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

Rouven Essig
SLAC National Accelerator Laboratory

Fermilab Theory Seminar, November 19th, 2009

based on:

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

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

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

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

RE, P. Schuster, N. Toro, B. Wojtsekhowski et.al. (to appear)

Probing dark forces

- New dark forces: Theory and Motivation

  + Hints from dark matter "anomalies"

- Indirect probe:

  γ-rays from DM annihilation in dwarf galaxies

- Direct probes:

  - Low-energy e^+e^- Colliders (e.g. BaBar, BELLE, ...)
  - (New) Fixed-Target Experiments (e.g. JLab, SLAC)

New "Dark" Forces?

Standard Model Dark Sector?

$$\mathbf{SU(3)_C} \times \mathbf{SU(2)_L} \times \mathbf{U(1)_Y} \times \mathbf{G_D}$$

Strong constraints if quarks and leptons charged under new force G_D

If uncharged, constraints much weaker... but still have very exciting possibilities!

Photon Mixing with New Gauge Boson

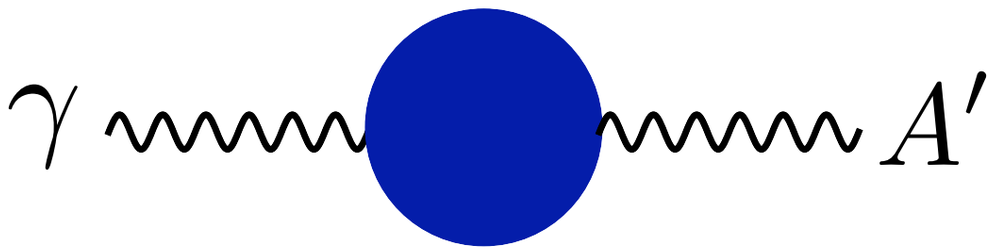
Standard Model

Dark Sector?

$$\mathbf{SU(3)_C} \times \mathbf{SU(2)_L} \times \mathbf{U(1)_Y} \times \mathbf{U(1)'}$$

↳ possibly $U(1)' \subset G_D$

Particles charged under U(1)$_Y$ & U(1)' generate kinetic mixing



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

[Holdom]

$$\epsilon \sim 10^{-7} - 10^{-2}$$

assume U(1)' is *broken*

$$\Delta\mathcal{L} = m^2_{A'} A'^{\mu} A'_{\mu}$$

$$m^2_{A'} \sim \epsilon M^2_W \sim \text{MeV}^2 \text{ - } \text{GeV}^2$$

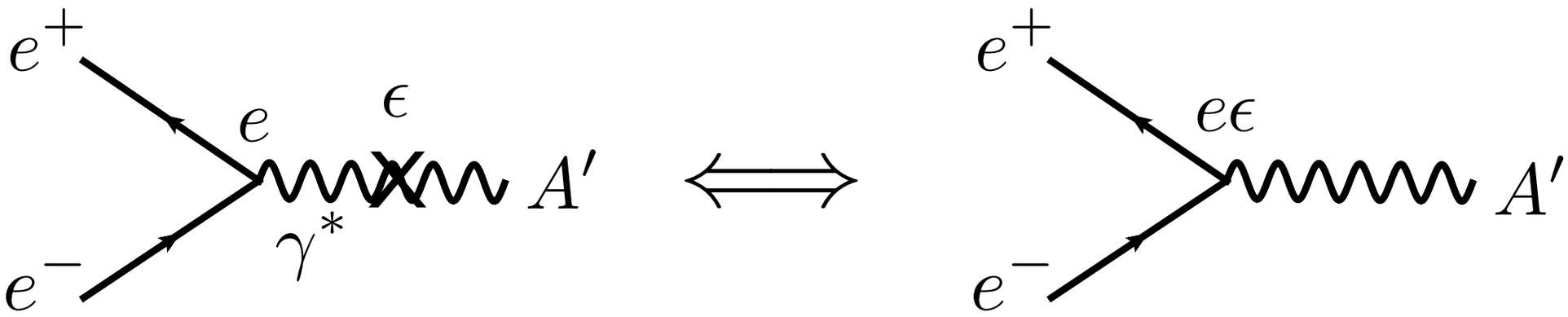
[Cheung, Ruderman, Wang, Yavin; Katz, Sundrum; Morrissey, Poland, Zurek]

Quarks & Leptons: milli-charged under A'

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

Diagonalize kinetic terms: $A_\mu \to A_\mu - \epsilon A'_\mu$

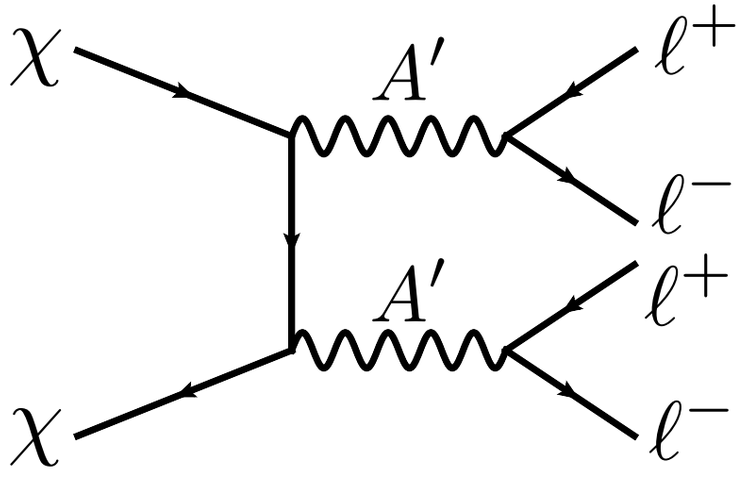
$$\Longrightarrow \mathcal{L} \supset e A_\mu J^\mu_{EM} \Longrightarrow \mathcal{L} \supset e\epsilon A'_\mu J^\mu_{EM}$$



$\Longrightarrow$ dark photon A' couples to quarks, leptons

$A' \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-, \ldots$ (depending on mass)

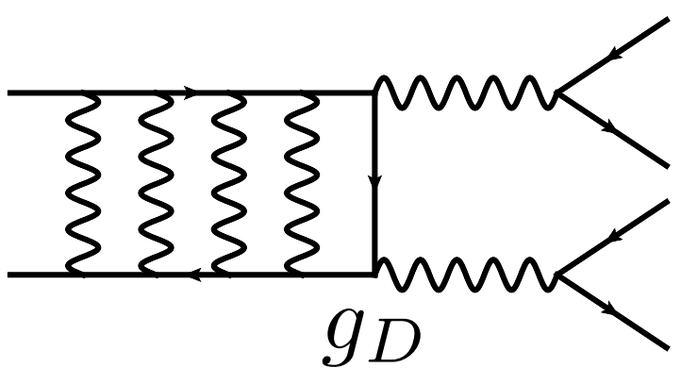
Striking implications if dark matter is charged under GeV-scale U(1)'



1) For $m_{A'} \lesssim 1\,\mathrm{GeV}$:

$A' \to \ell^+\ell^-, \pi^+\pi^-$

no anti-protons



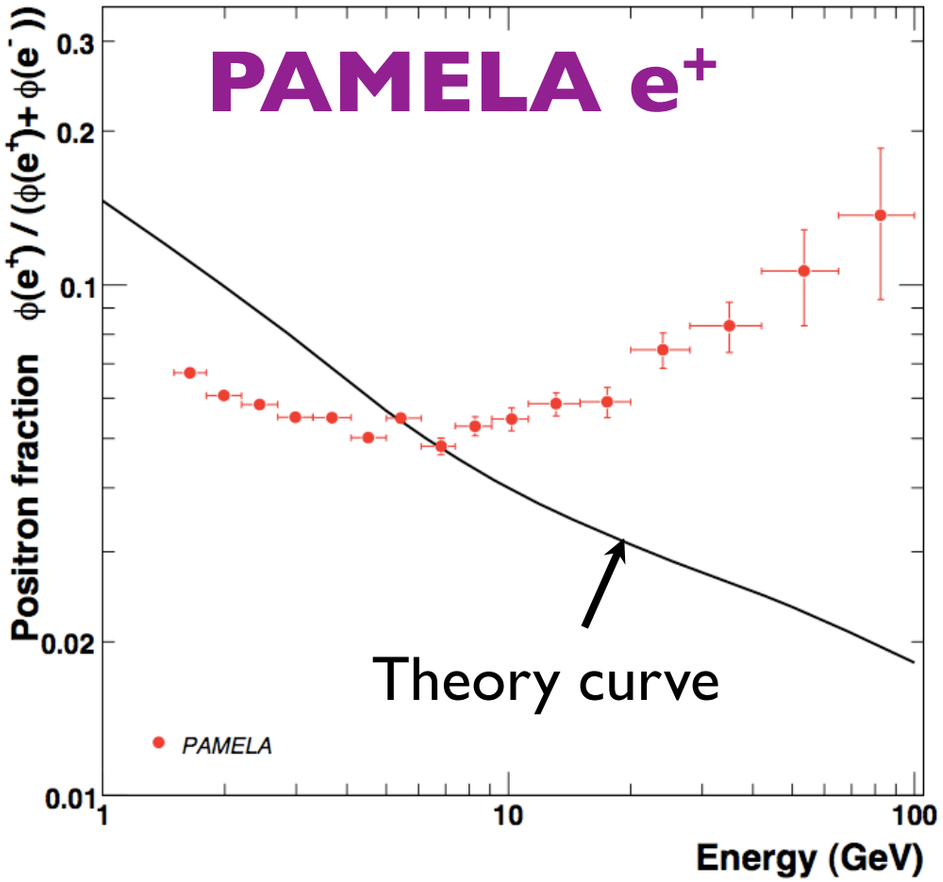
2) Sommerfeld enhancement:

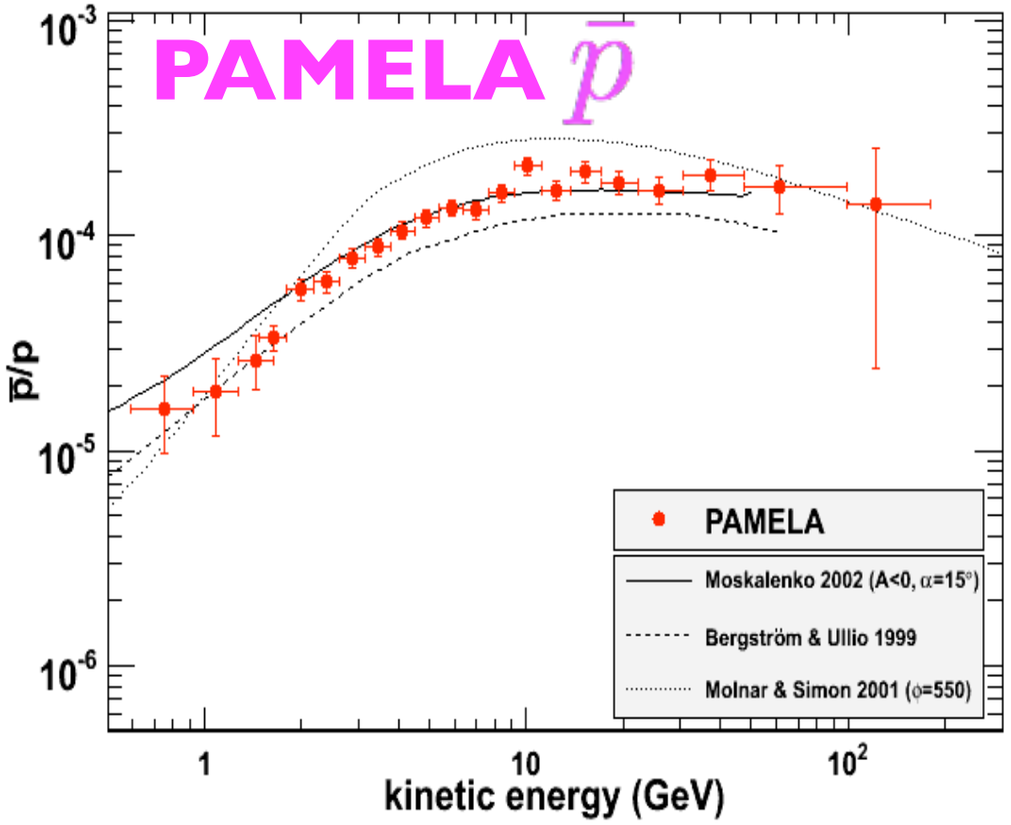
long-range force $V(r) = -\dfrac{\alpha_D}{r} e^{-m_{A'} r}$

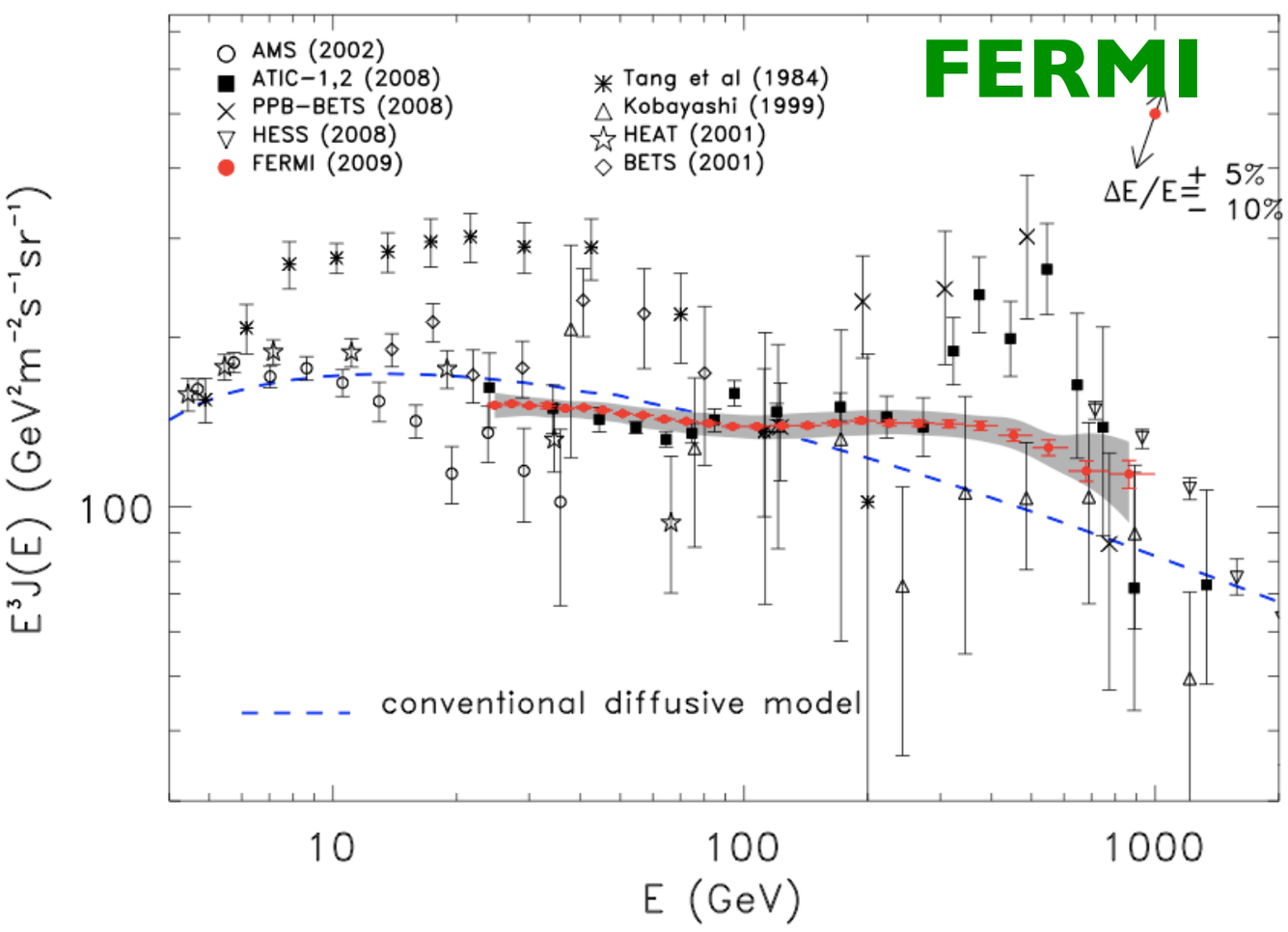
$\sigma v \propto \dfrac{1}{v} \implies$ large today, small at freeze-out

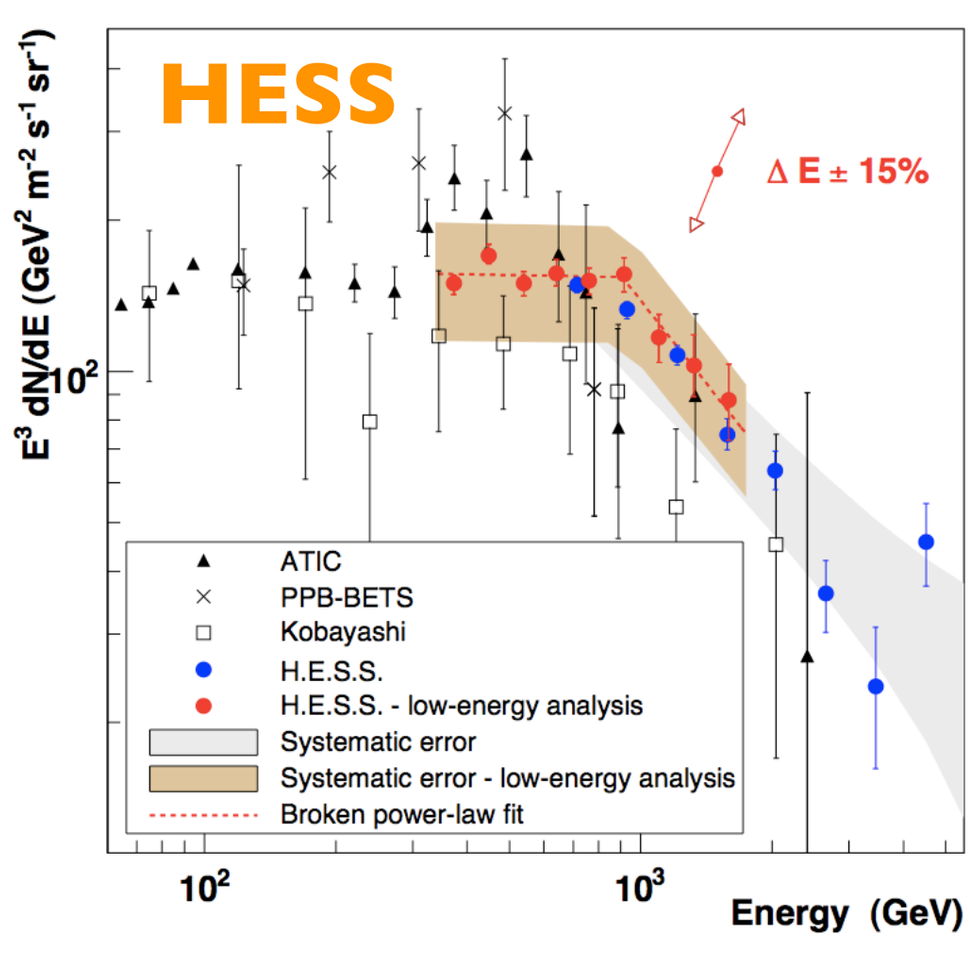
saturates when $v_\chi \lesssim m_{A'}/m_\chi$

Evidence for Dark Forces?









Suppose dark matter charged under $G_D = G_{NA} \times U(1)'$

1) Higgsed non-abelian G_{NA}:

[Arkani-Hamed et.al.]

[Baumgart et.al]

[Thomas, Wells]

- dark matter is multiplet of G_D;
- massive dark gauge bosons, W_D, give splittings:

$$\delta m_{DM} \sim \alpha_D m_{W_D} \sim (10^{-4})(1\,\mathrm{GeV}) \sim 100\,\mathrm{keV}$$

2) Confined G_{NA}:

[Alves et.al.]

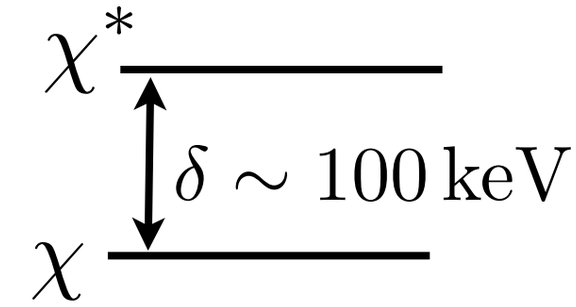
- dark matter is dark heavy flavor meson

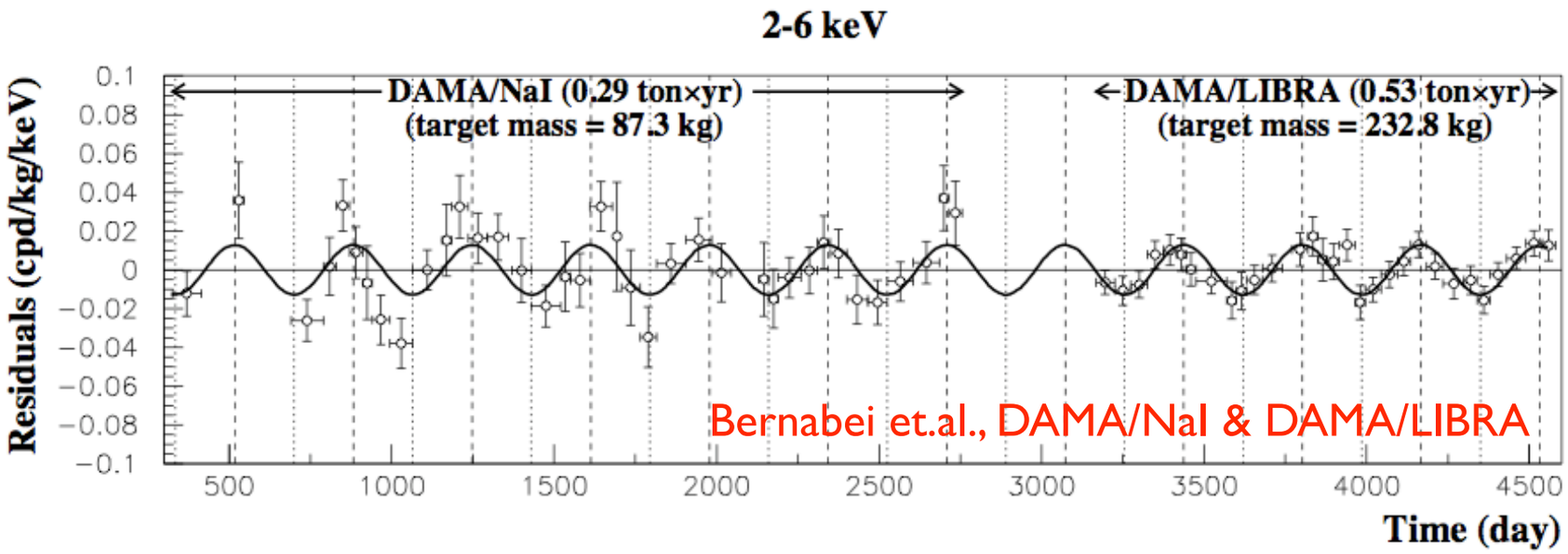
$$\delta m_{DM} \sim \frac{\Lambda_D^2}{m_{DM}} \sim \frac{(300\,\mathrm{MeV})^2}{1\,\mathrm{TeV}} \sim 100\,\mathrm{keV}$$ (hyperfine splitting)

DM states have mass splittings ~100 keV!

Many dark states in 10 MeV to GeV scale!

Evidence for 100 keV splitting?



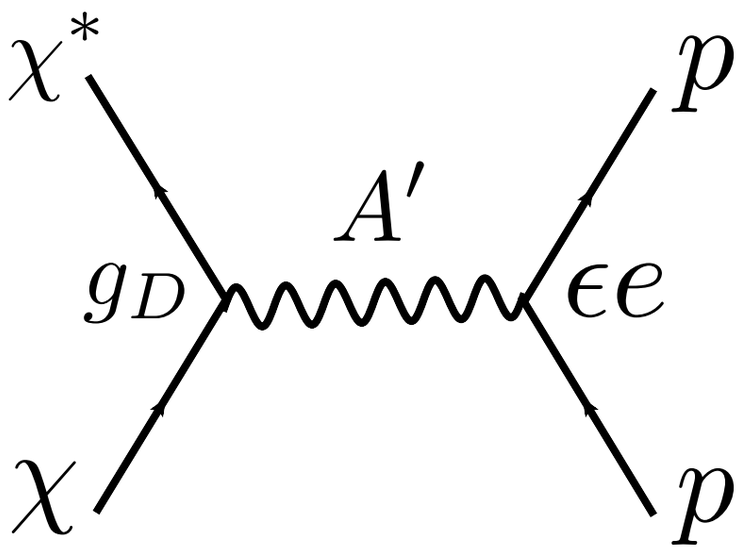


DAMA/LIBRA
annual modulation

Inelastic scattering:

[Tucker-Smith & Weiner]

DM scatters preferentially off heavier targets
explains null results of other experiments



A' can mediate scattering

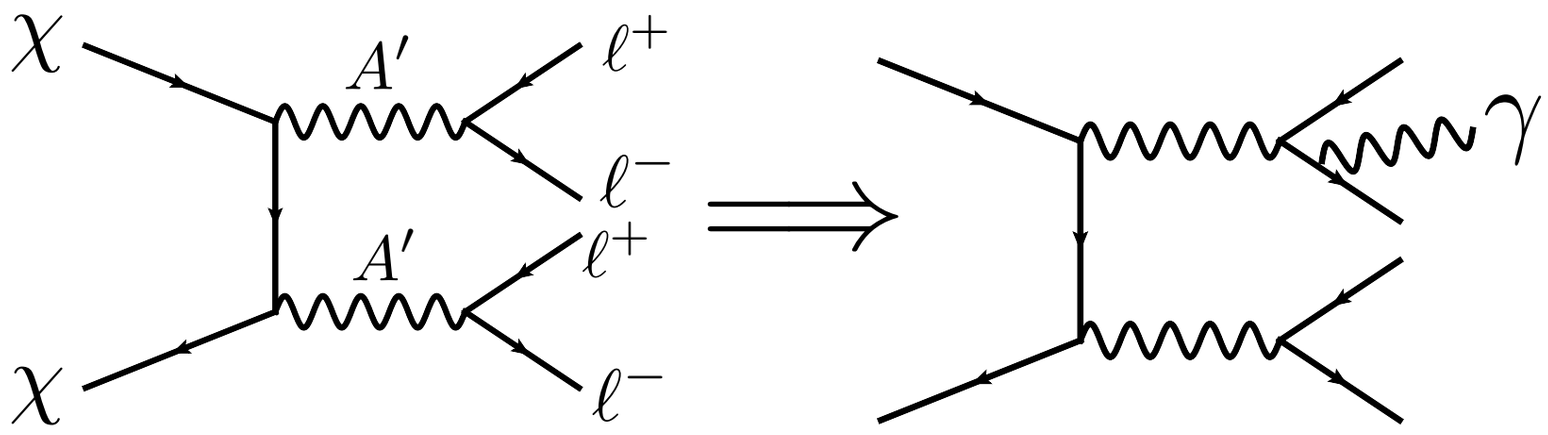
(will be tested decisively in ~one year by XENON-100, LUX)

Are there Dark Forces?

- Dark matter charged under new GeV-scale force explains astro/terrestrial 'anomalies'
- Hints from other anomalies, e.g. muon g-2? [Pospelov]
- GeV scale can be naturally generated [Cheung, Ruderman, Wang, Yavin; Katz, Sundrum; Morrissey, Poland, Zurek]
- Dark Forces are surprisingly unconstrained

How can we probe for such New Forces?

Experimental Probes of Dark Forces

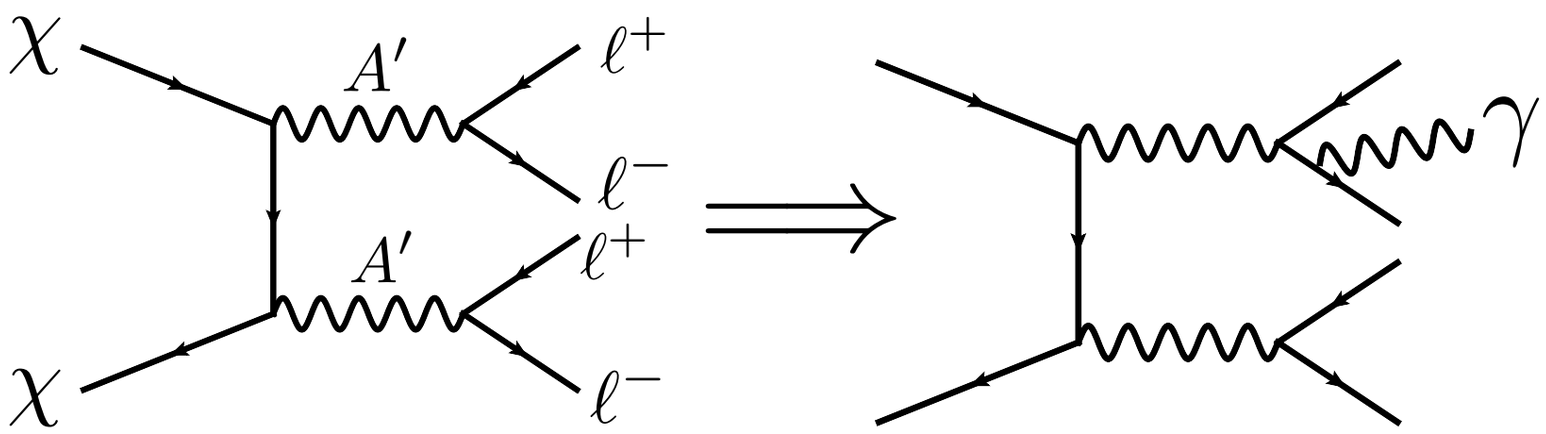
A) 

DM annihilation guarantees γ-rays!

(Fermi, ACT's)

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

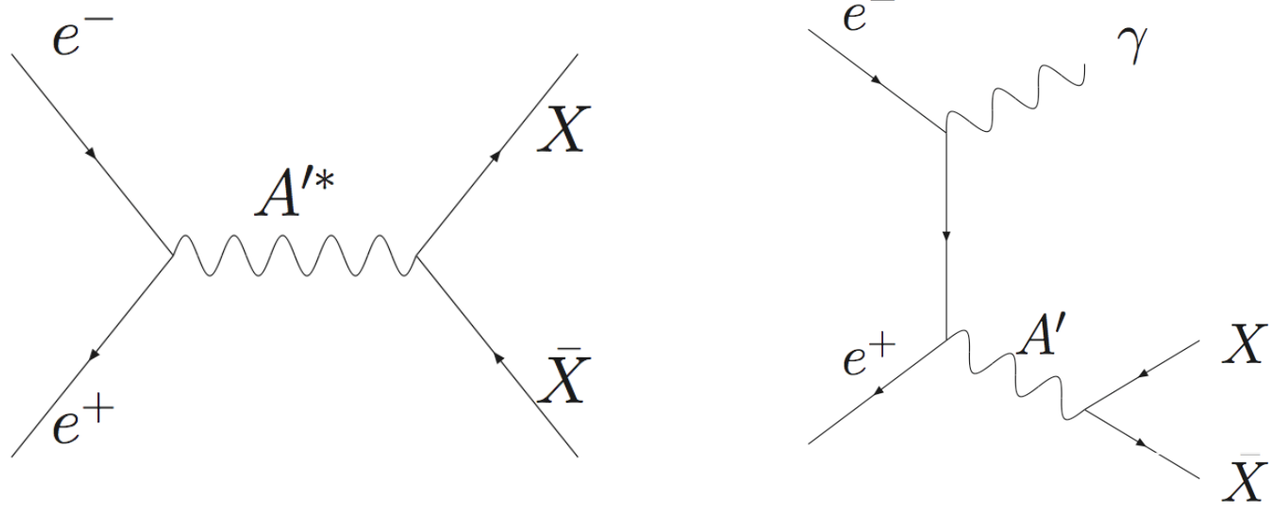
Experimental Probes of Dark Forces

A) 

DM annihilation guarantees γ-rays!

(Fermi, ACT's)

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

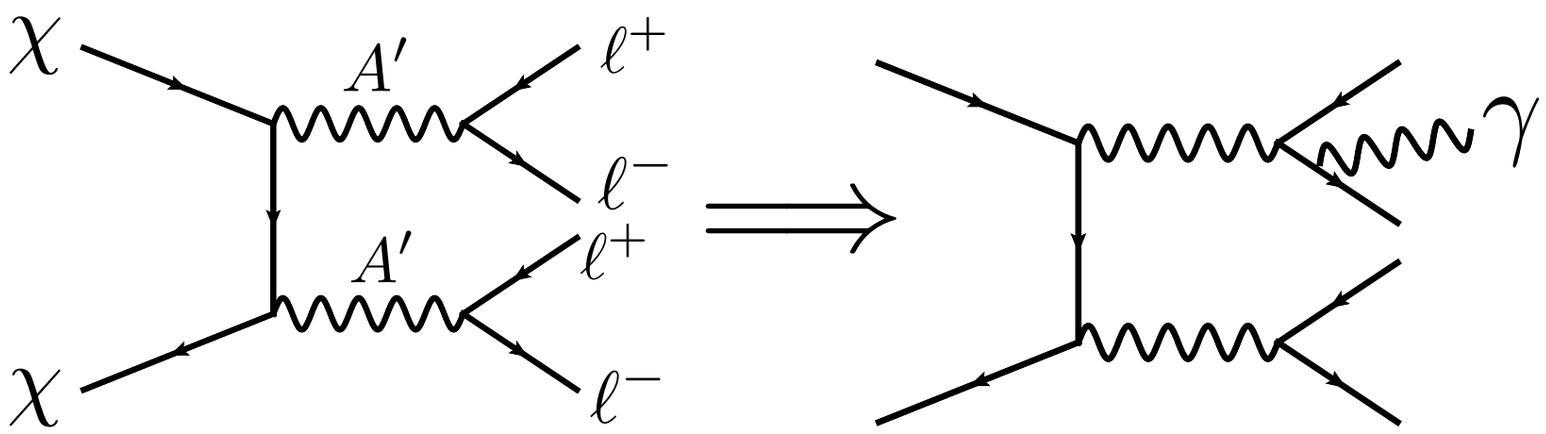
B) 

e^+e^- Colliders

(BaBar, BELLE, KLOE, BES-III)

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

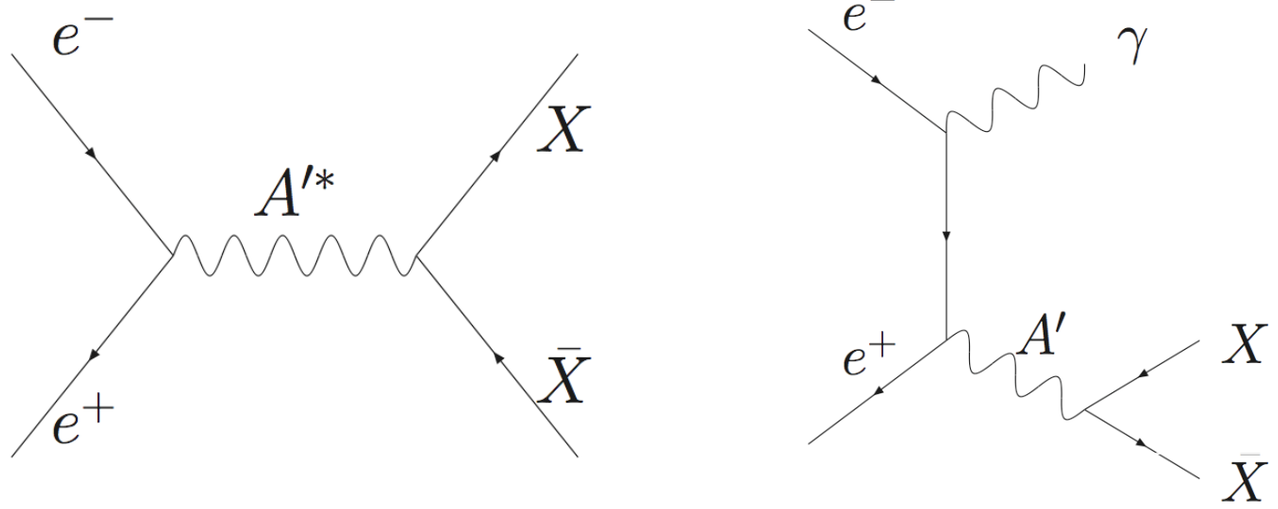
Experimental Probes of Dark Forces

A) 

DM annihilation guarantees γ-rays!

(Fermi, ACT's)

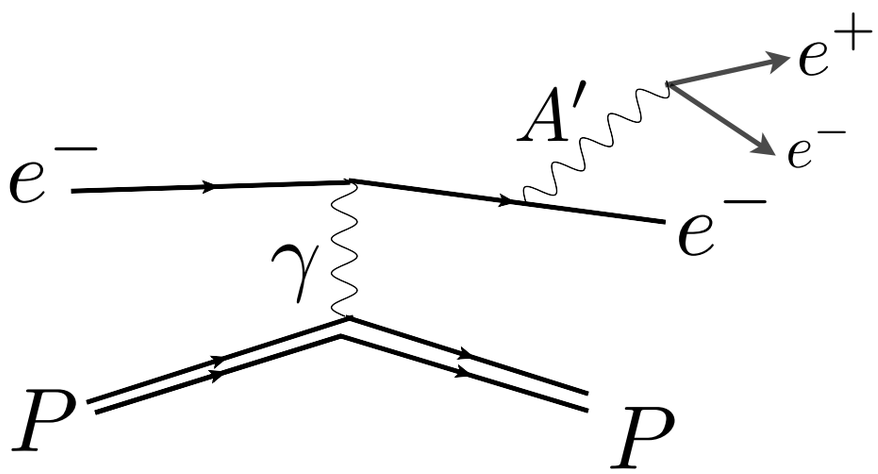
Dwarf galaxies: excellent targets ($v_{\rm dwarf} \sim v_{\rm halo}/20$)

B) 

e^+e^- Colliders

(BaBar, BELLE, KLOE, BES-III)

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

C) 

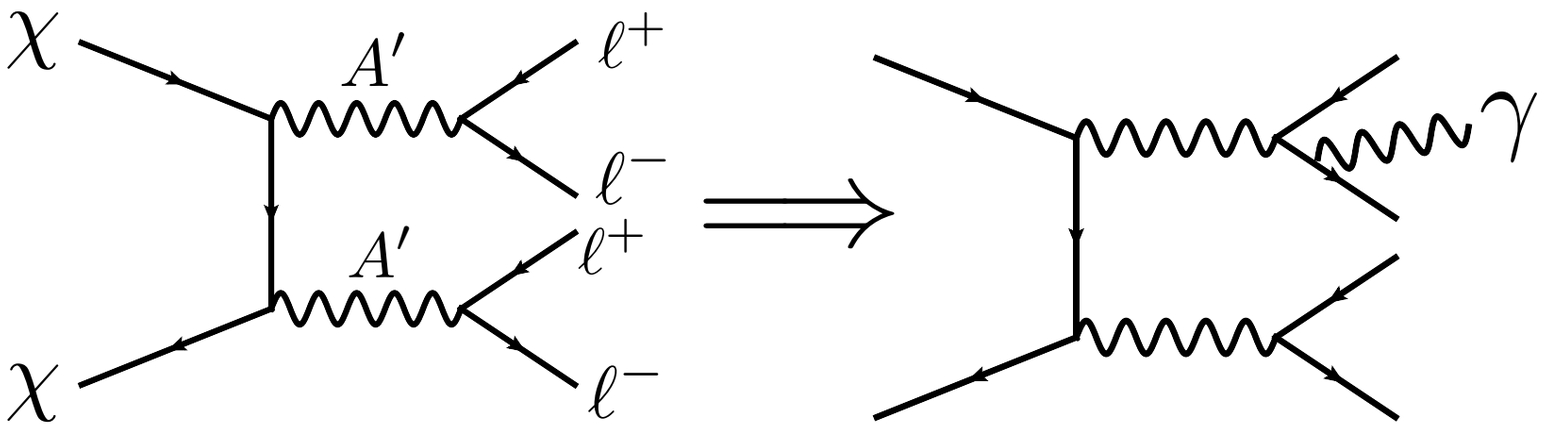
Fixed Target Exp's

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

Indirect probe: γ-rays from Dwarfs

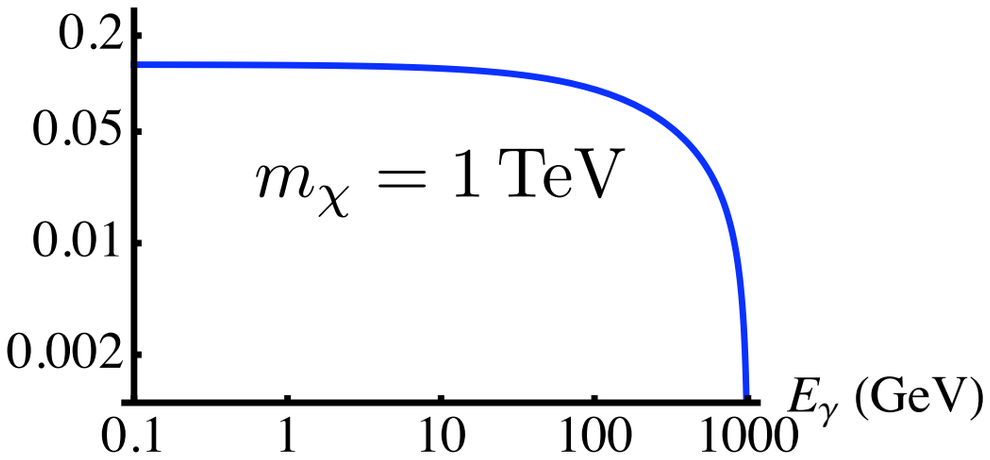
[RE, Sehgal, Strigari

[RE, Sehgal, Strigari, Geha, Simon]



γ-rays guaranteed!

$E_\gamma \frac{dN_\gamma}{dE_\gamma}$ Distinctive spectrum



Observe with:

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

Why dwarfs?

What are dwarf galaxies?

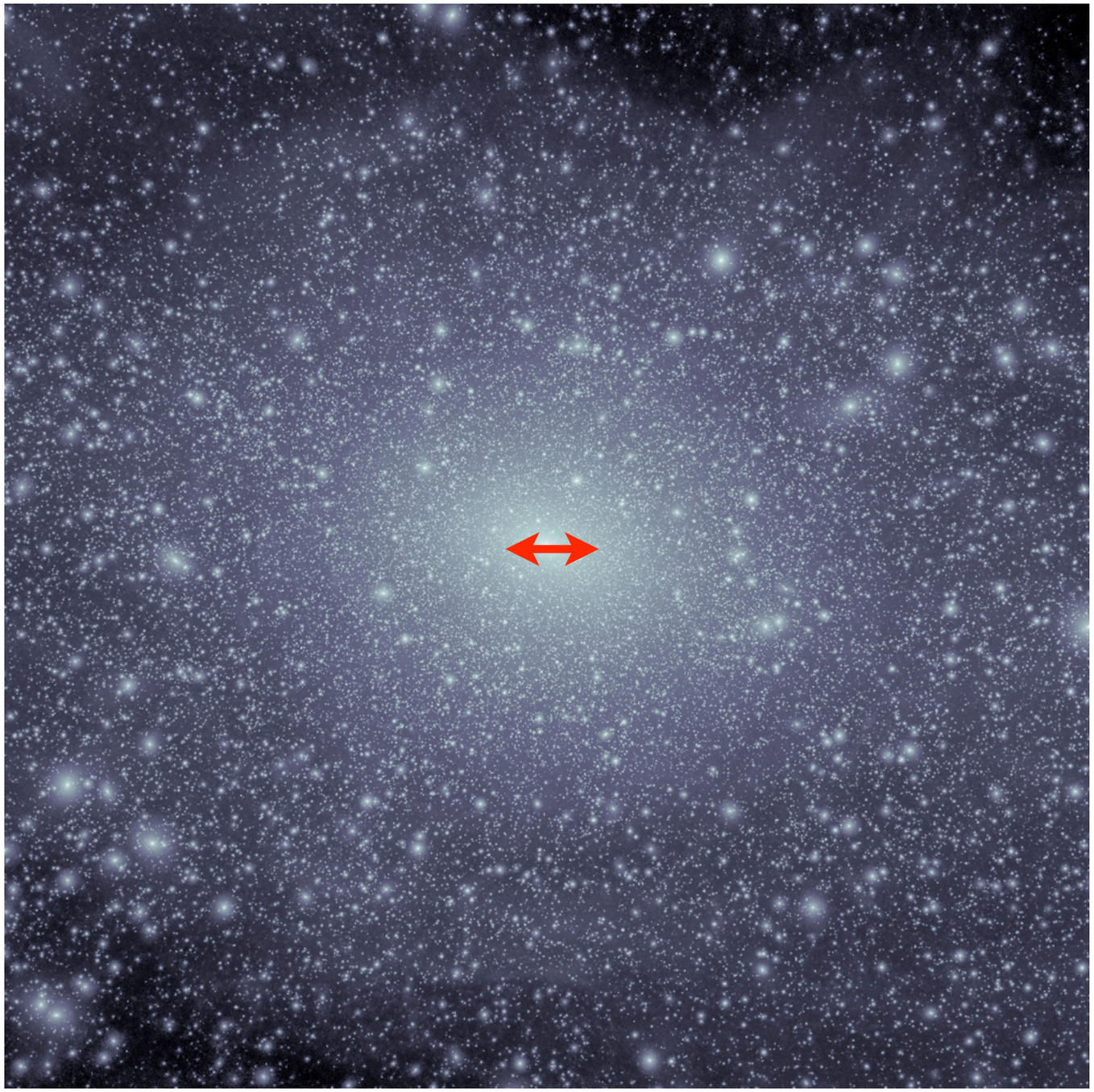
Via Lactea II
Simulation of Milky Way DM halo

(only DM, no baryons)

visible Milky Way galaxy ~30 kpc

some subhalos will contain stars and are dwarf galaxies

[Diemand et.al.]



800 kpc cube

Dwarf galaxies: Excellent Targets

Large Signal

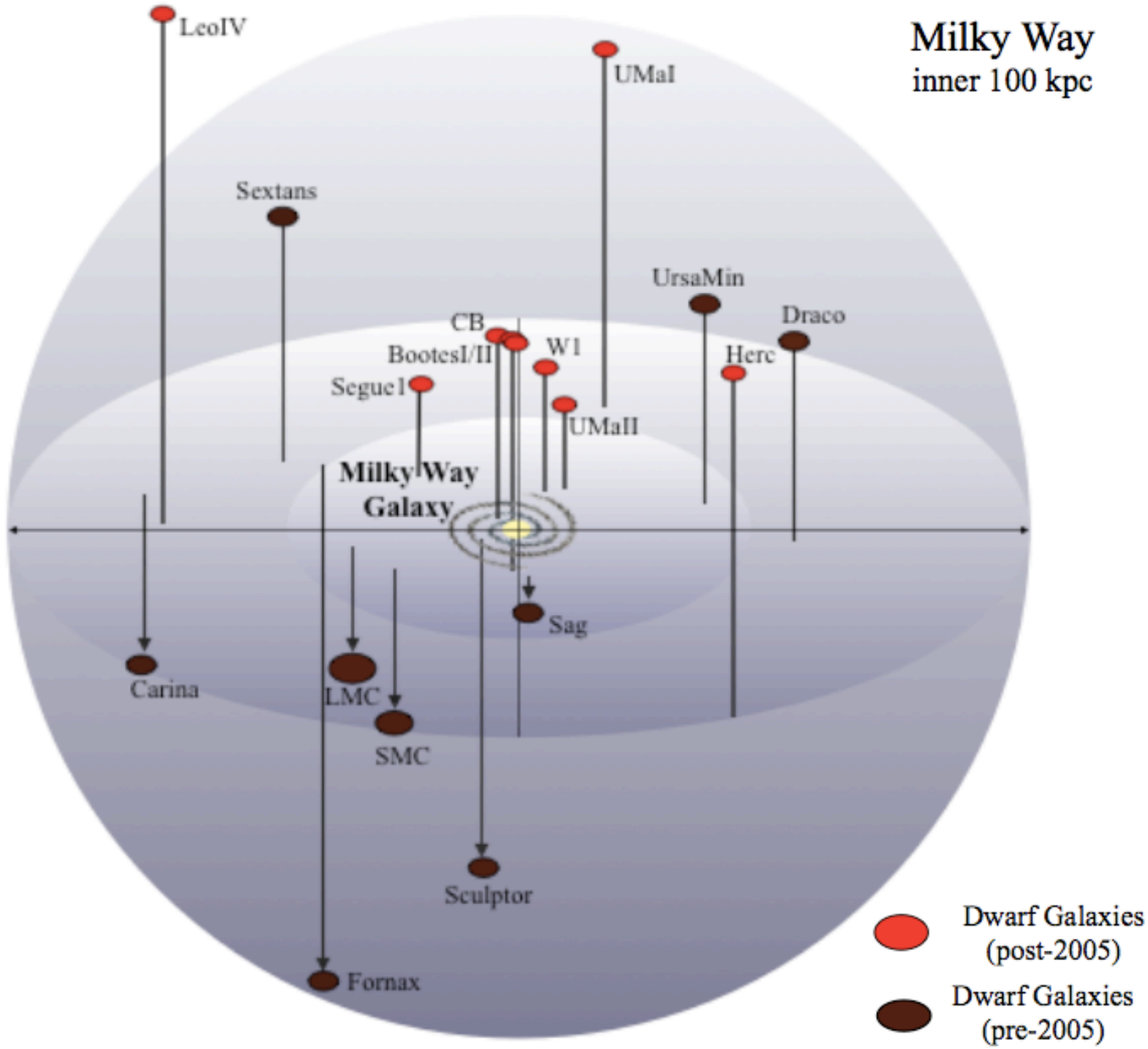
- Nearby
- Dark Matter dominated
- stellar kinematics determine expected flux
- low velocity dispersion: $v_{\rm dwarf} \sim v_{\rm halo}/20$

Low Background

- high galactic latitude
- no intrinsic gamma-ray sources

Any signal would be *very* suggestive of dark matter

Known Nearby Dwarf Galaxies

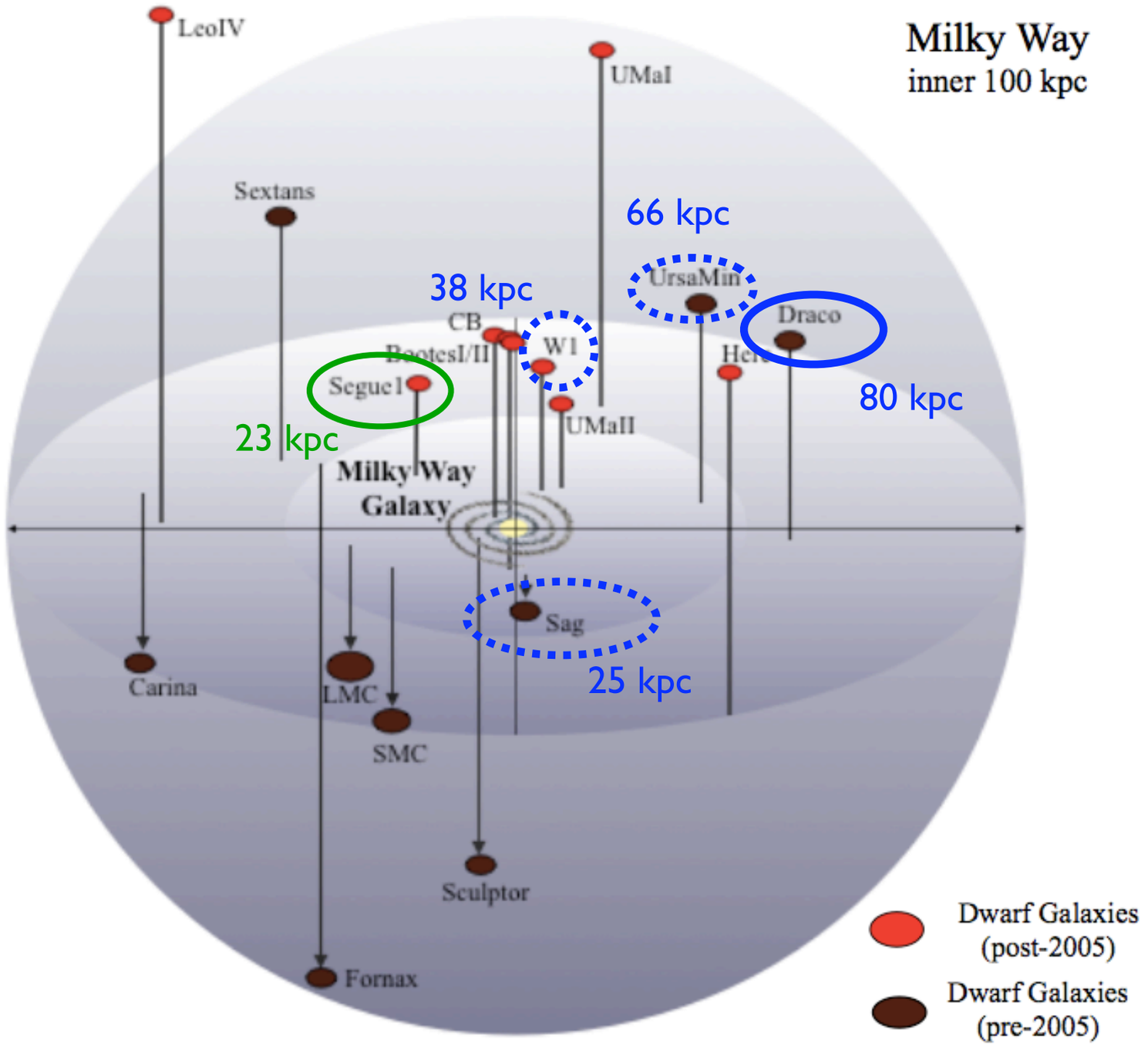


[Geha]

Fermi has data on all dwarfs

in blue:
Observed by ACTs

Draco:
most robust existing ACT constraint (VERITAS)



[Geha]

Segue 1:

Most promising dwarf target

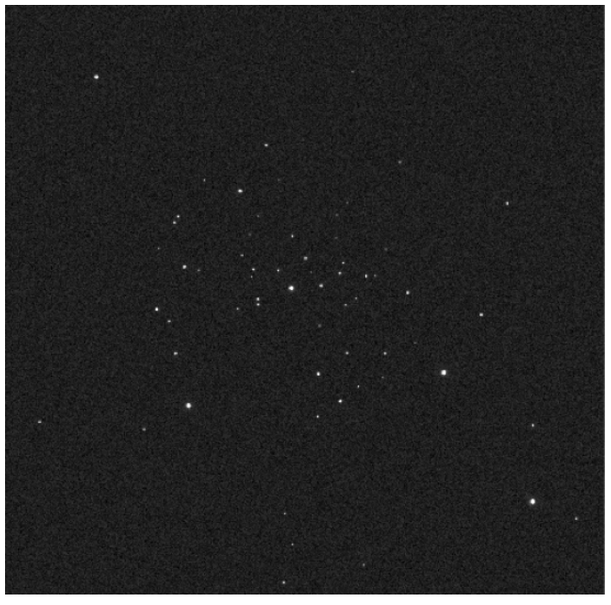
Existing constraints from Fermi
Data coming from MAGIC (+VERITAS & IceCube)

Draco

classical dwarf

data on >200 stellar velocities

Segue 1



ultra-faint dwarf

New stellar data!
(~65 stars)

[Geha et. al.; Simon et. al.]

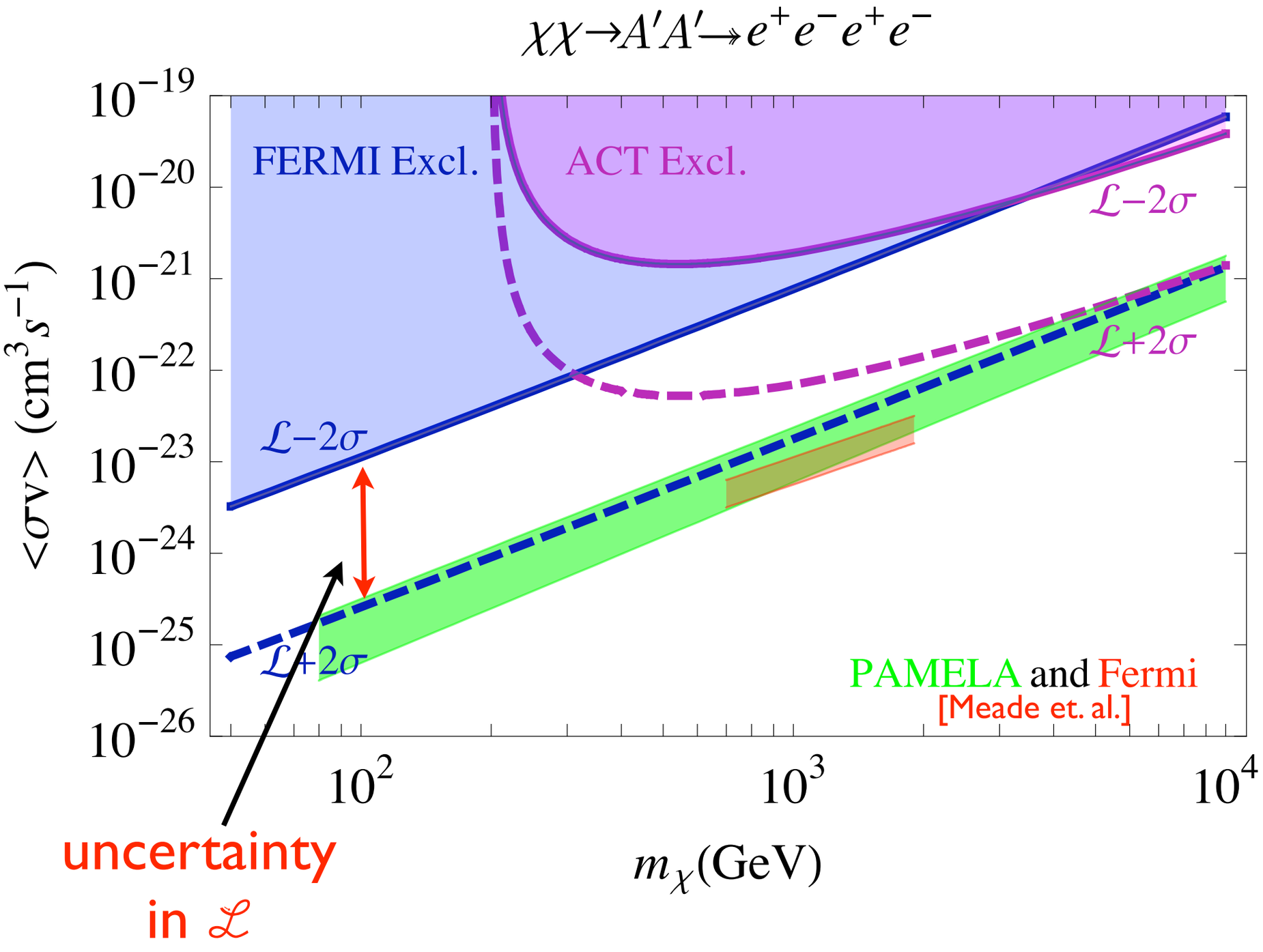
Flux $\propto \mathcal{L} \sim \int \rho^2$ determined from stellar velocities

$$\mathcal{L}_{\mathrm{Segue\ 1}} \sim 35\, \mathcal{L}_{\mathrm{Draco}}$$

Segue 1: Excellent target

Current Fermi & ACT limits

[RE, Sehgal, Strigari, Geha, Simon]



Fermi data:
9 months of data

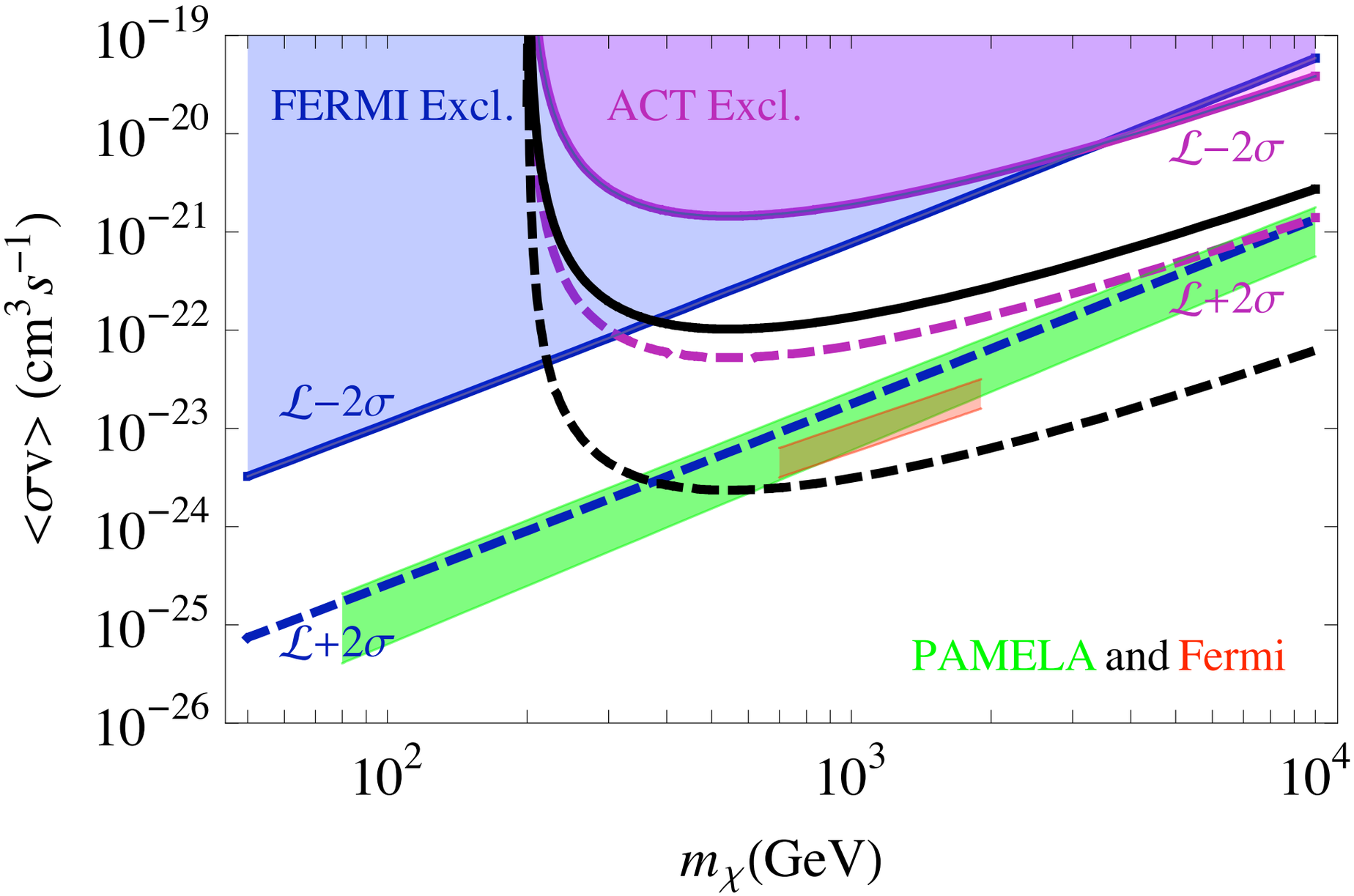
[Farnier, RICAP'09]
[Wang, CINC'09]

ACT data:
VERITAS obs. of Draco [0810.1913]

Prospects for MAGIC & VERITAS from Segue 1

[RE, Sehgal, Strigari, Geha, Simon]

$$\chi\chi \to A'A' \to e^+e^-e^+e^-$$



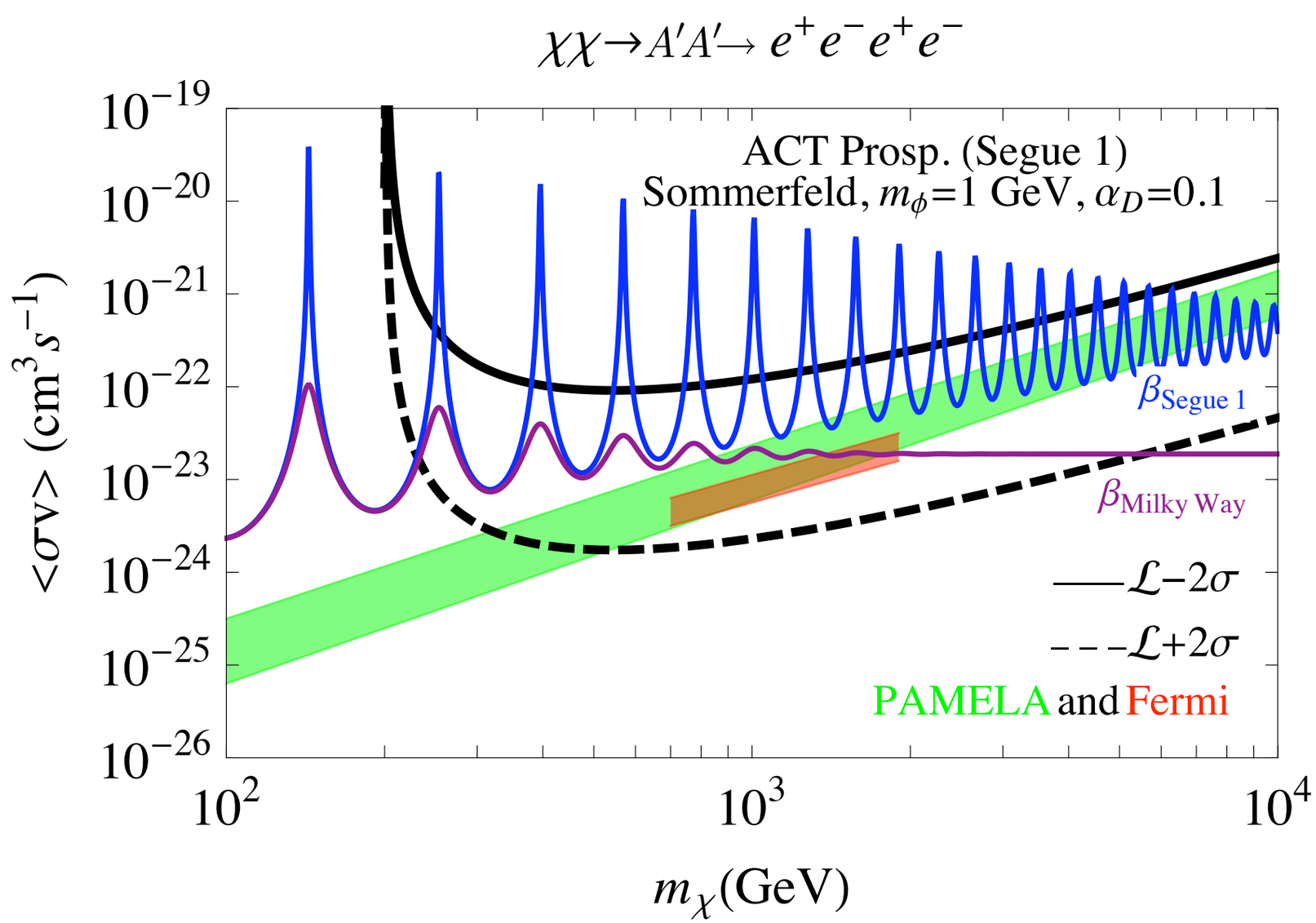
Conservative: same flux limit as for Draco (assumes softer spectrum!)
(only ~20 hours of observing!)

Constraining $m_{A'}$ with Dwarfs

$$V(r) = -\frac{\alpha_D}{r} e^{-m_{A'} r} \qquad S \sim \frac{\pi \alpha_D}{v_\chi} \qquad v_{\rm dwarf} \sim v_{\rm MW}/20$$

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

$\Longrightarrow$ can constrain low $m_{A'}$



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

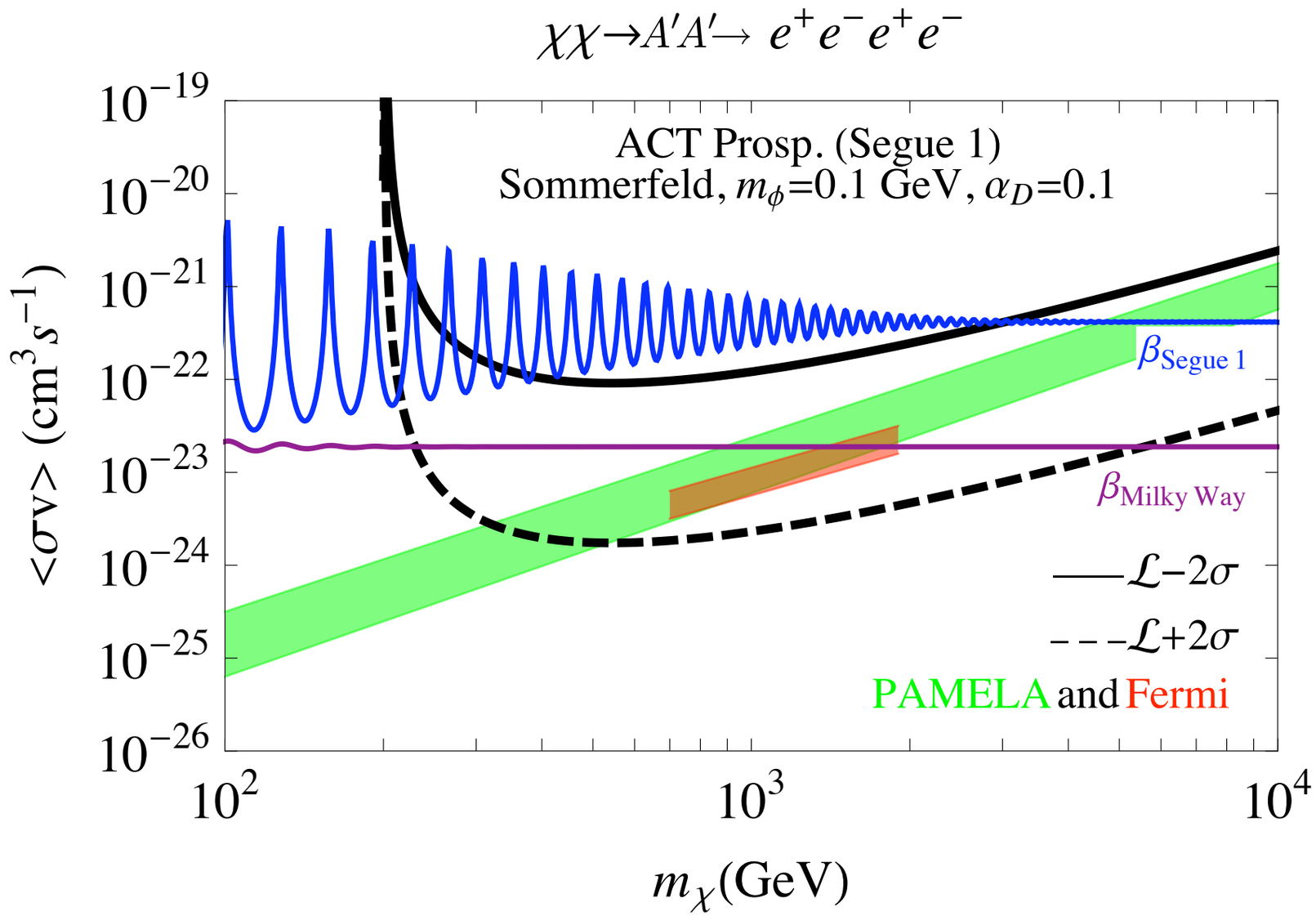
Resonances will be probed

Constraining $m_{A'}$ with Dwarfs

$$V(r) = -\frac{\alpha_D}{r} e^{-m_{A'} r} \qquad S \sim \frac{\pi \alpha_D}{v_\chi} \qquad v_{\rm dwarf} \sim v_{\rm MW}/20$$

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

$\Longrightarrow$ can constrain low $m_{A'}$



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

Excellent prospects!

Experimental Probes of Dark Forces

A)

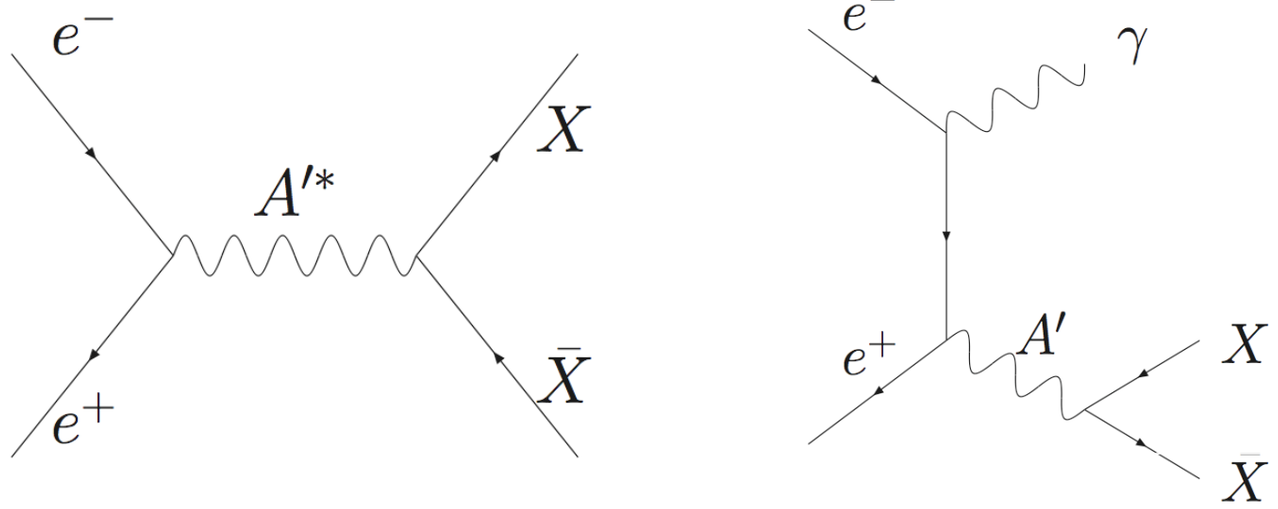
DM annihilation

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, KLOE, BES-III)

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

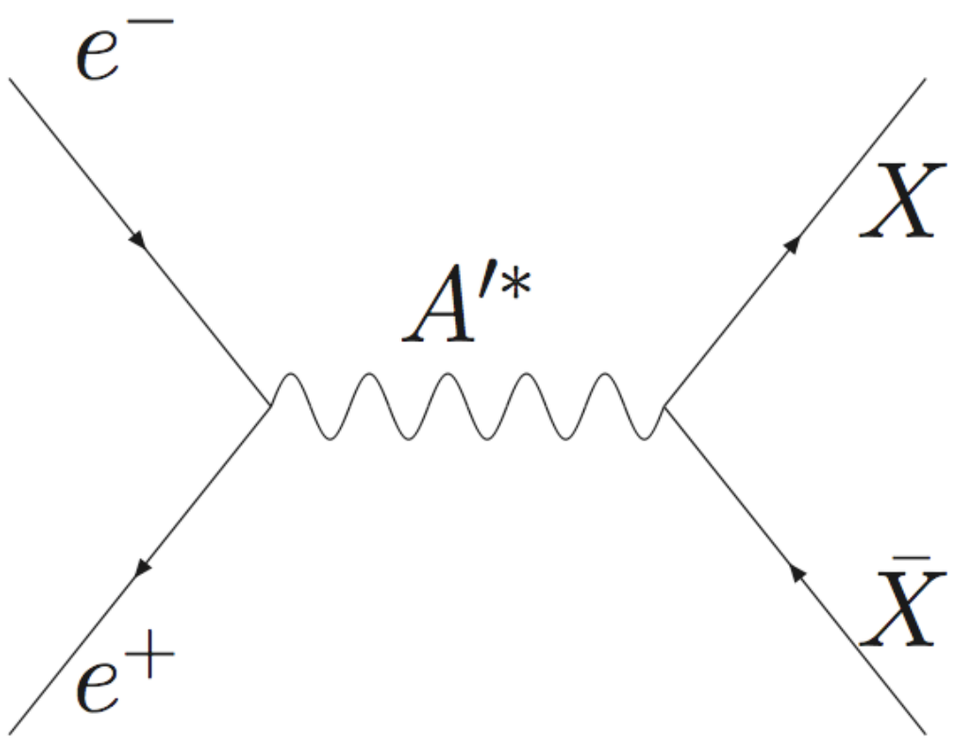
C)

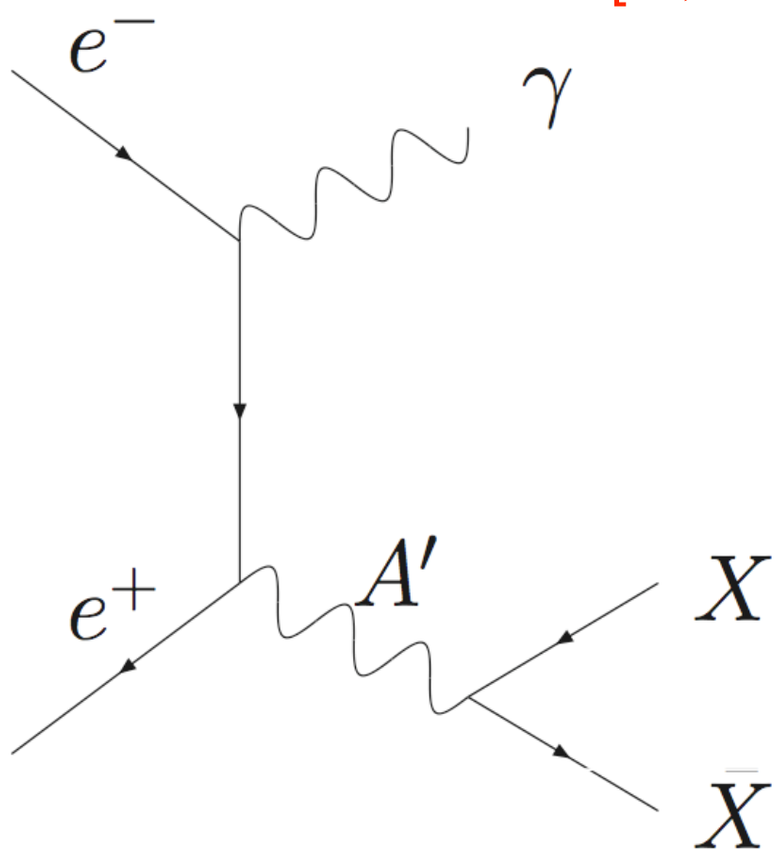
Fixed Target Exp's

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

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

[RE, Schuster, Toro]





$$\sigma \propto \frac{\epsilon^2}{E_{cm}^2}$$

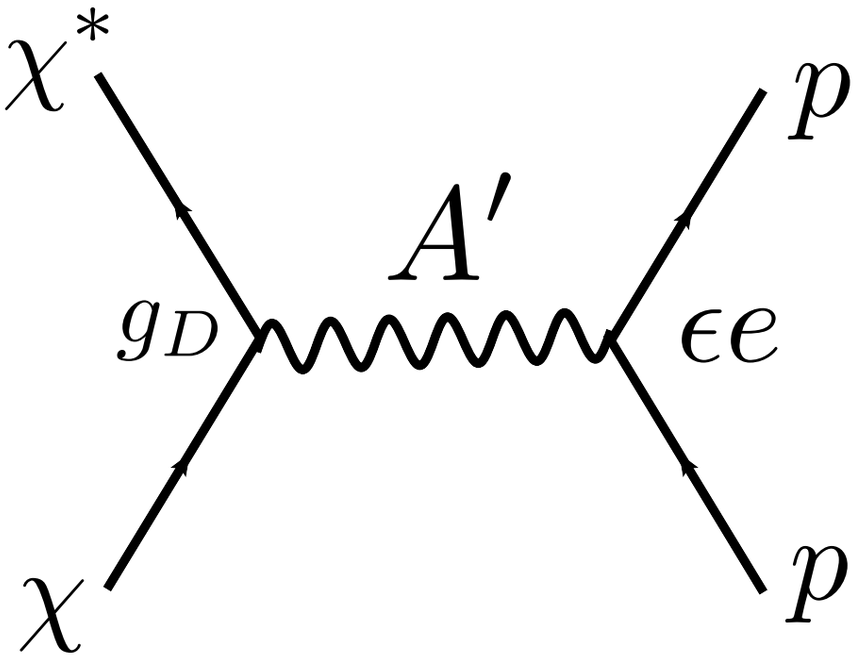
want *low*-energy collider
with *large integrated luminosity*

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

BaBar + BELLE have $\mathcal{L}_{\rm int} \sim 1.4\,{\rm ab}^{-1}$!

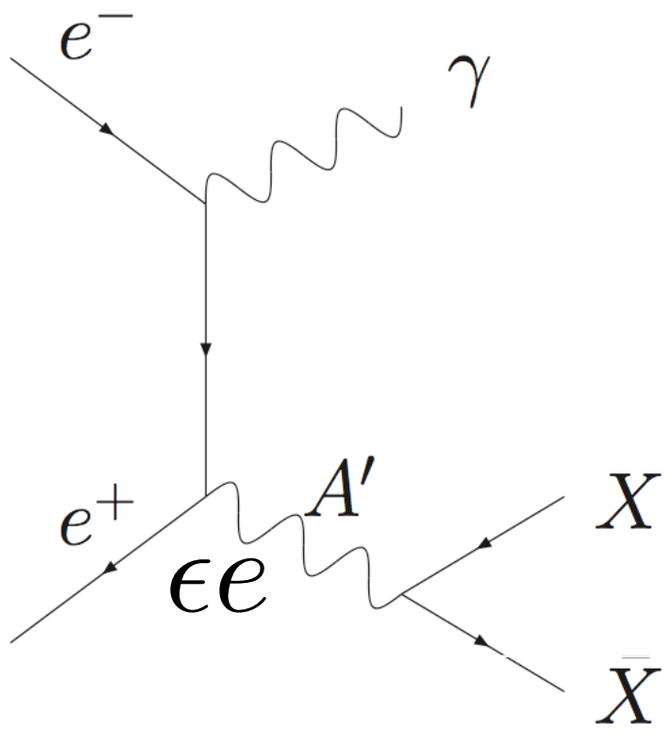
DAMA/LIBRA Normalized Production Rates

DAMA



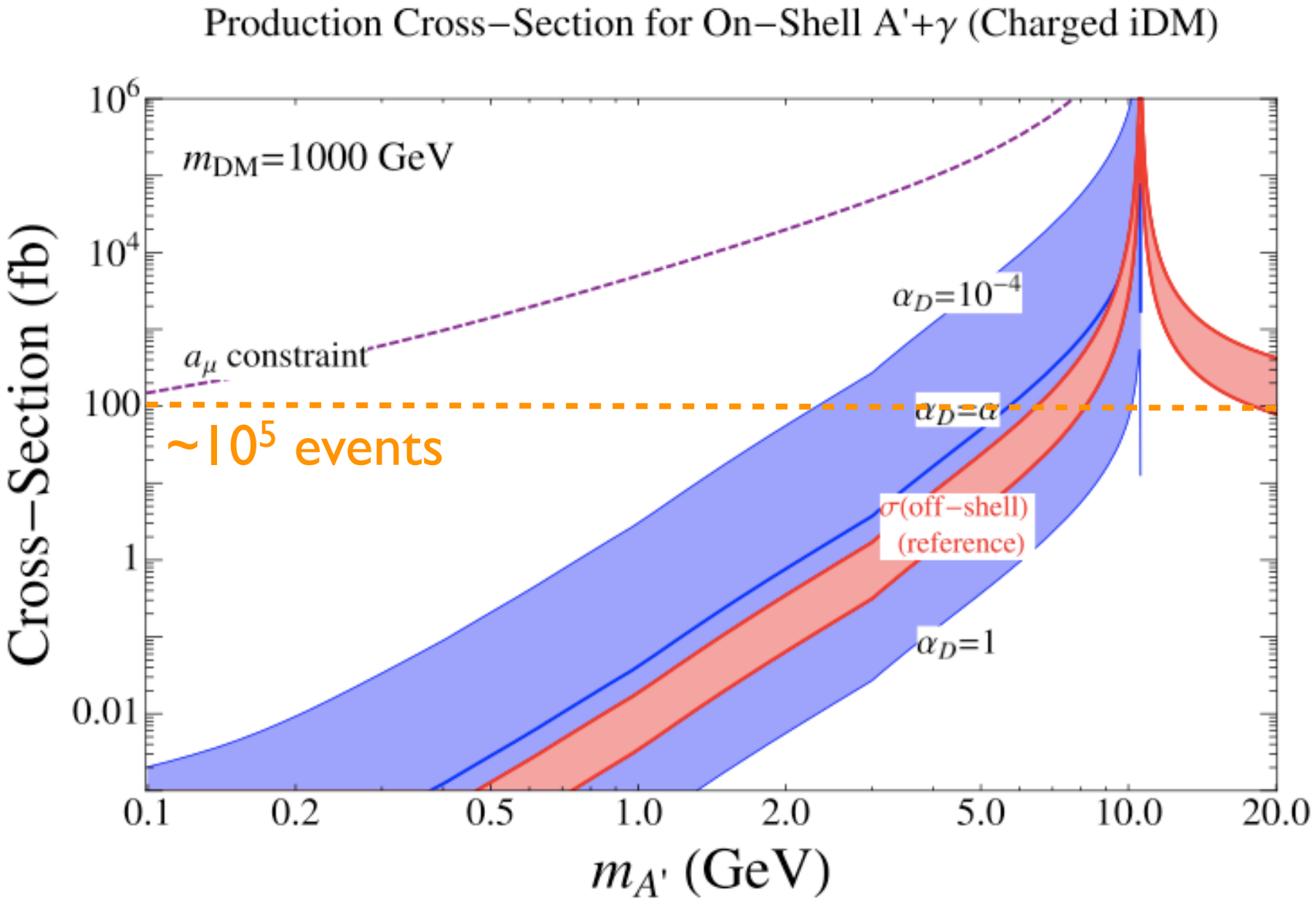
$\longleftrightarrow$

e^+e^- Colliders



$\Longrightarrow$ can normalize couplings to DAMA

DAMA-Normalized Production Rates for BaBar or BELLE



$\sqrt{s} \simeq 10.6\,\mathrm{GeV}$

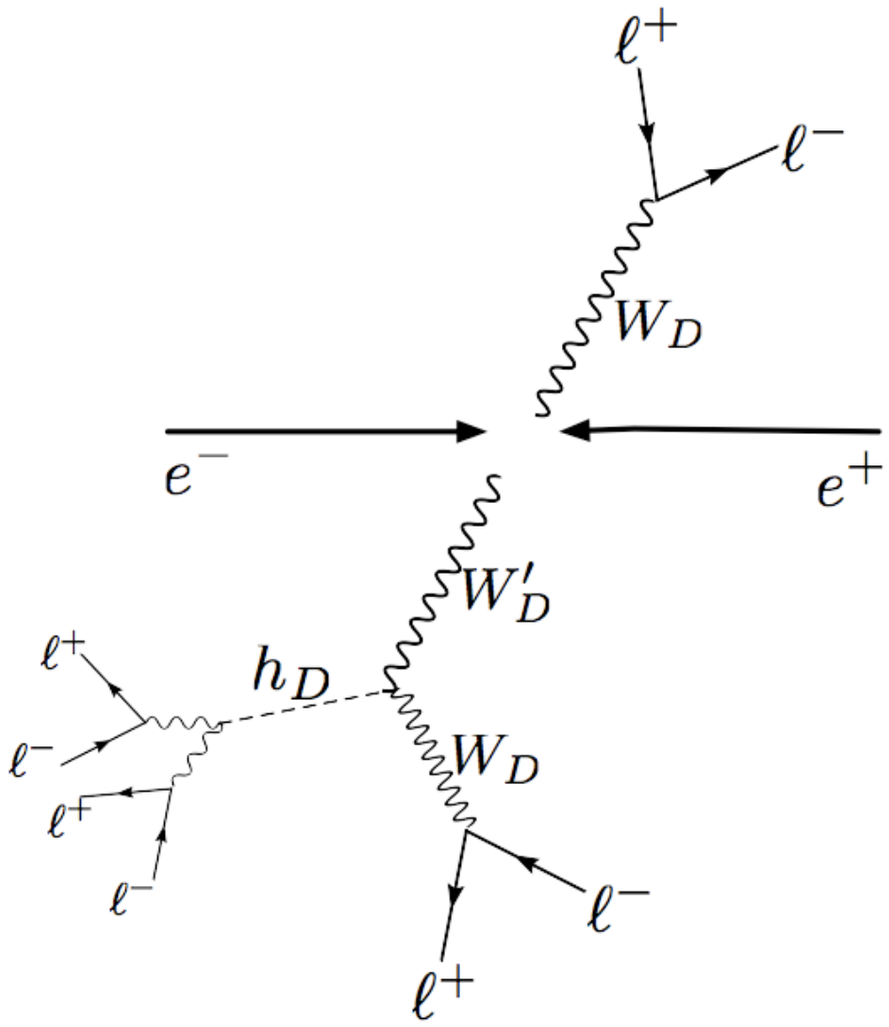
(KLOE similar)

Large # of events possible !

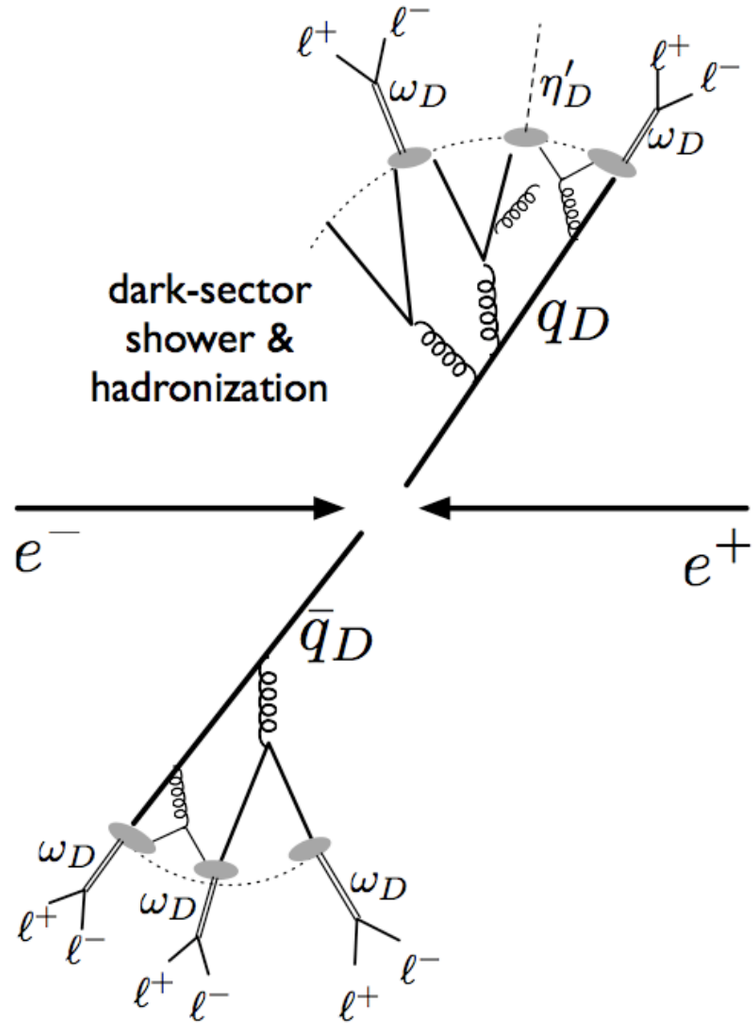
What do events look like?

Examples of spectacular events

Higgsed



Confined

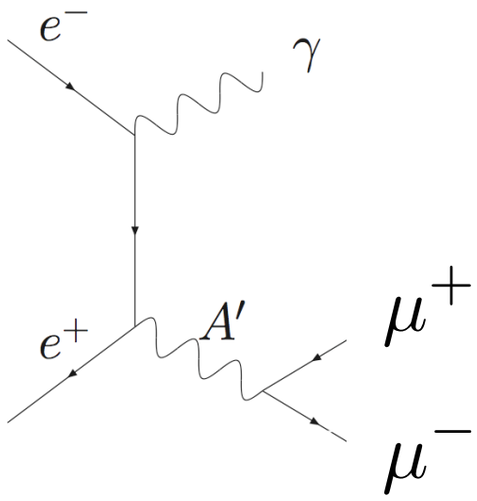


Very rich phenomenology!

Multi-leptons, resonances, displaced vertices, MET...

Many searches needed!

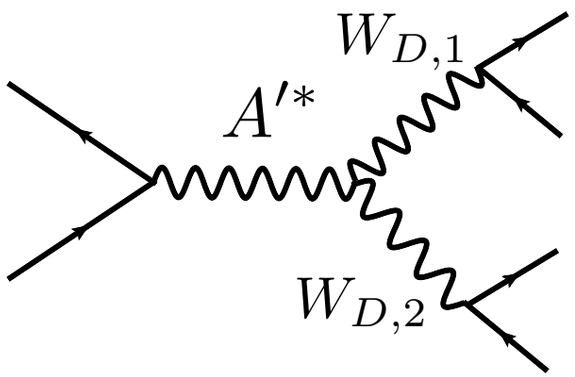
What searches have been done?



Done

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

BaBar



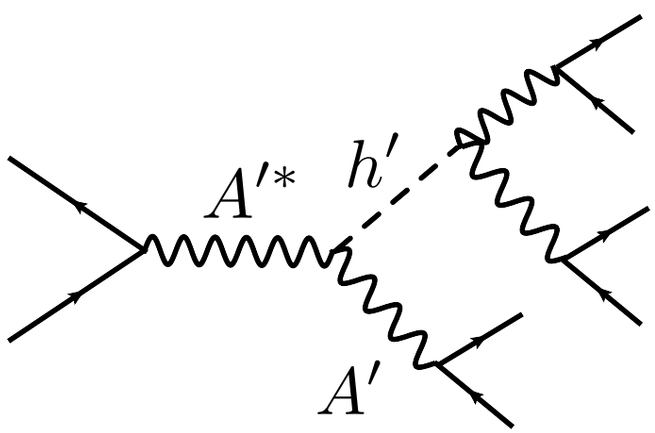
Done

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

BaBar

M. Graham & A. Roodman

not yet $\gamma + 4\ell$



Not yet

$2\ell, 6\ell$

Higgs'-strahlung

[Batell, Pospelov,Ritz]

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

Interest to do higher multiplicities (e.g. H'-strahlung) exists

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/

Experimental Probes of Dark Forces

A)

DM annihilation

guarantees γ-rays!

can also get $\nu's$

(Fermi, ACTs, IceCube)

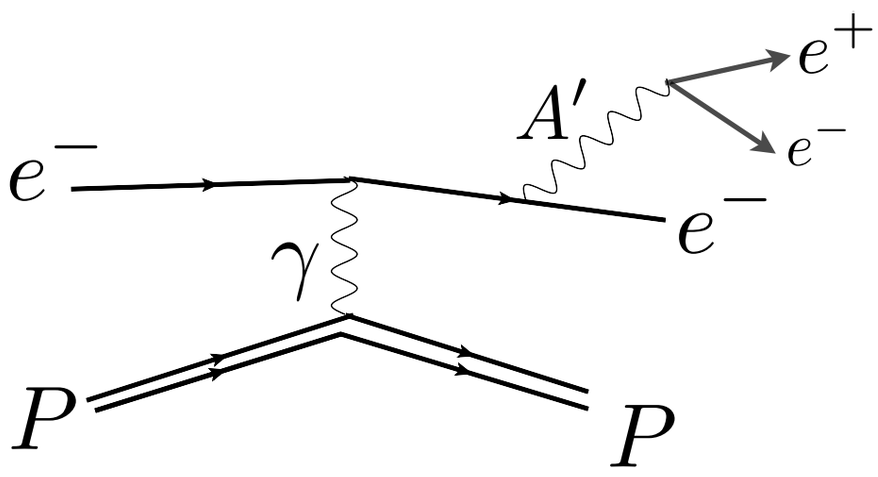
Dwarf galaxies: excellent targets ($v_{\rm dwarf} \sim v_{\rm halo}/20$)

B)

e^+e^- Colliders

(BaBar, BELLE, KLOE, BES-III)

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

C) 

Fixed Target Exp's

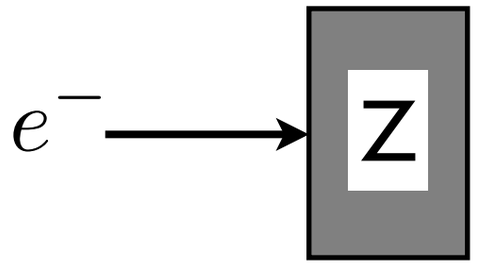
(E137, E141, JLab, SLAC, FNAL, COMPASS)

Why Fixed Target Experiments?

[Bjorken RE, Schuster, Toro]

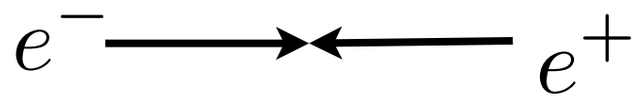
[see also Batell et.al.; Reece & Wang]

Higher Luminosity



majority of incident e⁻'s scatter

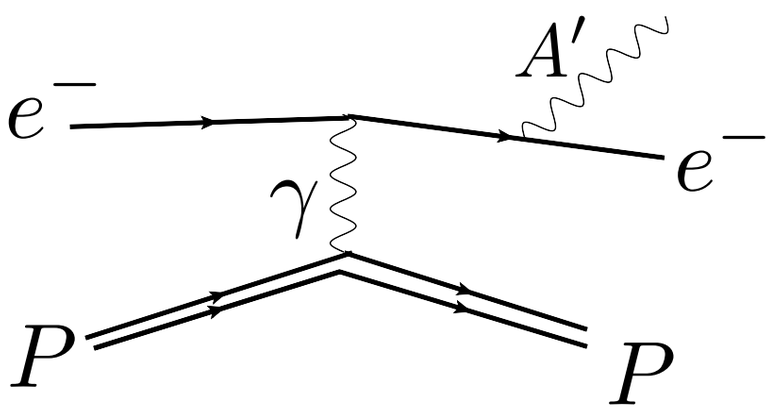
~ few ab^{-1}/*day*



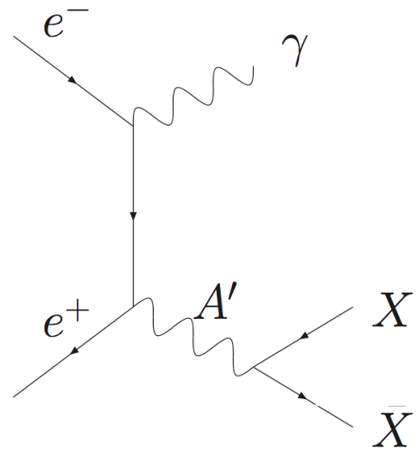
only ~1 e⁻ scatters per crossing

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

Larger Cross-section

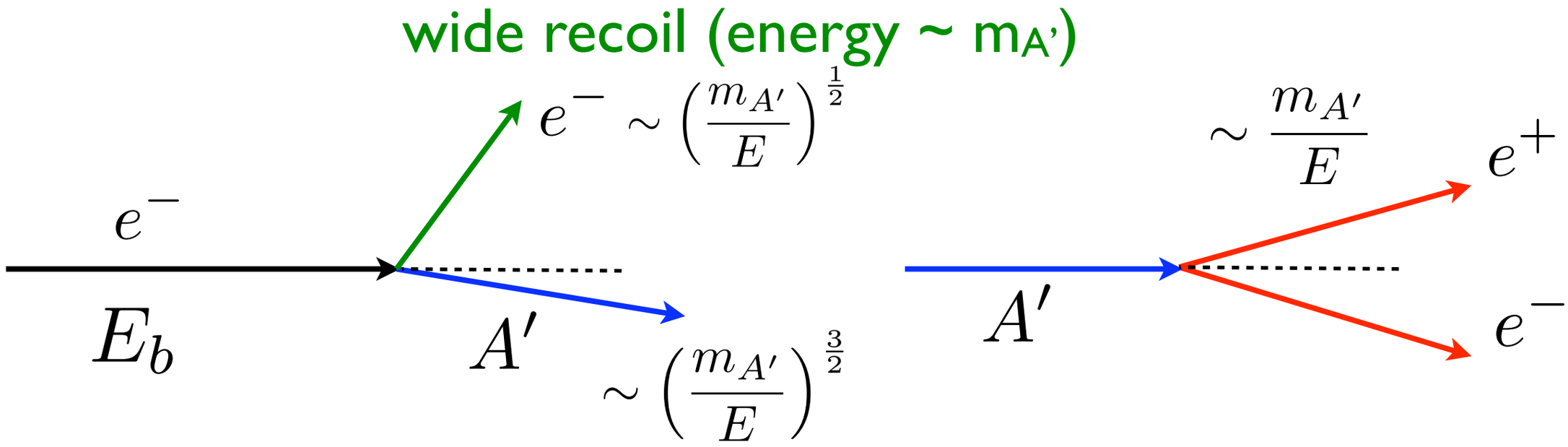


$$\sigma \propto \frac{\alpha^3 \epsilon^2 Z^2}{m_{A'}^2} \propto 1 \text{ pb}$$



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

Favorable Fixed-Target Kinematics



A' production very forward

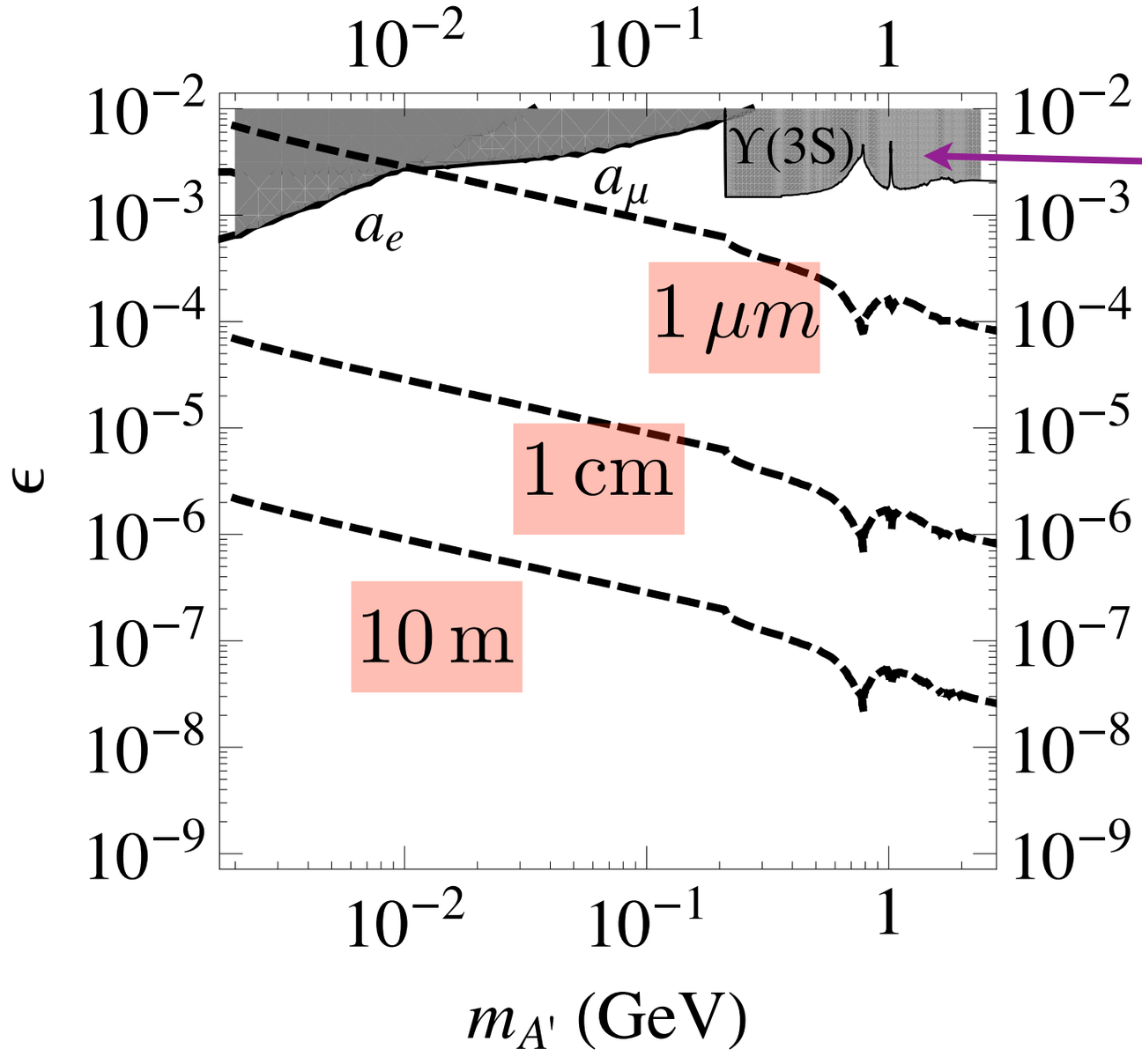
A' decay forward (but wider angle than most background!)

A' takes most of beam energy: $E_{A'} \sim E_b - m_{A'}$

(characteristic of *heavy* particle emission)

Cover huge range in mass and coupling

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

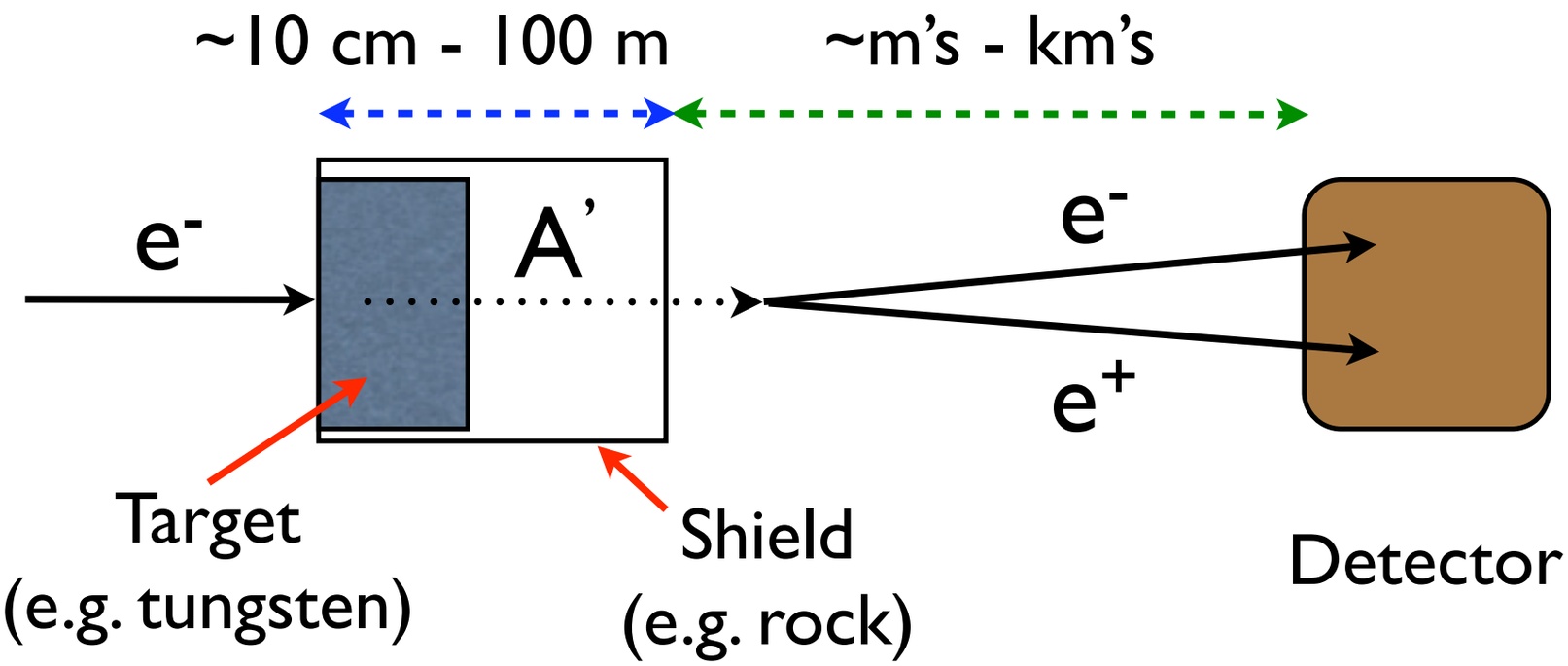


BaBar

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

Need various strategies to cover huge lifetime range

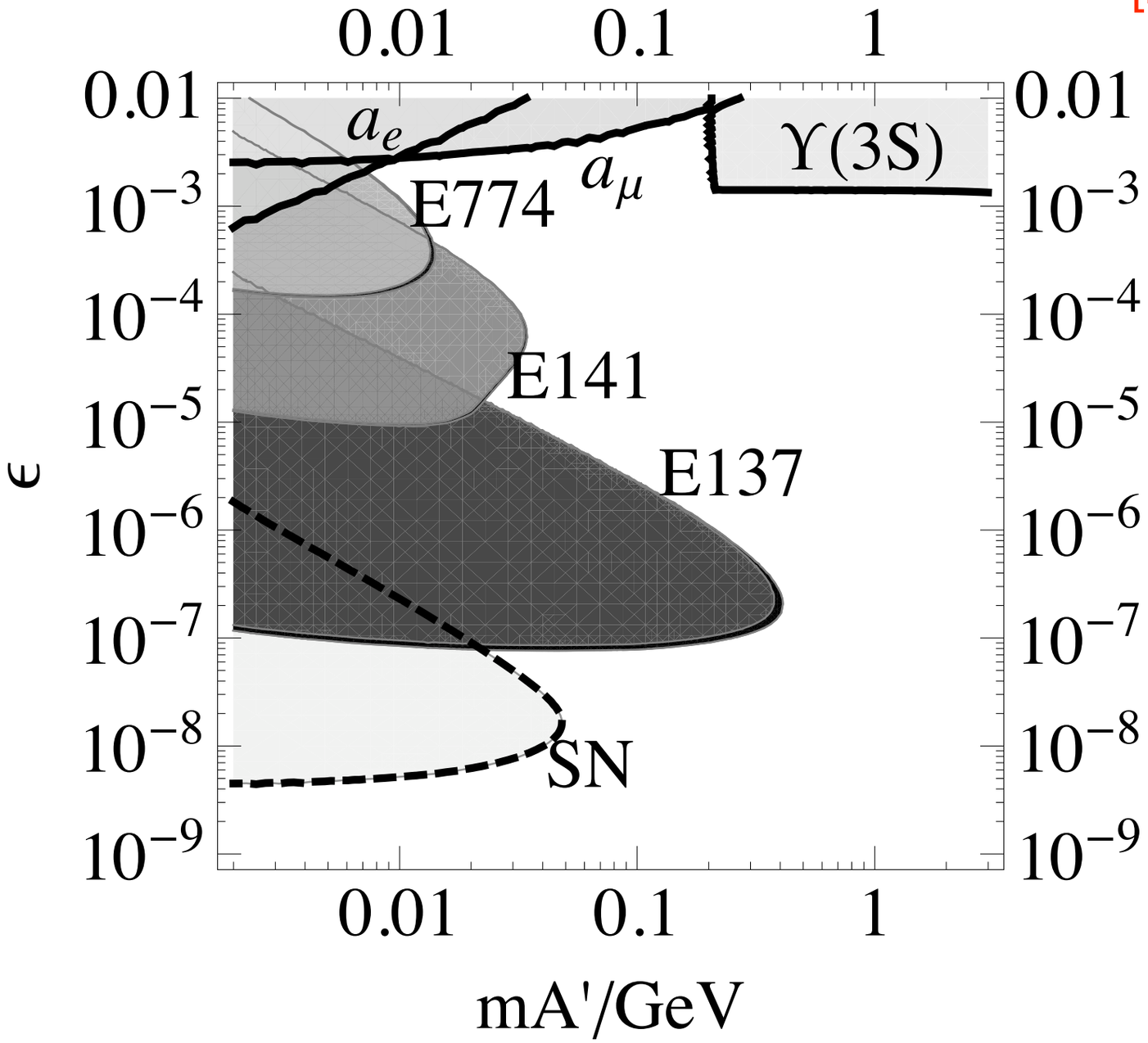
Old Beam Dumps



Exp.	Target/Shield	Beam	Charge dumped	
E141	W/12cm	9 GeV	10^{15} e^-	[Riordan, Bjorken et.al.]
E137	Al/200 m	20 GeV	10^{20} e^- !!	[Bjorken et.al.]
E774 (FNAL)	W/20cm	275 GeV	10^{10} e^-	[Bross et.al.]

Good Beam Dump Constraints exist

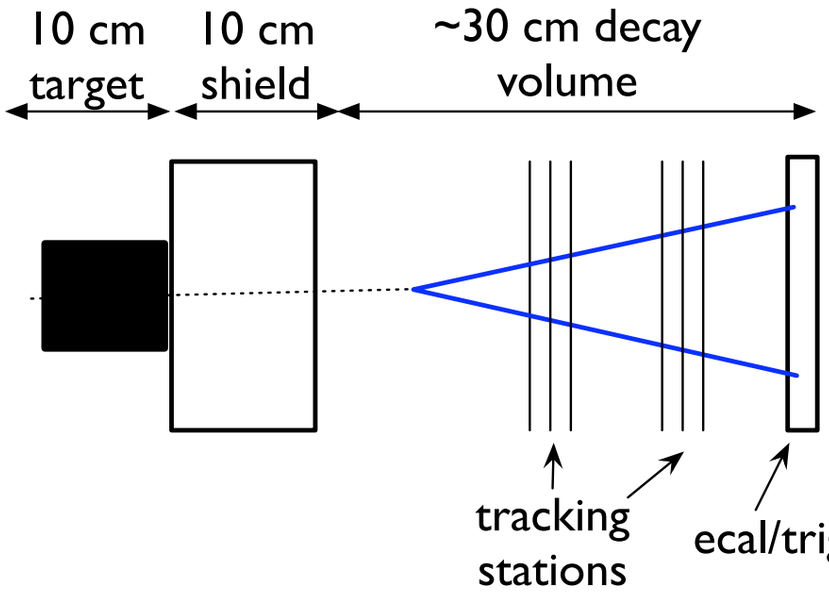
[Bjorken RE, Schuster, Toro]

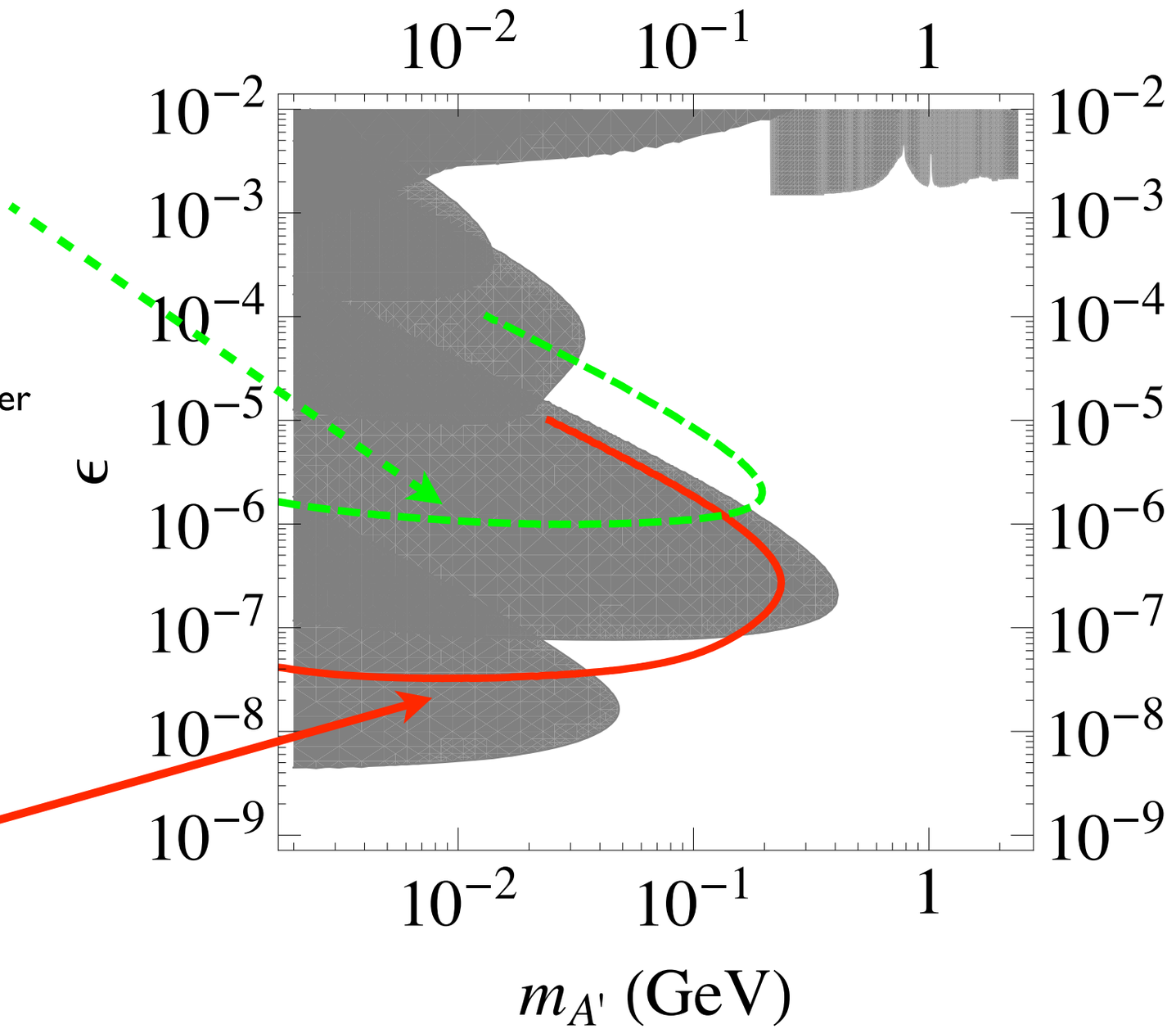


Need new experiments to cover remaining parameter space

Strategy 1: New Beam Dumps

[Bjorken RE, Schuster, Toro]



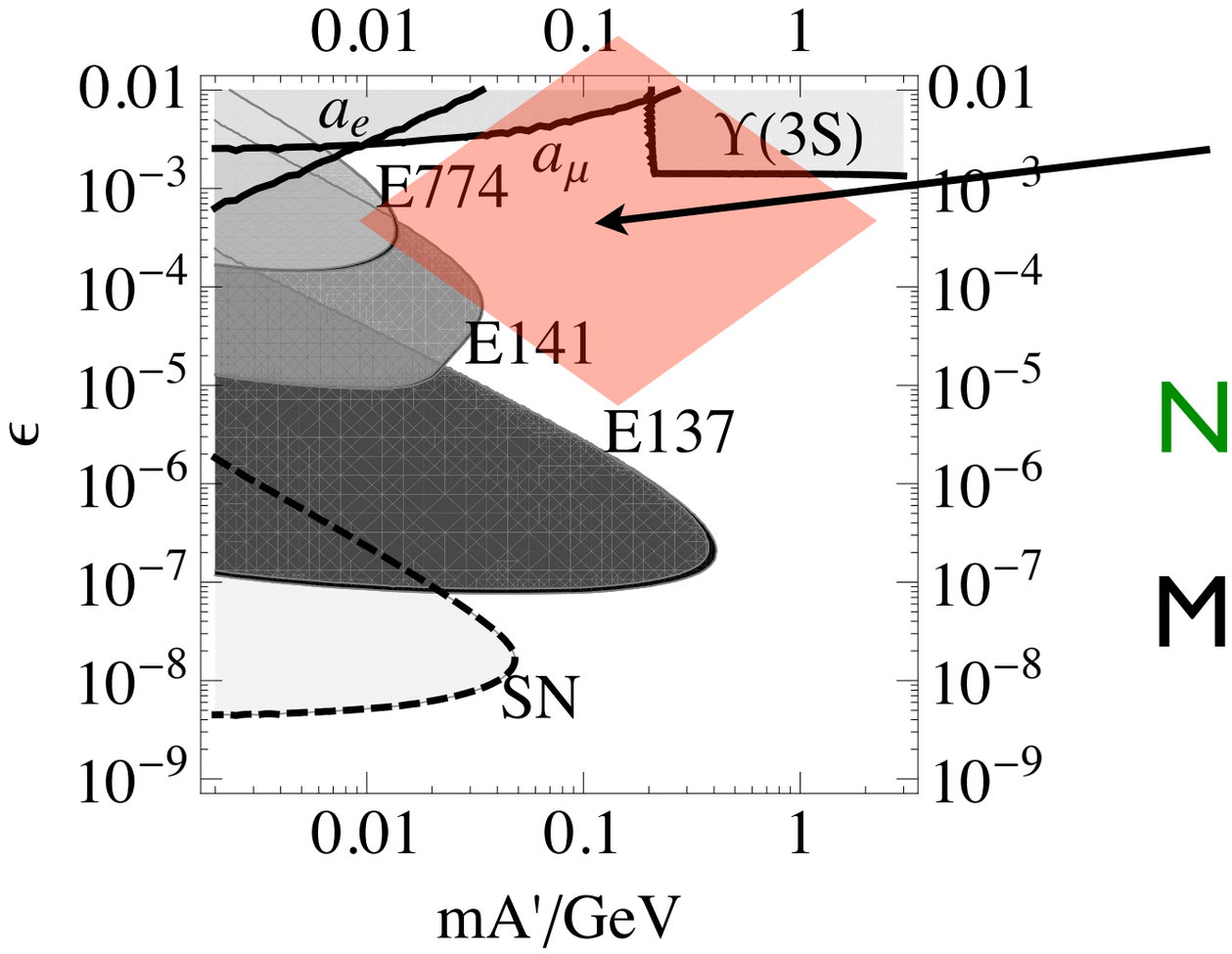


Larger shield,
1 MW power

@ SLAC, JLab, MAMI ?

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

[Bjorken RE, Schuster, Toro]



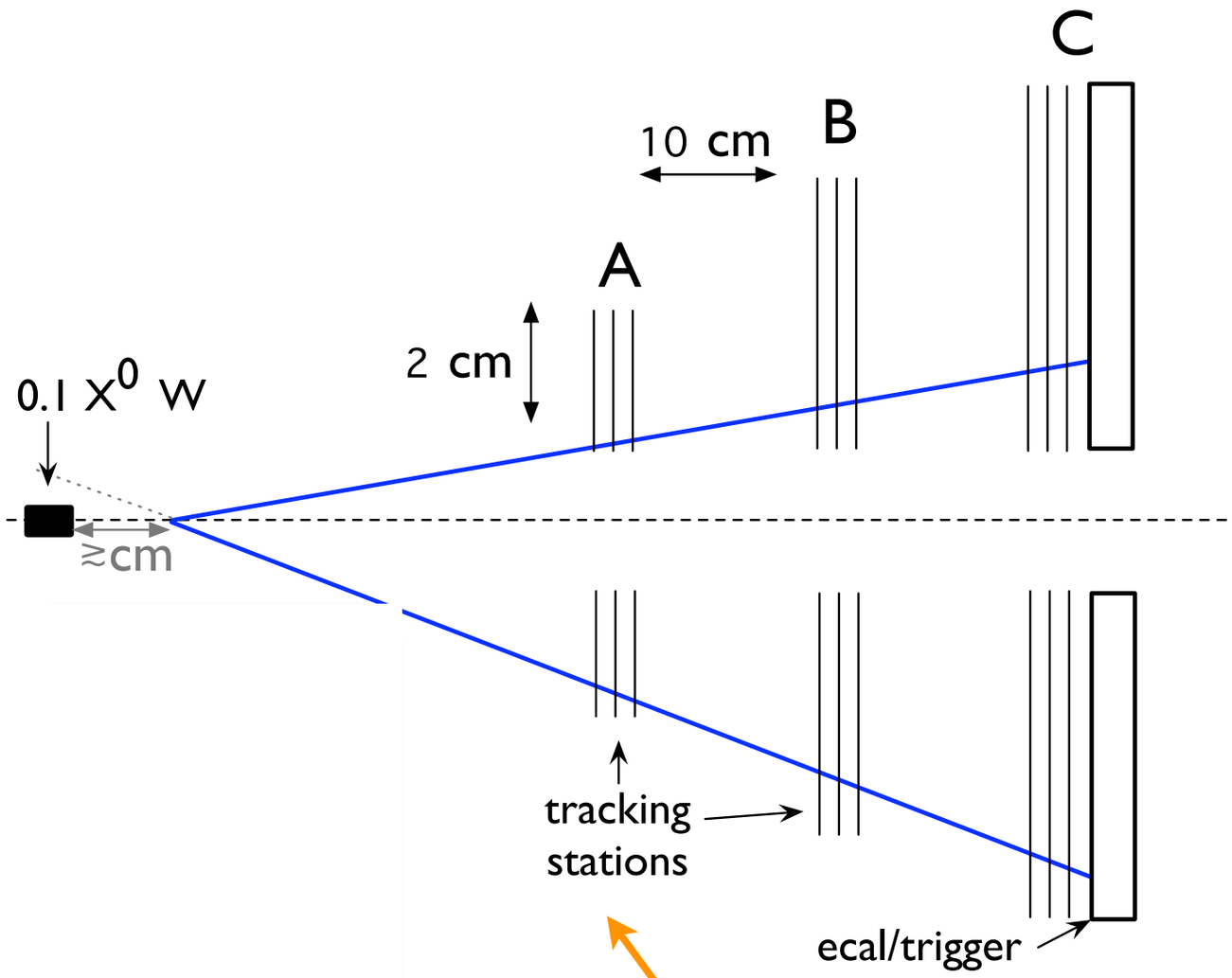
A' lifetime short,
so need *thin* target

Now have background too!

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

Use vertexing and/or bump hunt

Example: Forward two-arm spectrometer



small experiment

Want:

Mass resolution < 1%

Fast calorimeter

Fast trigger

Silicon tracking elements

Various geometries possible

several ideas to cover much of parameter space

Actively developing two proposals for JLab

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

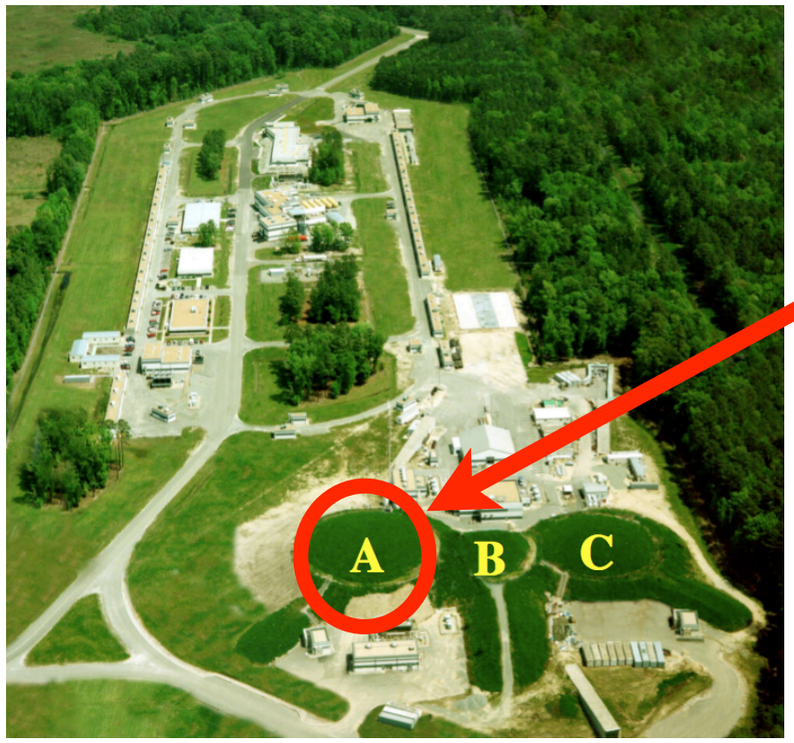
JLab
P. Bosted
S. Stepanyan
L. Weinstein
B. Wojtsekhowski

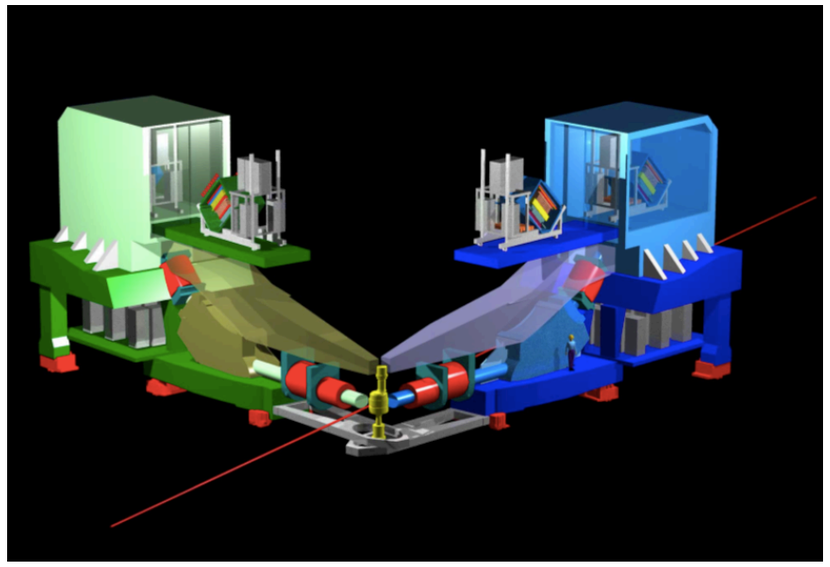
U. Oregon
R. Frey

1) JLab Hall A: Two High Resolution Spectrometers

2) JLab Hall B: New Commensal Experiment

1) JLab Hall A: Two High Resolution Spectrometers

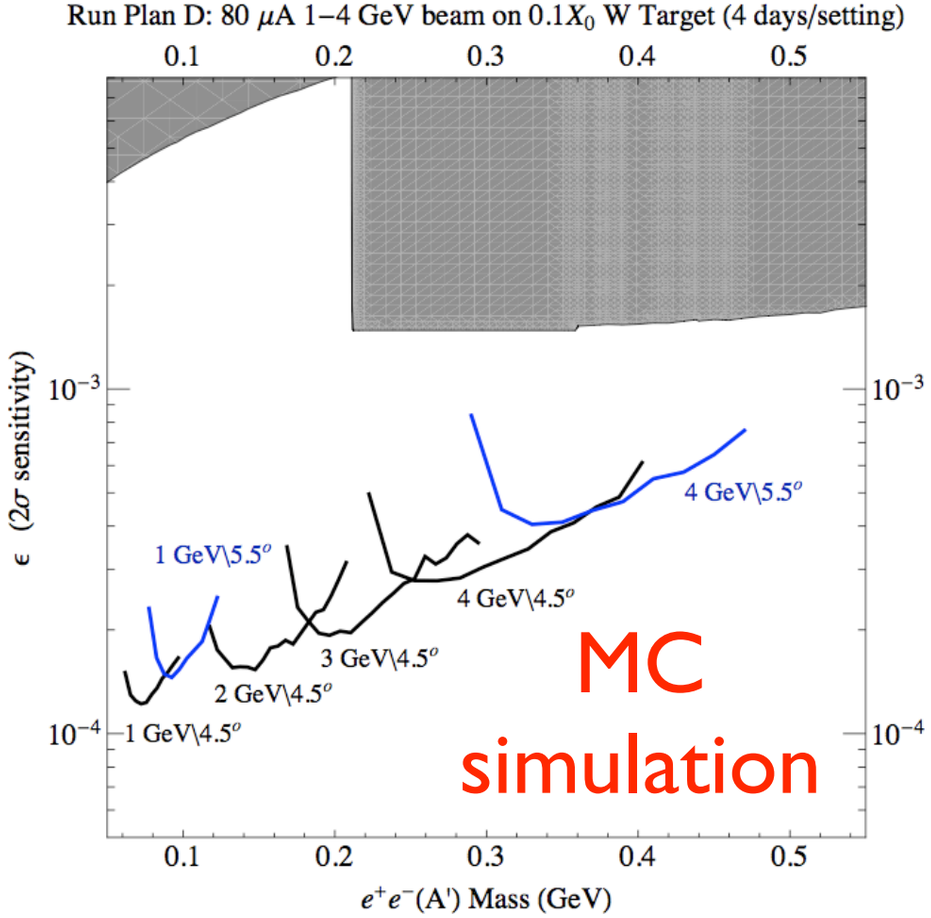


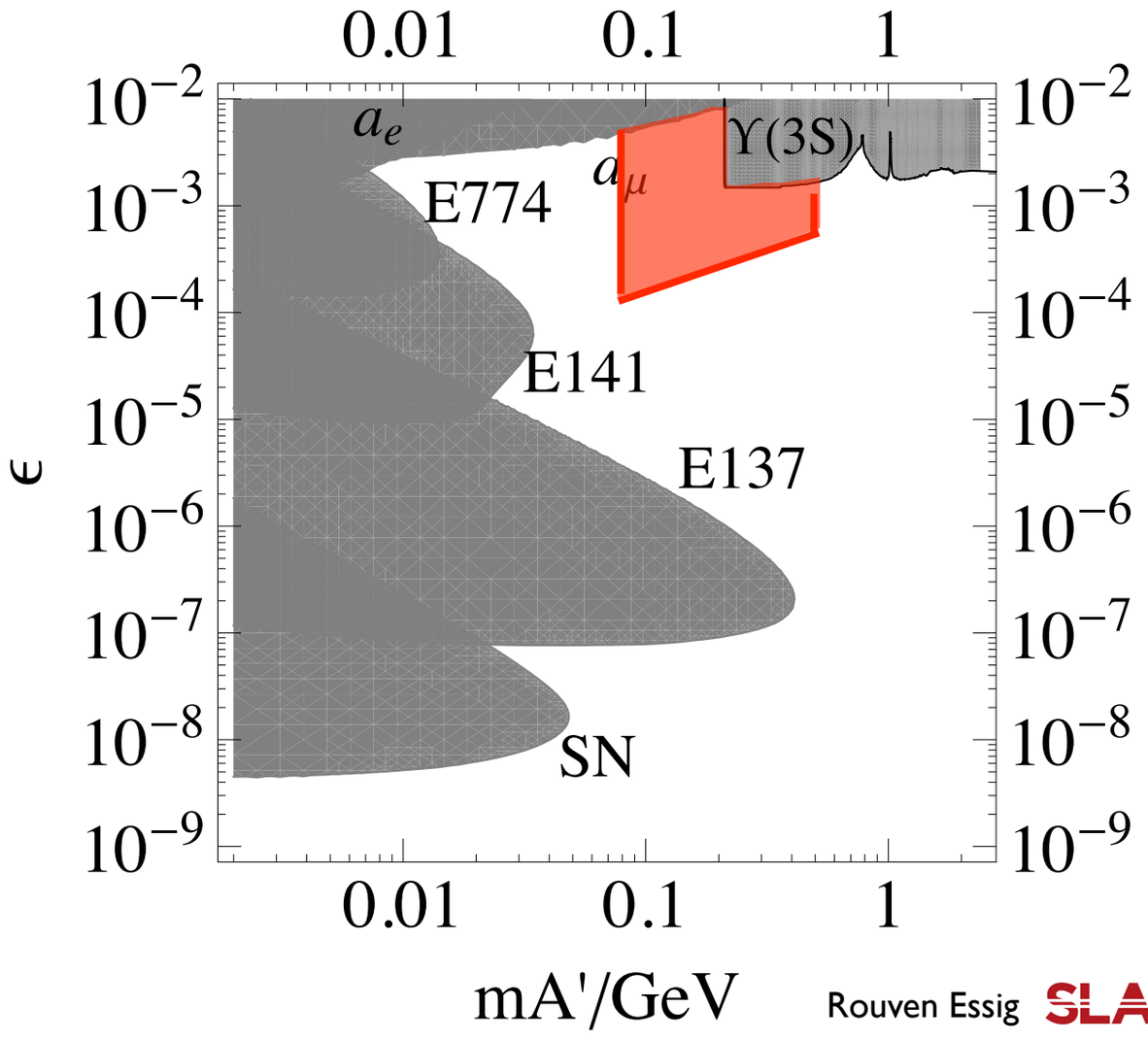


Proposal in Dec.

[RE, Schuster, Toro, Wojtsekhowski]

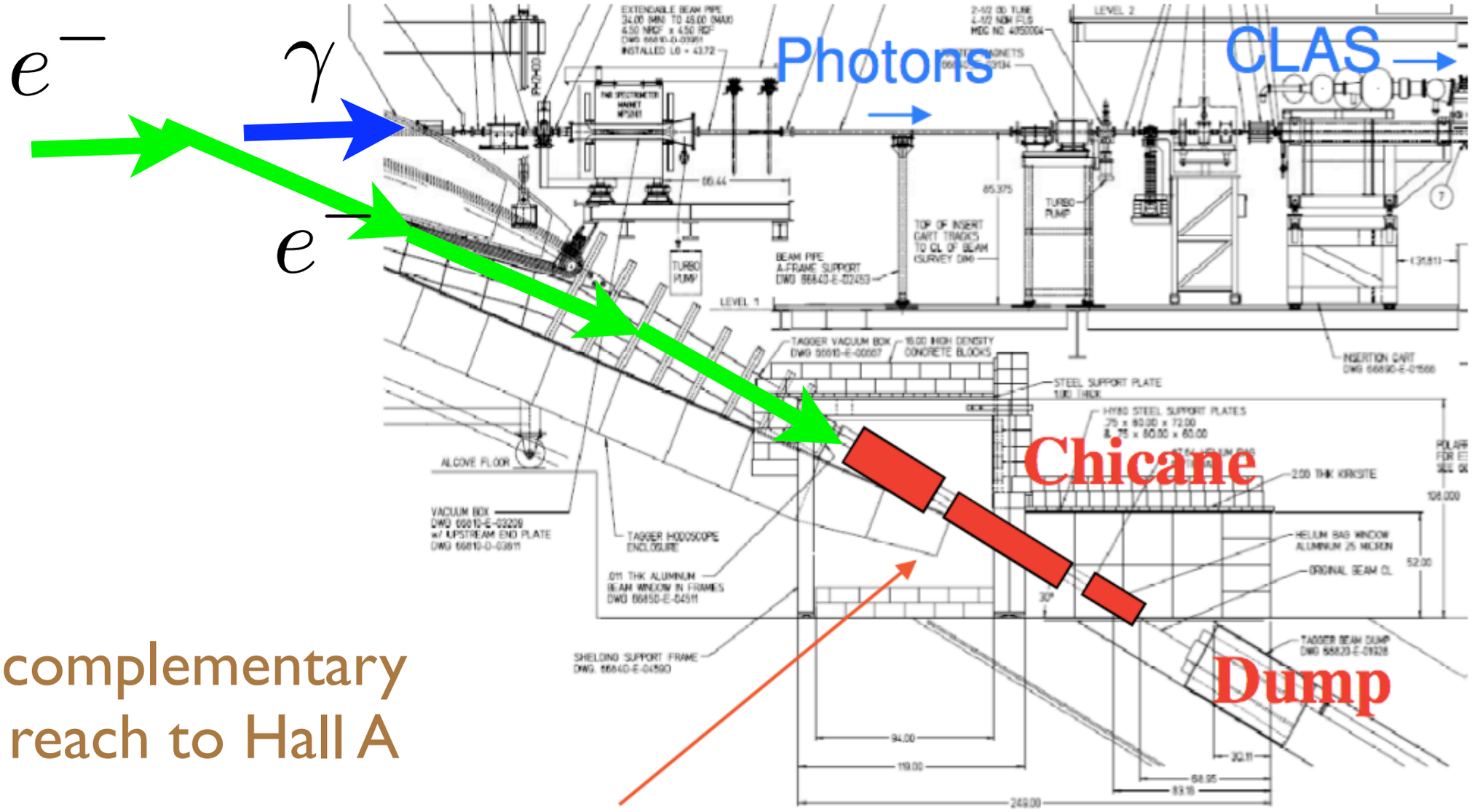
24 days running (next year)





2) JLab Hall B: New Commensal Experiment

see T. Maruyama's talk @ SLAC DF workshop



complementary reach to Hall A

Possible location for heavy photon search

also discover "True Muonium" + use as calibration signal !

Many possibilities not discussed...

- Muons beams: [RE, Harnik, Kaplan, Schuster, Toro]
  - MINOS + Minerva
  - COMPASS @ CERN
- Several proposals also from other groups
  [e.g. Freytsis, Ovanesyan, Thaler]
- LHC, Tevatron Searches [e.g. D0]
- Further details @ SLAC

  Dark Forces workshop

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 !