Search methods for ultralight scalar field dark matter with gravitational-wave detectors and its detectability

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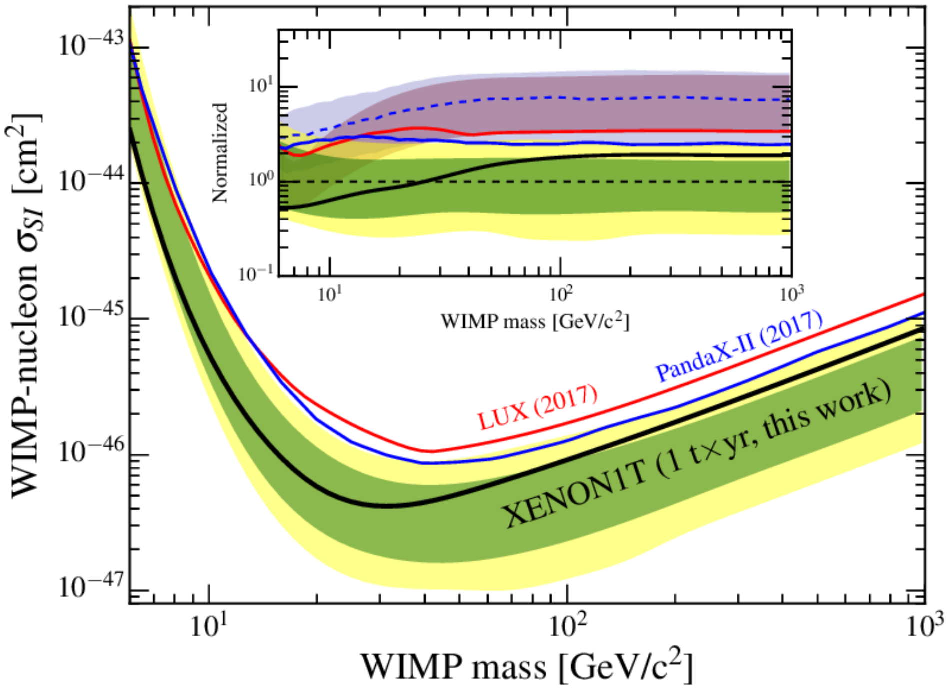
Based on **arXiv: 1811.05003**

COSMO’19 @ RWTH Aachen University.

Dark matter

Null results from searches for WIMPs.



Constraint on WIMP's cross section

PRL, 121(11):111302, 2018

Any other DM candidates?

Ultralight scalar field DM

- Non-thermal DM

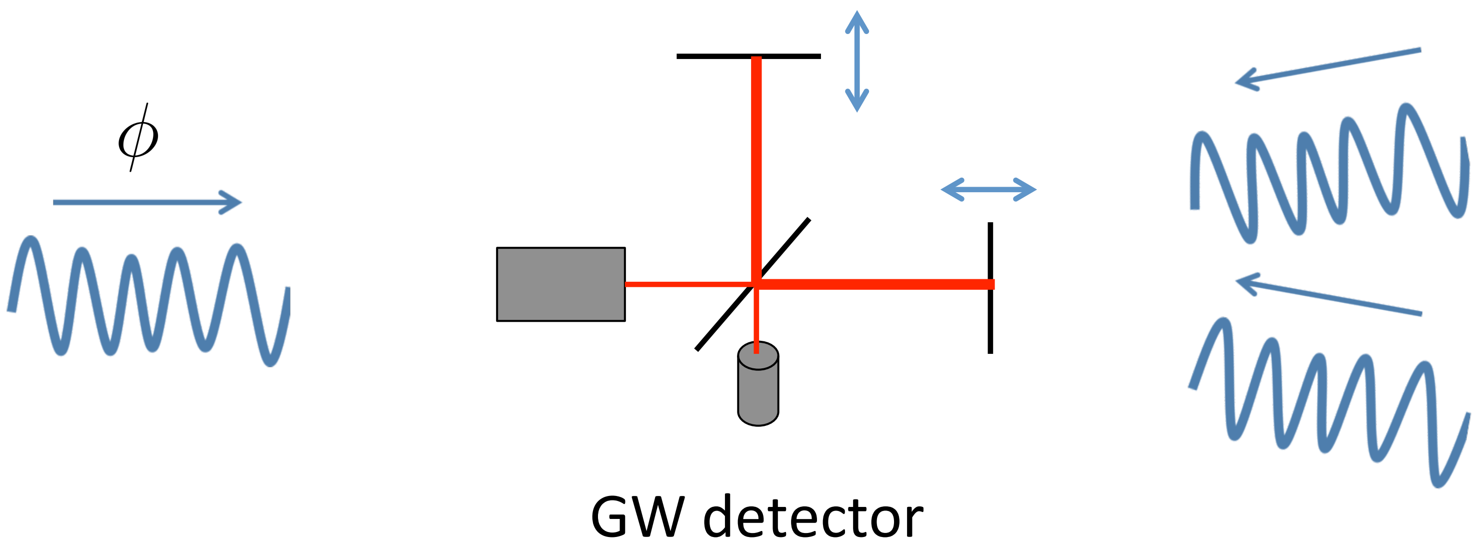
  → can be very light, $m_\phi \gtrsim 10^{-23}\ \mathrm{eV}$.

Wayne Hu et al., PRL, 85, 2000.

- Various searches
  - Fifth force experiments
  - Equivalence principle experiments
  - Pulsar timing array
  - Oscillation of physical constants

E. G. Adelberger et al., Nucl. Part. Sci., 53, 2003.
Thibault Damour and John F. Donoghue, PRD 82, 2010.
Andrei Khmelnitsky and Valery Rubakov, JCAP, 1402, 2014.
Asimina Arvanitaki et al.. PRD 91, 2015.

Search with GW detector



- Scalar-wave background in the galaxy
- Oscillate mirrors through interaction with SM particles

  → Can be detected with GW detectors

Asimina Arvanitaki et al.. PRD 91, 2015.

Our work

In this work, we

- calculated the expression of the signal, which can be compared with data.
- developed a data analysis method to detect this signal.
- estimated its detectability with our data analysis method.

Model

Assume linear couplings

Damour, Donoghue, '10

$$\mathcal{L} = \mathcal{L}_\phi + \mathcal{L}_{\rm SM} + \mathcal{L}_{\phi-{\rm SM}},$$

$$\mathcal{L}_\phi = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2,$$

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

$$(\kappa \equiv \sqrt{4\pi}/M_{\rm pl})$$

Model

Assume linear couplings

Damour, Donoghue, '10

$$\mathcal{L} = \mathcal{L}_\phi + \mathcal{L}_{\rm SM} + \mathcal{L}_{\phi-{\rm SM}},$$

$$\mathcal{L}_\phi = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2,$$

Mass of scalar field

$$\mathcal{L}_{\phi-{\rm SM}} = \kappa\phi\Big[\ldots 4e^2 \ldots \mu\nu \ldots 2g_3 \ldots \mu\nu G^{A\mu\nu}$$

[illegible]

$$- d_{m_e} m_e \bar{e}e - \sum_{i=u,d}(d_{m_i} + \gamma_{m_i} d_g) m_i \bar{\psi}_i \psi_i \Big].$$

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Couplings with SM particles $\sqrt{4\pi}/M_{\rm pl})$

Model

Assume linear couplings

Damour, Donoghue, '10

$$\mathcal{L} = \mathcal{L}_\phi + \mathcal{L}_{\rm SM} + \mathcal{L}_{\phi-{\rm SM}},$$

$$\mathcal{L}_\phi = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi -$$

Variate QCD energy scale

$$\mathcal{L}_{\phi-{\rm SM}} = \kappa\phi\left[\frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu} - \boxed{\frac{d_g\beta_3}{2g_3}G^A_{\mu\nu}G^{A\mu\nu}}\right.$$

$$\left. - d_{m_e}m_e\bar{e}e - \sum_{i=u,d}(d_{m_i} + \gamma_{m_i}d_g)m_i\bar{\psi}_i\psi_i\right].$$

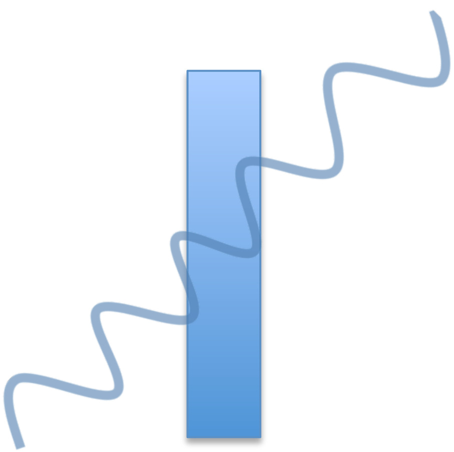
$$(\kappa \equiv \sqrt{4\pi}/M_{\rm pl})$$

Interaction with matter

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

Mass variates

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



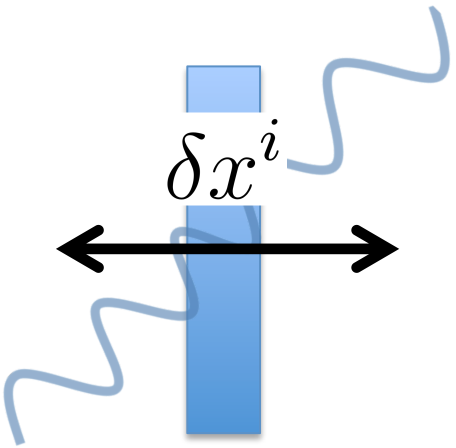
Mirror

Interaction with matter

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

Mass variates

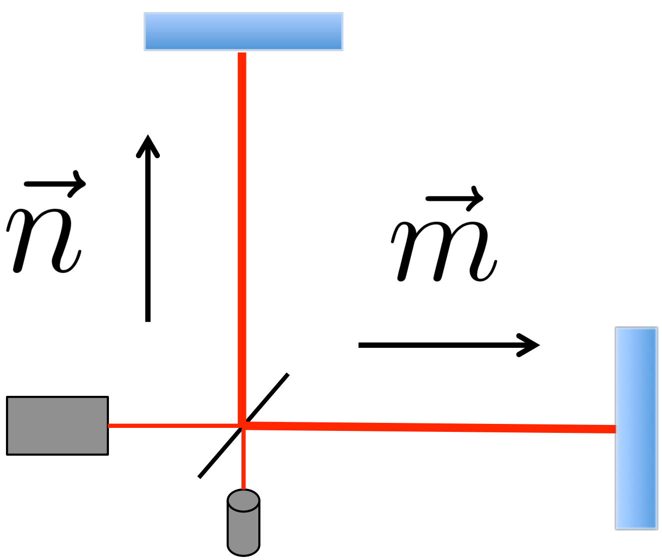
$$\phi = \phi_{\vec{k}} \cos(\omega_k t - \vec{k}\cdot\vec{x} + \theta_{\vec{k}}).$$



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

Signal expression

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

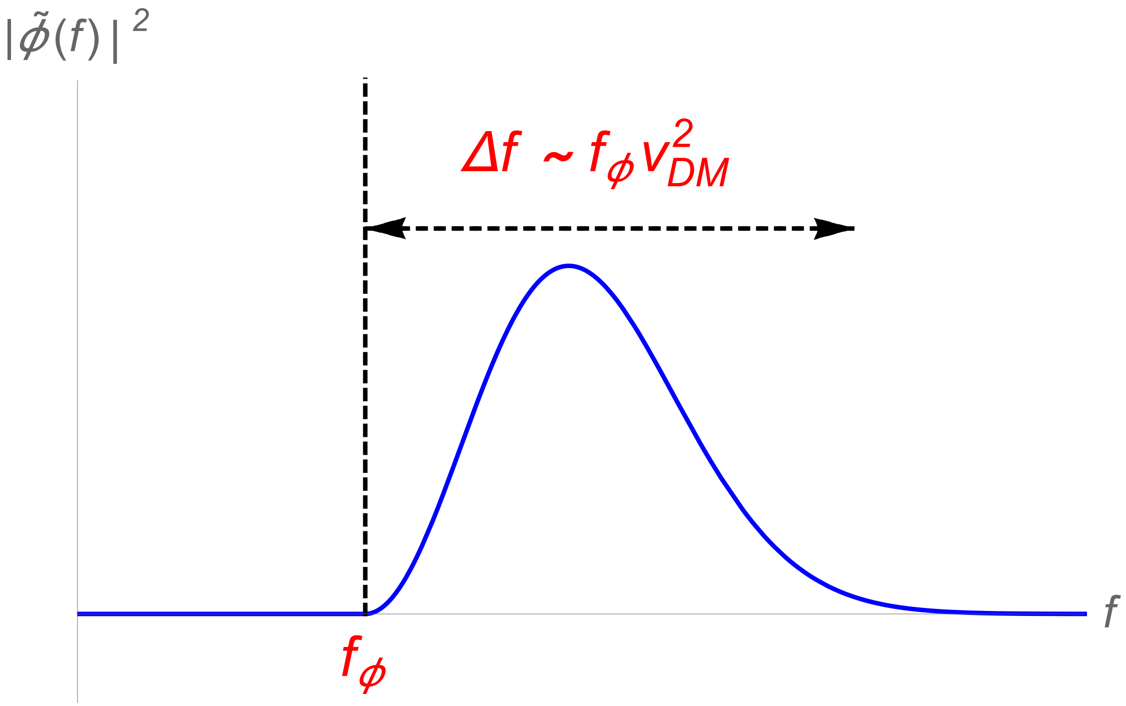


L: Arm length

Velocity dispersion

- Oscillate with frequency determined by mass.
- Tiny freq. dispersion due to velocity dispersion,

$$v_{\rm DM} \sim 10^{-3}$$

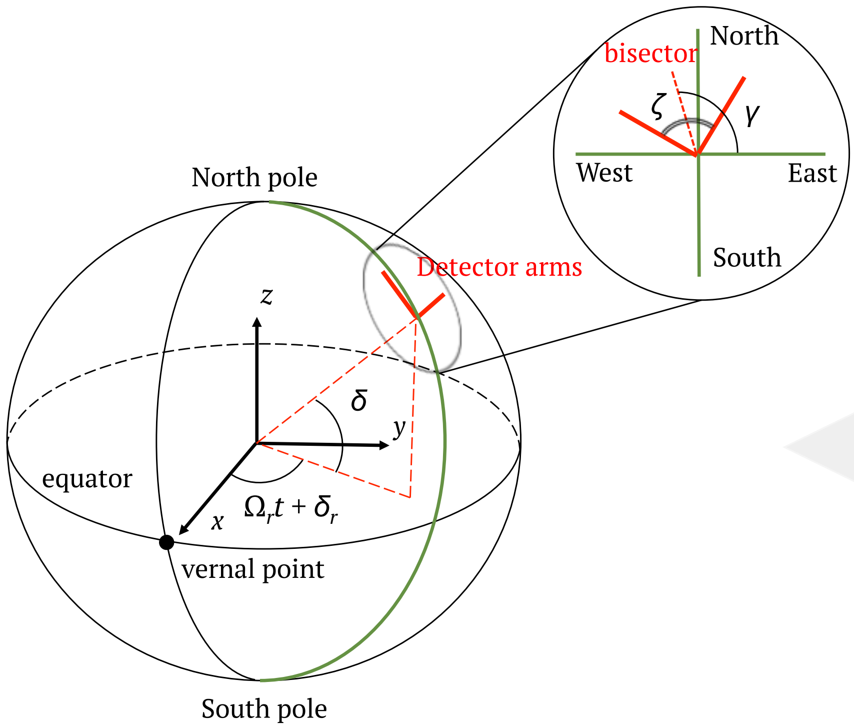


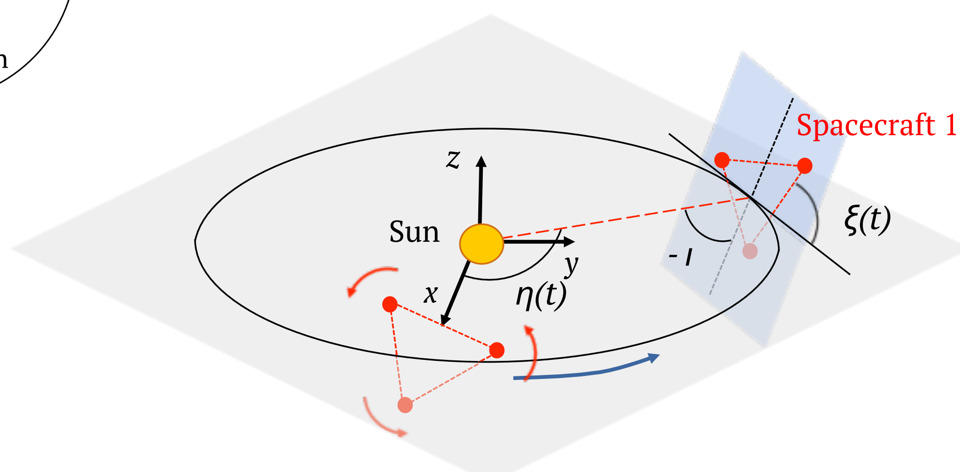
$$f \simeq f_\phi \equiv \frac{m_\phi}{2\pi},$$
$$\Delta f \sim f_\phi v_{\rm DM}^2.$$

Detector's motion

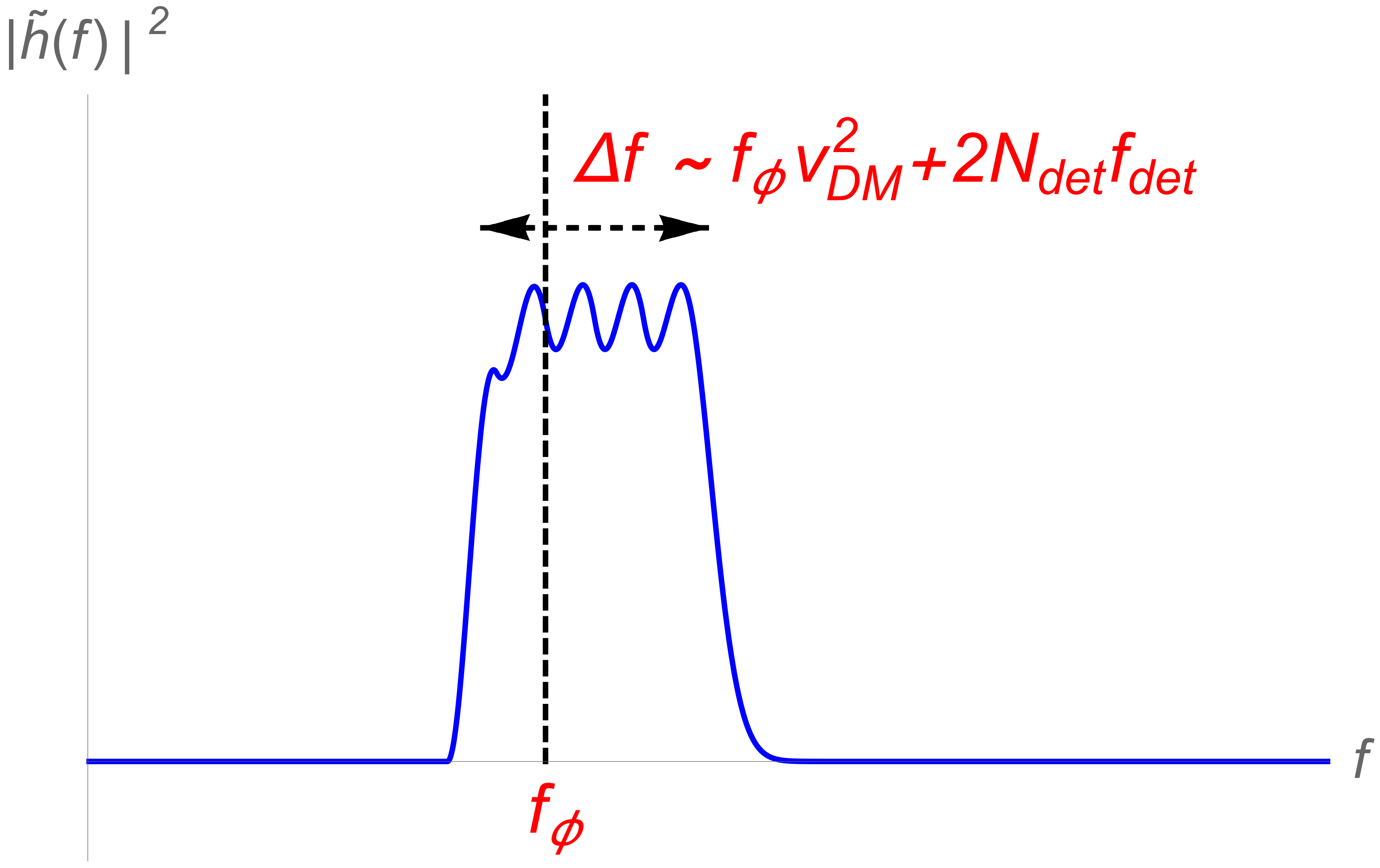
Detector's response variates with timescale of

- ~day for ground-based detectors
- ~year for space-based detectors



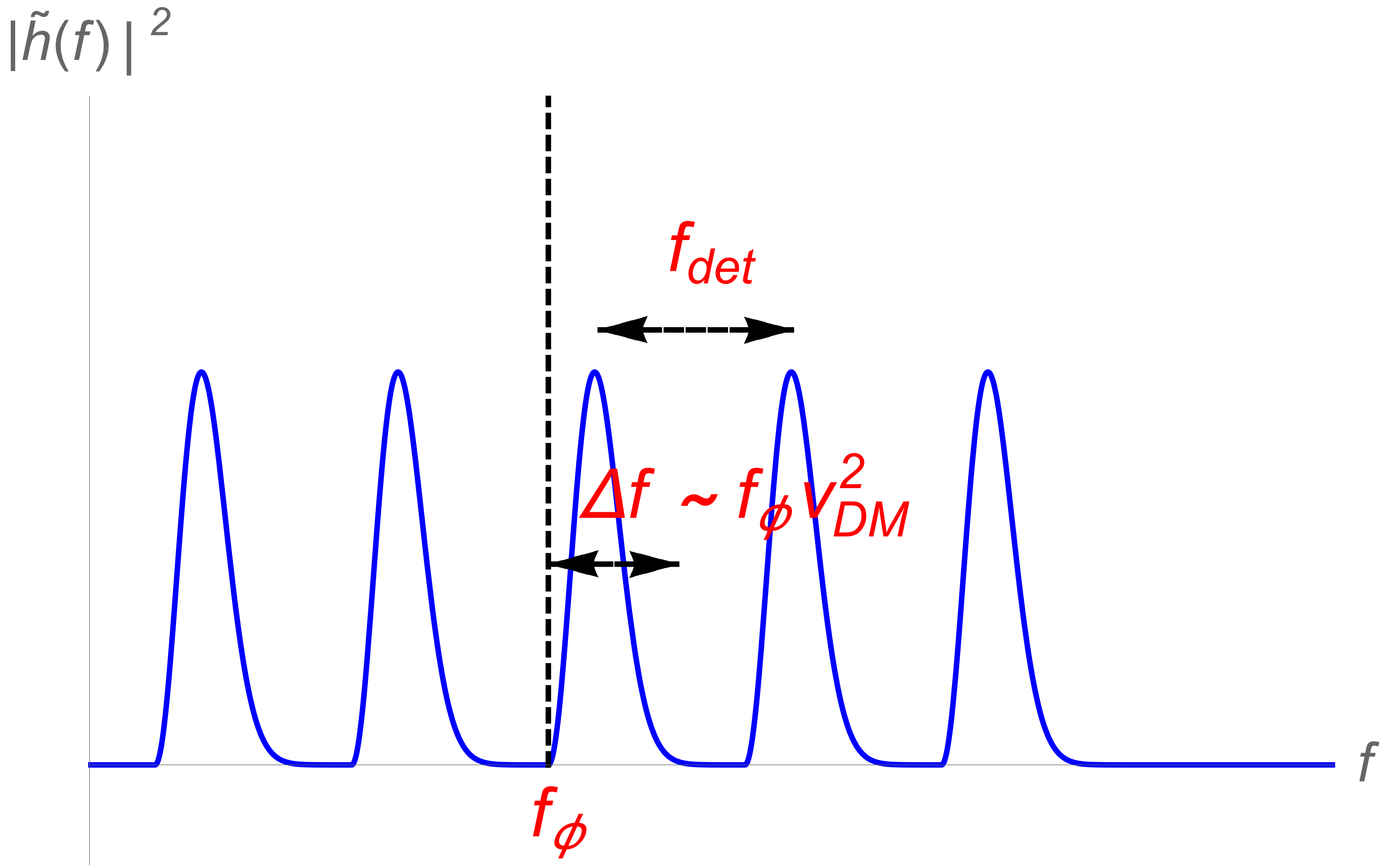


Spectrum



$$f_\phi v_{\rm DM}^2 \gtrsim f_{\rm det}$$

Spectrum

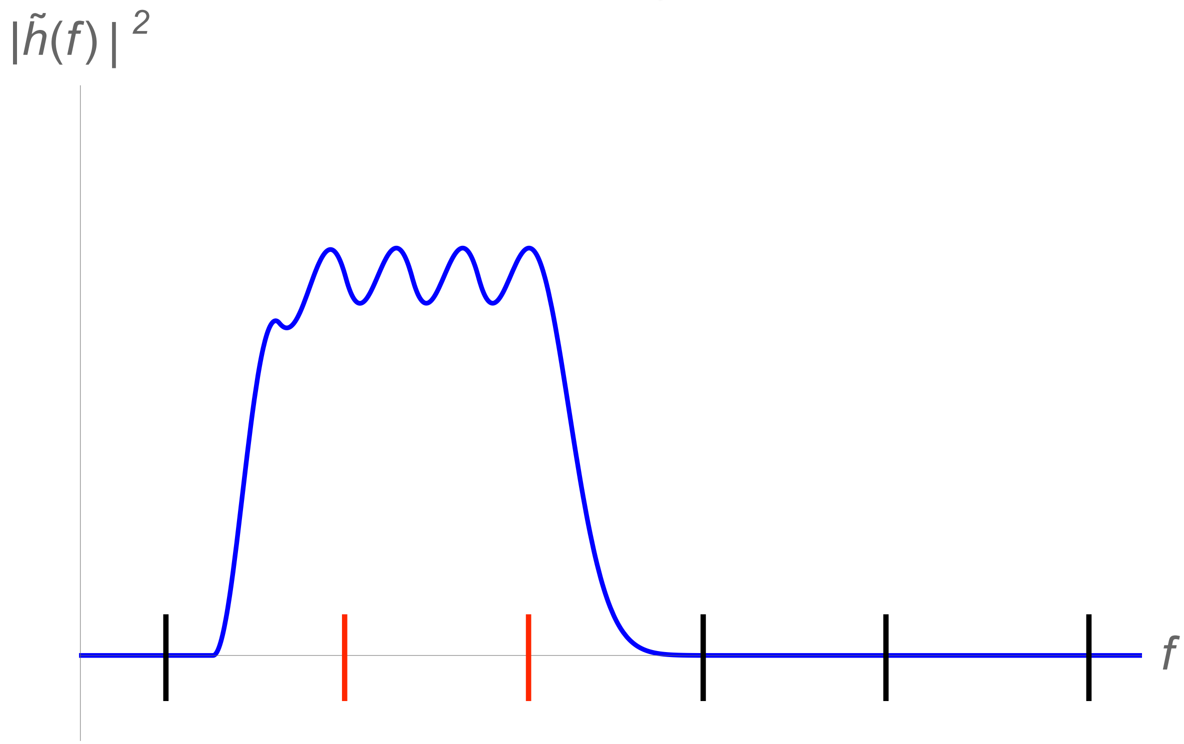


$$f_\phi v_{\rm DM}^2 \ll f_{\rm det}$$

Detection method

- Incoherent sum of the spectra

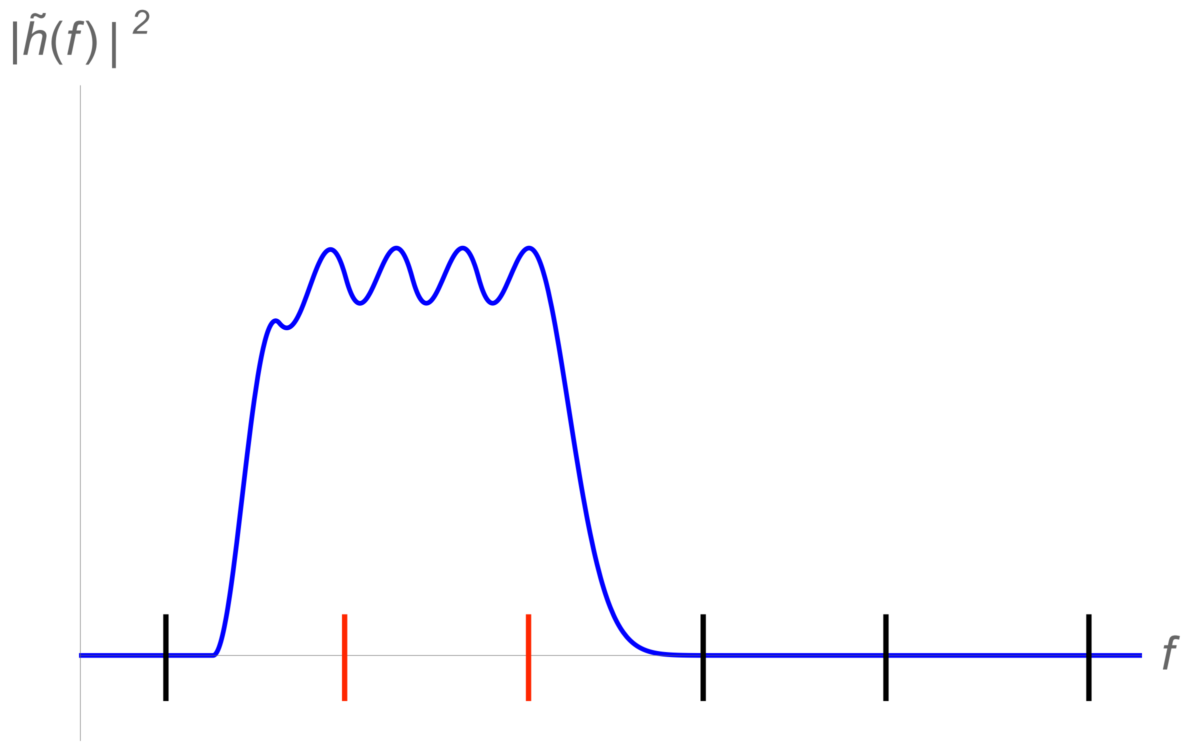
$$\rho(f_\phi) \equiv \sum_{f_k \in F(f_\phi)} \frac{2|\tilde{s}(f_k)|^2}{T_{\text{obs}} S(f_k)}$$



Detection method

- Narrow-band stochastic GW search

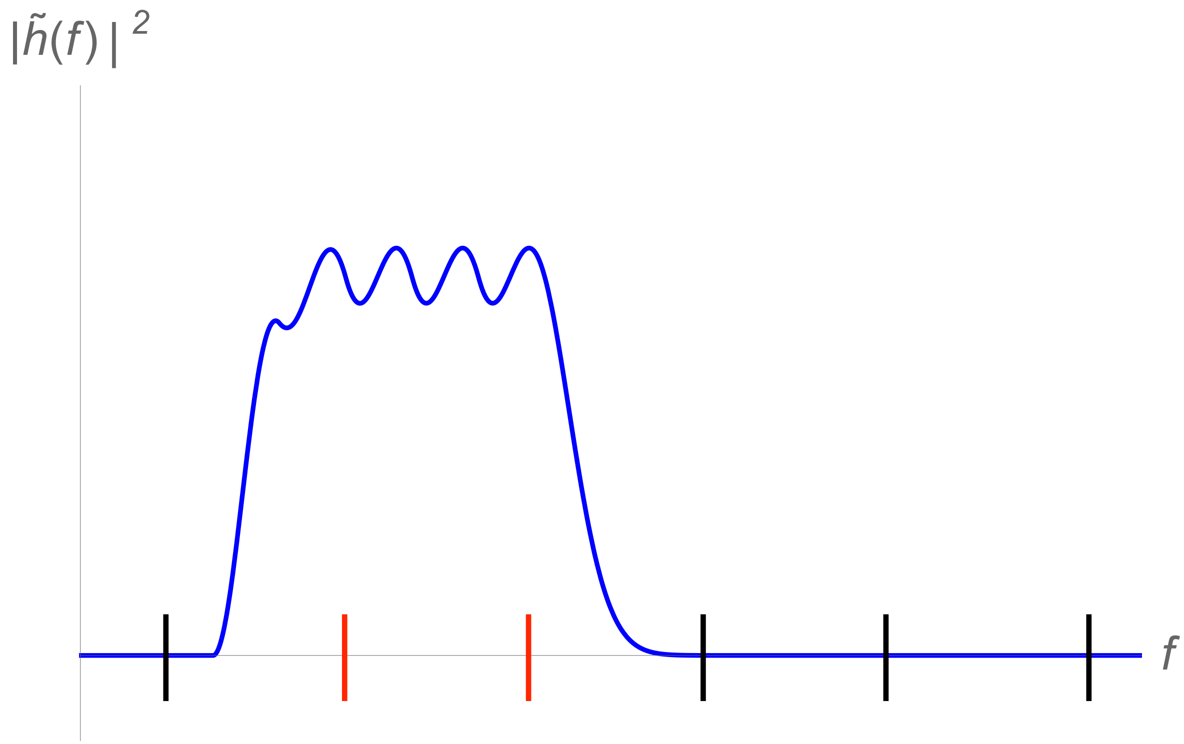
$$\rho(f_\phi) = \frac{1}{T_{\rm obs}} \sum_{k=-\infty}^{\infty} \tilde{s}_1^*(f_k)\tilde{s}_2(f_k)\tilde{Q}(f_k;f_\phi)$$



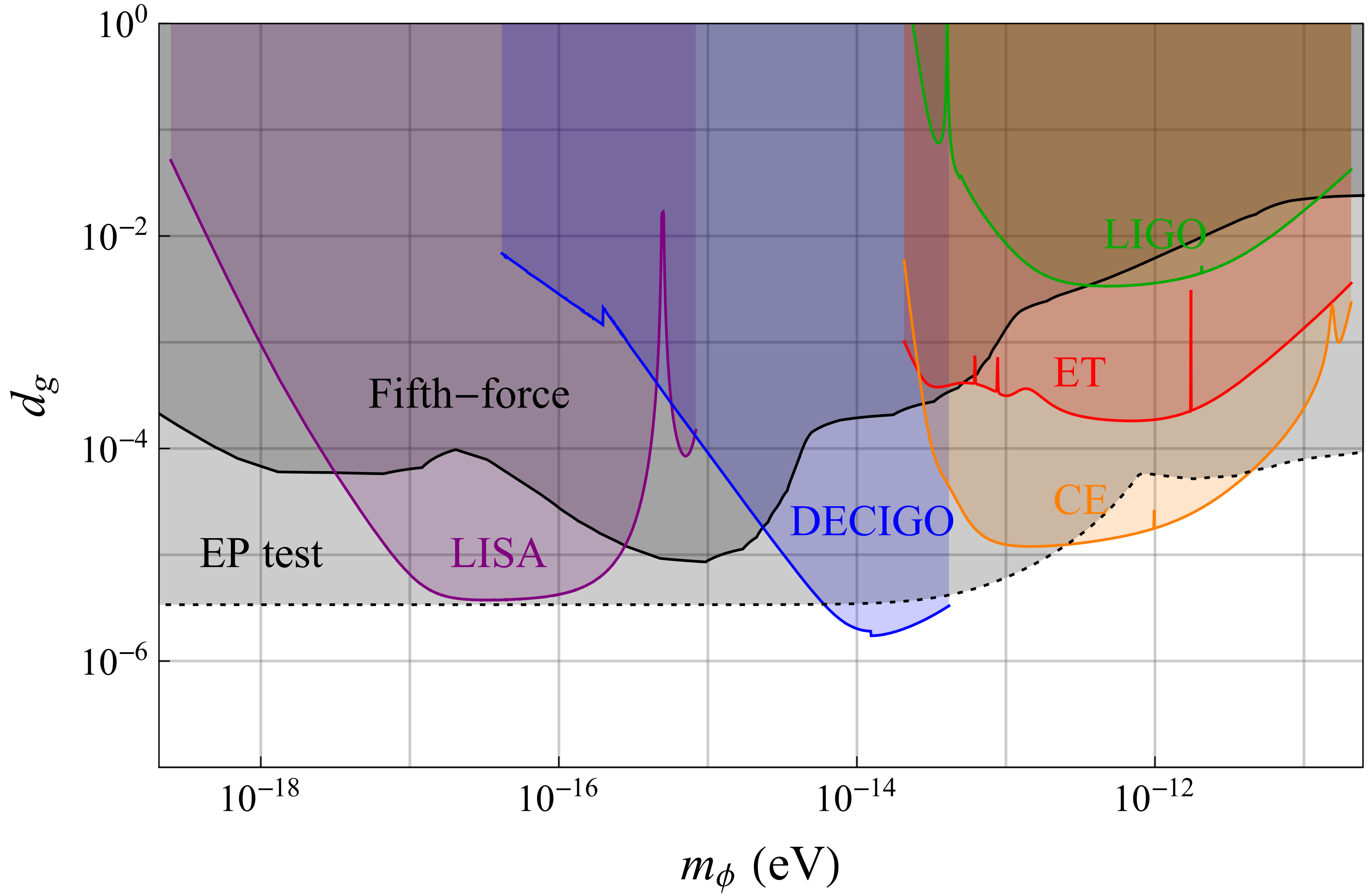
Detection method

- Incoherent sum of the spectra
- Narrow-band stochastic GW search

Both sensitivities are within the same order.



Detectability



$$d_{m_e} = d_{m_u} = d_{m_d} = d_e = 0$$

Comparison with EP test

- Composition independent effect: d_g

Constrained by GW obs.

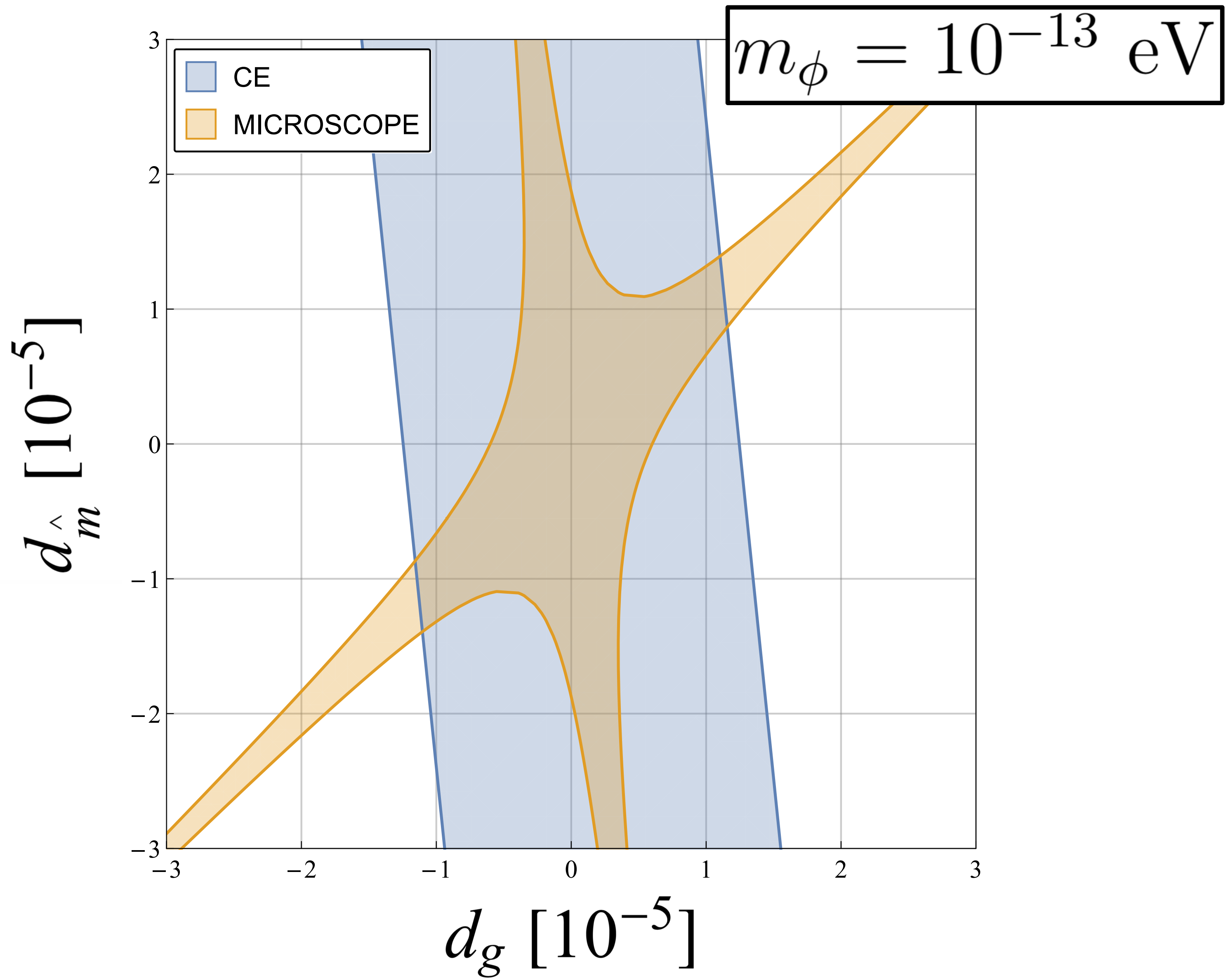
- Composition dependent effect:

$$d_g(d_{m_e} - d_g),\ d_g(d_{m_u} - d_g),$$
$$d_g(d_{m_d} - d_g),\ d_g d_e$$

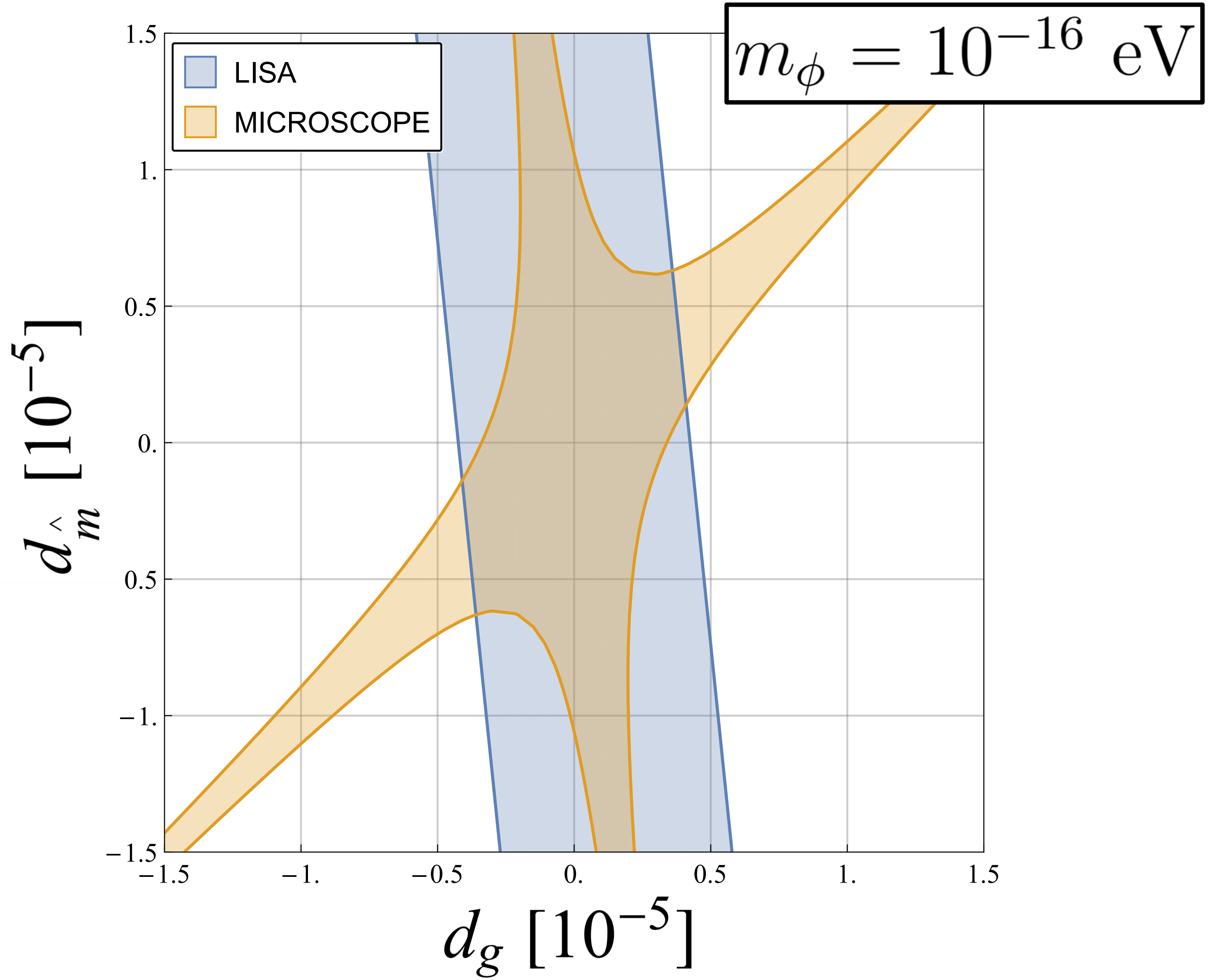
Constrained by EP test. Damour, Donoghue, '10

No constraints if they are suppressed

Comparison with EP test



Comparison with EP test

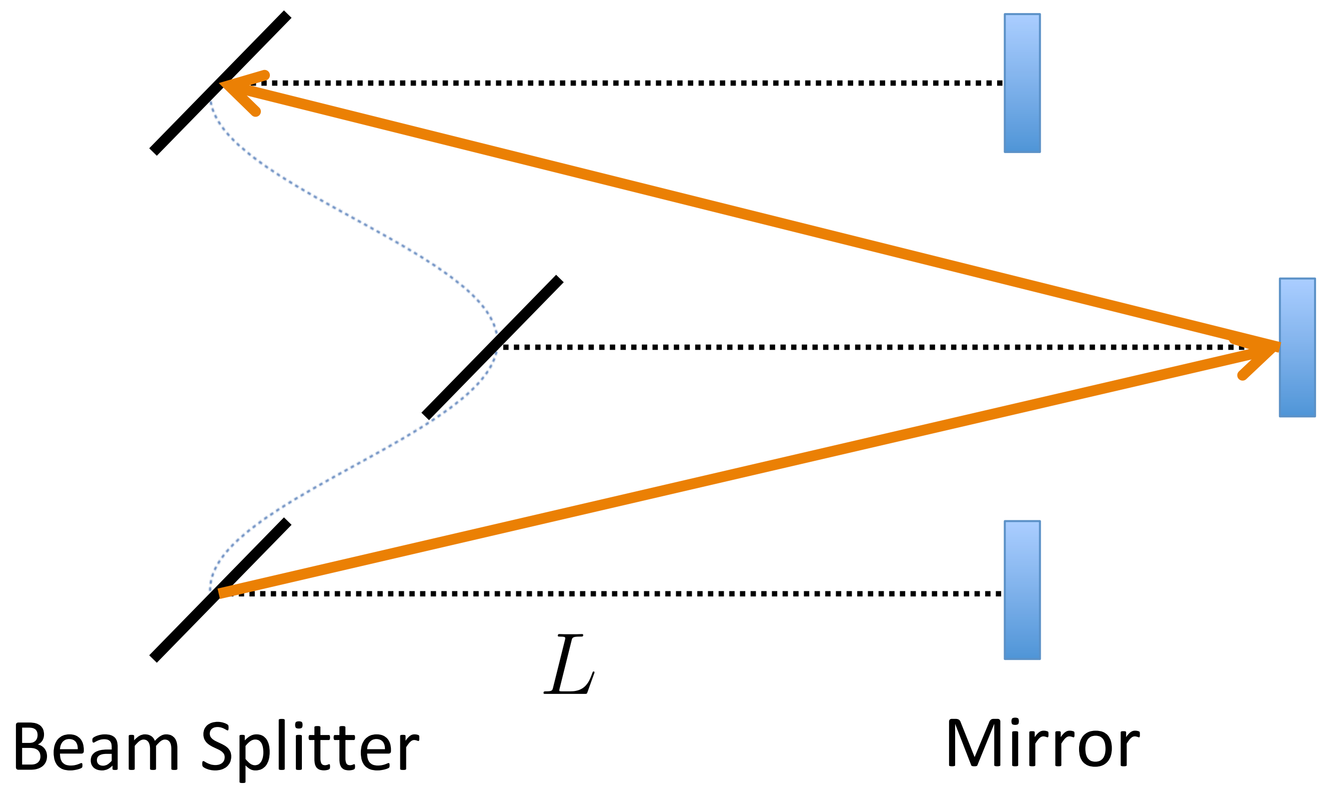


Conclusion

- We studied the spectra of the signal in a GW detector from ultralight scalar field dark matter.
- We developed data analysis methods to detect this signal.
- The constraint is improved by a factor of O(10) – O(100) compared to that from fifth-force experiments.
- Tests with GW detectors play a complementary role to the EP tests.

Signal expression

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



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