Detecting Dark Photon

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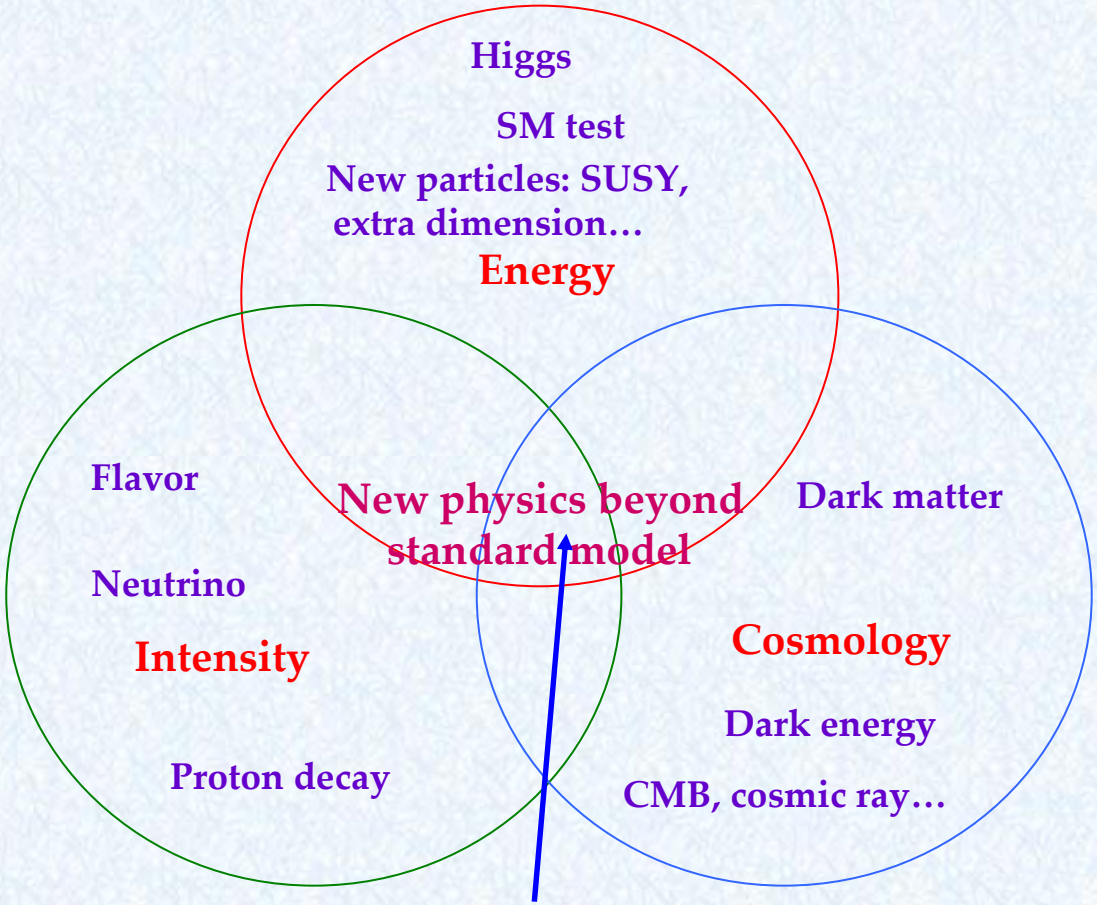
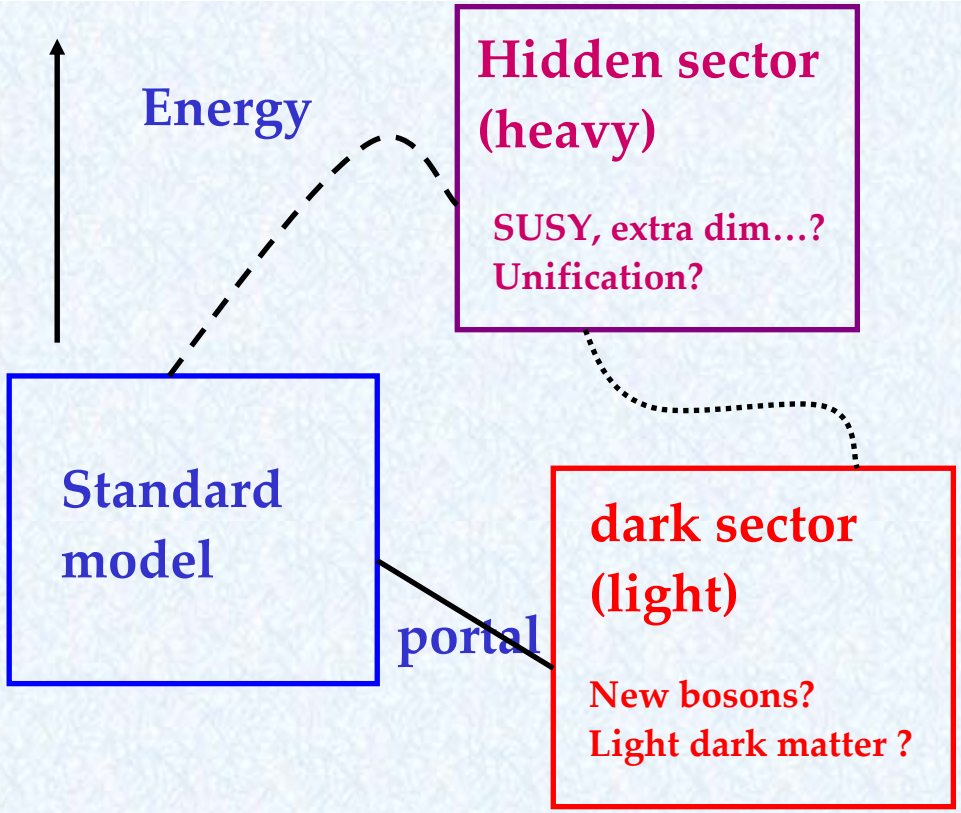
Three frontiers



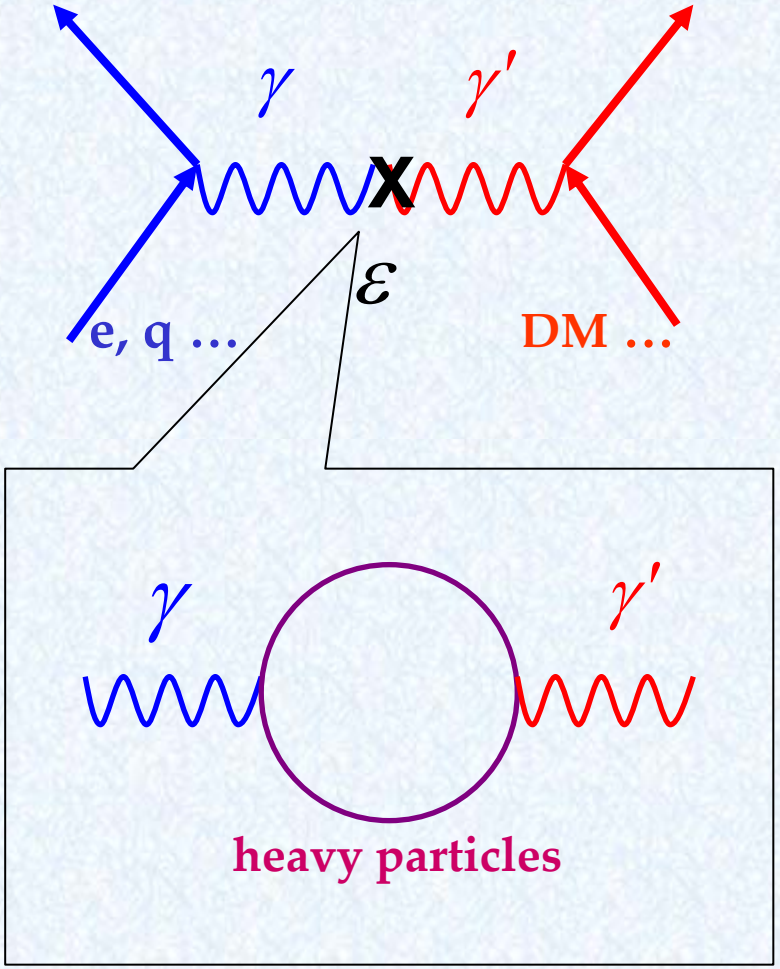
- Searching for new sub-GeV gauge boson
- Searching for new sub-GeV boson
- Searching for new dark sector

From SM to dark sector



Portal	Particles	Operator(s)
"Vector"	Dark photons	$-\frac{\epsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu}$
"Axion"	Pseudoscalars	$\frac{a}{f_a} F_{\mu\nu}\widetilde{F}^{\mu\nu}, \frac{a}{f_a} G_{i\mu\nu}\widetilde{G}_i^{\mu\nu}, \frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
"Higgs"	Dark scalars	$(\mu S + \lambda S^2) H^\dagger H$
"Neutrino"	Sterile neutrinos	$y_N L H N$

Kinetic mixing

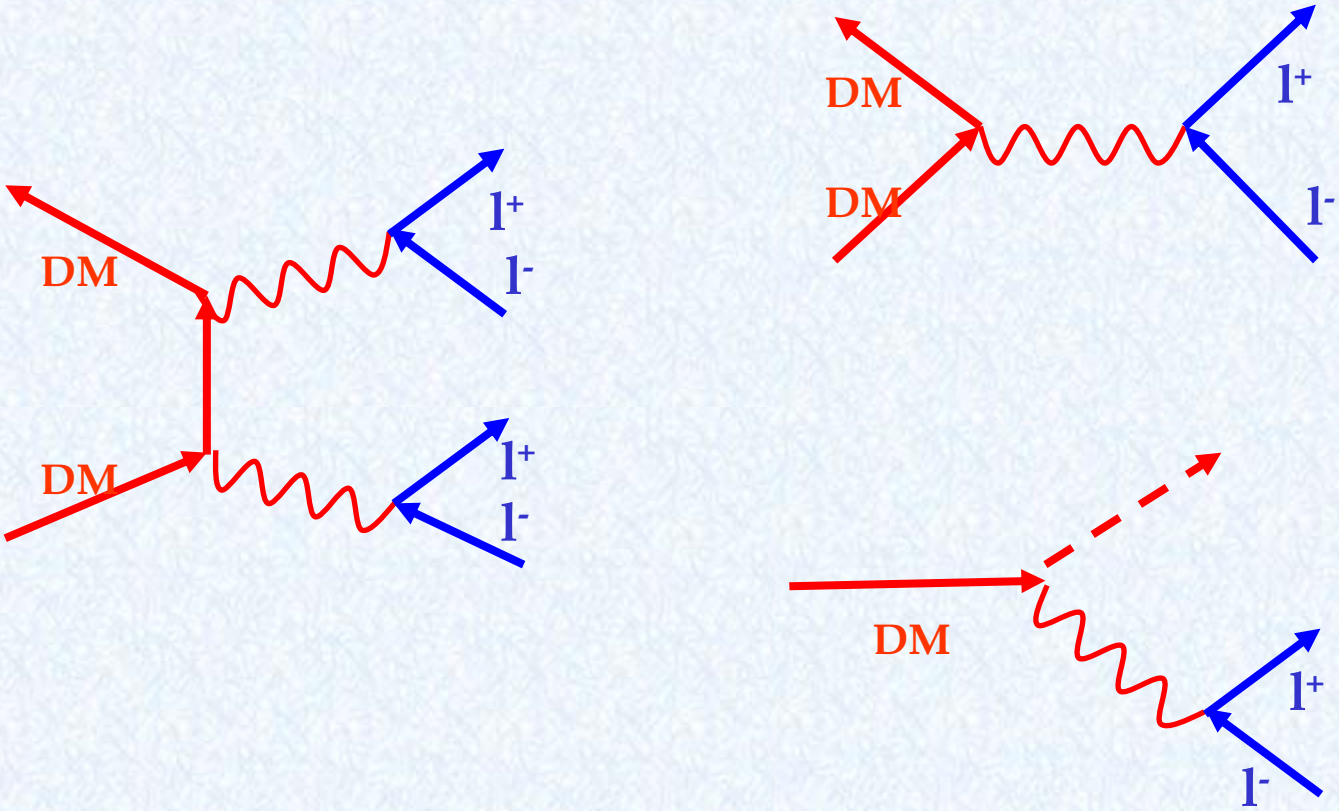


- Kinetic mixing between dark photon and photon
- Mixing can be generated by quantum loop mediated by some heavy particles
- Mixing is expected to be small

$$\varepsilon \sim \frac{g_D g_Y}{16\pi^2} \log \frac{\Lambda^2}{m_X^2} \sim 10^{-4} - 10^{-3}$$

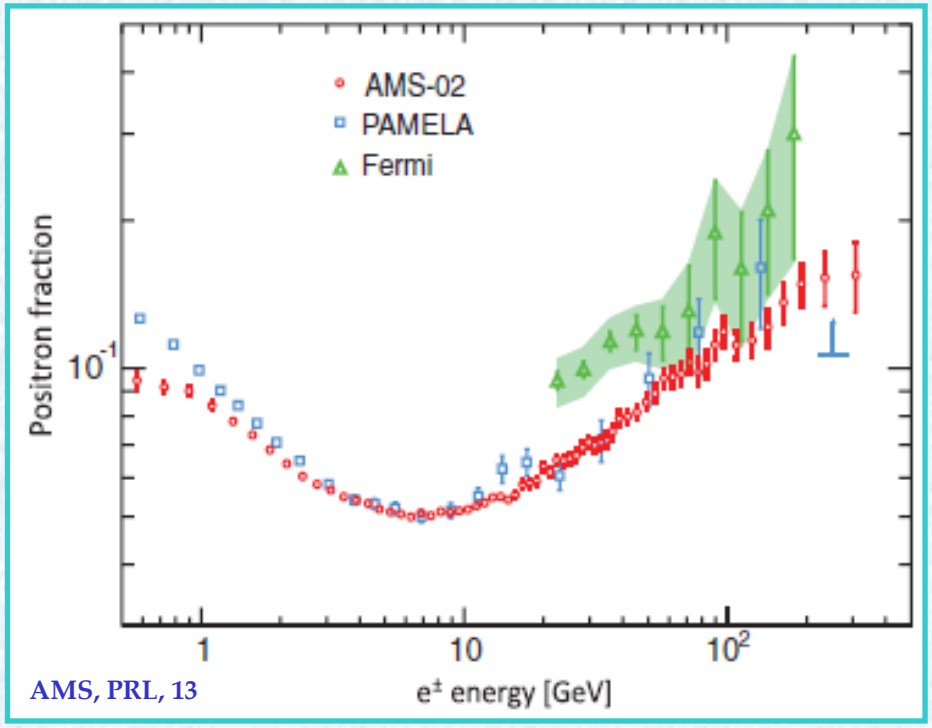
- In the SUSY model, the $U(1)_Y$ D term would get vev after EWSB, and induce effective FI term for U(1)′ via mixing operator. This term would give masses of particles in the dark sector ~ GeV

Dark photon in the SKY?

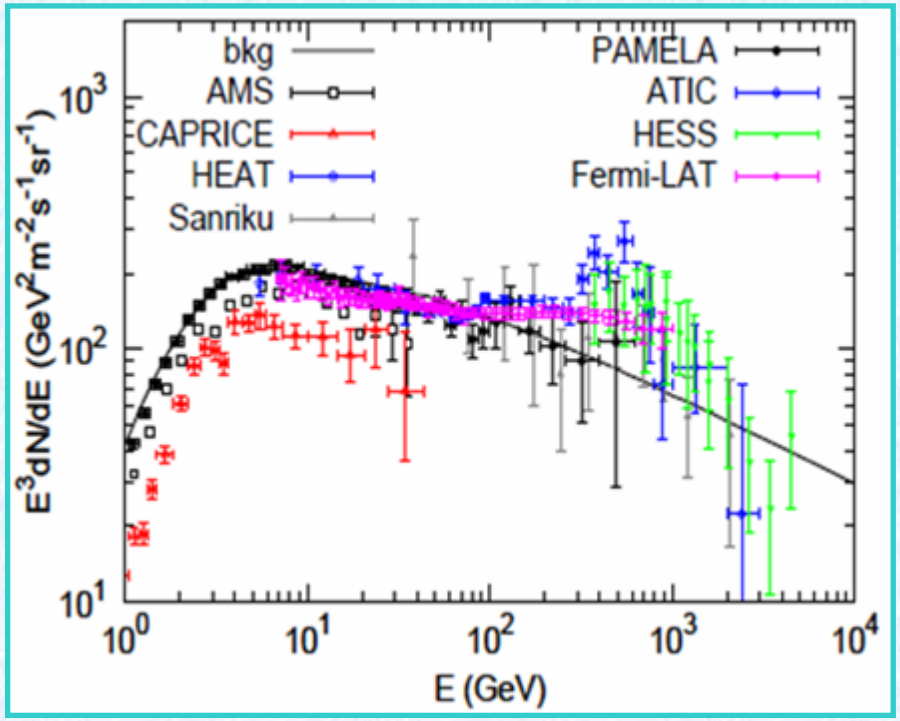


- DM can annihilate/decay into dark photons and produce energetic cosmic rays

Anomalous electron/positrons

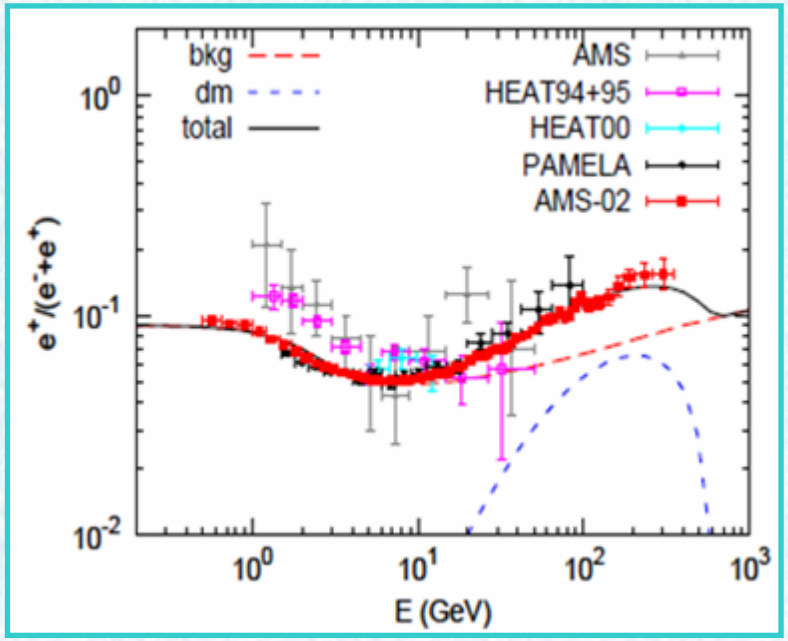


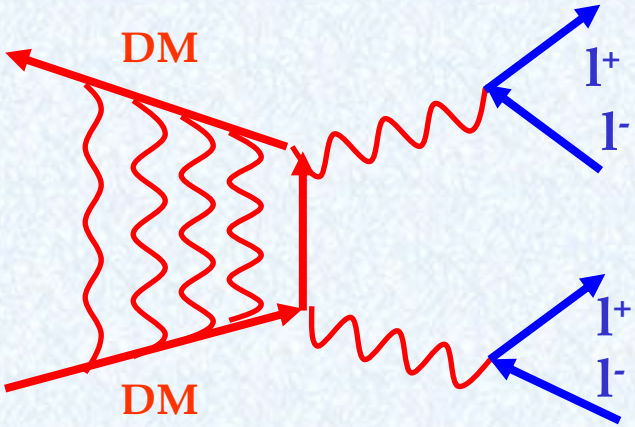
AMS, PRL, 13



- Observed by **PAMELA** in 2008, and confirmed by several CR experiments
- Need **extra primary electron/positron sources**
- Maybe the signatures from DM annihilations (decays)

DM interpretation with dark photon





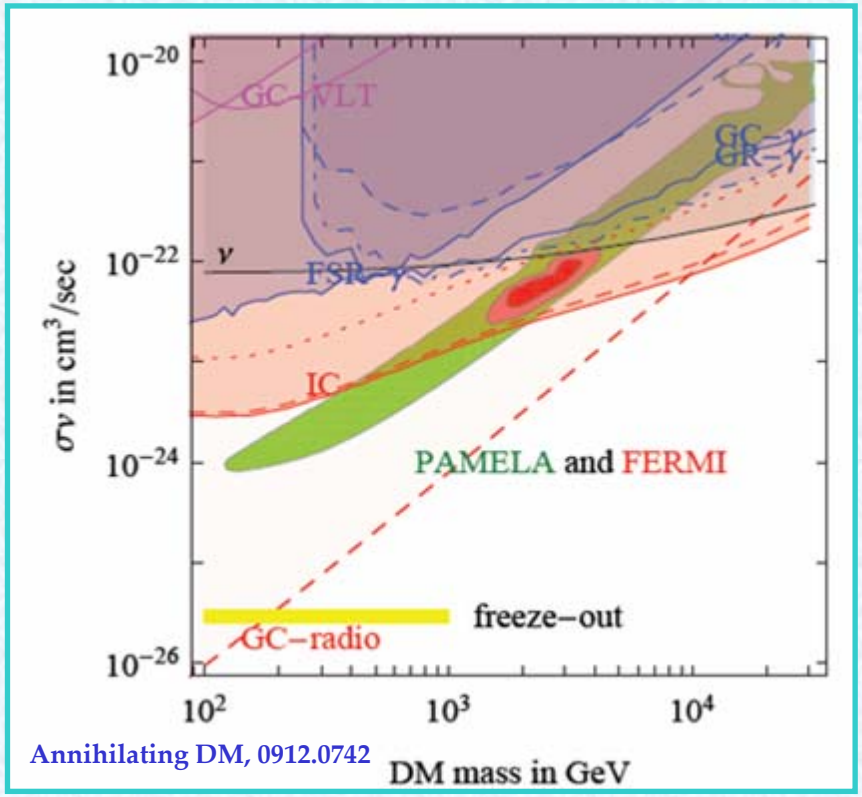
- Require large DM annihilation cross section which is much larger than the usually expected value by a factor of ~1000

  "Sommefeld" effect with light mediator can provide such annihilation cross section

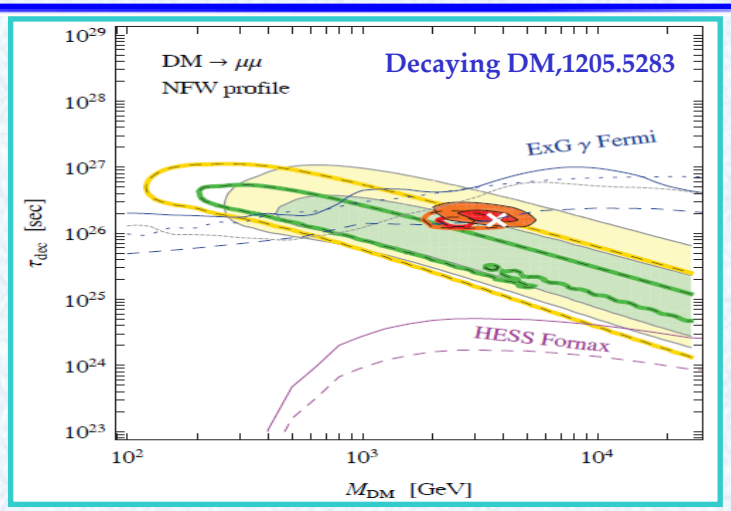
- No antiproton excess was observed. The coupling of DM to SM should be "leptophilic". If dark photons are light enough, they do not produce antiproton.

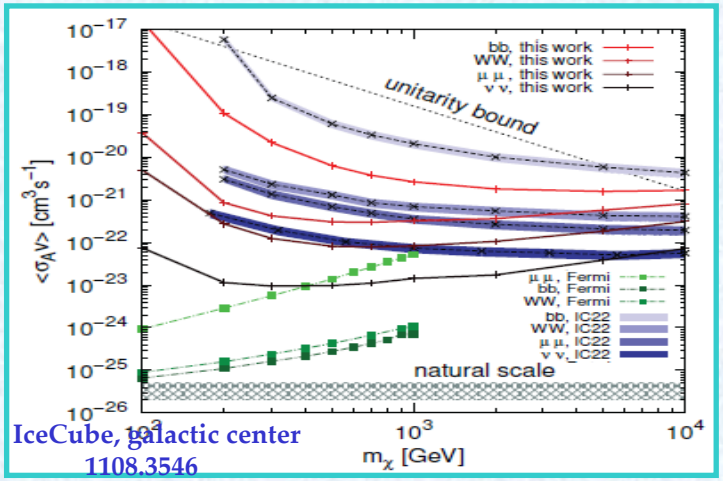
- The soft positron spectrum suggests decay products of dark photon are muons or taus

Constraints from other DM detections



Annihilating DM, 0912.0742



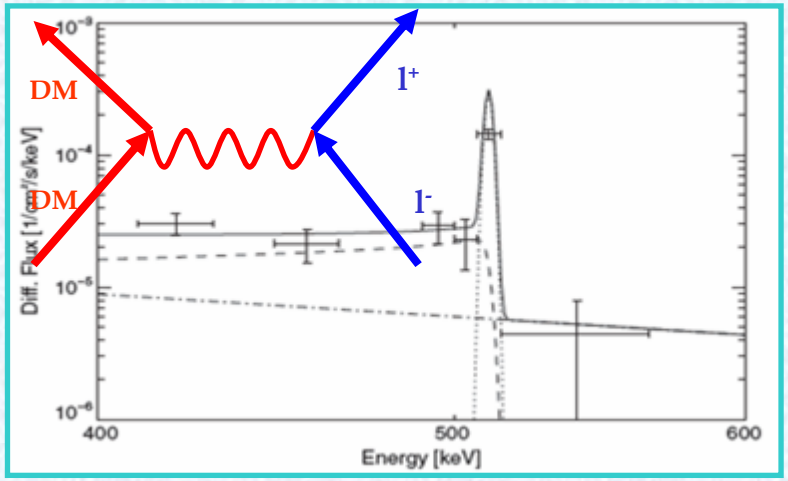


IceCube, galactic center 1108.3546

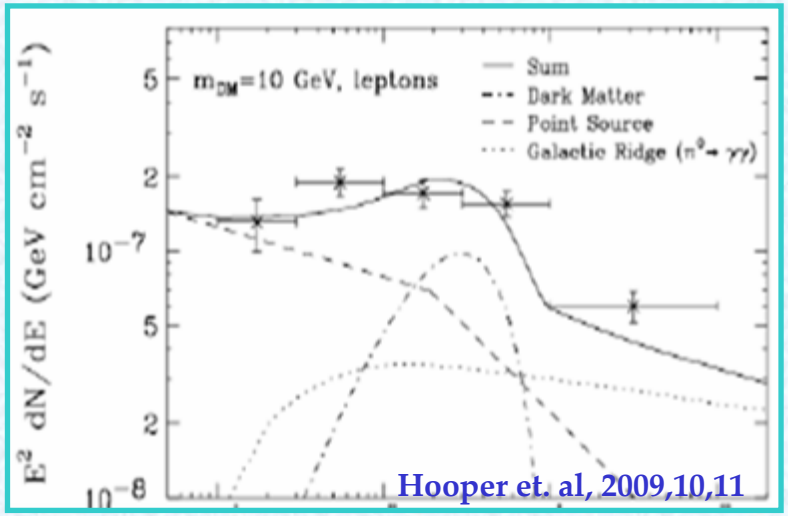
- large secondary high energy **photon** flux induced by cascade decay, final state radiation, inverse Compton scattering (with CMB, star light, IR photons)
- large high energy **neutrino** flux from muon/tau decays or DM-lepton interactions
- Five years after PAMELA result, more and more constraints given on the DM interpretation

Other possible DM signals

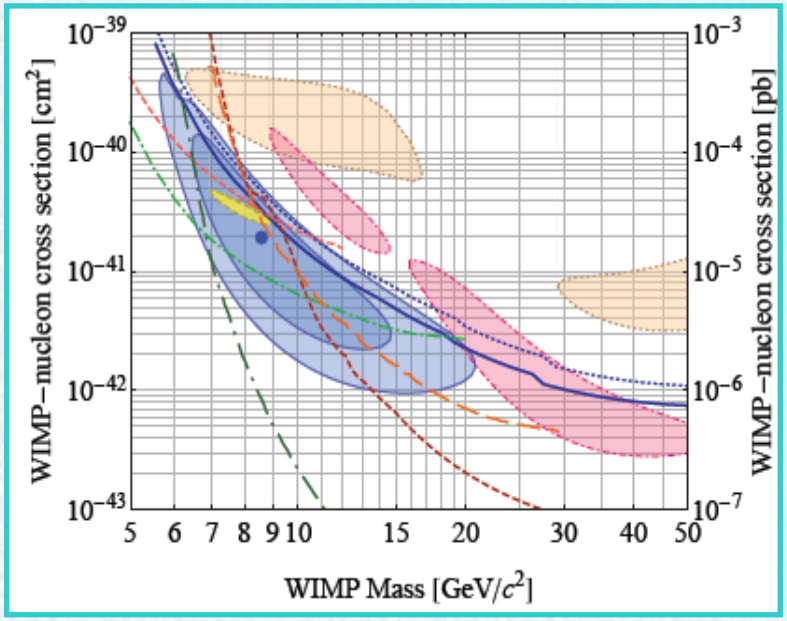
- INTEGRAL 511keV gamma ray line in the GC



- Fermi-LAT O(1)GeV gamma ray excess in the GC

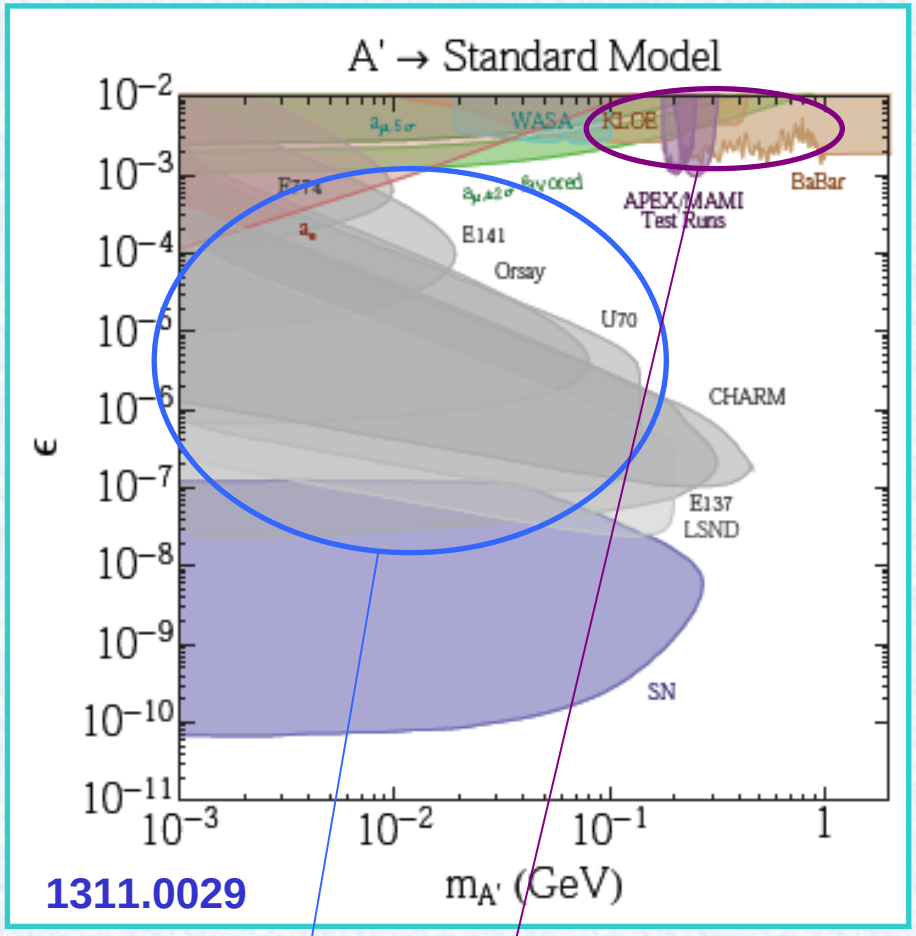


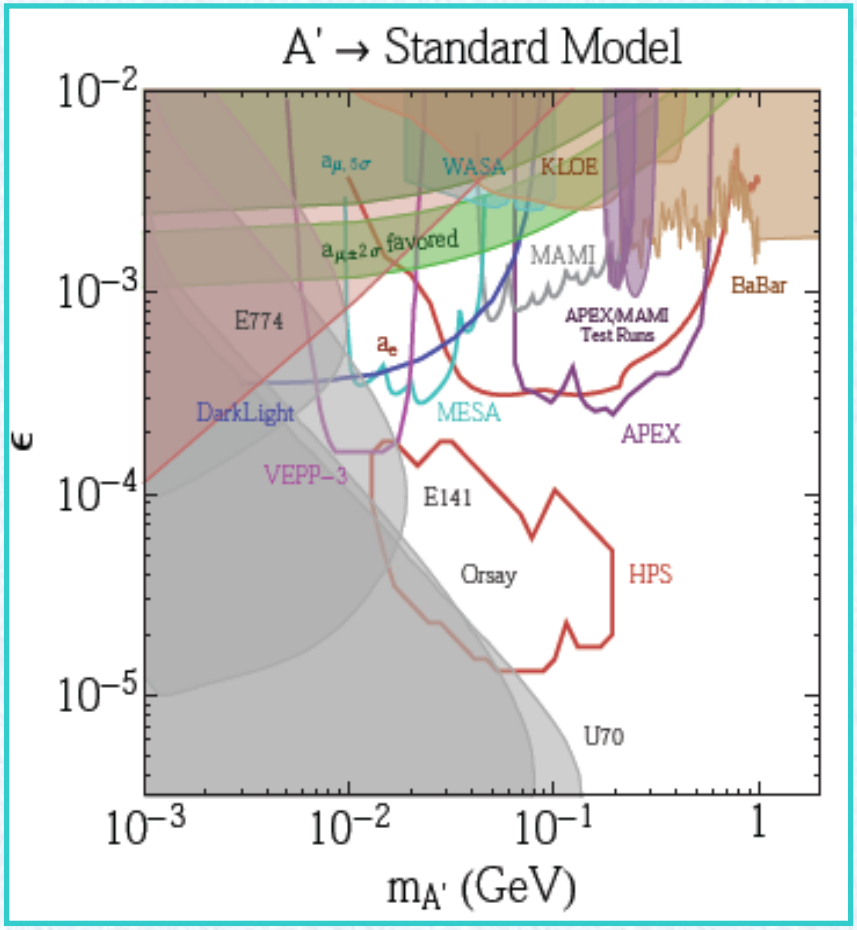
- Direct detection: DAMA, CoGeNT, CRESSTII, CDMS



- The nature of these anomalous results is still unclear

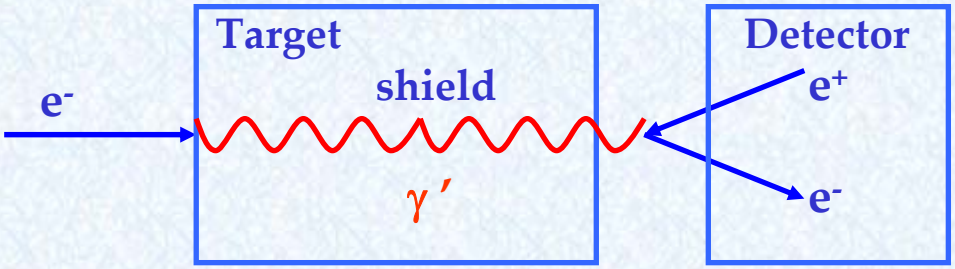
Current limits from terrestrial experiments ($m_{\gamma'}$>MeV)



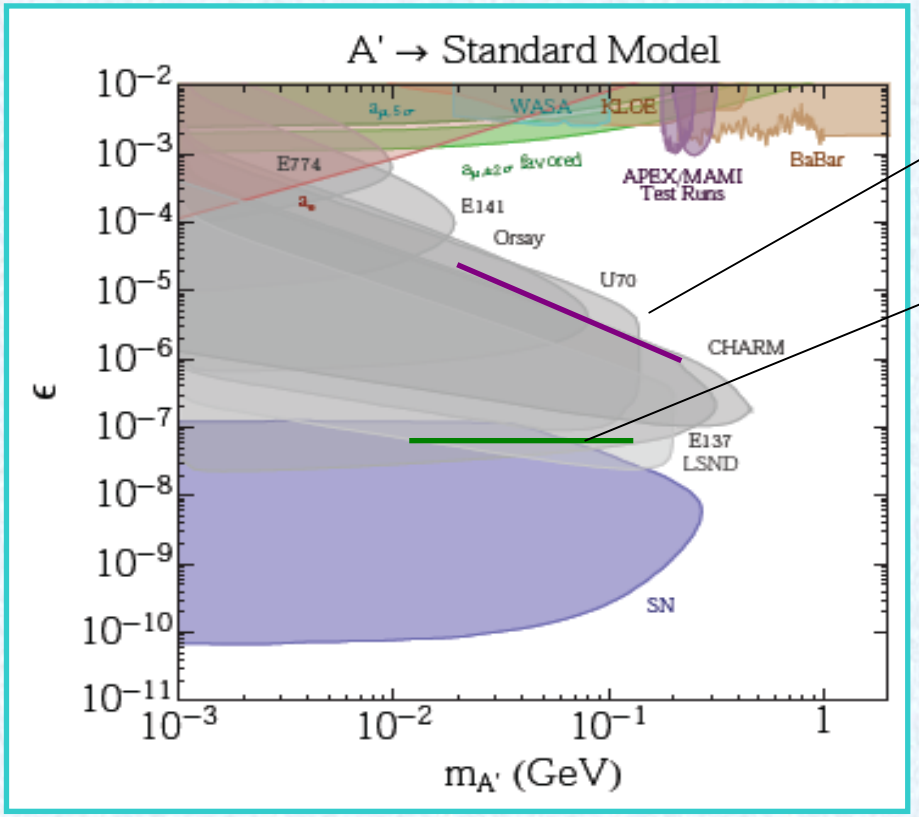


- Dark photon in this mass range can decay into charged leptons and mesons
- Fixed target experiments
- Low energy e^+e^- colliders: direct production, rare meson decay
- High energy colliders

Electron beam dump experiments



- ep collisions produce dark photons. Dark photons travel through the shield, and decay into electron-positron pairs in the detector
- Very high luminosity
- Constraints are set for particular parameter space
  - large mixing-> small lifetime of dark photon -> can not decay in the detector
  - small mixing-> small production of dark photon -> no enough statistic
- Experiments with shields of O(cm~100m)



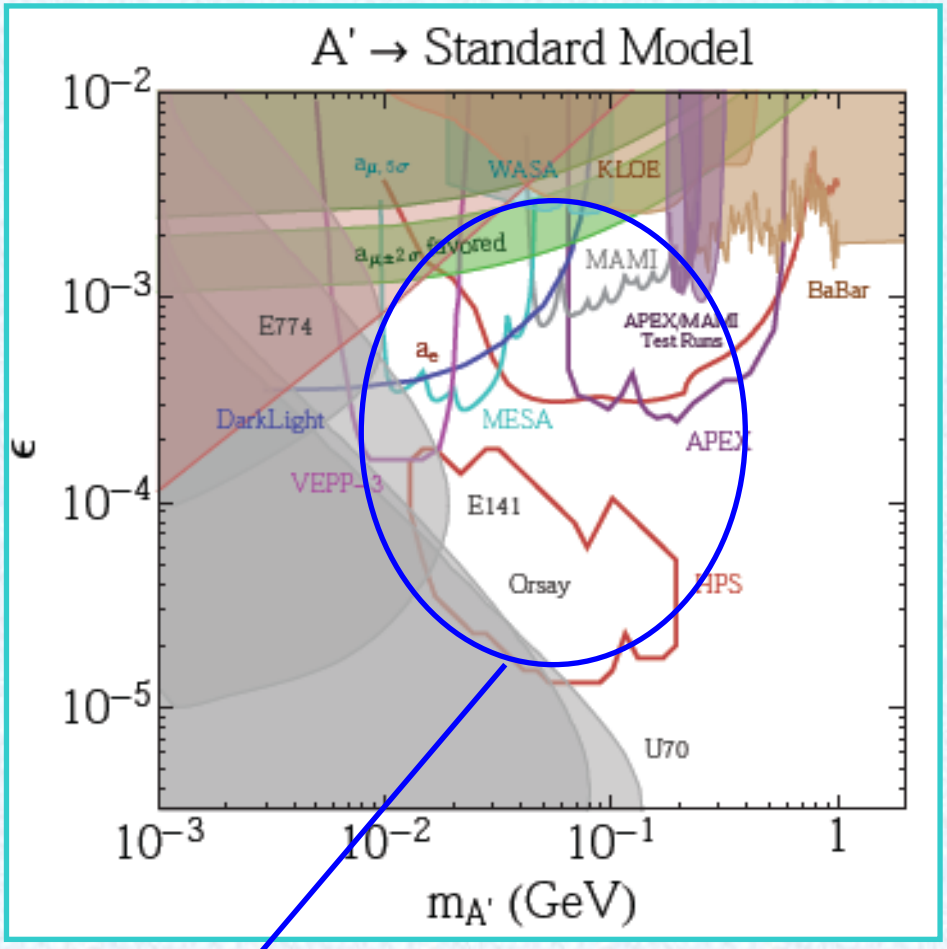
$$\sigma_{A'} \sim 100\ \mathrm{pb}\,(\epsilon/10^{-4})^2\,(100\,\mathrm{MeV}/m_{A'})^2$$

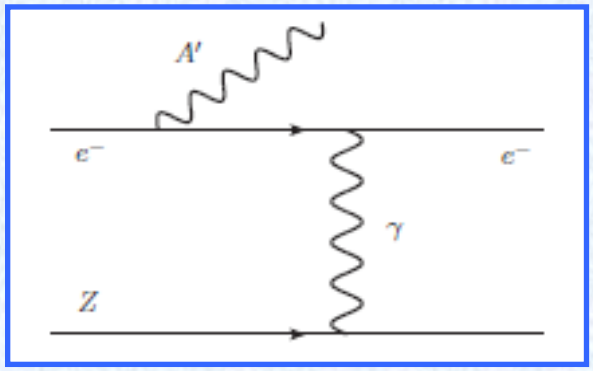
$$\gamma c\tau \sim 1\ \mathrm{mm}\,(\gamma/10)\,(10^{-4}/\epsilon)^2\,(100\,\mathrm{MeV}/m_{A'})$$

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

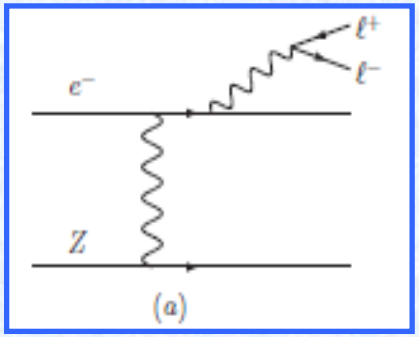
Bjorken et. al, 0906.0580

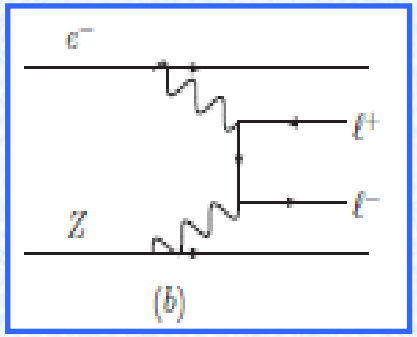
Other electron fixed target experiments





- Produced dark photons are extremely forward



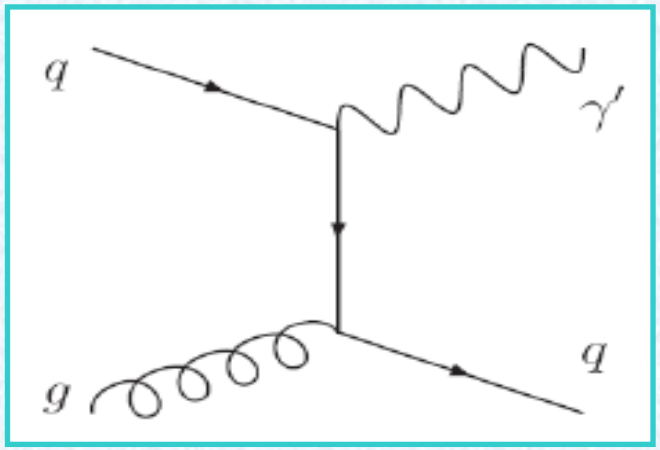


- Radiative and Bethe-Heitler BG
- Reconstruct the decay vertex and invariant mass of the dark photon to suppress BG

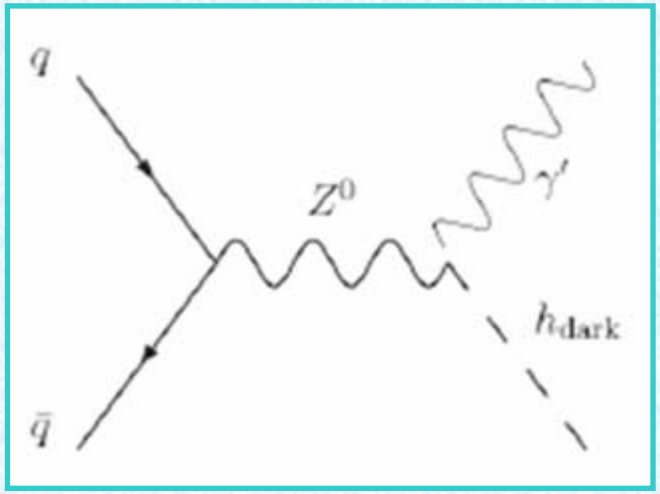
- The lifetime of dark photon is small (~<O(1) cm)
- Thin target

Researches at High energy colliders

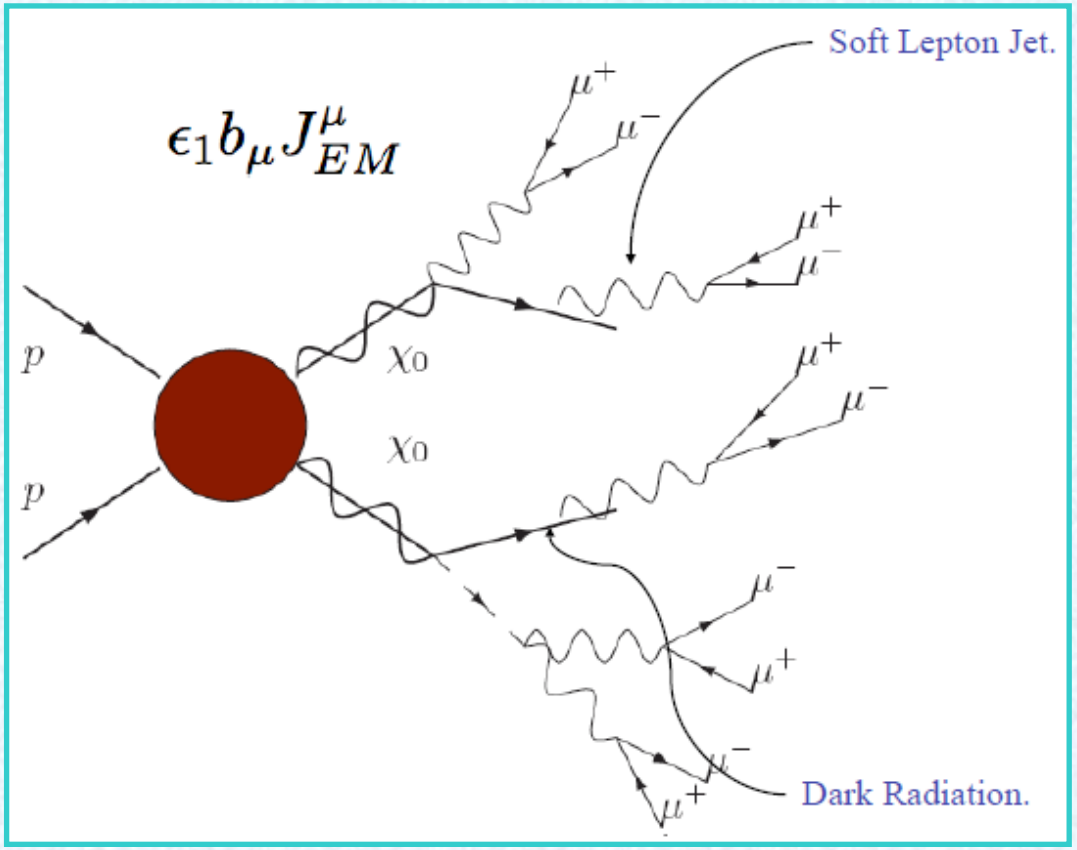
- Direct production (suppressed by small mixing)



- Dark higgs strahlung



- Cascade decay, e.g. from SUSY particles
  If LSP carry U(1)′ charge, NLSP would decay into dark photon without suppression



Since Higgs may also decay into dark particles, high precision measurement is needed

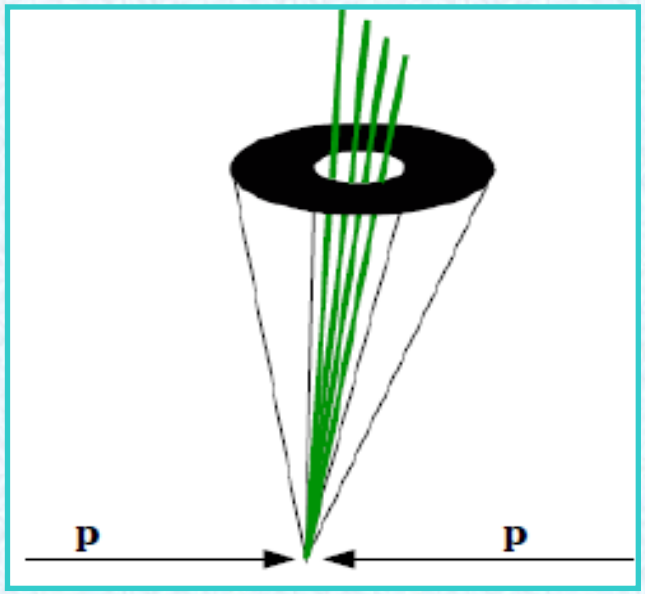
Lepton jets

- Since the dark photon is light, the leptons from its decay are highly boosted, and can be reconstructed as a lepton jet
- Selection (Yavin et. al)

  $\Delta R<0.1$, >=2 leptons with $p_t > 20$ GeV,

  hadronic isolation cut $\Sigma p_t < 3$ GeV

  $0.1<\Delta R<0.4$, isolation cut $\Sigma p_t < 3$ GeV



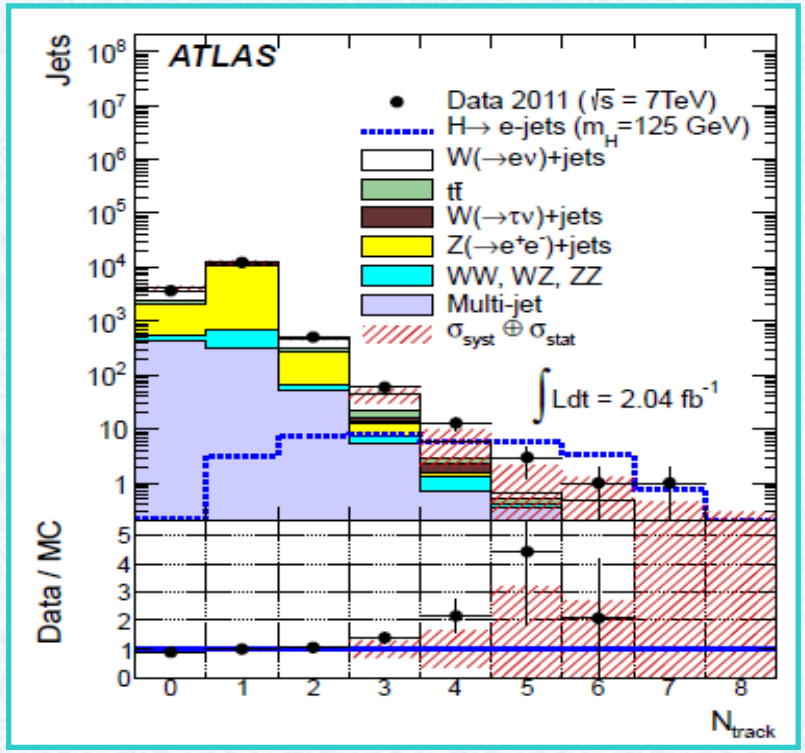
- Selection (ATLAS 1302.4403)

  $|\eta|<2.$, $p_t > 30$ GeV

  Jet electromagnetic fraction > 0.99

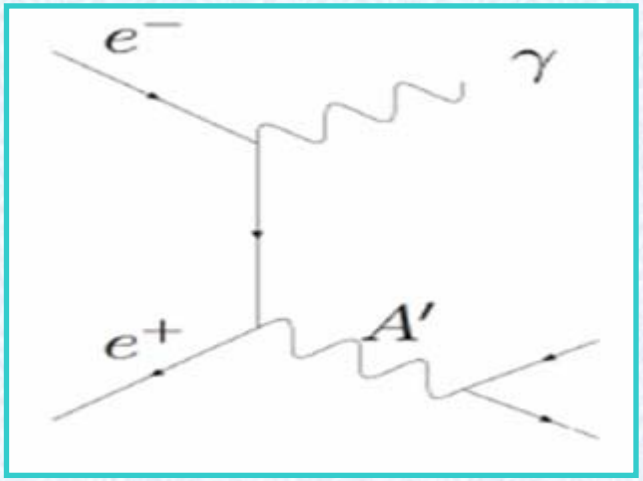
  Jet charged particle fraction >0.66

  Number of tracks >=2

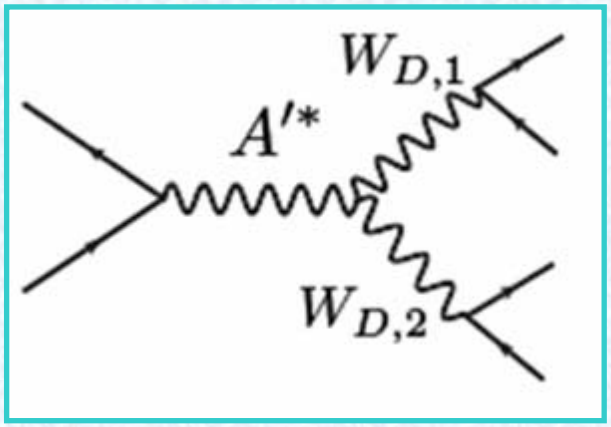


Dark photon production at e^+e^- colliders

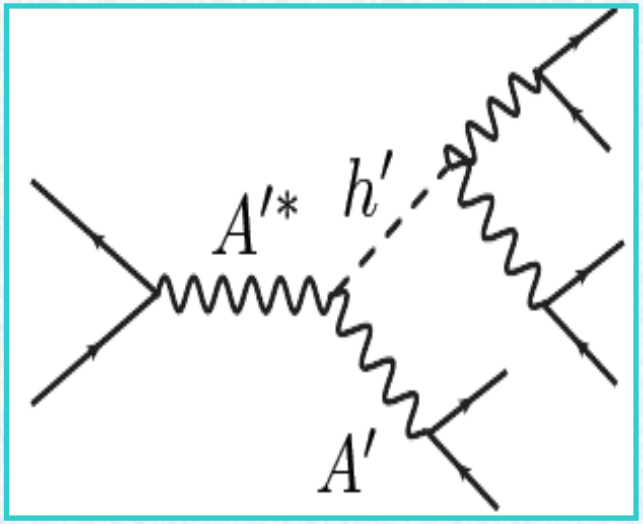
- Direct production, $e^+e^- \to \gamma\, l^+l^-$



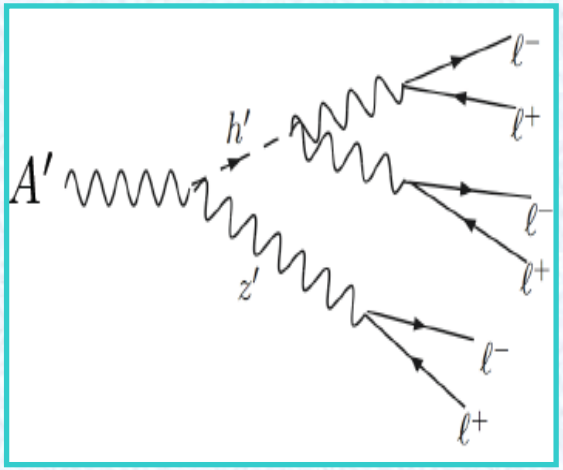
- Nonabelian gauge boson, $e^+e^- \to V'V' \to 2\, l^+l^-$

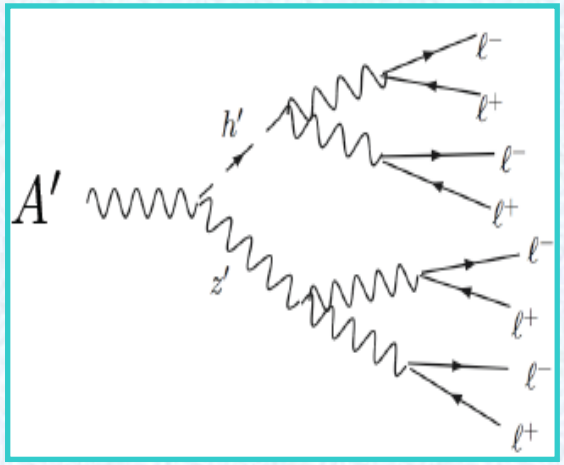


- Higgs strahlung, $e^+e^- \to \gamma\, 'h' \to 3\, l^+l^-$



- Other complicated decay chains





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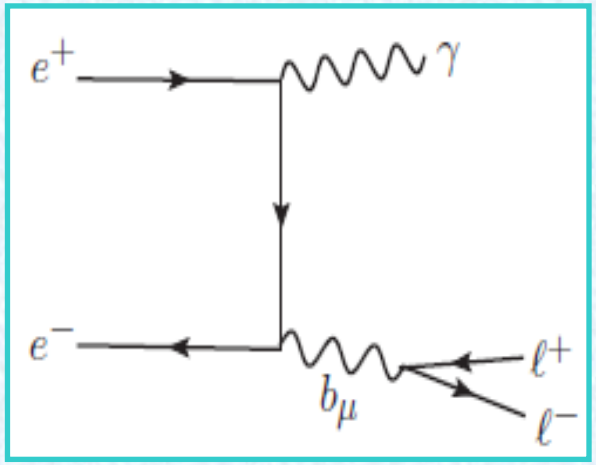
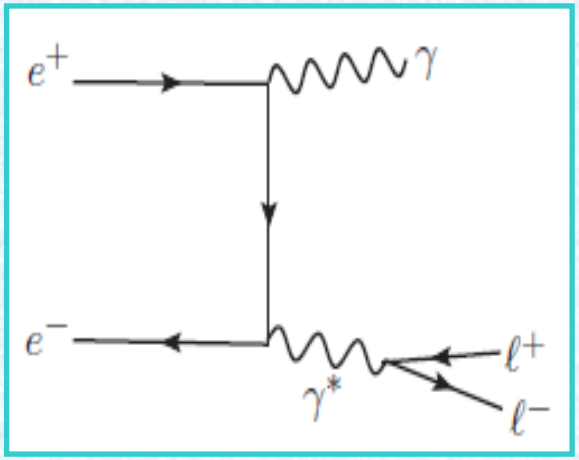
Reach for direct production





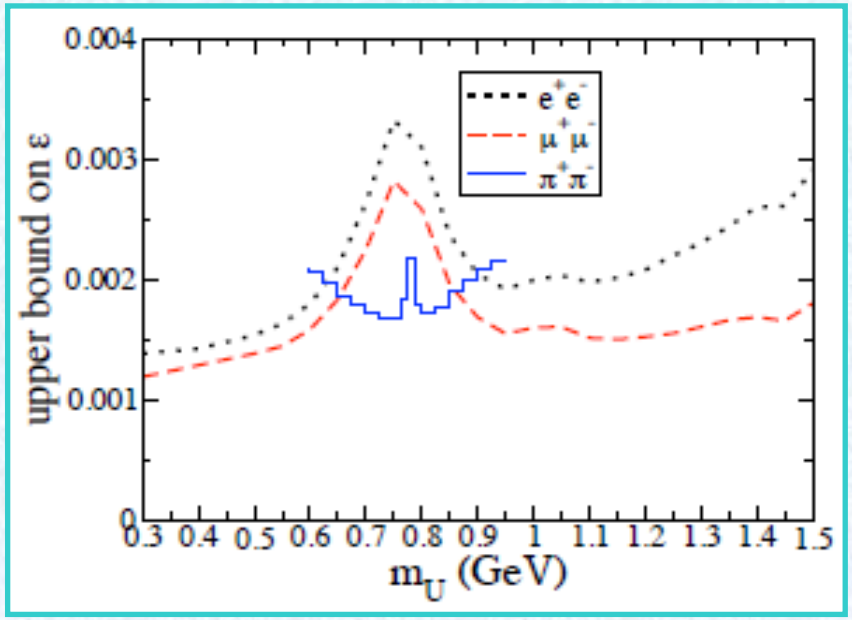
- It is better to produce dark photon at low energy, high luminosity colliders

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

- Large QED background reconstruct invariant mass to suppress the background

$$\frac{S}{\sqrt{B}} \sim \sqrt{\sigma_0 \mathcal{L}} \frac{\epsilon^2}{\sqrt{\alpha/\pi}} \sqrt{\frac{m_{b_\mu}}{\delta m}} \times \mathrm{BR}(U \to \ell^+\ell^-)$$

- luminosity ~100 fb^{-1}
- Resolution ~MeV
- Rate of $e^+e^- \to \gamma\gamma$ ~ 10^4pb
- Reach for ε is proportional to $L^{-1/4}$



Reece, Wang, 0904.1743

Meson decay

- Dark photon can be produced from decays of mesons, ρ, η, ϕ, Υ, J/ψ, with **BR~ε^2 BR(meson->γ)**

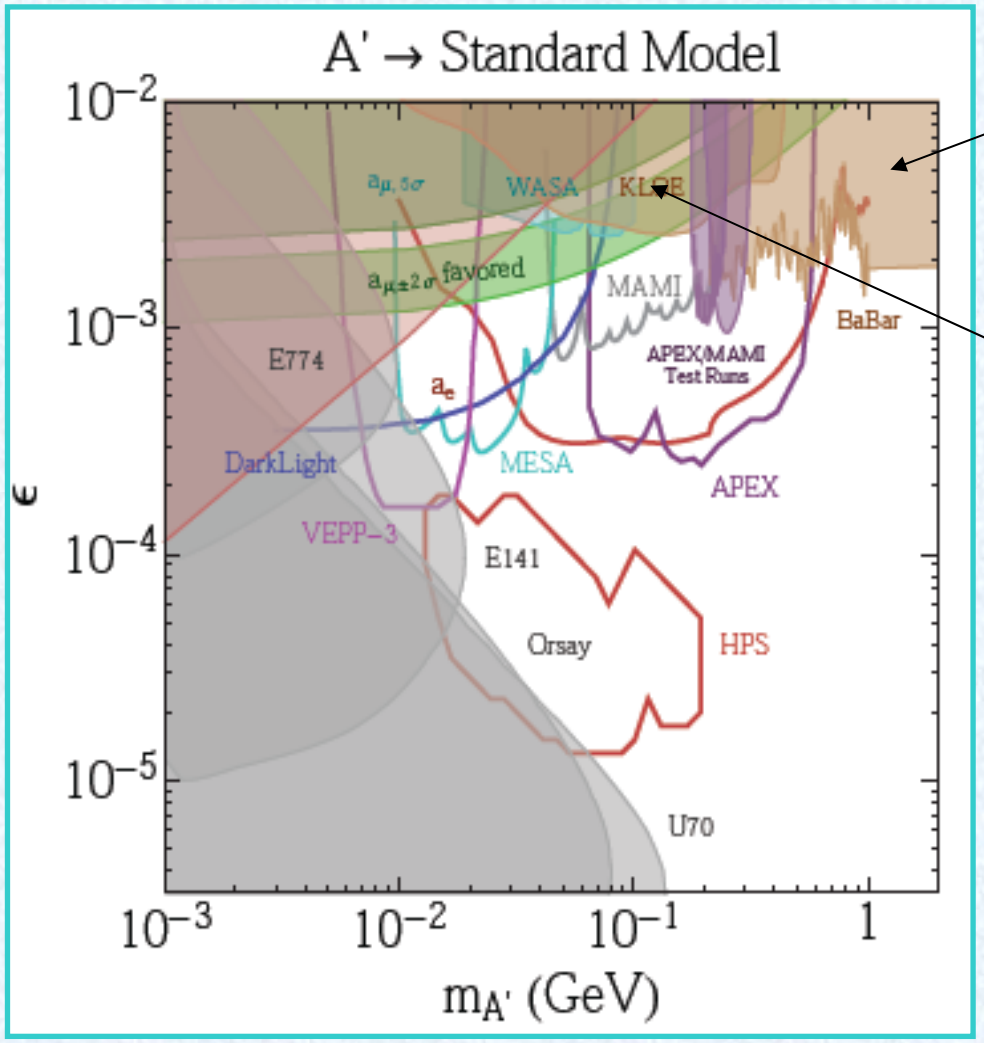
- Signal significance can be estimated as

$$\frac{S}{\sqrt{B}} \approx \sqrt{n_X}\frac{\epsilon^2 \times \mathrm{BR}(X \to Y + \gamma) \times \mathrm{BR}(U \to \ell^+\ell^-)}{\sqrt{\mathrm{BR}(X \to Y + \gamma^* \to Y + \ell^+\ell^-)}}\sqrt{\frac{m_U}{\delta m}\log\left(\frac{m_X - m_Y}{2m_\ell}\right)}$$

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

Reece, Wang, 0904.1743

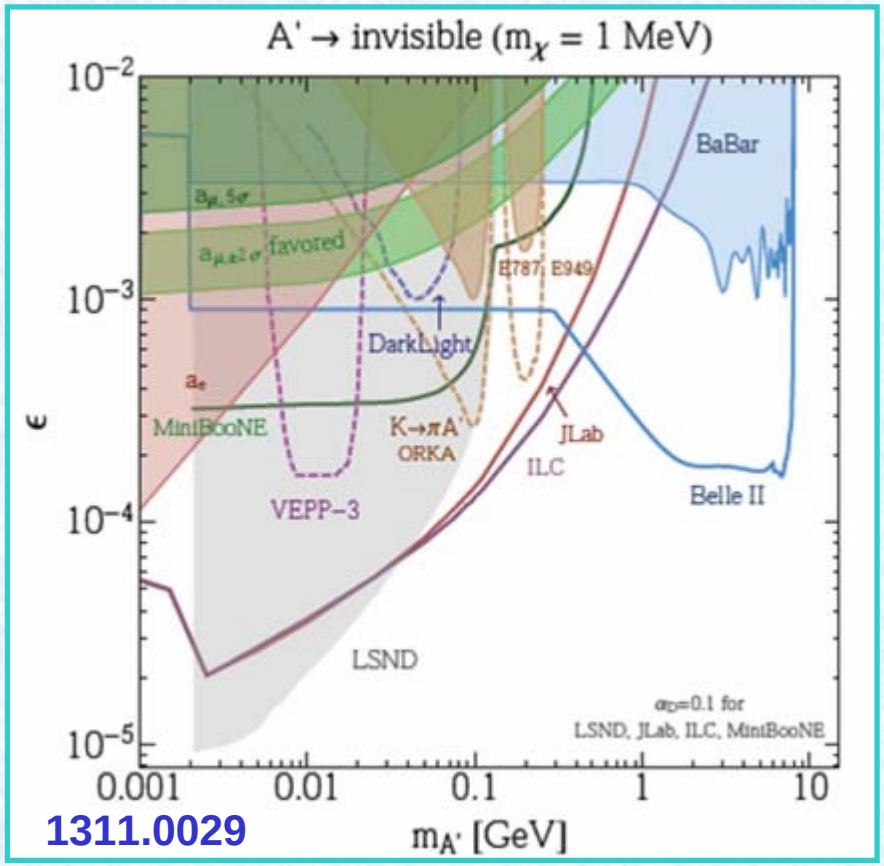
Some results



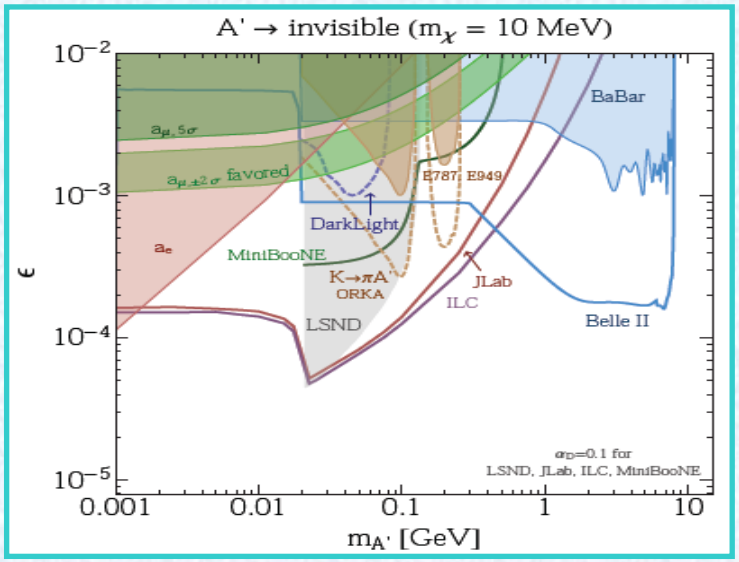
$$\Upsilon(2S,3S) \to \gamma A^0, A^0 \to \mu^+\mu^-$$

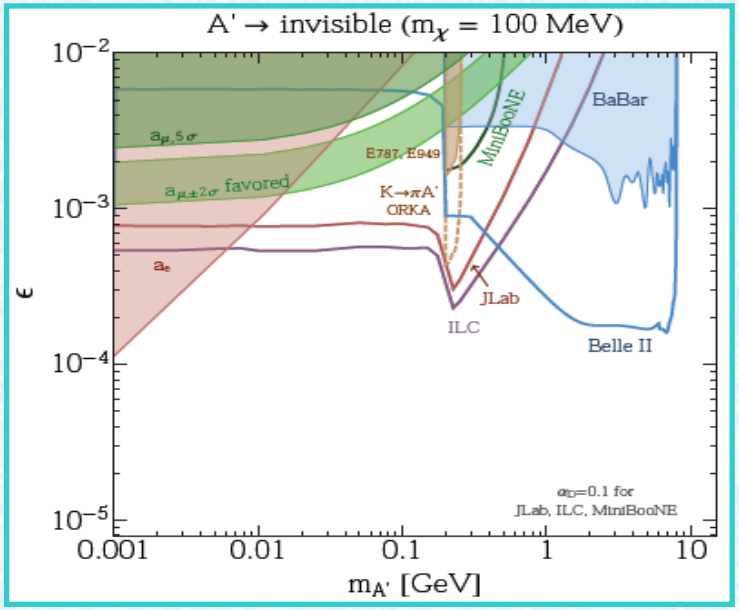
$$\phi(1020) \to \eta A', A' \to e^+e^-$$

Constraints on light DM

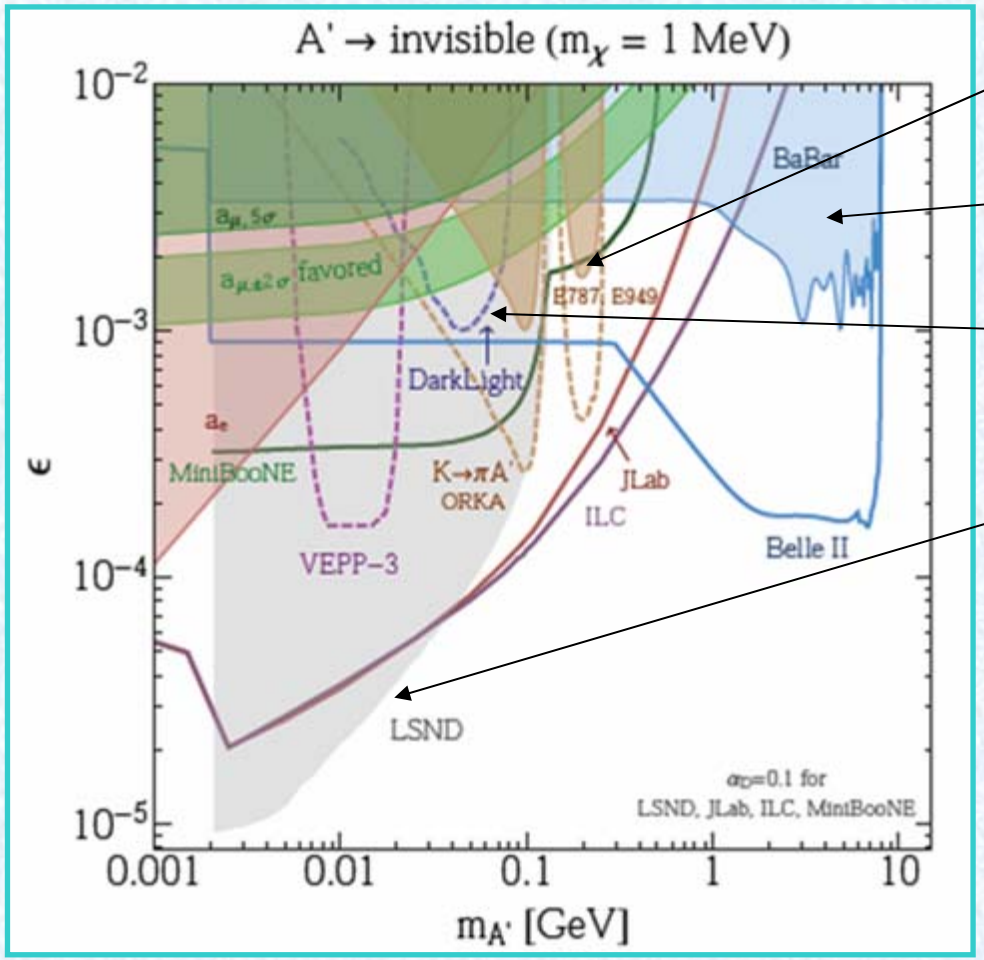


1311.0029





Constraints on light DM



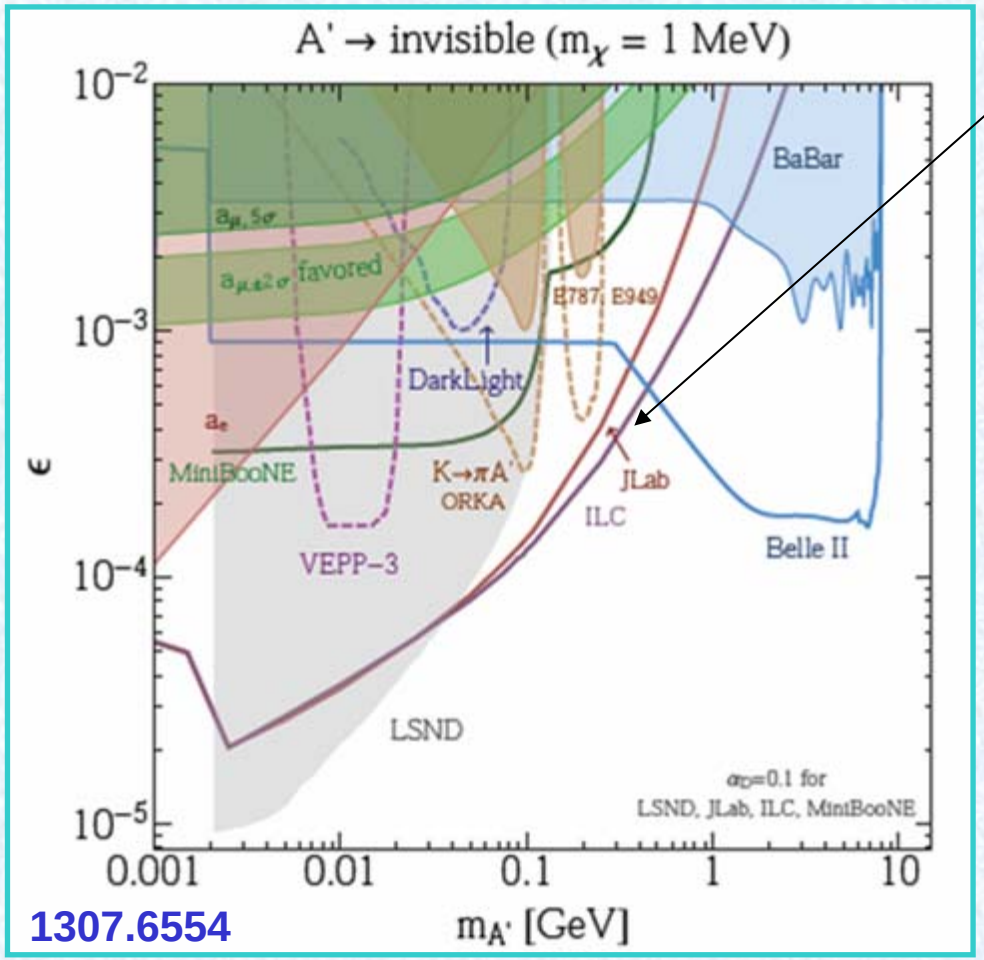
$K^+ \to \pi^+ A'$

$\Upsilon(3S) \to \gamma + A^0$

Mono-photon

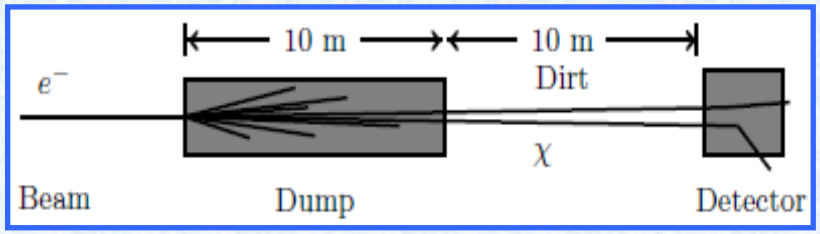
$\pi^0 \to \gamma A'$

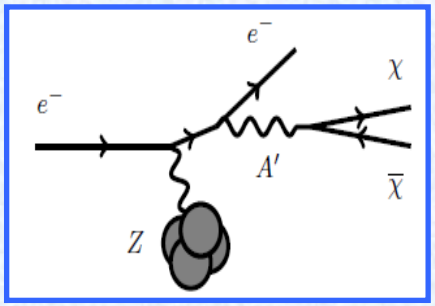
Constraints on light DM

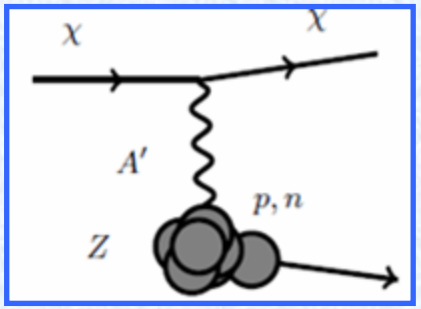


1307.6554

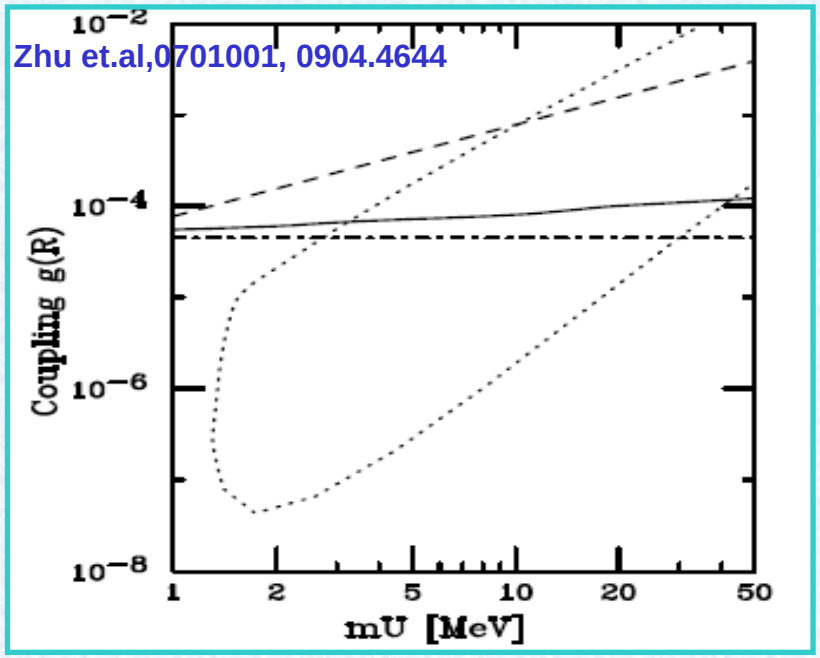
- Produce DM and then detect it directly

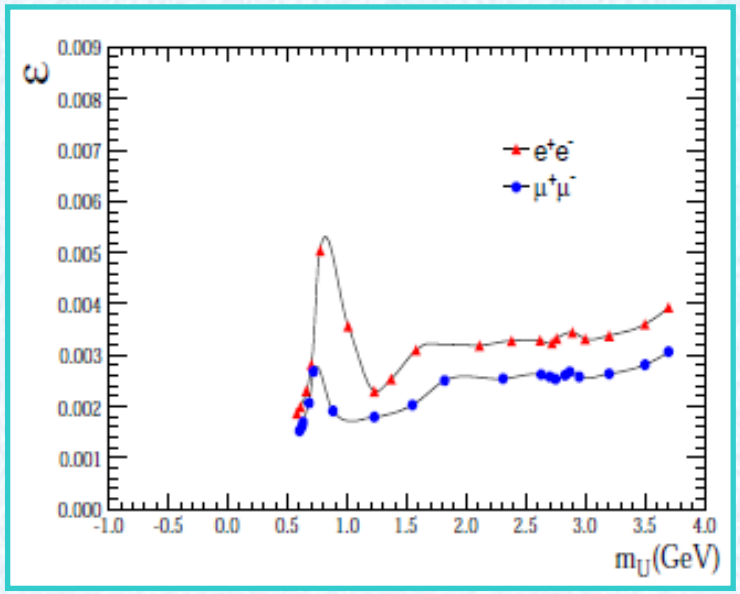


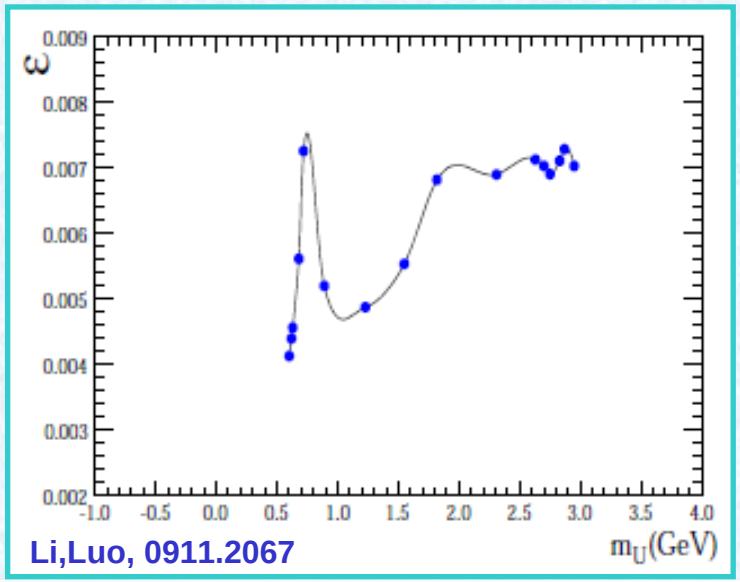




Dark sector at the BES







- Large number of J/ψ
- $e^+e^- \to \gamma\,\gamma' \to \gamma\, l^+l^-$
- $J/\psi \to \gamma'\, l^+l^- \to 4l$
- $\Psi(2S) \to \gamma'\, \chi_{c1,2} \to e^+e^-\, \chi_{c1,2}$
- $J/\psi \to \gamma'\, h' \to l^+l^- + \text{inv}$
- $J/\psi \to 3\gamma' \to 6l$

Conclusion

- (sub)GeV dark sector can be researched in three frontiers
- To discover dark sector in the intensity frontier is well-motivated
- Some parameter space is left to search for the future low energy collider with high luminosity

Conclusion

- (sub)GeV dark sector can be researched in three frontiers
- To discover dark sector in the intensity frontier is well-motivated. This is a very active and attractive topic in the high energy physics
- Some parameter space is left to search for the future low energy collider with high luminosity

Thank you !