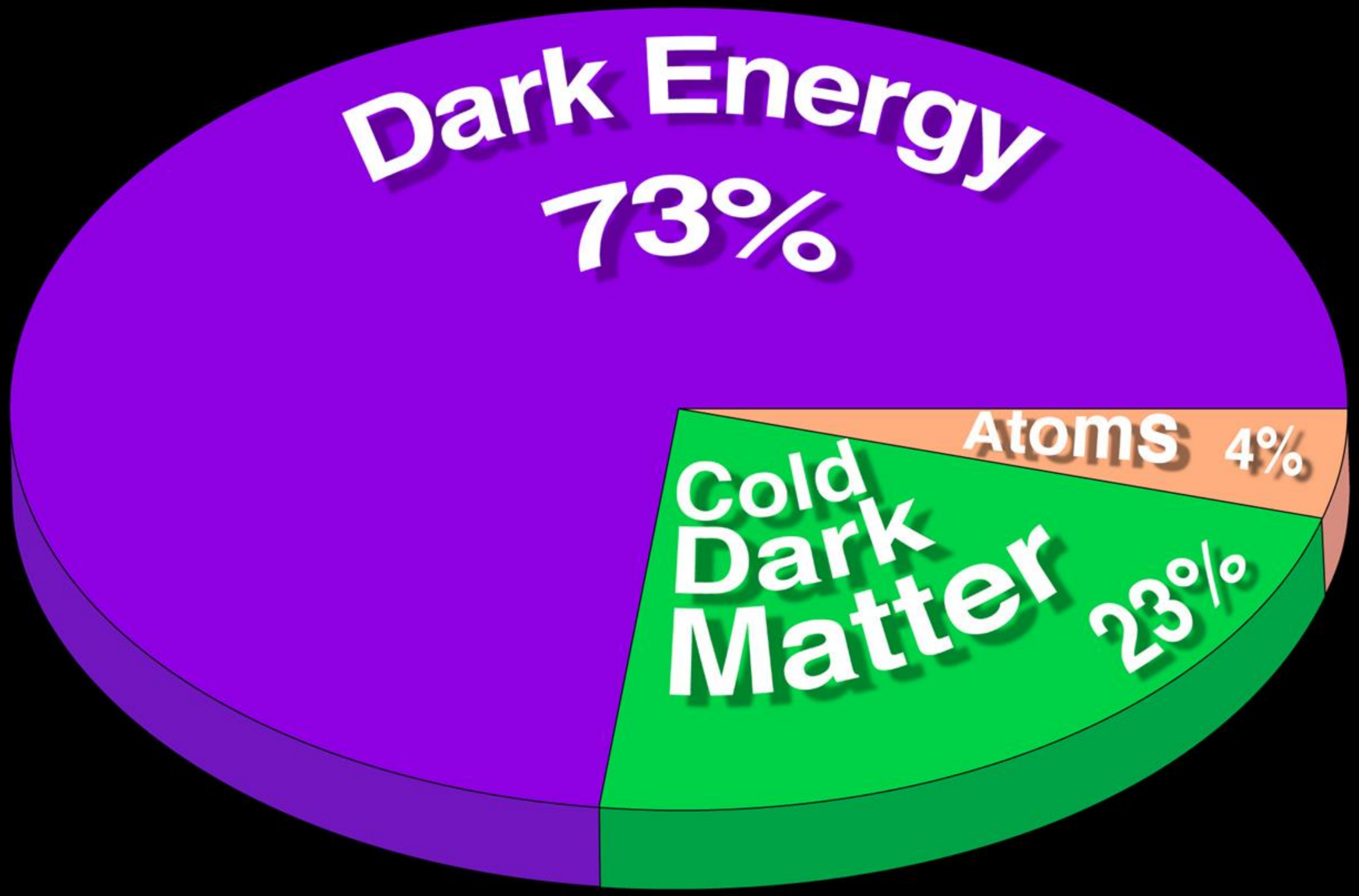
Probing ultralight scalar field dark matter with GW interferometers

Teruaki Suyama

Tokyo Institute of Technology

Ref: S.Morisaki and TS, 1811.05003

What is the nature of dark matter?



We must consider various possibilities and ideas of experiments.

Dawn of GW astronomy

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

Can we use GW interferometers to search dark matter?

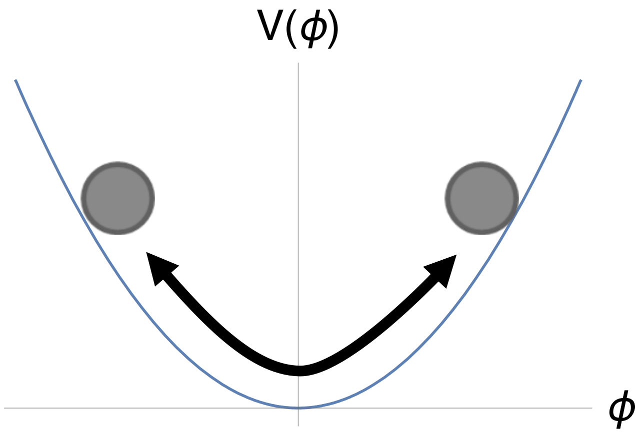
YES!!

But, GW interferometers are not perfect.

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

Arvanitaki, Huang, Tilburg '15

Ultralight scalar field as dark matter



After $m_\phi = H$, the field oscillates with its frequency given by $\omega = m_\phi$. (m_ϕ: mass of the field)

⟶ Behaves as dust.

CDM = (coherently) oscillating scalar field

$$\lambda_\phi \simeq \frac{1}{m_\phi v_{DM}} \qquad v_{DM} \sim 10^{-3}$$

Phenomenological Model

Damour, Donoghue, '10

We consider the following interaction between ϕ and SM particles.

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

EM field　　Gluon field　　Quark field

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

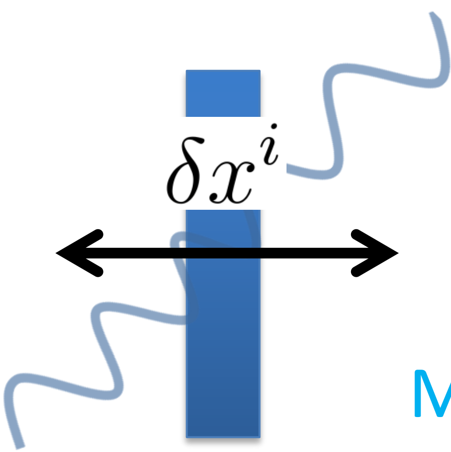
GW detectors are primarily sensitive to d_g.

Dependence of neucleon mass on ϕ

Detection of the scalar field by GW interferometers

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

→ Spatial variation of ϕ exerts force on body.
(Oscillations of the mirrors)



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

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

Mirror motion // propagation direction of ϕ

Detection of the scalar field by GW interferometers

GW interferometers can probe the scalar field for

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

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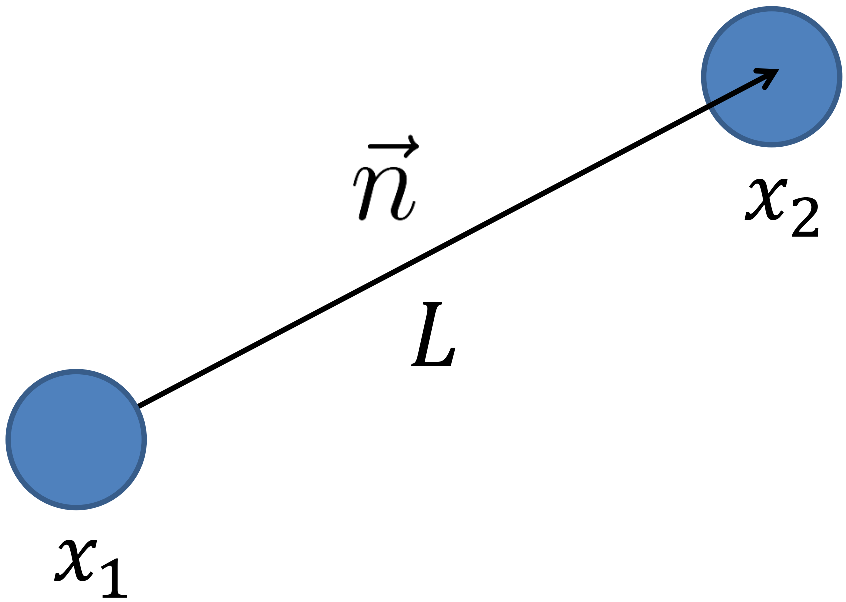
For LIGO-like detectors, $4 \times 10^{-13}\ \mathrm{eV} \simeq 100\ \mathrm{Hz}$

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

Signal

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

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



Perturbation of the round-trip time

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

Signal

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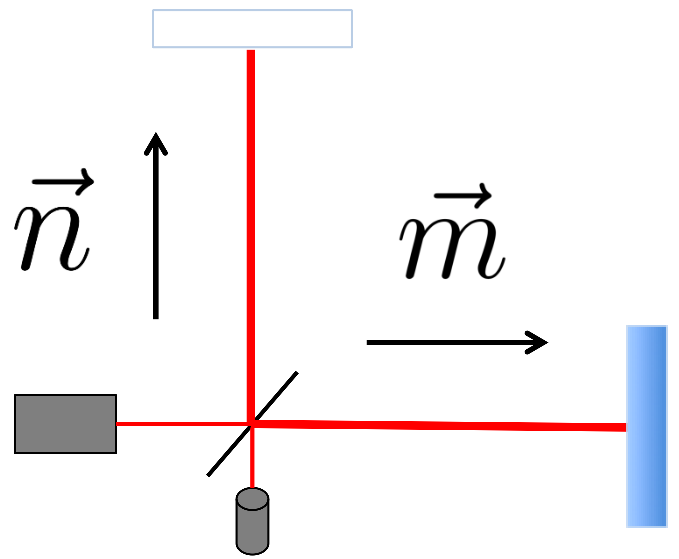
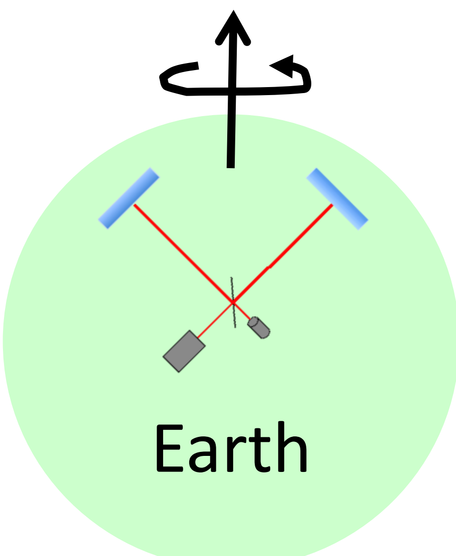
$$h(t) = d_g \kappa \left(2 \frac{\sin^2\left(\frac{m_\phi L}{2}\right)}{m_\phi^2 L} (n^i - m^i) \partial_i \phi(t, \vec{x}) + \frac{n^i n^j - m^i m^j}{m_\phi^2} \partial_i \partial_j \phi(t, \vec{x}) \right).$$

New term



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



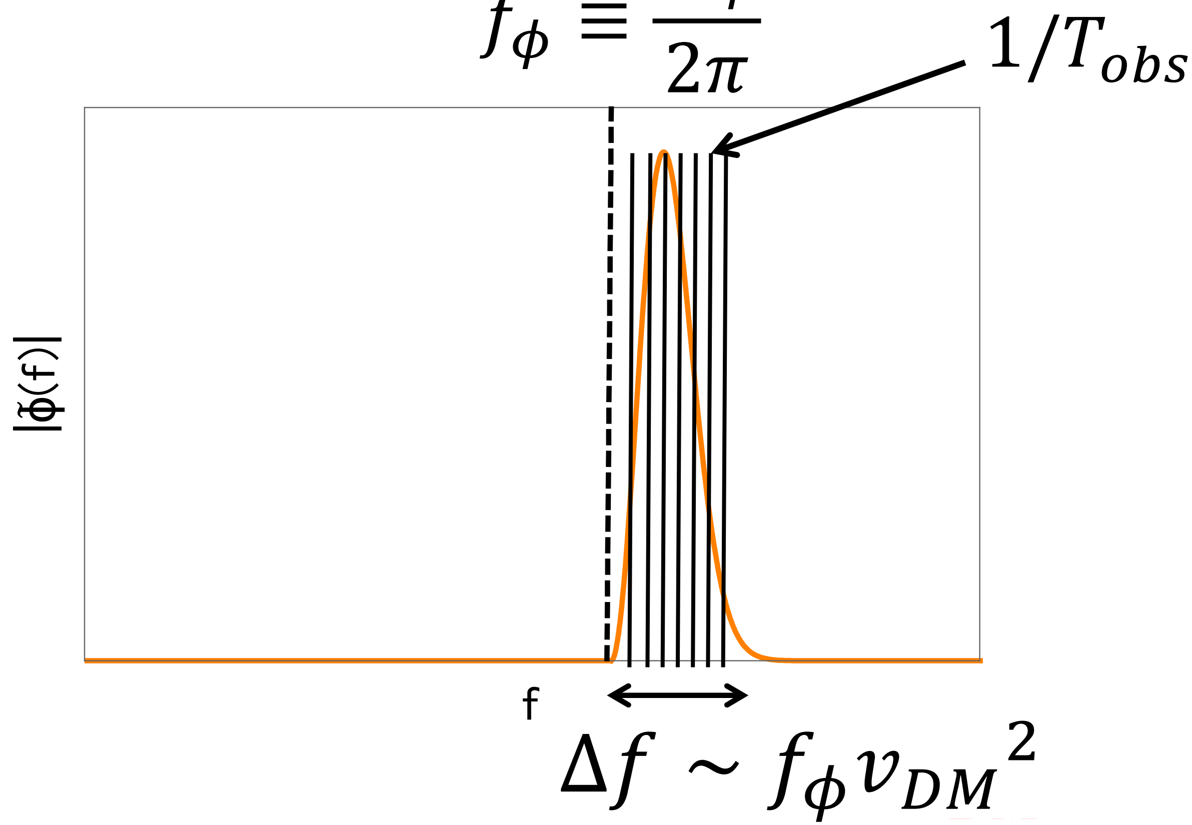
The signal is modulated over the timescale given by

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

Scalar field in the Galaxy

Velocity dispersion $v_{\rm DM} \sim 10^{-3}$ leads to

$$f_\phi \equiv \frac{m_\phi}{2\pi}$$



Spectrum of the scalar field has a width.

Upper limit on h

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

$$\rho(f_\phi) \equiv \sum_{f_k \in F(f_\phi)} \frac{2|\tilde{s}(f_k)|^2}{T_{\rm obs} S(f_k)}$$

Cumulative distribution function (noise only)

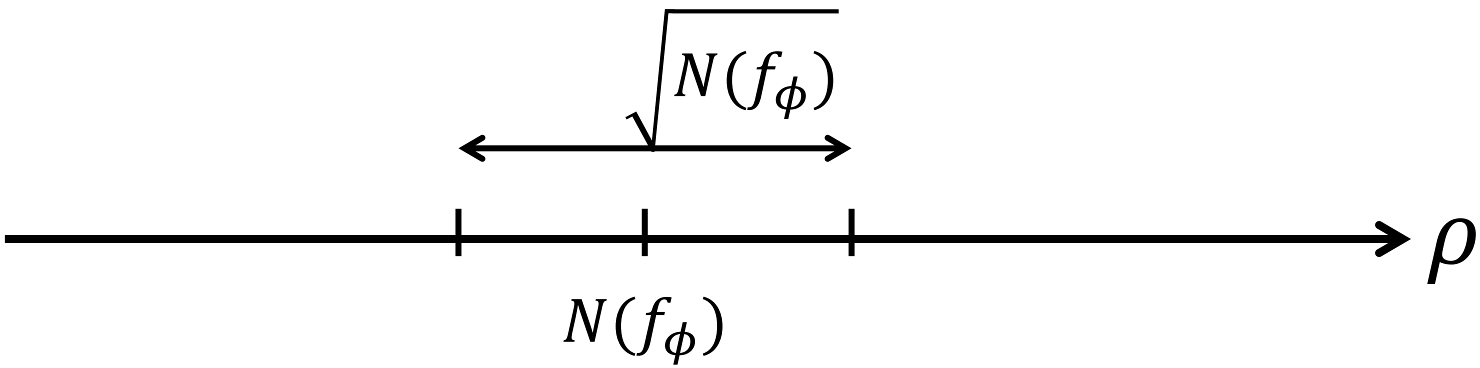
$$\text{CDF}\left[\rho(f_\phi) < \rho_{\rm c}\right] = \frac{\gamma(N(f_\phi), \rho_{\rm c})}{(N(f_\phi) - 1)!}$$

$$1 - \text{CDF}\left[\rho(f_\phi) < \rho_{\rm c}\right] = F$$

$$h_{\rm th}(f_\phi) = \sqrt{\frac{S(f_\phi)}{2T_{\rm obs}} \left(\rho_{\rm c} - N(f_\phi)\right)}$$

Crude estimate of the sensitivity

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

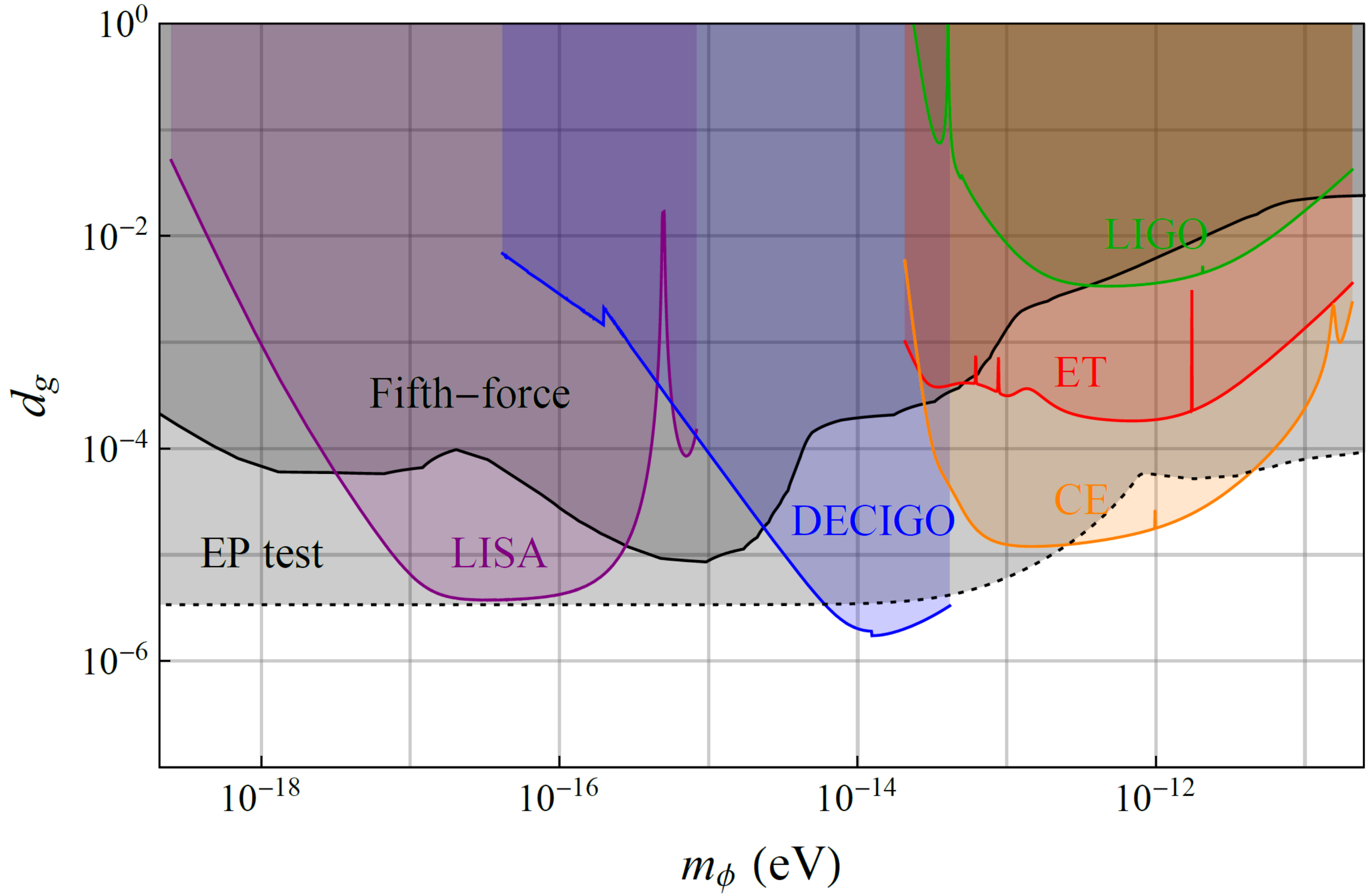


$$E[\rho(f_\phi)]_{s(t)=h(t)+n(t)} - E[\rho(f_\phi)]_{s(t)=n(t)} \simeq \frac{T_{\rm obs}}{S(f_\phi)}\overline{h^2},$$

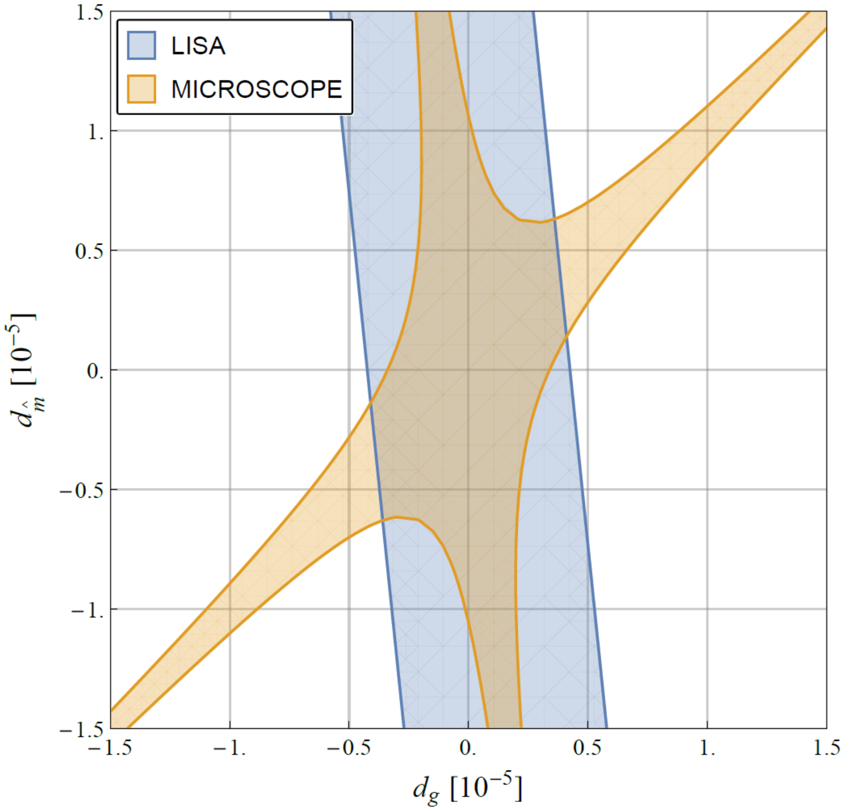
$$h_{\rm th}(f_\phi) \sim \frac{\sqrt{f_\phi v_{\rm DM}^2}}{N^{\frac{1}{4}}(f_\phi)}\sqrt{S(f_\phi)}$$

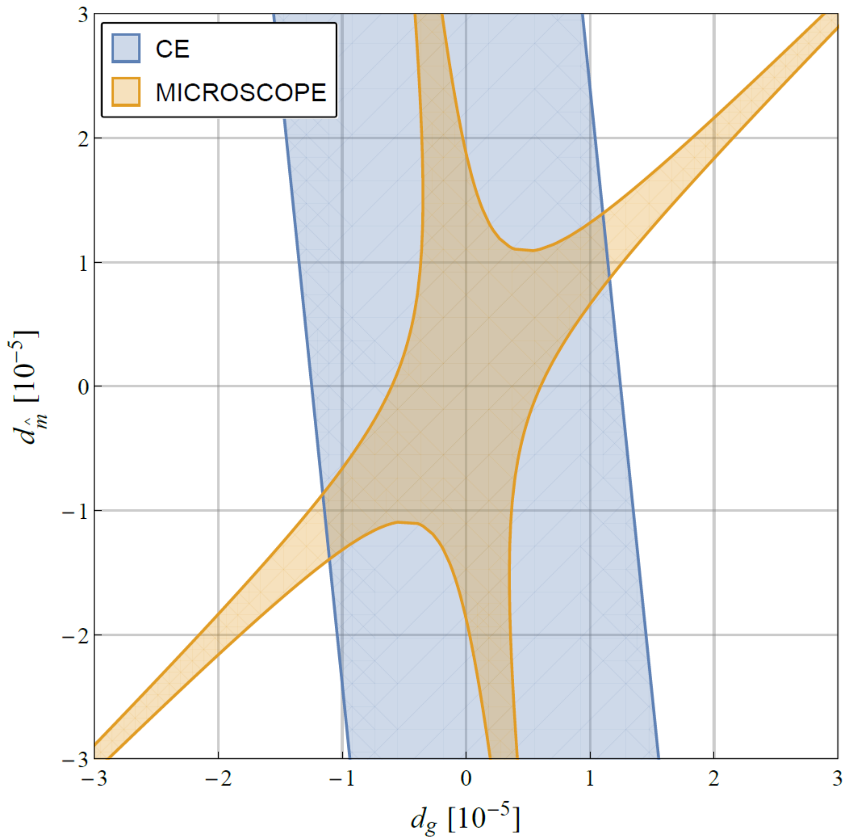
$\simeq$ 7 (overlooked in the literature)

Expected upper limit



GW interferometers are very powerful!





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