EuNPC

2015 European Nuclear Physics Conference

European Physical Society

university of groningen

kvi - center for advanced radiation technology

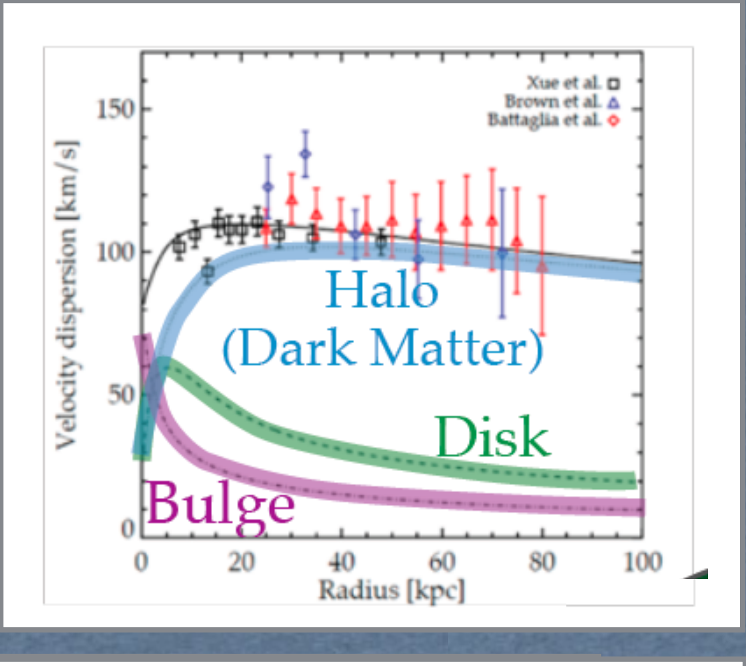
Groningen | 31 August - 4 September 2015 | www.EuNCP2015.org

Light Dark Matter search at accelerators

M.Battaglieri
INFN-GE Italy

Dark matter proofs

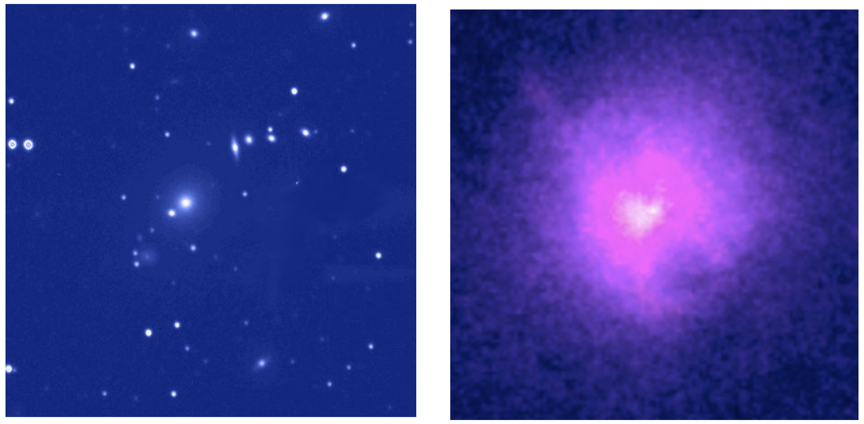
★ Galaxies rotation curve shows constant velocity despite *visible* mass is concentred at the center



Big portion of *invisible* mass in the outer regions (halo)

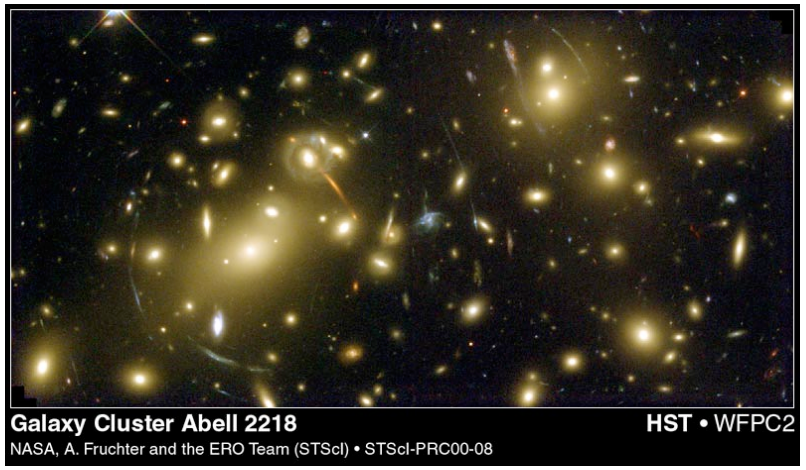
★ The mass of galaxy clusters can be estimated in different ways:

- **X-Ray emission**: hydrostatic equilibrium links pressure, Temperature, Density (mass)

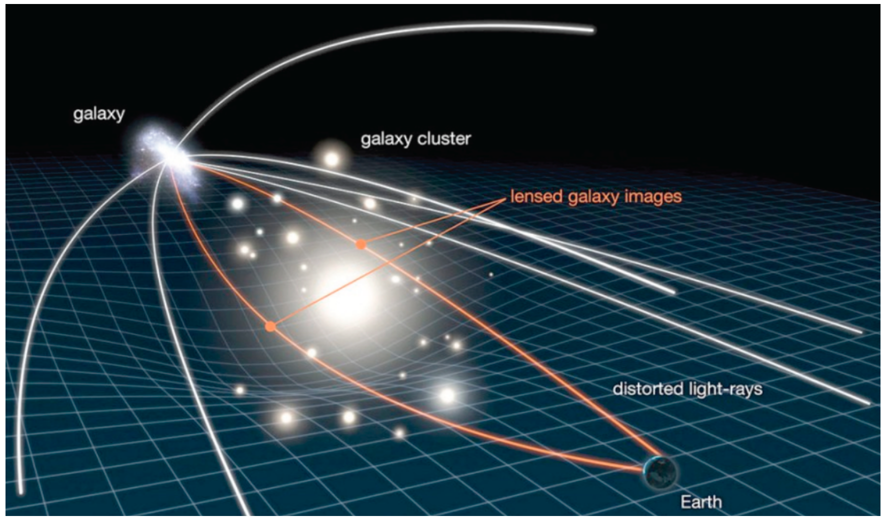


Hydra A galaxy cluster. Chandra X-ray observations reveal a large cloud of hot gas that extends throughout the cluster

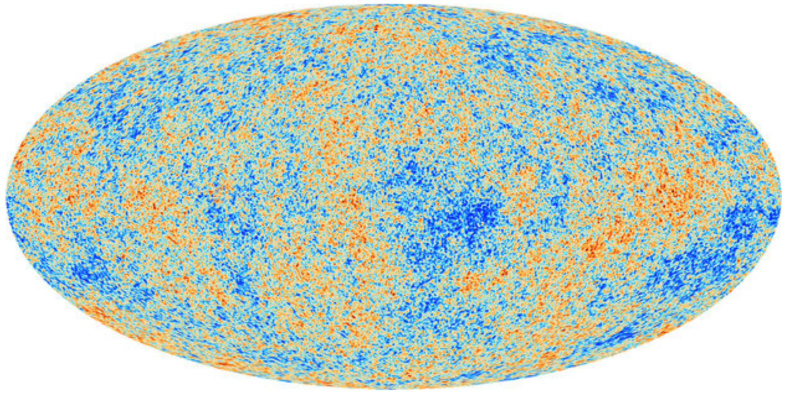
Mass balance
Total mass 10^{14} - 10^{15} $M_\odot$
Gas fraction ~16% (~ 13% ICM, ~ 3% galaxies).
Remaining 84% of the mass is in dark matter



- **Gravitational lensing**: a mass in between the source and the observer distorts the light propagation acting as a lens



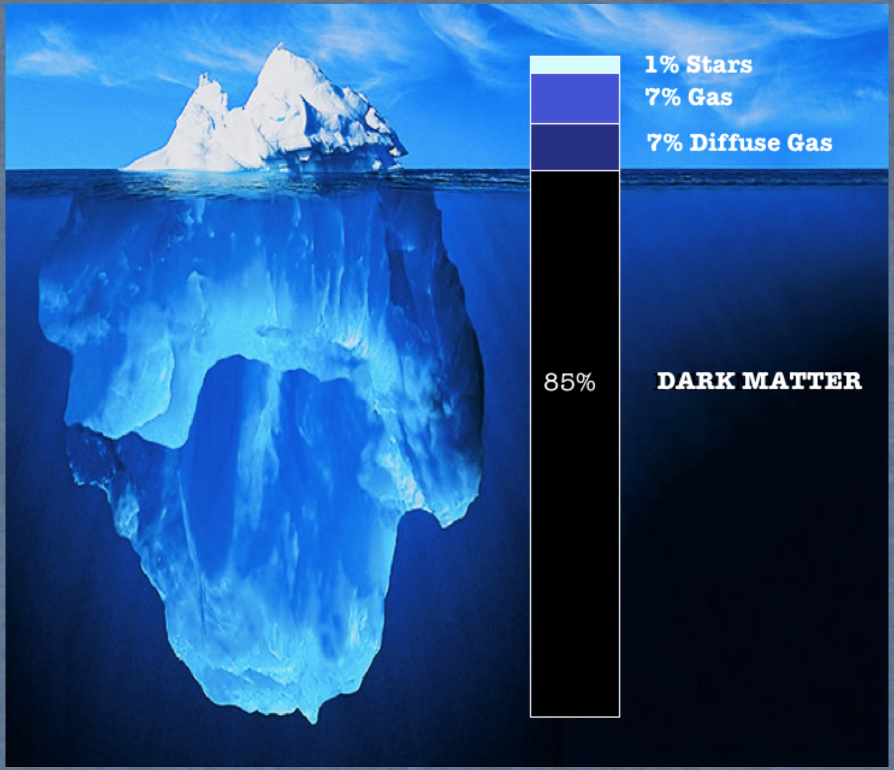
★ DM in CMB
★ Clusters of galaxies
★ Cluster collisions
★ …



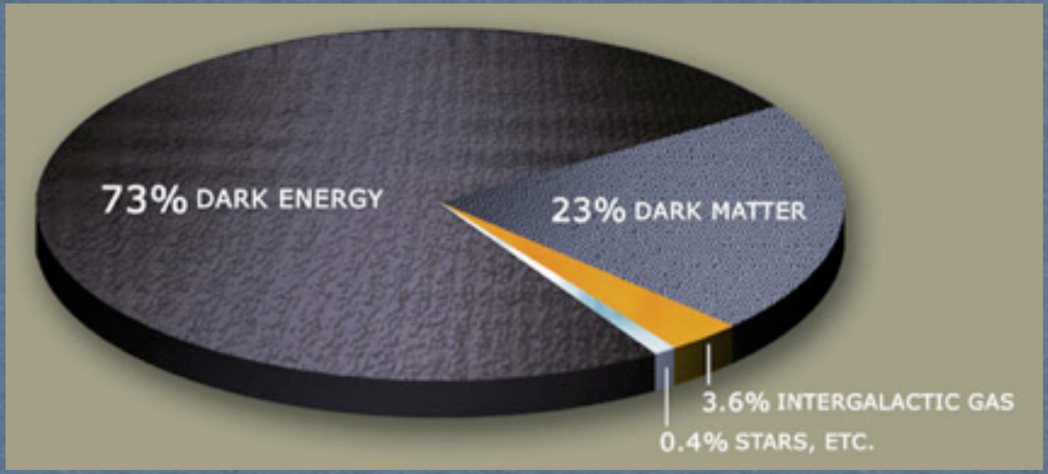
Compelling astrophysical indications about DM existence

Dark Matter (DM) vs Baryonic Matter (BM)

★ How much DM w.r.t. BM?



.. even worse if we consider the total balance



Only ~4% of the Universe is explained by the Standard Model of the elementary particles

★ Is DM undergoing to other interactions? is the DM made by 'particles' (such as the ones in the Standard Model)?

★ Constraint on DM mass and interactions

- should be '*dark*' (no em interaction)
- should weekly interact with SM particles
- should provide the correct relic abundance
- should be compatible with CMB power spectrum

… assuming that the gravity is not modified and DM undergoes to other interactions

★ We can use what we know about standard model particles to build a DM theory

Use the SM as an example: $SM = U(1)_{EM} \times SU(2)_{Weak} \times SU(3)_{Strong}$

Forces in nature

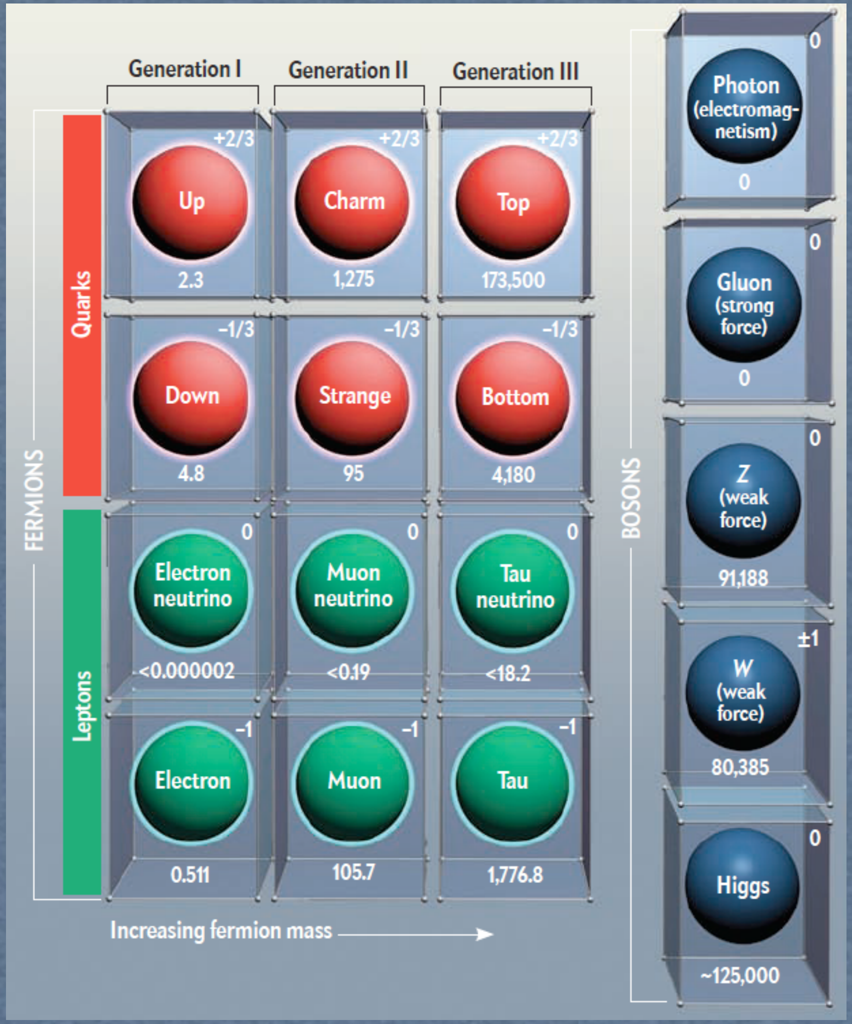
4 fundamental interactions known so far: strong, electromagnetic, weak and gravitational

Particles, interactions and symmetries

Known particles & new force-carriers

Particles:
quarks, leptons

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



Two options:

- ★ New matter interacting trough the same forces
- ★ New matter interacting trough new forces

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

Any guess about the DM mass and interaction?

★ DM as thermal relic from the hot early Universe

Minimal DM abundance is left over to the present day

Correct DM density for an annihilation xsec:

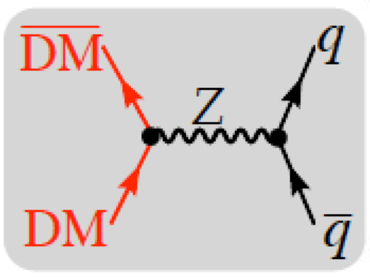
$\langle\sigma v\rangle \sim 3\text{x}10^{-26}\ \text{cm}^3/\text{s} \sim 1/(20\ \text{TeV})^2$

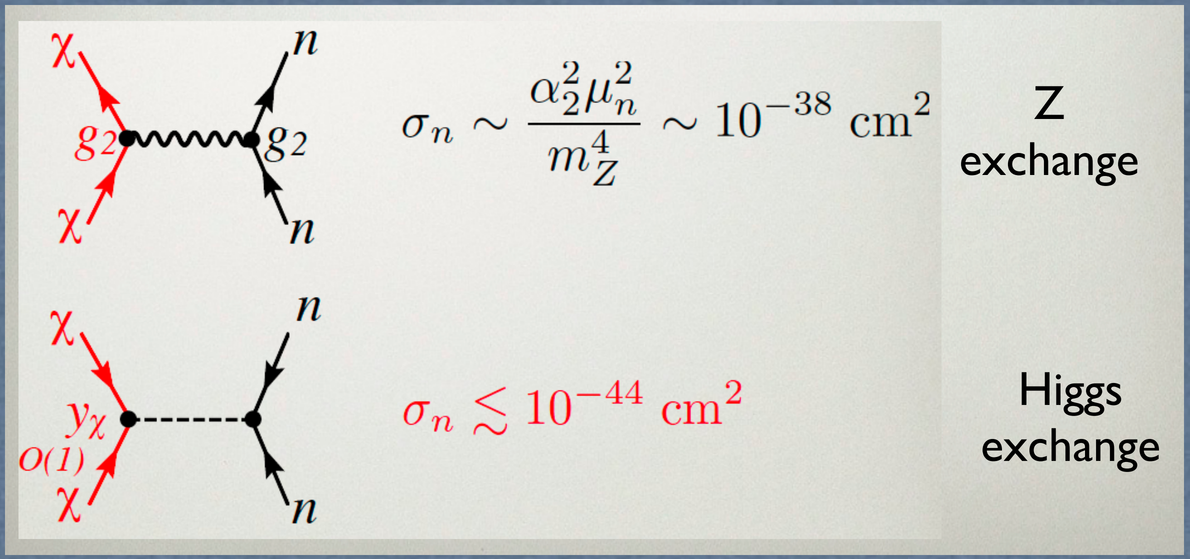
$\langle\sigma v\rangle \sim M^2{}_{DM}/M^4{}_{mediator}$

Thermal origin suggests DM interactions and mass in the vicinity of the weak-scale

★ WIMPs (Weakly Interacting Massive Particles)

- Massive DM with massive mediator
- For ~100 GeV DM mass, weak-scale mediators provide reasonable annihilation rate and range of DM-scattering rates





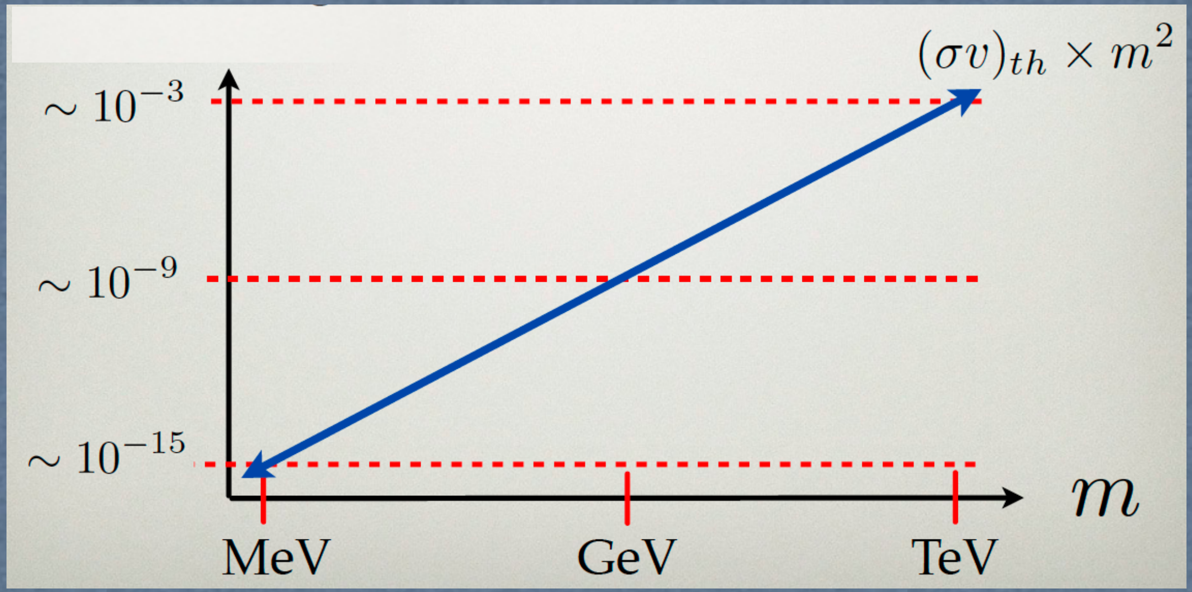
WIMPs paradigm is not the only option

Light Dark Matter

Light Dark Matter (<TeV) naturally introduces light mediators

what matter is:
$\langle\sigma v\rangle \times m^2$

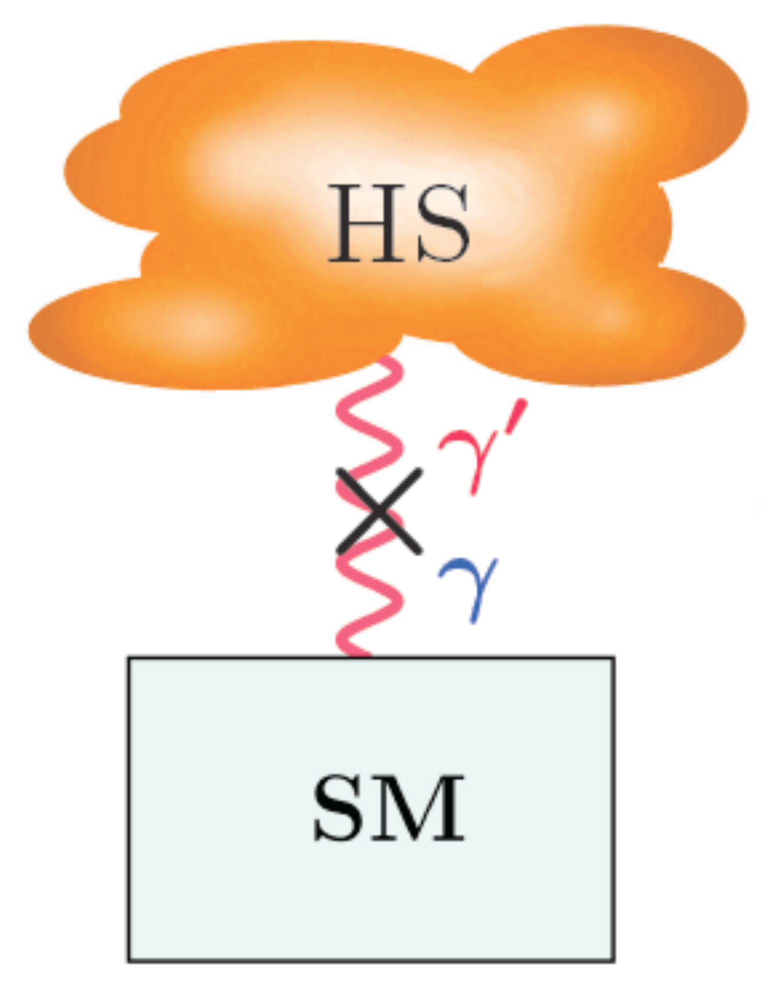
New (almost) weak interaction



Introducing a new force in nature

✳Hidden sector (HS)
present in string theory and super-symmetries

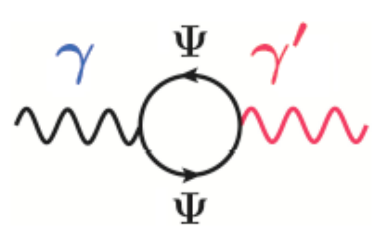
✳HS not charged under SM gauge groups (and v.v.)
no direct interaction between HS and SM
HS-SM connection via messenger particles



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

$SU(3)_C$ x $SU(2)_L$ x $U(1)_Y$ **x extra U(1)**
Color Electroweak Hypercharge Hidden sector

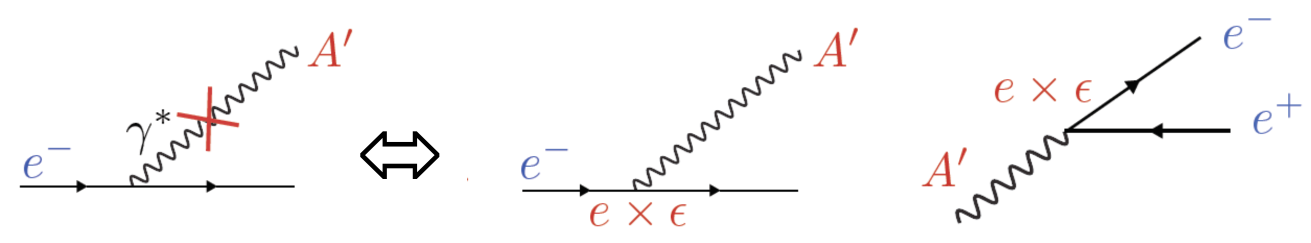
$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\chi}{2}\overset{\text{Hidden}}{X_{\mu\nu}}\underset{\text{Visible}}{F^{\mu\nu}} + \frac{m^2_{\gamma'}}{2}X_\mu X^\mu$$



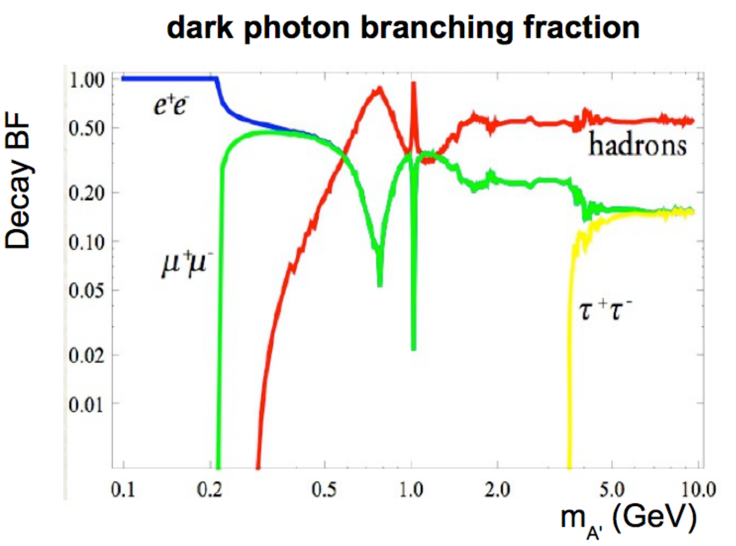
Ψ can be a huge mass scale particle (M_Ψ~1EeV) coupling to both SM and HS

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

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



Motivations for a new massive vector boson (A')

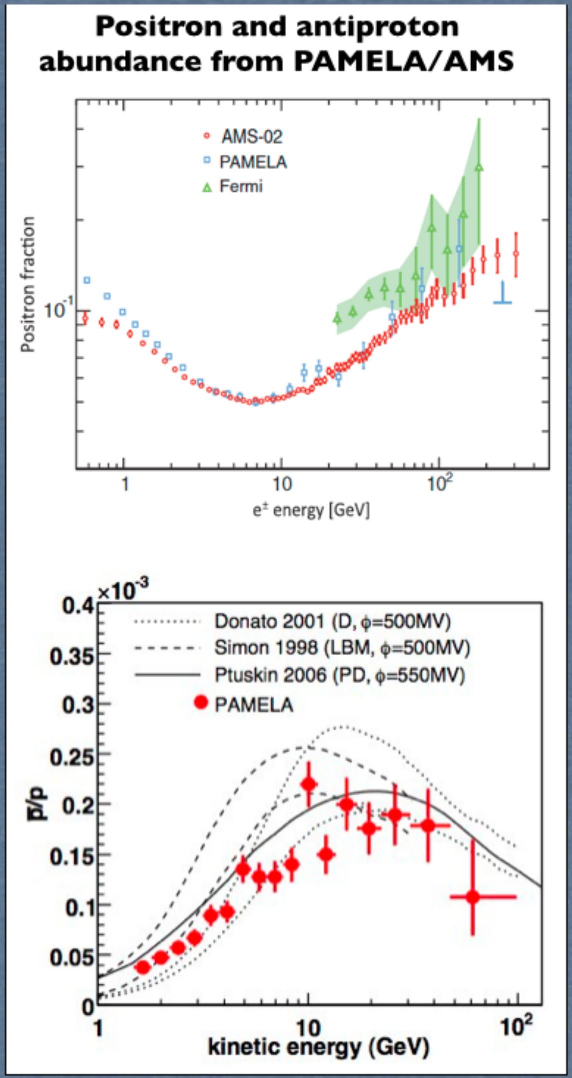


Assumptions:

$M_{A'}$>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



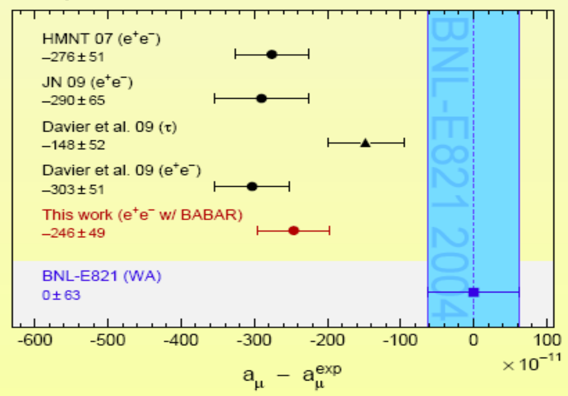
γ'/A' decays in leptons

→ abundance of e^+e^- in Universe

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

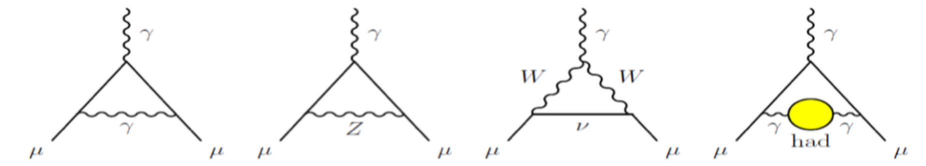
→ short range modification of EM interaction

g-2 of muon



Standard Model Prediction

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



Contribution to g-2 from dark photon

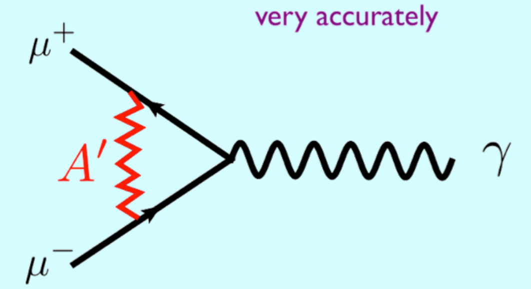
$$a_\mu^{\text{dark photon}} = \frac{\alpha}{2\pi}\varepsilon^2 F(m_V/m_\mu)\,,$$

magnetic dipole moment

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

spin

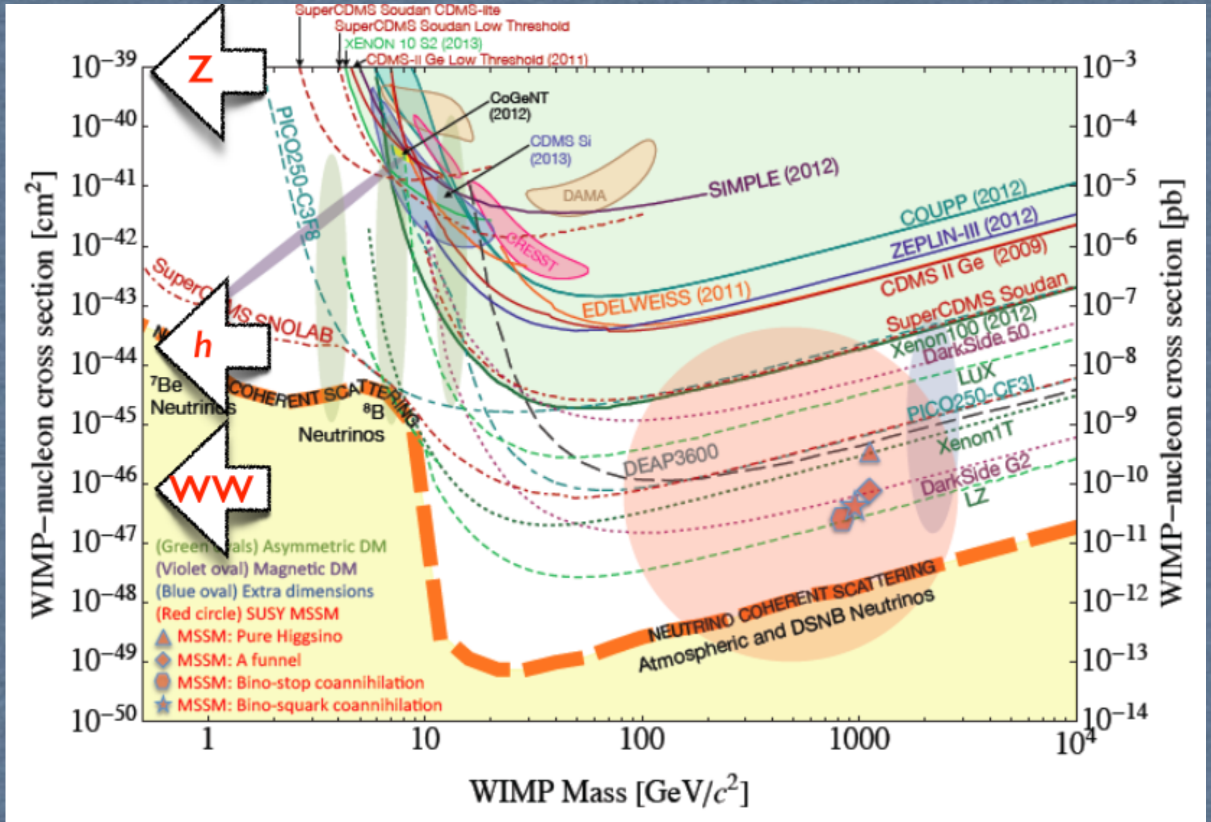
can be measured very accurately



$g_s \neq 2$

Exploring the WIMP’s option

★ Experimental limits



Slow-moving cosmological weakly interacting massive particles

- DM detection by measuring the (heavy)nucleus recoil
- Constraints on the interaction strength from the DM Direct Detection limits
  - Scattering trough Z boson ($\sigma \sim 10^{-39}$cm^2): ruled out
  - Approaching limits for scattering trough the Higgs ($\sigma \sim 10^{-45}$cm^2)
  - Close to unreducible neutrino background

Direct Detection

1 MeV

1 GeV

Mz

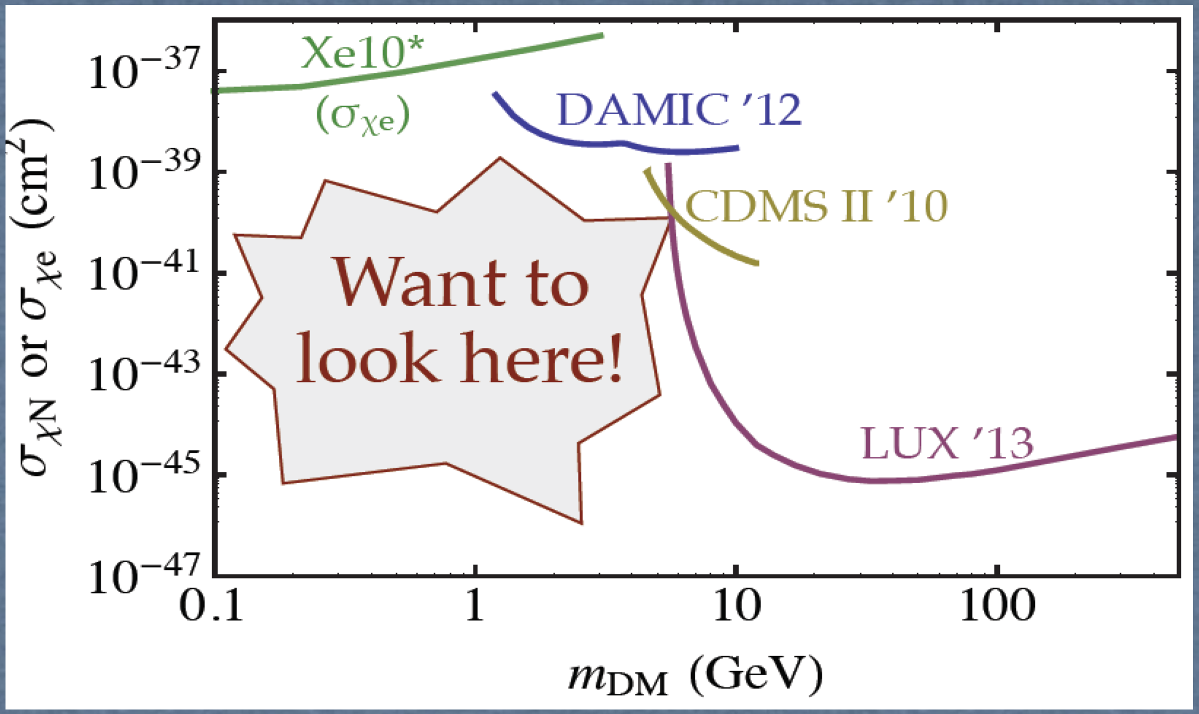
10 TeV

WIMPs

No signal in direct detection → no sensitivity to light DM (<1 GeV)

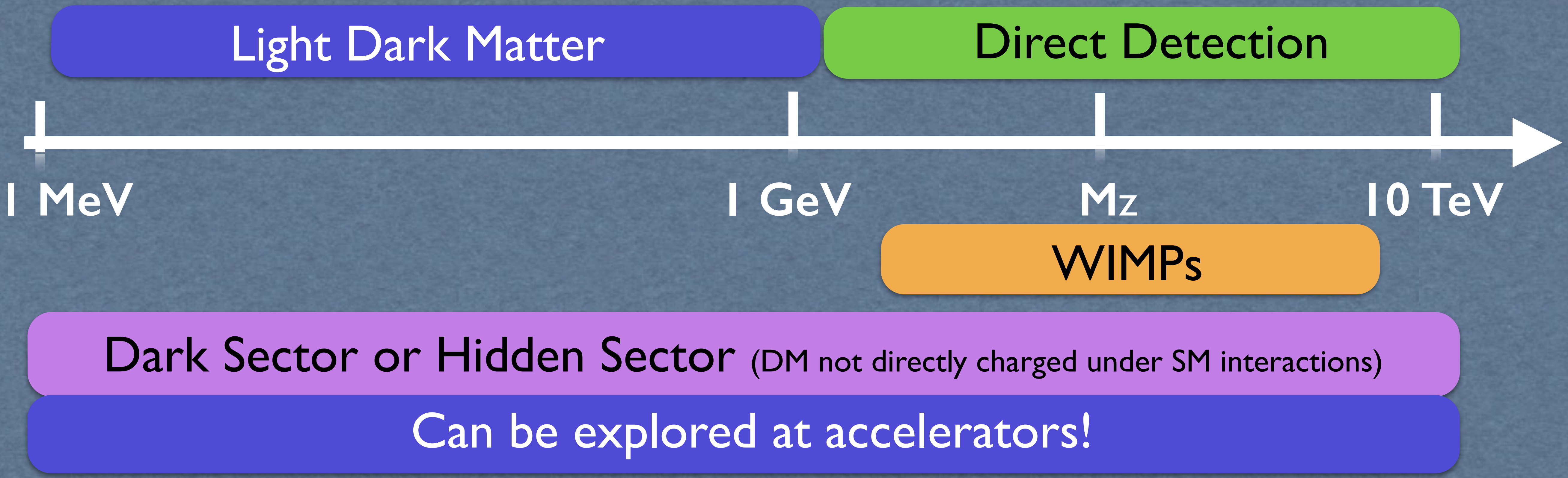
What if ...

★ Experimental limits



Light Dark Matter with a (almost) weak interaction (new force!)

- Direct Detection is (almost) impossible
  - Low mass elastic scattering on heavy nuclei produces small recoil
  - eV-range recoil requires a different detection technology
  - Directionality may help to go behind existing limits



Light Dark Matter

Direct Detection

1 MeV

1 GeV

Mz

10 TeV

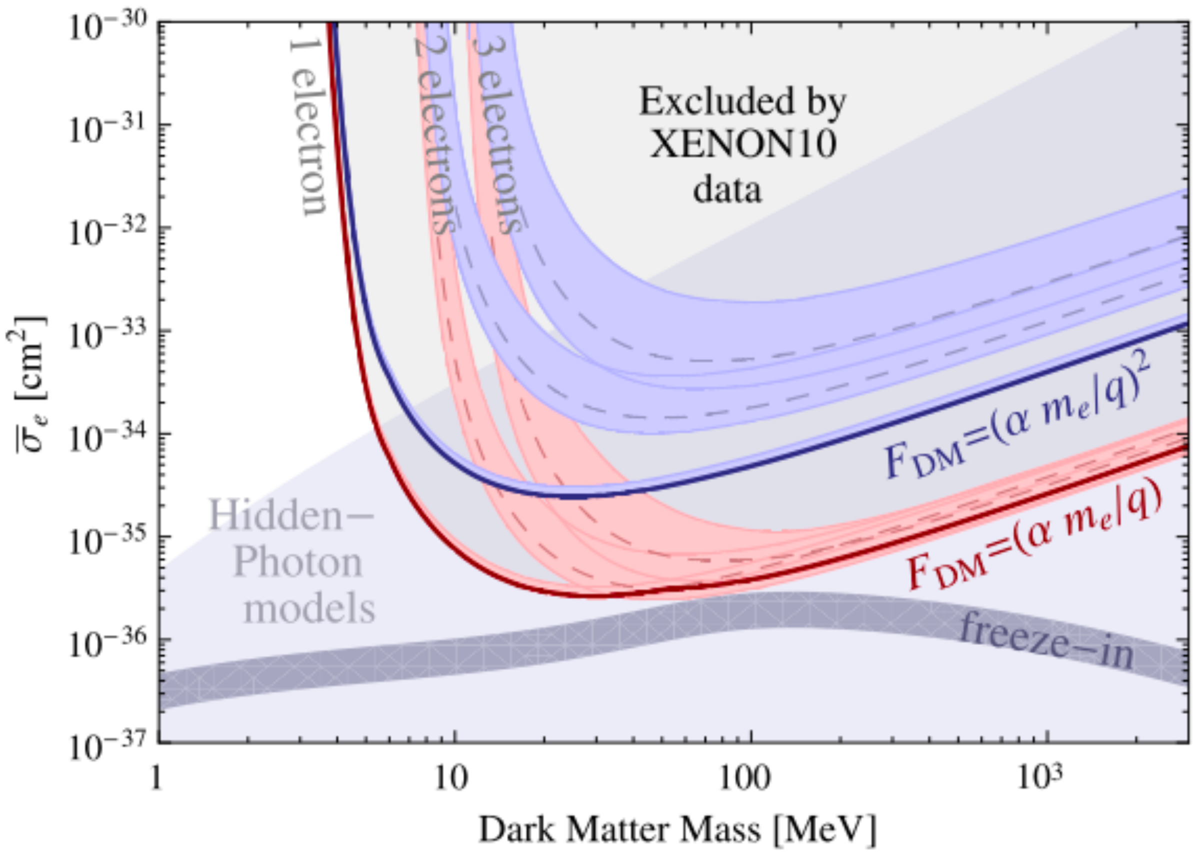
WIMPs

Dark Sector or Hidden Sector (DM not directly charged under SM interactions)

Can be explored at accelerators!

LDM - Direct Detection limits

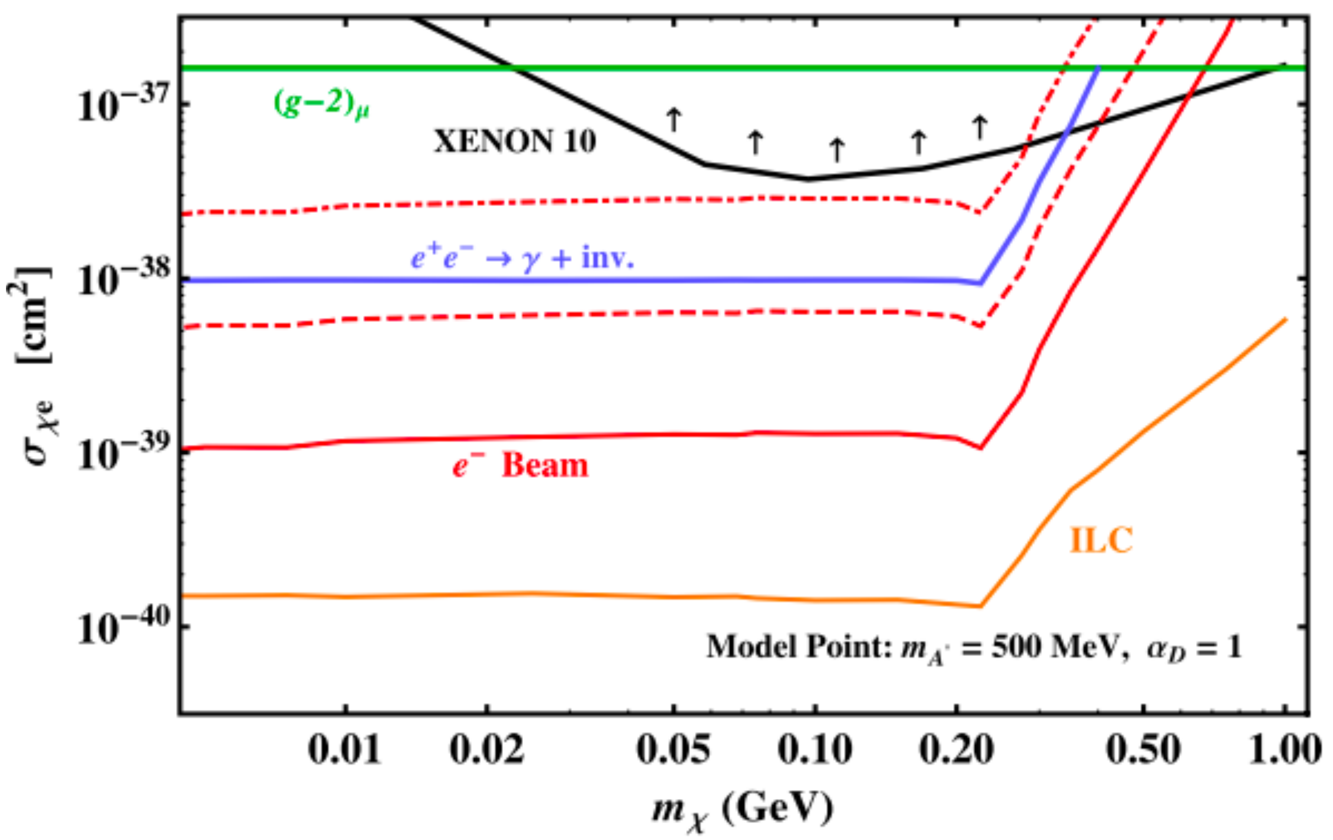
Limits from XENON10



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)
  - χ_{cosmic}-e scattering
  - 1-electron ionization sensitivity
  - No FF for the scattering

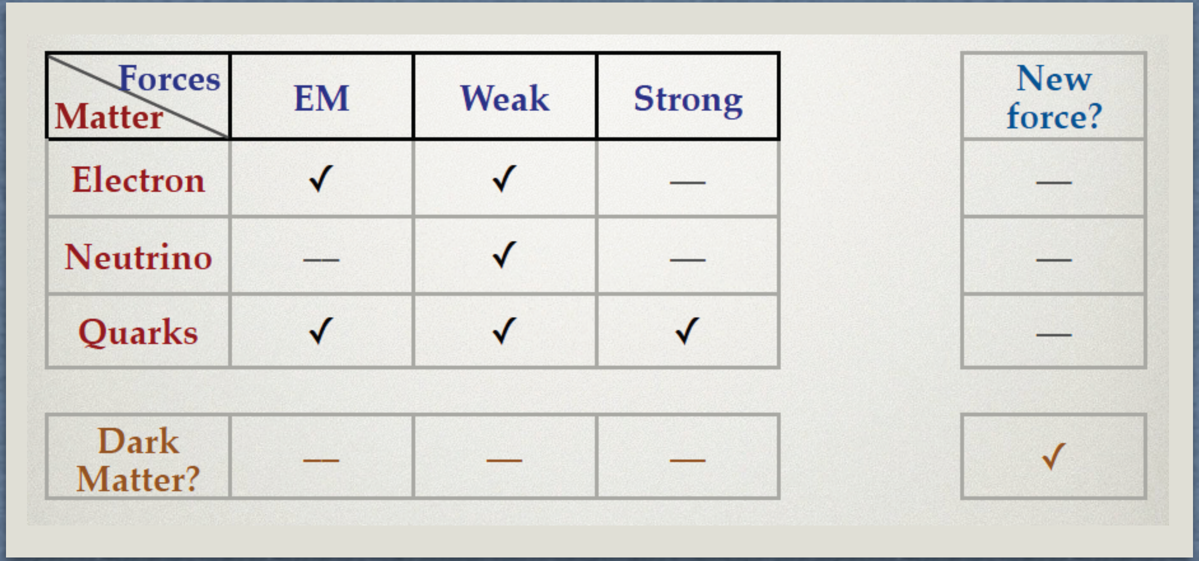
Fixed target & high intensity e^- beam



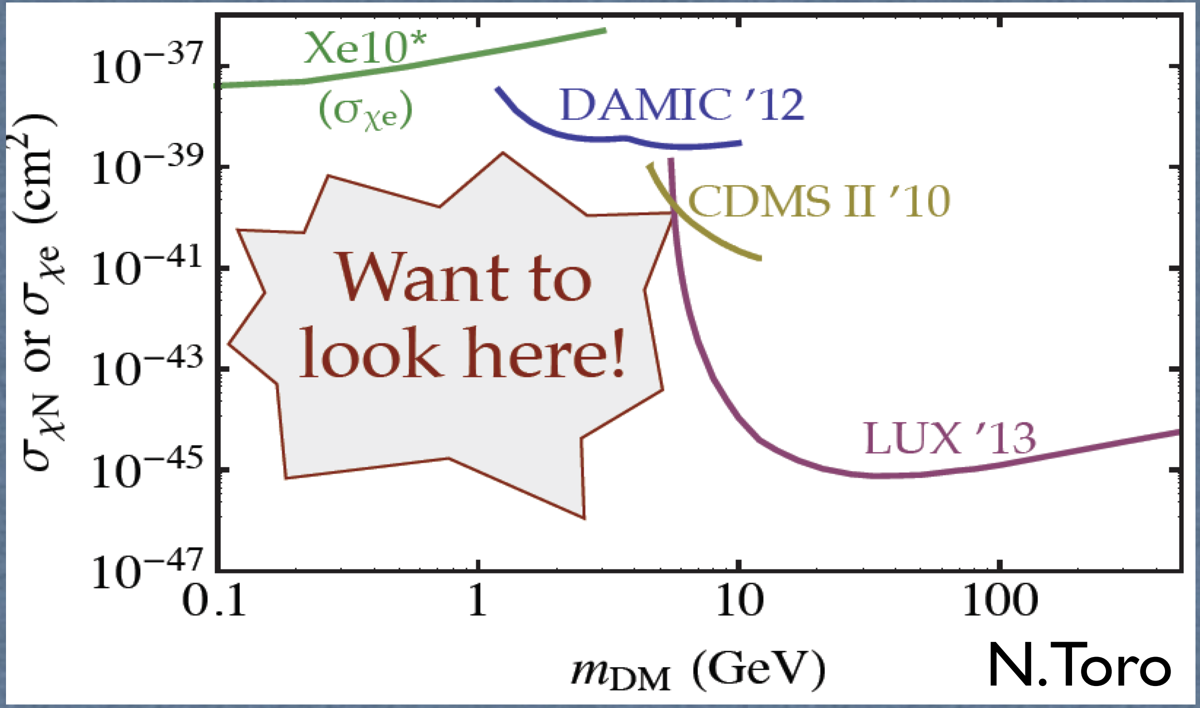
PhysRevD.88.114015 E.Izaguirre, G.Krnjaic, Gordan, P.Schuster, N.Toro

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

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 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

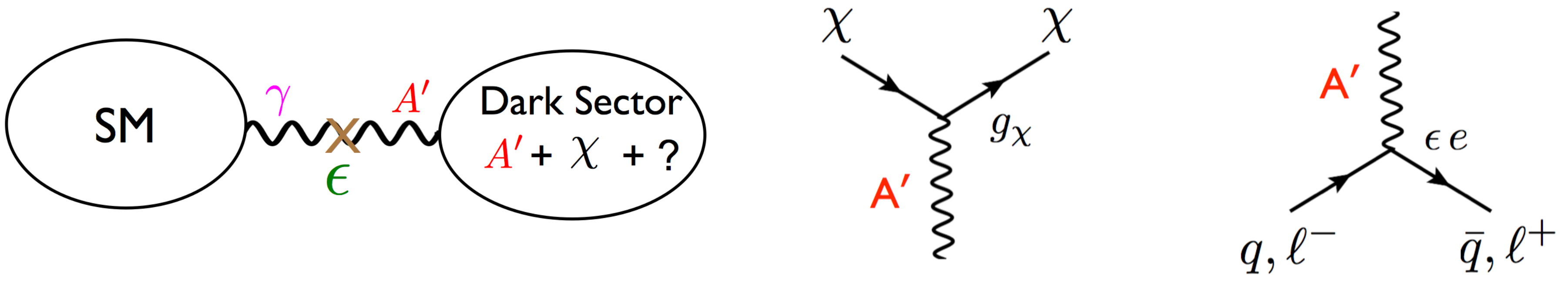
✳ Tagging wrt cosmic anomalies (clear way of distinguish DM from other effects)

✳ Unprecedented sensitivity in the keep-out zone for direct DM search

✳ High intensity electron beam available to play a significant role in LDM search

Dark forces and dark matter

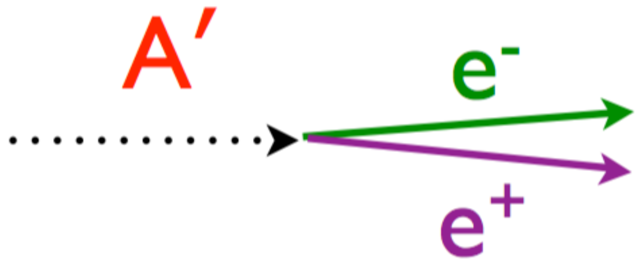
(Light WIMPs - light mediators)



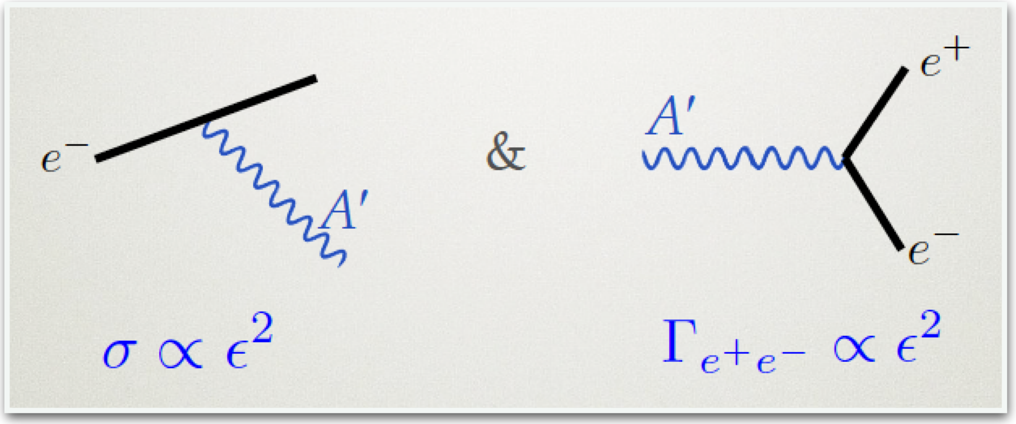
4 parameters: $m_\chi, m_{A'}, \epsilon, g_\chi$

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

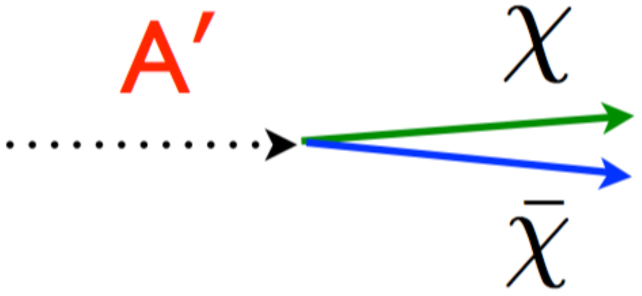
Visible



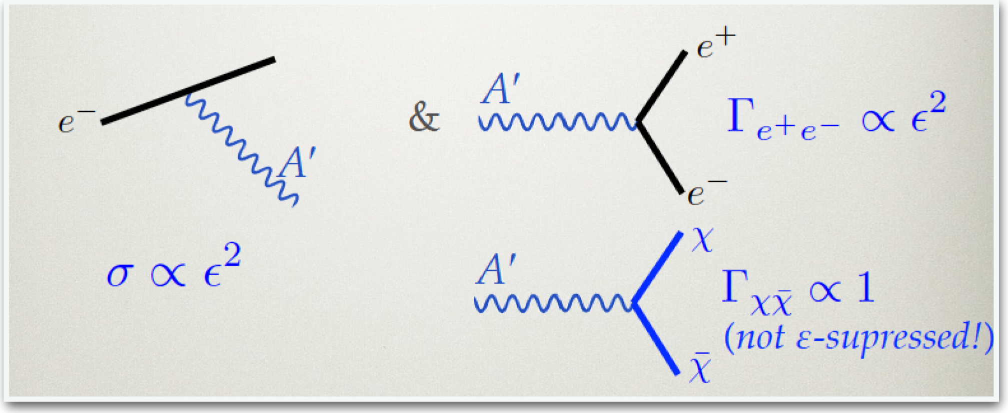
- *Minimal* decay
- Decay regulated by ε^2
- Independent on m_χ
- Requires $m_{A'}<2m_\chi$



Invisible



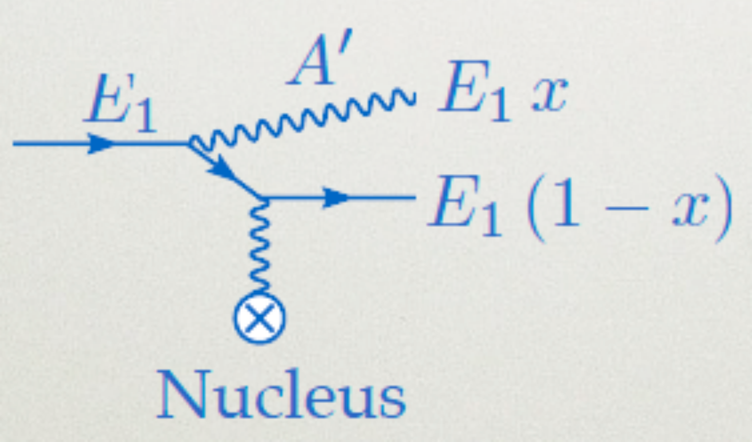
- $m_\chi < 2m_{A'}$
- i) stable and invisible
- ii) decays to SM particles
- Independent on ε

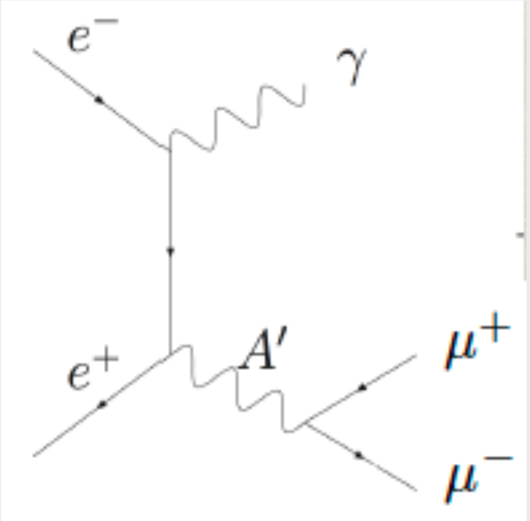


A’ production: fixed target vs. collider

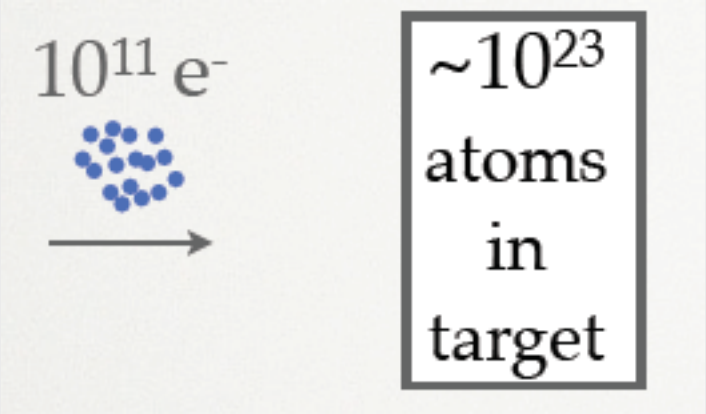
Fixed Target | e+e- colliders

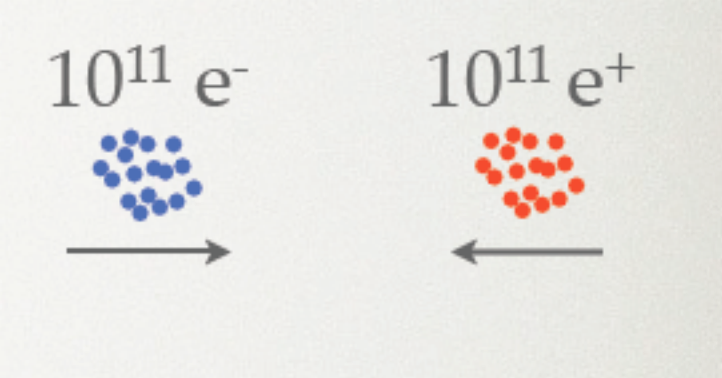
Process





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

Hunting for A' at accelerators

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

→ **JLAB, MAINZ**

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

→ **FERMILAB, SERPUKHOV**

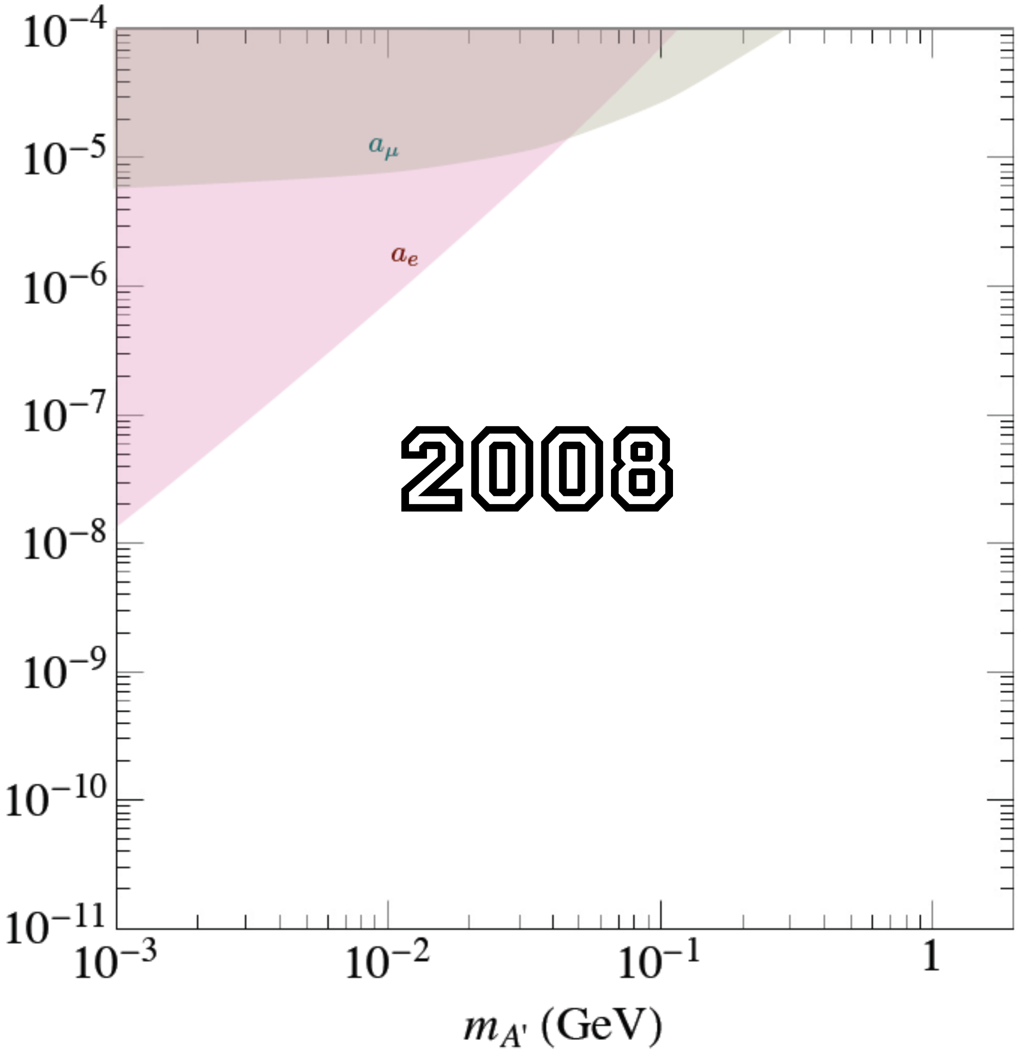
Annihilation: e+e- → γ' γ → $\mu\mu$ γ

→ **BABAR,BELLE,KLOE**

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

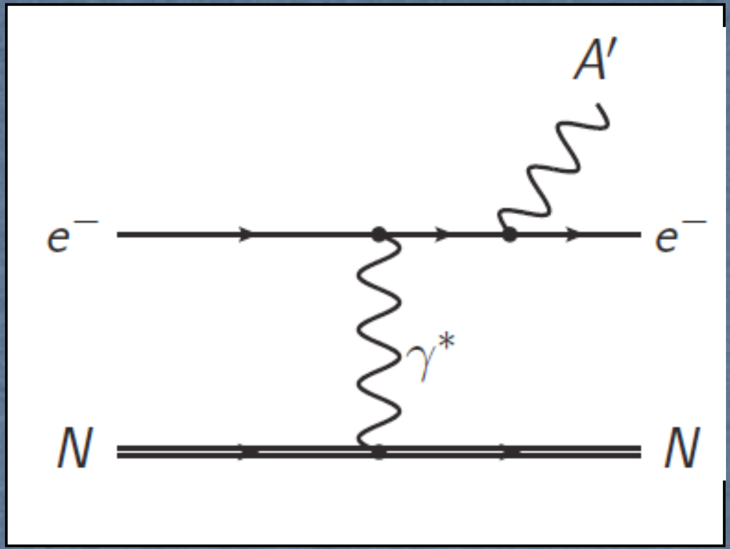
→ **KLOE, BES3, NA48, HC**

Parameter space
Coupling vs Mass



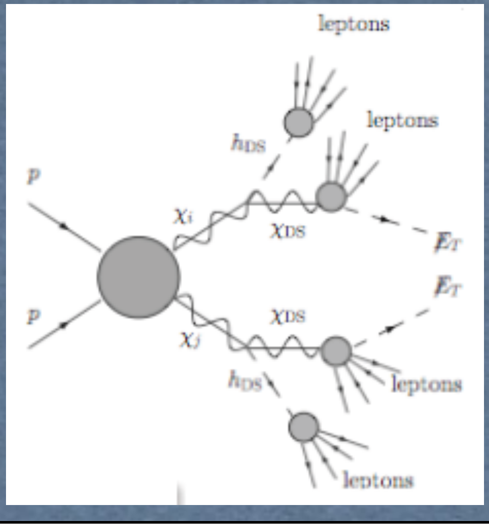
2008

Hunting for A’ at accelerators

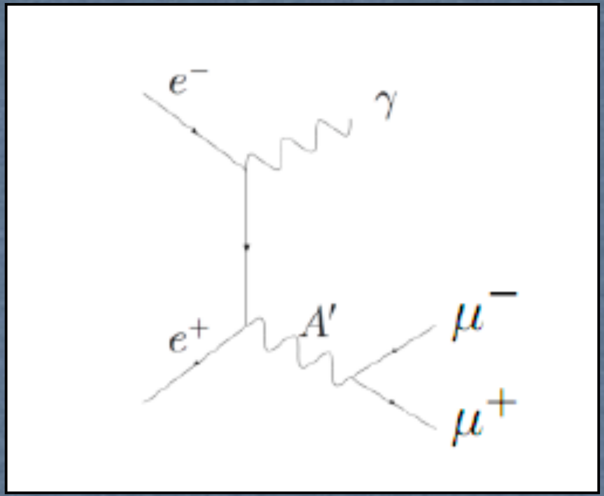


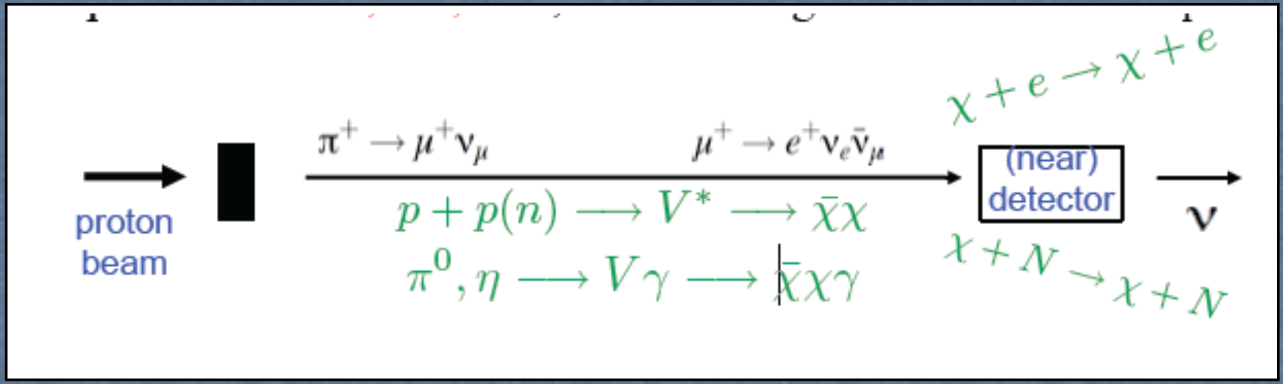
Fixed target:
e N →N γ’→ N Lepton Lepton+
→ **JLAB, MAINZ**

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



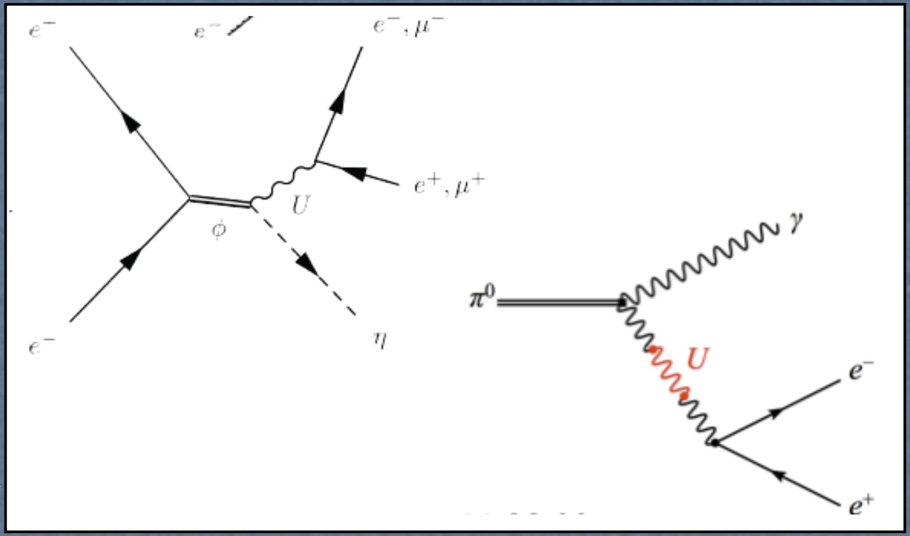
Annihilation:
e+e- → γ’ γ → μμ γ
→ **BABAR, BELLE,**
KLOE, CLEO





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

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



Hunting for A' at accelerators

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

→ **JLAB, MAINZ**

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

→ **FERMILAB, SERPUKHOV**

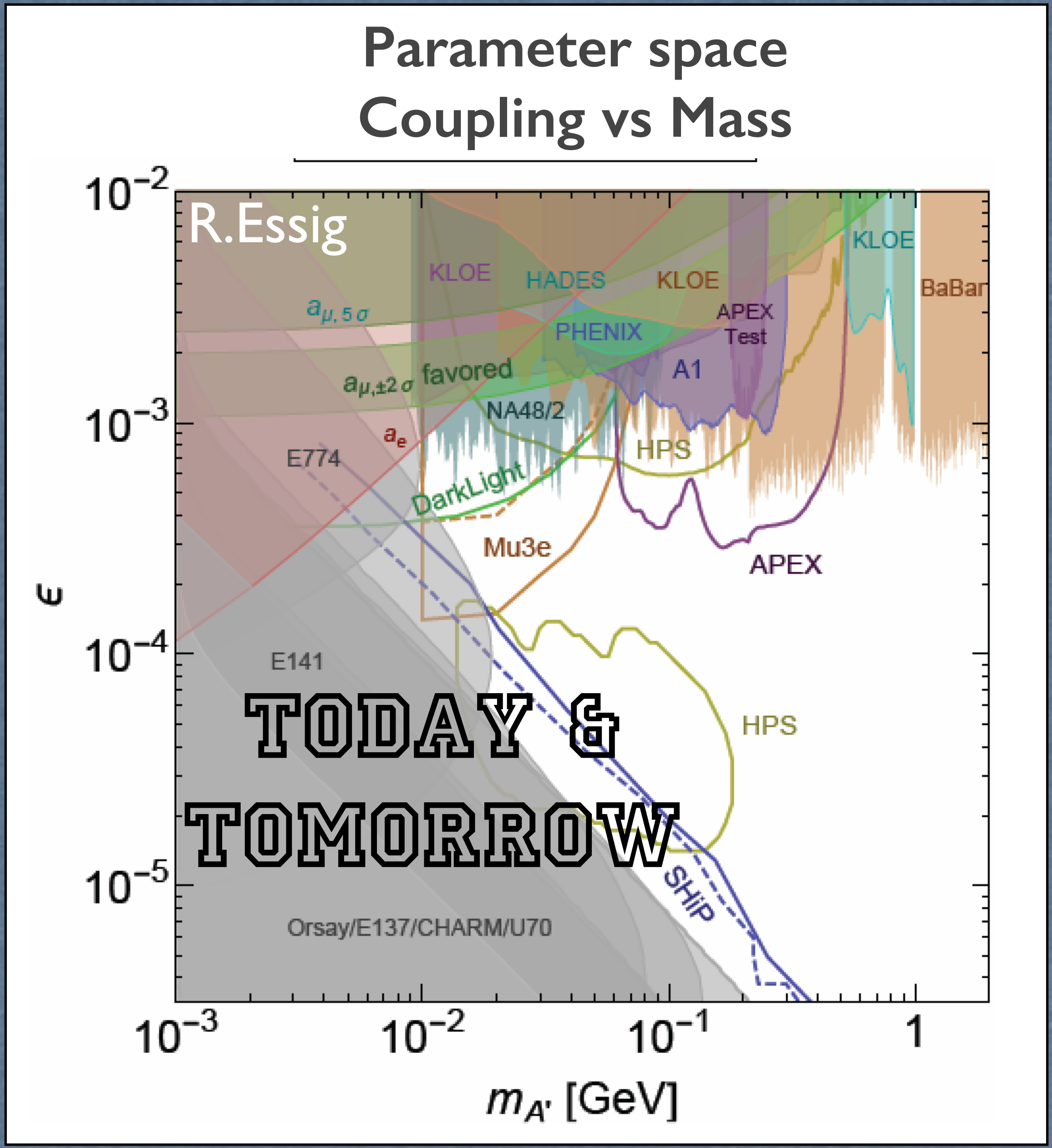
Annihilation: e+e- → γ' γ → μμ γ

→ **BABAR,BELLE,KLOE**

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

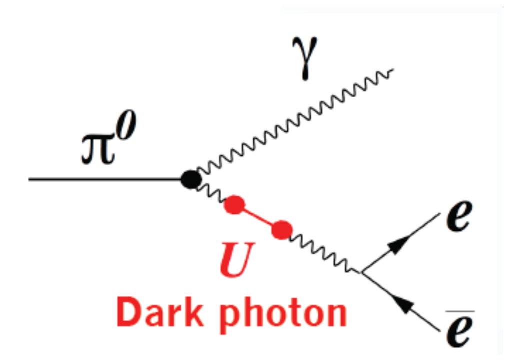
→ **KLOE, BES3, NA48, HC**

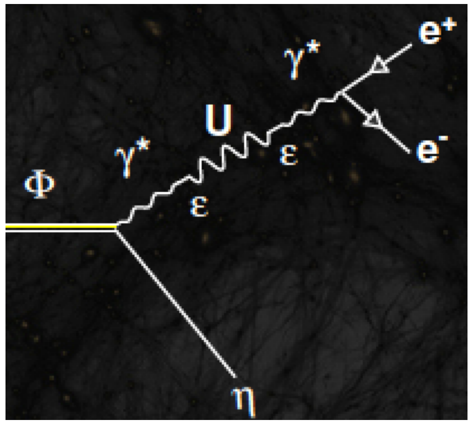
No positive signal (so far) but limits in parameter space coupling vs mass



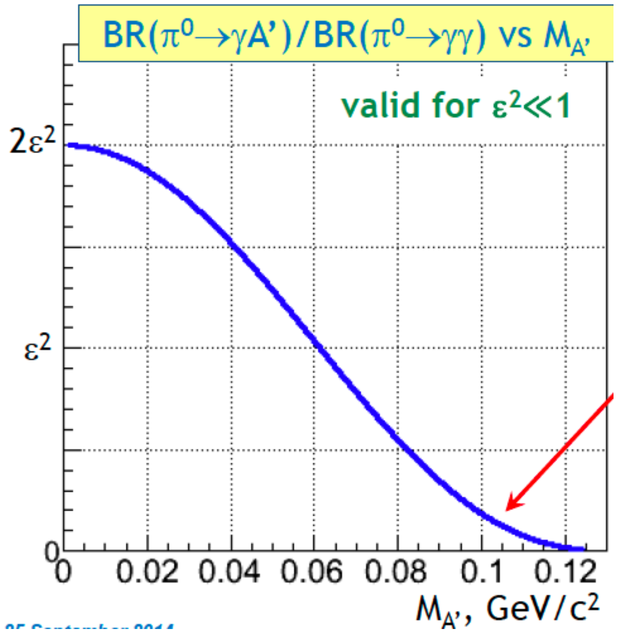
Parameter space
Coupling vs Mass

Meson Decay - The latest Results

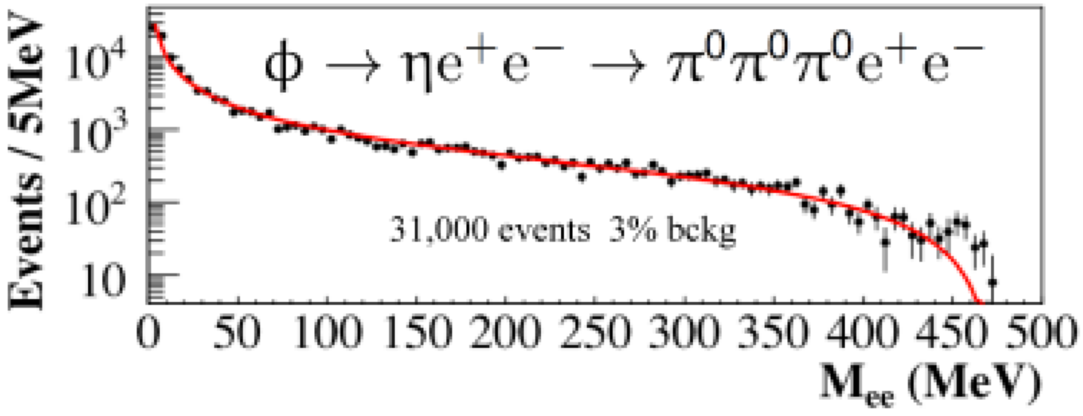


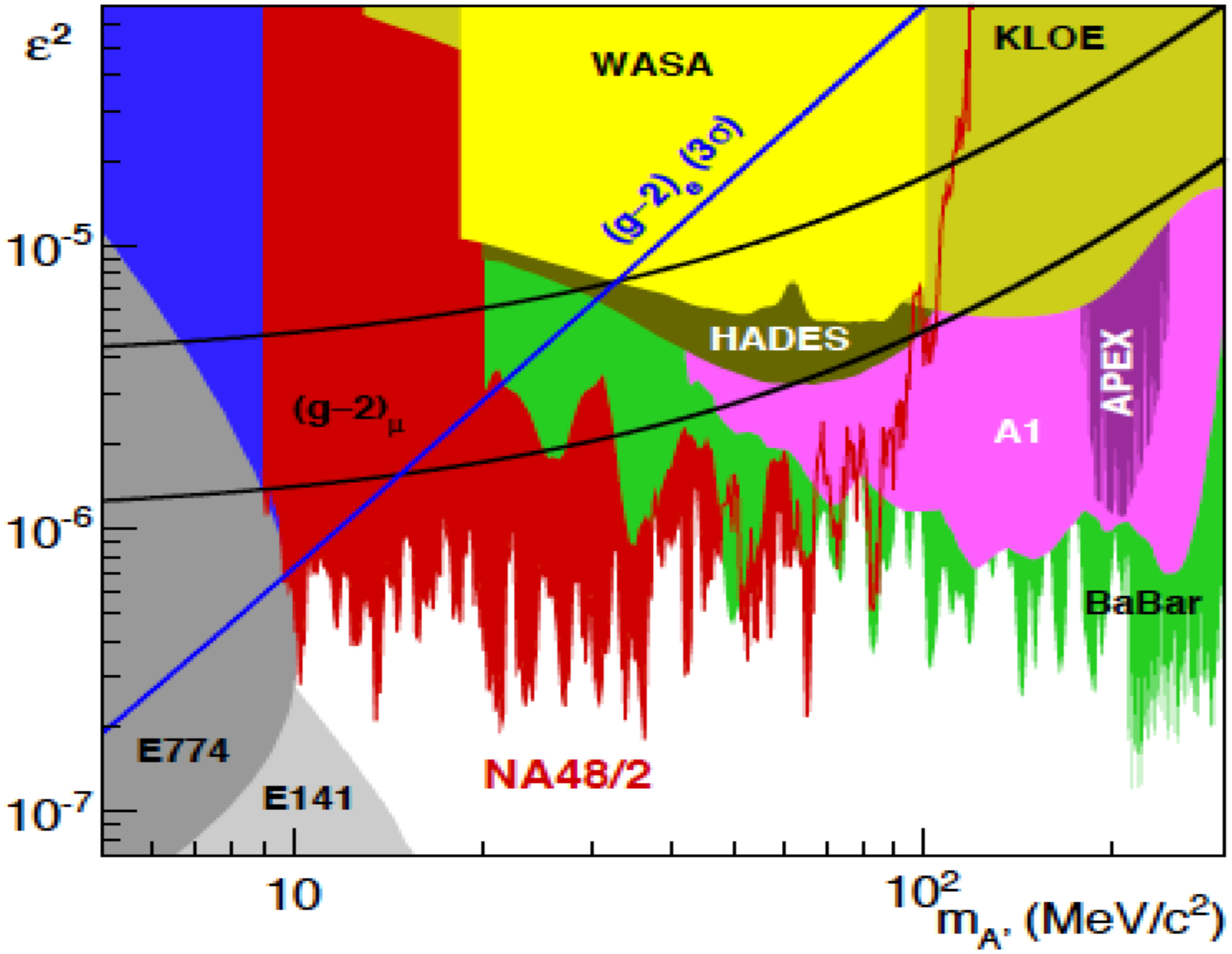


$K^\pm \to \pi^\pm \pi^0$, $\pi^0 \to \gamma A'$, $A' \to e^+e^-$.



- 4×10^{10} π^0
- Acceptance ~ 2.5%
- δM ~ 1% Mee

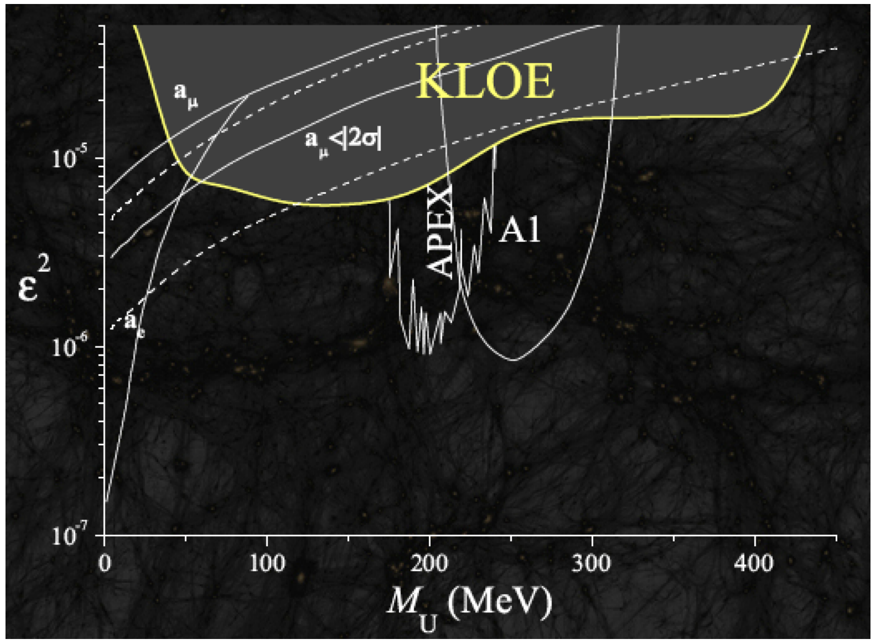




NA48/2

J.R.Batley et al.
Arxiv: 1504.00607

Phys. Lett. B 706 (2012) 251
Phys. Lett. B720 (2013) 111



HPS@JLab
Heavy Photon Search

Heavy photon signatures in HPS

1) Bump Hunting (BH)

Narrow e+e-resonance over a QED background

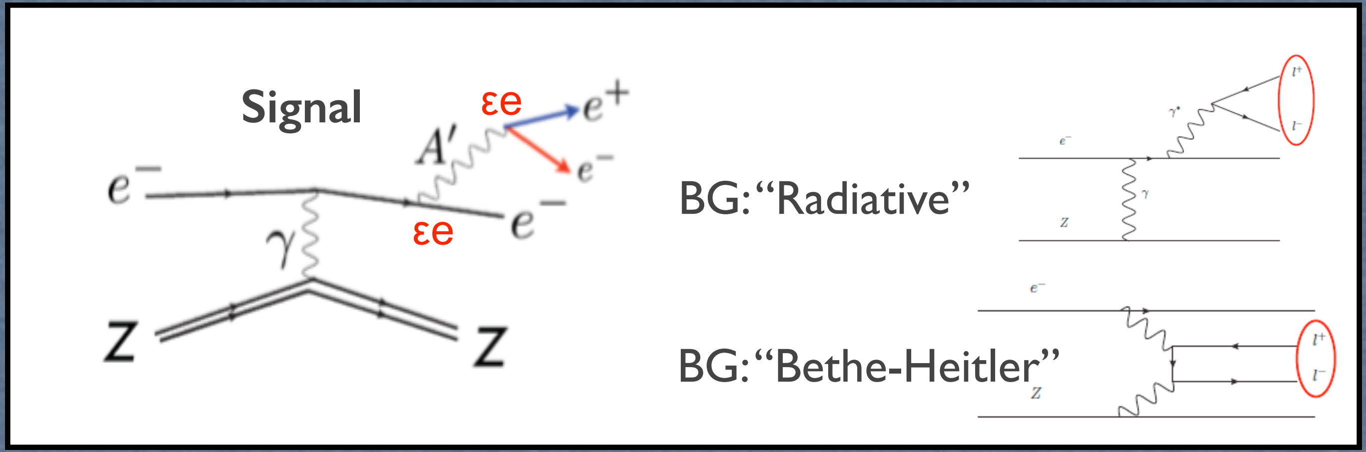
➥ good mass resolution: $\sigma_{A'mass}$~1 MeV

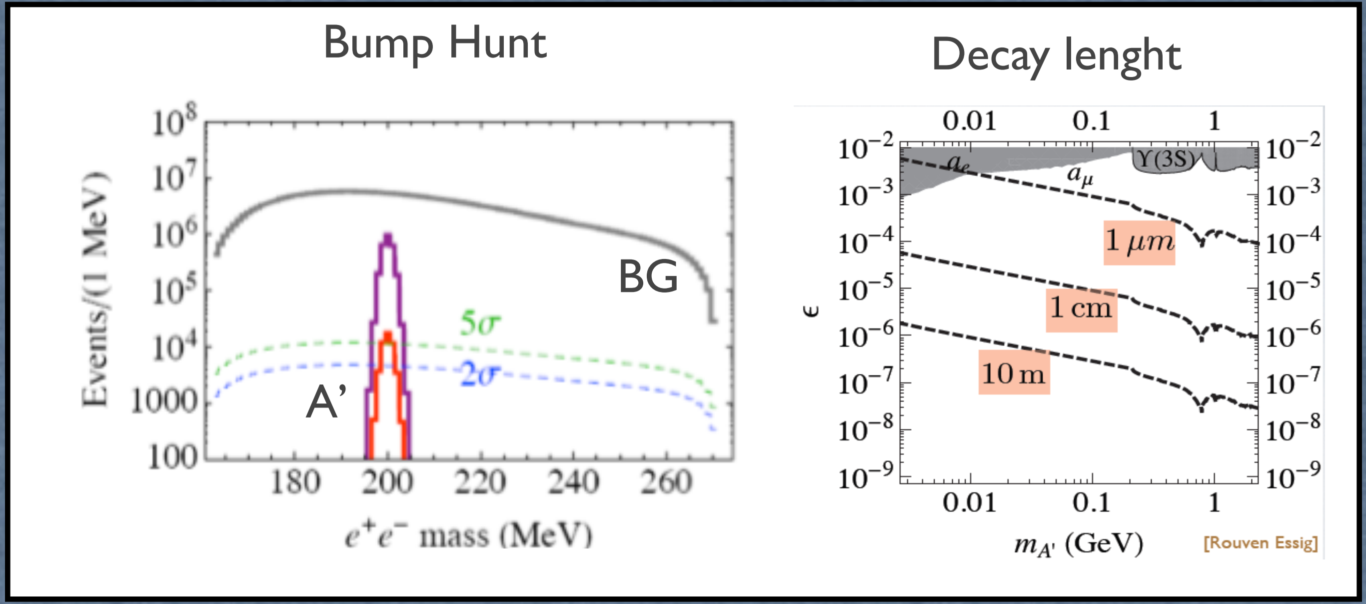
2) Secondary decay vertex (vertexing)

Detached vertex from few mm to tens cm

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

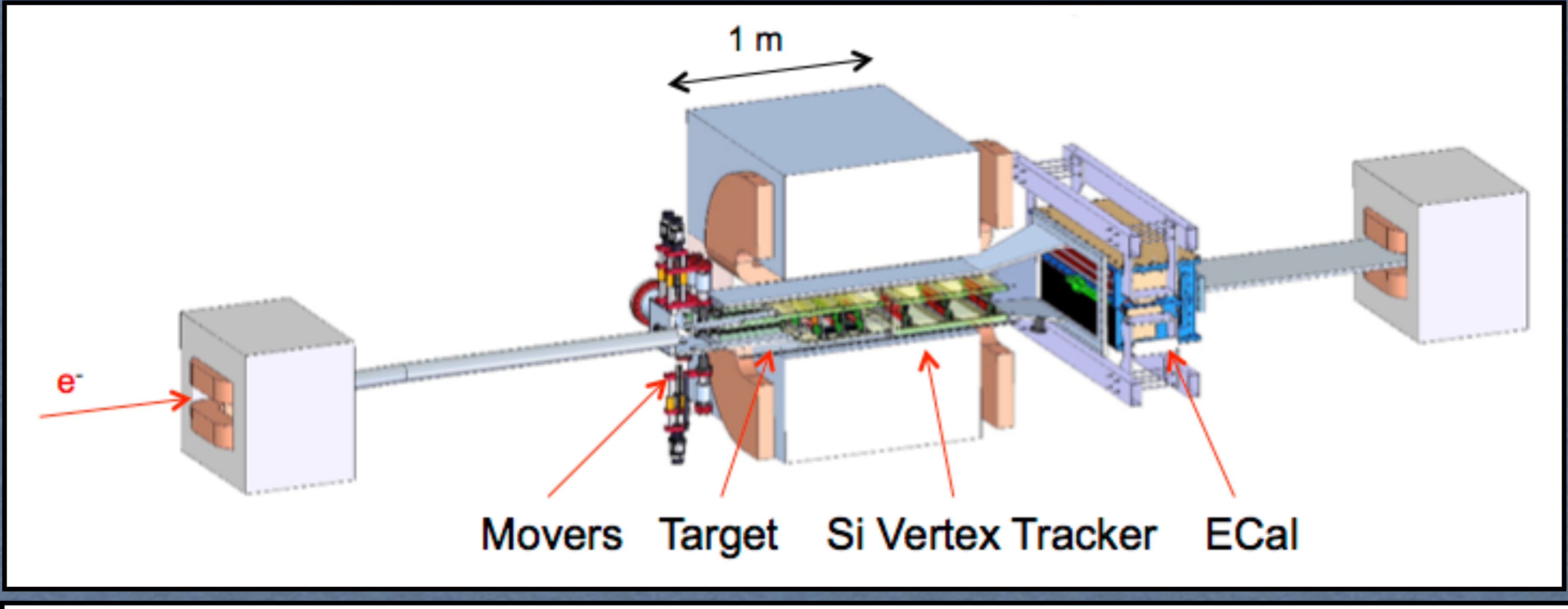
BH + Vertexing = enhanced experimental reach





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

The HPS Experiment

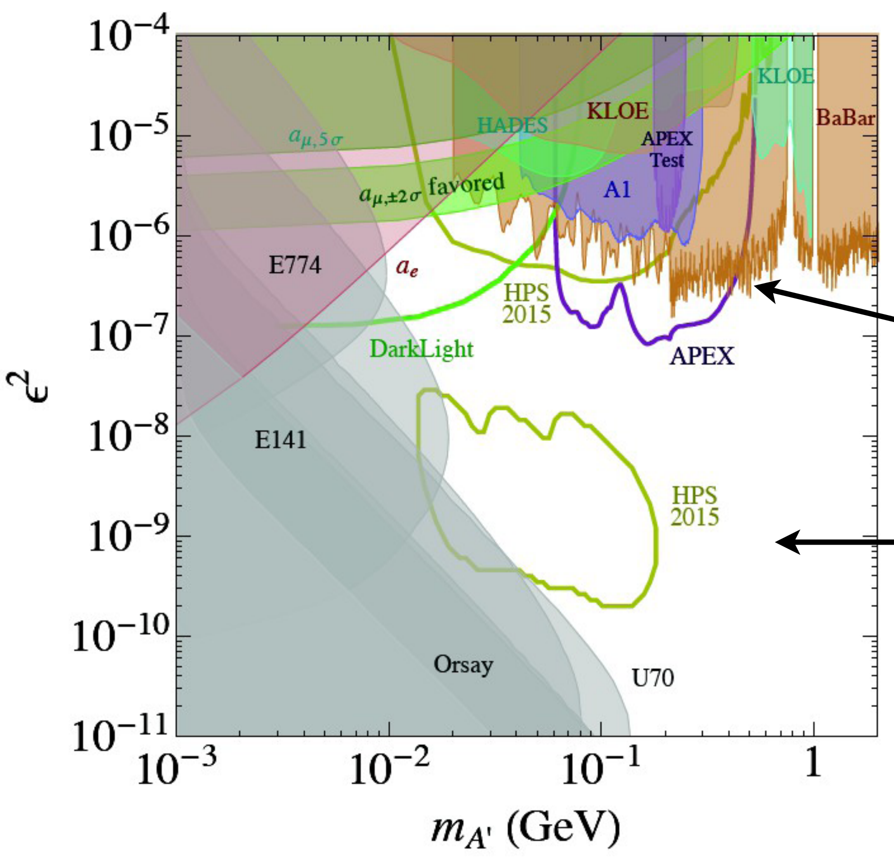


Requirements:

- forward angles coverage
- 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



Projected results

Bump hunting

Running now! 1 week 1.1 GeV
1 week 2.2 GeV
2 weeks 4.4 GeV

Phase I
2015

Bump hunting
+ vertexing

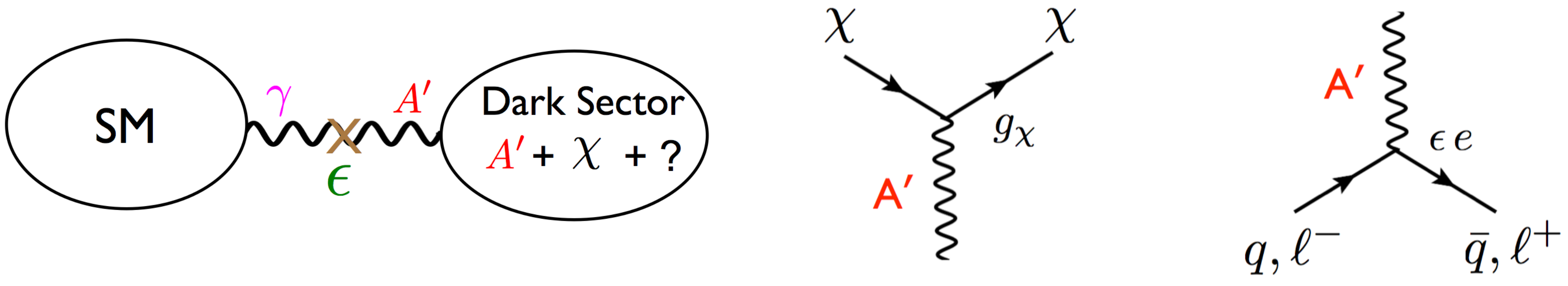
few months 2.2 GeV
few months 4.4 GeV
few months 6.6 GeV

Phase II
2017 -2019

JLab - PAC41 High impact rate

Dark forces and dark matter

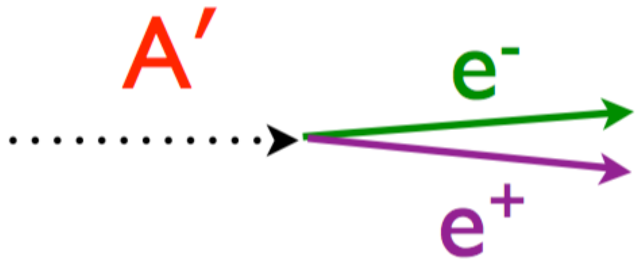
(Light WIMPs - light mediators)



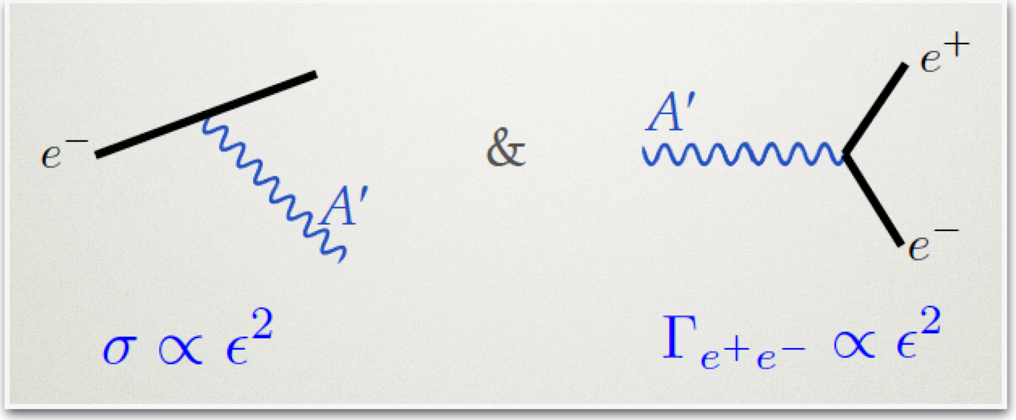
4 parameters: $m_\chi, m_{A'}, \epsilon, g_\chi$

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

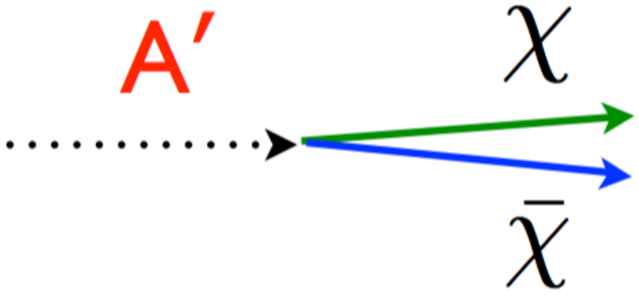
Visible



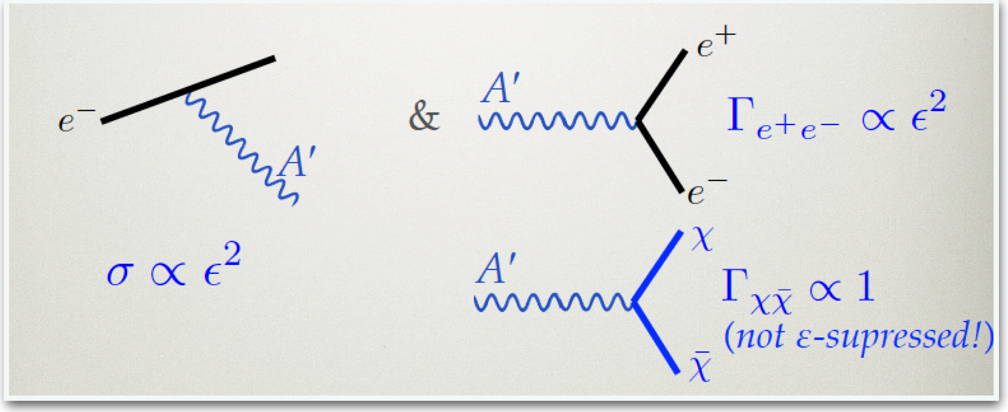
- *Minimal* decay
- Decay regulated by ε^2
- Independent on m_χ
- Requires $m_{A'}<2m_\chi$



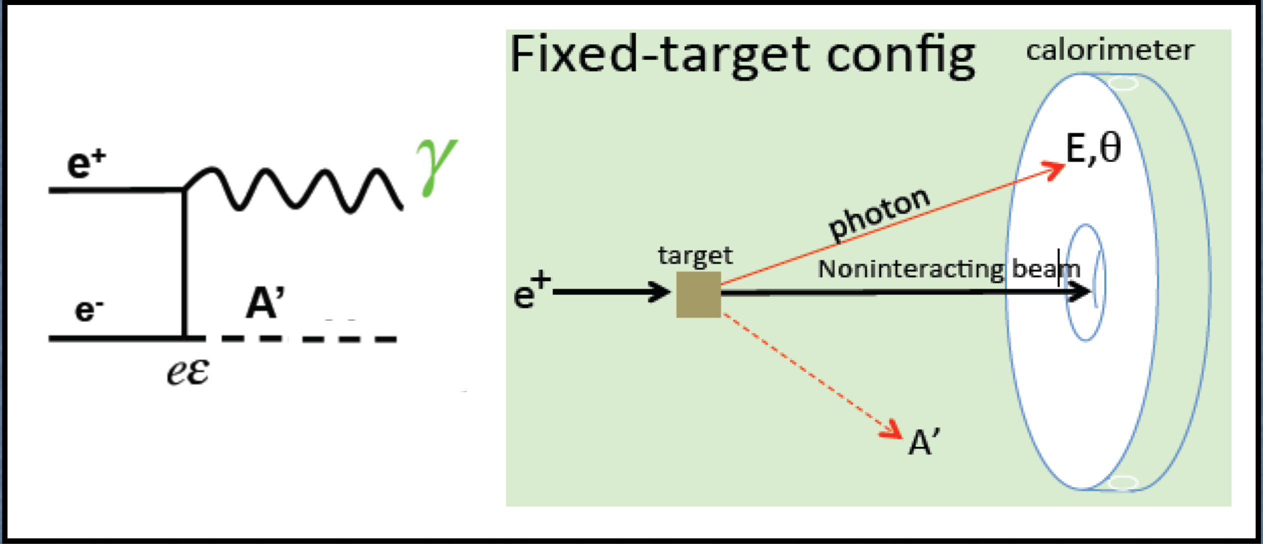
Invisible



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

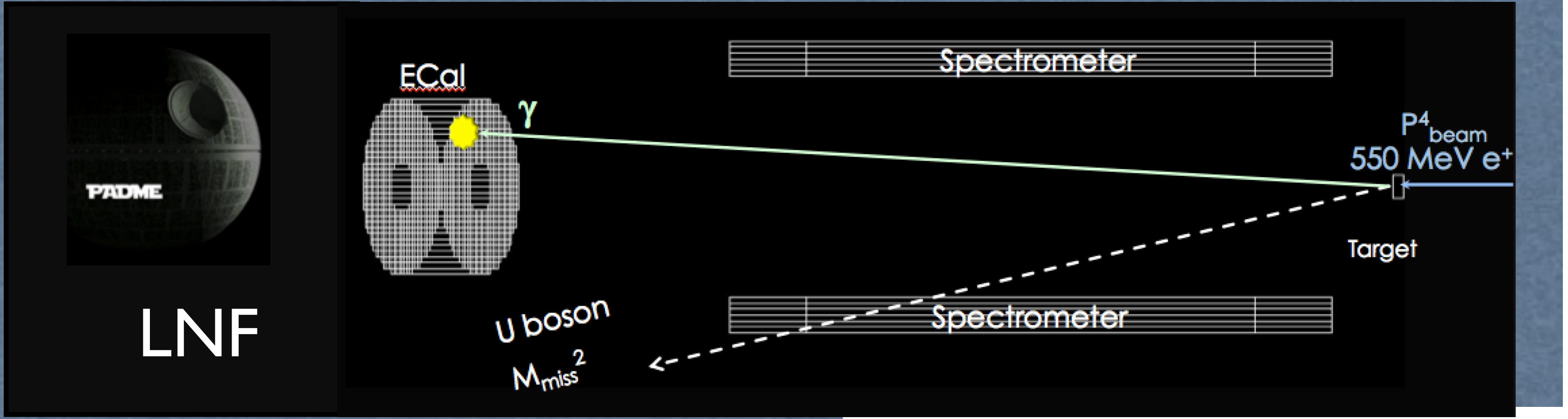


e^+ annihilation on fixed target: proposals



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

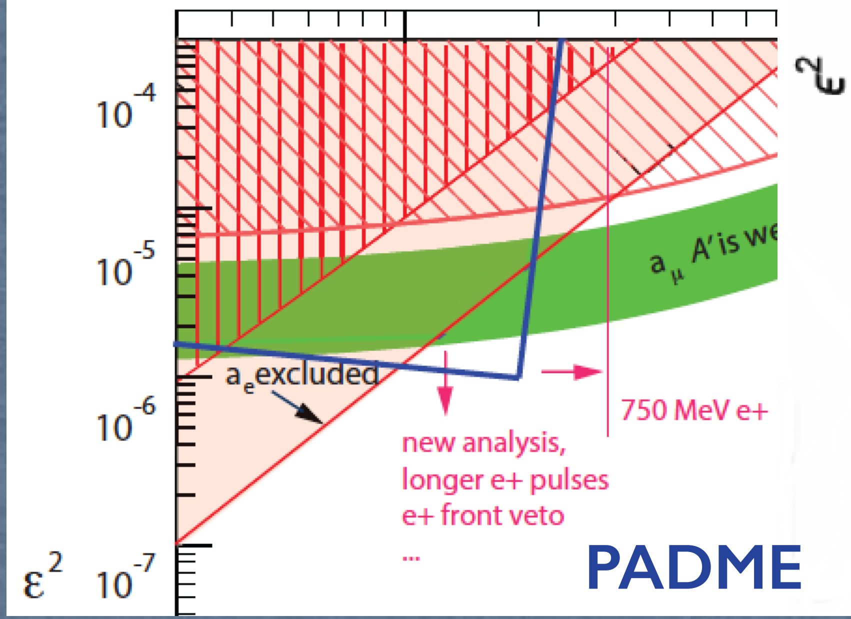
- **Novosibirsk**
- **LNF**
- **Cornell**

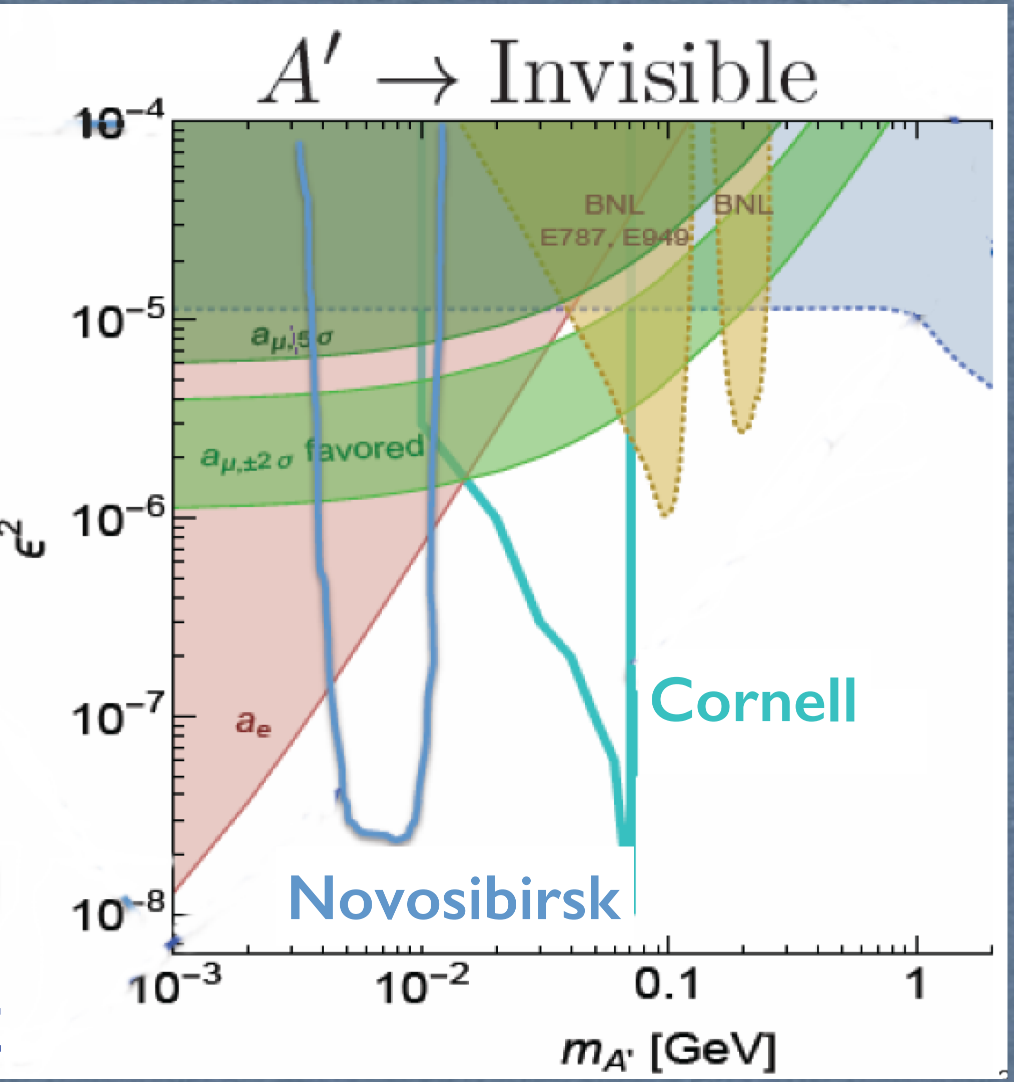


VEPP3
- E_{e+} = 500 MeV
- EOT ~ 10^{15} - 10^{16} year^{-1}

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}



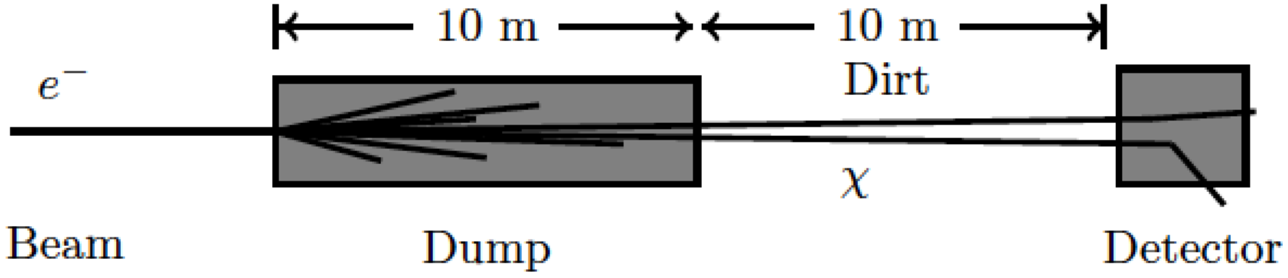


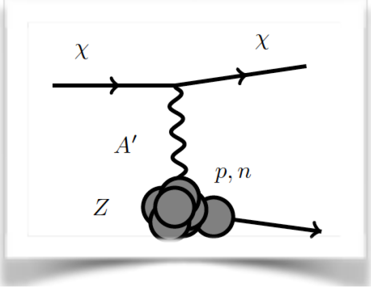
Fixed target DM production

Two steps process

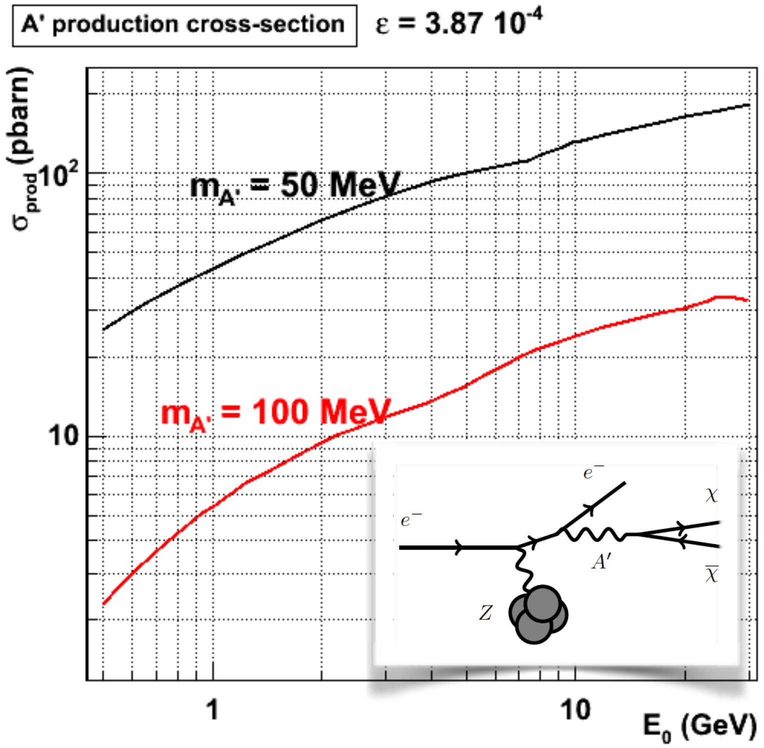
I) An electron irradiates an A' and the A' promptly decays to a χ (DM) pair

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





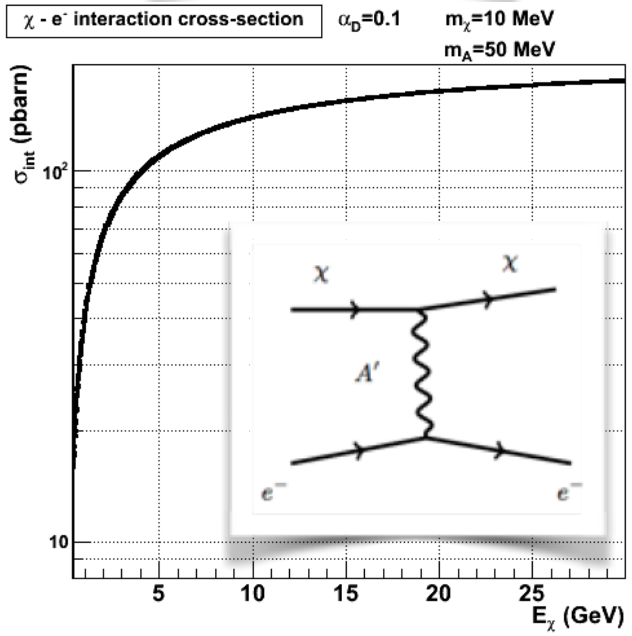
Elastic on nuclei



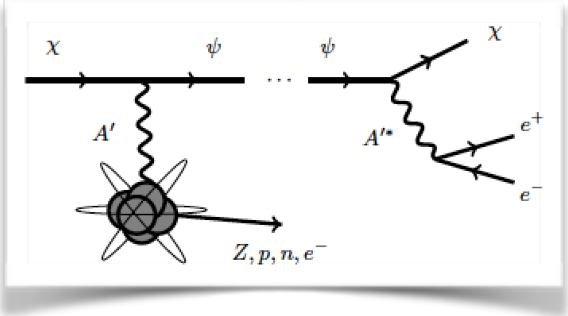
A' yield: $N_{A'} \propto \frac{\varepsilon^2}{m_{A'}^2}$

χ cross-section: $\sigma_{\chi e} \propto \frac{\alpha_D \varepsilon^2}{m_{A'}^2}$

Number of events: $N_\chi \propto \frac{\alpha_D \varepsilon^4}{m_{A'}^4}$



Elastic on electrons

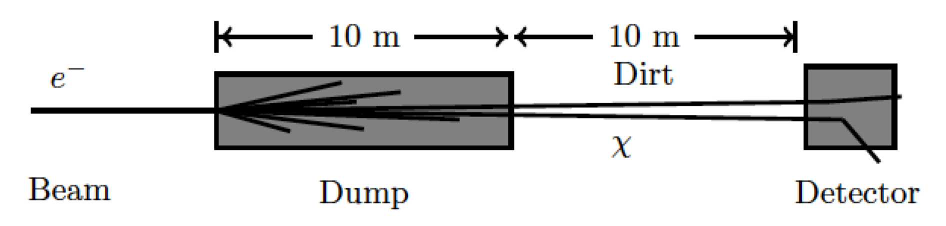


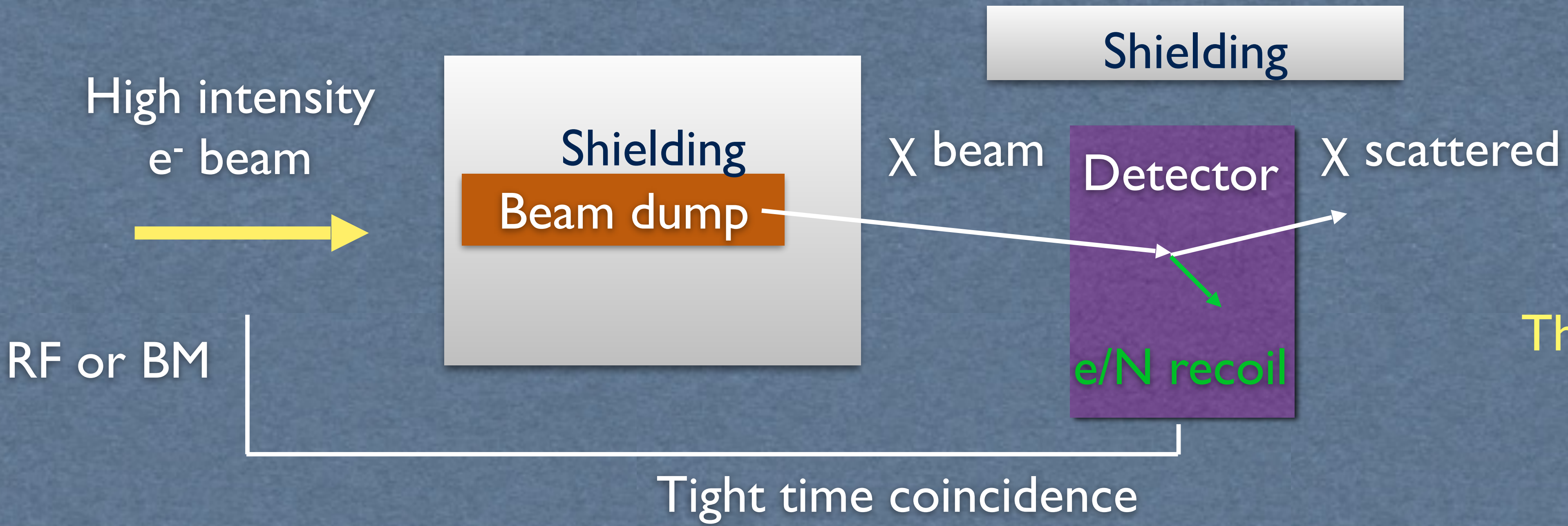
Inelastic on nuclei

- Weak Xsections dependence on E$_{beam}$ for E>few GeV
- At low energy detector acceptance can be an issue

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

Experimental set-up

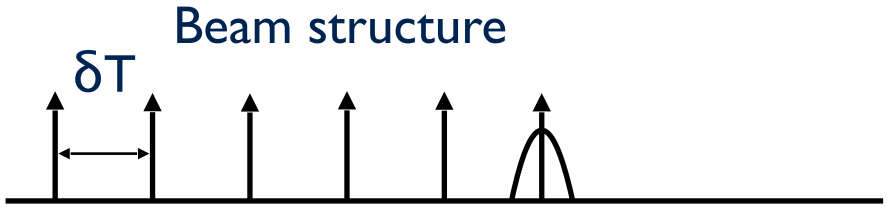




Experimental signature:

- proton (MeV)
- electron (GeV)

The simultaneous measurement of both provides a strong evidence of LDM existence

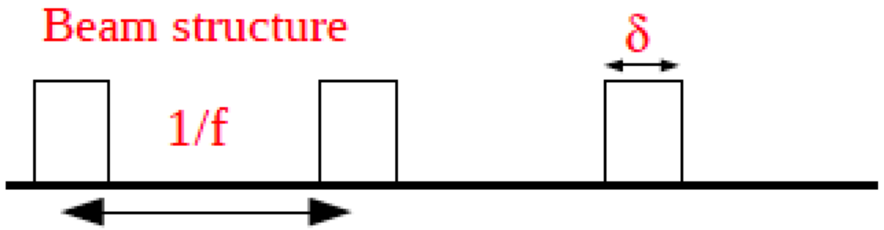


- **CW beam**: requires good detector time resolution

Background rejection factor

$$R \simeq \frac{\delta T}{3\sigma} <\simeq 100$$

σ = Detector Time Resolution (~ 0.1-1.0ns)

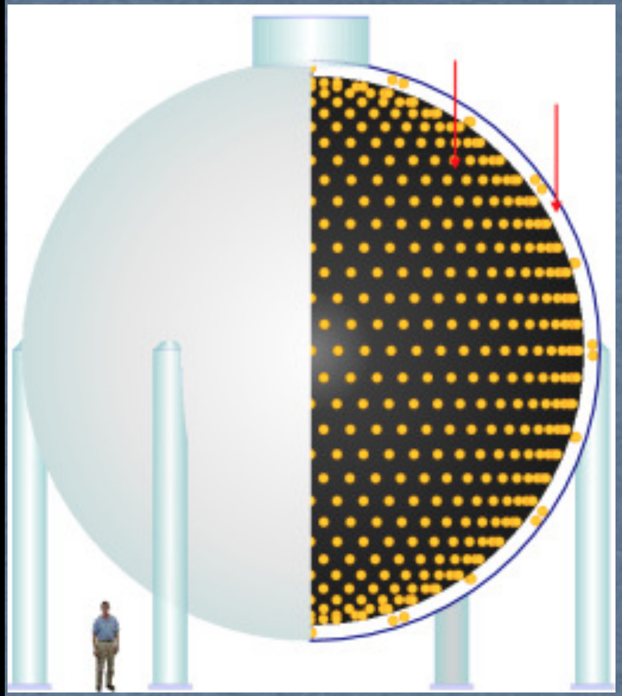


- **Pulsed beam**: less critical (if better than bunch size)

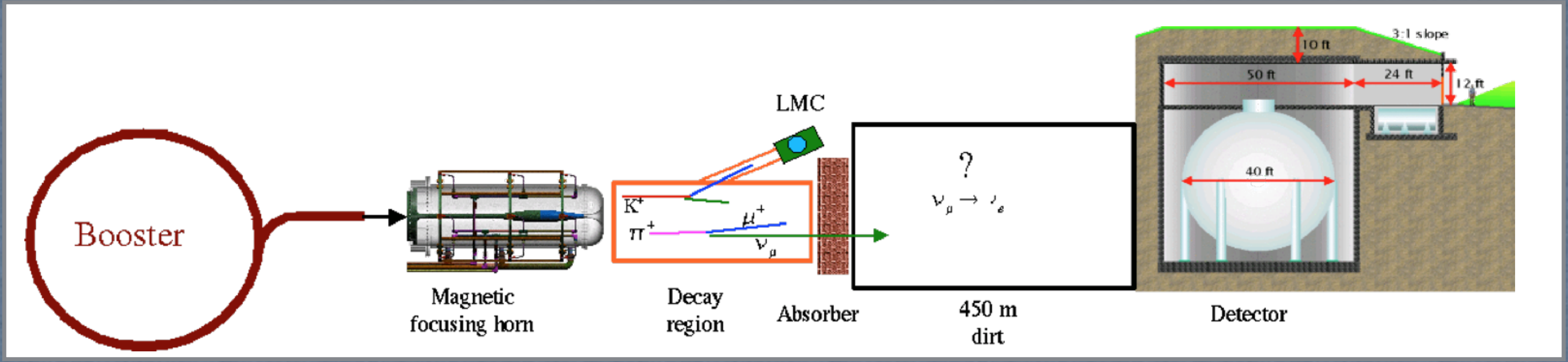
Background rejection factor

$$R = \frac{1}{f \cdot \delta} = 2 \cdot 10^5 \; @ \; 50\,Hz, 100\,ns$$

MiniBooNE@FERMILAB

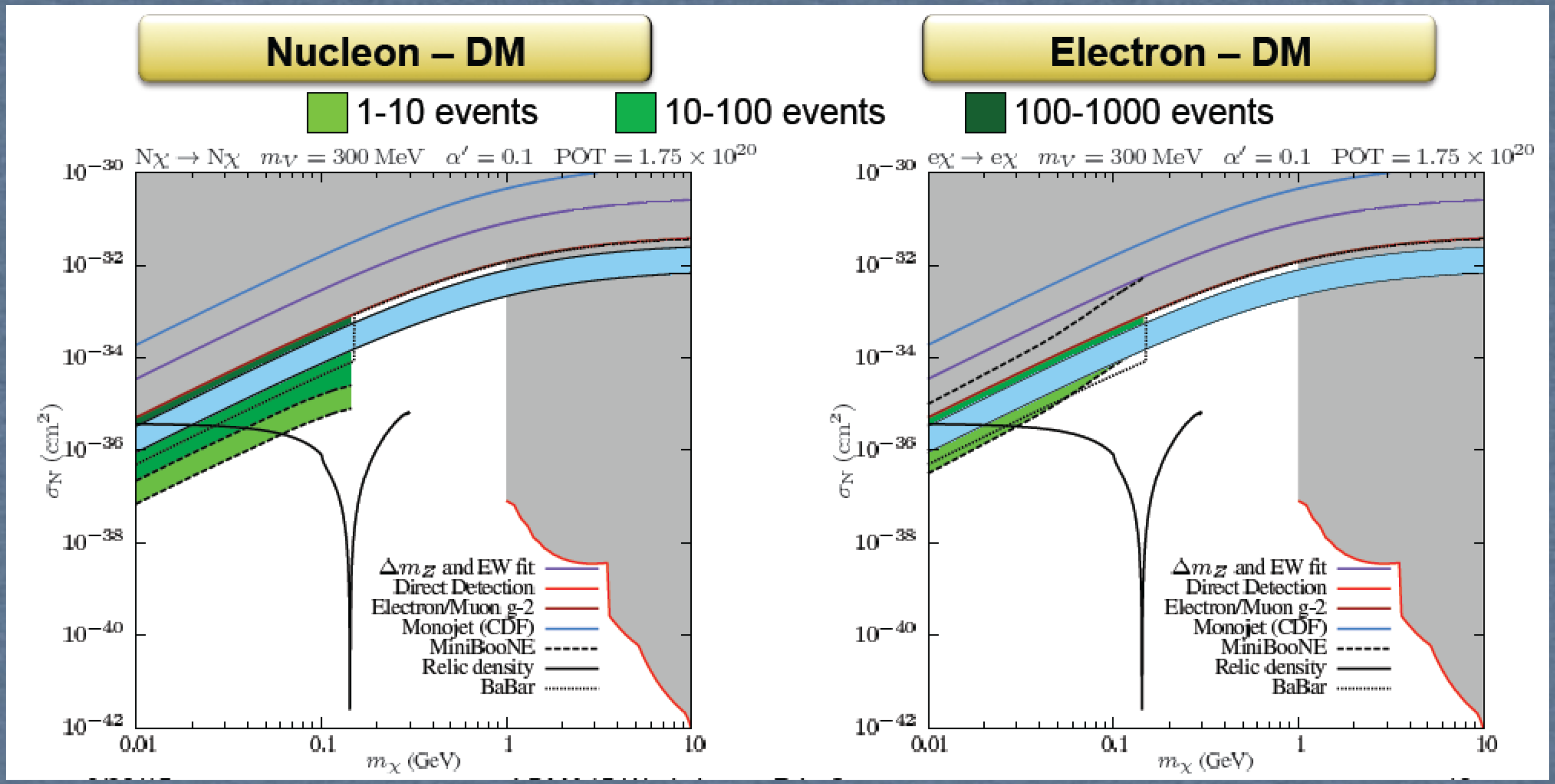


- 12 m spherical detector with 800 tons pure mineral oil (CH2)
- Cherenkov response with some scintillation from trace fluors
- Inner signal region 1280 8” PMTs + Outer veto region 240 8” PMTs



- 8.9 GeV Booster protons to BNB endstation (or Main Injector)
- At BNB, protons strike Be target (1.8 radiation lengths)
- Typical operation: 2x10^{20} protons on target (POT) per year

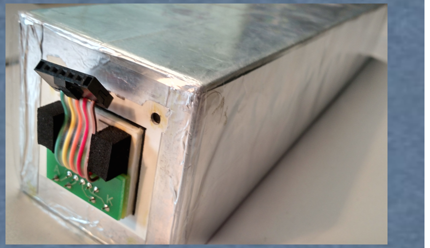
- Test run just ended
- Similar plans for T2K & ND280 (30 GeV p +50t near detector)

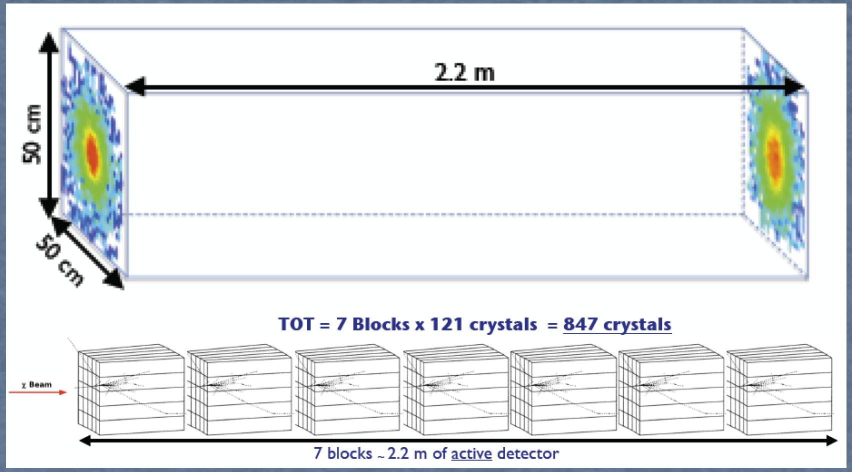


BDX - Dark matter search in a Beam Dump eXperiment

BDX@JLab reach

- 11 GeV, 10^{22} EOT (100 uA for 6 months, full parasitic)
- 1m3 detector





★ ~800 BaBar EndCup CsI(Tl) crystals

★ 11x11crystals (front face ~50x50 cm2) - 7 blocks (~total length :2.2 m)

★ Detection capability

>10MeV nucleon recoil

>100 MeV electromagnetic shower

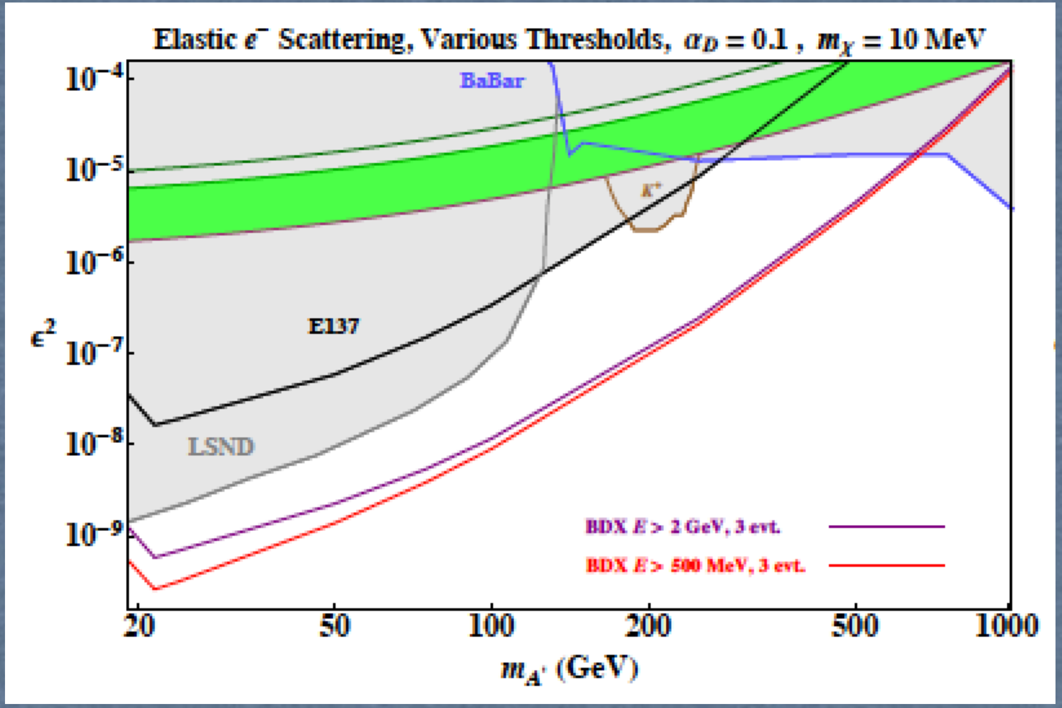
- Background simulations

★ Beam related: attenuated by using active and passive shielding

★ Cosmic: neutrino and neutrons are small while muon bg is sizeable

- Sim validation with bg measurement with a prototype

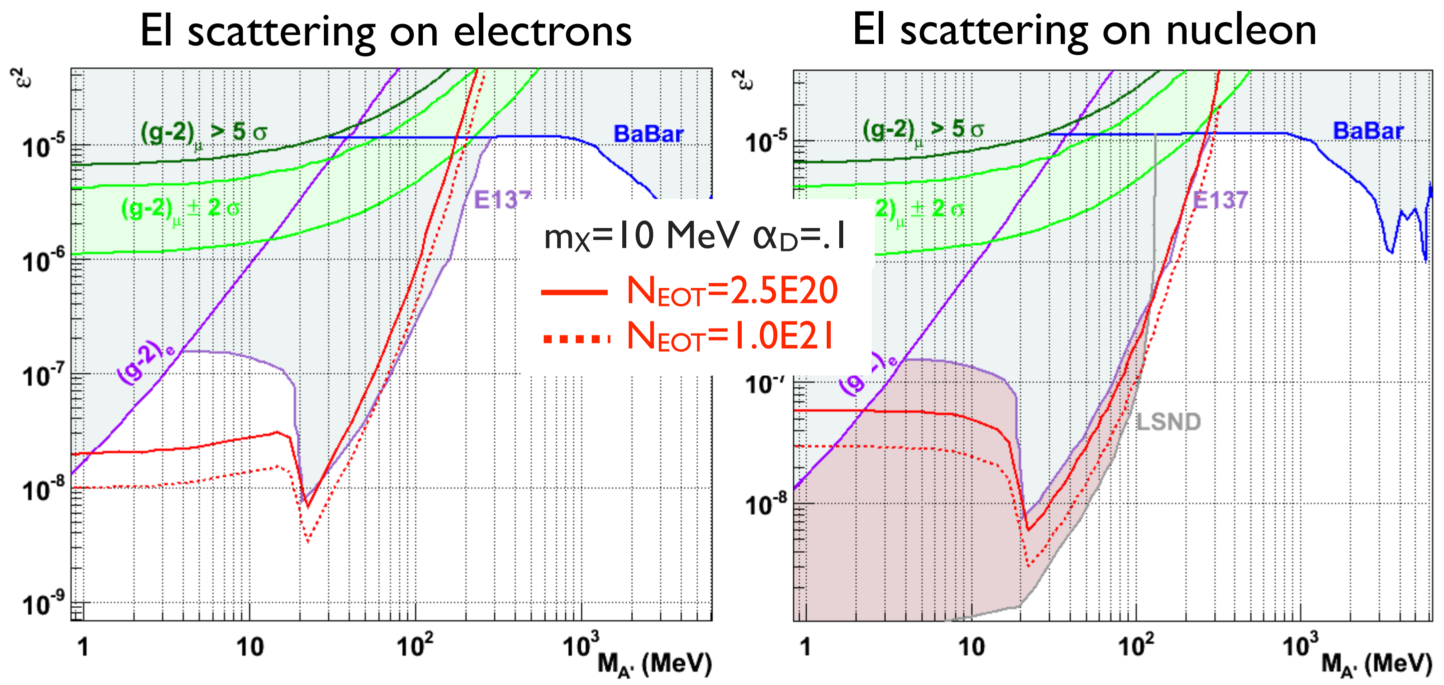
At least, two orders of magnitudes better than any previous experiments



✳BDX LOI submitted to JLAB PAC42 - August 2014 (http://arxiv.org/abs/1406.3028)

✳Positive feedback: physics case highly appreciated, encouraged to present a full proposal (expected in July 2016)

BDX test-runs at other facilities

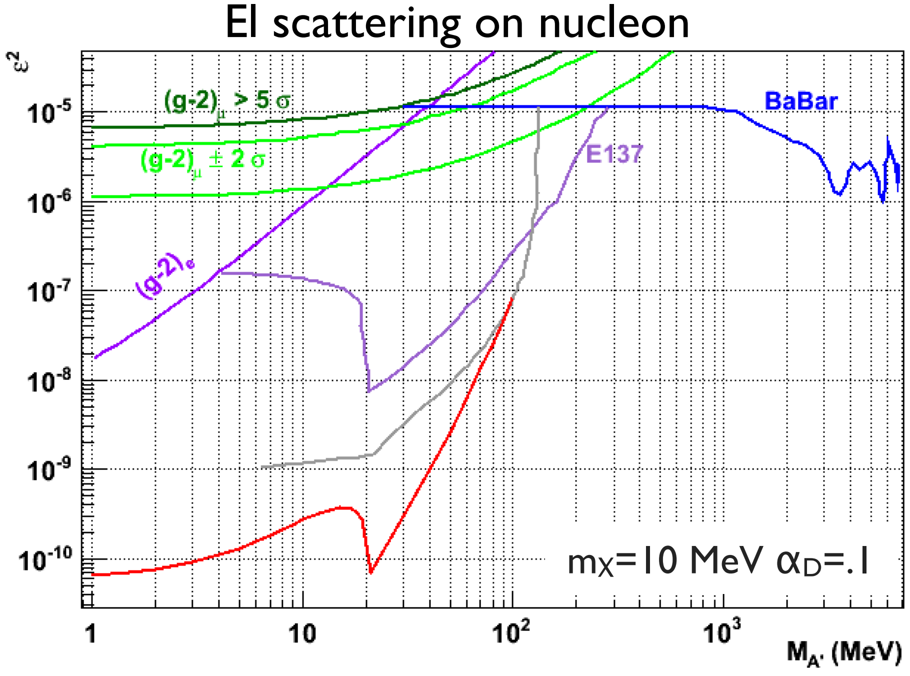


BDX @ LNF

- E_{e-} = 1.250 GeV (now 0.75GeV)
- EOT ~ 10^{20}-10^{21} year^{-1} (now 10^{19})
- Pulsed beam 50Hz
- Minimal infrastructure costs

- Re-use of BaBar crystals (~1080)
- Detector: 60x60x225 cm3 at 5m from the dump
- 1y run (within PADME Experiment)
- 2-3y from now

P.Valente



BDX@Cornell

- E_{e-} = 286 MeV
- EOT ~ 2.5 10^{24}
- CW beam
- Infrastructure costs ?
- Time line ?

- Re-use of BaBar or Cleo crystals (~1080)
- Detector: 60x60x225 cm3 at 5m from the dump

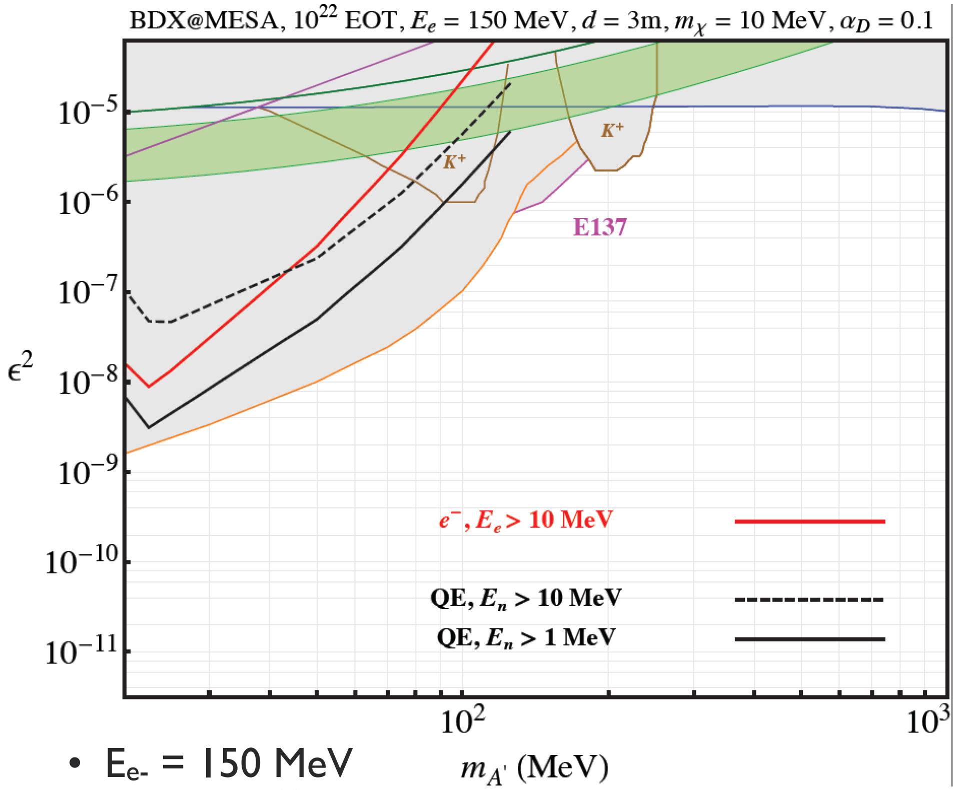
???

Not applicable for *energy recovery* beam

???

J.Alexander

BDX@Mainz (MESA)



- E_{e-} = 150 MeV
- EOT ~ 10^{22}
- CW beam (3ns)
- Infrastructure costs limited
- Time line ?

- Re-use of BaBar crystals (~1080)
- Detector: 60x60x225 cm3 at 3m from the dump
- 3y run (parasitic to PV exp)

- Proposal submitted

A.Denig

BDX@SLAC

- E_{e-} = 20 GeV
- EOT ~ 10^{22}
- Pulsed beam 180Hz
- Infrastructure costs limited
- Time line ?

Is the sweetest spot so close??

Conclusions

- ✳Existence of Dark Matter is a compelling reason to investigate new forces and matter over a broad range of mass
- ✳Accelerator-based (Light)DM search provides unique feature of distinguish DM signal from any other cosmic anomalies or effects
- ✳Visible A' decay searches are excluding a significant part of parameters space
- ✳Light Dark Matter (coupled to Dark Photon **invisible** decay) could explain null results resetting experimental limits
- ✳Many opportunities for experimental exploration and discovery with fixed target exps searching for LDM with orders of magnitude more sensitivity
- ✳Extensive experimental plans at high intensity e-facility: JLab, LNF, Cornell, Mainz (+ p beam at FNAL and CERN)
- ✳Discovery or decisive tests of simplest scenarios will possible in the next ~5-8 years!