Blowing in the Dark Matter Wind

Markus Luty
UC Davis

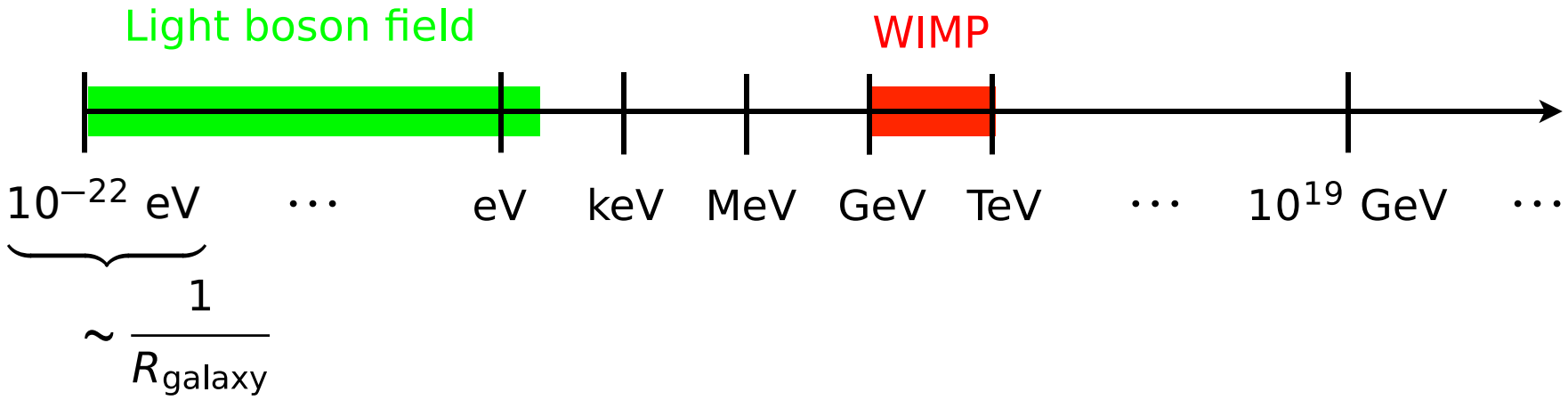
Work in progress with H. Day, D. Liu, Y. Zhao

Memories...

Eduardo Ponton

What is Dark Matter?

We have many ideas, but no clue...



Strategy: look everywhere we can!

This talk: scalar dark matter with $m_\phi \lesssim 10$ eV

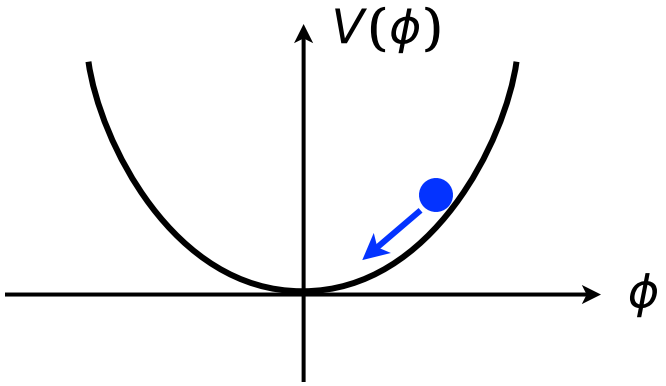
DM Production

Misalignment mechanism:

$$V(\phi) = \tfrac{1}{2} m_\phi^2 \phi^2$$

$H \gg m_\phi$: ϕ frozen

$H \lesssim m_\phi$: ϕ oscillates



Can account for DM density today

$$\phi(t) = \phi_0 \cos(m_\phi t)$$ coherent field

$$\rho_{\mathrm{DM}} = \tfrac{1}{2} m_\phi^2 \phi_0^2$$

Coupling to Standard Model

Expect leading coupling via lowest dimension SM operators:

$d = 2 : \quad H^\dagger H$ "Higgs portal"

$d = 4 : \quad F^2_{\mu\nu} \quad \cdots$

$\vdots$

Focus on Higgs portal:

$$\mathcal{L}_{\text{int}} = -\underbrace{b\phi H^\dagger H}_{\text{forbid by } \mathbb{Z}_2 \text{ symmetry}} - \tfrac{1}{2}\epsilon\phi^2 H^\dagger H \qquad \epsilon \ll 1$$

"$\mathbb{Z}_2$ Higgs portal"

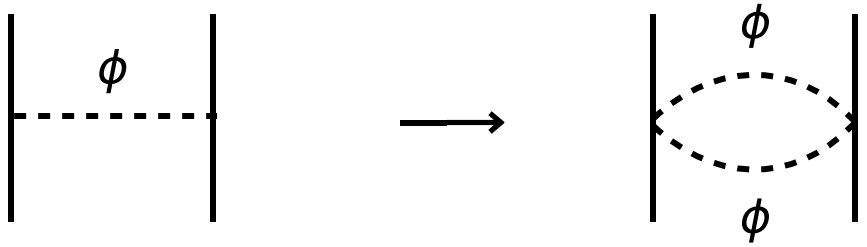
This talk: new DM signals

Forces From DM

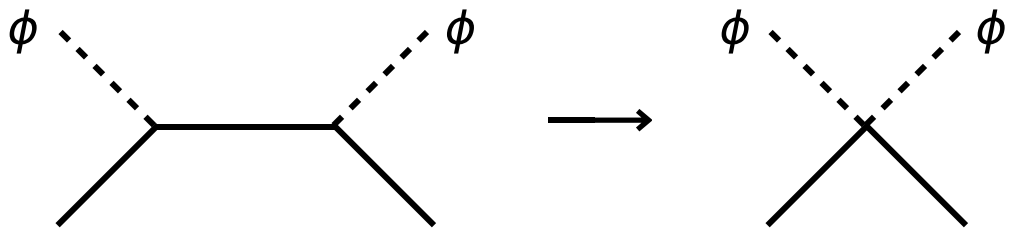
$E \ll$ GeV : $\mathcal{L}_{\text{eff}} = -\frac{1}{2f}\phi^2 \bar{N} N$ $N =$ nucleon

$$\frac{1}{f} \simeq \underbrace{\frac{\epsilon}{4m_h^2}}_{\delta v \propto \phi^2} \times \underbrace{\frac{2}{9} m_N}_{\substack{\text{QCD} \\ \text{running}}}$$

Equivalence principle violating forces suppressed:



Scattering enhanced:



Constraints

Star cooling:

$$NN \to NN\phi\phi \quad \Rightarrow \frac{1}{f} \lesssim 10^{11}\ \mathrm{GeV}^{-1}$$

[Olive, Pospelov, 2008]

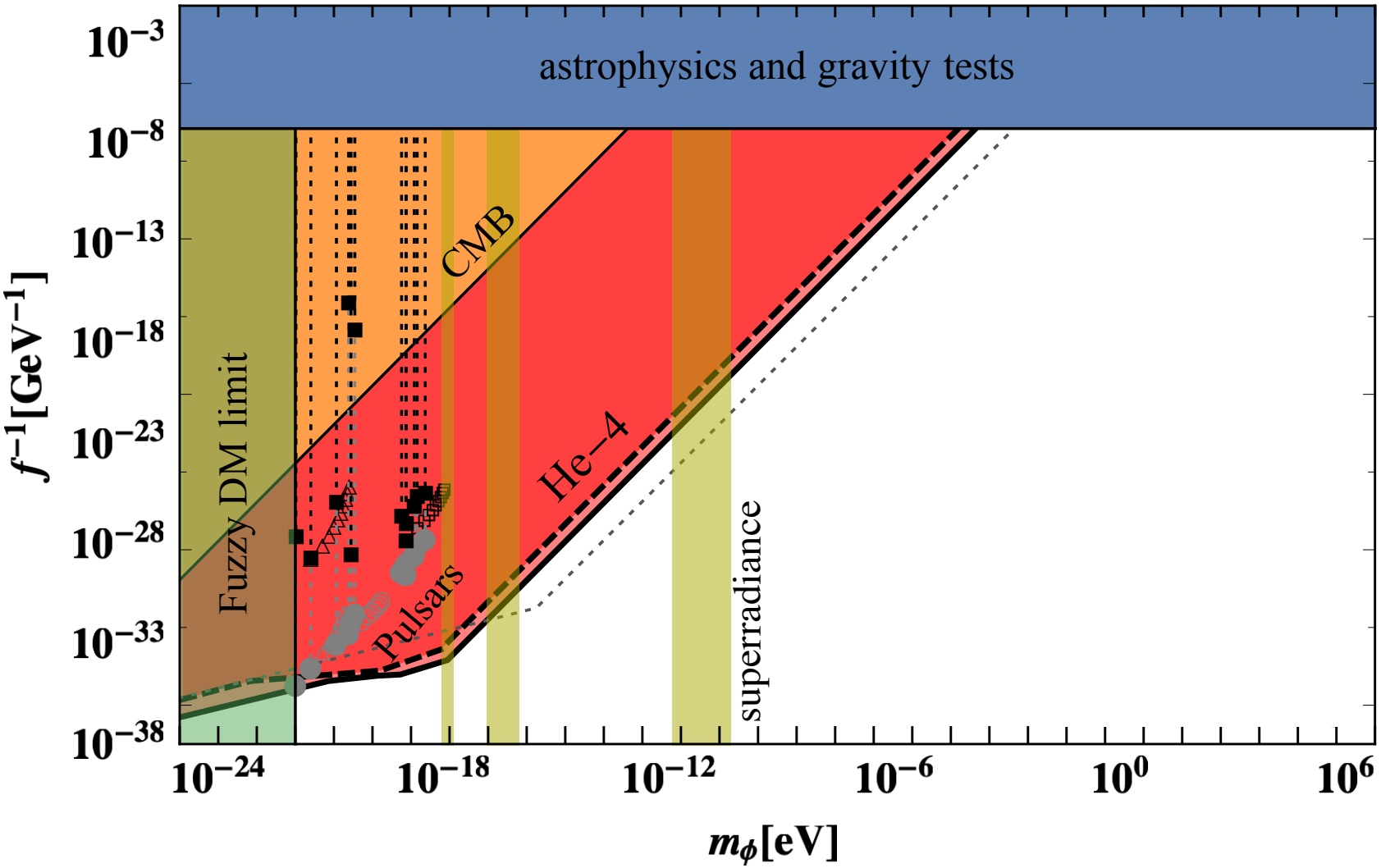
Nucleosynthesis:

$$\Delta(m_n - m_p) \propto \frac{1}{f}\langle\phi^2\rangle$$

$$\Rightarrow \frac{1}{f} \lesssim 10^{-11}\ \mathrm{GeV}^{-1}\left(\frac{m_\phi}{10^{-6}\ \mathrm{eV}}\right)^2$$

[Stadnik,Flambaum (2015)]

Constraints



[T.T. Yu]

Blowing in the Wind

Focus on experiments that average over DM oscillations

Coherence time:

$$t_{\text{coherence}} \sim \frac{\lambda_{\text{dB}}}{v} \sim 10^{-9}\ \text{sec} \left(\frac{m_\phi}{\text{eV}}\right)^{-1}$$

Experiments with shorter time resolution see a constant dark matter wind

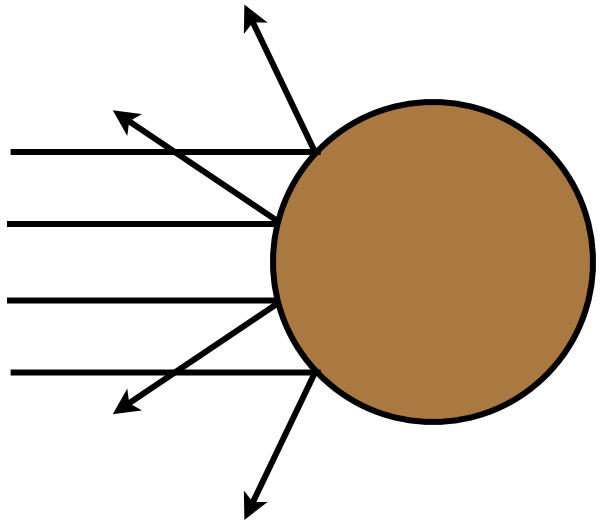
[Fukuda, Matsumoto, Yanagida (2019)]

Dark Forces

Maximum possible force given by incident momentum:

$$F_{\max} = \rho_{\mathrm{DM}} v^2 \times \text{Area}$$

$$= 10^{-14}\ \text{Newtons} \left(\frac{R}{\text{cm}} \right)^2$$



Remakably, this can be saturated!

Dark Forces

ϕ propagation in matter:

$$\mathcal{L}_{\text{eff}} = -\frac{1}{2f}\phi^2 \bar{N} N \quad \Rightarrow \quad \Delta m_\phi^2 = \frac{n_N}{f}$$

$$k_{\text{matt}}^2 = m_\phi^2 v_{\text{vac}}^2 - \Delta m_\phi^2 < 0$$

$\Rightarrow \phi$ exponentially suppressed in matter

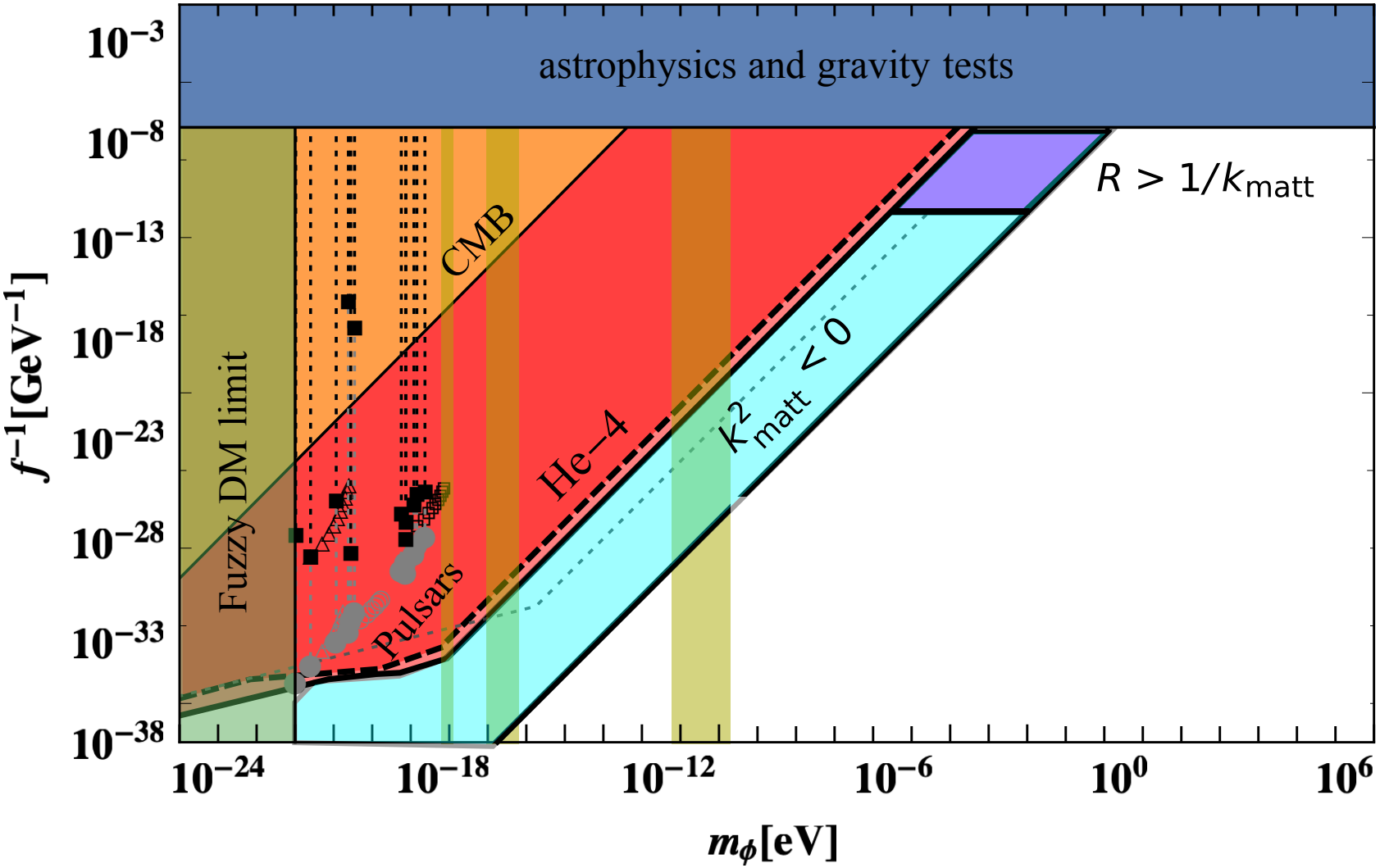
$$\frac{1}{f} \gtrsim 10^{-7}\ \text{GeV}^{-1} \left(\frac{m_\phi}{\text{eV}}\right)^2$$

"DM Meissner effect'

For complete reflection, target must be larger than skin depth

$$R \gtrsim \frac{1}{k_{\text{matt}}} \qquad \frac{1}{f} \gtrsim 10^{10}\ \text{GeV}^{-1} \left(\frac{R}{\text{cm}}\right)^2$$

Dark Forces

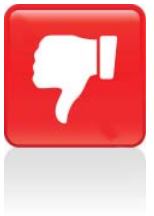

astrophysics and gravity tests
CMB
Fuzzy DM limit
He−4
Pulsars
$K^2_{\rm matt} < 0$
$R > 1/k_{\rm matt}$
10^{-3}
10^{-8}
10^{-13}
10^{-18}
10^{-23}
10^{-28}
10^{-33}
10^{-38}
f^{-1}[GeV^{-1}]
10^{-24}
10^{-18}
10^{-12}
10^{-6}
10^{0}
10^{6}
m_ϕ[eV]

Detecting the DM Wind

- Force has constant magnitude and direction
  in galactic reference frame

- Force $\propto$ area $\Rightarrow$ violates equivalence principle

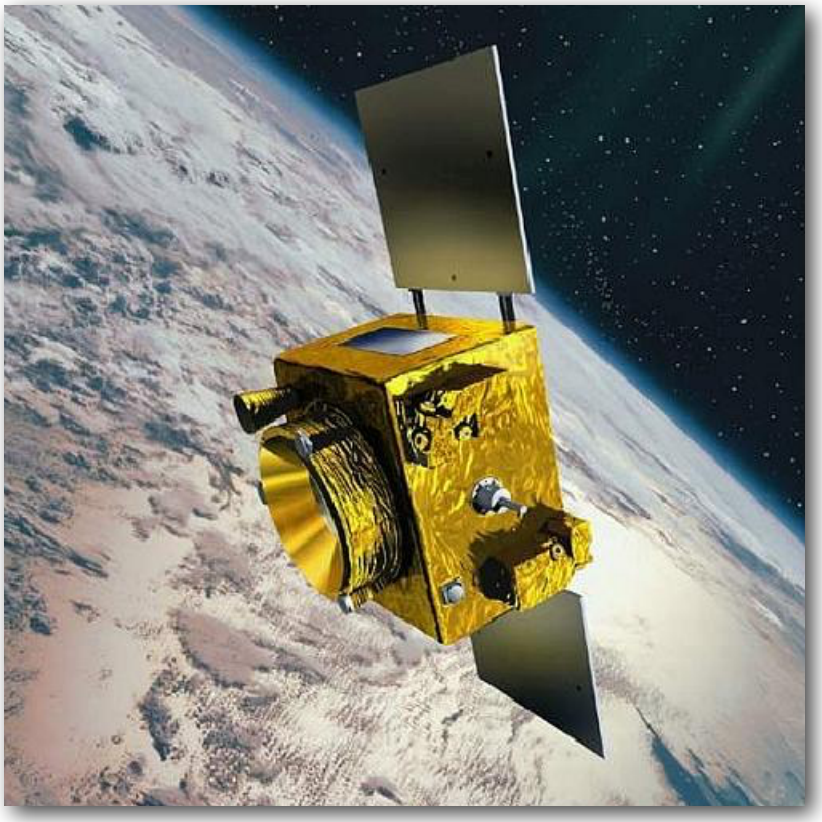
- When force is maximal, matter shields DM wind

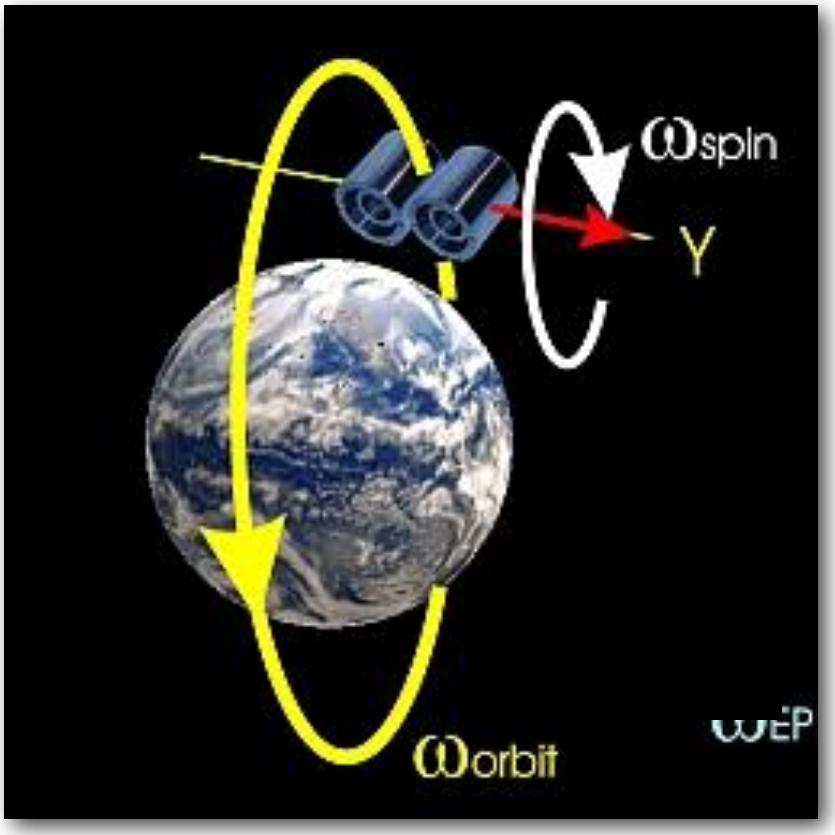


Need sensitive force measurements with minimal shielding

Satellite equivalence principle tests!

MICROSCOPE



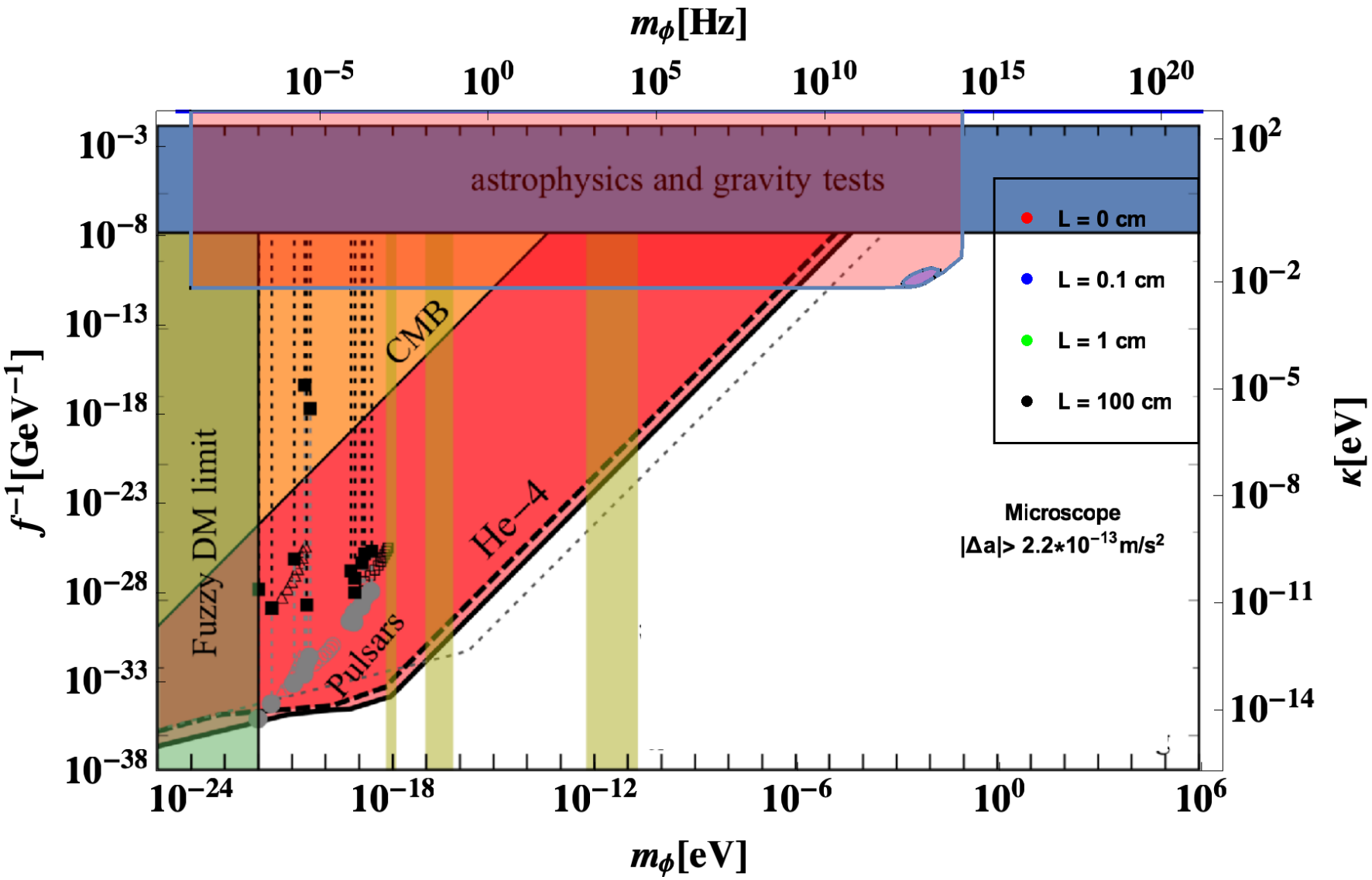


$|\delta a| \sim 10^{-13}$ m/s^2

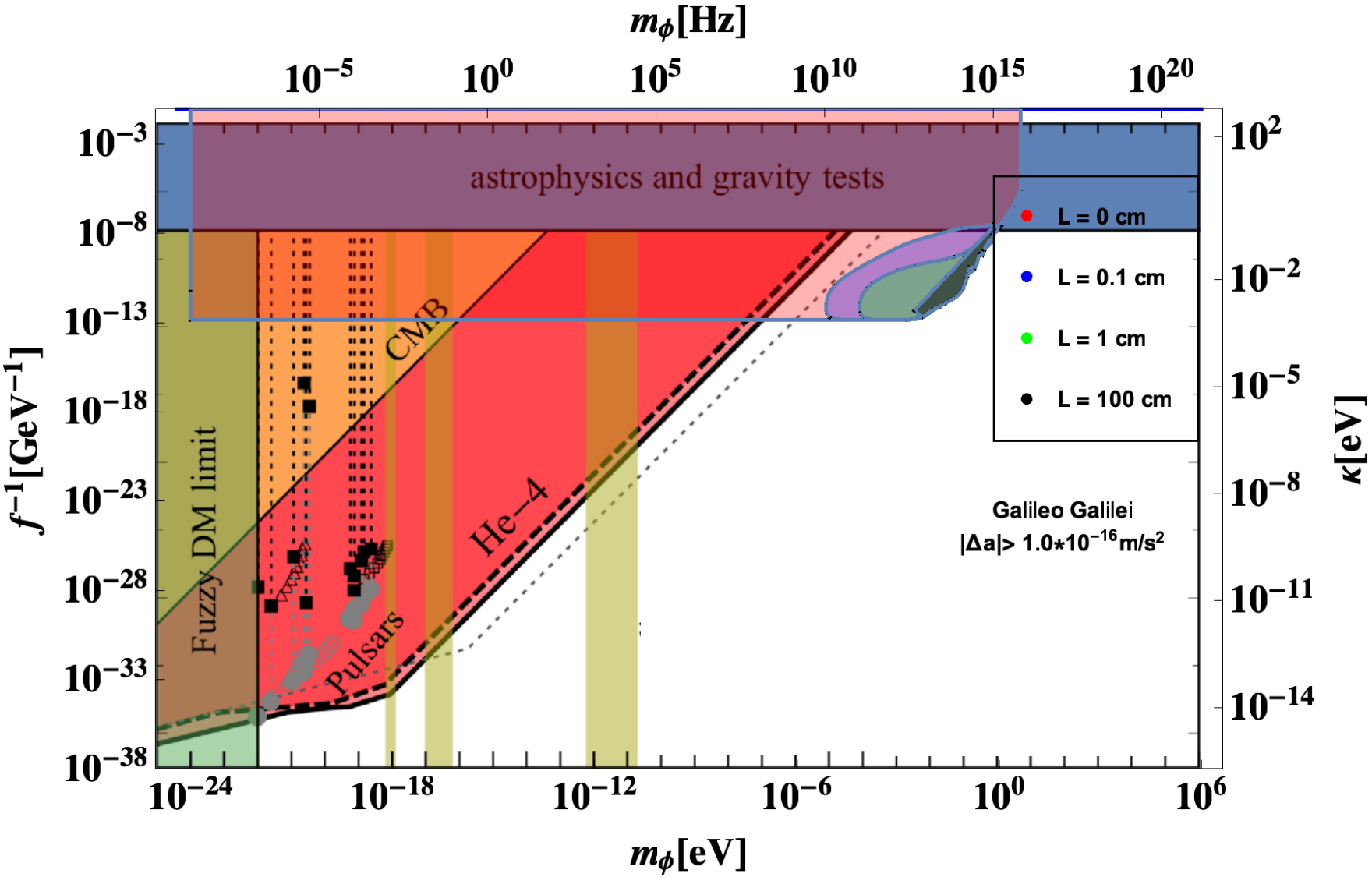
$M \simeq 300$ g

$R \simeq 3$ cm

MICROSCOPE


m_ϕ[Hz]
10^{-5}
10^{0}
10^{5}
10^{10}
10^{15}
10^{20}
10^{-3}
10^{-8}
10^{-13}
10^{-18}
10^{-23}
10^{-28}
10^{-33}
10^{-38}
f^{-1}[GeV^{-1}]
astrophysics and gravity tests
CMB
Fuzzy DM limit
Pulsars
He−4
L = 0 cm
L = 0.1 cm
L = 1 cm
L = 100 cm
Microscope
|Δa|> 2.2*10^{-13}m/s^2
10^{2}
10^{-2}
10^{-5}
10^{-8}
10^{-11}
10^{-14}
κ[eV]
10^{-24}
10^{-18}
10^{-12}
10^{-6}
10^{0}
10^{6}
m_ϕ[eV]

MICROSCOPE II



Future Prospects

- Reducing shielding improves sensitivity

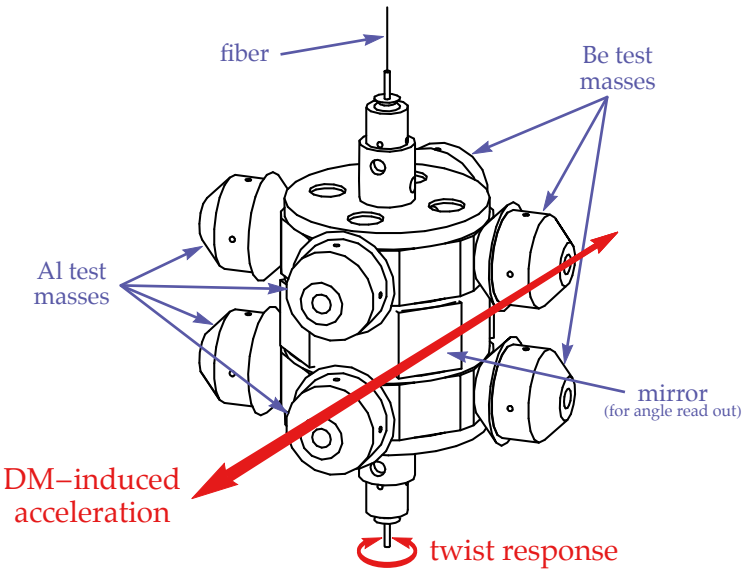
  Optimize satellite experiments (add windows?)

  Eot-Wash above ground?

$$|\delta a| \sim 10^{-15}\ \mathrm{m/s^2}$$

$$M \simeq 5\ \mathrm{g}$$

$$R \simeq 0.8\ \mathrm{cm}$$



- Take advantage of DM shadow from earth?

- Make friends with experimentalists!