Post-inflationary particle production: Sterile Neutrino with Secret Interactions

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Based on - A. Paul, A. Ghoshal, A. Chatterjee and S. Pal, arXiv:1808.09706 [astro-ph.CO] [1]

Outline of talk:

- Preheating
  - Analytic Understanding
  - Effect of Self Interaction term
  - Numerical Simulations (LATTICEEASY)
- Scenario: Sterile Neutrinos
  - Neutrino Anomalies and introducing Sterile Neutrinos
  - Effects of neutrinos in cosmology
  - Secret Interaction with Pseudoscalar
  - Production from Preheating and constraints
- Conclusion

Pointer: A general problem for all cosmology models which predict light bosonic degrees of freedom with negligible initial abundance - Sterile nu, light DM, asymmetric DM, non-standard neutrino interaction, leptogenesis models, etc. Enhanced production from inflationary reheating.

What is Preheating?

- Inflation:
  - Accelerated expansion of universe at the beginning to solve Horizon problem, Flatness problem, give initial seed fluctuation to explain structure formation
  - Driven generally by energy density stored in a Scalar field, Inflaton
- Dynamics of Inflaton after Inflation:
  - 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 form the classical oscillating inflaton field
  - Any field χ can be decomposed into fourier modes,

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

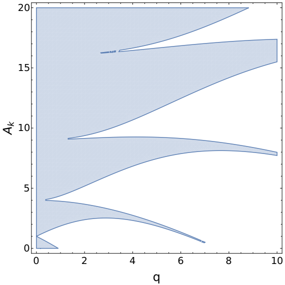
  - Dynamics of the modes χ_k of a field χ are given by Mathieu equation -

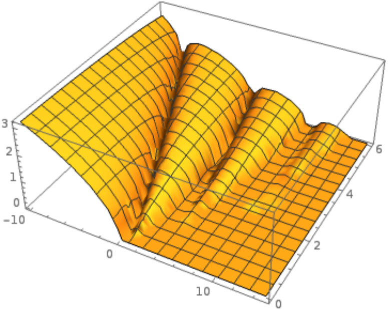
$$\frac{d^2\chi_k}{dz^2} + (A_k - 2q\cos(2z))\chi_k = 0$$

(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

- Mathieu equaton has oscillatory solution in certain regions (blue) of the $A_k - q$ parameter space, and exponentially growing solution at other regions (white) -

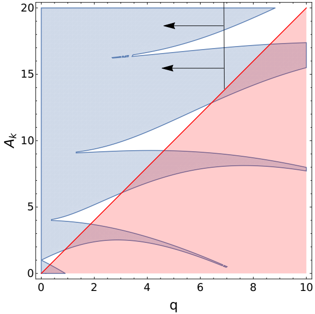




- Growing modes are interpreted as particle production
- For some q, lowest A_k has highest exponent of growing
- In terms of decay process of inflaton into bosons, this exponential growth in certain momentum modes can be understood as Bose enhancement, i.e. when a inflaton decays into two χ particles with momentum $m_\phi/2$, decayrate gets enhanced by a factor $(1 + 2n_k)$, resulting a exponential growth in those modes

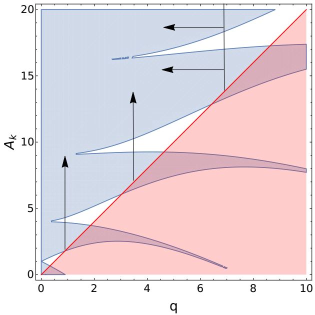
Identifying Growing modes with time

- We have, $q = \frac{\lambda_{\phi\chi}\Phi^2}{4m_\phi^2}$, $A_k = \frac{k^2}{m_\phi^2 a^2} + 2q$
- For an interaction $\frac{1}{2}\lambda_{\phi\chi}\phi^2\chi^2$, an effective mass term of inflaton emerges $m_\phi^{eff} = \sqrt{m_\phi^2 + \lambda_{\phi\chi}\langle\chi^2\rangle}$
- So, with time Φ decreases and m_ϕ^{eff} increases, resulting a decrement in q
- The bands of growing modes gets narrower, but lower momentum modes become growing modes



Effect of Quartic self-interaction of χ

- $\lambda_\chi \chi^4$ 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

Numerical Simulation: LATTICEEASY

- 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

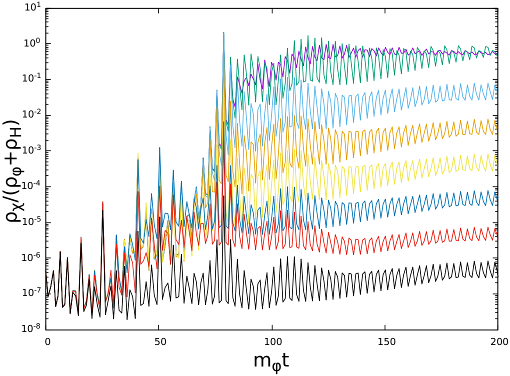


Figure: Quartic blocking - $\lambda_\chi = 10^i$ for i = -7 to 1 (from top to bottom)

Scenario 1: Sterile Neutrino Sector [1]

- 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,

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

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

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

Based on - A. Paul, A. Ghoshal, A. Chatterjee and S. Pal, arXiv:1808.09706 [astro-ph.CO] [1]

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

From Particle Physics and Cosmology

- Conclusions (from PP)-

  1. Neutrinos are massive (atleast (n-1) of n species) and oscillate between flavour eigenstates

  2. Neutrino anomalies can possibly be solved if an extra sterile neutrino with eV mass and sizable mixing with active neutrinos is postulated

- Cosmology is affected mainly by 2 parameters related to neutrinos -
  1. Total mass of neutrinos $\sum m_{\nu_i}$
  2. Effective number of neutrinos $N_{\rm eff}$

  - $\sum m_{\nu_i}$ affects cosmology through -

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

  - $N_{\rm eff}$ 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 neutrino species

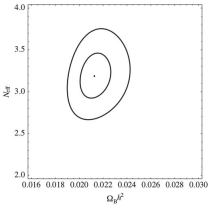
Big Bang Nucleosynthesis (BBN)

- Before nucleosynthesis protons and neutrons were in equilibrium by weak interactions through active neutrinos
- As long as equilibrium holds, n:p ratio decreases exponentially with time -

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

  unless interaction rate becomes comparable to expansion rate H
  $\rightarrow$ reaction seizes
  $\rightarrow$ equilibrium breaks down
  $\rightarrow$ neutrinos decouple and n:p ratio stays frozen
- 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

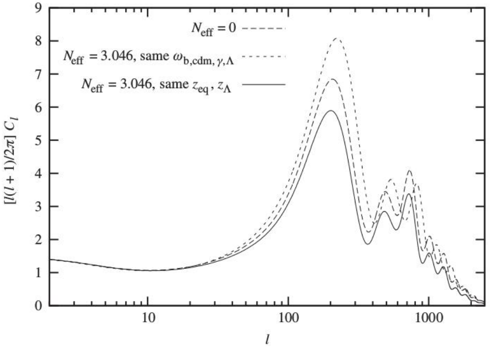
- Larger N_{eff}
  $\rightarrow$ larger radiation density
  $\rightarrow$ larger Hubble parameter
  $\rightarrow$ earlier neutrino decoupling
  $\rightarrow$ larger n:p at freezeout
  $\rightarrow$ larger ^4He abundance
- ^4He abundance data $\rightarrow$ N_{eff} is allowed upto 3.5 at 68% CL



Plot taken from Neutrino Cosmology, Lesgourgues et al

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 PS, adding the extra parameter N_{eff} with the other six, we can constrain N_{eff}



Plot taken from Neutrino Cosmology, Lesgourgues et al

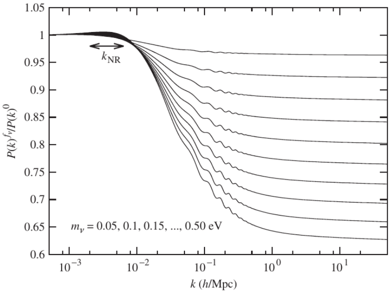
Large Scale Structure (LSS)

- 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 -

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



Plot taken from Neutrino Cosmology, Lesgourgues et al

Constraints from Cosmology and Saving Sterile Neutrino: Pseudoscalar Interaction

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

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

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

- Saving Sterile Neutrino: Hannested et al. 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 $g_s \lesssim 10^{-4}$

Problem with this model

- We start at the inflationary epoch and see if the model fits in there
- Our workplan -

Assume ϕ as inflaton with quadratic potential

$\downarrow$

Constrain related parameters from PLANCK

$\downarrow$

Produce χ and H by Preheating

$\downarrow$

Study energy density of χ and H with parameter variation

$\downarrow$

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

$\downarrow$

Find parameter ranges allowed by Cosmology

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

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

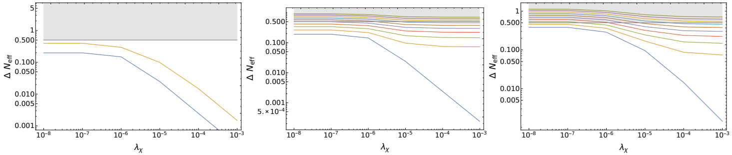
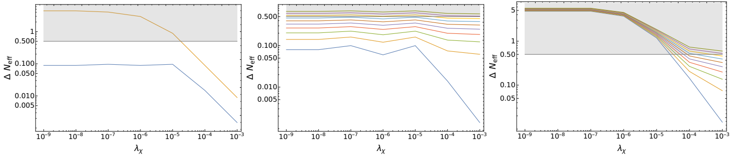


Figure: $\lambda_H = 10^{-7}$, $\sigma_{\phi H} = 10^{-10}\ M_{Pl}$, $\lambda_{\phi\chi} = \lambda_{\phi H} = 10^{-7}, 10^{-6}$ from bottom to top for the left panel. Plots in the centre and right panels correspond to the cases $\lambda_{\phi\chi} = \lambda_{\phi H} = 10^{-7}, 10^{-6}$, when a fraction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



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Additional bounds in $m_\chi - g_s$ plane

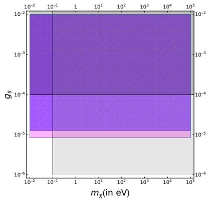


Figure: The blue and magenta regions correspond to the allowed regions in $m_\chi - g_s$ plane from $N_{\rm eff}$ constraints of BBN ($\triangle\ N_{\rm eff} \lesssim 0.5$) for $\theta_0 = 0.1$ *and* 0.05

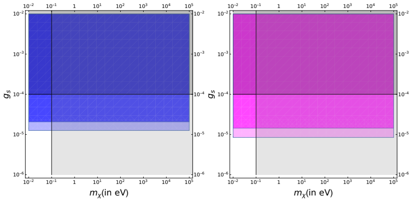


Figure: The region with lighter shade corresponds to the allowed region from $N_{\rm eff}$ constraints of BBN (for $\triangle N_{\rm eff} \lesssim 0.5$). The region with darker shade is the new bound, if χ being produced during (p)reheating leads to a $\triangle N_{\rm eff} = 0.4$. Left and right panels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

Conclusion

- Production of a scalar during preheating can be suppressed with a quartic self interaction term

Conclusion

- Production of a scalar during preheating can be suppressed with a quartic self interaction term
- **Scenario:**
  - A sterile neutrino (with eV mass and sizable 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
  - Secret interaction with χ is required to block ν_s production from ν_{active} upto BBN
  - 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 and/or late inflaton decay into H giving rise to a non-relativistic phase

Thank You

Scenario 2: Dark Matter [2]

- Presence of Dark Matter (DM) χ is motivationally well-established from observations at all scales - Astrophysical to Cosmological

- Production mechanism of DM is not so well-established
  - Standard mechanisms like freeze-out require SM-DM interactions
  - No such hint till now from direct or in-direct searches

- Interesting to explore DM production mechanisms without SM-DM interaction - Production of two uncoupled sectors (DM and SM) from (p)reheating ?

- 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

Based on - N. Bernal, A. Chatterjee and A. Paul, arXiv:1809.02338 [hep-ph] [2]

Initial ρ_χ/ρ_{SM} required

- $\rho_\chi/\rho_{SM} = 5.3$ now, ρ_χ if present from beginning, needs to start much low on density (as depending on their mass m_χ, they become non-relativistic, giving boost to their density)

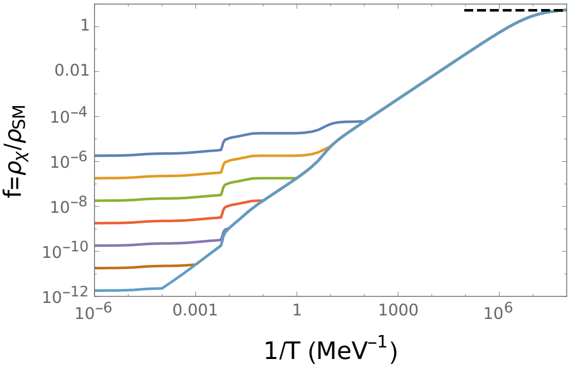


Figure: $m_\chi = 0.01, 0.05, 0.3, 2, 10, 50$ and 300 MeV (from top to bottom)

- BBN bounds are trivially satisfied for $m_\chi \gtrsim 0.01$ MeV as clear from figure

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)
  $\lambda_{\phi\chi} = \lambda_{\phi H} = 10^{-7}$ ($\gtrsim 10^{-8}$ for efficient preheating, higher value can ruin inflation)
  $\lambda_H = 10^{-7}$ (to prevent quartic blocking of Higgs)
  $\sigma_{\phi H} = 10^{-10}\ \mathrm{M_{pl}}$ (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 $\lambda_{\phi\chi} = \lambda_{\phi H} = 10^{-7}$

Production from Preheating with Quartic Blocking

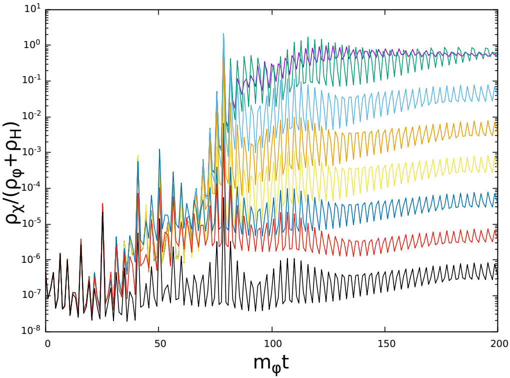
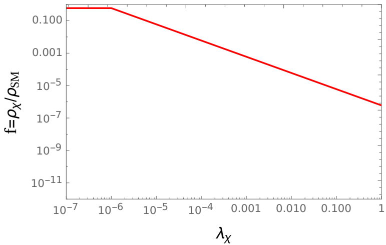
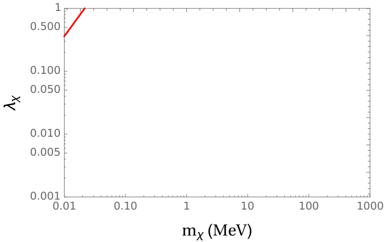


Figure: Result from LATTICEEASY with $\lambda_\chi = 10^i$ for i = -7 to 1 (from top to bottom)

Is Quartic Blocking enough for right DM relic ?





- **Yes**, for a very small range of m_χ

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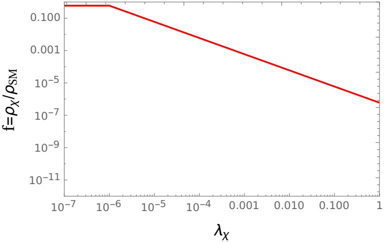

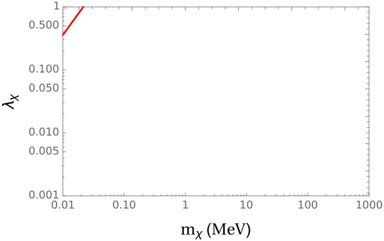

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- But, Bullet cluster excludes $\sigma/m_\chi > 1.25\ \text{cm}^2/\text{g}$

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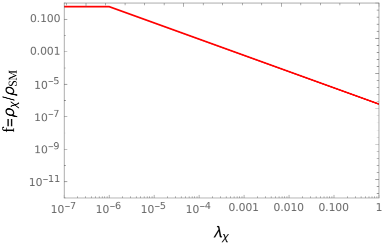

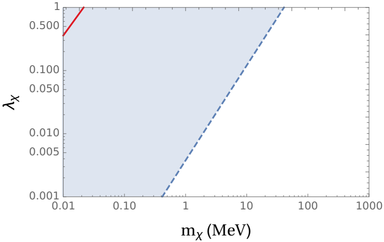

- **Yes**, for a very small range of m_χ
- But, Bullet cluster excludes $\sigma/m_\chi > 1.25\ \text{cm}^2/\text{g}$

Suppression due to non-relativistic phase of inflaton

- After preheating, a similar amount of energy density (like H) is still stored in inflaton
- Reheating ends when this left over energy density decays into other visible or dark sectors
- $\sigma_{\phi H}$ and $\sigma_{\phi\chi}$ helps to decay inflaton into H and χ
- $\sigma_{\phi\chi}$ is kept negligible *w.r.t* other parameters in order to avoid population of already overpopulated χ sector
- Decay energy scale of inflaton depends solely on $\sigma_{\phi H}$
- If inflaton decays (only to H) after it becomes non-relativistic, ρ_χ/ρ_{SM} gets additional depletion by a factor a_d/a_t (where a_d is scale factor during decay of inflaton and a_t id scale factor when inflaton becomes non-relativistic) as matter scales as $1/a^3$ and radiation scales as $1/a^4$
- So, by changing $\sigma_{\phi H}$ we can vary a_d/a_t, resulting additonal suppression as required to get right DM relic evading Bullet cluster bounds

Suppression by a_d/a_t

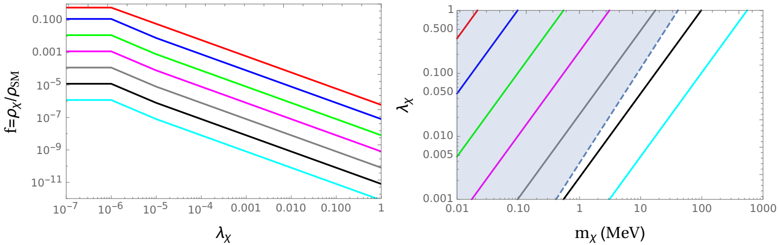

Figure: Lines from top to bottom corresponds to $a_d/a_t = 10^i$ for $i = 0$ to 6

Additional Depletion via Cannibalization

- Having a quartic self coupling $\lambda_\chi \chi^4$ gives rise to additional suppression of DM energy density through **cannibalization** mechanism
- This energy density suppression happens due to number depleting 4-2 scattering processes, described by Boltzman equation

$$\frac{dn}{dt} + 3\,H(T)\,n = -\langle \sigma v^3 \rangle_{4\to2} \left[n^4 - n^2\, n_{eq}^2 \right], \tag{1}$$

with $\langle \sigma v^3 \rangle_{4\to2} \sim \frac{27\sqrt{3}}{8\pi} \frac{\lambda_\chi^4}{m_\chi^8}$

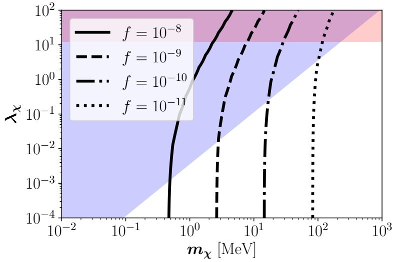

Figure: Values of f that yield the observed DM relic density, in the $(m_\chi,\ \lambda_\chi)$ plane

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  - Secret interaction with χ is required to block ν_s production from ν_{active} upto BBN
  - New production channel opens through $\chi\chi \to \nu_s\nu_s$
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- **Scenario 2:**
  - Standard DM production mechanisms like freeze-out require SM-DM interaction
  - Non-observation of any such hint in the direct and indirect searches lead us to explore non-thermal production processes without need of SM-DM interaction
  - We explore production of DM from preheating, and find that it generally overproduces
  - Quartic blocking can suppress production of DM during preheating, but that parameter region is excluded by Bullet cluster observations
  - Additional depletion of DM/SM ratio by a non-relativistic phase of inflaton before it decays to SM and Cannibalization mechanism can give right DM relic avoiding Bullet cluster bounds