Dark Matter Bound States and Collider Signature

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PRL 2016, arxiv:1510.05020, with H. An, B. Echenard, M. Pospelov

Dark Matter Exists in Nature

Overwhelming evidence for dark matter from galaxy rotational curve, bullet cluster, structure formation and cosmic microwave background.

Properties of Dark Matter

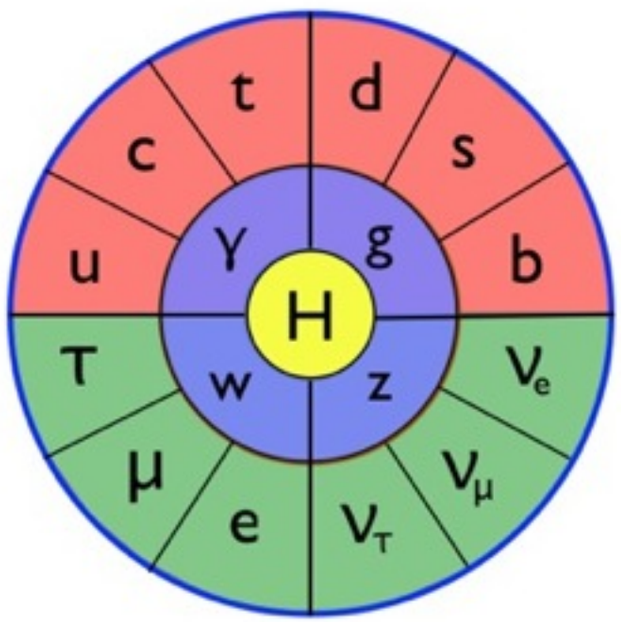
All are gravitational evidence so far, we still hope to rediscover dark matter in laboratories.

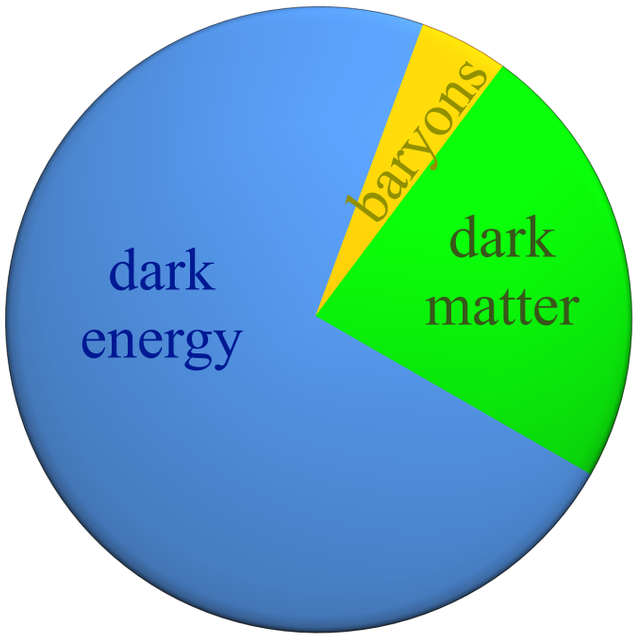
In this talk, I will assume dark matter is a particle.

- Stable or long lived
- Non-relativistic enough
- No strong or EM interaction
- Not too much dissipation

What is the Theory for Dark Matter?

New models are built by making analogy to existing theories.





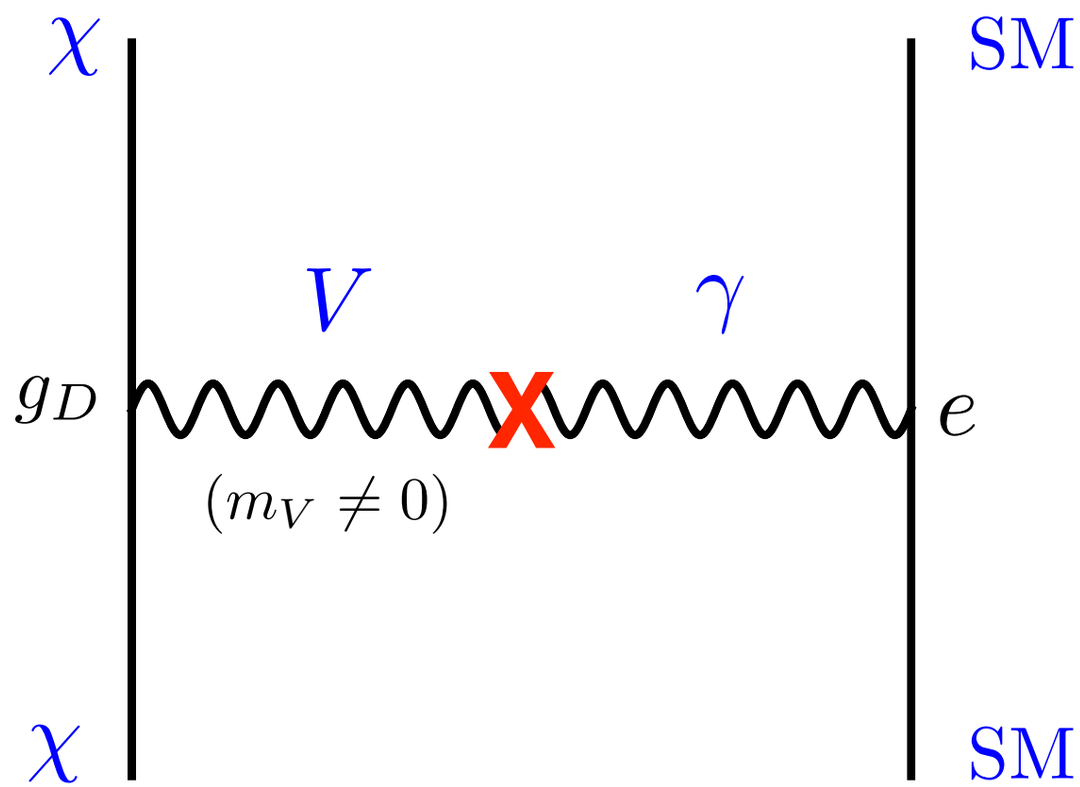
$\Omega_{\rm baryons} \simeq 5\%$

$\Omega_{\rm DM} \simeq 26\%$

Very natural if a dark force exists

A Renormalizable Model

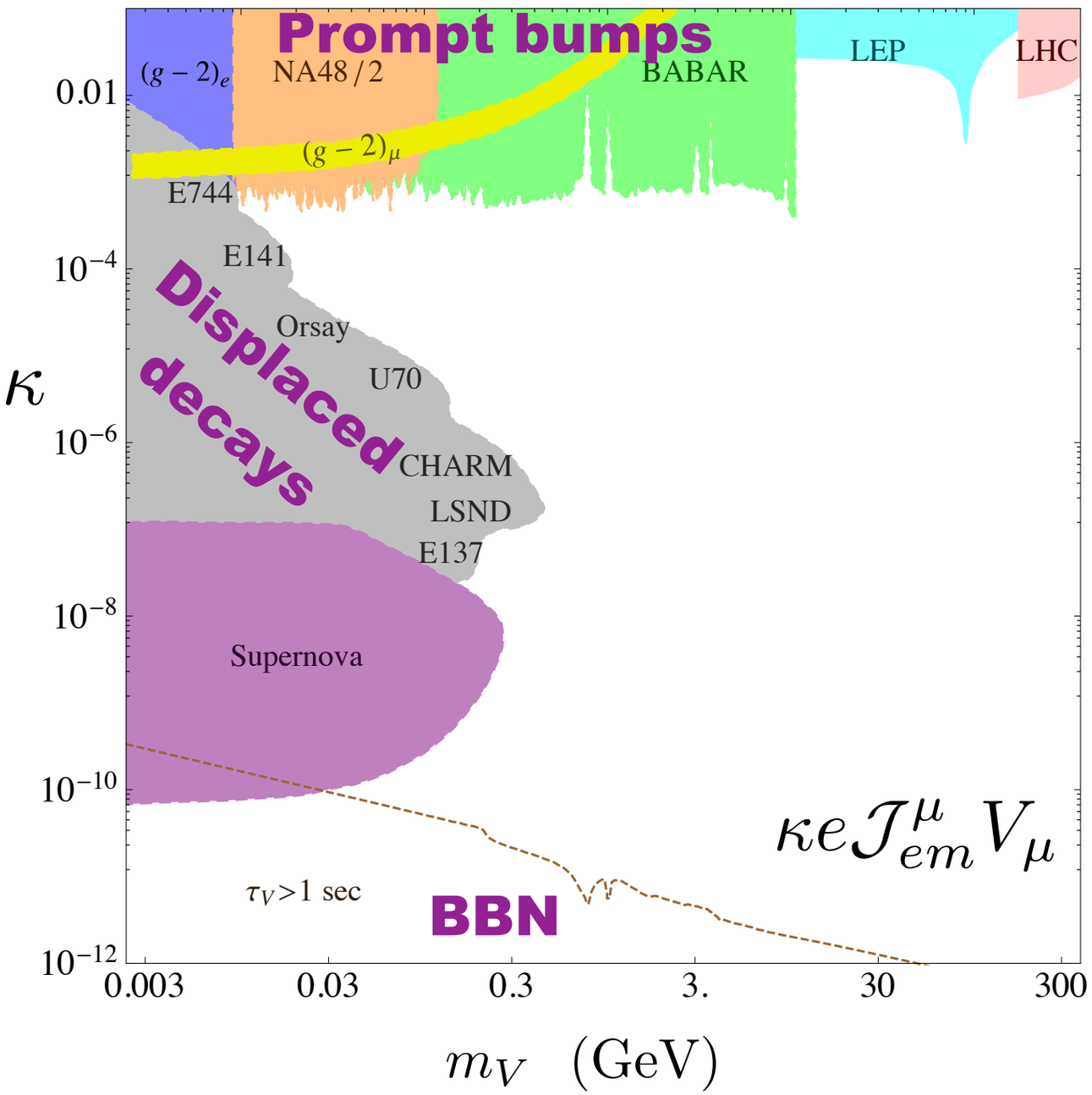
I will assume dark matter is a SM gauge singlet.



Dark photon acts on dark matter: $g_D \bar{\chi} \gamma^\mu \chi V_\mu$

Dark photon mixes with the visible photon: $\frac{\kappa}{2} F_{\mu\nu} V^{\mu\nu}$

Searches for Dark Photon



BaBar, LEP : $e^+e^- \to V\gamma \to \ell^+\ell^-\gamma$

NA48/2 : $\pi^0 \to V\gamma \to e^+e^-\gamma$

Beam dump : $e^- N \to e^- V + X$

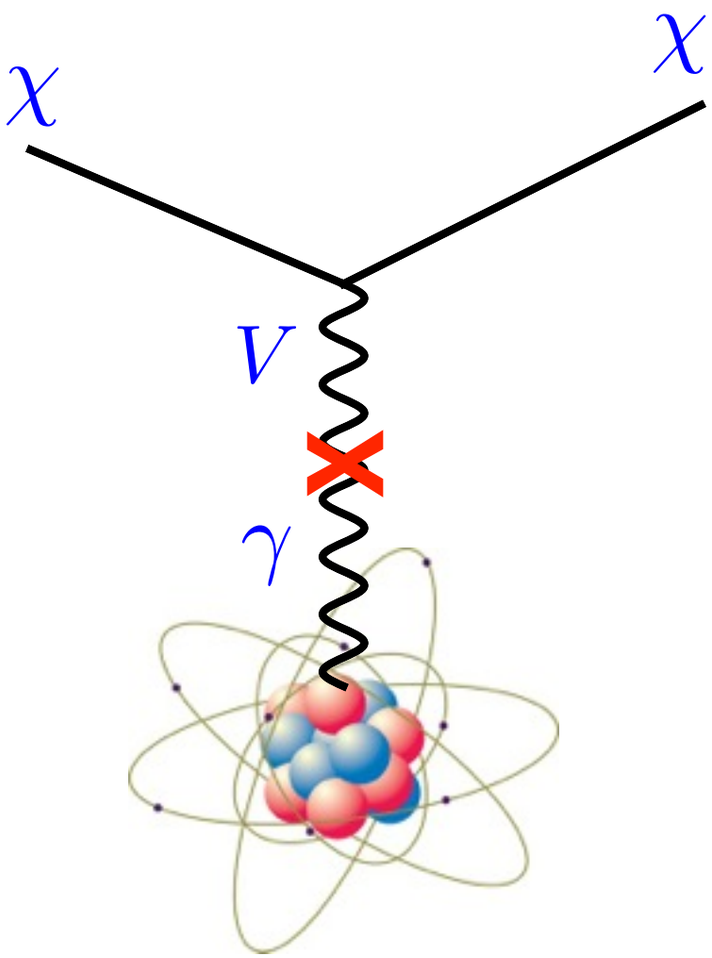
$pN \to V + X$

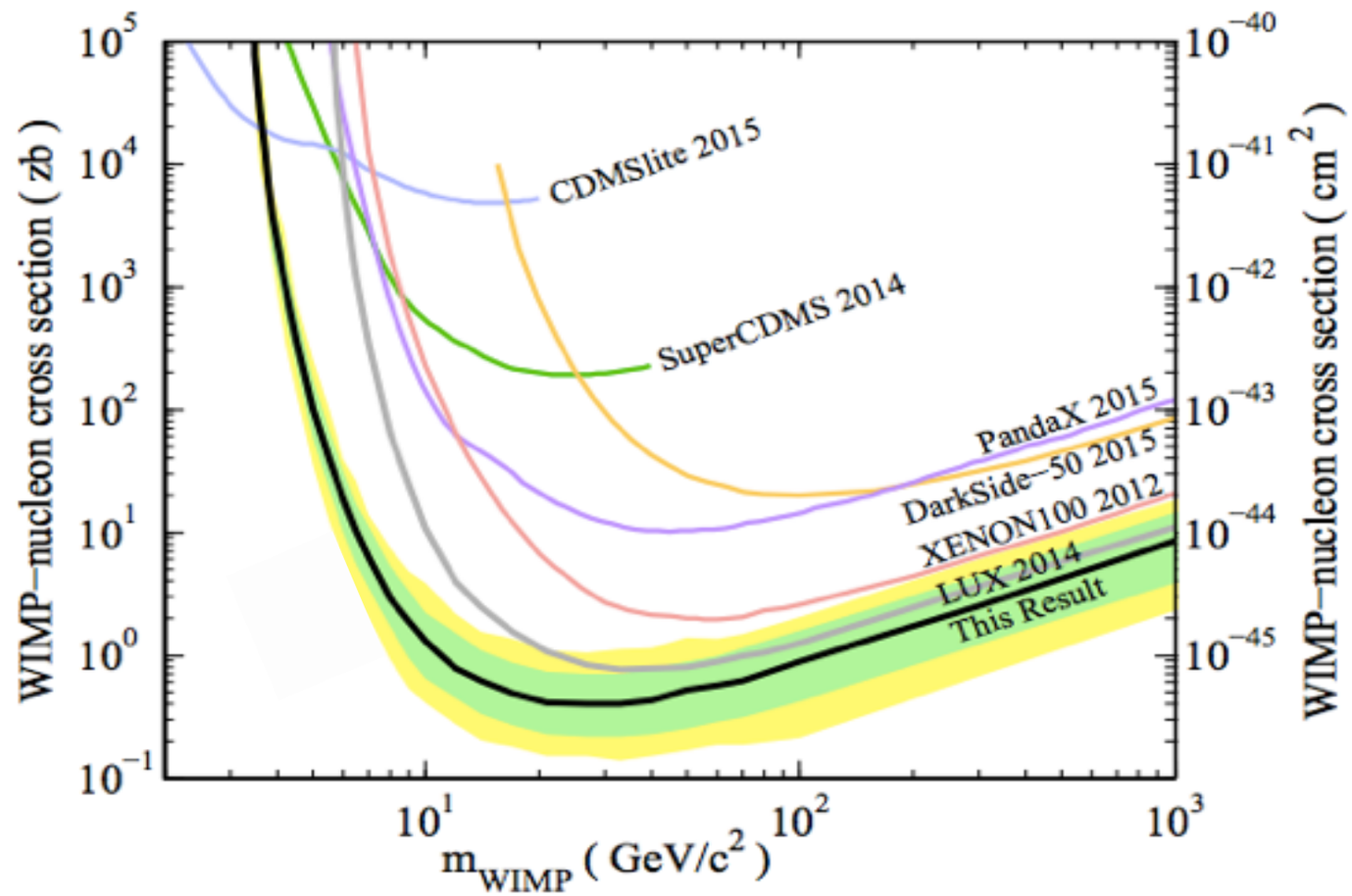
Supernova1987a : $pn \to pn + V$

V decays to SM charged particles by mixing with photon (κ)

Snowmass report (arXiv:1311.0029)

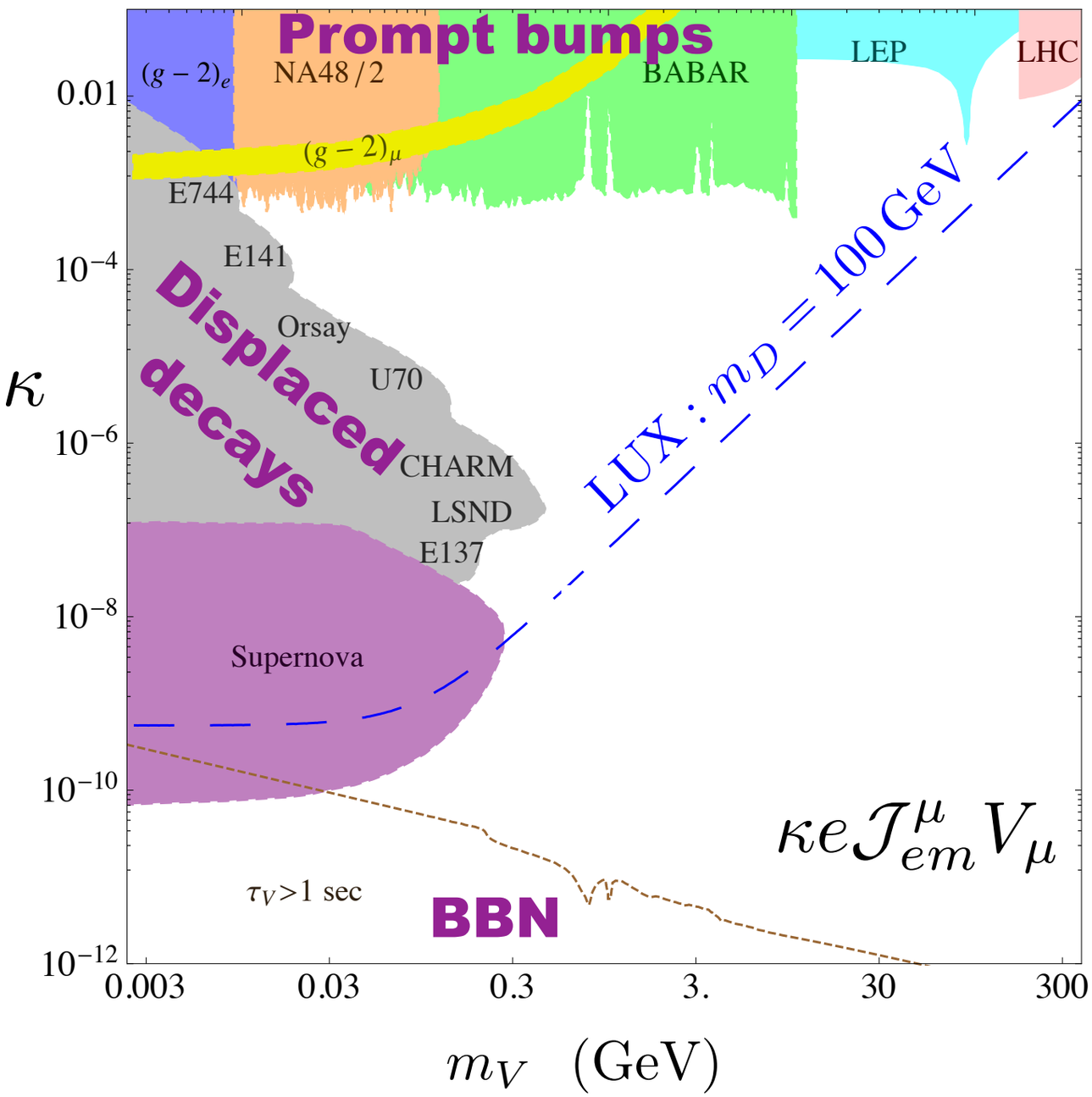
Dark Matter Direct Detection





LUX Collaboration (PRL 2016)

Constraints on Parameter Space

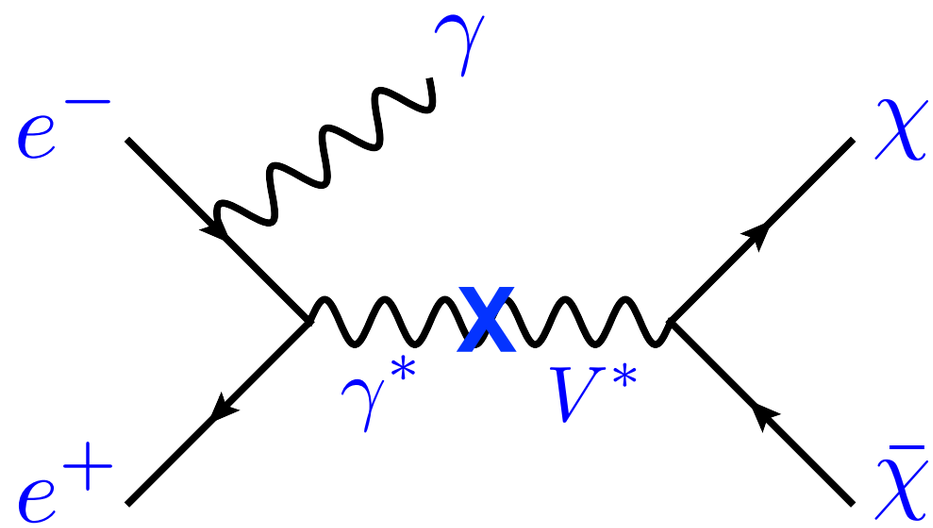


Direct detection bound can be relaxed if dark matter is lighter than ~ 5 GeV

Light Dark Matter at Colliders

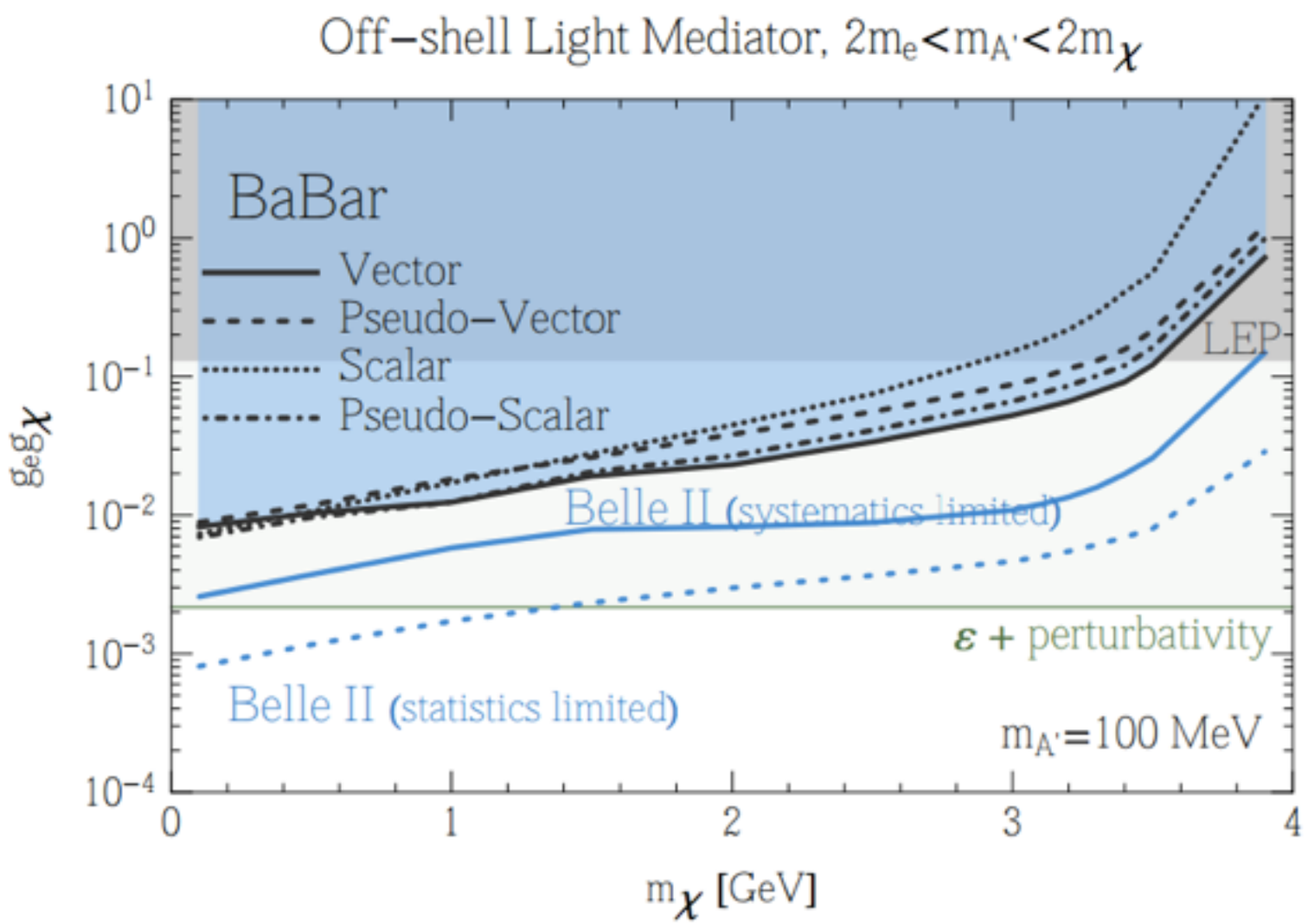
B-factories have suitable energy and very large luminosity.

Traditional search for dark matter: missing energy events



Monophoton : photon plus missing energy

Mono-photon Search at BaBar



$\Rightarrow \kappa \sim 10^{-2}$

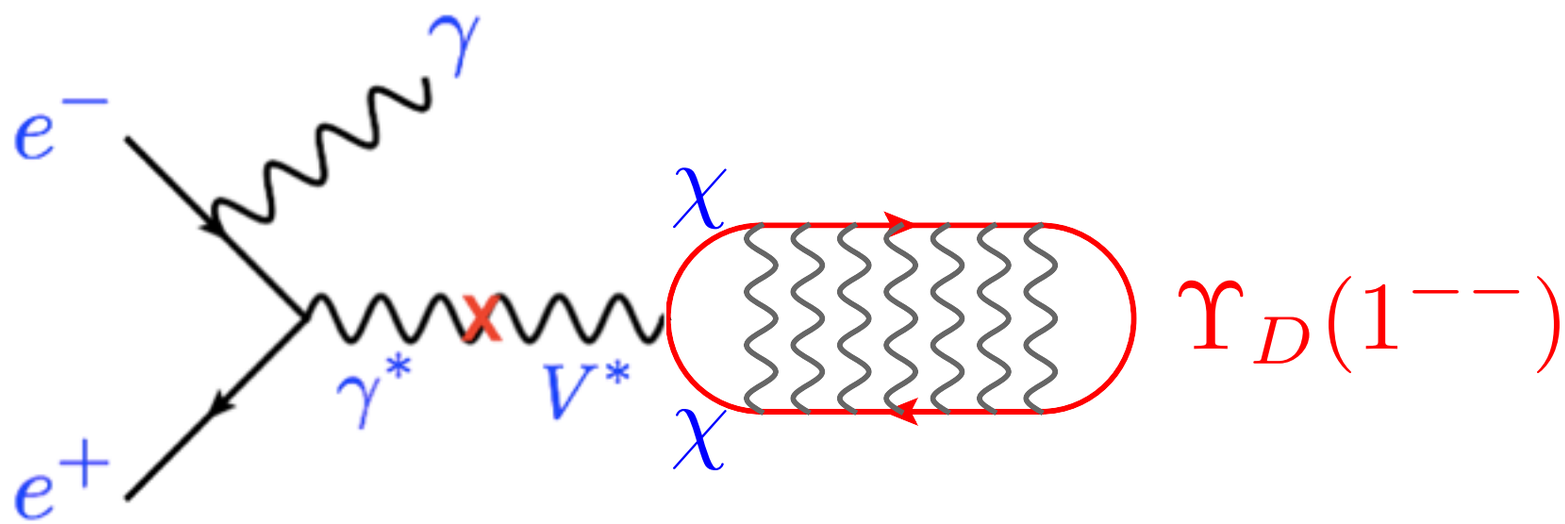
weaker than existing dark photon search

Essig, Mardon, Papucci, Volansky, Zhong (JHEP 2013)

Dark Matter Bound State Channel

In analogy to studying the heavy quarks:

- open dark flavor (missing energy).
- hidden dark flavor (darkonium resonances).

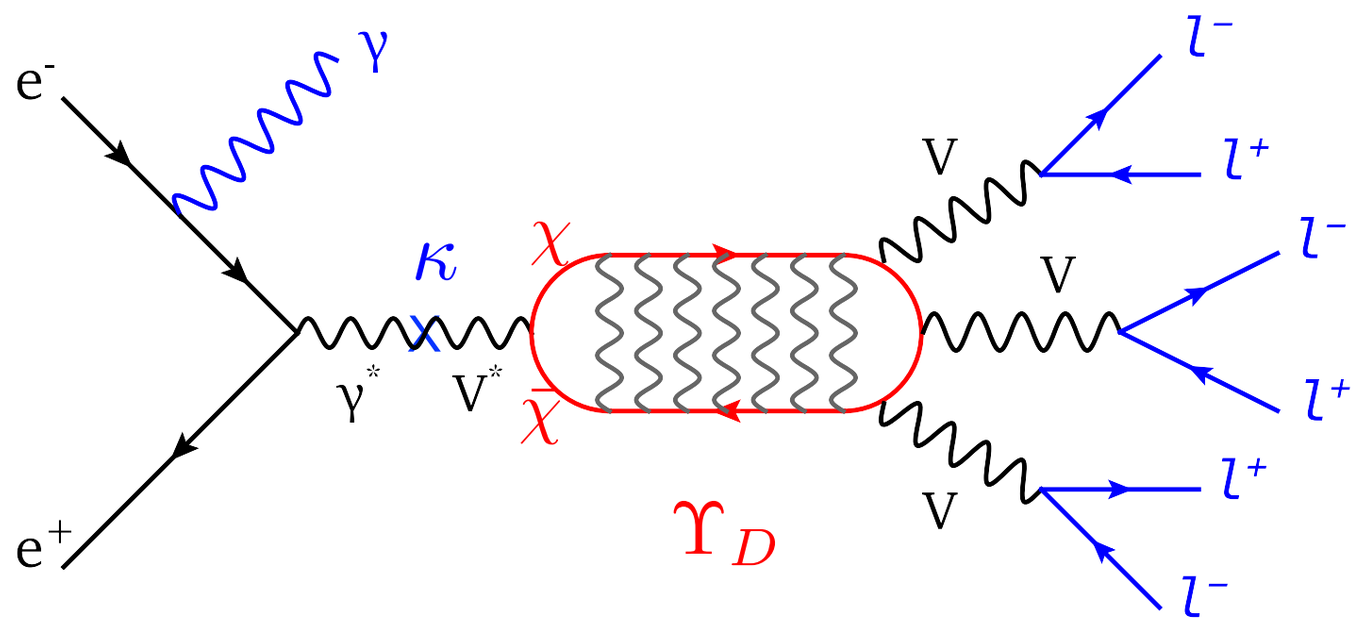


Ground state exists if $\alpha_D m_D > 1.67 m_V$

An, Echenard, Pospelov, **YZ** (PRL 2016)

Decay of Dark Matter Bound State

For $\kappa \ll \alpha_D^{3/2}$, $\Gamma(\Upsilon_D \to e^+e^-) \ll \Gamma(\Upsilon_D \to 3V)$



Very different from real Υ search

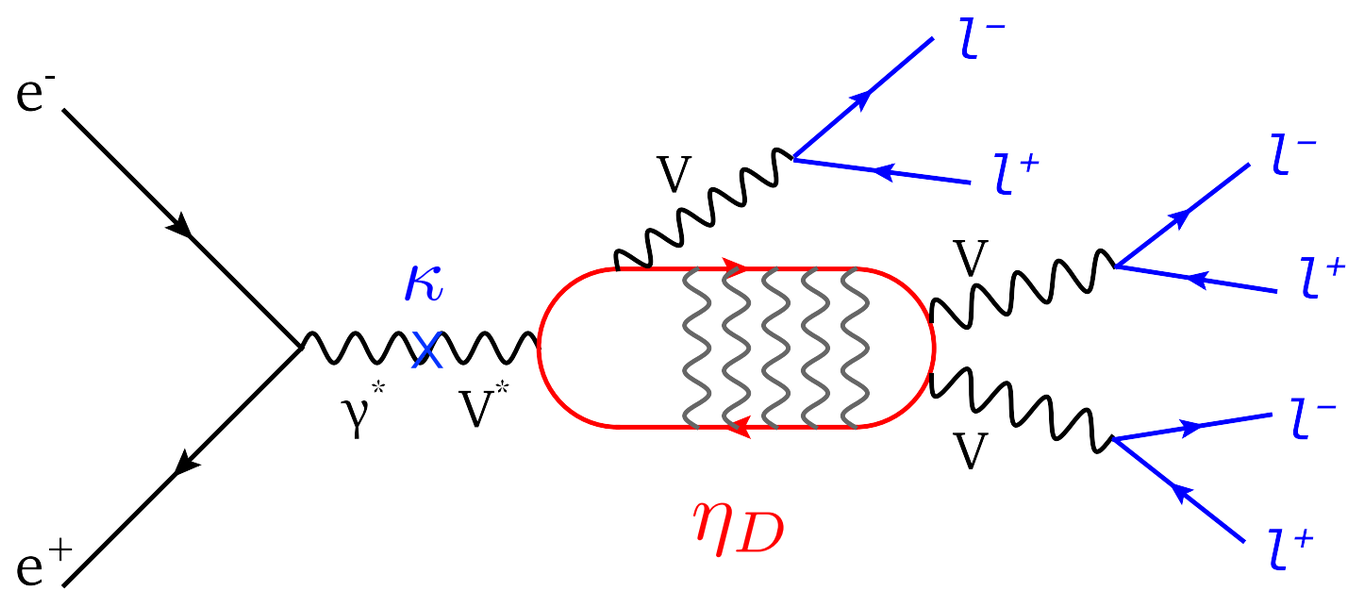
Multiple resonances – strong hint of a dark force

An, Echenard, Pospelov, **YZ** (PRL 2016)

Another Channel

I assume fermionic DM here, two ground states (L=0)

$\Upsilon_D\ (J^{PC} = 1^{--})$ $\qquad$ $\eta_D\ (J^{PC} = 0^{-+})$

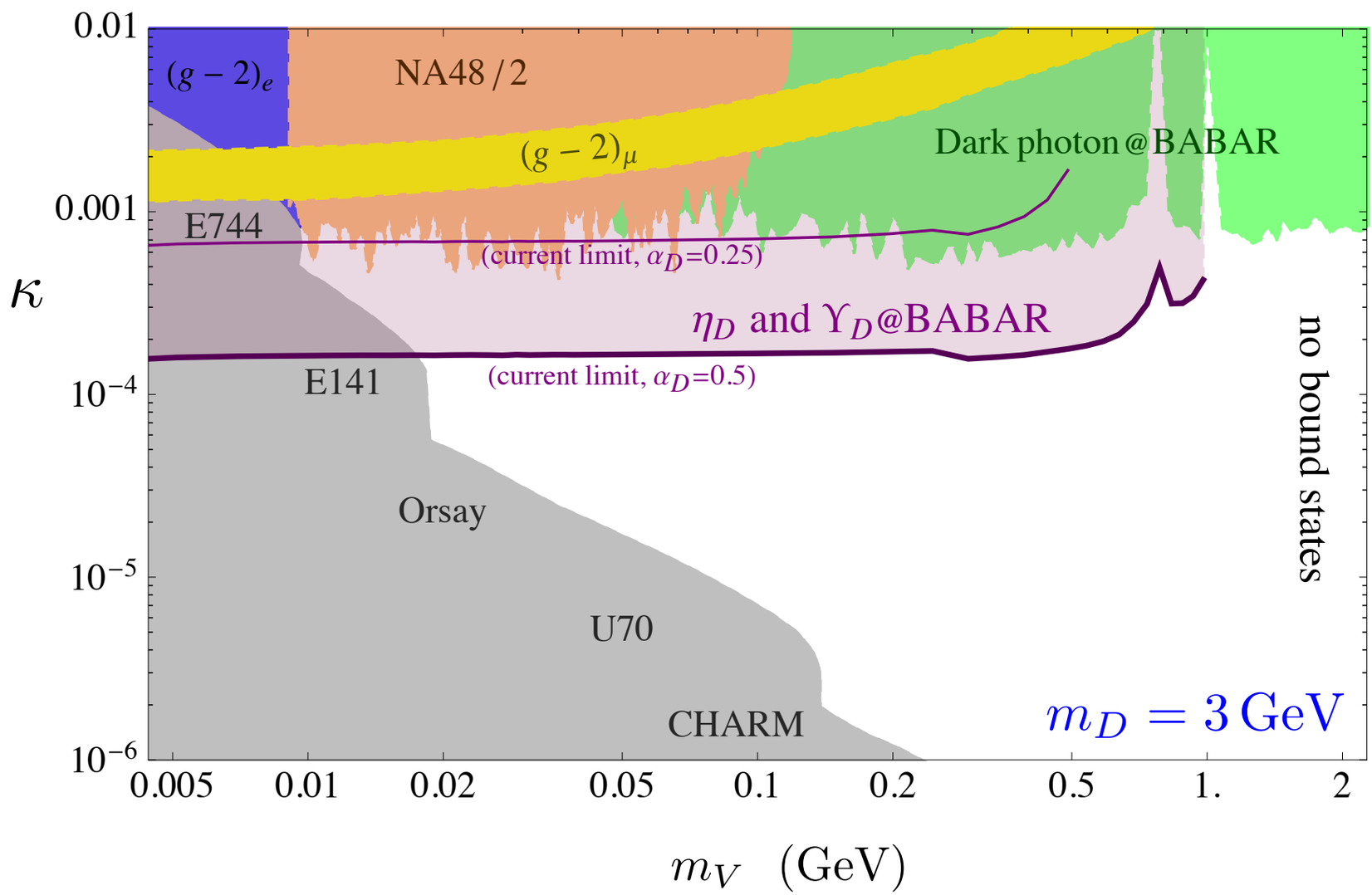


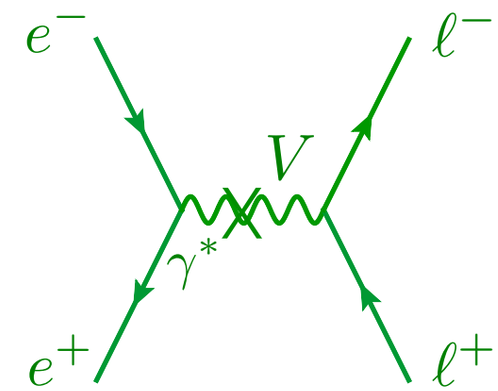
If scalar DM, 0^{++} is counterpart of η_D, but 1^{--} is excited state

An, Echenard, Pospelov, **YZ** (PRL 2016)

Better Limits

Stronger limit from bound state channel (6ℓ resonance), for $\alpha_D > 0.25$.





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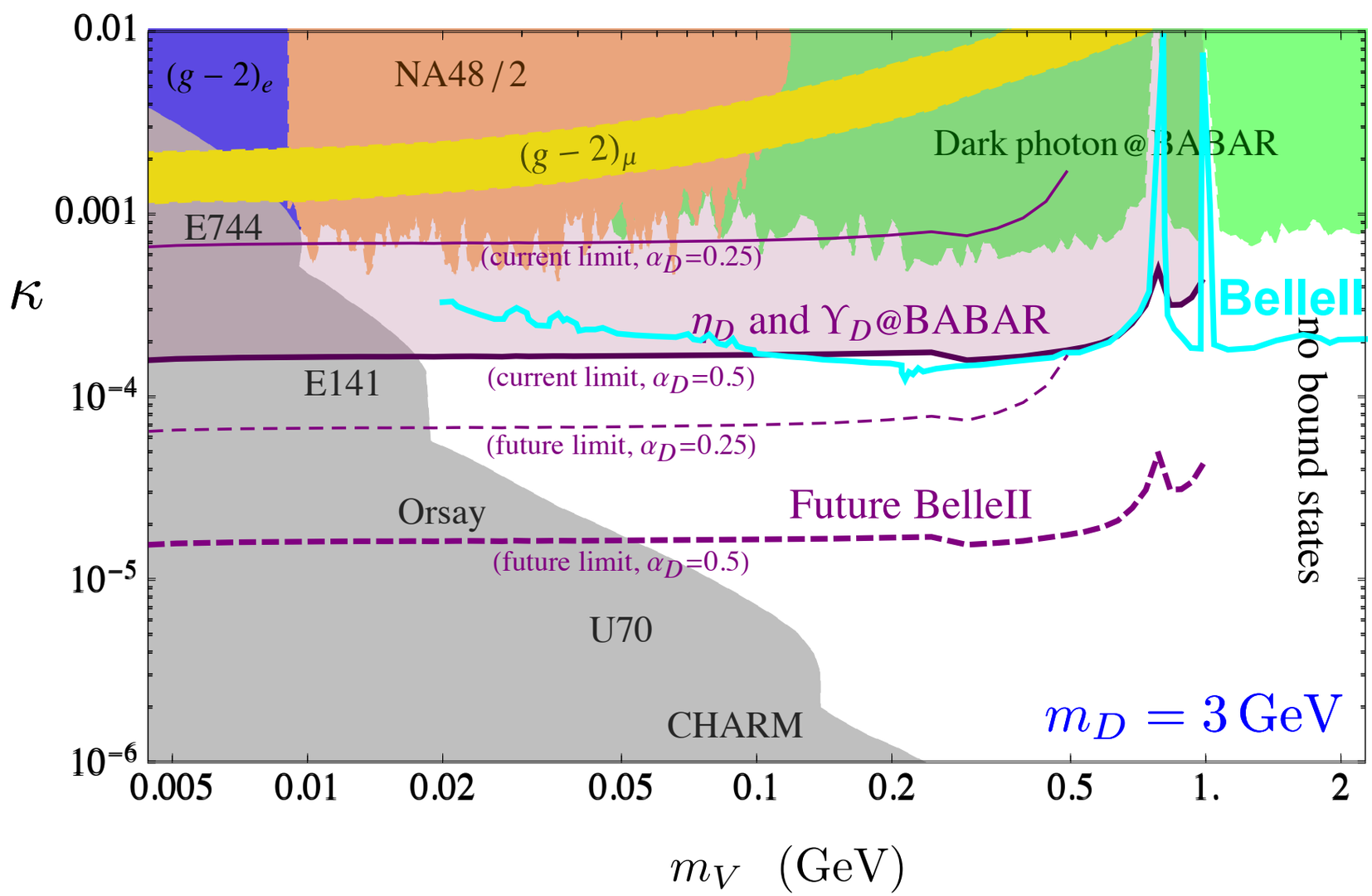
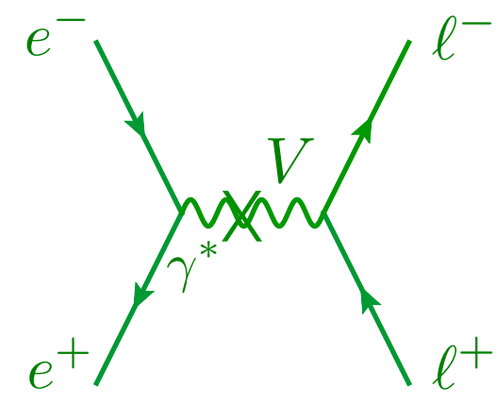
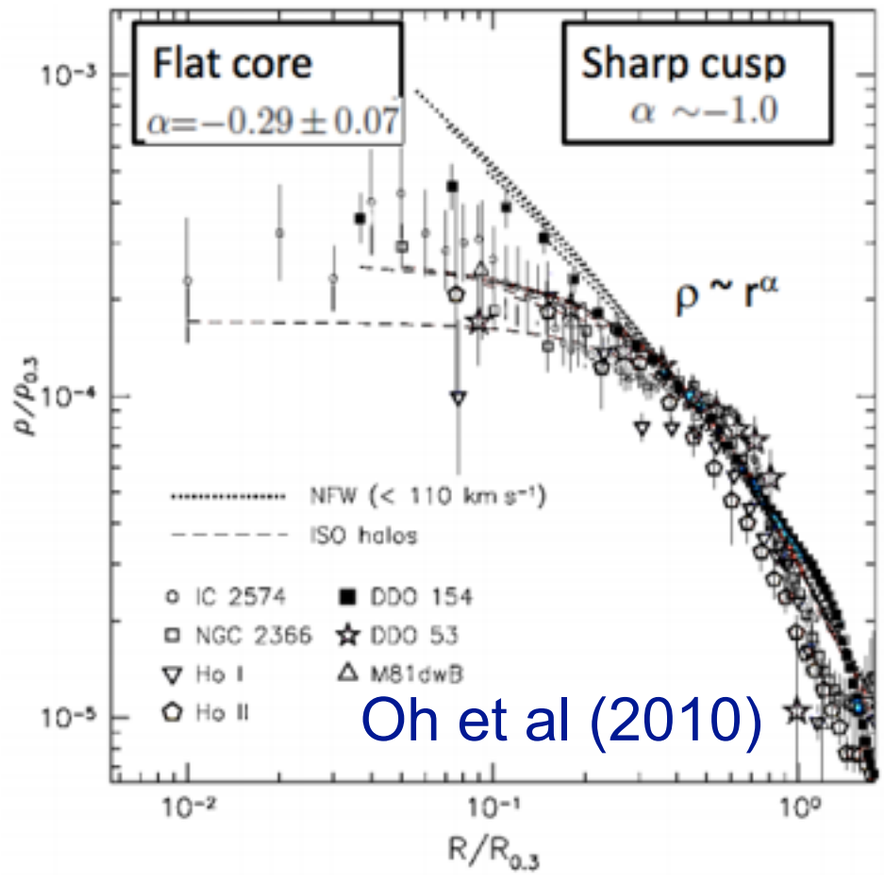
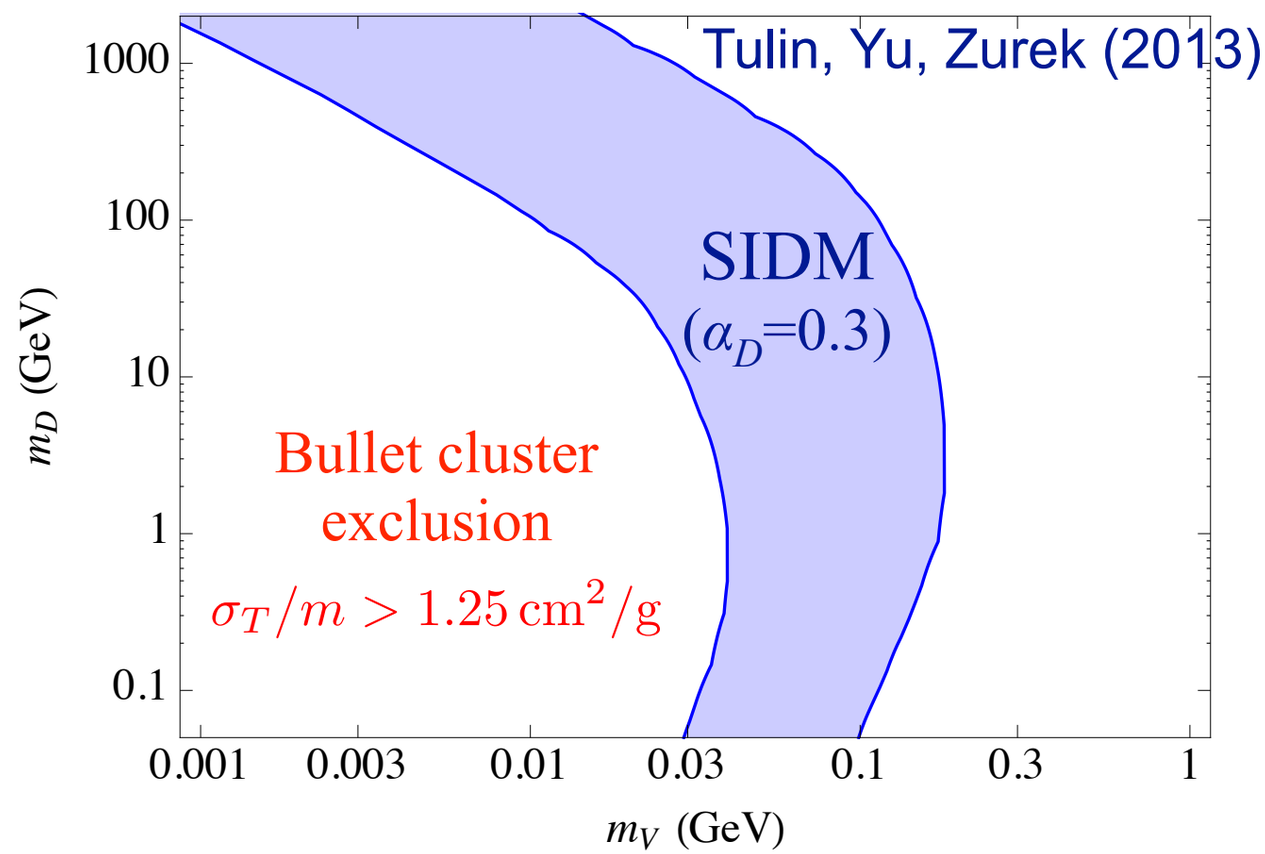




An, Echenard, Pospelov, **YZ** (PRL 2016)

Benefits of DM Self Interaction



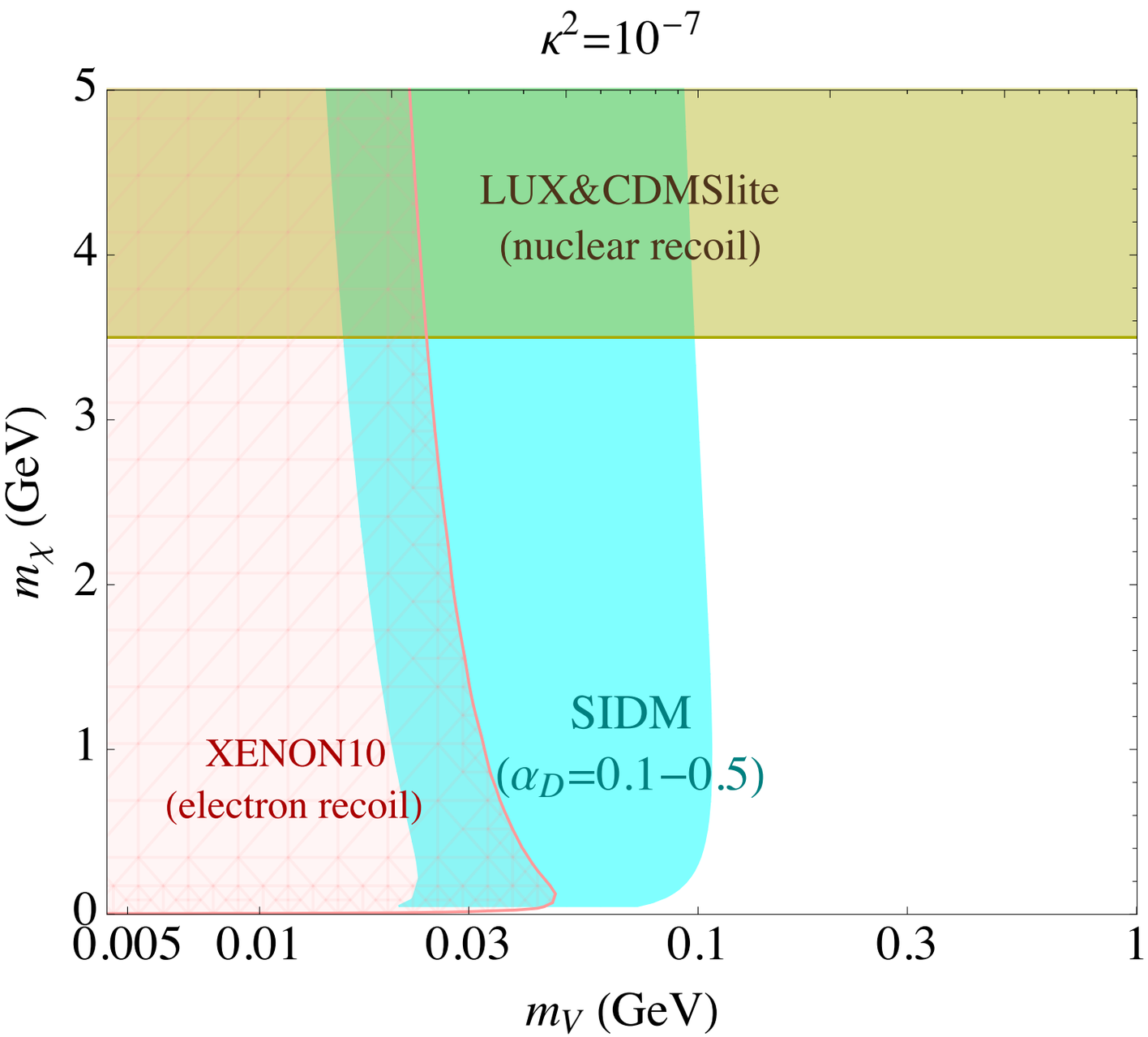


Core/Cusp problem $\Rightarrow$ Self-interacting DM $\quad \sigma_T/m \sim 1\,\mathrm{cm}^2/\mathrm{g}$

Spergel, Steinhardt (1999)

Recent study: baryons relax problems on small scales, Hopkins et al (1602.05957)

Implications for SIDM



An, Echenard, Pospelov, **YZ** (PRL 2016)

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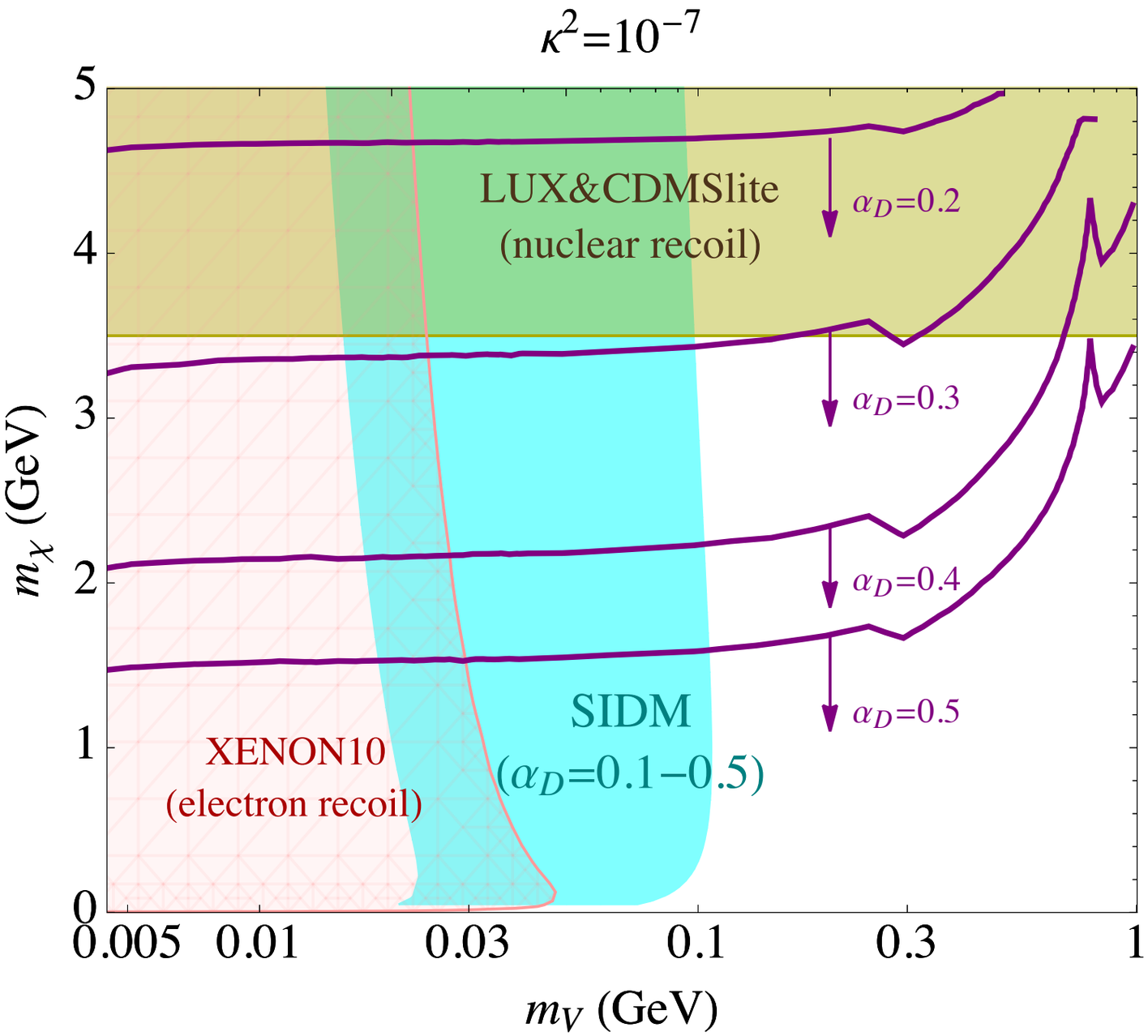
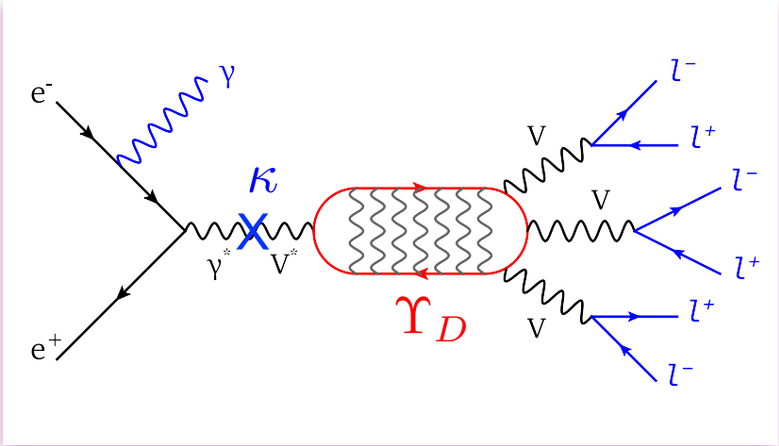
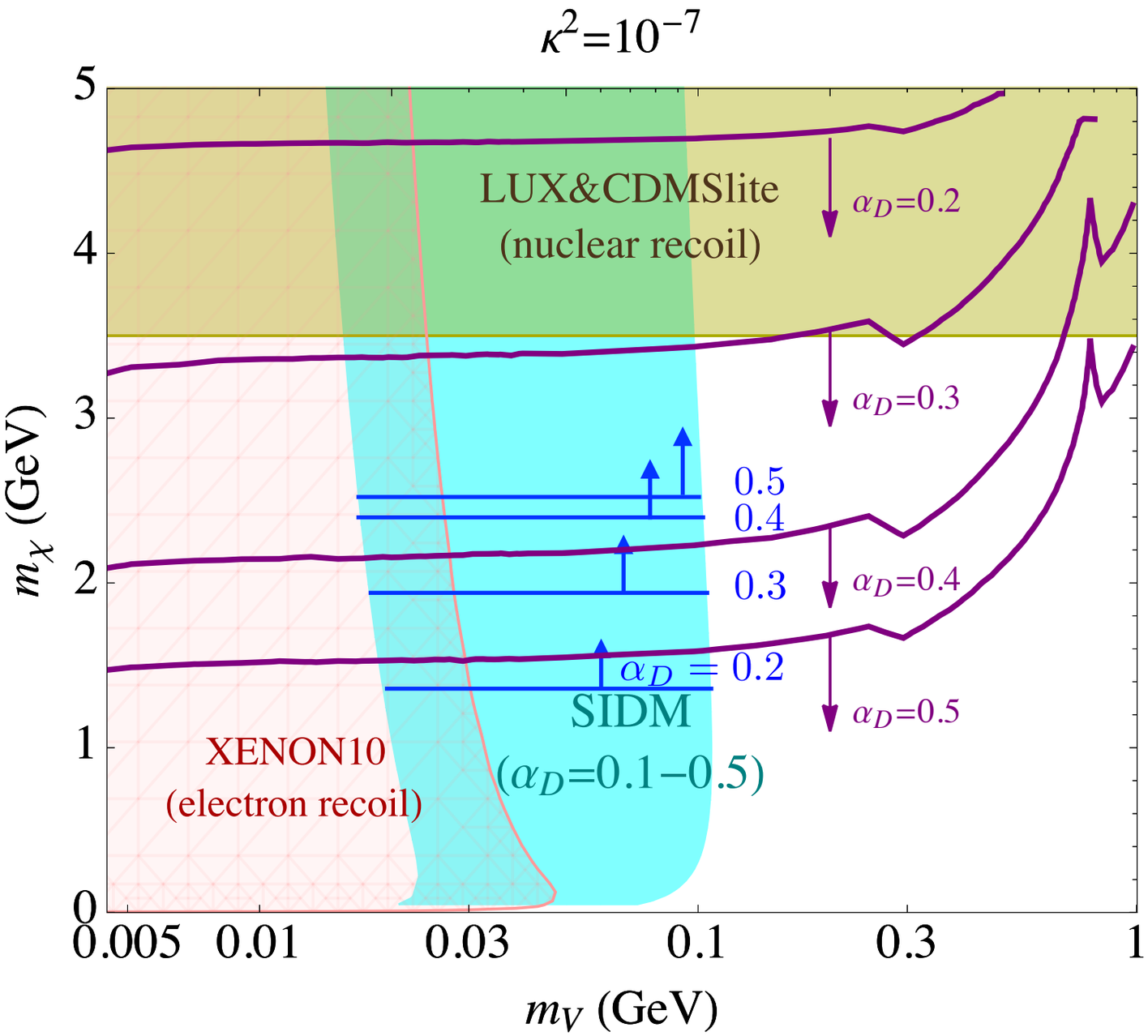


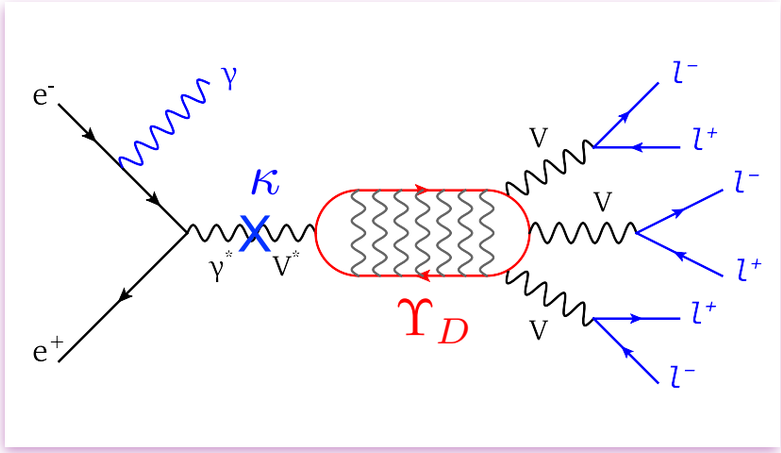


Darkonium resonance

An, Echenard, Pospelov, **YZ** (PRL 2016)

Implications for SIDM





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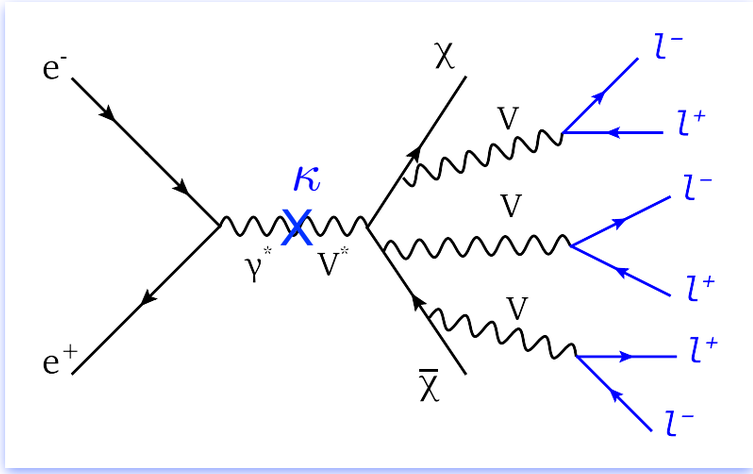
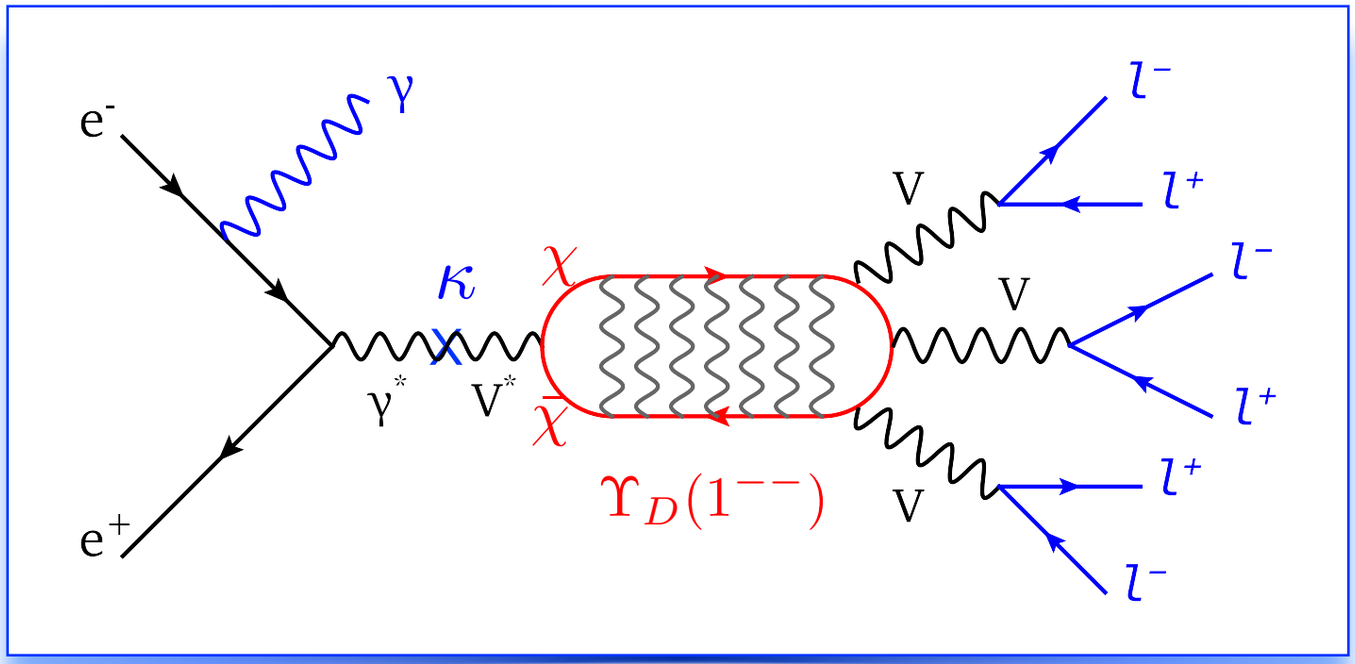


Final state radiation

An, Echenard, Pospelov, **YZ** (PRL 2016)

Conclusions

The nature of dark matter is an important and open question.

I discussed a simple model where dark matter is SM singlet and couples to a dark photon.

New opportunity for DM search at colliders (look for resonances).