Self-interacting sterile neutrino dark matter

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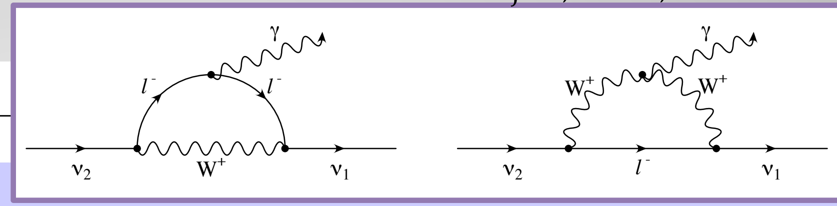
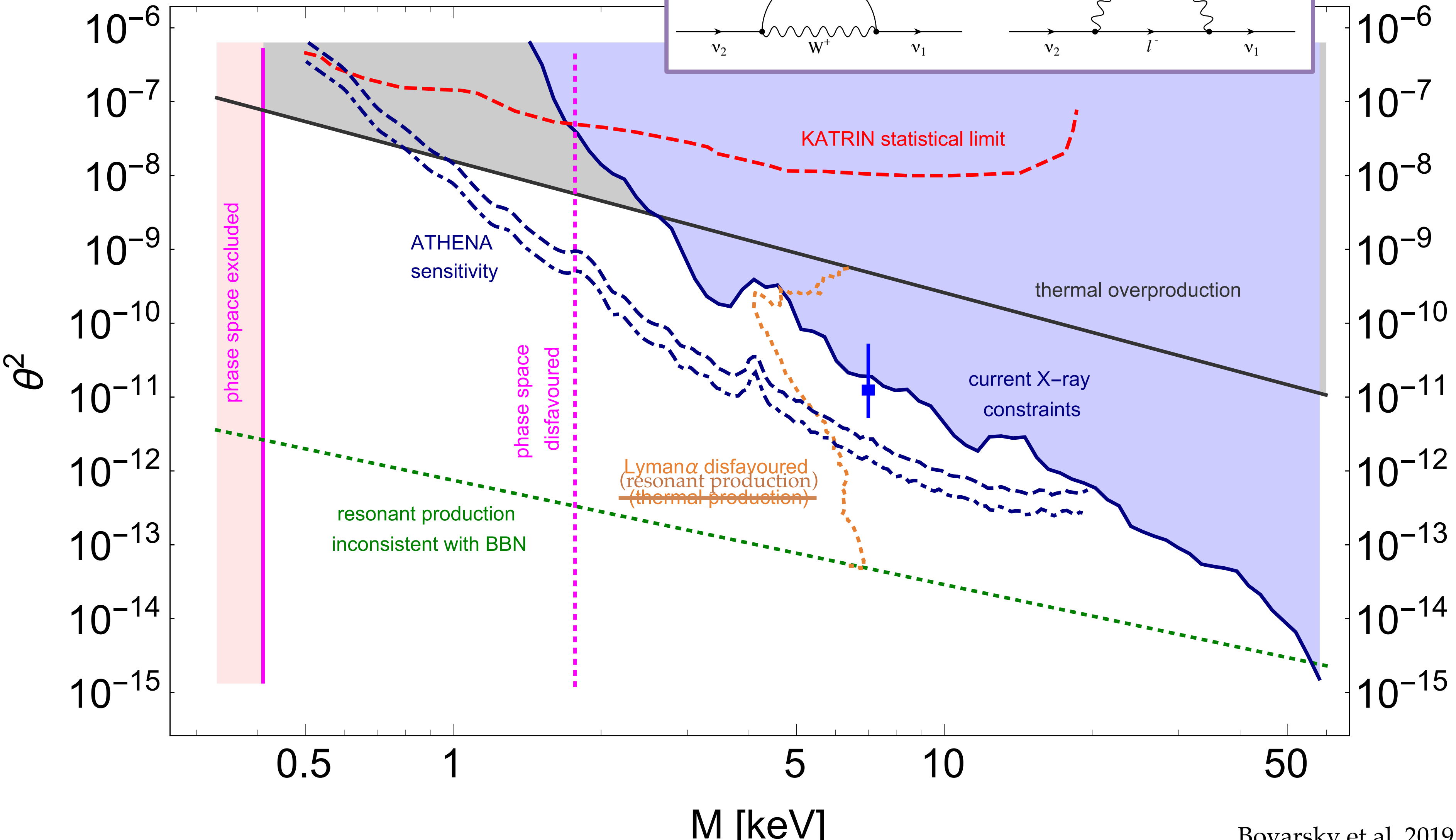
- ✧ **Dodelson-Widrow (thermal) production** is strongly disfavored.
- ✧ **Shi-Fuller (resonant) production** is viable in a limited window.*

* …which may encompass a **detection**.

Abazajian, Fuller, Tucker 2001

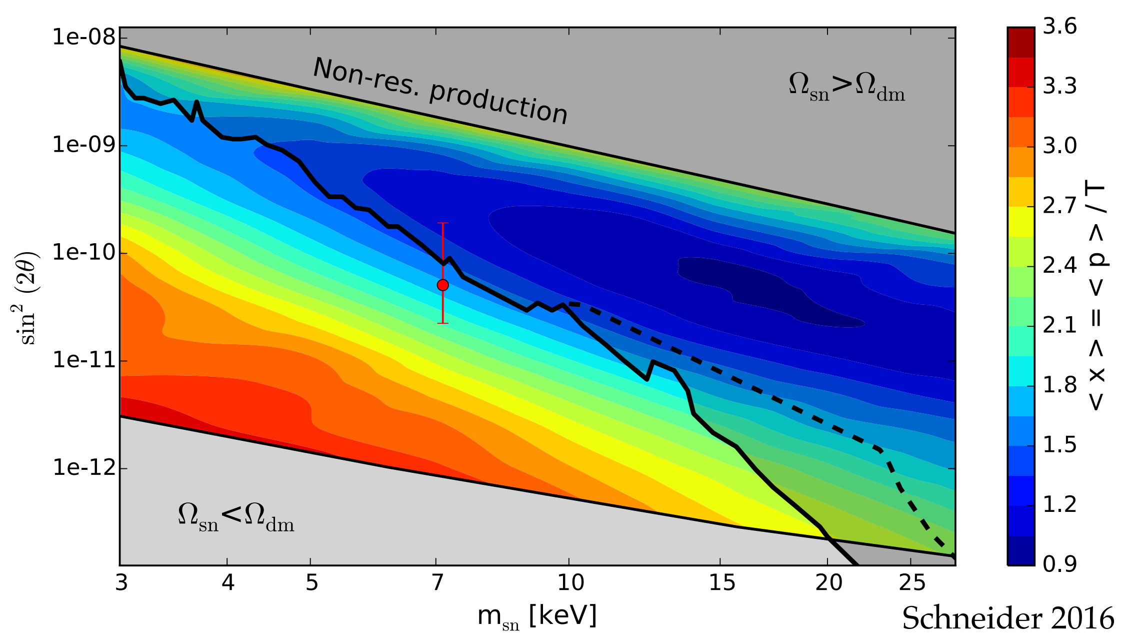


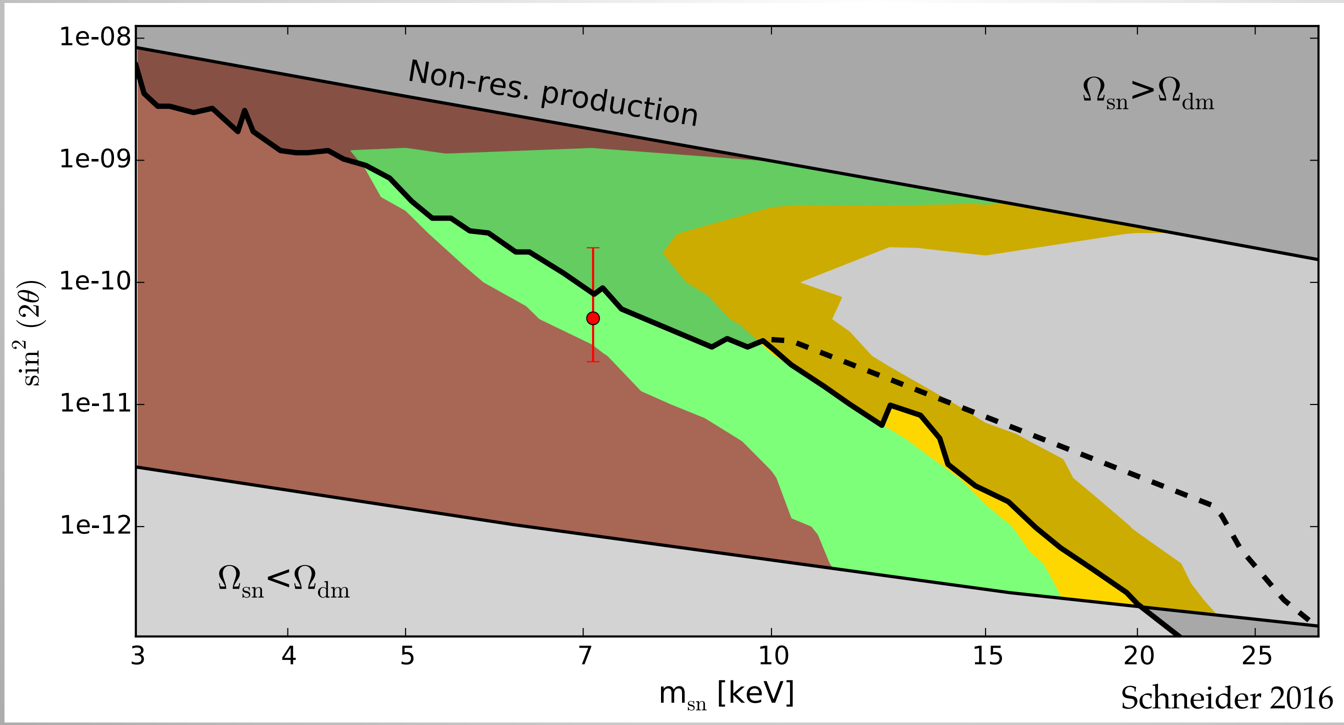


Boyarsky et al. 2019

Resonant production leads to **non-thermal spectra** that are typically colder than DW ones.

Shi & Fuller 1999
Abazajian, Fuller, Patel 2001





Subhalo counts and **Lyman-α constraints** (two different models)

Sterile neutrinos require **at least one other BSM ingredient** if they are to comprise all of the DM.

A large lepton number is one possibility. What else?

1. *Don't change* the dynamics of active-sterile mixing.
    - ✧ Another new particle **decays** to sterile neutrinos. — Shaposhnikov & Tkachev 2006; Petraki & Kusenko 2008
    - ✧ An overabundant population is **diluted** by new sources of entropy. — Asaka et al 2006; Bezrukov et al. 2010; Patwardhan et al. 2015
    - ✧ **Reheating** occurs at a low temp. — Gelmini et al. 2004
    - ✧ **Number-changing interactions** occur in the sterile sector. — Hansen & Vogl 2017; Herms et al. 2018

2. *Change* the dynamics of active-sterile mixing.
    - ✧ A (pseudo)scalar field alters the mixing in a **time-dependent** way. — Berlin & Hooper 2017; Bezrukov et al. 2017, 2018
    - ✧ **Sterile-sector interactions alter the mixing.** — **Johns** & Fuller 2019

Also discussed in connection with eV-scale sterile neutrinos.

Production through the neutrino portal can be calculated using a **Boltzmann-like equation**

$$\frac{df_s}{dt} = \frac{\Gamma_a}{4} \frac{\sin^2 2\theta_m}{1 + \left(\frac{\Gamma_a}{2\omega_m}\right)^2} (f_a - f_s)$$

Kainulainen 1990
Cline 1992
Shi 1996
Foot & Volkas 1997 (and sequels)
Dolgov 2002

Compare to the QKEs (with approximate collision term):

$$\frac{dP_0}{dt} = 2D\left(f_a^{\mathrm{eq}} - P_0 \frac{1+P_z}{2}\right)$$

$$\frac{d\mathbf{P}}{dt} = \omega_m \mathbf{B}_m \times \mathbf{P} - D\mathbf{P}_T - \frac{\dot{P}_0}{P_0}\mathbf{P} + \frac{\dot{P}_0}{P_0}\mathbf{z}$$

Assessing collision approximations in active-sterile oscillations:
Hannestad, Hansen, Tram, Wong 2015

Papers by Bell, Lee, Volkas, & Wong have shown that **repopulation terms** in the QKEs can be ignored if the mixing angle is small:

$$\frac{dP_0}{dt} = 0, \;\; f_a = f_a^{\mathrm{eq}}$$

The Boltzmann equation also follows directly from a **quantum relaxation-time approximation**:

$$iC = \{i\Gamma, \rho_C^{\mathrm{eq}} - \rho\}$$

$$i\frac{d\rho}{dt} = \{i\Gamma_{\mathrm{eff}}, \rho_F^{\mathrm{eq}} - \rho\}$$

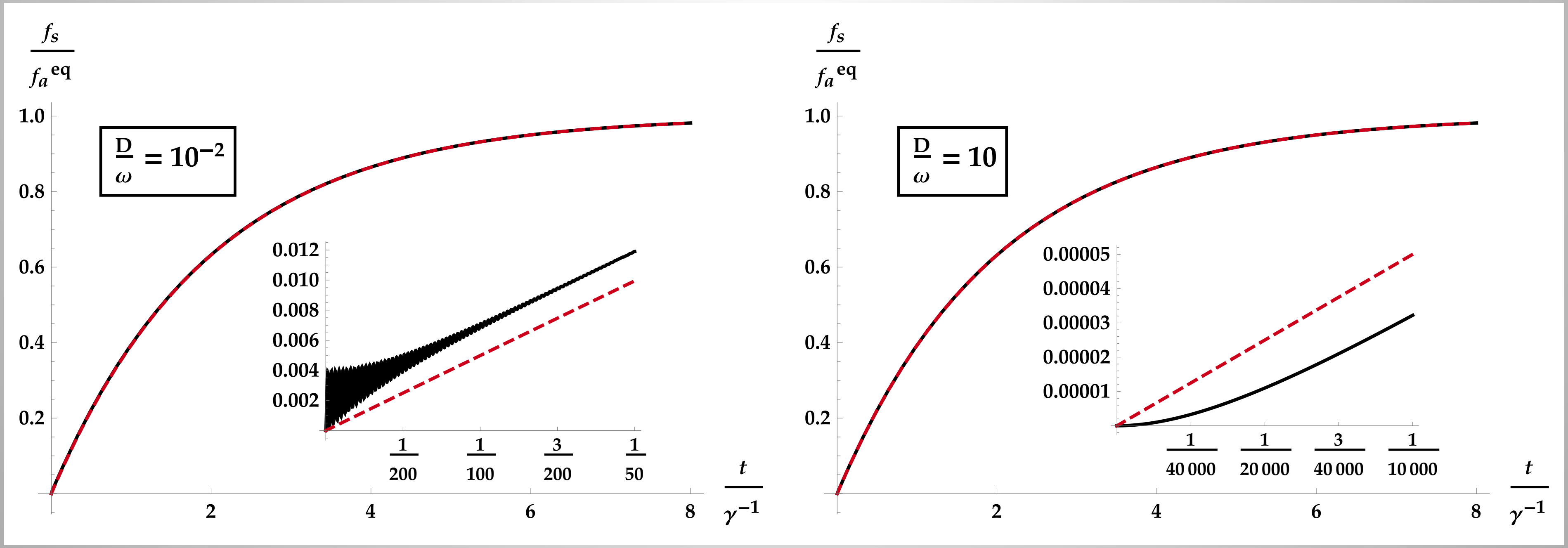
Johns 1908.04244

Relaxation ansatz:

$$\frac{d\rho}{dt} = \frac{\gamma_m}{2}\left(\rho_F^{\mathrm{eq}} - \rho\right)$$

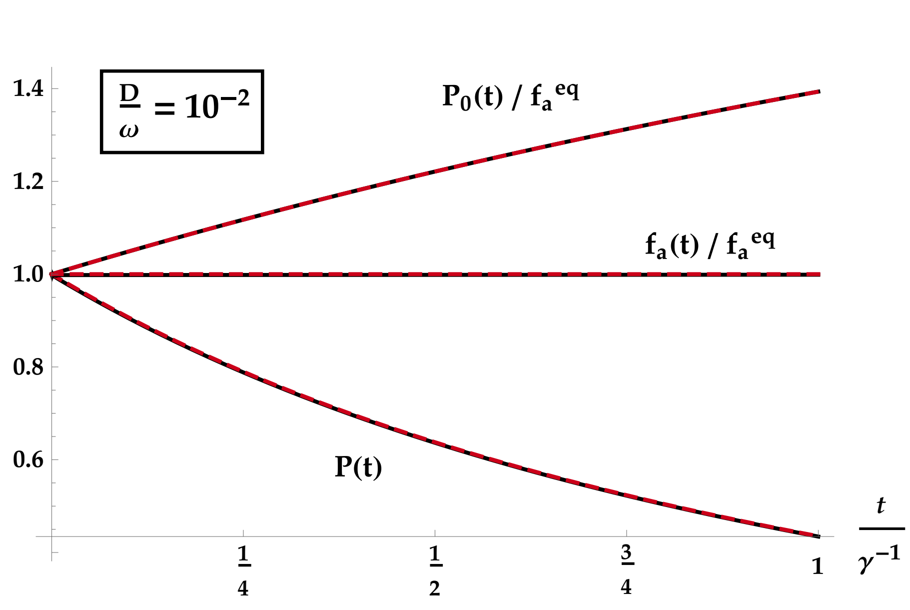
The prefactor is determined by
by equating this with the QKEs.

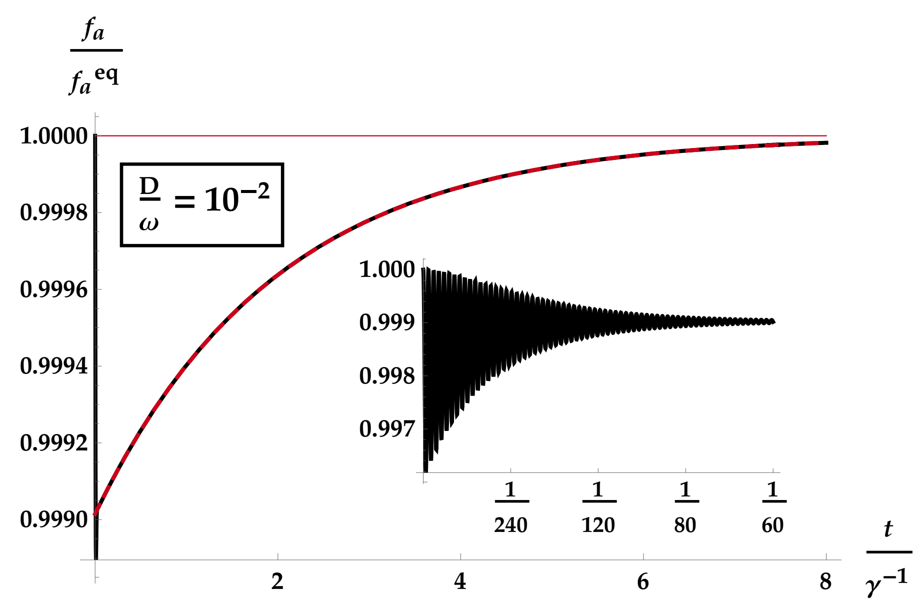
Agreement is strong between **QKE** and **Boltzmann** solutions (as expected):



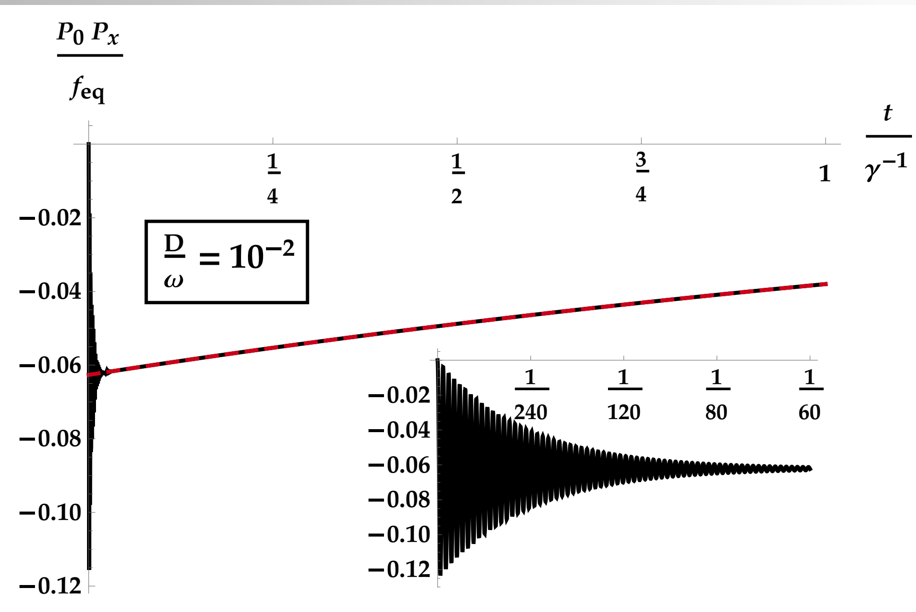
(time-independent parameters)

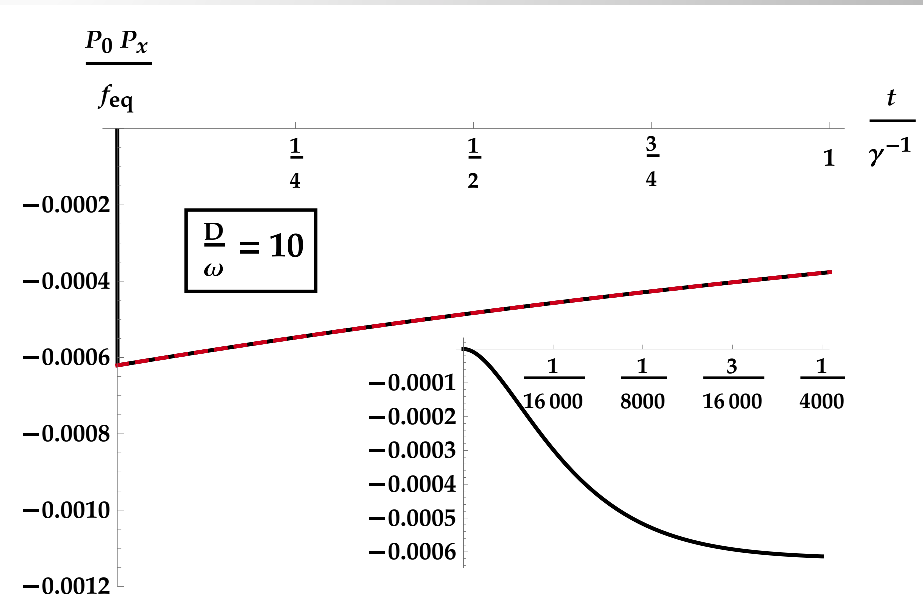
Repopulation is captured well by the ansatz:





As is **decoherence**:





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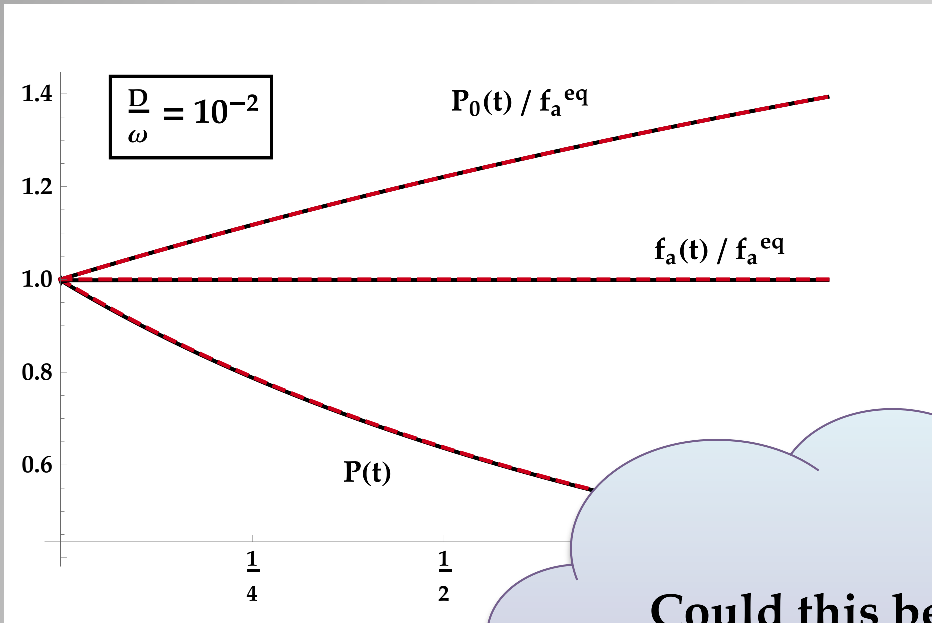
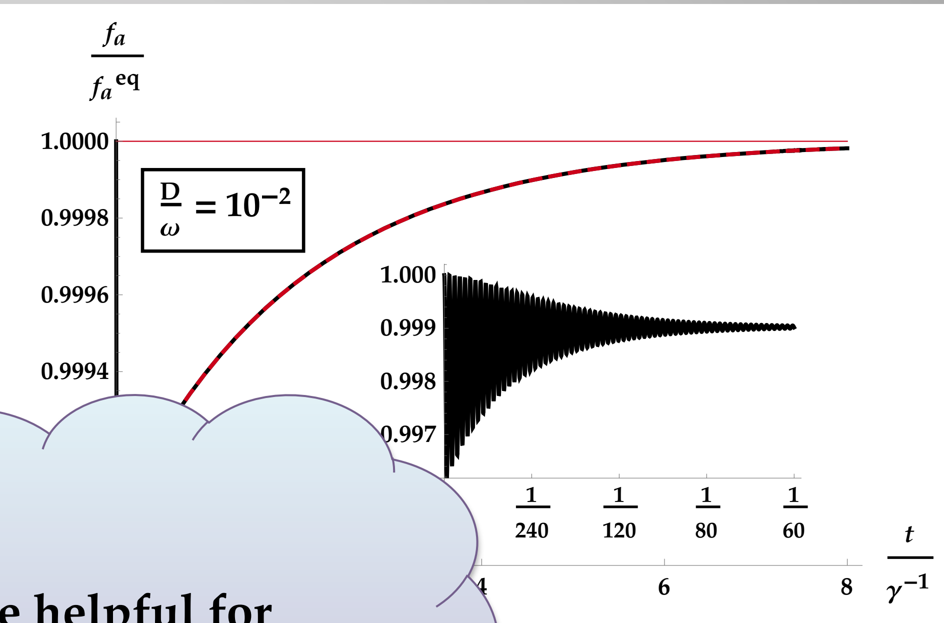
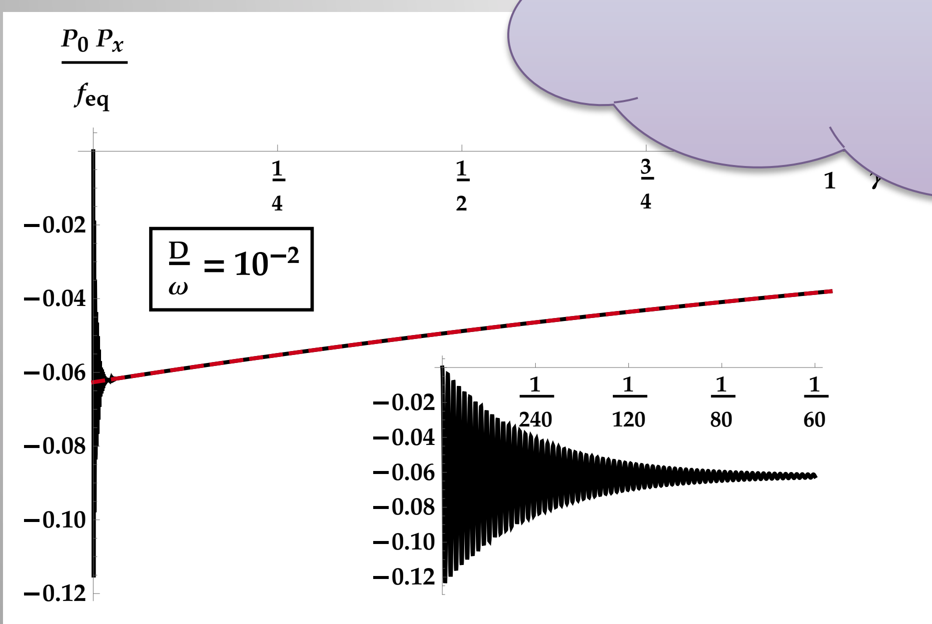
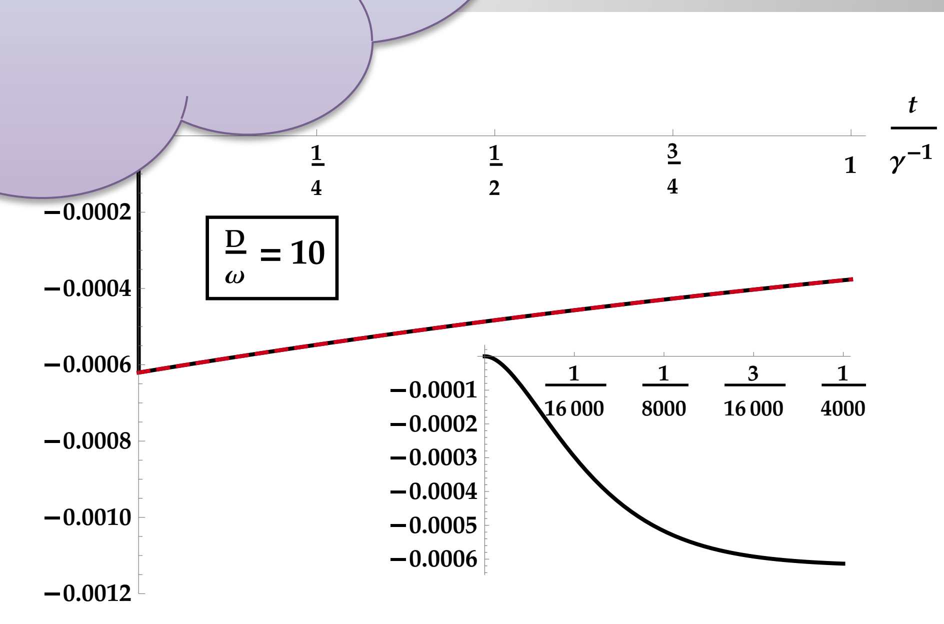




Could this be helpful for active-active mixing?

As is **decoherence**:





Adding in self-interactions…

$$\mathcal{V} = \mathcal{V}_\mu + \mathcal{V}_a + \mathcal{V}_s$$

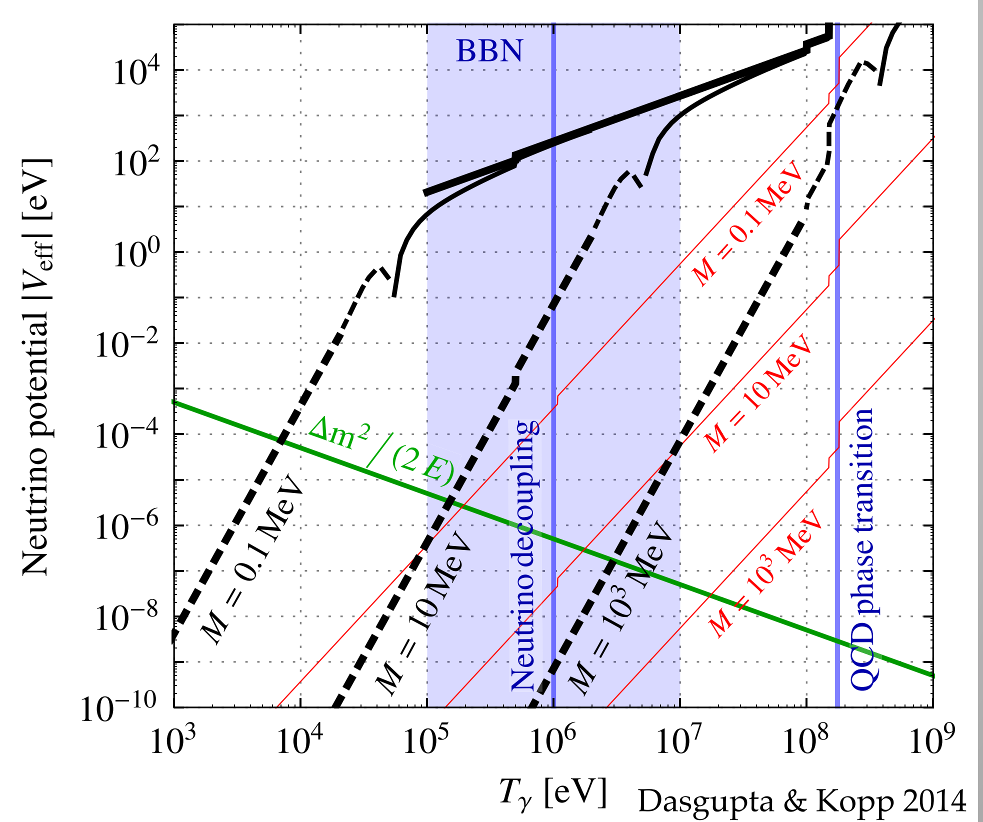
$$\frac{df_s}{dt} = \frac{\Gamma_a}{4} \frac{\sin^2 2\theta_m}{1 + \left(\frac{\Gamma_a}{2\omega_m}\right)^2} (f_a - f_s) + \mathcal{C}_s$$

$$D = \frac{\Gamma_a + \Gamma_s}{2}$$

These effects have been invoked as a way to **reconcile eV sterile neutrinos with cosmology**.

Hannestad, Hansen, & Tram 2014
Dasgupta & Kopp 2014

The goal there is to *suppress* the production of sterile neutrinos rather than enhance it.



Dasgupta & Kopp 2014

For simplicity, we'll let the self-interactions be mediated by a **heavy scalar**.

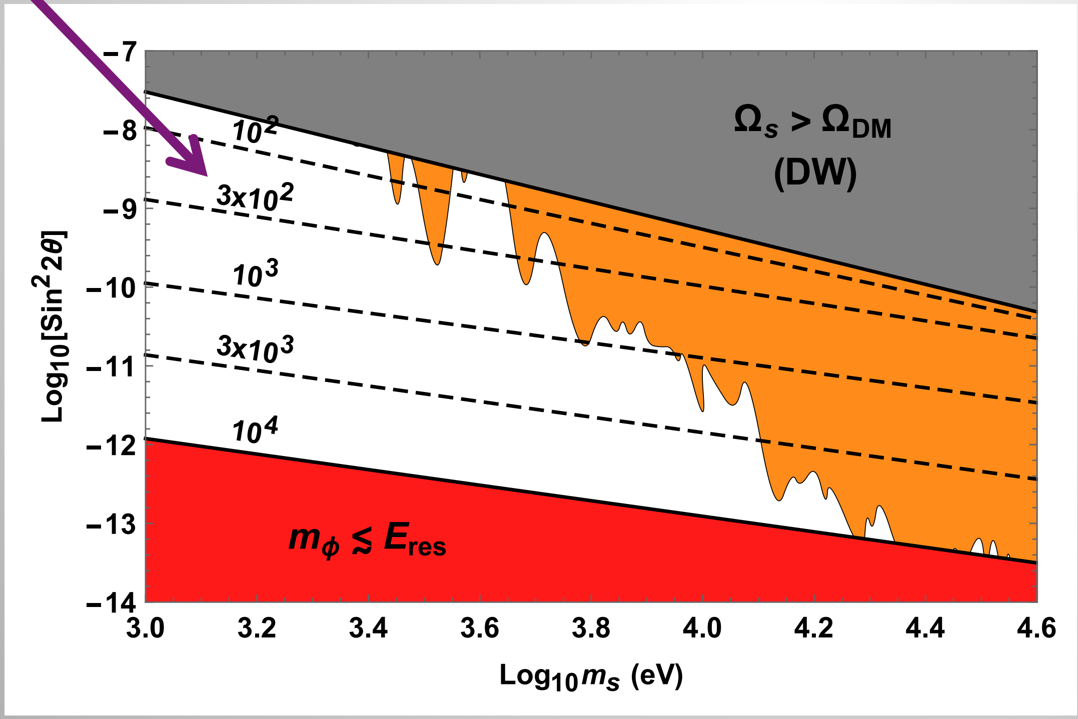
$$\mathcal{L}_s = \frac{1}{2}\bar{\psi}_s\left(i\partial\!\!\!/ - m_s\right)\psi_s + \frac{1}{2}(\partial_\mu\phi)^2 - \frac{1}{2}m_\phi^2\phi^2 - \frac{g_\phi}{2}\bar{\psi}_s\psi_s\phi.$$

Potential from sterile neutrinos coherently scattering on each other:

$$m_\phi \gtrsim 1\ \text{GeV}$$

$$\mathcal{V}_s = +\frac{G_\phi}{3m_\phi^2}\rho_s p$$

$$\frac{G_\phi}{G_F}$$

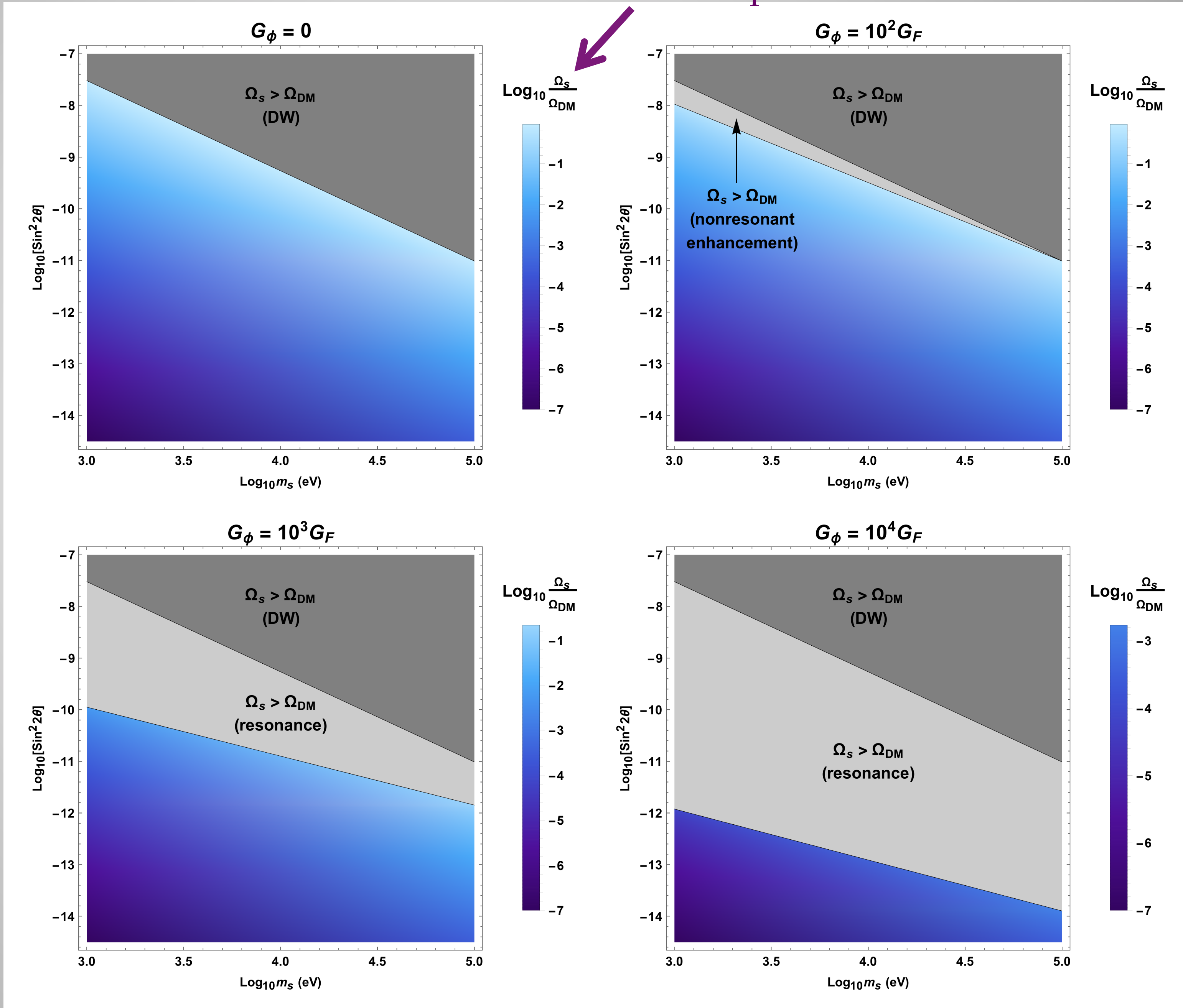


The **overproduction curves** shift to smaller mixing angle as the coupling is increased.

Johns & Fuller 2019

But in fact there's more to the story…

Fraction of dark matter produced

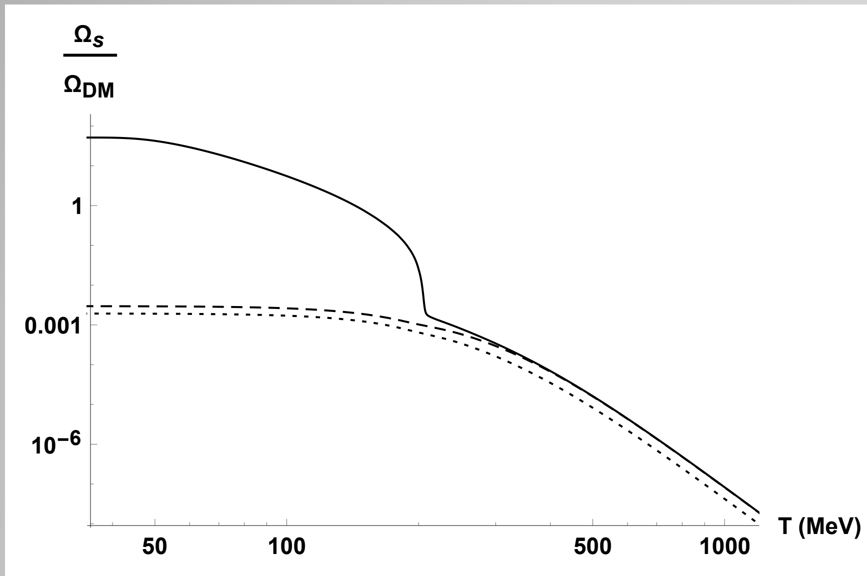


If the coupling is large enough to appreciably **enhance the scattering rate**, it's also large enough to **set up a resonance**.

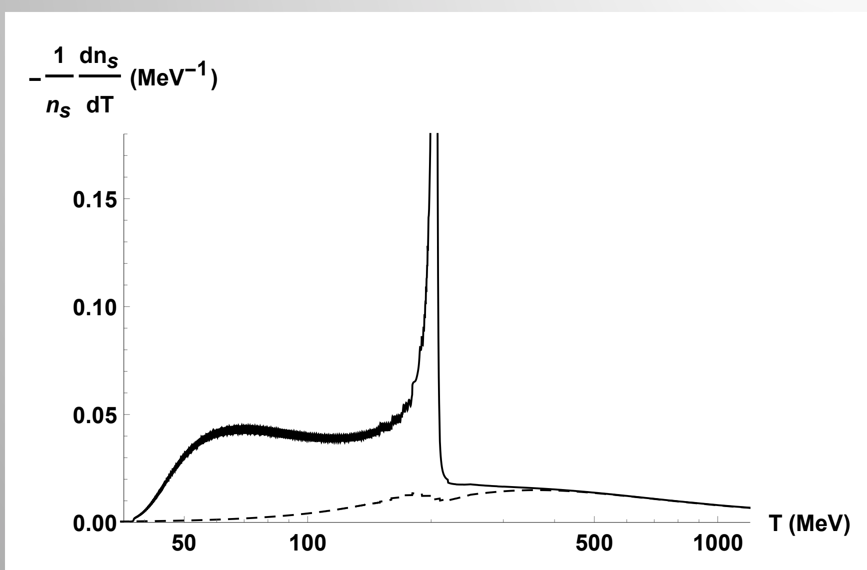
Nonlinearity then leads to **runaway production**.

Johns & Fuller 2019

Fraction of DM produced vs. temp:



Logarithmic production rate vs. temp:



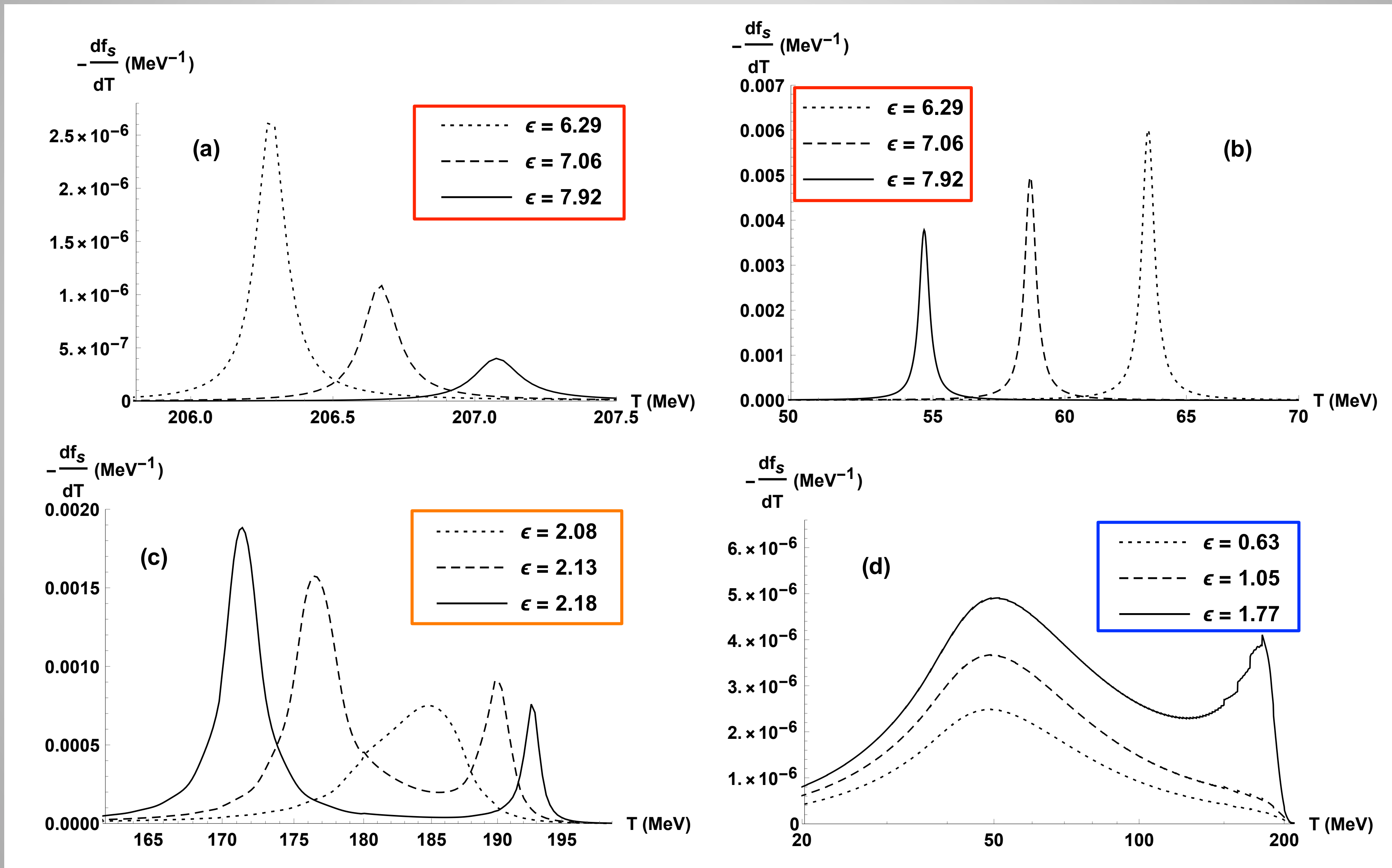
Why can't the scattering rate be boosted without generating a resonance?

$$\frac{\Gamma_s}{\Gamma_a} \gtrsim 1 \Longrightarrow \left|\frac{\mathcal{V}_s}{\mathcal{V}_a}\right| \gtrsim \frac{g_w}{g_\phi}$$

Conversely, resonance *can* occur with subdominant sterile scattering—but overproduction still ensues.

Johns & Fuller 2019

The resonance sweeps from high energy down to a cutoff, then doubles back…



Johns & Fuller 2019

Summary

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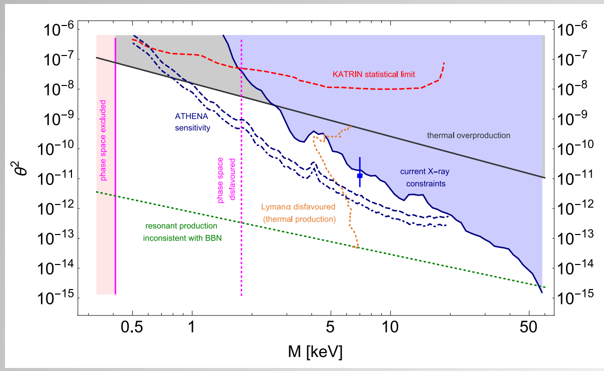

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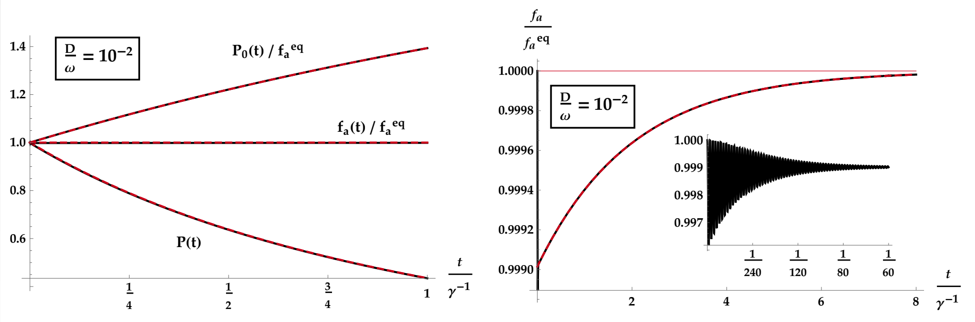

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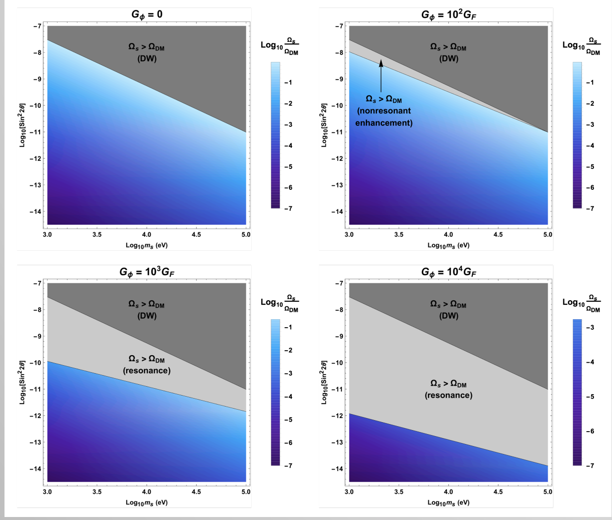

4. We're beginning to extend the analysis to **lighter mediators**.

   The **sub-keV** range (including models motivated by issues of small-scale structure) doesn't look promising.