(Entirely) Dark Decay of the Neutron

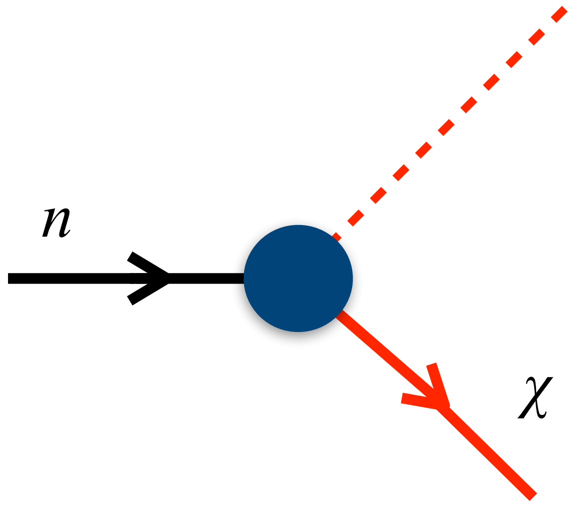
Jonathan Cornell

Based on Jim Cline, J.Cornell, arXiv:1803.04961

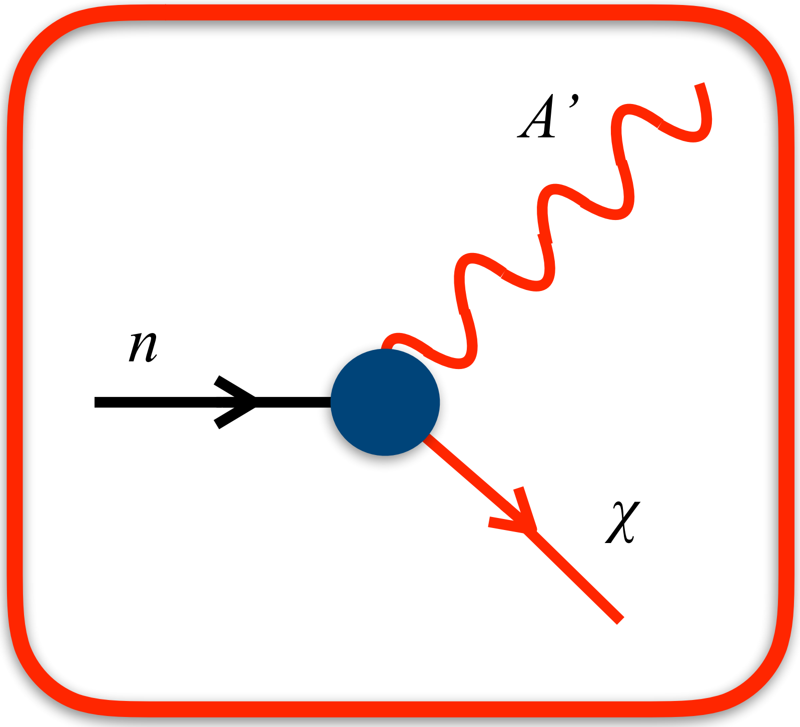
A Solution for the Neutron Lifetime Puzzle

Bottle: $\tau_n = 879.6 \pm 0.6$ s   Beam: $\tau_n = 888.0 \pm 2.0$ s

A neutron dark decay scenario which has not been directly experimentally tested:



Fornal, Grinstein, 2018



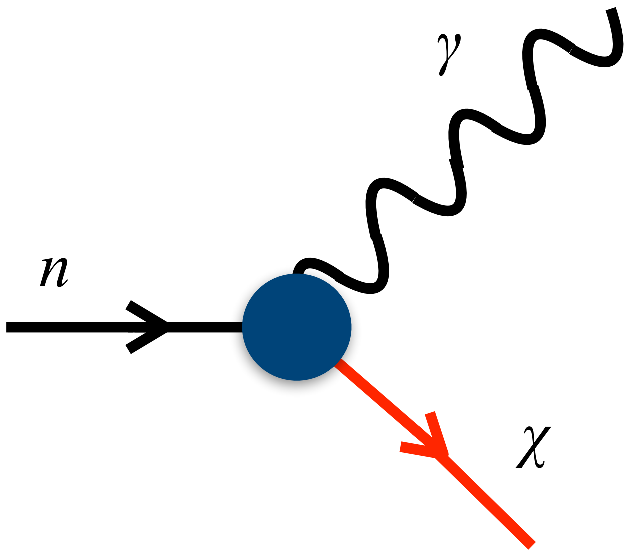
Neutron decays to fermion DM candidate and a dark boson.

Low Energy Effective Model

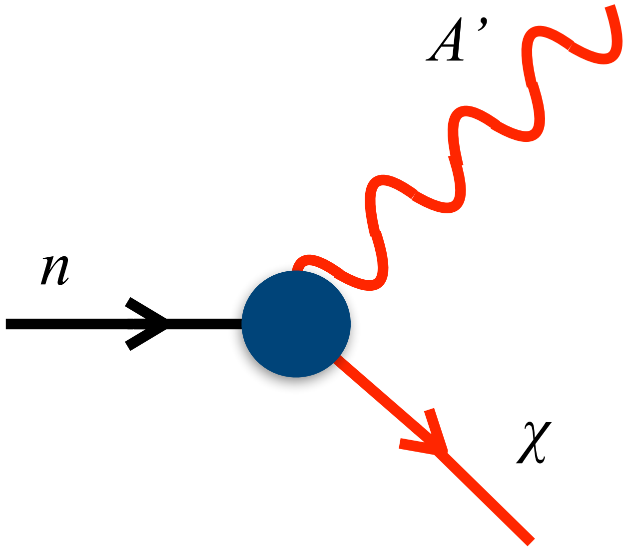
Two new fields:

- χ, Dirac fermion charged under *U(1)′*, carries baryon number
- A′, Dark photon

$$\mathcal{L}_{\mathrm{eff}} = \bar{\chi}(i\partial_\mu - \boxed{ig' A'_\mu} - m_\chi)\chi + \bar{n}\left(i\not{\partial} - m_n + \boxed{\mu_n \sigma^{\mu\nu} F_{\mu\nu}}\right) n$$
$$- \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}m^2_{A'}A'^{\mu}A'_\mu - \boxed{\delta m\, \bar{n}_R \chi_L} + \mathrm{h.c.} - \boxed{\frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu}}$$



$$\Gamma_{n\to\chi\gamma} \propto \frac{\mu_n^2(\delta m)^2}{m'^2_A}$$



$$\Gamma_{n\to\chi A'} \propto \frac{g'^2(\delta m)^2}{m'^2_A}$$

Mass Limits

- For the neutron to decay to $\chi + A'$: $m_\chi + m_{A'} < 939.6$ MeV
- For ^{9}Be to NOT decay to $\chi + \gamma$: $m_\chi > 937.8$ MeV
  (this also stabilizes the proton)
- *For* χ *to* NOT decay to a proton, electron and anti-neutrino:
  $m_\chi < 938.8$ MeV (viable DM component)

Our benchmark values:

$m_\chi = 937.9$ MeV

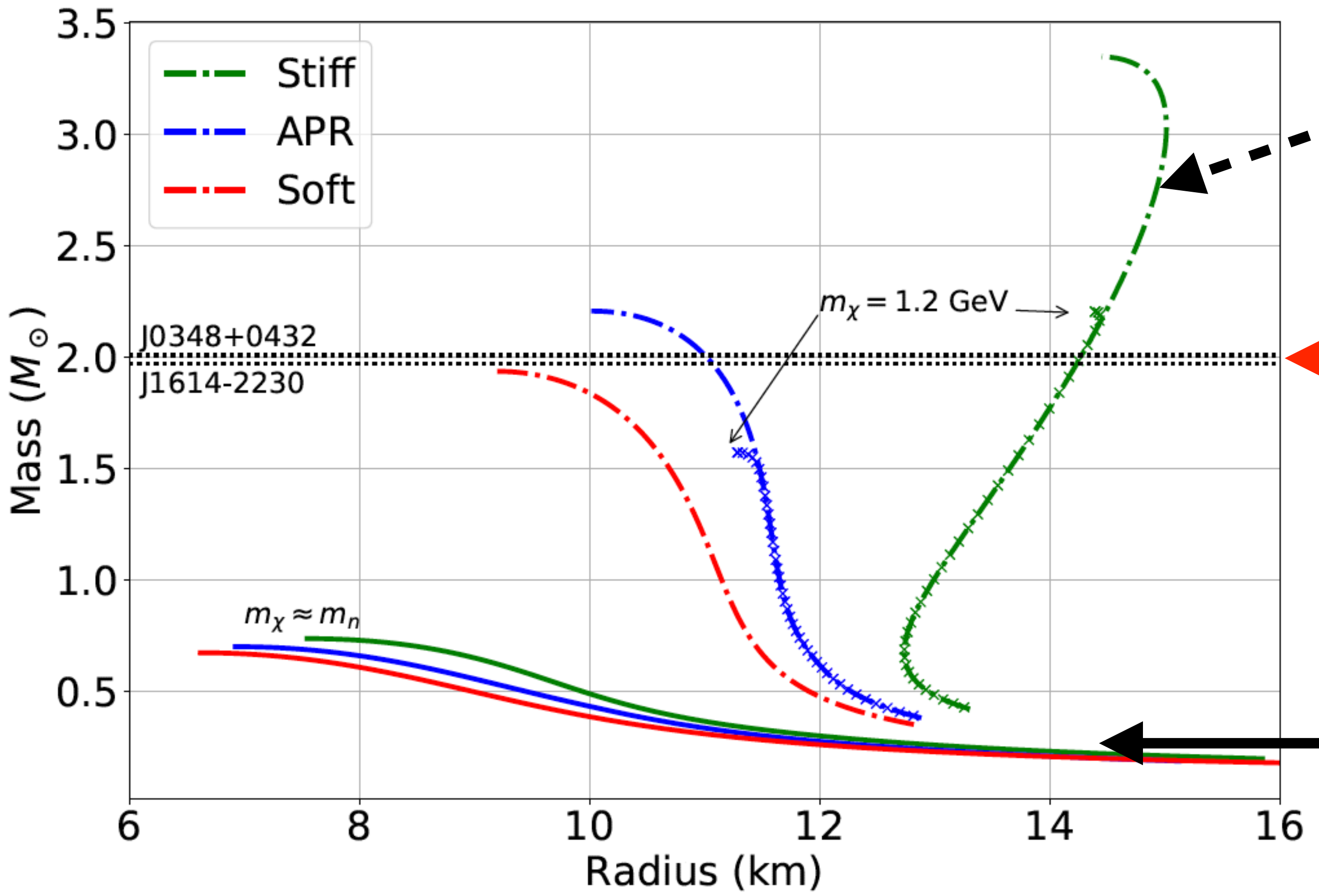
(**A**) $m_{A'} = 1.35$ MeV
$A' \rightarrow e^+ e^-$

(**B**) $m_{A'} = 0.5$ MeV
$A' \rightarrow 3\gamma$

Tolman–Oppenheimer–Volkoff Limit

$$\frac{dp}{dr} = -G(\rho(1+\epsilon/c^2)+p/c^2)\frac{m+4\pi r^3 p/c^2}{r(r-2Gm/c^2)}$$

Solve numerically to find where *p*=0. This gives the maximal size of a neutron star.



No *n*-DM conversion

Observed neutron star masses.

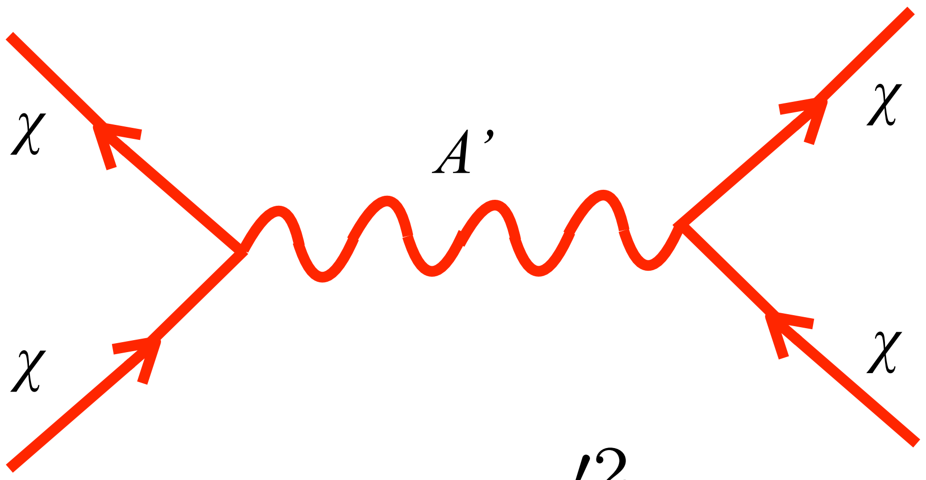
n-DM conversion allowed. The conversion reduces the neutron degeneracy pressure.

McKeen, et al., 2018

Baym, et al., 2018

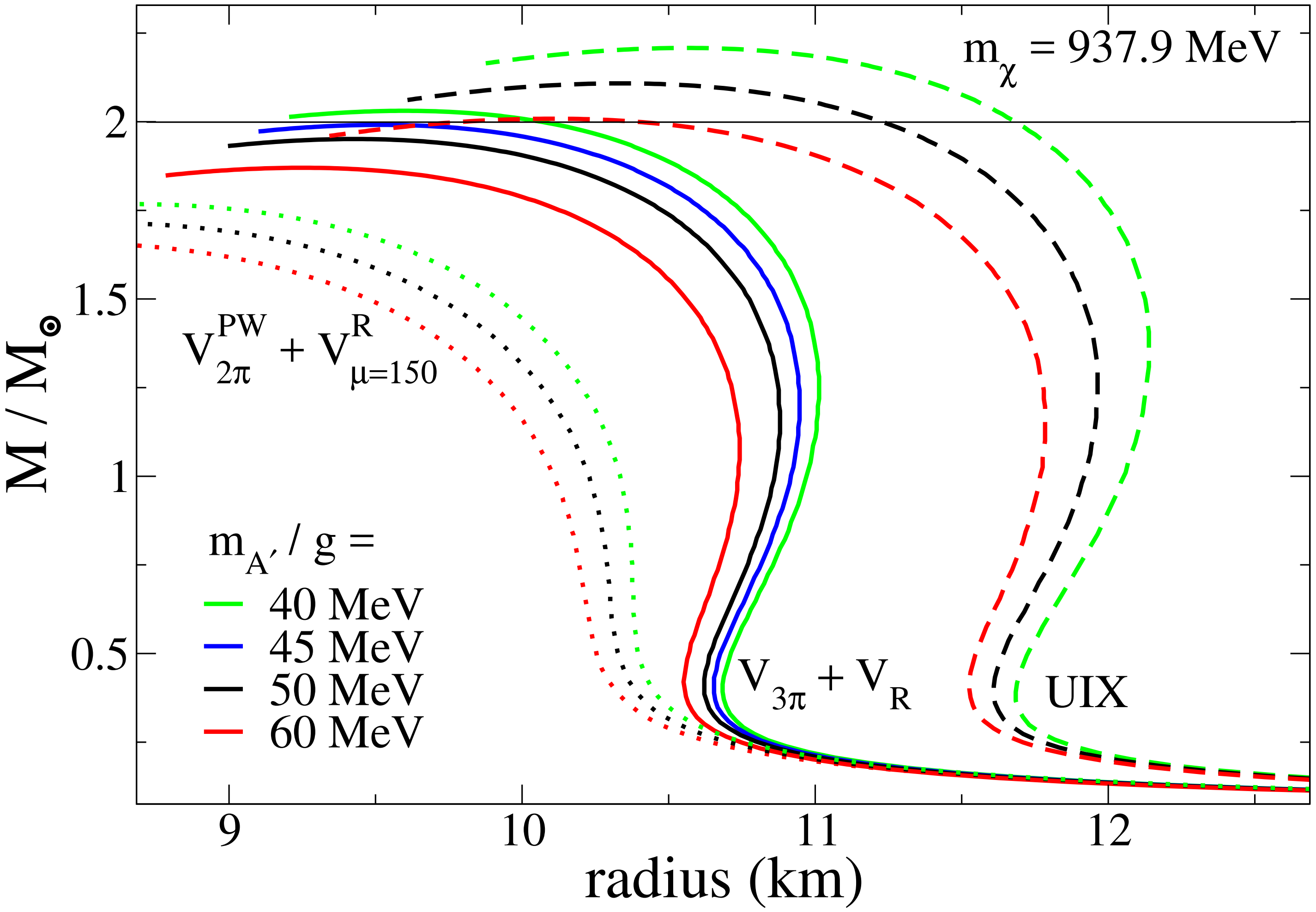
Motta, Guichon, Thomas, 2018

Self-interactions Lead to Large Neutron Stars



$$\delta p_\chi = \frac{g'^2}{2m'^2_A} n_\chi^2$$

The pressure from χ self-interactions ultimately causes their number density to decrease.



For 2 solar mass neutron star to exist:

$$\frac{m_{A'}}{g'} \lesssim (45 - 60)\ \mathrm{MeV}$$

Depending on nuclear equation of state.

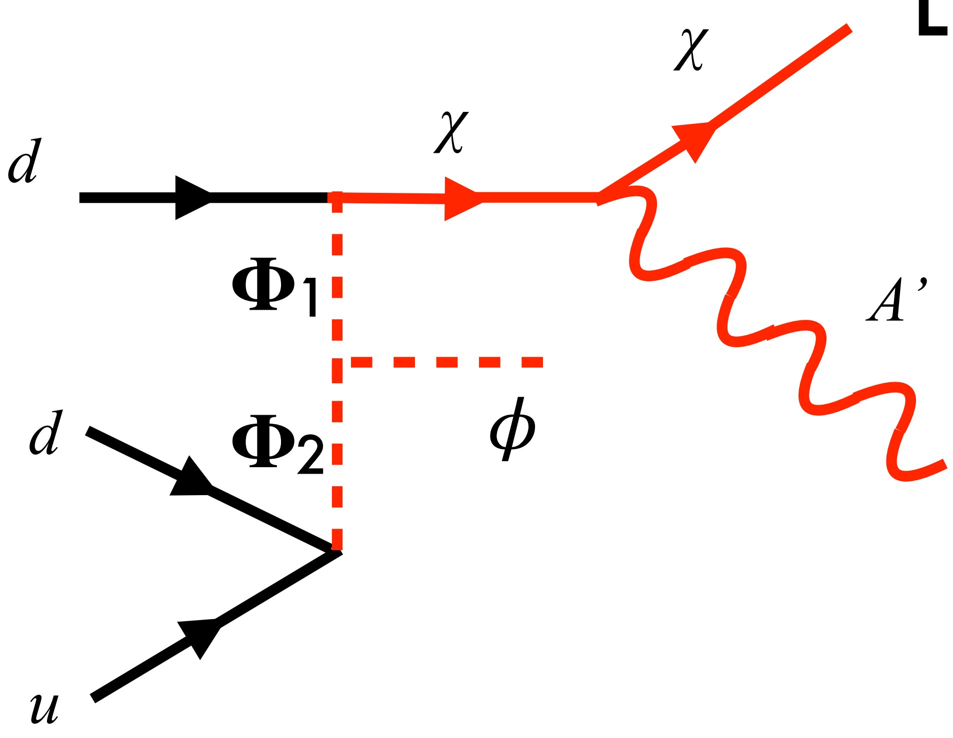
UV Model

We need to generate neutron-χ mixing (δm) and A' mass.

3 new complex scalars:

- Φ_1 – SU(3)c triplet, carries U(1)′ charge
- Φ_2 – SU(3)c triplet
- ϕ – carries U(1)′ charge, obtains v.e.v. (v'), giving mass to A′

$$\mathcal{L} \supset \lambda_1 \, \bar{d}^a P_L \chi \, \Phi_{1,a} + \lambda_2 \, \epsilon^{abc} \, \bar{u}^c_a P_R \, d_b \, \Phi_{2,c} + \mu \, \Phi_{1,a} \, \Phi_2^{*a} \, \phi$$



Leads to mixing term: $\dfrac{\beta \mu \lambda_1 \lambda_2 v'}{m^2_{\Phi_1} m^2_{\Phi_2}} \bar{n} P_L \chi$

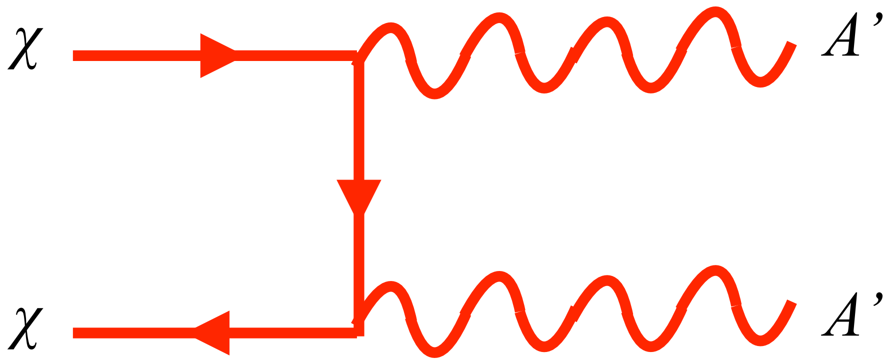
Masses:

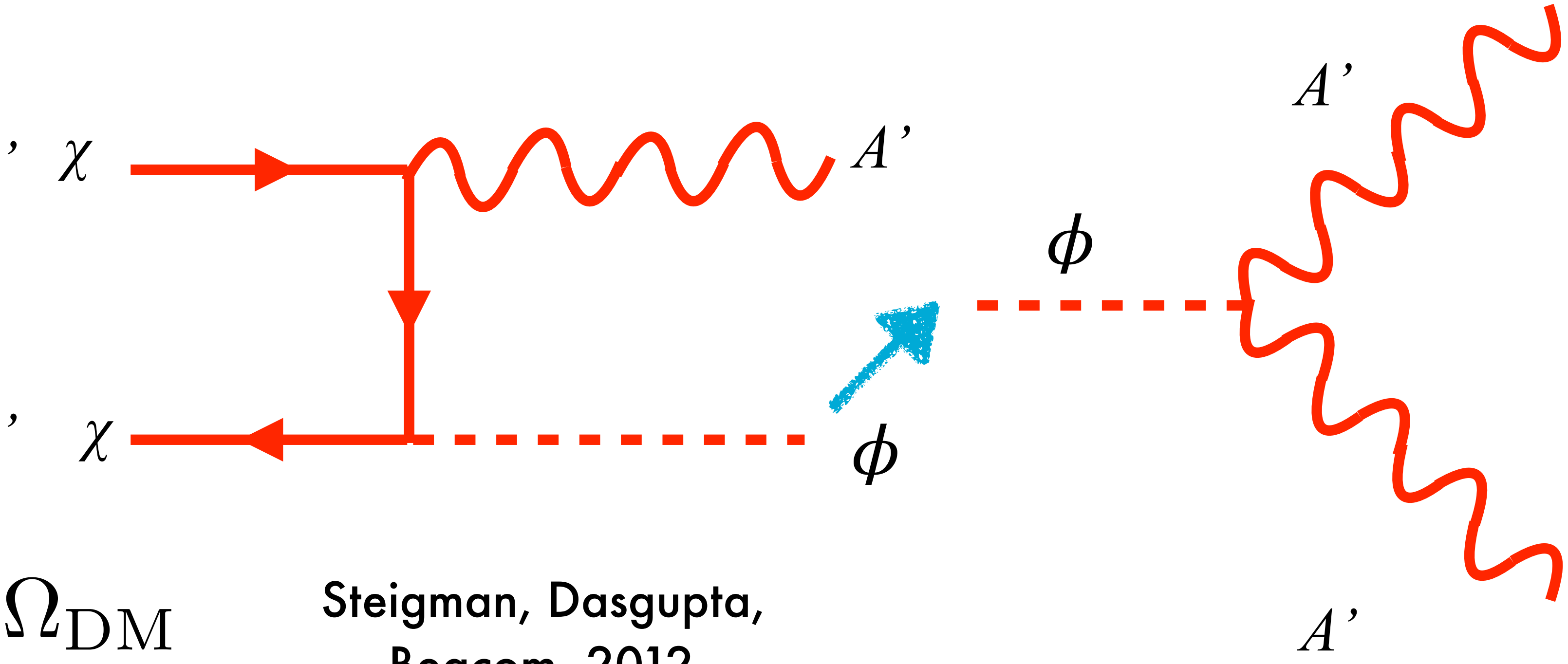
- m_Φ > 1.5 TeV to avoid LHC limits on colored scalars ATLAS, 2107
- m_ϕ = 70 MeV (benchmark value) to avoid $n \to \phi\chi$ decays

Relic Density of Dark Matter and Dark Radiation

We assume standard thermal freeze out production.

χ Relic Abundance:





$$\Omega_\chi = \frac{1\times 10^{-25}\mathrm{cm}^3/\mathrm{s}}{\langle \sigma_{\mathrm{ann}} v\rangle}\Omega_{\mathrm{DM}}$$

Steigman, Dasgupta, Beacom, 2012

A′ Relic Abundance:

- The A' are relativistic at freeze out with large number density.
- We require they decay before they make up half of the universe’s energy density, to avoid disturbing Big Bang Nucleosynthesis/ Cosmic Microwave Background. Cirelli, et al., 2016

(A) $m_{A'}$ = 1.35 MeV
$\tau_{A'} < 540$ s

(B) $m_{A'}$ = 0.5 MeV
$\tau_{A'} < 3920$ s

Limits on DM Annihilation

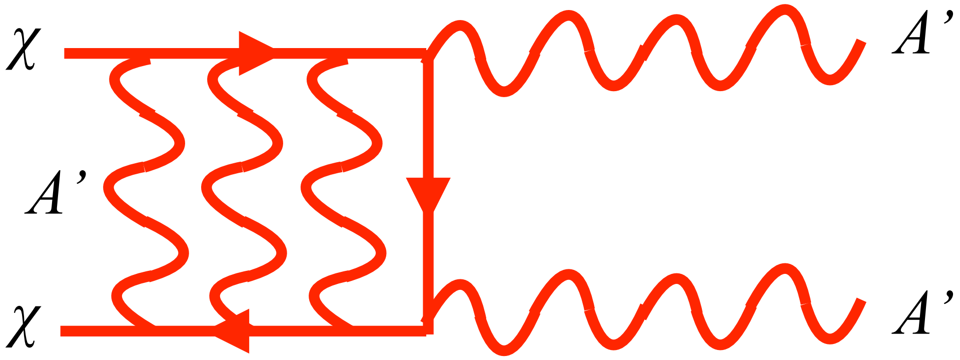
$$\Phi_{\gamma,e^\pm} \propto \rho_\chi^2 \langle \sigma v \rangle \propto \frac{1}{\langle \sigma v \rangle}$$

With thermal production, larger g′ ultimately leads to reduced annihilation rate.

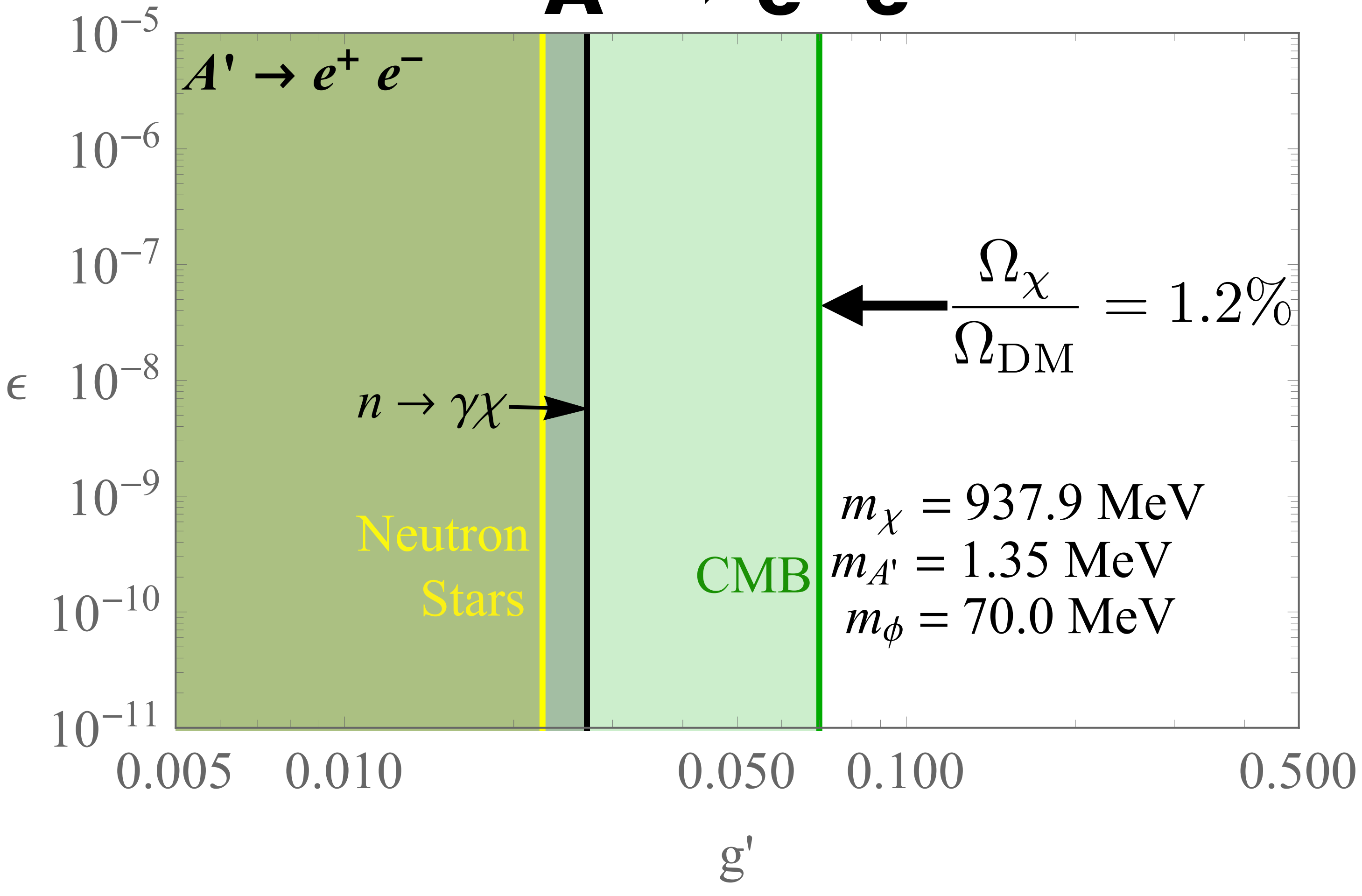
We consider limits on the annihilation rate from:

- Observations of dwarf spheroidal galaxies with *Fermi*-LAT
- Distortions of the CMB anisotropy spectrum as observed by *Planck*.

In both cases, Sommerfeld enhancement is important.



$A' \to e^+ e^-$



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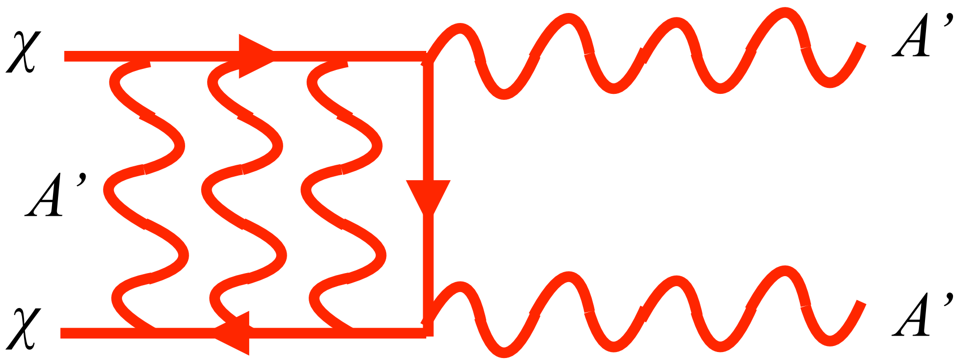
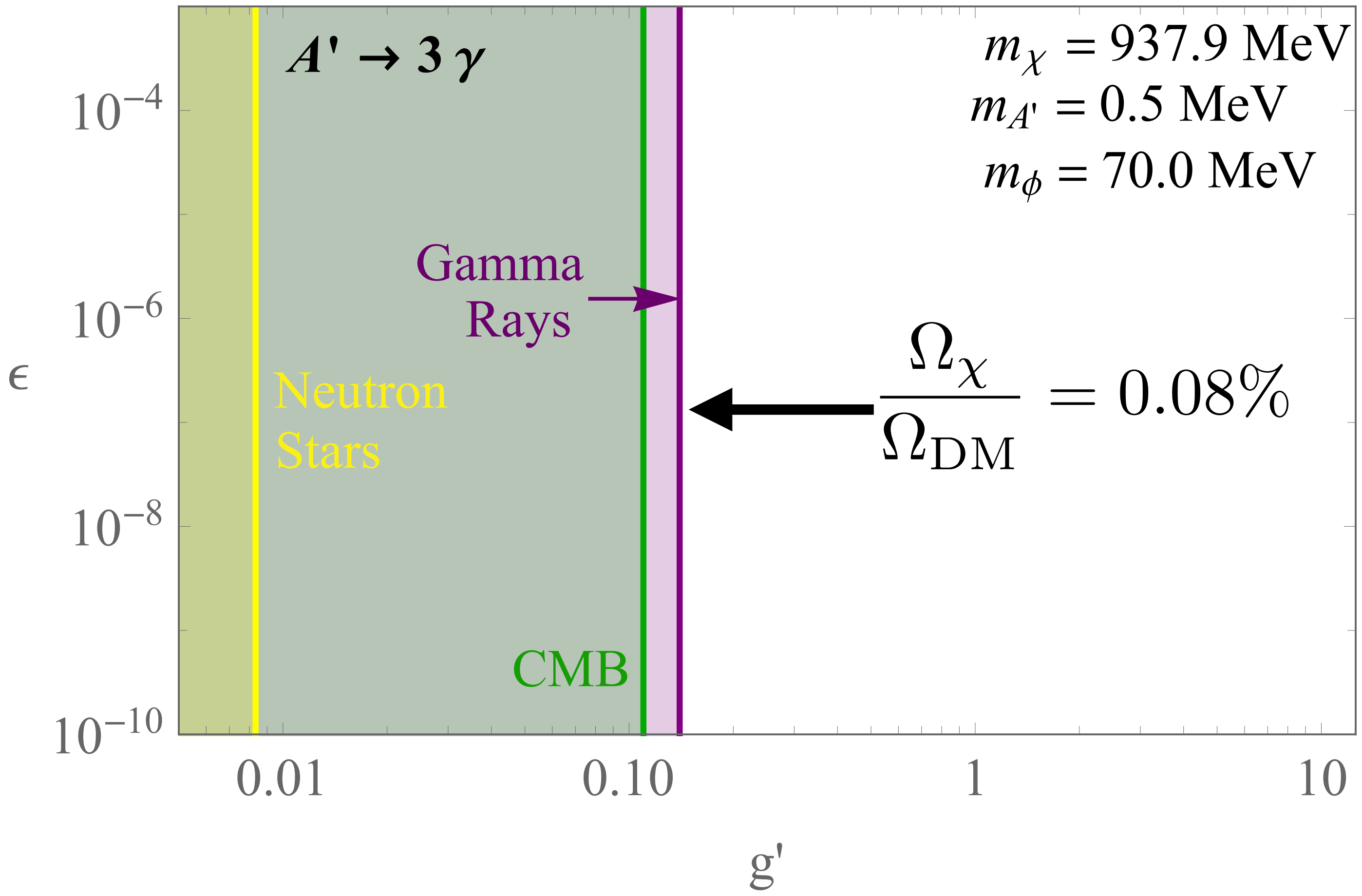


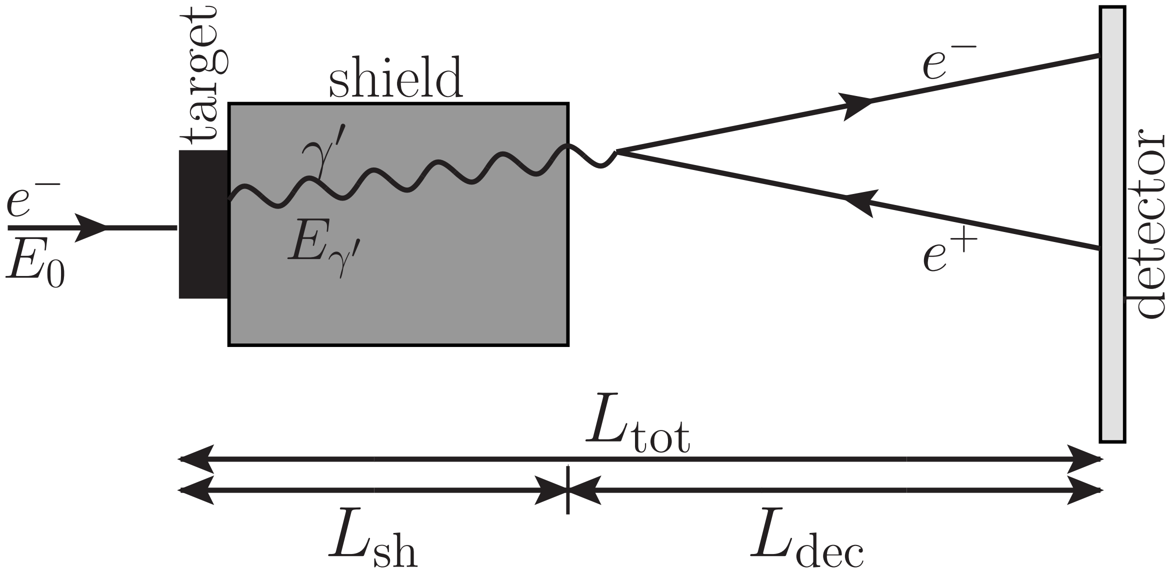
A′ → 3γ



Limits on Kinetic Mixing

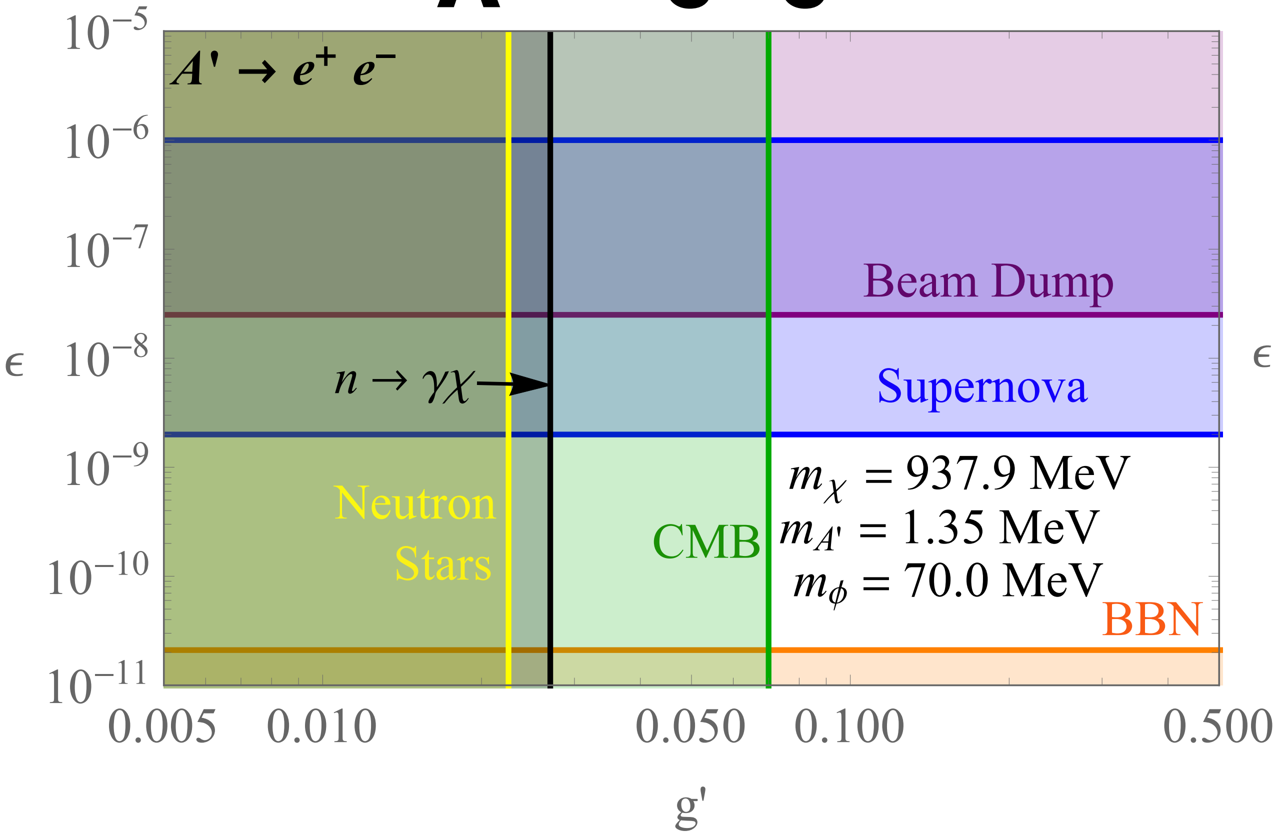
Limits on ε come from:

- Beam dump experiments, particularly E137
- Supernova cooling limits from observations of SN 1987A
  Chang, Essig, McDermott, 2016
- BBN/CMB

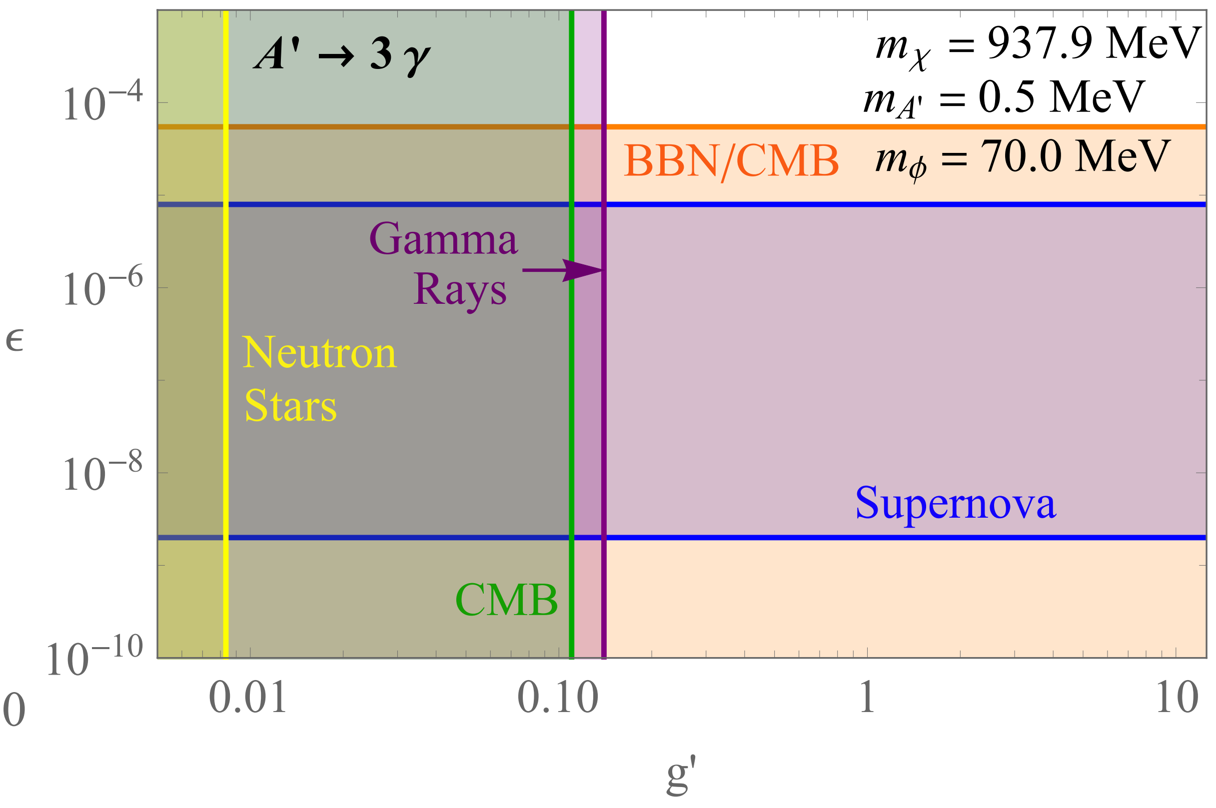


Andreas, Niebuhr, Ringwald, 2012

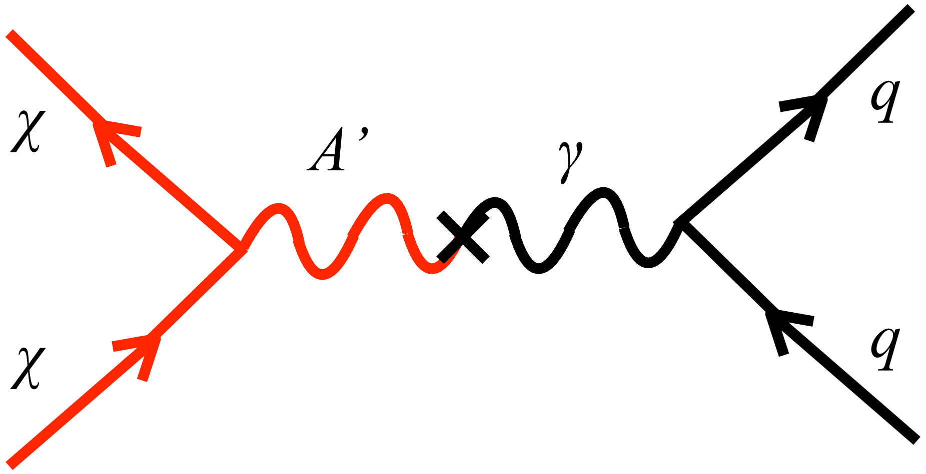
A′ → e⁺ e⁻



A′ → 3γ

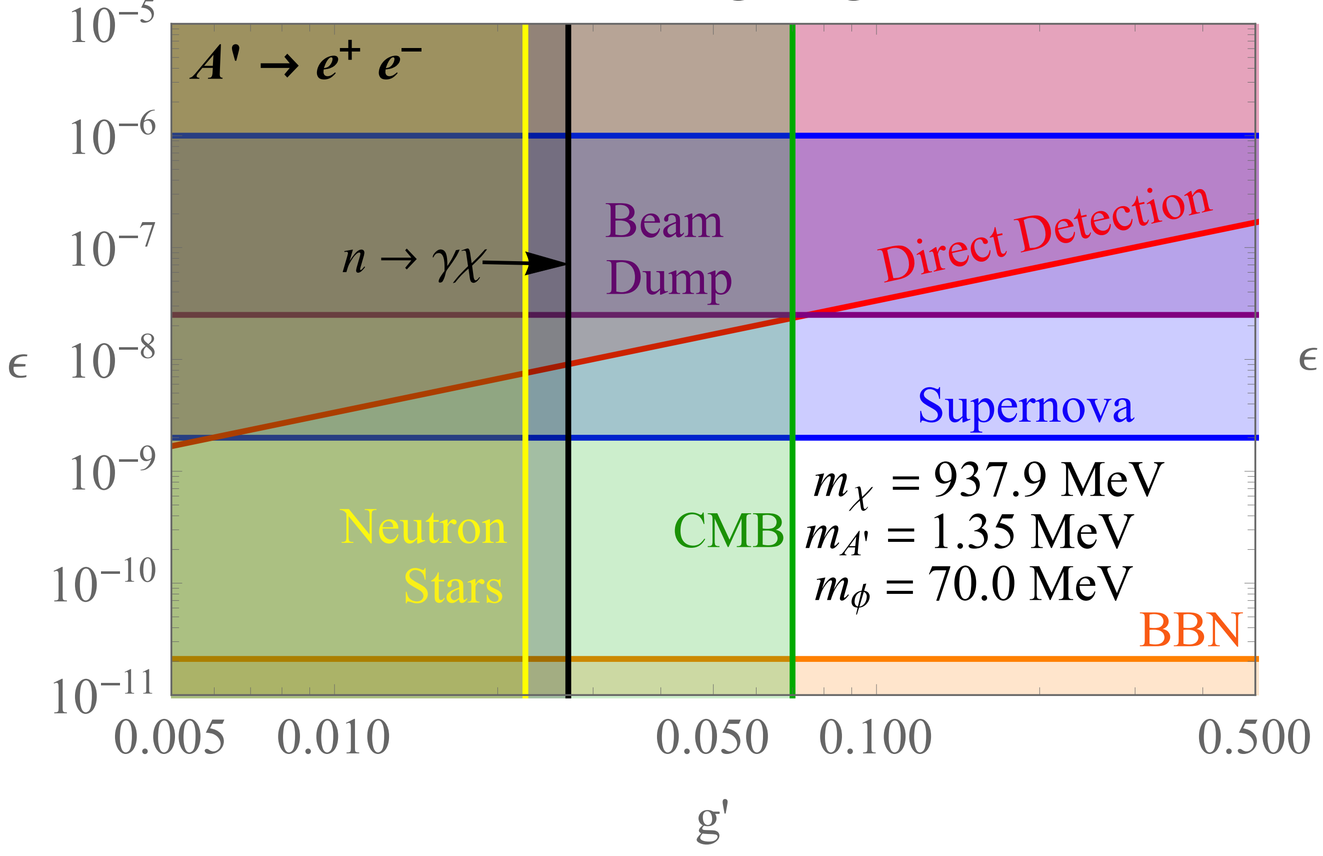


Direct Detection

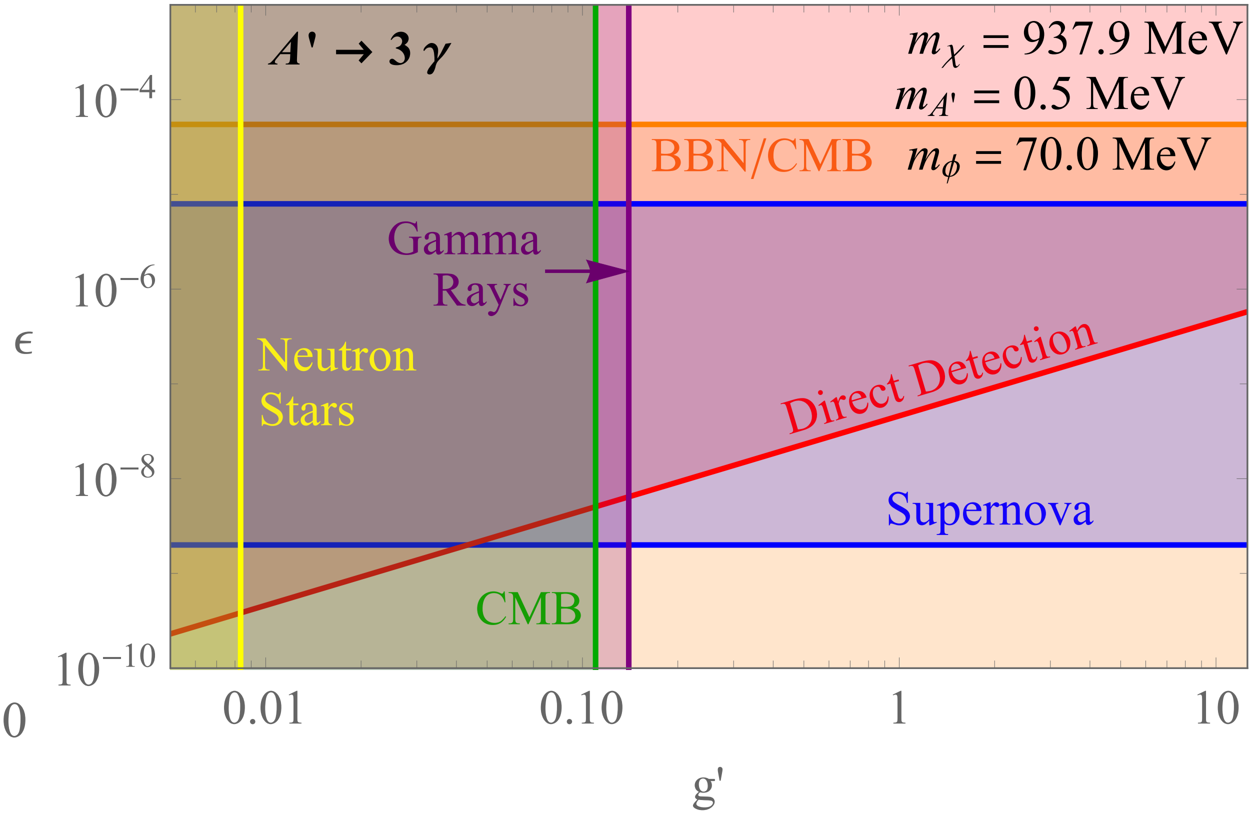


An observable which depends on both ε and *g*.
We use the recent limits from CRESST-III on light DM.

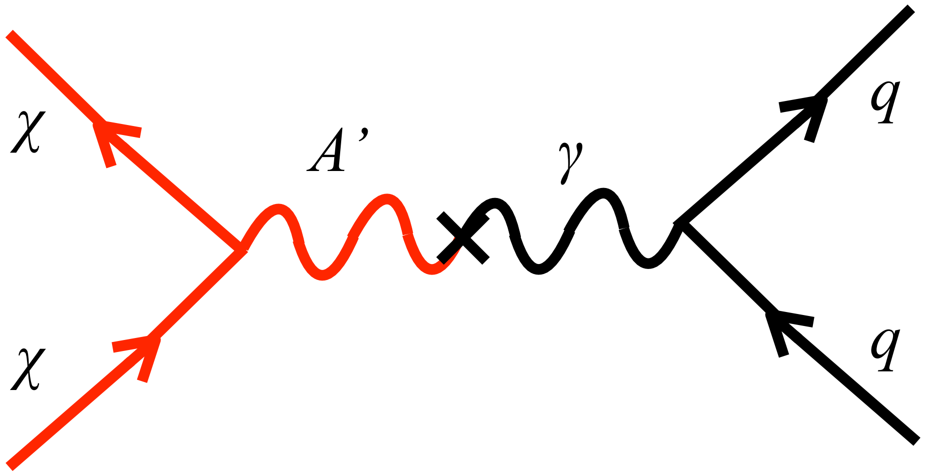
A′ → e⁺ e⁻



A′ → 3γ

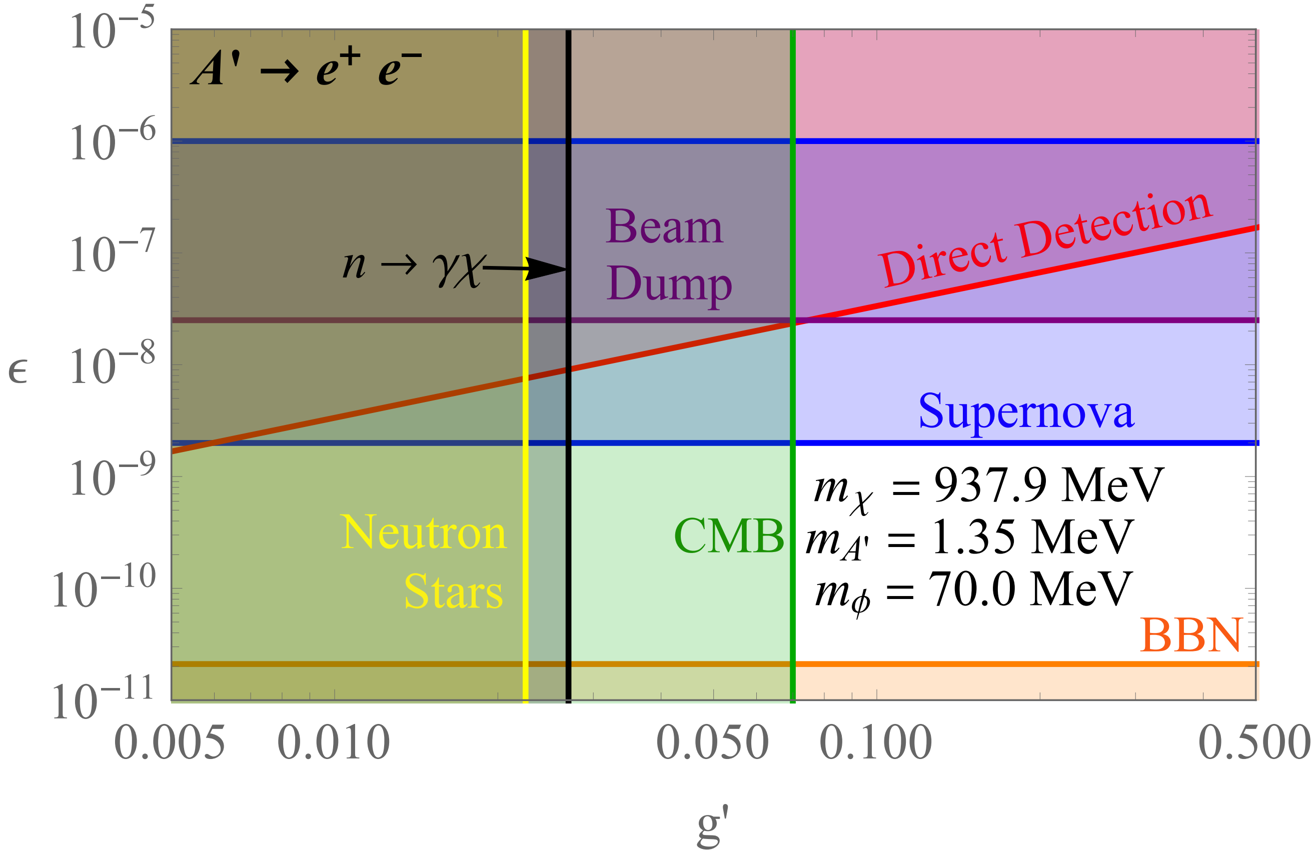


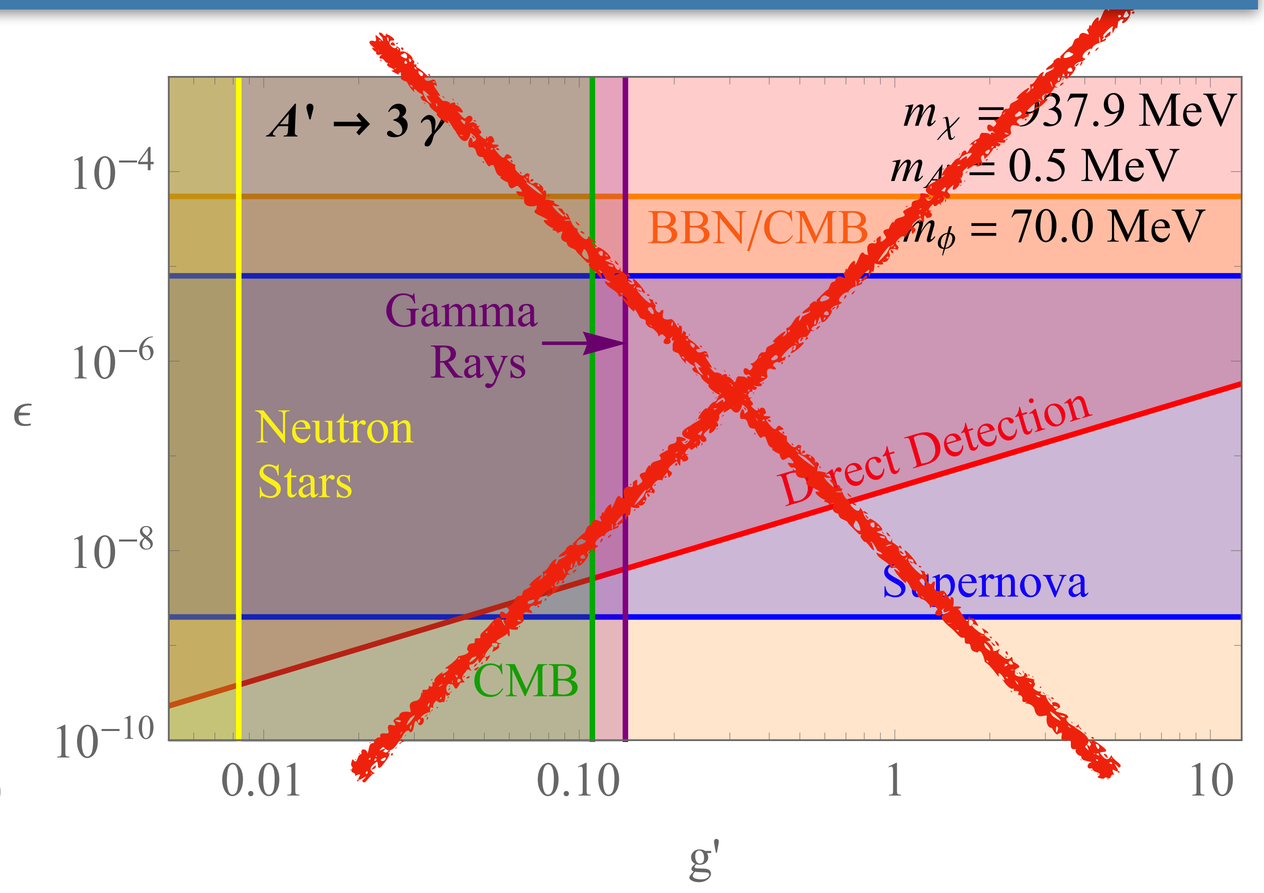
Direct Detection



$937.8\ \text{MeV} < m_\chi < 938.8\ \text{MeV}$

$1.0\ \text{MeV} < m_{A'} < 1.8\ \text{MeV}$





Summary

- Neutron decays to SM particles + DM have been largely experimentally ruled out as viable explanations for the neutron lifetime puzzle.
- Neutron decays to multiple dark sector particles are still viable!
- The dark particle that carries baryon number in these decays must have strong repulsive self-interactions to avoid neutron star bounds.
- A dark matter + dark photon model is one way to realize this.
- The dark matter candidate in such a model is strongly constrained by astrophysical observations and cosmological considerations. It can make up no more than roughly 1% of the total DM density.

Backups

DM Self-Scattering Limits

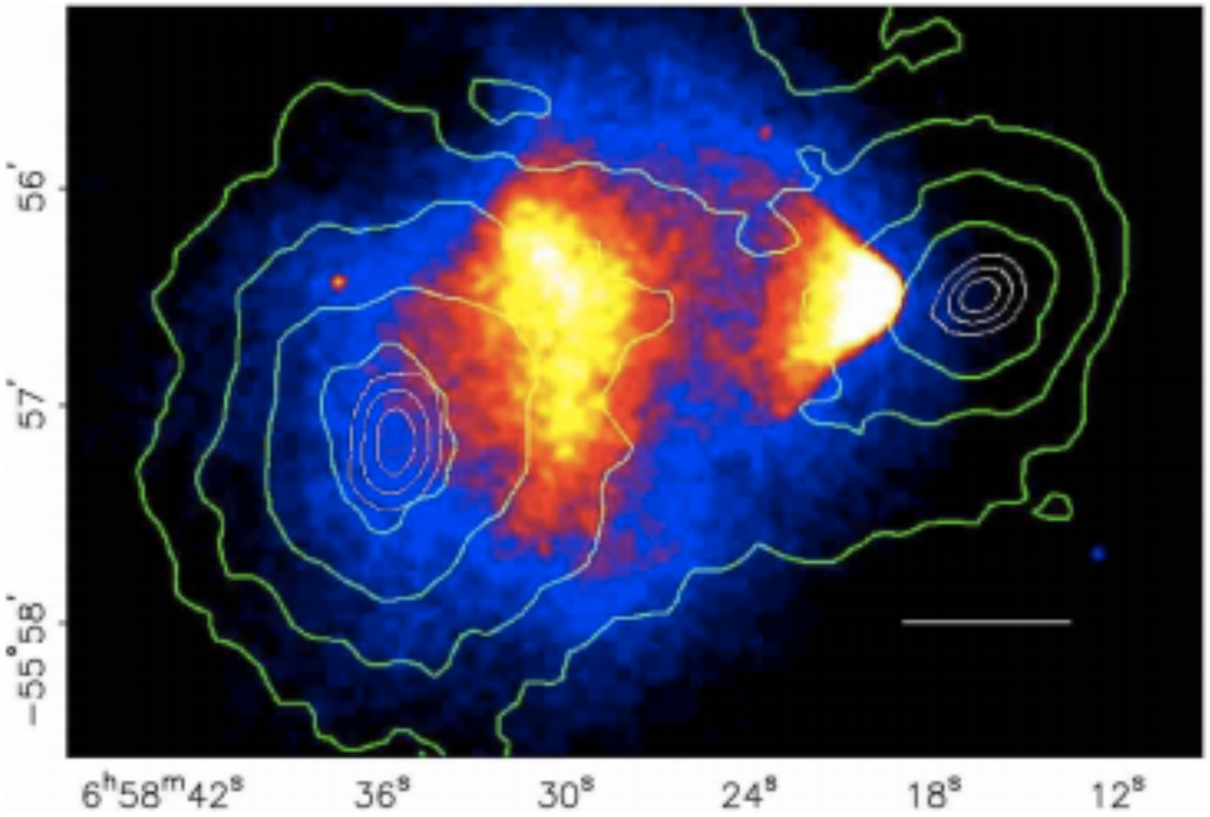
- Neutron stars limit the χ self-scattering cross section to be:

$$\sigma_{\chi\chi} = \frac{g'^4 m_\chi^2}{\pi m_{A'}^4} \gtrsim 3 \times 10^{-20}\,\mathrm{cm}^2$$

- Observations of the Bullet Cluster limit

$$\frac{\sigma_{\mathrm{DM\,DM}}}{m_{\mathrm{DM}}} < 2 \times 10^{-24}\,\frac{\mathrm{cm}^2}{\mathrm{GeV}}$$

Markevitch, et al., 2004



Clowes, et al., 2006

- These limits do not apply if less than roughly 10% of the DM is strongly self-interacting. Therefore χ can be no more than 10% of the DM.

Pollack, Spergel, Steinhard, 2014