Next Generation Electron Beam Dump Experiments to Search for Light Dark Matter

Gordan Krnjaic

Perimeter Institute

w/ Eder Izaguirre, Philip Schuster, Natalia Toro

1307.6554

UC Irvine

Joint Particle Seminar

January 22, 2014

Where Are We Now?

The LHC has found the Higgs

Other questions remain: one, two, many? ... natural or not ? etc.

Top question in particle physics “what triggers EWSB?” is ***answered***

Where Are We Now?

The LHC has found the Higgs

Other questions remain: one ... natural or not ? etc.

Top question in particle physic ggers EWSB?" is ***answered***

Where Are We Now?

The LHC has found the Higgs

Other questions remain: one ... natural or not ? etc.

Top question in particle physic ggers EWSB?" is ***answered***

85% of matter is totally mysterious

Strong evidence: rotation curves, CMB, lensing, galaxy surveys...

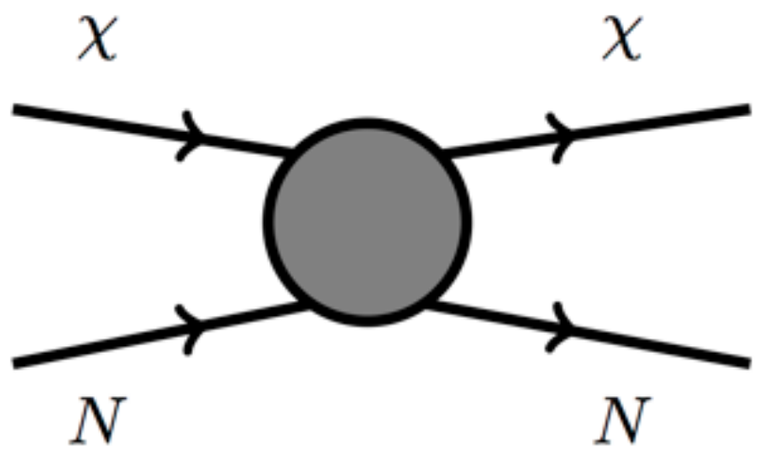
Uncovering its identity is, perhaps, the biggest question now

Null LHC searches (e.g. SUSY) undermine theoretical prejudices

DM is a fishing expedition, so what now?

Current Search Strategy

1. Direct Detection: XENON, CDMS, CoGeNT...



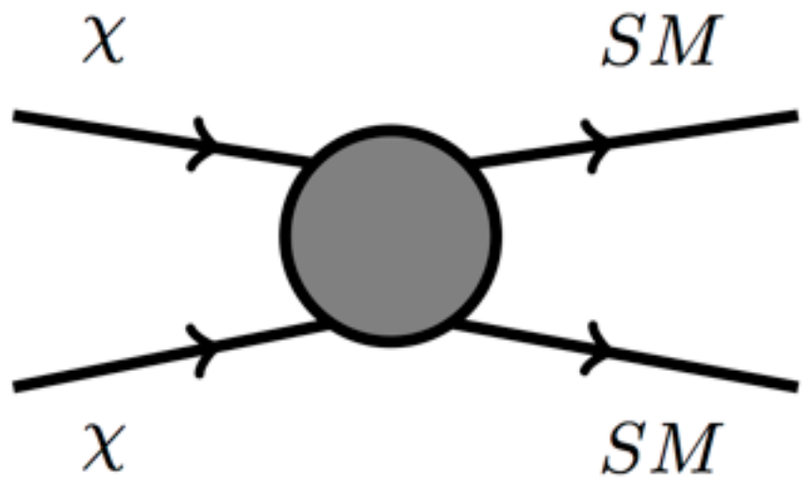
Sensitive to dominant, (meta)stable, dark species

Large BG, tiny recoils for $M <$ few GeV

Astrophysical uncertainties

Current Search Strategy

2. Indirect Detection: FGST, AMS, PAMELA...



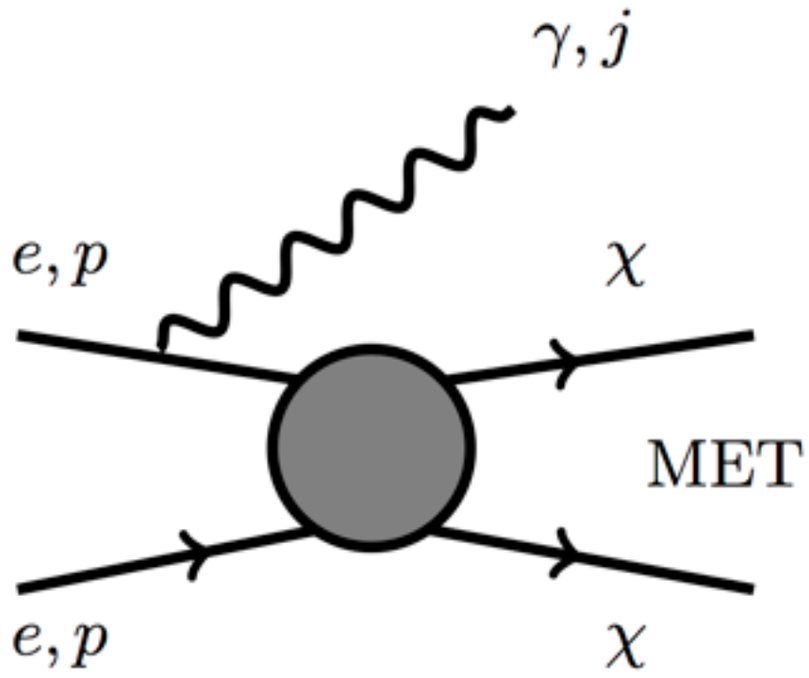
Sensitive to dominant, (meta)stable, dark species

Large BG for DM < few GeV

(Astrophysical uncertainties)^2

Current Search Strategy

3. Colliders: LHC, Tevatron,LEP, BaBar, Belle...



But: weak sensitivity < few -10 GeV

Overview

- A "light" dark sector?
- Why electron beams?
- What can be done *today*?
- … *tomorrow*?

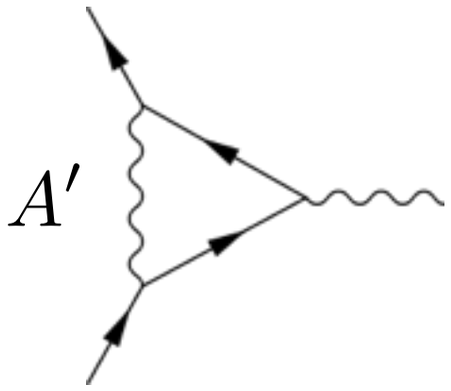
Overview

- A "light" dark sector?
- Why electron beams?
- What can be done *today*?
- … *tomorrow*?

"Light" MeV-GeV Dark States?

Can arise in many contexts:

Asymmetric DM, direct/indirect detection anomalies, missing satellites, self interacting DM, Sommerfeld enhancement, non-thermal dark matter, hidden valleys, $(g\text{-}2)_\mu$ ...



$\sim 3.5\,\sigma$ discrepancy

... but remain elusive in existing program

Motivates new strategies

Q: Does “Light” Make Sense?

Q: Does "Light" Make Sense?

Naive expectation: inefficient annihilation

$$\langle \sigma v \rangle \sim \frac{\alpha_D m_\chi^2}{M_{med}^4} \implies \Omega_\chi \gg (\Omega_{DM})_{obs.}$$

Q: Does "Light" Make Sense?

Naive expectation: inefficient annihilation

$$\langle \sigma v \rangle \sim \frac{\alpha_D m_\chi^2}{M_{med}^4} \implies \Omega_\chi \gg (\Omega_{DM})_{obs.}$$

But this merely implies additional light mediators

$$m_\chi > M_{med} \ , \ \langle \sigma v \rangle \sim \frac{\alpha_D^2}{m_\chi^2} \implies \frac{\Omega_\chi}{\Omega_{DM}} \sim 10^{-3} \left(\frac{\alpha}{\alpha_D} \right)^2 \left(\frac{m_\chi}{100 \text{ MeV}} \right)^2$$

Q: Does "Light" Make Sense?

Naive expectation: inefficient annihilation

$$\langle \sigma v \rangle \sim \frac{\alpha_D m_\chi^2}{M_{med}^4} \implies \Omega_\chi \gg (\Omega_{DM})_{obs.}$$

But this merely implies additional light mediators

$$m_\chi > M_{med} \ , \ \langle \sigma v \rangle \sim \frac{\alpha_D^2}{m_\chi^2} \implies \frac{\Omega_\chi}{\Omega_{DM}} \sim 10^{-3} \left(\frac{\alpha}{\alpha_D} \right)^2 \left(\frac{m_\chi}{100 \text{ MeV}} \right)^2$$

CMB bounds: late annihilations to leptons

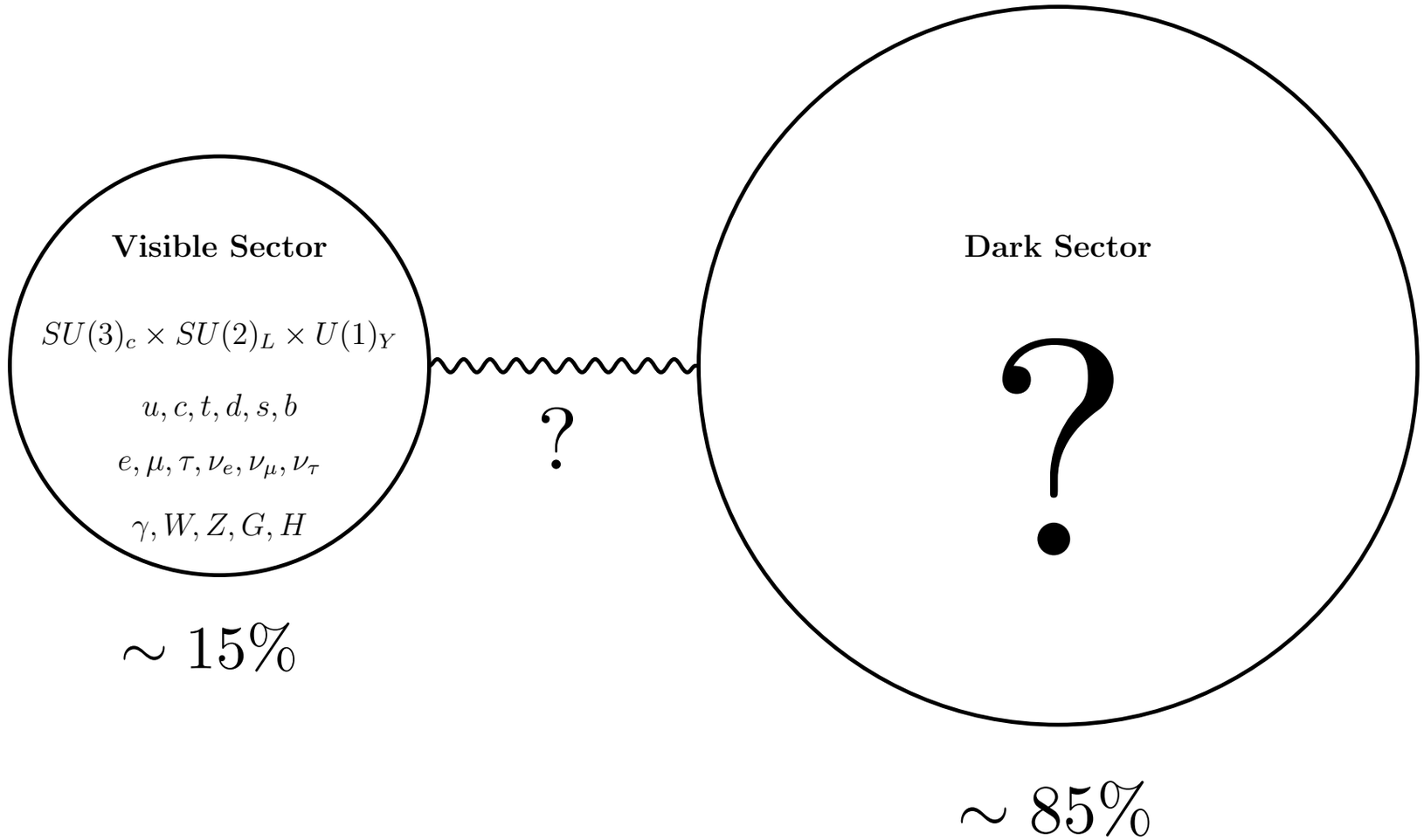
$$\Omega_\chi = \Omega_{DM} \implies \sigma_{\chi\chi \to \ell\ell} < 10^{-5} \left(\frac{m_\chi}{\text{MeV}} \right) \sigma_{thermal}$$

$$\Omega_\chi < \Omega_{DM} \implies \left(\frac{\Omega_\chi}{\Omega_{DM}} \right) < 10^{-3} \left(\frac{m_\chi}{100 \text{ MeV}} \right)$$

Model dependent

Q: Does "Light" Make Sense?

A: Yes, many possibilities...



If there are light particles, we should look for them!

Benchmark Model

A' w/ kinetic mixing:

$$\mathcal{L} \supset \frac{\epsilon}{2} F_{\mu\nu} F'_{\mu\nu} + \frac{m_{A'}}{2} A'^{\mu} A'_{\mu} + \bar{\chi}(i\not{D} + m_\chi)\chi$$

"Simplified model" proxy for light-mediator scenarios
w/ neutral-current interactions

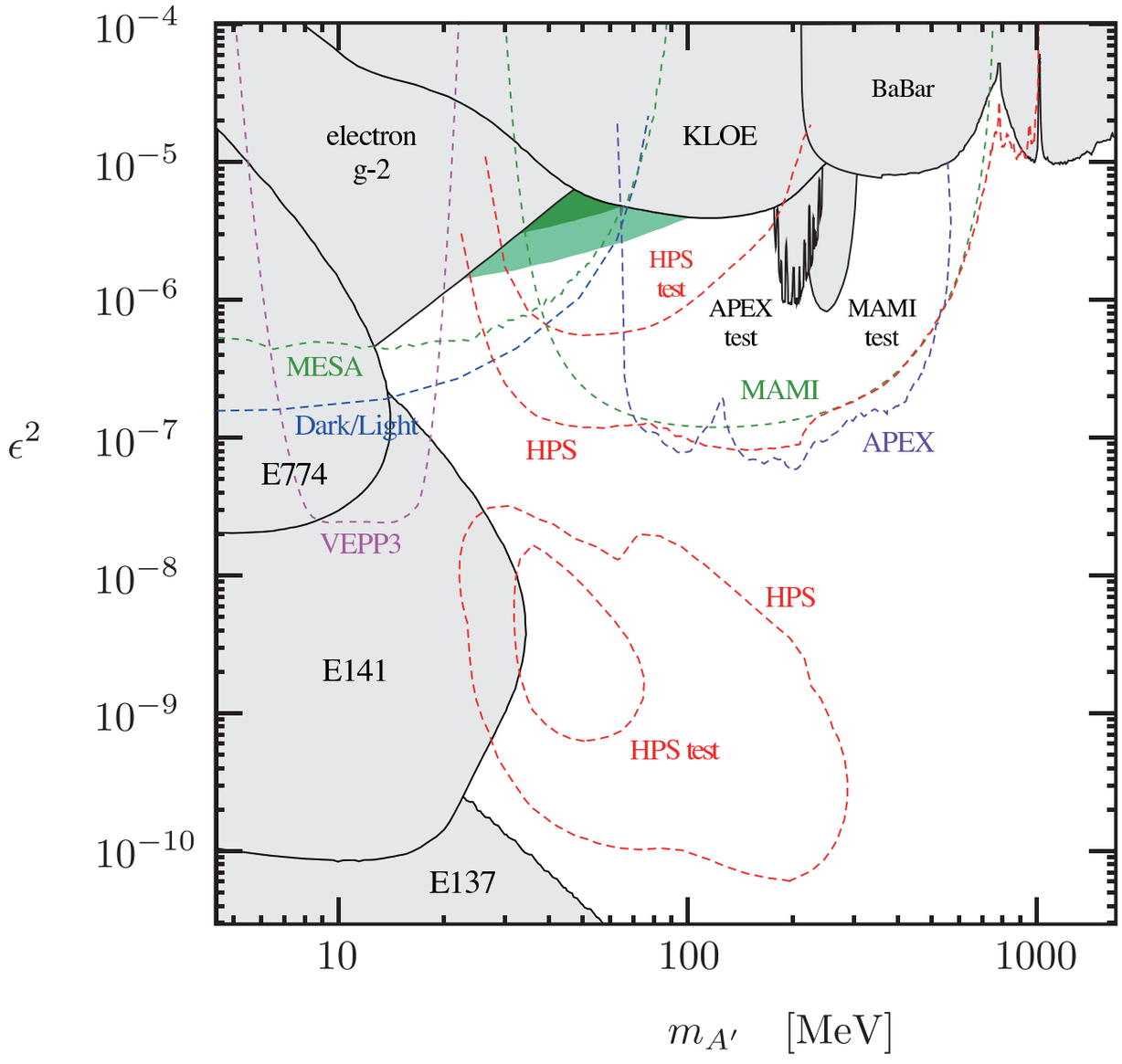
Parameters: $m_\chi, m_{A'} \sim \mathrm{MeV} - \mathrm{GeV}$

$$\alpha_D \sim 10^{-2} - 1$$

$$\epsilon \sim 10^{-5} - 10^{-2}$$

Ideally suited for fixed target searches

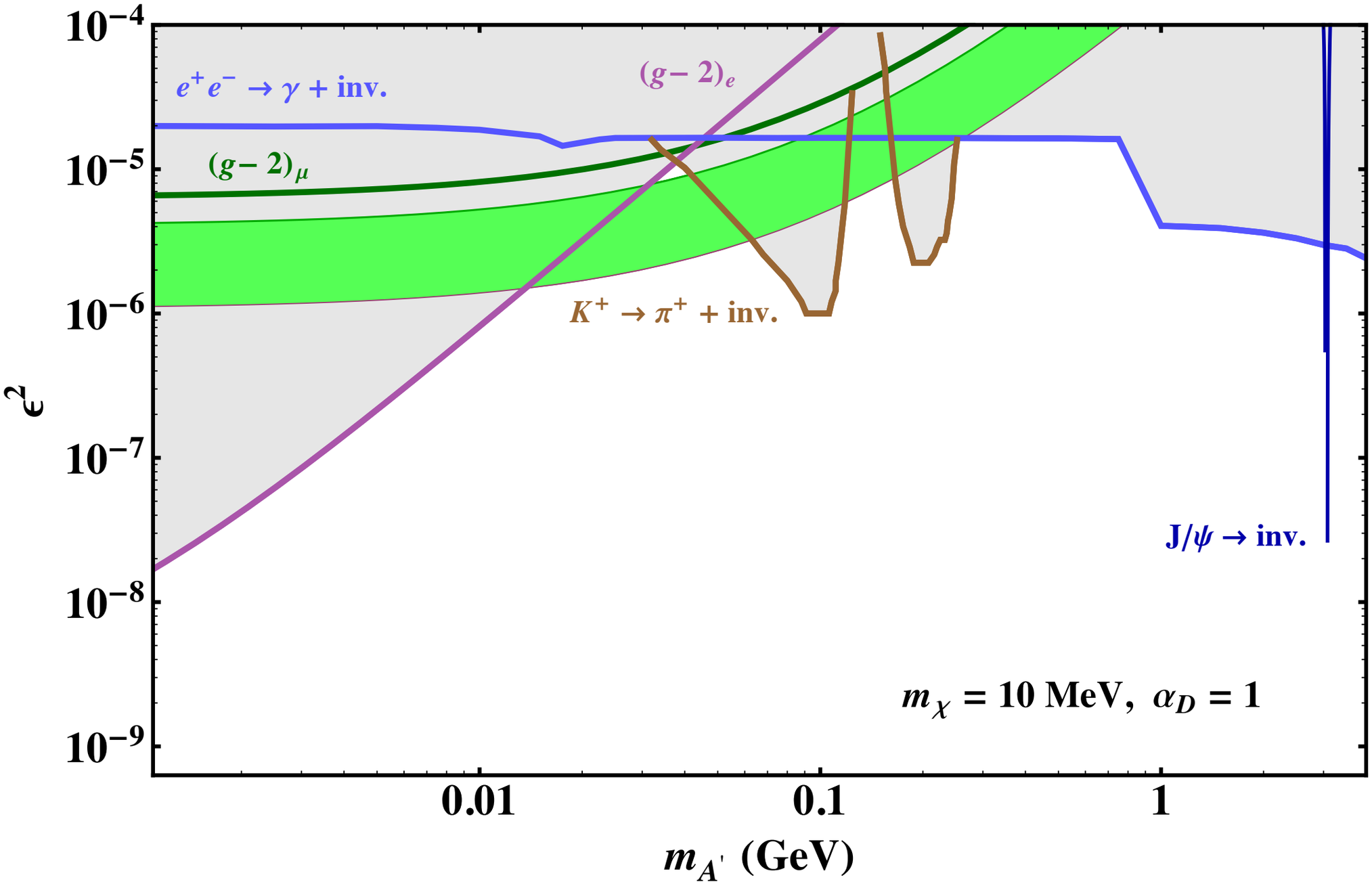
If A' Decays to the SM



Many experiments out there (arXiv:1209.2558)

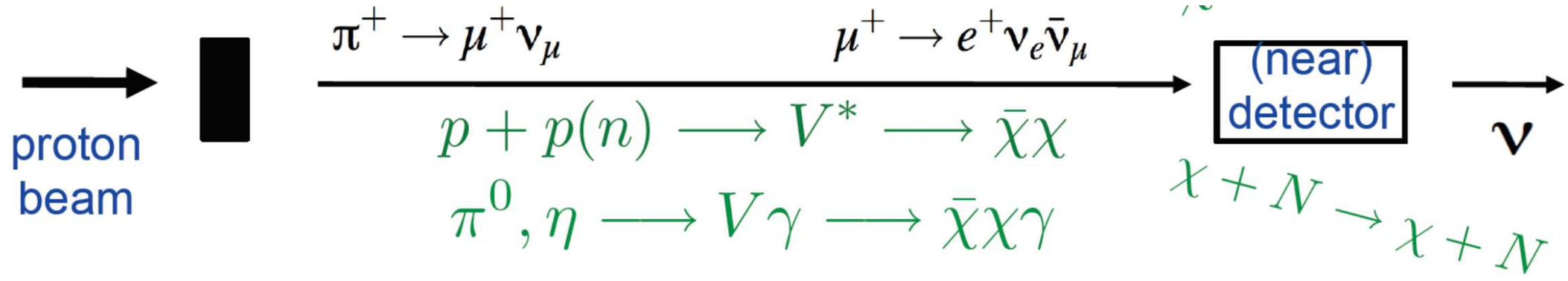
Much harder for *invisible* decays

If A' Decays *Invisibly*



NB: Only the g-2 curves are model independent

A' Decays Invisibly: Neutrino Factories

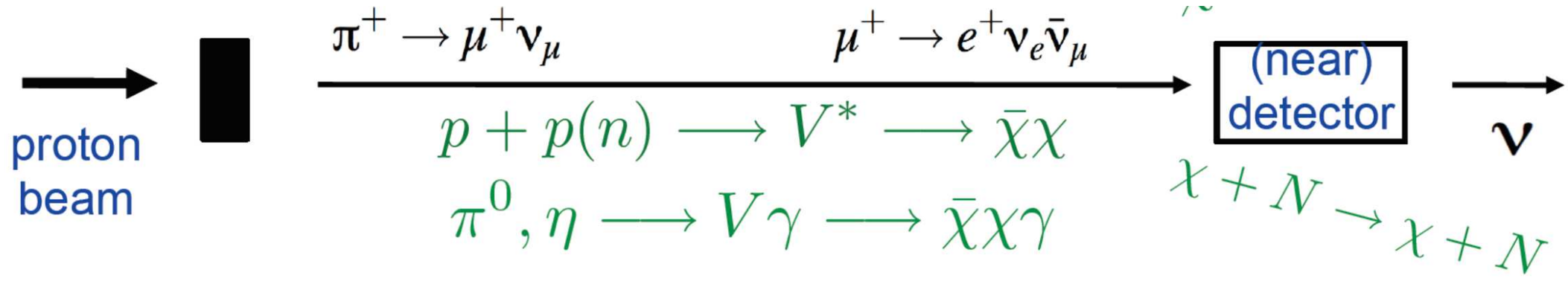


Proposed searches at MiniBooNE, LSND, T2K*

DM from decays, scatters downstream

(de Niverville, Pospelov, Ritz, Batell)

A' Decays Invisibly: Neutrino Factories



Proposed searches at MiniBooNE, LSND, T2K*

DM from decays, scatters downstream

(de Niverville, Pospelov, Ritz, Batell)

But:

Setup for neutrino oscillations = large NC backgrounds

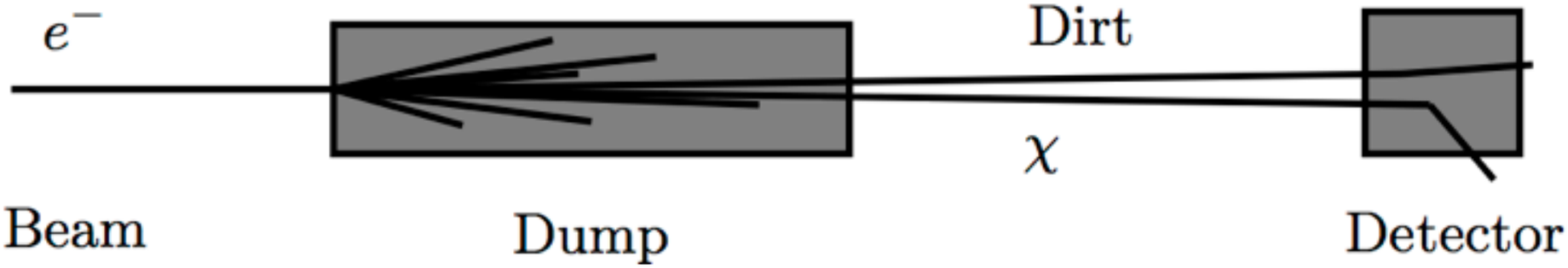
Large ~ O(100) m baseline degrades acceptance

Proper search expensive, requires dedicated beam time

Overview

- A "light" dark sector?
- Why electron beams?
- What can be done *today*?
- … *tomorrow*?

How to Search
0. General Setup



Basic Ingredients:

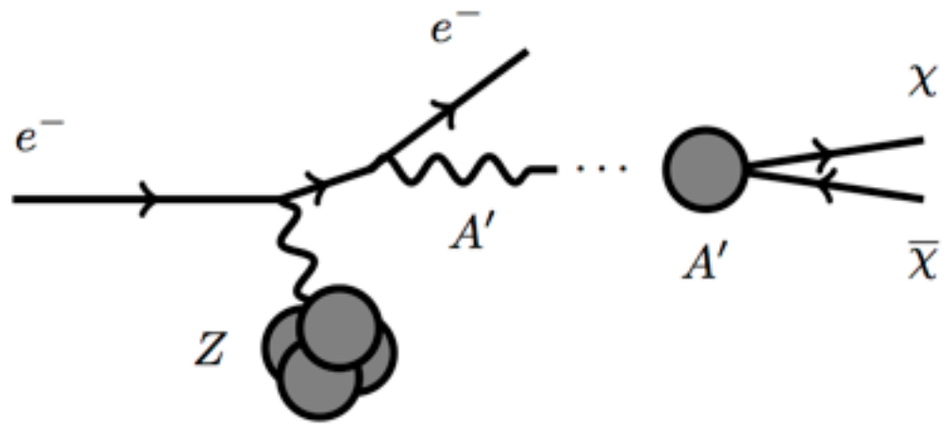
Electron beam (few-100) GeV, continuous or pulsed

Beam dump & dirt ~ few 10s m, range out beam BG

Detector sensitive to neutral currents: oil, plastic, LAr ...

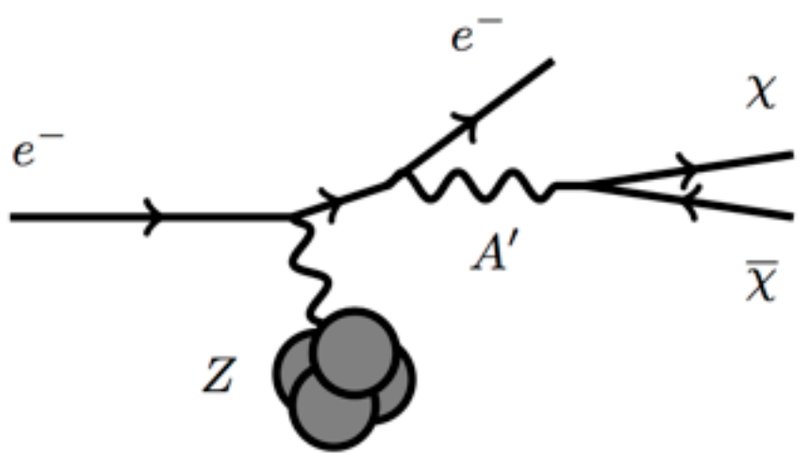
How to Search
1. Production

$m_{A'} > 2m_\chi \implies$ **on-shell A'-strahlung**



$$\sigma \sim \frac{\epsilon^2}{m^2_{A'}}$$

$m_{A'} < 2m_\chi \implies$ **off-shell radiative**



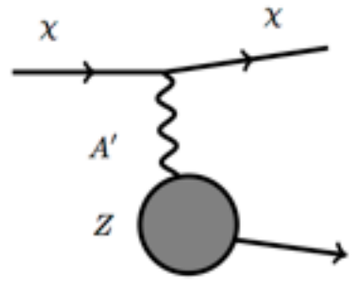
$$\sigma \sim \frac{\alpha_D \epsilon^2}{m^2_\chi}$$

How to Search
2. Downstream Detection

How to Search
2. Downstream Detection

Coherent Nuclear

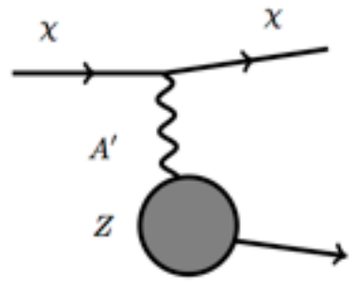
Low recoil energies, light mediator
Z^2 enhancement, form factor



How to Search
2. Downstream Detection

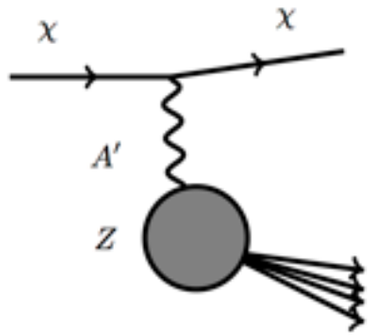
Coherent Nuclear

Low recoil energies, light mediator
Z^2 enhancement, form factor



Inelastic hadro-production

High recoil energies

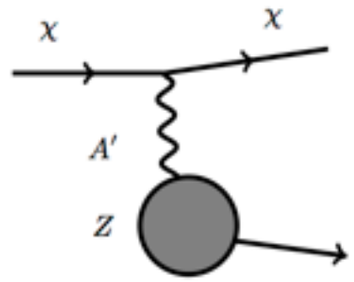


$\pi, \Delta, K \cdots$

How to Search
2. Downstream Detection

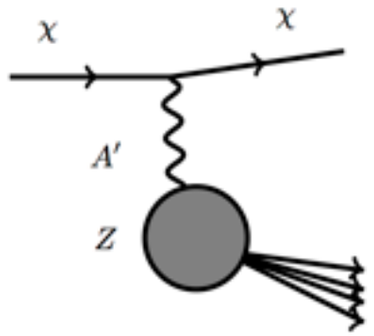
Coherent Nuclear

Low recoil energies, light mediator
Z^2 enhancement, form factor



Inelastic hadro-production

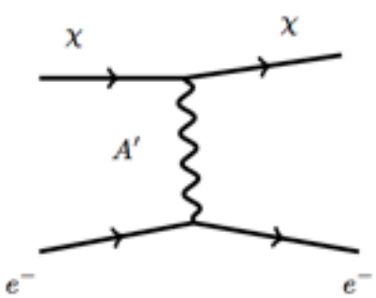
High recoil energies



$\pi, \Delta, K \cdots$

Electron Scattering

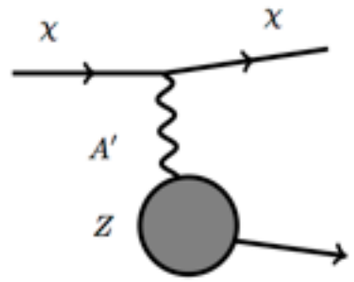
Low recoil energies, light mediator



How to Search
2. Downstream Detection

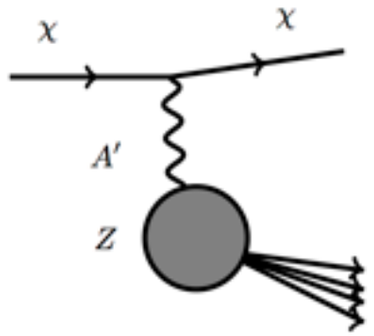
Coherent Nuclear

Low recoil energies, light mediator
Z^2 enhancement, form factor



Inelastic hadro-production

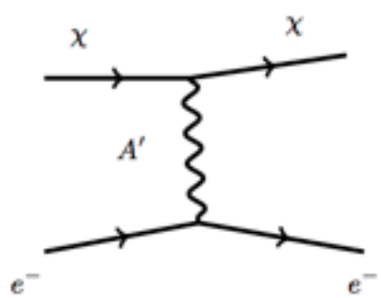
High recoil energies



$\pi, \Delta, K \cdots$

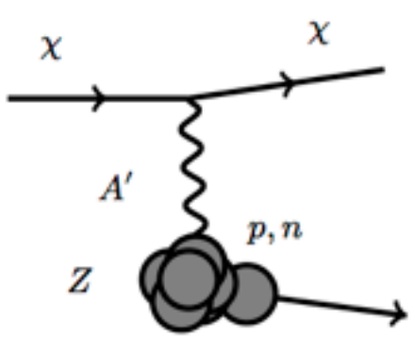
Electron Scattering

Low recoil energies, light mediator



Quasi-elastic Nucleon

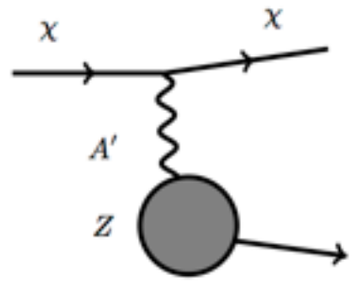
Higher recoil energies > 10s MeV,



How to Search
2. Downstream Detection

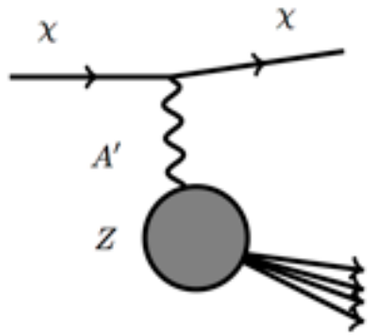
Coherent Nuclear

Low recoil energies, light mediator
Z^2 enhancement, form factor



Inelastic hadro-production

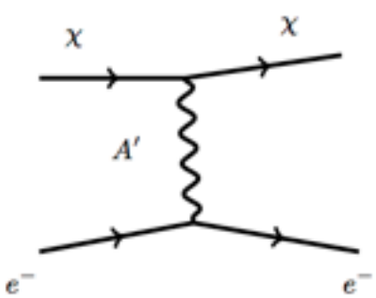
High recoil energies



$\pi, \Delta, K \cdots$

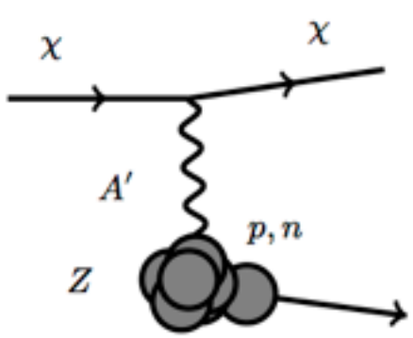
Electron Scattering

Low recoil energies, light mediator



Quasi-elastic Nucleon

Higher recoil energies > 10s MeV,



Why Electron Beams?

Why Electron Beams?

Production rate comparable to proton beams

Why Electron Beams?

Production rate comparable to proton beams

Beam related backgrounds: *negligible*

Why Electron Beams?

Production rate comparable to proton beams

Beam related backgrounds: *negligible*

Parasitic running: *existing* beams are powerful

Why Electron Beams?

Production rate comparable to proton beams

Beam related backgrounds: *negligible*

Parasitic running: *existing* beams are powerful

Small scale & inexpensive

Why Electron Beams?

Production rate comparable to proton beams

Beam related backgrounds: *negligible*

Parasitic running: *existing* beams are powerful

Small scale & inexpensive

High acceptance: nearby detector & forward kinematics

Why Electron Beams?

Production rate comparable to proton beams

Beam related backgrounds: *negligible*

Parasitic running: *existing* beams are powerful

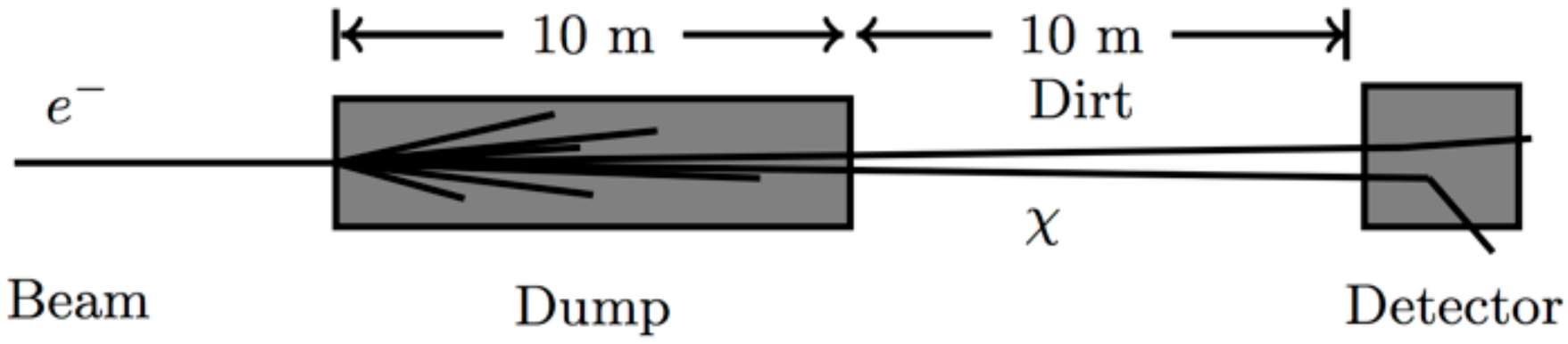
Small scale & inexpensive

High acceptance: nearby detector & forward kinematics

Cosmic backgrounds: *beatable & reducible*

"Benchmark" Setup

1. Layout



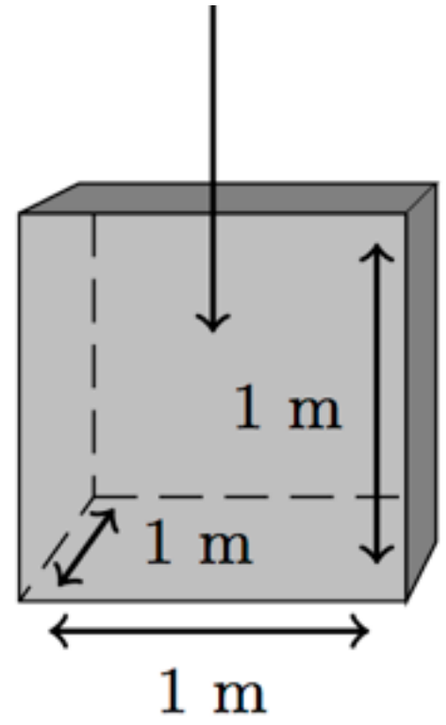
Aluminum dump, 12 GeV beam (pulsed)

Average current ~ $80\mu A$

10^{22} EOT (~ one year operation)

Duty cycle ~ 10^{-4}, live-time ~ 10^3s

Fiducial volume $= 1\text{m}^3$



Oil based detector (CH_2)*
Depth = 15 m.w.e.

"Benchmark" Setup

2.Beam Related Backgrounds

Neutrinos from beam π/μ

Nuclear recoil cut $E_{recoil} > 10$ MeV

$(0.1 - 1)$ BG event per $10^{22}\, e^-$

Consistent with SLAC mQ rates

"Benchmark" Setup

2.Beam Related Backgrounds

Neutrinos from beam π/μ

Nuclear recoil cut $E_{recoil} > 10$ MeV

$(0.1 - 1)$ BG event per $10^{22}\, e^-$

Consistent with SLAC mQ rates

Ejected "Fast" Neutrons

$E_n < 10\,\mathrm{MeV}$, below cuts

$\Longrightarrow$ **Beam backgrounds very small**

“Benchmark” Setup

3. Beam Unrelated Backgrounds

Cosmic muons

Decays in flight ~ 0.005 Hz (veto)

Stopped decays ~ 100 μs cut (veto)

"Benchmark" Setup

3. Beam Unrelated Backgrounds

Cosmic muons

Decays in flight ~ 0.005 Hz (veto)

Stopped decays ~ 100 μs cut (veto)

Cosmic neutrons

$$\Phi(E > 10\ \mathrm{MeV}) \approx 2 \times 10^{-2} \mathrm{m}^{-2} \mathrm{s}^{-1}$$

Consistent with CDMS-SUF (~ 10 m.w.e)

"Benchmark" Setup

3. Beam Unrelated Backgrounds

Cosmic muons

Decays in flight ~ 0.005 Hz (veto)

Stopped decays ~ 100 μs cut (veto)

Cosmic neutrons

$$\Phi(E > 10\ \mathrm{MeV}) \approx 2 \times 10^{-2} \mathrm{m}^{-2} \mathrm{s}^{-1}$$

Consistent with CDMS-SUF (~ 10 m.w.e)

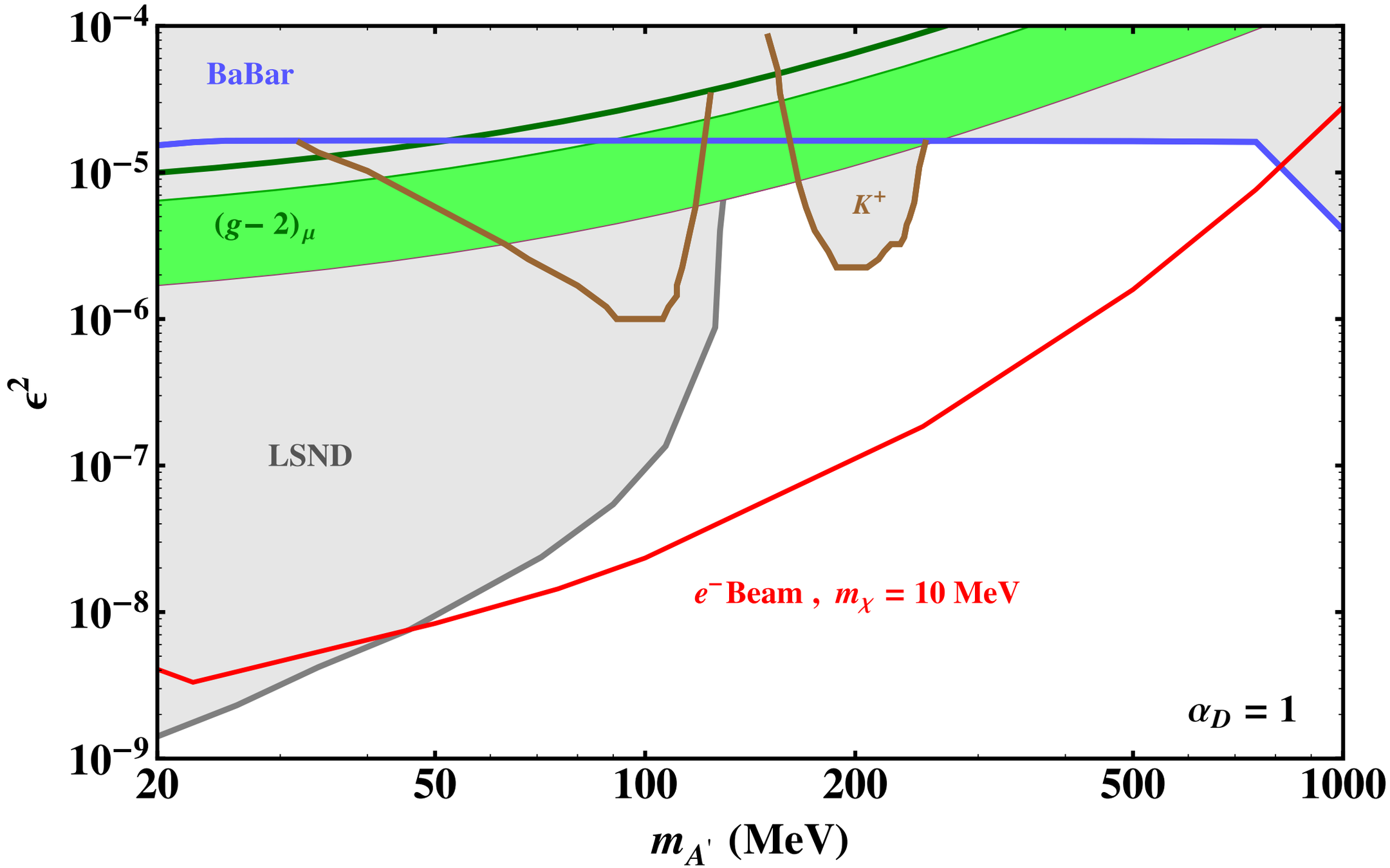
Pulsed beam ~ livetime 10^3 s , $\mathcal{O}(10)$ cosmic BG events

$\Longrightarrow$ ***Small, Measurable***

Sensitivity ~ 10 event signal yield

"Benchmark" Setup

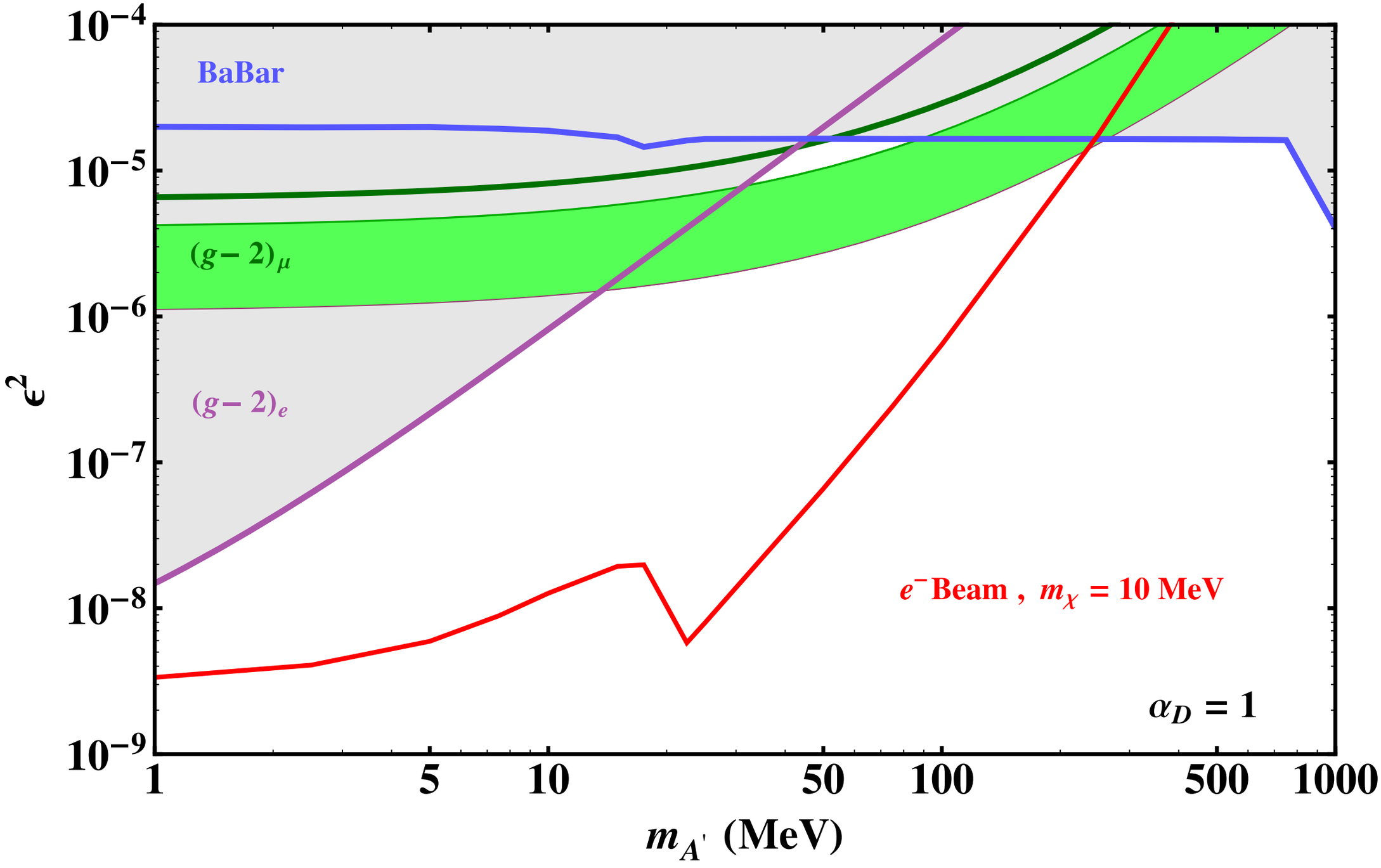
$E = 12$ GeV , 10^{22} EOT , Dist. = 20 m , Det = 1 m^3



Quasi-elastic nucleon , pulsed beam

"Benchmark" Setup

$E = 12$ GeV , 10^{22} EOT , Dist. = 20 m , Det = 1 m^3



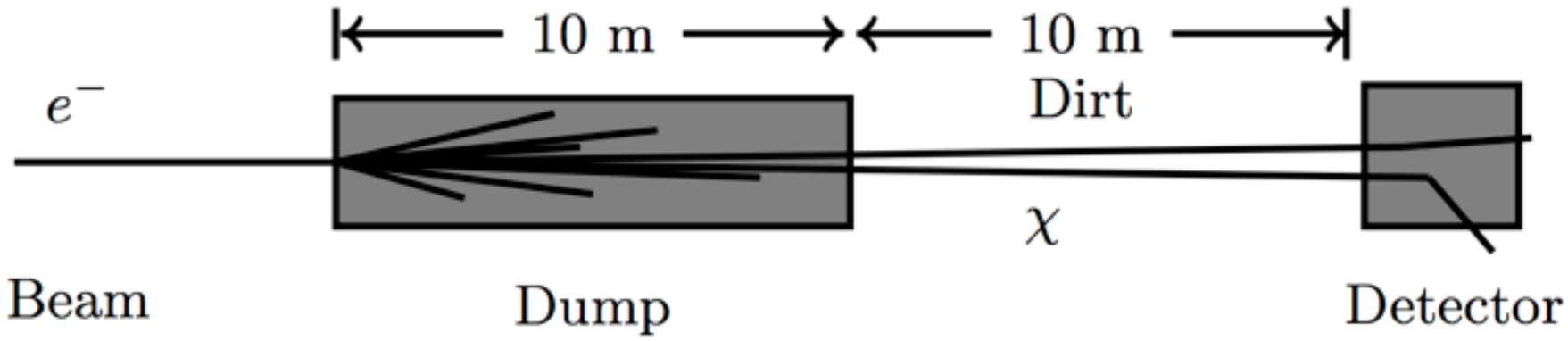
Leptophilic, pulsed beam

Overview

- A "light" dark sector?
- Why electron beams?
- What can be done *today*?
- … *tomorrow*?

What Can Be Done *Today*?

1. SLAC FACET-Beam

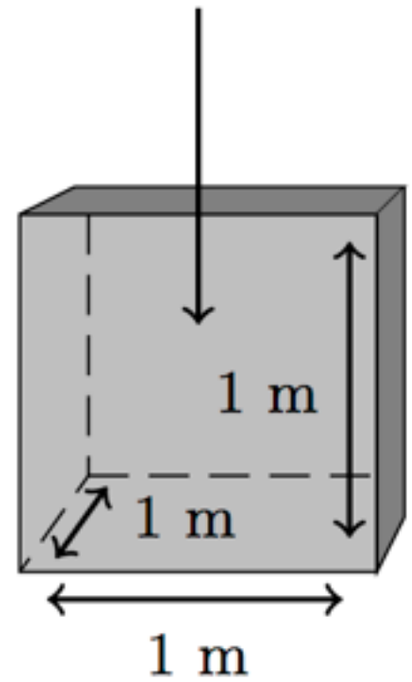


30 GeV electrons, Tungsten dump

Pulsed beam, negligible cosmics

Current $\mathcal{O}(\mu A) \implies \sim 10^{20}\, e^- /$ Yr.

Sensitivity ~ 10 signal events

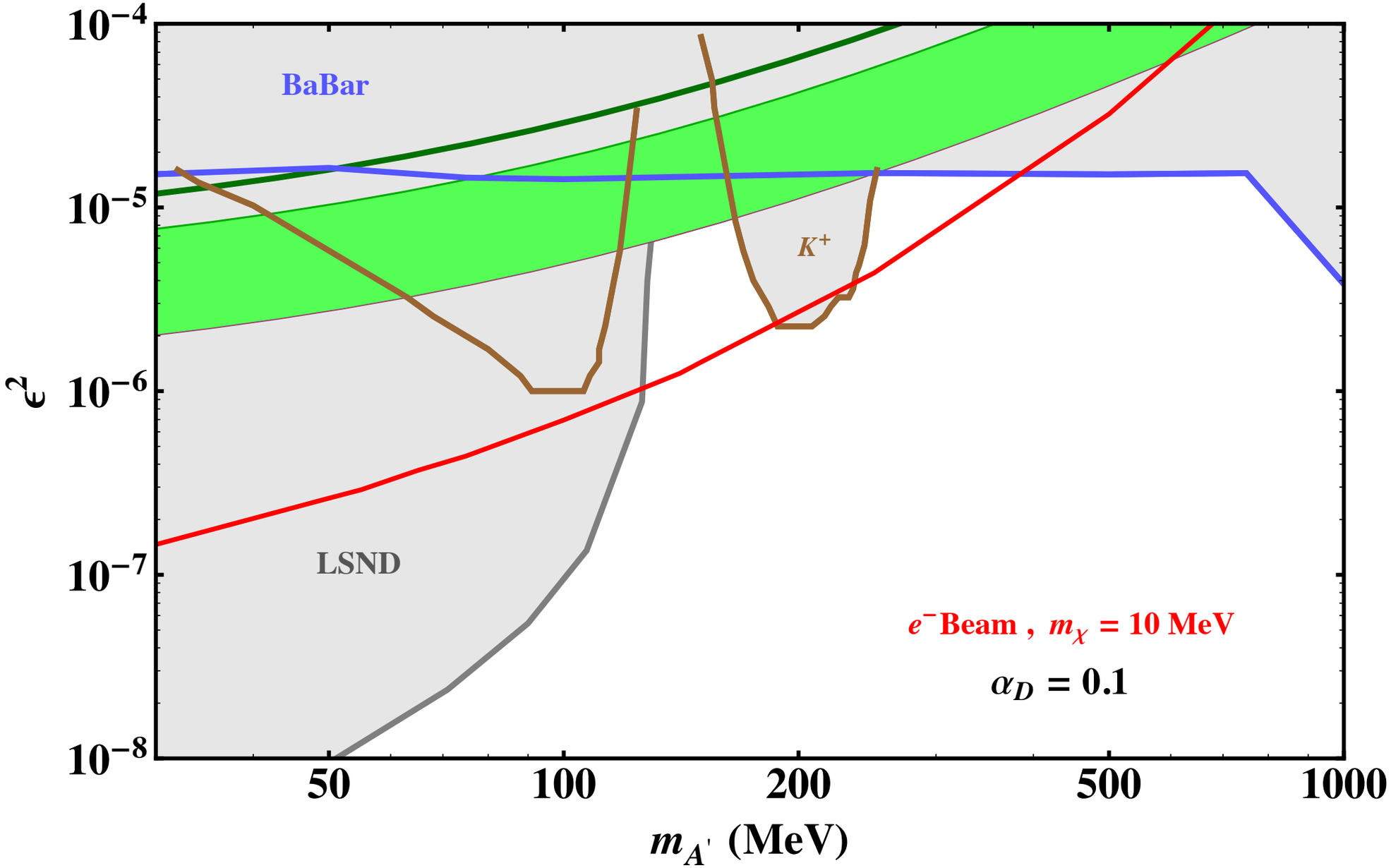


Oil based detector (CH_2)*
Depth = 15 m.w.e.

What Can Be Done *Today*?

1. SLAC FACET-Beam

E = 30 GeV , 10^{20} EOT , Dist. = 100 Ft. , Det = 1 m^3

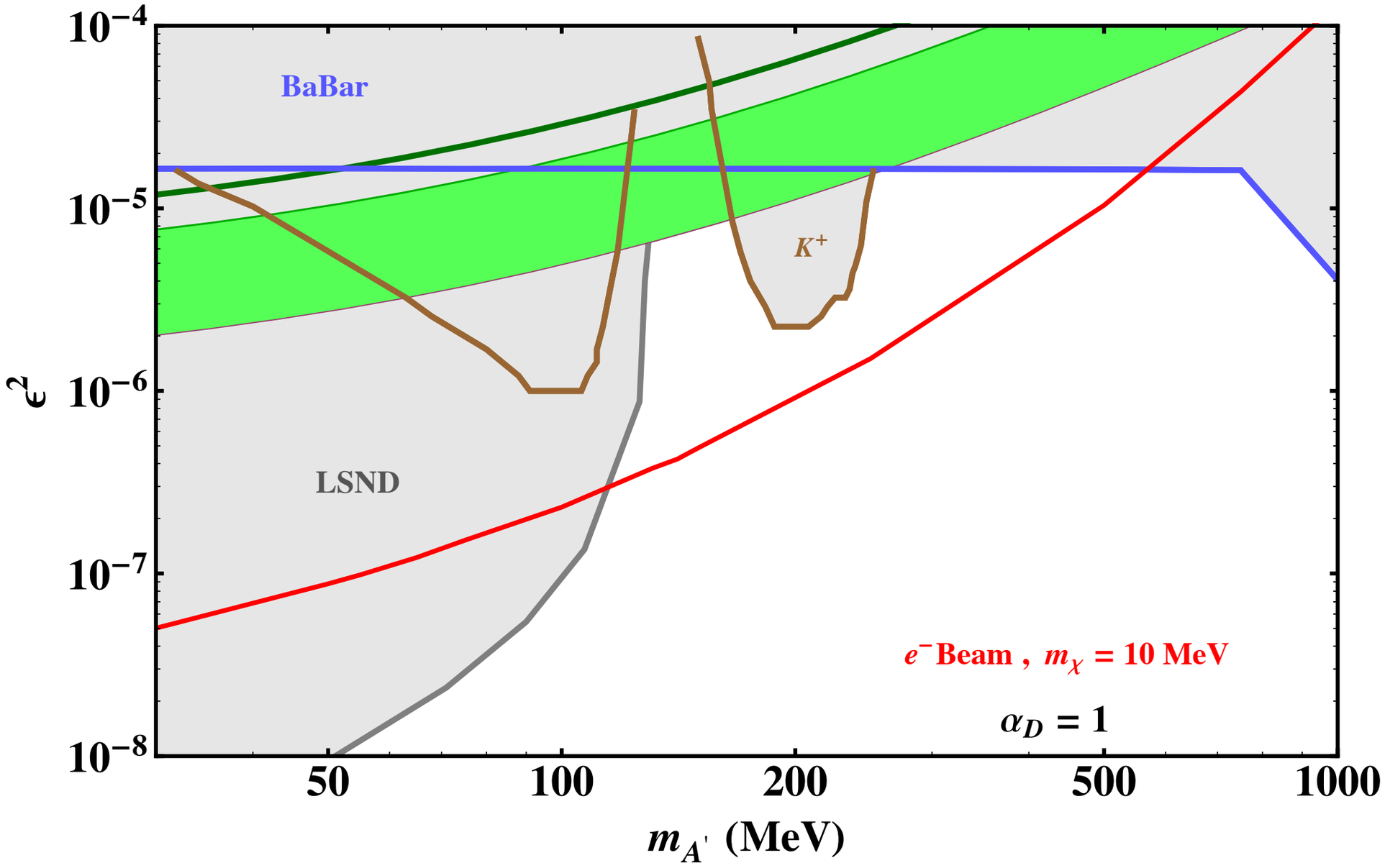


Quasi-elastic nucleon , pulsed beam

What Can Be Done *Today*?

1. SLAC FACET-Beam

E = 30 GeV , 10^{20} EOT , Dist. = 100 Ft. , Det = 1 m^3

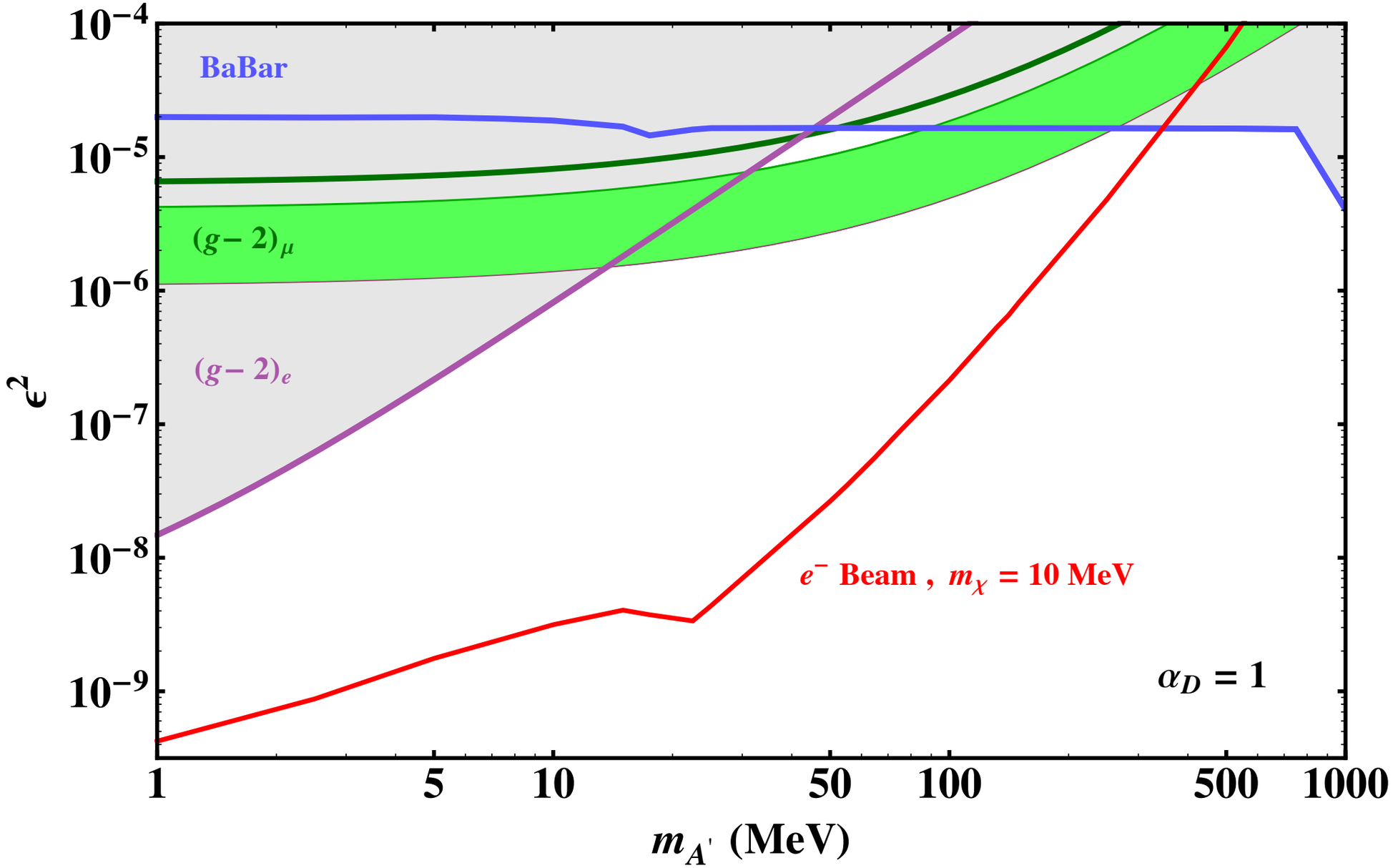


Quasi-elastic nucleon , pulsed beam

What Can Be Done *Today*?

1. SLAC FACET-Beam

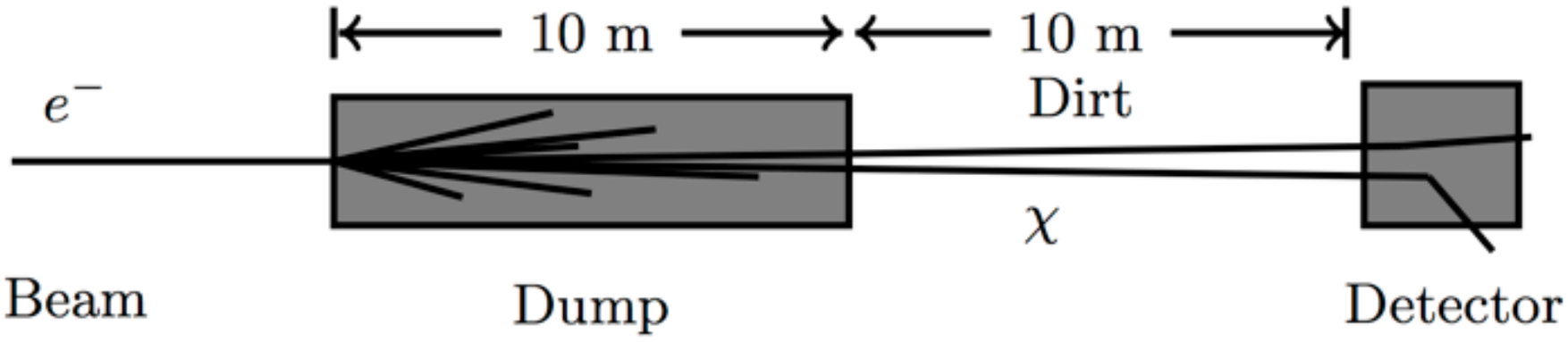
$E = 30$ GeV , 10^{20} EOT , Dist. = 100 Ft. , Det = 1 m^3



Leptophilic , pulsed beam

What Can Be Done *Today*?

2. JLab CEBAF



Continuous wave 12 GeV beam

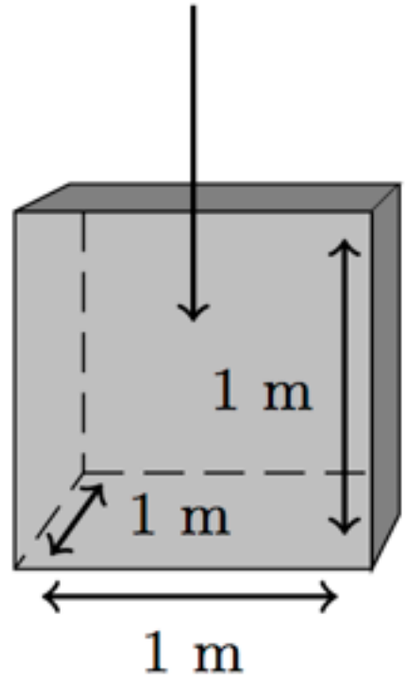
Aluminum beam dump

$80\mu A \implies \sim 10^{22}$ Electrons/Yr.

No neutron rejection (veto muons)

$N_n \sim 400,000$, Systematics $\sim 2.5\%$

Sensitivity ~ 20,000 signal events

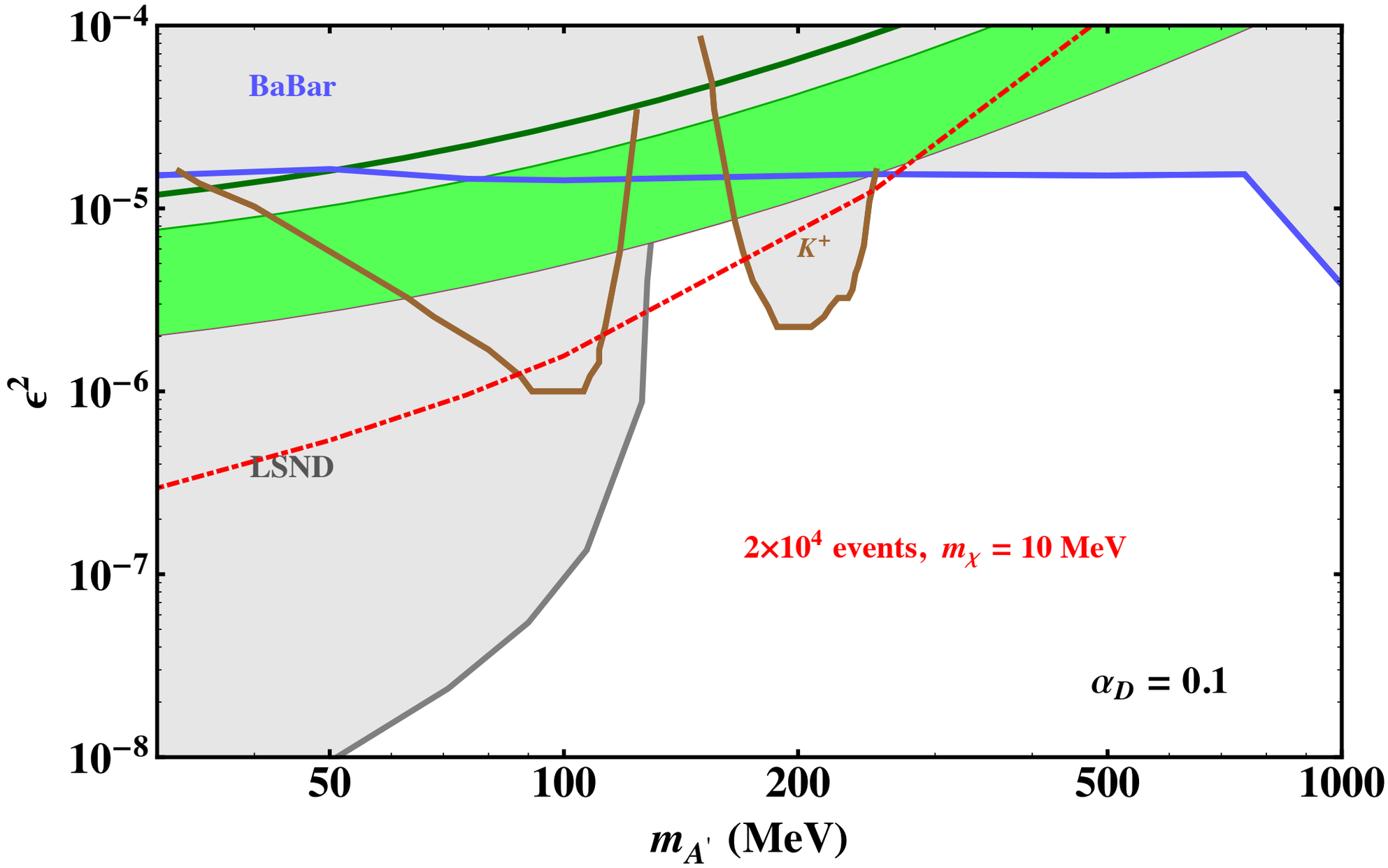


Oil based detector (CH_2)*
Depth = 15 m.w.e.

What Can Be Done *Today*?

2. JLab CEBAF

E = 12 GeV , 10^{22} EOT , Dist. = 20 m. , Det = 1 m^3

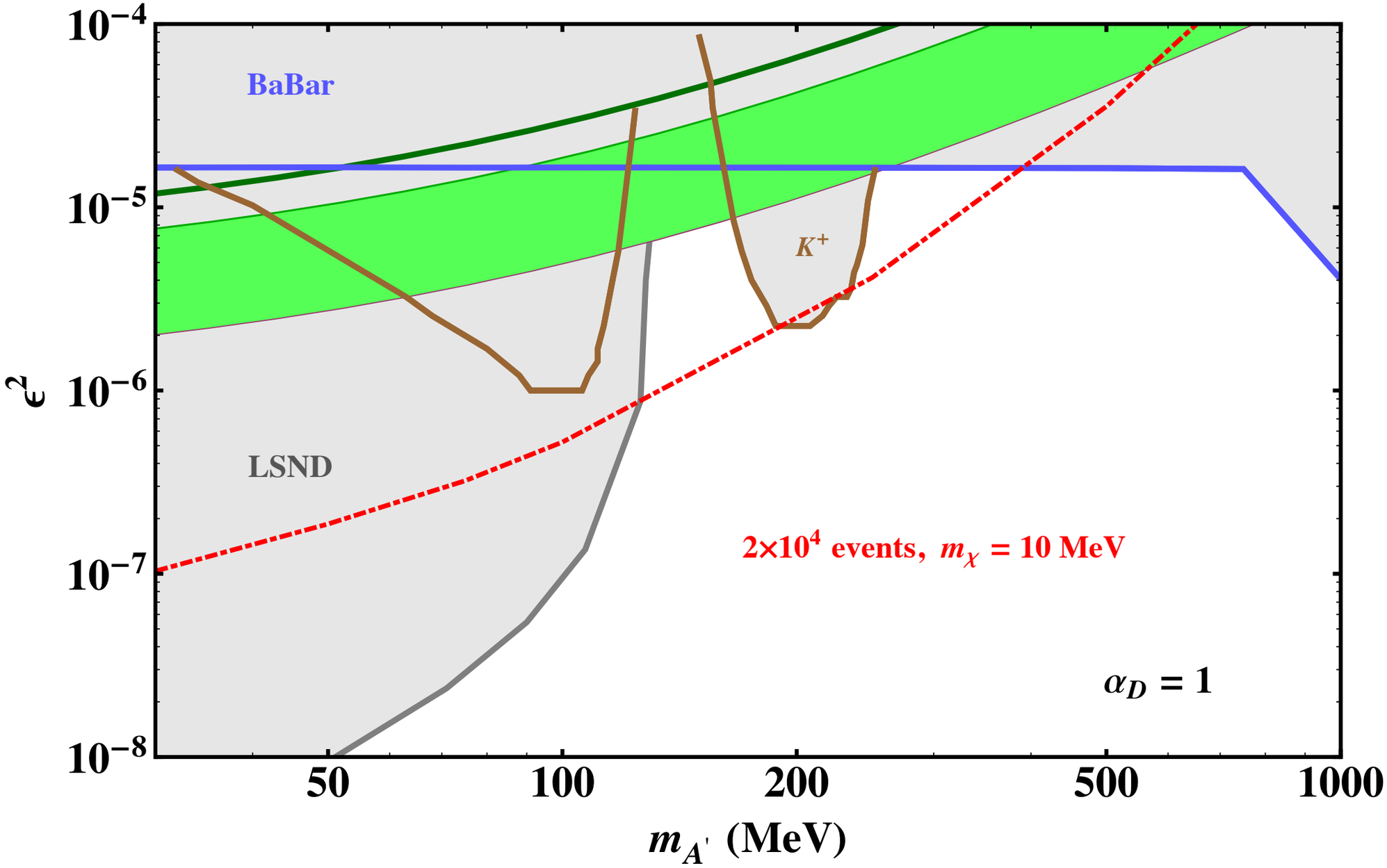


Quasi-elastic nucleon , continuous wave beam

What Can Be Done *Today*?

2. JLab CEBAF

$E = 12$ GeV , 10^{22} EOT , Dist. = 20 m. , Det = 1 m^3

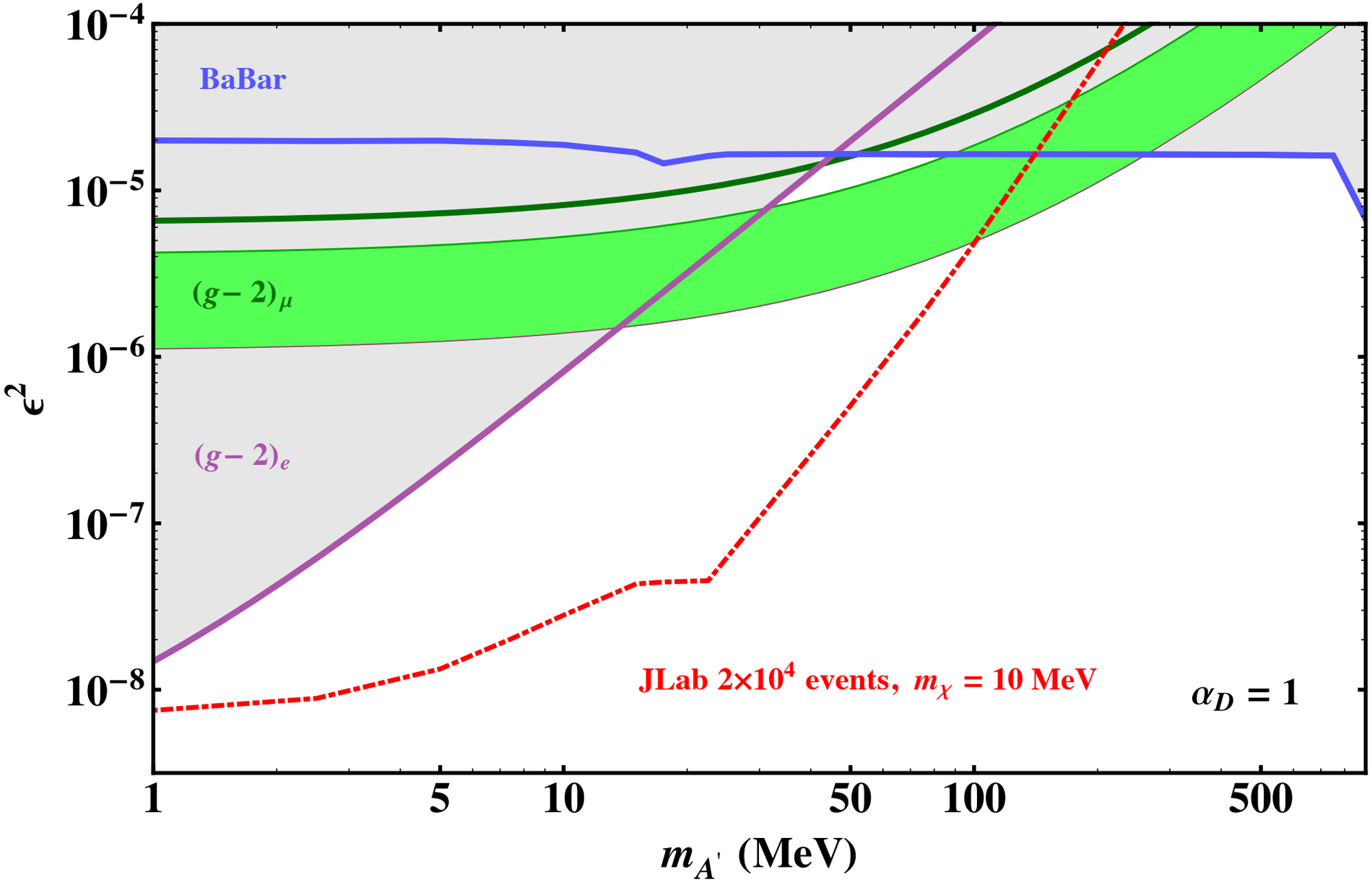


Quasi-elastic nucleon , continuous wave beam

What Can Be Done *Today*?

2. JLab CEBAF

E = 12 GeV (JLab) , 10^{22} EOT , Dist. = 20 m. , Det = 1 m^3

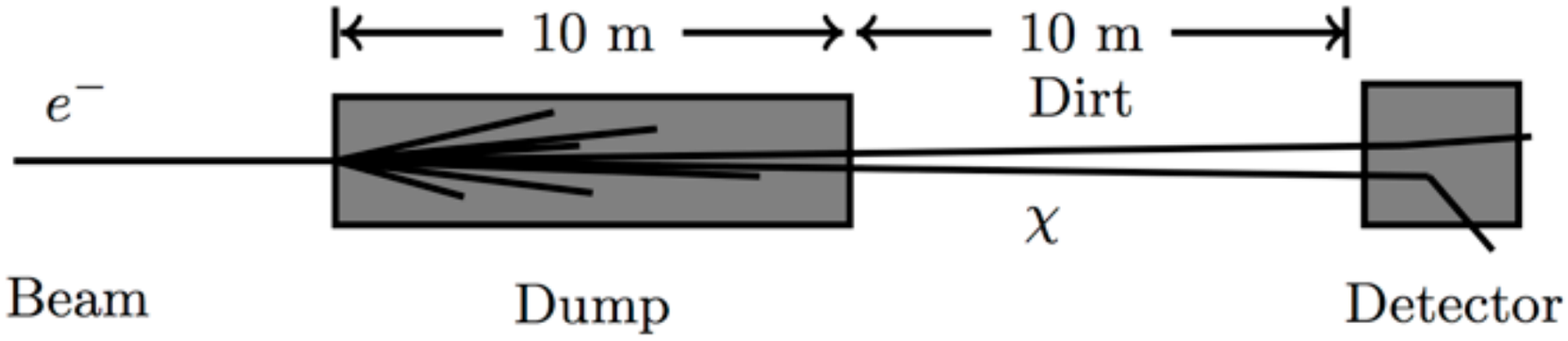


Leptophilic DM, continuous wave beam

Overview

- A "light" dark sector?
- Why electron beams?
- What can be done *today*?
- *... tomorrow?*

Around the Corner 1
Some BG reduction (JLab)



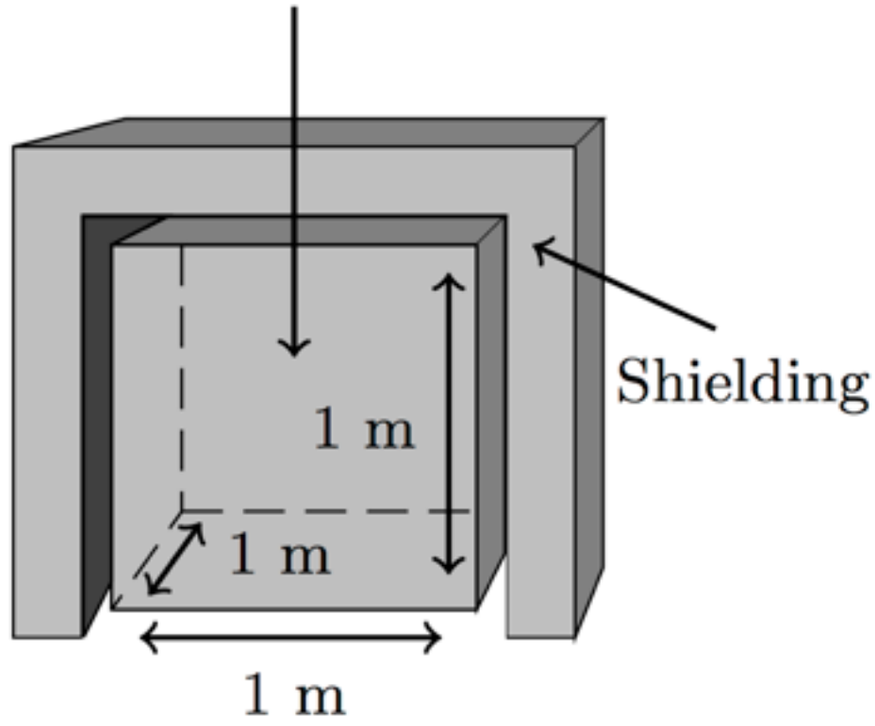
95% cosmic neutron reduction
Comparable to CDMS-SUF

2.5 % systematics (*n* flux)

Sensitivity ~ 1000 event signal yield

Need one/some:

Active neutron veto
Neutron moderator
Directional information

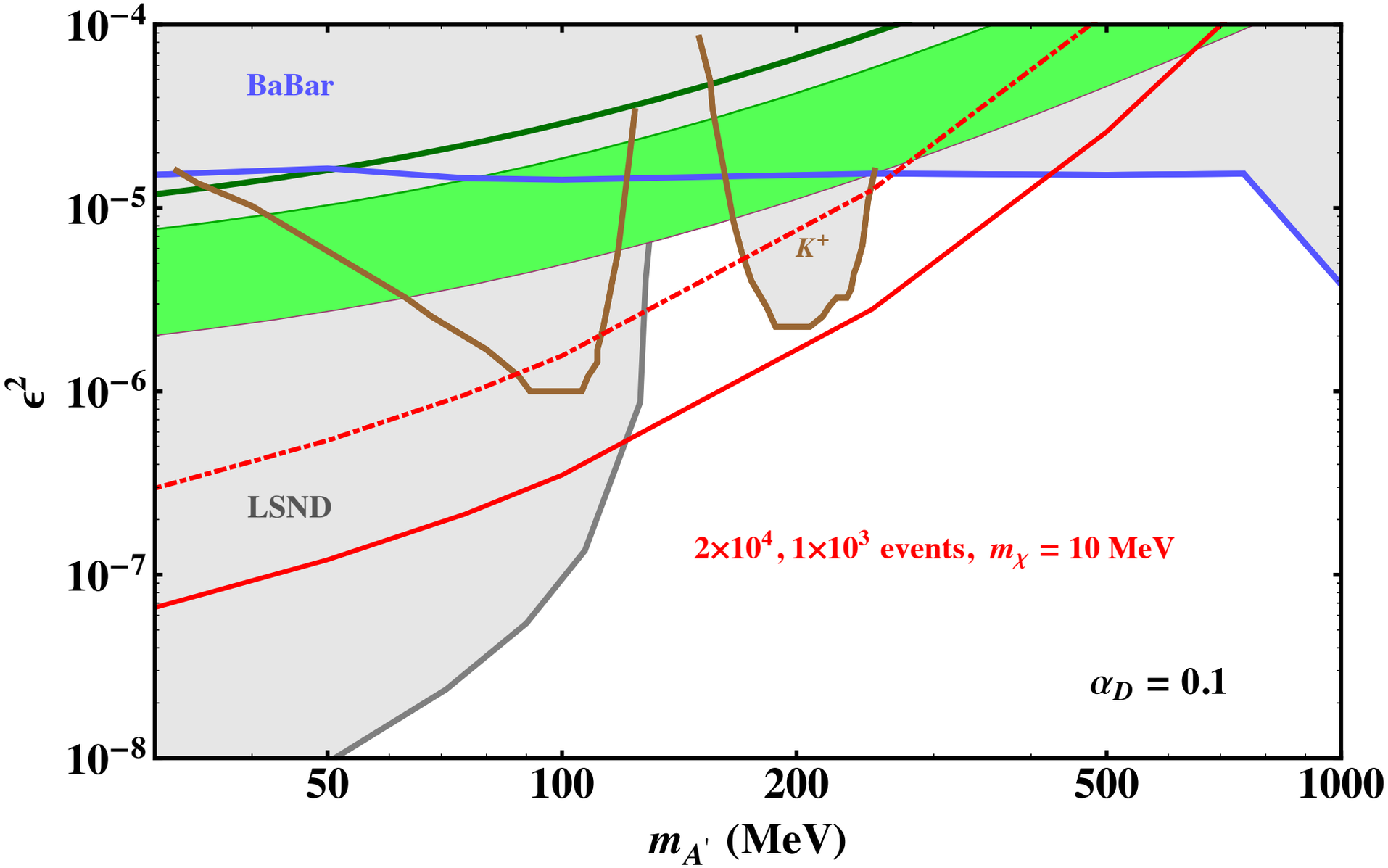


Oil-based, cubic-meter fiducial
Depth ~15 m.w.e

Around the Corner 1

Some BG reduction (JLab)

E = 12 GeV , 10^{22} EOT , Dist. = 20 m. , Det = 1 m^3

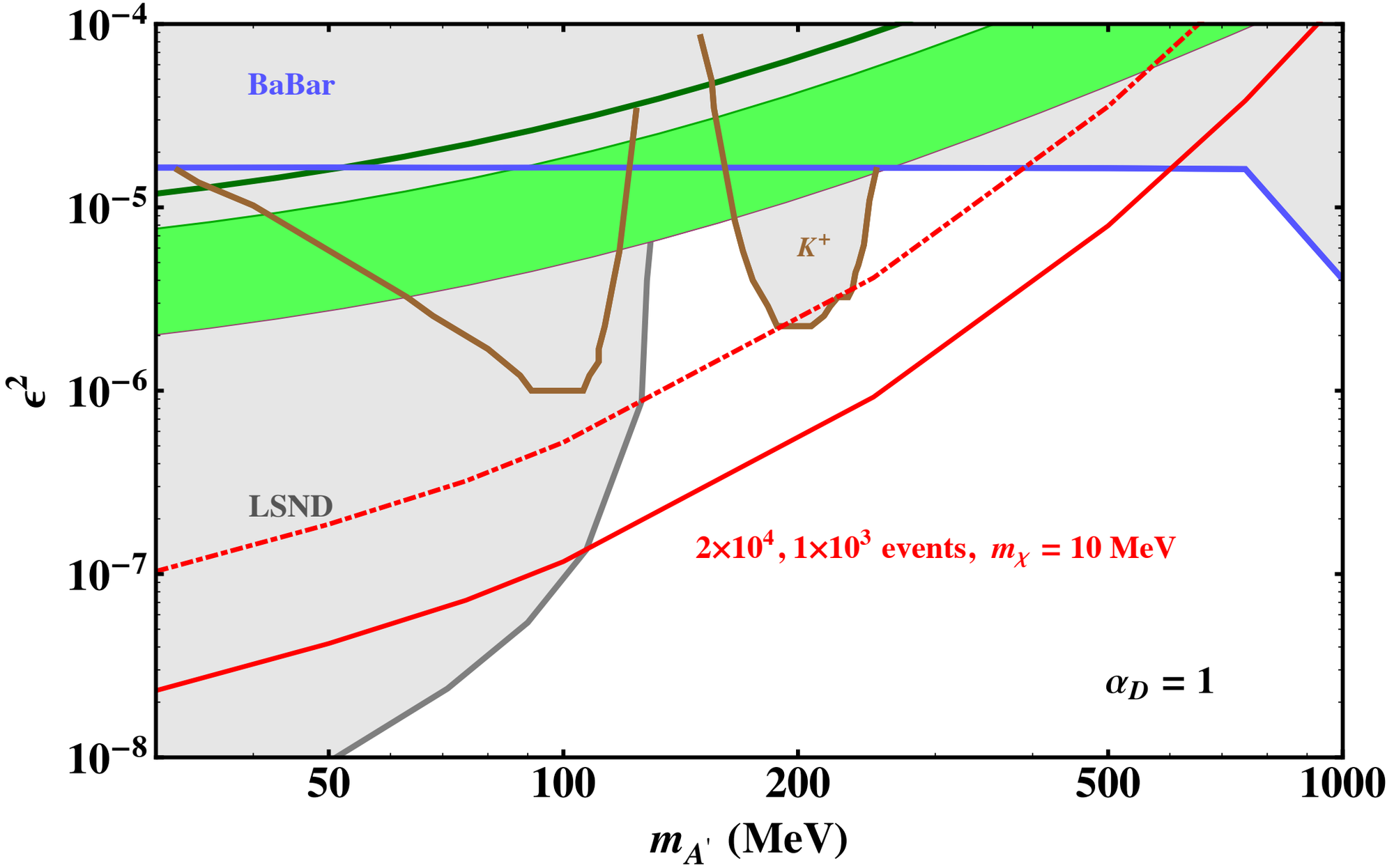


Quasi-elastic nucleon , continuous wave beam

Around the Corner 1

Some BG reduction (JLab)

E = 12 GeV , 10^{22} EOT , Dist. = 20 m. , Det = 1 m^3

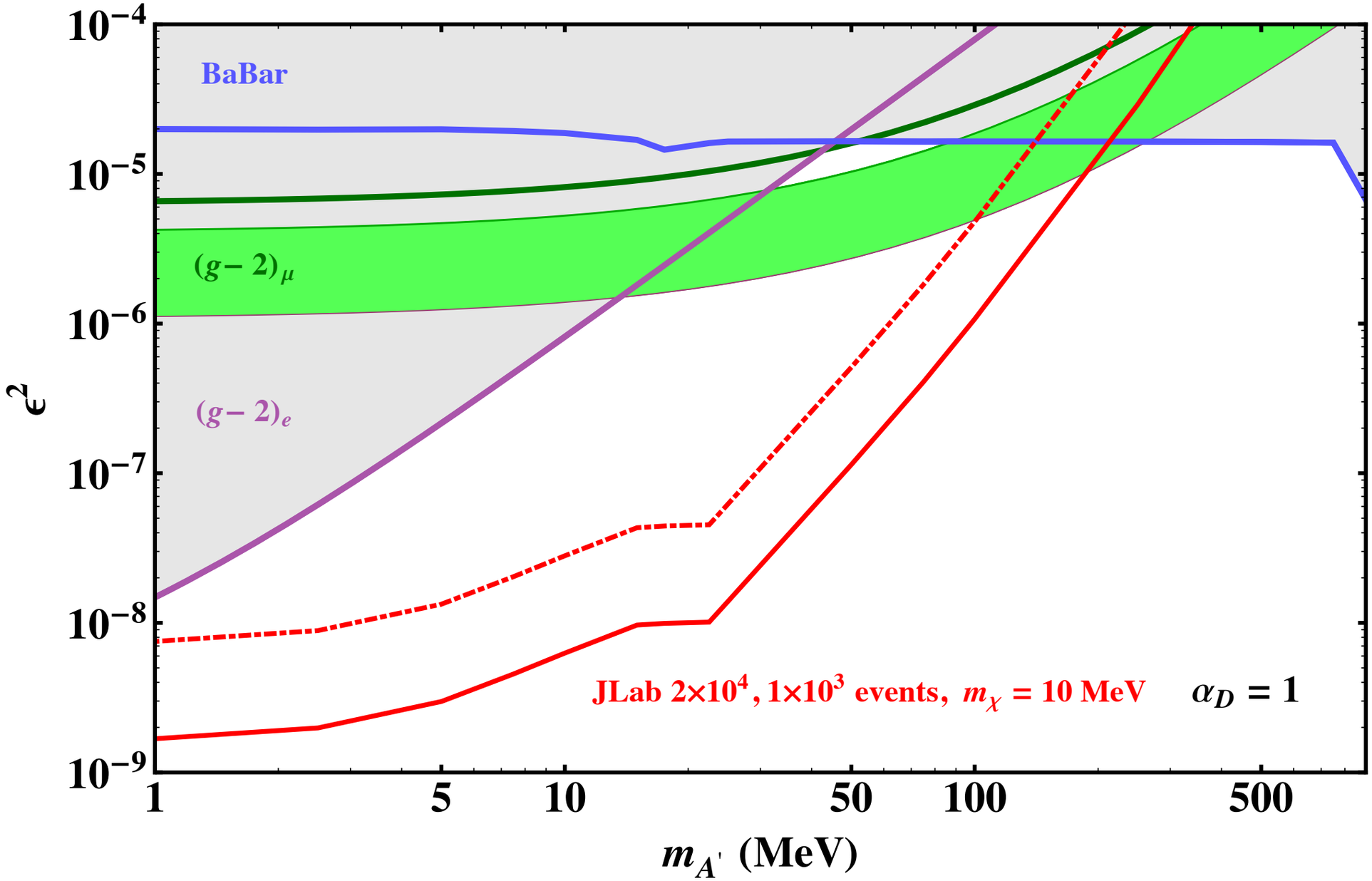


Quasi-elastic nucleon , continuous wave beam

Around the Corner 1

Some BG reduction (JLab)

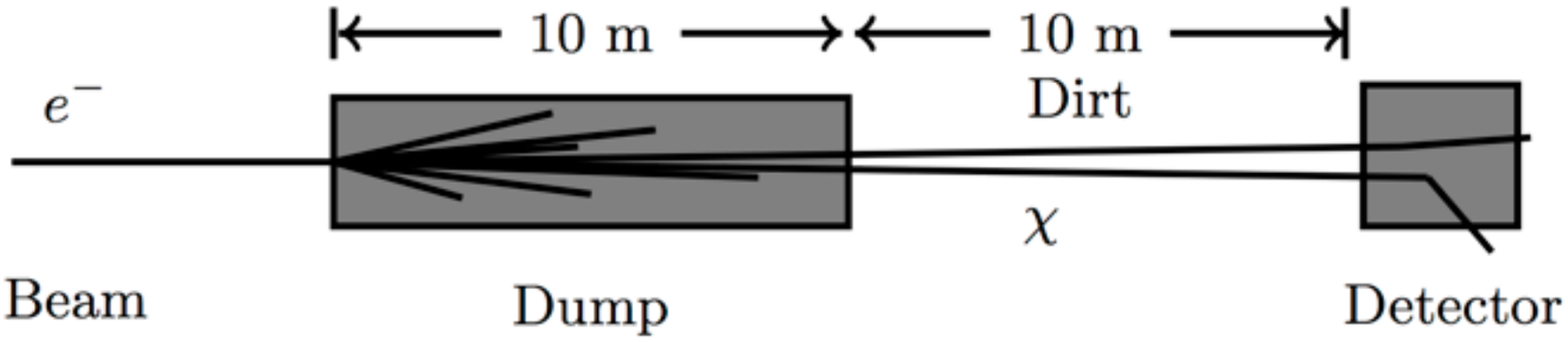
E = 12 GeV (JLab) , 10^{22} EOT , Dist. = 20 m. , Det = 1 m^3



Leptophilic DM, continuous wave beam

Around the Corner 2

Aggressive BG reduction (JLab)



99.9% background reduction ~ 400 events

Statistics dominated uncertainty

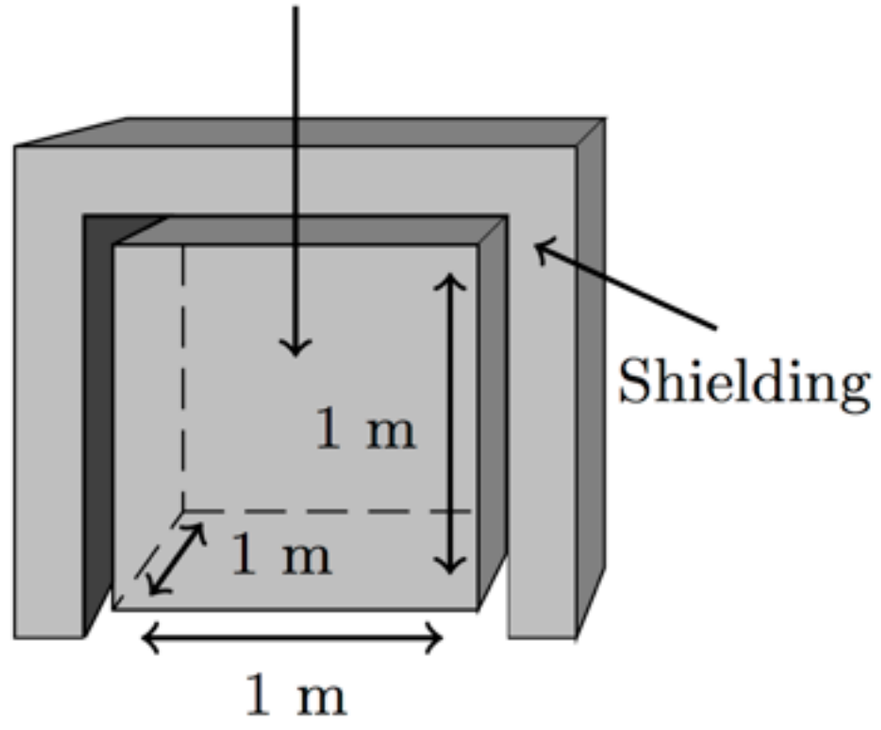
Sensitivity ~ 40 event signal yield

Need all (?) of these:

Active neutron veto

Neutron moderator

Directional information



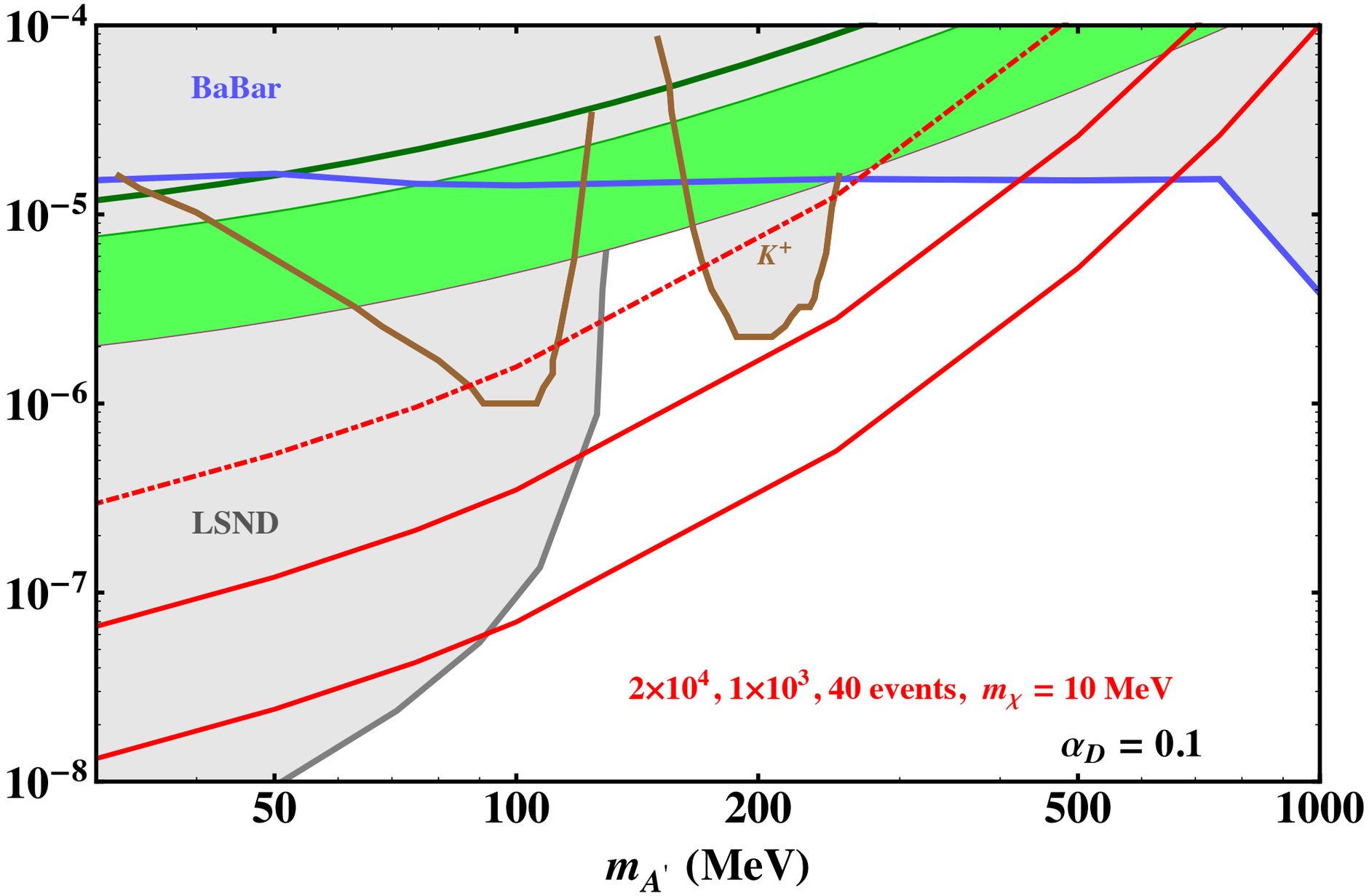
Oil-based, cubic-meter fiducial

Depth ~15 m.w.e

Around the Corner 2

Aggressive BG reduction (JLab)

E = 12 GeV , 10^{22} EOT , Dist. = 20 m. , Det = 1 m^3

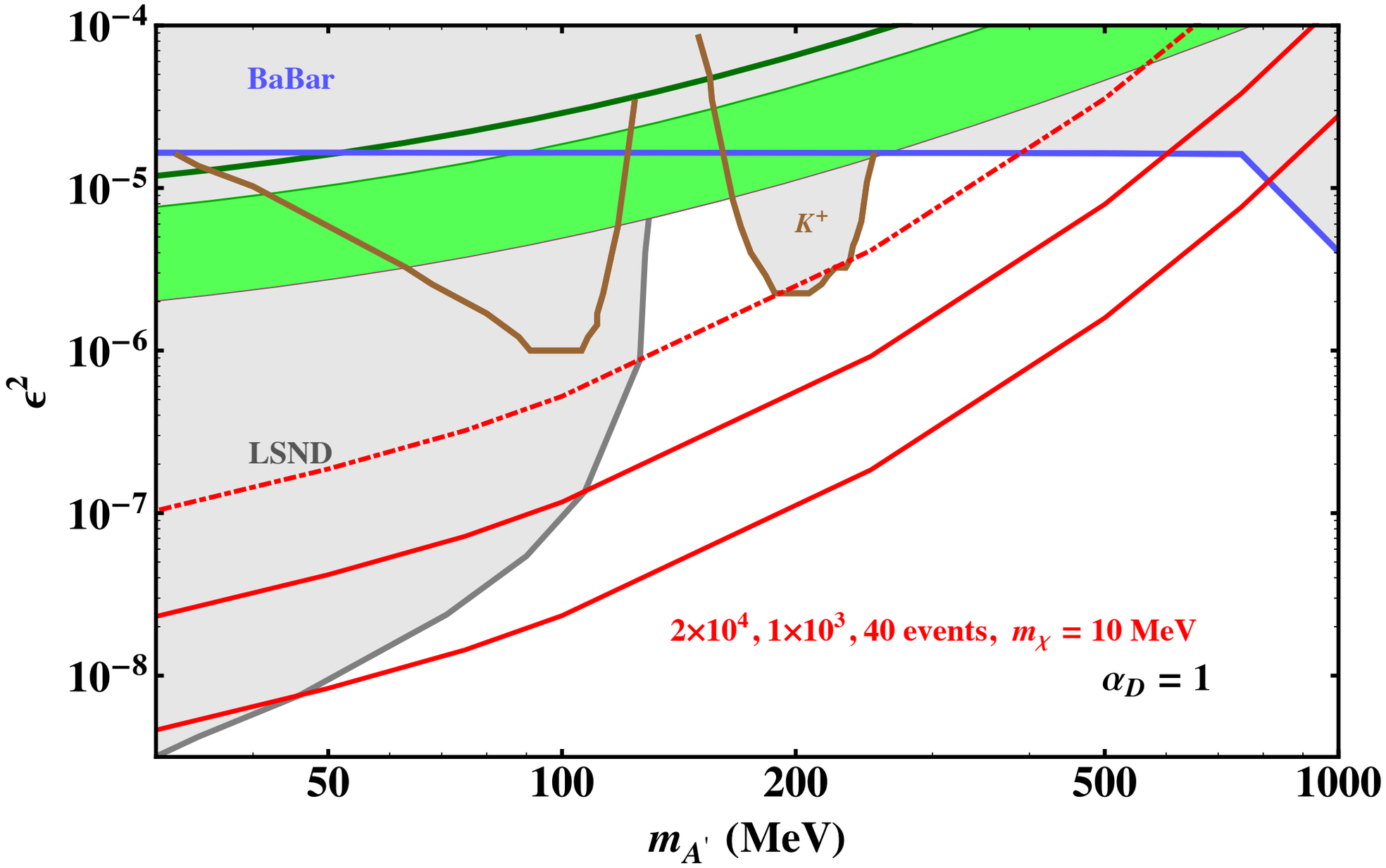


Quasi-elastic nucleon , continuous wave beam

Around the Corner 2

Aggressive BG reduction (JLab)

E = 12 GeV , 10^{22} EOT , Dist. = 20 m. , Det = 1 m^3

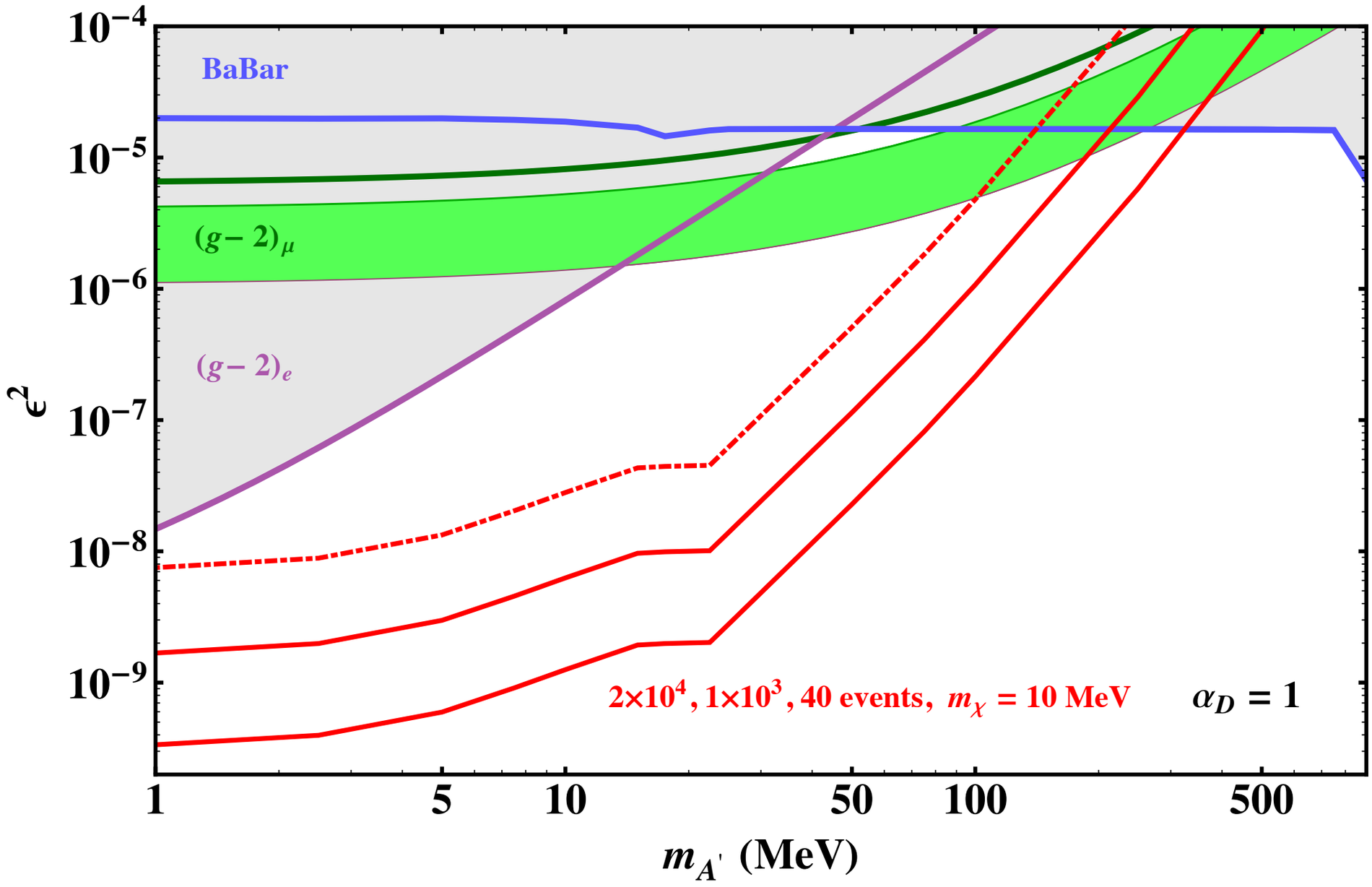


Quasi-elastic nucleon , pulsed beam

Around the Corner 2

Aggressive BG reduction (JLab)

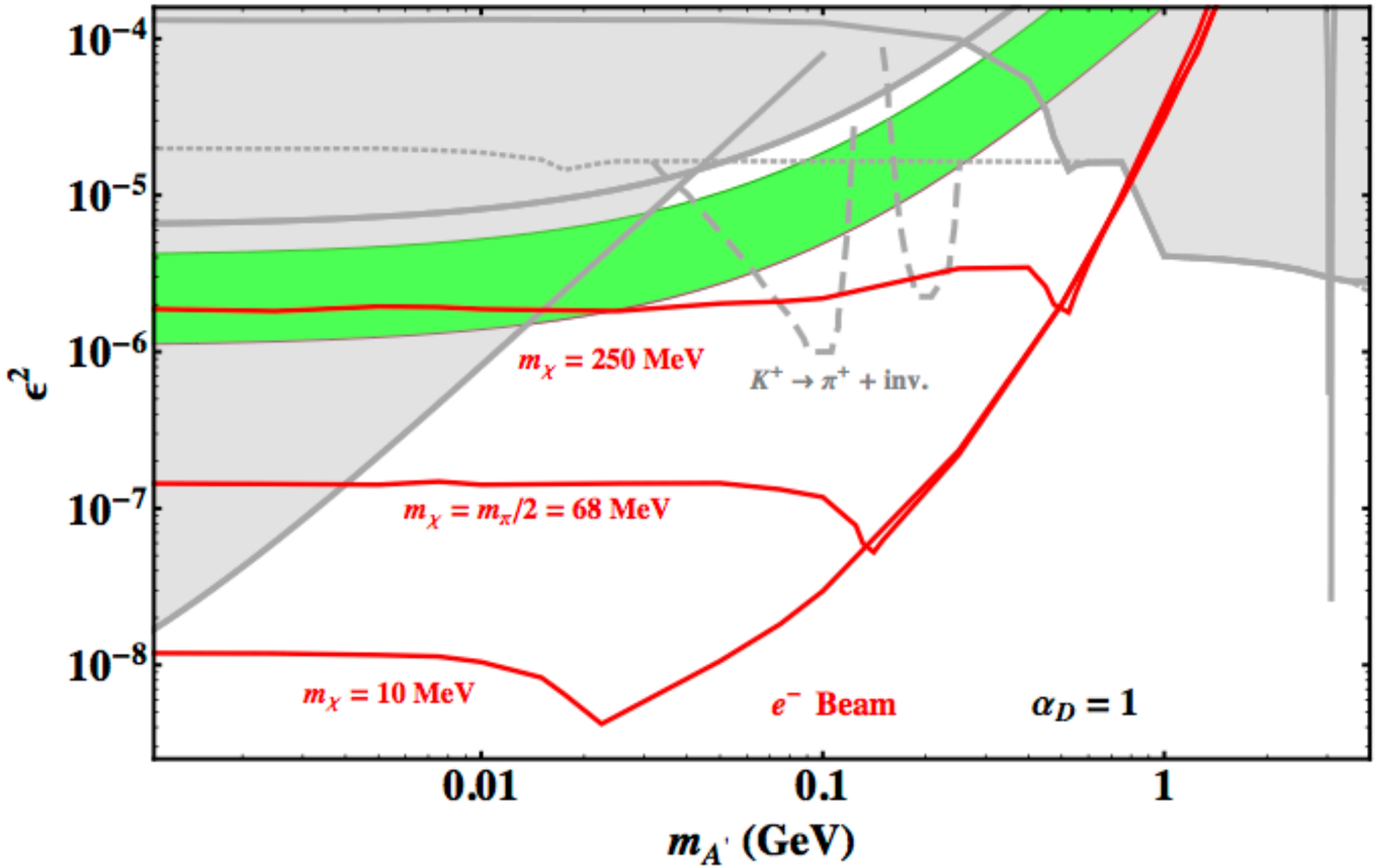
E = 12 GeV (JLab) , 10^{22} EOT , Dist. = 20 m. , Det = 1 m^3



Leptophilic DM, continuous wave beam

Around the Corner 2

Aggressive BG reduction (JLab)



40 event yields

Variations

This layout is only a proof of concept, not definitive!

Detector size, geometry, material, may all vary in a smarter setup

Variations

This layout is only a proof of concept, not definitive!

Detector size, geometry, material, may all vary in a smarter setup

Exploit high acceptance?

Setup cosmics limited. Smaller, closer detector, w/ more shielding?

Variations

This layout is only a proof of concept, not definitive!

Detector size, geometry, material, may all vary in a smarter setup

Exploit high acceptance?

Setup cosmics limited. Smaller, closer detector, w/ more shielding?

Different dump?

Beam related BG may not be negligible! May need deflectors

Variations

This layout is only a proof of concept, not definitive!

Detector size, geometry, material, may all vary in a smarter setup

Exploit high acceptance?

Setup cosmics limited. Smaller, closer detector, w/ more shielding?

Different dump?

Beam related BG may not be negligible! May need deflectors

Different beam?

CW: JLab, Mainz, DESY...

Pulsed: SLAC, SuperKEKB, ILC (?)...

Variations

This layout is only a proof of concept, not definitive!

Detector size, geometry, material, may all vary in a smarter setup

Exploit high acceptance?

Setup cosmics limited. Smaller, closer detector, w/ more shielding?

Different dump?

Beam related BG may not be negligible! May need deflectors

Different beam?

CW: JLab, Mainz, DESY...

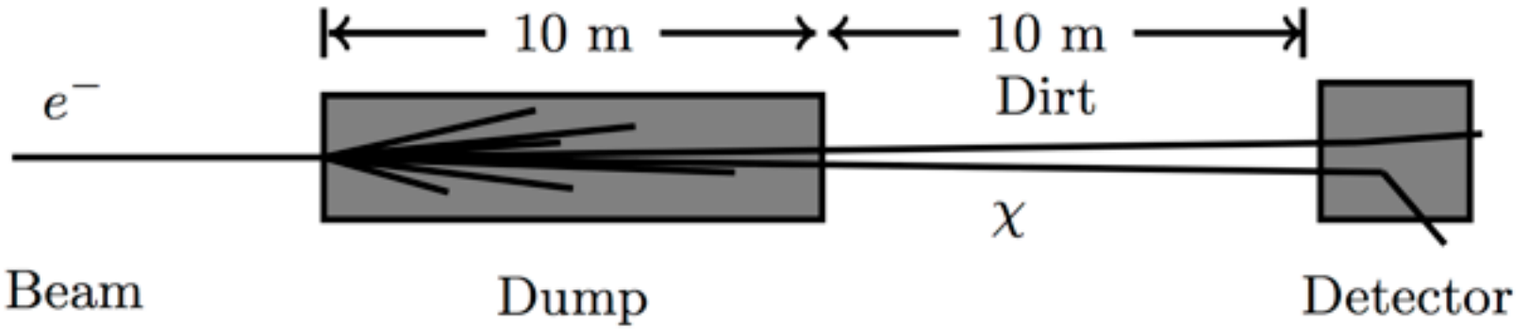
Pulsed: SLAC, SuperKEKB, ILC (?)...

Different cuts/signals (electron, inelastic...)?

Overview

- A "light" dark sector?
- Why electron beams?
- What can be done *today*?
- ~~*tomorrow*~~ ... *10-20 years?*

Down the Street : ILC



Pulsed 125 GeV beam

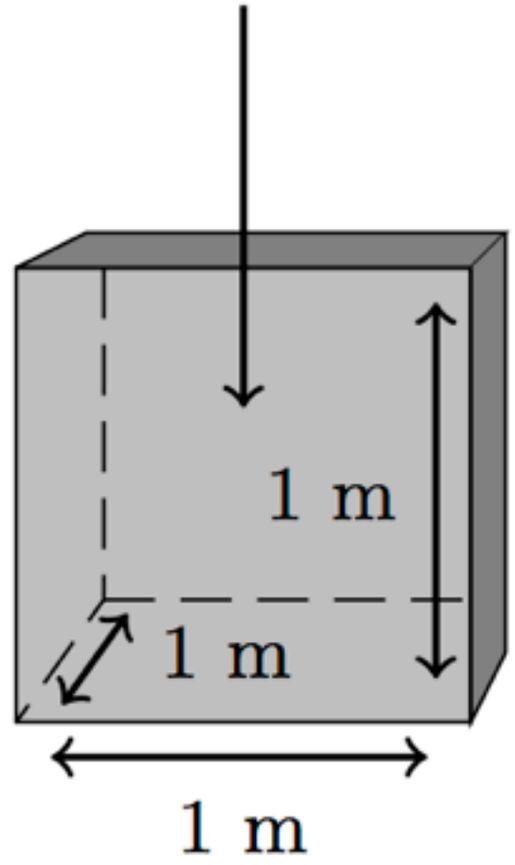
Aluminum dump

$80\mu A$ average current

$10^{22}\ e^-(\sim\ 1\ \text{year run})$

Duty cycle $\sim 10^{-4}$, livetime $\sim 10^3$ s

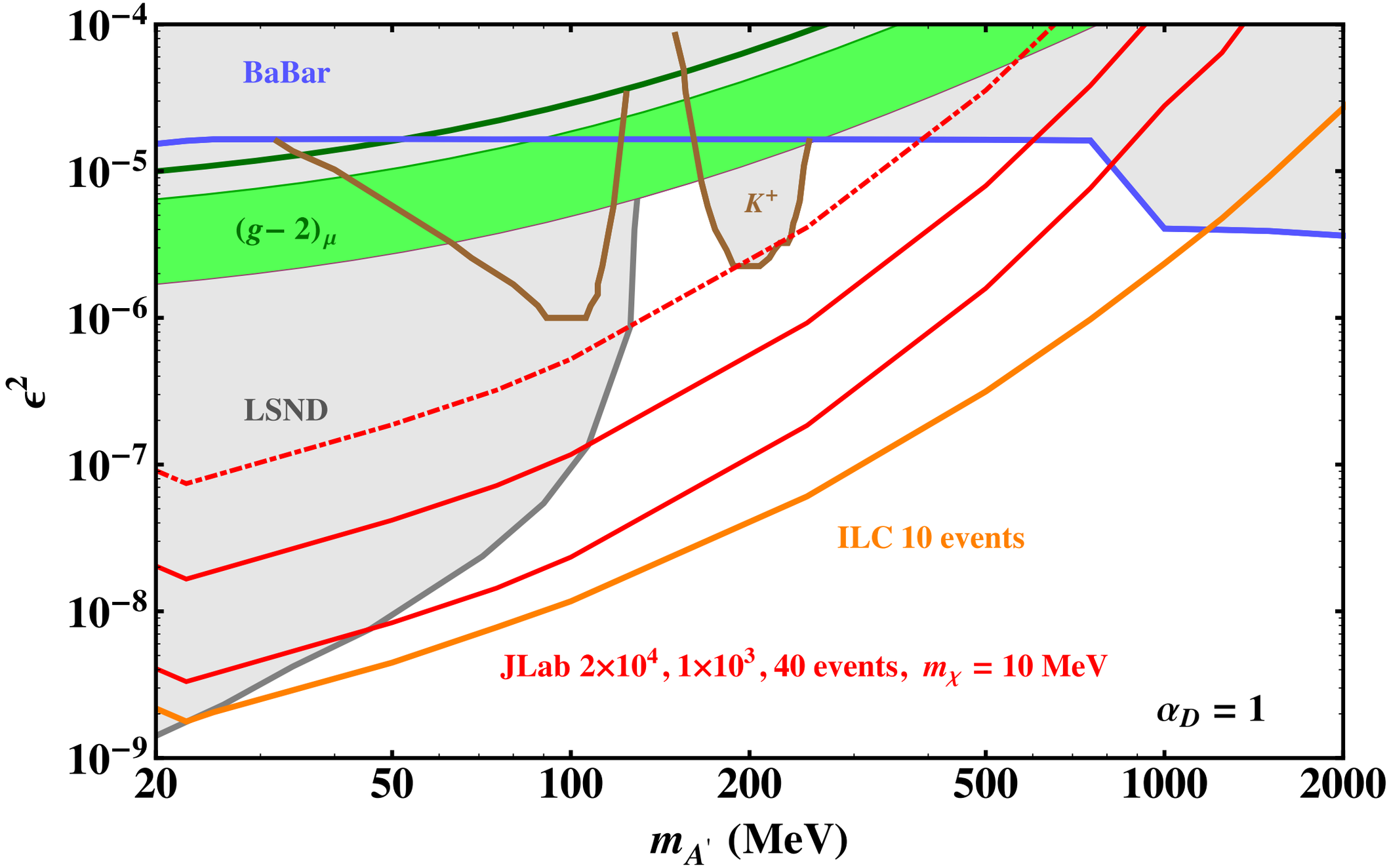
Sensitivity ~ 10 signal events*



Oil-based, cubic-meter fiducial
Depth ~15 m.w.e

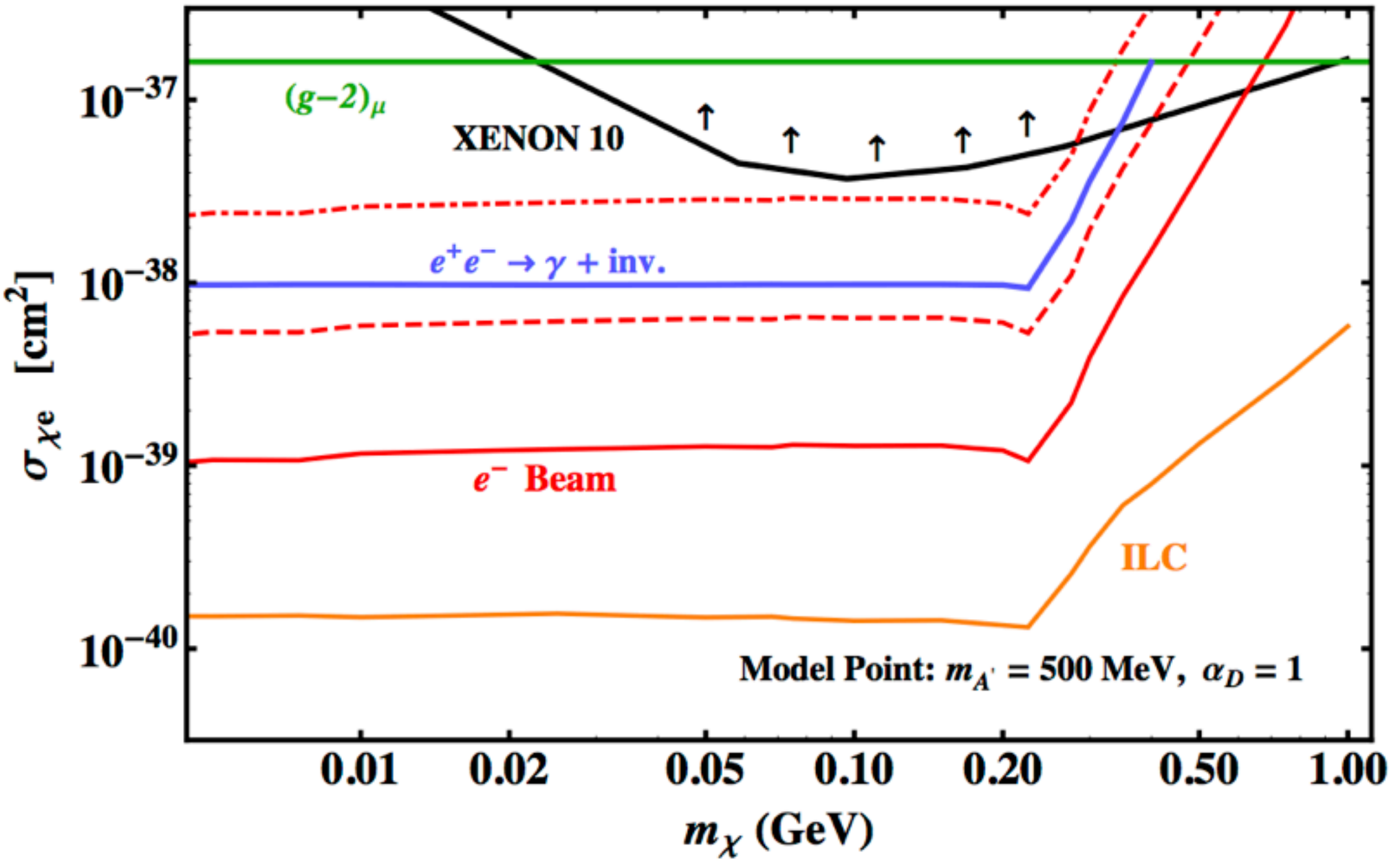
Down the Street : ILC

E = 125 GeV (ILC) , 10^{22} EOT , Dist. = 20 m. , Det = 1 m^3



Quasi-elastic nucleon , pulsed beam

Electron Scattering



40 event yields

Summary

Electron fixed-target searches are powerful

High acceptance, negligible beam BG, reducible cosmic BG

Probe almost entire, viable MeV – GeV range

Dedicated experiment can extend sensitivity by orders of magnitude
Simple setup: definitively cover (g-2)μ, complement visible searches,

Can run *parasitically* at existing facilities

JLab, SLAC, Mainz, DESY, Super KEK-B....

Small & cheap

Parasitic running, meter-scale (or smaller) detector,

This is just the beginning

We don't yet know the optimal setup...

Thanks!