Title: Light Hidden Sectors and the Hubble Tension

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Series: Particle Physics

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Abstract: The inference of the present expansion rate from the Cosmic Microwave Background and other early-time probes (assuming standard cosmology) is in significant tension with several direct measurements of the same quantity. If this discrepancy is not due to unresolved systematics, it could provide strong evidence for physics beyond the standard models of particle physics and cosmology. I will describe a few simple models that attempt to alleviate this Hubble tension. All of these scenarios contain additional energy density of new light particles at early times with interactions that modify the background cosmology and evolution of density perturbations in the early universe. First, I will motivate the existence of a decaying component of dark matter with a significant free-streaming length as a means of addressing this tension. Then I will consider models with self-interacting neutrino or dark radiation components. I will show that such scenarios face stringent cosmological and laboratory constraints. As a result, in these examples, the tension can be alleviated but not eliminated altogether.

Light Hidden Sectors and the Hubble Tension

Nikita Blinov

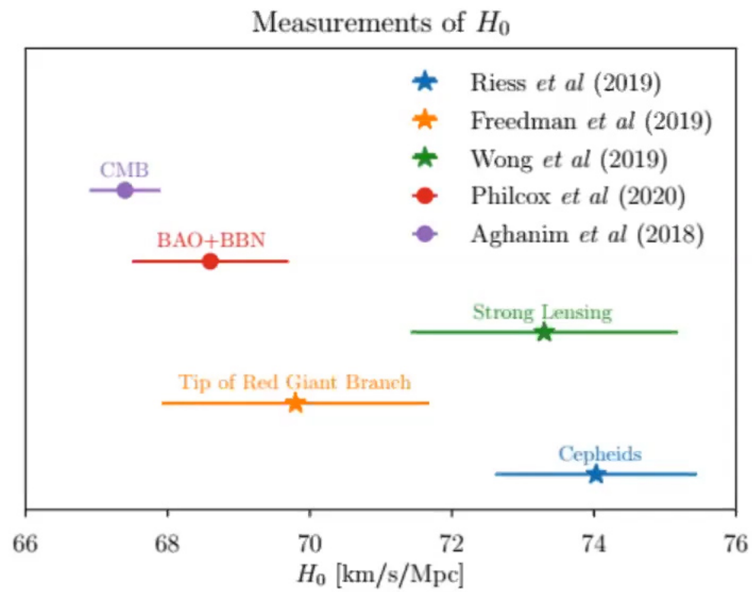
June 9, 2020

Perimeter Institute

Based on work with: Keith & Hooper (2004.06114); Marques -Tavares (2003.08387); Kelly, Krnjaic & McDermott (1905.02727)

The Tension

Long standing disagreement between direct ("local") measurements of H_0 and early-time inferences



See Raphael Flauger's Feb. 28 KITP seminar & Silvia Galli's EuCAPT May 5 colloquium & Verde, Treu & Riess (2019)

Hubble from the CMB and BAO

H_0 is ***inferred*** from the angular scale of CMB fluctuations $\theta_s \sim r_s / D_A$ where

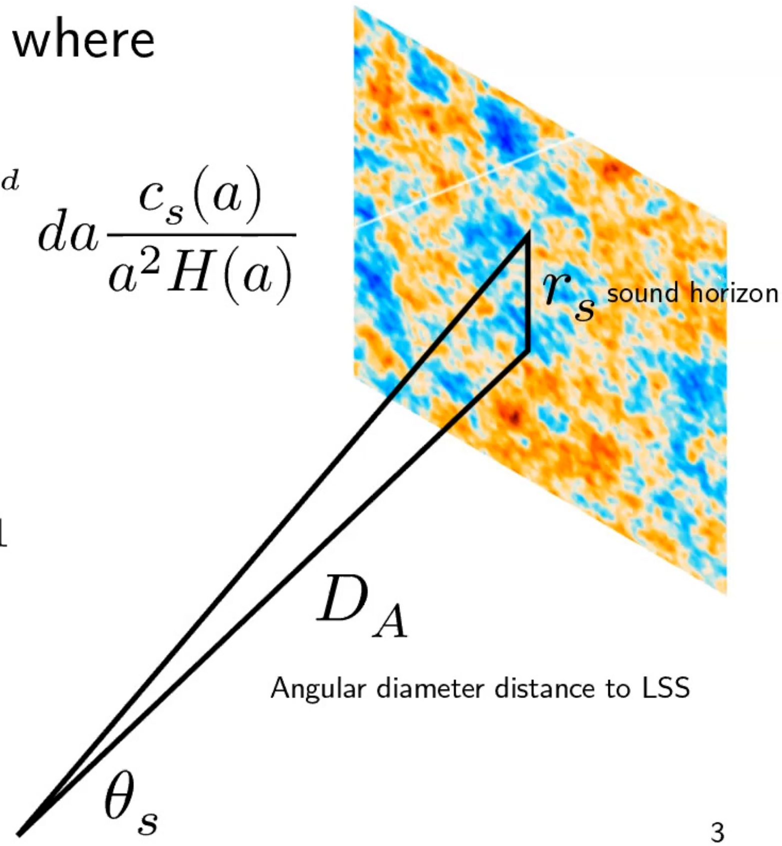
$$r_s = \int_0^{t_d} \frac{dt}{a(t)} c_s(a) = \int_0^{a_d} da \frac{c_s(a)}{a^2 H(a)}$$

Early time quantity

$$D_A = \int_{a_d}^{1} \frac{da}{a^2 H(a)} \propto H_0^{-1}$$

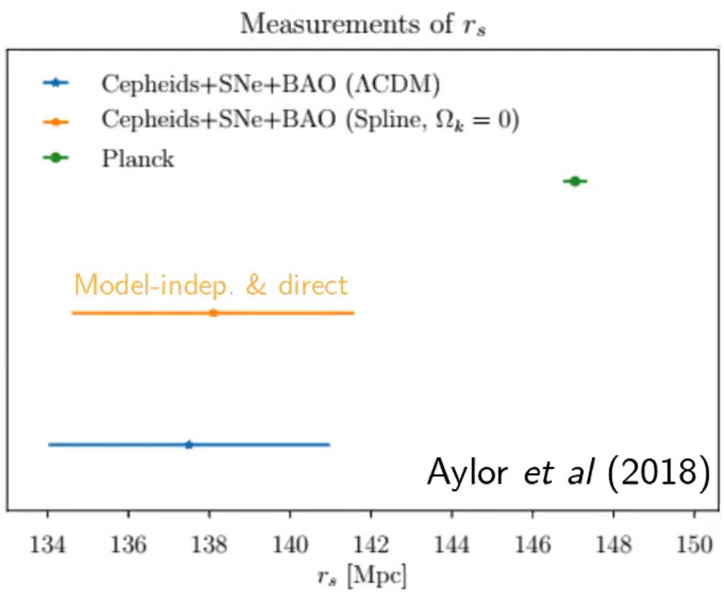
Late-time quantity

$$H_0 \propto \theta_s / r_s$$



Sound Horizon Tension

The tension can be phrased in terms of r_s



Need

$$\frac{\delta r_s}{r_s} \approx 7\%$$

Since r_s is an early-time quantity, cosmological solutions should operate **before** recombination*

*for careful discussions, see Aylor *et al* (2018), Knox & Millea (2019), Arendse *et al* (2019)

Connection to Particle Physics

- Sound horizon probes the contents of the universe before recombination

sensitivity to BSM contributions

- CMB shape depends on evolution of perturbations in cosmological fluids

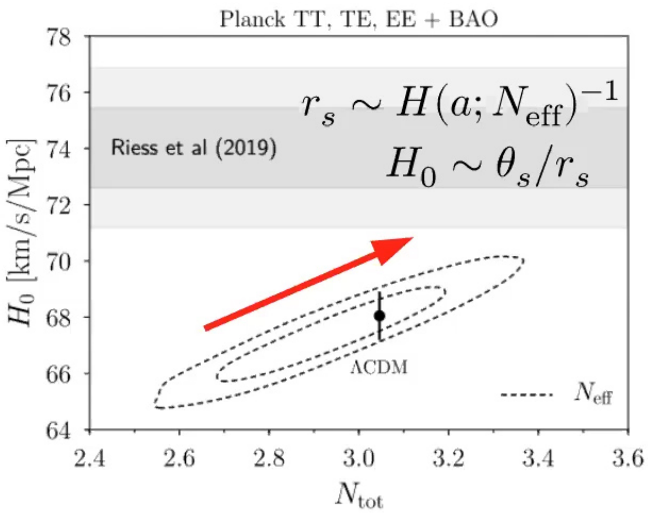
sensitivity to new interactions of SM particles or within dark sector

Extra Radiation

- Simplest BSM way to reduce sound horizon: non-interacting radiation/relativistic species

$$\rho_{\rm rad} = \rho_\gamma \left[1 + \frac{7}{8} N_{\rm eff} \left(\frac{4}{11}\right)^{4/3}\right]$$

- $N_{\rm eff} = 3$ in SM, $N_{\rm eff} > 3$ with dark radiation



$$\Delta\chi^2 = (\chi^2_{N_{\rm eff}} - \chi^2_{\Lambda{\rm CDM}})_{\rm min}$$

Data Set	$N_{\rm eff}$	
TTTEEE	+2.68	Worse fit to CMB tail
low-ℓ TT	−0.63	
low-ℓ EE	+0.09	
lensing	+0.17	
BAO	+0.39	
H_0	−4.99	Better fit to local H_0

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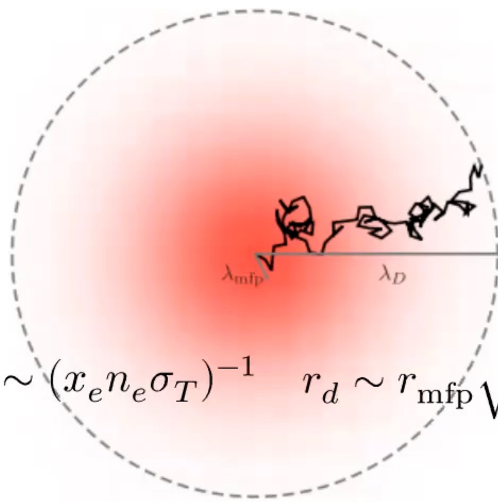
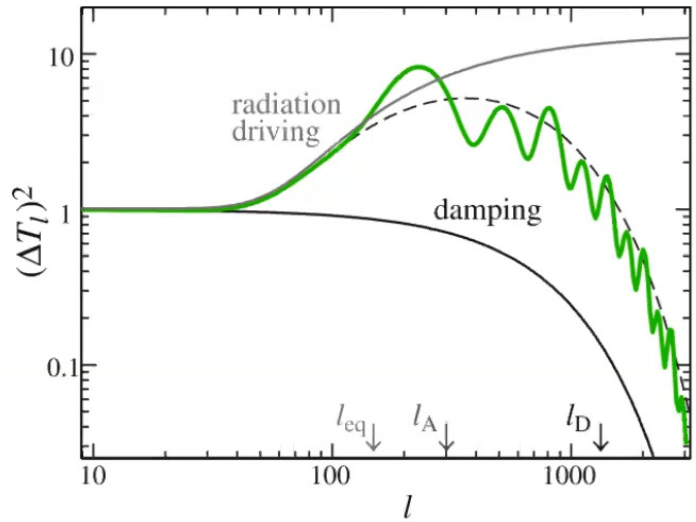
Photon Diffusion Damping



$$r_{\rm mfp} \sim (x_e n_e \sigma_T)^{-1} \qquad r_d \sim r_{\rm mfp}\sqrt{t/r_{\rm mfp}}$$

Hu, Fukugita, Zaldarriaga & Tegmark (2000)

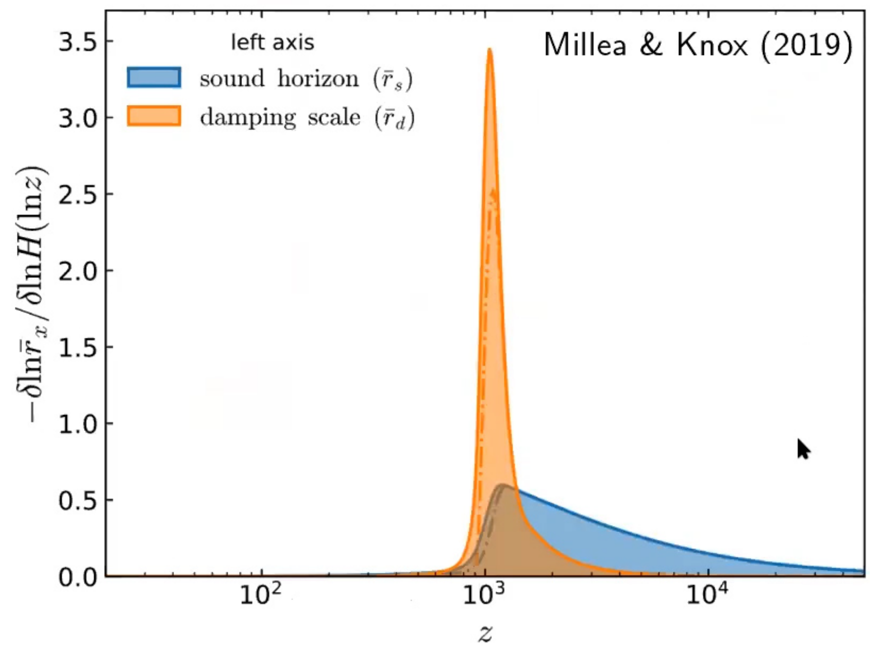


$$r_d^2 \sim \int_0^{a_d} \frac{da}{a^3 x_e n_e H(a) \sigma_T}$$

Precise measurements at large ℓ preclude large modifications to $r_{\rm d}$

Dependence on Expansion History

How do you shrink r_s without changing r_d/r_s?



BSM solution likely to have non-trivial time-dependence to fix r_s/r_d

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Checklist for a BSM Explanation

- Extra energy density at early times

  reduces r_s

- Non-trivial time evolution

  keeps r_d/r_s from changing too much

Caveat: these are background cosmology effects; perturbations also important

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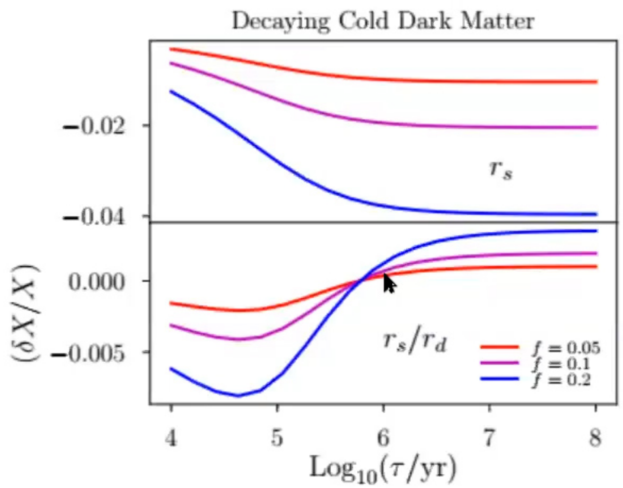
Decaying Cold Dark Matter (DCDM)

- Simplest possibility to realize time-dependent energy injection
- Fraction f of CDM decays into dark radiation with decay rate τ^{-1}

Allows a decrease of r_s without changing r_s/r_d



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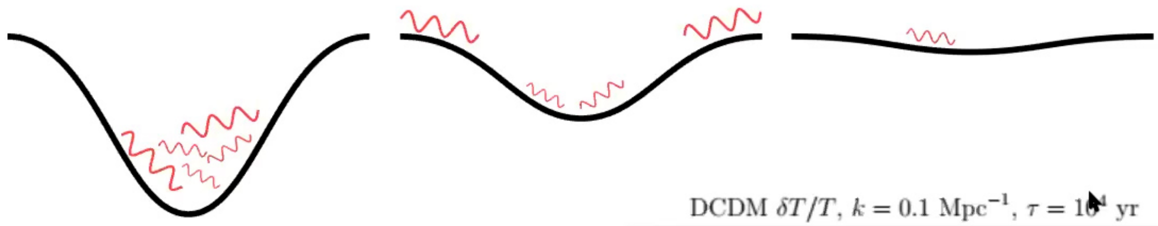
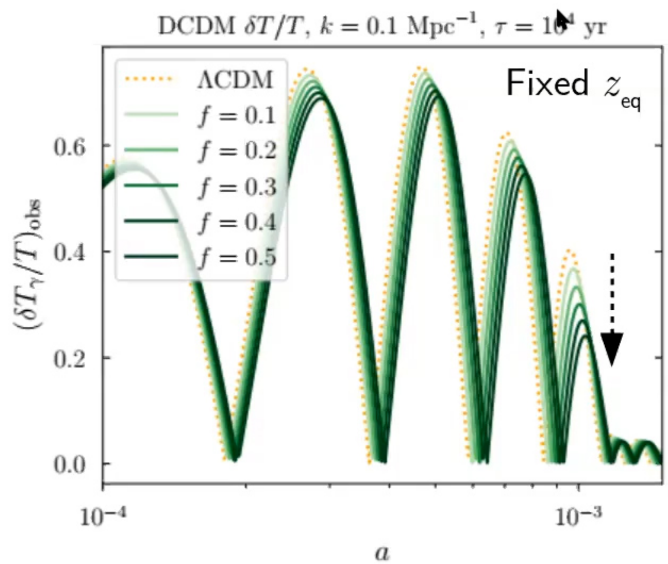
Impact of DCDM

- Gravitational potentials evolve during radiation domination



Additional matter before recombination modifies evolution of gravitational potentials

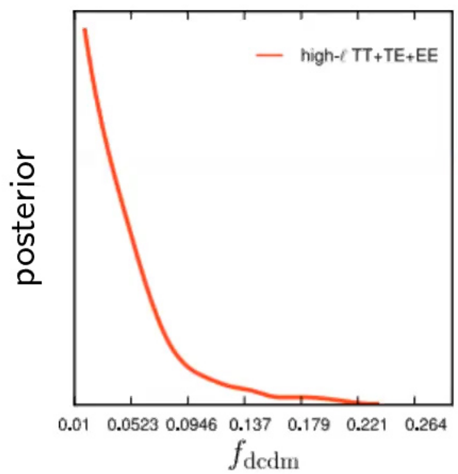


Evolution of photon temp. fluctuations

Constraints on DCDM

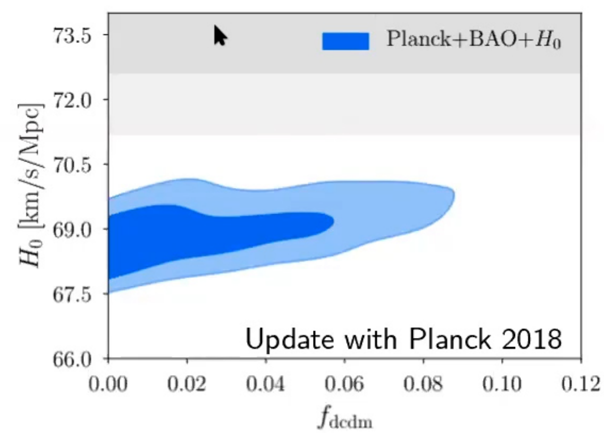
CMB data disfavours a DCDM contribution large enough to "fix" H_0

$\tau < 10^6$ years



Fraction of decaying DM

Poulin, Lesgourges & Serpico (2016)



Warm Decaying Dark Matter

Decaying Warm Dark Matter (DWDM)

Strong constraints on D**C**DM follow from its gravitational impact at early times

- Consider a decaying component that does not cluster the same as matter.
- Simplest possibility: a particle with a non-zero free-streaming length

$$\lambda_{\rm fs} = \int_0^{t_{\rm nr}} \frac{dt}{a(t)} \approx 30 \ {\rm Mpc} \left(\frac{T_x}{T}\right) \left(\frac{10 \ {\rm eV}}{m_x}\right)$$

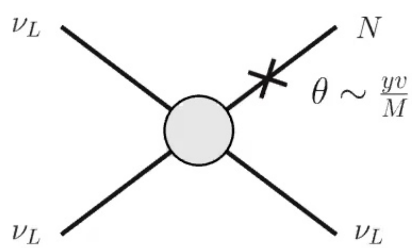
does not cluster on scales below $\lambda_{\rm fs}$

A DWDM Example

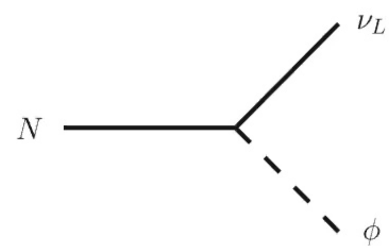
- E.g. Sterile neutrino with mass $\mathcal{O}(10\ \mathrm{eV})$

$$\mathcal{L} \supset -yLHN + \frac{1}{2}(M + \lambda\phi)NN + \mathrm{h.c.}$$

production



decay



Dodelson & Widrow (1993)

Production from SM bath gives quasi-thermal distribution with

$$T_x \approx T_\nu \quad \text{but} \quad \rho_N/\rho_\nu \approx 0.2\left(\frac{M}{10\ \mathrm{eV}}\right)\left(\frac{\theta}{3\times 10^{-3}}\right)^2$$

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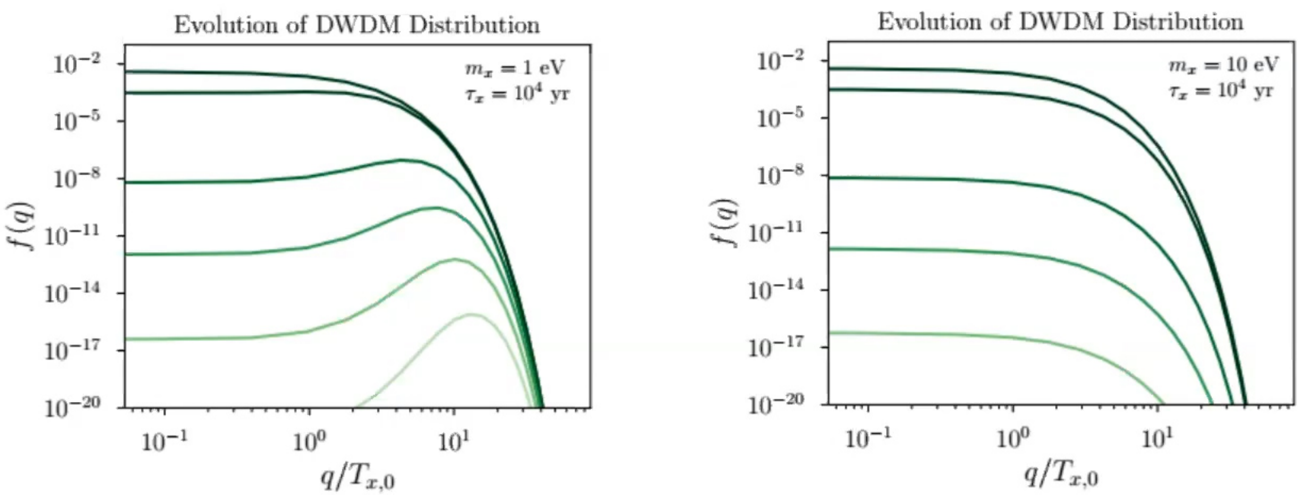
Cosmological Evolution (Background)

- Different regions of phase space decay at different times

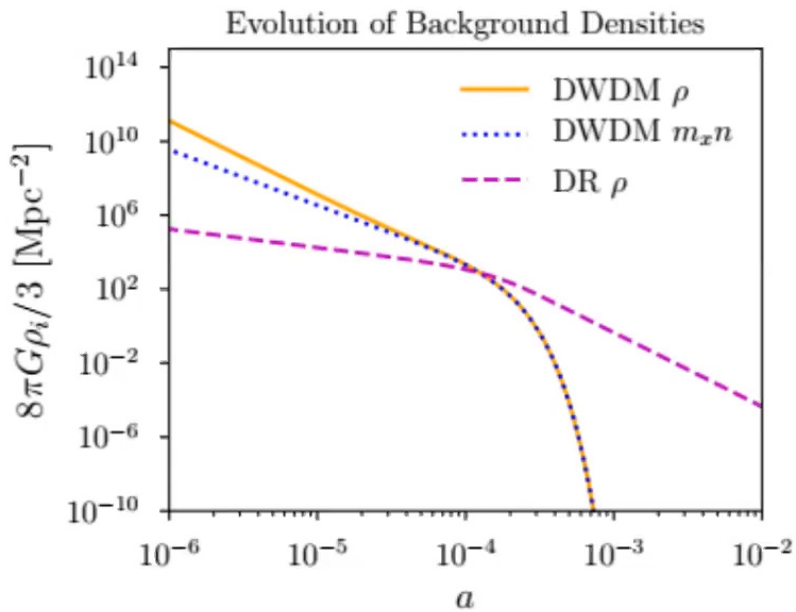
$$\frac{\partial f}{\partial t} - H\frac{p^2}{E}\frac{\partial f}{\partial E} = -\frac{1}{E}m_x\Gamma_x f(E)$$



Keith, NB, Hooper (2020) 16

Evolution of Densities

Phase space distribution integrated to find background energy, number, pressure densities



Early times

$\rho \propto a^{-4}, \quad n \propto a^{-3}$

When non-relativistic

$\rho = mn$

Amount of radiation at early times (constrained by BBN) different from late times

Cosmological Evolution (Perturbations)

- CMB sensitive to perturbations in phase space distribution

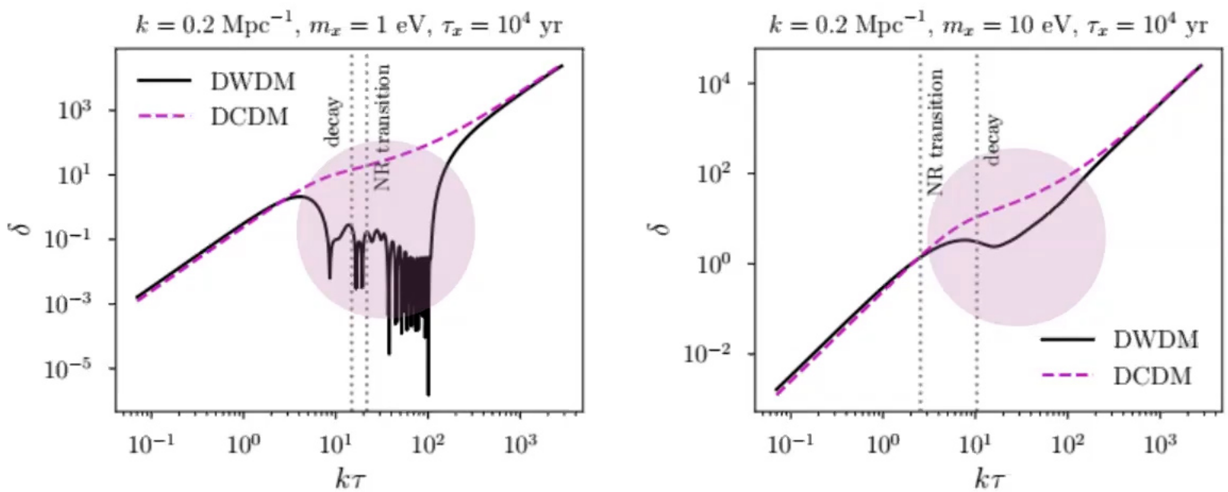
$$f = f^{(0)}(q)\left[1 + \Psi(\vec{q}, \vec{x}, t)\right]$$

- Perturbations in, e.g., energy density

$$\delta\rho \propto \int q^2 dq E(q) f^{(0)}(q) \Psi_0$$

source metric perturbations via Einstein's eq.

Cosmological Evolution (Perturbations)

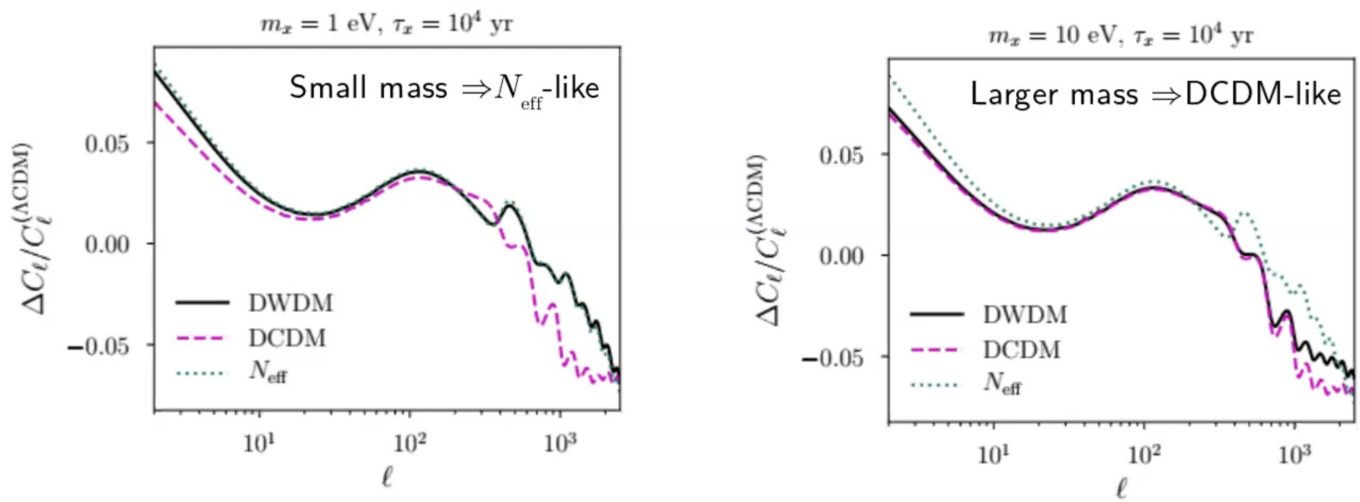


Free-streaming leads to suppression of density fluctuations, smaller impact on gravitational potentials

Impact on the CMB

- Implemented DWDM in Boltzmann code CLASS

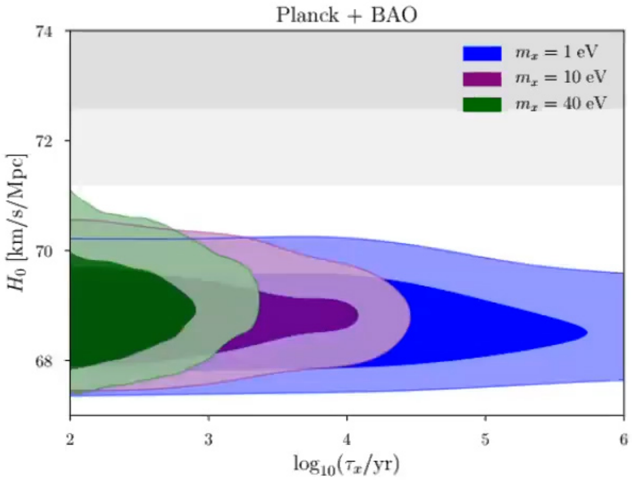
Blas, Lesgourgues & Tram (2011); Lesgourgues & Tram (2011)



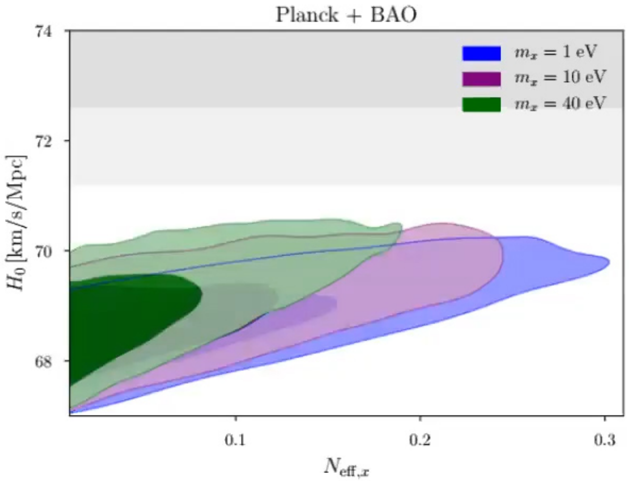
DWDM interpolates between DCDM and dark radiation

Cosmological Constraints

- Monte Carlo study performed with MontePython using final Planck data release + BAO



DWDM lifetime



Initial abundance of DWDM

CMB+BAO enforce short lifetimes or small mass – N_{eff} -like

Tension can be reduced by ~ 1.5 sigma

(at the cost of extra parameters)

Interacting Radiation

CMB Peak Phase Shifts

- Previous discussion boiled down H_0 extraction to a measurement of r_s, constraint on BSM coming from **amplitude** of peaks (via r_d and perturbation evolution)
- Peak **position** also depends on evolution of perturbations

$$\ell_{peak} \approx n(\pi - \delta\varphi)\frac{D_A}{r_s}$$

b/g evolution

Measured precisely

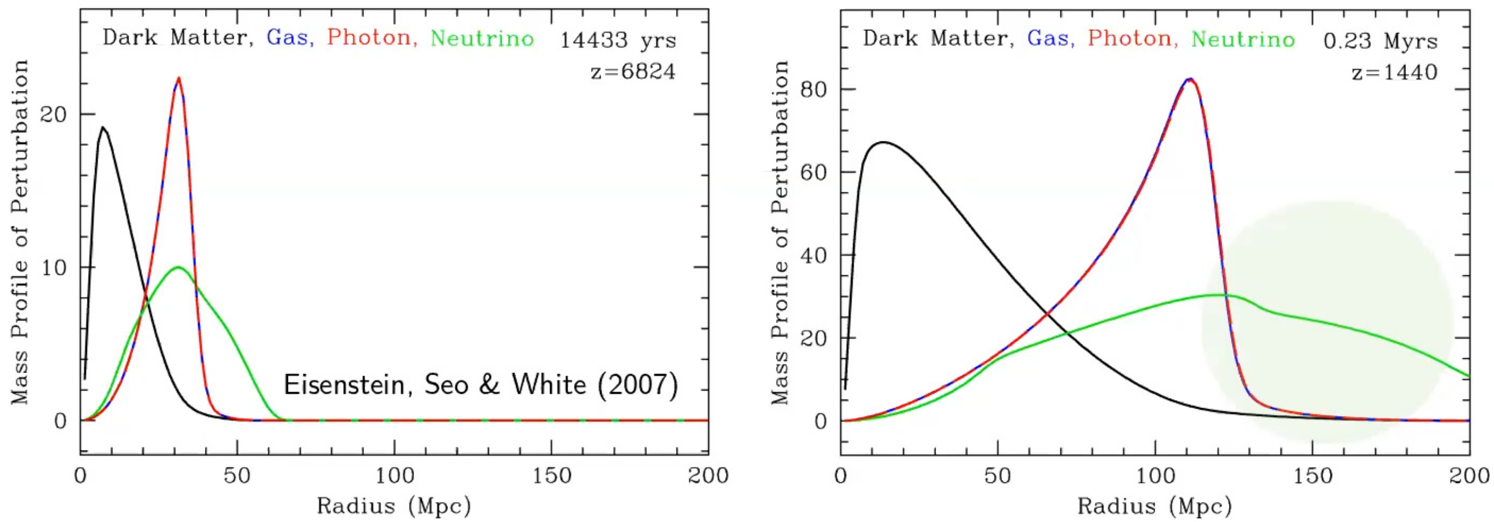
Evolution of perturbations

See, e.g., Pan, Knox, Mulroe & Narimani (2016)

Origin of Phase Shift

Free-streaming species propagate super-sonically

$$c > c_s = \sqrt{\frac{p}{\rho}} \approx \frac{1}{\sqrt{3}}$$



$$\delta\varphi \approx 0.191\pi \left(\frac{\rho_{\rm fs}}{\rho_{\rm rad}}\right)$$

Bashinsky & Seljak (2003)

Baumann, Green, Meyers & Wallisch (2016) 23

Non-Freestreaming/Interacting Radiation

- Consider extended cosmology with free-streaming and non-free-streaming radiation

$$\rho_{\rm rad} = \rho_\gamma \left[1 + \frac{7}{8}(N_{\rm eff} + N_{\rm fld}) \left(\frac{4}{11}\right)^{4/3}\right]$$

identical at background level; different perturbations

- Another parametrization:

$$N_{\rm tot} = N_{\rm eff} + N_{\rm fld}$$
$$f_{\rm fs} = N_{\rm eff}/N_{\rm tot}$$

Brust, Cui & Sigurdson (2017); Baumann, Green, Meyers & Wallisch (2016)

Impact of Interacting Radiation

Non-free-streaming species

1) Shift CMB to larger multipoles

$$\frac{\delta\ell_{peak}}{\ell_{peak}} \approx -0.2\left(\frac{\rho_{\rm fs}}{\rho_\gamma + \rho_{\rm fs} + \rho_{\rm non-fs}}\right)$$

relationship between ℓ and r_s modified!

2) Enhance amplitude of small scale γ perturbations

curvature perturbation

$$\Psi_i = -\frac{2\zeta}{3(1 + 4(\rho_{\rm fs}/\rho_{\rm tot})/15)}$$

Initial gravitational potential

$$\delta_\gamma \propto \Psi_i$$

"Gravitational Driving"
Hu & Sugiyama (1994)

relationship between extra radiation and r_d modified!

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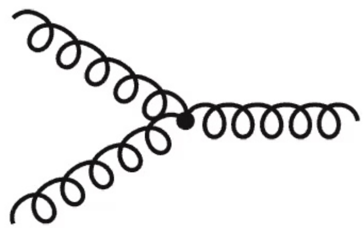
Interacting Radiation from Particle Physics I

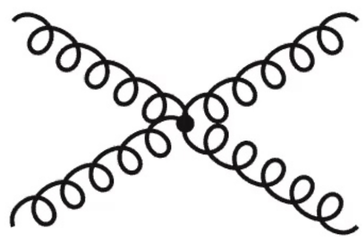
- Many scenarios can be mapped into $(N_{\rm tot}, f_{\rm fs})$

Example 1: Pure glue Non-Abelian dark sector with a low confinement scale



$$\Gamma \sim \alpha_d T_d$$

$$\Gamma_d > H(T_{cmb}) \Rightarrow \alpha_d \gtrsim 10^{-12}$$

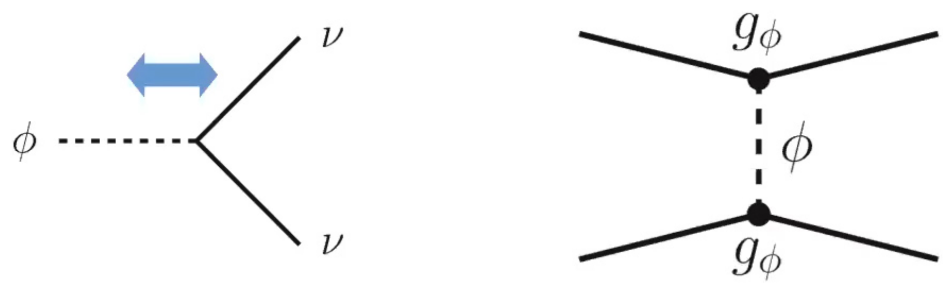


$$N_{\rm tot} > 3, \quad f_{\rm fs} < 1$$

See, e.g., Buen-Abad, Marques-Tavares & Schmaltz (2015)

Interacting Radiation from Particle Physics II

Example 2: Fraction of SM neutrinos **replaced** by self-interacting particles (or neutrinos self-scatter via light mediator < eV)



$$N_{\rm tot} \approx 3, \quad f_{\rm fs} < 1$$

A wide range of $(N_{\rm tot}, f_{\rm fs})$ can be realized in different scenarios

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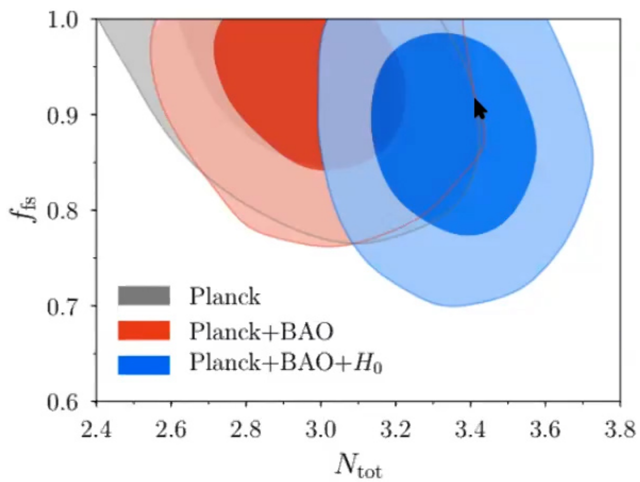
Constraints on Dark Radiation

Allow radiation density and free-streaming fraction to vary



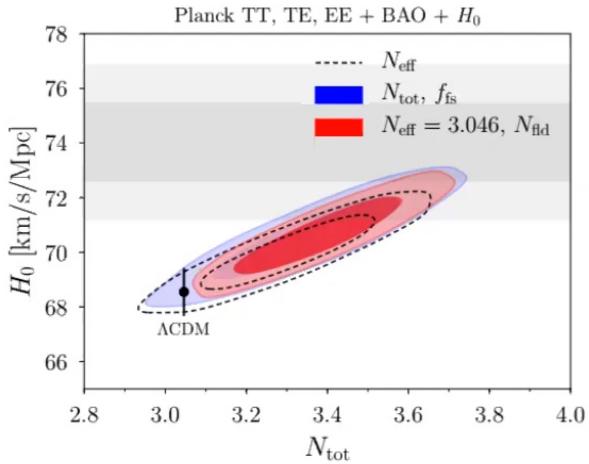
CMB+BAO: no preference for extra radiation or non-free-streaming.

+Riess *et al* (2019) H_0: larger radiation density, non-zero interacting component preferred

NB, Marques-Tavares (2020)

Consistency With Local Measurements

Data is consistent with a larger contribution of interacting radiation than free-streaming allowing for a better fit to H_0



$$\Delta\chi^2 = (\chi^2 - \chi^2_{\Lambda\mathrm{CDM}})_{\min}$$

Data Set	$N_{\rm eff}$	$N_{\rm eff} = 3.046,\ N_{\rm fld}$	$N_{\rm tot},\ f_{\rm fs}$
TTTEEE	+2.68	+6.24	+6.24
low-ℓ TT	−0.63	−0.56	−0.56
low-ℓ EE	+0.09	−1.06	−0.29
lensing	+0.17	+0.8	+0.39
BAO	+0.39	+0.73	+1.04
H_0	−4.99	−9.93	−10.81
total	−2.3	−3.81	−4.02

High ℓ temperature and polarization data key in constraining extra radiation (free-streaming or not)

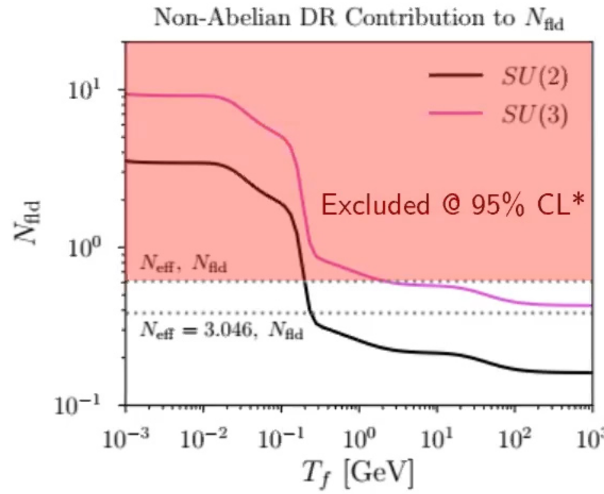
NB, Marques-Tavares (2020)

Constraints on Non-Abelian Dark Sectors

- Assuming the non-Abelian sector was in thermal equilibrium until temperature T_f, can predict abundance at CMB

$$\frac{1}{\Lambda^n} G_{d\,\mu\nu} G_d^{\mu\nu} \mathcal{O}_{\rm SM}$$

$$N_{\rm fld} = c \left[\frac{g_{*S}(T_\gamma)}{g_{*S}(T_f)}\right]^{4/3} (N^2 - 1)$$



*Assuming no non-SM entropy injections

NB, Marques-Tavares (2020)

Neutrino Self-Interactions

Neutrino Interactions in General

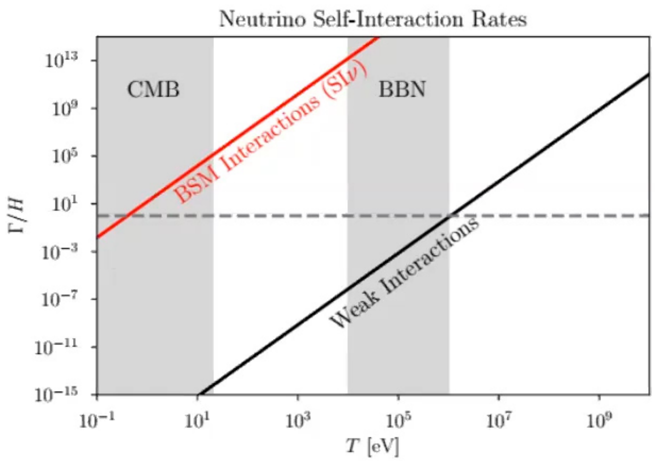
- Previously assumed interactions relevant at all times, i.e.

$$\Gamma \gg H(T_{\rm rec})$$

- In SM weak interactions freeze-out at $\sim$ MeV

- What happens when BSM interactions freeze-out during CMB era?

$$\Gamma_w \sim G_F^2 T^5$$

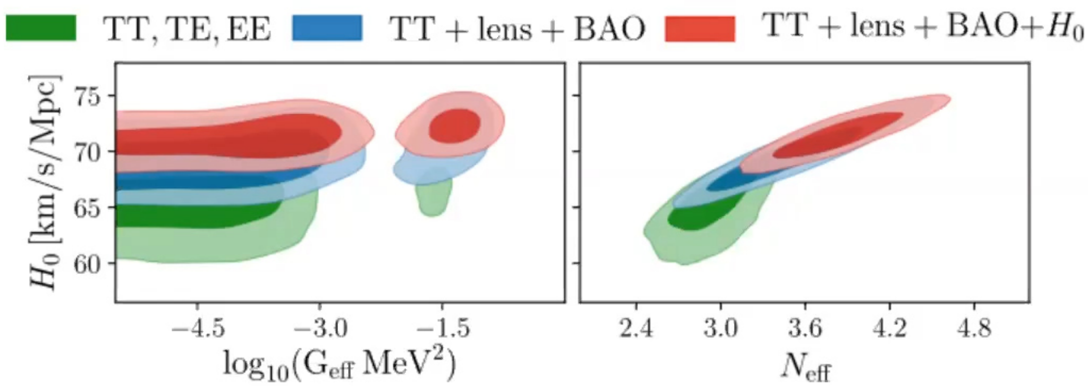


$$\Gamma \sim G_{\rm eff}^2 T^5 \gg \Gamma_w$$

Self-Interacting Neutrinos I

Consistent fit to CMB*+BAO and Riess *et al* (2019) H_0 obtained models with strong neutrino self-interactions

$$\mathcal{L} \supset G_{\rm eff}\nu\nu\nu\nu$$



Kreisch, Cyr-Racine & Doré (2019)

Model also studied previously in:
Cyr-Racine & Sigurdson (2013); Archidiacono & Hannestad (2014); Lancaster *et al* (2017); Oldengott *et al* (2017) +

Self-Interacting Neutrinos II

$$G_{\text{eff}} = \begin{cases} (4.7^{+0.4}_{-0.6}\text{MeV})^{-2} & (SI\nu) \\ (89^{+171}_{-61}\text{MeV})^{-2} & (MI\nu) \end{cases}$$

Best fit points have large departures from CDM in other cosmological parameters

$$N_{\text{eff}} \approx 4, \;\; \sum m_\nu = 0.4\text{ eV}, \ldots$$

Can one have such an enormous neutrino self-interaction in realistic models?

$$G_{\text{eff}}(\text{SI}\nu) \sim 10^9 G_F$$

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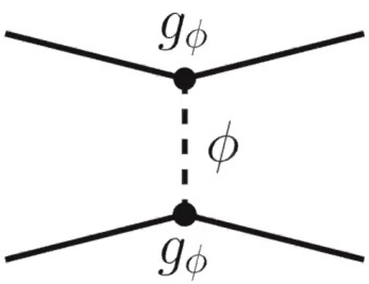
Towards the "Ultra-Violet"



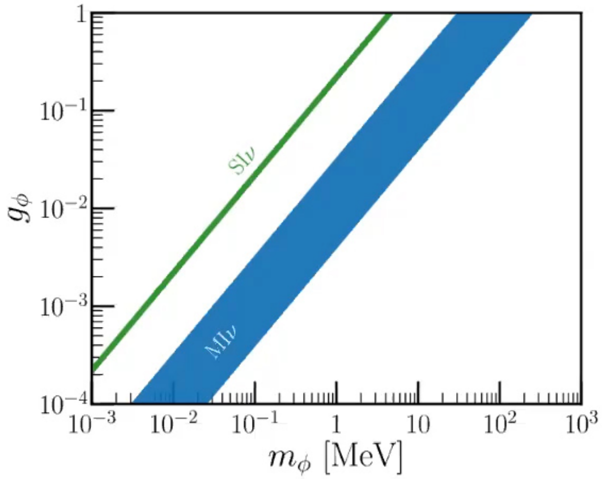
$$G_{\text{eff}}(\text{SI}\nu) \sim 10^9 G_F$$

$$G_{\text{eff}} \approx \frac{g_\phi^2}{m_\phi^2} = (10\ \text{MeV})^{-2}\left(\frac{g_\phi}{10^{-1}}\right)^2\left(\frac{\text{MeV}}{m_\phi}\right)^2$$

(EFT valid during CMB for $m_\phi \gg 100$ eV)

$$\mathcal{L} \supset g_\phi^{\alpha\beta}\nu_\alpha\nu_\beta\phi$$

Not SU(2) gauge invariant



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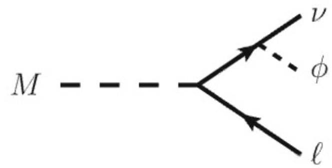
Bounds From Meson Decays

- Light mediator can be radiated in rare meson decay

$$M \to \ell^+ \nu \phi$$

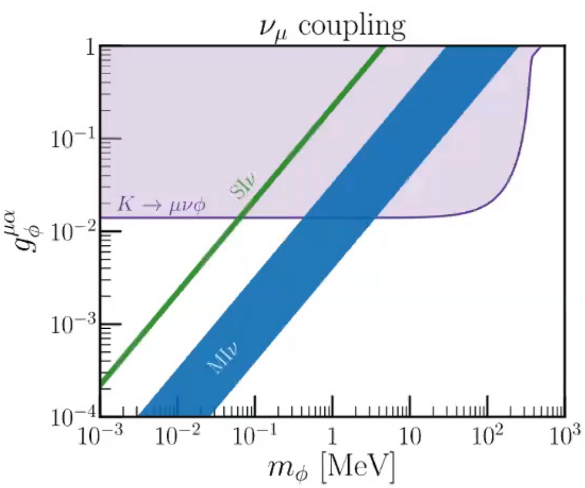


$$\frac{\Gamma(M^+ \to \nu \ell^+ \phi)}{\Gamma(M^+ \to \nu \ell^+)} \sim 10^{-3} |g_{\alpha\beta}|^2 \left(\frac{m_M}{m_\ell} \right)^2$$

Phase space

Helicity suppression lifted

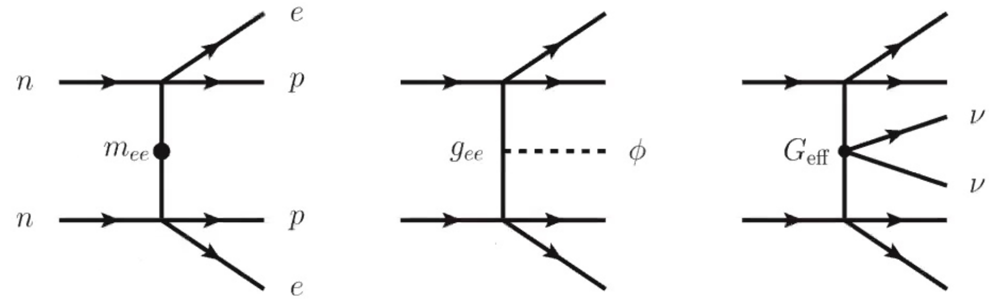
See, e.g., Blum, Hook & Murase (2014)



NB, Kelly, Krnjaic, McDermott (2019)

Even stronger bounds on electron coupling from $K^+ \to \nu_e e^+ \phi$

Bounds from $0\nu\beta\beta$ Searches (ee coupling)

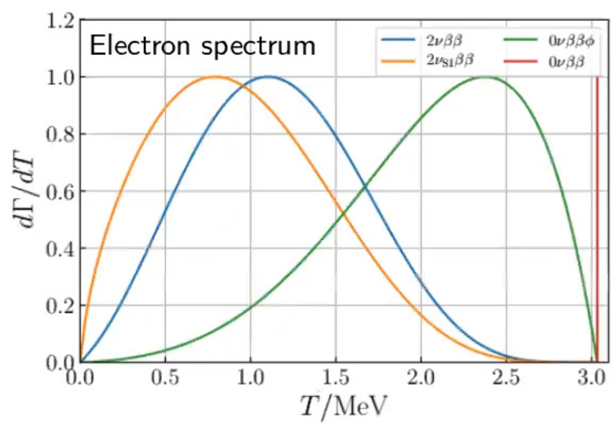


$g_{ee} \gtrsim 10^{-5}$ or $G_{\text{eff},ee} > 0.3 \times 10^{9} G_F$ excluded

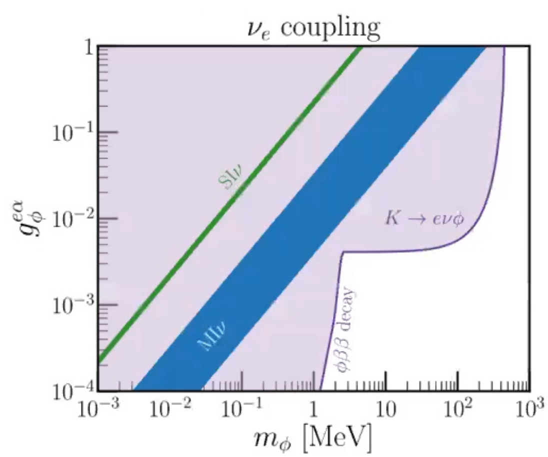
(from EXO-200)

Blum, Nir & Shavit (2018)

Deppisch, Graf, Rodejohann & Xu (2020)



Deppisch, Graf, Rodejohann & Xu (2020)



NB, Kelly, Krnjaic, McDermott (2019)

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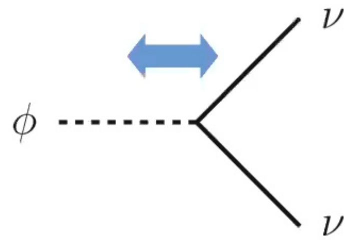
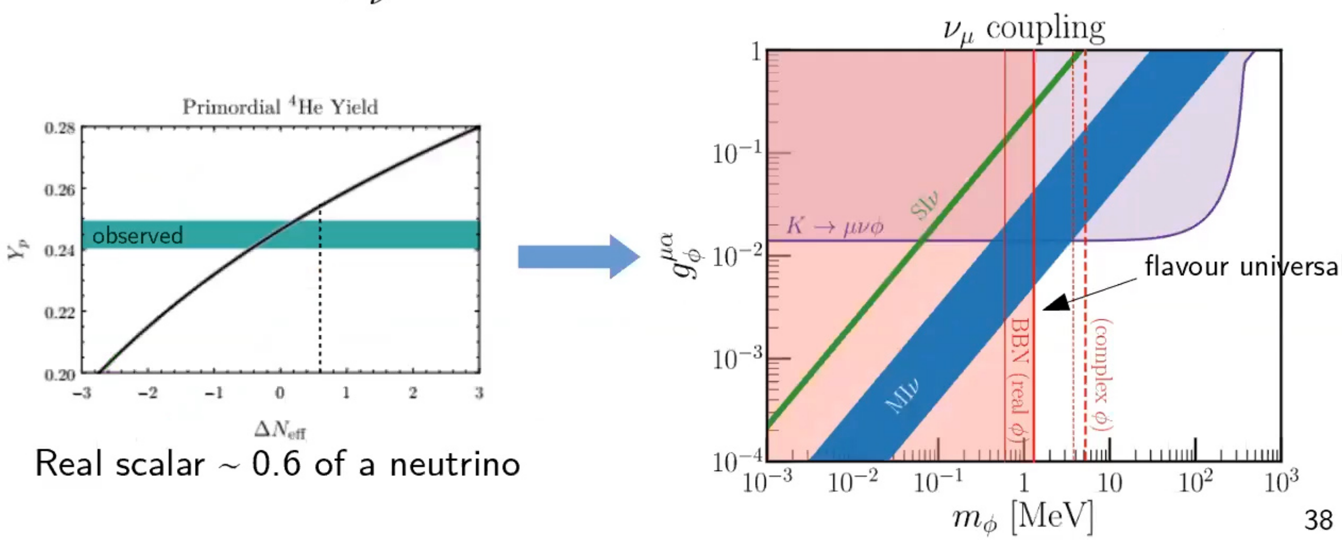
Bounds from Nucleosynthesis

- Mediator coupling large enough to bring mediator into thermal equilibrium before BBN (T~MeV) if



$$|g_{\alpha\beta}| \gtrsim 10^{-10}\left(\frac{\text{MeV}}{m_\phi}\right) \Rightarrow \rho_\phi \sim T^4$$



Real scalar ~ 0.6 of a neutrino

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NB, Kelly, Krnjaic, McDermott (2019)

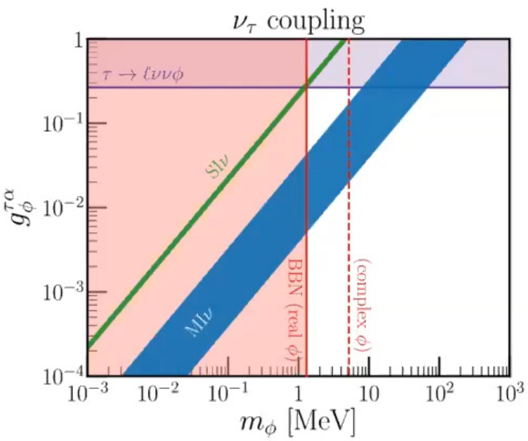
Consequences of Gauge Invariance

- $\mathcal{L} \supset g_\phi^{\alpha\beta} \nu_\alpha \nu_\beta \phi$ not gauge invariant
- UV complete models (e.g. type I/II/inv. see-saw) generate

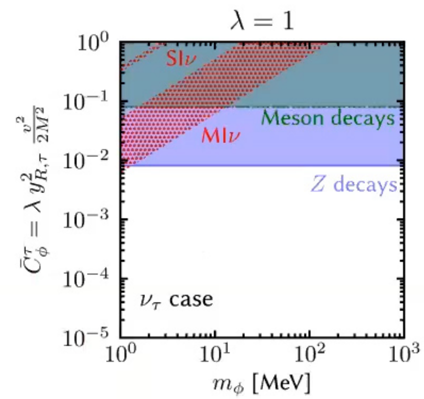
$$(LH)(LH) \qquad \phi(LH)(LH) \qquad (LH)^\dagger i\partial \cdot \bar{\sigma}(LH)$$

Contribution to mass — BSM self-interaction — Shifts to EW couplings (after EOM)

Lyu, Stamou & Wang (2020)



$$\frac{g}{2c_W}(1+2\bar{C})\bar{\nu}_L \not{Z} \nu_L$$



Even ν_τ-only self-interactions severely constrained! 39

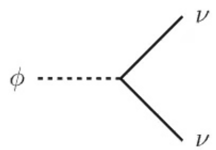
A Workaround

- **Replace** neutrinos by a sterile, self-interacting species

1) Must be done after BBN

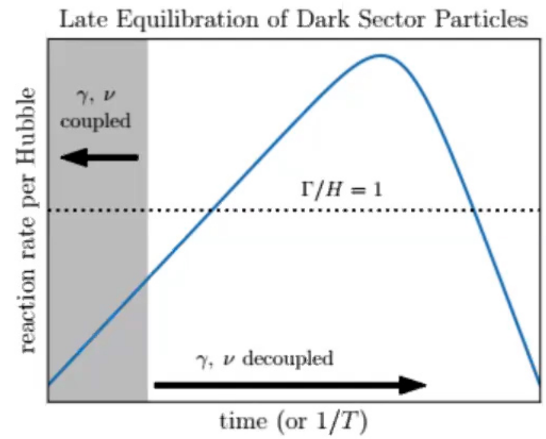
2) Dark sector equilibrates after neutrino-photon decoupling via DS-SM interactions through a **light** mediatior

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



$$\Gamma \sim \lambda^2 m_\phi^2/T$$

3) DS states endowed with strong self-interactions which are less-constrained



Chacko *et al* (2003); Berlin & NB (2017)

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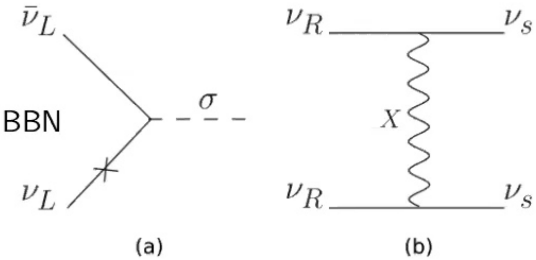
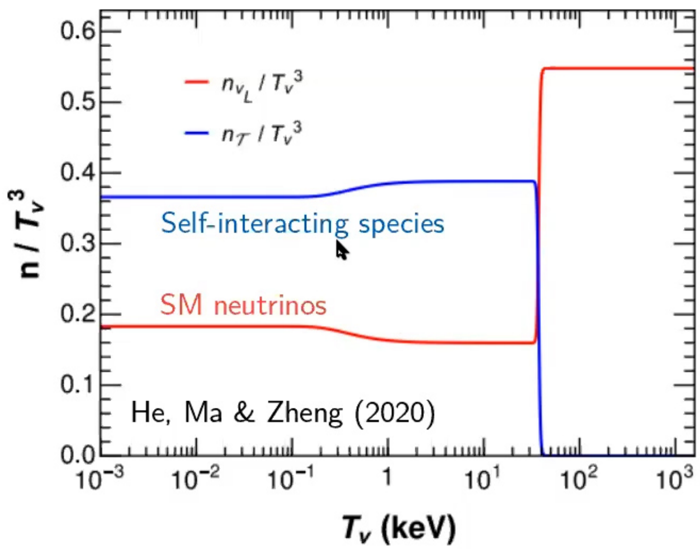
A Workaround

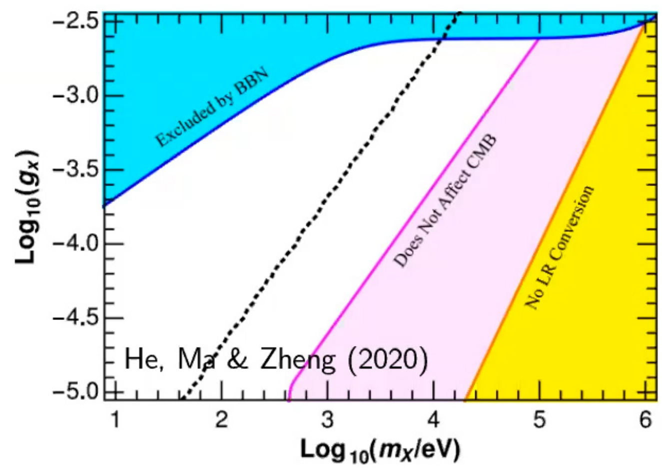
- Replace neutrinos by a sterile self-interacting species

Production of steriles after BBN



Self-interaction of steriles





Mediator mass

He, Ma & Zheng (2020)
Berbig, Jana, Trautner (2020)

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Conclusion

- Hubble tension is significant and could point to new physics
- Simple models face constraints both from cosmology and laboratory experiments
- More CMB data, independent H_0 measurements will sharpen tension and possible explanations