Elastically Decoupling Relic (ELDER) Dark Matter

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U.S. Cosmic Visions: New Ideas in Dark Matter

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Kuflik, MP, Rey-Le Lorier, Tsai, 1512.04545 (PRL) + work in progress

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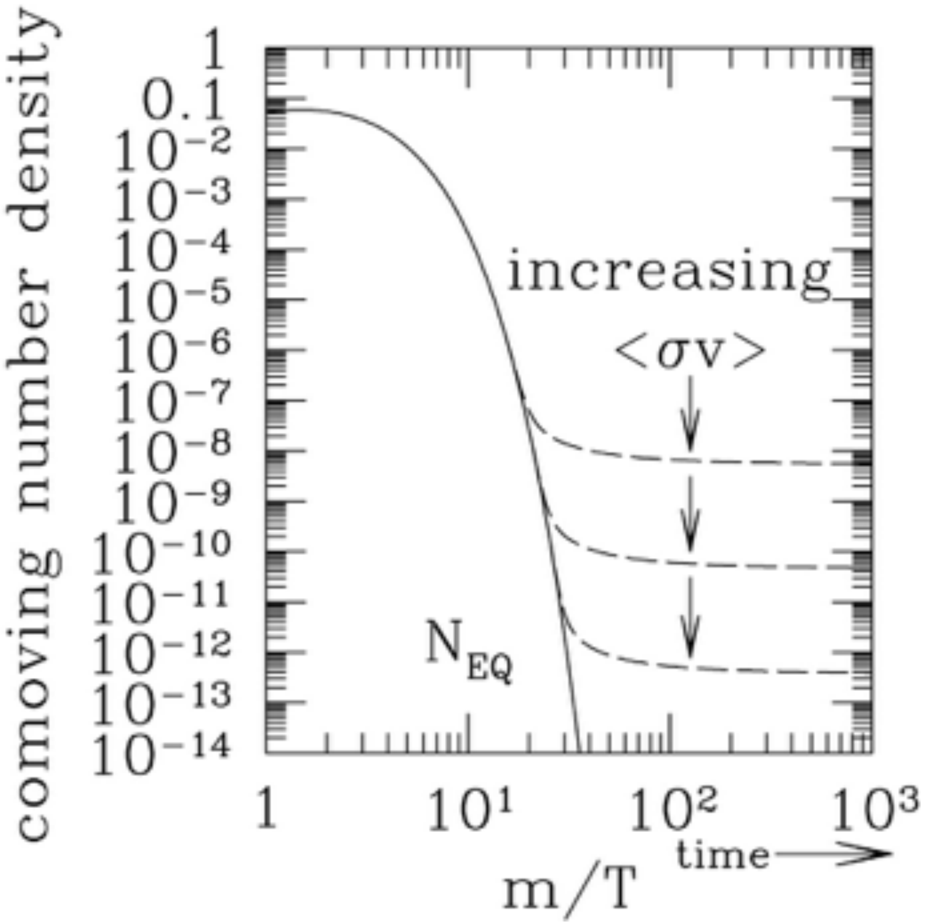
LABORATORY FOR ELEMENTARY-PARTICLE PHYSICS

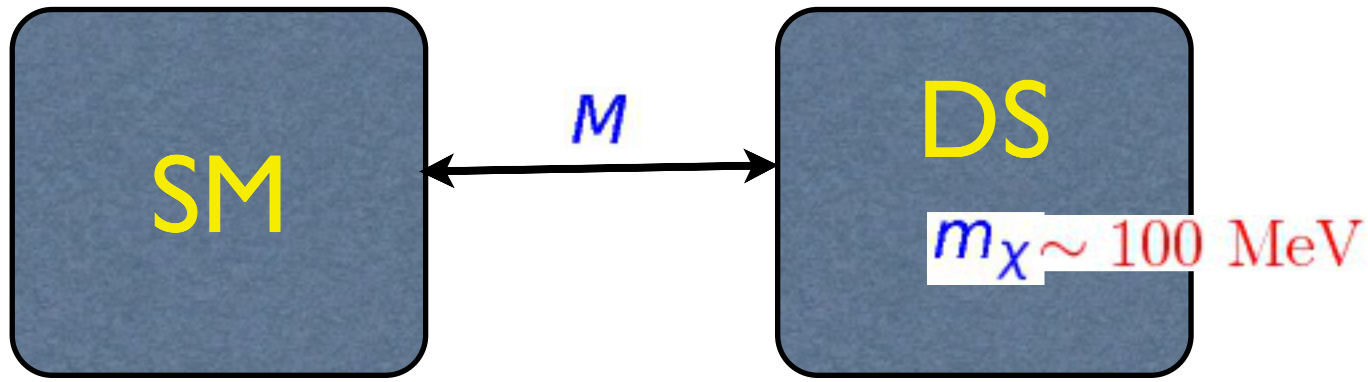
Thermal Relic DM



- Thermal Relic: DM in thermal and chemical equilibrium with SM plasma at high temperatures (=early times)
- Predictive: DM-SM Scattering cross section → decoupling time → present density

- "Non-Relativistic" Decoupling: due to exponential drop in equilibrium density of DM particle once $T < M_\chi$
- Relic density: $\Omega_\chi \approx \frac{10^{-26}\ \mathrm{cm}^3 \mathrm{sec}^{-1}}{\langle \sigma_{an} v \rangle}$ $\quad \sigma_{an} \equiv \sum_{\mathrm{SM}} \sigma(\chi\chi \to \mathrm{SM}+\mathrm{SM})|_{v_\chi \sim 0.1}$
- WIMP Miracle: $\Omega_\chi \sim 1$ when $\sigma_{an} \sim \frac{\alpha^2}{M_{\mathrm{weak}}^2}$ $\quad (m_\chi \sim M \sim M_{\mathrm{weak}})$

"Light" Thermal Relic

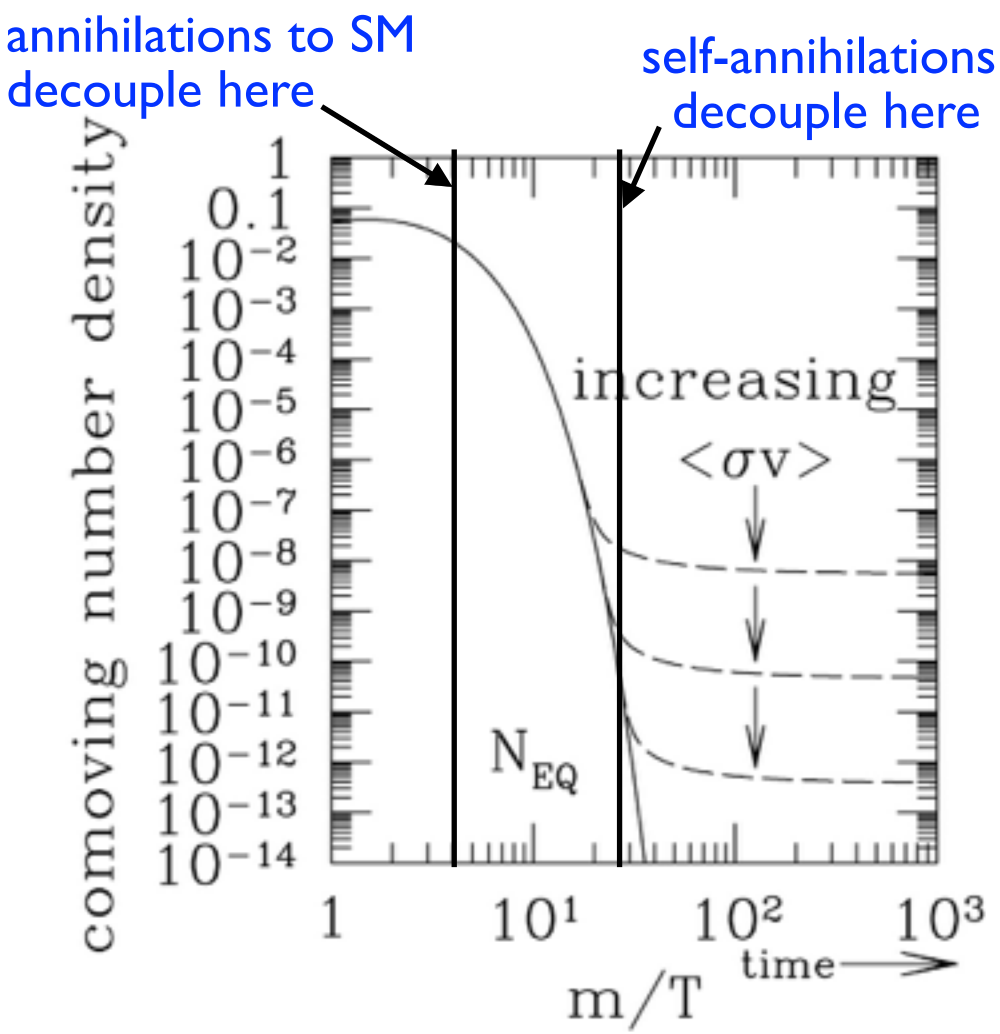


- No definite discovery of weak-scale new physics so far motivates thinking about DM at different mass scales
- What if the DM particle mass is at ~QCD scale?
- Confining dynamics at ~QCD scale in the dark sector appears naturally in "mirror SM"/"twin-Higgs" models
- "Dark pions" can be a natural DM candidate, if stable
- Can adjust mediator mass and couplings to obtain the correct relic density via annihilation to SM, but no "miracle"!

The SIMP Miracle

- A big "WIMP assumption": DM annihilation to SM is the only relevant process
- Obviously, only DM-number changing processes are relevant*
- What about non-DM-number-conserving self-interactions? (NB: in QCD pion number not conserved, e.g. WZW term)
- Strongly Interacting Massive Particle: $2\chi \leftrightarrow 3\chi$ process remains in equilibrium after $2\chi \leftrightarrow \ \mathrm{SM}+\mathrm{SM}$ decouples
- Relic density determined by $\langle \sigma_{\mathrm{self-an}} v^2 \rangle|_{v_\chi \sim 0.1}, \quad \sigma_{\mathrm{self-an}} \equiv \sigma(3\chi \to 2\chi)$
- SIMP Miracle: $\Omega_\chi \sim 1$ when $\sigma_{\mathrm{self-an.}} \sim \dfrac{1}{(100\ \mathrm{MeV})^5}$ [Hochberg, Kuflik, Volansky, Wacker, '14]
- "SIMP Assumption": Elastic SM-DM scattering maintains the two sectors at the same temperature until freeze-out

Riding Down the Hill



- Equilibrium NR number density: $n_\chi^{\rm eq} \sim (m_\chi T)^{3/2} e^{-m_\chi/T}$
- SIMP follows the trajectory due to 3-to-2 self-annihilations
- This process releases kinetic energy: $\dot{K}_\chi = m\frac{\dot{n}}{n} \approx -m_\chi^2 H T^{-1}$

- Elastic SM-DM scattering must be fast enough to transfer this energy to the SM plasma, allow them to remain at same T

$$\dot{K}_\chi \sim \Gamma_{\rm el} v_\chi^2 T \sim T^5 \epsilon^2 / m_\chi^3$$

$$\Gamma_{\rm el} = n_{\rm SM} \langle \sigma_{\rm el} v \rangle \qquad \lim_{T\to 0} \langle \sigma_{\rm el} v \rangle \equiv \frac{\epsilon^2}{m_\chi^2}$$

- "Elastic Decoupling": $T_d \sim \epsilon^{-1/2} m_\chi^{5/4} M_{\rm Pl}^{-1/4}$

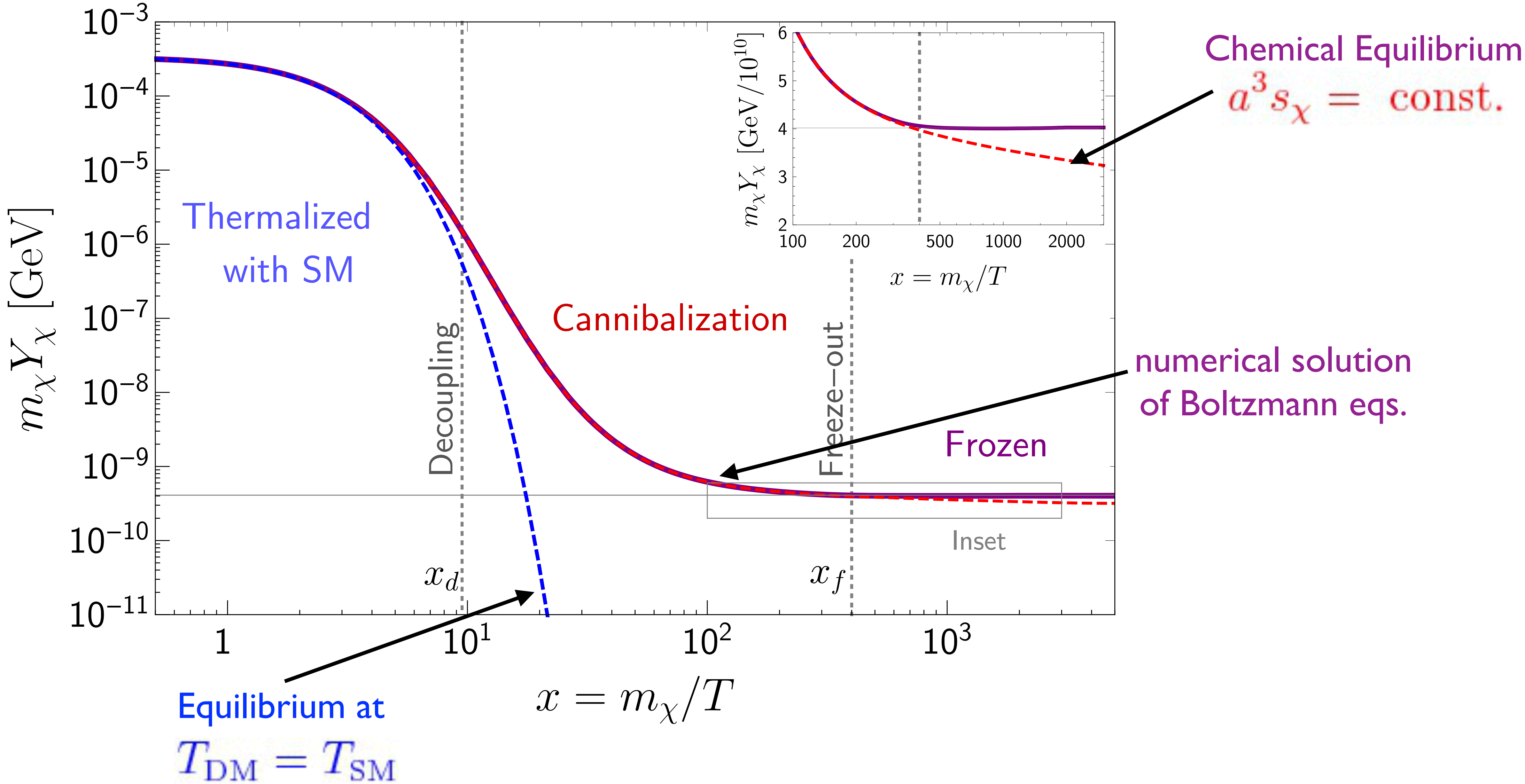
Beware: Cannibals!

- Self-annihilations decoupling: $n_\chi^2 \langle \sigma_{\rm self-an} v^2 \rangle \sim H$ @ t_F
- SIMP scenario: freeze-out before kinetic decoupling $t_F < t_d$
- Our work: what if $t_d < t_F$?
- At $t > t_d$, DM gas is in chemical equilibrium with no chemical potential (due to active self-annihilations), BUT $T_{\rm DM} \neq T_{\rm SM}$
- DM temperature determined by DM entropy conservation:

$$a^3 s_\chi = \text{const} \;\rightarrow\; T_\chi^{1/2} e^{-m_\chi/T_\chi} \propto T_{\rm SM}^3 \;\rightarrow\; T_\chi \approx \frac{T_d}{1 + 3x_d^{-1} \log T_D/T_{\rm SM}}$$

- "Cannibal" phase: Kinetic energy released in self-annihilations is used to "keep warm" in an expanding Universe [Carlson, Machacek, Hall, '92]
- DM density changes as log(scale factor) during this phase!

Thermal History

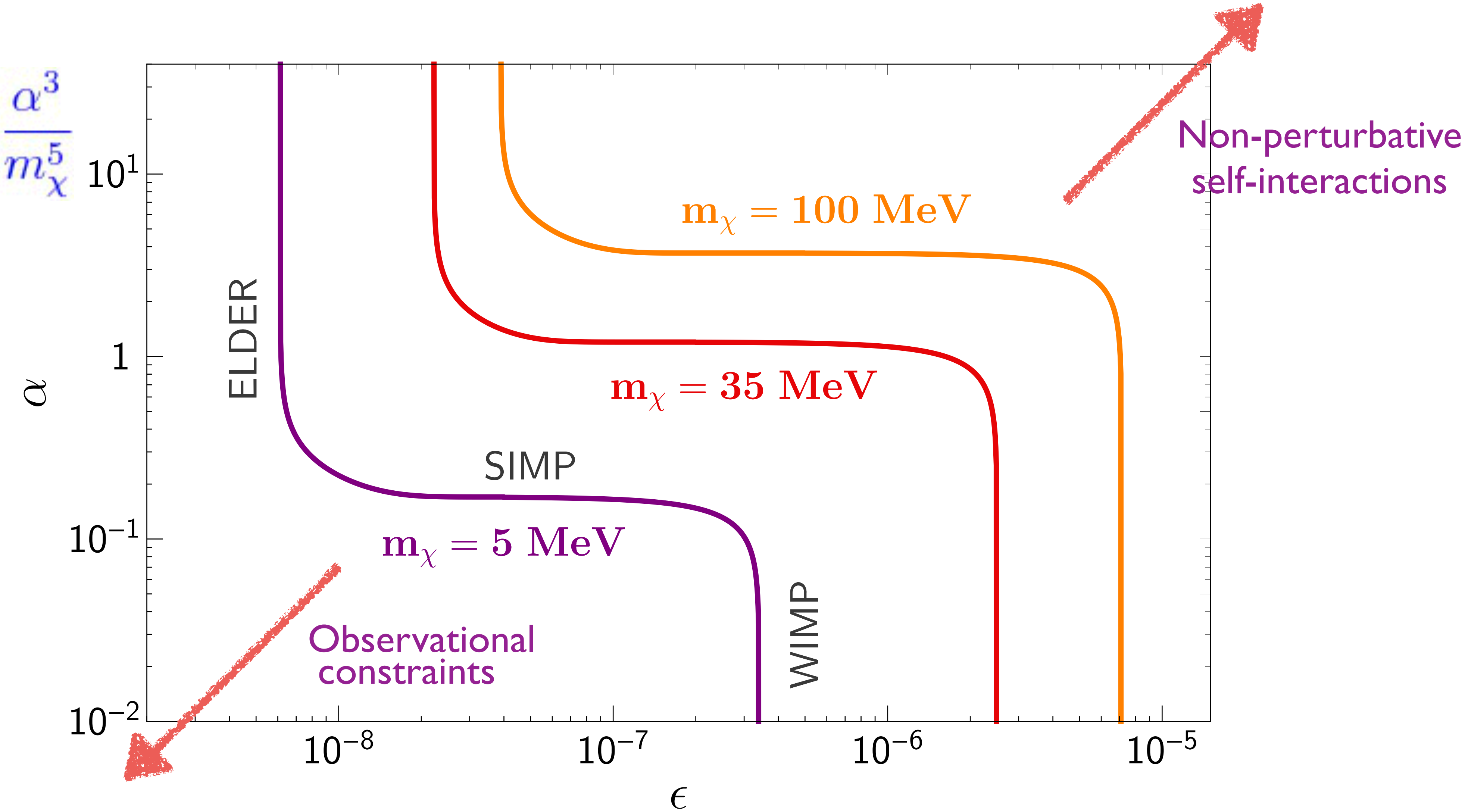


- Eventually, self-annihilations decouple, DM density frozen-in

$$x_F \approx \frac{3}{4}\log\left(\frac{M_{\rm Pl}}{m_\chi}\right) - \frac{x_d}{2} + \frac{9}{4}\log\alpha$$

Meet the ELDER

$$\langle \sigma_{2\to3} v^2 \rangle = \frac{\alpha^3}{m_\chi^5}$$



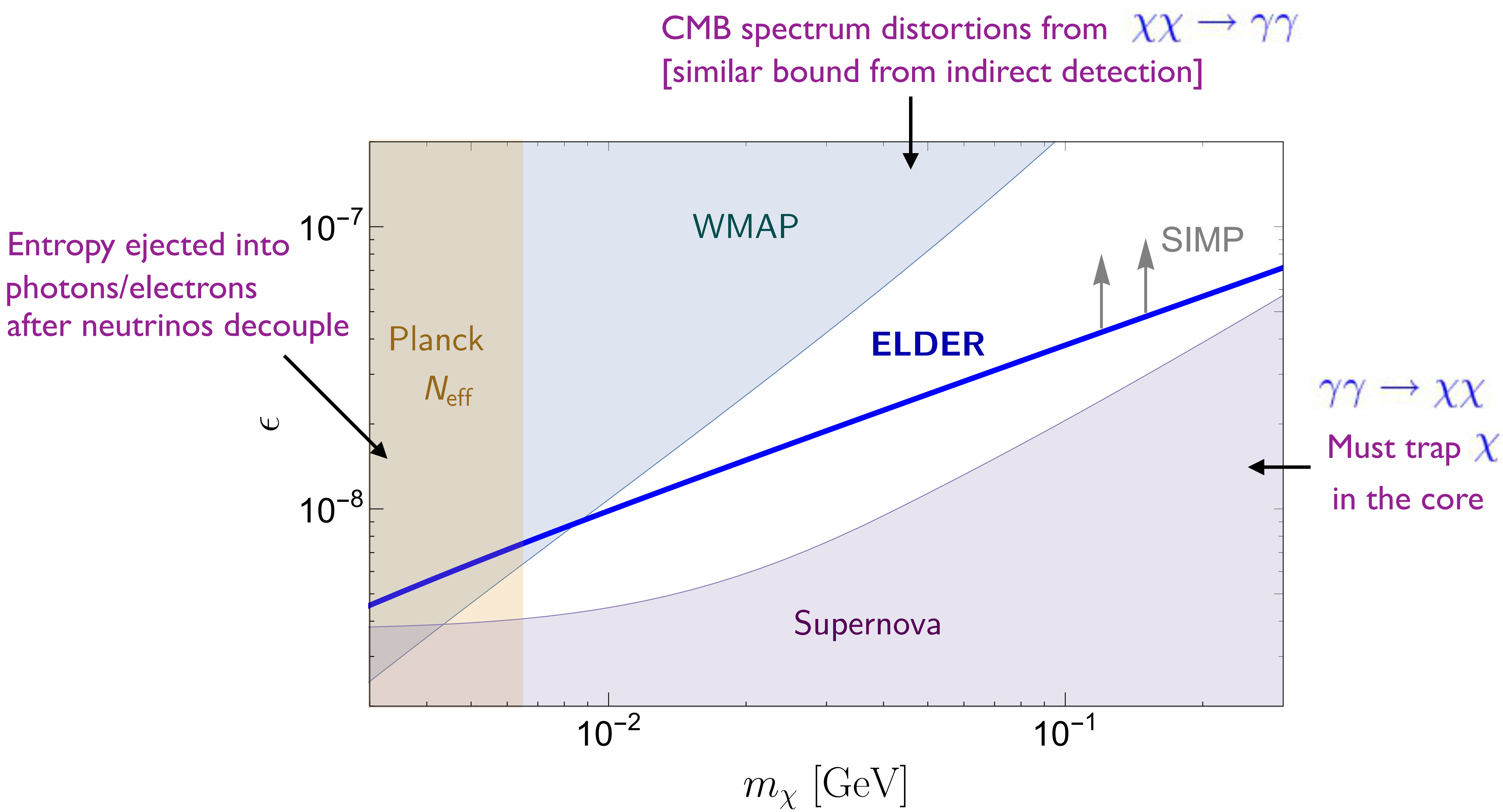
Exponential sensitivity
to elastic cross section!

- Relic density: $\Omega_\chi \sim \dfrac{10^6 m_{\mathrm{MeV}} \exp(-10\epsilon_{-9}^{1/2} m_{\mathrm{MeV}}^{-1/4})}{1 + 0.07 \log \alpha}$

Very weak sensitivity
to self-annihilation cross section

ELastically DEcoupling
Relic (ELDER)

Observational Constraints



- DM coupling to photons only assumed here

- Similar constraints if DM coupling is primarily to electrons; weaker constraints if coupled to neutrinos (only 3 choices!)

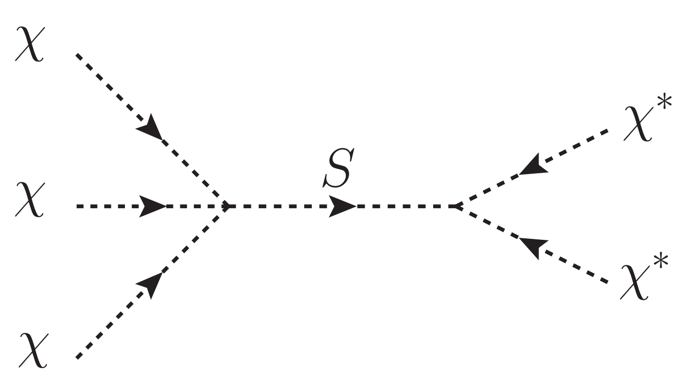
Explicit Model

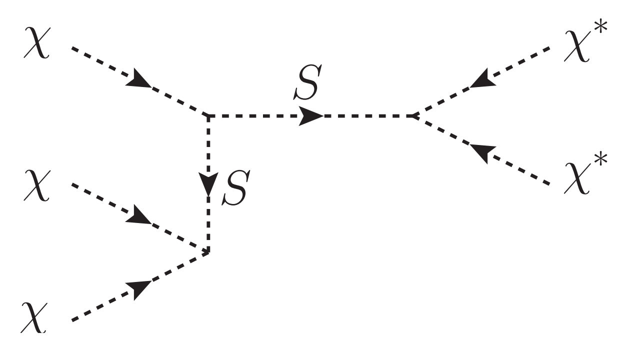
[a la Choi, Lee, 1601.0356]

- Consider a simple renormalizable model:

$$\mathcal{L} = \lambda_1 m_\chi S^2 \chi^\dagger + \lambda_2 m_\chi S \chi^2 + \frac{1}{6}\lambda_3 S^\dagger \chi^3 + \text{h.c.}$$

- Global U(1) ensures stability of the DM particle χ, but allows 3-to-2 self-annihilations:





- DM can be coupled to electrons via dark photon exchange:

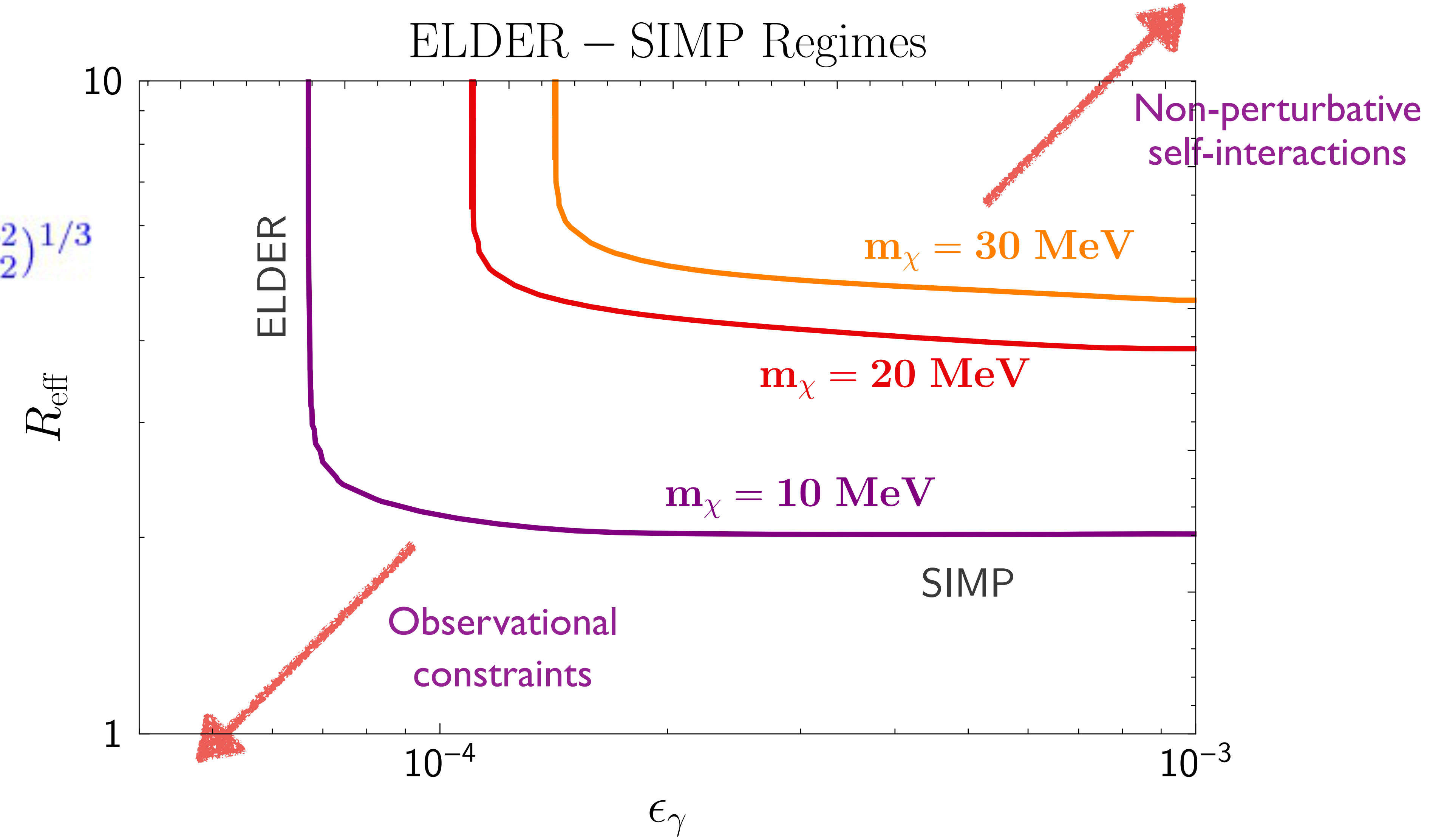
$$\mathcal{L}_{\text{km}} = \frac{1}{2}\frac{\epsilon}{\cos\theta_W} B_{\mu\nu} F_D^{\mu\nu}$$

- Resonant enhancement of self-annihilation for $m_S \approx 3m_\chi$

Relic Density

$R_i = \frac{v_D \lambda_i}{\sqrt{2} m_\chi}$

$R_{\rm eff} = (R_1 R_2^2)^{1/3}$

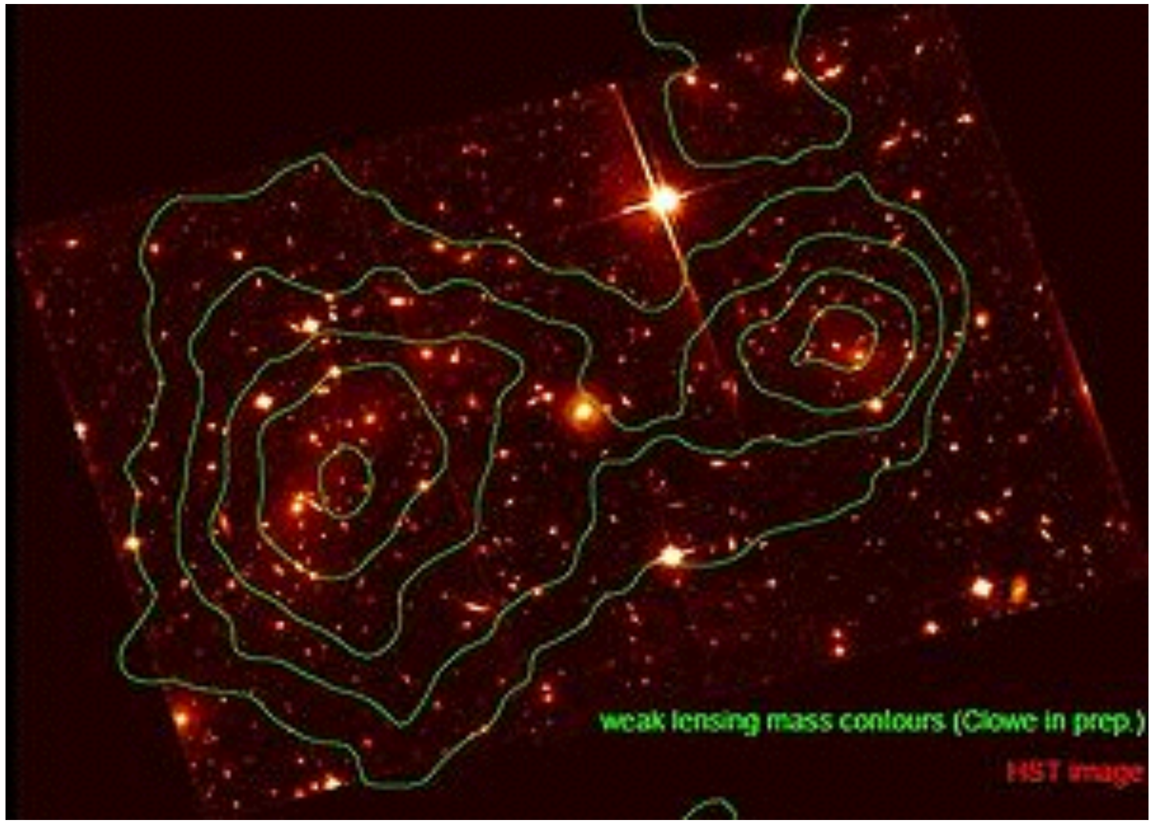


$m_S = 3.2 m_\chi, m_V = 10 m_\chi, \alpha_D = 1/4\pi$

- Viable ELDER DM for $\epsilon \sim 10^{-4}, m_D \sim 100$ MeV - nice target for dark photon searches

- ELDER target is the lower boundary of the SIMP range:

Elastic Self-Interaction



- Strong DM self-annihilation would generically be accompanied by strong DM elastic self-scattering

- Small-scale simulation "issues" possibly hint at

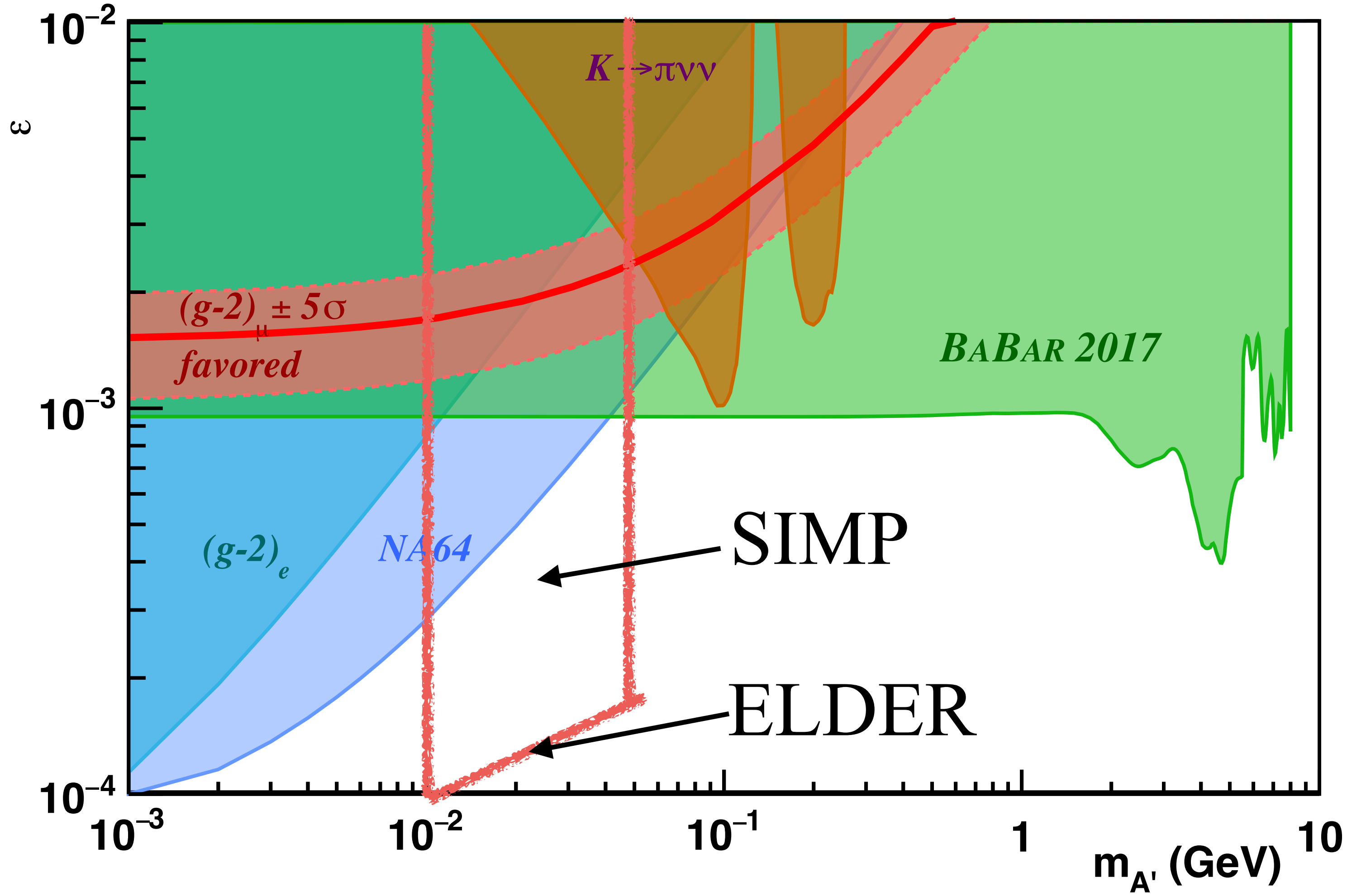
$$\frac{\sigma_{XX\to XX}}{m_\chi} \sim 0.1 - 1\ \mathrm{cm}^2/\mathrm{g}$$

- Constraint (Bullet cluster, halo shapes): $\frac{\sigma_{XX\to XX}}{m_\chi} < 1\ \mathrm{cm}^2/\mathrm{g}$

- Constraint is stronger at low DM masses, becomes difficult to satisfy for $m_\chi < 10\ \mathrm{MeV}$ in our model

- Similar lower bound on m_χ from CMB (N_{eff} bound), BBN

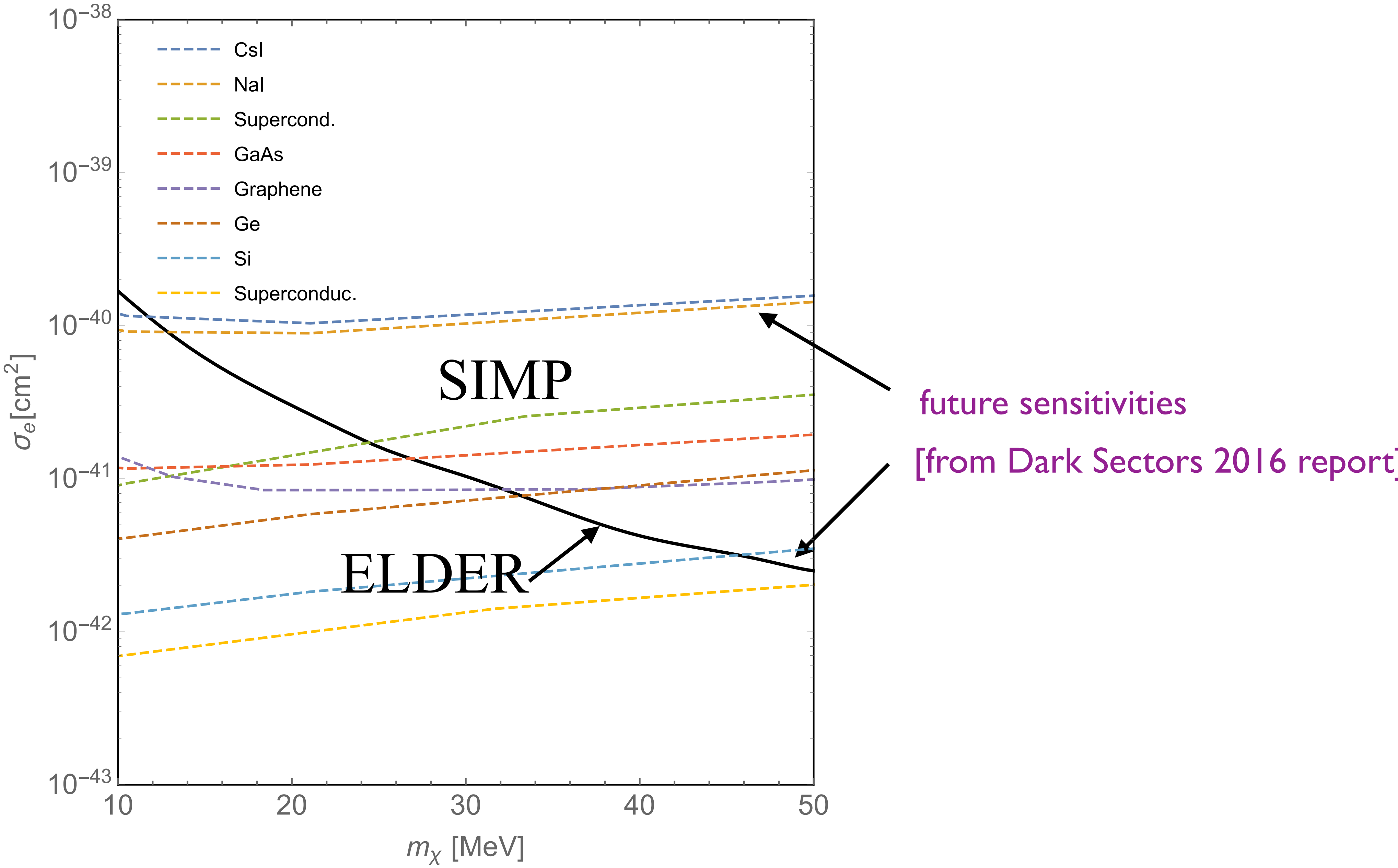
ELDER in Dark Photon Searches



[BaBar, 1702.03327]

- Since $m_V > 2m_\chi$, the Dark Photon decays invisibly to DM pairs
- A factor of 10 improvement in sensitivity would explore preferred SIMP/ELDER parameter space

ELDER in Direct Detection



- Relic density constraint completely fixes direct detection cross section as a fn. of mass! Interesting range for future experiments.

- Again, the ELDER curve is the lower boundary of the SIMP region

Conclusions

- Considered a thermal relic with ~QCD-scale mass, number-changing self-annihilation process
- Two regimes: SIMP and ELDER (with unusual thermal history involving "cannibalization" epoch)
- ELDER relic abundance determined dominantly by the cross section of elastic scattering of DM on SM (not a number-changing process!)
- Interesting predictions for DM direct detection and dark photon searches