Title: 5th forces and astrophysical probes

Speakers: Peter Graham

Collection: School on Table-Top Experiments for Fundamental Physics

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# 5th Forces and Astrophysical Probes

Peter Graham

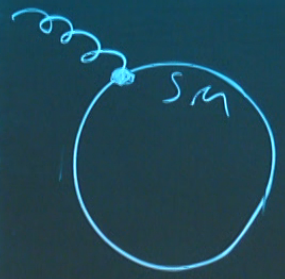
Stanford

# Why look for a 5th force?

1. Theoretically reasonable
2. Specific forces arise from motivated theories
   - Strong CP problem ➜ new force from QCD axion
   - Supersymmetry ➜ new forces from light moduli
3. Similar to modification of gravity
   - e.g. CC problem motivates changing gravity (see e.g. Sundrum (2003))

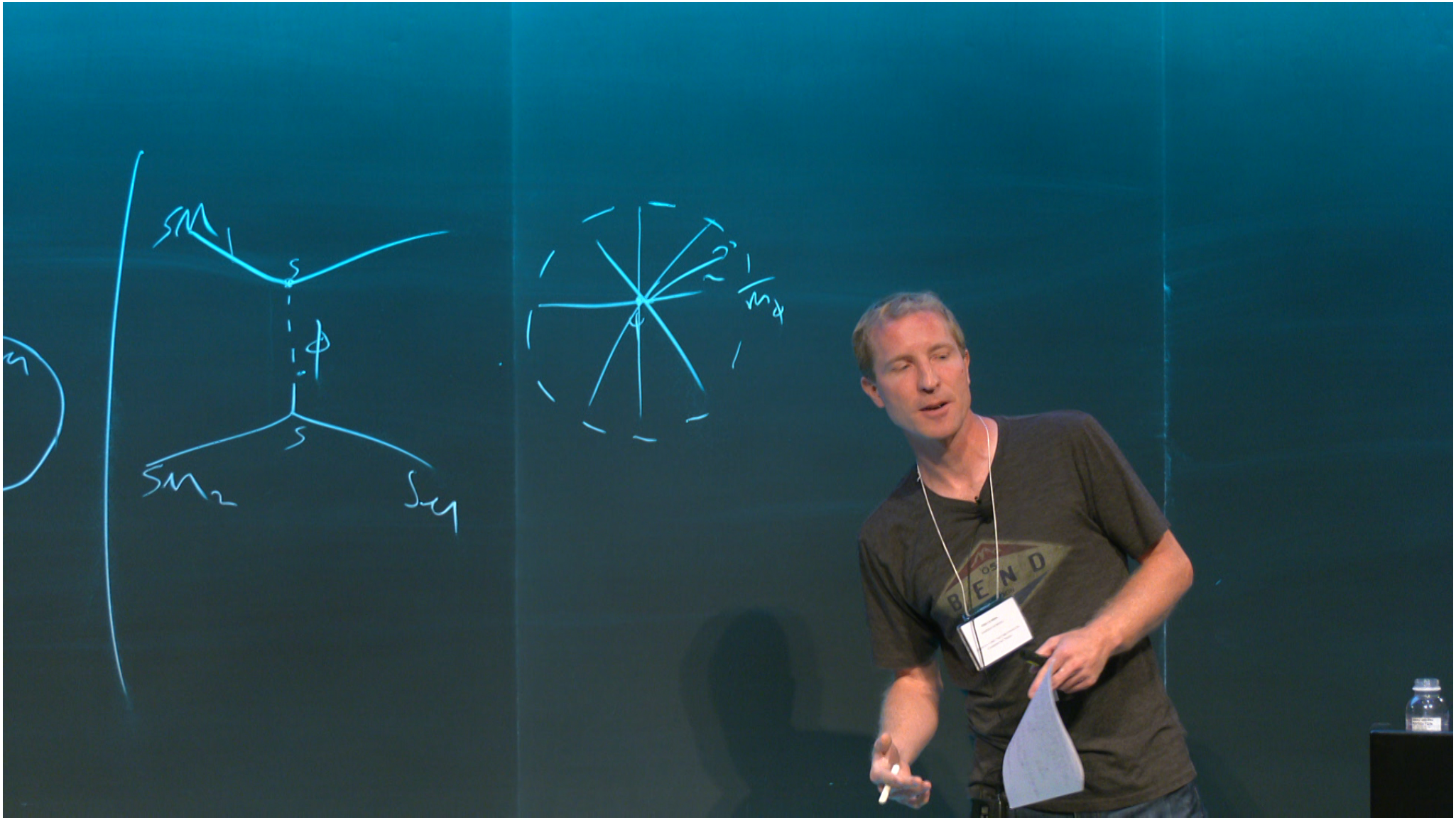
# CC Problem

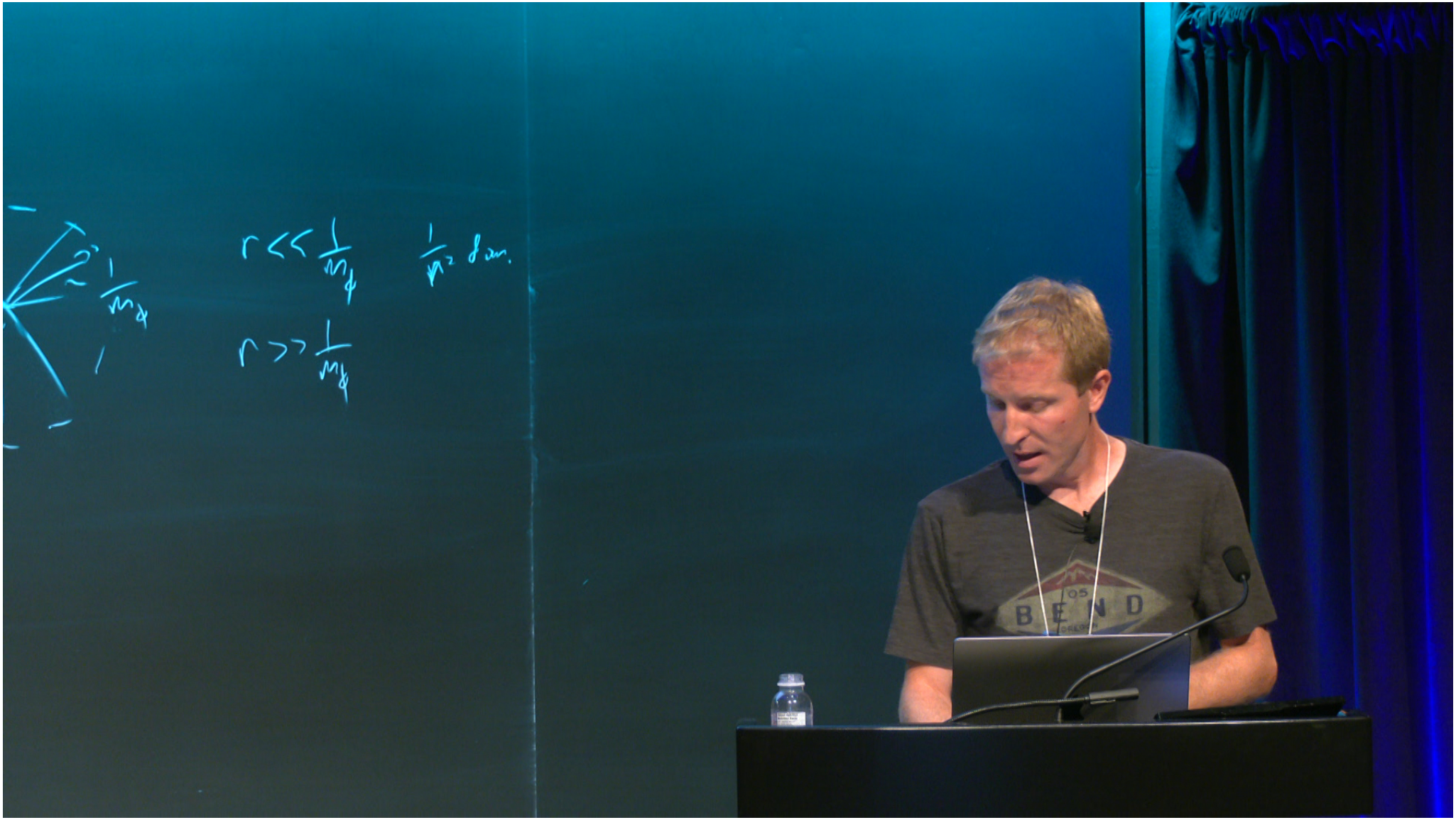
$M_{Pl}^4$ or $TeV^4$




$CC \sim (meV)^4$

$\hbar = c = 1$ $\quad meV \sim mm^{-1}$


SM1
s
φ
s
SM2
SM4
2
1
M4


r << 1/m_φ
1/r² dom.
r >> 1/m_φ
1/m_φ
BEND

# Scalar-mediated forces

see e.g. Moody & Wilczek (1984)

| | Monopole (scalar) | Dipole (spin or pseudoscalar) |
|---|---|---|
| Possible couplings: | $\mathcal{L} \ni g_s \phi \overline{\psi}_{\rm SM} \psi_{\rm SM}$ | $\mathcal{L} \ni g_P \phi \overline{\psi}_{\rm SM} i\gamma_5 \psi_{\rm SM}$ |

## monopole-monopole (scalar-scalar)

$$V(r) = g_s^{(1)} g_s^{(2)} \frac{1}{4\pi r} e^{-m_\phi r}$$

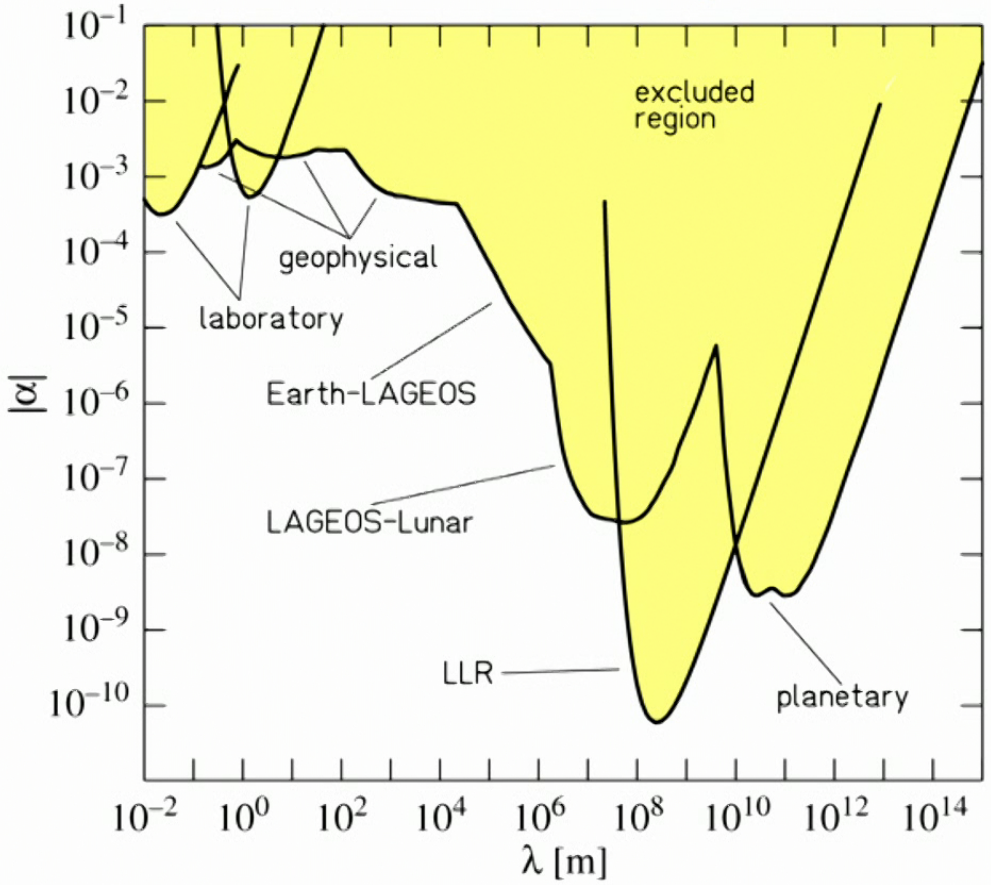
## monopole-dipole (spin-scalar)

$$V(r) = g_s^{(1)} g_p^{(2)} \frac{\sigma_2 \cdot \hat{r}}{8\pi M_2} \left( \frac{1}{r^2} + \frac{m_\phi}{r} \right) e^{-m_\phi r}$$

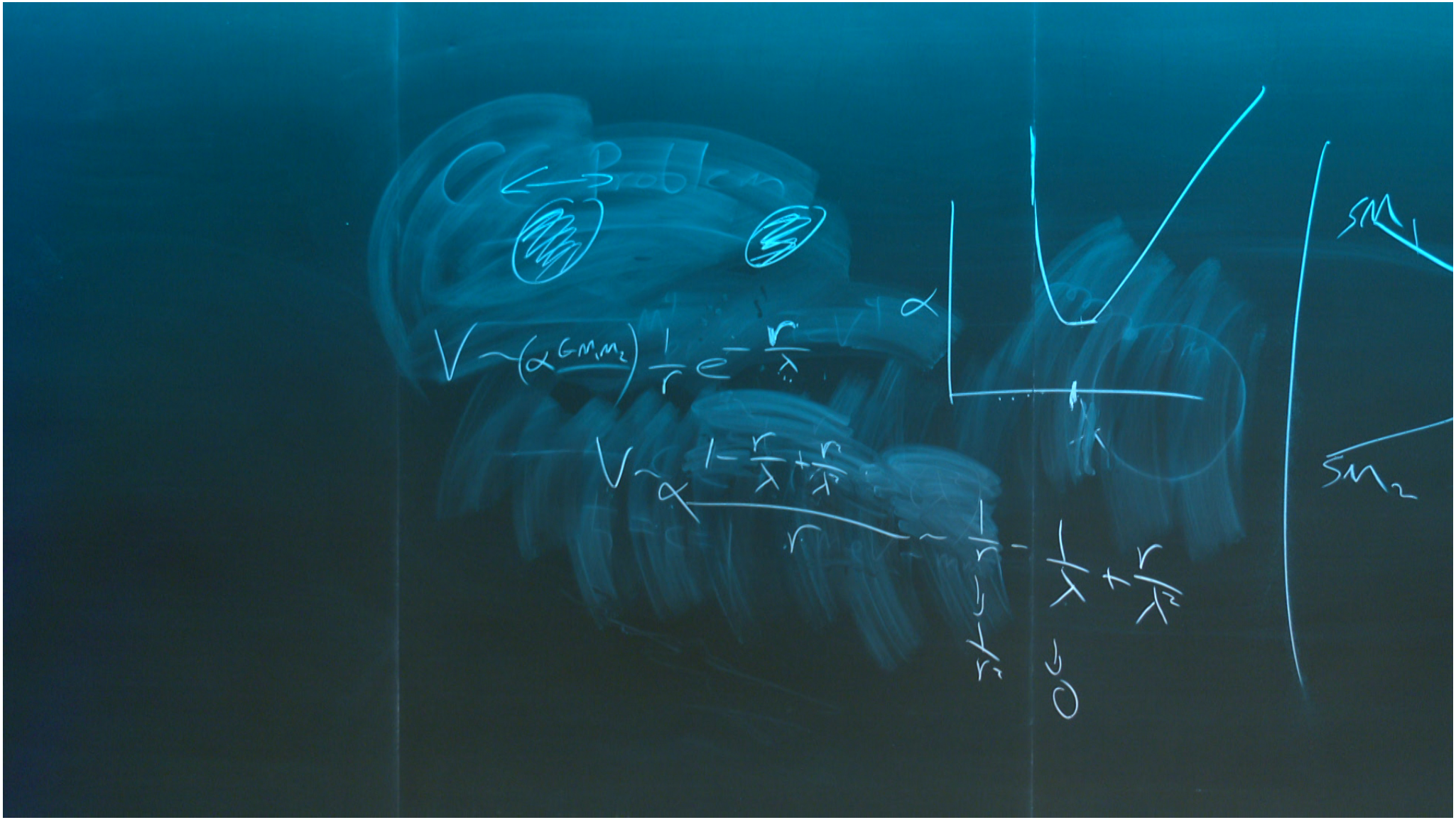
## dipole-dipole (spin-spin)

$$V(r) = \frac{g_p^{(1)} g_p^{(2)}}{16\pi M_1 M_2} \left( (\sigma_1 \cdot \sigma_2) \left( \frac{1}{r^3} + \frac{m_\phi}{r^2} + \frac{4\pi}{3}\delta(r) \right) - (\sigma_1 \cdot \hat{r})(\sigma_2 \cdot \hat{r}) \left( \frac{3}{r^3} + \frac{3m_\phi}{r^2} + \frac{m_\phi^2}{r} \right) \right) e^{-m_\phi r}$$

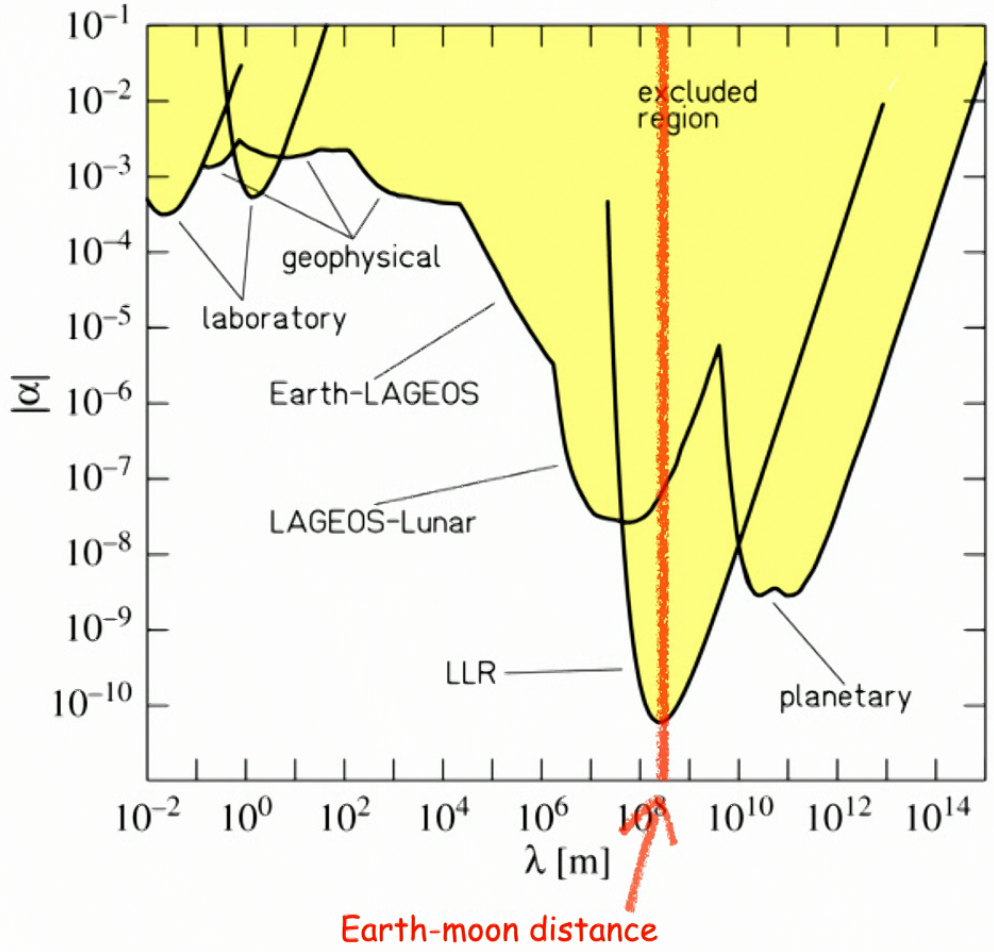
# Limits on "Yukawa" forces




Adelberger, Heckel, & Nelson (2003)


Problem
$V \sim (\alpha G M_1 M_2) \frac{1}{r} e^{-\frac{r}{\lambda}}$
$V \sim \alpha \frac{1 - \frac{r}{\lambda} + \frac{r}{\lambda}}{r}$
$\sim \frac{1}{r} - \frac{1}{\lambda} + \frac{r}{\lambda^2}$
$r \to 0$
$SM_1$
$SM_2$

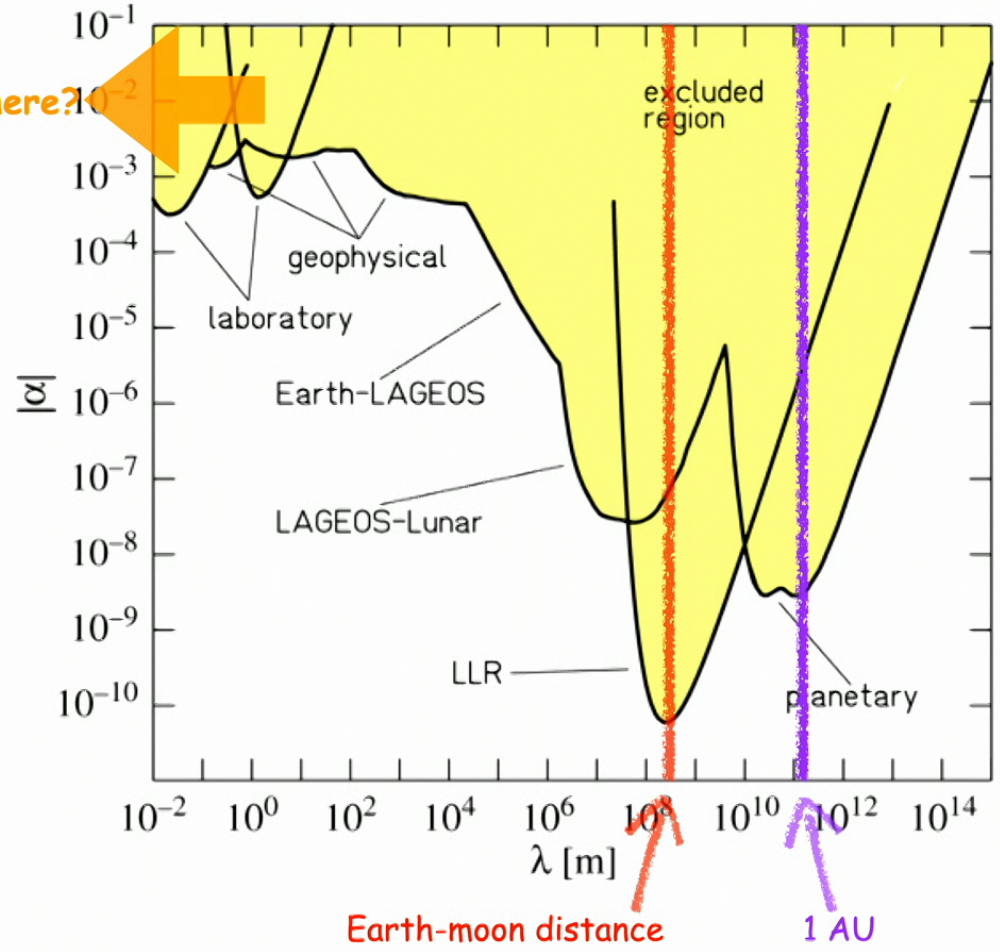
# Limits on "Yukawa" forces




Adelberger, Heckel, & Nelson (2003)

# Limits on "Yukawa" forces

What about here?

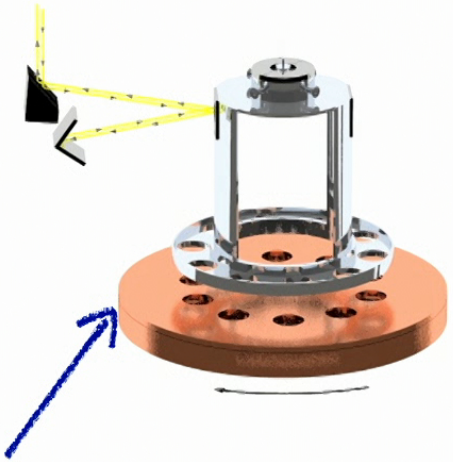



Adelberger, Heckel, & Nelson (2003)

# E.g. Torsion Pendulums

high sensitivity possible: use laser readout of angle

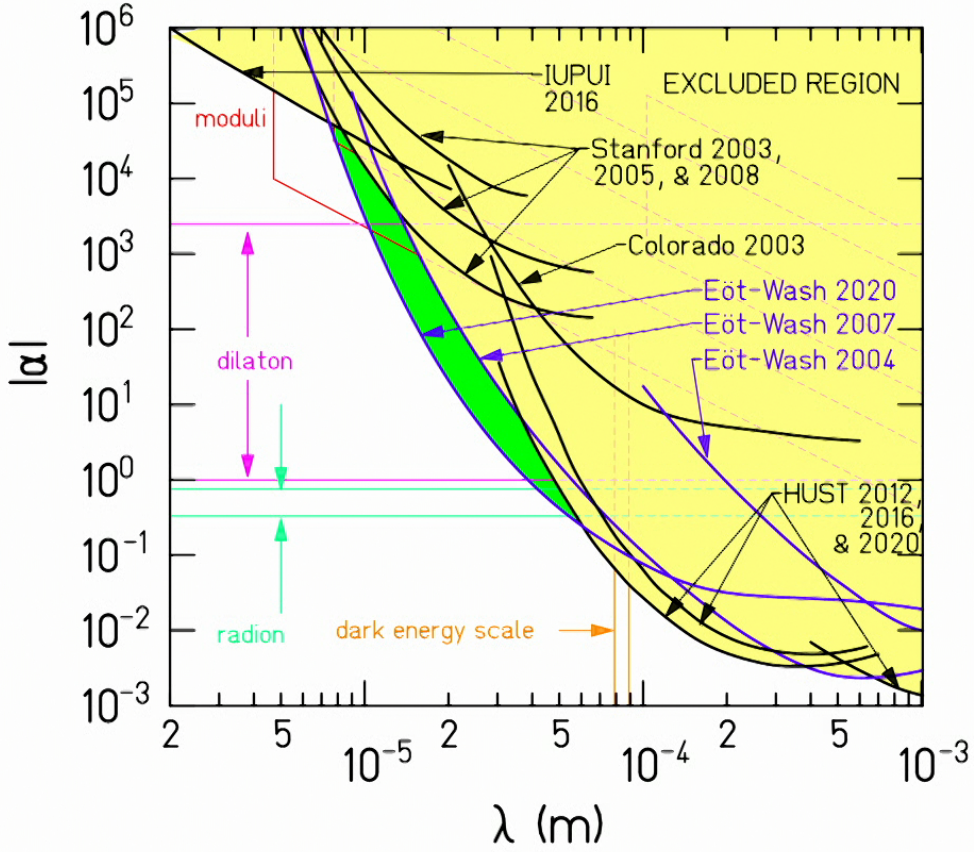
Eot-Wash collaboration



backgrounds:
fiber thermal noise,
laser readout noise,
EM forces (Casimir),
gravity gradients

Source mass is two unequal thickness disks
holes drilled to cancel torques on test mass
Tests distance-dependance of force

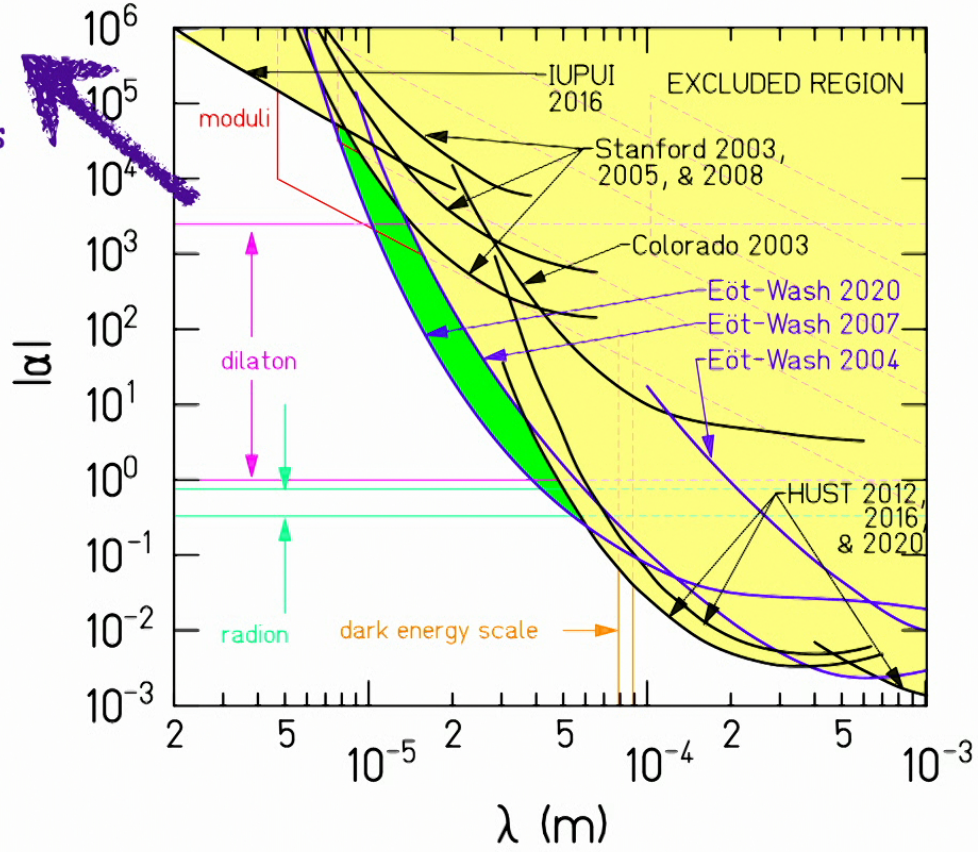
# Limits on short-range forces




From Eot-Wash: Lee, Adelberger, Cook, Fleischer, & Heckel (2020)

# Limits on short-range forces

many other tests,
eventually colliders

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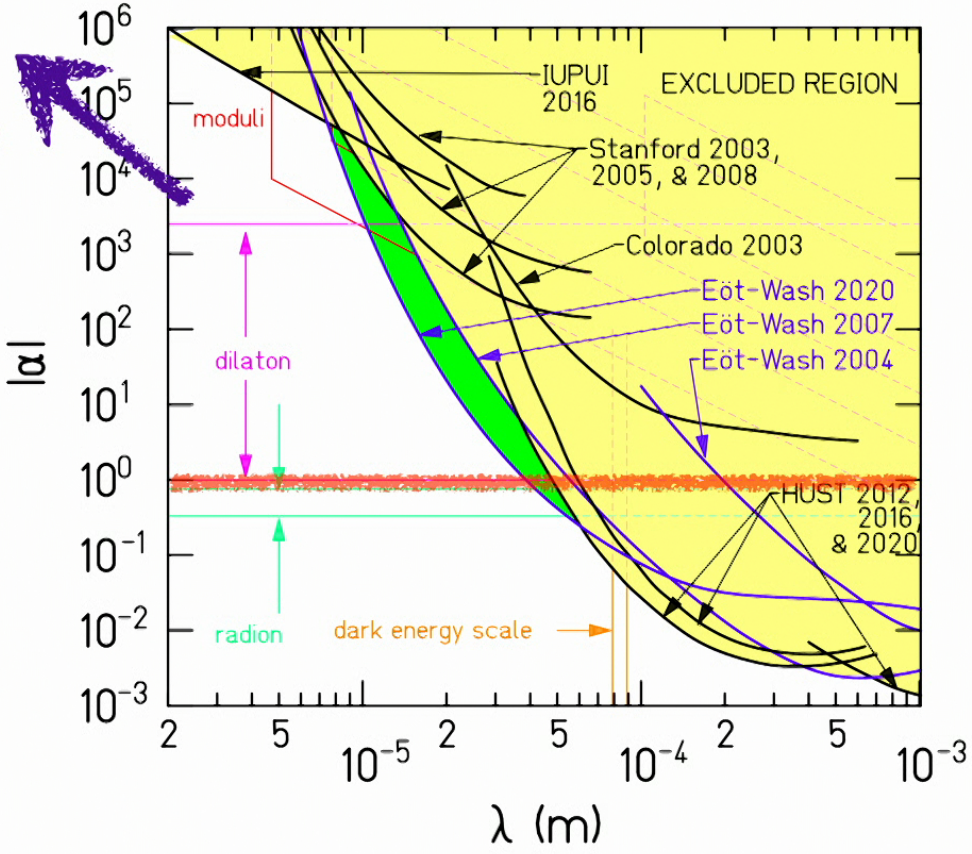


Tested Newtonian gravity down to ~ 40 μm

From Eot-Wash: Lee, Adelberger, Cook, Fleischer, & Heckel (2020)

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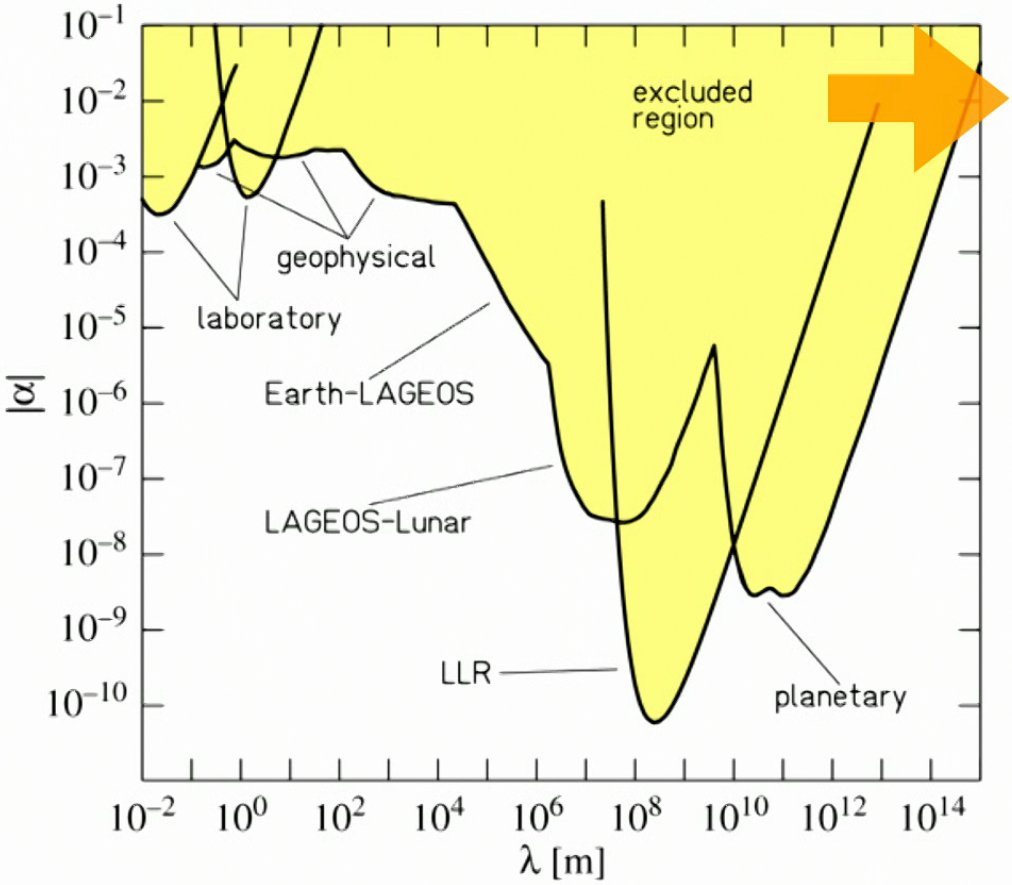



What about here?

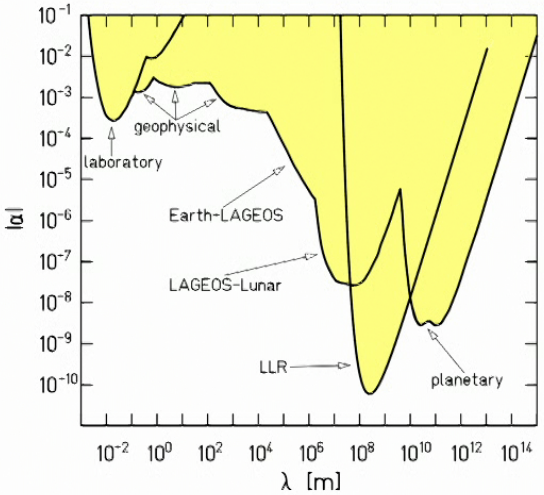
Adelberger, Heckel, & Nelson (2003)

# Equivalence Principle

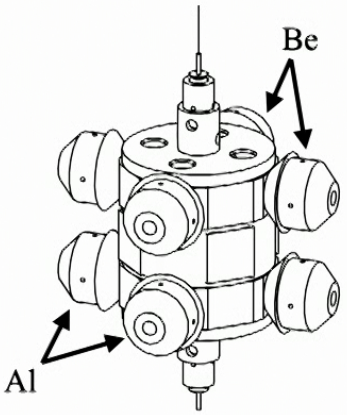
current limits ~ few x $10^{-15}$ from Microscope Satellite PRL (2022)


can see forces ~6000 km or longer

HW: is a short-range EP test interesting?




Torsion Balances



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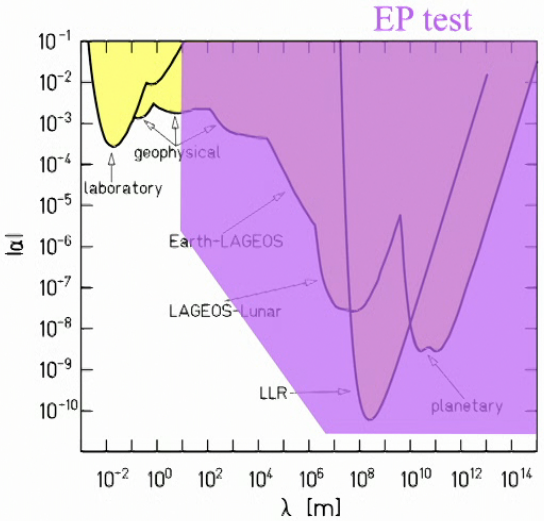
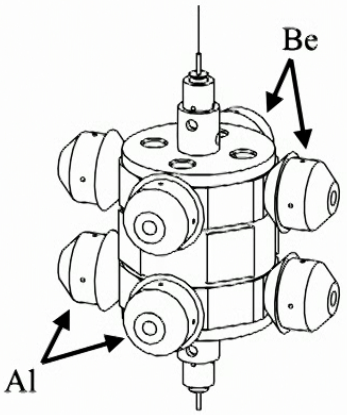



Torsion Balances

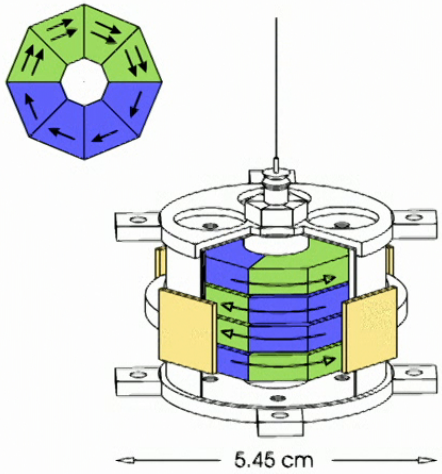


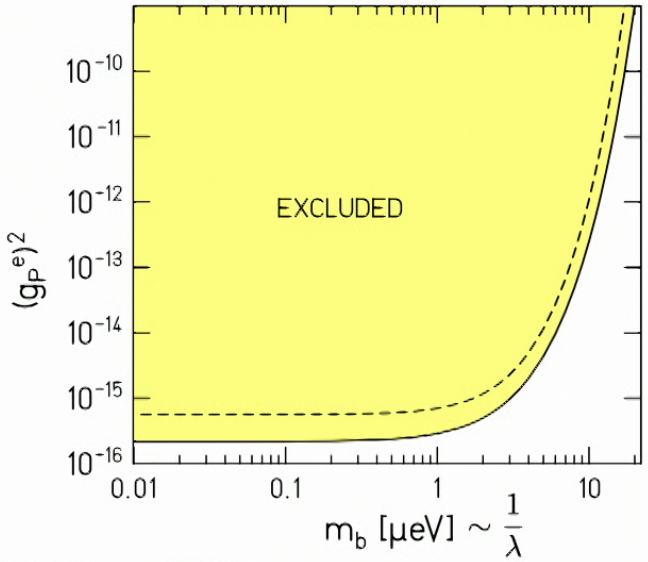
# Spin-Dependent Forces

Can also search for spin-dependent forces (e.g. axion - pseudoscalar)

Automatically distinguishable from gravity

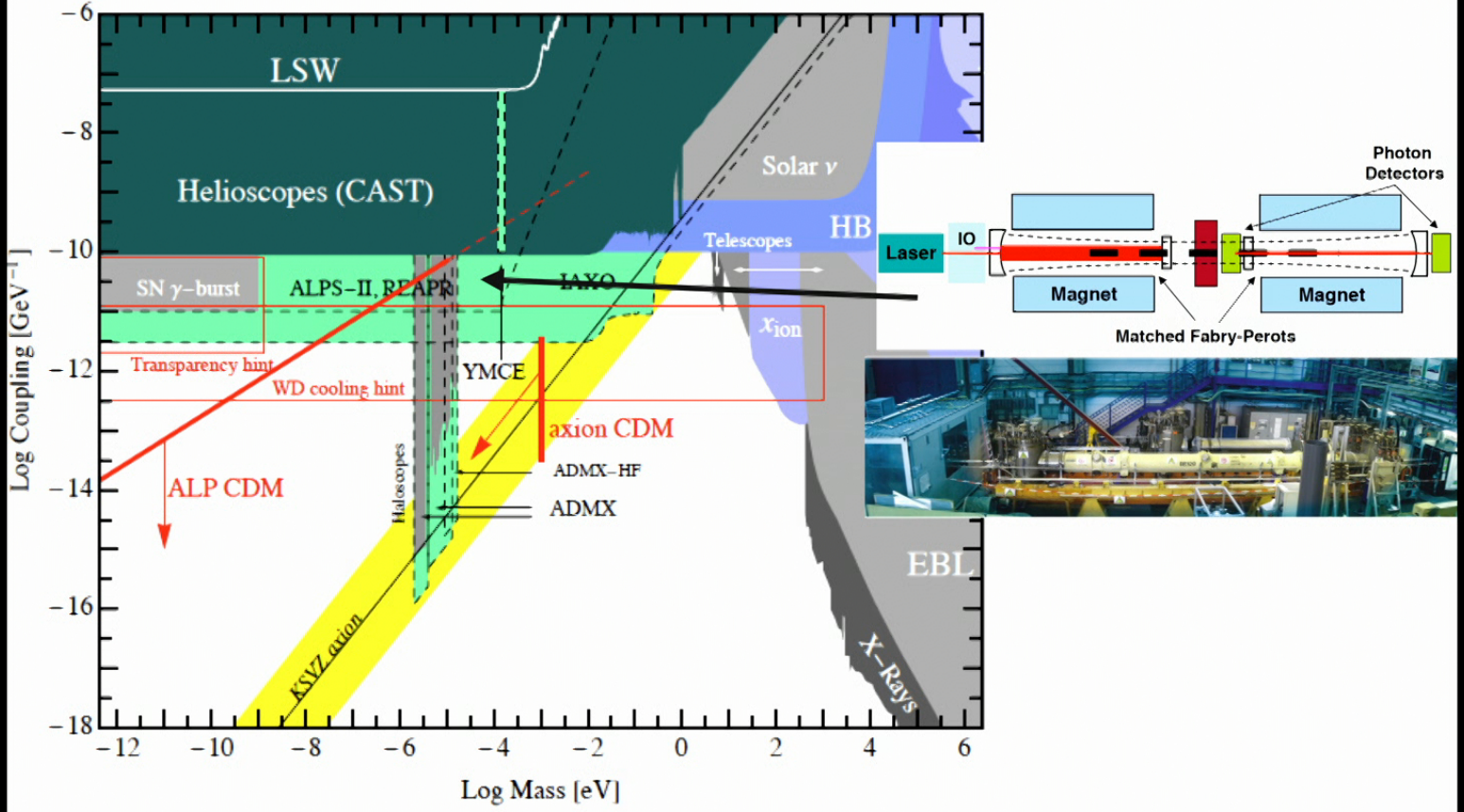
detect e.g. with spin-polarized torsion pendulum

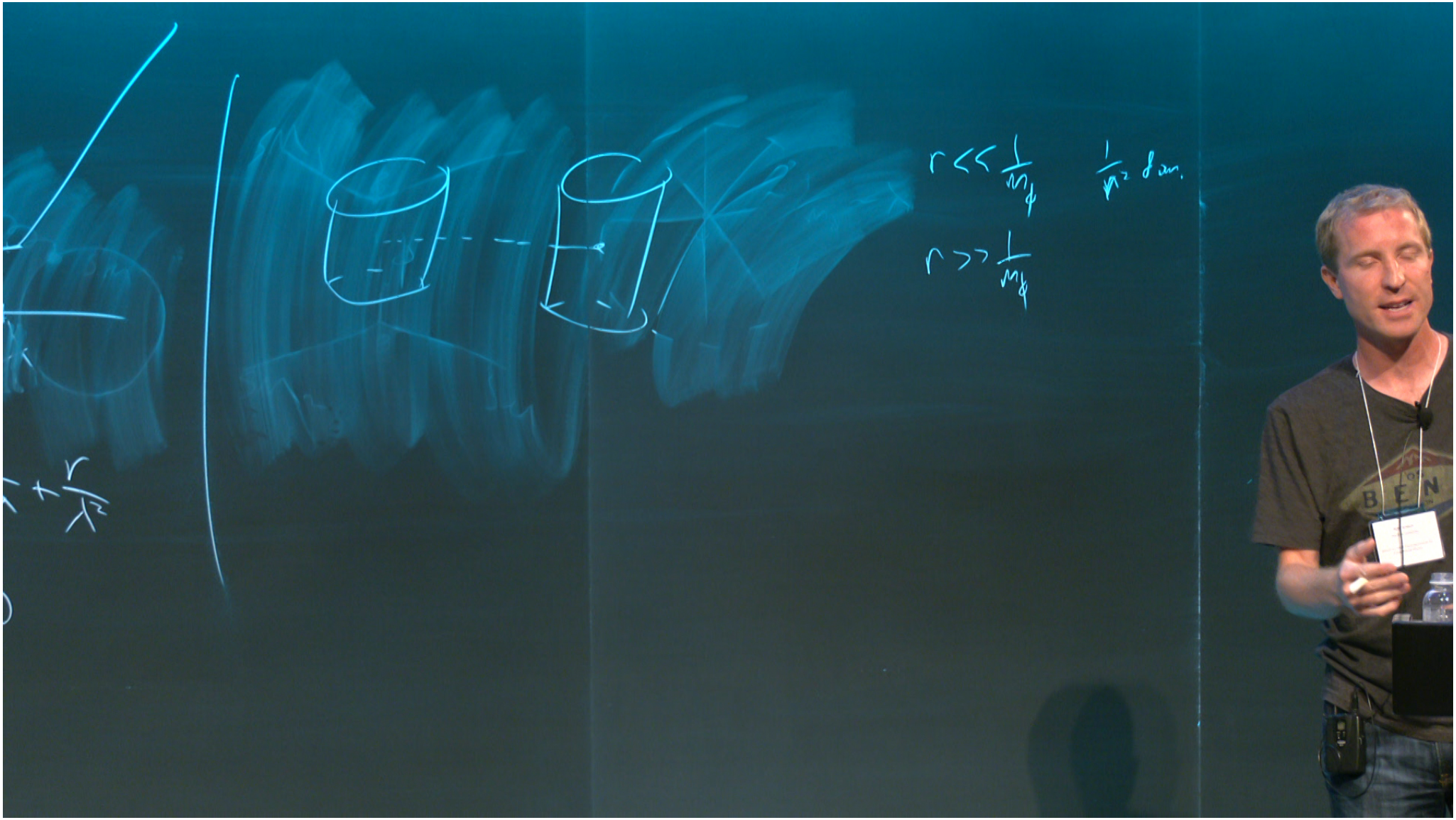



Heckel, Terrano, & Adelberger (2013)

# Light-Through-Walls




r << 1/m_φ
r >> 1/m_φ
1/m² dim.