Incontro Nazionale di Fisica Nucleare 2014

Padova, 24 - 26 marzo 2014
Aula Magna del Palazzo del Bo e Centro Culturale San Gaetano

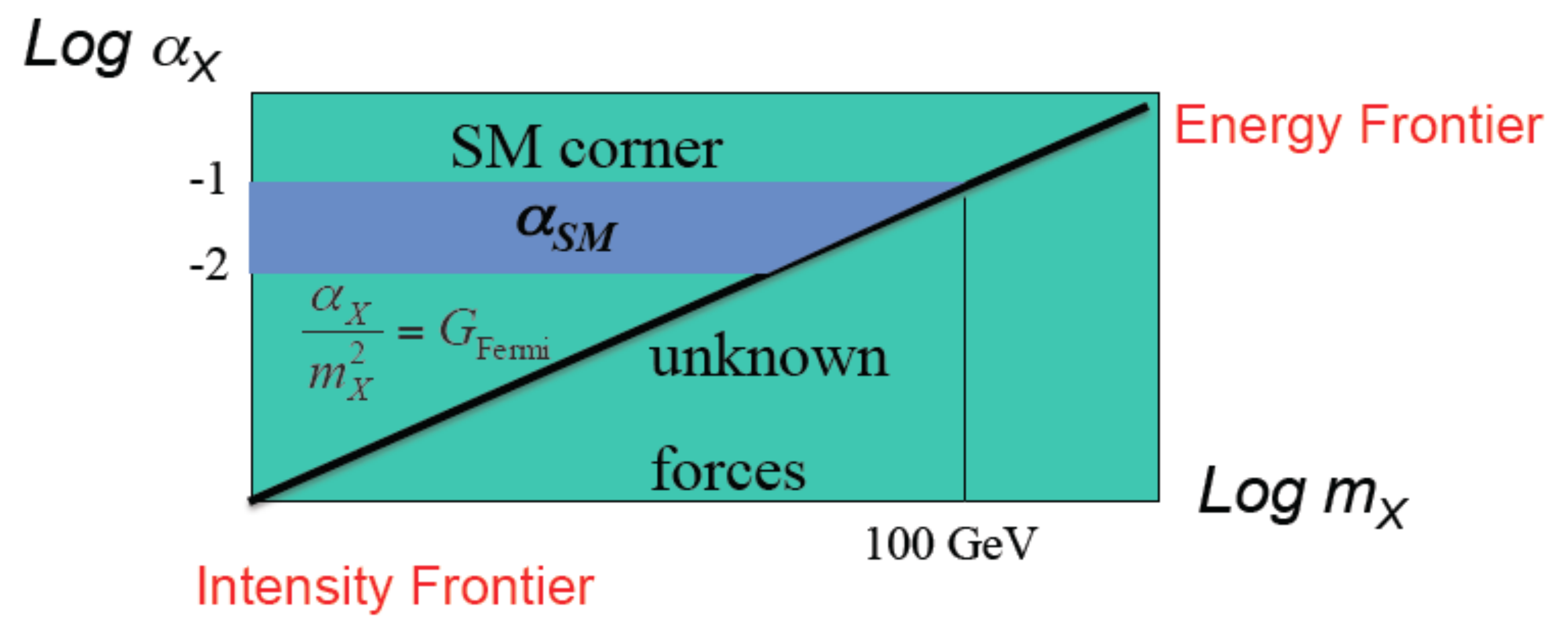
La "Intensity Frontier": ricerca di evidenze (in)dirette di nuova Fisica oltre il Modello Standard

Dark forces searches in fixed target experiments

M.Battaglieri
INFN-GE, Italy

- Physics case (top-down)
- Experimental evidence (bottom-up)
- Fixed target experiments (electron-beam)

How to look for new physics



LHC range: m_x~1TeV, α_x~α_{SM}

First results show no hints of new strongly-interacting states or new heavy EW bosons (other than Higgs)

What about if: m_x~1GeV, $\alpha_x < 10^{-6}$?

Important progress in neutrino physics, dark matter sensitivity, precise frontier measurements

Precise experiments at low/moderate energy!

Forces in nature

4 fundamental interactions known so far: strong, electromagnetic, weak and gravitational

Are there other interactions? how could we know about?
what could be their properties?

Particles, interactions and symmetries

Known particles & new force-carriers

Particles:
quarks, leptons

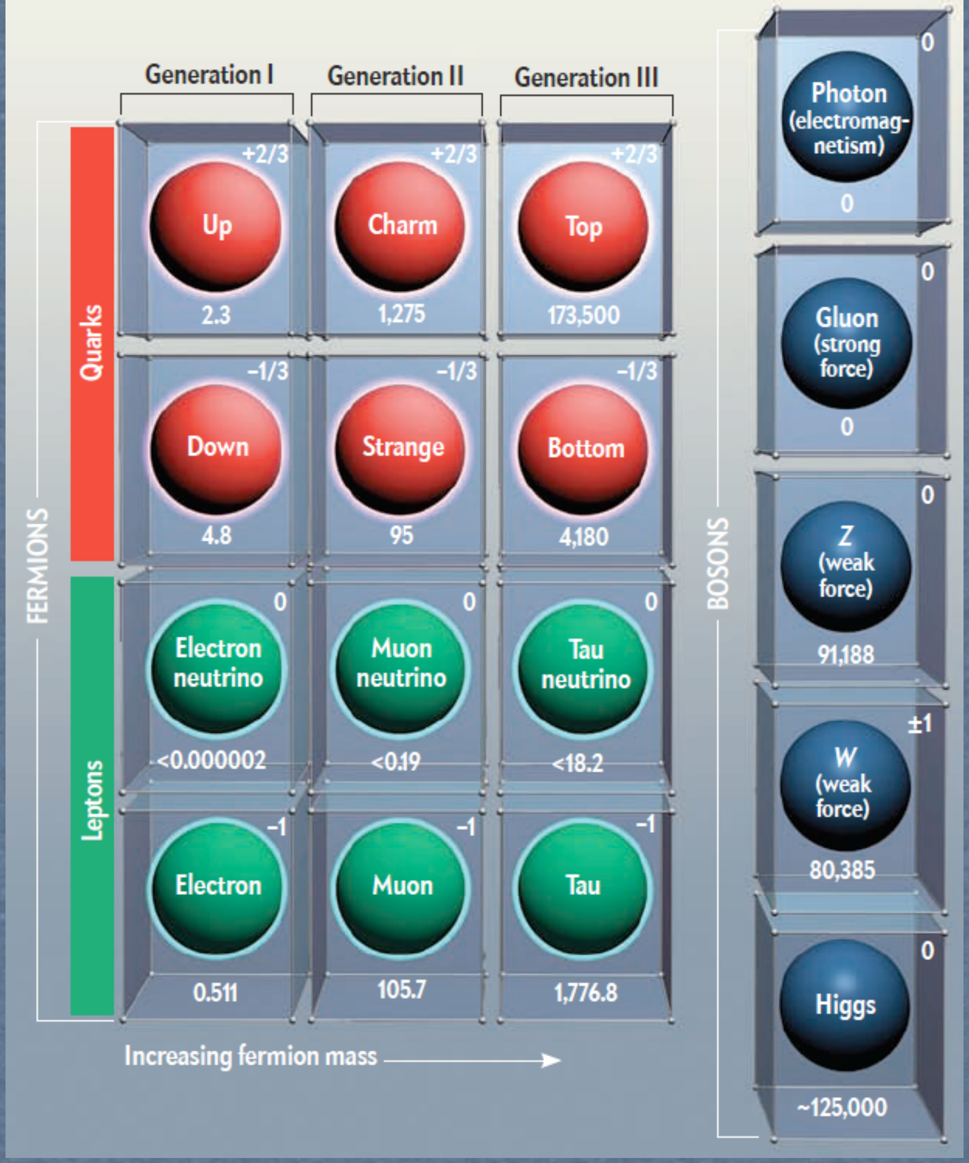
Force-carriers:
gluons, γ, W, Z, graviton (?), Higgs, ...

New particles & new force-carriers

Dark Matter

Spin-1: U bosons ('hidden' or 'dark' photons)
Spin-0: Axions (or axion-like particles)
Spin-0 (scalars): Higgs-like

New bosons are expected to mediate new interactions



Neutral doors (*Portals*) to include DM in the SM

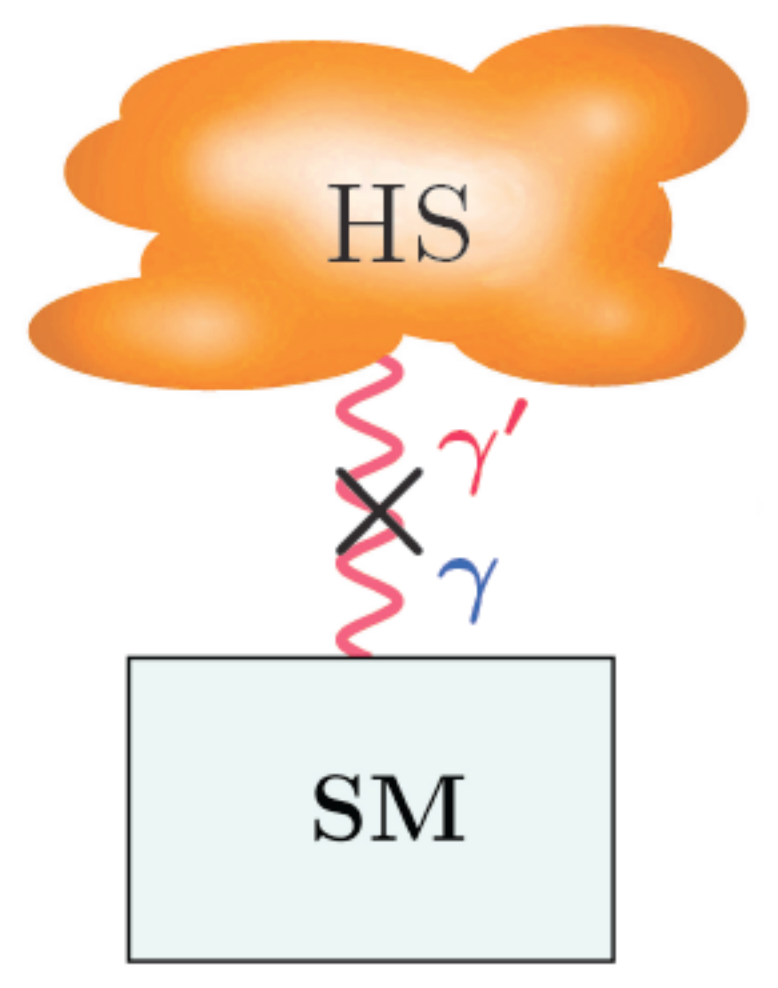
✳There are (many) possible ways to include the DM into the SM

✳ Some of them can be tested directly (e.g. rare B-decays)

A simple way to go beyond the SM (not yet excluded!):

$SU(3)_C \times SU(2)_L \times U(1)_Y$ **x extra U(1)**

Color Electroweak Hypercharge Hidden sector



✳Hidden sector (HS)

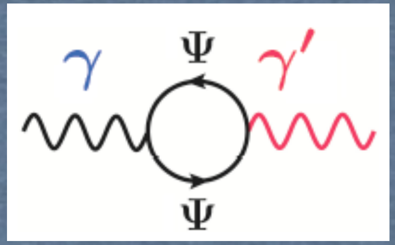
present in string theory and super-symmetries

✳HS not charged under SM gauge groups (and v.v.)

no direct interaction between HS and SM

HS-SM connection via messenger particles

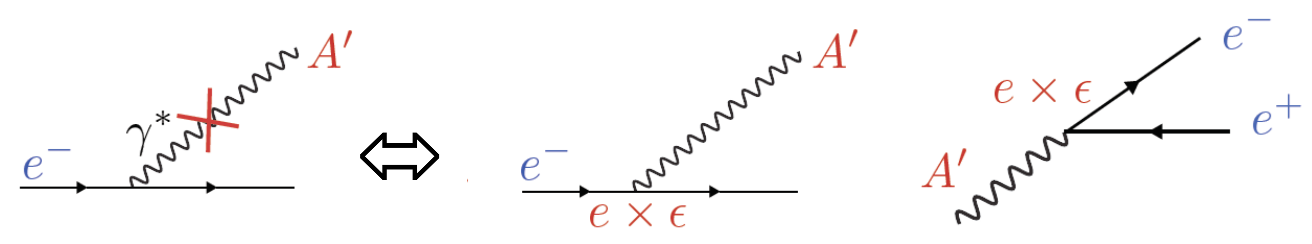
$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\chi}{2} \overset{\text{Hidden}}{X_{\mu\nu}} \underset{\text{Visible}}{F^{\mu\nu}} + \frac{m^2_{\gamma'}}{2} X_\mu X^\mu$$



Ψ can be a huge mass scale particle (M~1EeV) coupling to both SM and HS

γ'/A' couples to SM via electromagnetic current (kinetic mixing)

→ $A_\mu \rightarrow A_\mu + \varepsilon a_\mu$ $\chi = \varepsilon \sim 10^{-6}\text{-}10^{-2}$ ($\alpha^{\rm DarkPhoton} = \varepsilon^2 \alpha_{\rm em}$)



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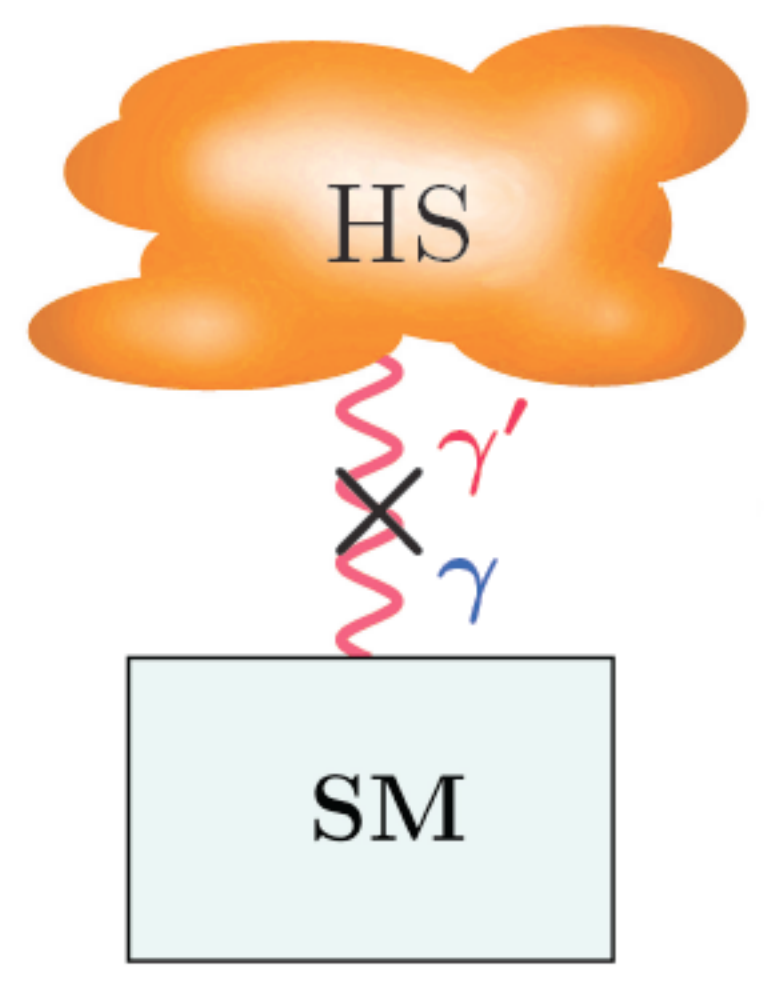

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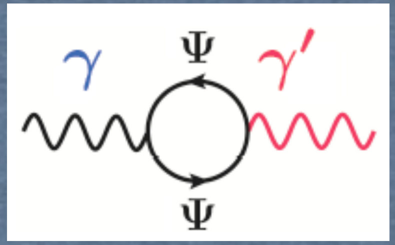

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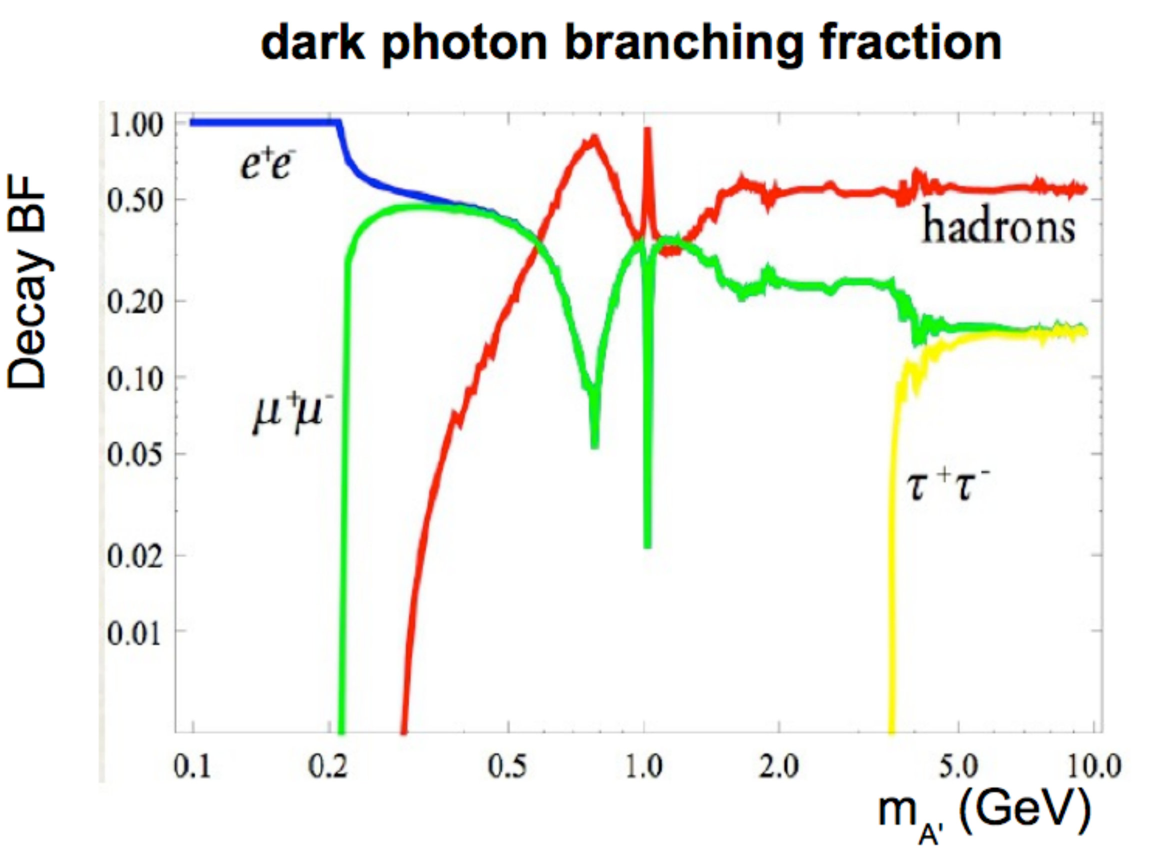
γ'/A' mass depends on the model

→ $\mathbf{m^2_{\gamma'}} \sim \chi M^2_{EW}$ (M_Z or TeV) ~ **MeV - GeV scale**

Consequences



Assumptions:

$M_{A'}$>1 MeV and no light dark fermions

- γ'/A' decay back to SM particles
- Prompt decay
- BF (A'→hadrons/A'→leptons) ~ M^2(A')

Above 1.2 GeV hadronic decays dominate

γ'/A' decays in leptons

→ **abundance of e^+e^- in Universe**

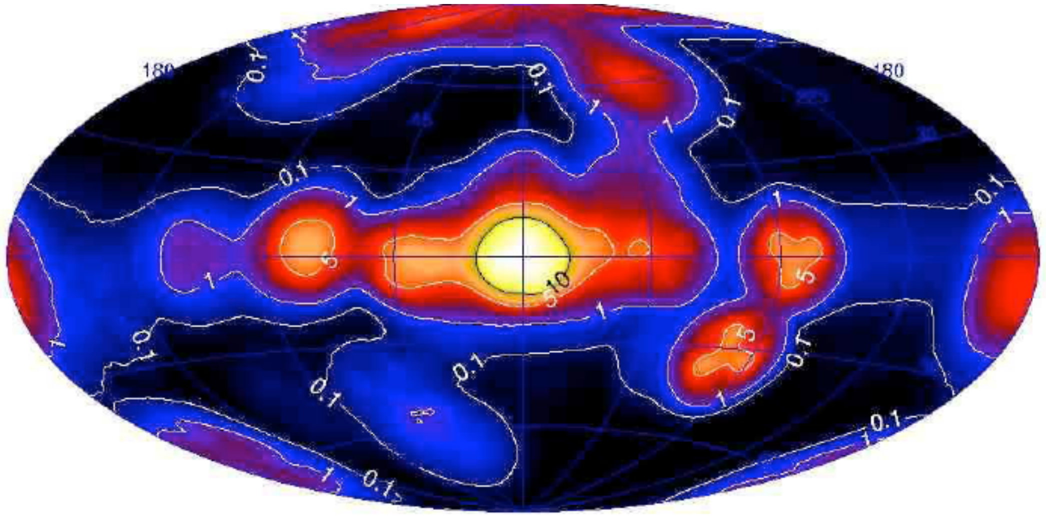
γ'/A' couples to SM via electromagnetic current (kinetic mixing)

→ **short range modification of EM interaction**

γ'/A' couples weakly to SM particles

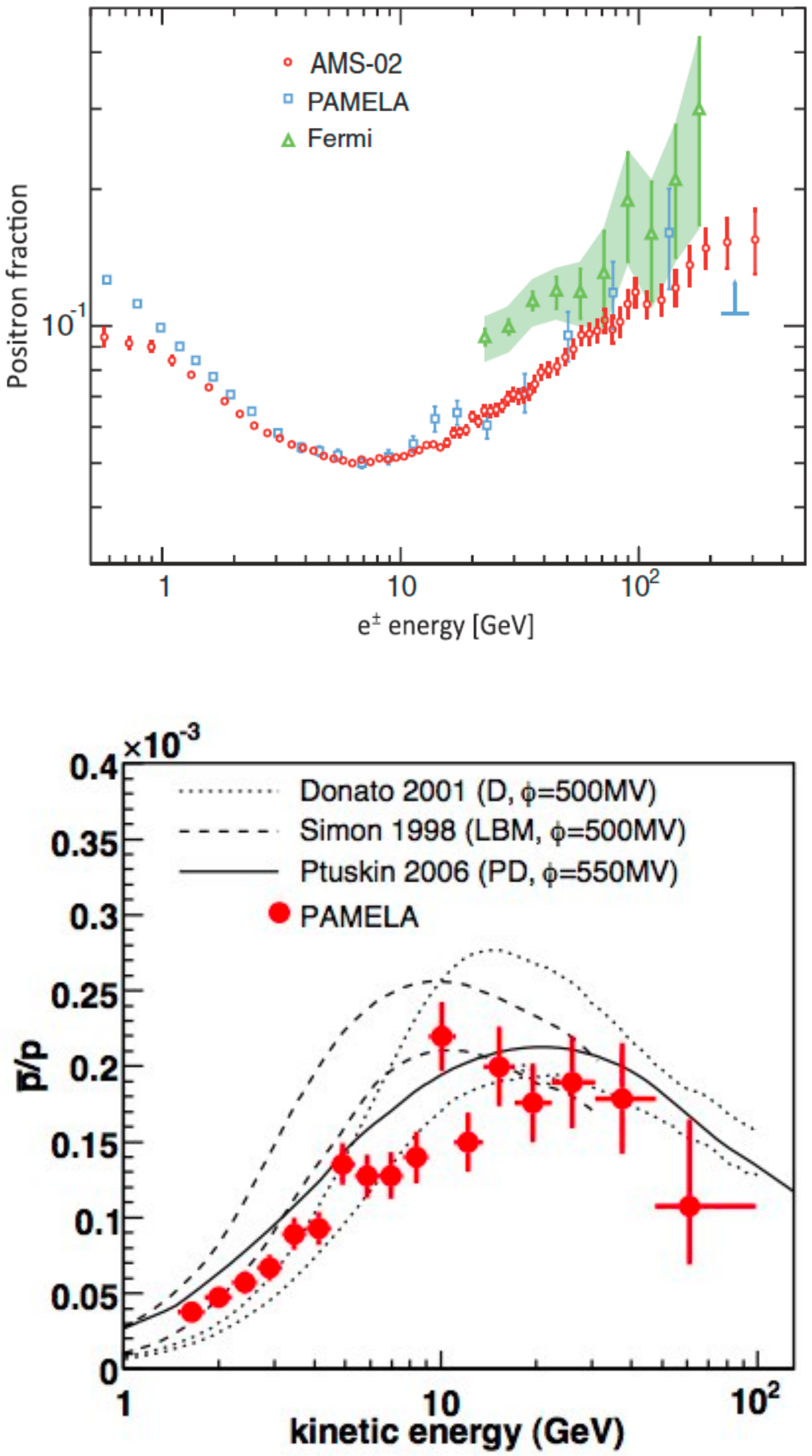
→ **long lived states**

Astrophysical motivation: the 511γ keV line



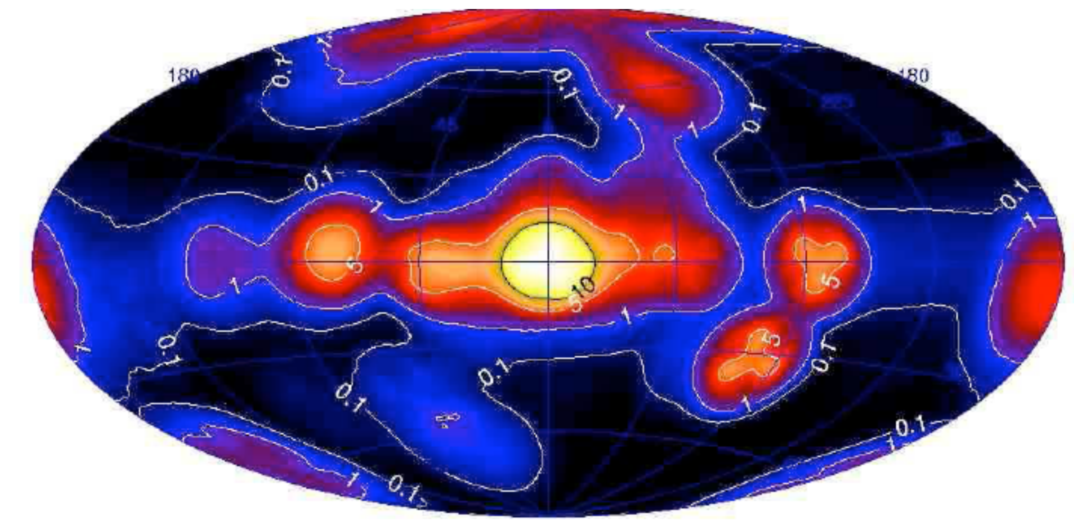
511 keV line map from GRAL/SPI data

Positron and antiproton abundance from PAMELA/AMS



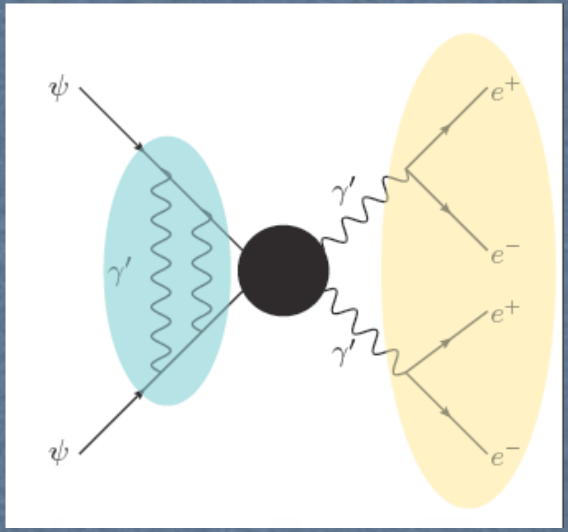
- ✳ Unexplained concentration of 511 keV line from the galactic center
- ✳ Diffuse emission of e+ e- annihilation (?)
- ✳ Increasing fraction of e+/e- measured by PAMELA
- ✳ No surprise with antiprotons (sub GeV mass gauge boson?)
- ✳ It is very difficult to explain PAMELA results with standard DM (WIMPS): needs a boost of 100-1000

Astrophysical motivation: the 511γ keV line

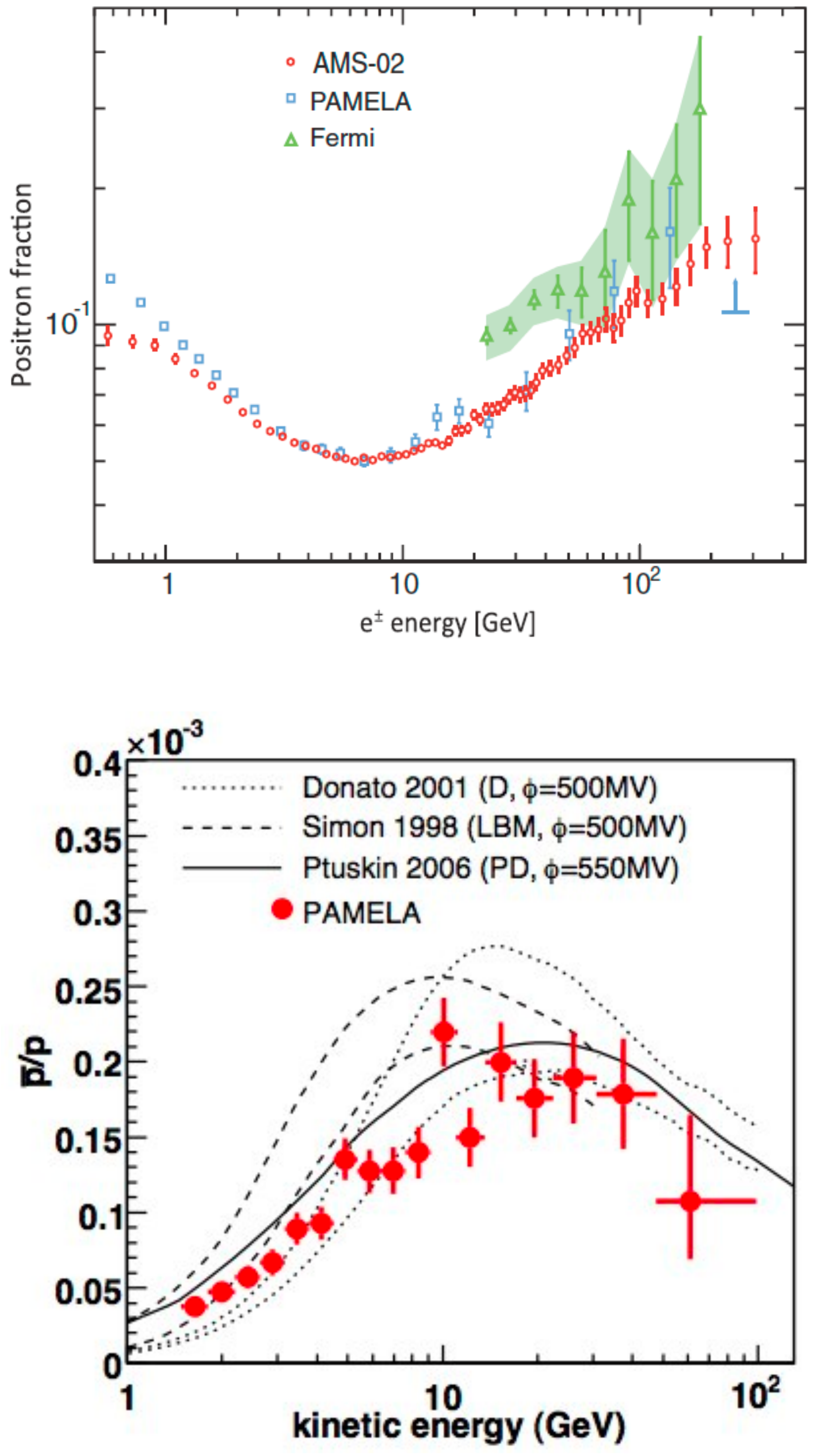


511 keV line map from GRAL/SPI data

Dark forces may explain it by
DM annihilation in A’ ➜ decay to e+e-



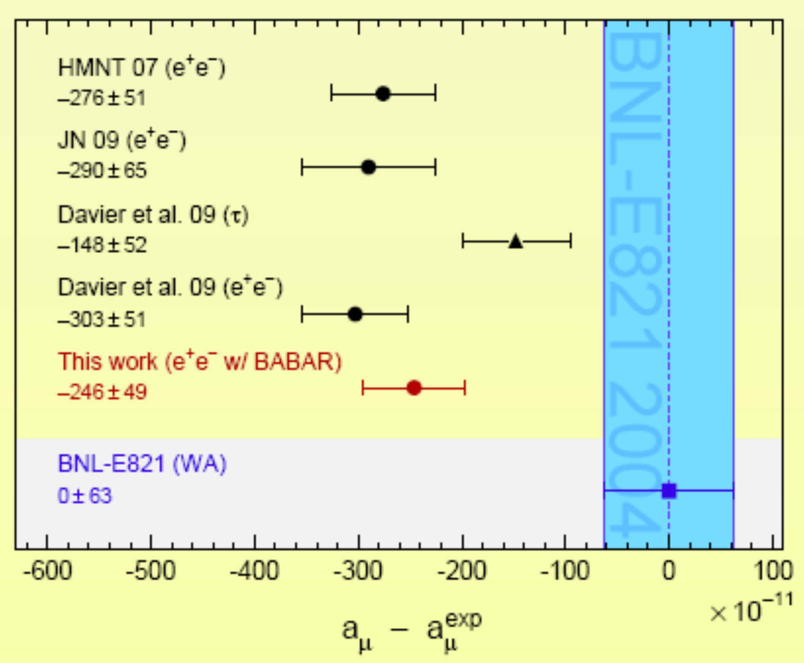
1) enhancement in e+ yield
2) hard e+ spectrum
3) no anti-p excess if $M_{A'}<2\ M_p$



Positron and antiproton abundance from PAMELA/AMS

Modification of EM

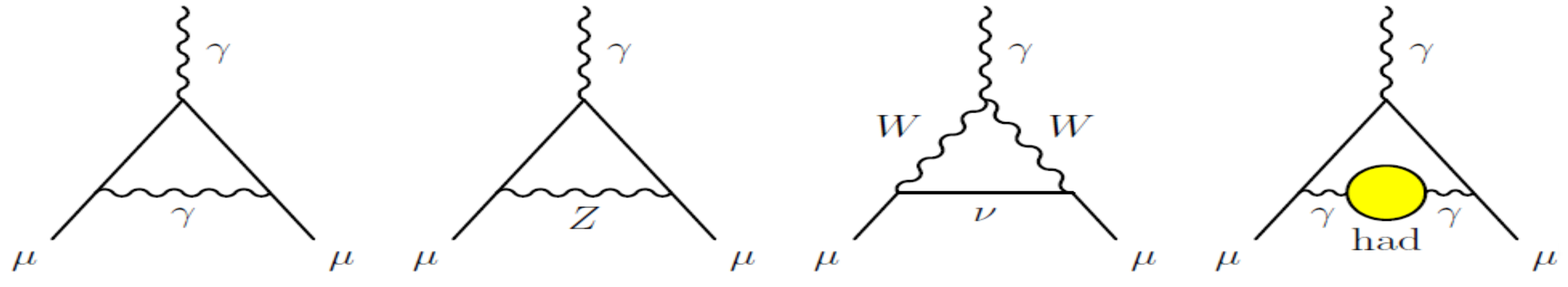
g-2 of muon



- g-2 is expected to be 0
- Discrepancy >3σ
- Some (complicated) strong interaction dynamic?
- New physics?

Standard Model Prediction

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{Hadronic}$$



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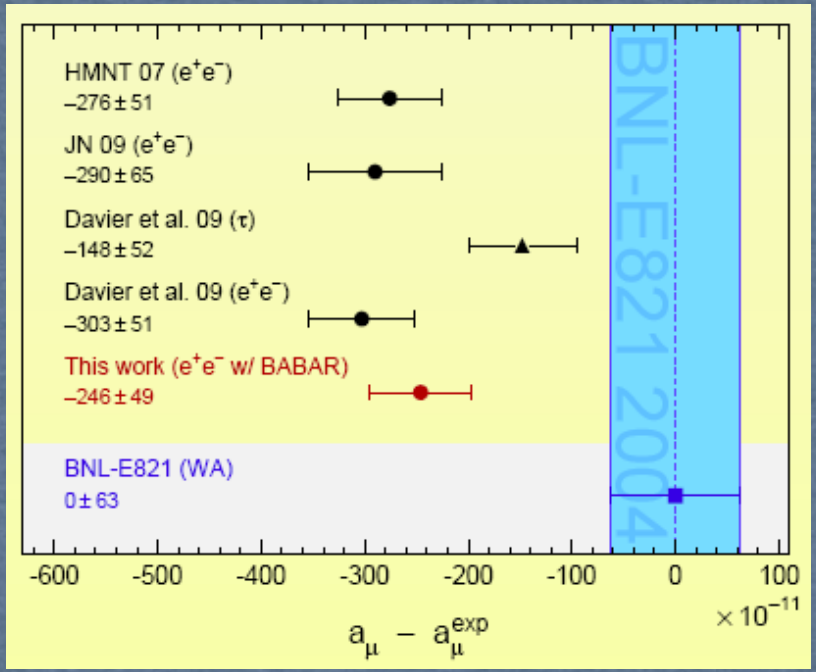
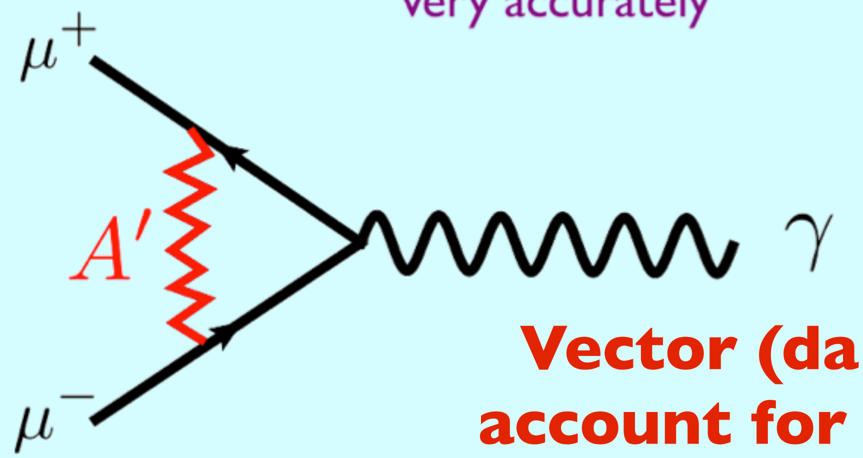


magnetic dipole moment

$$\vec{\mu} = \boxed{g_s}\left(\frac{q}{2m}\right)\vec{s}$$

spin

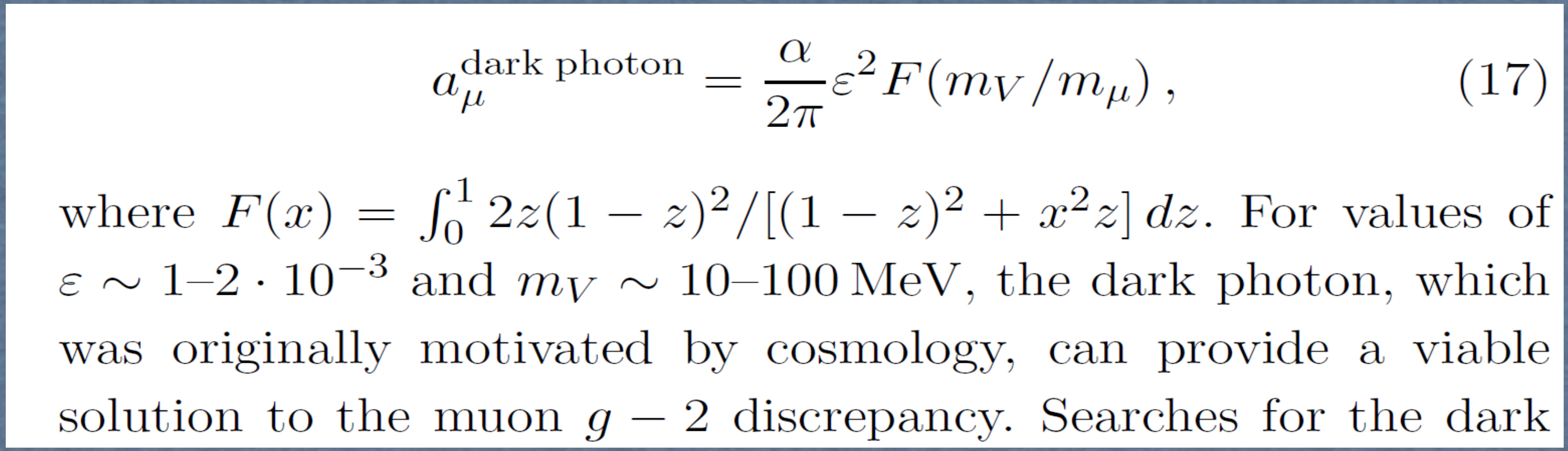
can be measured very accurately



$g_s \neq 2$

Vector (dark) force could account for the discrepancy

Contribution to g-2 from dark photon

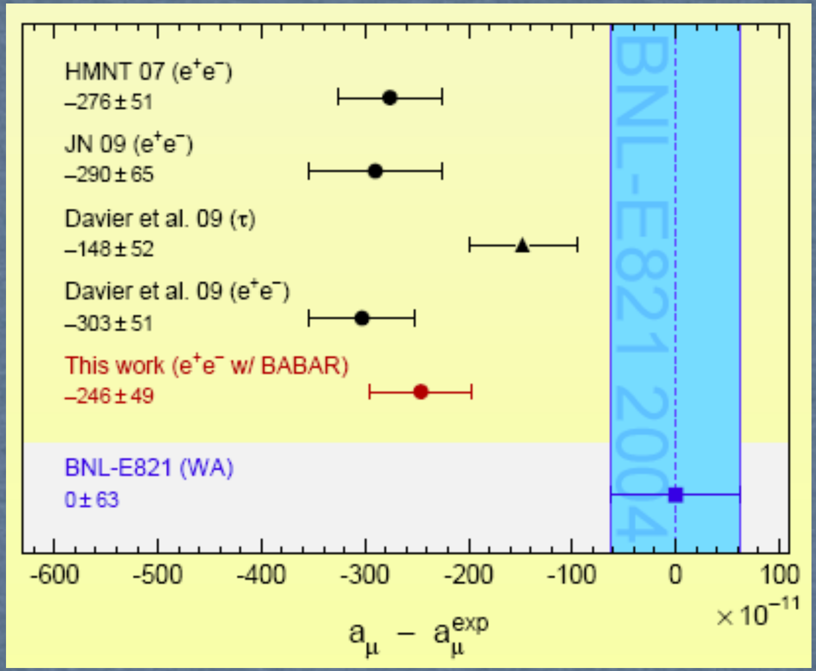


$$a_\mu^{\text{dark photon}} = \frac{\alpha}{2\pi}\varepsilon^2 F(m_V/m_\mu)\,, \qquad (17)$$

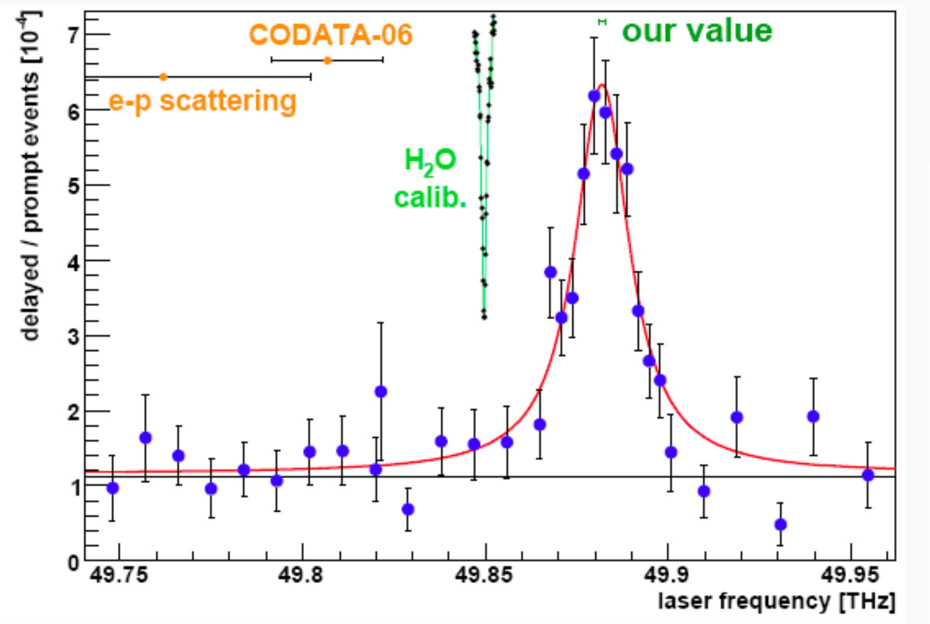
where $F(x) = \int_0^1 2z(1-z)^2/[(1-z)^2 + x^2 z]\,dz$. For values of $\varepsilon \sim 1\text{–}2 \cdot 10^{-3}$ and $m_V \sim 10\text{–}100\,\text{MeV}$, the dark photon, which was originally motivated by cosmology, can provide a viable solution to the muon $g-2$ discrepancy. Searches for the dark

Modification of EM

g-2 of muon



muonic hydrogen Lamb shift



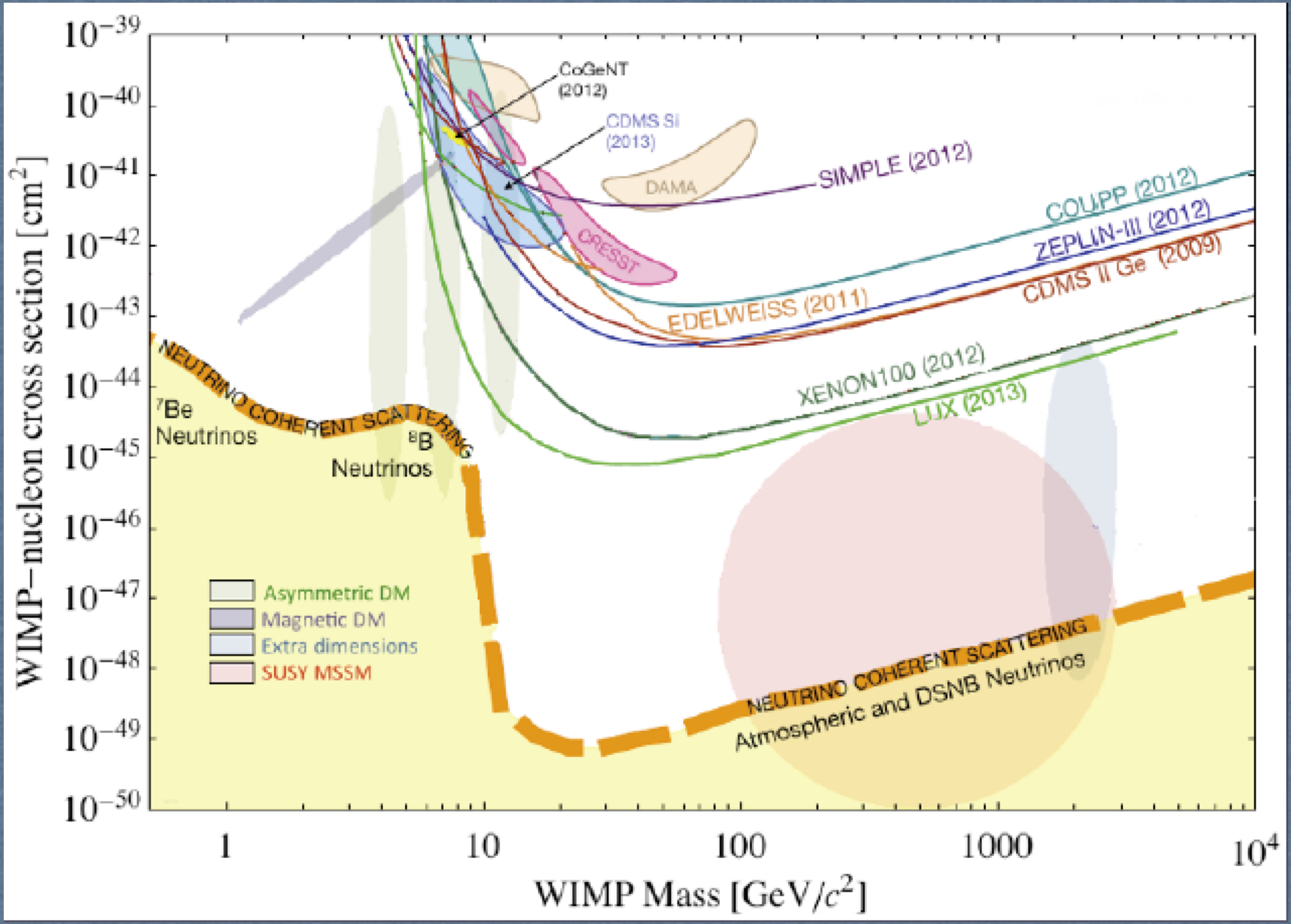
$$\boxed{r_p = 0.84184(67) \text{ fm} \qquad u_r^{th} = 8 \times 10^{-4}}$$

CODATA 2006: $r_p = (0.8768 \pm 0.0069)$ fm, from H

e-p scattering: $r_p = (0.895 \pm 0.018)$ fm (2%)

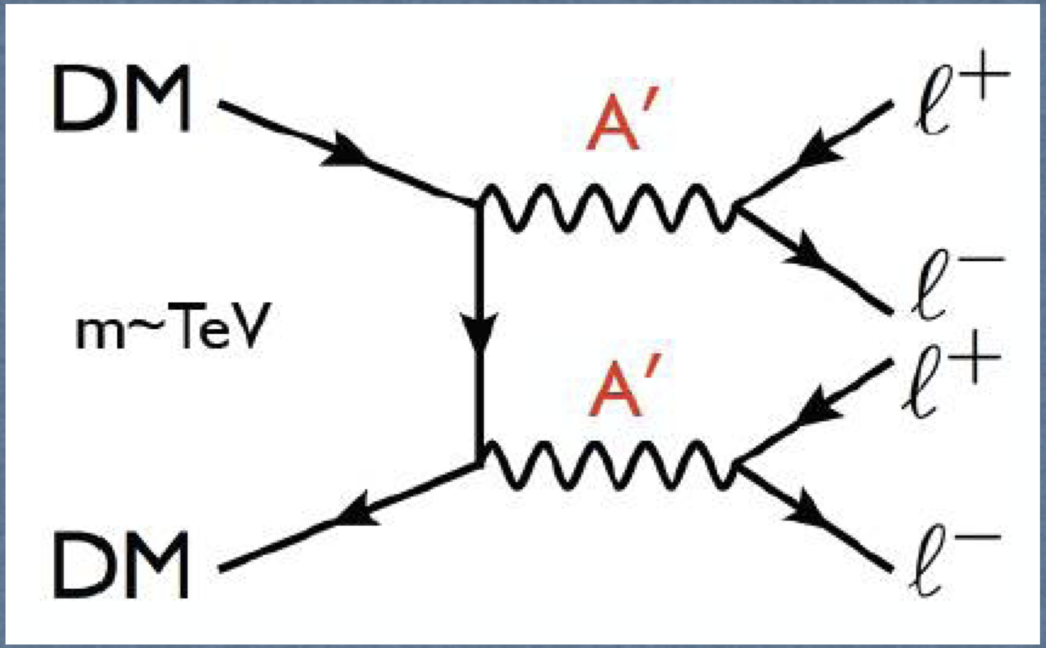
- ✴ muon 200 times closer to p (w.r.t. hydrogen)
- ✴ New forces for muon?

Dark Matter Search
Direct measurements



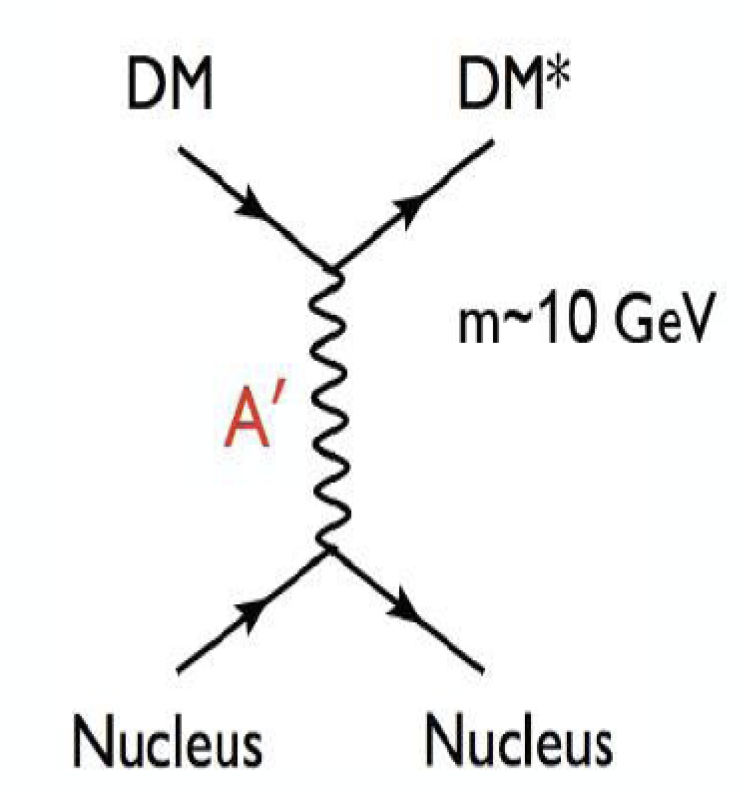
Dark forces and dark matter (heavy WIMP - light mediators)

Annihilation - Decay



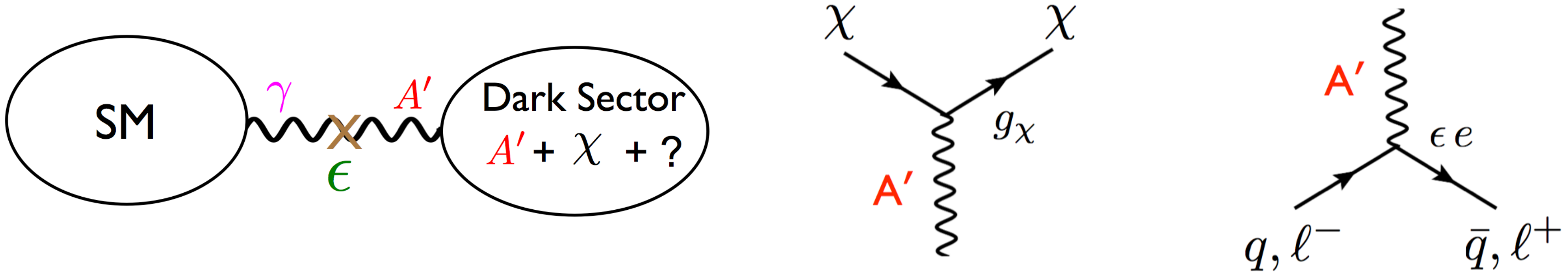
- ✳ e+ excess seen by PAMELA, AMS

Direct detection



- ✳ Elastic scattering on nuclei mediated by A’
- ✳ Comparison with experiments
- ✳ DAMA/LIBRA claims

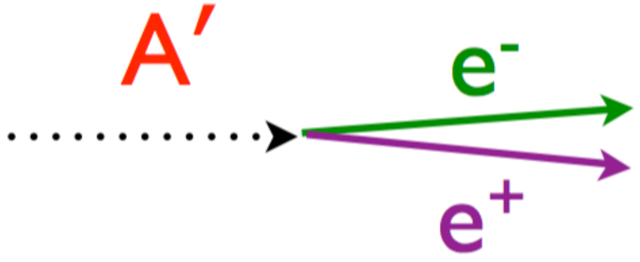
Dark forces and dark matter (Light WIMP - light mediators)



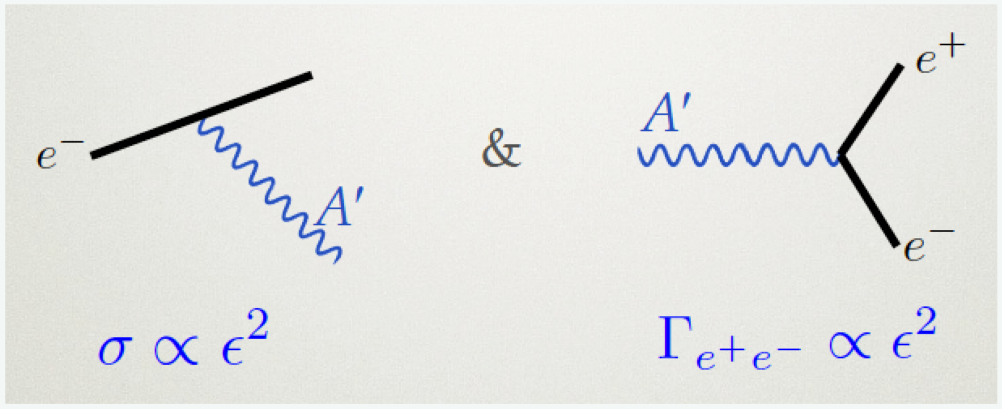
4 parameters: $m_\chi, m_{A'}, \epsilon, g_\chi$

$m_\chi \sim m_{A'} \sim \mathrm{MeV} - 5\ \mathrm{GeV}$

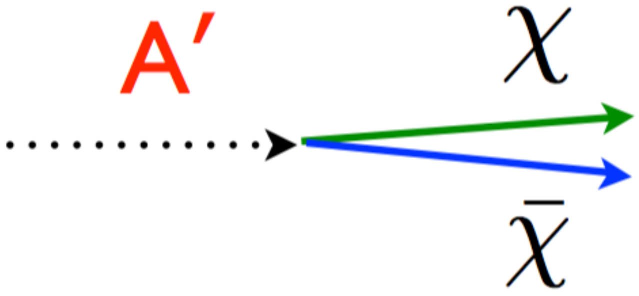
Visible



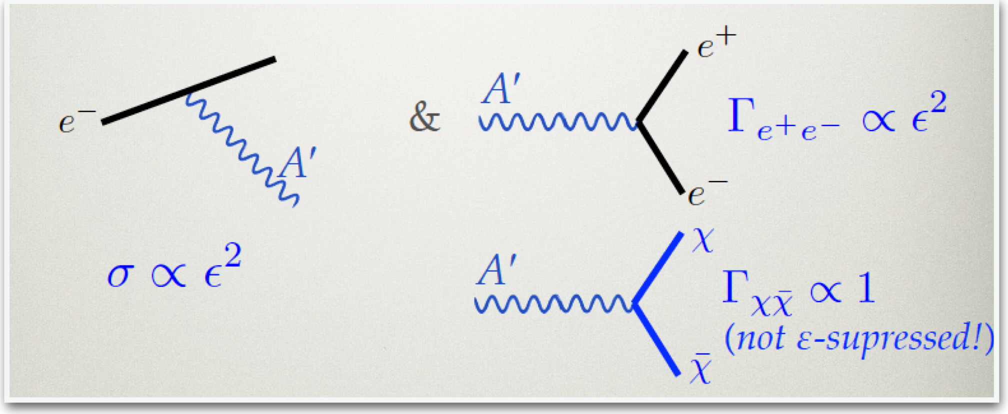
- *Minimal* decay
- Decay regulated by ε^2
- Independent on m$_\chi$
- Requires m$_{A'}$<2m$_\chi$



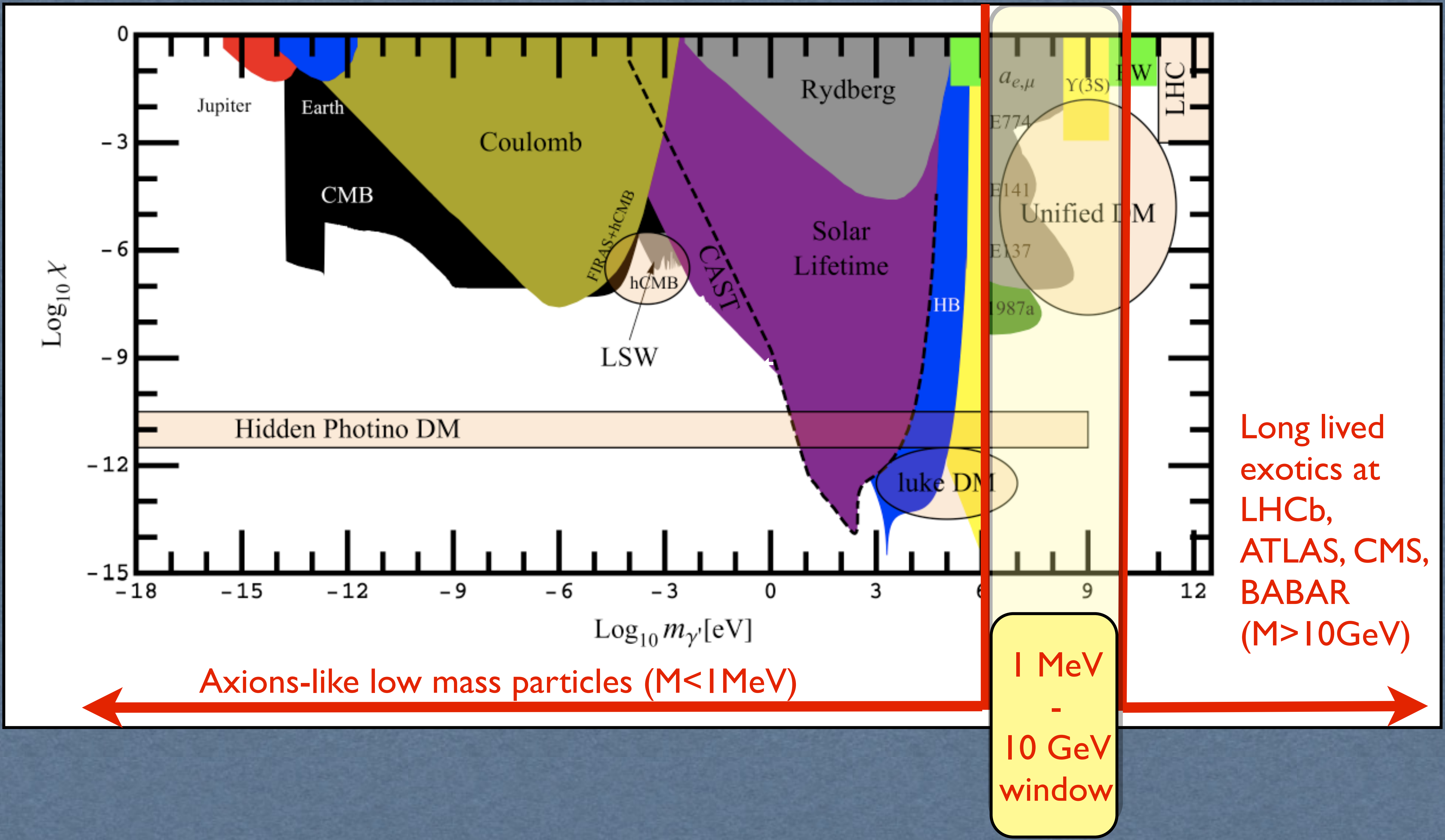
Invisible



- m$_\chi$ <2m$_{A'}$
- i) stable and invisible
- ii) decays to SM particles
- Independent on ε



Where to look for it?

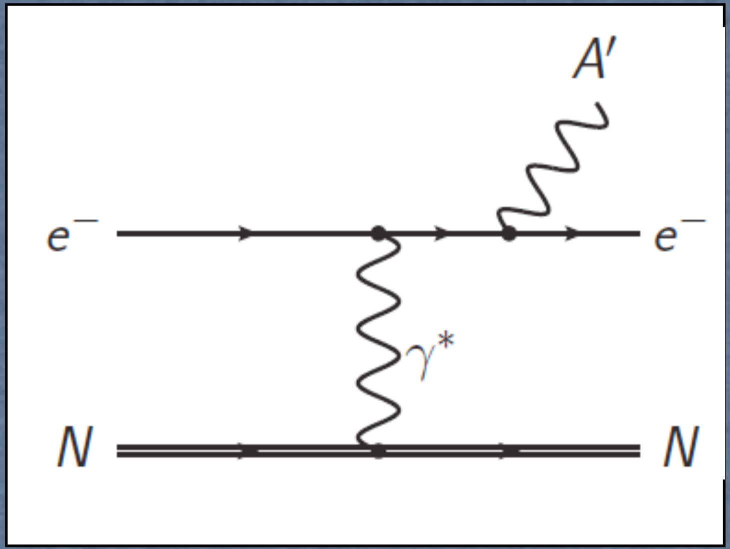


Long lived exotics at LHCb, ATLAS, CMS, BABAR (M>10GeV)

Axions-like low mass particles (M<1MeV)

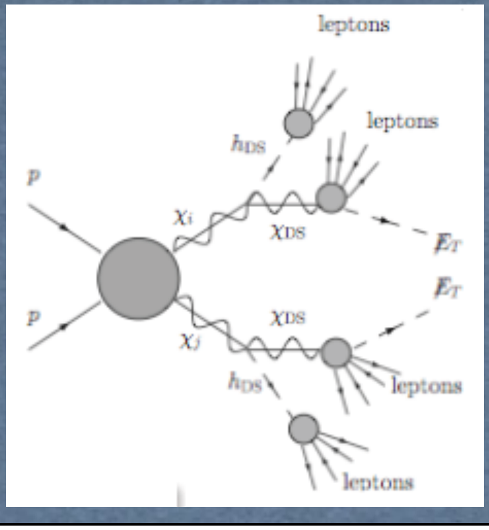
1 MeV - 10 GeV window

Particle physics search of A'/γ' (hidden photon)

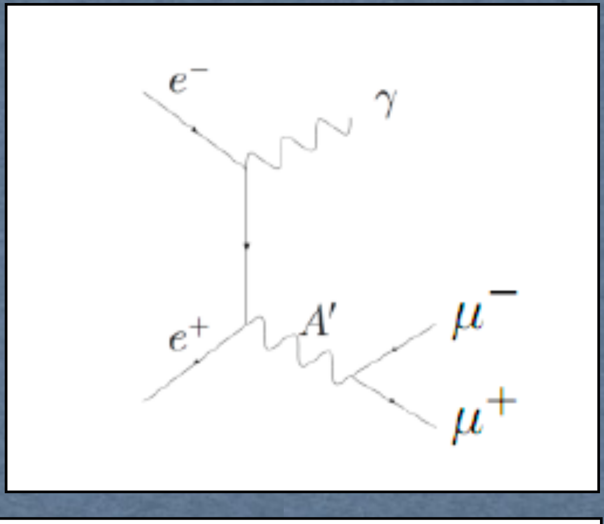


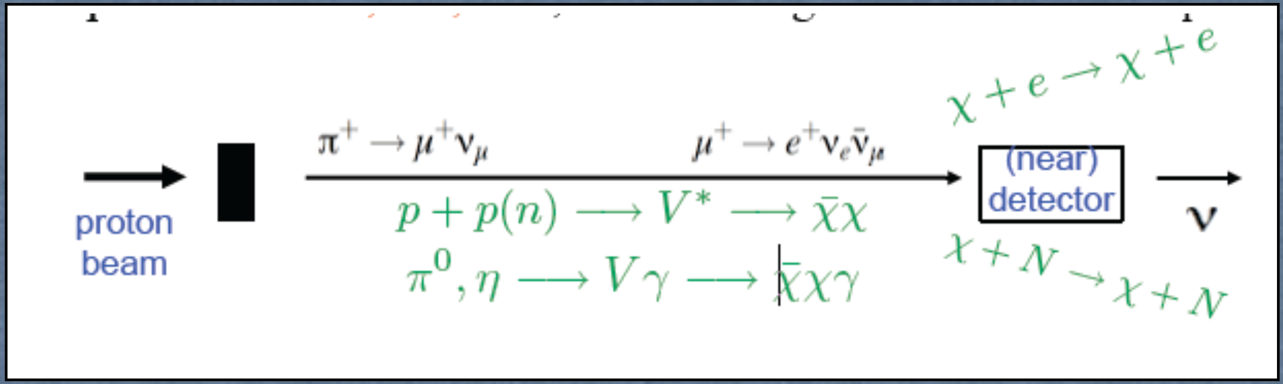
Fixed target:
e N →N γ'→ N Lepton Lepton+
→ **JLAB, MAINZ**

High Energy
Hadron Colliders:
pp → lepton jets
→ **ATLAS, CMS, CDF&D0**



Annihilation:
e+e- → γ' γ → μμ γ
→ **BABAR, BELLE, KLOE, CLEO**

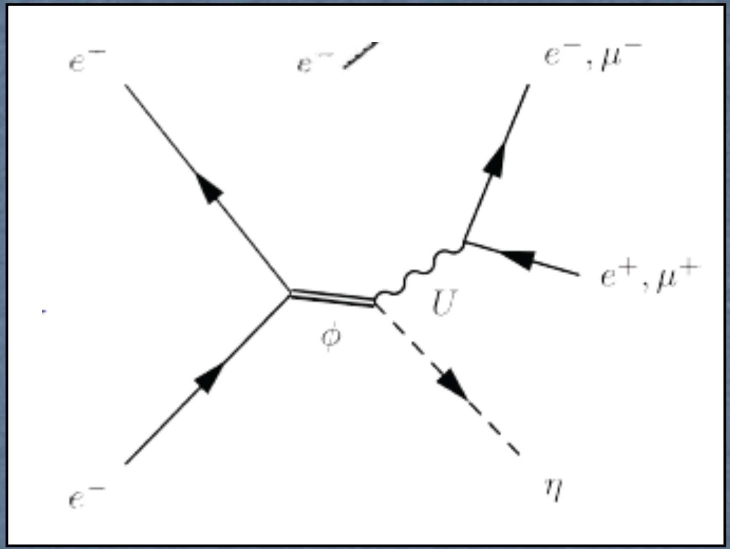




Fixed target:
p N →N γ'→ p Lepton Lepton+
→ **FERMILAB, SERPUKHOV**

electron scattering
cleaner than proton

Meson decays:
π^0, η, η', ω,' → γ' γ (M)
→Lepton Lepton + γ (M)
→ **KLOE, BES3, WASA-COSY**

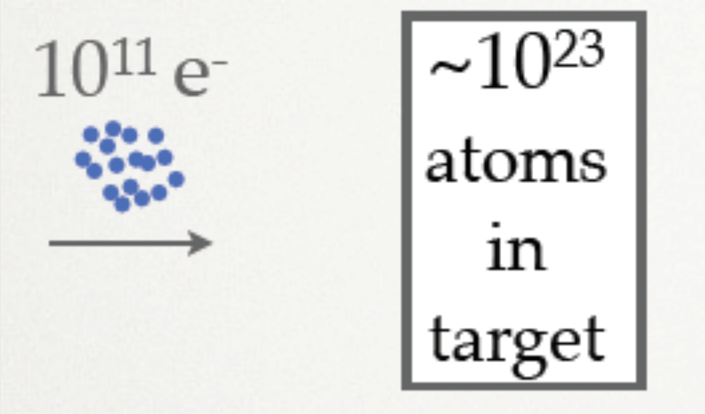


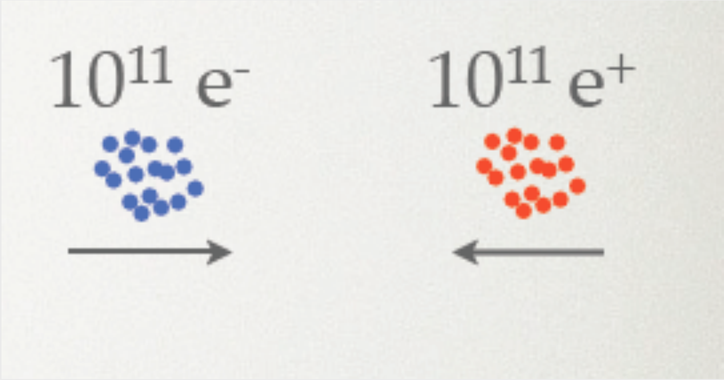
Fixed target searches

Fixed Target

e+e- colliders

Luminosity





Cross-Section

✳1/$M_{A'}$ .vs.1/E_{beam}
✳Coherent scattering from Nucleus (~Z^2)

$$\sigma \sim \frac{\alpha^3 Z^2 \epsilon^2}{m^2} \sim O(10\ pb)$$

$$\sigma \sim \frac{\alpha^2 \epsilon^2}{E^2} \sim O(10\ fb)$$

- high backgrounds
- limited A' mass

- low backgrounds
- higher A' mass

Particle physics search of A'/γ' (hidden photon)

Fixed target: e N →N γ'→ N Lepton$^-$ Lepton$^+$

→ **JLAB, MAINZ**

Fixed target: p N →N γ'→ p Lepton$^-$ Lepton$^+$

→ **FERMILAB, SERPUKHOV**

Annihilation: e+e- → γ' γ → $\mu\mu$ γ

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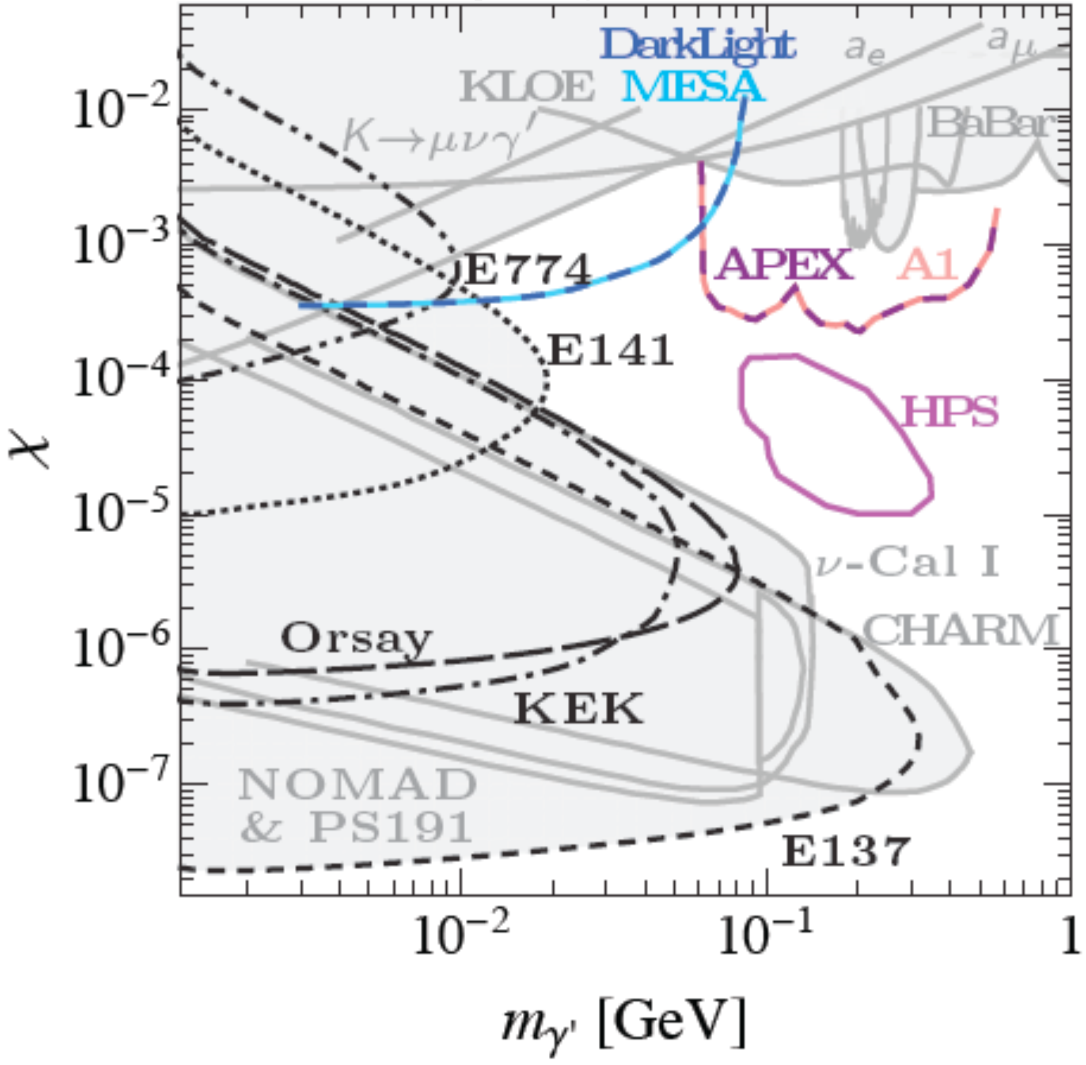
Meson decays: π^0, η, η', ω,' → γ' γ → Lepton$^-$ Lepton$^+$ γ

→ **KLOE, BES3, WASA-COSY**

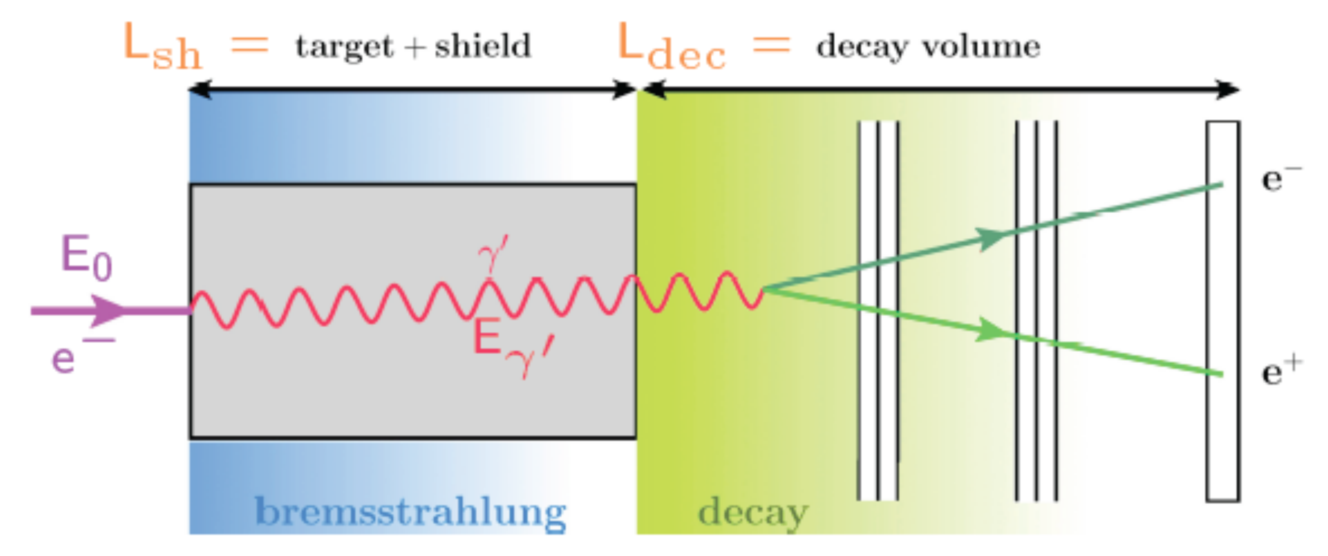
No positive signal (so far) but limits in parameter space coupling vs mass

Parameter space
Coupling vs Mass

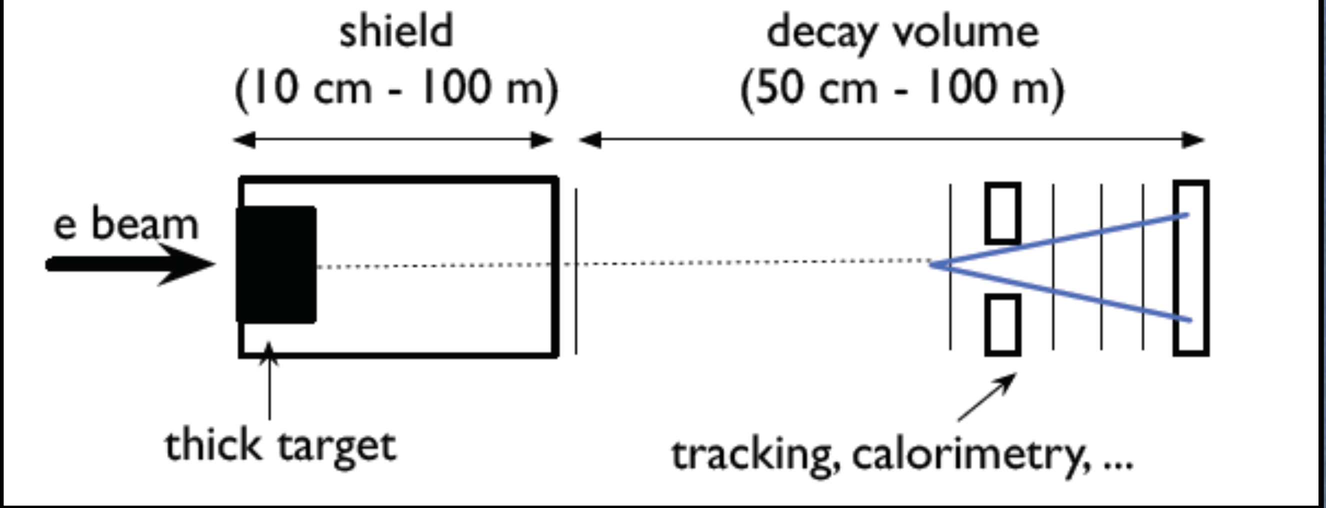


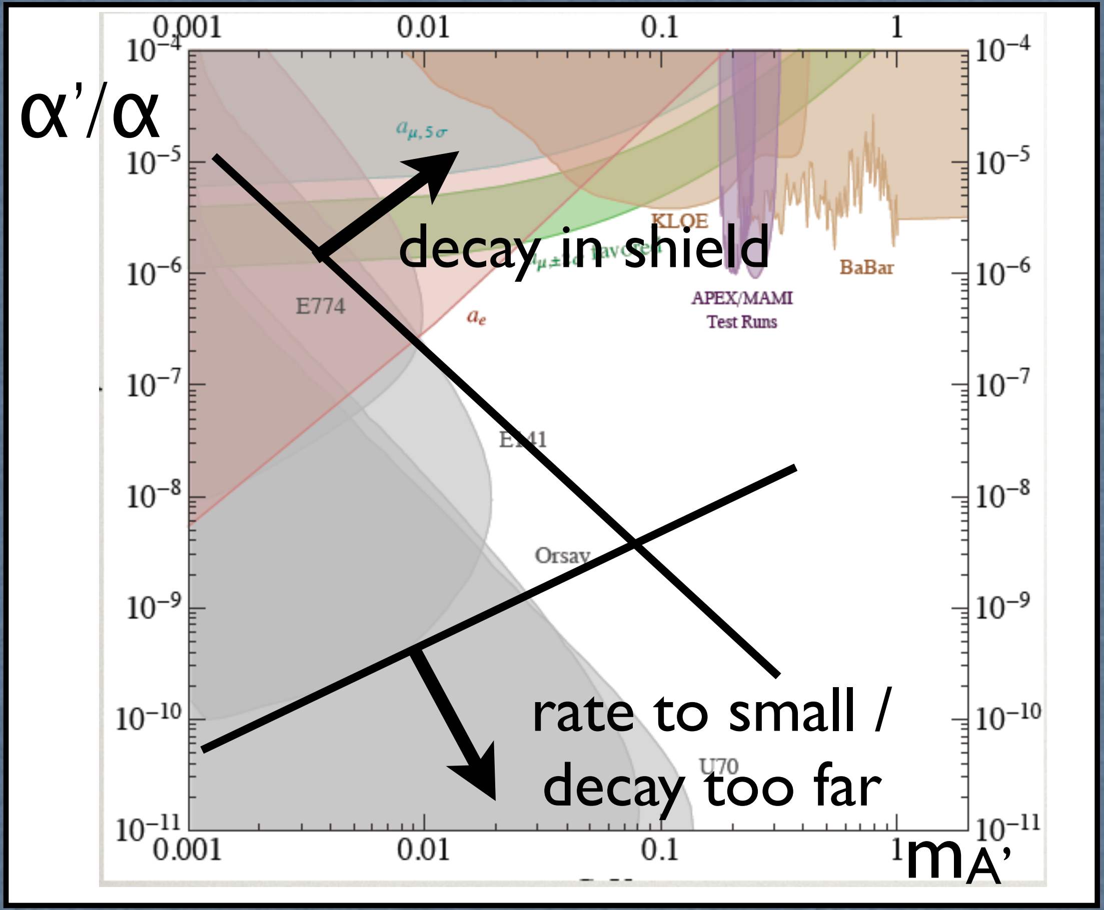
1st generation fixed target exp: beam dump

- ✳ e- beam incident on thick target
- ✳ A’ is produce in a process similar to ordinary Bremsstrahlung
- ✳ A’ carries most of the beam energy
- ✳ A’ emitted forward at small angle
- ✳ A’ decays before the detector



$$\gamma c\tau \approx 1\ \mathrm{mm}\,(\gamma/10)\,\left(10^{-8}\alpha/\alpha'\right)$$
$$\times\,(100\ \mathrm{MeV}/m_{A'})$$





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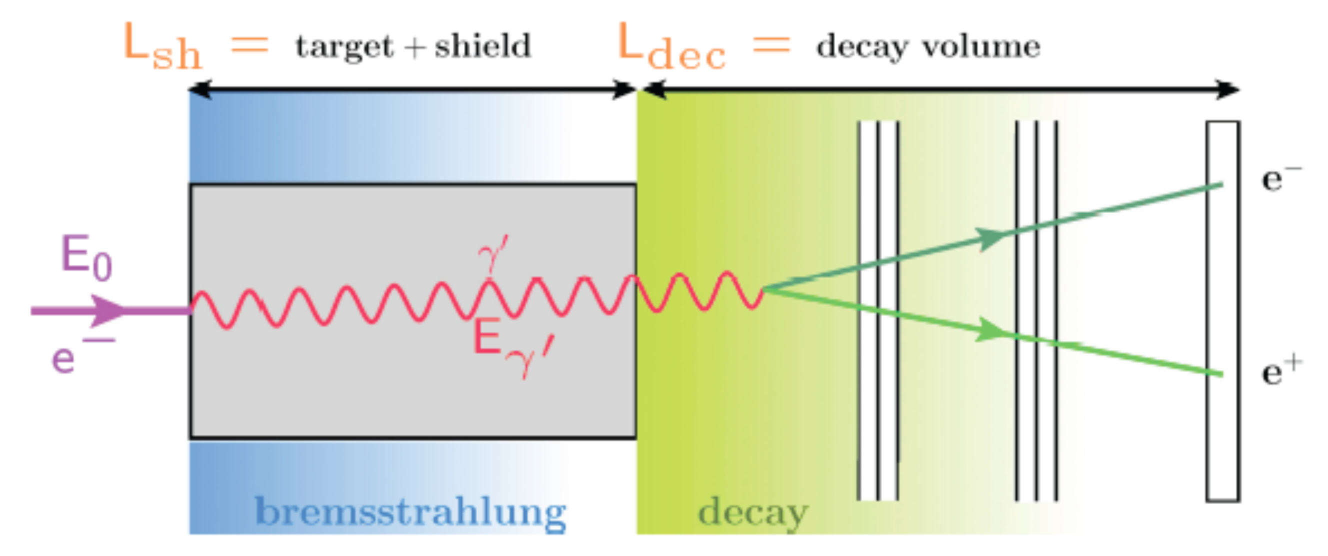
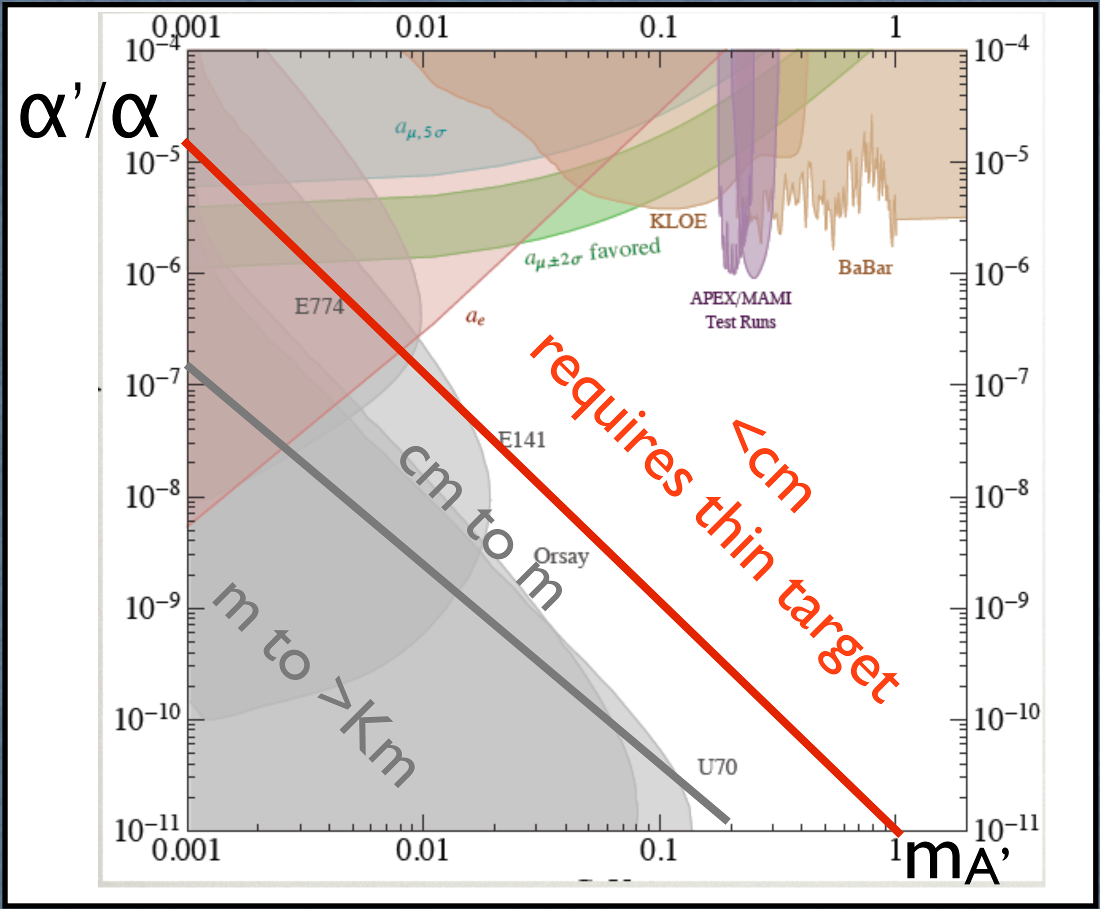


$$\gamma c\tau \approx 1\ \mathrm{mm}\,(\gamma/10)\,(10^{-8}\alpha/\alpha')$$
$$\times\,(100\ \mathrm{MeV}/m_{A'})$$

Multiple experimental approaches, with different strategies for fighting backgrounds:

- – l_d ≫ cm: beam dump; low background
- – l_d ~ cm: vertex; limited by instrumental bg
- – l_d ≪ cm: bump hunt; fight bg with high intensity, resolution



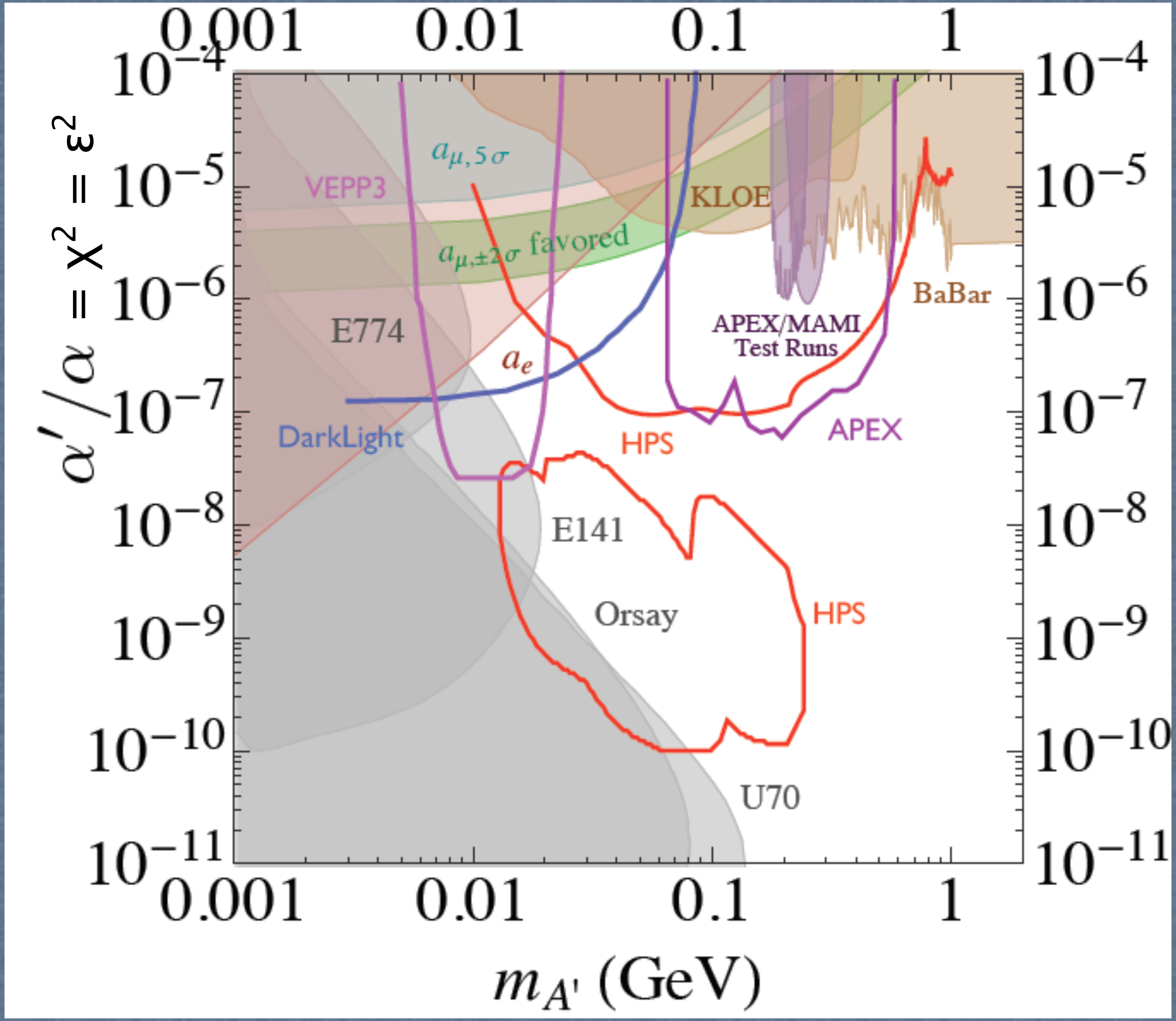
Current generation fixed target exp: thin target JLab and Mainz

JLab

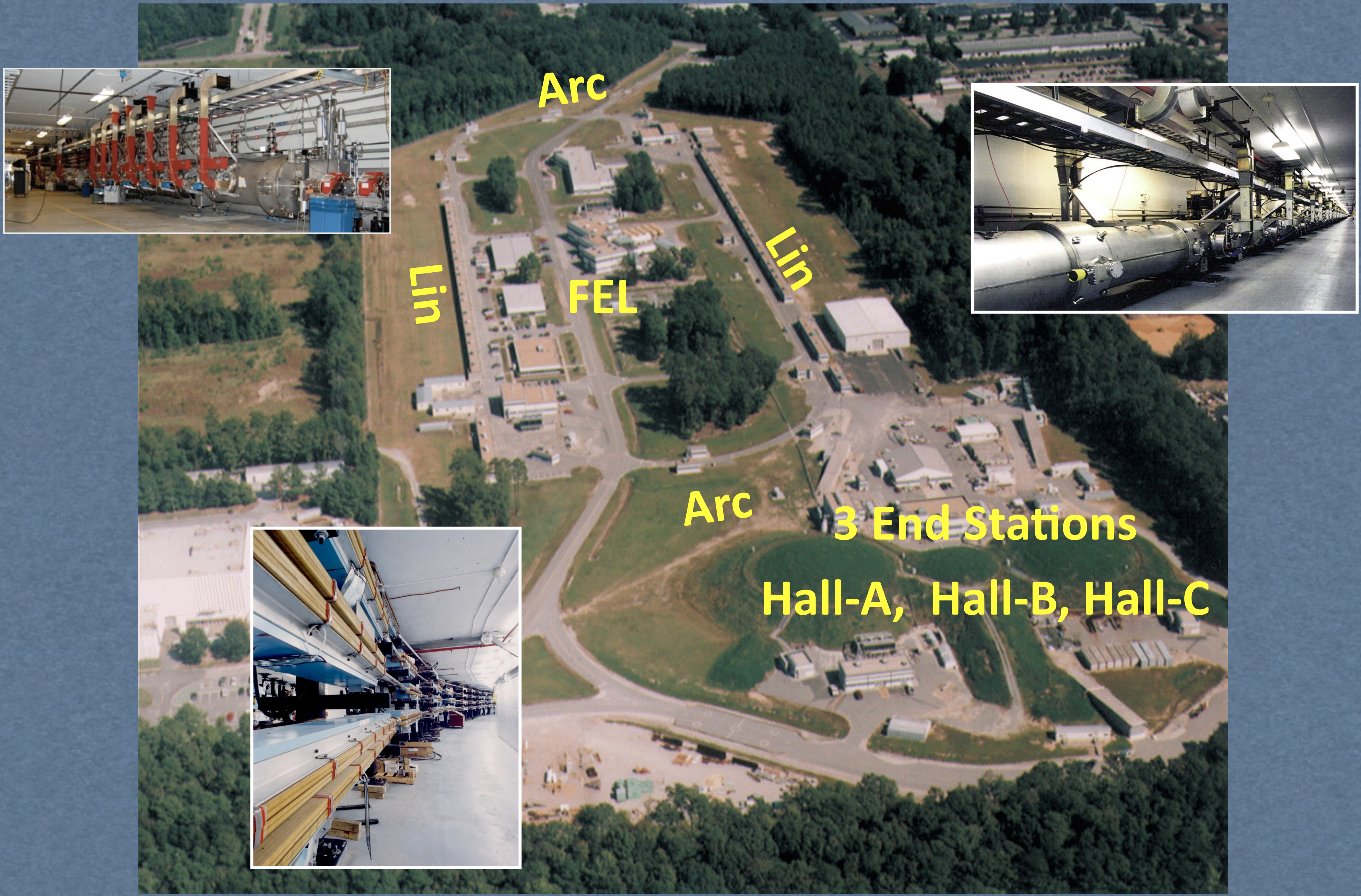
- ✳ DARK LIGHT (FEL)
- ✳ APEX (Hall-A)
- ✳ HPS (Hall-B)
  - Unconventional use of the CEBAF
  - PAC approval (max rating conditioned to technical feasibility)
  - Positive run-tests
  - Experiments begin: 2015-16

Mainz

- Magnetic spectrometers (A1)
- Pilot run in 2012
- Future plans



Jefferson Lab and the CEBAF



The CEBAF parameters

- ✳ Primary Beam: Electrons
- ✳ Beam Energy: 6 GeV (12 GeV soon)
  + Free Electron Laser (FEL)
- ✳100% Duty Factor (cw) Beam
- ✳ Polarization (beam and reaction products)

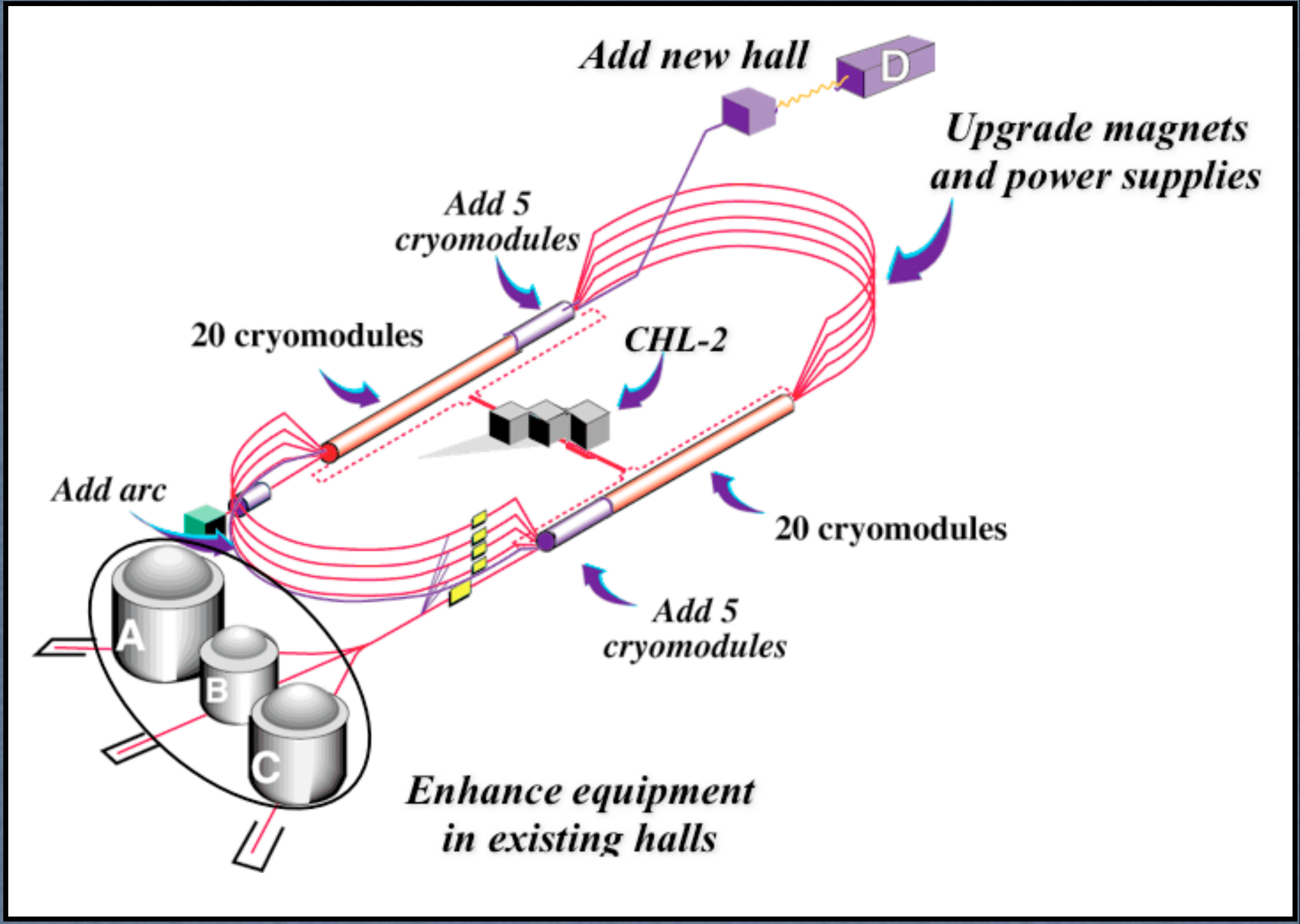
L > 10^6 x SLAC at the time of the original DIS experiments!

JLab12 luminosity will increase by 10 x

12 GeV upgrade

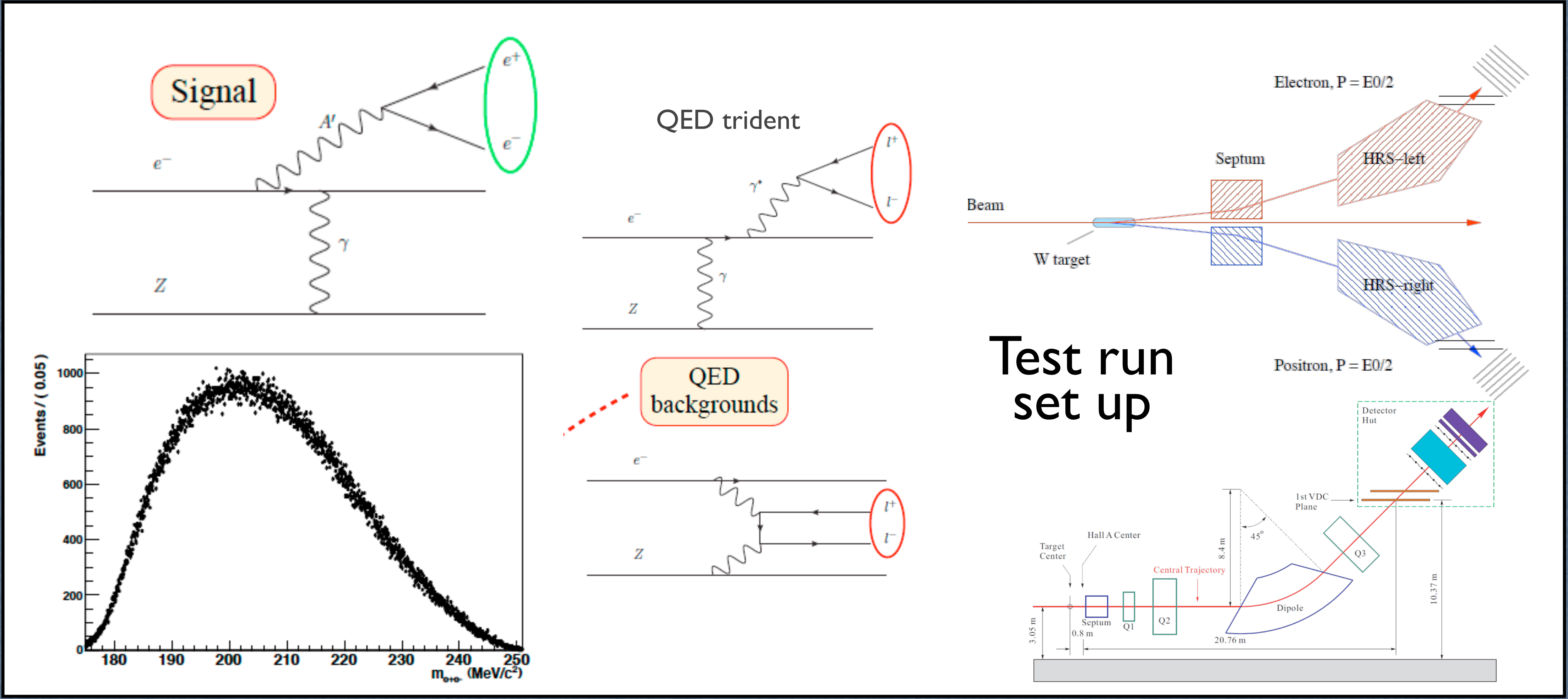
- ✳ Upgrade of the accelerator
- ✳ Construction of new equipment for
  Hall A, B and C
- ✳ Construction of new experimental Hall (D)

16-month installation:	**May 2012 – Sept 2013**
Hall A commissioning start	**Apr 2014**
Hall D commissioning start	**Oct 2014**
Halls B/C commissioning start	**Sept 2015**
Project Completion	**March 2016**



JLab experiments
APEX (A-Prime EXperiment)

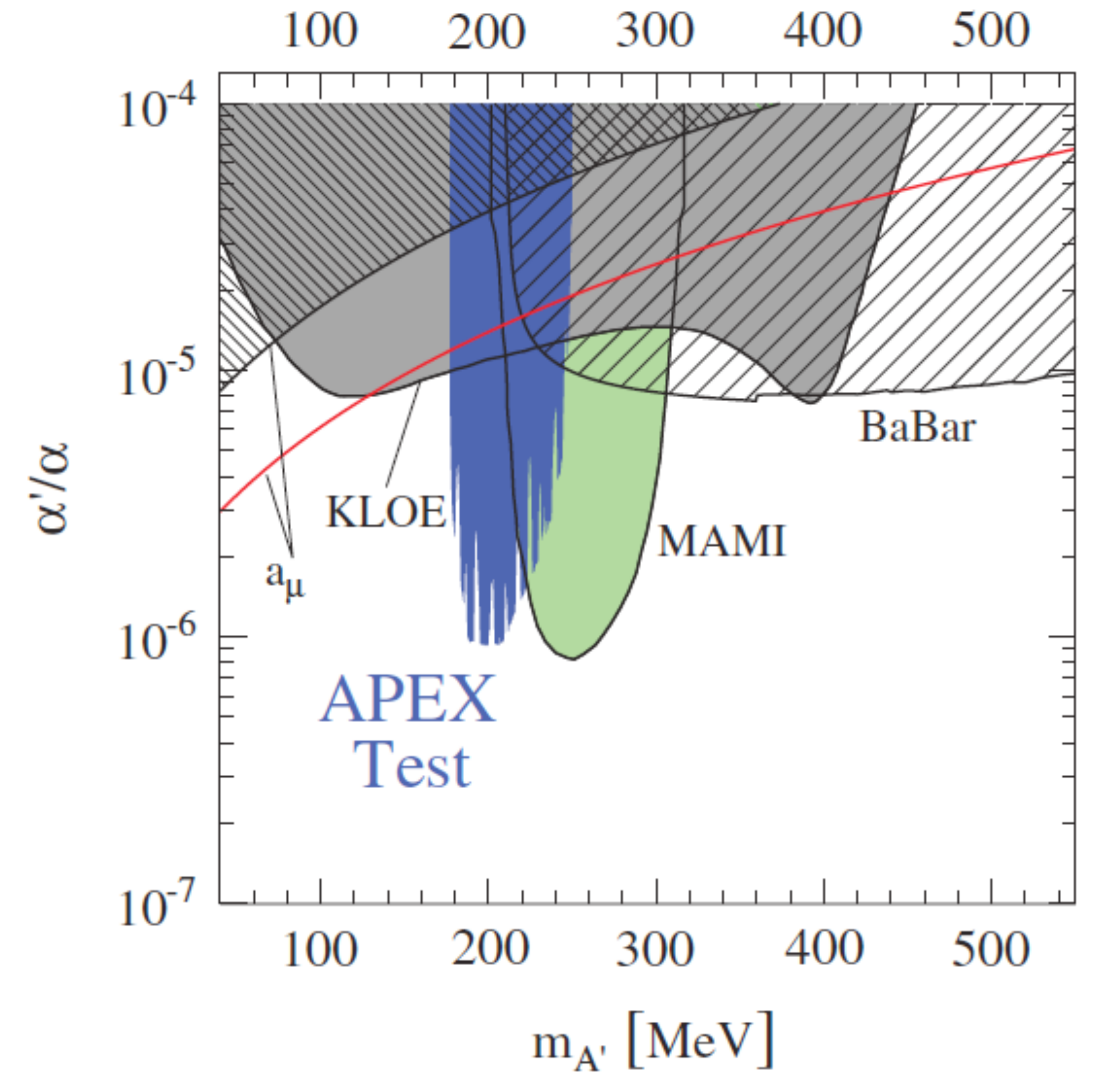
- Dark photon search in fixed target experiment in Hall-A at Jefferson Lab
- Looking for a small, narrow bump on top of a smooth histogram of QED processes
- Excellent mass resolution required (~ 0.85 - 1.1MeV)



Test run set up

JLab experiments

APEX



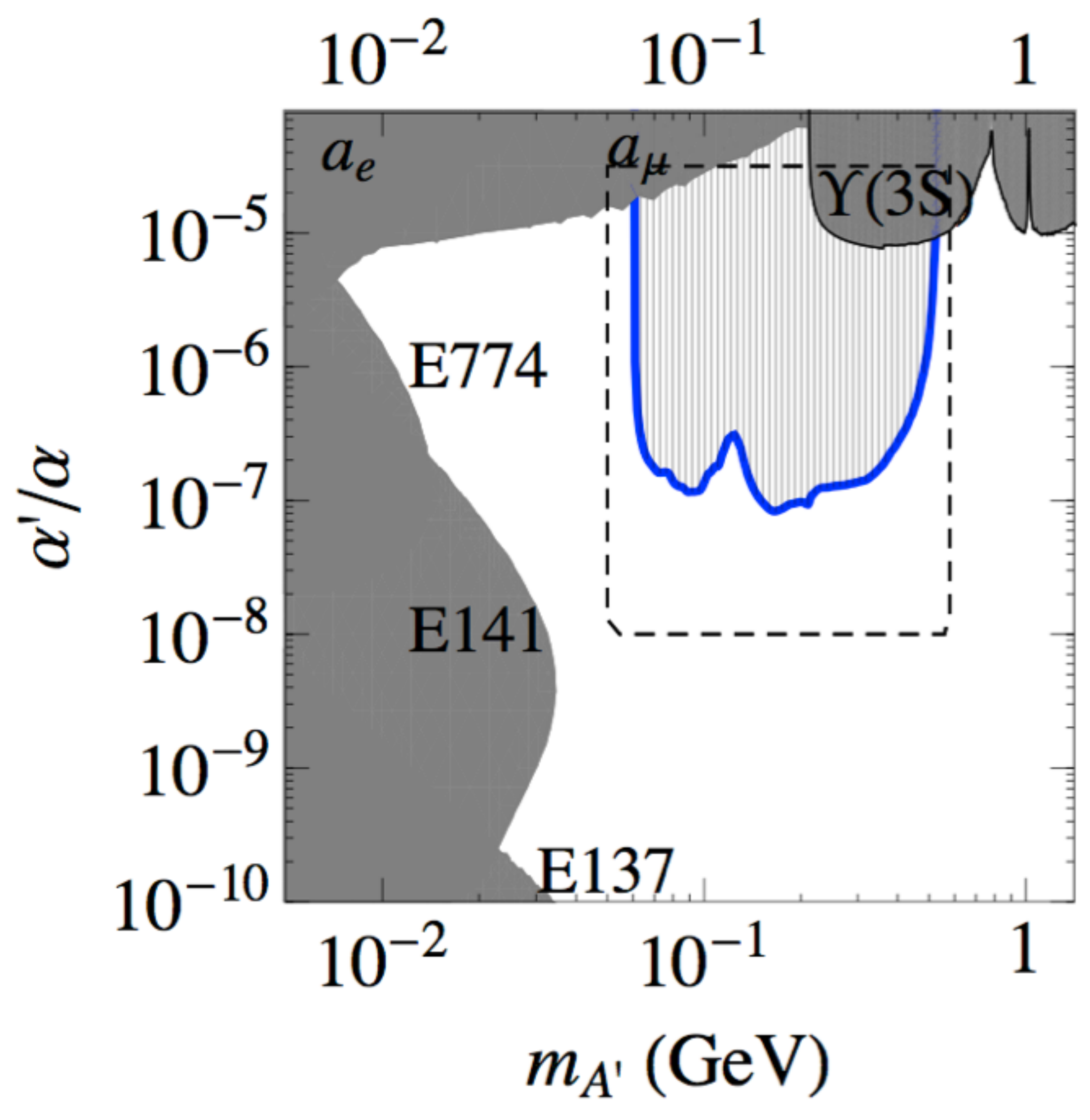
APEX test run

Relevant Characteristics

- Beam current up to 150μA
- Target: Ta foil, 22 mg/cm2
- HRS Central momenta: 1.13 GeV
- Momentum acc: ± 4.5%
- Electron beam energy: 2.26 GeV
- Solid angle acceptance: ~2.8 msr

APEX full run projected sensitivity

- e+e- statistics 200x
- a'/a 2 orders of magnitude below current limits
- Beam energy from 1.1 GeV to 4.4 GeV
- Beam current: 60-100 μA
- Ready to run after resuming operations



The HPS experiment
Heavy Photon Search

Heavy photon signatures in HPS

1) Bump Hunting (BH)

Narrow e+e-resonance over a QED background

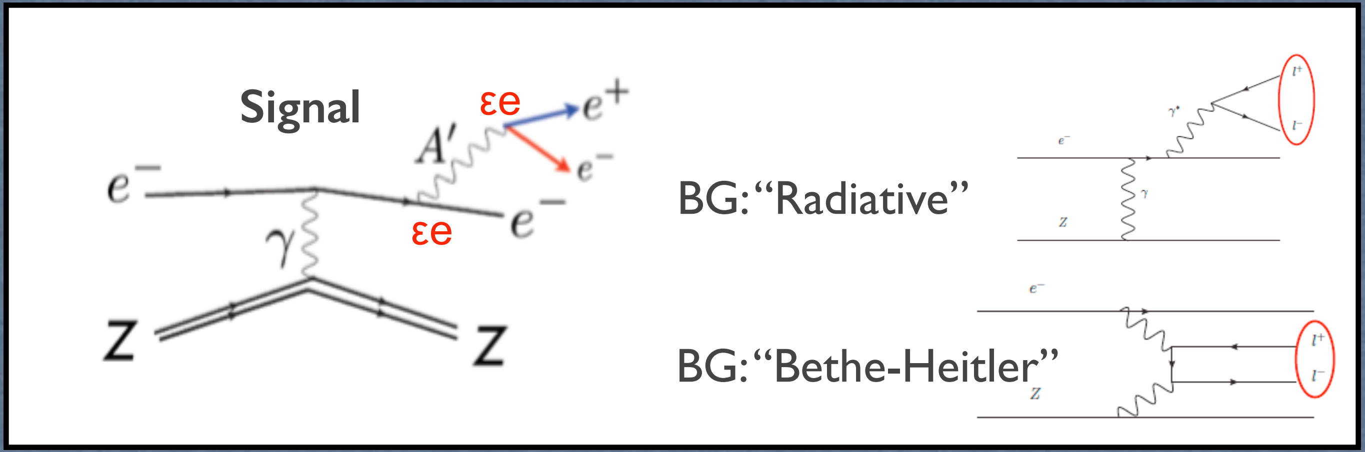
➥ good mass resolution: $\sigma_{A'mass}$~1 MeV

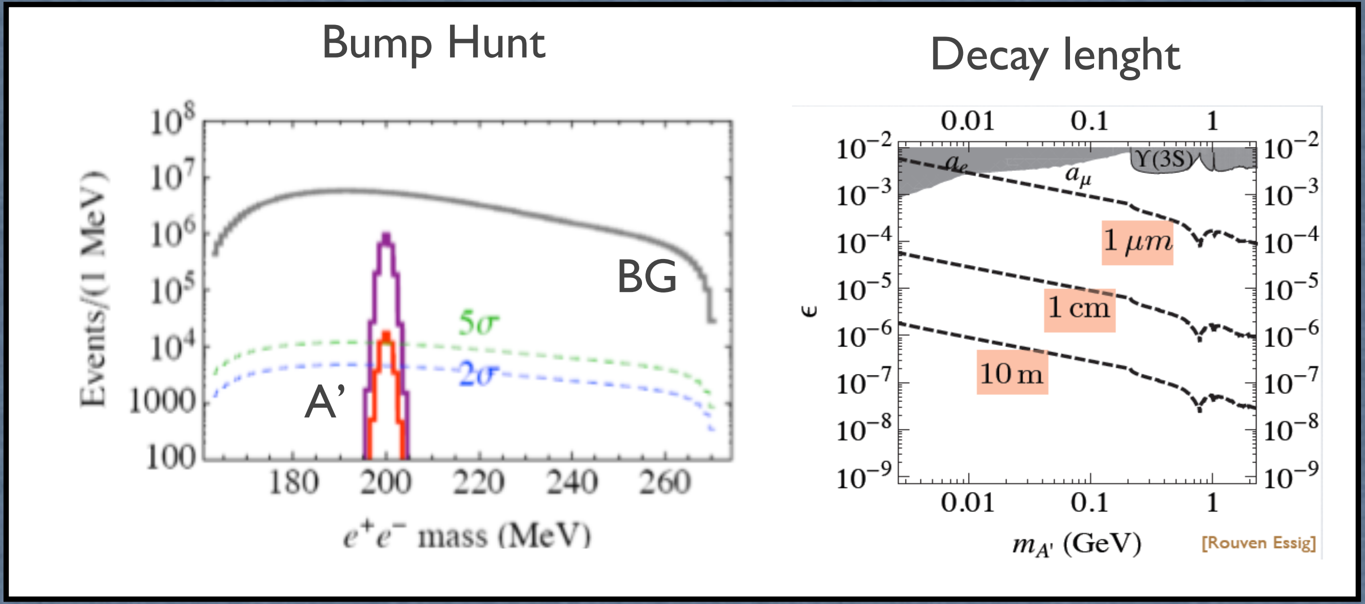
2) Secondary decay vertex (vertexing)

Detached vertex from few mm to tens cm

➥ good spacial resolution: σ_{vertex}~1mm

BH + Vertexing = enhanced experimental reach




Bump Hunt

Decay lenght

$$l_{\gamma'} \sim \frac{E_{\gamma'}}{\alpha\chi^2 m_{\gamma'}^2} \sim 10\mathrm{cm}\,\frac{E_{\gamma'}}{1\mathrm{GeV}}\left(\frac{10^{-4}}{\chi}\right)^2\left(\frac{10\mathrm{MeV}}{m_{\gamma'}}\right)^2 \sim \mathcal{O}(\mathrm{mm}-\mathrm{km})$$

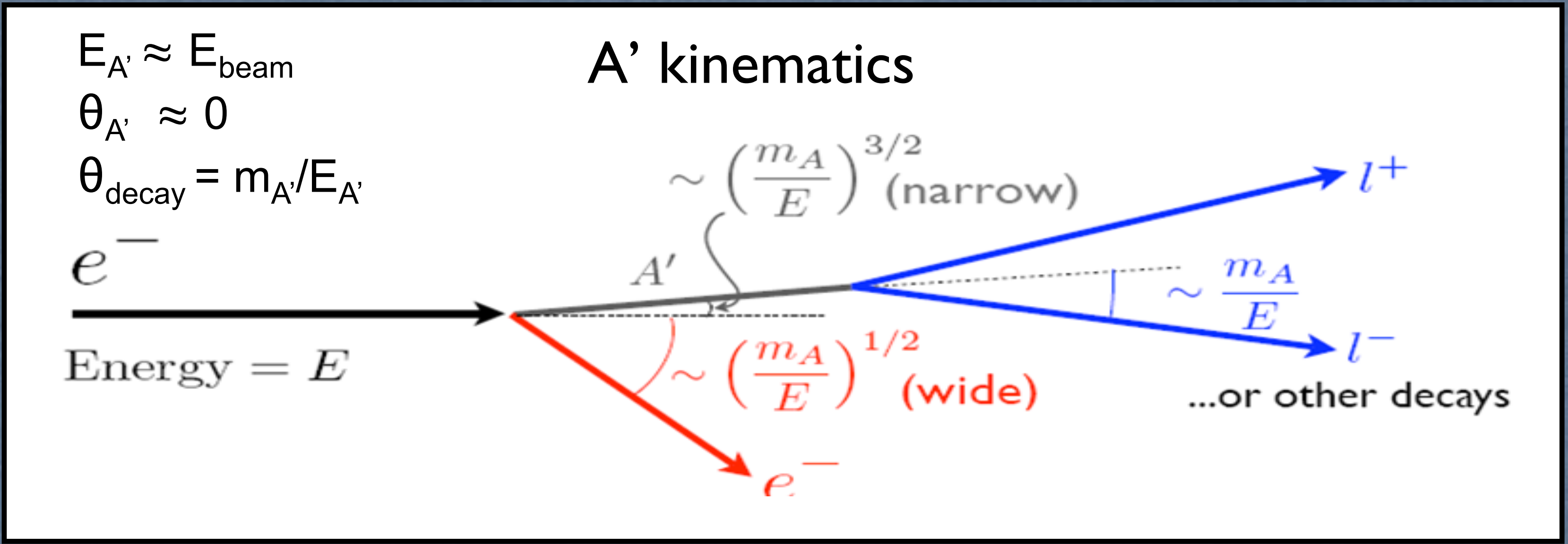
The HPS set-up

Requirements:

- forward angles coverage
- detector close to the target
- good spacial resolution: σ_{vertex}~1mm (vertexing)
- good mass resolution: $\sigma_{A'mass}$~1 MeV (bump hunting)

Experimental set-up

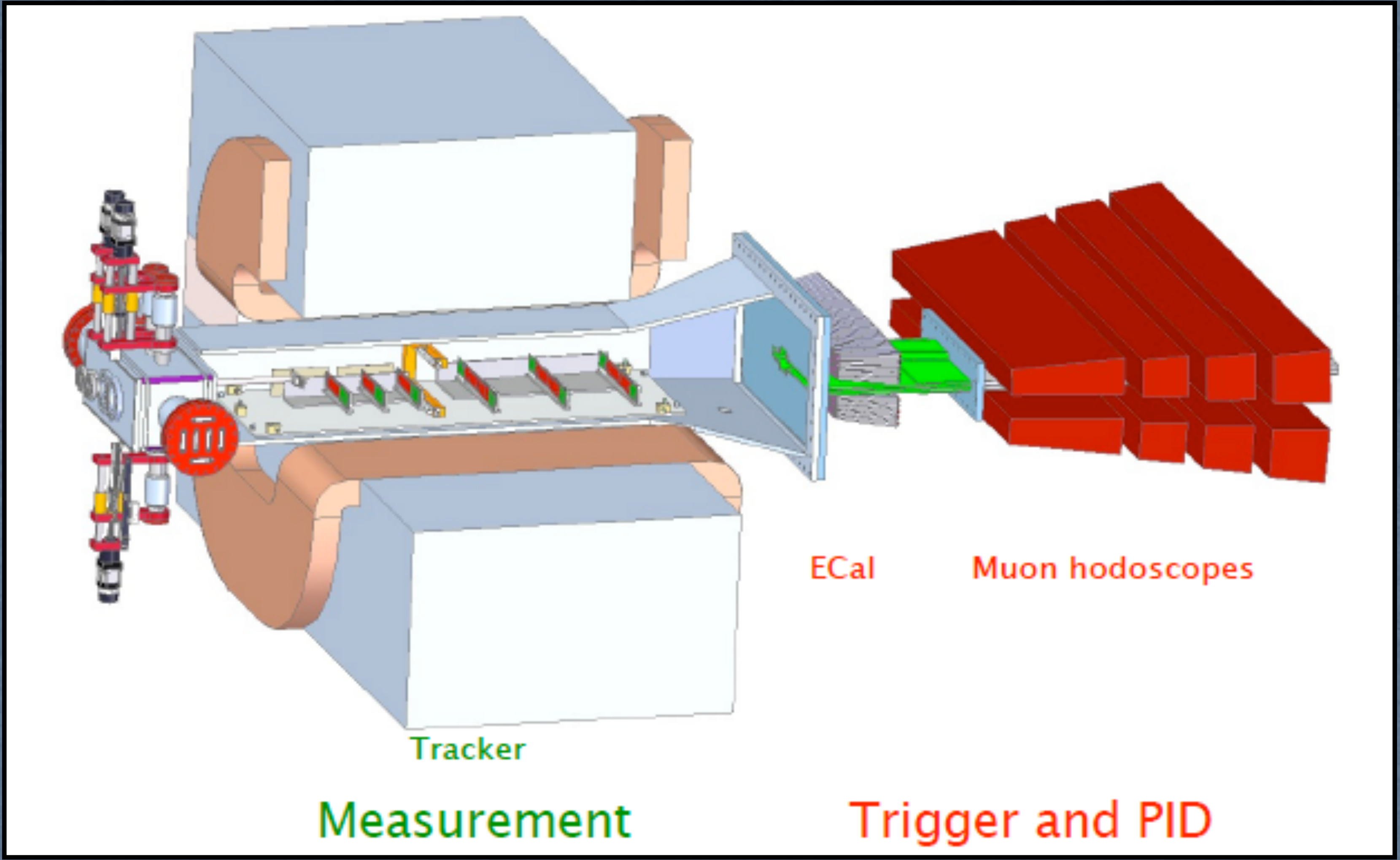
- B field to bend e+/e- pairs
- Si TRCK for vertexing
- EM cal for triggering
- (Muon detector for A' →$\mu^+\mu^-$)


A' kinematics

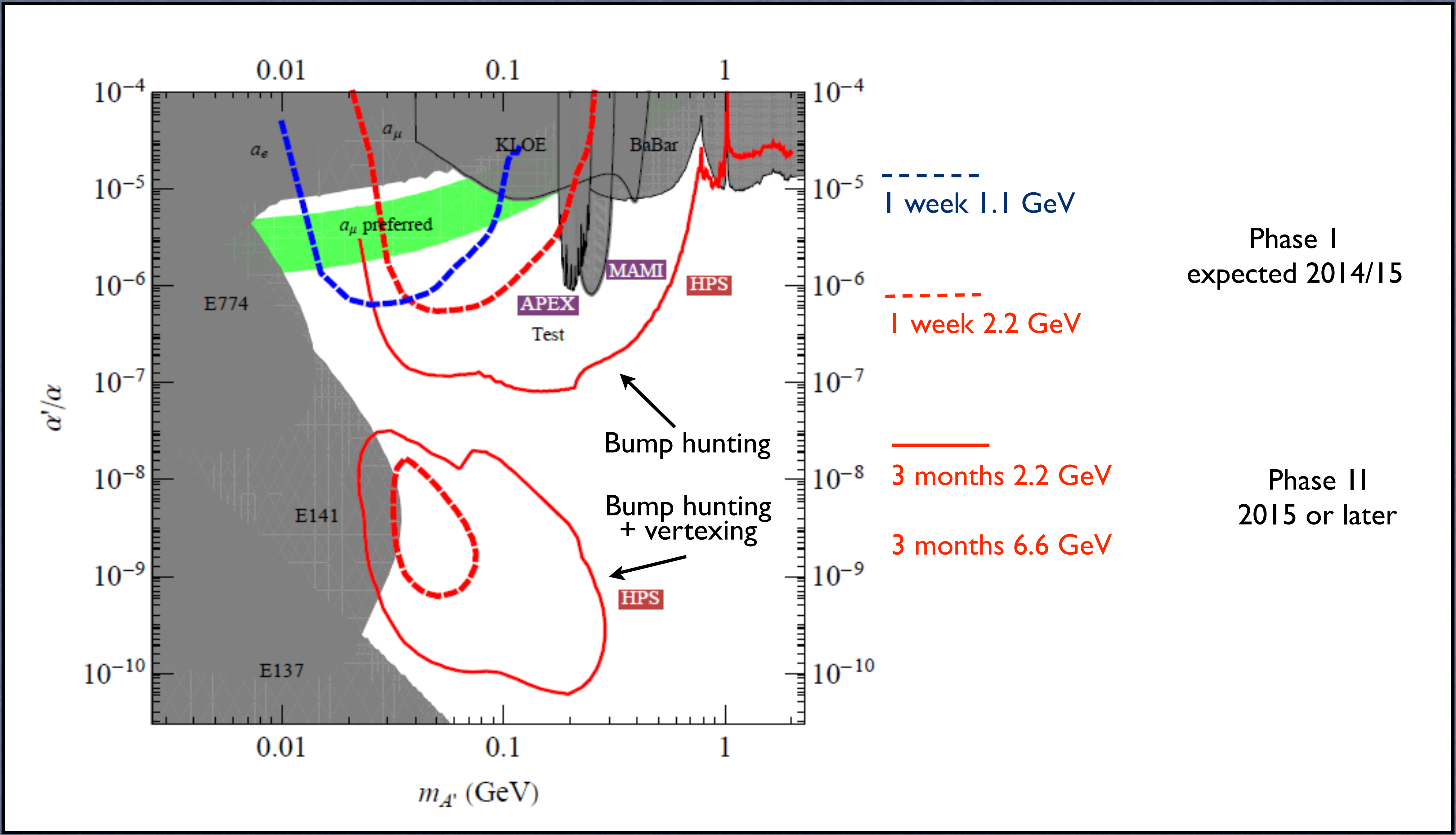
$E_{A'} \approx E_{beam}$

$\theta_{A'} \approx 0$

$\theta_{decay} = m_{A'}/E_{A'}$



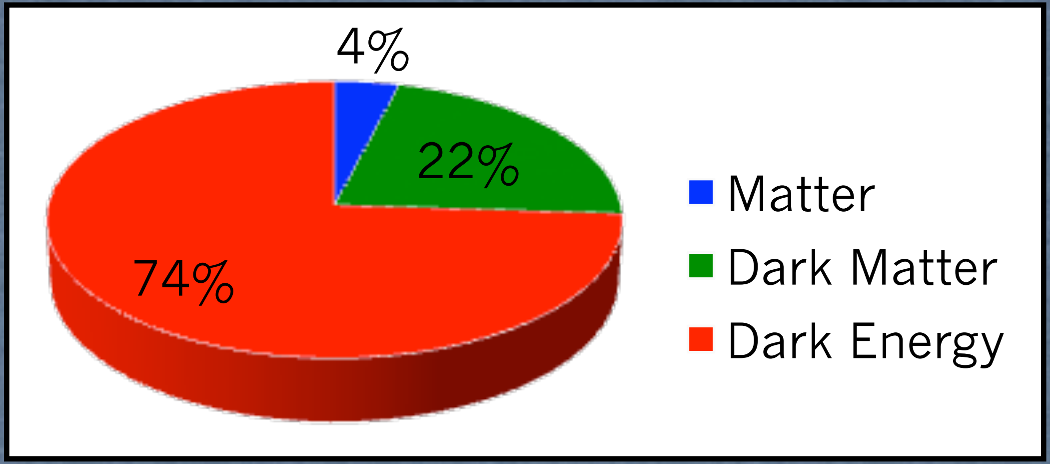
HPS projected results



Phase I
expected 2014/15

Phase II
2015 or later

Conclusions



✳ It seems established that hadronic matter only accounts for the 4% of the total mass in the Universe

✳ Strong physics motivation for the possible existence of GeV-scale hidden/dark photons:
- top-down: extra U(1)s in string models
- bottom-up: anomalies associated with dark matter (PAMELA, FERMI) and $(g-2)\mu$

✳Fixed target experiments well suited to search for dark forces

✳ JLab is one of the major player in the MeV-GeV mass range search

✳ Results will come shortly!