

Exploring the Positronium Frontier

New Physics in Positronium

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Positronium : Scientific Scope

Medical Imaging
(PET R&D phase)

Quantum Technologies

Ps₂ molecules and BEC
studies

Development of Compton telescope
for astronomy, nuclear emission
detection, etc. (applications from
defense to oil & gas industries)



Fundamental Physics

Precision QED tests

CPT and Lorentz violation tests

New physics searches

Material Science (PALS)



This will be the focus of
this talk

BSM in Positronium : Philosophy

The philosophy before and in the early part of the golden age of colliders:

Figure out fundamental physics by probing all energies, all systems accessible

Dominant Philosophy in the last few decades:

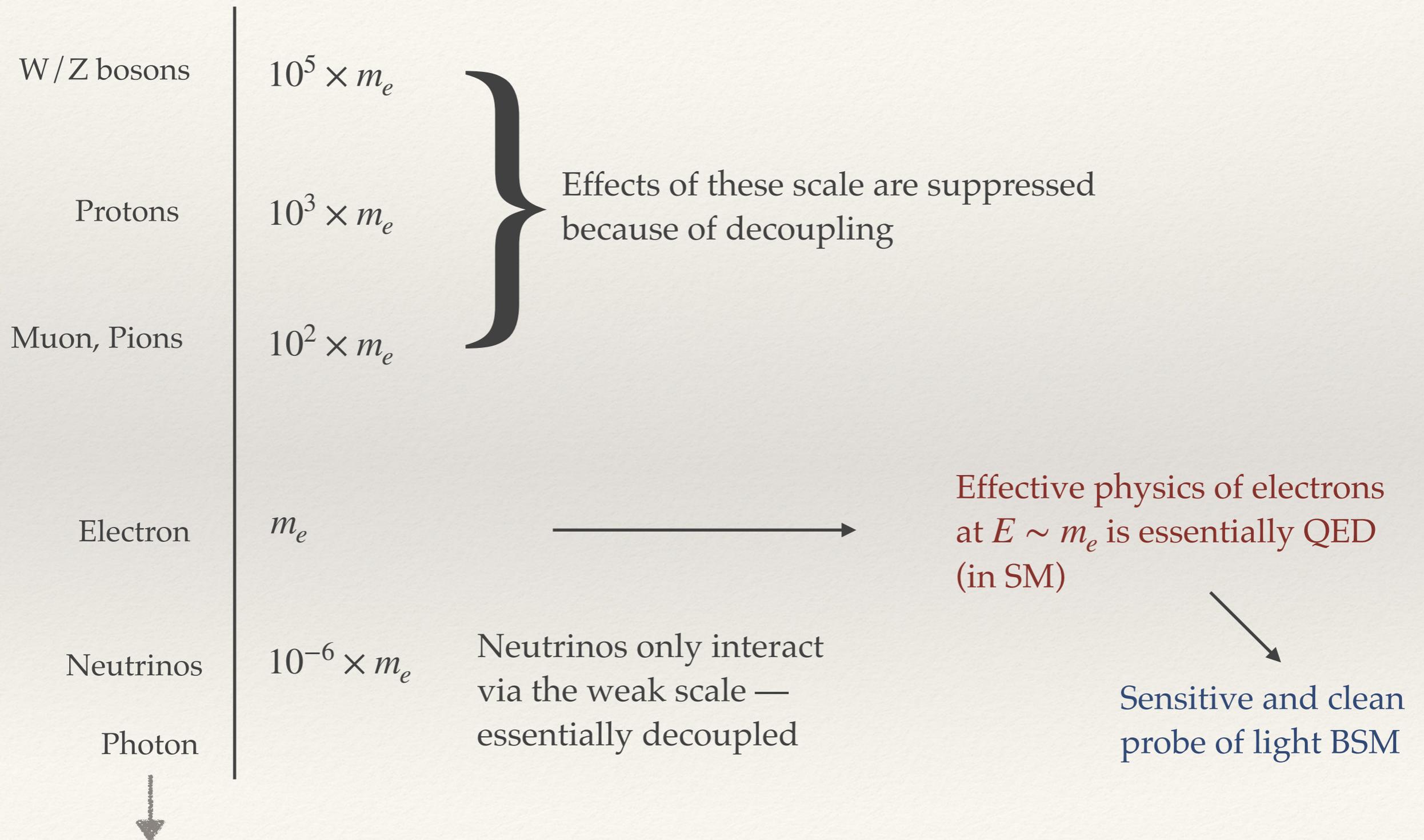
Start by theory motivation such as the hierarchy problem, dark matter etc. : this dominates our search strategies

Philosophy here:

Construct a system well under control experimentally and theoretically - and search for all possible new physics that is accessible.

Why Positronium

Scales in the Standard Model



Physics of Positronium

- A bound state of an electron and a positron : lightest purely leptonic atom in nature.



Mass:

$$M_{\text{Ps}} \simeq 2m_e = 1.022 \text{ MeV}$$

Energy levels:

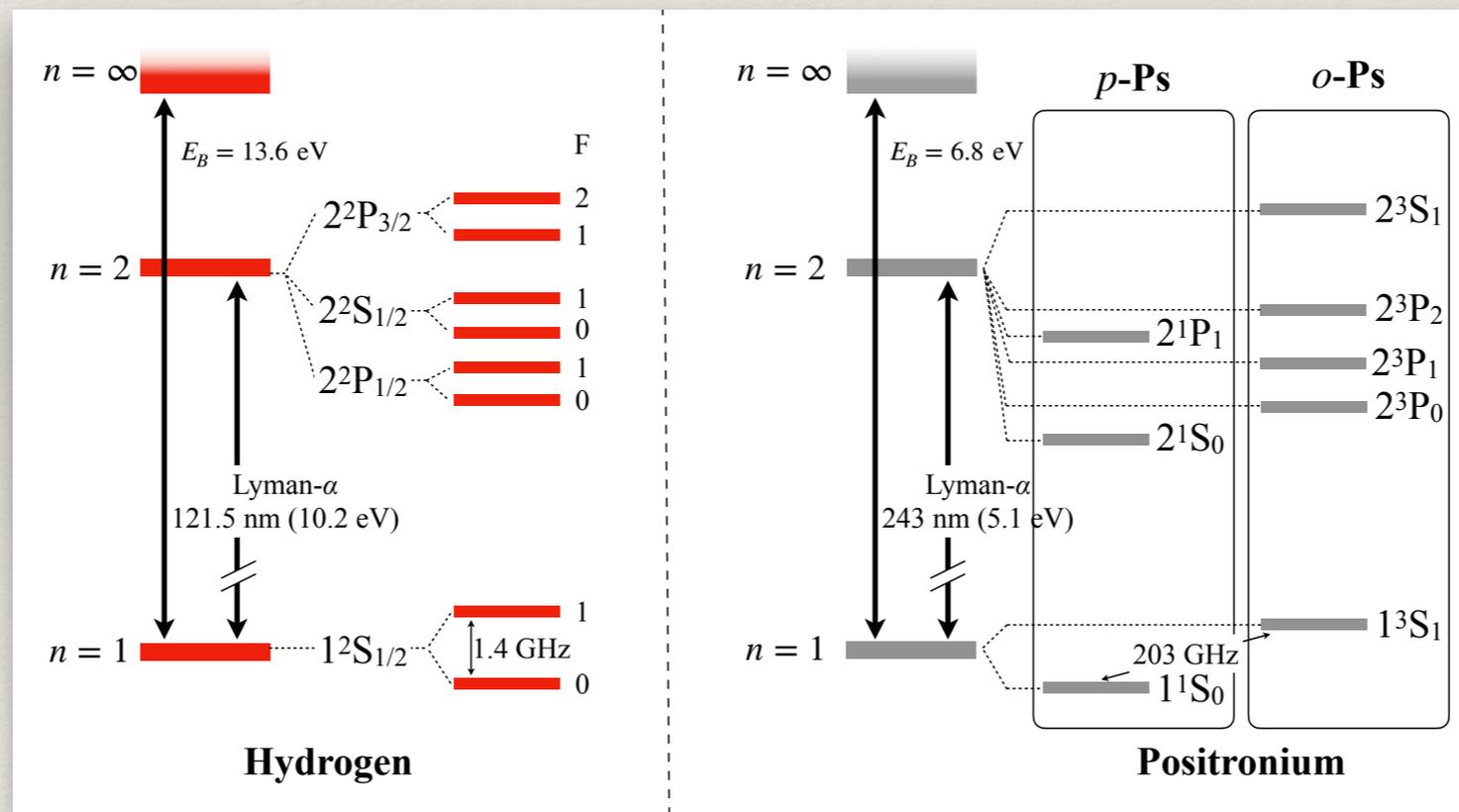
$$E_n = -\frac{\mu\alpha^2}{2n^2}, \quad \text{with} \quad \mu = \frac{m_e}{2}$$

Ground state binding energy:

$$E_1 \Big|_{\text{Ps}} = \frac{1}{2} E_1 \Big|_{\text{Hyd}} = 6.8 \text{ eV}$$

Bohr radius :

$$a \Big|_{\text{Ps}} = \frac{2}{m_e\alpha} = 2a \Big|_{\text{Hyd}} = 2.6 \times 10^{-4} \text{ eV}^{-1}$$



Physics of Positronium

- Selection rules for positronium decays



$$\text{p-Ps } ({}^1S_0) \rightarrow 2\gamma, 4\gamma, \dots$$

$$\text{o-Ps } ({}^3S_1) \rightarrow 3\gamma, 5\gamma, \dots$$

$$\Gamma_{1S_0 \rightarrow 2\gamma} \simeq \frac{1}{2} m_e \alpha^5 \quad \Longrightarrow \quad \tau = 0.125 \text{ ns}$$

$$\Gamma_{3S_1 \rightarrow 3\gamma} \simeq \frac{2}{9\pi} (\pi^2 - 9) m_e \alpha^6 \quad \Longrightarrow \quad \tau = 142 \text{ ns}$$

$$\text{Br}({}^1S_0 \rightarrow 4\gamma) \sim 10^{-6}$$

$$\text{Br}({}^1S_0 \rightarrow \gamma \nu \bar{\nu}) \sim \begin{cases} 10^{-24} & \text{for } \nu_e \\ 10^{-27} & \text{for } \nu_\mu, \nu_\tau \end{cases}$$

$$\text{Br}({}^3S_1 \rightarrow 5\gamma) \sim 10^{-6}$$

$$\text{Br}({}^3S_1 \rightarrow \nu \bar{\nu}) \sim \begin{cases} 10^{-18} & \text{for } \nu_e \\ 10^{-21} & \text{for } \nu_\mu, \nu_\tau \end{cases}$$

$$\text{Br}({}^1S_0 \rightarrow \gamma \nu \bar{\nu}) \sim 10^{-21}$$

basic signal : Ps \rightarrow $n\gamma$ + Missing Momentum & combinations

Additional handles : vertexing & timing

BSM in Positronium : Status Quo

- Basic reason positronium is a good case for New physics



p-Ps (1S_0) : same quantum number of a massive pseudo-scalar

o-Ps (3S_1) : same quantum number of a massive gauge boson

They carry no other quantum number!

BSM Physics:

$$\text{o-Ps} \rightarrow 2\gamma, 4\gamma, \dots$$

$$\text{o-Ps} \rightarrow X_\mu$$

$$\text{o-Ps} \rightarrow \gamma + X$$

$$\text{o-Ps} \rightarrow \gamma + X (X \rightarrow 2\gamma)$$

$$\text{o-Ps} \rightarrow \gamma + X (X \rightarrow \gamma + Y_\mu)$$

...

$$\text{p-Ps} \rightarrow 3\gamma, 5\gamma, \dots$$

$$\text{p-Ps} \rightarrow X$$

$$\text{p-Ps} \rightarrow \gamma + X_\mu$$

$$\text{p-Ps} \rightarrow \gamma + X_\mu (X_\mu \rightarrow 3\gamma)$$

$$\text{p-Ps} \rightarrow \gamma + X_\mu (X_\mu \rightarrow \gamma + Y)$$

...

In the second half I will go through fundamental physics inspirations

BSM in Positronium : Status Quo

- Basic reason positronium is a good case for New physics

p-Ps (1S_0) : same quantum number of a massive pseudo-scalar

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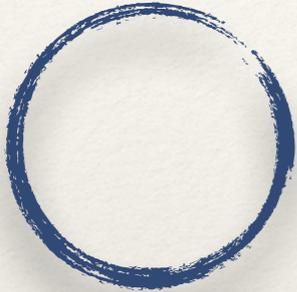


Table 3. Upper limits on the branching ratios of several exotic *o*-Ps decays

Decay mode	90% upper limit, ppm	Comments	Group
$\gamma + X$	5–1	Long-lived <i>X</i> -boson $m_X \sim 100\text{--}900$ keV	CERN [50]
	1.1	$m_X < 800$ keV	Tokyo [54]
	340	$m_X < 30$ keV	Moscow [59]
$\gamma + X \rightarrow \gamma + 2\gamma$	28	Short-lived <i>X</i> -boson $m_X < 30$ keV	Moscow [57]
	300	$m_X < 500$ keV	Tokyo [55]
$\gamma\gamma$	233	Forbidden by angular momentum conservation	Michigan [52]
	350		Tokyo [53]
$\gamma\gamma\gamma$	2.6	Forbidden by <i>C</i> -parity	Tokyo [51], Berkeley [66]
	3.7		
$\gamma + X_1 + X_2$	44	$m_{X_1} + m_{X_2} < 900$ keV	ETHZ-Moscow [64]
Invisible	2.8	Not in vacuum	Tokyo [63]
	540		Moscow [65]

$$BR(\text{p-Ps} \rightarrow 3\gamma / \text{p-Ps} \rightarrow 2\gamma) < 2.8 \times 10^{-6} \text{ at } 68\% \text{C.L.} \quad [11] \quad (23)$$

$$BR(\text{o-Ps} \rightarrow 4\gamma / \text{o-Ps} \rightarrow 3\gamma) < 2.6 \times 10^{-6} \text{ at } 90\% \text{C.L.} \quad [12] \quad (24)$$

$$BR(\text{p-Ps} \rightarrow 5\gamma / \text{p-Ps} \rightarrow 2\gamma) < 2.7 \times 10^{-7} \text{ at } 90\% \text{C.L.} \quad [13] \quad (25)$$

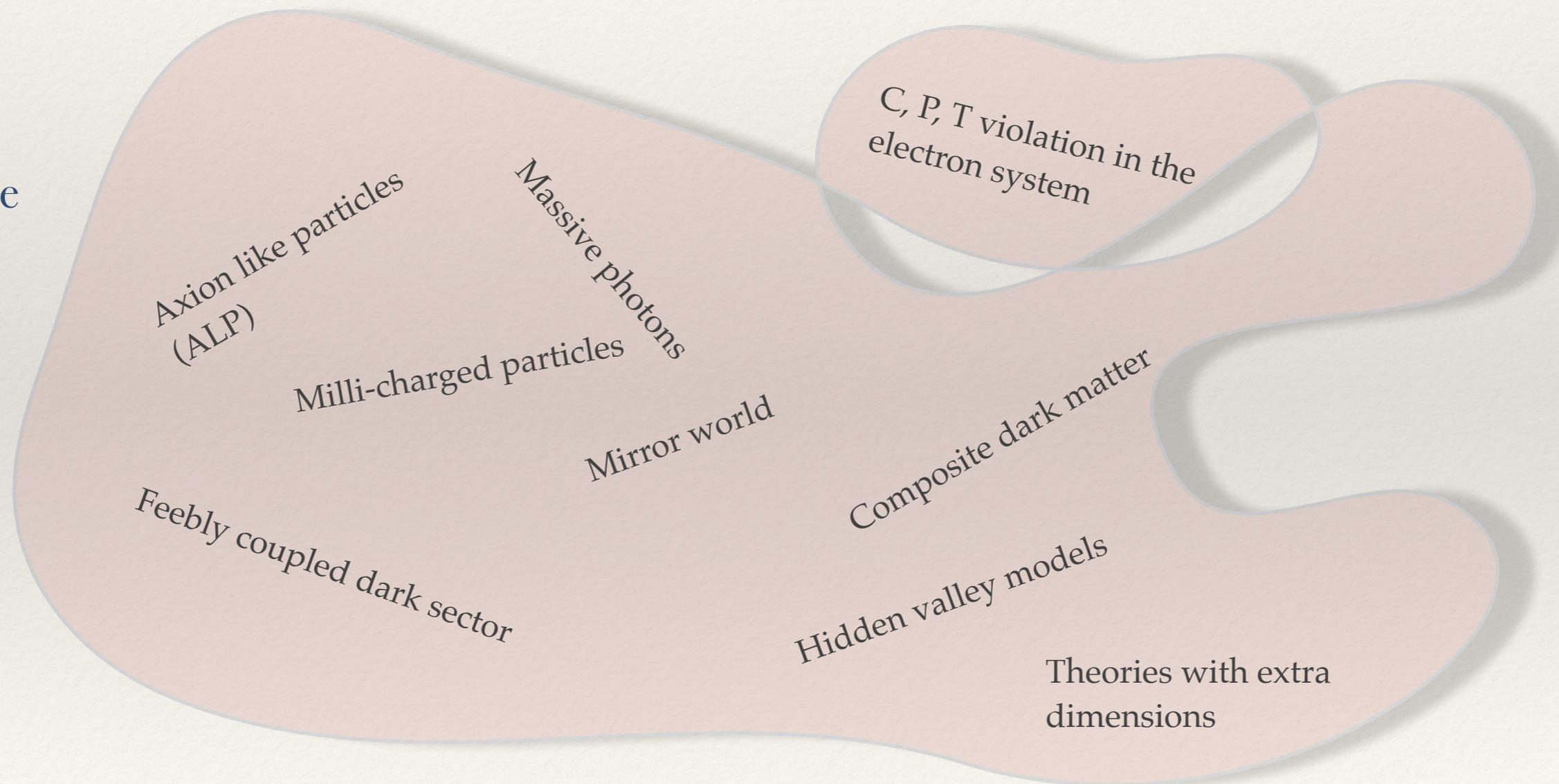
We have probed branching of (few) PPM level

BSM in Positronium : the theory landscape

Signal space :

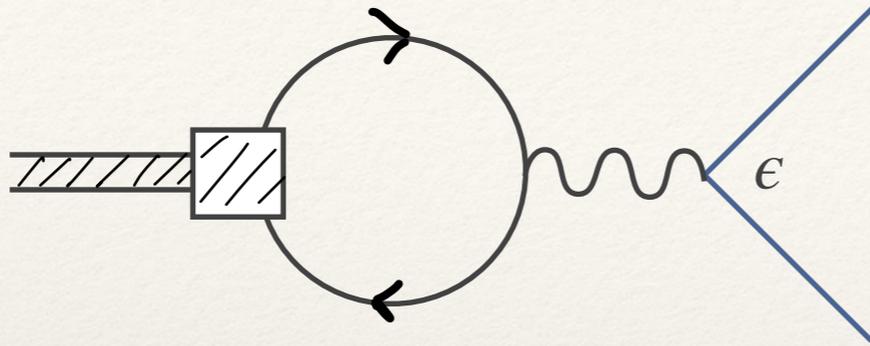
- $\text{Ps} \rightarrow n\gamma + \text{Missing Momentum \& combinations}$
- Additional handles : vertexing & timing

Theory Space



I will describe NP in a bottom-up effective way to map the signal space to theory space

BSM in Positronium : the simplest BSM

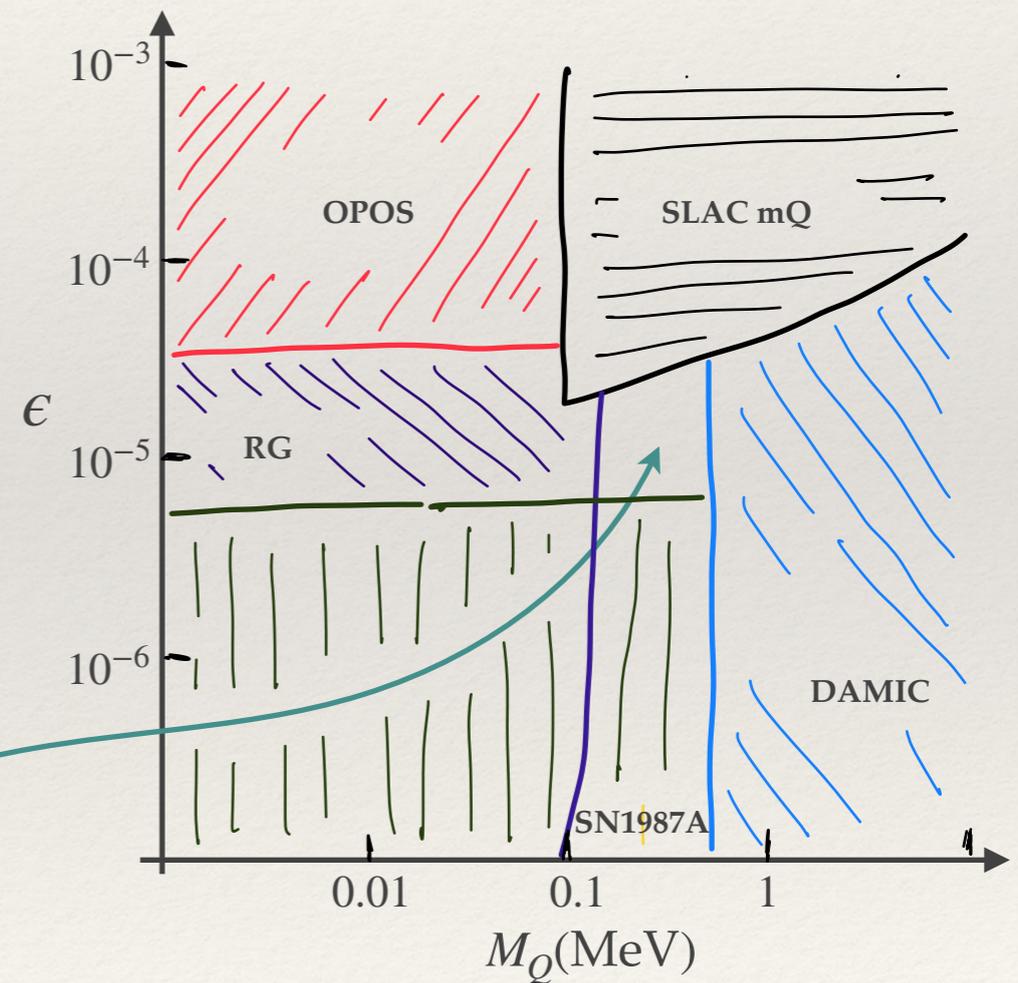


Milli-charged particles

Only two parameters define physics

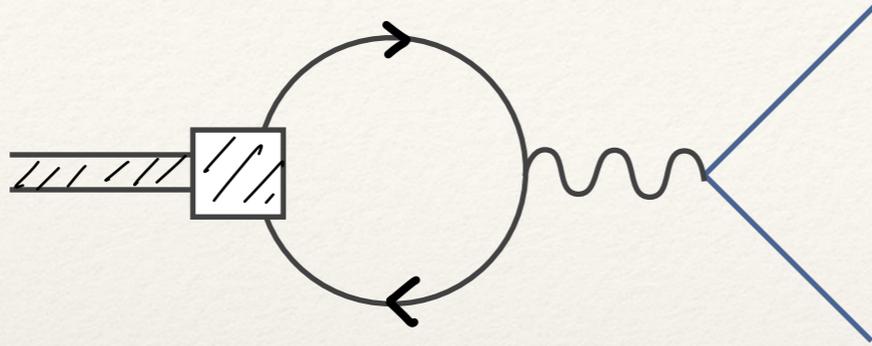
- Mass of the new particle (M_Q)
- Charge of the new particle (ϵ)

Interpreting bounds on Invisible decays of o-Ps gives a bounds on ϵ



Unexplored territories requires
Br sensitivity at 10^{-7}

BSM in Positronium : the simplest BSM



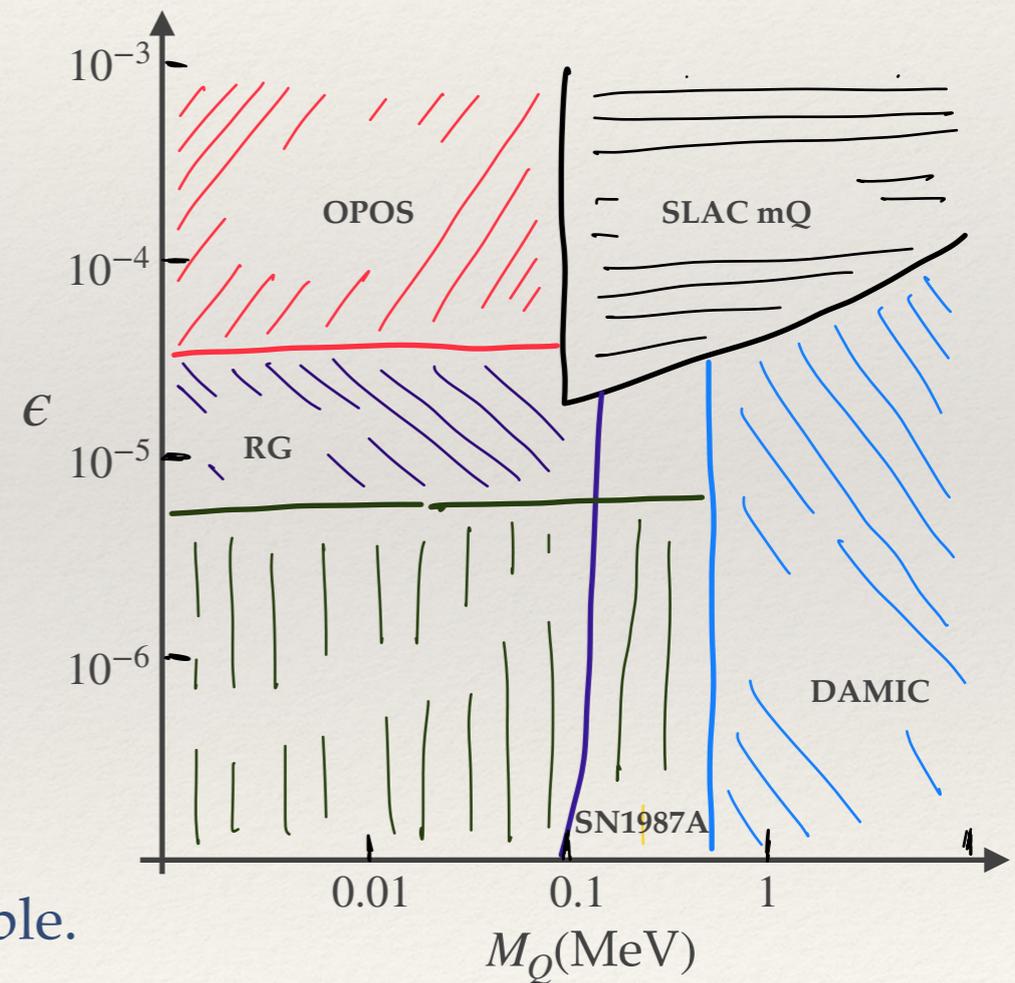
Milli-charged particles also charged under a new force (Infra-color)

One extra parameter to define physics

- Mass of the new particle (M_Q)
- Charge of the new particle (ϵ)
- The Infrared-QCD scale (Λ_I)

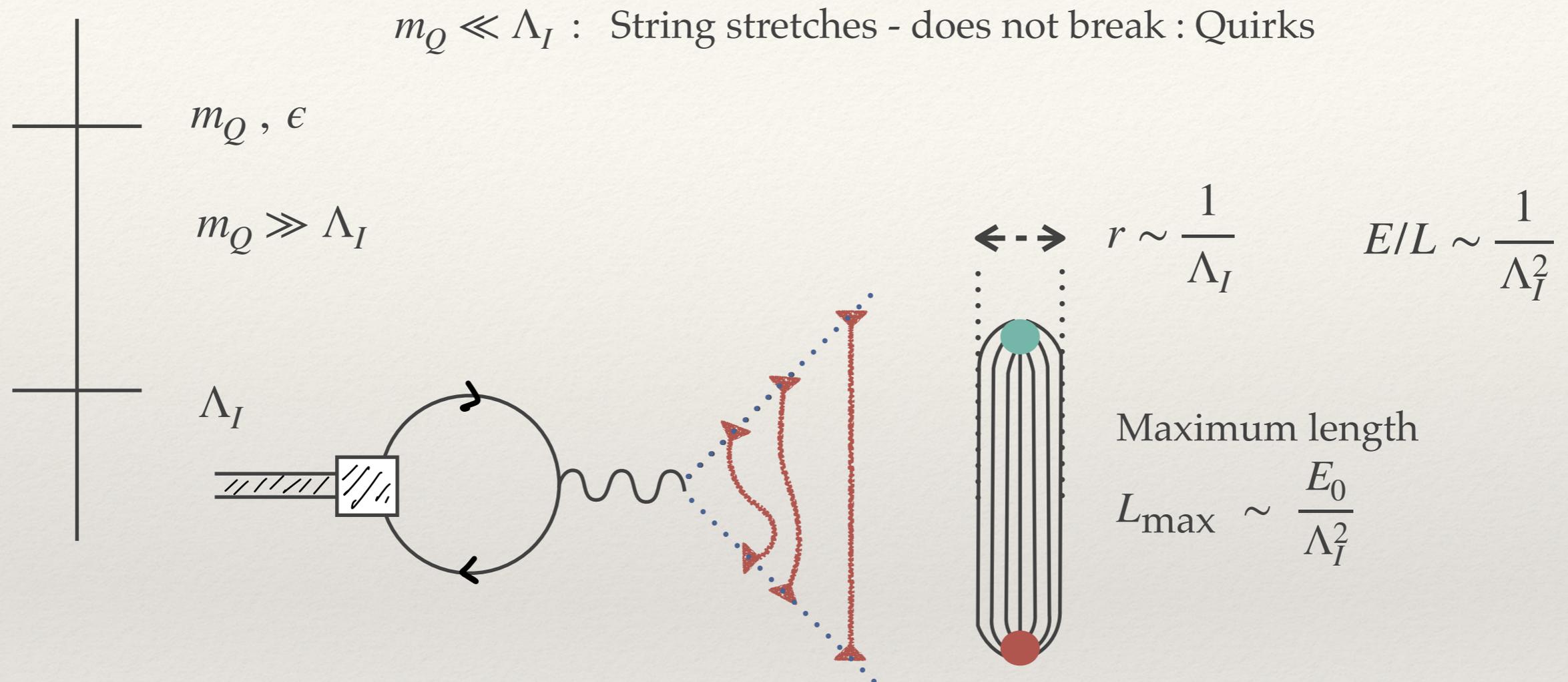
Astrophysical & Cosmological bounds break down

Milli-charged bounds from HE colliders remains reliable.



However, new (exotic) phenomenon in Ps decay

BSM in Positronium : Quirks

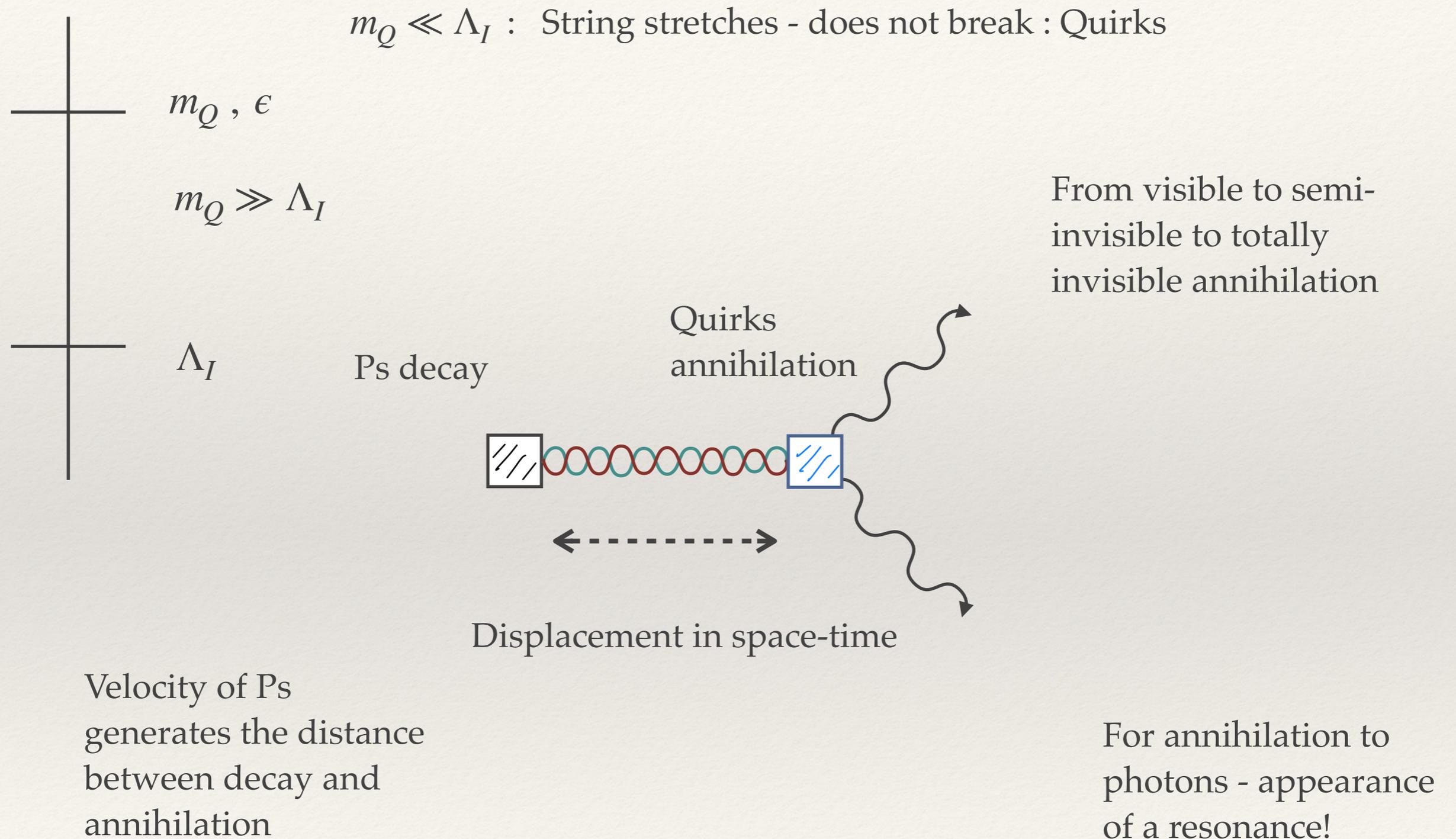


In case, $\Lambda_I \lesssim m_Q/10$

It is energetically more favorable to convert all kinetic energy into potential energy with quirks turning back

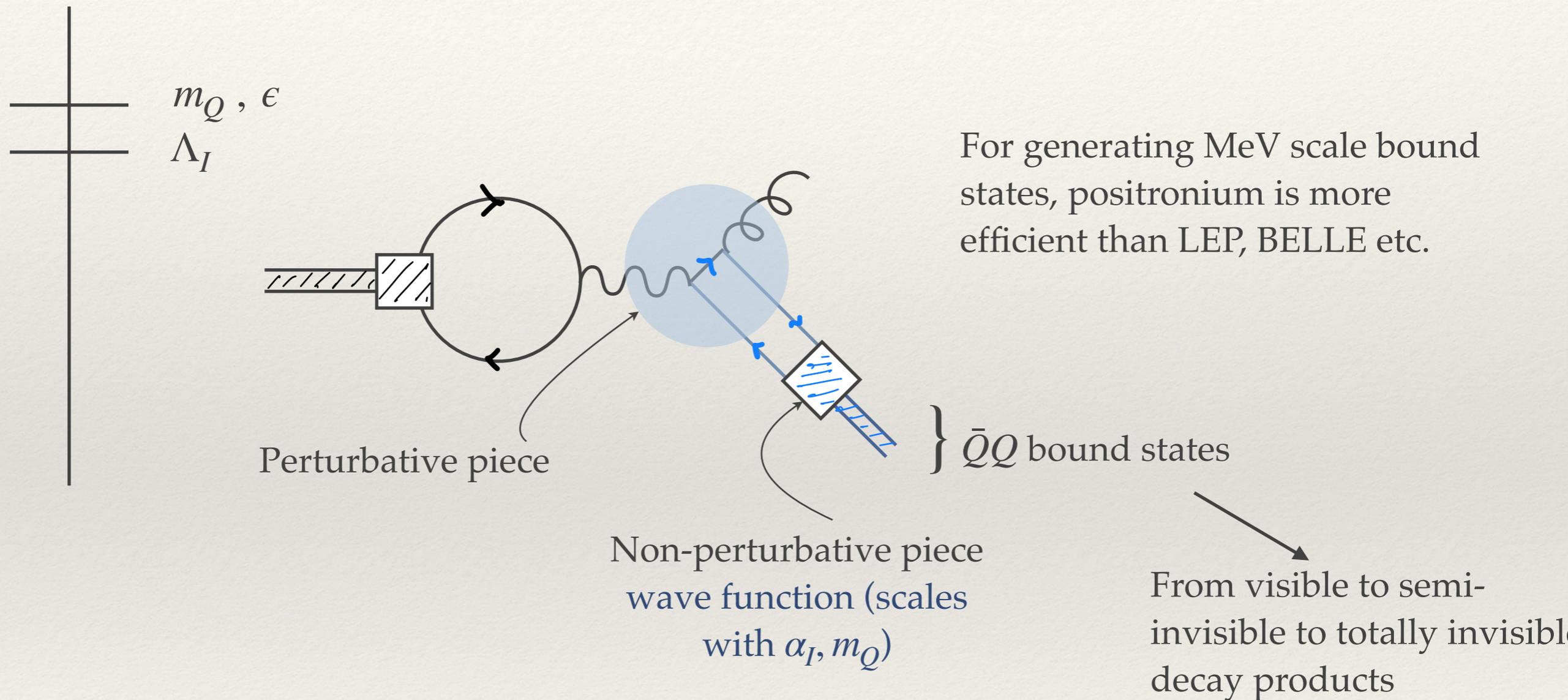
Probability of string breaking $\sim e^{-(m_Q^2/\Lambda_I^2)}$

BSM in Positronium : Quirks



BSM in Positronium : non-relativistic bound states

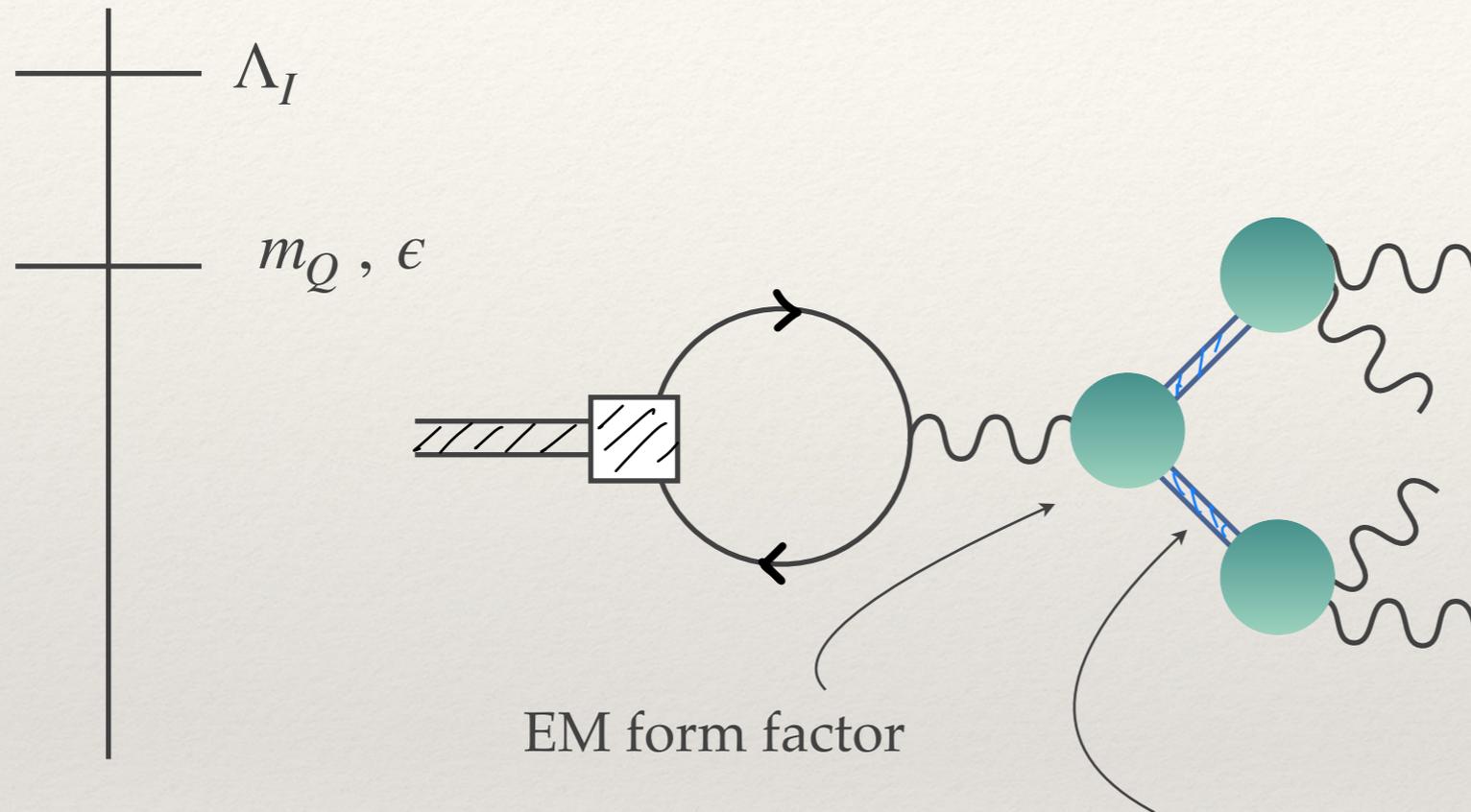
$m_Q \gtrsim \Lambda_I$: Non-Relativistic bound states in positronium physics



One requires NRQCD like calculations followed by reinterpretation of $Ps \rightarrow n\gamma + ME$

BSM in Positronium : relativistic bound states

$m_Q \gtrsim \Lambda_I$: Relativistic bound states in positronium physics



From visible to semi-invisible to totally invisible decay products

Pseudo scalar pNGBs (pions) of infra-color with electromagnetic form factors

This state looks like a composite axion like particle

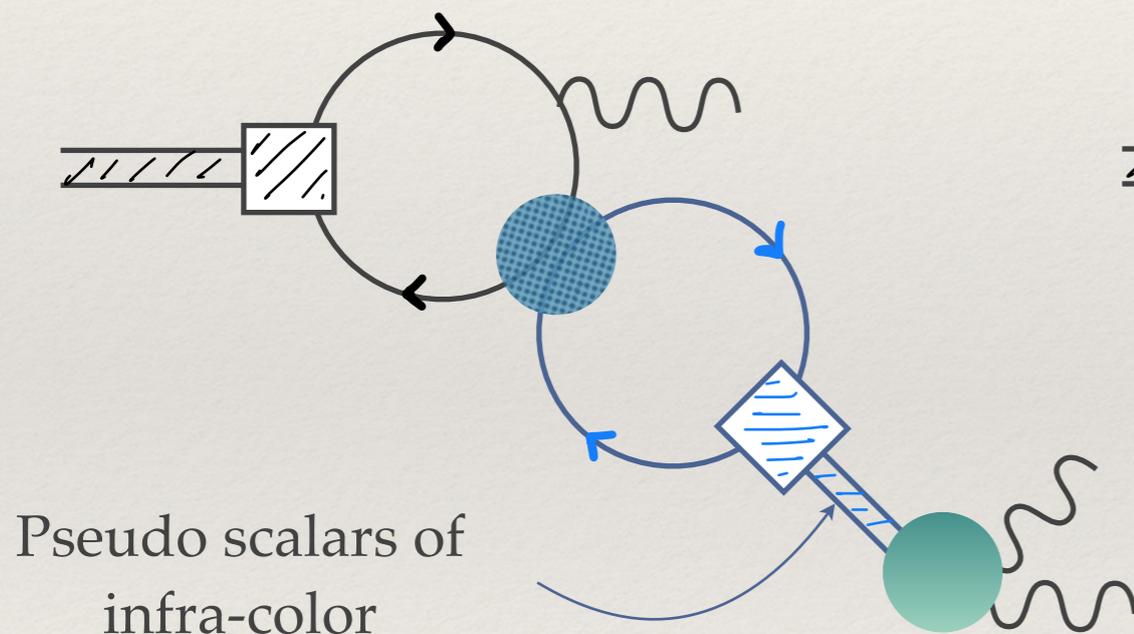
One requires χ -PT like calculations followed by reinterpretation of $\text{Ps} \rightarrow n\gamma + \text{ME}$

BSM in Positronium : bound states from contact operators

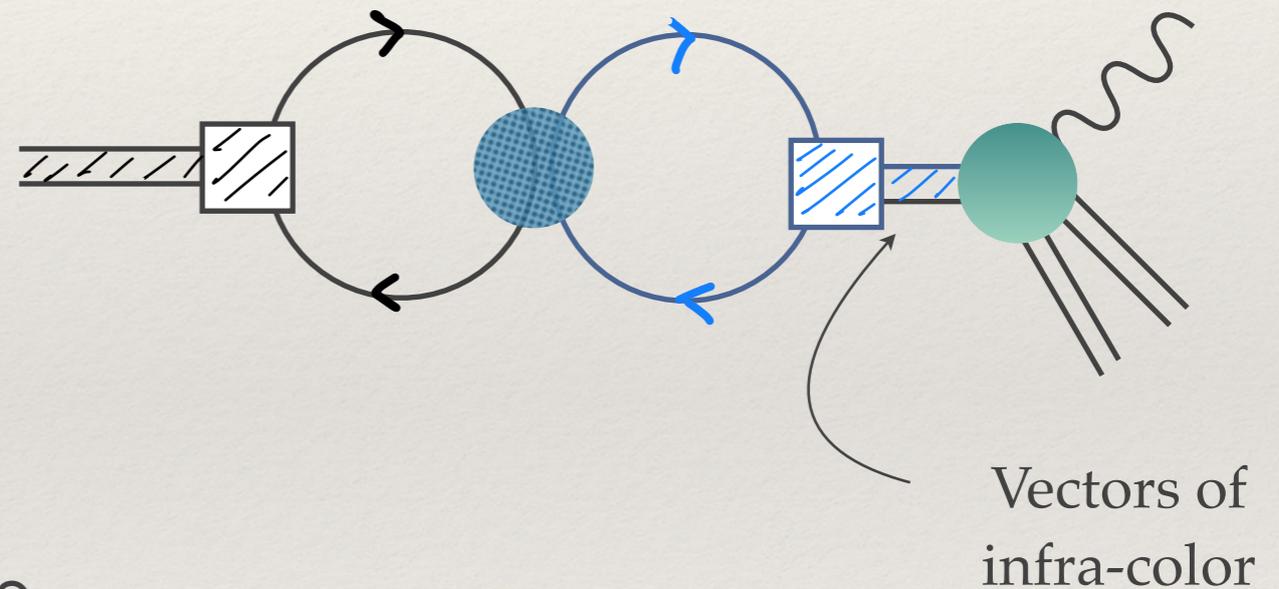
Do we always need to have milli-charged states to portal to new physics?

Not really. Consider for example contact interaction

$$\frac{\epsilon}{\Lambda_I^2} \bar{e} \Gamma_A e \bar{Q} \Gamma_A Q$$



This state looks like a composite axion



This state looks like a composite Z'

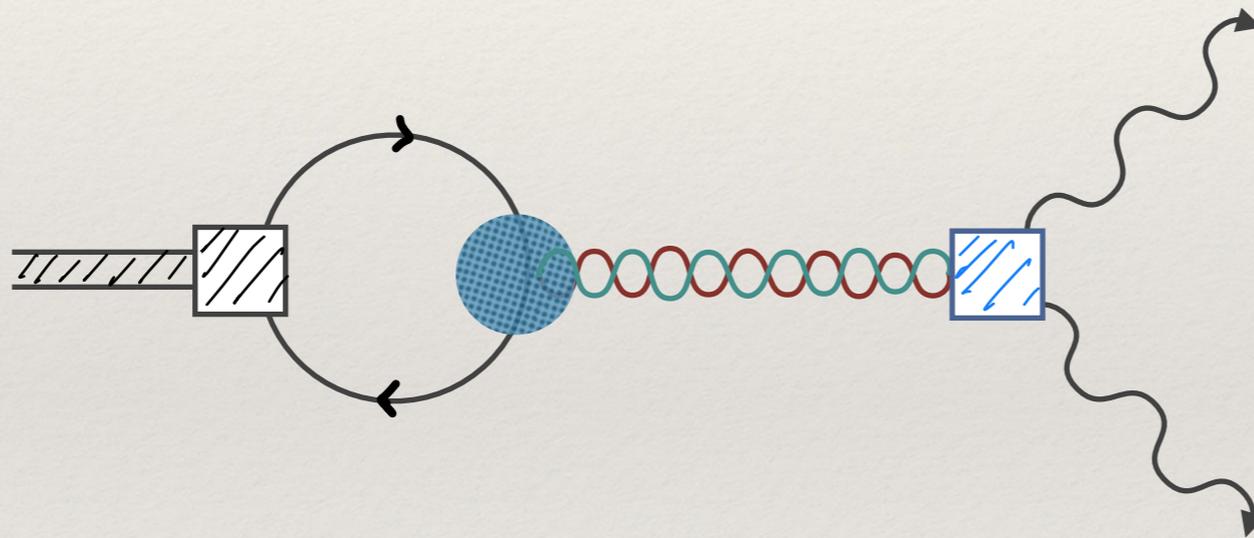
From visible to semi-invisible to totally invisible decay products

BSM in Positronium : quirks from contact operators

Do we always need to have milli-charged states to portal to new physics?

Not really. Consider for example contact interaction

$$\frac{\epsilon}{m_Q^2} \bar{e} \Gamma_A e \bar{Q} \Gamma_A Q$$



Displaced vertex + out of time decay products

From visible to semi-invisible to totally invisible decay products

Summary

- Positronium is a clean and well understood system
 - ➔ It is sufficiently decoupled from all UV scales and the only other light d.o.f (i.e. neutrinos) — a playground for precision QED.
- It is an ideal system to look for physics beyond the Standard Model
 - ➔ Especially for light sectors that are feebly coupled to the Standard model, a topic which has become a key focus of the particle physics community recently.
- The simplest BSM that can be explored in positronium is for light milli-charged particles
 - ➔ amazingly, there are regions of unexplored parameter space that can be probed in the next generation positronium experiments.
- Light composite sector can generate a plethora of interesting signals in positronium decays — can mimic signal topologies associated with for example ALPs, massive photons etc.
 - ➔ However, because of the existence of various scales, connecting high energy experiments to low energy experiments to cosmology / astrophysics observables can be tricky - these rely on omitting essential details and utilizing additional simplifying assumptions - reinterpretation in these scenarios should be done carefully.