Type II Seesaw leptogenesis

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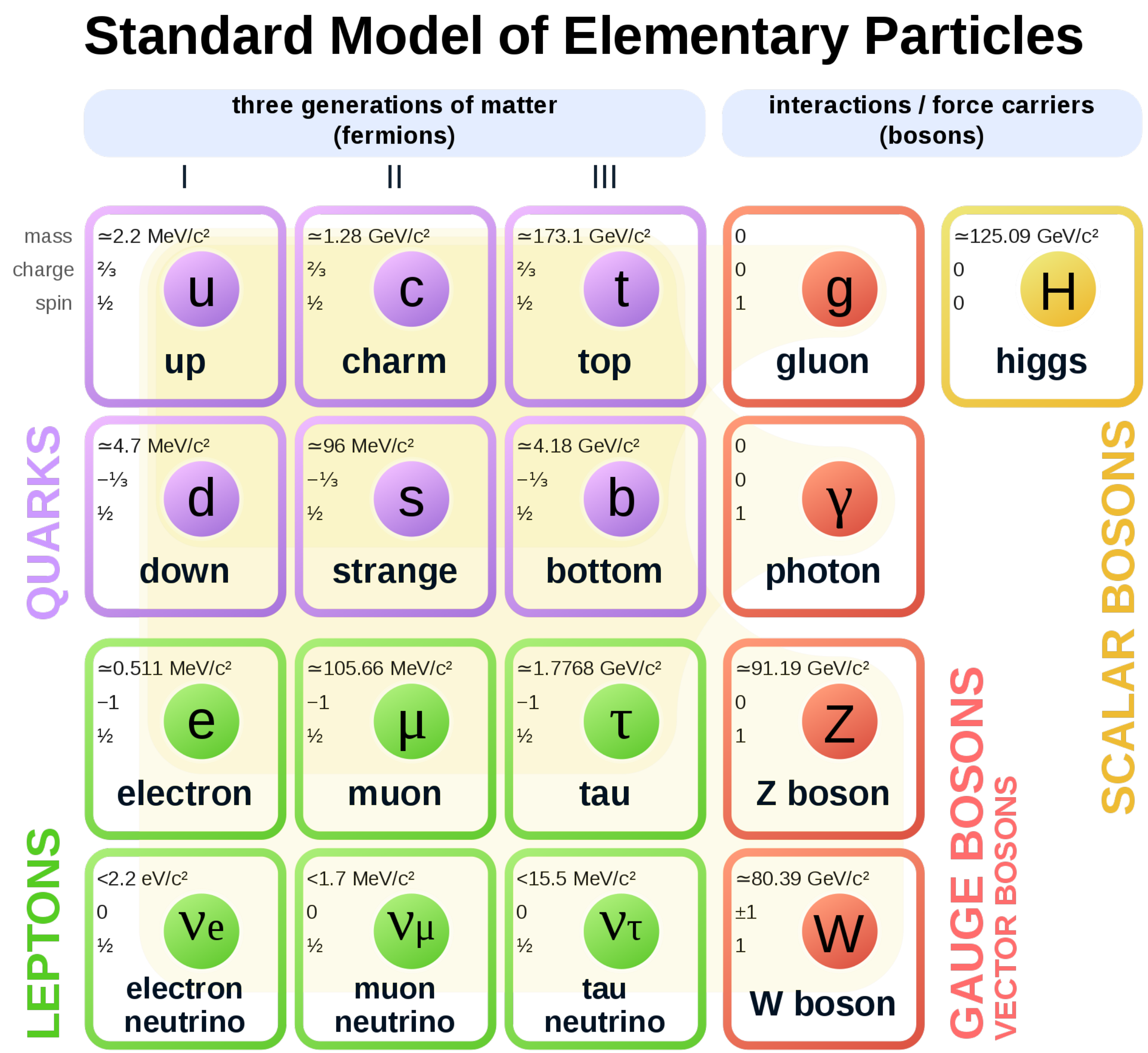
arXiv:2204.08202(JHEP 05 (2022) 160)

Korea Institute for Advanced Study (KIAS)

2023.8.10

Standard model



Very successful describing low energy scale physics

Observation requiring new physics

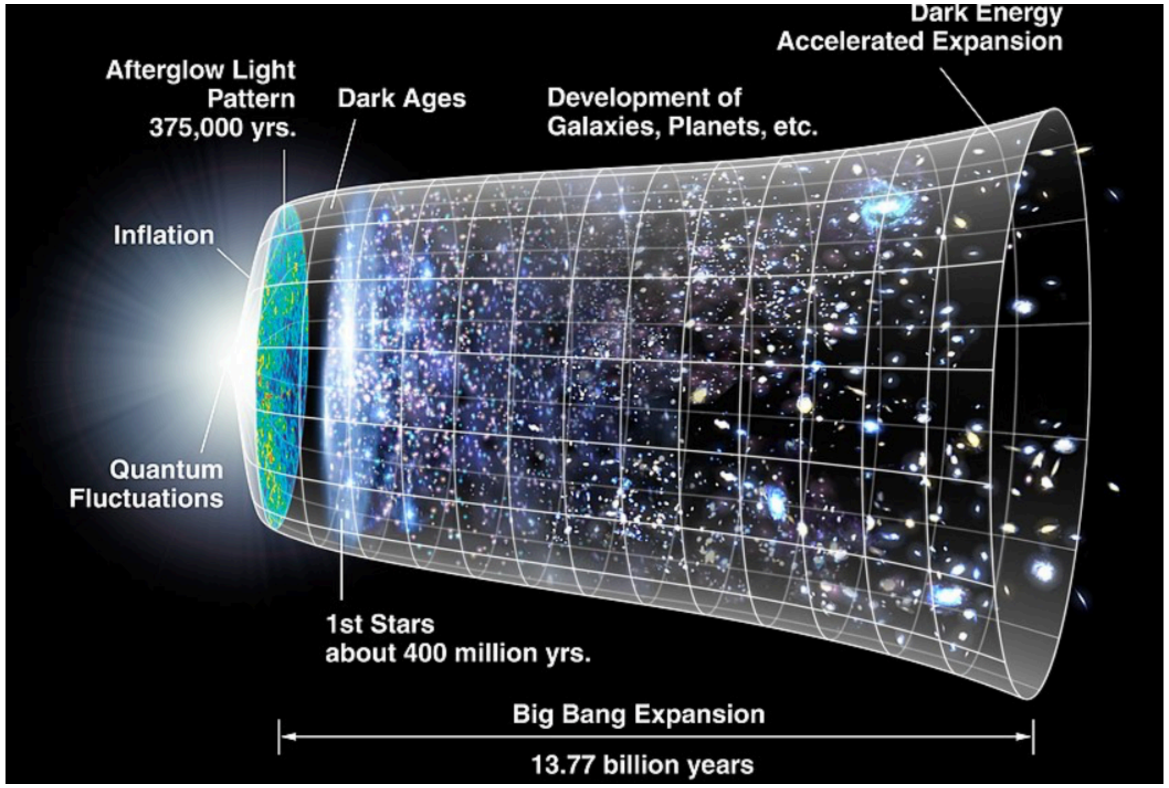
- Inflation
- Neutrino masses
- Baryon asymmetry of our universe

today's talk

- Dark matter
- Others(muon g-2? W mass?)

Inflation

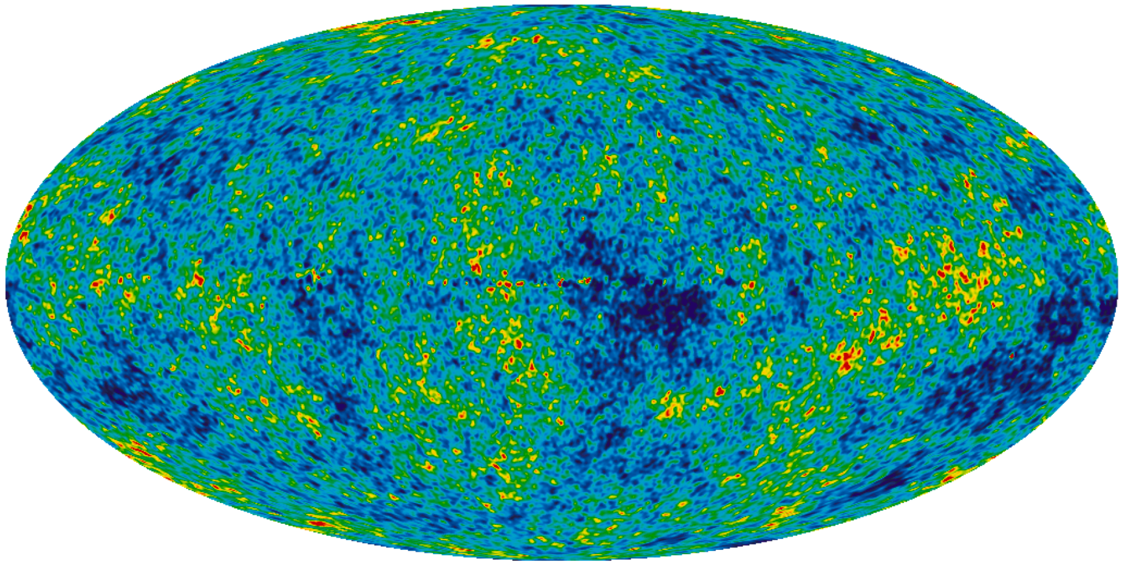
Rapid expansion of the universe in the early time



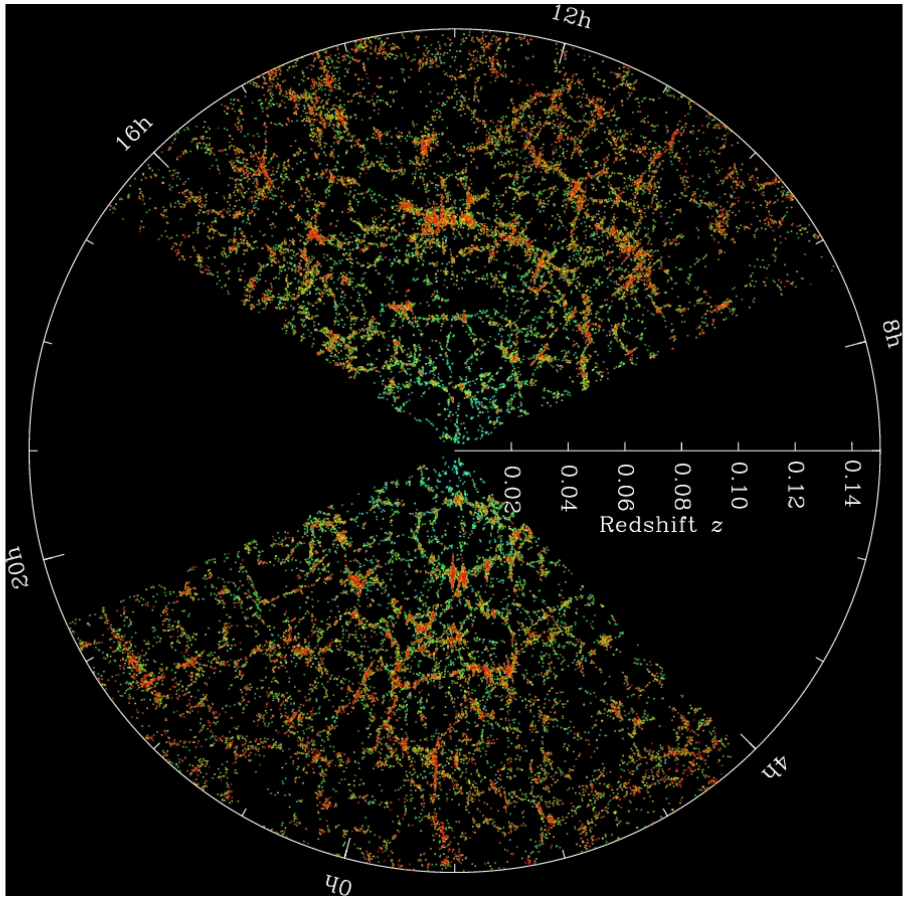
- Flatness problem
- Horizon problem
- Seeding the primordial anisotropies in CMB

Inflation

Stretching quantum fluctuations to large scale



dark matter →



$$\frac{\delta T}{T} \sim 10^{-5}$$

Such small fluctuations finally develops the large structure of our universe

Slow-roll inflation

Assuming a scalar field, with equation of motion

$$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V}{\partial \phi} = 0$$

$$H^2 = \frac{1}{3}\left(\frac{1}{2}\dot{\phi}^2 + V(\phi)\right)$$

Slow roll condition $\dot{\phi}^2 \ll V(\phi) \qquad |\ddot{\phi}| \ll |3H\dot{\phi}|\,,\, |V_{,\phi}|$

$$\epsilon_{\rm v}(\phi) \equiv \frac{M_{\rm pl}^2}{2}\left(\frac{V_{,\phi}}{V}\right)^2 \qquad \eta_{\rm v}(\phi) \equiv M_{\rm pl}^2 \frac{V_{,\phi\phi}}{V} \qquad \epsilon_{\rm v}, |\eta_{\rm v}| \ll 1$$

$$H^2 \approx \frac{1}{3}V(\phi) \approx \text{const.}$$

$$\dot{\phi} \approx -\frac{V_{,\phi}}{3H}\,,$$

$\longrightarrow$ $a(t) = a_0 e^{Ht} \qquad Ht \gtrsim 60$

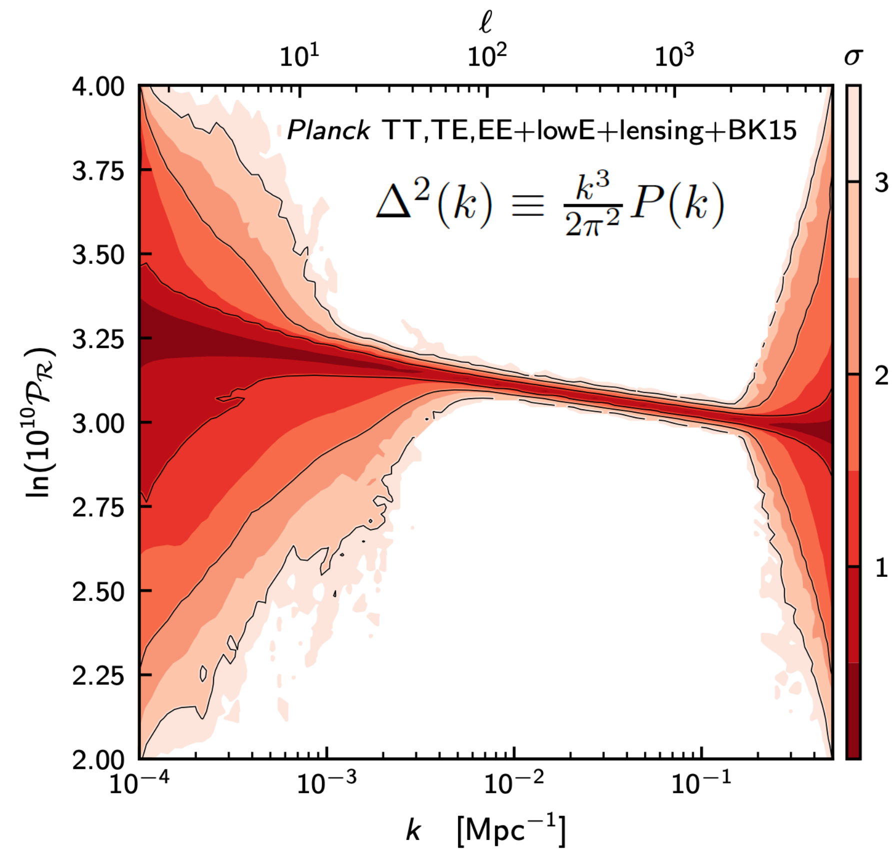
Daniel Baumann, TASI Lectures on Inflation

Slow-roll inflation

Power spectrum $\Delta_s^2(k) \equiv \frac{k^3}{2\pi^2}\langle\delta\phi(k)\delta\phi(k')\rangle$

$$\Delta_{\rm s}^2(k) \approx \frac{1}{24\pi^2}\frac{V}{M_{\rm pl}^4}\frac{1}{\epsilon_{\rm V}}\bigg|_{k=aH}$$

$$\Delta_{\rm t}^2(k) \approx \frac{2}{3\pi^2}\frac{V}{M_{\rm pl}^4}\bigg|_{k=aH}$$



$$n_{\rm s} - 1 \equiv \frac{d\ln\Delta_{\rm s}^2}{d\ln k} = 2\eta_{\rm V} - 6\epsilon_{\rm V}$$

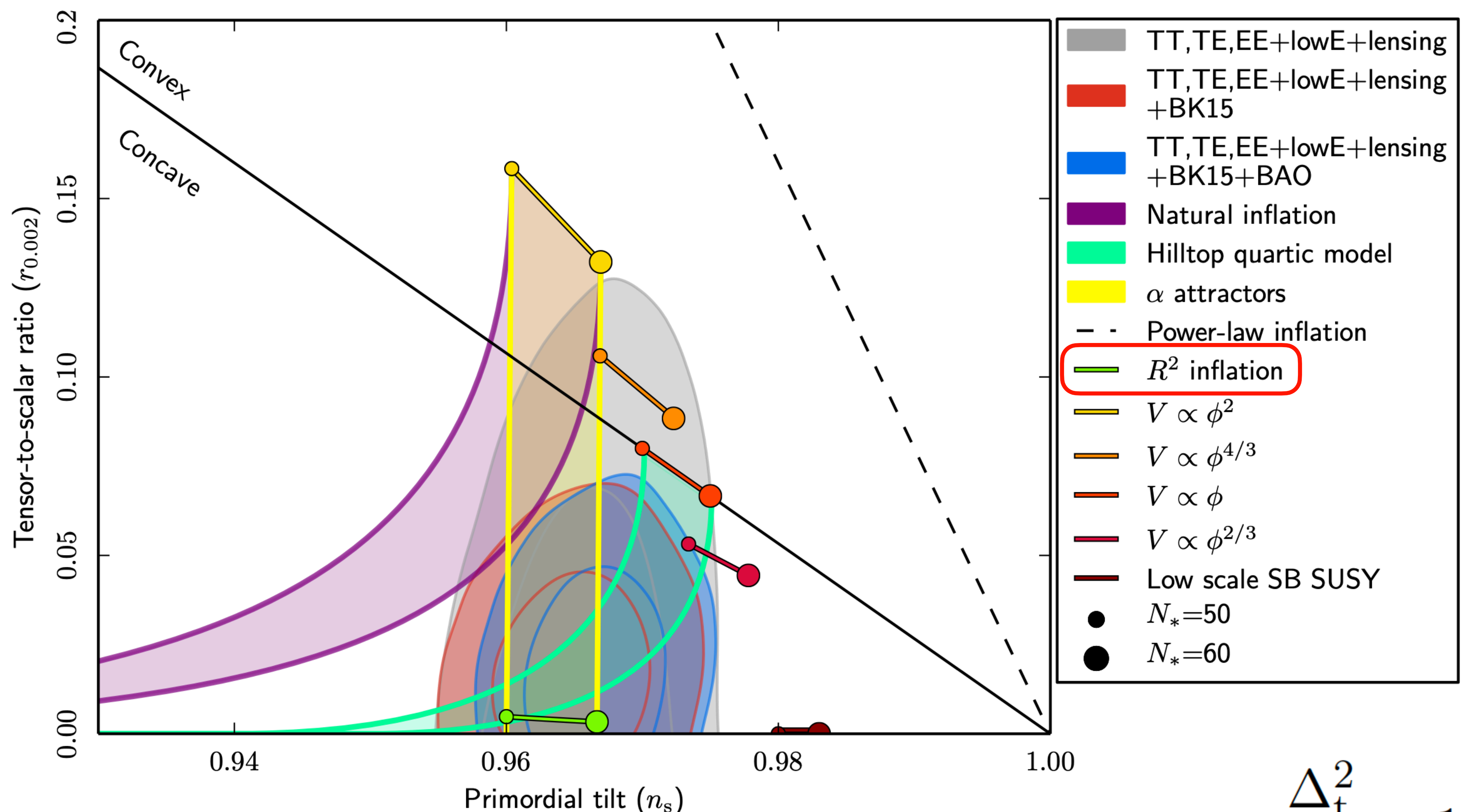
$$r \equiv \frac{\Delta_{\rm t}^2}{\Delta_{\rm s}^2} = 16\epsilon_{\rm V}$$

$n_s \simeq 0.965$

$r \lesssim 0.056$ tensor-scalar ratio

- Perturbation close to scale invariant
- Primordial gravitational wave(not observed yet)

Observation

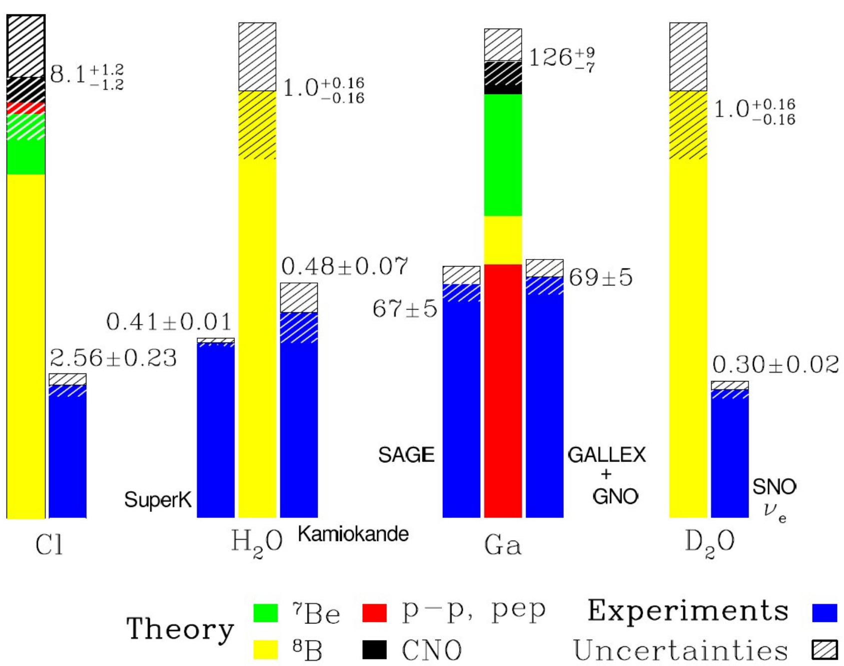


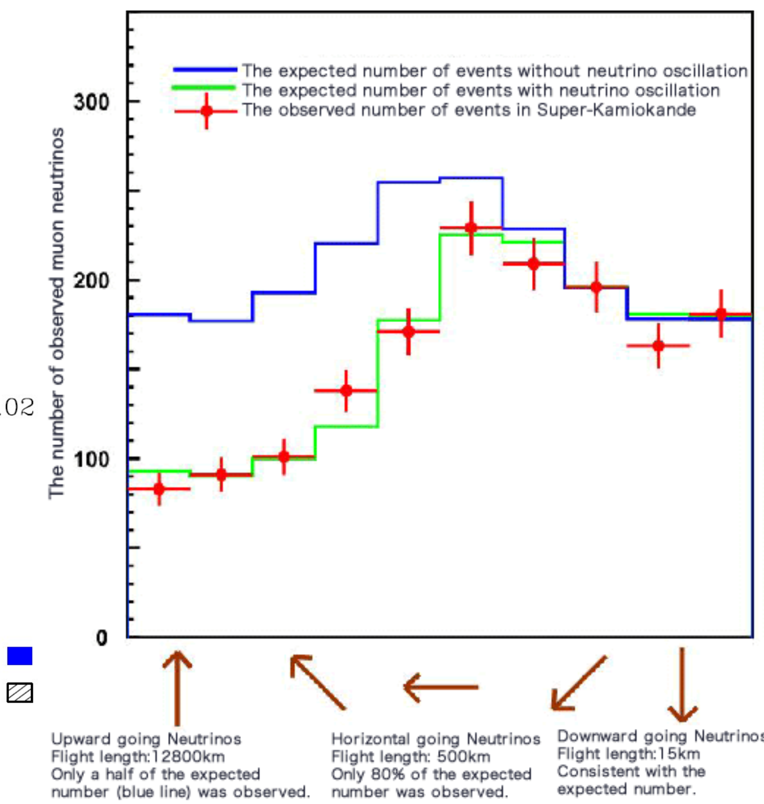
$$r \equiv \frac{\Delta_t^2}{\Delta_s^2} = 16\epsilon_V$$

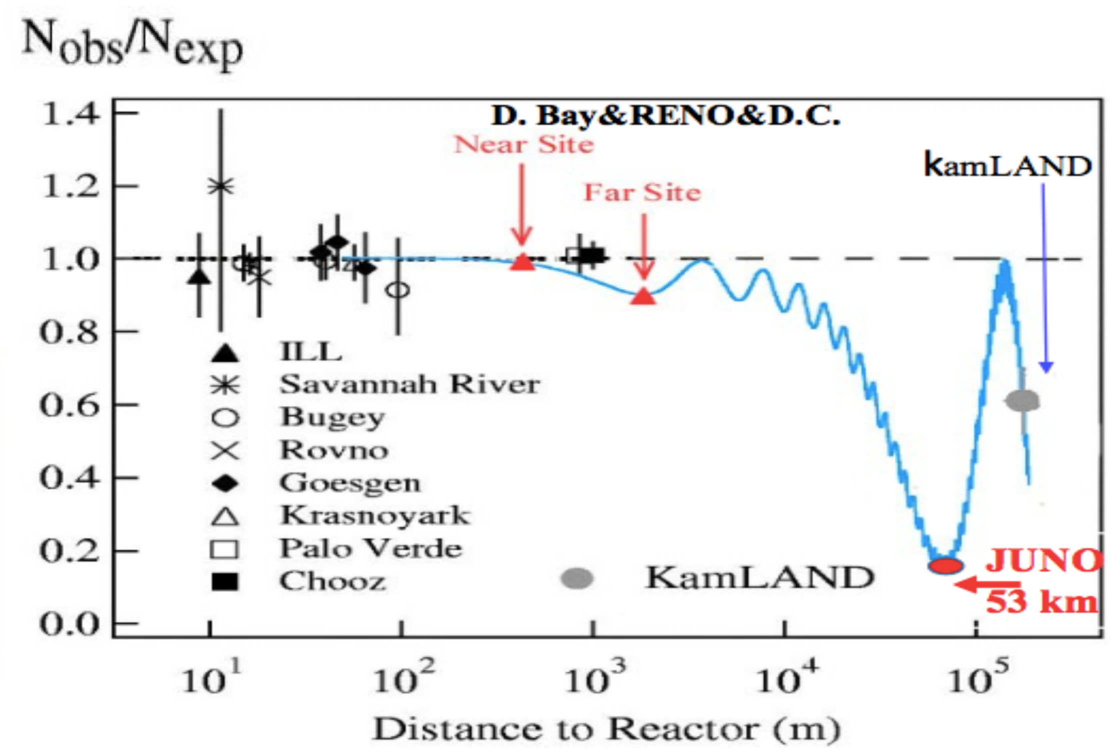
$V(\phi) \propto \phi^n$ seems not consistent with observation

too large r due to the non-flat of the potential

Neutrino oscillation requiring massive neutrinos







Solar Neutrino oscillations Atmospheric Neutrino Oscillations Reactor Neutrino Oscillations

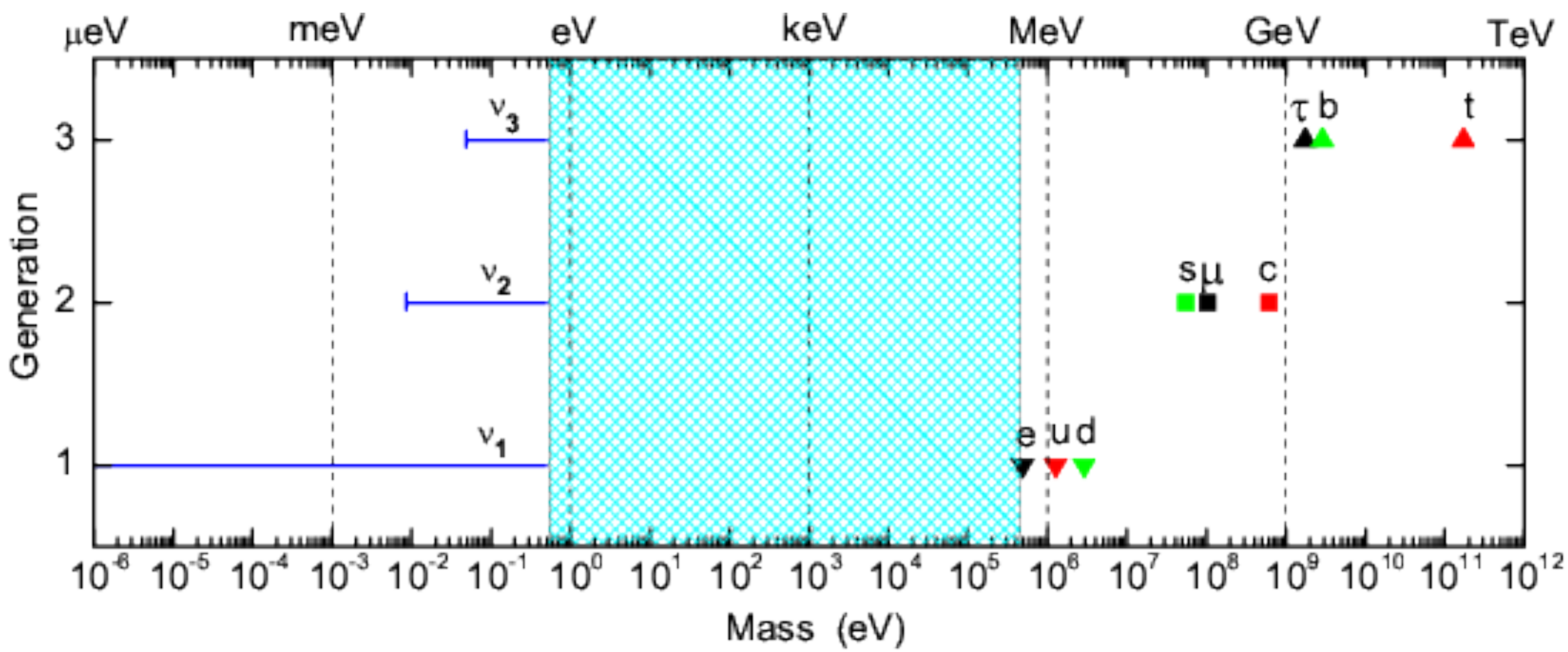
θ_{12} θ_{23} θ_{13}

$$\Delta m^2_{21} \simeq 7.42 \times 10^{-5}\ \mathrm{eV}^2 \qquad |\Delta m^2_{13}| \approx |\Delta m^2_{23}| \simeq 2.5 \times 10^{-3}\ \mathrm{eV}^2$$

At least a neutrino mass larger or similar to 0.05 eV

Neutrino masses vs other fermion masses

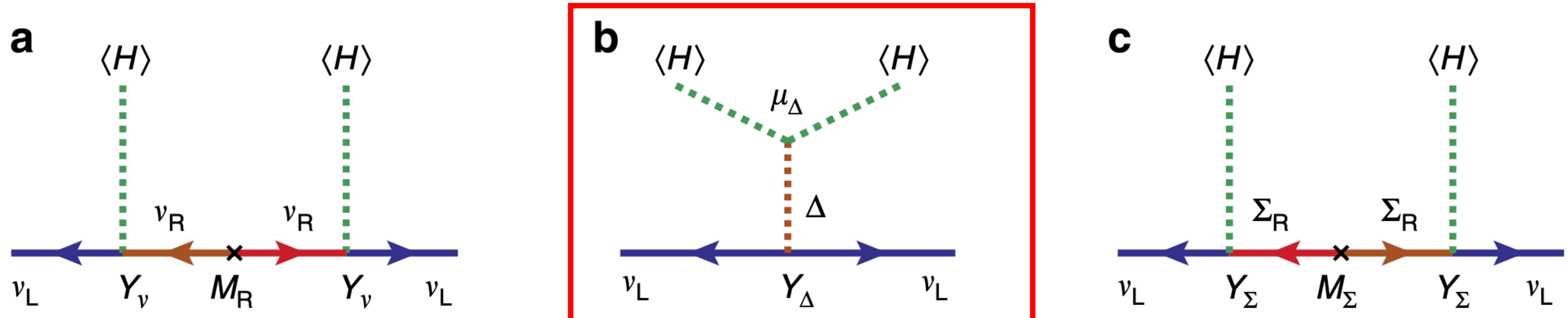
A large hierarchy comparing with other fermion masses



Origin of neutrino masses

Three types of seesaw model(tree level)

Tommy Ohlsson, Shun Zhou, Nature Commun. 5 (2014) 5153



$M_\nu = -\langle H\rangle^2 Y_\nu M_R^{-1} Y_\nu^T$

$M_\nu = \langle H\rangle^2 Y_\Delta \mu_\Delta / M_\Delta^2$

$M_\nu = -\langle H\rangle^2 Y_\Sigma M_\Sigma^{-1} Y_\Sigma^T$

SM + 3 singlets fermions

SM + 1 triplet Higgs

SM + 3 triplet fermions

Minkowski, Gell-Mann, Glashow, Yanagida

Magg, Wetterich

Foot, Lew, He, Joshi

scalar

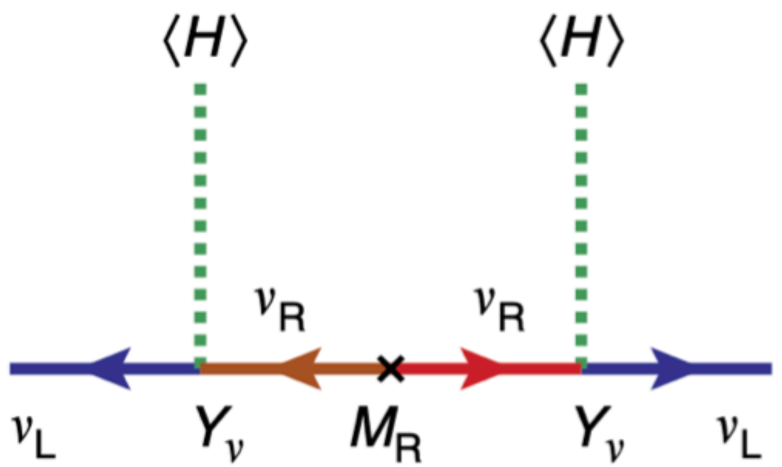
Origin of neutrino masses: type I seesaw

Adding three gauge singlets N(1, 1, 0)

$$\mathcal{L} = \mathcal{L}_{SM} + y_\nu \tilde{H}\bar{L}N - M_R \bar{N}^c N$$

$$M = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}$$

$$m_\nu \sim \frac{m_D^2}{M_R} = \frac{1}{2}\frac{y_\nu^2 < H >^2}{M_R}$$



$M_\nu = -\langle H\rangle^2 Y_\nu M_R^{-1} Y_\nu^T$

Neutrino mass is suppressed

Origin of neutrino masses: type II seesaw

Type II seesaw: introducing a triplet Higgs directly couple to leptons

$$H(2,1/2),\ \Delta(3,1),\ L(2,-1/2)$$

$$H = \begin{pmatrix} h^+ \\ h \end{pmatrix},\quad \Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$

$$\mathcal{L}_{Yukawa} = \mathcal{L}^{\rm SM}_{\rm Yukawa} - \boxed{\frac{1}{2} y_{ij} \bar{L}^c_i \Delta L_j} + h.c.$$

$$\downarrow$$

$$\frac{1}{2} y_{ij} \Delta^0 \bar{\nu}^c \nu + h.c.$$

- Giving neutrino mass matrix with vev of Delta
- Delta get a lepton number -2

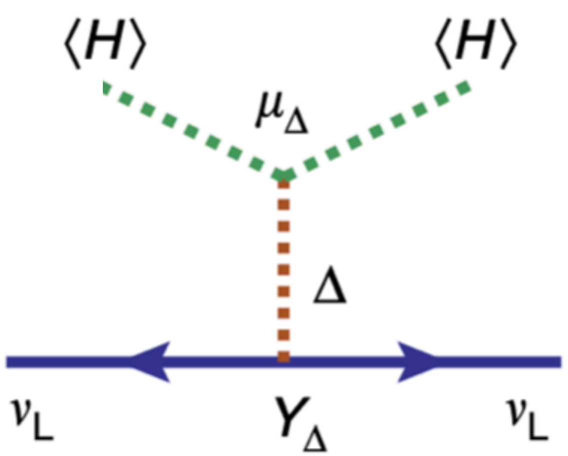
Origin of neutrino masses: type II seesaw

$$H(2,1/2),\ \Delta(3,1),\ L(2,-1/2)$$

$$\begin{aligned} V(H,\Delta) &= -m_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + m_\Delta^2 \mathrm{Tr}(\Delta^\dagger \Delta) + \lambda_1 (H^\dagger H)\mathrm{Tr}(\Delta^\dagger\Delta) \\ &+\lambda_2 (\mathrm{Tr}(\Delta^\dagger\Delta))^2 + \lambda_3 \mathrm{Tr}(\Delta^\dagger\Delta)^2 + \lambda_4 H^\dagger \Delta\Delta^\dagger H \\ &+ \left[\mu(H^T i\sigma^2 \Delta^\dagger H) + h.c.\right] + \ldots \end{aligned}$$

U(1)L breaking term

$$\langle \Delta^0 \rangle \simeq \frac{\mu v_{\mathrm{EW}}^2}{2 m_\Delta^2}$$



$$M_\nu = \langle H \rangle^2 Y_\Delta \mu_\Delta / M_\Delta^2$$

EW precision measurement

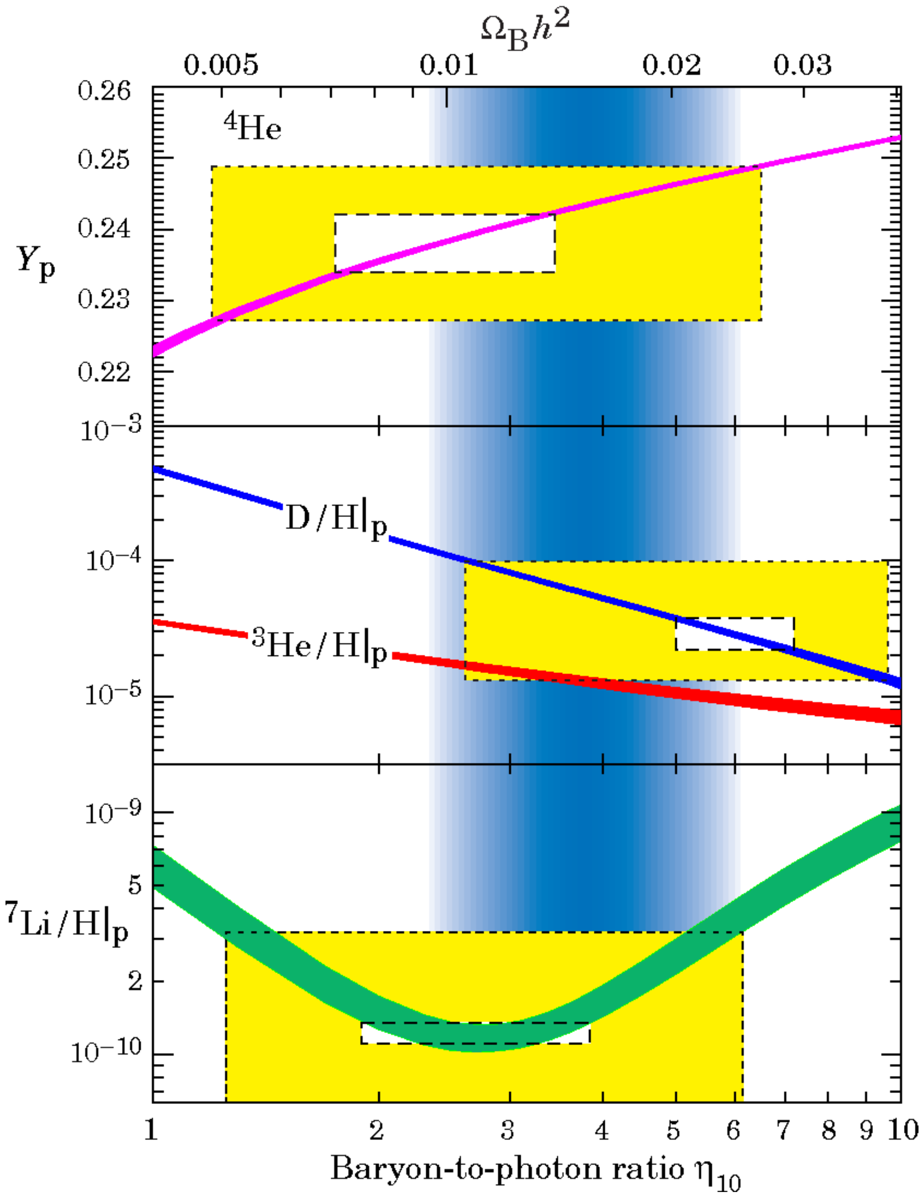
$$\mathcal{O}(1)\ \mathrm{GeV} > |\langle \Delta^0 \rangle| \gtrsim 0.05\ \mathrm{eV}$$

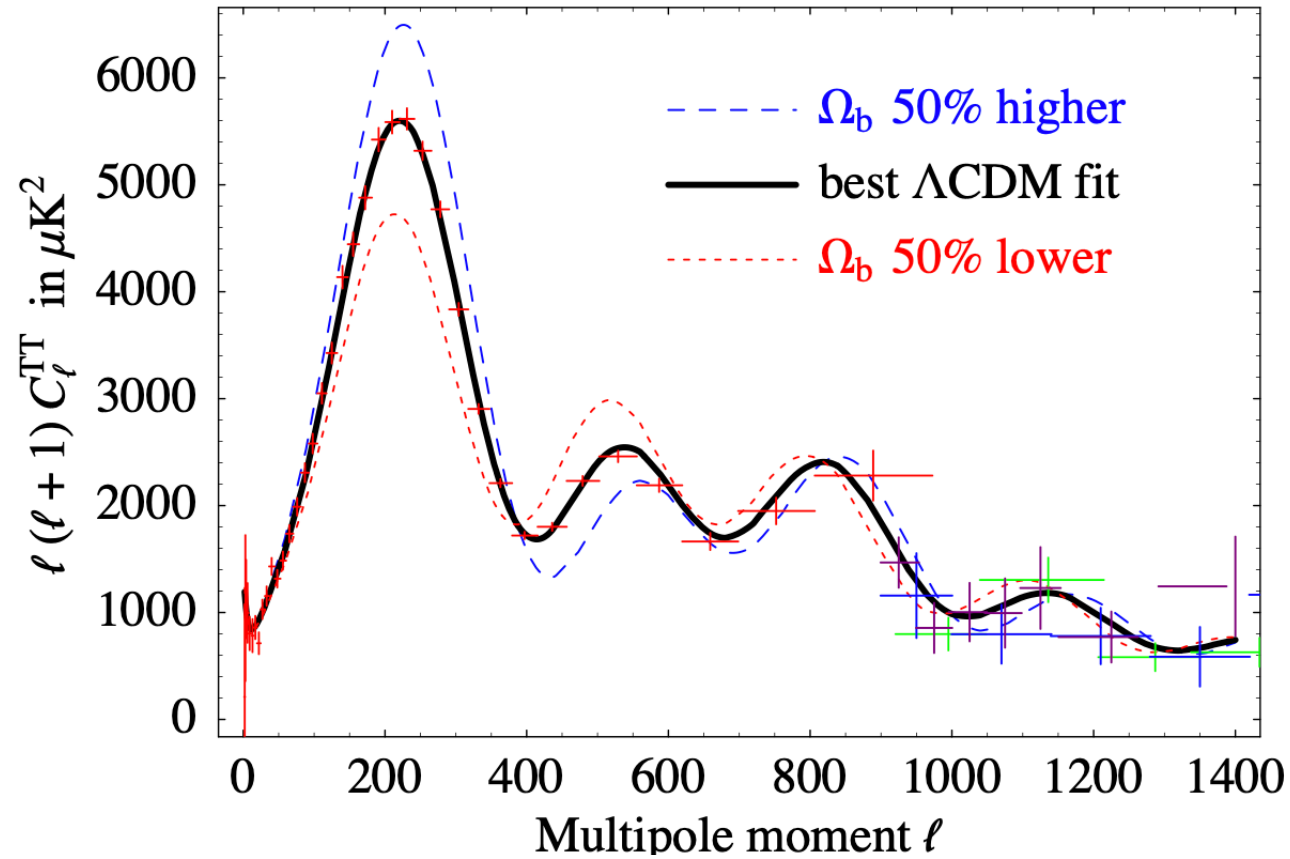
required by neutrino masses

Neutrino masses connecting another important problem:

Baryon asymmetry of our universe

Baryon asymmetry of our universe





Parameter	Plik best fit	Plik [1]	CamSpec [2]	([2] − [1])/σ_1	Combined
$\Omega_b h^2$	0.022383	0.02237 ± 0.00015	0.02229 ± 0.00015	−0.5	0.02233 ± 0.0001
$\Omega_c h^2$	0.12011	0.1200 ± 0.0012	0.1197 ± 0.0012	−0.3	0.1198 ± 0.0012

BBN

$$\eta = \frac{n_b - n_{\bar{b}}}{s} \sim 10^{-10}$$

Without baryon asymmetry: too less matter

$$\frac{n_b}{s} = \frac{n_{\bar{b}}}{s} \sim 10^{-20}$$

How to generate baryon asymmetry?

Assuming no baryon asymmetry in the beginning
(if any, diluted by inflation)

Sakharov conditions

1. B number violation

2. C and CP violation

3. Out of thermal equilibrium

SM has (1) (2) but not enough CP violation, (3) does not

Three popular ways to generate baryon asymmetry

- Electroweak baryogenesis

Rubakov and Shaposhnikov, 1996'
D. E. Morrissey and M. J. Ramsey-Musolf, 2012'

First order phase transition (adding scalars) + additional $\not{C}P$

- Baryogenesis via thermal leptogenesis

Fukugita and Yanagida, 1986'

Connection to neutrino masses

$$n_B = \frac{28}{79}(\mathcal{B} - \mathcal{L})_i$$

- Baryogenesis from Affleck-Dine mechanism

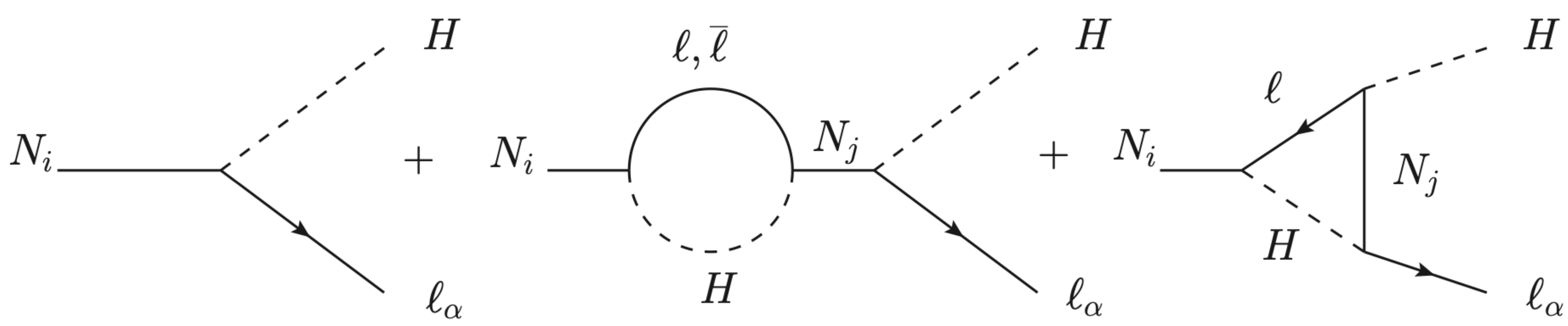
Affleck and Dine, 1985'

A well-known mechanism for SUSY

Baryogenesis via leptogenesis from Type I seesaw

Baryogenesis Without Grand Unification (**4000+ citations**), Fukugita and Yanagida, 1986'

$$\mathcal{L}_I = \mathcal{L}_{SM} + i\overline{N_{R_i}}\not{\partial} N_{R_i} - \left(\frac{1}{2} M_i \overline{N^c_{R_i}} N_{R_i} + \epsilon_{ab} Y_{\alpha i} \overline{N_{R_i}} \ell^a_\alpha H^b + h.c.\right)$$



$$\epsilon_{i\alpha} = \frac{\gamma\left(N_i \to \ell_\alpha H\right) - \gamma\left(N_i \to \overline{\ell_\alpha} H^*\right)}{\sum_\alpha \gamma\left(N_i \to \ell_\alpha H\right) + \gamma\left(N_i \to \overline{\ell_\alpha} H^*\right)}$$

$$n_B = \frac{28}{79}(\mathcal{B} - \mathcal{L})_i$$

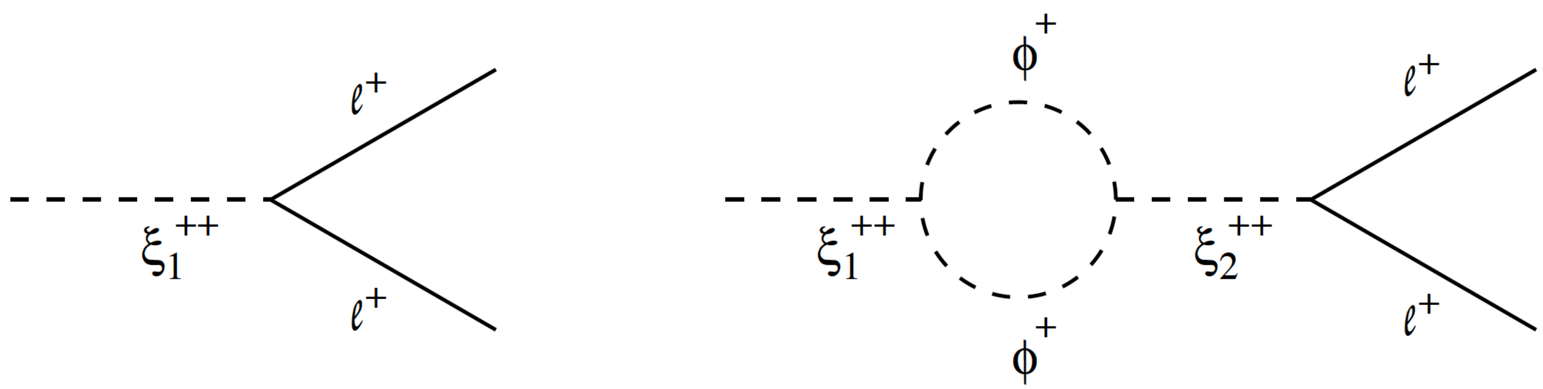
Generally N mass > 10^7 GeV, difficult to probe

How about type II seesaw leptogenesis?

Leptogenesis from type II seesaw?

Type II seesaw Neutrino Masses and Leptogenesis with Heavy Higgs Triplets (**500+ citations**)
E. Ma, U. Sarkar, Phys.Rev.Lett. 80 (1998) 5716-5719

$M \sim 10^{13}$ GeV



$$\delta_i = 2\left[B\left(\psi_i^- \to ll\right) - B\left(\psi_i^+ \to l^c l^c\right)\right]$$

$$\delta_i = \frac{Im\left[\mu_1\mu_2^* \sum_{k,l} y_{1kl}y_{2kl}^*\right]}{8\pi^2(M_1^2 - M_2^2)}\left[\frac{M_i}{\Gamma_i}\right]$$

At least two triplet Higgs are needed to generate the baryon asymmetry

But one triplet Higgs is enough to give neutrino masses

Leptogenesis from type II seesaw

PHYSICAL REVIEW LETTERS **128,** 141801 (2022)

Affleck-Dine Leptogenesis from Higgs Inflation

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We find that the triplet Higgs of the type-II seesaw mechanism can simultaneously generate the neutrino masses and observed baryon asymmetry while playing a role in inflation. We survey the allowed parameter space and determine that this is possible for triplet masses as low as a TeV, with a preference for a small vacuum expectation value for the triplet $v_\Delta < 10$ keV. This requires that the triplet Higgs must decay dominantly into the leptonic channel. Additionally, this model will be probed at the future 100 TeV collider, upcoming lepton flavor violation experiments such as Mu3e, and neutrinoless double beta decay experiments. Thus, this simple framework provides a unified solution to the three major unknowns of modern physics—inflation, the neutrino masses, and the observed baryon asymmetry—while simultaneously providing unique phenomenological predictions that will be probed terrestrially at upcoming experiments.

Type II Seesaw leptogenesis

JHEP

Neil D. Barrie,[a] Chengcheng Han[b] and Hitoshi Murayama[c,d,e,1]

Affleck-Dine mechanism

Assuming phi is a complex scalar with B charge

$$V(\phi) = \frac{1}{2}m^2|\phi|^2 + [c_{n,m}\phi^n(\phi^*)^m + h.c] \quad m \neq n$$

(B violation)

$$j_B^\mu = i(\phi^* \partial^\mu \phi - \phi \partial^\mu \phi^*)$$

ϕ is spatially constant

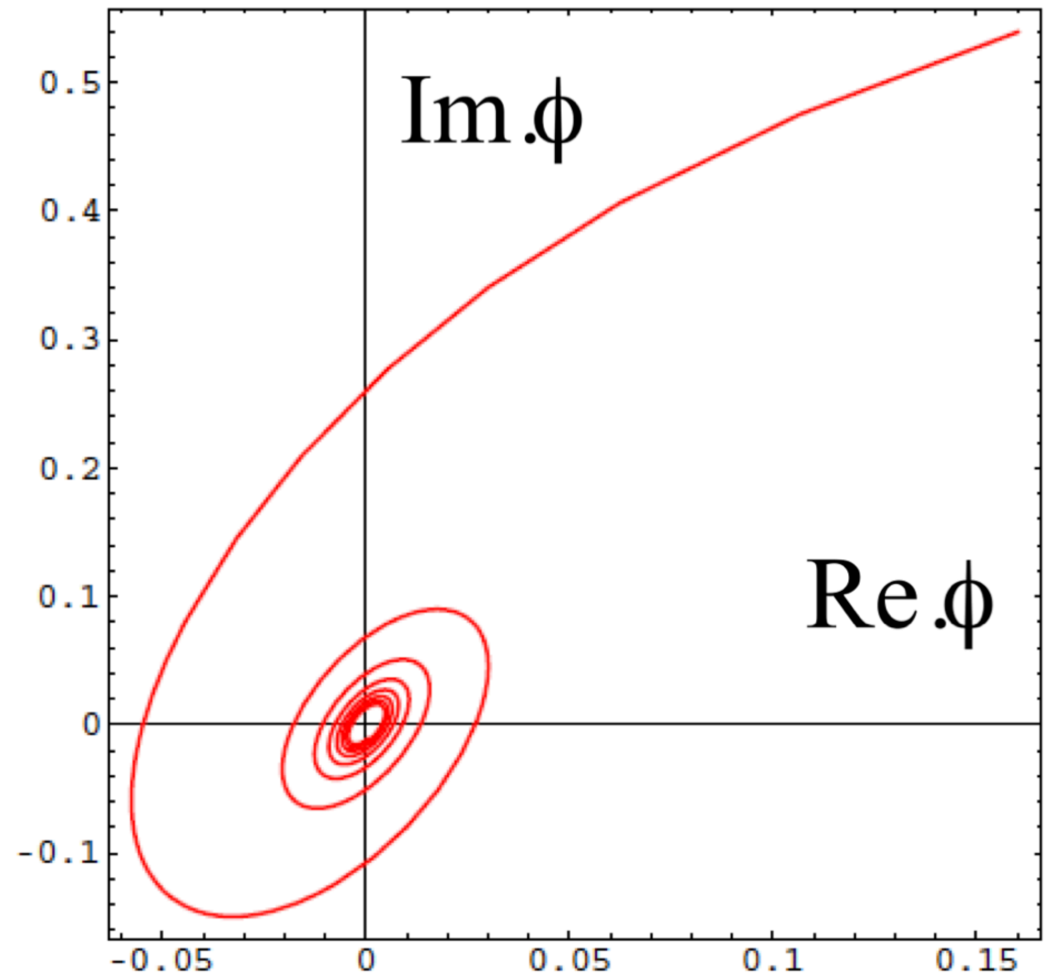
$$n_B = i(\phi^* \dot{\phi} - \phi \dot{\phi}^*) = \rho_\phi^2 \dot{\theta} \qquad \phi = \frac{1}{\sqrt{2}}\rho_\phi e^{i\theta}$$

$$\dot{n}_B + 3Hn_B = \mathrm{Im}\left(\phi \frac{\partial V}{\partial \phi}\right)$$

Only from U(1) breaking term

A motion of theta will generate baryon number

Affleck-Dine mechanism



- Scalar particle taking B/L charge
- Small B/L violation term in the potential(charge neutral)
- Scalar particle with initial displaced vacuum

Affleck-Dine mechanism in SUSY

- Sfermions taking B/L charge
- Flat directions(charge neutral and easily displaced during infaltion)

Baryogenesis from Flat Directions of the Supersymmetric Standard Mode
M. Dine, L. Randall, S. Thomas, Nucl.Phys.B458:291-326,1996

	$B-L$
$H_u H_d$	0
$L H_u$	-1
$\bar{u}\bar{d}\bar{d}$	-1
$QL\bar{d}$	-1
$LL\bar{e}$	-1
$QQ\bar{u}\bar{d}$	0
$QQQL$	0
$QL\bar{u}\bar{e}$	0
$\bar{u}\bar{u}\bar{d}\bar{e}$	0

For example,

$$H_u = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \phi \end{pmatrix}, \quad L = \frac{1}{\sqrt{2}}\begin{pmatrix} \phi \\ 0 \end{pmatrix}$$

$$V = m^2|\phi|^2 + \left[\frac{A}{M^{n-3}}\phi^n + h.c\right]$$

m, A term from SUSY breaking

Affleck-Dine mechanism for type II seesaw

Three conditions for Affleck-Dine mechanism

	Type II seesaw
● Scalar particle taking B/L charge	✓
● Small B/L violation term in the potential	✓
● Scalar particle with initial displaced vacuum	?

No flat direction without SUSY

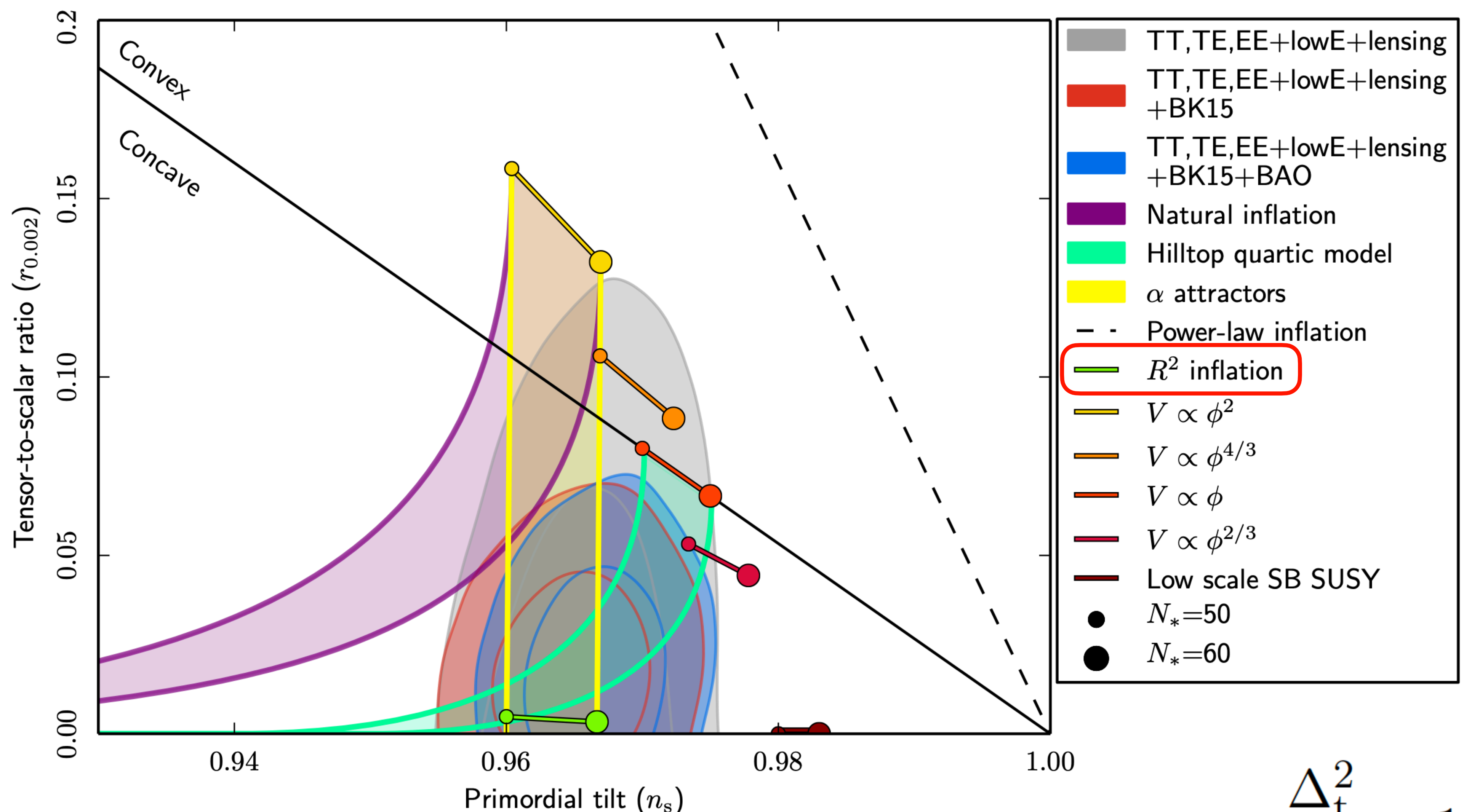
Affleck-Dine mechanism for type II seesaw

Three conditions for Affleck-Dine mechanism

	Type II seesaw
● Scalar particle taking B/L charge	✓
● Small B/L violation term in the potential	✓
● Scalar particle with initial displaced vacuum	✓

If the scalar plays the role of inflaton

Problem with inflation



$$r \equiv \frac{\Delta_t^2}{\Delta_s^2} = 16\epsilon_V$$

$V(\phi) \propto \phi^n$ seems not consistent with observation

too large r due to the non-flat of the potential

Adding non-minimal coupling

Similar idea of Higgs inflation

Bezrukov and Shaposhnikov, Phys.Lett.B 659 (2008) 703-706

$$S_J = \int d^4x \sqrt{-g_J} \left[\frac{M_P^2}{2} \left(1 + \frac{\xi\phi^2}{M_P^2} \right) R_J - \frac{1}{2} |\partial_\mu \phi|^2 - V_J(\phi) \right]$$

Weyl transformation

$$g_{\mu\nu} = \Omega(\phi)^2 g_{J\mu\nu} \qquad \Omega^2 = 1 + \frac{\xi\phi^2}{M_P^2}$$

$$R_J = \Omega^2 \left(R + 6\Box \ln\Omega - 6 g^{\mu\nu} \partial_\mu \ln\Omega \, \partial_\nu \ln\Omega \right)$$

Adding non-minimal coupling

$$\frac{d\chi}{d\phi} = \left(\frac{1 + \xi(1+6\xi)\phi^2/M_P^2}{(1+\xi\phi^2/M_P^2)^2} \right)^{1/2}$$

$$S = \int d^4x\sqrt{-g}\left[\frac{M_P^2}{2}R - \frac{1}{2}g^{\mu\nu}\partial_\mu\chi\partial_\nu\chi - V(\chi)\right]$$

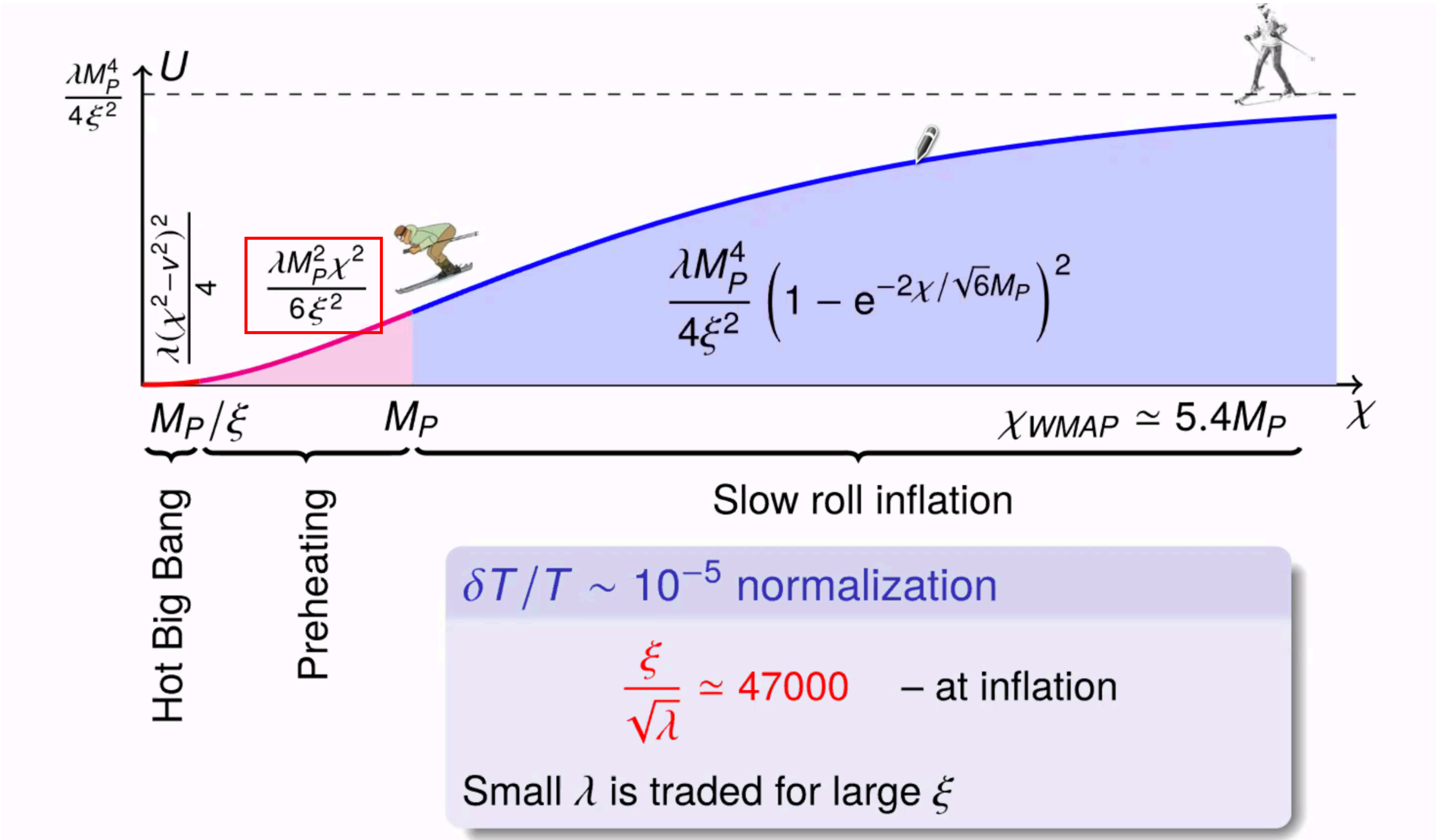
$$V(\chi) \equiv V_J(\phi(\chi))/\Omega^4(\phi(\chi)) \qquad \Omega^2 = 1 + \frac{\xi\phi^2}{M_P^2}$$

$$V_J = \frac{\lambda}{4}\phi^4 \xrightarrow{M_p/\xi \ll \phi < M_p} V = \frac{\lambda}{4\xi^2}M_p^4$$

Potential becomes flat when chi(phi) becomes large

Adding non-minimal coupling

Plot borrowed from Bezrukov



SM+Type II seesaw

To be consistent with inflation, we need add non-minimal couplings

$$\frac{\mathcal{L}}{\sqrt{-g}} = -\frac{1}{2}M_P^2 R - f(H,\Delta)R - g^{\mu\nu}(D_\mu H)^\dagger(D_\nu H)$$
$$-g^{\mu\nu}(D_\mu\Delta)^\dagger(D_\nu\Delta) - V(H,\Delta) + \mathcal{L}_{\text{Yukawa}}$$

$$h \equiv \frac{1}{\sqrt{2}}\rho_H e^{i\eta} \qquad \Delta^0 \equiv \frac{1}{\sqrt{2}}\rho_\Delta e^{i\theta}$$

$$F(H,\Delta) = \xi_H|h|^2 + \xi_\Delta|\Delta^0|^2 = \frac{1}{2}\xi_H\rho_H^2 + \frac{1}{2}\xi_\Delta\rho_\Delta^2$$

SM+Type II seesaw

During inflation(Oleg Lebedev and Hyun Min Lee, arXiv:1105.2284)

$$\frac{\rho_H}{\rho_\Delta} \equiv \tan\alpha = \sqrt{\frac{2\lambda_\Delta \xi_H - \lambda_{H\Delta}\xi_\Delta}{2\lambda_H \xi_\Delta - \lambda_{H\Delta}\xi_H}}$$

$$\rho_H = \varphi \sin\alpha, \;\; \rho_\Delta = \varphi\cos\alpha$$

$$\xi \equiv \xi_H \sin^2\alpha + \xi_\Delta \cos^2\alpha$$

Similar to SUSY case, but mixing with a general angle

SM+Type II seesaw

Finally the model can be simplified as

$$\frac{\mathcal{L}}{\sqrt{-g}} = -\frac{M_p^2}{2}R - \frac{\xi}{2}\varphi^2 R - \frac{1}{2}g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi - \frac{1}{2}\varphi^2\cos^2\alpha\; g^{\mu\nu}\partial_\mu\theta\partial_\nu\theta - V(\varphi,\theta)$$

$$V(\varphi,\theta) = \frac{1}{2}m^2\varphi^2 + \frac{\lambda}{4}\varphi^4 + 2\varphi^3\left(\tilde{\mu} + \frac{\tilde{\lambda}_5}{M_p}\varphi^2\right)\cos\theta$$

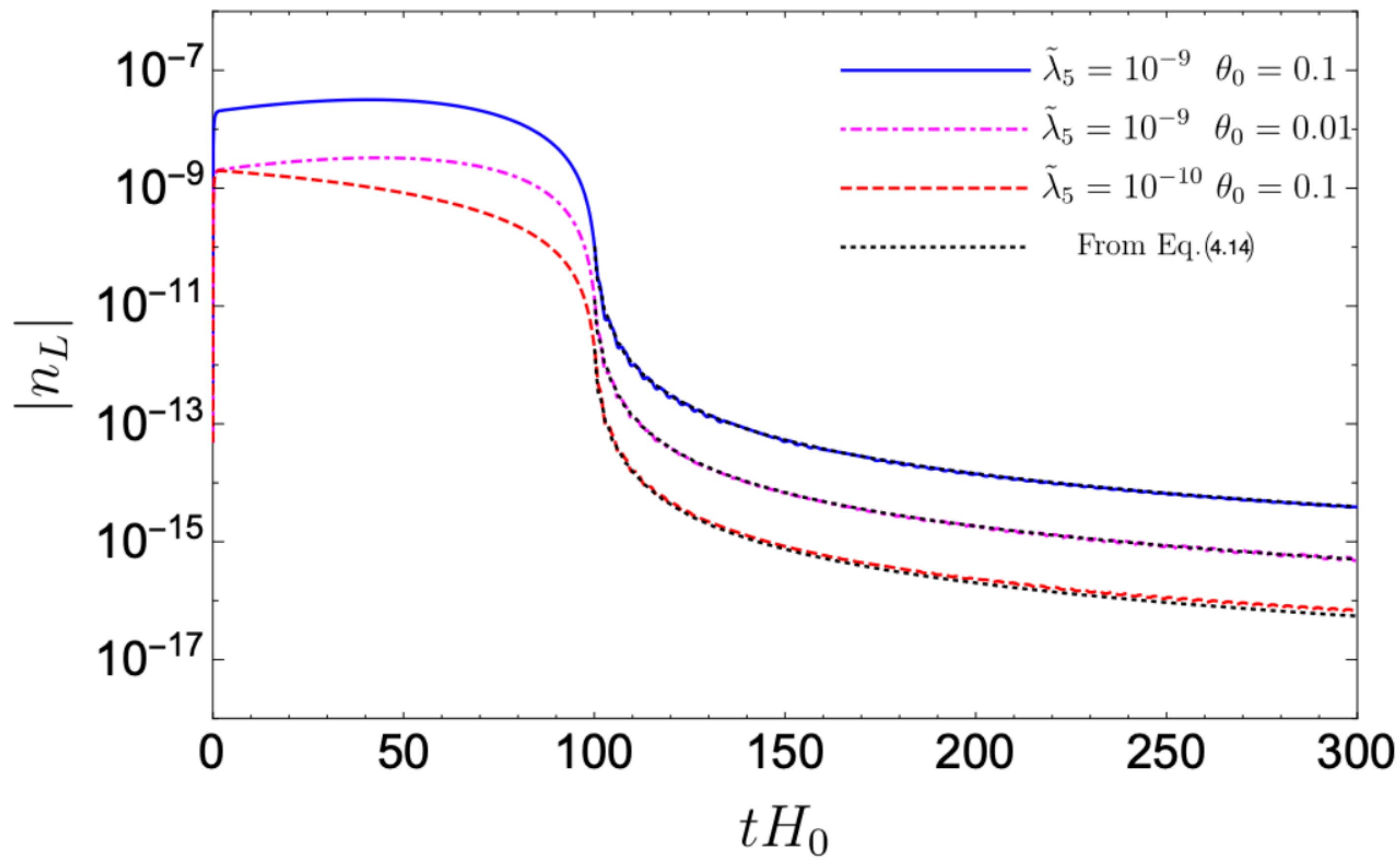
We need keep the theta term, because

$$n_L = Q_L\varphi^2\dot{\theta}\cos^2\alpha$$

Lepton number generation

$\xi = 300,\ \lambda = 4.5 \cdot 10^{-5}$

$\chi_0 = 6.0 M_p,\ \dot{\chi}_0 = 0$, and $\theta_0 = 0$



- Lepton number is generated during inflation
- After inflation, Lepton number is conserved

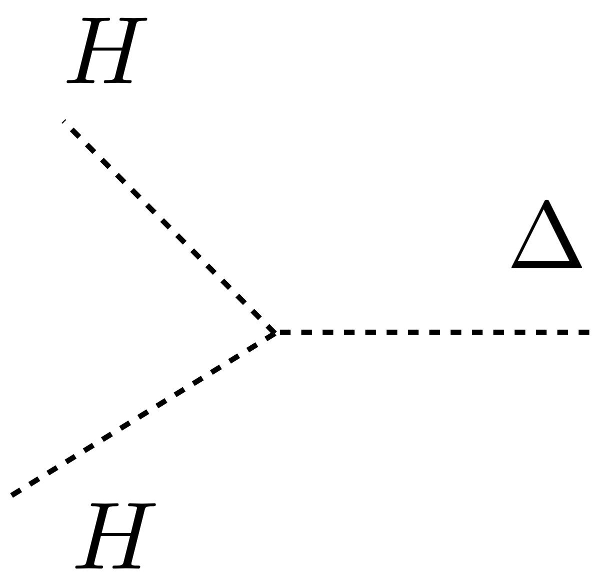
SM+Type II seesaw

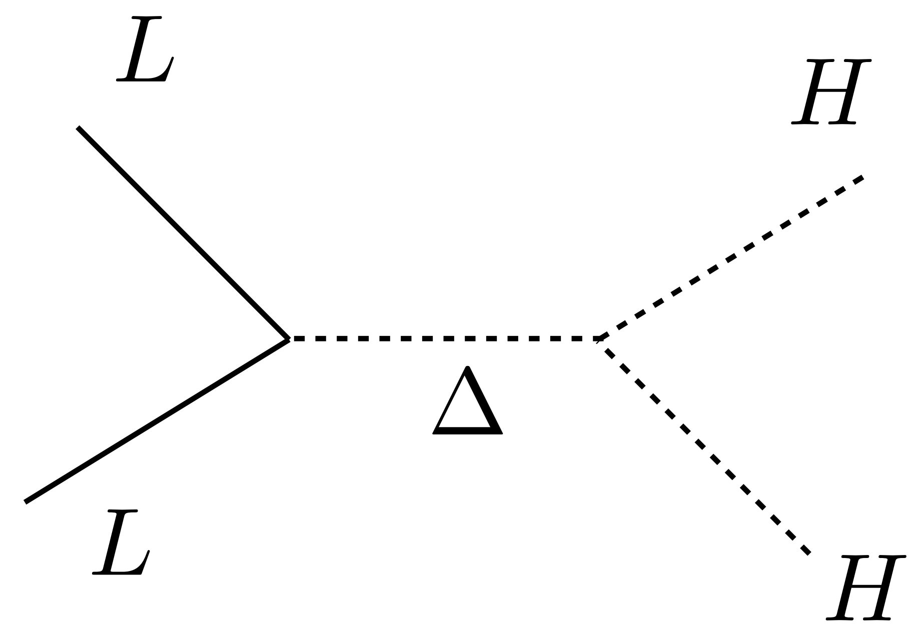
$T_{\rm reh} \approx 2.2 \cdot 10^{14}$ GeV

$$\eta_B = \frac{n_B}{s}\bigg|_{\rm reh} = \eta_B^{\rm obs} \left(\frac{|n_{L_{\rm end}}|/M_p^3}{1.3 \cdot 10^{-16}} \right) \left(\frac{g_*}{112.75} \right)^{-\frac{1}{4}}$$

$$\tilde{\lambda}_5 = 7 \cdot 10^{-15} \text{ for } \theta_0 = 0.1$$

Wash out process



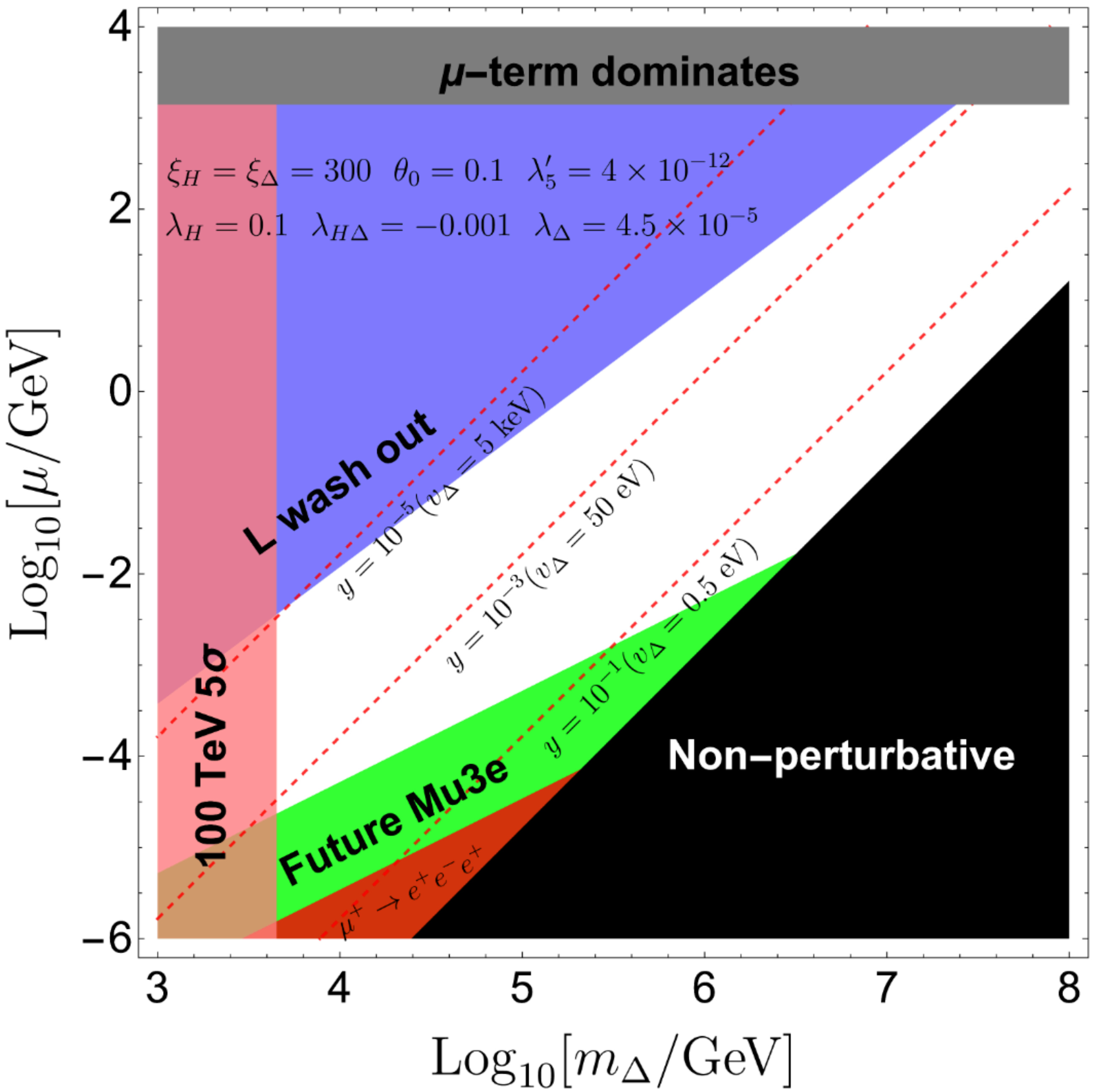


$$\frac{\mu^2}{8\pi m_\Delta} < H(m) = \frac{m_\Delta^2}{M_P}$$

$$m_\Delta < 10^{12}\ \text{GeV}$$

A small mu term is preferred

SM+Type II seesaw

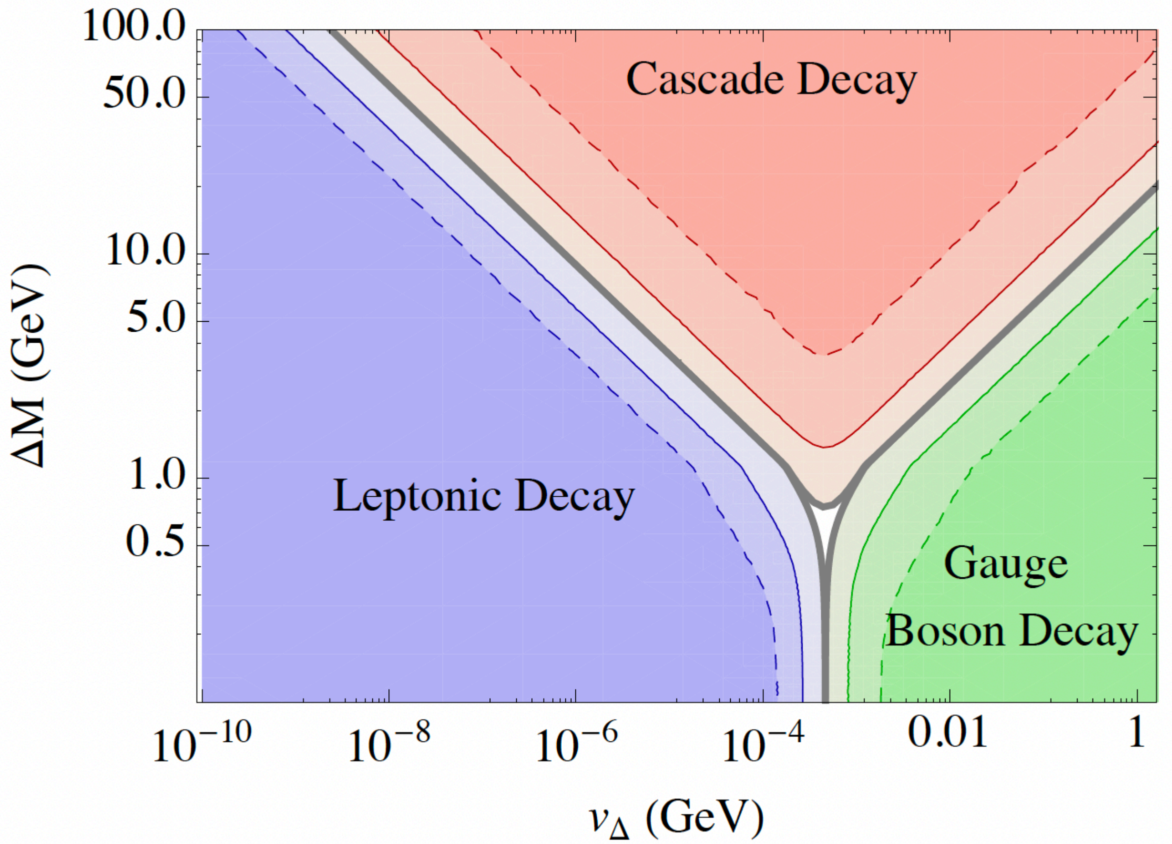


- Triplet Higgs could be as light as TeV
- Vacuum value < 10 keV, traditional type II seesaw < 1 GeV

Phenomenology implications I: collider physics

Decay of the doubly-charged Higgs

$$\Delta M = m_{\Delta^{++}} - m_{\Delta^{+}}$$



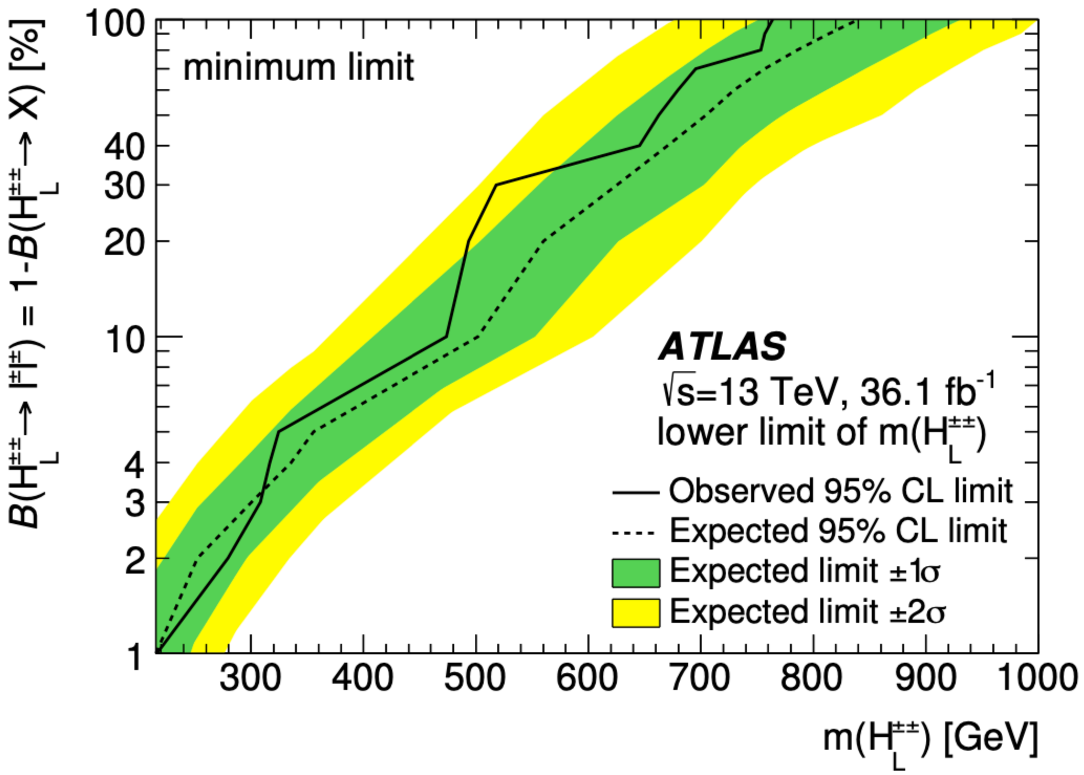
For v > 1 MeV, mainly decay gauge bosons

For v < 0.1 MeV, mainly decay leptons

Phenomenology implications I: collider physics

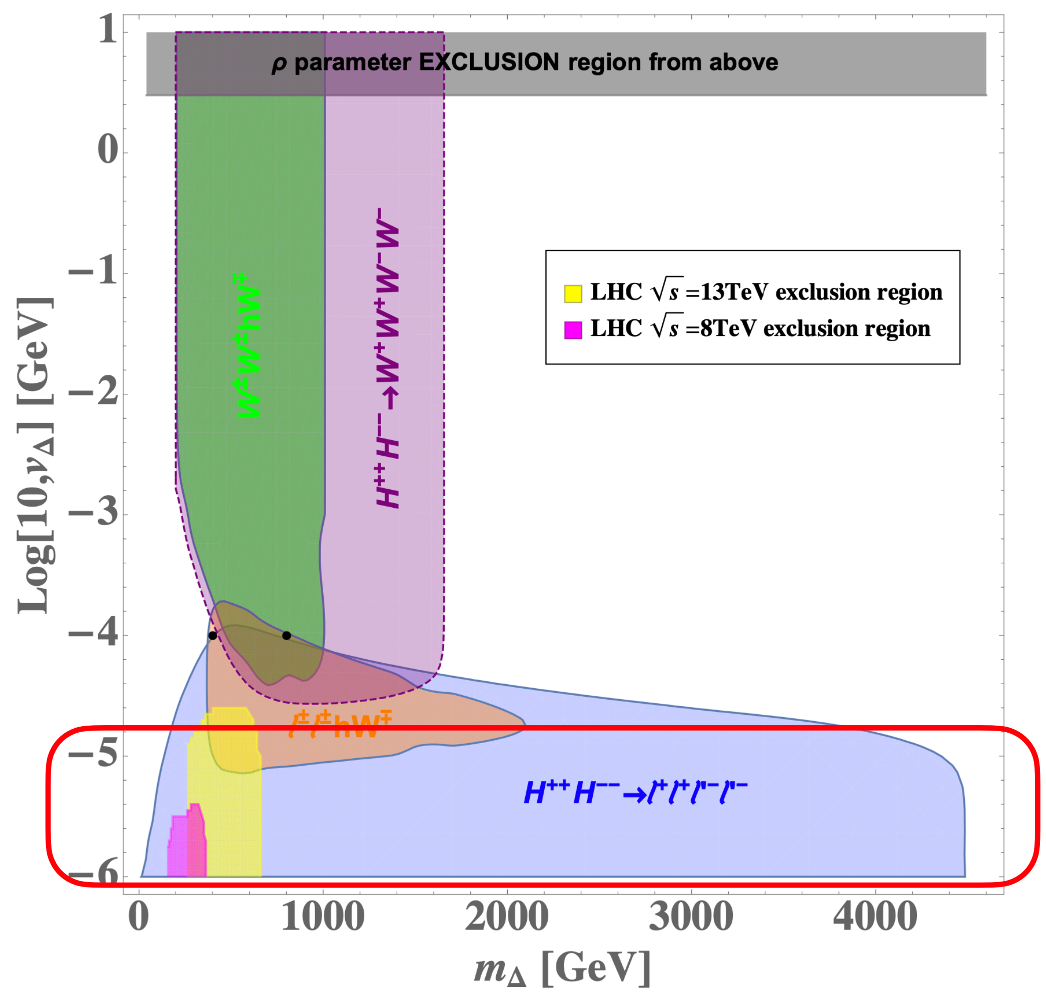
Current limit from LHC

ATLAS, Eur. Phys. J. C 78 (2018) 199



Future reach

Y. Du, A. Dunbrack, M. J. Ramsey-Musolf, J. Yu, JHEP01(2019)101

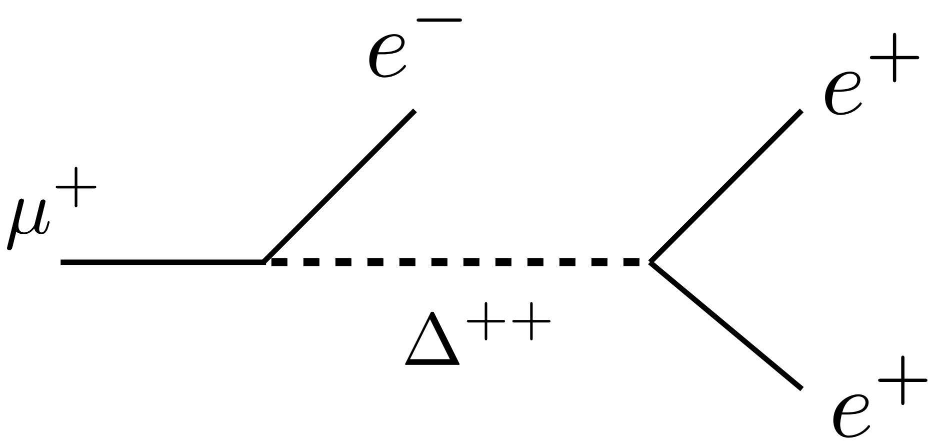


5 sigma discover region @100 TeV collider

Smoking gun: observing doubly-charged Higgs from leptonic channel

Phenomenology implications II: flavor physics

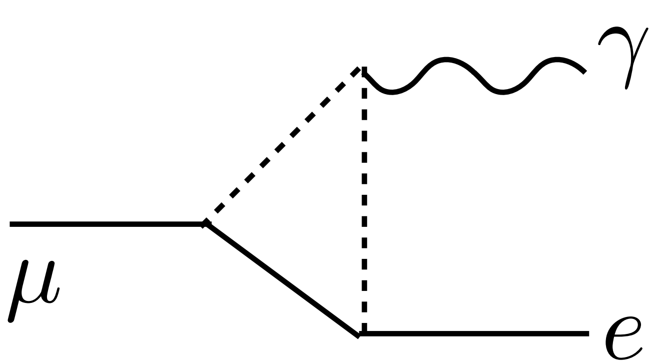
$$\mathcal{B}(\mu^+ \to e^+ e^- e^+) = \frac{|y_{\mu e} y^\dagger_{ee}|^2}{16 G_F^2 m^4_{\Delta^{++}}}$$



$$\mathcal{B}(\mu^+ \to e^+ e^- e^+) \leqslant 1.0 \times 10^{-12}$$

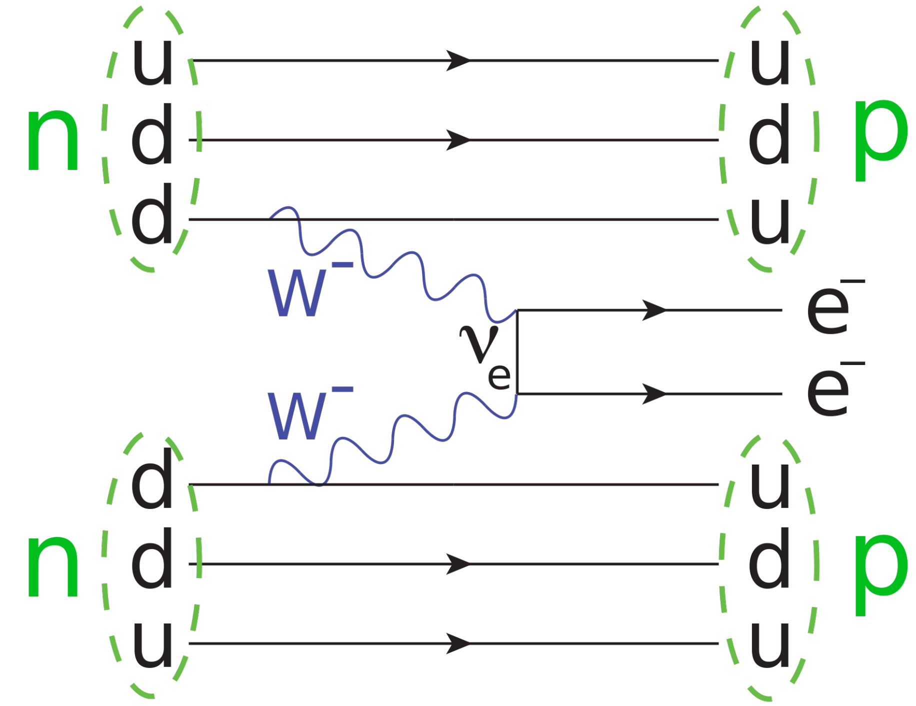
$$\mathcal{B}(\mu \to e\gamma) \simeq \frac{\alpha}{3072\pi} \frac{\left|(y^\dagger y)_{e\mu}\right|^2}{G_F^2} \left(\frac{1}{m^2_{\Delta^+}} + \frac{8}{m^2_{\Delta^{++}}} \right)^2$$

$$\mathcal{B}(\mu \to e\gamma) < 4.2 \times 10^{-13}$$

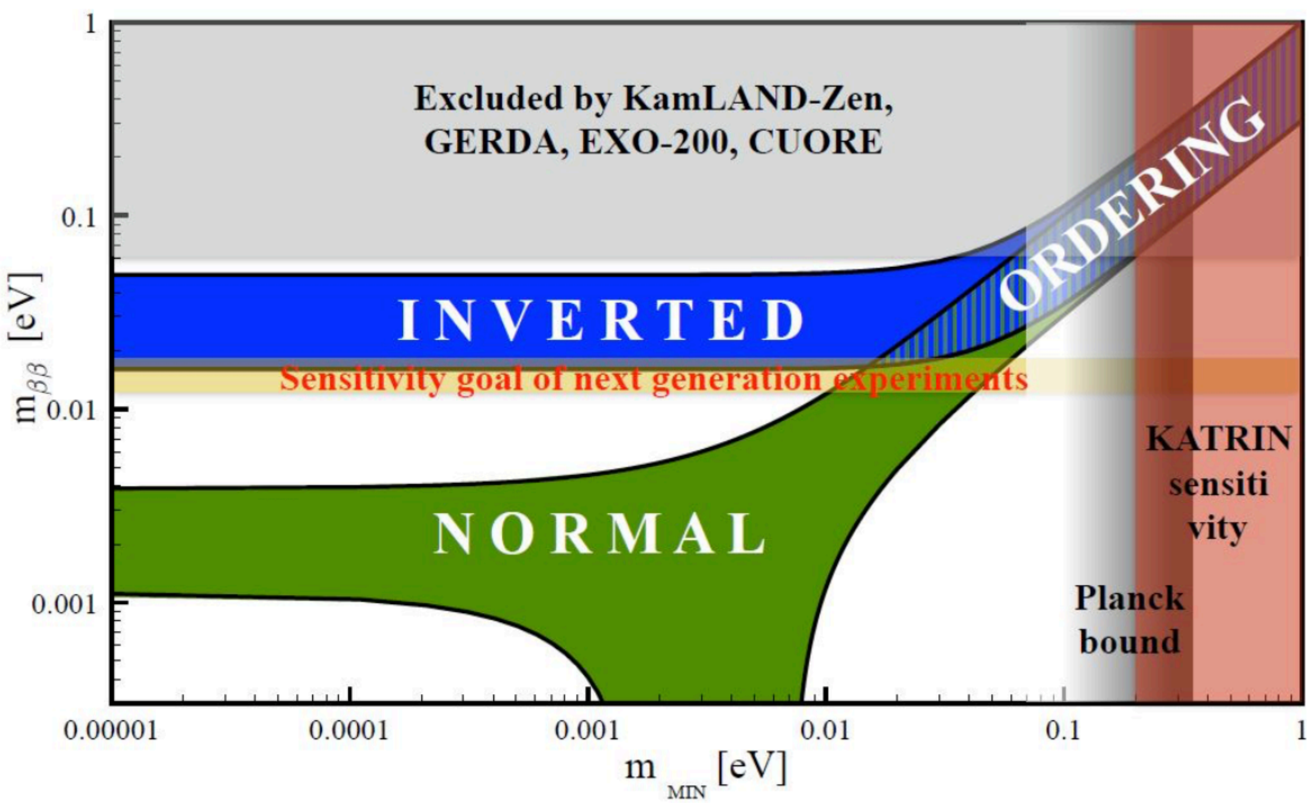


Phenomenology implications III: neutrino physics

- Neutrino must be majorana type

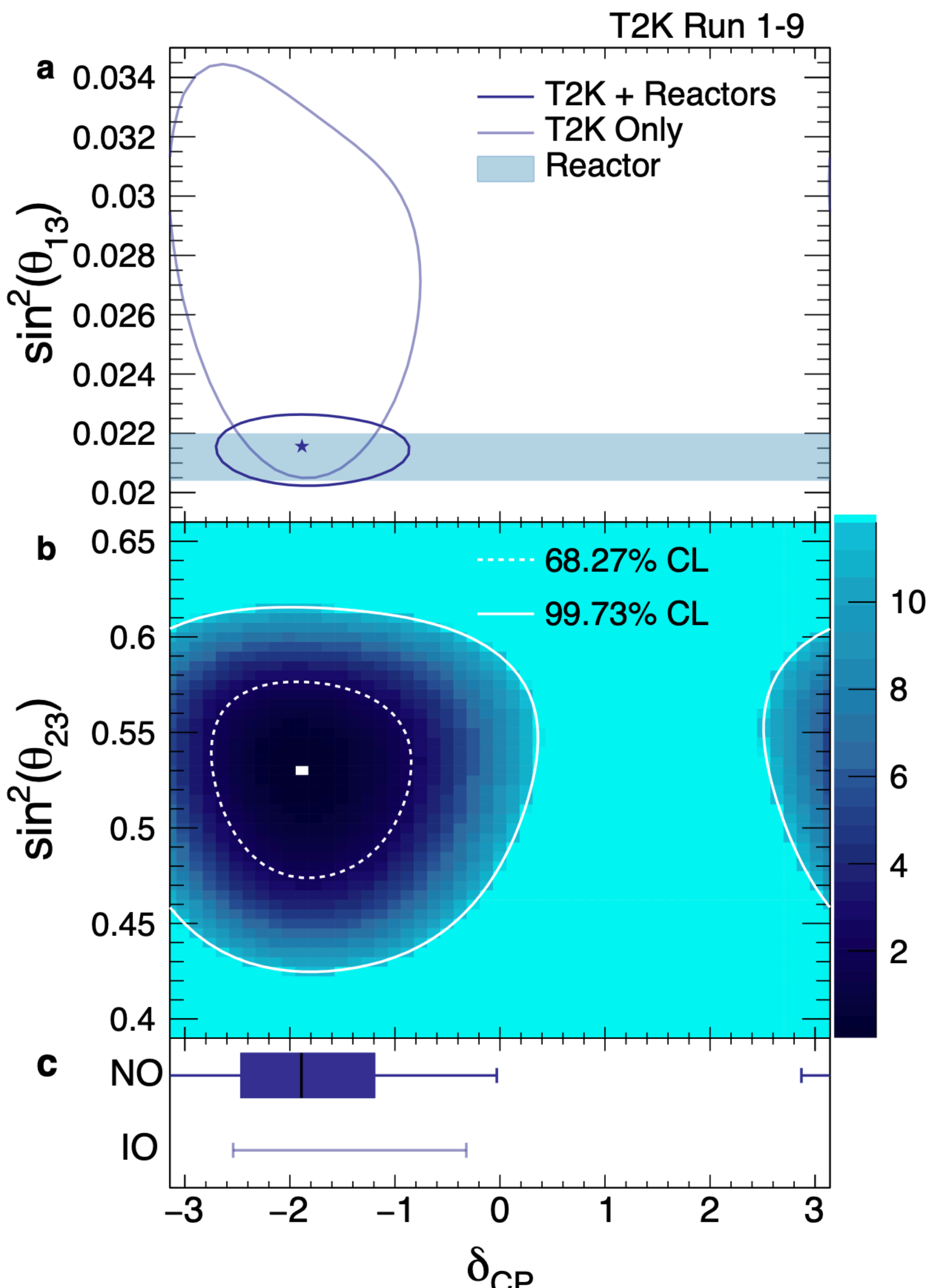


Neutrinoless double beta decay

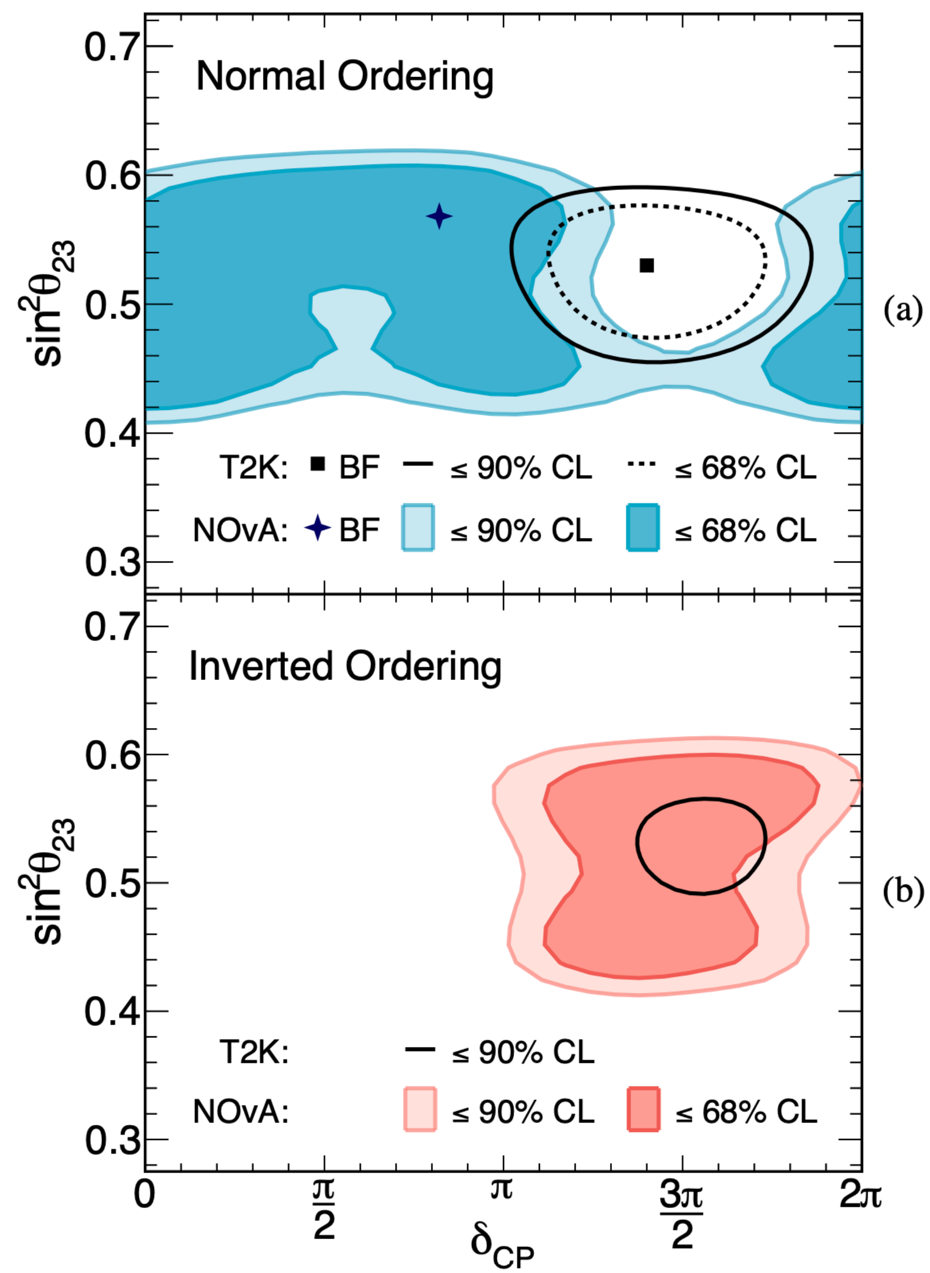


- CP violation in neutrino sector

T2K, 19'



Nova, 21'



Leptogenesis even without CP violation

Phenomenology implications IV: cosmological signal

- Tensor to scalar ratio, within the future reach of LiteBIRD

$$0.0033 < r < 0.0048$$

- Non-Gaussian signature, model dependent

- Imprint of isocurvature signature from baryon matter

- Gravitational wave from preheating

Summary

- One simple extension of SM, three problems can be solved: inflation, baryogenesis and neutrino masses

- Unique signatures at collider, LFV violation, neutrino experiments and astronomy observations

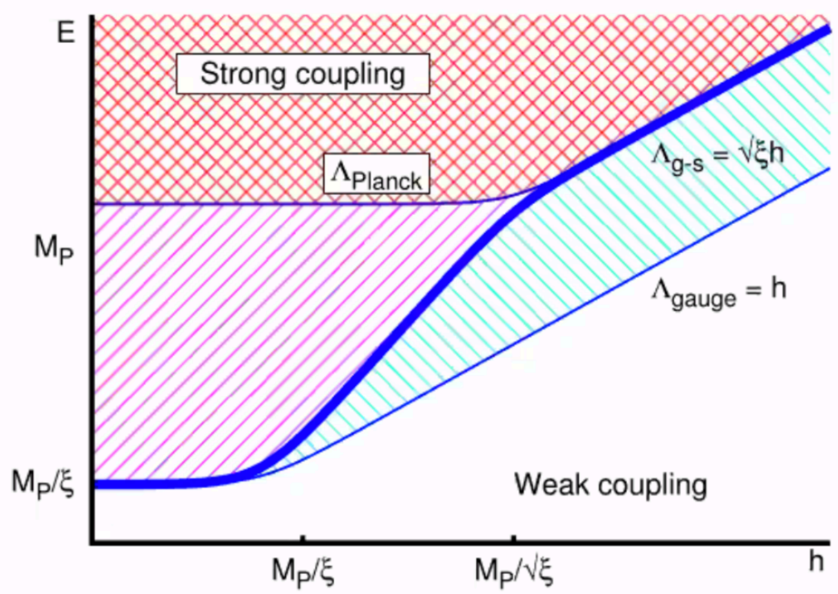
Thanks

Back up

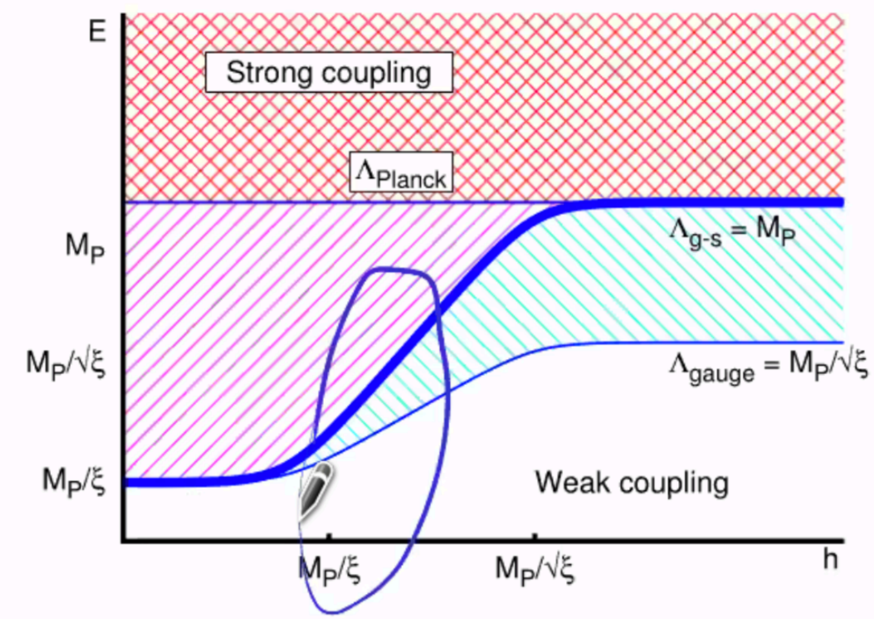
Unitary problem for Higgs inflation

Cut-off grows with the field background

Jordan frame



Einstein frame



Relation between cut-offs in different frames:

$$\Lambda_{\text{Jordan}} = \Lambda_{\text{Einstein}}\Omega$$

Relevant scales at inflation

Hubble scale $H \sim \lambda^{1/2}\frac{M_P}{\xi}$

Energy density at inflation

$$V^{1/4} \sim \lambda^{1/4}\frac{M_P}{\sqrt{\xi}}$$

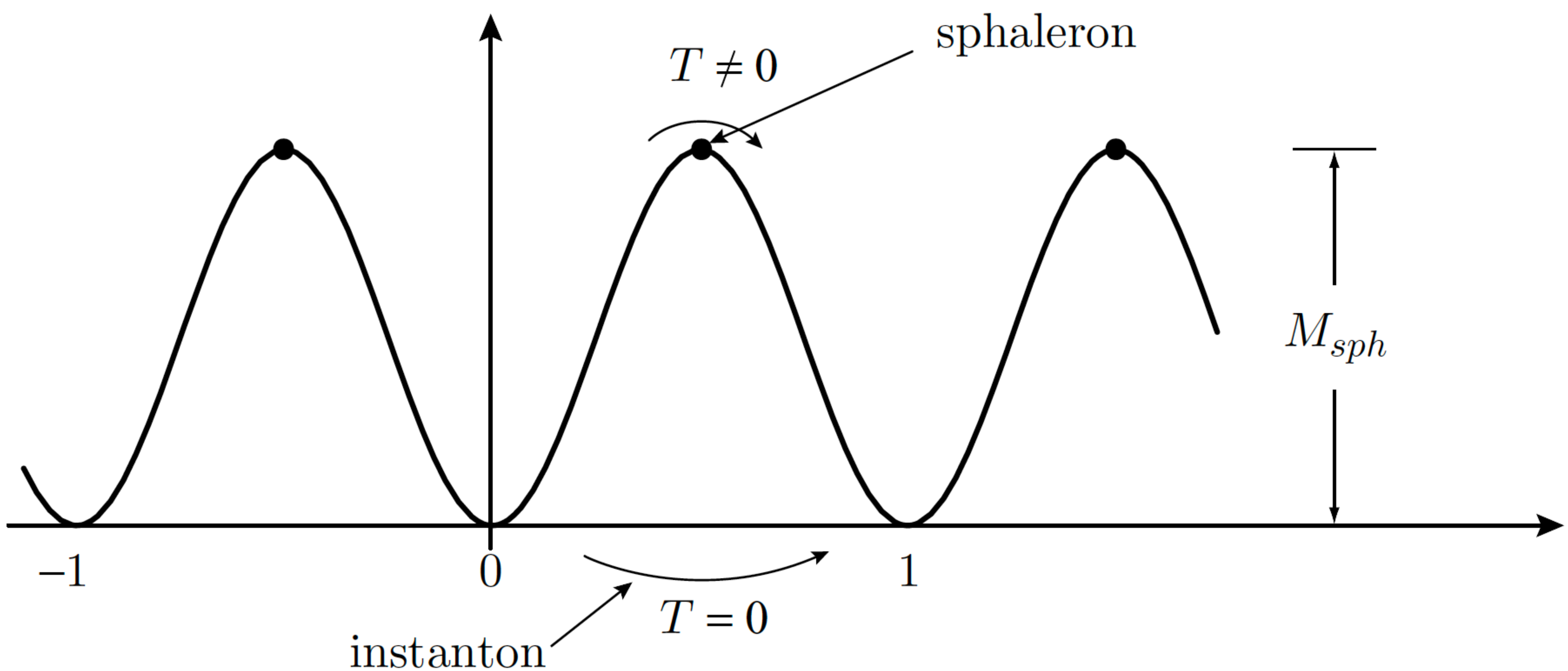
Reheating temperature $M_P/\xi < T_{\text{reheating}} < M_P/\sqrt{\xi}$

Problems during reheating

Instanton, sphaleron process

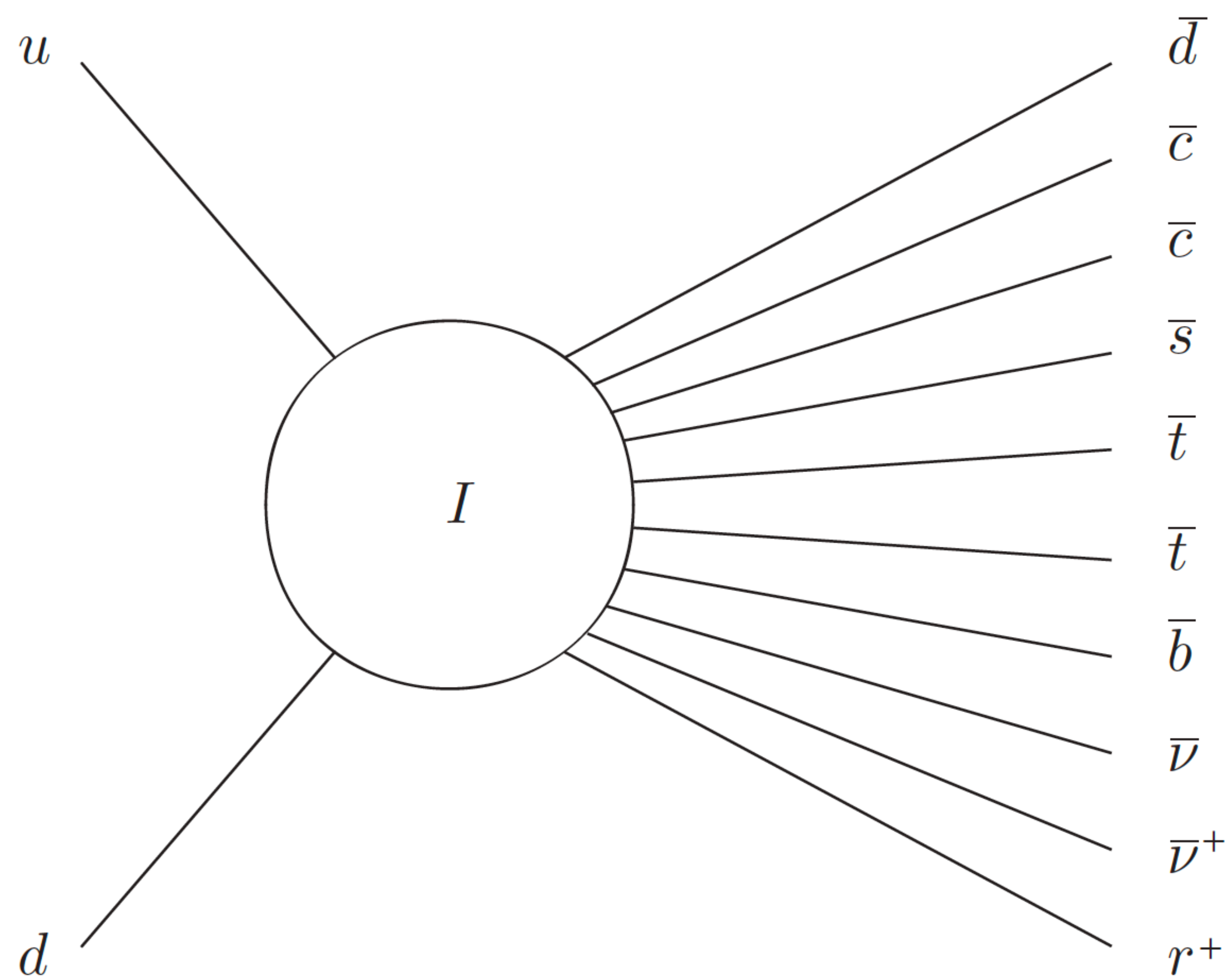
Effective for T> 100 GeV

$$\exp\left(-\frac{M_{sph}(T)}{T}\right) \sim \exp\left(-2\pi\frac{M_W(T)}{\alpha_w T}\right)$$



$$\Gamma \propto \exp\left(-\frac{4\pi}{\alpha}\right)$$

Instanton, sphaleron



Baryon asymmetry via leptogenesis

1. the sphaleron interactions themselves:

$$\sum_i (3\mu_{q_i} + \mu_{\ell_i}) = 0$$

2. a similar relation for QCD sphalerons:

$$\sum_i (2\mu_{q_i} - \mu_{u_i} - \mu_{d_i}) = 0.$$

3. vanishing of the total hypercharge of the universe:

$$\sum_i \left(\mu_{q_i} - 2\mu_{\bar{u}_i} + \mu_{\bar{d}_i} - \mu_{\ell_i} + \mu_{\bar{e}_i}\right) + \frac{2}{N}\mu_H = 0$$

4. the quark and lepton Yukawa couplings give relations:

$$\mu_{q_i} - \mu_\phi - \mu_{d_j} = 0, \quad \mu_{q_i} - \mu_\phi - \mu_{u_j} = 0, \quad \mu_{\ell_i} - \mu_\phi - \mu_{e_j} = 0.$$

$$B = \frac{8N + 4}{22N + 13}(\mathcal{B} - \mathcal{L})_i$$

Adding non-minimal coupling

Similar idea of Higgs inflation

Bezrukov and Shaposhnikov, Phys.Lett.B 659 (2008) 703-706

$$S_J = \int d^4x\sqrt{-g_J}\left[\frac{M_P^2}{2}\left(1+\frac{\xi\phi^2}{M_P^2}\right)R_J - \frac{1}{2}|\partial_\mu\phi|^2 - V_J(\phi)\right]$$

Weyl transformation

$$g_{\mu\nu} = \Omega(\phi)^2 g_{J\mu\nu} \qquad \Omega^2 = 1 + \frac{\xi\phi^2}{M_P^2}$$

$$R_J = \Omega^2\left(R + 6\Box\ln\Omega - 6g^{\mu\nu}\partial_\mu\ln\Omega\,\partial_\nu\ln\Omega\right)$$

Adding non-minimal coupling

$$\frac{d\chi}{d\phi} = \left(\frac{1 + \xi(1+6\xi)\phi^2/M_P^2}{(1+\xi\phi^2/M_P^2)^2} \right)^{1/2}$$

$$S = \int d^4x \sqrt{-g} \left[\frac{M_P^2}{2} R - \frac{1}{2} g^{\mu\nu} \partial_\mu \chi \partial_\nu \chi - V(\chi) \right]$$

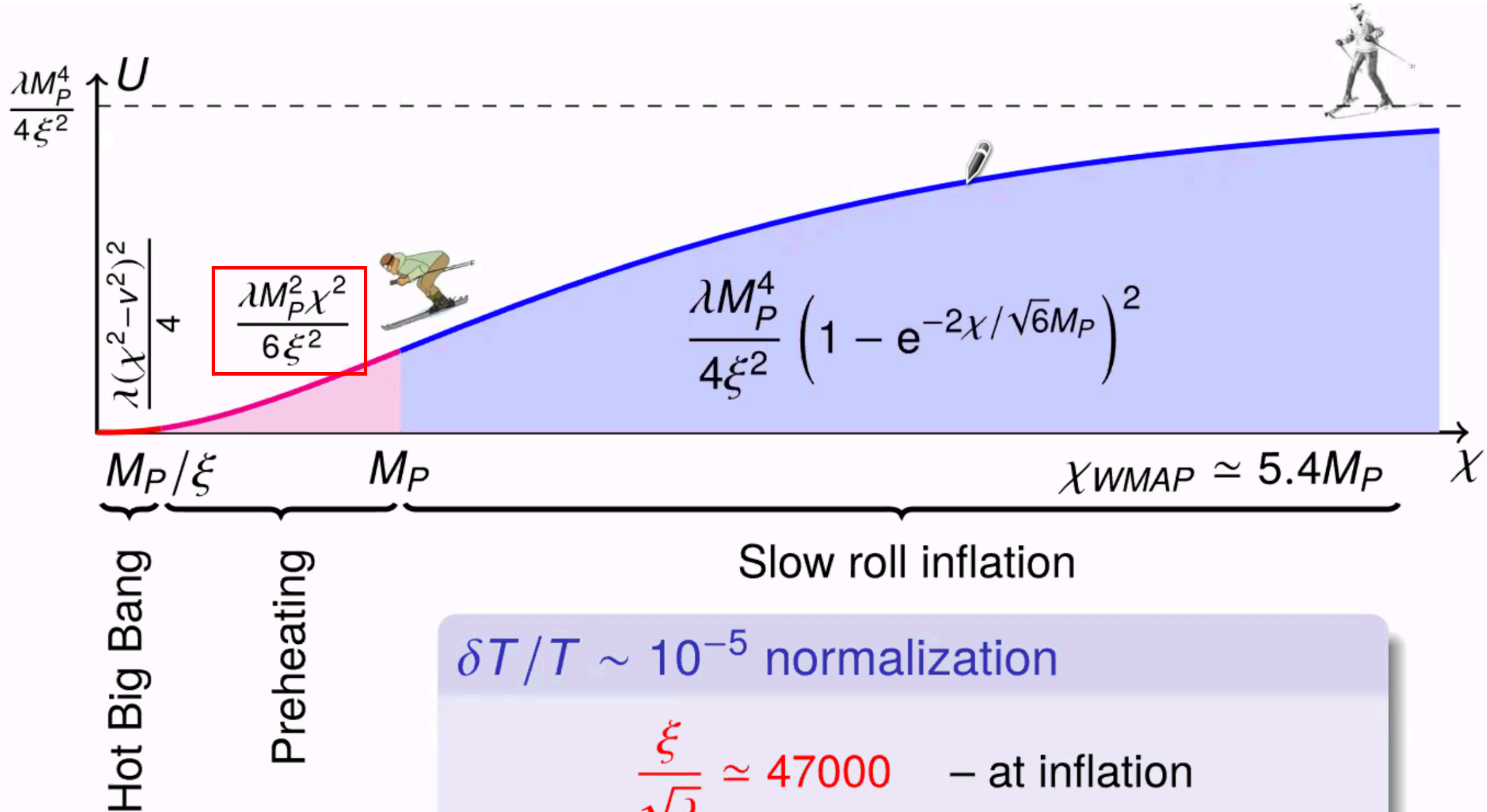
$$V(\chi) \equiv V_J(\phi(\chi))/\Omega^4(\phi(\chi)) \qquad \Omega^2 = 1 + \frac{\xi\phi^2}{M_P^2}$$

$$V_J = \frac{\lambda}{4}\phi^4 \xrightarrow{M_p/\xi \ll \phi < M_p} V = \frac{\lambda}{4\xi^2} M_p^4$$

Potential becomes flat when chi(phi) becomes large

Adding non-minimal coupling

Plot borrowed from Bezrukov



$\delta T/T \sim 10^{-5}$ normalization

$$\frac{\xi}{\sqrt{\lambda}} \simeq 47000 \quad \text{– at inflation}$$

Small λ is traded for large ξ

Adding non-minimal coupling

Prediction of the model

$$n_s \simeq 1 - \frac{2}{N_*} \ , \quad \text{and} \quad r \simeq \frac{12}{N_*^2}$$

$$0.96 \lesssim n_s \lesssim 9.667$$
$$0.0033 \lesssim r \lesssim 0.0048$$

Current observation

$$n_s = 0.9649 \pm 0042 \quad (68\%\text{C.L.})$$
$$r_{0.002} < 0.056 \quad (95\%\text{C.L.})$$

What is phi? SUSY case

- Many scalars take B/L charge
- Flat directions(quartic coupling vanish)

Baryogenesis from Flat Directions of the Supersymmetric Standard Mode
M. Dine, L. Randall, S. Thomas, Nucl.Phys.B458:291-326,1996

	$B-L$
$H_u H_d$	0
$L H_u$	-1
$\bar{u}\bar{d}\bar{d}$	-1
$QL\bar{d}$	-1
$LL\bar{e}$	-1
$QQ\bar{u}\bar{d}$	0
$QQQL$	0
$QL\bar{u}\bar{e}$	0
$\bar{u}\bar{u}\bar{d}\bar{e}$	0

$$\langle \phi_i \rangle = \frac{1}{\sqrt{n}} \phi$$

$$V = m^2 |\phi|^2 + \left[\frac{A}{M^{n-3}} \phi^n + h.c \right]$$

m, A term from SUSY breaking

Affleck-Dine mechanism for SUSY

For example,

$$H_u = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \phi \end{pmatrix}, \quad L = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi \\ 0 \end{pmatrix}$$

$$H_u^0 = \phi \sin\alpha \qquad L^0 = \phi \cos\alpha \qquad \alpha = \frac{\pi}{4}$$

$$W = \frac{1}{M}(LH_u)^2 = \frac{1}{2M}\phi^4 \qquad M \sim 10^{15}\ \mathrm{GeV}$$

Weinberg operator in SUSY version, giving neutrino masses

Affleck-Dine mechanism for SUSY

Including the SUSY breaking (supergravity mediation)

$$V(\phi) = m^2|\phi|^2 + \boxed{(\frac{2A}{M}\phi^4 + h.c)} + \frac{4}{M^2}|\phi|^6$$

U(1)L breaking term

m, A are SUSY breaking parameters $m, A \sim m_{3/2}$

Affleck-Dine mechanism

Equation of motion in an expansion of universe

$$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V}{\partial \phi^*} = 0$$

An approximation

Only from U(1) breaking term

$$\dot{n}_B + 3Hn_B = \boxed{\mathrm{Im}\left(\phi \frac{\partial V}{\partial \phi}\right)}$$

At $t_0 = 1/H \sim 1/m$ $\quad V = \frac{1}{2}m^2|\phi|^2 + [c_n\phi^n + h.c]$

$$n_{B0} \sim \frac{nc_n\phi^n}{m} \sim \frac{nc_n\rho^n \boxed{\sin n\theta_0}}{2^{n/2}m} \qquad n_B \sim n_{B0}\left(\frac{a_0}{a}\right)^3$$

Importance of flat direction(scalars during inflation)

$$V(\phi) = \frac{1}{2}m^2|\phi|^2 + [c_{n,m}\phi^n(\phi^*)^m + h.c] \quad m \neq n$$

Equilibrium state of a self-interacting scalar field in the De Sitter background,
Starobinsky and Yokoyama, 94'

$$m \ll H_{inf} \qquad \langle\phi^2\rangle = \frac{3H_{inf}^4}{8\pi^2 m^2}\left(1 - e^{-\frac{2m^2}{3H^2}t}\right)$$

Correlation length $R_c = \frac{1}{H_{inf}} \exp\left(\frac{3}{2}\log 2\frac{H_{inf}^2}{m^2}\right)$

$m < 0.01H_{inf}$ ϕ_0 θ_0 as a constant in our universe

Small m is also preferred by limit of baryonic isocurvature

Importance of flat direction(scalars during inflation)

For a general model without supersymmetry

$$V(\phi) = \frac{1}{2}m^2|\phi|^2 + \lambda|\phi|^4 + [c_{n,m}\phi^n(\phi^*)^m + h.c] \quad m \neq n$$

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$$\langle\phi^2\rangle = 0.13\lambda^{-1/2}H_{inf}^2$$

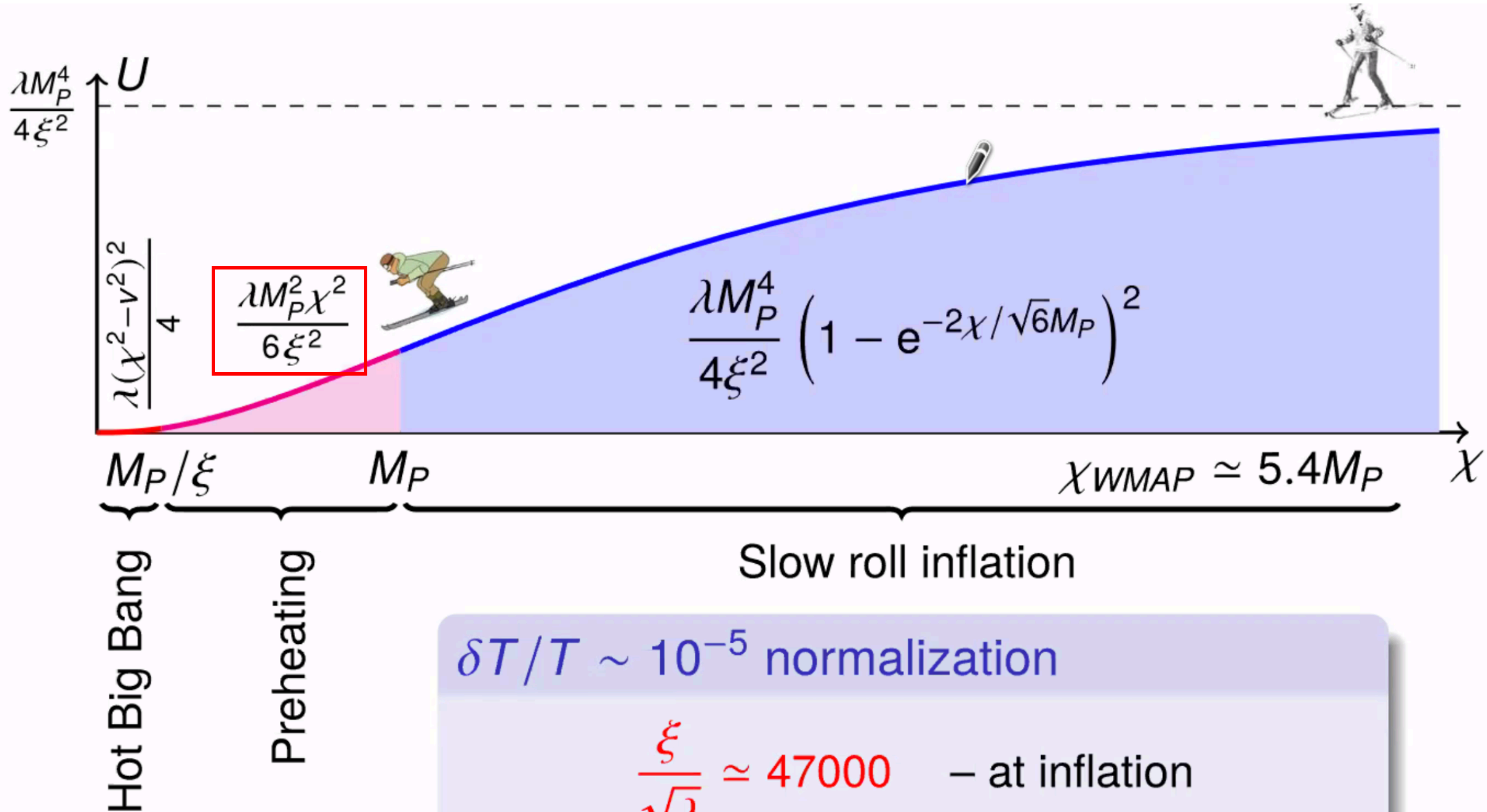
$$R_c \approx \frac{1}{H_{inf}} \exp\left(3.8\lambda^{-1/2}\right)$$

$\lambda \sim 0.1$ θ_0 is random distributed

Different patches of universe different baryon number, average close 0

Adding non-minimal coupling

Plot borrowed from Bezrukov



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