Inflation in $f(\mathscr{R}, \Phi)$ Gravity and Leptogenesis and Dark Matter Production During Reheating

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From Big Bang to Now : A Theory-Experiment Dialogue

January 23, 2025

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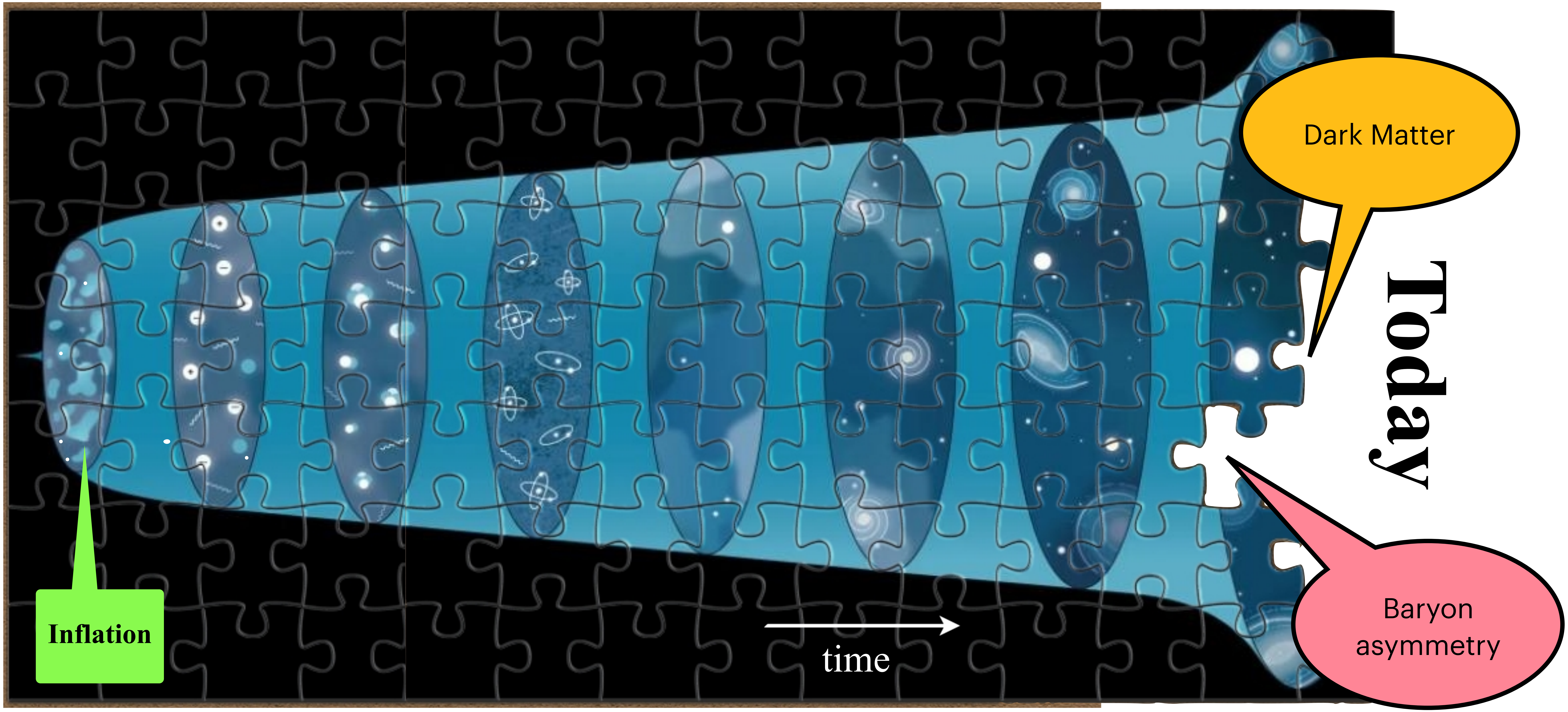
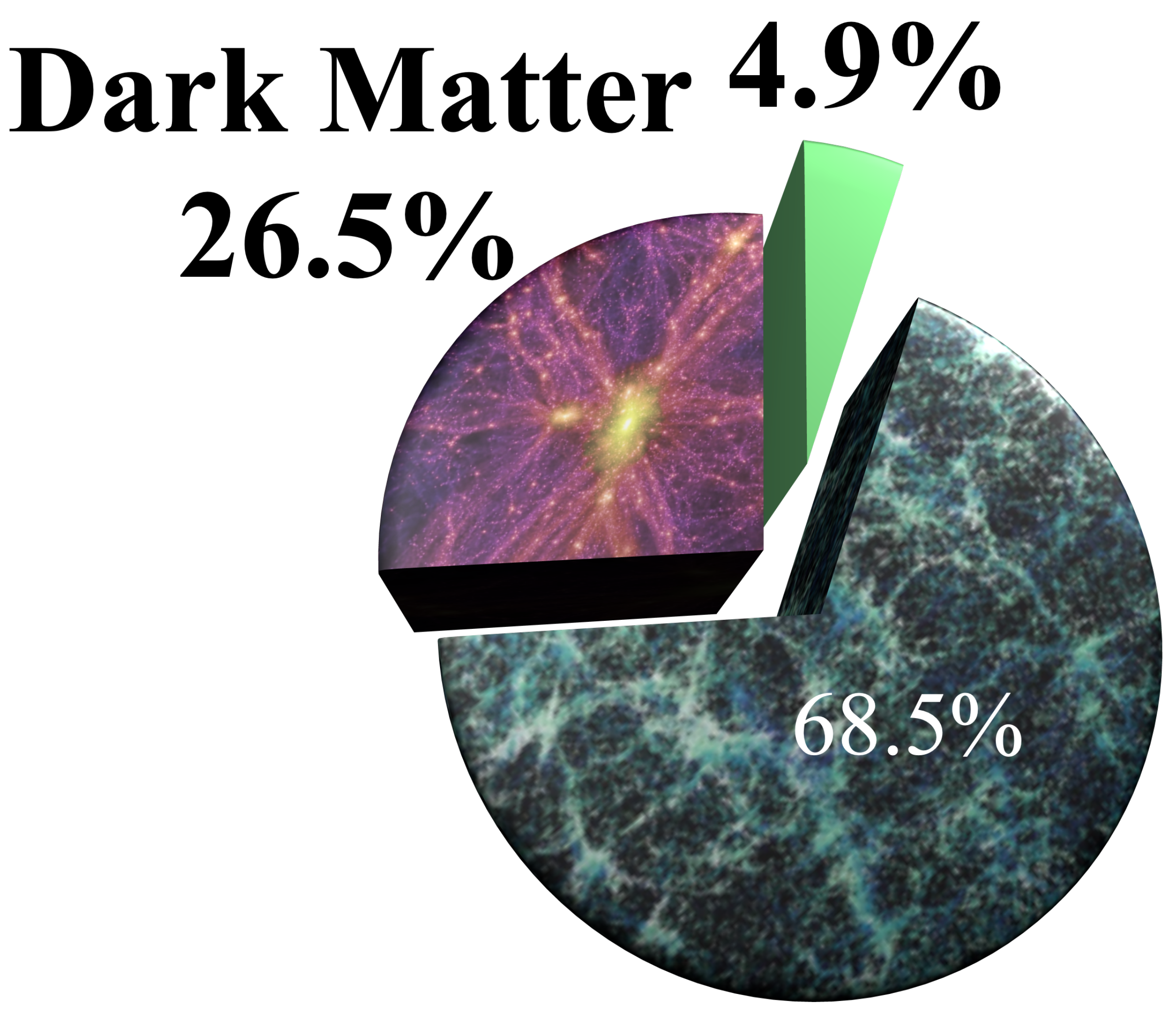
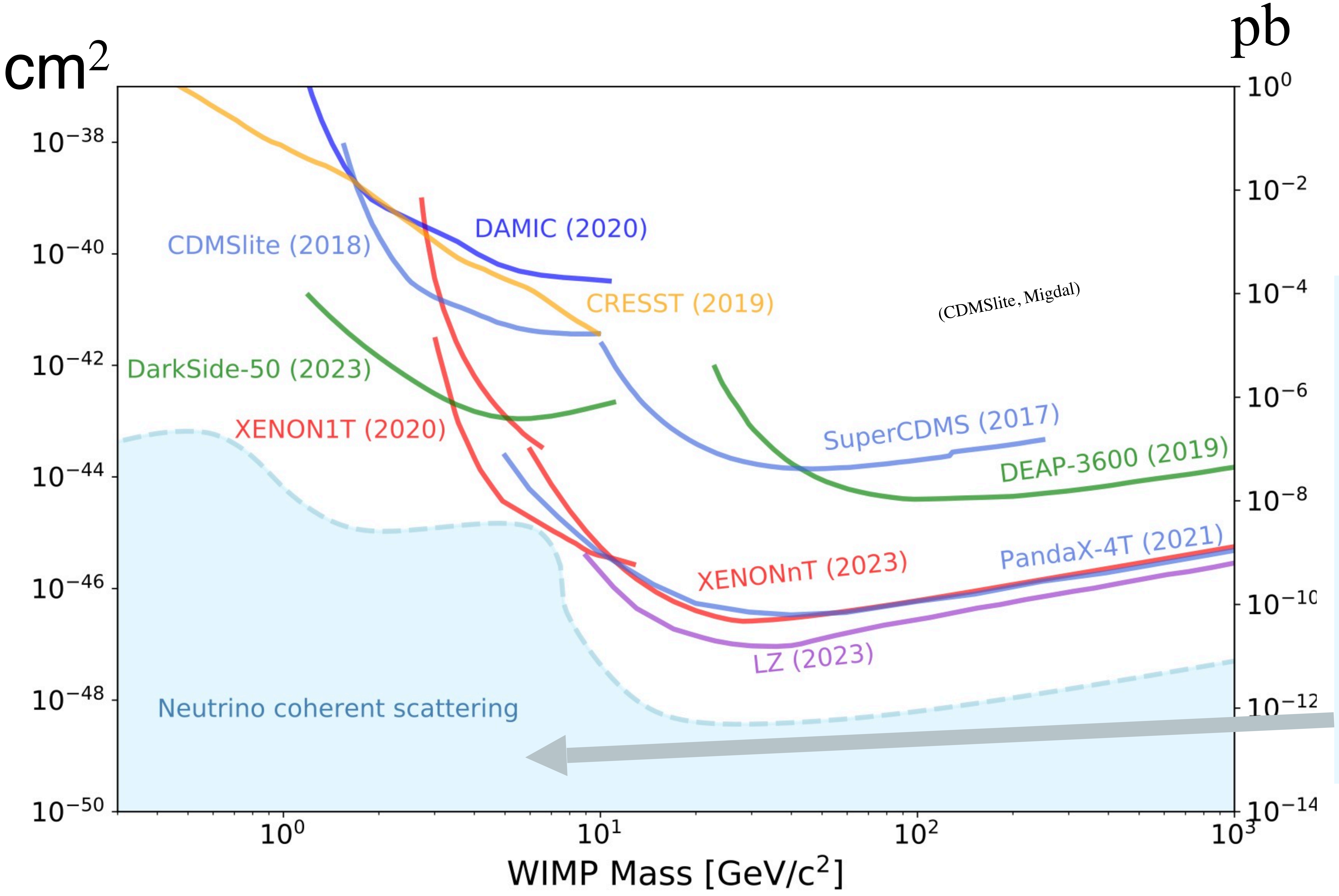
SCHOOL OF NATURAL SCIENCES

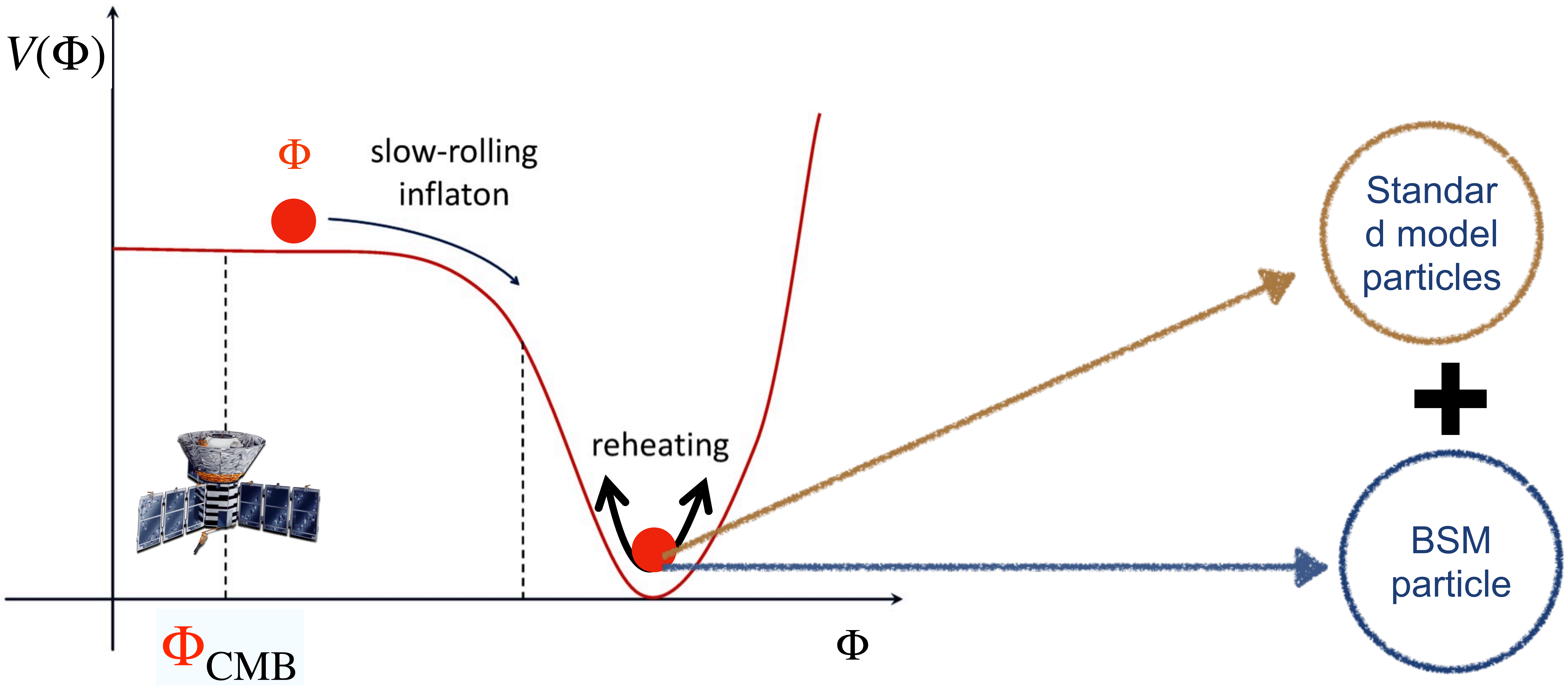

Dark Matter
Today
Inflation
time
Baryon
asymmetry



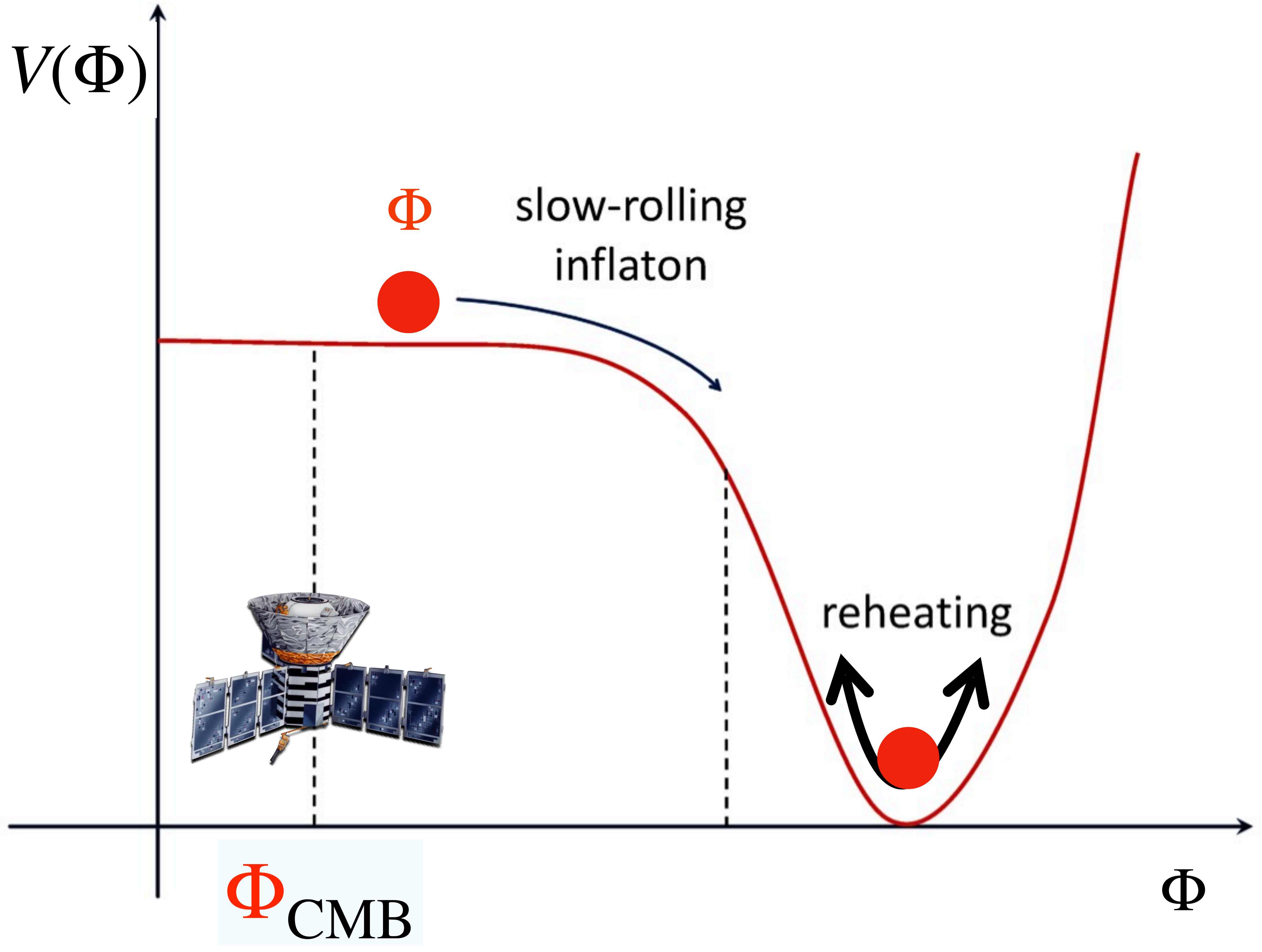


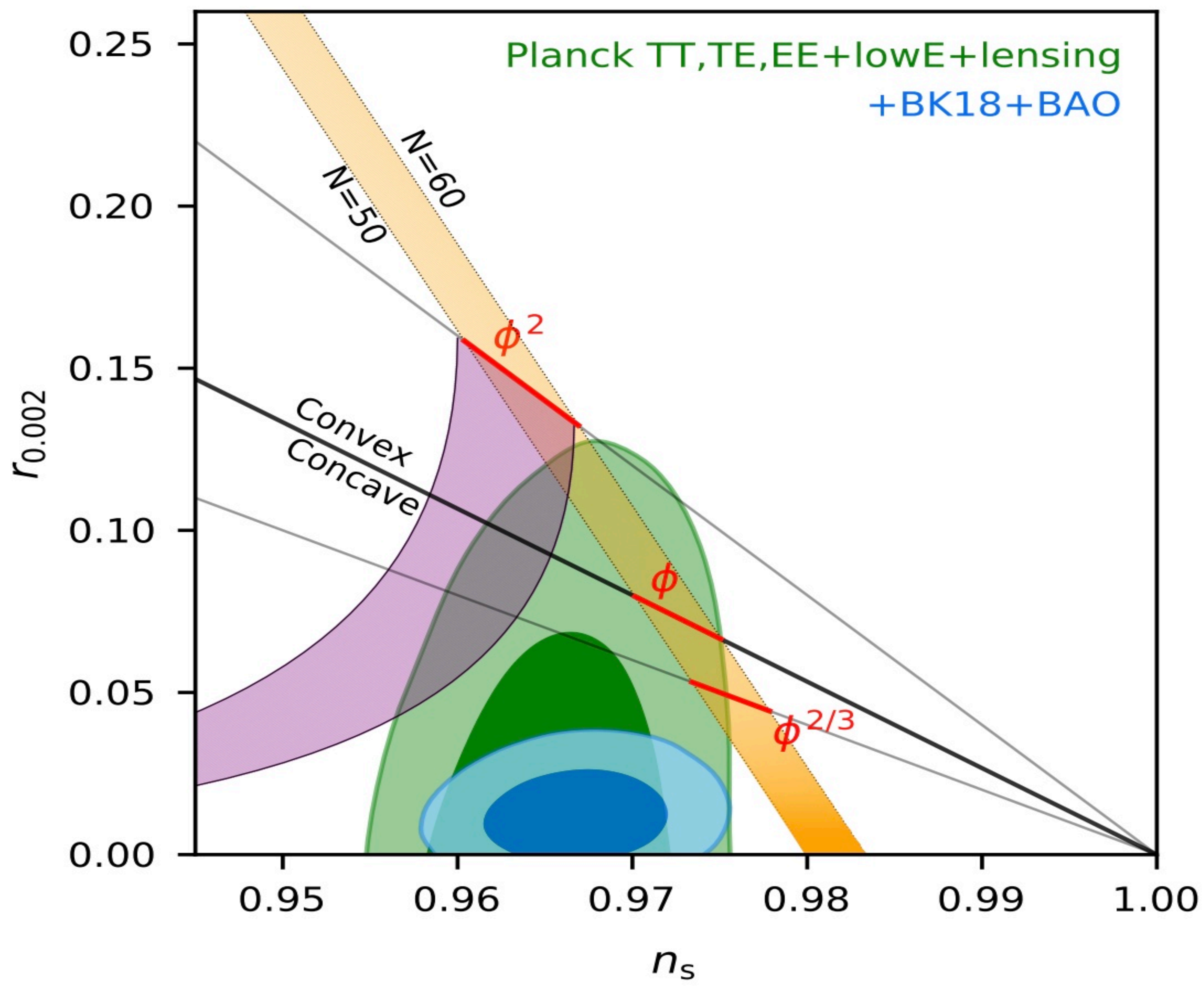
neutrino coherent **scattering** from solar neutrinos, atmospheric neutrinos and diffuse supernova neutrinos will dominate.

thermal WIMP is no loger the favorite one



$V(\Phi)$
Φ
slow-rolling inflaton
reheating
Φ_{CMB}
Φ
Standard model particles
+
BSM particle





$$\mathscr{P}_s(k) = A_s\left(\frac{k}{k_*}\right)^{n_s-1+(1/2)\alpha_s\ln(k/k_*)+(1/6)\beta_s(\ln(k/k_*))^2}$$

$$\mathscr{P}_t(k) = A_t\left(\frac{k}{k_*}\right)^{n_t+(1/2)dn_t/d\ln k\ln(k/k_*)+\cdots}$$

$$r = \frac{A_t}{A_s}$$

$$\mathcal{S} = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{\alpha}{2}\mathscr{R}^2 + \frac{1}{2}G(\Phi)\mathscr{R} - \frac{1}{2}g^{\mu\nu}\partial_\mu\Phi\,\partial_\nu\Phi - V(\Phi)\right]$$

$$V(\Phi) = \frac{1}{4}\lambda(\Phi)\Phi^4 + \Lambda^4$$

$$\lambda(\Phi) \simeq \lambda(v_\Phi) + \beta(v_\Phi)\ln\left(\frac{\Phi}{v_\Phi}\right) + \cdots$$

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

$$\mathcal{S} = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{\alpha}{2}\mathscr{R}^2 + \frac{1}{2}G(\Phi)\mathscr{R} - \frac{1}{2}g^{\mu\nu}\partial_\mu\Phi\,\partial_\nu\Phi - V(\Phi)\right]$$

Auxiliary field $\varphi = 2\alpha\mathscr{R}$

$$\mathscr{L} \supset \frac{1}{2}(\varphi + G(\Phi))\mathscr{R}$$

Weyl transformation: from Jordan to Einstein frame

$$g_{\mu\nu} \to [\varphi + G(\Phi)]g_{\mu\nu} \equiv \zeta^2 g_{\mu\nu}$$

$$\mathcal{S} = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{\alpha}{2}\mathcal{R}^2 + \frac{1}{2}G(\Phi)\mathcal{R} - \frac{1}{2}g^{\mu\nu}\partial_\mu\Phi\,\partial_\nu\Phi - V(\Phi)\right]$$

Auxiliary field $\varphi = 2\alpha\mathcal{R}$

Weyl transformation: from Jordan to Einstein frame $\quad g_{\mu\nu} \rightarrow \zeta^2 g_{\mu\nu}$

metric formalism

Lagrangian contains $\nabla^\mu\zeta\,\nabla_\mu\zeta$

Palatini formalism

No such term

$$\mathcal{S} = \int \mathrm{d}^4x \sqrt{-g}\left[\frac{\alpha}{2}\mathcal{R}^2 + \frac{1}{2}G(\Phi)\mathcal{R} - \frac{1}{2}g^{\mu\nu}\partial_\mu\Phi\,\partial_\nu\Phi - V(\Phi)\right]$$

Auxiliary field $\zeta = 2\alpha\mathcal{R}$

Weyl transformation: from Jordan to Einstein frame

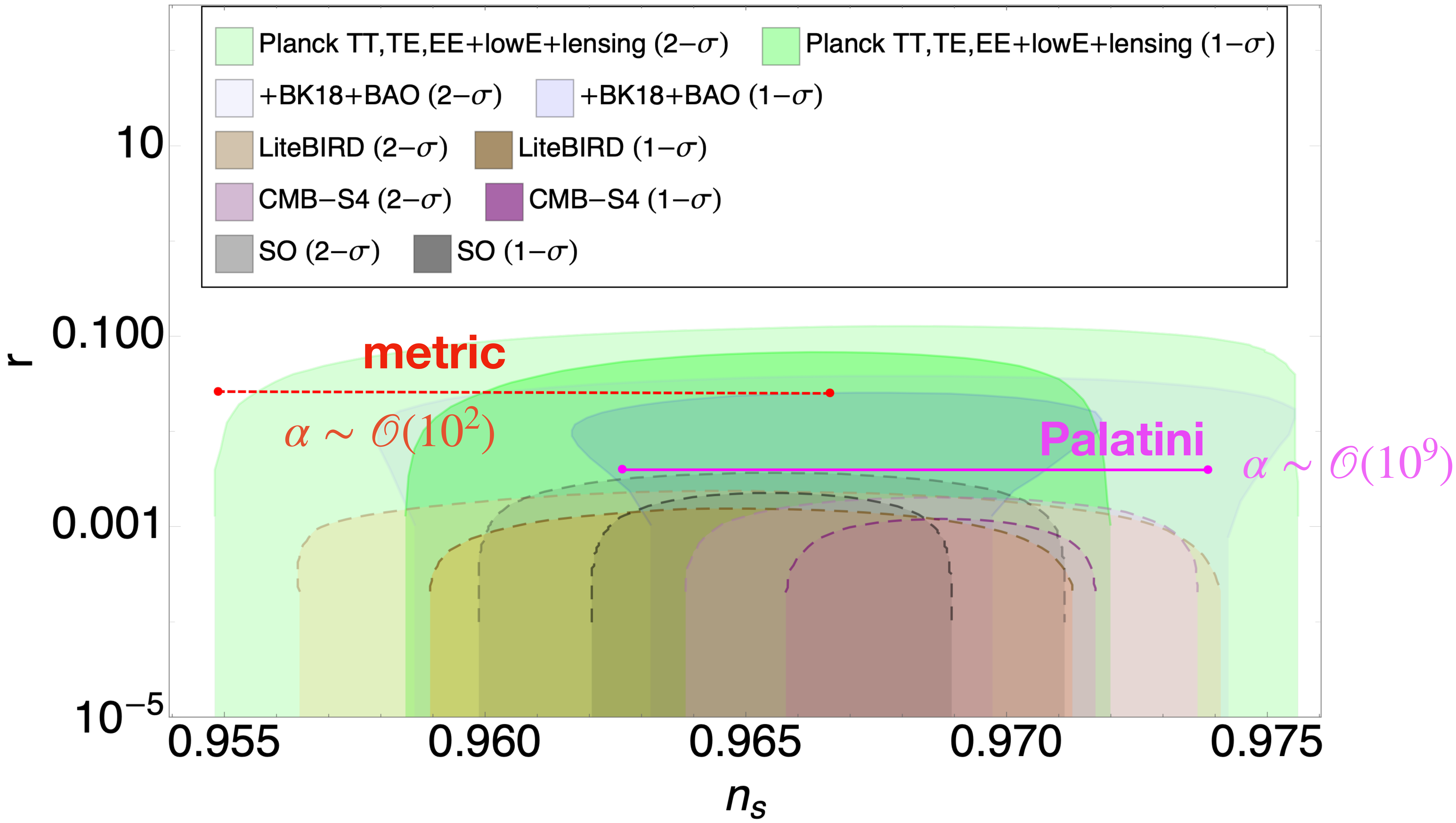
metric formalism

Lagrangian contains $\nabla^\mu\zeta\nabla_\mu\zeta$

Single field inflation

Palatini formalism

No such term


Planck TT,TE,EE+lowE+lensing (2−σ)
Planck TT,TE,EE+lowE+lensing (1−σ)
+BK18+BAO (2−σ)
+BK18+BAO (1−σ)
LiteBIRD (2−σ)
LiteBIRD (1−σ)
CMB−S4 (2−σ)
CMB−S4 (1−σ)
SO (2−σ)
SO (1−σ)
metric
$\alpha \sim \mathcal{O}(10^2)$
Palatini
$\alpha \sim \mathcal{O}(10^9)$
r
10
0.100
0.001
10^{-5}
0.955
0.960
0.965
0.970
0.975
n_s

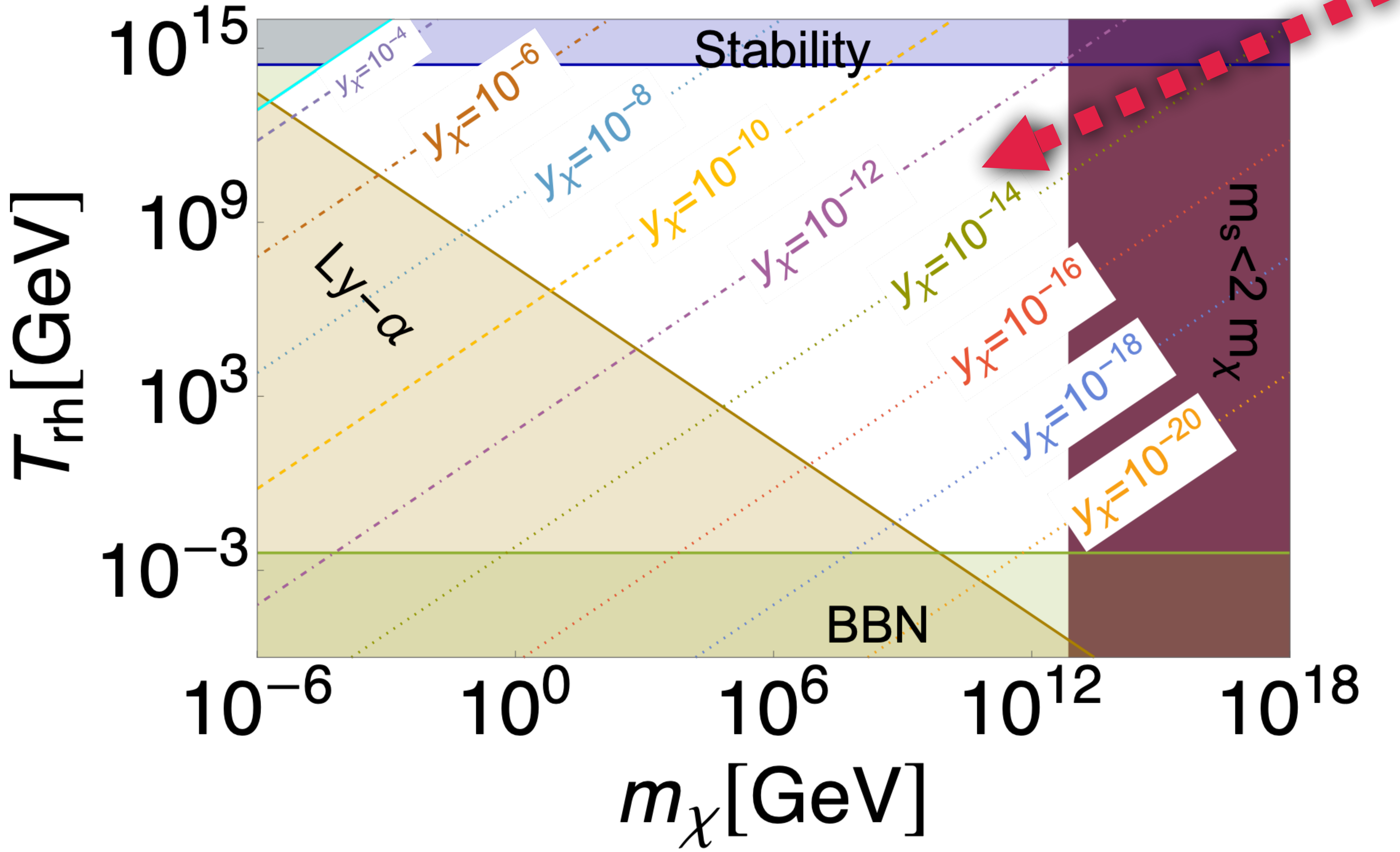
Dark Matter production from decay of inflaton

$$\boxed{\rho_\Phi\big|_{T=T_{rh}} = \rho_{\text{radiation}}\big|_{T=T_{rh}}}$$

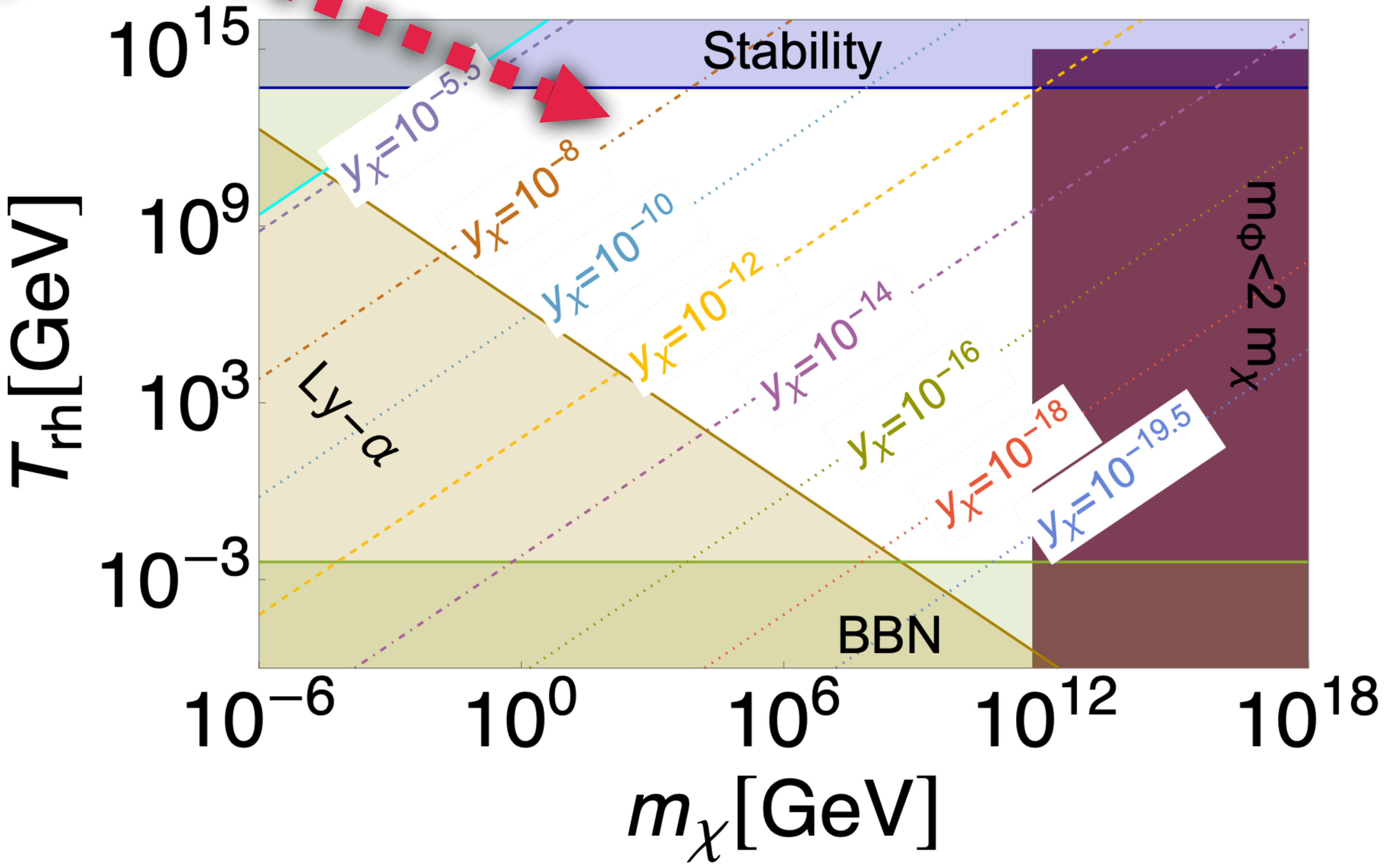
$$\mathscr{L}_{\rm rh} = -y_\chi \phi\bar{\chi}\chi - \lambda_{12}\phi H^\dagger H + \text{h.c.} + \cdots$$

$$T_{\rm rh} \simeq 6.49 \times 10^{25} y_\chi^2 m_\chi$$

metric formalism



Palatini formalism



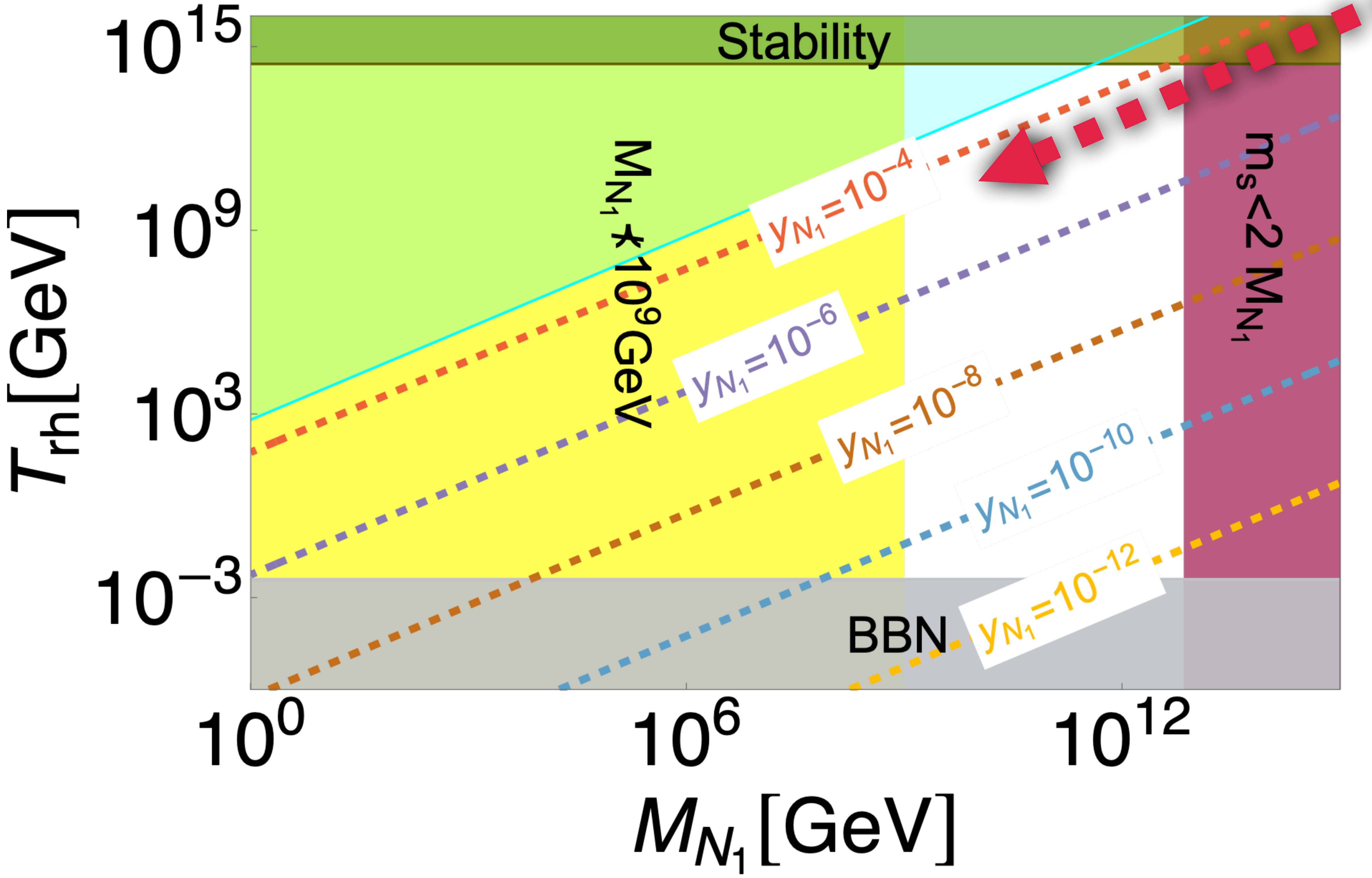
Sterile neutrino production from decay of inflaton

$$\mathscr{L}_{\rm lepto} = i\sum_j \overline{N^c}_j \gamma_\mu \partial^\mu N_j - \frac{1}{2}\overline{N^c}_j M_{N_j} N_j - \sum_{d=e,\mu,\tau}\sum_j \left(\mathscr{Y}_{dj}\overline{\Psi}_{d,L}\widetilde{H} N_j + \text{h.c.}\right) + \mathscr{L}_{\rm reh}$$

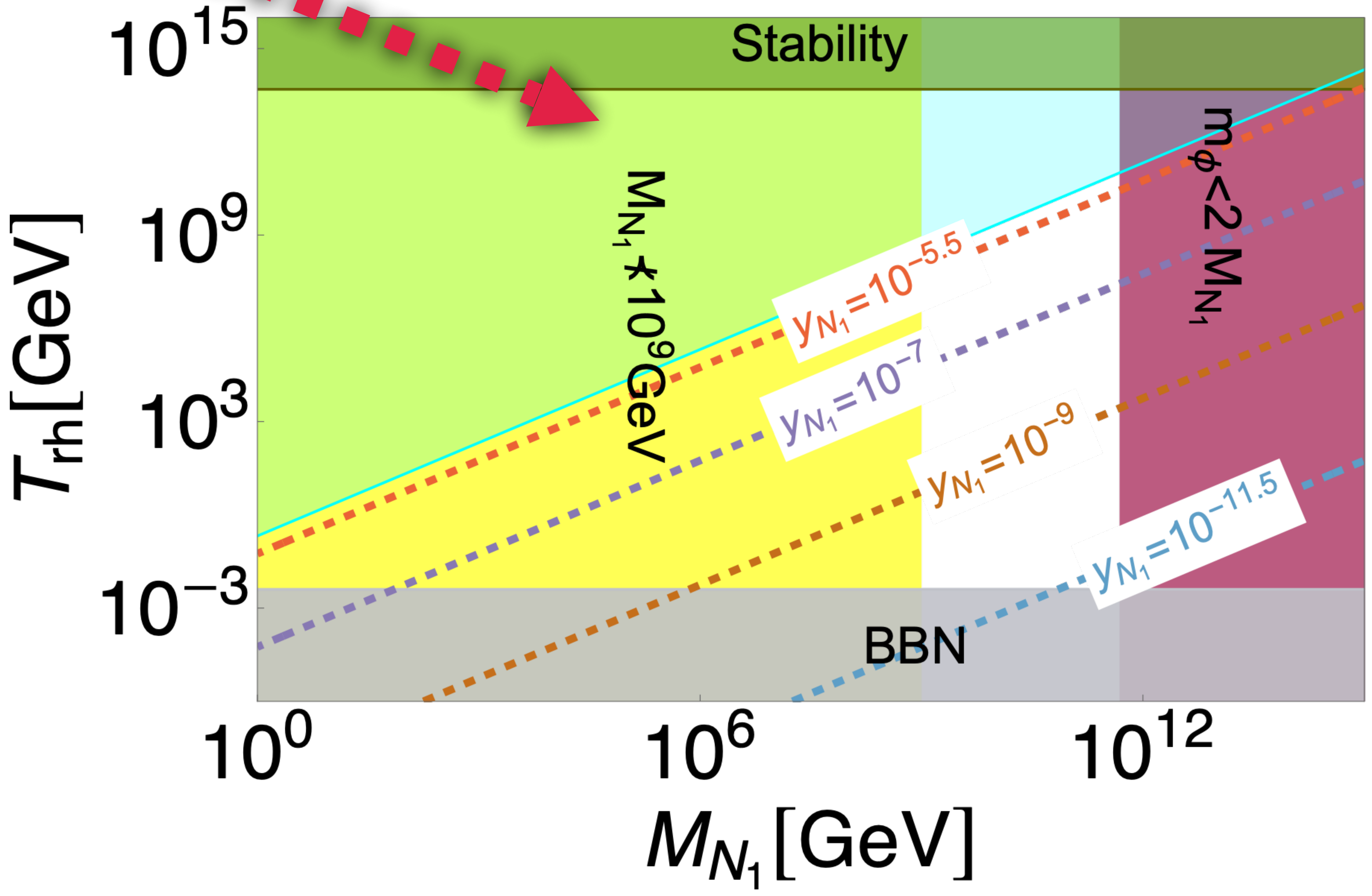
$$\mathscr{L}_{\rm rh} = -\, y_{N_j}\phi \overline{N^c} N_j - \lambda_{12}\phi H^\dagger H + \text{h.c.} + \cdots$$

$$T_{\rm rh} \simeq 5.607 \times 10^9 y_{N_1}^2 m_{N_1}$$

metric formalism

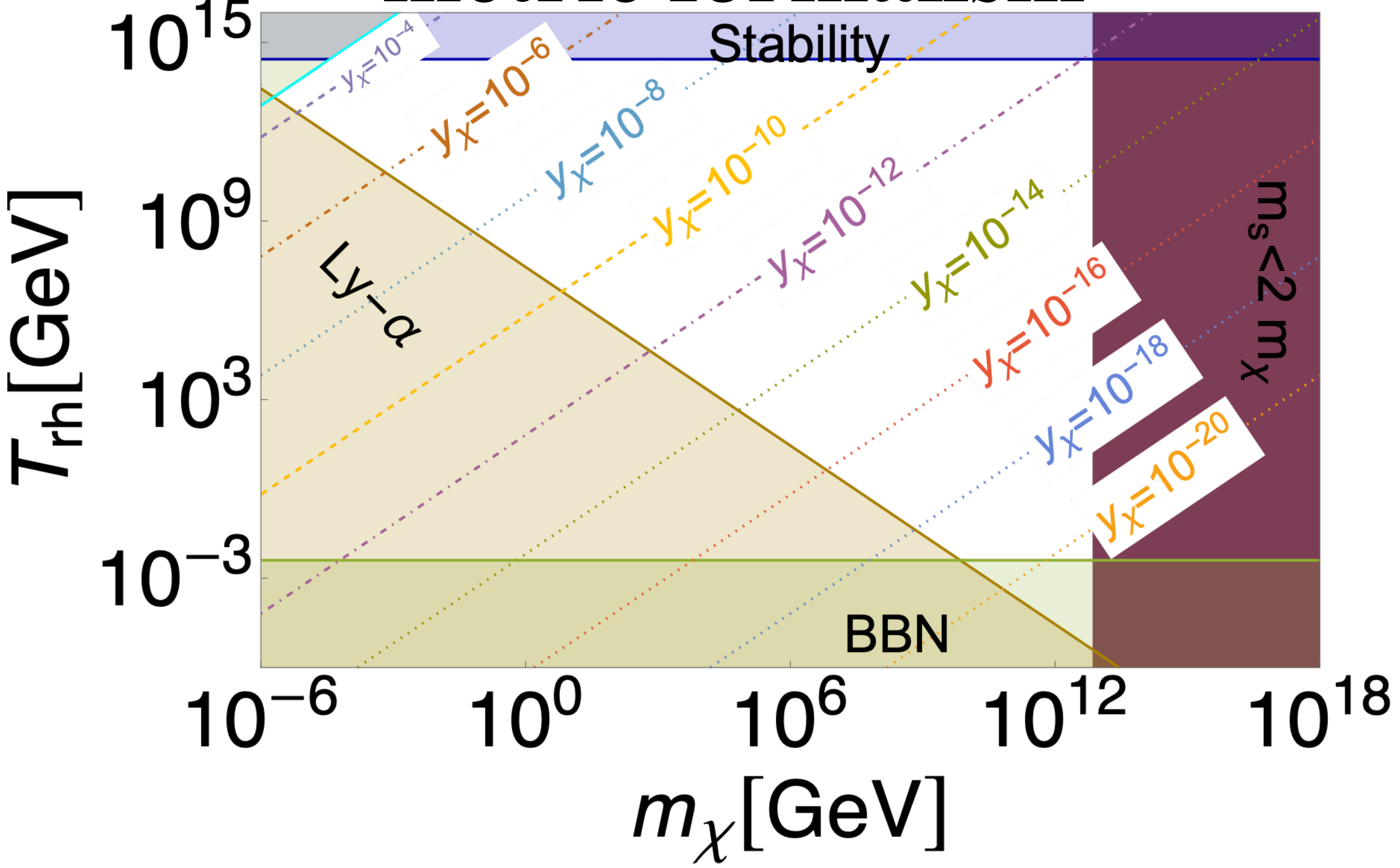


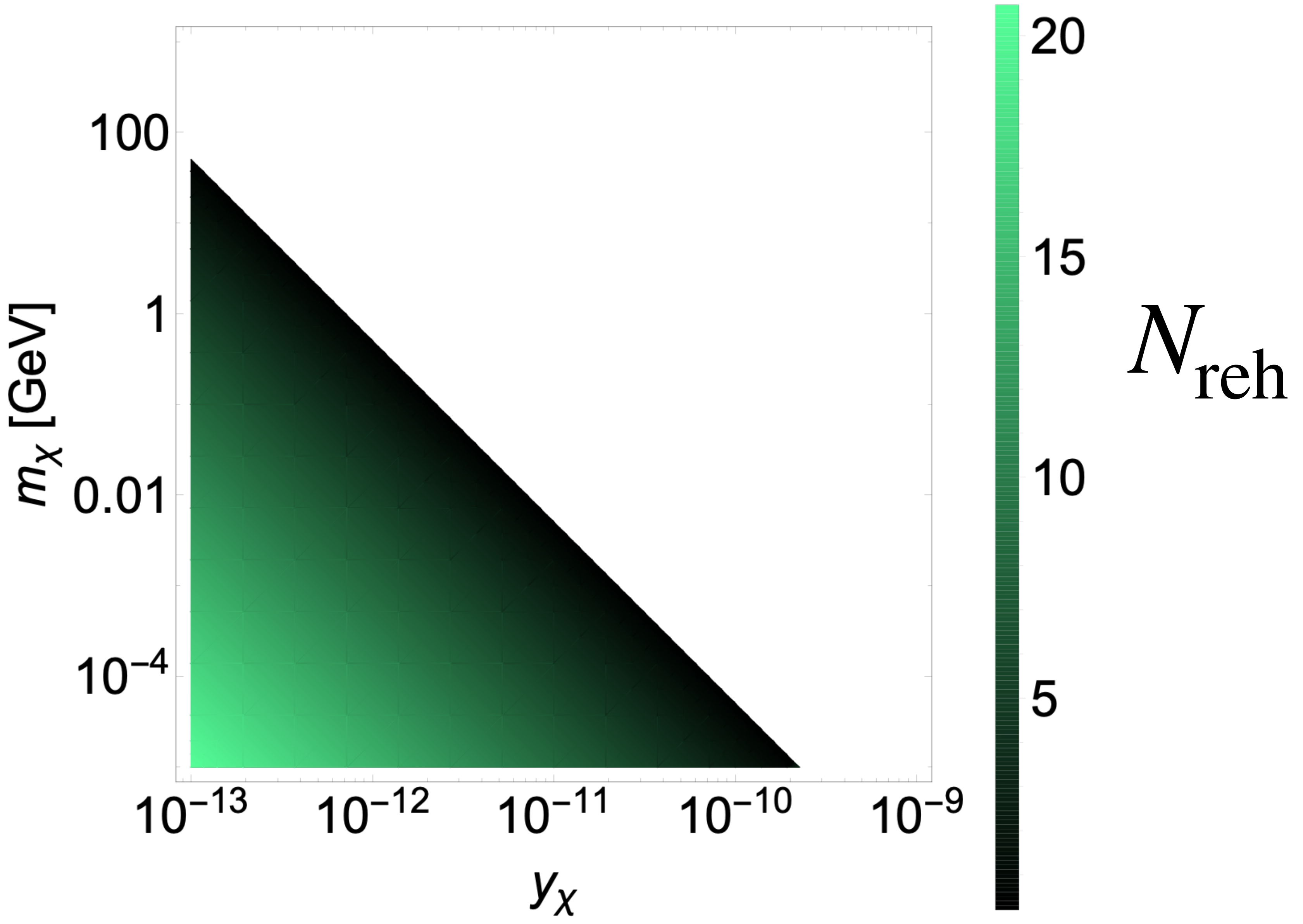
Palatini formalism



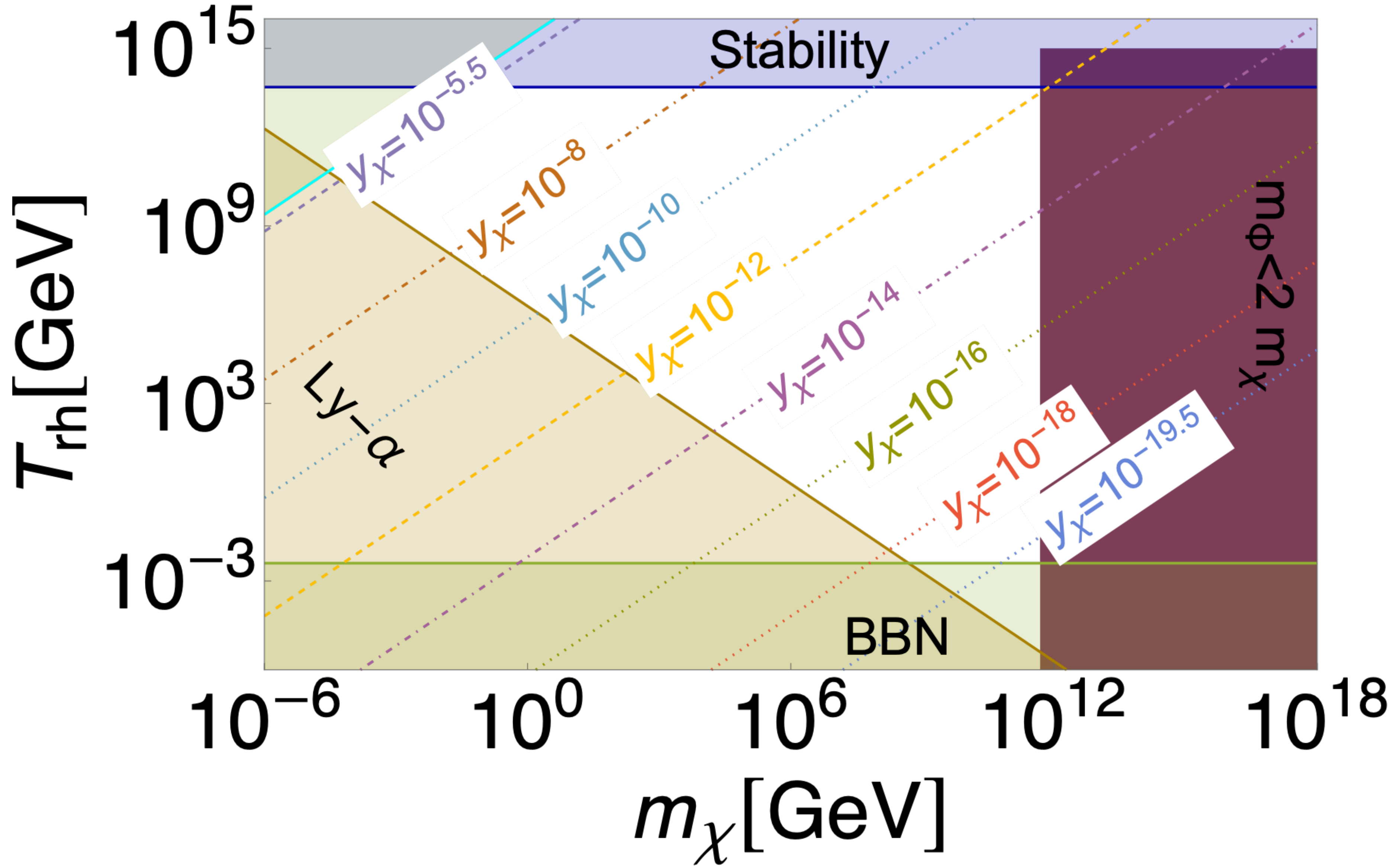
Dark Matter production from decay of inflaton

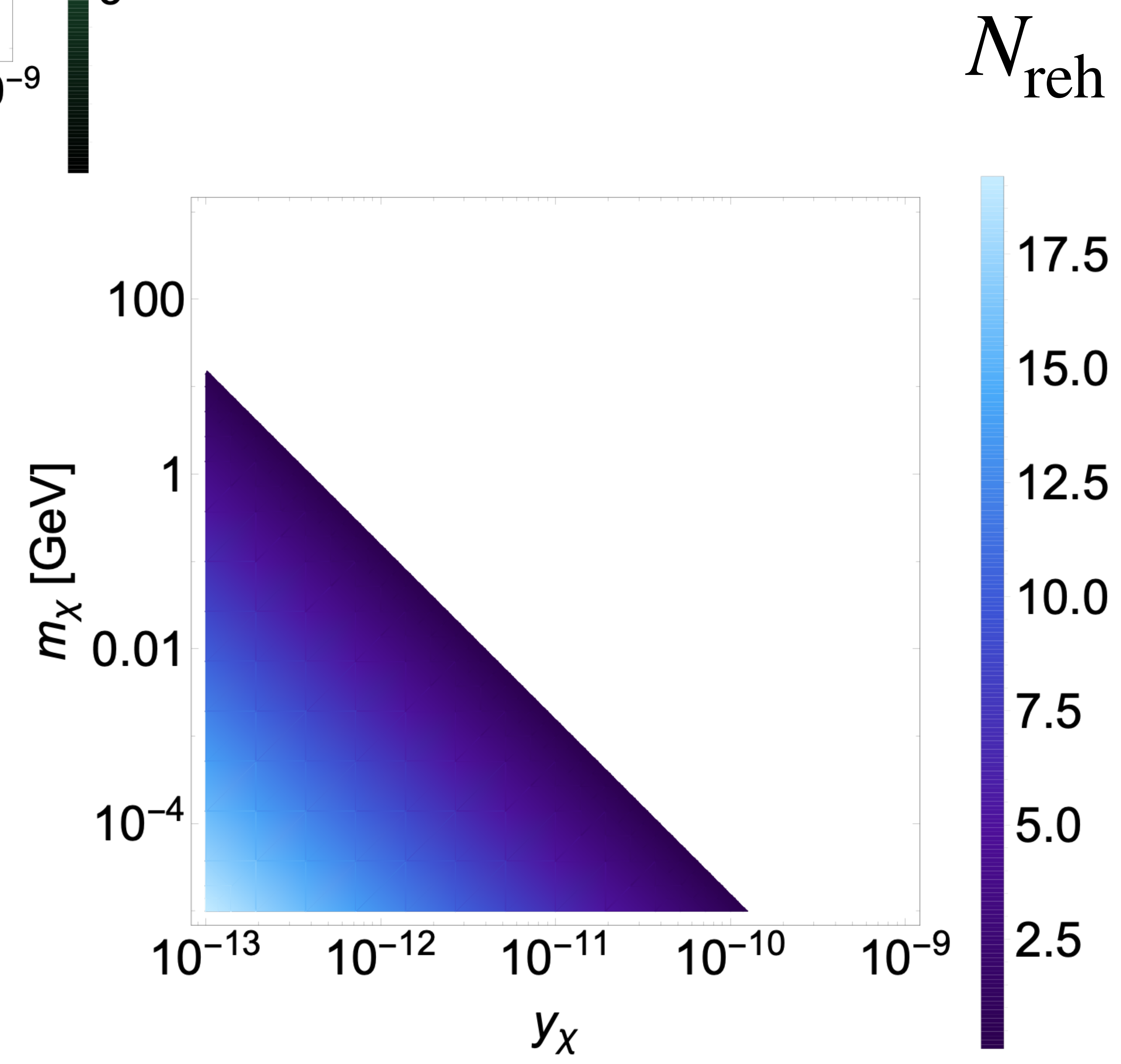
metric formalism





Palatini formalism





Conclusion

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- We incorporated $\mathscr{R}^2$ in the Lagrangian density: predicted values of n_s and r falls within $1-\sigma$ best-fit contour of PLANCK+BICEP data: for metric formalism $\alpha \sim \mathcal{O}(10^2)$ and for Palatini $\alpha \sim \mathcal{O}(10^9)$ is required.

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- A BSM particle χ behaving as DM.
  - metric formalism: $10^{-4} \gtrsim y_\chi \gtrsim 10^{-20}$, for $\mathcal{O}\left(10^{-6}\right)\mathrm{GeV} \lesssim m_\chi \lesssim \mathcal{O}\left(10^{12}\right)\mathrm{GeV}$.
  - Palatini formalism: $10^{-5.5} \gtrsim y_\chi \gtrsim 10^{-19.5}$, for $\mathcal{O}\left(10^{-5}\right)\mathrm{GeV} \lesssim m_\chi \lesssim \mathcal{O}\left(10^{11}\right)\mathrm{GeV}$).
  - Considering finite duration of reheating, the permissible range reduces to

    in metric formalism: $y_\chi \lesssim 10^{-13}$ for $m_\chi \sim \mathcal{O}(100)\mathrm{GeV}$,

    in Palatini formalism: $y_\chi \lesssim 10^{-13}$ for $m_\chi \sim \mathcal{O}(10)\mathrm{GeV}$.

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- Production of sterile neutrino
  - metric formalism: $10^{-4} \gtrsim y_{N_1} \gtrsim 10^{-12}$.
  - Palatini formalism: $10^{-5.5} \gtrsim y_{N_1} \gtrsim 10^{-11.5}$.

Thank You.

I appreciate your time and interest in this presentation