Dark Matter in a Hidden Sector

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Fermilab Particle Astrophysics Seminar

in collaboration with M. Goodsell, C. Niebuhr, A. Ringwald & B. Zaldivar

based on: Phys.Rev. D86 (2012) 095019, Phys.Rev. D87 (2013) 025007, arXiv:1306.1168

Hidden Sectors

HS

SM singlets

Hidden Sector (HS)

- set of SM-neutral particles
- charged under additional gauge group

SM

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

Visible Sector

- Standard Model (SM) particles and interactions

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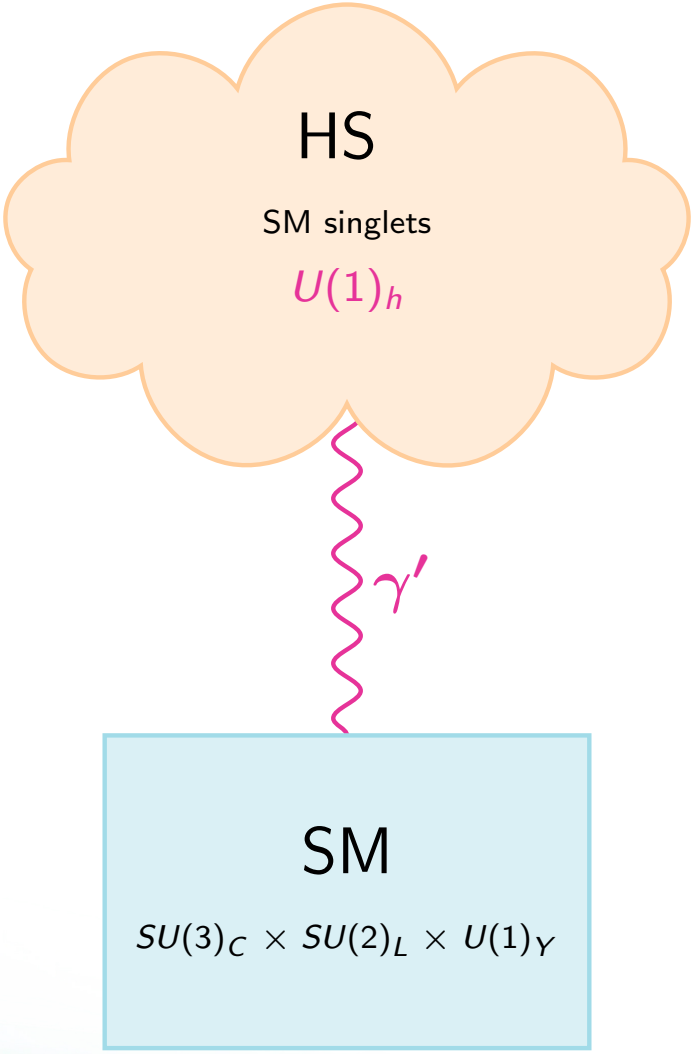

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Messenger

- mediates interaction
- *here:* hidden photon γ'

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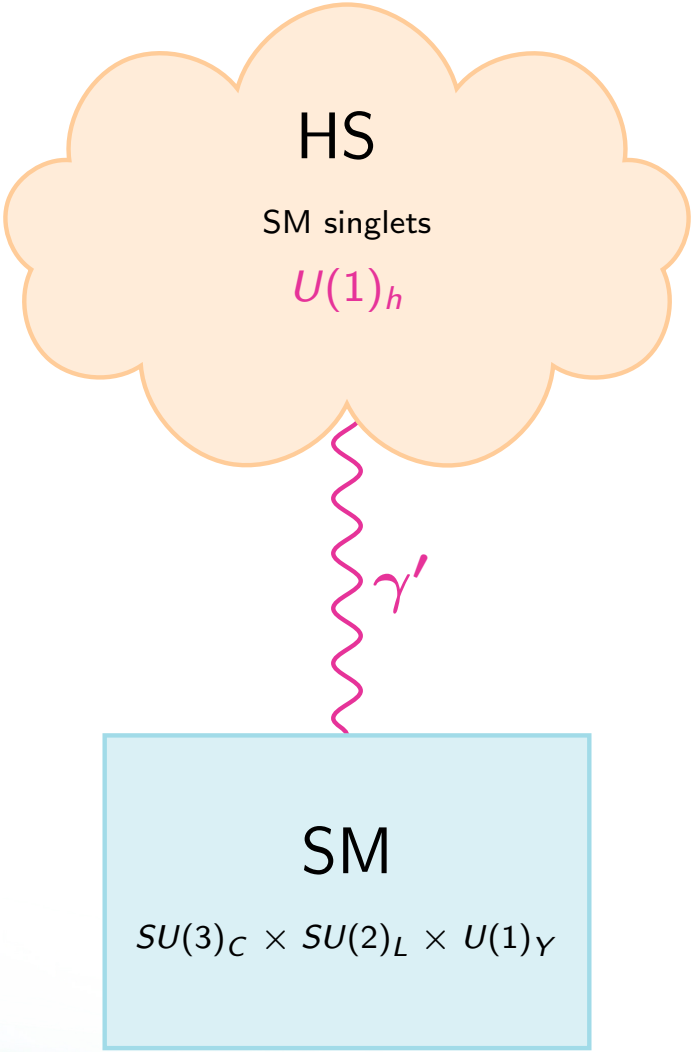

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- in many SM extensions
  breaking of large gauge groups yields extra $U(1)$s
  e.g. compactifications of heterotic or type II string theory

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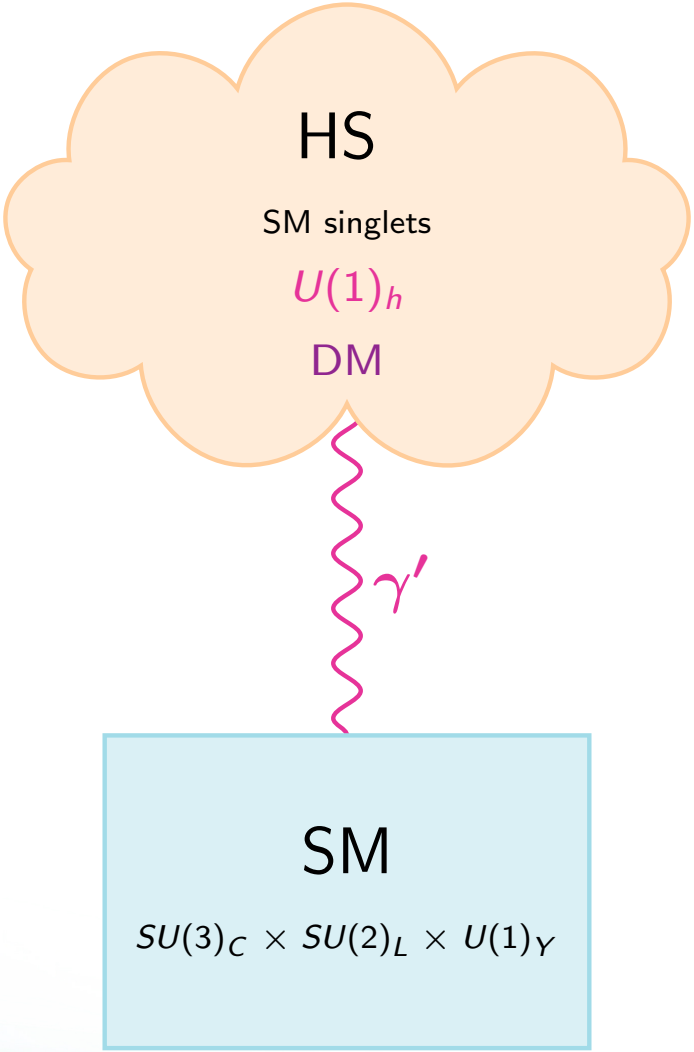

Hidden Sector (HS)

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- charged under additional gauge group
  here: extra $U(1)_h$
- in many SM extensions
  breaking of large gauge groups yields extra $U(1)$s
  e.g. compactifications of heterotic or type II string theory
- good hideout for Dark Matter (DM)

Messenger

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Visible Sector

- Standard Model (SM) particles and interactions

Outline

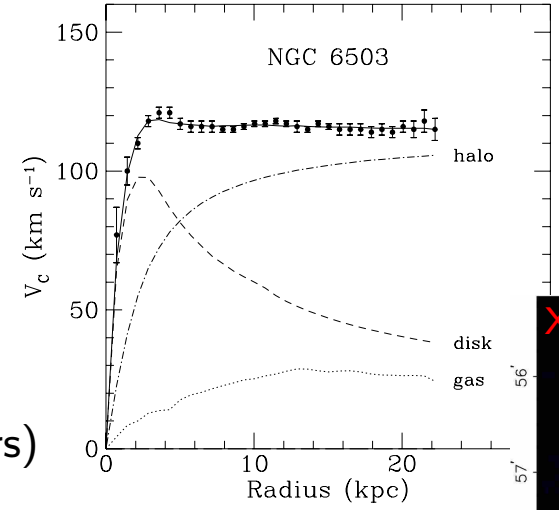
1. Introduction & Motivation
2. Constraints on Hidden Sectors with Hidden Photon
3. Hidden Sectors with Dark Matter
4. Conclusions

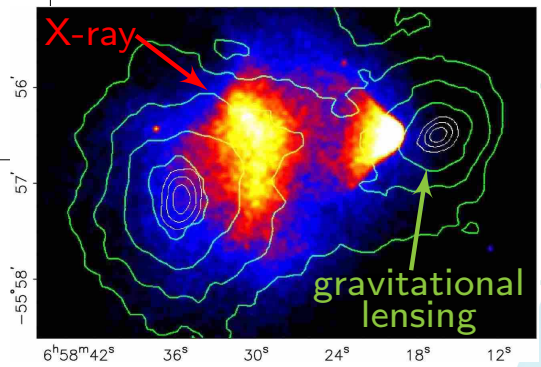
Dark Matter

evidence different observations

- rotation curves of spiral galaxies
- "Bullet cluster" (colliding galaxy clusters)
- Cosmic Microwave Background (CMB)[Planck '13]

[Bertone, Hooper, Silk '05]





[Clowe *et al.* '06]

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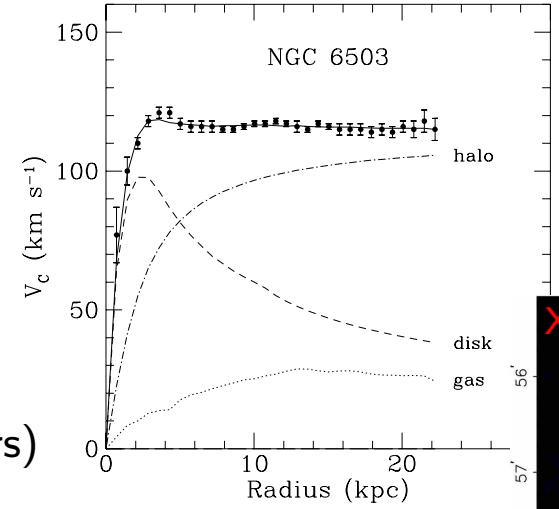

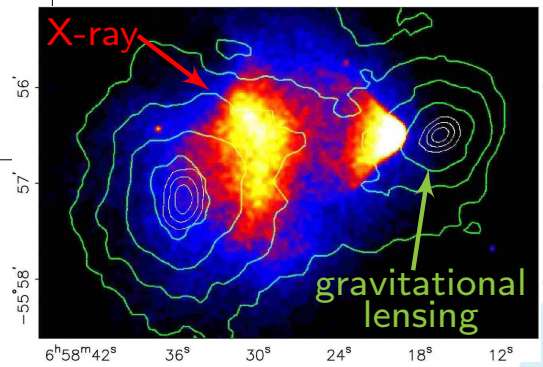

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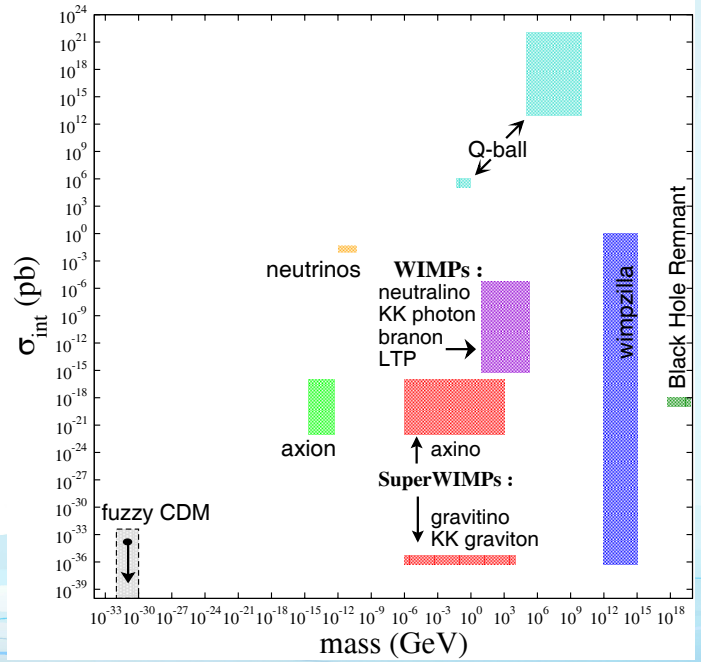
particle candidates from SM extensions

- prominent candidates: WIMPs

Some Dark Matter Candidate Particles



[E.-K. Park '07]

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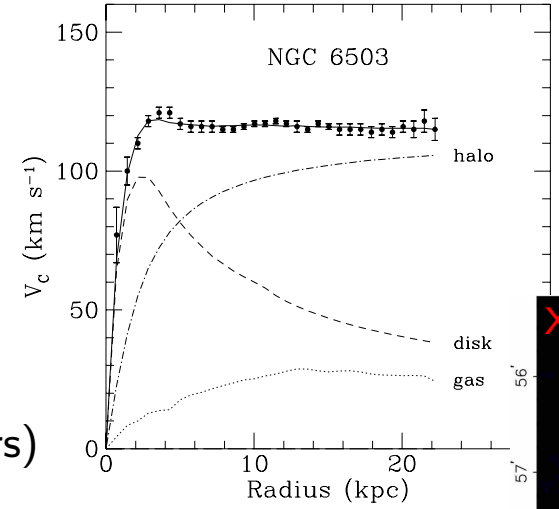

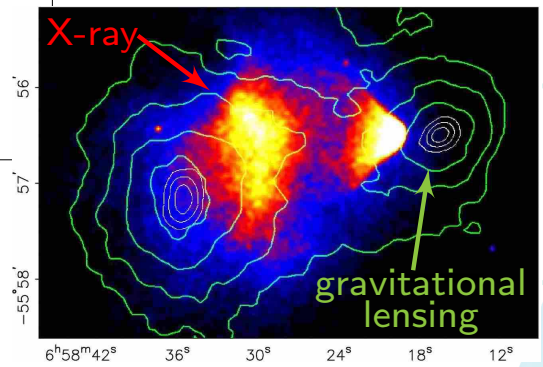

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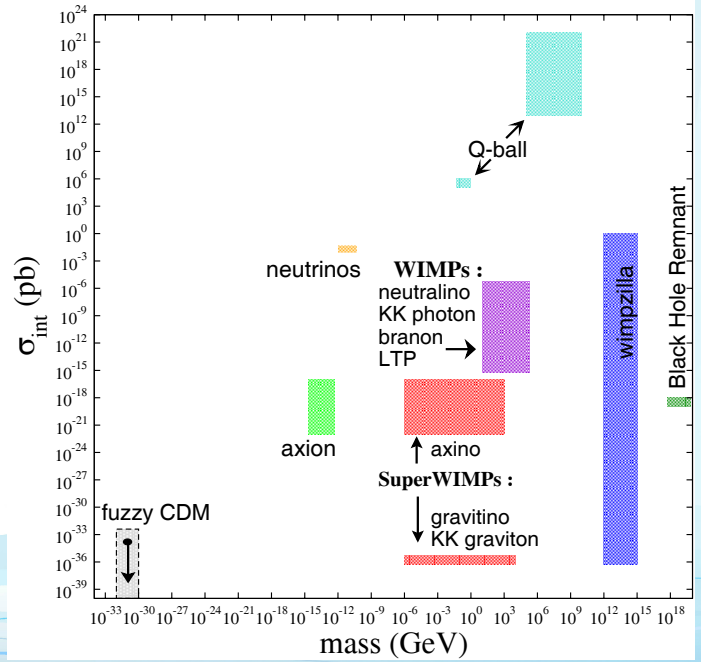
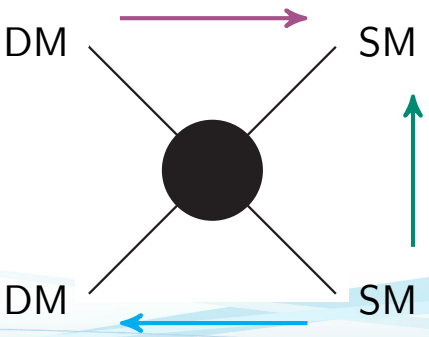


[E.-K. Park '07]

try to detect non-gravitational interaction

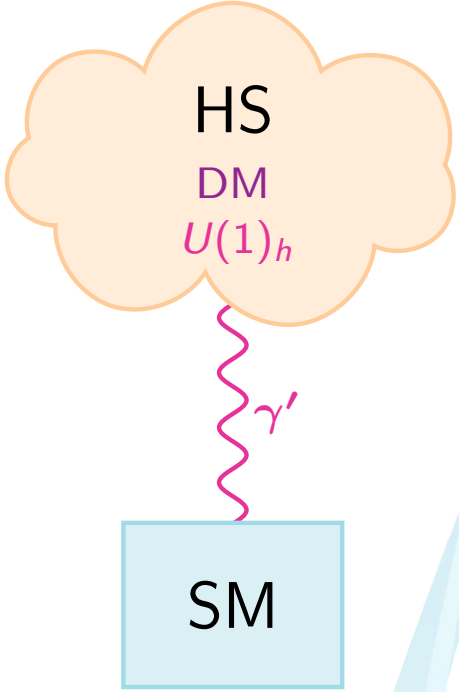
- indirect detection
- direct detection
- colliders



Dark Matter in Hidden Sectors

interaction via a messenger e.g. γ'

$\Rightarrow$ phenomenologically interesting features:



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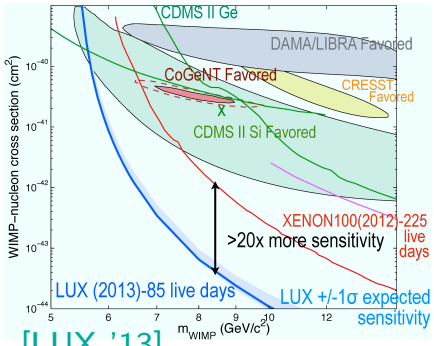

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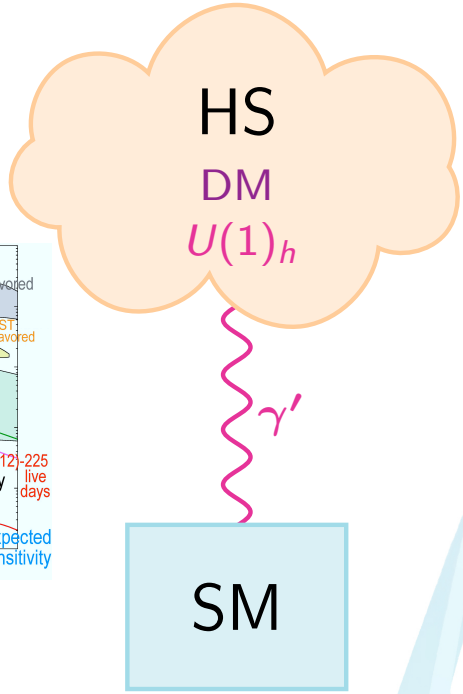

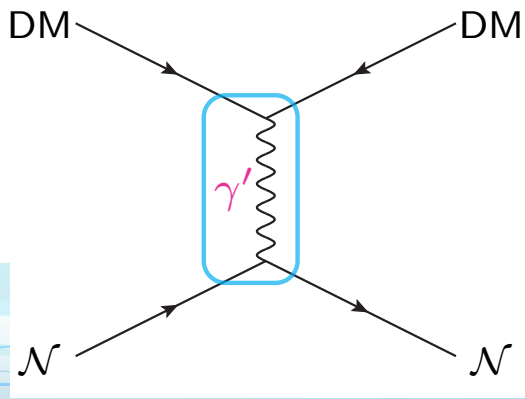

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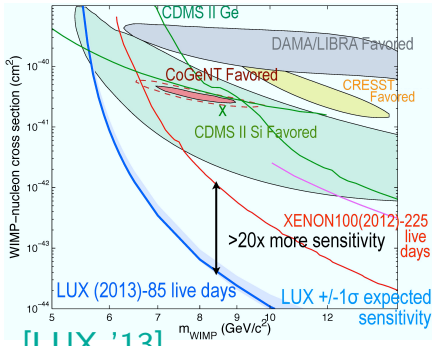

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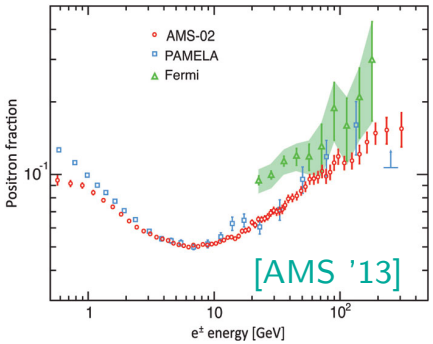

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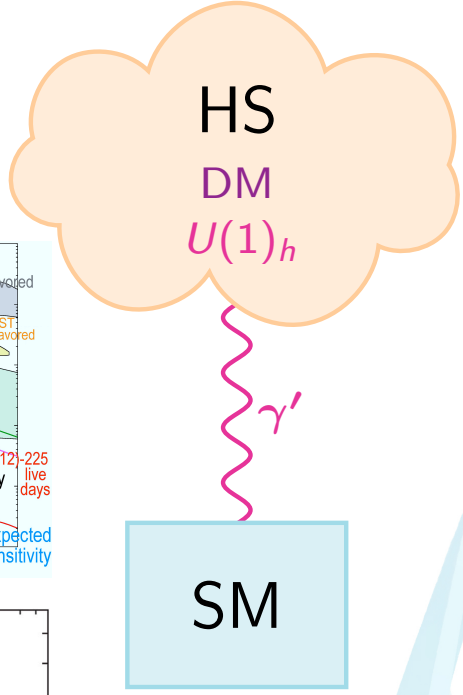

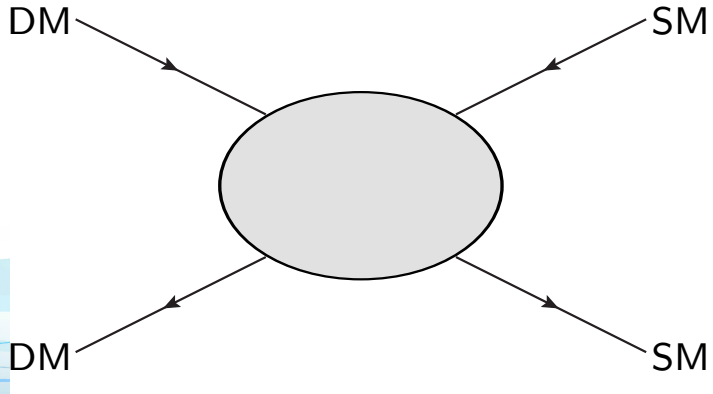

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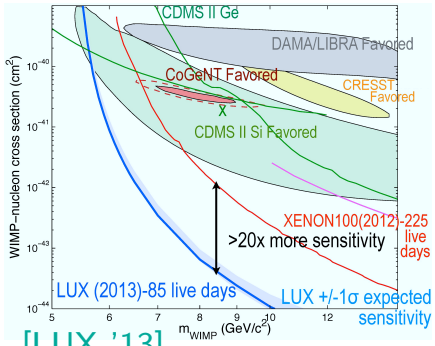

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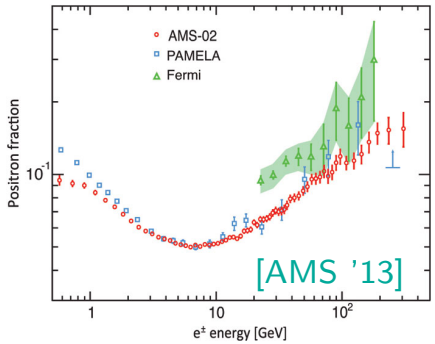

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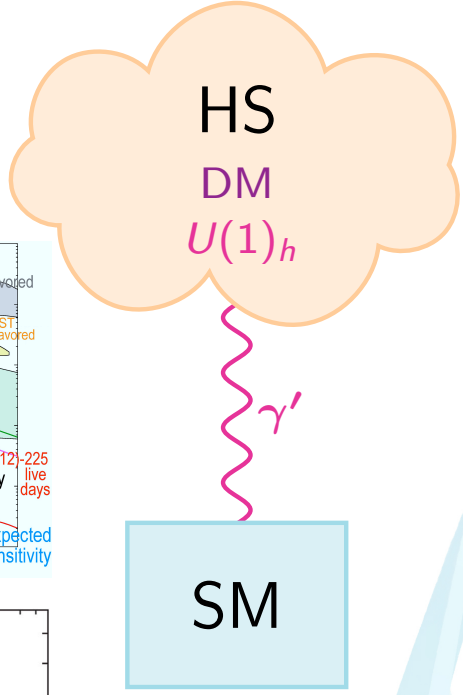

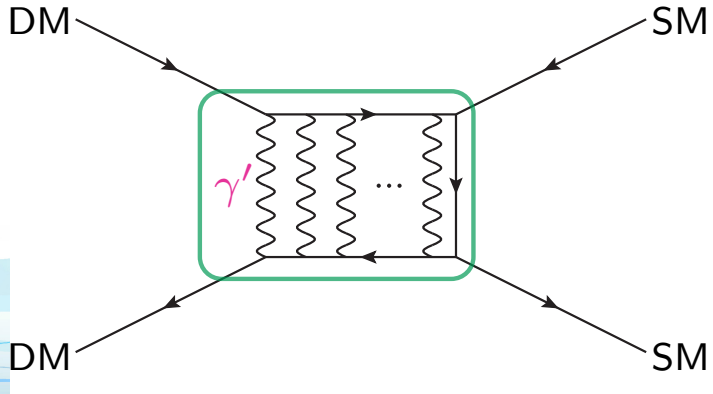

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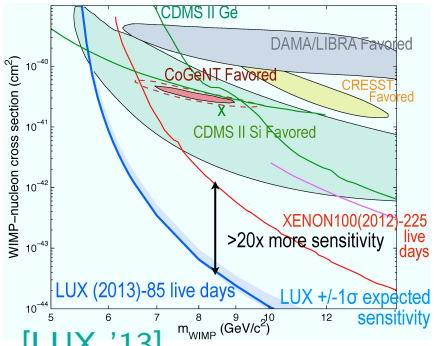

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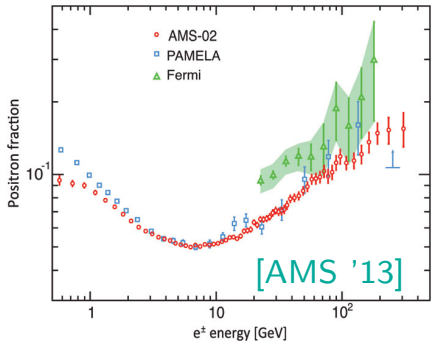

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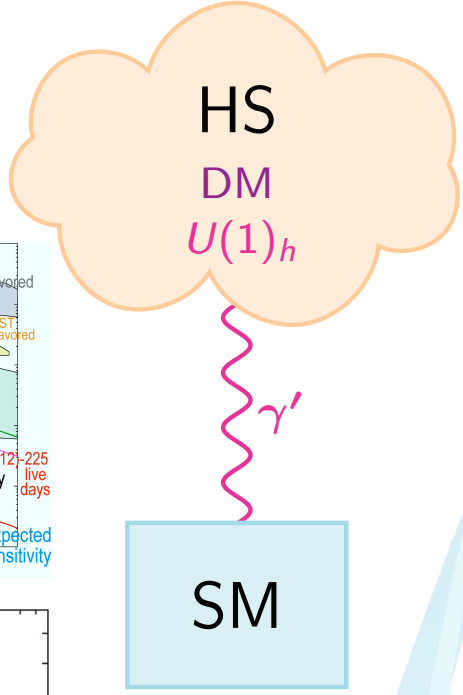

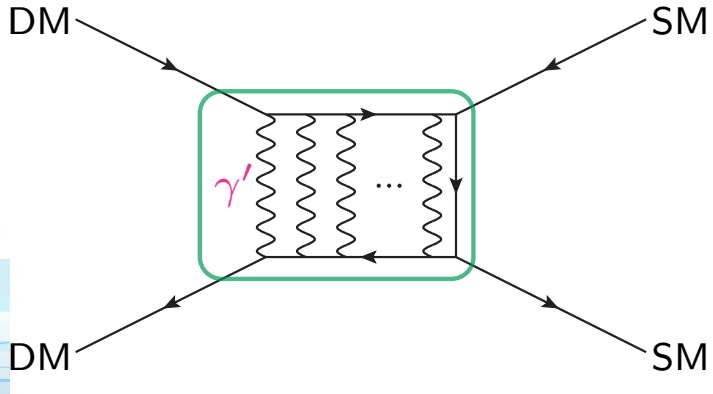

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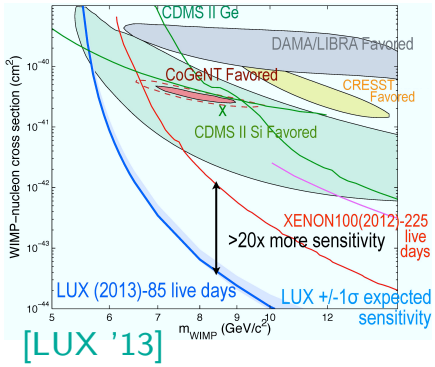
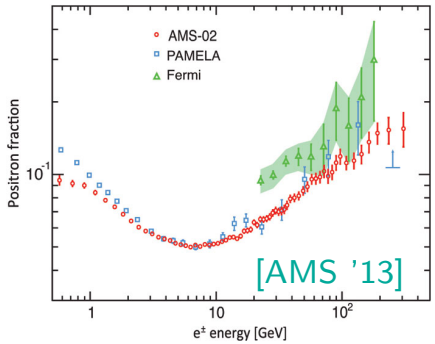
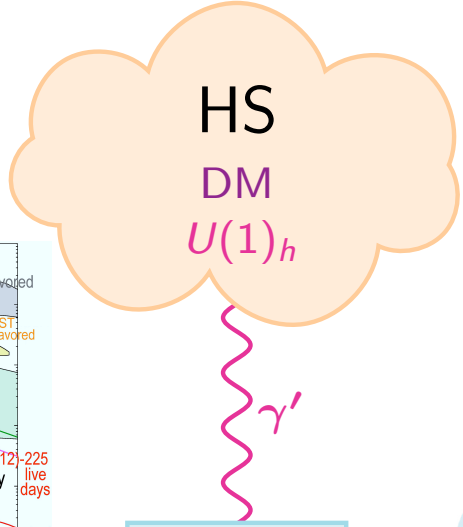
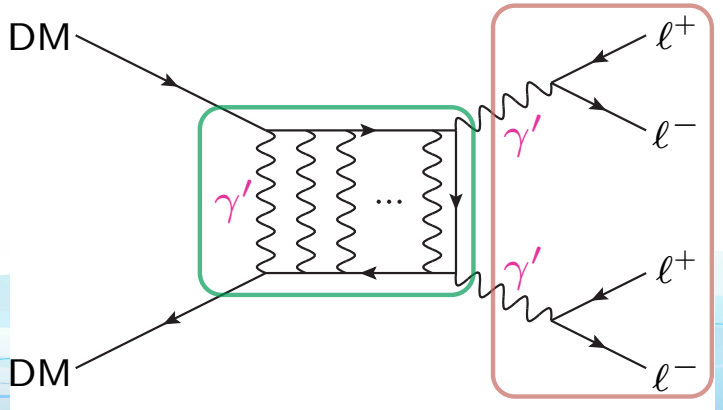
  - decay of light messenger naturally leptophilic

$\Rightarrow$ MeV to GeV scale hidden photon









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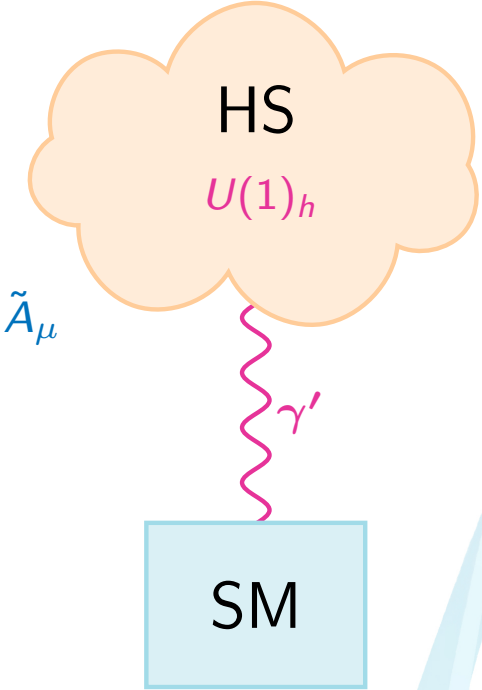
Hidden Photon

- low energy effective Lagrangian

$$\mathcal{L}_{\text{eff}} \supset -\frac{1}{4}\tilde{F}_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{4}\tilde{X}_{\mu\nu}\tilde{X}^{\mu\nu} + \frac{\chi}{2}\tilde{X}_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\tilde{m}^2_{\gamma'}\tilde{X}_\mu\tilde{X}^\mu + e j^\mu_{\text{em}}\tilde{A}_\mu$$



Hidden Photon and Kinetic Mixing

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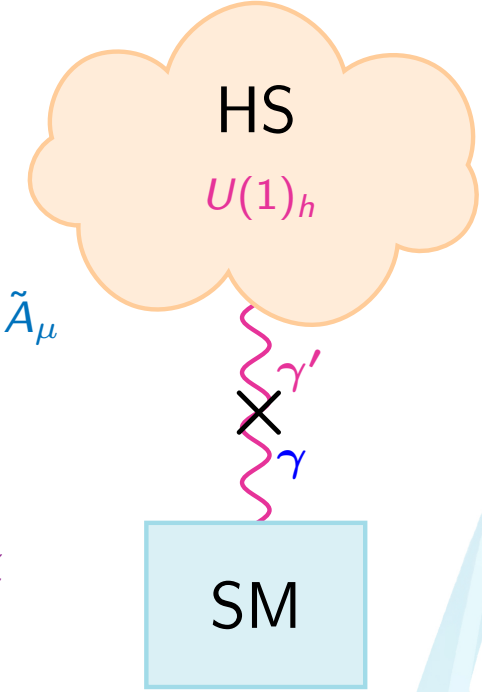
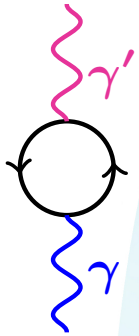
- dominant interaction: kinetic mixing of hidden & visible $U(1)$
  - ◇ renormalisable term with dimensionless kinetic mixing parameter χ
  - ◇ integrating out heavy particles charged under both $U(1)$s
  - ◇ χ generated at loop level: $\chi \sim 10^{-3} - 10^{-4}$





[Okun '82; Holdom '86; Galison, Manohar '84]

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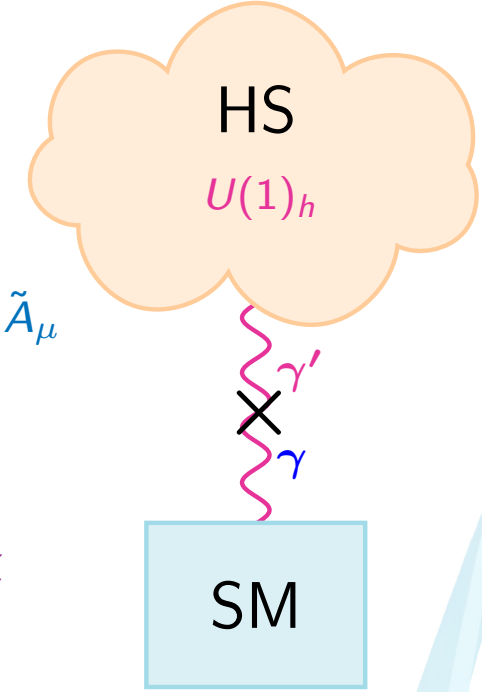

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- diagonalize kinetic terms: $\tilde{A}_\mu = A_\mu + \frac{\chi}{\sqrt{1-\chi^2}}X_\mu\,, \quad \tilde{X}_\mu = \frac{1}{\sqrt{1-\chi^2}}X_\mu$

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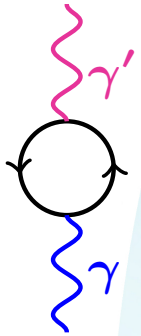

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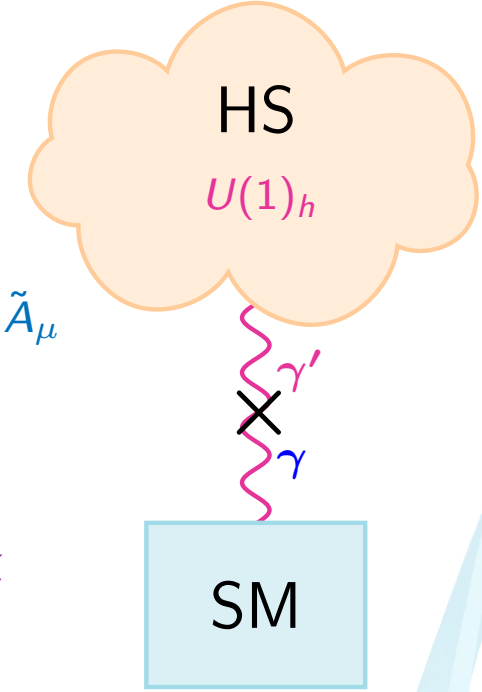

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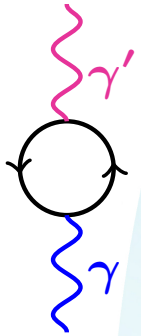
- diagonalize kinetic terms: $\tilde{A}_\mu = A_\mu + \frac{\chi}{\sqrt{1-\chi^2}}X_\mu\,, \quad \tilde{X}_\mu = \frac{1}{\sqrt{1-\chi^2}}X_\mu$

$$\mathcal{L}_{\text{eff}} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{1}{2}m^2_{\gamma'}X_\mu X^\mu + e j^\mu_{\text{em}}A_\mu + \boxed{e\chi j^\mu_{\text{em}}X_\mu} + \mathcal{O}(\chi^2)$$



[Okun '82; Holdom '86; Galison, Manohar '84]

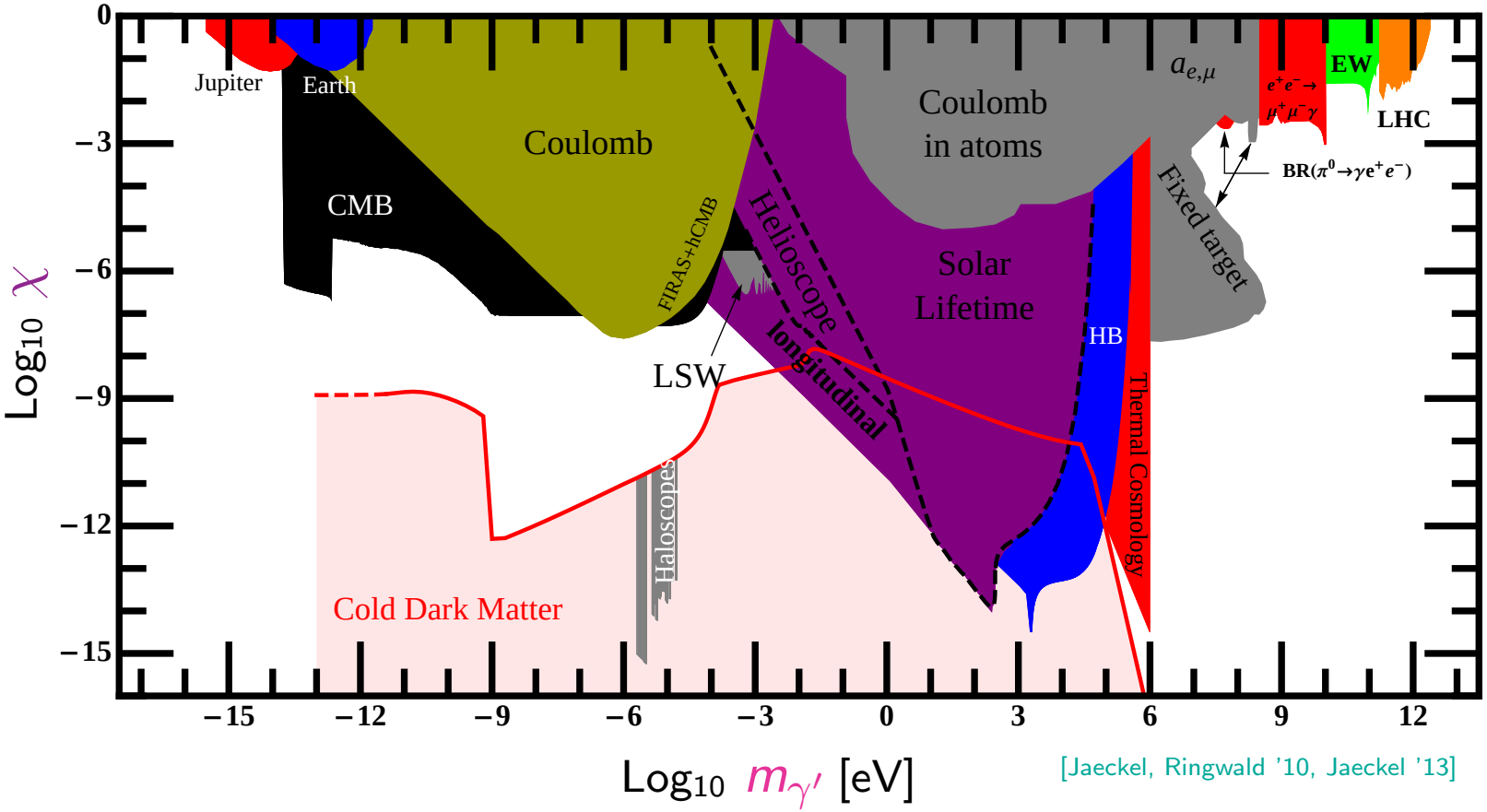
- broken by Higgs or Stückelberg mechanism

  light hidden photon with $m_{\gamma'} \sim \text{MeV} - \text{GeV}$

  $\Rightarrow \gamma'$ decays into e^+e^- and can solve discrepancy in a_μ [Pospelov '09]

Parameter Space

wide range of hidden photon masses $m_{\gamma'}$ and kinetic mixing values χ



[Jaeckel, Ringwald '10, Jaeckel '13]

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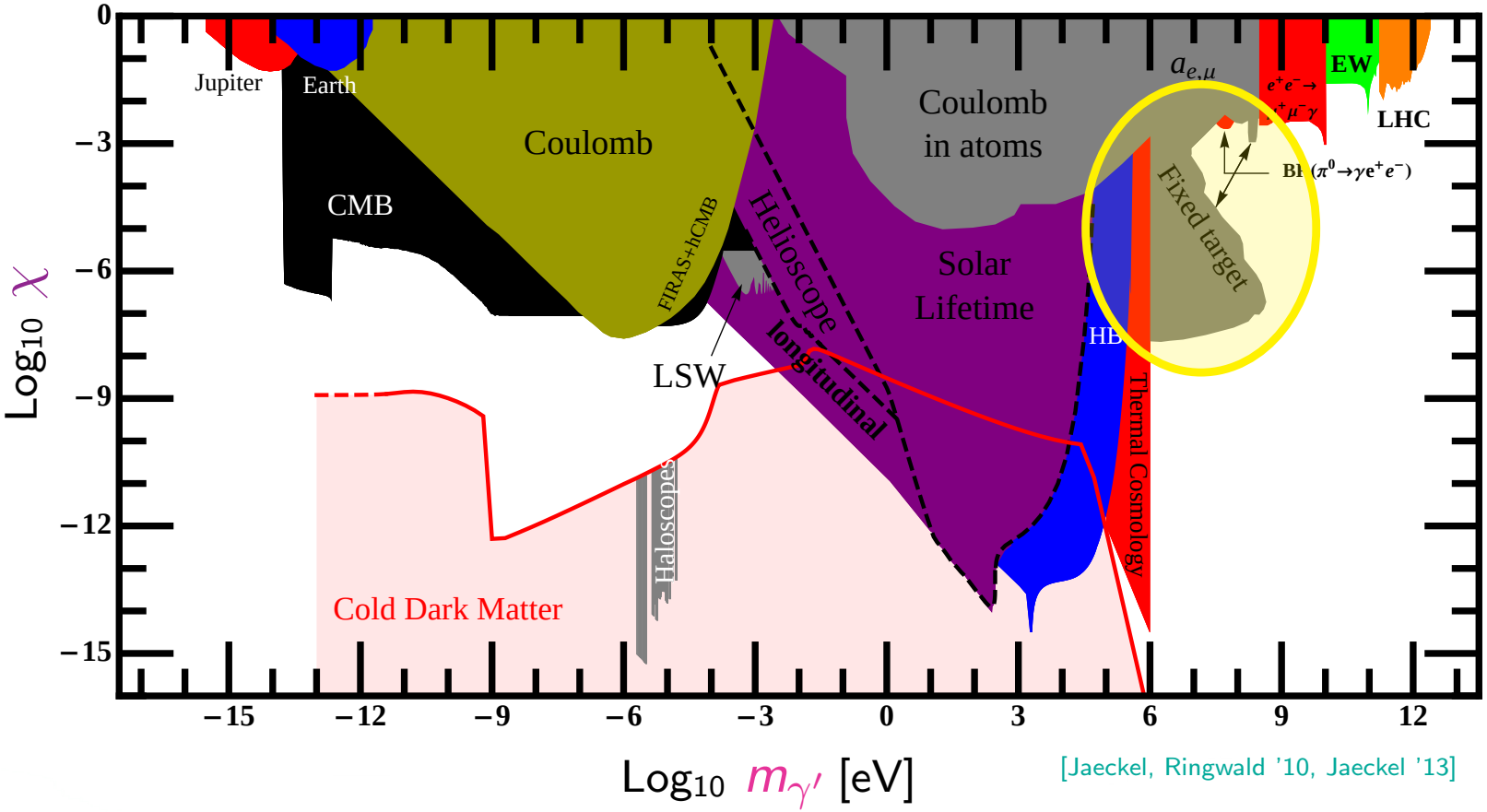


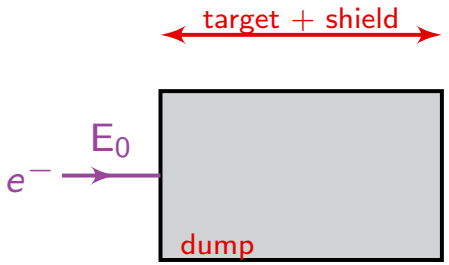
[Jaeckel, Ringwald '10, Jaeckel '13]

focus of this talk: MeV to GeV range

$\Rightarrow$ constraints from electron beam dump experiments

e^- Beam Dump Experiments: γ' Production

- e^--beam dumped onto target



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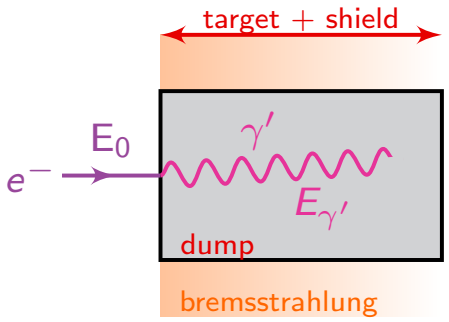


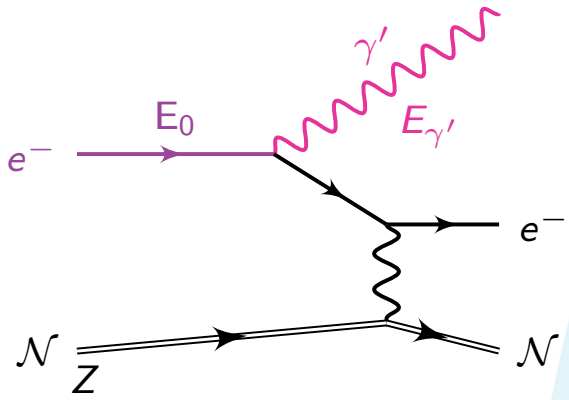
- γ' emitted from e^--beam

  process similar to ordinary bremsstrahlung

  γ' highly boosted in forward direction

- production cross section

$$\sigma_{\gamma'} \propto \alpha^3 Z^2 \frac{\chi^2}{m_{\gamma'}^2} \sim \mathcal{O}(\text{pb})$$



[Kim, Tsai '73; Tsai '74; Tsai '86;
Bjorken, Essig, Schuster, Toro '09
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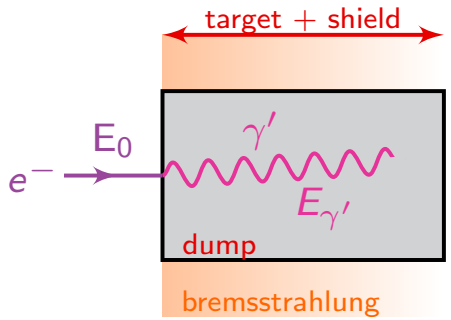

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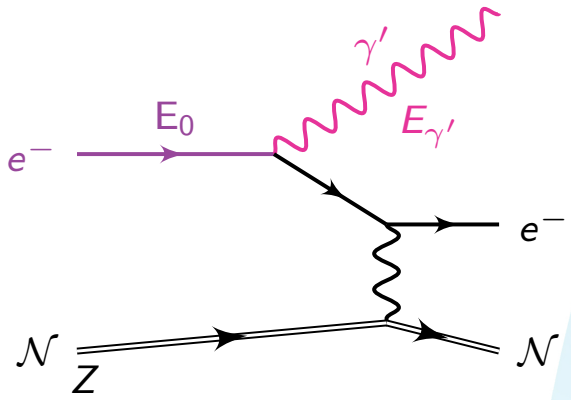
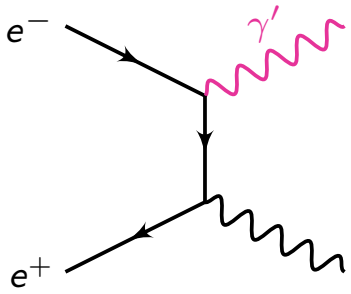


compared to e^+e^- collider case:

$$\sigma_{\gamma'} \propto \frac{\alpha^2 \chi^2}{E^2} \sim \mathcal{O}(\text{fb})$$

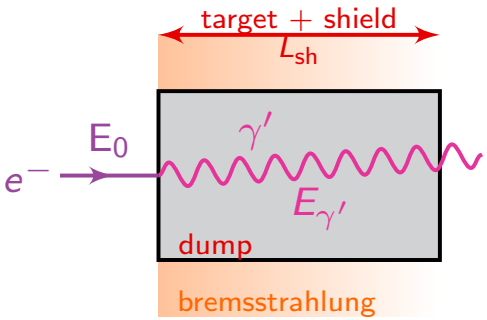


[Kim, Tsai '73; Tsai '74; Tsai '86; Bjorken, Essig, Schuster, Toro '09 SA, Niebuhr, Ringwald '12]

e^- Beam Dump Experiments: γ' Decay & Detection

- γ' can traverse the shield

  no SM background (if shield long enough)



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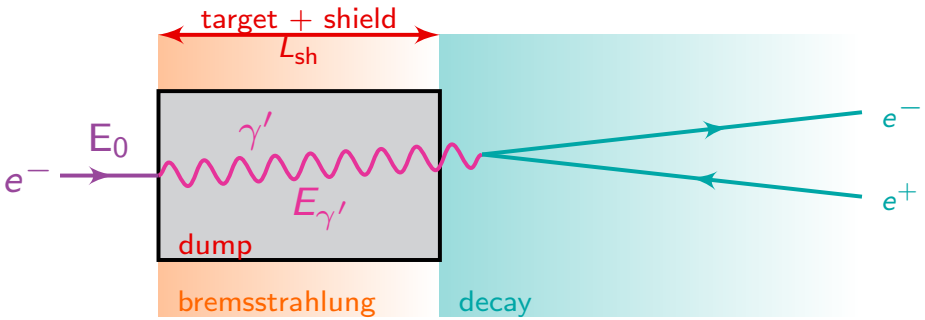
$$l_{\gamma'} \sim 10\text{cm} \frac{E_{\gamma'}}{1\text{GeV}} \left(\frac{10^{-4}}{\chi}\right)^2 \left(\frac{10\text{MeV}}{m_{\gamma'}}\right)^2$$

$$\sim \mathcal{O}(\text{mm} - \text{km})$$



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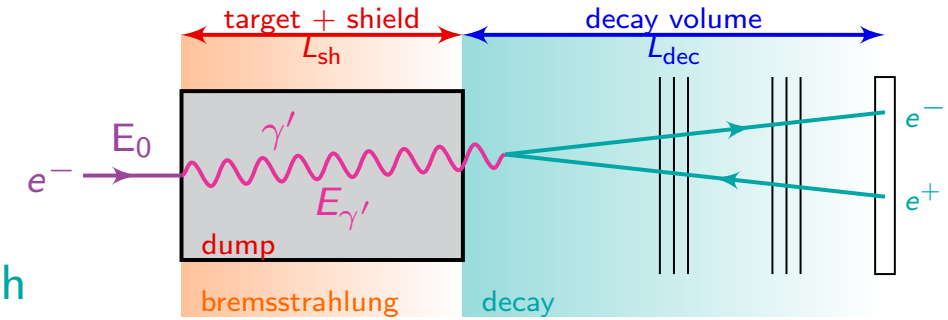

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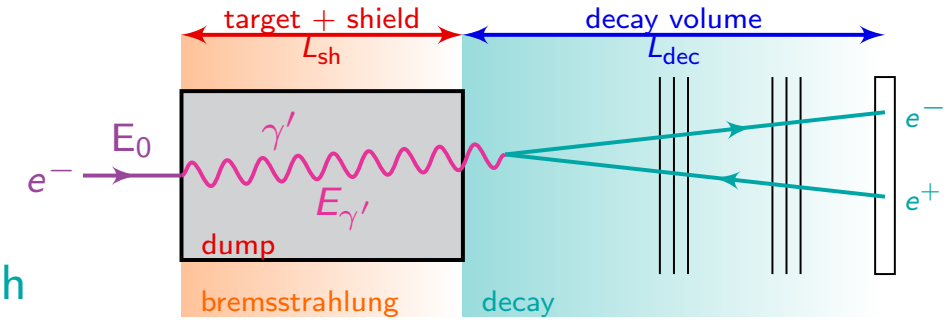
- detect decay products (mostly e^+e^-)

- number of expected events:

$$N_{\text{events}} \sim \int dE_{\gamma'} \int dE_e \int dl \; \frac{d\sigma_{\gamma'}}{dE_{\gamma'}} \; e^{-L_{\text{sh}}/l_{\gamma'}} \left(1 - e^{-L_{\text{dec}}/l_{\gamma'}}\right) \; N_e \; I_e(E_0, E_e, l) \; \text{BR}_{e^+e^-}$$

energy distribution $I_e(E_0, E_e, l)$ of electrons in dump

e^- Beam Dump Experiments: γ' Decay & Detection



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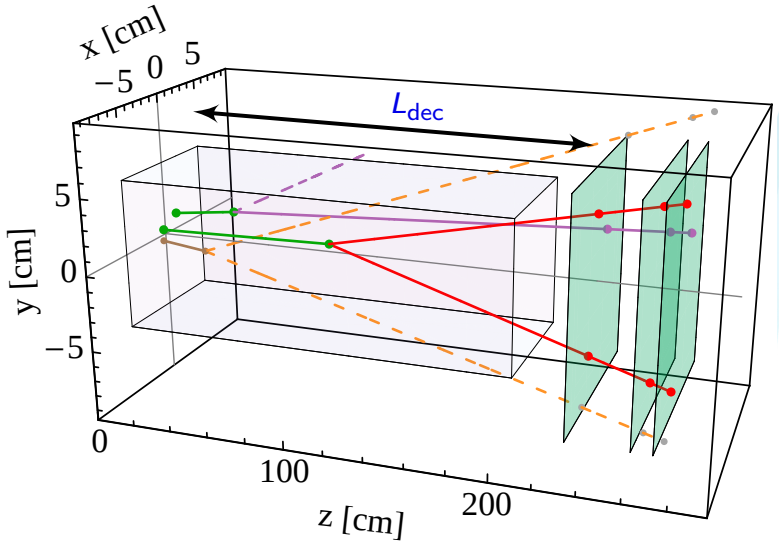

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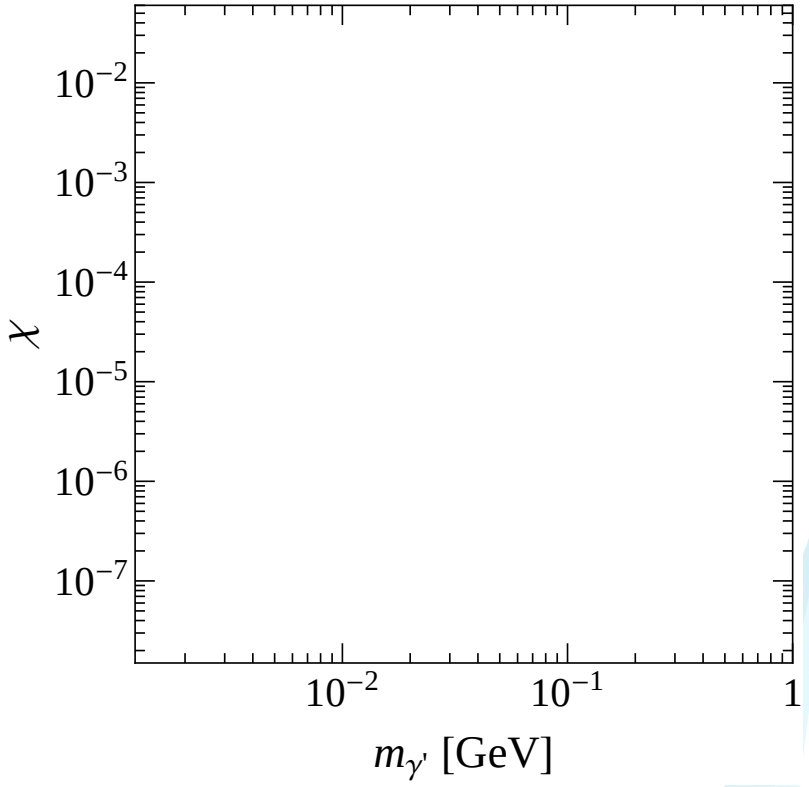
energy distribution $l_e(E_0, E_e, l)$ of electrons in dump

experimental acceptance A_{exp} from Monte Carlo simulations

Experimental Constraints



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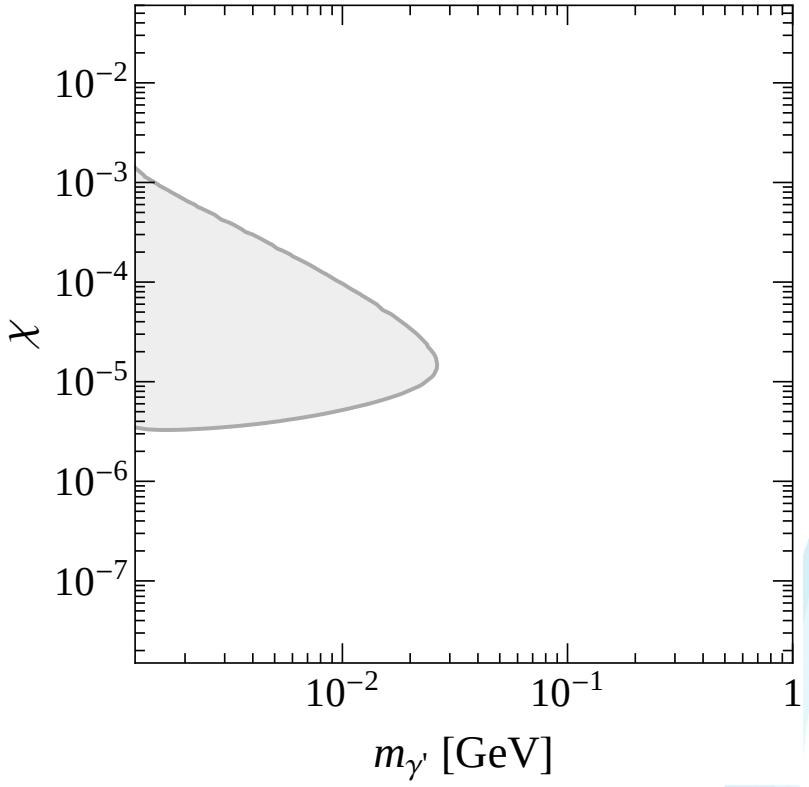

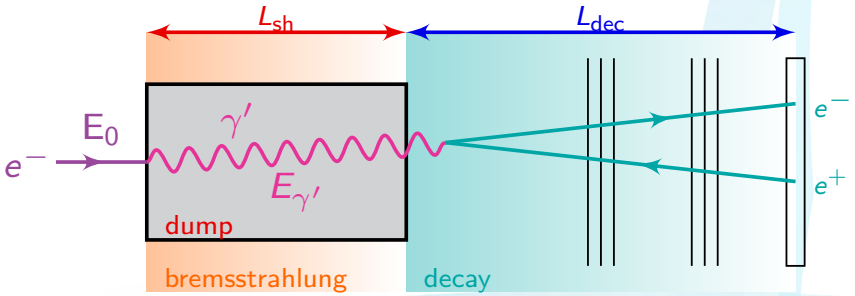

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γ' has to traverse shield

for small $l_{\gamma'} \ll L_{sh}$: $N_{events} \propto N_e \, e^{-L_{sh}/l_{\gamma'}}$

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enough decays within decay volume

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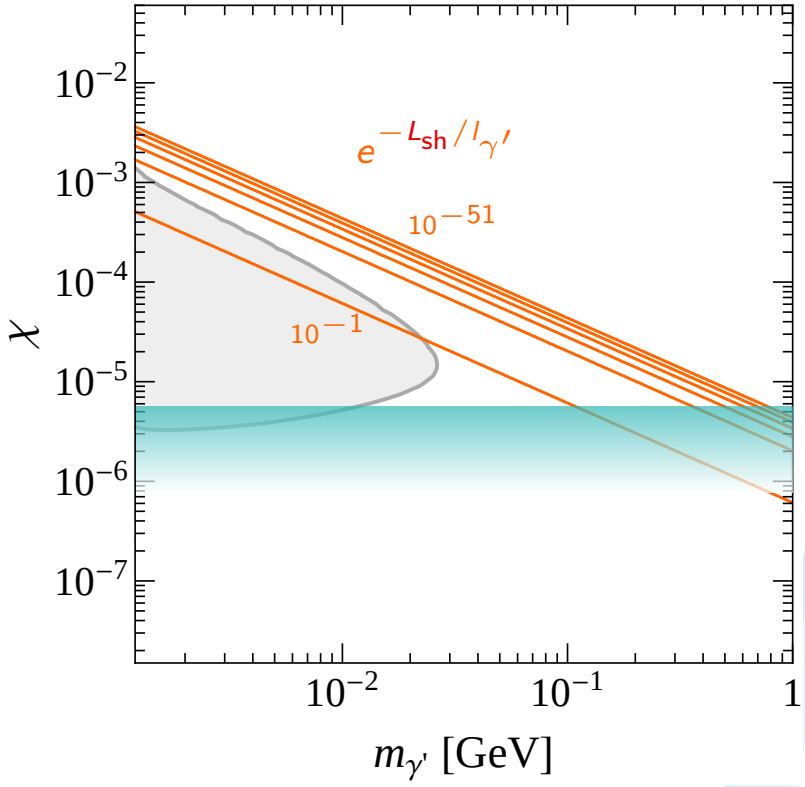

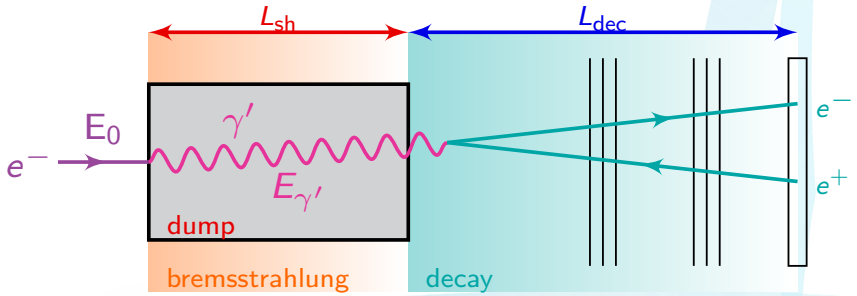

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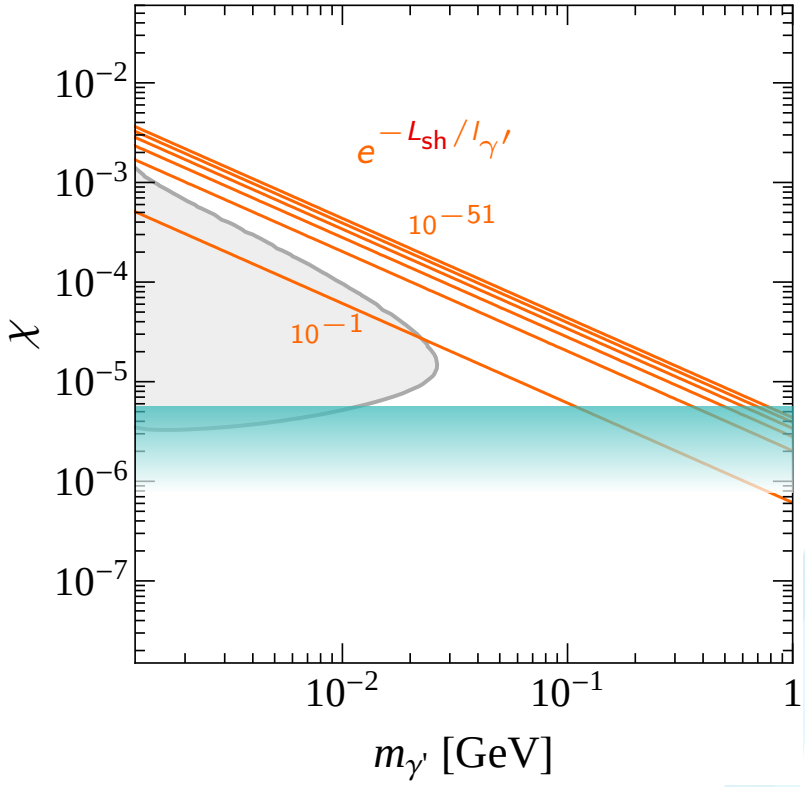

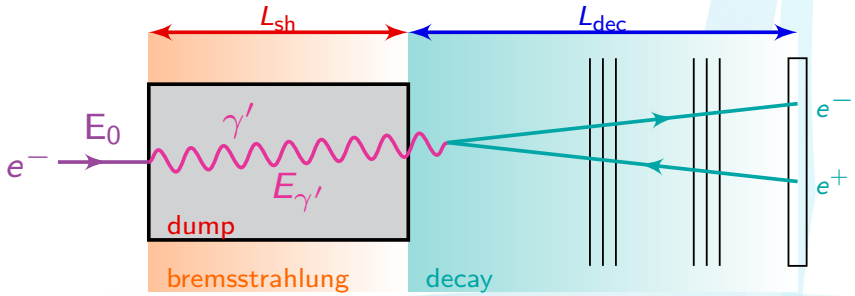

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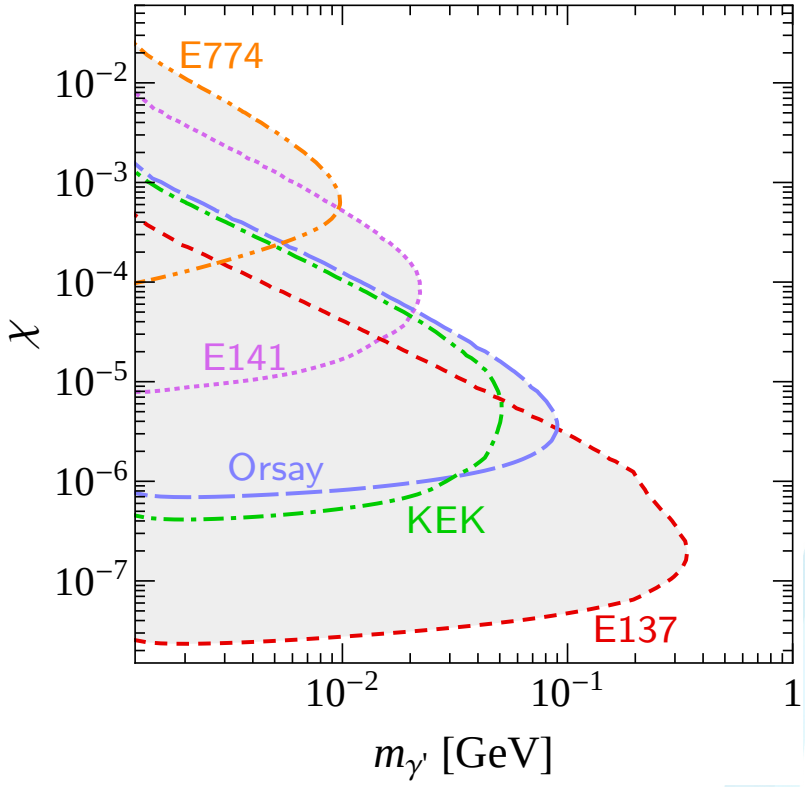

- KEK Japan (1986) [Konaka *et al.* '86]
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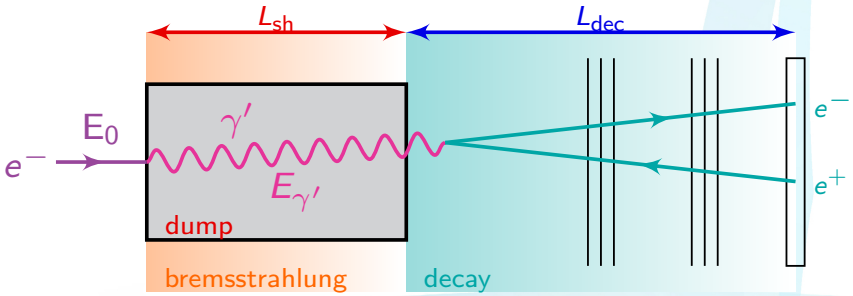

[Bjorken, Essig, Schuster, Toro '09; SA, Niebuhr, Ringwald '12]

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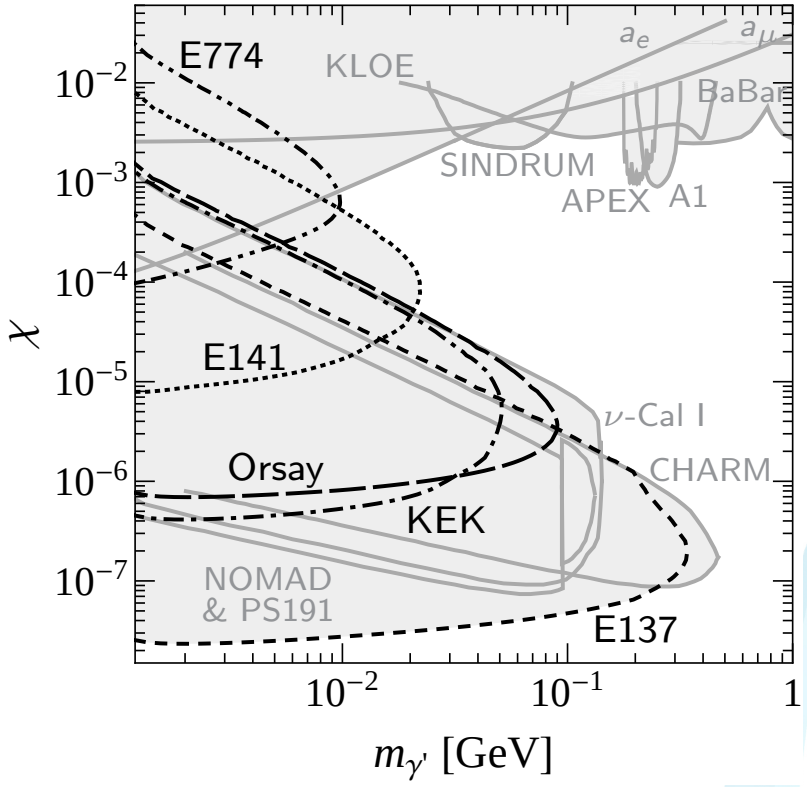

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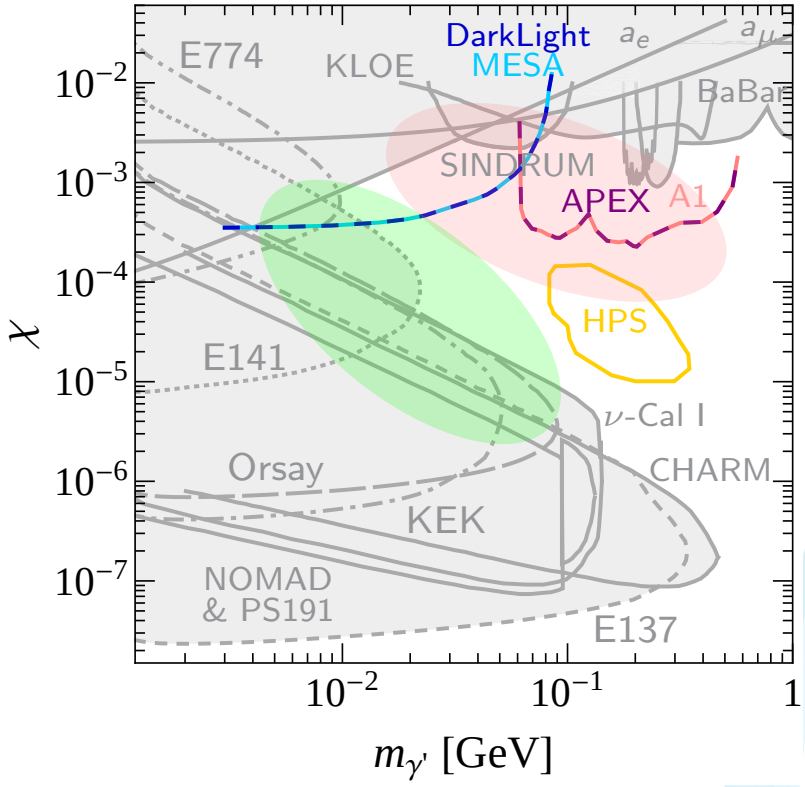


- current constraints

- future searches
  - thin target experiments
  - new beam dump experiments

Outline

1. Introduction & Motivation
2. Constraints on Hidden Sectors with Hidden Photon
3. Hidden Sectors with Dark Matter
4. Conclusions

Toy Model: Dirac fermion DM

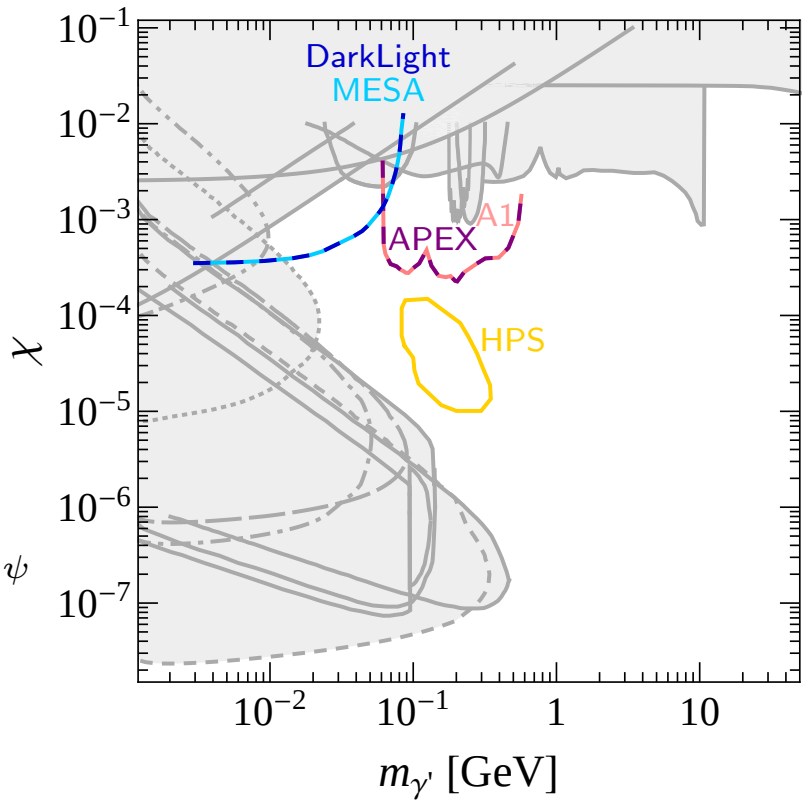
simplest hidden sector with DM

- hidden photon γ'
- Dirac fermion ψ

$\Rightarrow$ extra parameter m_ψ

$$\mathcal{L}_{\text{eff}} \supset -\frac{1}{4}\tilde{X}_{\mu\nu}\tilde{X}^{\mu\nu} + \frac{\chi_Y}{2}\tilde{X}_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{\tilde{m}^2_{\gamma'}}{2}\tilde{X}_\mu\tilde{X}^\mu + g_h\bar{\psi}\gamma^\mu\psi\tilde{X}^\mu + m_\psi\bar{\psi}\psi$$

$$\boxed{\chi = g_h\frac{g_Y c_W}{16\pi^2} \times \kappa} \quad (0.1 \leq \kappa \leq 10)$$



[SA, Goodsell, Ringwald '11, '13]

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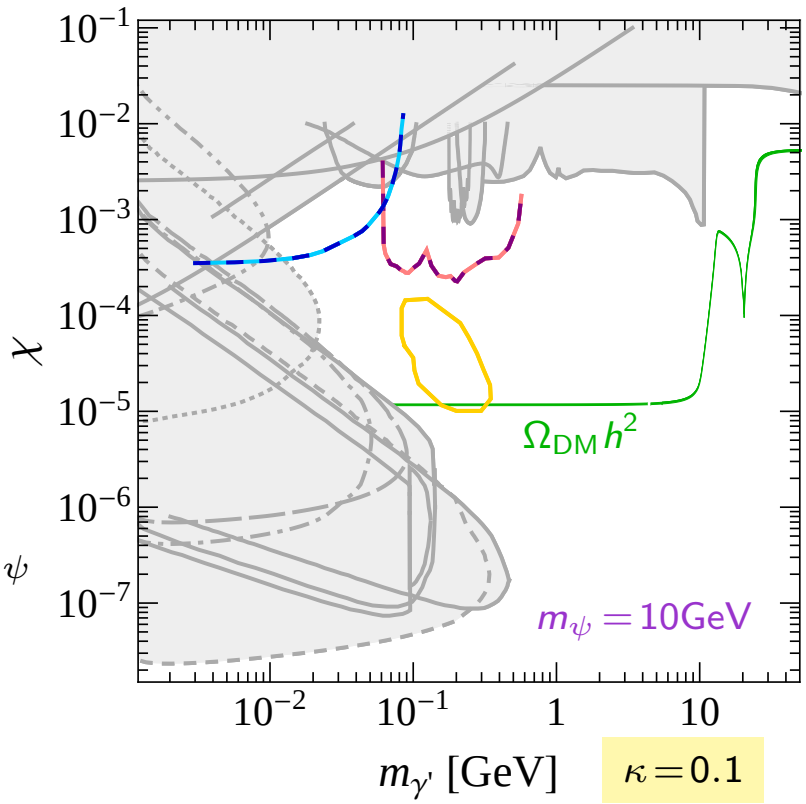
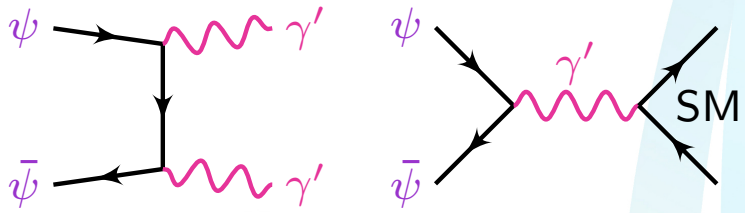


Relic abundance Ωh^2

$\Rightarrow$ ψ total DM

- annihilation of ψ through and into γ'
- t-channel only when $m_\psi > m_{\gamma'}$
- s-channel: resonance for $m_{\gamma'} = 2\ m_\psi$



$$\langle\sigma_A v\rangle \propto \frac{\chi^4}{m_\psi^2\,\kappa^4} \qquad \propto \frac{\chi^4 e^2}{\kappa^4}\frac{m_\psi^2}{(4m_\psi^2 - m_{\gamma'}^2)^2}$$

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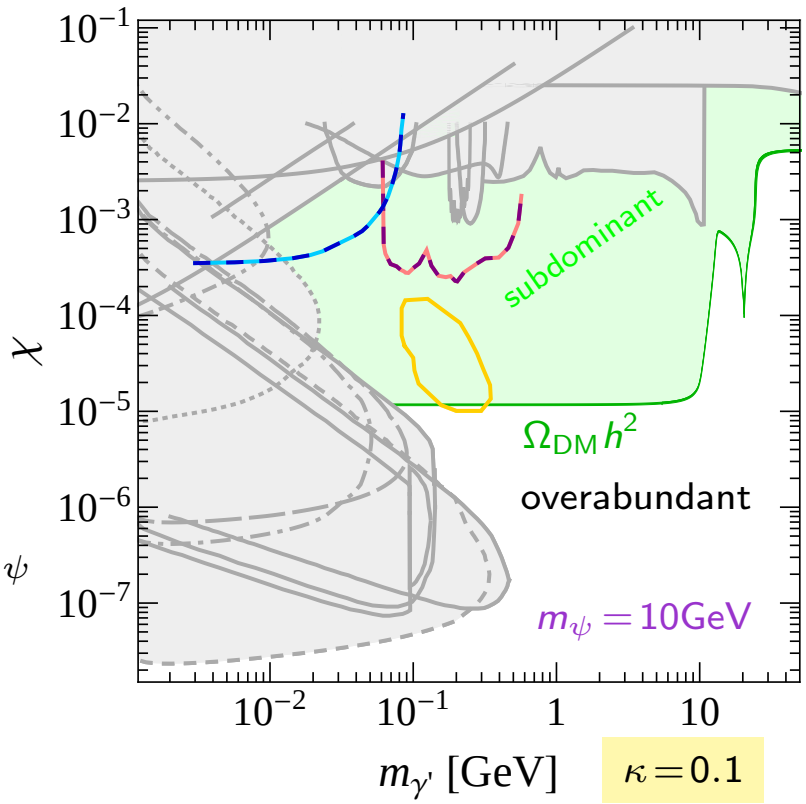

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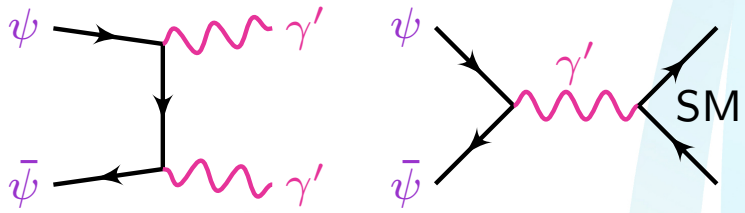

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Toy Model: Dirac fermion DM

Direct Detection

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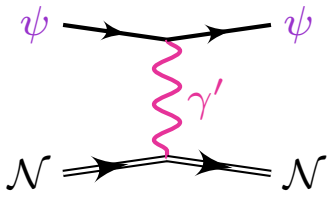
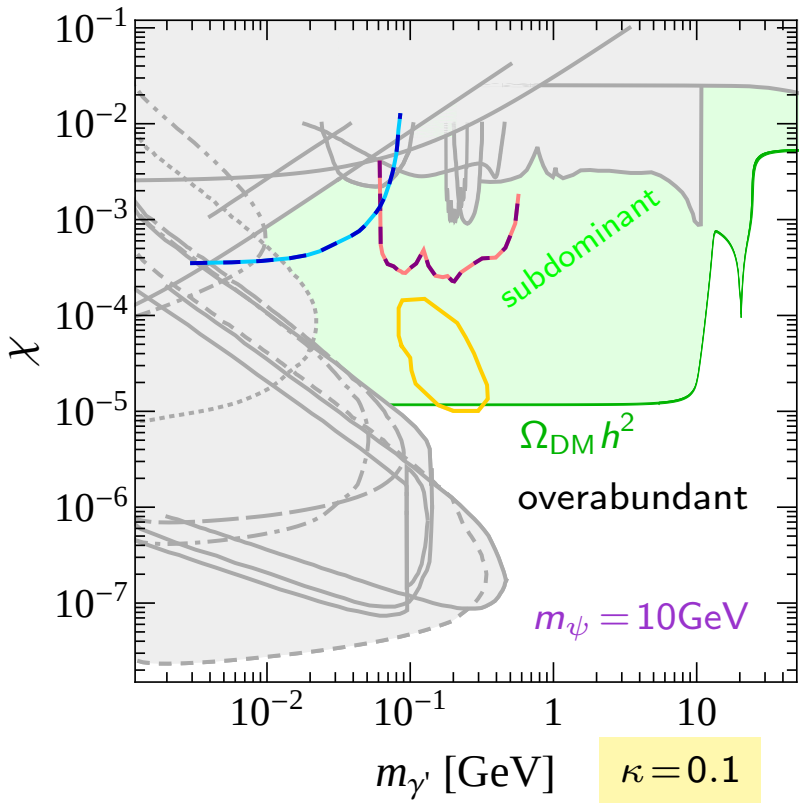
- elastic scattering essentially on p
- spin-independent vector-like interaction



$$\sigma^{\mathrm{SIp}} \propto \frac{\chi^2 g_h^2}{m_{\gamma'}^4} \propto \frac{\chi^4}{m_{\gamma'}^4}$$

$$\sigma^{\mathrm{SIp}}_{\mathrm{resc}} \propto \sigma^{\mathrm{SI}} \frac{\Omega_\psi}{\Omega_{\mathrm{DM}}} \propto \frac{\chi^4}{m_{\gamma'}^4} \frac{1}{\langle \sigma_{\mathrm{A}} v \rangle} \propto \frac{1}{m_{\gamma'}^4}$$



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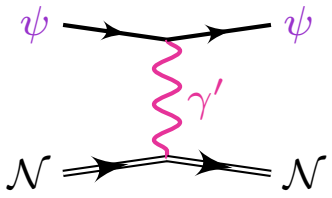

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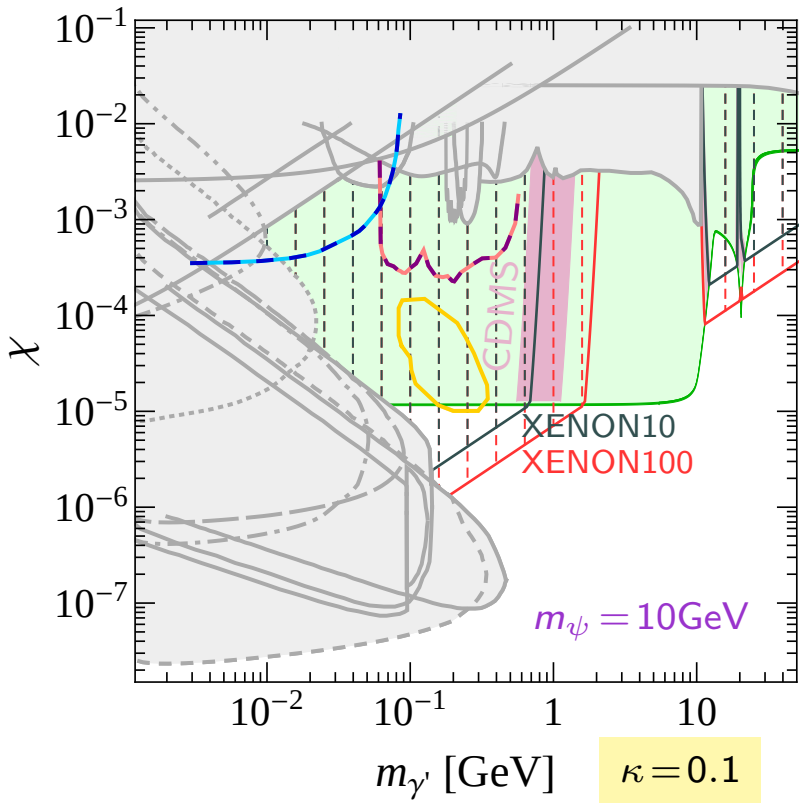
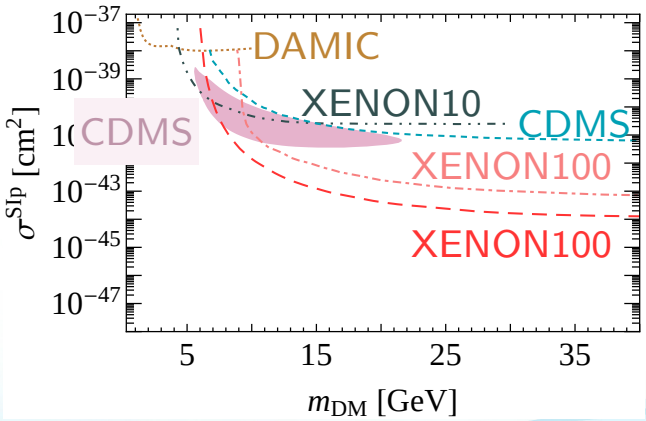


DD limits and signals

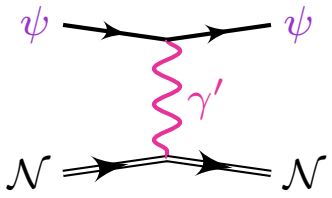


[SA, Goodsell, Ringwald '11, '13]

Toy Model: Dirac fermion DM

Direct Detection

- mediated by γ'
- elastic scattering essentially on p
- spin-independent vector-like interaction



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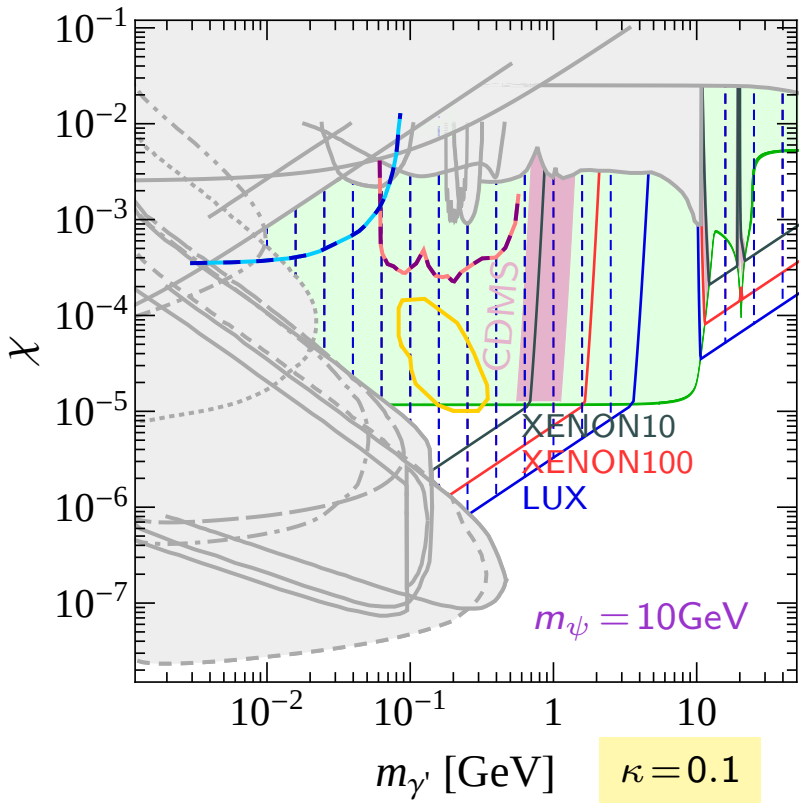

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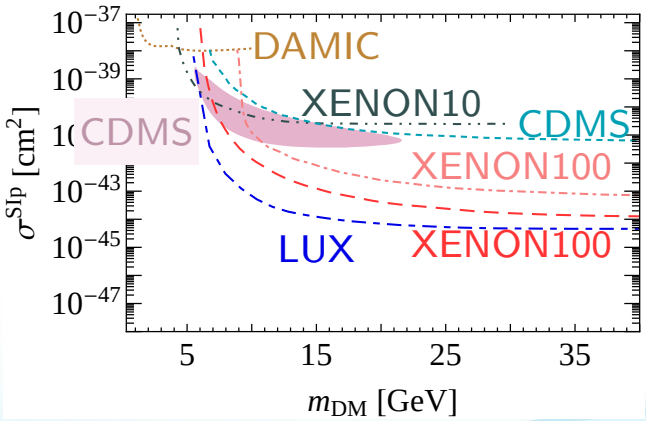
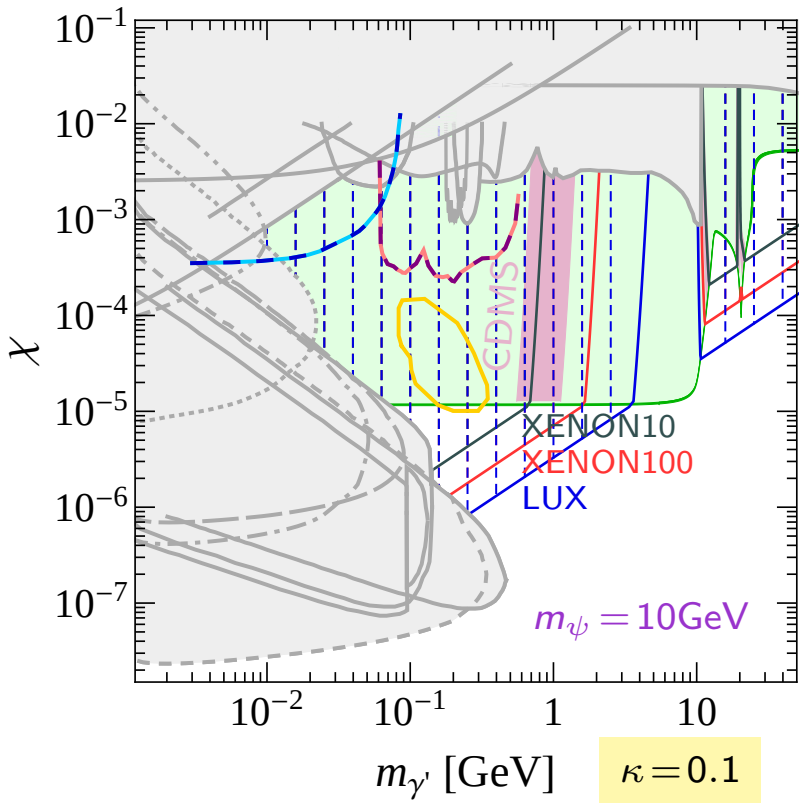
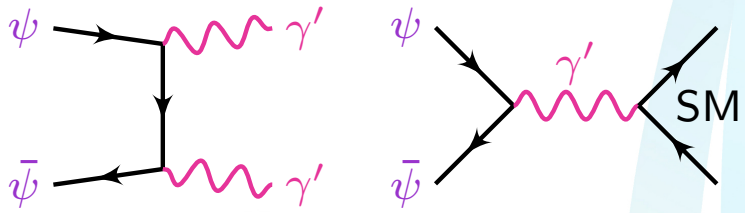


[SA, Goodsell, Ringwald '11, '13]

Indirect Detection Constraints

- from DM annihilations into SM particles
- same processes relevant for Ωh^2





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e.g. Synchrotron Emission from GC

- DM annihilations produce e^+, e^-
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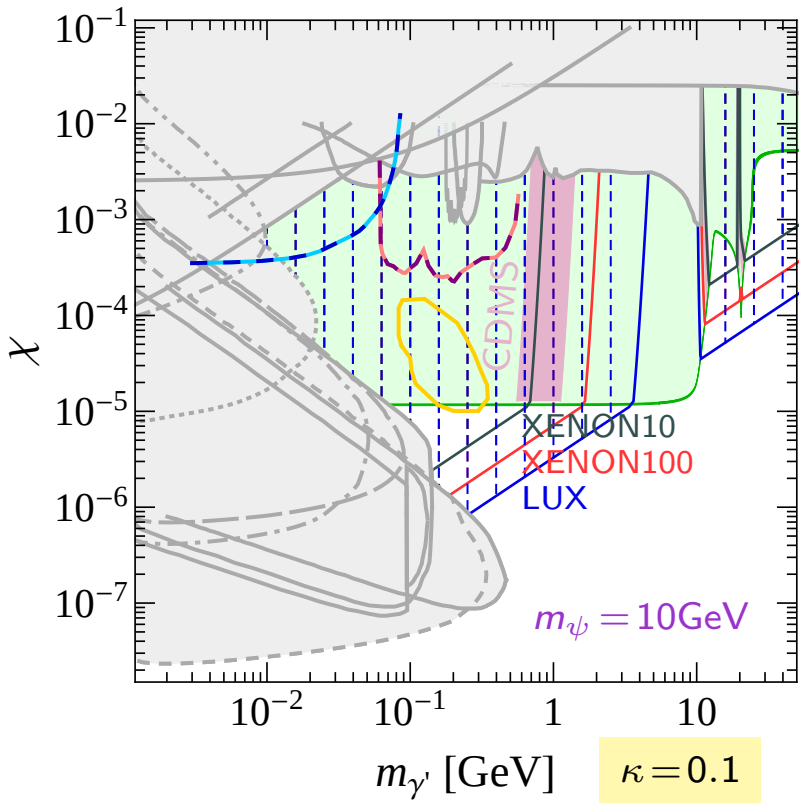

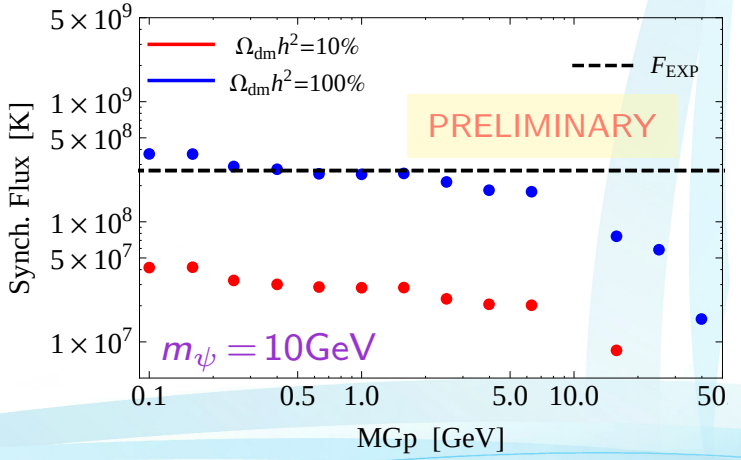

[SA, Goodsell, Zaldivar *in prep.*]

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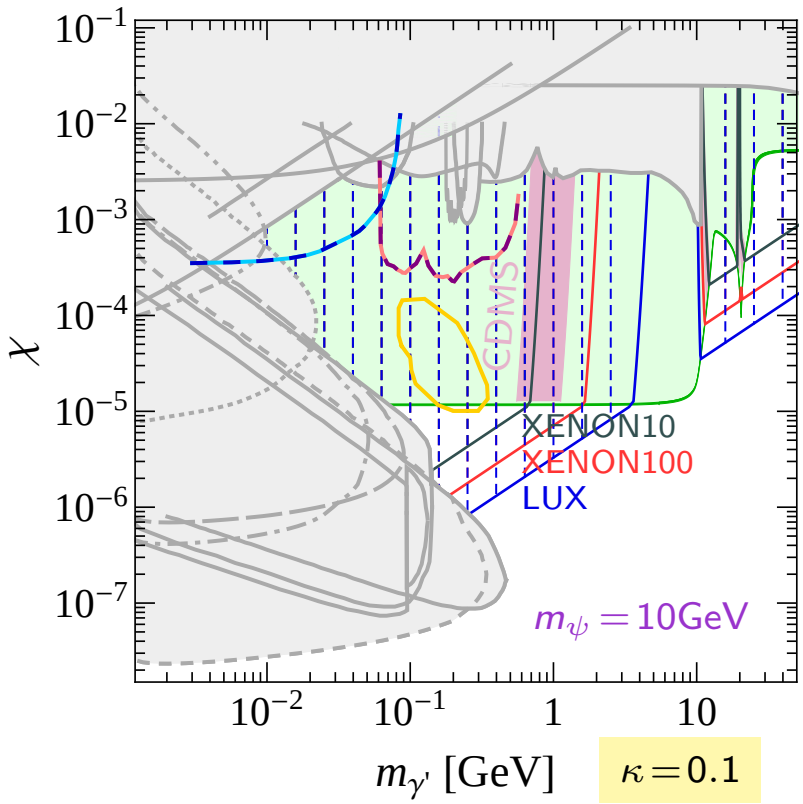
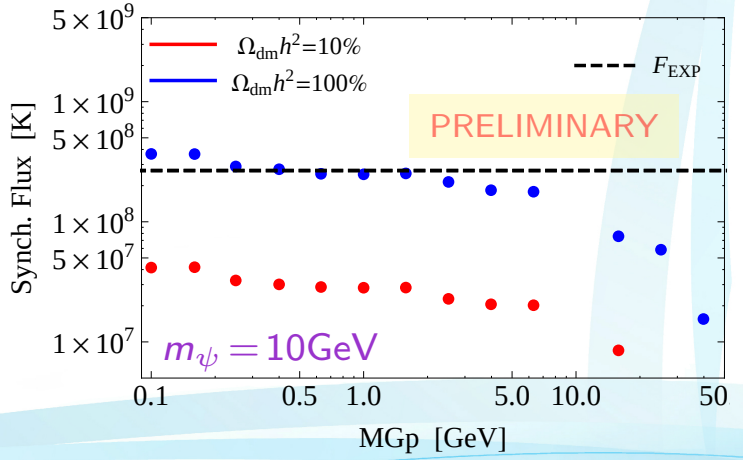
further constraints

- effect on CMB temperature & polarization anisotropies in early universe [Madhavacheril *et al.* '13]
- diffuse gamma-ray emission [Tavakoli *et al.* '13]
- positrons, antiprotons,...





[SA, Goodsell, Zaldivar *in prep.*]

Supersymmetric Dark Force Models

- most simple anomaly-free HS:
  - three chiral superfields S, H_+, H_- charged under $U(1)_h$
  - superpotential: $W \supset \lambda_S \, S H_+ H_-$

    (assume MSSM in visible sector)

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    (assume MSSM in visible sector)
- hidden gauge symmetry breaking:
  - radiative breaking domination
  - visible sector induced breaking
- DM can consist of stable hidden sector particle
- relation between g_h and χ: $\chi = g_h \frac{g_Y c_W}{16\pi^2} \kappa$

Radiative Breaking Domination

- running of Yukawa coupling λ_S induces breaking of hidden gauge symmetry
  - choose masses & couplings at high scale

[SA, Goodsell, Ringwald '11, '13]

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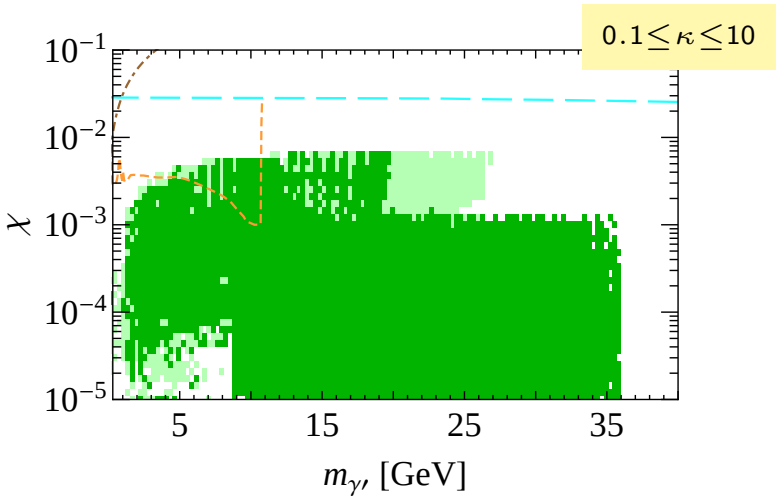

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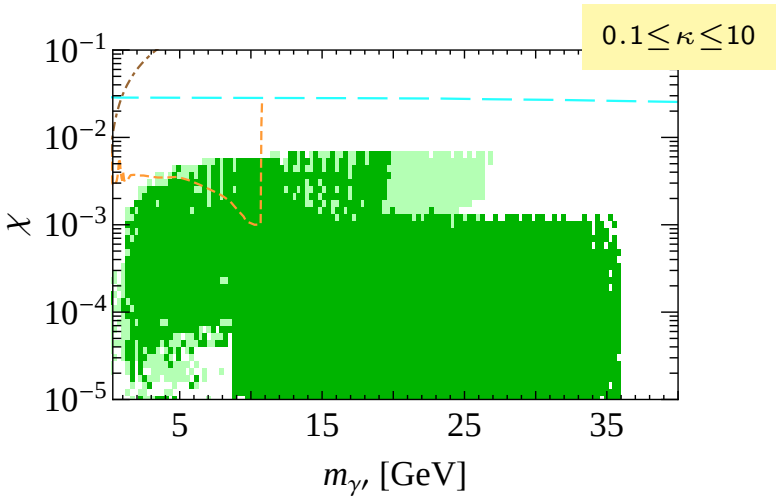
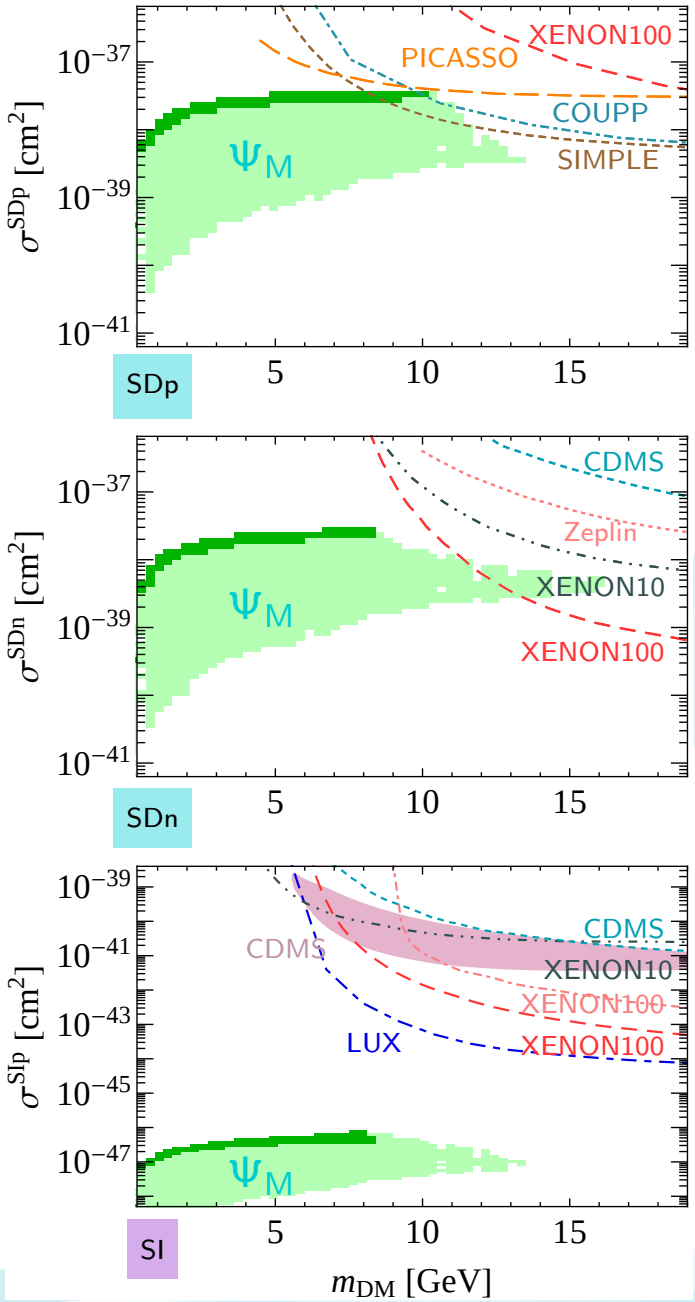
Radiative Breaking Domination

- running of Yukawa coupling λ_S induces breaking of hidden gauge symmetry
  - choose masses & couplings at high scale
- Majorana fermion Ψ_M: total & subdominant DM
  - axial coupling generates SD scattering
  - minor SI scattering





$\Rightarrow$ SD in reach of experiments SI beyond reach

[SA, Goodsell, Ringwald '11, '13]

Visible Sector Induced Breaking

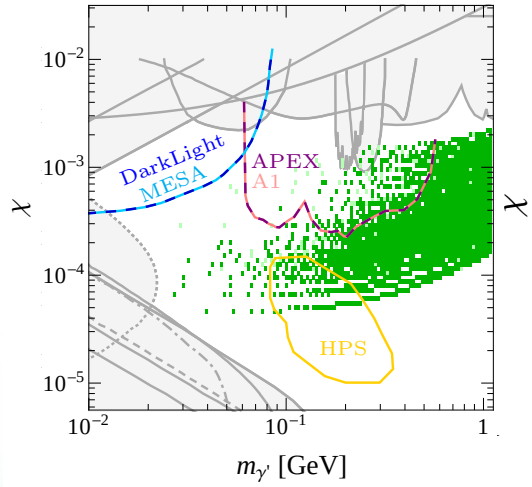
- hidden gauge symmetry broken via effective Fayet-Iliopoulos term

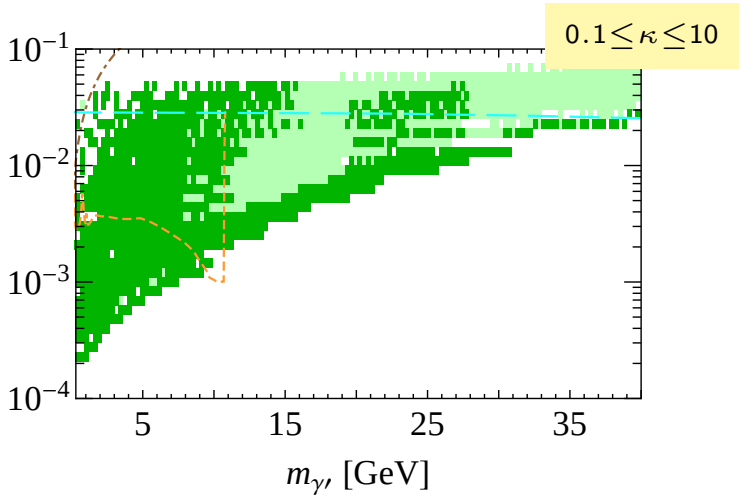
[SA, Goodsell, Ringwald '11, '13]

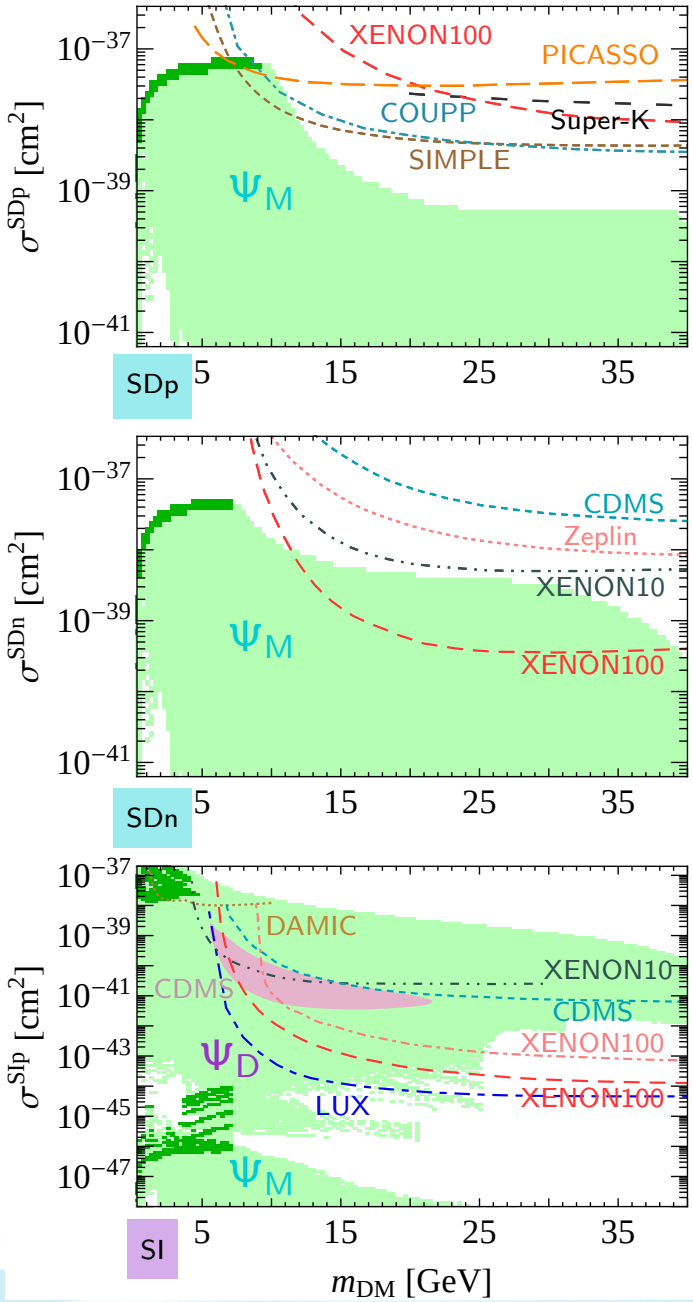
Visible Sector Induced Breaking

- hidden gauge symmetry broken via effective Fayet-Iliopoulos term

- Majorana Ψ_M or Dirac Ψ_D fermion as DM
  - Ψ_M: mostly SD (like rad. breaking)
  - Ψ_D: mostly SI (like Toy-Model, but $m_{DM} < m_{\gamma'}$)







$\Rightarrow$ SI probe Ψ_D SD probe Ψ_M

[SA, Goodsell, Ringwald '11, '13]

Scenarios with invisible Hidden Photons & very light DM

- if hidden sector DM with $m_\psi < \frac{m_{\gamma'}}{2}$, decay of γ' is dominantly invisible: $\gamma' \to \psi\psi$

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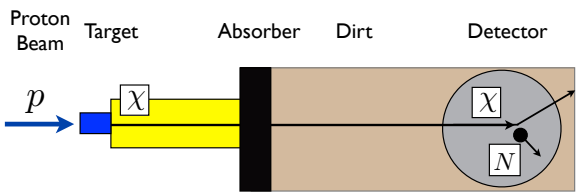
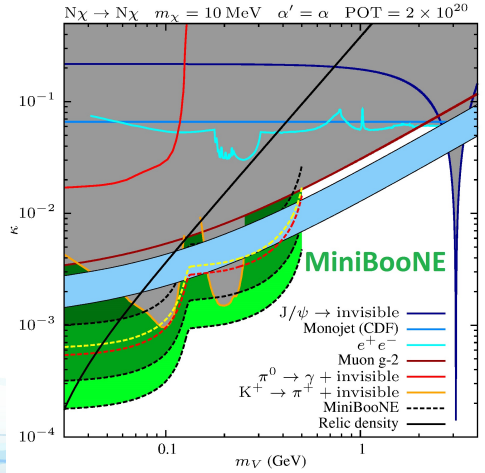
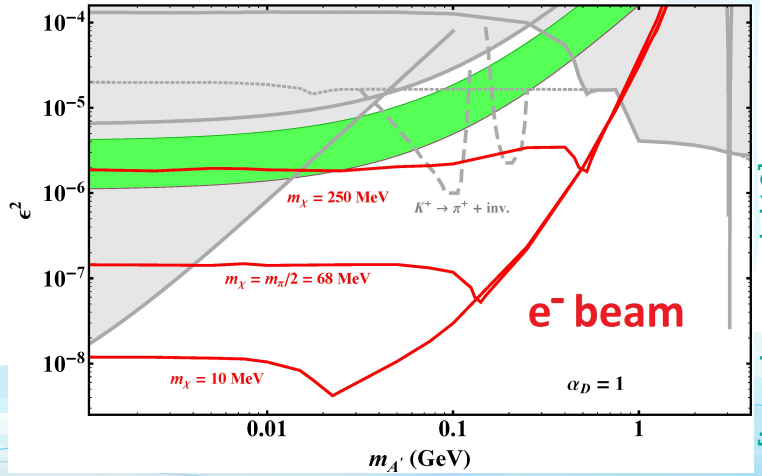
- other limits e.g. from white dwarf and supernova cooling [Dreiner *et al.* '13 Dreiner *et al.* '13]
  ψ can be pair-produced and escape WD/SN
- detect light DM particle from γ' decay via scattering
  - ◇ proton beam and existing neutrino detector [Batell *et al.* '09, DeNiverville *et al.* '11 DeNiverville *et al.* '12]
    e.g. MiniBooNE at Fermilab [Aguilar-Arevalo *et al.* '12]
  - ◇ electron beam [Izaguirre *et al.* '13]



[Brain Batell '13]



[Aguilar-Arevalo *et al.* '12]



[Izaguirre *et al.* '13]

Outline

1. Introduction & Motivation
2. Constraints on Hidden Sectors with Hidden Photon
3. Hidden Sectors with Dark Matter
4. Conclusions

Conclusions

- Hidden Sector
  - theoretically well motivated in many BSM scenarios
  - interesting phenomenology and possible connection to dark matter
- Hidden Photons
  - probed with high intensity experiments, e.g. beam dumps
  - new experiments needed to further probe the parameter space
- Dark Matter in Hidden Sector
  - viable DM candidates
  - probed by DD experiments
  - constraints from indirect detection - *work in progress*
  - light DM can make γ' decay invisible and be searched at beam dumps

Thank you!