Gravitational Production of Right-handed Neutrinos after Quintessential Inflation

Phys. Lett. **B798** (2019) 135024 (arXiv:1905.12423 [hep-ph])

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E Lab. seminar @ Nagoya University 15th Jan. 2020

NOTATION

I will use following notations throughout this talk.

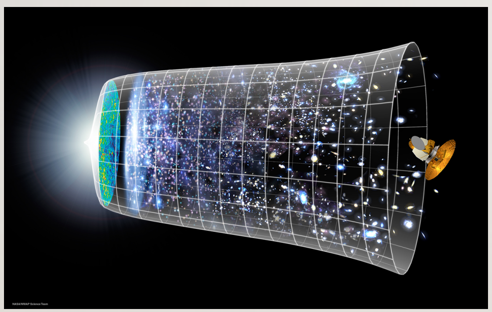
- Natural units : $c = \hbar = k_B = 1$
- Planck mass : $M_G = \sqrt{\hbar c / 8\pi G} \approx 2.4\times 10^{18}\ \mathrm{GeV}$
- Minkowski metric : $\eta_{\mu\nu} = \mathrm{diag}(-,+,+,+)$

OUTLINE

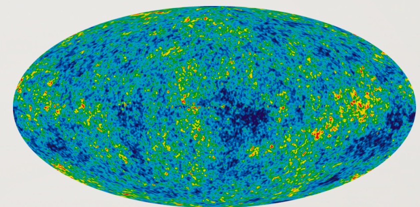
1. Motivation
2. Mechanism
3. Conditions & Constraints
4. Discussion

> 1. Motivation
2. Mechanism
3. Conditions & Constraints
4. Discussion

INFLATIONARY COSMOLOGY WORKS VERY WELL!



INFLATION



Primordial fluctuation

Flatness

Homogeneity & Isotropy

BUT... REMAINING PROBLEMS

- Baryon asymmetry
- Dark matter
- Dark energy
- Reheating

⋮

Solve by

Right-handed Majorana neutrinos
+
Quintessential inflation

1. Motivation
2. Mechanism
3. Conditions & Constraints
4. Discussion

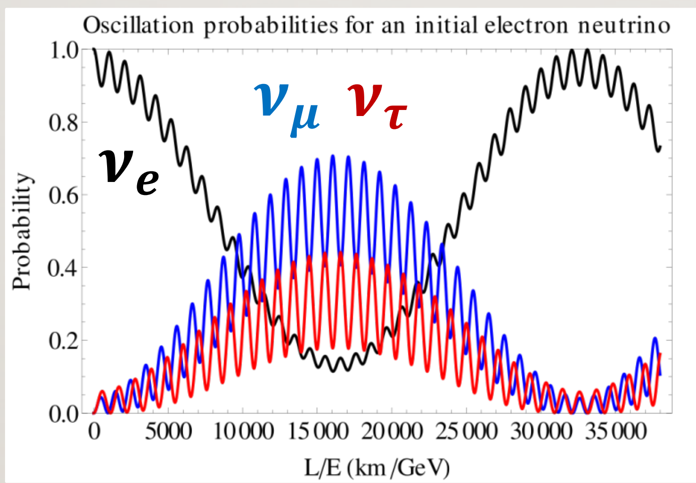
BARYOGENESIS VIA LEPTONS

Y. Fukuda *et al.* (Super-Kamiokande), *Phys. Rev. Lett.* **81** (1998) 1562.

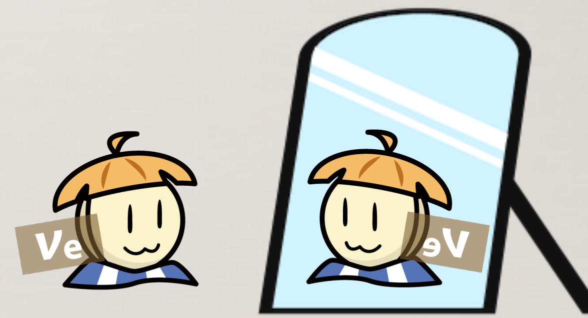
- Right-handed neutrinos

  Left-handed neutrinos are massive (*cf.* neutrino oscillation)

  ⇒ Right-handed neutrinos **MUST** exist



Wolfram Demonstrations Project



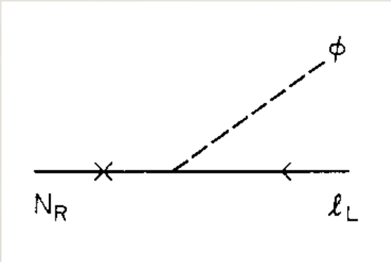
BARYOGENESIS VIA LEPTONS

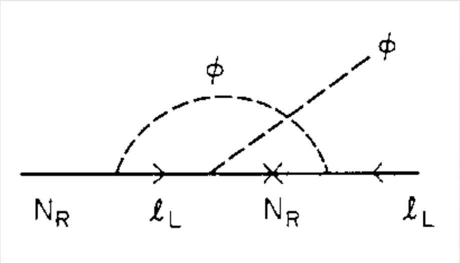
M. Fukugita and T. Yanagida, *Phys. Lett.* **B174** (1986) 45.

- Leptogenesis

  A net lepton number can be produced by **the decay of right-handed Majorana neutrinos**

$$\mathcal{L}_N = M_i \overline{N}_i^c N_i + h_{i\alpha} N_i L_\alpha H^\dagger$$





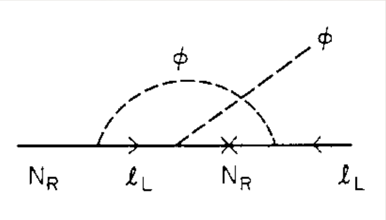
Lepton number $\xrightarrow{\text{Sphaleron}}$ Baryon number

BARYOGENESIS VIA LEPTONS

W. Buchmüller and M. Plümacher, *Phys. Lett.* **B431** (1998) 354.

- CP violation

  Produced net lepton number per N_i decay is



$$\epsilon_i \equiv \frac{\Gamma(N_i \to l + h) - \Gamma\left(N_i \to \bar{l} + \bar{h}\right)}{\Gamma_i}$$

$$= -\frac{1}{8\pi} \frac{\sum_{\alpha \neq i} \mathrm{Im}\left[\left\{\left(hh^{\dagger}\right)_{i\alpha}\right\}^2\right]}{(hh^{\dagger})_{ii}} \left\{ f^V\left(\frac{M_\alpha^2}{M_i^2}\right) + f^M\left(\frac{M_\alpha^2}{M_i^2}\right)\right\},$$

Mixing between N_3 & N_2

One-loop vertex

One-loop self-energy

BARYOGENESIS VIA LEPTONS

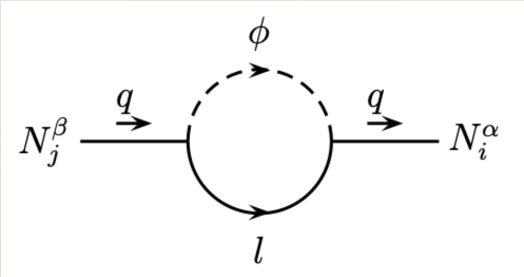
W. Buchmüller and M. Plümacher, *Phys. Lett.* **B431** (1998) 354.

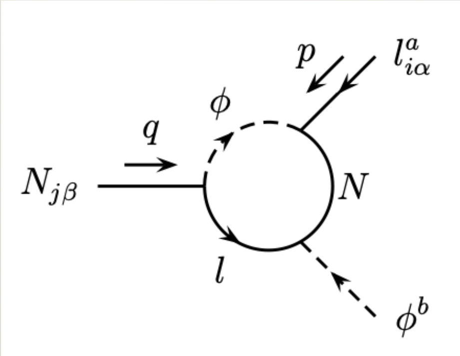
- CP violation

  where

$$f^V(x) = \sqrt{x}\left[-1 + (x+1)\ln\left(1+\frac{1}{x}\right)\right]$$

$$f^S(x) = \frac{\sqrt{x}}{x-1}$$





BARYOGENESIS VIA LEPTONS

W. Buchmüller and M. Plümacher, *Phys. Lett.* **B431** (1998) 354.

- CP violation

  * This formula is valid when the masses are **not so degenerate!** (compared with the decay width $\Gamma_{i,j}$)

1. $|M_i - M_j| \gg \Gamma_{i,j}$: Our case
2. $|M_i - M_j| \sim \Gamma_{i,j}$: ARS mechanism (Akhmedov+ 1998)
   Resonant leptogenesis (Pilaftsis+ 2004)
3. $|M_i - M_j| = 0$: no CP violation ($\epsilon_i = 0$)

NEUTRINO AS DARK MATTER

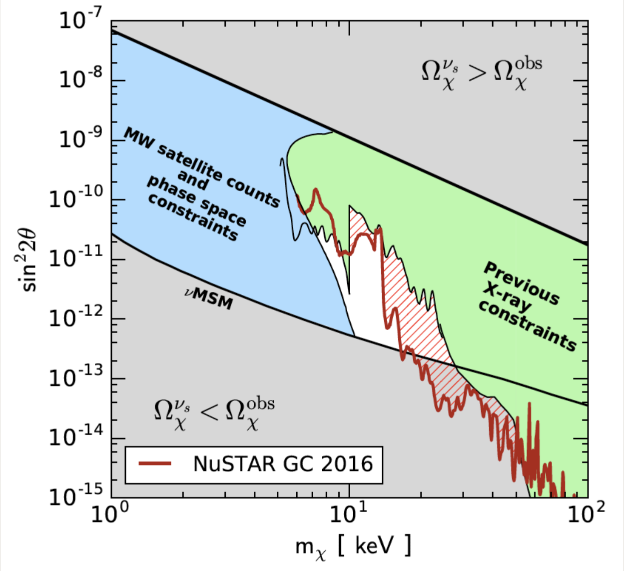
S. Dodelson and L. M. Widrow, *Phys. Rev. Lett.* **72** (1994) 17. *etc.*

- Sterile neutrino

  Right-handed neutrinos have NO weak interaction

  ⇒ **Sterile neutrino**

  $\sim 10\mathrm{keV}$ sterile neutrino could account for whole dark matter!



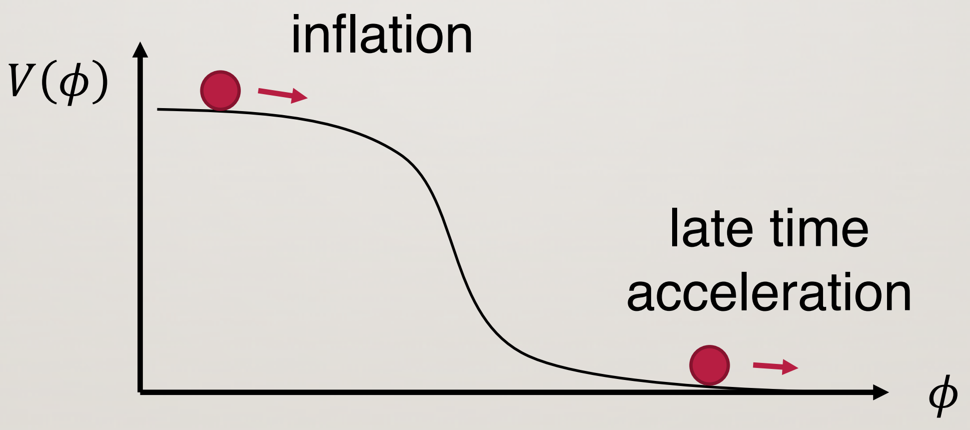
K. Perez *et al.*, *Phys. Rev.* **D95** (2017) 123002.

QUINTESSENTIAL INFLATION

P. J. E. Peebles and A. Vilenkin, *Phys. Rev.* **D59** (1999) 063505.

- Quintessence

  Inflation and late time acceleration by **the same field**



QUINTESSENTIAL INFLATION

A. D. Linde, *Phys. Lett.* **108B** (1982) 389.

- Slow-roll inflation

  If the universe is dominated by perfect fluid with $p = w\rho$, the scale factor a obeys the Friedmann equation,

$$\frac{\ddot{a}}{a} = -\frac{1}{6M_G^2}(1+3w)\rho$$

p : pressure
ρ : energy density

$$w < -1/3 \;\; \Rightarrow \;\; \ddot{a} > 0 \;\; \text{(accelerating)}$$

Especially, if $w = -1$, then $\rho = const.$ and $a \propto e^{Ht}$

inflation

QUINTESSENTIAL INFLATION

A. D. Linde, *Phys. Lett.* **108B** (1982) 389.

- Slow-roll inflation

In case of a scalar field, its energy density is

$$\rho = \frac{1}{2} g^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi + V(\varphi)$$

⇓ homogeneity & isotropy

$$\rho = \frac{1}{2}\dot{\varphi}^2 + V, \qquad p = \frac{1}{2}\dot{\varphi}^2 - V$$

$\Rightarrow \; \dot{\varphi}^2 \ll V$ realizes $p \approx -\rho$

slow roll **inflation**

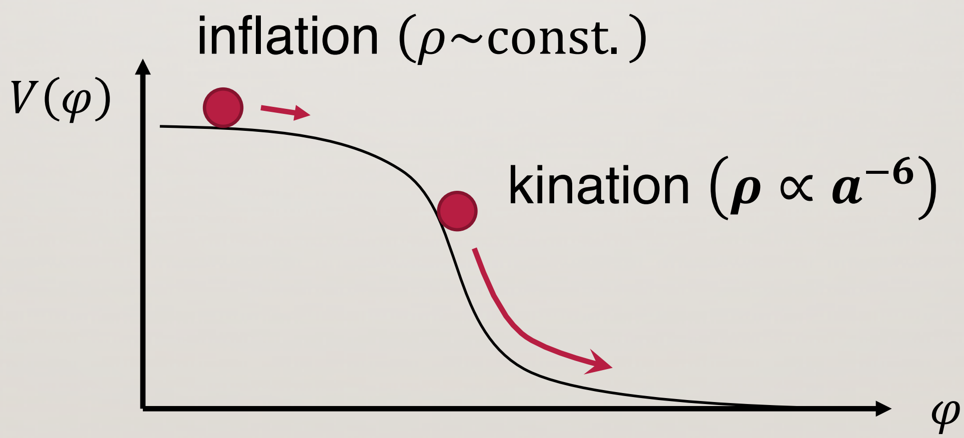
QUINTESSENTIAL INFLATION

P. J. E. Peebles and A. Vilenkin, *Phys. Rev.* **D59** (1999) 063505.

- End of inflation

  Inflation ends when the inflaton starts to roll **fast** $(\dot{\varphi}^2 \gg V)$

  → Kinetic energy dominates the Universe (**kination**)



QUINTESSENTIAL INFLATION

P. J. E. Peebles and A. Vilenkin, *Phys. Rev.* **D59** (1999) 063505.

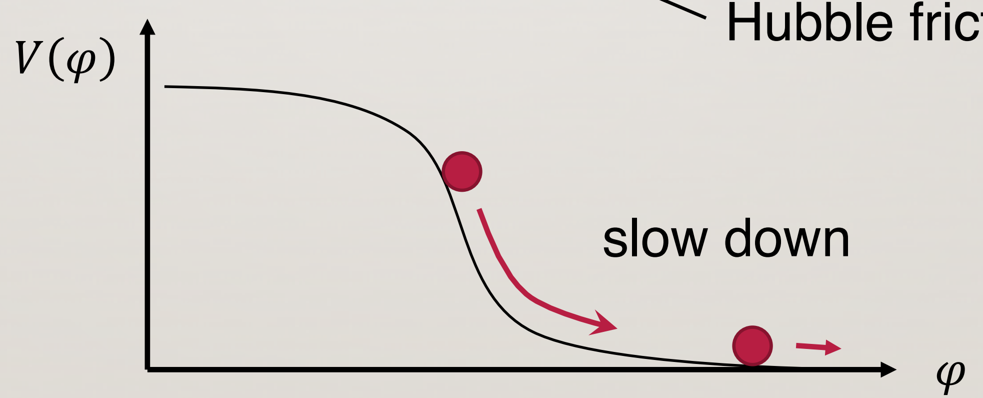
- Late time accelerating expansion

  The inflaton **decelerates** by the Hubble friction,

  and finally, satisfies **the slow roll condition** again

EOM of the inflaton: $\ddot{\varphi} + \underline{3H\dot{\varphi}} + V'(\varphi) = 0$

Hubble friction



REHEATING AFTER INFLATION

A. D. Dolgov and A. D. Linde, *Phys. Lett.* **116B** (1982) 329 *etc.*

- Reheating

Inflation : Exponential expansion

→ Temperature extremely decreases ($\lesssim e^{-50}T_0$)

↓ the Universe must be **reheated**

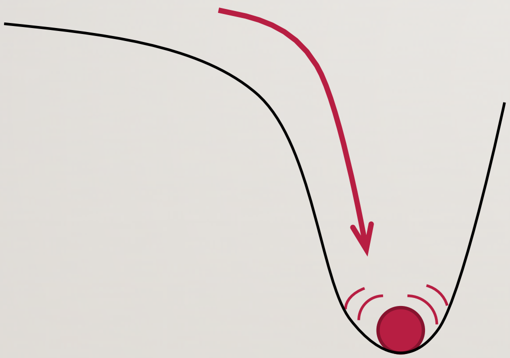
Big bang : Starts from quite high temperature ($\gtrsim 1\ \mathrm{MeV}$)

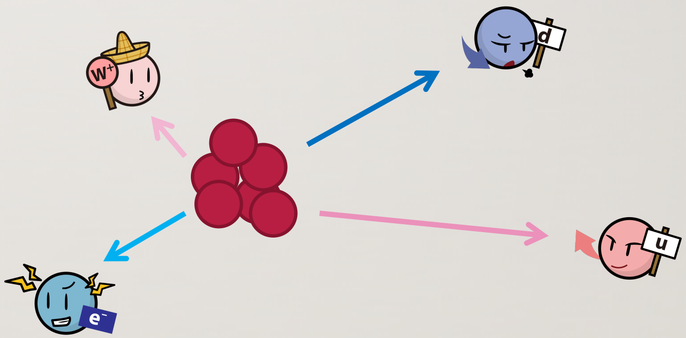
REHEATING AFTER INFLATION

A. D. Dolgov and A. D. Linde, *Phys. Lett.* **116B** (1982) 329 *etc.*

- Reheating by coherent oscillation

  If the inflaton rolls down into a potential minimum,





coherent oscillation = condensate of massive particle

⬇

decay into radiation via **direct coupling**

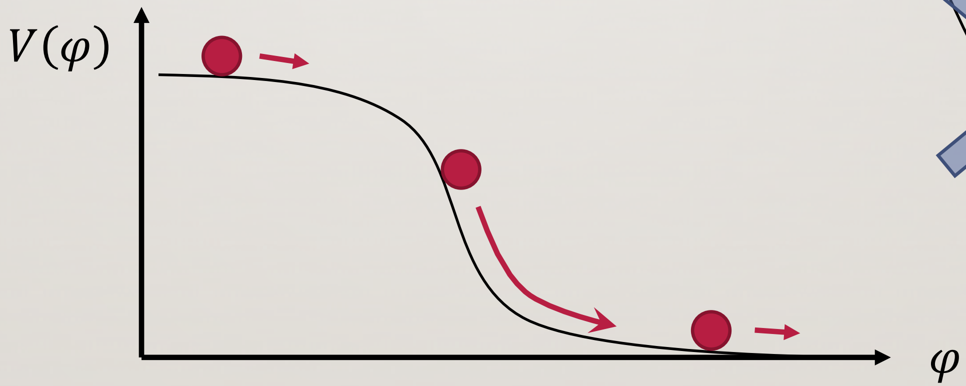
REHEATING AFTER INFLATION

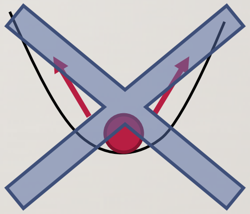
A. D. Dolgov and A. D. Linde, *Phys. Lett.* **116B** (1982) 329 *etc.*

- Reheating by coherent oscillation

  But, **no coherent oscillation** after quintessential inflation!

  → We must use another mechanism





GRAVITATIONAL REHEATING

L. Parker, *Phys. Rev.* **183** (1969) 1057.

- Gravitational particle production

  Vacuum state itself changes in **a curved spacetime**

  → Particle number increases

spacetime

new spacetime

vacuum state

$\hat{a}|0\rangle_i = 0$

new vacuum

$\hat{b}|0\rangle_f = 0$

former vacuum

$\boldsymbol{\hat{b}|0\rangle_i \neq 0}$

GRAVITATIONAL REHEATING

L. Parker, *Phys. Rev.* **183** (1969) 1057.

- Gravitational particle production

Lagrangian for the conformally coupled massive scalar field χ in a curved spacetime is

$$\mathcal{L}_{\varphi} = \sqrt{-\det(g_{\mu\nu})}\left(-\frac{1}{2}g^{\mu\nu}\partial_{\mu}\chi\partial_{\nu}\chi - \frac{1}{2}m^{2}\chi^{2} - \underline{\frac{1}{12}R\chi^{2}}\right)$$

conformal coupling
(No direct effect from curvature)

GRAVITATIONAL REHEATING

L. Parker, *Phys. Rev.* **183** (1969) 1057.

- Gravitational particle production

  Then, Equation of motion for the conformally coupled massive scalar field in terms of mode function χ_k is

$$\frac{d^2\chi_k(\eta)}{d\eta^2} + \left(k^2 + m^2 \underline{a^2(\eta)}\right)\chi_k(\eta) = 0$$

η : conformal time $a\,d\eta = dt$

Form of $a(\eta)$ changes

⇒ Form of solution $\chi_k(\eta)$ changes (if **NOT** conformal invariant)

⇒ **Vacuum state changes!**

GRAVITATIONAL REHEATING

L. Parker, *Phys. Rev.* **183** (1969) 1057.

- Gravitational particle production

  The states of field and vacuum evolve differently

	$t = t_0$	obey EOM during $t_0 \sim t_1$	$t = t_1$
Field	$\lvert\chi(t_0)\rangle = \lvert 0\rangle_i$	→	$\lvert\chi(t_1)\rangle$
	$\parallel$		$\nparallel$
Vacuum	$\lvert 0\rangle_i$		$\lvert 0\rangle_f$
	↑ EOM at $t = t_0$		↑ EOM at $t = t_1$

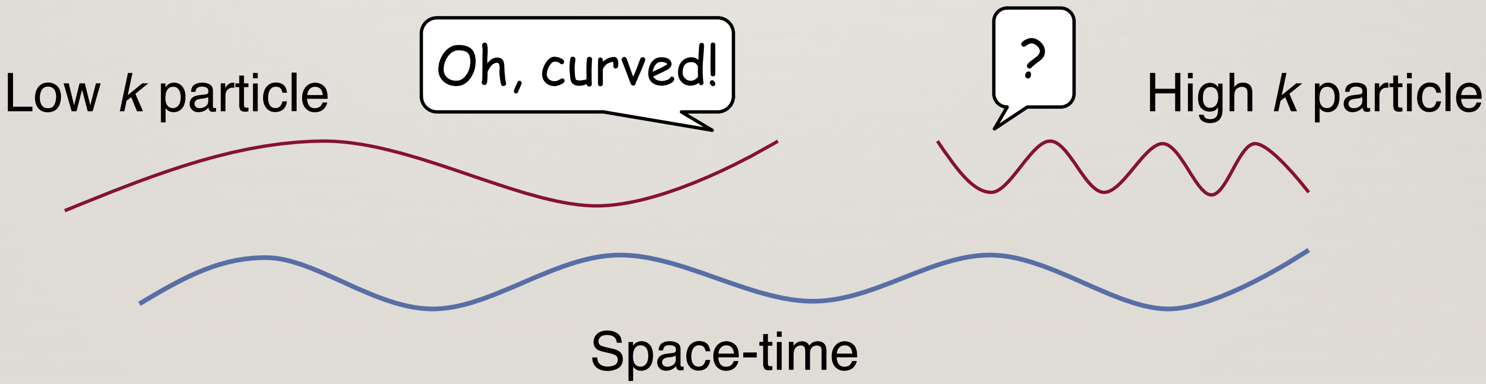
GRAVITATIONAL REHEATING

T. S. Bunch and P. C. W. Davies, *Proc. Roy. Soc. Lond.* **A360** (1978) 117.

- Adiabatic vacuum

  How to define the 'vacuum' state in curved spacetime?

"State which coincides with the vacuum state in flat spacetime $\chi_k = \frac{1}{\sqrt{2k}} e^{-ik\eta}$ **at the adiabatic limit** $k \to \infty$**"**



GRAVITATIONAL REHEATING

T. S. Bunch and P. C. W. Davies, *Proc. Roy. Soc. Lond.* **A360** (1978) 117.

- Adiabatic vacuum

  e.g. In the case of de-Sitter space (= during inflation),

$$\chi_k = \frac{\sqrt{\pi|\eta|}}{2} H_\nu^{(1)}(k|\eta|)$$

Bunch-Davies vacuum

GRAVITATIONAL REHEATING

SH and J. Yokoyama, *Phys. Lett.* **B798** (2019) 135024.

- Produced fermion energy density

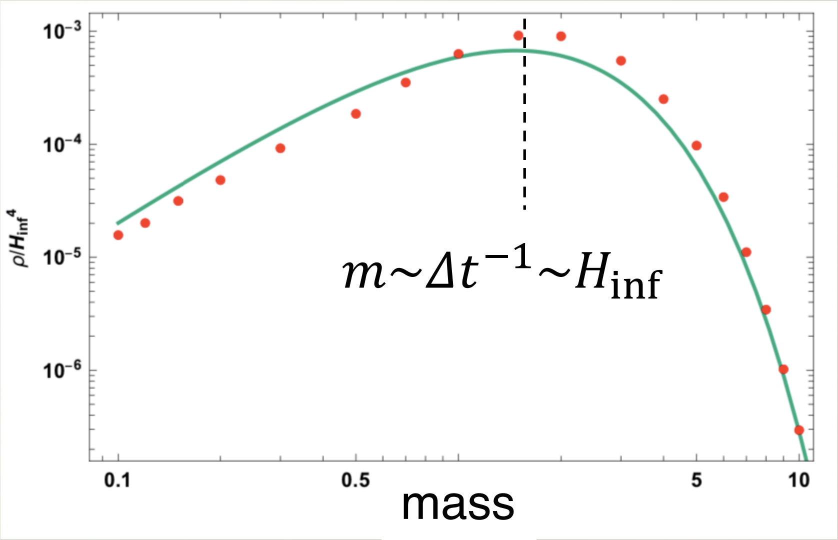
$$\rho \cong 2\times 10^{-3} e^{-4m\Delta t} m^2 H_{\rm inf}^2$$

m : Fermion mass

Δt : Transition time scale

$H_{\rm inf}$: Hubble parameter during inflation

Coupling with inflaton is **NOT** needed!



GRAVITATIONAL REHEATING

SH and J. Yokoyama, *Phys. Lett.* **B798** (2019) 135024.

- Produced fermion energy density

$$\boldsymbol{\rho \cong 2\times 10^{-3} e^{-4m\Delta t} m^2 H_{\mathrm{inf}}^2}$$

$$= \frac{\rho_{\mathrm{inf}}}{3M_G^2} \quad (\because \text{Friedmann eq.})$$

Planck suppressed
(∵ gravitational)

OUR MODEL

- Right-handed majorana neutrinos

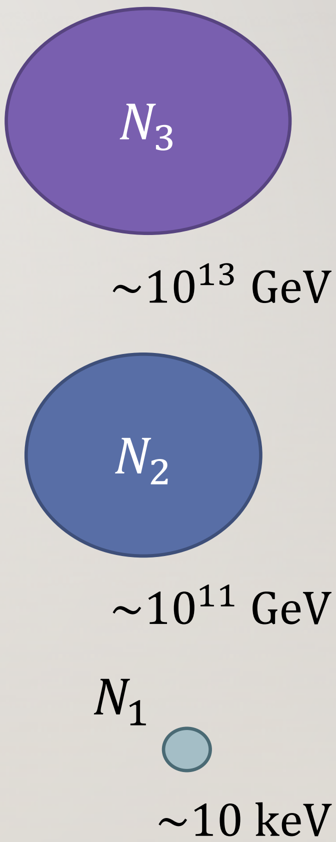
N_3 : $M_3 \sim 10^{13}$ GeV → Reheating

N_2 : $M_2 \sim 10^{11}$ GeV → Baryogenesis

N_1 : $M_1 \sim 10$ keV → Dark matter

$$\mathcal{L}_N = M_i \overline{N}_i^c N_i + h_{i\alpha} N_i L_\alpha H^\dagger$$

In quintessential inflation with $H_{\text{inf}} \sim 10^{13}$ GeV



1. Motivation
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› 3. Conditions & Constraints
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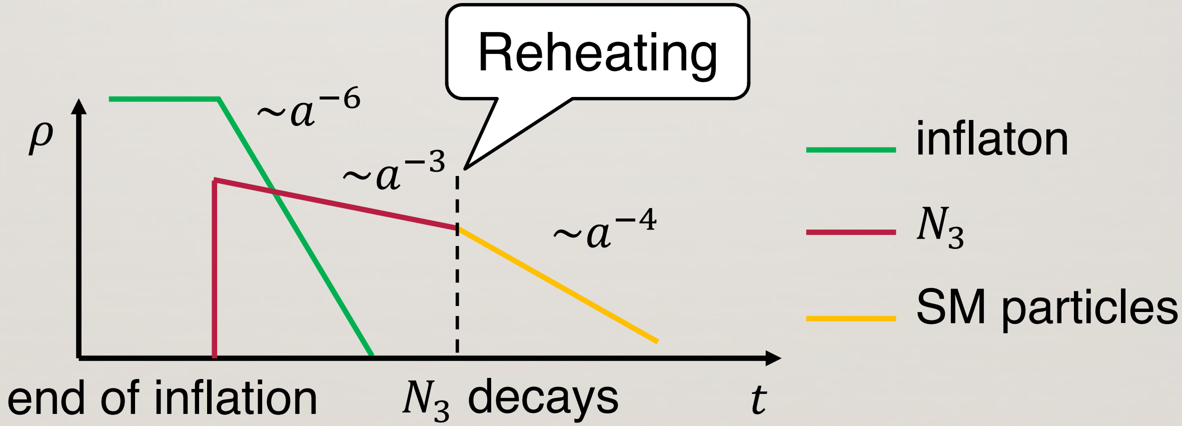
N_3 FOR REHEATING

- Decay of N_3

  N_3 decays into SM particles with decay rate Γ_3

$$\Gamma_3 = \frac{1}{4\pi} \sum_{\alpha} |h_{i\alpha}|^2 M_3$$



N_3 FOR REHEATING

- Reheating temperature

$$T_{RH} \cong \mathbf{6{\times}10^7} \left(\frac{\sum_\alpha |h_{3\alpha}|^2}{10^{-12}}\right)^{-\frac{1}{4}} e^{-3M_3\Delta t} \left(\frac{M_3}{10^{13}\mathrm{GeV}}\right)^{\frac{5}{4}} \left(\frac{H_{\mathrm{inf}}}{10^{13}\mathrm{GeV}}\right)^{\frac{3}{4}} \mathrm{GeV}$$

- Concealment of graviton

$$\sum_{\boldsymbol{\alpha}} |\boldsymbol{h}_{\mathbf{3}\boldsymbol{\alpha}}|^{\mathbf{2}} < \mathbf{8.5{\times}10^{-11}}$$

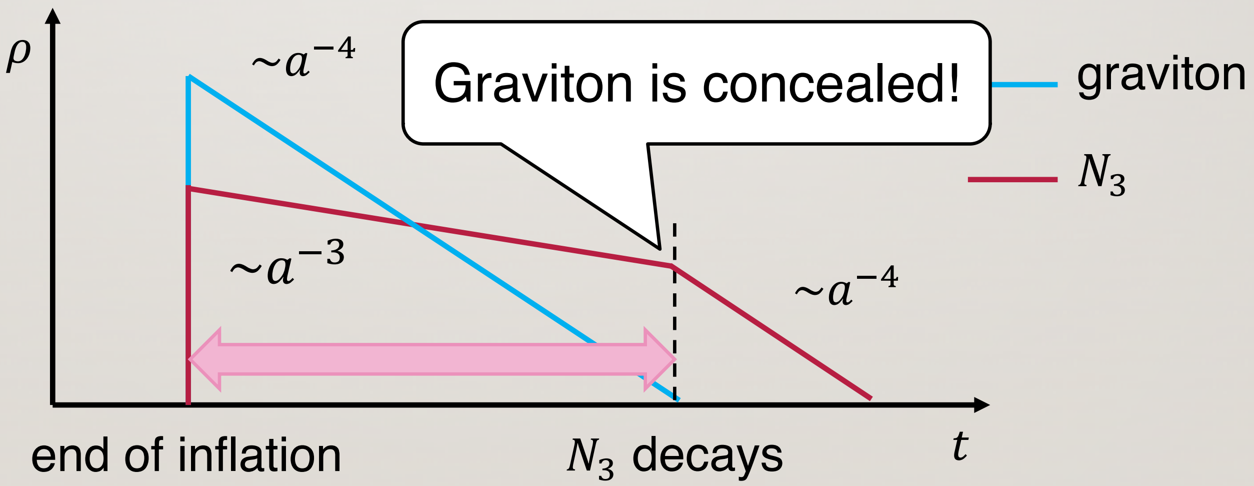
~ Yukawa coupling of electron

“CONCEALMENT” OF GRAVITON

Gravitons are also gravitationally produced

They affect CMB spectrum and BBN (abundance of ^{4}He)

Hence, they should be “concealed” by radiation



N_2 FOR BARYOGENESIS

- Baryon asymmetry

$$\frac{n_B}{s} = \frac{28}{79}\frac{n_L}{s}$$

$$\approx 1\times 10^{-3}\frac{\mathrm{Im}\left[\left\{\left(hh^\dagger\right)_{32}\right\}^2\right]}{(hh^\dagger)_{33}}\left(e^{-M_3\Delta t}\ln\frac{M_3}{M_2}\right)\left(\sum_\alpha |h_{3\alpha}|^2\right)^{\frac{1}{4}}\frac{M_2}{M_3}\left(\frac{M_3}{H_{\mathrm{inf}}}\right)^{-\frac{1}{4}}$$

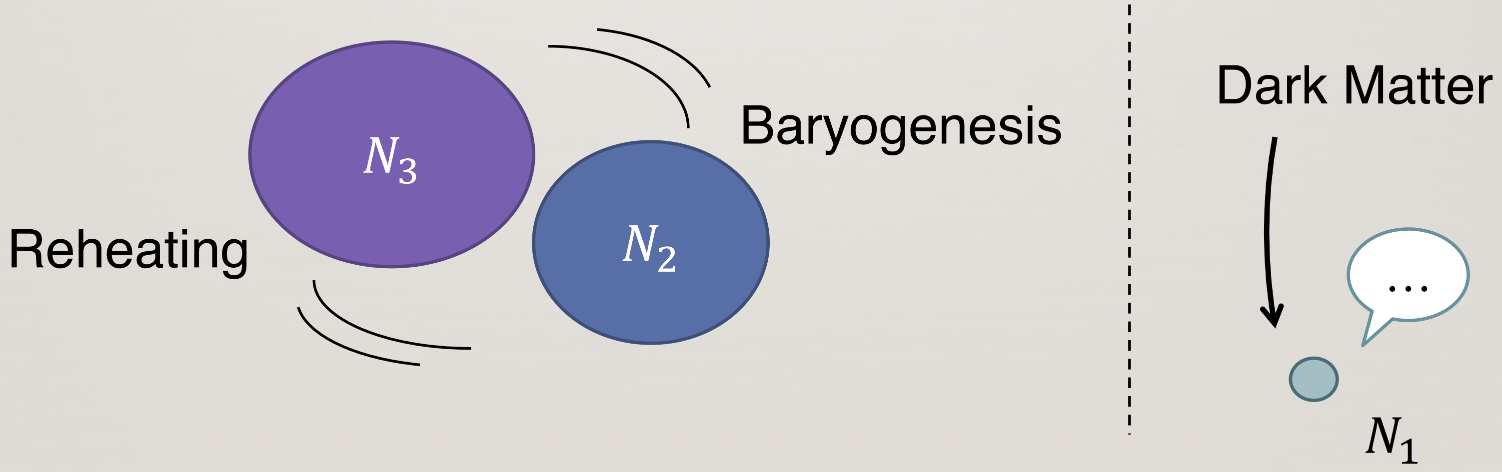
$\downarrow$ $n_B/s \approx 8.65(6)\times 10^{-11}$

$$\boldsymbol{M_2 \gtrsim 10^{11}\ \mathrm{GeV}} \quad \text{and} \quad \boldsymbol{h_{22}\ \text{or}\ h_{23} \gtrsim 10^{-3}\sqrt{M_3/M_2}}$$

N_1 FOR DARK MATTER

- Split seesaw

  If N_1 is light ($\sim 10\ \mathrm{keV}$) while N_3 and N_2 are very heavy, these right-handed neutrinos can explain baryon asymmetry as well as dark matter (Kusenko+ 2010)



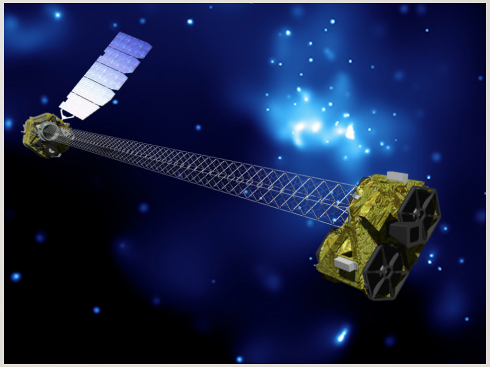
N_1 FOR DARK MATTER

- Stability

X-ray observations give constraints on decay rate of N_1

For $M_1 \sim 10\ \mathrm{keV}$,

$$\sum_{\alpha} |h_{1\alpha}|^2 < 10^{-26}$$



Nu-STAR

1. Motivation
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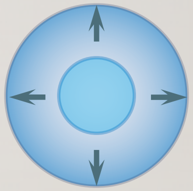
ADEQUATE CREATION OF N_1

- (In)efficiency of production

  Efficiency of gravitational particle production depends on **deviation from conformality**.

  conformality: invariance under conformal transformation (*e.g.* expansion)



How to violate conformality?

- Mass term ⟵ Too small...
- Non-conformal coupling ⟵ Can we use this?

ADEQUATE CREATION OF N_1

- Non-minimal coupling with scalar curvature

$$\frac{R}{\mu}\bar{\psi}\psi$$

μ : constant with unit mass dimension

$R = 12H_{\mathrm{inf}}^2$ during inflation, then this term gives **huge effective mass** to the fermion

(After inflation, R quickly vanishes)

ADEQUATE CREATION OF N_1

- Non-minimal coupling with scalar curvature

$$\frac{R}{\mu}\bar{\psi}\psi$$

μ : constant with unit mass dimension

↘ Gravitationally produce

$$n \cong 1.1\times10^{-1}\, H_{\rm inf}^5/\mu^2 \quad \left(\Delta t \approx H_{\rm inf}^{-1}\right)$$

For adequate production,

$$\boldsymbol{\mu \sim 10^{15}\ \mathrm{GeV}}$$

But undesirable instability appears…?

RELAXATION OF TUNING

L. Randall and R. Sundrum, *Phys. Rev. Lett.* **83** (1999) 3370.

- RS brane-world scenario

RS brane-world scenario can explain

	4D		5D
Large mass hierarchy	M_i	$=$	$\kappa_i v_{\mathrm{B-L}} \dfrac{2m_i}{M(e^{2m_i l}-1)}$
Extremely small coupling	$h_{i\alpha}$	$=$	$\dfrac{\lambda_{i\alpha}}{\sqrt{M}} \sqrt{\dfrac{2m_i}{e^{2m_i l}-1}}$

4D parameters		5D parameters	
$M_3 \sim 10^{13}$ GeV	$h_{3\alpha} < 3\times10^{-6}$	$m_3 \sim 2.3 l^{-1}$	$\lambda_{3\alpha} < 3\times10^{-4}$
$M_2 \sim 10^{11}$ GeV	$h_{22,\,23} \sim 10^{-2}$	$m_2 \sim 3.6 l^{-1}$	$\lambda_{22,\,23} \sim 1$
$M_1 \sim 10$ keV	$h_{1\alpha} < 10^{-13}$	$m_1 \sim 24 l^{-1}$	$\lambda_{1\alpha} < 10^{-2}$

TESTABILITY

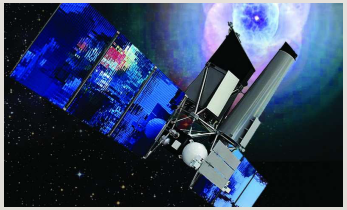
- Detection of N_1

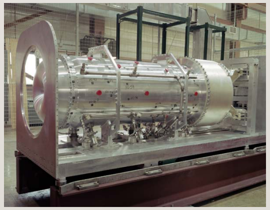
  X-ray observations have already given stringent constraints (*i.e.* $\sum_\alpha |\tilde{h}_{1\alpha}|^2 < 10^{-26}$)

  → Future X-ray observation may detect a signal of N_1

  Of course, there are also base-line experiments and direct detection experiments


XRISM
(2021) -


eROSITA
2019 -


MiniBooNE
2002 -


DANSS
2016 -

etc.

TESTABILITY

- Detection of N_2 and N_3

  Since N_2 and N_3 are quite heavy and fragile, they no longer remain nor are produced today

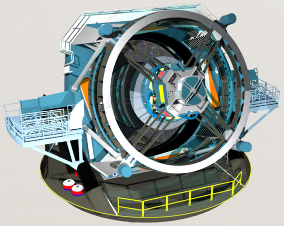
  = It is very difficult to directly detect them…

TESTABILITY

Y. Akrami *et al.*, *JCAP* **1806** (2018) 041.

- Traces of quintessential inflation

  However, quintessential inflation can be distinguished by **large scale structure**



LSST

(2020) -

DESI

2019 -

SKA

(2020) -

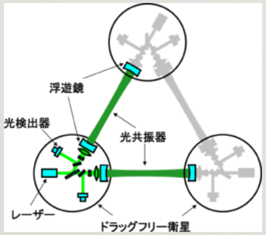
4. Discussion

TESTABILITY

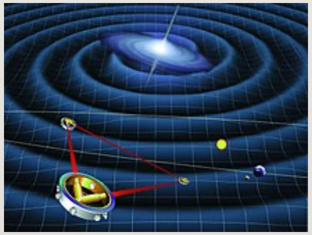
H. Tashiro *et al.*, *Class. Quant. Grav.* **21** (2004) 1761.

- Traces of quintessential inflation

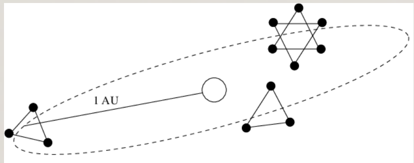
  However, quintessential inflation can be distinguished by large scale structure and **primordial gravitational wave**



DECIGO

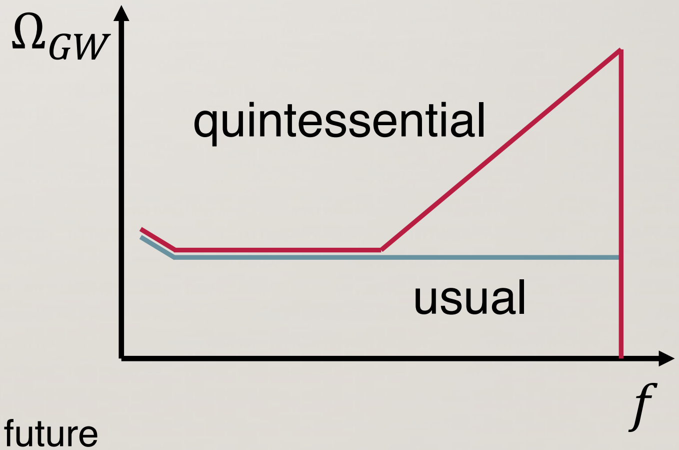


LISA



BBO

in 'near' future



TESTABILITY

- Traces of quintessential inflation

  However, quintessential inflation can be distinguished by large scale structure and primordial gravitational wave

  → Their data tell us the properties of N_2 and N_3 (mass, decay rate *etc.*)

SUMMARY

- Gravitationally produced **right-handed neutrinos** after **quintessential inflation** can explain reheating, baryon asymmetry and dark energy simultaneously.

- **Non-minimal coupling** of right-handed neutrinos can provide adequate amount of dark matter.

Thank you for listening!

Another choice of profile picture →

in Tanna, Vanuatu