威海新物理研讨会

2022年 7 月31日
— 8 月 7 日

轻 子 生 成
理论框架与最新进展

周 也 铃, HIAS, 2022-08-02

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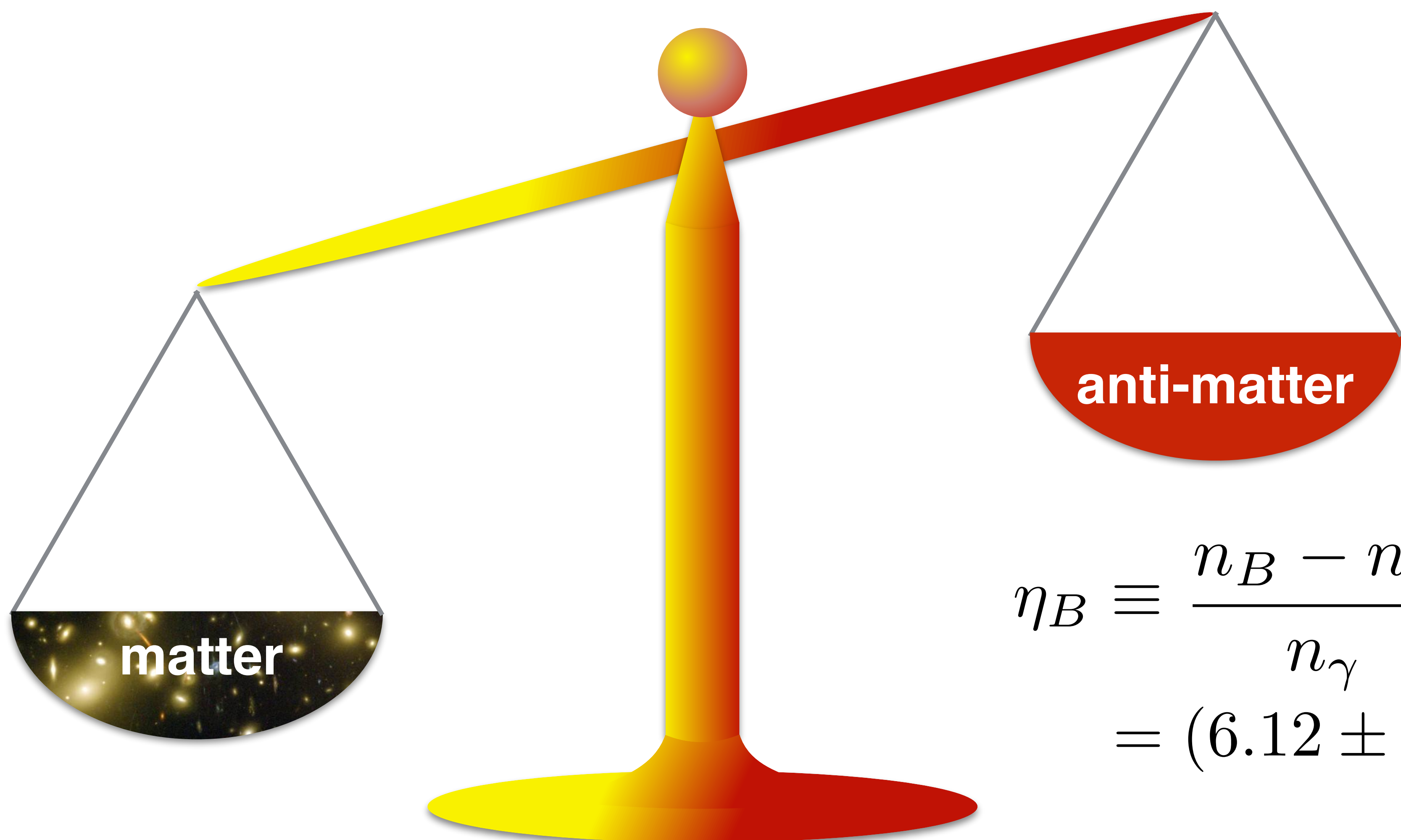
Baryon asymmetry

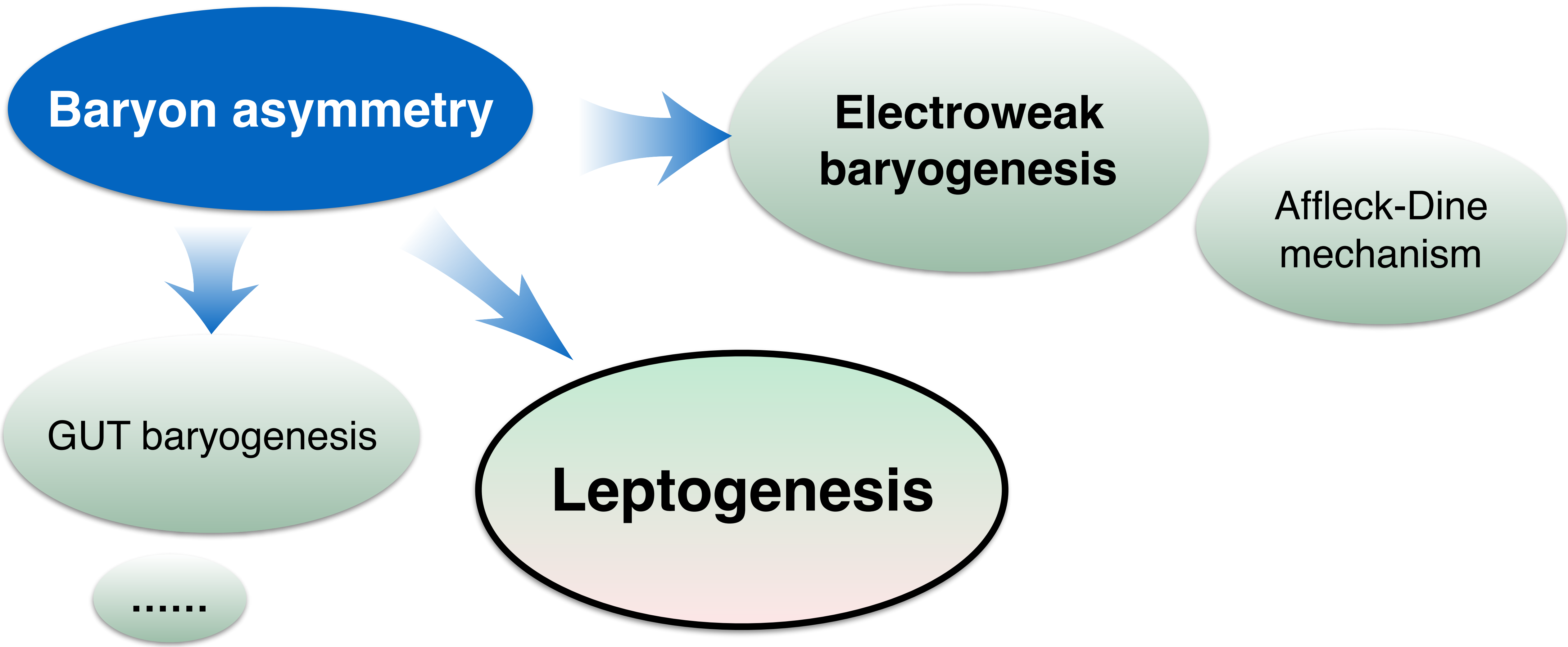


$$\eta_B \equiv \frac{n_B - n_{\overline{B}}}{n_\gamma} = (6.12 \pm 0.04) \times 10^{-10}$$

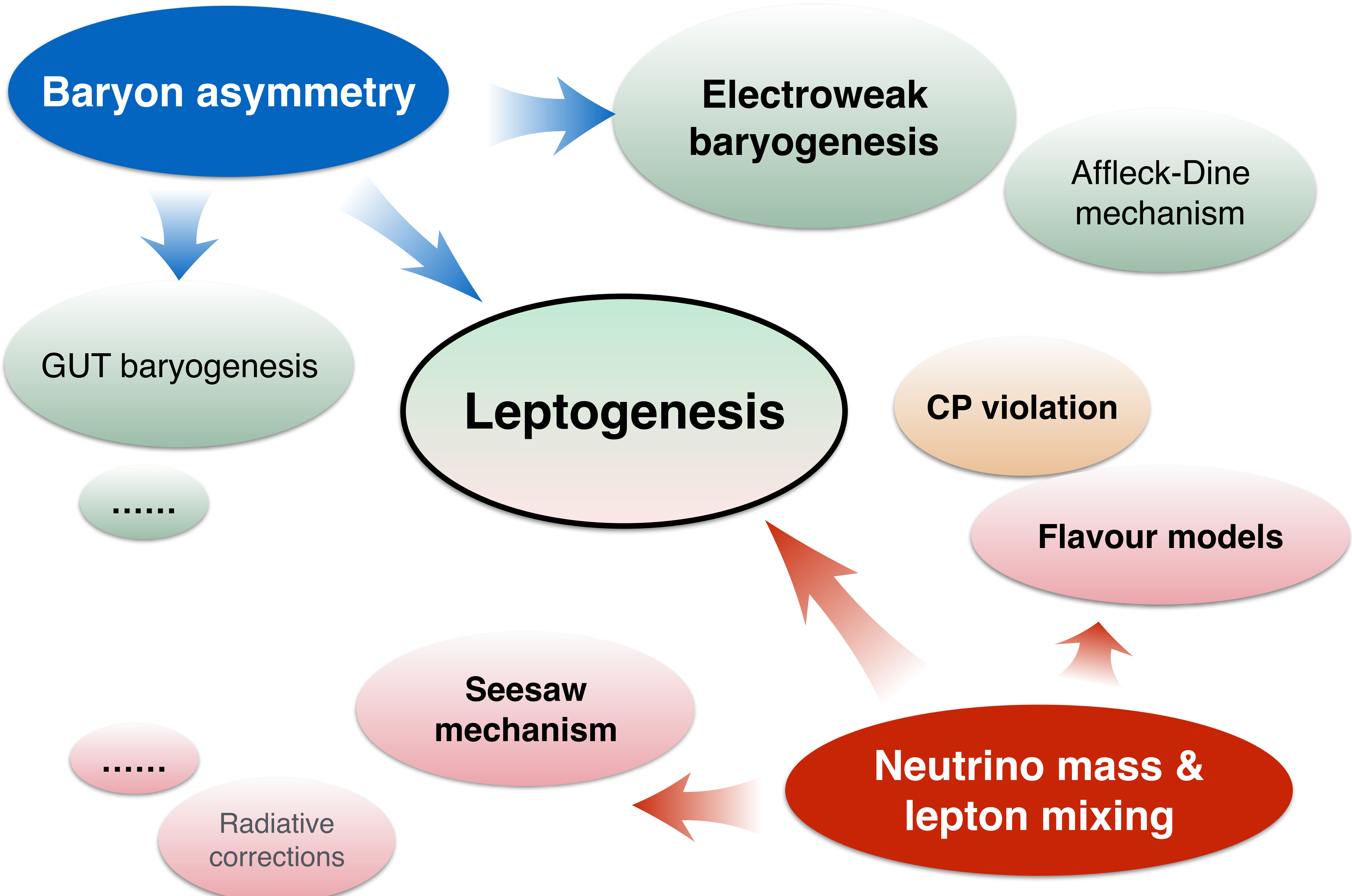
Planck 2018

Parameter(s)	$\Omega_b h^2$	$\Omega_c h^2$	$100\theta_{MC}$	H_0	n_s	$\ln(10^{10} A_s)$
Base ΛCDM	0.02237 ± 0.00015	0.1200 ± 0.0012	1.04092 ± 0.00031	67.36 ± 0.54	0.9649 ± 0.0042	3.044 ± 0.014
r	0.02237 ± 0.00014	0.1199 ± 0.0012	1.04092 ± 0.00031	67.40 ± 0.54	0.9659 ± 0.0041	3.044 ± 0.014
$dn_s/d\ln k$	0.02240 ± 0.00015	0.1200 ± 0.0012	1.04092 ± 0.00031	67.36 ± 0.53	0.9641 ± 0.0044	3.047 ± 0.015
$dn_s/d\ln k, r$	0.02243 ± 0.00015	0.1199 ± 0.0012	1.04093 ± 0.00030	67.44 ± 0.54	0.9647 ± 0.0044	3.049 ± 0.015
$d^2n_s/d\ln k^2, dn_s/d\ln k$.	0.02237 ± 0.00016	0.1202 ± 0.0012	1.04090 ± 0.00030	67.28 ± 0.56	0.9625 ± 0.0048	3.049 ± 0.015
N_{eff}	0.02224 ± 0.00022	0.1179 ± 0.0028	1.04116 ± 0.00043	66.3 ± 1.4	0.9589 ± 0.0084	3.036 ± 0.017

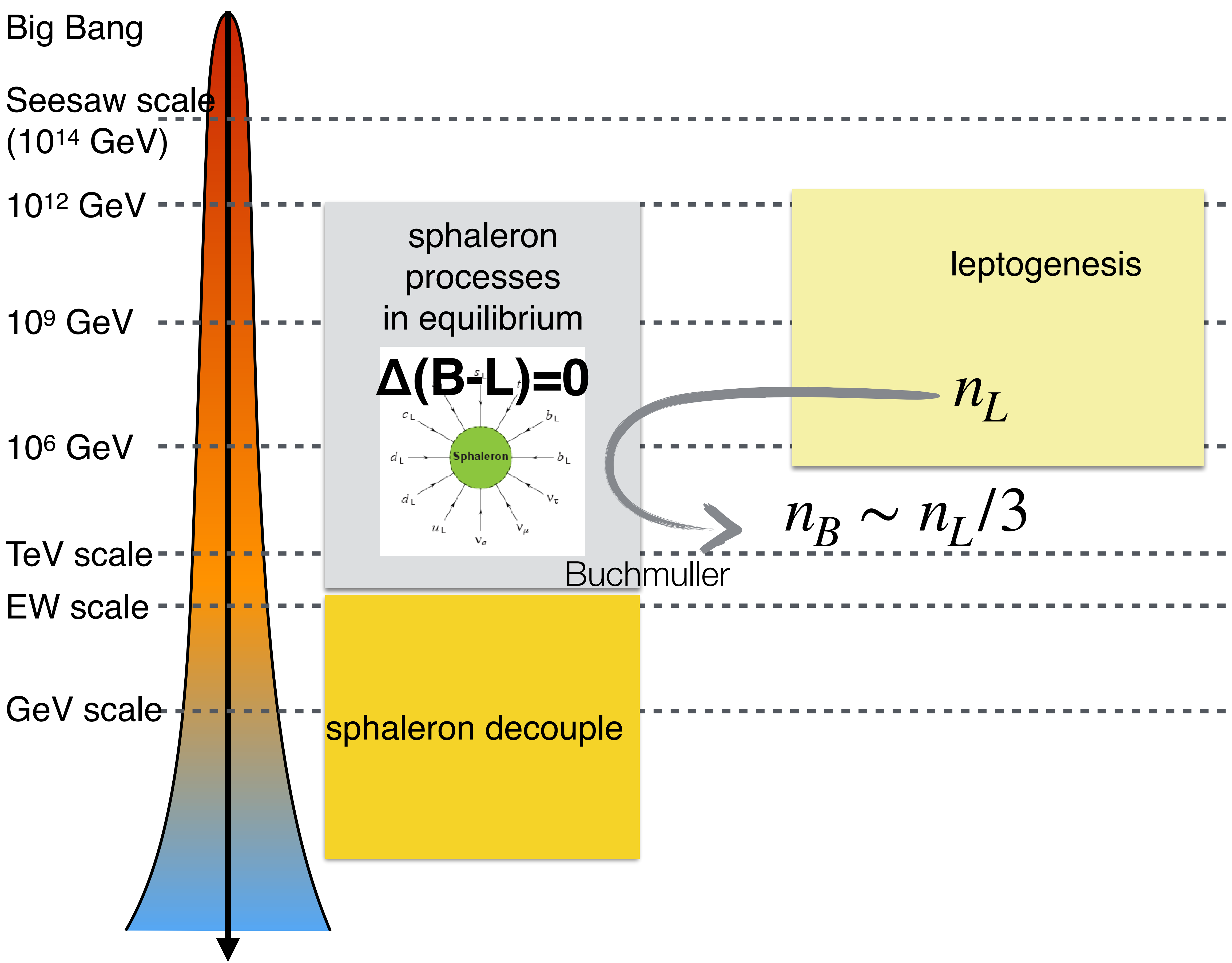
Baryogenesis



Baryogenesis via leptogenesis



Baryogenesis via leptogenesis



提纲

- 几种常见机制的简介
- 理论进展
- 实验验证
- 当前的重要问题

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Sakharov conditions for baryogenesis

B violation

C/CP violation

Out of equilibrium dynamics

在满足洛伦兹不变、局域、厄密的标准场论框架下，Sakharov三条件是必要条件

Sakharov conditions for leptogenesis

SM L/B-L violation

C/CP violation

Out of equilibrium dynamics

依然是必要条件吗? $L_{\rm SM} = L_e + L_\mu + L_\tau$

Origin of neutrino masses

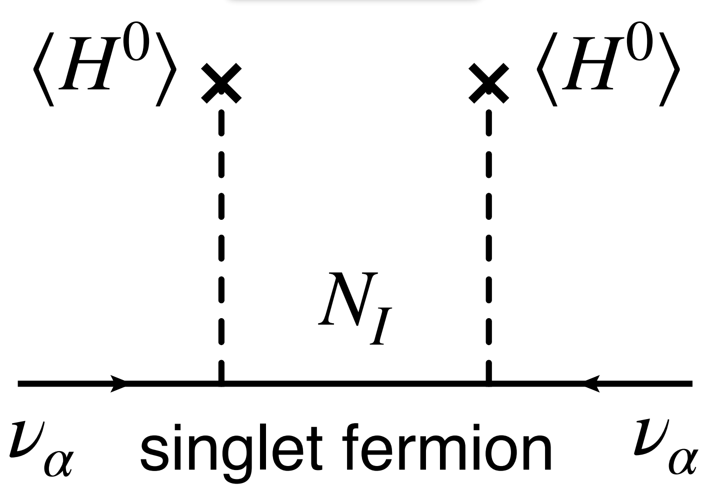
- Weinberg Operator $\mathcal{L}_W = \frac{\lambda_{\alpha\beta}}{\Lambda} \ell_{\alpha L} H C \ell_{\beta L} H + \text{h.c.}$

Lepton number violation **Majorana masses**

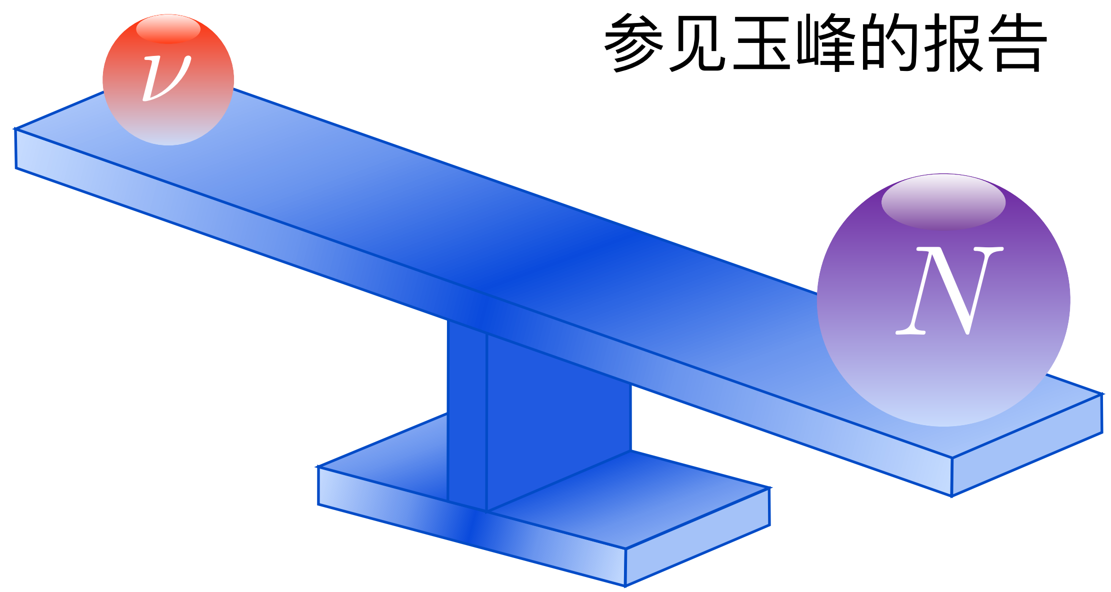
$$m_\nu = \lambda \frac{v_H^2}{\Lambda} \qquad \frac{\Lambda}{\lambda} \sim 10^{15}\ \text{GeV}$$

- Seesaw mechanism

Type I



参见玉峰的报告



$\alpha = e, \mu, \tau$

$$\mathscr{L} \supset Y_{\alpha I} \overline{L}_\alpha \tilde{H} N_I + M_I \overline{N}_I N_I^c + \text{h.c.} \qquad (M_\nu)_{\alpha\beta} = \sum_I \frac{Y_{\alpha I} Y_{\beta I}}{M_I} v^2 \qquad = M_D M_R^{-1} M_D^T$$

Minimal seesaw: $I = 1{,}2$; General: $I = 1{,}2{,}3$

Classical thermal leptogenesis

- Recipes of thermal leptogenesis (in type I seesaw)

RH neutrino N	C & CP violation	Out of equilibrium
$\Downarrow$	$\Downarrow$	$\Downarrow$
L violation	Complex Yukawas	Decay of lightest N_1

[Fukugita, Yanagida, 1986]

- Boltzmann equation $z = M_1/T$

$$
\begin{aligned}
\frac{dN_{N_1}}{dz} &= -(D+S)\,(N_{N_1} - N_{N_1}^{\rm eq})\,, \\
\frac{dN_{B-L}}{dz} &= -\varepsilon_1\, D\,(N_{N_1} - N_{N_1}^{\rm eq}) - W\, N_{B-L}\,,
\end{aligned}
$$

Decay and inverse decay $D = \Gamma_D/Hz$

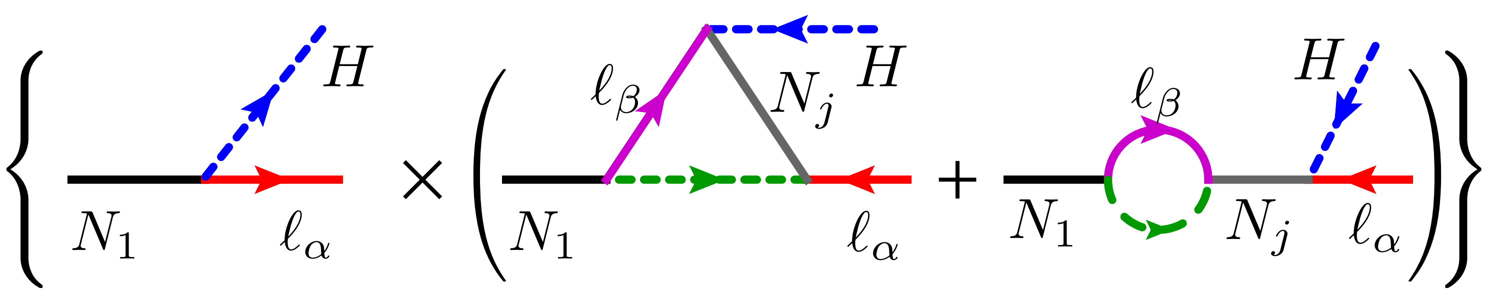
Scattering $S = \Gamma_S/Hz$

Washout $W = \Gamma_W/Hz$

- CP asymmetry

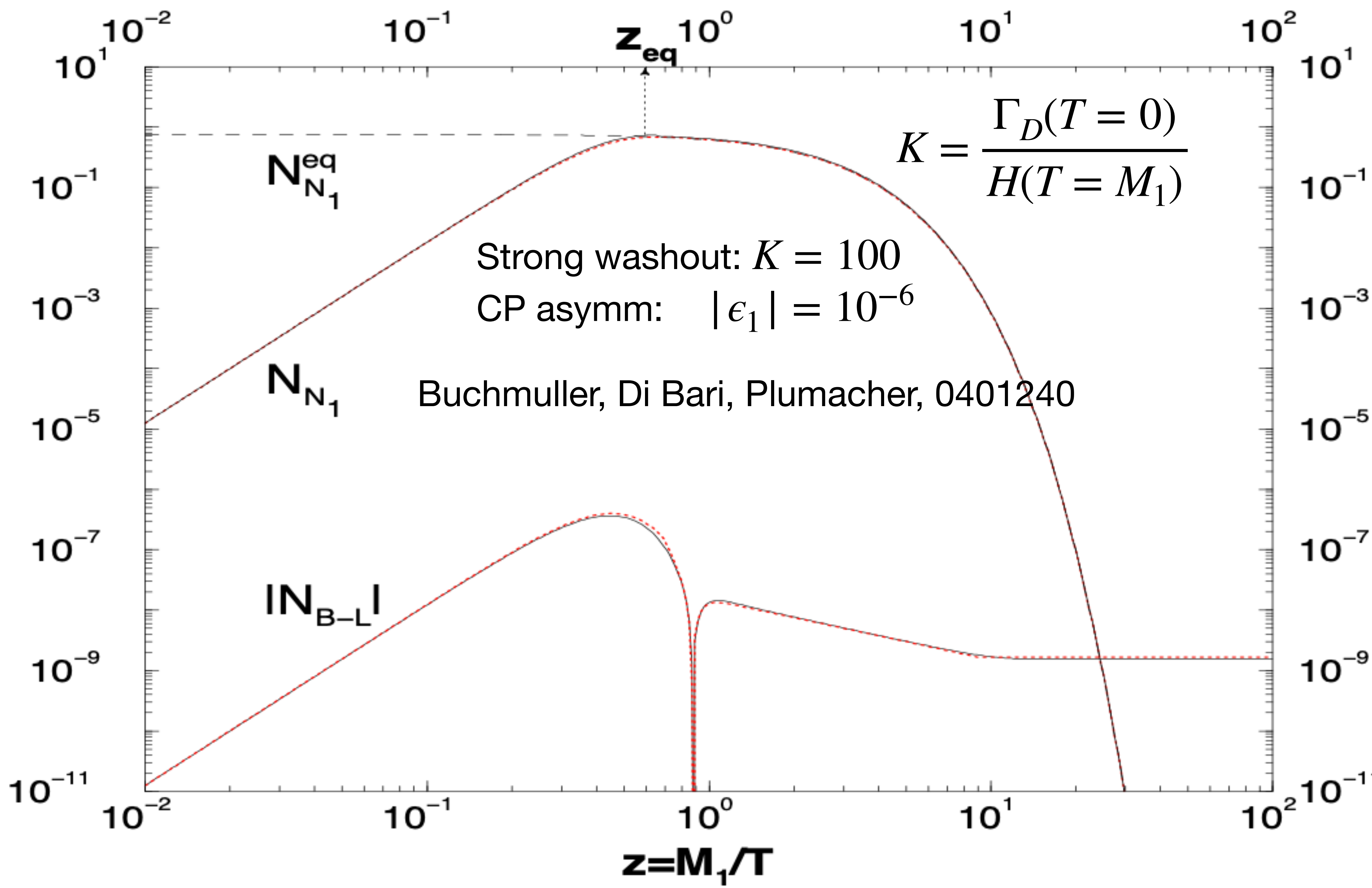
$$
\varepsilon_1 = \sum_{\alpha=e,\mu,\tau} \frac{\Gamma(N_1 \to L_\alpha H) - \Gamma(N_1 \to \overline{L}^c_\alpha H^\dagger)}{\Gamma(N_1 \to L_\alpha H) + \Gamma(N_1 \to \overline{L}_\alpha H^\dagger)}
$$

$\propto \mathrm{Im} \sum_{\alpha=e,\mu,\tau}$



Covi, Roulet, Vissani, hep-ph/9605319

An example



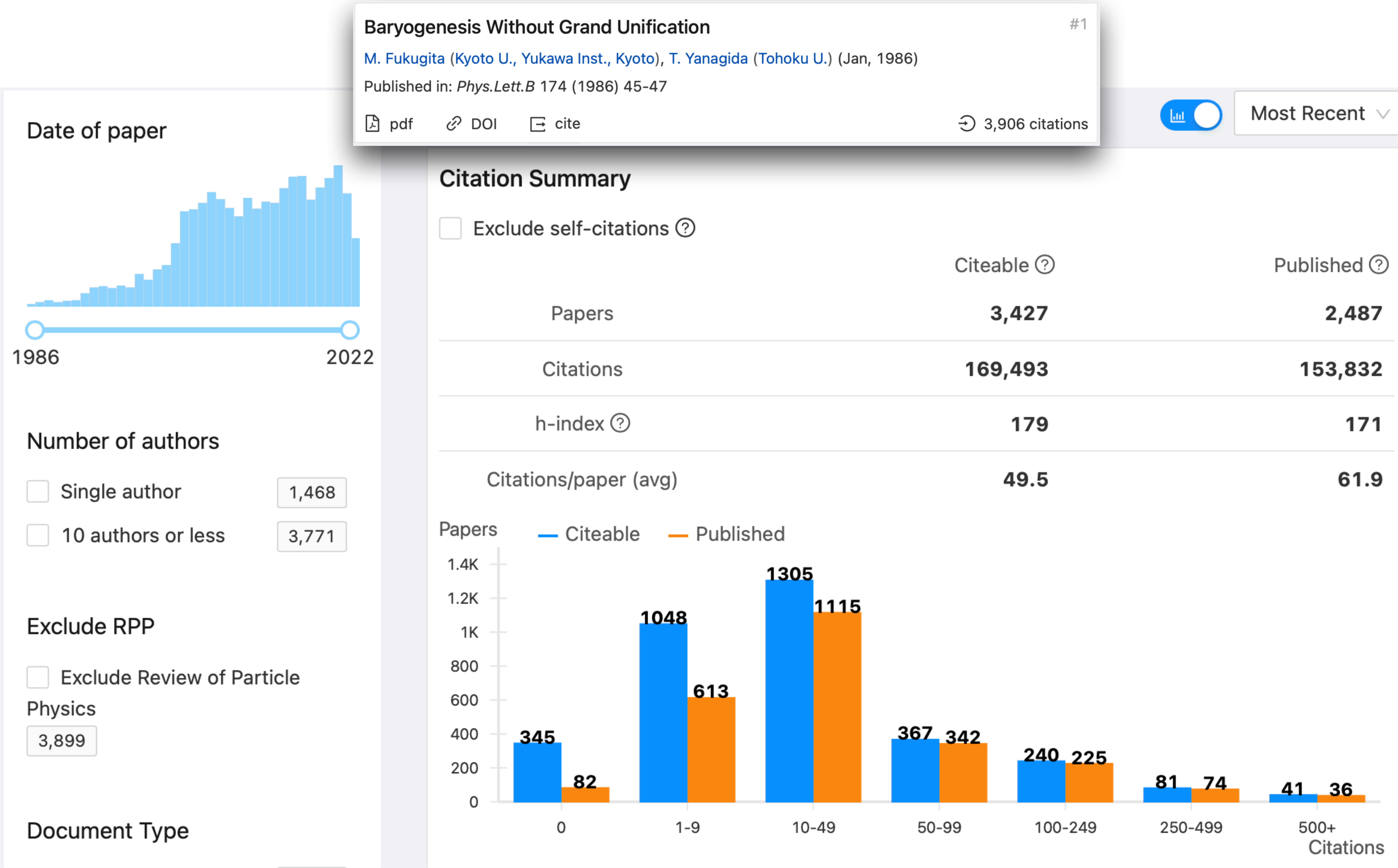
$$K = \frac{\Gamma_D(T=0)}{H(T=M_1)}$$

Strong washout: $K = 100$

CP asymm: $|\epsilon_1| = 10^{-6}$

Buchmuller, Di Bari, Plumacher, 0401240

Evolution of leptogenesis works



500+ citations

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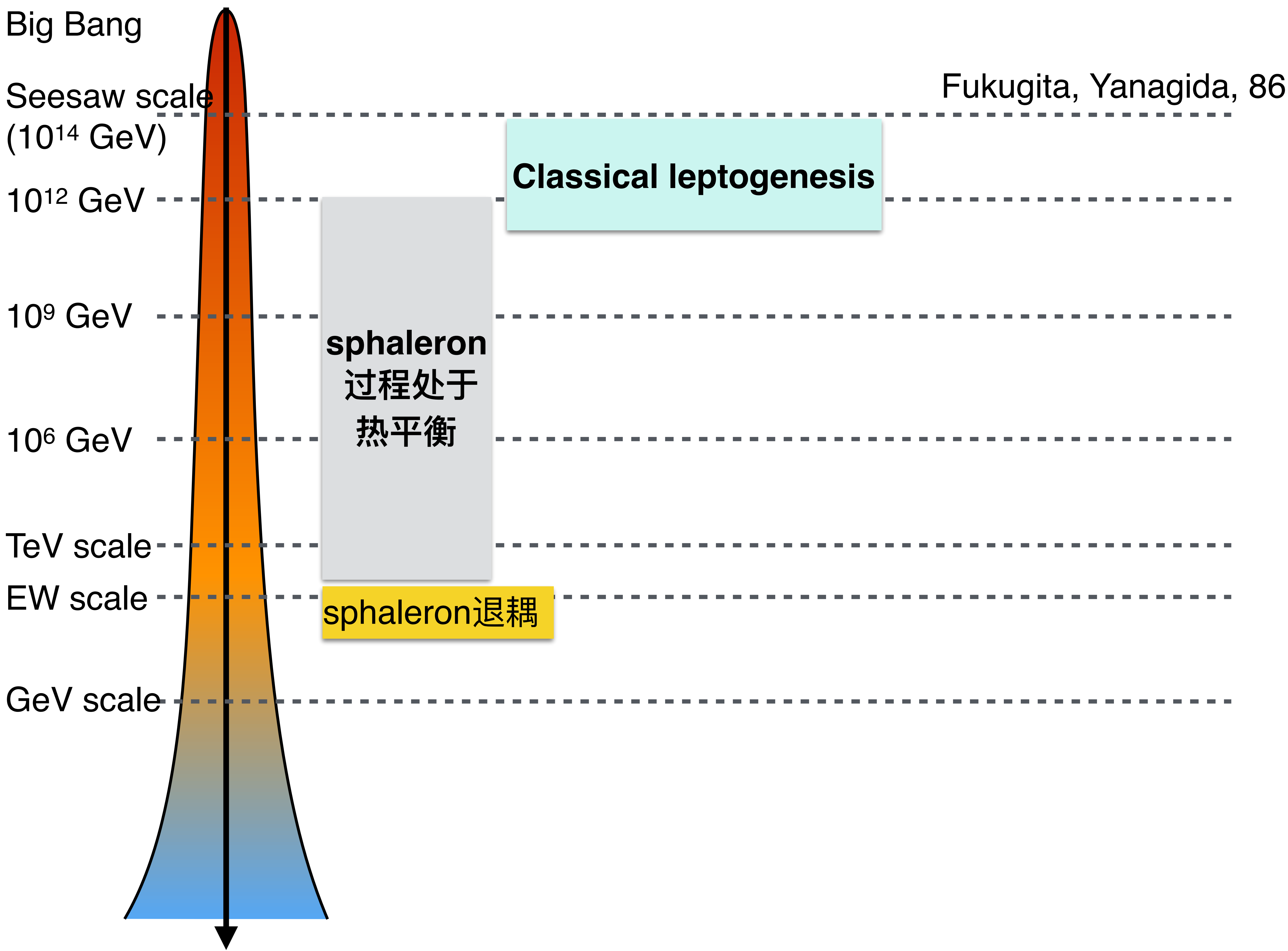
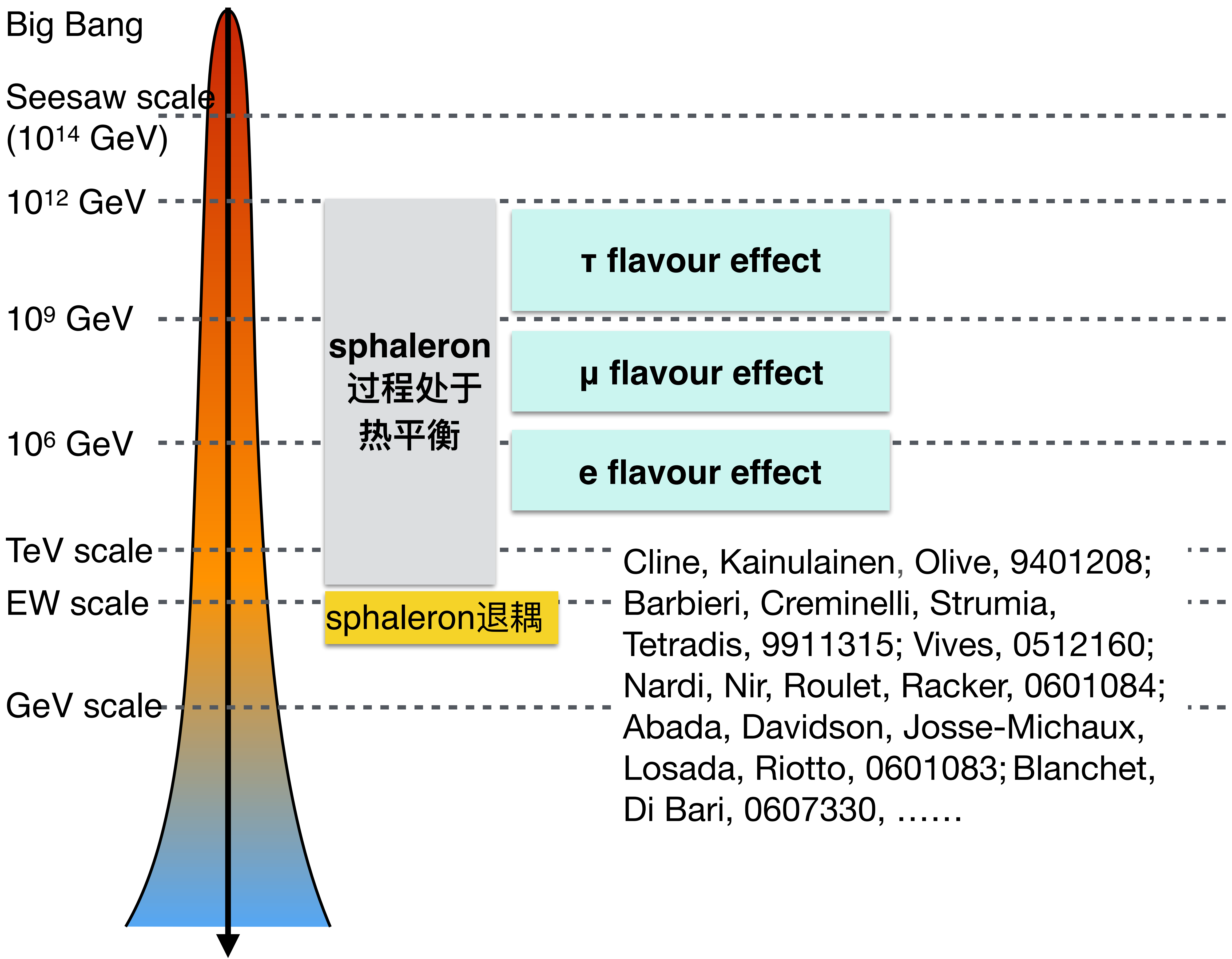
pdf DOI cite 915 citations

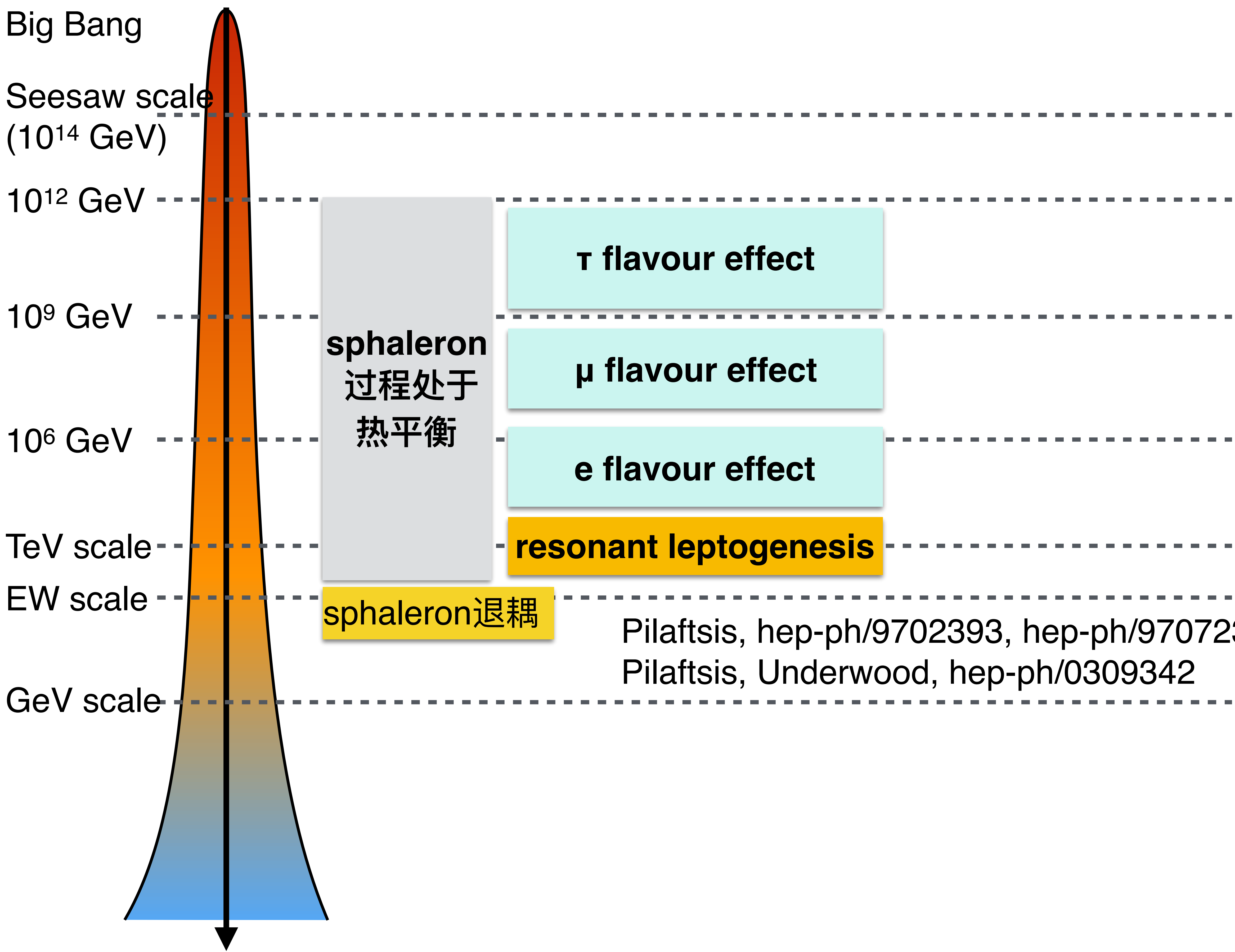
Variations of leptogenesis



Variations of leptogenesis

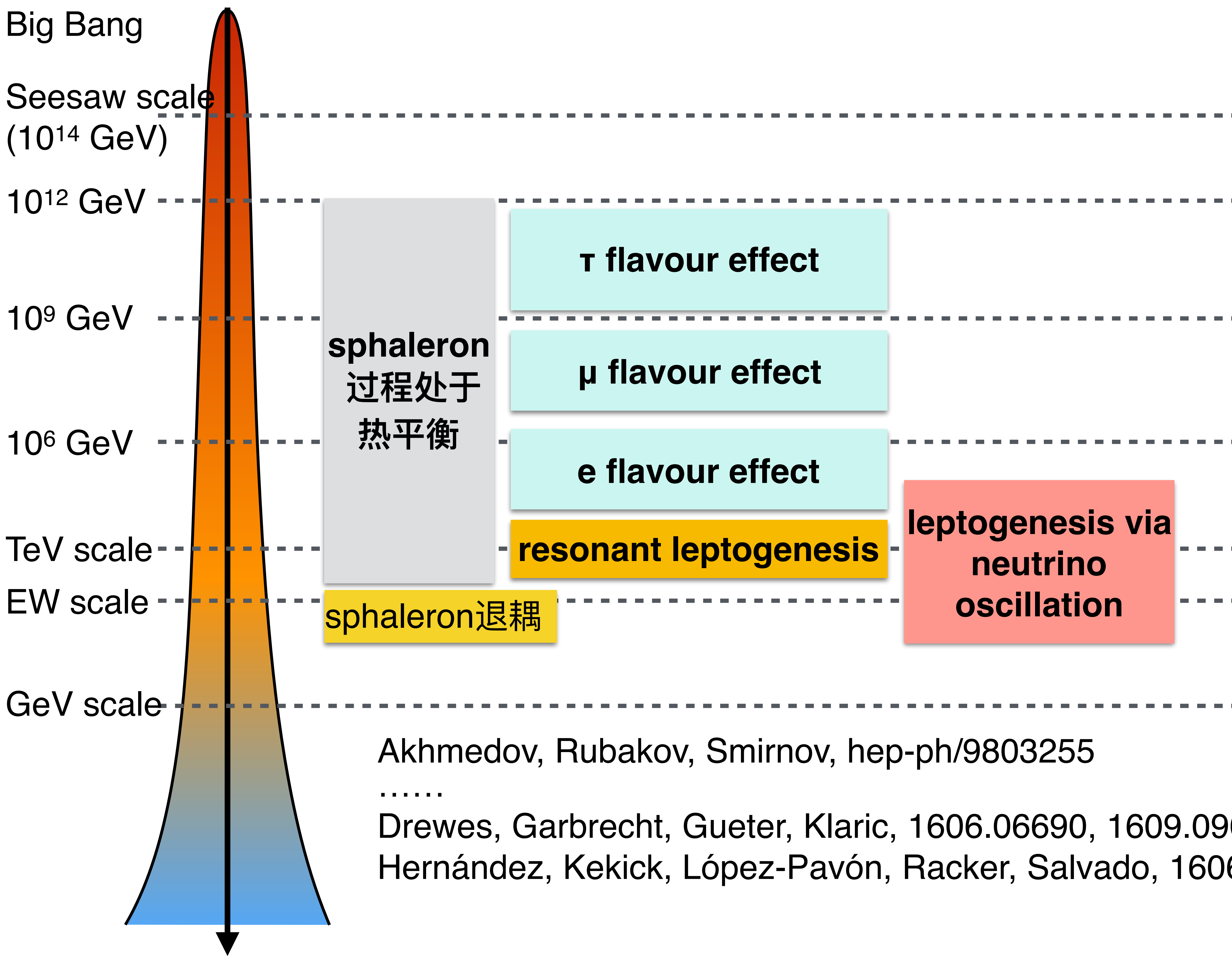


Variations of leptogenesis



Pilaftsis, hep-ph/9702393, hep-ph/9707235;
Pilaftsis, Underwood, hep-ph/0309342

Variations of leptogenesis



Akhmedov, Rubakov, Smirnov, hep-ph/9803255

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Drewes, Garbrecht, Gueter, Klaric, 1606.06690, 1609.09069;

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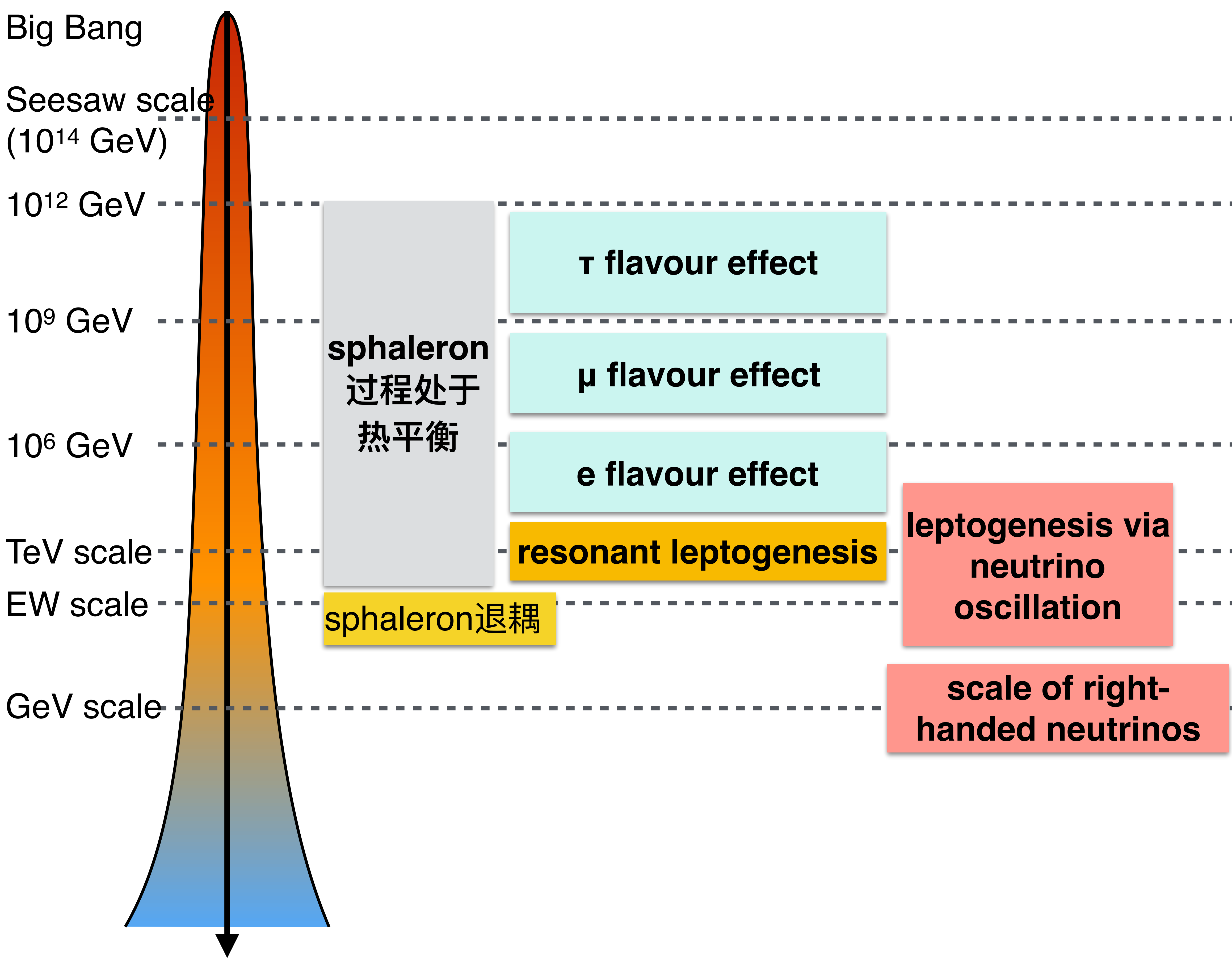
Variations of leptogenesis



Flavour effects

味效应是否需要考虑 ——取决于e, μ, τ的Yukawa耦合是否在sphaleron导致的重子与轻子的转化过程中发生作用

- $\Gamma_{L_\tau \leftrightarrow \tau_R (+\mathrm{Higgs})} \simeq 5 \cdot 10^{-3} \times y_\tau^2 T$ vs $H \simeq 1.66 g_\star T^2 / M_{\mathrm{pl}}$
- $T > 10^{12}$ GeV, $\tau_R \not\leftrightarrow L_\tau \leftrightarrow B$, $\mu_R \not\leftrightarrow L_\mu \leftrightarrow B$
- $10^9 < T < 10^{12}$ GeV, $\tau_R \leftrightarrow L_\tau \leftrightarrow B$, $\mu_R \not\leftrightarrow L_\mu \leftrightarrow B$
- $T > 10^6$ GeV, $e_R \leftrightarrow L_e \leftrightarrow B$

Resonant leptogenesis

Pilaftsis, 9707235; 9702393; 9812256

- CP asymmetry used in classical thermal leptogenesis

$$\varepsilon_{N_1} = \frac{\Gamma(N_1 \to lH) - \Gamma(N_1 \to \bar{l}H^\dagger)}{\Gamma(N_1 \to lH) + \Gamma(N_1 \to \bar{l}H^\dagger)}$$

$$= -\frac{1}{8\pi}\sum_{\beta\neq 1}\frac{\Im\left[\left(\lambda^\dagger\lambda\right)^2_{\beta 1}\right]}{(\lambda^\dagger\lambda)_{11}}\left\{\left[-\frac{M_\beta}{M_1}\left(1-\left(1+\frac{M_\beta^2}{M_1^2}\right)\right)\ln\left(1+\frac{M_1^2}{M_\beta^2}\right)\right]+\left[\frac{M_1/M_\beta}{1-(M_1^2/M_\beta^2)}\right]\right\}$$

$$\simeq -\frac{3}{16\pi}\sum_{\beta\neq 1}\frac{\Im\left[\left(\lambda^\dagger\lambda\right)^2_{\beta 1}\right]}{(\lambda^\dagger\lambda)_{11}}\frac{M_1}{M_\beta} \qquad (\text{For } M_1 \ll M_\beta)$$

摘自周顺的报告

[L. Covi, E. Roulet and F. Vissani, PLB384 (1996)]

- CP asymmetry in the limit $M_1 \approx M_2$

$$\epsilon_i = \frac{1}{(\lambda^\dagger\lambda)_{ii}}\frac{\mathrm{Im}[(\lambda^\dagger\lambda)^2_{21}]}{8\pi}\frac{M_1M_2(M_2^2-M_1^2)}{(M_2^2-M_1^2)^2+A^2} \qquad A = M_i\Gamma_i - M_j\Gamma_j$$

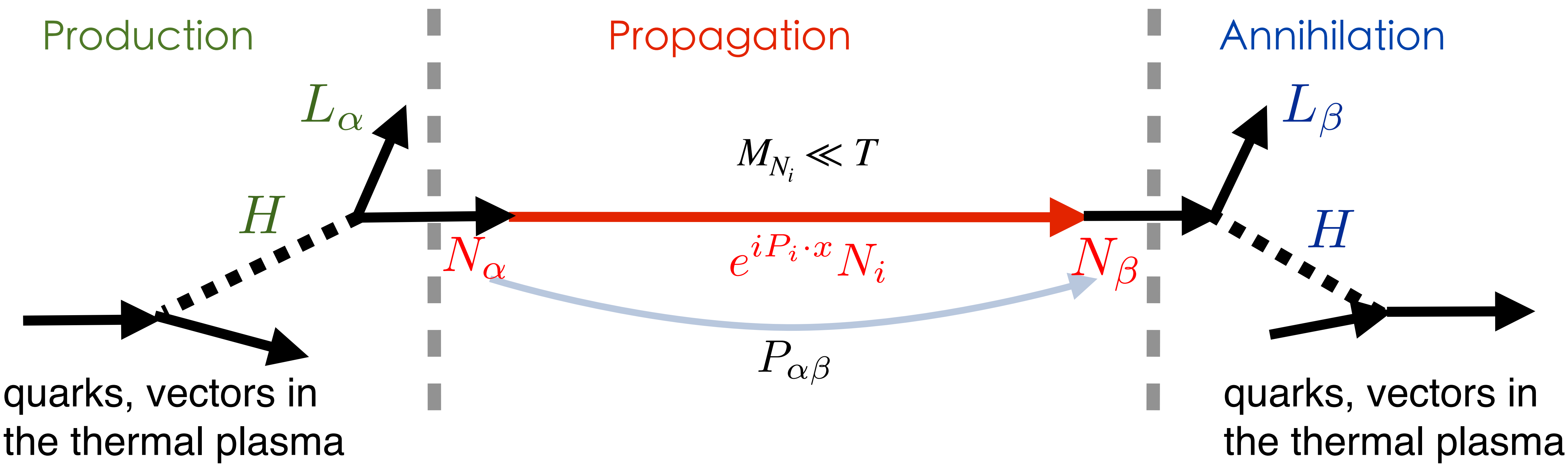
Enhanced in the resonant region

- These results are all obtained at zero temperature

Leptogenesis via RH neutrino oscillation

Sterile neutrino oscillation in early Universe

Akhmedov, Rubakov, Smirnov, hep-ph/9803255



The “generalised” lepton number $\mathbf{L} = L + L_N$ is conserved.

$$P(N_\alpha \to N_\beta) - P(\overline{N}_\alpha \to \overline{N}_\beta) \propto \mathrm{Im}\{\exp(-i\int_0^t \frac{\Delta M_{ij}^2}{2E} a(t)dt)\} \times \mathrm{Im}\{Y_{\alpha i} Y_{\beta i}^* Y_{\alpha j}^* Y_{\beta j}\}$$

CP不对称产生于震荡过程中，而非衰变过程中，这是量子力学效应

νMSM (neutrino minimal Standard Model): 2 GeV RHN + 1 keV vDM

提纲

- 几种常见机制的简介
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Theory development I: density matrix approach

- Oscillations of interaction states → 宏观的量子相干效应

e.g., oscillation of active neutrinos $i\frac{d}{dt}|\nu_\alpha\rangle = \sum_{\beta=e,\mu,\tau} H_{\nu,\alpha\beta}|\nu_\beta\rangle$

$$H_\nu = \frac{1}{2E}M_\nu M_\nu^\dagger + H_{\rm matter}$$

- Damping and Boltzmann evolution → 经典的粒子数密度的演化

e.g., evolution of RHN and SM lepton number densities in classical leptogenesis

- Combined together → **Density Matrix** formalism Raffelt, Sigl, 93
- Density matrix approach in ARS leptogenesis

Hernández, Kekic, López-Pavón, Racker, Salvado, 1508.03676; 1606.06719

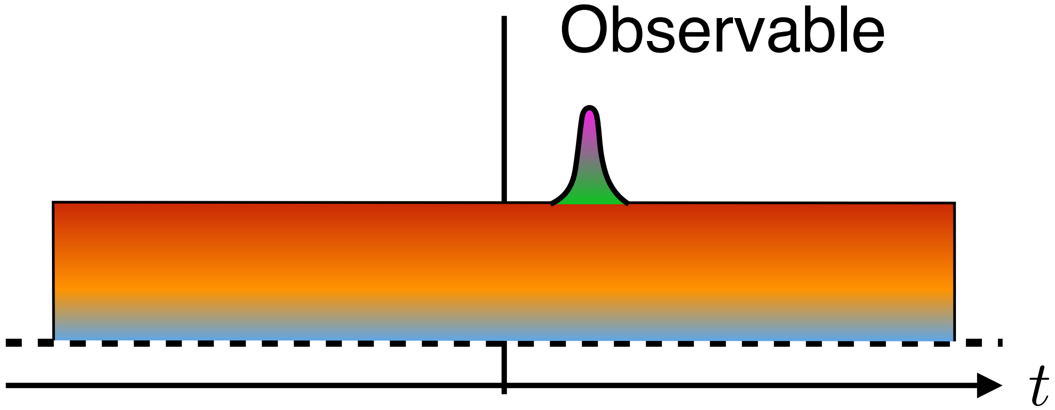
$$\rho_{N,ij} = |N_i\rangle\, f_{ij}\, \langle N_j| \qquad\qquad H_N = \frac{1}{2E}M_N M_N^\dagger + \frac{T^2}{8E}\lambda^\dagger\lambda$$

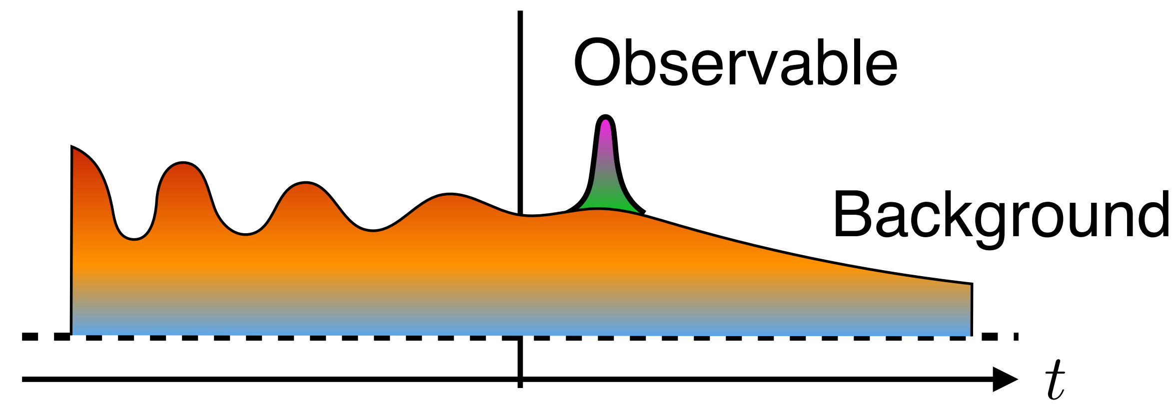
$$\frac{d\rho_N}{dt} = -i[H_N,\,\rho_N] + \{\Gamma_N^a,\,\rho_N\} + \{\Gamma_N^{\rm p},\,\rho_N^{\rm eq} - \rho_N\}$$

$\frac{d}{dt} \to aH\frac{d}{da}$ oscillation annihilation production

Theory development II: closed-time-path approach

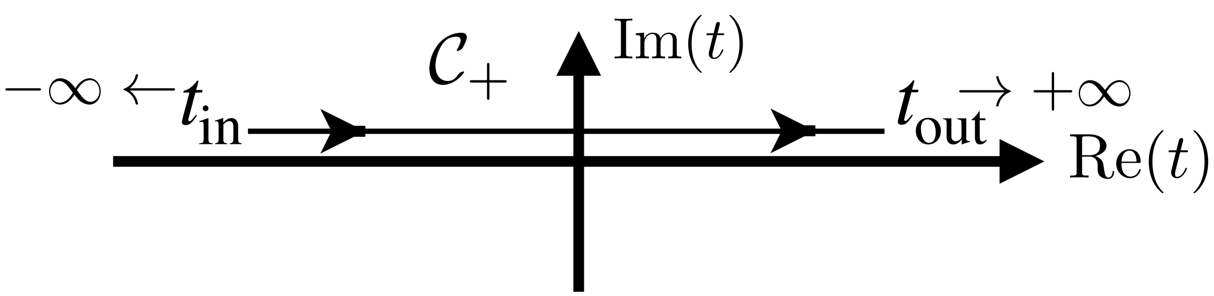
- QFT at zero temperature or in thermal equilibrium
- QFT in non-equilibrium case

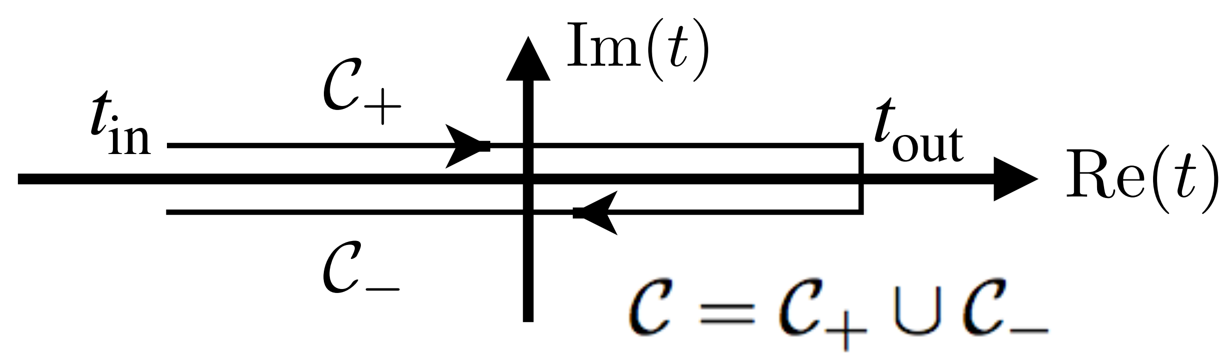




基态是时间平移不变的

如果基态是随时间变化，就需要约定好某个初始时间$t_{\rm in} = t_0$，考虑系统从此刻开始演化





in-out formalism $\langle \Omega(t_{\rm in}) \,|\, \mathcal{O} \,|\, \Omega(t_{\rm out}) \rangle$

$\langle \Omega(t_{\rm in}) \,|\, \mathcal{O} \,|\, \Omega(t_{\rm in}) \rangle$ **in-in formalism**

Reviews e.g., Quiros, hep-ph/9901312; Berges, hep-ph/0409233

Outline

References

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Physics Reports

Volume 118, Issues 1–2, February 1985, Pages 1-131

Equilibrium and nonequilibrium formalisms made unified

Kuang-chao Chou, Zhao-bin Su *, Bai-lin Hao, Lu Yu

Show more

Theory development II: closed-time-path approach

- Propagators

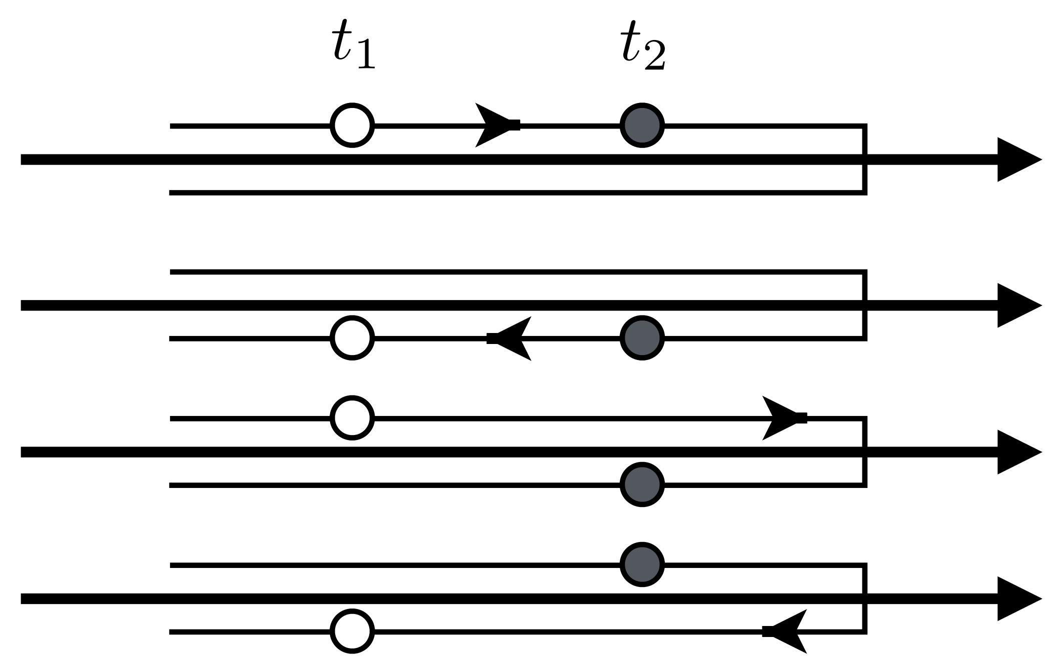
Feynman $S^{T}_{\alpha\beta}(x_1,x_2) = \langle T[\ell_\alpha(x_1)\bar{\ell}_\beta(x_2)]\rangle$

Dyson $S^{\overline{T}}_{\alpha\beta}(x_1,x_2) = \langle \overline{T}[\ell_\alpha(x_1)\bar{\ell}_\beta(x_2)]\rangle$

Wightman

$S^{<}_{\alpha\beta}(x_1,x_2) = -\langle \bar{\ell}_\beta(x_2)\ell_\alpha(x_1)\rangle$

$S^{>}_{\alpha\beta}(x_1,x_2) = \langle \ell_\alpha(x_1)\bar{\ell}_\beta(x_2)\rangle$



$x_1^\mu = (t_1, \vec{x}_1)$ $x_2^\mu = (t_2, \vec{x}_2)$

- Kadanoff-Baym equation

$S^H = S^T - S^+$ $\Sigma^H = \Sigma^T - \Sigma^+$

$$(i\partial\!\!\!/ - M)S^+ - \Sigma^H S^+ - \Sigma^H S^H = \frac{1}{2}(\Sigma^> S^< - \Sigma^< S^>)$$

Kinetic & oscillation **Self energy** **Dispersion** **Collision term**

- Applying CTP approach in EW baryogenesis and phase transition

周五晁伟的报告

Classical formalism vs CTP formalism

- Applying CTP in leptogenesis

Higgs H

Leptons L & N

$$\Delta_q^{<,>} = \frac{-2\varepsilon(q^0)\mathrm{Im}\Pi_q^R}{[q^2+\mathrm{Re}\Pi_q^R]^2+[\mathrm{Im}\Pi_q^R]^2}\left\{\vartheta(\mp q^0)+f_{B,|q^0|}(x)\right\},$$

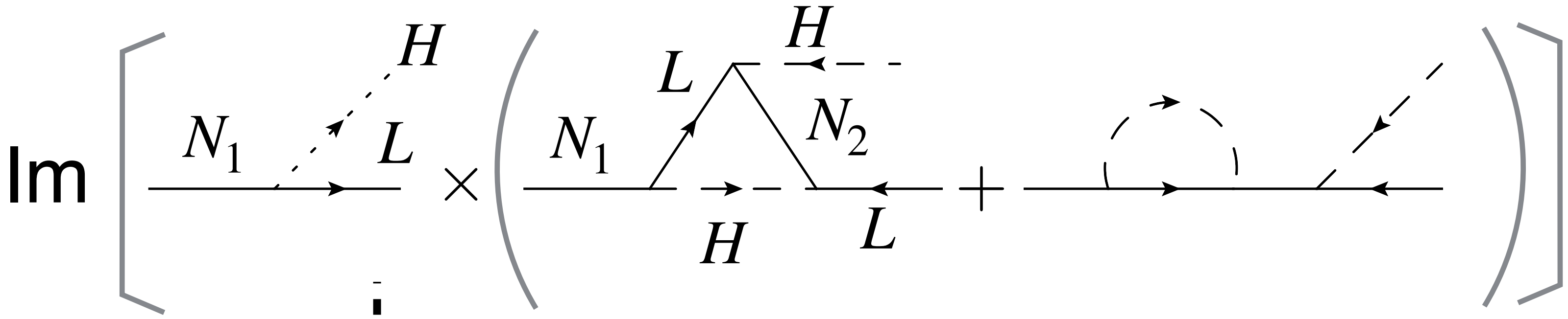
$$S_k^{<,>} = \frac{-2\varepsilon(k^0)\mathrm{Im}\Sigma_k^{R\,2}}{[k^2+\mathrm{Re}\Sigma_q^{R\,2}]^2+[\mathrm{Im}\Sigma_q^{R\,2}]^2}\left\{\vartheta(\mp k^0)-f_{F,|q^0|}(x)\right\}P_L \not{k} P_R\,,$$

Lepton number density obtained from Wightman operator

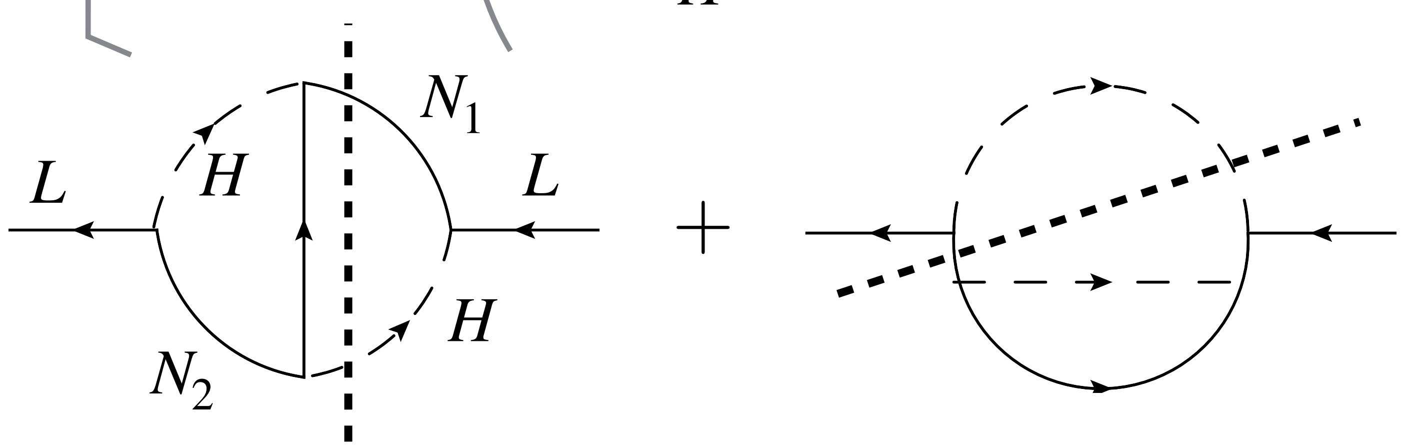
$$\boxed{n_L \sim \mathrm{tr}(\gamma^0 S_L^+)} \qquad S_L^+ = \frac{1}{2}(S_L^> + S_L^<)$$

- CP violation source ——Either in oscillation or collision terms

- CPV source in RHN decay



CPV source in classical formalism

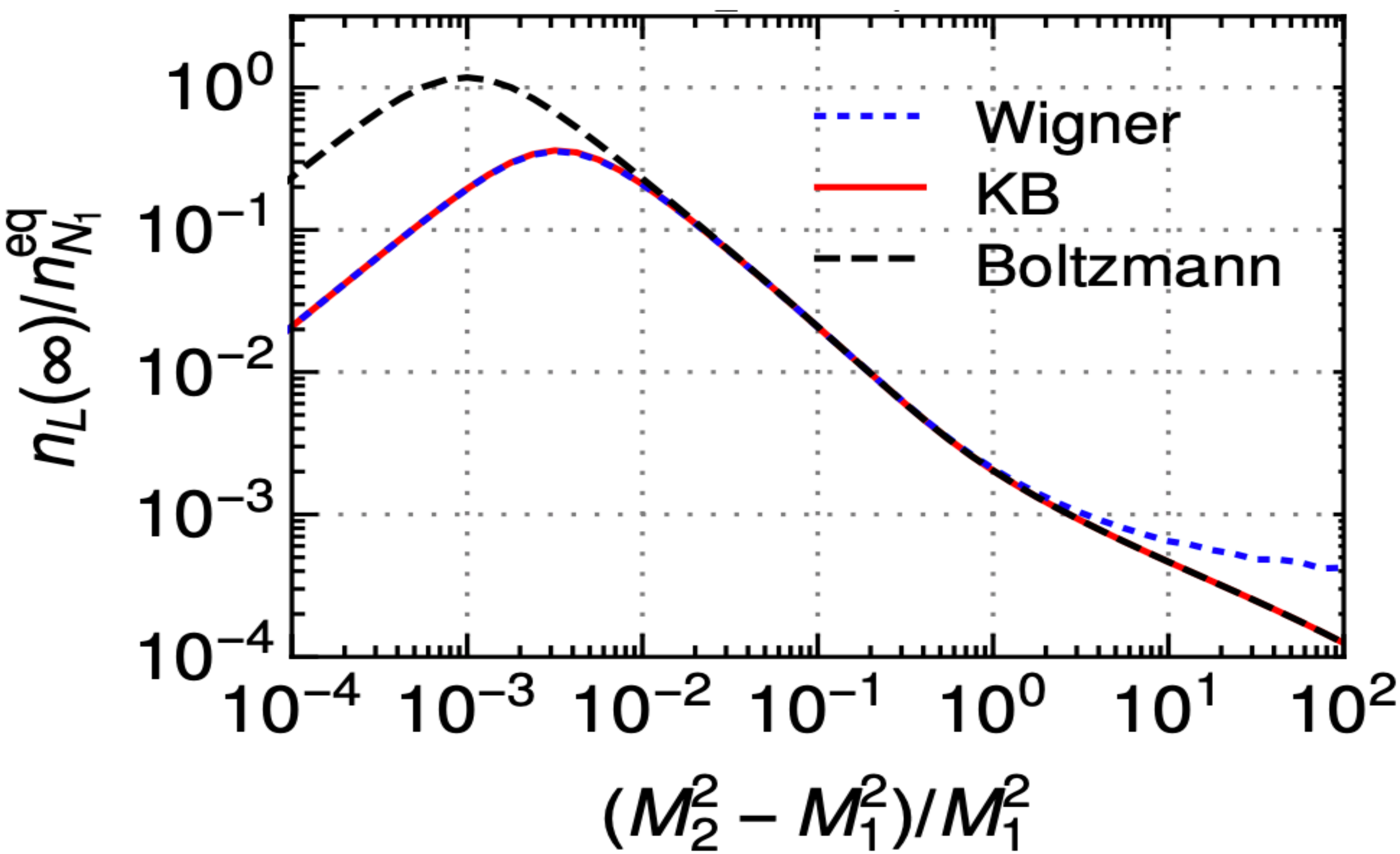


Self energies including CPV source in CTP formalism

Anisimov, Buchmuller, Drewes, Mendizabal, 1012.5821

Comparison with the classical calculation

Dev, Garny, Klaric, Millington, Teresi, 1711.02863.



KB: a general Kadanoff-Baym approach, two-time evolution

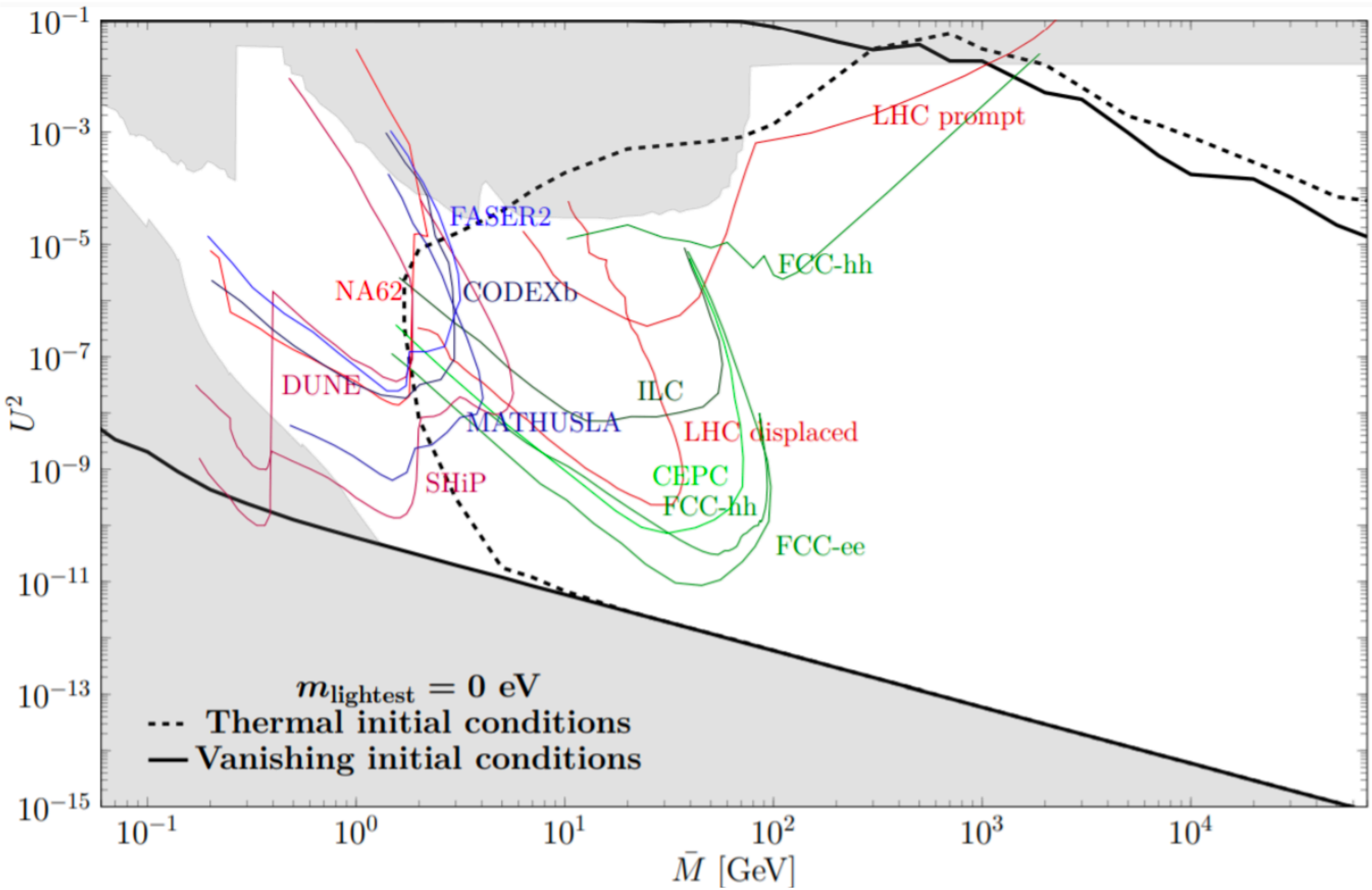
Wigner: one-time treatment of KB approach as follows

$$iS_{Nij}(p,X) \;=\; \int \mathrm{d}^4 r\; e^{ip\cdot r} S_{Nij}(X+r/2, X-r/2)$$

提纲

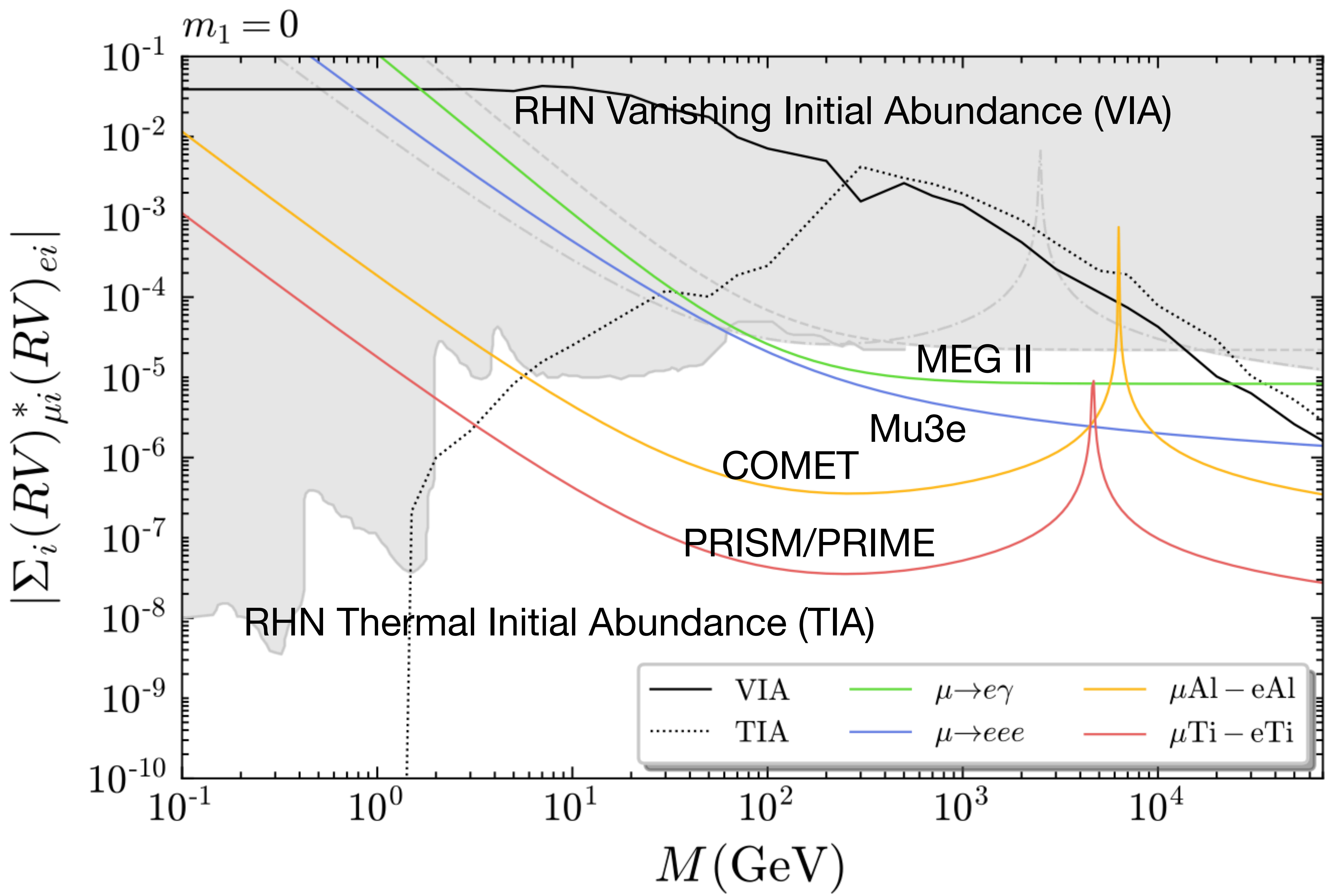
- 几种常见机制的简介
- 理论进展
- 实验验证
- 当前的重要问题

Direct test of leptogenesis



$|M_i - M_j| \ll \bar{M} = (M_1 + M_2 + M_3)/3$ Drewes, Georis, Klaric, 2106.16226

Leptogenesis vs charged LFV



$\mathrm{BR}(\mu \to e\gamma) < 4.2 \times 10^{-13}$ (90% C.L.) ,

$\mathrm{BR}(\mu \to eee) < 1.0 \times 10^{-12}$ (90% C.L.) ,

$\mathrm{CR}(\mu\, {}^{48}_{22}\mathrm{Ti} \to e\, {}^{48}_{22}\mathrm{Ti}) < 4.3 \times 10^{-12}$ (90% C.L.) ,

$\mathrm{CR}(\mu\, {}^{197}_{79}\mathrm{Au} \to e\, {}^{197}_{79}\mathrm{Au}) < 7.0 \times 10^{-13}$ (90% C.L.) .

Leptogenesis vs neutrino oscillation experiments

中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences
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首页 概况 机构 科研队伍 科研成果 研究生 博士后 院地合作 国际交流 创新文化 科学传播 党群园地 信息公开 网上博展馆 图片库 视频库
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大亚湾中微子实验发现新的中微子振荡

2012-03-08 | 文章来源： | 【大 中 小】

被多个实验证实。第三种振荡则一直未被发现，甚至有理论预言其根本不存在（即其振荡几率为零）。

中国科学院高能物理研究所的科研人员2003年提出设想，利用我国大亚湾核反应堆群产生的大量中微子，来寻找中微子的这第三种振荡，其振荡几率用$\sin^2 2\theta_{13}$表示。中国高能物理学会理事长赵光达院士表示，“θ_{13}不仅是物理学中的一个基本参数，其数值的大小也对未来中微子物理的发展方向起着决定性的作用。如果它足够大，我们就能进行下一代实验来测量中微子振荡中的宇称和电荷对称性(CP)破坏，以理解宇宙中物质-反物质不对称现象，即宇宙中‘反物质消失之谜’。否则我们就不知道如何进行下一代实验”。

大亚湾中微子实验位于深圳市区以东约50公里的大亚湾核电站群附近的山洞内，地理位置优越，紧邻世界上最大的核反应堆群之一的大亚湾

如果它 (θ_{13}) 足够大，我们就能进行下一代实验来测量中微子振荡中的宇称和电荷对称性(CP)破坏，以理解宇宙中物质-反物质不对称现象，即宇宙中’反物质消失之谜’。

Connecting leptogenesis with low-energy experiments

Casas-Ibarra Parametrisation

$$M_\nu = Y M_N^{-1} Y^T v^2 \qquad \Rightarrow \qquad Y = \frac{1}{v} U \sqrt{\hat{M}_\nu} R \sqrt{\hat{M}_N}$$

(3 RHN assumed)

PMNS matrix

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix}$$

Complex orthogonal matrix

$$R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_1 & s_1 \\ 0 & -s_1 & c_1 \end{pmatrix} \begin{pmatrix} c_2 & 0 & s_2 \\ 0 & 1 & 0 \\ -s_2 & 0 & c_2 \end{pmatrix} \begin{pmatrix} c_3 & s_3 & 0 \\ -s_3 & c_3 & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad R^T R = R R^T = 1$$

$$c_I = \cos(x_I + i y_I) \qquad s_I = \sin(x_I + i y_I)$$

New parameters from the heavy sector: $M_I,\ x_I + i y_I$ for $I = 1,2,3$

Leptogenesis from low-energy CP violation

In minimal seesaw (only 2 RHNs)

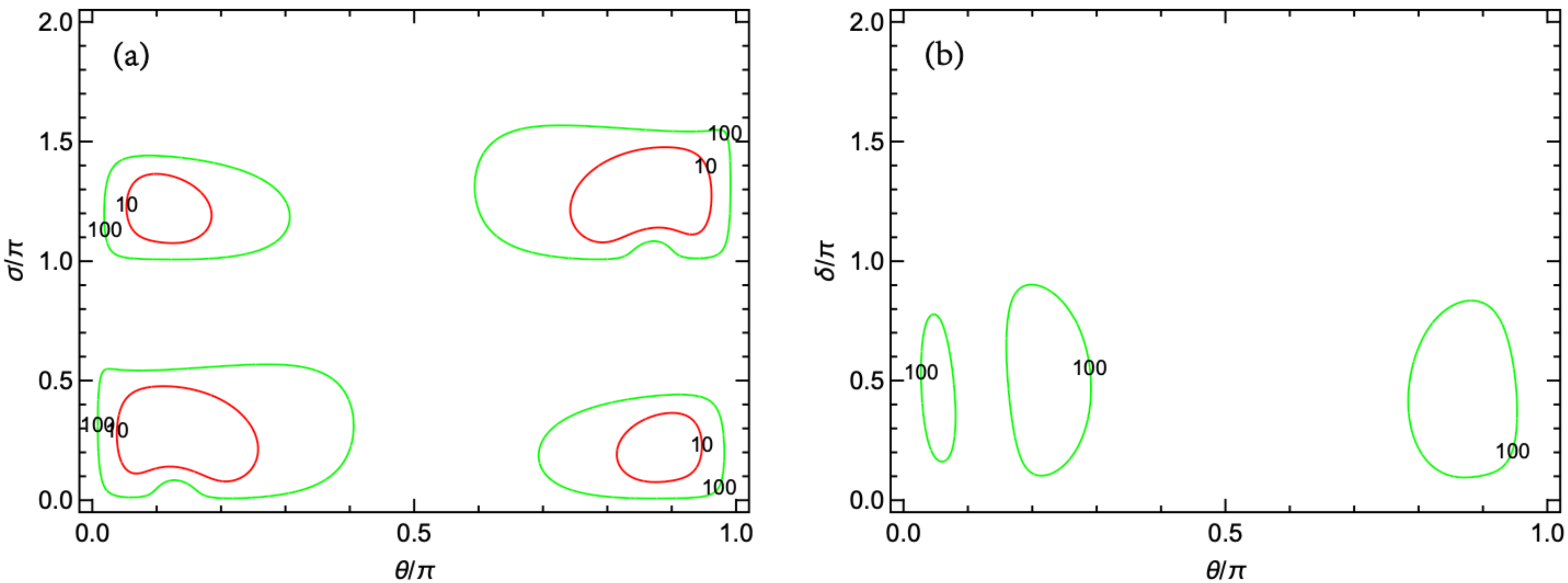


Figure 4.2. In the $m_1 = 0$ case with z being real (i.e., $z = \theta$), the contour lines of $M_1/(10^{10}\ \text{GeV})$ for successful flavored leptogenesis are shown (a) in the θ-σ plane by assuming $\delta = 0$ and (b) in the θ-δ plane by assuming $\sigma = 0$.

Xing, Zhao, 2008.12090

Leptogenesis from low-energy CP violation

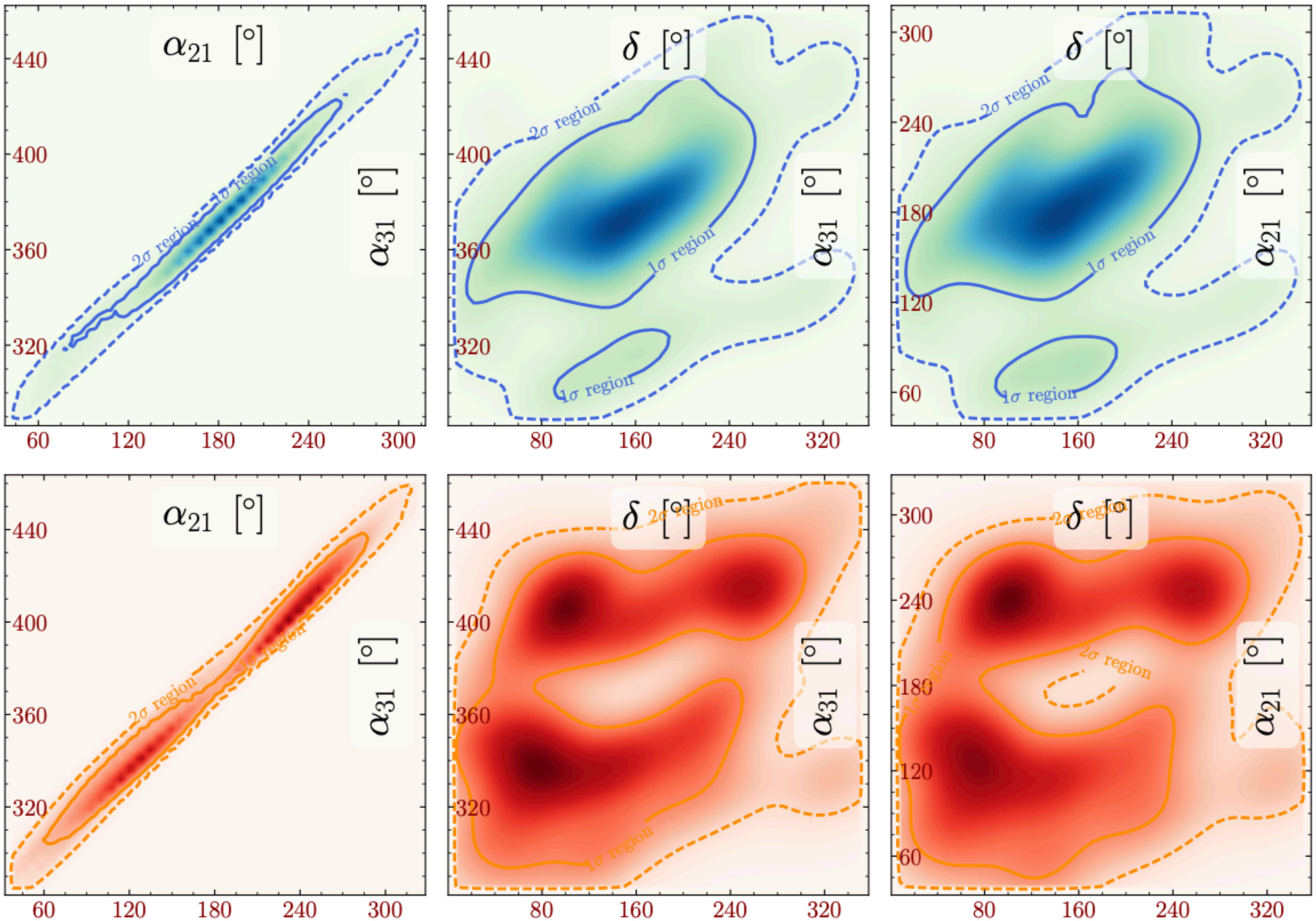


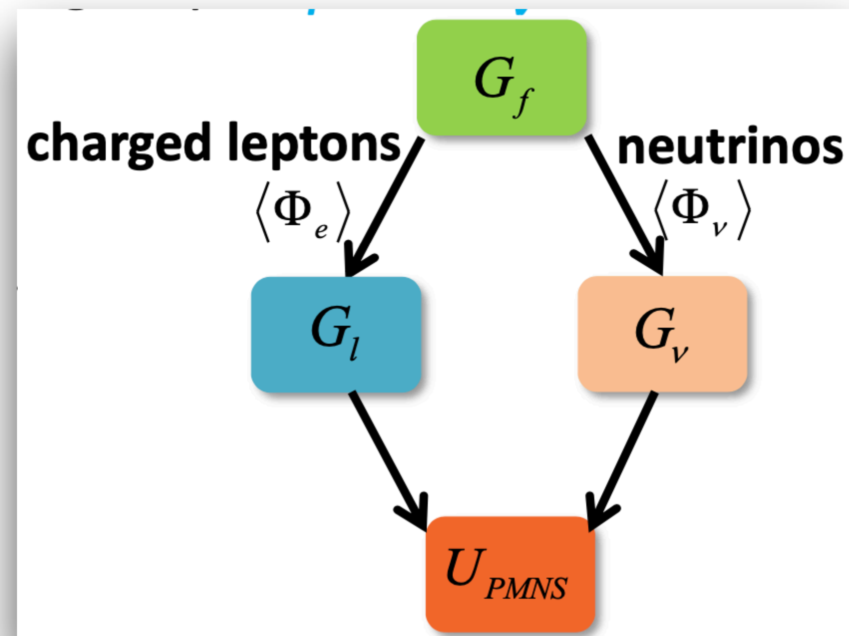
Figure 9: The two-dimensional projections for intermediate scale leptogenesis with $M_1 = 1.29 \times 10^8$ GeV for $x_1 = 0$, $y_2 = 0$, $x_3 = 180°$, $y_1 = y_2 = 180°$, with CP violation provided

Moffat, Pascoli, Petcov, Turner, 1809.08251

Leptogenesis with flavour textures

当前中微子理论家偏向于具有特殊味道结构的费米子质量矩阵或者味混合矩阵

参考丁桂军的报告



Top-down

$$m_\nu = \begin{pmatrix} a & b & b^* \\ b & c & d \\ b^* & d & c^* \end{pmatrix}$$

Bottom-up

- Lepton mixings are large

[NuFIT 5.1 (2022)]

$$|U|_{3\sigma}^{\text{w/o SK-atm}} = \begin{pmatrix} 0.801 \to 0.845 & 0.513 \to 0.579 & 0.143 \to 0.156 \\ 0.232 \to 0.507 & 0.459 \to 0.694 & 0.629 \to 0.779 \\ 0.260 \to 0.526 & 0.470 \to 0.702 & 0.609 \to 0.763 \end{pmatrix}$$

Leptogenesis with flavour textures

Resonant leptogenesis in minimal seesaw with TM1 mixing

Xing, S. Zhou, 0607302

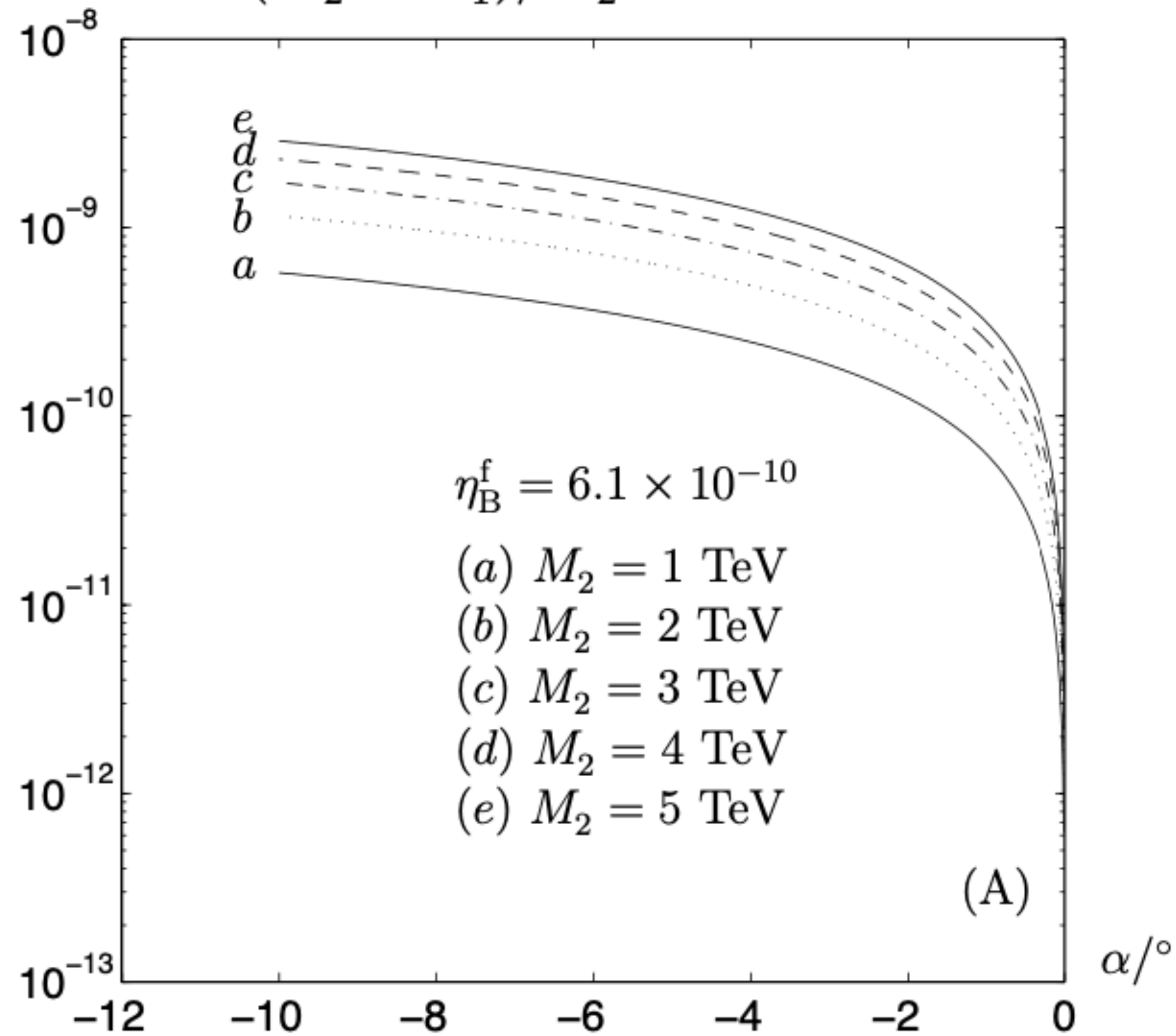
$$M_{\rm D}^{(1)} = V_0 \begin{pmatrix} 0 & 0 \\ x & 0 \\ 0 & y \end{pmatrix} U$$

$$V_0 = \begin{pmatrix} 2/\sqrt{6} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \\ 1/\sqrt{6} & -1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

$$\sin^2\theta_{12} = (1 - 2\tan^2\theta_{13})/3.$$

$$\theta_{23} = \frac{\pi}{4}\,, \qquad \delta = -\frac{\pi}{2}\,,$$

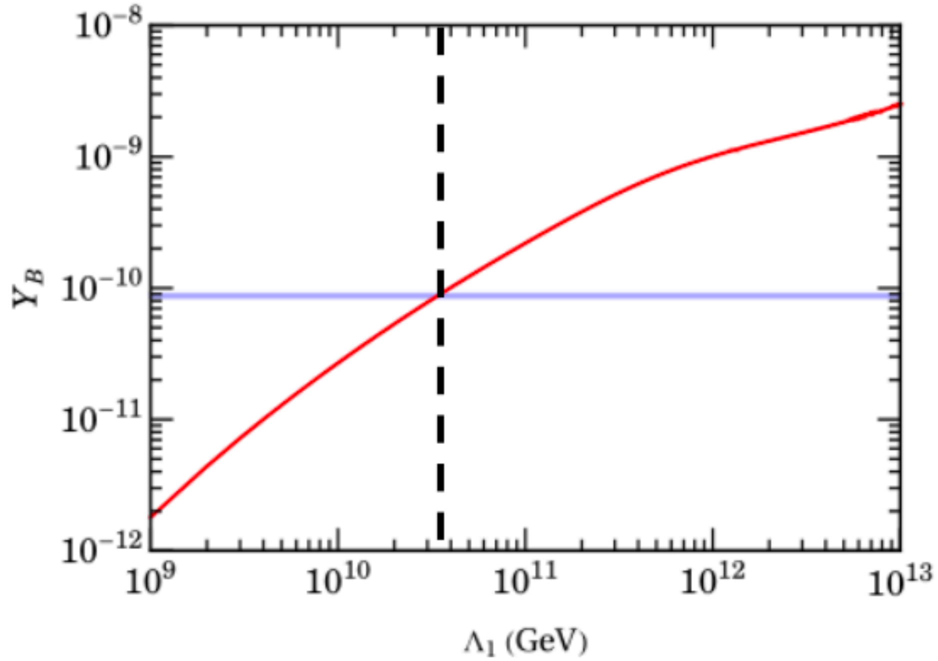
$r \equiv (M_2 - M_1)/M_2$

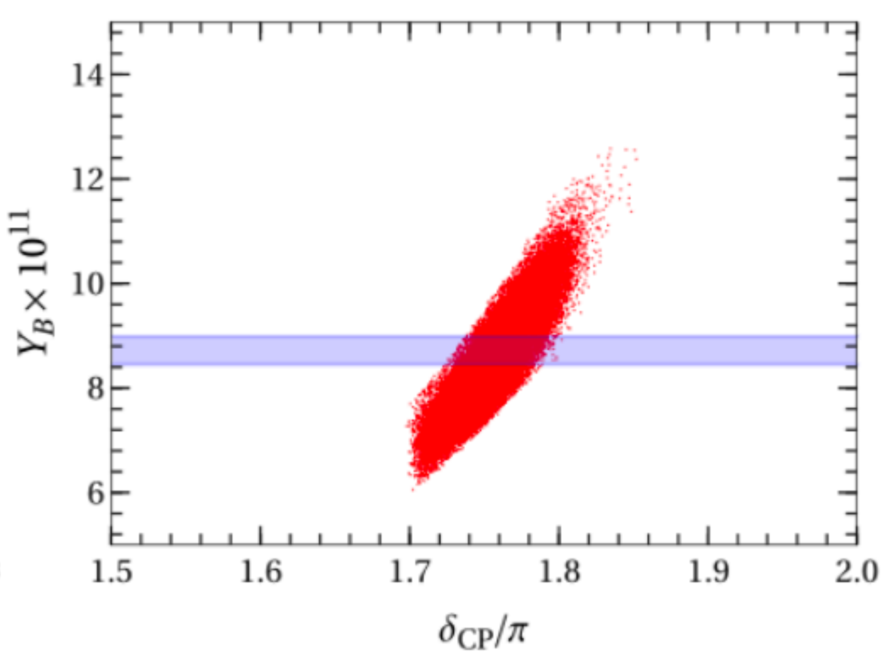


$\alpha \sim \theta_{13}\sqrt{3}$

Leptogenesis with modular-type flavour texture

The observed baryon asymmetry allows to determine the flavor scale Λ_1





[Qu,Liu,Ding,2208.xxxxx]

$\Lambda_1 = 3.4 \times 10^{10}$ GeV → $Y_B = 8.721 \times 10^{-11}$

Right-handed neutrino mass:

$M_1 = 7.844 \times 10^{10}$ GeV, $M_2 = 1.826 \times 10^{11}$ GeV, $M_3 = 2.517 \times 10^{11}$ GeV

ULYSSES: Universal LeptogeneSiS Equation Solver

- a python package calculating the baryon and lepton asymmetry in type-I seesaw

https://github.com/earlyuniverse/ulysses

Model	example input file	Description
1DME	1N3F.dat	DME 1 RHN
2DME	2N3F.dat	DME 2 RHN
3DME	3N3F.dat	DME 3 RHN
1BE1F	1N1F.dat	one-flavoured BE 1 RHN
1BE2F	1N2F.dat	two-flavoured BE 1 RHN
1BE3F	1N3F.dat	three-flavoured BE 1 RHN
2BE1F	2N1F.dat	one-flavoured BE with 2 RHN
2BE2F	2N2F.dat	two-flavoured BE with 2 RHN
2BE3F	2N3F.dat	three-flavoured BE with 2 RHN
3DMEsct	3N3F.dat	DME 3 RHN including scattering effects
1BE1Fsf	1N1F.dat	1BE1F evolving in scale factor
2RES	Res.dat	2BE3F in the resonant regime
2RESsp	Res.dat	2RES including spectator processes

Density Matrix Equation

Boltzmann Equation

Table 1: Overview of built-in plugins. We abbreviate density matrix equations, Boltzmann equations and (decaying) right-handed neutrino as DME, BE and RHN respectively. The evolution variable is $z = M_1/T$ for all plugins other than 1BE1Fsf which evolves in the cosmological scale factor.

提纲

- 几种常见机制的简介
- 最新理论进展
- 实验检验
- 当前的重要问题

New mechanisms?

- In the framework of Type-II seesaw
  - Type-II leptogenesis — Ma, Sarkar, 9802445

    CP violation from triplet Higgs decay $\Delta \to LL$ and $\Delta^\dagger \to \overline{L}\overline{L}$
  - Via Affleck-Dine Mechanism 下午韩成成的报告

    Barrie, Han, Murayama, 2106.03381; 2204.08202
- Lepton asymmetry directly generated from phase transition
  - Only a time-varying Weinberg operator

    Pascoli, Turner, Zhou, 1609.07969; 1808.00470; 1808.00475
  - Including RH neutrinos

    Long, Tesi, Wang, 1703.04902; Huang, Xie, 2206.04691
- CPT violation/Lorentz violation

  Barenboim, Salvado; Fujikawa, Tureanu; Sarkar …

Testability

- Most well-motivated: neutrino oscillation experiments
  —— test only mixing parameters and low-energy CP violation

- Direct detection
  —— GeV ~ 10 TeV RHN, for ARS/resonant leptogenesis

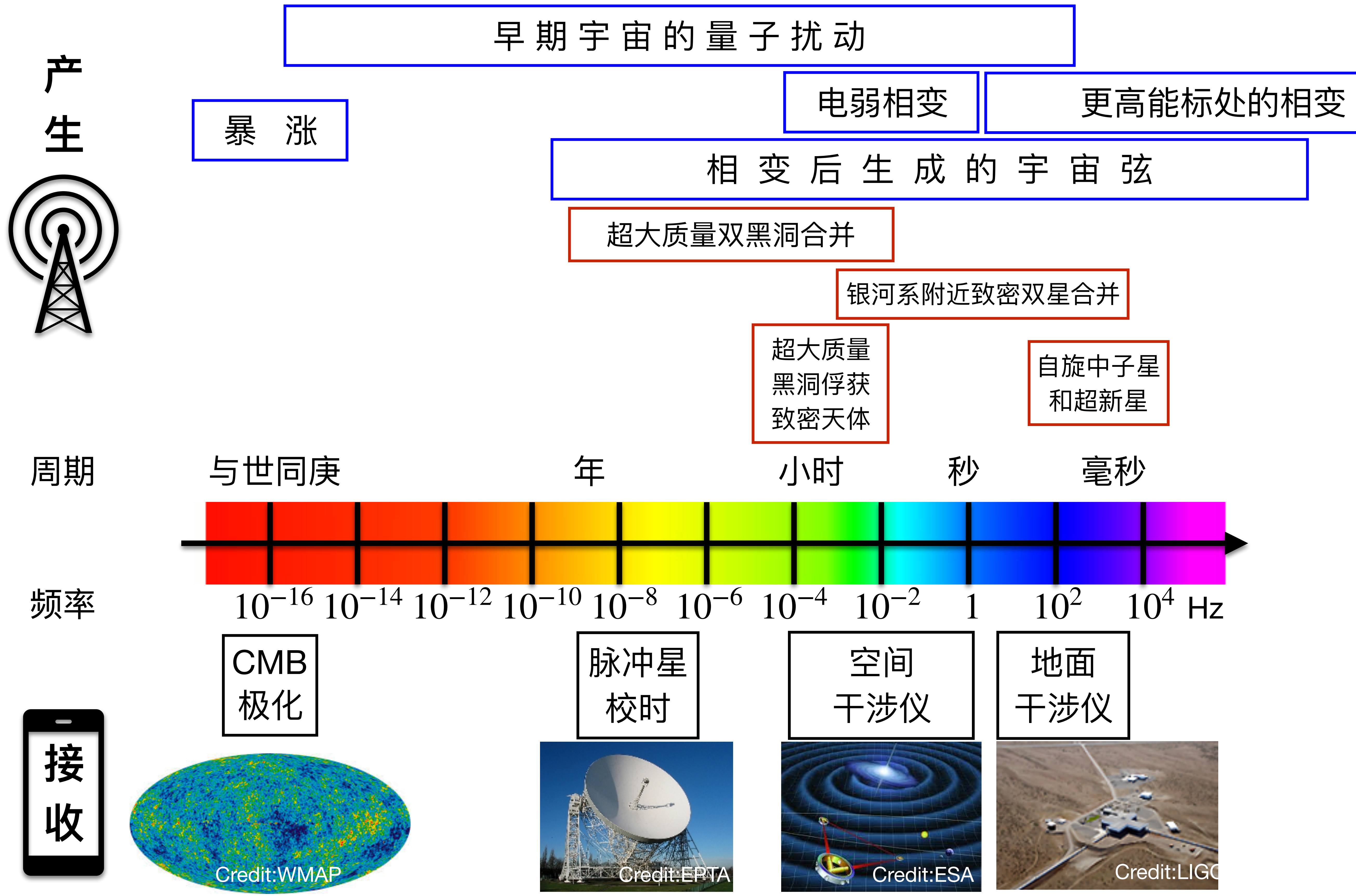
- Indirect constraints by Charged LFV
  —— up to 10^4 TeV RHN

- New test: Stochastic GW background detection
  - GW generated from phase transitions
    —— for phase transition temperature up to 10^8 TeV
  - GWs generated from cosmic strings
    —— requires U(1) breaking
    —— for the symmetry-breaking scale up to 10^{14} TeV

  —— requires RHN gain masses from a Spontaneous Symmetry Breaking

$$\lambda_{N,IJ}\,\phi\,\overline{N}_I N_J^c \Longrightarrow \qquad M_R = \lambda_N v_\phi$$

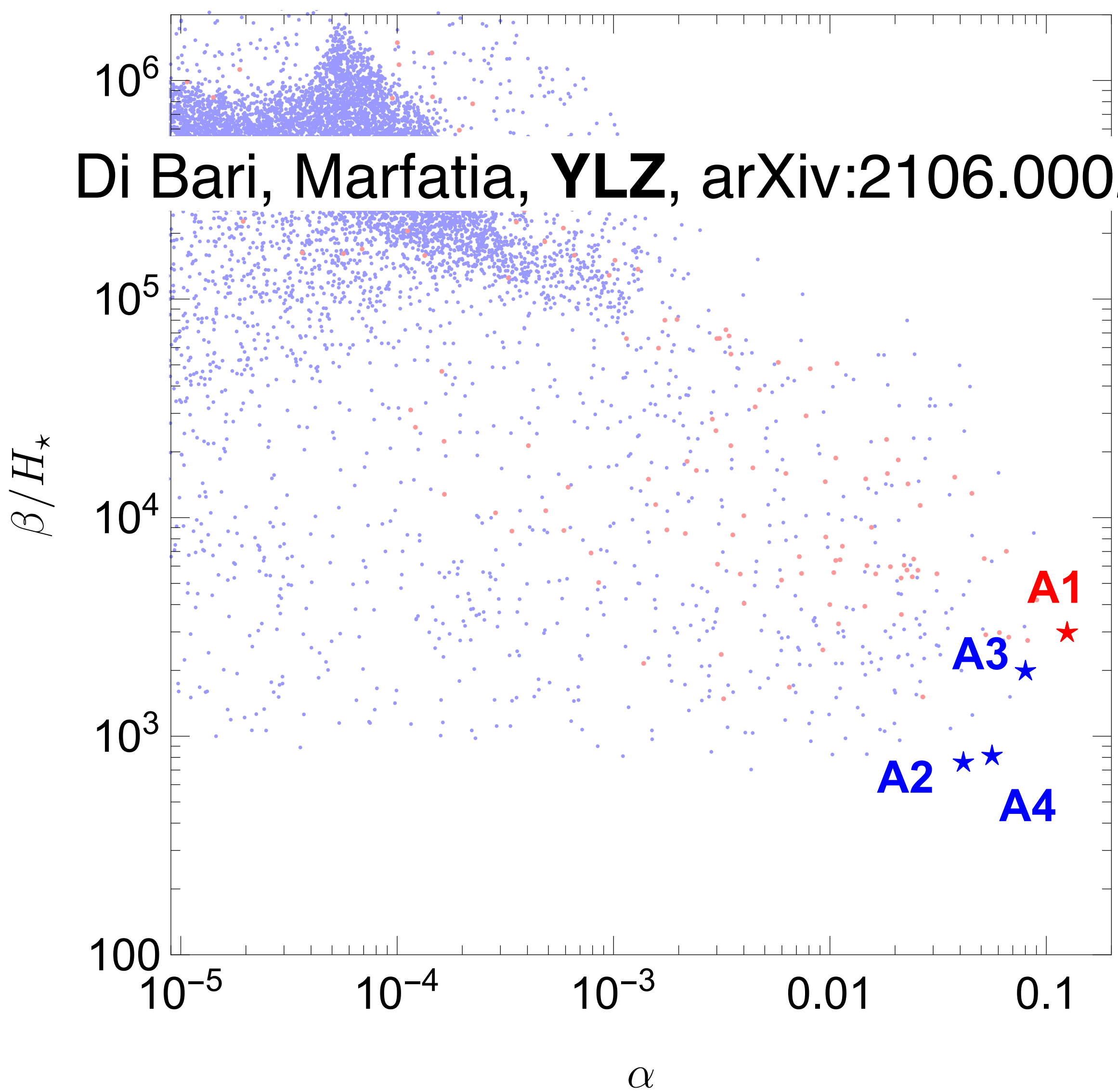
引力波的产生与探测

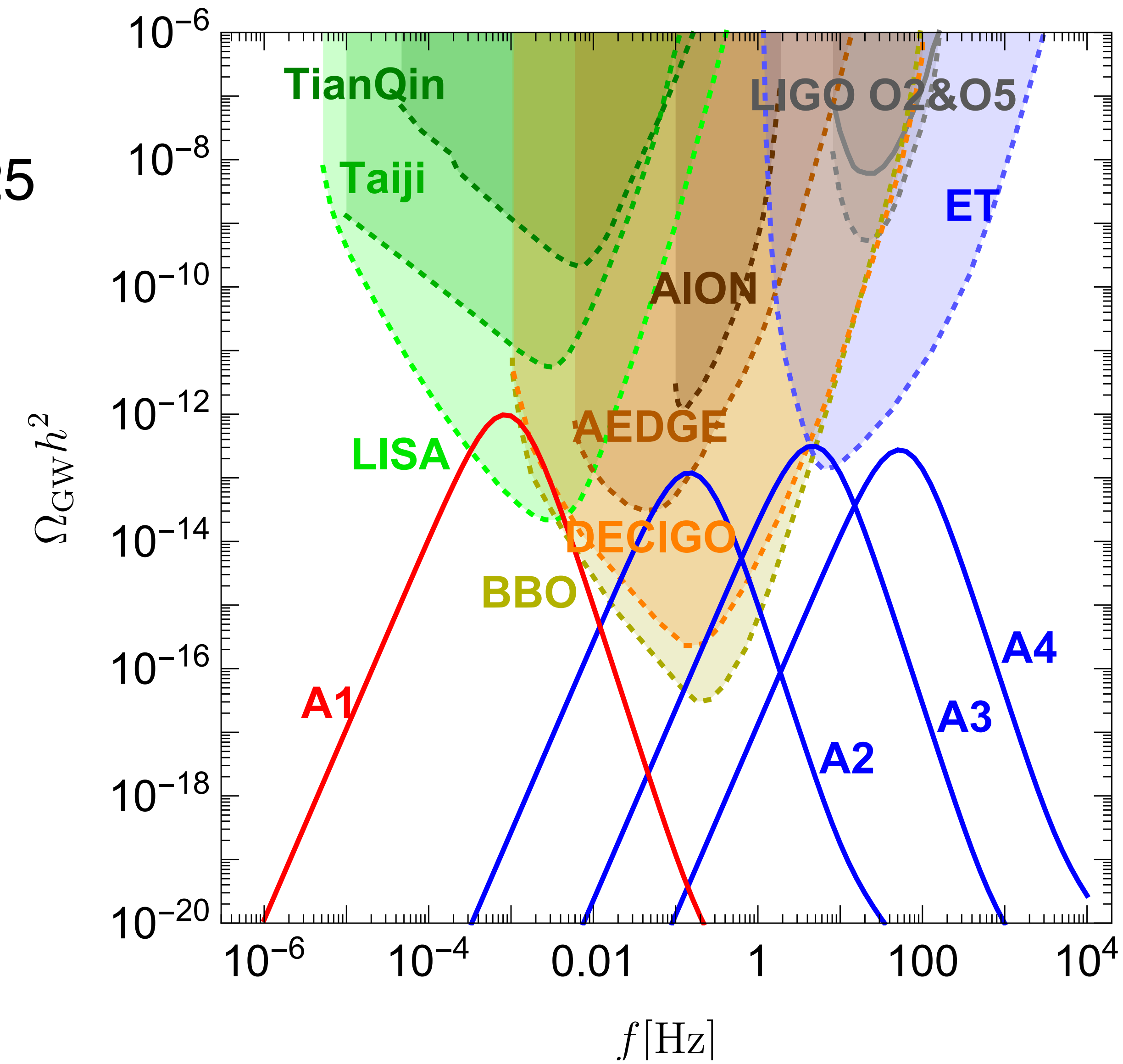


产生
早期宇宙的量子扰动
电弱相变
更高能标处的相变
暴 涨
相 变 后 生 成 的 宇 宙 弦
超大质量双黑洞合并
银河系附近致密双星合并
超大质量黑洞俘获致密天体
自旋中子星和超新星
周期
与世同庚
年
小时
秒
毫秒
频率
10^{-16} 10^{-14} 10^{-12} 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 1 10^{2} 10^{4} Hz
CMB极化
脉冲星校时
空间干涉仪
地面干涉仪
接收
Credit:WMAP
Credit:EPTA
Credit:ESA
Credit:LIGO

An example: GWs in Majoron model

Di Bari, Marfatia, **YLZ**, arXiv:2106.00025

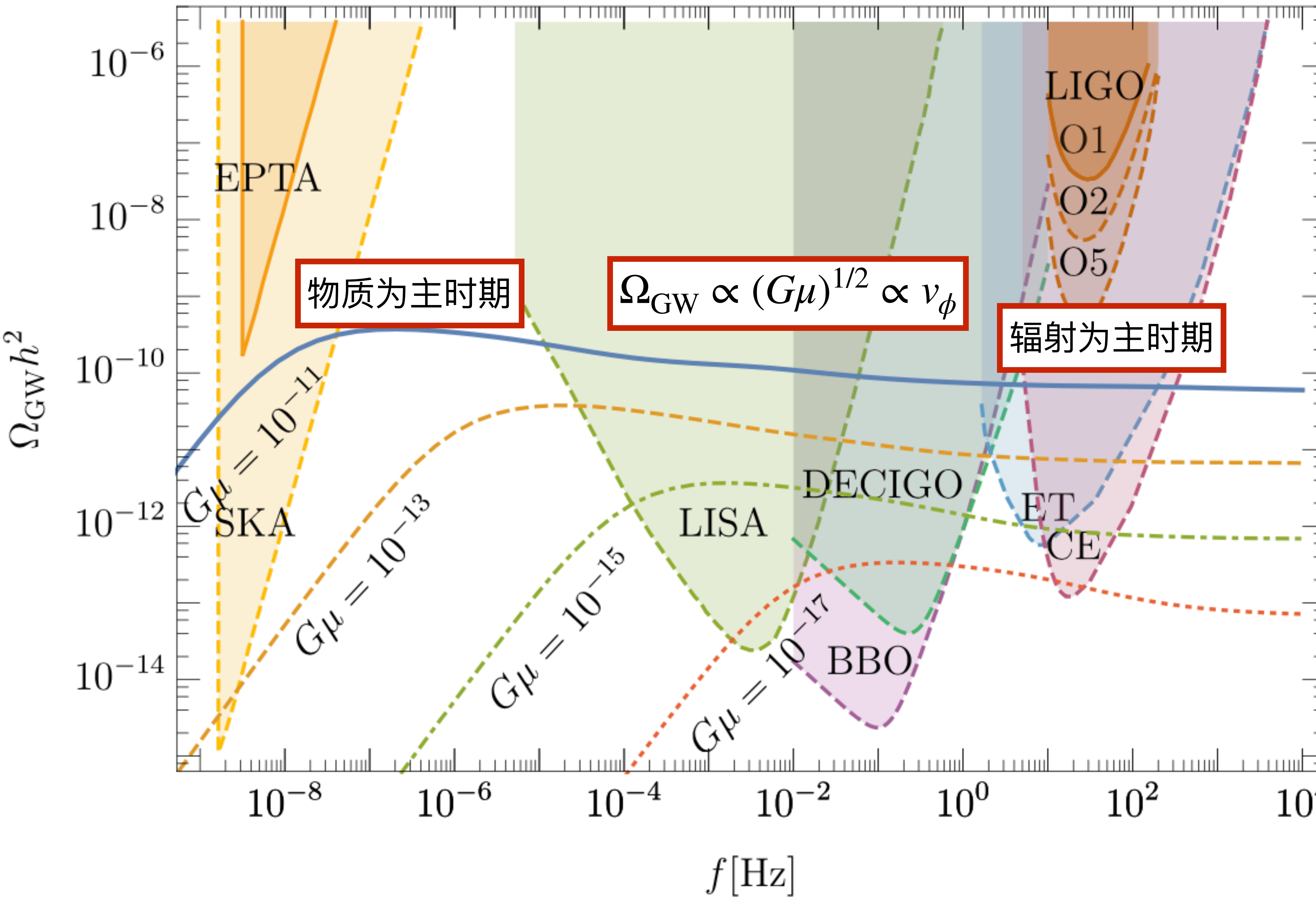




	Inputs				Predictions			
	m_S/GeV	$\tilde{\mu}/\mathrm{GeV}$	M/GeV	v_0/GeV	$T_\star/\mathrm{GeV}$	α	$\beta/H_\star$	a_0
A1	0.06190	0.0005857	0.5361	3.5873	0.6504	0.1248	2966	0.05951
A2	156.2	13.15	465.6	1014	721	0.04139	754.8	0.3886
A3	1036	13.72	7977	44424	9180	0.08012	1975	0.06268
A4	43874	1856	181099	567378	247807	0.05611	809.7	0.1944

GW from cosmic strings

Cui, Lewicki, Morrissey, Wells, 1808.08968



Towards a complete theory — GUT

- RHN with a U(1) symmetry can be easily embedded into a SO(10) GUT

- In GUTs, quark and lepton's masses and mixing are correlated together. RHN neutrino mass spectrum are not free.

$$
\begin{aligned}
M_u &= M_{10} + M_{126} + M_{120}, \\
M_d &= r_1 M_{10} + r_2 M_{126} + r_3 M_{120}, \\
M_e &= r_1 M_{10} - 3 r_2 M_{126} + A r_4 M_{120}, \\
M_\nu^D &= M_{10} - 3 M_{126} + A M_{120},
\end{aligned}
$$

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

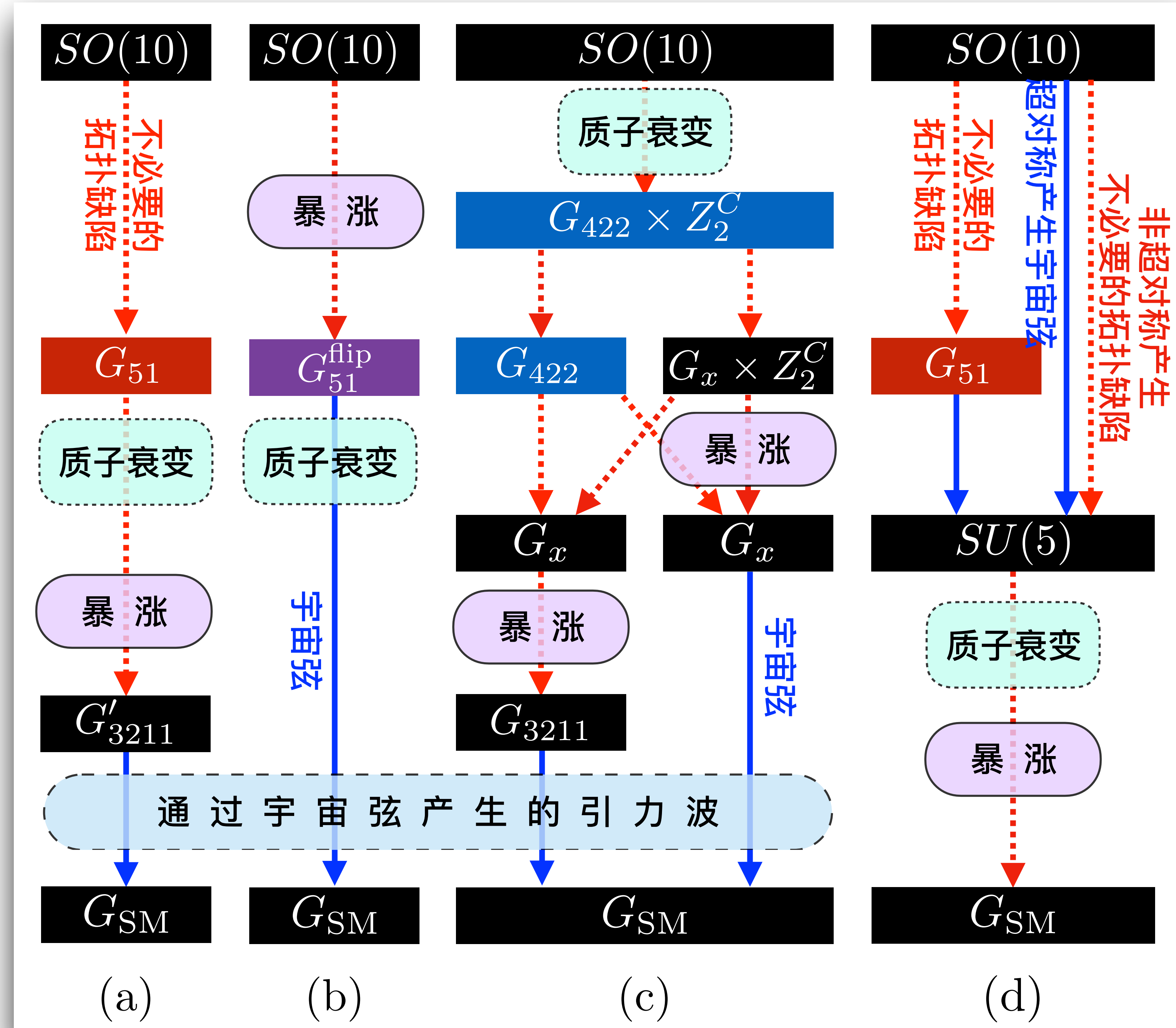
$$M_R = M_{126} v_R / v_{\mathrm{ew}}$$

Dutta, Mimura, Mohapatra, 0406262

- N_1 leptogenesis or $N_{2,3}$ leptogenesis?
  ——In some GUT theory, mass and Yukawa coupling of N_1 may not allow N_1 leptogenesis. N_2 leptogenesis main dominate the lepton asymmetry.

Di Bari, Riotto, 1012.2343; Di Bari, King, 1507.06431

Towards a complete theory — GUT



不必要的拓扑缺陷：
包括磁单极和畴壁

$G_x = G_{3221}$ or G_{421}

在任何大统一理论的破缺链中，都不得不引入暴涨用来稀释不必要的拓扑缺陷。

King, Pascoli, Turner, **YLZ**, 2005.13549

谢 谢