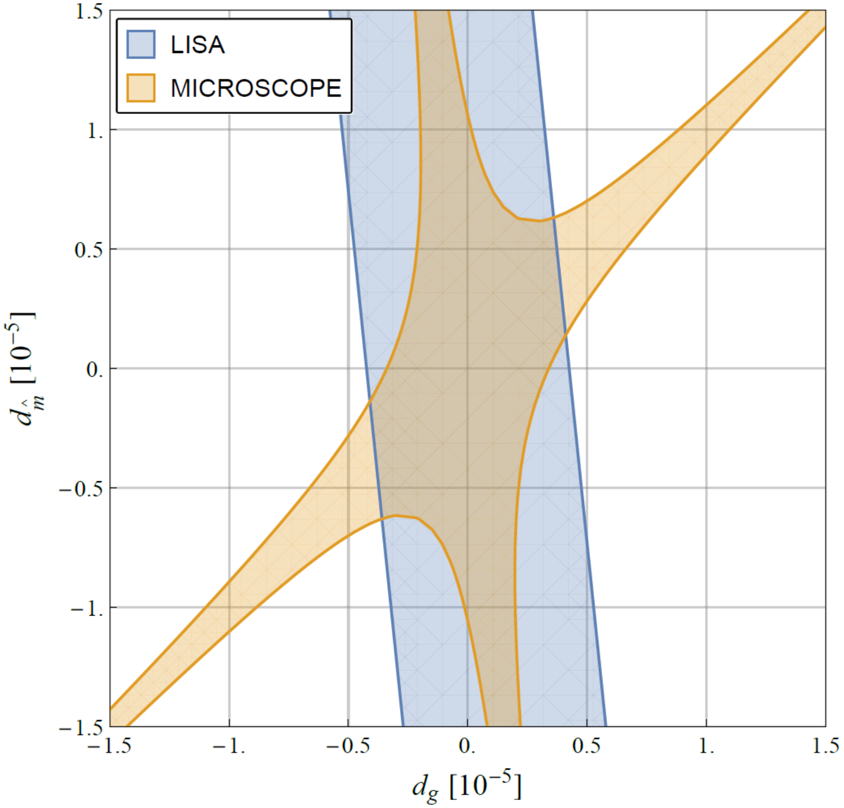
$$h_{\rm th}(f_\phi) \sim \frac{\sqrt{f_\phi v_{\rm DM}^2}}{\boxed{N^{\frac{1}{4}}(f_\phi)}}\sqrt{S(f_\phi)}$$

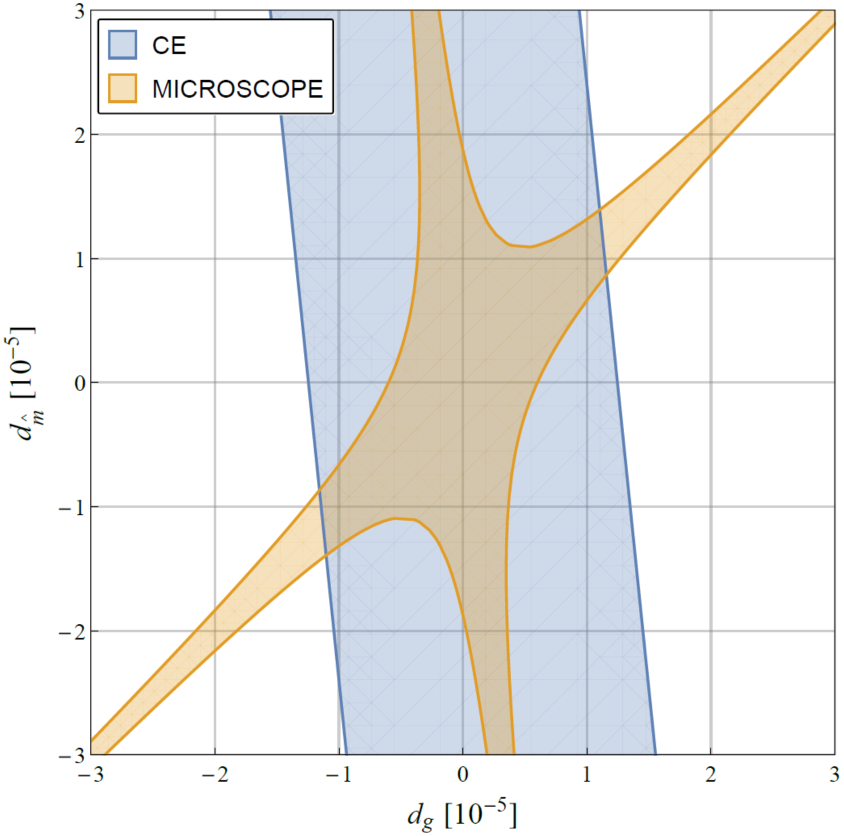
$\simeq$ 7 (overlooked in the literature)

Expected upper limit



GW interferometers are very powerful!





Colored region: not constrained

EP(equivalence principle) tests probe different region of the parameter space

Summary

Ultralight scalar field is a candidate of dark matter.

GW interferometers are powerful to test this hypothesis.

Future: use of real data