Post-inflationary Production of Light Dark Sectors

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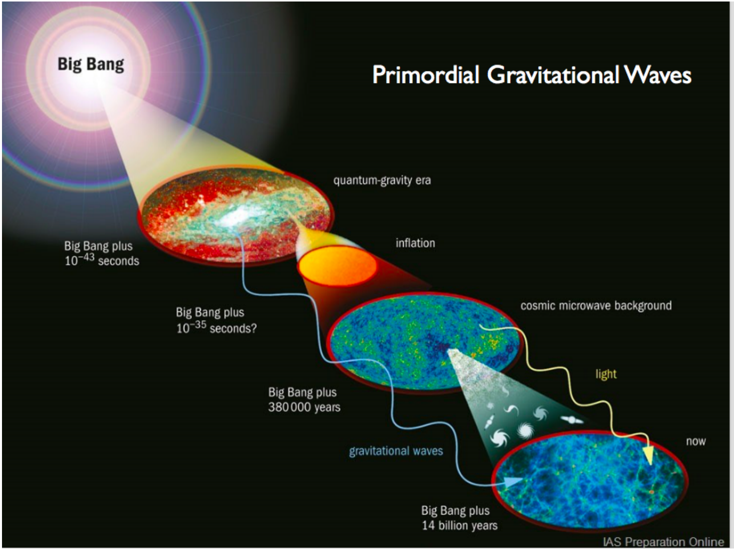
Outline of talk:

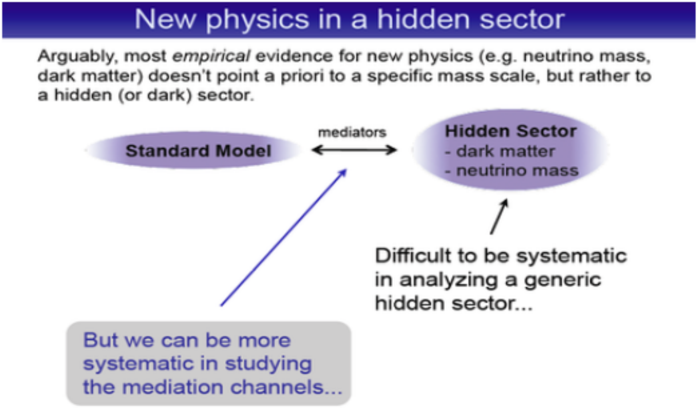
- Light Dark Sectors in Particle Physics
- (P)reheating the Universe after Inflation
- Sterile Neutrinos & Cosmological Bounds
- Dark Matter Production
- Conclusion

History of the Universe



Motivation for Light Dark Sector

Many motivated particle physics scenarios requires such bosonic mediators: sterile neutrinos, thermal and non-thermal dark matter, asymmetric dark matter.....



(P)reheating: Concepts

- Cosmic Inflation:
  - Accelerated expansion of universe to solve Horizon problem, Flatness problem, generate initial seed fluctuation to explain structure formation
  - Candidate: a Scalar field known as the Inflaton.
- Post-inflationary Dynamics:
  - After slow-roll ends, inflaton field oscillates around the minima of potential
  - Energy density of oscillating inflaton field evolves as matter $\sim 1/a^3$ for quadratic inflation
  - Oscillating inflaton field is interpreted as collection of stationary inflaton particles which decay **perturbatively** - Reheating
- Preheating:
  - **Non-perturbative** production of particles from the classical oscillation of the inflaton field.
  - Any field χ can be decomposed into fourier modes,

$$\chi(t, x) = \int \frac{d^3k}{(2\pi)^{3/2}} \left(a_k \chi_k e^{-ik.x} + a_k^\dagger \chi_k^* e^{ik.x} \right)$$

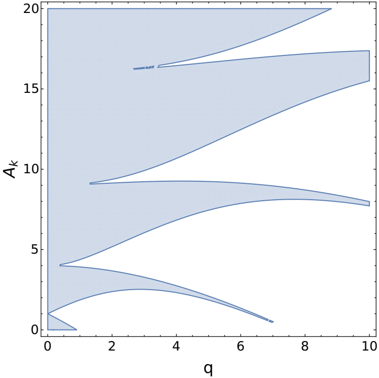
  - Dynamics of the modes χ_k of a field χ are given by Mathieu Equation -

$$\frac{d^2\chi_k}{dz^2} + (A_k - 2q\cos(2z))\chi_k = 0$$

(where $z = m_\phi t$, $q = \frac{\lambda_{\phi\chi}\Phi^2}{4m_\phi^2}$, $A_k = \frac{k^2}{m_\phi^2 a^2} + 2q$, a=Scale factor, t=time, Φ=Amplitude of ϕ oscillation, the potential is $\frac{1}{2}m_\phi^2\phi^2 + \frac{1}{2}\lambda_{\phi\chi}\phi^2\chi^2$)

Mathieu instability bands

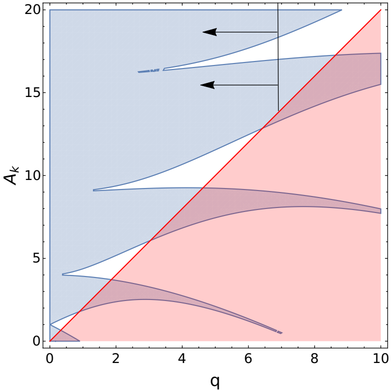
- Oscillatory solution in (blue), exponentially growing solution in (white) regions.



- Growing modes are interpreted as particle production during inflation.
- For some q, lowest A_k has highest exponent of growing - *exponential particle production*.

Identifying Growing modes with time

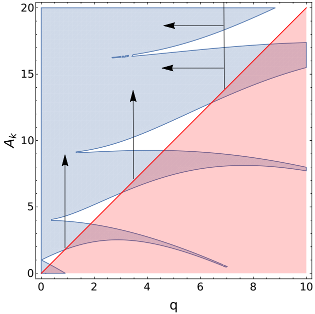
- $q = \frac{\lambda_{\phi\chi}\Phi^2}{4m_\phi^2}$, $A_k = \frac{k^2}{m_\phi^2 a^2} + 2q$,
- $\frac{1}{2}\lambda_{\phi\chi}\phi^2\chi^2$-term acts as an inflaton effective mass $m_\phi^{eff} = \sqrt{m_\phi^2 + \lambda_{\phi\chi}\langle\chi^2\rangle}$.
- So, with time Φ decreases and m_ϕ^{eff} increases, resulting a decrement in q.
- Growing modes bands get narrower; lower momentum modes become growing modes.



Effect of Quartic self-interaction of χ

Let's pretend this slide is absent for the time being !

- $\lambda_\chi \chi^4$ gives rise to effective mass term of χ, $m_\chi^{eff} = \sqrt{\lambda_\chi \langle \chi^2 \rangle}$.
- A_k gets modified into $A_k = \frac{k^2}{m_\phi^2 a^2} + \frac{m_\chi^2}{m_\phi^2} + 2q$.

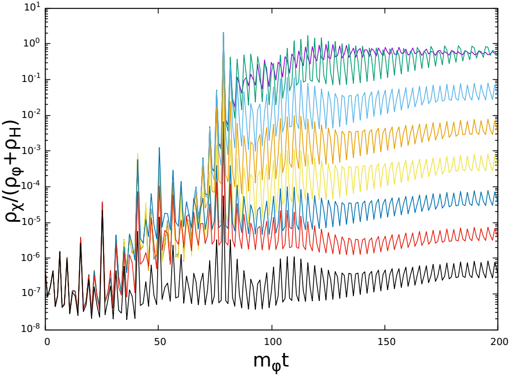


- Blocks lower momentum modes to come into play - Quartic Blocking.
- It becomes more difficult to produce χ-particles with larger λ_χ-values.

Numerical Simulation: LATTICEEASY

Let's pretend this slide is absent for the time being !

- As time goes and the fluctuations grow, these effects begin to show up, Mathieu equation becomes insufficient to describe the preheating dynamics
- Numerical simulations become important to get accurate dynamics
- We use publicly available code LATTICEEASY for the simulation



- Transfer of energy density with growing values of $\lambda_\chi = 10^{-7} - 1$.

Scenario: Sterile Neutrino Sector

- Neutrino oscillation: Neutrinos can change flavour
- A flavour eigenstate is linear combination of mass eigenstates (which evolve in time as hamiltonian eigenstates)

$$|\nu_\alpha >= \sum_{k=1}^{3} U^*_{\alpha k} |\nu_k >$$

$$|\nu_\alpha(t) >= \sum_{k=1}^{3} U^*_{\alpha k} e^{-iE_k t} |\nu_k >$$

- Probability of detecting another flavour at time t,

$$P_{\nu_\alpha \to \nu_\beta} = | < \nu_\beta | \nu_\alpha(t) > |^2 = \sum_{k,j=1}^{3} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} e^{-i(E_k - E_j)t}$$

- For relativistic neutrinos,

$$E_i = \sqrt{|\overrightarrow{p}|^2 + m_i^2} \approx |\overrightarrow{p}| + \frac{m_i^2}{2|\overrightarrow{p}|}$$

$$P_{\nu_\alpha \to \nu_\beta} = \sum_{k,j=1}^{3} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} exp\left(-i \frac{\triangle\ m^2_{kj}}{2|\overrightarrow{p}|} t\right)$$

$\Rightarrow$ *Neutrino Oscillation* (depends on momentum and mass squared difference)

Neutrino Anomalies

- Small Baseline Experiments:
  - LSND and MiniBooNE observed excess in $\bar{\nu}_\mu \to \bar{\nu}_e$ channel
  - MiniBooNE have also indicated an excess of ν_e in the ν_μ beam
- Within a 3+1 framework, MiniBooNE result hints towards the existence of a sterile neutrino with eV mass at 4.8σ significance, which raises to 6.1σ when combined with the LSND data

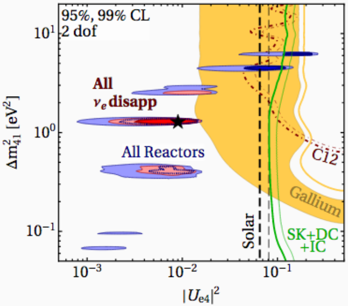
- Daya Bay, NEOS, DANSS and other reactor experiments probed the ν_e disappearance in the $\bar{\nu}_e \to \bar{\nu}_e$ channel
- GALLEX ,SAGE have performed similar measurements in the $\nu_e \to \nu_e$ channel

- Caution: $\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e)$ appearance in LSND and MiniBooNE are in tension with strong constraints on ν_μ disappearance, mostly from MINOS and IceCUBE, while attempting to fit together using a 3+1 framework

- Although debatable in 3+1 framework, such a light additional sterile neutrino, with mixing $\sin\theta \lesssim \mathcal{O}(0.1)$ with the active neutrino species, can be consistent with constraints from various terrestrial neutrino experiments

Neutrino Anomaly

The global picture:



Analysis	Δm^2_{41} [eV^2]	$\lvert U_{e4}\rvert$	$\lvert U_{\mu4}\rvert$	$\chi^2_{\rm min}$/DOF	GOF
$\overset{(-)}{\nu}_e$ disapp (flux fixed)	1.3	0.1	–	552.8/588	85%
$\overset{(-)}{\nu}_e$ disapp (flux free)	1.3	0.095	–	542.9/586	90%

MD, Hernández-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, "Updated Global Analysis of Neutrino Oscillations in the Presence of eV-Scale Sterile Neutrinos," JHEP, 2018

Cosmological Allowance

Cosmology for this extra eV-scale sterile neutrino can be parameterized by 2 main parameters:

1. Total mass of neutrinos $\sum m_{\nu_i}$

$$\Omega_\nu = \frac{\sum m_{\nu_i} n_{\nu,0}}{\rho_{cr,0}} = \frac{\sum m_{\nu_i}}{eV} \frac{1}{94.1(93.1)h^2}$$

2. Effective number of neutrinos $N_{\rm eff}$ $N_{\rm eff}$ affects cosmology through -

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

These equations assume thermalization of the neutrino species. We will next look into the $N_{\rm eff}$ bounds from BBN, CMB & LSS observations.

Constraints from Cosmology: eV sterile neutrino ruled out

- The bounds (from Big Bang Nucleosynthesis, Cosmic Microwave Background & Large Scale Structure) summarized:

$$\triangle N_{\rm eff} \lesssim 0.5$$

$$\sum m_{\nu_i} < 0.16\ eV\ (\mathrm{PLANCK\ TT + Low\ E + BAO})$$

- Conclusion from Standard Cosmology-
Extra neutrino species needed by particle physics is not allowed in cosmology if thermalized

Rescue: If sterile neutrinos involve light dark sectors generating secret interactions within them, they help to relax the bounds.

Saving Sterile Neutrino: Pseudoscalar Interaction

- Saving Sterile Neutrino: Archidiacono et. al. (2014) showed that adding a pseudoscalar interaction can solve the tension -
$$\mathcal{L} \sim g_s \chi \overline{\nu}_s \gamma_5 \nu_s$$
- MSW like potential induced by new interaction with $10^{-4} \gtrsim g_s \gtrsim 10^{-6}$ suppress sterile neutrino production by suppressing mixing angle until after neutrino decoupling, thus not letting it thermalise with plasma
- At late time, annihilation of ν_s to χ particles with chosen $m_\chi \lesssim 0.1$eV can evade the mass bound of neutrinos
- From supernova energy loss argument $g_s \lesssim 10^{-4}$
- Similar results with vector interactions (Dasgupta et. al. (2013)).

Key Assumption: Primoridal density of χ bosons needs to be negligible to avoid these constraints.

Problem with this model

- We investigate from the inflationary epoch

Assume ϕ as inflaton with quadratic potential

$\downarrow$

Constrain $n_s - r$ parameters from PLANCK

$\downarrow$

Produce χ and H by Preheating

$\downarrow$

Study energy density of χ and H

$\downarrow$

ν_s production through $\chi\chi \to \nu_s \nu_s$

$\downarrow$

Understand the parameter space allowed by Cosmology

- A pseudoscalar χ coupled to the inflaton gets produced copiously during preheating
- Such an extra relativistic species in direct conflict with $N_{\rm eff}$ bounds.
- Need to suppress production of χ from preheating - Quartic Blocking.

Now let's go back to the earlier slides we pretended to be absent !

Potential and Parameter Choice

- The scalar potential is,

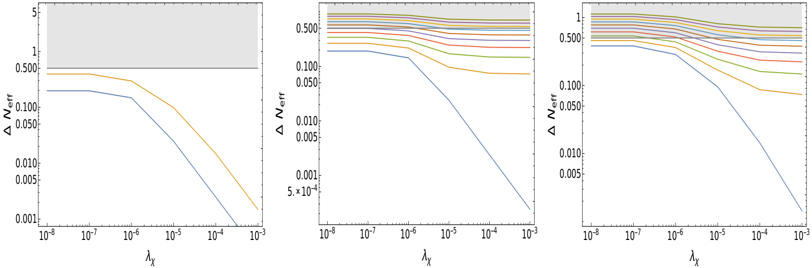
$$V = \frac{m_\phi^2}{2}\phi^2 + \frac{\lambda_\phi}{4}\phi^4 + \frac{\lambda_\chi}{4}\chi^4 + \frac{\lambda_H}{4}|H|^4 + \frac{\sigma_{\phi\chi}}{2}\phi\chi^2 + \frac{\sigma_{\phi H}}{2}\phi|H|^2 + \frac{\lambda_{\phi\chi}}{2}\phi^2\chi^2 + \frac{\lambda_{\phi H}}{2}\phi^2|H|^2 + \frac{\lambda_{\chi H}}{2}\chi^2|H|^2$$

- **Parameter choices:** $m_\phi = 10^{-6}$ $\mathrm{M_{pl}}$ (successful inflation with small non-minimal coupling to gravity $\mathcal{O}(10^{-3})$)
  $\lambda_\phi = 10^{-14}$ (even if kept 0, will be generated through RGE)
  $\lambda_{\phi\chi} = \lambda_{\phi H} = 10^{-7}, 10^{-6}$ ($\gtrsim 10^{-8}$ for efficient preheating, higher value can ruin inflation)
  $\sigma_{\phi H} = 10^{-10}$ and 10^{-8} $\mathrm{M_{pl}}$ (to show two scenarios, one with a non-relativistic phase and one without)
  $\lambda_H = 10^{-7}$ and 10^{-4} (to keep minima of potential at 0,0,0 in field space, avoiding any additional mass term for χ or H)
  $\sigma_{\phi\chi}$ neglected (to avoid additional χ population during decay of ϕ)
  $\lambda_{\chi H}$ neglected (to avoid thermalisation between χ and H)
  λ_χ kept variable to suppress χ production variably

- Isocurvature bounds ($m_H, m_\chi > H$ during inflation) are trivially satisfied for parameter choice of $\lambda_{\phi\chi} = \lambda_{\phi H} = 10^{-7}$

$\triangle N_{\rm eff}$ contribution from χ produced in (p)reheating

Some Results:



- $\lambda_H = 10^{-7}$ &
- $\sigma_{\phi H} = 10^{-10}\ M_{Pl}$.
- $\lambda_{\phi\chi} = \lambda_{\phi H} = 10^{-7}, 10^{-6}$ from bottom to top left panel.
- Central panel: $\lambda_{\phi\chi} = \lambda_{\phi H} = 10^{-7}$, when a fraction of the inflaton ϕ (in decreasing order from bottom to top) decays into χ respectively.
- Right panel: Same as central panel but with $\lambda_{\phi\chi} = \lambda_{\phi H} = 10^{-6}$.

The case for Dark Matter:

- Non-thermal Production of Dark Matter from inflationary (p)-reheating.
- No well-established Detection of DM yet - - points towards feeble DM - SM interactions.
- To keep in mind:
  - Right DM relic, i.e. $\rho_\chi/\rho_{SM} = 5.3$ now
  - BBN bounds on extra relativistic species, i.e. $\rho_\chi/\rho_{SM} \lesssim 0.051$ during BBN
  - Isocurvature bounds

- "Non-thermal production of Dark Matter after Inflation", JCAP (December 2018)

Conclusion: Light Dark Sectors

- Particle production of scalar fields during (p)reheating can be suppressed with a quartic self interaction term.
- **Sterile Neutrino**
  - A sterile neutrino (with eV mass and size-able mixing with active neutrinos) is required to solve neutrino anomalies
  - This species, if thermalised with SM, is highly constrained by $N_{\rm eff}$ bounds from BBN, CMB & LSS.
  - Secret interaction with χ blocks ν_s production from ν_{active} but new production channel opens through $\chi\chi \to \nu_s\nu_s$.
  - To suppress this production channel, χ needs to be of sub-dominant energy-density after (p)reheating.
  - This can be achieved through Quartic blocking.
- **Non-thermal Dark Matter**
  - Production of DM during (p)reheating is novel mechanism.
  - However there is huge transfer of energy density from the inflaton sector to the dark sector.
  - In order to satisfy the relic, Quartic blocking and/or late inflaton decay into H giving rise to a non-relativistic phase & subsequent non-standard evolution like cannibalism, etc. is required.

There will be Gravitational Wave production from such violent preheating. Study currently underway.

Thank You

$$\rho = \frac{1}{2} f_0 \begin{pmatrix} P_a & P_x - iP_y \\ P_x + iP_y & P_s \end{pmatrix}, \qquad (32)$$

where f_0 is the Fermi-Dirac distribution function. The QKEs are now

$$\dot{P}_a = V_x P_y + \Gamma_a \left[2 - P_a\right],$$
$$\dot{P}_s = -V_x P_y + \Gamma_s \left[2 \frac{f_{\mathrm{eq},s}(T_{\nu_s}, \mu_{\nu_s})}{f_0} - P_s\right],$$
$$\dot{P}_x = -V_z P_y - D P_x,$$
$$\dot{P}_y = V_z P_x - \frac{1}{2} V_x (P_a - P_s) - D P_y.$$

and the potentials are:

$$V_x = \frac{\delta m_{\nu_s}^2}{2p} \sin 2\theta_s,$$
$$V_z = -\frac{\delta m_{\nu_s}^2}{2p} \cos 2\theta_s - \frac{14\pi^2}{45\sqrt{2}} p \frac{G_F}{M_Z^2} T^4 n_{\nu_s} + V_s,$$

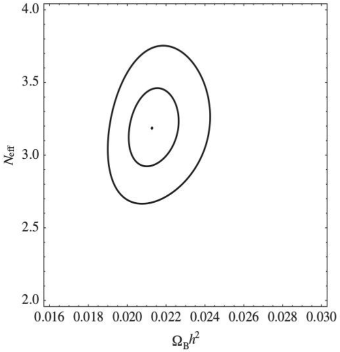
Big Bang Nucleosynthesis (BBN)

- Before nucleosynthesis protons and neutrons were in equilibrium by weak interactions through active neutrinos &

$$\frac{n}{p} = exp\left(\frac{-\triangle\ m}{T}\right)$$

- When $\sigma \sim H$, neutrinos decouple and n:p ratio freezes out.
- Nucleosynthesis (production of light neuclei $^2H, ^3He, ^4He, ^7Li$ from neutron and proton) happens
- Neutrons are unstable $\rightarrow$ only primordial n's present today are preserved in atoms mostly in ^4He

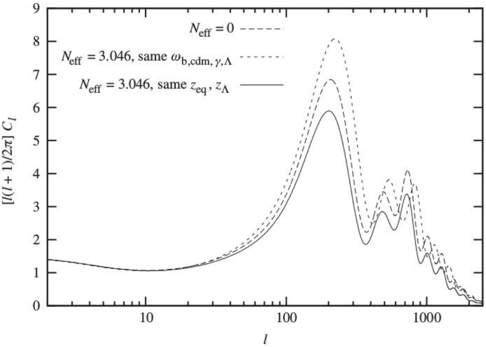
- Larger N_{eff}
  $\rightarrow$ larger radiation density
  $\rightarrow$ larger Hubble parameter
  $\rightarrow$ earlier neutrino decoupling
  $\rightarrow$ larger n:p at freezeout
  $\rightarrow$ larger ^4He abundance
- ^4He abundance data $\rightarrow$ N_{eff} upto 3.5 at 68% CL



- - Lesgourgues et. al. (Neutrino Cosmology)

Cosmic Microwave Background (CMB)

- Larger N_{eff}
  $\rightarrow$ larger radiation density
  $\rightarrow$ later matter radiation equality
  $\rightarrow$ less time between equality and photon decoupling
  $\rightarrow$ smaller sound horizon
  $\rightarrow$ CMB TT peaks at higher l values with higher peak heights
- From CMB Power-Spectrum, analysing Planck data with $\Lambda CDM + N_{eff}$ 7 parameters one can constrain N_{eff}



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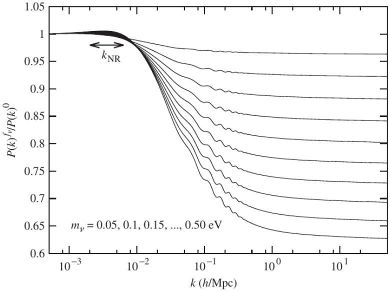
Large Scale Structure (LSS)

- In linear scalar perturbation theory, modes evolve as -

$$\delta_i'' + \frac{a'}{a}\delta_i' + \left(k^2 - \frac{3a^2\mathcal{H}^2}{c_s^2}\right) c_s^2 \delta_i = 0$$

- Neutrino density enters the equation through $\mathcal{H}$ and $\mathcal{H}^2$ term by Friedman equation
- A freestreaming length can be defined under which length scale the perturbation is suppressed -

$$\lambda_{fs}(\eta) = a(\eta)\frac{2\pi}{k_{fs}} = 2\pi\sqrt{\frac{2}{3}}\frac{c_\nu(\eta)}{\mathcal{H}(\eta)}$$



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Suppressed Production

Evolving Boltzmann Equation:

$$\left(\frac{\partial}{\partial t} - HE\frac{\partial}{\partial E}\right) f_{\nu_s}(E,t) = C_{\chi\chi\longrightarrow\nu_s\nu_s} + \frac{1}{2}\sin^2(2\theta_M(E,t)\Gamma(E,t)) \times f_a(E,t) \qquad (15)$$

$$\sin^2(2\theta_M) = \frac{\sin^2(2\theta_0)}{\left(\cos(2\theta_0) + \frac{2E}{\delta m^2}V_{eff}\right)^2 + \sin^2(2\theta_0)}$$

$$V_{\rm eff}^{\rm bubble} = -\frac{7\pi^2 g_s^2 E T_\chi^4}{180 m_\chi^4}$$

On the $m_\chi - g_s$ plane

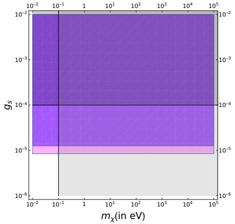

Figure: The blue and magenta regions correspond to the allowed regions in $m_\chi - g_s$ plane from $N_{\rm eff}$ constraints of BBN ($\triangle\ N_{\rm eff} \lesssim 0.5$) for $\theta_0 = 0.1$ *and* 0.05

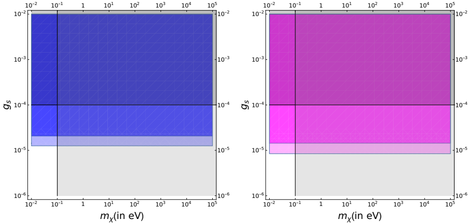

Figure: The region with lighter shade corresponds to the allowed region from $N_{\rm eff}$ constraints of BBN (for $\triangle N_{\rm eff} \lesssim 0.5$). The region with darker shade is the new bound, if χ being produced during (p)reheating leads to a $\triangle N_{\rm eff} = 0.4$. Left and right panels correspond to $\theta_0 = 0.1$ and 0.05.

Some Results:

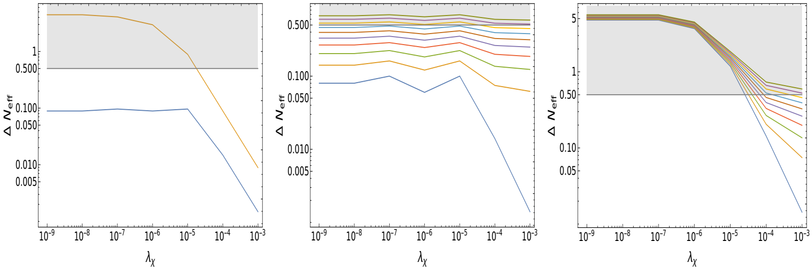

Figure: $\lambda_H = 10^{-4}$, $\sigma_{\phi H} = 10^{-8}\ M_{Pl}$, $\lambda_{\phi\chi} = \lambda_{\phi H} = 10^{-7}, 10^{-6}$ from bottom to top for the left panel. Plots in the centre and right panels correspond to the cases $\lambda_{\phi\chi} = \lambda_{\phi H} = 10^{-7}, 10^{-6}$, when a fraction of the inflaton (0 to 0.1 in steps of 0.01, from bottom to top) decays into χ respectively.