Dark Decay of the Neutron

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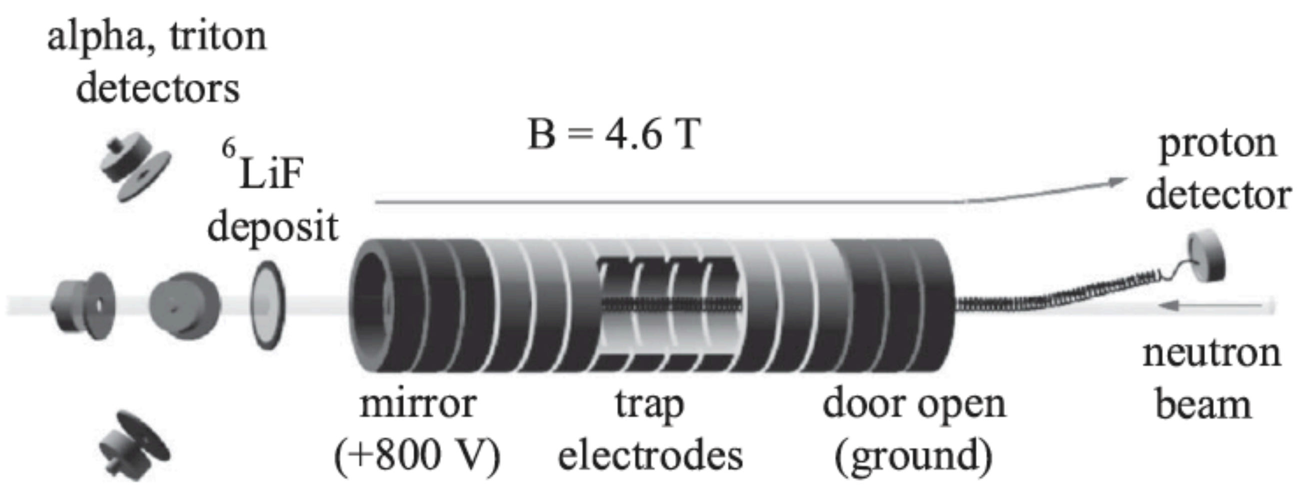
Based on Jim Cline, J.Cornell, JHEP 1807 (2018) 081 [arXiv:1803.04961], and work in progress with Torsten Bringmann and Jim Cline

The Neutron Lifetime Anomaly

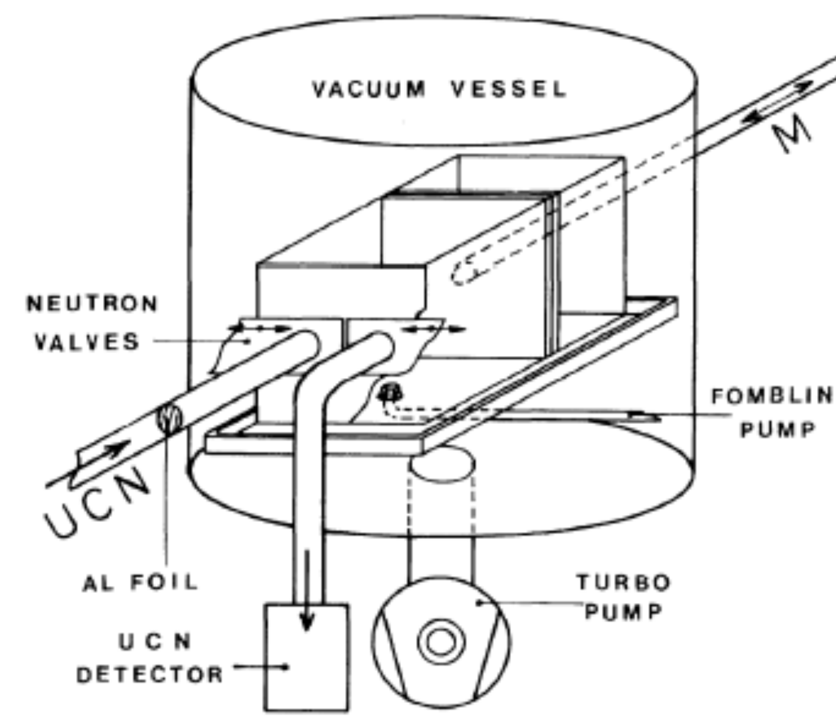
Beam Experiments



NIST, 2015

Neutron lifetime determined by measuring number of **protons** from neutron decay

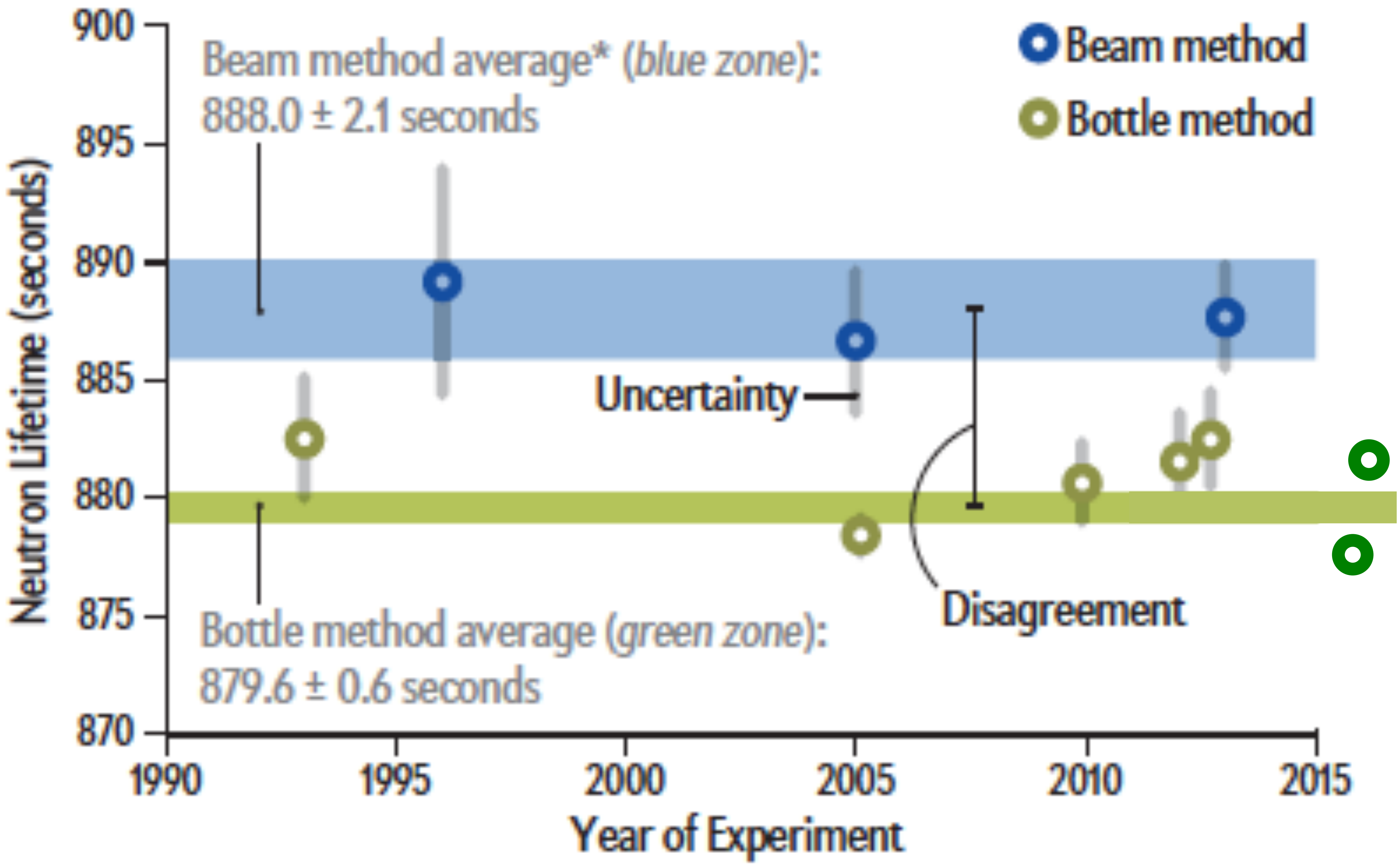
Bottle Experiments



MAMBO, 1993

Neutron lifetime determined by measuring number of **neutrons** at beginning and end of experiment

The Discrepancy

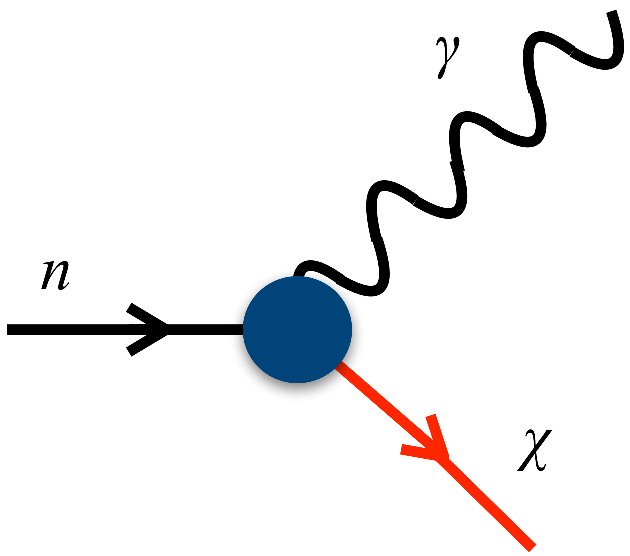


Green, Geltenbort, 2016

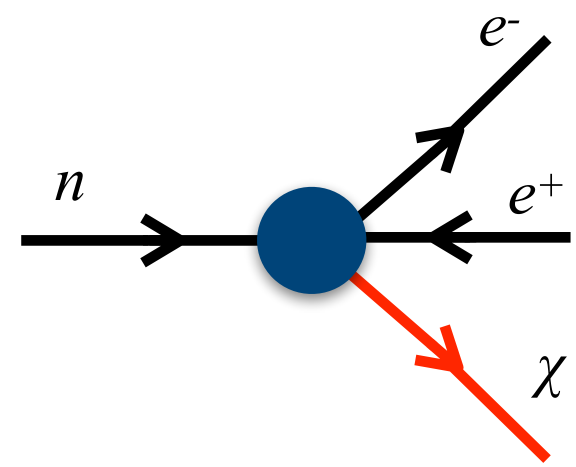
Are the Beam Experiments Missing Decays?

3 possibilities that can avoid proton decay:

Fornal, Grinstein, 2018



Neutron decays to DM and photon



Neutron decays to DM, electron, positron

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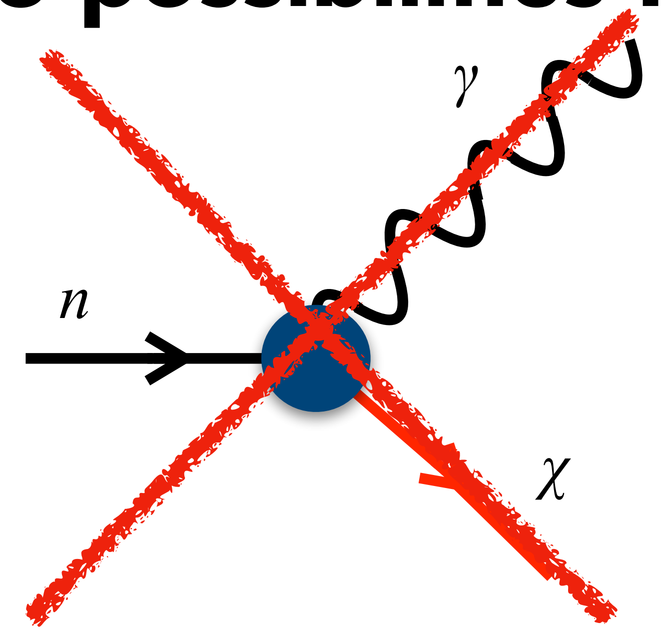

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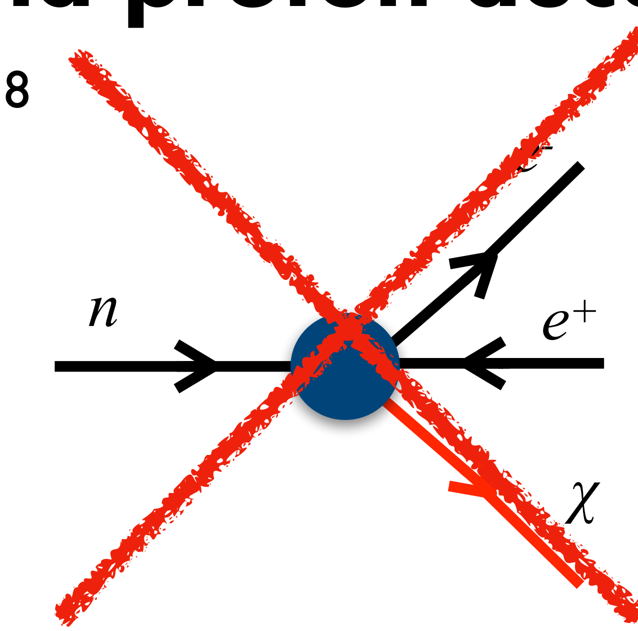

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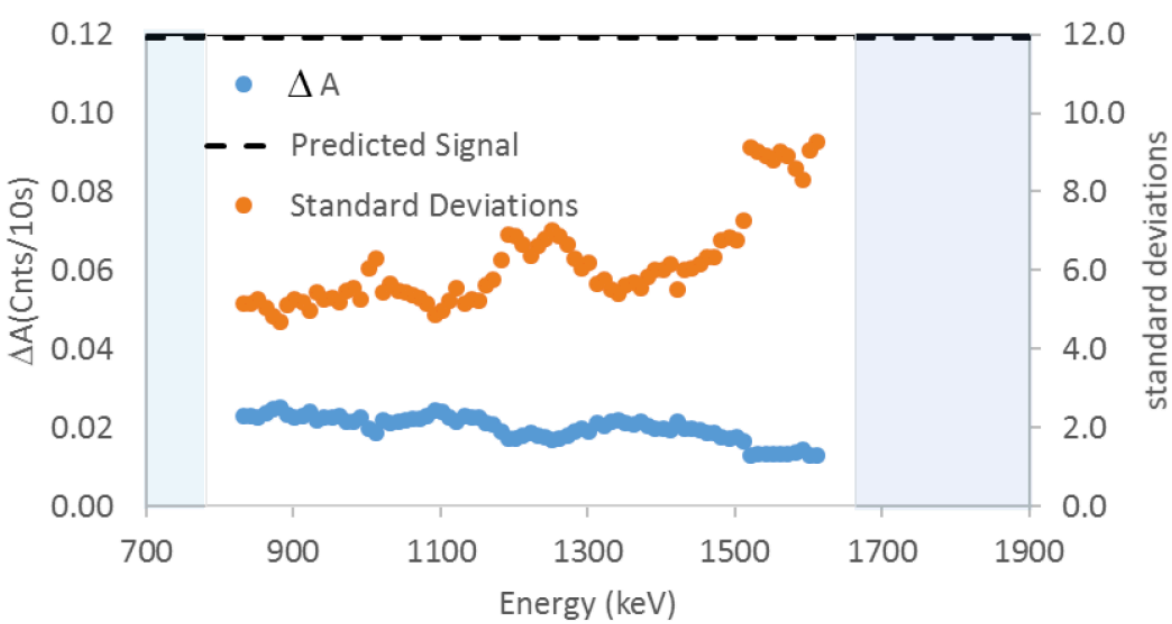
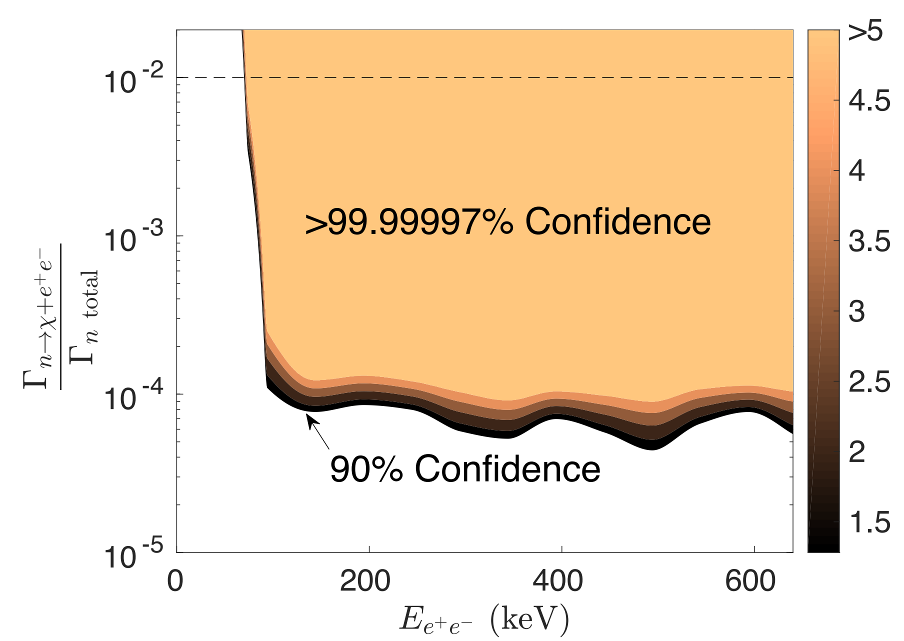


UCNτ Collaboration, Z. Tang, et al., 2018



UCNA Collaboration, X. Sun, et al., 2018

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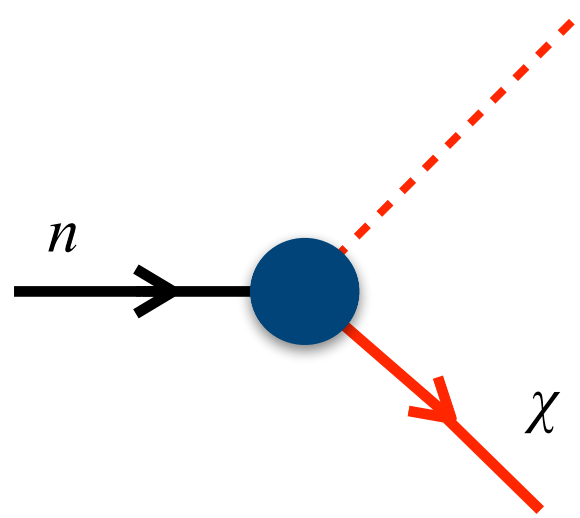
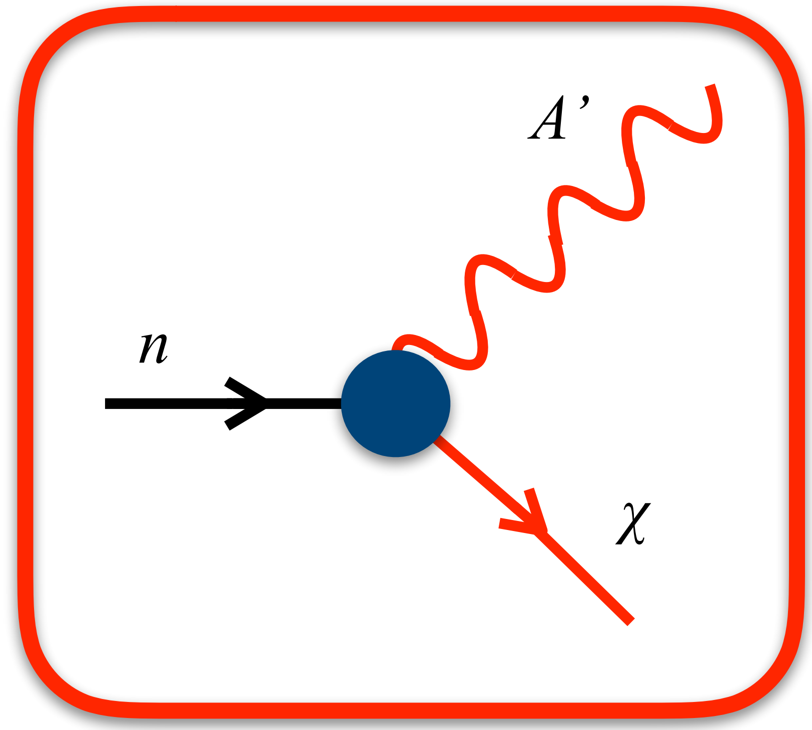




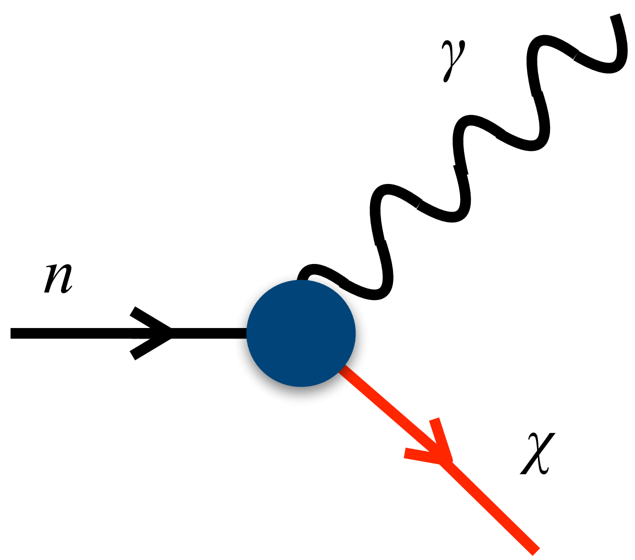
Neutron decays to fermion DM and invisible boson (dark photon or scalar).

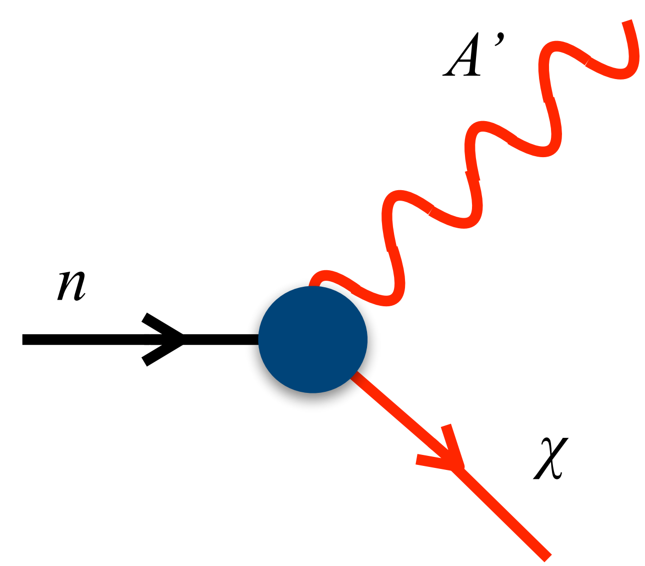
Low Energy Effective Model

Two new fields:

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

$$\mathcal{L}_{\rm eff} = \bar{\chi}(i\partial_\mu - ig' A'_\mu - m_\chi)\chi + \bar{n}\left(i\partial\!\!\!/ - m_n + \mu_n \sigma^{\mu\nu} F_{\mu\nu}\right) n$$
$$- \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - \frac{1}{2} m^2_{A'} A'^{\mu} A'_\mu - \delta m\, \bar{n}_R \chi_L + \text{h.c.} - \frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu}$$





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

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

Mass Limits

- For the neutron to decay to $\chi + A'$: $m_\chi + m_{A'} < 939.6$ MeV
- For ^{9}Be to NOT decay to $\chi + \gamma$: $m_\chi > 937.9$ MeV
  (this also stabilizes the proton)

Our benchmark values:

$m_\chi = 937.9$ MeV

$m_{A'} = 1.35$ MeV

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

$m_{A'} < 2m_{e^-}$ ($A' \to 3\gamma$) disfavoured by BBN

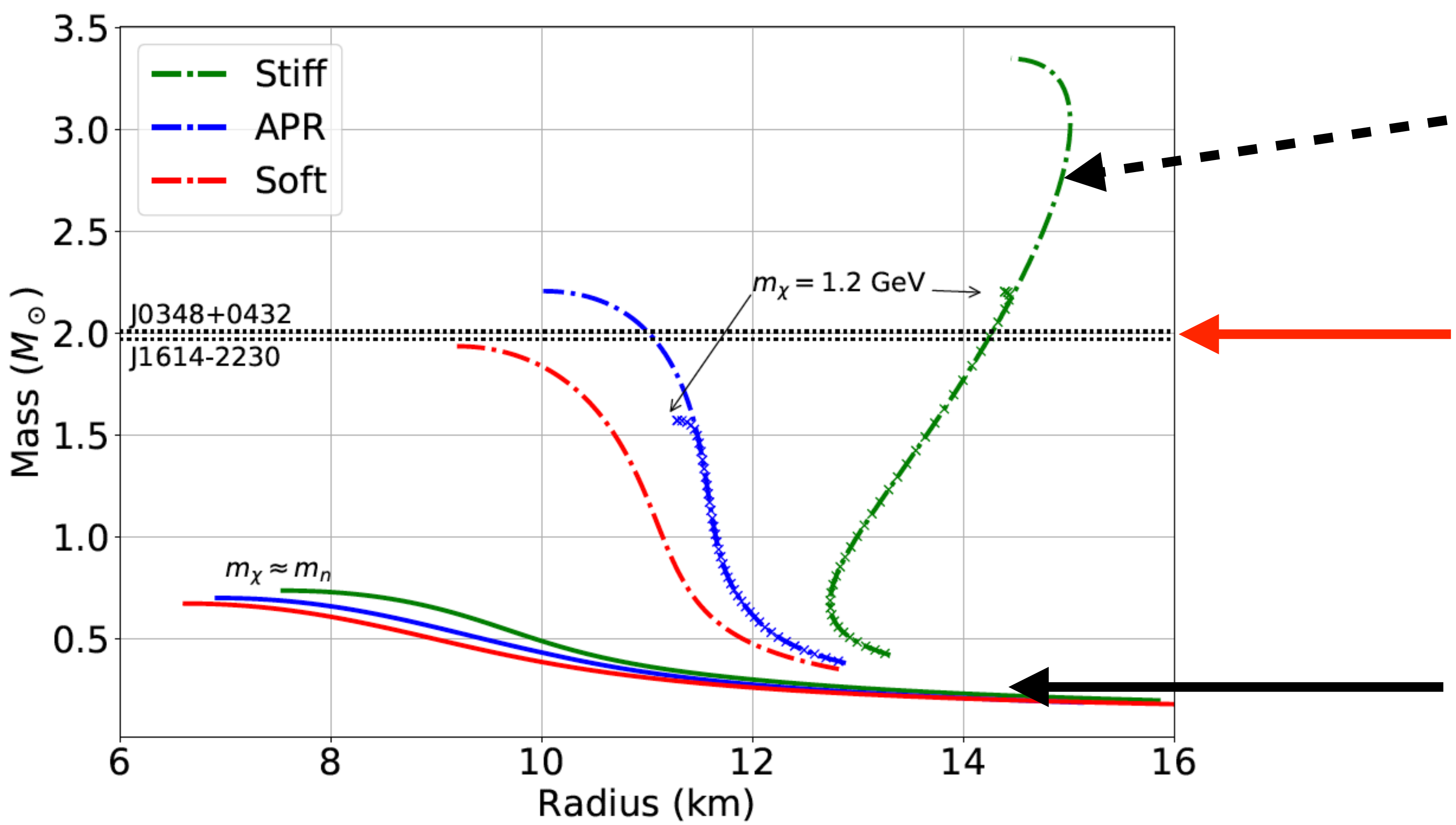
Tolman–Oppenheimer–Volkoff Limit

$$\frac{dP}{dr} = -\frac{Gm\epsilon}{r^2}\left(1+\frac{P}{\epsilon}\right)\left(1+\frac{4\pi r^3 P}{m}\right)\left(1-\frac{2Gm}{r}\right)$$

$$\frac{dm}{dr} = 4\pi r^2 \epsilon$$

Equation of state: $P = f[\epsilon]$

Solve numerically to find where *P*=0 to get the radius and mass of a neutron star. Vary the central pressure to find the maximum mass.



McKeen, et al., 2018

Baym, et al., 2018

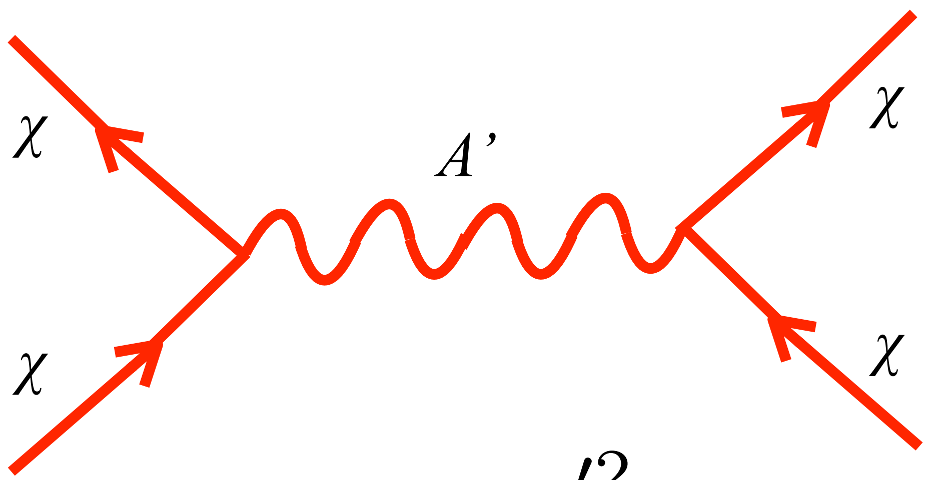
Motta, Guichon, Thomas, 2018

No *n*-DM conversion

Observed neutron star masses.

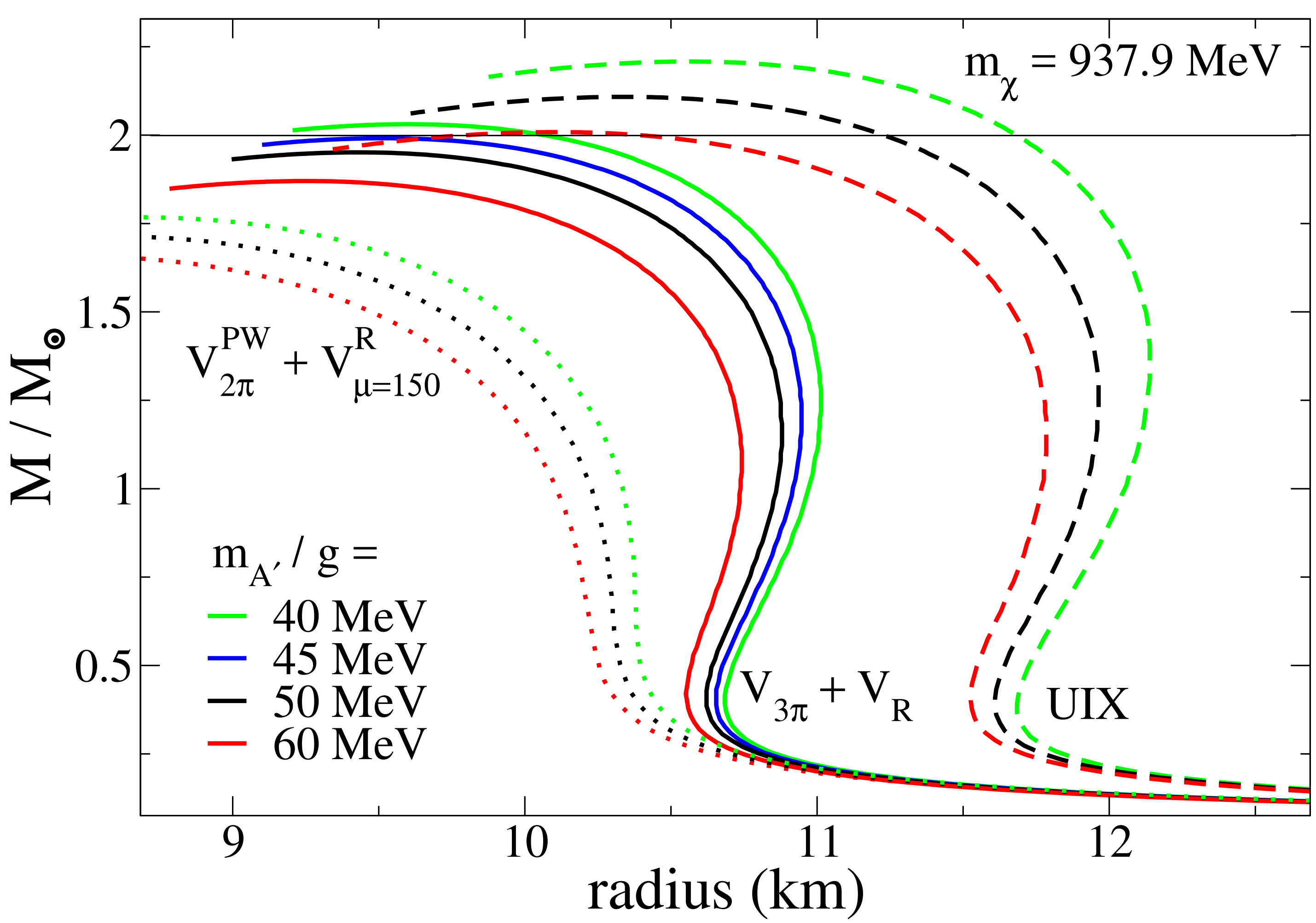
n-DM conversion allowed. The conversion reduces the neutron pressure.

Self-interactions Lead to Large Neutron Stars



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

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.

Limits on Symmetric DM Annihilation

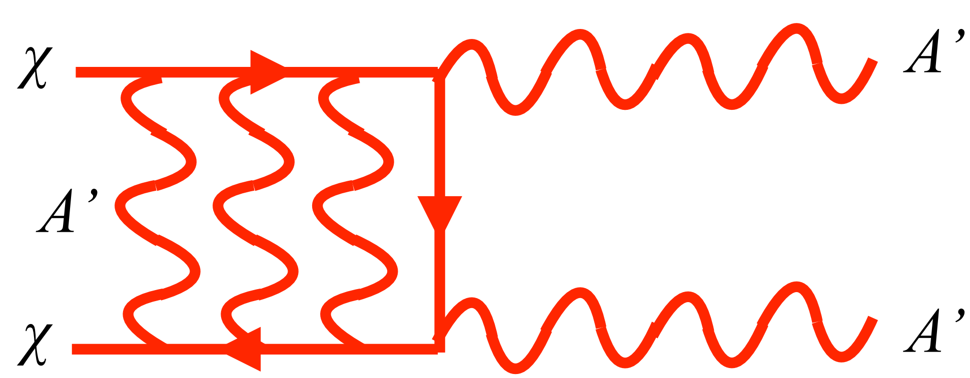
$$\Phi_{\gamma,e^\pm} \propto \rho_\chi^2 \langle \sigma v \rangle \propto \frac{1}{\langle \sigma v \rangle}$$

Assuming χ is thermally produced, larger g′ ultimately leads to reduced annihilation rate.

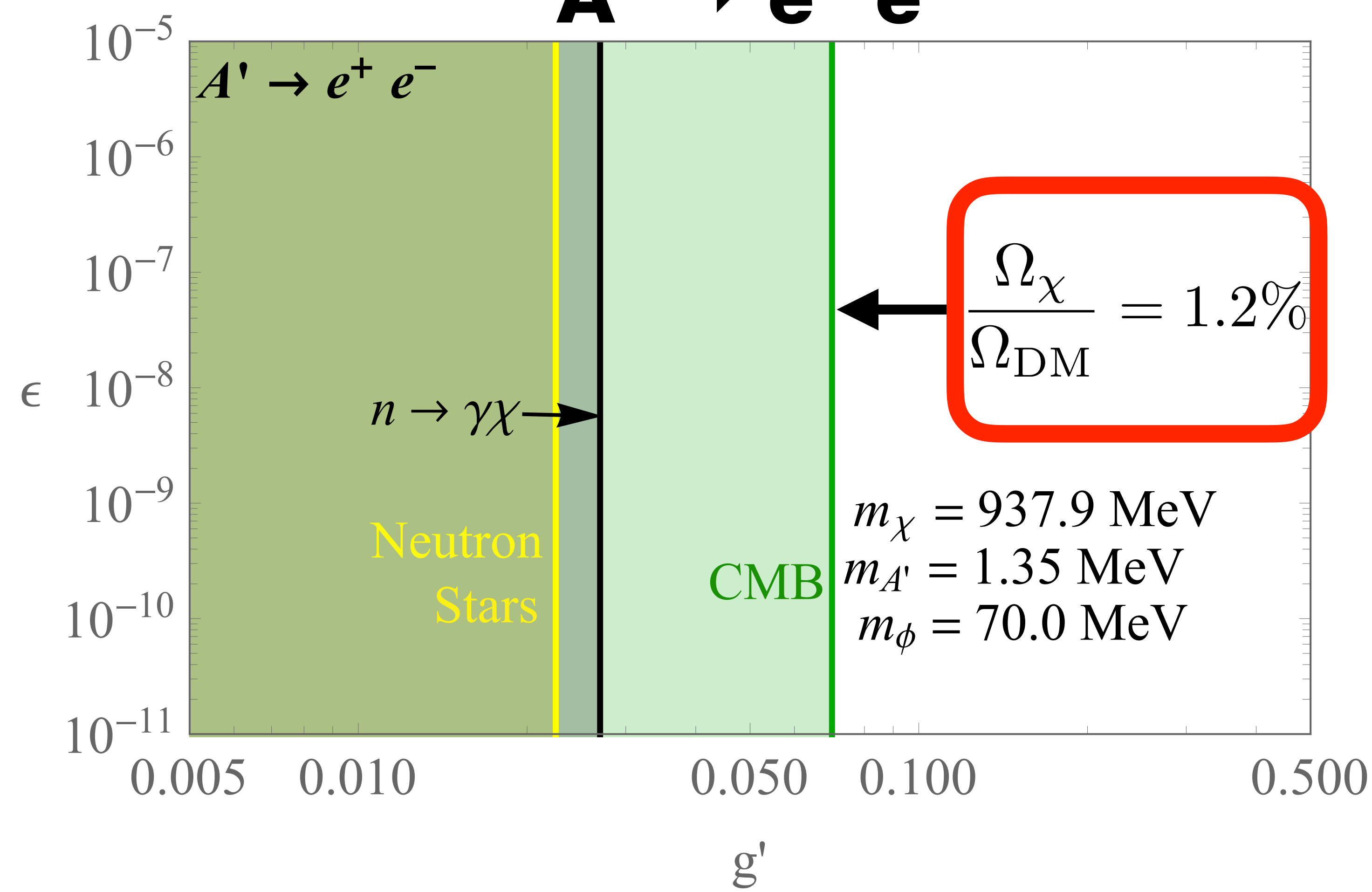
We consider limits on the annihilation rate from:

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

In both cases, Sommerfeld enhancement is important.

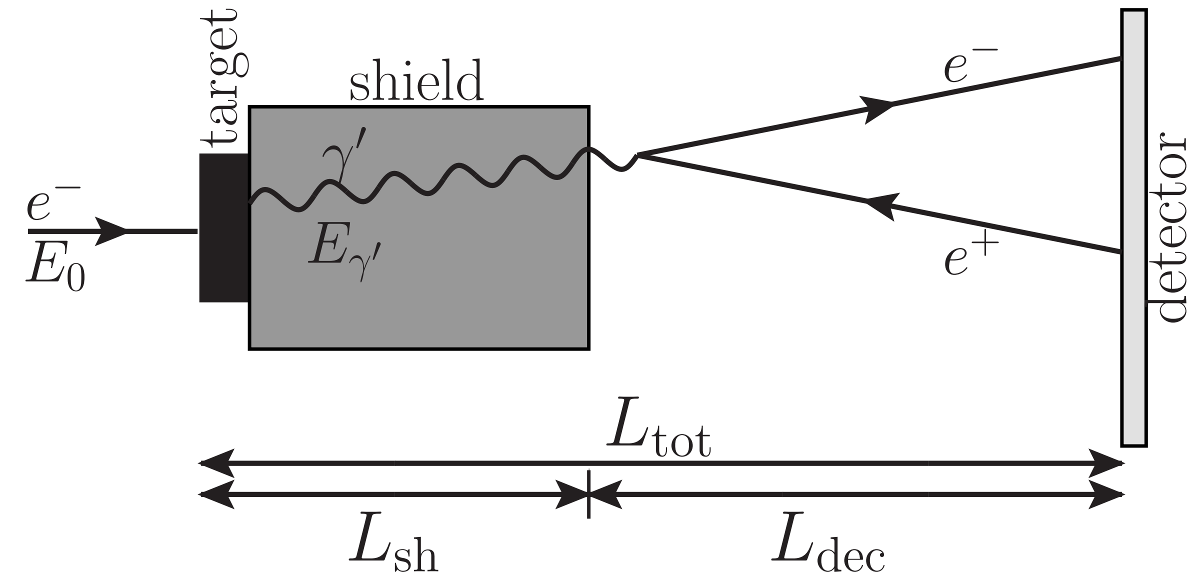


A′ → e⁺ e⁻

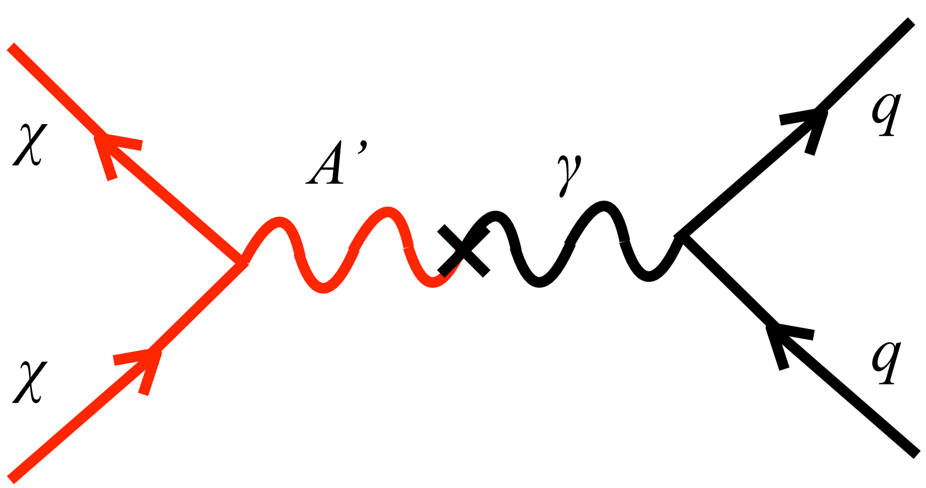


Limits on Kinetic Mixing

- Beam dump experiments, particularly E137
- Supernova cooling limits from observations of SN 1987A
  Chang, Essig, McDermott, 2016
- Presence of A′ during big bang nucleosynthesis
  Hufnagel, Schmdit-Hoberg, Wild, 2018
- Direct detection (CRESST III)



Andreas, Niebuhr, Ringwald, 2012



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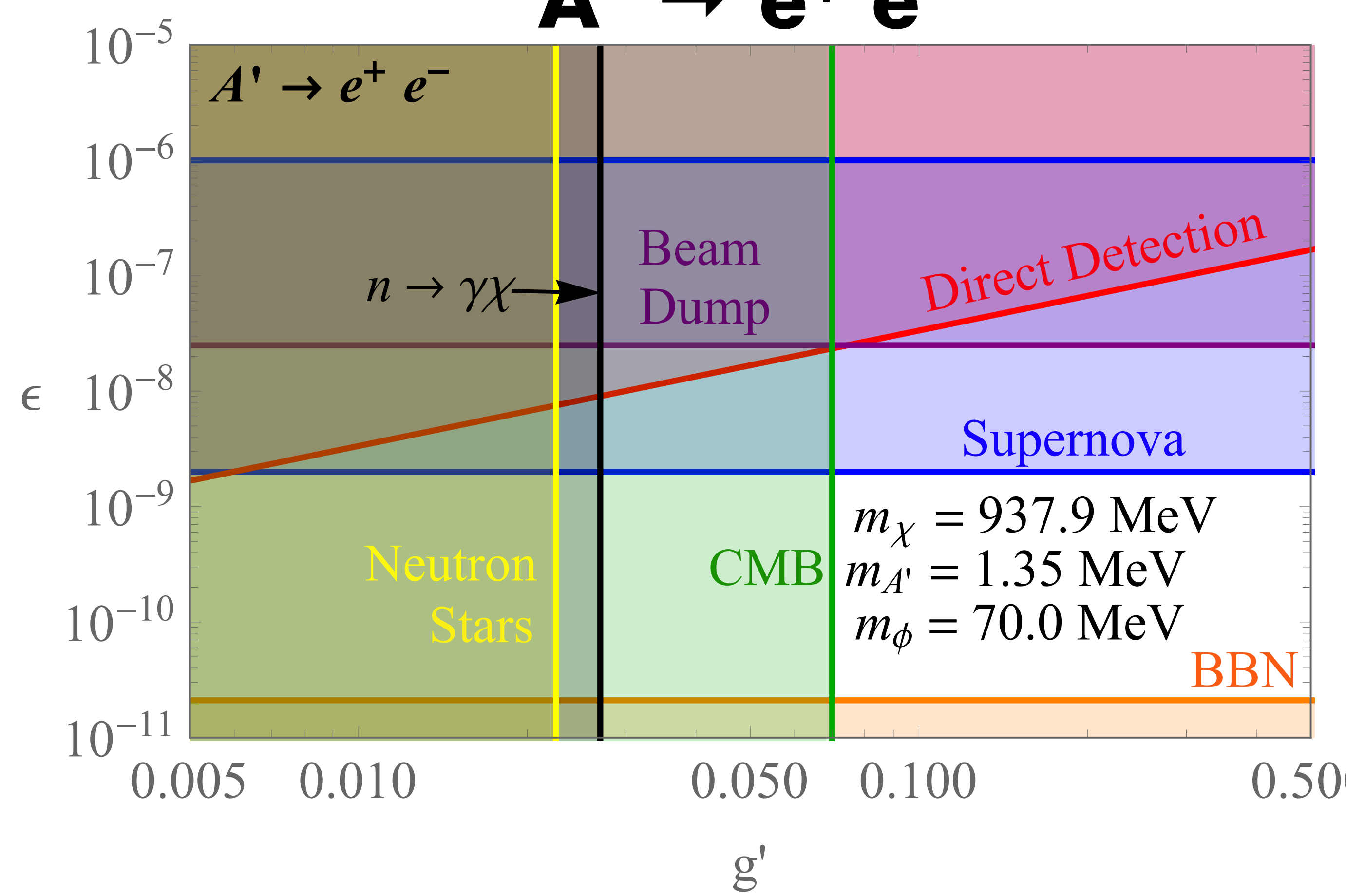
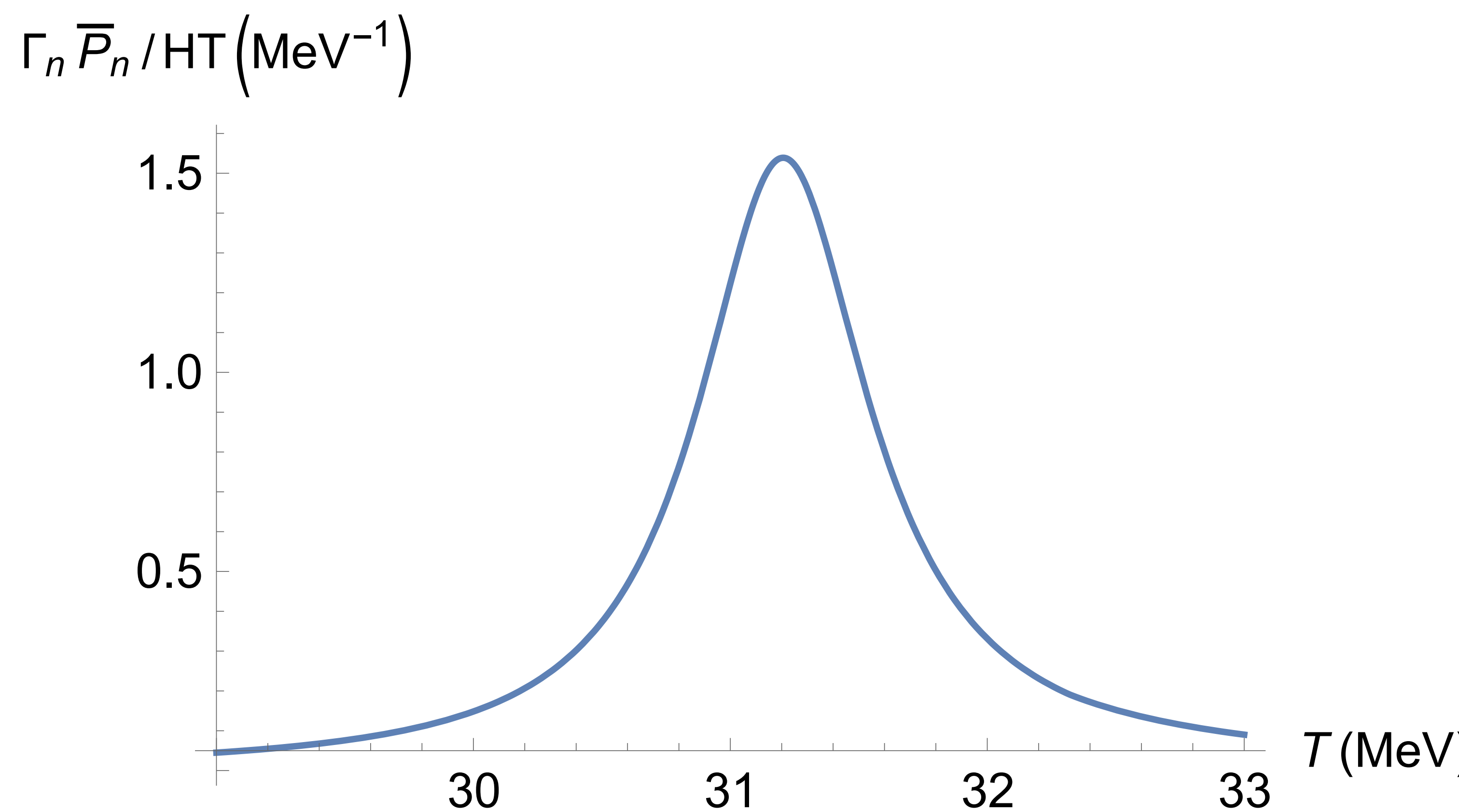


The Asymmetric Alternative

- An asymmetric χ is not constrained by indirect detection, and can make up all of the dark matter.
- Could the χ asymmetry be transferred to the neutrons?

$$\mathcal{L}_{\rm eff} \supset -\delta m\, \bar{n}_R \chi_L$$

$$\Delta m \equiv m_n - m_\chi$$



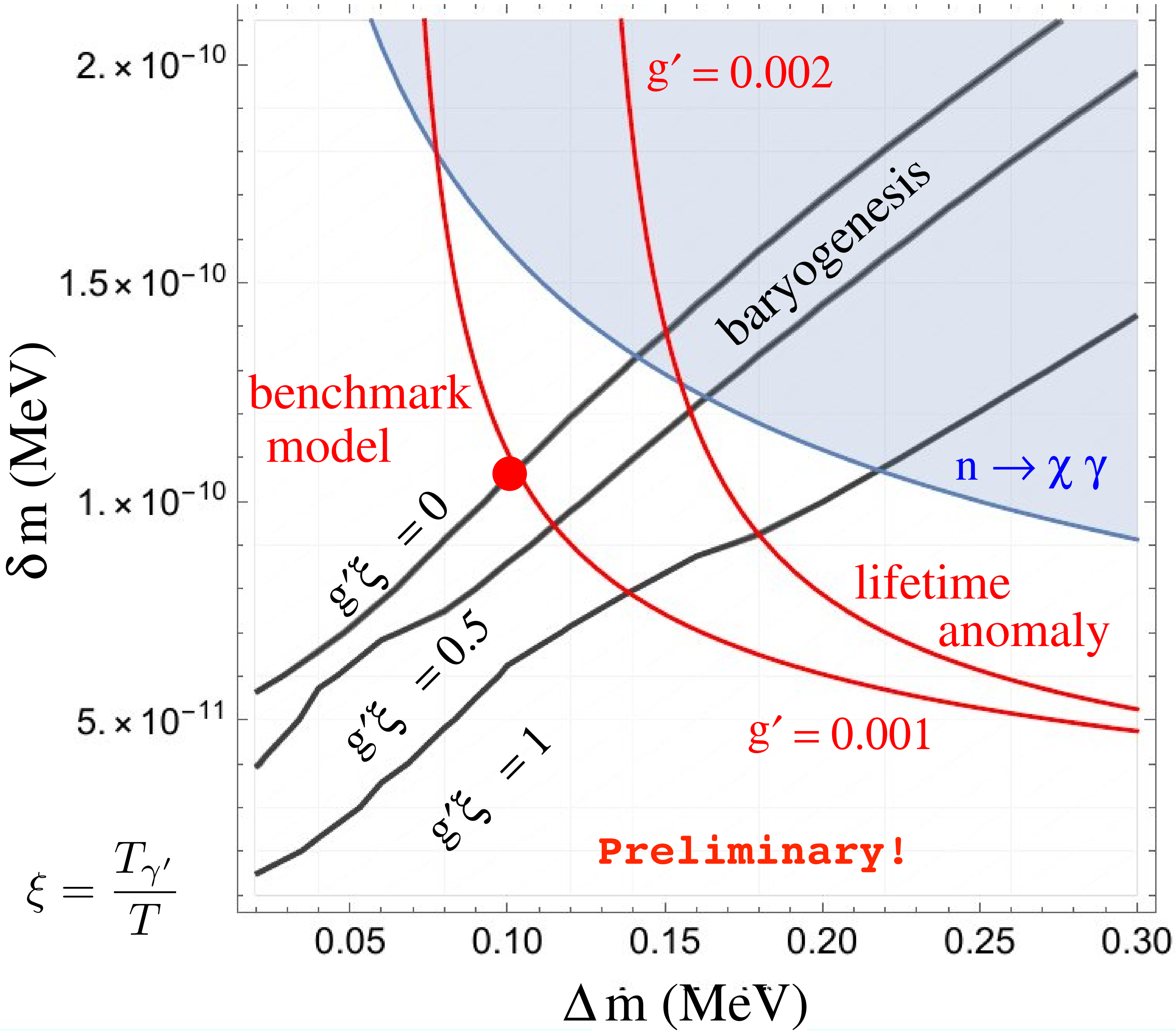
Mixing angle:

$$\tan(2\,\theta) = \frac{2\,\delta m}{\Delta m + \Delta E_n - \Delta E_\chi}$$

Thermal contributions to masses.

χ → n enhanced at resonance temperature.

Conditions for Succesful Cogenesis



$$\xi = \frac{T_{\gamma'}}{T}$$

As $m_\chi \approx m_n$, we need 16% of χ to convert to neutrons to get:

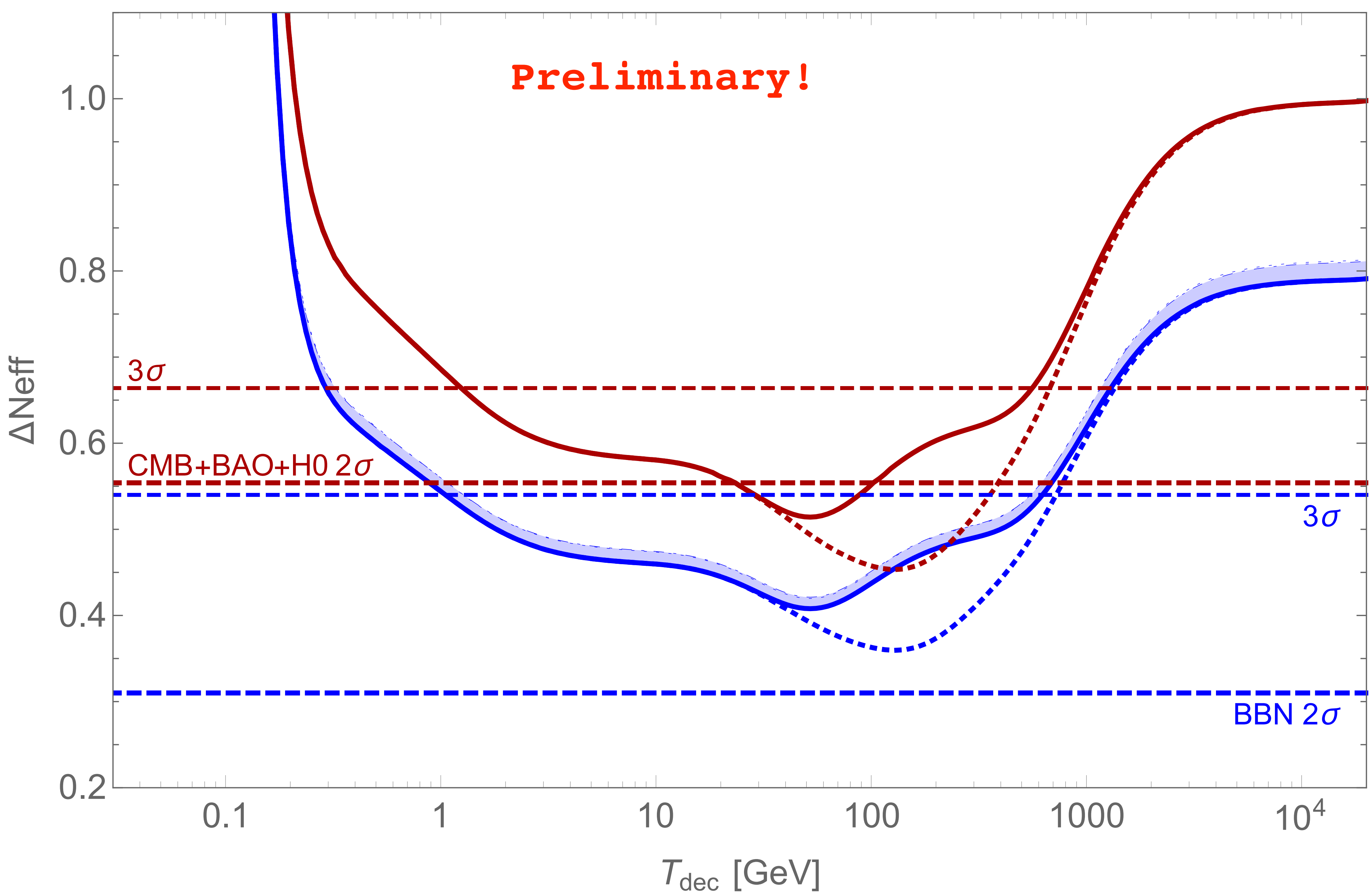
$$\frac{\Omega \chi}{\Omega_B} = 5.3$$

$g' \leq 0.002$, so neutron star constraints limit $m_{A'} \leq 100$ keV

$A' \to \bar{\nu}'\nu'$

$A' \to 3\gamma$ is constrained, so we add dark neutrinos for A' to decay into. There is also a dark Higgs.

CMB and *BBN* constraints on ΔN_{eff}



ΔN_{eff} at time of BBN ΔN_{eff} at recombination $m_{A'}$ = 60 keV m_ϕ = 60 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.
- This setup also allows for an asymmetry in the dark sector to be transferred to the visible sector, explaining the baryon asymmetry of the universe.

Backups

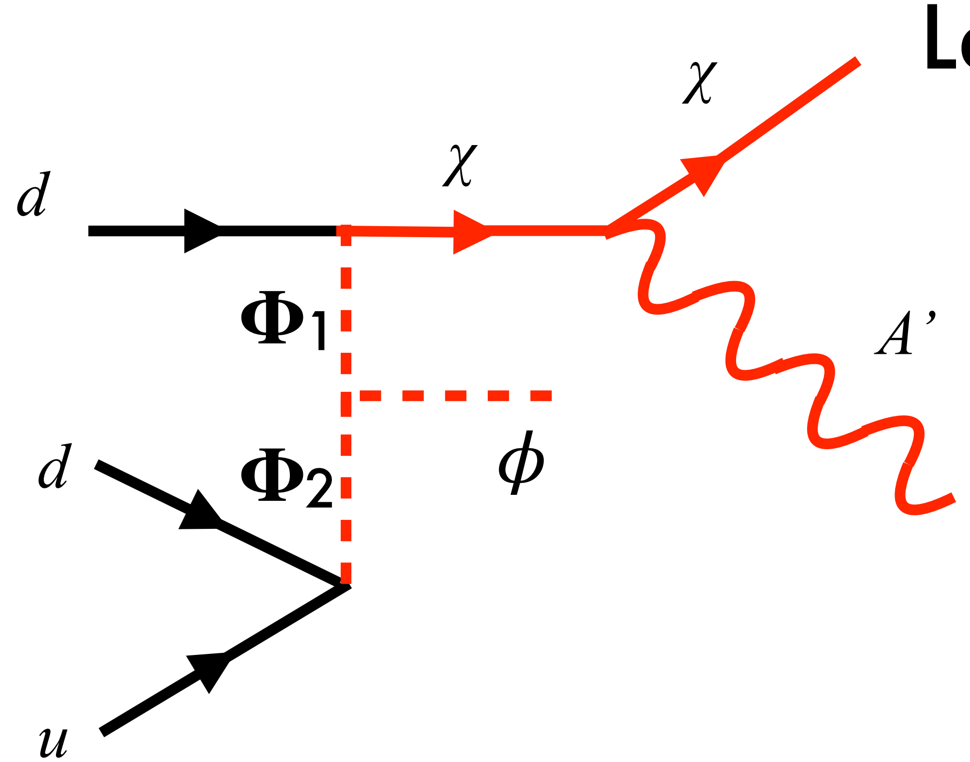
UV Model

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

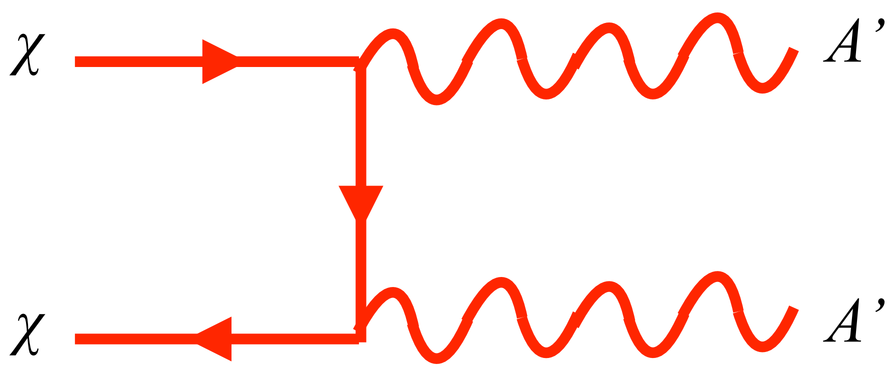
Masses:

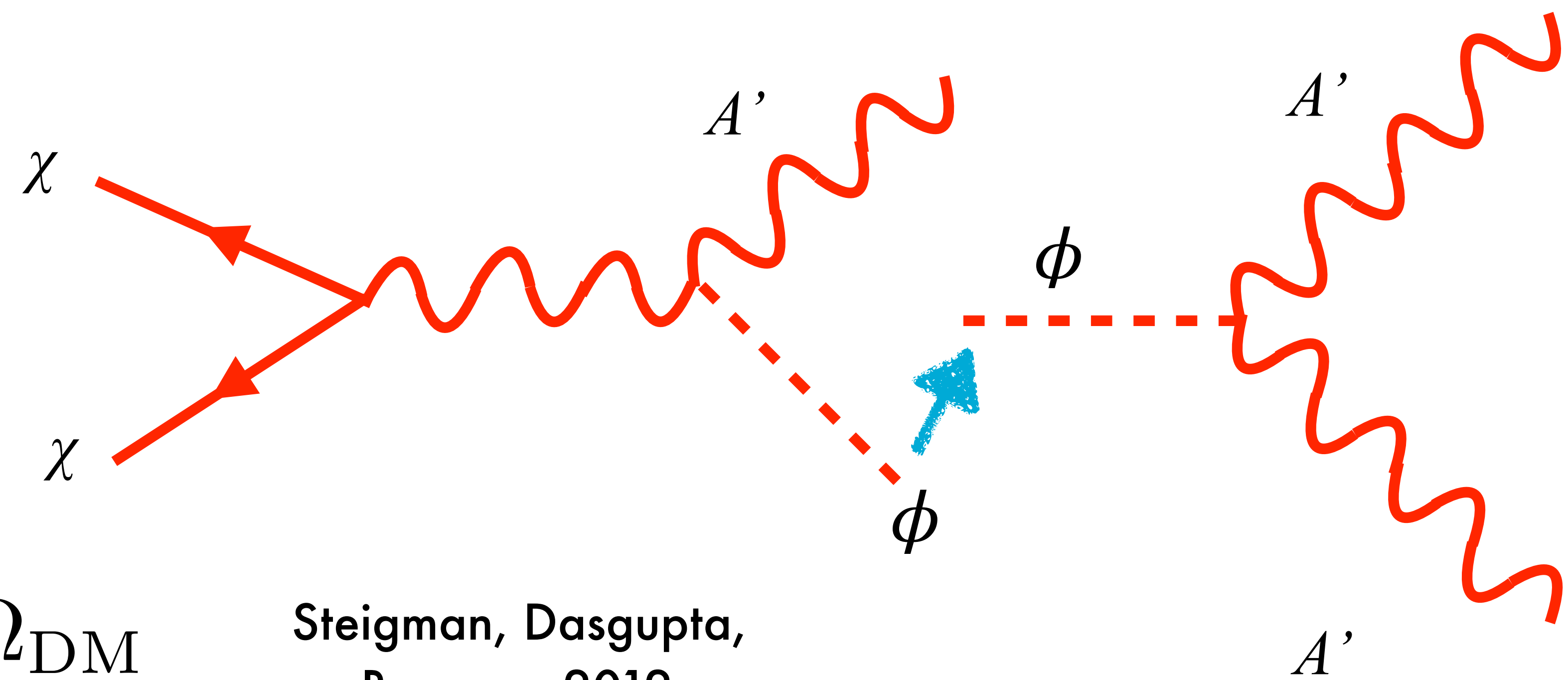
- m_Φ > 1.5 TeV to avoid LHC limits on colored scalars ATLAS, 2107
- m_ϕ = 70 MeV (benchmark value) to avoid $n \to \phi\chi$ decays

Relic Density of Dark Matter and Dark Radiation

For symmetric DM, we assume standard thermal freeze out.

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.

$m_{A'}$ = 1.35 MeV

$\tau_{A'}$ < 540 s

Cirelli, et al., 2016

Hufnagel, Schmidt-Hoberg, Wild, 2018