New Probes for Physics Beyond the Standard Model
April 19 2018
Santa Barbara

Using positron to search for light dark matter in beam-dump experiments

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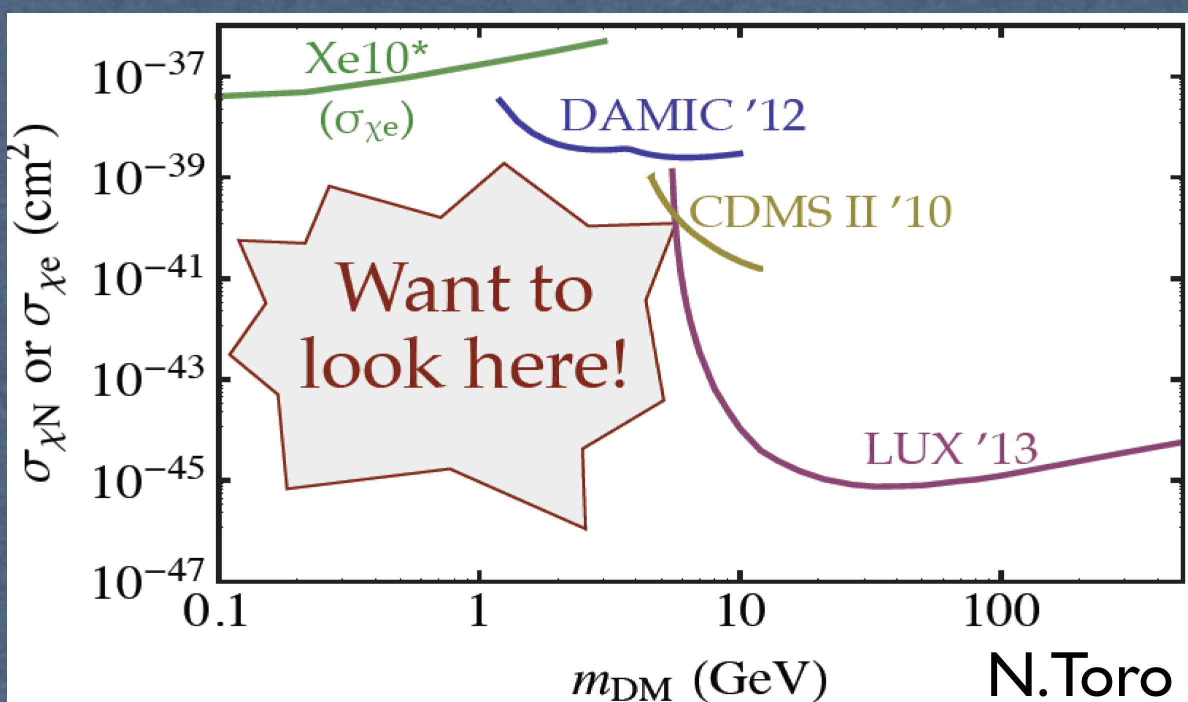
LDM search at accelerators

Forces / Matter	EM	Weak	Strong	New force?
Electron	✓	✓	—	—
Neutrino	—	✓	—	—
Quarks	✓	✓	✓	—
Dark Matter?	—	—	—	✓



Neutral doors (portals) to include DM into the SM

- ★ The new force should be weak
- ★ Different combination of DM and mediator masses are possible:
  - heavy WIMPs / heavy mediators
  - heavy WIMPs /light mediators
  - light WIMPs / light mediators
  - light WIMPs / heavy mediators

Accelerators-based DM search

covers an unexplored mass region extending the reach outside the classical DM hunting territory

- **High intensity**
- **Low/Medium energy**

Many theoretical suggestions and experimental attempts to extend the search region to lower mass:

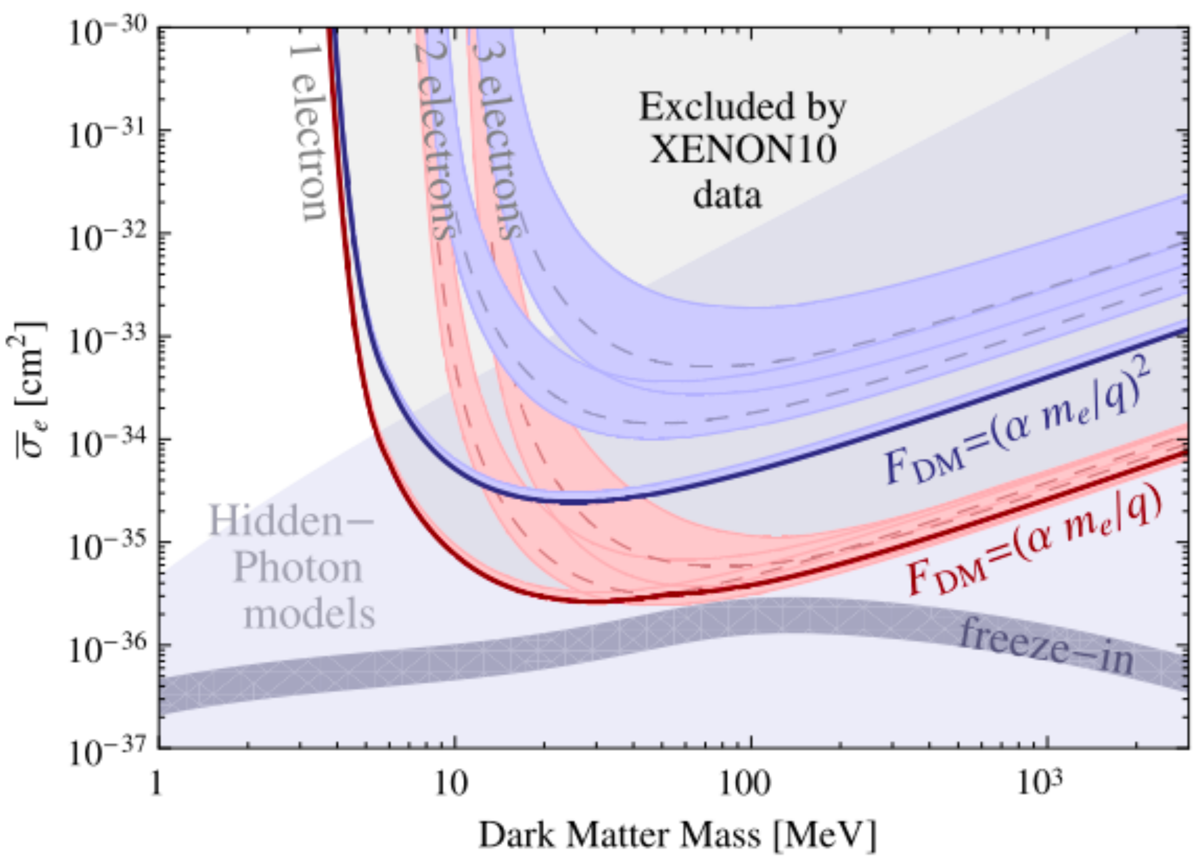
MiniBoone@FNAL, SPS@CERN, BDX@JLab, PADME@LNF

Unique features of accelerator-based (L)DM search

- ✳ Tagging wrt cosmic anomalies (clear way of distinguish DM from other effects)
- ✳ Unprecedented sensitivity in the keep-out zone for direct DM search
- ✳ High intensity electron beam available to play a significant role in LDM search

LDM - Direct Detection limits

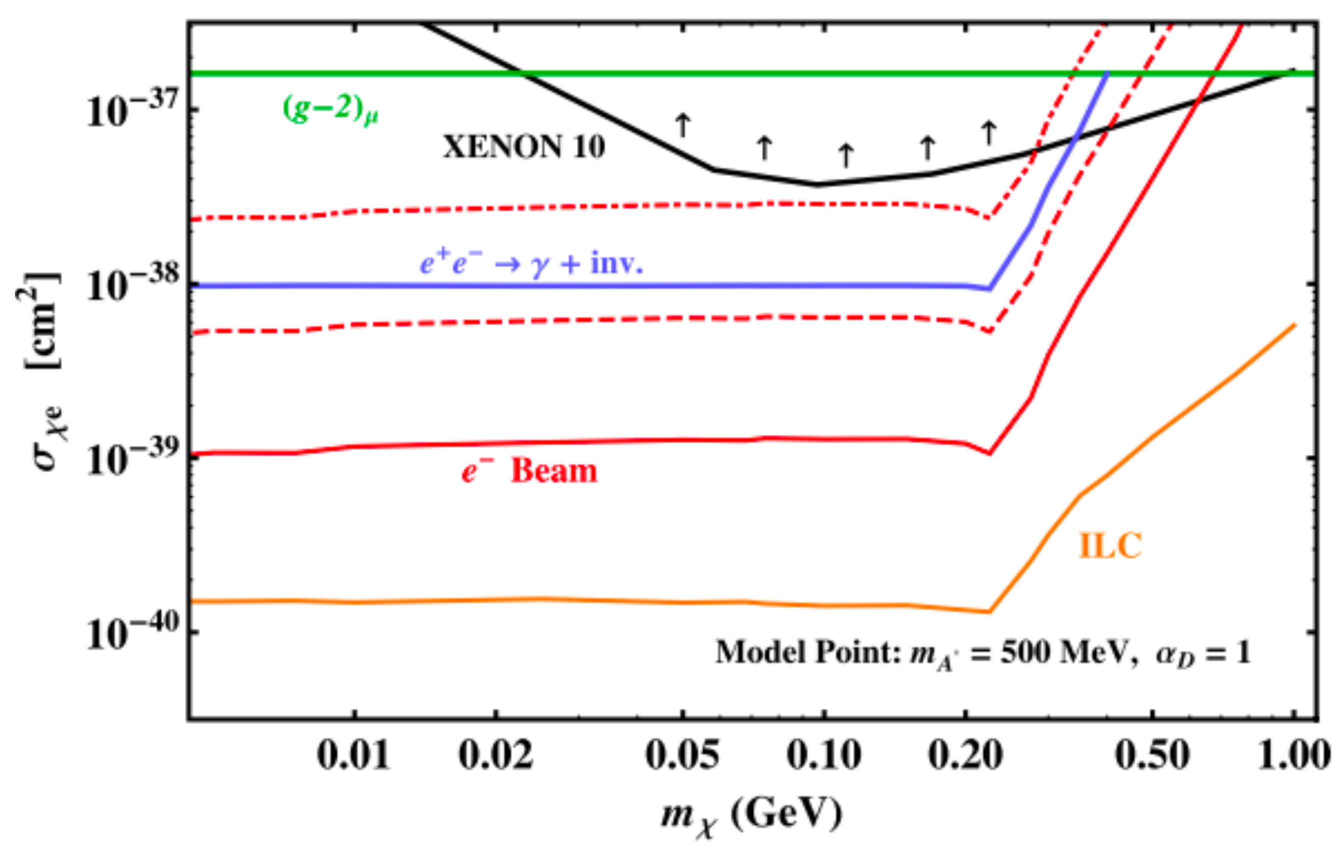
Limits from XENON10



PhysRevLett. 109.021301 R.Essig, A.Manalaysay, J.Mardon, P.Sorensen, T.Volansky,

- Best limits on LDM interaction cross section obtained by direct DM detection (XENON10 and LUX)
  - χ_{cosmic}-e scattering
  - 1-electron ionization sensitivity
  - No FF for the scattering

Fixed target & high intensity e$^-$ beam

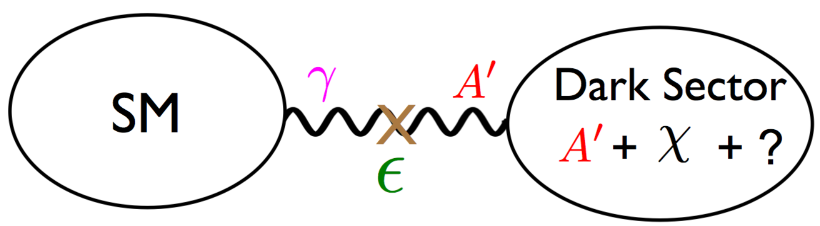


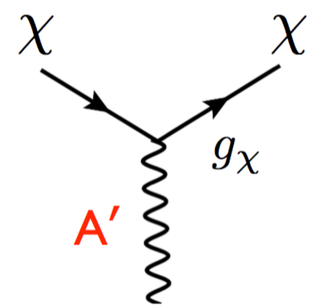
PhysRevD.88.114015 E.Izaguirre, G.Krnjaic, Gordan, P.Schuster, N.Toro

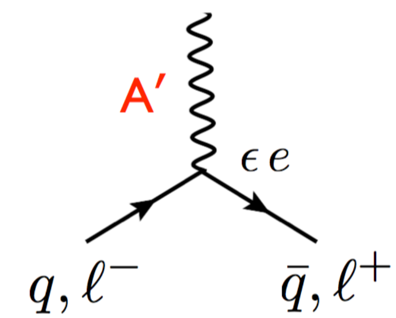
- Fixed target electron beam experiments can be 10^3 - 10^4 more sensitive in the 1 MeV - 1 GeV mass range

- Only one experiment (NA64) designed to measure LDM (all limits come from reinterpretation of old experiments)

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



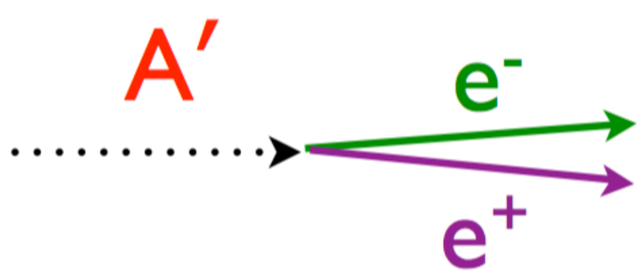




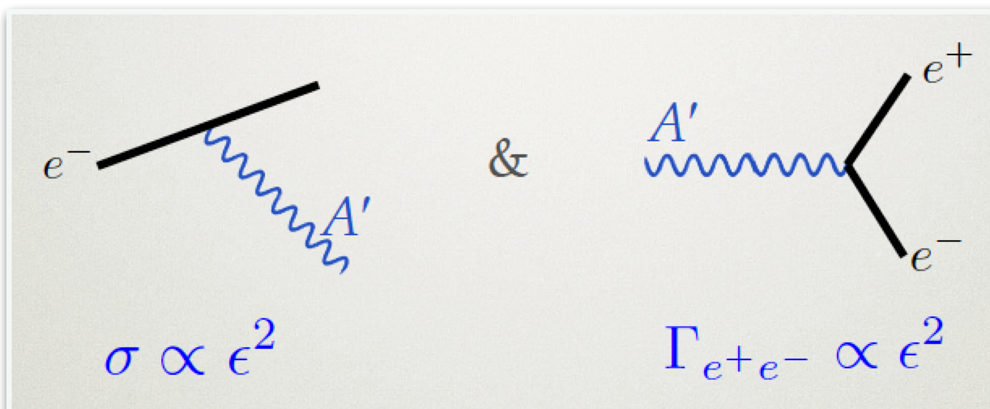
4 parameters: $m_\chi, m_{A'}, \epsilon, g_\chi$

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

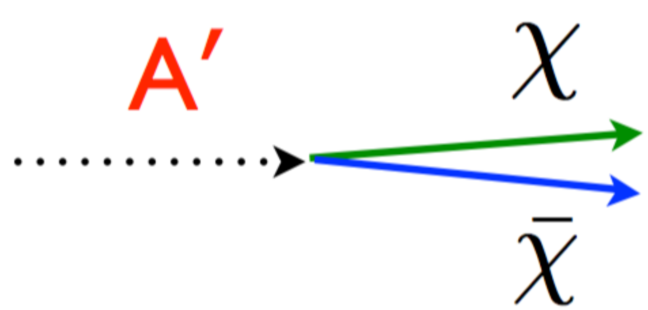
Visible



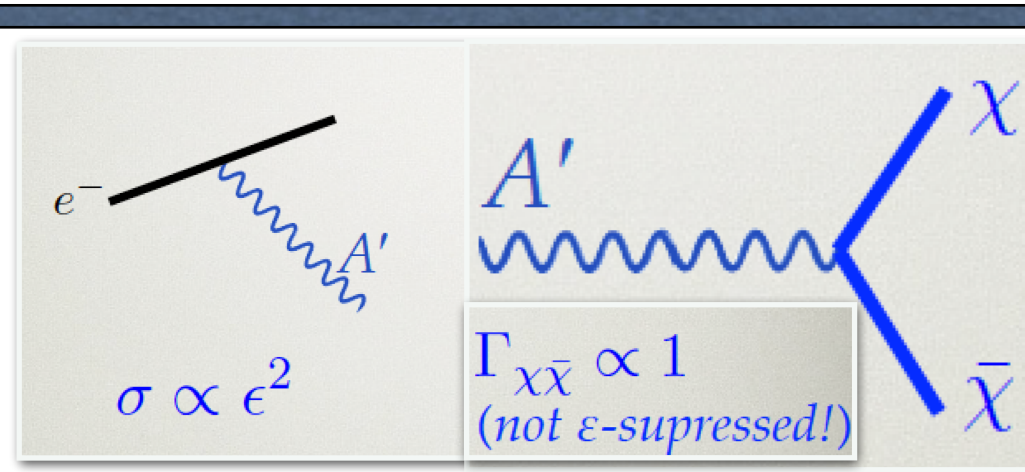
- *Minimal* decay
- Decay regulated by ε^2
- Independent of m_χ
- Requires $m_{A'} < 2m_\chi$



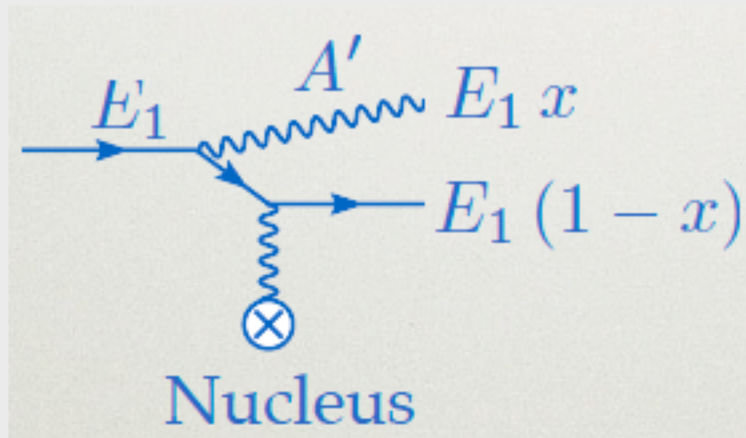
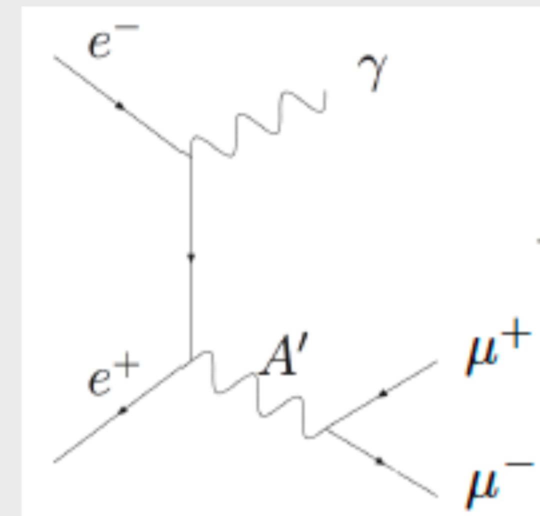
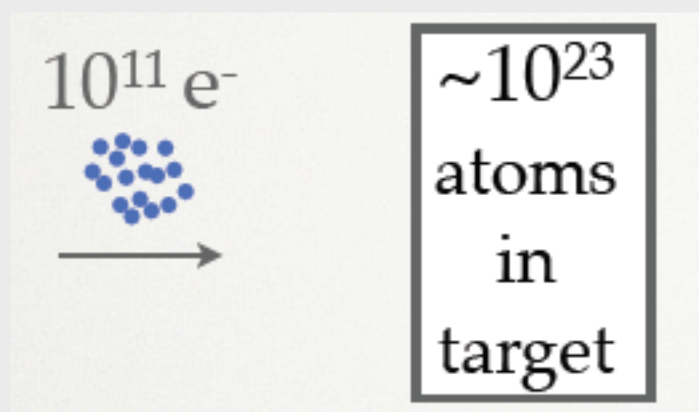
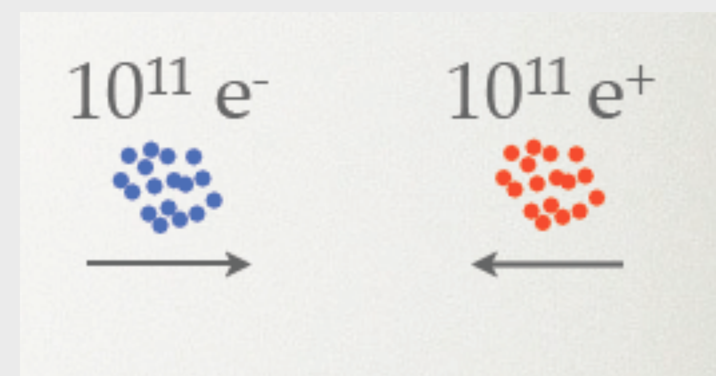
Invisible



- Depends on 4 parameters
- $m_{A'} > 2m_\chi$ (on-shell)
- $\alpha_D = g^2_\chi/4\pi >> \varepsilon^2\alpha_{EM}$



A’ production: fixed target vs. collider

	Fixed Target	e+e- colliders
Process		
Luminosity		
Cross-Section	$\sigma \sim \frac{\alpha^3 Z^2 \epsilon^2}{m^2} \sim O(10\ pb)$	$\sigma \sim \frac{\alpha^2 \epsilon^2}{E^2} \sim O(10\ fb)$

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

Fixed Target:
- high backgrounds
- limited A’ mass

e+e- colliders:
- low backgrounds
- higher A’ mass

Particle physics search of A’

Fixed target: e N →N γ’→ N Lepton⁻ Lepton⁺

→ **JLAB, MAINZ**

Fixed target: p N →N γ’→ p Lepton⁻ Lepton⁺

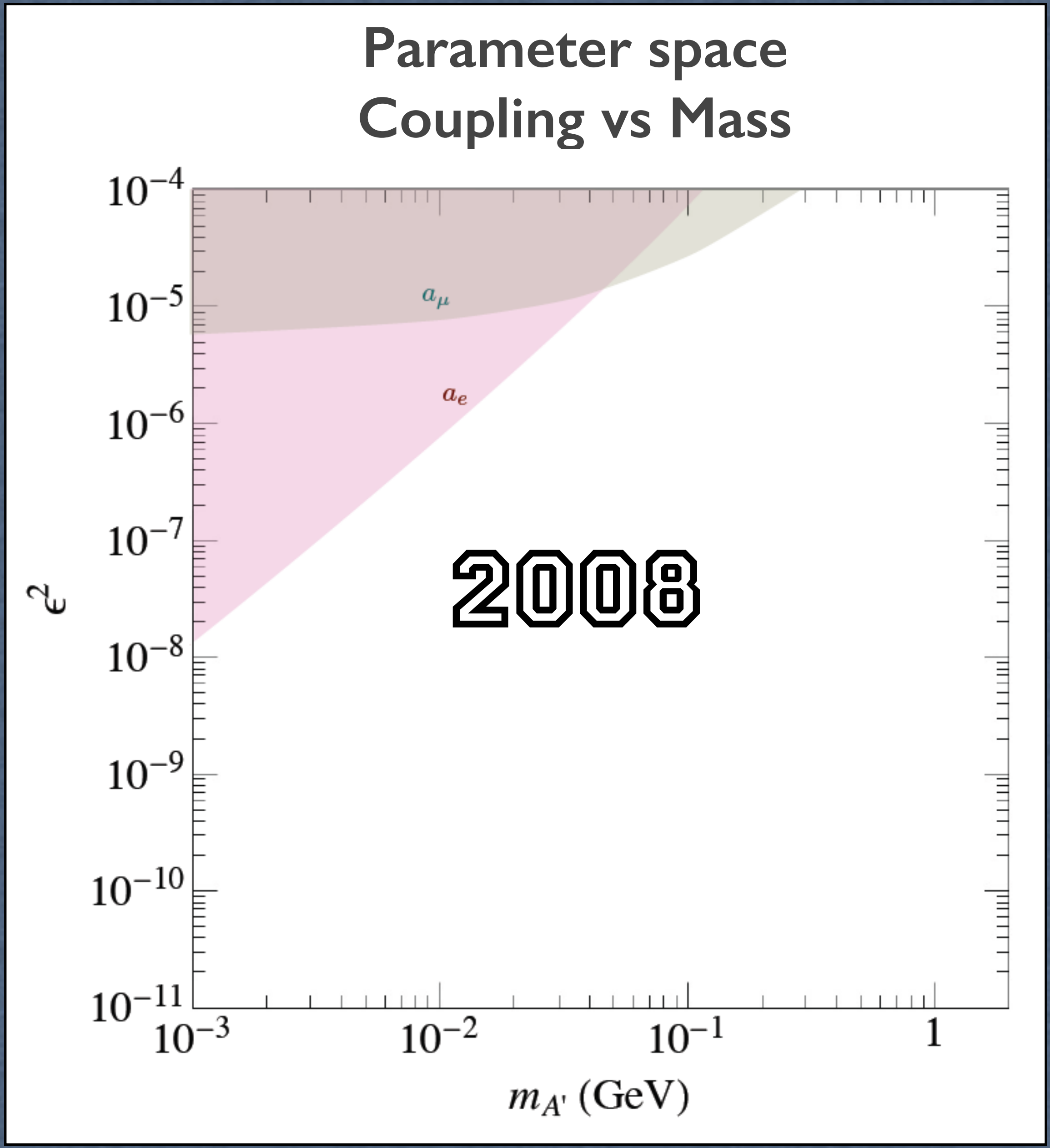
→ **FERMILAB, SERPUKHOV**

Annihilation: e+e- → γ’ γ → μμ γ

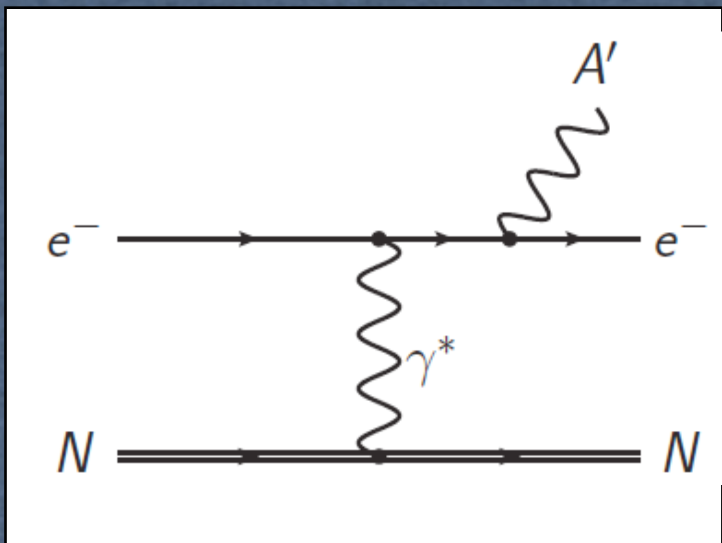
→ **BABAR,BELLE,KLOE**

Meson decays: π^0, η, η’, ω,’ → γ’ γ → Lepton⁻ Lepton⁺ γ

→ **KLOE, BES3, NA48, HC**

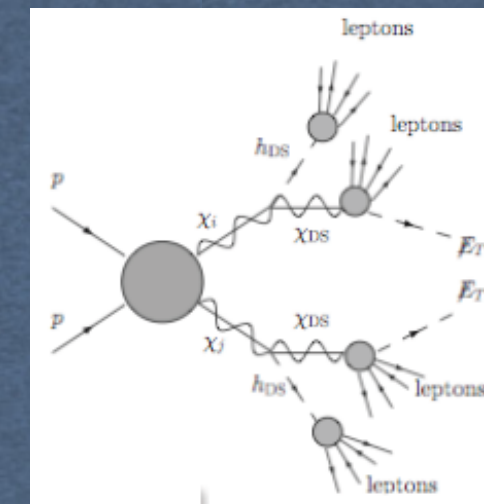


Particle physics search of A'/γ' (hidden photon)

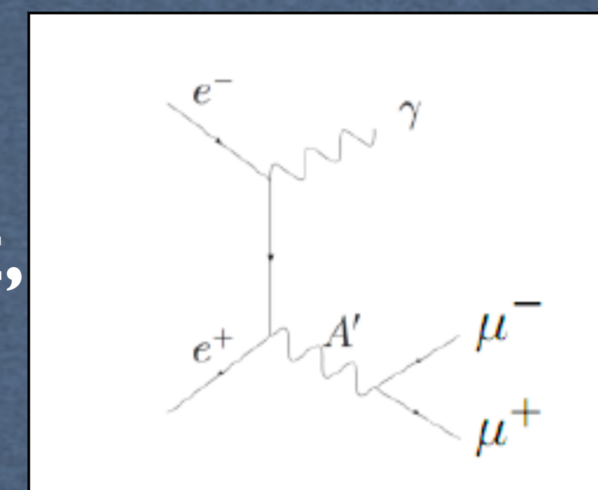


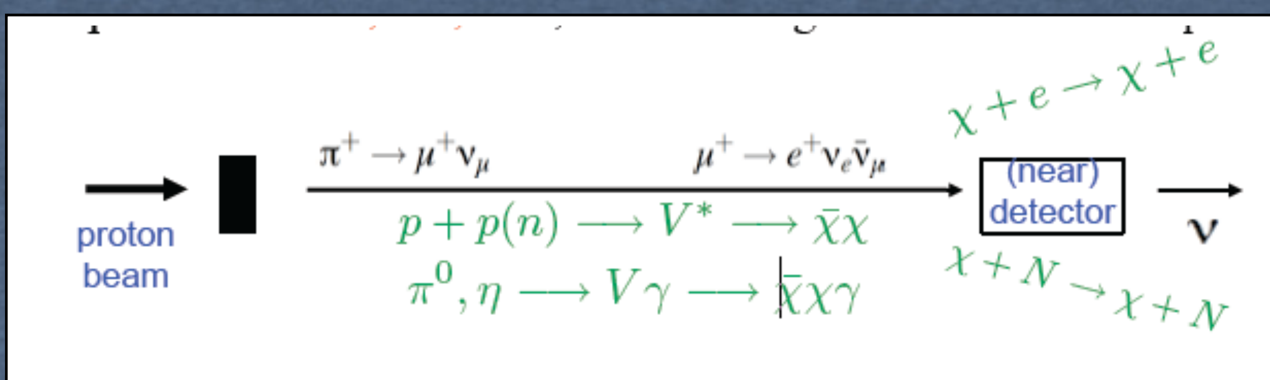
Fixed target:
e N →N γ'→ N Lepton Lepton+
→ **JLAB, MAINZ**

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



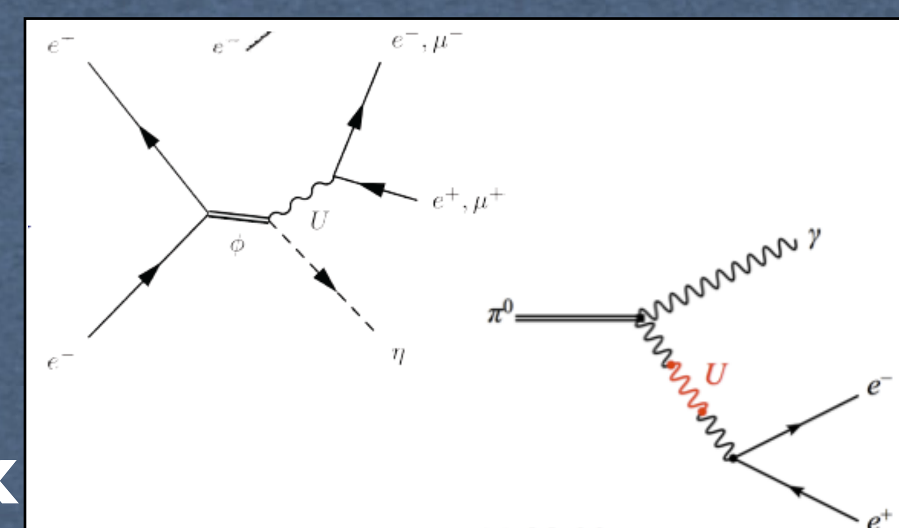
Annihilation:
e+e- → γ' γ → μμ γ
→ **BABAR, BELLE,**
KLOE, CLEO





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

Meson decays:
π⁰, η, η', ω,' → γ' γ (M)
→Lepton Lepton + γ (M)
→ **KLOE, BES3,**
WASA-COSY, PHENIX



Particle physics search of A’

Fixed target: $e\,N \rightarrow N\,\gamma' \rightarrow N$ Lepton$^-$ Lepton$^+$

→ **JLAB, MAINZ**

Fixed target: $p\,N \rightarrow N\,\gamma' \rightarrow p$ Lepton$^-$ Lepton$^+$

→ **FERMILAB, SERPUKHOV**

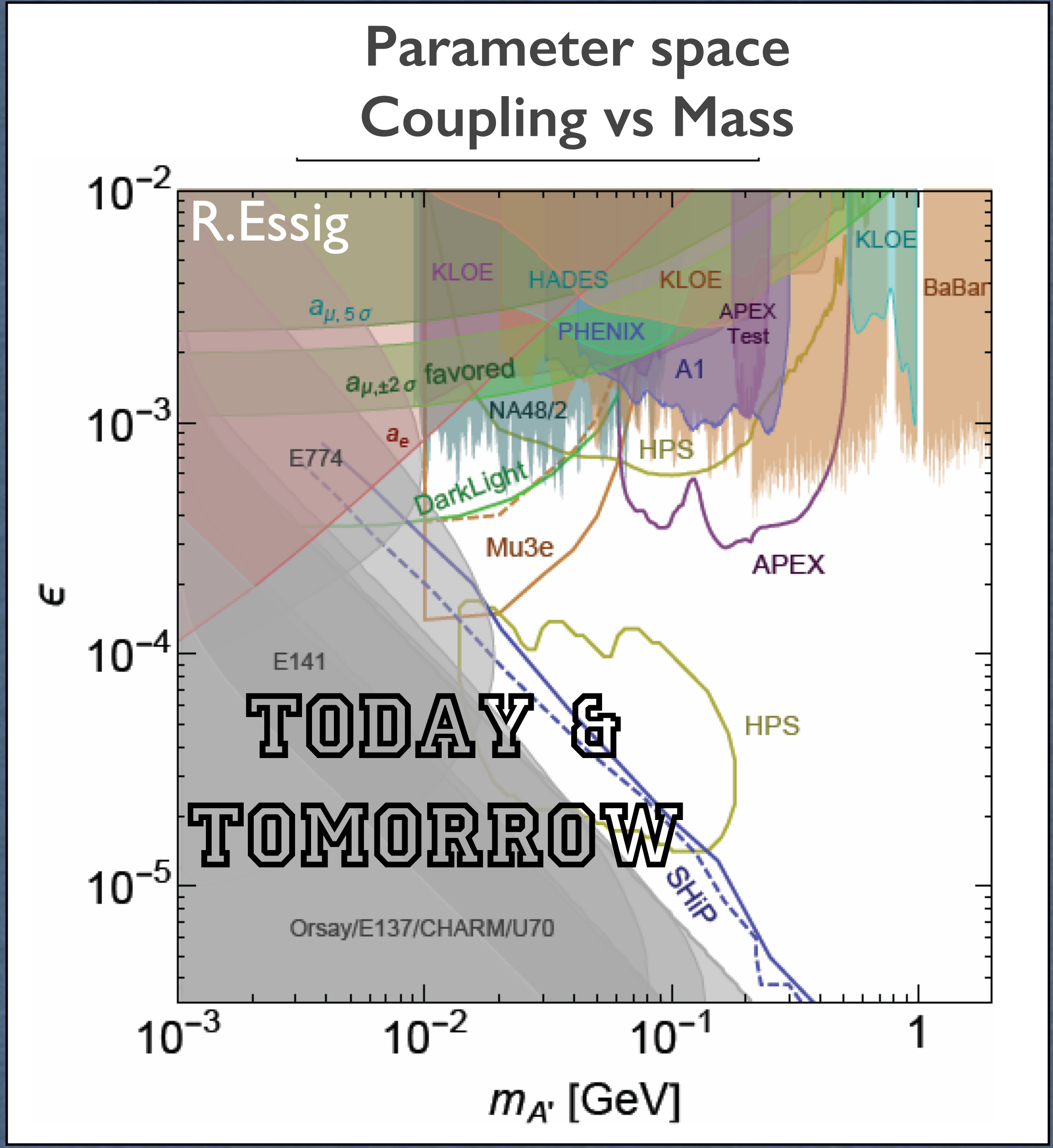
Annihilation: $e^+e^- \rightarrow \gamma'\,\gamma \rightarrow \mu\mu\,\gamma$

→ **BABAR,BELLE,KLOE**

Meson decays: $\pi^0, \eta, \eta', \omega' \rightarrow \gamma'\,\gamma \rightarrow$ Lepton$^-$ Lepton$^+$ γ

→ **KLOE, BES3, NA48, HC**

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



Particle physics search of A'
- invisible -

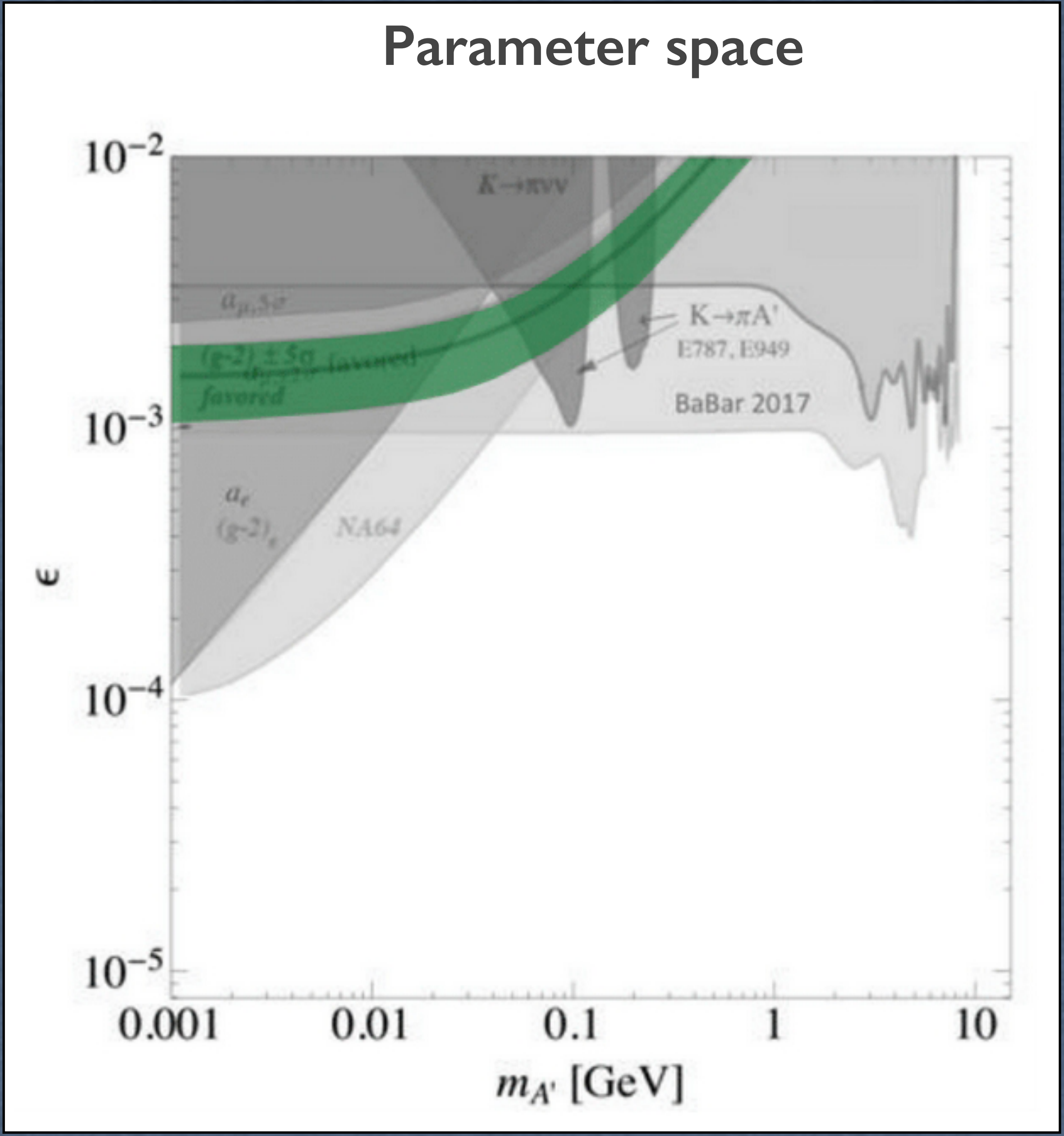
Fixed target: e N →N γ'→ N Lepton⁻ Lepton⁺
→ **JLAB, MAINZ**

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

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

Meson decays: π^0, η, η', ω,' → γ' γ → Lepton⁻ Lepton⁺ γ
→ **KLOE, BES3, NA48, HC**

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

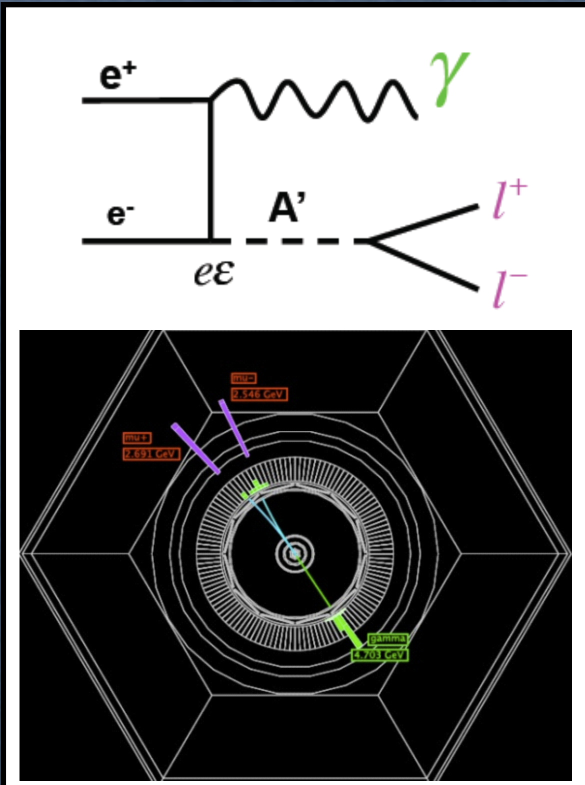


Positrons in light DM searches

Experiment	Lab	Production	Detection	Vertex	Mass(MeV)	Mass Res. (MeV)	Beam	Ebeam (GeV)	Ibeam or Lumi	Machine	1st Run	Next Run
APEX	JLab	e-brem	$\ell^+\ell^-$	no	$65-600$	0.5%	e^-	1.1–4.5	150 μA	CEBAF(A)	2010	2018
A1	Mainz	e-brem	e^+e^-	no	$40-300$	?	e^-	0.2–0.9	140 μA	MAMI	2011	–
HPS	JLab	e-brem	e^+e^-	yes	$20-200$	1–2	e^-	1–6	50–500 nA	CEBAF(B)	2015	2018
DarkLight	JLab	e-brem	e^+e^-	no	< 80	?	e^-	0.1	10 mA	LERF	2016	2018
MAGIX	Mainz	e-brem	e^+e^-	no	$10-60$	?	e^-	0.155	1 mA	MESA	2020	–
NA64	CERN	e-brem	e^+e^-	no	$1-50$	?	e^-	100	2×10^{11} EOT/yr	SPS	2017	2022
Super-HPS	SLAC	e-brem	vis	yes	< 500	?	e^-	$4-8$	1 μA	DASEL	?	?
(TBD)	Cornell	e-brem	e^+e^-	?	< 100	?	e^-	0.1-0.3	100 mA	CBETA	?	?
VEPP3	Budker	annih	invis	no	$5-22$	1	e^+	0.500	10^{33} cm^{-2}s^{-1}	VEPP3	2019	?
PADME	Frascati	annih	invis	no	$1-24$	$2-5$	e^+	0.550	$\lesssim 10^{14}\, e^+$OT/y	Linac	2018	?
MMAPS	Cornell	annih	invis	no	$20-78$	$1-6$	e^+	6.0	10^{34} cm^{-2}s^{-1}	Synchr	?	?
KLOE 2	Frascati	several	vis/invis	no	< 1.1 GeV	1.5	e^+e^-	0.51	2×10^{32} cm^{-2}s^{-1}	DAϕNE	2014	-
Belle II	KEK	several	vis/invis	no	$\lesssim 10$ GeV	$1-5$	e^+e^-	4×7	$1\sim10$ ab^{-1}/y	Super-KEKB	2018	-
SeaQuest	FNAL	several	$\mu^+\mu^-$	yes	$\lesssim 10$ GeV	$3-6$%	p	120	10^{18} POT/y	MI	2017	2020
SHIP	CERN	several	vis	yes	$\lesssim 10$ GeV	$1-2$	p	400	2×10^{20} POT/5y	SPS	2026	-
LHCb	CERN	several	$\ell^+\ell^-$	yes	$\lesssim 40$ GeV	~ 4	pp	6500	~ 10 fb^{-1}/y	LHC	2010	2015

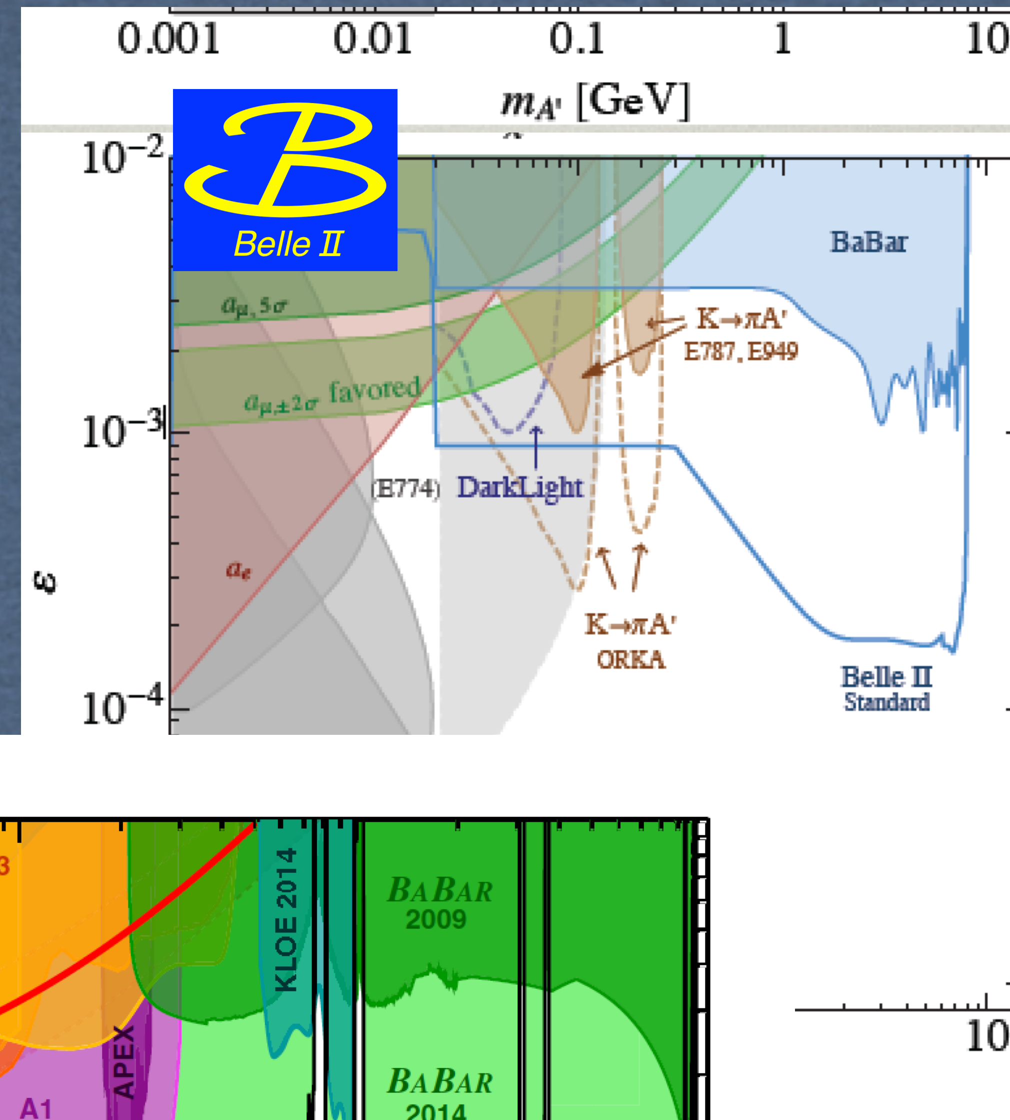
arXiv:1608.08632v1 [hep-ph] 30 Aug 2016

e+e- Colliders Recent & future results

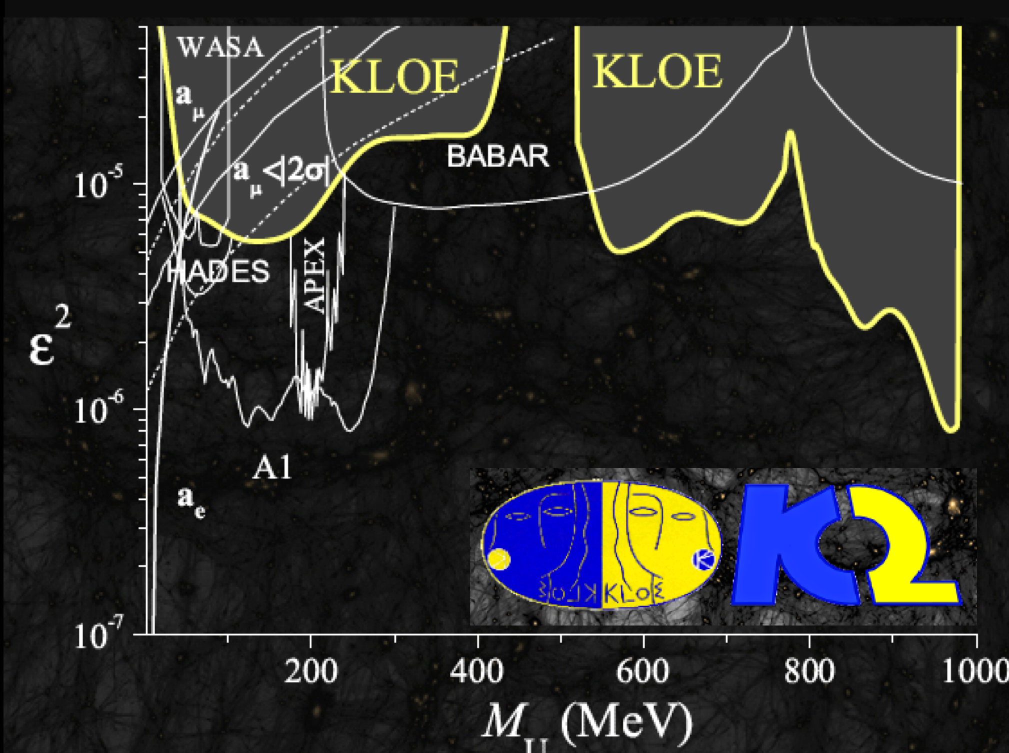


BABAR

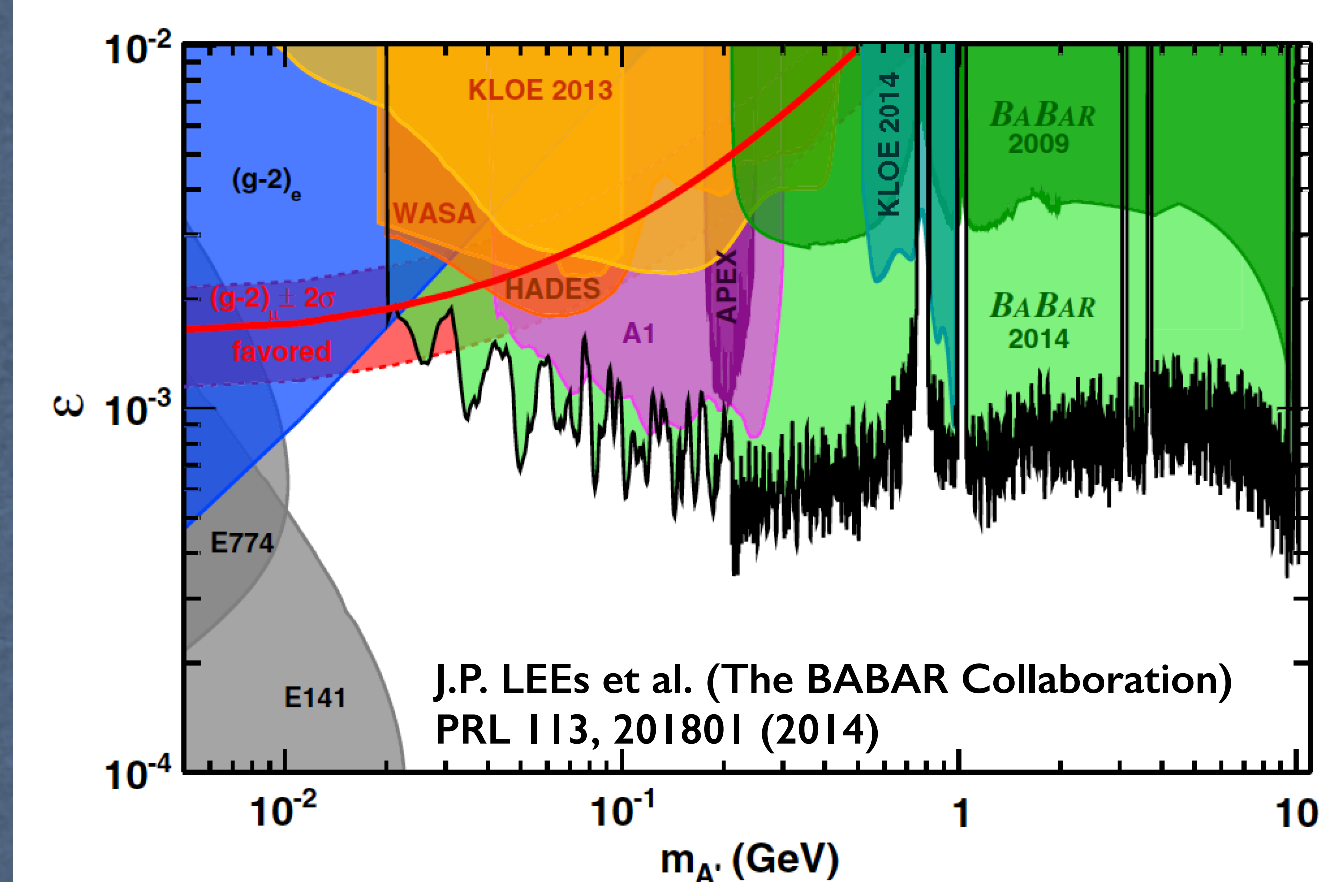
- 1gamma + 2 opposite leptons
- Di-lepton mass fit to a bg
- Mass resolution: 1.5 MeV - 8 MeV
- Int (L) = 514 fb^{-1}



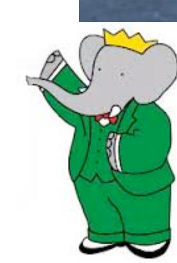
Phys. Lett. B 736 (2014) 459



- Events with μ+μ- detected
- L~ 240 pb^{-1}

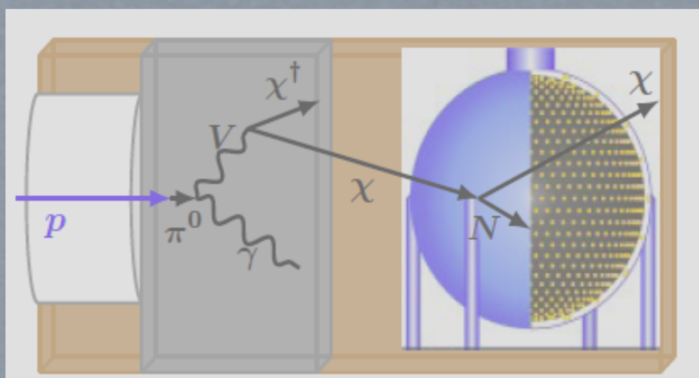


J.P. LEEs et al. (The BABAR Collaboration)
PRL 113, 201801 (2014)



New experimental results in 2017

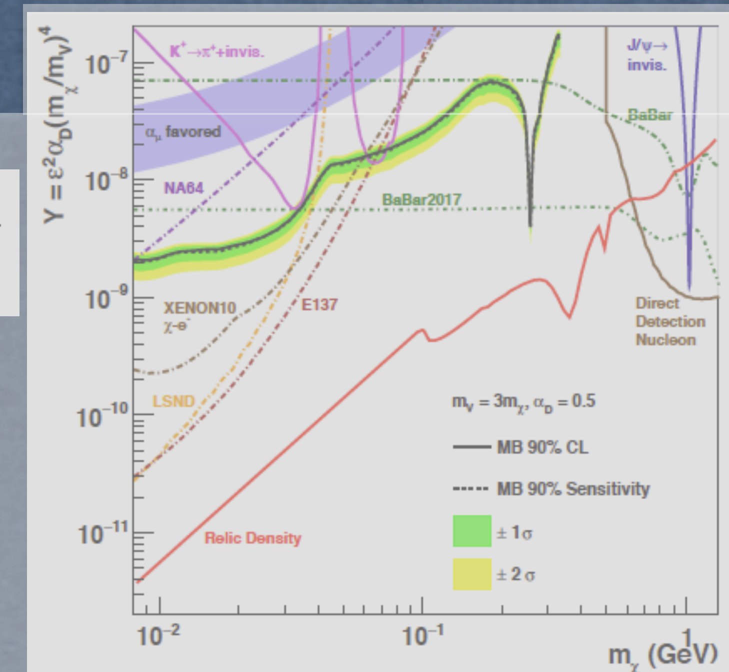
MiniBooNE@FERMILAB



PRL 118, 221803 (2017) PHYSICAL REVIEW LETTERS week ending 2 JUNE 2017

Dark Matter Search in a Proton Beam Dump with MiniBooNE

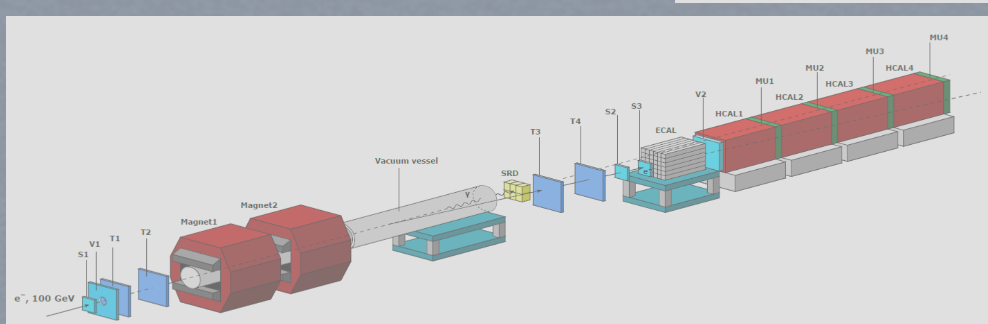
- BDX-like with an 8 GeV proton beam
- Cherenkov response of 12 m spherical detector with 800 tons mineral oil (CH2)
- Typical operation: 2×10^{20} protons on target (POT) per year



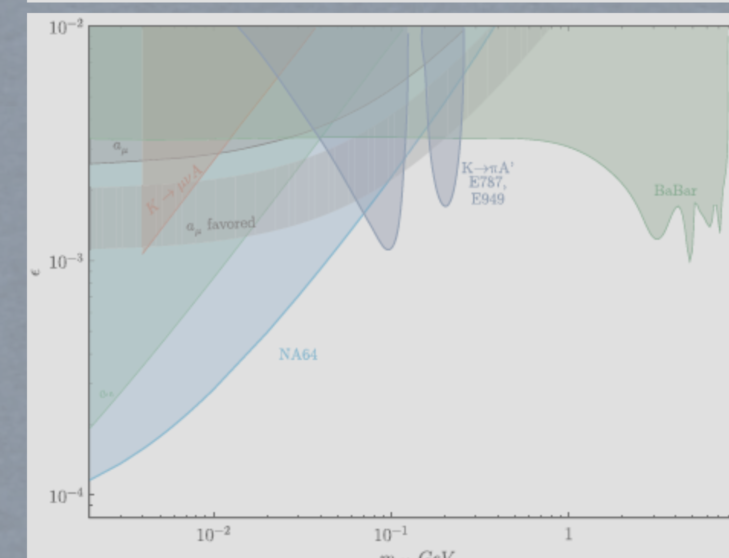
NA64@CERN

PRL 118, 011802 (2017) PHYSICAL REVIEW LETTERS week ending 6 JANUARY 2017

Search for Invisible Decays of Sub-GeV Dark Photons in Missing-Energy Events at the CERN SPS



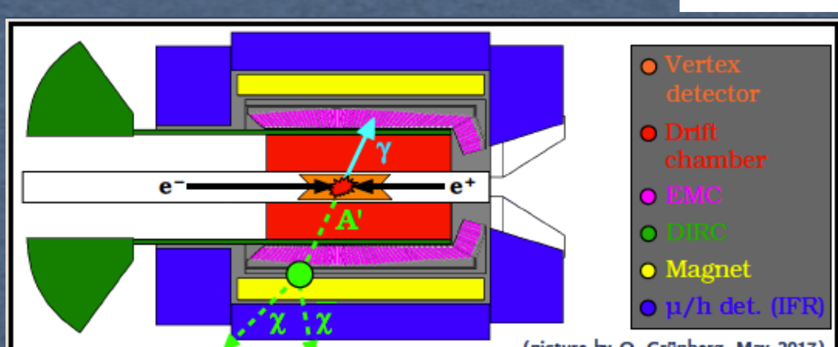
- Missing energy exp (e Z → e Z' A' with A' → invisible)
- 100 GeV SPS electron beam at SPS
- Active target (calorimeter)
- Exclusion plots based on 3×10^9 EOT



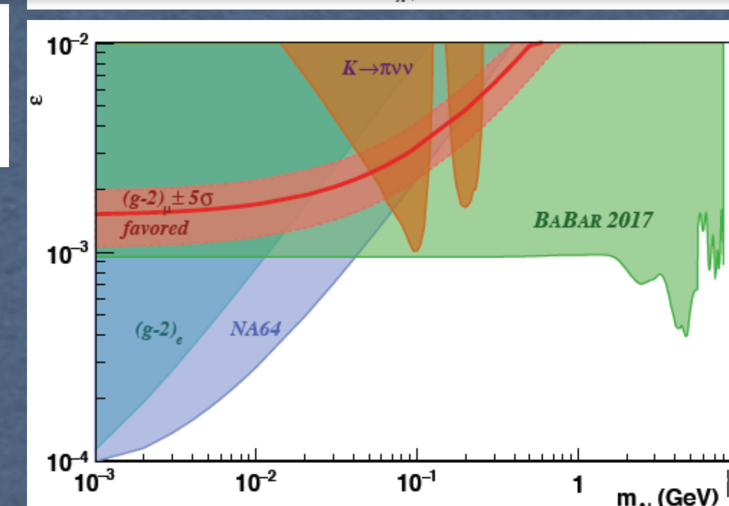
BaBar@SLAC

BABAR-PUB-17/001
SLAC-PUB-16923
arXiv:1702.03327v1 [hep-ex] 10 Feb 2017

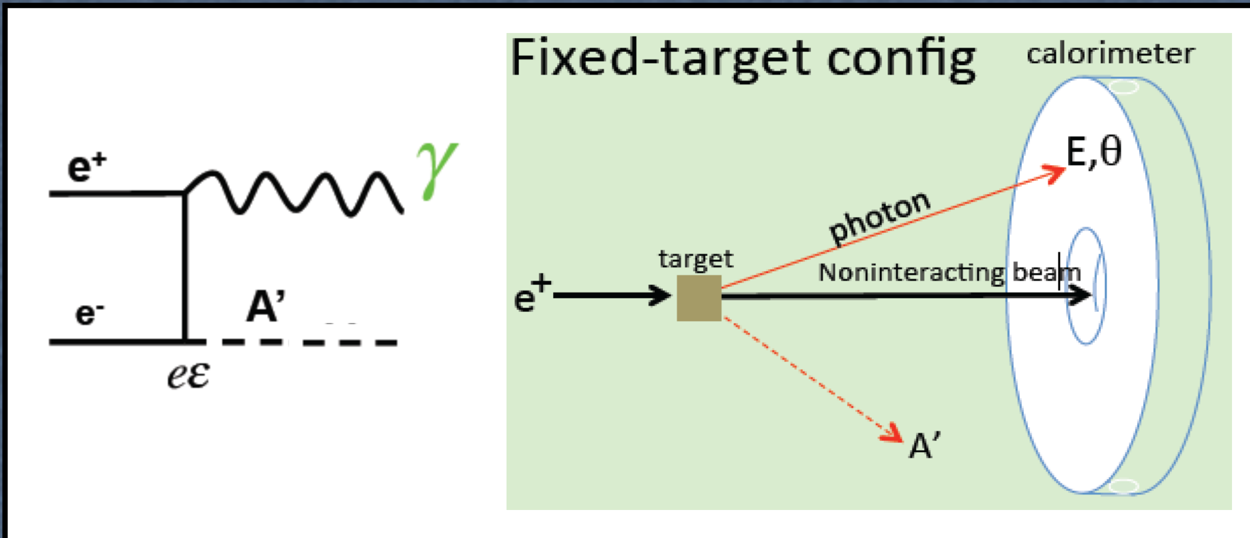
Search for invisible decays of a dark photon produced in e^+e^- collisions at BABAR



- Missing mass exp (e- e+ → γ A' with A' → invisible)
- Mono-photon trigger
- Exclusion plots based on ~50 fb⁻¹

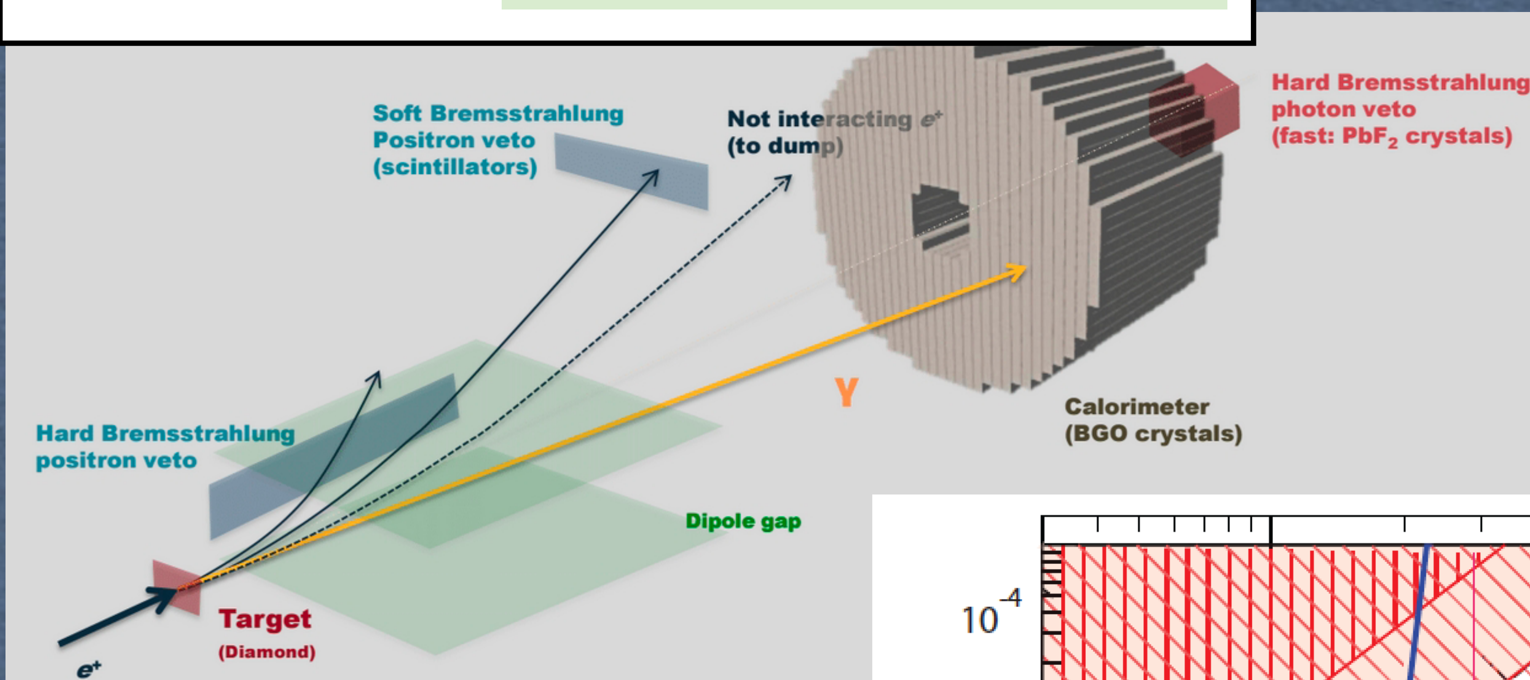


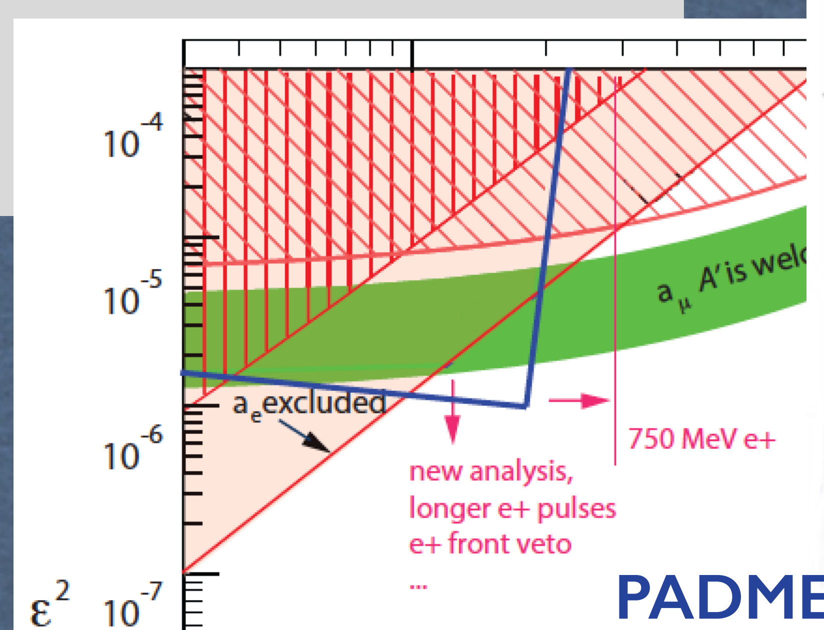
e^+ annihilation on fixed (thin) target

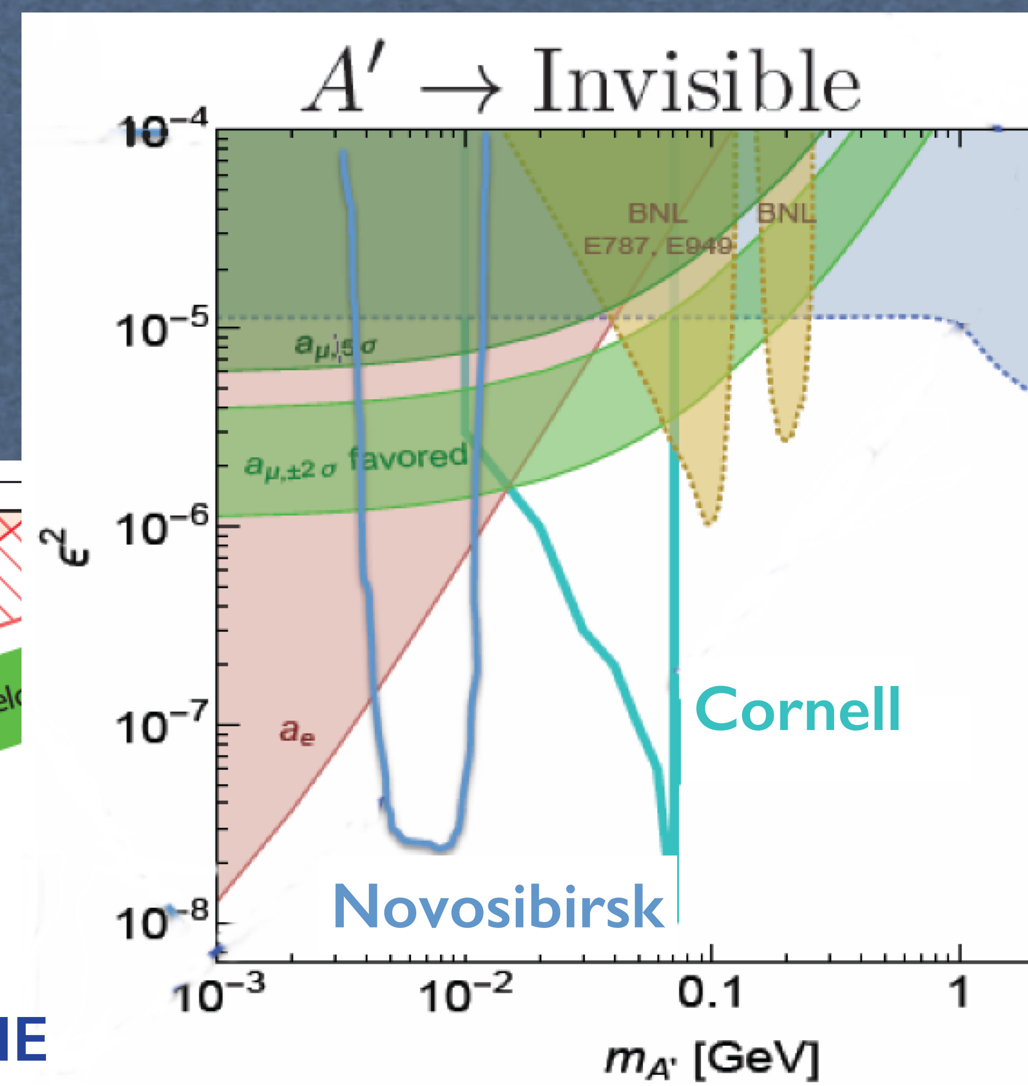


Missing mass search:
- Independent of A' decay mechanism
- Bump hunt (monophoton@collider)
- Need a positron beam
- Limited $M_{A'}$ accessible
  - 1 GeV beam: MA' < 31 MeV
  - 5 GeV beam: MA' < 71 MeV

- **Novosibirsk**
- **LNF**
- **Cornell**







VEPP3
- E_{e+} = 500 MeV
- EOT ~ 10^{15} - 10^{16} year^{-1}

LNF
- E_{e+} = 550 MeV
- EOT ~ 10^{13} - 10^{14} year^{-1}

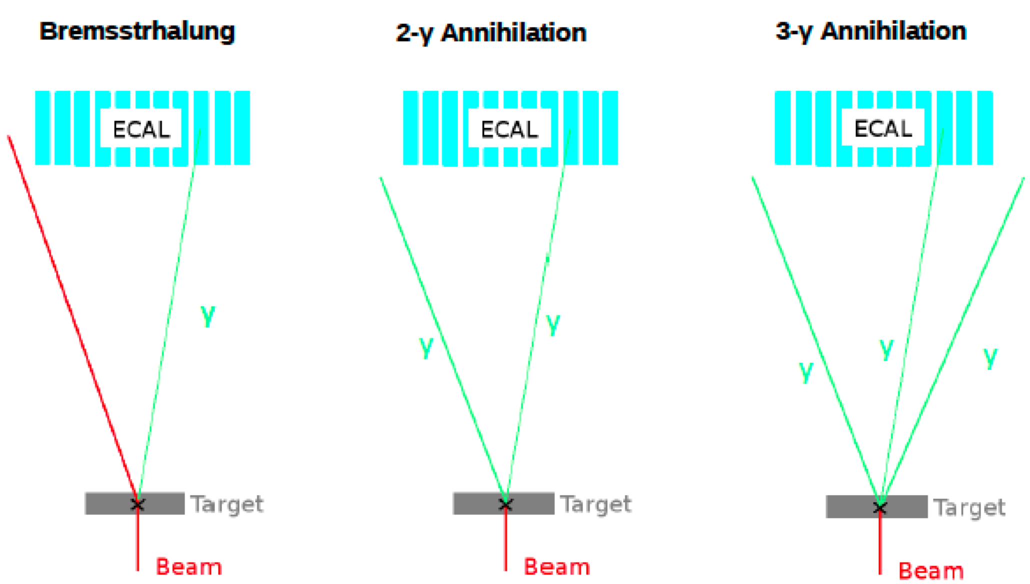
Cornell
- E_{e-} = 5.3 GeV
- EOT ~ 10^{17} - 10^{18} year^{-1}

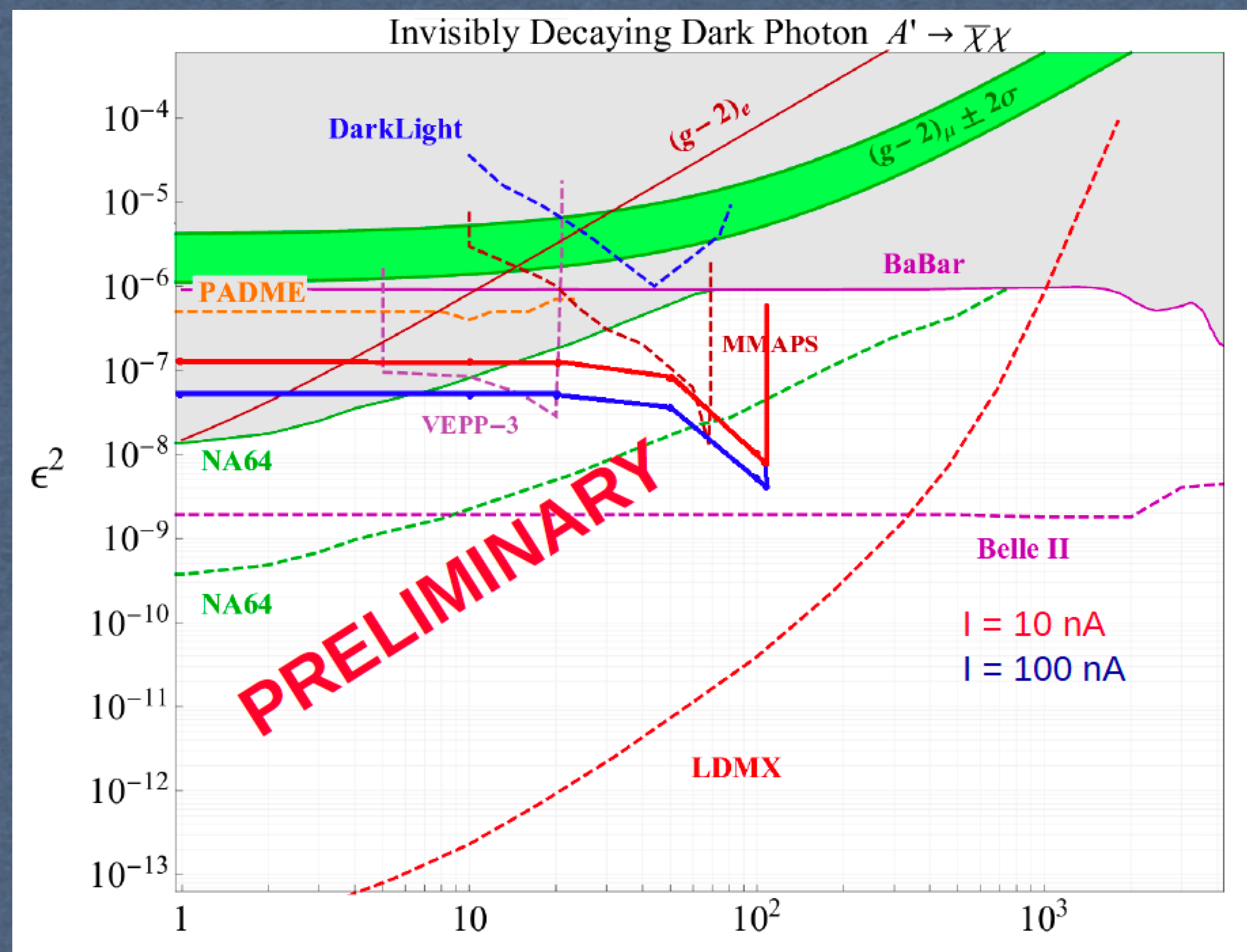
e^+ annihilation on fixed (thin) target

- Main limitation: limited energy in the CM ~ sqrt(E_{beam})
- High energy positron beams are not (yet) available
- The highest energy at JLab (~11 GeV) Max $m_{A'}$ ~ 106 MeV

Main Background Processes

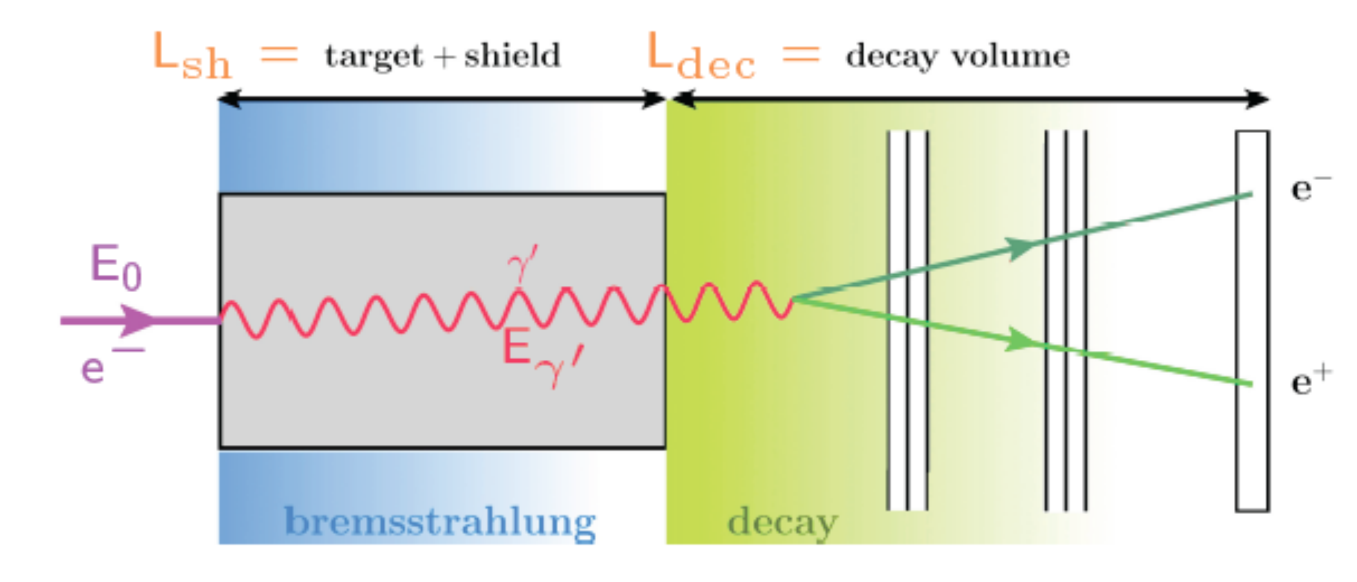
Main processes that result in a single gamma hitting the ECal:

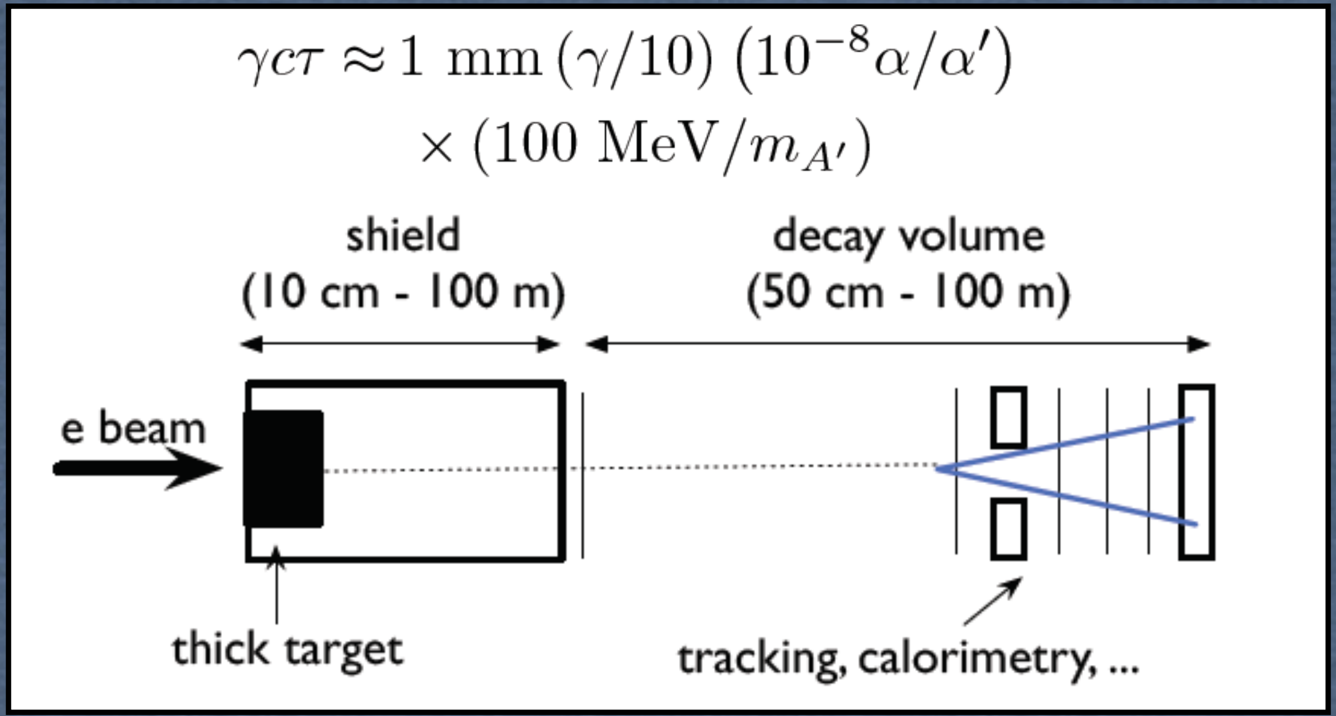


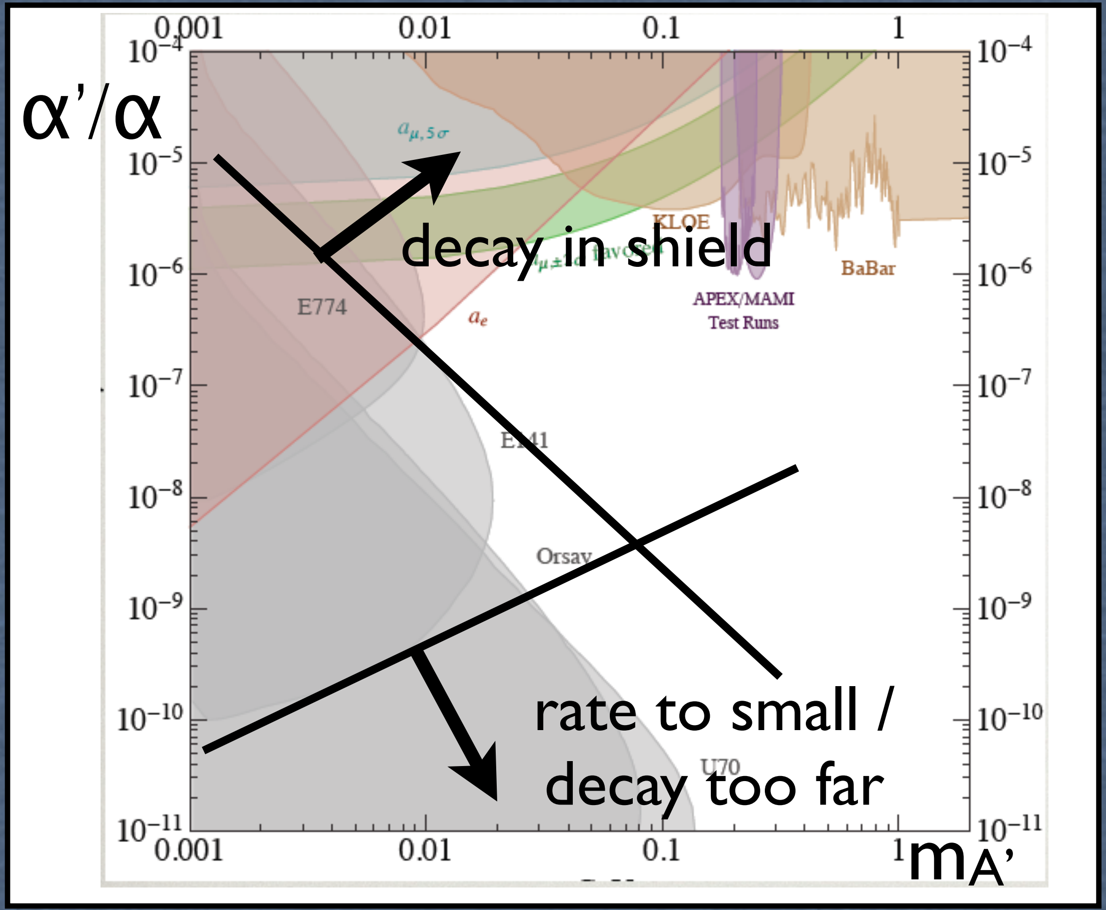


Beam-dump experiments - visible -

- 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





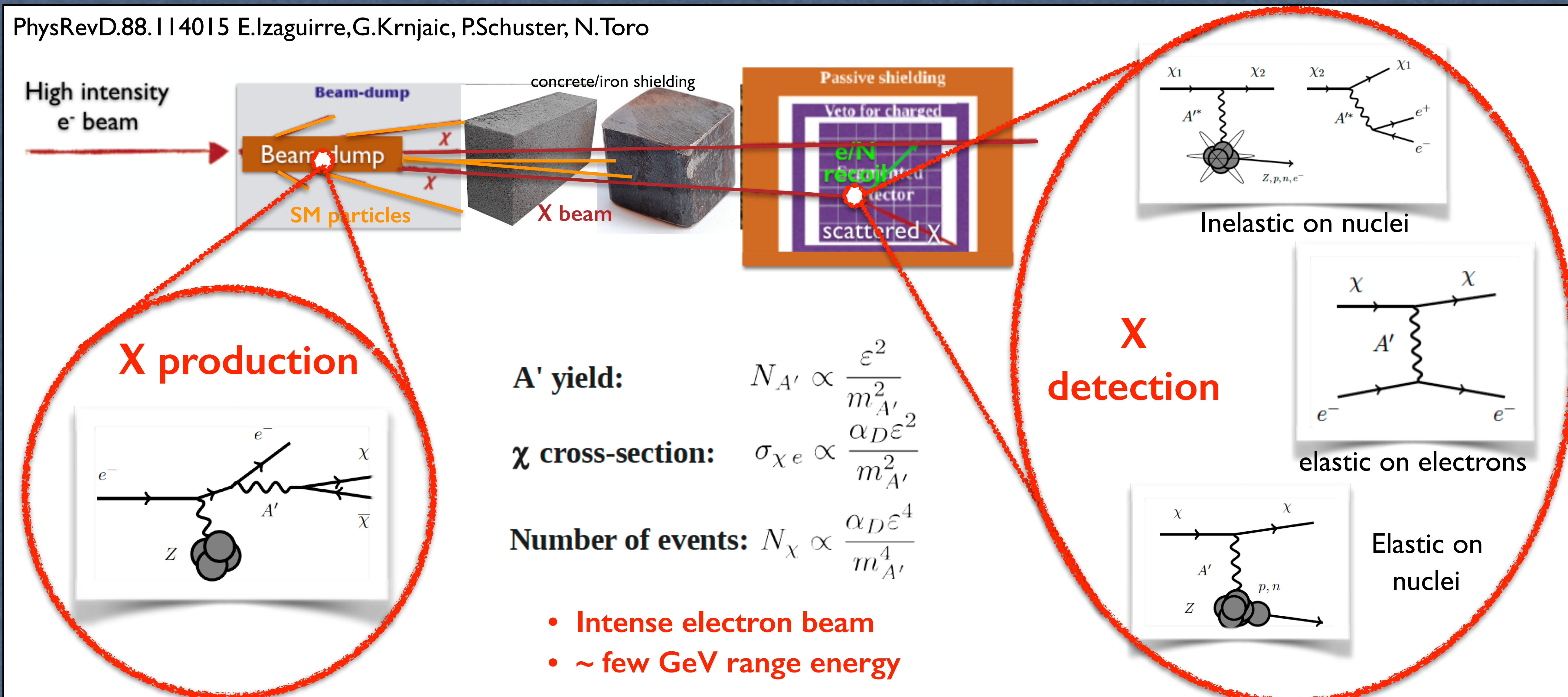


Beam-dump experiments - invisible -

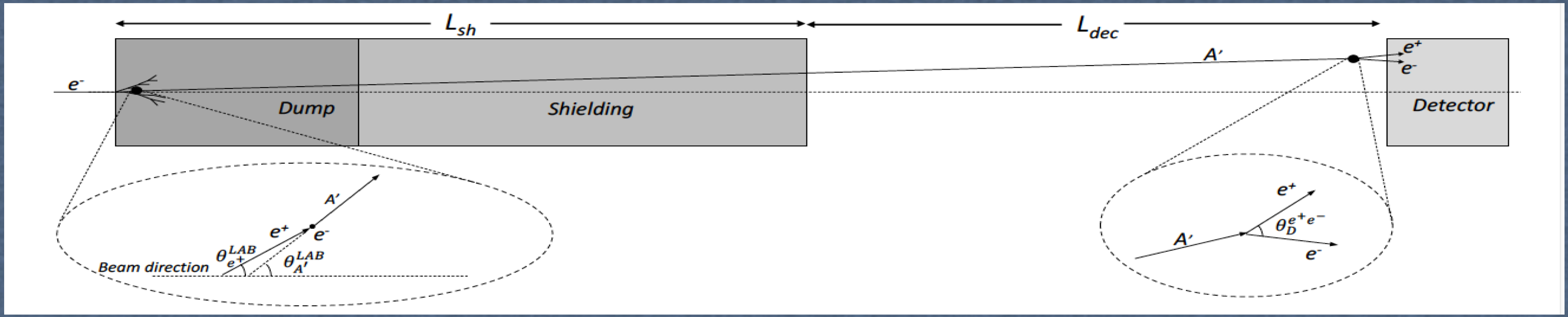
Two step process

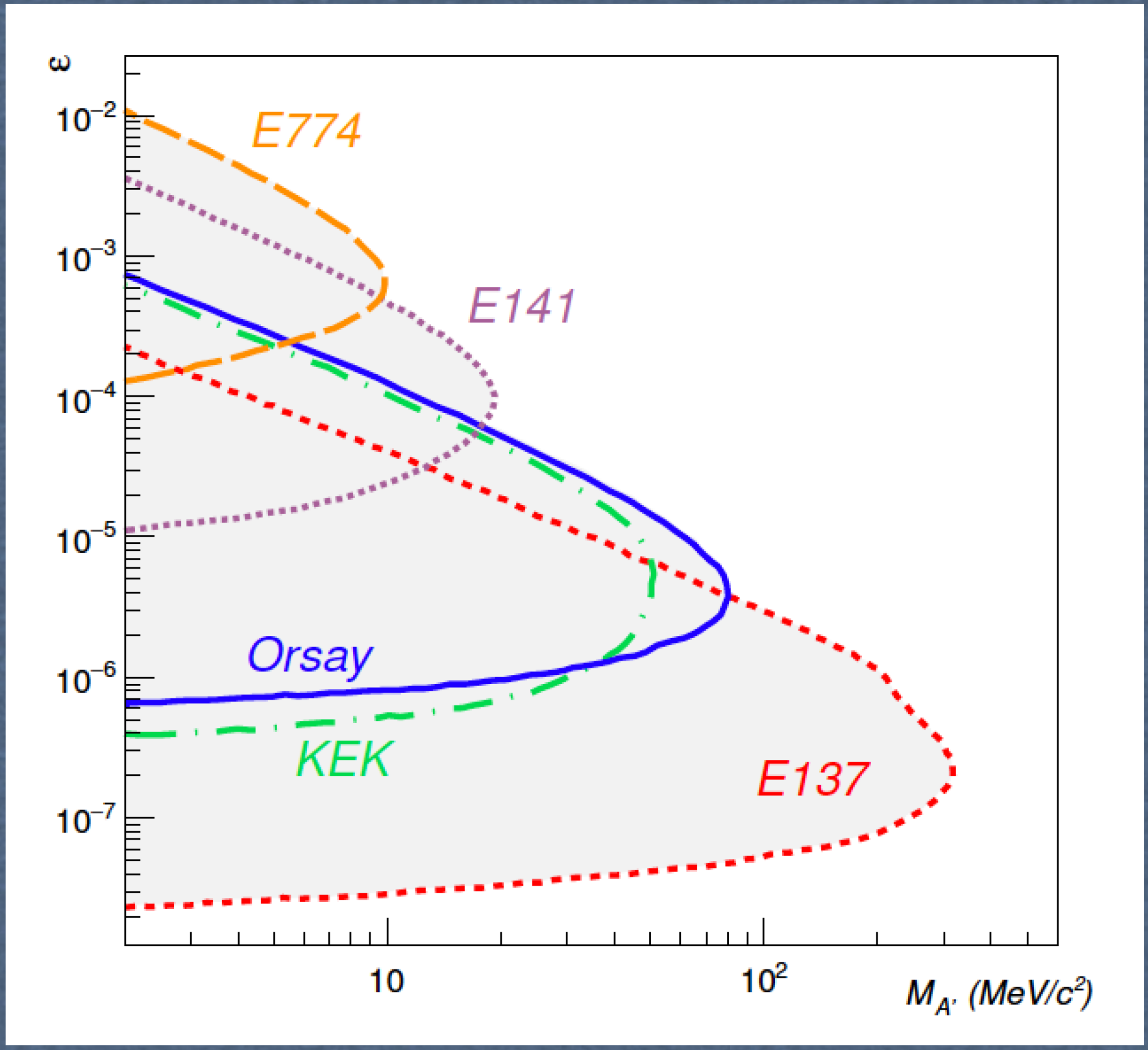
I) An electron radiates an A' and the A' promptly decays to a χ (DM) pair

II) The χ (in-)elastically scatters on a e⁻/nucleon in the detector producing a visible recoil (GeV)



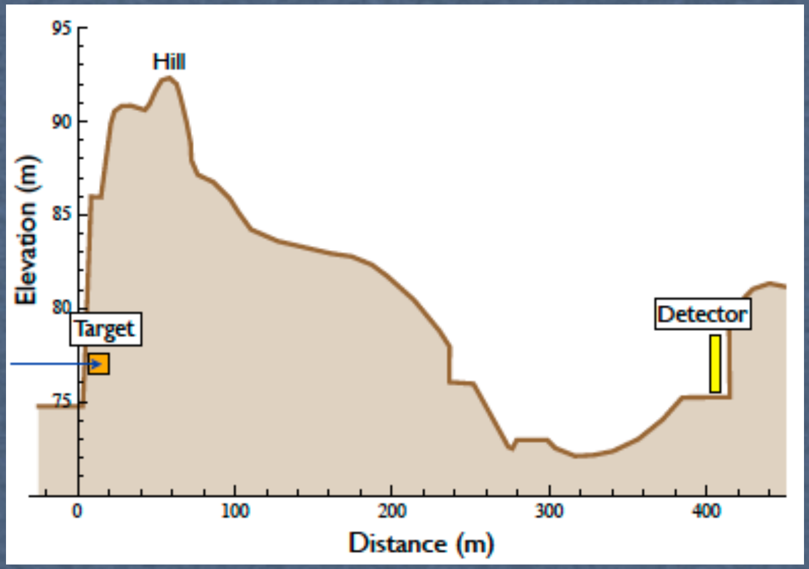
Exclusion limits (BD - visible)





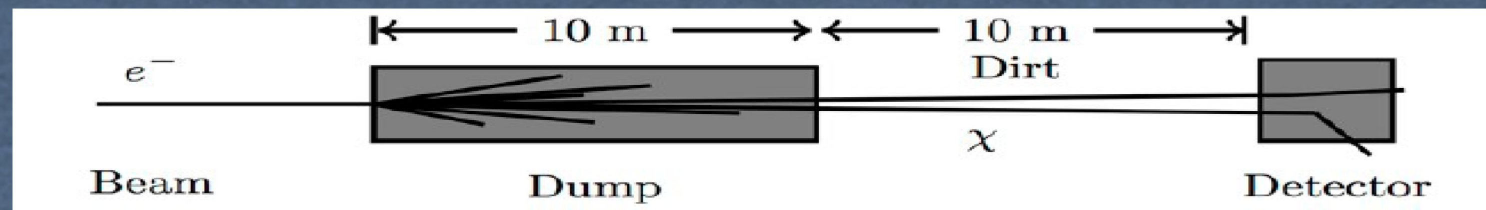
Best exclusion limit from E137

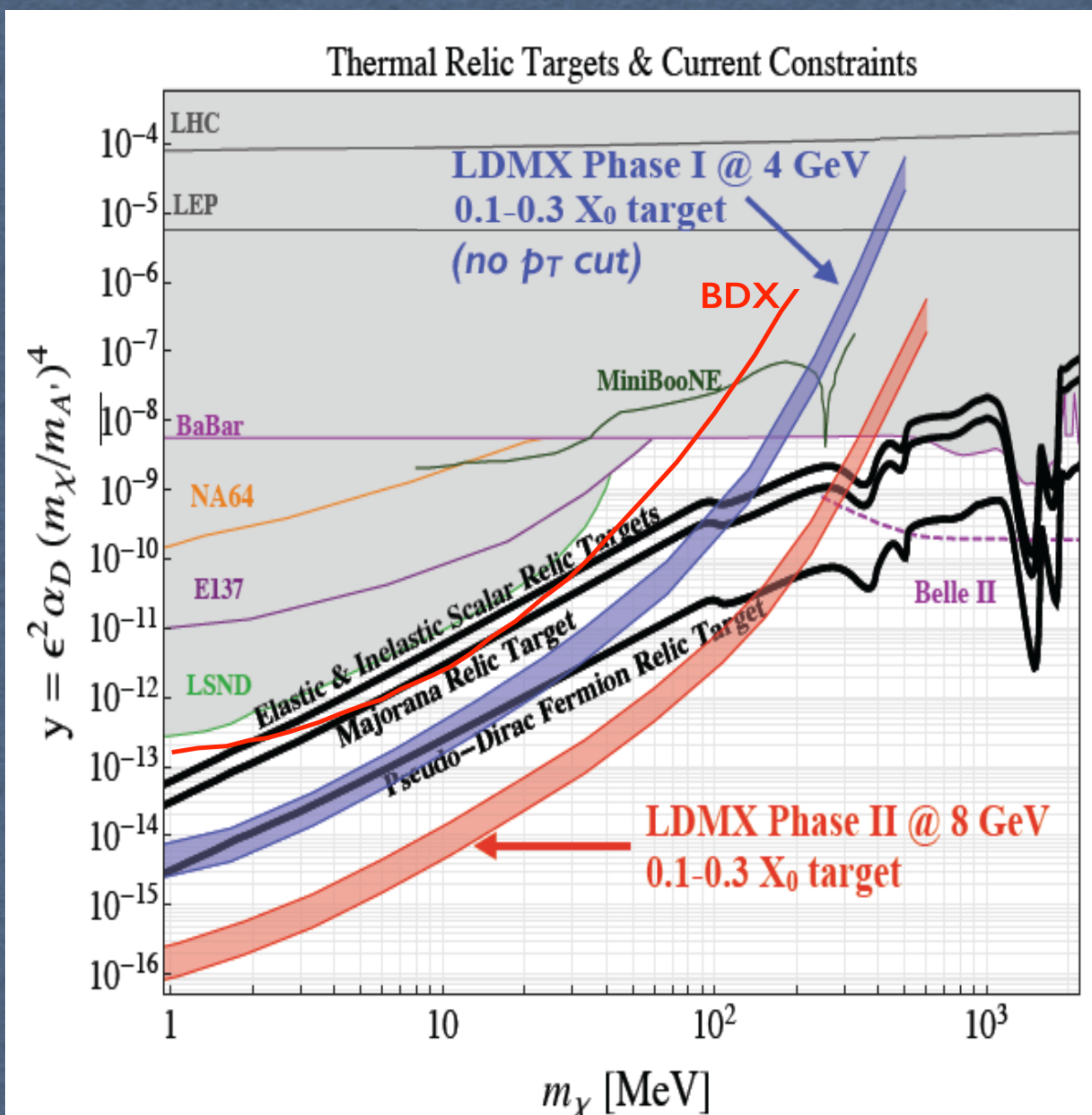
- SLAC electron beam: 20 GeV, 2x10^{20} EOT
- Detector: 8 r.l. em calorimeter (hodo + cvrt + MWPC)
- Size: 1.5m x1.0 m at ~380m from the BD
- Cosmic bg suppressed by directionality and time coincidence



- Detection Thr (X-e scattering only): 1-2 GeV
- 0 EVENTS DETECTED

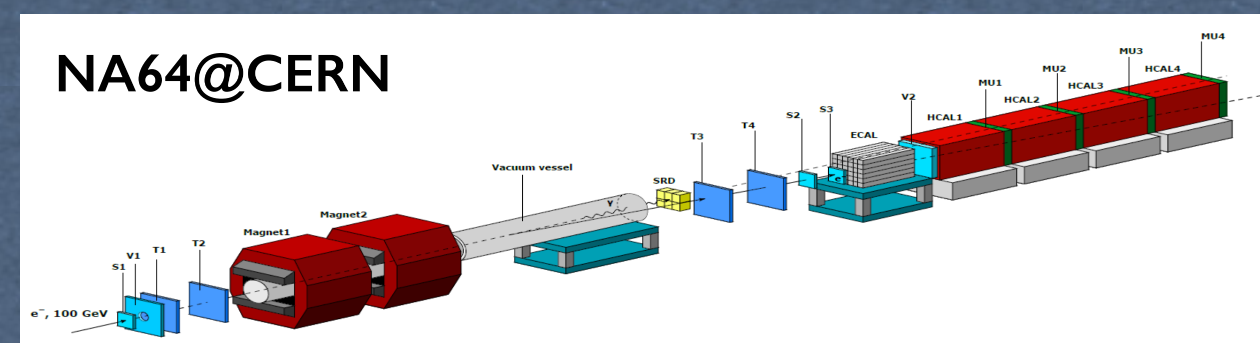
Exclusion limits (BD - invisible)





Present …

- E137 and NA64: null results interpreted as invisible decay search
- No showering effects included



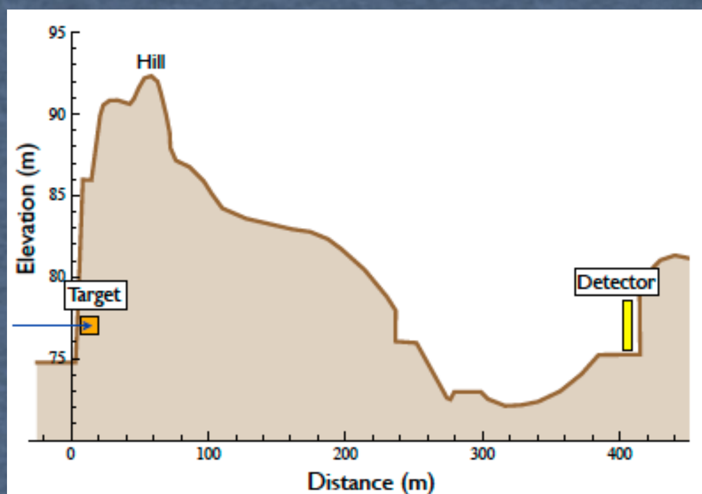
- *Active* beam-dump experiment
- Missing energy exp (e Z → e Z' A' with A' → invisible)
- 100 GeV SPS electron beam at SPS
- Active target (calorimeter)
- Exclusion plots based on 3×10^9 EOT

… and future BD experiments

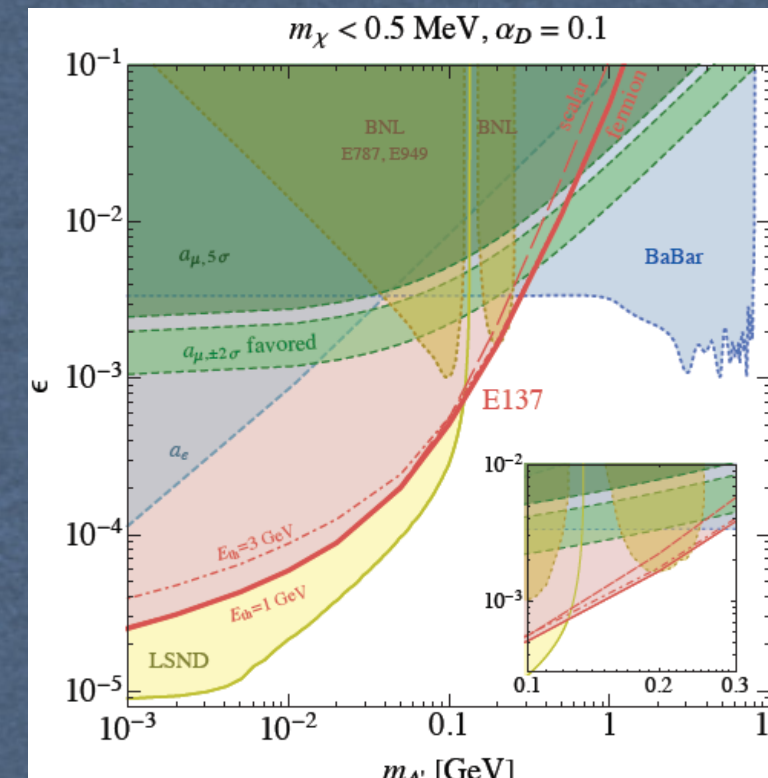
- LDMX: missing momentum exp proposed at SLAC-LCLS-II 4 GeV e- beam, (*Active* beam-dump)
- BDX: beam-dump exp proposed at JLAB 11 GeV e- beam with 10^{22} EOT in 1y run

A critical review of upper limits derived from old experiments

E137@SLAC (<1988)

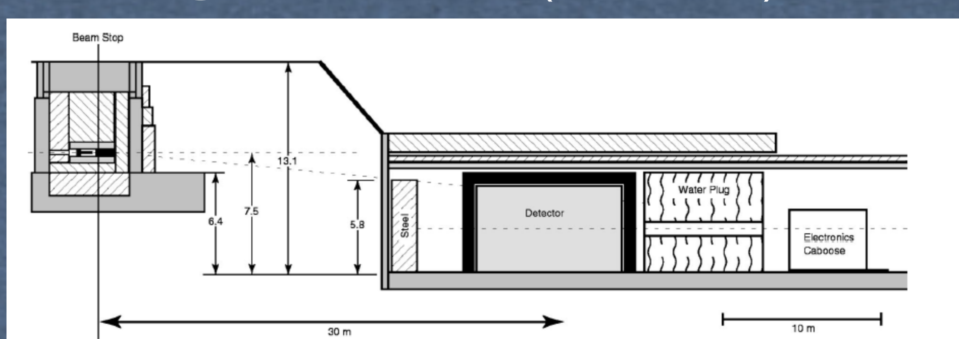


- SLAC electron beam: 20 GeV 2×10^{20} EOT
- Detector: 8 r.l. em calorimeter (hodo + converter + MWPC)
- Size: 1.5m x1.0 m at ~380m from the BD
- Cosmic bg suppressed by directionality and time coincidence
- Detection Threshold: 1-2 GeV
- 0 events detected

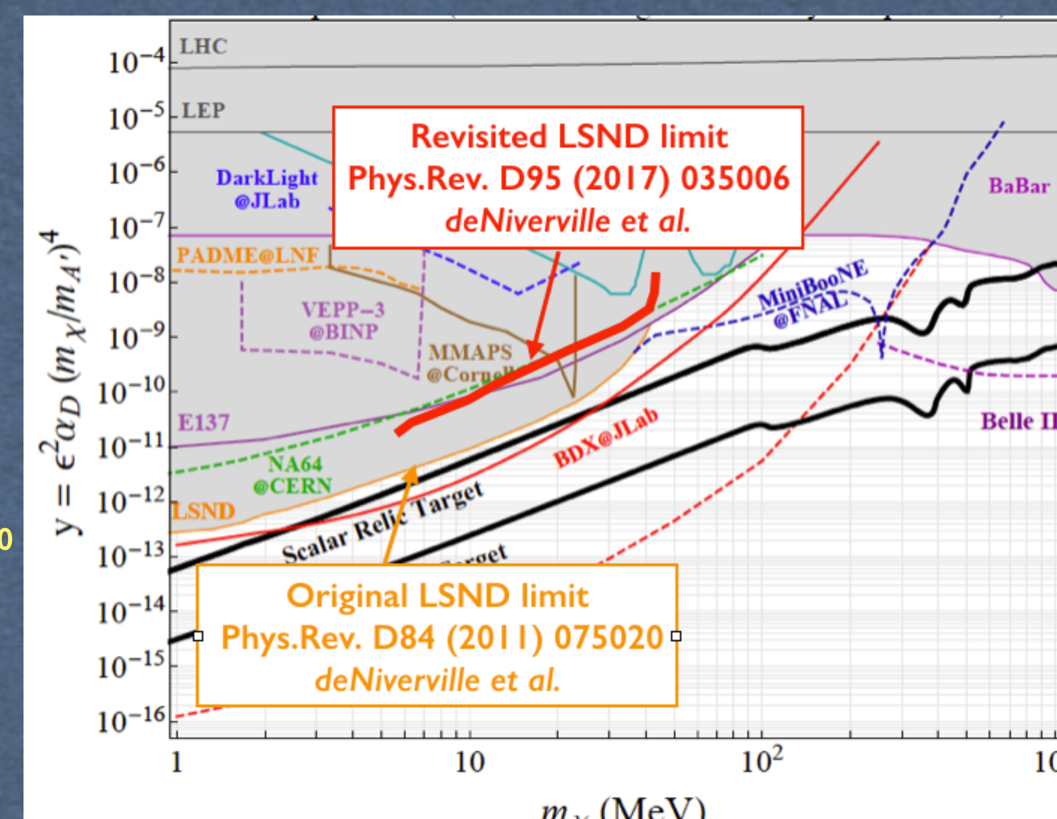


- Extracted upper limits suffer by poor knowledge of experimental details
- No e$^-$ showering in the BD included: softer DM E spectrum and defocused DM beam
- Limits are overestimated by a factor ~3-4 (depending on the kinematics)

LSND@LosAlamos (1994/98)



- 800 MeV protons to LANSCE beam dump
- From $\pi^0 \rightarrow A' \gamma$ decay (and $A' \rightarrow X X$)



- Upper limits extracted in 2011 using a wrong π^+ spectrum to normalise π^0
- Recently recalculated, fund to be overestimated by a factor ~4-5

BDX is the first beam-dump experiment optimised for LDM searches

Conclusions

✳ Accelerator-based (Light)DM search provides unique feature to distinguish DM signal from any other cosmic anomalies or effects

✳ Extensive experimental plans at high intensity e-facility: JLab, LNF, Cornell, Mainz, SLAC (+ p beam at FNAL and CERN)

✳ Results were already obtained in the visible decay sector

✳ A new generation of fixed target experiments using intense lepton (electron) beams has been proposed for the near future

✳ Electron-positron annihilation has been considered in collider experiment

✳ A significant reach is possible in e+ annihilation on thin target too

✳ Due to the intrinsic kinematics high energy beams are needed

✳ New high intensity positrons beam will open a new window in LDM searches