What next LNF: Perspectives of fundamental physics at the Frascati Laboratory

10-11 November 2014 *INFN - Laboratori Nazionali di Frascati*
Europe/Rome timezone

Light Dark Matter searches at accelerators

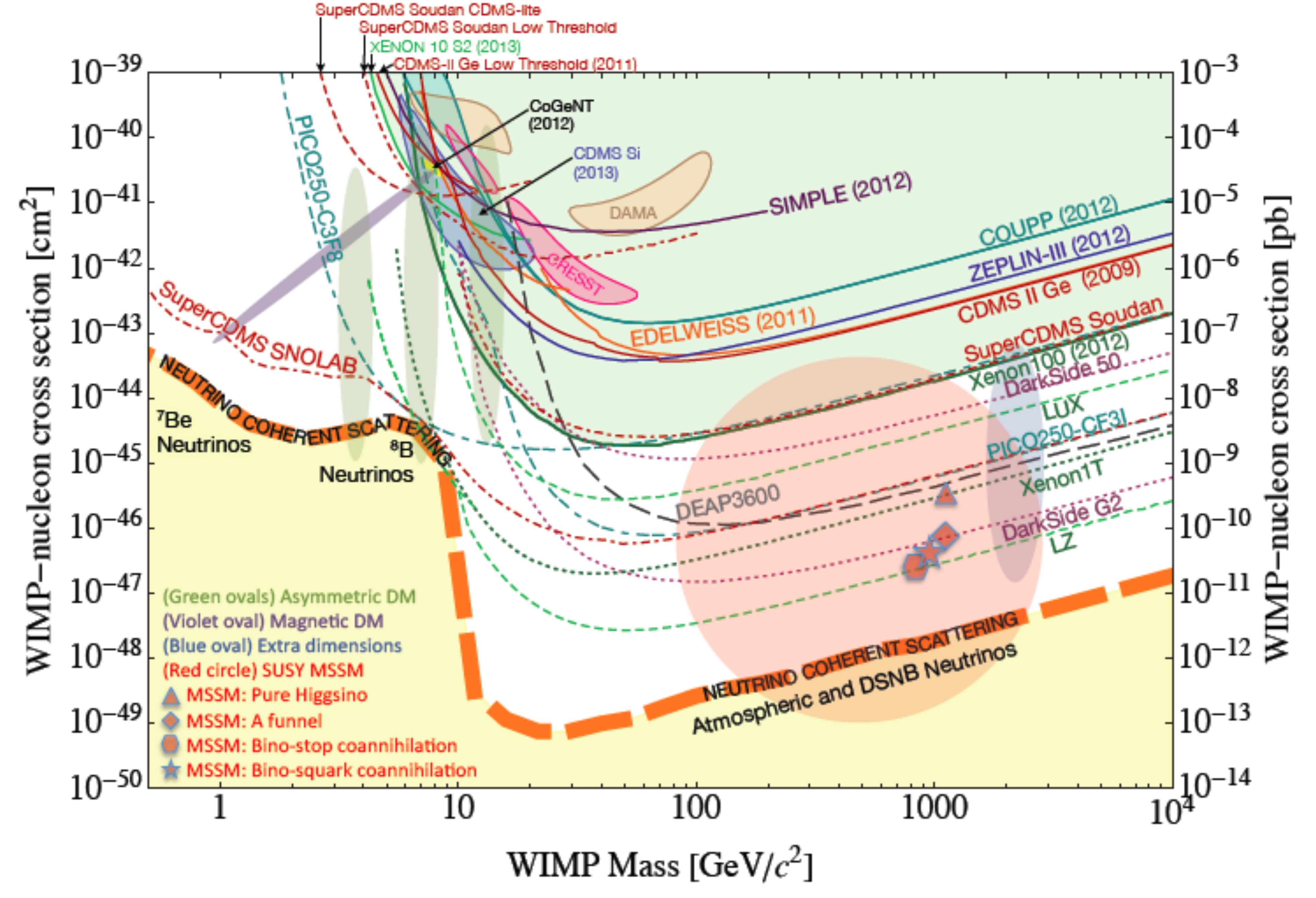
M.Battaglieri
INFN-GE, Italy

✳New forces and the vector portal (dark photon)
✳Dark photon visible decay
✳Light dark matter

Dark Matter search - Direct measurements

Dark matter (DM) direct search mainly focused in the mass region 10 GeV -10 TeV

- WIMP: weakly interacting massive particles with weak scale mass provides the correct DM relic abundance
- No signal in direct detection



DM detection by measuring the (heavy) nucleus recoil of slow moving cosmological DM

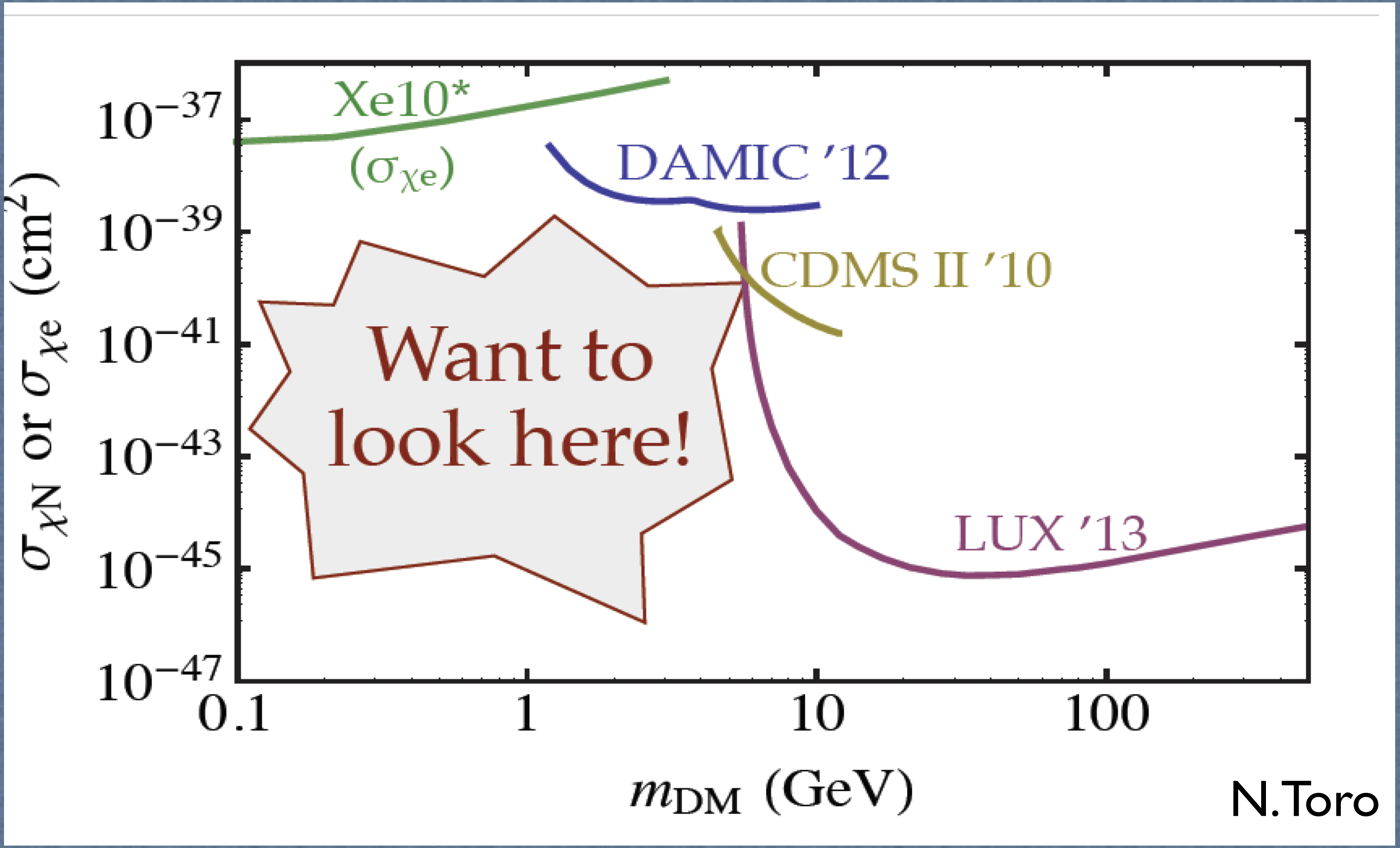
→ no experimental sensitivity to light DM (<1 GeV)

Accelerators-based DM search

Accelerators-based DM search is covering a similar mass region but can extend the reach outside the classical DM hunting territory

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

- **Higher mass (> 10 TeV)**
  LHC, Rare decays, …
- **Lower Mass (<10 GeV)**
  MiniBoone@FNAL, SPS@CERN, BDX@JLab, PADME@LNF,



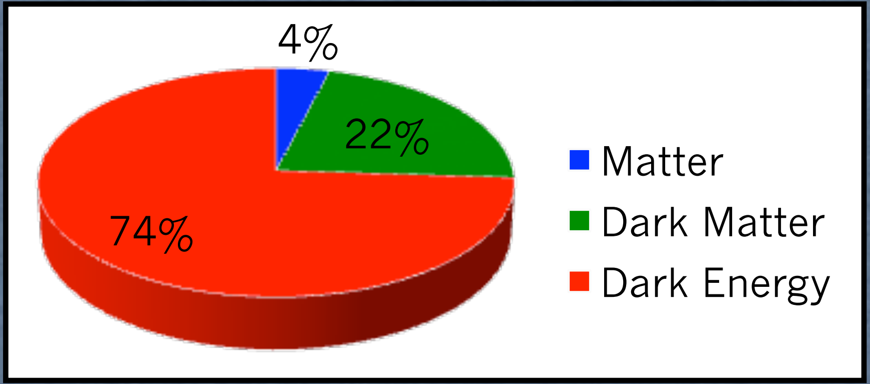
N.Toro

Beam dump experiments can provide unprecedented sensitivity to light dark matter
High intensity electron beam can play a significant role in light DM search

New fundamental forces?

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

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



Particles, interactions and symmetries

Known particles & new force-carriers

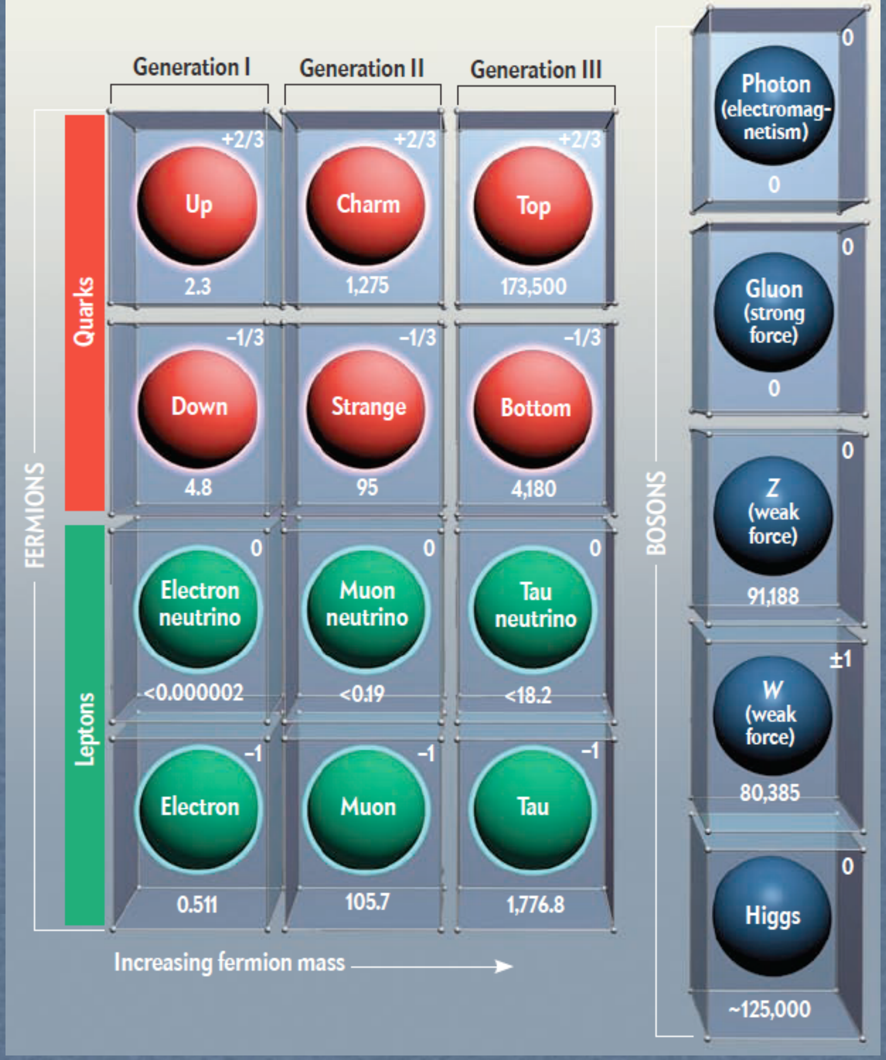
Particles:
quarks, leptons

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

New particles & new force-carriers

Dark Matter

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

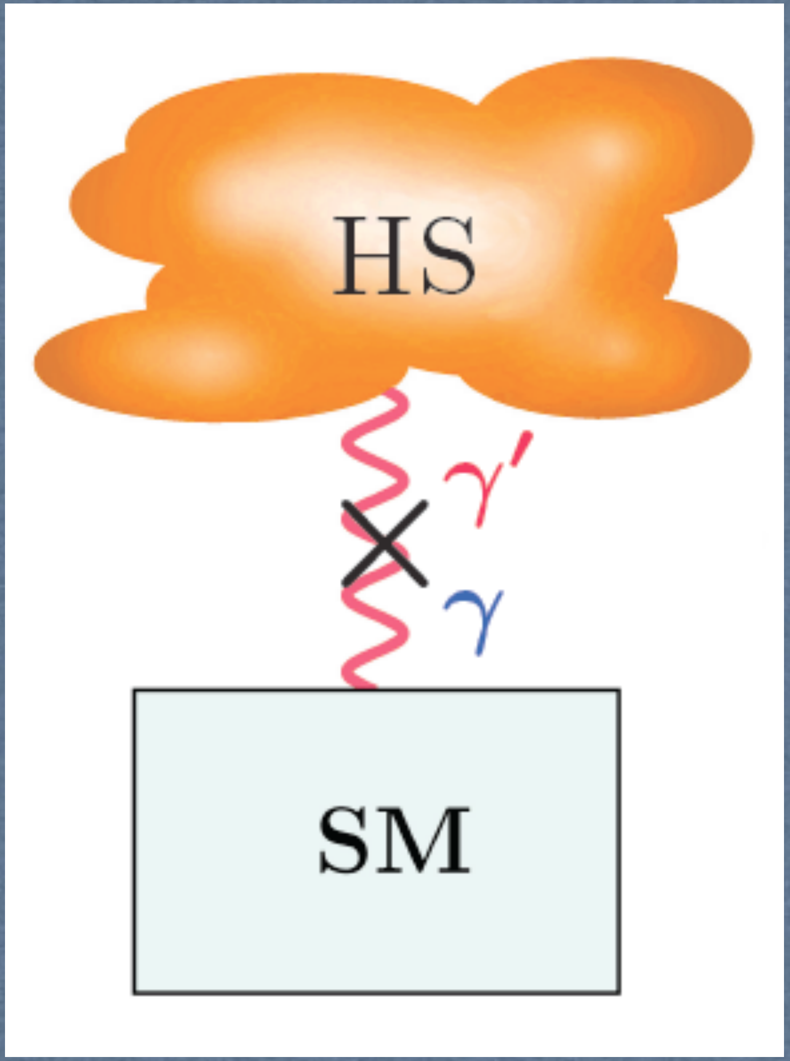


New bosons are expected to mediate new interactions

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

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

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



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

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

Color Electroweak Hypercharge Hidden sector

✳Hidden sector (HS)

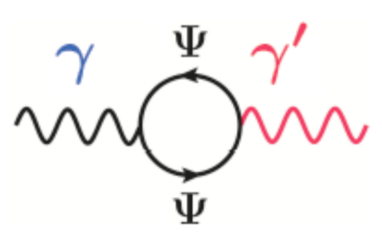
present in string theory and super-symmetries

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

no direct interaction between HS and SM

HS-SM connection via messenger particles

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



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

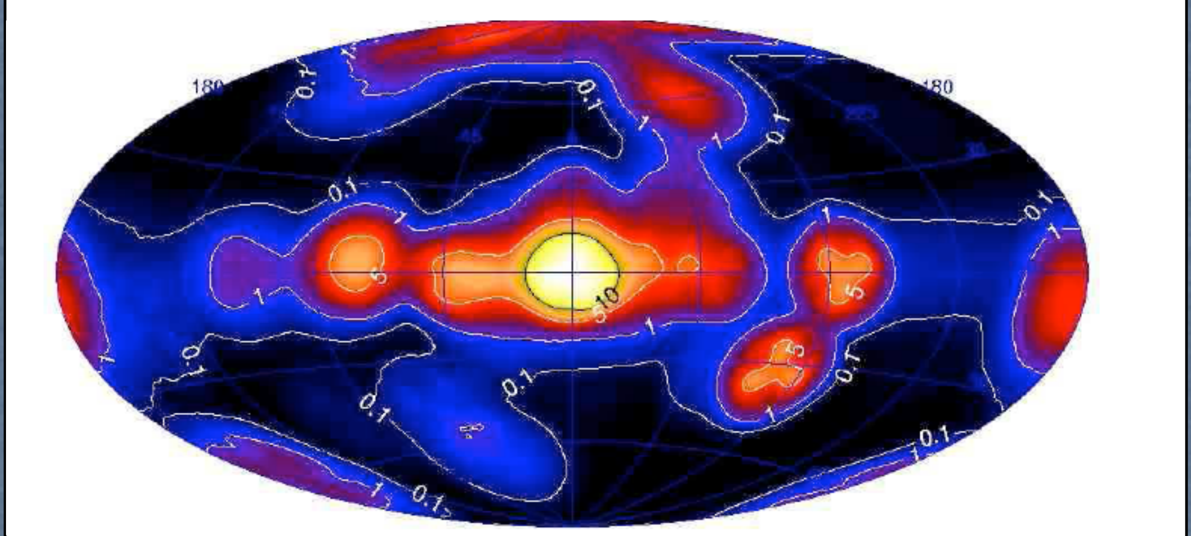
γ'/A' couples to SM via electromagnetic current (kinetic mixing)

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

γ'/A' mass depends on the model

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

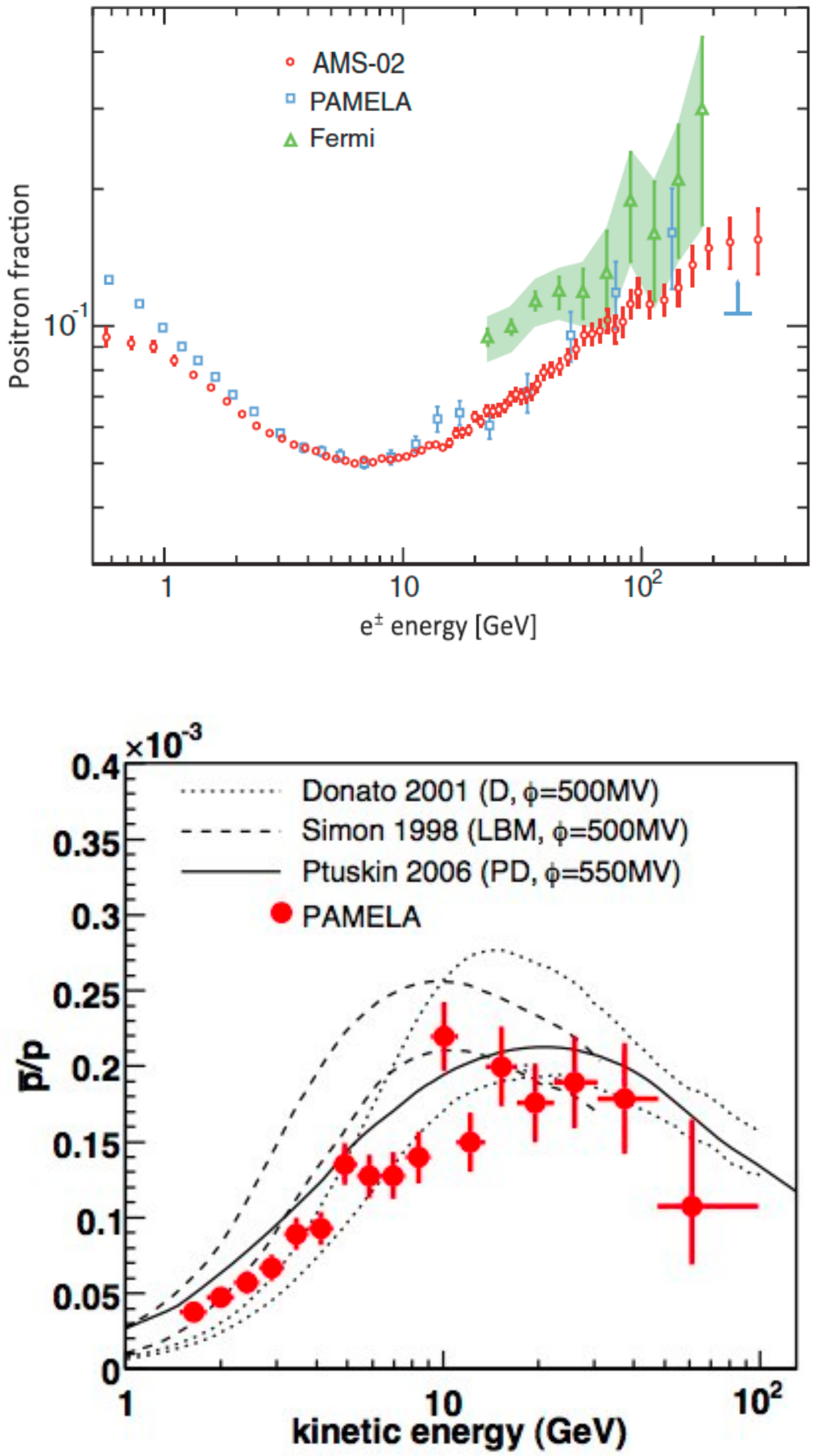
Astrophysical motivation: the 511γ keV line



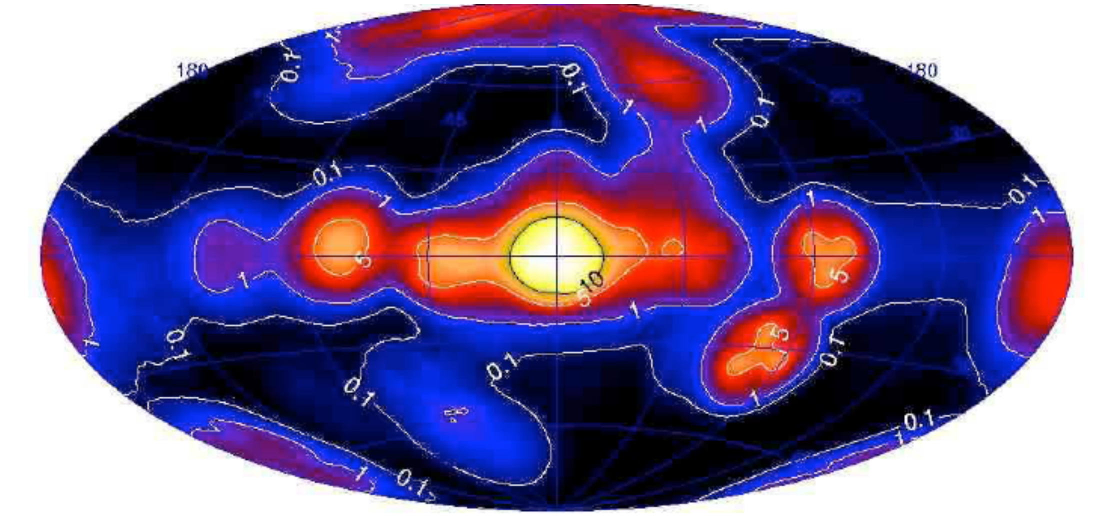
511 keV line map from GRAL/SPI data

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

Positron and antiproton abundance from PAMELA/AMS

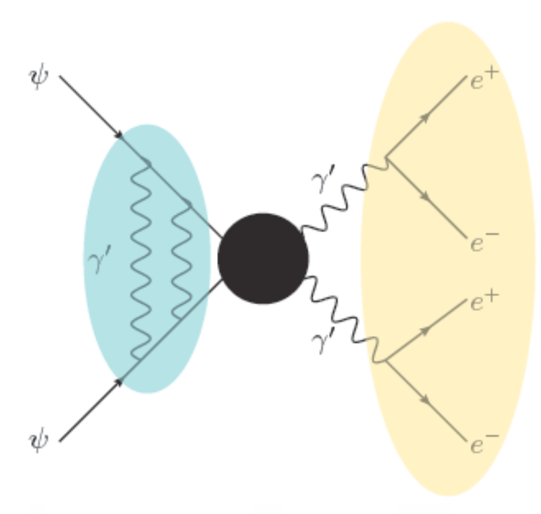


Astrophysical motivation: the 511γ keV line



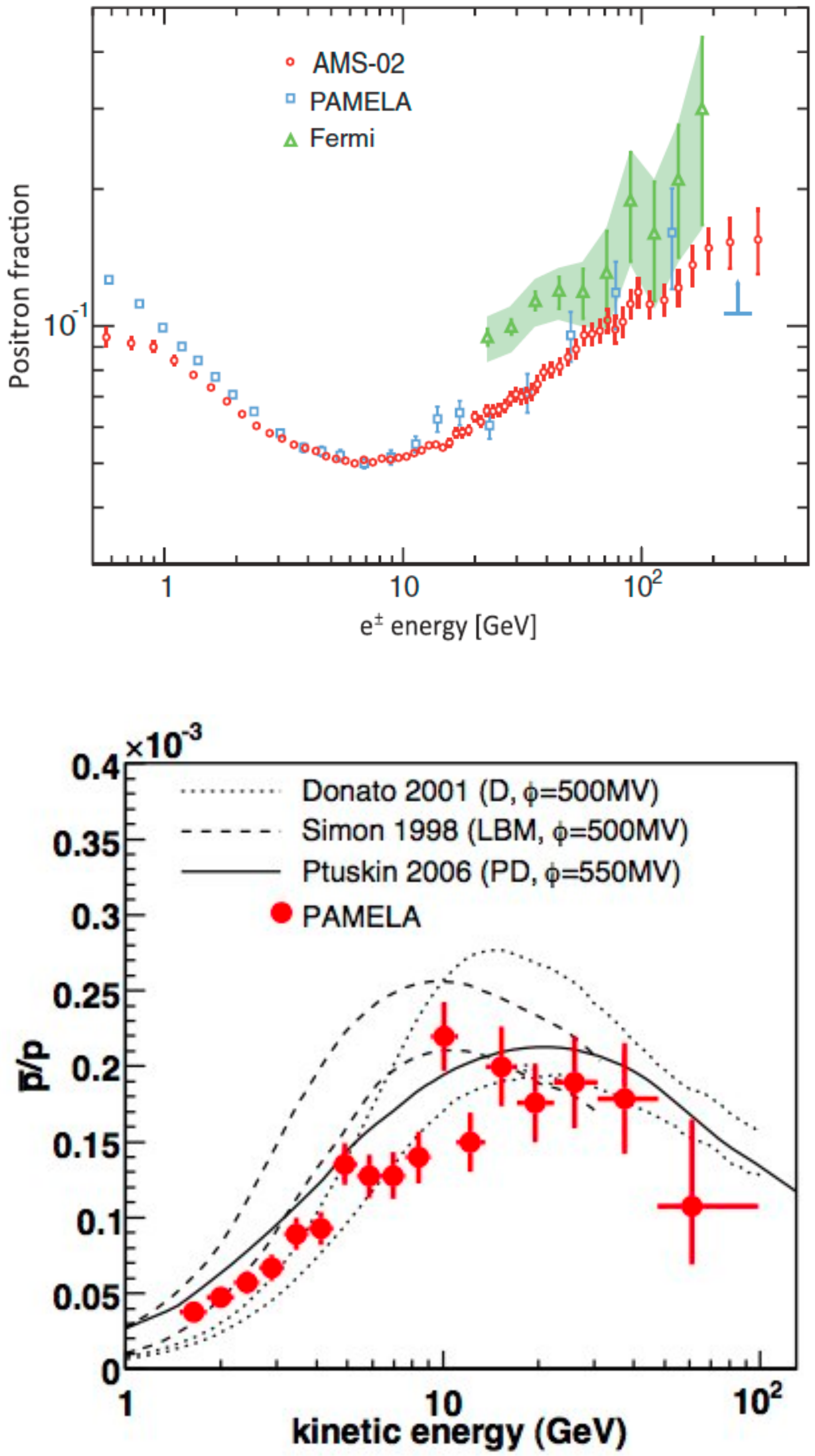
511 keV line map from GRAL/SPI data

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



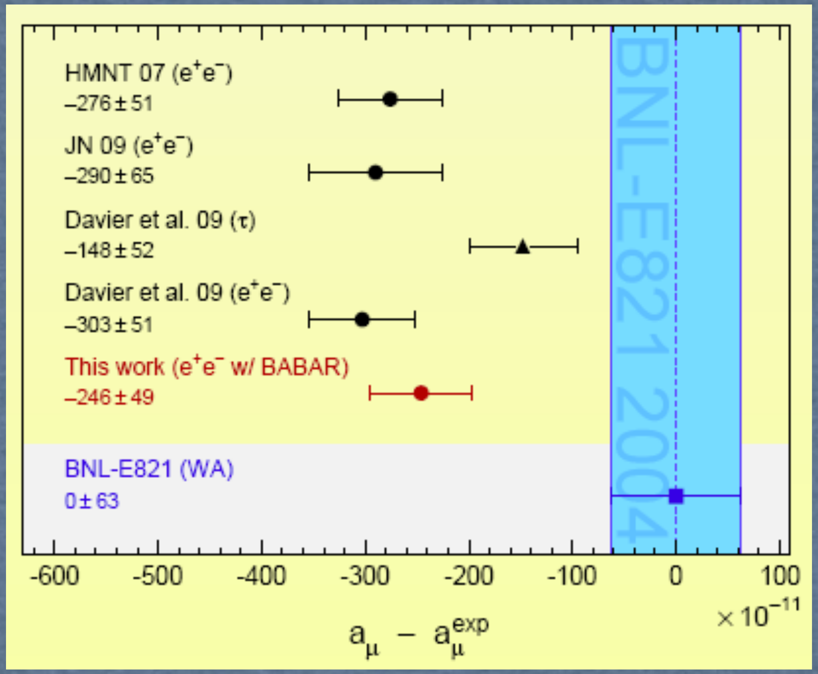
1) enhancement in e+ yield
2) hard e+ spectrum
3) no anti-p excess if $M_{A'} < 2\ M_p$

Positron and antiproton abundance from PAMELA/AMS



Modification of EM

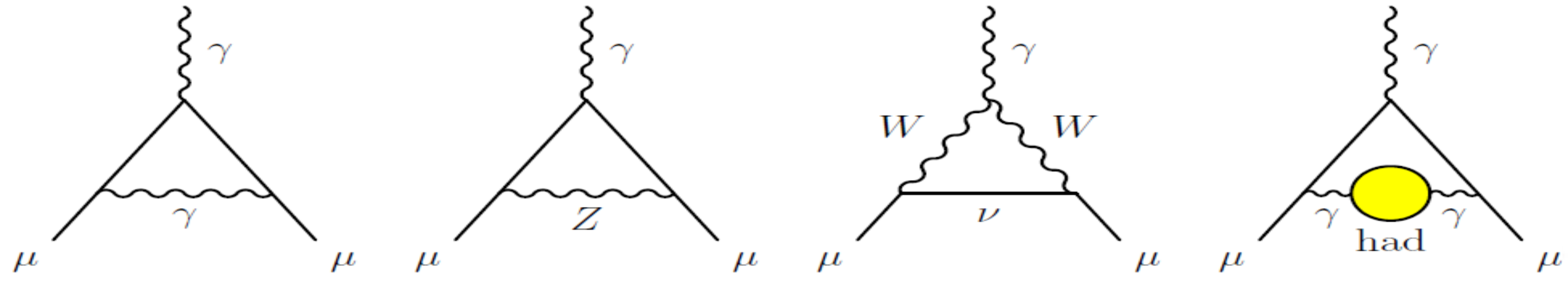
g-2 of muon



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

Standard Model Prediction

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



Modification of EM

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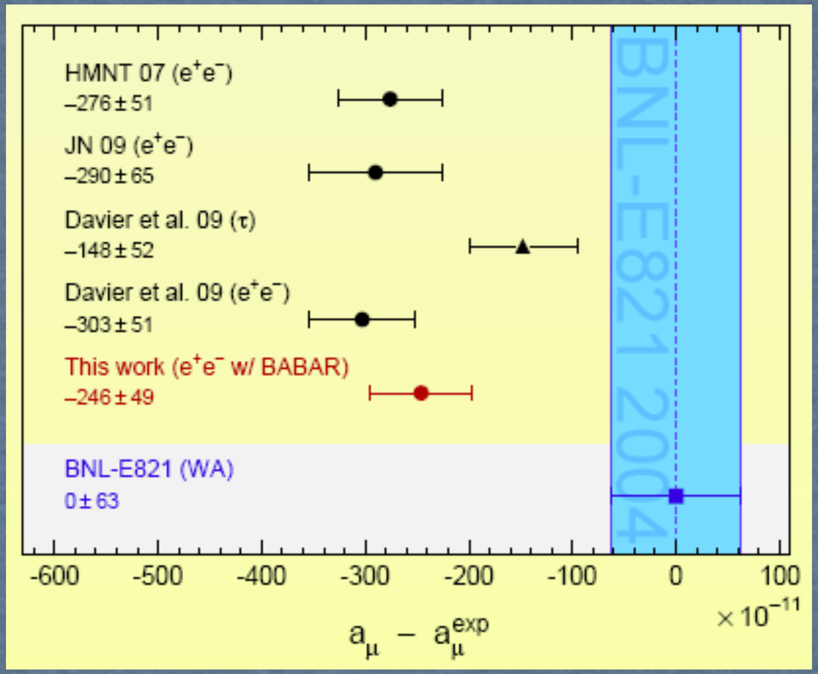
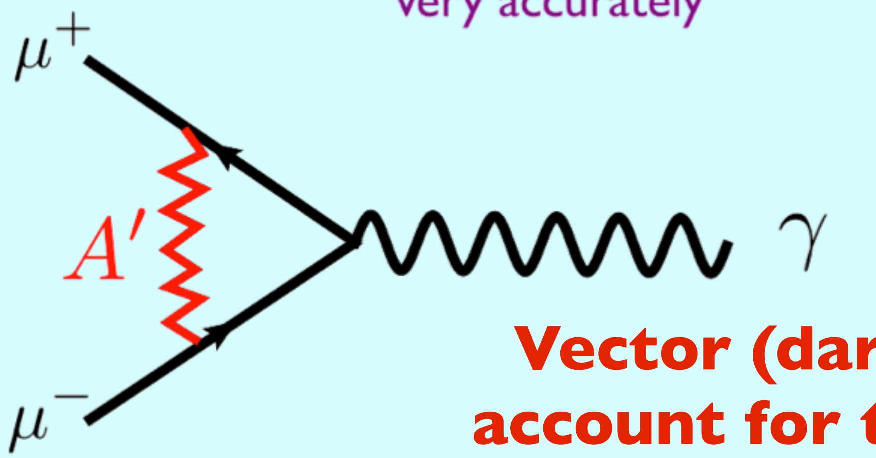


magnetic dipole moment

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

can be measured very accurately

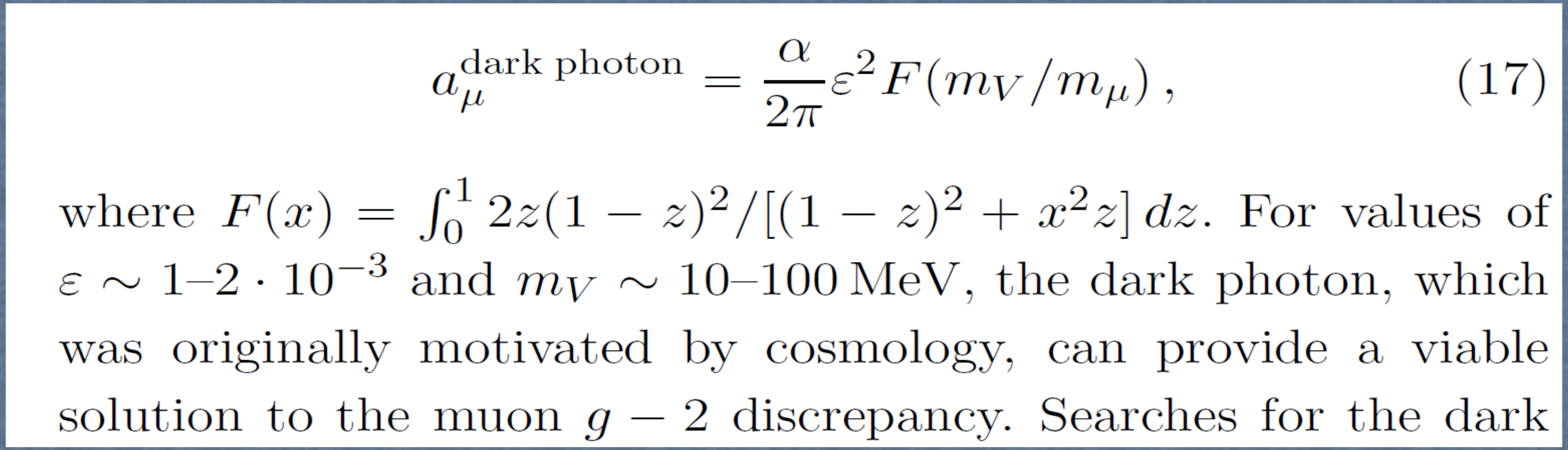
spin



$g_s \neq 2$

Vector (dark) force could account for the discrepancy

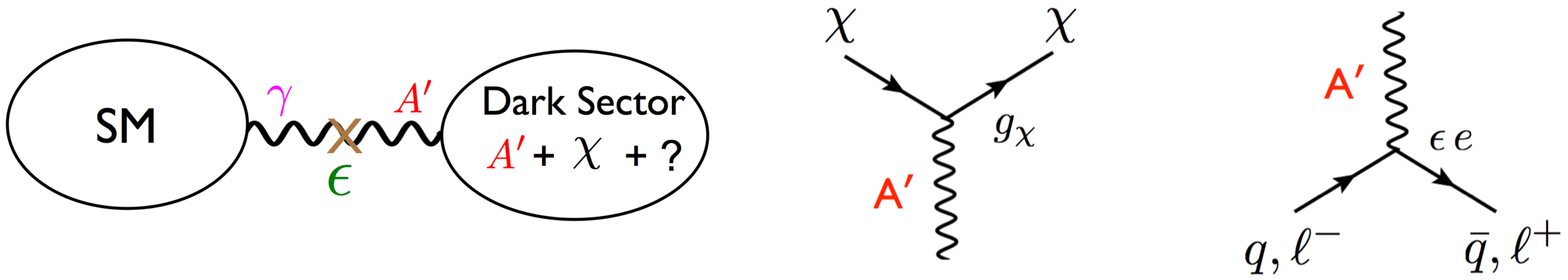
Contribution to g-2 from dark photon



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

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

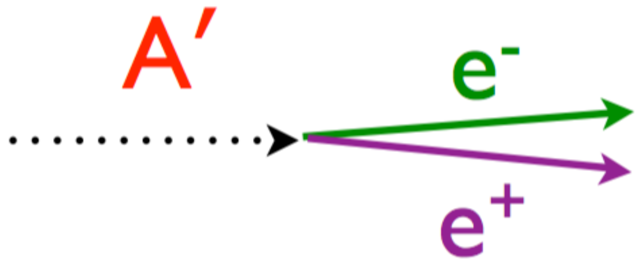
Dark forces and dark matter (Light WIMP - light mediators)



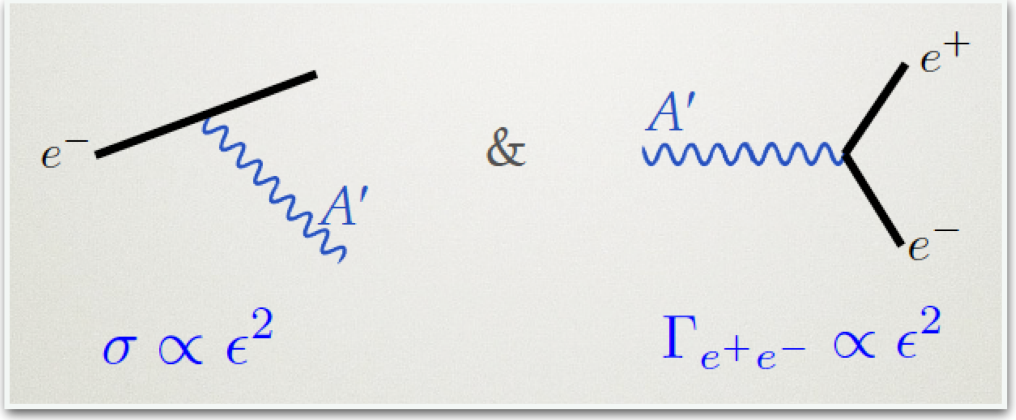
4 parameters: $m_\chi, m_{A'}, \epsilon, g_\chi$

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

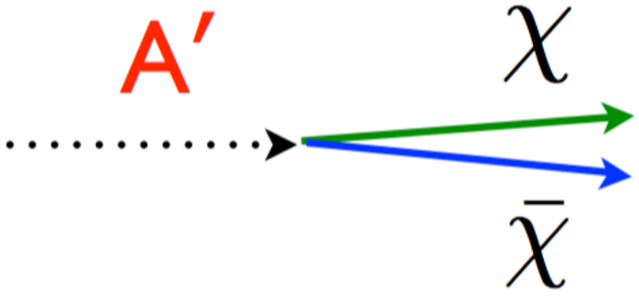
Visible



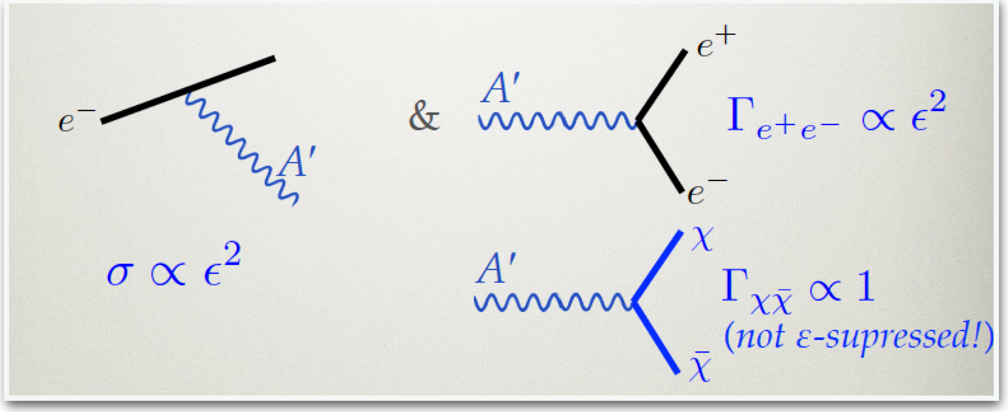
- *Minimal* decay
- Decay regulated by ε^2
- Independent on m_χ
- Requires $m_{A'}<2m_\chi$



Invisible



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

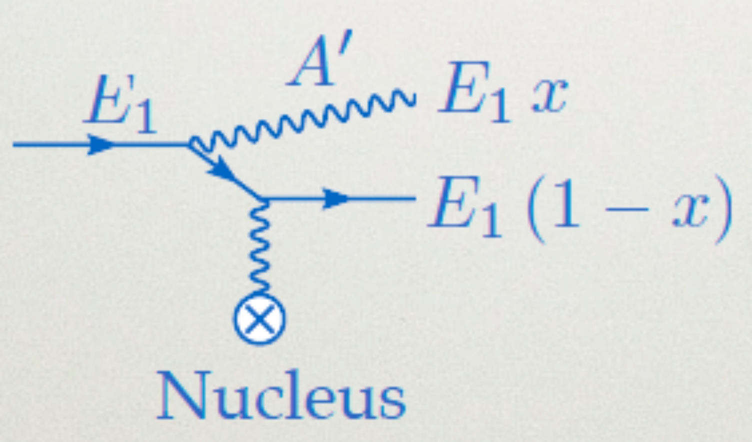


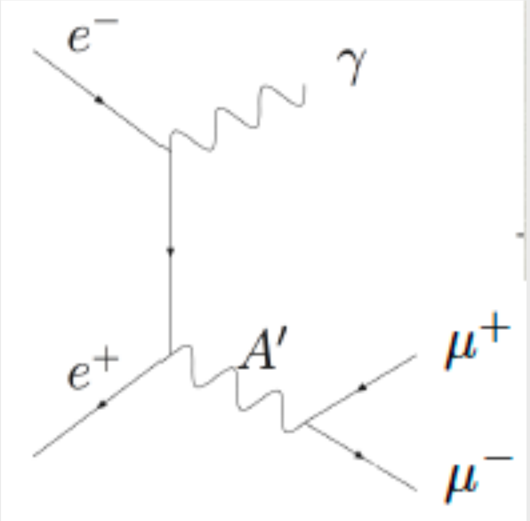
A’ production: fixed target vs. collider

Fixed Target

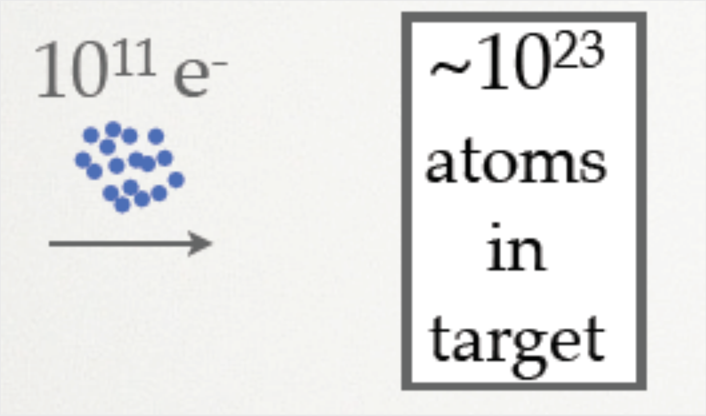
e+e- colliders

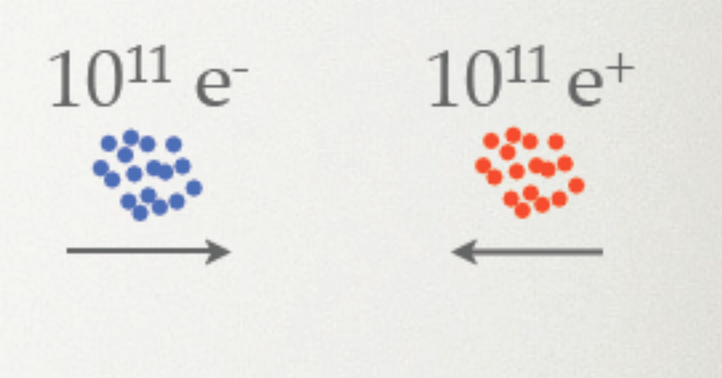
Process





Luminosity





Cross-Section

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

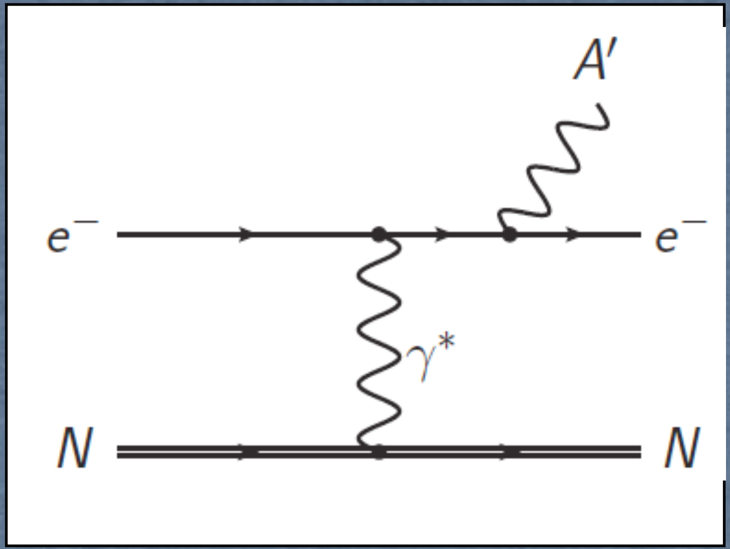
$$\sigma \sim \frac{\alpha^2 \epsilon^2}{E^2} \sim O(10\ fb)$$

✶1/M$_{A'}$ .vs.1/E$_{beam}$
✶Coherent scattering from Nucleus (~Z^2)

- high backgrounds
- limited A’ mass

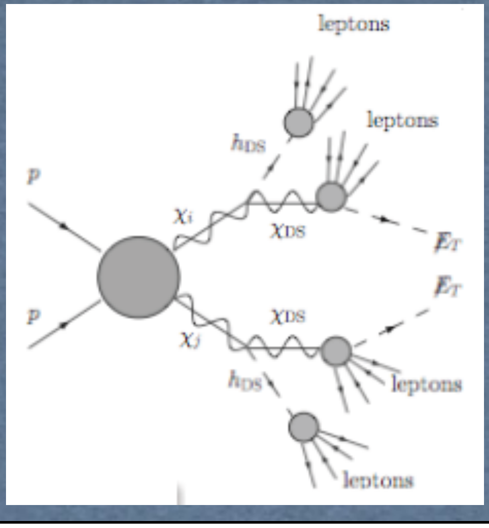
- low backgrounds
- higher A’ mass

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

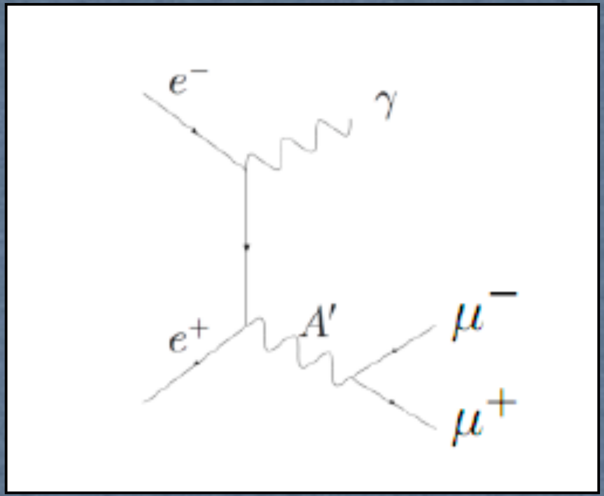


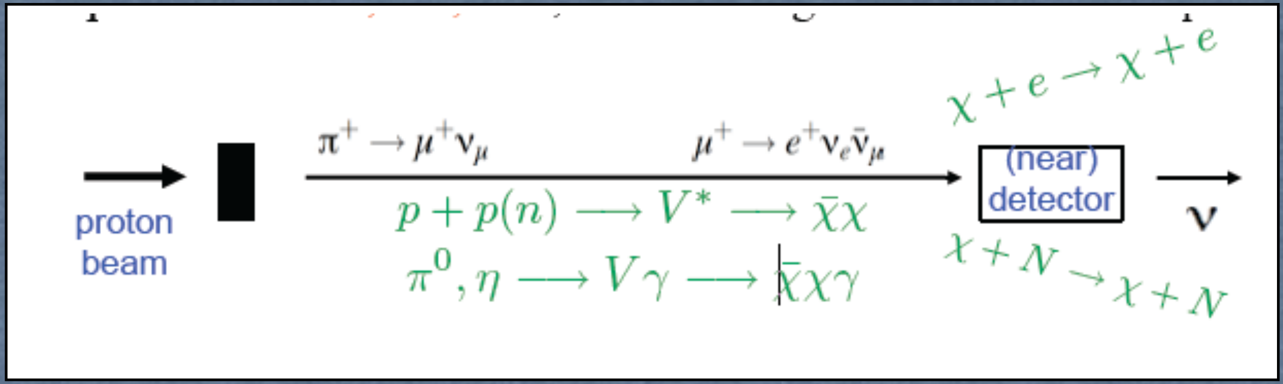
Fixed target:
e N →N γ'→ N Lepton Lepton+
→ **JLAB, MAINZ**

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



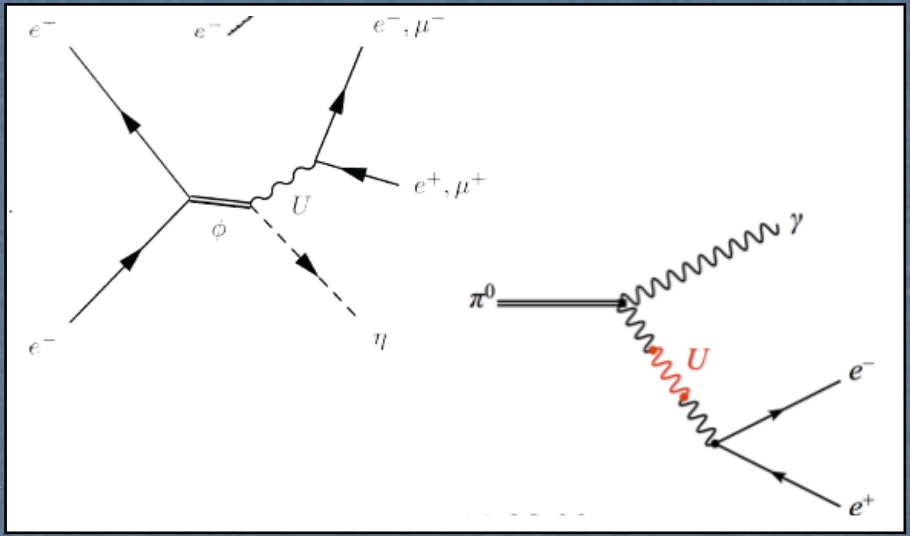
Annihilation:
e+e- → γ' γ → μμ γ
→ **BABAR, BELLE, KLOE, CLEO**



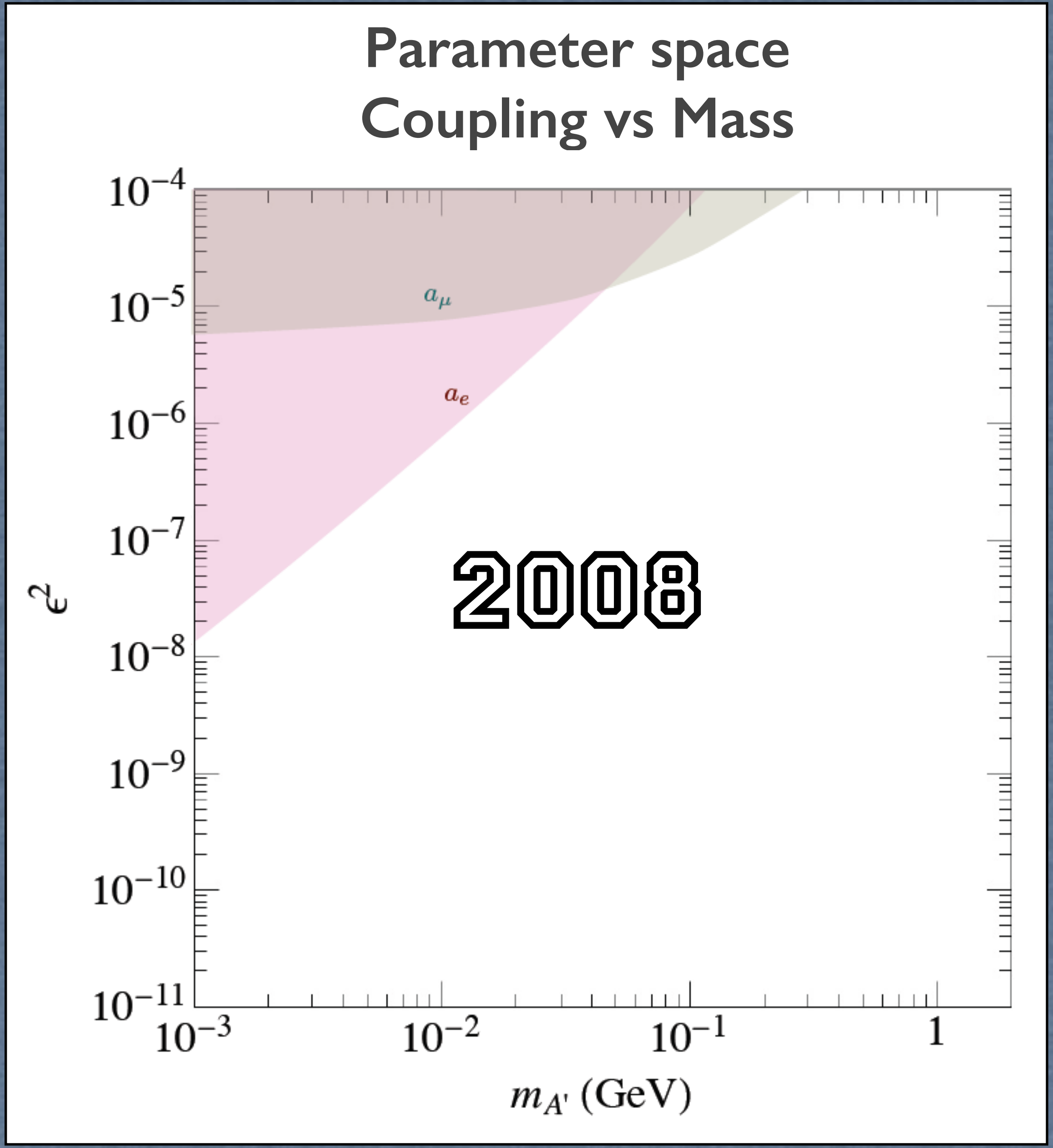


Fixed target:
p N →N γ'→ p Lepton Lepton+
→ **FERMILAB, SERPUKHOV**

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



Particle physics search of A'/γ' (visible decay)



- From 2008: reanalysis of existing data
- New (test) runs
- Full runs expected in 2015-2017

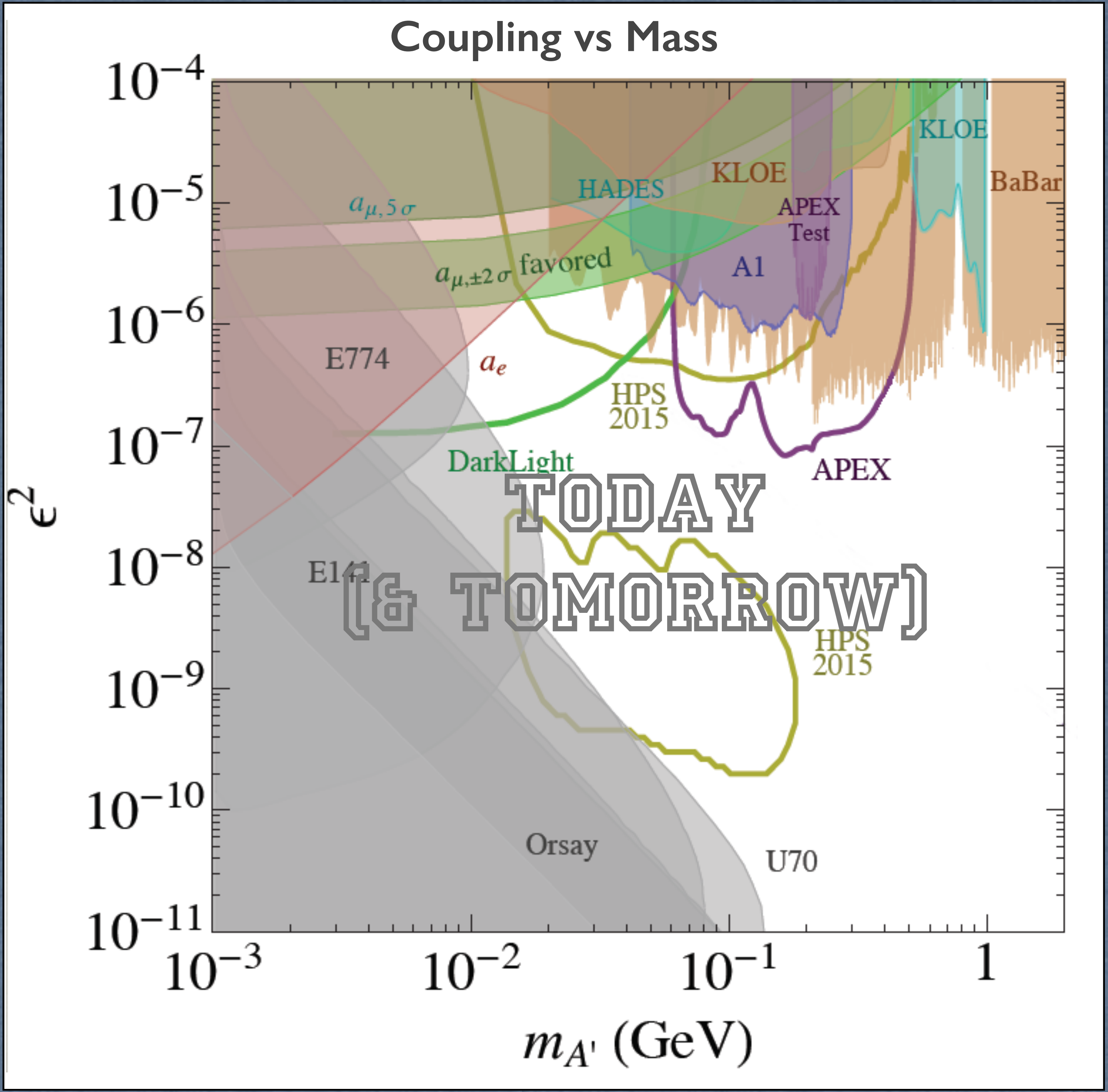
Fixed target: e N →N γ'→ N Lepton$^-$ Lepton$^+$
→ **JLAB, MAINZ**

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, WASA-COSY**

Particle physics search of A'/γ' (visible decay)

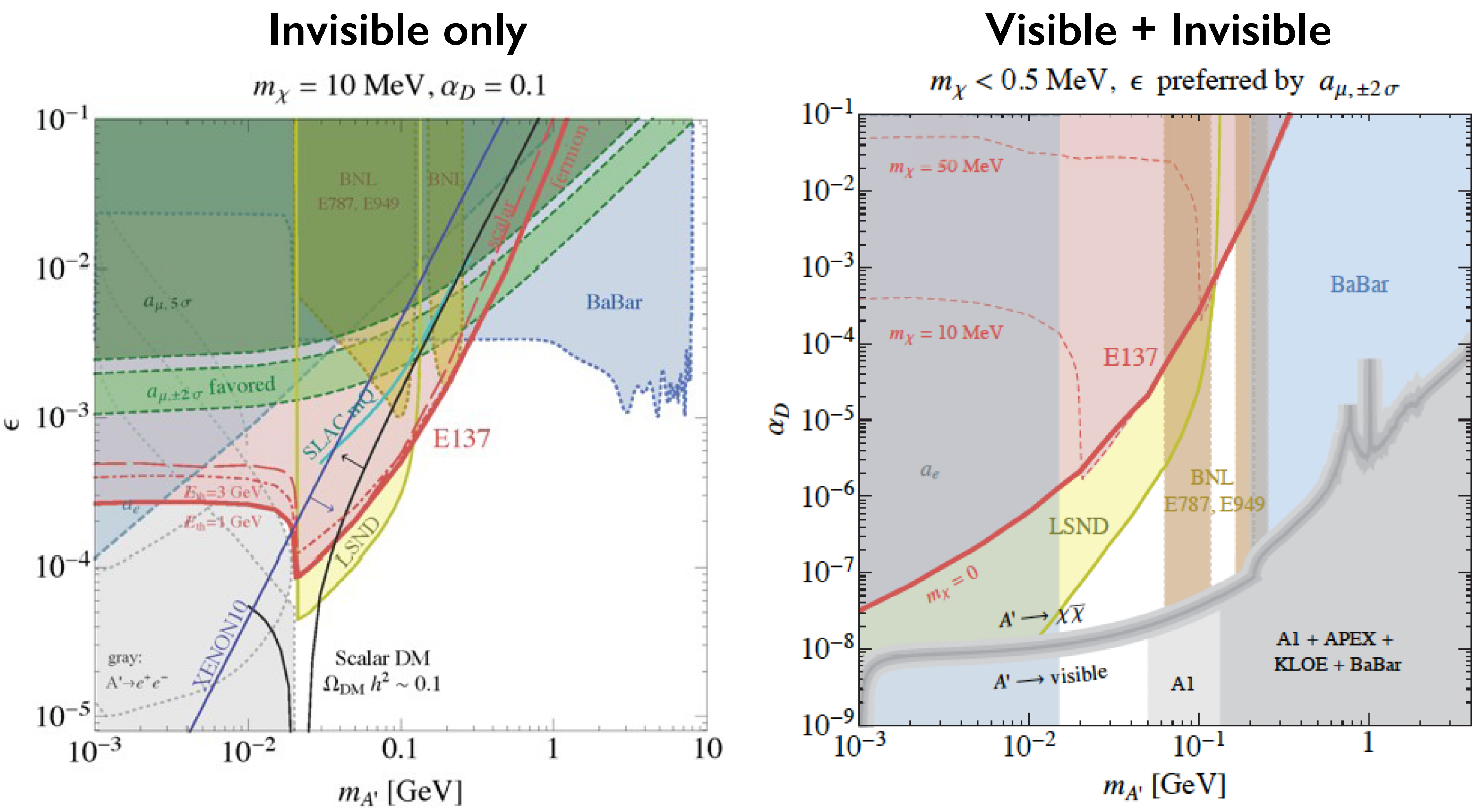


Visible decay:
no positive signal (so far) but strong limits in parameter

A broad experimental program will explore a significant territory in the next few year

What about the 'invisible decay'?

Visible vs Invisible: complementarity $(g\text{-}2)_\mu$



Invisible only

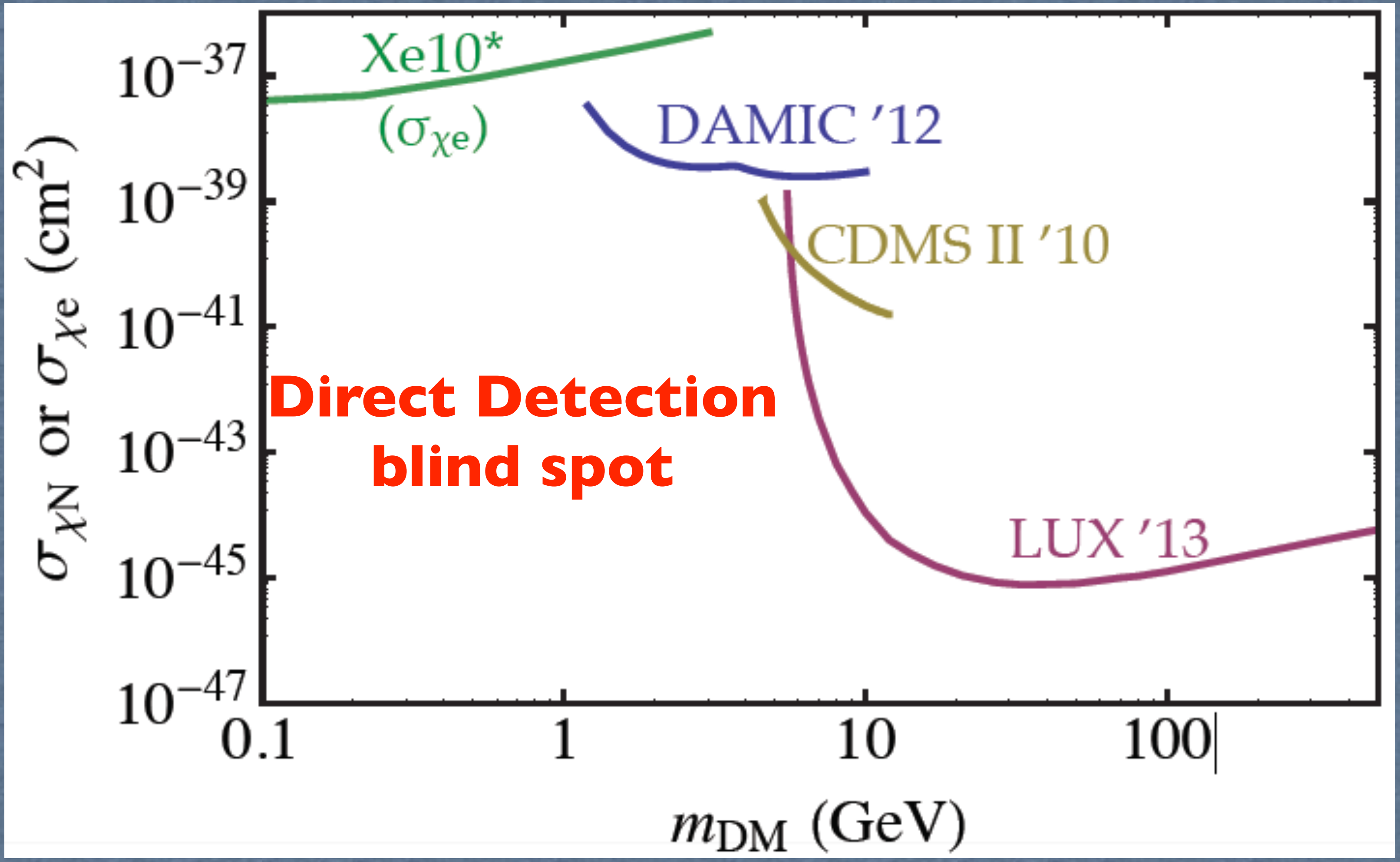
Visible + Invisible

Strong Constraints on Sub-GeV Dark Matter from SLAC Beam Dump E137
http://arxiv.org/abs/1406.2698 Brian Batell, Rouven Essig, Ze'ev Surujon

- Reinterpretation of existing data are ruling out *$(g\text{-}2)_\mu$* favoured region
- Exclusion limits are model dependent: if invisible decay is included limits do not hold!

From Dark Forces to Dark Matter

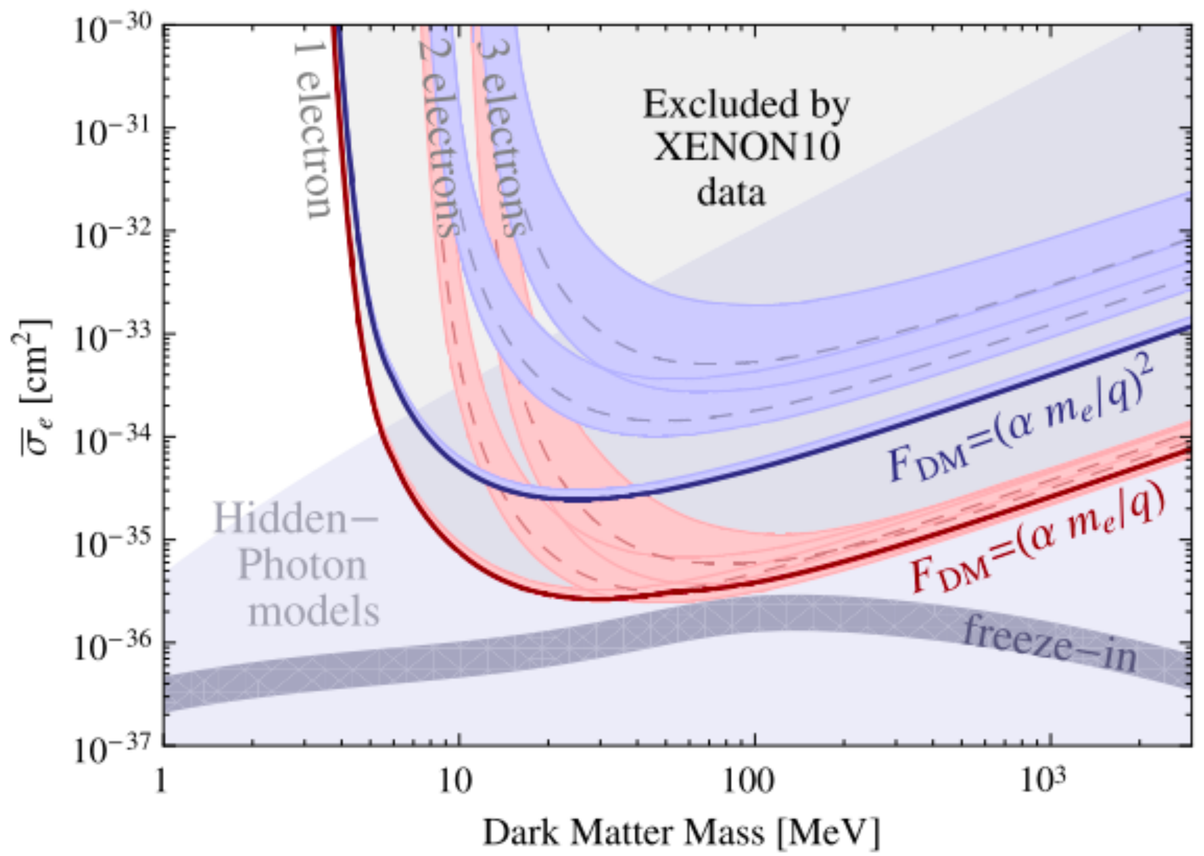
- ★ Null results from LHC and DM direct detection
- ★ Change in 'standard' BSM paradigm' for weak-scale physics and DM
- ★ General shift in thinking: explore more broadly!
- ★ Light Dark Matter relatively unexplored frontier



Accessible to high intensity GeV-scale experiments

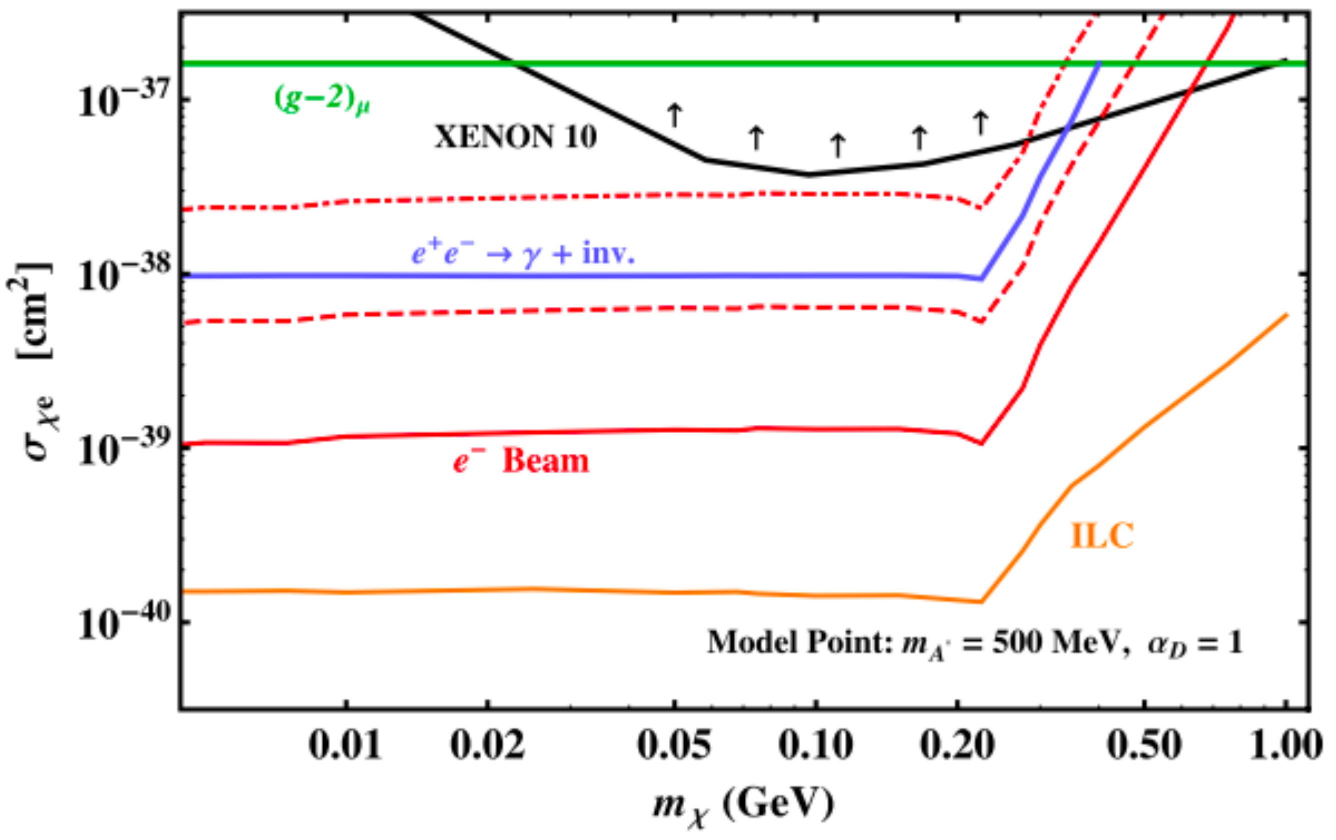
Light Dark Matter limits from direct detection

Limits from XENON10



- 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



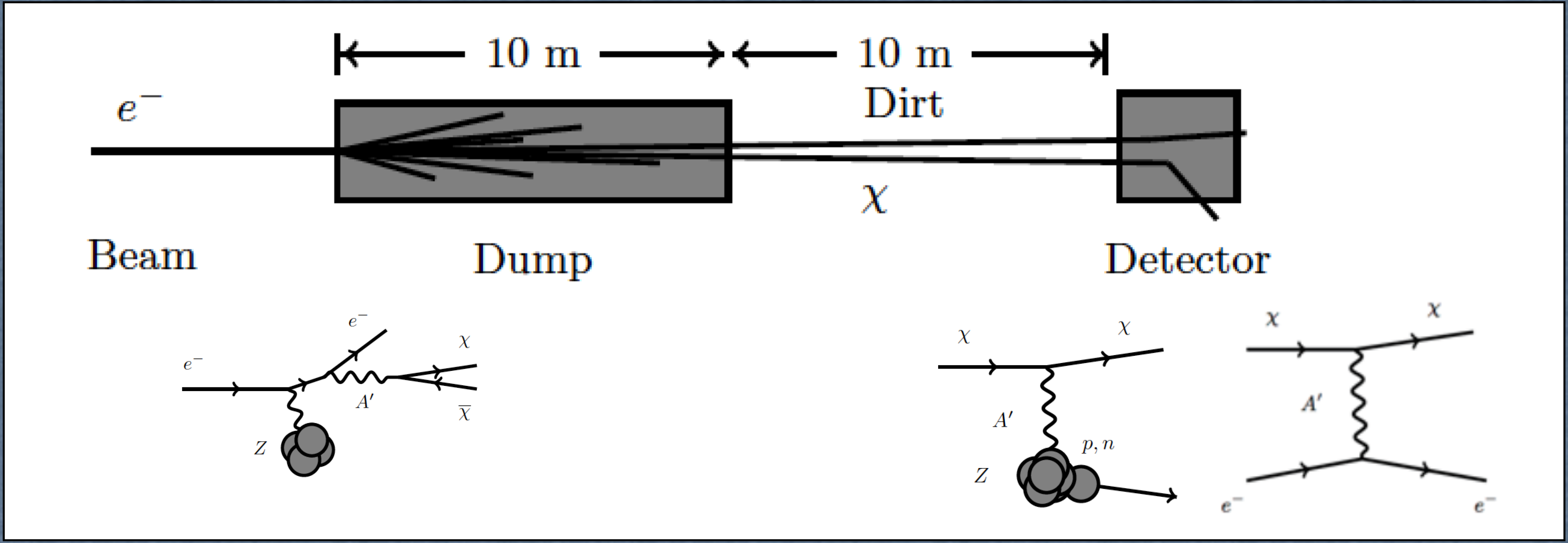
- Fixed target electron beam experiments can be 10^3 - 10^4 more sensitive in the 1 MeV - 1 GeV mass range

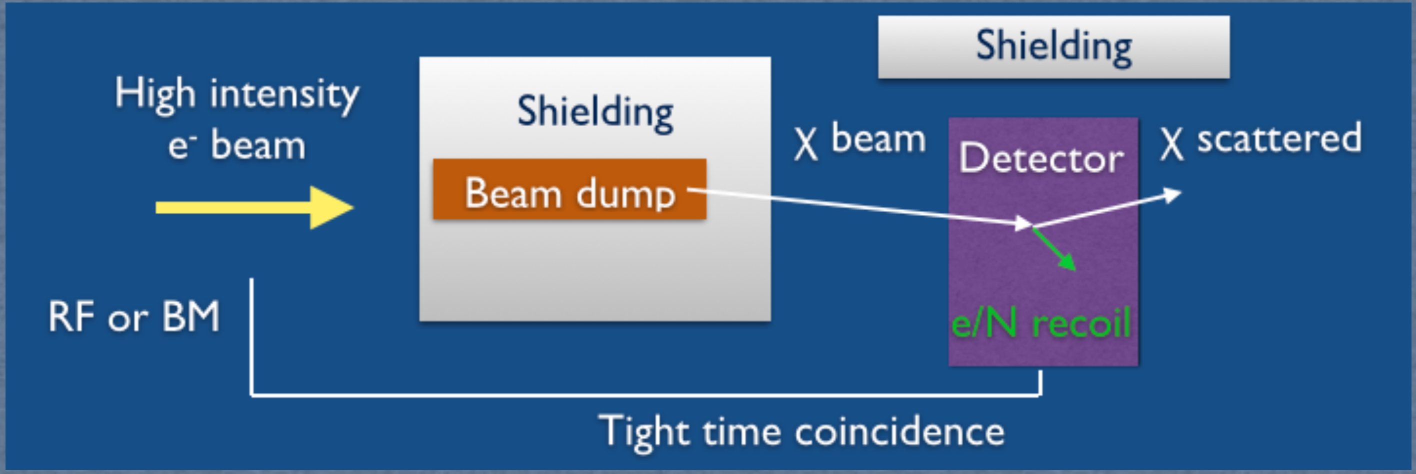
Fixed target DM production

Two steps process:

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

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





High intensity e$^-$ beam

Shielding

Beam dump

Shielding

χ beam

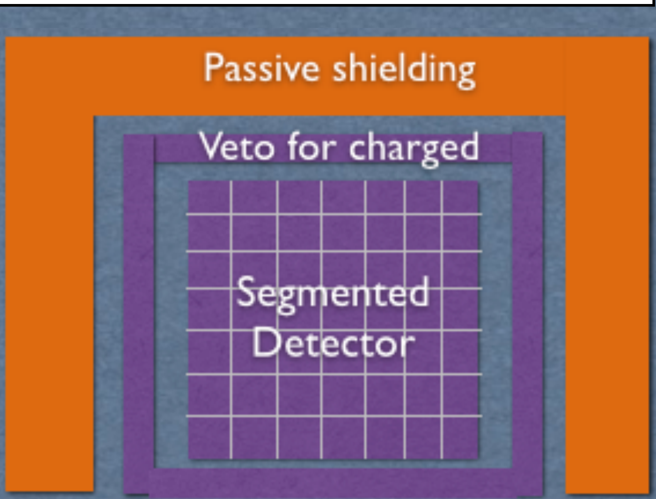
Detector

χ scattered

e/N recoil

RF or BM

Tight time coincidence



Passive shielding

Veto for charged

Segmented Detector

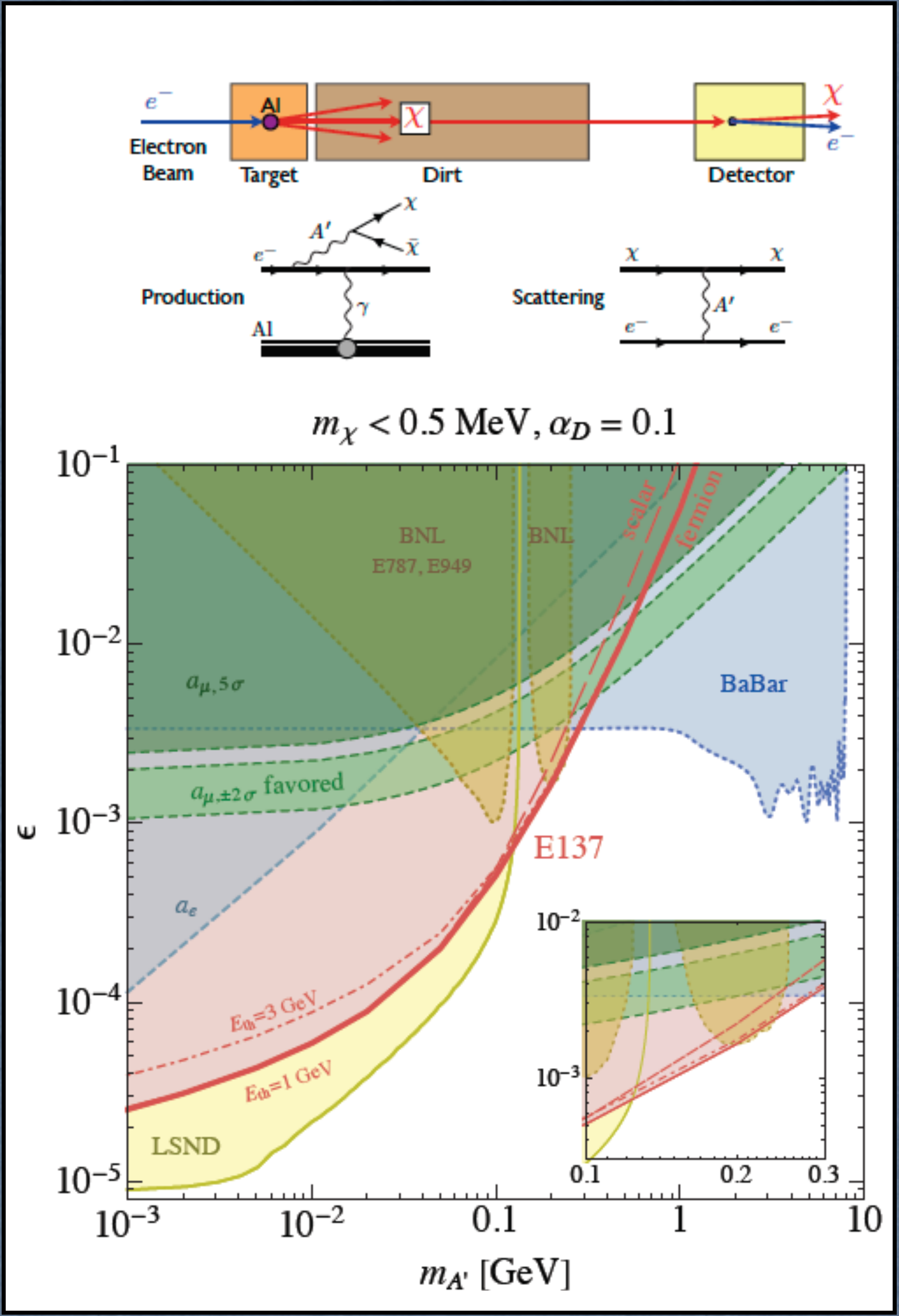
Experimental signature:

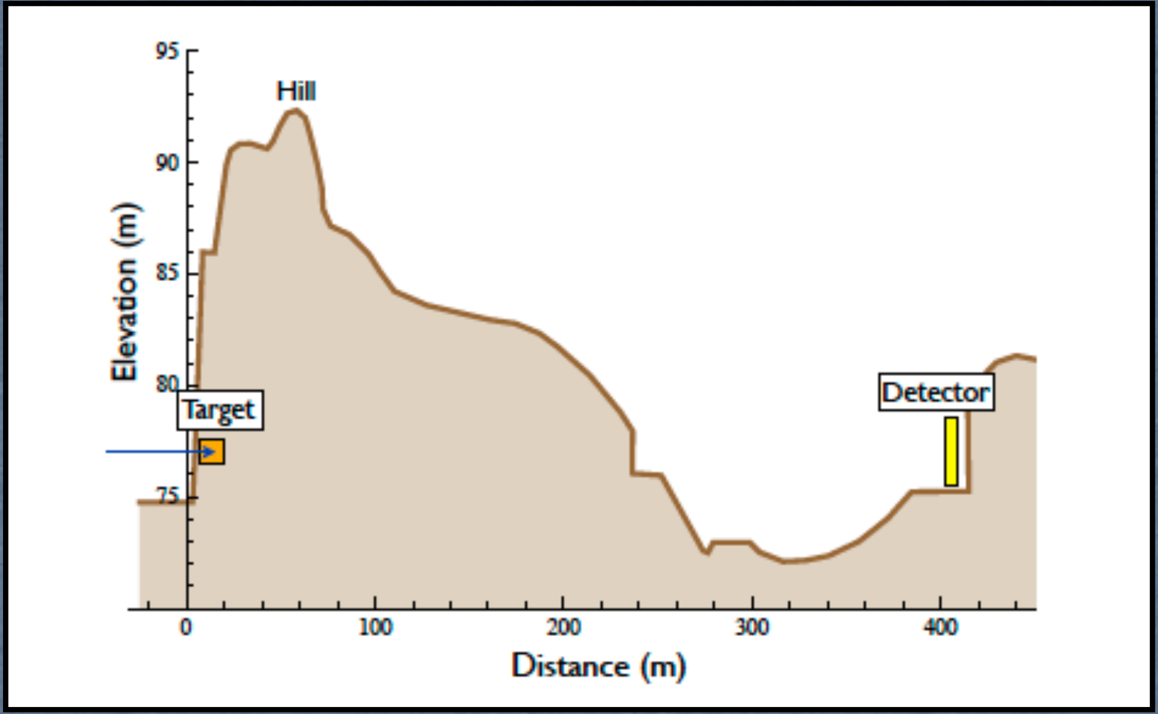
- proton (MeV)
- electron (GeV)

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

Reinterpreting old data: E137@SLAC (<1988)

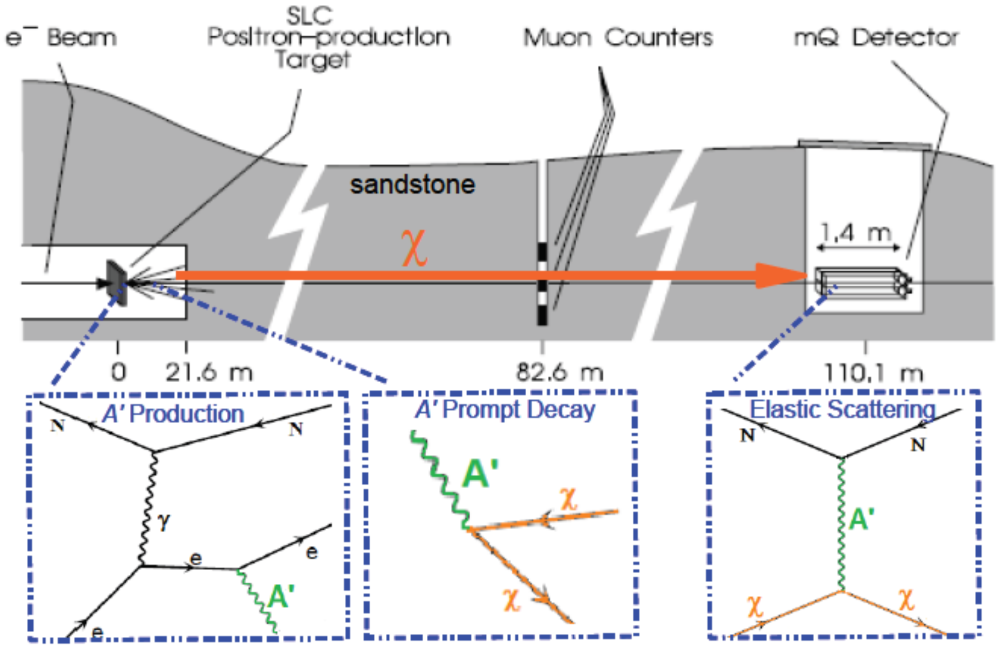
- SLAC electron beam: 20 GeV, 1.6us pulse length, 180 pulse/s, 2x10^{20} EOT
- Detector: 8 r.l. em calorimeter (hodo + converter + MWPC)
- Size: 1.5m x1.0 m at ~380m from the BD
- Cosmic bg suppressed by directionality and time coincidence
- Detection Thr (<u>X-e scattering only</u>): 1-2 GeV
- 0 EVENTS DETECTED

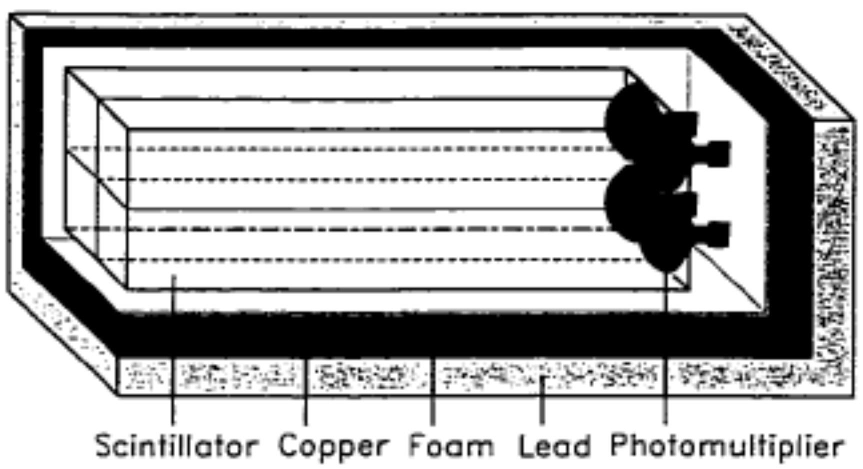


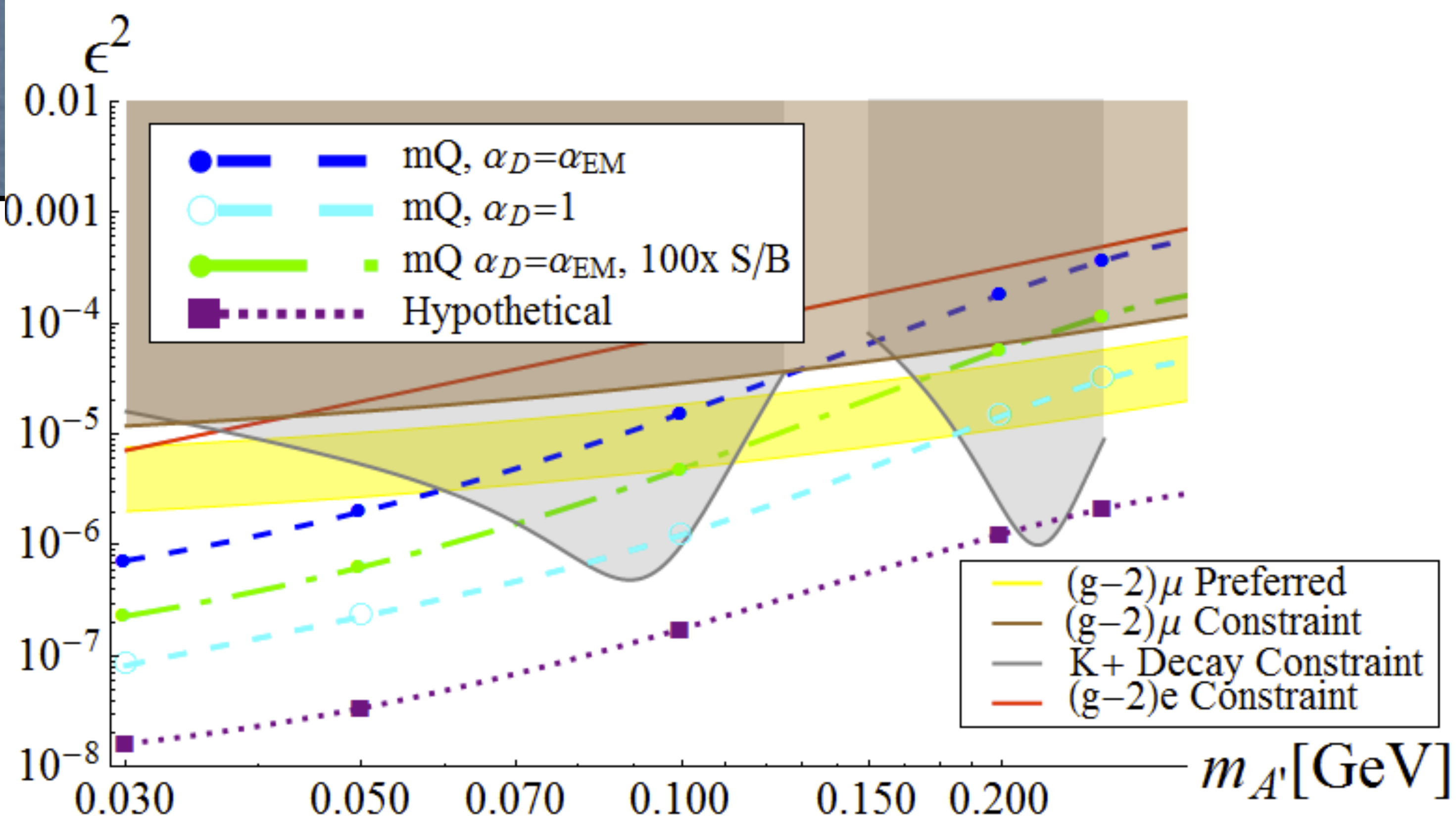


Reinterpreting old data: mCharge@SLAC (<1998)

- SLAC electron beam: 29.5 GeV, ~20-30ps pulse length, 120 pulse/s, 10^{19} EOT
- Detector: (0.4x0.4)x1.3m plastic scintillator ~110m from the BD
- Cosmic bg suppressed by 250ns window with acc signal
- Detection Thr (X-N scattering only): 1pe - 100keV
- 146k 1pe bg counts





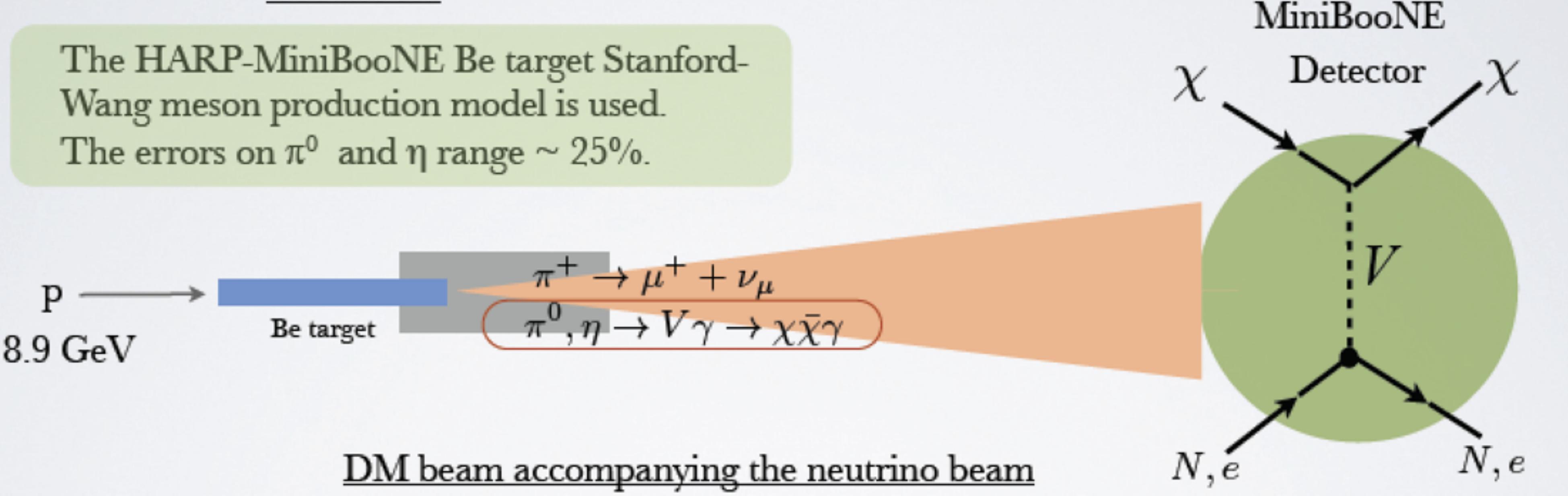


New dedicated experiment: MiniBooNE@FNAL (<2014)

WIMP production and detection mechanism

Production

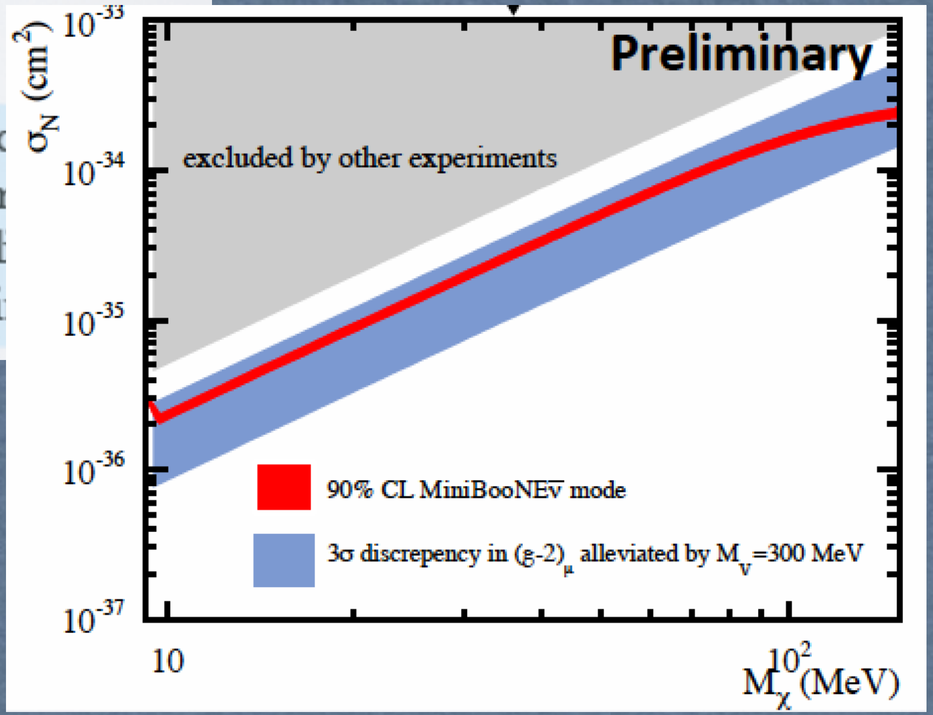
The HARP-MiniBooNE Be target Stanford-Wang meson production model is used.
The errors on π^0 and η range ~ 25%.



DM beam accompanying the neutrino beam

Detection

The DM particles scatter off of nuc
electrons in the detector medium, n
NCE scattering, but possibly with d
kinematics (momentum, angle, timi



The test run just ended!

PADME at LNF >2015(?)

See M.Raggi and V.Kozhuarov talks

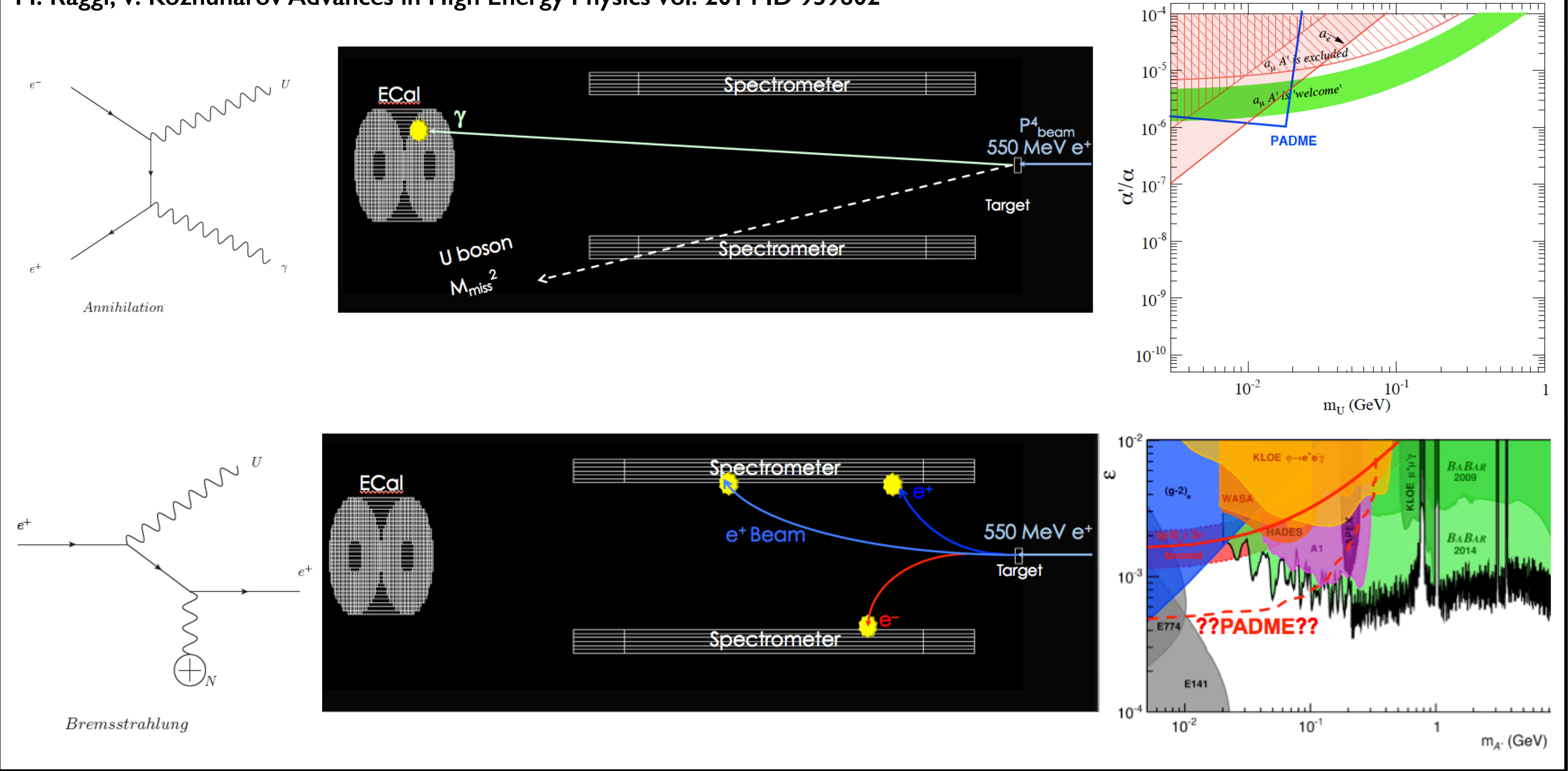
Present BTF

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

Future Upgrade

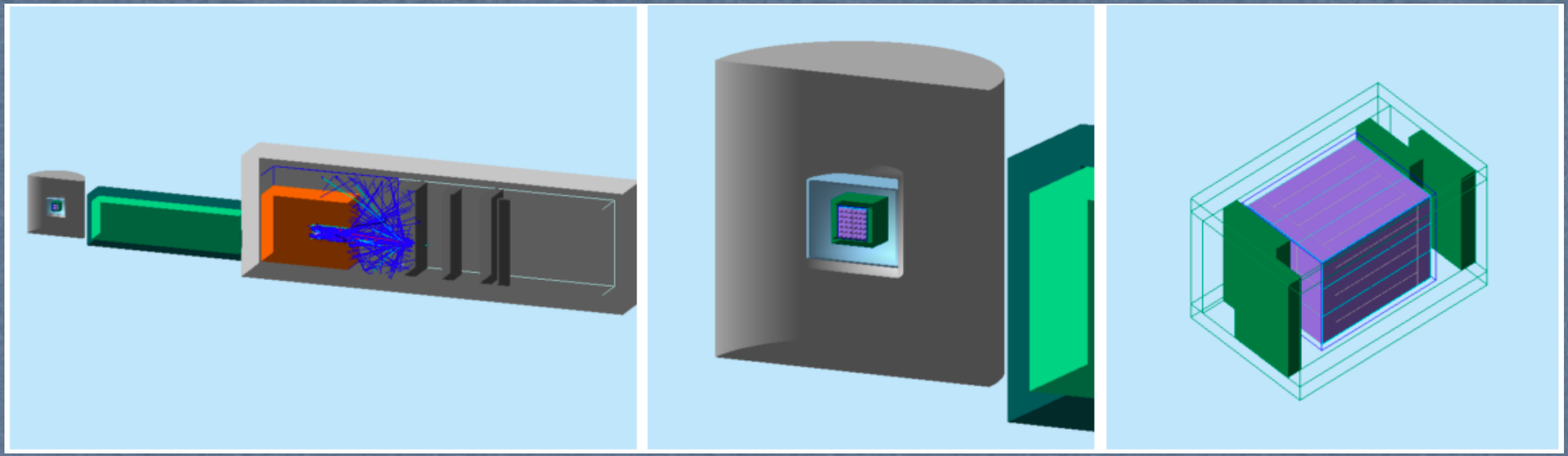
- E_{e-} = 1.250 GeV
- EOT ~ 10^{19} - 10^{20} year^{-1}
- LINAC + BTF beam-dump (BDX@LNF)

M. Raggi, V. Kozhuarov Advances in High Energy Physics Vol. 2014 ID 959802



BDX - Dark matter search in a Beam Dump eXperiment at JLab >2017(?)

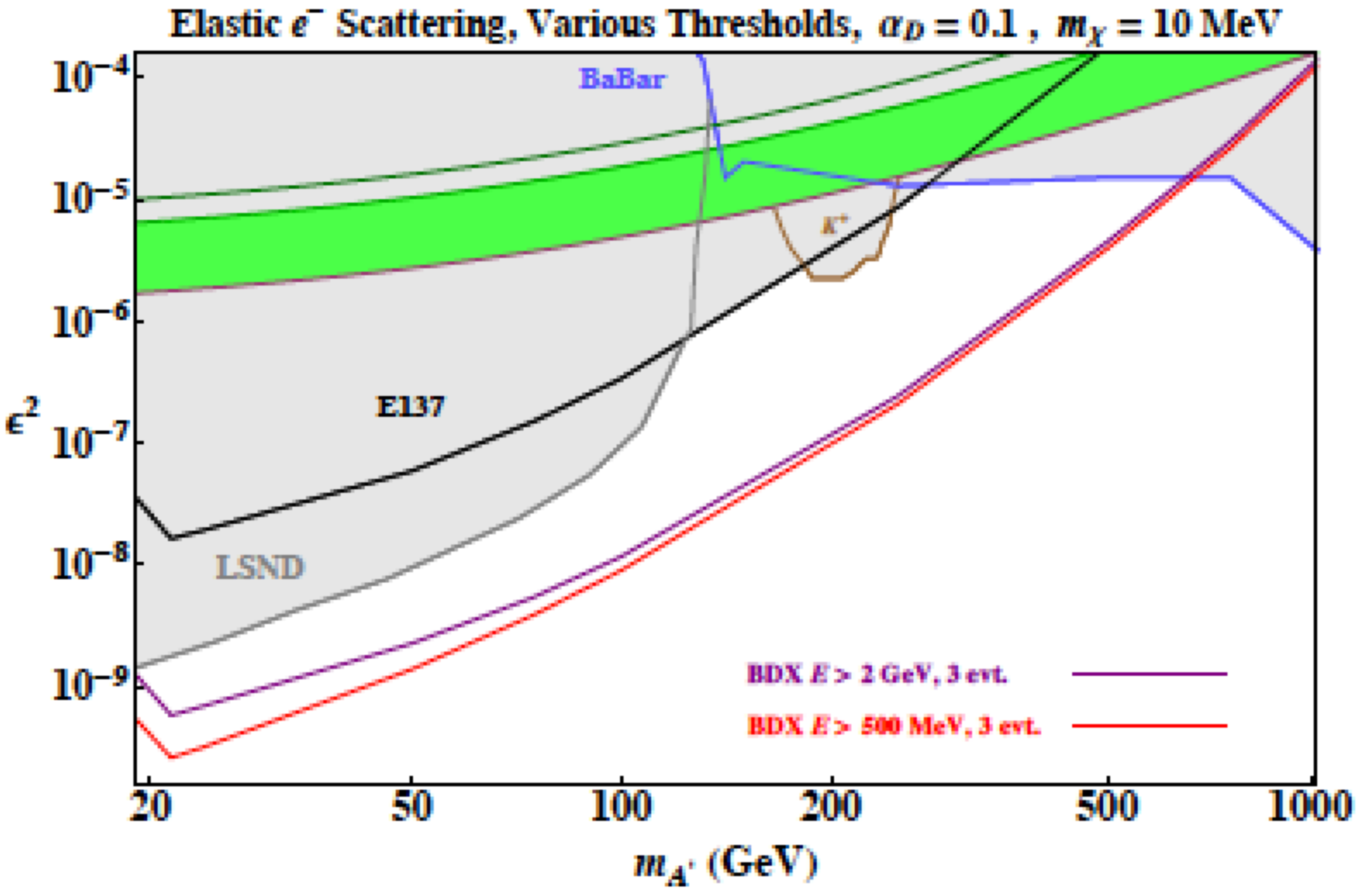
- 11 GeV, 100 uA, continuous electron beam (4ns bunch separation)
- 1 ton detector, 10^{22} EOT (100 uA for 6 months, full parasitic)

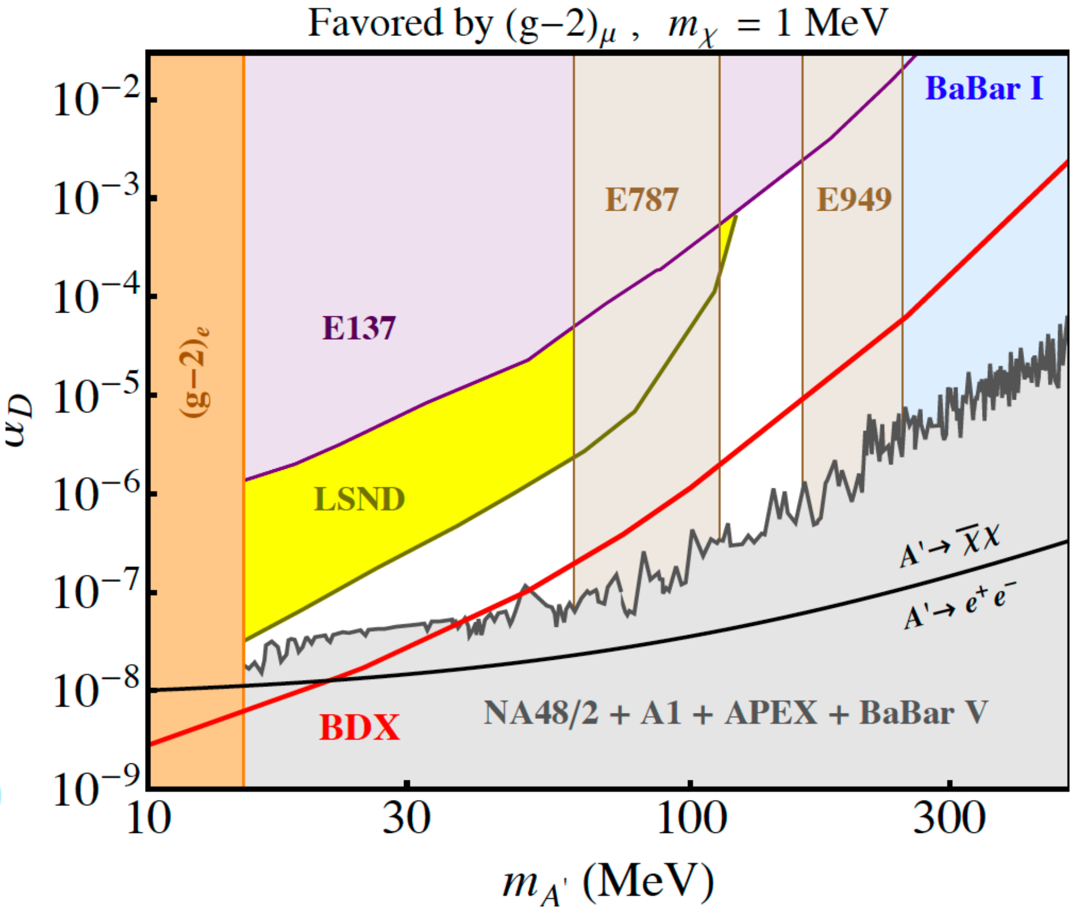


- Plastic scintillator or crystals to reduce the detector footprint
- Cosmogenic background: planned tests at LNS — See M. De Napoli talk
- Beam-related background: new MC techniques — See R. De Vita talk
- BDX LOI published http://arxiv.org/abs/1406.3028 and reviewed by JLab PAC42
- Full proposal expected for 2016

BDX - Dark matter search in a Beam Dump eXperiment at JLab >2017(?)

- More than two orders of magnitudes better than any previous experiments
- Unique capability of measuring both electron and nucleon scattering simultaneously



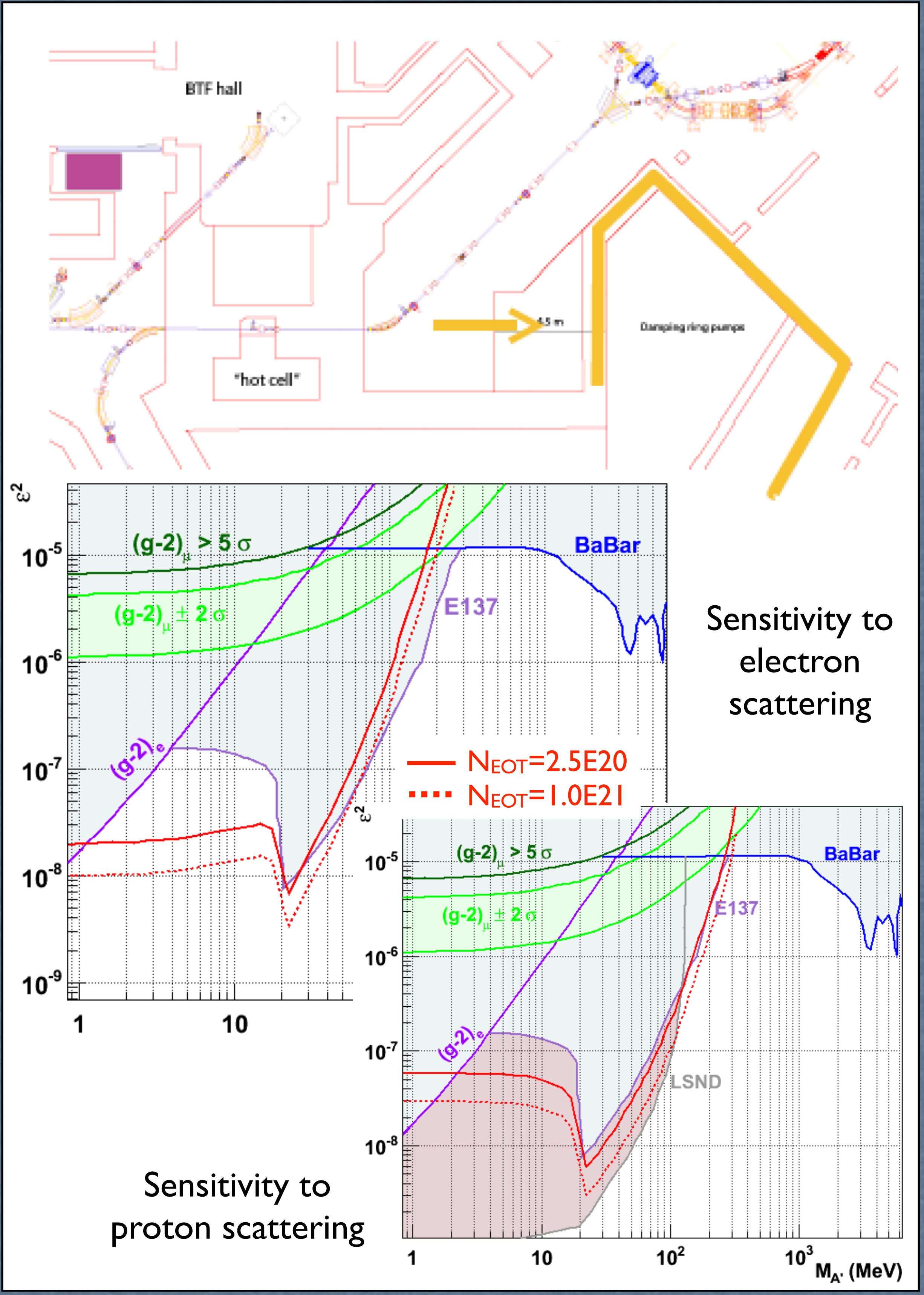


BDX together with the visible decay results will close the $(g-2)_\mu$ favoured region

Beam dump (e^-) experiments can provide unprecedented sensitivity to light dark matter Jefferson Lab will play a significant role in light DM search

BDX @ LNF ~2016(?)

- E_{beam}~1GeV, 10^{21} EOT enough to explore a significant region of parameter space
- 50 Hz pulsed beam helps in reducing cosmic background (rejection~10^{-5})
- Detector: homogen. em calorimeter based on inorganic scintillator + 2x active veto + passive shield
- Reuse of BaBar CsI(Tl) crystals (6580 ~5x5x30 cm^3 available and ready-to-use)
- Service-Hall downstream of the linac injector
- Limited costs and simplified logistics makes BDX@LNF a cheap option ready in 1-2 years
- Project presented in CSNI as part of the PADME
- A major upgrade of the machine (E_{beam}~10 GeV, 10^{23} EOT) and an optimised detector would make LNF the leading facility for LDM search in next 10 years



Sensitivity to electron scattering

Sensitivity to proton scattering

All details in A. Celentano talk tomorrow morning

Putting BDX into context

Report of the Particle Physics Project Prioritization Panel (P5) (May ’14)

Building for Discovery

Strategic Plan for U.S. Particle Physics in the Global Context

Report of the Particle Physics Project Prioritization Panel (P5)

May 2014

Premises

… The dark matter may be composed of ultra-light (less than a GeV), very weakly interacting particles. Searches for such states can be carried out with high-intensity, low-energy beams available at Jefferson Lab or with neutrino beams aimed at large underground detectors.

Recommendations

Dark Matter

The experimental challenge of discovery and characterization of dark matter interactions with ordinary matter requires a multi-generational suite of progressively more sensitive and ambitious direct detection experiments. This is a highly competitive, rapidly evolving field with excellent potential for discovery. **The second-generation direct detection experiments are ready to be designed and built, and should include the search for axions, and the search for low-mass (<10 GeV) and high-mass WIMPs.** Several experiments are needed using multiple target materials to search the available spin-independent and spin-dependent parameter space. This suite of experiments should have substantial cross-section reach, as well as the ability to confirm or refute current anomalous results. Investment at a level substantially larger than that called for in the 2012 joint agency announcement of opportunity will be required for a program of this breadth.

Recommendation 19: Proceed immediately with a broad second-generation (G2) dark matter direct detection program with capabilities described in the text. Invest in this program at a level significantly above that called for in the 2012 joint agency announcement of opportunity.

Conclusions

- Existence of Dark Matter is a compelling reason to investigate new forces and matter over a broad range of mass

- The vector portal (Dark Photon) is a theoretically grounded search territory

- Searches for Dark Photon **visible** decay are excluding a significant part of parameters space

- Light Dark Matter (coupled to DP **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

- BDX@LNF (and PADME) could run in next 2-3 years putting Frascati forward as a leading facility for LDM searches

- Discovery or decisive tests of simplest scenarios possible in the next ~5-8 years!