Post-inflationary Production of Light Dark Sectors

Anish Ghoshal

Laboratorie Nazionale Frascati - INFN
University Roma Tre

anishghoshal1@gmail.com

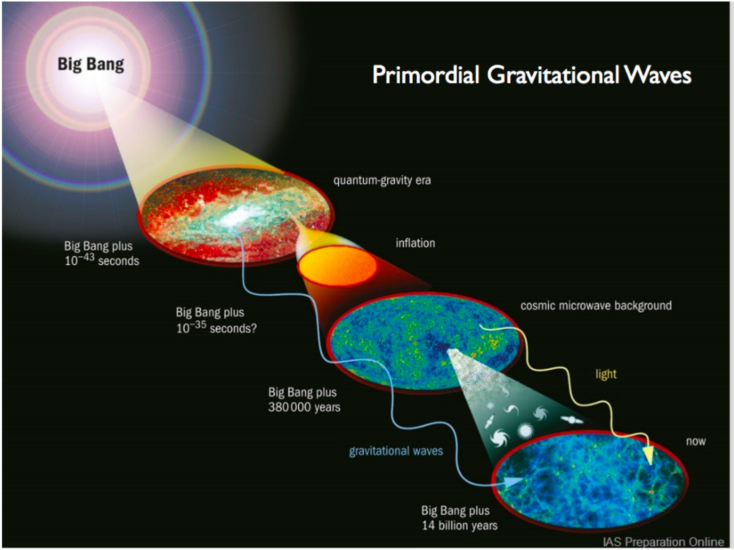
November, 2019 LNF-INFN

Based on - arXiv:1808.09706
arXiv:1809.02338
arXiv: 2001.xxxxx

Outline of talk:

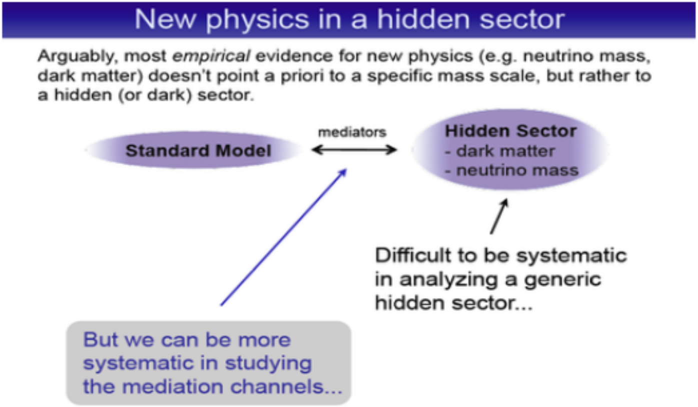
- Light Dark Sectors in Particle Physics
- Inflationary (P)reheating
  - Analytic Understanding
  - Bose Enhancement
  - Numerical Simulations (`LATTICEEASY`)
- Scenario: Sterile Neutrinos
  - Neutrino Anomalies - Sterile Neutrinos
  - Cosmological Bounds.
  - Secret Interaction in Dark Sector.
  - Production from Preheating and constraints
- Scenario: Dark Matter
  - Non-thermal Dark Matter.
  - New Production Mechanism from (P)reheating.
  - Secret Interaction in Dark Sector.
  - Production from Preheating and constraints.
- Primordial Gravitational Waves.
- 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.....



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,

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

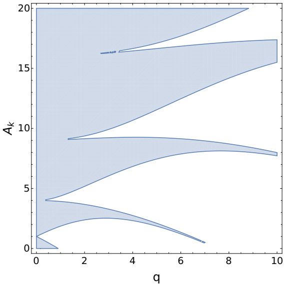
  - Dynamics of the modes χ_k of a field χ are given by Mathieu equation -

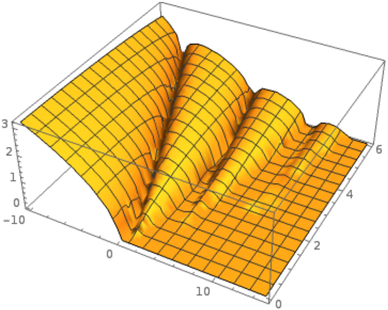
$$\frac{d^2\chi_k}{dz^2} + (A_k - 2q\cos(2z))\chi_k = 0$$

(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

Quantum process

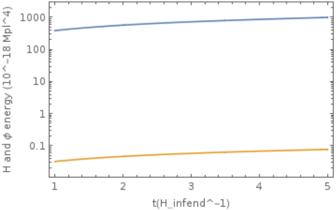
- Energy of each mode -

$$E_k = \frac{1}{2}(\dot{\chi_k}^2 + \omega_k^2 \chi_k^2) - \frac{1}{2}\omega_k$$

- Total energy stored as particles -

$$E \sim \int_0^\infty E_k k^2 dk$$

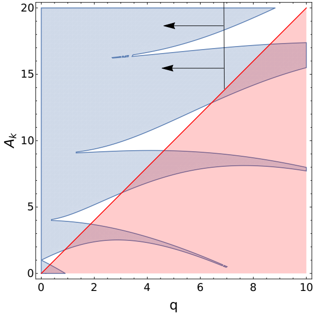
- Typical plot of energy vs time for $\lambda \sim 10^{-12}$, $\frac{\lambda_{H\phi}}{\lambda} \sim 10^3$ -



- 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

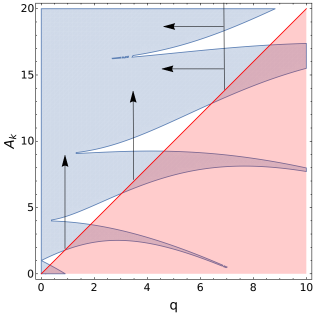
- We have, $q = \frac{\lambda_{\phi\chi}\Phi^2}{4m_\phi^2}$, $A_k = \frac{k^2}{m_\phi^2 a^2} + 2q$
- For an interaction $\frac{1}{2}\lambda_{\phi\chi}\phi^2\chi^2$, an effective mass term of inflaton emerges $m_\phi^{eff} = \sqrt{m_\phi^2 + \lambda_{\phi\chi}\langle\chi^2\rangle}$
- So, with time Φ decreases 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

Let's pretend this slide is absent !

- $\lambda_\chi \chi^4$ 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

Let's also pretend this slide is absent !

- 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

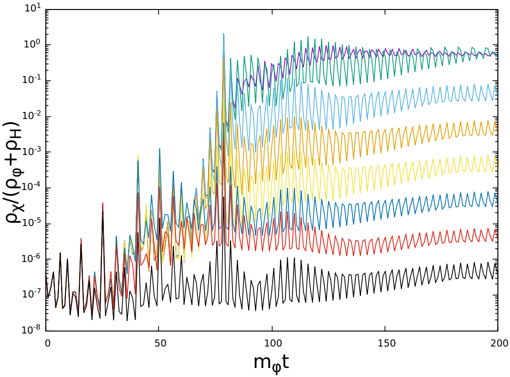


Figure: Quartic blocking - $\lambda_\chi = 10^i$ for i = -7 to 1 (from top to bottom)

Scenario: 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,

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

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

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

Neutrino Anomalies

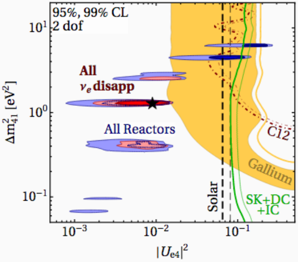
- Small Baseline Experiments:
  - LSND and MiniBooNE observed excess in $\bar{\nu}_\mu \to \bar{\nu}_e$ channel
  - MiniBooNE have also indicated an excess of ν_e in the ν_μ beam
- Within a 3+1 framework, MiniBooNE result hints towards the existence of a sterile neutrino with eV mass at 4.8σ significance,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



Analysis	Δm^2_{41} [eV^2]	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	χ^2_{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

From Particle Physics and Cosmology

- Conclusions (from PP)-
  1. Neutrinos are massive 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_{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_{eff} affects cosmology through -

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

  - 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 -

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

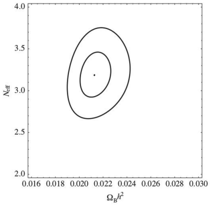
  unless interaction rate becomes comparable to expansion rate H

  $\rightarrow$ 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

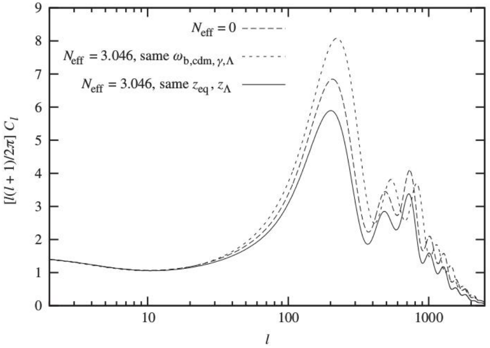
- Larger N_{eff}
  $\rightarrow$ larger radiation density
  $\rightarrow$ larger Hubble parameter
  $\rightarrow$ earlier neutrino decoupling
  $\rightarrow$ larger n:p at freezeout
  $\rightarrow$ larger ^4He abundance
- ^4He abundance data $\rightarrow$ N_{eff} is allowed upto 3.5 at 68% CL



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

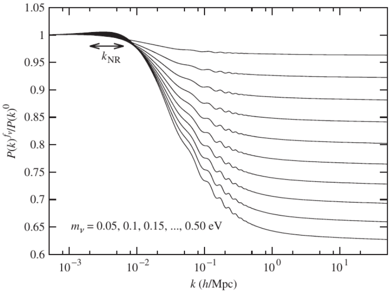
Large Scale Structure (LSS)

- 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: eV sterile neutrino ruled out

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

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

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

How to save: Involve light dark sectors among the neutrinos. They help to loosening the bounds.

Saving Sterile Neutrino: Pseudoscalar Interaction

- 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 $g_s \lesssim 10^{-4}$

Most Imp: Primoridal density of χ bosons needs to be negligible to avoid these constraints.

Suppressed Production

Boltzmann Equation:

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

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

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

Problem with this model

Now let's stop pretending !

- 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_{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

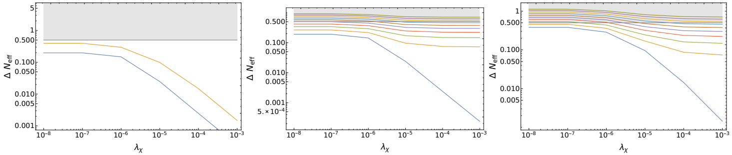


Figure: $\lambda_H = 10^{-7}$, $\sigma_{\phi H} = 10^{-10}\ M_{Pl}$, $\lambda_{\phi\chi} = \lambda_{\phi H} = 10^{-7}, 10^{-6}$ from bottom to top for the left panel. Plots in the centre and right panels correspond to the cases $\lambda_{\phi\chi} = \lambda_{\phi H} = 10^{-7}, 10^{-6}$, when a fraction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

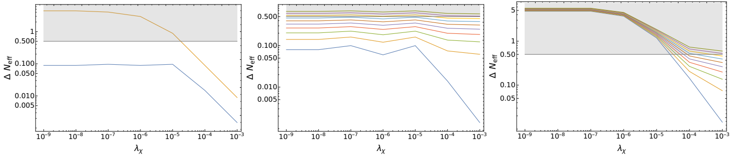


Figure: $\lambda_H = 10^{-4}$, $\sigma_{\phi H} = 10^{-8}\ M_{Pl}$, $\lambda_{\phi\chi} = \lambda_{\phi H} = 10^{-7}, 10^{-6}$ from bottom to top for the left panel. Plots in the centre and right panels correspond to the cases $\lambda_{\phi\chi} = \lambda_{\phi H} = 10^{-7}, 10^{-6}$, when a fraction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

On the $m_\chi - g_s$ plane

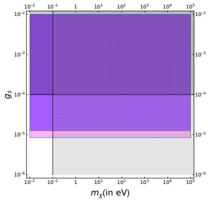


Figure: The blue and magenta regions correspond to the allowed regions in $m_\chi - g_s$ plane from $N_{\rm eff}$ constraints of BBN ($\triangle\ N_{\rm eff} \lesssim 0.5$) for $\theta_0 = 0.1$ *and* 0.05

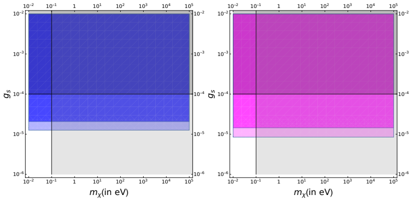


Figure: The region with lighter shade corresponds to the allowed region from $N_{\rm eff}$ constraints of BBN (for $\triangle N_{\rm eff} \lesssim 0.5$). The region with darker shade is the new bound, if χ being produced during (p)reheating leads to a $\triangle N_{\rm eff} = 0.4$. Left and right panels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

Scenario: Dark Matter

- 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]

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)

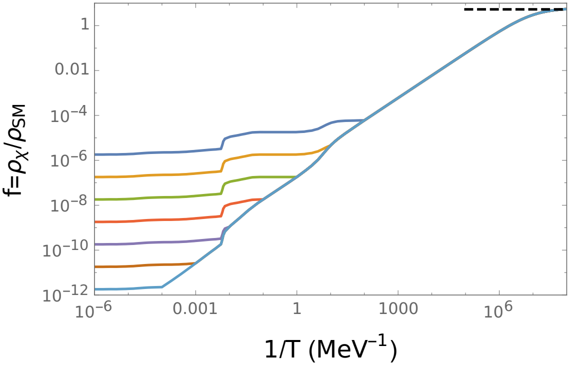


Figure: $m_\chi = 0.01, 0.05, 0.3, 2, 10, 50$ and 300 MeV (from top to bottom)

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

Potential and Parameter Choice

- The scalar potential is,

$$
\begin{aligned}
V \quad = \quad & \frac{m_\phi^2}{2}\phi^2 + \frac{\lambda_\phi}{4}\phi^4 + \frac{\lambda_\chi}{4}\chi^4 + \frac{\lambda_H}{4}|H|^4 + \frac{\sigma_{\phi\chi}}{2}\phi\chi^2 + \frac{\sigma_{\phi H}}{2}\phi|H|^2 \\
& + \frac{\lambda_{\phi\chi}}{2}\phi^2\chi^2 + \frac{\lambda_{\phi H}}{2}\phi^2|H|^2 + \frac{\lambda_{\chi H}}{2}\chi^2|H|^2
\end{aligned}
$$

- **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

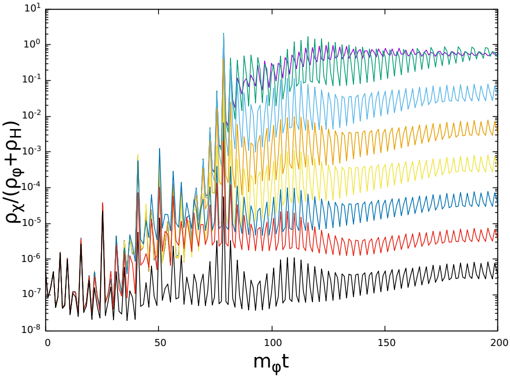
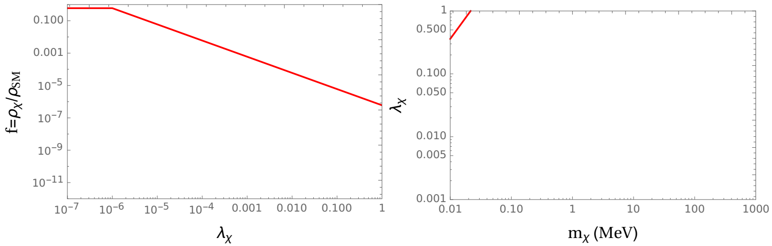


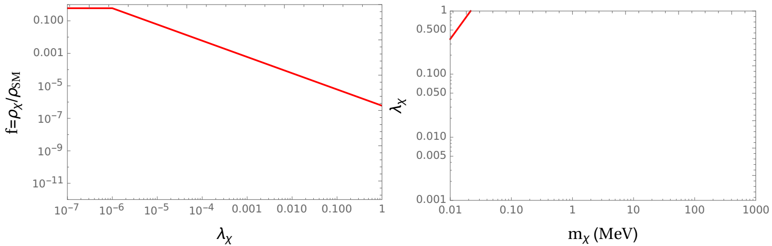
Figure: Result from LATTICEEASY with $\lambda_\chi = 10^i$ for i = -7 to 1 (from top to bottom)

Is Quartic Blocking enough for right DM relic ?



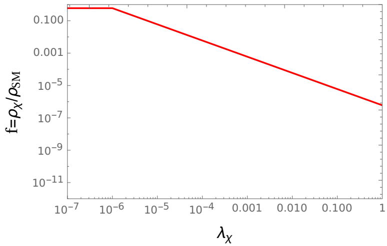
- **Yes**, for a very small range of m_χ

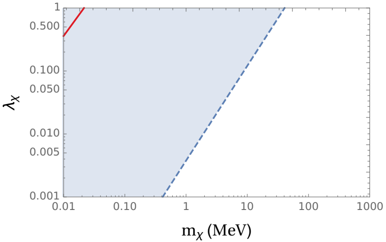
Is Quartic Blocking enough for right DM relic ?



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

Is Quartic Blocking enough for right DM relic ?





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

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

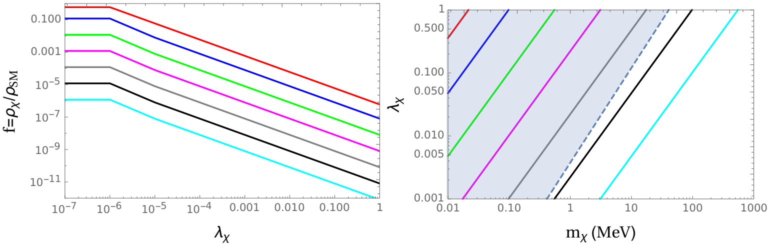


Figure: Lines from top to bottom corresponds to $a_d/a_t = 10^i$ for $i = 0$ to 6

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

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

with $\langle \sigma v^3 \rangle_{4\to 2} \sim \frac{27\sqrt{3}}{8\pi} \frac{\lambda_\chi^4}{m_\chi^8}$

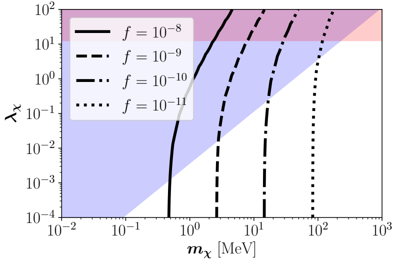


Figure: Values of f that yield the observed DM relic density, in the $(m_\chi,\ \lambda_\chi)$ plane

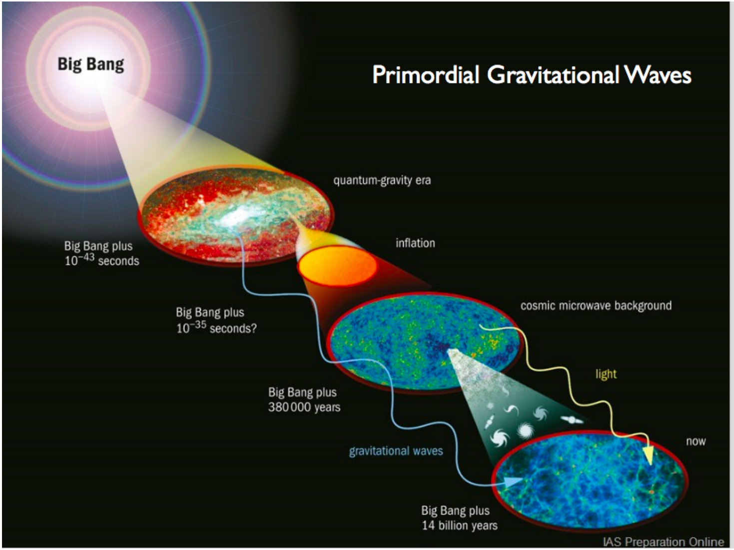
Conclusion: Light Dark Sectors

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

Conclusion: Light Dark Sectors

- Production of a scalar during preheating can be suppressed with a quartic self interaction term
- **Scenario: 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
  - 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
- **Scenario: DM**
  - Non-thermal DM candidates are motivated from null results from DM experiments.
  - Production of DM during (p)reheating is novel mechanism for dark matter production.
  - However there is huge transfer of energy density in the dark sector.
  - This is achieved by postulating depletion factors, or
  - 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

History of the Universe



Propagation of Primordial GW generated during Inflation:

$$\ddot{h}_{ij} + 3H\,\dot{h}_{ij} + \frac{k^2}{a^2} h_{ij} = 16\pi\, G\, \Pi_{ij}^{TT}\,, \tag{2}$$

Solution:

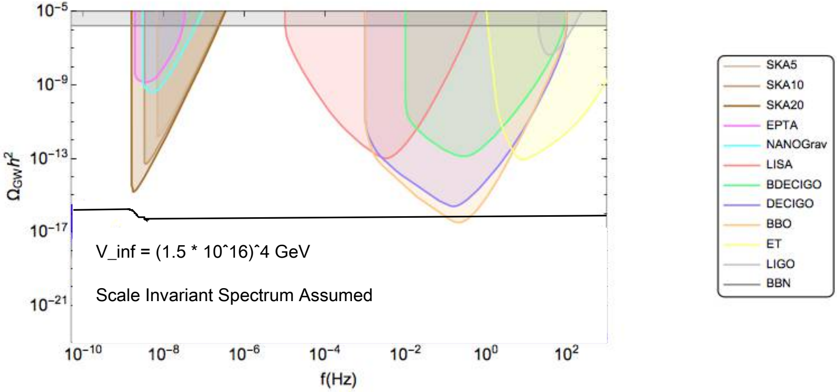
$$h_{ij}(t,\vec{x}) = \sum_P \int \frac{d^3k}{(2\pi)^3}\, h^P(t,\vec{k})\, \epsilon_{ij}^P(\vec{k})\, e^{i\,\vec{k}\cdot\vec{x}}, \tag{3}$$

$$h_{\vec{k}}^P = h_{\vec{k},0}^P\, U(t,k)\,, \tag{4}$$

$$\Pi_{ij} = \frac{T_{ij} - p\, g_{ij}}{a^2} \tag{5}$$

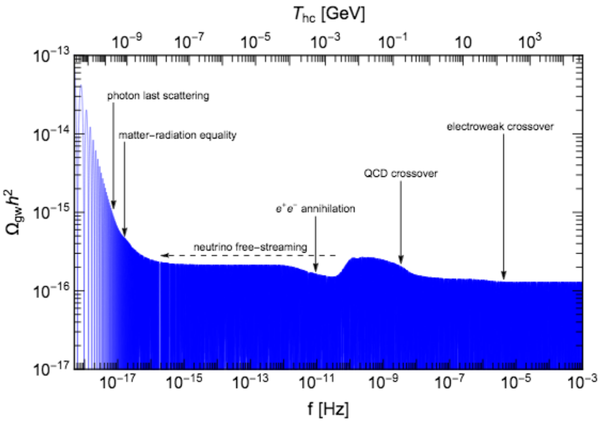
$$\Omega_{GW}(\eta,k) = \frac{1}{12\, a^2(\eta)\, H^2(\eta)} \mathcal{P}_T(k)\, \left[U'(\eta,\ k)\right]^2 \tag{6}$$

On the GW sensitivity Map



$$P_T = \frac{2}{3\pi^2}\frac{V_{inf}}{M_{pl}^4}.$$

History of the Universe



[Ref. 1803.01038]

Questions to Answer:

- Can we have large signal even if initial Amplitude is small ?
- Probes of new physics under these scenarios ?

Thank You

Backup:Suppressed Production

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

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

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

and the potentials are:

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

Figure: