Exploring dark sectors with low-energy experiments

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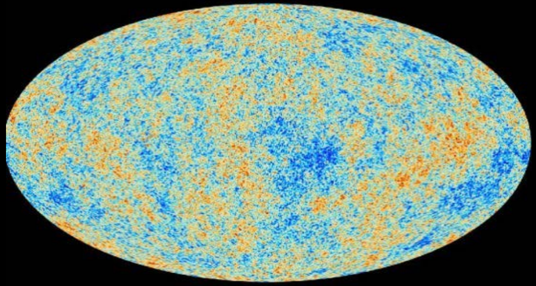
Caltech

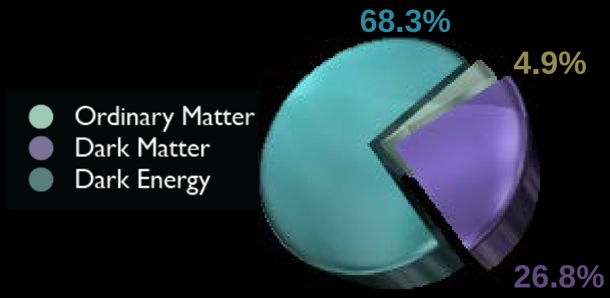
UCI Joint Particle Seminar
UCI – February 2015

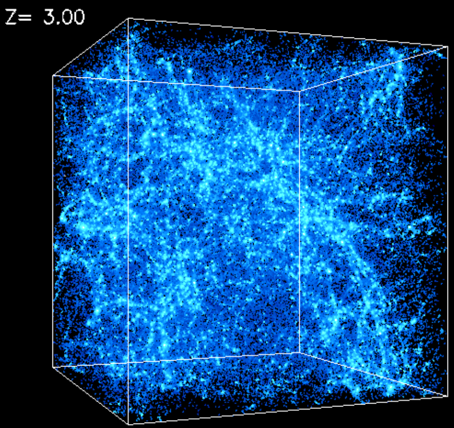
Dark matter

Gravitational lensing

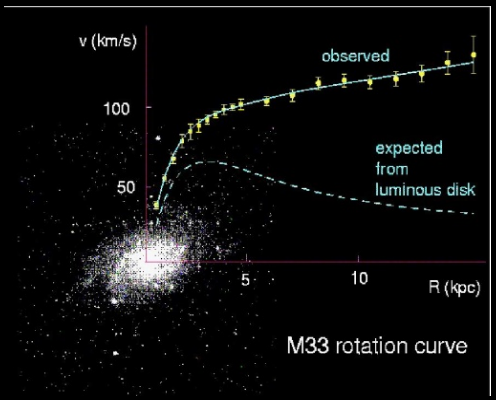
CMB



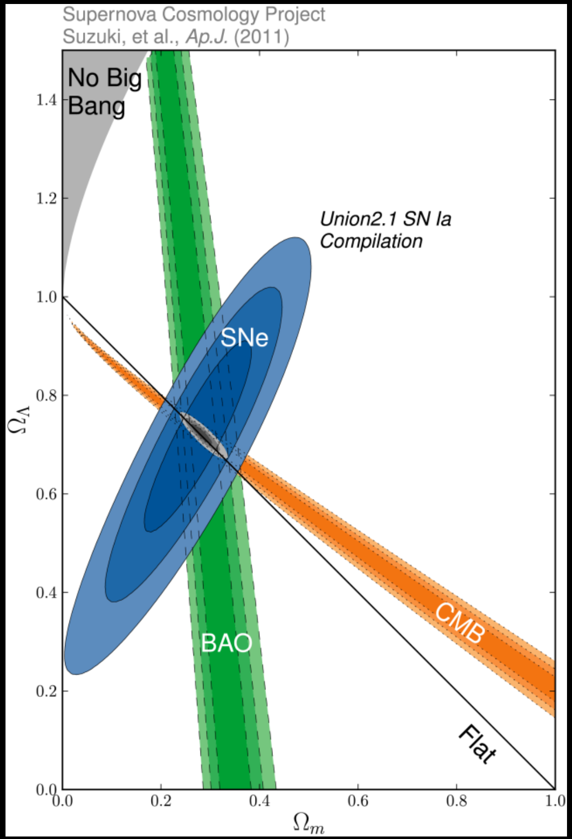




Structure

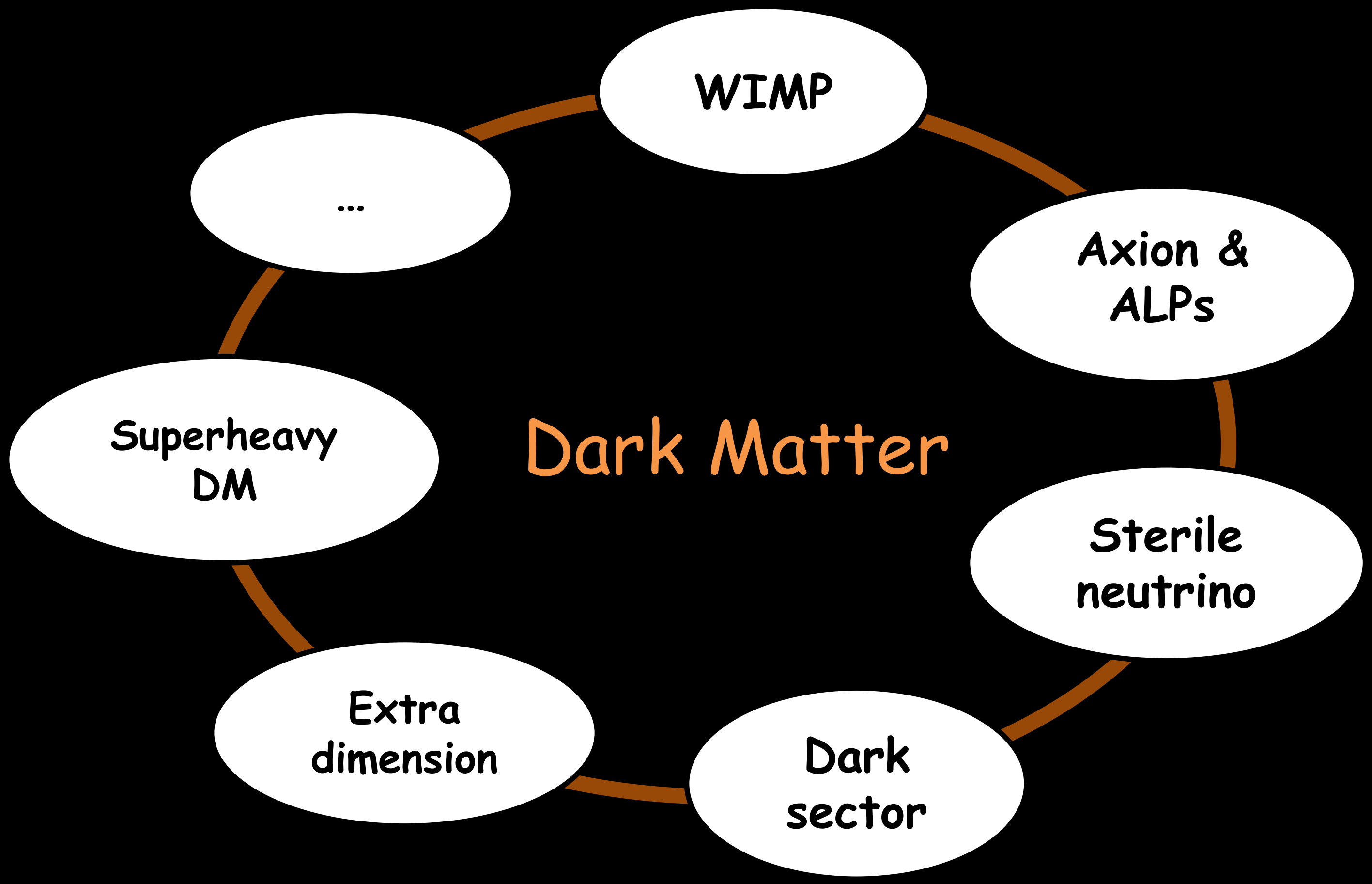


Rotation curve



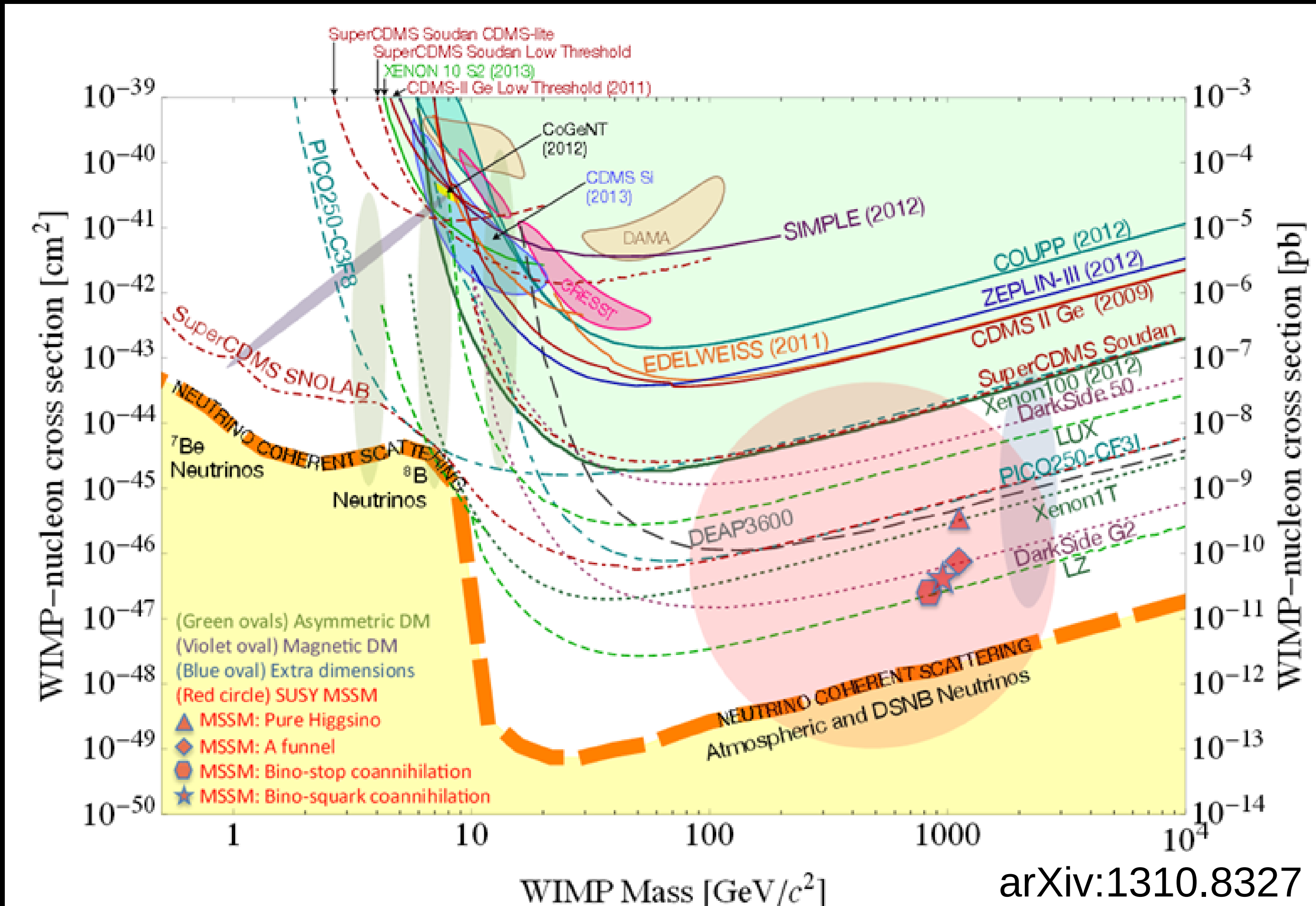
Strong evidence for dark matter

A dizzying list of candidates…

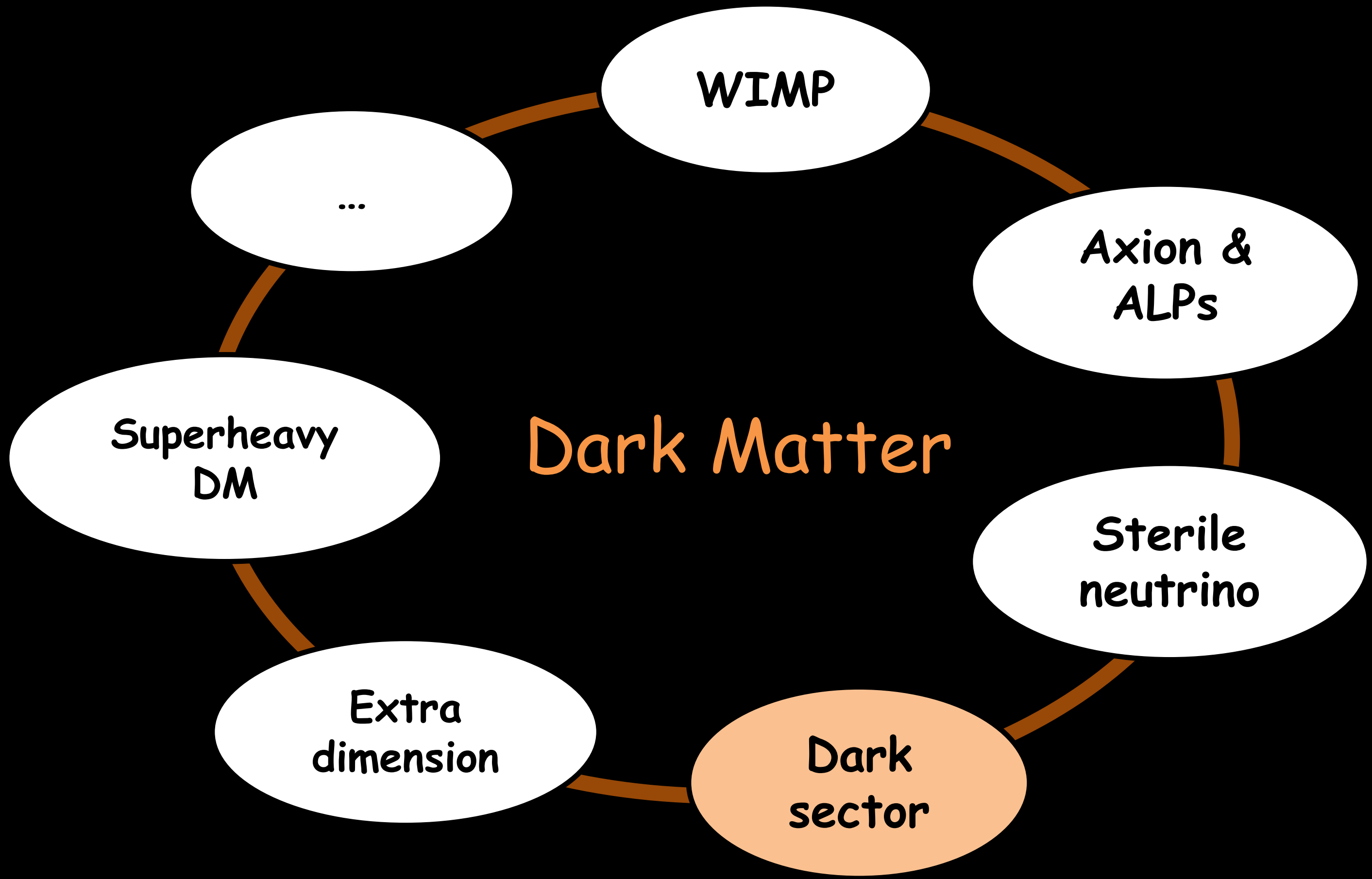


The WIMP (Weakly Interacting Massive Particle) paradigm is often considered as the most appealing scenario.

Direct dark matter detection program



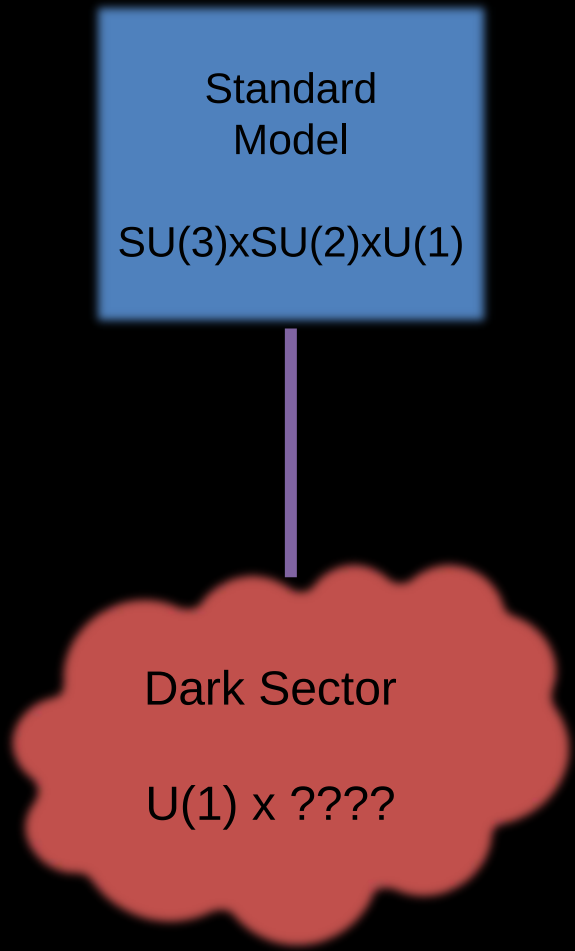
So far, no sign of WIMP and New Physics at the LHC!



Recent results from the LHC and direct detection experiments "challenge" the traditional WIMP paradigm and motivate the exploration of new ideas.

A new possibility – dark sectors

- Recent anomalies observed by satellite and terrestrial experiments have motivated dark matter models introducing a new sector with a 'dark' force.
- Dark sector = new particles that do not couple directly to the SM content, but…
- There are "portals" between the dark sector and the SM.
- Implications for astrophysics, cosmology and particle physics.
- In particular, low-energy colliders and fixed target experiments offer an ideal environment to probe these new ideas.



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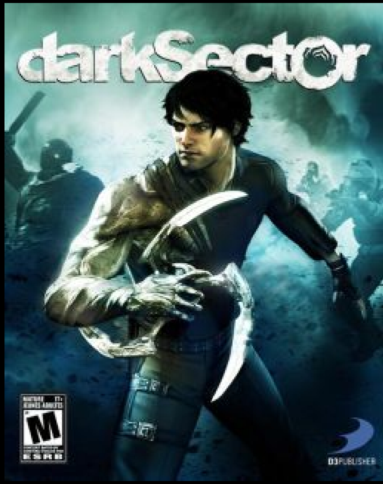
Notation confusion

dark sector
=
hidden sector
=
secluded sector

Tip:
Do not try to google "dark sector" anymore, use hidden sector instead!

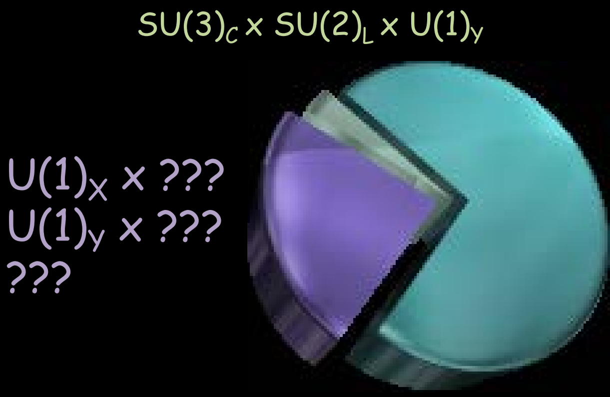


There might be dark sectors

- New sectors that don't couple directly to the Standard Model.
- Theoretically motivated: string theory and many BSM scenarios include dark sectors with extra U(1).
- Holdum's question ('86) : are there additional U(1)? (PLB 166 (1986) 196)
- Dark photons (A') are the corresponding U(1) gauge bosons, mediating this dark force.

Dark matter could be part of a dark sector

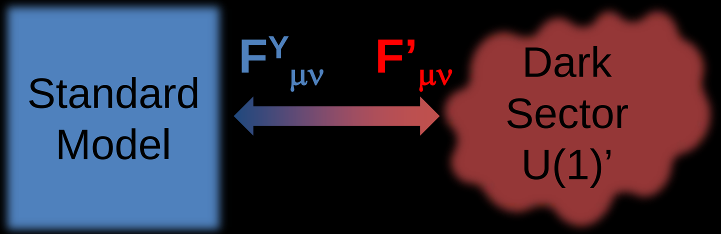
- Dark matter and other new particles may reside in dark sectors.
- Could have a very rich structure.



How could we detect them?

- Interaction between dark sector and SM occurs through high-dimension operator, referred to as "portals". At low-energy, the "vector portal" is dominant.

Dark sector and vector portal



- Dark sector with a new gauge group U(1)' (similar to QED)

- One can add an effective interaction of the following form to the SM

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

between the SM hypercharge and U(1)' fields, called kinetic mixing, with a mixing strength ε_Y

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

Dark sector and vector portal

- Dark sector with a new gauge group U(1)′ (similar to QED)

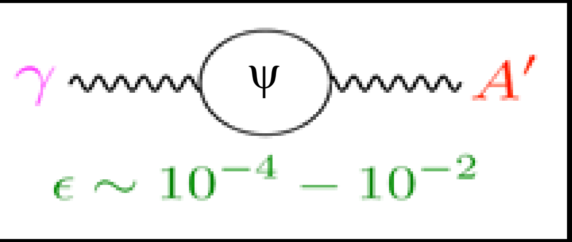
- One can add an effective interaction of the following form to the SM (kinetic mixing)

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

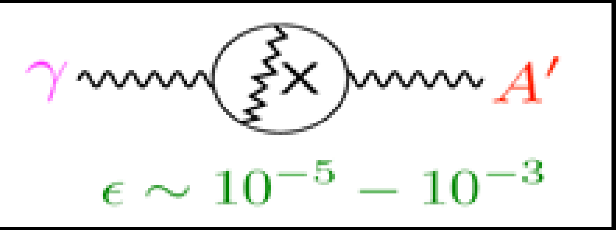
between the SM hypercharge and U(1)′ fields, called kinetic mixing, with a mixing strength ε_Y

- Could be realized by new heavy particles charged under both gauge groups.

heavy particle ψ with both dark and EM charges.



GUT (2 loops)



(→10^{-7} if both U(1)'s are in unified groups)

typically $\varepsilon_Y \sim 10^{-5} - 10^{-2}$

e.g. Arkani-Hamed & Weiner;
Cheung, Ruderman, Wang, Yavin;
Morrissey, Poland, Zurek;
Essig, Schuster, Toro;

Dark sector and vector portal

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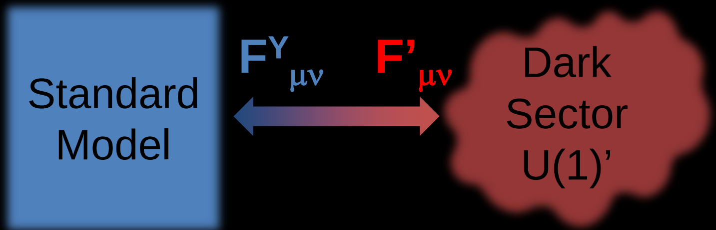
- After EWSB, there is a coupling between the dark photon and the photon (also the Z), i.e. a dark photon – SM fermion coupling.



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

↓ EWSB

$$\Delta\mathcal{L} = \frac{\varepsilon}{2} F^{EM,\mu\nu} F'_{\mu\nu} \; (+Z)$$

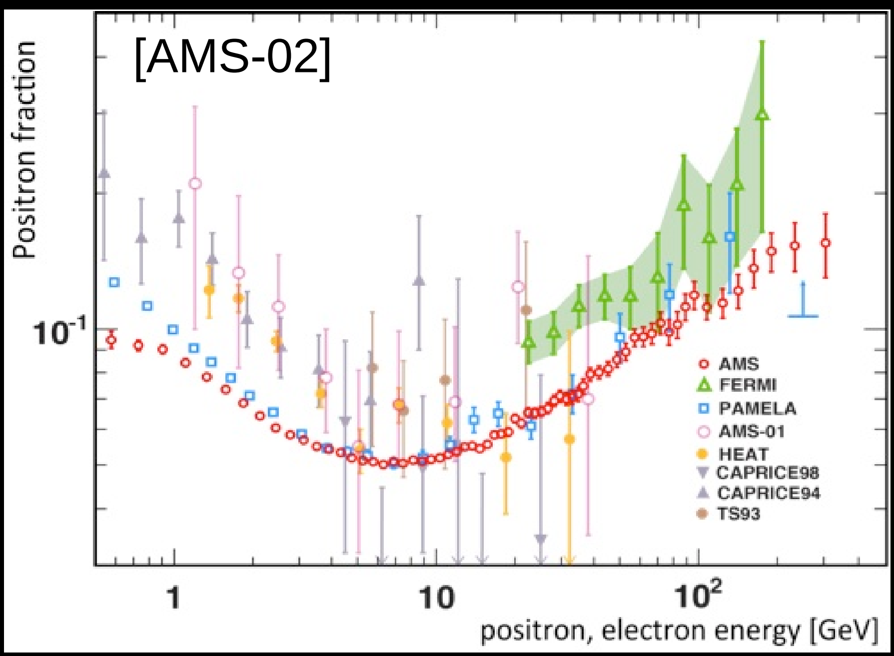
$$\varepsilon = \varepsilon_Y \cos\theta_W$$

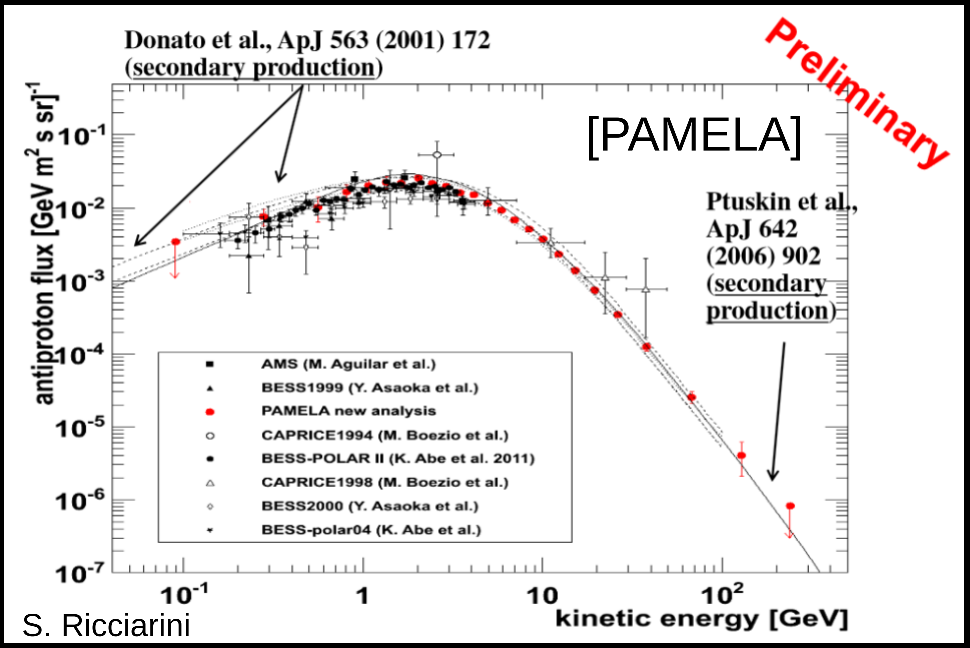
dark photon – SM fermion coupling with strength $\alpha' = \varepsilon^2\alpha$

Connection to dark matter?

Excess of electrons/positrons in the cosmic rays, first seen by Pamela, confirmed by Fermi & AMS-02.

No comparable enhancement of antiprotons!

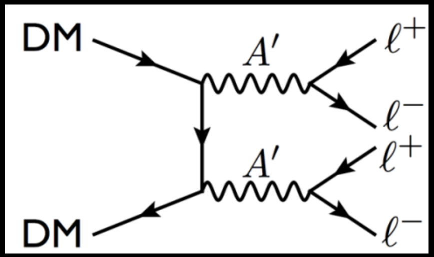




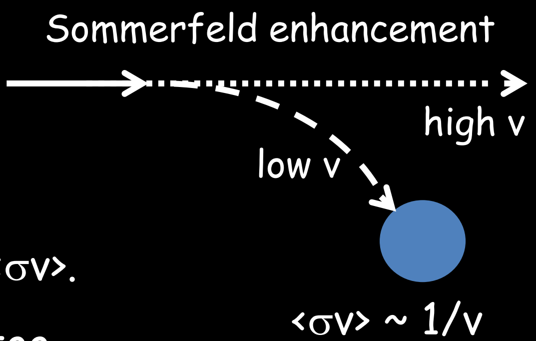
Could be explained by a simple dark sector model

The original idea: a light dark sector model

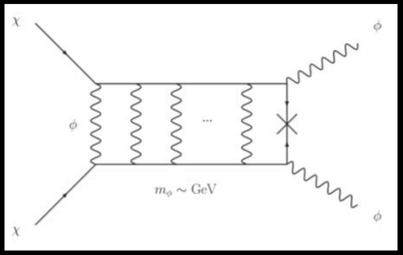
Wimp-like TeV-scale dark matter particles annihilate into light dark photons (10 MeV – few GeV range), which subsequently decay to electrons/positrons (Arkani-Hamed et al., Pospelov & Ritz):



- Large branching fraction to leptons
- Protons kinematically suppressed
- Hard energy spectrum
- Correct relic abundance with Sommerfeld enhancement



  - Relic abundance depends on annihilation rate $\Omega_{DM} \sim 1/\langle\sigma v\rangle$.
  - Annihilation rate derived from cosmic flux gives Ω_{DM} too low by a factor 100-1000 (“boost” factors invoked to solve this problem for many models).
  - Cross-section is enhanced at low velocities for light A′, boosting Ω_{DM} to observed values.

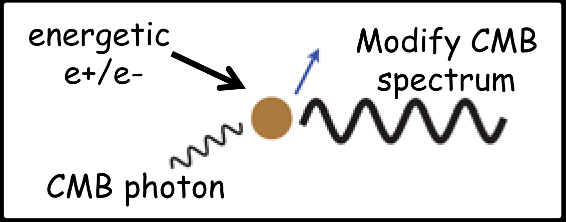


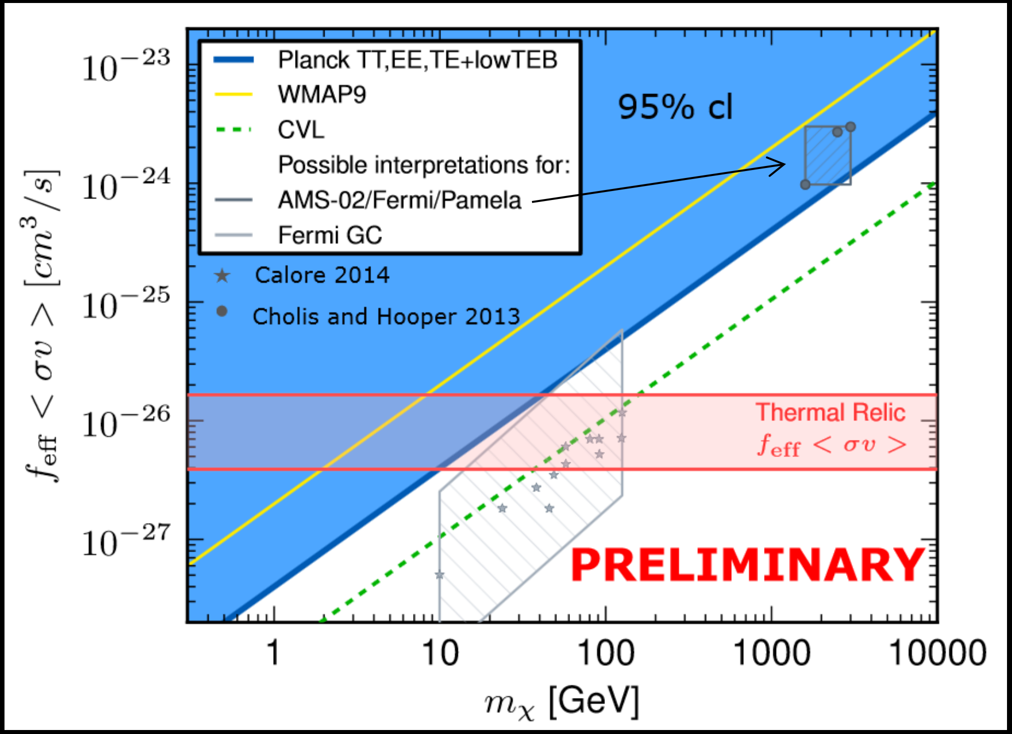
Sparked a wide interest in this class of models, there is just a tiny issue….

Cosmological constraints

If DM annihilation into light dark photons is the source of e-/e+ excess, other astrophysical phenomena should be observable (e.g. diffuse gamma ray emission, CMB).

In particular, primordial DM annihilation injects energy in the CMB → distorts spectrum





Planck collaboration

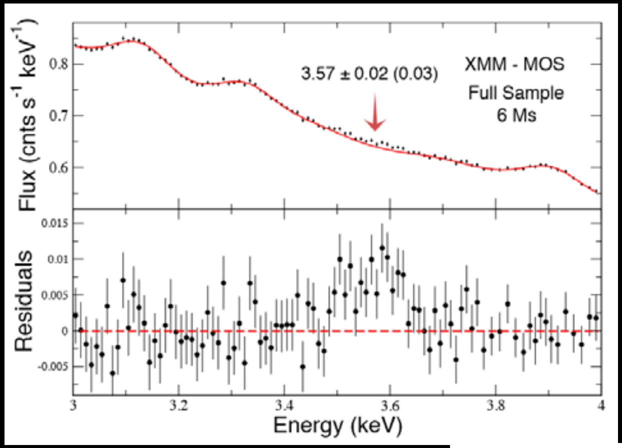
Severe constraints from recent Planck measurement

There are still a few uncertainties, but plausible dark matter models of the Pamela excess that could explain all the current constraints are a very specific subset

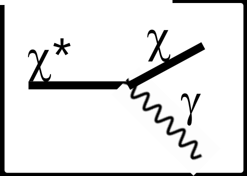
Any other anomalies?

Other anomalies

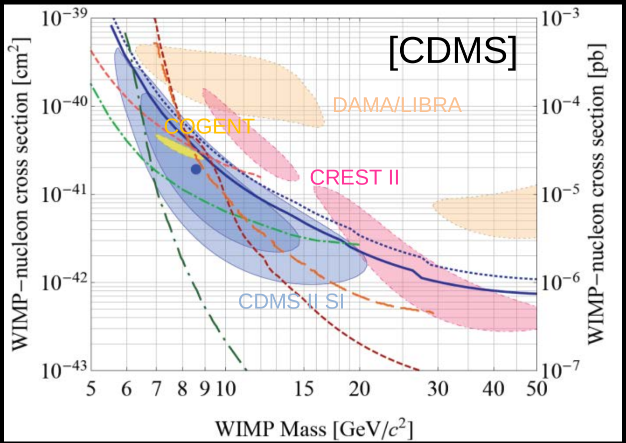
Line at 3.55 keV



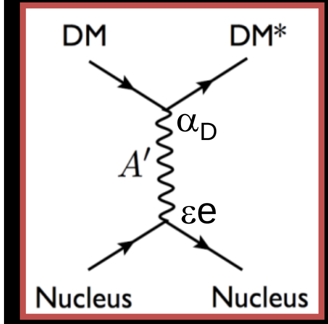
[Bulbul *et al*],
[Boyarsky *et al*]



Direct detection anomalies

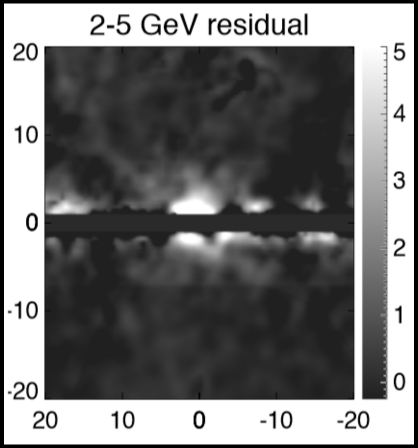


CDMS, arXiv:1304.4279



[Slatyer, Schuster&Toro,…]

Galactic center



[Daylan *et al*],

And many others….

Could have other explanation: pulsars, instrumental effects, other new particles,…

When you have a dark hammer, you tend to see everything as a dark nail!

At this point…

New theory of dark matter based on dark sector(s)

- Light new mediator (dark photon A') with a MeV – GeV mass
- Mixing between dark sector – SM with $\varepsilon \sim 10^{-5} - 10^{-2}$ (could be smaller)
- Could have a rich structure

Anomalies from astrophysical data, direct detection and precision measurements

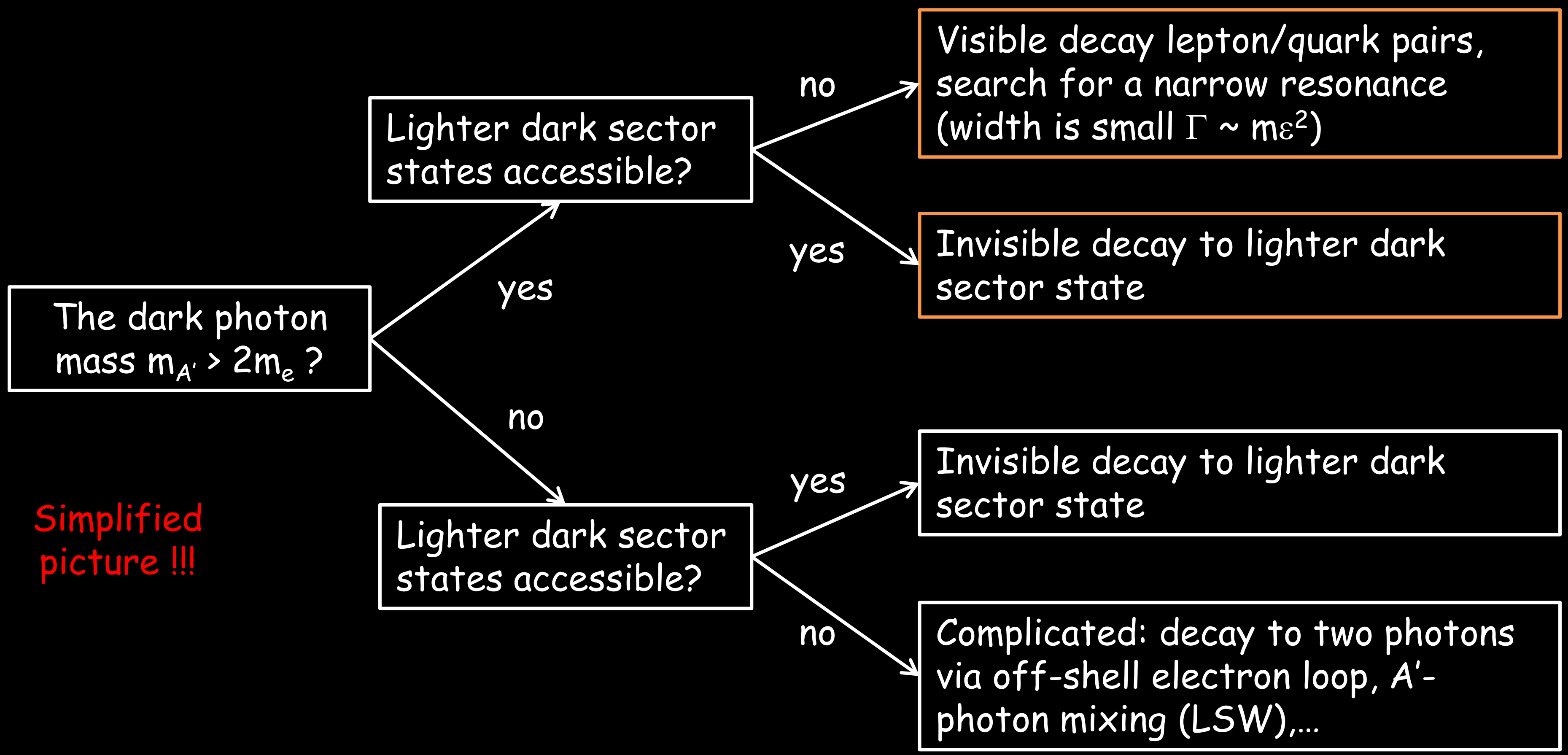
- Could be explained by dark sector
- Could have another origin, be statistical fluctuations or instrumental effects
- Dark matter could be composite with a dark sector sub-component
- …

But it made us realize the amazing possibilities at the GeV-scale in a more general context, and the possibilities to probe them in laboratory at low energies !

Probing dark sectors

at low-energy (and high-energy) colliders

Particle physics experiments can produce dark photons. In fact, photons in any process can be replaced by dark photons (with an extra factor of ε^2).

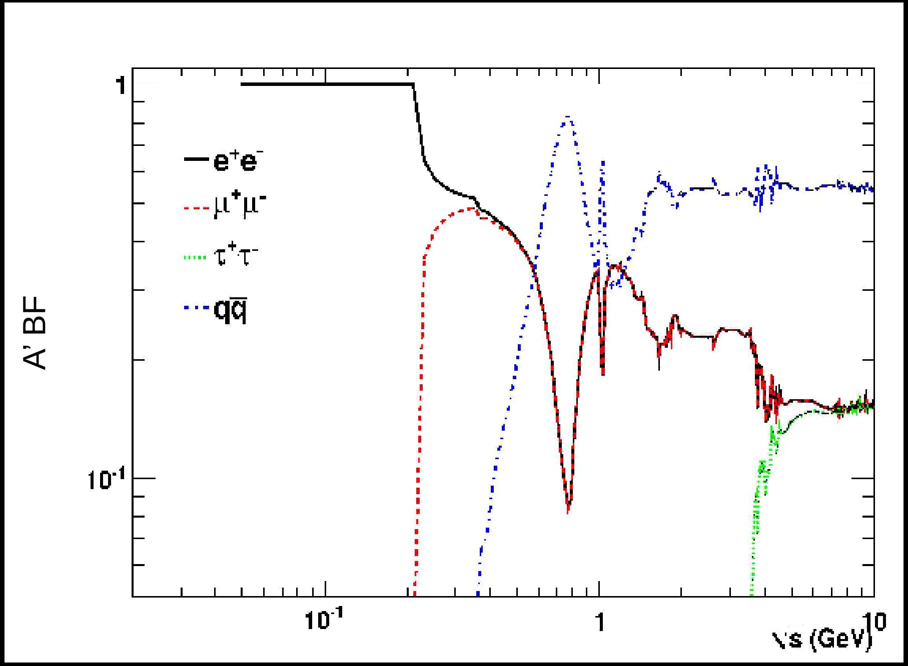


Search strategies depends on the mass hierarchy.

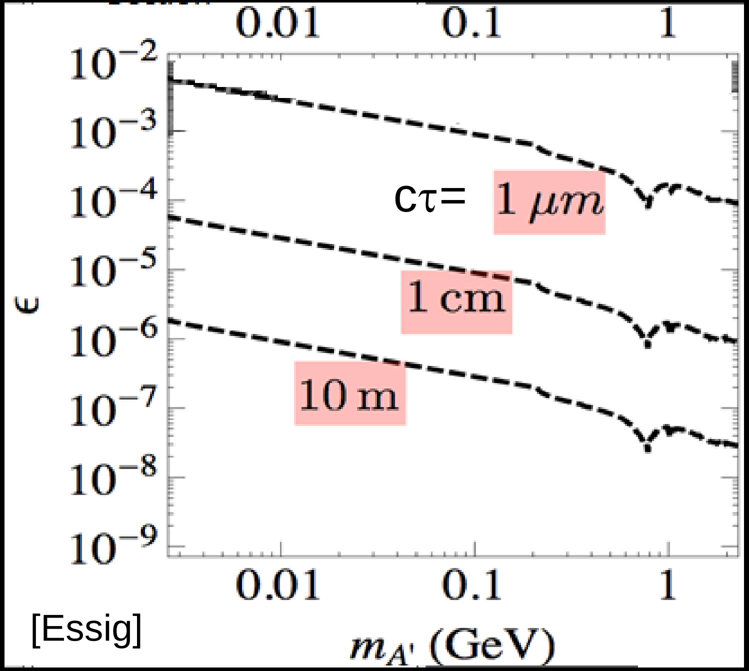
Particle physics implications

Dark photon branching fraction into leptons depends only on the fermion electric charge.

Dark photon is small (~mε^2) and could be short or long-lived, depending on the parameters of the theory. Dark photon decays can either be prompt or displaced (visible case)



Lepton contribution dominates at low masses, still ~30% at high masses!

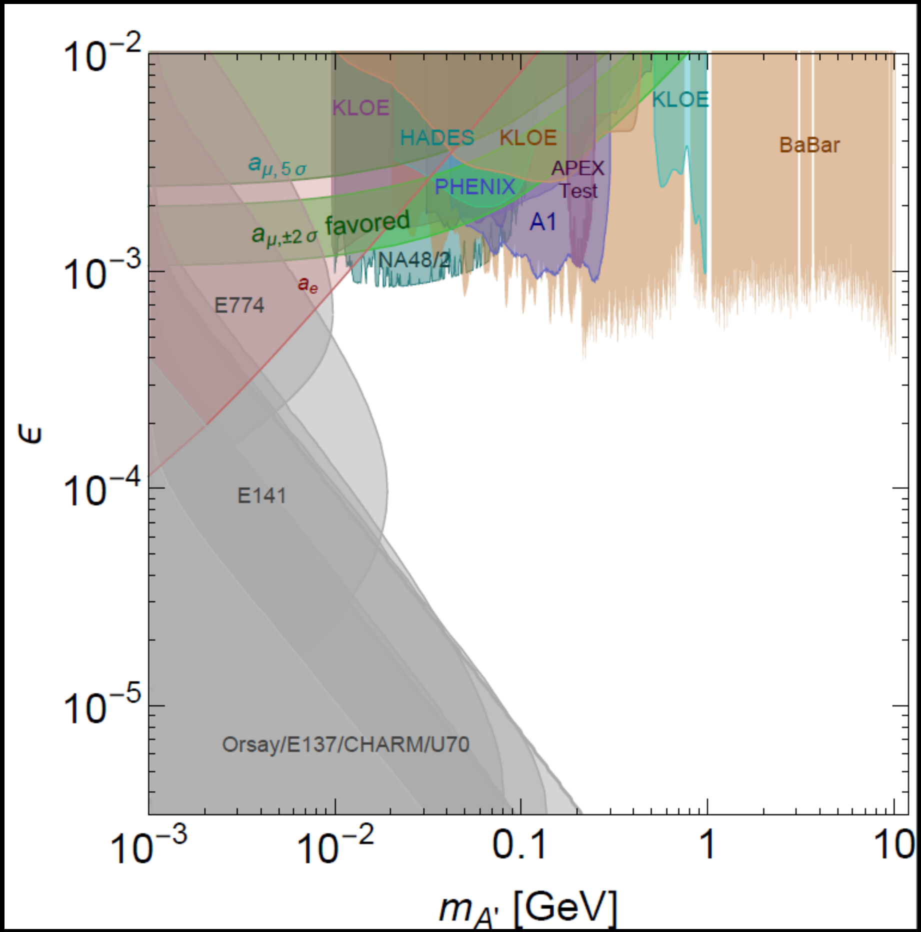


Particle physics implications

Current constraints on the mixing parameter ε *vs.* the dark photon mass $m_{A'}$ for visible A' decays

- electron/muon g-2,
- beam dump experiments
- fixed target experiments
- neutral meson decays
- e^+e^- colliders

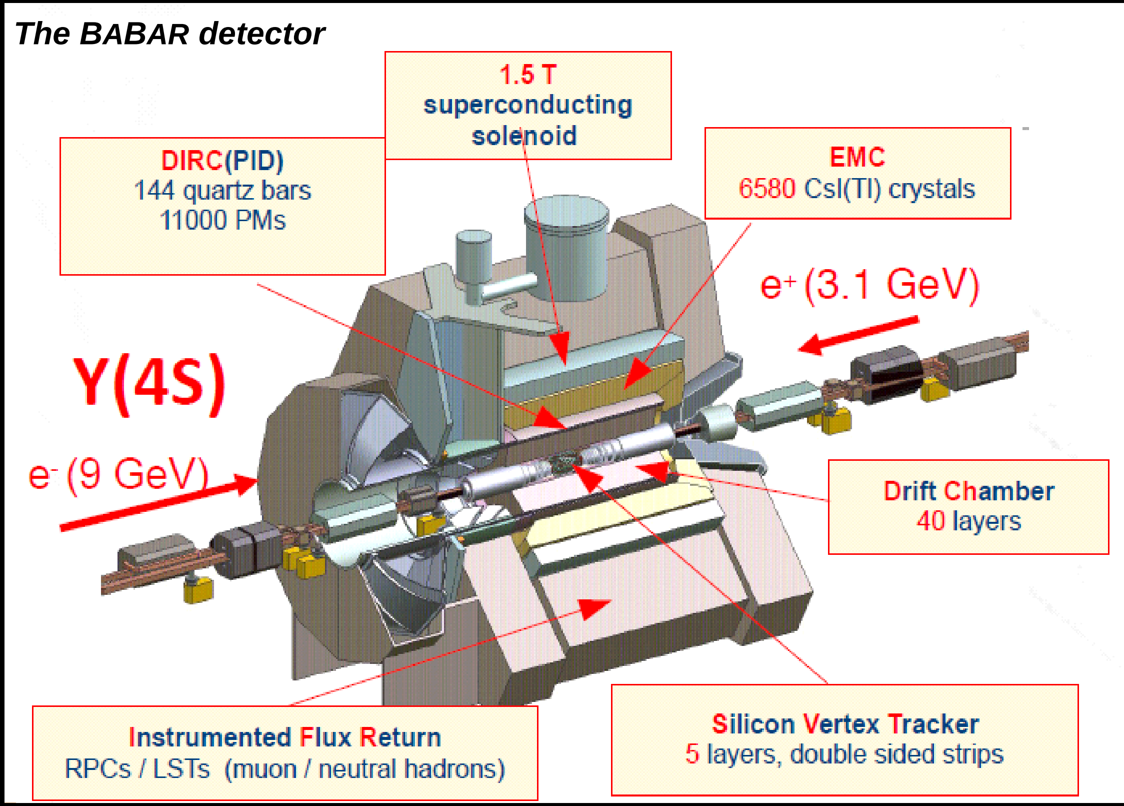
Constraints from many type of experiments probing different regions of parameter space.

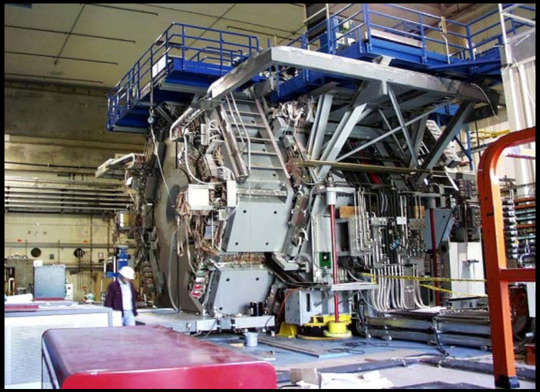


See arXiv:1311.0029

Low-energy high-luminosity e^+e^- colliders offer a low-background environment to search for MeV/GeV-scale dark sector (in particular high masses) and probe their structure

BABAR collected around 500 fb^{-1} of data around the Υ(4S) resonance





B-factories offer an ideal environment to search for dark sector particles

Possible dark sector searches at e^+e^- colliders

Search for dark photon

$e^+e^- \to \gamma A'$, $A' \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-$
$e^+e^- \to \gamma A'$, $A' \to$ invisible
$\pi^0 \to \gamma l^+l^-$, $\eta \to \gamma l^+l^-$, $\phi \to \eta l^+l^-$,...

Search for dark Higgs boson

$e^+e^- \to h' A'$, $h' \to A' A'$
$e^+e^- \to h' A'$, $h' \to$ invisible

Search for dark boson(s)

$e^+e^- \to \gamma A' \to W' W''$

Search for dark hadrons

$e^+e^- \to \pi_D + X$, $\pi_D \to e^+e^-, \mu^+\mu^-$

Search for dark scalar (s) and dark pseudoscalar (a)

$B \to K^{(*)}s \to K^{(*)} l^+l^-$
$B \to K^{(*)}a \to K^{(*)} l^+l^-$
$B \to ss \to 2(l^+l^-)$
$B \to K\, 2(l^+l^-)$
$B \to 4(l^+l^-)$

Search for "muonic/tauonic dark force"

$e^+e^- \to \mu^+\mu^- Z'$, $Z' \to \mu^+\mu^-, \tau^+\tau^-$, inv.
$e^+e^- \to \tau^+\tau^- Z'$, $Z' \to \mu^+\mu^-, \tau^+\tau^-$, inv.

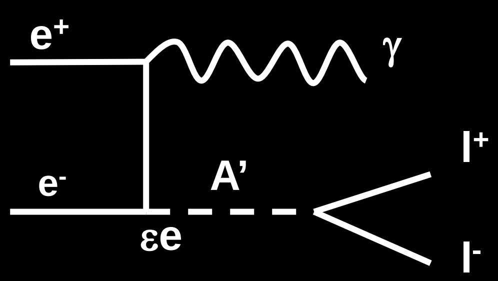
Search for leptophilic dark scalar

$e^+e^- \to \tau^+\tau^- h'$, $h' \to \mu^+\mu^-$ (4 leptons + MET)

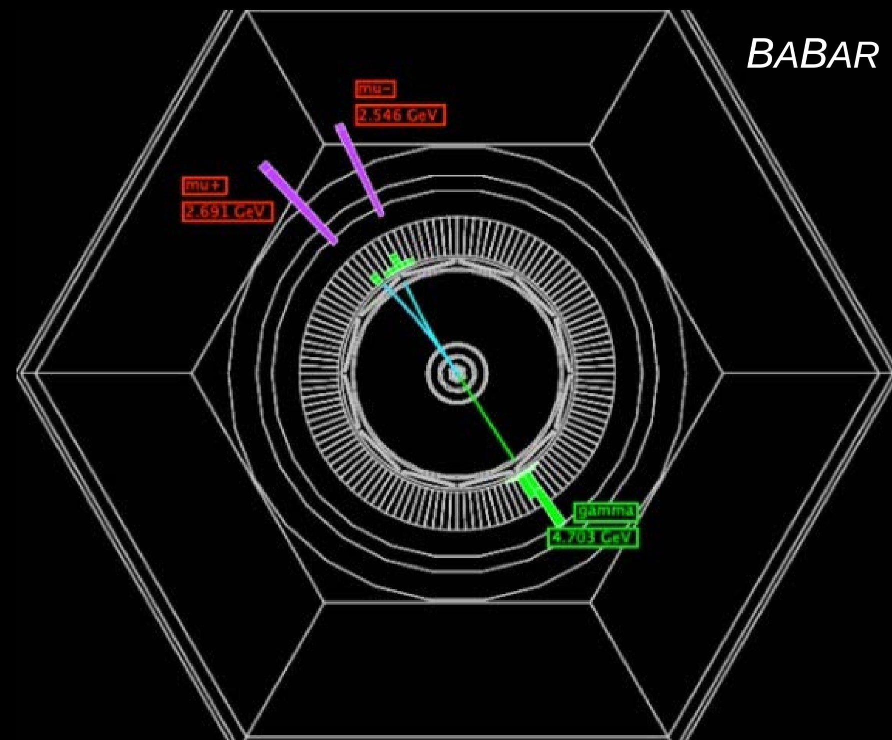
Large set of channels (few experiments can explore all these at once), can study the properties of a dark sector in detail

A dark photon can be produced in

$e^+e^- \to \gamma A', A' \to e^+e^-, \mu^+\mu^-$



Typical event



Tracks
Photon
Signal in muon/hadron detector

Event selection

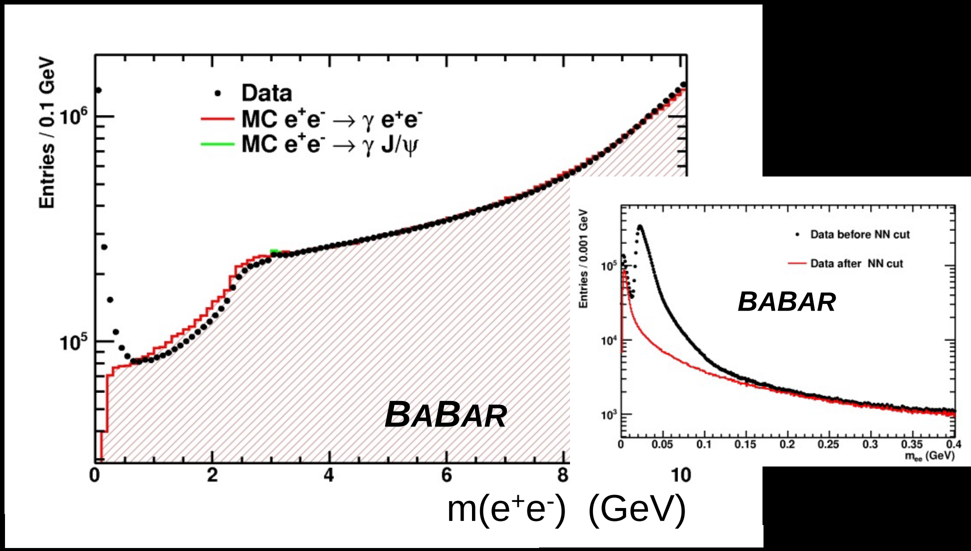
- 2 tracks + 1 photon
- Constrained fit to the beam energy and beam spot
- Particle identification (e/mu)
- Kinematic cuts to improve purity
- Quality cuts on tracks and photons

Direct dark photon production

PRL 113 (2014) 201801

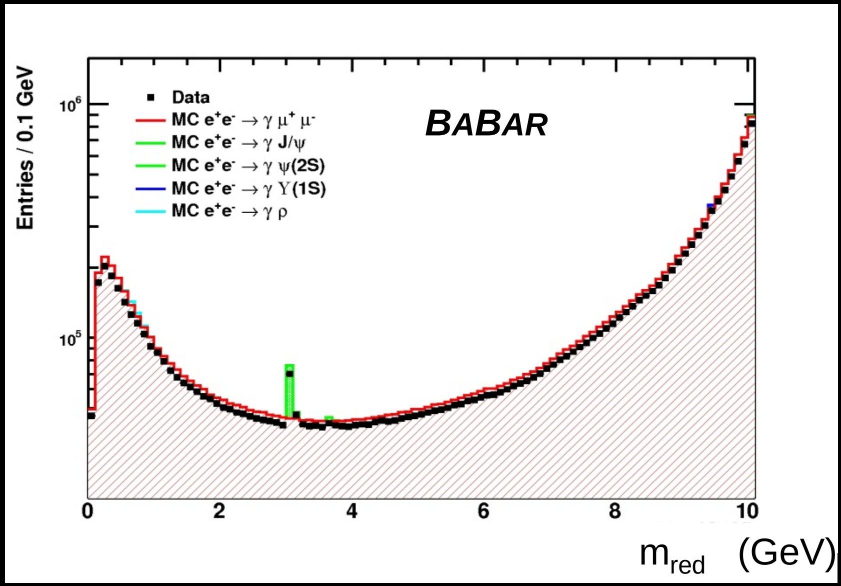
Di-electron mass spectrum

- Globally well reproduced by BHWIDE above 1 GeV, cut-off in the MC (co-linear tracks) affects low mass region. Madgraph reproduces well the low mass region.
- Background from photon conversions suppressed by neural network



Di-muon mass spectrum

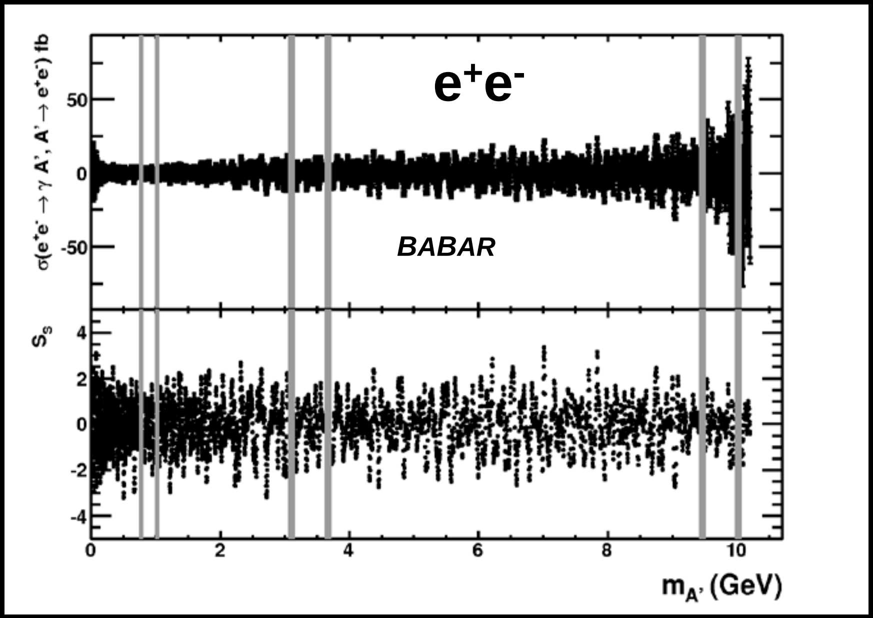
- Plot the reduced mass (smoother near threshold): $m_{red} = (m_{\mu\mu}^2 - 4\, m_\mu^2)^{1/2}$
- Globally well reproduced by KK2F, correct for differences in efficiencies

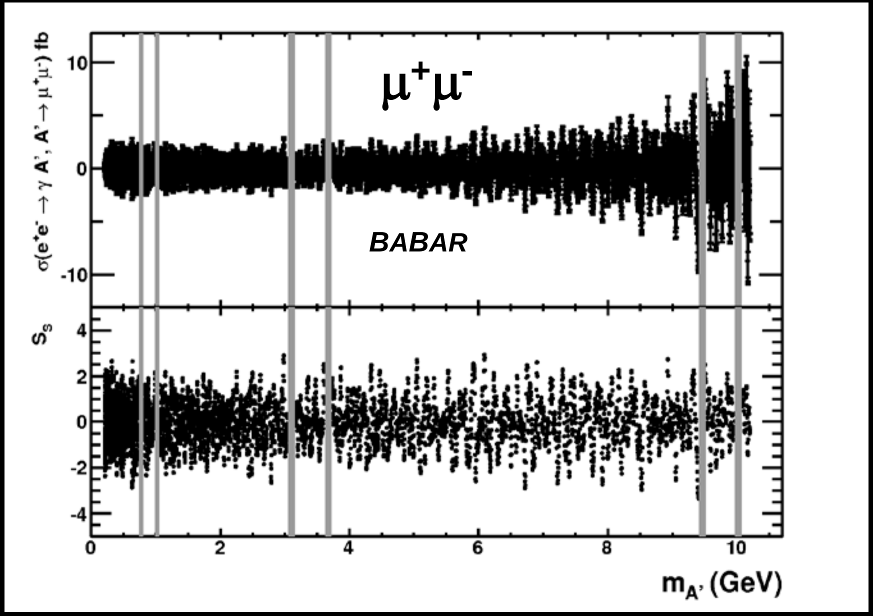


Good data-MC agreement at the J/ψ, $\Psi(2S)$, $\Upsilon(1S)$ resonances

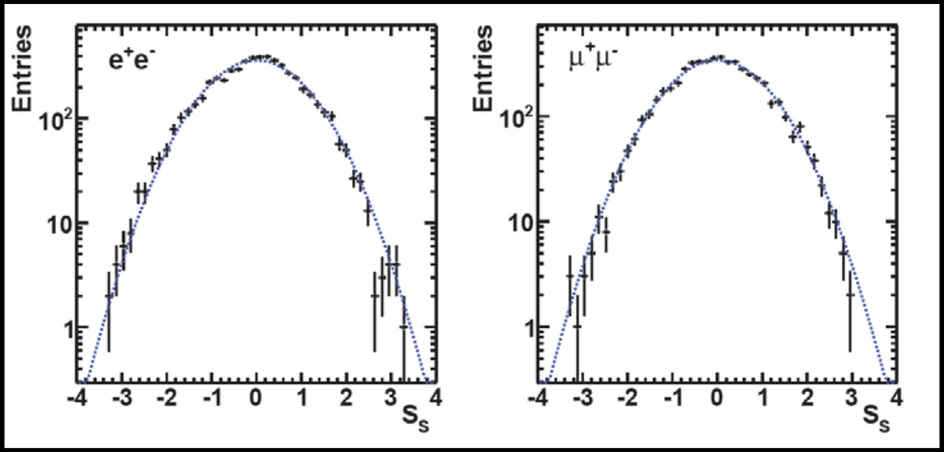
Results – cross sections

PRL 113 (2014) 201801





Distribution of statistical significances



Largest significances:

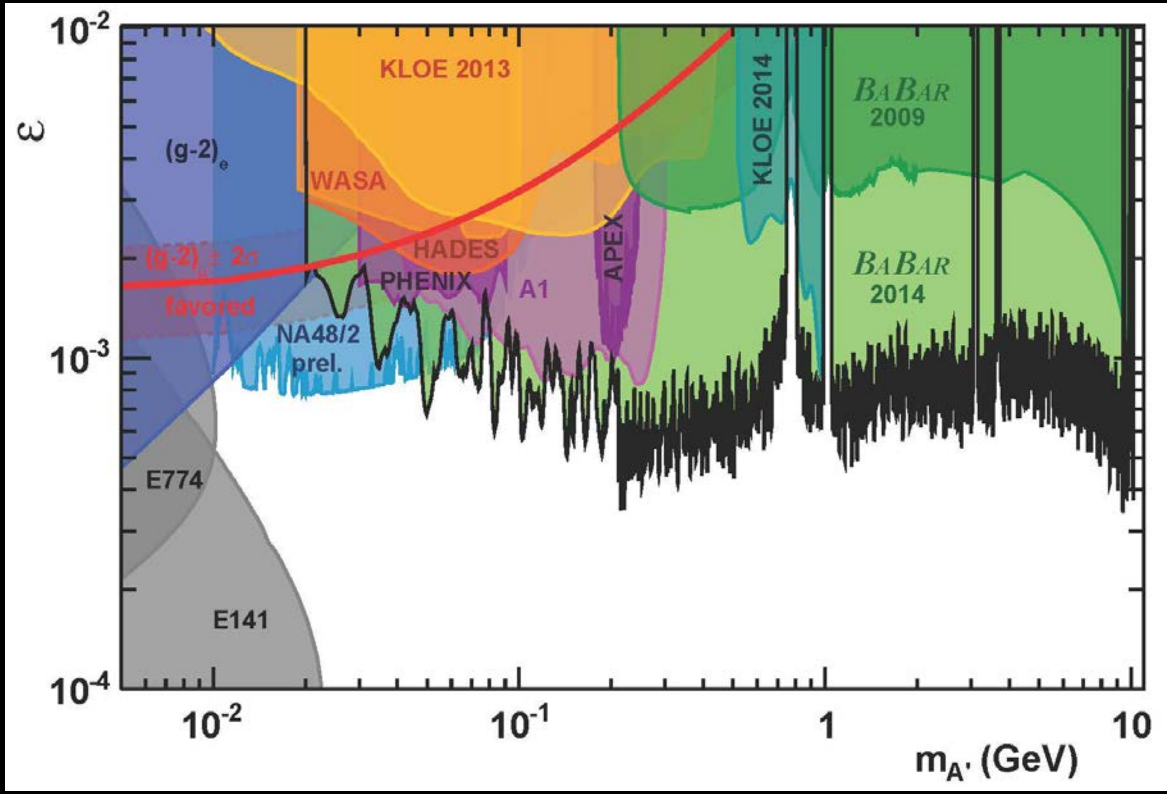
- 3.4σ for electrons @ 7.02 GeV
  $\rightarrow 0.6\sigma$ with trial factors
- 2.9σ for muons @ 6.09 GeV
  $\rightarrow 0.1\sigma$ with trial factors

Consistent with null hypothesis

Results – dark sector mixing

PRL 113 (2014) 201801

- Low mass has from large backgrounds and sub-optimal trigger efficiency, but still competitive
- The $e^+e^- \rightarrow \gamma A', A' \rightarrow \pi^+\pi^-$ final state can further probe the region near the ρ meson, currently difficult to access by other experiments.



Together with PHENIX and NA48/2, the full "g-2 band" is excluded for purely visible decays

There is still plenty of interesting parameter space to explore!

arxiv:0808.0017

Invisible dark sector

- Several scenarios where dark photons decay to invisible final states, e.g lighter dark sector particles (sub-GeV),...

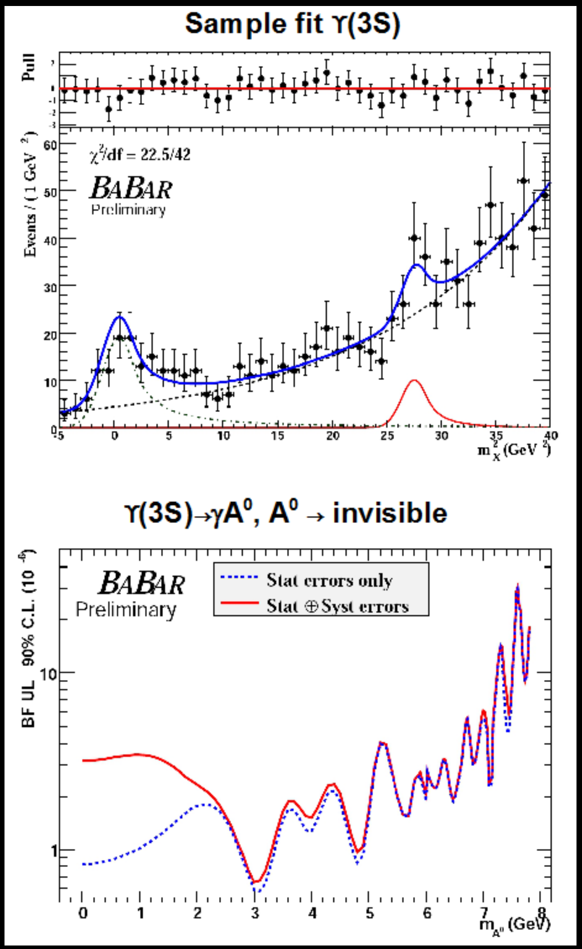
- At e^+e^- colliders, we can search for

$$e^+e^- \rightarrow \gamma A' \;,\;\; A' \rightarrow \text{invisible}$$

by tagging the recoil photon in "single photon" events.

- Currently only a measurement of
$\Upsilon(2S,3S) \rightarrow \gamma A^0,\; A^0 \rightarrow$ invisible
at *BABAR* with A^0 a light CP-odd Higgs

$\Upsilon(3S) \rightarrow \gamma A^0$, $A^0 \rightarrow$ invisible,
new analysis in progress + extension to A'



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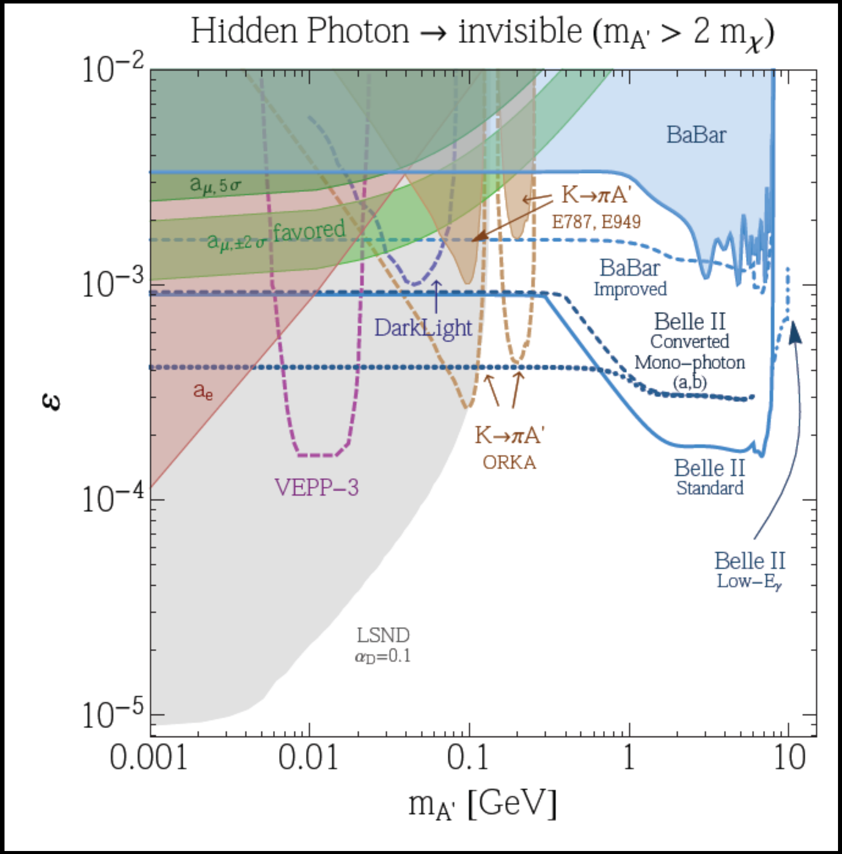
  at *BABAR* with A^0 a light CP-odd Higgs

- Analysis extended to full dataset and the dark photon case, expect limits on ε at the level of 10^{-3}.

- Constraints from many other experiments!

Essig *et al.*, arXiv:1309.5084



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by tagging the recoil photon in "single photon" events.

- Currently only a measurement of

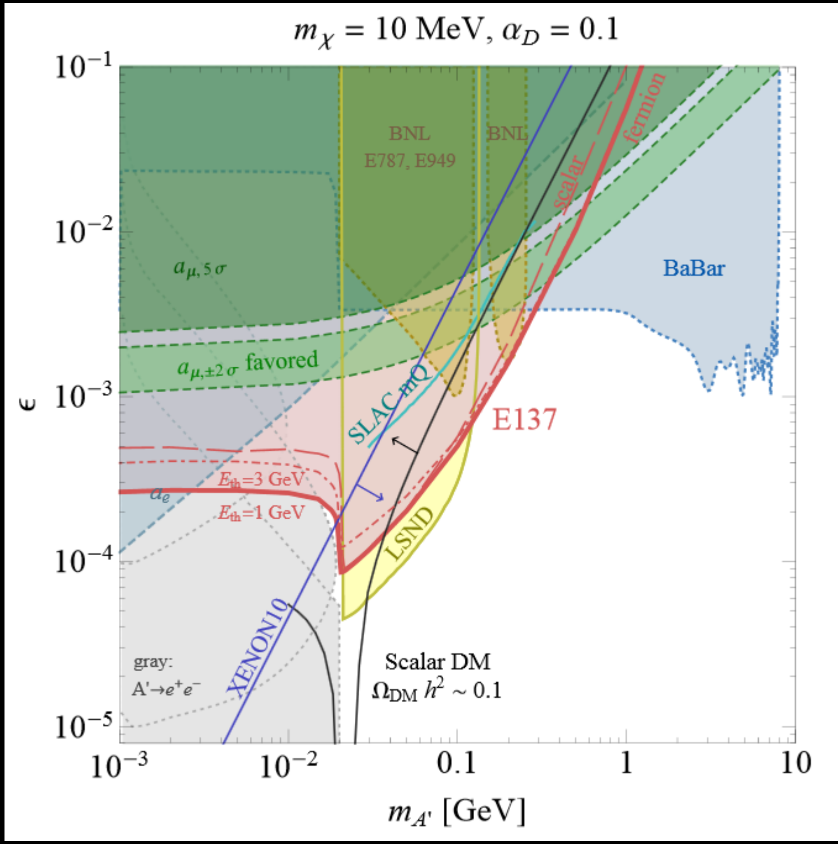
$$\Upsilon(2S,3S) \rightarrow \gamma A^0, A^0 \rightarrow \text{invisible}$$

at *BABAR* with A^0 a light CP-odd Higgs

- Analysis extended to full dataset and the dark photon case, expect limits on ε at the level of 10^{-3}.

- Constraints from many other experiments!

Batell *et al.*, arXiv:1406.2698

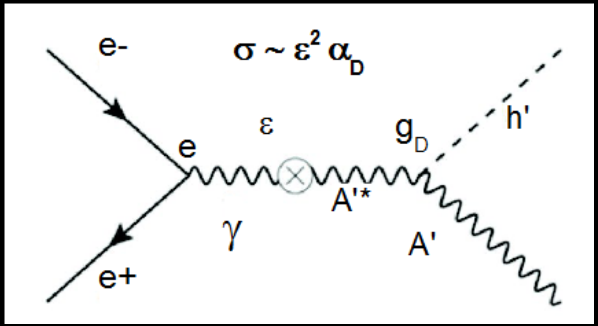


Some of the limits are model dependent!

The dark photon mass is usually generated via the Higgs mechanism, adding a dark Higgs boson (h') to the theory, which could be light.

A minimal scenario has a single dark photon and a single dark Higgs boson.

The h' could be produced in the Higgsstrahlung process $e^+e^- \rightarrow A'^* \rightarrow h' A'$, which is also sensitive to the dark sector coupling constant $\alpha_D = g_D^2 / 4\pi$

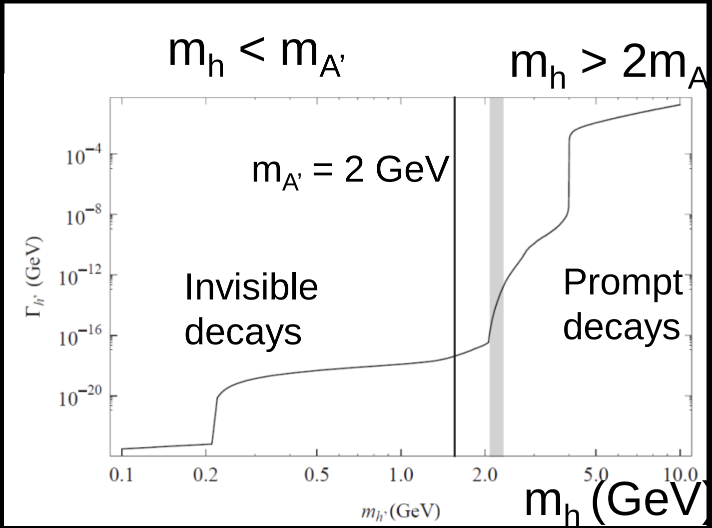


Only suppressed by ε^2

Decay topology depends on the mass hierarchy:

- $m_{h'} > 2m_{A'}$: prompt decays
- $m_{h'} < 2m_{A'}$: displaced and invisible decays

Dark Higgs decay topology



Searches for prompt h' decays at BABAR / Belle:

$e^+e^- \rightarrow A'^* \rightarrow h' A', h' \rightarrow A' A'$

Dark Higgs boson

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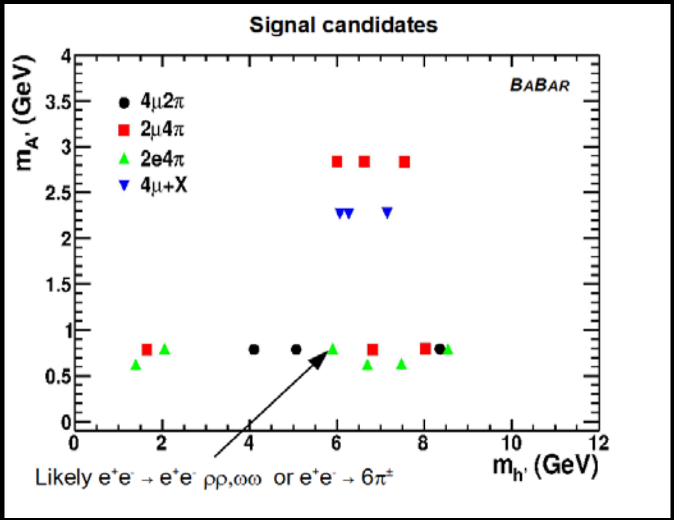
Signal candidates (3 entries / event)



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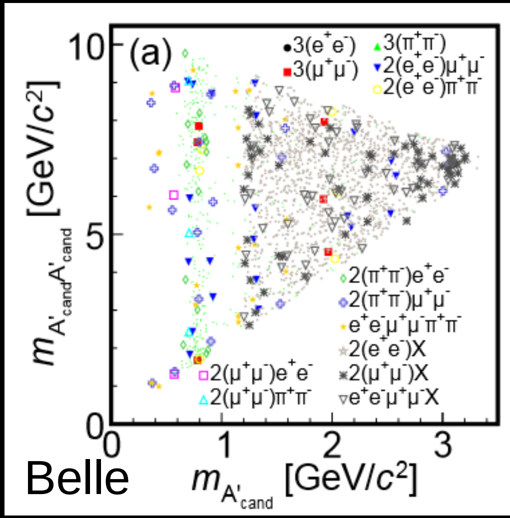

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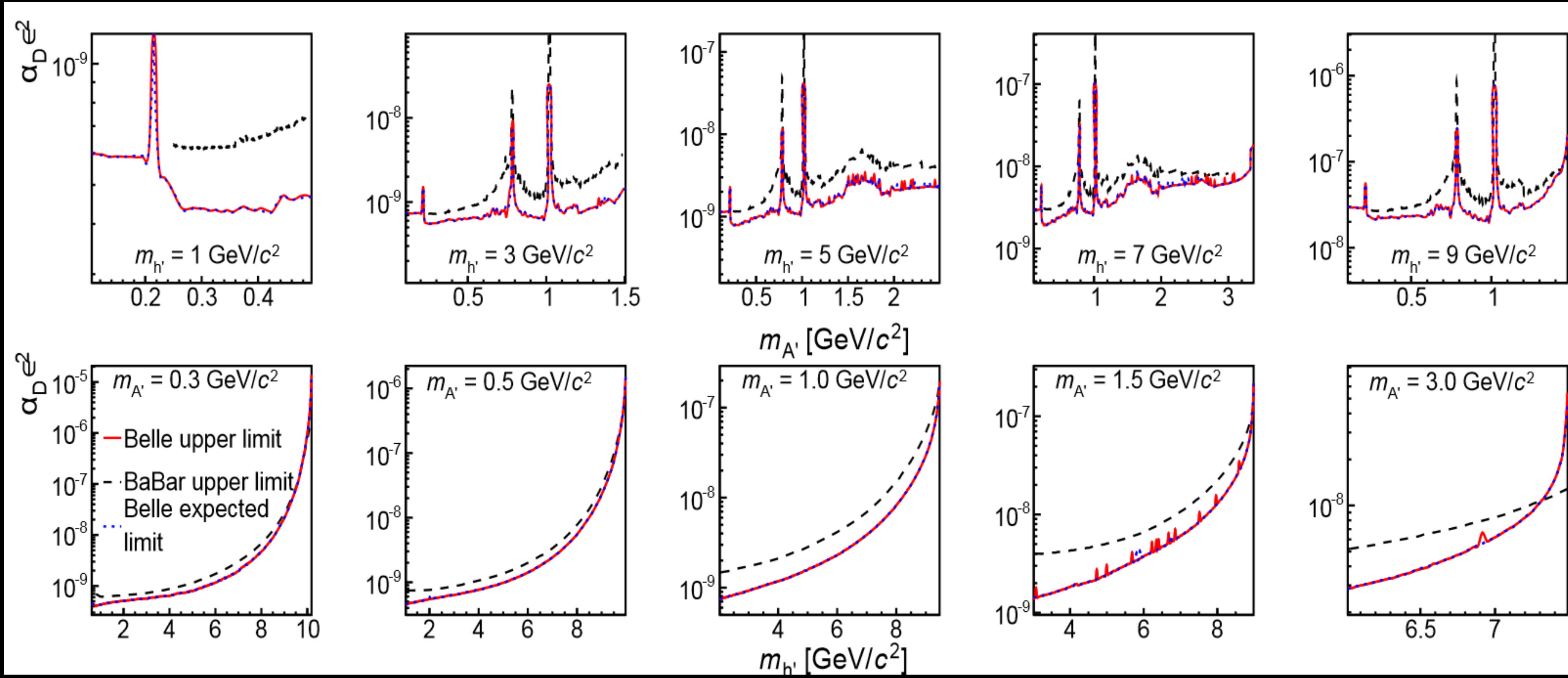
$e^+e^- \to A'^* \to h' A', h' \to A' A'$

Dark Higgs boson

Belle Collaboration, arXiv:1502.0084
BABAR Collaboration, PRL *108 (2012) 211801*

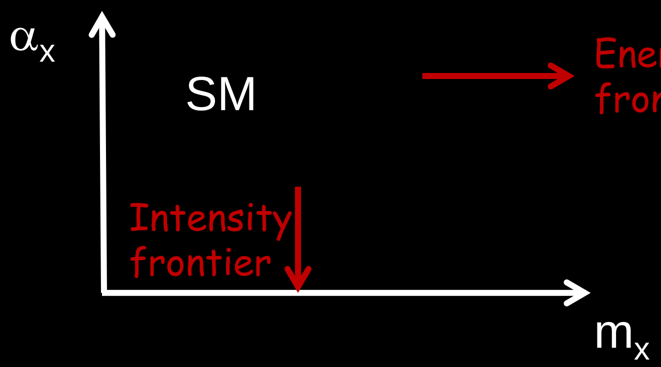
No significant signal observed, set limits on the product $\alpha_D\varepsilon^2$



Colliders are well suited to explore these possibilities

Dark sector searches at LHC

Direct production of dark photon suppressed at high energy



$$\text{Amplitude} \sim \frac{\alpha_X}{q^2 + m_X^2}$$

Difficult to probe $\alpha_X < 10^{-6}$ and $m_x \sim$ GeV at LHC
(hard ISR emission also suppressed)

Instead, new particles (e.g SUSY) could decay into dark sector particles with a large BF.

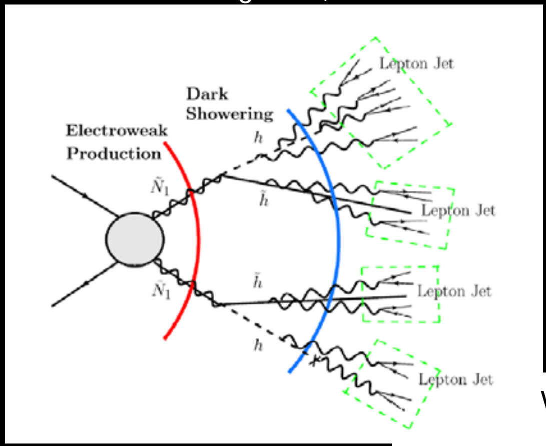
In case of SUSY, bottom of cascade no longer stable, decays into dark photons → lepton jets.

Main characteristics:

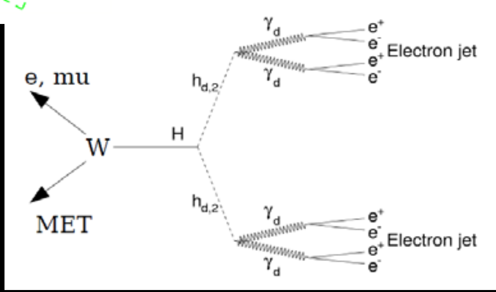
- Many leptons final state (e.g. lepton jets)
- Boosted dark sector particles → displaced vertices

But New Physics needed in some models !!!

Cheung et al., arXiv:0909.0290



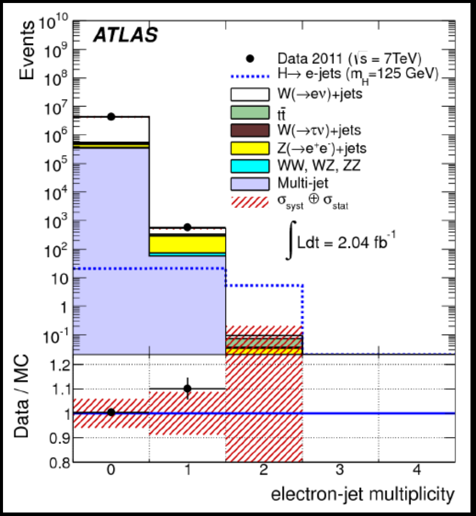
W+H → e- jet [A. Haas]

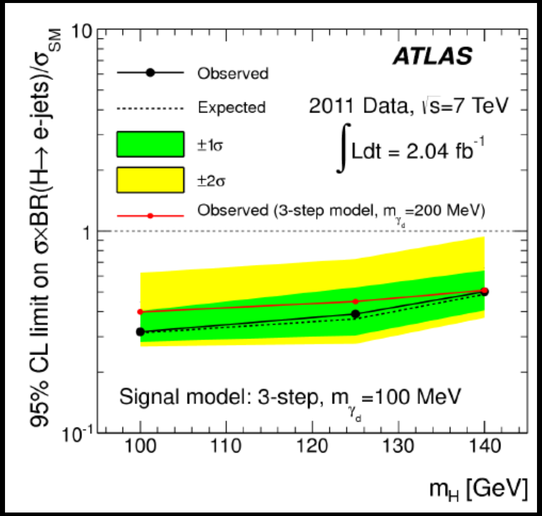


ATLAS Collab., New J.Phys. 15 (2013) 043009

Search for
W+H → electron-jets + X

No excess of events with two electron jets observed

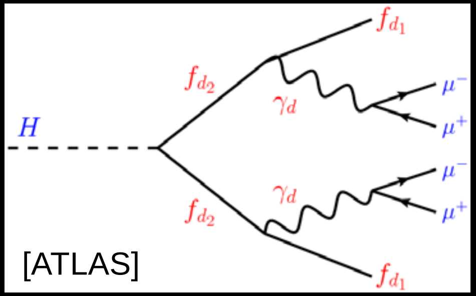


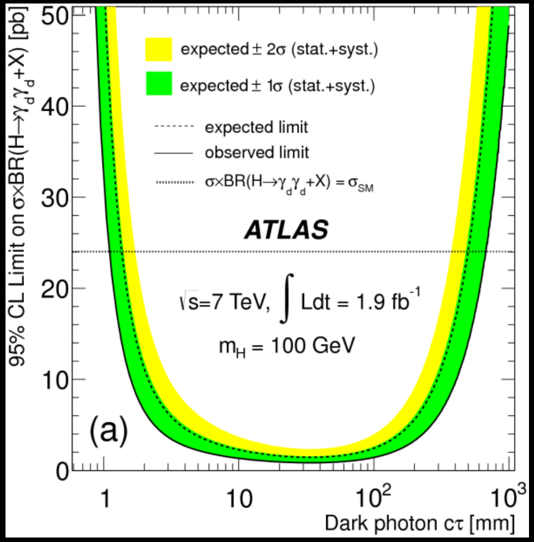


Atlas Collab., PLB 721 (2013) 32

Search for
H → A' A' + X

No signal observed



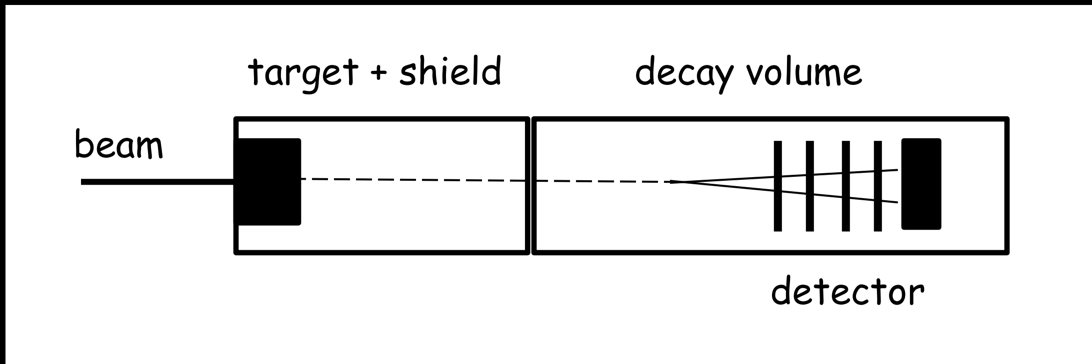


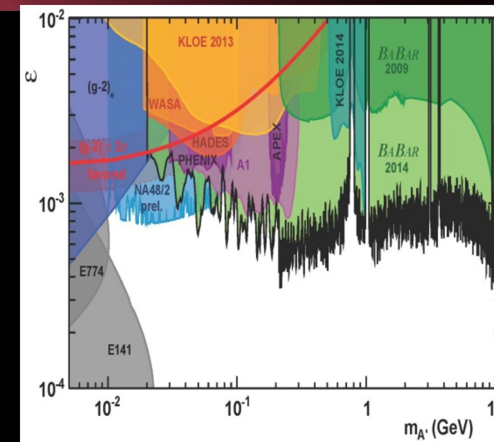
+ searches for SUSY lepton jets, H→muon jets
and possible searches for direct production, rare Z decays,..

Interesting program pursued at LHC

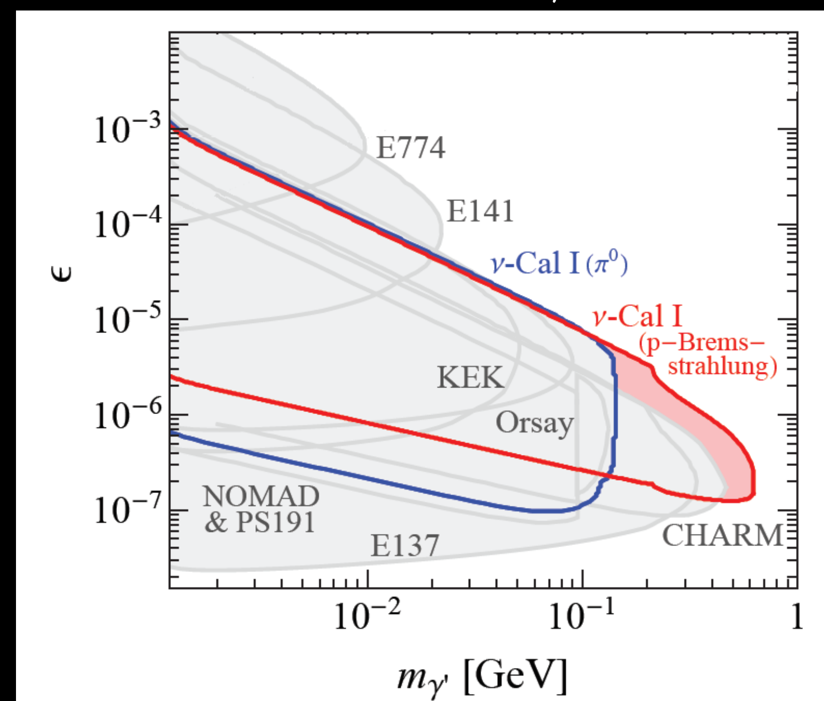
Other constraints and future initiatives

Beam dump experiments





Blumlein & Brunner, arXiv: 1311.3870

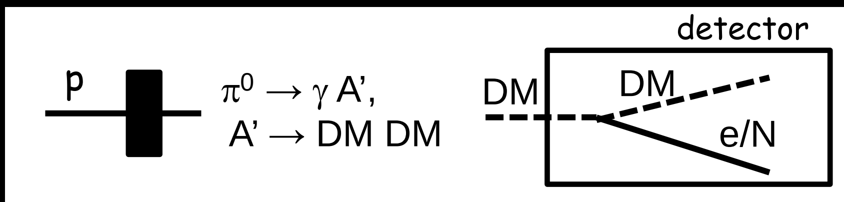


- Beam produces hadronic and/or EM shower
- Secondary particles emit A'
- Dark photons can decay near the detector, and be reconstructed as narrow resonances
- Original experiments looking for ν, axions, light Higgs,… have been reinterpreted as constraints on dark photon production
- Sensitive to low mixing values at large masses, complementary to other approaches

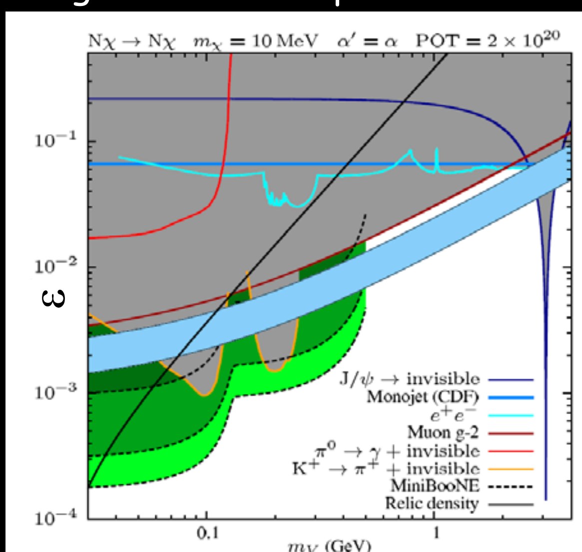
Beam dump and invisible A' decays

Proton-beam

- Invisible DM produced in pion decay
- Neutrino factory ideal for probing this scenario (MicroBoone, Nova, LBNE,...)



e.g MiniBoone expected reach

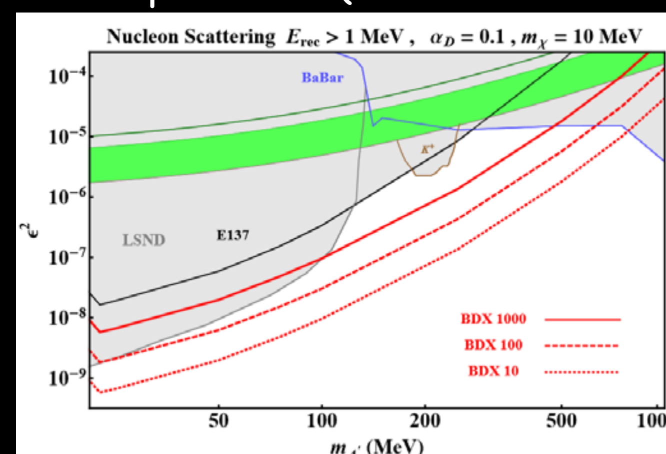


Aguilar-Arevalo *et al.*, arXiv:1211.2258

Electron-beam

- Low background
- Small mass detector
- Favorable kinematics

BDX experiment (arXiv:1406.3028)

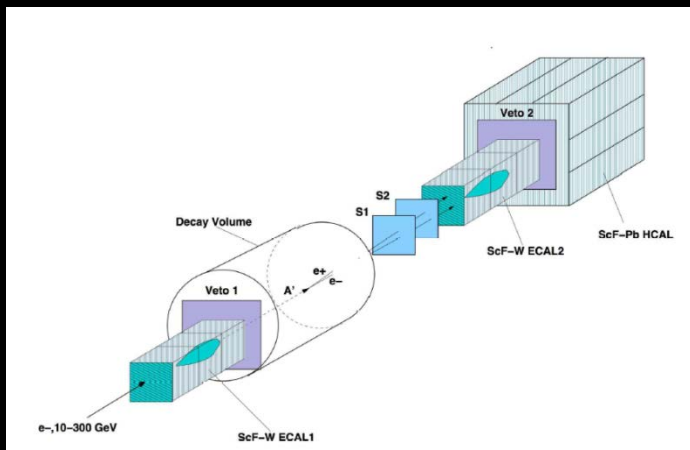


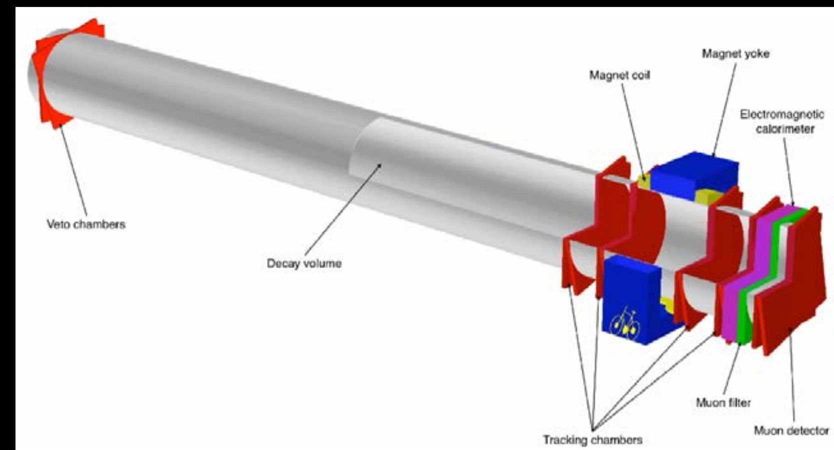
Even better @ arXiv:1411.1404

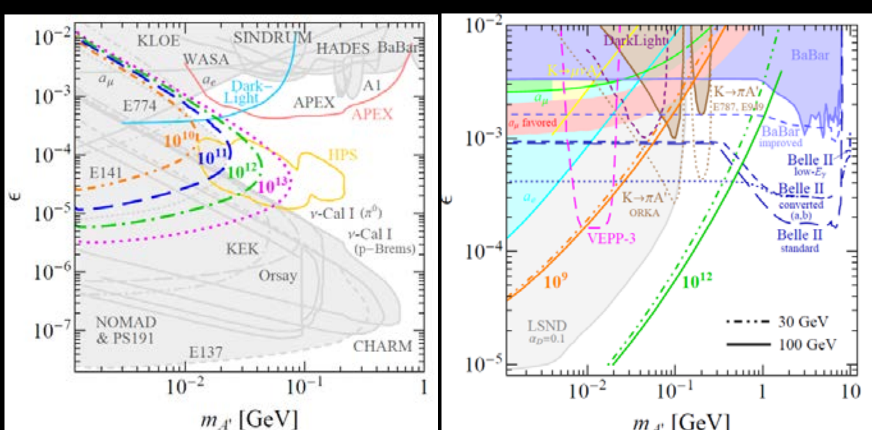
Beam dump experiment proposal at CERN

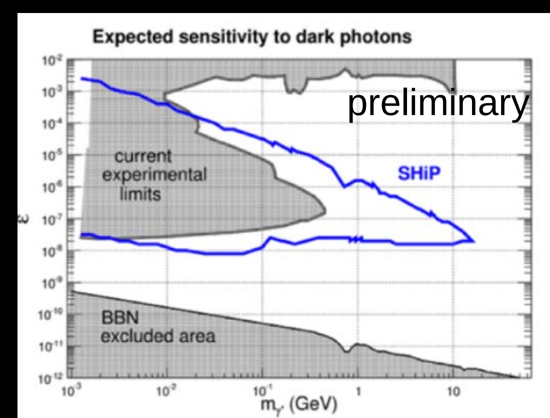
Using the CERN SPS e- beam (arXiv:1312.3309)

The SHIP proposal at CERN (http://ship.web.cern.ch/ship/)



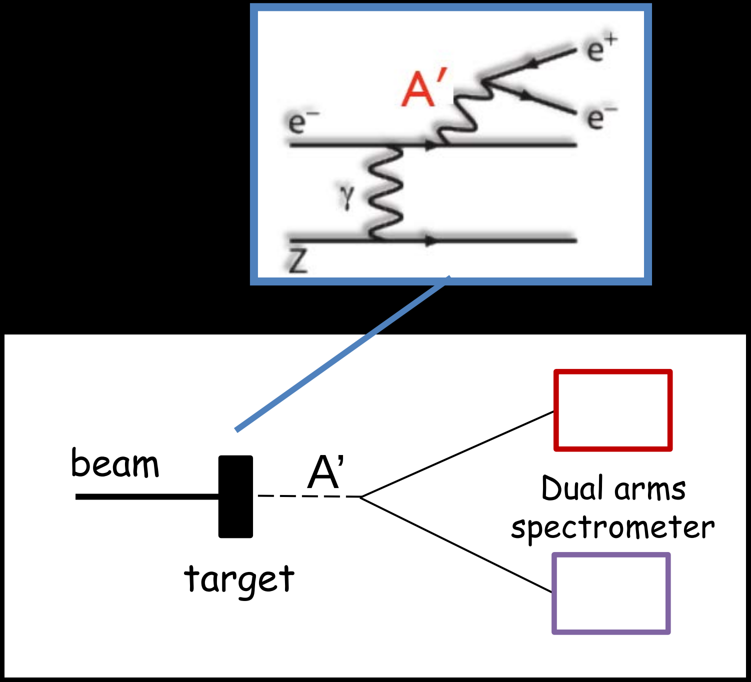






W. Bonivento

Fixed target experiments



Fixed target experiments

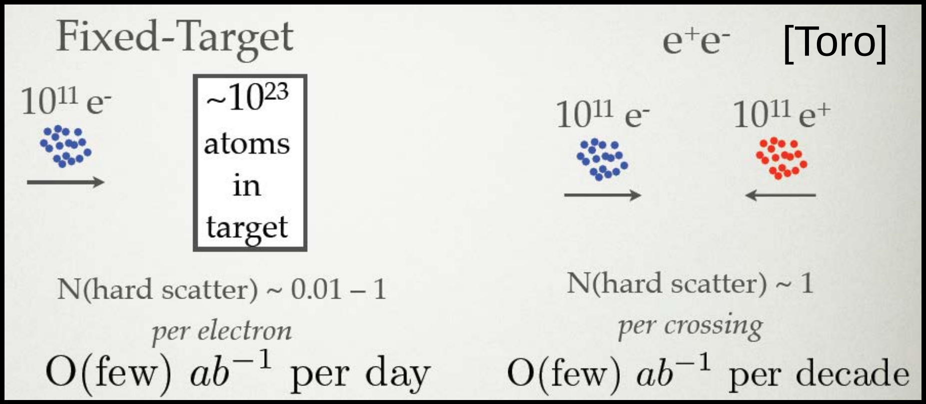
- Electron beam on fixed target radiates A'
- Decay product detected by dual arm spectrometer

Fixed target have huge luminosity

- Much denser target
- Cross-section $\propto Z^2$ and $1/m^2$

But small signal and large background

- Small bump on top of background
- Displaced vertices boosts sensitivity



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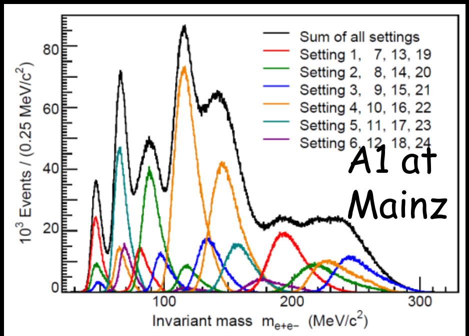
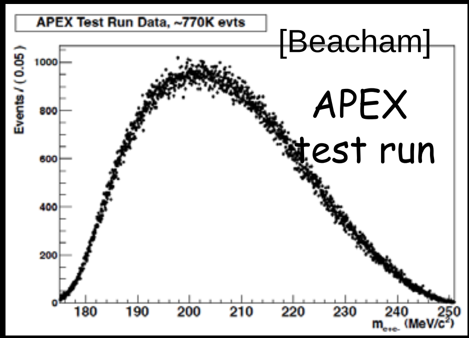
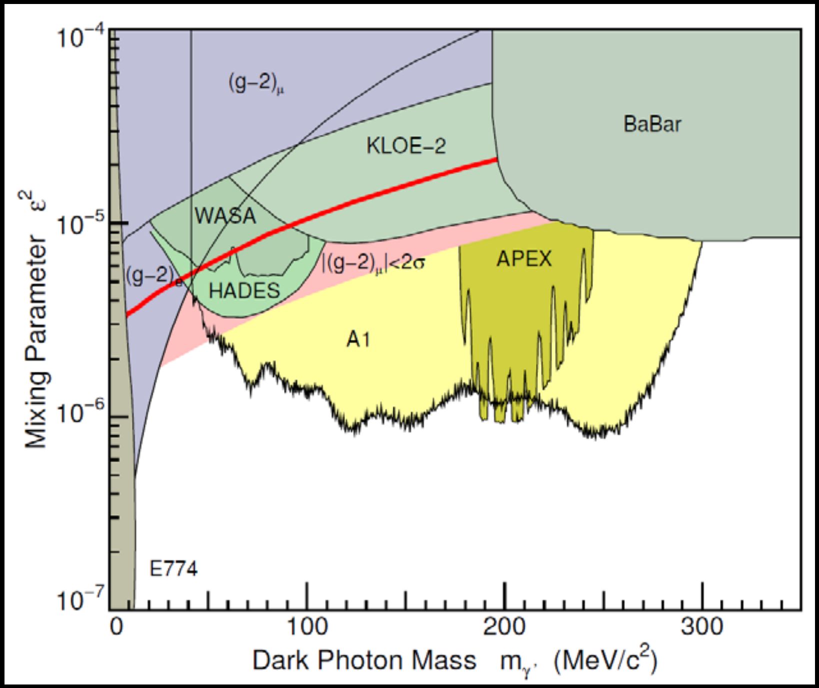
Recent results

- A1 at Mainz: 850 MeV e^- beam
- APEX at Jlab: 6 GeV e^- beam





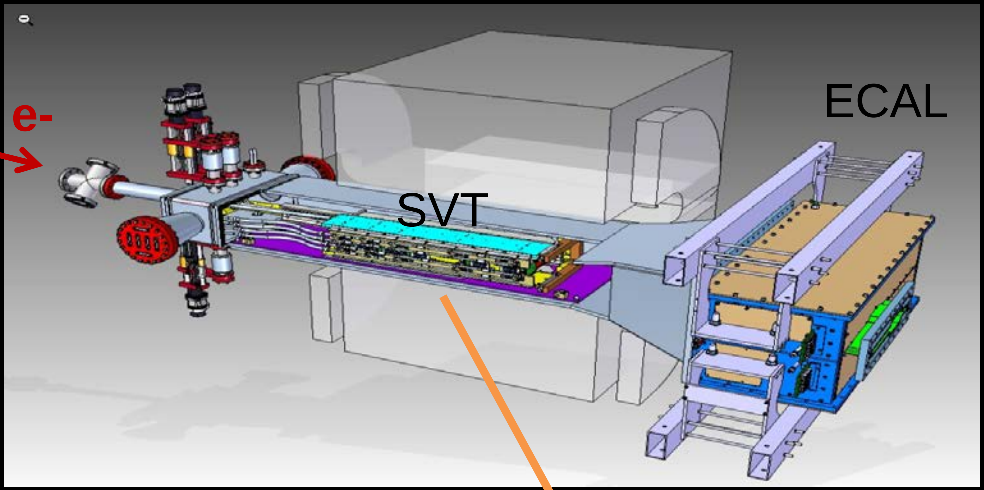


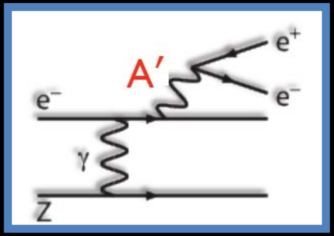
Expect to improve sensitivity in near future

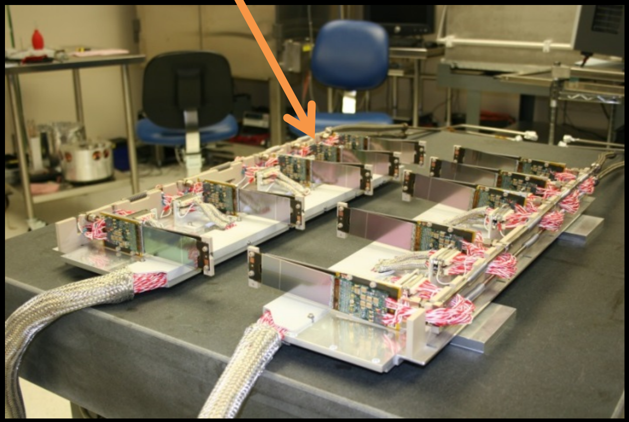
HPS proposal*

Heavy Photon Search experiment at JLab

- Large forward-acceptance spectrometer
- Electron beam hits a target, radiates dark photons whoch converts into an e^+e^- pair.
- Silicon vertex tracker to measure e^+e^- mass and vertex position
- $PbWO_4$ crystal calorimeter to identify e^+e^- and trigger
- High rate trigger and DAQ
- Search for prompt (bump hunt) and displaced A′ decays (vertex)
- Scheduled to be running spring 2015







*https://confluence.slac.stanford.edu/display/hpsg/HPS+Proposals

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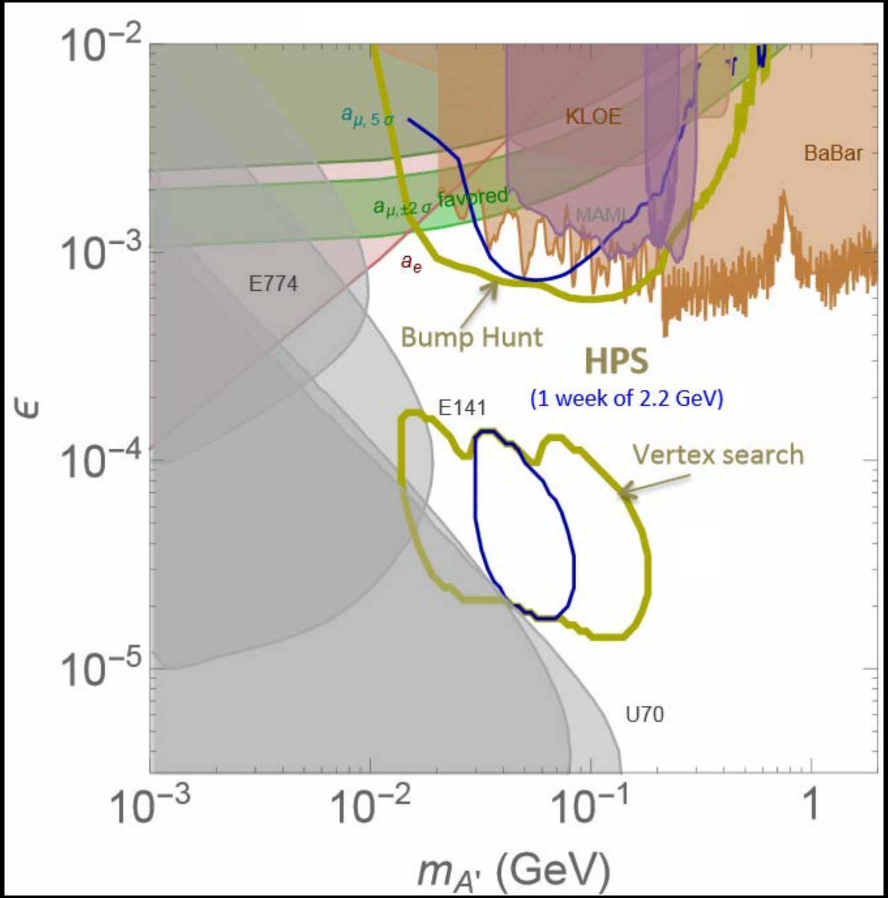
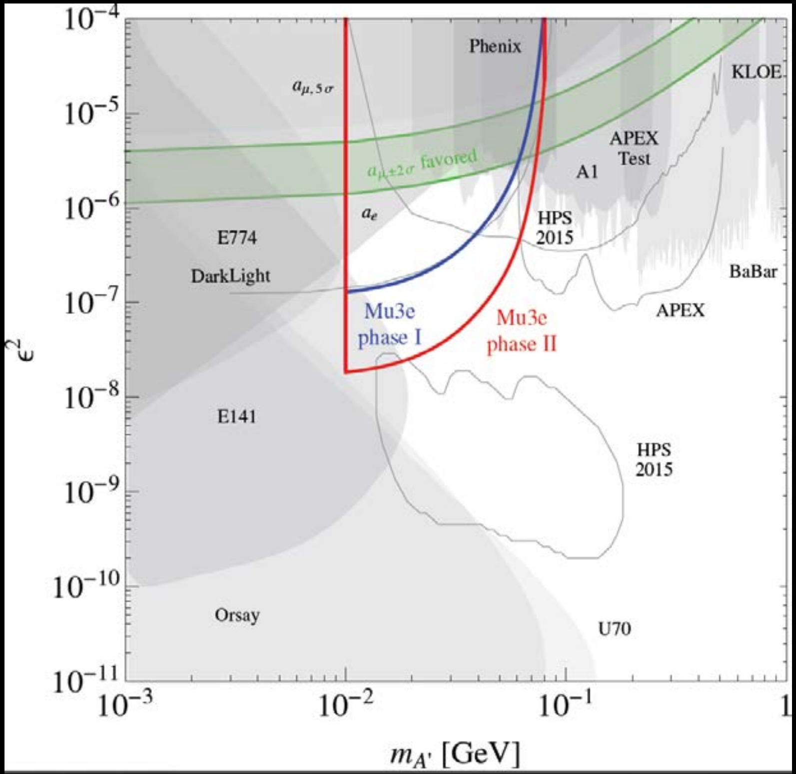


1 week 1.1 GeV
+1 weeks 2.2 GeV
+2 weeks 4.4 GeV

*https://confluence.slac.stanford.edu/display/hpsg/HPS+Proposals

Mu3e experiment at PSI

- Search for Lepton Flavor Violation (LFV) in muon decay $\mu \rightarrow eee$ with a sensitivity down to 10^{-16}.
- Low mass silicon vertex detector, high granularity and precision
- The decay $\mu \rightarrow e\nu\nu\gamma$ has a large branching fraction. This is ideal to…
- … search for $\mu \rightarrow e\nu\nu A'$, $A' \rightarrow ee$. Final state contains also three electrons and missing energy. Main background is $\mu \rightarrow eee\nu\nu$ (BF = 3.6×10^{-5}).
- Search for narrow peak over smooth background (prompt decays)
- Experiment should start in 2015 with lower beam intensity, 2018 for upgraded beam.



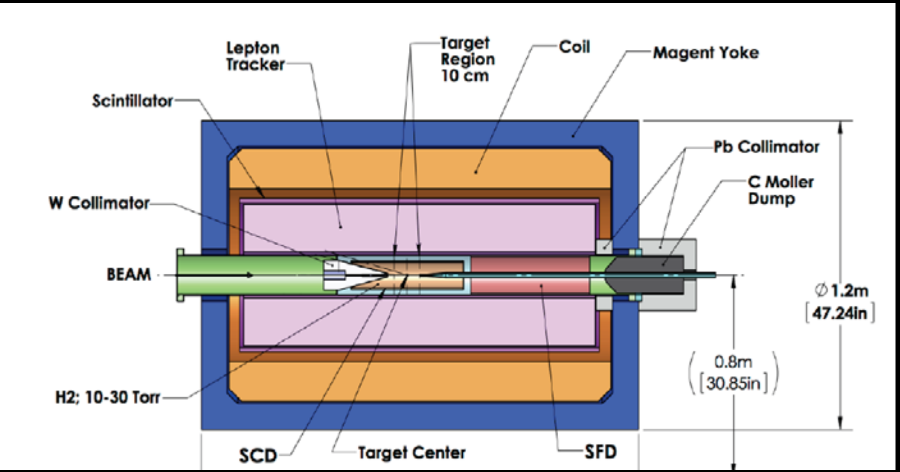
BE, R. Essig, Y. Zhong, arXiv: 1411.1770

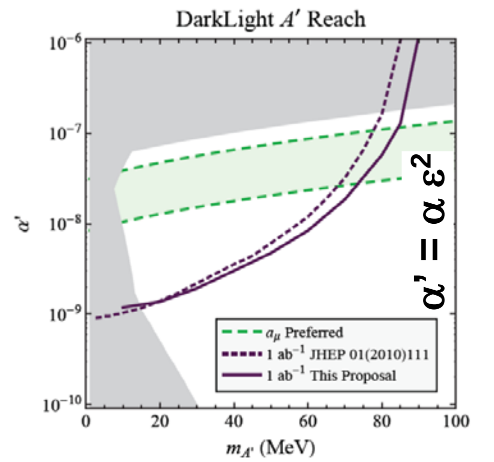
Can probe low mass region

DarkLight proposal

DarkLight* at Jlab

- Compact 4π detector
- Electron beam (100 MeV) on gaseous hydrogen target
- Measure the full reaction
  $e^- p \rightarrow e^- p A'$
- Measure visible and invisible A′ decays for $m_{A'} < 90$ MeV
- Test run at Jlab FEL to demonstrate concept
- Expect to run in 2016





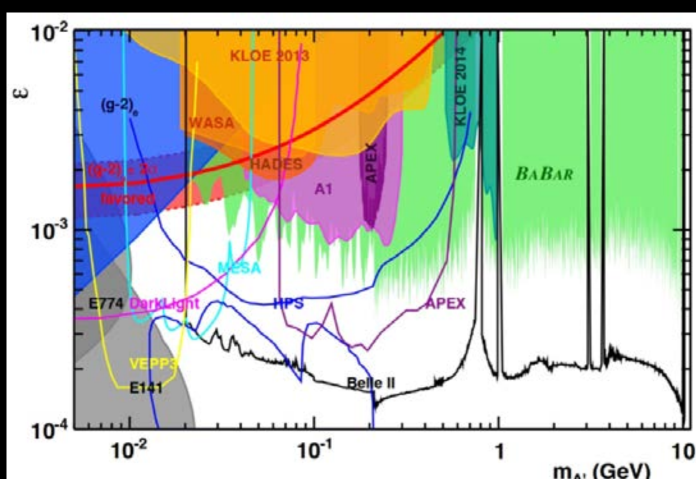
*DarkLight = Detecting A Resonance Kinematically with eLectrons Incident on a Gaseous Hydrogen Target

http://dmtpc.mit.edu/DarkLight/DarkLightProposal_PAC39.pdf

Belle II experiment

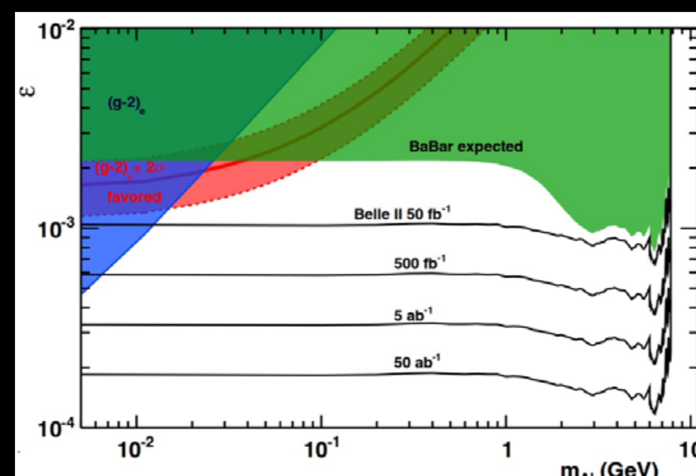
- High luminosity e+e- collider at the Υ(4S) center-of-mass energy at KEKB (Japan)
- Collect 100x more data than BABAR
- Will start taking physics data late 2016
- Expected to probe $A' \to$ visible and $A' \to$ invisible decays and considerably improve current constraints.

$A' \to$ visible



C. Hearty

$A' \to$ invisible



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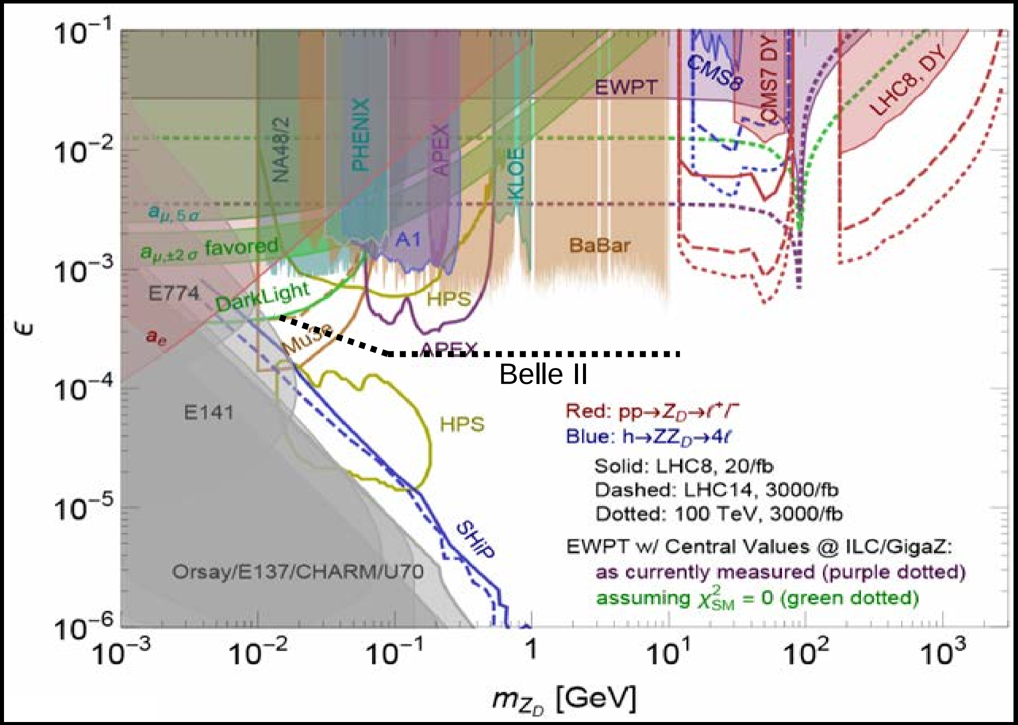
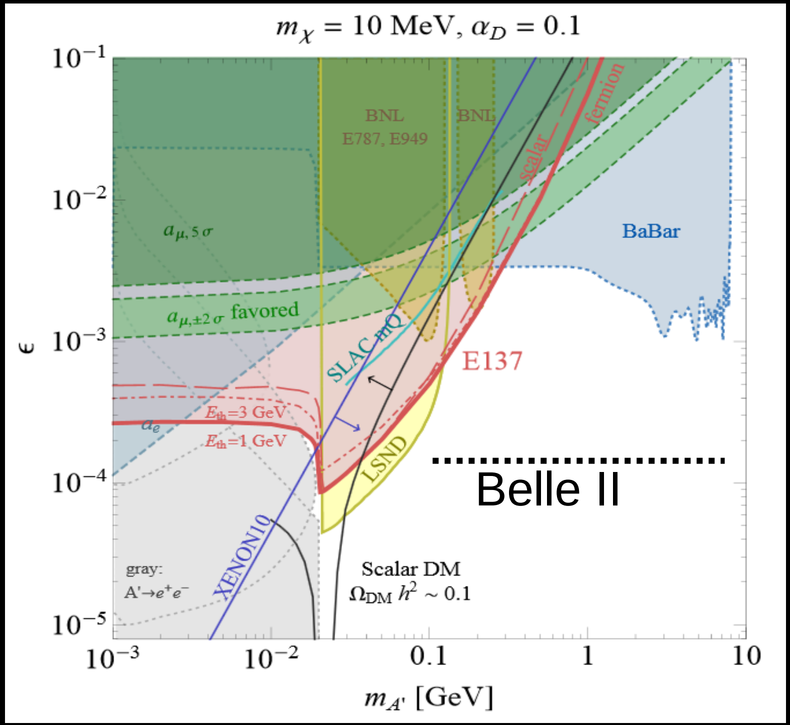
A′ → visible



A′ → invisible



Future experiments will probe a large fraction of the low mass region, but there is still a lot of ground to cover !

Dark fun

People often ask me what are the practical implications of my research.

Living in LA, it seems natural to point them towards entertainment…

Dark fun

Summary

- There are still many intriguing possibilities to explore at the GeV scale, and dark forces open a new window on physics far beyond the SM.
- A fraction of the dark photon parameter space has already been probed by current experiments: g-2, fixed target, beam dump, e^+e^- colliders,…
- But there is still a lot of uncharted territory!
- New experiments at existing facilities will further explore this parameter space, hopefully resulting in a game-changing discovery.

And remember, nothing bad ever happens when you work with dark force!