Sterile neutrino dark-matter from inflaton decay

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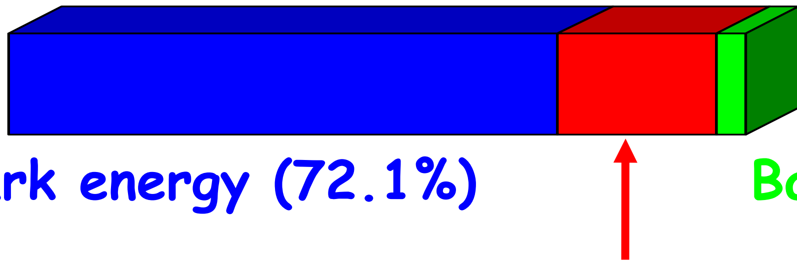
with H. Nagao and N. Tsutsumi @Niigata Univ.

Dark Matter

- Content of the universe



- What is dark matter???
  - No candidate in the MSM

New Physics !!

Dark Matter

- Content of the universe

Sterile Neutrino
as
Dark Matter

New Physics !!

Neutrino oscillations

- Evidence of neutrino oscillations
  - → Non-zero neutrino masses
  - **Atmospheric** $\Delta m^2_{\rm atm} \simeq 2.5 \times 10^{-3}\,{\rm eV}^2$
    - Atmospheric neutrino exps. (…, SuperK)
    - Long-baseline accelerator exps. (K2K, MINOS)
  - **Solar** $\Delta m^2_{\rm sol} \simeq 8.0 \times 10^{-5}\,{\rm eV}^2$
    - Solar neutrino exps. (…, SuperK, SNO)
    - Reactor exp. (KamLand)
- Neutrinos are massless in the MSM

New Physics !!

The νMSM

TA, Blanchet, Shaposhnikov
TA, Shaposhnikov

- Adding **three right-handed neutrinos**

  N1, N2, N3

$$\mathcal{L}_{\nu\mathrm{MSM}} = \mathcal{L}_{\mathrm{MSM}} + i\overline{N}_I \partial\!\!\!/ N_I - F_{\alpha I}\overline{L}_\alpha \Phi N_I - \frac{M_I}{2}\overline{N}_I^c N_I + h.c.$$

  - Dirac and Majorana masses of neutrinos

$$M_D = F\langle\Phi\rangle \qquad M_M = M_I$$

- Key point

$$|M_D| \ll M_M < \mathcal{O}(\Lambda_{\mathrm{EW}}) = 10^2 \text{ GeV}$$

The νMSM (2005)

- Lightest RH neutrino can be DM

  [Dodelson, Widrow,…]

- Oscillation of RH neutrinos can account for baryon asymmetry of the universe

  [Akhmedov, Rubakov, Smirnov/TA, Shaposhnikov]

- Physics of RH neutrinos can potentially tested by experiments

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Simplest scenario
is ruled out!!

- Physics of RH neutrinos can potentially tested by experiments

The νMSM + scalar (2007~)

[Shaposhnikov, Tkachev]

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Dark Matter in the νMSM

Dark matter in the νMSM

- Unique candidate:

  lightest sterile (RH) neutrino N1

  Dodelson, Widrow / Shi, Fuller / Dolgov, Hansen / Abazajian, Fuller, Patel

  - Massive active neutrinos cannot be dark matter !!

    Too "hot" (hot dark matter) [WMAP 5yr]

    $$\sum m_\nu < 0.61\,\mathrm{eV} \Rightarrow \Omega_\nu h^2 = \frac{\sum m_\nu}{93\,\mathrm{eV}} < 0.0066$$

    But, we need $\Omega_{\rm dm} h^2 = 0.1143 \pm 0.0034$

Decays of sterile neutrino

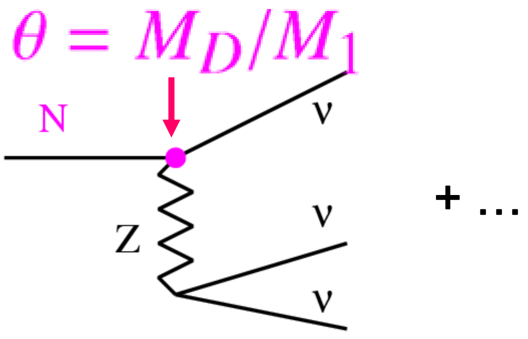
- N1 is not completely stable particle !
  - Dominant decay:

    $N_1 \to 3\nu$ for $M_1 \sim$ keV

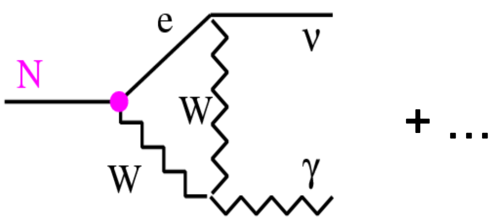
  - **Lifetime can be very long**

$$\tau_{N_1} \simeq 5 \cdot 10^{26}\text{sec}\left(\frac{\text{keV}}{M_1}\right)^5\left(\frac{10^{-8}}{\theta^2}\right)$$

$$[\tau_{\text{Univ}} \sim 10^{17}\,\text{sec}]$$



- N1 is not completely dark !
  - Subdominant decay: $N_1 \to \nu + \gamma$



Production of sterile neutrino

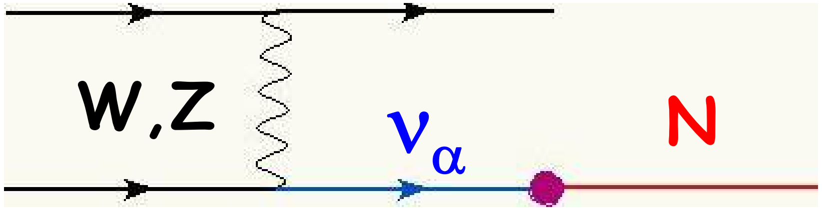
- To realize sterile neutrino DM, $\Omega_{N_1} = \Omega_{\mathrm{dm}}$
  - *How are they produced???*
- In the early universe,
  - Interaction rate of N1 was very small:
    - Typically, $\Gamma_{\mathrm{int}} \sim f_\nu^2 T$

$$\Gamma_{\mathrm{int}} > H \sim T^2/M_{\mathrm{pl}} \Rightarrow \quad f_\nu \gtrsim \sqrt{\frac{T}{M_{\mathrm{pl}}}} \sim 10^{-8} \left(\frac{T}{100\mathrm{GeV}}\right)^{1/2}$$

  - We will be interested in $f_\nu = O(10^{-12})$
    → N1 was not thermalized !

Production of sterile neutrino

- Dodelson-Widrow scenario:
  - Production via active-sterile neutrino mixing θ



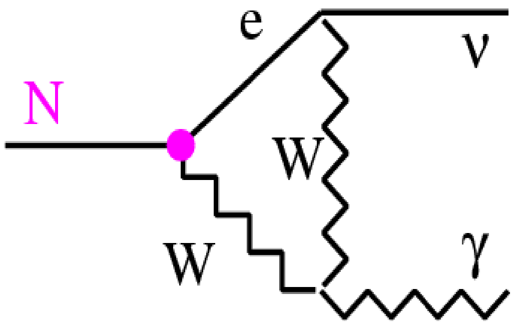
  - Dominant production at $T_* \simeq 100\text{MeV}\,(M_1/\text{keV})^{1/3}$

- Recently, we improve the estimate of the abundance

TA, Laine, Shaposhnikov JHEP06 ('06) 053 [hep-ph/0606209]
TA, Laine, Shaposhnikov [hep-ph/0612182]

Constraints from X-rays

- Radiative decays of sterile neutrino DM



via active-sterile mixing θ

- feature in X-ray background spectrum
- line X-ray from clusters, galaxies, dwarf galaxies…
  - TEST for sterile neutrino DM!
  - No signal → Upper bound on mixing angle !

Constraints from structure formation

- Light sterile neutrino = WDM

$$\lambda_{FS} \sim \text{Mpc}\left(\frac{\text{keV}}{M_1}\right)\frac{\langle|\mathbf{q}_s|\rangle}{\langle|\mathbf{q}_a|\rangle}$$

  - Lower bound on mass $M_1 > \frac{\langle|\mathbf{q}_s|\rangle}{\langle|\mathbf{q}_a|\rangle} M_0$

- From Ly-α forest observations

(1) $M_0 \simeq 10\text{keV}$	Viel et al '06	$M_1 > 8\text{keV}$
(2) $M_0 \simeq 14\text{keV}$	Seljak et al '06	$M_1 > 12\text{keV}$
(3) $M_0 \simeq 28\text{keV}$	Viel et al '08	$M_1 > 22\text{keV}$

We find: $\frac{\langle|\mathbf{q}_s|\rangle}{\langle|\mathbf{q}_a|\rangle} \simeq 0.8$ for $M_1 \simeq 10\text{keV}$

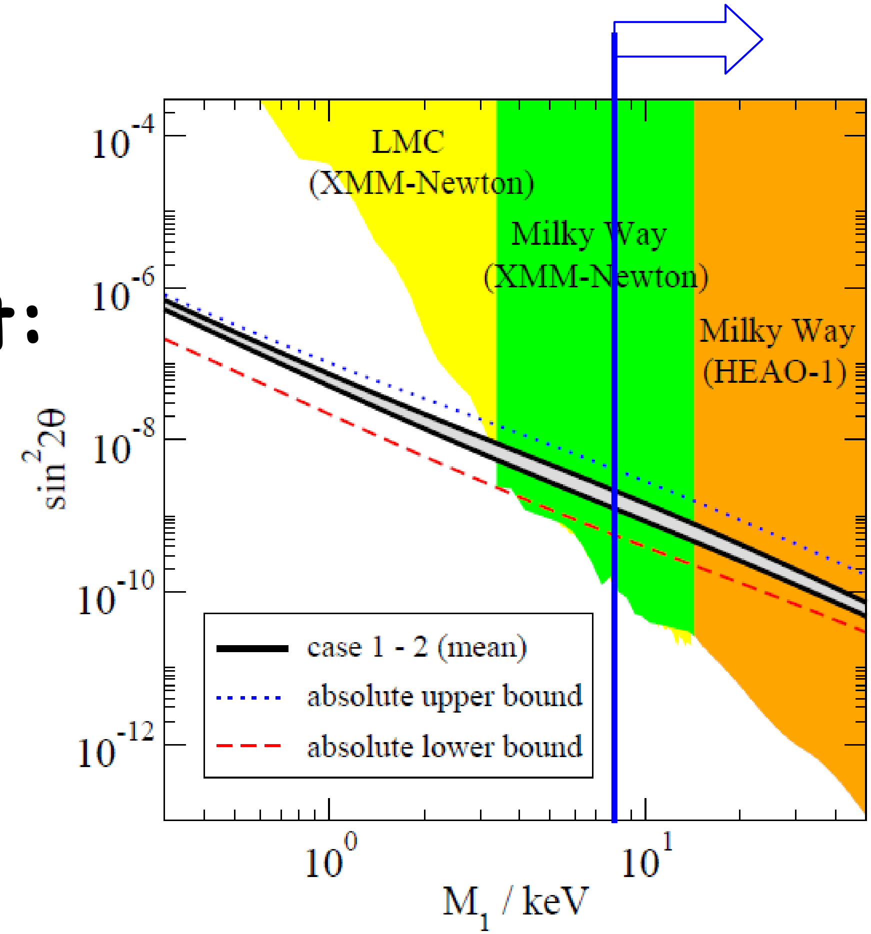
Parameter space

- **X-ray constraint:**

  $M_1 \lesssim 6$ keV

- **Ly-alpha constraint:**

  $M_1 \gtrsim 8\text{keV}$



The Dodelson-Widrow scenario is ruled out in spite of all theoretical uncertainties !

The νMSM (2007)

- ~~Lightest RH neutrino can be DM~~
  ~~[Dodelson, Widrow,…]~~
- Oscillatio… RH neutrinos can account for bary… e
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The νMSM + scalar (2007~)

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- A scalar causes cosmic inflation

  [Shaposhnikov, Tkachev]

Sterile neutrino dark-matter from inflaton decay

The νMSM + inflaton [Shaposhnikov, Tkachev]

- Adding **a real scalar** χ

$$\mathcal{L} = \mathcal{L}_{\mathrm{MSM}}[-V(\Phi)] + i\overline{N}_I \partial\!\!\!/ N_I - F_{\alpha I}\overline{L}_\alpha \Phi N_I + h.c. + \frac{1}{2}(\partial_\mu \chi)^2 - \frac{y_I}{2}\chi \overline{N_I^c} N_I + h.c. - V(\Phi,\chi)$$

- Roles of χ
  - Origin of Majorana masses

$$M_I = y_I \langle \chi \rangle$$

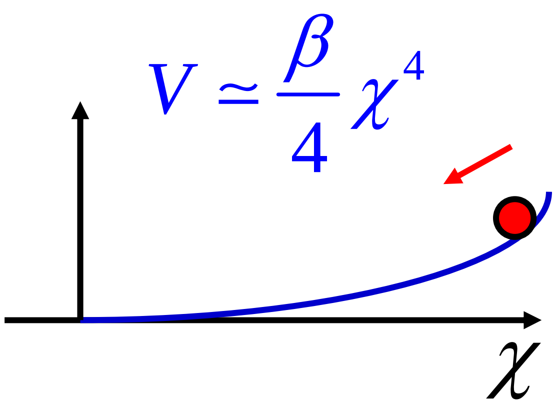
  - Cosmic inflation

Chaotic inflation

$$V = \lambda\left(|\Phi|^2 - \frac{\alpha}{\lambda}\chi^2\right)^2 + \frac{\beta}{4}\chi^4 - \frac{m_0^2}{2}\chi^2$$ → almost scale invariant

- Along the flat direction

  "chaotic inflation" occurs



- To explain the CMBR fluctuations,

$$\beta = 1.4 \times 10^{-13}$$

Dark matter in this scenario

- Lightest sterile neutrino **N1**
- Z2-symmetry: $N_1 \leftrightarrow -N_1$ for $F_{\alpha 1} \to 0$

$$\mathcal{L}_{N_1} = i\overline{N}_I \partial\!\!\!/ N_I - F_{\alpha 1}\overline{L}_\alpha \Phi N_1 - \frac{y_1}{2}\chi \overline{N}_I^c N_I + h.c.$$

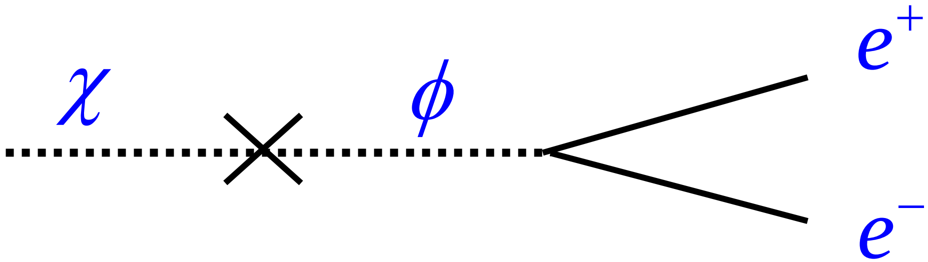
  - N1 becomes completely stable !
    → No X-ray constraint

- N1 is produced by inflaton decay

$$\mathcal{L}_{\text{int}} = -\frac{y_I}{2}\chi \overline{N}_I^c N_I + h.c.$$

Production of dark matter

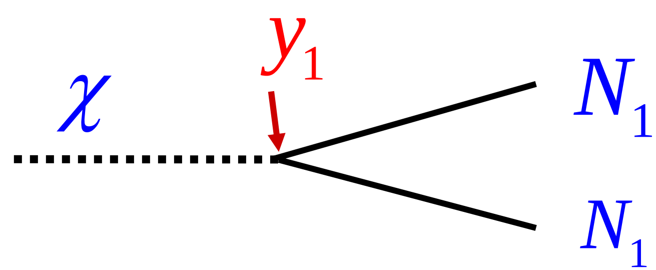
- Light inflaton was thermalized



→ **Inflaton was abundant for** $T > m_\chi$

- Decay of such an inflaton produces sterile neutrinos

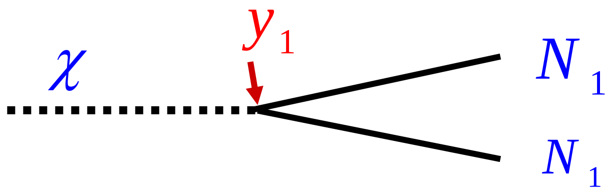
$$\mathcal{L}_{\rm int} = -\frac{y_I}{2}\chi \overline{N_I^c} N_I + h.c.$$



Abundance of dark matter

- **Kinetic eq. for distribution function** f_{N_1}

$$\frac{\partial f_{N_1}(t,q)}{\partial t} - Hq\frac{\partial f_{N_1}(t,q)}{\partial q} = \frac{2m_\chi \Gamma}{q^2}\int f_\chi(t,q)\,dE$$



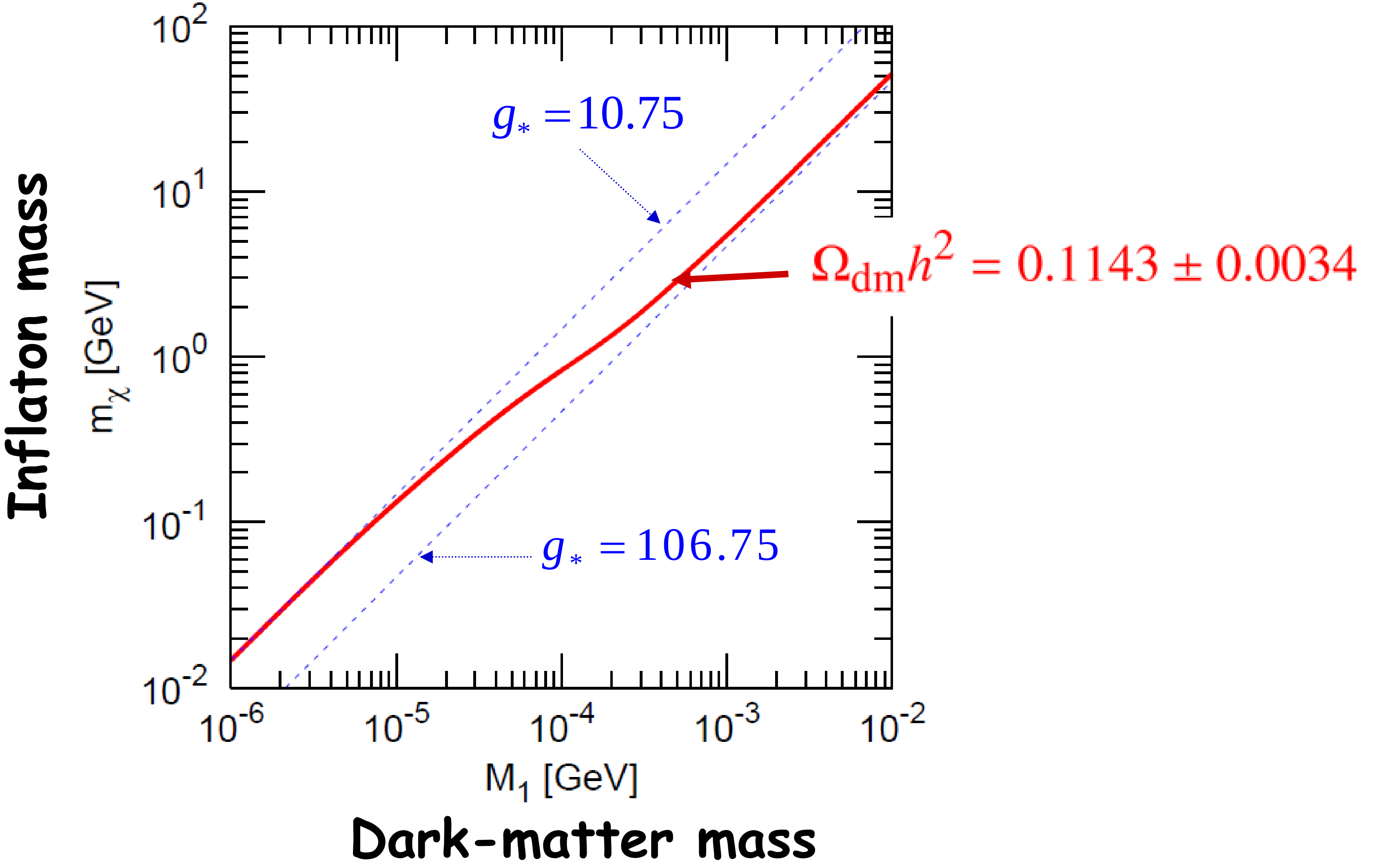
$$\Gamma = \frac{y_1^{\,2} m_\chi}{16\pi} \qquad f_\chi = 1/(e^{E/T}-1)$$

$$y_1^{\,2} = \frac{M_1^{\,2}}{\langle\chi\rangle^2} = 2\beta\frac{M_1^{\,2}}{m_\chi^{\,2}} \qquad [\beta = 1.4\times10^{-13} \leftarrow \text{inflation}]$$

- **Abundance is determined by masses**

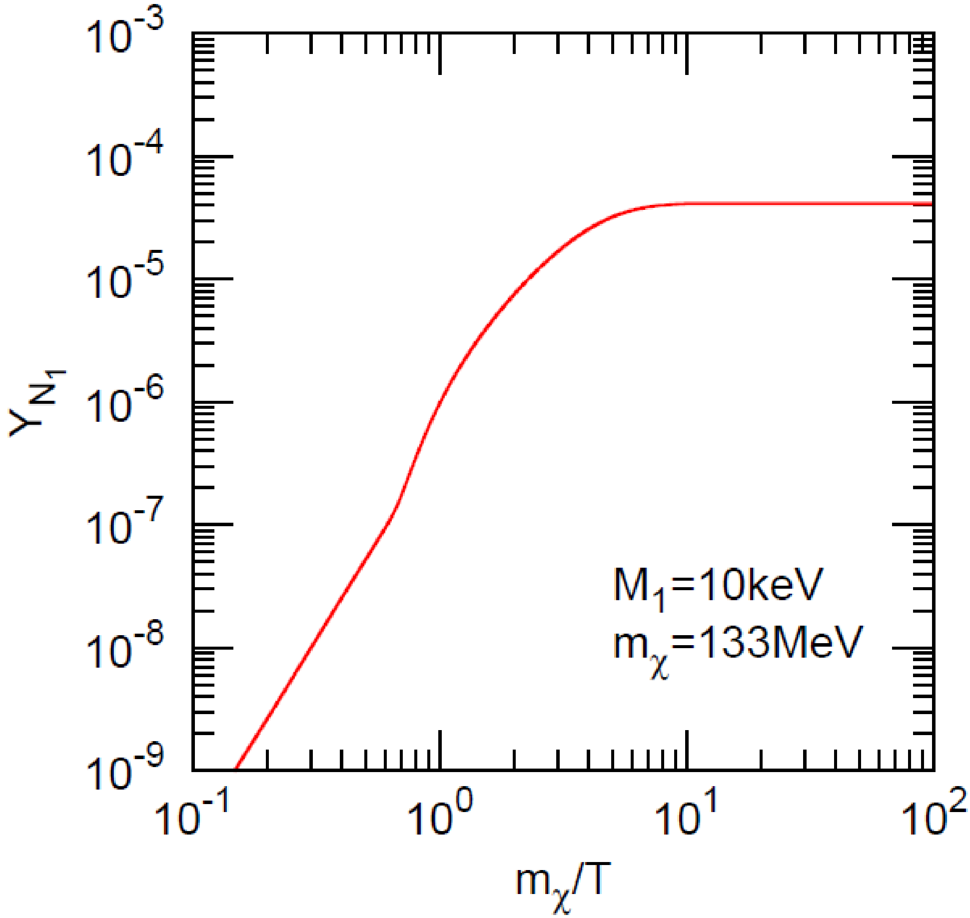
$$\Omega_{N_1} = \Omega_{N_1}(M_1, m_\chi)$$

Parameter space



Production time

$$Y_{N_1} = \frac{n_{N_1}}{s}$$



Dominant production occurs at $T \sim m_\chi / 5$

→ Abundance is insensitive to high temp. physics!

Cosmological constraints

- X-ray
  - No constraint,
    since N1 can be completely stable as F→0
- Structure formation
  - $$M_1 > \frac{\langle|\mathbf{q}_s|\rangle}{\langle|\mathbf{q}_a|\rangle} M_0$$

(1) $M_0 \simeq 10\text{keV}$	Viel et al '06
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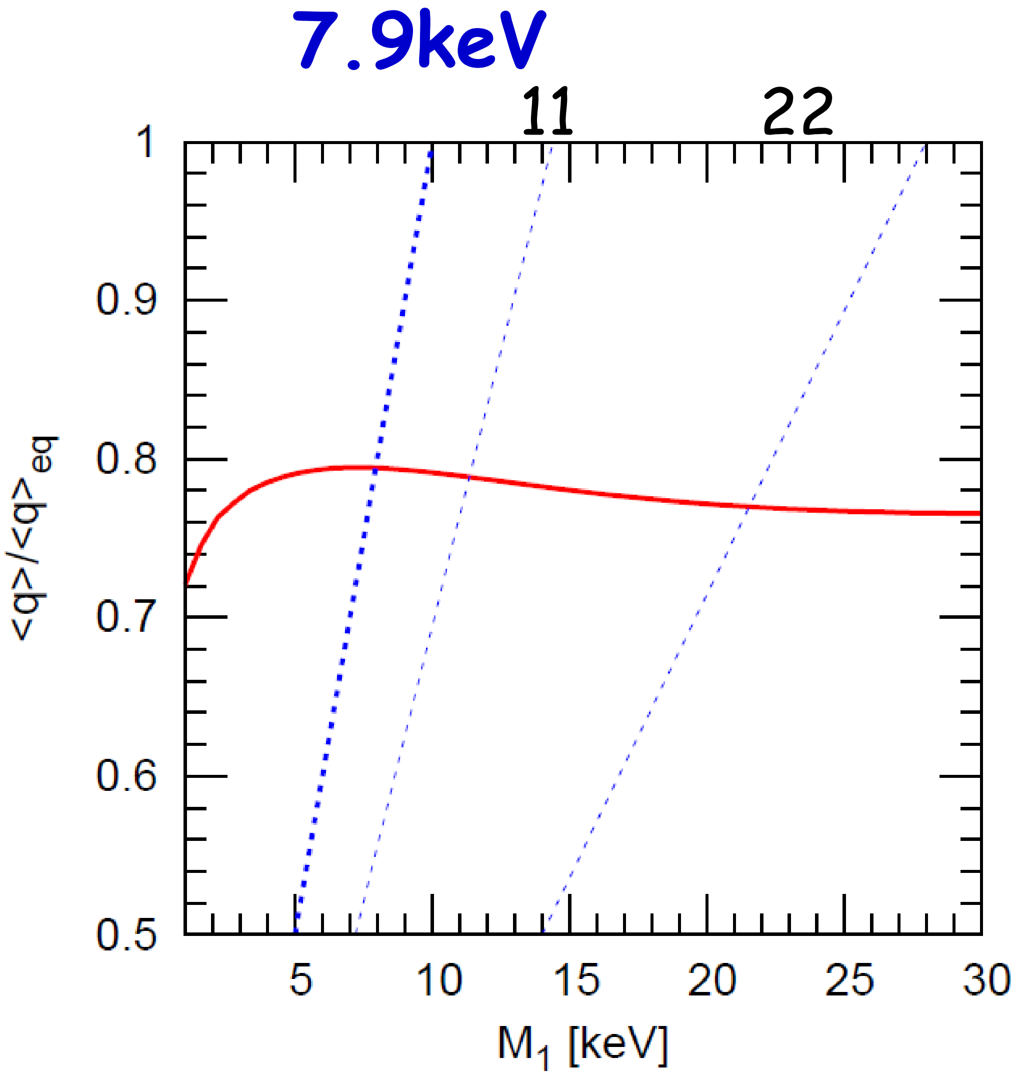
Averaged momentum

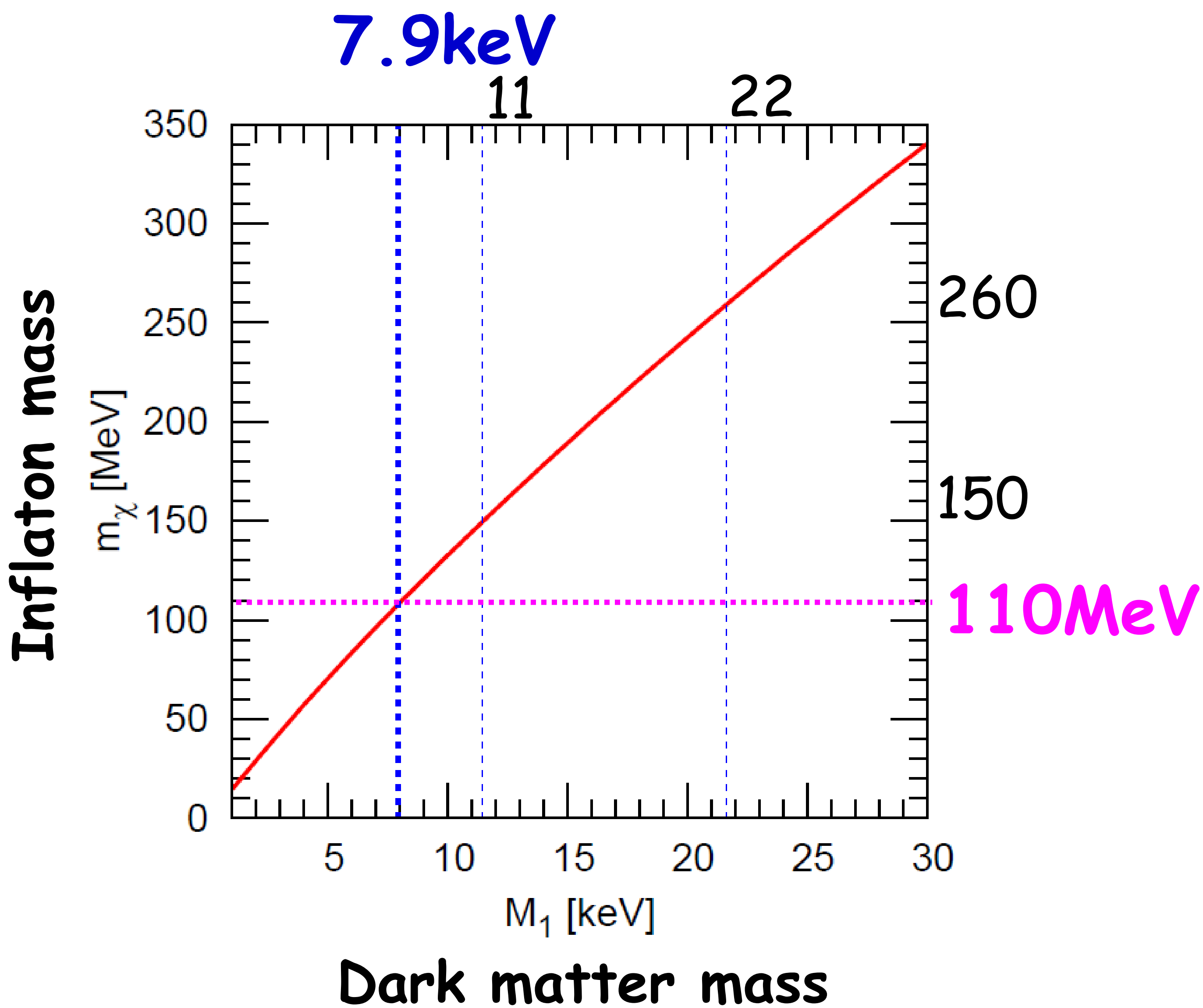
- Ly-alpha constraint

$$M_1 > \frac{\langle|\mathbf{q}_s|\rangle}{\langle|\mathbf{q}_a|\rangle} M_0$$

Lower bound on dark-matter mass



Lower bounds on masses



Summary

- We discussed the νMSM + inflaton
  - Neutrino oscillations + Dark Matter
    + Density fluctuations + Baryon Asymmetry

- Sterile neutrino from inflaton decay
  - No X-ray constraint
  - Ly-alpha constraint
    → bounds on masses

    Dark matter: $M_1 > 7.9\ \mathrm{keV}$

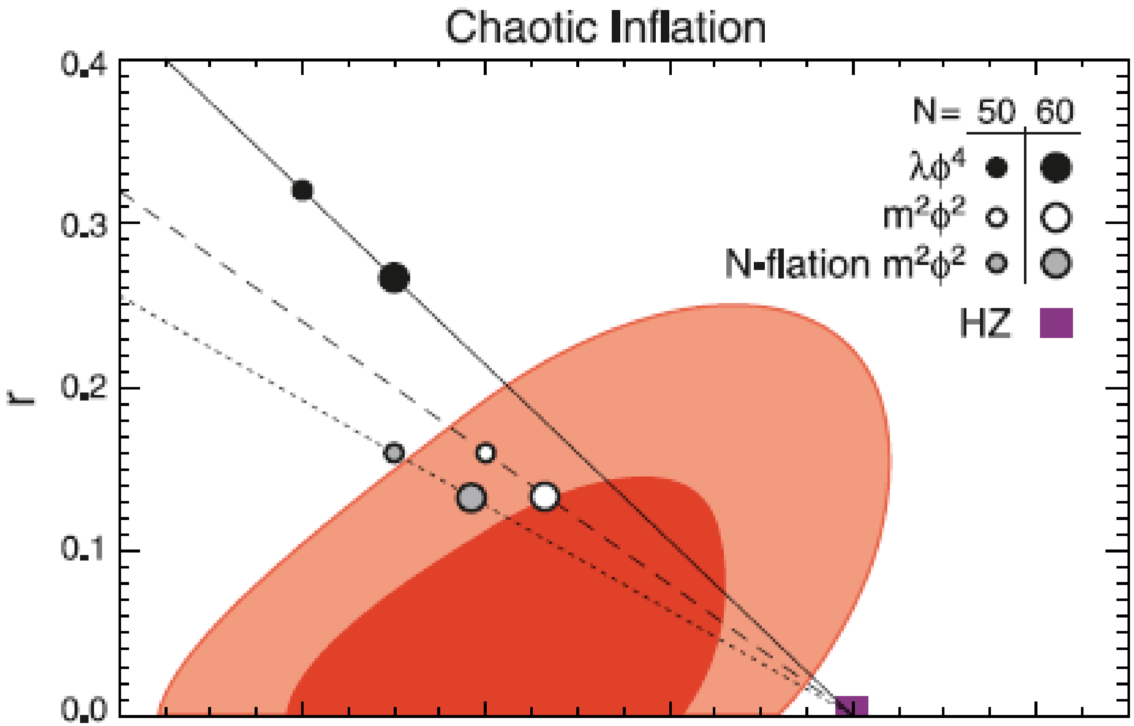
    Inflaton: $m_\chi > 110\ \mathrm{MeV}$

Summary (2)

- Light inflaton may be interesting in
  - collider experiments
  - cosmology
- The scenario can be applied to "viable" inflation models
- Further studies is now going on…

Status of chaotic inflation

- **WMAP 5yr**



QCD equation of state

$$\rho = \frac{\pi^2 T^4}{30} g_{\rm eff}$$

$$s = \frac{2\pi^2 T^3}{45} h_{\rm eff}$$

- **Time-temperature relation:**

$$\frac{dT}{dt} = -\left(\frac{90}{\pi^2 g_{\rm eff}(T)}\right)^{\frac{1}{2}} \frac{M_P}{T^3}\left[1 + \frac{T}{3h_{\rm eff}(T)}\frac{dh_{\rm eff}(T)}{dT}\right]$$

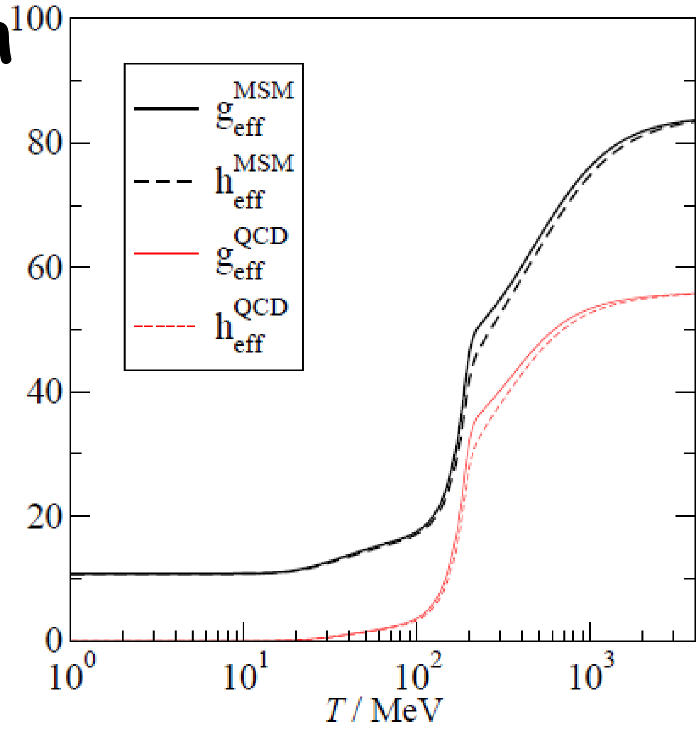
➡ hadronic uncertainty

- **Phenomenological approach**

Laine, Schröder

- For high temperatures
  perturbative results (resummed 4-loop)
  Kajantie, Laine, Rummukainen, Schroder
- For low temperatures
  a dilute gas of resonances
- Interpolate two regions smoothly

$$\tilde{T}_c = 200^{+40}_{-40}\,\text{MeV}$$



Spectrum of sterile neutrino

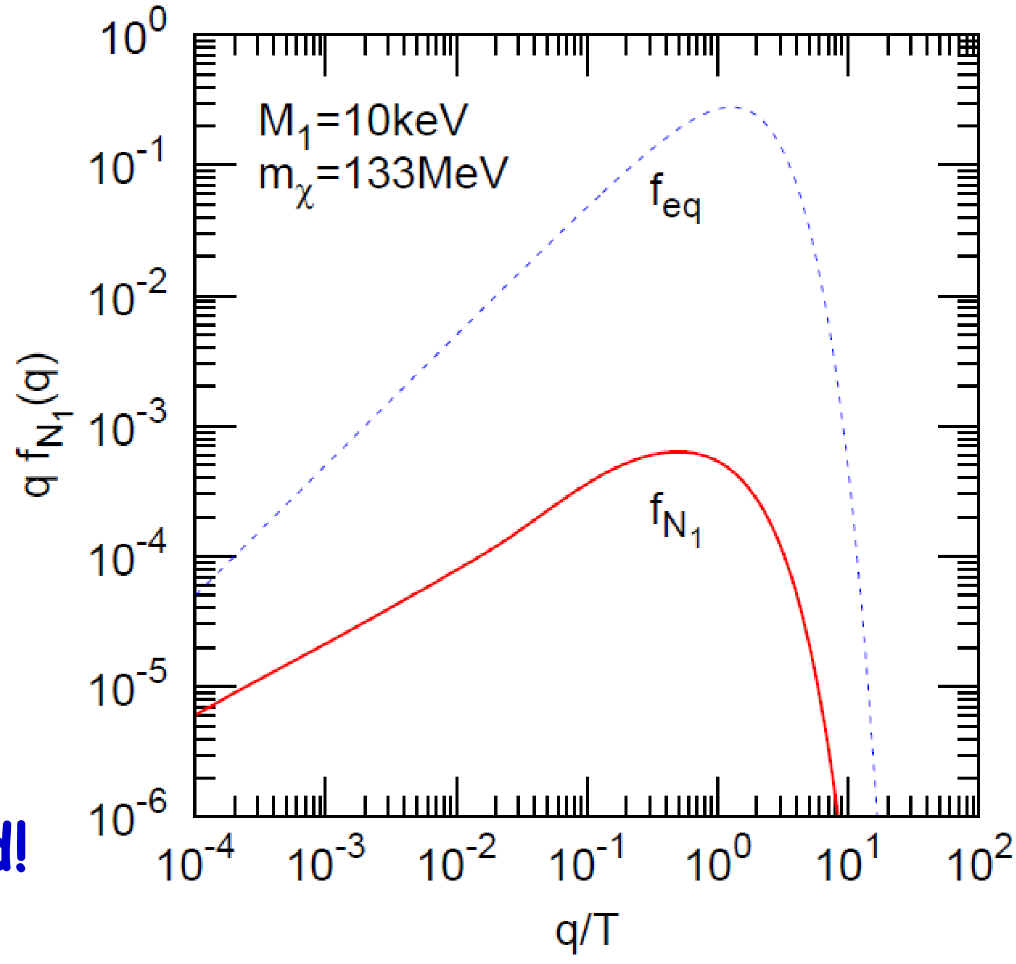
~~$f_{N_1}(q) \propto f_{eq}(q)$~~

⬇

Suppression of $\frac{\langle|\mathbf{q}_s|\rangle}{\langle|\mathbf{q}_a|\rangle}$

⬇

Weaken Ly-alpha bound!



Mass eigenstates of neutrinos

- If Majorana masses >> Dirac masses,

$$\begin{pmatrix} 0 & M_D \\ M_D^T & M_M \end{pmatrix} \Rightarrow \begin{pmatrix} M_\nu & 0 \\ 0 & M_M \end{pmatrix}$$

$$M_\nu = -M_D^T \frac{1}{M_M} M_D$$

$$M_M = diag(M_1, M_2, M_3)$$

  - active neutrinos

$$\nu_1,\ \nu_2,\ \nu_3\ (m_1 \le m_2 \le m_3) \qquad U^T M_\nu U = diag(m_1, m_2, m_3)$$

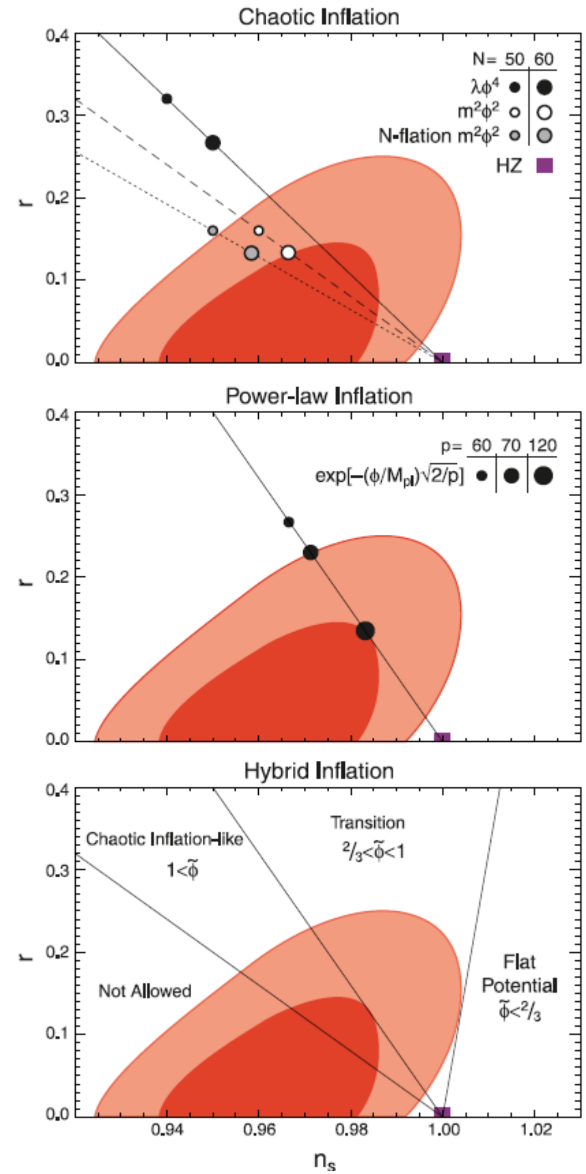
  - sterile neutrinos

$$N_1,\ N_2,\ N_3\ (M_1 \le M_2 \le M_3)$$

- Mixing in CC current

$$\underset{(\alpha = e, \mu, \tau)}{\nu_\alpha} = U_{\alpha a}\ \underset{(a = 1,2,3)}{\nu_a} + \theta_{\alpha I}\ \underset{(I = 1,2,3)}{N_I^c}$$

$$\theta_{\alpha I} = (M_D)_{\alpha I} / M_I \ll 1$$ active-sterile mixing


Chaotic Inflation
N= 50 60
λφ⁴
m²φ²
N-flation m²φ²
HZ
r
Power-law Inflation
p= 60 70 120
exp[−(φ/M_pl)√2/p]
r
Hybrid Inflation
Chaotic Inflation-like
1<φ̃
Transition
²/₃<φ̃<1
Not Allowed
Flat
Potential
φ̃<²/₃
r
0.0
0.1
0.2
0.3
0.4
0.94
0.96
0.98
1.00
1.02
n_s