中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

基于暴胀子衰变非热产生的轻子生成机制研究

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高能所博士后学术交流会，2022年6月30日

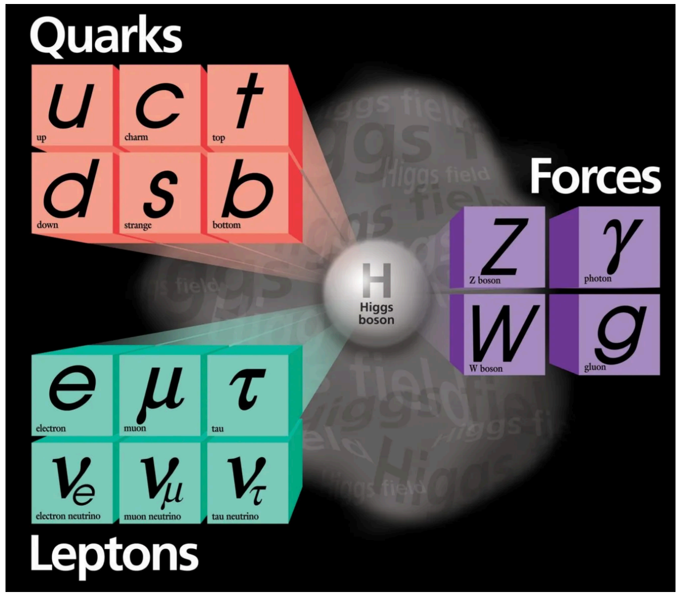
物理问题

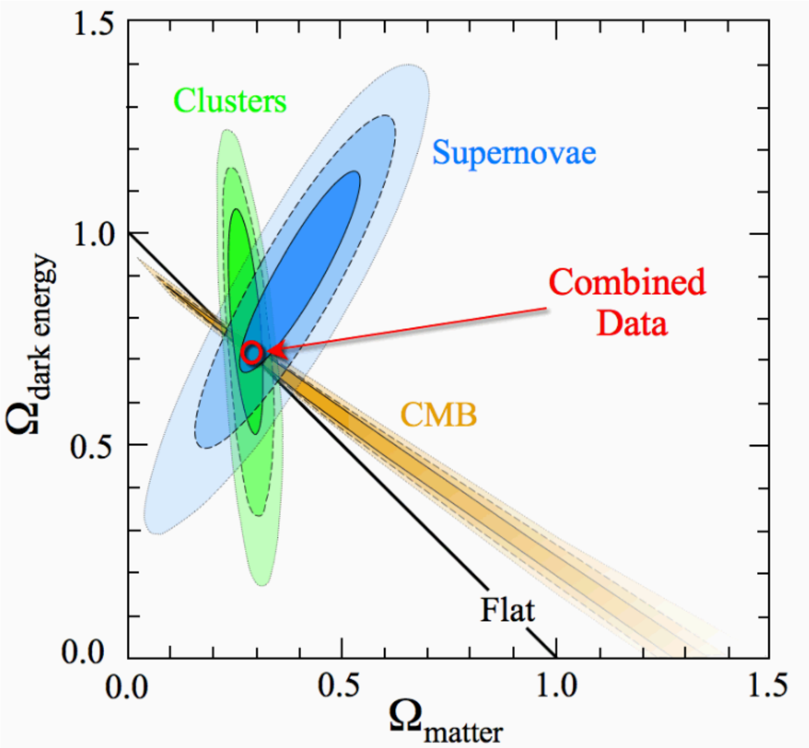
粒子物理标准模型未解决的问题：

- 质量起源
- 中微子质量起源
- 暗物质
- 强CP问题
- Higgs质量问题
- 电弱真空稳定性问题
- 反常（例如，CDF的W质量）
- ……

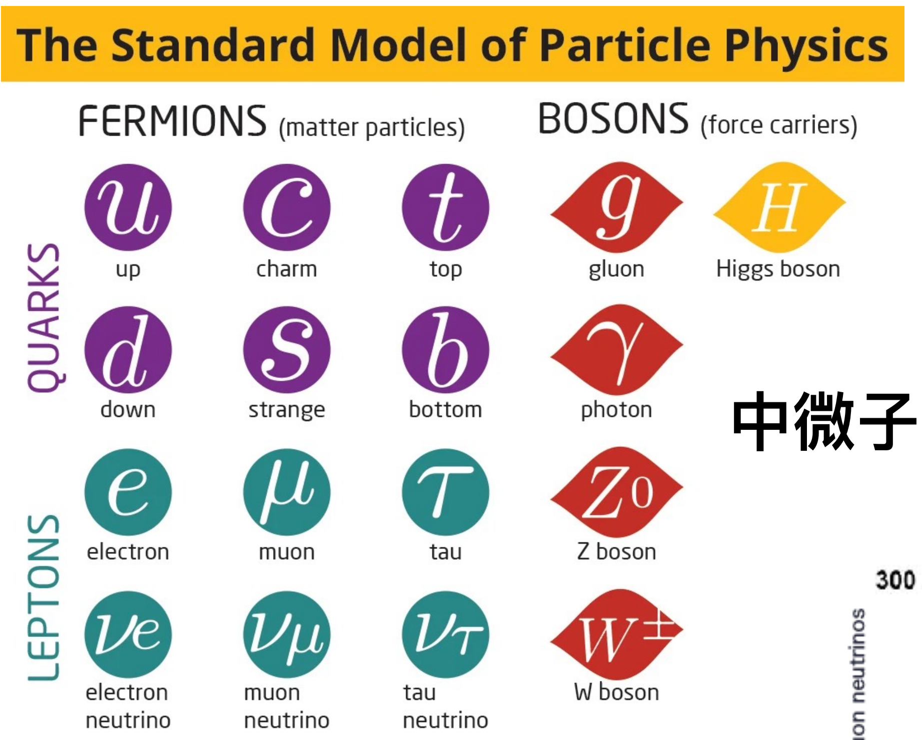
标准宇宙学模型(ΛCDM)未解决的问题：

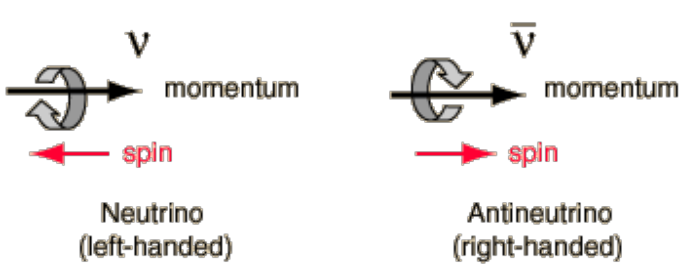
- 暴胀
- 暗能量
- 暗物质
- 物质–反物质不对称
- ……



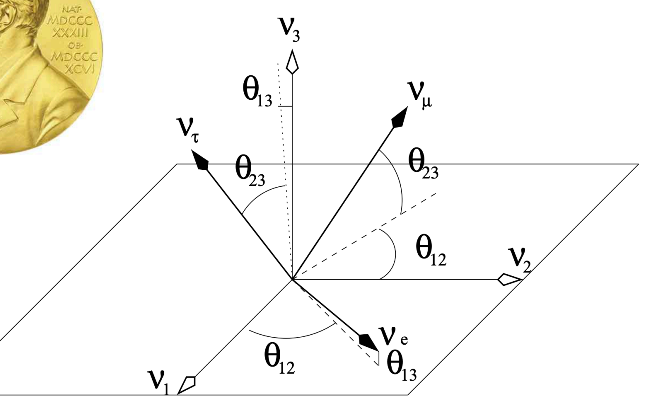


中微子质量





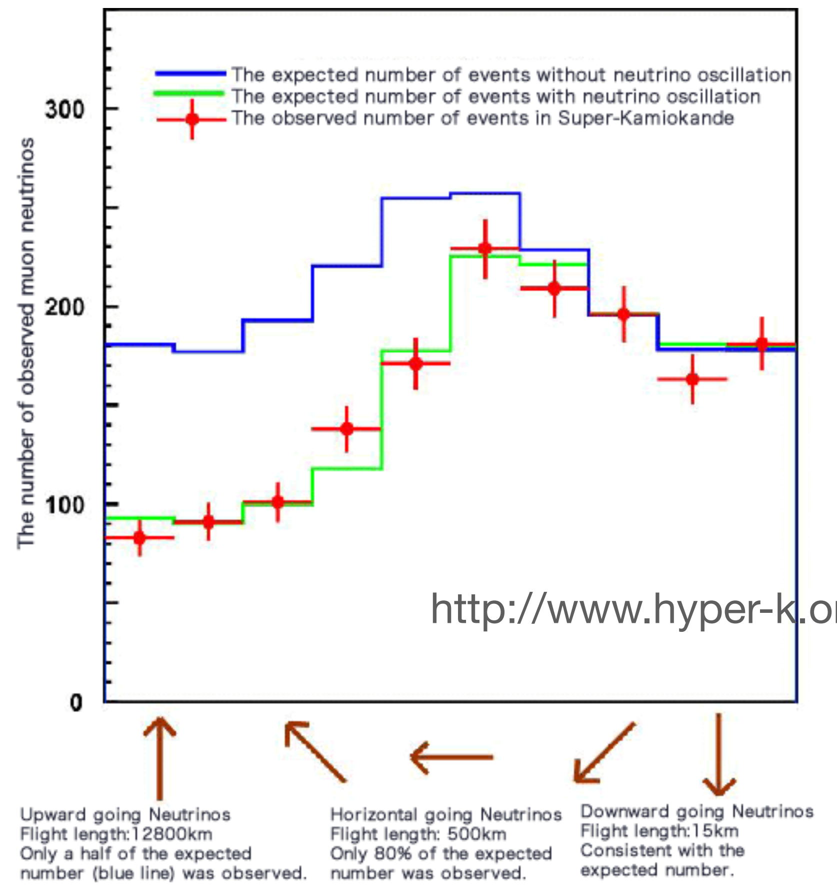
2015 Nobel Prize in Physics: T. Kajita and A. B. McDonald, "for the discovery of neutrino oscillations, which shows that neutrinos have mass".



S. F. King, 0310204

超出标准模型的新物理

中微子振荡现象说明中微子有质量且有混合



http://www.hyper-k.org/

粒子物理标准模型

中微子无质量

中微子物理待解决的问题：

- 是Majorana还是Dirac粒子
- 中微子质量和混合的起源
- CP破坏的存在性及大小
- 质量顺序
- 绝对质量
- 是否存在惰性中微子
- 是否能作为暗物质
- 宇宙遗迹中微子
- ……

Xing and Zhou, Neutrinos in particle physics, astronomy and cosmology 2011

实验：振荡实验(JUNO, T2K, DUNE, …),

非振荡实验(GERDA, KamLAND-Zen, EXO, KATRIN, …)

宇宙物质—反物质不对称

宇宙重子—反重子不对称 （CMB, LSS, BBN 观测）

$$Y_B = \frac{n_B - n_{\bar{B}}}{s} = (8.72 \pm 0.08) \times 10^{-11}$$

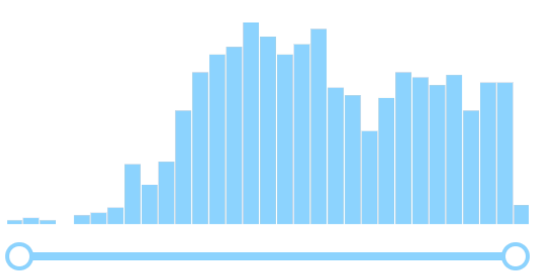
粒子物理、宇宙学基本问题

构建完整粒子物理理论、了解早期宇宙演化必需

动力学产生Y_B——重子生成机制

- 轻子生成 和中微子物理关联，是最重要的重子生成机制之一 Fukugita & Yanagida 1986
- 电弱重子生成 Rubakov & Shaposhnikov 1996
- Affleck-Dine 机制 Affleck & Dine 1985, Dine, Randall & Thomas 1996
- ……

Date of paper



至今依然活跃

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- Single author 394
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	Citeable	Published
Papers	1,174	849
Citations	39,879	38,332
h-index	91	91
Citations/paper (avg)	34	45.1

Papers — Citeable — Published

轻子生成研究主要问题：

- 检验
- CP源
- 模型独立特征

轻子生成综述：Davidson, Nardi & Nir 2008, Xing & Zhao 2021

暴胀物理

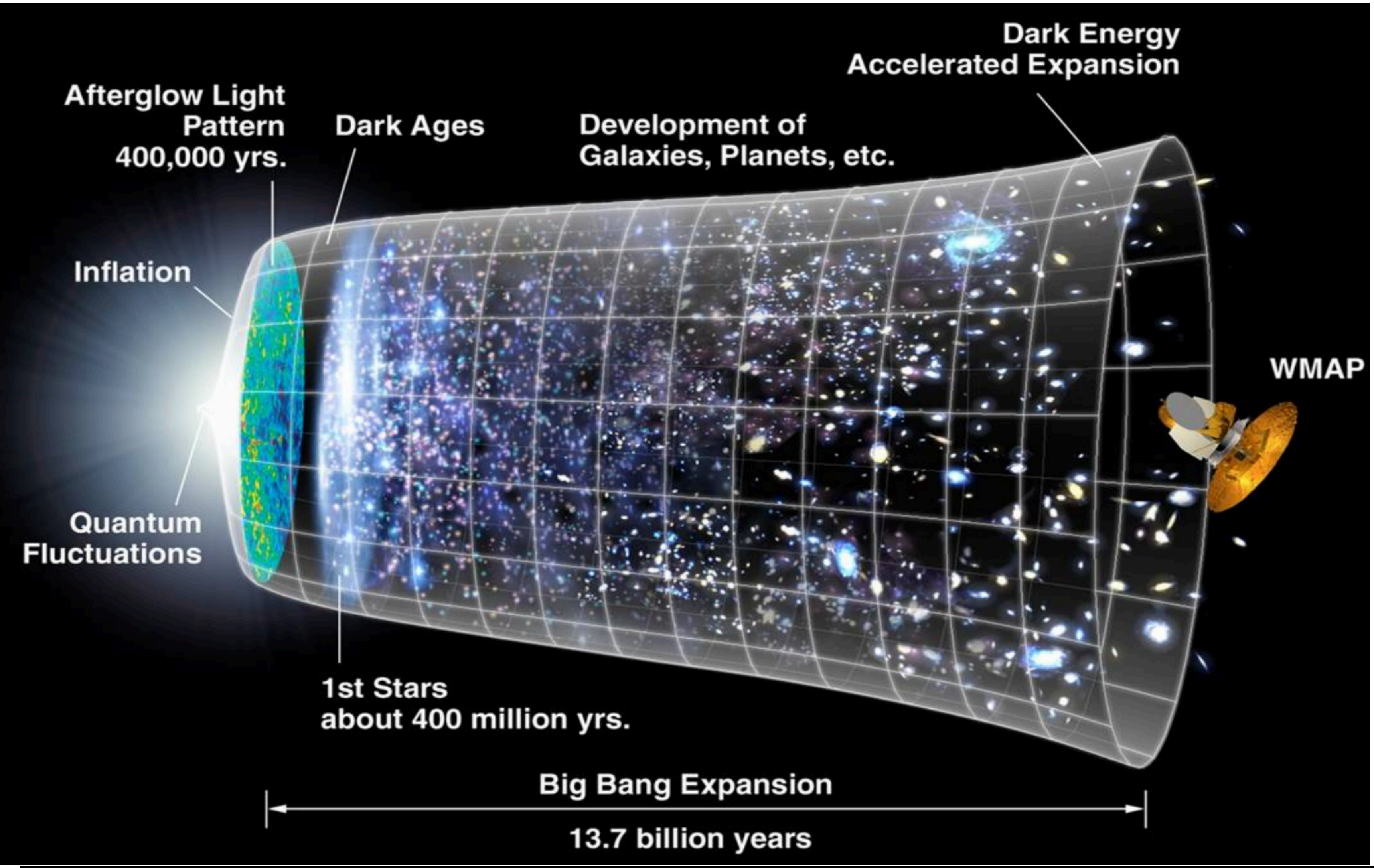
2014 Kavli Prize
for invention of inflation

理论支持：解决平坦性、视界问题，量子涨落→大尺度结构

观测支持：CMB观测近标度不变的标量功率谱

Guth 1981
Kazanas 1980
Starobinsky 1980
Sato 1981

标准宇宙学/ΛCDM



暴胀物理的主要问题：

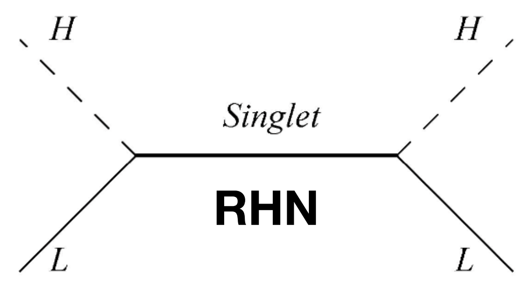
- “现实”暴胀模型（暴胀理论）
- 单场/多场
- 暴胀子的粒子物理本质
- 有效场论描述
- 相互作用处理→重加热
- 张量模式（原初引力波）
- 非高斯性
- 温度效应
- 修改引力效应
- ……

暴胀综述： Lyth & Riotto 1999,
Bassett, Tsujikawa & Wands 2006,
Martin, Ringeval & Vennin 2014

轻子生成

Introduce right-handed neutrinos (RHNs) to SM

Light neutrino mass is explained through **type-I seesaw**



P. Minkowski,1977; T. Yanagida, ,1979;
J. Schechter and J. W. F. Valle, 1980

To generate the BAU dynamically (**baryongenesis**), Sakharov (1967) proposes three conditions:

- **Baryon number violation**
- **C and CP violation**
- **Deviation from equilibrium**

In (type-I seesaw) leptogenesis, RHNs decay out-of-equilibrium, generating a CP asymmetry (also a L asymmetry), which converts to a B asymmetry via SM sphalerons

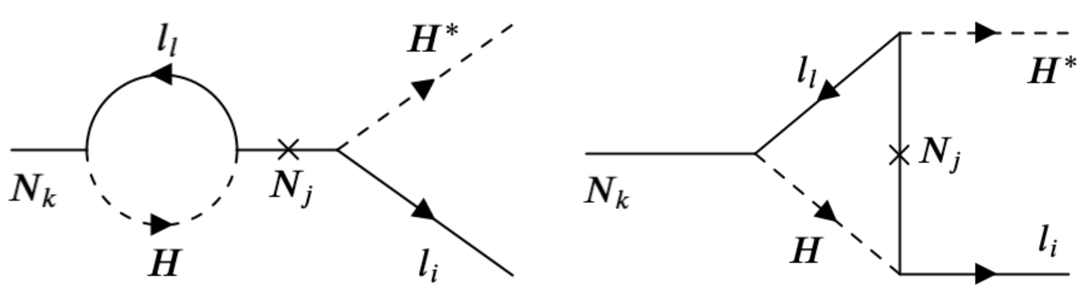
Thermal leptogenesis: Fukugita & Yanagida 1986

RHNs are produced in thermal bath (zero initial abundance/thermal distribution)

Non-thermal leptogenesis:

RHNs are produced non-thermally (e.g., via heavy particle decay)

inflaton



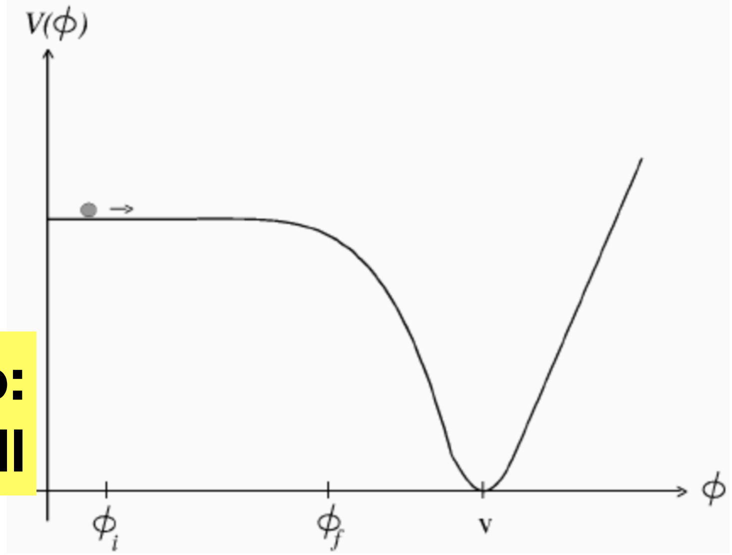
$$\epsilon_{N_K} = \sum_i \frac{\Gamma(N_k \to l_i H^*) - \Gamma(N_k \to \bar{l}_i H)}{\Gamma(N_k \to l_i H^*) + \Gamma(N_k \to \bar{l}_i H)},$$

基本想法

Introduce right-handed neutrinos (RHNs) to SM,

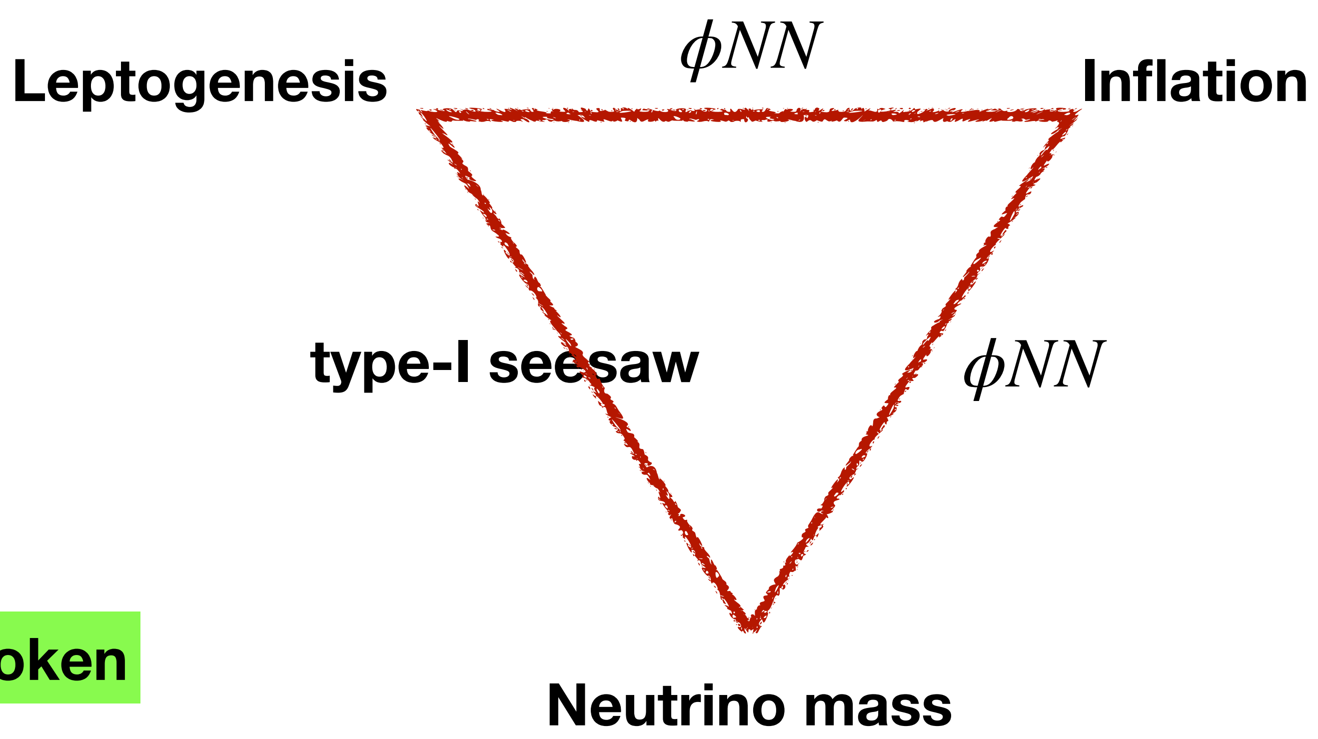
- ✓ Neutrino mass via type-I seesaw
- ✓ Leptogenesis
- ? more

Simplest inflationary scenario:
Single-field slow-roll



Both leptogensis and inflation happen at high scale, could connect more directly

Let ϕNN be the key!
ϕ inflaton
N RHN



When ϕ acquires a vev,
a Majorana mass for RHN is generated

Extra bonus: lepton number spontaneously broken

基本框架

Scalar field charged under lepton number

$$\mathcal{L} \supset \overline{N} i \partial\!\!\!/ N + (\partial^\mu \sigma^\dagger)(\partial_\mu \sigma) - \bar{L} Y_\nu \widetilde{H} N - y_N \sigma \overline{N^c} N - V(H, \sigma) + \text{h.c.}$$

RHNs

RHNs get masses once lepton number spontaneously broken

Important quantities

Inflaton decay rate $\Gamma_\phi = y_N^2 \frac{M_\phi}{4\pi}$

Reheating temperature $T_{\rm RH} = \left(\frac{45}{4\pi^3 g_*}\right)^{\frac{1}{4}} \sqrt{\Gamma_\phi m_{\rm pl}}$

Effectively parametrize y_N

RHN decay rate $\Gamma_N = H(M_1) K \frac{K_1(z)}{K_2(z)}$

Decay parameter $K = \tilde{m}_1 / m_*$

$$\tilde{m}_1 = \frac{(Y_\nu^\dagger Y_\nu)_{11} v^2}{M_1} = \frac{8\pi v^2}{M_1^2} \tilde{\Gamma}_N$$

Effectively the Yukawa strength

$$m_* = \frac{8\pi v^2}{M_1^2} H(M_1) \,,$$

Solve Boltzmann equations for the system $\{\phi, N, R\}$

$$Y_{\rm B} = \frac{n_{\rm B}}{s} = \frac{c_{\rm sph}\epsilon}{s} n_N$$

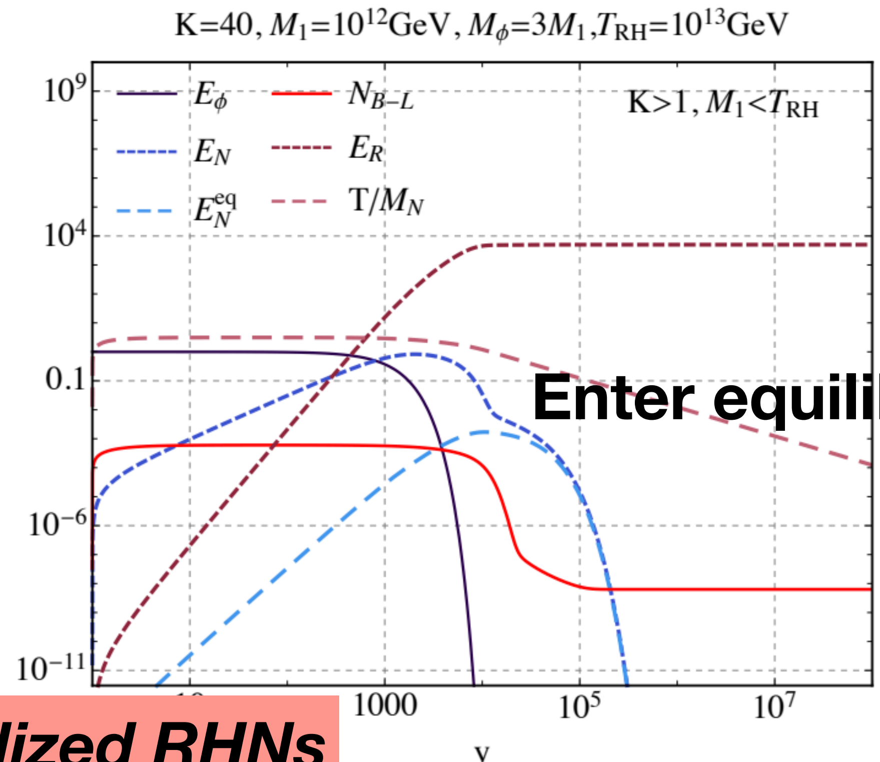
四种极限

- Non-thermal leptogenesis
  - Instantaneous RHN decay: $\Gamma_N \gg \Gamma_\phi$
    - *Instantaneous reheating*: $K \ll 1,\ T_* \gg T_{\rm RH}$
    - *Strongly non-thermal RHNs*: $K \gg 1,\ M_1 > T_{\rm RH}$
    - Both lead to: $$Y_{\rm B} = \frac{3}{2} c_{\rm sph} \epsilon \frac{T_{\rm RH}}{M_\phi}$$
  - Delayed RHN decay: $\Gamma_N \ll \Gamma_\phi$
    - *RHN dominance*: $K \ll 1,\ T_* < T_{\rm RH}$ (NR); $K \ll 1,\ T_* < T_{\rm dom}$ (R)
      - $$Y_{\rm B} = \frac{3}{4} c_{\rm sph} \epsilon \frac{T_*}{M_1}$$
    - *Thermalized RHNs*: $K \gg 1,\ M_1 < T_{\rm RH}$

RHNs produced non-thermally, but enter equilibrium via quick interactions

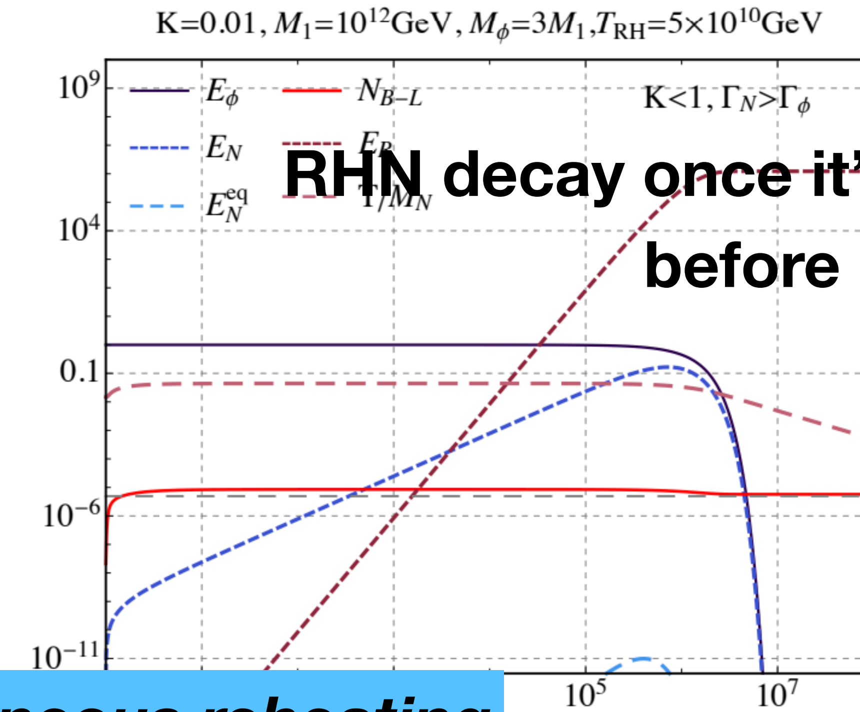
RHNs never enter equilibrium

四种情形演化行为



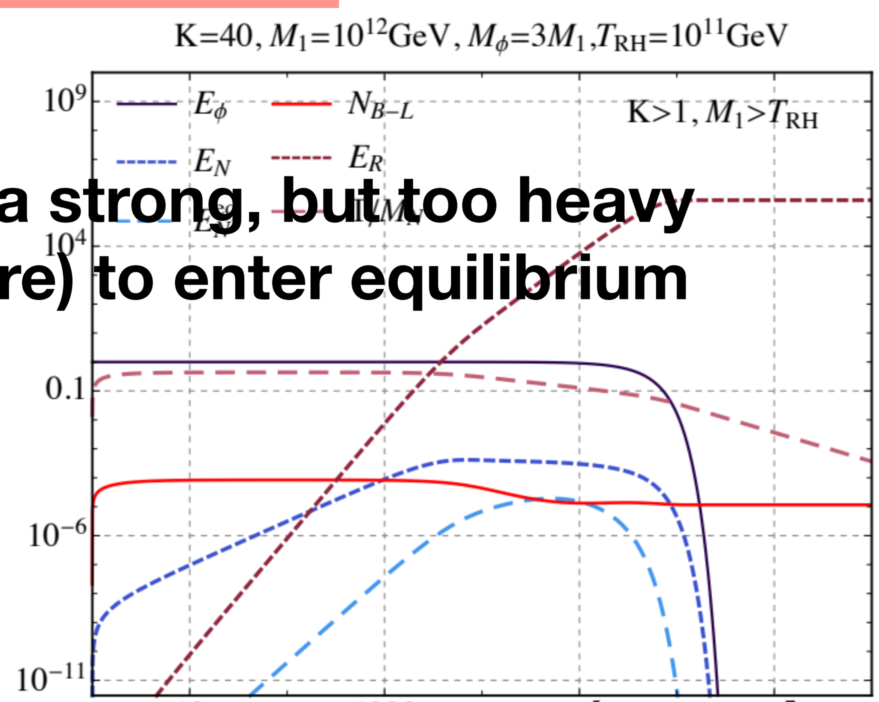
Enter equilibrium

Thermalized RHNs



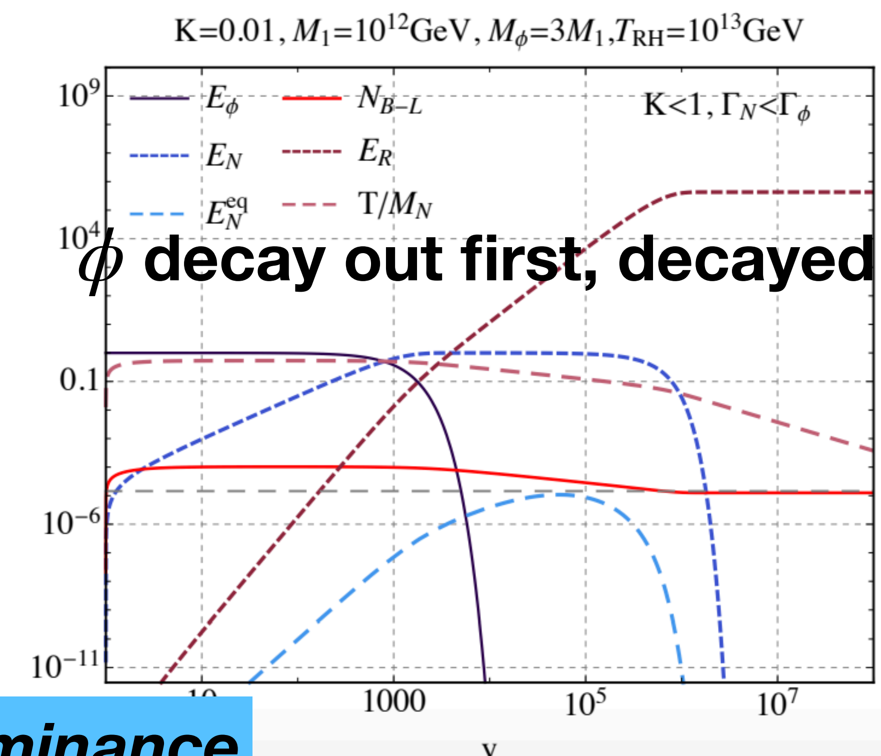
RHN decay once it's produced, before ϕ decay out

Instantaneous reheating



Yukawa strong, but too heavy (too rare) to enter equilibrium

Strongly non-thermal RHNs



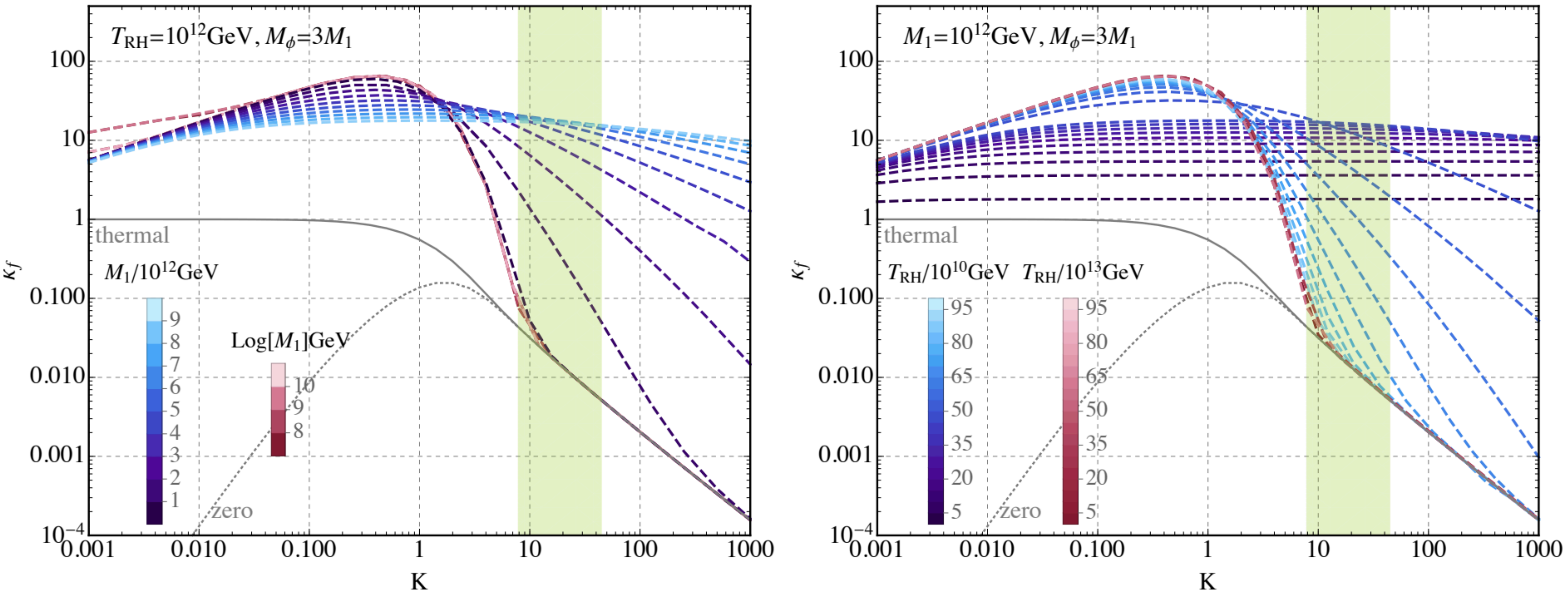
ϕ decay out first, decayed RHN decay

RHN dominance

效率因子比较

Define **final efficiency factor κ_f**

$$\eta_{\rm B-L} = \frac{n_{\rm B-L}}{n_\gamma^{\rm eq}} = -\frac{3}{4}\epsilon\kappa_f$$



All three truly non-thermal cases have κ_f larger than thermal leptogenesis

联合暴胀观测限制的结果

Inflaton potential: Coleman-Weinberg

$$V(\phi) = A\phi^4 \left[\ln\left(\frac{\phi}{v_\phi}\right) - \frac{1}{4}\right] + \frac{1}{4}Av_\phi^4$$

Inflation-observation-compatible benchmark values

$$A = 2.41 \times 10^{-14}, v_\phi = 22.1 M_{\rm pl}$$

$$\rightarrow \quad M_\phi = 1.65 \times 10^{13}\ \text{GeV}$$

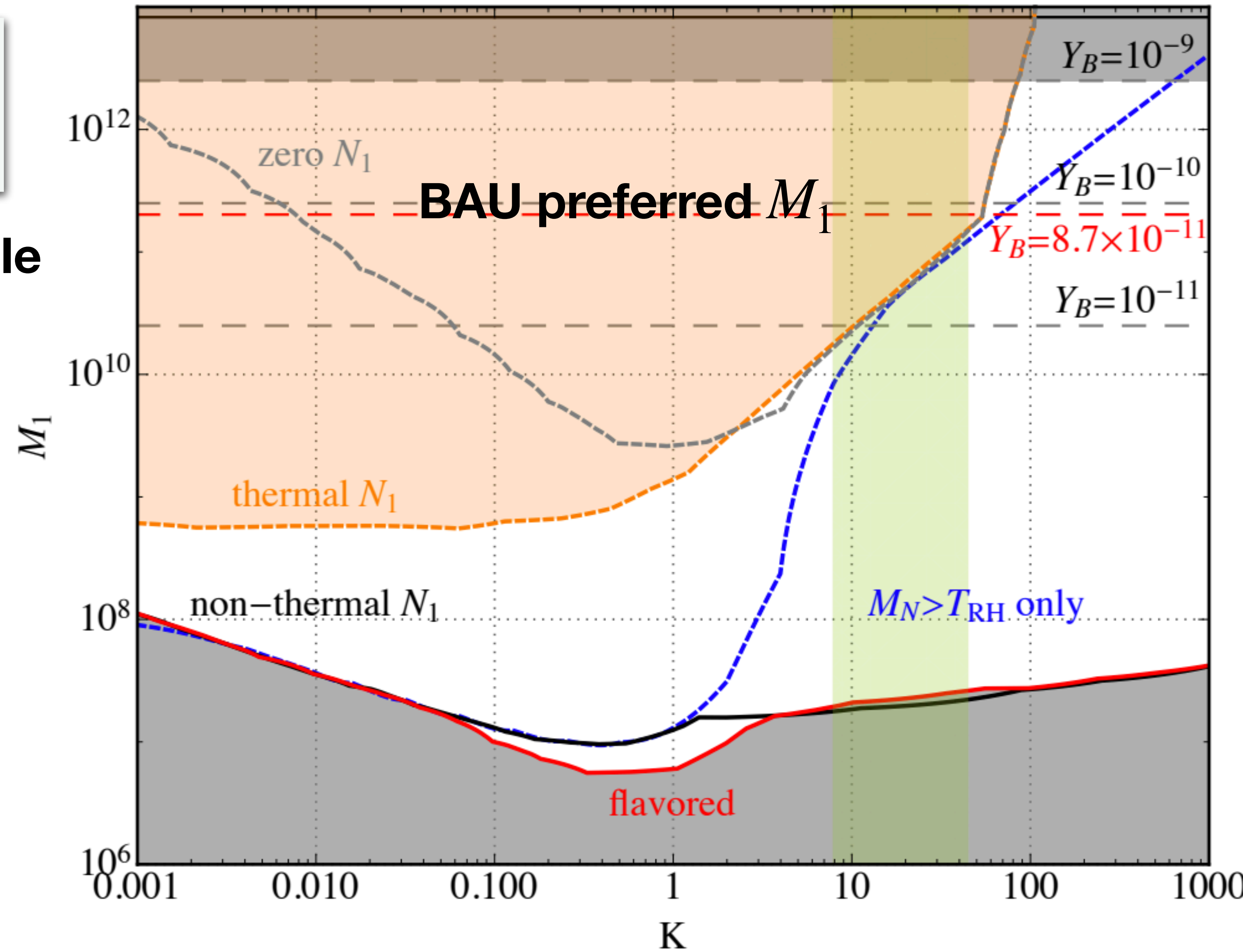
BAU constrains M_1

$\rightarrow y_N \rightarrow T_{\rm RH}$

Viable parameter space satisfy

$$T_{\rm RH} \simeq 10^{-5} M_1$$

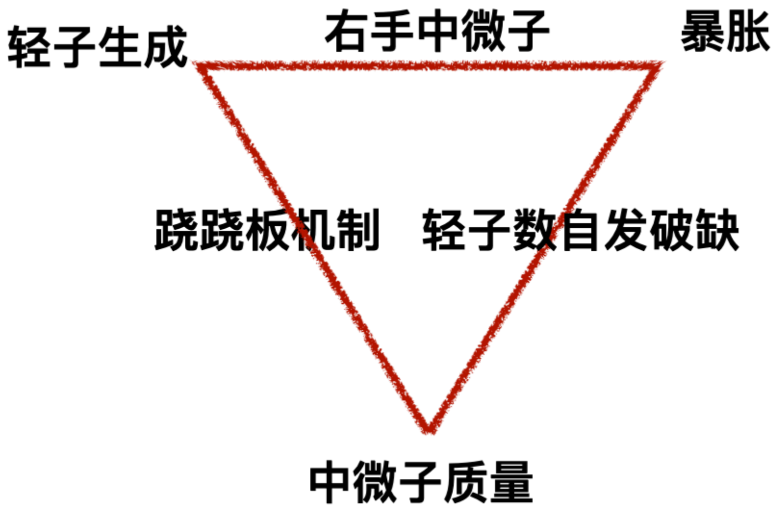
Strongly non-thermal RHNs preferred



结论

首次系统分析了基于暴胀子衰变的非热产生轻子生成机制

- 提出四种极限情形：
  - 其中 Strongly non-thermal RHNs 情形可显著降低重加热温度$T_{\rm RH} \geq 10^3$GeV, 同时降低M_1下限至2×10^7GeV;
  - 三种右手中微子不进入热平衡的情形，效率因子均大于热轻子生成机制。
- 联合暴胀观测限制，可进一步限制参数空间为 Strongly non-thermal RHNs 区间
- 提供了一个简单、自然的框架，同时解释中微子质量、重子不对称，并和暴胀物理建立自然且可供未来实验、观测检验的关联



在站期间完成工作

已发表论文

- Y. Reyimuaji and **X. Zhang**, Warm-assisted natural inflation, **JCAP** 04 (2021) 077
- Y. Reyimuaji and **X. Zhang**, Natural inflation with a nonminimal coupling to gravity, **JCAP** 03 (2021) 059
- **X. Zhang** and S. Zhou, Inverse Seesaw Model with a Modular S_4 Symmetry: Lepton Flavor Mixing and Warm Dark Matter, **JCAP** 09 (2021) 043
- **X. Zhang**, C. Y. Chen and Y. Reyimuaji, Modified gravity models for inflation: In conformity with observations, **Phys.Rev.D** 105 (2022) 4, 043514

其他论文

- C. Y. Chen, Y. Reyimuaji and **X. Zhang**, Slow-roll inflation in f(R,T) gravity with a RT mixing term, arXiv: 2203.15035 [gr-qc]
- **X. Zhang** and S. Zhou, Towards a systematic study of non-thermal leptogenesis from inflaton decays
- **X. Zhang** and S. Zhou, A Novel Parametrization of Neutrino Masses and Flavor Mixing
- J. T. Penedo, Y. Reyimuaji, **X. Zhang**, Axionic Dirac seesaw and electroweak vacuum stability


谢谢大家!