Universal extra dimensions

- All Standard Model fields propagate in the extra dimension(s)
- Translation invariance $\Rightarrow$ momentum conservation

  e.g. $\langle \phi_n \phi_m \phi_l \rangle \propto \delta_{n+m+l,0}$ $\quad$ ϕ_n : n-th KK excitation of ϕ
- No tree-level contribution to SM processes involving only 0-modes
- However chirality $\Rightarrow$ orbifolding e.g. S^1 (circle) $\rightarrow S^1/\mathbb{Z}_2$ (interval)

  $\Rightarrow$ translation invariance is broken
- But KK-parity remains : KK-number even/odd $\rightarrow$ KK-parity +/-1

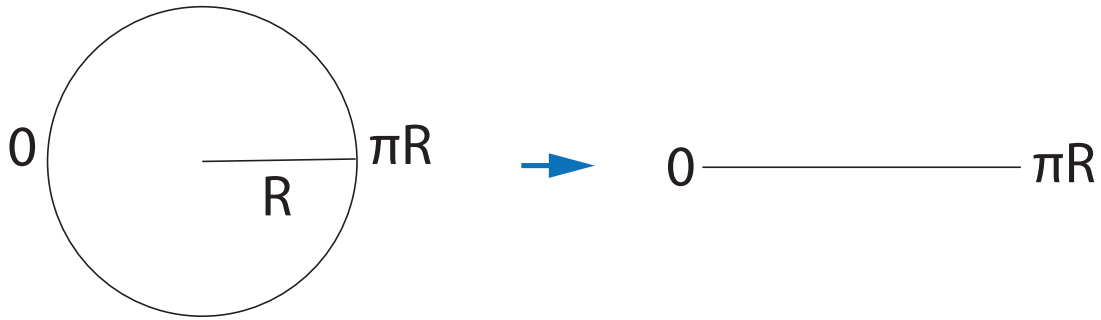
  $\Rightarrow$ lightest KK-odd particle is stable
- All SM gauge bosons have internal components $A_M, M = 0 \ldots D-1$

  - one gets eaten to give mass to 4d KK-vectors

  - the remaining $D-5$ form adjoint scalars (no extra scalar in $D=5$)

Orbifolds

$S^1 : y \equiv y + 2\pi R \ / \ y \to -y \quad \longrightarrow \quad S^1/\mathbb{Z}_2$



$\mathbb{Z}_2$ acts also on fermion chirality $(L \to L, R \to -R) \Rightarrow$ 4d chiral 0-modes

Fields can be even or odd under $\mathbb{Z}_2$

$\mathbb{Z}_2$ even : $\Phi_e(x^\mu, y) = \sum_n \Phi_e^{(n)}(x) \cos \frac{n}{R} y$

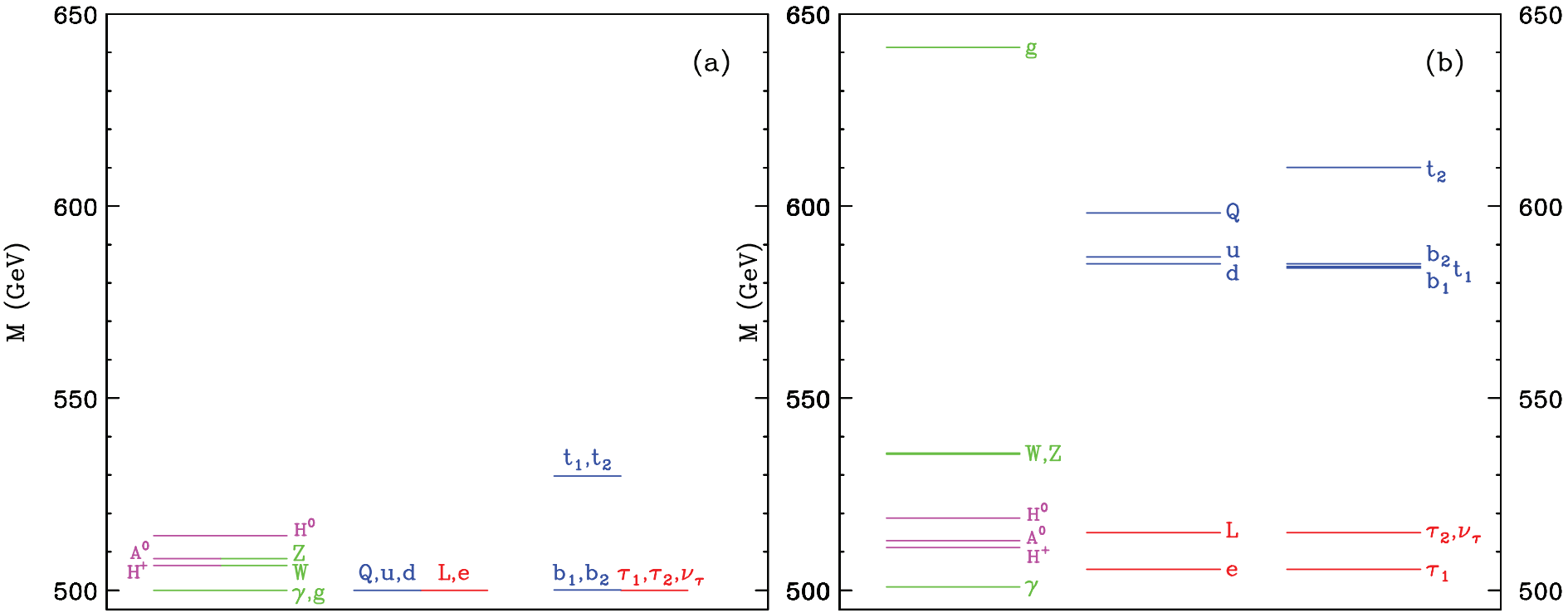
$\mathbb{Z}_2$ odd : $\Phi_o(x^\mu, y) = \sum_n \Phi_o^{(n)}(x) \sin \frac{n}{R} y$

Odd fields have no 4d zero-modes

Mass spectrum

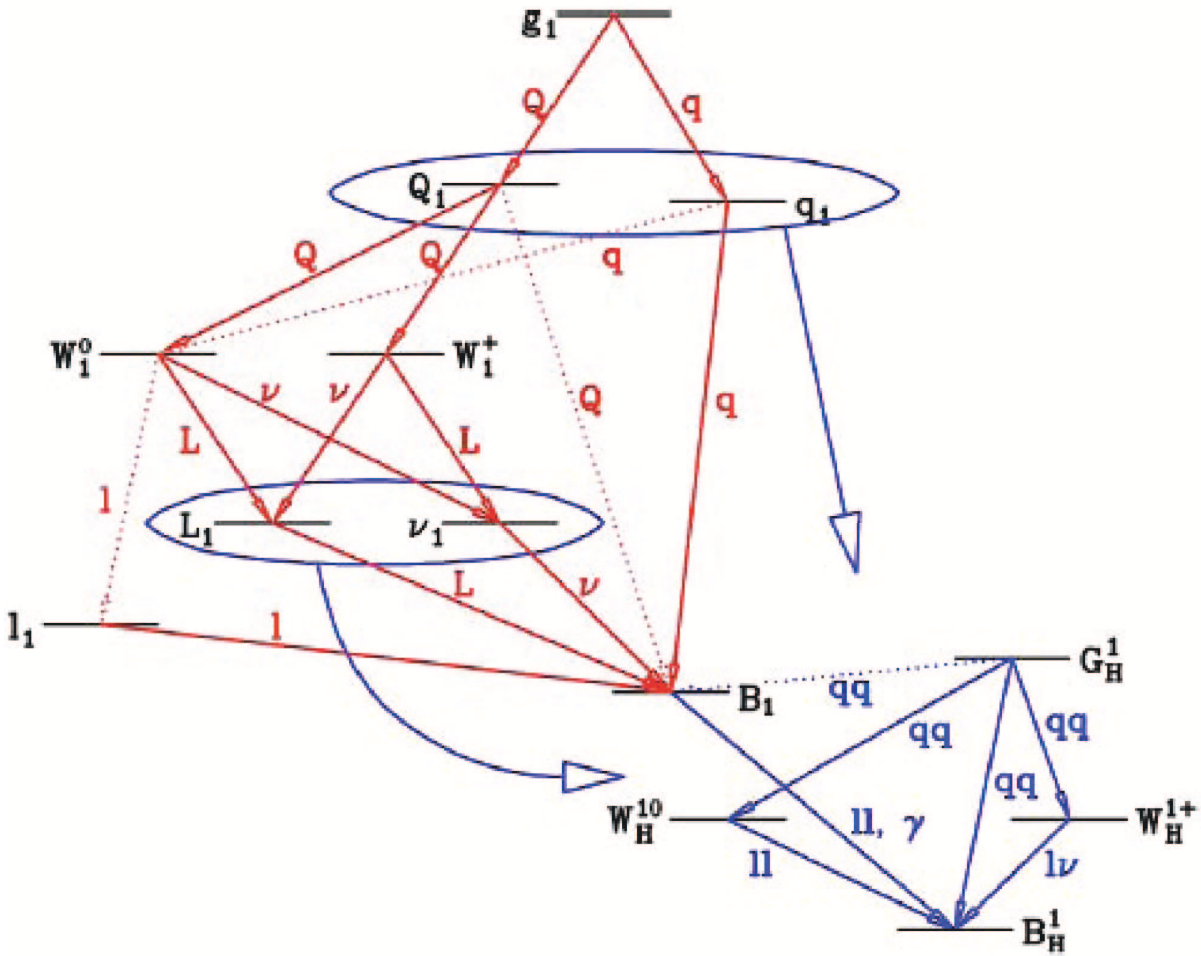
Radiative corrections $\Rightarrow$ mass shifts that lift degeneracy at lowest KK level

divergent sum over KK modes in the loop $\Rightarrow$ cutoff scale $\Lambda \simeq 10/R$



Lightest KK Particle (LKP)

1st KK of hypercharge boson B_1^μ in $D = 5$ or adjoint scalar B_H^1 in $D = 6$



UED hadron collider phenomenology

- large rates for KK-quark and KK-gluon production

  LHC: 1-100 pb for $R^{-1} \lesssim 800$ GeV

- cascade decays via KK-W bosons and KK-leptons

  determine particle properties from different distributions

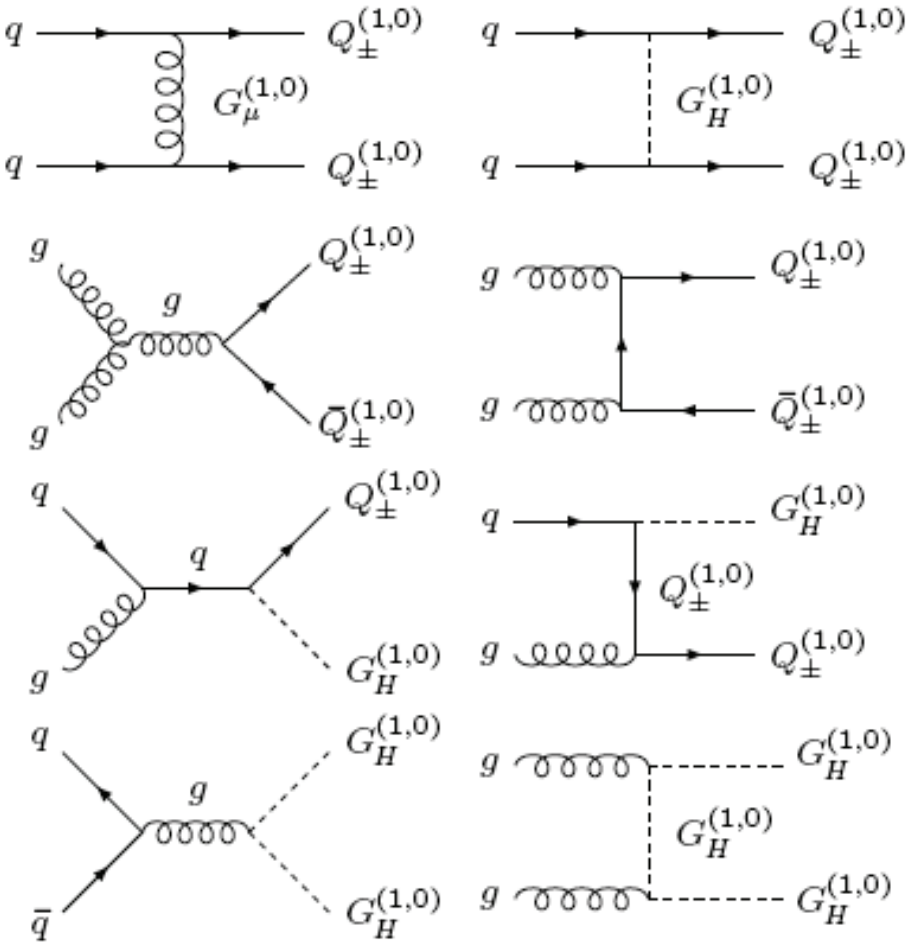
- missing energy from LKP: weakly interacting escaping detection

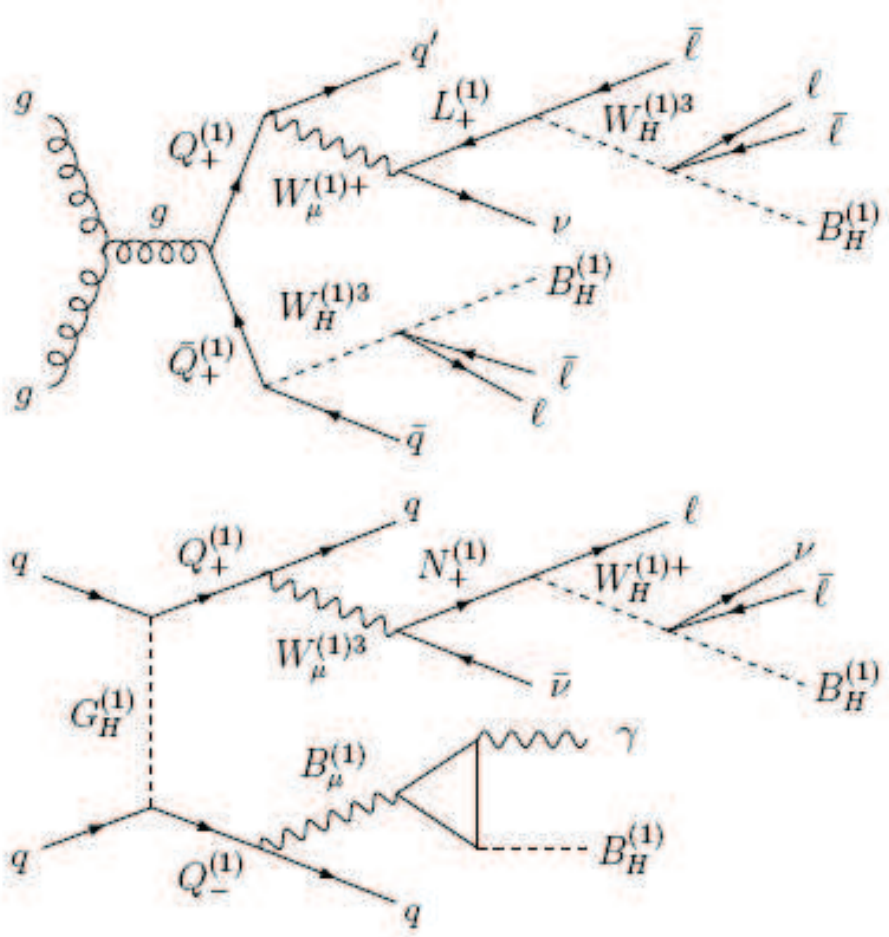
- phenomenology similar to supersymmetry [27]

  spin determination important for distinguishing SUSY and UED

gluino	1/2	KK-gluon	1
squark	0	KK-quark	1/2
chargino	1/2	KK-W boson	1
slepton	0	KK-lepton	1/2
neutralino	1/2	KK-Z boson	1

Production at hadron colliders

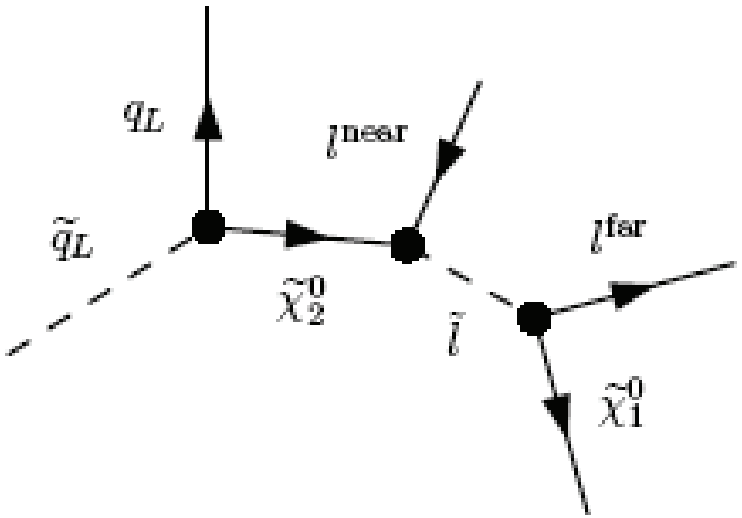




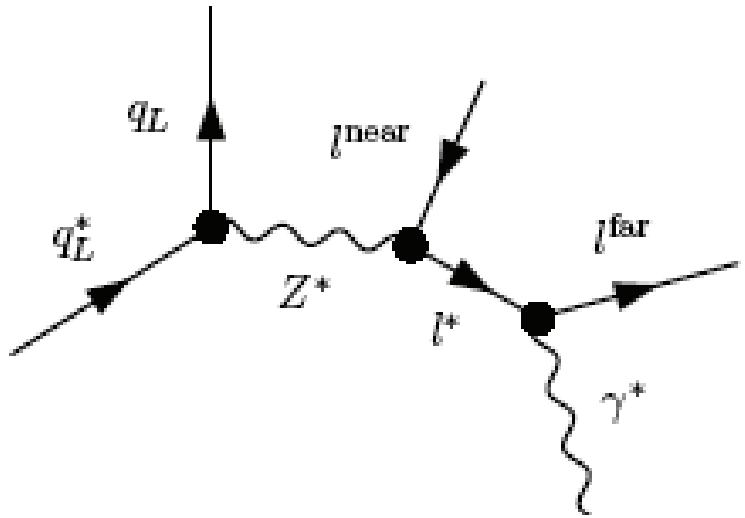
SUSY vs UED signals

Example: jet dilepton final state [25]

SUSY



UED



microgravity experiments

- change of Newton's law at short distances

  detectable only in the case of two large extra dimensions

- new short range forces

  light scalars and gauge fields if SUSY in the bulk

  or broken by the compactification on the brane

  such as radion and lepton number

  volume suppressed mass: $(\mathrm{TeV})^2/M_P \sim 10^{-4}$ eV $\rightarrow$ mm range

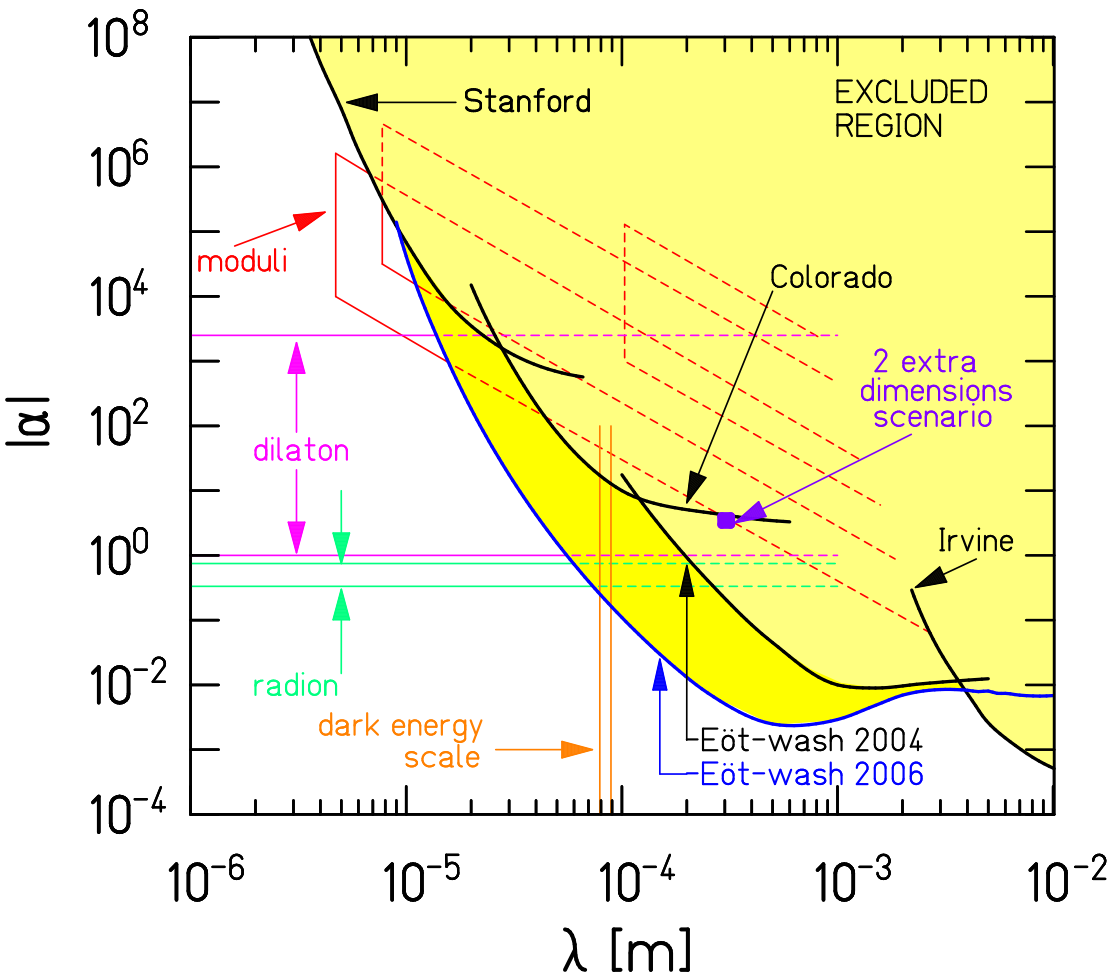
  can be experimentally tested for any number of extra dimensions

  - Light $U(1)$ gauge bosons: no derivative couplings

    $\Rightarrow$ for the same mass much stronger than gravity: $\gtrsim 10^6$

Experimental limits on short distance forces

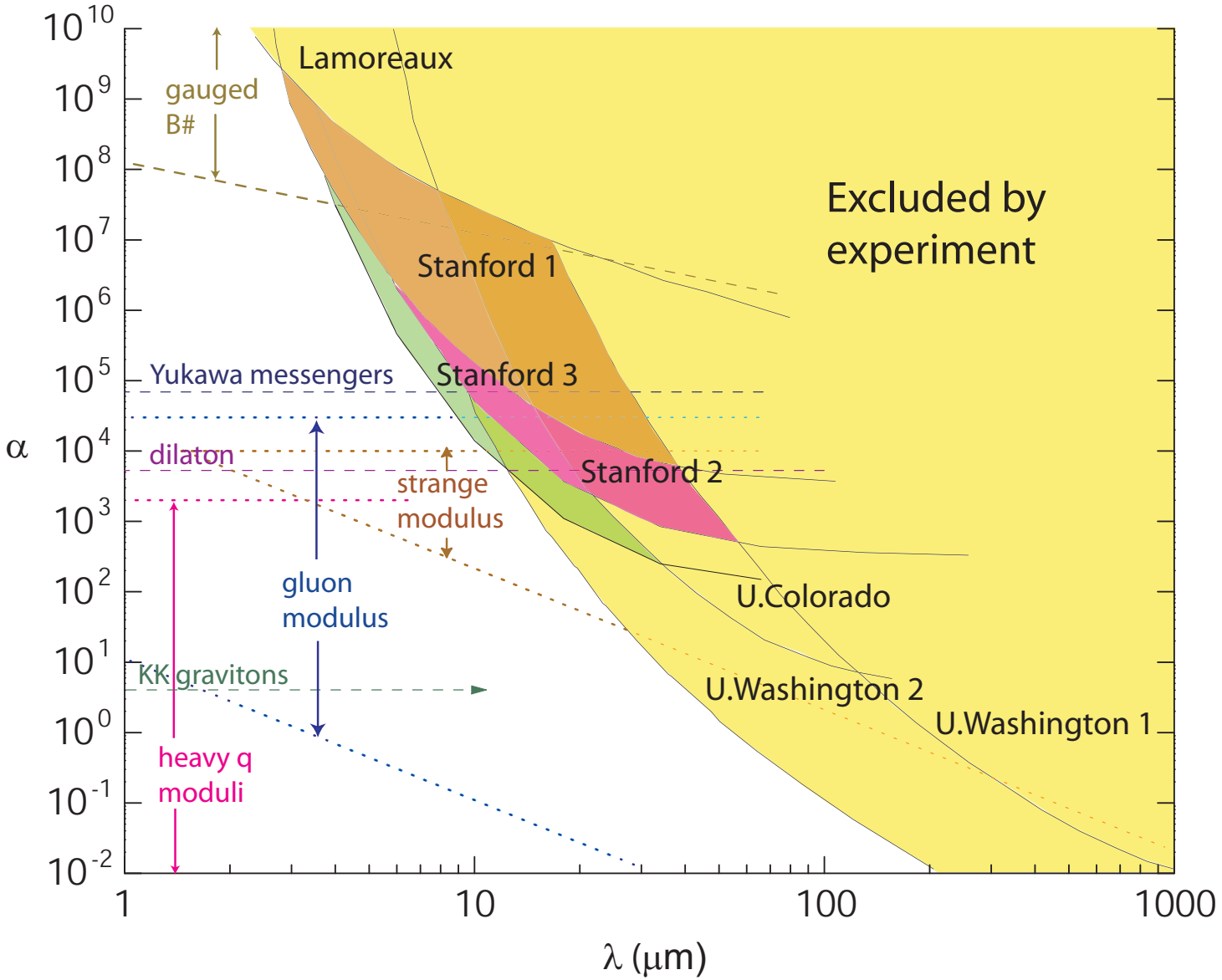
$$V(r) = -G\,\frac{m_1 m_2}{r}\left(1+\alpha e^{-r/\lambda}\right)$$

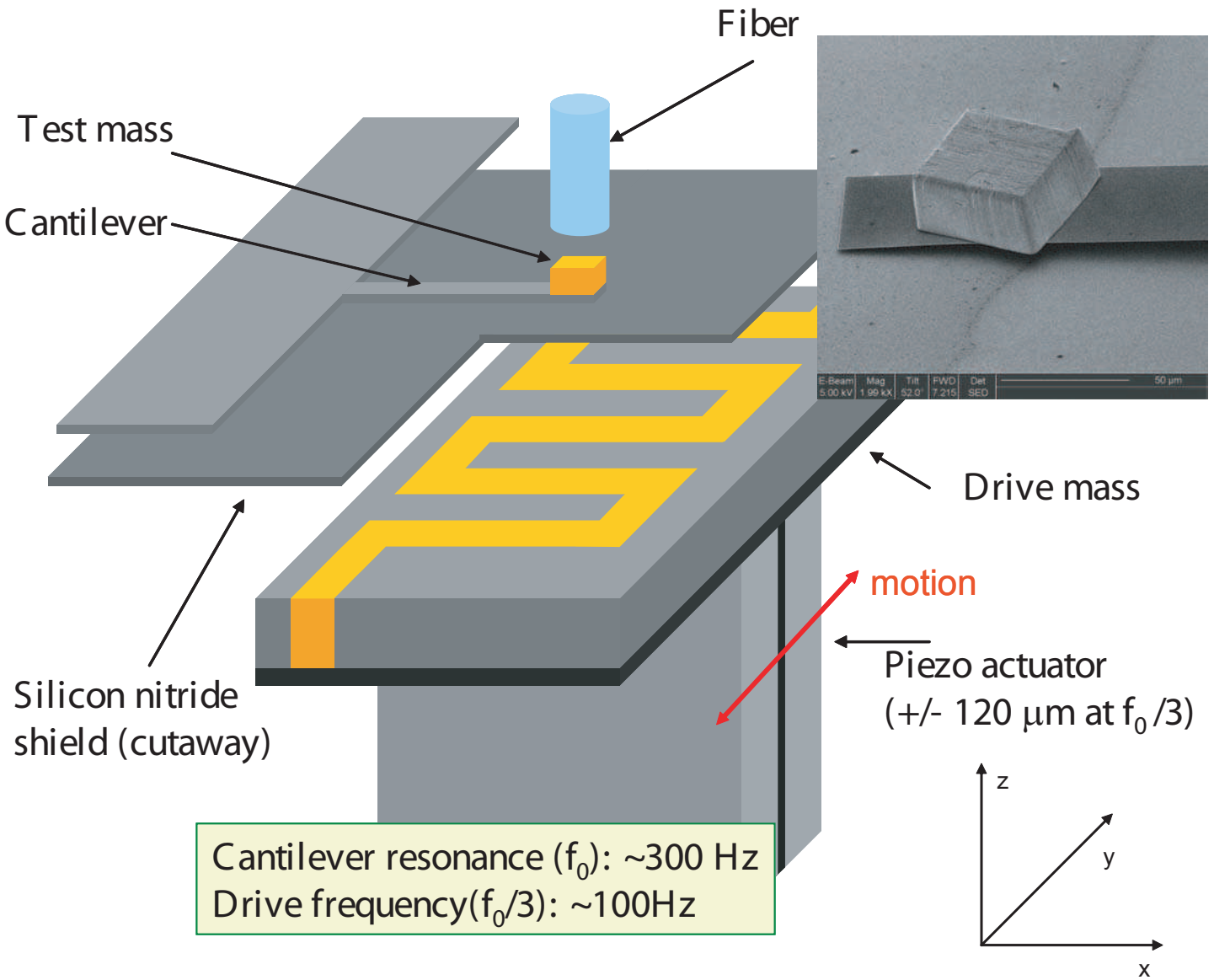


Radion $\Rightarrow M_* \gtrsim 6$ TeV 95% CL Adelberger et al. '06

improved bounds in the range 5-15 μm

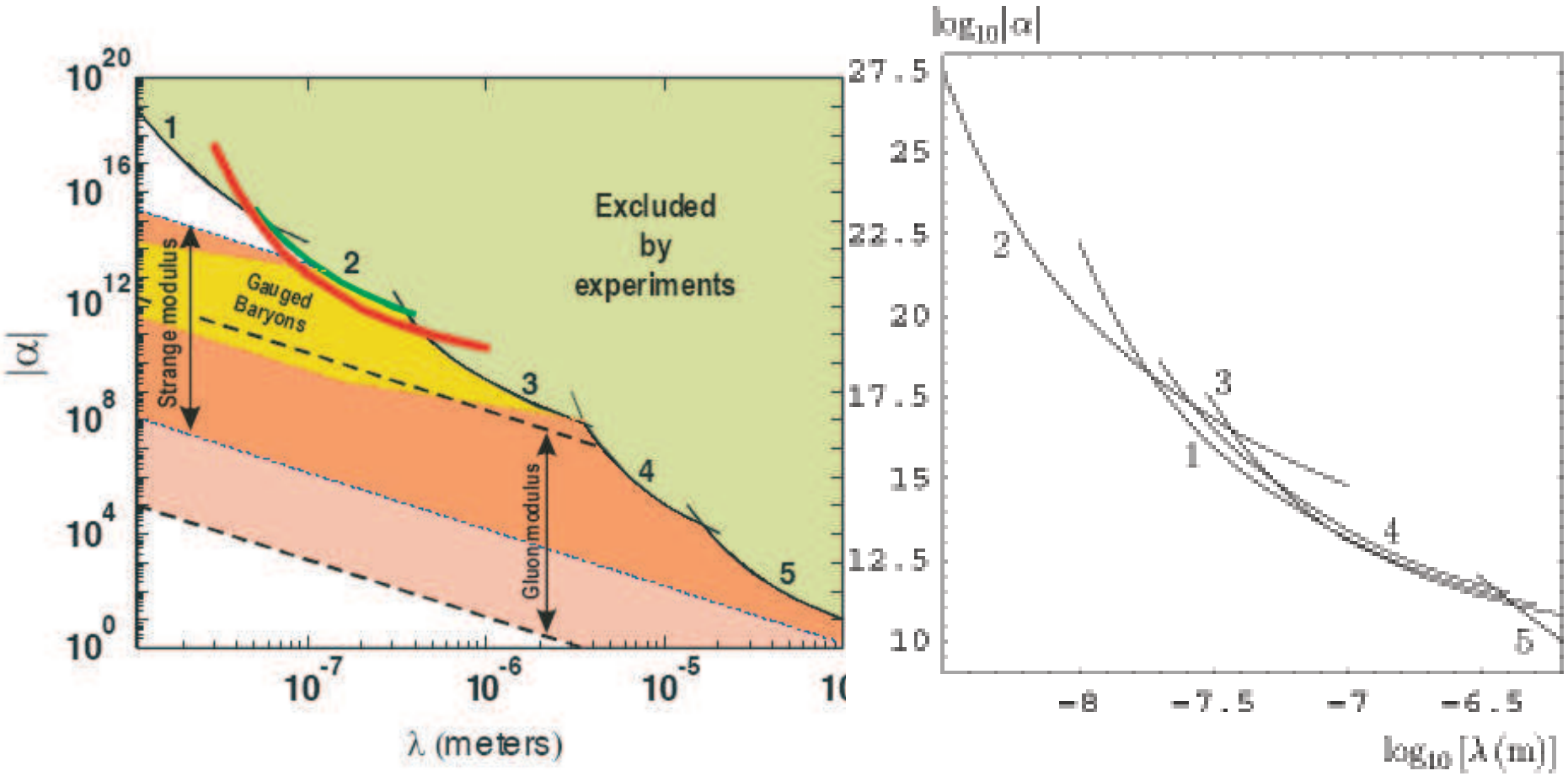
Geraci-Smullin-Weld-Chiaverini-Kapitulnik '08



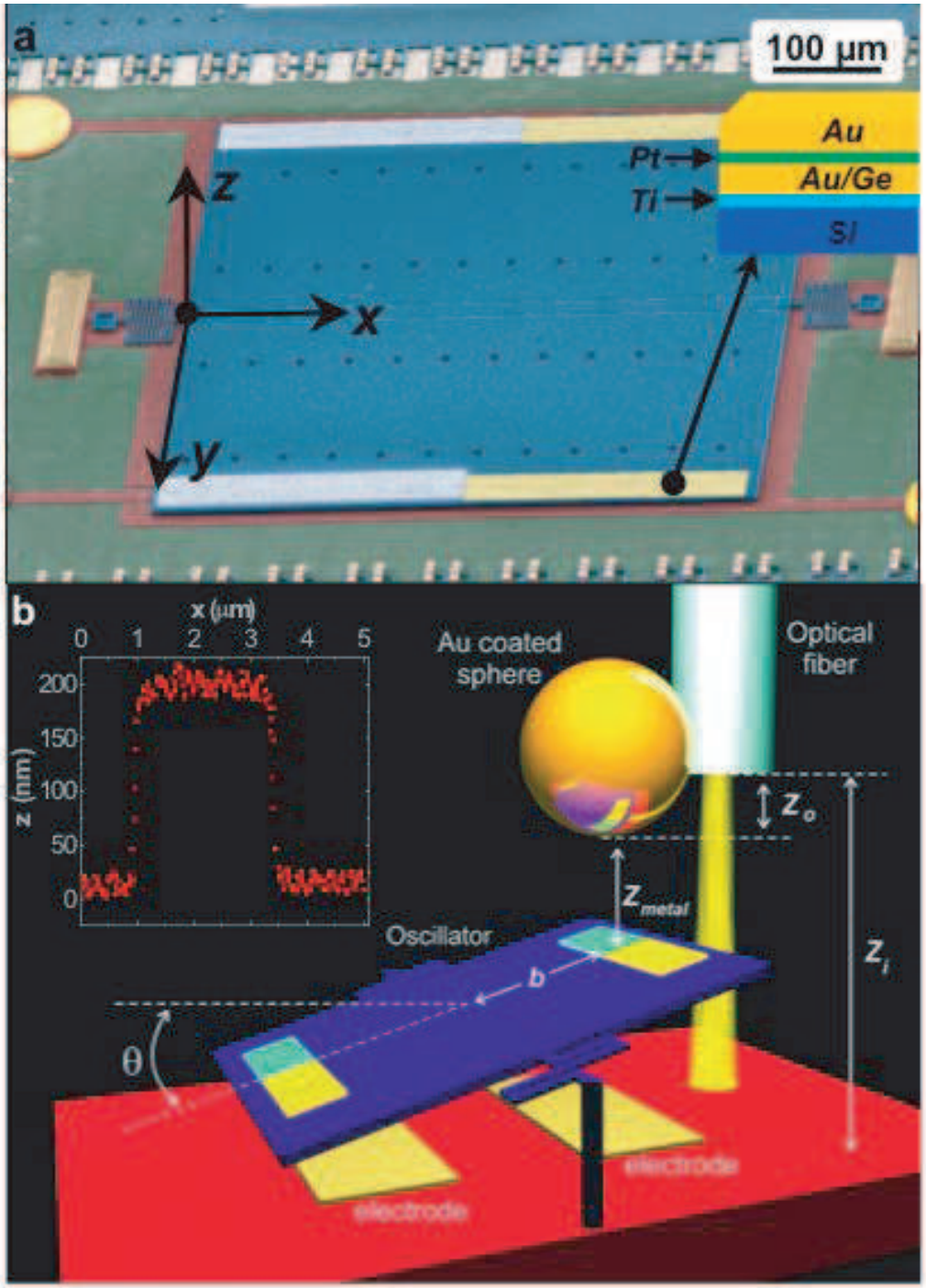

Fiber
Test mass
Cantilever
Drive mass
motion
Piezo actuator
(+/- 120 μm at f0 /3)
Silicon nitride
shield (cutaway)
Cantilever resonance (f0): ~300 Hz
Drive frequency(f0/3): ~100Hz
z
y
x

improved bounds from Casimir effect in the nm range

Decca-Fischbach et al '07, '08



5: Colorado 4: Stanford 3: Lamoureaux 1: Mohideen et al.

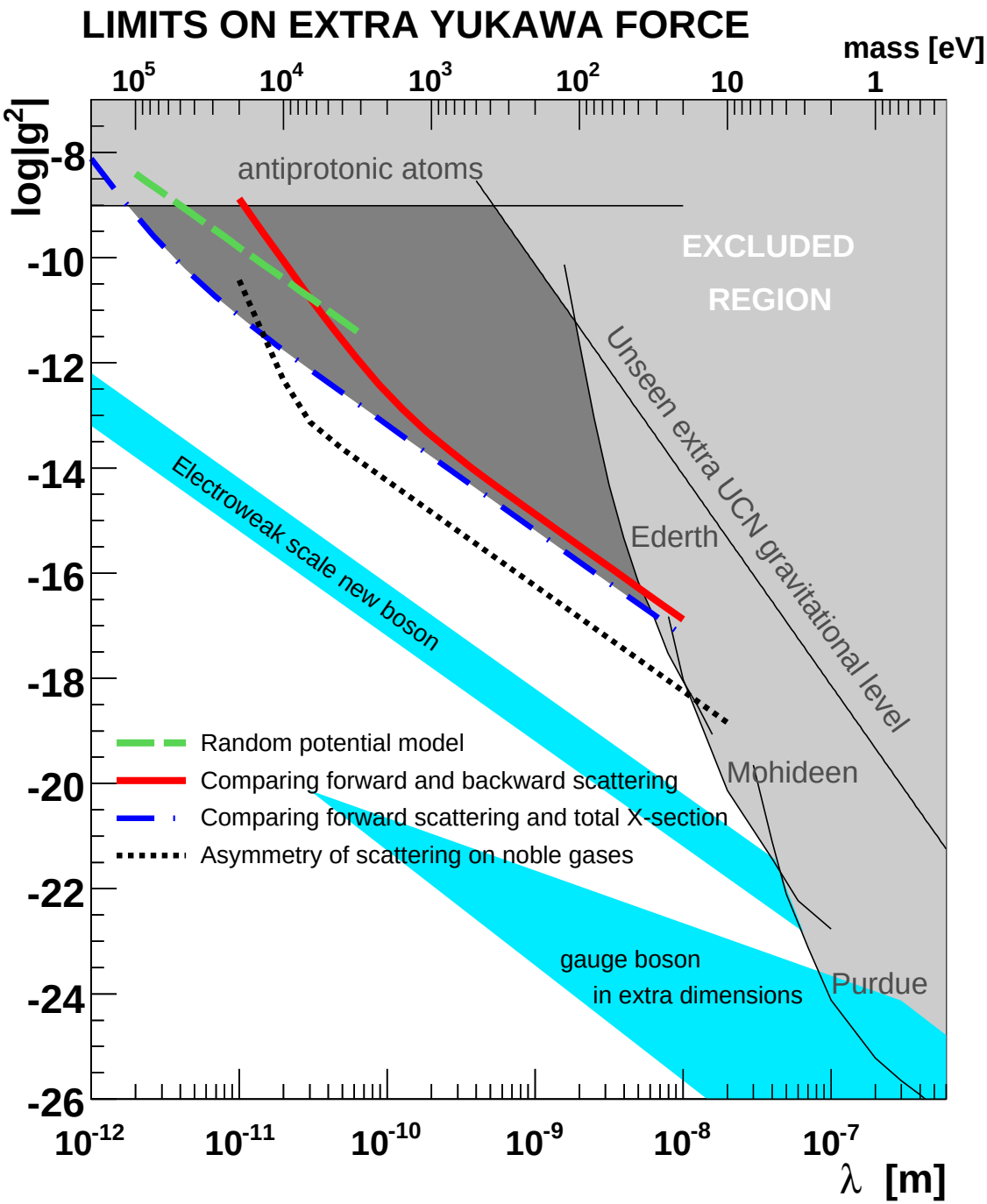

a
100 μm
Au
Au/Ge
Si
Pt
Ti
z
x
y
b
x (μm)
0 1 2 3 4 5
200
150
100
50
0
z (nm)
Au coated sphere
Optical fiber
z_o
z_{metal}
z_i
Oscillator
b
θ
electrode
electrode

Neutron scattering:

bounds in the range

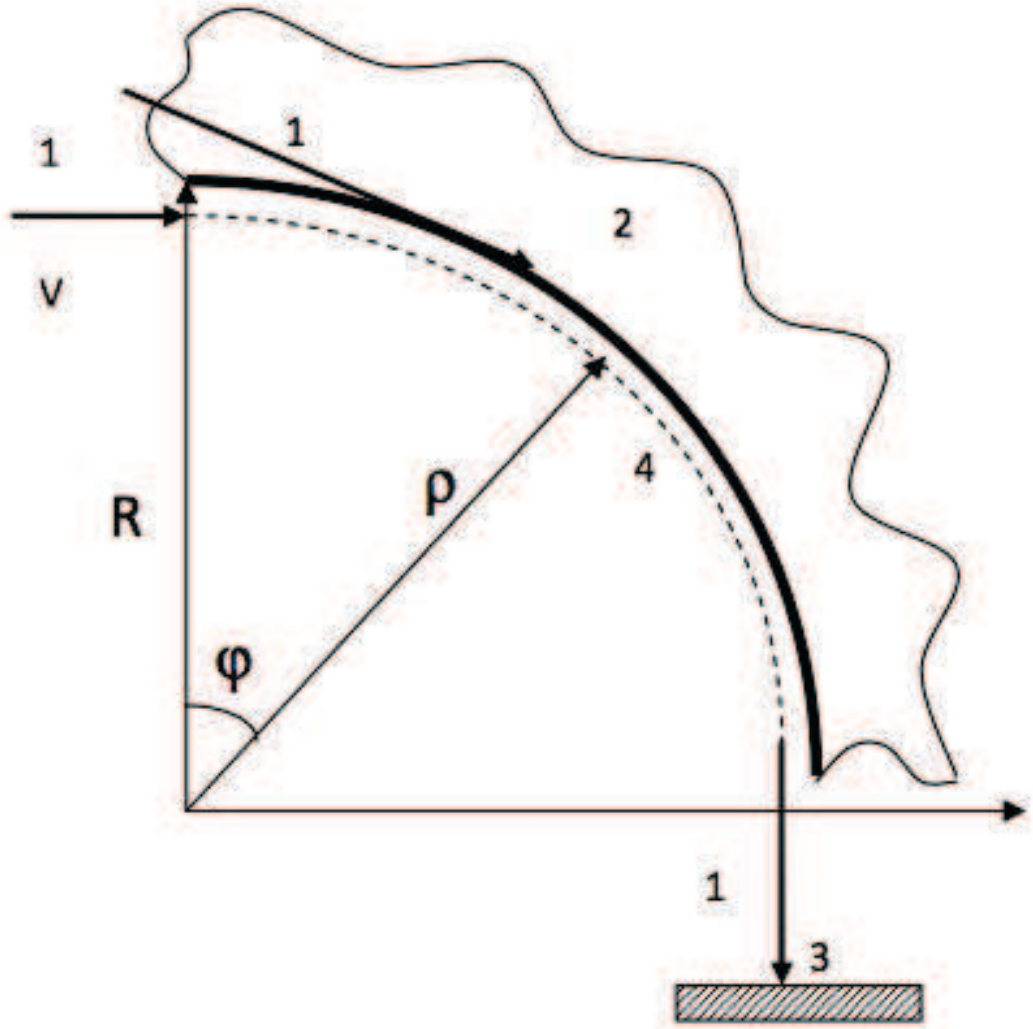
$\sim$ 1pm - 1nm

Nesvizhevsky-Pignol-Protasov '07



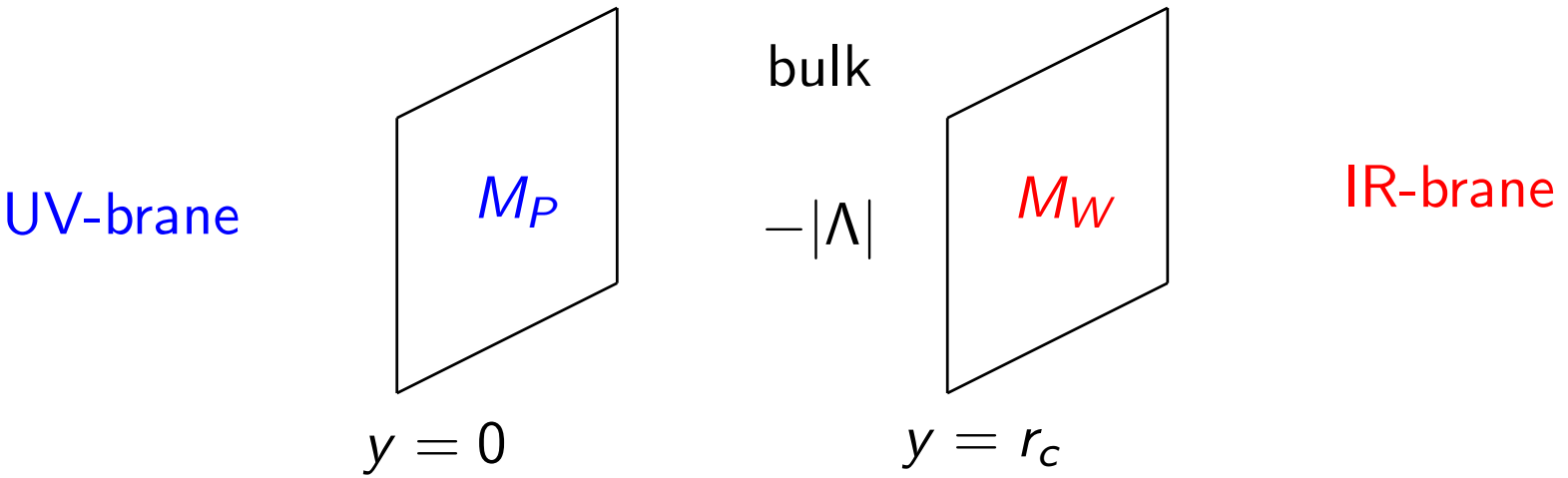
Neutron whispering gallery

Centrifugal quantum states of neutrons



Randal Sundrum models

spacetime = slice of AdS_5 : $ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$ $k^2 \sim \Lambda/M_5^3$



- fine-tuned tensions: $T = -T' = 24M_5^3 k$
- exponential hierarchy: $M_W = M_P e^{-2kr_c}$ $M_P^2 \sim M_5^3/k$

  $M_5 \sim M_{GUT}$
- 4d gravity localized on the UV-brane, but KK gravitons on the IR

- main prediction: spin-2 resonances at the TeV scale

  $m_n = c_n\, k\, e^{-2kr_c} \sim \text{TeV} \qquad c_n \simeq (n + 1/4)$ for large n

  $\Rightarrow$ spin-2 TeV resonances in di-lepton or di-jet channels

- weakly coupled for $m_n < M_5\, e^{-2kr_c} \qquad \Rightarrow k < M_5$

- viable models: SM gauge bosons in the bulk, Higgs on the IR-brane

- AdS/CFT duals to strongly coupled 4d field theories

  composite Higgs models, technicolor-type $\qquad g_{YM} = M_5/k > 1$

RS2

IR-brane can move to infinity: $r_c \to \infty$

$M_P^2 = M^3 \, \frac{1-e^{-2\pi k r_c}}{k} \leftarrow$ internal volume V finite $\Rightarrow$

- always 4d gravity localized on the UV-brane

  potential: $\frac{1}{r} + \frac{1}{k^2 r^3} \leftarrow$ deviations ($r_c \to \infty$)

  $k^{-1} \lesssim 0.1$ mm $\Rightarrow M > 10^8$ GeV, $T^{1/4} > 1$ TeV