

Title: The Search for New GeV-scale Forces

Date: Feb 09, 2011 11:00 AM

URL: <http://pirsa.org/11020111>

Abstract: A new force mediated by a new vector boson with mass in the MeV to GeV range and with very weak coupling to ordinary matter appears naturally in many theoretical models and could also explain a variety of observed anomalies. Such anomalies include the discrepancy between the predicted and the experimentally observed value for the muon anomalous magnetic moment, and recent cosmic-ray data that can be explained by dark matter interacting through this force with ordinary matter. This talk will review the motivation for such a force and present a broad array of probes of this physics. These probes include high-luminosity e^+e^- colliders, such as BaBar and BELLE, whose existing data sets may contain thousands of spectacular events; new high-intensity fixed-target experiments at electron accelerators such as Jefferson Laboratory; and indirect astrophysical probes such as gamma-ray observations of Milky-Way dwarf satellite galaxies, which constitute some of the least luminous and most dark matter dominated galaxies known.

The Search for New GeV-scale Forces

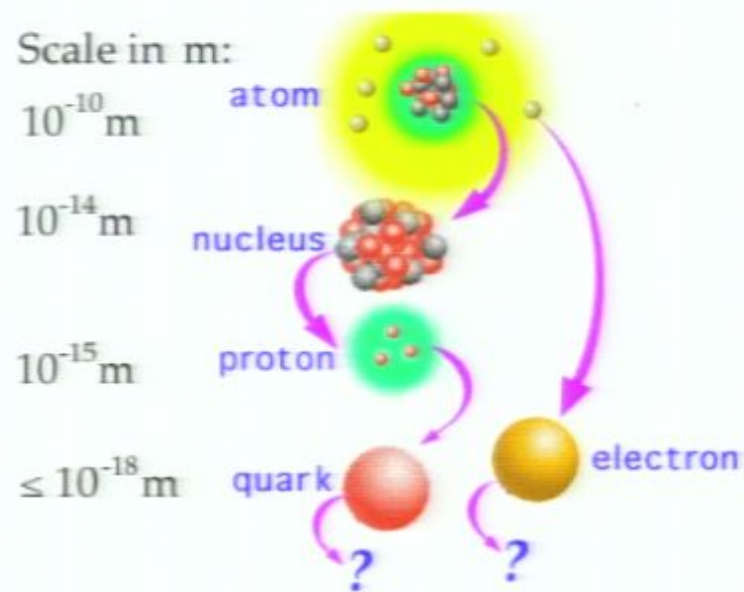
Rouven Essig

Theory Group, SLAC National Accelerator Laboratory

Perimeter Institute, Feb. 9, 2011

A particle physicist's quest

understand the fundamental constituents
of matter and their interactions



The Standard Model

Quarks: u d s c b t

Leptons: e μ τ ν_e ν_μ ν_τ

3 Forces: strong weak electromagnetic
 g W^\pm, Z γ

enormously successful... but incomplete

The Standard Model

Quarks: u d s c b t

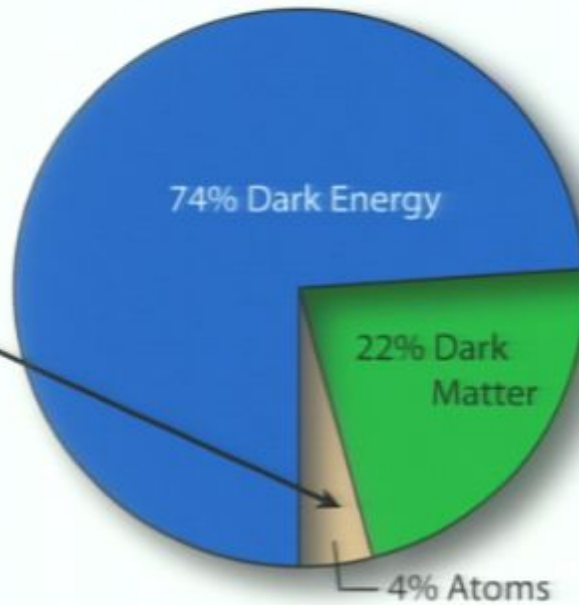
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Physics Beyond the Standard Model

SM only describes this

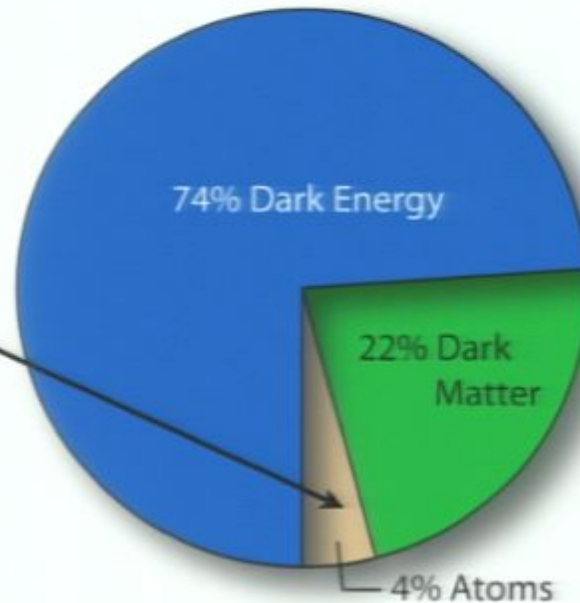


Dark Energy?

Dark Matter?

Physics Beyond the Standard Model

SM only describes this



Dark Energy?

Dark Matter?

Massive W/Z bosons?

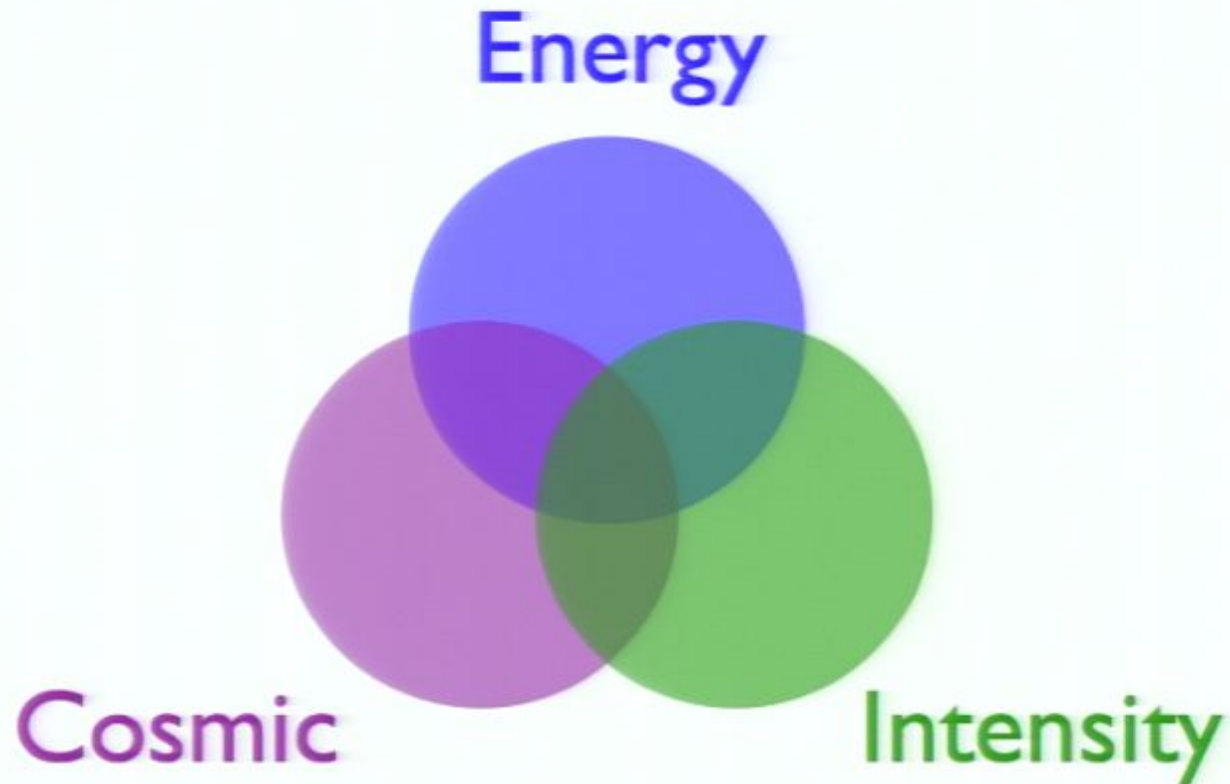
Baryon asymmetry?

Massive particles?

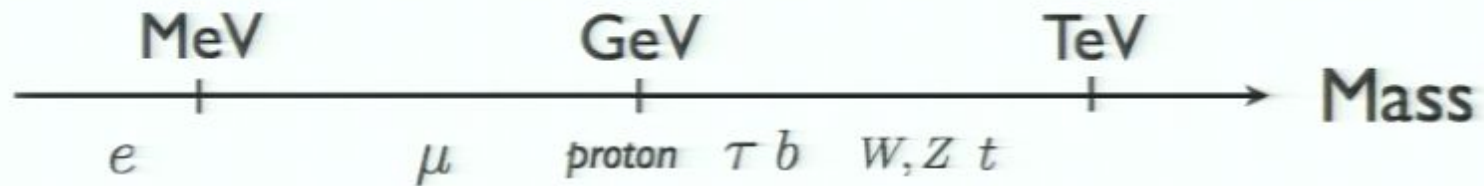
...

Many outstanding questions suggest new physics!

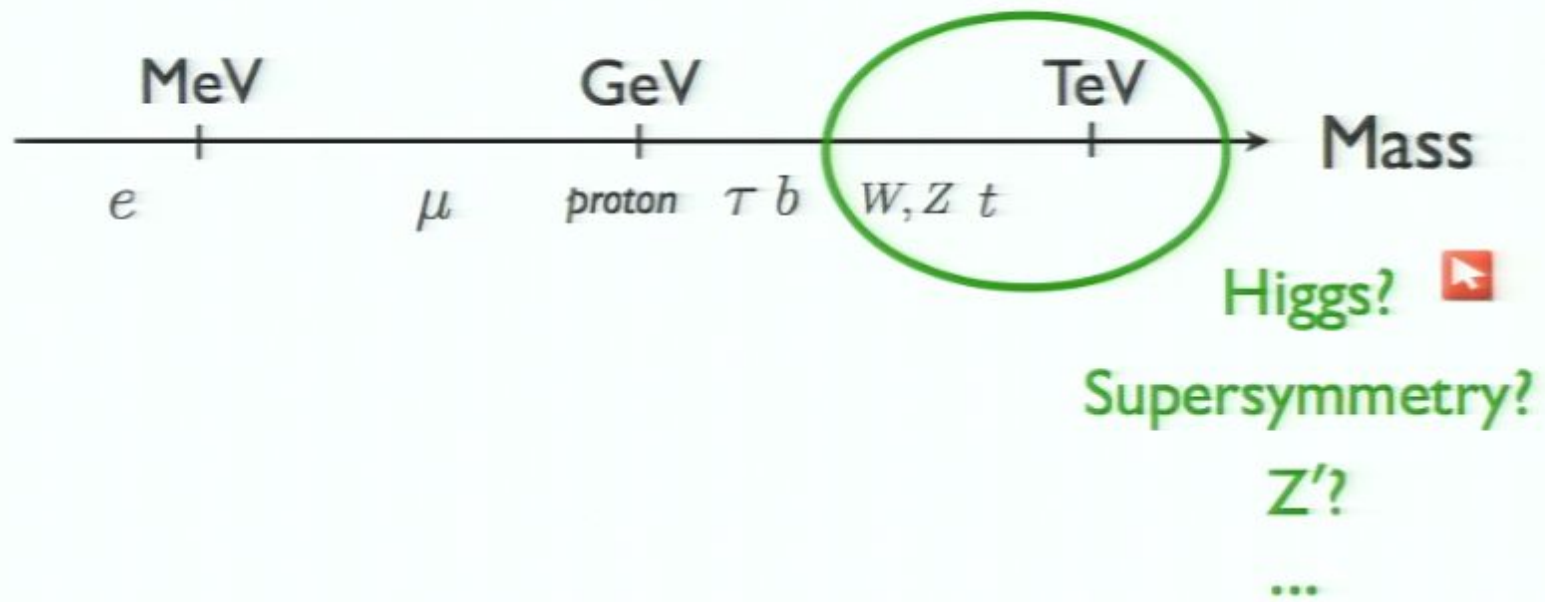
Three Frontiers in Particle Physics



What lies at the energy frontier?

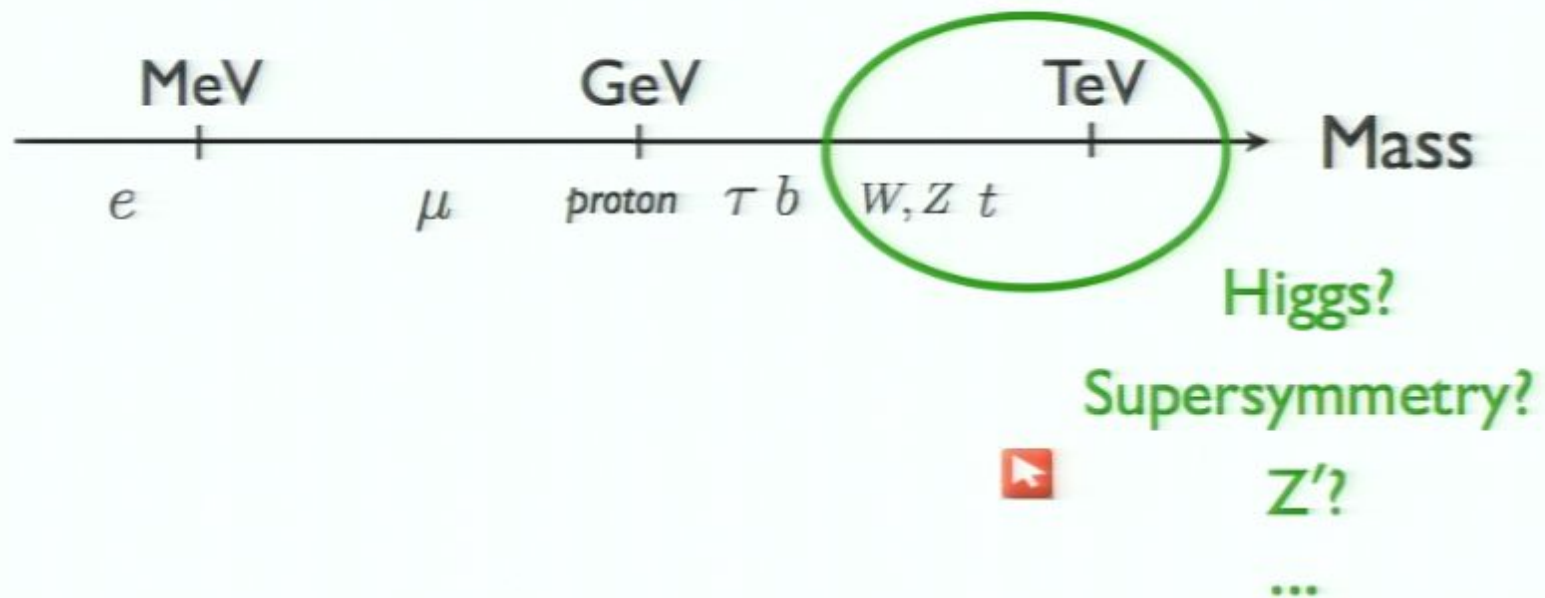


What lies at the energy frontier?



The LHC era has begun!

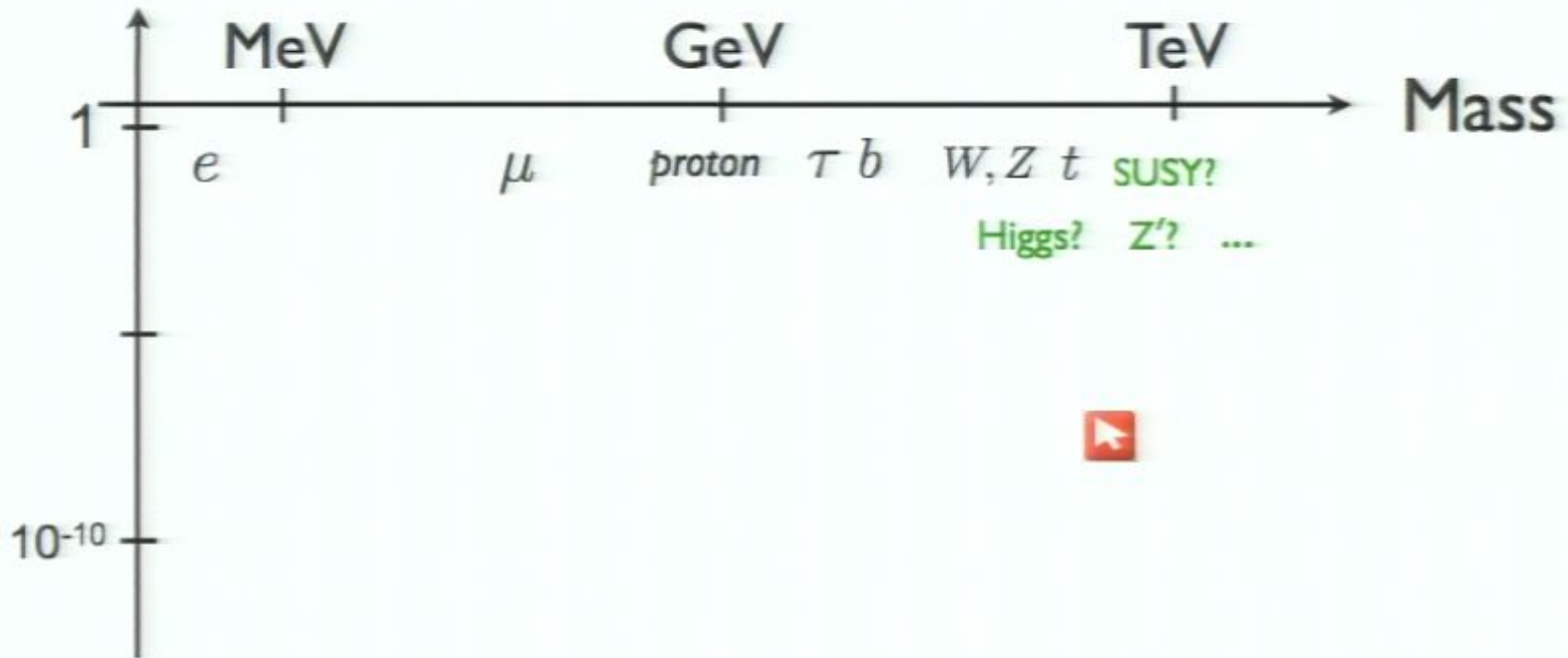
What lies at the energy frontier?

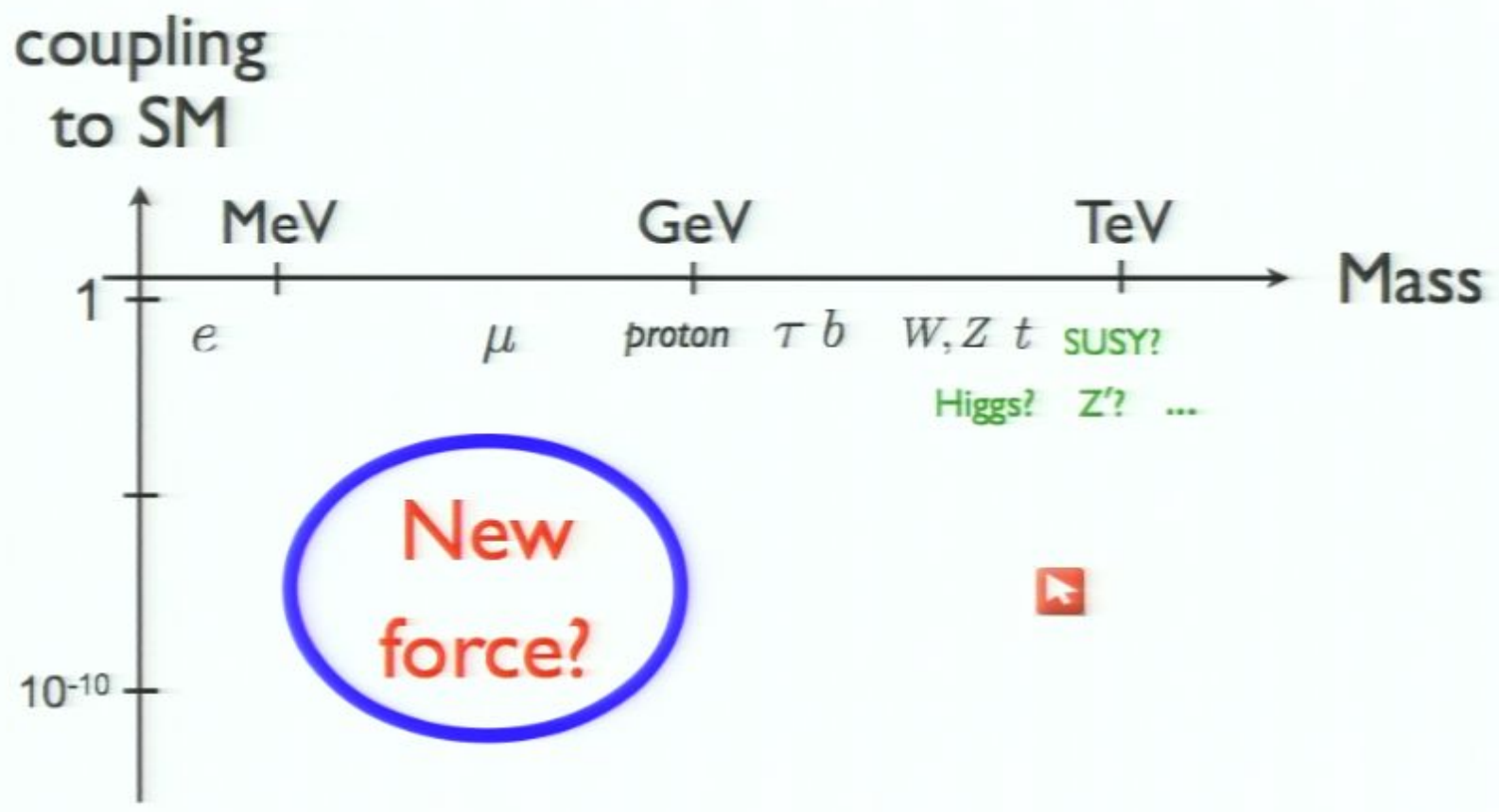


The LHC era has begun!

but there is an orthogonal axis...

coupling
to SM

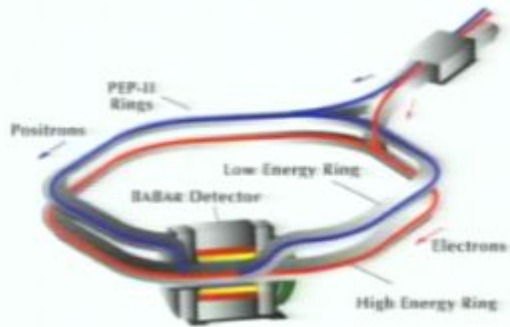




Is there a **new force** mediated by a **low-mass** particle, with very **weak coupling** to ordinary matter?

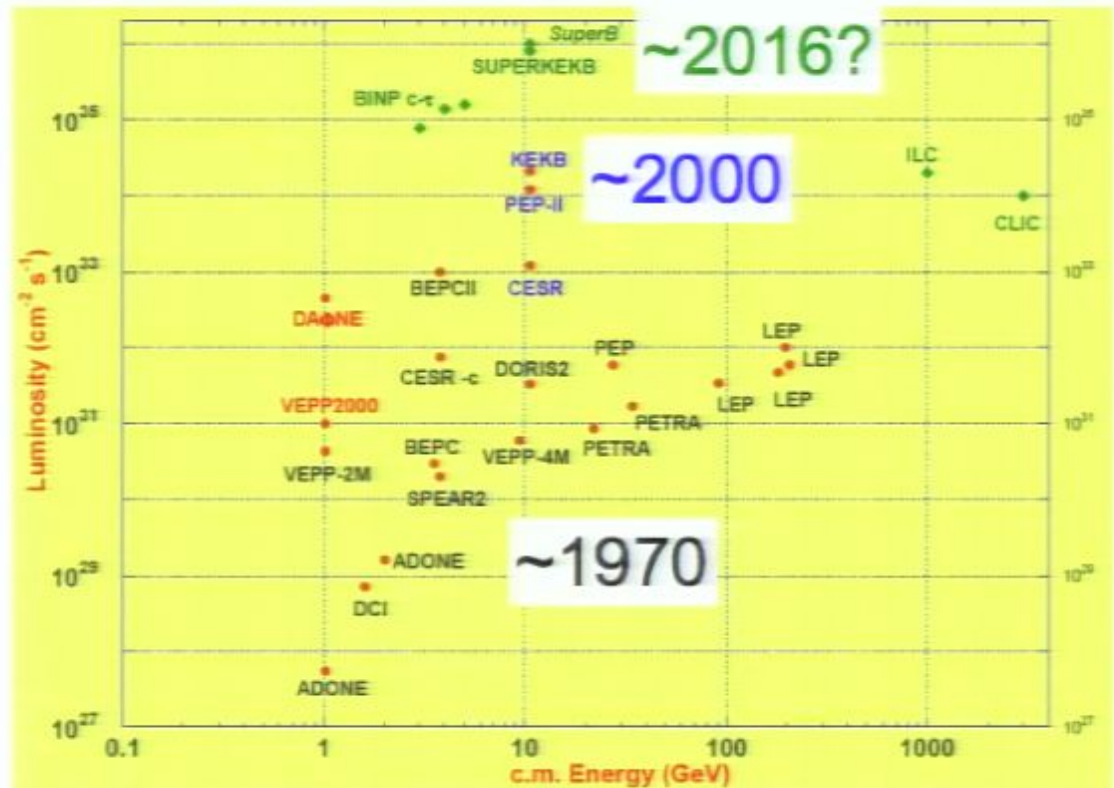
Probe at the Intensity Frontier!

e^+e^- collider



e.g.  **BABAR**

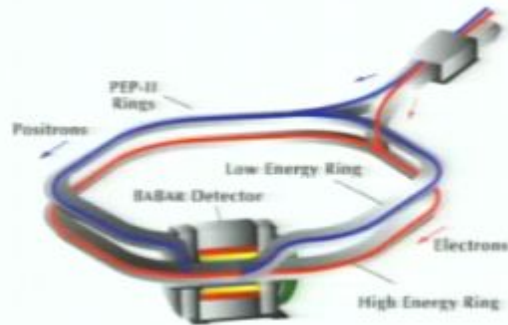
@ PEP-II



linearcollider.org

Probe at the Intensity Frontier!

e^+e^- collider



e.g.



@ PEP-II

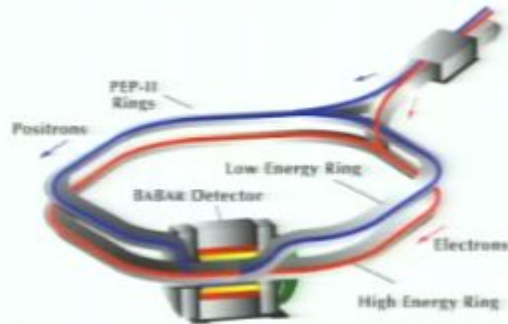
e^- beam on a fixed target



e.g. Jefferson Lab

Probe at the Intensity Frontier!

e^+e^- collider



e.g.



@ PEP-II

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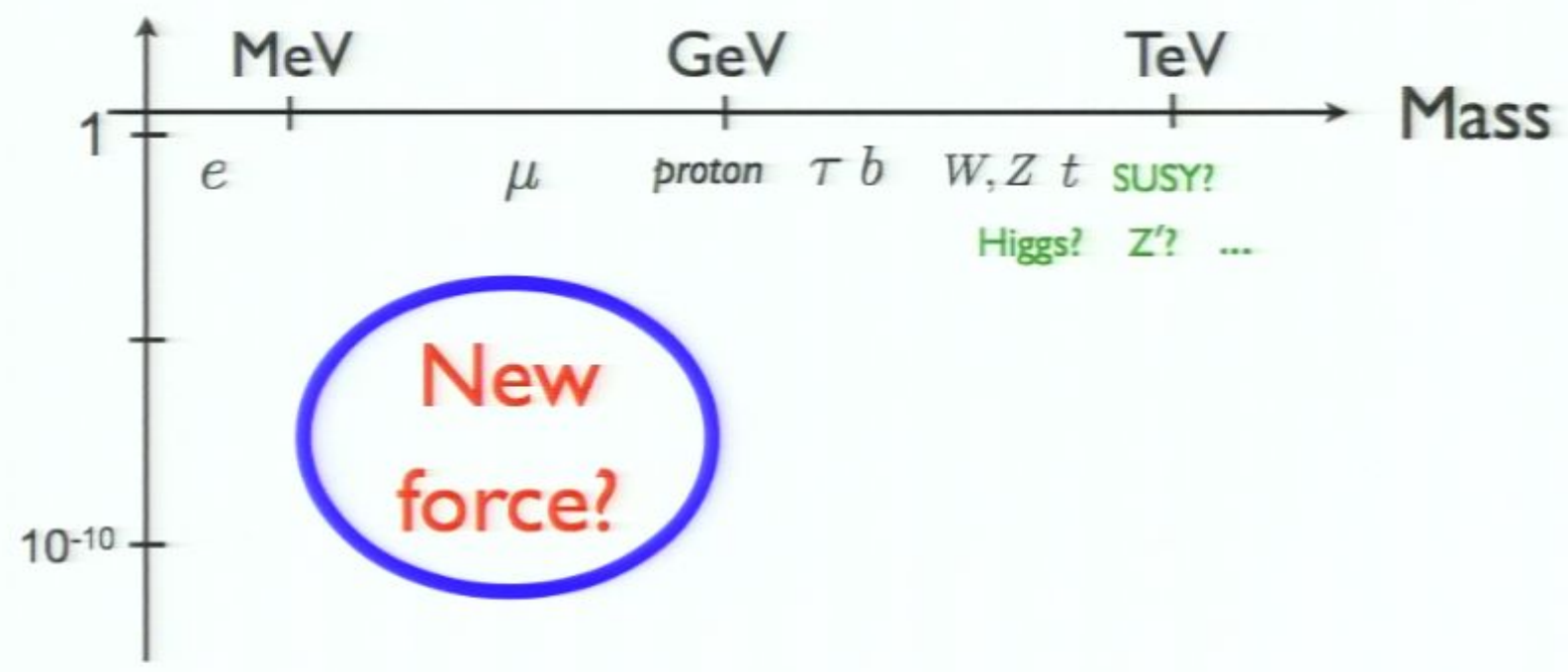


e.g. Jefferson Lab

New experimental research program is underway!

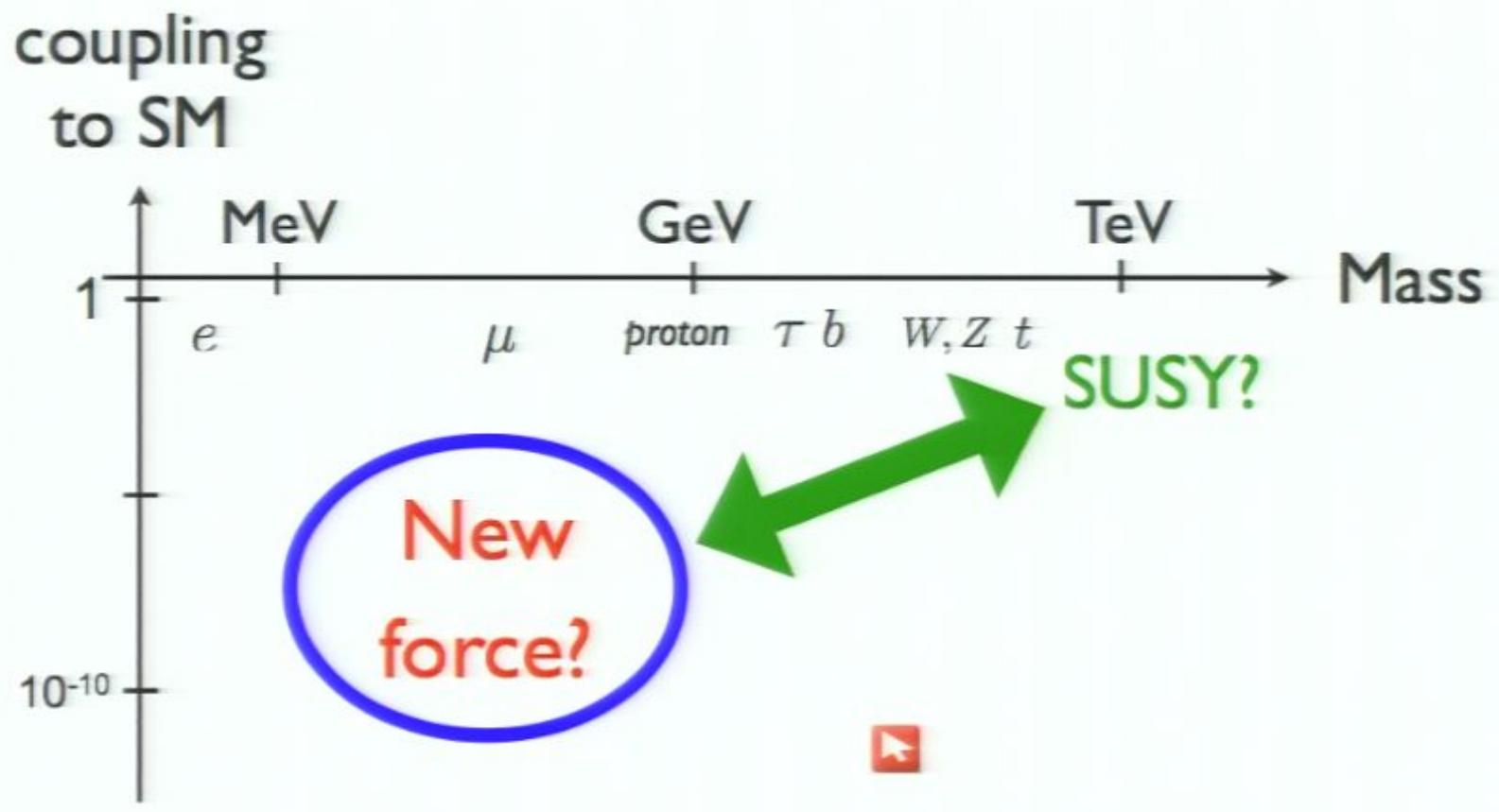
Systematic exploration for new GeV-scale forces

coupling
to SM



Hints of new dark matter interactions?

Exciting implications for cosmic frontier!



Dramatic signals also possible at Energy Frontier!

(but no time to discuss today)

Outline

- The idea: new forces
 - Hints for a new force?
- Cosmic Frontier
 - dark matter annihilation in dwarf galaxies
- Intensity Frontier
 - e^+e^- colliders
 - fixed target

The idea

Standard Model

quarks, leptons

g W^\pm, Z γ

The idea

Standard Model

quarks, leptons

g W^\pm, Z γ

Known Forces

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

The idea

A hidden sector, with particles that do not couple to known forces

Standard Model

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A hidden sector, with particles that do not couple to known forces

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Known Forces

$SU(3)_C \times SU(2)_L \times U(1)_Y$

Hidden Sector

dark matter?

A' (massive)

New force

$U(1)'$

Coupling?

Standard Model

quarks, leptons

g W^\pm, Z γ

?

Hidden Sector

dark matter?

A' (massive)



The photon and A' can mix !



Standard Model

quarks, leptons

g W^\pm, Z γ



Bob Holdom

Hidden Sector

dark matter?

A' (massive)



Rouven Essig [desk]

our photon γ  A' "heavy photon"

ϵ = mixing strength

Rouven Essig [desk]

our photon γ  A' "heavy photon"

$\epsilon =$ mixing strength

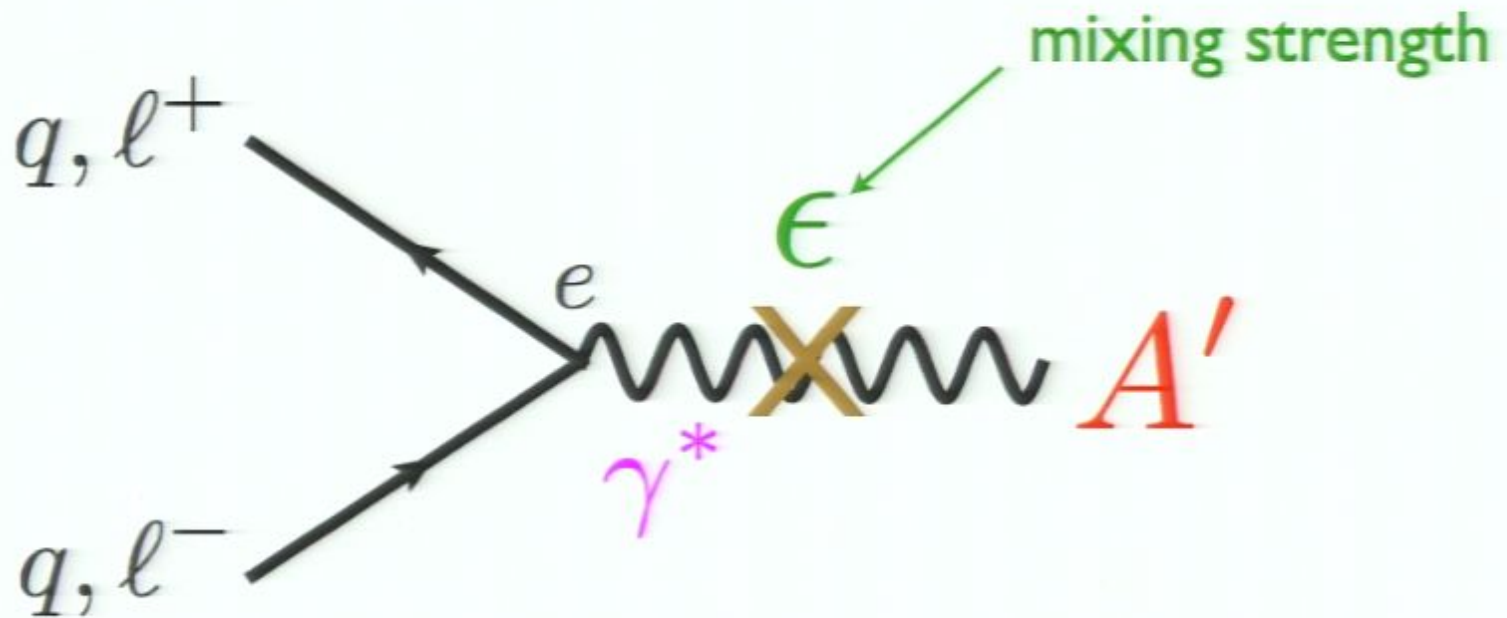
Generated by heavy particles
X interacting with γ and A'



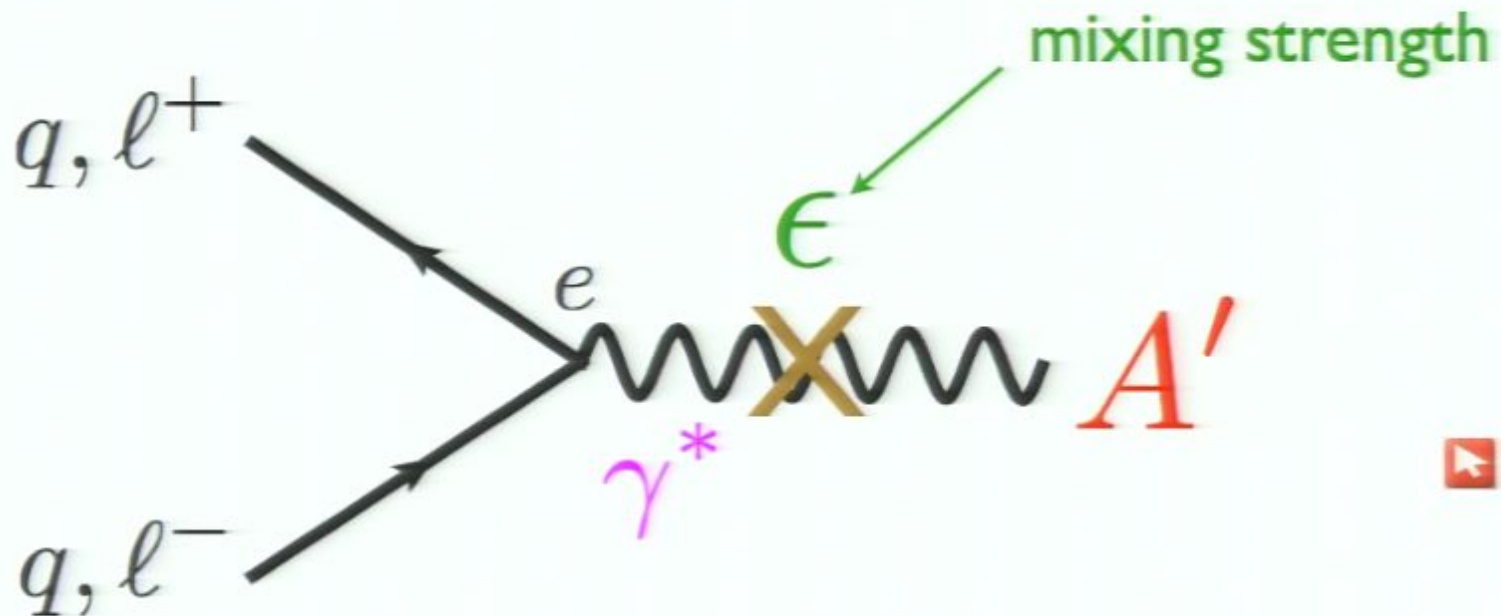
$$\Delta\mathcal{L} = \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu} \quad \text{"Kinetic Mixing"}$$

ϵ could even be $O(1)$ (theoretically)

A' couples to Quarks and charged Leptons



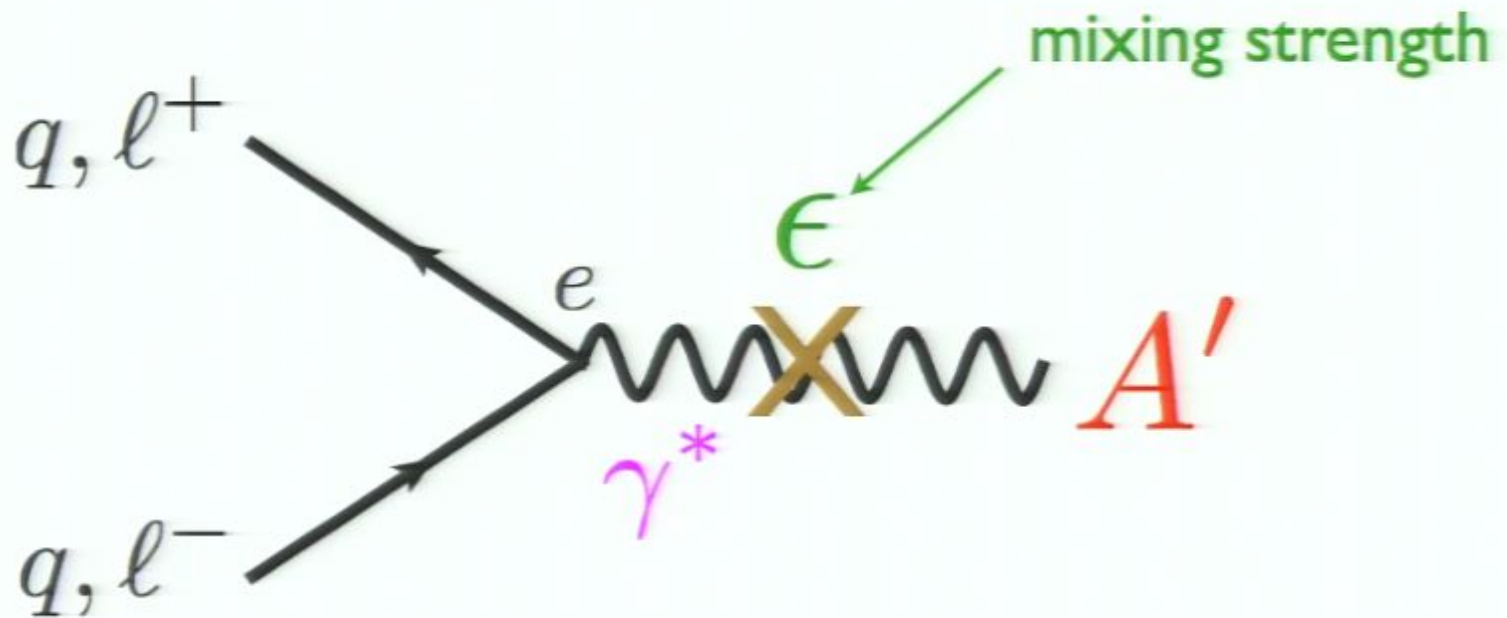
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Mass of A' $\sim 1 \text{ MeV} - 1 \text{ GeV}$

(theoretically natural, motivated from data)

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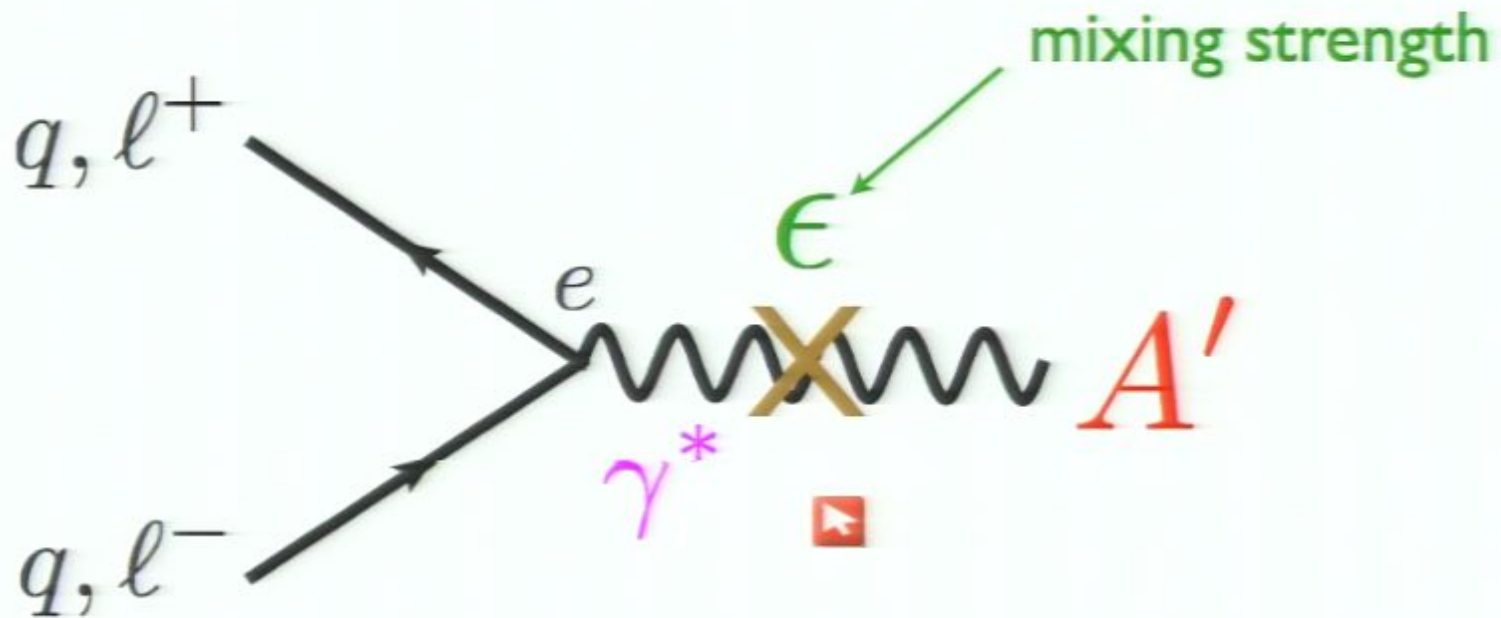


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Hints for A' ?

A' couples to Quarks and charged Leptons



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Hints for A' ?

Hint from muon's anomalous magnetic moment?

magnetic dipole
moment

$$\vec{\mu} = g_s \left(\frac{q}{2m} \right) \vec{s}$$

spin

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$$\vec{\mu} = g_s \left(\frac{q}{2m} \right) \vec{s}$$

can be measured
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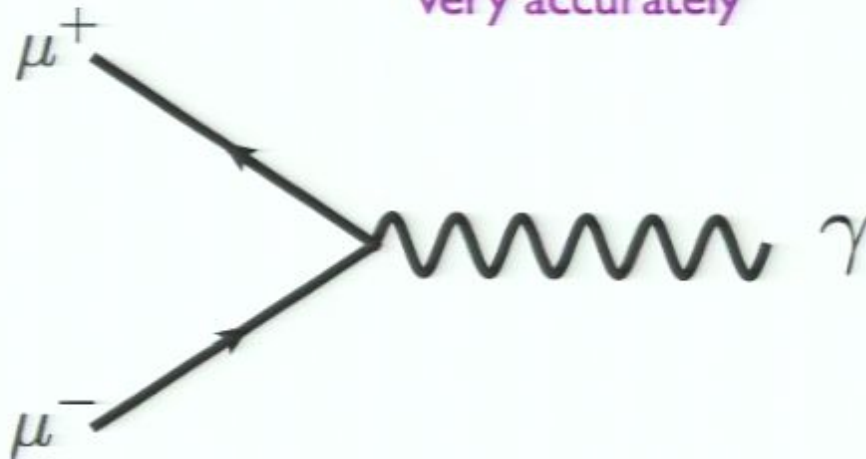
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$$g_s = 2$$

(Dirac)

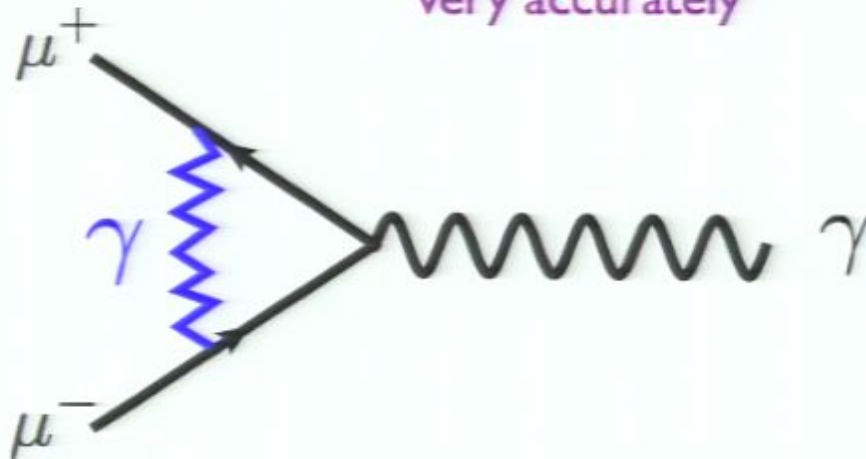
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$$g_s \neq 2$$

(Standard Model)

Standard Model $(g_s - 2)_\mu$ versus Data $\sim 3.4 \sigma$ deviation

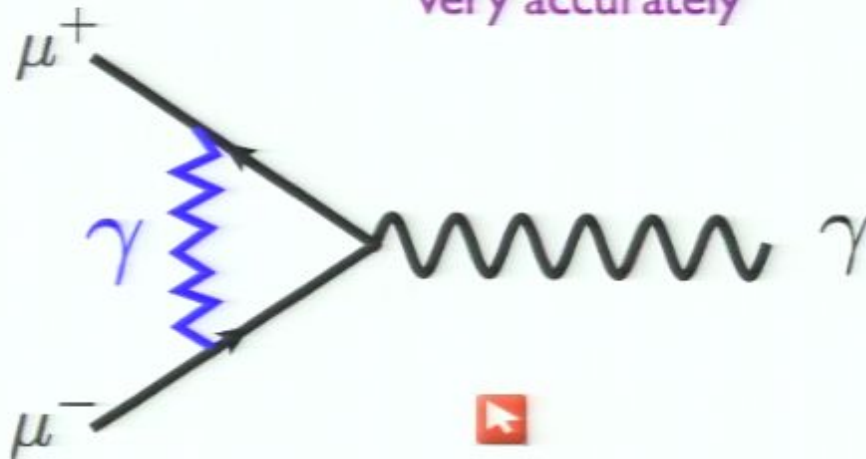
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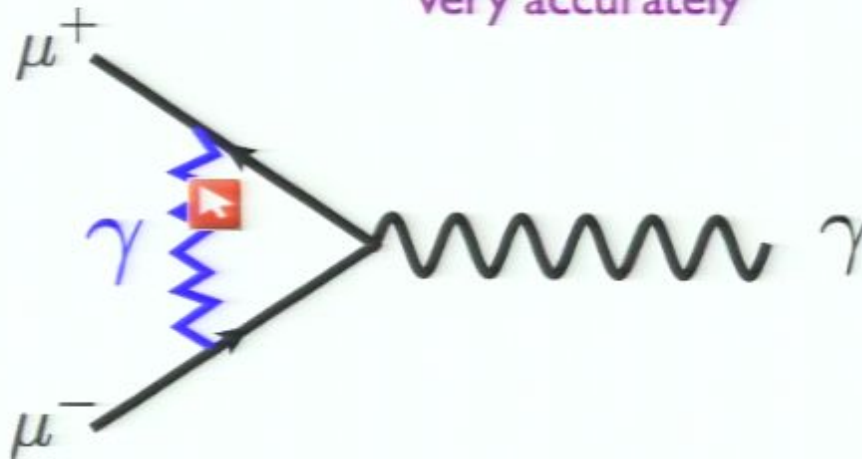
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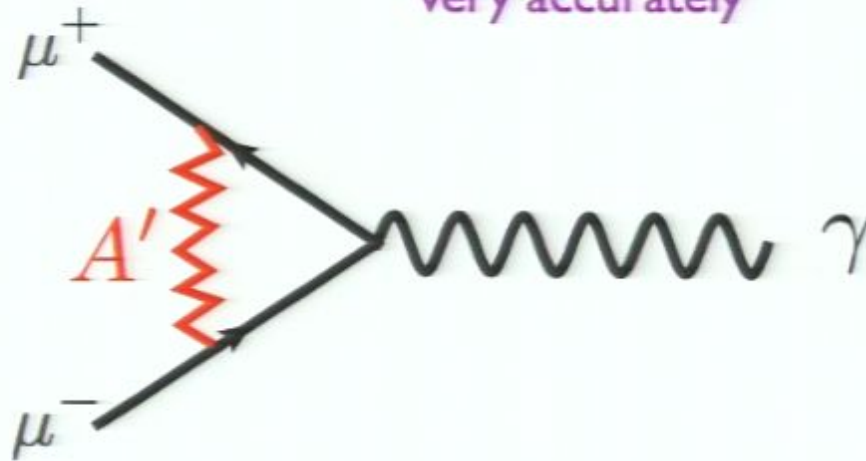
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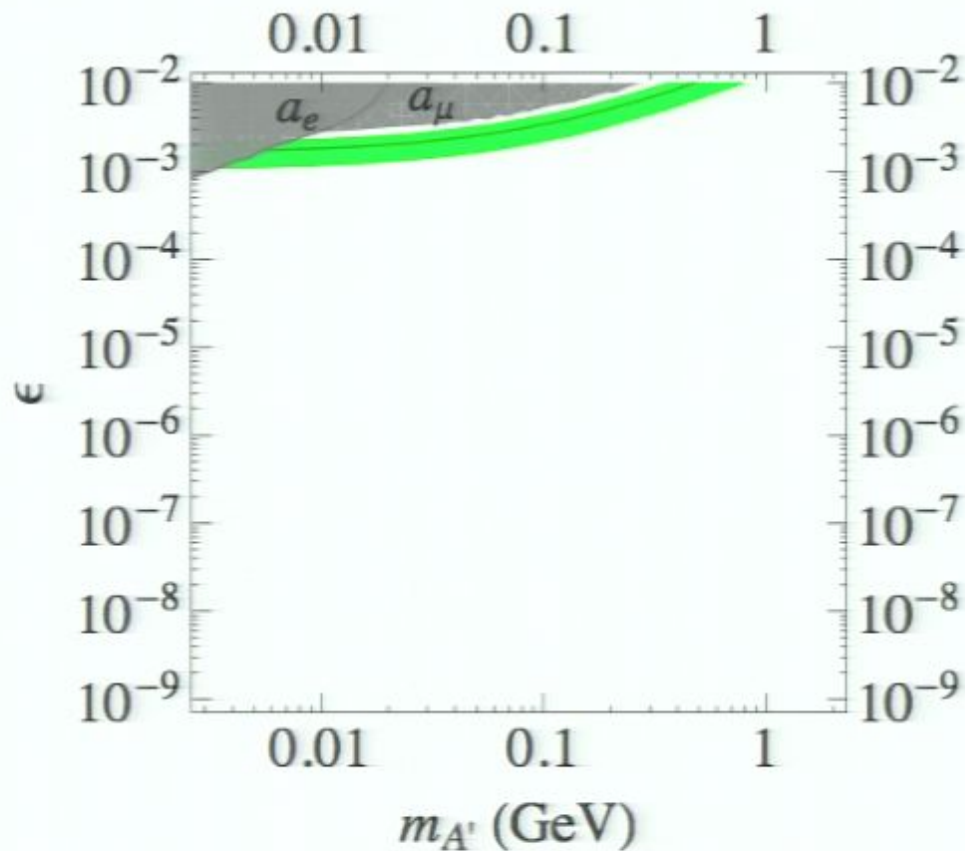


$$g_s \neq 2$$

[Pospelov]

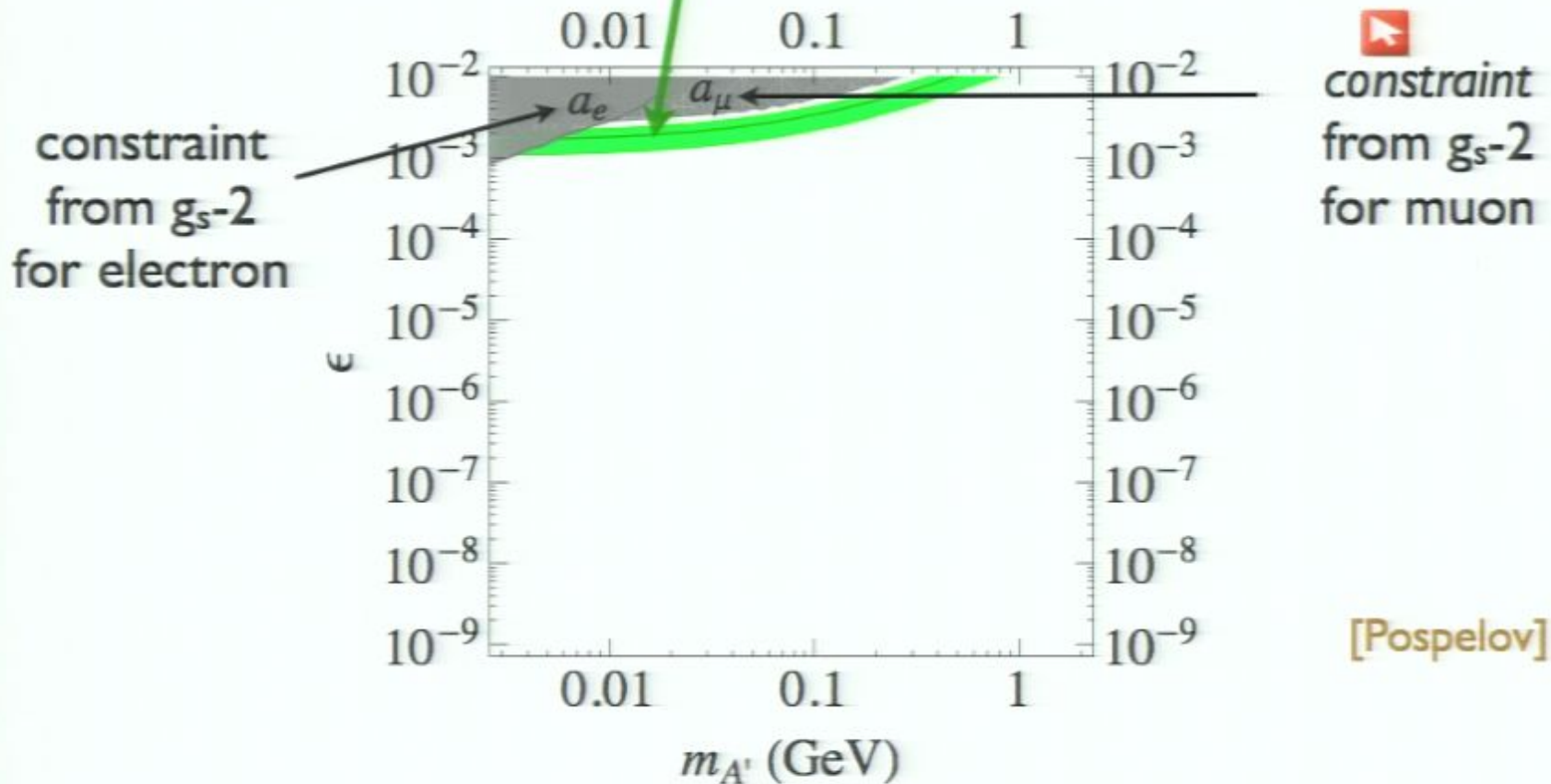
A' may explain observed $(g_s - 2)_\mu$!

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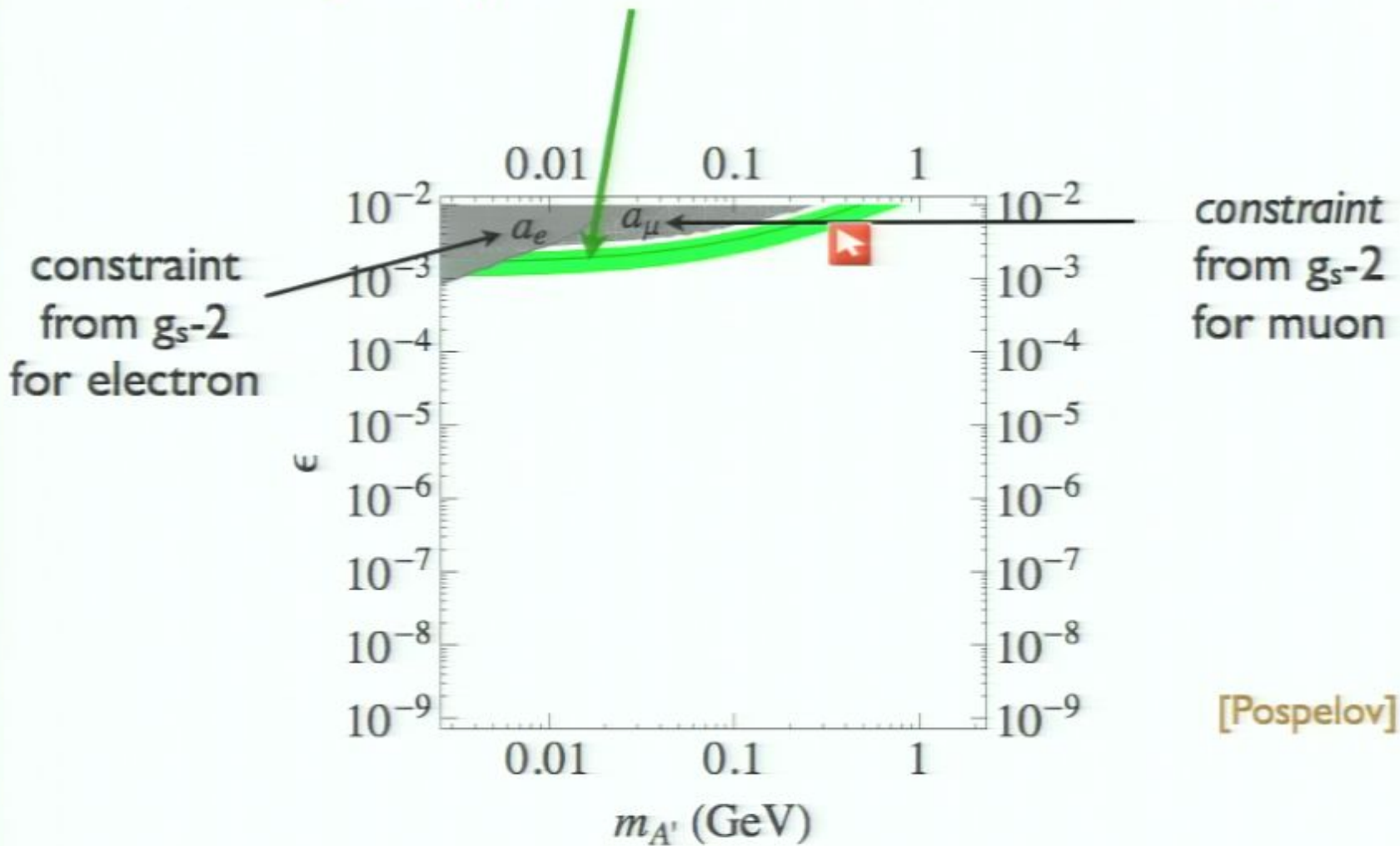


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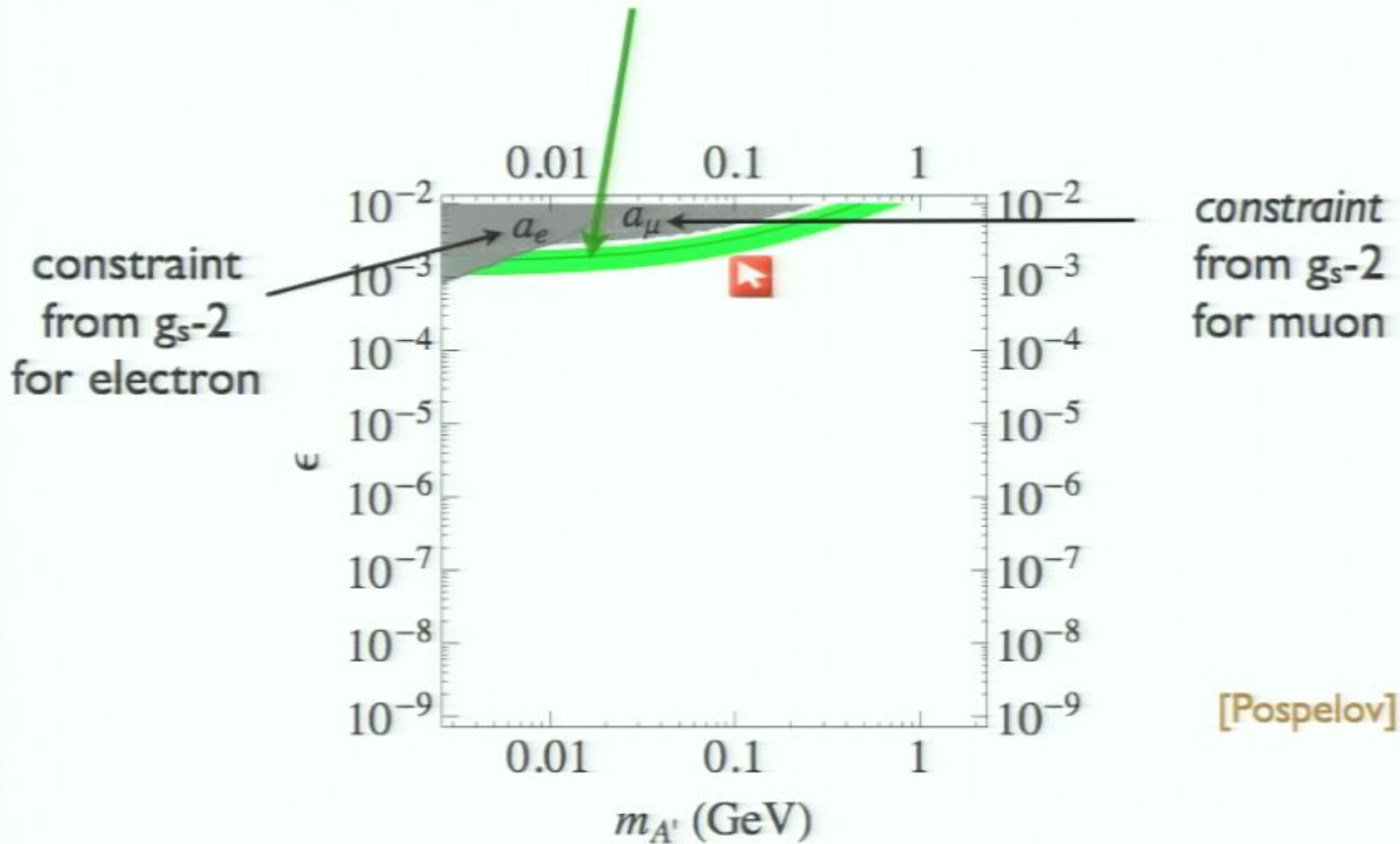
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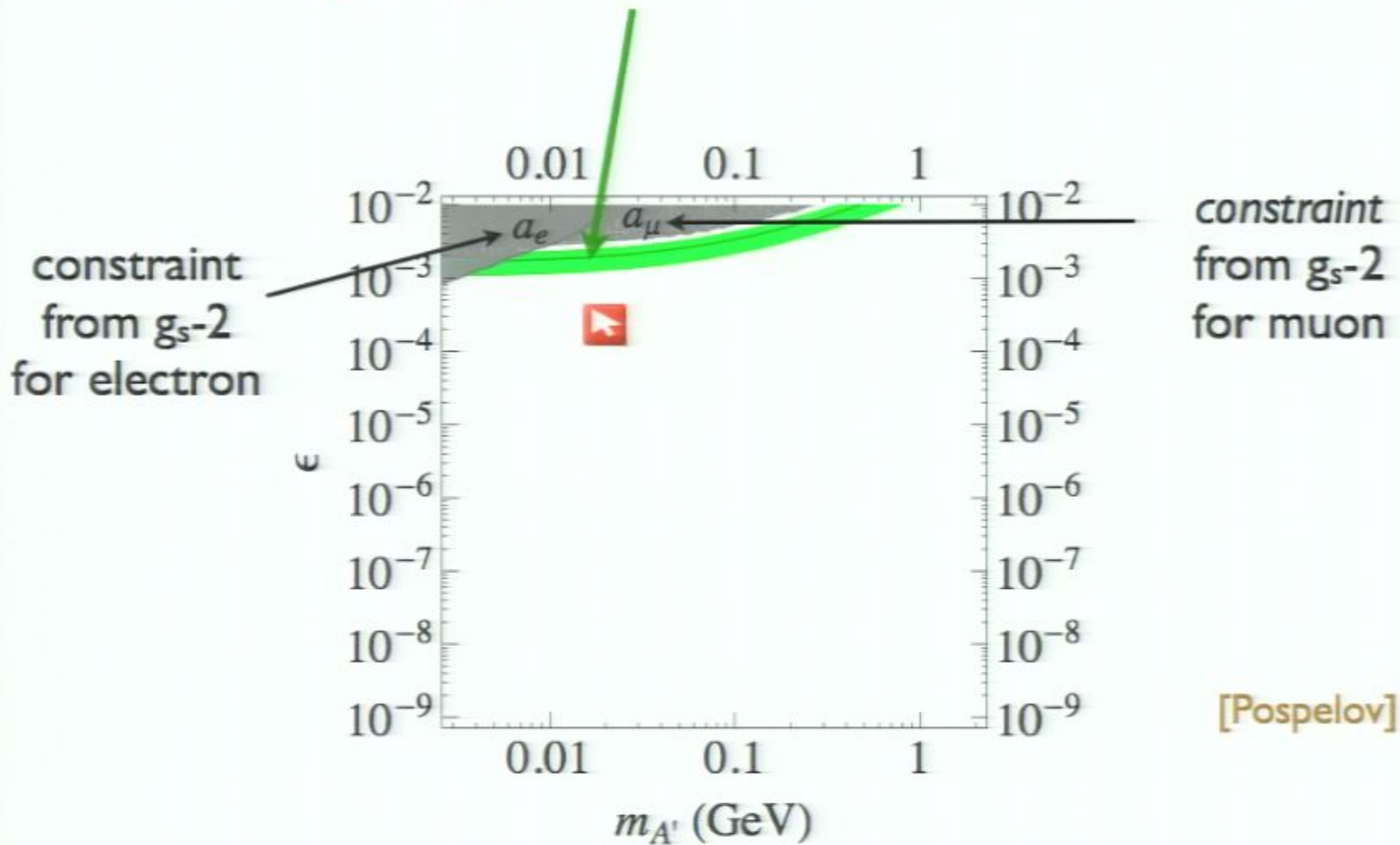


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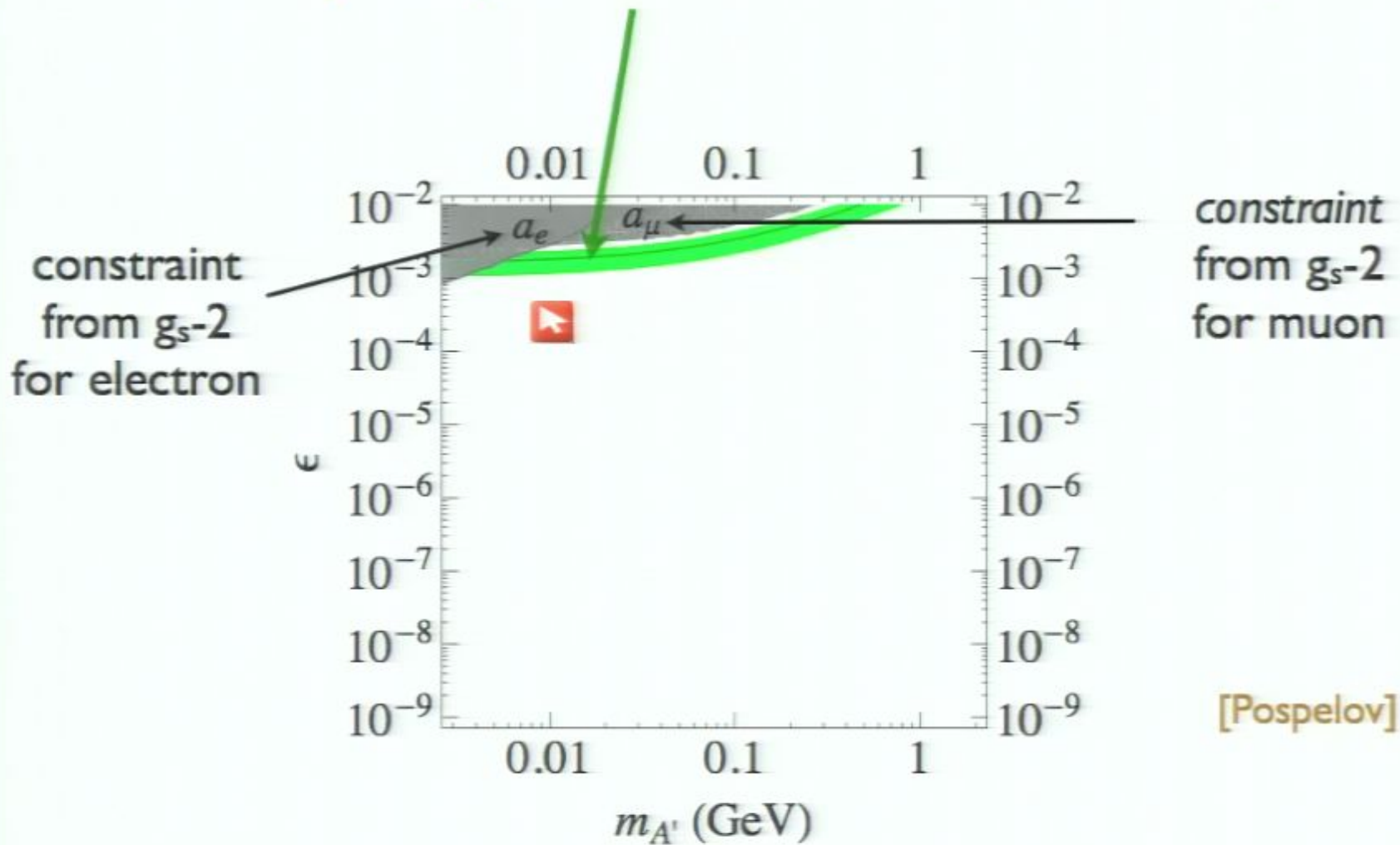
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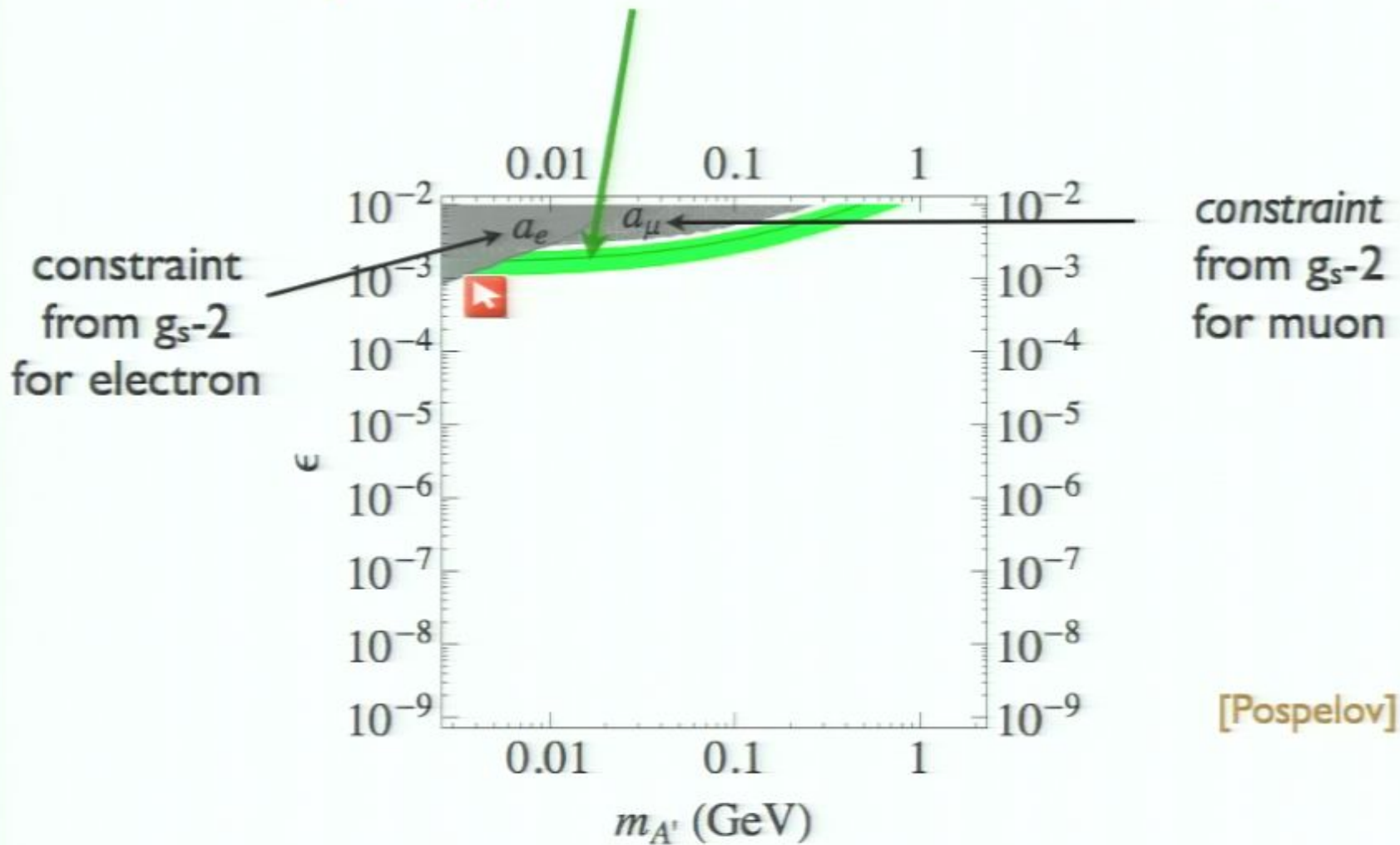
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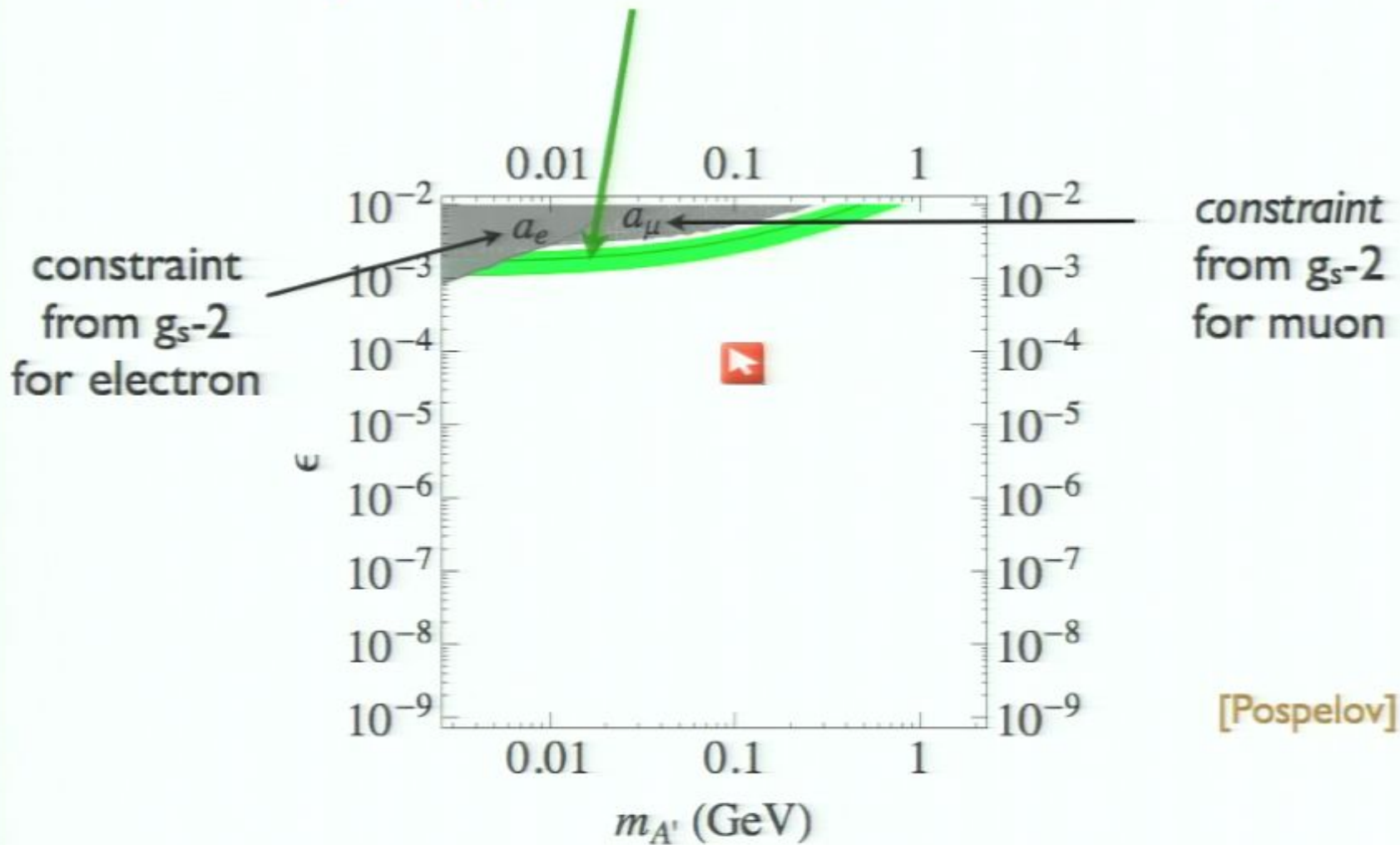


[Pospelov]

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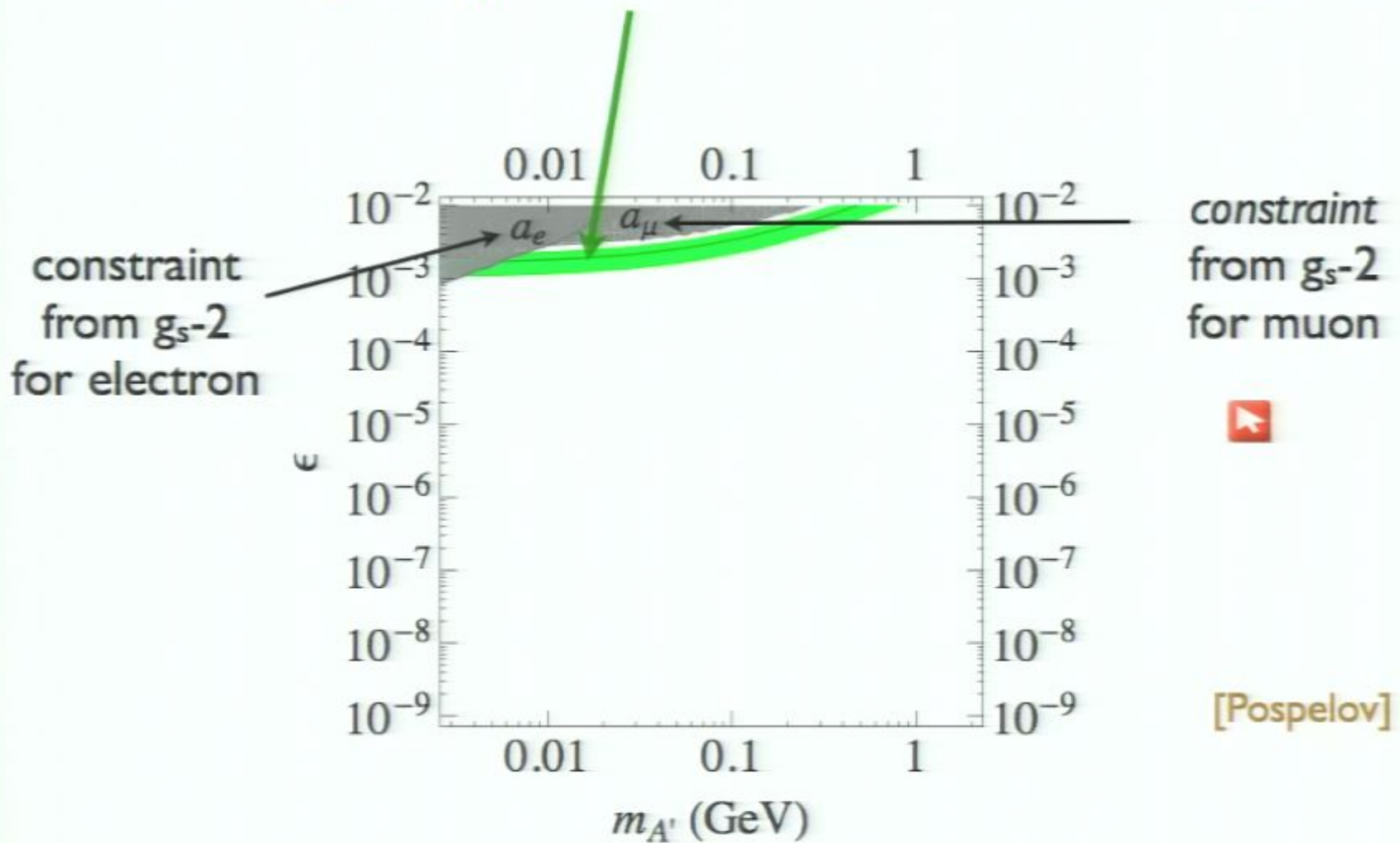


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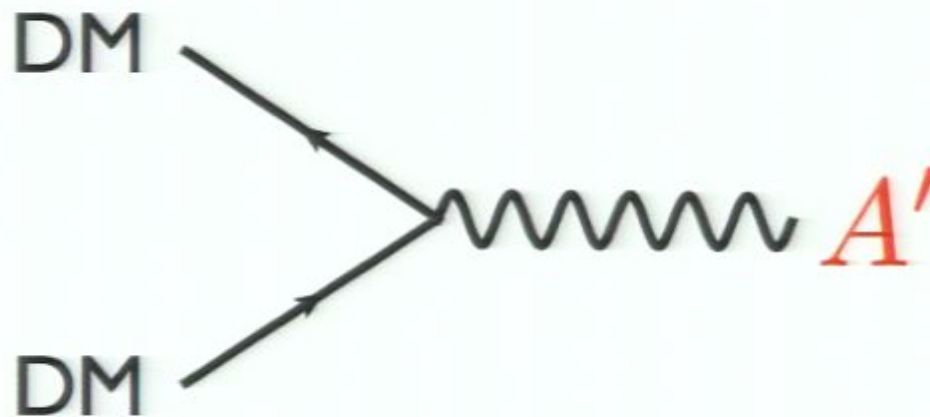
[Pospelov]

A' may explain observed $(g_s - 2)_\mu$



Hints from the cosmic frontier?

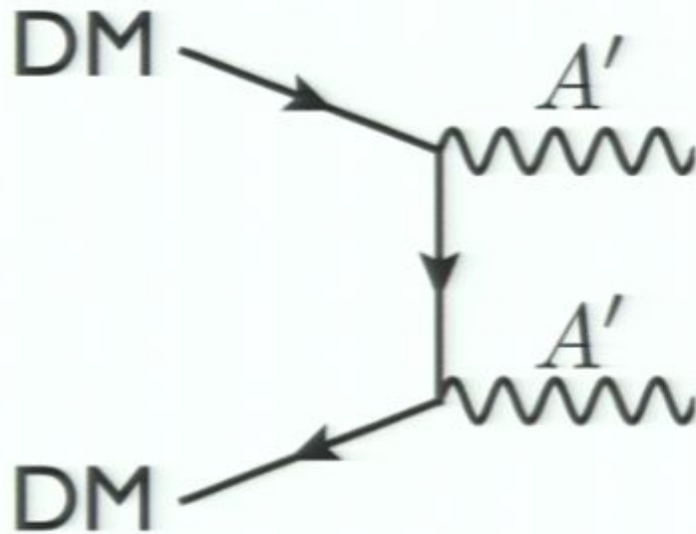
What if dark matter couples to A' ?



Provides new interaction between
dark matter and ordinary matter!

Dark matter can annihilate to A' 's

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

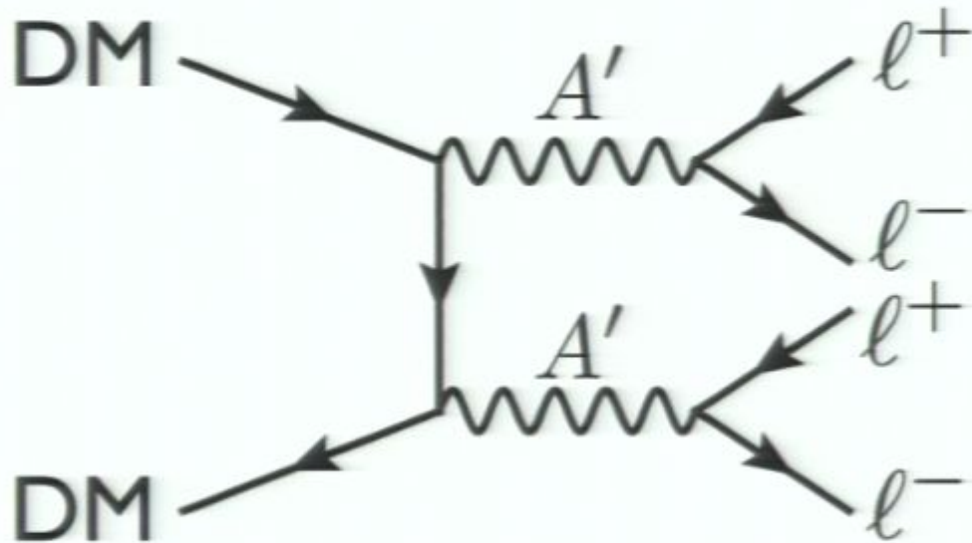


$$m_{\text{DM}} \sim \text{TeV}$$

$$\text{MeV} \lesssim m_{A'} \lesssim \text{GeV}$$

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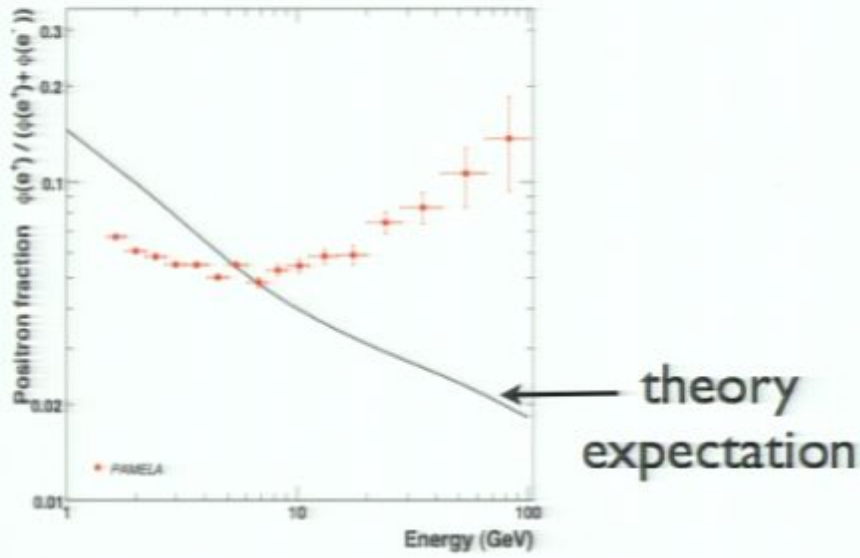
no
antiprotons!

produces high-energy (~ 100 GeV)
cosmic-ray electrons and positrons

Can explain observed cosmic-ray excesses!

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

PAMELA:
 e^+ excess!



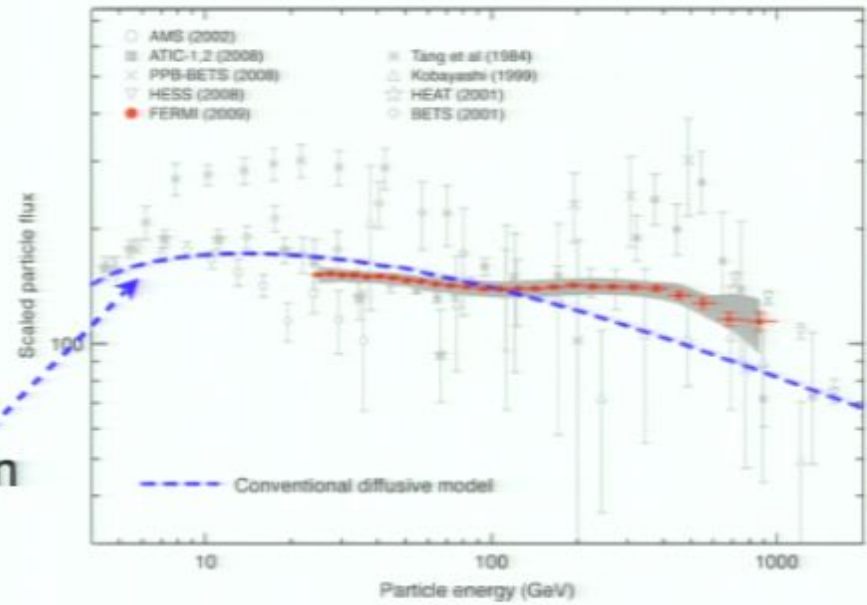
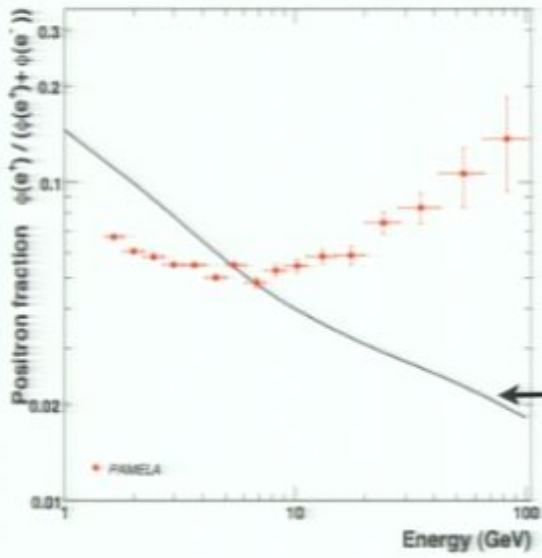
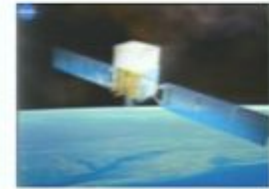
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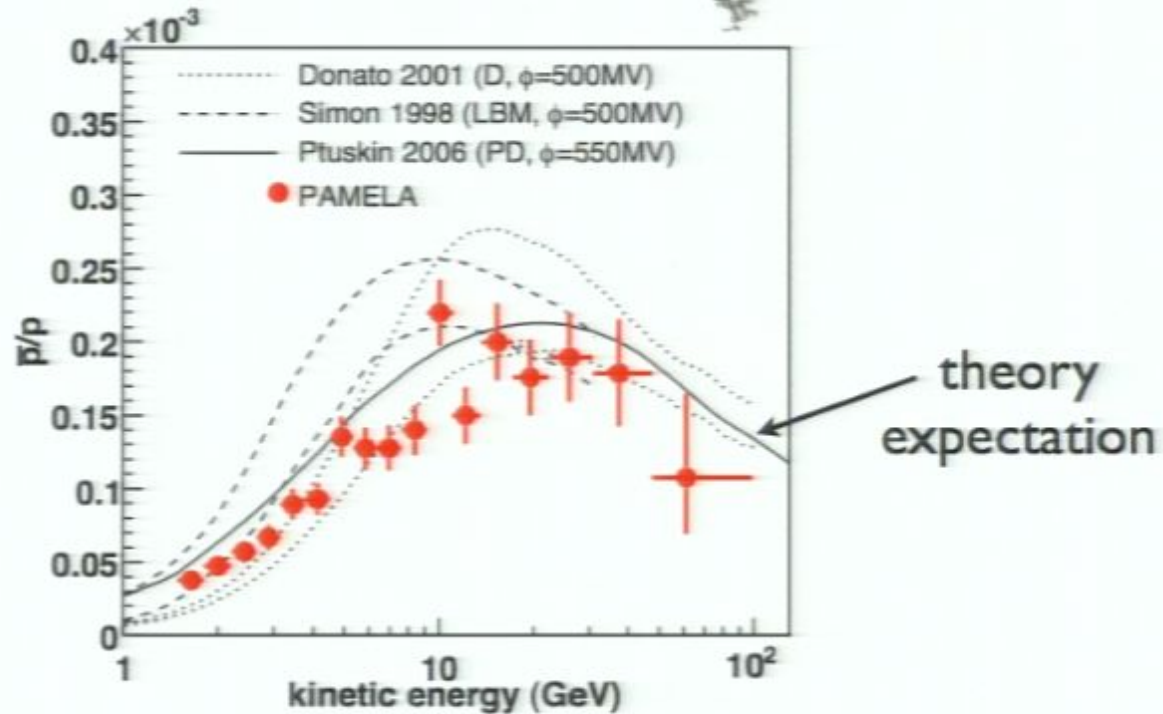
Fermi:
 $e^+ + e^-$ excess!



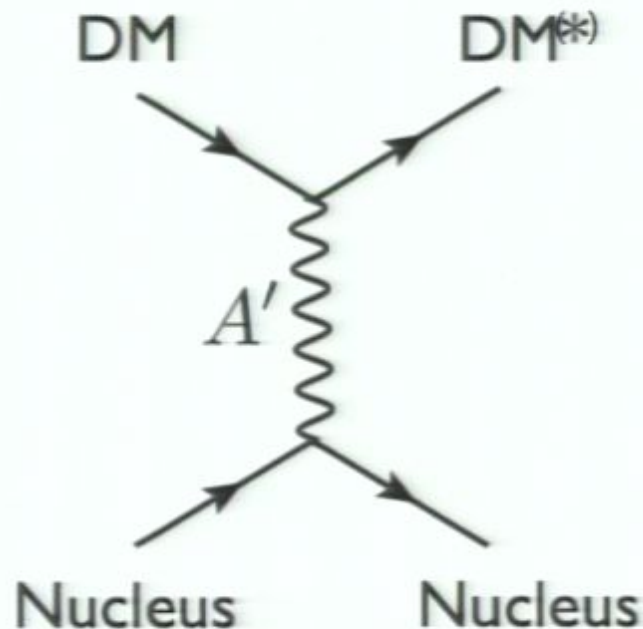
...and explains absence of antiproton excess!

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

PAMELA: \bar{p} fraction



Dark matter can also scatter off nuclei



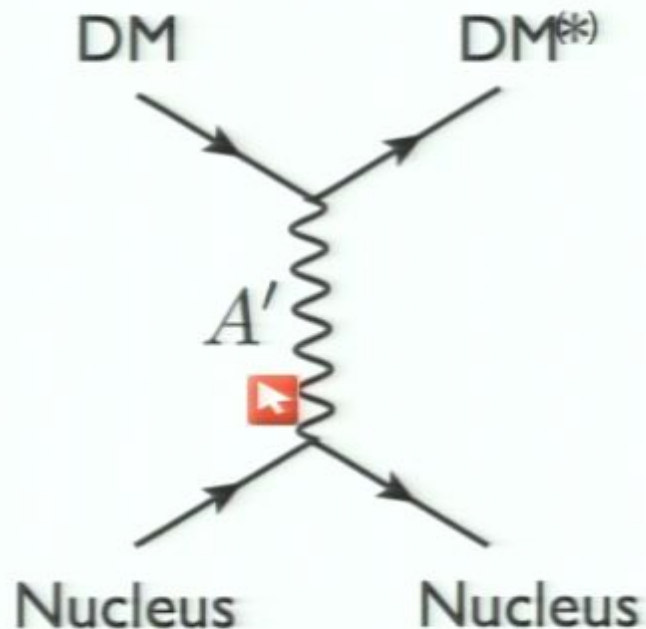
Tucker-Smith & Weiner;
Arkani-Hamed et al.;
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Morrissey, Poland, Zurek;

RE, Kaplan, Schuster, Toro;
(2010)

could explain anomalies in direct
detection experiments

(e.g. DAMA, CoGeNT, ...)

Dark matter can also scatter off nuclei



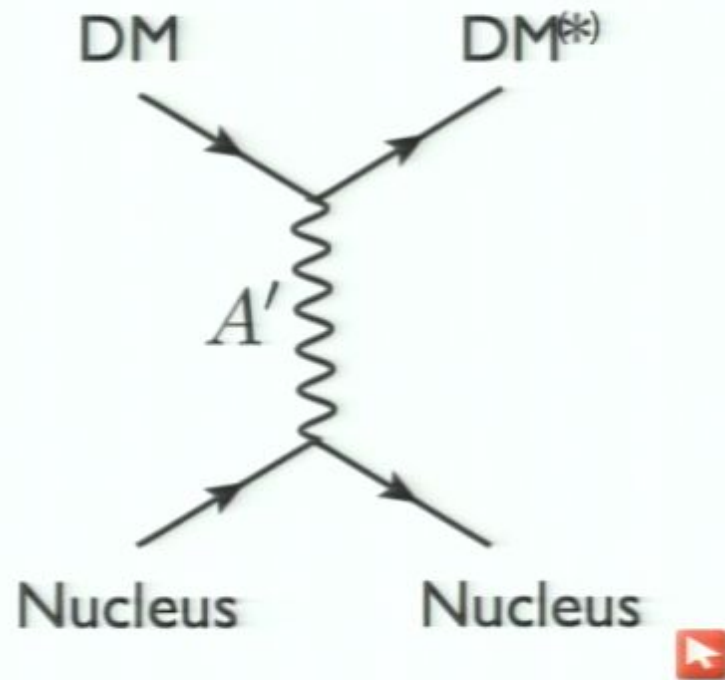
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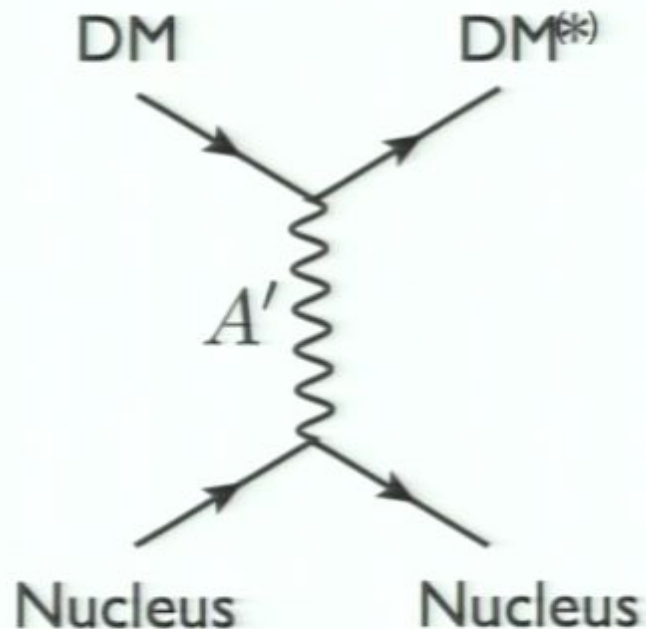


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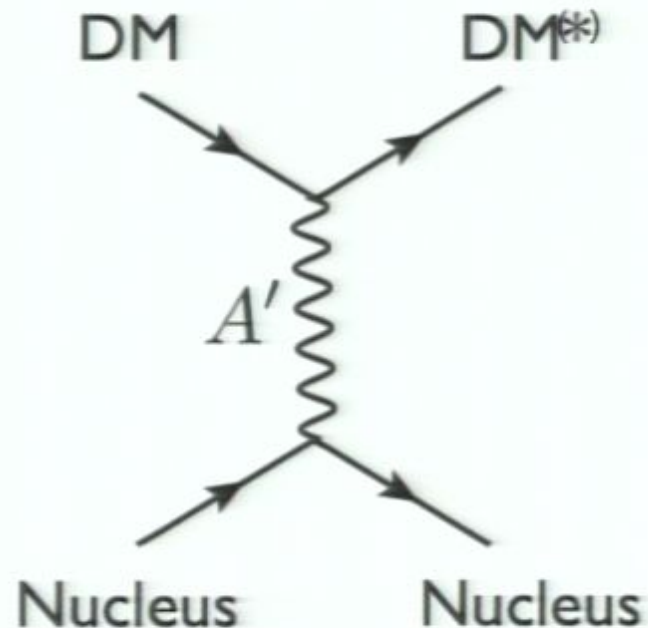


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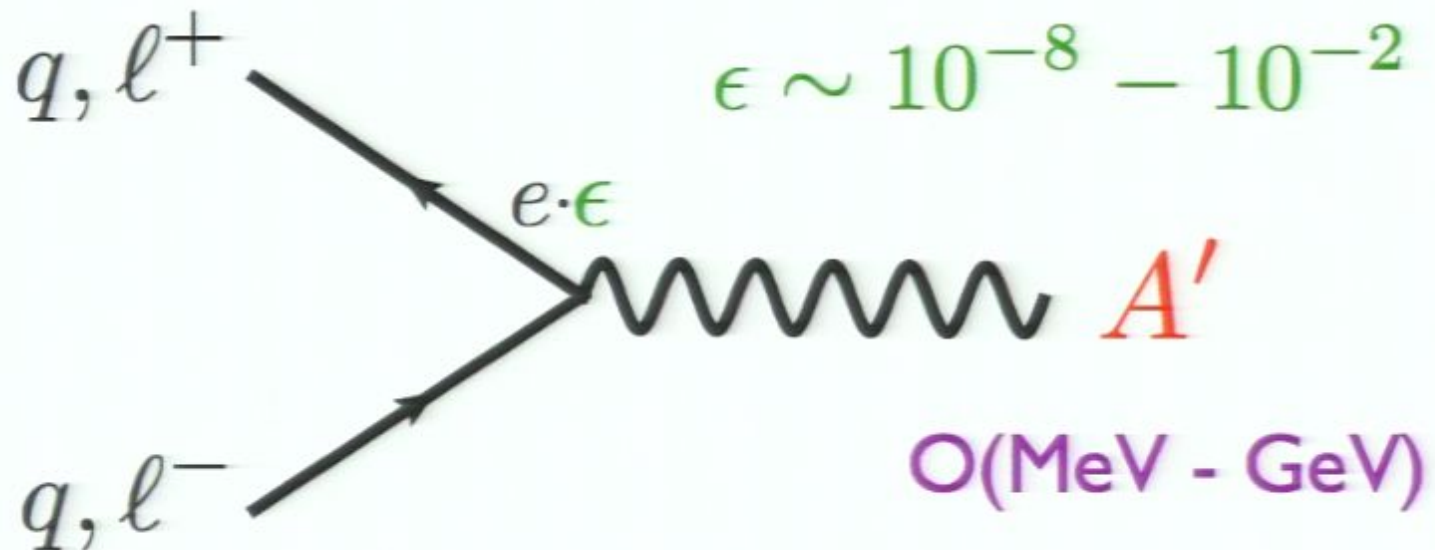
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Summary

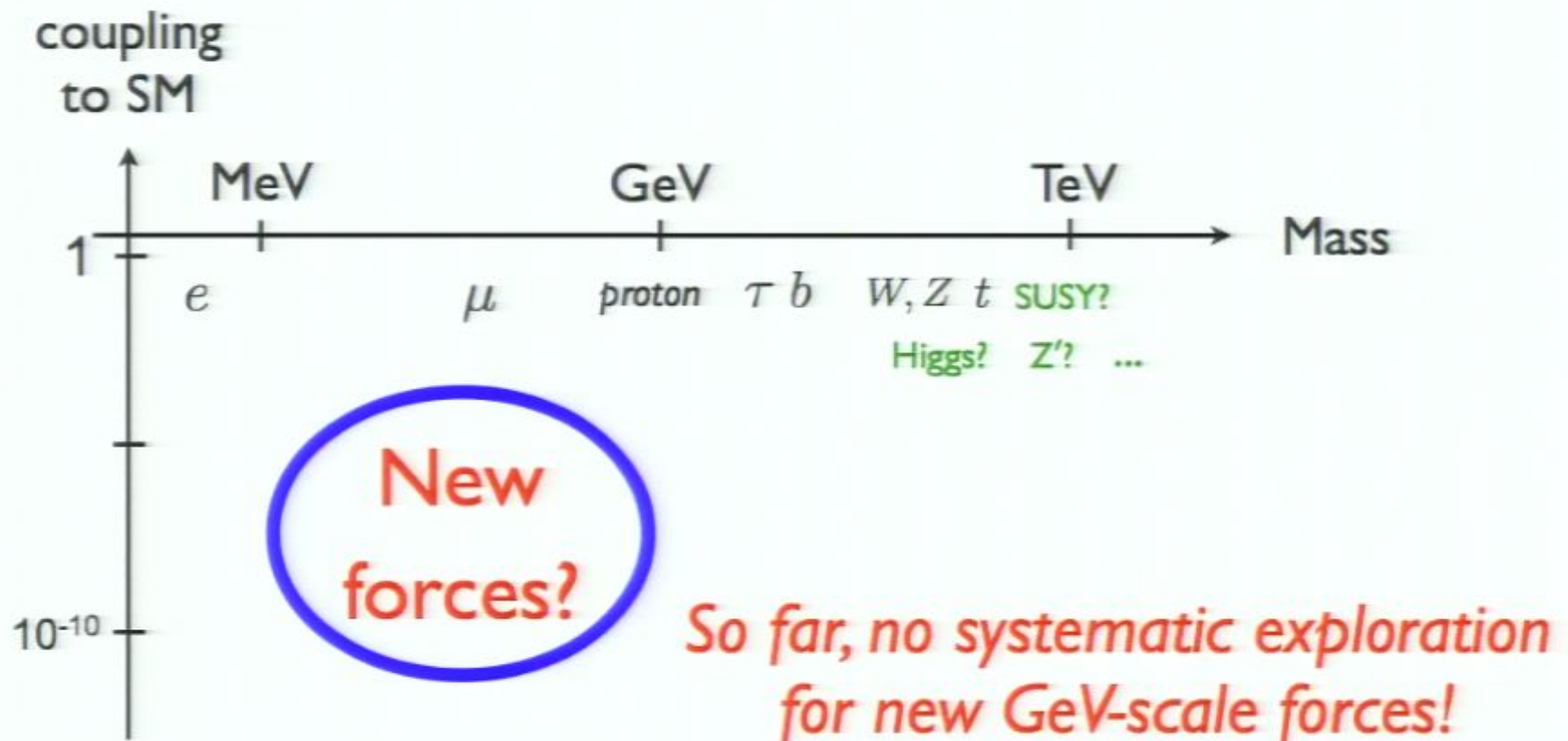
Quarks & charged Leptons couple to A'



Theoretically natural

Hints from $(g_s - 2)$, dark matter anomalies, ...

Irrespective of (speculative) hints...



Speculative, but potential impact could rival LHC

How can we test this?

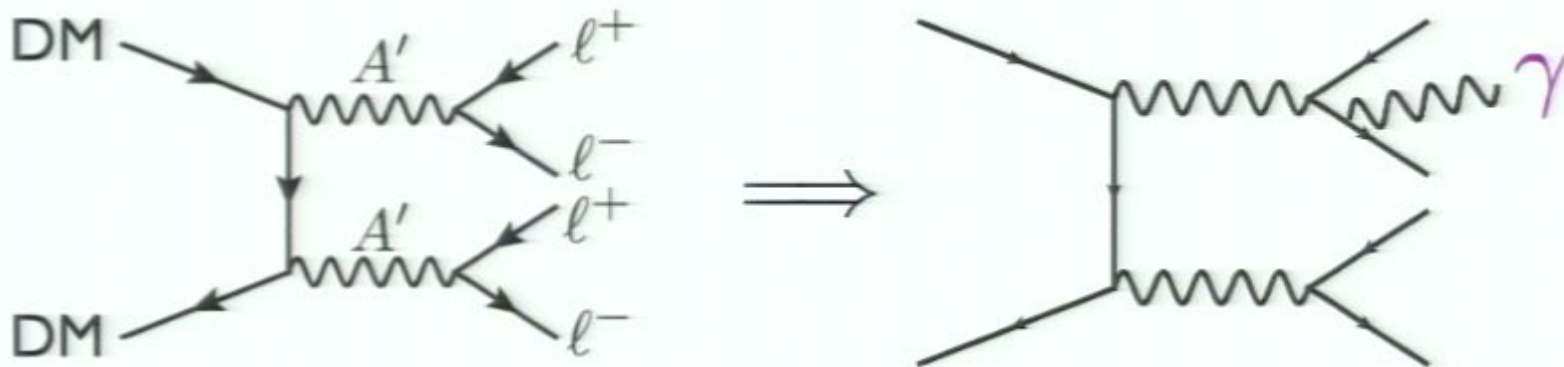
Outline

- The idea: new forces
- Cosmic Frontier
 - dark matter annihilation in dwarf galaxies
- Intensity Frontier
 - e^+e^- colliders
 - fixed target

(assumes dark matter annihilates to A')

DM annihilation to A' guarantees gamma-rays

Final state radiation



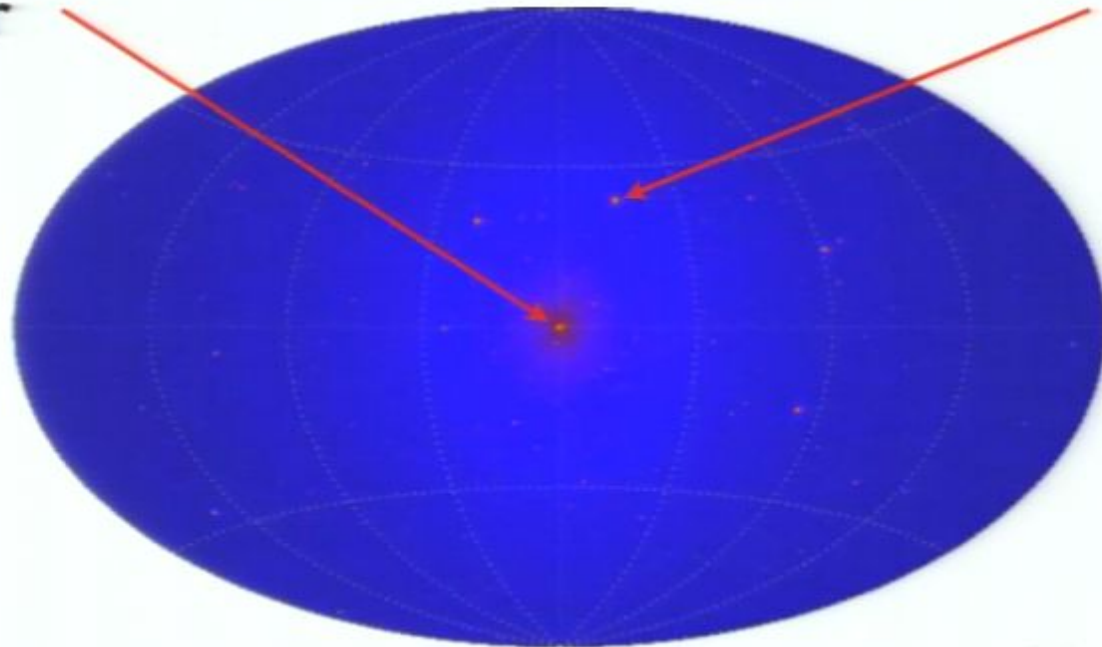
Observe with:

- **Fermi**
- **Atmospheric Cherenkov Telescopes**
(VERITAS, HESS, MAGIC...)

Where look for gamma-rays?

Galactic
Center

Dwarf
Galaxies



Simulation:

Gamma rays from DM annihilation

[0908.0195]

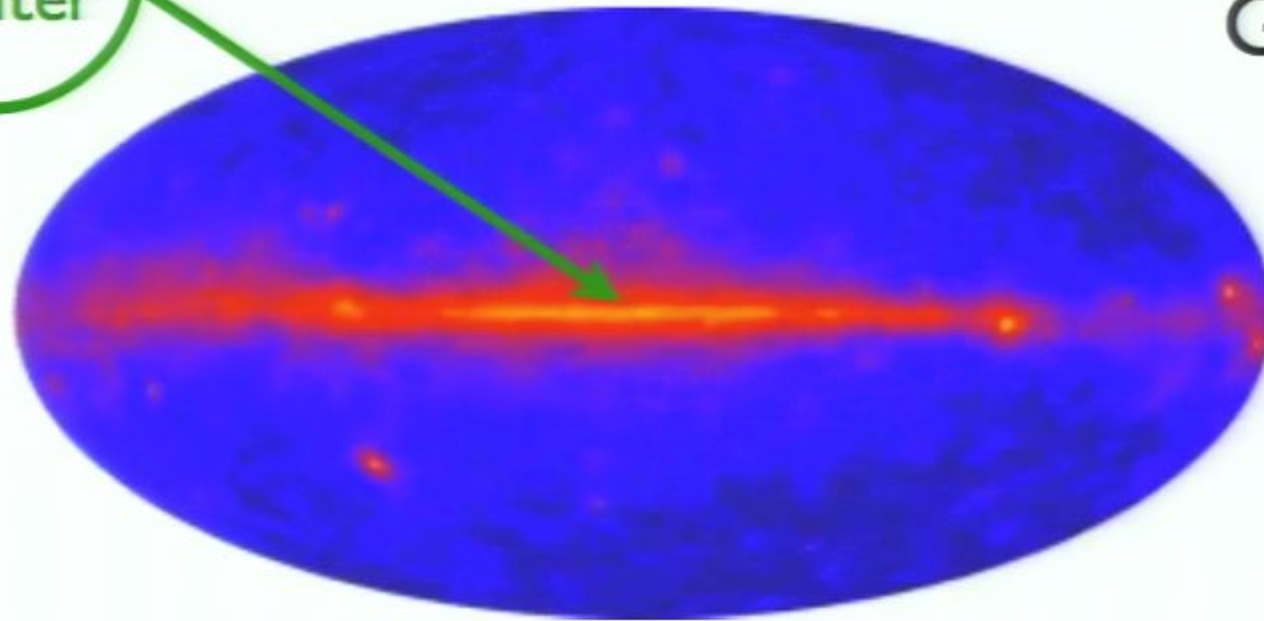
Where look for gamma-rays?

Messy!

Difficult to find
dark matter here

Galactic
Center

Dwarf
Galaxies



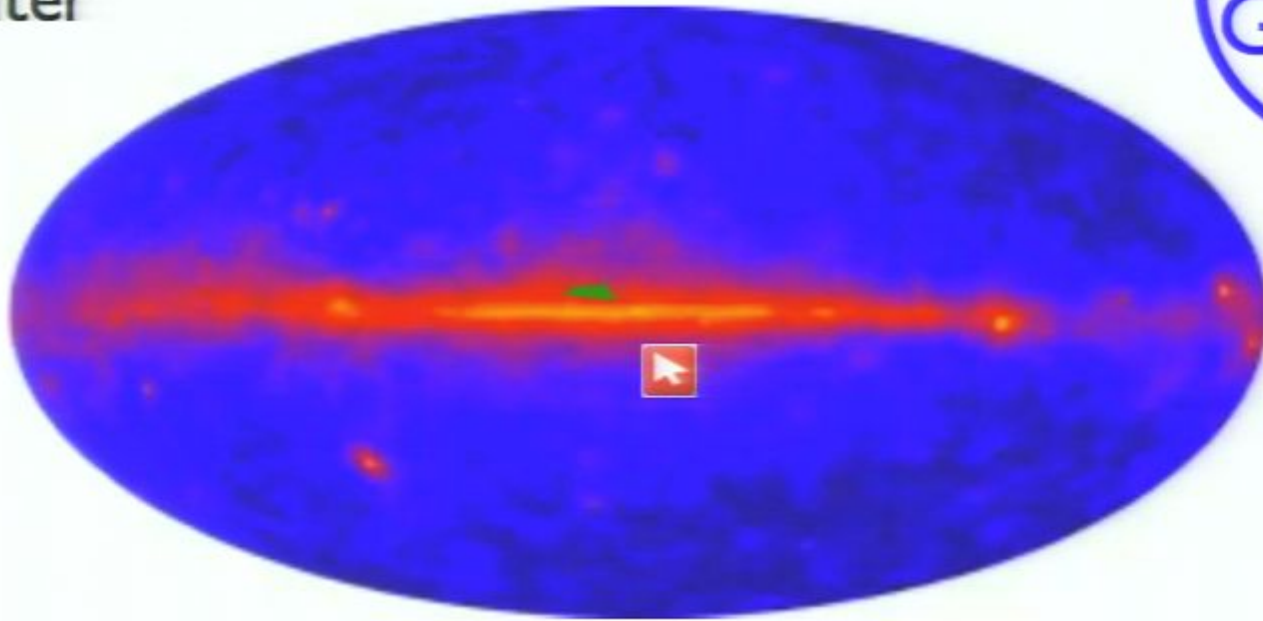
The *observed* gamma-ray
background is complicated!
(Fermi)

Where look for gamma-rays?

a great choice, especially
for A' scenario!

Galactic
Center

Dwarf
Galaxies



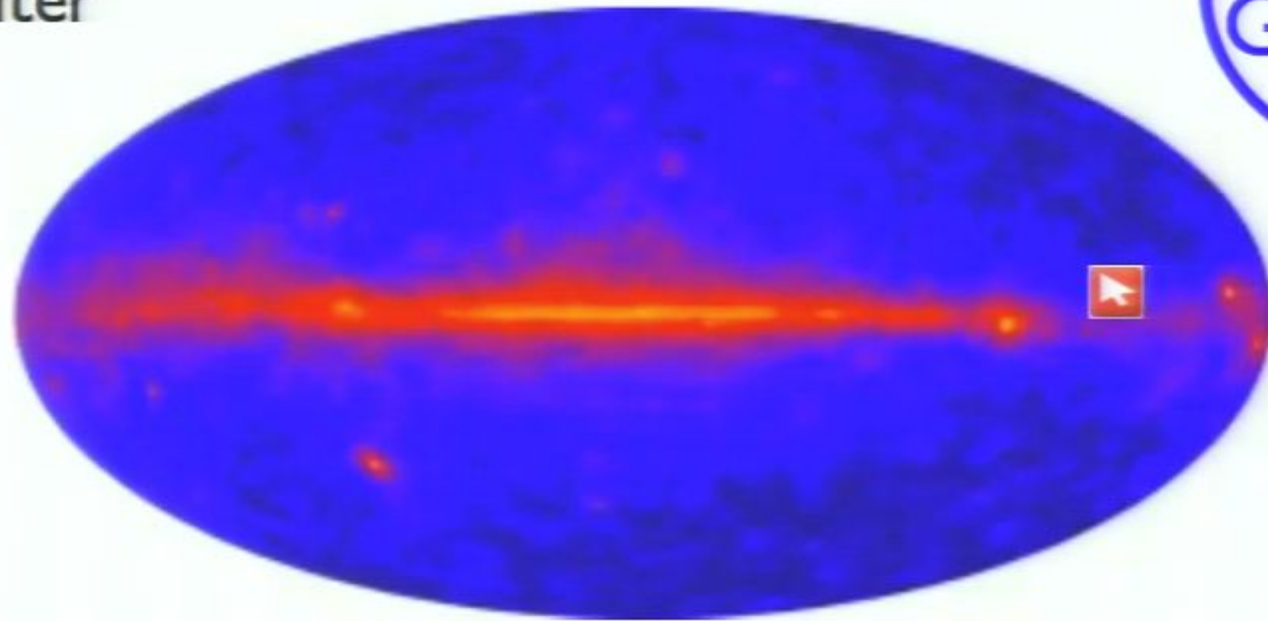
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Dwarf
Galaxies



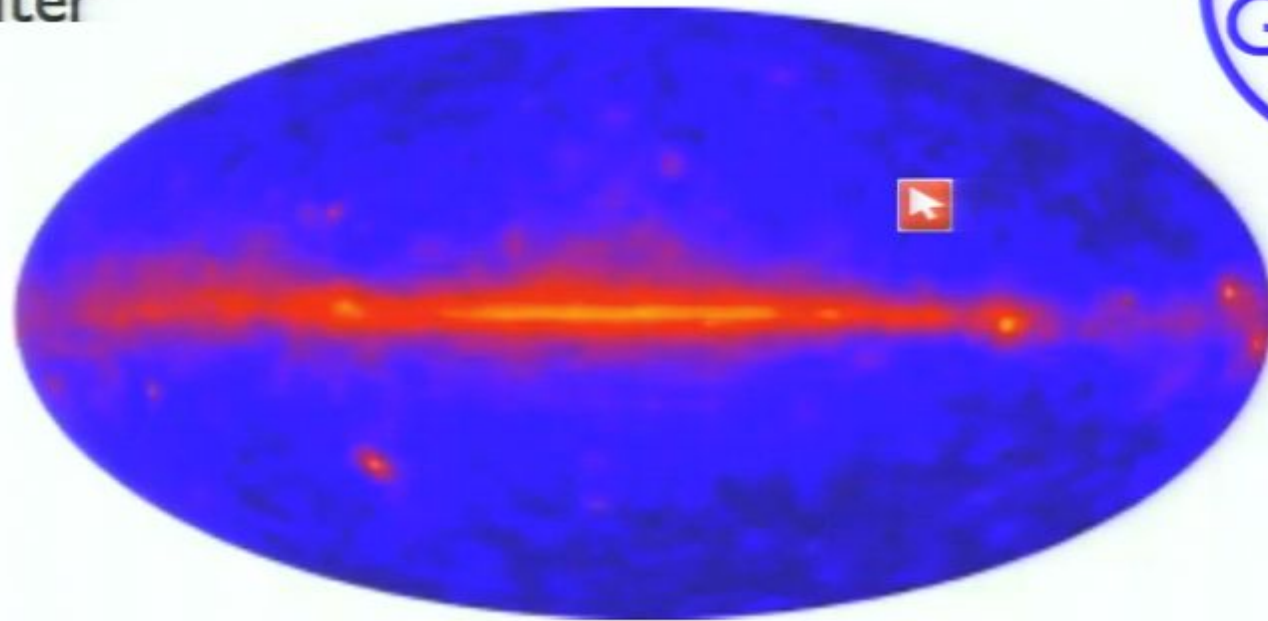
The *observed* gamma-ray
background is complicated!
(Fermi)

Where look for gamma-rays?

a great choice, especially
for A' scenario!

Galactic
Center

Dwarf
Galaxies



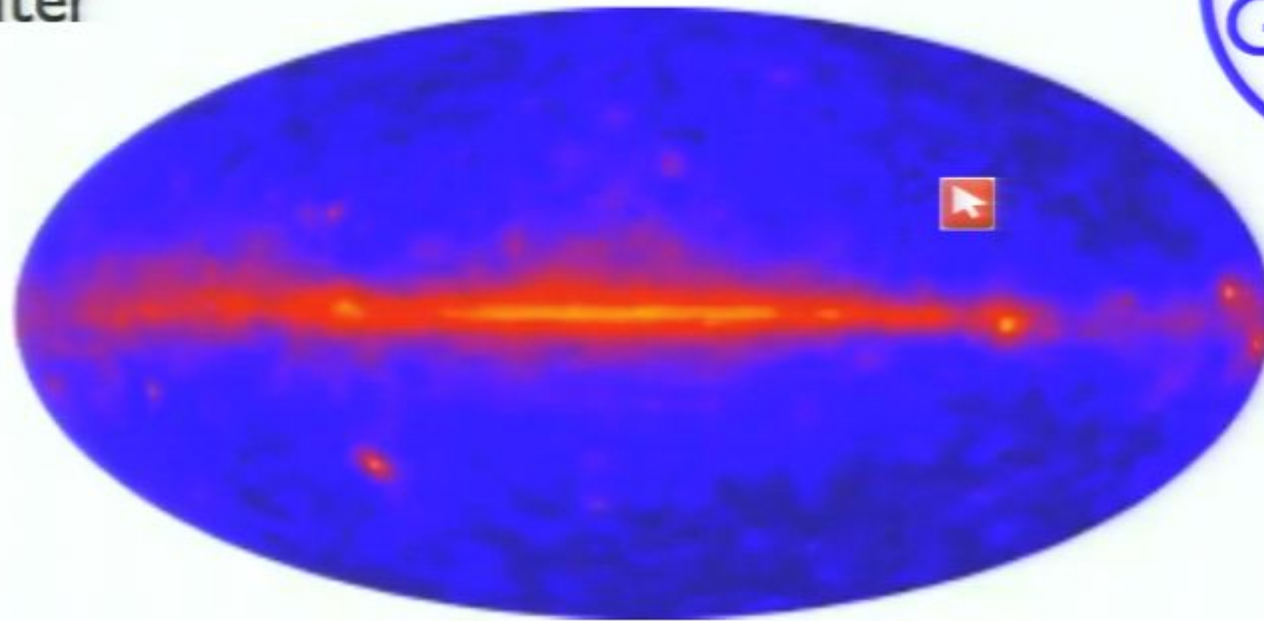
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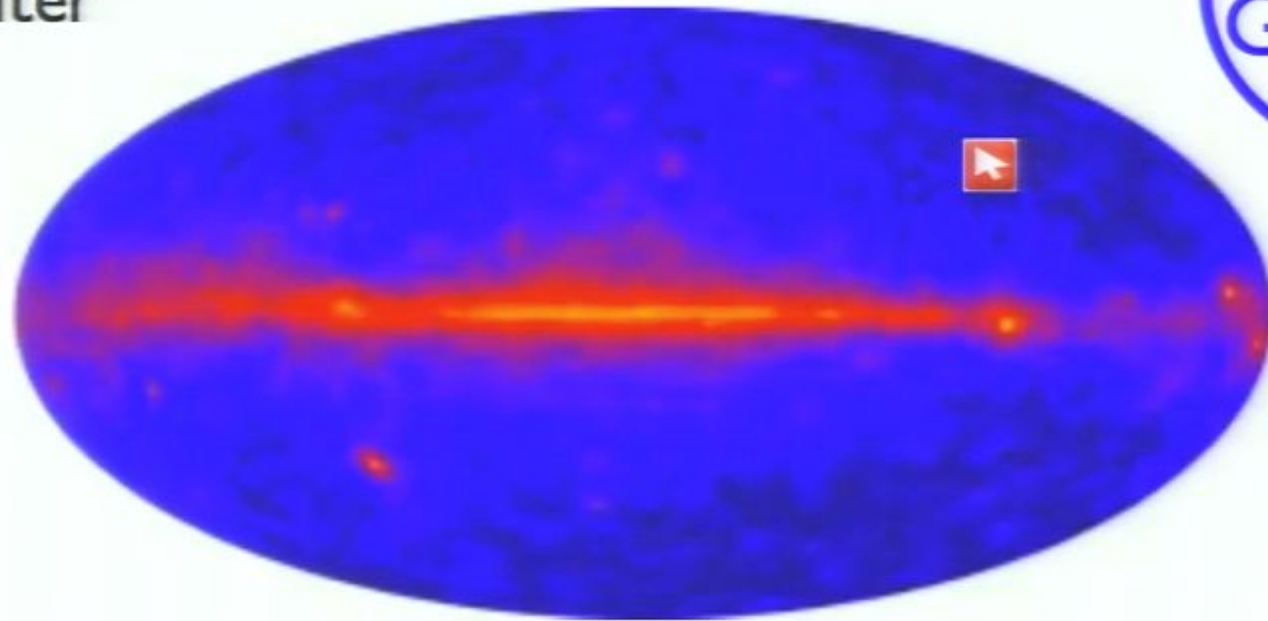
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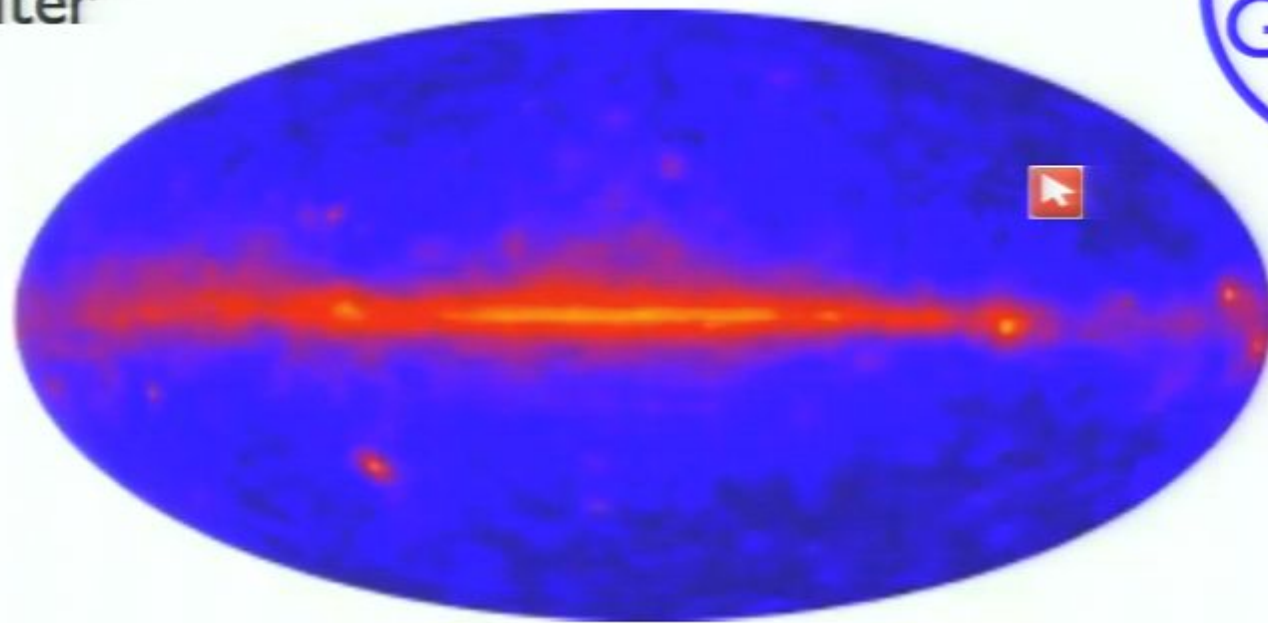
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Dwarf galaxies: Excellent Targets

- dark matter dominated
- nearby, low background
- dark matter velocity is low...

$$v_{\text{dwarf}} \sim v_{\text{halo}}/20$$

Light A' mediates long-range force

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

similar to gravity...

Planet 1



Planet 2

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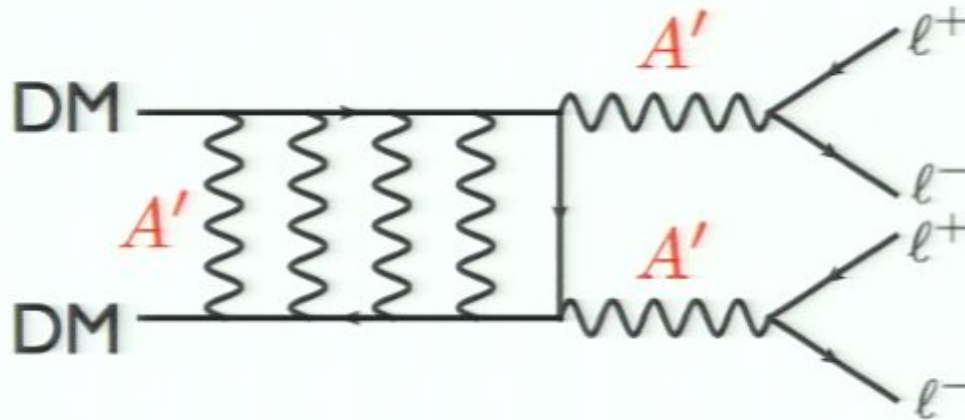
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$$\langle \sigma v \rangle \propto \frac{1}{v}$$

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“Sommerfeld enhancement”

$$\langle \sigma v \rangle \text{ saturates when } v_{\text{DM}} \lesssim \frac{m_{A'}}{m_{\text{DM}}}$$

\Rightarrow for small $m_{A'}$ and small v_{DM} , $\langle \sigma v \rangle$ is large

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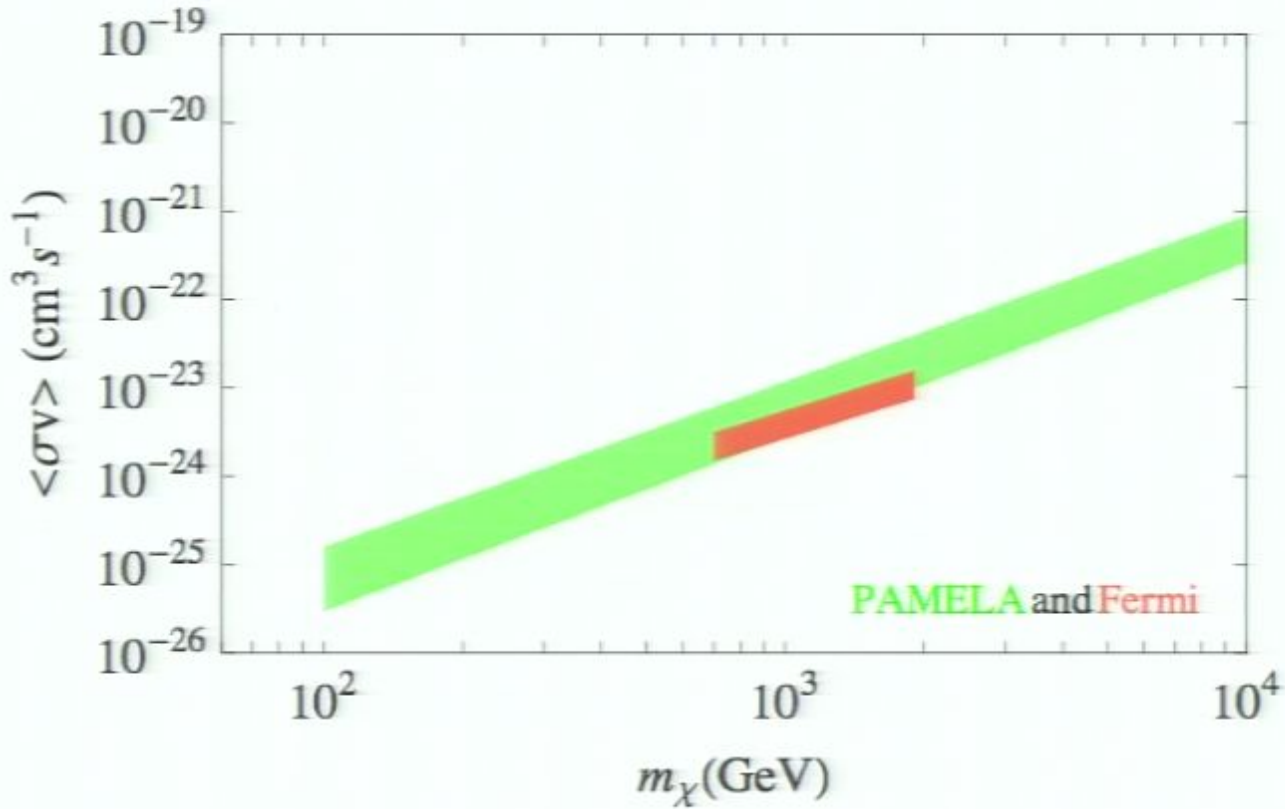
$$v_{\text{dwarf}} \sim v_{\text{halo}}/20$$

⇒ larger Sommerfeld
enhancement for small $m_{A'}$

⇒ dwarfs can probe small $m_{A'}$

PAMELA and Fermi (cosmic-rays) preferred regions

$$\text{DM DM} \rightarrow A' A' \rightarrow e^+ e^- e^+ e^-$$



Dwarf galaxies: Excellent Targets

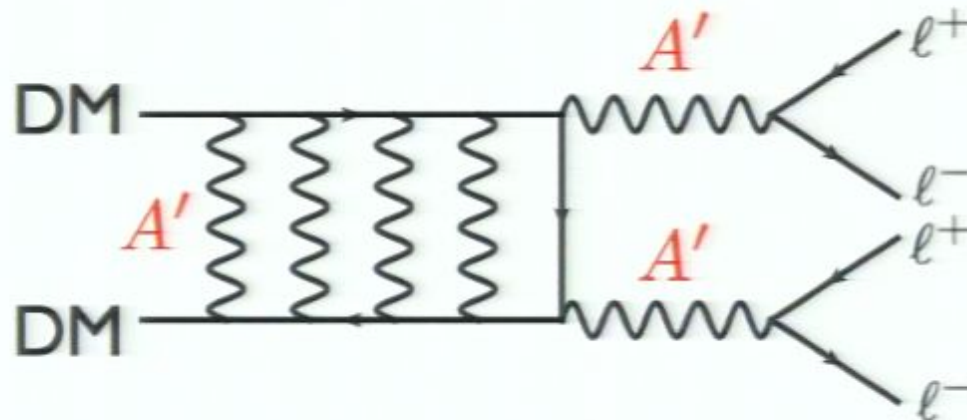
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Rouven Essig [desk]

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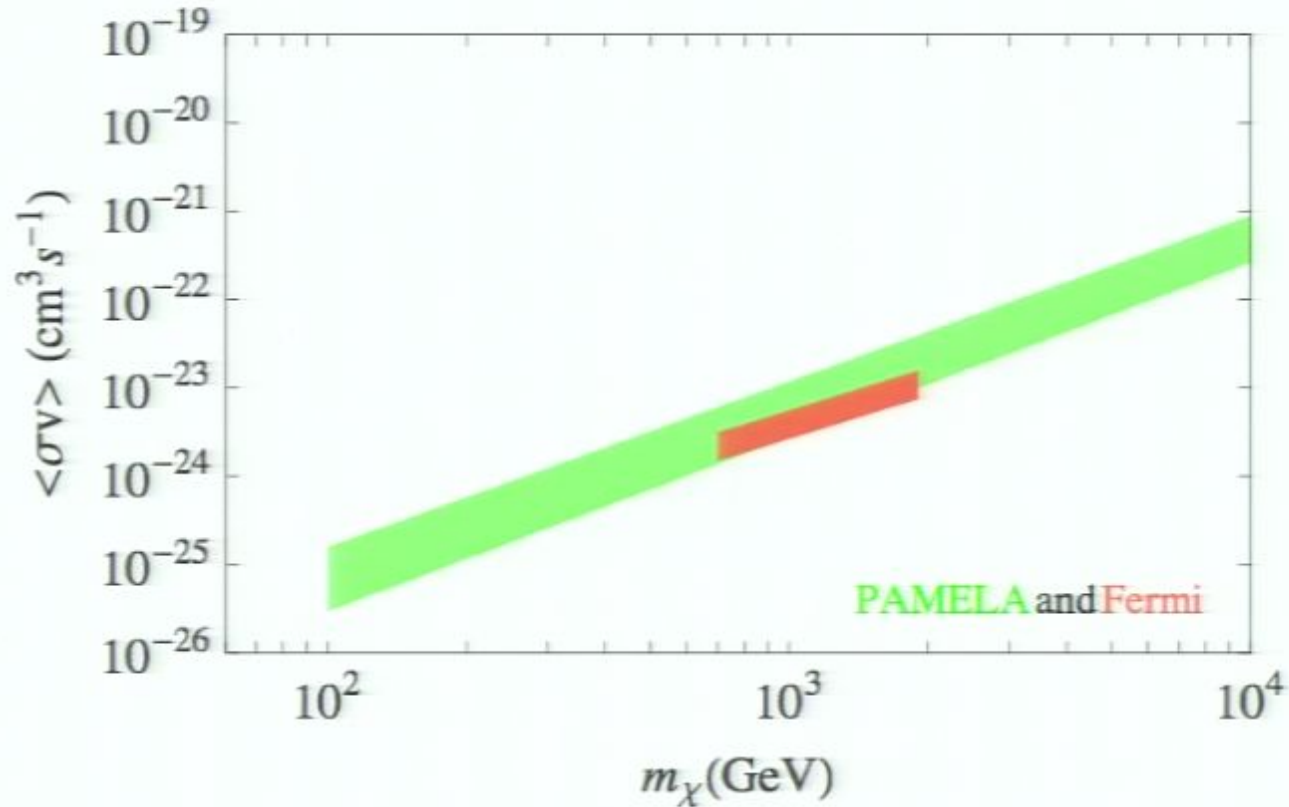
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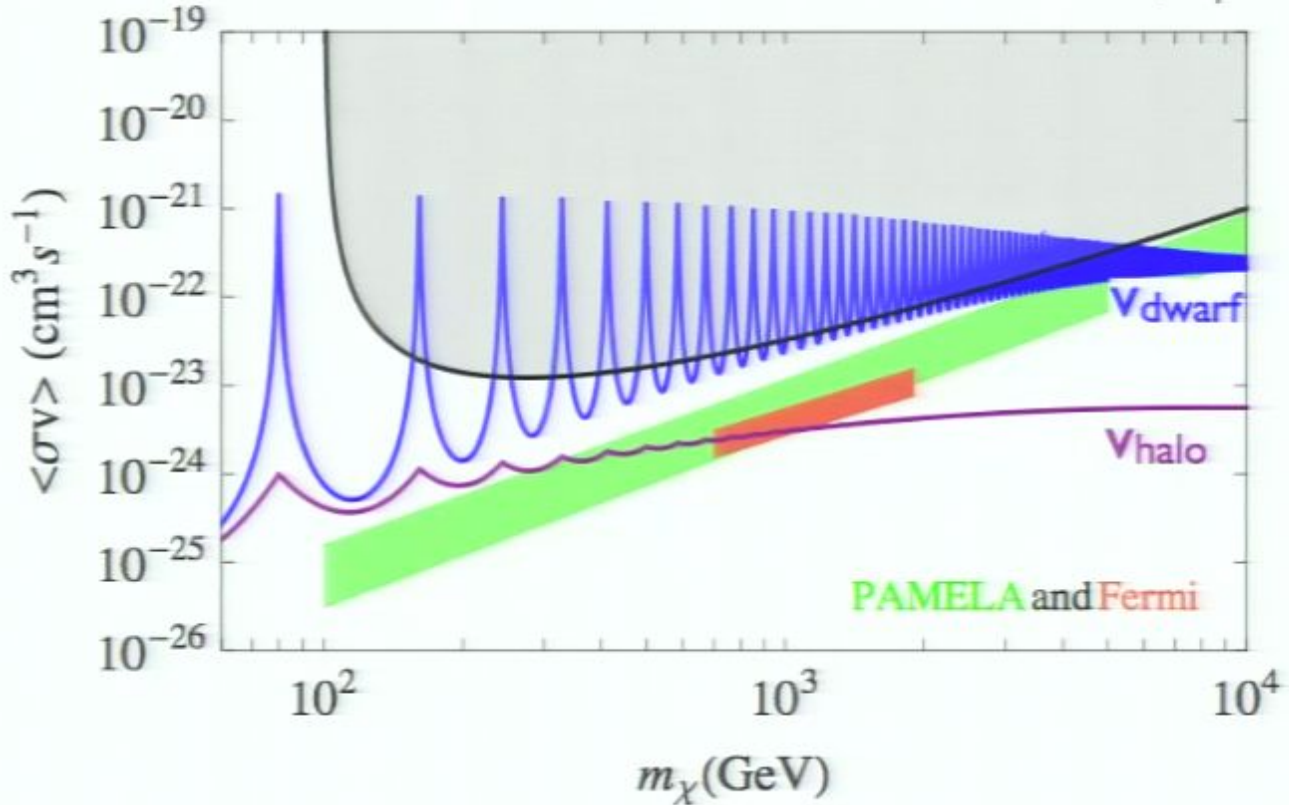


MAGIC γ -ray constraints from dwarf

RE, Sehgal, Strigari, Geha, Simon [PRD 2010]

RE, Sehgal, Strigari [PRD 2009]

$$\text{DM DM} \rightarrow A' A' \rightarrow e^+ e^- e^+ e^- + \gamma$$



disfavors $m_{A'} = 0.1 \text{ GeV}$

but there is uncertainty in the expected flux!

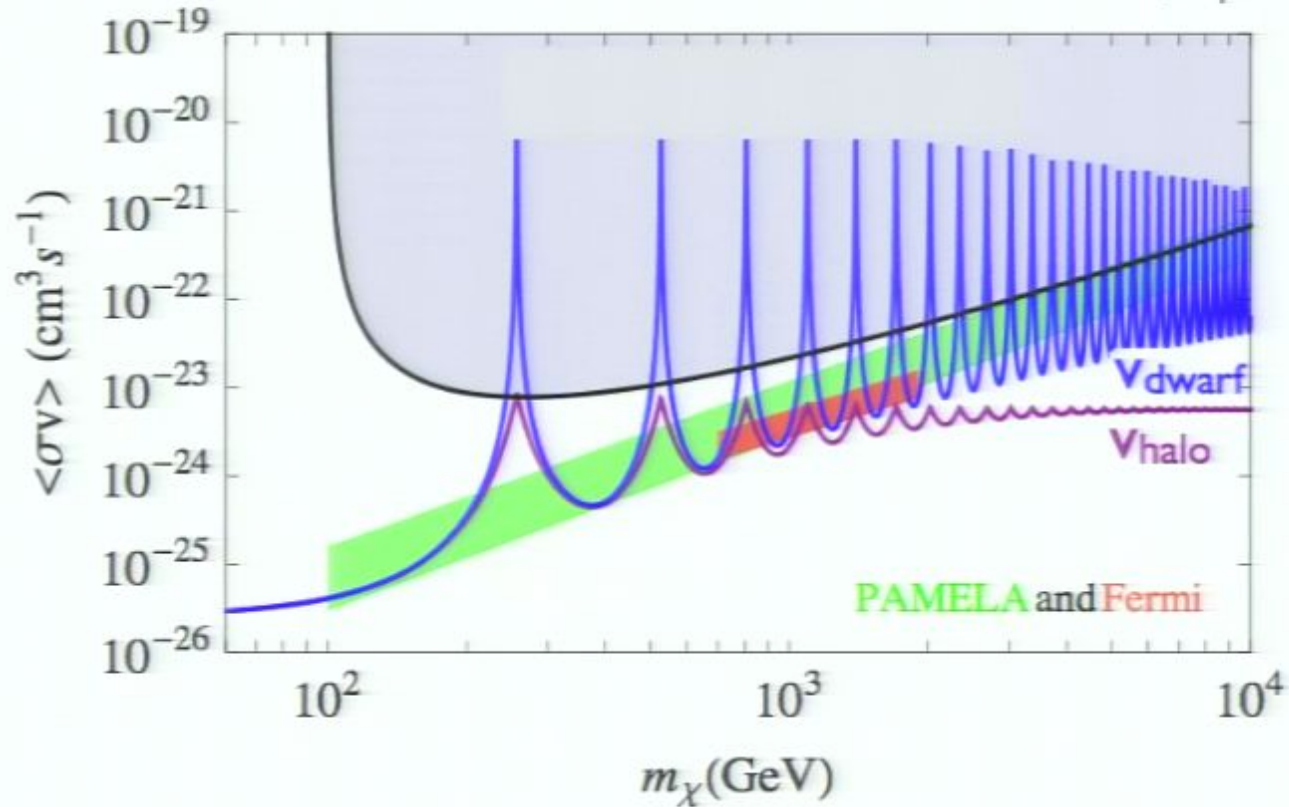
Rouven Essig [desk]

Larger A' masses ok

RE, Sehgal, Strigari, Geha, Simon [PRD 2010]

RE, Sehgal, Strigari [PRD 2009]

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$$m_{A'} = 1.0 \text{ GeV}$$

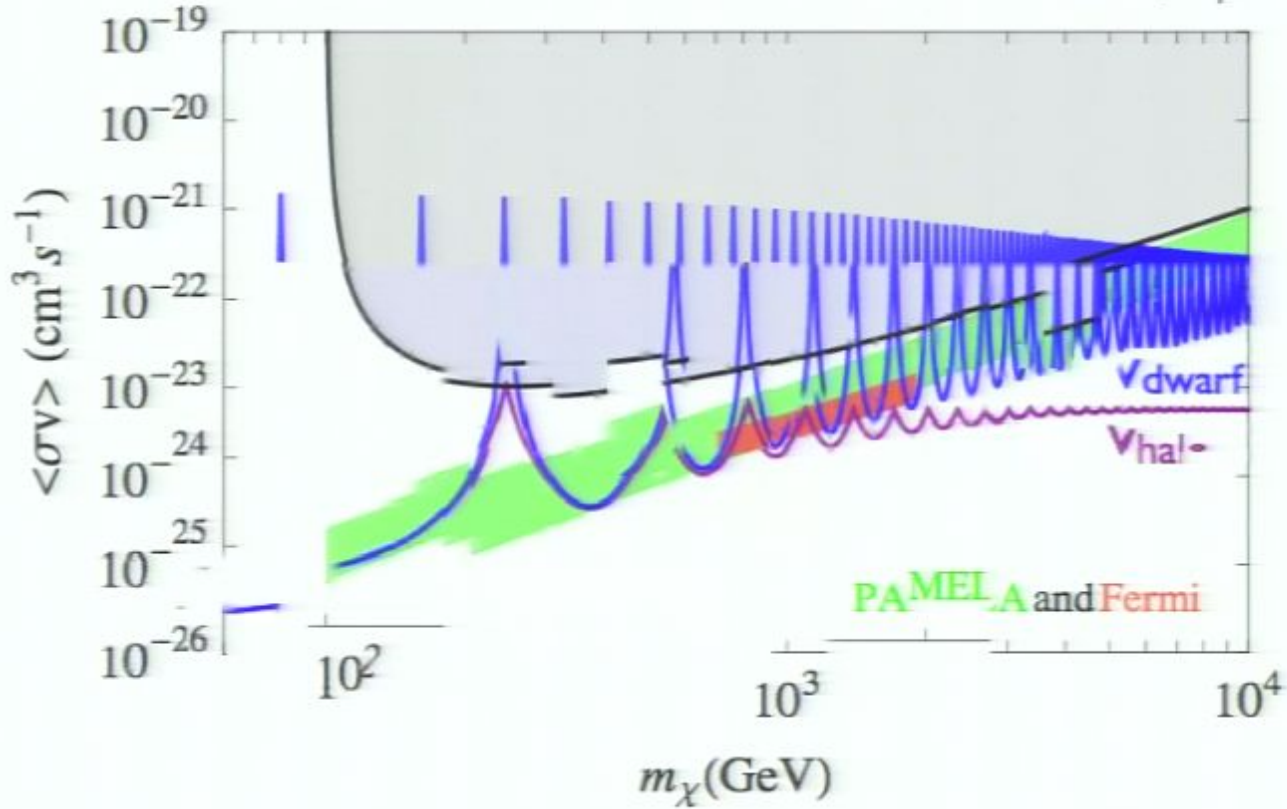


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Outline

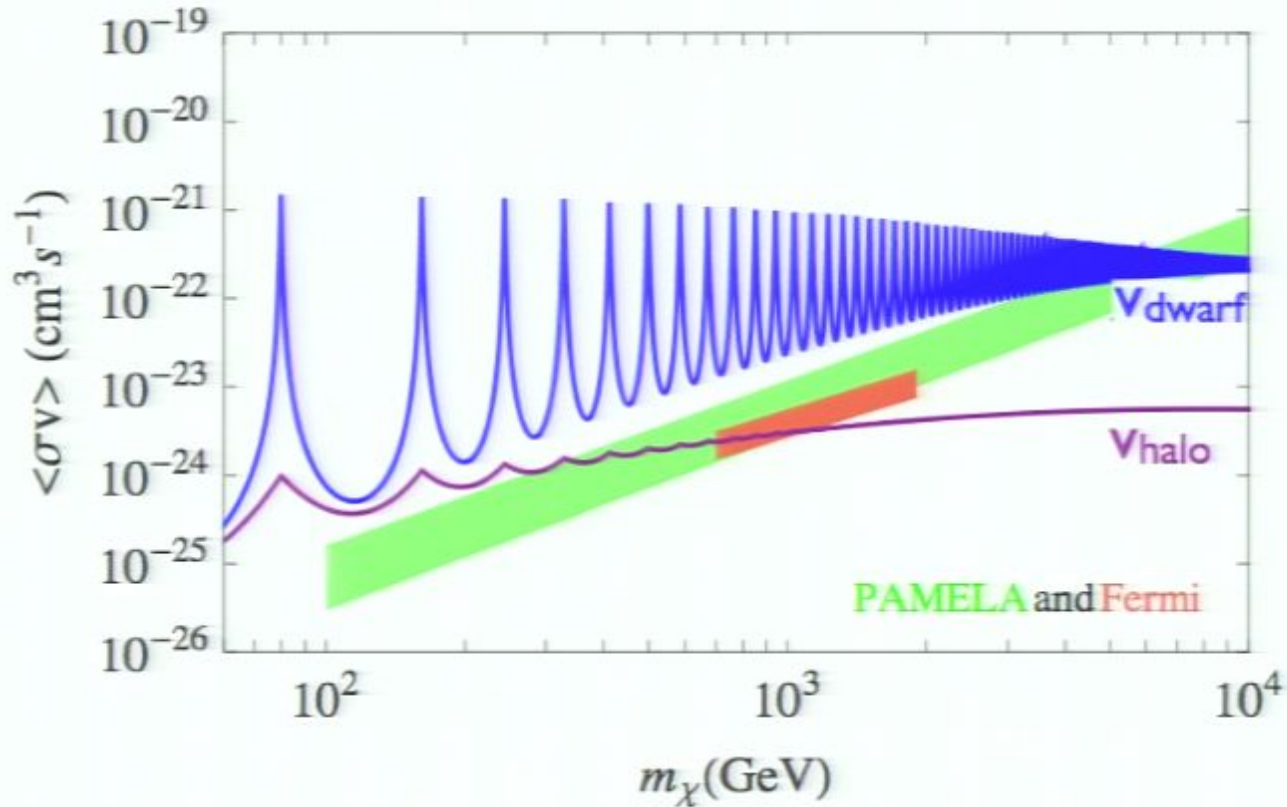
- The idea: new forces
- Cosmic Frontier
 - dark matter annihilation in dwarf galaxies
- Intensity Frontier
 - e^+e^- colliders
 - fixed target

Sommerfeld cross-section in dwarf "Segue 1"

RE, Sehgal, Strigari, Geha, Simon [PRD 2010]

RE, Sehgal, Strigari [PRD 2009]

$$\text{DM DM} \rightarrow A' A' \rightarrow e^+ e^- e^+ e^-$$



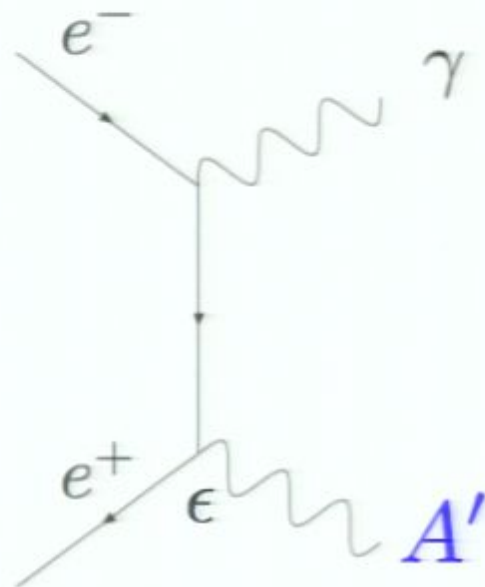
cross-section assumes

correct thermal relic abundance

$$m_{A'} = 0.1 \text{ GeV}$$

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

RE, Schuster, Toro
Batell, Pospelov, Ritz
Reece, Wang

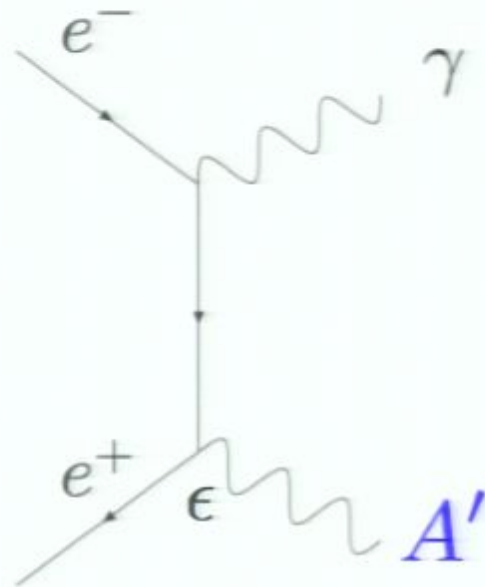


$$\sigma \propto \frac{\epsilon^2}{E_{cm}^2}$$

\Rightarrow want low-energy (1-10 GeV), high intensity colliders (BaBar, BELLE, KLOE, ...)

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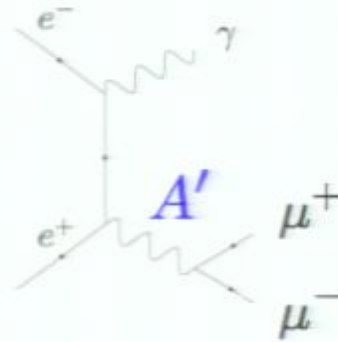
$A' \rightarrow e^+e^-, \mu^+\mu^-, \dots$ ($A' \rightarrow$ hidden sector also possible)

Broad array of searches needed and now underway!

Constraint

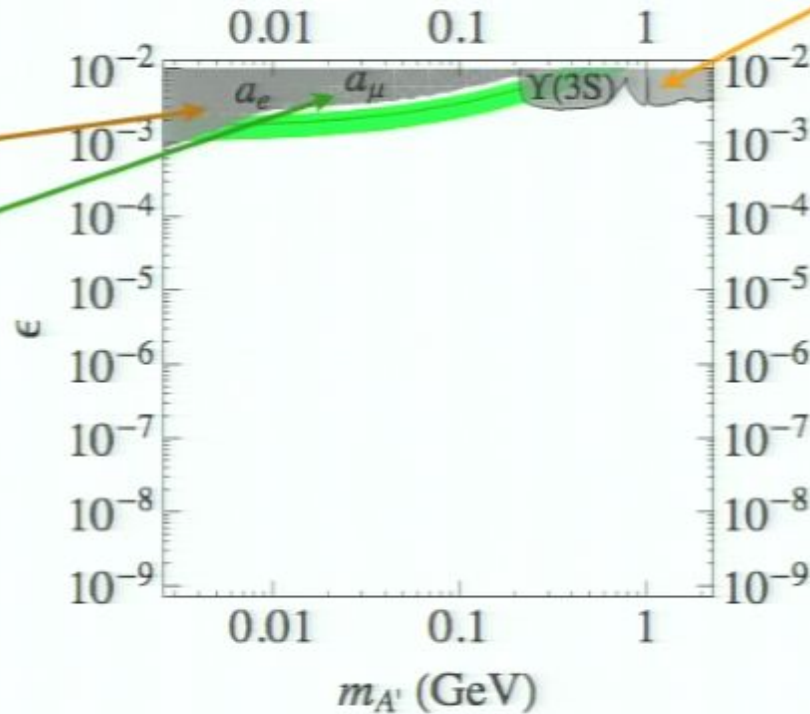
RE, Schuster, Toro, Wojtsekhowski

Reece, Wang



BaBar
(partial data set)

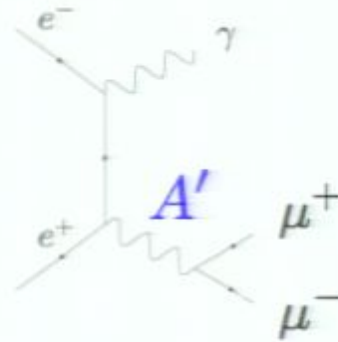
g-2 for
electron
and muon



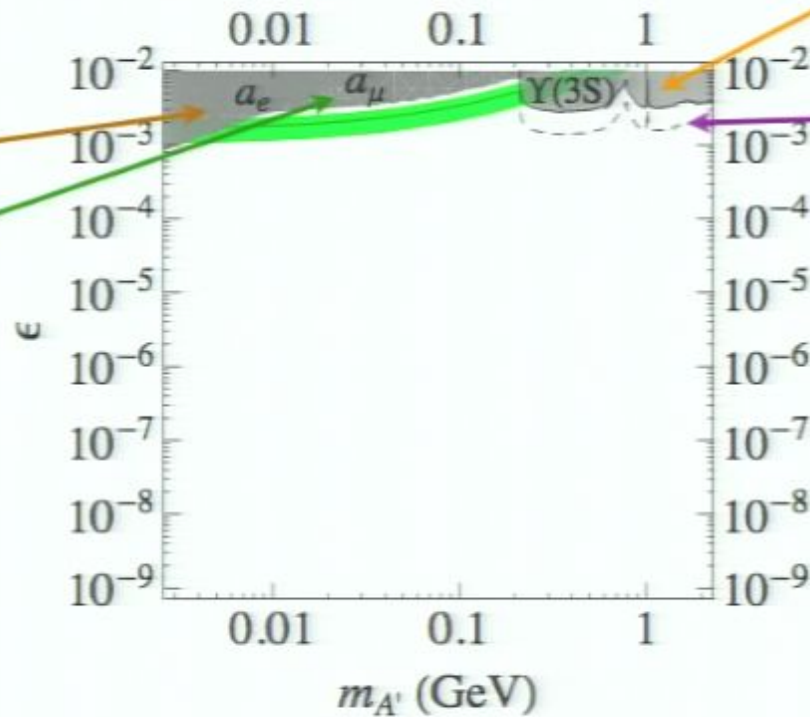
Constraint

RE, Schuster, Toro, Wojtsekhowski

Reece, Wang



g-2 for
electron
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BaBar
(partial data set)

Belle
(full dataset)

Outline

- The idea: new forces
- Cosmic Frontier
 - dark matter annihilation in dwarf galaxies
- Intensity Frontier 
 - e^+e^- colliders
 - fixed target: APEX & HPS

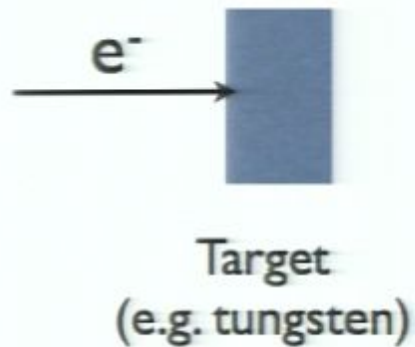
Fixed-Target Experiments

[Bjorken, RE, Schuster, Toro]

[Reece & Wang]

[Freytsis, Ovanesyan, Thaler]

Produce A' via bremsstrahlung off e^- beam on fixed target



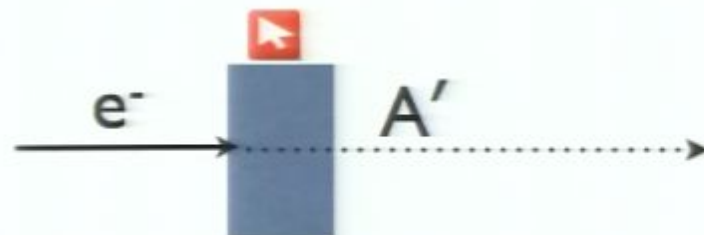
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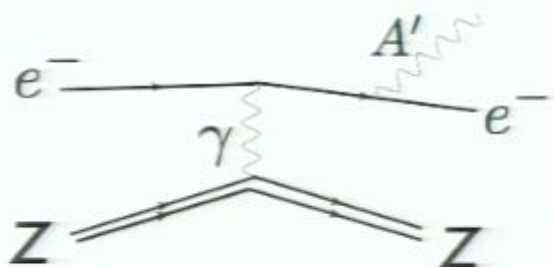
[Reece & Wang]

[Freytsis, Ovanesyan, Thaler]

Produce A' via bremsstrahlung off e^- beam on fixed target



Target
(e.g. tungsten)



A' produced forward,
carries most of E_{beam}

$$\sigma \propto \frac{\epsilon^2 Z^2}{m_{A'}^2}$$

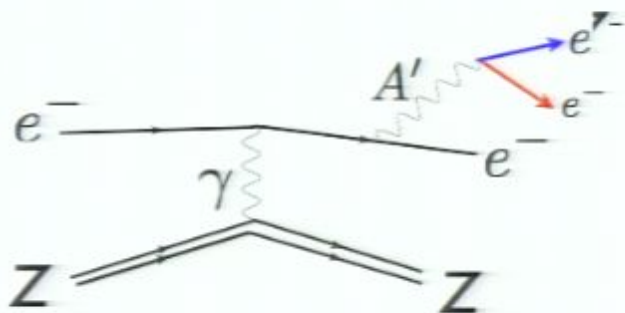
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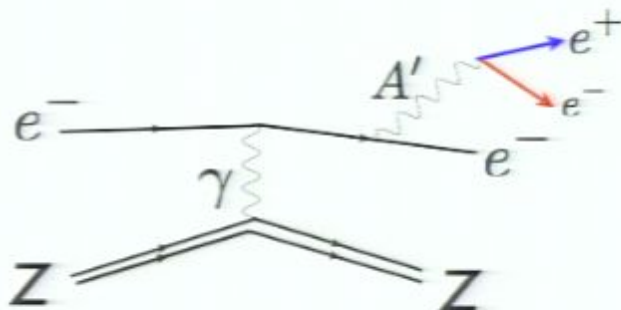
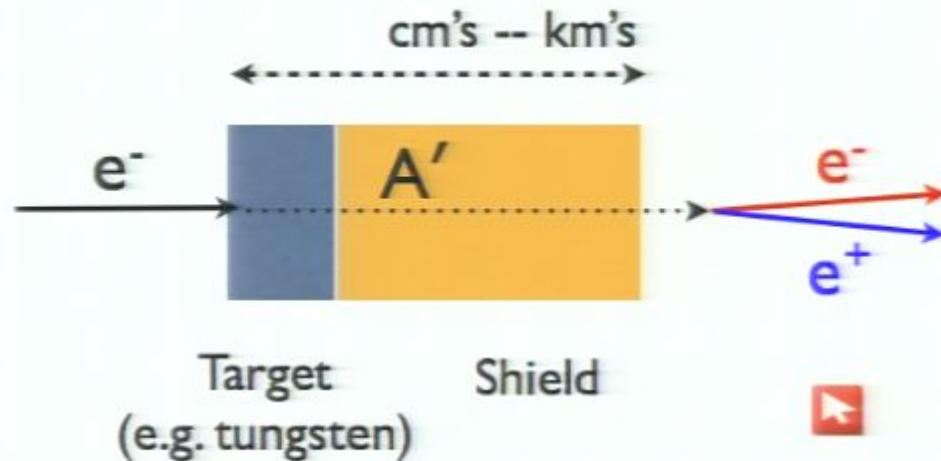
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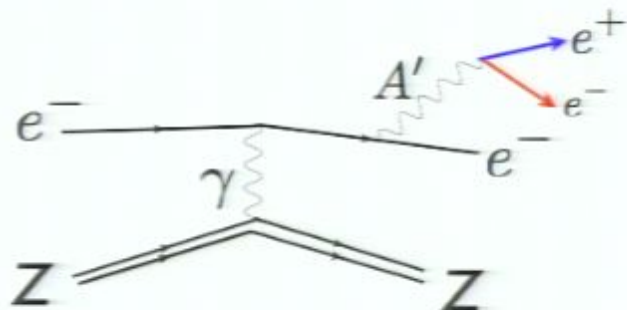
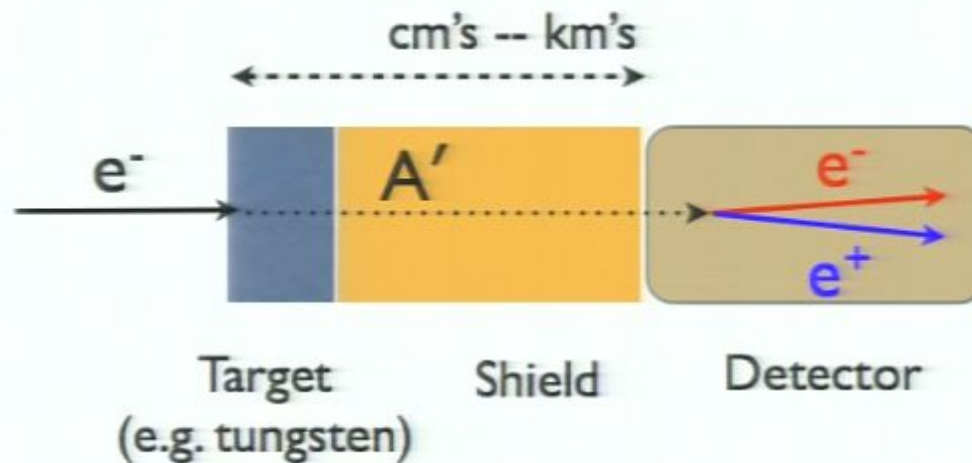
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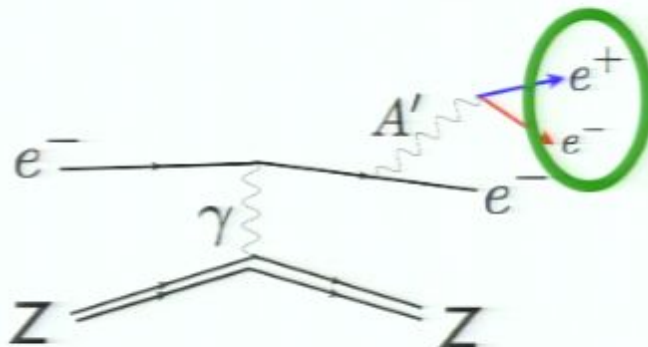
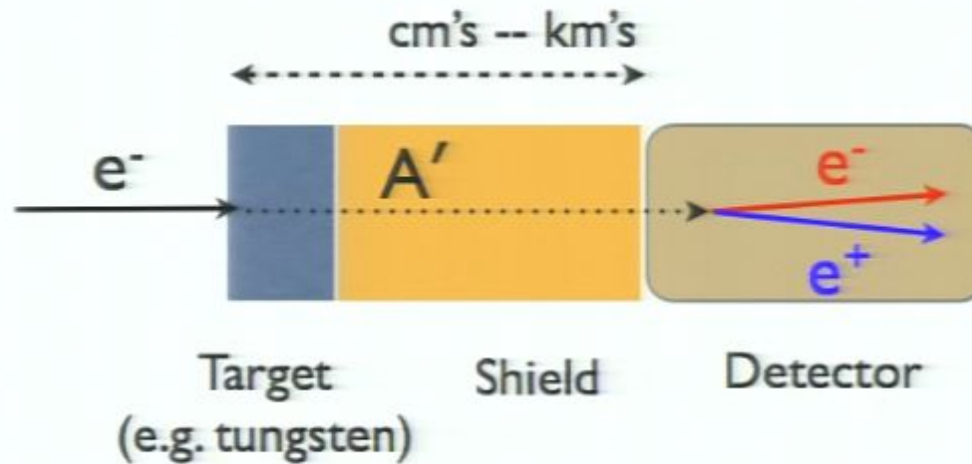
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Produce A' via bremsstrahlung off e^- beam on fixed target



invariant mass
of $e^+e^- = m_{A'}$

resonance helps distinguish
signal from background

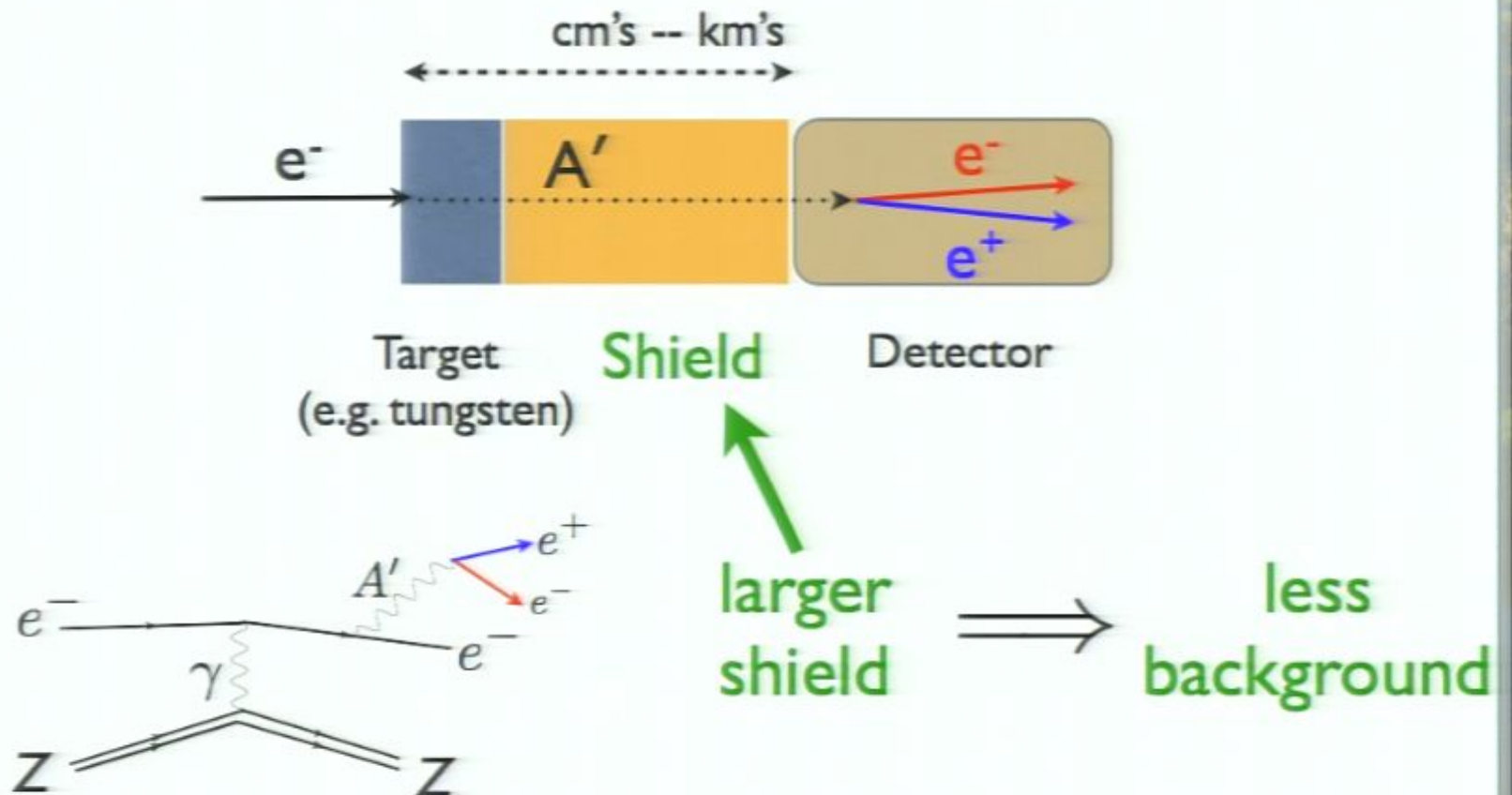
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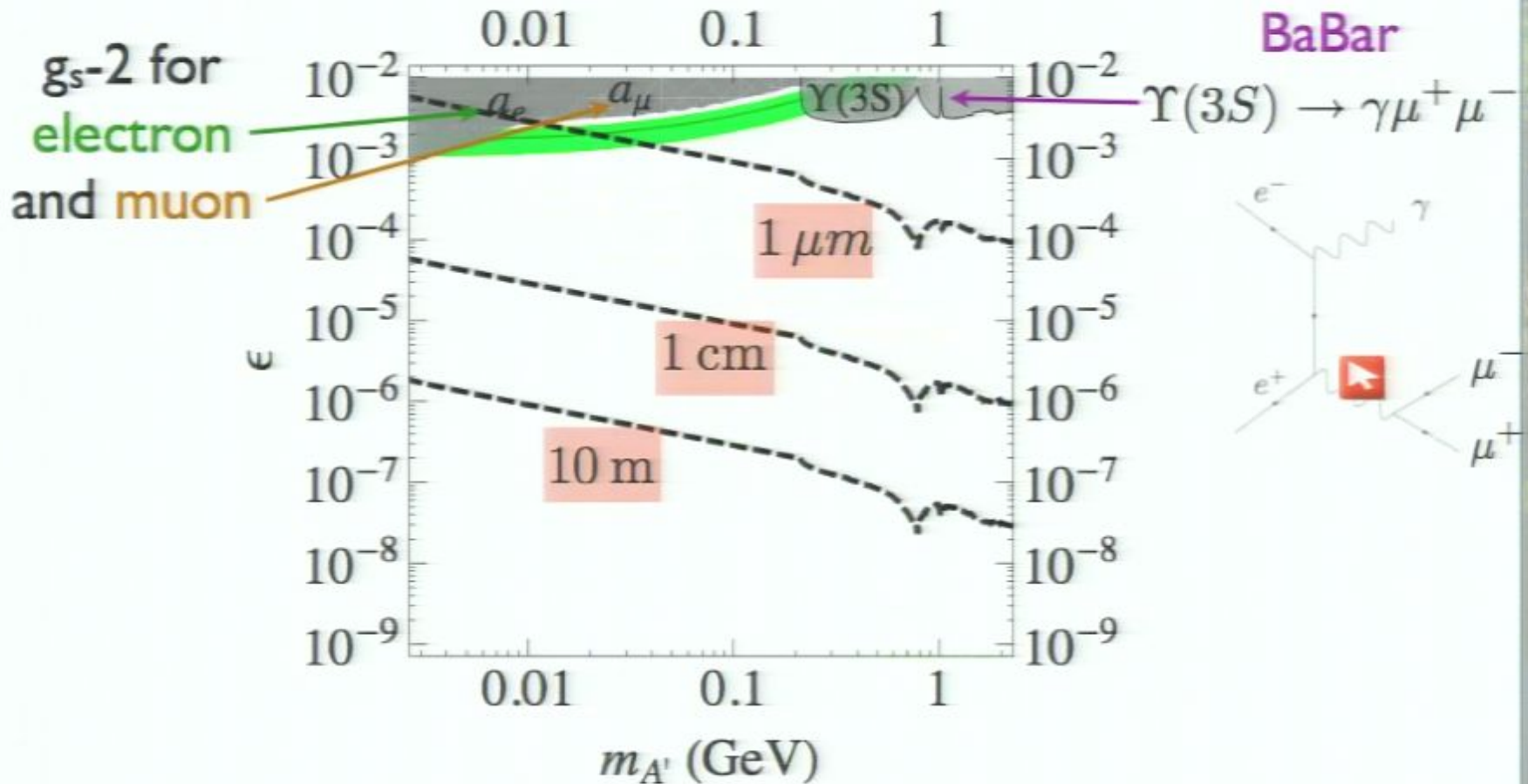
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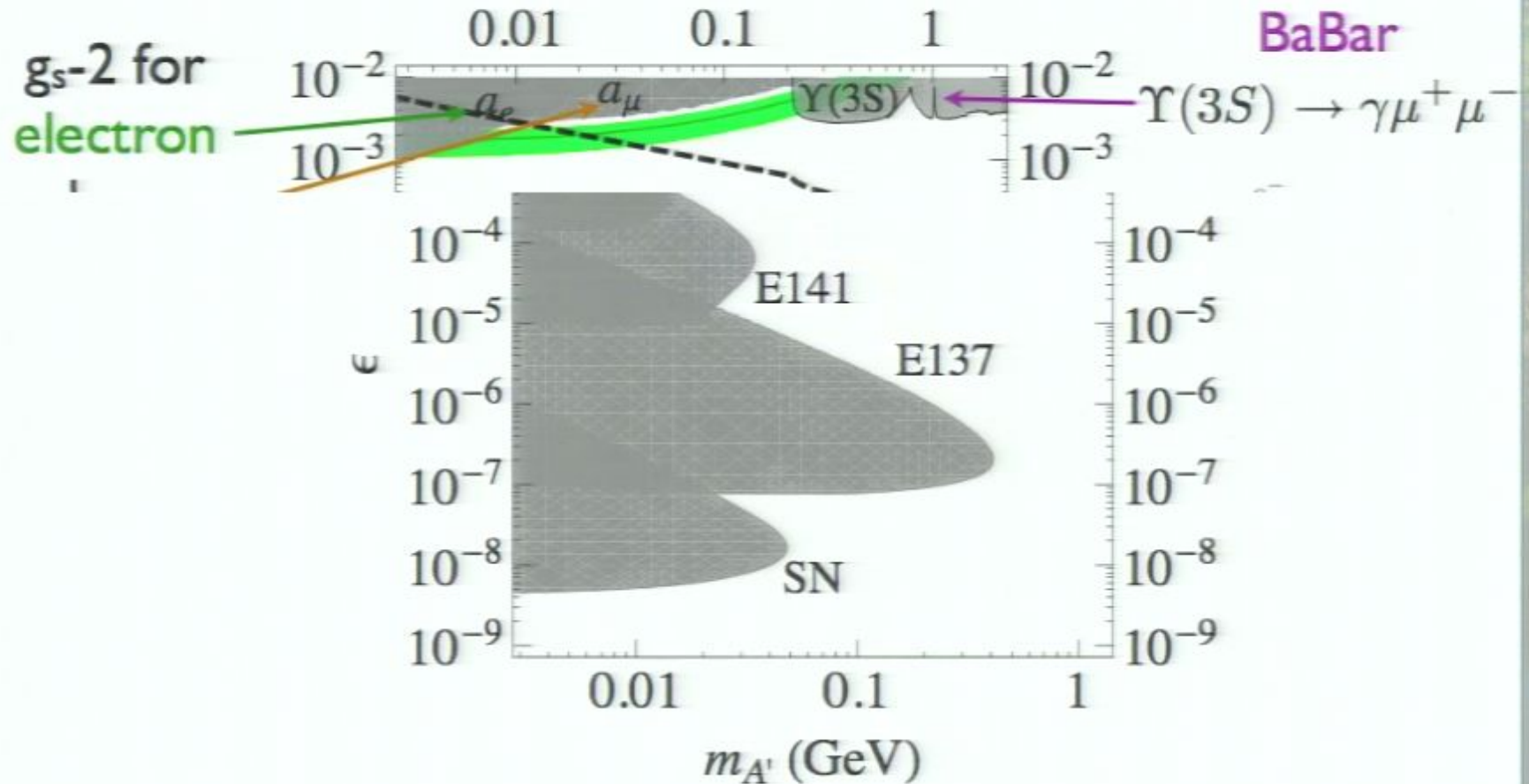


A' lifetime varies by orders of magnitude



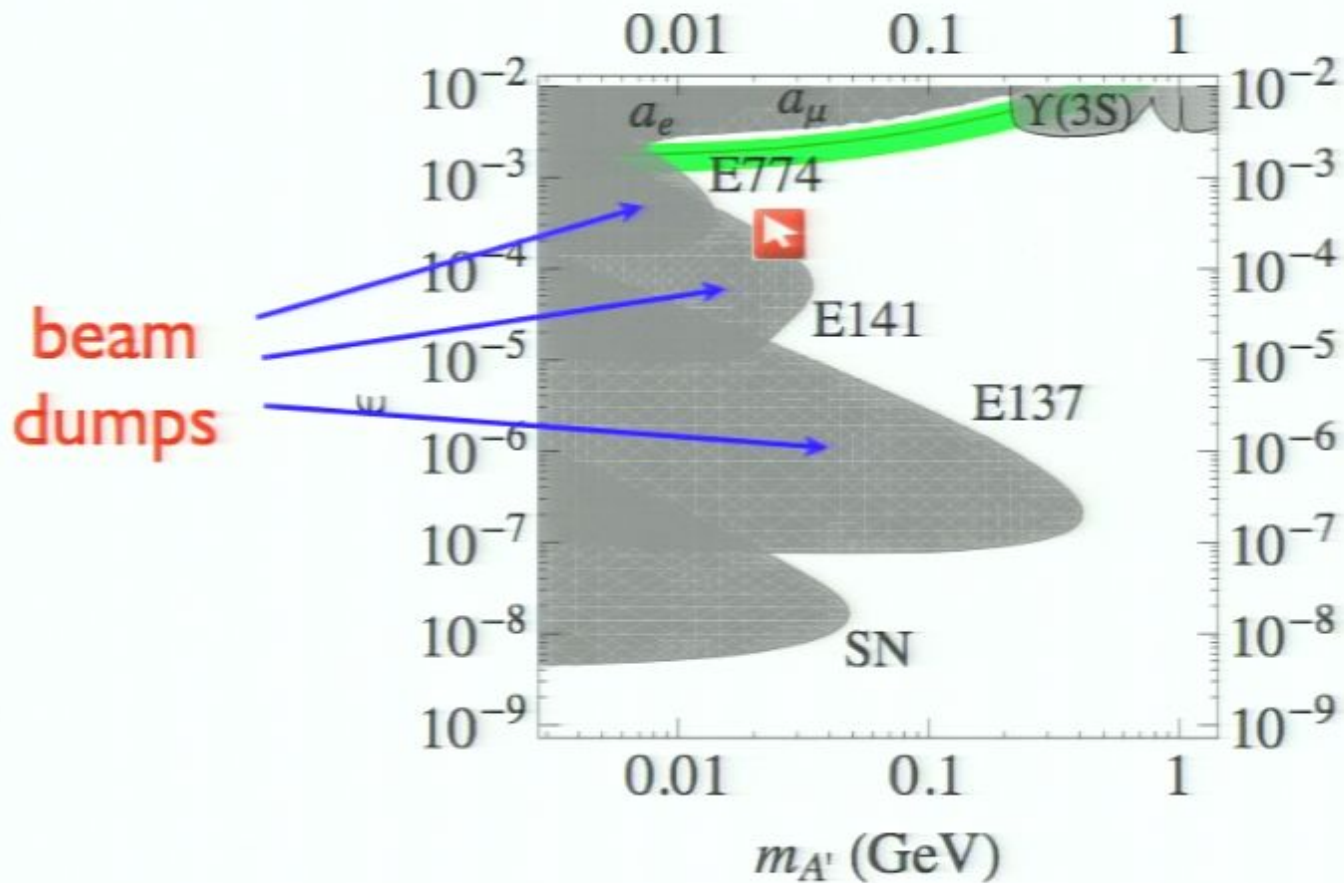
Need various strategies to cover whole range

A' lifetime varies by orders of magnitude



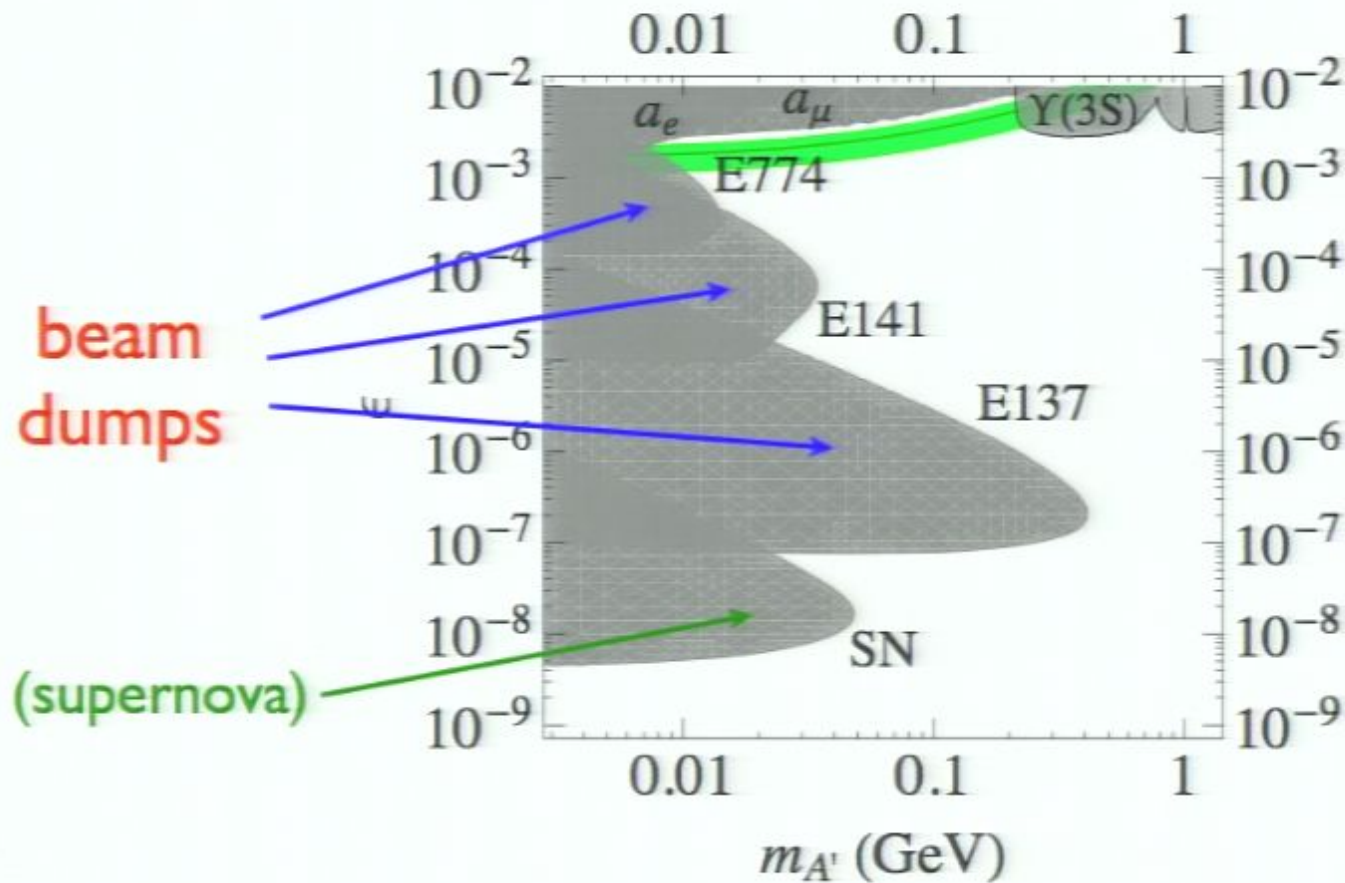
Good beam dump constraints exist

Bjorken, RE, Schuster, Toro



Good beam dump constraints exist

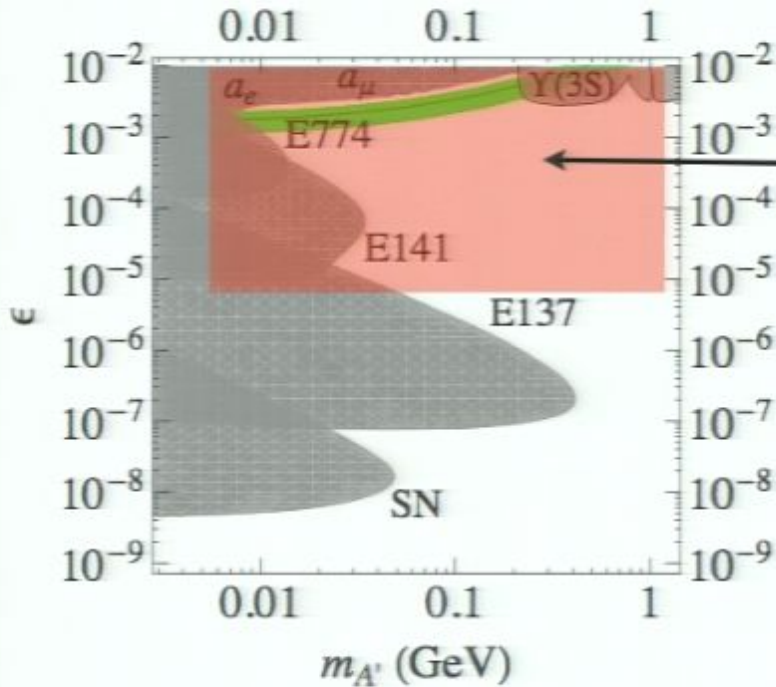
Bjorken, RE, Schuster, Toro



(proton beams can also set interesting constraints)

Need new experiments

Bjorken, RE, Schuster, Toro

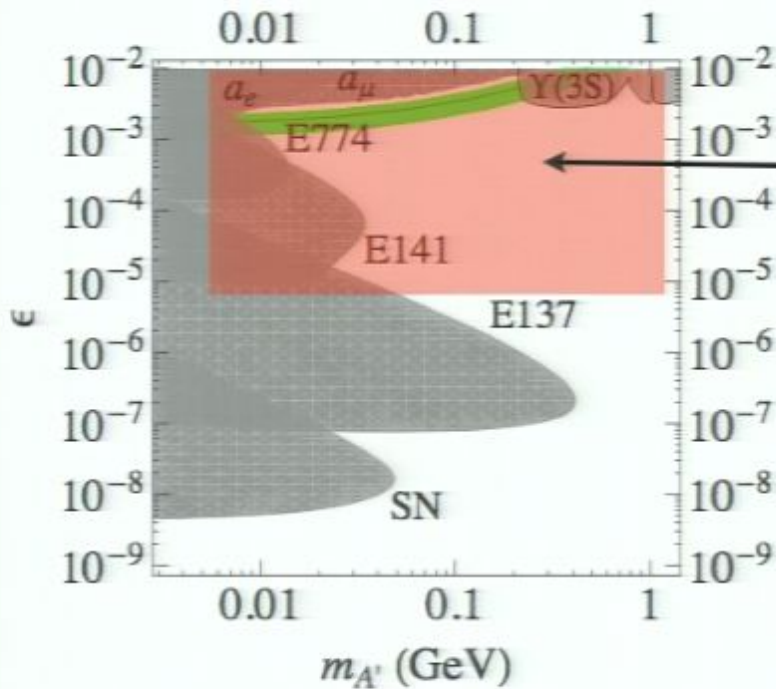


Interesting
unexplored region

A' lifetime short,
so need *thin* target

Need new experiments

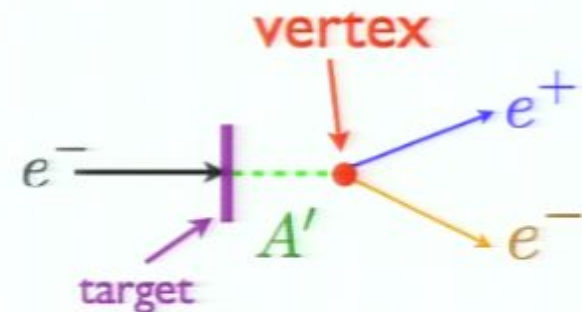
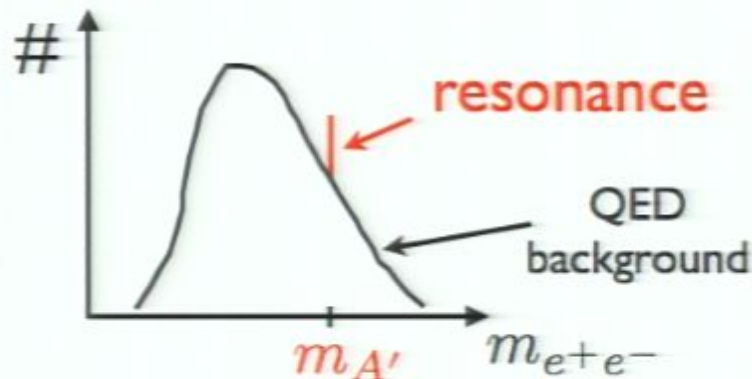
Bjorken, RE, Schuster, Toro



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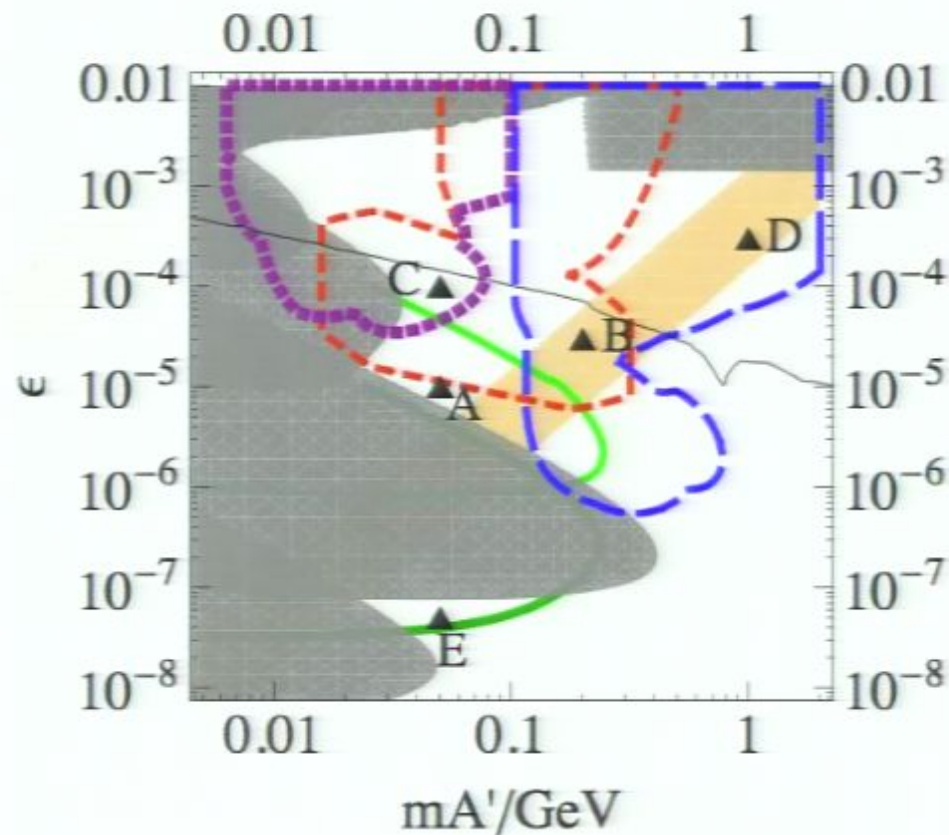
A' lifetime short, so need *thin* target

Large background, but: look for **resonance** or **vertex**



A new experimental search program

Bjorken, RE, Schuster, Toro



June 2009

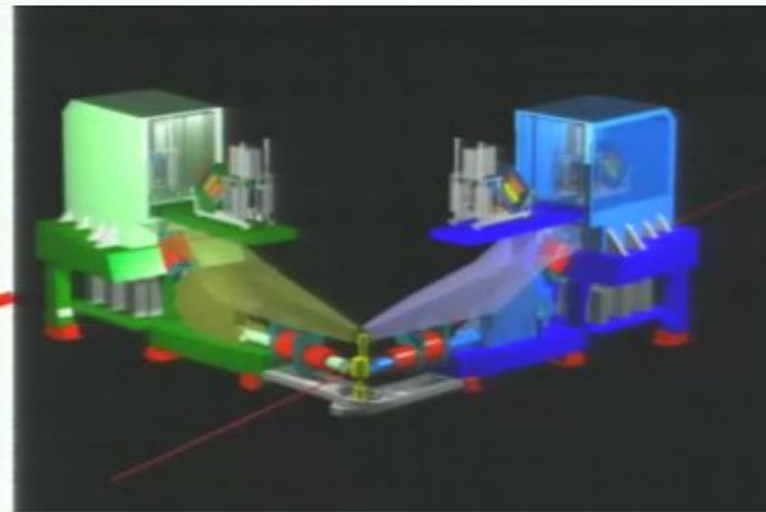
several real proposals developed since June 2009

A' EXperiment (APEX) @ JLab Hall A

Spokespeople: RE, P. Schuster, N. Toro, B. Wojtsekhowski

Collaboration of >100 people from ~30 institutions

mostly uses existing equipment -- cheap!



Two High Resolution Spectrometers

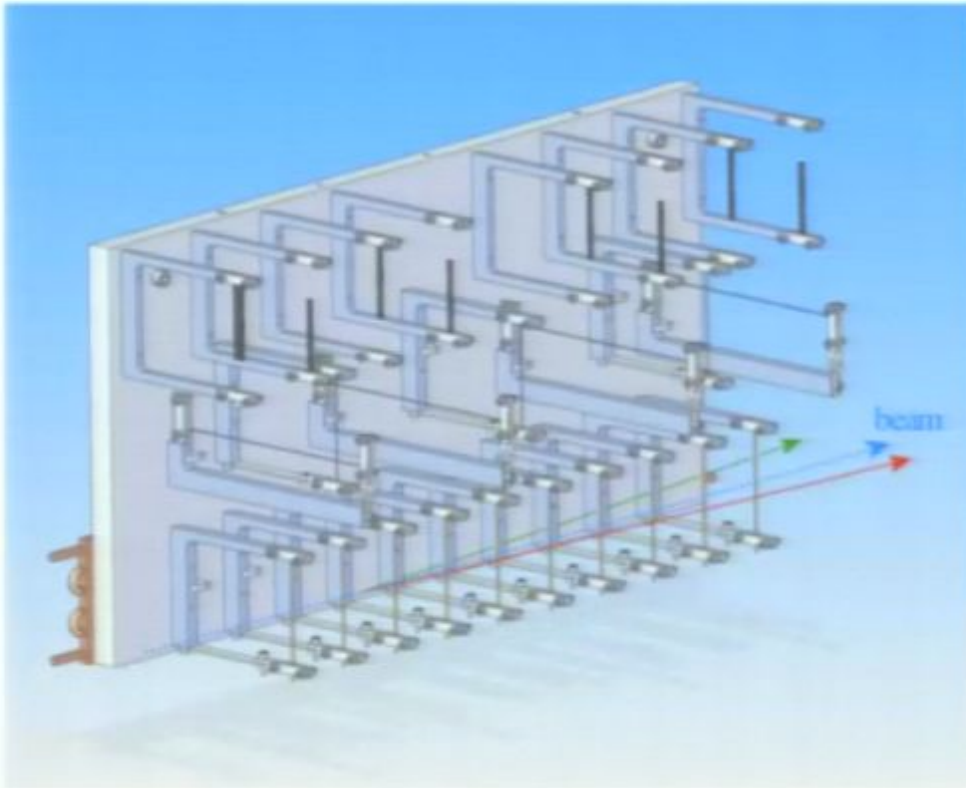
A' EXperiment (APEX) @ JLab Hall A

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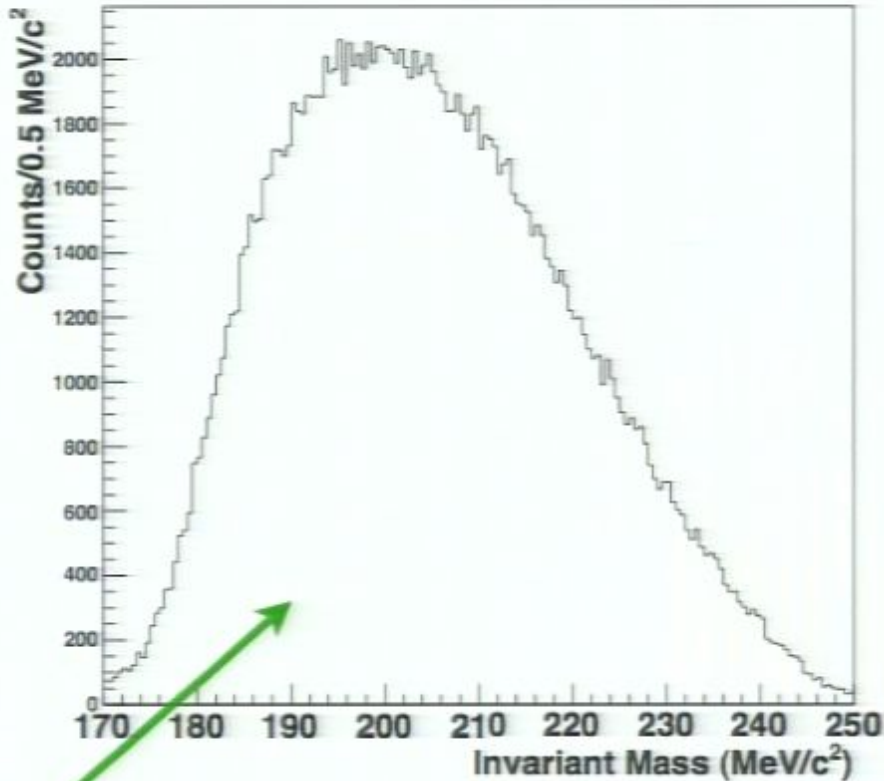
Collaboration of
mostly use



APEX's thin target system

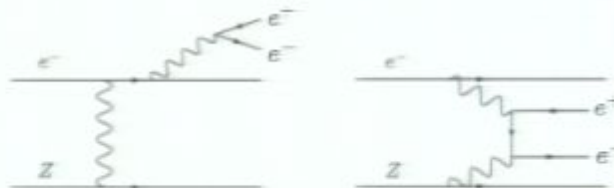


Data (10%) from our test run in June 2010

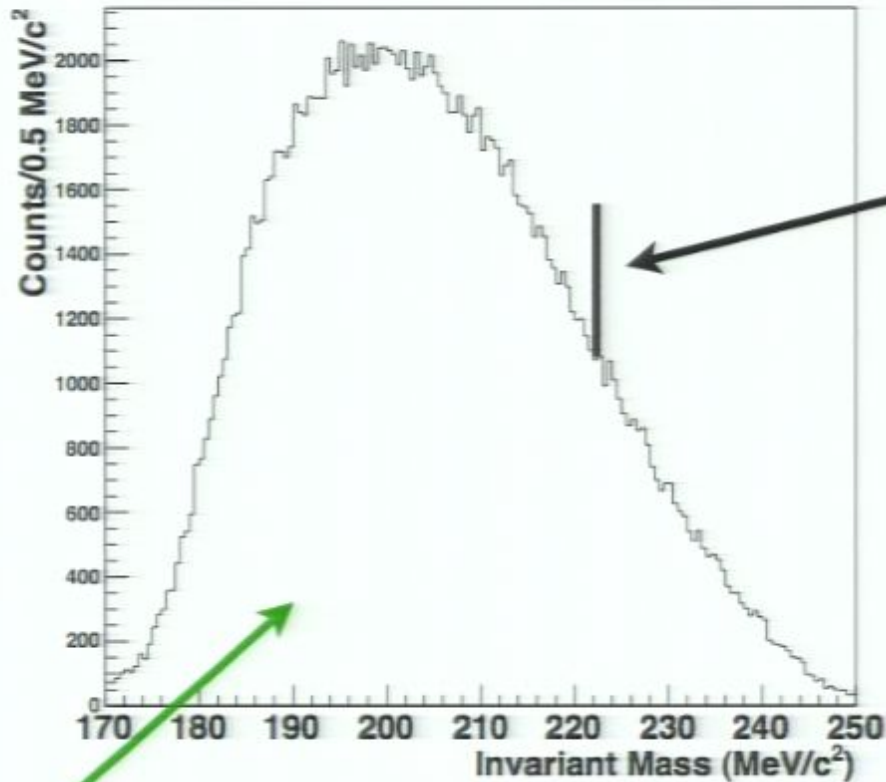


e^+e^- invariant mass spectrum

Large QED background



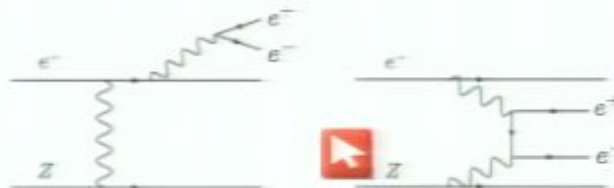
Data (10%) from our test run in June 2010



An A' would look like this
(APEX has excellent mass resolution)

e^+e^- invariant mass spectrum

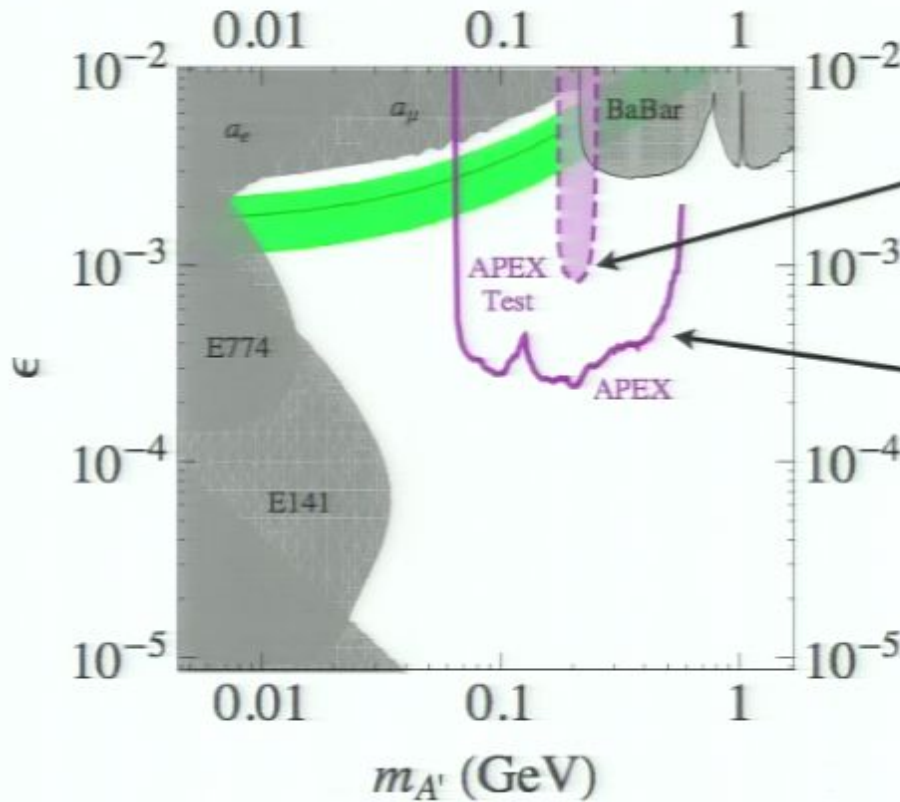
Large QED background



resonance search

Projected Reach

[RE, Schuster, Toro, Wojtsekhowski]



Projected test run
sensitivity
(June/July 2010)

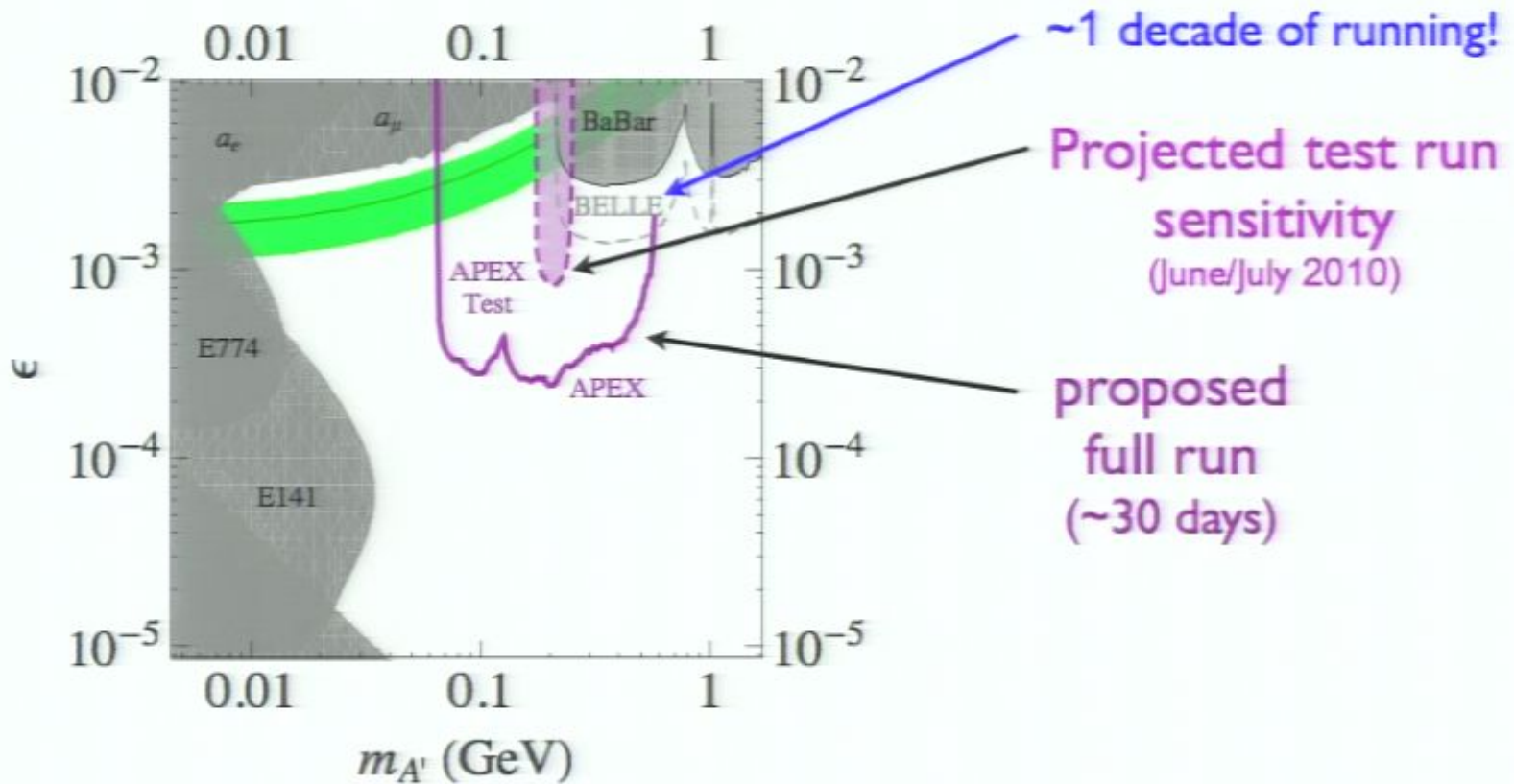
proposed
full run
(~30 days)

Experiment has been fully approved last month!

full data expected in 2-3 years?

Projected Reach

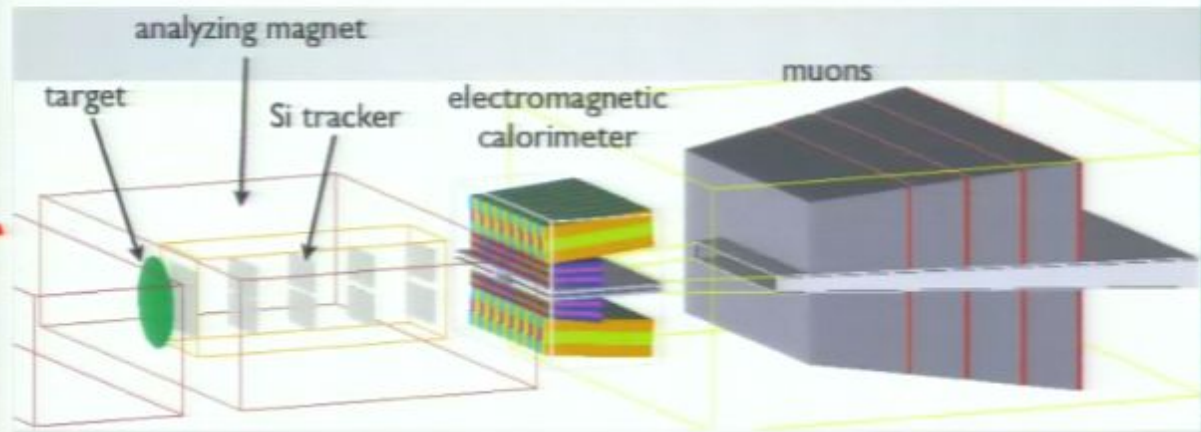
[RE, Schuster, Toro, Wojtsekhowski]



Experiment has been fully approved last month!

full data expected in 2-3 years?

Heavy Photon Search (HPS) @ JLab Hall B



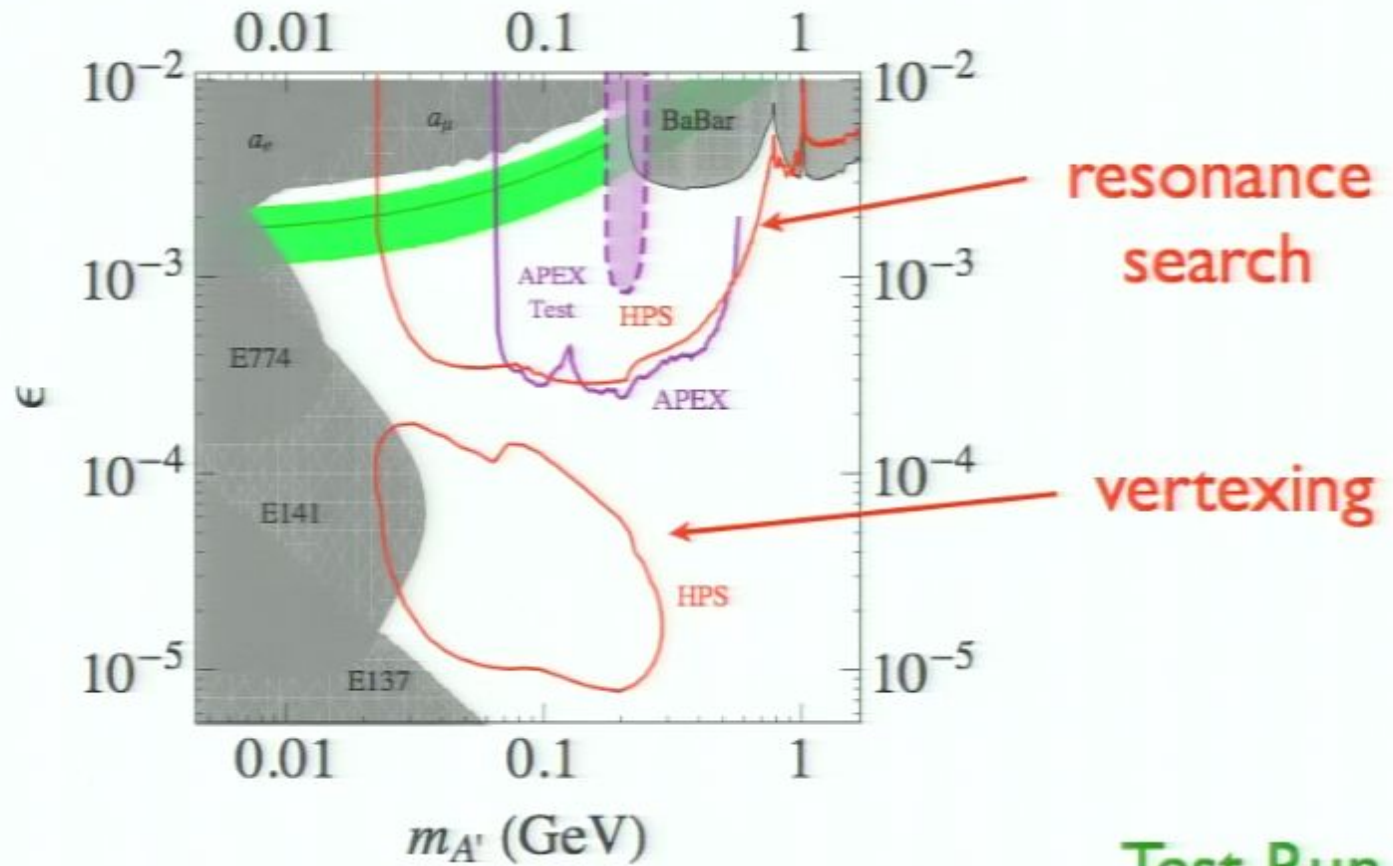
~60 collaborators

~16 institutions

a **vertexing** experiment

experiment costs only ~ \$3 million

Projected Reach

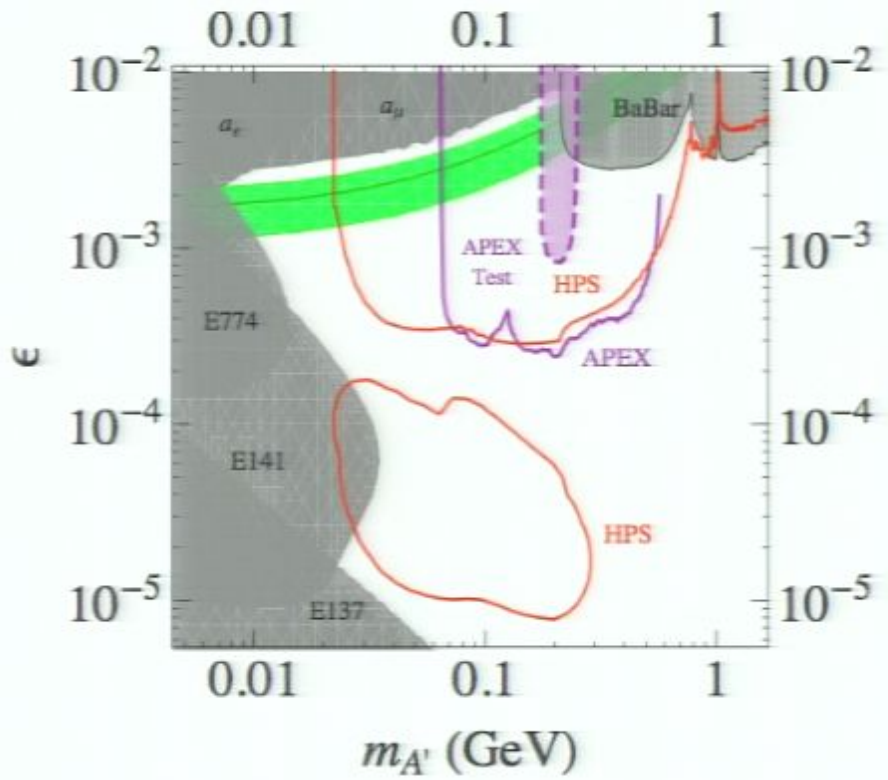


run time ~1 year

Test Run approved

will also discover true muonium, a $(\mu^+ \mu^-)$ bound state that decays like an A' !

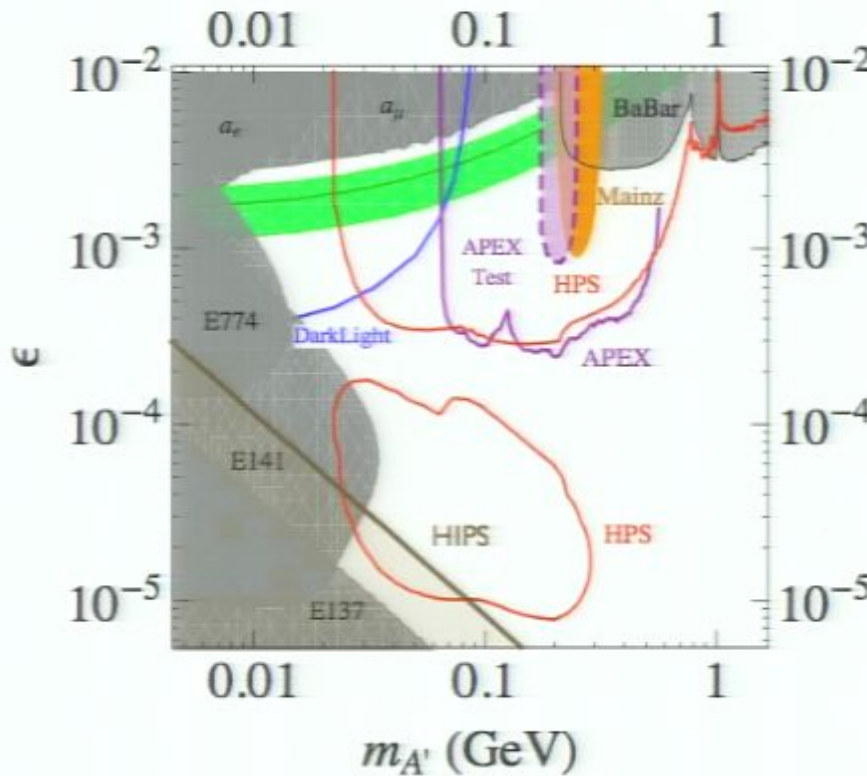
Summary



APEX

Heavy Photon Search

Summary



APEX

Heavy Photon Search

Other experiments, e.g.:

Mainz (test run shown)

DarkLight (MIT)

HIPS @ DESY

Experiments will initiate systematic exploration for weakly-coupled GeV-scale forces

Conclusions

- new GeV-scale forces: exciting and well-motivated
- indirectly probed with dwarf galaxies
- direct searches at:
 - e^+e^- colliders
 - new fixed target experiments
- searches also at Tevatron/LHC,

new experimental research program underway

Era of data: major fundamental discoveries possible
at the cosmic, intensity, and energy frontiers

Hint from muon's anomalous magnetic moment?

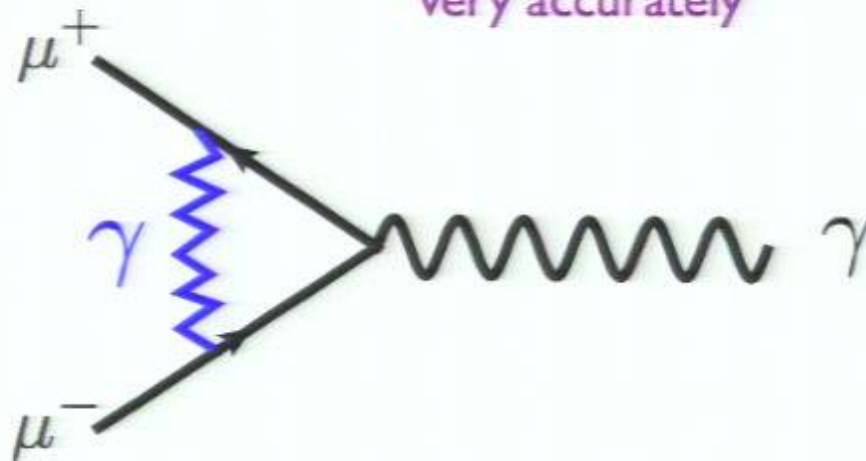
magnetic dipole moment

$$\vec{\mu} = g_s \left(\frac{q}{2m} \right) \vec{s}$$



spin

can be measured
very accurately



$$g_s \neq 2$$

(Standard Model)

Standard Model
($g_s - 2$) $_{\mu}$ versus Data $\sim 3.4 \sigma$ deviation