Light Dark Matter search using electron beams

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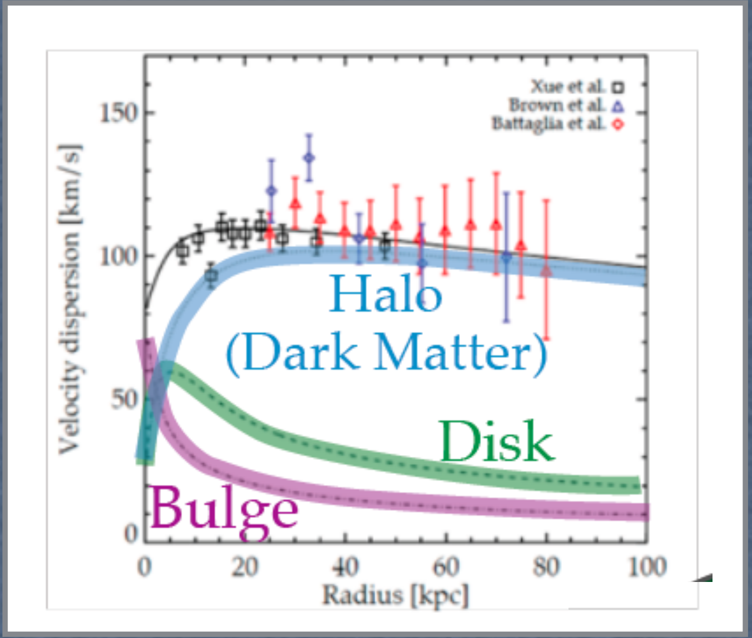
Dark matter proofs

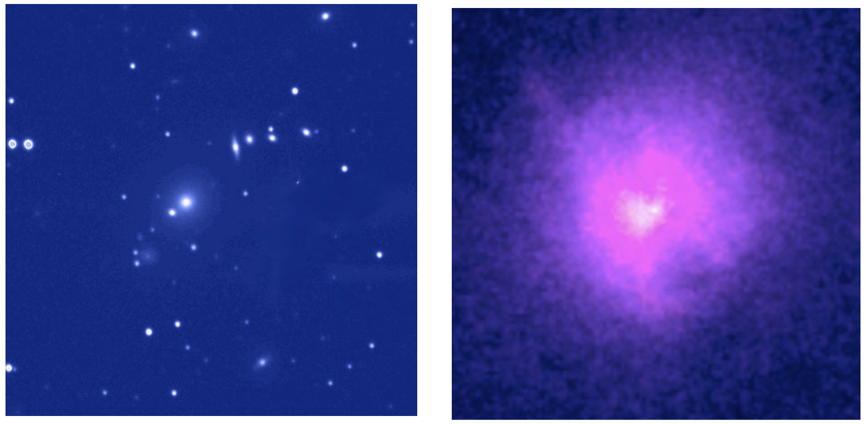
★ Galaxies rotation curve shows constant velocity despite *visible* mass is concentred at the center



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

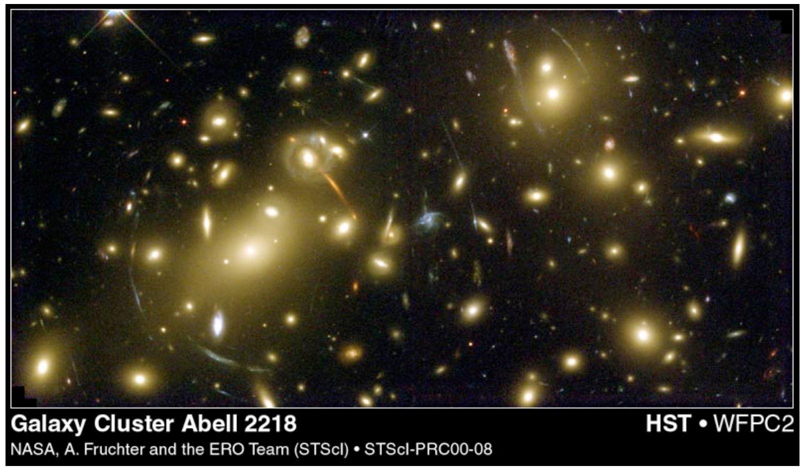
★ The mass of galaxy clusters can be estimated in different ways:

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



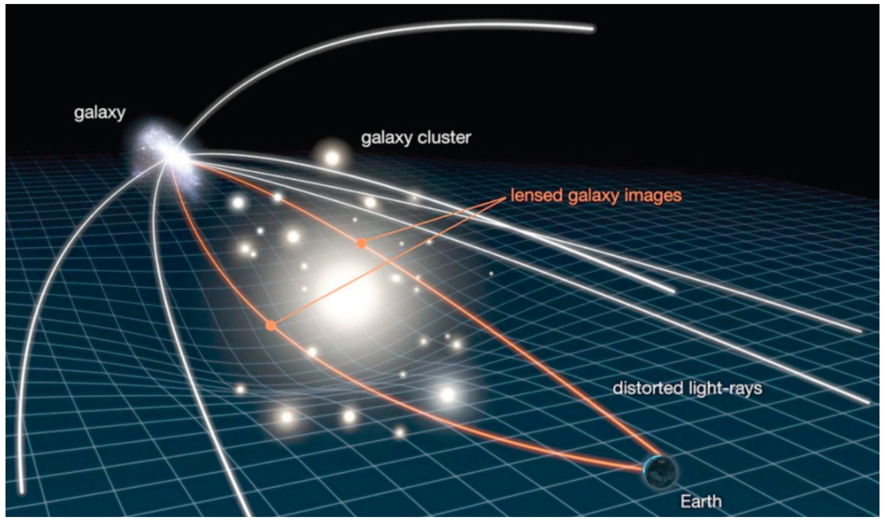
Hydra A galaxy cluster. Chandra X-ray observations reveal a large cloud of hot gas that extends throughout the cluster

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

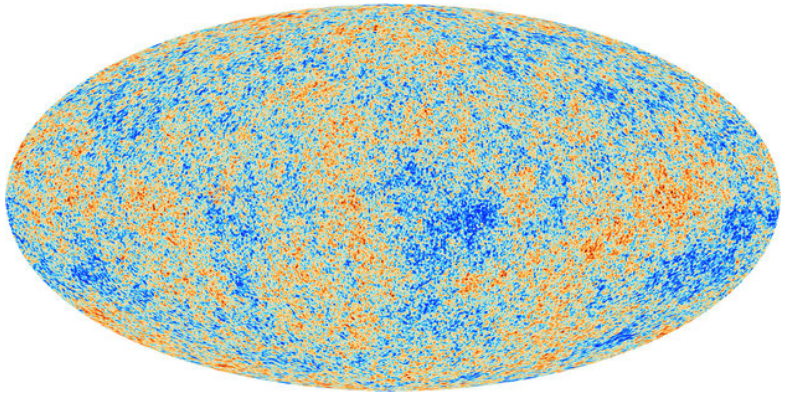


Galaxy Cluster Abell 2218 HST • WFPC2
NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08

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



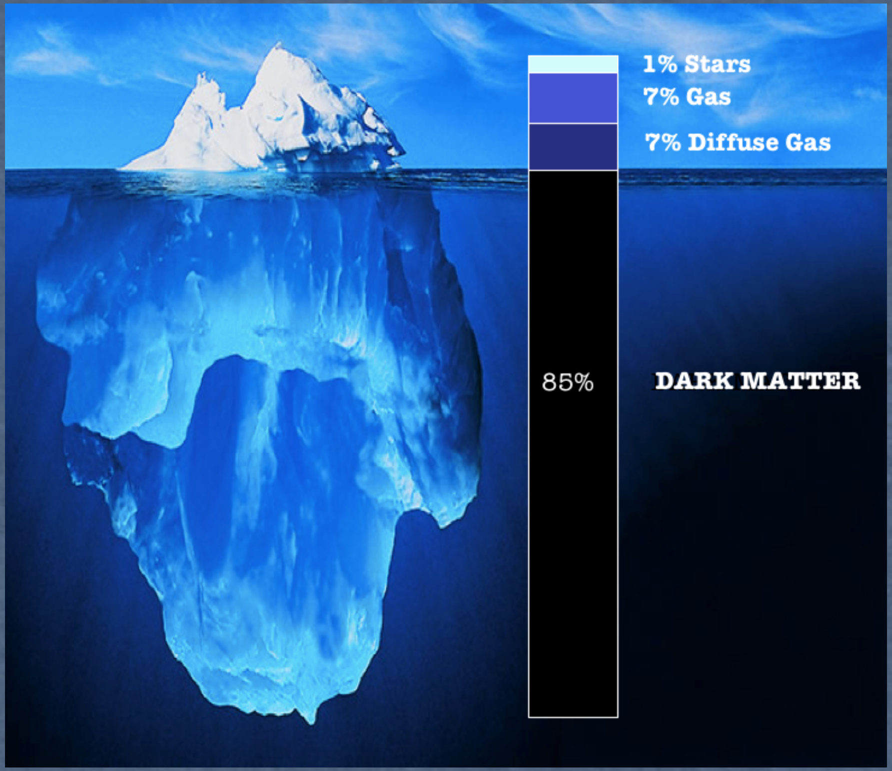
★ DM in CMB
★ Clusters of galaxies
★ Cluster collisions
★ …



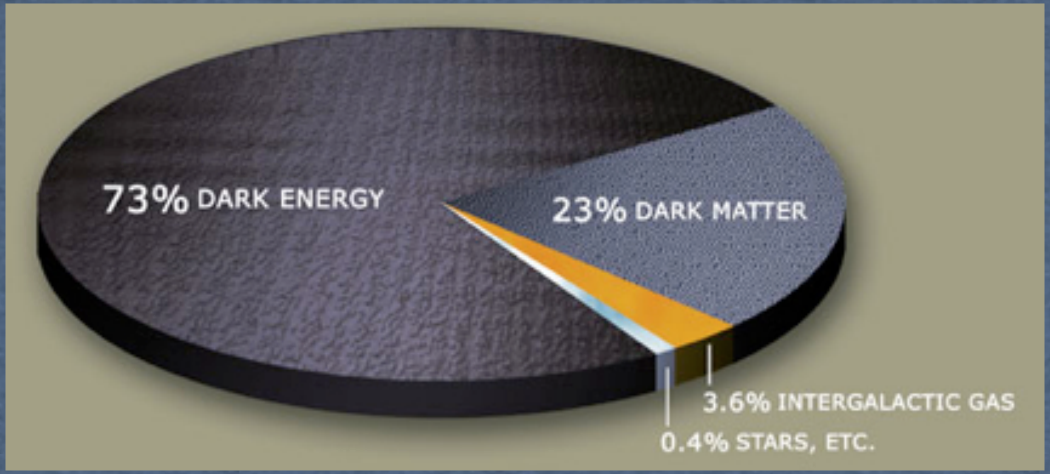
Compelling astrophysical indications about DM existence

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

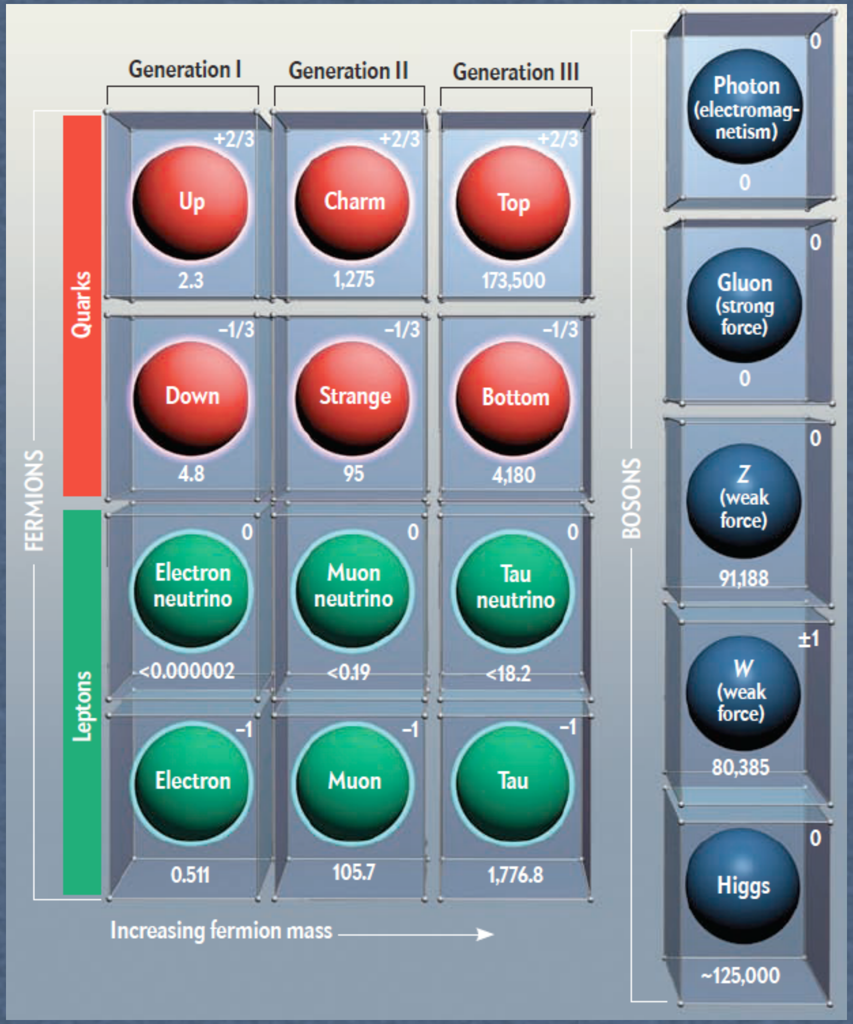
4 fundamental interactions known so far: strong, electromagnetic, weak and gravitational

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?

Yes, if we do a couple of assumptions:

★ DM thermal origin

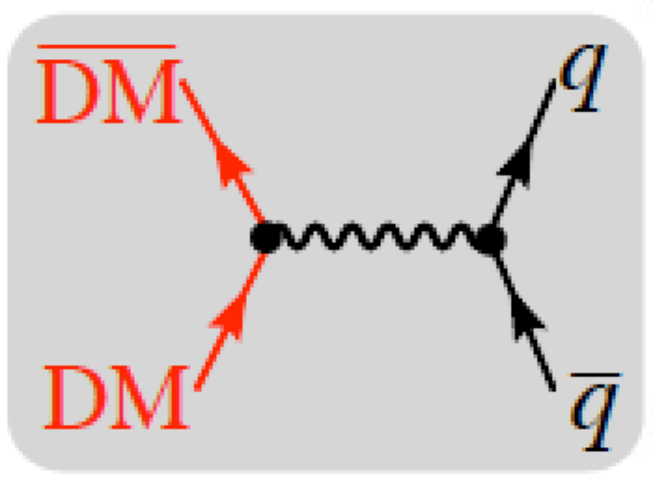
in the early Universe DM was in thermal equilibrium with regular matter (via annihilation)

★ 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:

$\langle \sigma v \rangle \sim 3x10^{-26}\ cm^3/s \sim 1/(20\ TeV)^2$

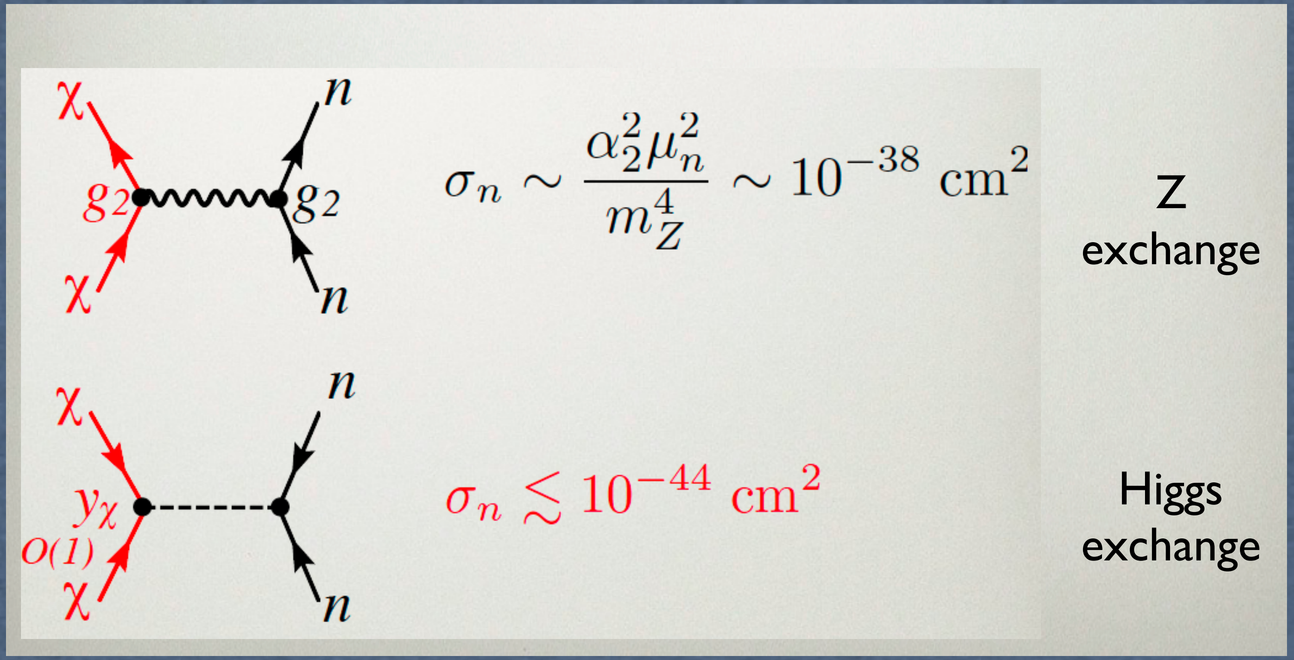


$\langle \sigma v \rangle \sim M^2_{DM}/M^4_{mediator}$

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

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



$$\sigma_n \sim \frac{\alpha_2^2 \mu_n^2}{m_Z^4} \sim 10^{-38}\ \mathrm{cm}^2$$

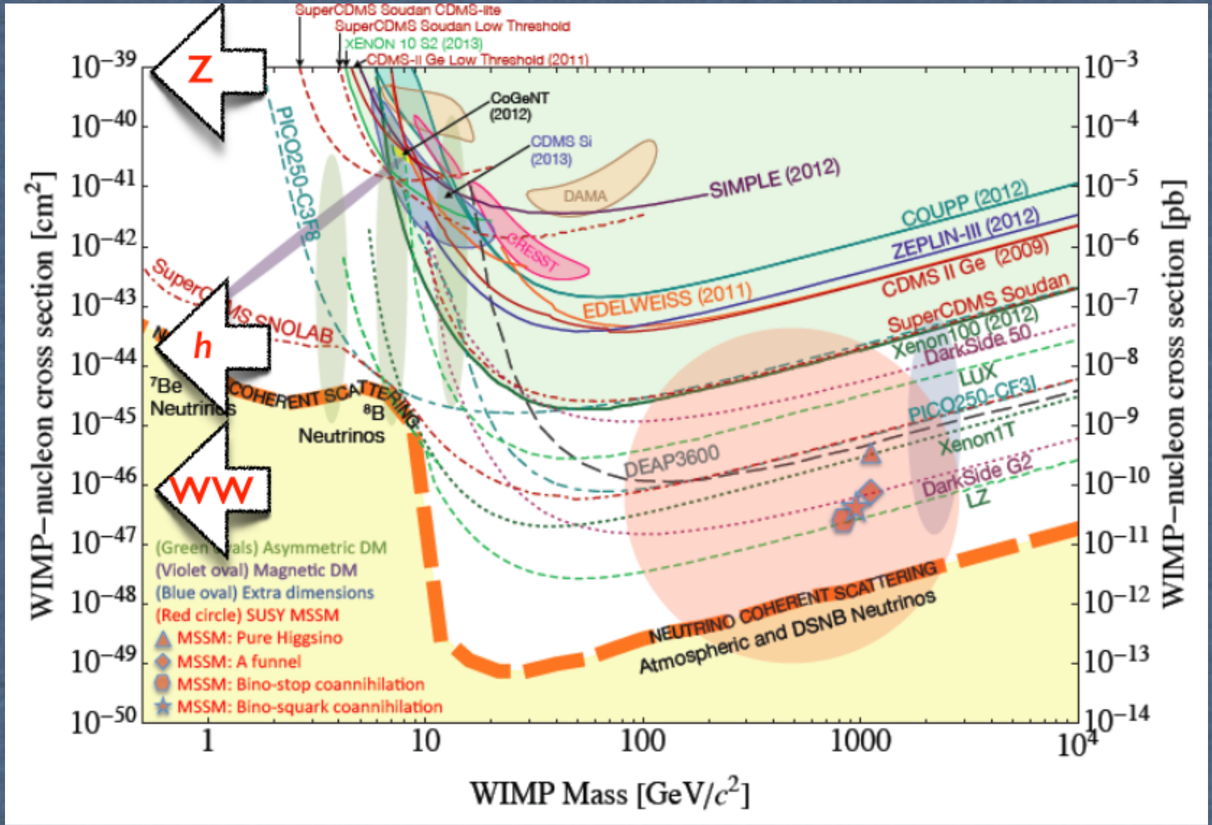
Z exchange

$$\sigma_n \lesssim 10^{-44}\ \mathrm{cm}^2$$

Higgs exchange

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 through Z boson ($\sigma \sim 10^{-39}$cm^2): ruled out
  - Approaching limits for scattering through the Higgs ($\sigma \sim 10^{-45}$cm^2)
  - Close to irreducible neutrino background

Direct Detection

1 MeV

1 GeV

Mz

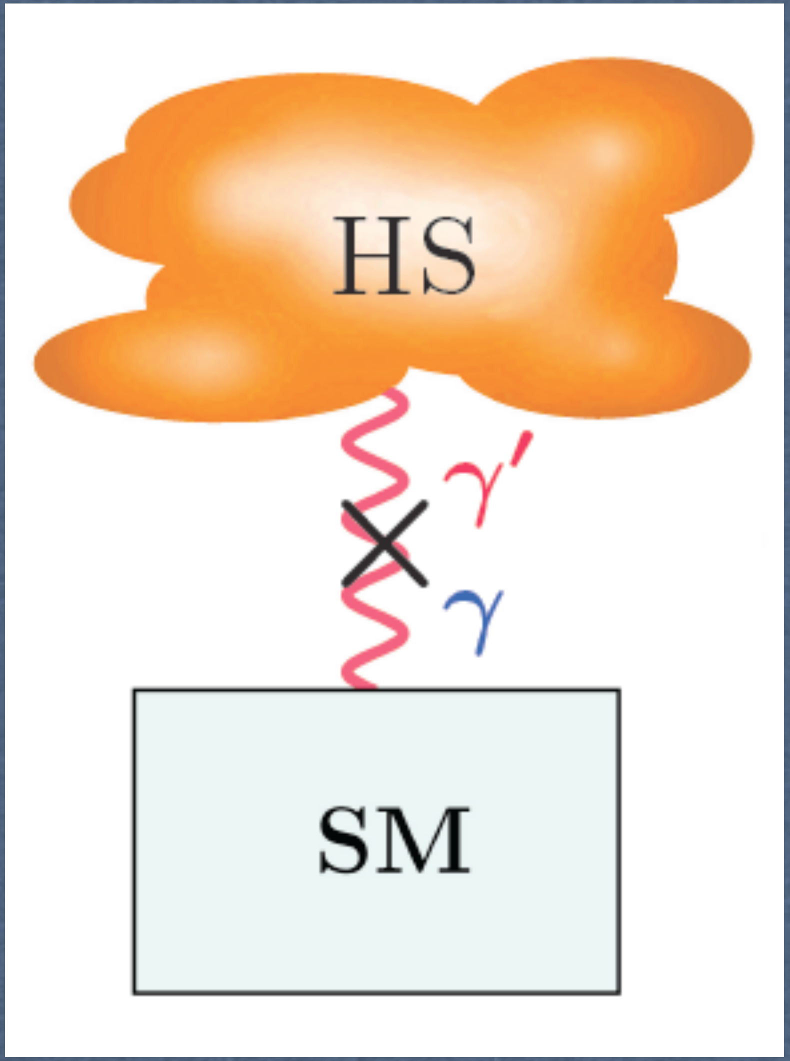
10 TeV

WIMPs

✳ No signal in direct detection

✳ Experiments have (almost) no sensitivity to (light) DM (<1 GeV)

Introducing a new force in nature



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

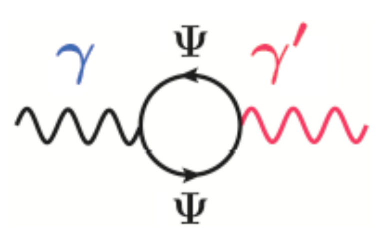
✳HS not charged under SM gauge groups (and v.v.)
no direct interaction between HS and SM
HS-SM connection via messenger particles

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

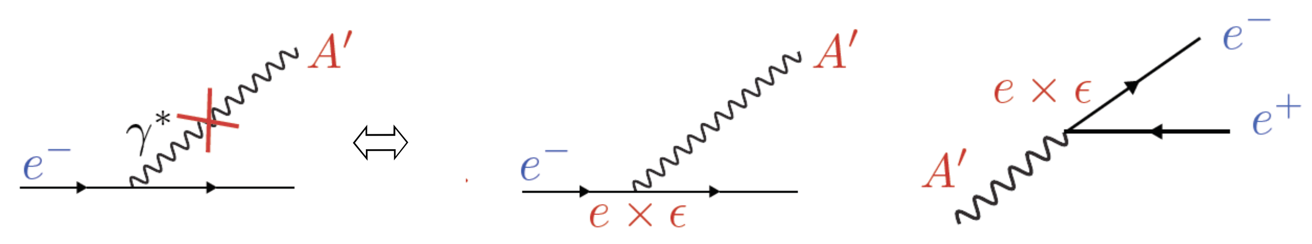
$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\chi}{2}X_{\mu\nu}\overset{\text{Hidden}}{\underset{\text{Visible}}{F^{\mu\nu}}} + \frac{m^2_{\gamma'}}{2}X_\mu X^\mu$$



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

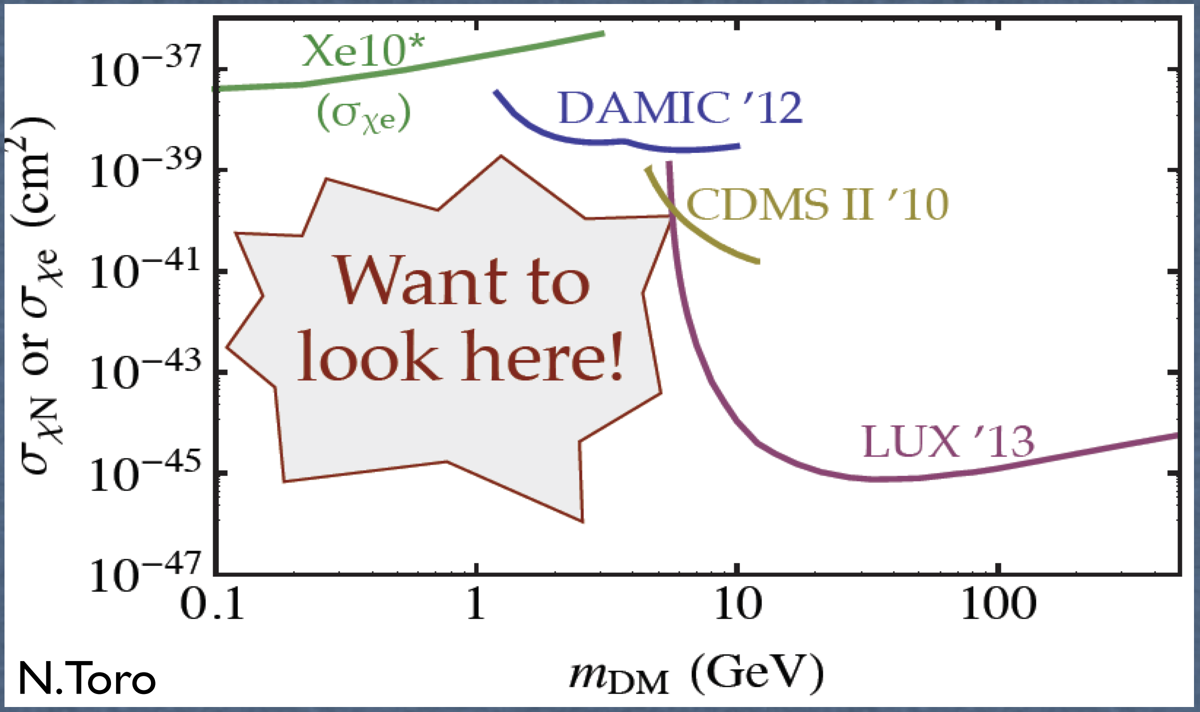
γ'/A' couples to SM via electromagnetic current (kinetic mixing)

➜ $A_\mu \rightarrow A_\mu + \varepsilon a_\mu$ $\chi=\varepsilon$ ~ 10^{-6}-10^{-2} ($\alpha^{\Delta\alpha\rho\kappa\Pi\eta o\tau o\nu} = \varepsilon^2 \alpha_{\varepsilon\mu}$)



Light Dark Matter

★ Experimental limits



N.Toro

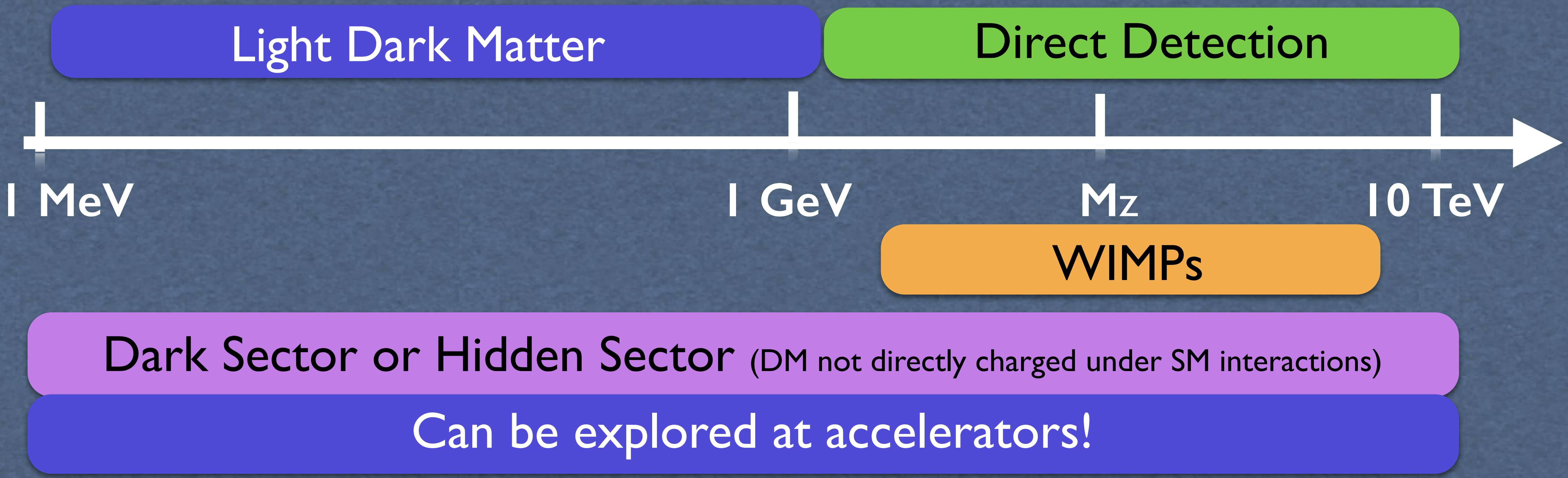
Light Dark Matter with a (almost) weak interaction (new force!)

- 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 at large masses

Accelerators-based DM search

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

- **High intensity**
- **Moderate energy**



Light Dark Matter

Direct Detection

1 MeV

1 GeV

Mz

10 TeV

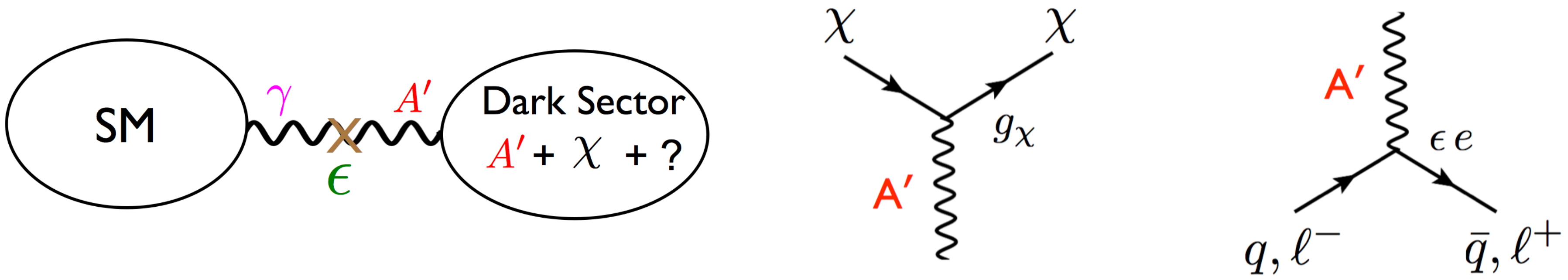
WIMPs

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

Can be explored at accelerators!

Dark forces and dark matter

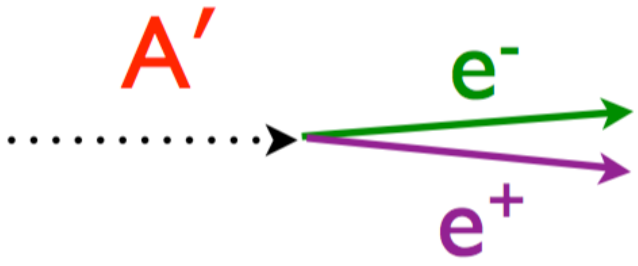
(Light WIMPs - light mediators)



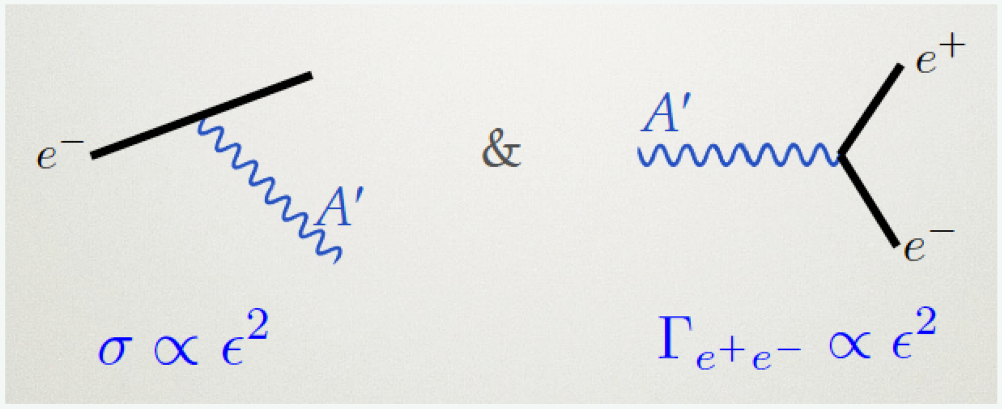
4 parameters: $m_\chi, m_{A'}, \epsilon, g_\chi$

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

Visible



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



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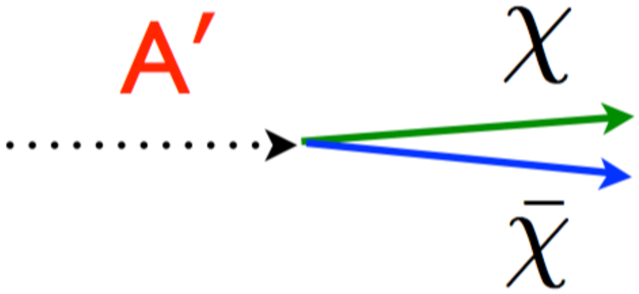
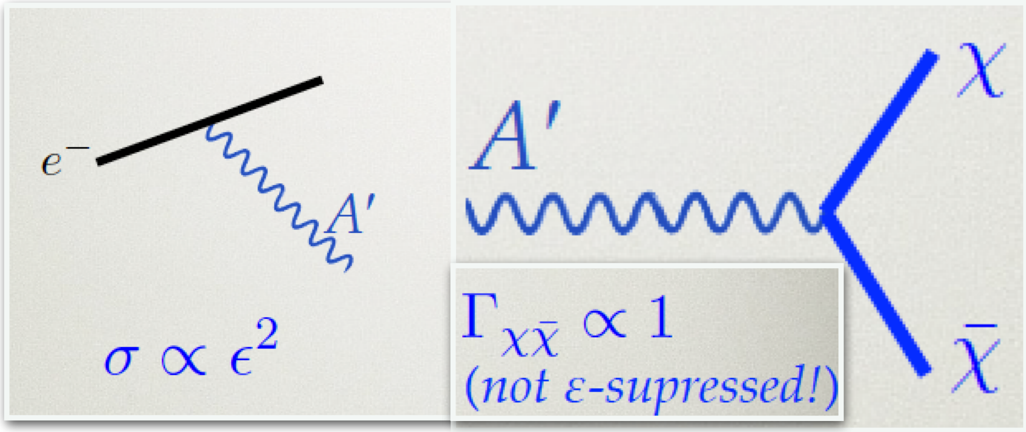


- Depends on 4 parameters
- $m_{A'} > 2m_\chi$ (on-shell)
- $\alpha_D= g^2_\chi/4\pi >> \varepsilon^2\alpha_{EM}$

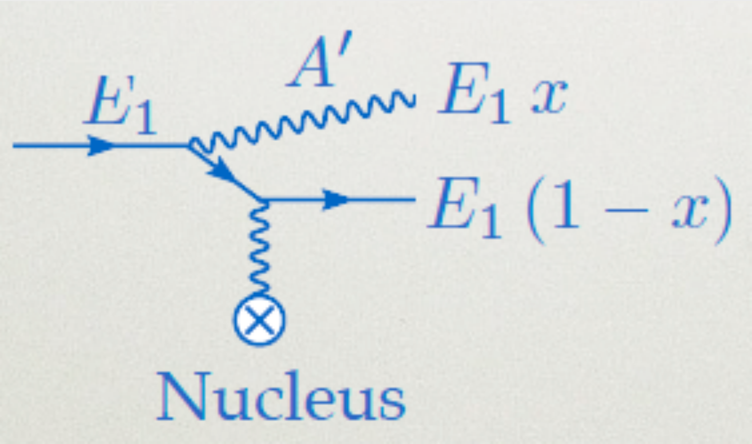


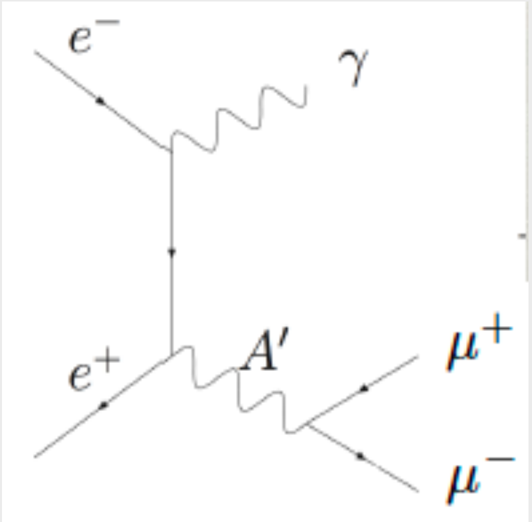
Fixed target vs. collider

Fixed Target

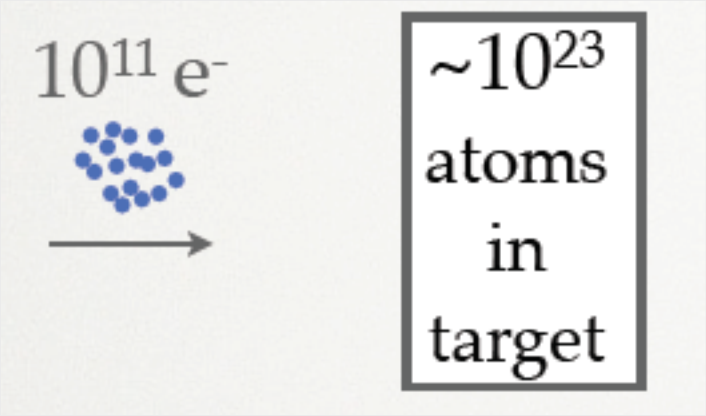
e+e- colliders

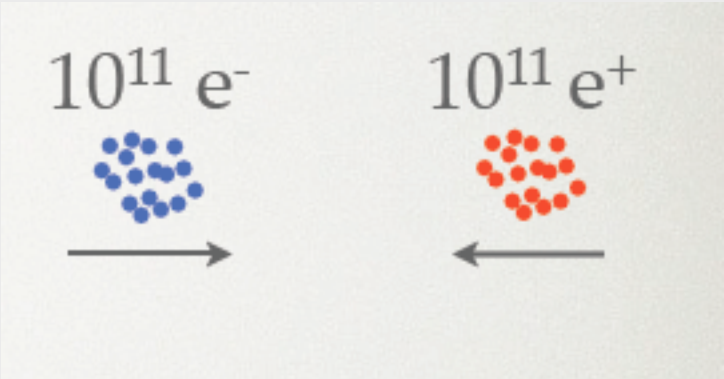
Process





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)

- high backgrounds
- limited A' mass

- low backgrounds
- higher A' mass

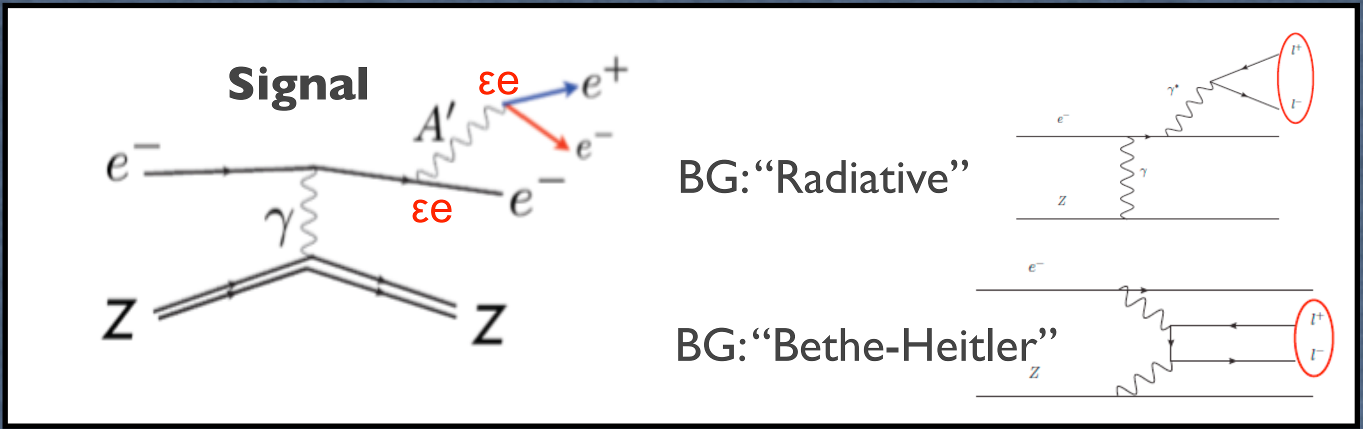
HPS@JLab
Heavy Photon Search

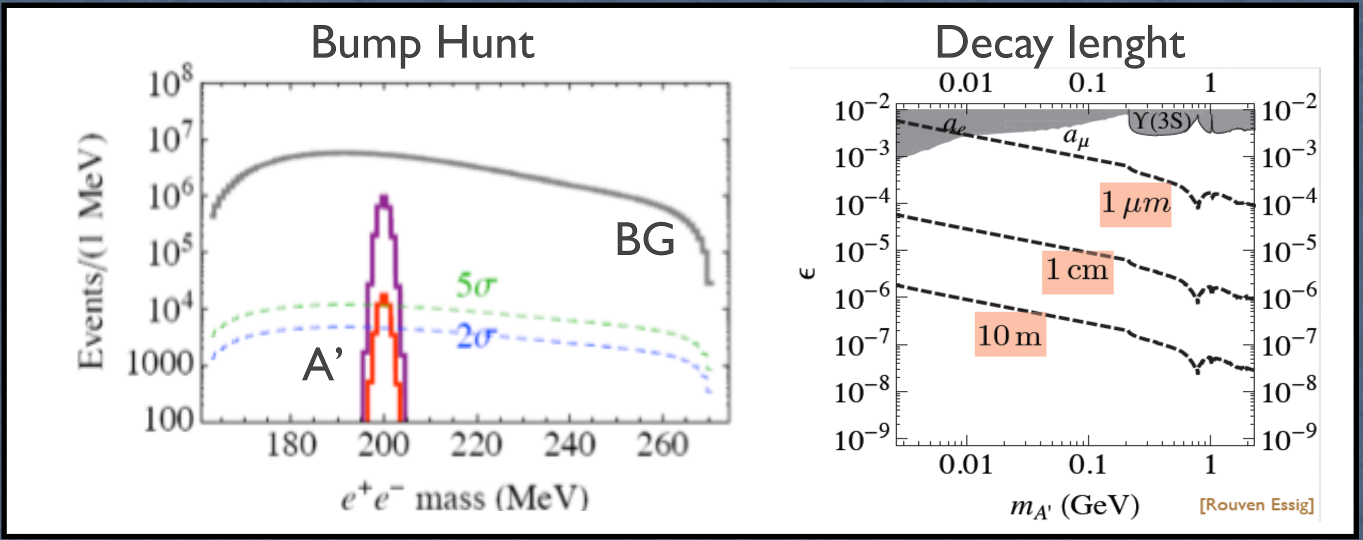
Heavy photon signatures in HPS

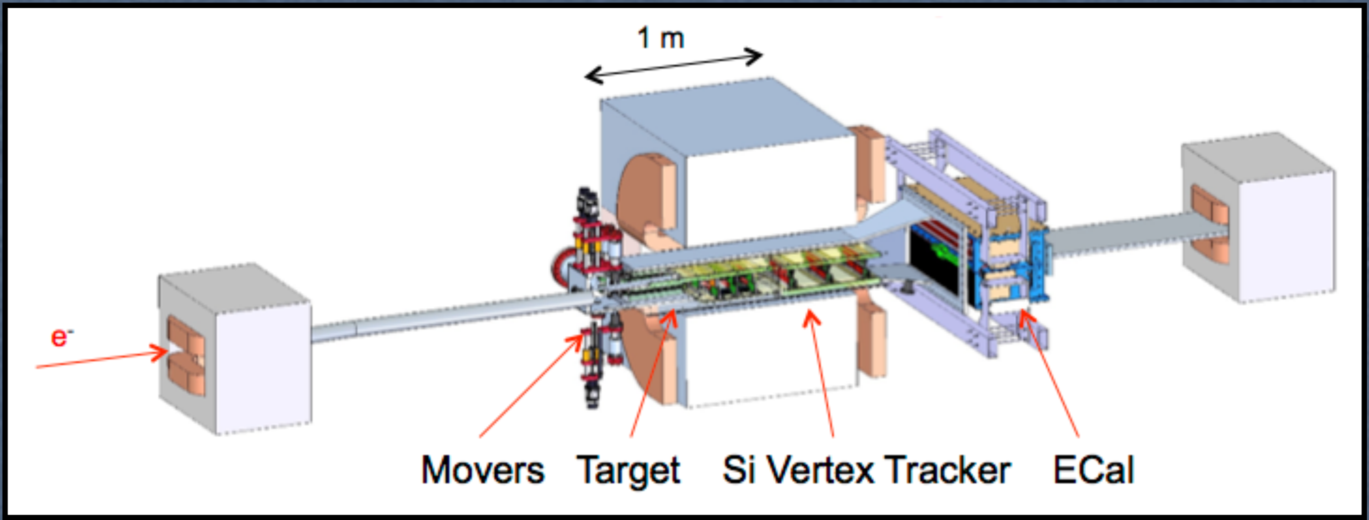
1) Bump Hunting (BH)
Narrow e+e-resonance over a QED background
➥ good mass resolution: $\sigma_{A'mass}$~1 MeV

2) Secondary decay vertex (vertexing)
Detached vertex from few mm to tens cm
➥ good spacial resolution: σ_{vertex}~1mm

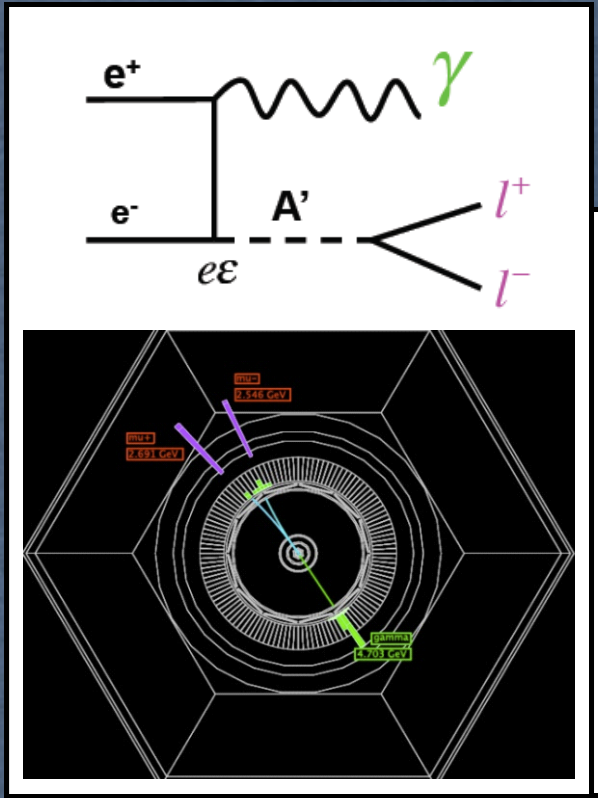
BH + Vertexing = enhanced experimental reach





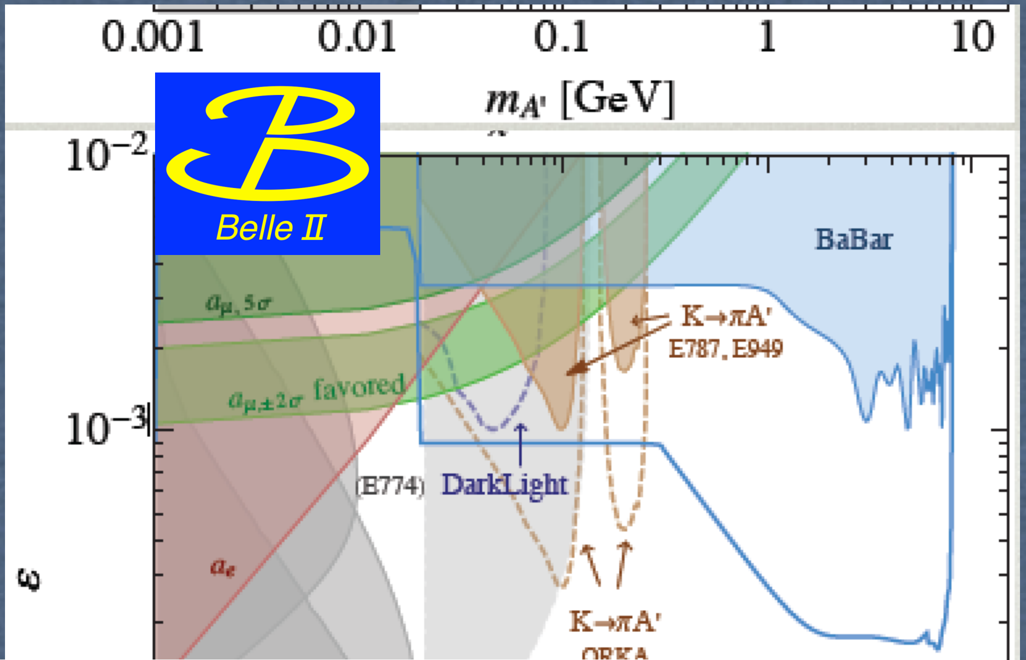


e+e- Colliders Recent & future results
- visible -

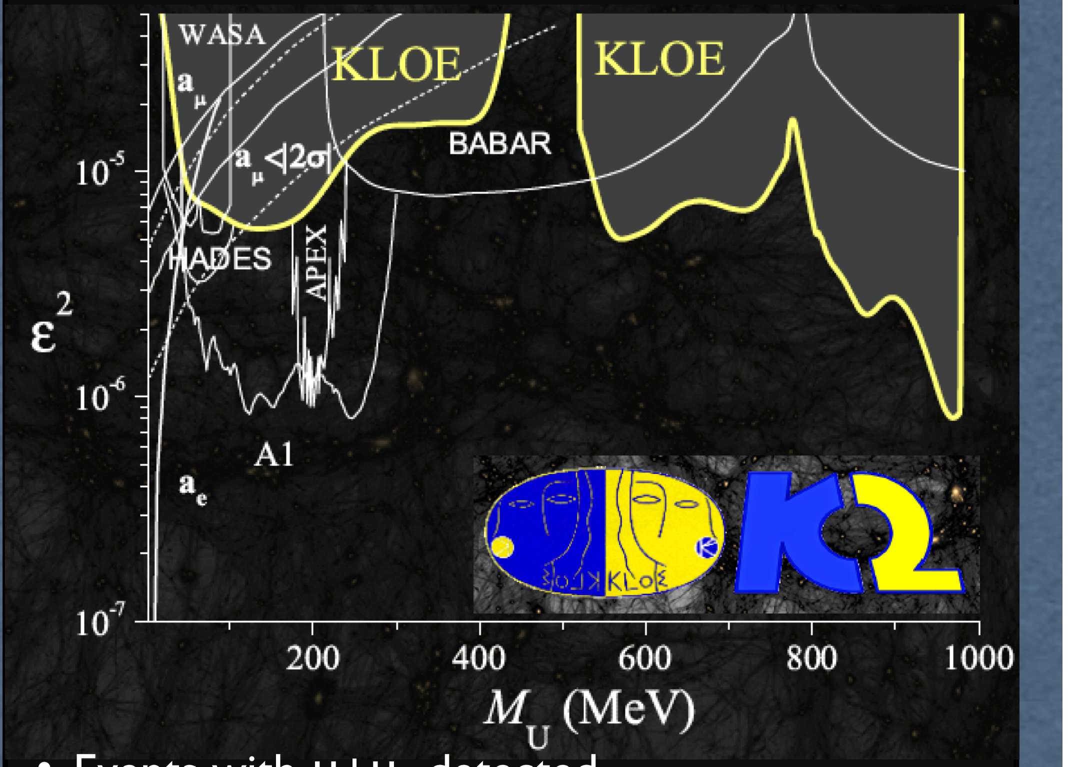


BABAR

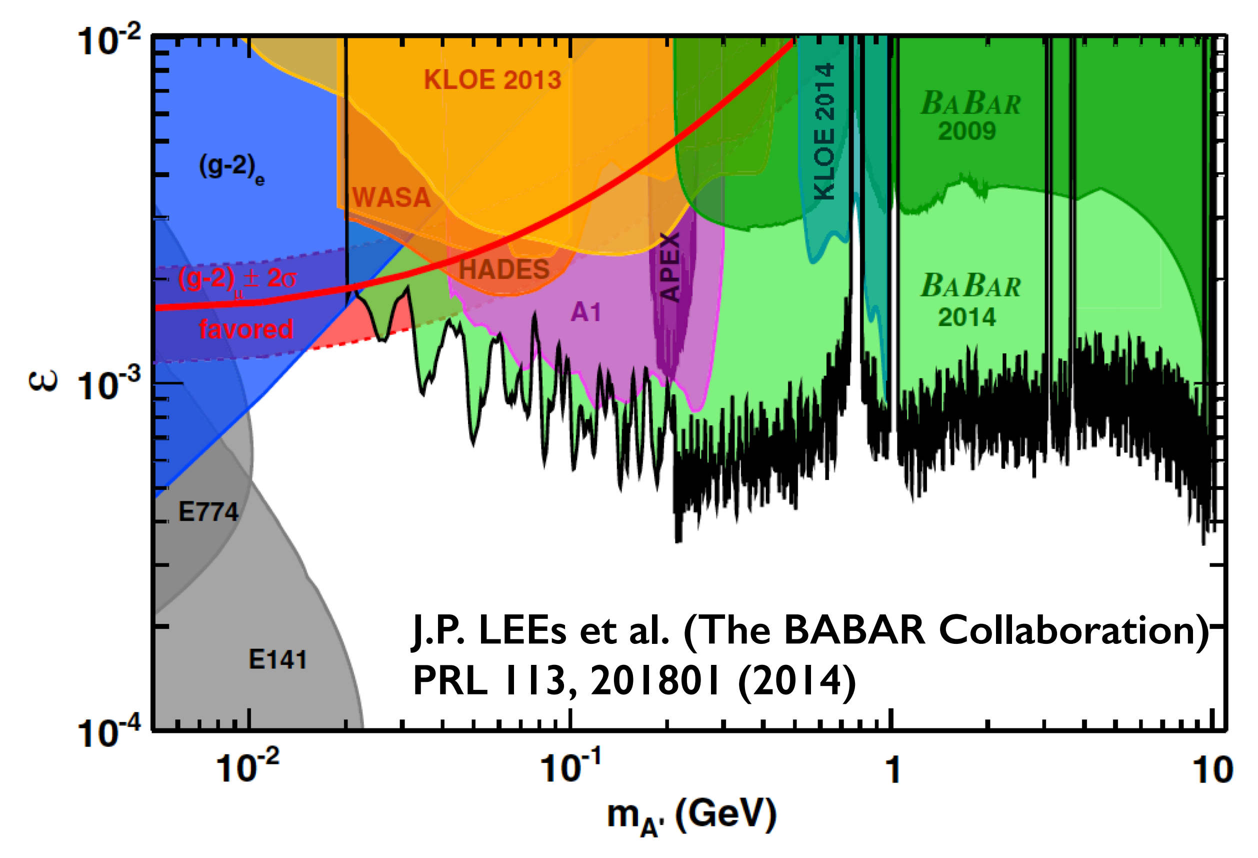
- 1gamma + 2 opposite leptons
- Di-lepton mass fit to a bg
- Mass resolution: 1.5 MeV - 8 MeV
- Int (L) = 514 fb^{-1}



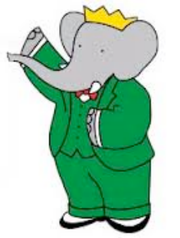
Phys. Lett. B 736 (2014) 459



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



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

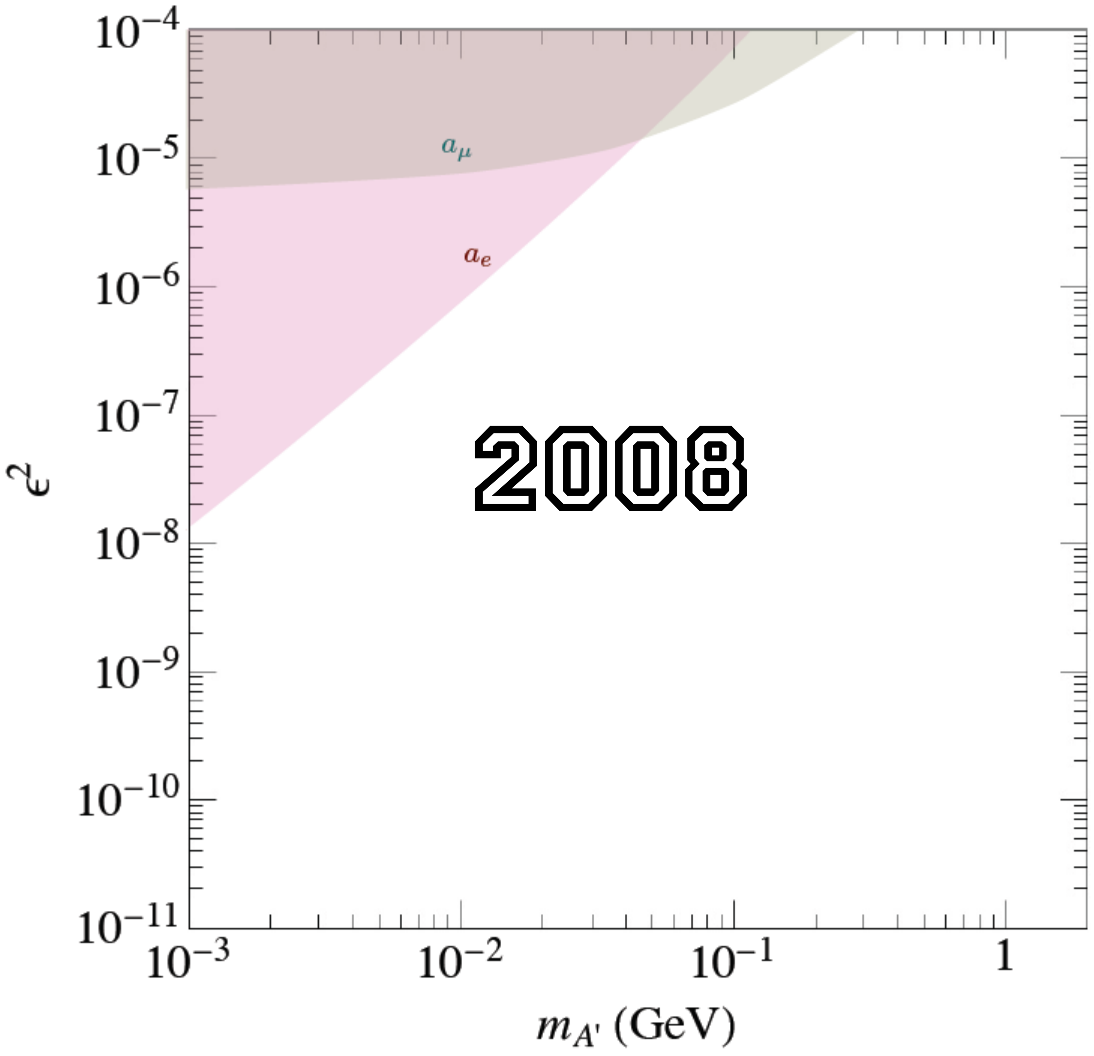


Hunting for A' at accelerators

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- → $\gamma' \gamma$ → $\mu\mu \gamma$
→ **BABAR,BELLE,KLOE**
Meson decays: $\pi^0, \eta, \eta', \omega'$, → $\gamma' \gamma$ → Lepton⁻ Lepton⁺ γ
→ **KLOE, BES3, NA48, HC**

coupling vs mass

Parameter space
Coupling vs Mass



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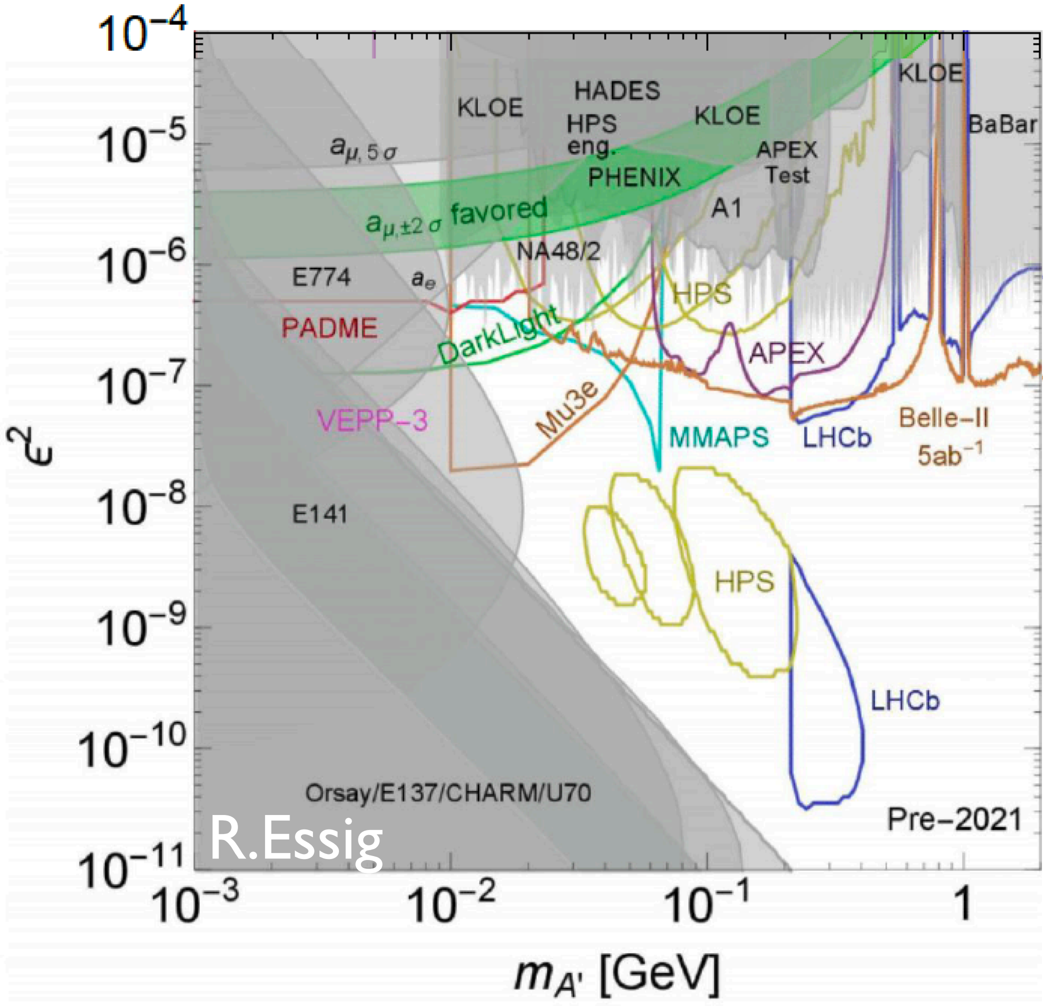
No positive signal (so far) but limits in parameter space coupling vs mass

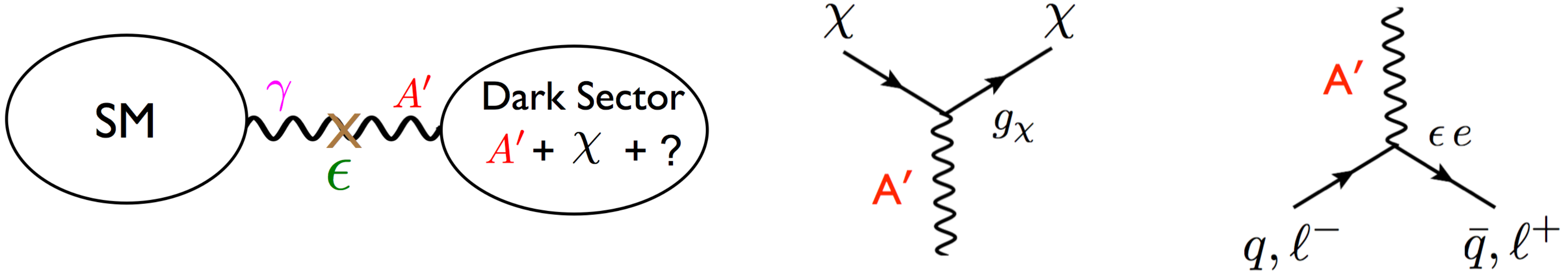
Parameter space
Coupling vs Mass



R.Essig

Dark forces and dark matter

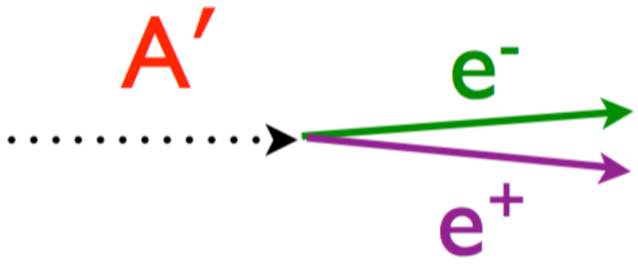
(Light DM - light mediators)



4 parameters: m_χ, $m_{A'}$, ε, α_D

m_χ, ~ $m_{A'}$: MeV - GeV

Visible



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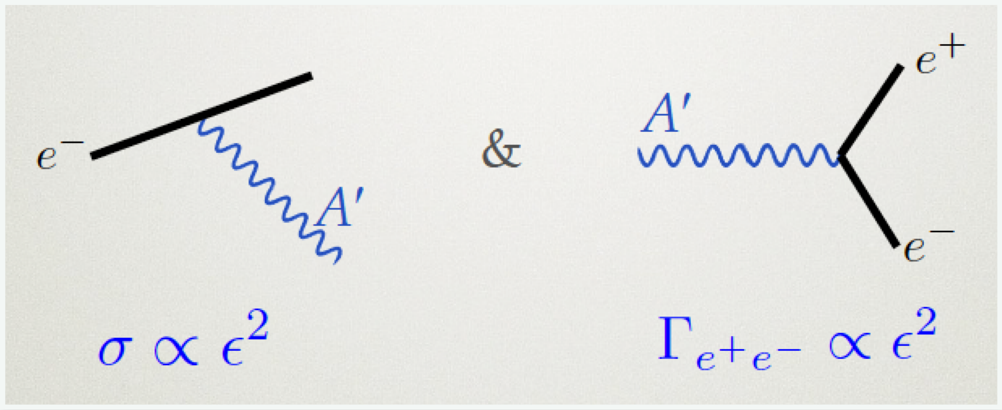

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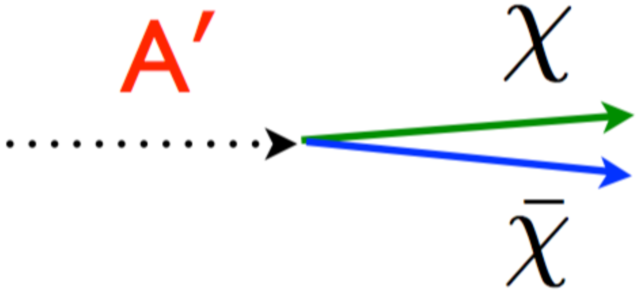

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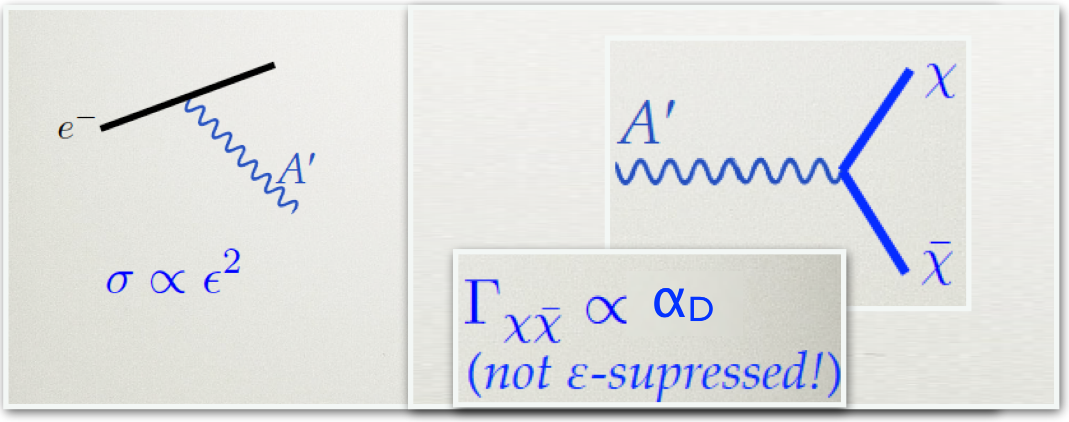

Particle physics search of A'
- invisible -

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 → $\mu\mu$ γ

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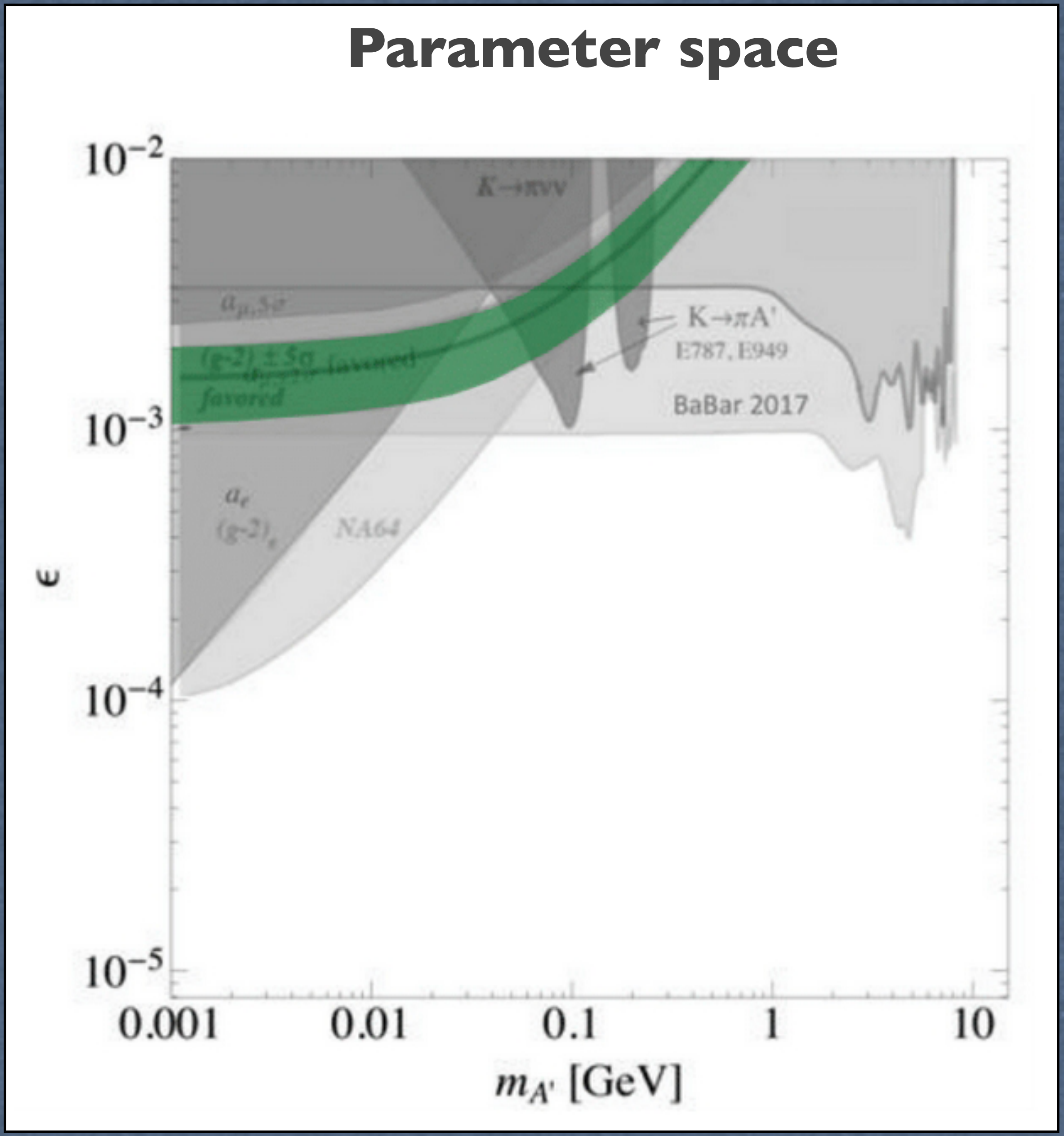
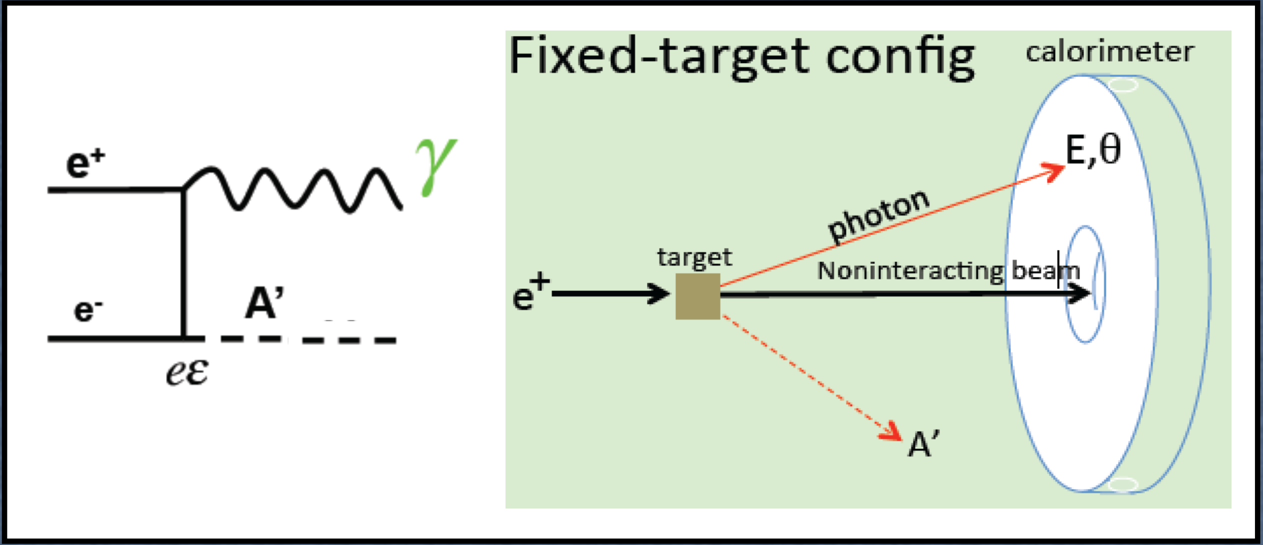


Parameter space

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

e^+ annihilation on fixed (thin) target - invisible -



Missing mass search:

  - Independent of A' decay mechanism
  - Bump hunt (monophoton@collider)
- Need a positron beam
- Limited $M_{A'}$ accessible
  - 1 GeV beam: $M_{A'}$ < 31 MeV
  - 5 GeV beam: $M_{A'}$ < 71 MeV
  - 11GeV beam: $M_{A'}$ < 106 MeV

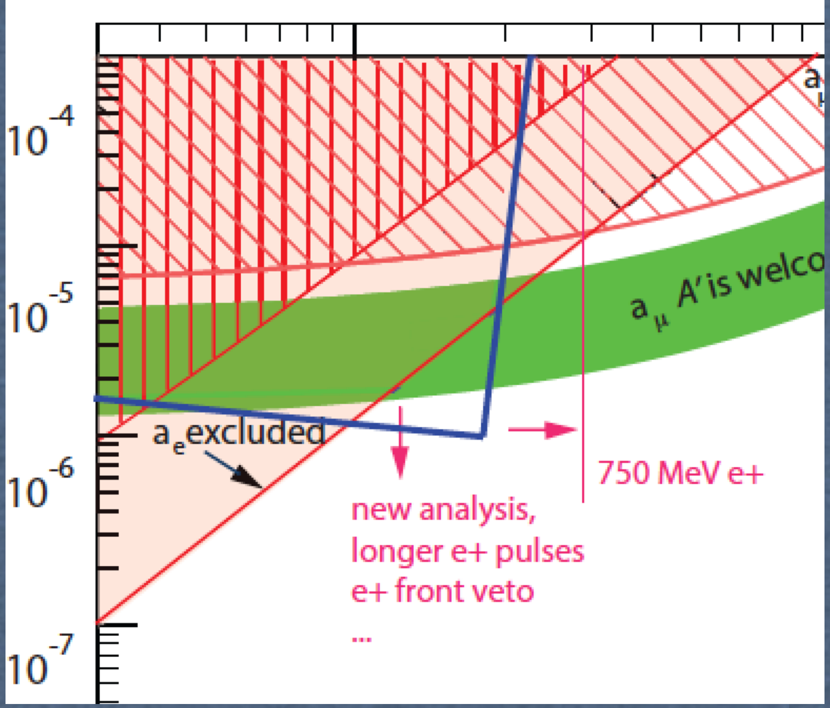
- **Novosibirsk**
- **LNF**
- **Cornell**
- **Jefferson Lab**

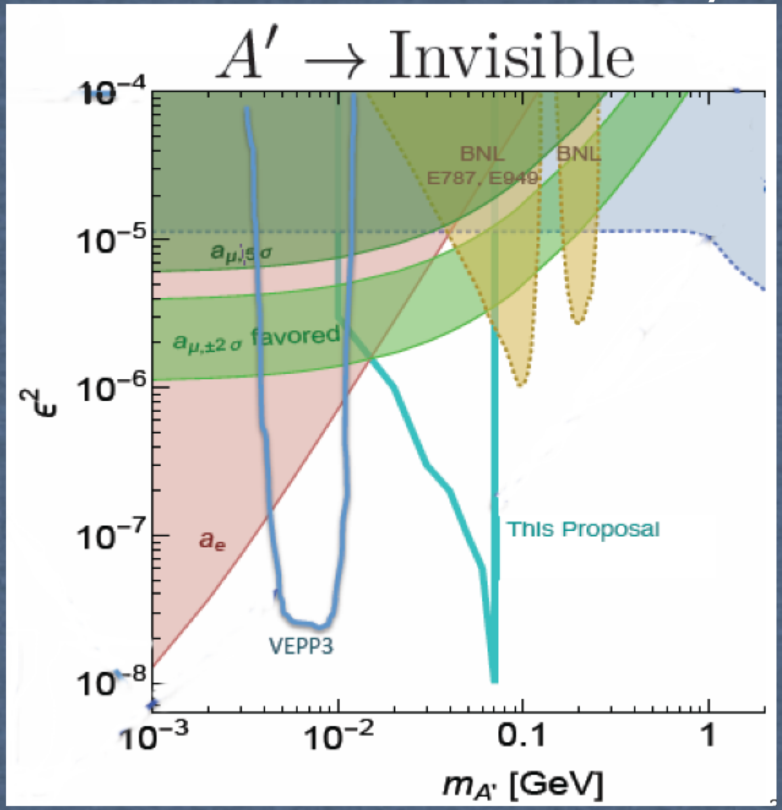
Cornell
- E_{e-} = 5.3 GeV
- EOT ~ 10^{17} - 10^{18} year^{-1}

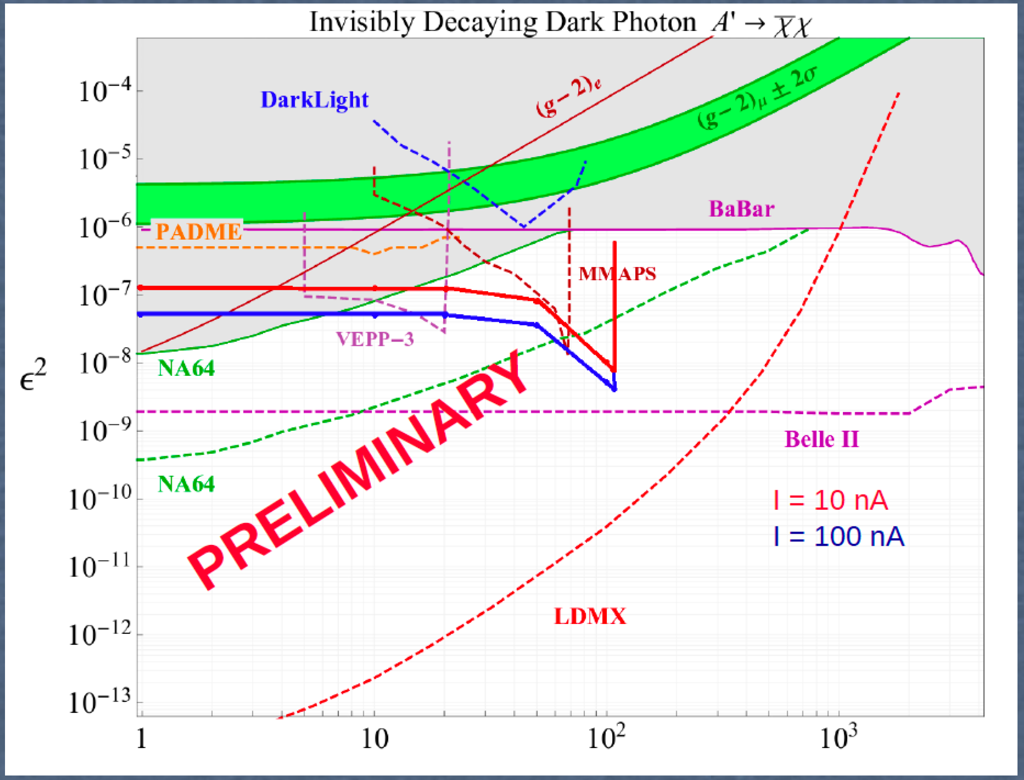
LNF
- E_{e+} = 550 MeV
- EOT ~ 10^{13} - 10^{14} year^{-1}

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

JLab
- E_{e-} = 11 GeV
- EOT ~ 10^{18} - 10^{19} year^{-1}







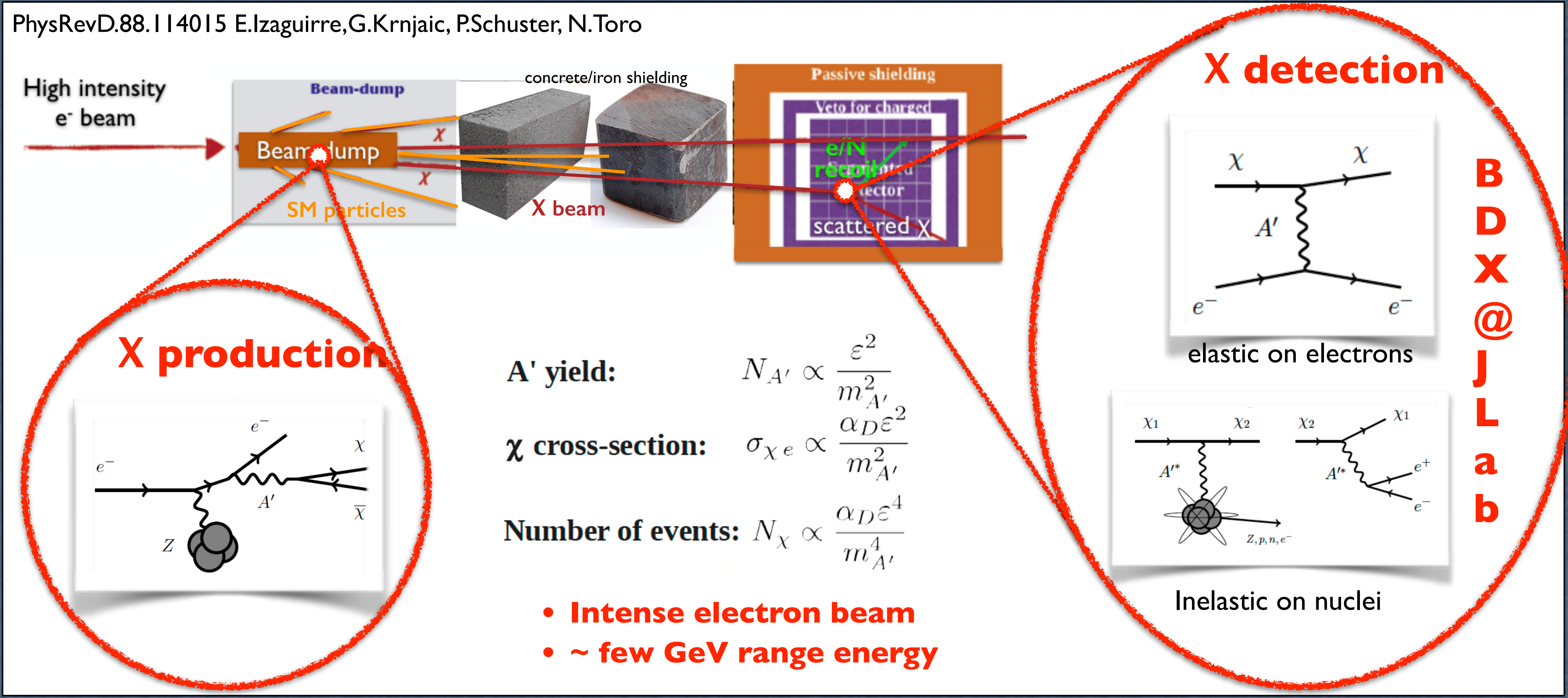
The BDX experiment

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)

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



elastic on electrons

Inelastic on nuclei

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

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

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

- **Intense electron beam**
- **~ few GeV range energy**

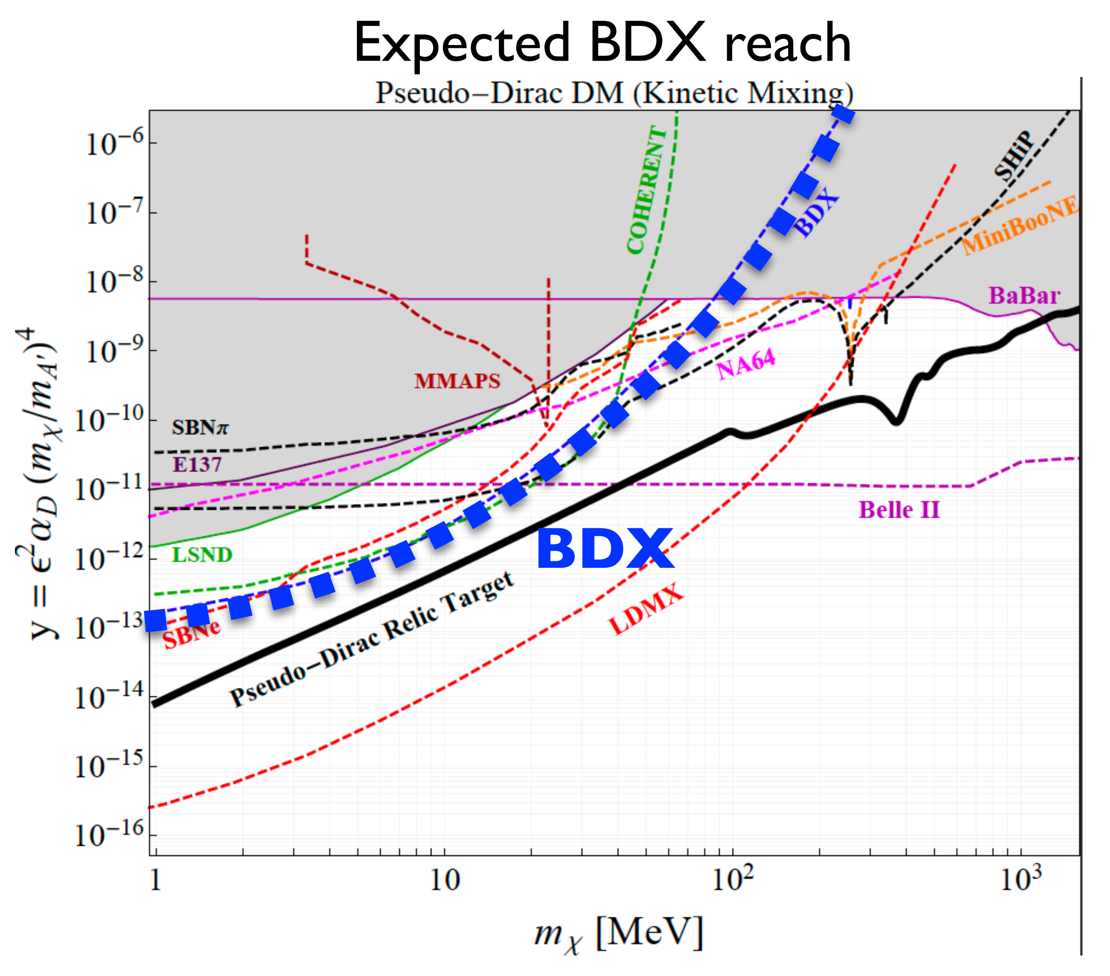
Experimental signature in the detector:

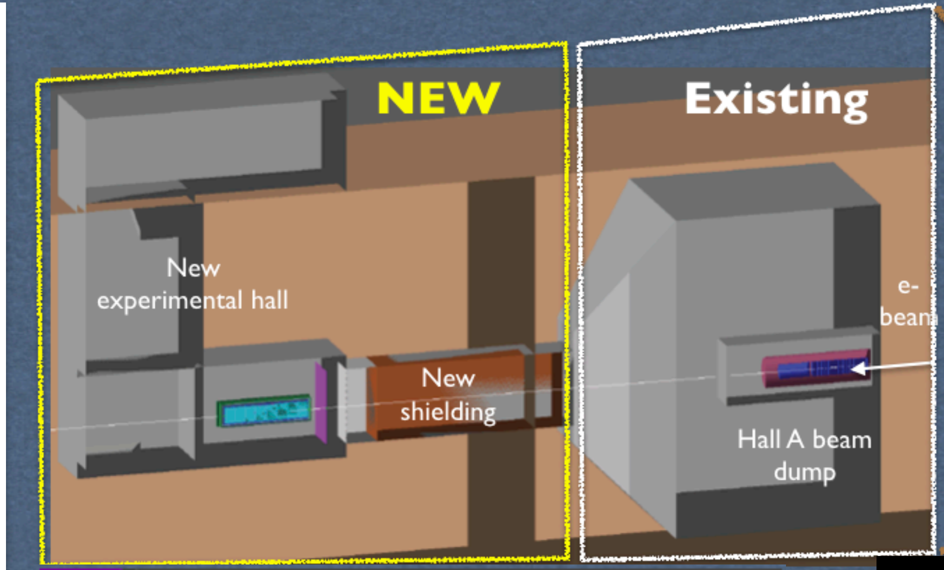
X-electron → EM shower ~GeV energy

BDX @ JLab

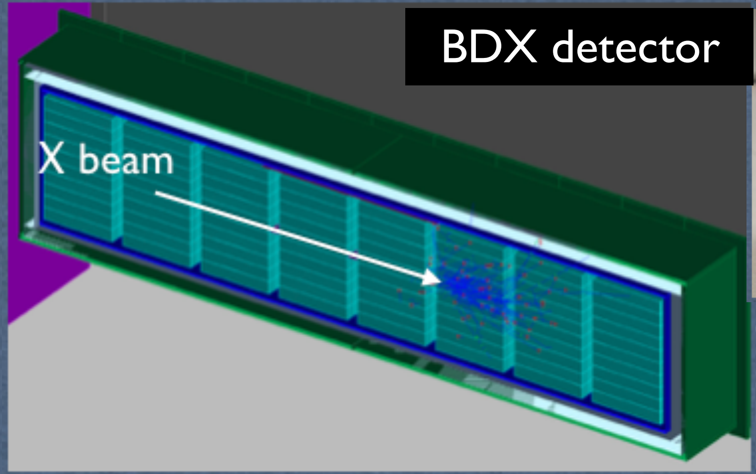
approved by JLab 2018 PAC with max rate (A)

- ★ High energy beam available: 11 GeV
- ★ The highest available electron beam current: ~65 uA
- ★ The highest integrated charge: 10^{22} EOT (41 weeks)
- ★ New experimental hall (~2$M) at JLab
- ★ BDX detector (recycling BaBar CsI crystals) ~$1M
- ★ Expected to run in ~2y

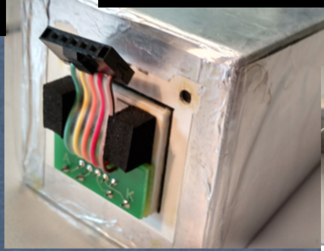




BDX detector



BaBar CsI(Tl) crystal



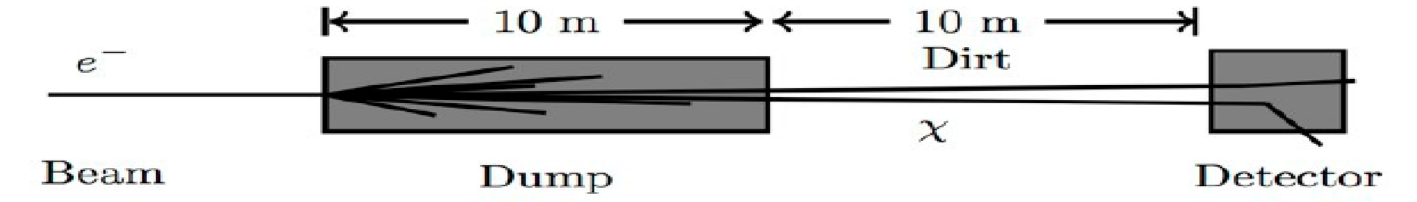
BDX prototype to asses cosmic bg

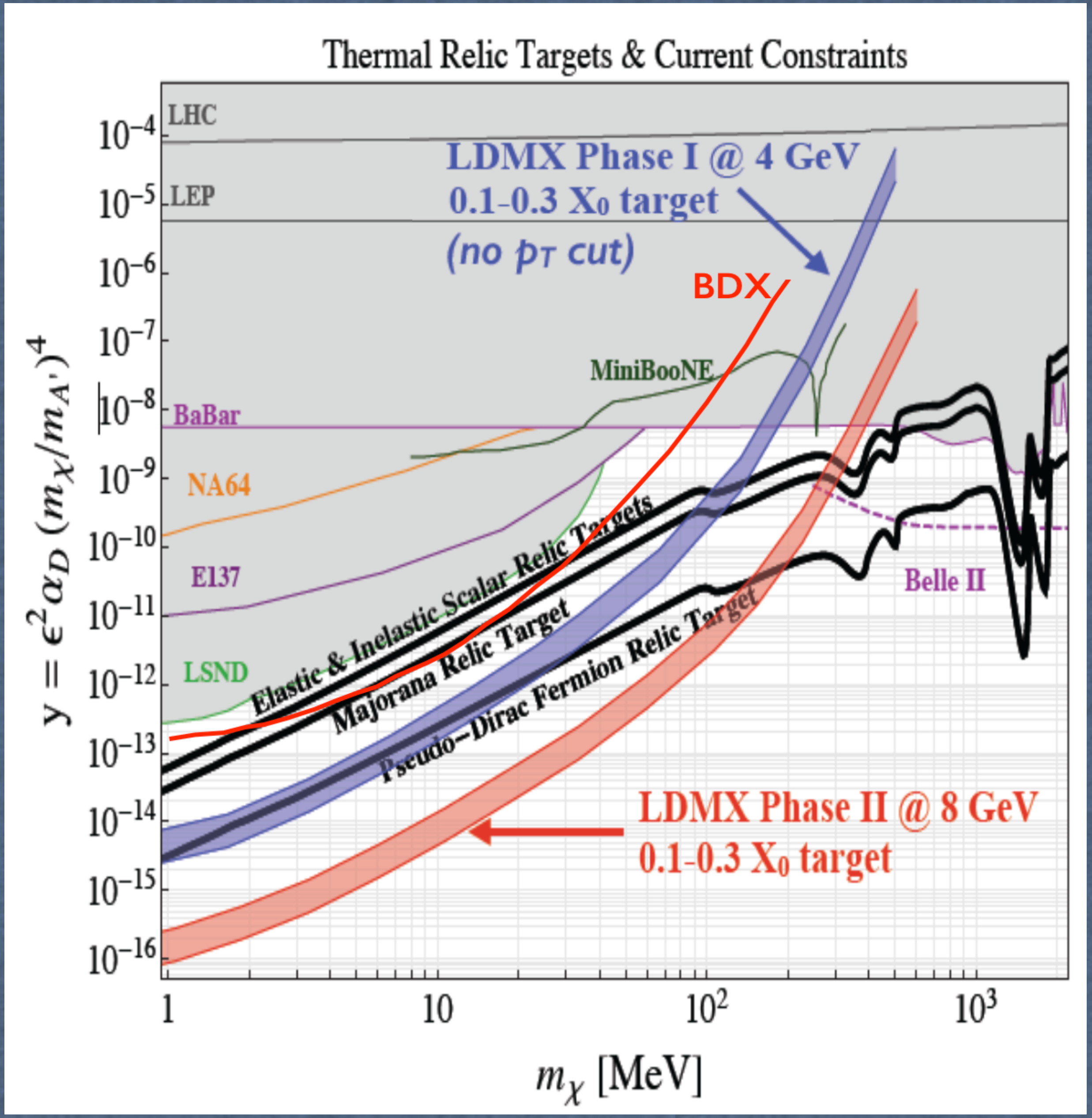
Accumulating 10^{22} EOT in ~1y BDX sensitivity is 10-100 times better than existing limits on LDM

BDX detector: E.M. Calorimeter + Veto

- 8 modules 10x10 crystals each
- 800 CsI(Tl) crystals (from BaBar EMCal)
- 6x6 mm^2 Hamamatsu SiPM readout
- Plastic scintillator + WLS fibres, sips RO

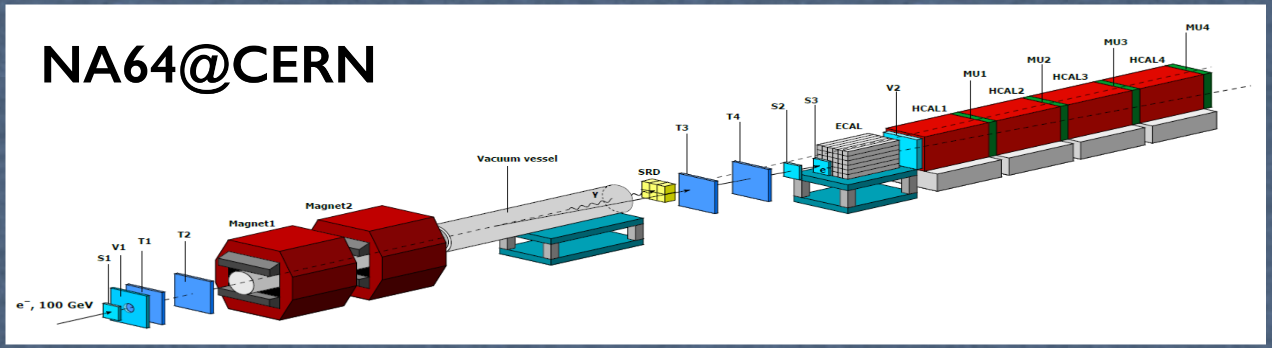
Missing energy/momentum BD experiments





Present …

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

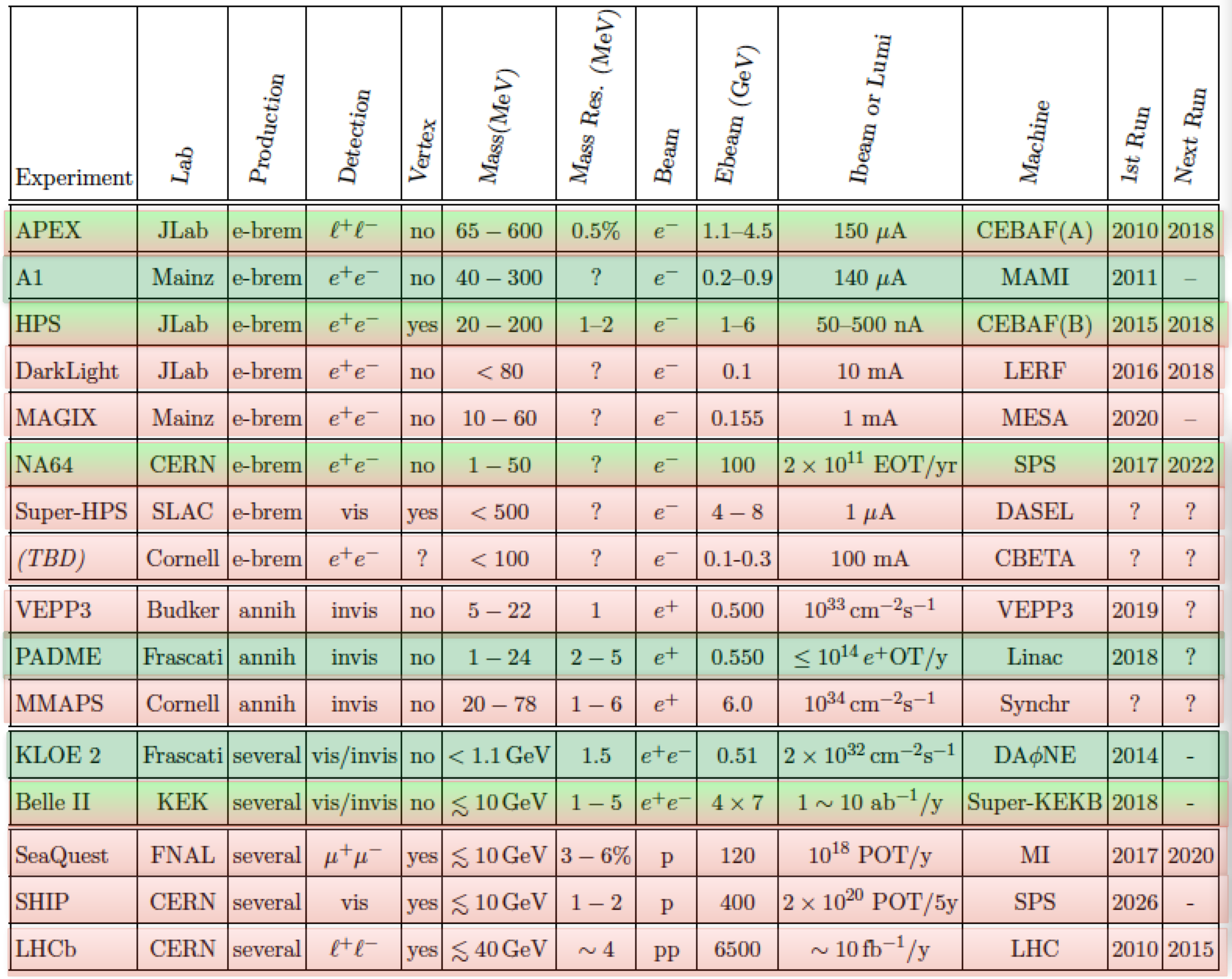


- *Active* beam-dump experiment
- Missing energy exp (e Z → e Z' A' with A' → invisible)
- 100 GeV SPS electron beam at SPS
- Active target (calorimeter)
- Exclusion plots based on 3x10⁹ EOT

… 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

Status and perspectives



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	$10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	VEPP3	2019	?
PADME	Frascati	annih	invis	no	$1-24$	$2-5$	e^+	0.550	$\leq 10^{14}\,e^+$OT/y	Linac	2018	?
MMAPS	Cornell	annih	invis	no	$20-78$	$1-6$	e^+	6.0	$10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	Synchr	?	?
KLOE 2	Frascati	several	vis/invis	no	< 1.1 GeV	1.5	e^+e^-	0.51	$2\times10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	DAϕNE	2014	-
Belle II	KEK	several	vis/invis	no	$\lesssim 10$ GeV	$1-5$	e^+e^-	4×7	$1\sim10\,\mathrm{ab}^{-1}$/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	$\sim 10\,\mathrm{fb}^{-1}$/y	LHC	2010	2015

Dark Sectors 2016 Workshop arXiv:1608.08632

Dark Matter Basic Research Needs Workshop

15-18 October 2018
Gaithersburg Marriott Washingtonian Center
US/Eastern timezone

n coming soon!

U.S. Cosmic Visions: New Ideas in Dark Matter

23-25 March 2017 *Stamp Student Union, University of Maryland, College Park*
US/Eastern timezone

"To respond to the 2014 P5 report recommendations in the search for dark matter particles and maintaining a diversity of project scales in our program, **DOE Office of High Energy Physics (HEP) is interested in identifying new, small projects for dark matter searches in areas of parameter space (i.e. mass ranges or types of particles) not currently being (or on track to be) explored.** HEP is asking for community input in the spring 2017 timeframe in order to plan the program forward. Input is requested on the possibilities for small (the whole project is ~ $10 million or less) dark matter projects in unexplored parameter space. A community workshop, followed by a White Paper would be a good path to provide the input needed. We encourage you to collect information from the community, including theorists and experimentalists involved in non-accelerator

RN) workshop to ass
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next ten years. One
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LDMA'17
2ND INTERNATIONAL WORKSHOP
ON LIGHT DARK MATTER SEARCH AT ACCELERATORS

ODOLA | ISOLA D'ELBA

nds for light dark matter |
ccelerators | Dark forces searches |
detection and cosmology |
n and experimental techniques |

WORKSHOP ON
DARK 2016
SECTORS

The existence of dark matter directly suggests new physics beyond the Standard Model. In the past 5 years, an international program of new experiments has expanded dark sector searches to include new forces and matter at the GeV-scale and below, motivated by both data and theory. While this program has made impressive progress, there are considerable challenges that must be overcome to fully explore the most viable dark sector scenarios. The goal of this workshop is to tackle these challenges, finding solutions to problems of principle and technology that are currently limiting our ability to fully explore light dark matter, dark photons, and other dark sector physics interacting with familiar matter.

SLAC National Accelerator Laborator

Organizing Committee:
Rouven Essig (Stony Brook)
Matt Graham (SLAC)
John Jaros (SLAC)
Tim Nelson (SLAC)
Philip Schuster (SLAC)
Natalia Toro (SLAC)

www-conf.slac.stanford.edu/darksect

SLAC NATIONAL ACCELERATOR LABORATORY

Light Dark Matter search @ Accelerators

LDMA-2015
International workshop
Camogli, Italy
June 24-26 2015

Local Organizing Committee
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C. Sfienti (Gutenberg Universitä
E. Smith (Jefferson Lab)
S. Stepanyan (Jefferson Lab)
M. Taiuti (Università of Genova)

website: http://ldma2015.ge.infn.it email: ldma2015@ge.infn.

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
- ✳ Extensive experimental plans at high intensity e-facility: JLab, LNF, Cornell, Mainz, SLAC (+ p beam at FNAL and CERN)
- ✳ A new generation of dedicated and optimised experiments at high intensity frontier will test the relic (light) dark matter scenario
- ✳Many experiments run at electron-beam facilities excluding a significant fraction of parameter space
- ✳ … and more are expected in the future
- ✳ Discovery or decisive tests of simplest scenarios will possible in the next ~5-8 years!