Freeze-in, Misalignment, and Non-Standard Thermal Histories

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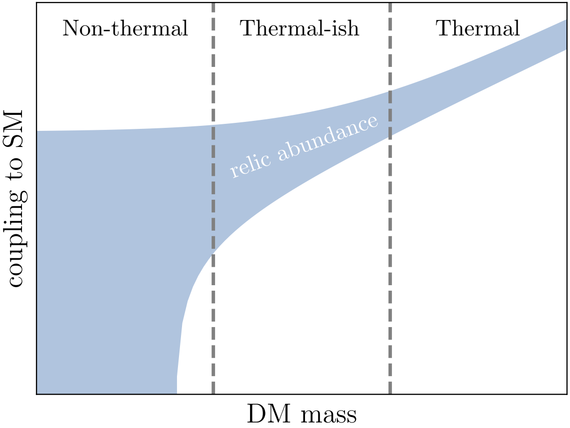
Fermilab

Outline


Non-thermal
Thermal-ish
Thermal
relic abundance
coupling to SM
DM mass

Thermal Equilibrium

- Interactions probed by DD lead to SM $\leftrightarrow$ DM energy transfer

- Qualitatively different cosmo/astro if DM/mediator efficiently produced in thermal environments

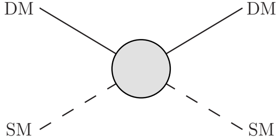
  Green and Rajendran (2017)

  Knapen, Lin and Zurek (2017)

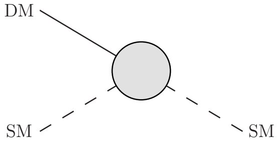
- DM/mediator attains equilibrium at some point if

$$\Gamma/H > 1$$

Scattering



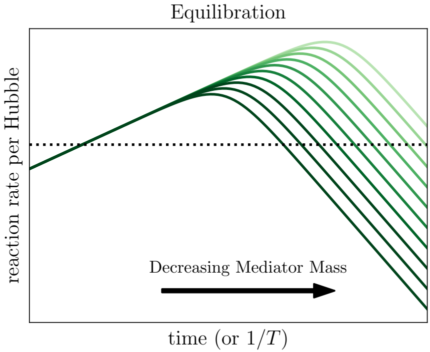
Emission/Absorption

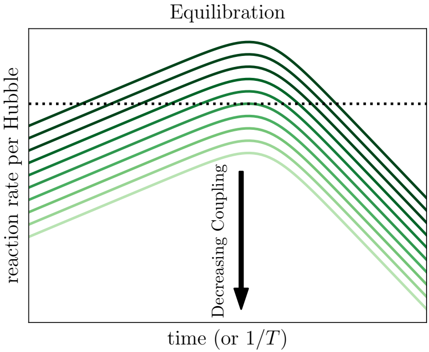


Cosmology with Light Particles

Reaction rates at finite temperature have the form

$$\Gamma/H \propto \begin{cases} \lambda^2/T^n & \text{light mediator} \\ \lambda^2\, T^n/m^4 & \text{heavy mediator} \end{cases}$$

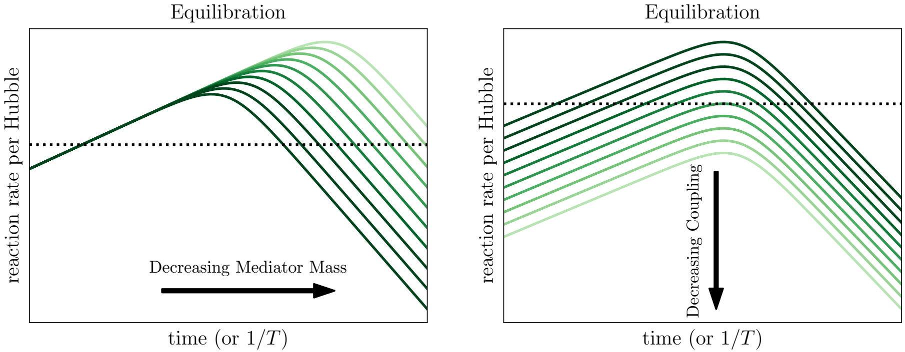




Cosmology with Light Particles

If equilibrium attained before BBN (i.e. at $T \gtrsim 5\ \mathrm{MeV}$) and $m \lesssim 10\ \mathrm{MeV}$:

- $\rho_\chi \sim \rho_\gamma$ modifies the expansion rate
- Heat injection from decay/freeze-out dilutes T_ν/T_γ, baryon density η_b



Constraints from BBN

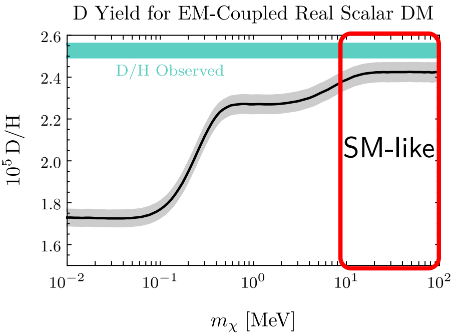
- Primordial ^{4}He and D yields measured precisely ($\lesssim 2\%$)

  Aver, Olive & Skillman (2013); Cooke, Pettini & Steidel (2017)

- These are in $\sim 1\sigma$ agreement with standard BBN

- Light thermal DM particles can modify
  1. Expansion rate: $N_{\text{eff}} \propto (T_\nu / T_\gamma)^4$
  2. Baryon density η_b

  see, e.g., Nollett and Steigman (2013)



Success of standard BBN ⇒ thermal, EM-coupled relics have $m \gtrsim$ few MeV

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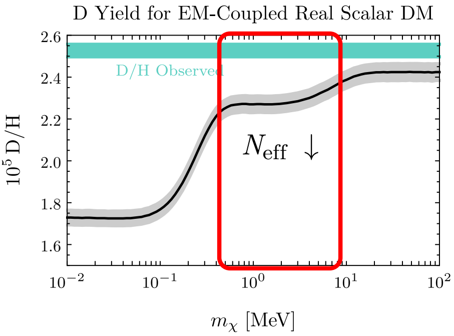

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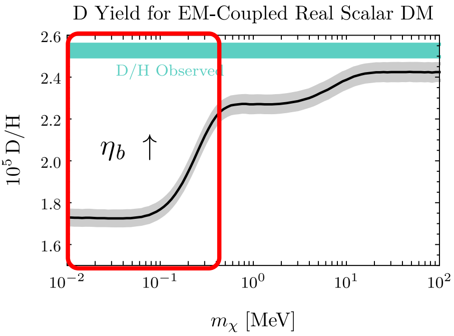

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Constraints from the CMB

CMB sensitive to energy density in free-streaming species ($N_{\rm eff}$)

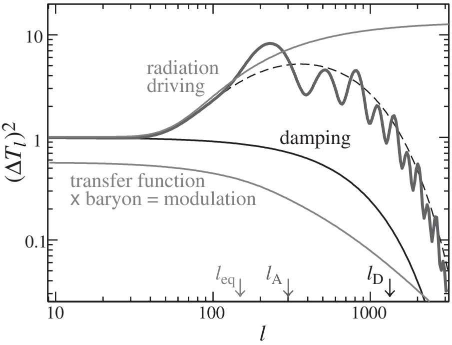
- Photon diffusion exponentially damps density perturbations for

$$\ell \gtrsim \ell_D \sim \sqrt{\frac{n_e \sigma_T}{H}} \ell_A$$

- Planck constraint on $N_{\rm eff}$ translates into

$$m_\chi \gtrsim \text{few MeV}^*$$

EM-coupled scalar. * Extra "dark radiation" can off-set $N_{\rm eff}$ decrease and weaken CMB and BBN bounds.



Hu, Fukugita, Zaldarriaga and Tegmark (2001)

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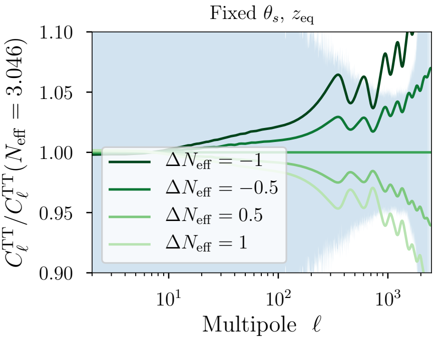


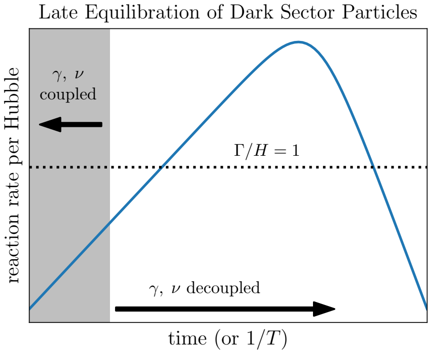
Bashinsky and Seljak (2004), Hou et al (2011)

Late equilibration

Do the CMB+BBN constraints imply that DM with $m \lesssim$ few MeV cannot be thermal?

If equilibration occurs after neutrino-photon decoupling ($T \sim 2$ MeV),

- Energy conservation ensures $N_{\rm eff}$ is close to SM value
- Thermal neurtrino-coupled relics avoid BBN + CMB bounds
- EM-coupled relics still constrained by BBN (large modifications of η_b)

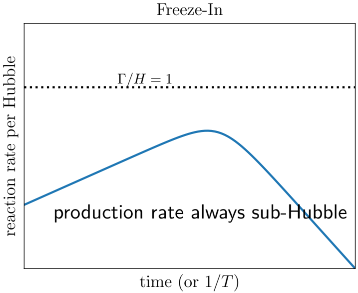


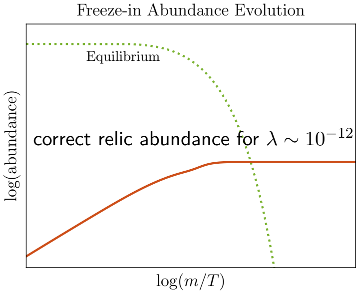
Bartlett & Hall (1991); Chacko *et al* (2003, 2004); Berlin & NB (2017); Berlin, NB & Li (2019)

Freeze-in

- Equilibrium never achieved, density builds up gradually
- Generic and predicive, but hidden assumption: initial abundance tiny

  $\Rightarrow$ non-trivial constraint on cosmology, see Adshead, Cui & Shelton (2016)
- DD-accessible models feature light $m_\phi < \alpha m_e$ mediator





Dodelson and Widrow (1993); Hall, Jedamzik, March-Russell and West (2009)

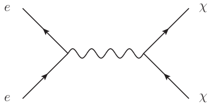
Freeze-in Through Dark Photon/Millicharge Portal

- Mediators other than (dark) photon too constrained

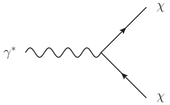
$$\mathscr{L} \supset eQ_\chi \bar{\chi}\gamma_\mu \chi A^\mu, \quad Q_\chi \ll 1$$

- Arises as fundamental millicharge or via A'-γ mixing
- Plasmon decay contribution previously missed; lowers preferred coupling by a factor of $\gtrsim 3$ for

Annihilation



Plasmon decay



Dvorkin, Lin and Schutz (2019)

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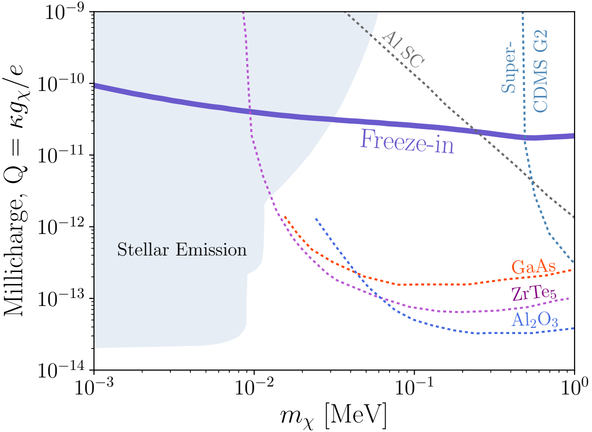


Dvorkin, Lin and Schutz (2019)

Additional Constraints

DM still produced from thermal SM particles $\Rightarrow$ additional constraints

- BSM cooling mechanisms change distribution of stars

  Brighter Red Giants (later $^4\mathrm{He}$ ignition), fewer Horizontal Branch stars (faster $^4\mathrm{He}$ burn)

  Raffelt (1996)$++$; Hardy and Lasenby (2016)

- For $m \lesssim 100\ \mathrm{keV}$, these forbid thermal contact and put severe constraints on detectable models

  Green and Rajendran (2017) , Knapen, Lin and Zurek (2017)

- Frozen-in DM is produced with $v_\chi \lesssim 1$ (similar to warm DM)

$$m_\chi \gtrsim 20\ \mathrm{keV}$$

Dvorkin, Lin and Schutz (In progress)

Fully non-thermal production mechanisms are required for $m_\chi \lesssim 100\ \mathrm{keV}$

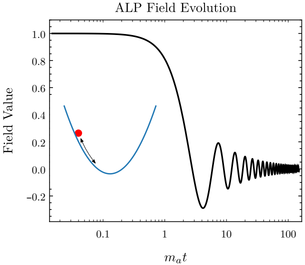
Misalignment

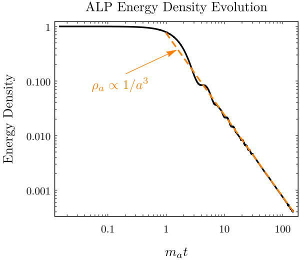
- Generic mechanism for light bosonic DM, a (axions, ALPs, moduli,...)
- Scalar displaced from the origin of its potential with $a_i = \theta_0 f_a$
- Oscillations about origin begin when

$$m_a \sim H$$

- Energy density redshifts as matter:

$$\rho_a \propto 1/a^3$$



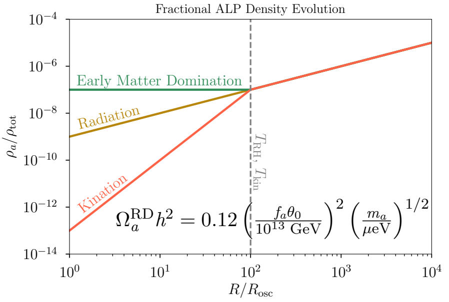


Sensitivity to Early Cosmology

- Final abundance depends on evolution of the total energy density
- Evolution before nucleosynthesis $T \gtrsim 5\,\mathrm{MeV}$ unknown:

$$\rho_{\text{tot}} \propto \begin{cases} a^{-4} & \text{radiation} \\ a^{-3} & \text{matter} \\ a^{-6} & \text{kination} \end{cases}$$

- correct abundance obtained for different values of m_a, f_a depending on cosmology



Visinelli & Gondolo (2009)+
NB, Dolan, Draper & Kozaczuk (2019)

Smaller $f_a \Rightarrow$ larger coupling to SM $g_{a\gamma\gamma} \propto 1/f_a$

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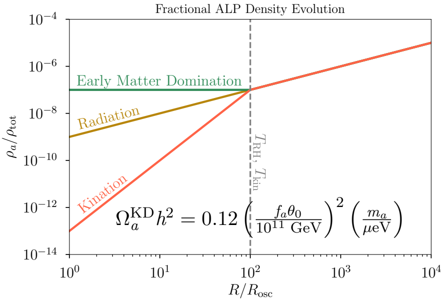

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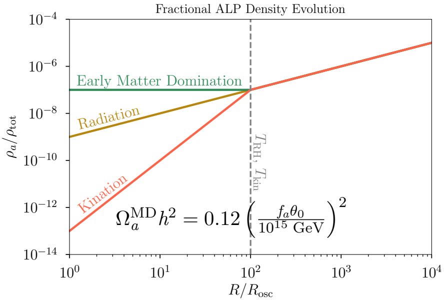

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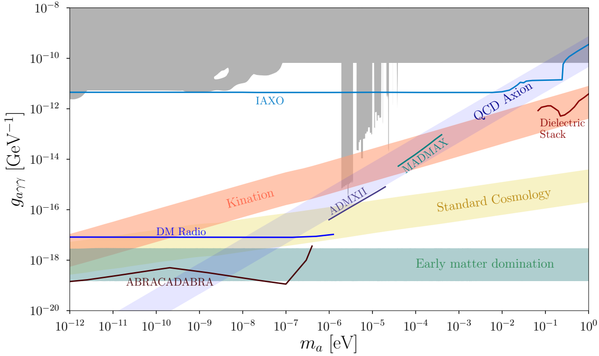
Plentitude of Targets for ALP Searches

Since $g_{a\gamma\gamma} \propto 1/f_a$, kination (early matter domination) easier (harder)



NB, Dolan, Draper & Kozaczuk (2019)

Non-cosmological modifications can lead to easier-to-reach targets

Farina *et al* (2017); Agrawal *et al* (2017)

Dark Photon Dark Matter

- In the simplest models, misalignment does not work:

$$\rho_{A'}(t) \sim m_{A'}^2 g_{\mu\nu} A^\mu A^\nu \propto \exp(-2Ht) \text{ during inflation}$$

- Inlfationary fluctuations produce A'; correct relic abundance is obtained for

$$m_{A'} = 5 \times 10^{-8}\ \mathrm{eV} \times \left(\frac{3 \times 10^{14}\ \mathrm{GeV}}{H_I} \right)^4$$

Graham, Mardon and Rajendran (2016), Planck (2018)

- Planck bounds H_I: A' with smaller masses must be produced via other mechanisms

Other Contributions to Relic Abundance

- Misalignment with a non-minimal coupling to gravity

  Arias et al (2012); Alonso-Alvarez, Hugle Jaeckel (2019);...

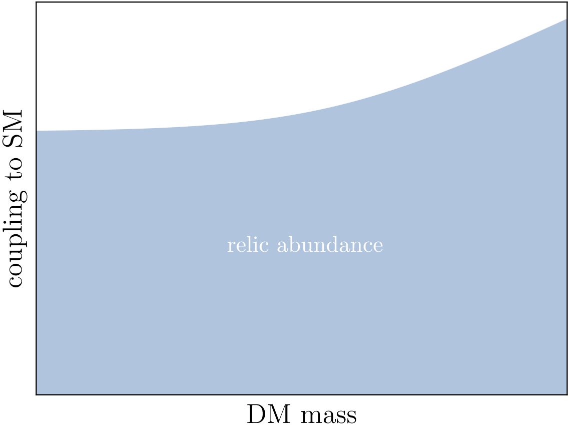
- "Decays" of other relics into light A'

  e.g. Co et al (2018)$++$; Long and Wang (2019)

- Entropy dumps or a little inflation can solve overproduction issues

  e.g., Gelmini et al (2011); Hooper (2013); Davoudiasl, Hooper and McDermott (2015)$+$

Other Contributions to Relic Abundance



DM Substructure in Non-Thermal Cosmology

Are non-thermal models distinguishable in principle?

- Non-thermally produced DM can feature enhanced sub-structure
- Early matter domination and kination have a period of early perturbation growth

Erickcek & Sigurdson (2011); Redmond, Trezza & Erickcek (2018);Visinelli & Redondo (2019)

- Inflationary production of dark photons makes clumps with a characteristic size

Graham, Mardon and Rajendran (2016), Planck (2018)

- DM clumps enhance or worsen DD prospects

Higher ρ_{cdm}, but less frequent encounters

- Can be searched for in astrophysical data

Gaia: Van Tilburg, Taki & Weiner (2018); Pulsar timing: Dror *et al* (2019)

Conclusion

- Detectable light DM constrained by cosmo and astro

  Couplings bounded so DM is not in thermal equilibrium with SM

- Non-thermal production inherently less predictive than thermal

  Larger range of couplings compatible with relic abundance

- Non-thermal production sensitive to *early* universe cosmology

  A new window into pre-nucleosynthesis universe?

- Several high-value targets accessible to direct detection

Thank you!

Backup

Cosmic Expansion

Expansion determined by energy content via Friedmann equation:

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3M_{\rm Pl}^2}\left(\rho_\gamma + \rho_\nu + \rho_X\right), \quad \rho_i \sim T_i^4$$

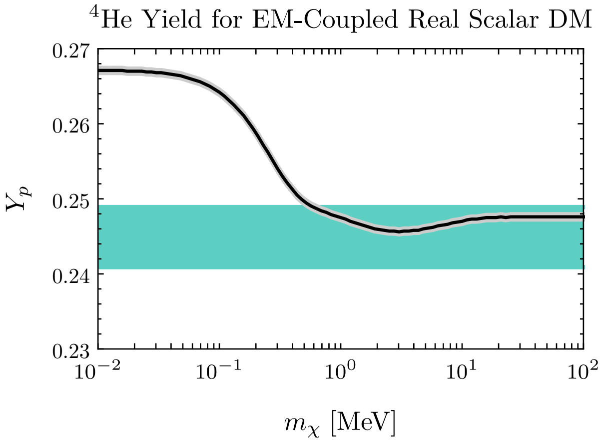
The total energy density is often parametrized as

$$\rho_{\rm tot} = \rho_\gamma\left[1 + cN_{\rm eff}(T)\right], \quad N_{\rm eff} = \frac{1}{c}\left(\frac{\rho_\nu + \rho_X}{\rho_\gamma}\right)$$

In the SM, $N_{\rm eff} \approx N_\nu = 3$ at late times ($T < m_e$).

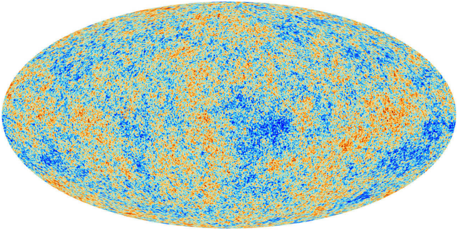
Beyond SM, $N_{\rm eff}$ is modified through T_ν / T_γ or additional d.o.f's

^{4}He Yield

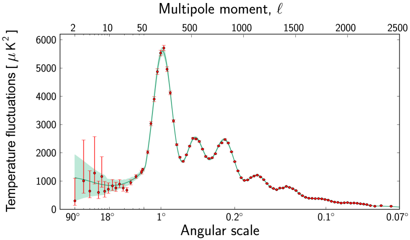


^{4}He Yield for EM-Coupled Real Scalar DM
0.27
0.26
0.25
0.24
0.23
Y_p
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
m_χ [MeV]

Cosmic Microwave Background



$$\delta T = T - T_{\mathrm{CMB}}$$



$$\langle \frac{\delta T}{T}(\hat{p}_1)\frac{\delta T}{T}(\hat{p}_2)\rangle$$

Planck (2015)/esa.int

N_{eff} During CMB: Damping Tail

Photons diffuse out of hot (overdense) regions

$$\lambda_D \sim \sqrt{N(t)}\lambda_{\text{mfp}}$$

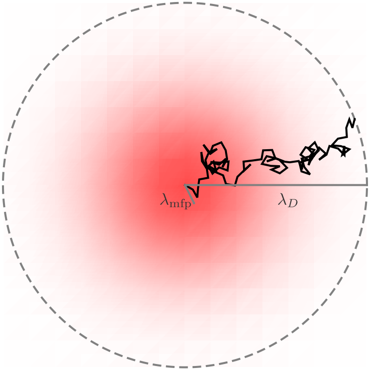
N collisions with free e^-:
$\lambda_{\text{mfp}} \sim 1/n_e\sigma_T$, $N \approx 1/(\lambda_{\text{mfp}}H)$,

$$\lambda_D \sim 1/\sqrt{Hn_e\sigma_T}$$

Perturbations of size $< \lambda_D$ washed out

Note: degeneracy with

$$n_e = n_p^{\text{free}} \propto \rho_b(1 - Y_p)$$



N_{eff} During CMB: Damping Tail

$$\lambda_D \sim 1/\sqrt{H n_e \sigma_T}$$

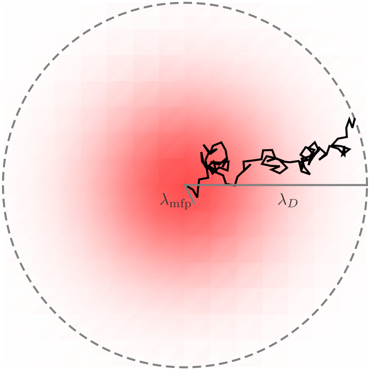
$N_{\text{eff}} \uparrow \Rightarrow \lambda_D \downarrow$
However, only angular scales observed:

$$\theta_D = \lambda_D / D_A,$$

D_A obtained from angular scale of sound horizon

$$\theta_s \sim \frac{1/H}{D_A}$$

θ_s measured precisely from position of 1st peak



$N_{\rm eff}$ During CMB: Damping Tail

θ_s measurement determines $D_A \sim 1/H$, so

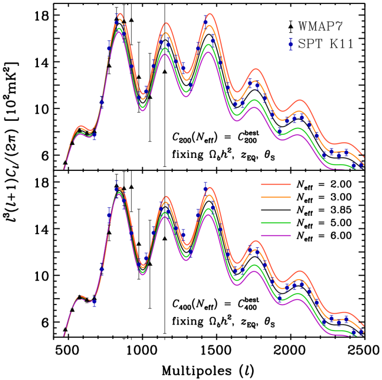
$$\theta_D = \sqrt{H/n_e \sigma_T},$$

$\therefore$ θ_D grows with $N_{\rm eff}$, even though $\lambda_D \downarrow$

As $N_{\rm eff} \uparrow$, more damping at small scales

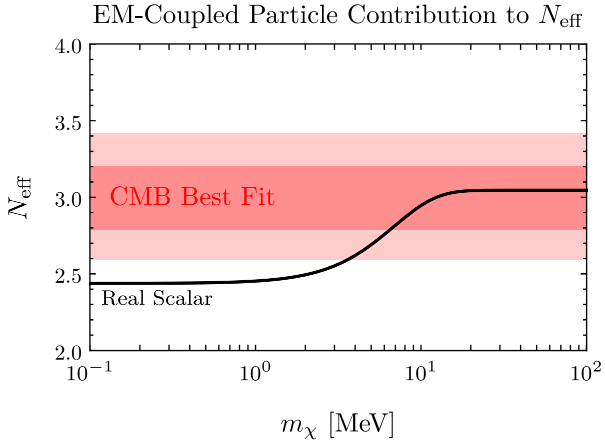
Note: degeneracy with

$$n_e = n_p^{\rm free} \propto \rho_b (1 - Y_p)$$



Bashinsky and Seljak (2004), Hou et al (2011)

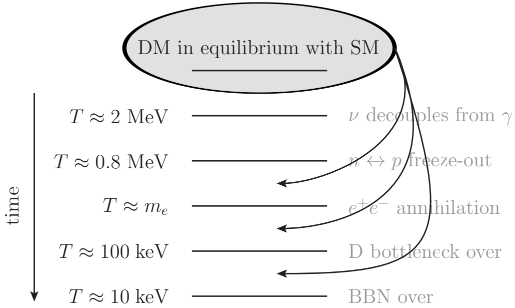
CMB Constraints



Late Equilibration with Neutrinos (I)

What if dark sector equilibrates after neutrinos and photons have already decoupled?

After $T \approx 2$ MeV, γ and ν evolve independently



Equilibration of DS and ν conserves total energy

Late Equilibration with Neutrinos (II)

Equilibration of DS and ν conserves total energy

$$d(U_{\rm ds} + U_\nu) + (p_\nu + p_{\rm ds})dV = dQ + (-dQ) = 0$$

$$\Rightarrow (\rho_\nu + \rho_{\rm ds})/\rho_\gamma = \text{const.} \quad \Rightarrow \quad \Delta N_{\rm eff} = 0!$$

Lower T_ν compensates for new d.o.f. s.t. $N_{\rm eff}$ is unchanged!

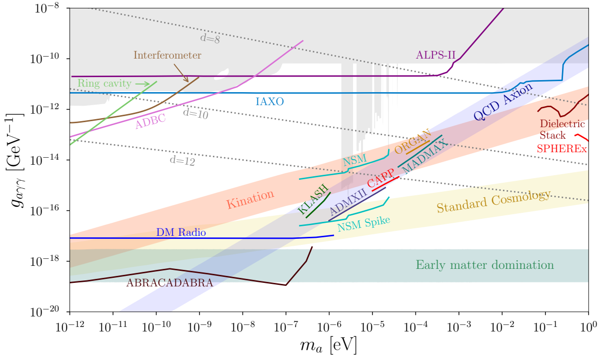
$N_{\rm eff}$ does change when DS states go non-relativistic, heating neutrinos

$$N_{\rm eff} \approx 3\left(1+\frac{g_X}{g_\nu}\right)^{4/3} \underbrace{\left(1+\frac{g_X}{g_\nu}\right)^{-1}}_{\propto (T_\nu/T)^4 \text{ before f.o.}} \gtrsim 3.18 \text{ for } g_X \geq 1,$$

Late equilibration significantly reduces modification to $N_{\rm eff}$

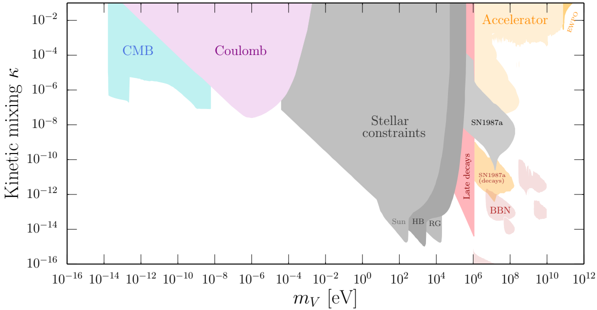
Bartlett and Hall (1991), Chacko et al (2003, 2004), Berlin and NB (2017)

Targets for ALP Searches



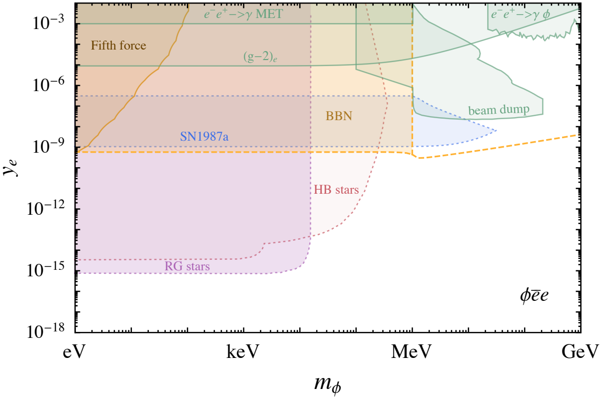
NB, Dolan, Draper & Kozaczuk (2019)

Constraints on Light Mediators: Dark Photon



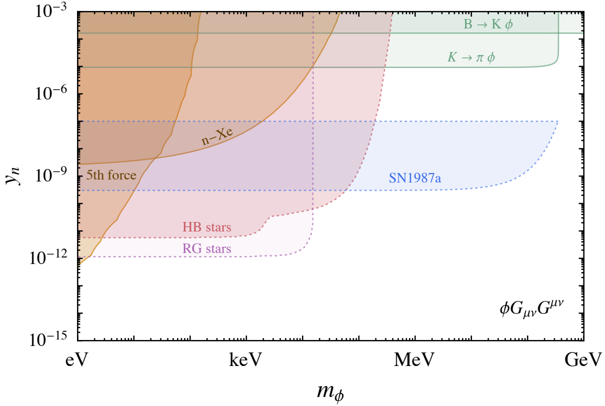
Lin (2019)

Constraints on Light Mediators: e^--coupled Scalar



Knapen, Lin and Zurek (2017)

Constraints on Light Mediators: g-coupled Scalar



Knapen, Lin and Zurek (2017)