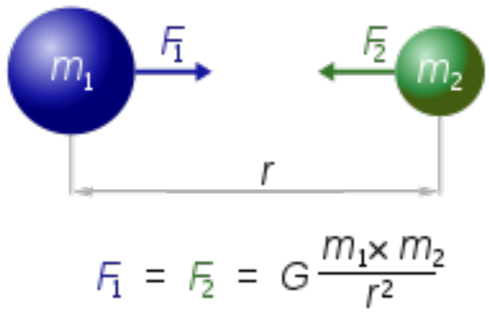
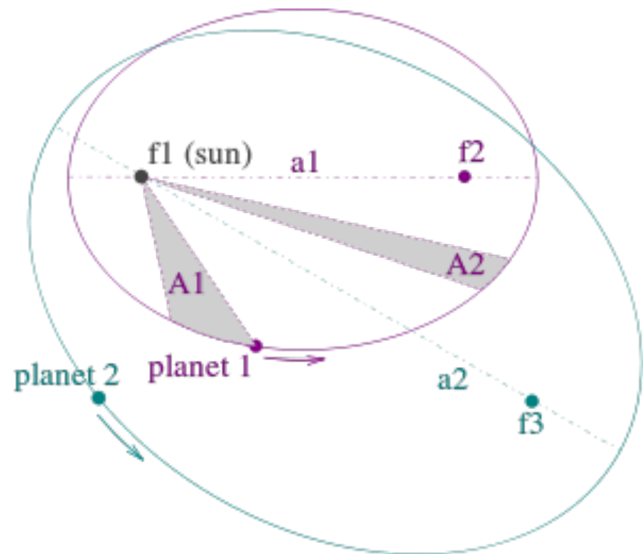
Search for a Heavy Photon

Bogdan Wojtsekhowski, Jefferson Lab

- Motivation
  - A theory of DM, a DF mediator
  - Collider is the best tool
  - Low energy range
- Proposal for the storage ring VEPP-3

Where is new physics





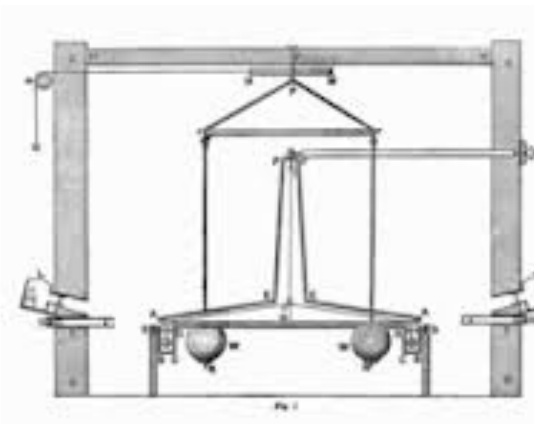
In the middle of the 18th century:

Clairaut suggested that the strength of gravity was proportional not to $\frac{1}{r^2}$, but the more complicated

$$\frac{1}{r^2} + \frac{c}{r^4}$$

for some constant c. Over large distances, the c/r^4 term would effectively disappear, accounting for the utility of the inverse square law over large distances. He then began

Where is new physics



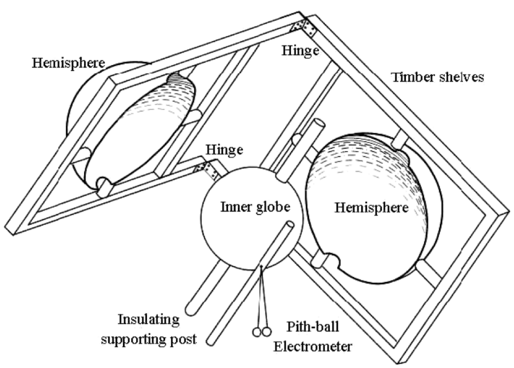


Table I. Results of various tests of Coulomb's law and tests for a nonzero photon rest mass.

	Coulomb's Law violation of form r^{2+q} q	$\mu^2 = (\frac{m_0 c}{\hbar})^2$	Photon rest mass m_0
Cavendish (1773)	2×10^{-2}		
Coulomb (1785)	4×10^{-2}		
Maxwell (1873)	4.9×10^{-5}		
Plimpton and Lawton (1936)	2.0×10^{-9}	$1.0 \times 10^{-12}\,cm^{-2}$	$\leq 3.4 \times 10^{-44}\,g$
Cochran and Franken (1967)	9.2×10^{-12}	$7.3 \times 10^{-15}\,cm^{-2}$	$\leq 3 \times 10^{-45}\,g$
Bartlett, Goldhagen, Phillips (1970)	1.3×10^{-13}	$1 \times 10^{-16}\,cm^{-2}$	$\leq 3 \times 10^{-46}\,g$
Williams, Faller, Hill	$(2.7 \pm 3.1) \times 10^{-16}$	$(1.04 \pm 1.2) \times 10^{-19}\,cm^{-2}$	$\leq 1.6 \times 10^{-47}\,g$
Schroedinger (1943)	Test of Ampere's Law from Geo-magnetic Data	$3 \times 10^{-19}\,cm^{-2}$	$\sim 2 \times 10^{-47}\,g$
Gintsburg (1963)		$5 \times 10^{-20}\,cm^{-2}$	$\leq 8 \times 10^{-48}\,g$
Nieto and Goldhaber (1968)		$1.3 \times 10^{-20}\,cm^{-2}$	$\leq 4 \times 10^{-48}\,g$
Feinberg (1969) [a]	Dispersion of light	$8 \times 10^{-14}\,cm^{-2}$	$10^{-44}\,g$

SM tests, constraints on new physics (per PDG)

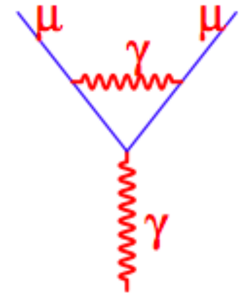
column denoted Pull gives the standard deviations for the principal fit with M_H free, while the column denoted Dev. (Deviation) is for $M_H = 124.5$ GeV [215] fixed.

Quantity	Value	Standard Model	Pull	Dev.
m_t [GeV]	173.4 ± 1.0	173.5 ± 1.0	-0.1	-0.3
M_W [GeV]	80.420 ± 0.031	80.381 ± 0.014	1.2	1.6
	80.376 ± 0.033		-0.2	0.2
$g_V^{\nu e}$	-0.040 ± 0.015	-0.0398 ± 0.0003	0.0	0.0
$g_A^{\nu e}$	-0.507 ± 0.014	-0.5064 ± 0.0001	0.0	0.0
$Q_W(e)$	-0.0403 ± 0.0053	-0.0474 ± 0.0005	1.3	1.3
$Q_W(\mathrm{Cs})$	-73.20 ± 0.35	-73.23 ± 0.02	0.1	0.1
$Q_W(\mathrm{Tl})$	-116.4 ± 3.6	-116.88 ± 0.03	0.1	0.1
τ_τ [fs]	291.13 ± 0.43	290.75 ± 2.51	0.1	0.1
$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})$	$(4511.07 \pm 0.77) \times 10^{-9}$	$(4508.70 \pm 0.09) \times 10^{-9}$	3.0	3.0

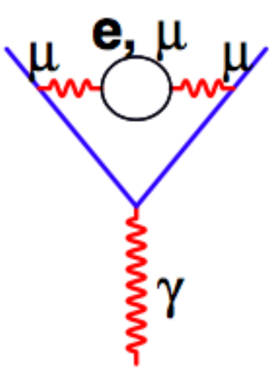
SM tests, constraints on new physics (per PDG)

g - 2 for the muon

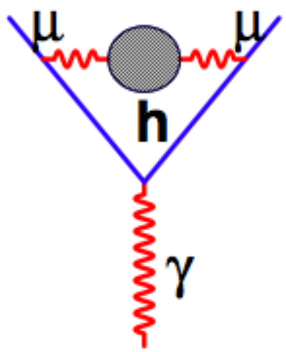
Largest contribution : $a_\mu = \frac{\alpha}{2\pi} \approx \frac{1}{800}$



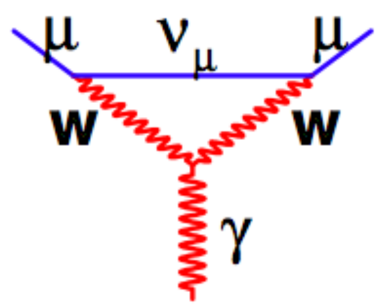
Other standard model contributions :

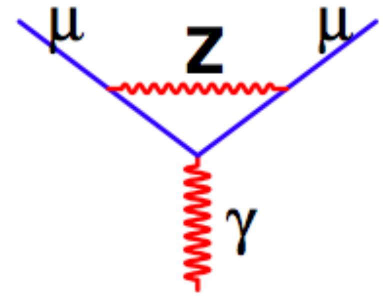


QED



hadronic





weak

from STORY05, Y. Semertzidis

The motivation is the nature of dark matter

1985ApJ...295..422C

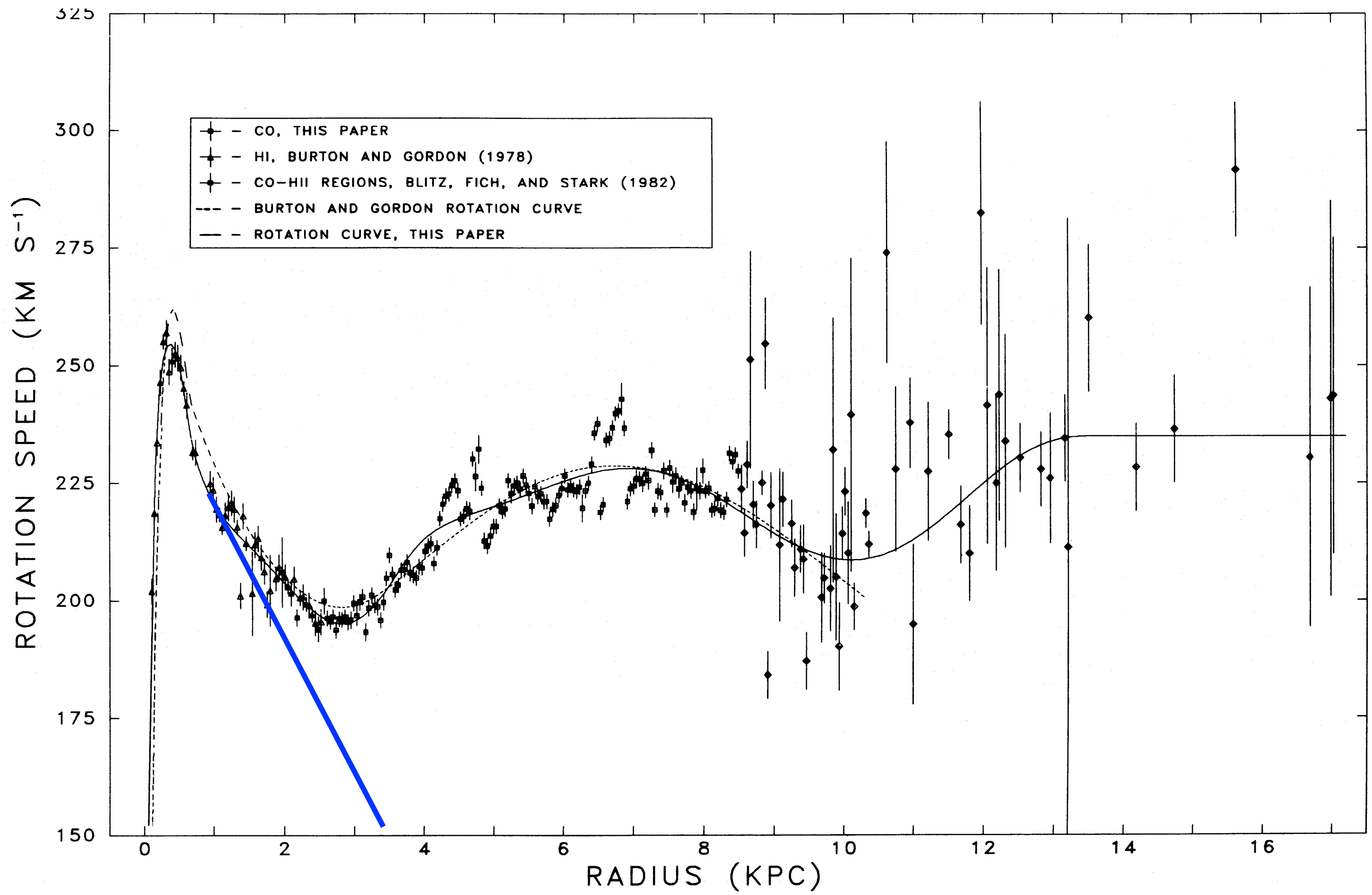
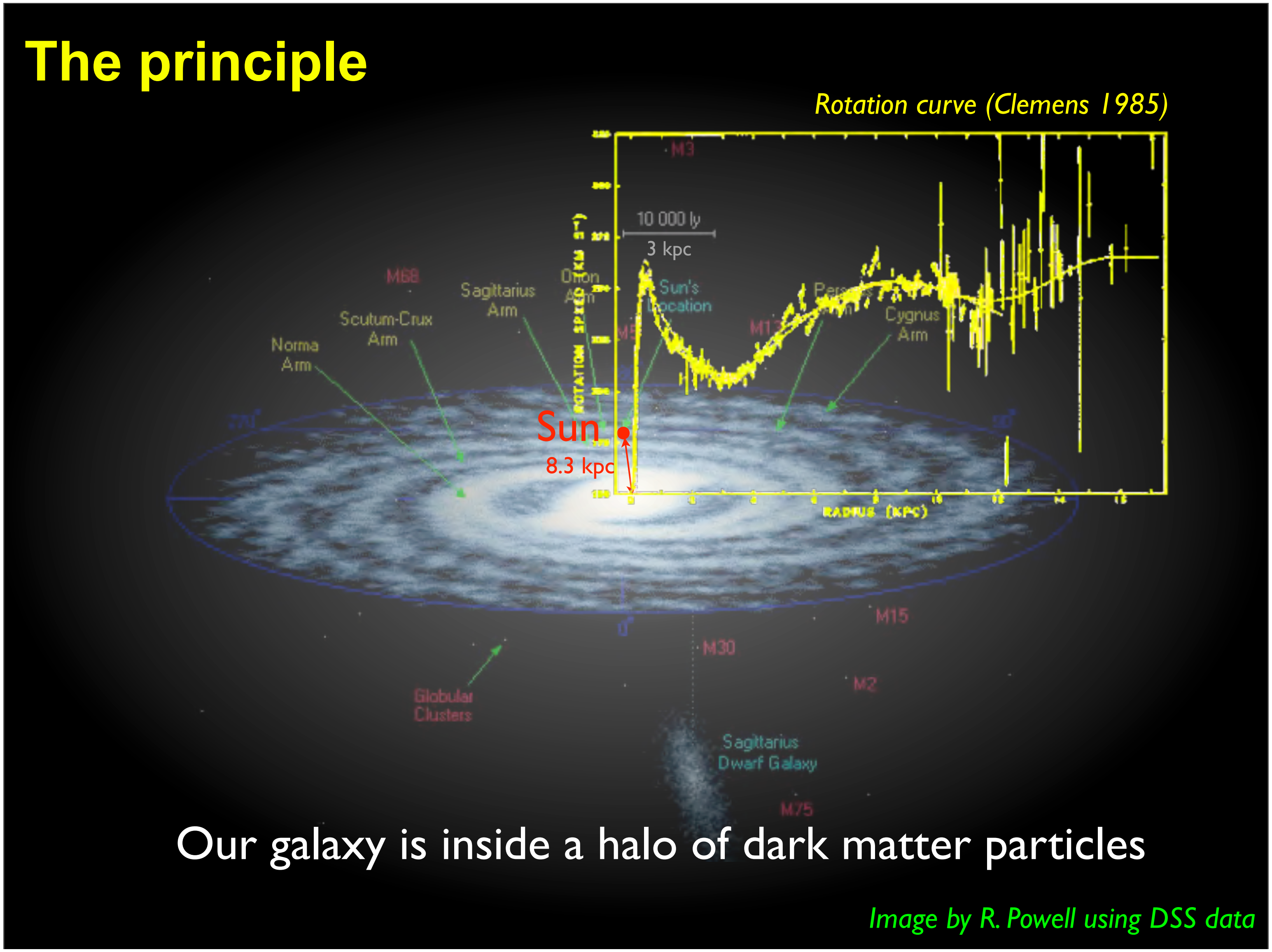


FIG. 3.—Plots of the rotation speed versus galactocentric radius. The solid lines correspond to the polynomials, and the dashed lines are the BG rotation curve. (*upper panel*)(R_0, θ_0) = (10 kpc, 220 km s^{-1}); (*lower panel*) (8.5 kpc, 220 km s^{-1}).

Dark Matter: In 1933 by F. Zwicky. This plot from D. Clemens, 1985

The motivation is the nature of dark matter



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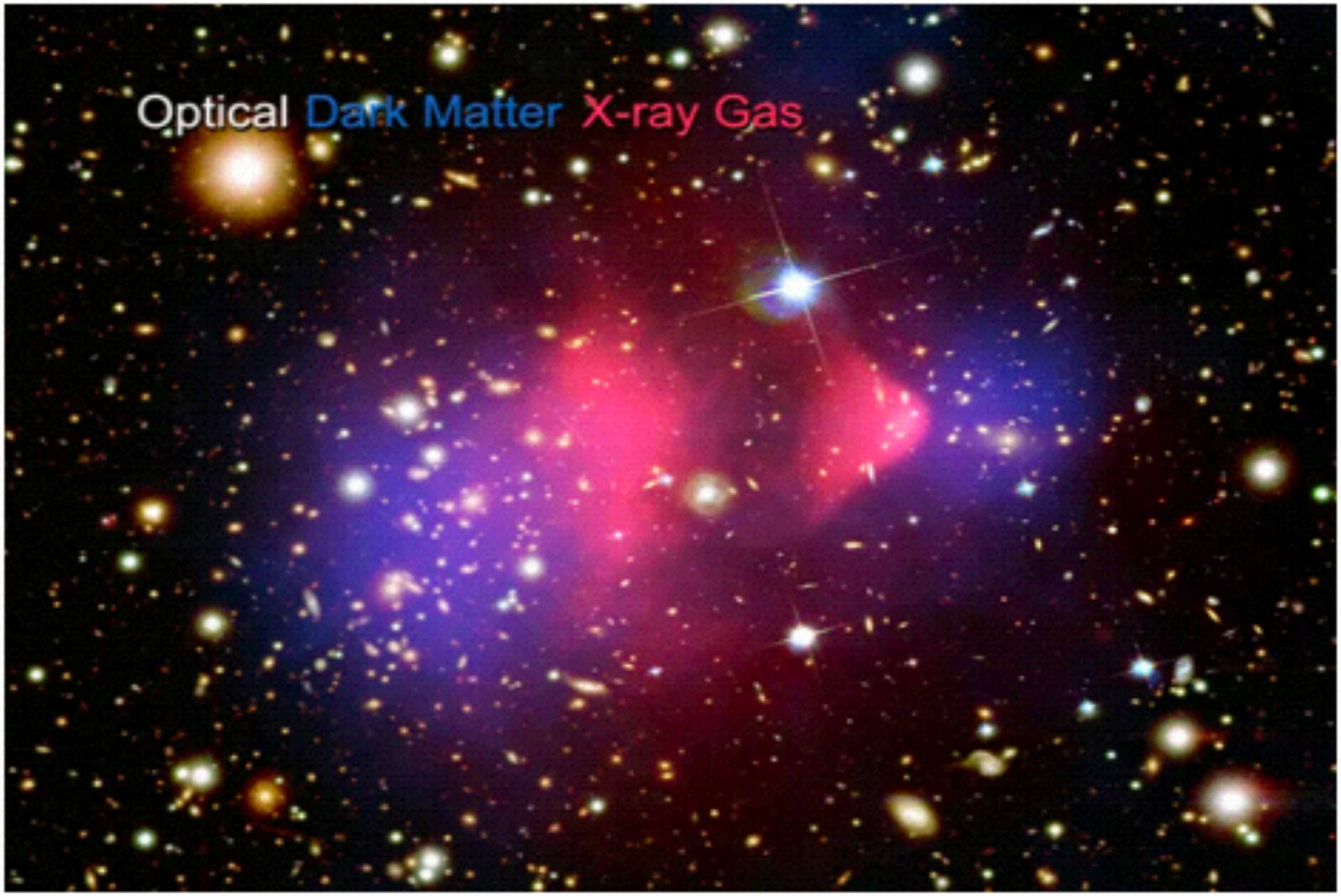
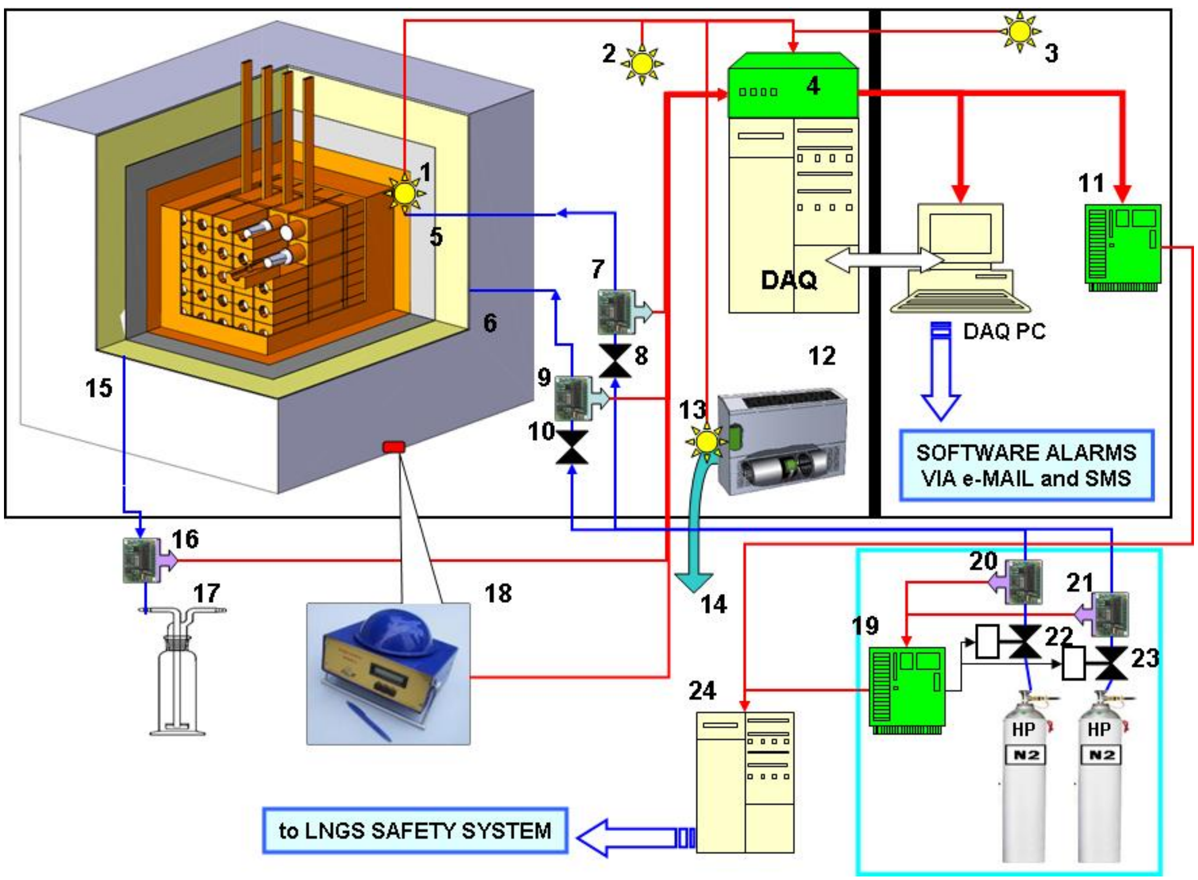


D. Clowe et al., ”A direct empirical proof of the existence of dark matter”, Astrophys. J., Vol.648, L109 (2006). doi:10.1086/508162

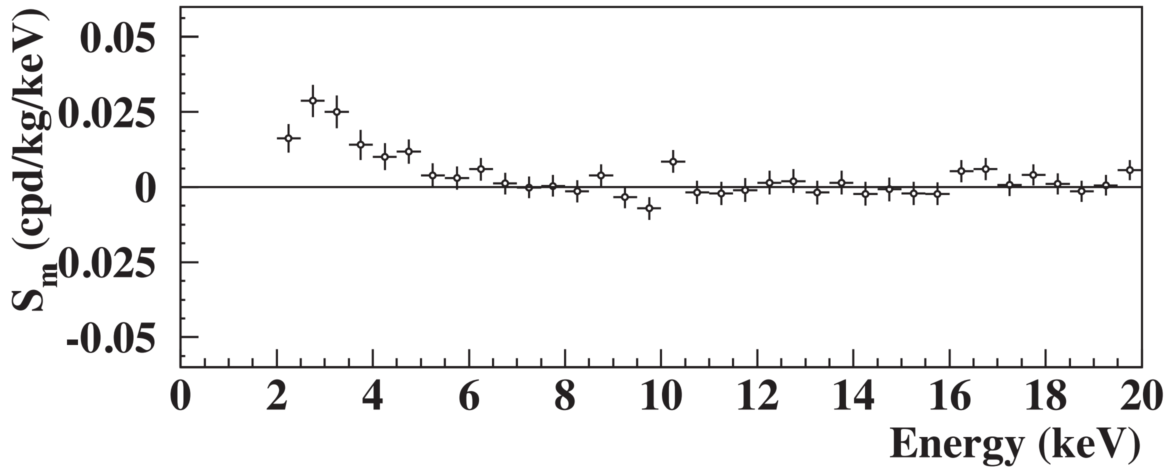
The DAMA/LIBRA experiment

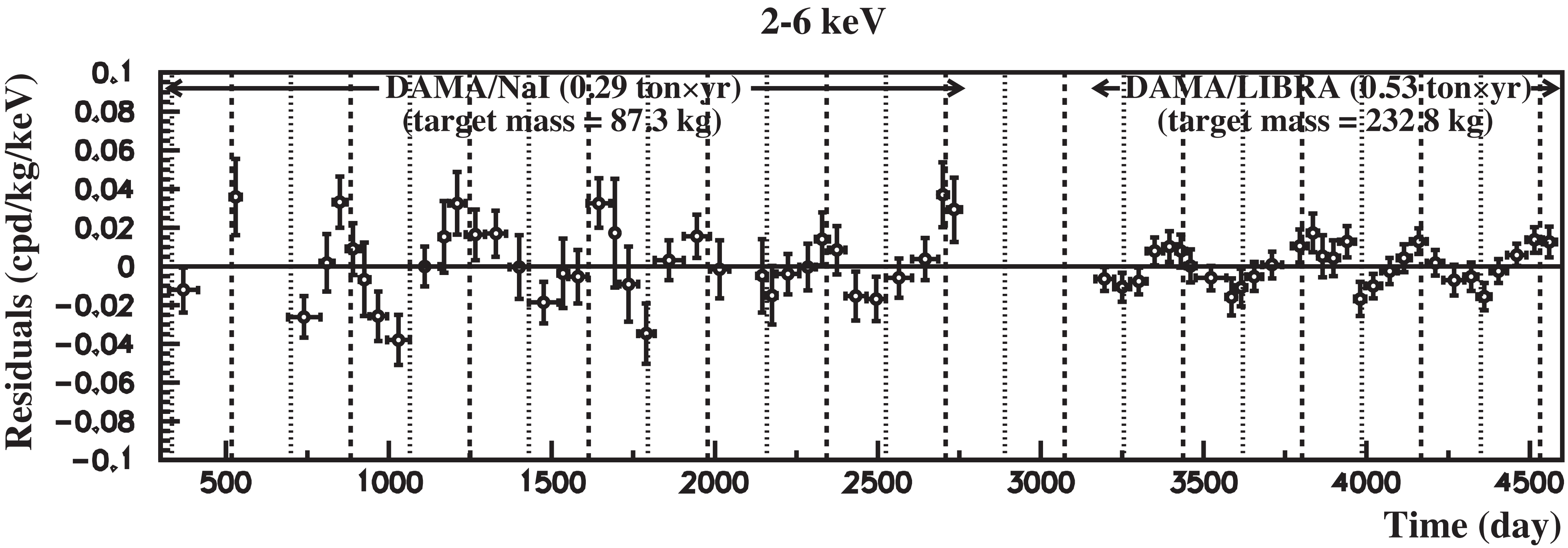


Bernabei et al.
250 kg radiopure NaI(Tl)
the Gran Sasso

NIM A592:297-315,2008

The DAMA/LIBRA experiment





DAMA collab., arXiv:0884.2741

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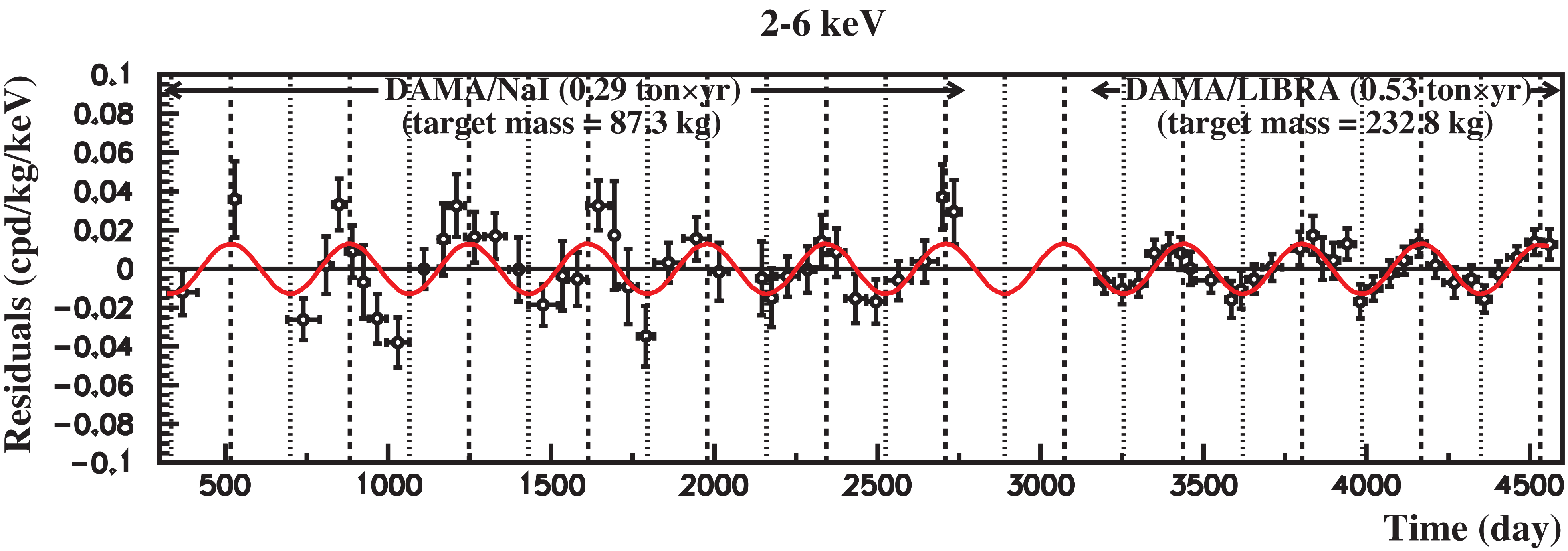


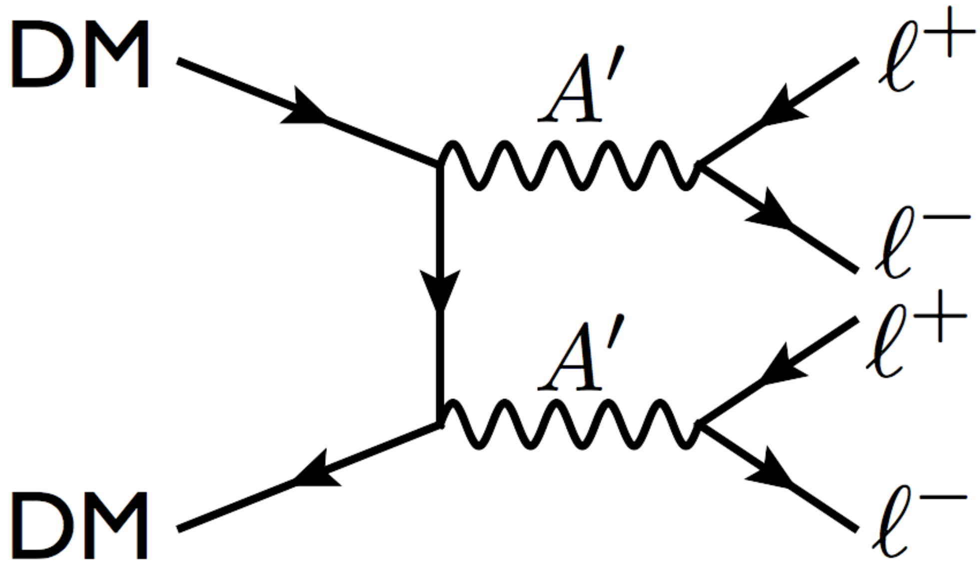
DAMA collab., arXiv:0884.2741

Recoil detection of the massive particle.

Where is the gauge boson?

The theory of DM

Arkani-Hamed, Finkbeiner, Slatyer, Weiner
Pospelov & Ritz

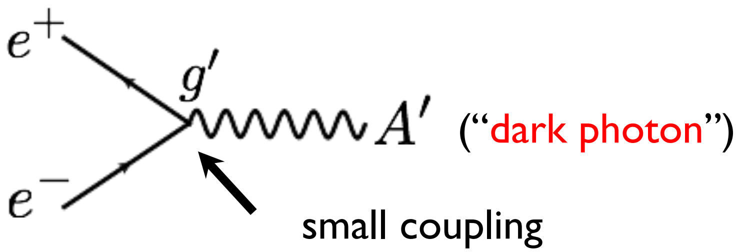


m_{DM} ~ TeV $m_{A'}$ ~ GeV   no anti-protons

also: A′ generates long-range force
(Sommerfeld enhancement)

$$\langle \sigma v \rangle \propto \frac{1}{v}$$

Motivation for light dark photon

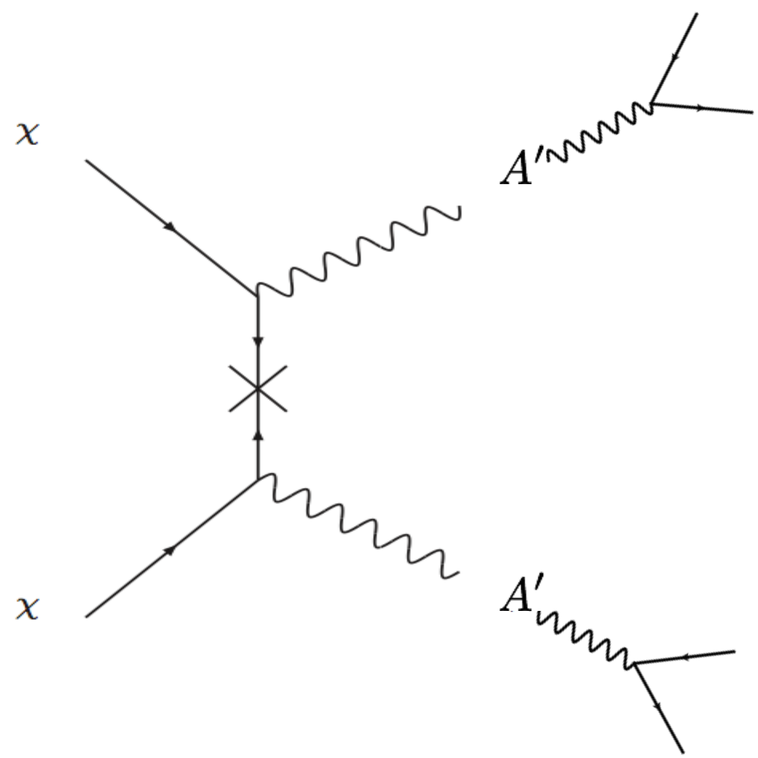


$$\alpha' \equiv \frac{g'^2}{4\pi}$$

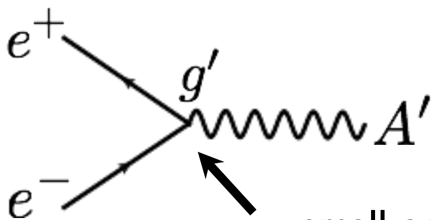
- Large interest in A′ search
- Number of considerations

naturally give A′ mass ~ 1 - 100s MeV

DM annihilation



Motivation for light dark photon



("dark photon")

$$\alpha' \equiv \frac{g'^2}{4\pi}$$

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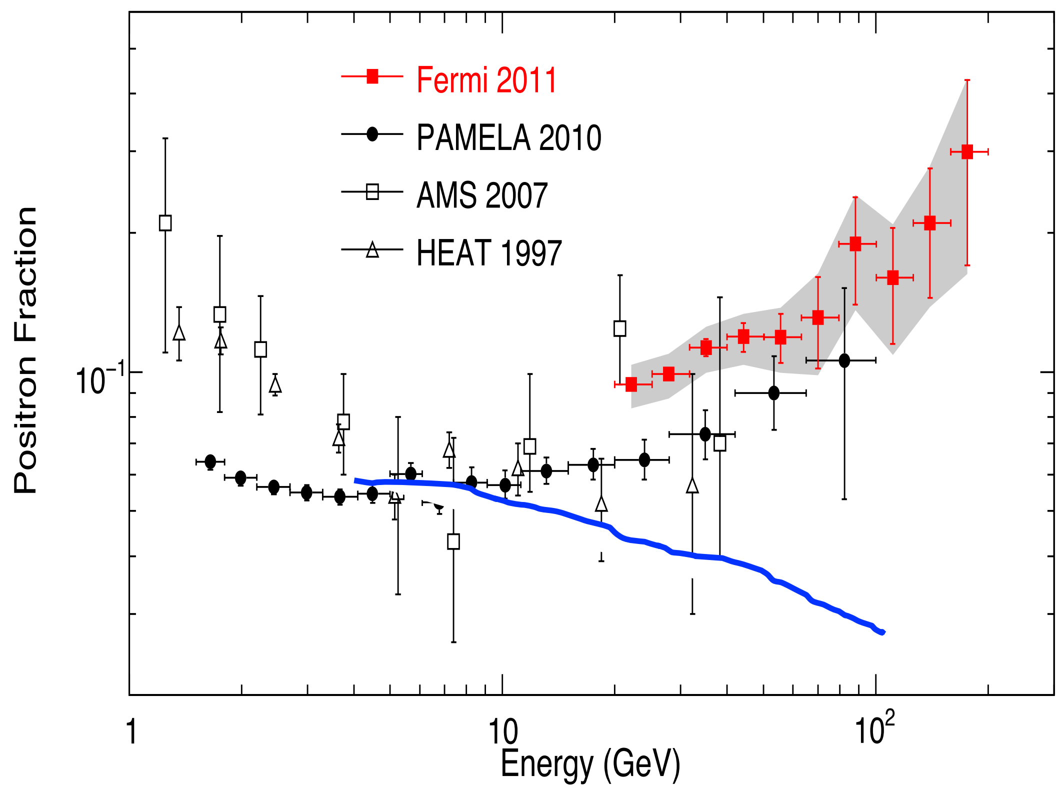
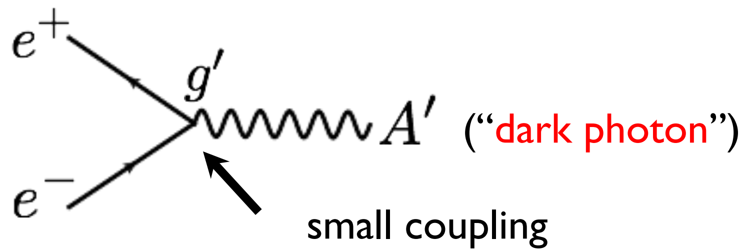
Positron/electron intensity ratio



Motivation for light dark photon

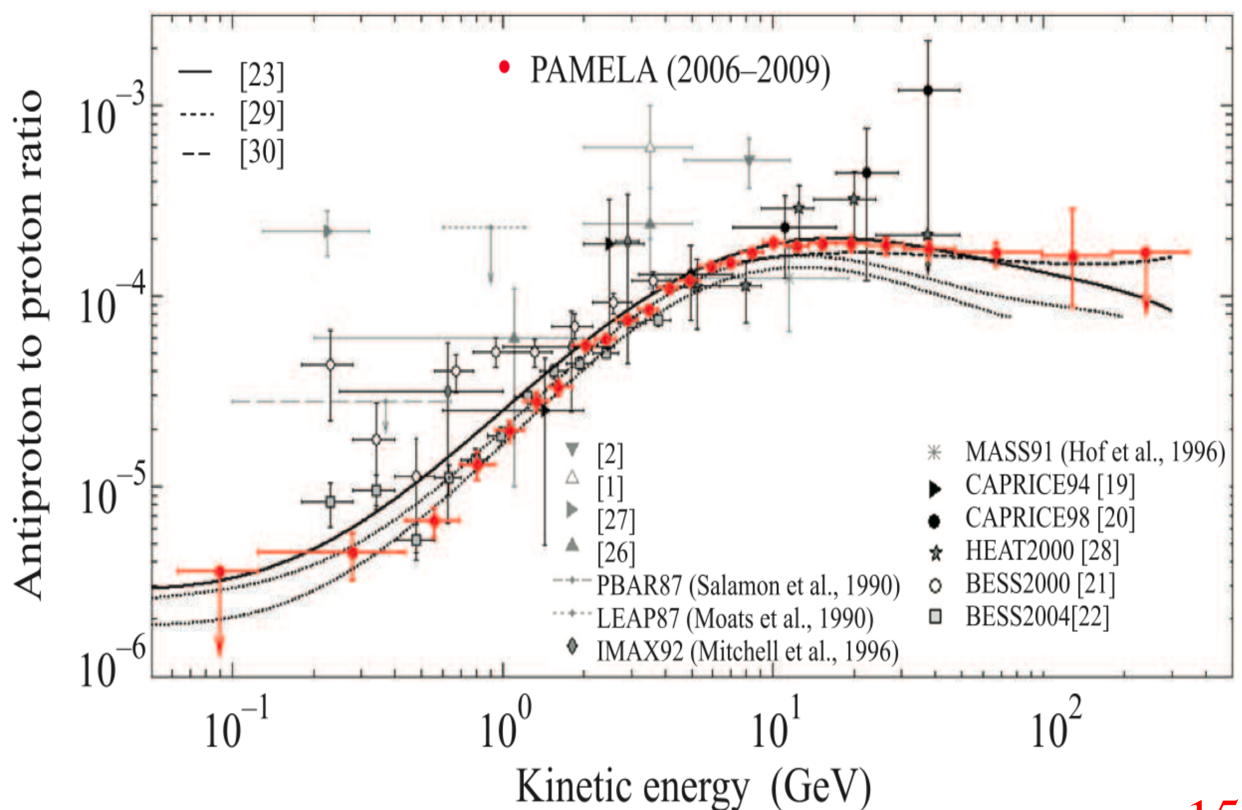


$$\alpha' \equiv \frac{g'^2}{4\pi}$$

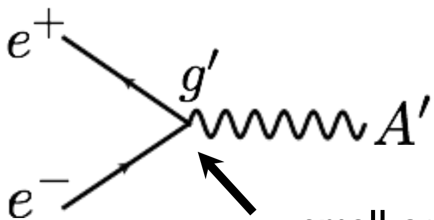
- Large interest in A′ search
- Number of considerations

naturally give A′ mass ~ 1 - 100s MeV

Antiproton/proton intensity ratio



Motivation for light dark photon



("dark photon")

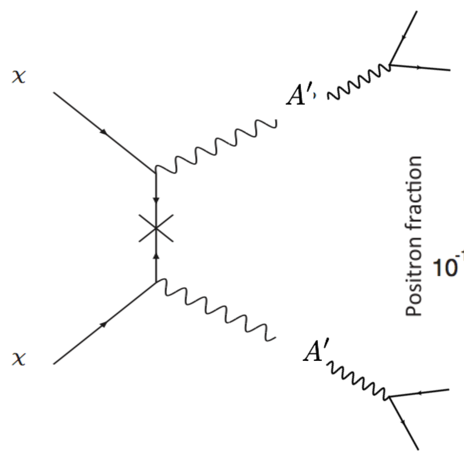
small coupling

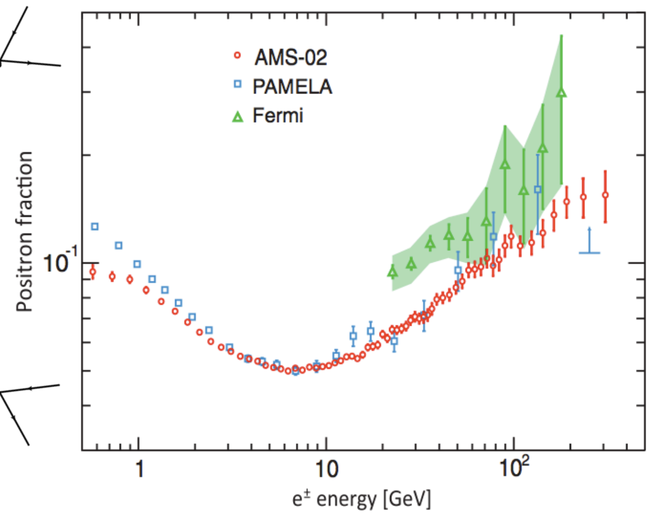
$$\alpha' \equiv \frac{g'^2}{4\pi}$$

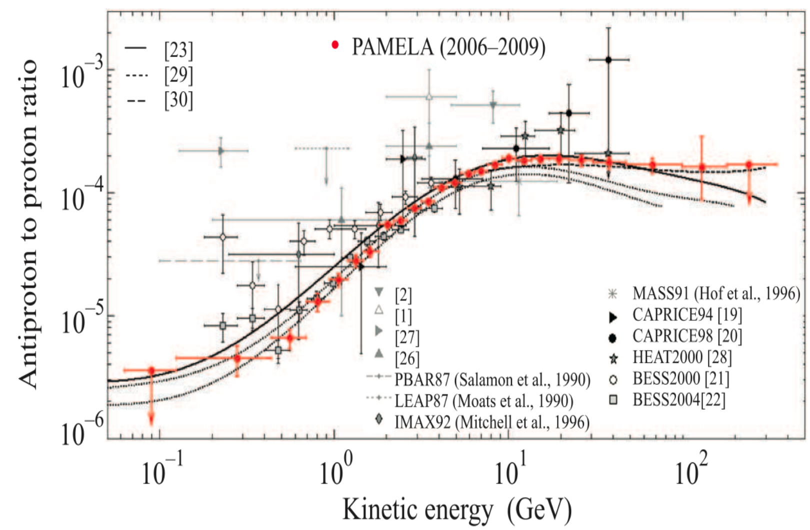
- Large interest in A′ search
- Number of considerations

naturally give A′ mass ~ 1 - 100s MeV

DM annihilation   Positron/electron   Antiproton/proton







Recent summary of the searches

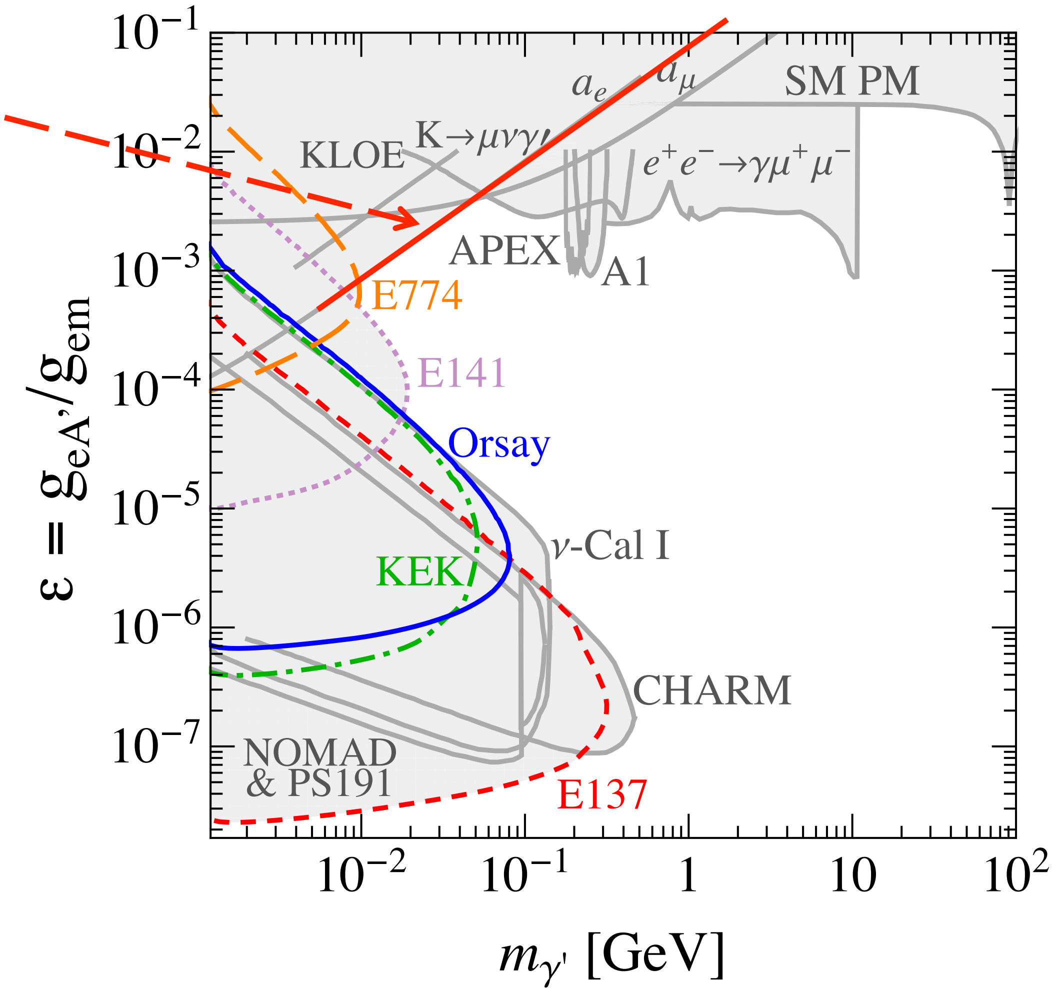
g-2 of muon and electron

Missing particle in e+e- to ..

Decay to SM (e+/e-) -

Beam Dump

Mass reconstruction



S. Andreas, C. Niebuhr, A. Ringwald, arXiv:1209.6083

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Missing particle in e+e- to γA'

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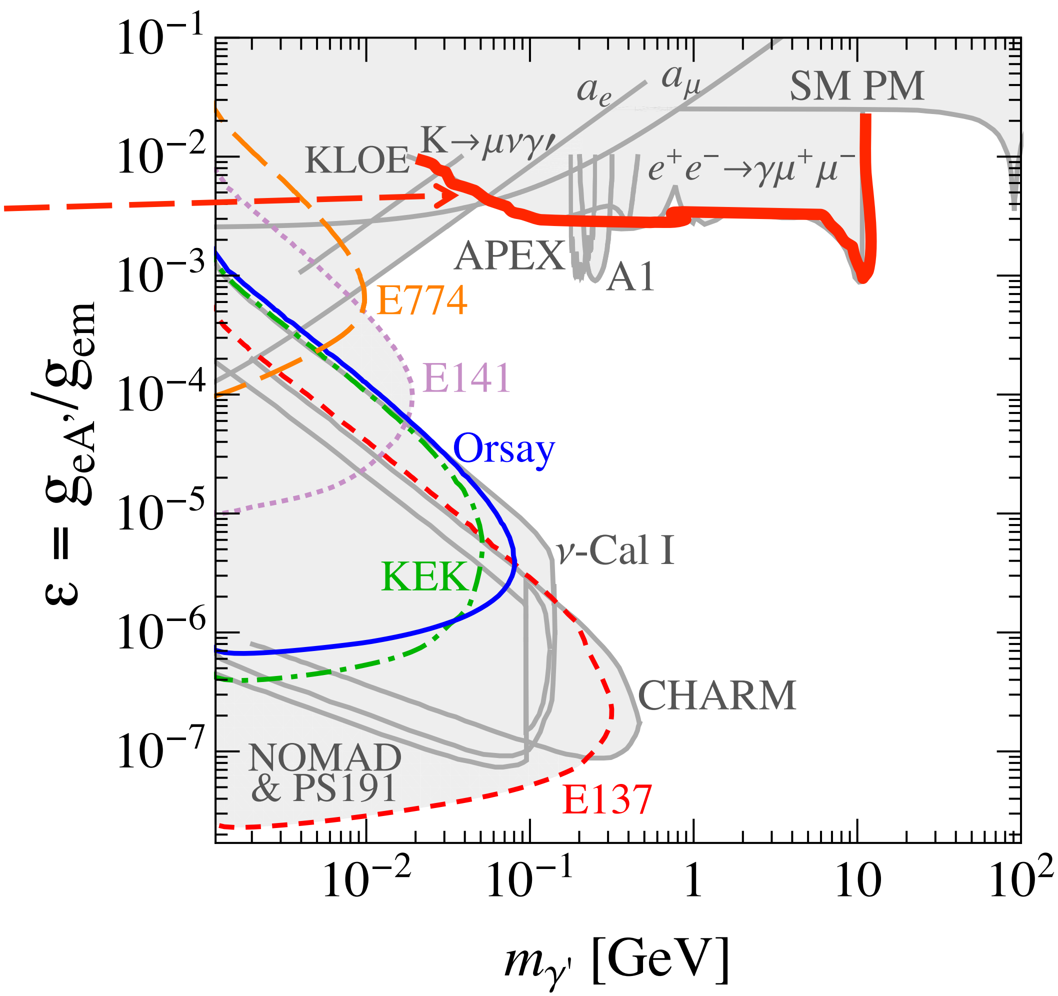

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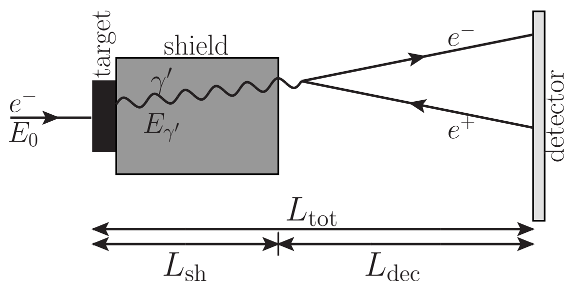
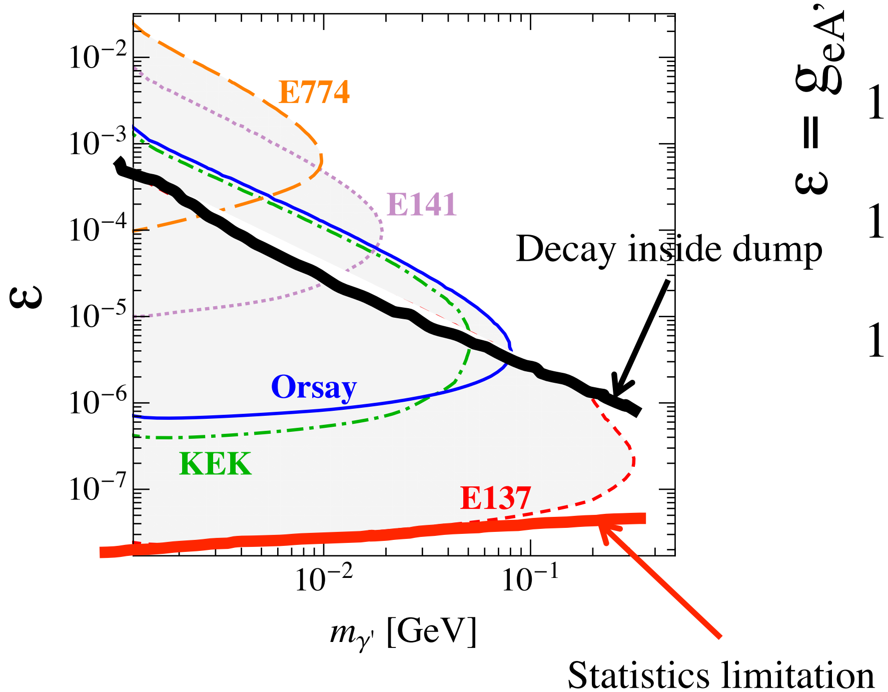
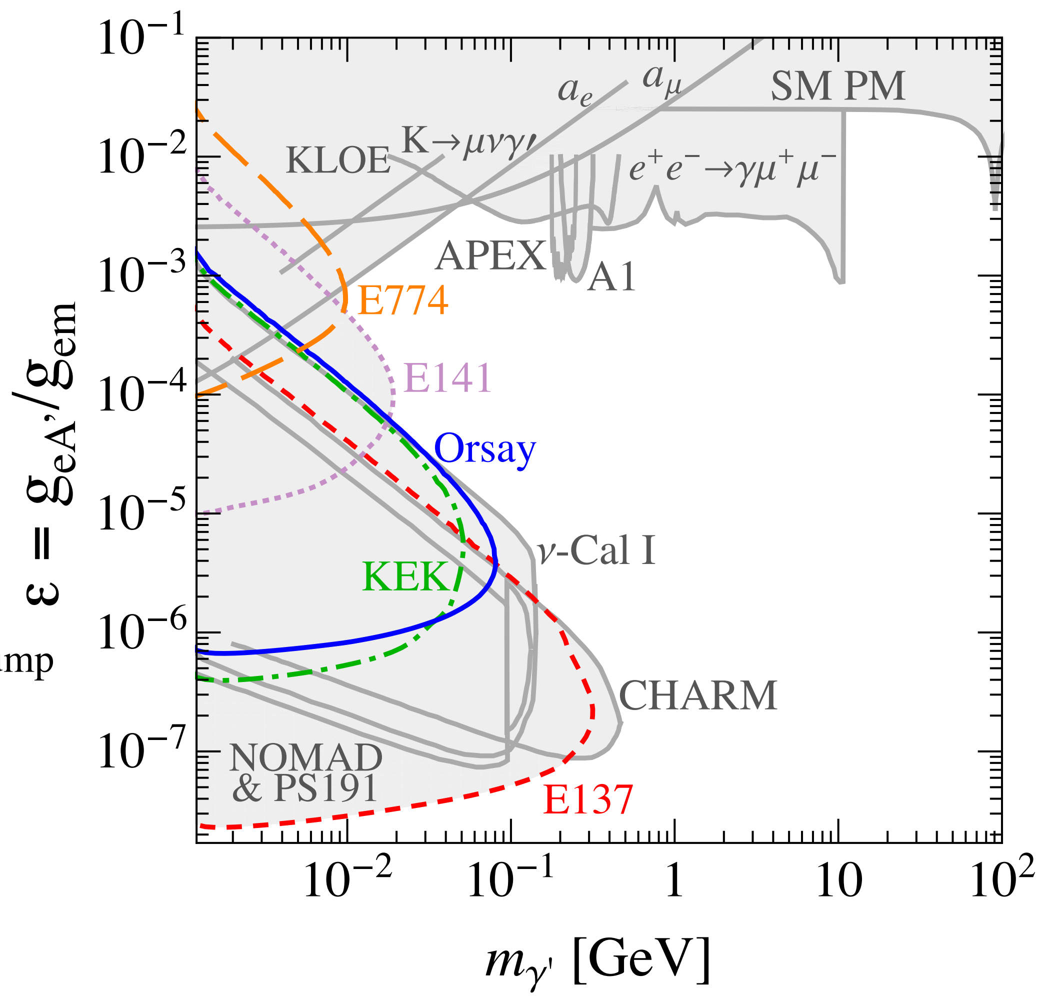


No mass reconstruction





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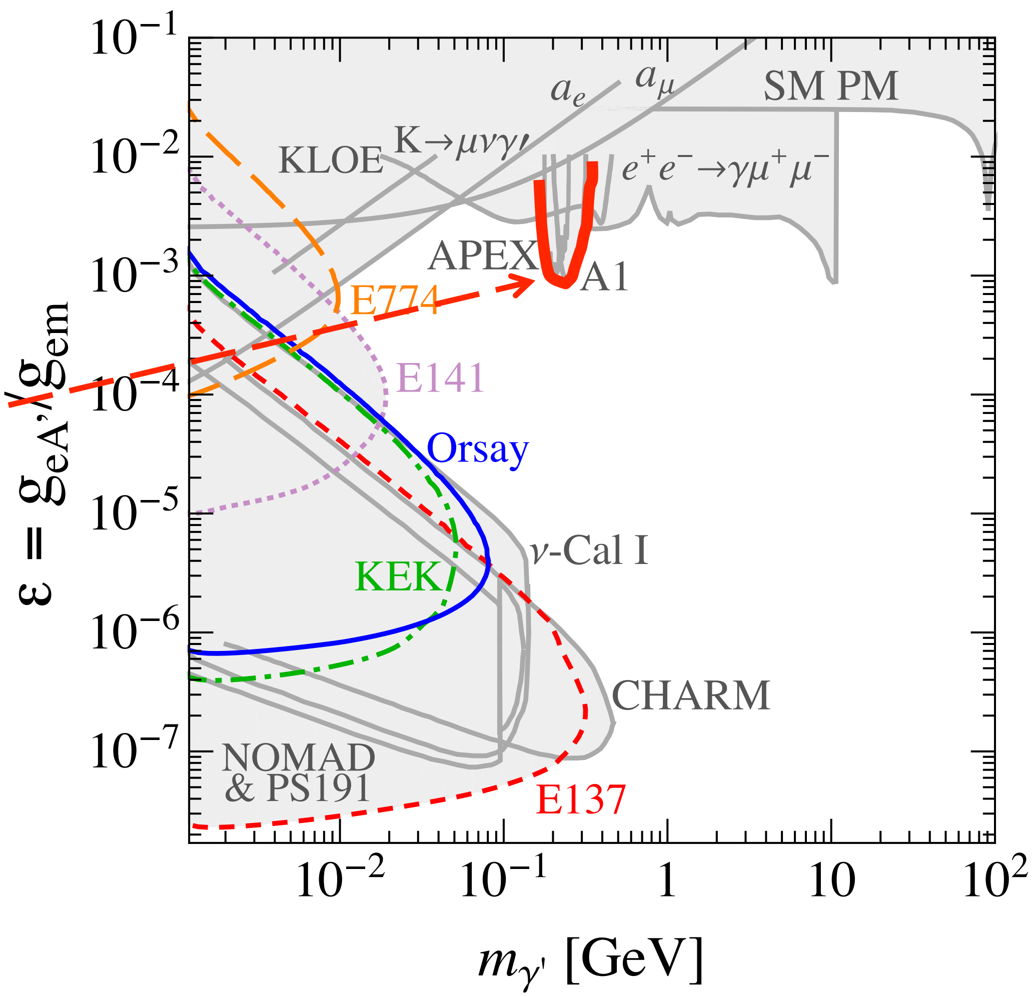
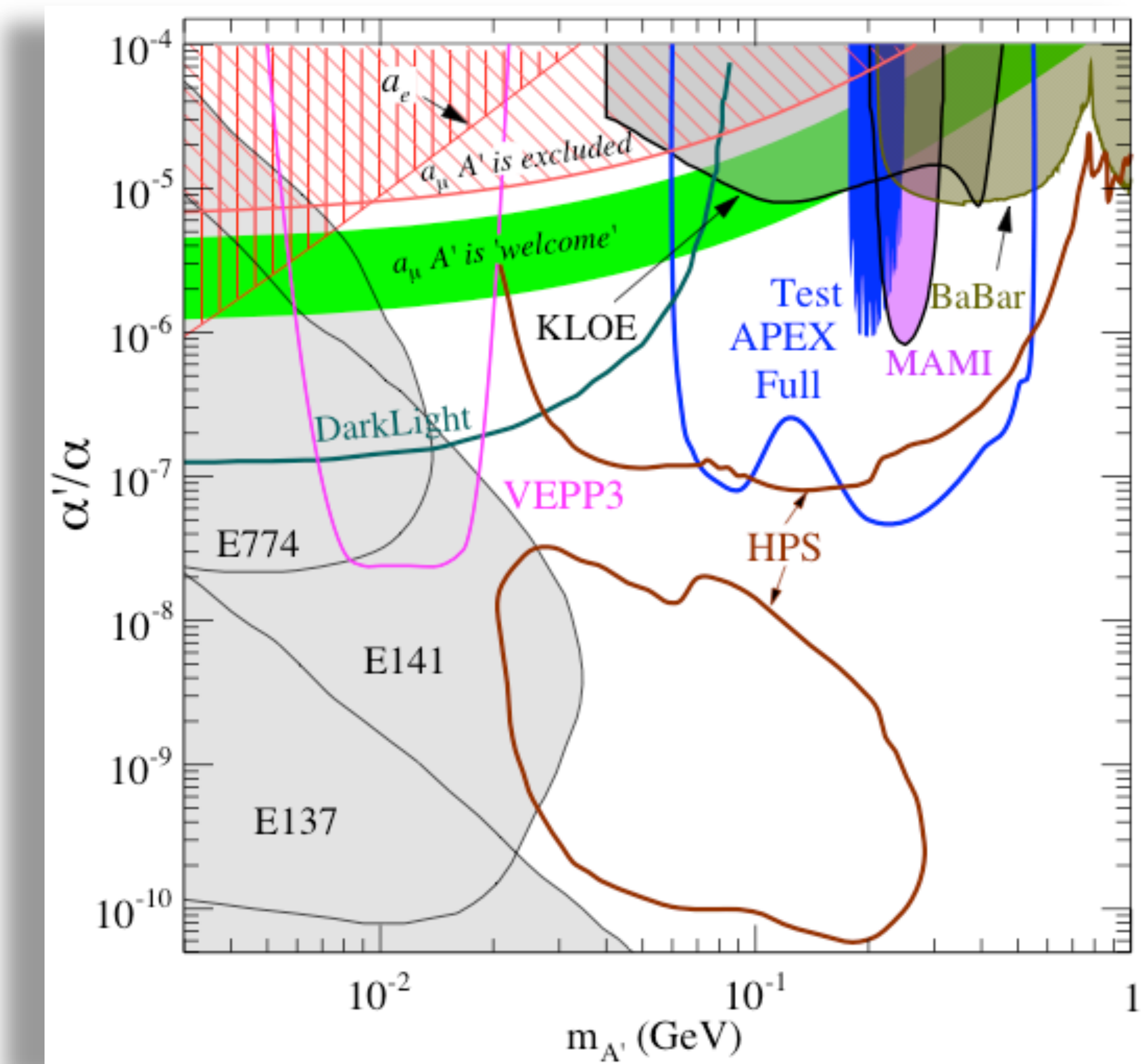


S. Andreas, C. Niebuhr, A. Ringwald, arXiv:1209.6083

Searches for a gauge boson A’



only g-2= a_e, a_μ,

VEPP-3 and
a portion
of DarkLight

are sensitive

to “invisible”
A’ decay modes

Options for an e^+e^- experiment at low s

A "very" low energy, $s^{1/2} \sim$ 10-30 MeV

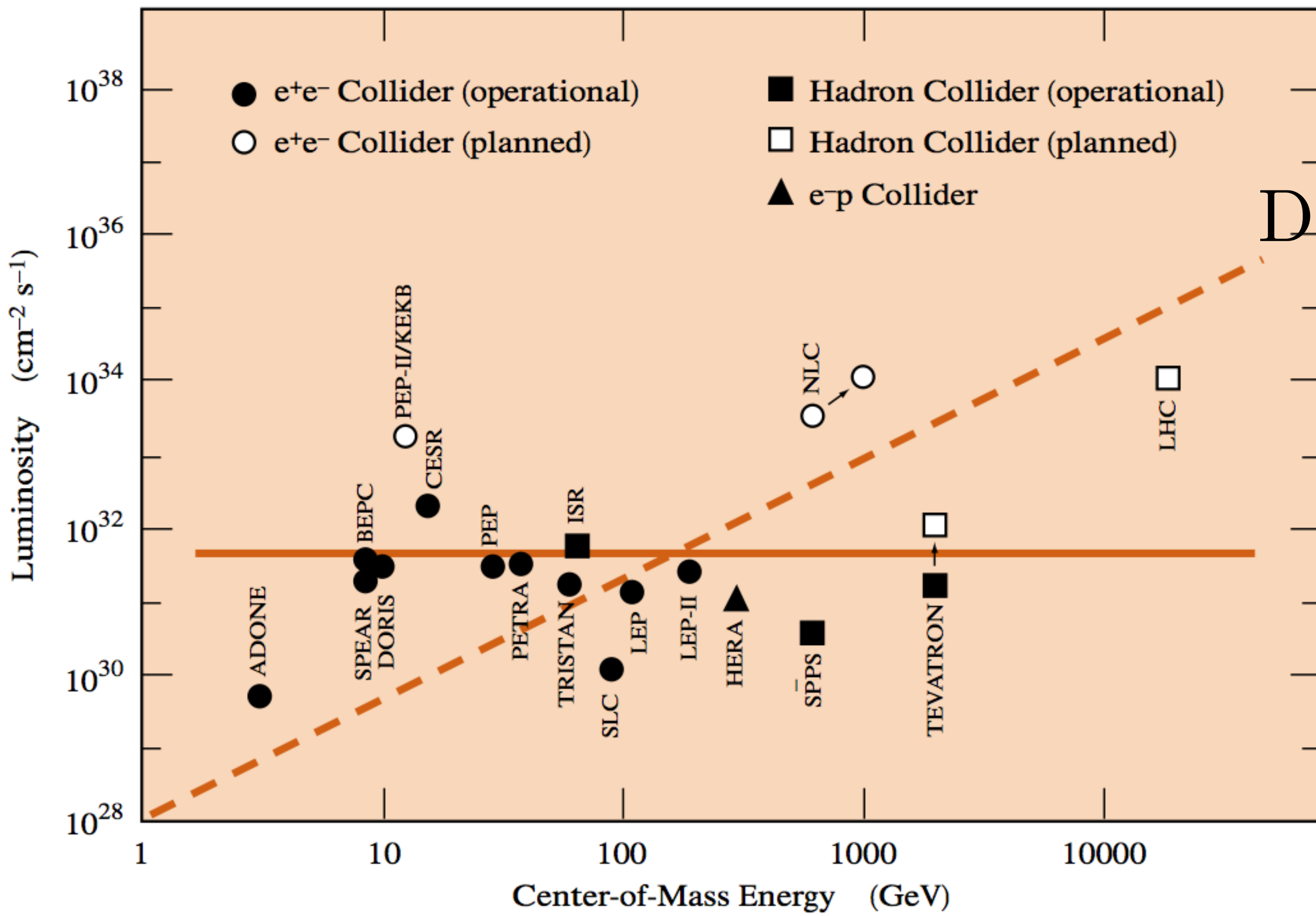
a) 5 MeV x 5 MeV head-head collider of e+e- => $\mathcal{L} \sim 10^{24}$

b) Sliding beams of e+e- (250 MeV x 250 MeV)=>
Project needs a specialized accelerator with two rings

c) Current approach is a positron beam + atomic electrons

Luminosity of the colliders

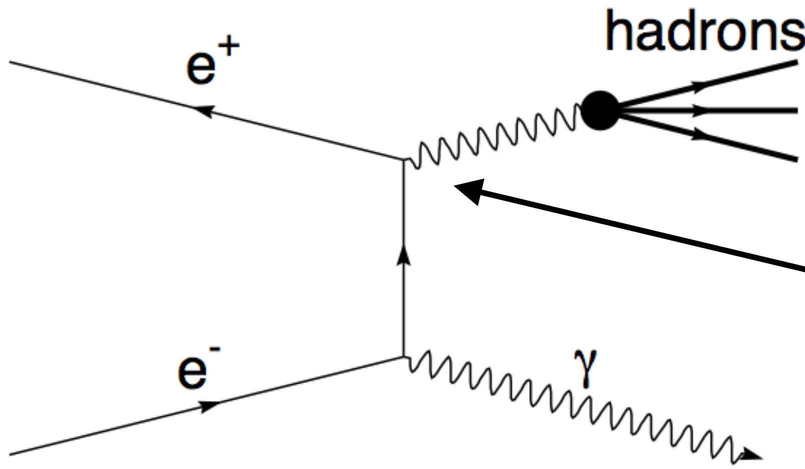
from W. Panovsky's article in BEAM LINE



Dashed line is $\mathcal{L} \propto E_{cm}^2$

For E_{cm}=100 MeV $\mathcal{L} \sim 10^{26} - 10^{29} cm^{-2}/s$

Luminosity using initial state radiation



$s \sim 4E_+ \cdot (E_- - E_\gamma)$

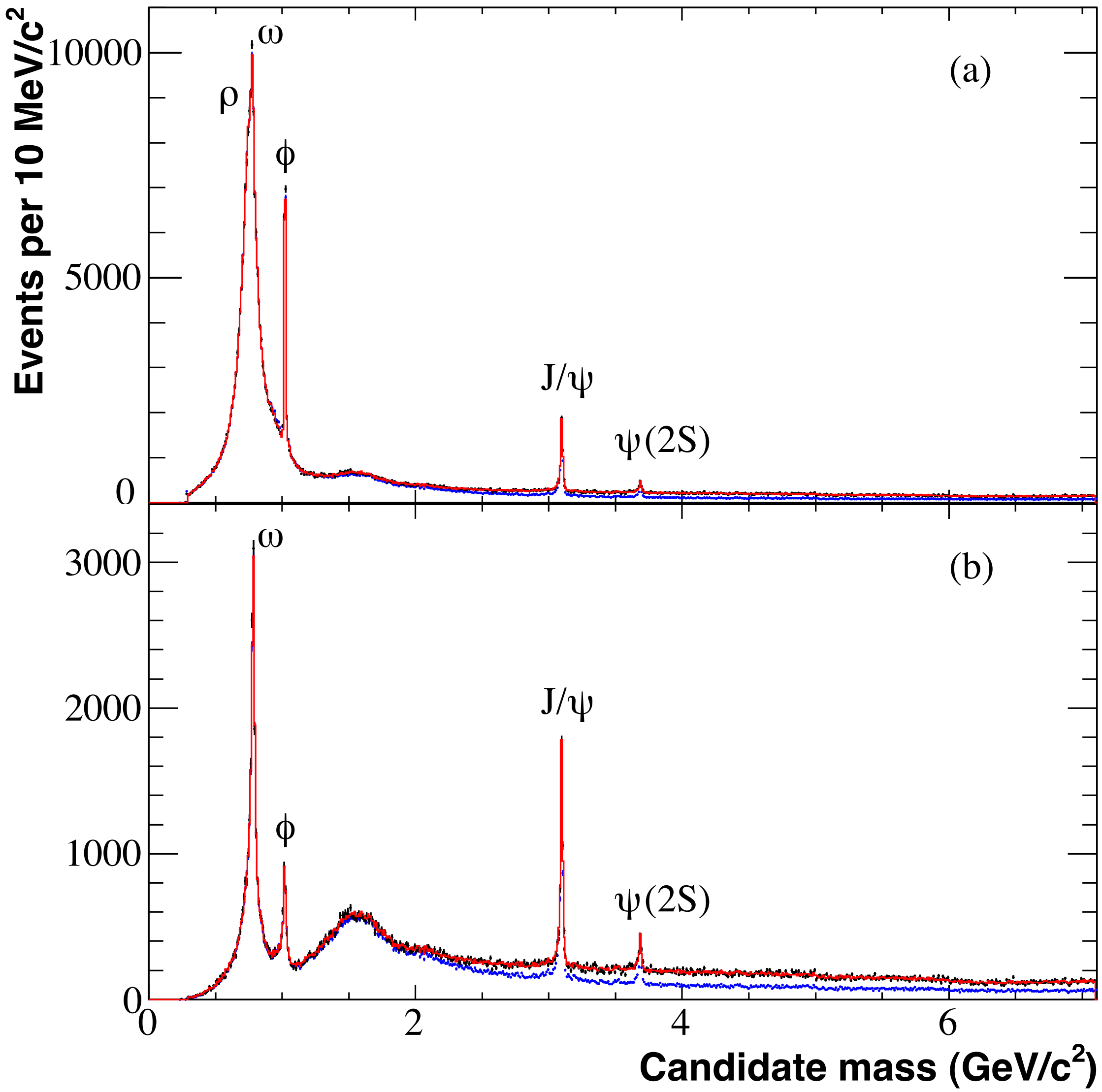
FIG. 2 The lowest-order Feynman diagram describing the initial state radiation process $e^+e^- \to \gamma +$ hadrons.

$$\Delta\mathcal{L} \propto \mathcal{L} \times \frac{\Delta s}{s_{\max}}$$

when $s_{max} = 10$ GeV and $\Delta s \sim 100$ MeV (APEX)

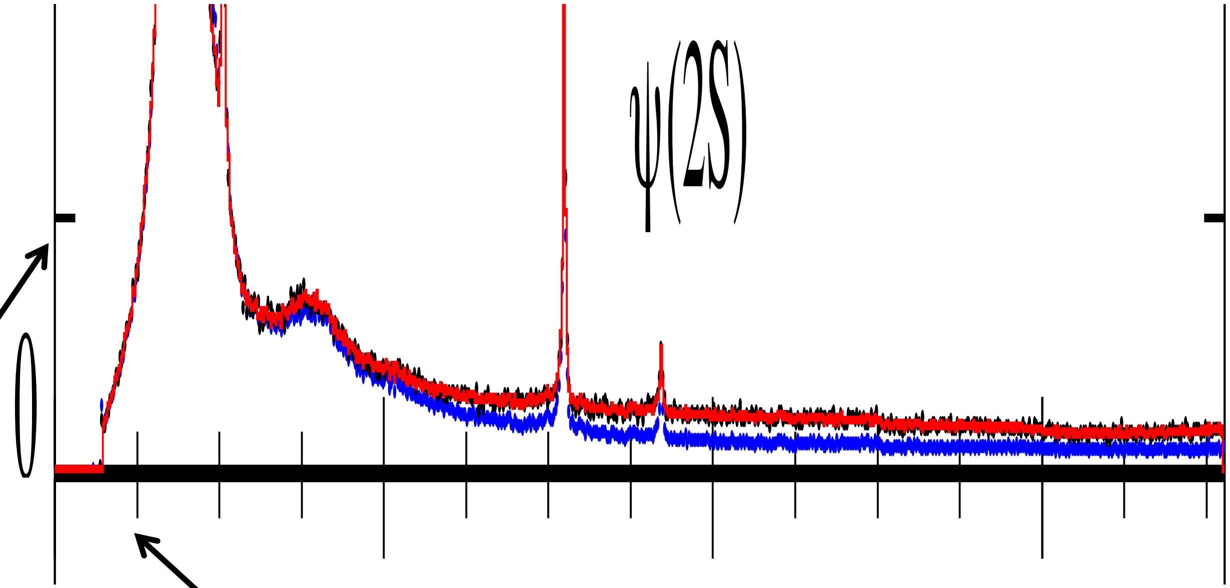
$$\Delta\mathcal{L} \sim 10^{-4}\mathcal{L}$$

BABAR search using initial state radiation



PRL 107, 221803 (2011)
Search for Hadronic
Decays of a
Light Higgs Boson
in the Radiative Decay

BABAR search using initial state radiation

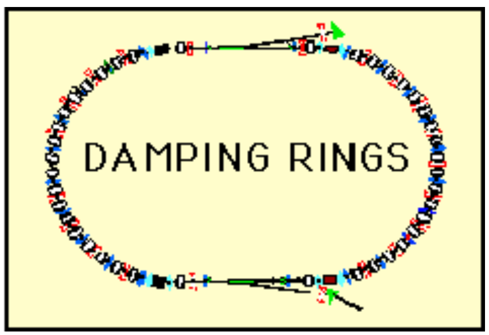


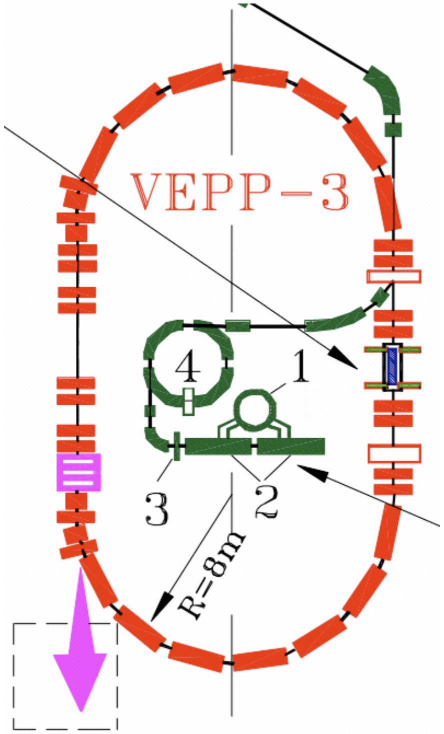
M = 500 MeV

10k events/10 MeV

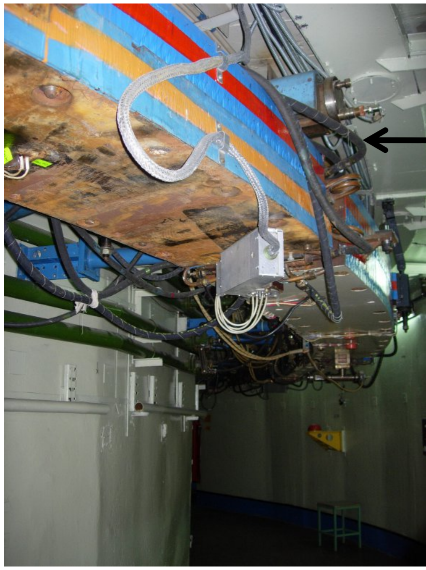
Where to find a positron beam?

- VEPP-3 energy of 0.5-2 GeV, 50 mA
- Beam of 1 μA was used for SLC (120 Hz)
- SLAC positron damping ring up to 1.2 GeV, 200 mA
- Frascati 500 MeV positron ring
- Cornell positron source!





A few pictures of VEPP-3

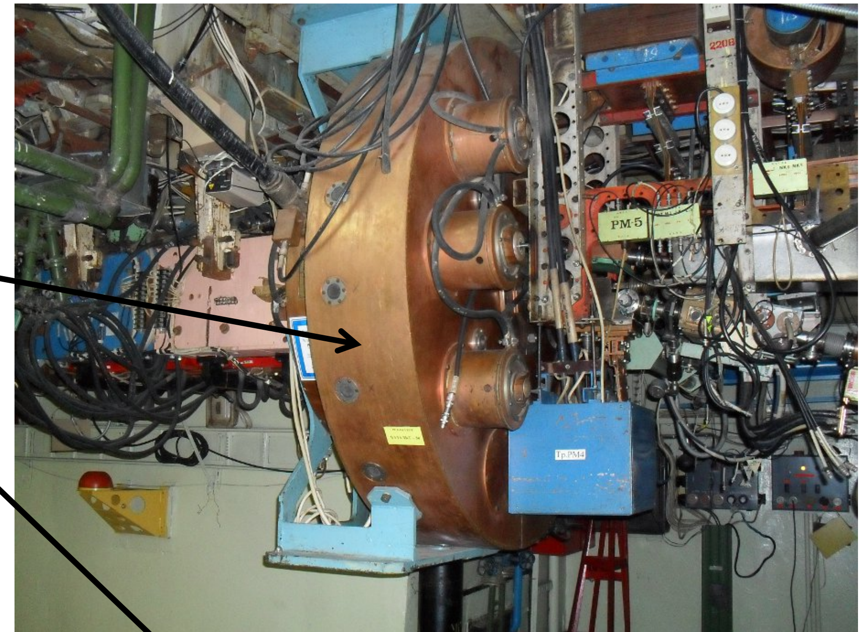


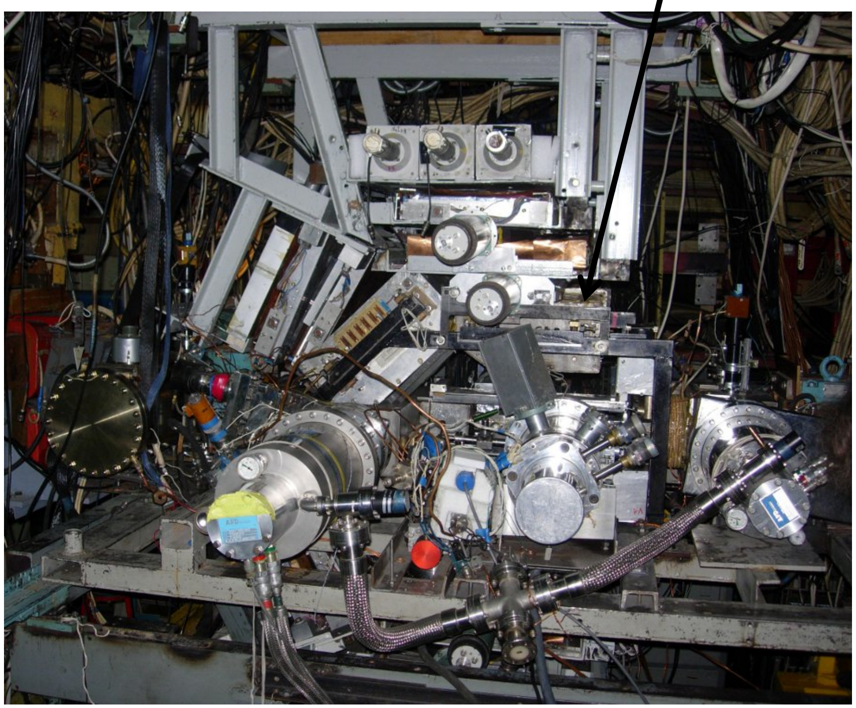
Bend magnets

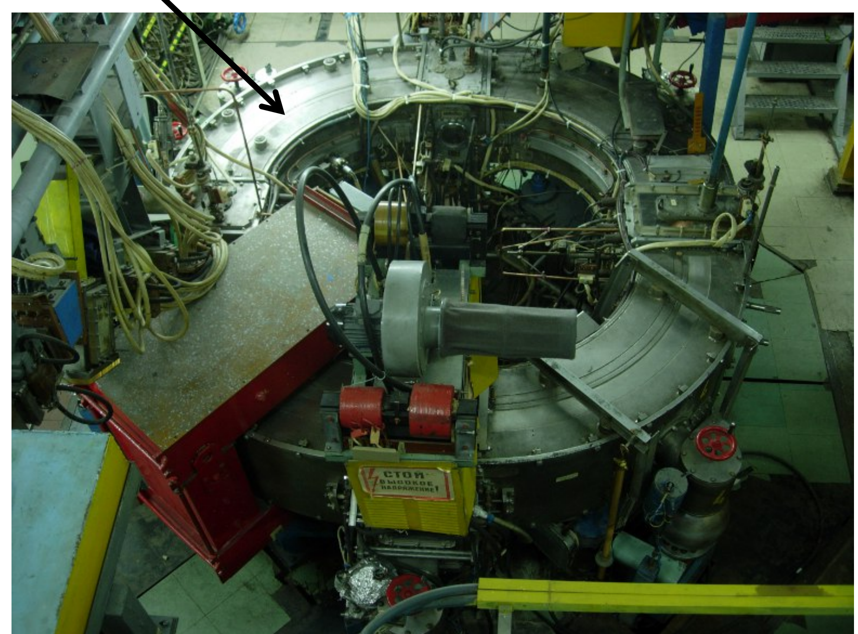
RF cavity

Injector

Fix target expt.







The photo-production processes

Search for : $e^+e^- \rightarrow \gamma U$ *(peak below main)*

Basic QED: $e^+e^- \rightarrow \gamma\gamma$ (mono-energetic)

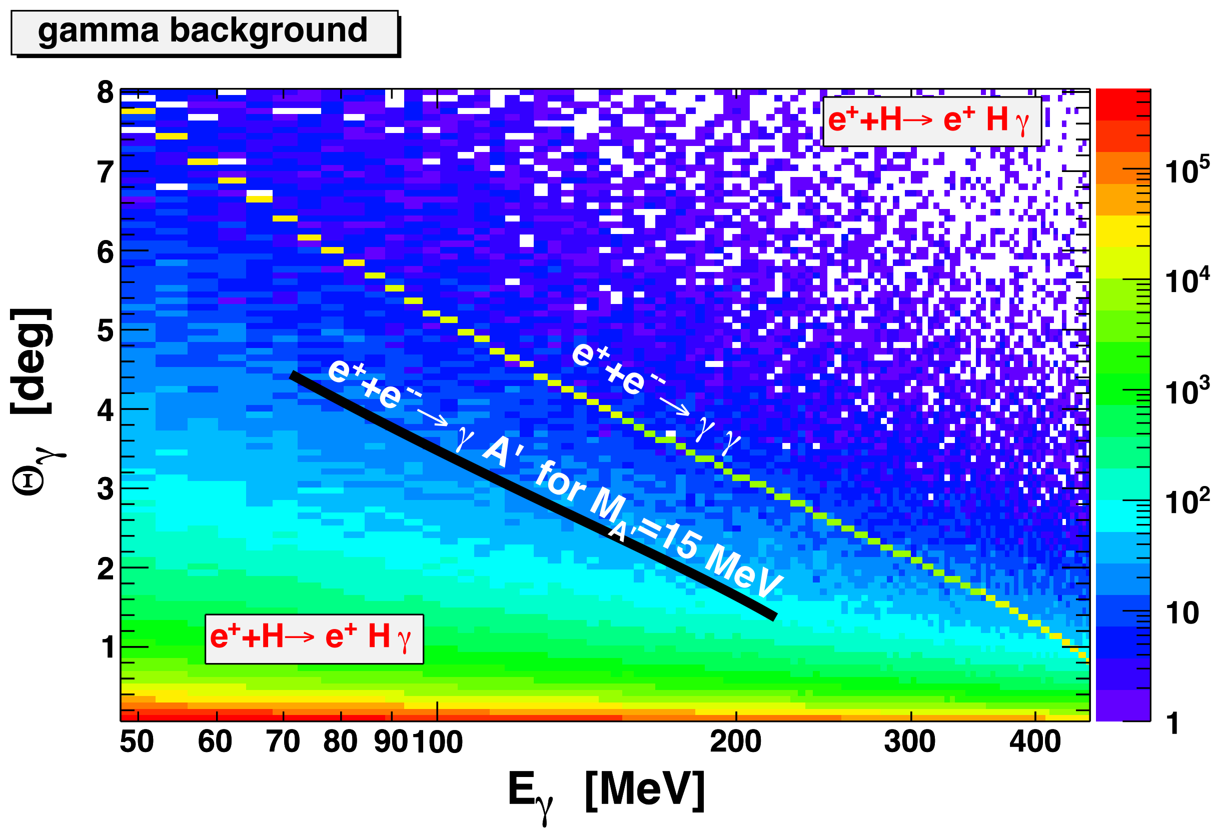
Basic QED: $e^+Z \rightarrow \gamma$ (smooth brems.)

- Detect γ at fixed angle with the beam:

  reconstruct the mass
- Variation with the angle:

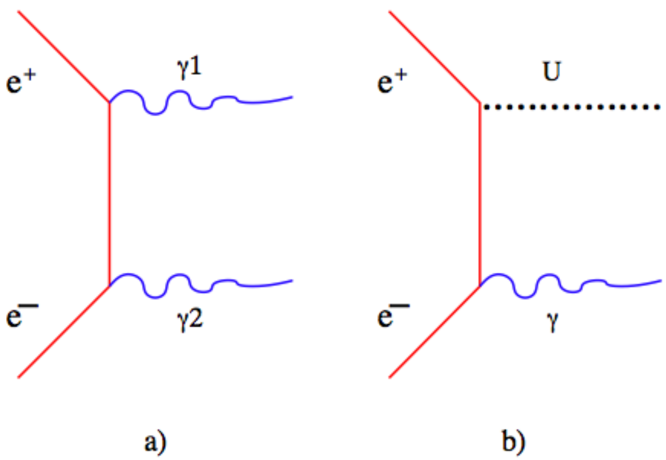
  control systematic
- Target Z

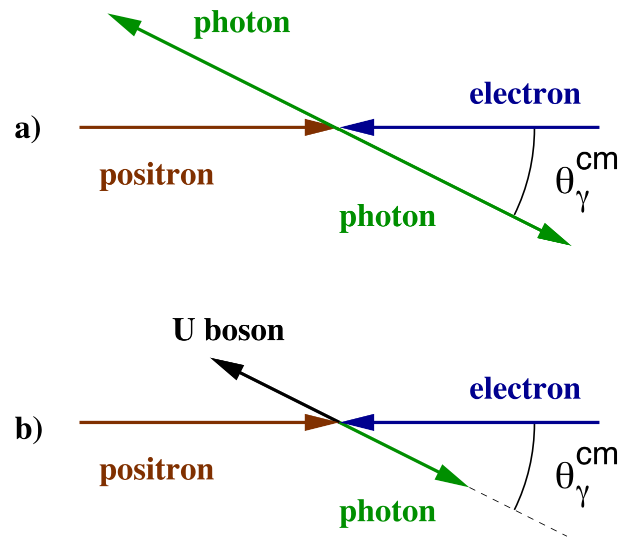
  Hydrogen vs. ^{12}C

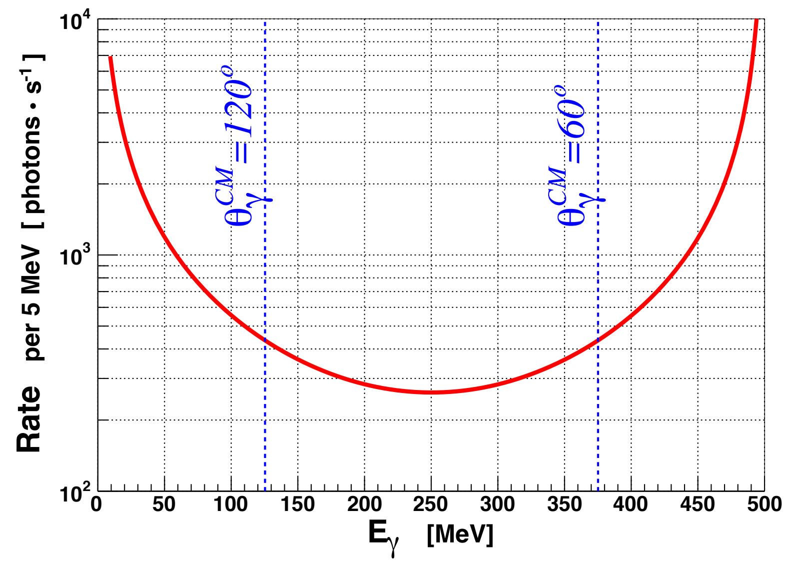


Concept of an experiment with a positron beam

Kinematics







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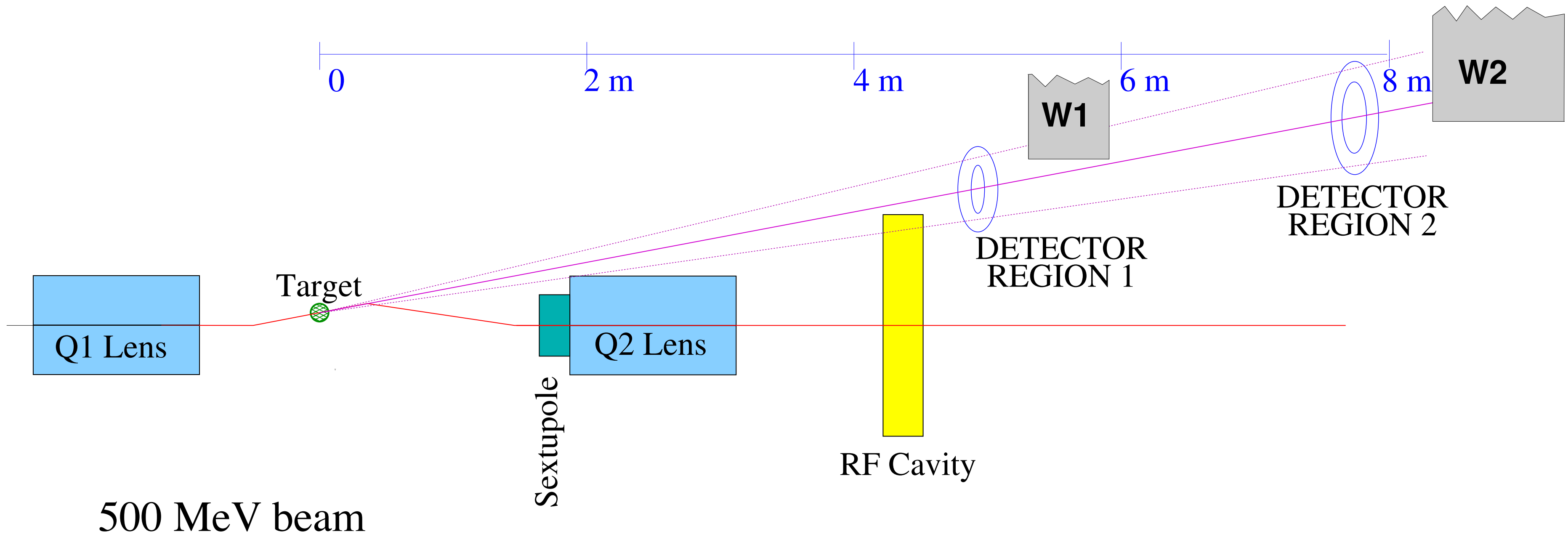
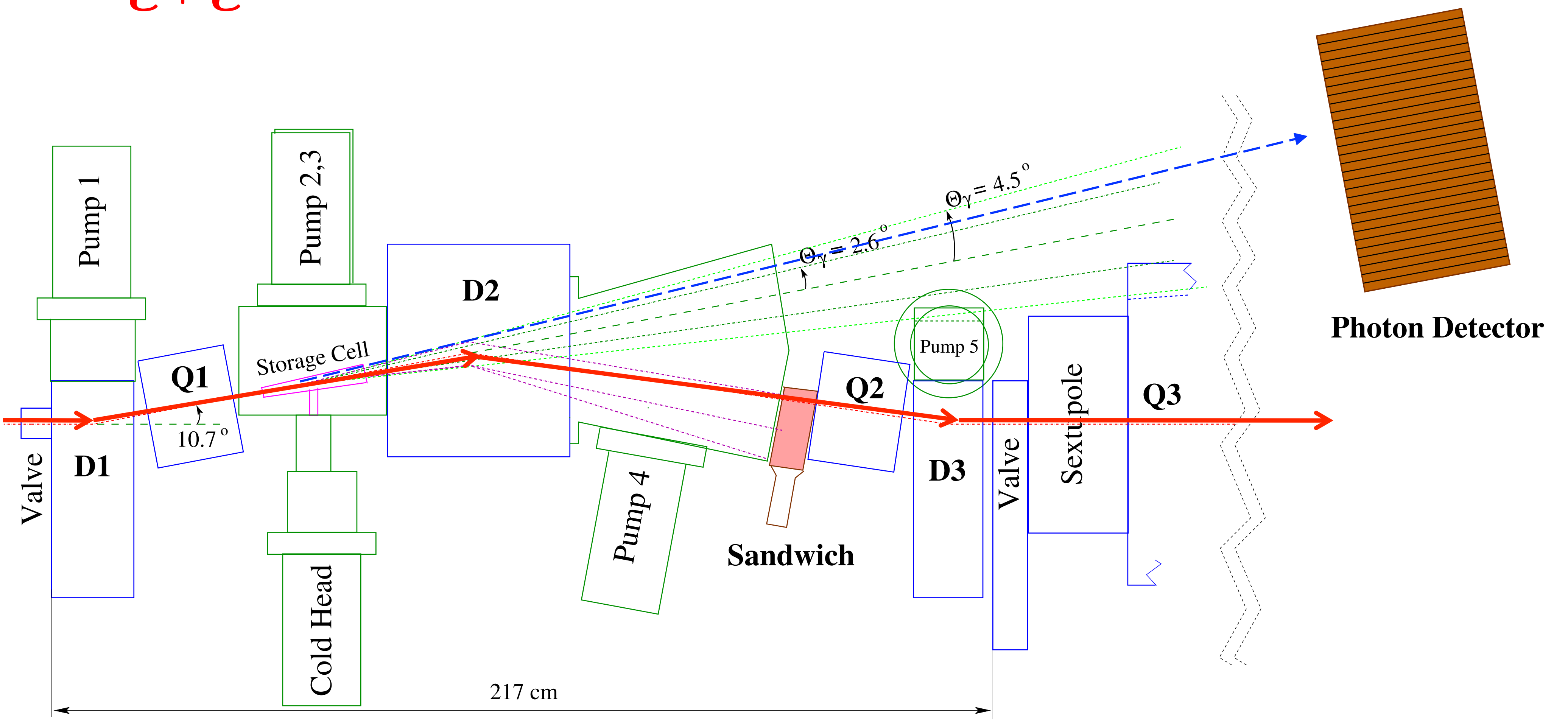


Proposal of an experiment at VEPP-3:
BW, Nikolenko, Rachek, arXiv:1207.5089

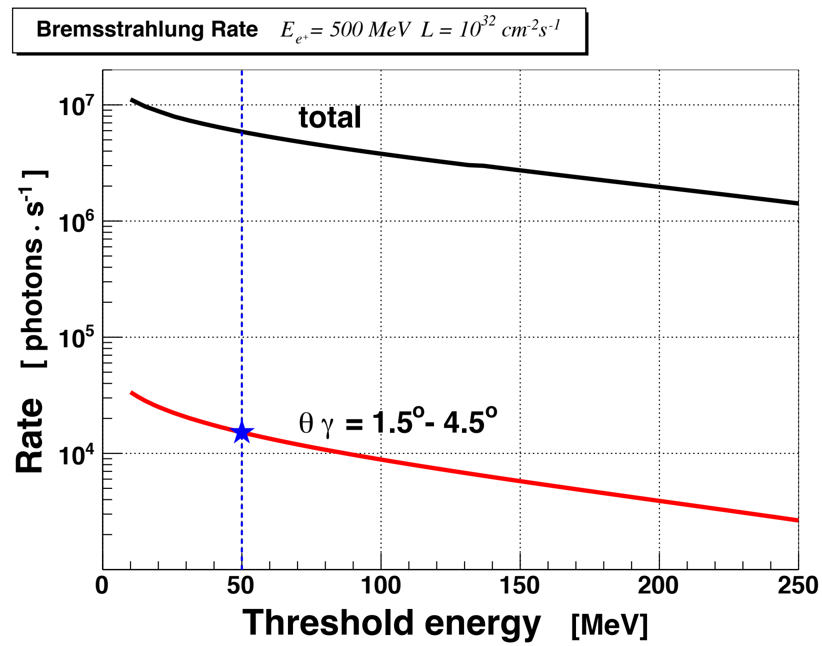
Experimental layout

$$\mathcal{L}_{e^+e^-} \sim \mathbf{10^{32}}$$

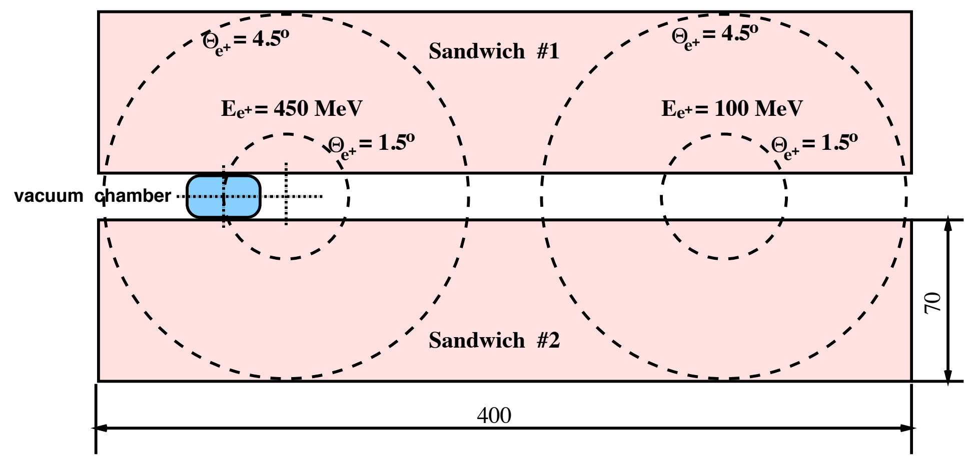


Positron beam on internal Hydrogen target

Physics background is the bremsstrahlung radiation



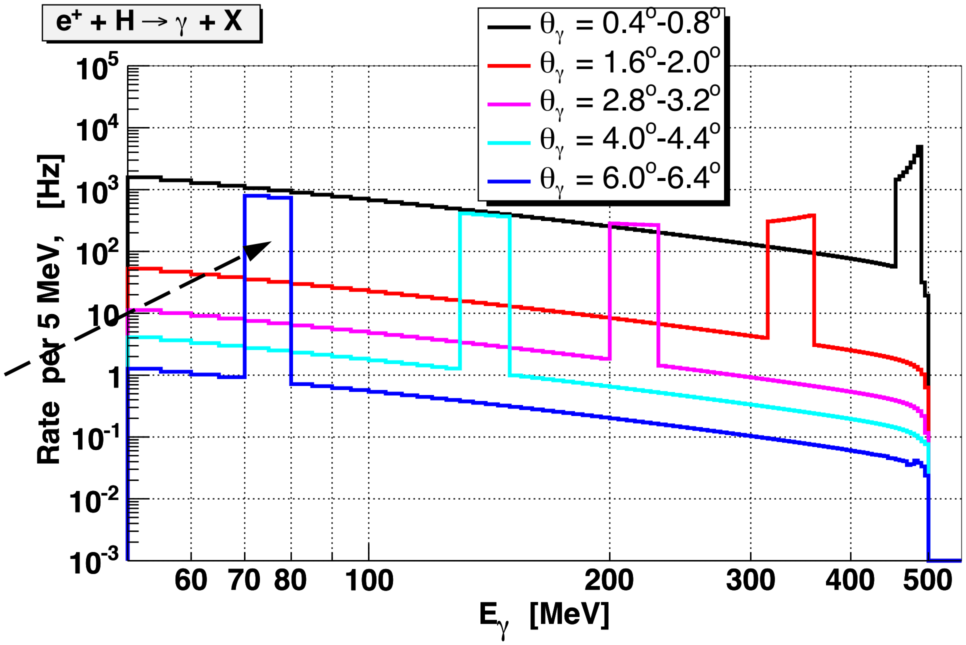
Anti-coincidence with the positron counters reduce QED background



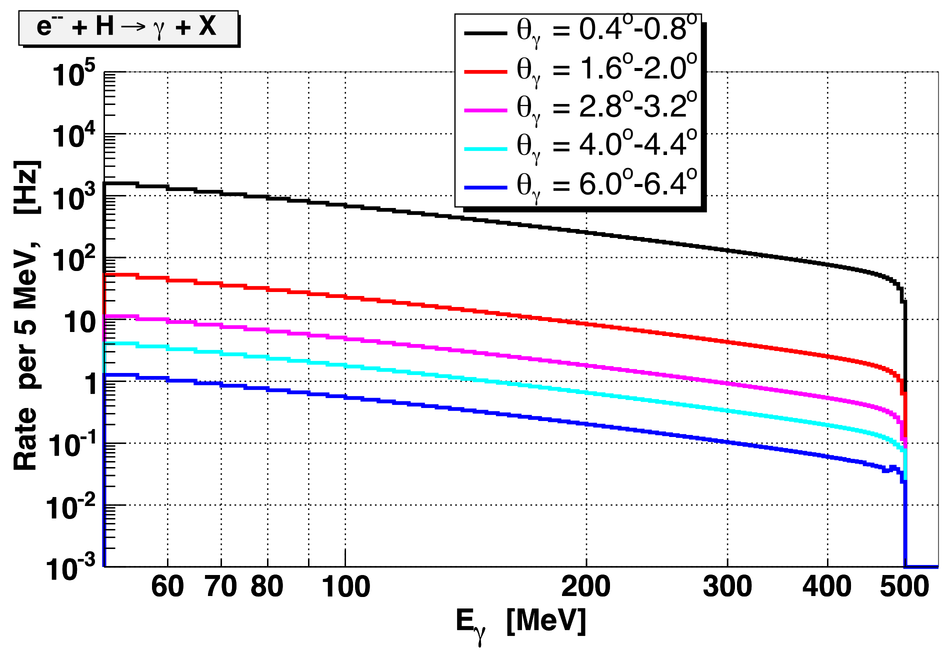
Positron beam on internal Hydrogen target

Projected event rate

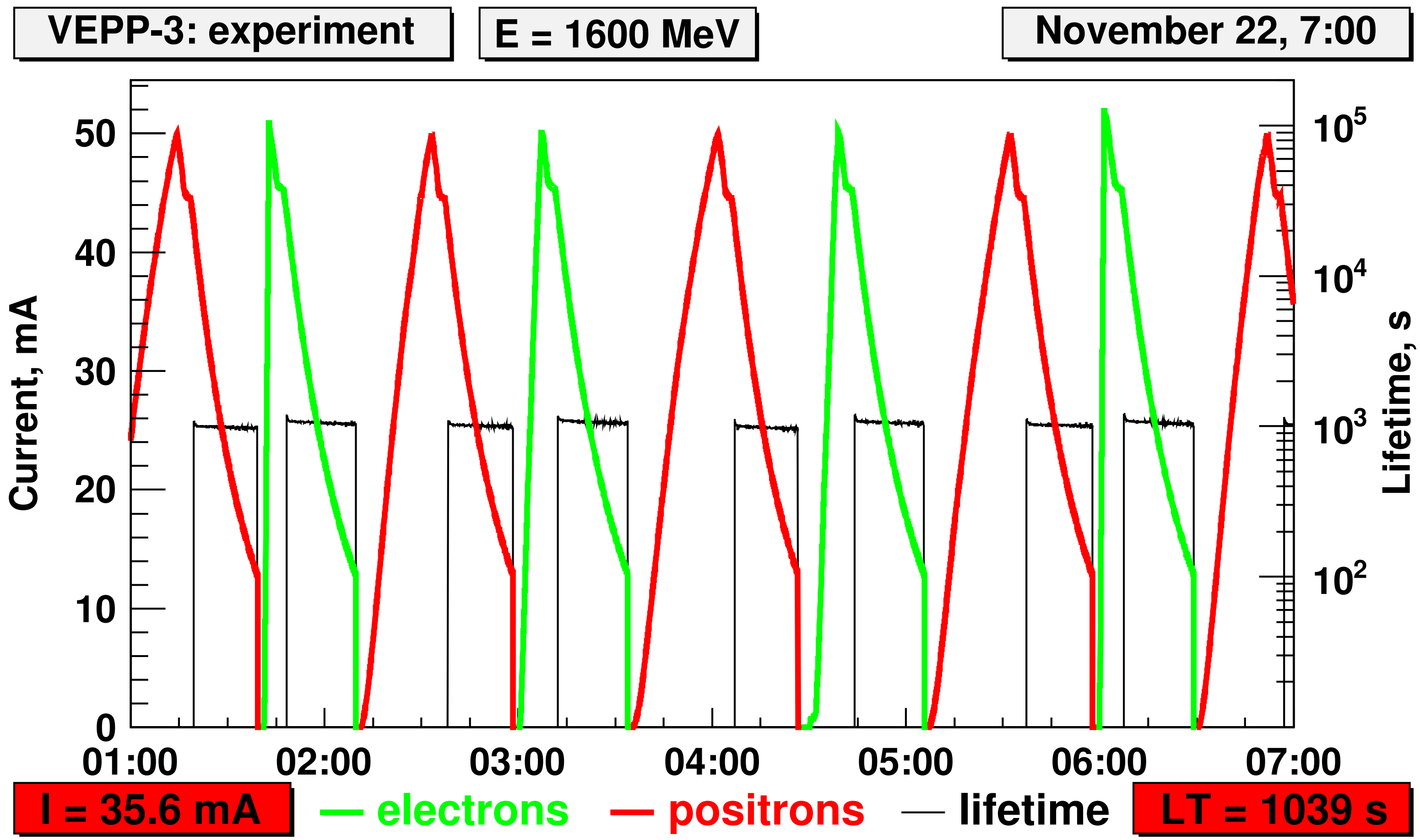
A bump is $e^+e^- \rightarrow 2\gamma$



Projected for an electron beam for systematic check



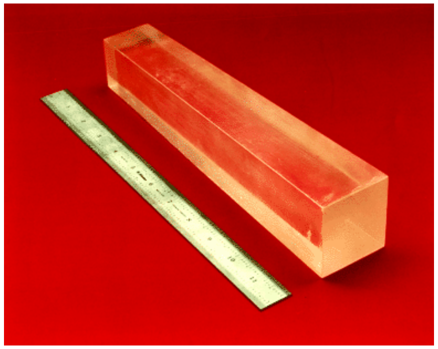
VEPP-3 operation during
Two-Photon Exchange experiment



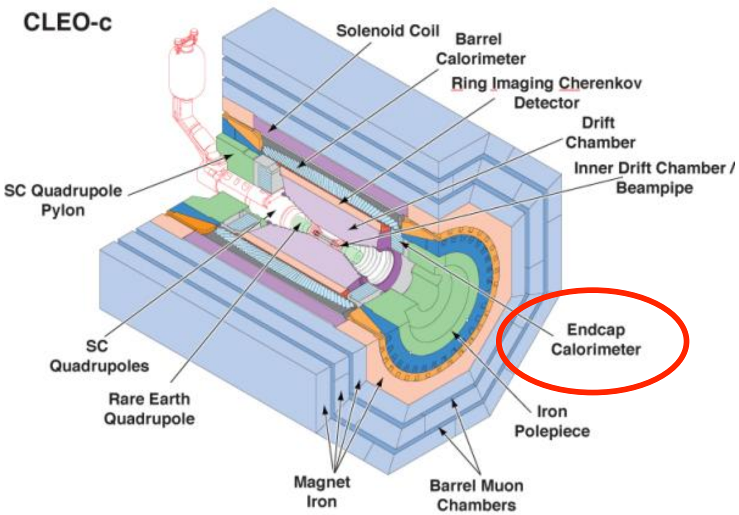
Photon detector

The photon detector can be placed at a distance of between 4 m and 8 m from the target. The requirements for the detector are:

- Energy resolution on the level of $\sigma_E/E = 5\%$ for photons with energy $E_\gamma = 100 - 450$ MeV.
- Angular resolution on a level of $0.1°$.
- Angular acceptance as defined by a requirement to detect both photons from two-photon annihilation:
  - in ϕ : either total 2π, or two symmetrical sectors, e.g. (ϕ_1, ϕ_2) and $(\phi_1+\pi, \phi_2+\pi)$;
  - in θ : symmetrical range in θ_γ^{CM} around $90°$, e.g. $\theta_\gamma^{CM} = 60° - 120°$, which corresponds to $\theta_\gamma^{LAB} = 1.5° - 4.5°$.
- The detector should be able to sustain a modest photon rate of several hundred kHz over its whole area.



Potential source of crystals:

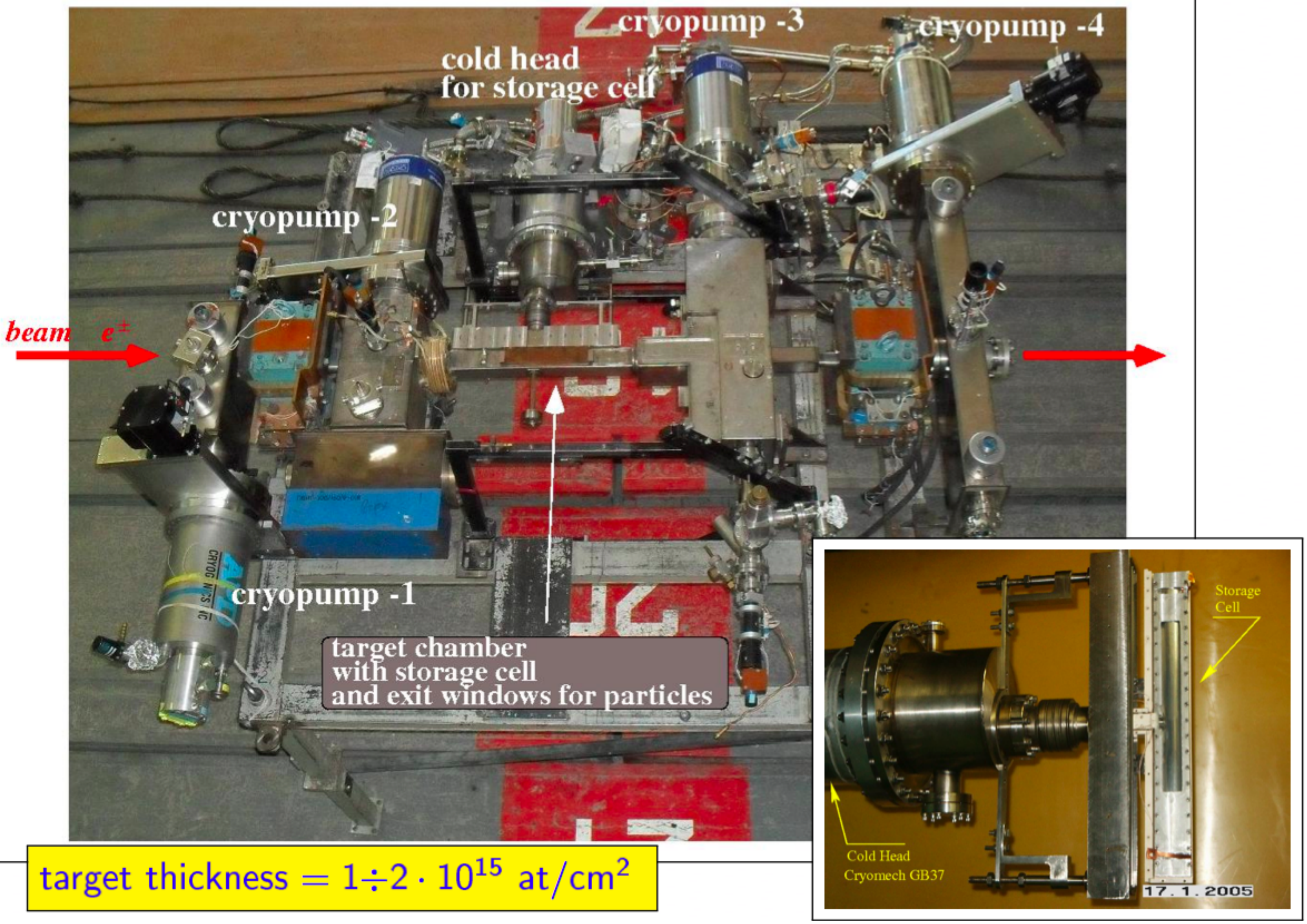


The electromagnetic calorimeter of the CLEO-II detector[35] consists of 8000 CsI(Tl) crystals of $5 \times 5 \times 30$ cm^3 size ($16.2X_0$). It is used to measure electron and photon energy in a wide range; therefore, a direct measurement of its performance at a photon energy of interest for the proposed experiment is available:

$$\delta E/E = 3.8\% \quad \text{and} \quad \delta x = 12 \text{ mm} \quad \text{for } E_\gamma = 180 \text{ MeV}$$

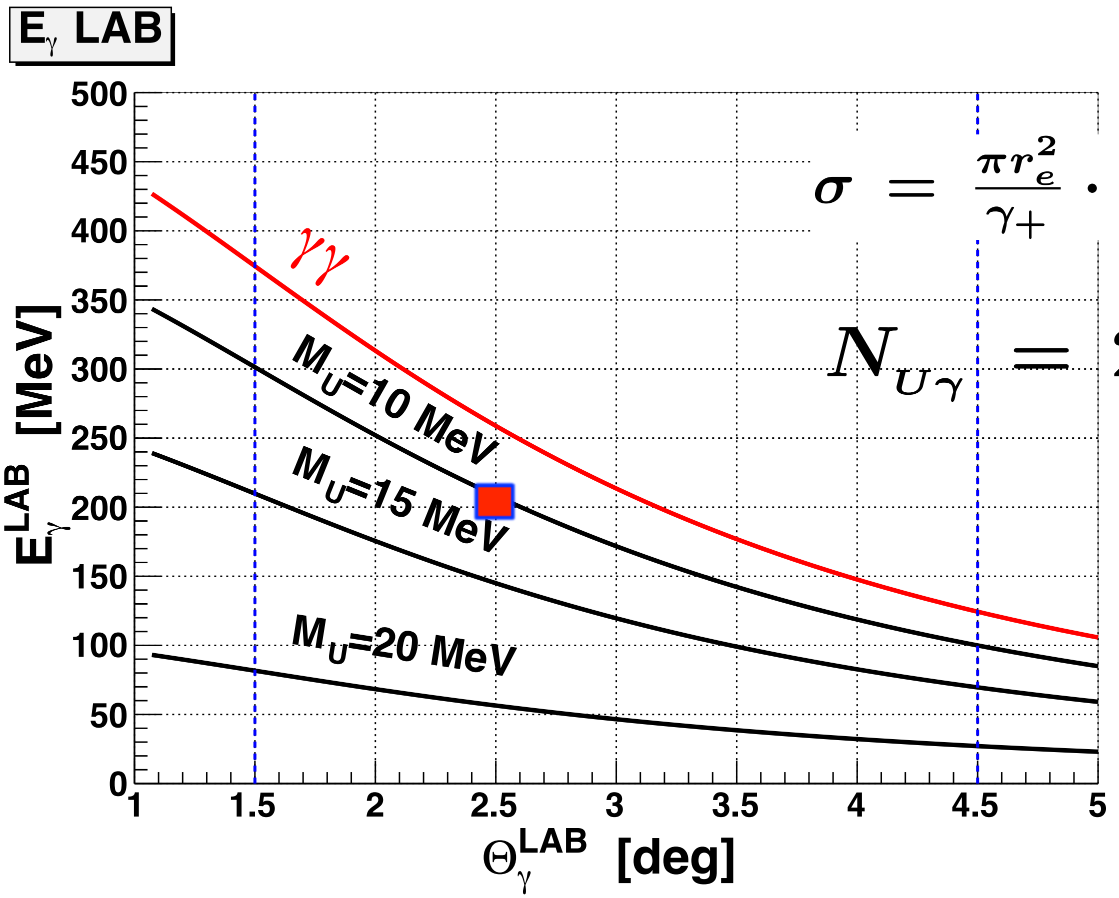
One can see that in the energy range of the proposed experiment, a CsI(Tl)–based calorimeter provides better energy resolution but a worse spatial one than that based on $PbWO_4$–crystals. Therefore, the CsI(Tl)–calorimeter must be placed as far as possible from the target, i.e. about 8 m. In this case it would take about 800 crystals to cover the required angular ra

Internal target for
Two-Photon Exchange experiment



target thickness = $1 \div 2 \cdot 10^{15}$ at/cm^2

Kinematical correlation



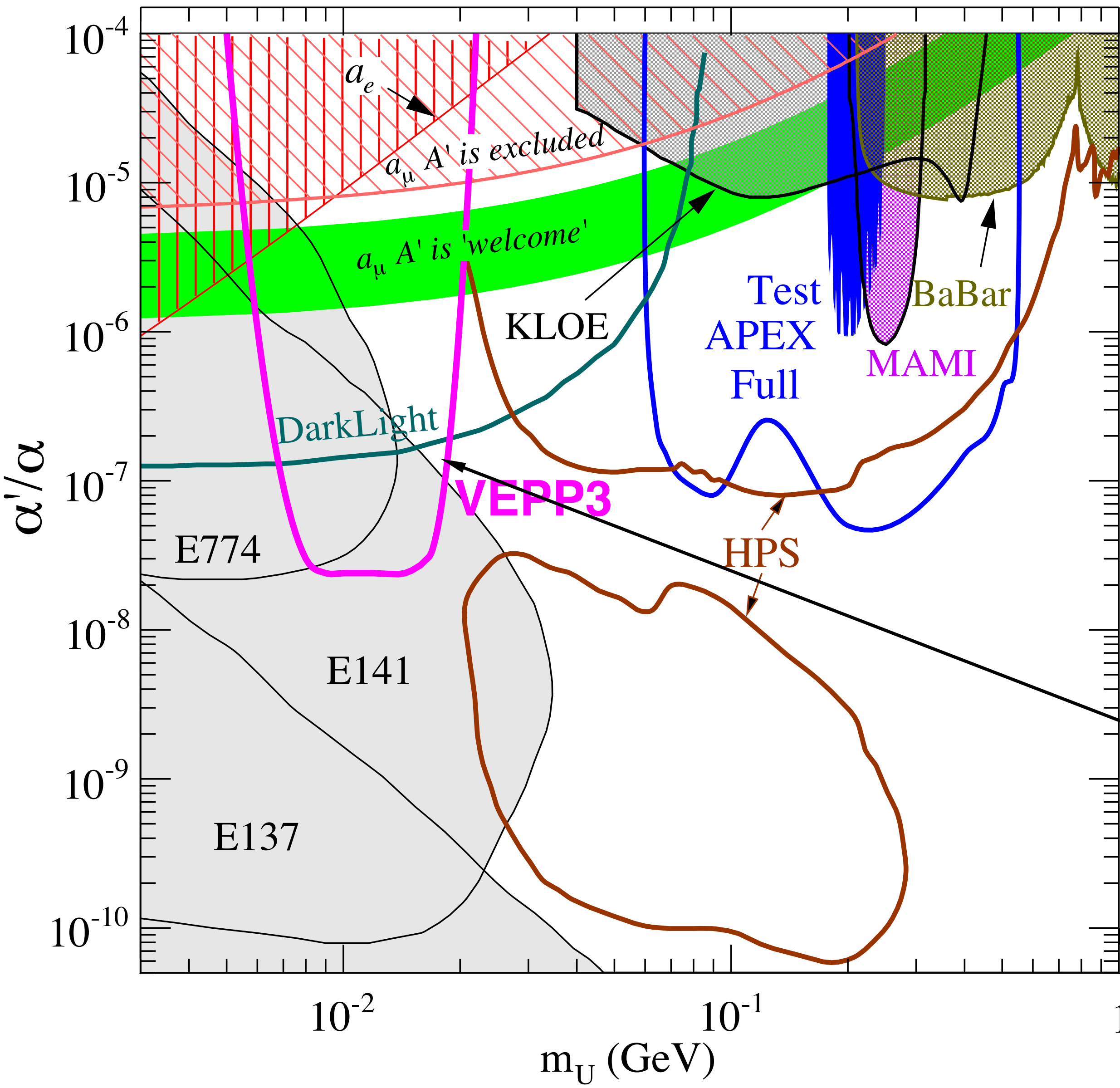
$$\sigma = \frac{\pi r_e^2}{\gamma_+} \cdot (\ln 2\gamma_+ - 1)$$

$$N_{U\gamma} = 2\frac{\alpha'}{\alpha} \cdot N_{\gamma\gamma}$$

$$E^{lab}_{\gamma(A'\gamma)} = E^{lab}_{\gamma(\gamma\gamma)} \cdot (1 - M^2_{A'}/s)$$

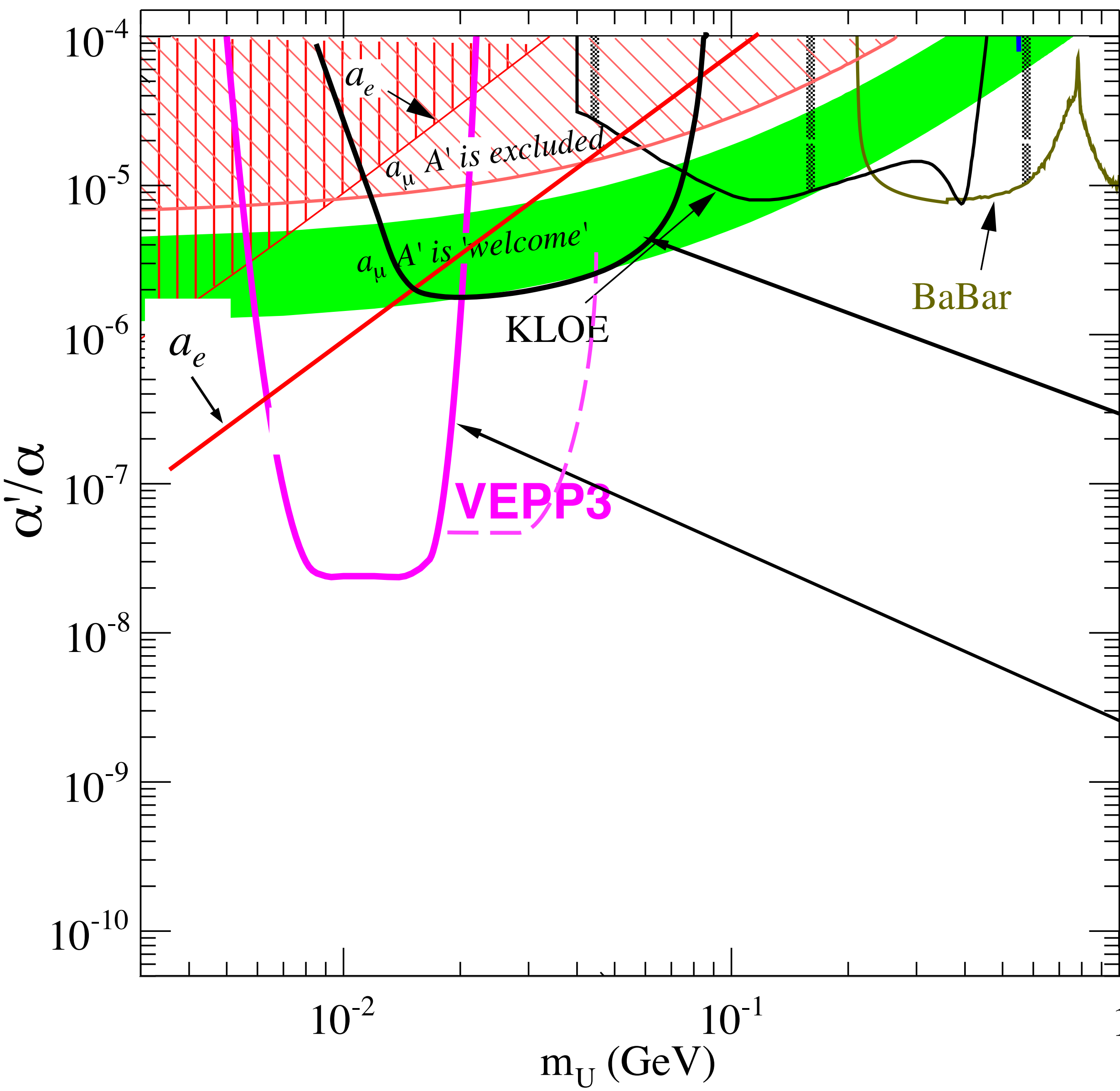
The U(or A') mass resolution ~ 3%

Projected sensitivity in the parameter space



Projected sensitivity for the VEPP-3 measurement at $L_{ep} = 10^{32}$ cm^{-2}/s (aver. current of 25 mA) in the six-month run

Projected sensitivity in the parameter space



These searches are sensitive to "invisible"

DarkLight (to "invisible")
Y. Kahn, J. Thaler, arXiv:1209.0777

Projected sensitivity for VEPP-3 (at 500 MeV) measurement at $L_{ep} = 10^{32}$ cm^{-2}/s (aver. current of 25 mA) in the six-month run

- - - with 5 GeV beam

Summary

- Search for the A'/U boson in the photon recoil spectra is possible using a positron beam and internal hydrogen target in the 500 MeV storage ring.
- Available luminosity (~10^{32}) allows a 10-100+ improvement over the (g-2) limit in mass range 7-15 MeV. The range could be extended to 50 MeV with 5 GeV beam.
- Segmented high-resolution electromagnetic calorimeter is a key new part of the setup.