Probing GeV-scale Dark Forces with Dwarf Galaxies, Low Energy e+e- Colliders, and New Fixed-Target Experiments

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Seminar, Cornell University, March 17th, 2010

with:

N. Sehgal, L.E. Strigari (arXiv: 0902.4750, PRD)

N. Sehgal, L.E. Strigari, M. Geha, J.D. Simon (to appear)

P. Schuster, N. Toro (arXiv: 0903.3941, PRD)

J.D. Bjorken, P. Schuster, N. Toro (arXiv: 0906.0580, PRD)

P. Schuster, N. Toro, B. Wojtsekhowski et.al. (arXiv:1001.2557)

Outline

- Theory and Motivation
  (and hints from dark matter)
- Probing GeV-scale Dark Forces
  - Indirect probe:

    γ-rays from DM annihilation in dwarf galaxies
  - Direct probes:
    - Low-energy e^+e^- Colliders (BaBar, BELLE, CLEO, ...)
    - Fixed-Target Experiments (e.g. @ JLab)

Theory and Motivation

Standard Model

strong weak electromagnetic

g $W^{\pm}, Z$ γ

Theory and Motivation

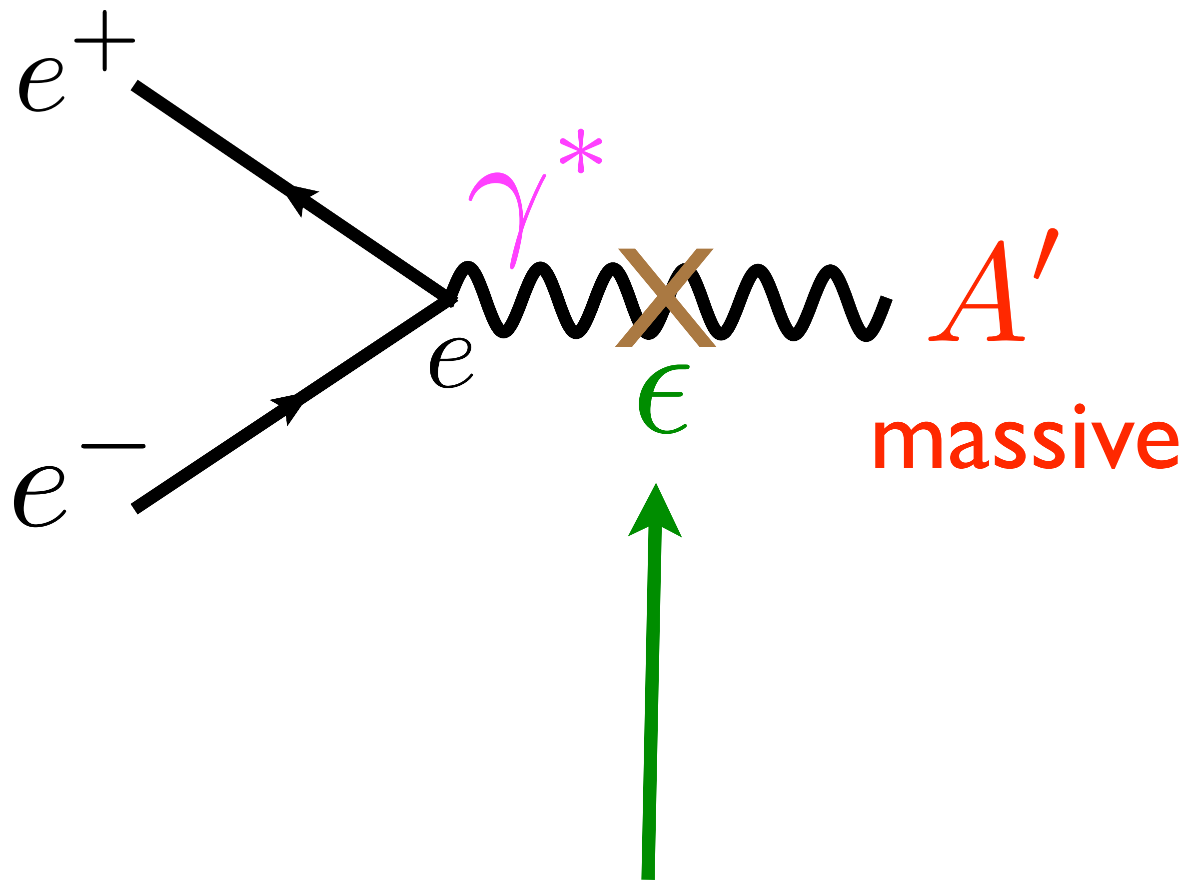
Standard Model			Hidden Sector?
strong	weak	electromagnetic	new force?
g	$W^{\pm}, Z$	γ	A'

Strong constraints exist on light new matter with Standard Model interactions

New, very weak interactions of ordinary matter with a hidden sector are allowed and an exciting possibility!

Generic Coupling of Standard Model to Hidden Sector

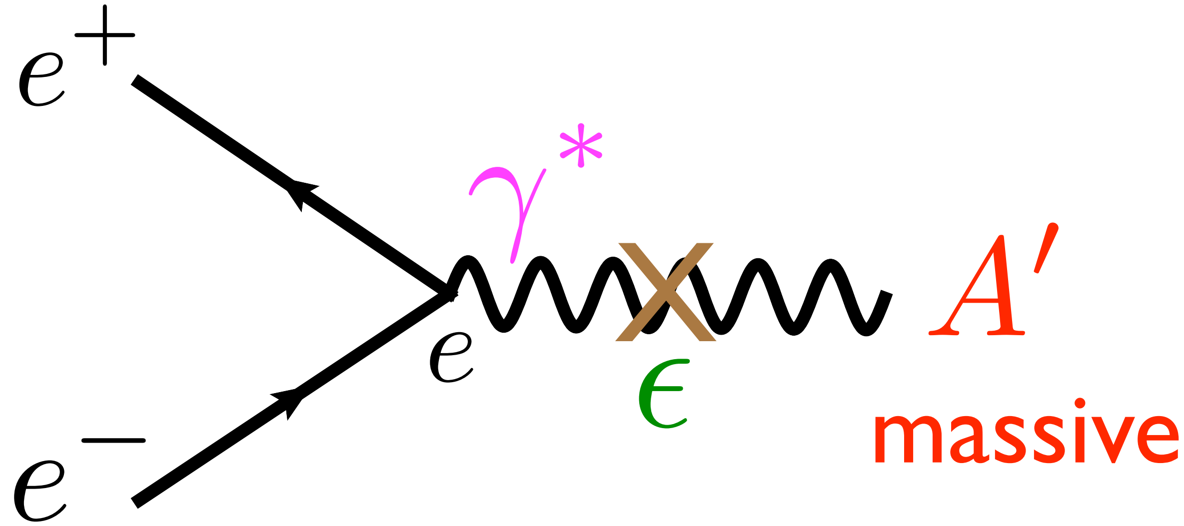
Photon can mix with a new Vector Boson A'

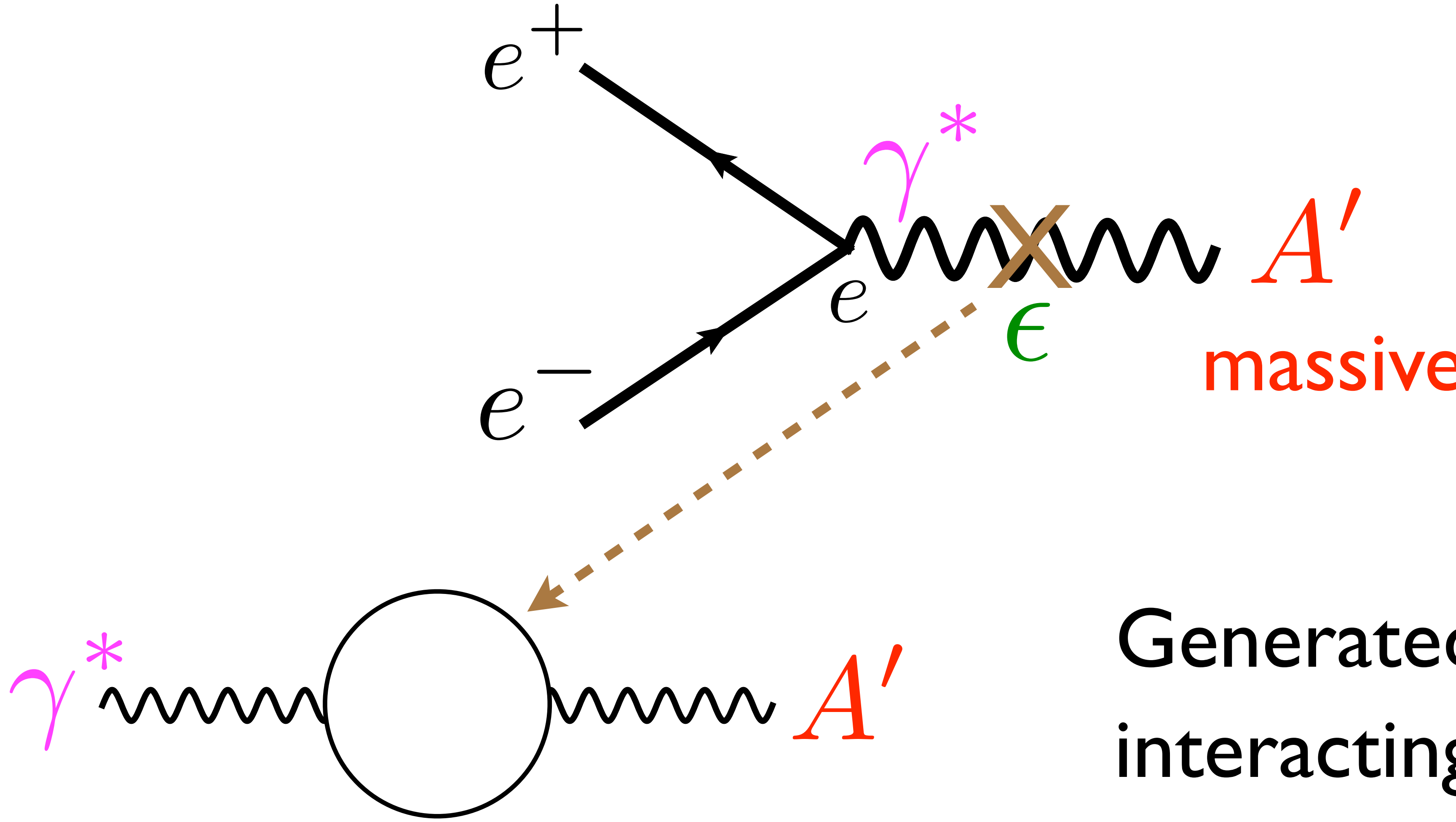


Hidden sector
U(1)

a *generic* portal from Standard Model to a Hidden Sector

[Holdom]

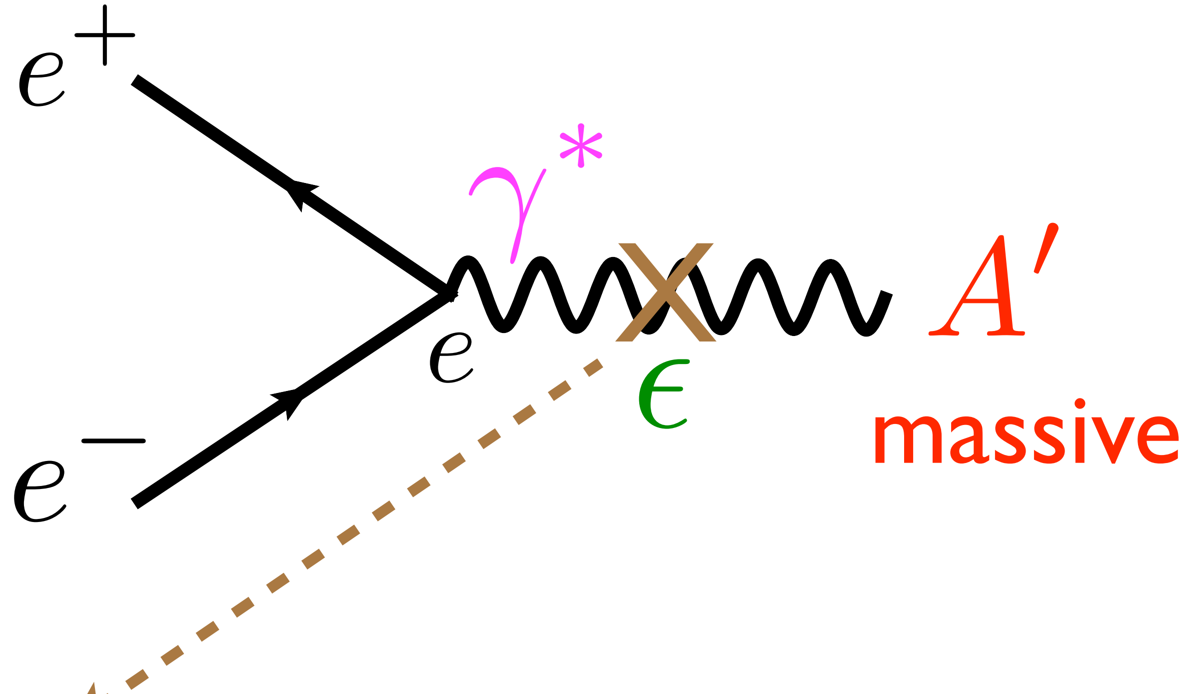

e^+
γ^*
A'
e
ϵ
massive
e^-

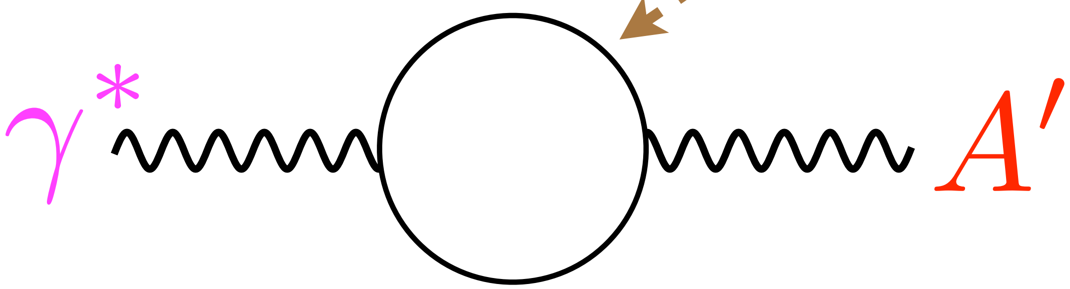


Generated by heavy particles interacting with γ and A'

$$\Delta\mathcal{L} = \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$

"Kinetic Mixing" [Holdom]





Generated by heavy particles interacting with γ and A'

$$\Delta\mathcal{L} = \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$

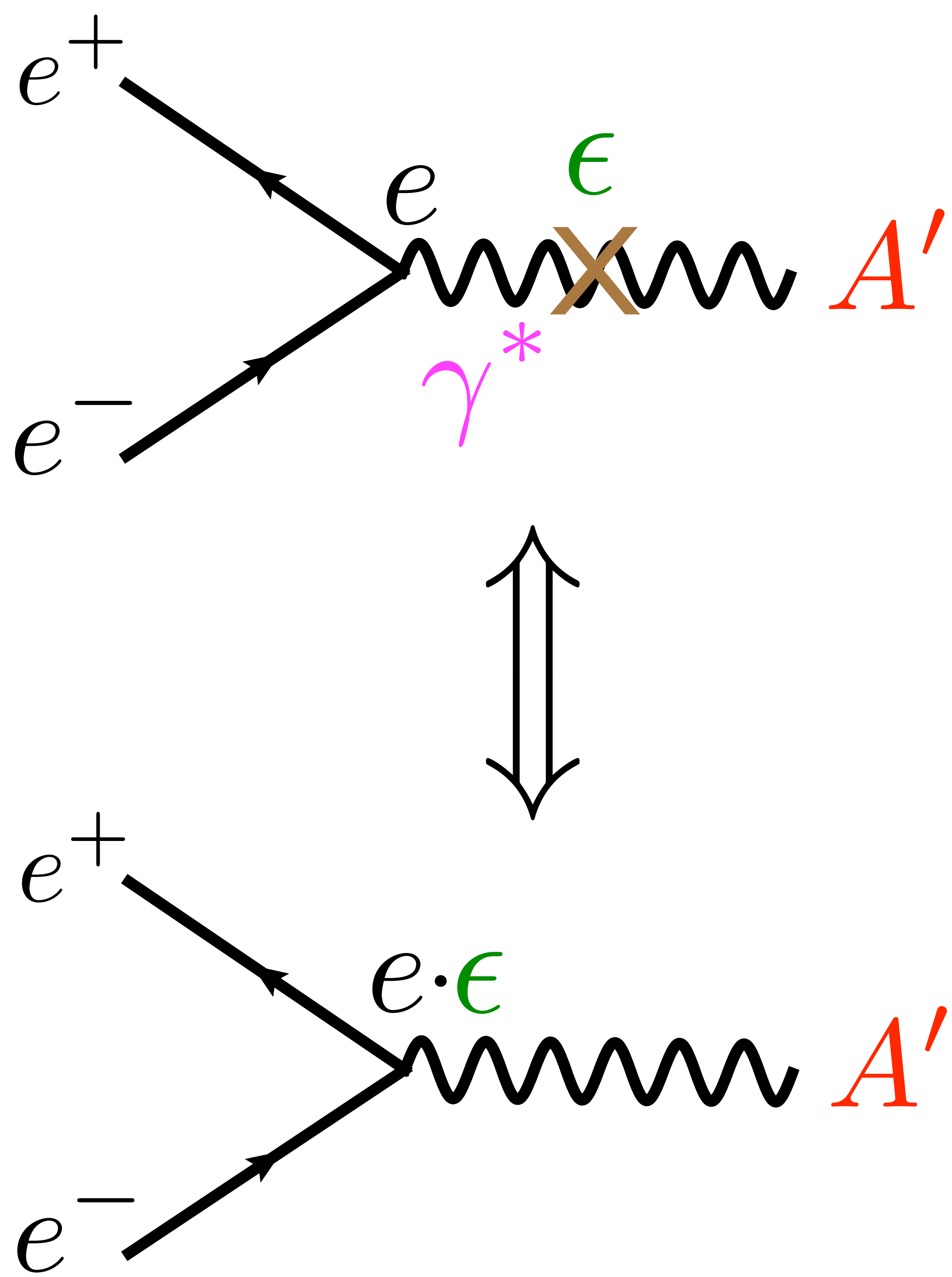
"Kinetic Mixing" [Holdom]

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

current constraint from BaBar and $(g\text{-}2)_{\mu,e}$:

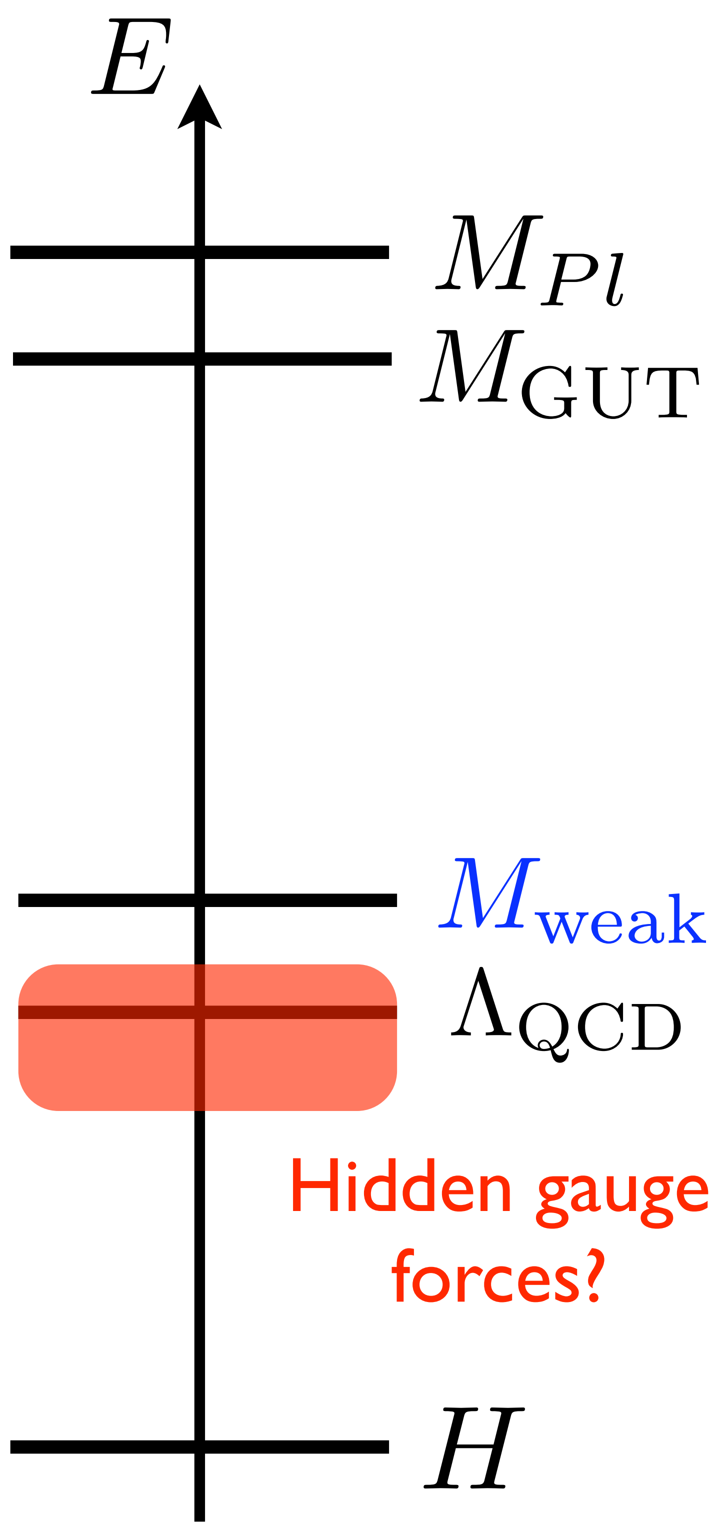
$$\epsilon \lesssim (0.3 - 1) \times 10^{-2}$$

Useful to think about this in different way



Quarks & charged Leptons: milli-charged under A'

What is the mass of the A'?



A priori, mass could be anywhere.

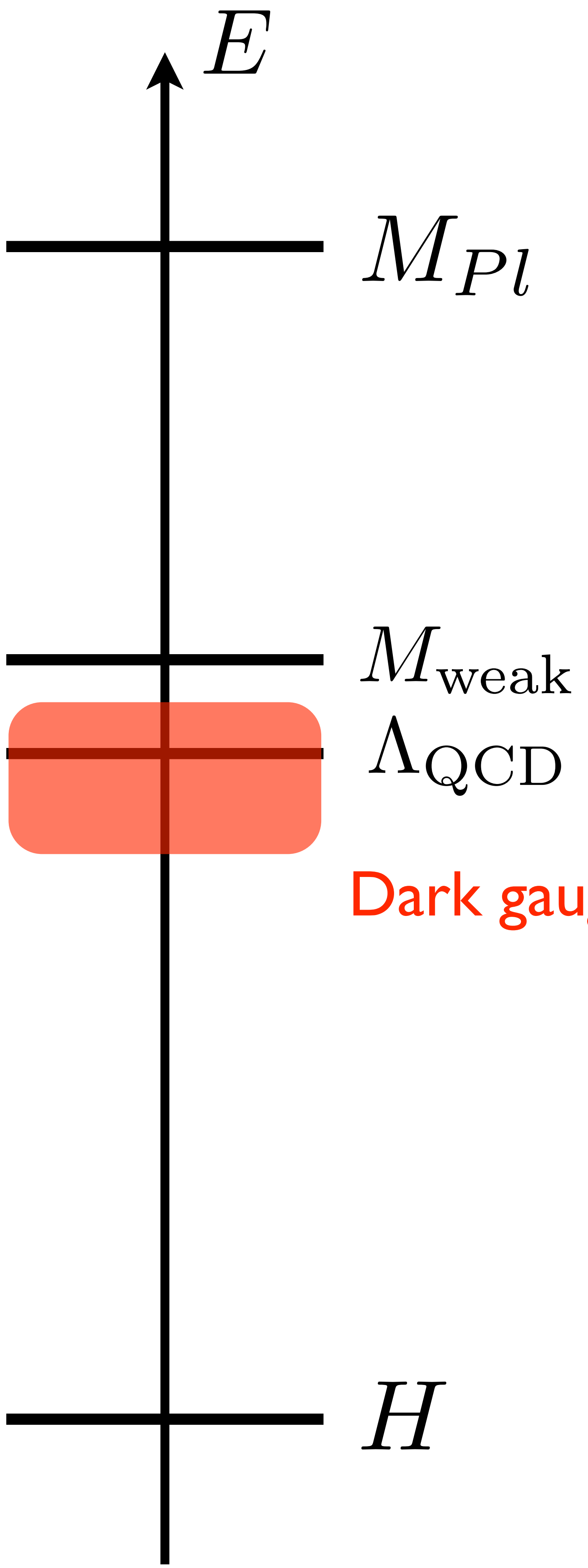
However, it is very natural for $m_{A'}$ to be tied to $M_{\rm weak}$

SUSY can naturally give A' near GeV-scale

e.g.

$$m_{A'} \sim \sqrt{\epsilon g_D}\, m_W \sim 0.1 - 1\,\mathrm{GeV}$$

[Arkani-Hamed, Weiner; Dienes, Kolda, March-Russell; Baumgart, Cheung, Ruderman, Wang; Katz, Sundrum; Morrissey, Poland, Zurek]

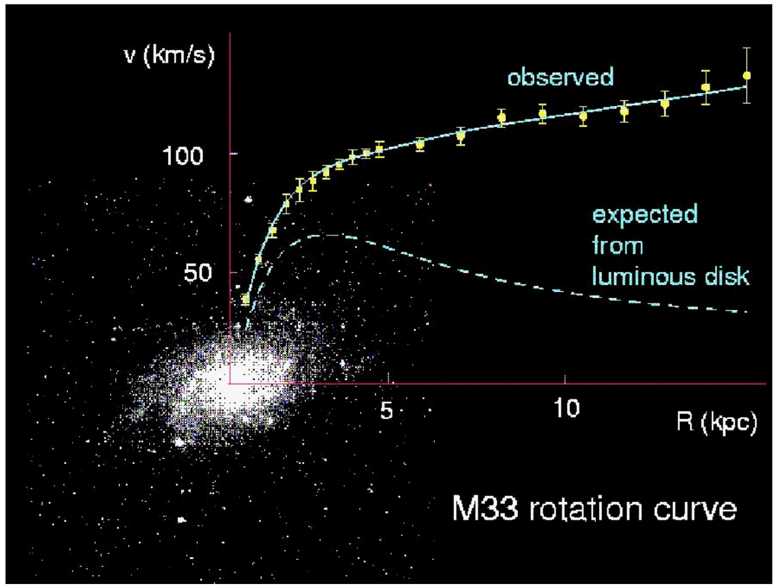


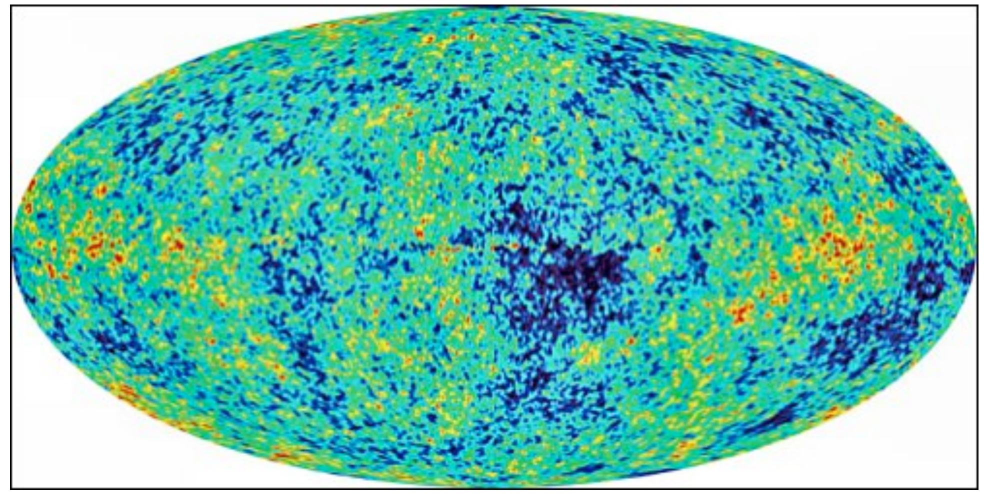
Dark gauge forces?

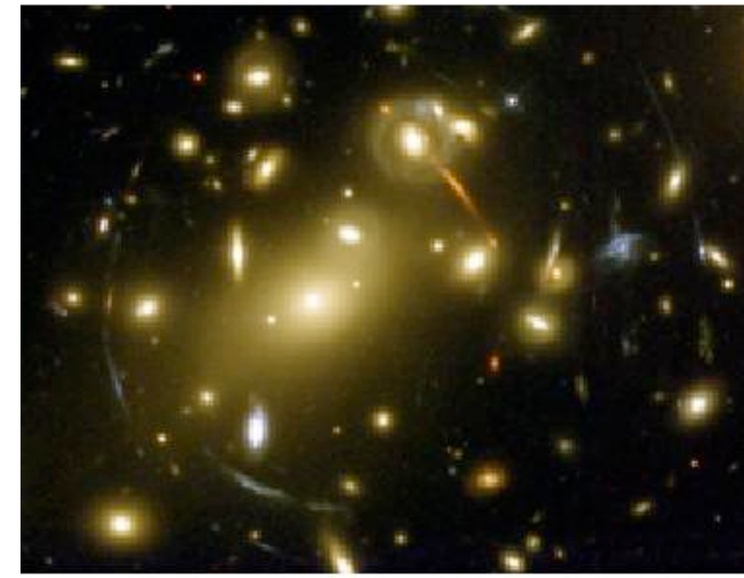
We see that GeV-scale A’ is weakly constrained and theoretically natural

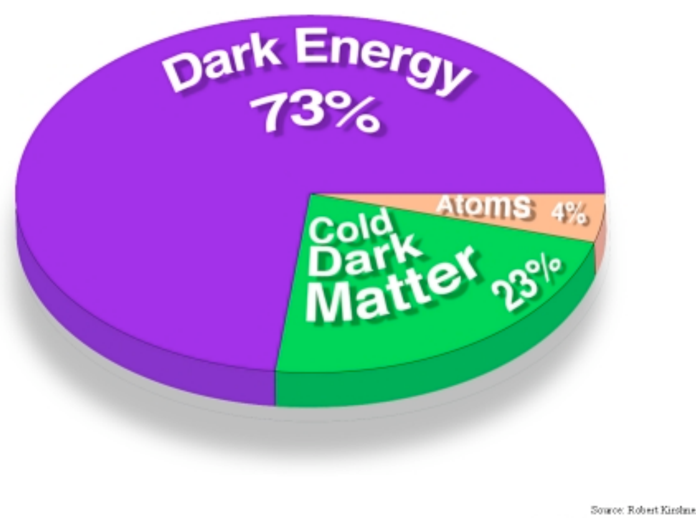
There are hints for new GeV-scale forces from anomalies related to dark matter

What do we know about Dark Matter?







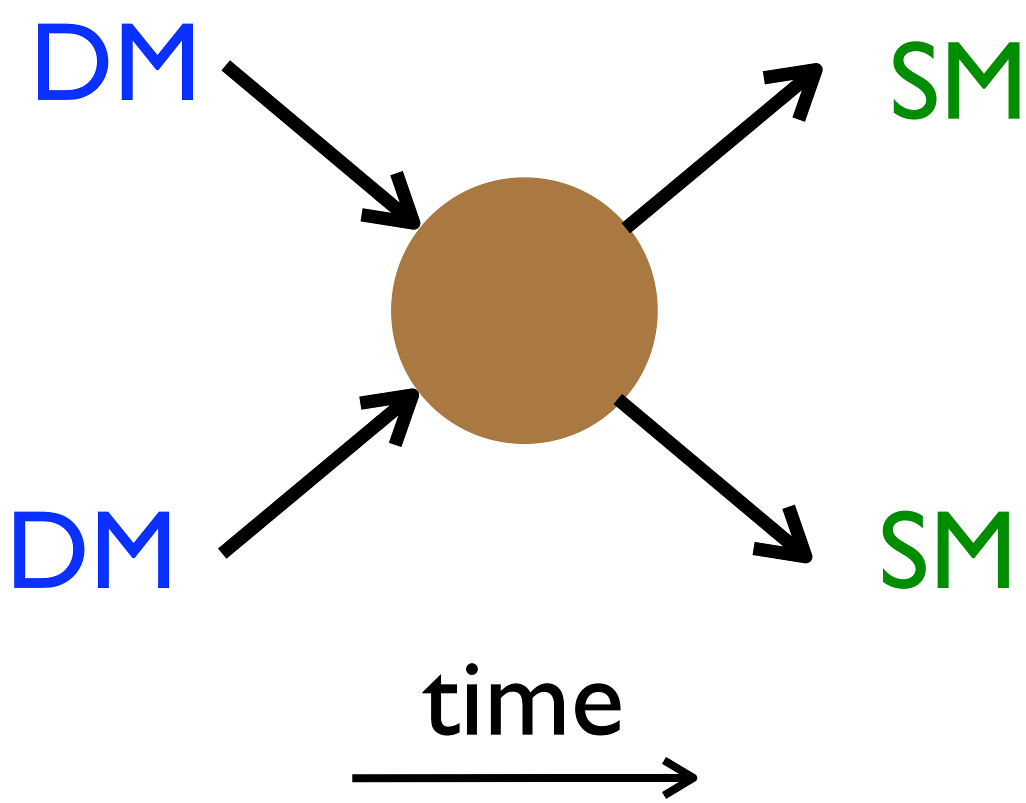


Existence
well-established !

Dark Matter interacts with us through *gravity*

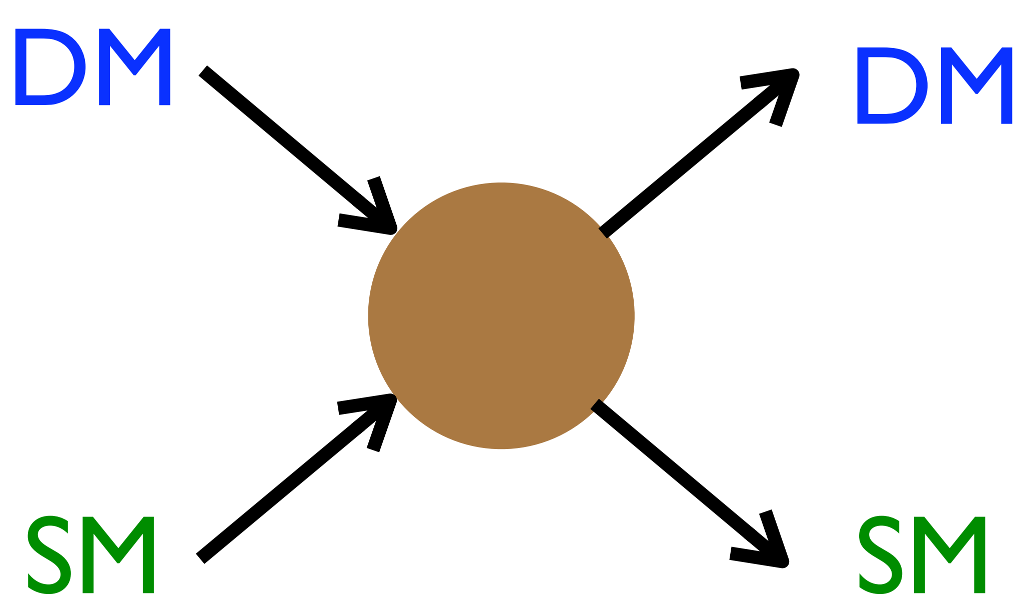
But does it have *other interactions* with us ?

Dark Matter interactions with ordinary matter?



Indirect detection:
Cosmic-rays, photons, ...

PAMELA, Fermi, HESS,
ATIC, ACTs, WMAP



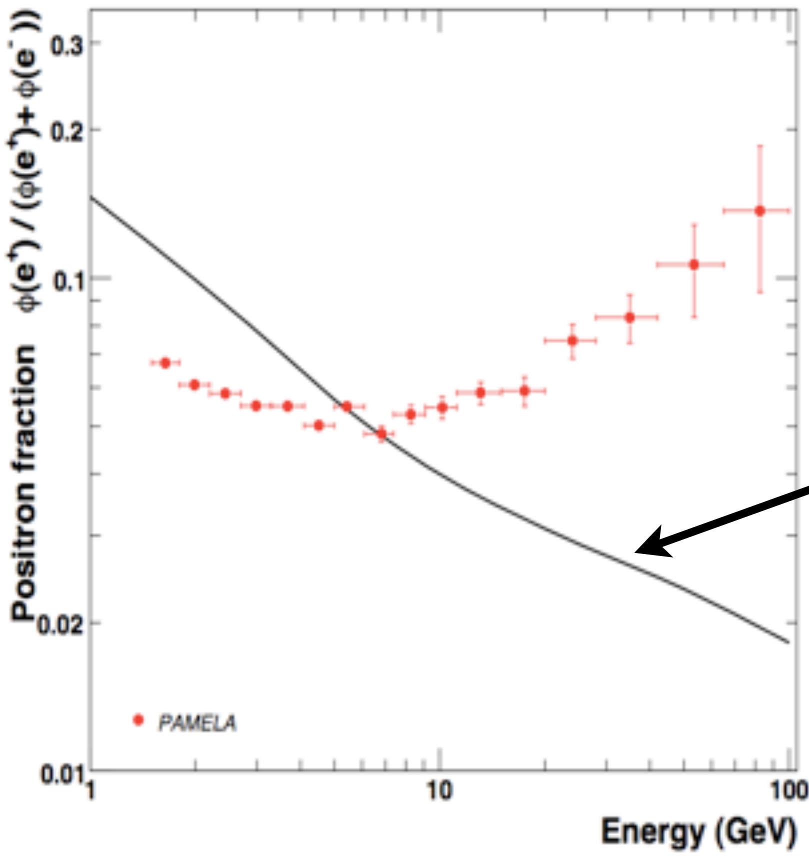
Direct detection

CDMS, DAMA/LIBRA, XENON,
CRESST, LUX, COUPP, KIMS, ...

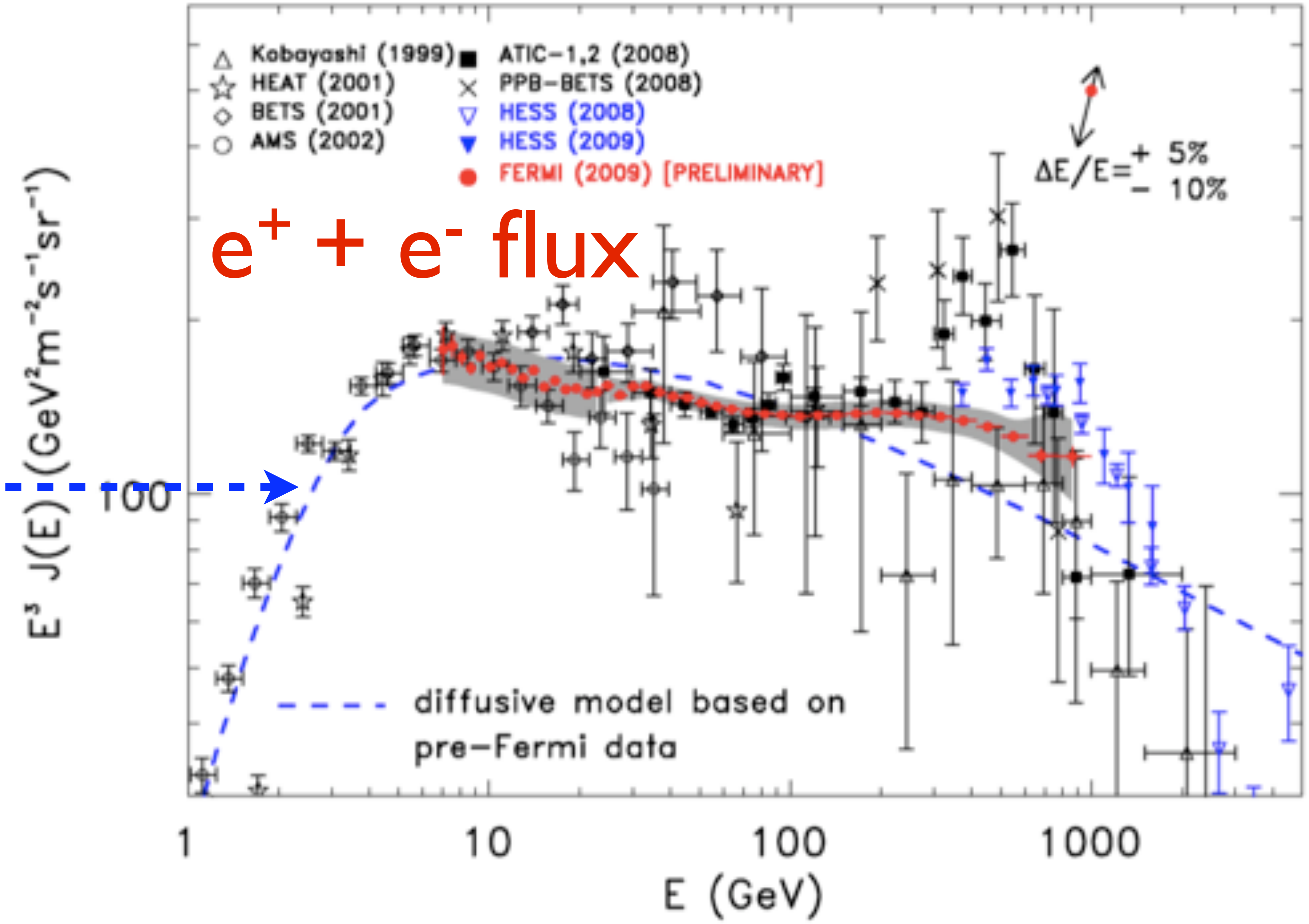
Abundance of data suggests non-gravitational interactions

PAMELA satellite

Fermi satellite



theory expectation

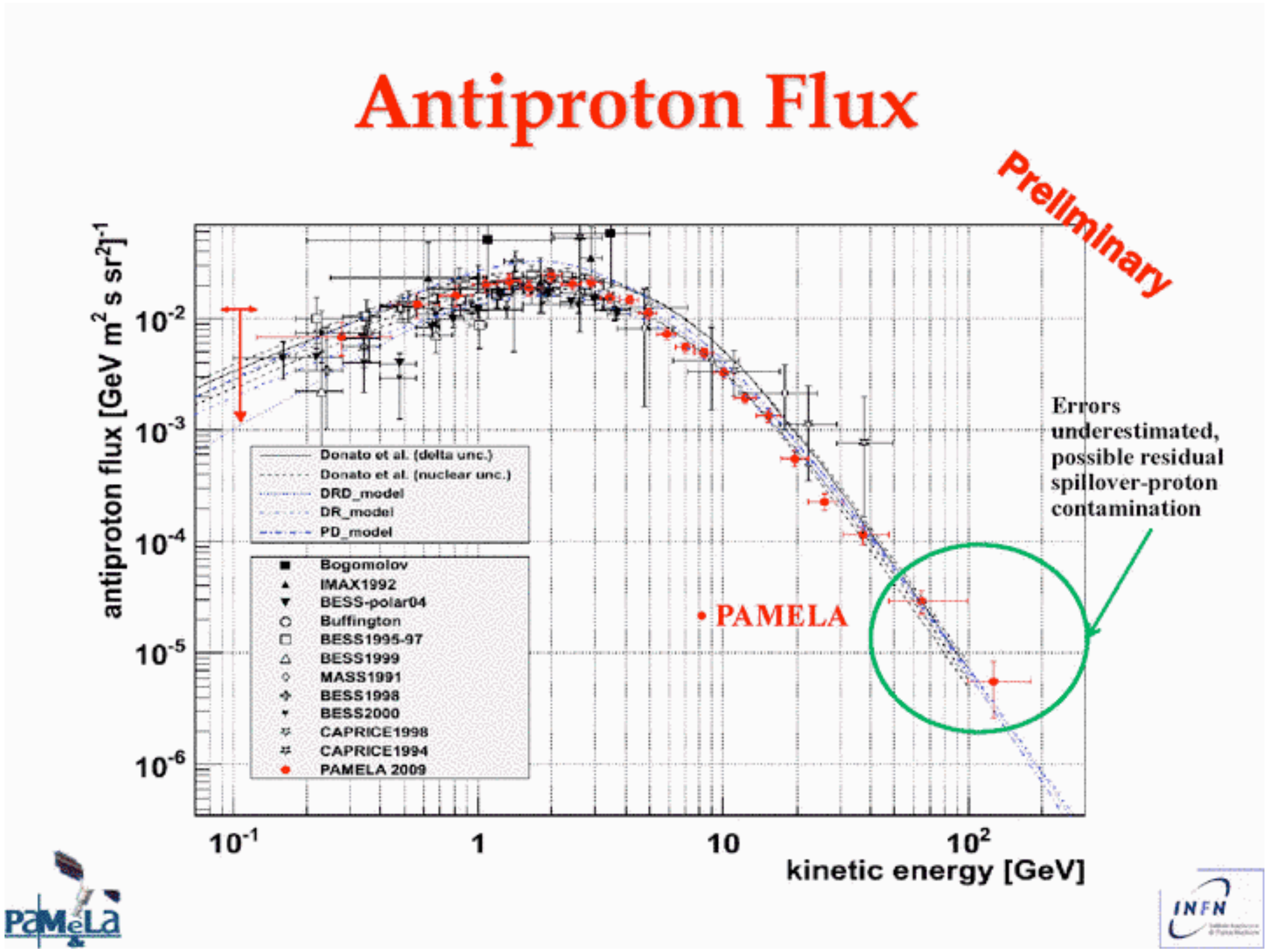


Excesses at high energies ~100–1000 GeV

Very suggestive of DM annihilation

DM must couple to ordinary matter, but how?

No antiproton excess



PAMELA satellite

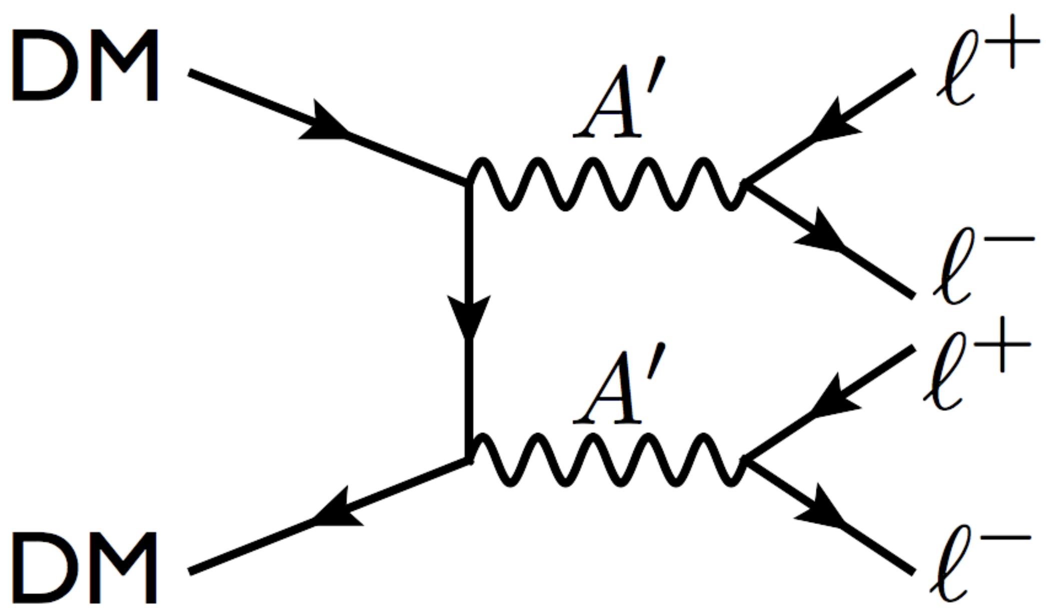
Lack of excess forbids DM annihilation to hadrons

Slide from M. Boezio KITP DM workshop

Anomalies imply DM annihilation into leptons

A new force carrier A' with $m_{A'} \lesssim 1\,\mathrm{GeV}$ mediating the annihilation naturally gives only leptons from simple kinematics

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

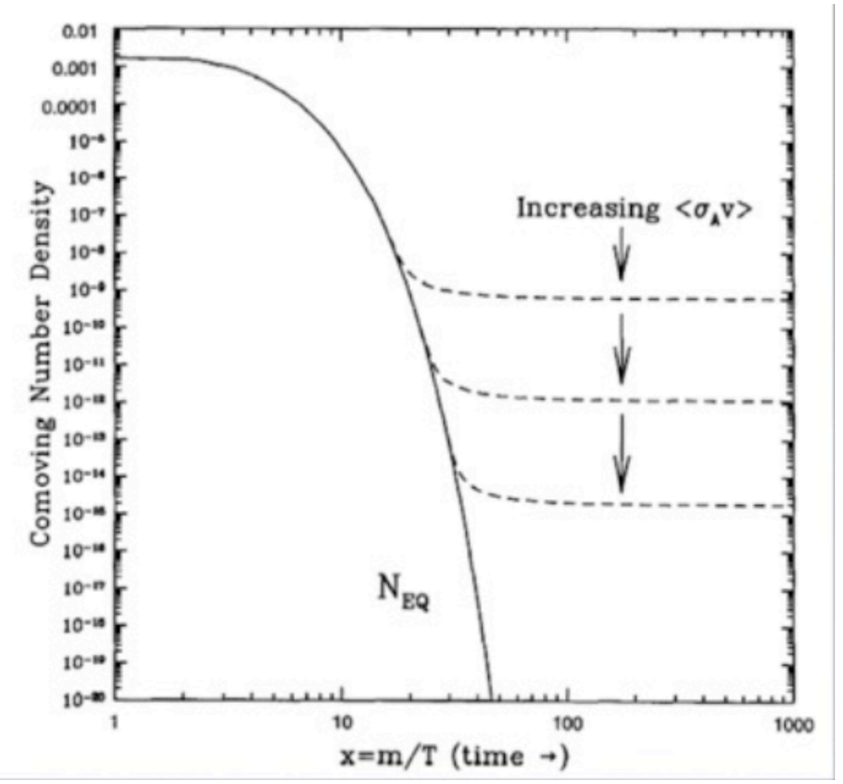


produces leptons, no anti-protons!

Need large boost factors to fit anomalies

DM relic abundance is determined in early Universe:

$$\Omega_{\rm DM} \propto \frac{1}{\langle \sigma v \rangle}$$



If $\langle \sigma v \rangle$ is too large, then $\Omega_{\rm DM}$ is too small

To fit cosmic-ray e^+ & e^- excess requires:

$\langle \sigma v \rangle$ ~100-1000 times too large to obtain correct $\Omega_{\rm DM}$

Light A' mediates long-range force

Sommerfeld enhancement

[e.g. Arkani-Hamed et.al;
Pospelov, Ritz; Hisano et.al;
March-Russell et.al;
Cirelli et.al]

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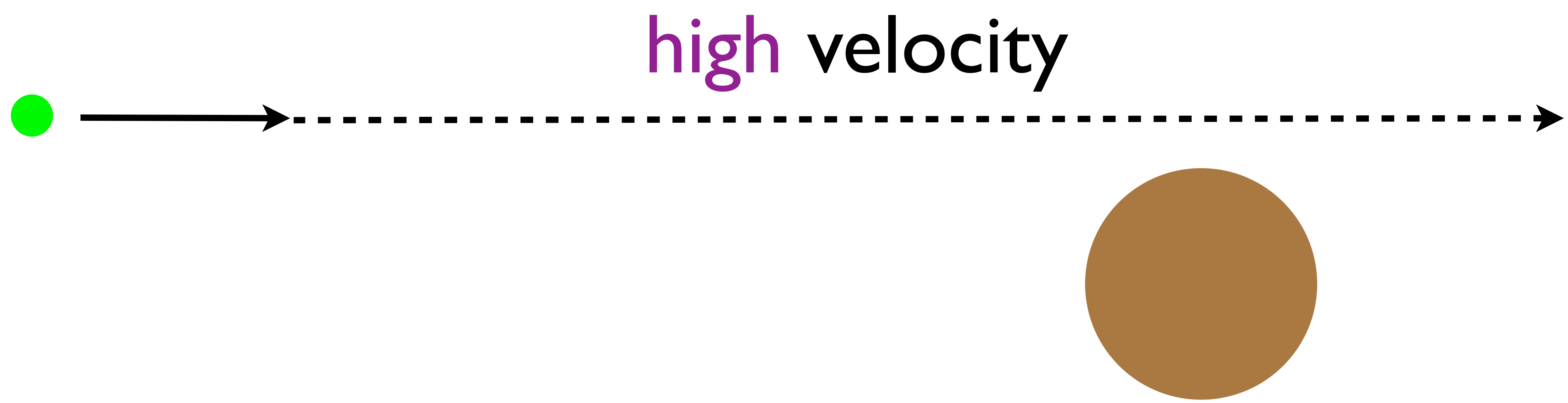

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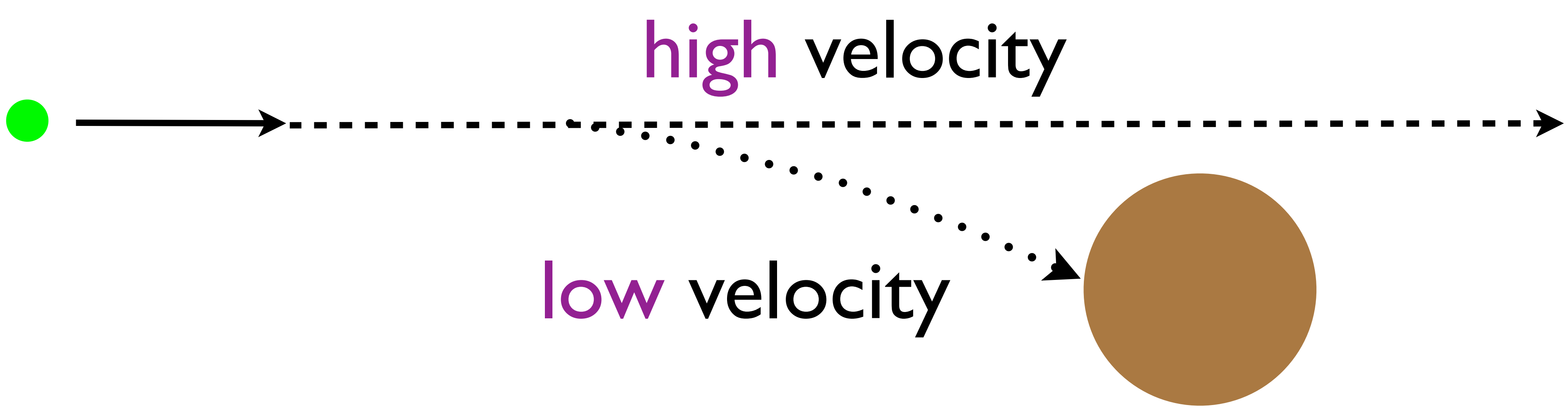

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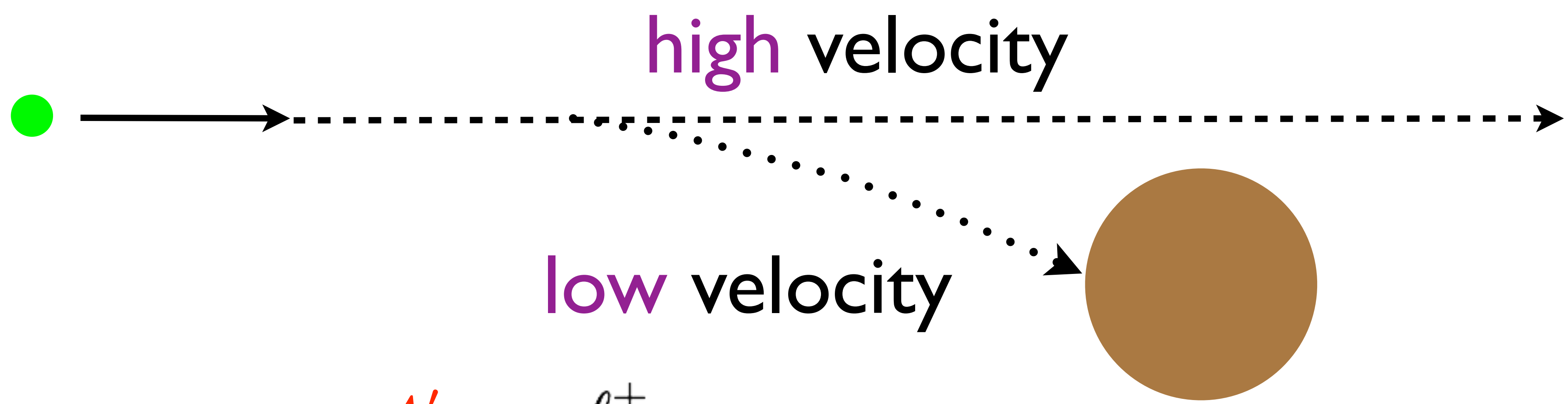
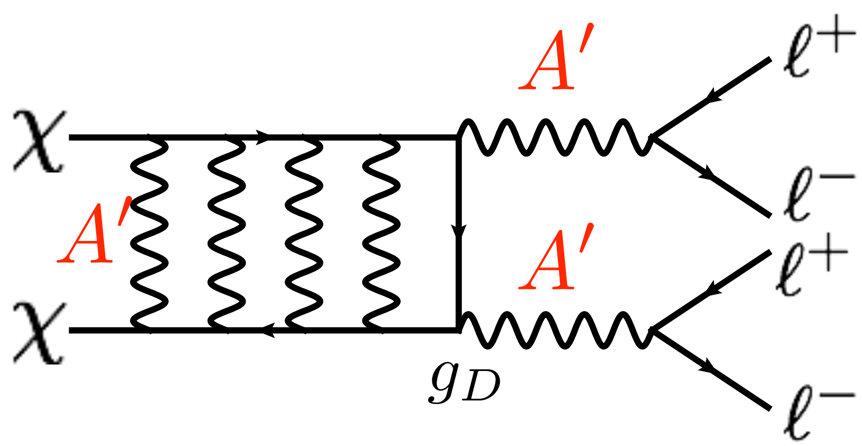


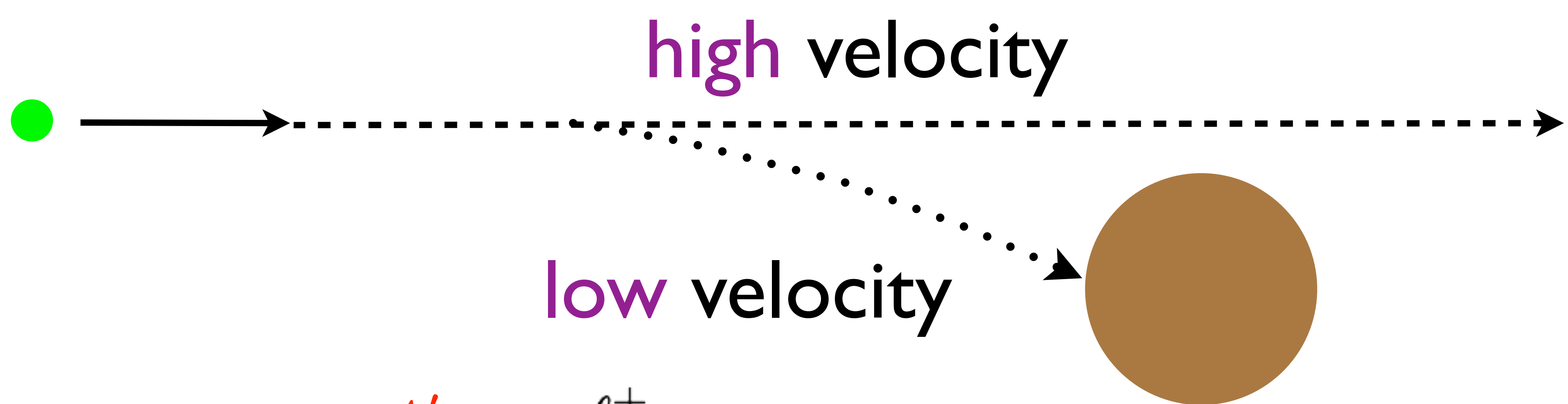


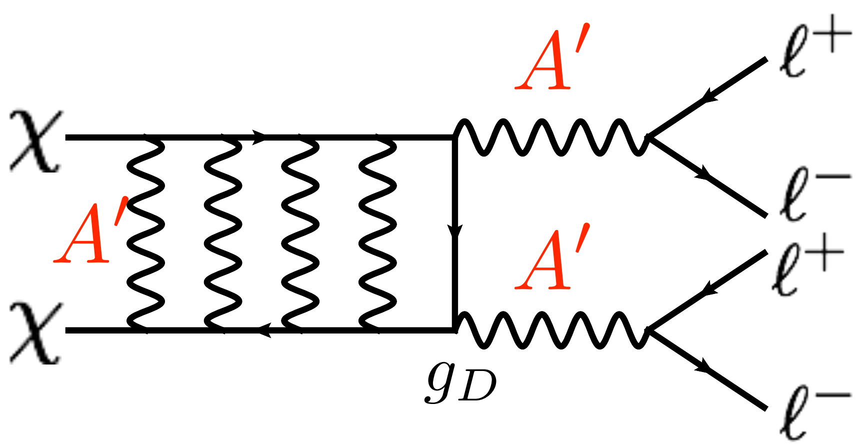
$$\langle \sigma v \rangle \propto \frac{1}{v}$$

Light A' mediates long-range force

Sommerfeld enhancement

[e.g. Arkani-Hamed et.al; Pospelov, Ritz; Hisano et.al; March-Russell et.al; Cirelli et.al]





$$\langle \sigma v \rangle \propto \frac{1}{v}$$

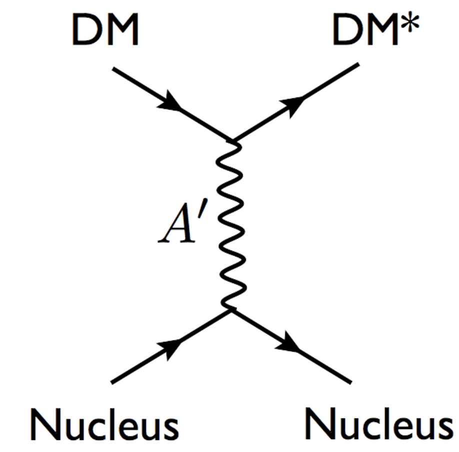
Today in halo: v small, so $\langle \sigma v \rangle$ is large

In Early Universe: v large, so $\langle \sigma v \rangle$ is small

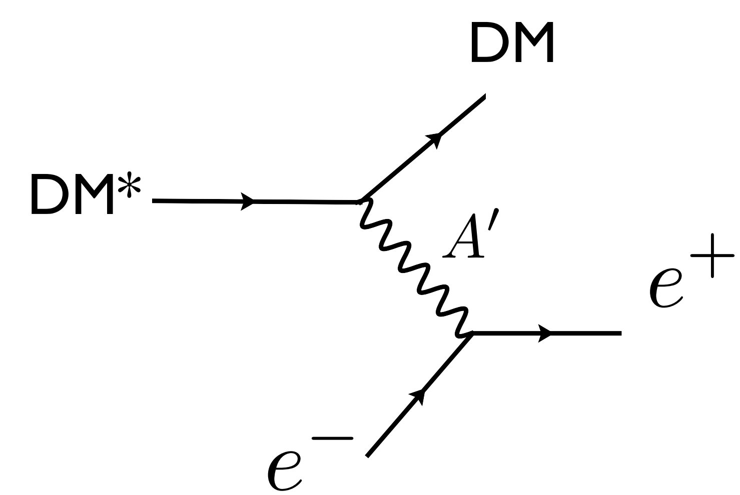
can obtain correct relic abundance & explain anomalies

Further hints for new forces

Many other Dark Matter anomalies:



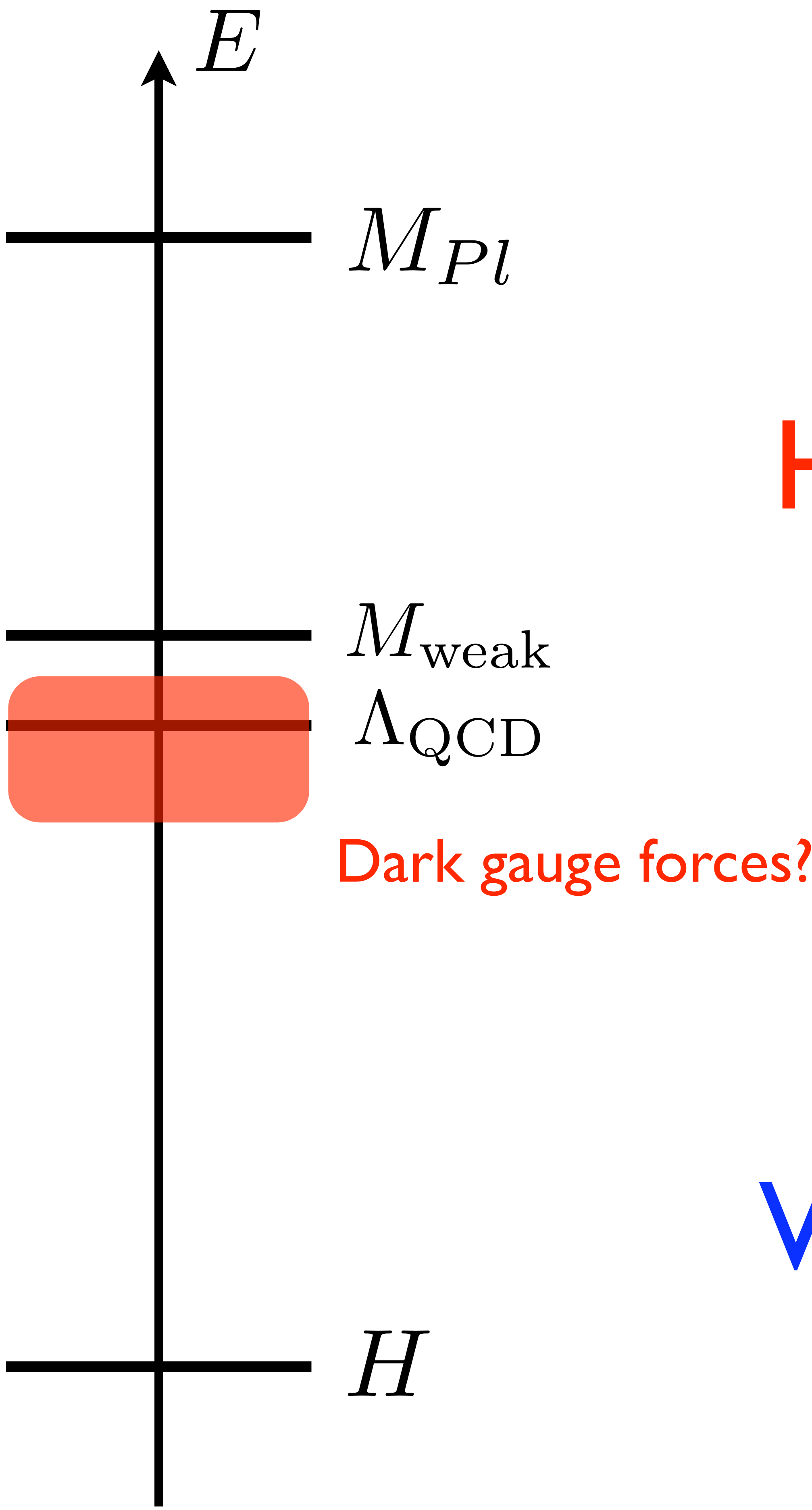
- WMAP+Fermi "Haze"
  [Finkbeiner, Dobler et.al.]
- DAMA/LIBRA annual modulation
  [Bernabei et.al., Tucker-Smith & Weiner]
- INTEGRAL 511 keV line
  [Finkbeiner & Weiner]



Other hints:

- anomalous muon g-2 [Pospelov]

Irrespective of anomalies: new GeV–scale force carriers are important category of new physics



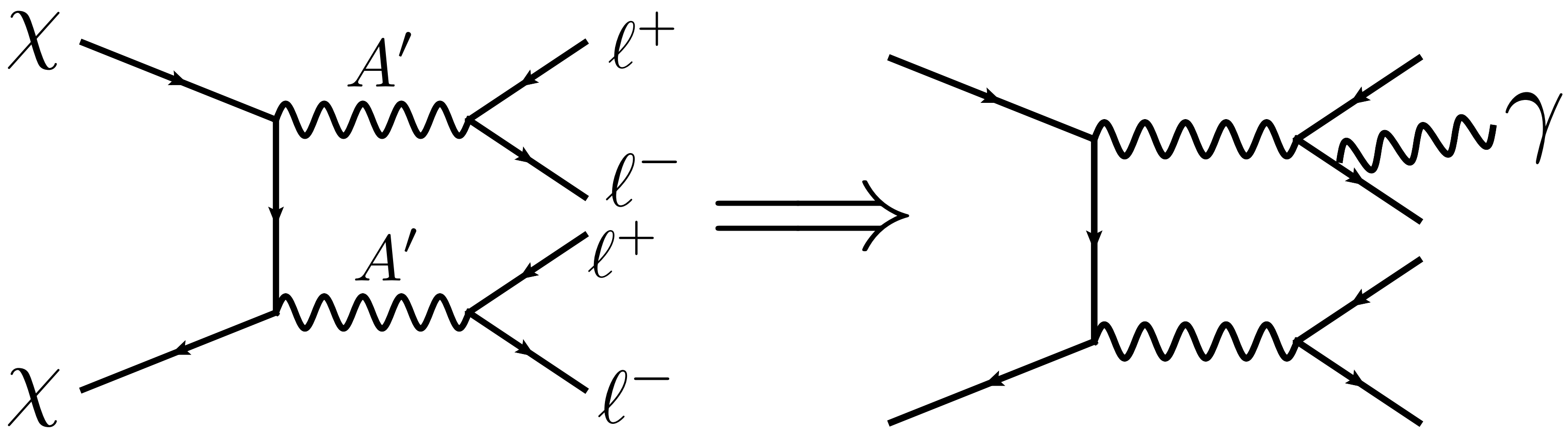
Remainder of Talk:

How can we probe for such New Forces?

Will discuss three ways

Experimental Probes of Dark Forces

A)



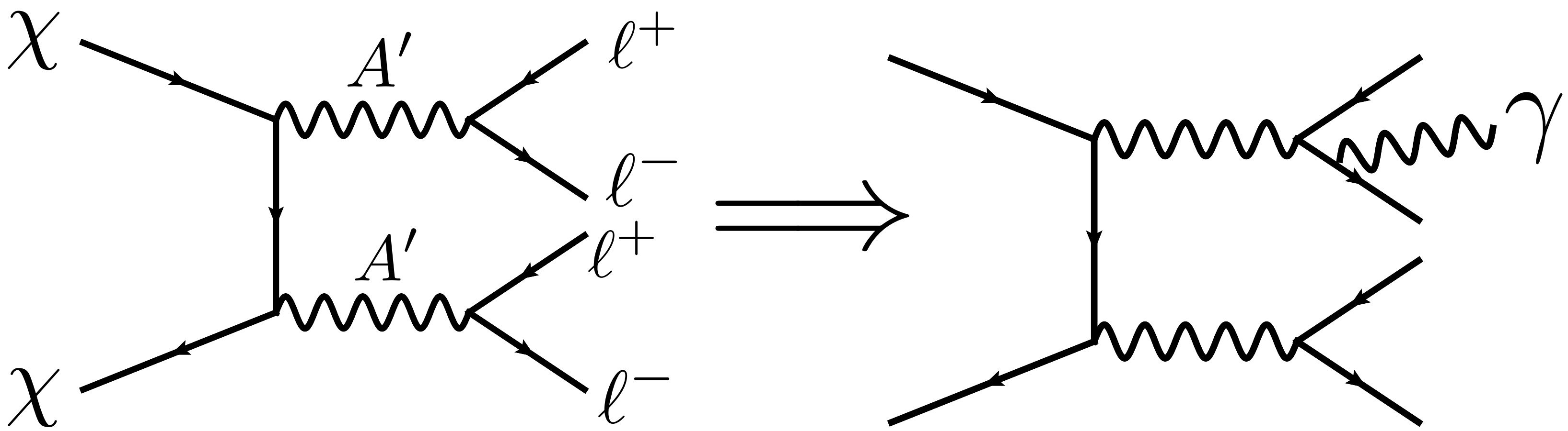
γ-rays guaranteed!

(Fermi, ACT's)

Dwarf galaxies: excellent targets

Experimental Probes of Dark Forces

A)



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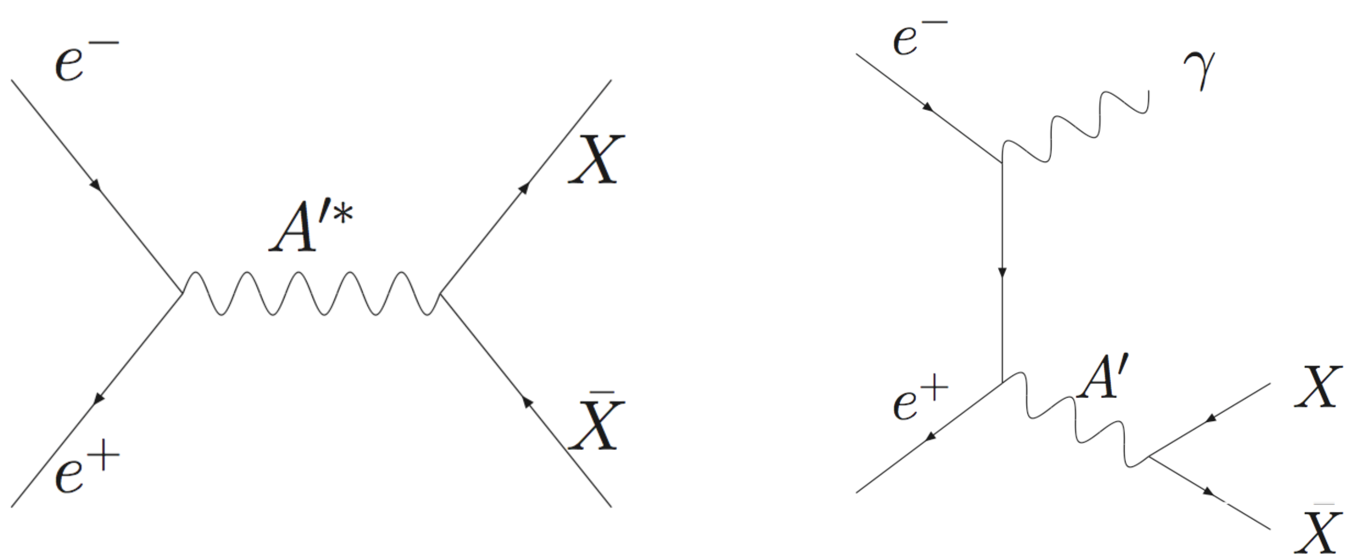
B)



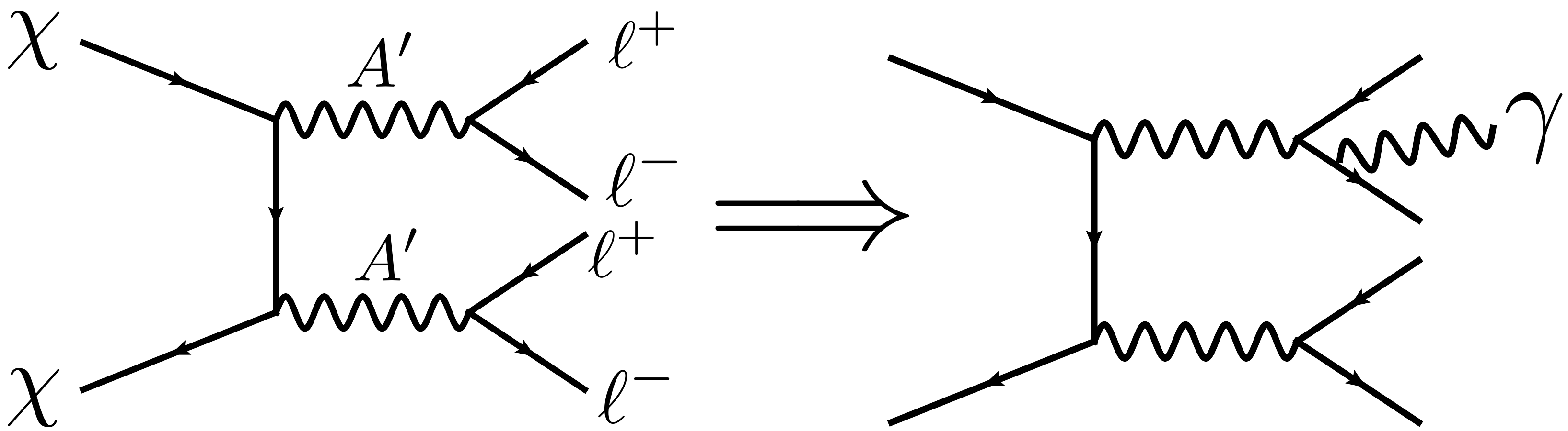
e^+e^- Colliders

(BaBar, BELLE, CLEO, KLOE)

X = dark gauge/higgs bosons, pions, etc.

Experimental Probes of Dark Forces

A)



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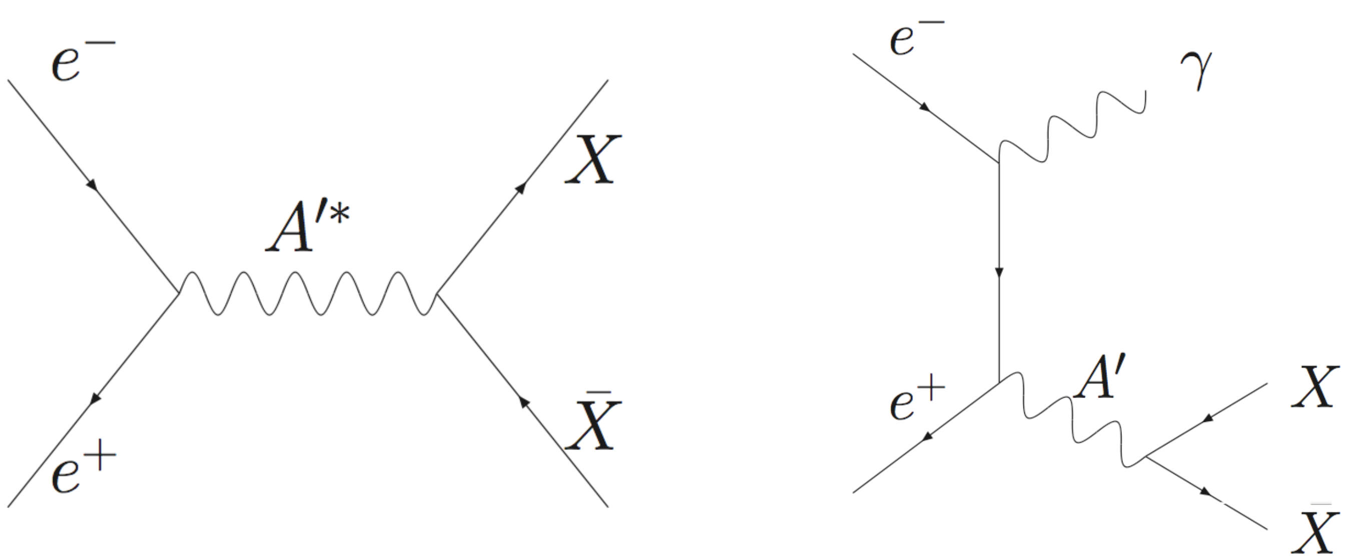

e$^+$e$^-$ Colliders

(BaBar, BELLE, CLEO, KLOE)

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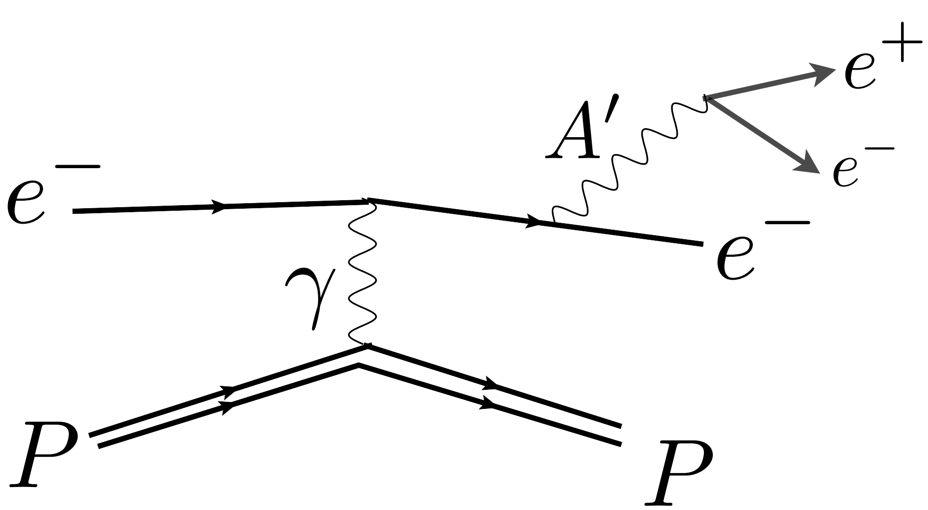
C)



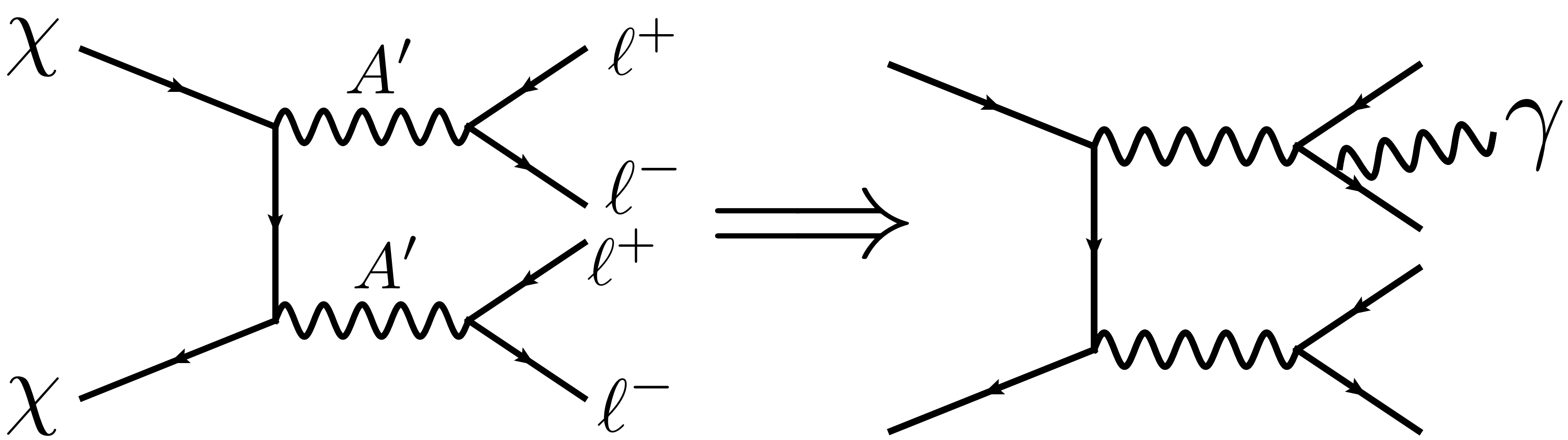
Fixed Target Experiments

(E137, JLab, SLAC, FNAL, MINOS, COMPASS)

Indirect probe: γ-rays from Dwarfs

[RE, Sehgal, Strigari]

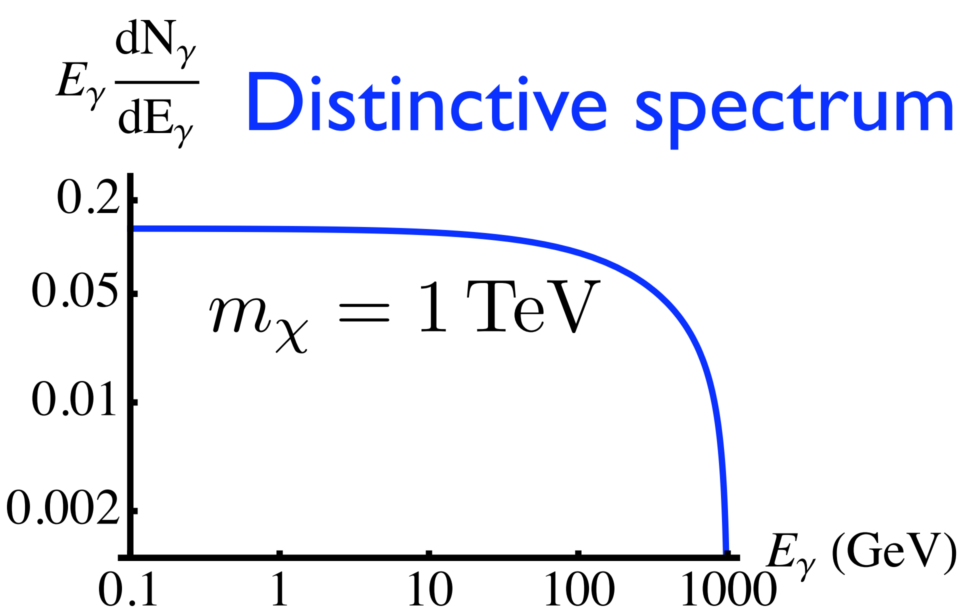
[RE, Sehgal, Strigari, Geha, Simon]



γ-rays guaranteed!

[Beacom et.al.; Birkedal, Matchev, Perelstein, Spray; Bringmann et.al.]

Distinctive spectrum



Observe with:

- Fermi LAT
- Atmospheric Cherenkov Telescopes (MAGIC, VERITAS, HESS)

$\nu' s$ also possible (IceCube)

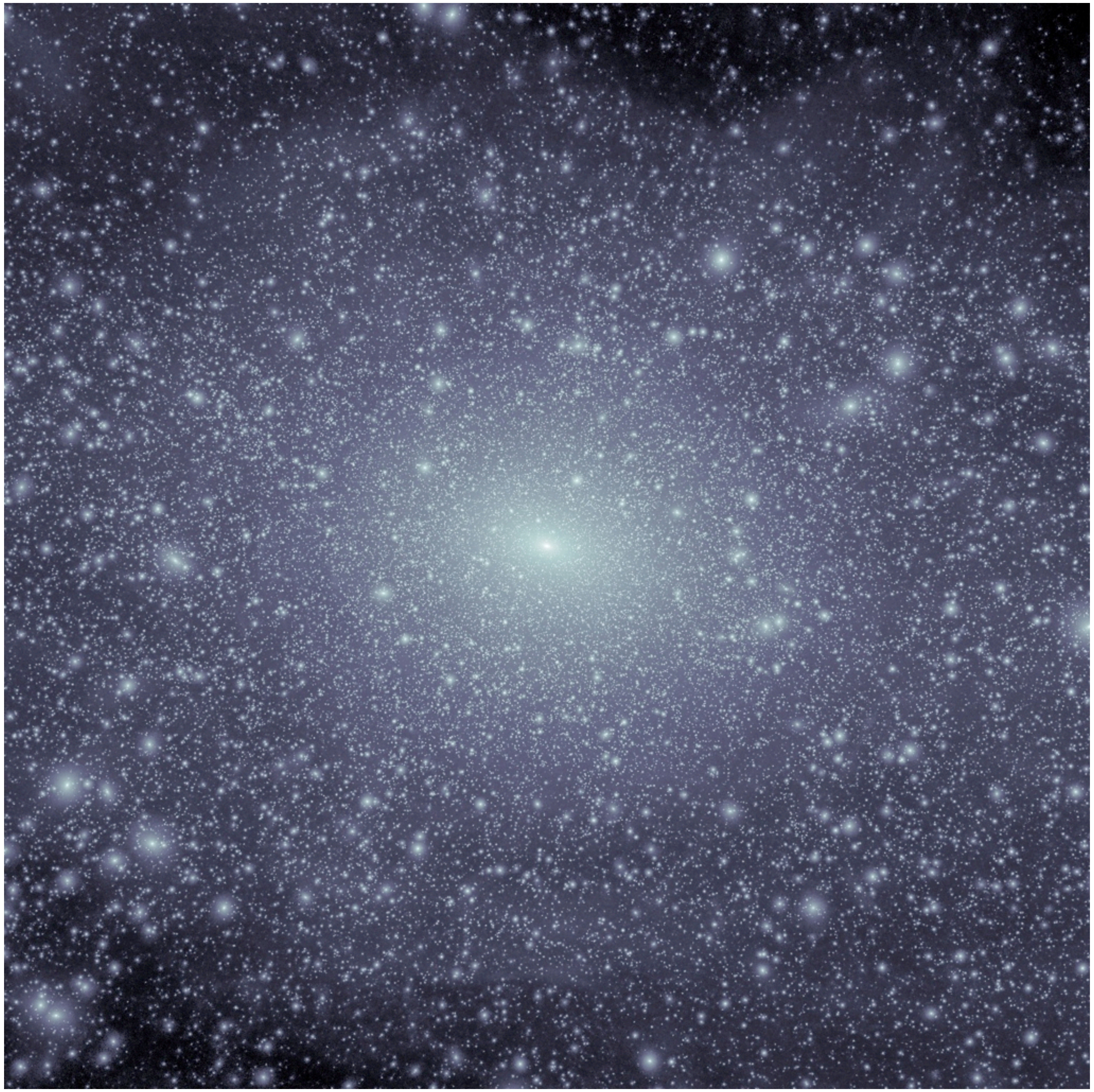
Why dwarfs?

A Milky-Way DM Halo

[Diemand et.al.]

Via Lactea II
Simulation

(only DM, no baryons)



800 kpc cube

A Milky-Way DM Halo

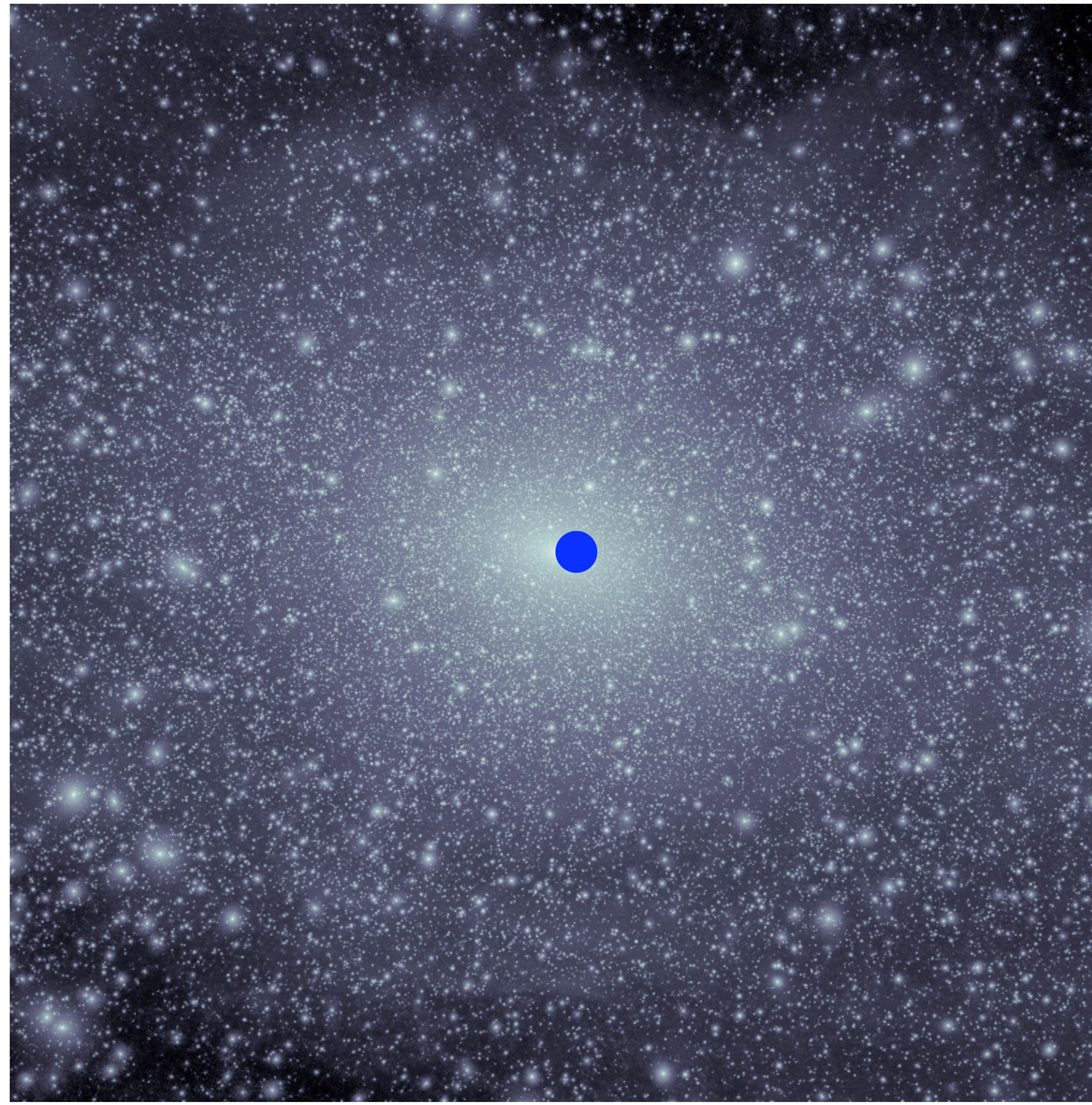
[Diemand et.al.]

Via Lactea II
Simulation

(only DM, no baryons)

visible Milky Way galaxy ~30 kpc

some subhalos will form stars and become dwarf galaxies



800 kpc cube

Dwarf galaxies: Excellent Targets

Sizeable Signal

- Nearby, DM dominated
- use stellar kinematics to determine expected flux
- low velocity dispersion: $v_{\rm dwarf} \sim v_{\rm halo}/20$

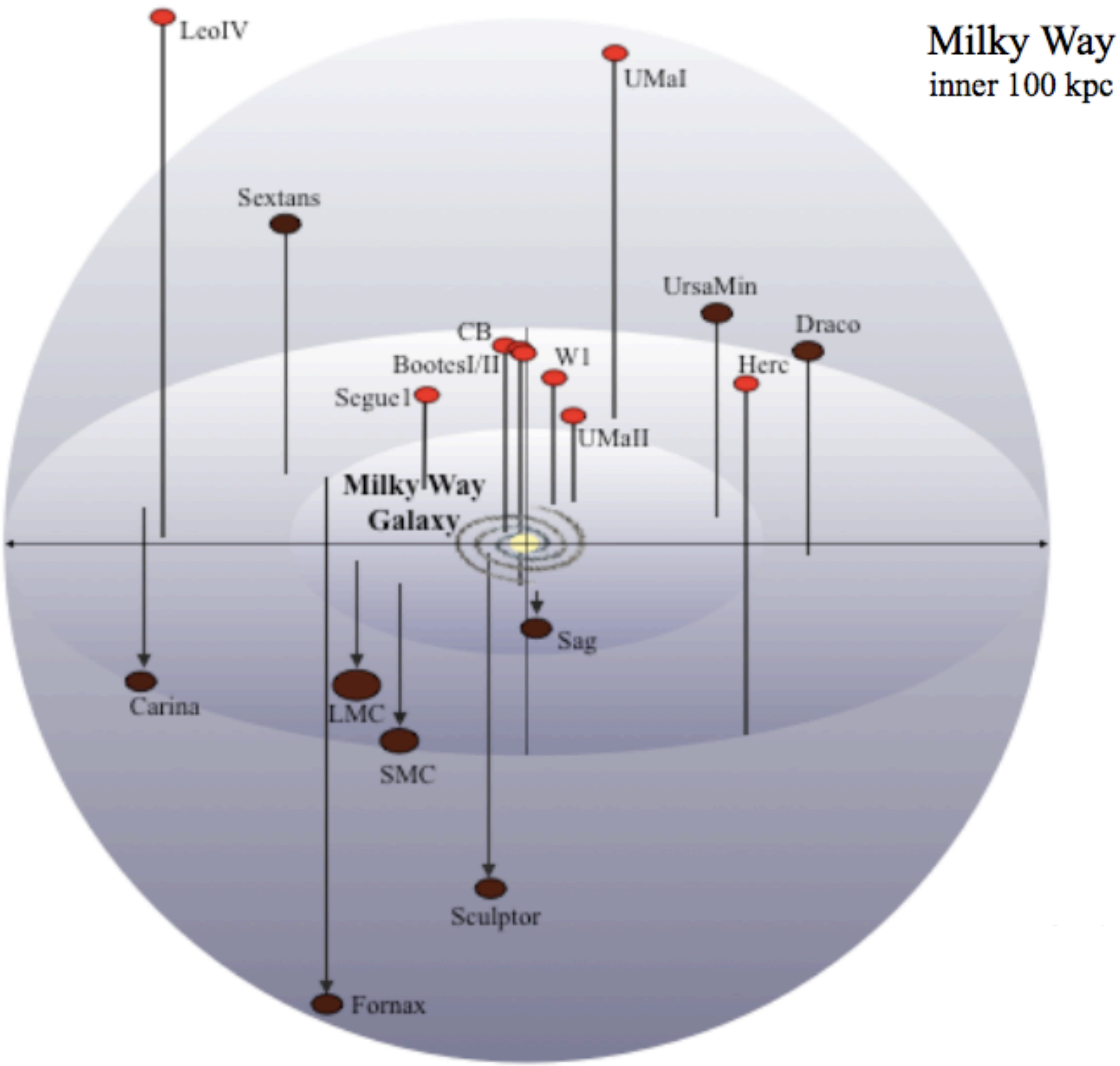
  (Sommerfeld enhanced DM annihilation?)

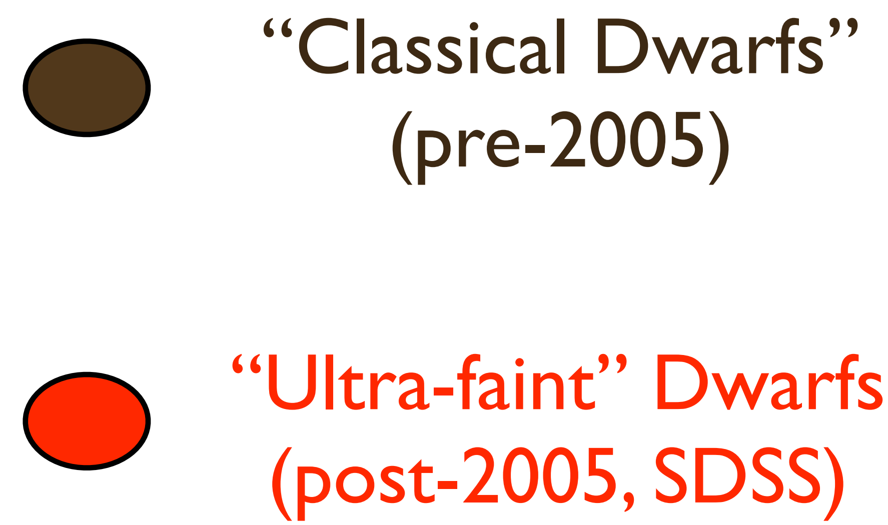
Low Background

- high galactic latitude
- no intrinsic gamma-ray sources

Any signal would be *very* suggestive of dark matter

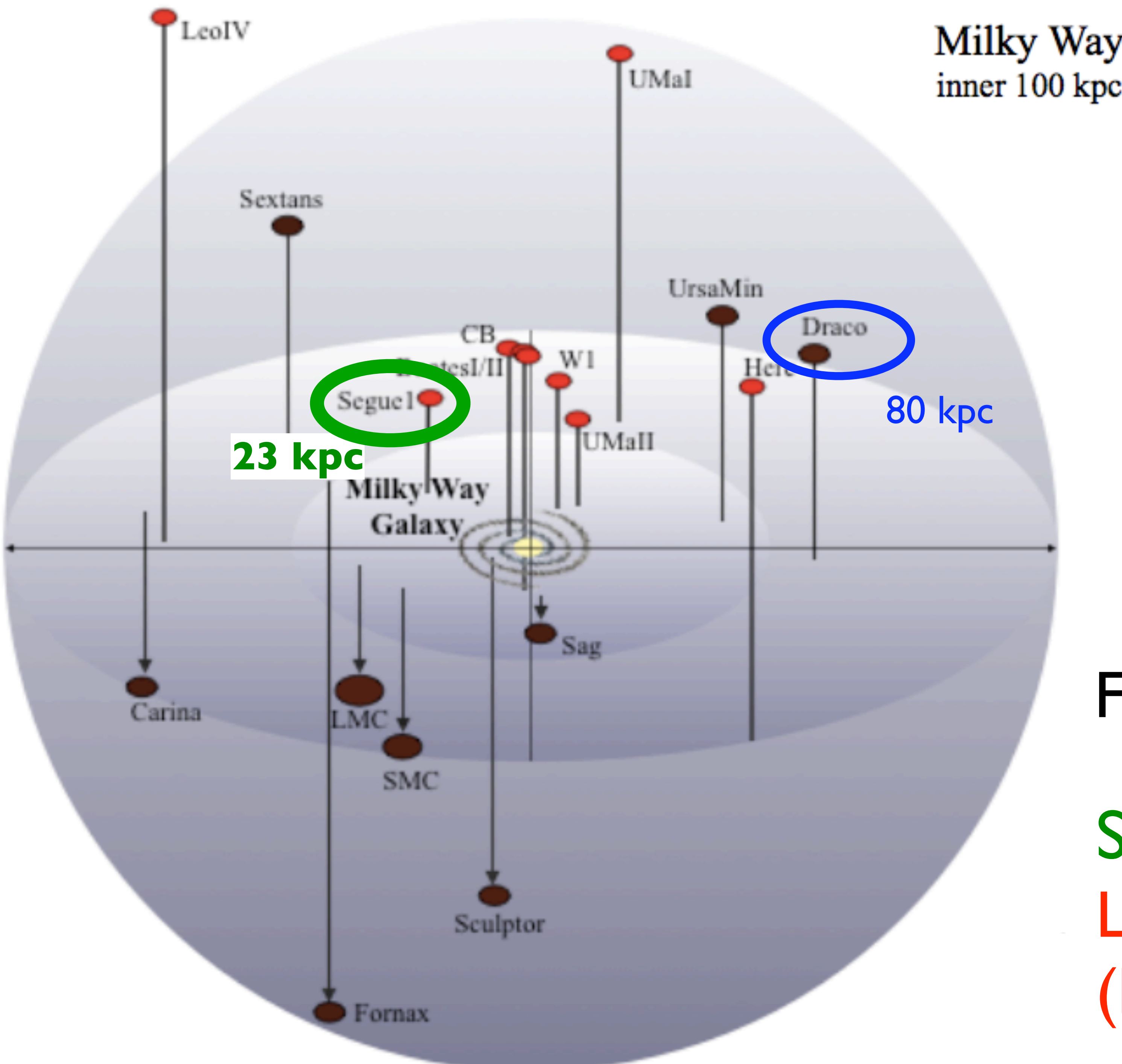
Known Nearby Dwarf Galaxies





[Geha]

Known Nearby Dwarf Galaxies



[Geha]

"Classical Dwarfs" (pre-2005)

"Ultra-faint" Dwarfs (post-2005, SDSS)

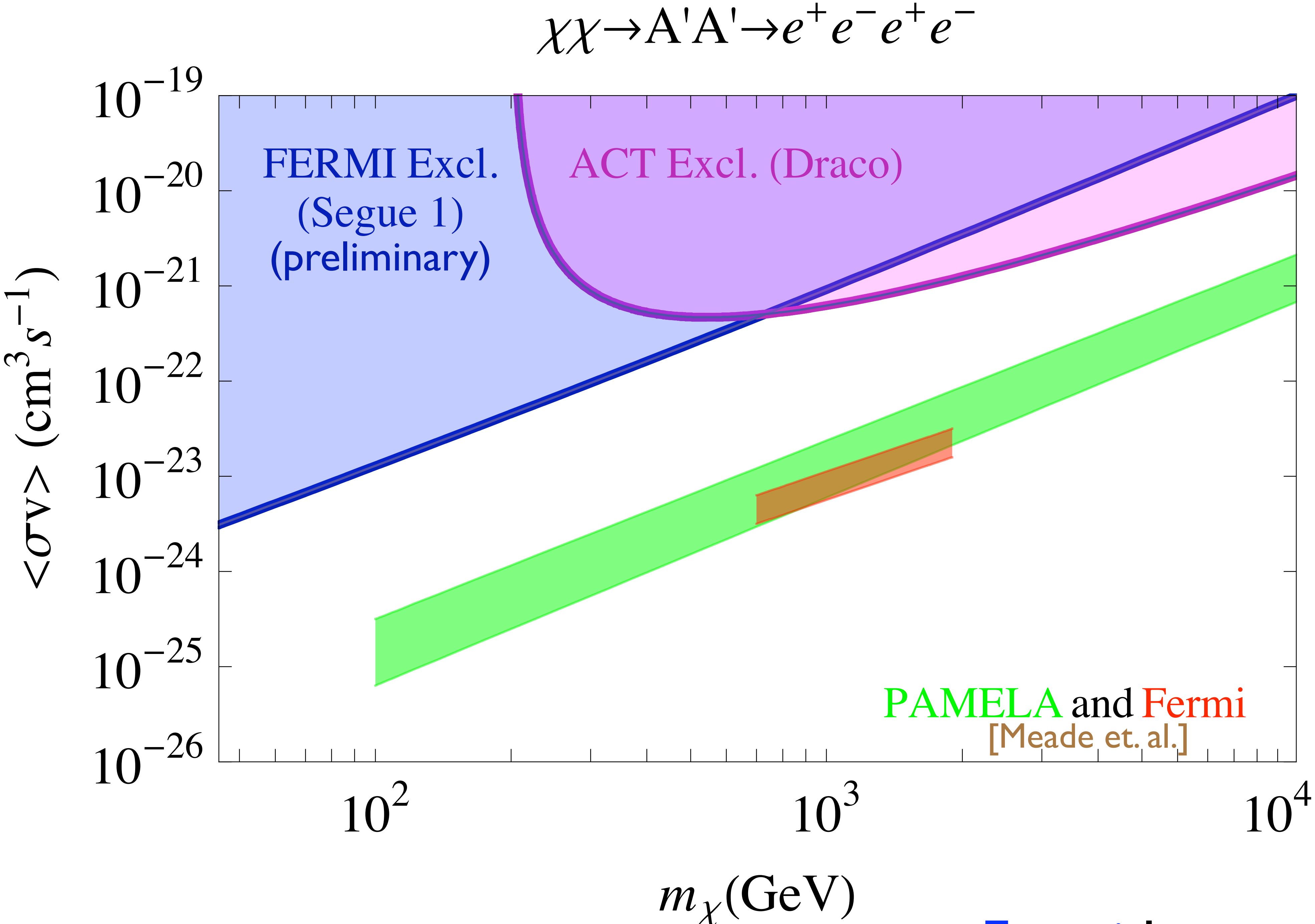
Focus on Draco and Segue 1

Segue 1: best dwarf target?
Least luminous galaxy known (M/L~1000) [Geha et.al.]

MAGIC & VERITAS are analyzing data!

Current Fermi & ACT limits

[RE, Sehgal, Strigari, Geha, Simon]



Fermi data:

9 months of data

[Farnier, RICAP'09]
[Wang, CINC'09]

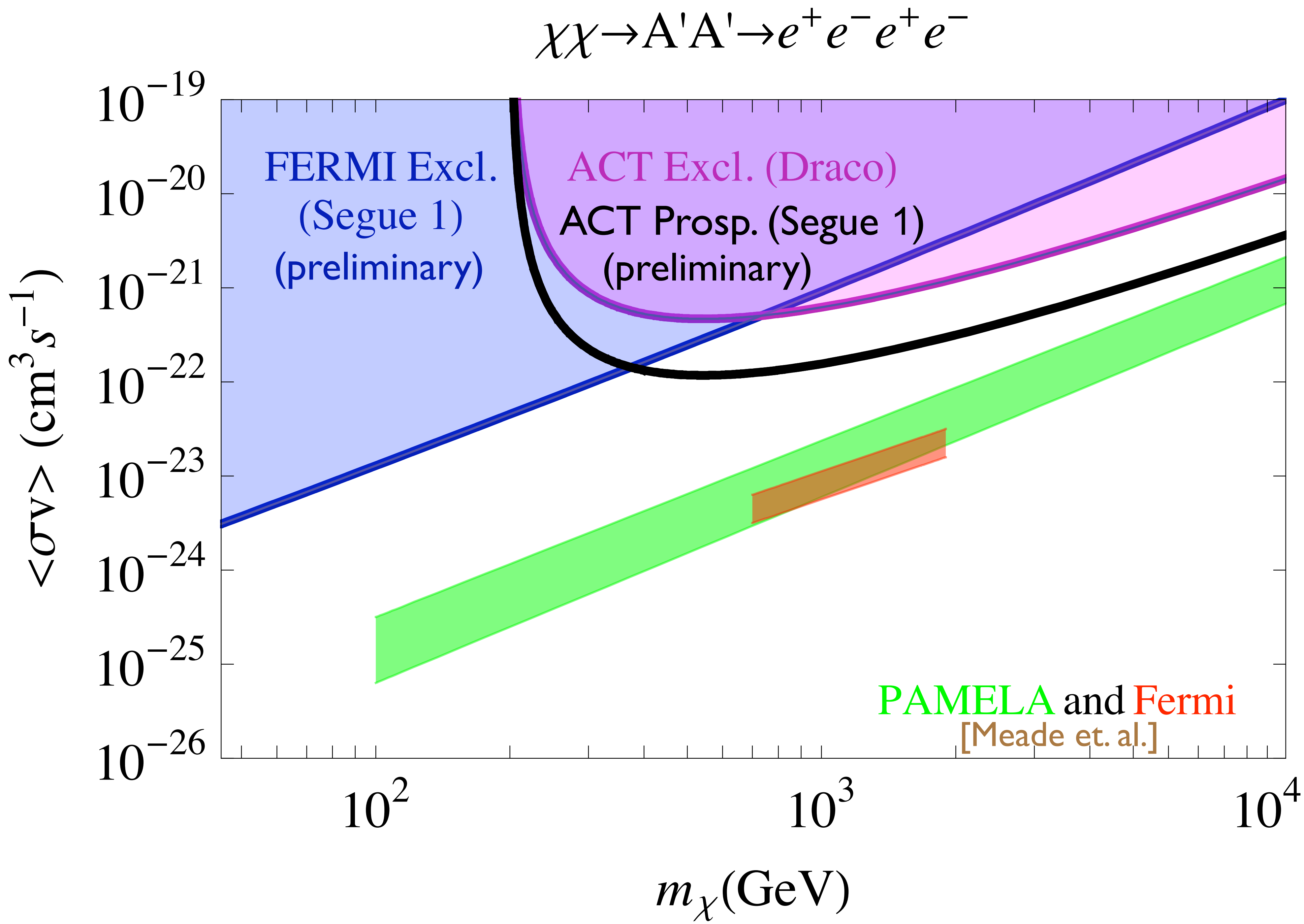
ACT data:

VERITAS obs. of Draco [0810.1913]

Fermi better at lower masses, ACTs at higher masses

Prospects for MAGIC & VERITAS from Segue 1

[RE, Sehgal, Strigari, Geha, Simon]



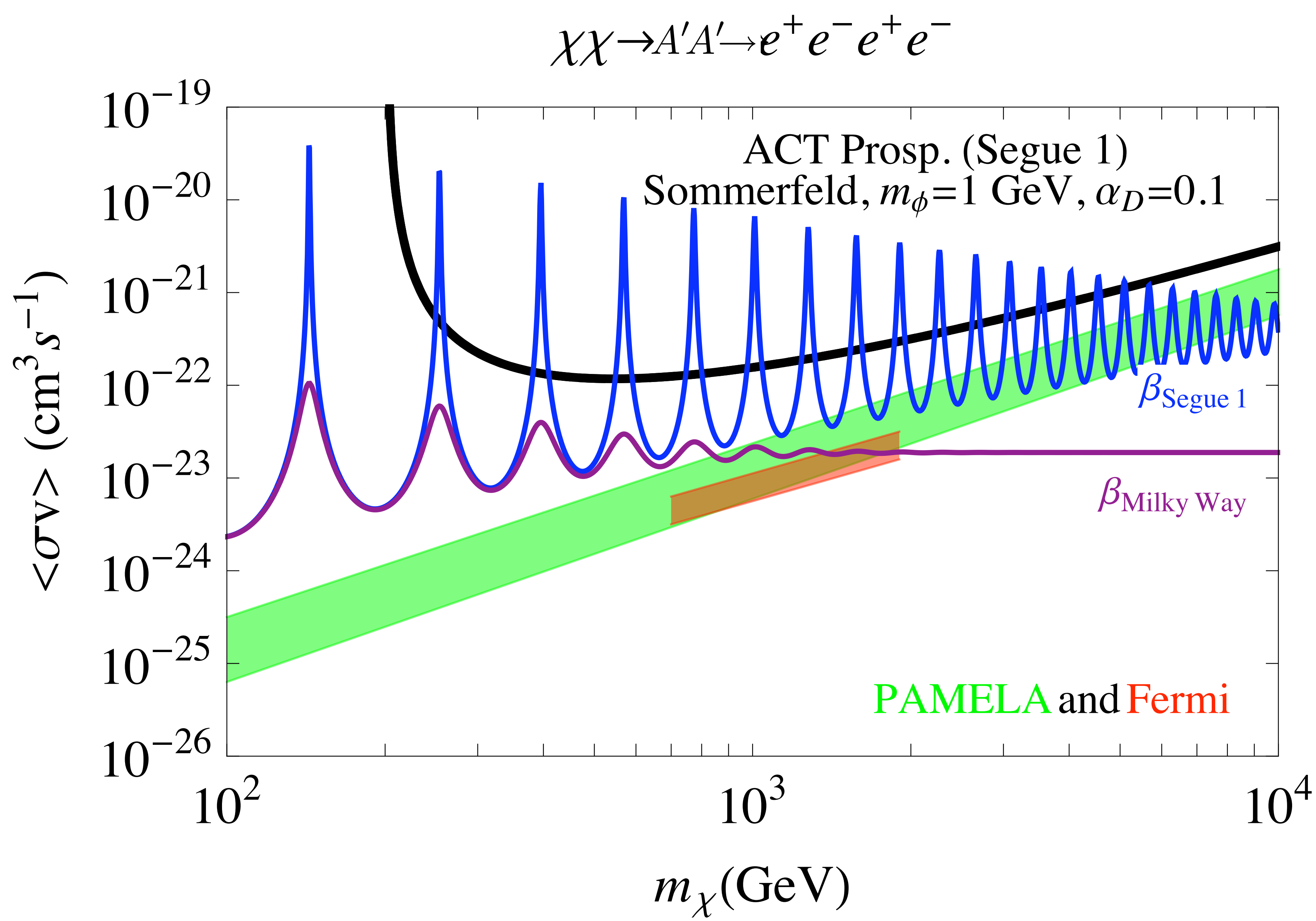
Constraining Sommerfeld enhancement

[RE, Sehgal, Strigari, Geha, Simon]

$$\frac{v_{\rm dwarf}}{v_{\rm halo}} \sim \frac{1}{20}$$

signal potentially enhanced at dwarf !

enhancement saturates when $v_\chi \lesssim m_{A'}/m_\chi$



$$m_{A'} = 1\,\text{GeV}$$

Will probe resonances

Constraining Sommerfeld enhancement

[RE, Sehgal, Strigari, Geha, Simon]

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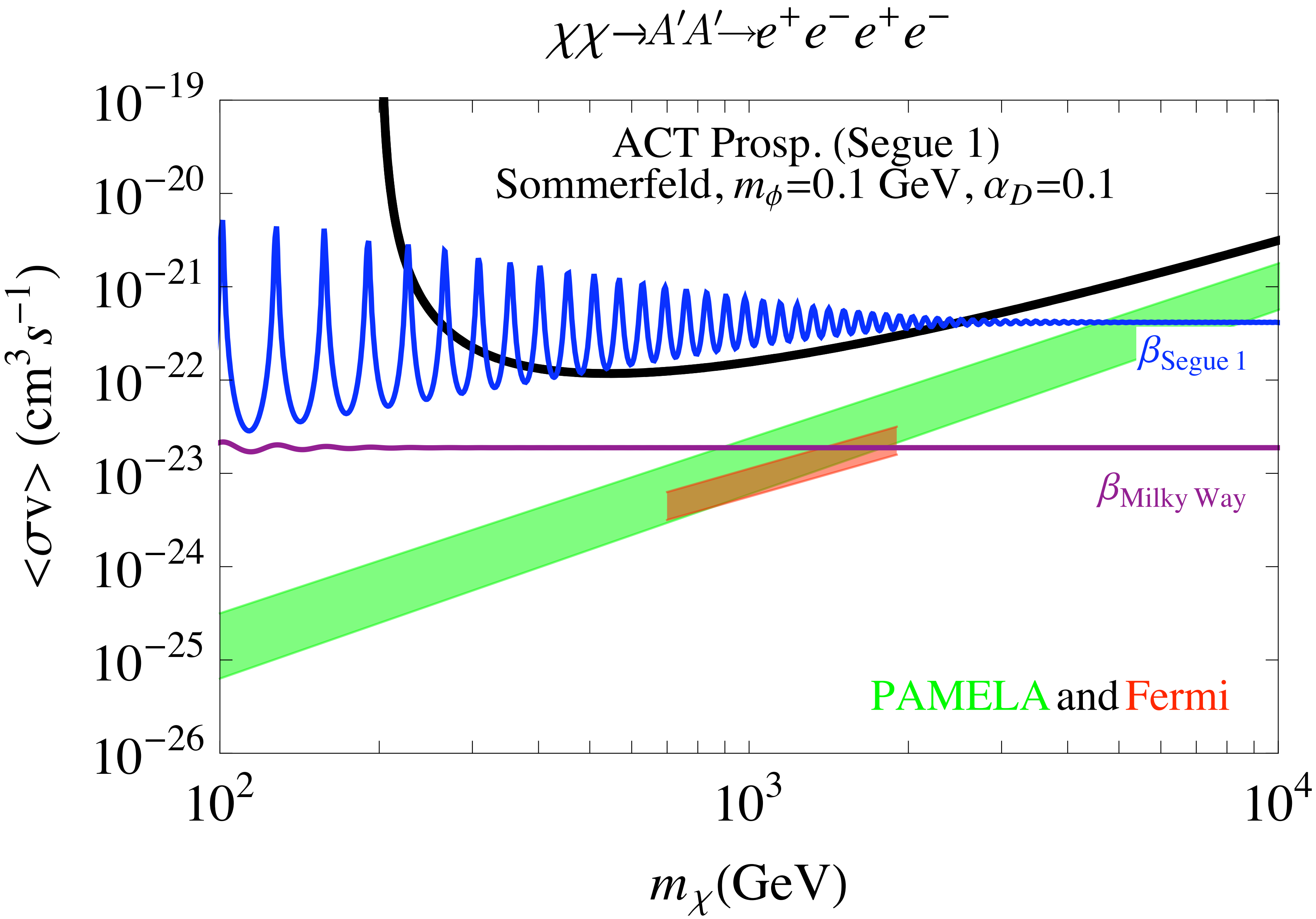


$m_{A'} = 0.1\,\mathrm{GeV}$

Intriguing prospects!

Can probe low-mass A's

Experimental Probes of Dark Forces

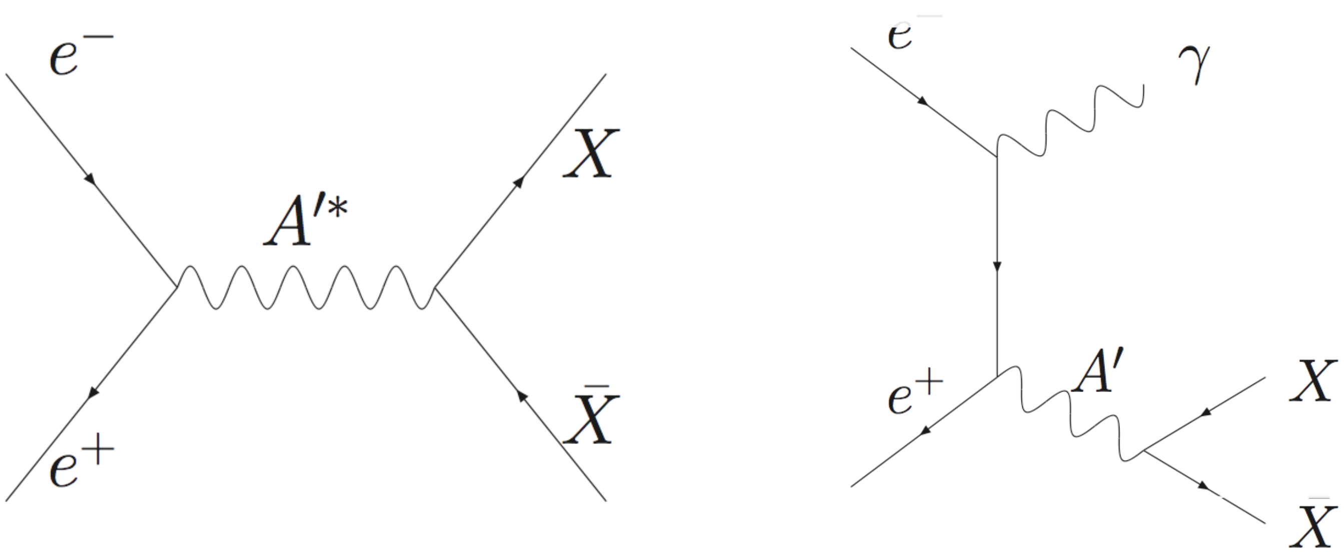
A)

γ-rays guaranteed!

(Fermi, ACT's)

Dwarf galaxies: excellent targets

B)



e^+e^- Colliders

(BaBar, BELLE, CLEO, KLOE)

X = dark gauge/higgs bosons, pions, etc.

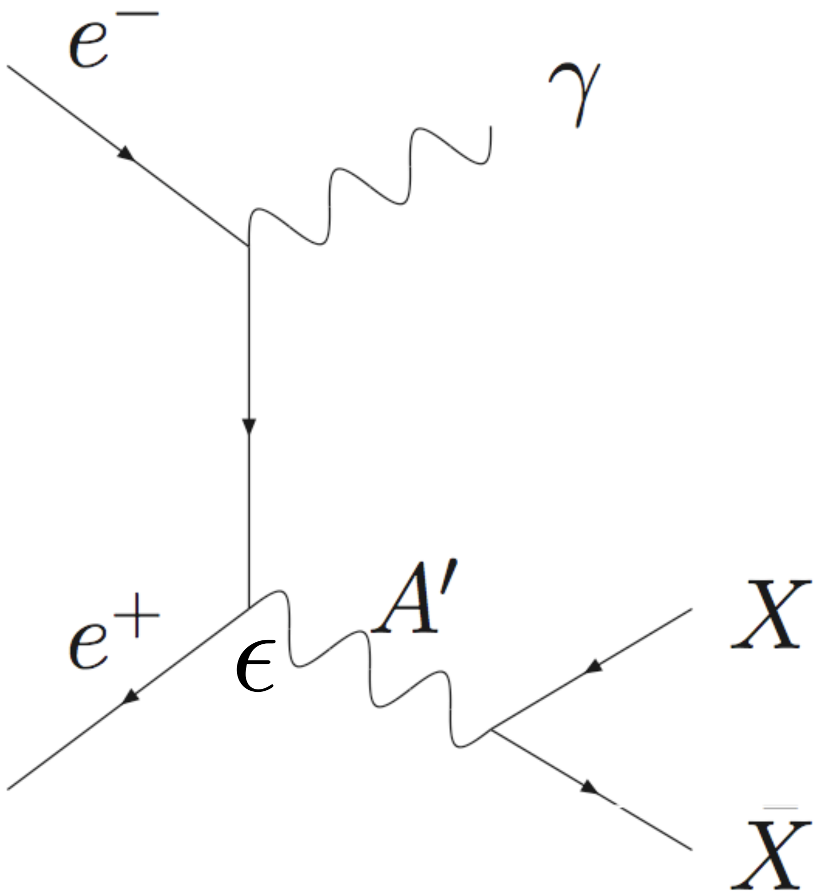
C)

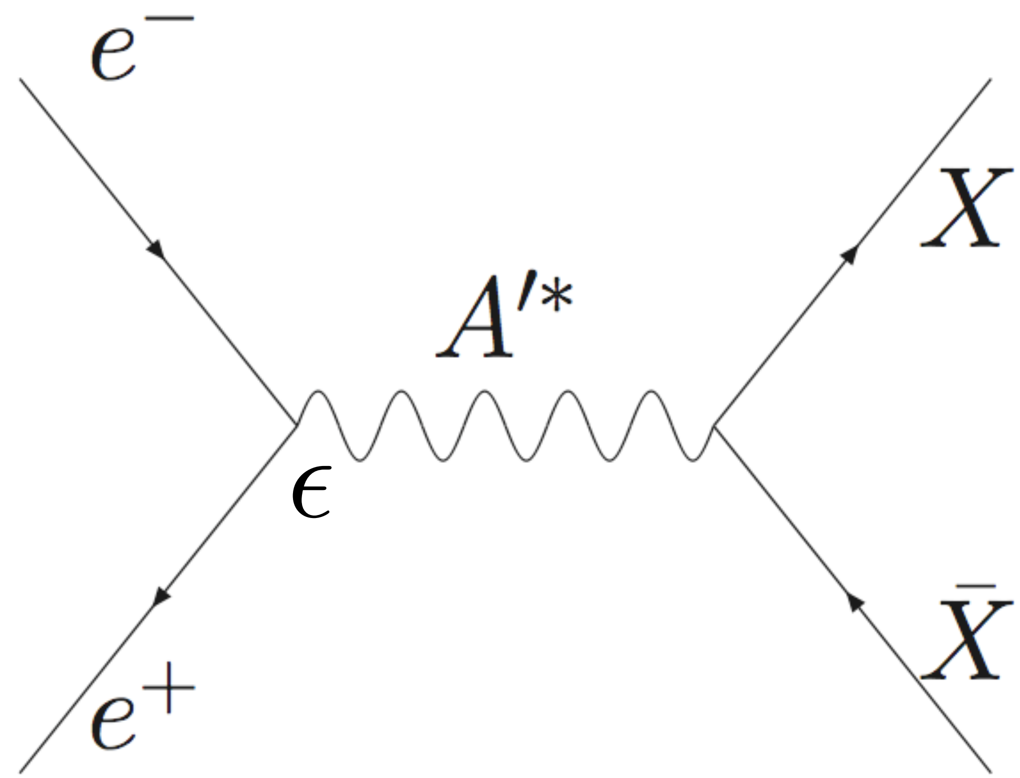
Fixed Target Experiments

(E137, JLab, SLAC, FNAL, MINOS, COMPASS)

Probe GeV-scale directly with e$^+$e$^-$ Colliders

[RE, Schuster, Toro]





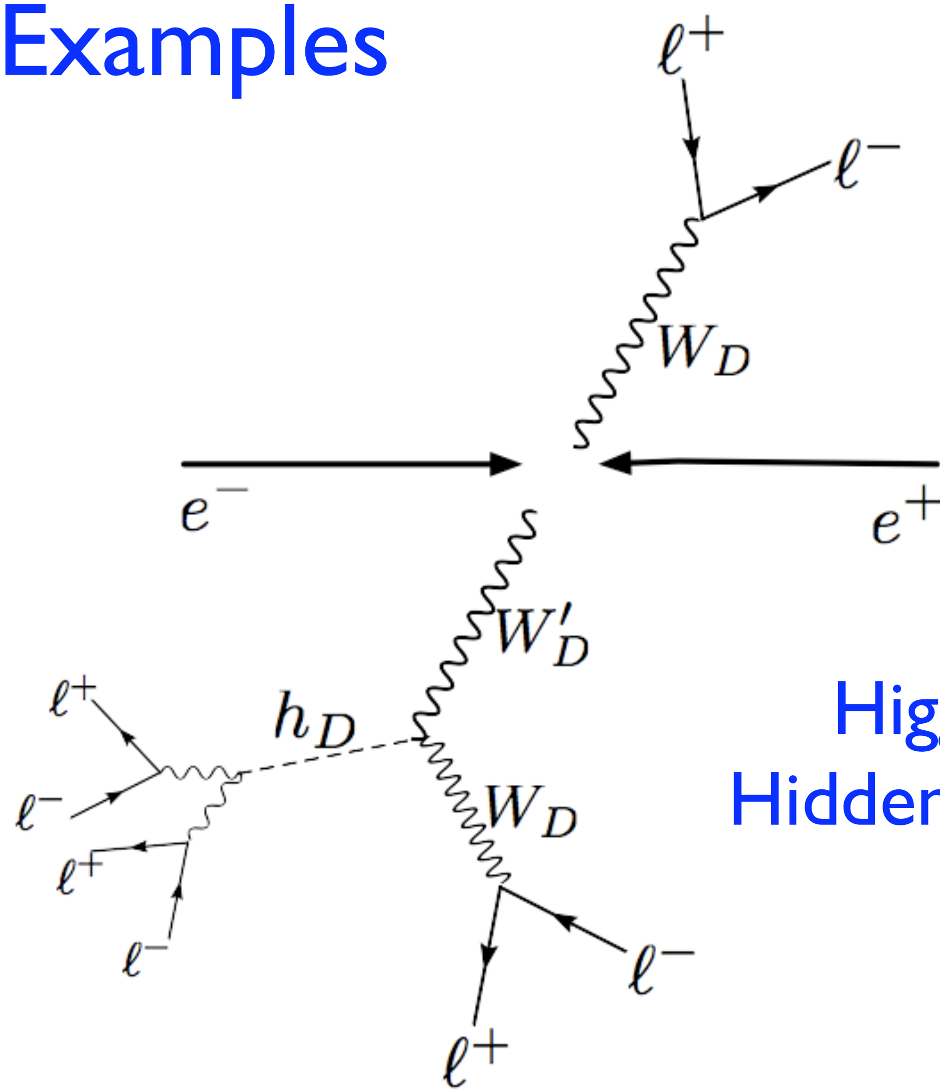
X = Standard Model or hidden-sector particle

$$\sigma \propto \frac{\epsilon^2}{E_{cm}^2} \Longrightarrow$$ want low-energy, high-luminosity collider

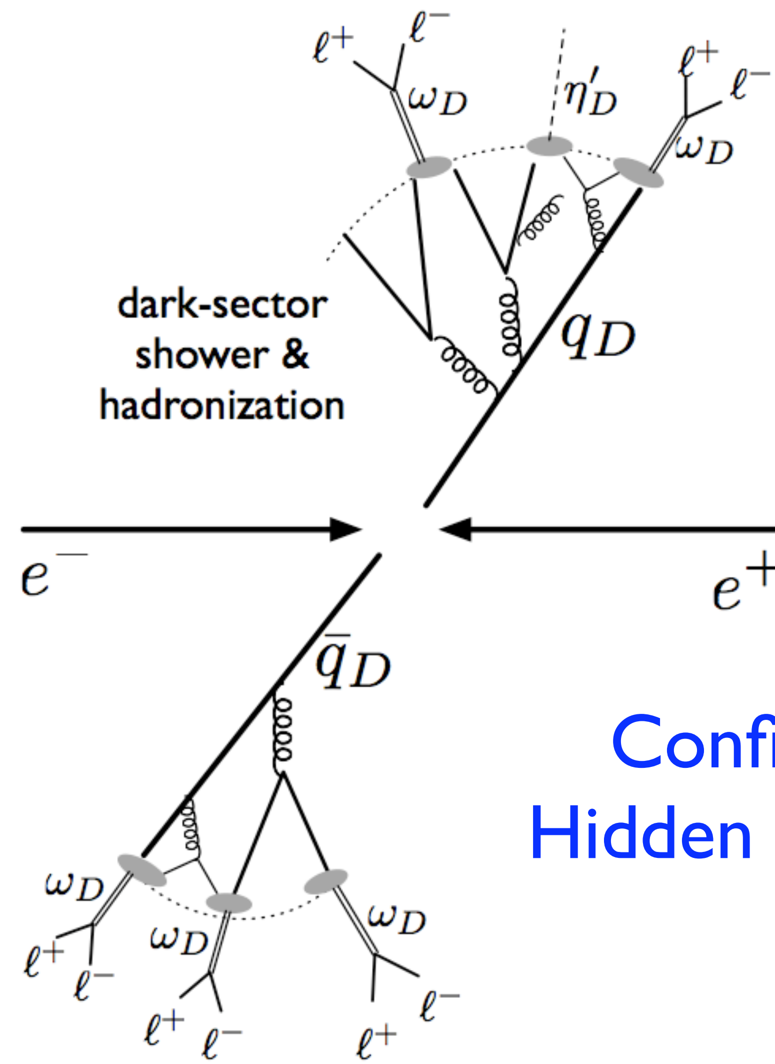
$\Longrightarrow$ BaBar, BELLE, KLOE, CLEO-c, BESIII, ...

Large # of spectacular events possibly contained in existing data sets!

Examples



Higgsed Hidden Sector



Confined Hidden Sector

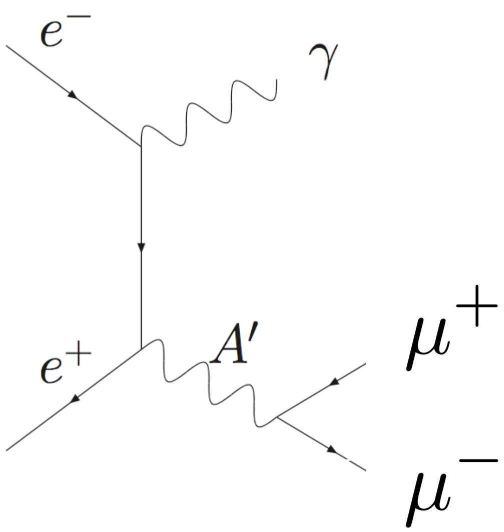
Very rich phenomenology!

Multi-leptons, resonances, displaced vertices, missing energy...

Broad array of searches needed!

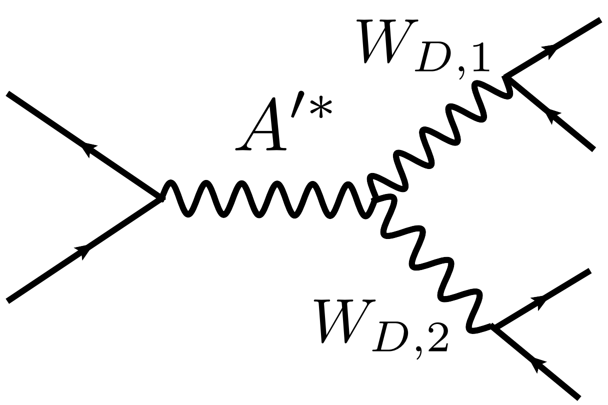
Rouven Essig SLAC

What searches have been done?



Done
$\gamma\mu^+\mu^-$

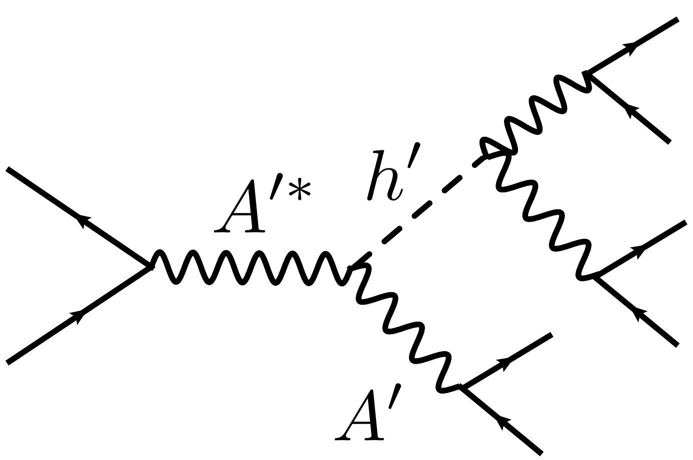
BaBar



Done
$4e, 4\mu, 2e + 2\mu$

BaBar

not yet $\gamma + 4\ell$



Not yet
$2\ell, 6\ell$

Higgs'-strahlung
[Batell, Pospelov,Ritz]

Typical sensitivity: $\epsilon \sim 10^{-4} - 10^{-3}$

Rare meson decays also have good reach

[Reece, Wang; Batell, Pospelov,Ritz; Freytsis, Ligeti, Thaler]

Experimental Probes of Dark Forces

A)

DM annihilation guarantees γ-rays!

can also get $\nu' s$

(Fermi, ACTs, IceCube)

Dwarf galaxies: excellent targets ($v_{\rm dwarf} \sim v_{\rm halo}/20$)

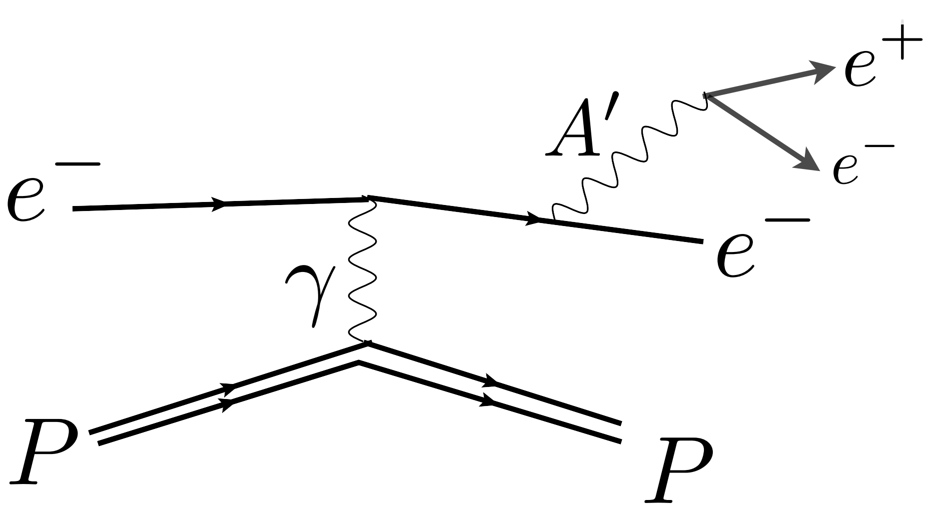
B)

e$^+$e$^-$ Colliders

(BaBar, BELLE, CLEO, KLOE)

X = dark gauge/higgs bosons, pions, etc.

C)



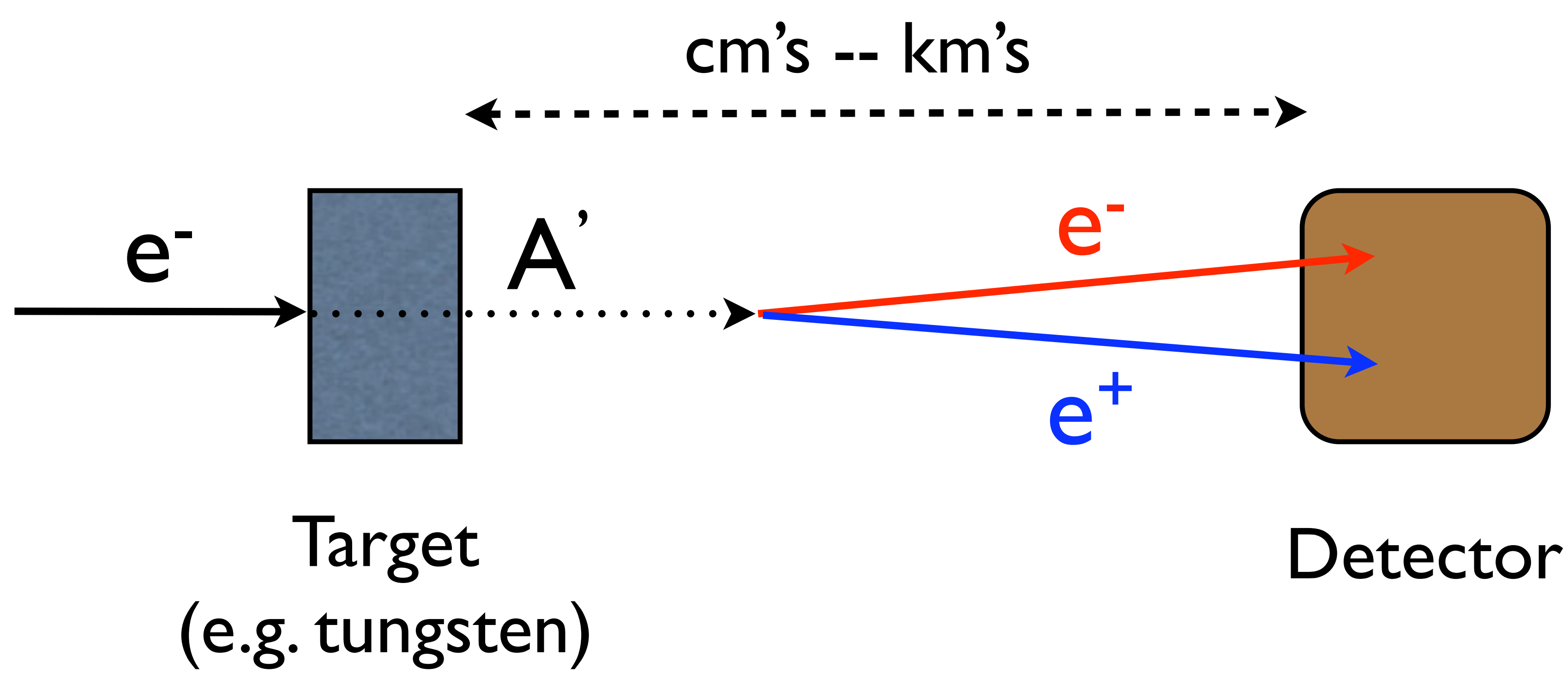
Fixed Target Exp's

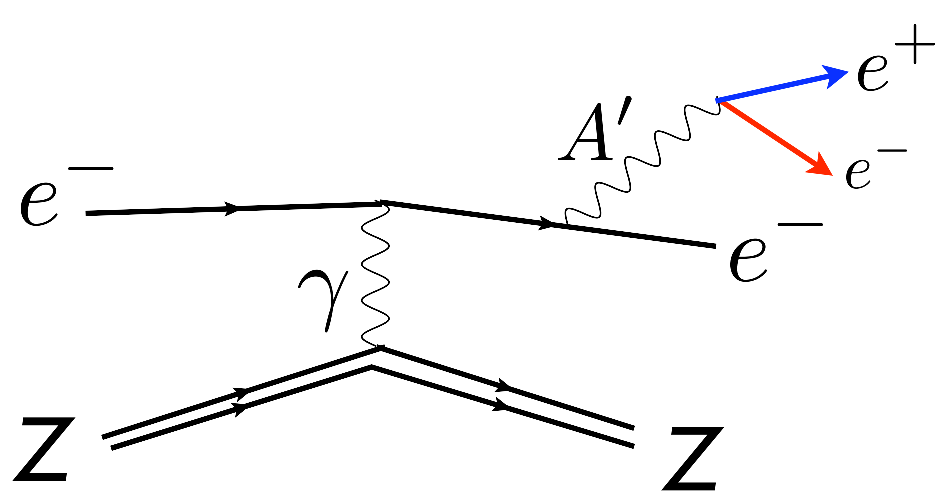
(E137, E141, JLab, SLAC, FNAL, COMPASS)

Fixed-Target Experiments

[Bjorken RE, Schuster, Toro]
[see also Batell et.al.;
Reece & Wang]

Produce A' via bremsstrahlung off e⁻ beam on fixed target





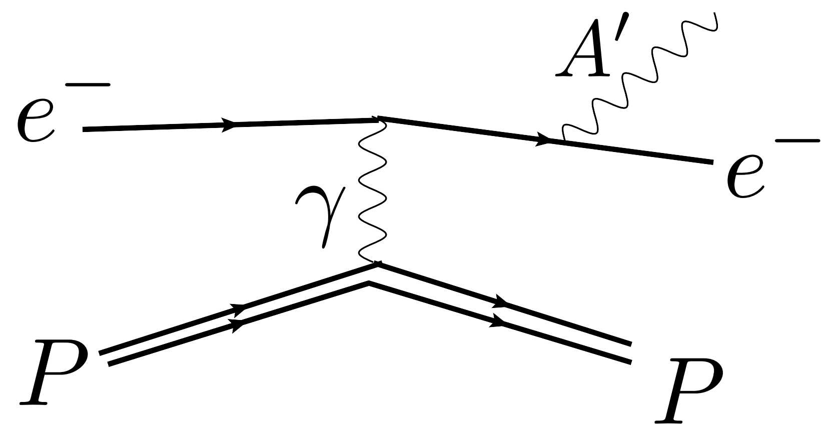
A' produced forward carrying most of energy & decays to e^+e^- pair

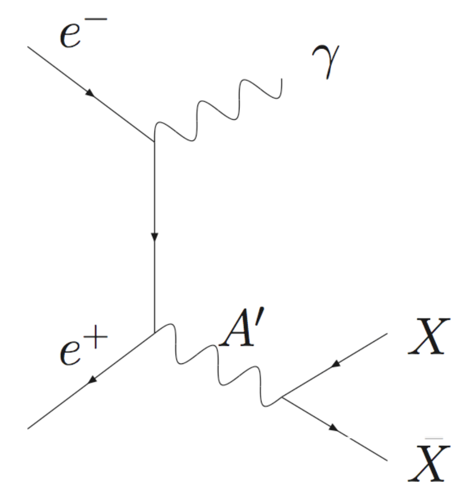
(remainder of talk: assume this simplest possibility)

Fixed Target advantages over Colliders

[Bjorken RE, Schuster, Toro]
[see also Batell et.al.;
Reece & Wang]

Larger Cross-section

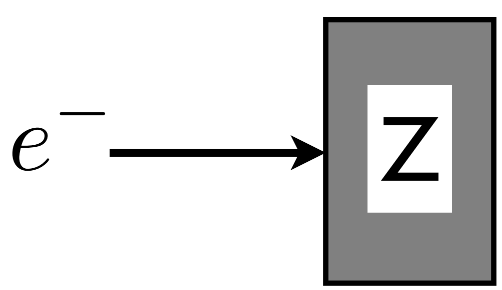




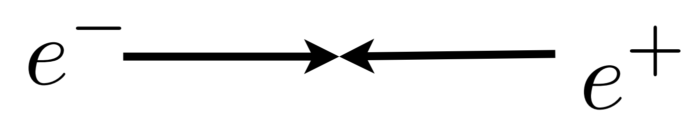
$$\sigma \propto \frac{\alpha^3 \epsilon^2 Z^2}{m_{A'}^2} \propto 1 \text{ pb}$$

$$\sigma \propto \frac{\alpha^2 \epsilon^2}{E_{cm}^2} \propto 1 \text{ fb}$$

Higher Luminosity



majority of incident
e^-'s scatter



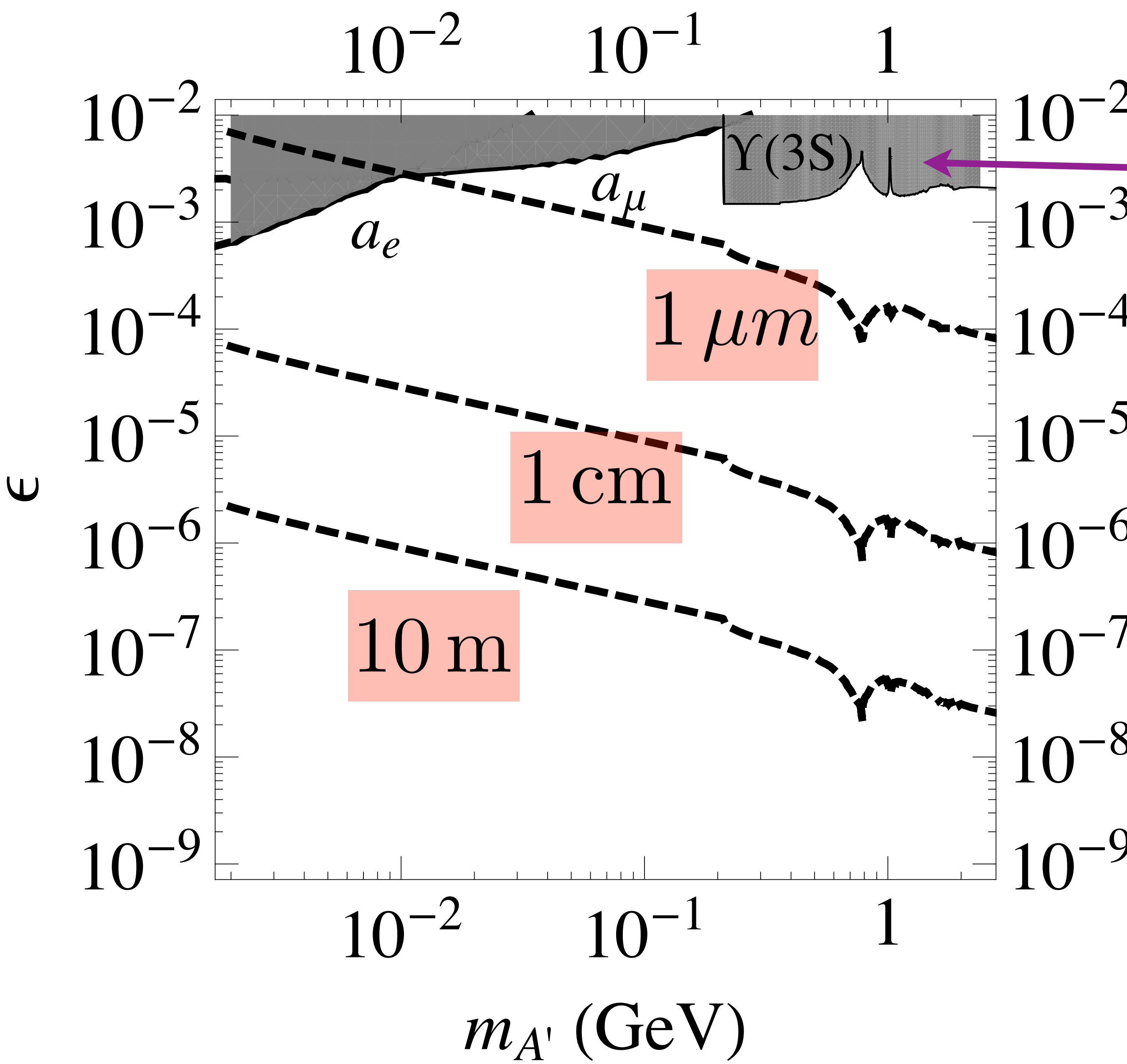
only ~1 e^- scatters
per crossing

~ few ab^{-1}/*day*

~ few ab^{-1}/*decade*

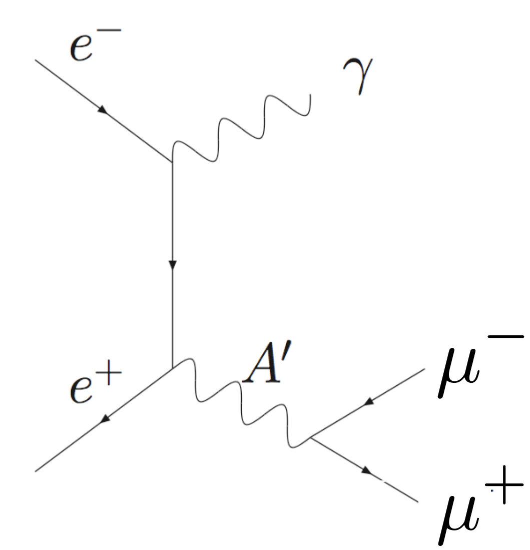
Cover huge range in mass and coupling

$$c\tau(A' \to \ell^+\ell^-) \sim 1\,\mathrm{m}\left(\frac{10^{-6}}{\epsilon}\right)^2\left(\frac{100\,\mathrm{MeV}}{m_{A'}}\right)$$



BaBar

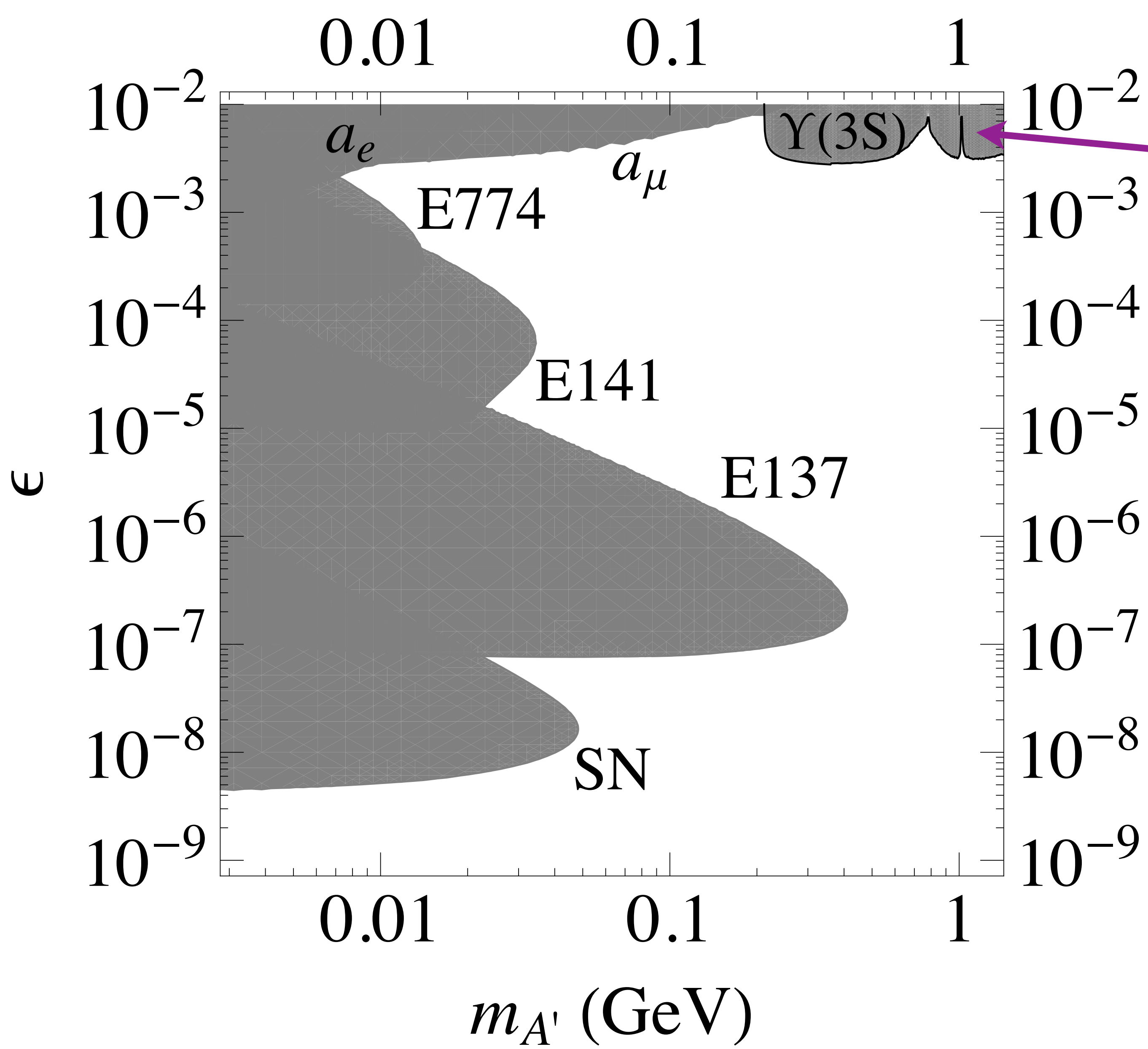
$\Upsilon(3S) \to \gamma\mu^+\mu^-$



Need various strategies to cover huge lifetime range

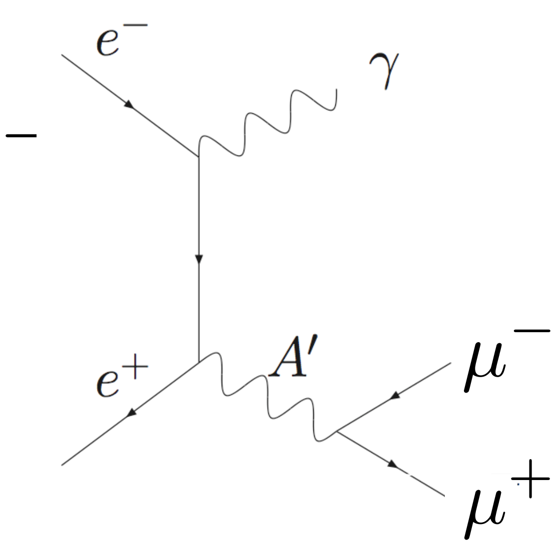
Good Beam Dump Constraints exist

[Bjorken RE, Schuster, Toro]



BaBar

$\Upsilon(3S) \to \gamma\mu^+\mu^-$

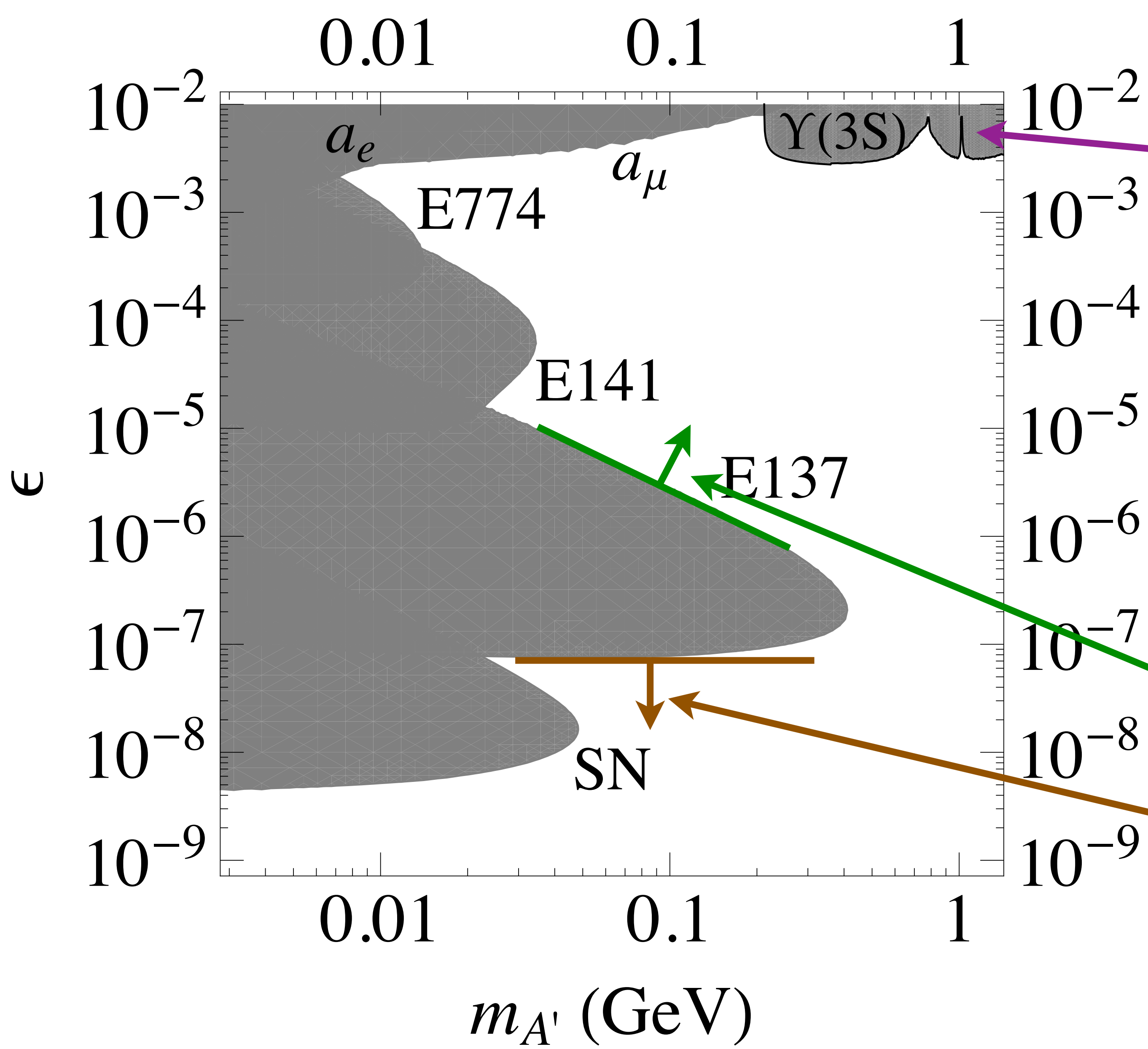


Beam dumps:
E137, E141, E774

Need new experiments to
cover remaining parameter space

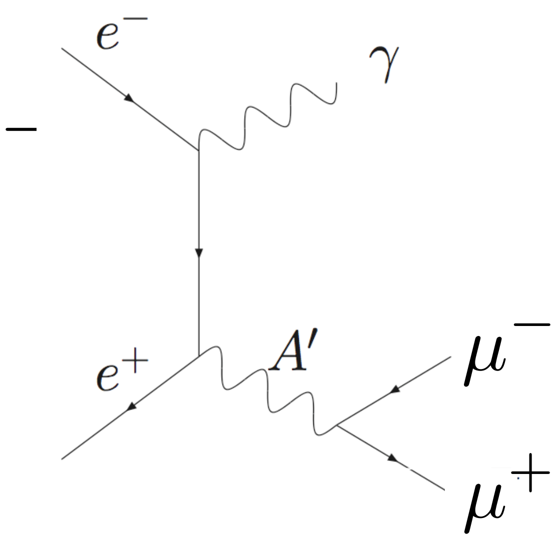
Good Beam Dump Constraints exist

[Bjorken RE, Schuster, Toro]



BaBar

$$\Upsilon(3S) \to \gamma \mu^+ \mu^-$$



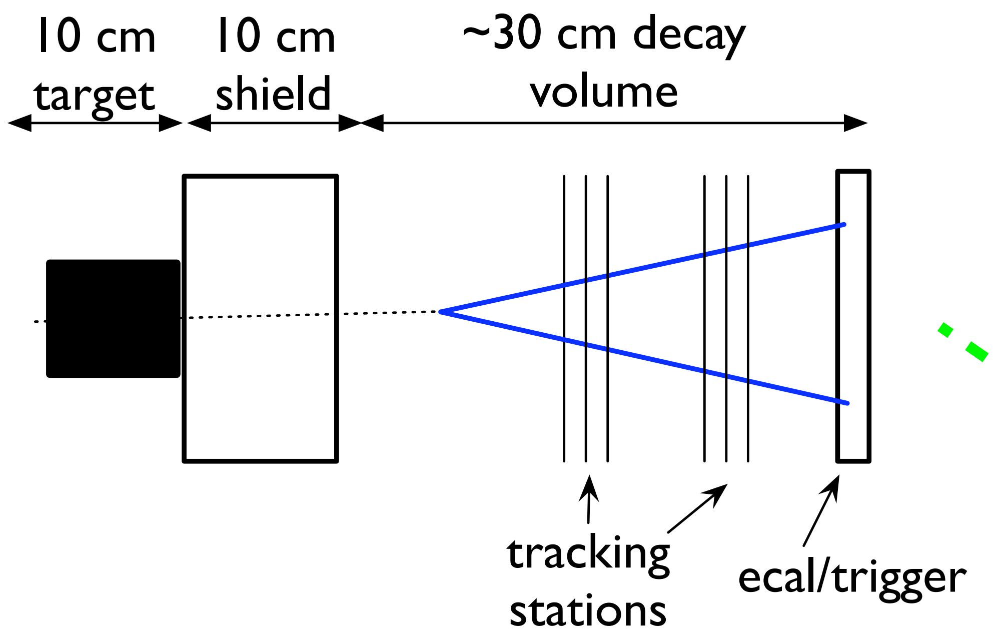
Beam dumps:
E137, E141, E774

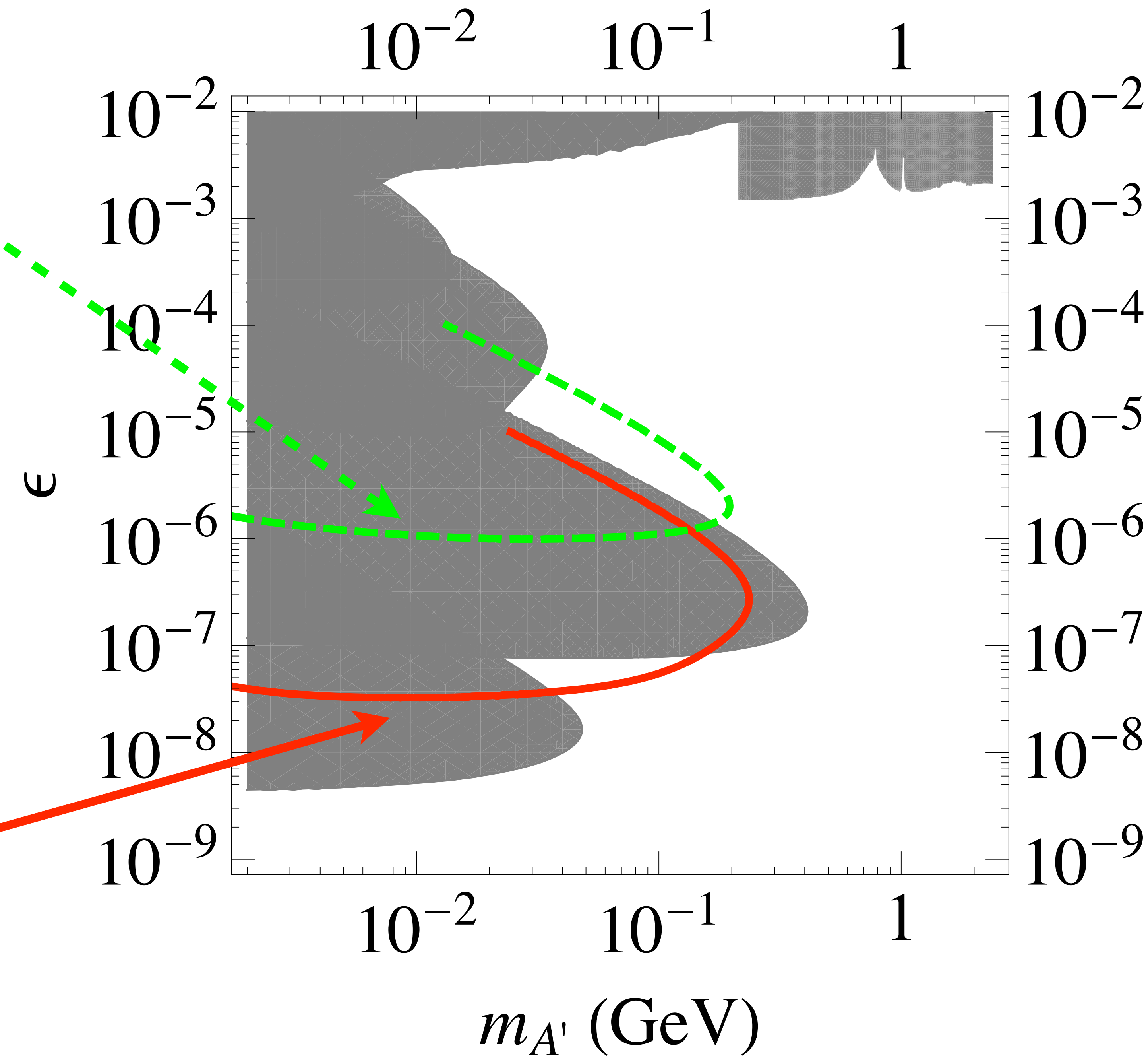
- A' decay products decay in shield (since lifetime too small)
- luminosity too small (since cross-section too small)

Need new experiments to cover remaining parameter space

Strategy 1: New Beam Dumps

[Bjorken RE, Schuster, Toro]



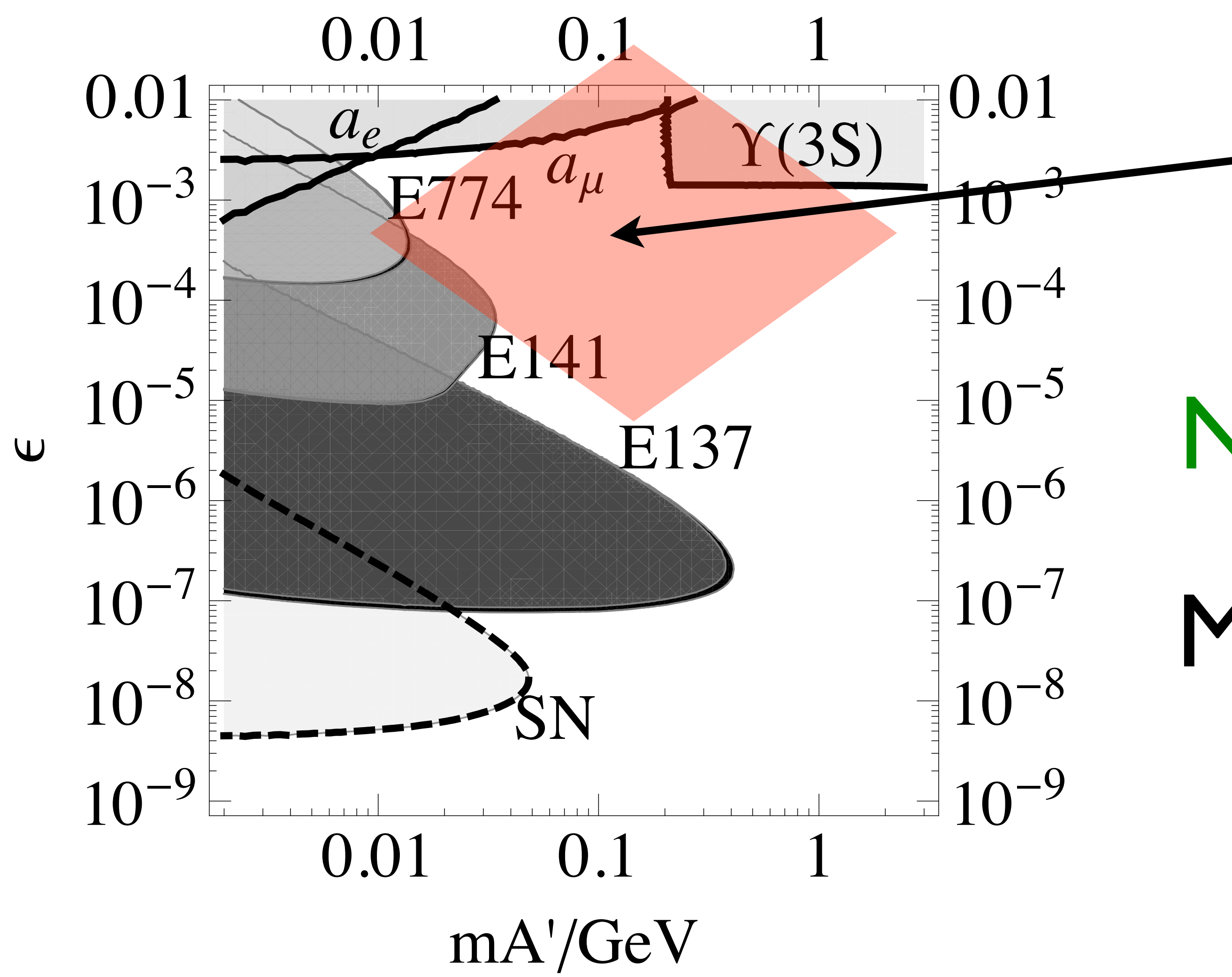


Larger shield,
1 MW power

@ SLAC, Jefferson Lab, DESY,
Mainz Mictrotron?

Strategy 2: Thin targets for high $m_{A'}$, high ϵ

[Bjorken RE, Schuster, Toro]



A' lifetime short,
so need *thin* target

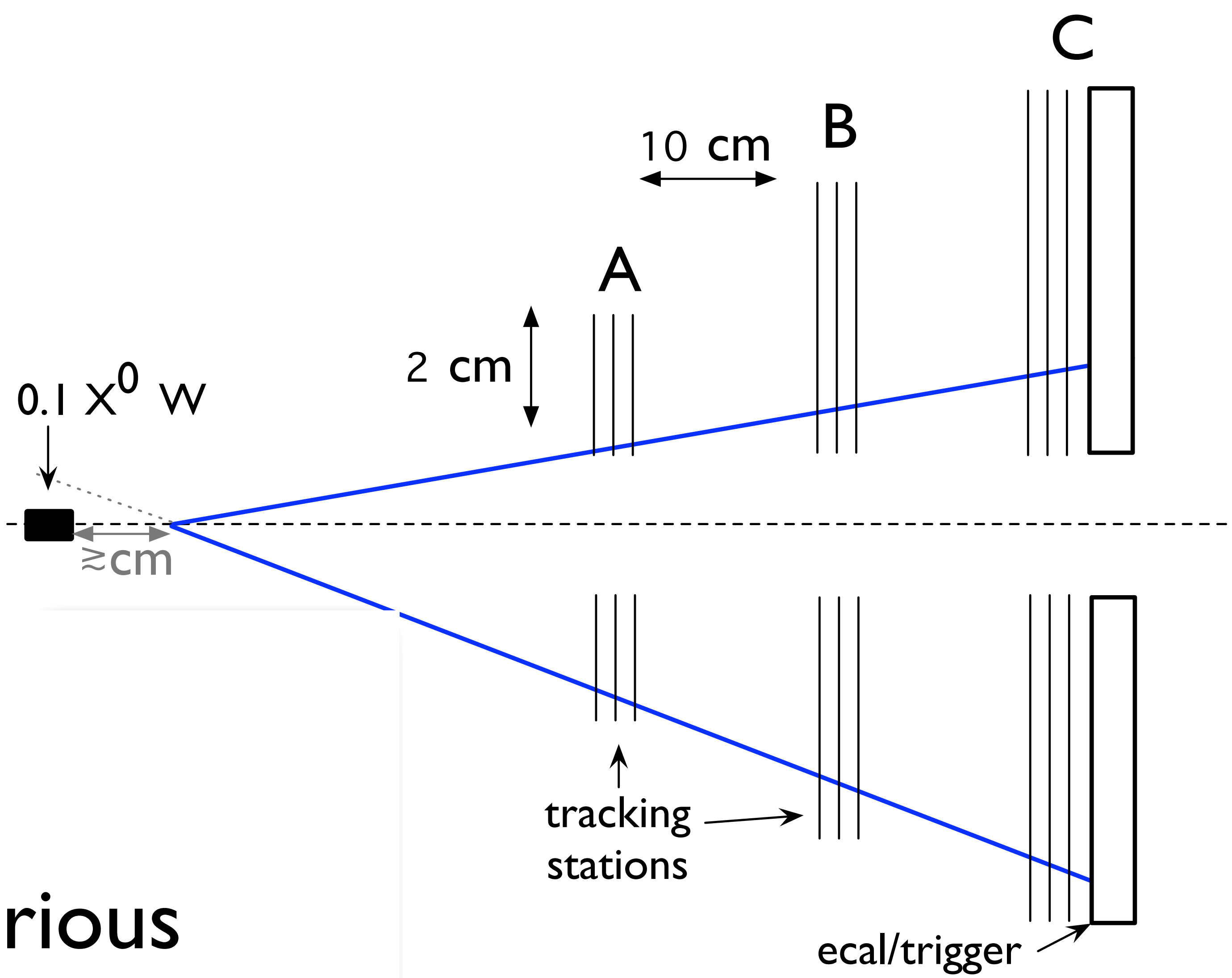
Now have background too!

Most background is forward
and softer, but not all...

Use vertexing and/or bump hunt

Example: Forward two-arm spectrometer

[Bjorken RE, Schuster, Toro]



small, simple & cheap experiments

Want:

Mass resolution < 1%

Fast calorimeter

Fast trigger

Various geometries possible

several ideas to cover much of parameter space

some are being turned into real experimental proposals

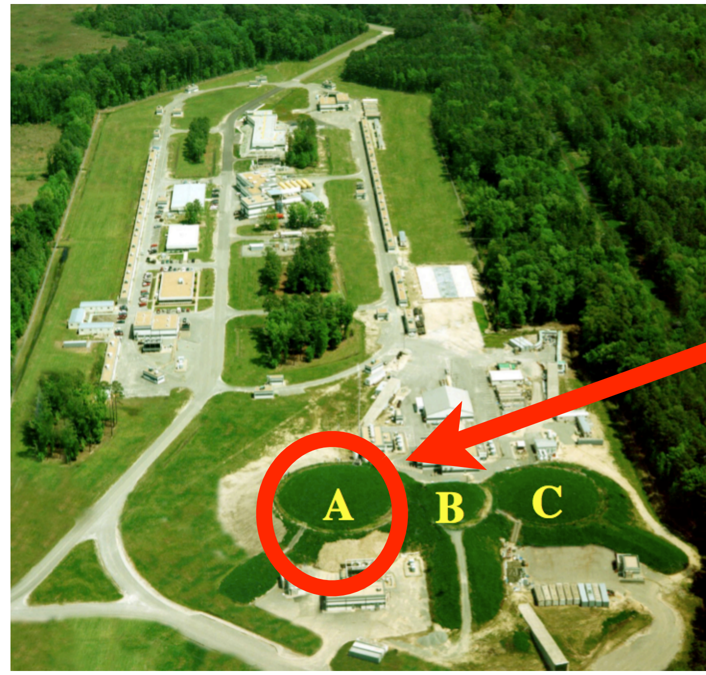
A' EXperiment (APEX) @ JLab Hall A

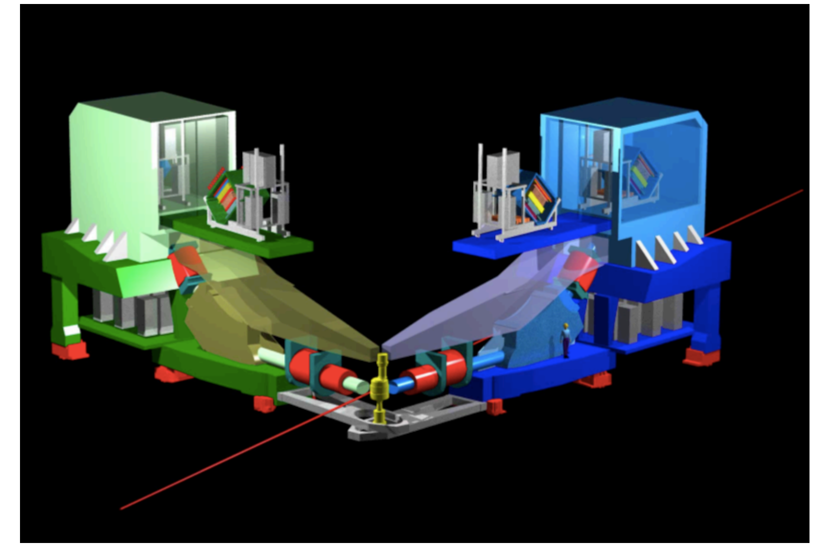
Proposal by
RE, Schuster, Toro, Wojtsekhowski
(collaboration of ~70 people)

[see arXiv: 1001.2557]

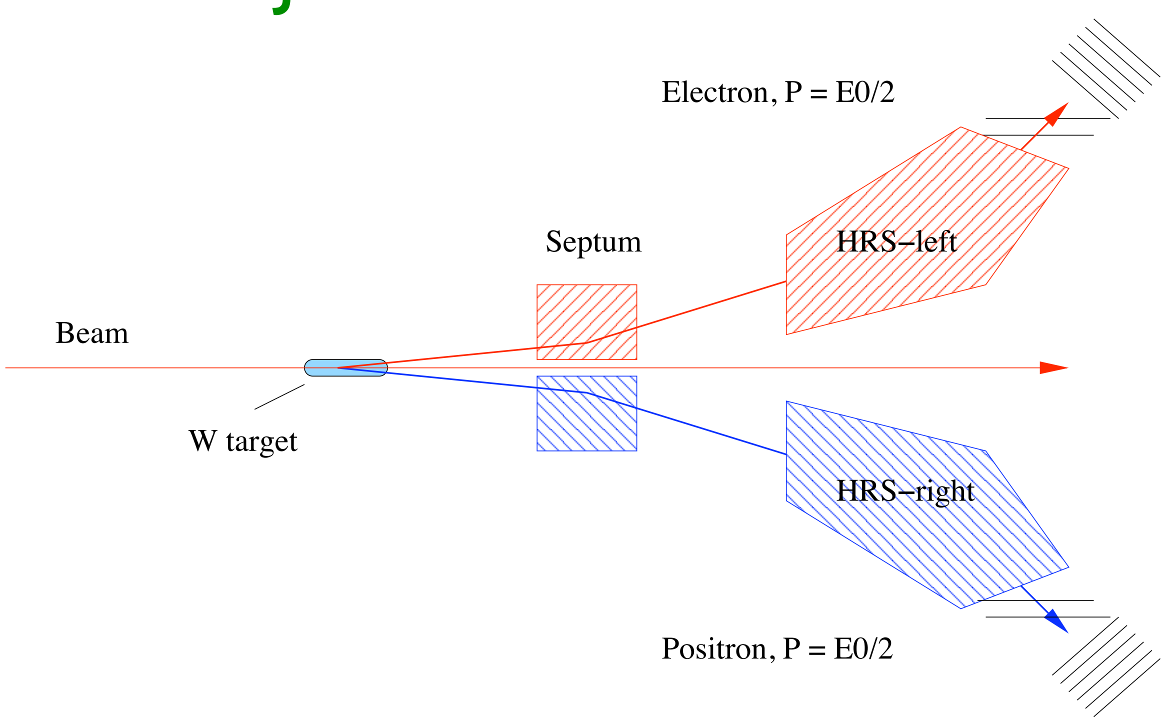
Conditional approval

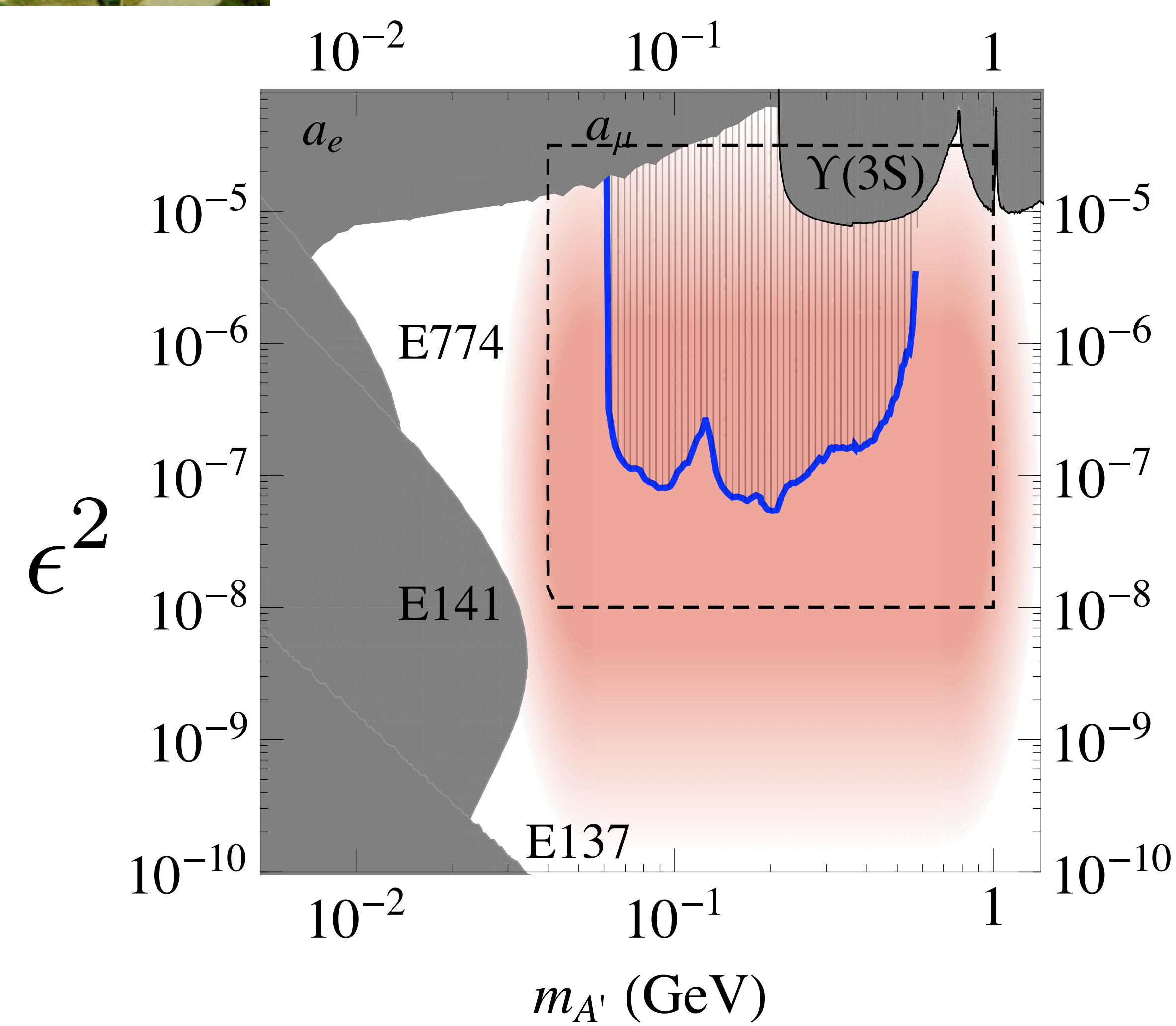
Preparing for a Test Run in June 2010





Two High Resolution Spectrometers





only ~30 days of running needed

Rouven Essig SLAC

Heavy Photon Search Working Group

SLAC
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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

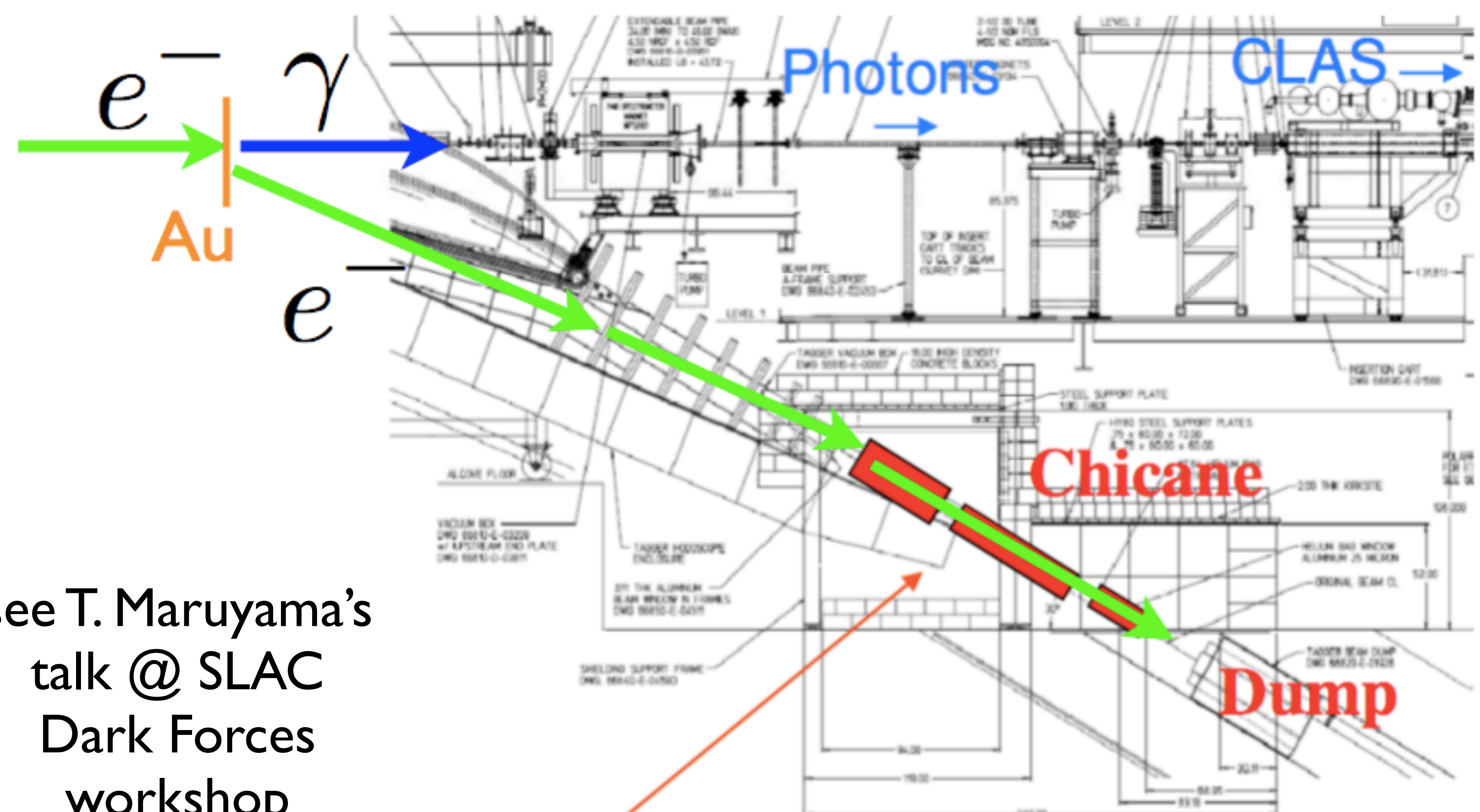
U. Oregon
R. Frey

Developing new experiment @ JLab Hall B

parasitic and non-parasitic options are being considered

complementary reach to APEX

could also discover "True Muonium", a $\mu^+\mu^-$ bound state that decays like an A' !



see T. Maruyama's talk @ SLAC Dark Forces workshop

Possible location for heavy photon search

(parasitic option)

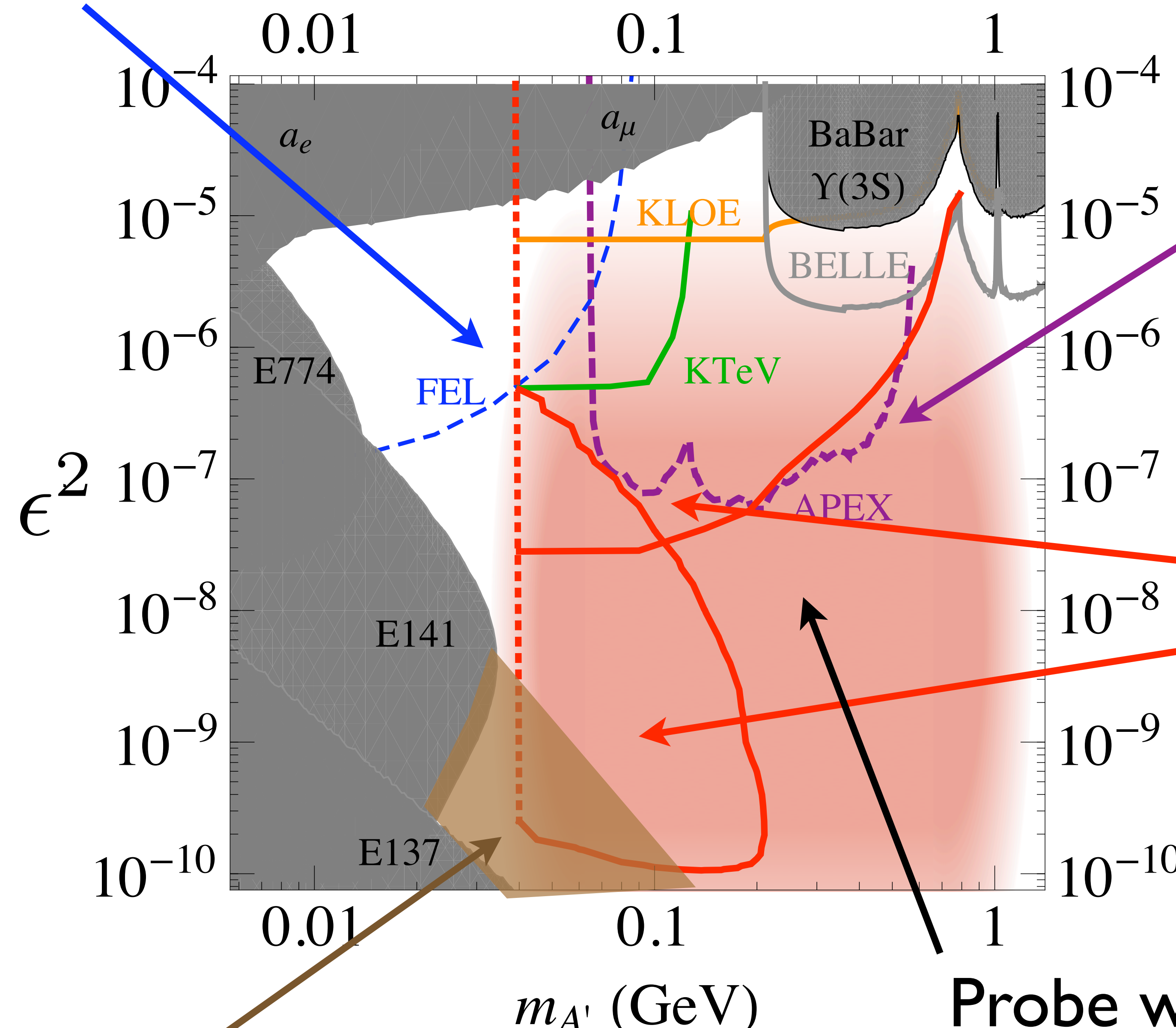
Summary of experiments to probe interesting region

JLab Free-Electron Laser
[see Freytsis, Ovanesyan, Thaler]

Rare meson decays (potential constraints using existing data)

APEX @ JLab Hall A

SLAC/JLab Hall B (vertexing & bump hunt)



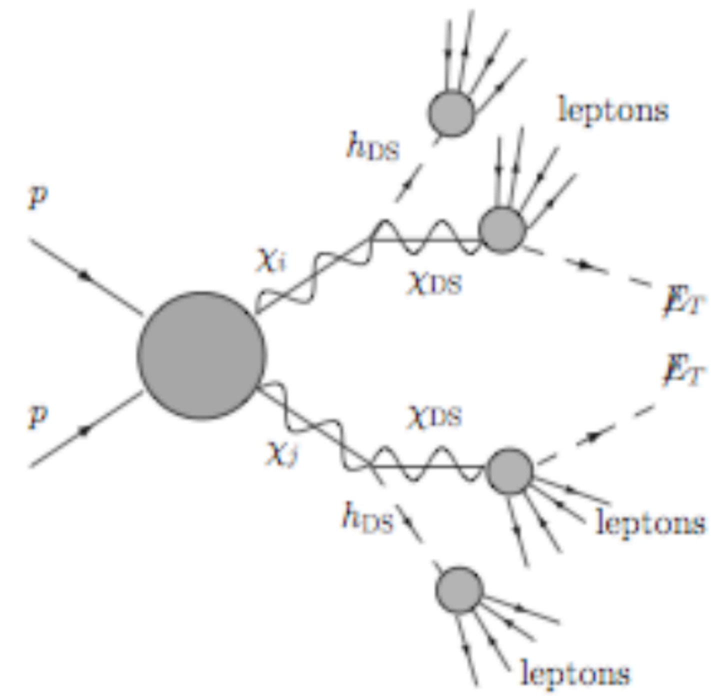
Beam dump @ DESY "DarkDESY"

Probe with an experiment with better acceptance & pixel tracking

[see talk by A. Ringwald http://www.desy.de/~ringwald/axions/talks/flc.pdf]

Many possibilities not discussed...

- Muons beams: [RE, Harnik, Kaplan, Schuster, Toro - to appear]
  - MINOS + Minerva
  - COMPASS @ CERN
- LHC, Tevatron Searches [e.g. D0] ("lepton-jets")



- Further details @ SLAC Dark Forces workshop

http://www-conf.slac.stanford.edu/darkforces2009/

Conclusions

- New dark forces: an exciting possibility
- Indirectly probed with dwarf galaxies
- Large existing data sets at e^+e^- Colliders may contain spectacular signals
- New Fixed Target Experiments are relatively easy to build and have extensive reach

Short timescale for many new analyses & experiments

Thank you !

Ultra-faint Segue 1: Best dwarf target?

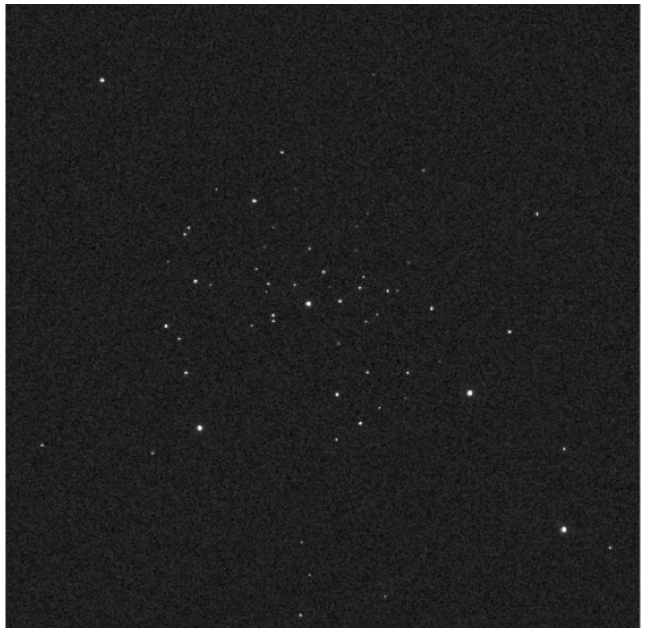
Draco

Distance: 80 kpc

data on >200 stellar velocities

classical dwarf
(discovered 1954)

Segue 1



Distance: 23 kpc

New stellar data is being analyzed (~65 stars)

[Simon et. al.]

ultra-faint dwarf
(discovered 2006)

γ, ν flux ∝ $\mathcal{L} \sim \int \rho^2$ determined from stellar velocities

Current analysis suggests $\mathcal{L}_{\rm Segue1} \gtrsim \mathcal{L}_{\rm Draco}$ Preliminary!

Many more details can be found at
SLAC Dark Forces Workshop

Searches for New Forces at the GeV-scale

Organizers:

R. Essig, M. Graham, M. Peskin, A. Roodman, P. Schuster, N. Toro, J. Wacker

http://www-conf.slac.stanford.edu/darkforces2009/

see also Perimeter Conference "New Lights on Dark Matter"

http://www.perimeterinstitute.ca/en/Events/New_Lights_on_Dark_Matter/New_Lights_on_Dark_Matter/

SUSY can generate GeV scale naturally

[Dienes, Kolda, March-Russell; Baumgart, Cheung, Ruderman, Wang; Katz, Sundrum; Morrissey, Poland, Zurek]

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

$$\mathcal{L} \supset - \frac{\epsilon}{2} \int d^2\theta \, W_Y W' + \text{h.c.}$$

This includes the usual $\frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$

But also, hypercharge U(1)$_Y$ and dark U(1)' D-terms mix

$V_{\text{mix}} = \epsilon \langle D_Y \rangle D'$ induces effective FI term for U(1)'

$$\rightarrow \epsilon \left(\frac{1}{2} g_Y v_{\text{SM}}^2 \right) D' \sim 1\,\text{GeV}^2 D'$$

SUSY can generate GeV scale naturally

[Dienes, Kolda, March-Russell; Baumgart, Cheung, Ruderman, Wang; Katz, Sundrum; Morrissey, Poland, Zurek]

Assume there is dark-sector matter charged under U(1)'

e.g. $W = \mu' H_+ H_-$ $W = \lambda S H_+ H_-$

Dark U(1)' D-term potential is

$$V_D \sim \frac{1}{2}\left(g_D \sum_i x_i |\phi_i|^2 - \epsilon \frac{g_Y}{2} v_{\rm SM}^2\right)^2$$

U(1)$_Y$ D-term

Electroweak-symmetry breaking triggers dark U(1)' breaking

$$m_{A'}^2 \sim \epsilon \frac{g_Y g_D}{g_2^2} m_W^2 \sim 1\,\mathrm{GeV}^2$$