Title: The Theory and Experimental Frontier of Dark Forces at the GeV Scale

Date: Dec 01, 2009 01:00 PM

URL: http://pirsa.org/09120020

Abstract:

What about everything else?

Standard Model

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Is there structure beneath the Planck scale beyond known interactions?

Dark Sector

Standard Model

Sector with new gauge interactions

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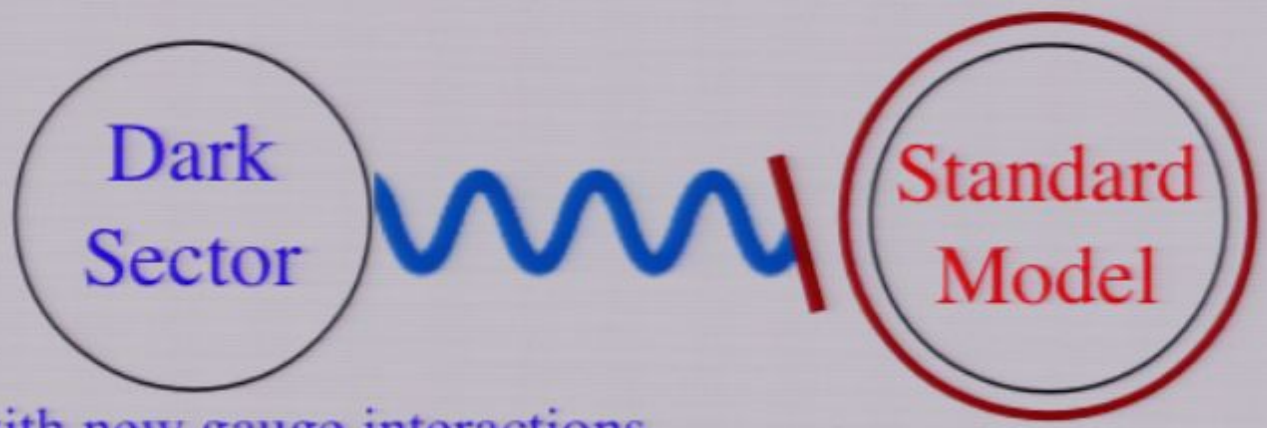

Sector with new gauge interactions

Standard Model gauge symmetries largely forbid couplings to other sectors

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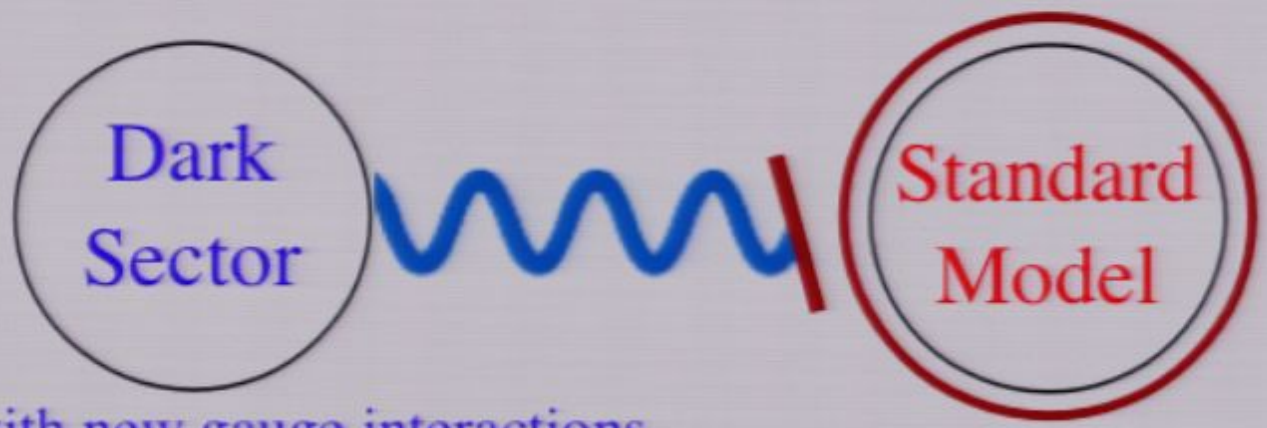


Sector with new gauge interactions

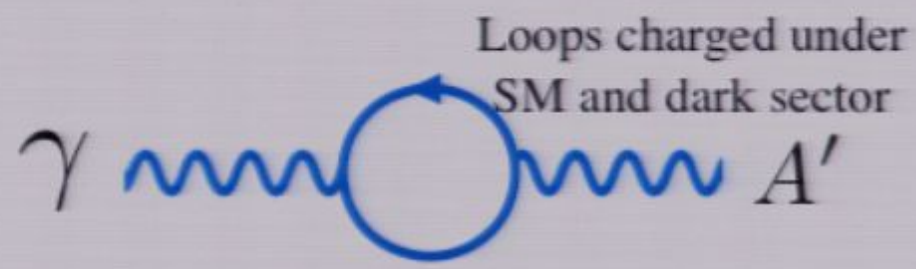
Standard Model gauge symmetries largely forbid couplings to other sectors

We nonetheless suspect that new sectors exist - SUSY breaking sectors...etc

A Simple U(1) Example

Gauge kinetic mixing is a "portal" that can link the Standard Model to new dark forces

$$\delta L = \epsilon F_Y F_{A'}$$



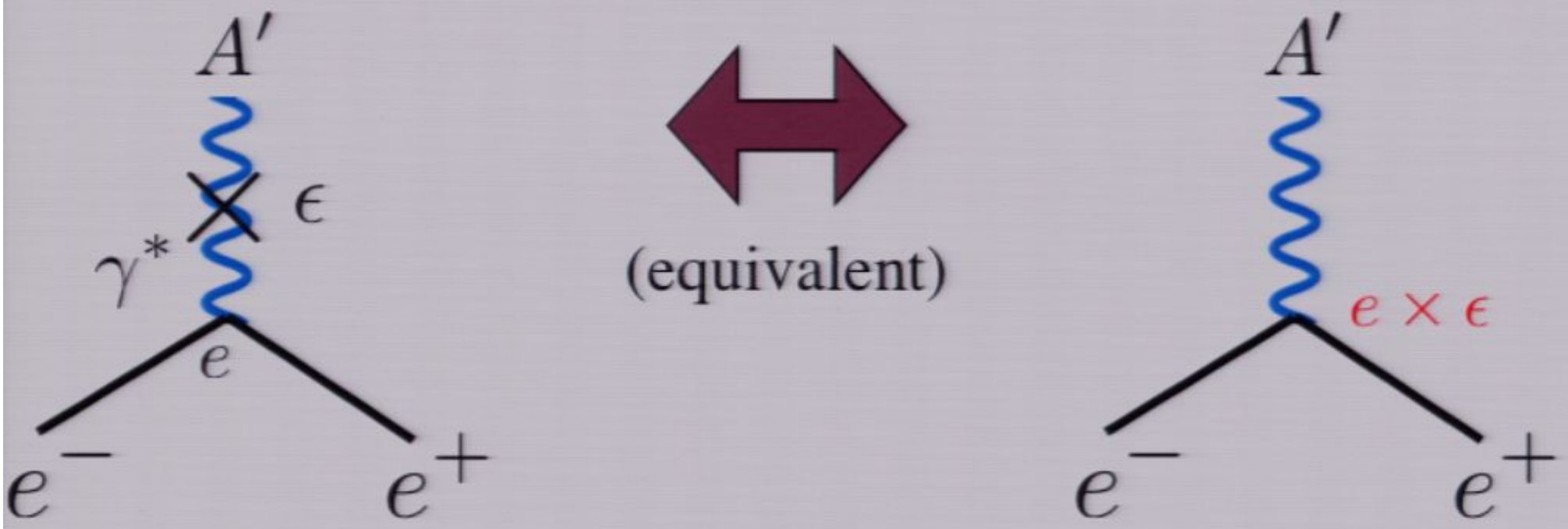
GUT or Planck scale quantum corrections

[Holdom '86]

$$\epsilon \approx \frac{g_D g_Y}{16\pi^2} \sum_i q_{D,i} Y_i \ \ln \frac{\Lambda^2}{\mu_i^2} \ \sim 10^{-4} - 10^{-3}$$

Ordinary Matter and Dark Forces

Photon mixing with massive A' is equivalent to electrically charged matter acquiring a milli-charge under the A'



Mass Scales

M_{Pl}

M_W

Λ_{QCD}

H

Weak coupling to dark sector is natural, but what about the mass scale?

GUT or Planck scale?

Massless?

Nearly massless?

Anywhere (technicolor like dark sector) ?

What about the weak-scale?

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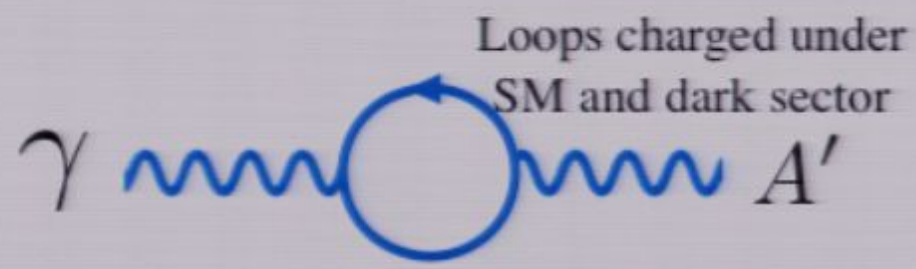

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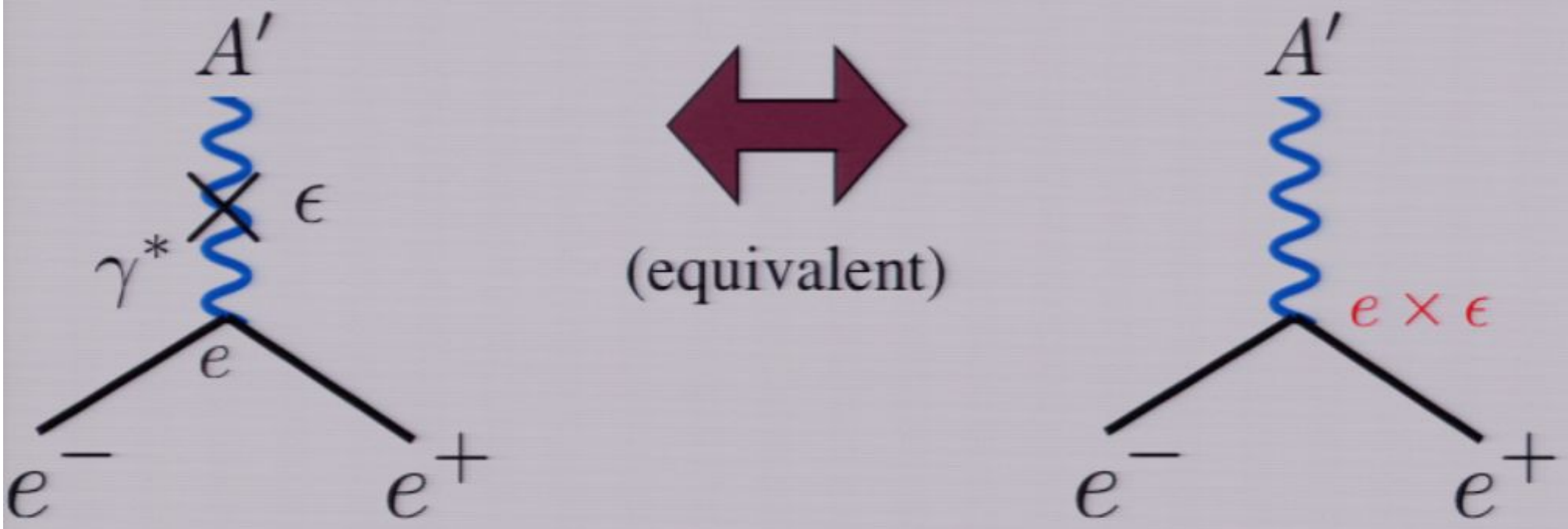

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New U(1) Near The Weak-Scale

Assume that weak-scale SUSY exists, and couple the Standard Model to a dark sector via kinetic mixing.

Supersymmetric kinetic mixing:

$$\mathcal{L} \supset \int d^2\theta \frac{\epsilon}{2} W_Y^\alpha W_{A\ \alpha} + \text{h.c.}$$

Dark sector matter:

$$W = \mu_D H_+ H \qquad \text{or} \qquad W = \lambda S H_+ H_-$$

[Cheung, Ruderman, Wang, Yavin; Katz and Sundrum; Morrissey, Poland, Zurek]

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New U(1) Near The Weak-Scale

Dark U(1) and hypercharge U(1) D-terms mix

Dark Sector D-term Potential:

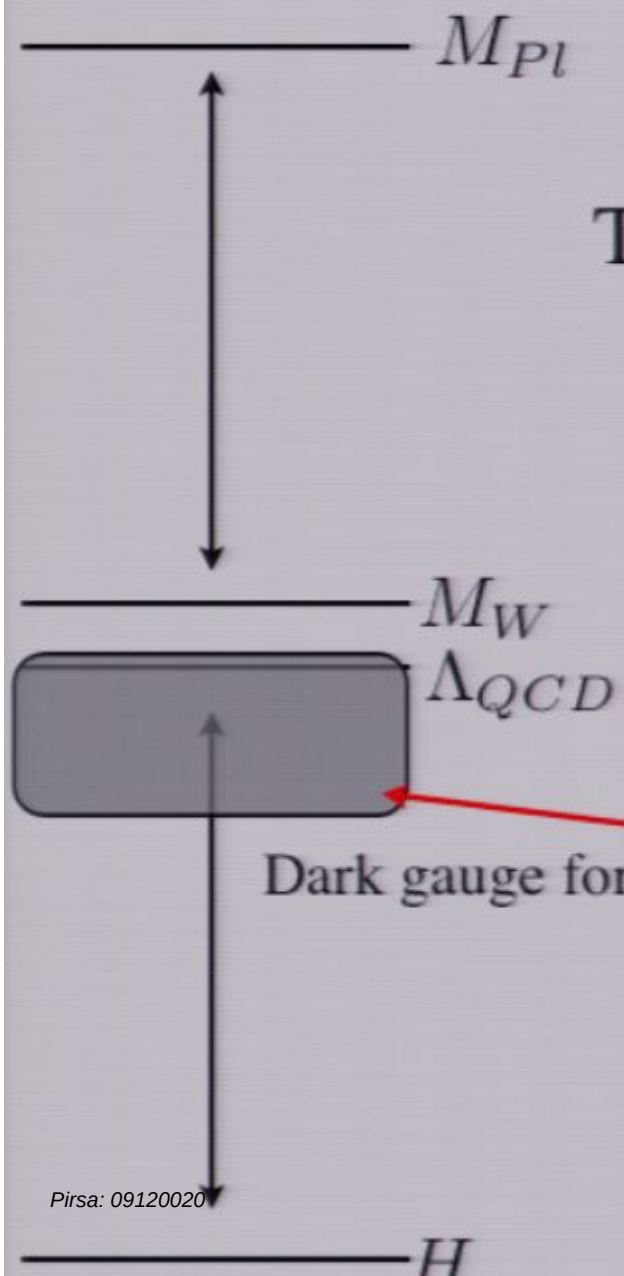
$$V_D = \frac{g_D^2}{2}\left(\sum_i q_{D,i}|\phi_i|^2 - \epsilon\frac{\cos 2\beta}{2 g_D g_Y} M_W^2\right)^2$$

Electro-weak symmetry breaking triggers dark U(1) breaking:

$$m_{A'}^2 = \epsilon\frac{q_i g_D \cos 2\beta}{2 g_Y} M_W^2 \lesssim (1\mathrm{GeV})^2$$

[Cheung, Ruderman, Wang, Yavin; Katz and Sundrum; Morrissey, Poland, Zurek]

New Dark Gauge Forces - Where to Look?



Theoretical Region of Interest:

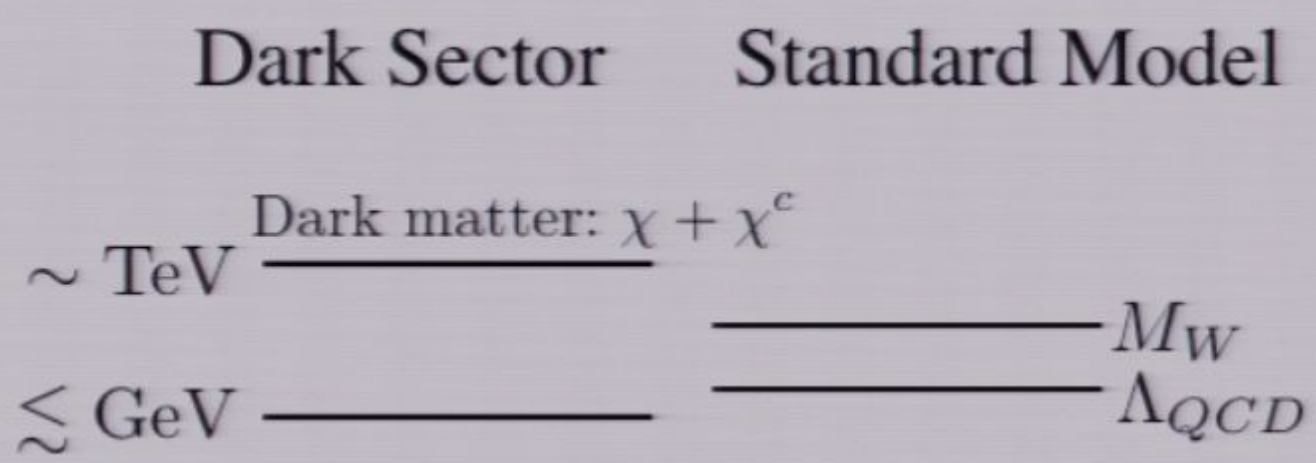
New weakly coupled gauge interactions with mass scale beneath the weak scale

A good place to explore!

Phenomenological Motivation

What if dark matter belongs to a dark sector

Suppose that dark matter is a TeV mass thermal relic charged under a dark U(1) that kinetically mixes with the photon



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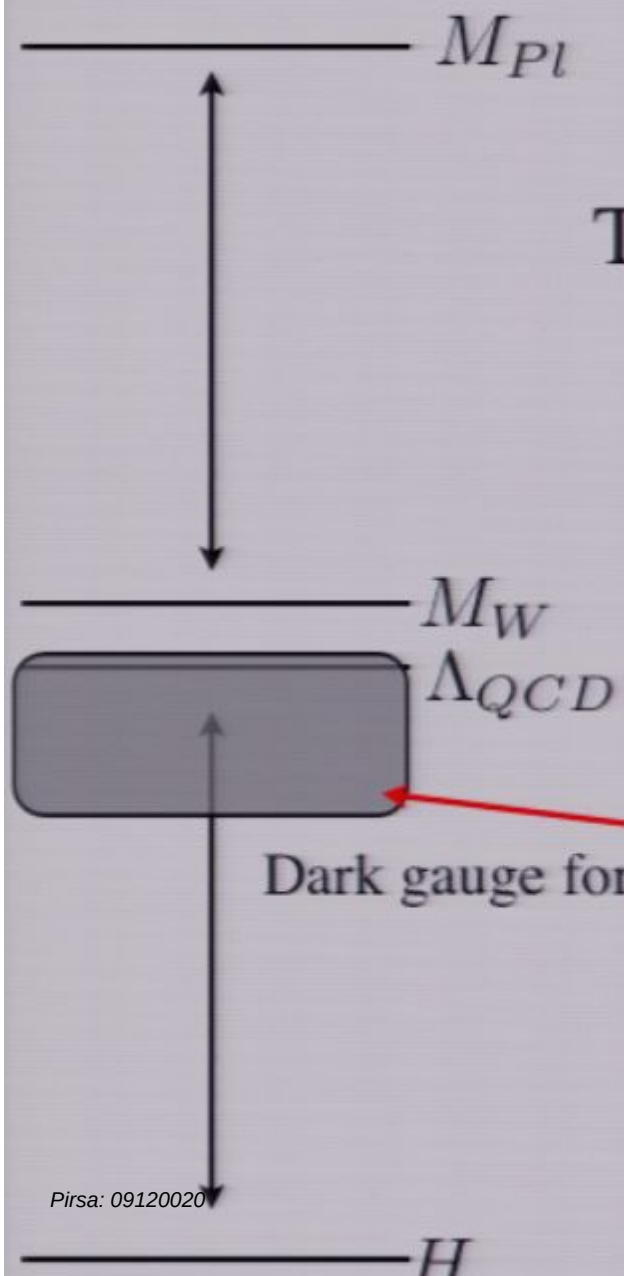

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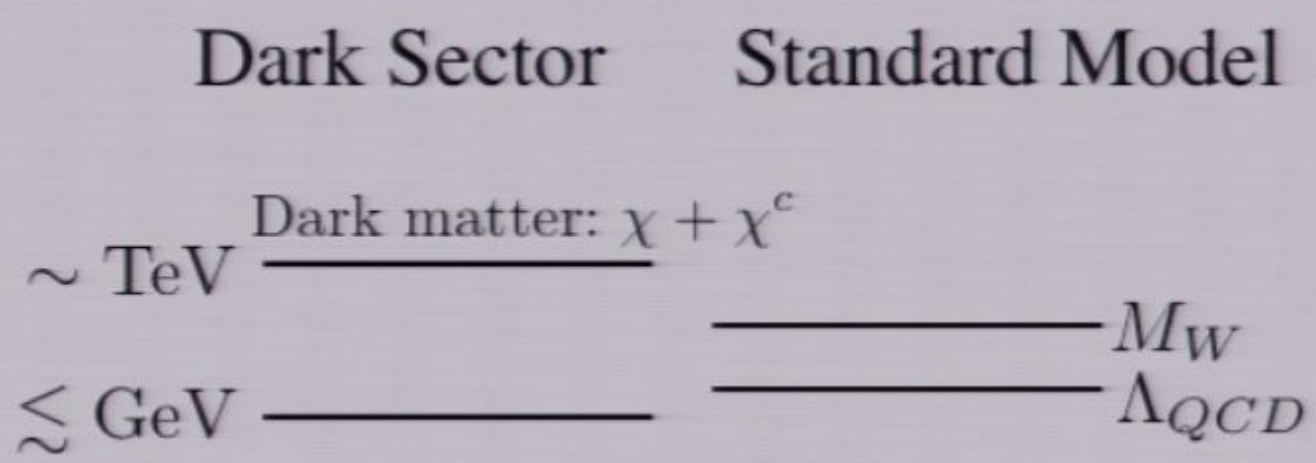


Dark Matter Charged Under a GeV-Scale Gauge Force

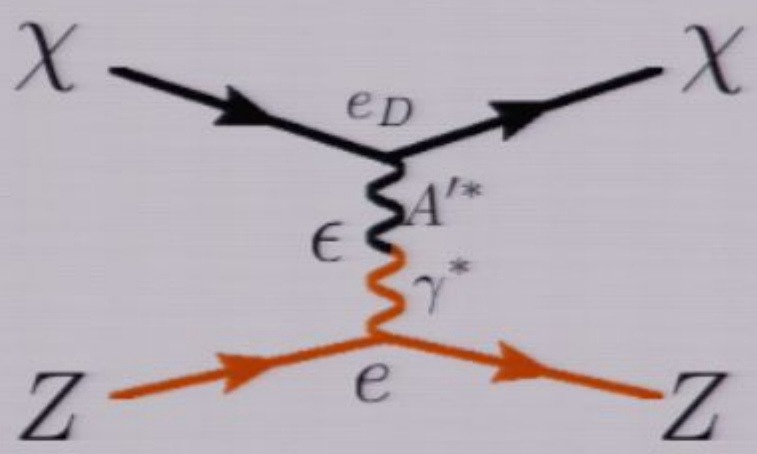
Several Striking Consequences:

- Annihilation enhanced at low velocities
- Annihilation into light, not heavy states

- Excited states split by O(MeV)
- Scattering off matter:
  - rate similar to neutral current
  - scattering into excited state, enhanced modulation

Dark Matter and Dark Forces

Direct Detection Rates:



$$m_{A'}^2 = \epsilon \frac{q_i g_D \cos 2\beta}{2 g_Y} M_W^2$$

$$A \sim \frac{e_D e \epsilon}{m_{A'}^2} \sim \frac{e^2}{M_W^2}$$

Despite lack of SM charge, dark matter can naturally have weak-scale scattering rates with ordinary matter!

Dark Matter and Dark Forces

Very small dark matter mass scales:

[Tucker-Smith and Weiner;
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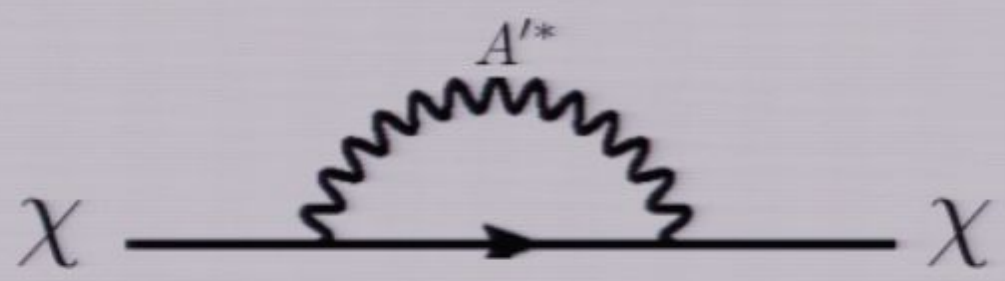
In Non-Abelian dark sectors, radiative effects can split dark matter states



$$\delta M_{DM} \sim \alpha_D \delta M_{gauge} \sim \alpha_D^2 M_{gauge} \sim 100 \text{ keV}$$

(radiative splittings)

(custodial symmetry breaking)

Dark Matter and Dark Forces

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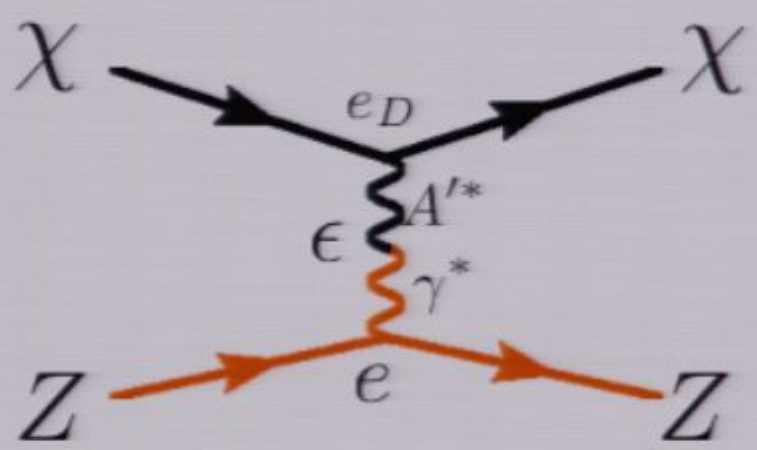

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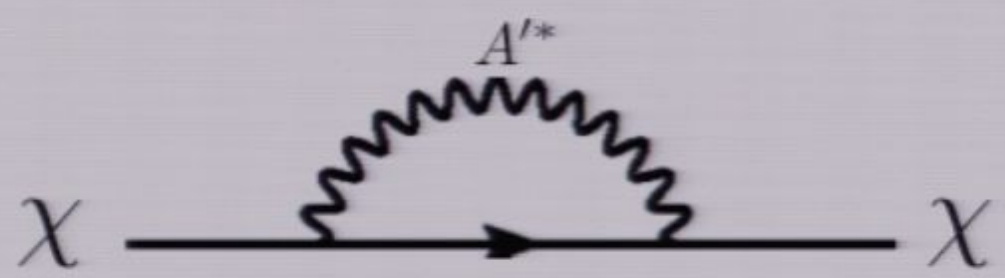

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Inelastic Scattering:

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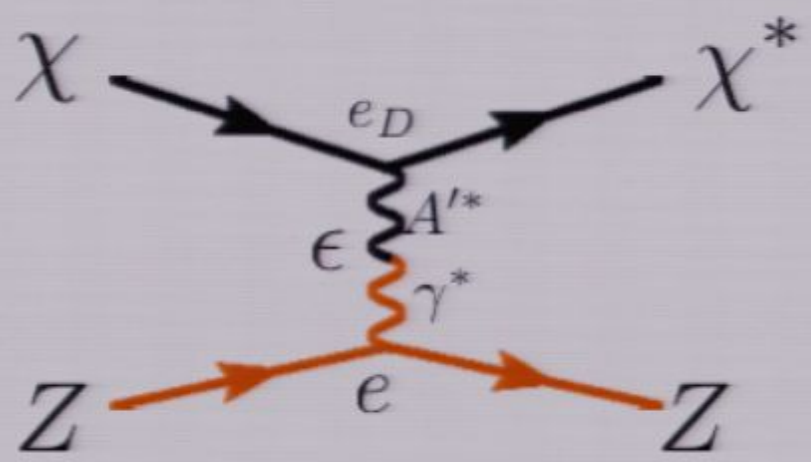
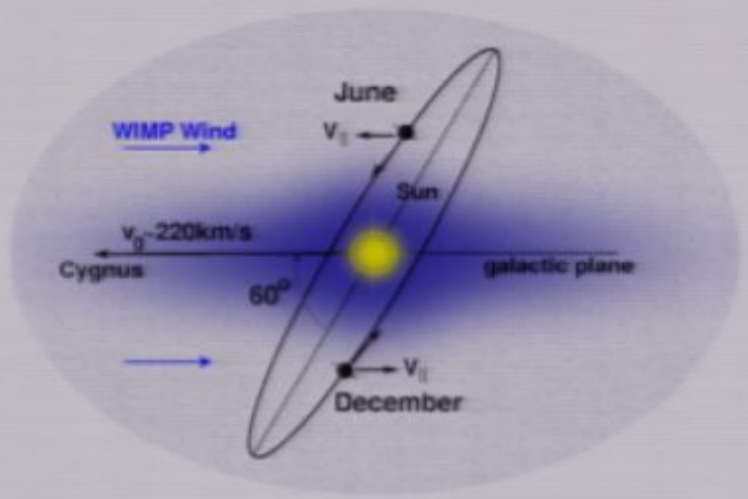


Vector mediated scattering is automatically inelastic, with a 100s keV energy splitting

A' Mediation of Inelastic DM-Nuclei Scattering



Dark matter mass splitting:
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Large modulation amplitude, characteristics of recoil spectrum, and null results of other experiments explained by inelastic collisions

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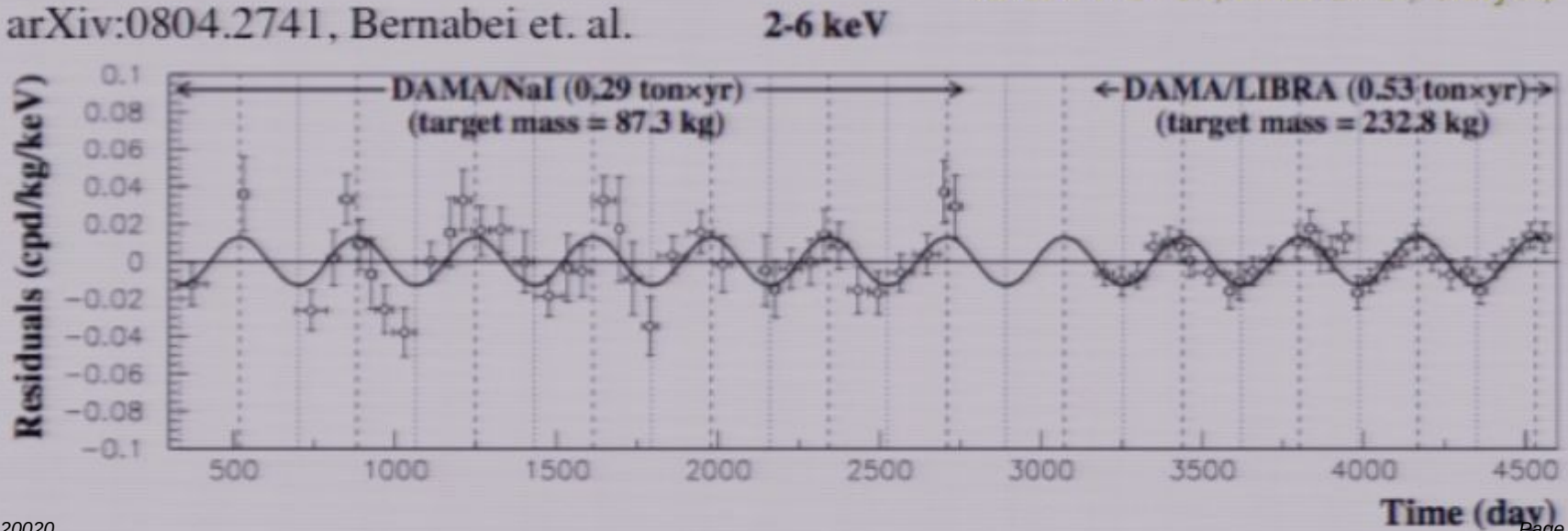

The Origin of a 100 keV Dark Sector Splitting

Non-Abelian Higgsed Sector:

Dark matter is a charged multiplet [Arkani-Hamed, Finkbeiner, Slatyer, Weiner]

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Dark matter is a dark heavy flavor meson [Alves, Behbahani, PS, Wacker]

$$\underbrace{\delta M_{DM}}_{\text{(hyperfine splittings)}} \sim \frac{\Lambda_{Dark}^2}{M_{DM}} \sim 100 \text{ keV} \rightarrow \Lambda_{Dark} \sim \text{GeV}$$

New particles at the GeV-scale are required

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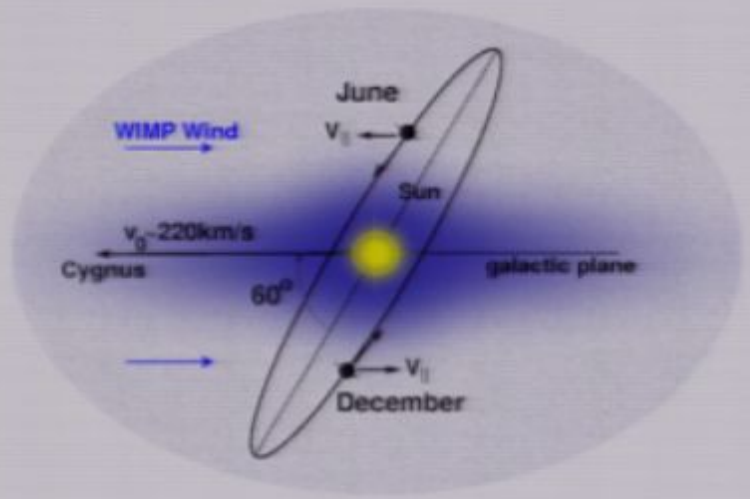

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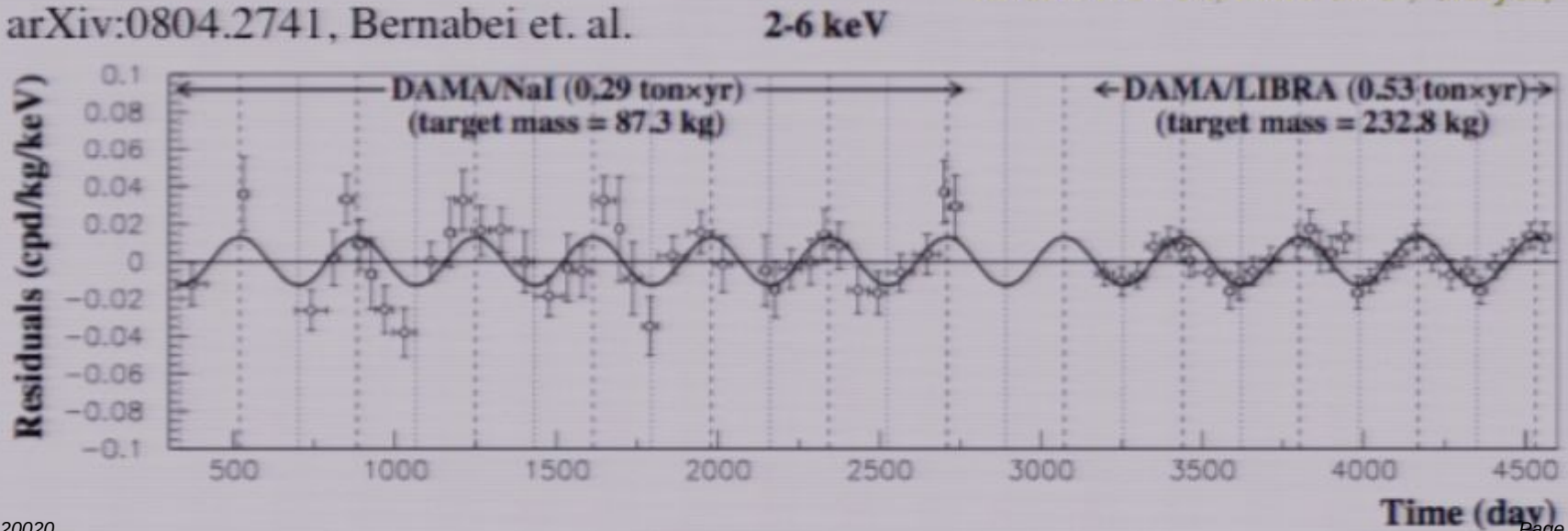

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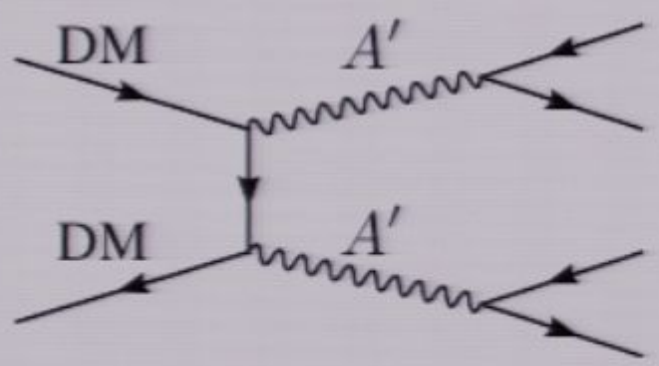
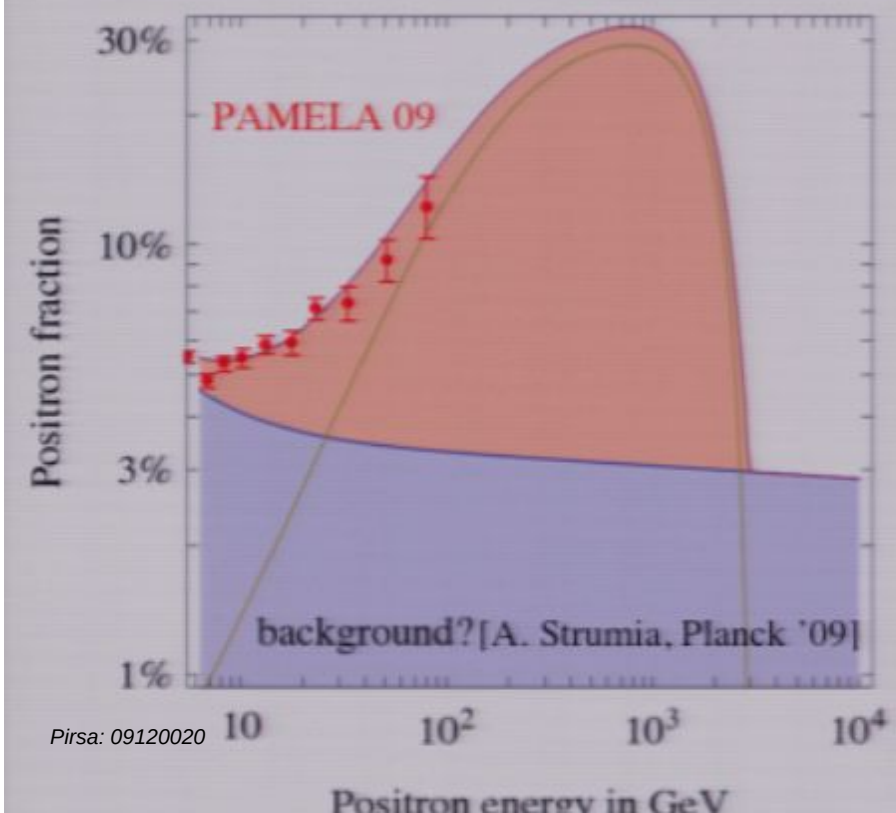
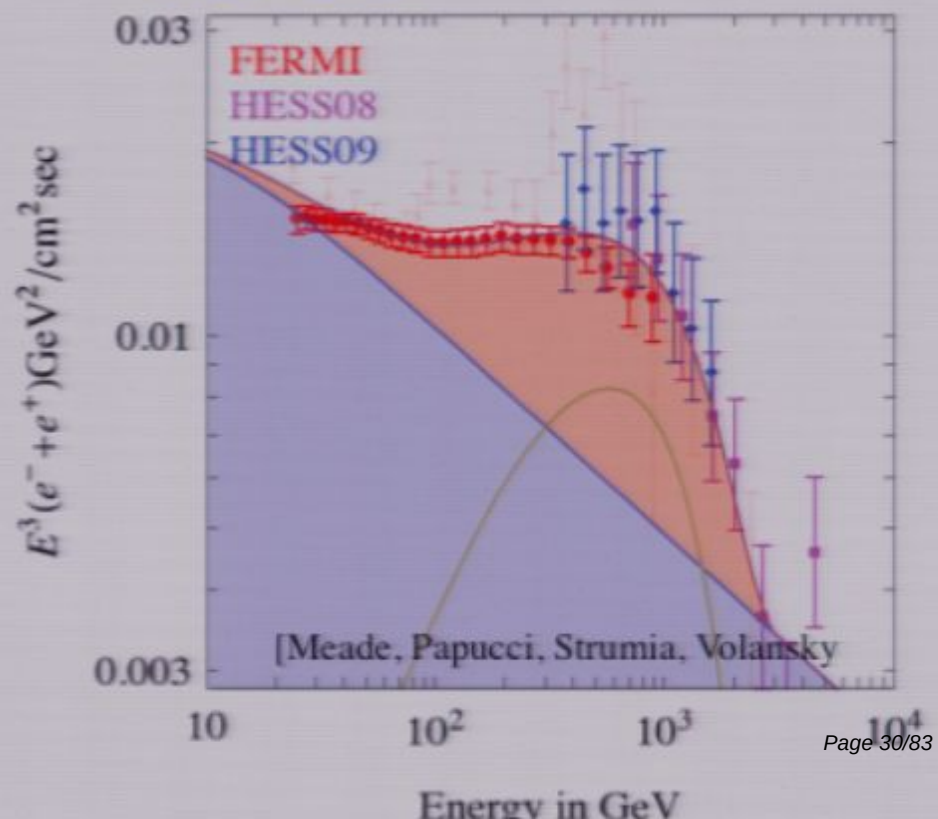
Annihilation into Leptons



Standard Model Particles ($m<m_{A'}/2$)

[Arkani-Hamed, Finkbeiner, Slatyer, Weiner; Cholis, Finkbeiner, Goodenough, Weiner; Pospelov & Ritz]





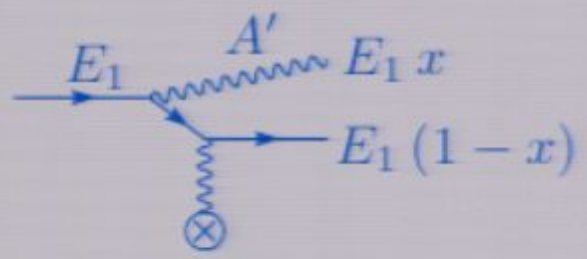
New Gauge Forces

Are there new gauge forces? – an intriguing possibility

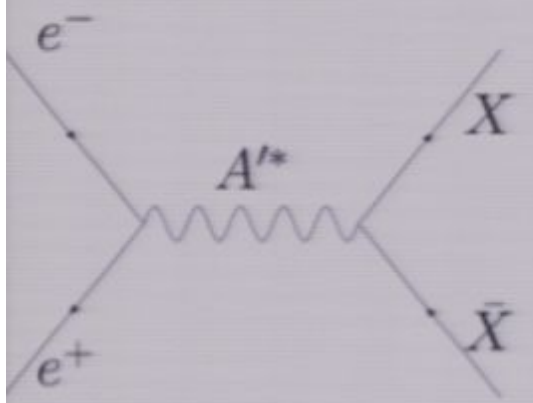
Do new gauge forces explain astro/direct-detection data?

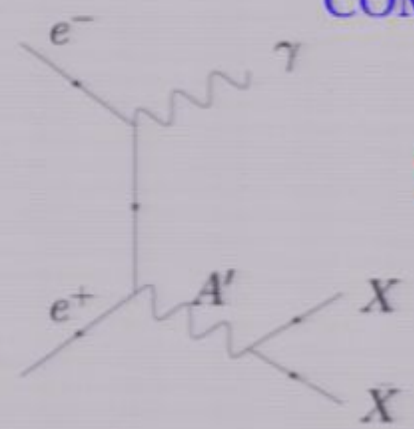
Insight from laboratory experiments needed!

Production Mechanisms

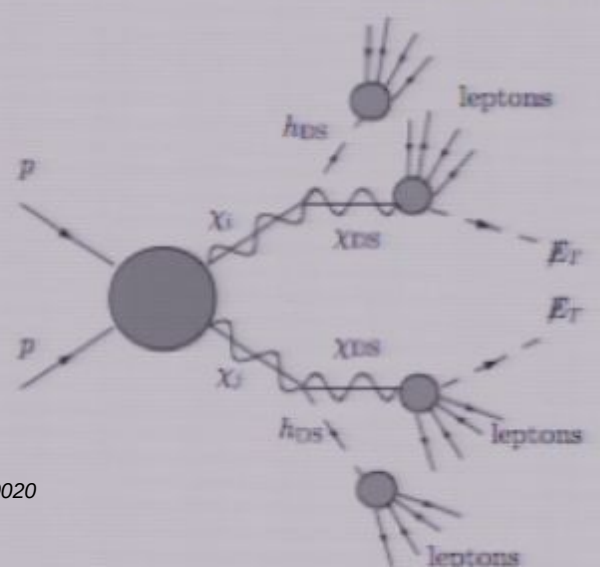


Fixed-Target: Electron or Proton collisions, A' decays to di-lepton, pions, multiple channels (Jefferson Lab (Hall A, Hall B/CLAS), SLAC, MAMI (Mainz), ELSA (Bonn), XFEL (DESY), COMPASS (CERN), FNAL, ...)





Colliding e+e-: On- or Off- shell A', X=dark sector or leptons & pions (BELLE, BaBar, BES-III, KLOE, CLEO)

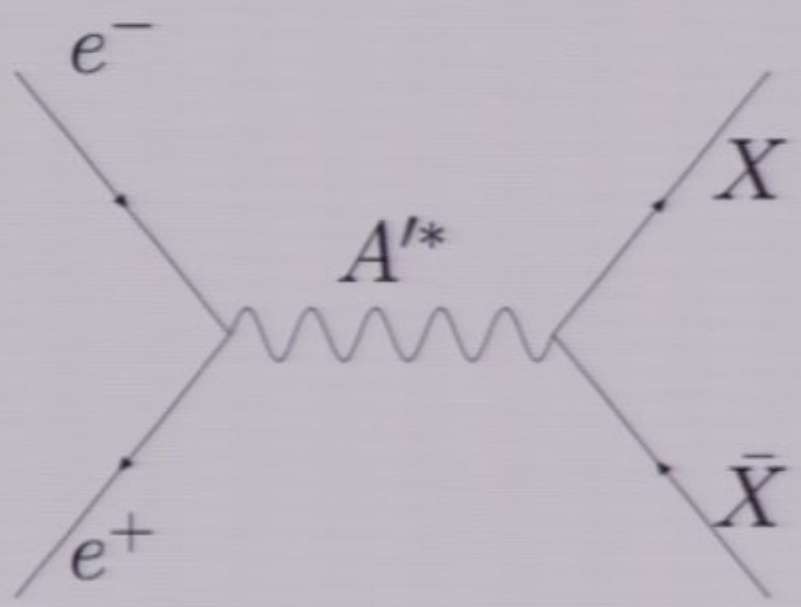


High Energy Hadron Colliders: New heavy particles decaying into dark sector (lepton jets) (CDF & D0)

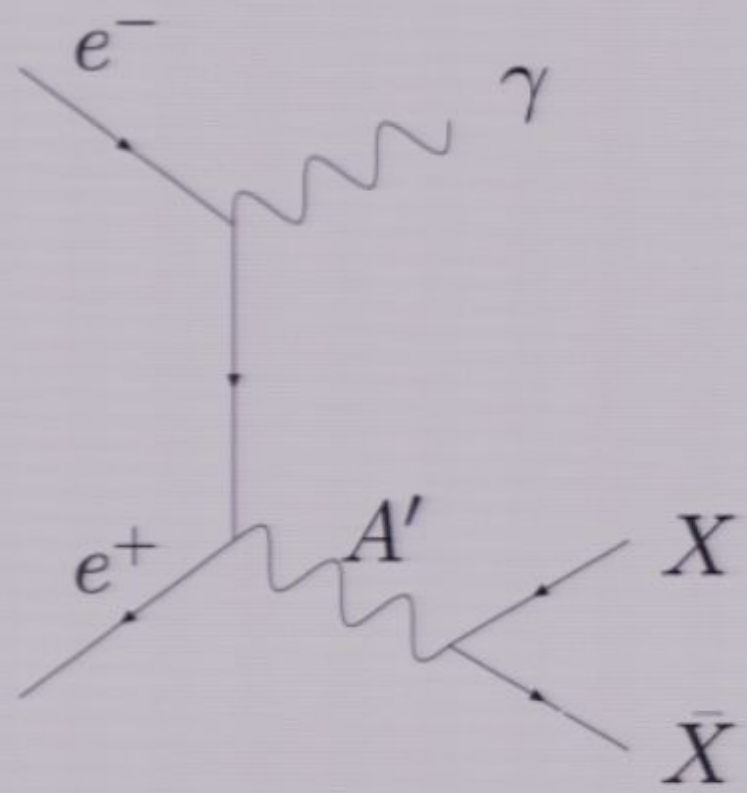
Dark Forces at the GeV Scale

- Theory of New Vector Bosons (and hints from dark matter)
- e+e- Collider Searches (Babar, Belle, KLOE)
- Fixed-Target Experiments (e.g. @ JLab)

Dark Sector Collider Production



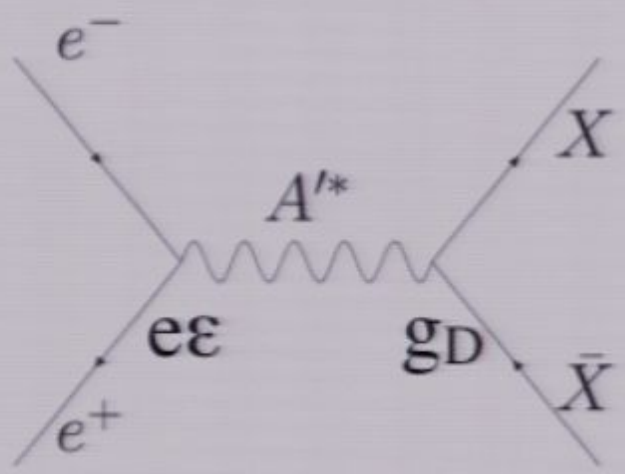
Off-Shell A′



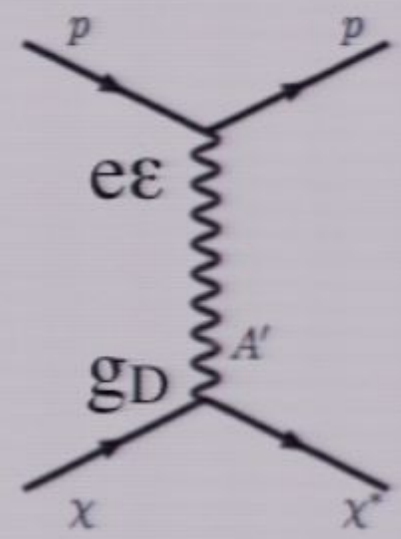
Radiative return

$\sigma \propto \epsilon^2/s$ → High-luminosity GeV-scale colliders

Normalizing Production Rates from DAMA/LIBRA



$\propto$

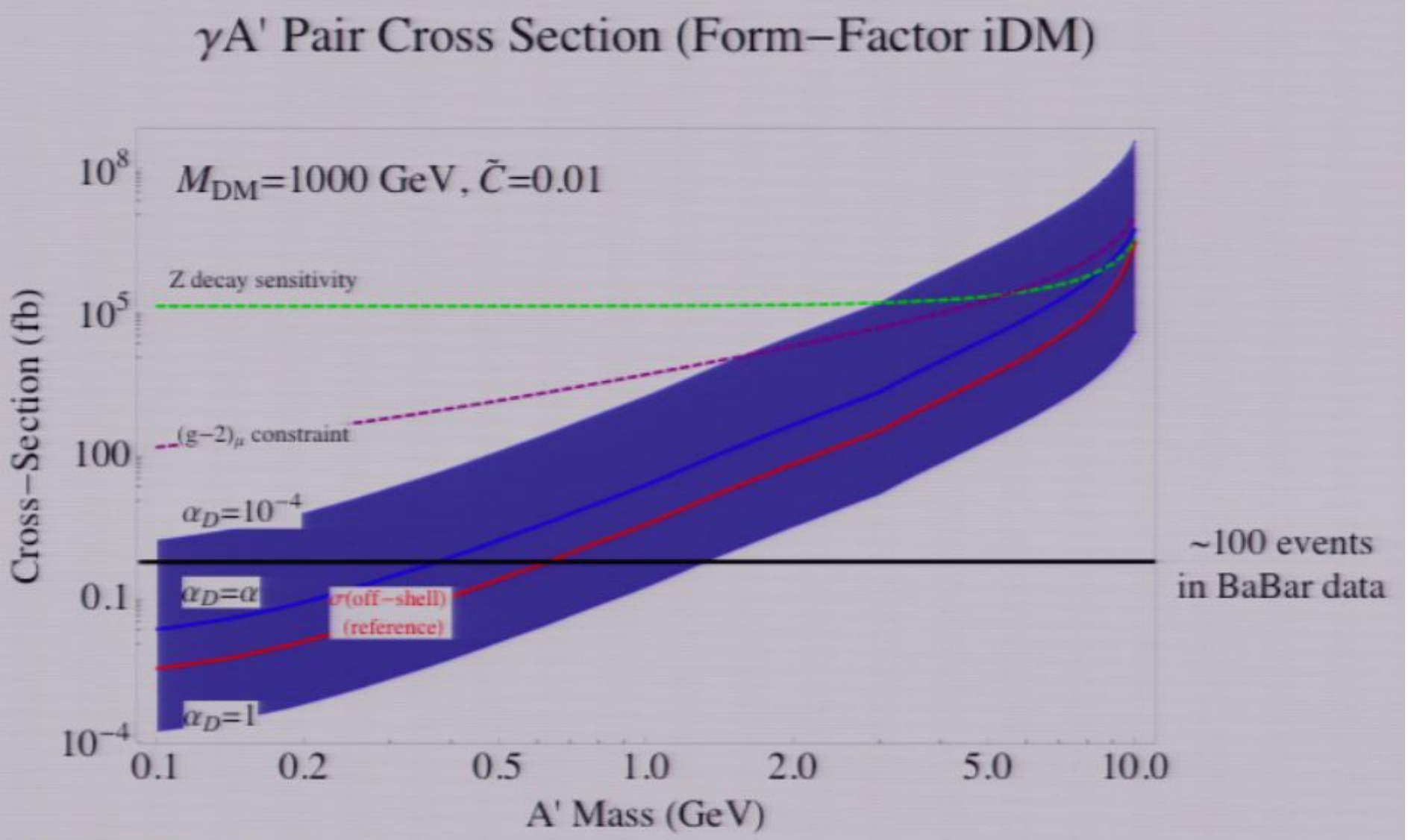


$q^2 = s = (10.58\ \mathrm{GeV})^2$

$q^2 = \mu^2 v^2 \ll m_{A'}^2$

Can estimate production cross-section from DAMA/LIBRA scattering cross-section

DAMA-Normalized Production Rates



[see: Essig, PS, Toro]

GeV-Scale Colliders

Figure of Merit is: $\mathcal{L}_{int}/s$

BELLE	BaBar	KLOE	CLEO-C	BES III
$\frac{725\ \text{fb}^{-1}}{(10.6\ \text{GeV})^2}$	$\frac{430\ \text{fb}^{-1}}{(10.6\ \text{GeV})^2}$	$\frac{2.5\ \text{fb}^{-1}}{(1\ \text{GeV})^2}$	$\frac{\approx 1\ \text{fb}^{-1}}{(4\ \text{GeV})^2}$	$\frac{??\ \text{fb}^{-1}}{(4\ \text{GeV})^2}$

No. of events for $\alpha_D = \alpha$, $\epsilon = 10^{-2}$ (approx):

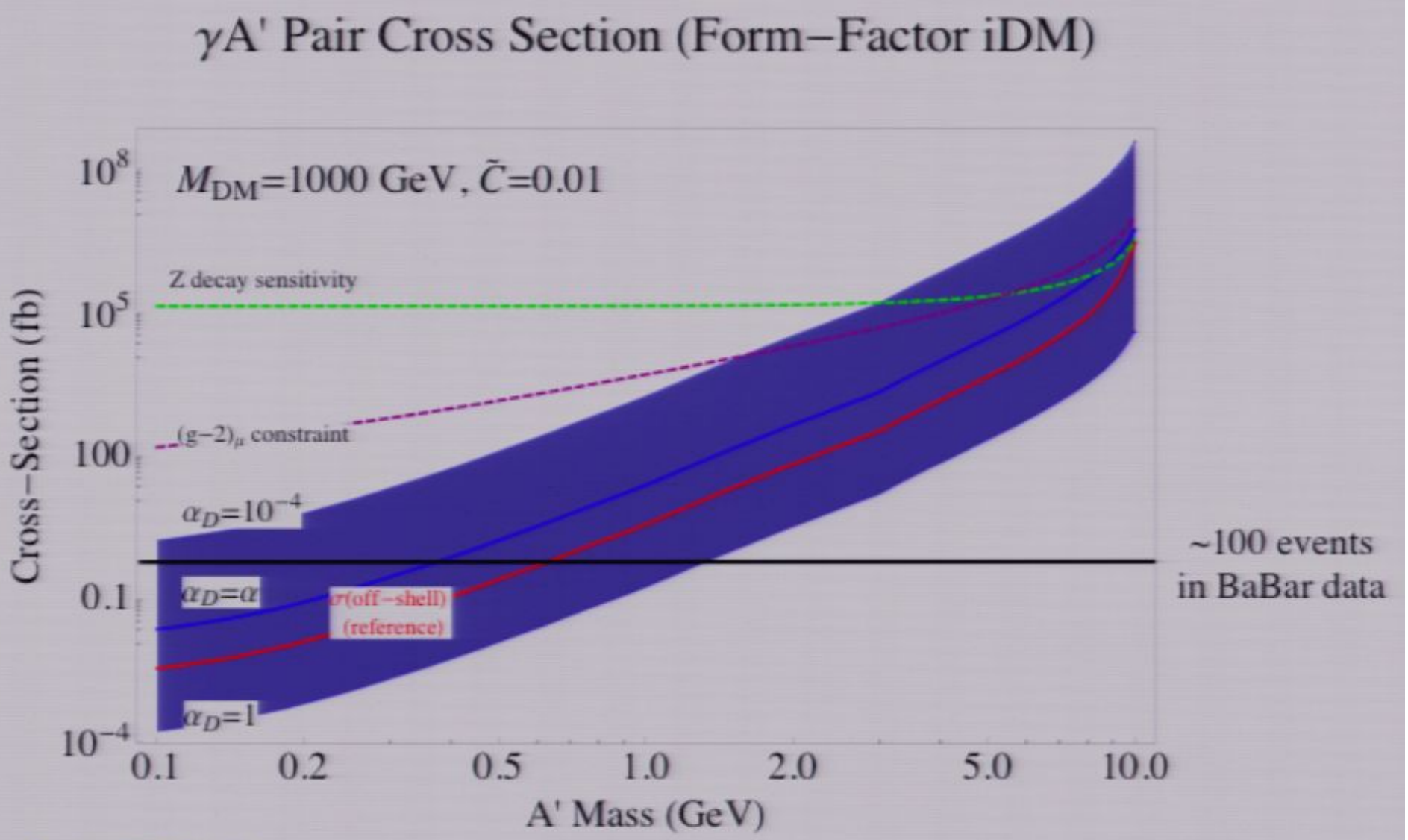
170,000	100,000	50,000	1,000

Missing from numerical comparison:

- accessible mass range
- kinematic acceptance & **visibility** of events

Broad range of searches needed

DAMA-Normalized Production Rates



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BELLE	BaBar	KLOE	CLEO-C	BES III
$\frac{725\ \text{fb}^{-1}}{(10.6\ \text{GeV})^2}$	$\frac{430\ \text{fb}^{-1}}{(10.6\ \text{GeV})^2}$	$\frac{2.5\ \text{fb}^{-1}}{(1\ \text{GeV})^2}$	$\frac{\approx 1\ \text{fb}^{-1}}{(4\ \text{GeV})^2}$	$\frac{??\ \text{fb}^{-1}}{(4\ \text{GeV})^2}$

No. of events for $\alpha_D = \alpha$, $\epsilon = 10^{-2}$ (approx):

170,000	100,000	50,000	1,000

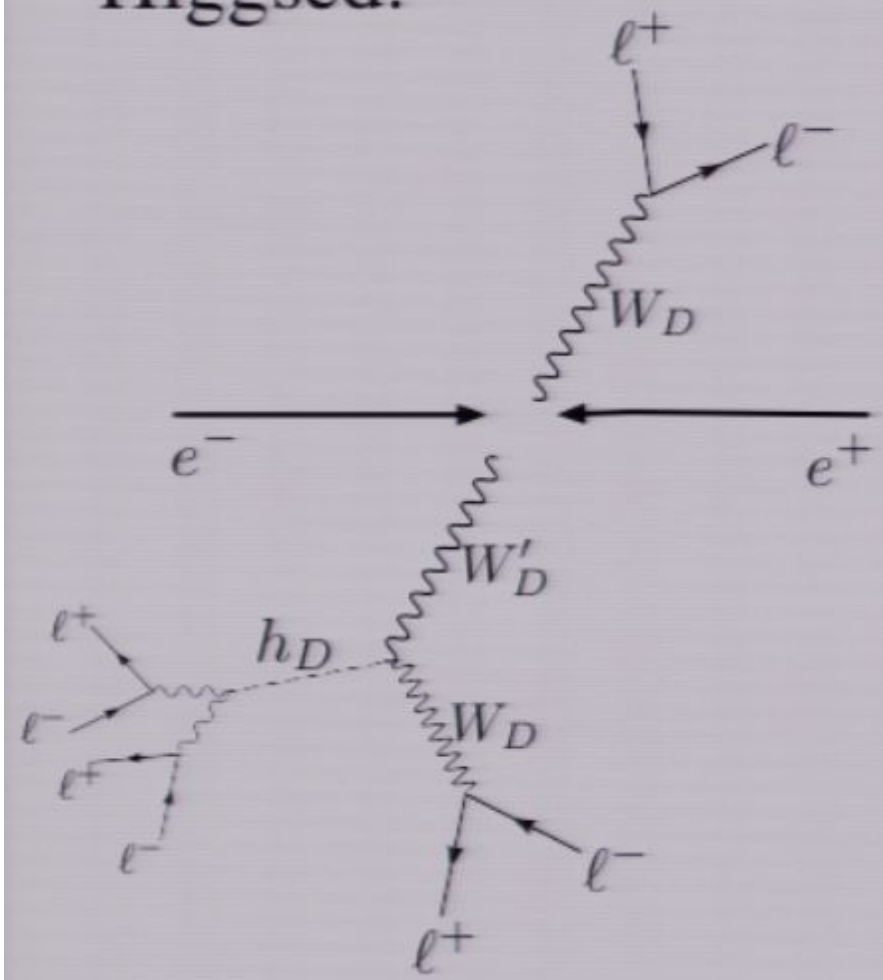
Missing from numerical comparison:

- accessible mass range
- kinematic acceptance & **visibility** of events

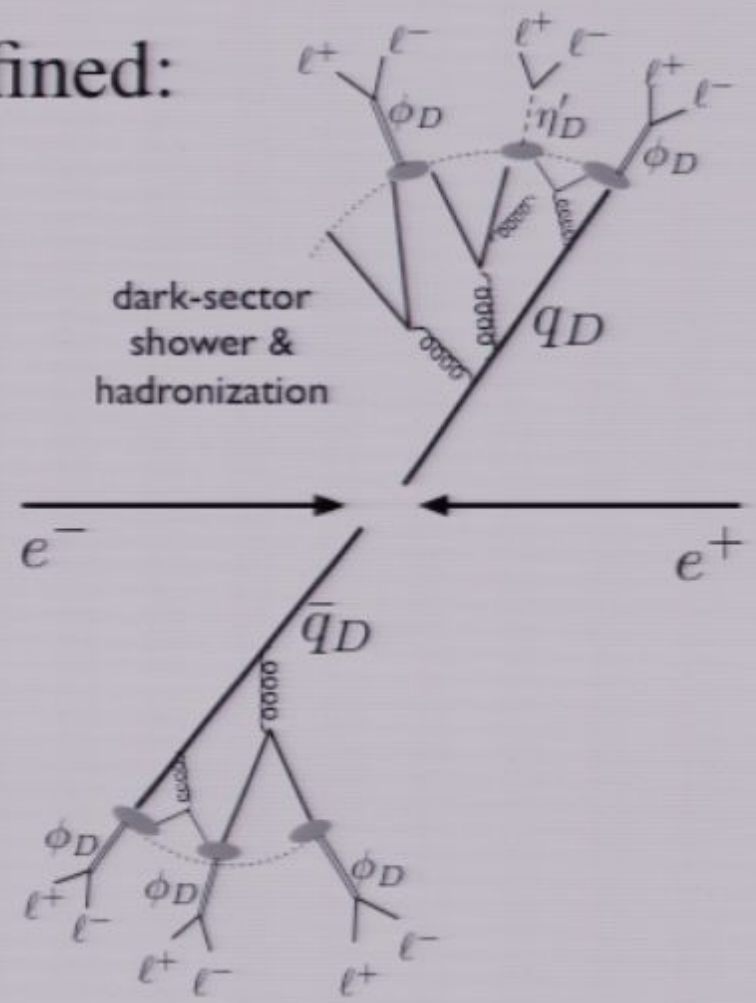
Broad range of searches needed

Higgsed/Confined Dark Sector Signatures

Higgsed:



Confined:

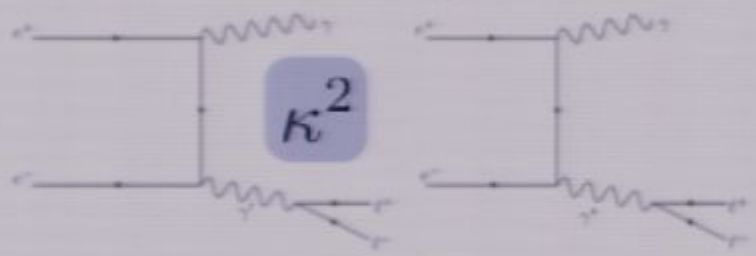


[see: Essig, PS, Toro; Batell, Pospelov, Ritz]

Wide variety of multi-lepton final states

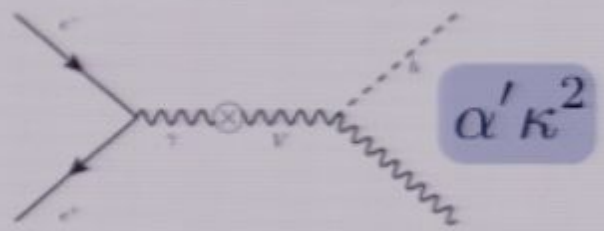
Final States (direct production)

- "Generic": $e^+e^- \to \gamma l^+ l^-$



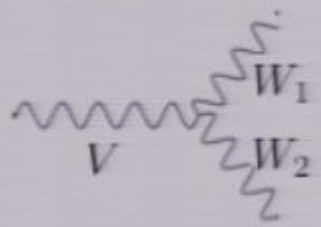
- BaBar [via Υ-decay search, H. Kim] ✓?
- Belle [Y. Kwon, J. Rorie]
- BES-III [H. Li, Y. Zheng]
- KLOE [F. Bossi]

- "Generic + higgs": $e^+e^- \longrightarrow Vh' \longrightarrow 6l \;\; (or\; 2l + \not{E})$



- not yet!
  [interest from BaBar, Belle, BES-III, KLOE]

- "Nonabelian": $e^+e^- \to V^* \to 4l$



- BaBar [4l, M. Graham] ✓

Also: higher multiplicity (confining), 4l + $\not{E}_T$, ...

8

From e+e- working group summary (SLAC Dark Forces workshop)

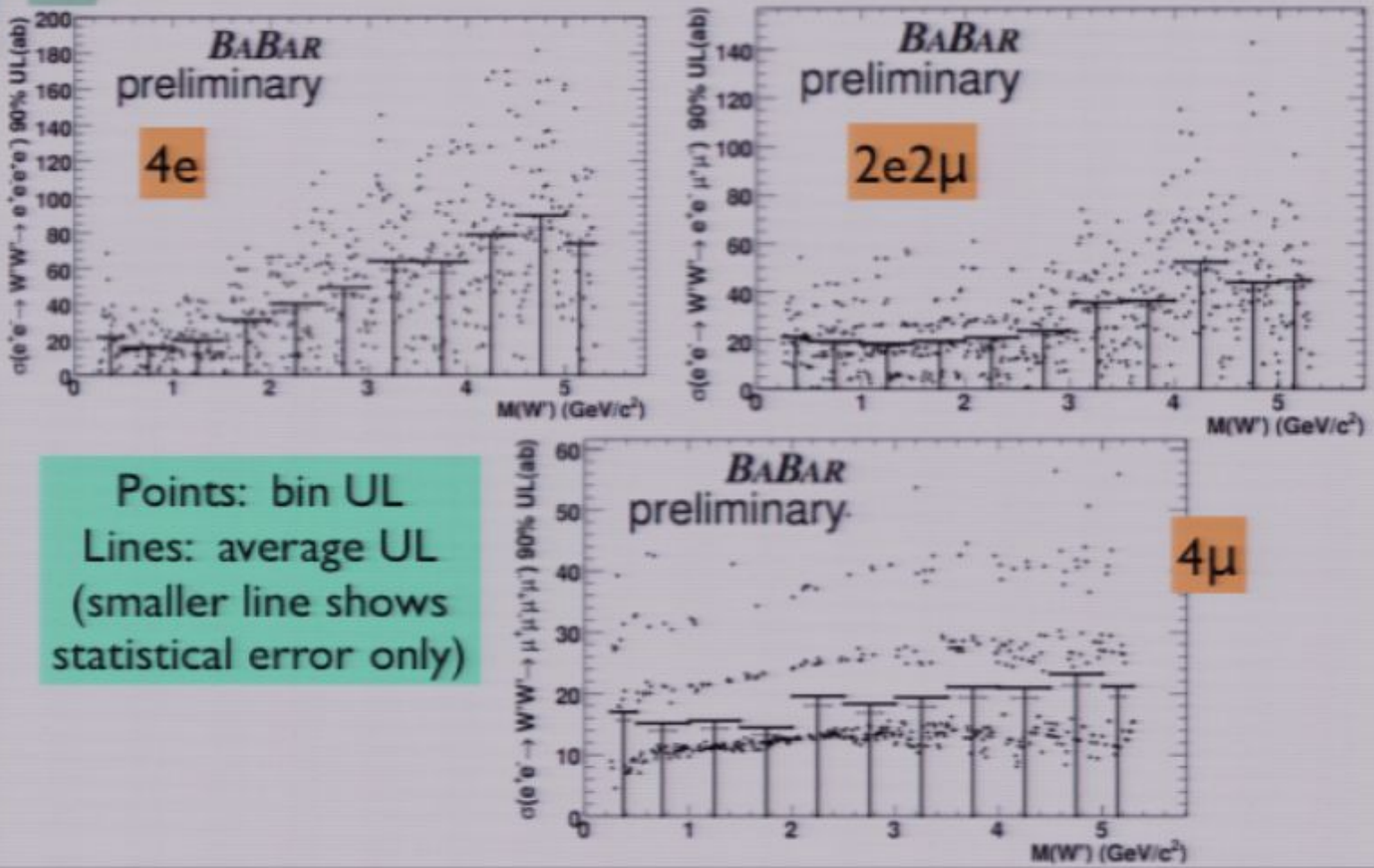
Search for narrow resonance pairs in $e^+e^- \to 4$ lepton @ BaBar

Matt Graham, SLAC
September 25, 2009

Sensitivity to $\epsilon \sim 10^{-4}$

[M. Graham, arXiv:0908.2821]

Cross Section Upper Limits



Points: bin UL
Lines: average UL
(smaller line shows statistical error only)

Rare Meson Decays

Existing data sets provide sensitivity to $\epsilon \sim 10^{-3}$

$X \to YU$	n_X	$m_X - m_Y$ (MeV)	BR($X \to Y + \gamma$)	BR($X \to Y + \ell^+\ell^-$)	$\epsilon \leq$
$\eta \to \gamma U$	$n_\eta \sim 10^7$	547	$2 \times 39.8\%$	6×10^{-4}	2×10^{-3}
$\omega \to \pi^0 U$	$n_\omega \sim 10^7$	648	8.9%	7.7×10^{-4}	5×10^{-3}
$\phi \to \eta U$	$n_\phi \sim 10^{10}$	472	1.3%	1.15×10^{-4}	1×10^{-3}
$K_L^0 \to \gamma U$	$n_{K_L^0} \sim 10^{11}$	497	$2 \times (5.5 \times 10^{-4})$	9.5×10^{-6}	2×10^{-3}
$K^+ \to \pi^+ U$	$n_{K^+} \sim 10^{10}$	354	-	2.88×10^{-7}	7×10^{-3}
$K^+ \to \mu^+ \nu U$	$n_{K^+} \sim 10^{10}$	392	6.2×10^{-3}	7×10^{-8a}	2×10^{-3}
$K^+ \to e^+ \nu U$	$n_{K^+} \sim 10^{10}$	496	1.5×10^{-5}	2.5×10^{-8}	7×10^{-3}

[Reece & Wang '09]

Good sensitivity in additional channels:

$\pi \to ee\gamma$ Sensitivity to $\epsilon \lesssim 10^{-3}$ (Babar, Belle, kTeV)

$J/\psi \to 6l$ Sensitivity to $\epsilon \sim 10^{-4} - 10^{-3}$ (BES-III in 1 year)

Searches ongoing...

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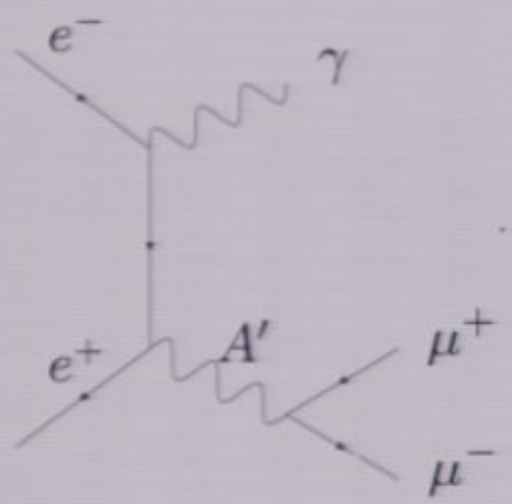
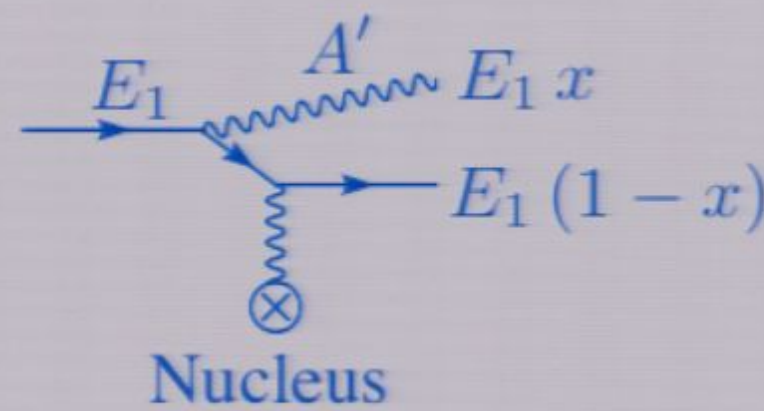
Searches ongoing...

Dark Forces at the GeV Scale

- Theory of New Vector Bosons (and hints from dark matter)
- e+e- Collider Searches (Babar, Belle, KLOE)
- Fixed-Target Experiments (e.g. @ JLab)

Collider vs. Fixed-Target





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

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

O(few) ab^{-1} per decade

O(few) ab^{-1} per day

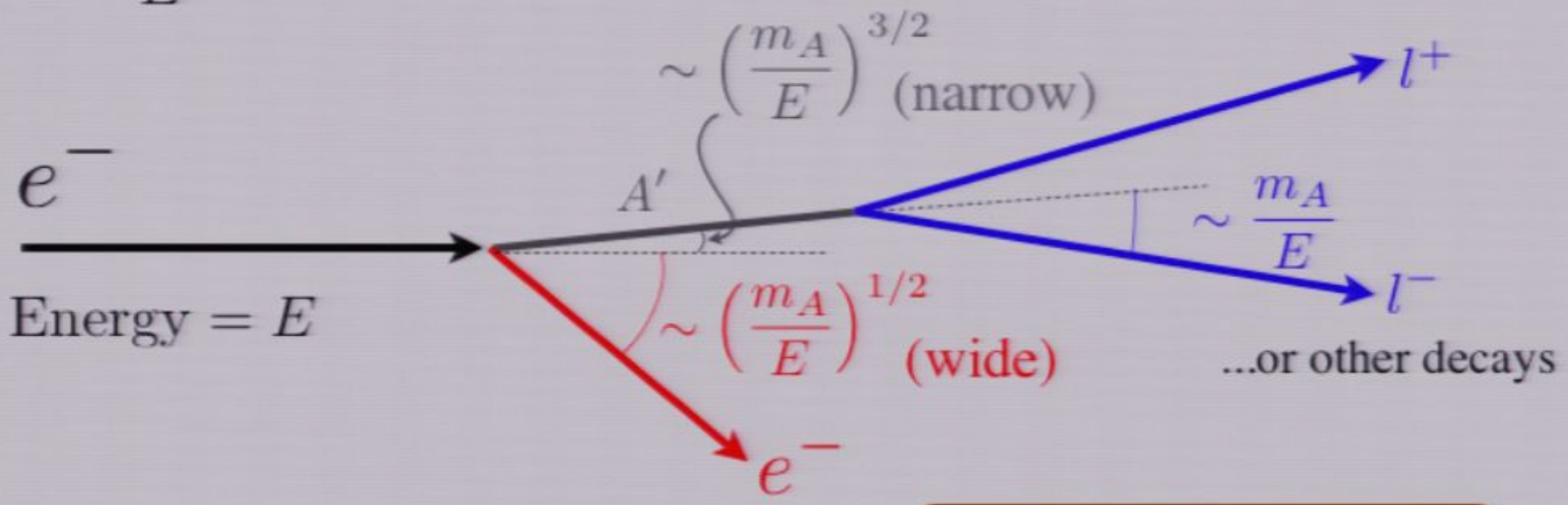
Unique Fixed-Target Kinematics

[see: Bjorken, Essig, PS, Toro]

$$\frac{d\sigma}{dx} \propto \frac{\alpha^3}{\pi} \frac{\epsilon^2}{m_e^2 \cdot x + m_A^2(1-x)/x}$$

$$x = \frac{E_A}{E}$$

Kinematics **very different** from massless photon bremsstrahlung



Heavier product (here A') takes most of beam energy

$$E_A \sim E - m_A$$
$$E_e \sim m_A$$

Lifetime

A' decays directly back to Standard Model:

$$\gamma c\tau \approx 1 \text{ mm } (\gamma/10)\ (10^{-4}/\epsilon)^2\ (100\text{MeV}/m_{A'})$$

A' decay to dark scalars: $h_D \to l^+ l^-$ $\quad l = e, \mu, \pi$

$$\gamma c\tau \approx 2 \times 10^8 \text{ cm } (\gamma/10)\ (\alpha/\alpha_D) \times (10^{-3}/\epsilon)^4\ (m_{A'}/\text{GeV})^2\ (\text{GeV}/m_{h_D})$$

...etc

A' production vs. decay product lifetime determine existing constraints and search strategies

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[see: Bjorken, Essig, PS, Toro]

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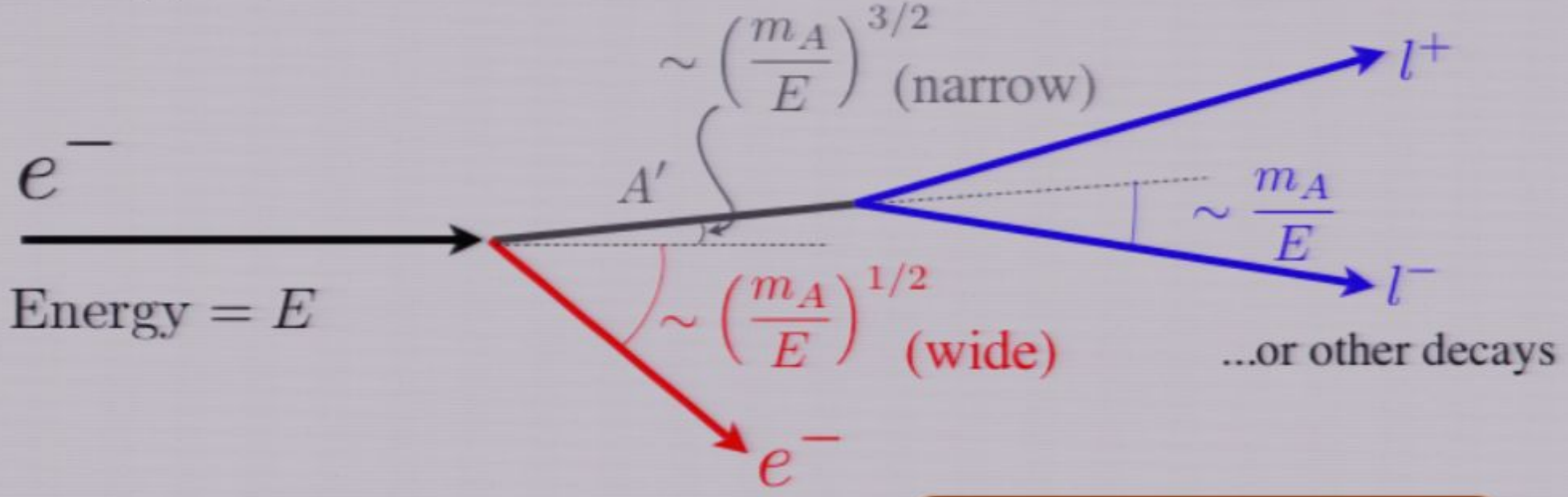

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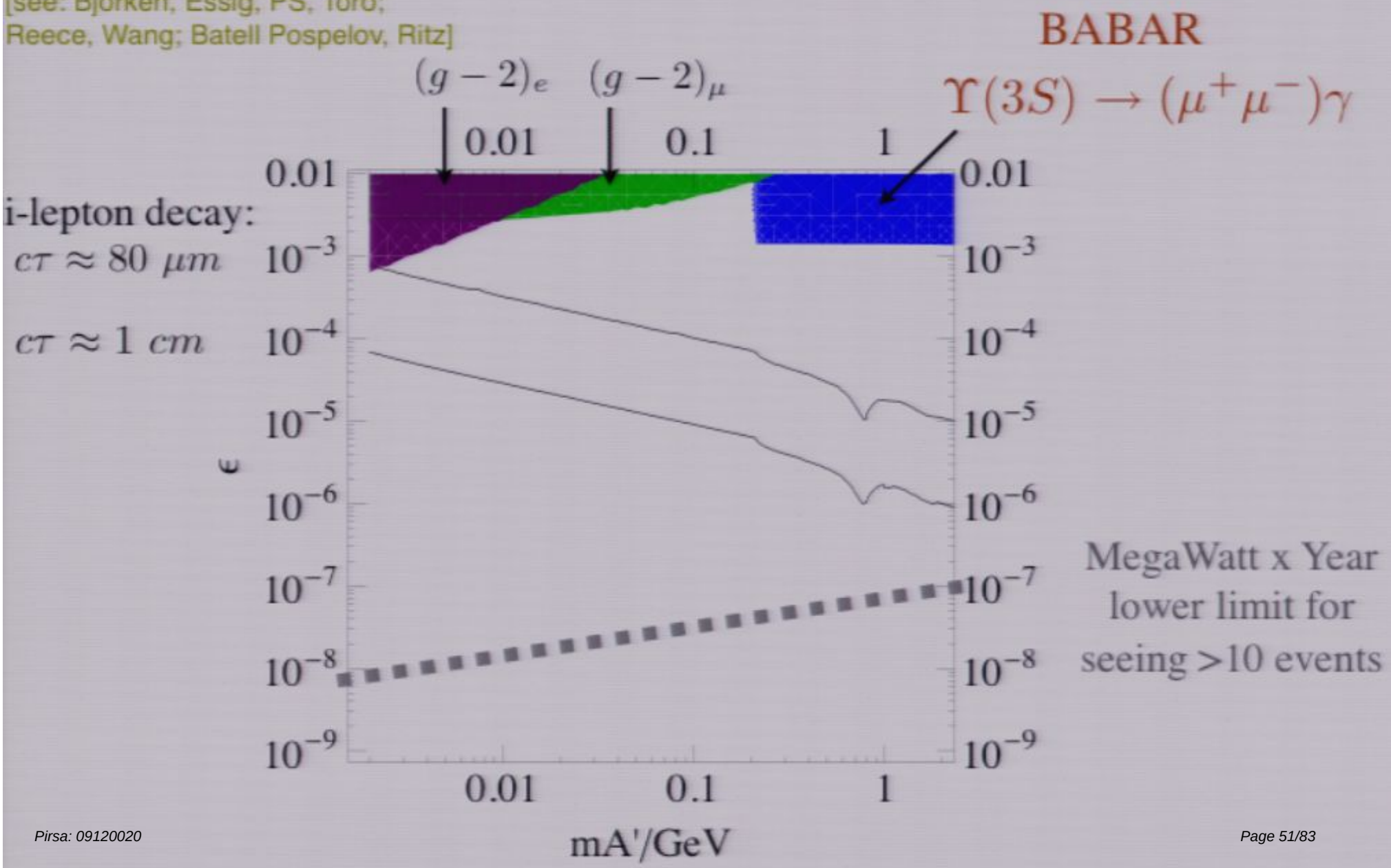
...etc

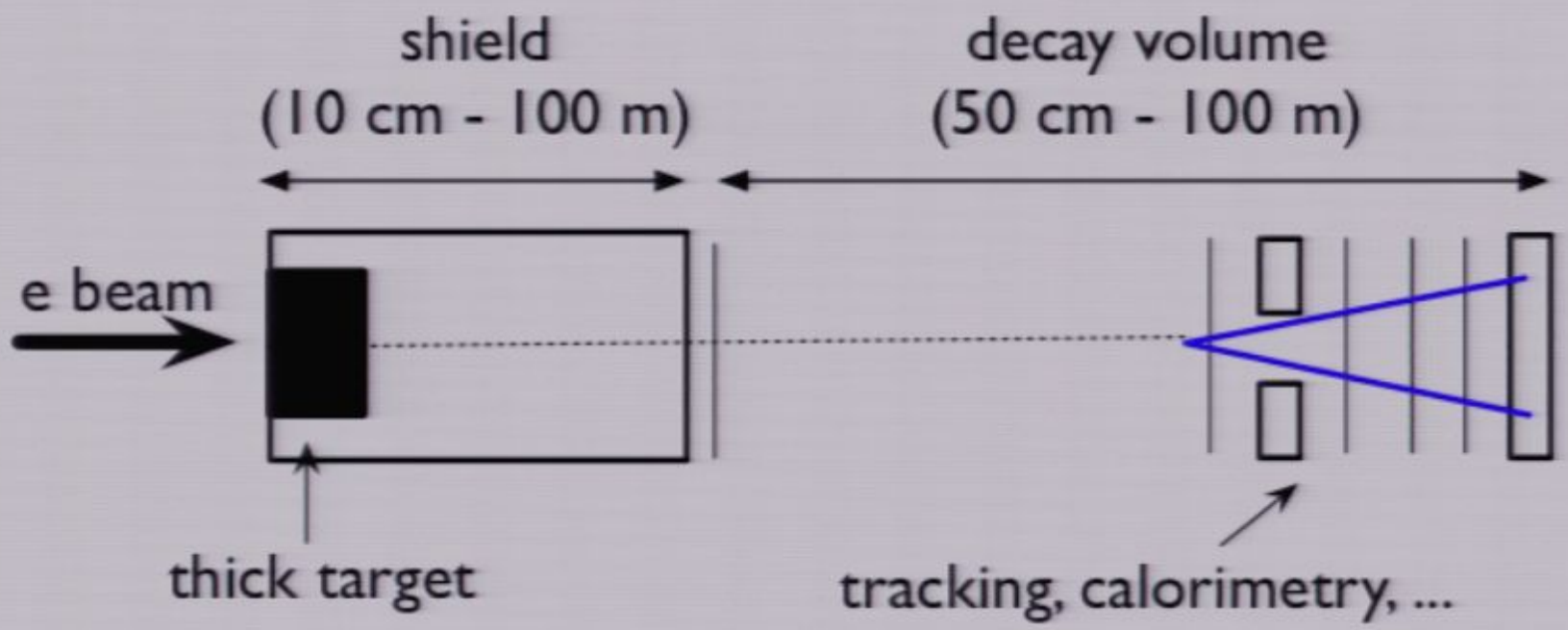
A' production vs. decay product lifetime determine existing constraints and search strategies

Fixed-Target Territory

[see: Bjorken, Essig, PS, Toro; Reece, Wang; Batell Pospelov, Ritz]



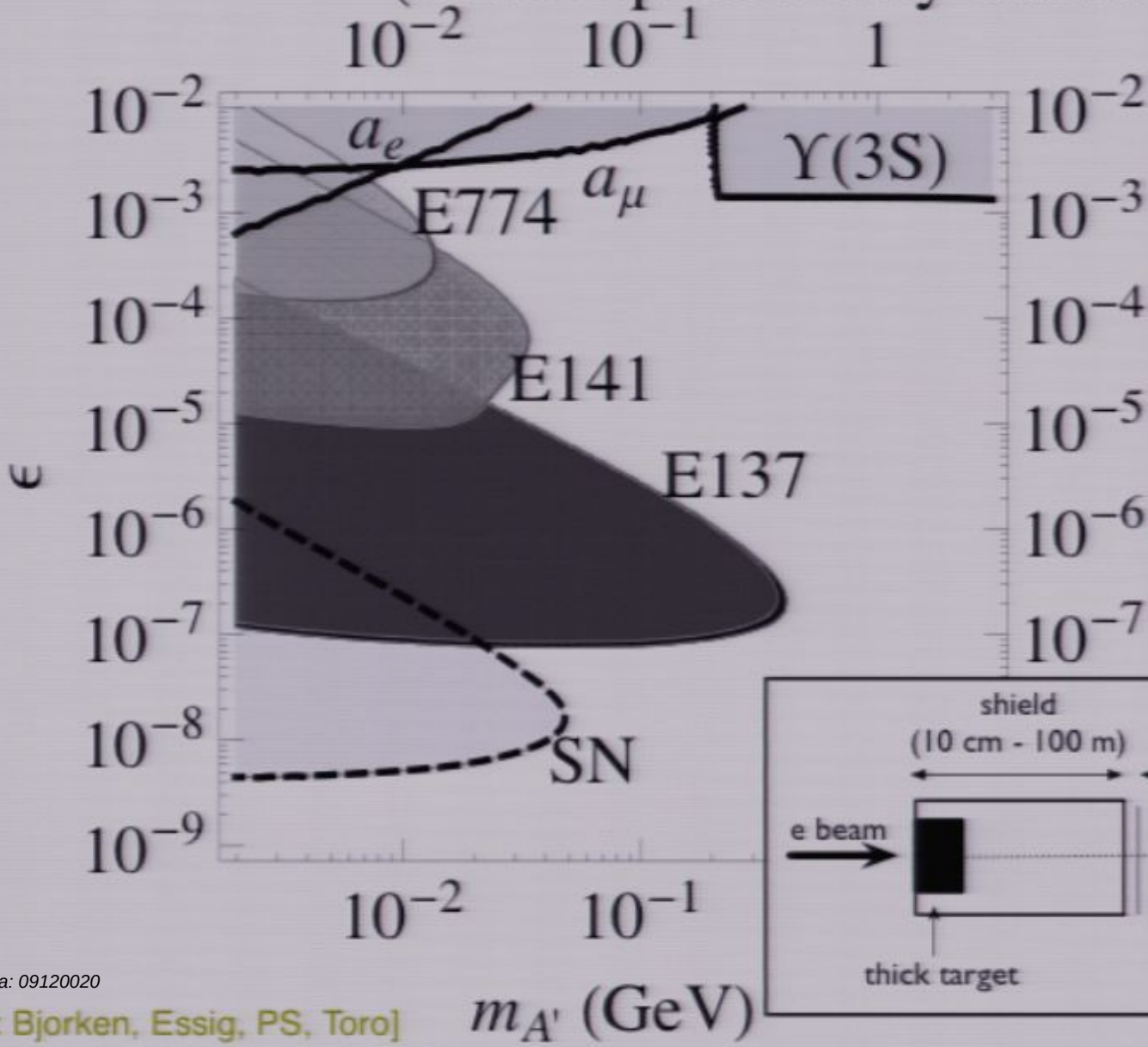
Beam Dump Experiments



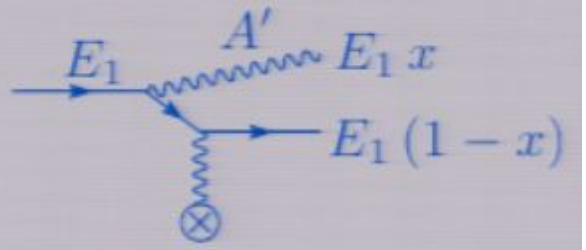
SLAC E137:	10^{20} e^- (30 C)	at 20 GeV,	200m shield
SLAC E141:	10^{16} e^-	at 9 GeV,	12 cm W target
FNAL E774:	10^{10} e^-	at 275 GeV,	20 cm W target

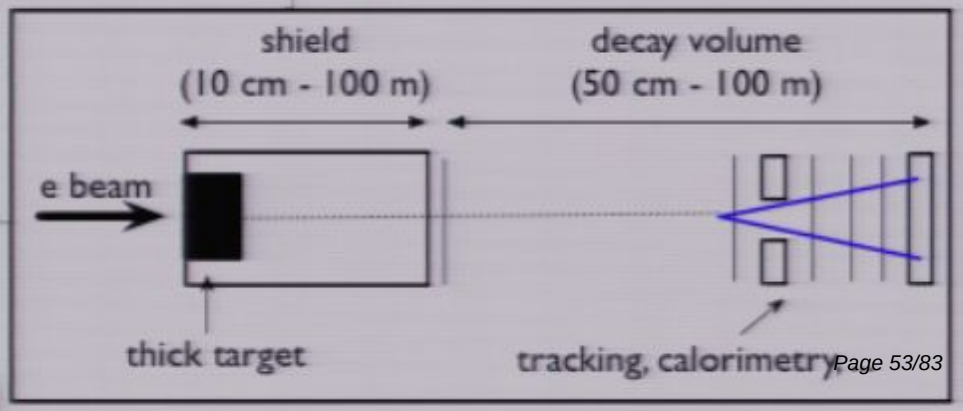
Past Beam Dump Limits

(A' di-lepton decay modes)



Production Mode:





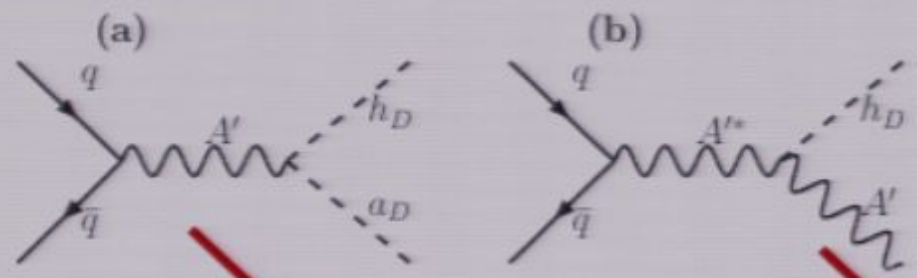
[see: Bjorken, Essig, PS, Toro]

Past Beam Dump Limits

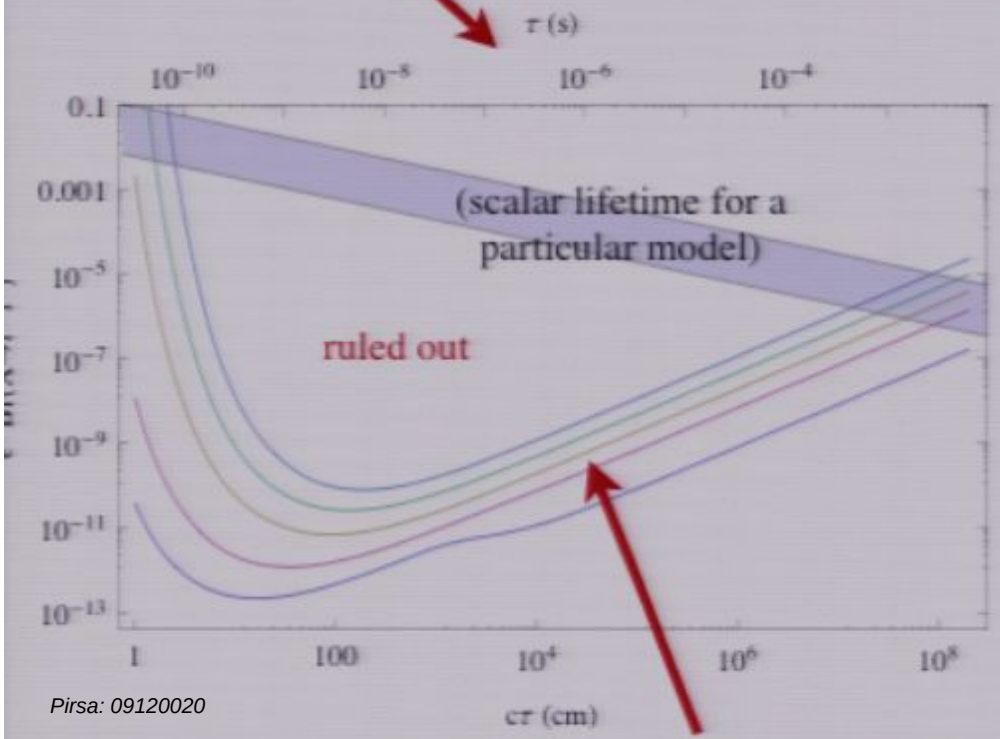
[see: PS, Yavin, Toro;
Batell, Pospelov, Ritz, Shang]

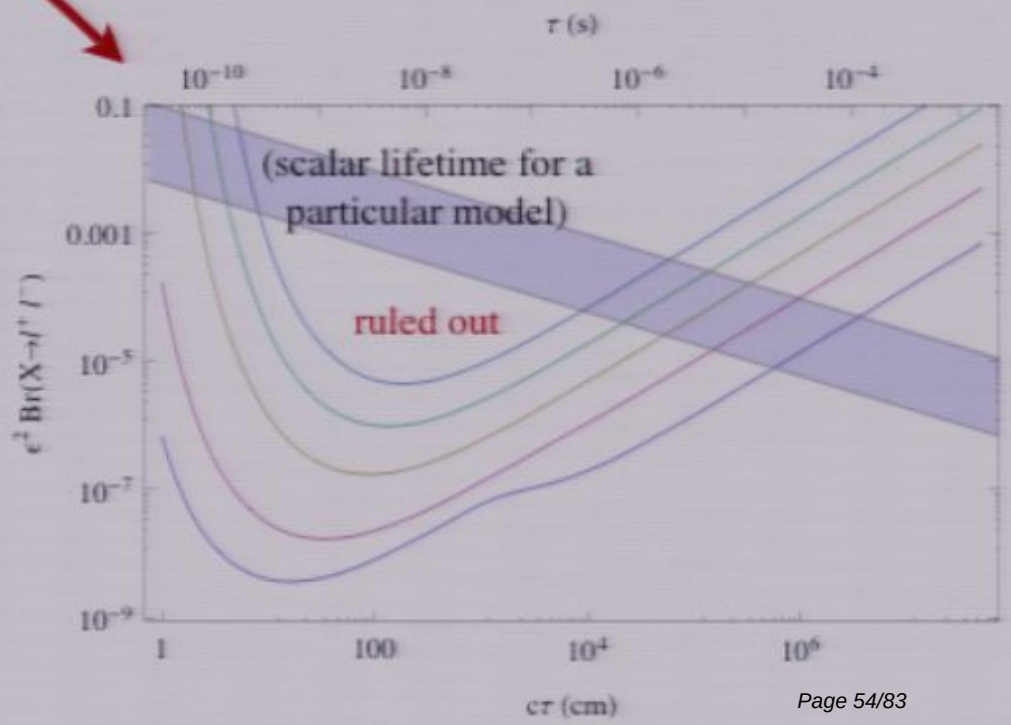
(scalar decay modes)

Production Mode:



CHARM axion search:
proton beam dump,
~1 C at 400 GeV



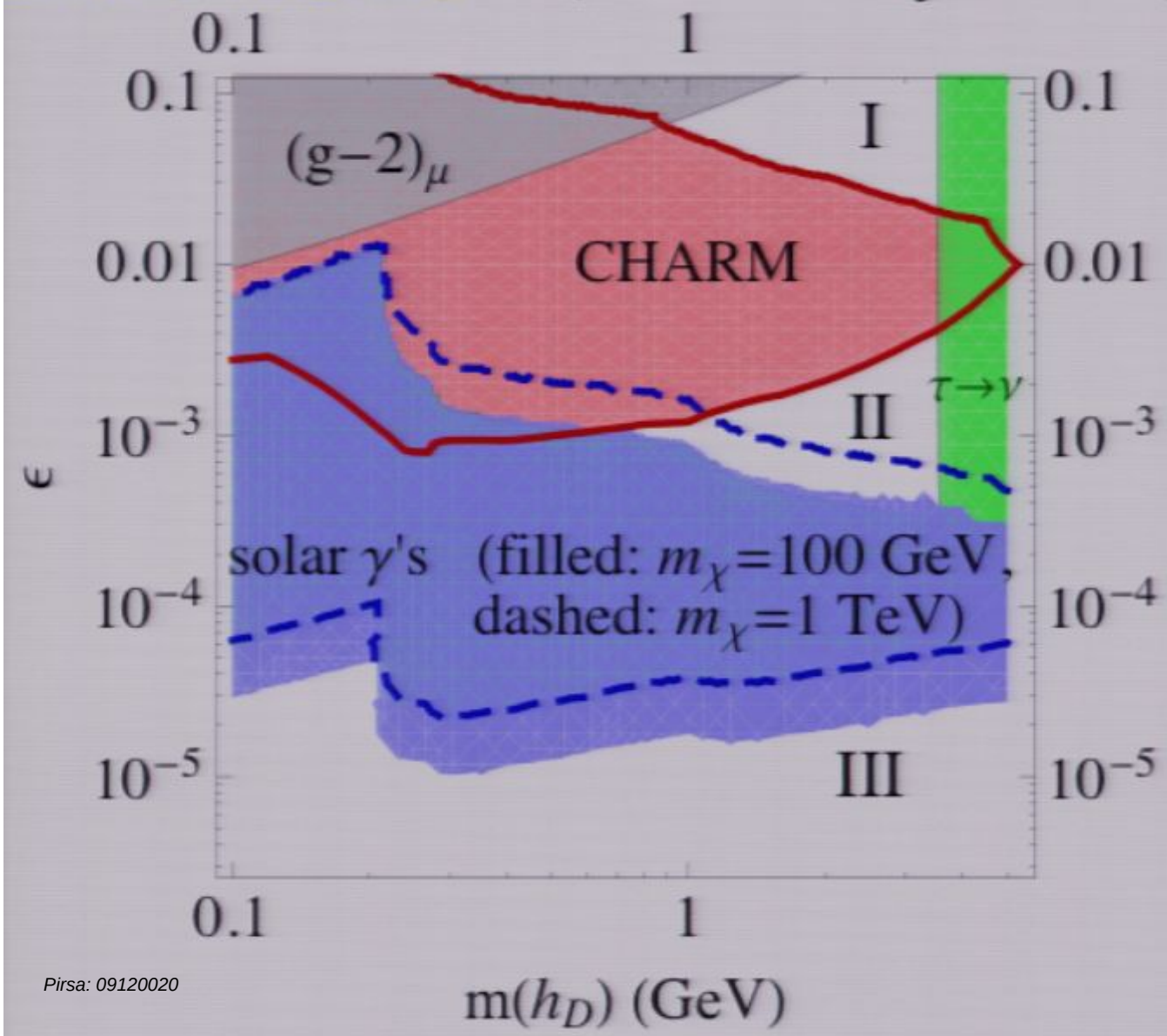


curves from bottom to top: $m_{A'} = 0.6, 1, 2, 3, 4$ GeV

Past Beam Dump Limits

[see: PS, Yavin, Toro;
Batell, Pospelov, Ritz, Shang]

(scalar decay modes)



Strong laboratory constraints in the DAMA/LIBRA region of interest

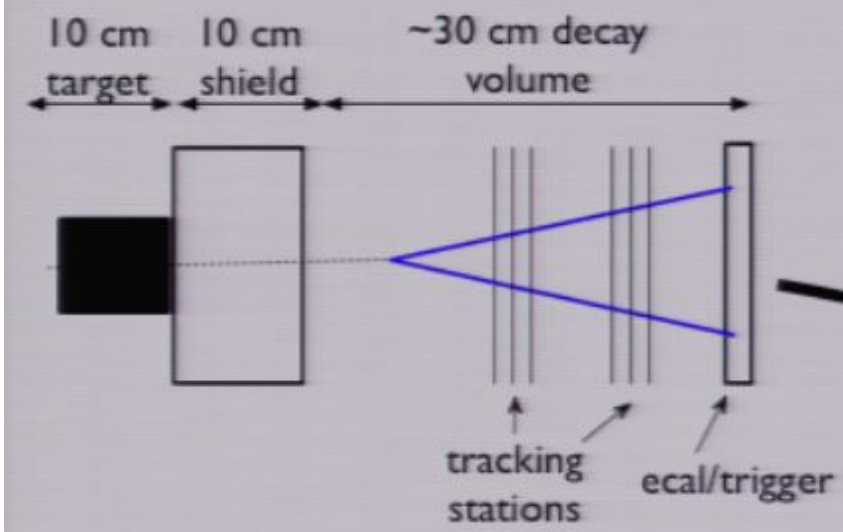
If dark matter can annihilate into dark sector states, then there are constraints from solar capture of dark matter

New Experiments?

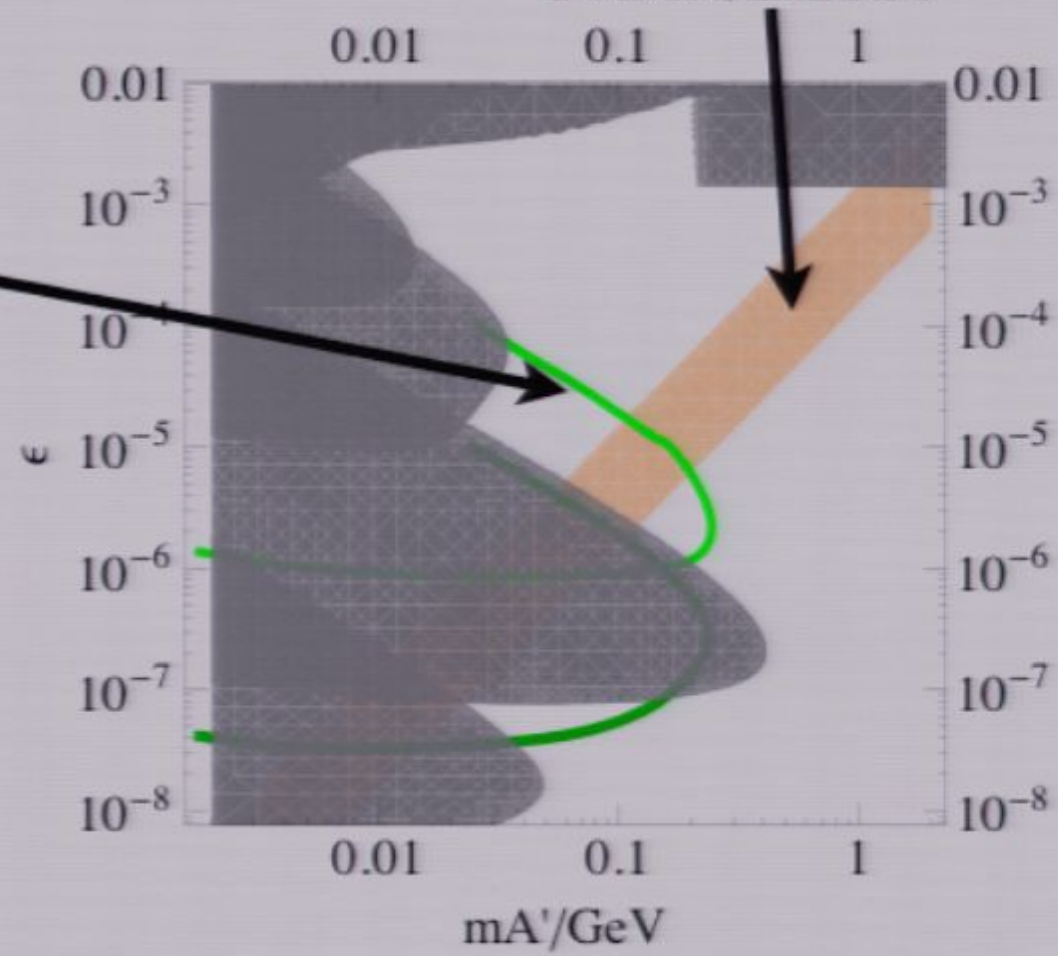
Focus on di-lepton (electron, muon, pion) parameter space given existing constraints on non-direct dark sector decay modes

New Beam Dump Reach

Di-lepton
decay channel



"D-term" line – also explains
DAMA/LIBRA



Good Beams:

- FEL at JLab
- SLAC
- Duke
- ELSA, Mainzer Mikrotron (MAMI), Max-lab

[see: Bjorken, Essig, PS, Toro]

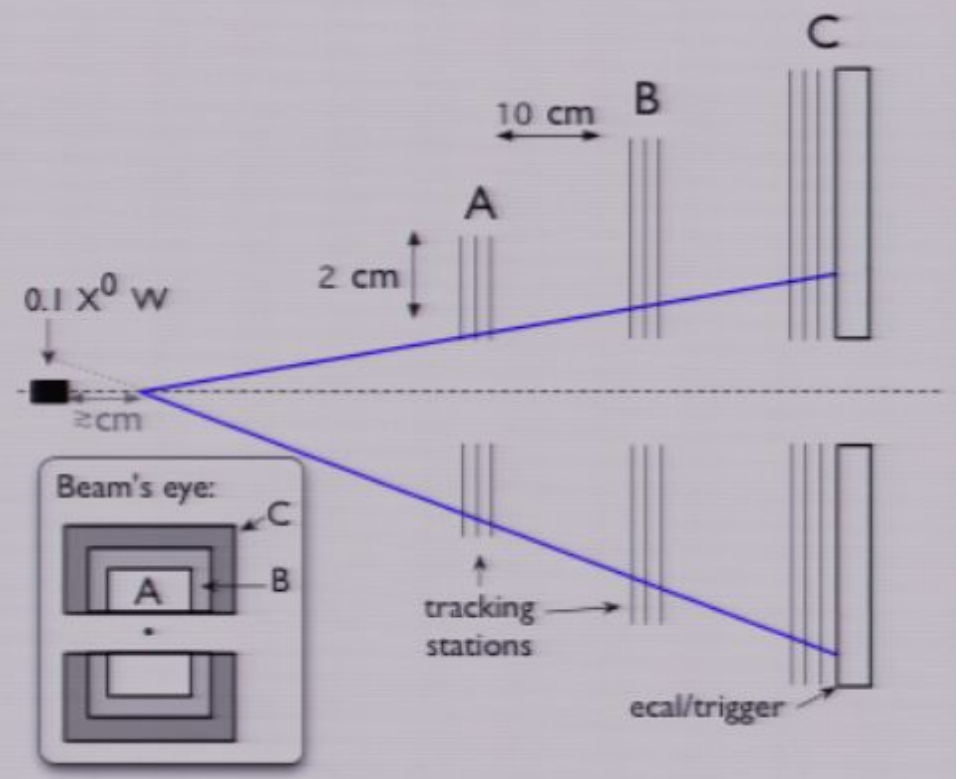
Beyond Beam Dumps

- Electron beam dump experiments set strongest bounds.
- To see higher ϵ, m_A (best DM region) need thinner target – now beam gets through, too!
  (work hard to keep S/B large, not just stat. significance!)
- Two strategies:
  - Resonance Search
  - Vertex and recoil tagging

Approaches for New Experiments

Features of conceptual design: Two-arm spectrometer

- Very good forward coverage
  (signal production is peaked forward)
- Fast trigger (high event rate)
- Fast detector and continuous beam
  (control coincidence backgrounds)
- 1% or better mass resolution
  (kinematic discrimination)
- Silicon good for fast precision
  tracking (use vertex discrimination)



Small with variable geometry

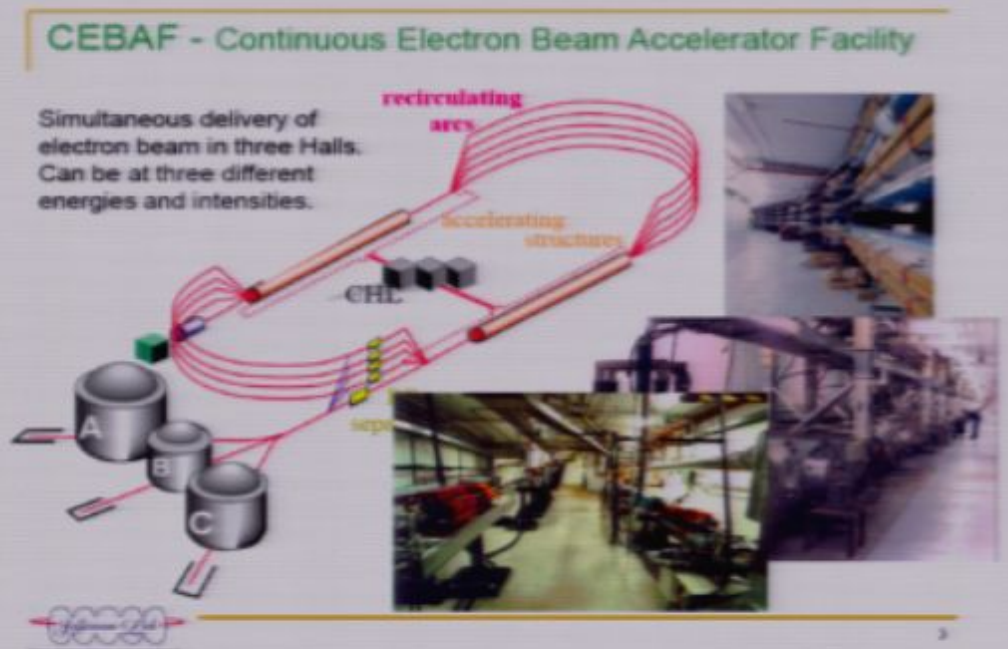
Heavy Photon Search Working Group

SLAC
R. Essig
C. Field
M. Graham
J. Jaros (Chair)
C. Kenney
T. Maruyama
K. Moffeit
A. Odian
R. Partridge
P. Schuster
J. Sheppard
C. Spencer
N. Toro

FNAL
M. Demarteau

JLab
P. Bosted
S. Stepanyan
L. Weinstein
B. Wojtsekhowski

U. Oregon
R. Frey



Developing:

New experiment (parasitic) in JLab Hall B

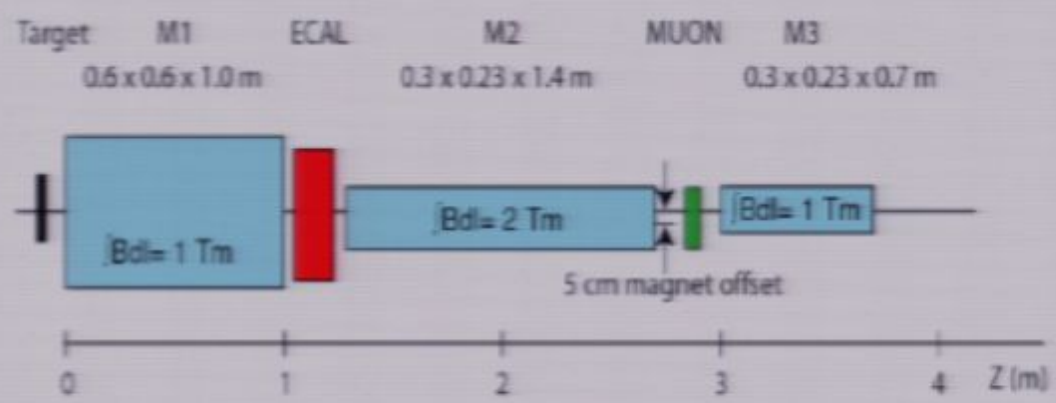
New Parasitic Experiment in JLab Hall B

Introduction
Available beam
JLab Hall B "Photon Dump"
Experimental Apparatus
Simulation
Backgrounds
- Occupancy
- Track multiplicity

Performance
- Acceptance
- Mass resolution
- Vertex resolution

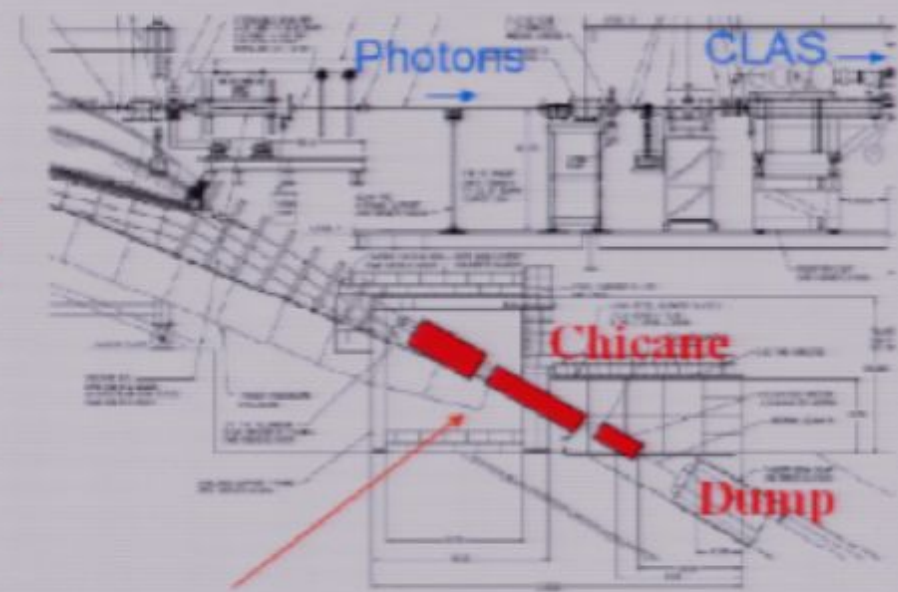
Experimental reach
Conclusions

Experimental Apparatus



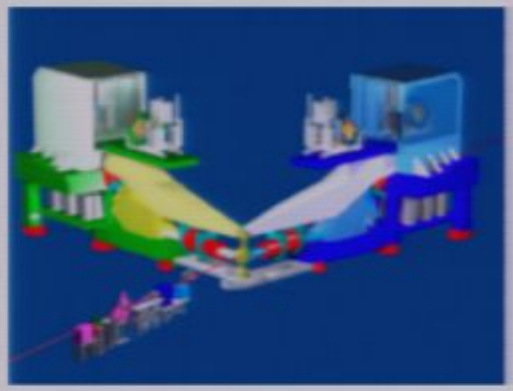
Beam:
- 6 GeV e- 100 nA

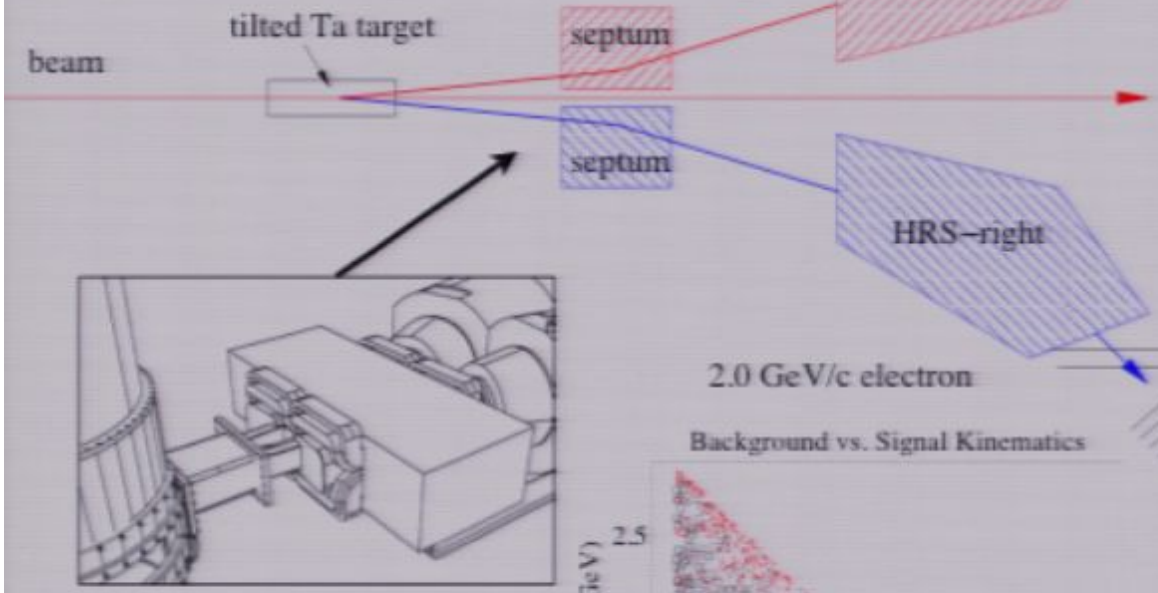
Target:
- 0.01 X_0 Tungsten

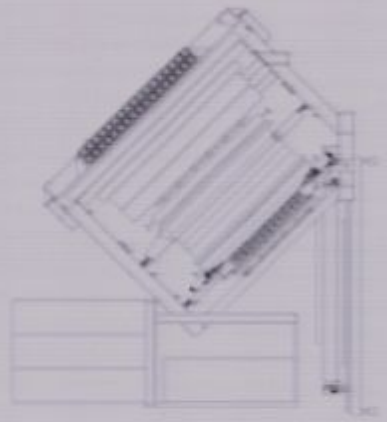


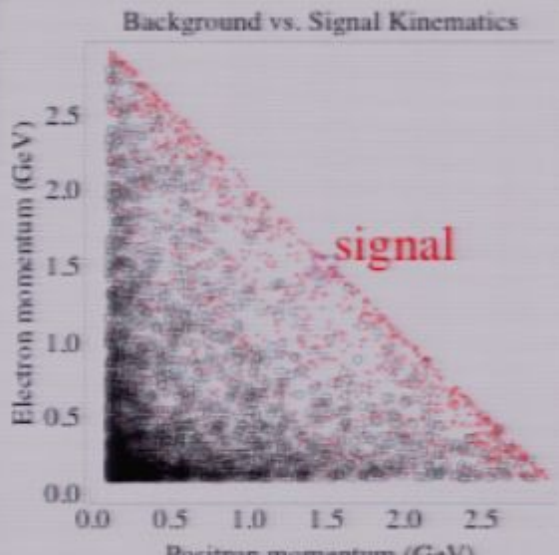
See T. Maruyama Talk at the SLAC Dark Forces Workshop

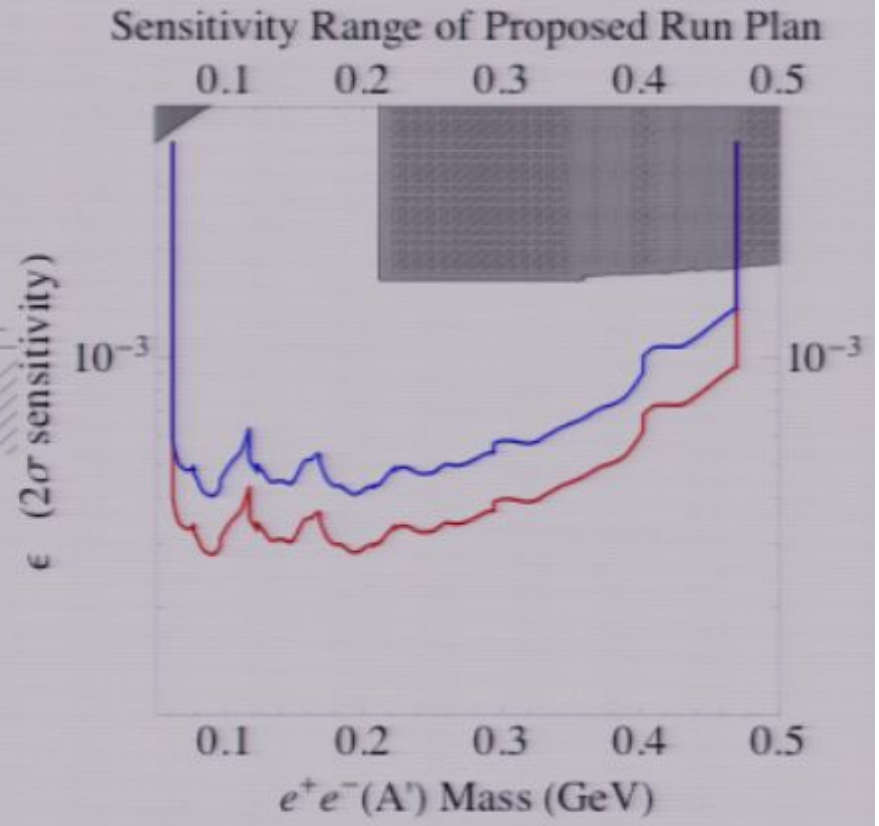
JLab Hall A











$\epsilon_{sens} \sim (2) \times 10^{-4}$

for the final reach

Proposal by:

R. Essig, PS

N. Toro,

B. Wojtsekhowski

New Parasitic Experiment in JLab Hall B

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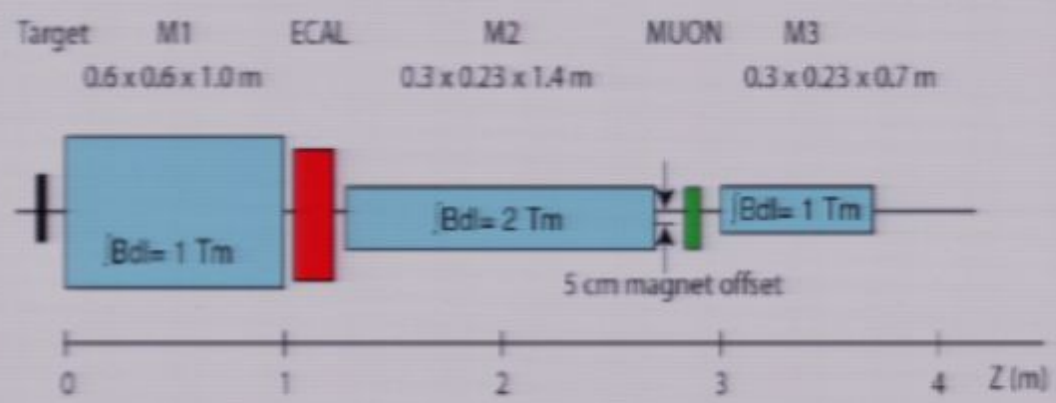

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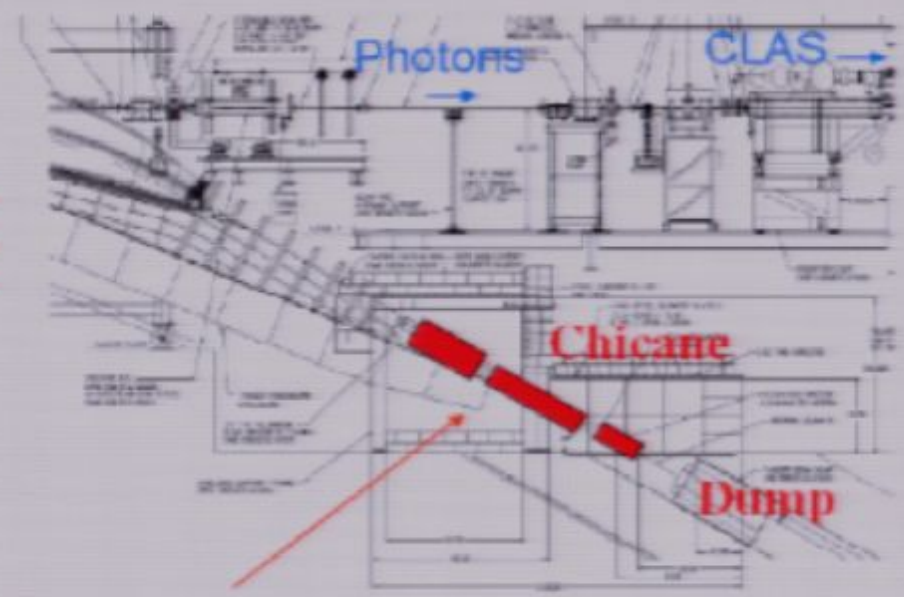
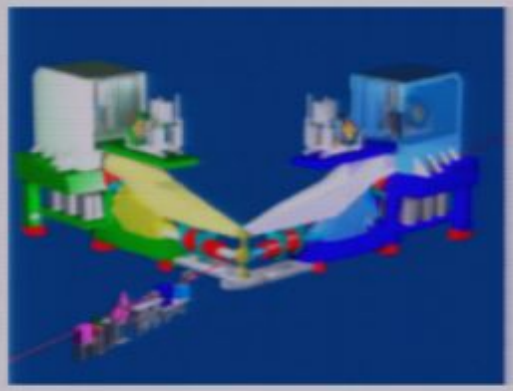
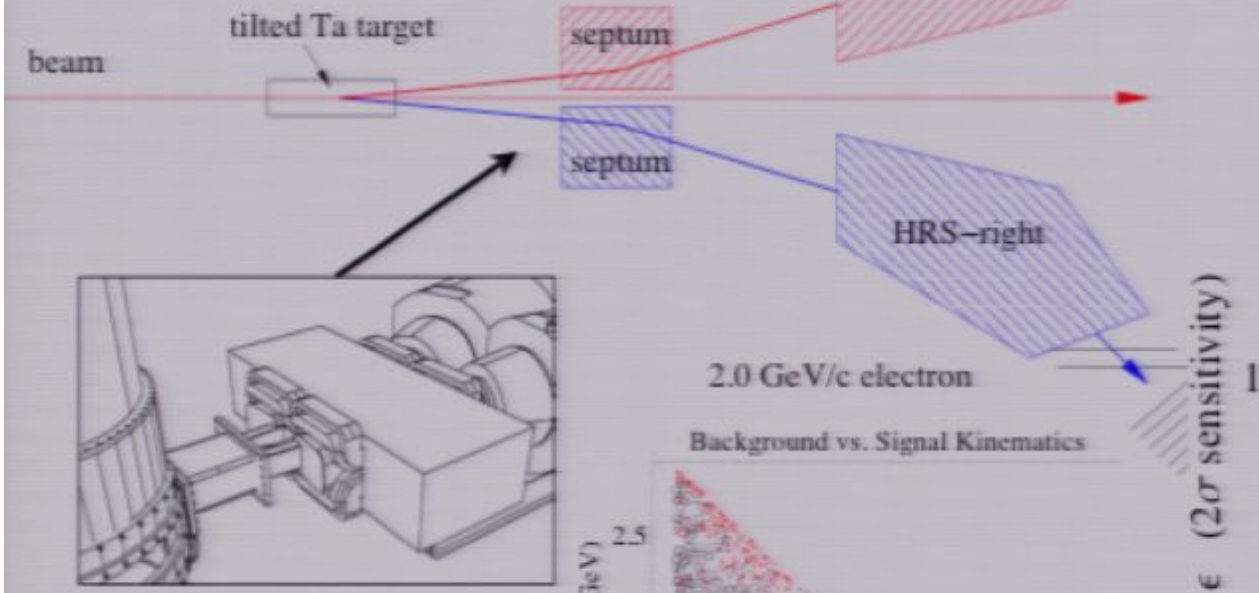
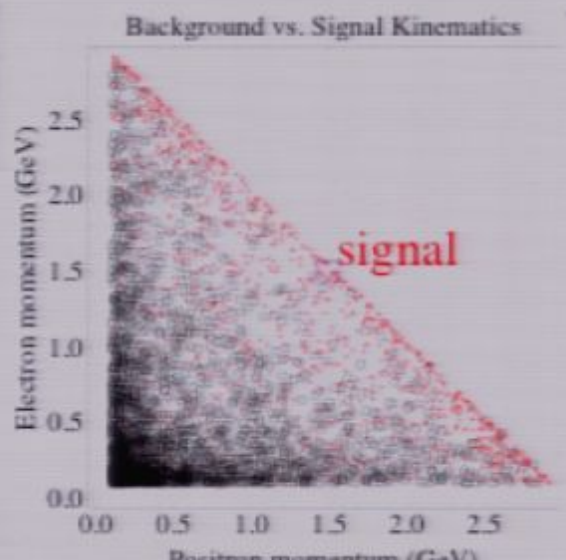


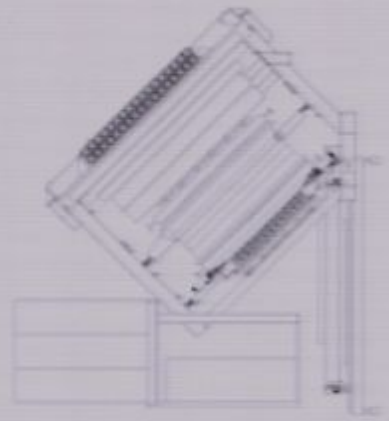
See T. Maruyama Talk at the SLAC Dark Forces Workshop

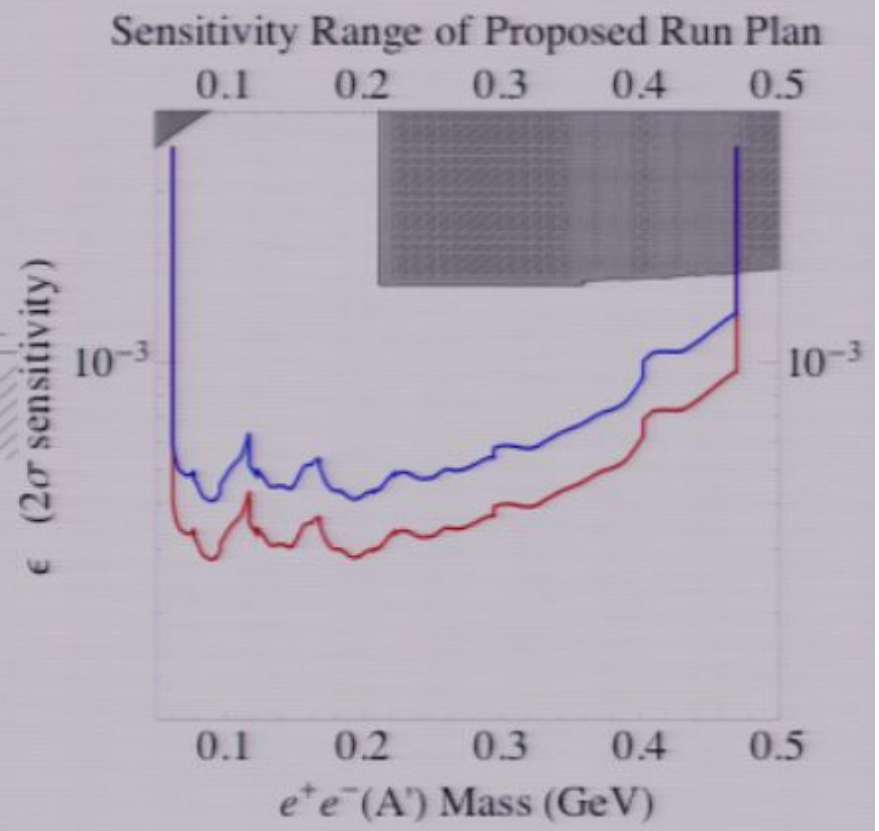
JLab Hall A











$\epsilon_{sens} \sim (2) \times 10^{-4}$

for the final reach

Proposal by:

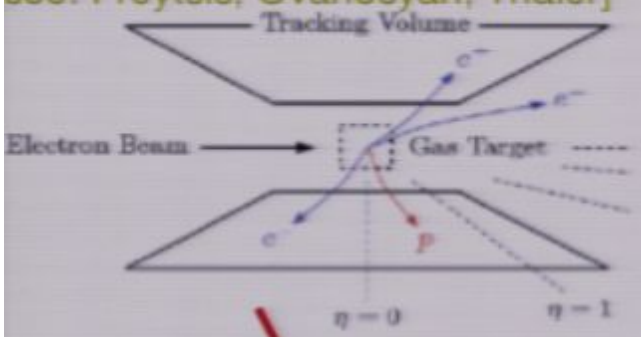
R. Essig, PS

N. Toro,

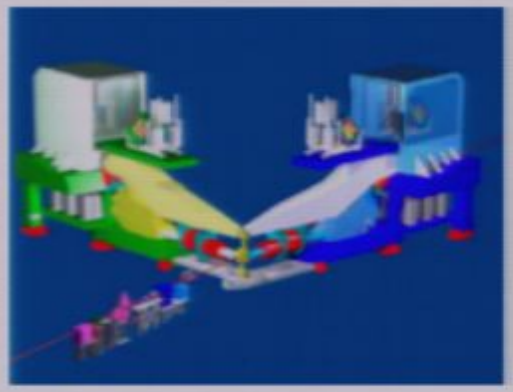
B. Wojtsekhowski

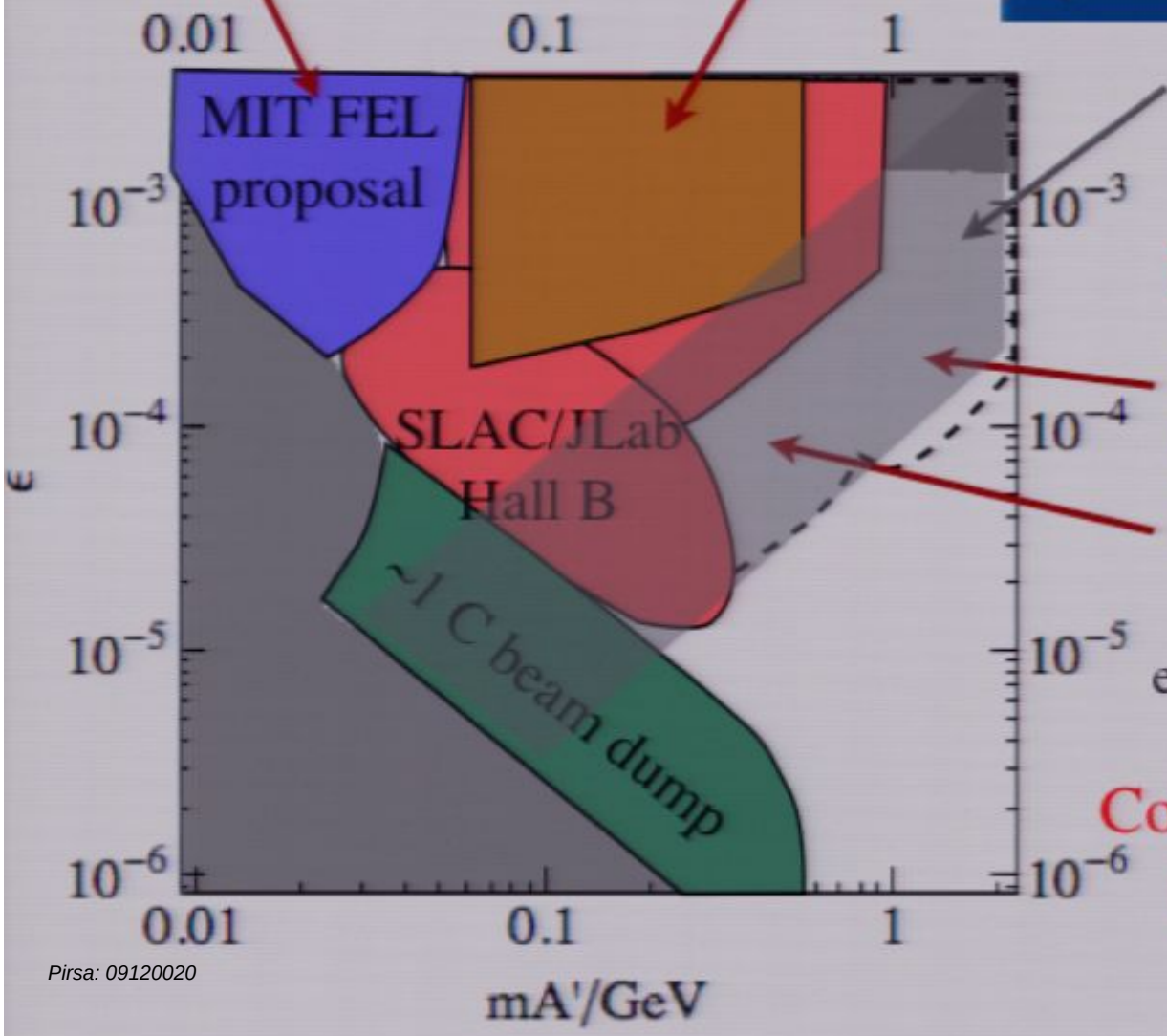
A Fixed-Target Experimental Program to Search for New Gauge Interactions

see: Freytsis, Ovanesyan, Thaler]



JLab
Hall A
(24 days)





DAMA/LIBRA
region of interest

Improvements:

Sensitivity with existing beams but better acceptance

Pixel tracking extends reach

Final version of SLAC/JLab experiment may have extended reach

Complementary coverage from B-factories: higher mass, multi-lepton channels

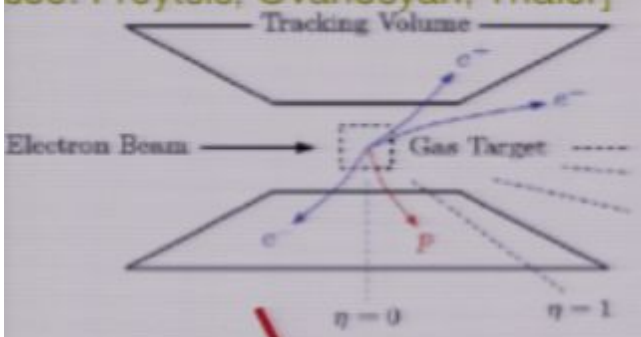
Summary

- Dark forces are an intriguing possibility, well-motivated by existing data
- Laboratory tests are crucial and complementary to astro/direct-detection hints and upcoming data

- Broad array of experimental investigation is possible
- Sensitivity to many decades in mass and cross section with existing data and new small-scale experiments

New searches and experiments on ~year timescale!

see: Freytsis, Ovanesyan, Thaler]



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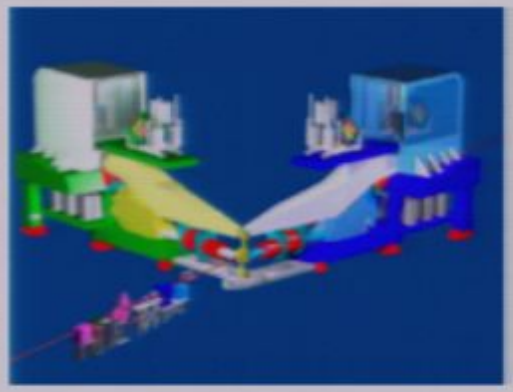

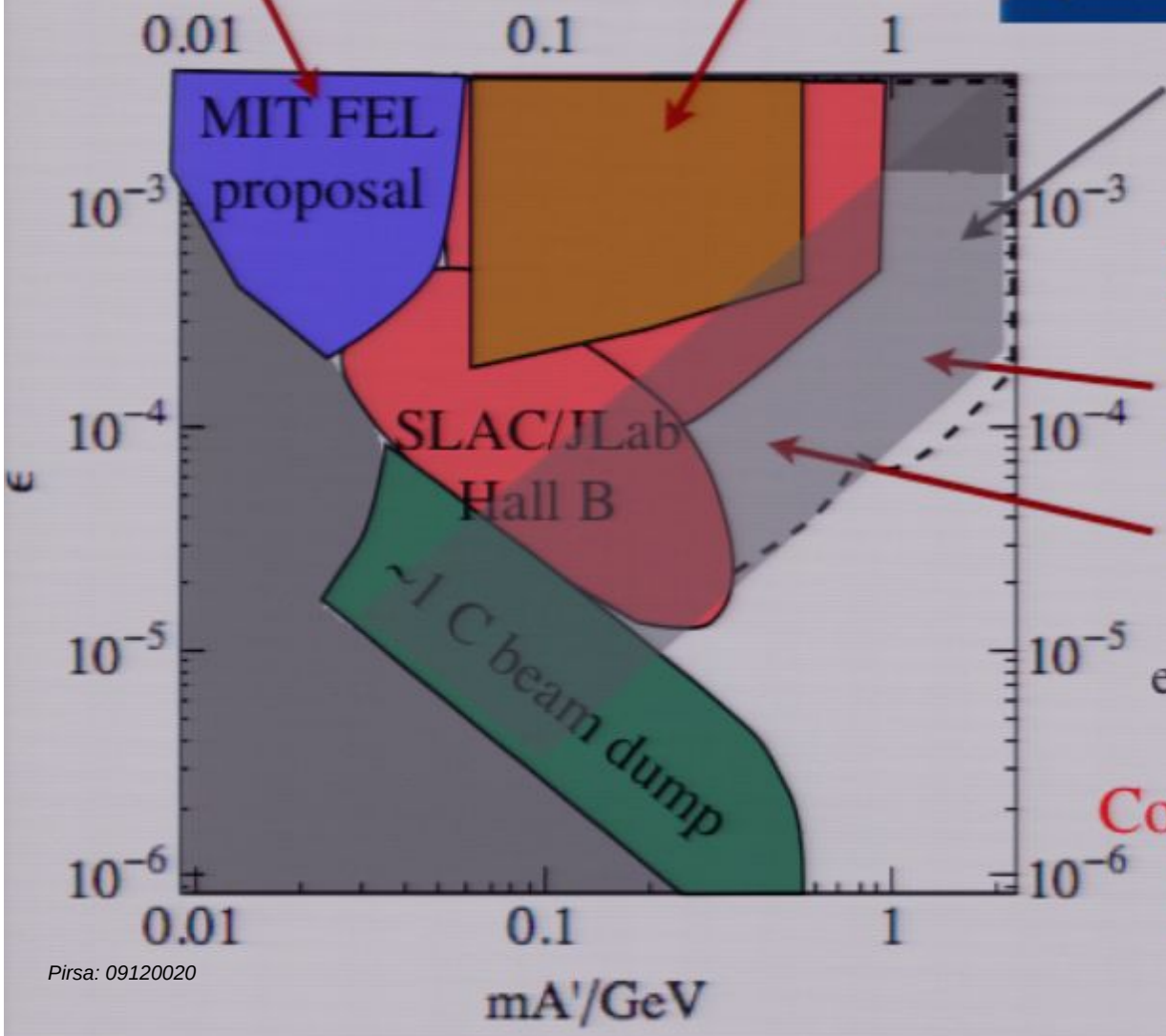

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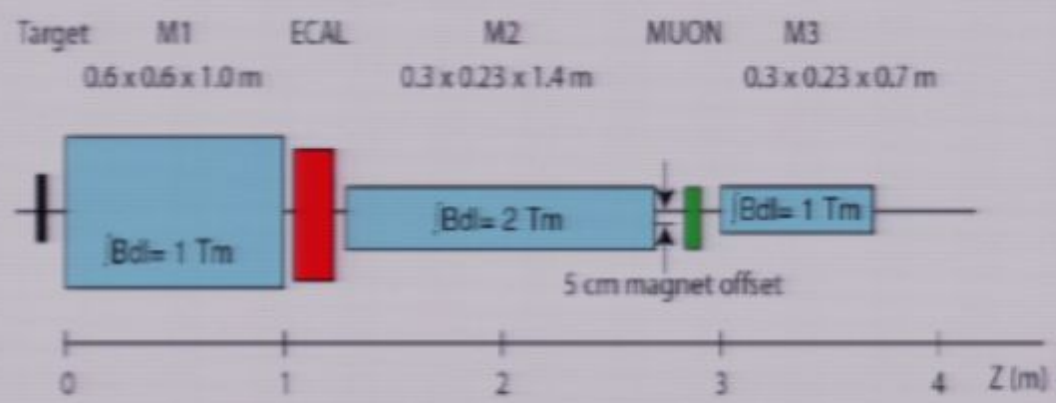

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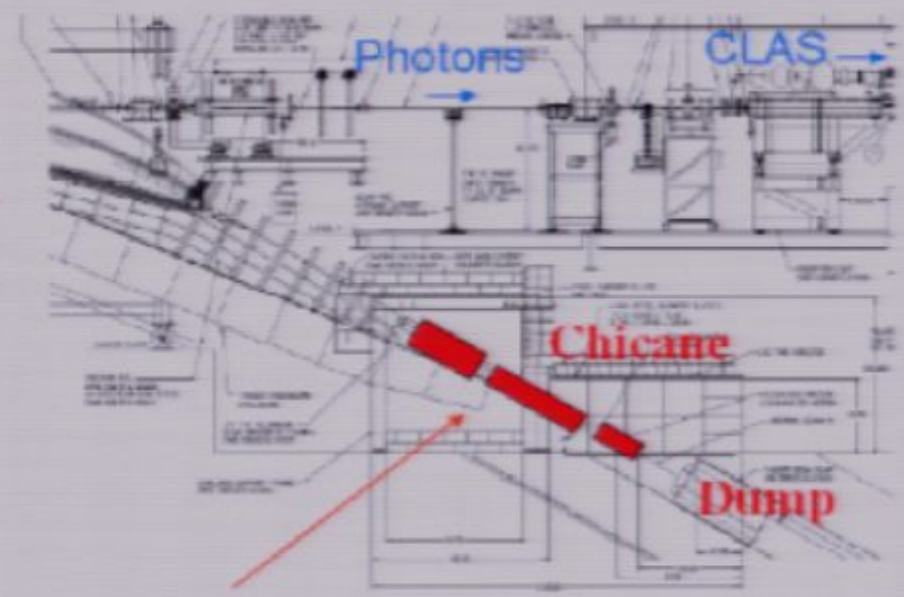


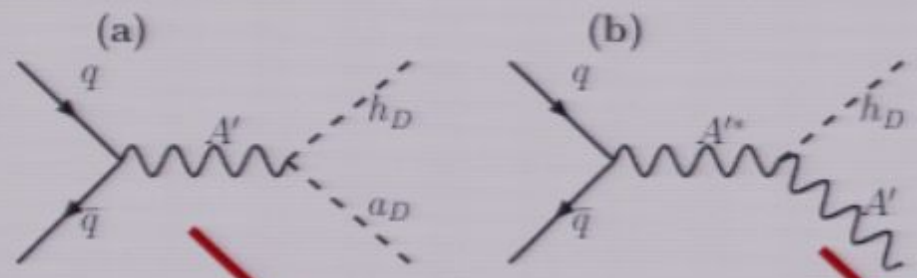
See T. Maruyama Talk at the SLAC Dark Forces Workshop

Past Beam Dump Limits

[see: PS, Yavin, Toro;
Batell, Pospelov, Ritz, Shang]

(scalar decay modes)

Production Mode:



CHARM axion search:
proton beam dump,
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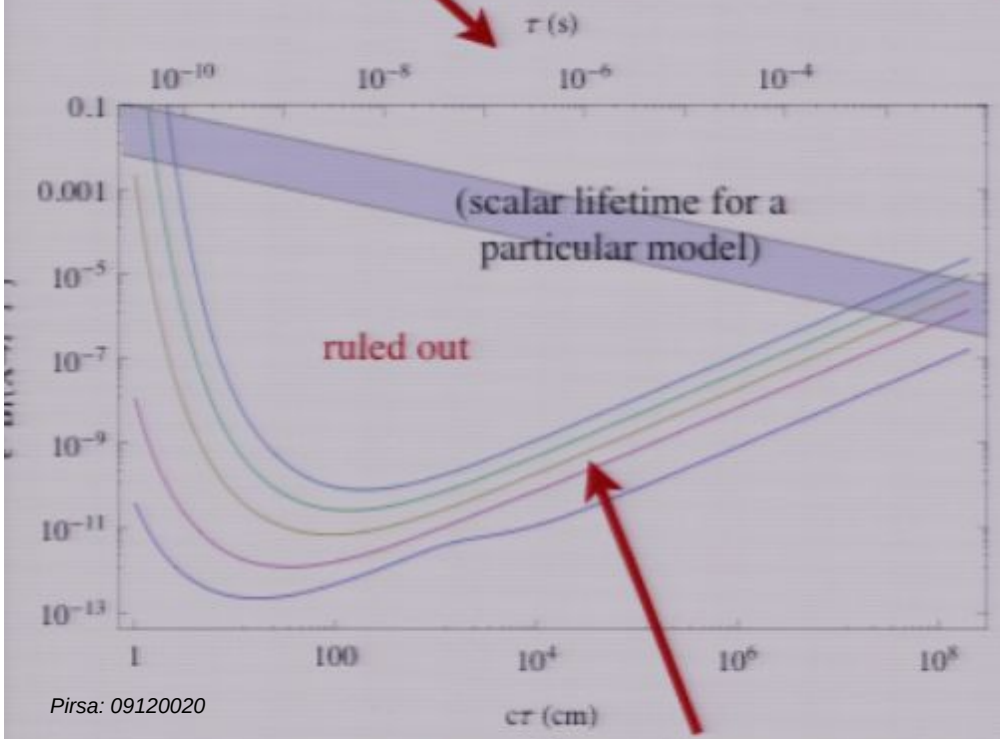

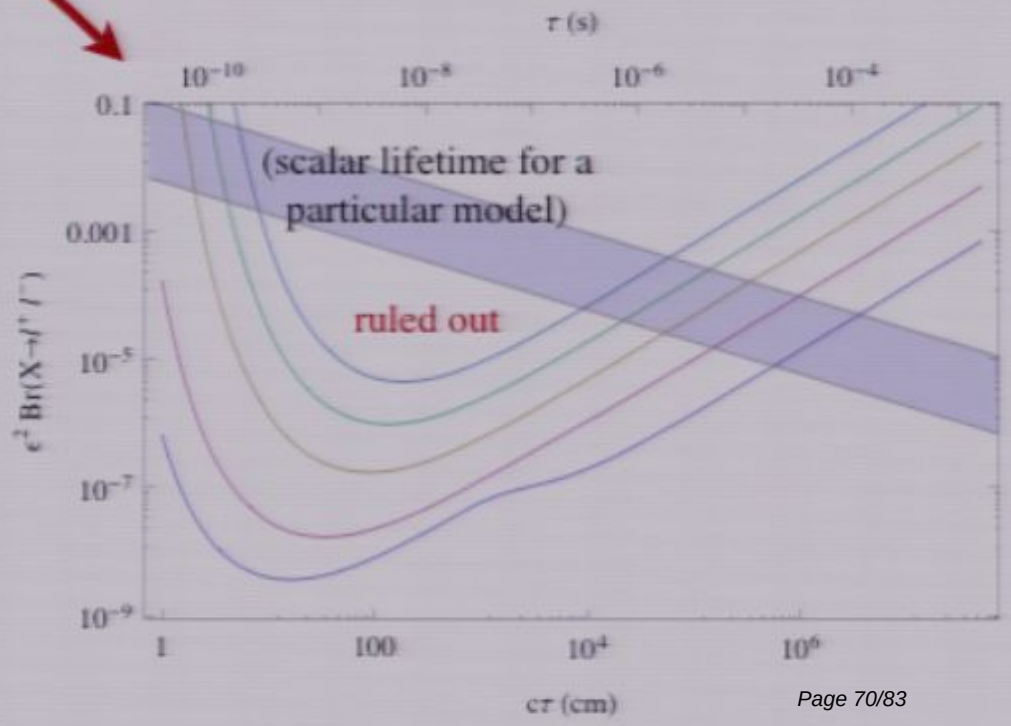

curves from bottom to top: $m_{A'} = 0.6, 1, 2, 3, 4$ GeV

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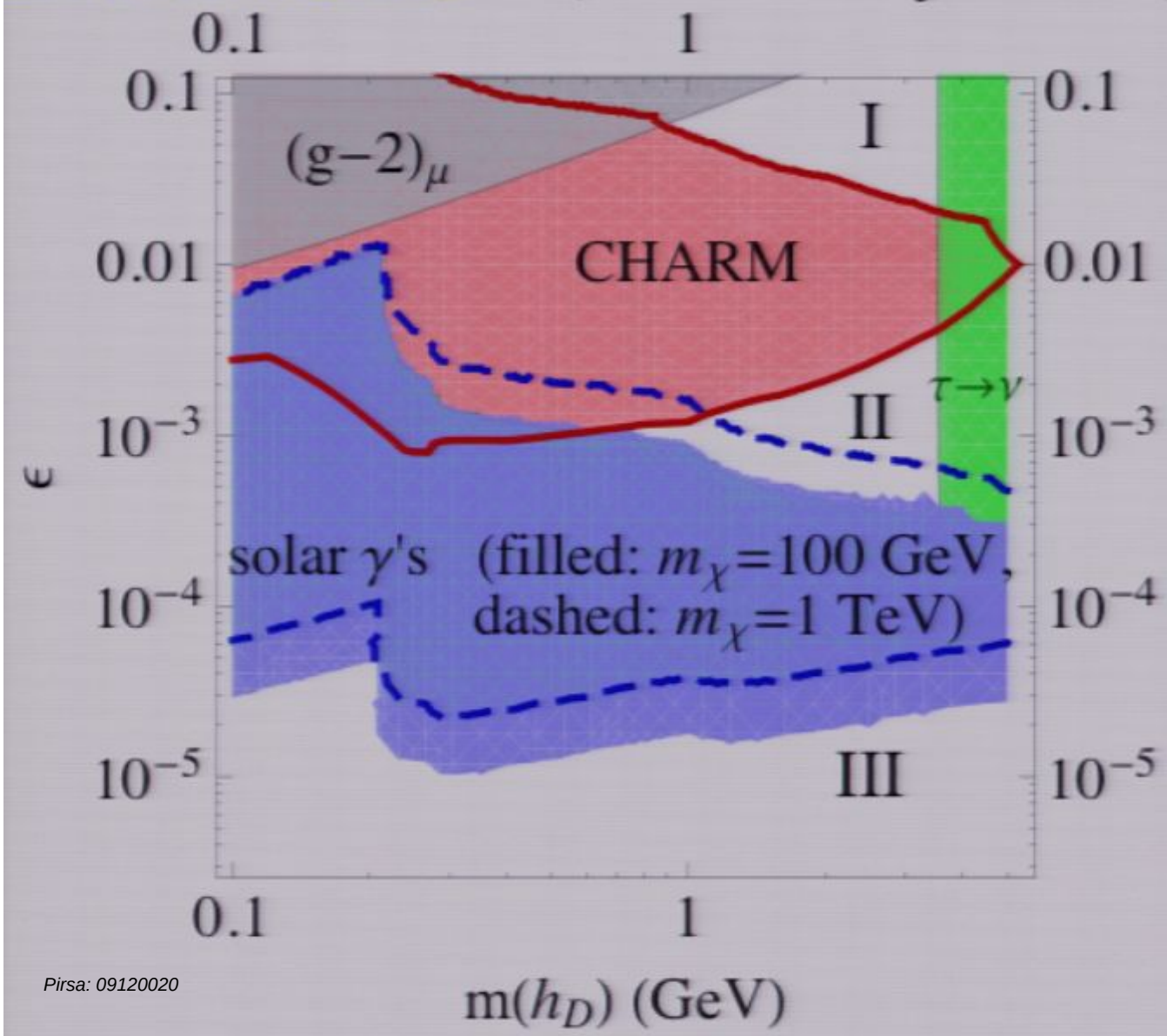

Strong laboratory constraints in the DAMA/LIBRA region of interest

If dark matter can annihilate into dark sector states, then there are constraints from solar capture of dark matter

Past Beam Dump Limits

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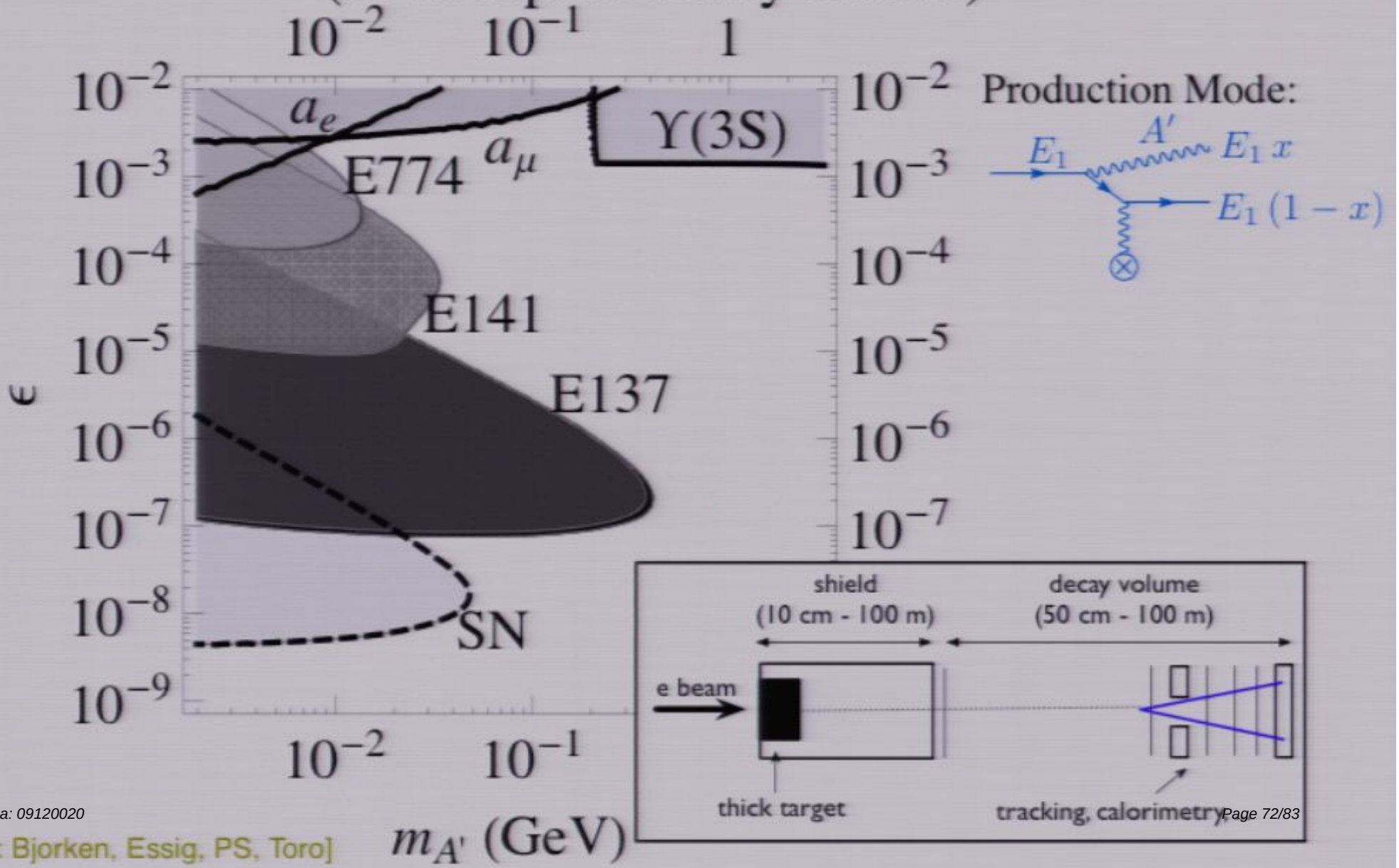

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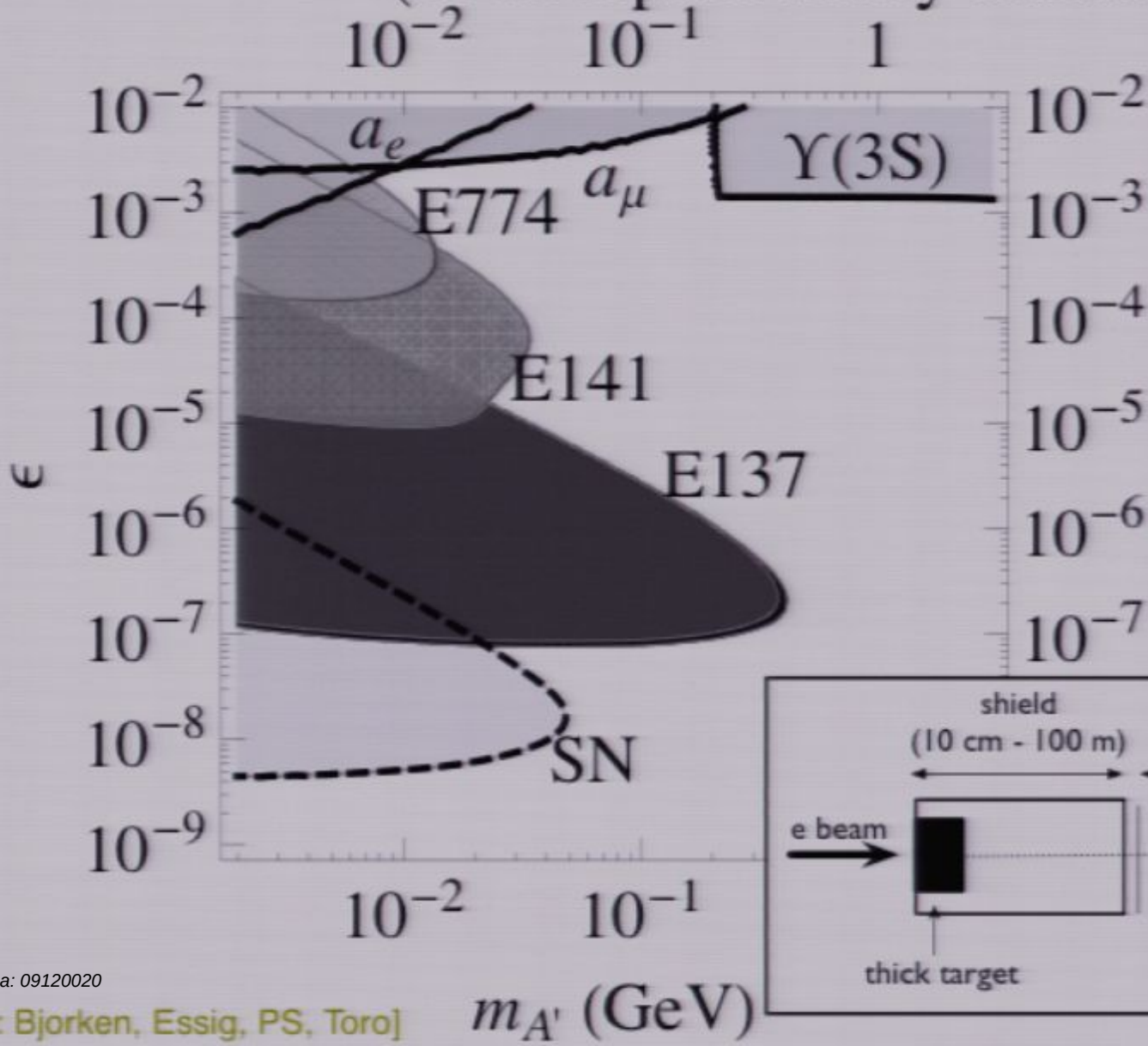

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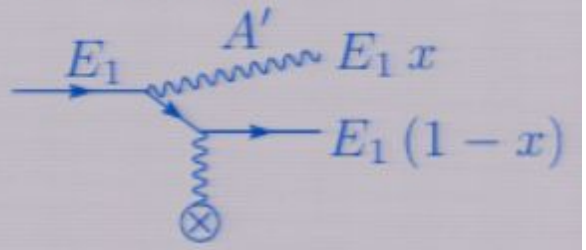

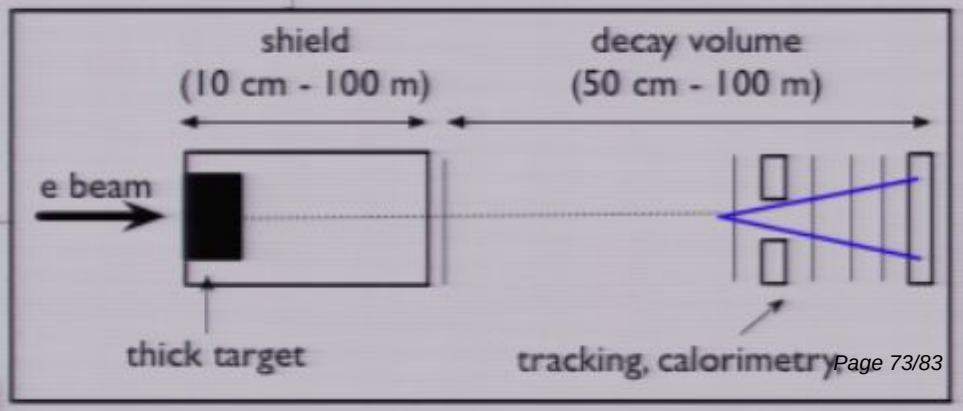

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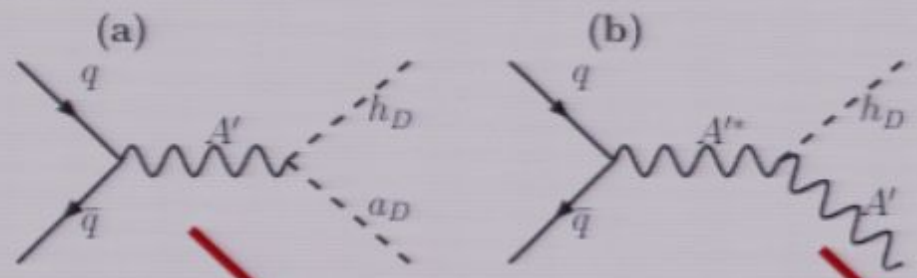

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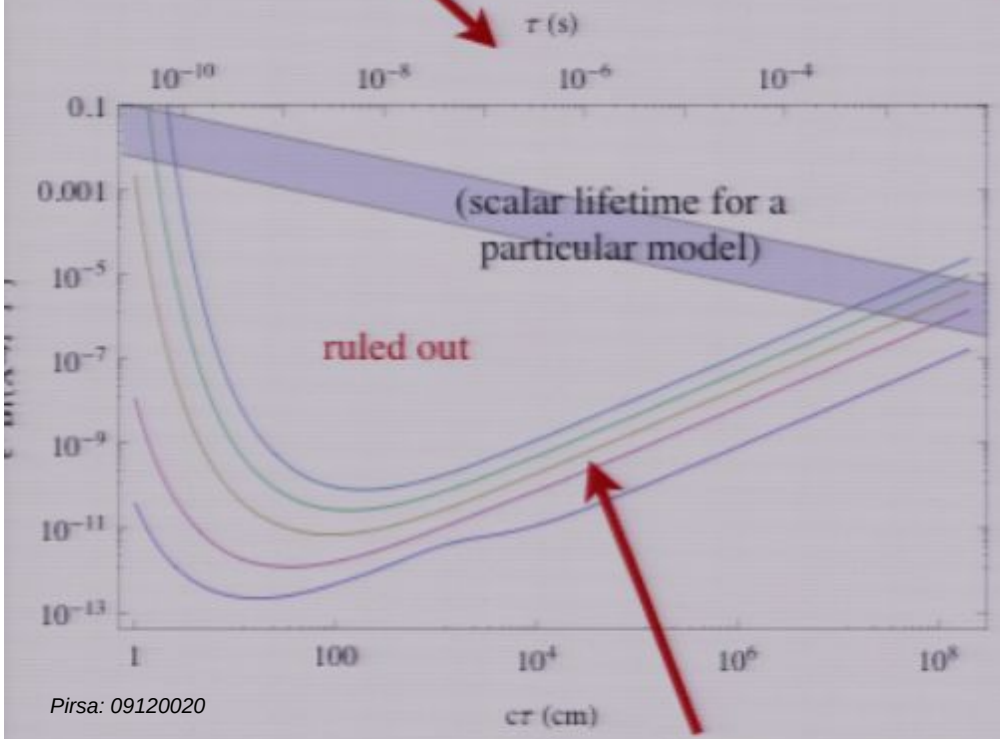

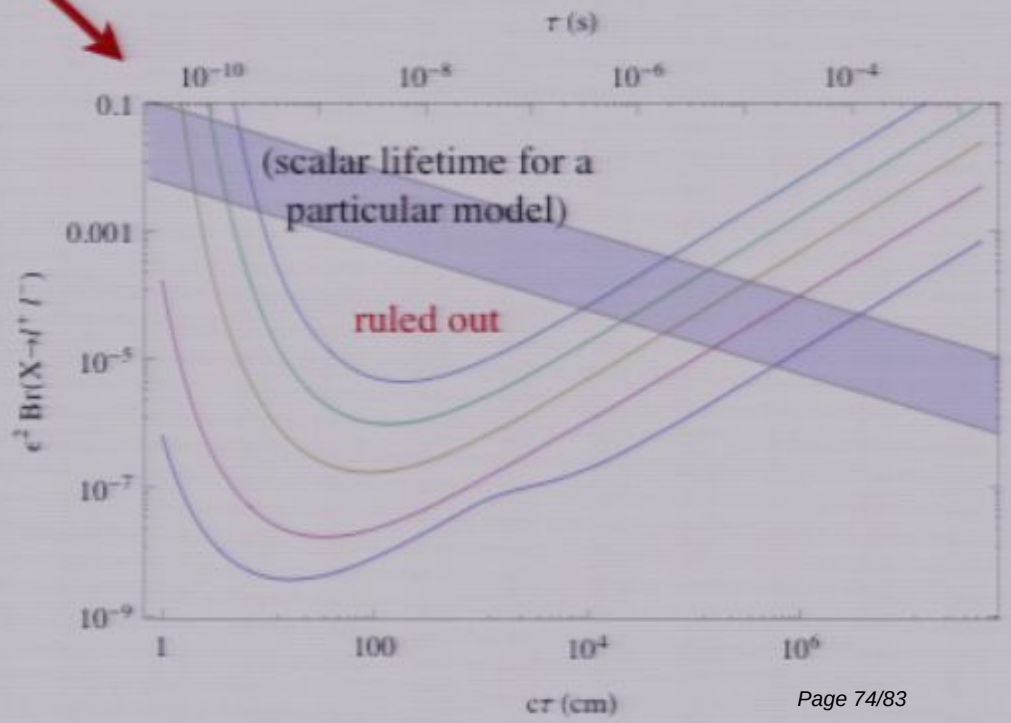

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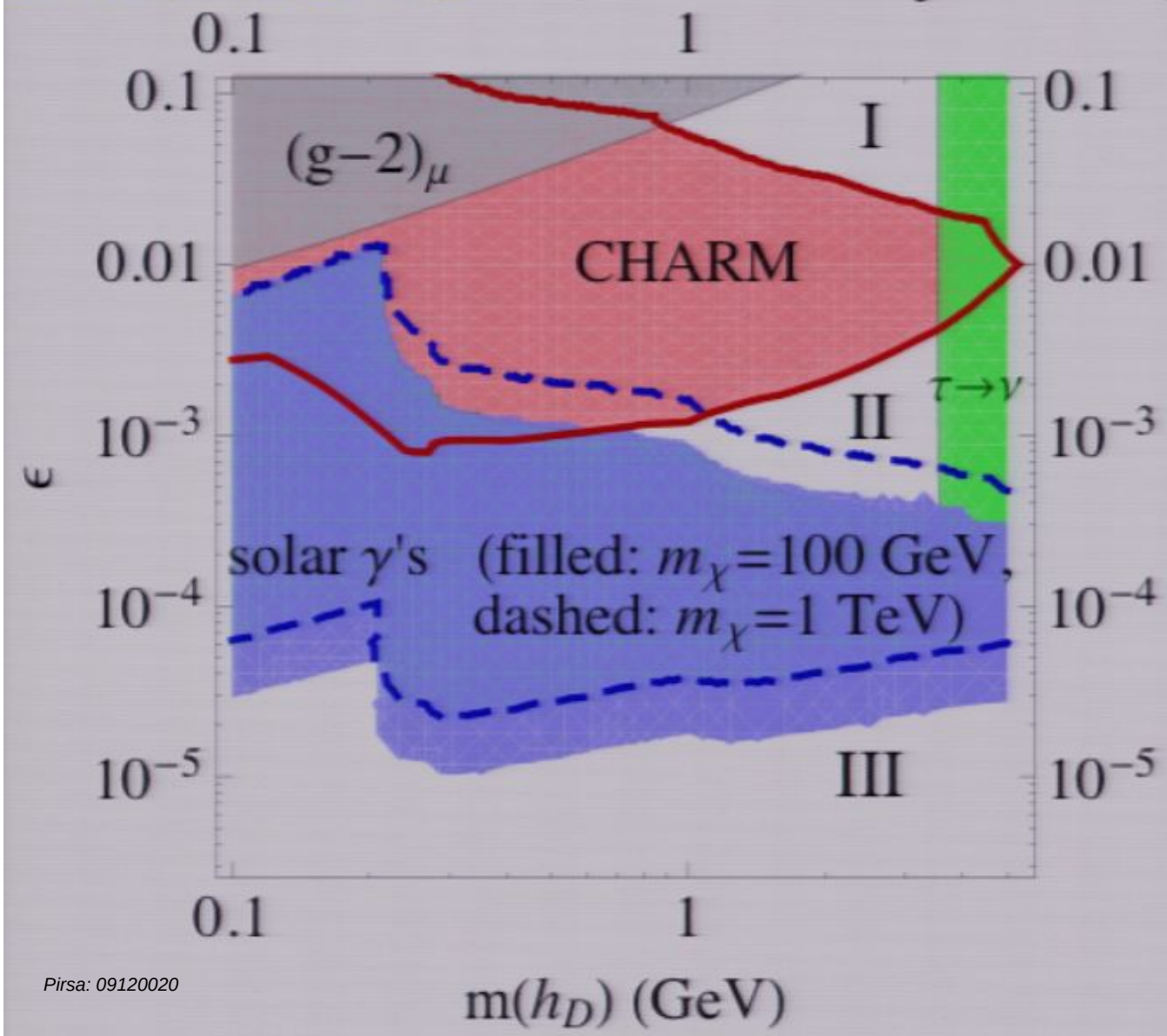

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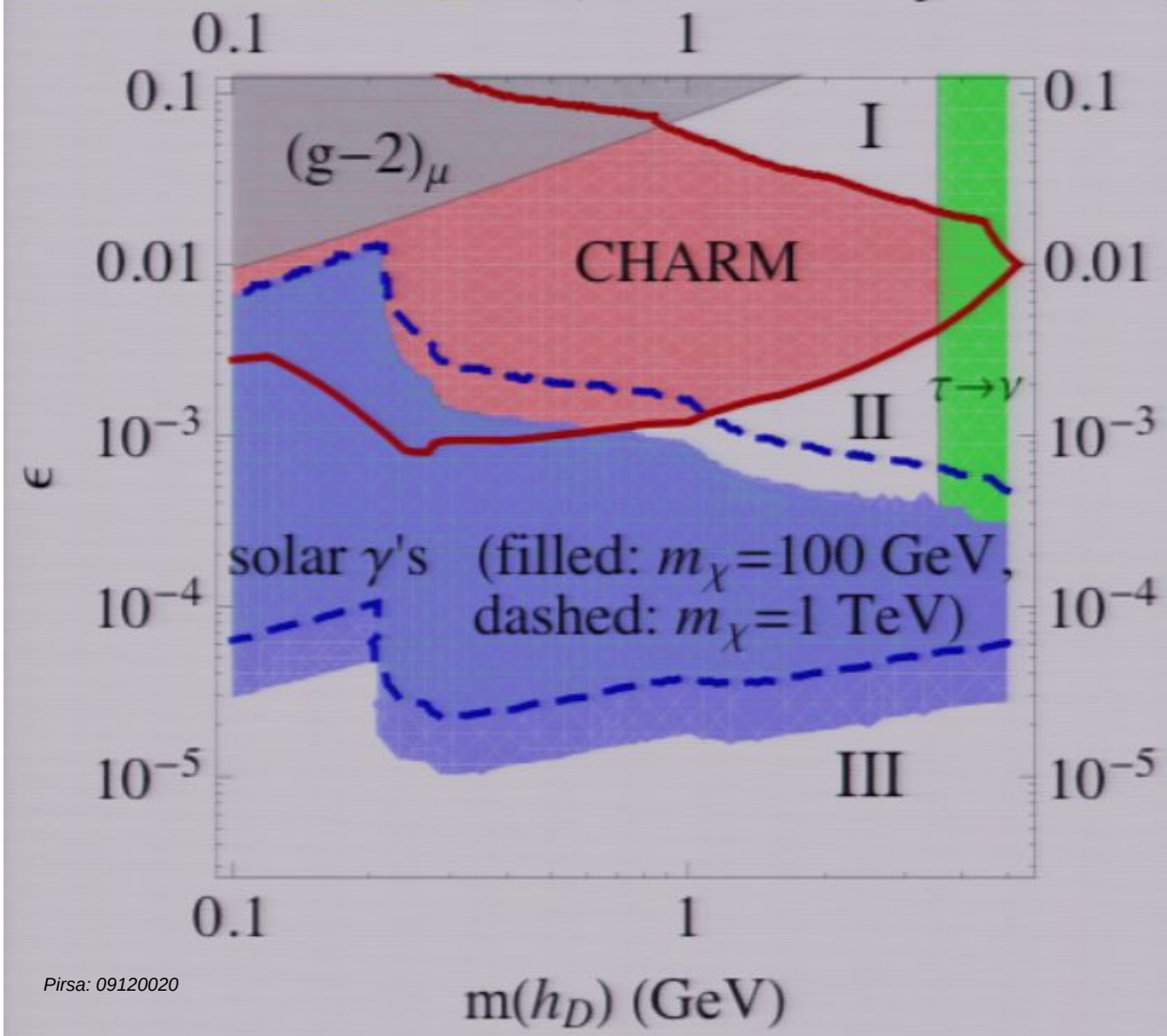

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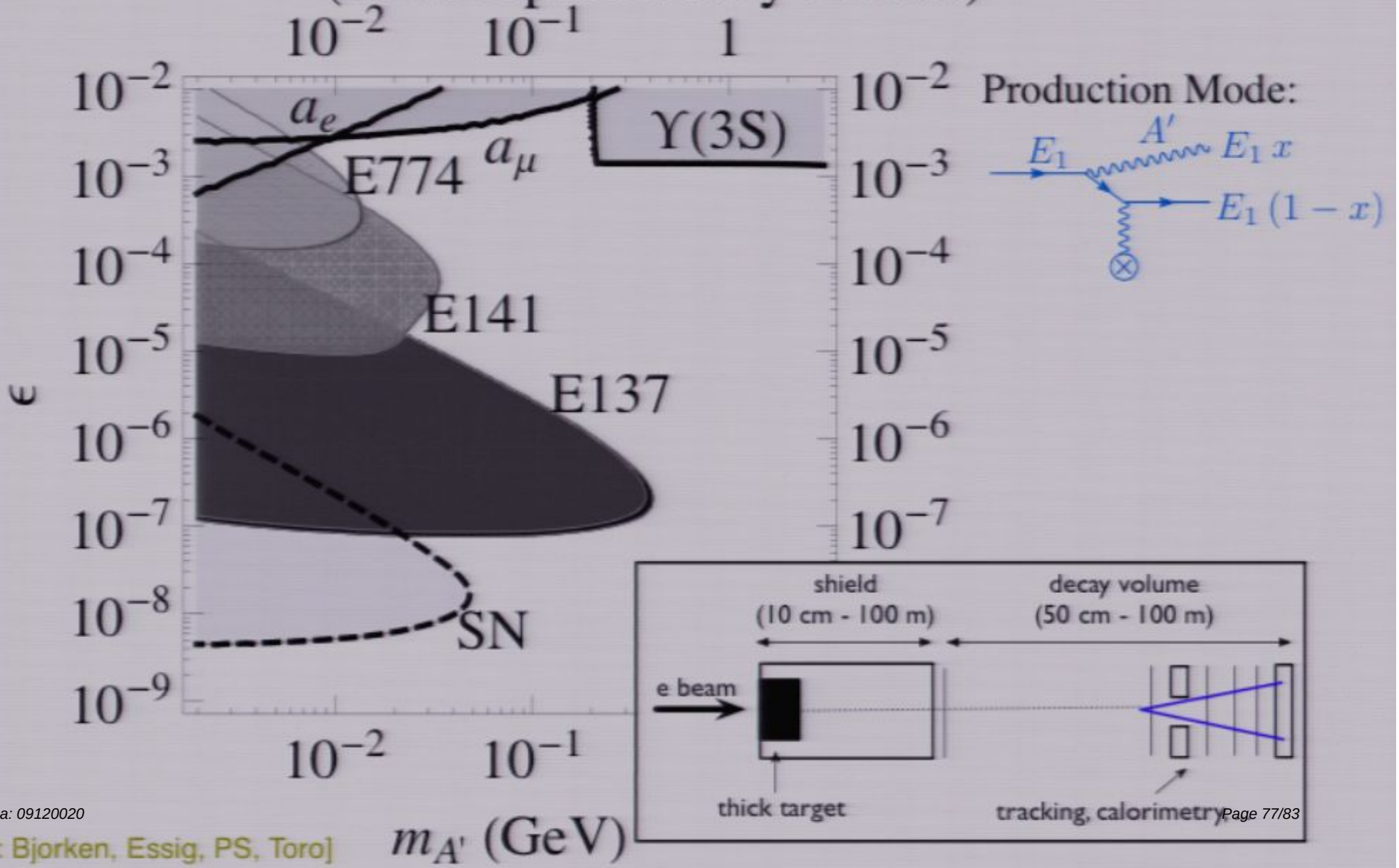

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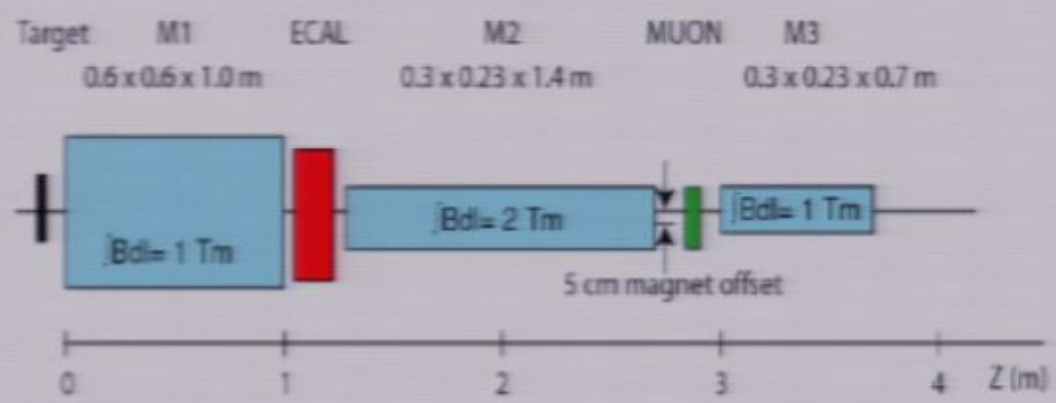

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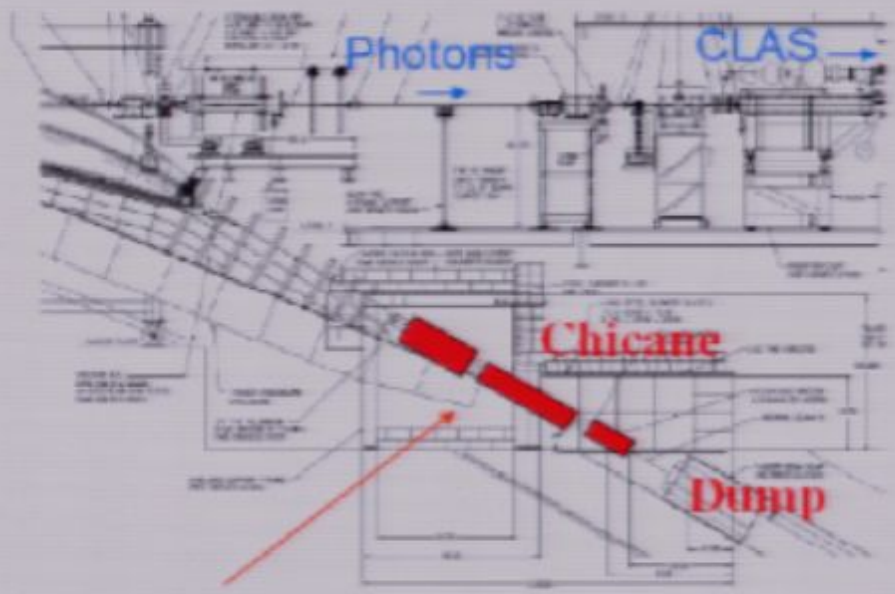

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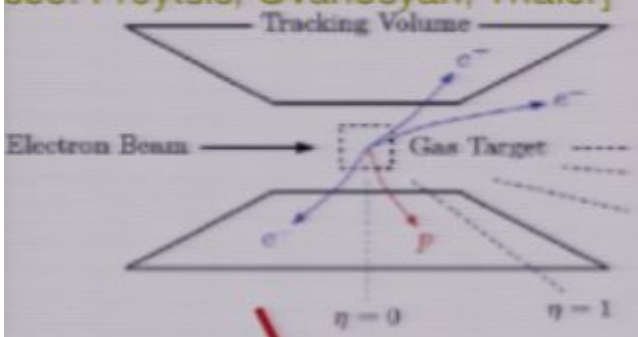

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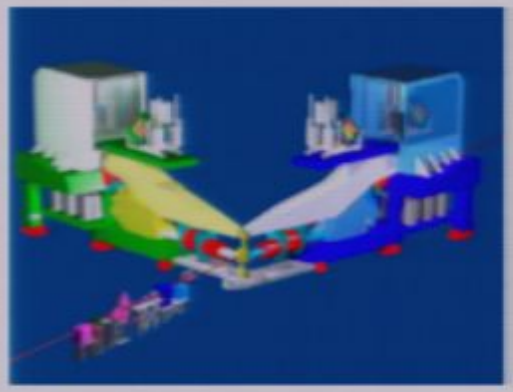

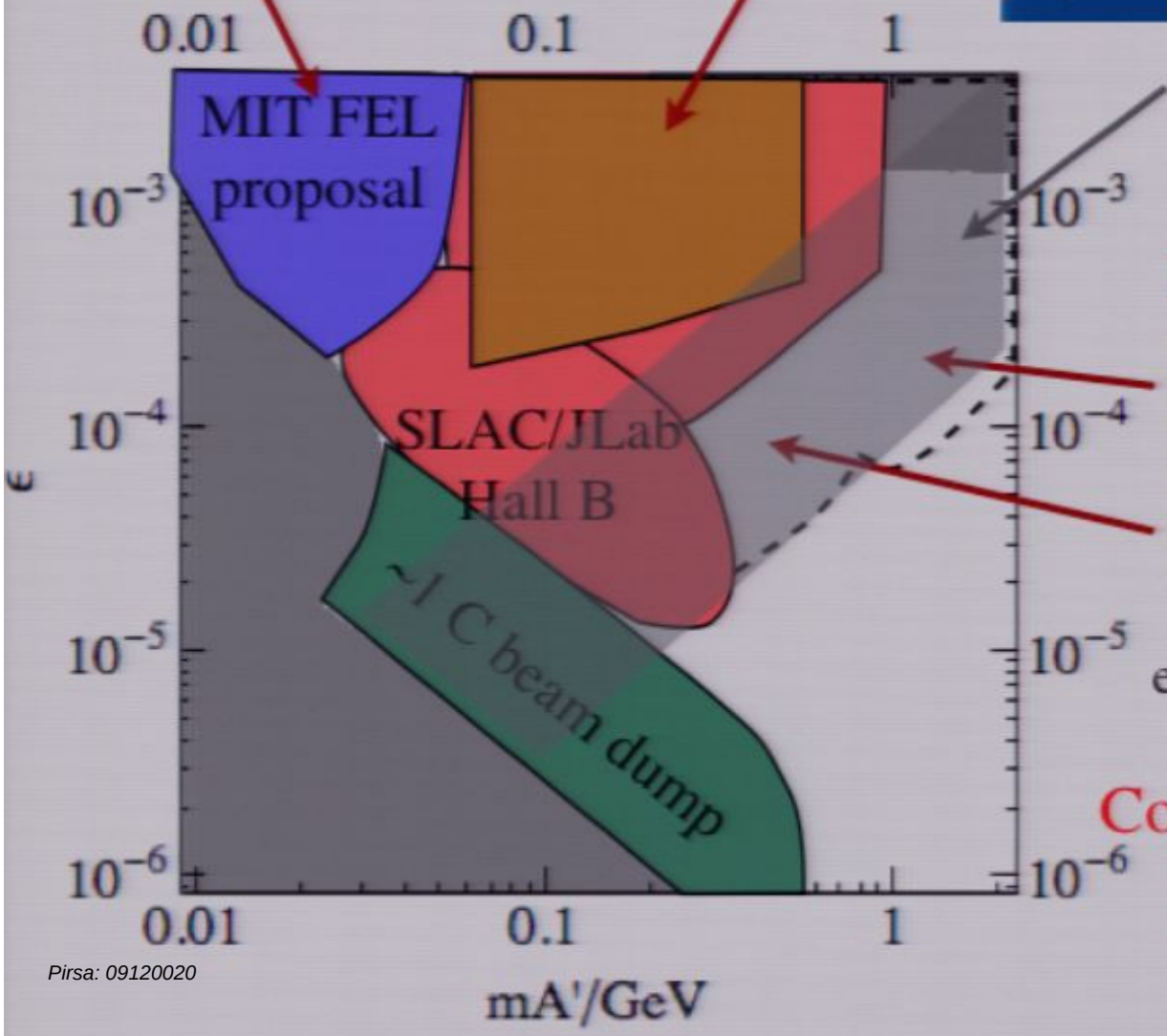

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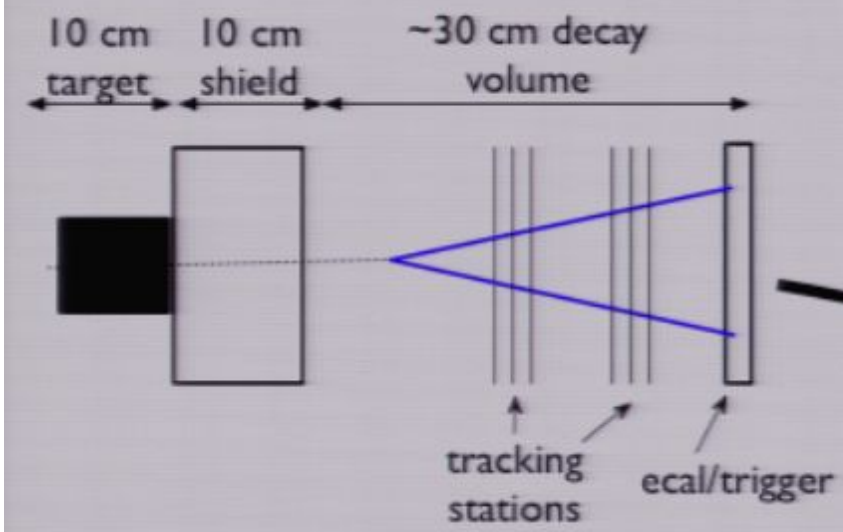
Di-lepton
decay channel



"D-term" line – also explains
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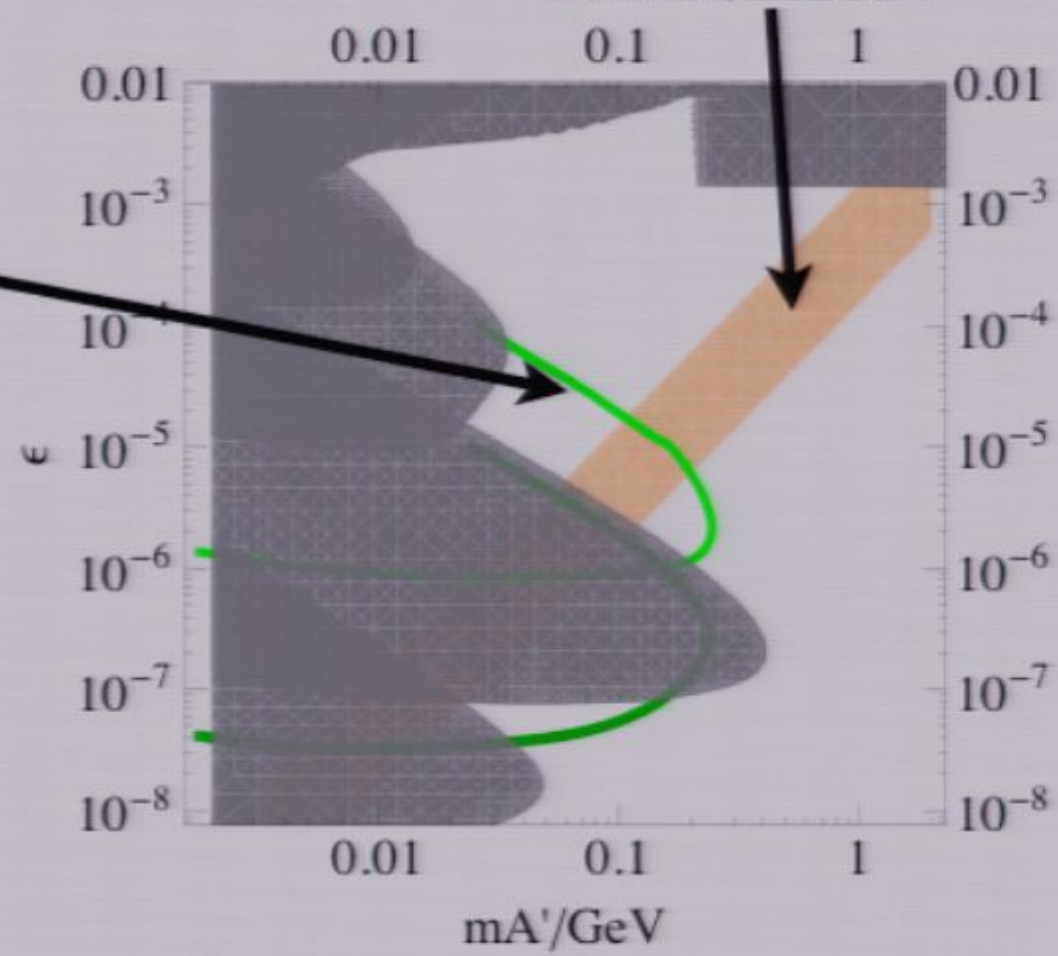

Good Beams:

- FEL at JLab
- SLAC
- Duke
- ELSA, Mainzer Mikrotron (MAMI), Max-lab

[see: Bjorken, Essig, PS, Toro]

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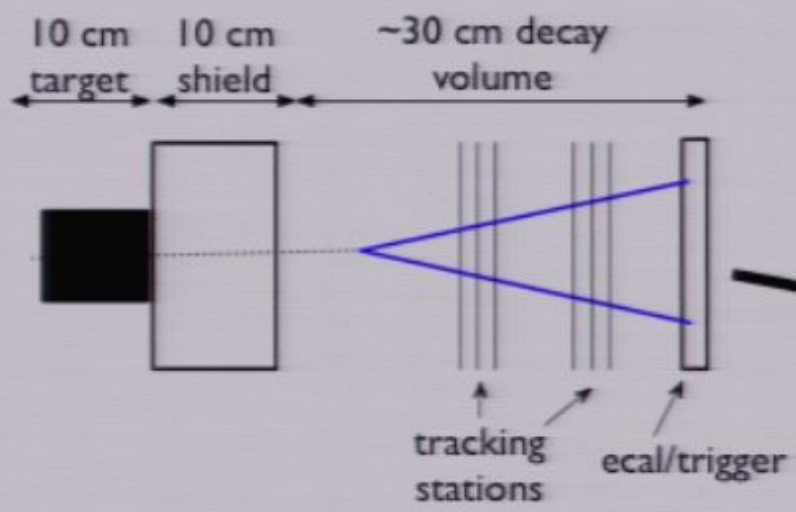

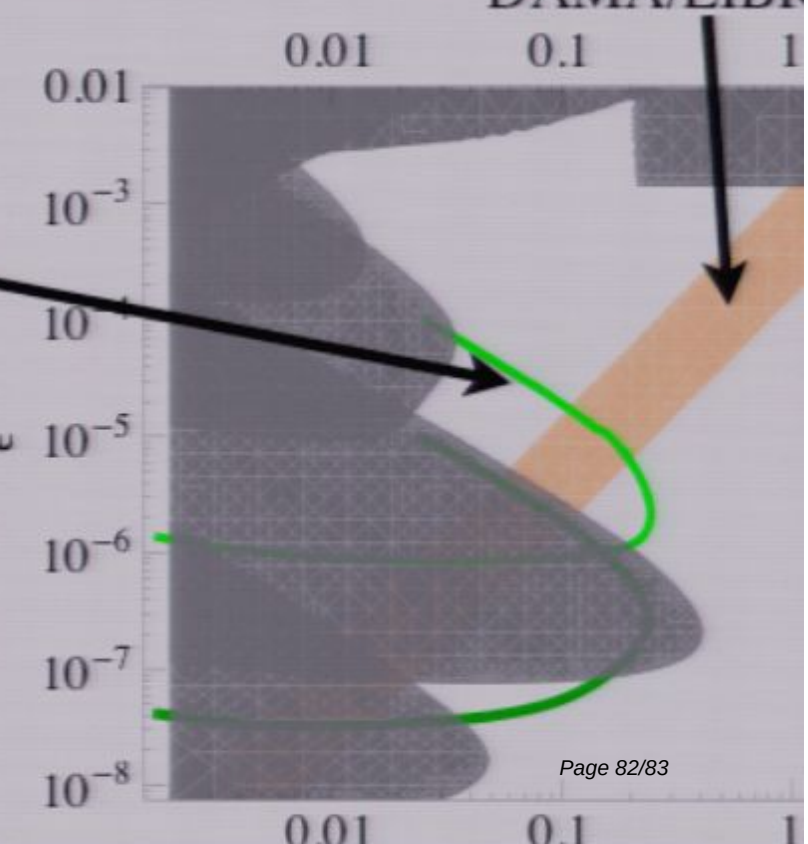

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No Signal

VGA-1