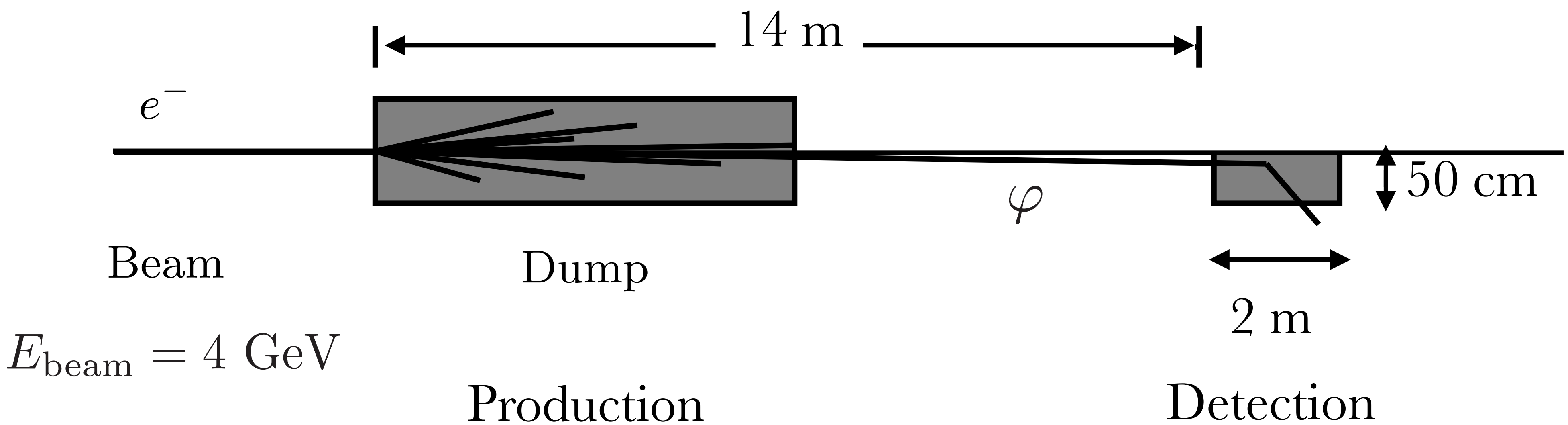
Dark Matter at a LCLS-II Beam-Dump Experiment

Eder Izaguirre

Perimeter Institute for Theoretical Physics

w/Gordan Krnjaic, Philip Schuster, Natalia Toro

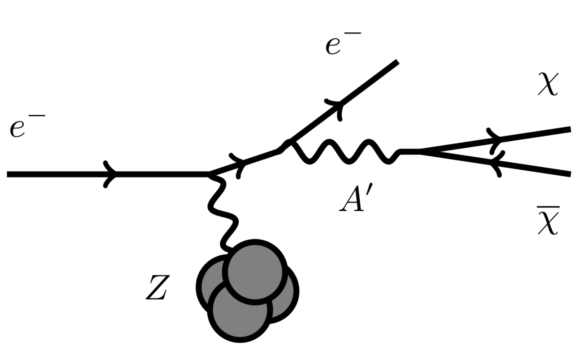
DM production at LCLS-II Beam Dump



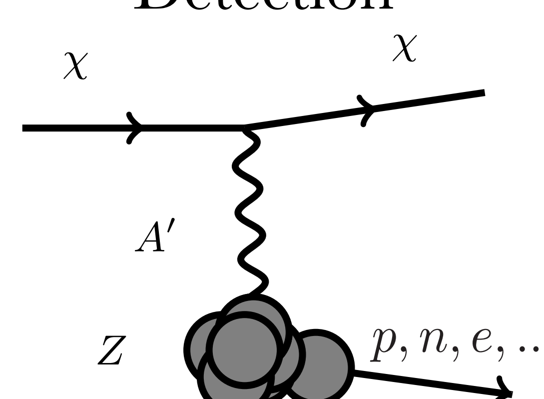
I'm assuming the dump is made out of aluminum

Detection takes place at a 50cm x 50 cm x 200 cm CsI prototype

Production

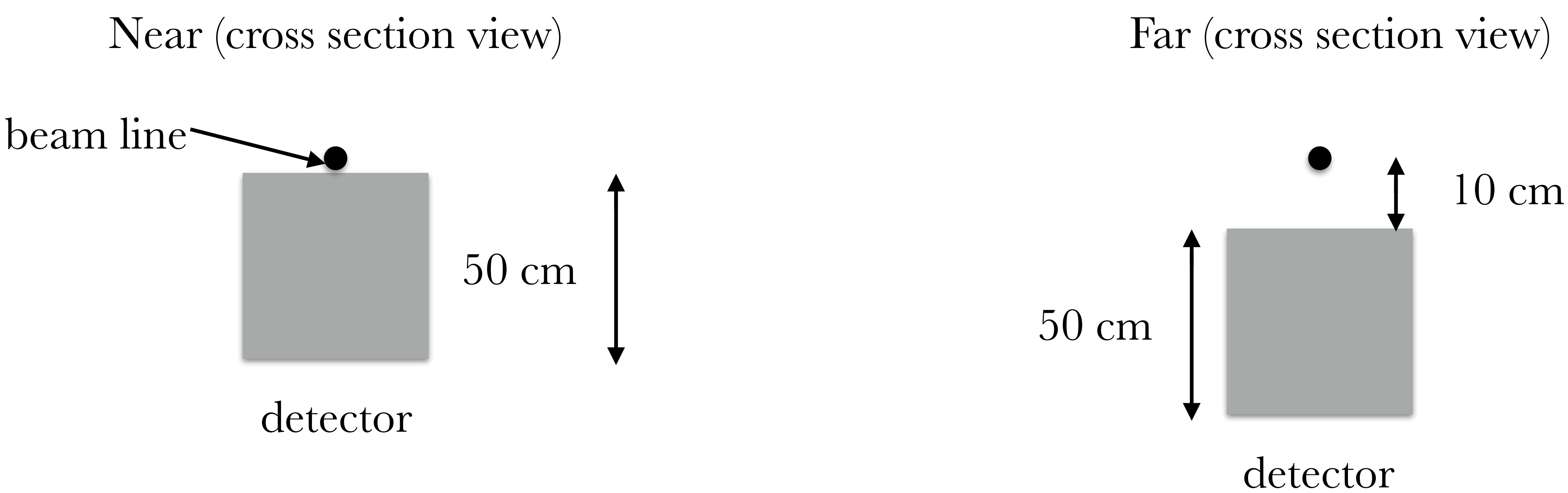


Detection



DM production at LCLS-II Beam Dump

I will show yields for two detector placement geometries



And for two detection channels for each geometry and model scenario:
Electron recoils and Nucleon recoils (E_R > 10 MeV for each)

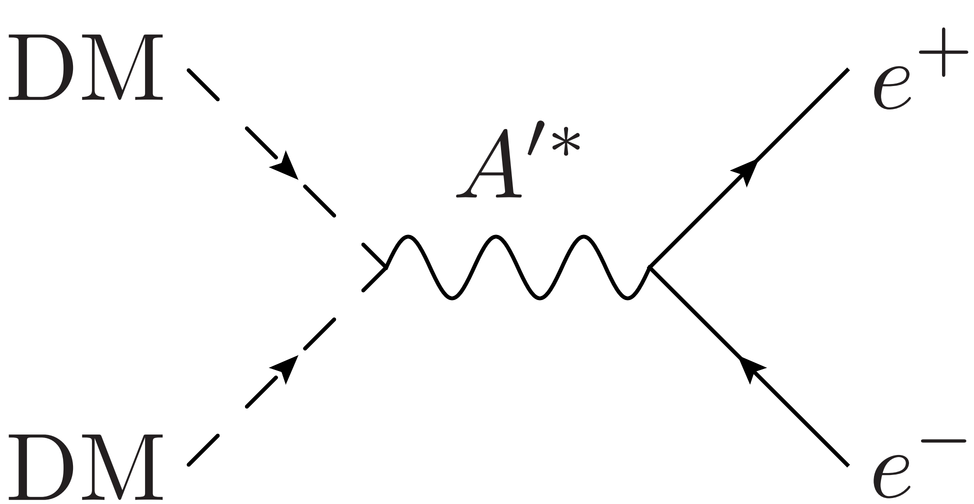
Light Thermal DM

In the early universe, DM in thermal contact with the SM

DM "freezes-out" at late times when its annihilation rate into SM smaller than expansion rate

The requirement to obtain today's DM's observed abundance sets a minimum annihilation rate

Example: scalar QED scenario, assuming $2m_{\rm DM} < m'_A$

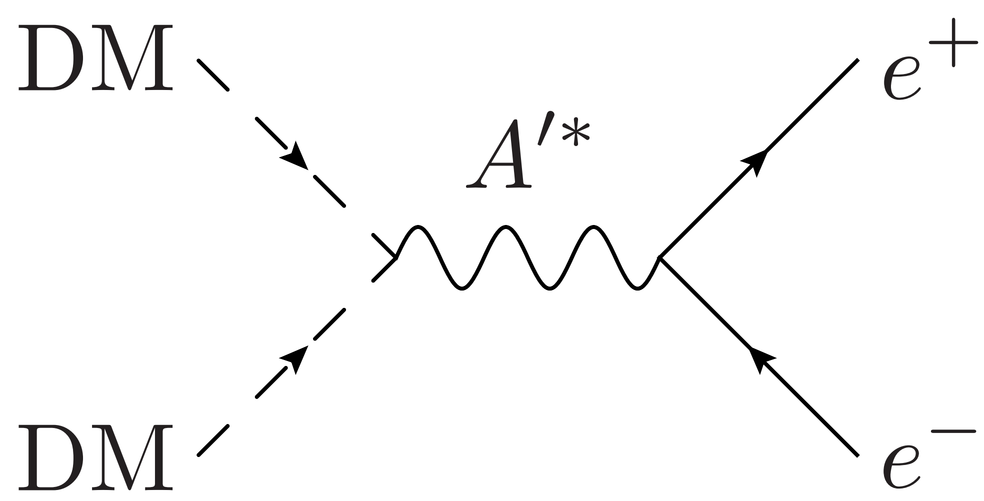


We then need

$$\langle \sigma v \rangle = \langle \sigma v \rangle_{\rm min}$$

where $\langle \sigma v \rangle_{\rm min}$ is the required rate for today's abundance

Light Thermal DM



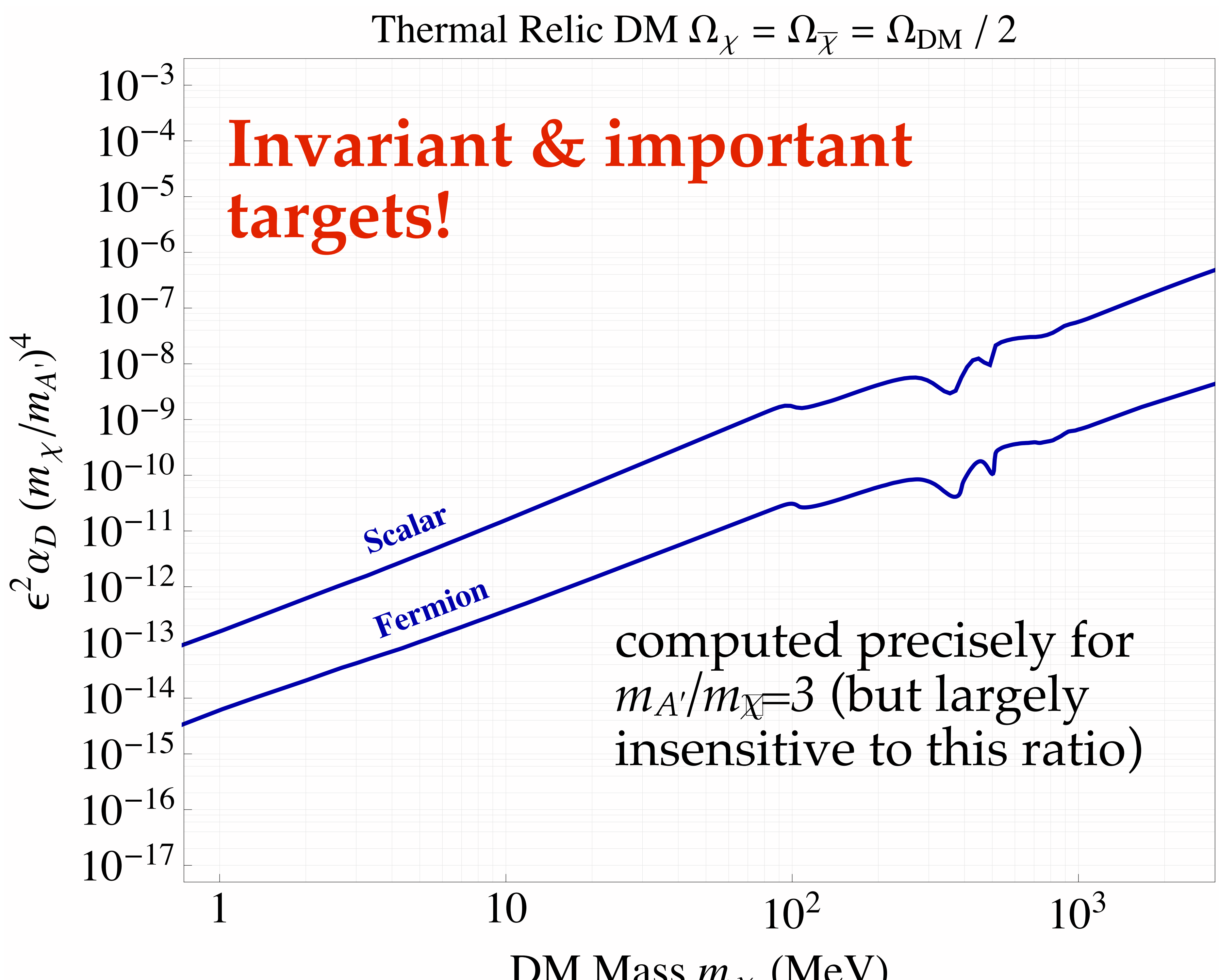
gives an annihilation rate which goes as

$$\langle \sigma v \rangle \propto \epsilon^2 \alpha_D \frac{m_\varphi^2}{m_{A'}^4} = \epsilon^2 \alpha_D \frac{m_\varphi^4}{m_{A'}^4} \frac{1}{m_\varphi^2} = \frac{y}{m_\varphi^2}$$

Then, for fixed DM mass
annihilation rate invariant
under the dimensionless combination

$$y = \epsilon^2 \alpha_D \frac{m_\varphi^4}{m_{A'}}$$

Light Thermal DM Target

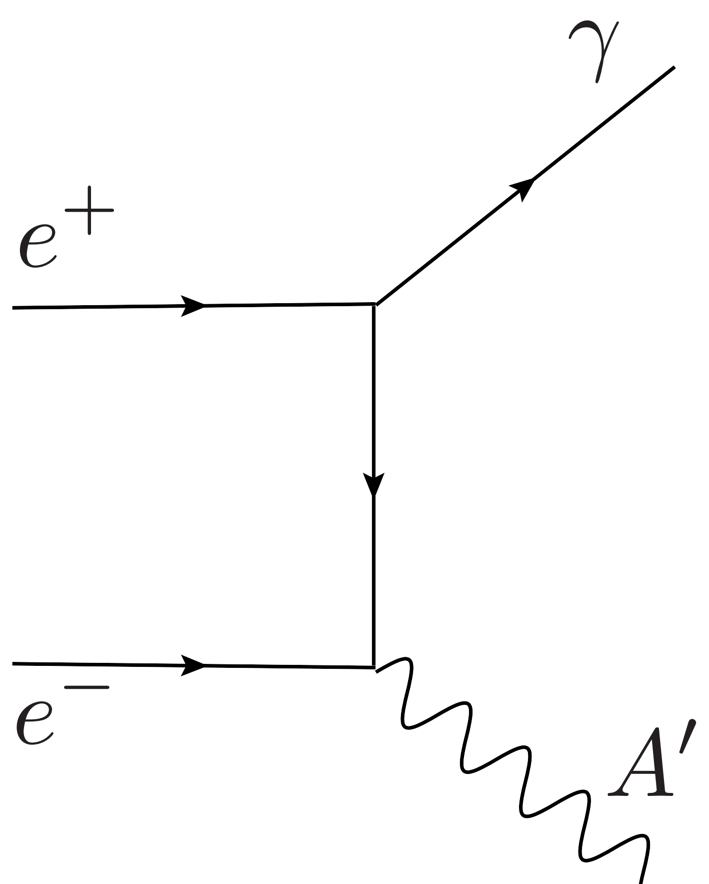


Conservative Presentation of Existing Constraints

The DM annihilation rate gives a thermal-relic DM target that is invariant under y for fixed DM mass

However, the sensitivity of different experiments does not usually scale simply with y

Example: B-factories



This search is sensitive only to ϵ^2

Conservative Presentation of Existing Constraints

Recall $$y = \epsilon^2 \alpha_D \frac{m_\varphi^4}{m_{A'}}$$

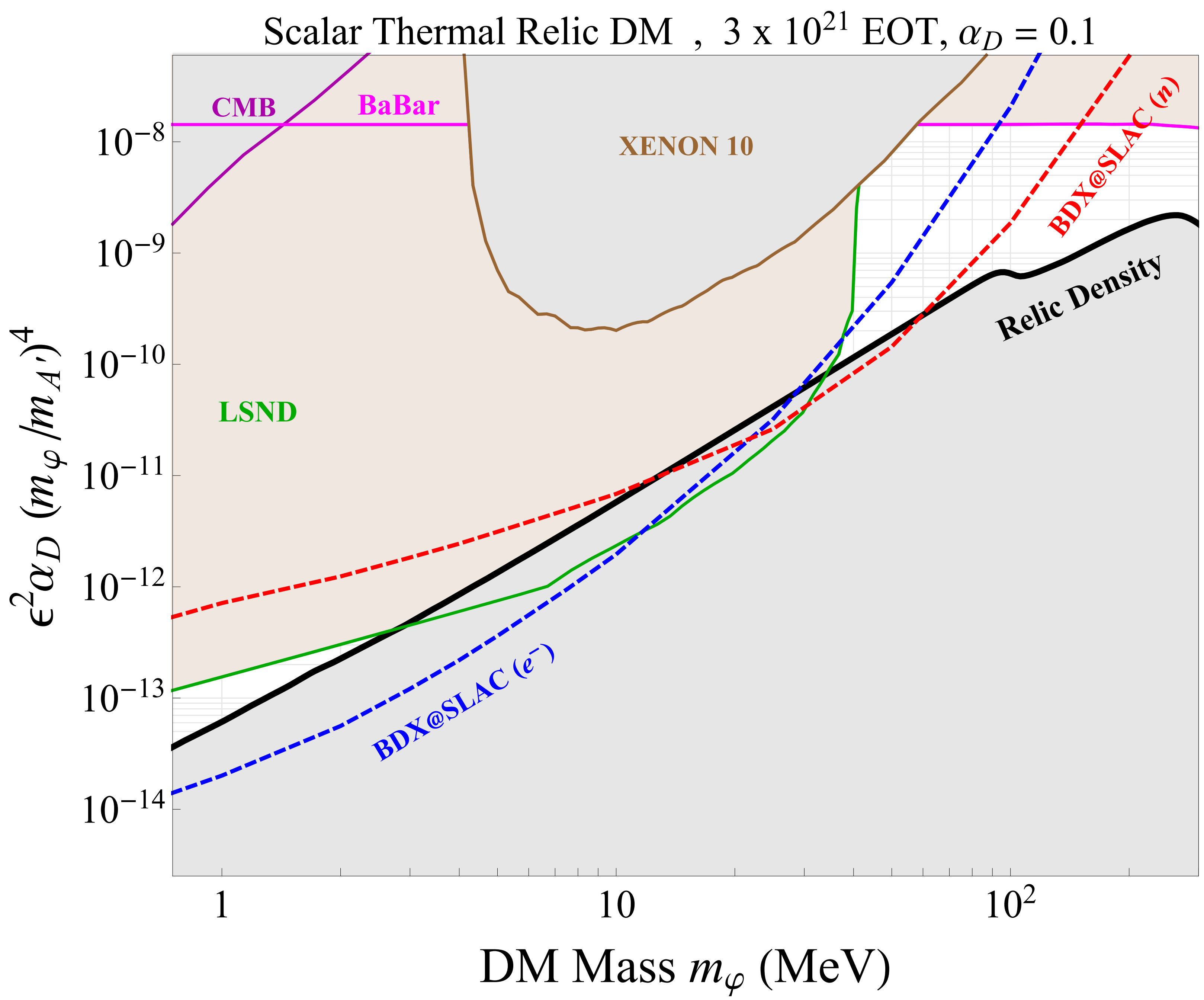
To compare B-factories sensitivity to the thermal-relic target must make assumptions on the other model parameters to compute "y"

In what follows, to be conservative and not overstate any one experiment's sensitivity we choose O(1) values for the other parameters

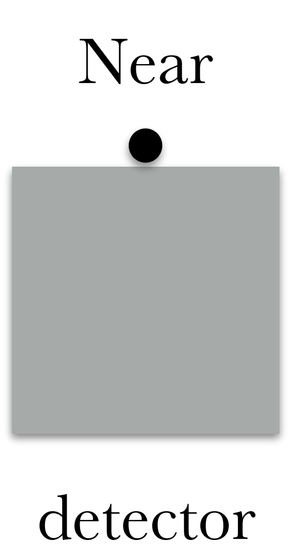
$\alpha_D = 0.1$ dark gauge coupling much larger runs non-perturbative

$\frac{m_\varphi}{m_{A'}} = \frac{1}{3}$ much smaller ratio overstates B-factories' bounds

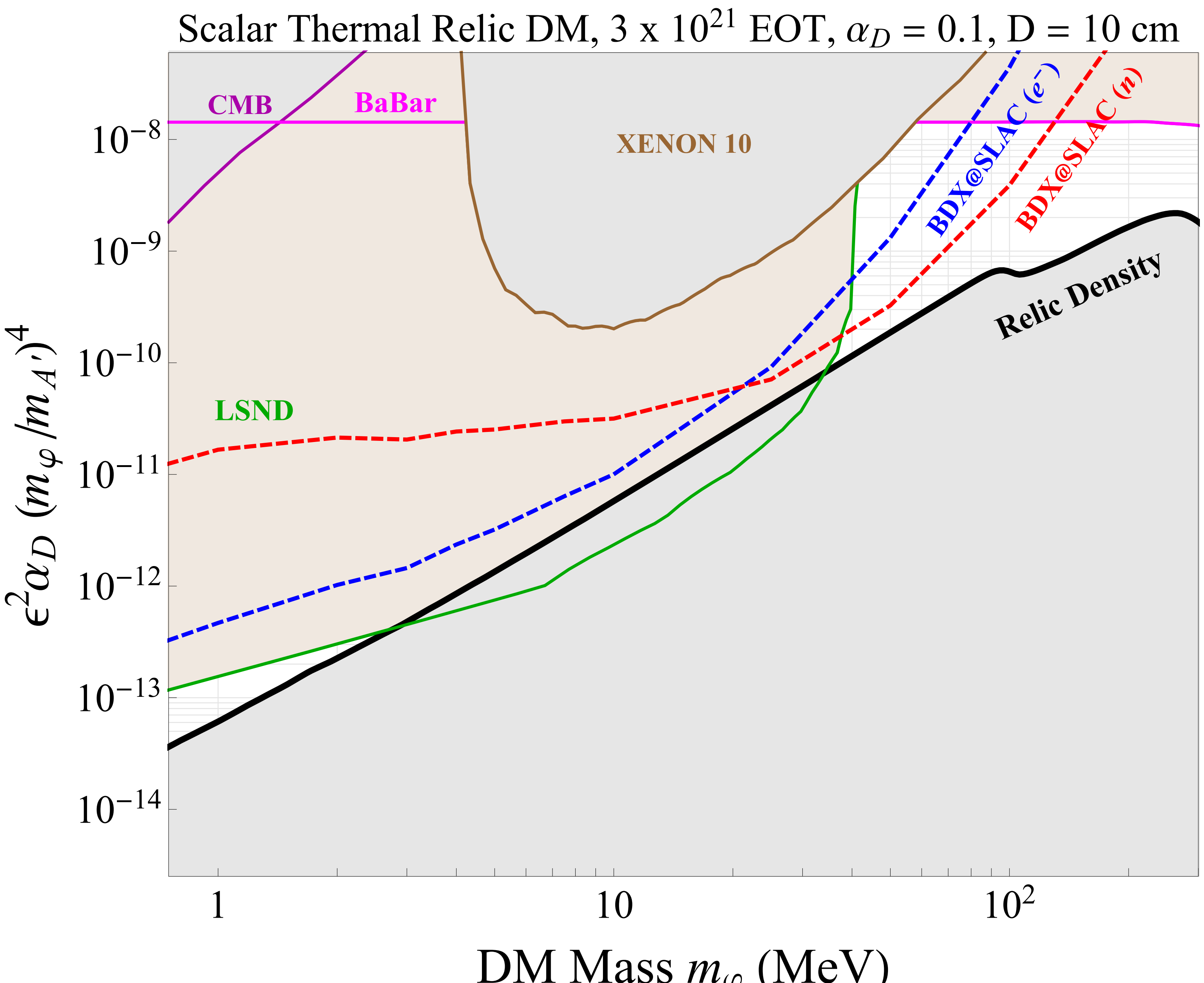
LCLS-II DM yields: Scalar QED Model



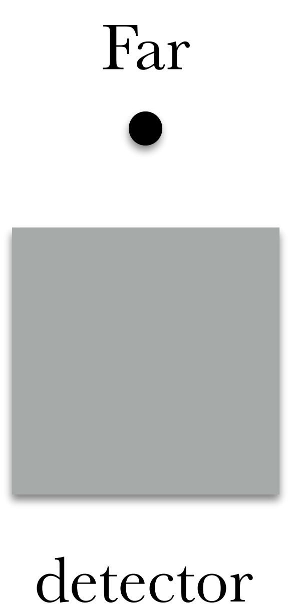
$$\frac{m_\varphi}{m_{A'}} = \frac{1}{3}$$



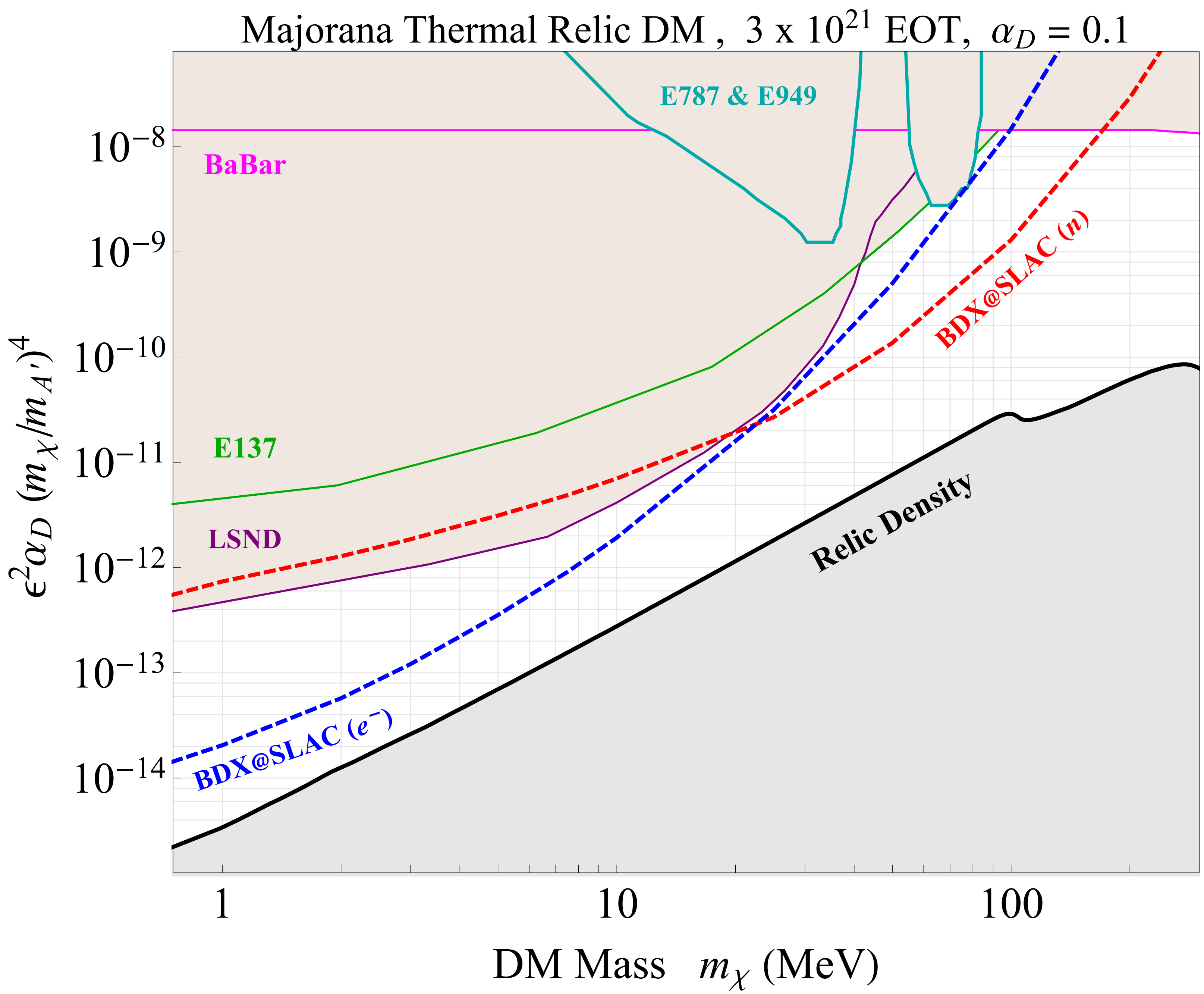
LCLS-II DM yields: Scalar QED Model



$$\frac{m_\varphi}{m_{A'}} = \frac{1}{3}$$



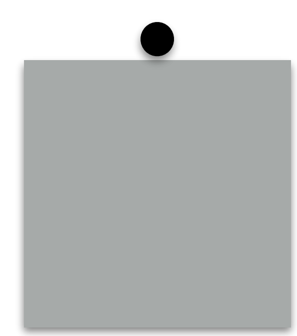
LCLS-II DM yields: iDM Model



$$\frac{m_\chi}{m_{A'}} = \frac{1}{3}$$

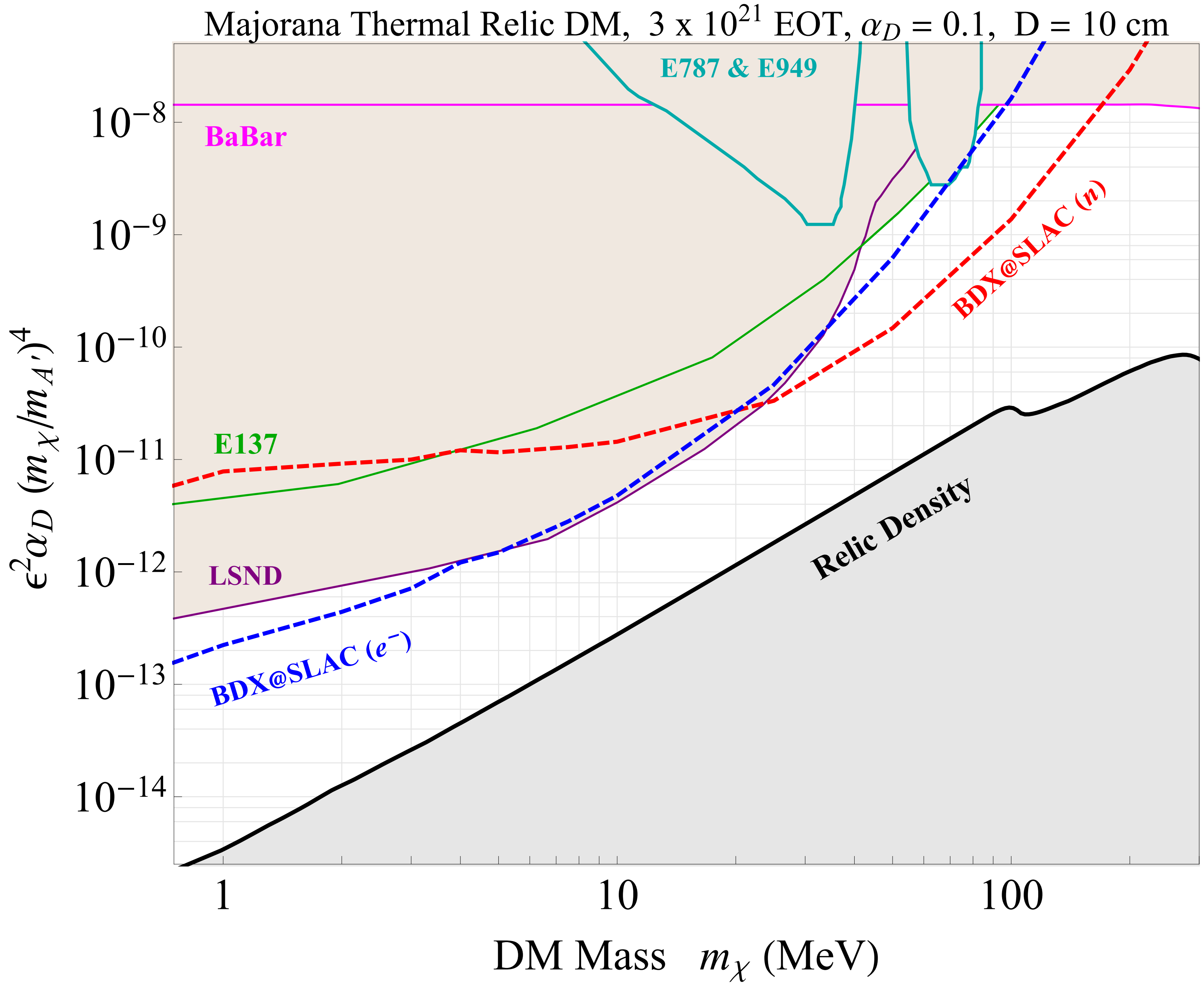
$$\Delta = 1 \text{ MeV}$$

Near



detector

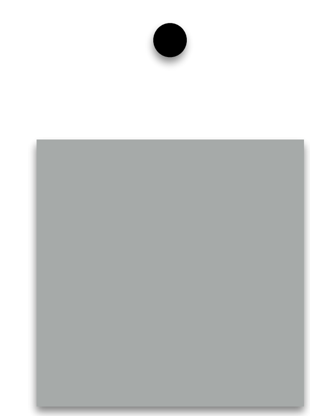
LCLS-II DM yields: iDM Model



$$\frac{m_\chi}{m_{A'}} = \frac{1}{3}$$

$$\Delta = 1\ \mathrm{MeV}$$

Far



detector

Note

The signal yields I showed were for a "worst case" scenario

In particular, the variable "y", for beam dump experiments scales as $\epsilon^4 \alpha_D$

Example

If you let $\alpha_D = 0.1 \to 0.01$

$$y \to \sqrt{0.01/0.1}y$$

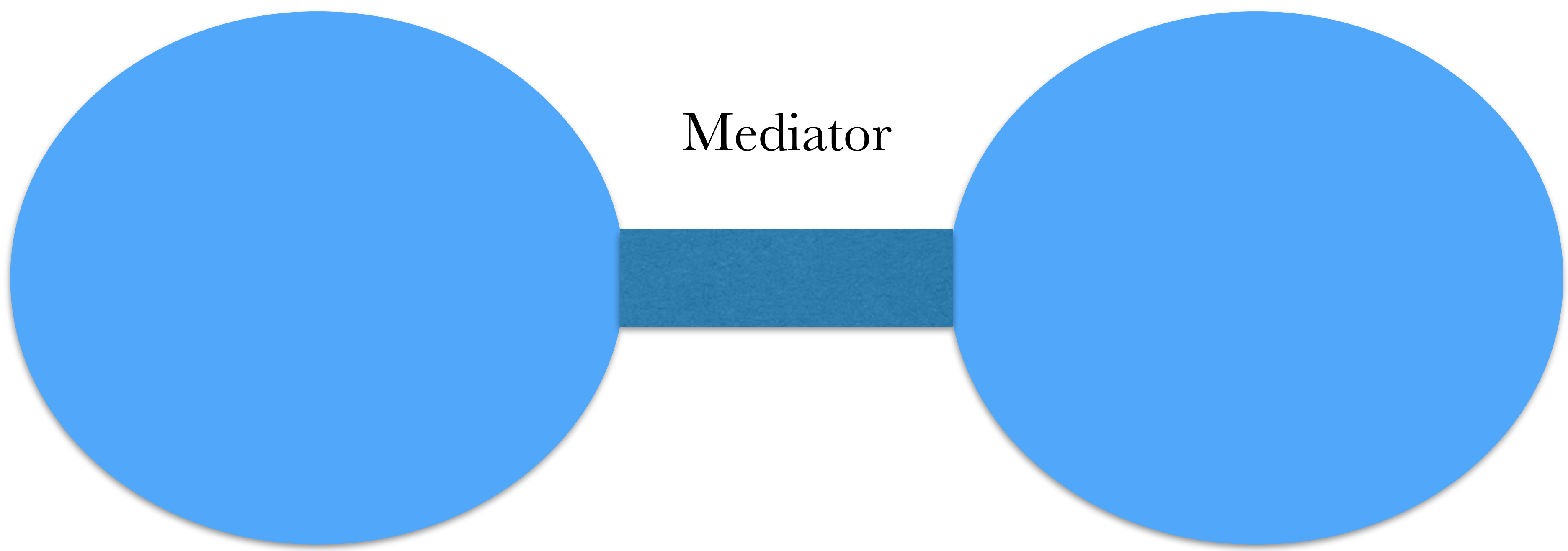
Meanwhile

$y_{\text{(thermal)}}$ stays constant

Supplement

Hidden Sector Paradigm

An increasingly popular effort to probe beyond the SM physics that lives in a "dark sector"



Well-motivated by e.g. light (thermal) DM
For light DM interactions between the DS and SM mediated by a light field

One organizing principle for probing it: focus on dimension-4 operators:
vector portal, Higgs portal, neutrino portal

I will focus on the vector portal

The Vector Portal

Can connect the dark sector to us through kinetic mixing

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{\epsilon_Y}{2} F'^{\mu\nu} B_{\mu\nu} - \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} + \frac{1}{2} m_{A'} A'^2$$

Can re-define the kinetic mixing term away by

$$B^\mu \to B^\mu + \epsilon_Y A'^\mu$$

Inducing a coupling between the dark photon and SM fermions

$$g_{A'\bar{f}f} \sim \epsilon e Q_f$$

where $\epsilon \equiv \epsilon_Y \cos\theta_W$

Matter in the Dark Sector: Two scenarios

1. Scalar QED

A complex scalar field with (dark) vector current $\mathcal{J}_D^\mu = i\varphi^* \partial^\mu \varphi + c.c.$

and mass $-m_\varphi^2 \varphi^* \varphi$

We then have the following interactions for the dark photon

$$\mathcal{L}_{int} = A'_\mu(\epsilon e \mathcal{J}_{EM}^\mu + g_D \mathcal{J}_D^\mu)$$

Matter in the Dark Sector: Two scenarios

2. Inelastic Dark Matter

Fermionic iDM (analogous case for scalar iDM)

Start with a Dirac fermion $\psi = \begin{pmatrix} \eta & \xi^\dagger \end{pmatrix}$ charged under a $U(1)_D$ symmetry

The (dark) vector current is diagonal

$$\mathcal{J}_D^\mu = \overline{\psi}\gamma^\mu\psi = \eta^\dagger\overline{\sigma}^\mu\eta - \xi^\dagger\overline{\sigma}^\mu\xi$$

Gauge invariance only allows a Dirac mass
But when symmetry is spontaneously broken can also write Majorana mass

$$-\mathcal{L} \supset m_D\eta\xi + \frac{m_\eta}{2}\eta\eta + \frac{m_\xi}{2}\xi\xi + \text{h.c.}$$

Matter in the Dark Sector: Two scenarios

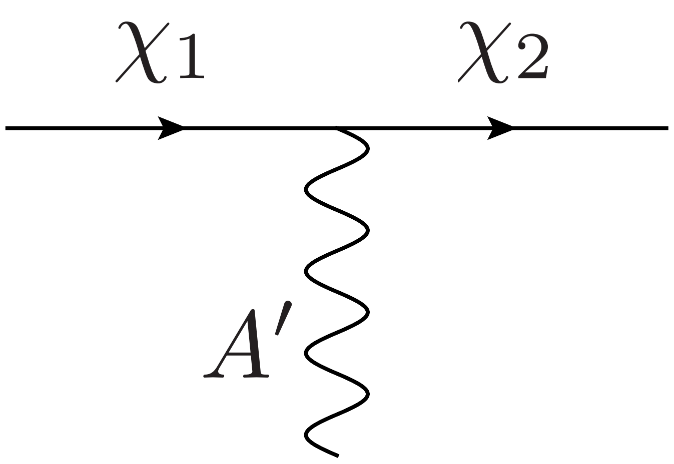
2. Inelastic Dark Matter

The mass eigenstates

$$\chi_1 = i(\eta - \xi)/\sqrt{2}\ ,\ \ \chi_2 = (\eta + \xi)/\sqrt{2}$$

now have (dominantly) off-diagonal interactions

$$\mathcal{J}^\mu = i(\chi_1^\dagger \overline{\sigma}^\mu \chi_2 - \chi_2^\dagger \overline{\sigma}^\mu \chi_1)$$



Interactions

$$\mathcal{L}_{int} = A'_\mu(\epsilon e \mathcal{J}^\mu_{EM} + g_D \mathcal{J}^\mu_D)$$

Keeping track of free parameters

DM mass: m_φ / m_χ

Excited state mass (for iDM): $m_{\chi^*} = m_\chi + \Delta$

Dark photon mass: $m_{A'}$

Kinetic mixing: ϵ

Dark gauge coupling $\alpha_D \equiv \dfrac{g_D^2}{4\pi}$

How do we analyze the parameter space of these models?
Fortunately, a thermal-relic DM target simplifies this task!

What do we know about the DM mass?

Hubble-sized axion-like particle - Black hole/MACHO

Unfortunately many of these scenarios are undiscoverable

But, a thermal origin give us a target to aim for

Below 10's KeV: too hot DM, can spoil structure formation

Above 10-100 TeV: over-closure and/or unitarity bound

This talk: MeV - GeV range target of opportunity

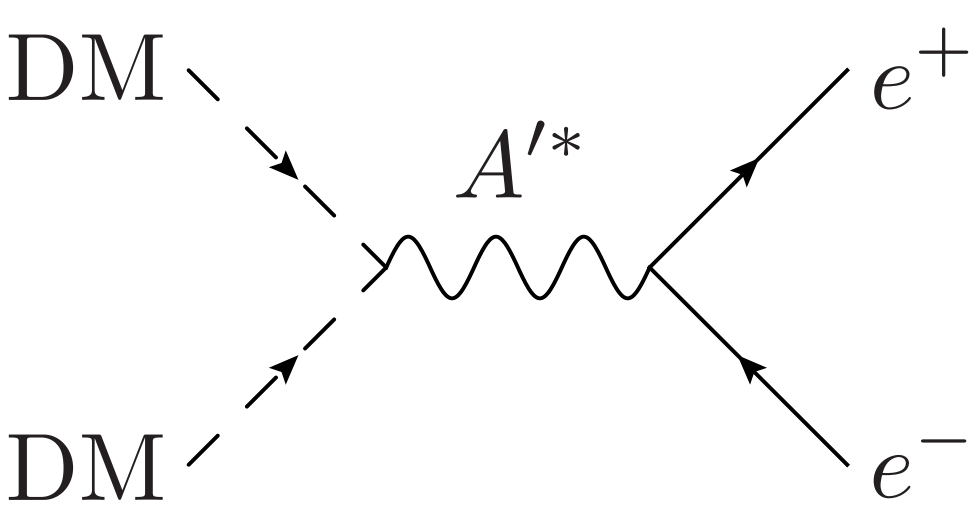
Light Thermal DM

In the early universe, DM in thermal contact with the SM

DM "freezes-out" at late times when its annihilation rate into SM smaller than expansion rate

The requirement to obtain today's DM's observed abundance sets a minimum annihilation rate

Example: scalar QED scenario, assuming $2m_{\rm DM} < m'_A$

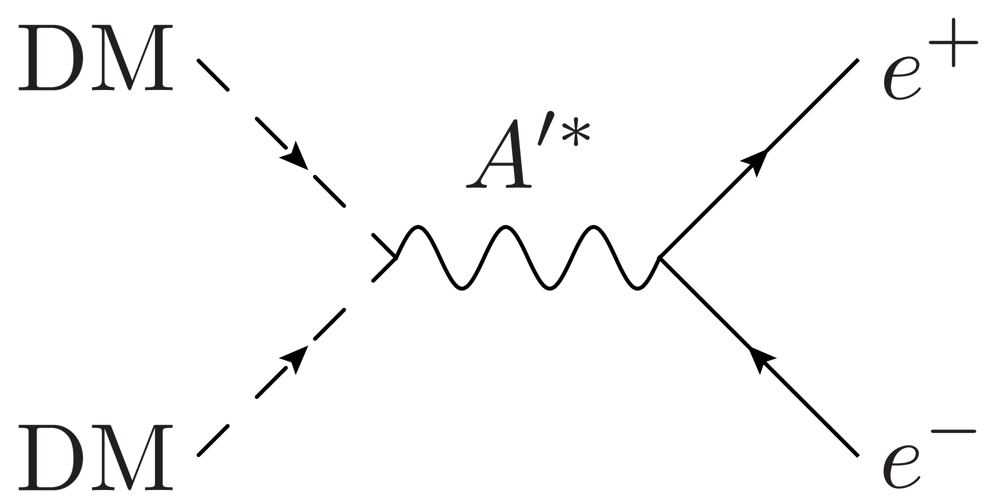


We then need

$$\langle \sigma v \rangle = \langle \sigma v \rangle_{\rm min}$$

where $\langle \sigma v \rangle_{\rm min}$ is the required rate for today's abundance

Light Thermal DM



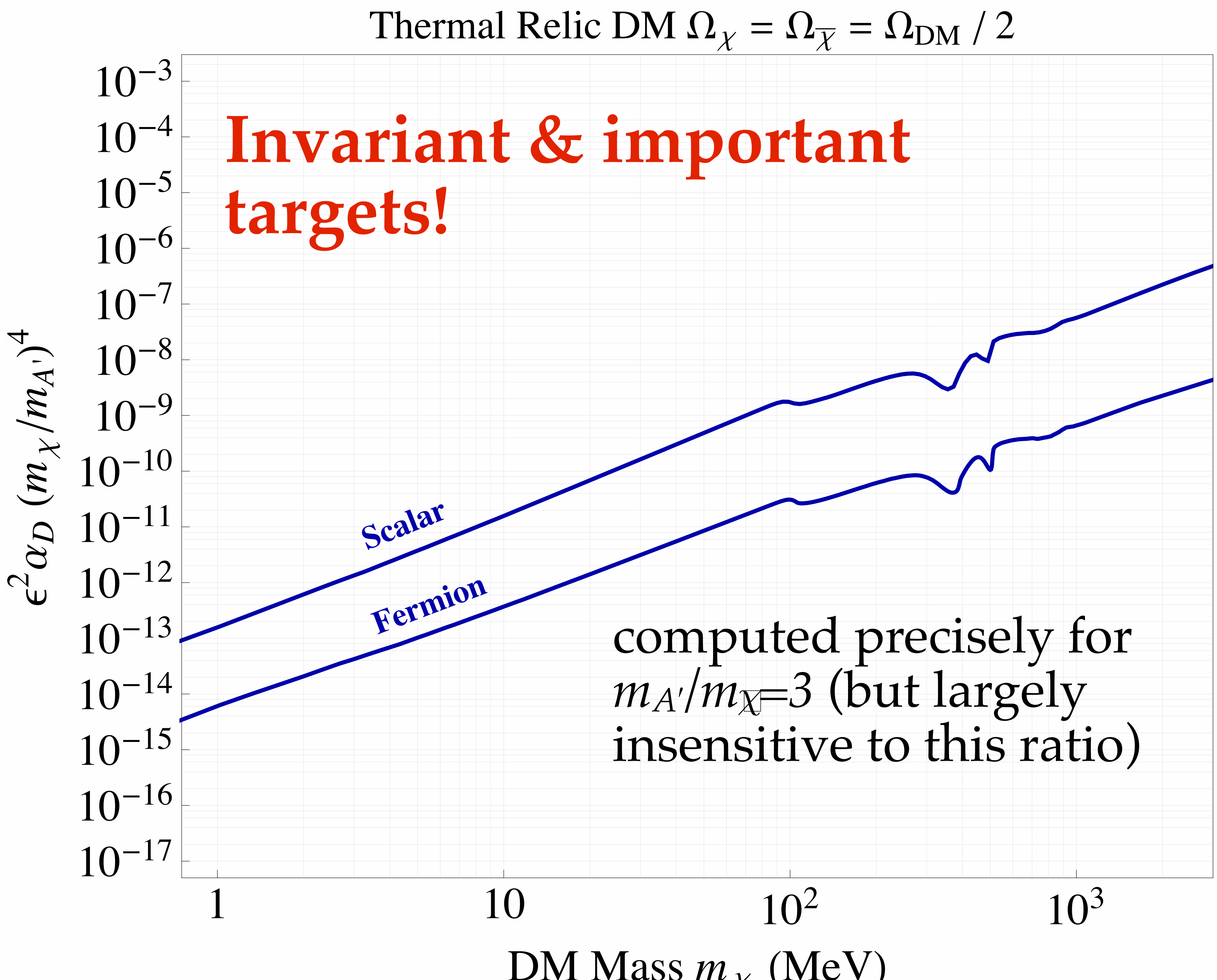
gives an annihilation rate which goes as

$$\langle \sigma v \rangle \propto \epsilon^2 \alpha_D \frac{m_\varphi^2}{m_{A'}^4} = \epsilon^2 \alpha_D \frac{m_\varphi^4}{m_{A'}^4} \frac{1}{m_\varphi^2} = \frac{y}{m_\varphi^2}$$

Then, for fixed DM mass
annihilation rate invariant
under the dimensionless combination

$$y = \epsilon^2 \alpha_D \frac{m_\varphi^4}{m_{A'}}$$

Light Thermal DM Target

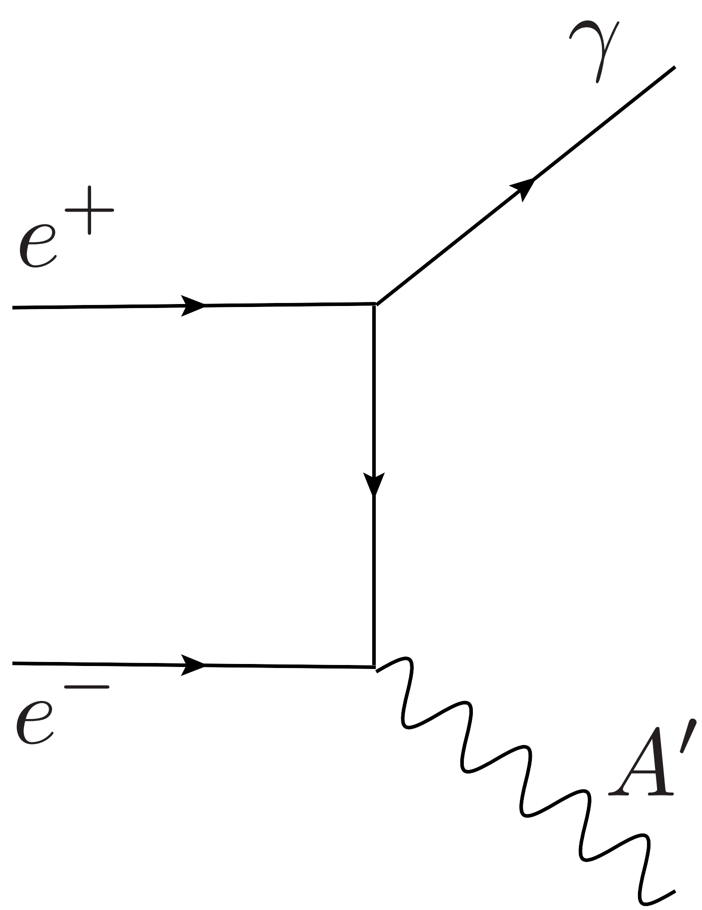


Conservative Presentation of Existing Constraints

The DM annihilation rate gives a thermal-relic DM target that is invariant under y for fixed DM mass

However, the sensitivity of different experiments does not usually scale simply with y

Example: B-factories



This search is sensitive only to ϵ^2

Conservative Presentation of Existing Constraints

Recall $$y = \epsilon^2 \alpha_D \frac{m_\varphi^4}{m_{A'}}$$

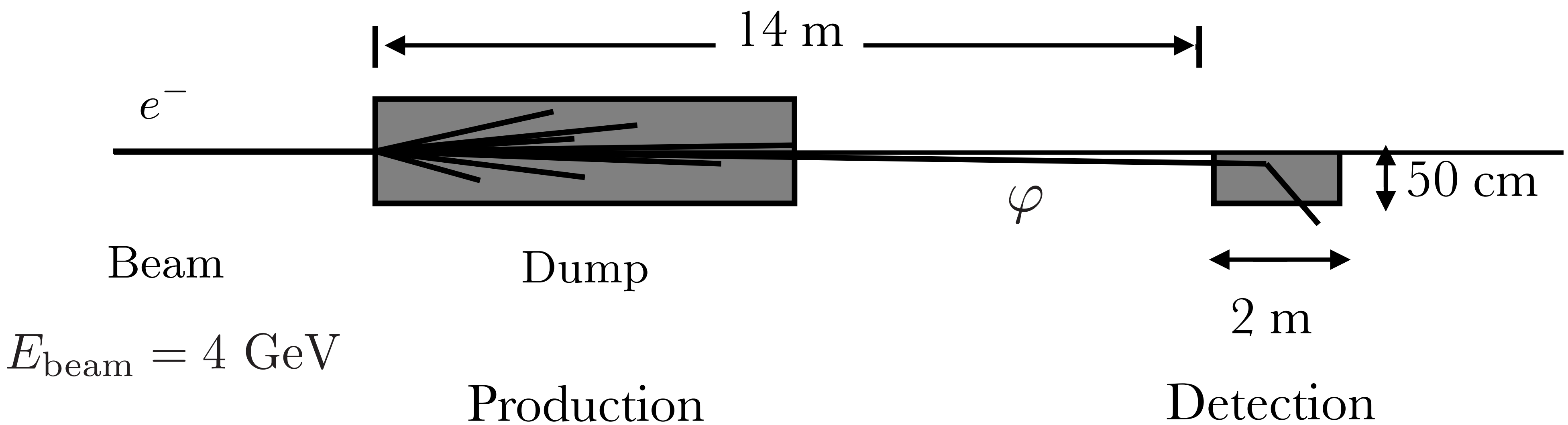
To compare B-factories sensitivity to the thermal-relic target
must make assumptions on the other model parameters to compute "y"

In what follows, to be conservative and not overstate any one experiment's sensitivity
we choose O(1) values for the other parameters

$\alpha_D = 0.5$ — dark gauge coupling much larger runs non-perturbative

$\frac{m_\varphi}{m_{A'}} = \frac{1}{3}$ — much smaller ratio overstates B-factories' bounds

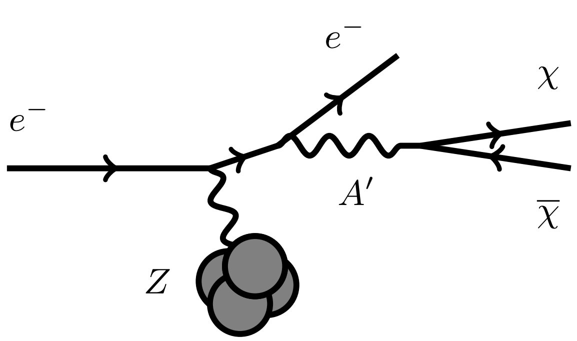
DM production at LCLS-II Beam Dump



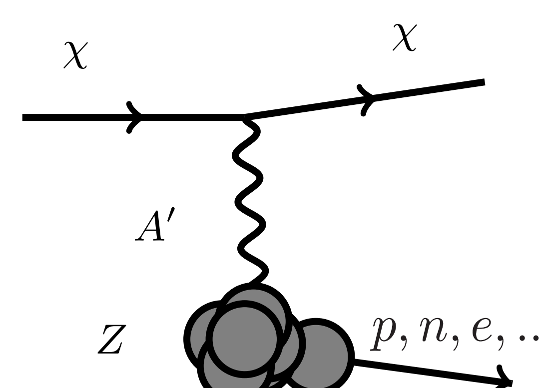
I'm assuming the dump is made out of aluminum

Detection takes place at a 50cm x 50 cm x 200 cm CsI prototype

Production



Detection



Current Constraints

LHC: monojet + MET recast at 8 TeV with 20/fb

LEP: shift in the mass of the Z boson arising from mixing with A'

E787 and E949: Rare Kaon decays into a pion and missing energy

Babar: Monophoton bump search recast

CMB: late time annihilation DM DM > leptons modifies the power spectrum

LSND: ~ 800 MeV proton beam-dump experiment. Production of A' from decay or neutral pions

SIDM: Bound from bullet cluster sets an upper bound on DM self-interaction