Dark Sector at the low energy

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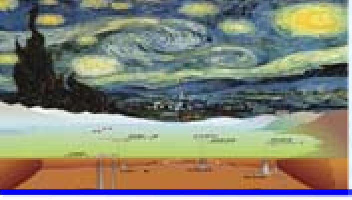
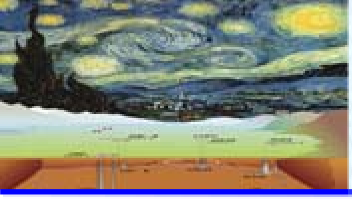
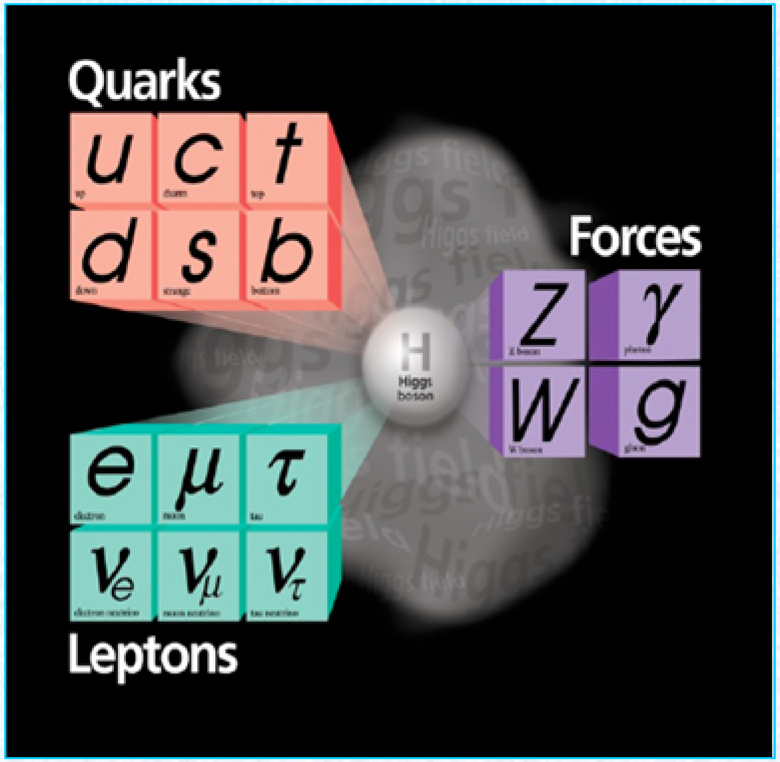


Outline

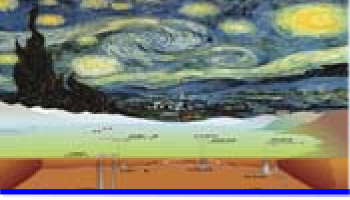
- Motivation of studying on the dark sector
- Some "hints" for the dark photon
- Searches for the dark photon and dark sector
  - High energy collider
  - Beam dump and fixed target experiments
  - Low energy e^+e^- collider
- Searches for the dark photon at BES



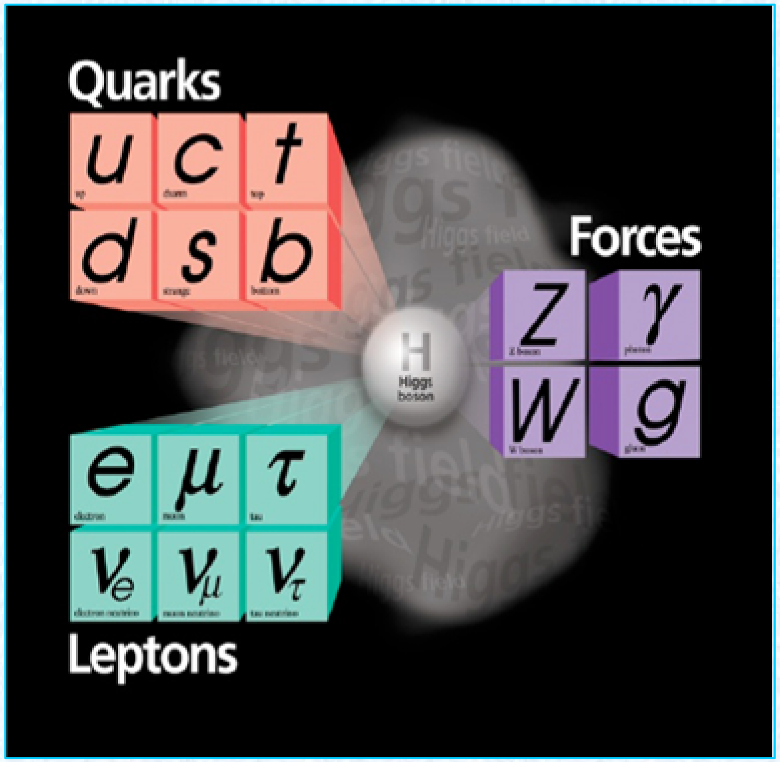
Standard model ! What's the next?



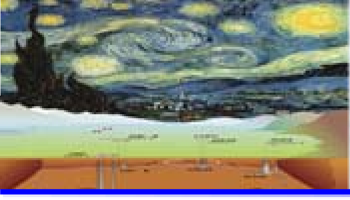
- SM is remarkably successful
- Most of predictions are tested at high precision
- Where is the new physics beyond SM (BSM)?



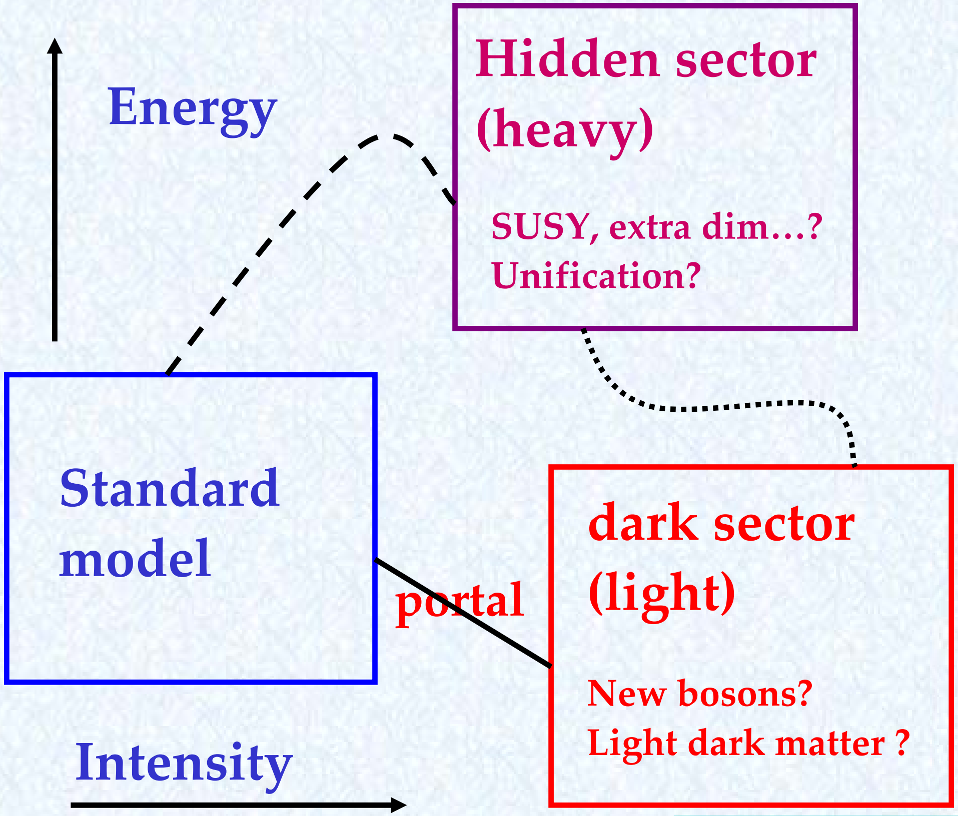
Standard model ! What's the next?



- SM is remarkably successful
- Most of predictions are tested at high precision
- Where is the new physics beyond SM (BSM)?
  - No BSM at all !
    Quite strange… So many problems are unresolved: the origin of mass, flavor, CP-violation, neutrino mass,
    the dark universe…
  - BSM at very high energy scale !
    Commonly believed… But no one knows where is the next scale…
  - BSM interacts weakly with SM at low energy scale !
    Low energy experiments in the intensity frontier have capability to discover the new sector;
    Complementary to high energy experiments



SM, dark sector, and portal



- The interactions between the SM and BSM can be described by effective operators

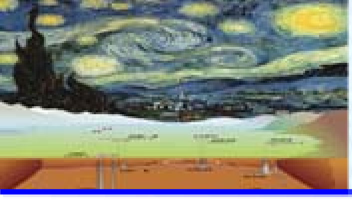
$$L_{eff} = L_{SM} + \sum \frac{f_i^{(5)}}{\Lambda} O_i^{(5)} + \sum \frac{f_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

They are always suppressed by the energy scale

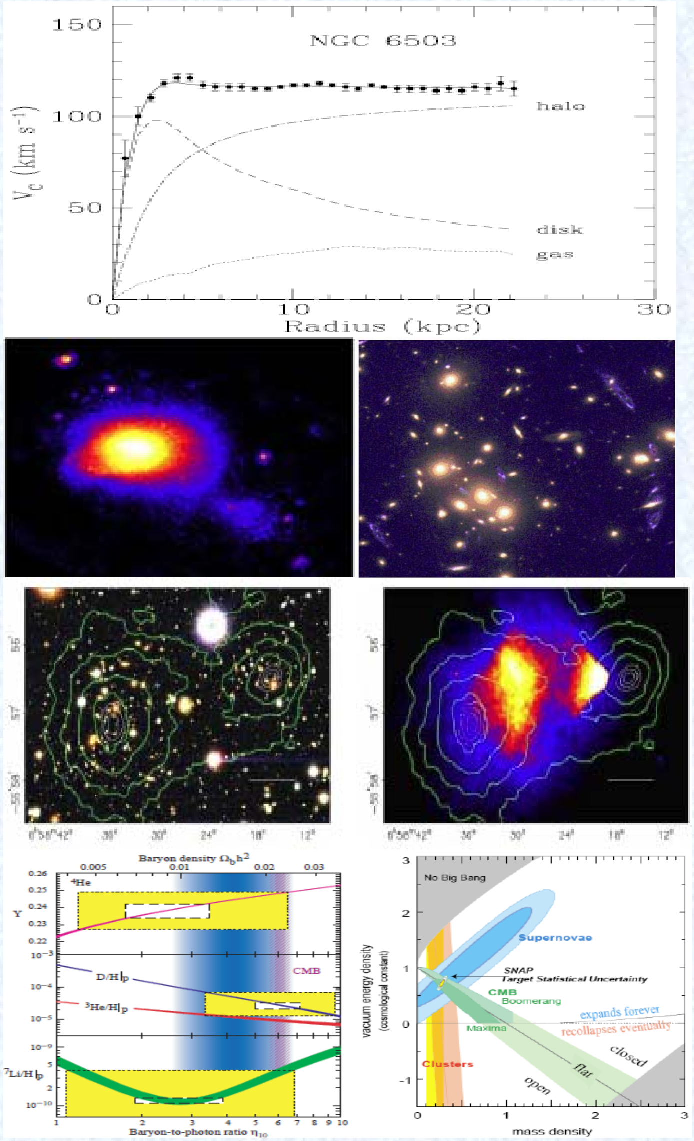
- Difficult to be tested at low energy scale experiments. Only via indirect effects ?
- There may be new light particles connecting the dark sector to SM !

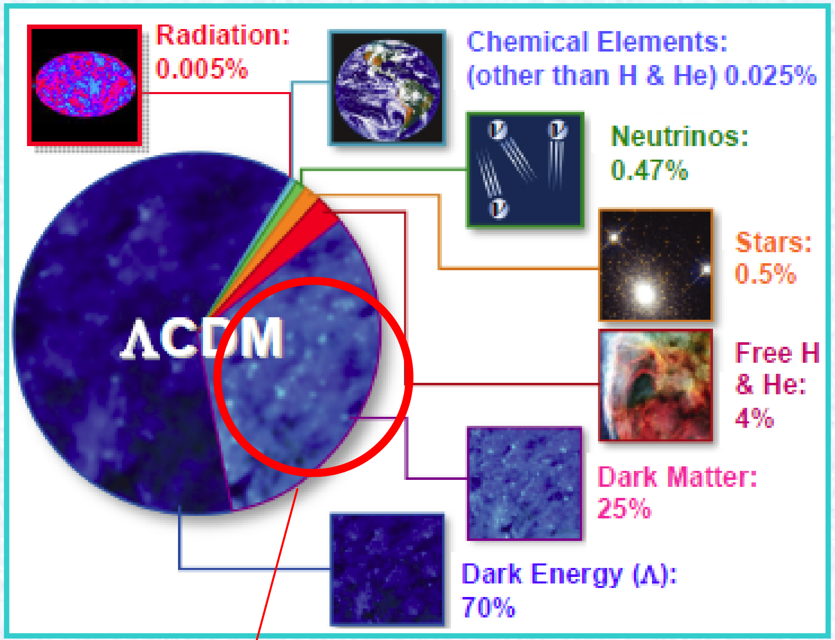
Portal	Particles	Operator(s)
"Vector"	Dark photons	$-\frac{\epsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu}$
"Axion"	Pseudoscalars	$\frac{a}{f_a} F_{\mu\nu} \widetilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i\mu\nu} \widetilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$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

- It is also called hidden photon, heavy photon, A′, γ′, b_μ, Z_D or U boson in the literature

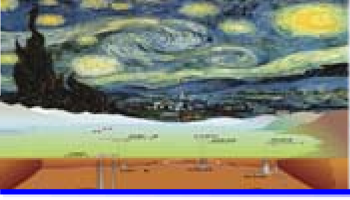


The dark universe! The dark sector?

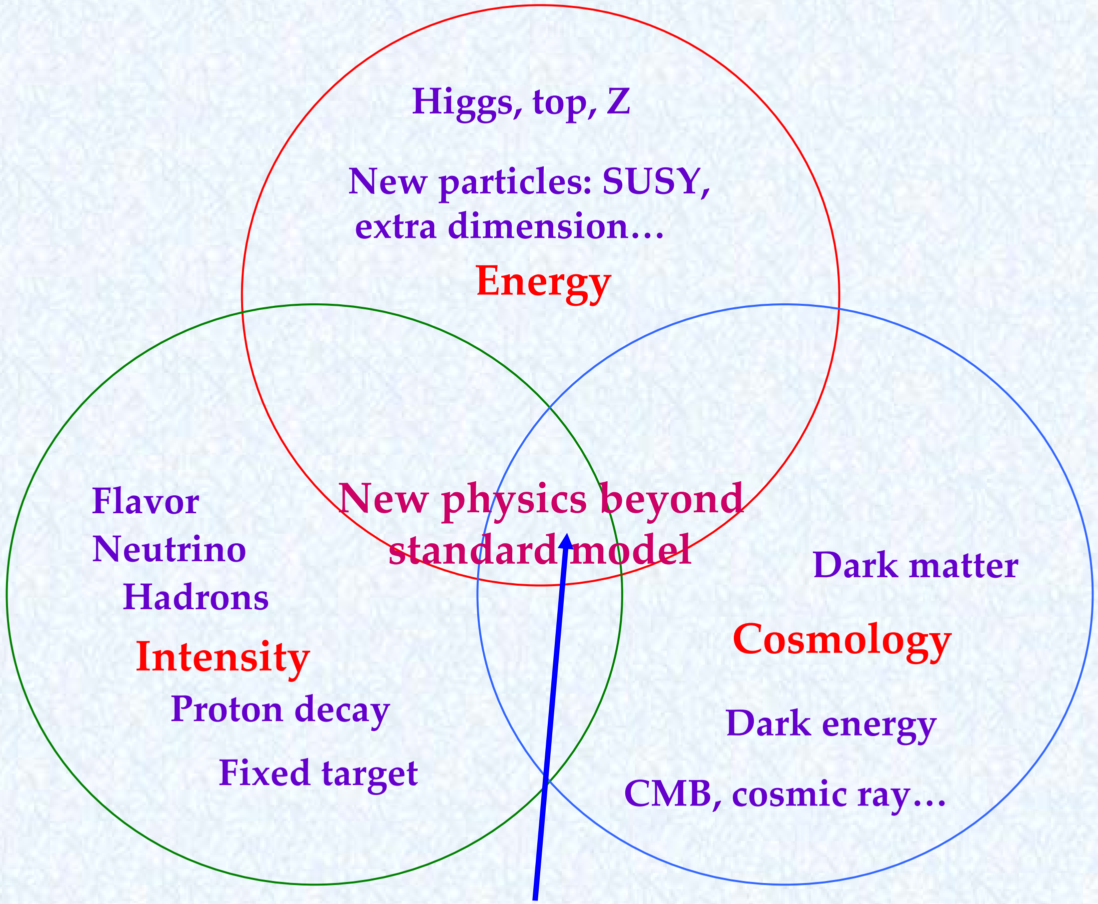




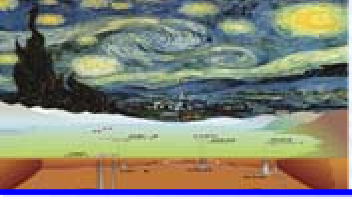
- Many results from astrophysical and cosmology observations have confirmed the existence of dark matter (DM)
- The particles nature of DM is still unknown
  - Only a WIMP ?
  - No! There may exist a dark sector with complicated structure !



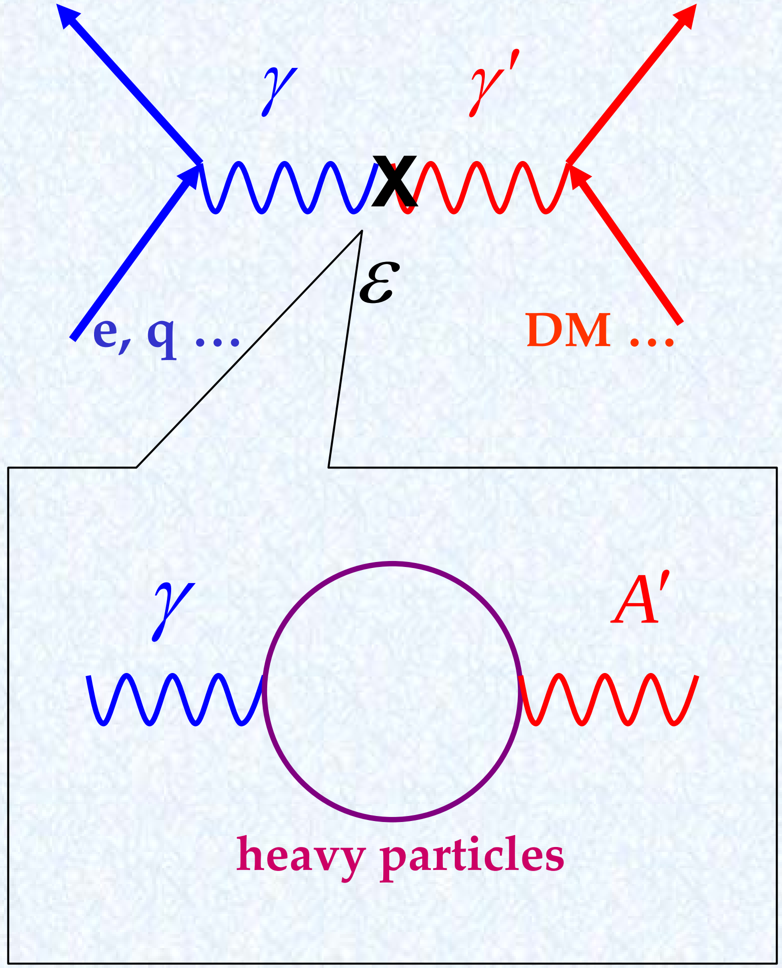
Three frontiers for the BSM



- **Search for new sub-GeV gauge boson**
- **Search for new sub-GeV boson**
- **Search for new dark sector**



Kinetic mixing



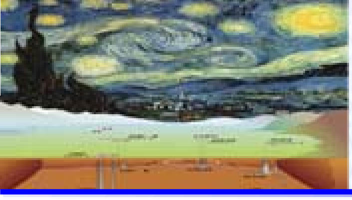
- **Kinetic mixing between dark photon and photon**
- **Mixing can be generated by quantum loop mediated by some heavy particles**
- **Mixing is expected to be small**

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

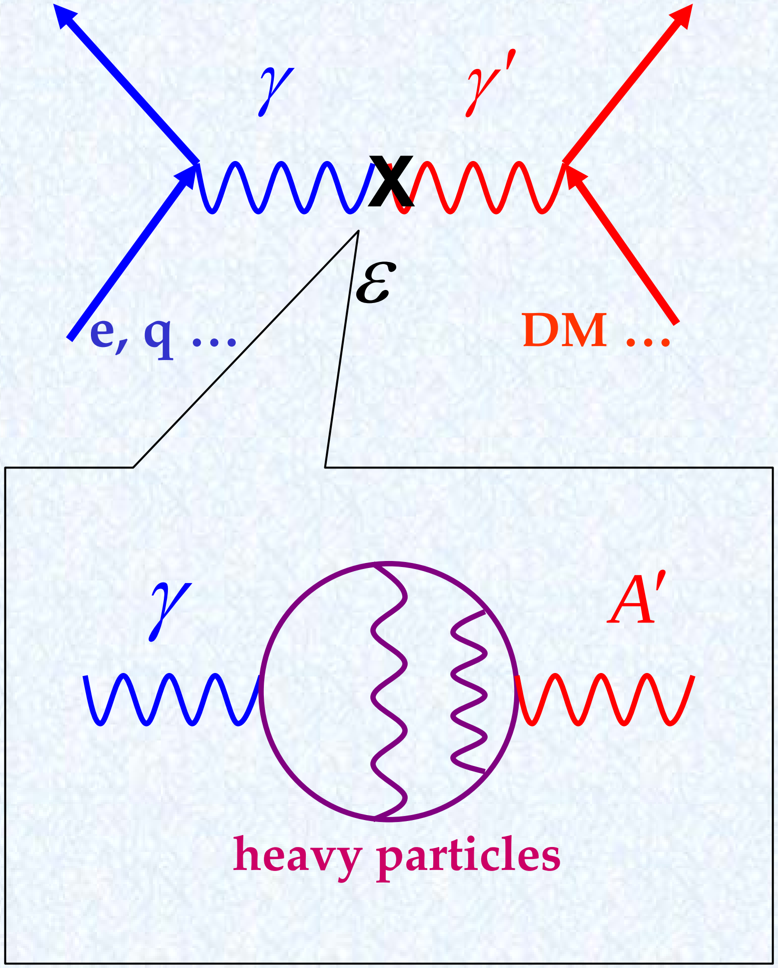
- **Induce effective interactions with the SM**

$$\varepsilon e A' J_{EM}$$

- **If the mixing is induced by higher order effects (GUT), it can be very small ~10^{-7}**
- **Some BSM models (such as SUSY) can also explain the origin of the mass scale ~$\sqrt{\varepsilon} m_Z$ ~MeV-GeV**



Kinetic mixing



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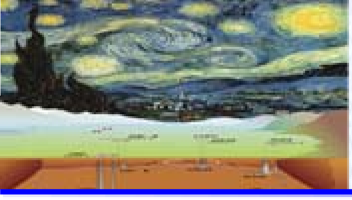
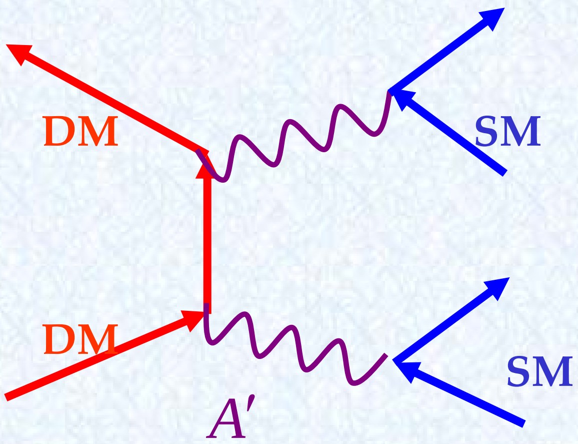
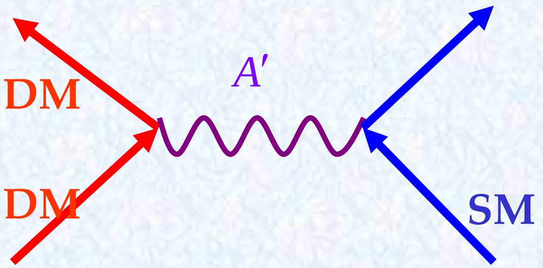
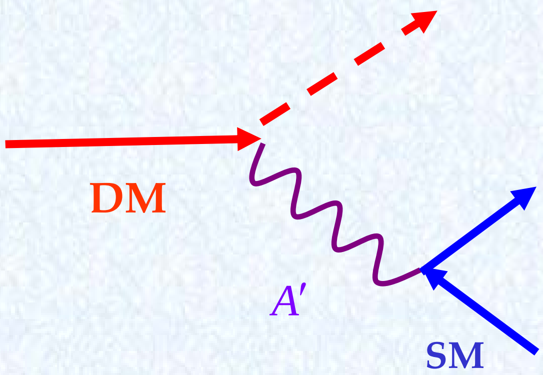


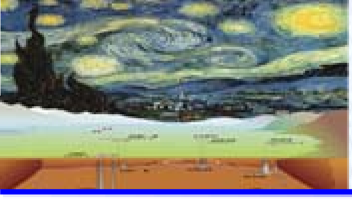
Dark photons in the SKY?



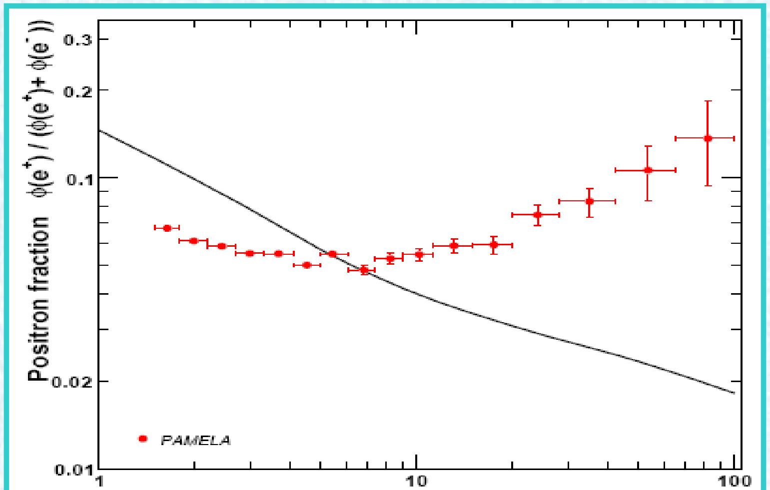




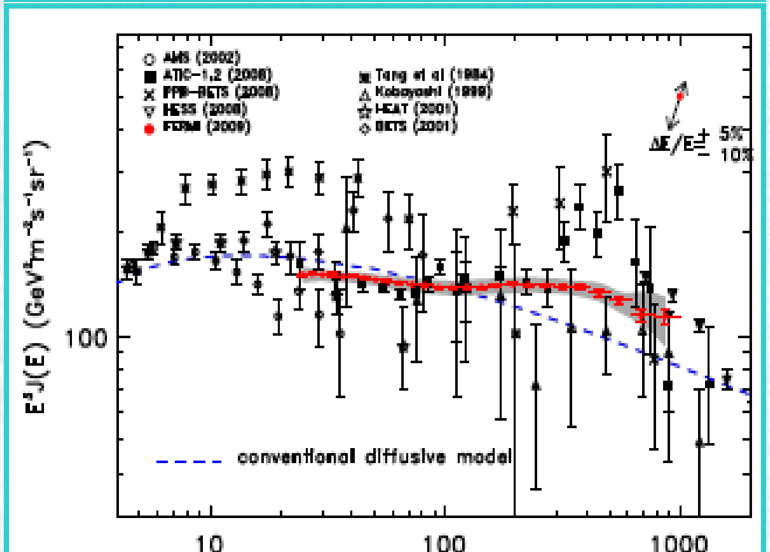
- DM can annihilate/decay into dark photons and produce energetic cosmic rays



CR positron/electron excess



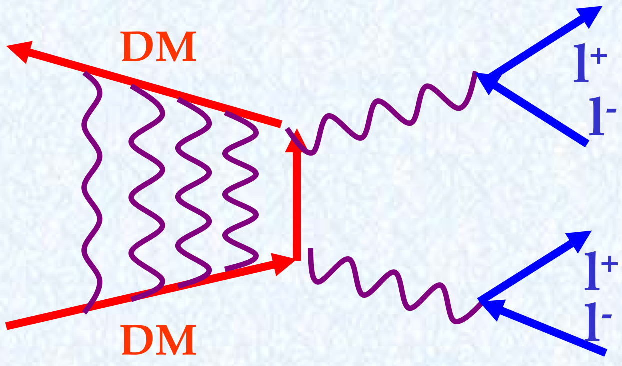
PAMELA, 2008

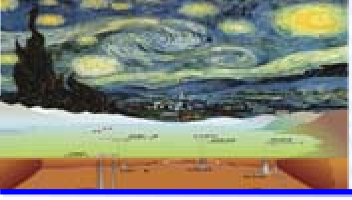


Fermi, 2009

- Observed by PAMELA, Fermi, ATIC and HESS. Recently confirmed by AMS02 with high precision
- DM interpretation requires large DM annihilation cross section .

  Can be explained by the "Sommefeld" effect mediated by light dark photons ~GeV
- No antiproton excess. If dark photons are light enough, they do not produce antiprotons.
- However, the DM interpretation is severely constrained by high energy gamma-ray observations from Fermi-LAT





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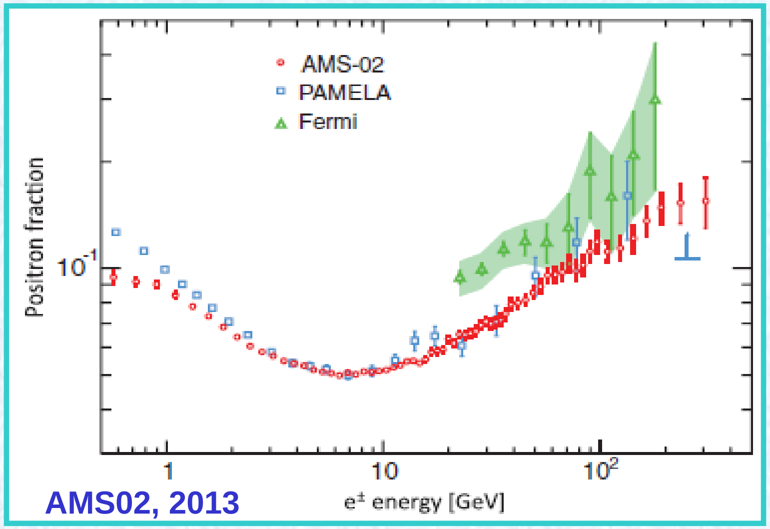
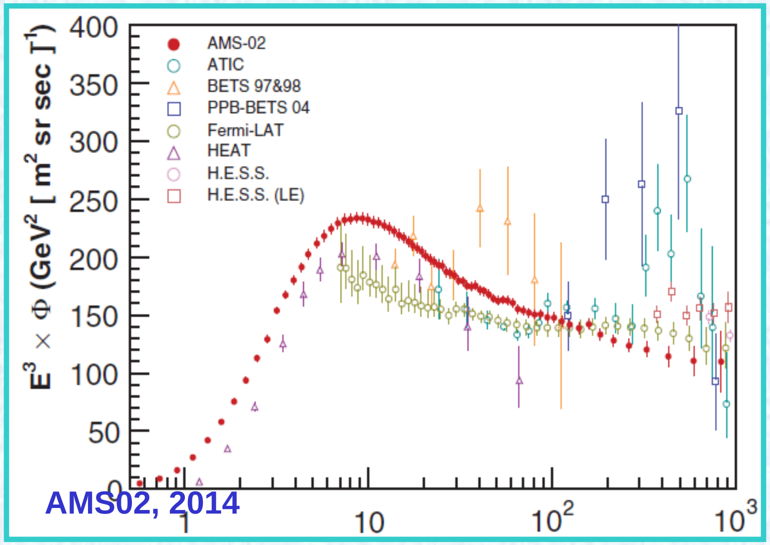
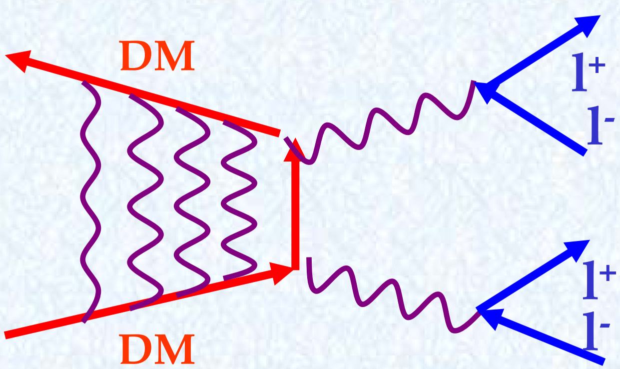
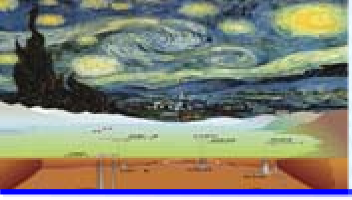




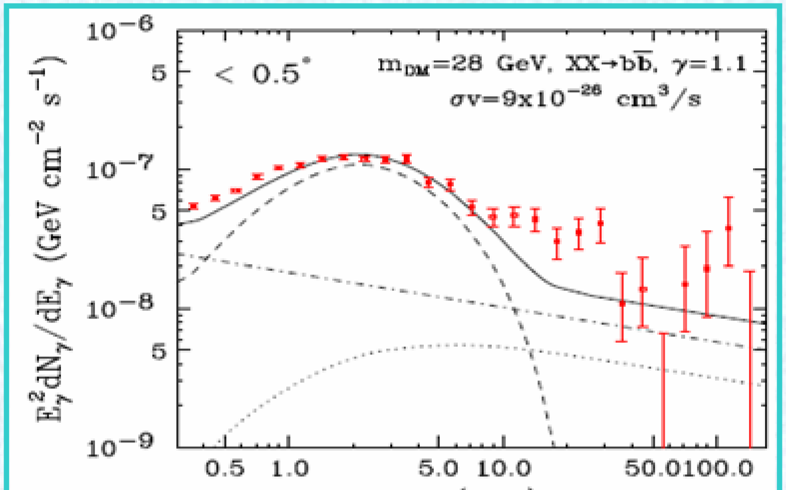
- Observed by PAMELA, Fermi, ATIC and HESS. Recently confirmed by AMS02 with high precision
- DM interpretation -> large DM annihilation cross section ->"Sommefeld" effect

  -> light dark photons ~GeV
- No antiproton excess -> dark photons are light enough <GeV (do not decay into antiprotons).
- However, the DM interpretation is severely **constrained** by high energy gamma-ray observations from Fermi-LAT

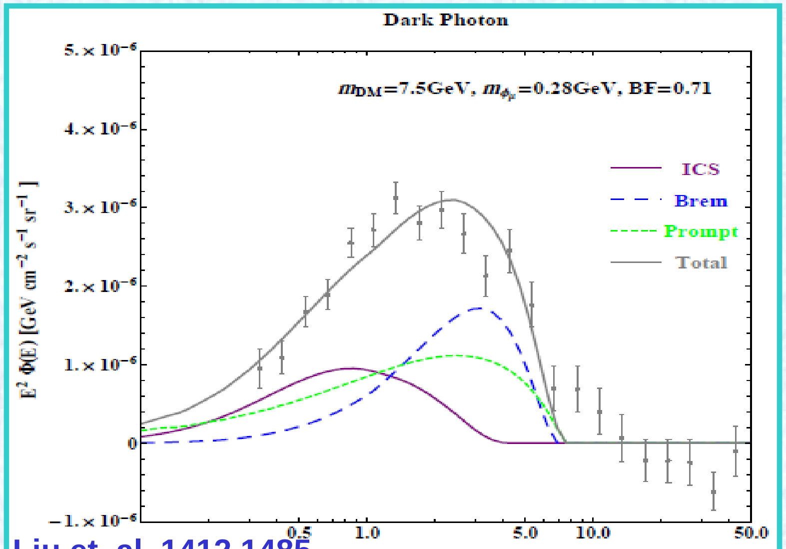




GeV gamma-ray excess in the Galactic Center

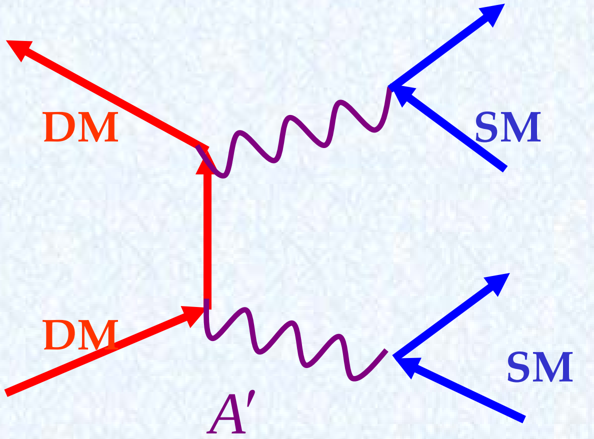


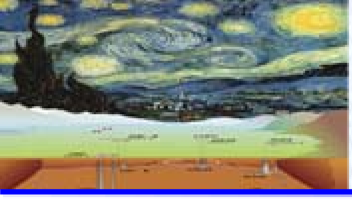
Hooper et. al, 0910.2998



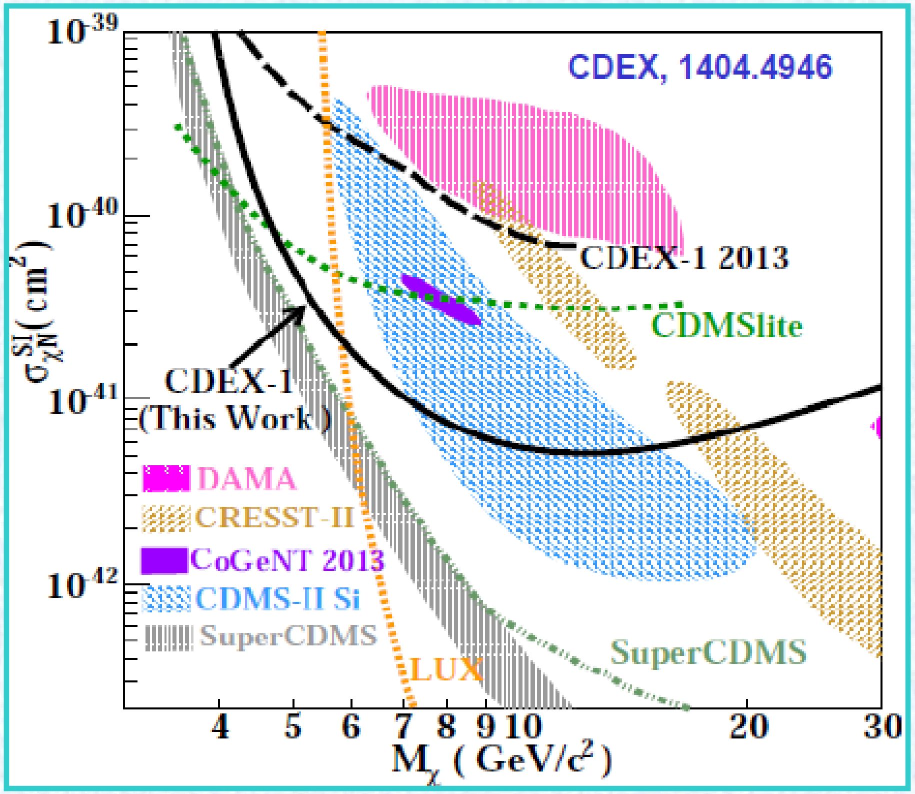
Liu et. al, 1412.1485

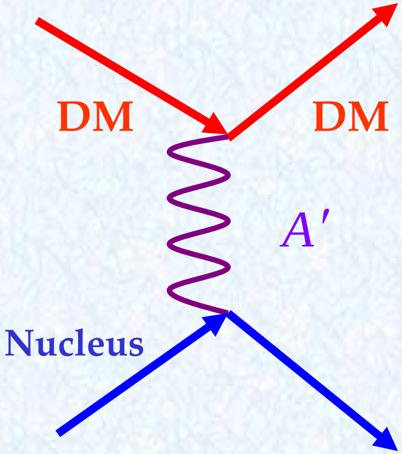
- An extended gamma-ray excess with a high significance peaking at a few GeV in the Fermi-LAT data was reported by Hooper and Goodenough in 2009.
- This excess is found in the Galactic center and inner galaxy, and is confirmed by many groups in 2013 and 2014.
- Can be explained by DM annihilations into b quarks. But constrained by the anti-proton data.
- This excess can also be explained by DM annihilations into dark photons.





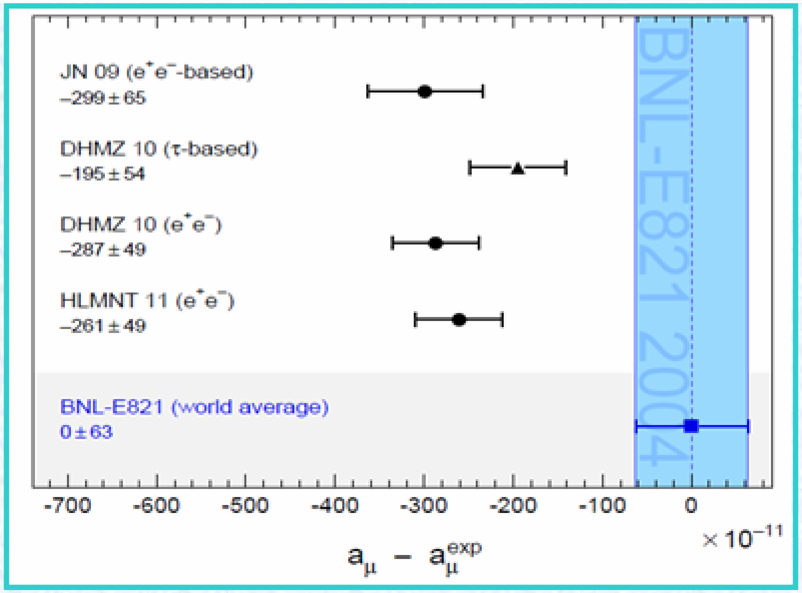
Dark photon in the DM direct detection

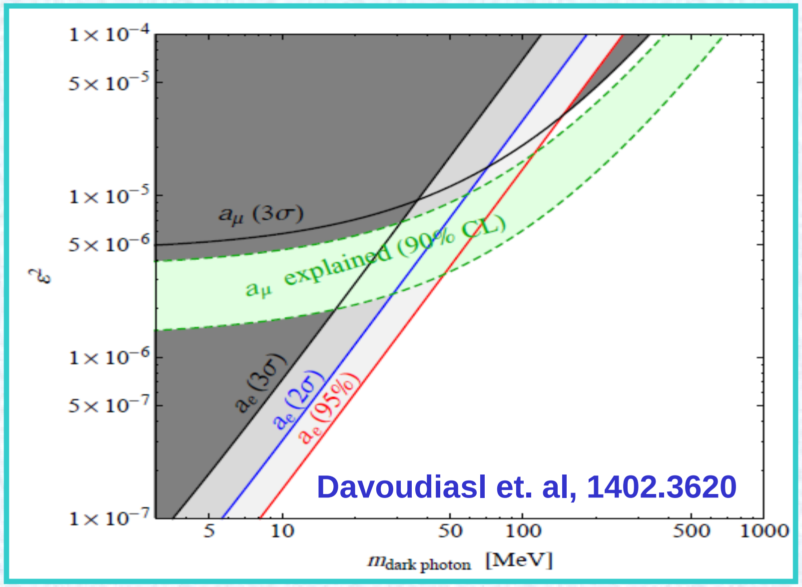


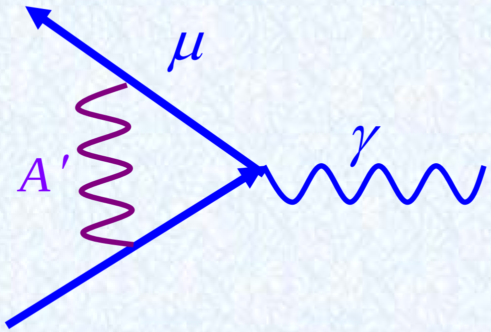


- Some direct detection experiments claimed the hints of light DM ~GeV-O(10) GeV, such as DAMA, CoGeNT, CRESST, and CDMS-Si
- Can be easily explained by the exchange of dark photon
- But the nature of these anomaly is still unclear. Severely constrained by other experiments, such as XENON, LUX, Super-CDMS, CDEX…

Anomalous muon g-2



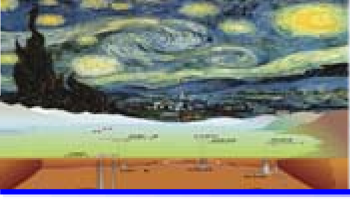




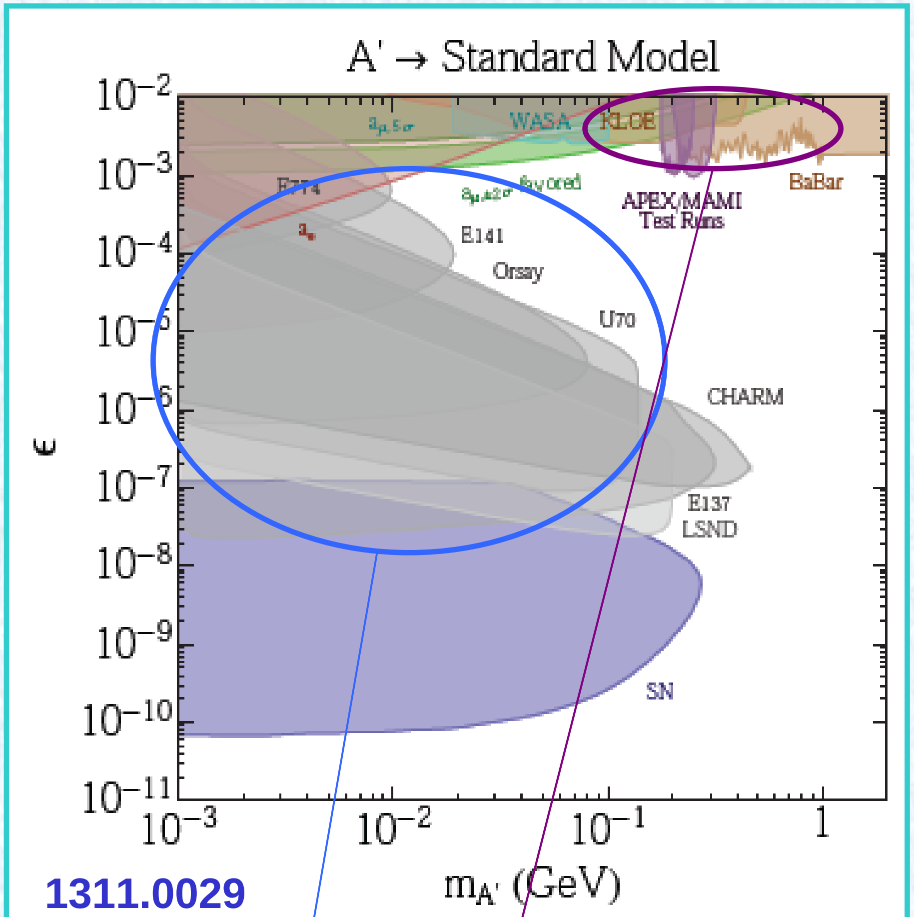
- The discrepancy between the theoretical predictions and experimental results is ~3σ.
- Hint for BSM, new particles in the loop, SUSY?
- Can be explained by the dark photon

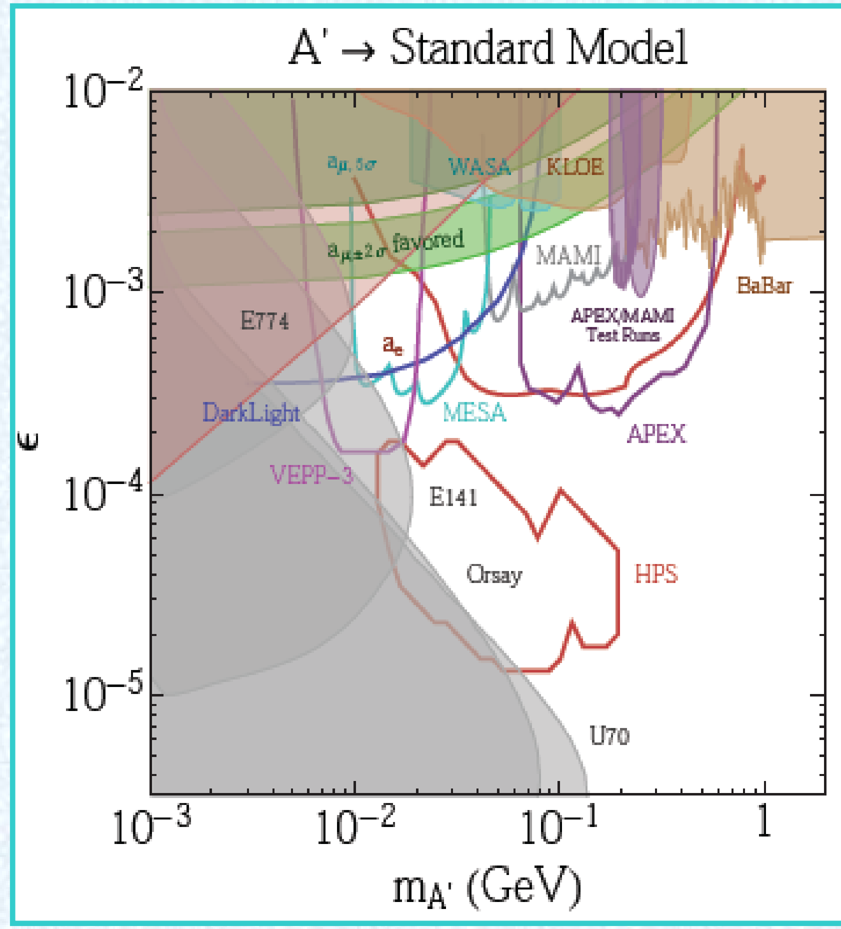
$$\varepsilon^2 \frac{\alpha}{2\pi} \sim 10^{-9}$$

- But the parameter space is severely constrained

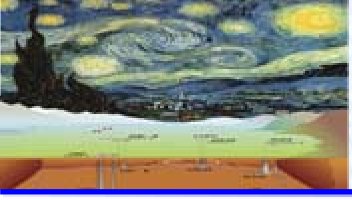


Current limits from terrestrial experiments ($m_{\gamma'}>$MeV)

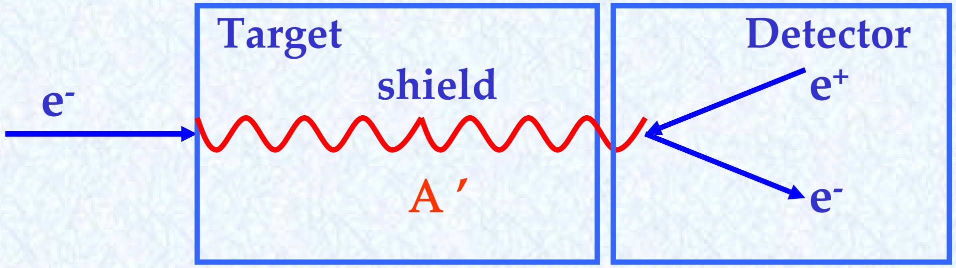




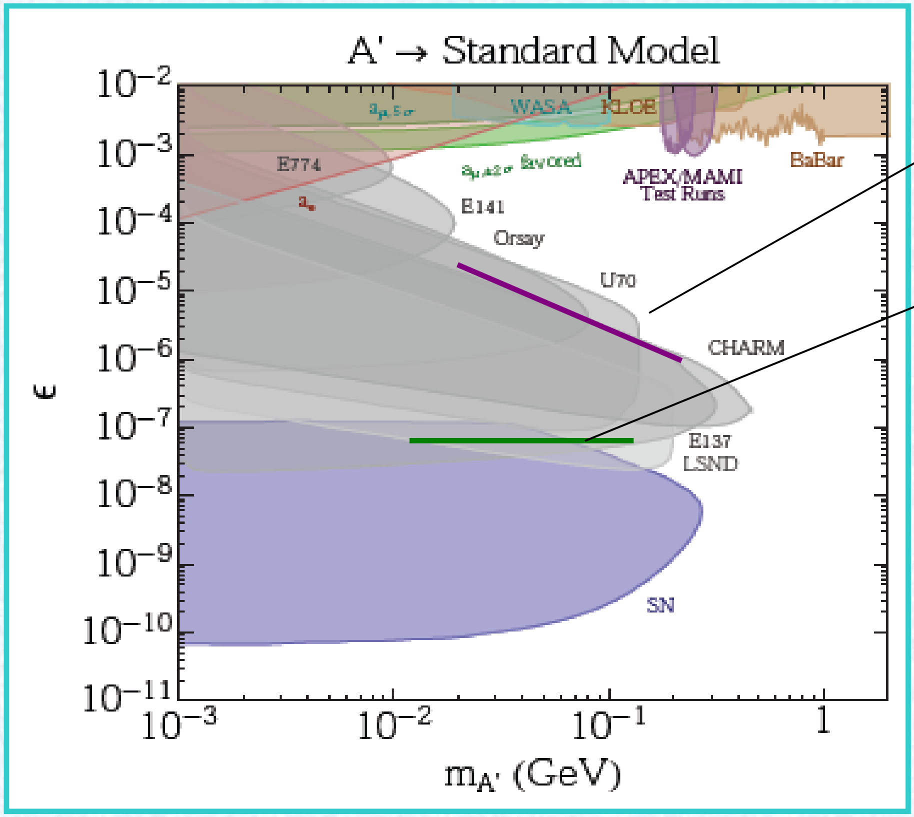
- Dark photon in this mass range can decay into charged leptons and mesons
- Beam dump experiments; Fixed target experiments
- Low energy e^+e^- colliders: direct production, rare meson decay
- High energy colliders



Electron beam dump experiments



- ep collisions can 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)

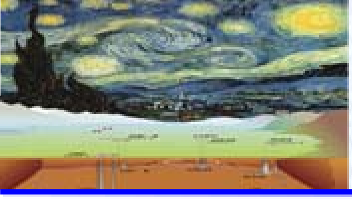


$$\sigma_{A'} \sim 100\ \mathrm{pb}\,(\epsilon/10^{-4})^2\,(100\ \mathrm{MeV}/m_{A'})^2$$

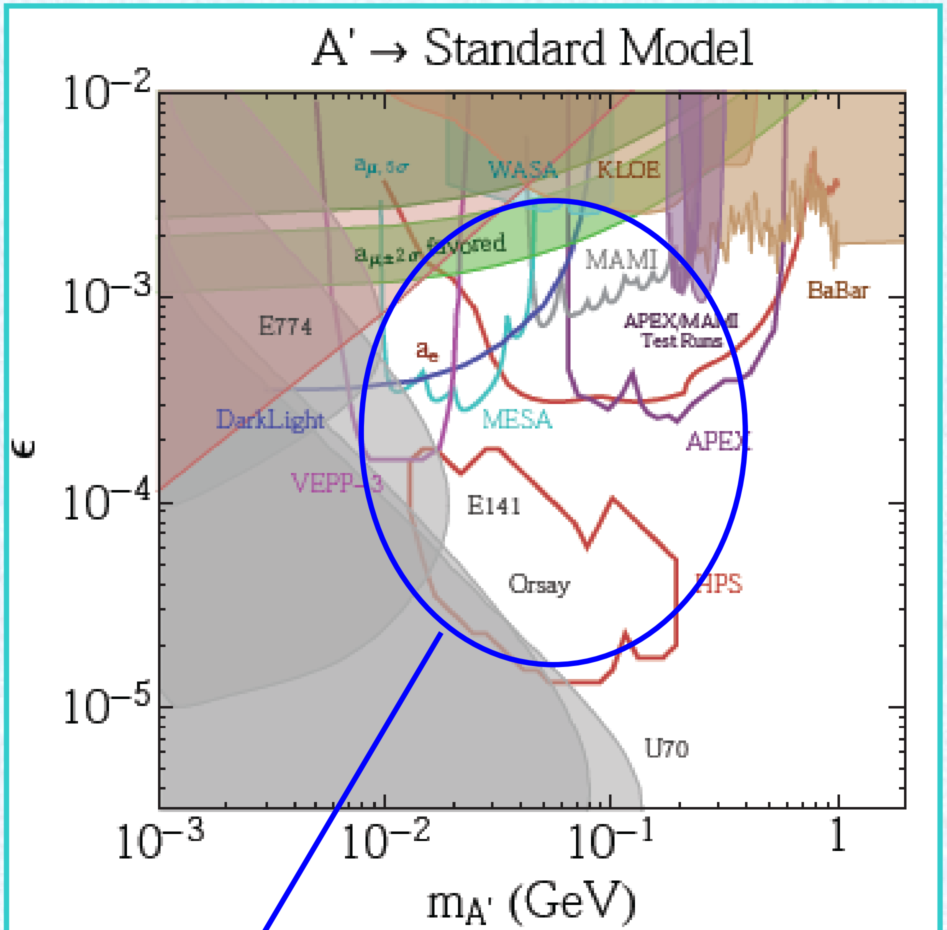
$$\gamma c\tau \sim 1\ \mathrm{mm}\,(\gamma/10)\,(10^{-4}/\epsilon)^2\,(100\ \mathrm{MeV}/m_{A'})$$

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

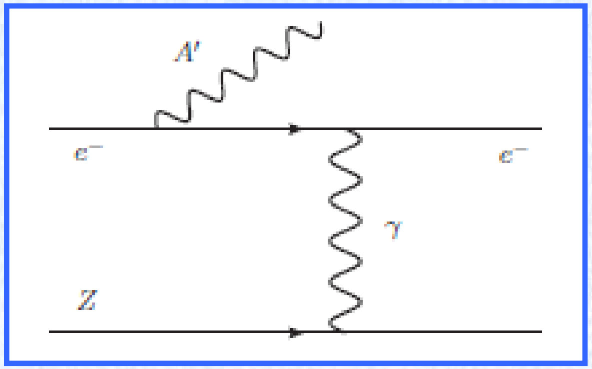
Bjorken et. al, 0906.0580



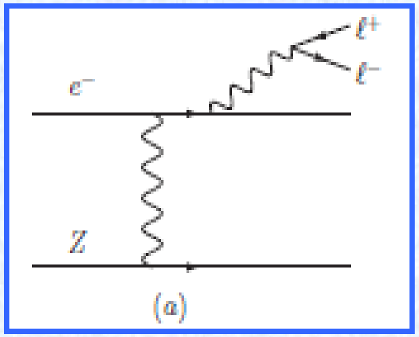
Electron fixed target experiments

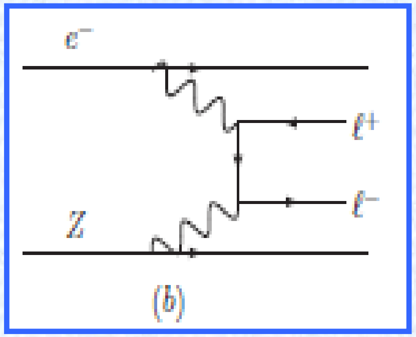


- The lifetime of dark photon is small (~<O(1) cm)
- Need thin target

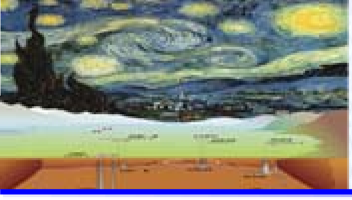


- Produced dark photons are extremely forward



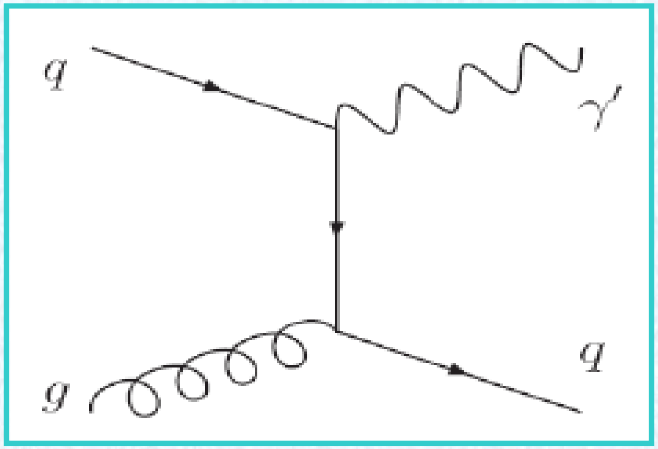


- Radioactive and Bethe-Heitler BG
- Reconstruct the **displaced decay vertex** and **invariant mass** of the dark photon to suppress BG

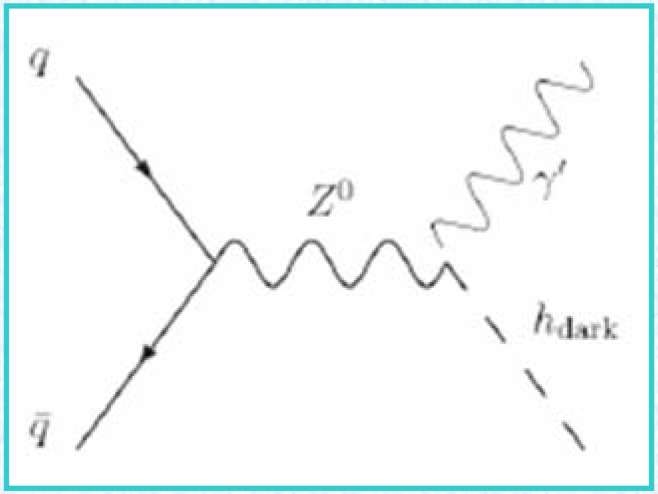


Research at High energy colliders

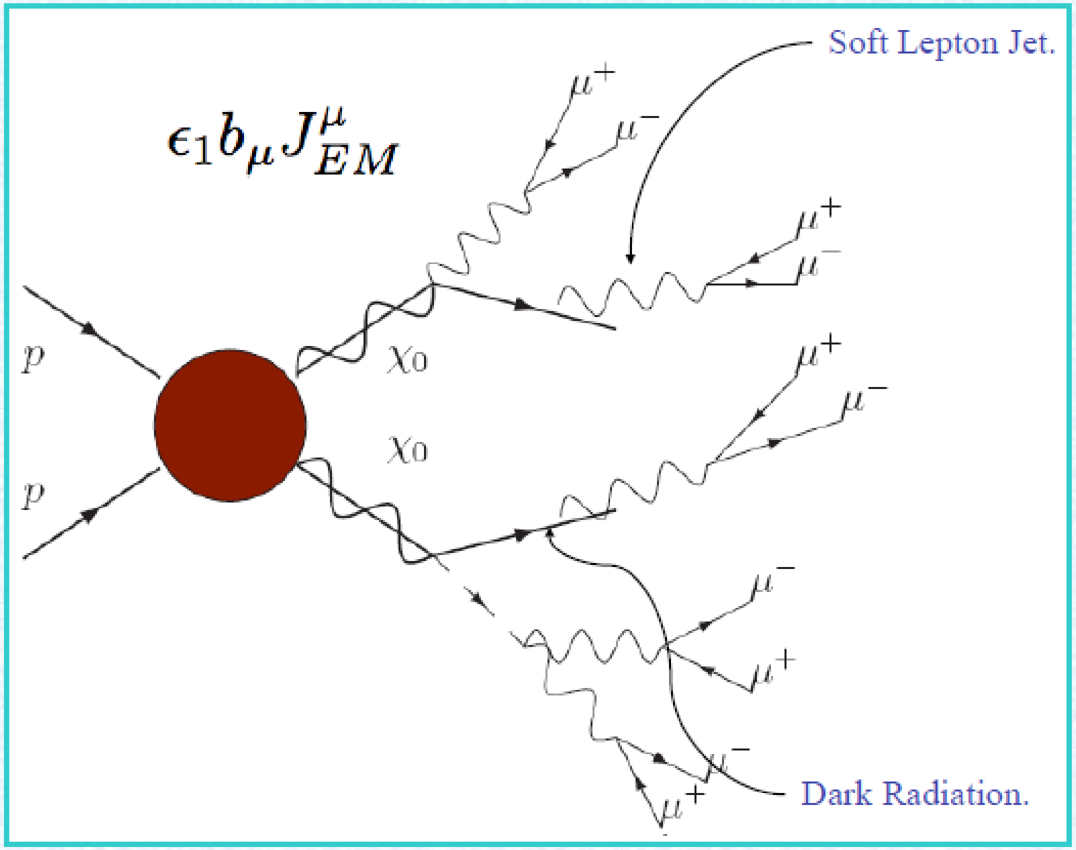
- Direct production (suppressed by small mixing)



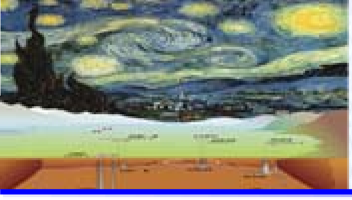
- Dark higgs strahlung



- Cascade decay, e.g SUSY particles would decay into dark photon without suppression

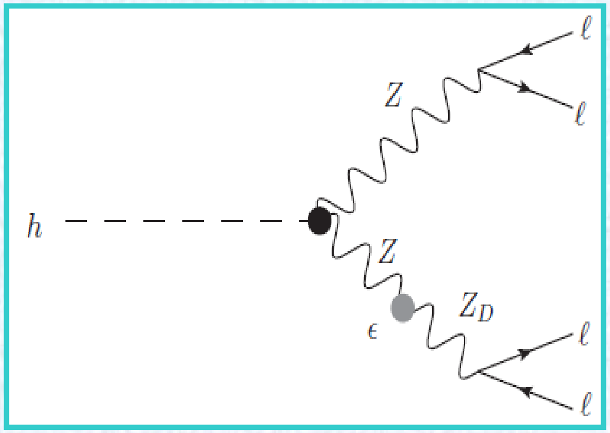


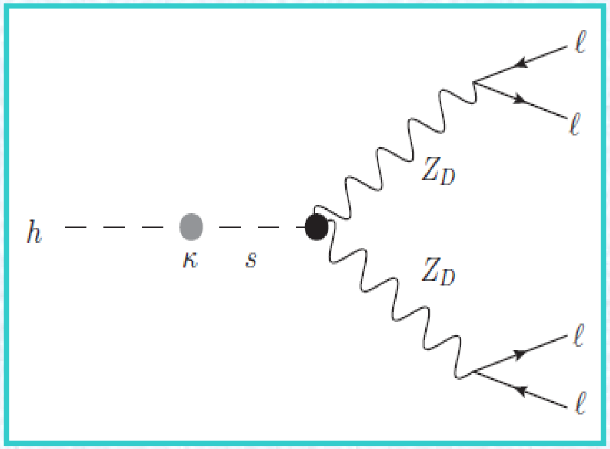
The typical signal is highly boosted lepton pair-"**lepton jet**"



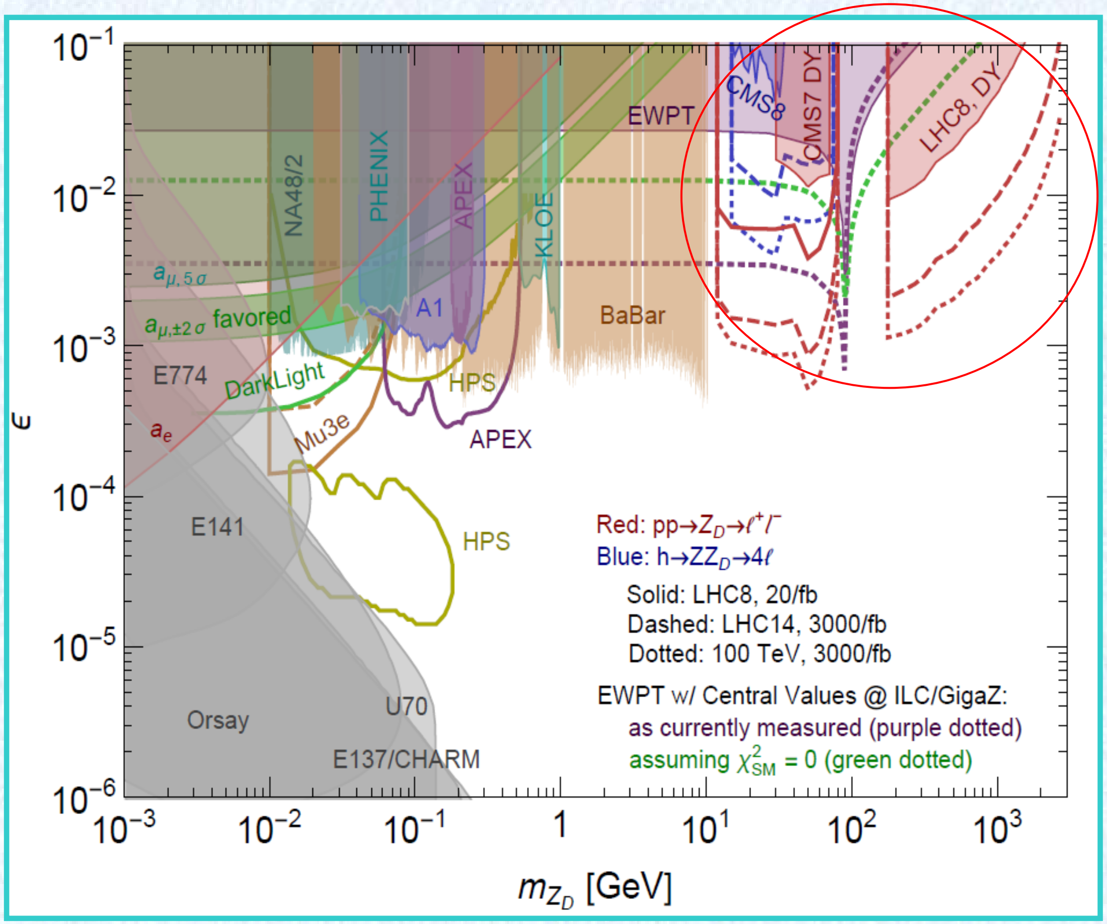
Research at High energy colliders

- Exotic higgs decay

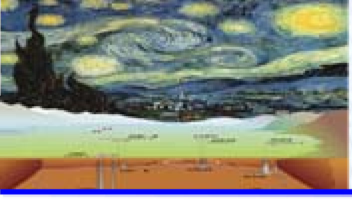




Curtin et. al, 1412.0018

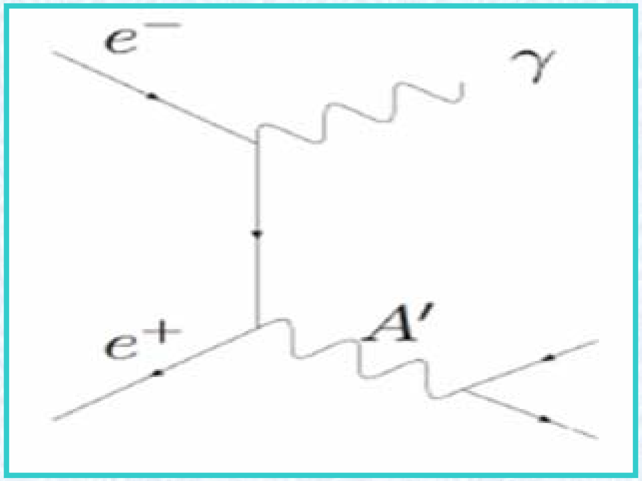


- Hadron colliders cover the region of heavy dark photon

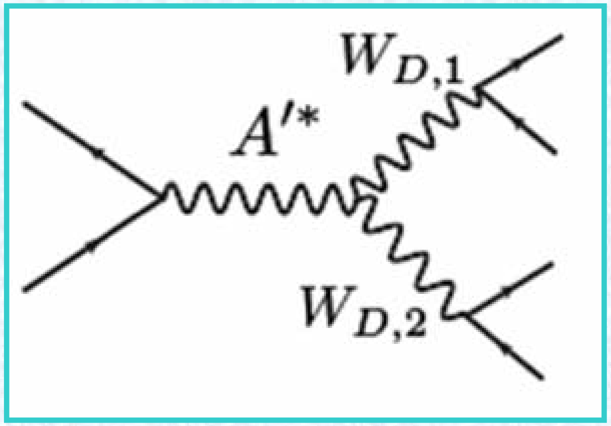


Dark photon production at e^+e^- colliders

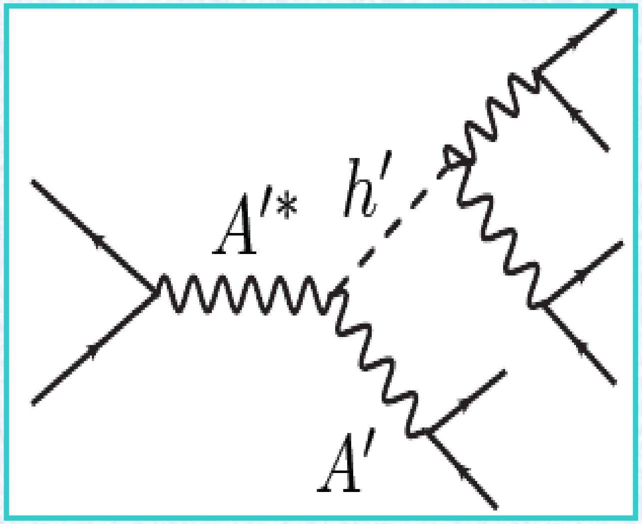
- Direct production, $e^+e^- \to \gamma\, l^+l^-$



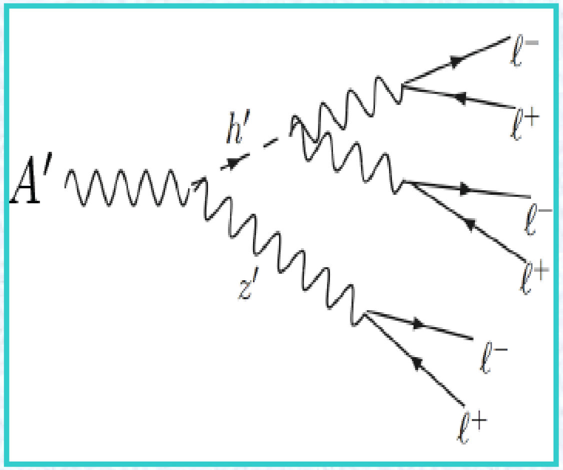
- Non-abelian gauge boson, $e^+e^- \to V'V' \to 2\, l^+l^-$

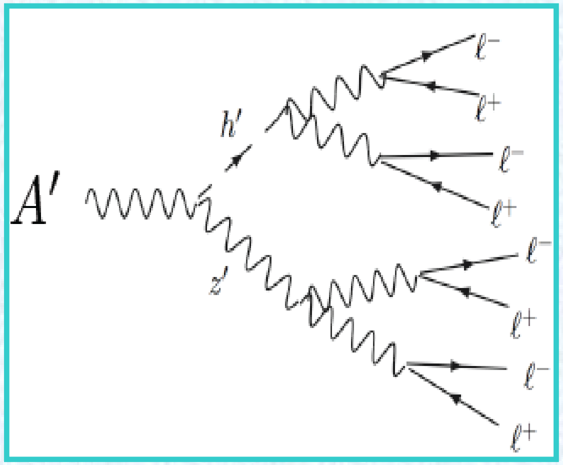


- Higgs strahlung, $e^+e^- \to \gamma$ 'h′' $\to 3\, l^+l^-$



- Other complicated decay chains





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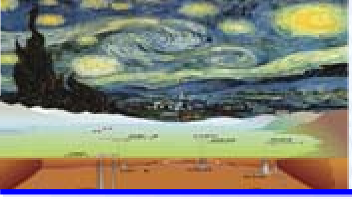
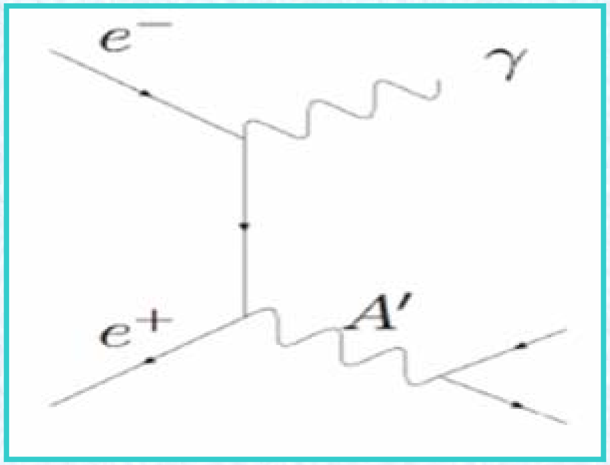
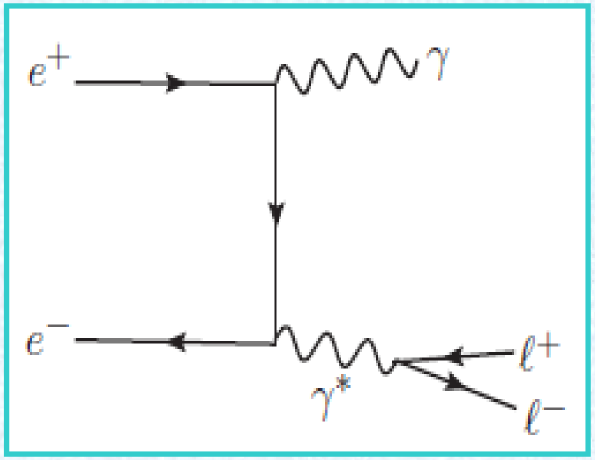


Production and decay of dark photon

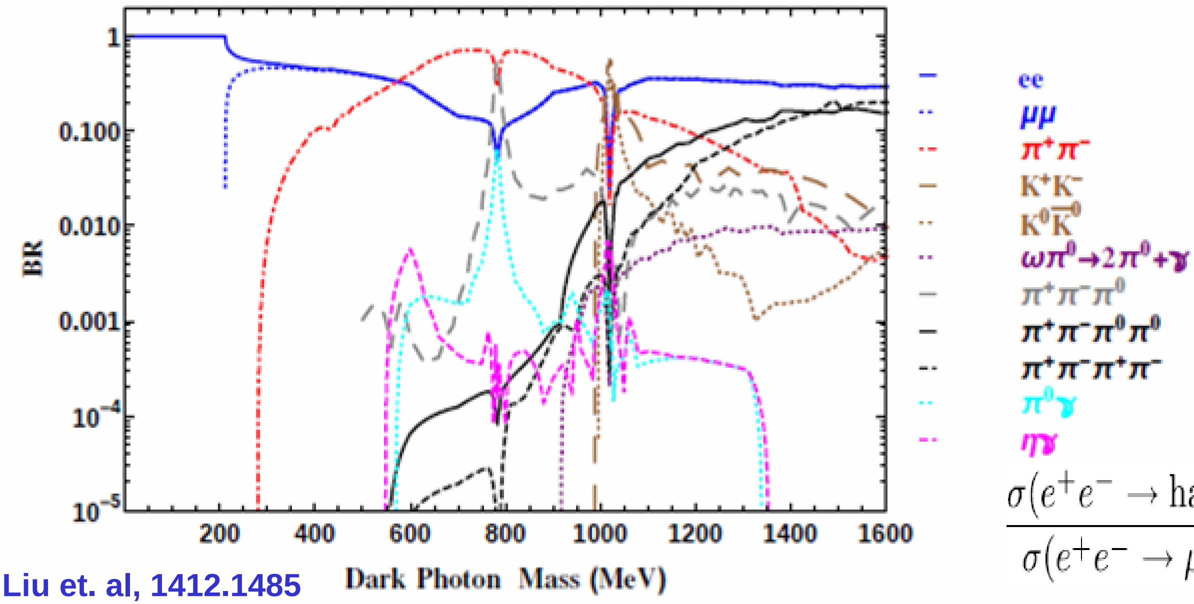




- It is better to produce dark photon at low energy colliders with high luminosity

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

- Large QED background
- Reconstructing invariant mass to suppress the background
- Decay branching ratios can be derived from e^+e^- collision results



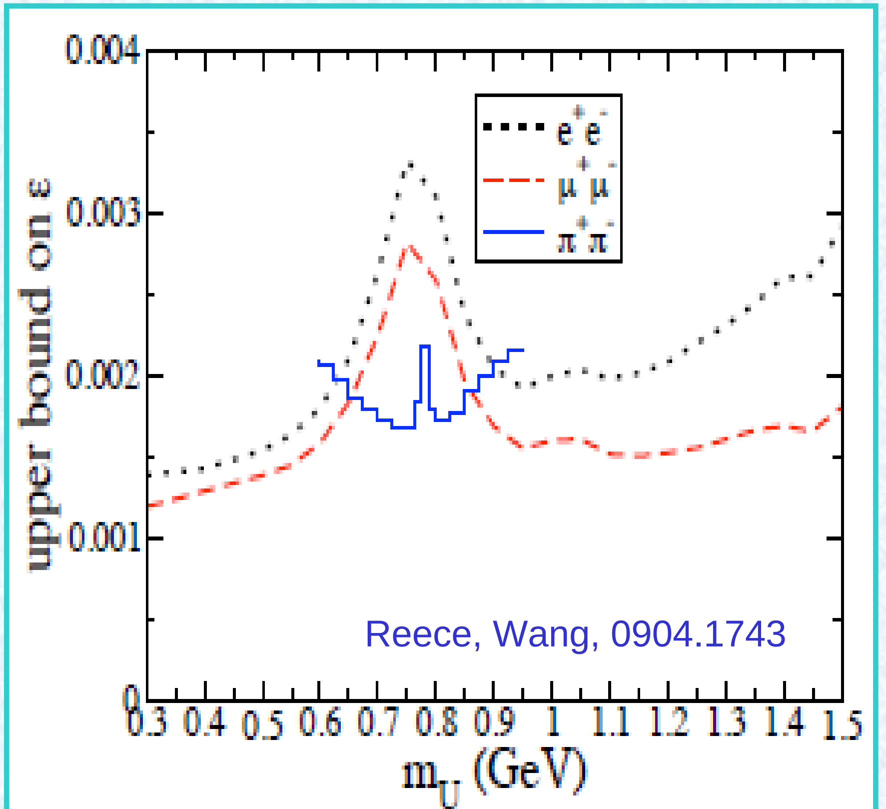
Liu et. al, 1412.1485

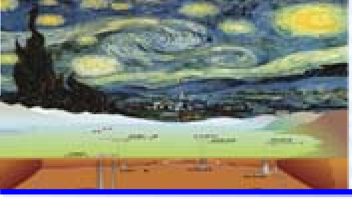
$$\frac{\sigma(e^+e^- \to \text{hadrons},\ s)}{\sigma(e^+e^- \to \mu^+\mu^-,\ s)} = \frac{BR(b_\mu \to \text{hadrons})}{BR(b_\mu \to \mu^+\mu^- (\text{or } e^+e^-))}$$

Reach for direct production

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

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





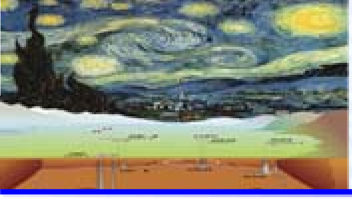
Meson decay

- 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

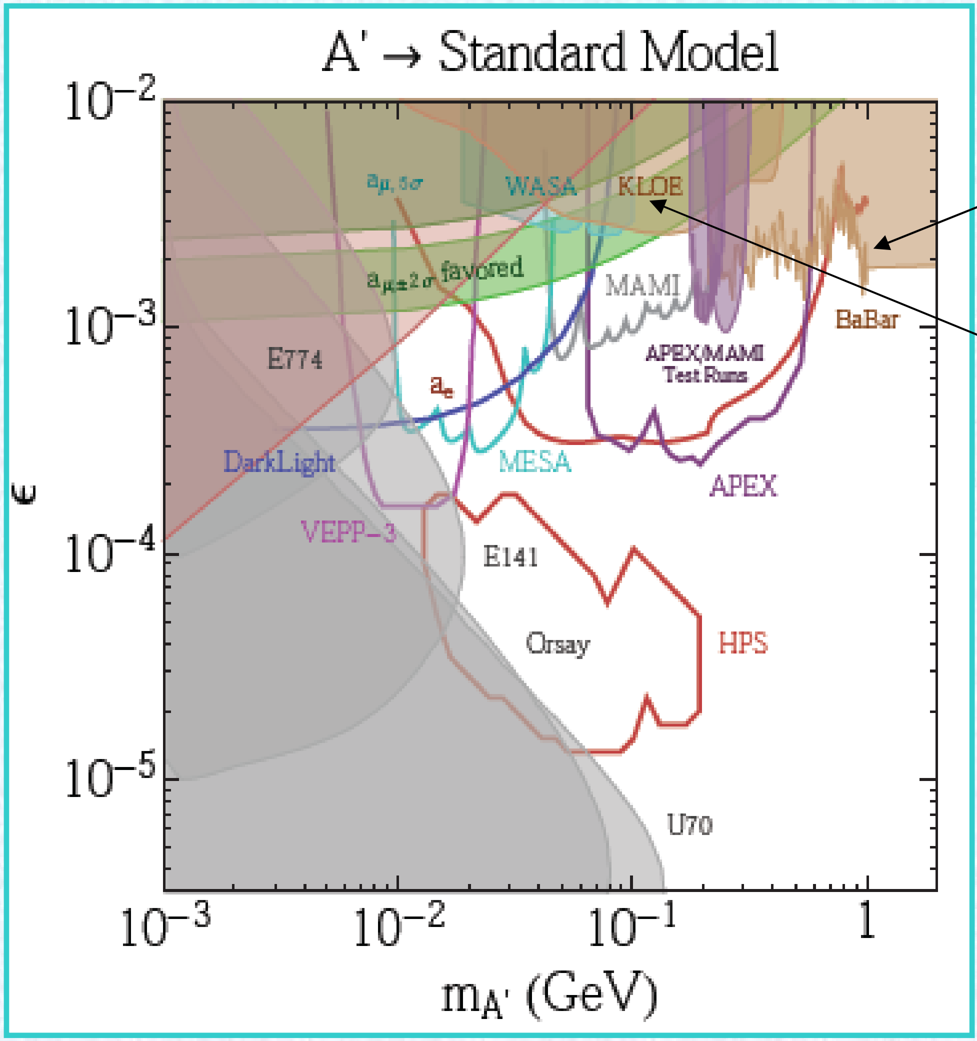
$$\frac{S}{\sqrt{B}} \approx \sqrt{n_X}\frac{\epsilon^2 \times BR(X \to Y + \gamma) \times BR(U \to \ell^+\ell^-)}{\sqrt{BR(X \to Y + \gamma^* \to Y + \ell^+\ell^-)}}\sqrt{\frac{m_U}{\delta m}\log\left(\frac{m_X - m_Y}{2m_\ell}\right)}$$

$X \to YU$	n_X	$m_X - m_Y$ (MeV)	$BR(X \to Y + \gamma)$	$BR(X \to Y + \ell^+\ell^-)$	$\epsilon \leq$
$\eta \to \gamma U$	$n_\eta \sim 10^7$	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



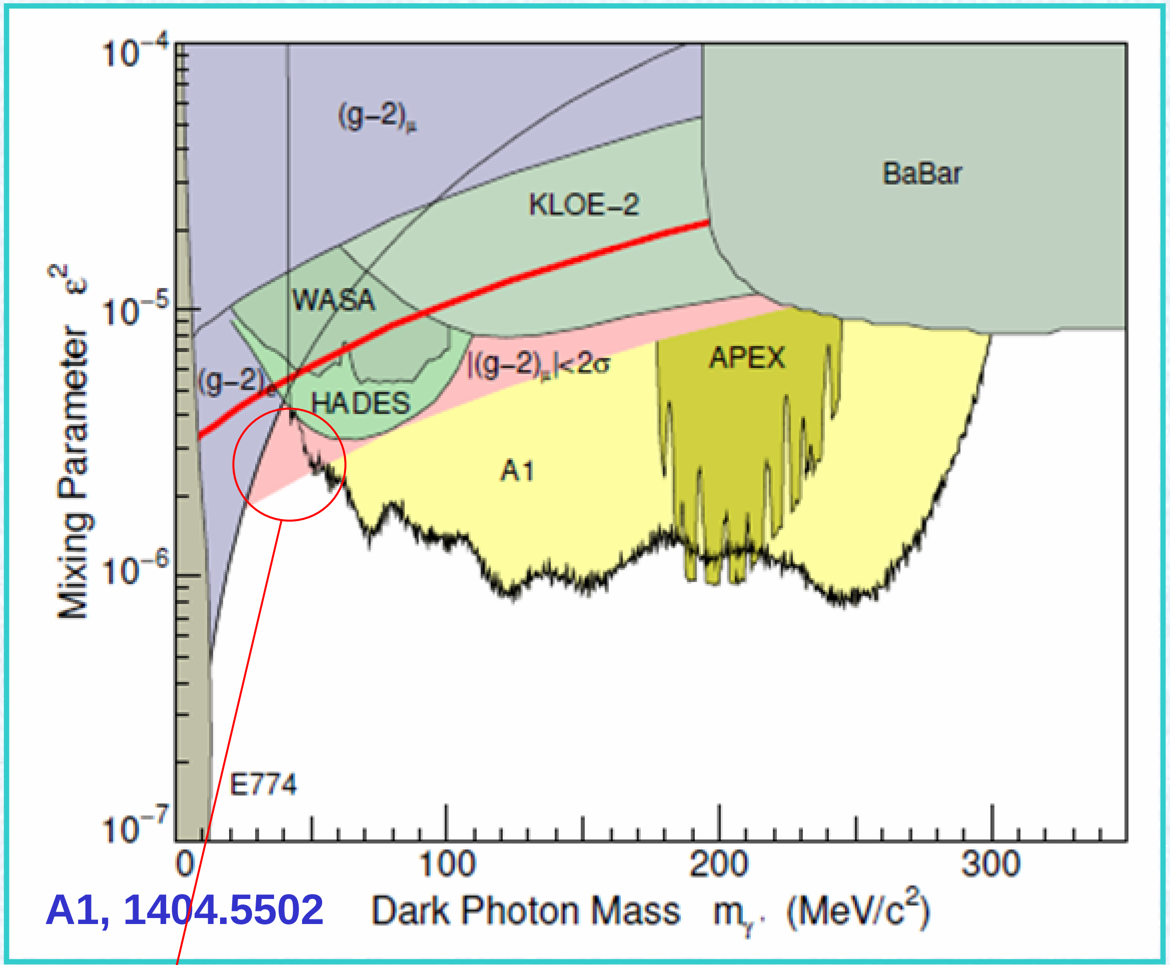
Some results from e^+e^- colliders



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

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

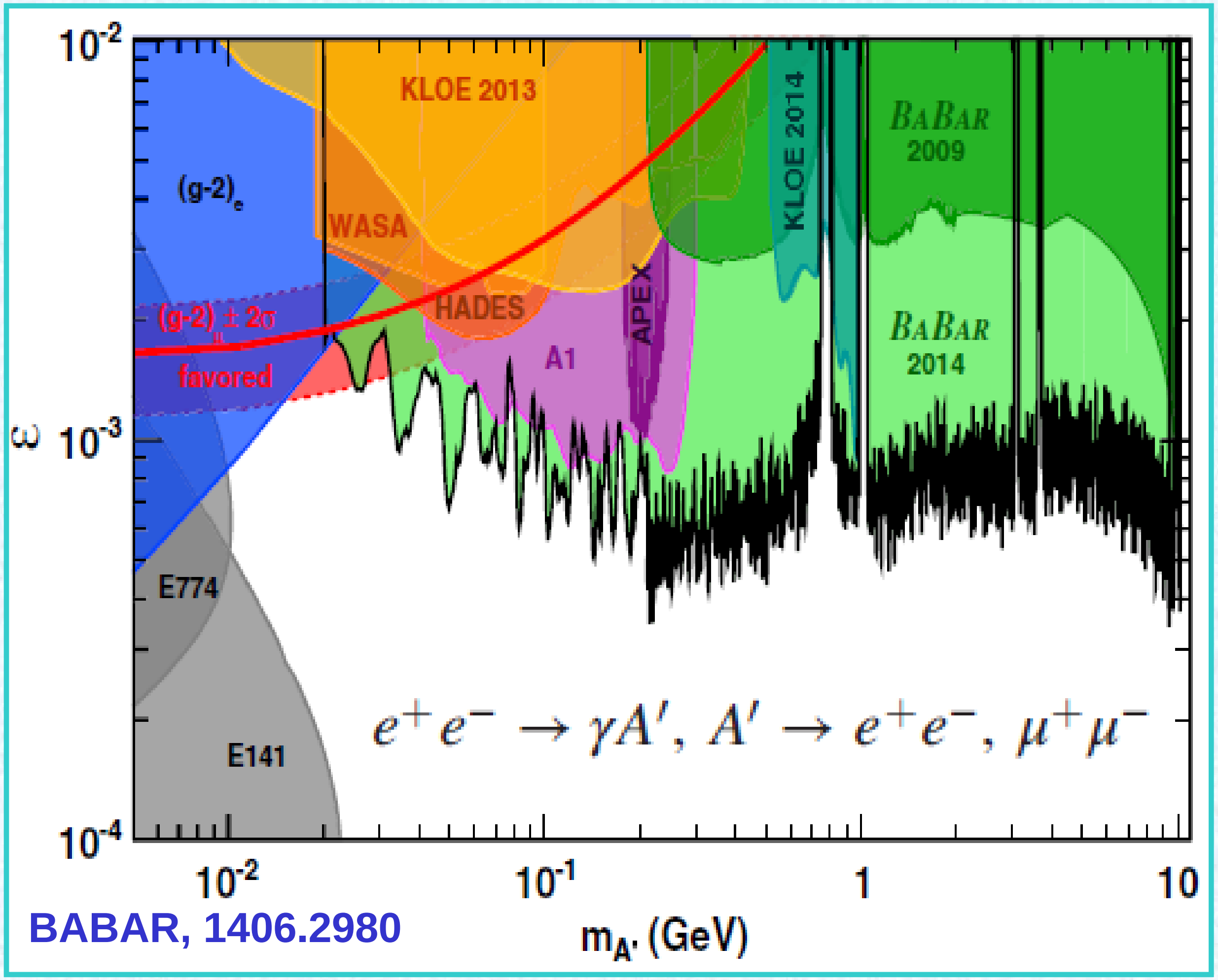
Recent result from MAMI



A1, 1404.5502

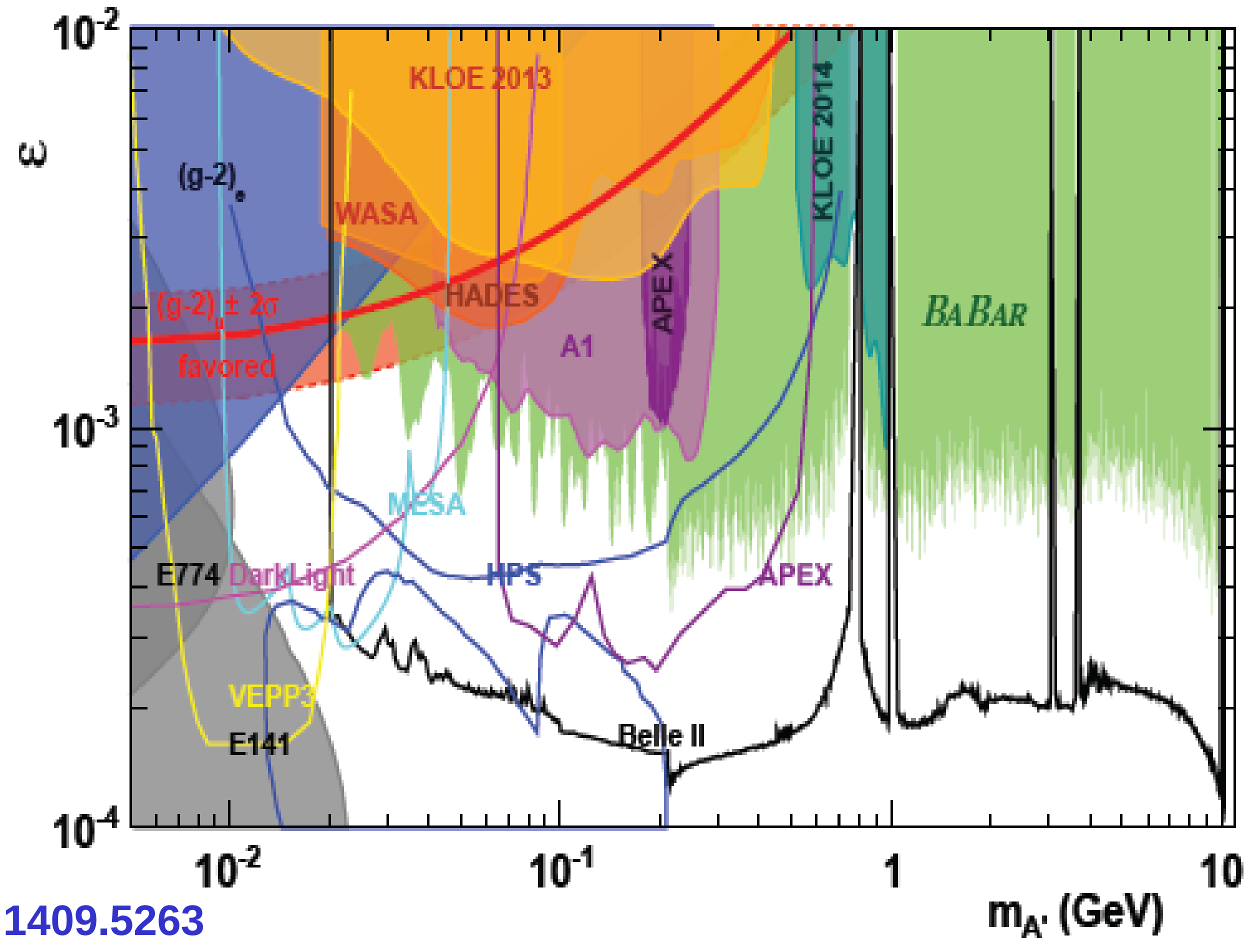
- Results from MAMI have excluded most of parameter space for muon g-2
- Only a small window ~10-50 MeV is still alive

Recent result from BABAR



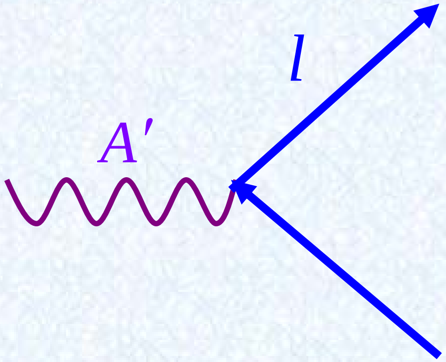
- The limit on the mixing parameter is $O(10^{-4})$

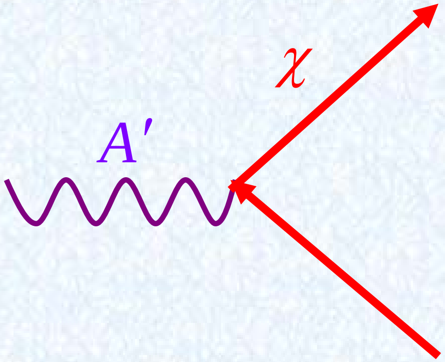
Sensitivities of future experiments



1409.5263

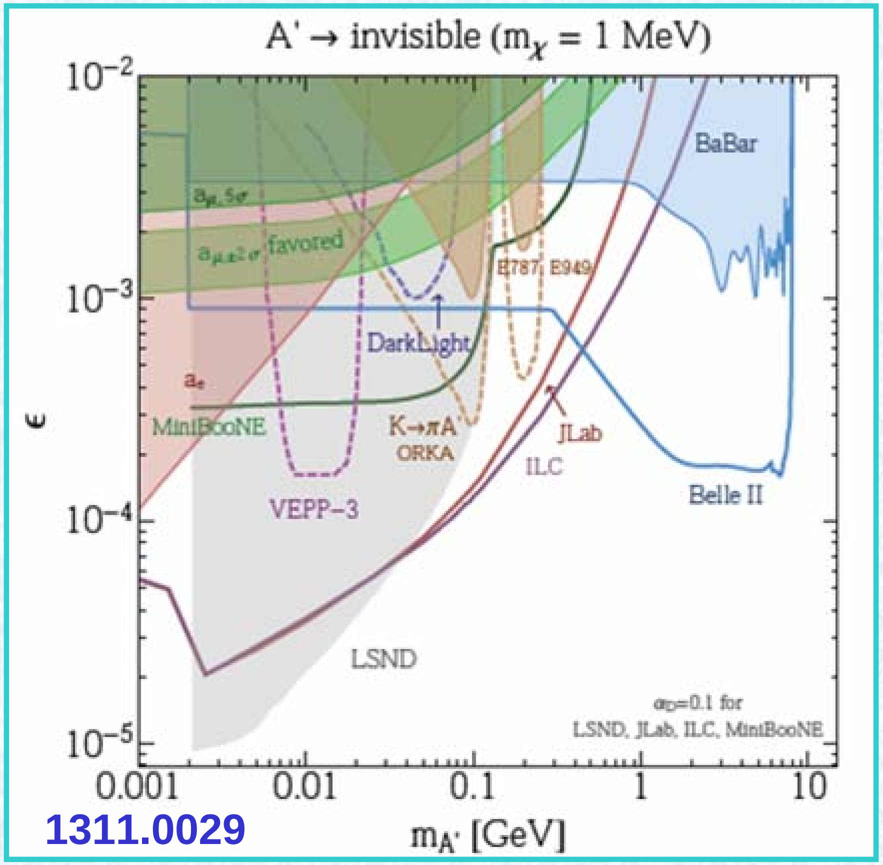
Invisible decay of the dark photon



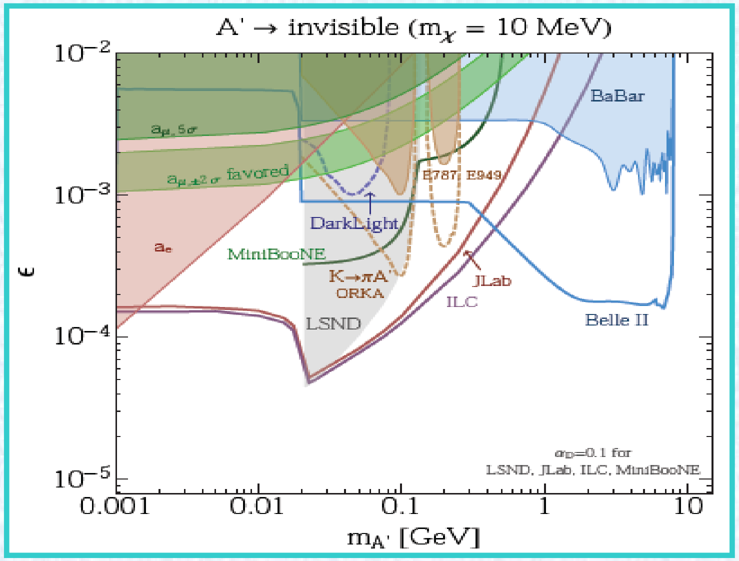


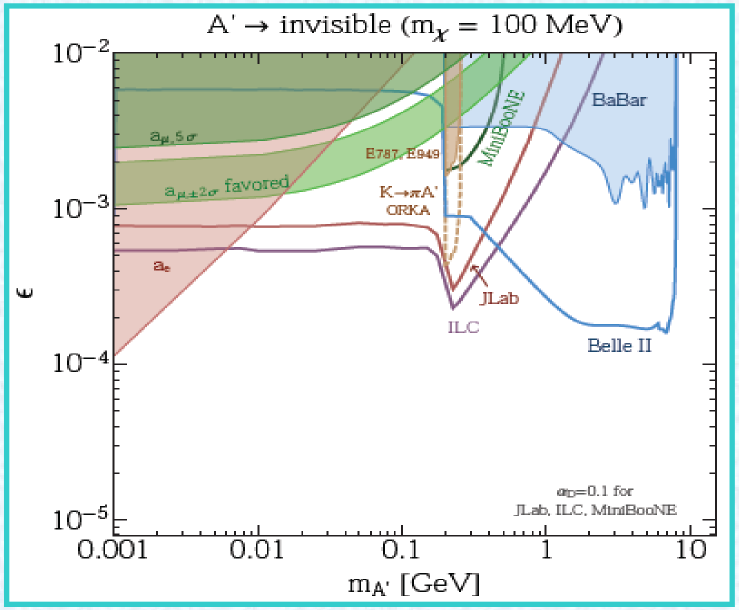
- **If the DM particle is light enough, dark photon can decay into a pair of DM**
- **In this case, visible decay is suppressed by a factor of ε^2, but invisible decay is not suppressed**
- **The constraints from previous studies may be changed**

Constraints on the invisible dark photon



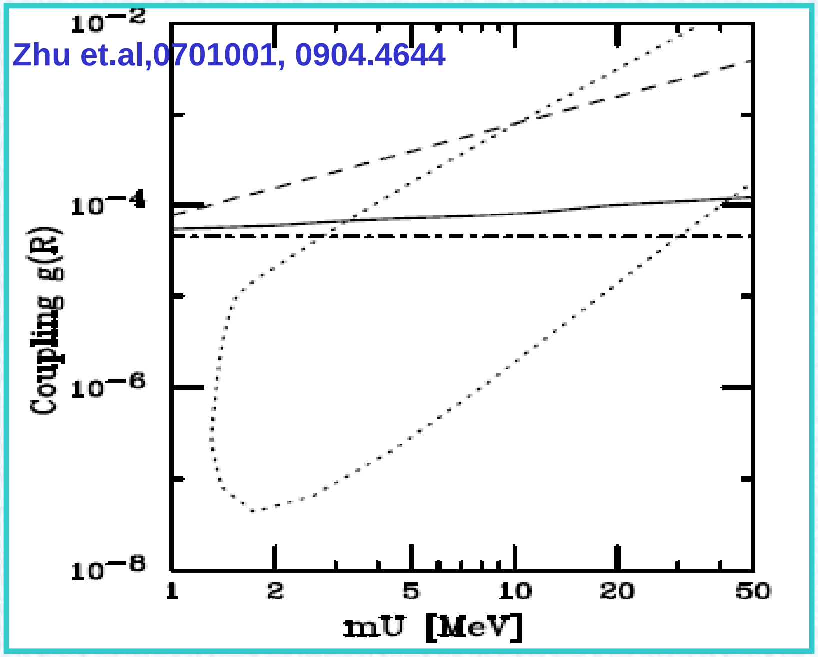
1311.0029



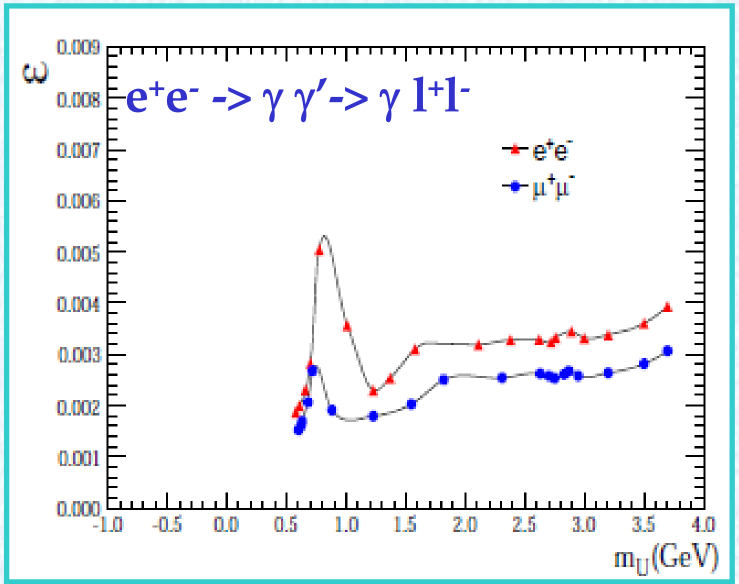


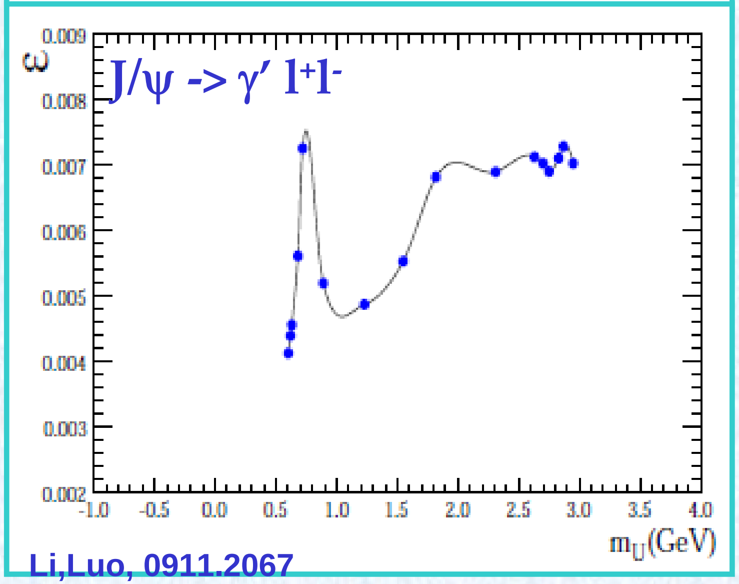
- The constraints also depend on the DM mass

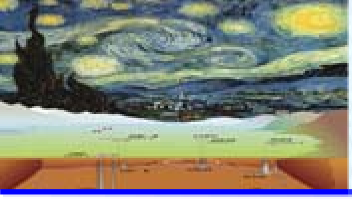
Dark sector at BES



- Large number of J/ψ
- e^+e^- -> γ γ′-> γ l^+l^-
- J/ψ -> γ′ l^+l^- -> 4l
- Ψ(2S)-> γ′ $\chi_{c1,2}$ -> e^+e^- $\chi_{c1,2}$
- J/ψ -> γ′ h′ -> l^+l^- + inv
- J/ψ -> 3γ′ -> 6l







Invisible decay at BESIII

J/ψ decay mode	Number of events /10 billion J/ψ decays
$J/\psi \to \phi\eta$	$(31.4 \pm 3.4) \times 10^5$ $(25.7 \pm 2.8) \times 10^5$
$J/\psi \to \phi\eta'$	$(16.2 \pm 1.9) \times 10^5$ $(9.6 \pm 1.2) \times 10^5$
$J/\psi \to \omega\eta$	$(13.9 \pm 1.4) \times 10^6$ $(6.2 \pm 0.6) \times 10^6$
$J/\psi \to \omega\eta'$	$(1.5 \pm 0.2) \times 10^6$ $(0.7 \pm 0.1) \times 10^6$
$J/\psi \to \rho^0\eta$	$(1.9 \pm 0.2) \times 10^6$ $(0.8 \pm 0.09) \times 10^6$
$J/\psi \to \rho^0\pi^0$	$(55.3 \pm 5.8) \times 10^6$

$\psi(2S)$ decay mode	Number of events expected
$\psi(2S) \to \pi^+\pi^- J/\psi$	9.3×10^8
$\psi(2S) \to \pi^0\pi^0 J/\psi$	5.6×10^8
$\psi(2S) \to \eta J/\psi$	9.3×10^7
$\psi(2S) \to \pi^0 J/\psi$	3.7×10^6
$\psi(2S) \to \gamma\chi_{c0}$	2.7×10^8
$\psi(2S) \to \gamma\chi_{c1}$	2.6×10^8
$\psi(2S) \to \gamma\chi_{c2}$	2.5×10^8
$\psi(2S) \to \gamma\eta_c(1S)$	7.8×10^6
$J/\psi \to \gamma\eta_c(1S)$	1.3×10^8

Li,Zhu, 1202.2955

- With huge J/ψ and ψ(2S) samples at BESIII, the rare decays is feasible

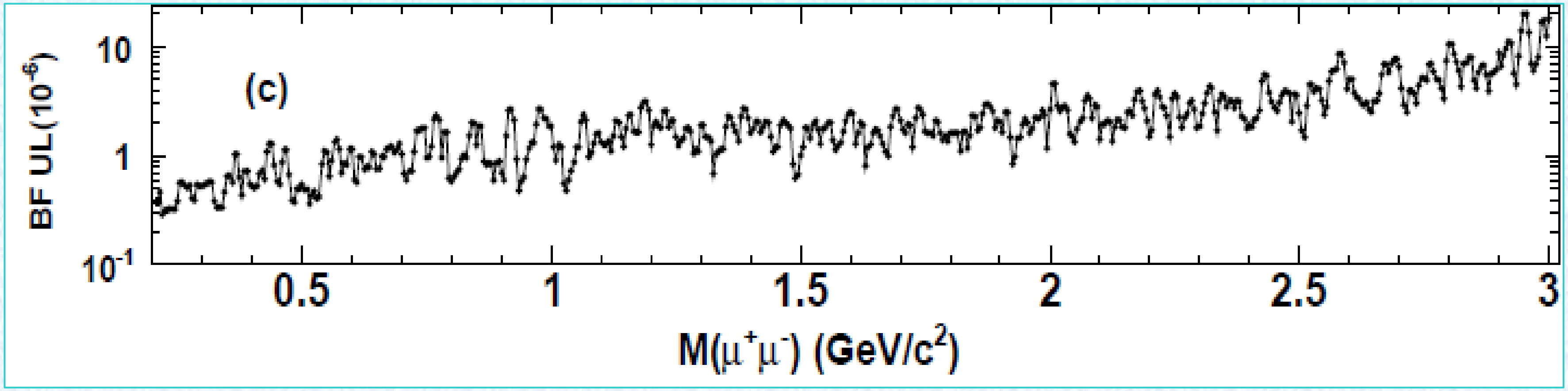
Some results from BESIII

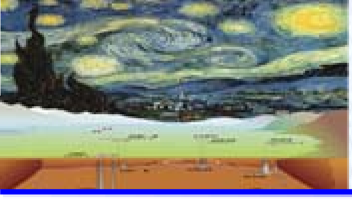
- Invisible decay
  - Search for $J/\psi \rightarrow \phi\eta(\eta') \rightarrow K^+K^-$+inv
  - Sample ~$2.25X10^8$ J/ψ
  - $Br(\eta\text{->}inv)/Br(\eta\text{->}\gamma\gamma) < 2.6X10^{-4}$
  - $Br(\eta'\text{->}inv)/Br(\eta'\text{->}\gamma\gamma) < 2.6X10^{-4}$

BESIII, 1209.2469
PRD 87 012009(2013)

- Visible decay
  - Search for ψ' -> $\pi^+\pi^-$ J/ψ, J/ψ->γX(->μ+μ-)
  - Sample ~$1.06X10^8$ ψ'
  - Limits on the exotic decay from $4X10^{-7}$ to $2.1X10^{-5}$

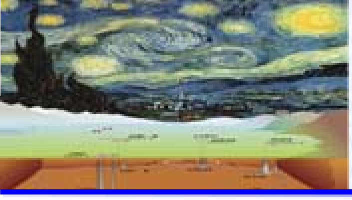
BESIII, 1111.2112
PRD 85 092012(2012)





Summary

- (sub)GeV dark sector can be tested in three frontiers
- Search for the dark sector in the intensity frontier is well-motivated. This is a very active and attractive topic.
- Some parameter spaces are left for the future low energy high luminosity collider



Summary

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Thank you !