

Marco Drewes, Université catholique de Louvain

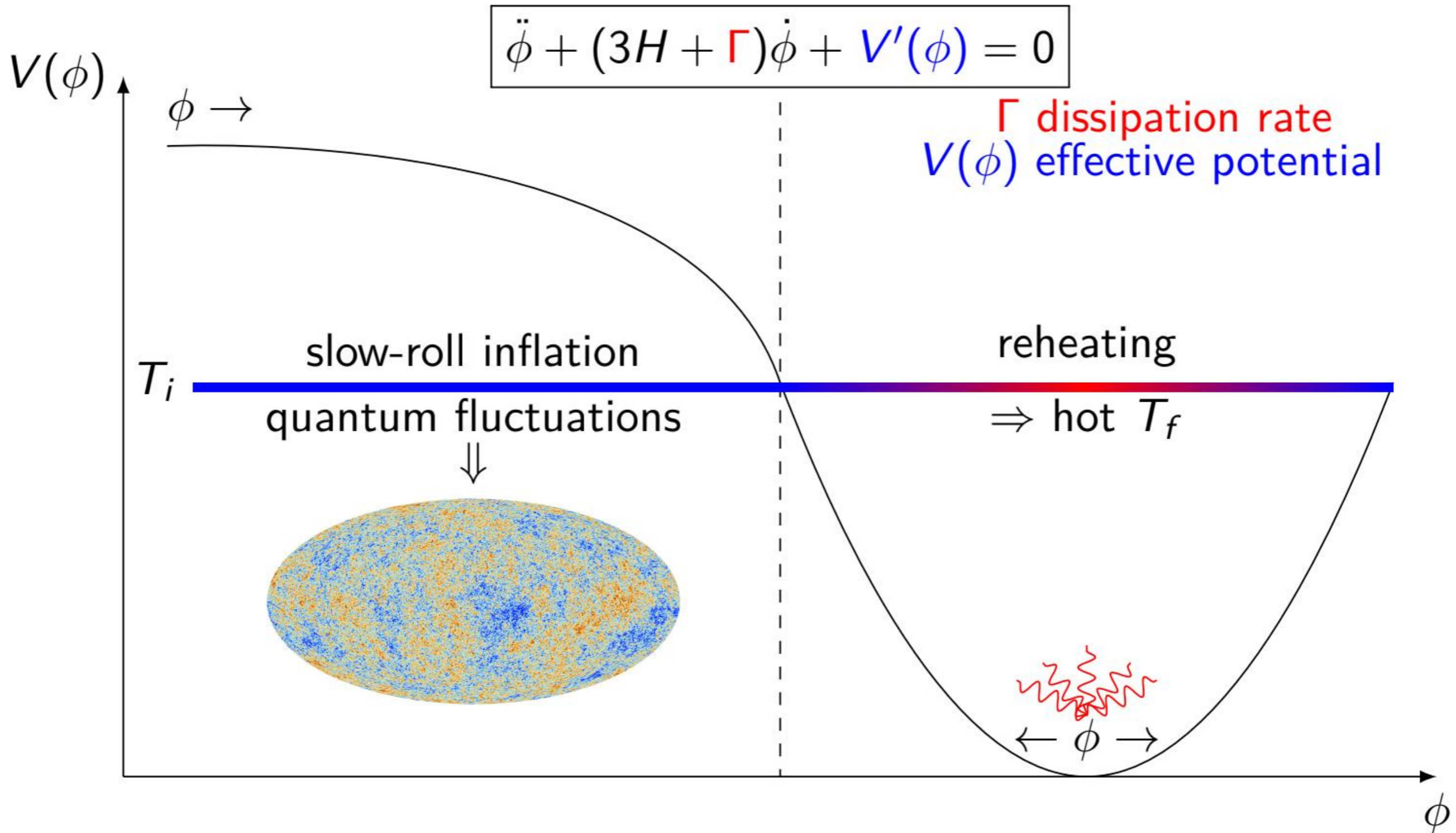
**Connecting Inflation to
Particle Physics with Next
Generation CMB and LSS
Observations**

27.07.2023

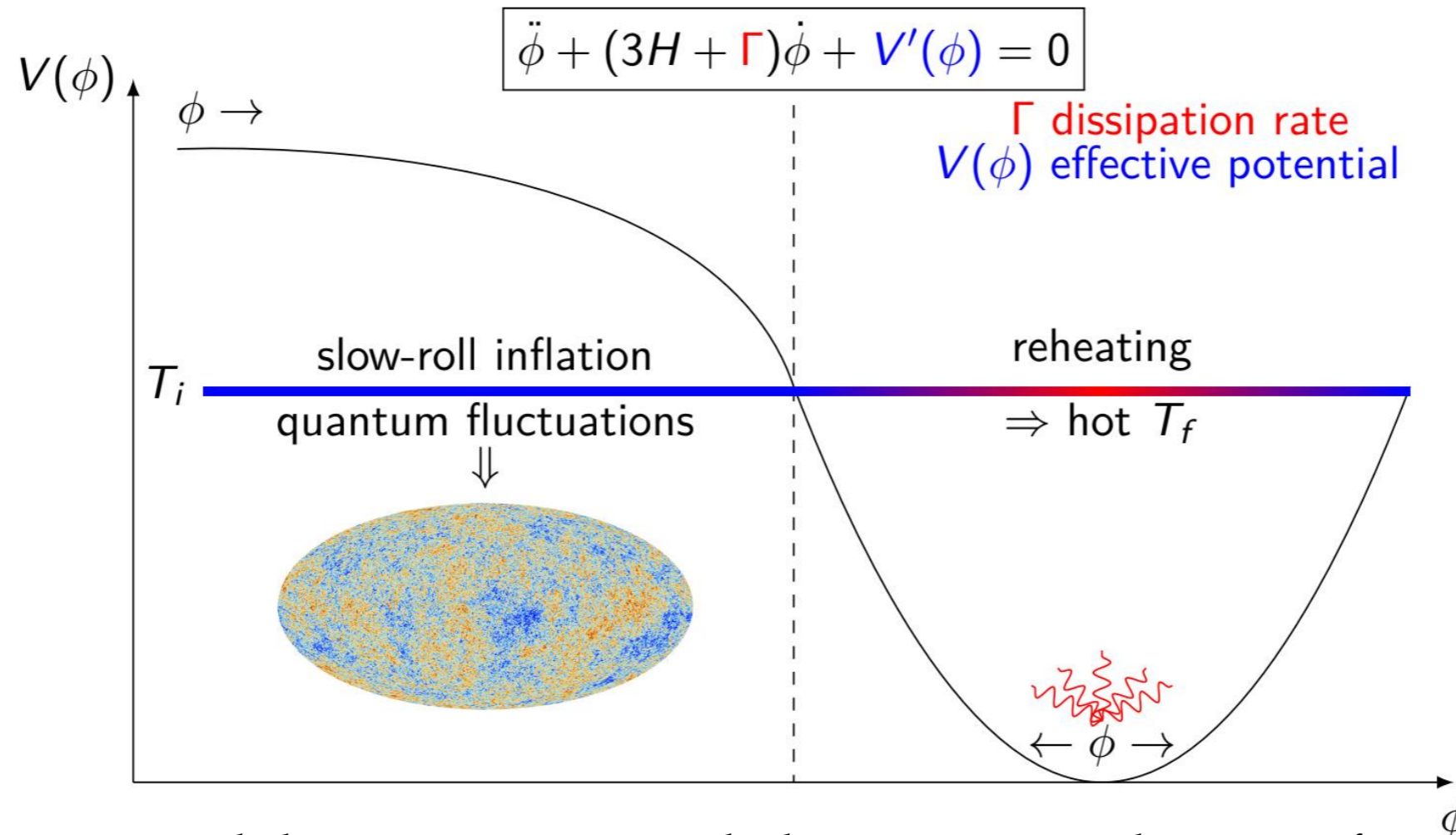
6th CPPC Meeting

Sydney, Australia

Dissipation during/after inflation



Dissipation during/after inflation



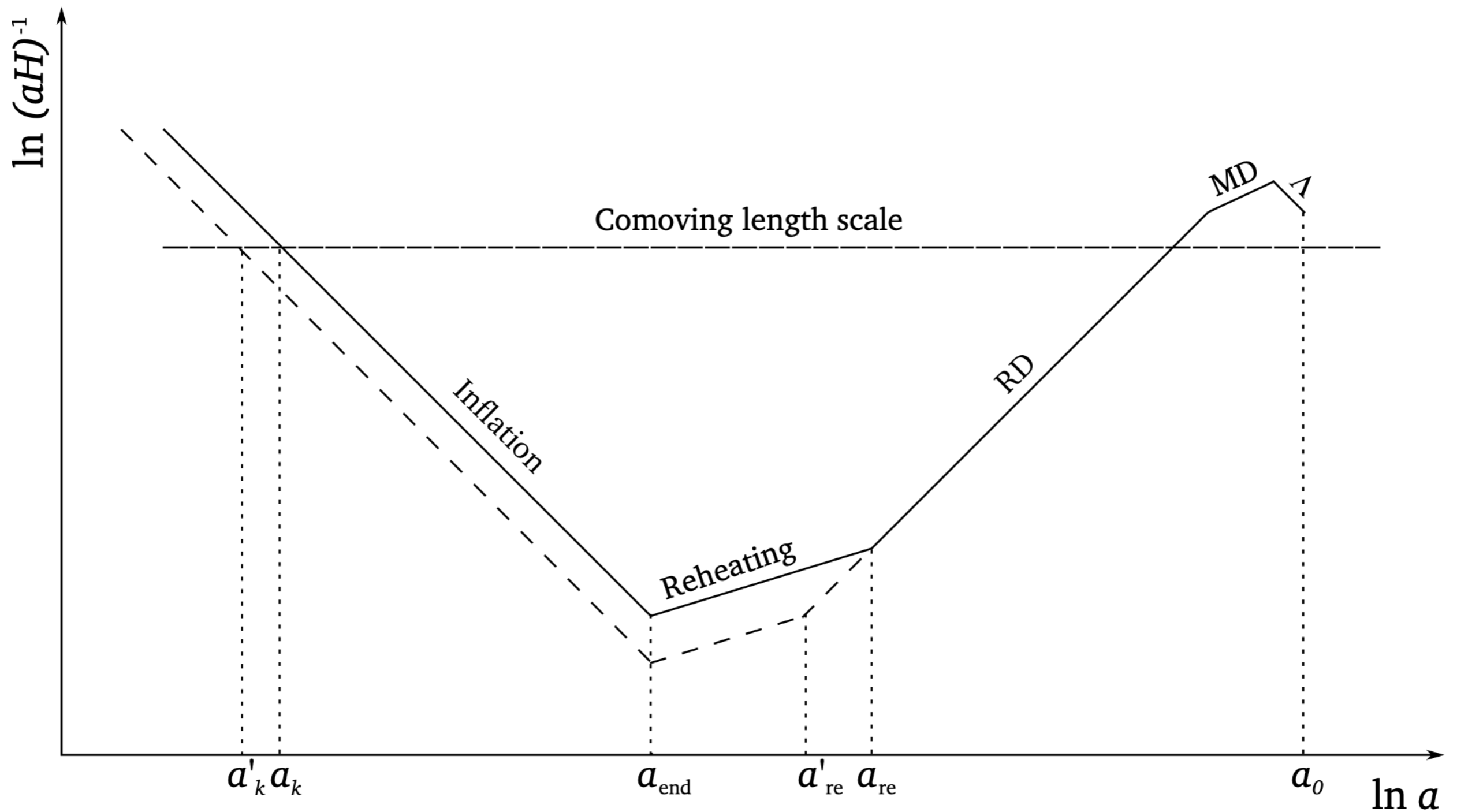
- Inflaton potential determines primordial cosmic perturbations after inflation
- Redshifting of perturbations during reheating affects observed CMB, amount of redshifting depends on the duration of the reheating epoch
- Duration of reheating depends on efficiency of dissipation governed by Γ , which is calculable in terms of microphysical quantities, in particular inflaton couplings
- **CMB is sensitive to microphysical parameters that connect inflation to particle physics**

Part I:

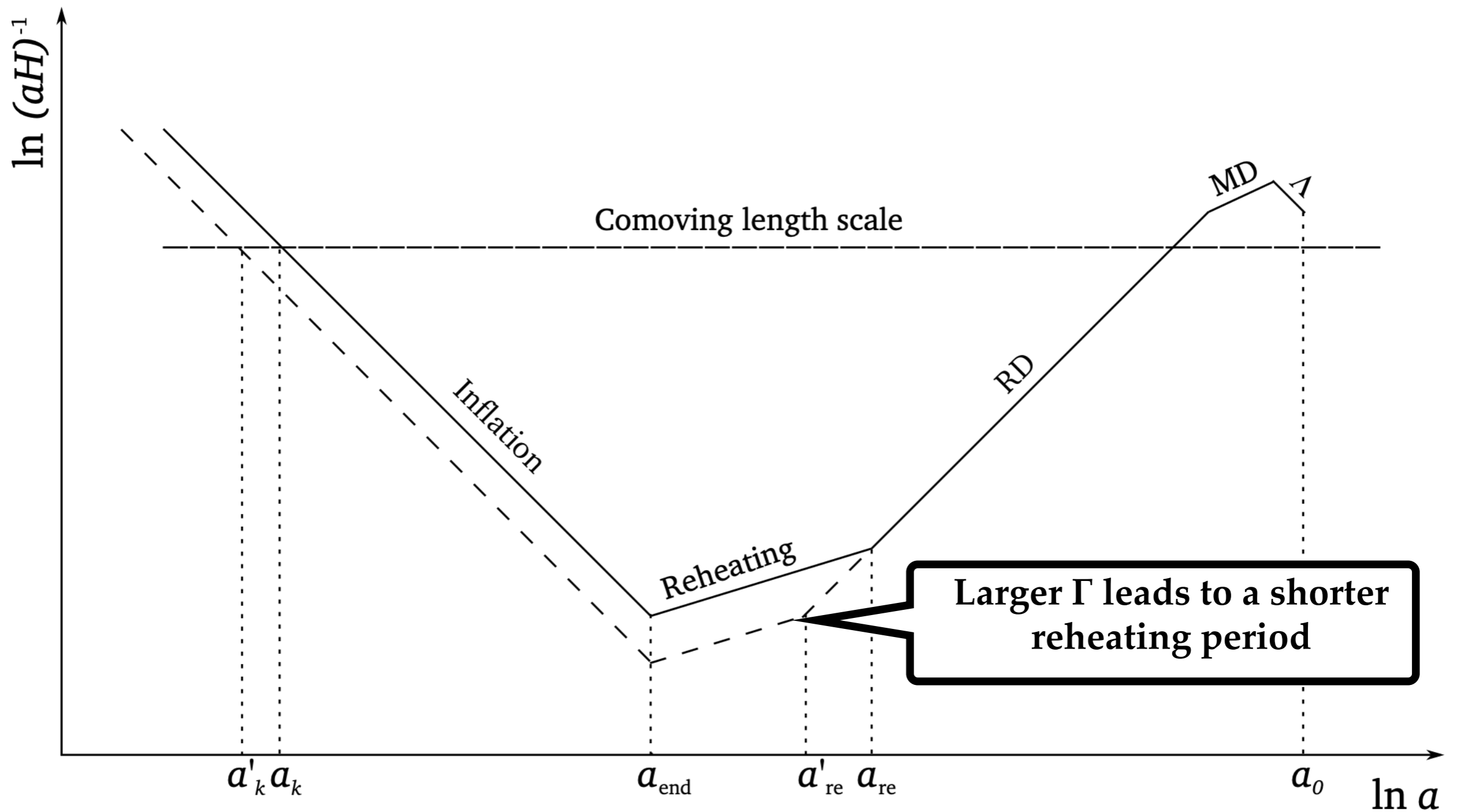
Can one in principle constrain the inflaton coupling from CMB data?

In collaboration with: Wenyuan Ai, Gilles Buldgen, Drazen Galvan, Jin U Kang, Ui Ri Mun

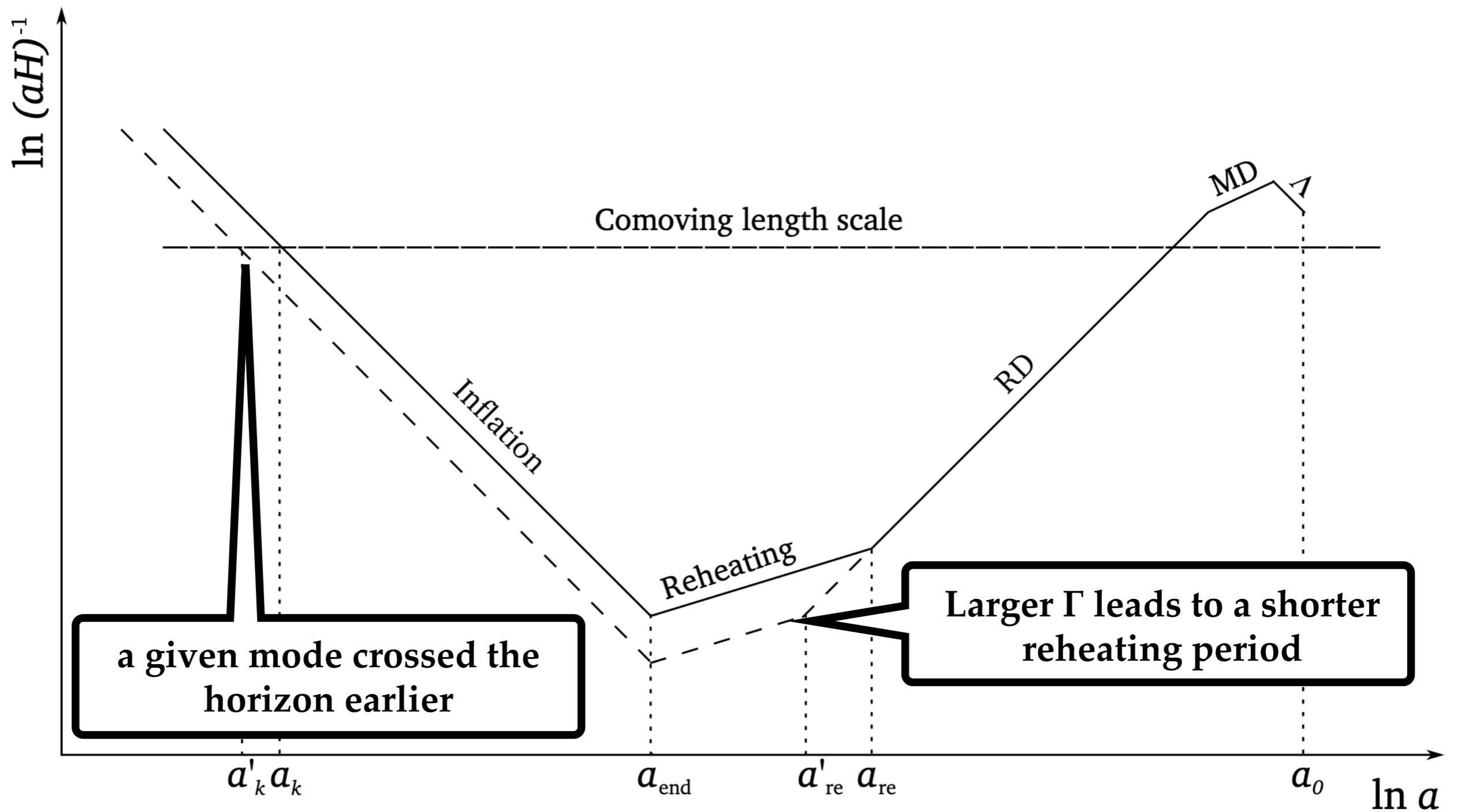
Effect on CMB Modes



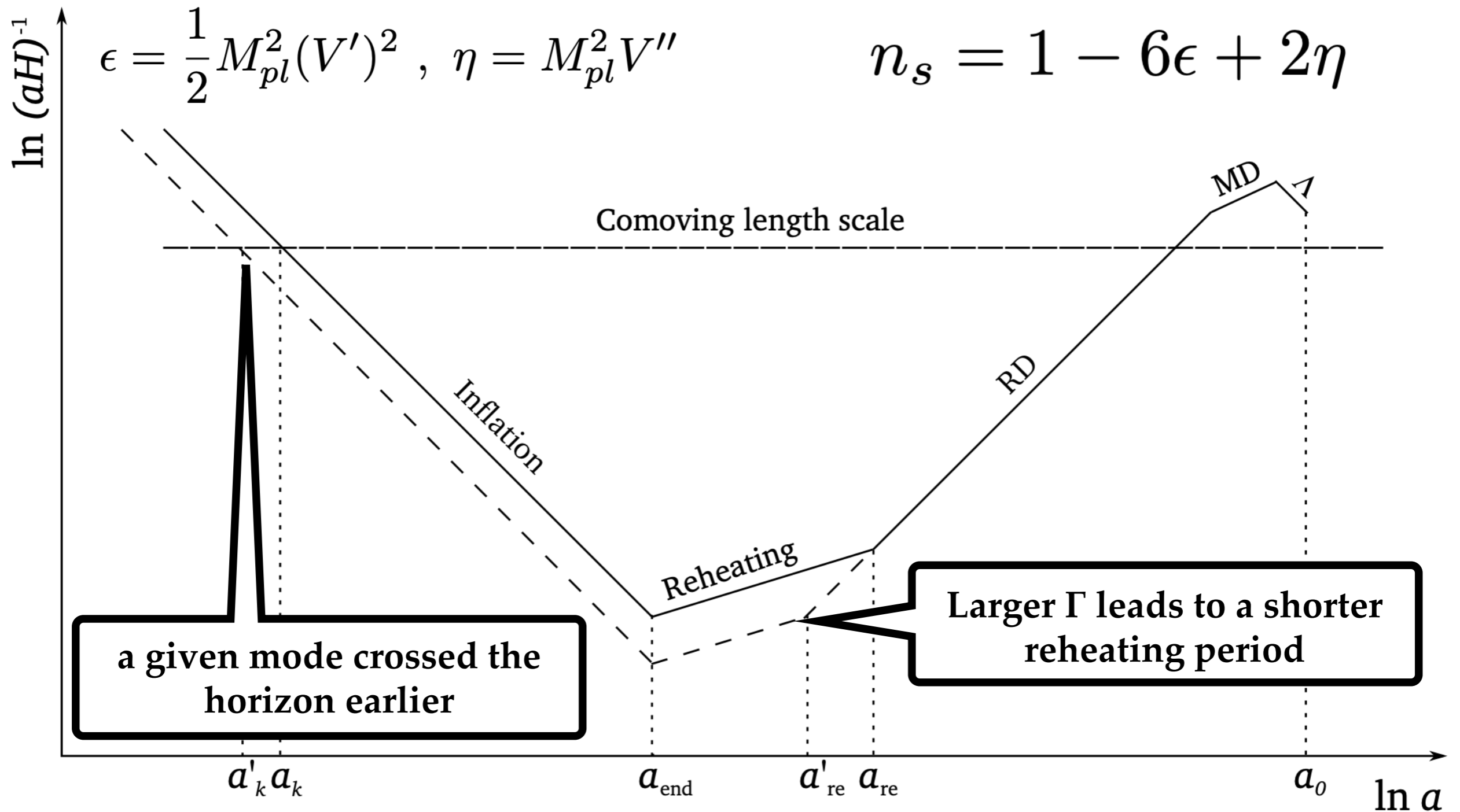
Effect on CMB Modes



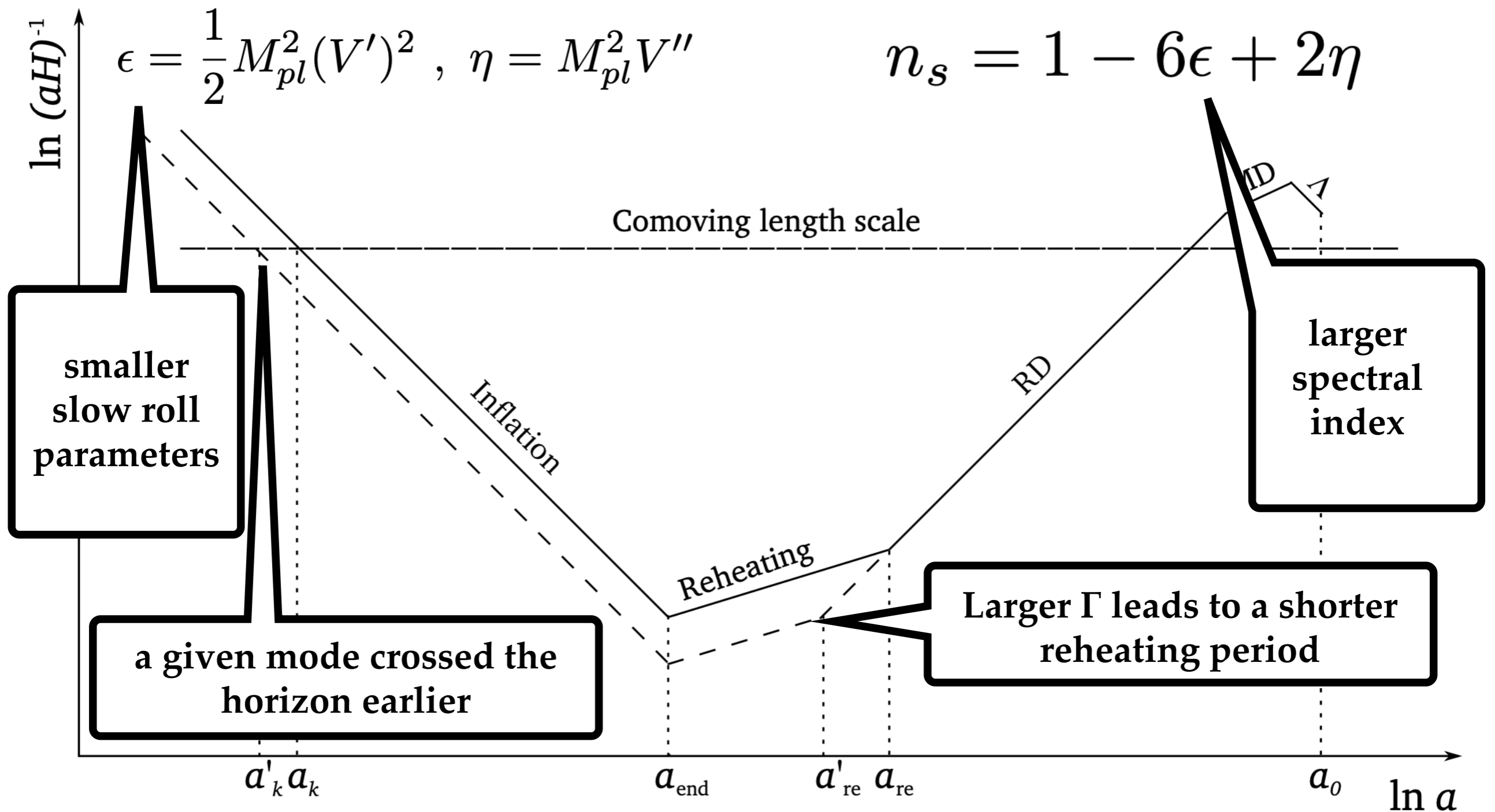
Effect on CMB Modes



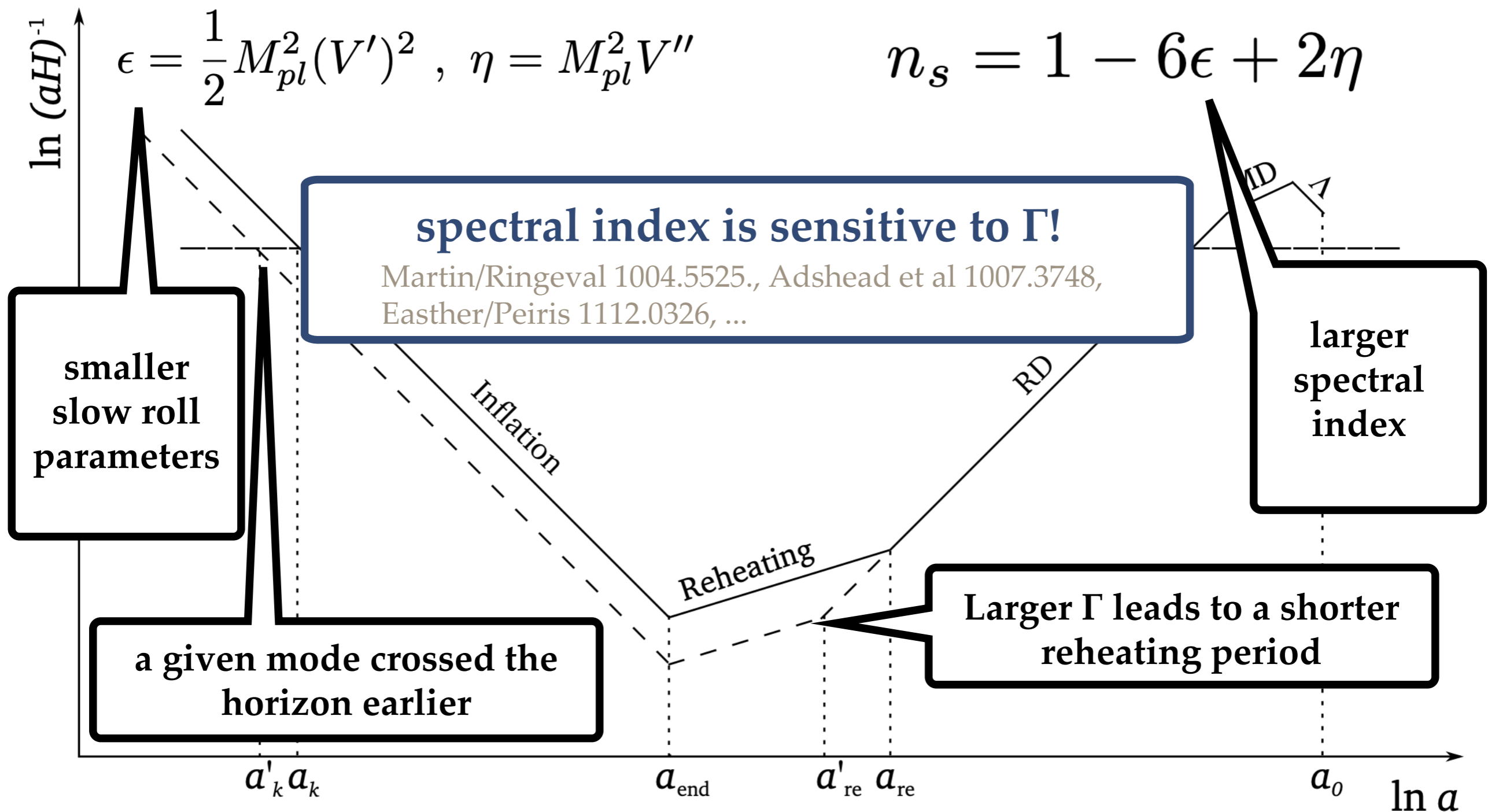
Effect on CMB Modes



Effect on CMB Modes



Effect on CMB Modes



What the CMB is sensitive to

- Spectrum of perturbations at end of inflation is given by choice of potential
- Energy density is also determined by the potential

$$\rho_{\text{end}} \simeq \frac{4}{3} \mathcal{V}_{\text{end}}$$

- Impact of reheating is determined by
 - the averaged equation of state
(also calculable for a given potential, as inflaton dominates during reheating)

$$\bar{w}_{\text{re}} = \frac{1}{N_{\text{re}}} \int_0^{N_{\text{re}}} w(N) dN$$

- the duration of the reheating epoch N_{re} .
- Equivalently can use $\rho_{\text{re}} = \rho_{\text{end}} \exp(-3N_{\text{re}}(1 + \bar{w}_{\text{re}}))$ to obtain reheating temperature:

$$\frac{\pi^2 g_*}{30} T_{\text{re}}^4 \equiv \rho_{\text{re}} \quad T_{\text{re}} = \exp \left[-\frac{3(1 + \bar{w}_{\text{re}})}{4} N_{\text{re}} \right] \left(\frac{40 \mathcal{V}_{\text{end}}}{g_* \pi^2} \right)^{1/4}$$

- T_{re} is the only quantity that is not calculable for a given potential

Connection to Observables

- We use only a small number of observables (A_s, n_s, r)
(in principle the CMB and LSS contain more bytes, but let's start with this...)
- Need relation between observables and potential parameters and

$$T_{\text{re}} = \exp \left[-\frac{3(1 + \bar{w}_{\text{re}})}{4} N_{\text{re}} \right] \left(\frac{40\mathcal{V}_{\text{end}}}{g_*\pi^2} \right)^{1/4}$$

N_{re} can be written as

$$N_{\text{re}} = \frac{4}{3\bar{w}_{\text{re}} - 1} \left[N_k + \ln \left(\frac{k}{a_0 T_0} \right) + \frac{1}{4} \ln \left(\frac{40}{\pi^2 g_*} \right) + \frac{1}{3} \ln \left(\frac{11g_{s*}}{43} \right) - \frac{1}{2} \ln \left(\frac{\pi^2 M_{\text{pl}}^2 r A_s}{2\sqrt{\mathcal{V}_{\text{end}}}} \right) \right]$$

where N_k can be obtained from

$$N_k = \ln \left(\frac{a_{\text{end}}}{a_k} \right) = \int_{\varphi_k}^{\varphi_{\text{end}}} \frac{H d\varphi}{\dot{\varphi}} \approx \frac{1}{M_{\text{pl}}^2} \int_{\varphi_{\text{end}}}^{\varphi_k} d\varphi \frac{\mathcal{V}}{\partial_\varphi \mathcal{V}}$$

and φ_k is obtained by solving

$$n_s = 1 - 6\epsilon_k + 2\eta_k, \quad r = 16\epsilon_k$$

A subscript k means: evaluated at the moment when the mode k crosses the horizon.

Constraining Microphysics

- Reheating ends when $\Gamma = H$. Using this and $H^2 = \frac{\rho_{\text{end}}}{3M_{pl}^2} e^{-3N_{\text{re}}(1+\bar{w}_{\text{re}})}$ one finds

$$\Gamma|_{\Gamma=H} = \frac{1}{M_{pl}} \left(\frac{\rho_{\text{end}}}{3} \right)^{1/2} e^{-3(1+\bar{w}_{\text{re}})N_{\text{re}}/2}.$$

- Hence we can constrain Γ from observation....
...and Γ in principle is calculable in terms of microphysical parameters!

Hence, we can not only constrain the reheating temperature, but also the microphysics of reheating...

...which connects inflation to particle physics!

MaD [1511.03280](#), MaD [1903.09599](#)

Parameters

- We use only a small number of observables (A_s, n_s, r)
- We can therefore only derive a meaningful constraint on microphysical parameters when Γ depends only on a small number of them, ideally only on one.
- We shall distinguish three classes of parameters:

$\{v_i\}$ the parameters in the inflaton potential $V(\varphi)$ define the “**model of inflation**”.

$$\mathcal{V}(\varphi) = \sum_j \frac{v_j}{j!} \frac{\varphi^j}{\Lambda^{j-4}}$$

$\{g_i\}$ the **inflaton couplings** between the inflaton and other fields connect the “model of inflation” to an underlying “model of particle physics”.

$\{a_i\}$ all other parameters of the “particle physics model”,
e.g. masses and gauge interactions amongst the produced particles..

Our Goal: Assume that reheating is primarily driven by one interaction with coupling g , identify parameter region where g can be measured without having to specify details of the underlying particle physics model and the $\{a_i\}$

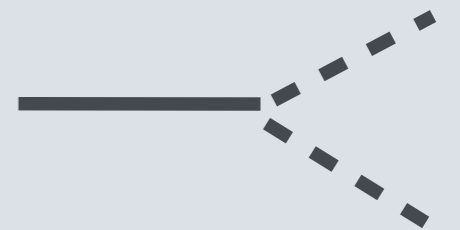
Inflaton Decay

- Reheating ends when $\Gamma = H$. Using this and $H^2 = \frac{\rho_{\text{end}}}{3M_{pl}^2} e^{-3N_{\text{re}}(1+\bar{w}_{\text{re}})}$ one finds

$$\Gamma|_{\Gamma=H} = \frac{1}{M_{pl}} \left(\frac{\rho_{\text{end}}}{3} \right)^{1/2} e^{-3(1+\bar{w}_{\text{re}})N_{\text{re}}/2}.$$

- Hence we can constrain Γ from observation....
...and Γ in principle is calculable in terms of microphysical parameters!
- If inflaton decays via $1 \rightarrow 2$ or $1 \rightarrow 3$ decays then Γ has the form $\Gamma = g^2 m_\phi / \#$.
- We assume Yukawa coupling, simple rescaling allows to constrain other interactions

	Yukawa	scalar	axion-like	scalar
interaction	$y\Phi\bar{\psi}\psi$	$g\Phi\chi^2$	$\frac{\sigma}{\Lambda}\Phi F_{\mu\nu}\tilde{F}^{\mu\nu}$	$\frac{h}{3!}\Phi\chi^3$
g	y	$\tilde{g} = g/m_\phi$	$\tilde{\sigma} = \sigma m_\phi/\Lambda$	h
$\#$	8π	8π	4π	$3!64(2\pi)^3$
rescaling factor	1	1	$\frac{1}{\sqrt{2}}$	$8\sqrt{6}\pi$



Parameter Degeneracies

- However in general Γ is not a simple function of one single coupling: Once occupation numbers in the plasma reach $O[1]$, feedback effects bring in dependence on the properties of the produced particles, and hence the $\{a_i\}$
- Moreover, other effects can also cause a dependence on the $\{a_i\}$:
 - Unknown value of g^* in early universe
 - Non-standard expansion history
 - Plasma equilibration
 - Gravitational waves produced after inflation
 - Radiative corrections to the potential
 - Non-instantaneous inflaton decay
 - Multifield effects
 - Foreground and late time effects
- Within effective single field picture, avoiding feedback from produced particles turns out to be the strongest restriction

Avoiding Feedback

- Expanding the potential as $\mathcal{V}(\varphi) = \sum_j \frac{v_j}{j!} \frac{\varphi^j}{\Lambda^{j-4}}$,

feedback can be avoided if

$$v_i \ll \left(\frac{m_\phi}{\varphi_{\text{end}}} \right)^{j-\frac{5}{2}} \min \left(\sqrt{\frac{m_\phi}{M_{pl}}}, \sqrt{\frac{m_\phi}{\varphi_{\text{end}}}} \right) \left(\frac{m_\phi}{\Lambda} \right)^{4-j}$$

- And the couplings to other fields $g\Phi^j \Lambda^{4-D} \mathcal{O}[\{\mathcal{X}_i\}]$ are smaller than

$$g \ll \left(\frac{m_\phi}{\varphi_{\text{end}}} \right)^{j-\frac{1}{2}} \min \left(\sqrt{\frac{m_\phi}{M_{pl}}}, \sqrt{\frac{m_\phi}{\varphi_{\text{end}}}} \right) \left(\frac{m_\phi}{\Lambda} \right)^{4-D}$$

- For plateau models, the above roughly simplifies to

$$|v_j| \ll (3\pi^2 r A_s)^{(j-2)/2}, \quad |g| \ll (3\pi^2 r A_s)^{j/2}$$

Summary I

- The inflaton coupling can in principle be “measured” in the CMB in a model-independent way if its value is small enough.

- In plateau-models the upper bound roughly reads

$$|v_j| \ll (3\pi^2 r A_s)^{(j-2)/2}, \quad |g| \ll (3\pi^2 r A_s)^{j/2}$$

- Practically this restricts us to models where
 - The field elongation at the end of reheating is small enough for **oscillations to take place in a mildly non-linear regime**
 - The inflaton couplings to other fields are weak (**hidden sector inflation**)
- It can be compared to the lower bound from the requirement to ensure successful reheating

$$g > g_*^{1/4} \frac{T_{\text{BBN}}}{\sqrt{m_\phi M_{\text{pl}}}} \sqrt{\#} \simeq \frac{T_{\text{BBN}}}{M_{\text{pl}}} \left(\frac{g_*}{A_s r} \right)^{1/4} \sqrt{\#}.$$

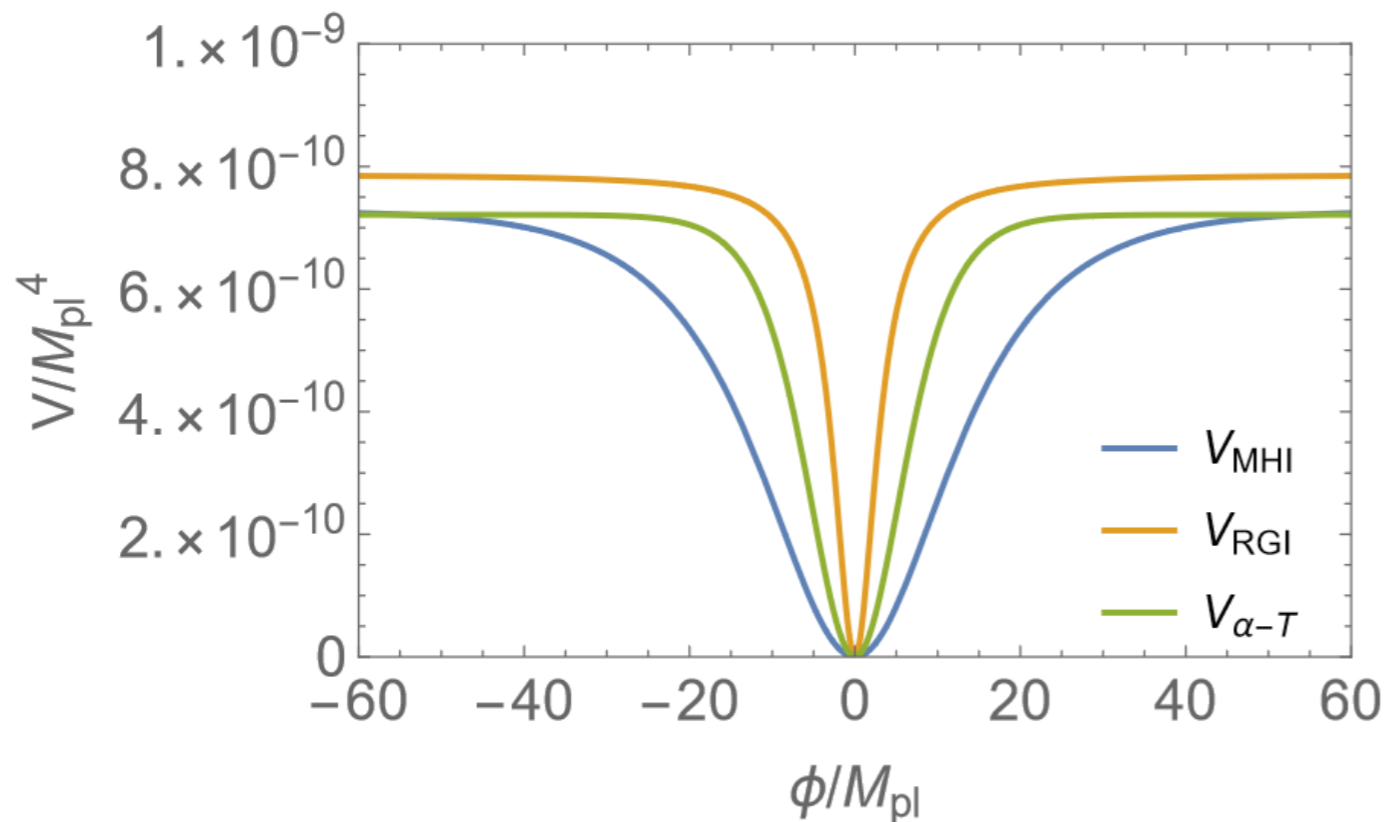
- Together this imposes a lower bound of 10^5 GeV on the inflaton mass

Part II:

Can near future observations in practice do the measurement?

In collaboration with: Jin U Kang, Lei Ming, Ui Ri Mun, Isabel Oldengott

Specific Examples



- Potentials have three parameters
 - M determines the scale of inflation
 - α determines the inflaton mass
- Together with the inflaton coupling there are three parameters...
- ...and in principle three observables

$$(A_s, n_s, r)$$

Mutated Hilltop Inflation (MHI)

$$\mathcal{V}(\varphi) = M^4 \left[1 - \frac{1}{\cosh(\alpha\varphi/M_{pl})} \right]$$

Radion Gauge Inflation (RGI)

$$\mathcal{V}(\varphi) = M^4 \frac{(\varphi/M_{pl})^2}{\alpha + (\varphi/M_{pl})^2}$$

α -attractor T model (α -T)

$$\mathcal{V}(\varphi) = M^4 \tanh^{2n} \left(\frac{\varphi}{\sqrt{6\alpha}M_{pl}} \right)$$

Example: RGI Model

Potential

$$\mathcal{V}(\varphi) = M^4 \frac{(\varphi/M_{pl})^2}{\alpha + (\varphi/M_{pl})^2} = \frac{1}{2}m_\phi^2\varphi^2 + \frac{g_\phi}{3!}\varphi^3 + \frac{\lambda_\phi}{4!}\varphi^4 + \mathcal{O}[\varphi^5]$$

Scale of inflation

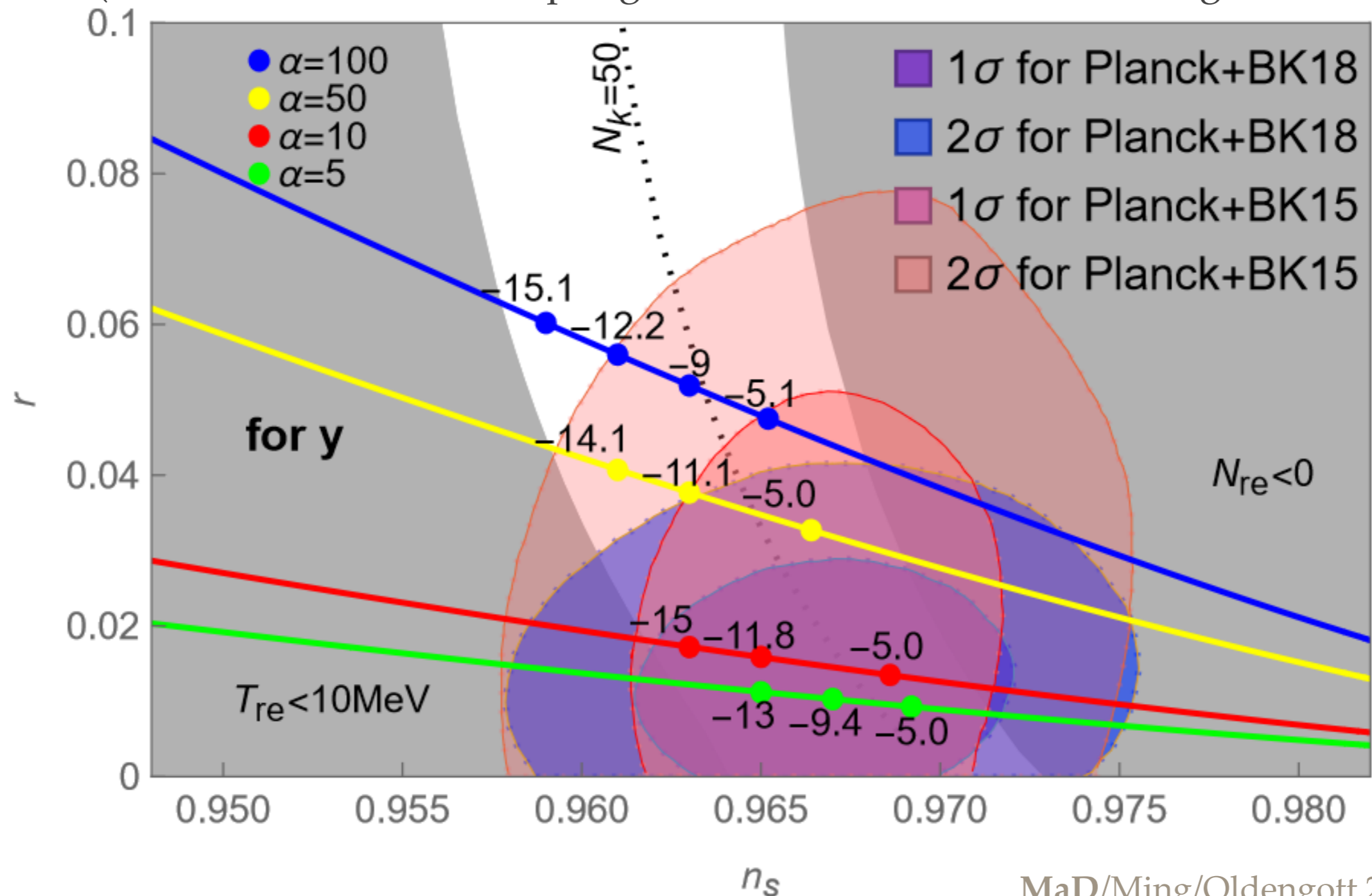
$$M = M_{pl} \left(\frac{3\pi^2}{2} r A_s \left(1 + \alpha \frac{M_{pl}^2}{\varphi_k^2} \right) \right)^{1/4} \quad \alpha = \frac{432r^2}{(8(1 - n_s) + r)^2(4(1 - n_s) - r)}$$

Inflaton mass and self-interaction

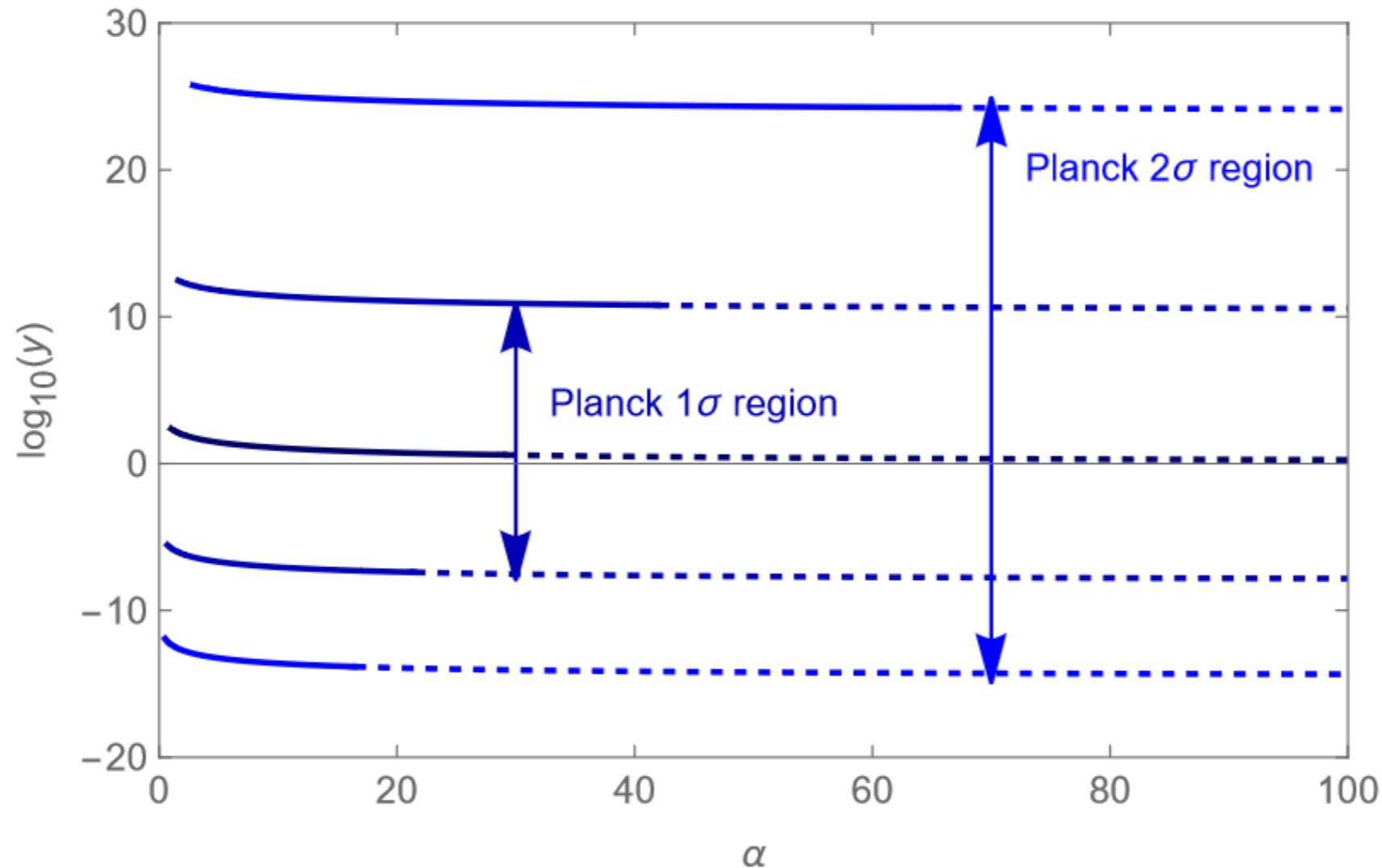
$$m_\phi = \sqrt{\frac{2}{\alpha}} \frac{M^2}{M_{pl}}, \quad g_\phi = 0, \quad \lambda_\phi = -\frac{24M^4}{\alpha^2 M_{pl}^4}$$

CMB Prediction in RGI Models

Example: reheating through a Yukawa coupling y
 (constraints on other couplings can be obtained with rescaling table in Part I)

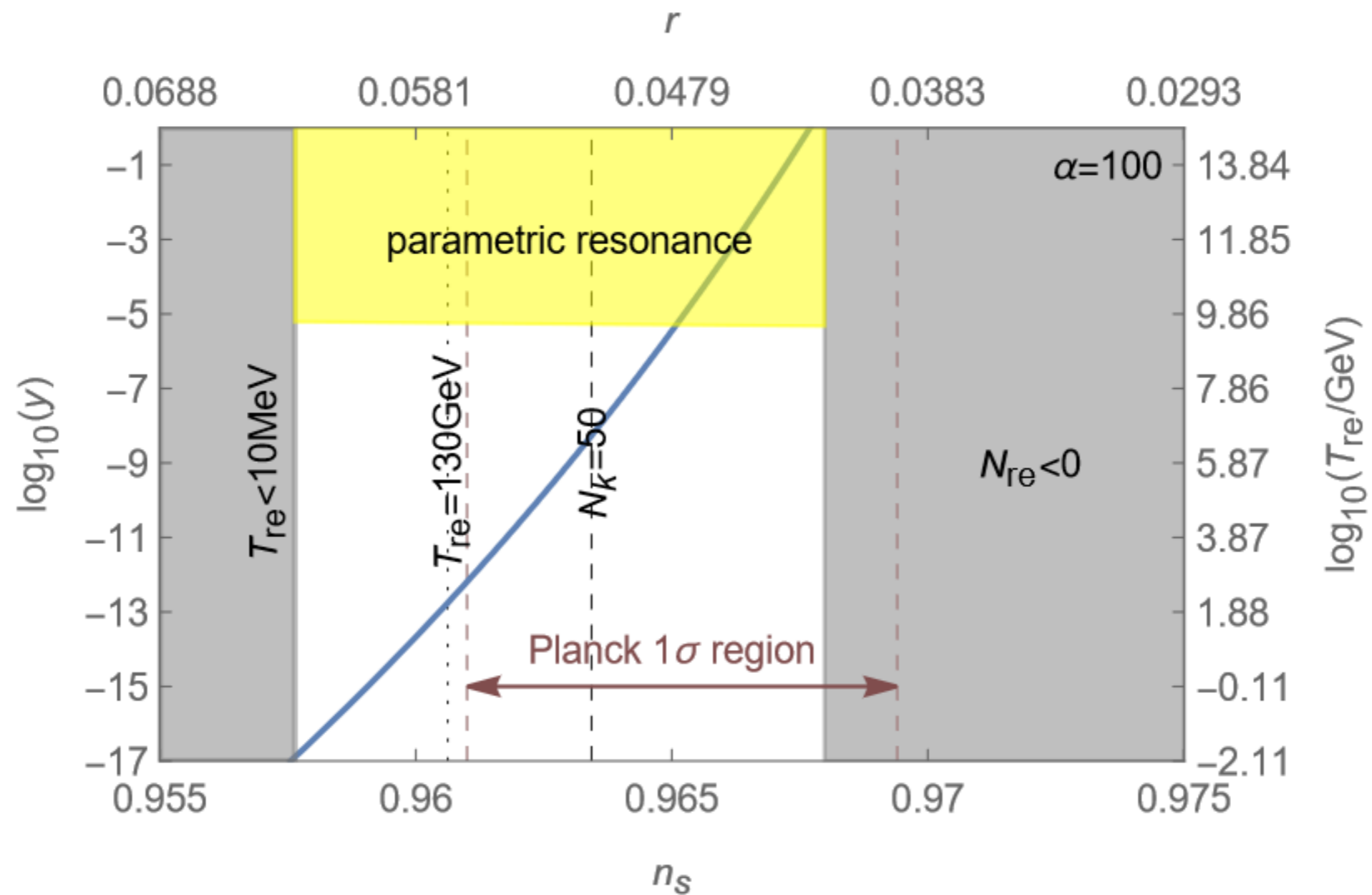


Practical Problems



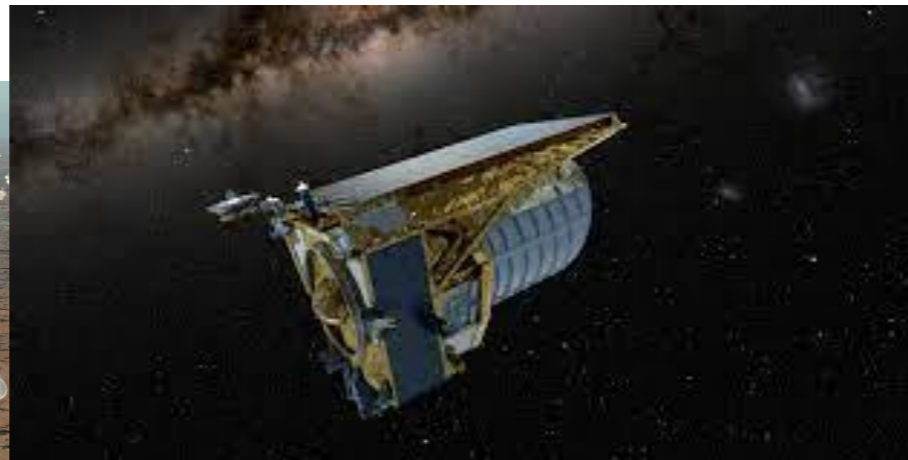
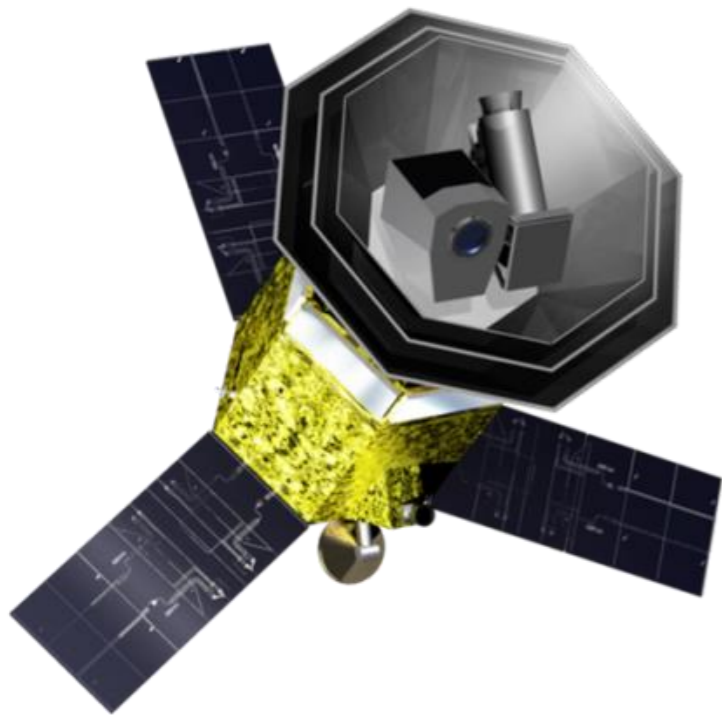
- Error bar on spectral index is too large to fix all three parameters from observation; here we fix α by hand (e.g. by model building), which defines a family of models
- Range of allowed values for α is restricted by requirement to avoid feedback during reheating (conditions from Part I)

Current Constraints



- Current data does not permit to impose a meaningful constraint

Future Observations



Future Sensitivities

We employed two methods to estimate the sensitivities of future observations:

- An analytic method that simply assumes a Gaussian likelihood for the sensitivities in n_s and r MaD/Ming [2208.07609](#)
- An Forecasts with a modified version of CLASS and MontePython with the free parameters MaD/Ming/Oldengott [2303.13503](#)

$$X = \{\omega_b, \omega_{\text{cdm}}, 100\theta_s, \tau_{\text{reio}}\} + \log_{10}(y) + M ;$$

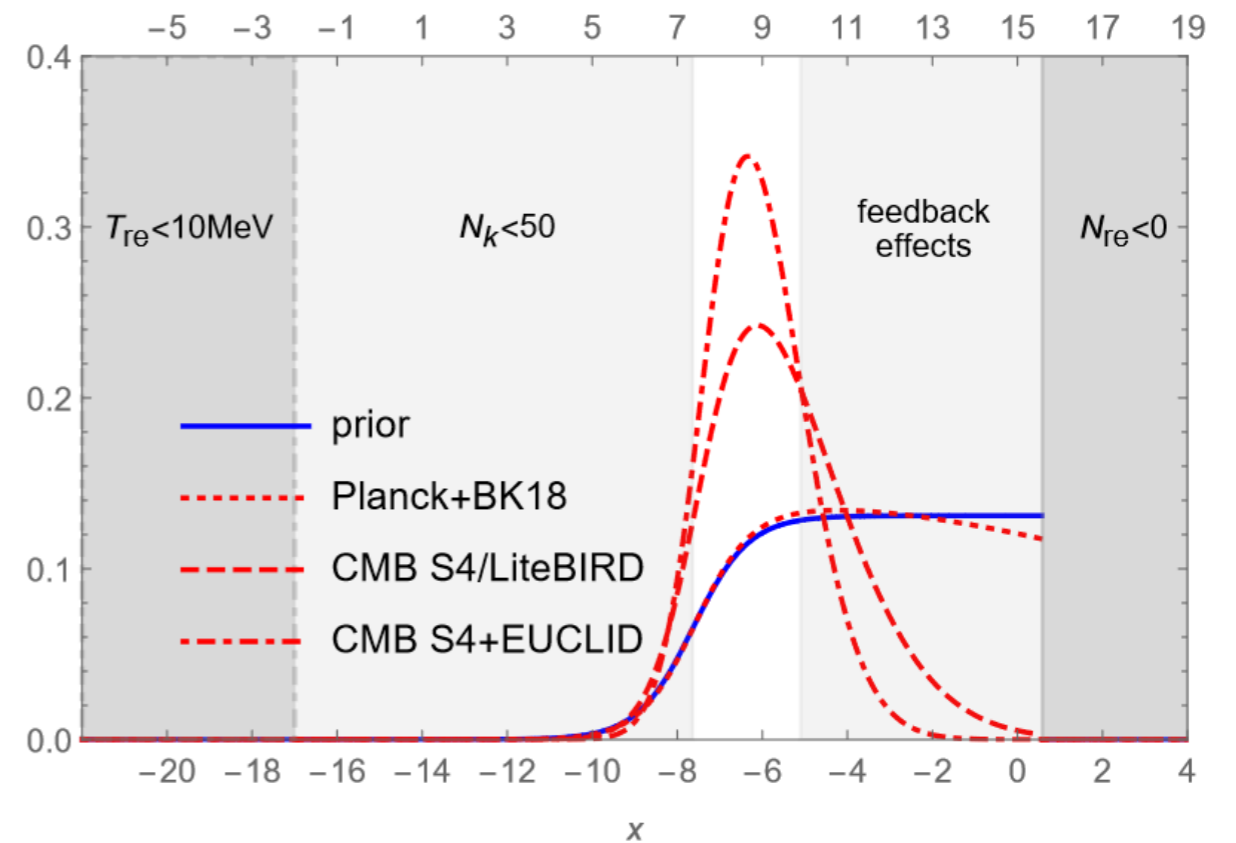
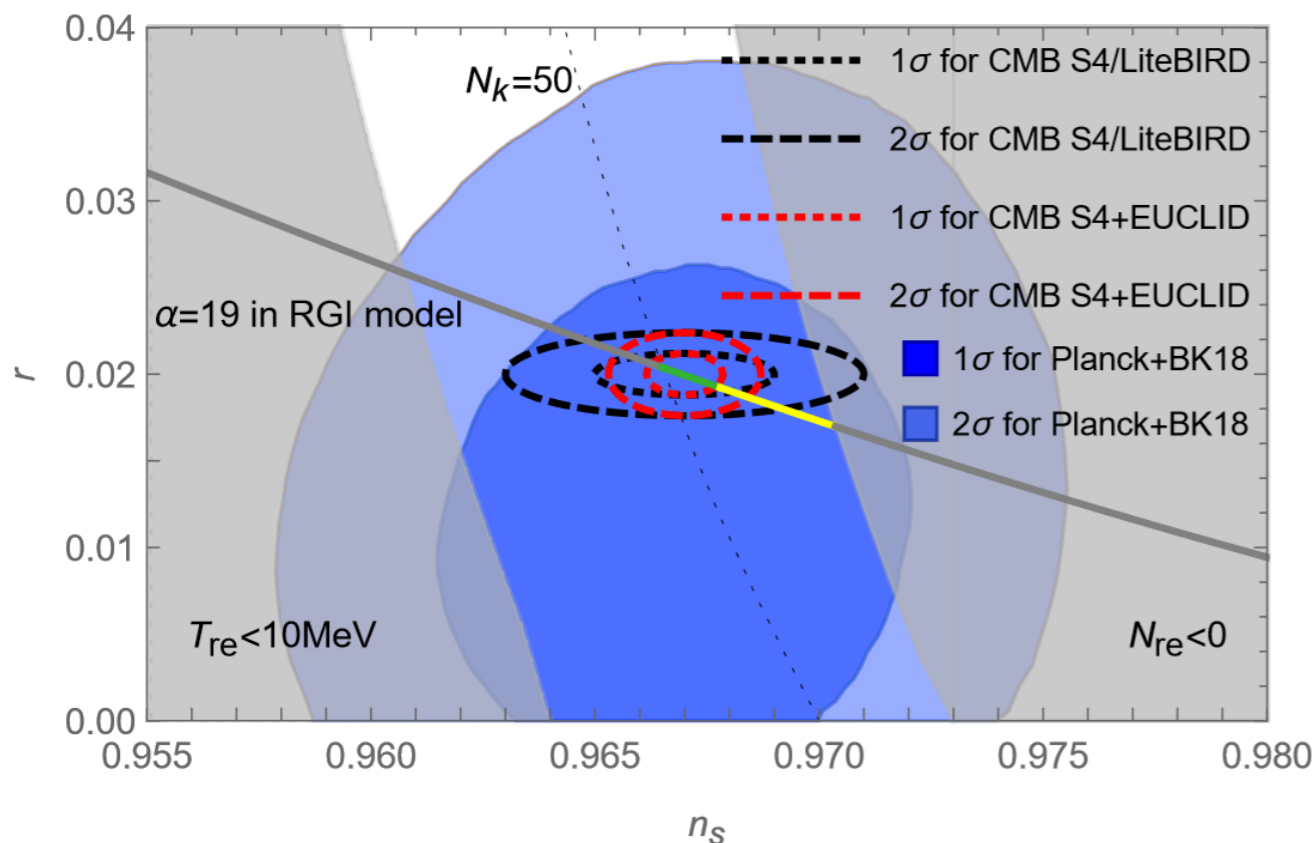
(using build-in functions for LiteBIRD and CMB-S4)

Analytical Method

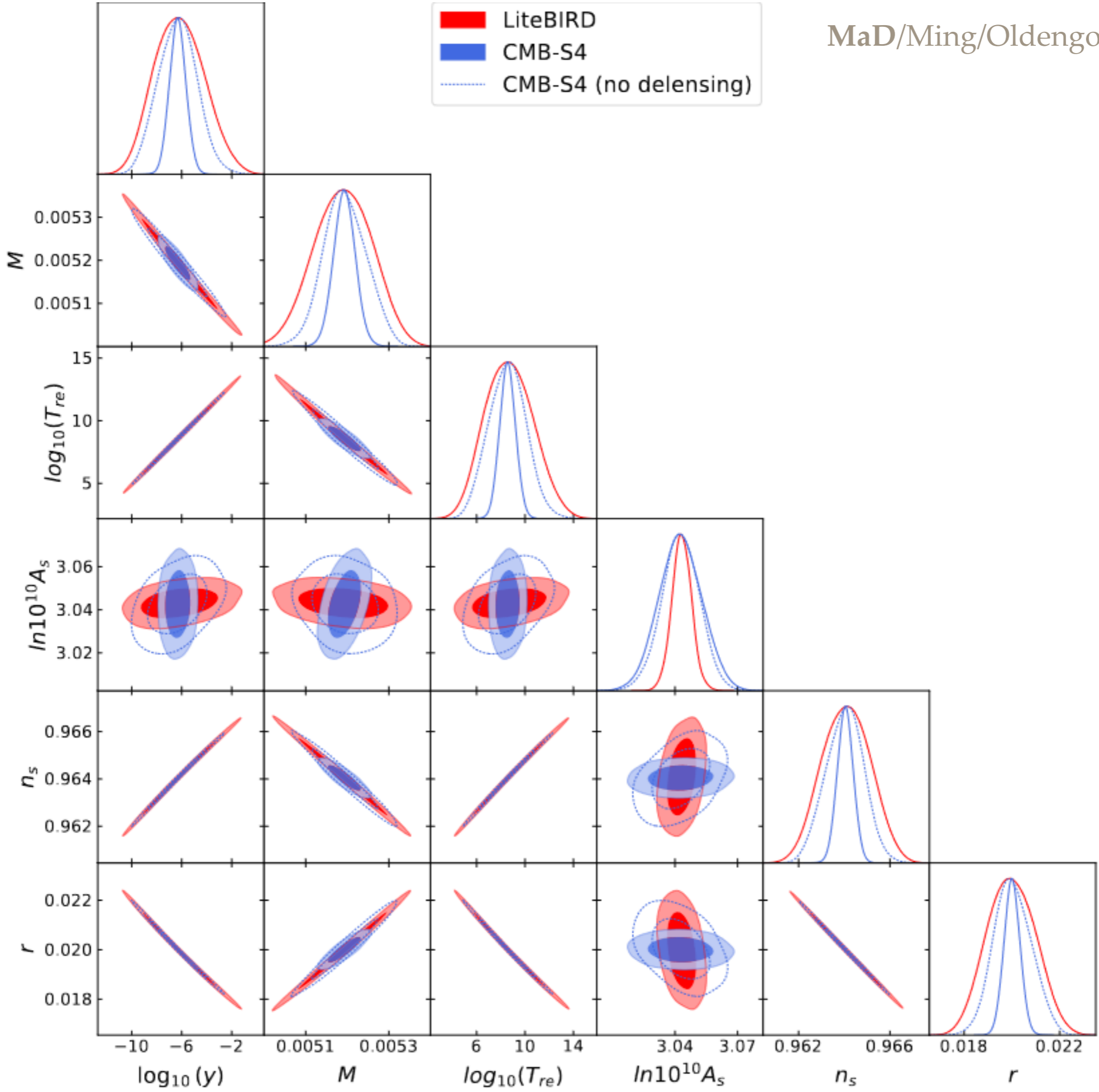
Define prior in $x=\ln(y)$ $P(\mathcal{D}|x) = c_2 \mathcal{N}(n_s(x), r(x) | \bar{n}_s, \sigma_{n_s}; \bar{r}, \sigma_r) \theta(r) \tilde{\gamma}(x),$

With 2dimensional Gaussian in n_s and r

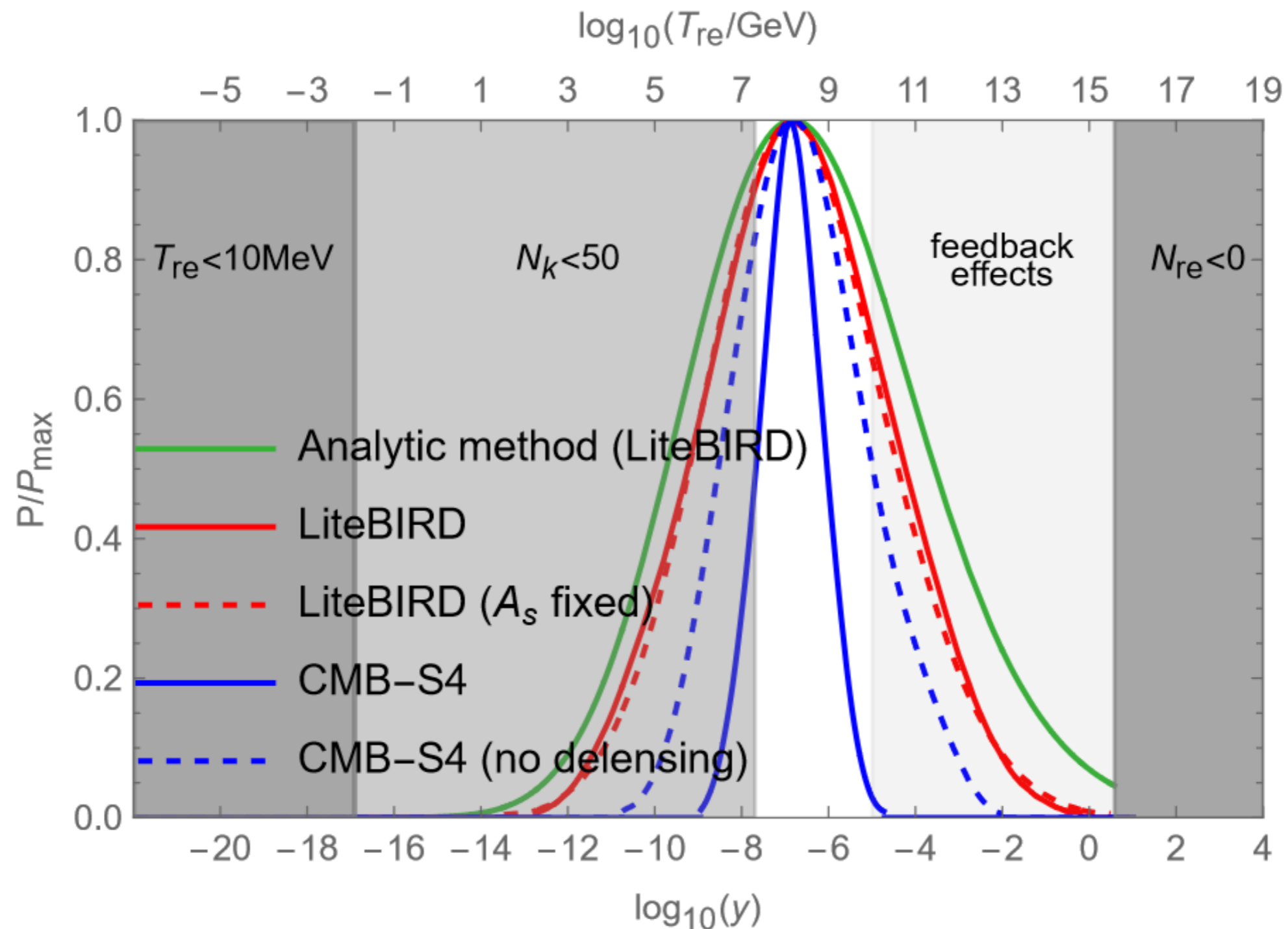
$$\mathcal{N}(n_s, r | \bar{n}_s, \sigma_{n_s}; \bar{r}, \sigma_r) = \frac{1}{2\pi\sigma_{n_s}\sigma_r} \exp\left(-\frac{1}{2} \left(\frac{n_s - \bar{n}_s}{\sigma_{n_s}}\right)^2 - \left(\frac{r - \bar{r}}{\sigma_r}\right)^2\right).$$



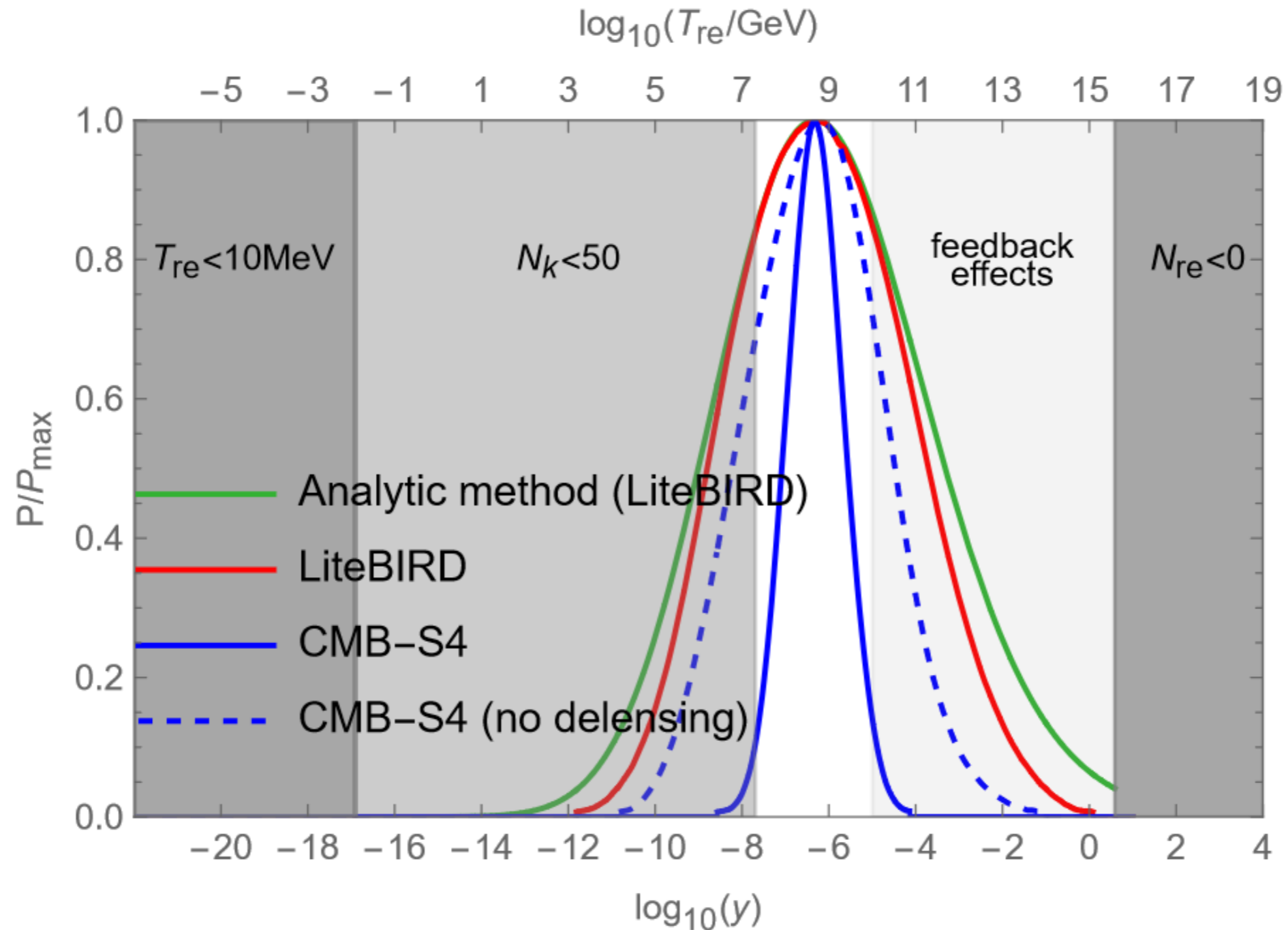
Next generation observations can probe T_{re} and the inflaton coupling!



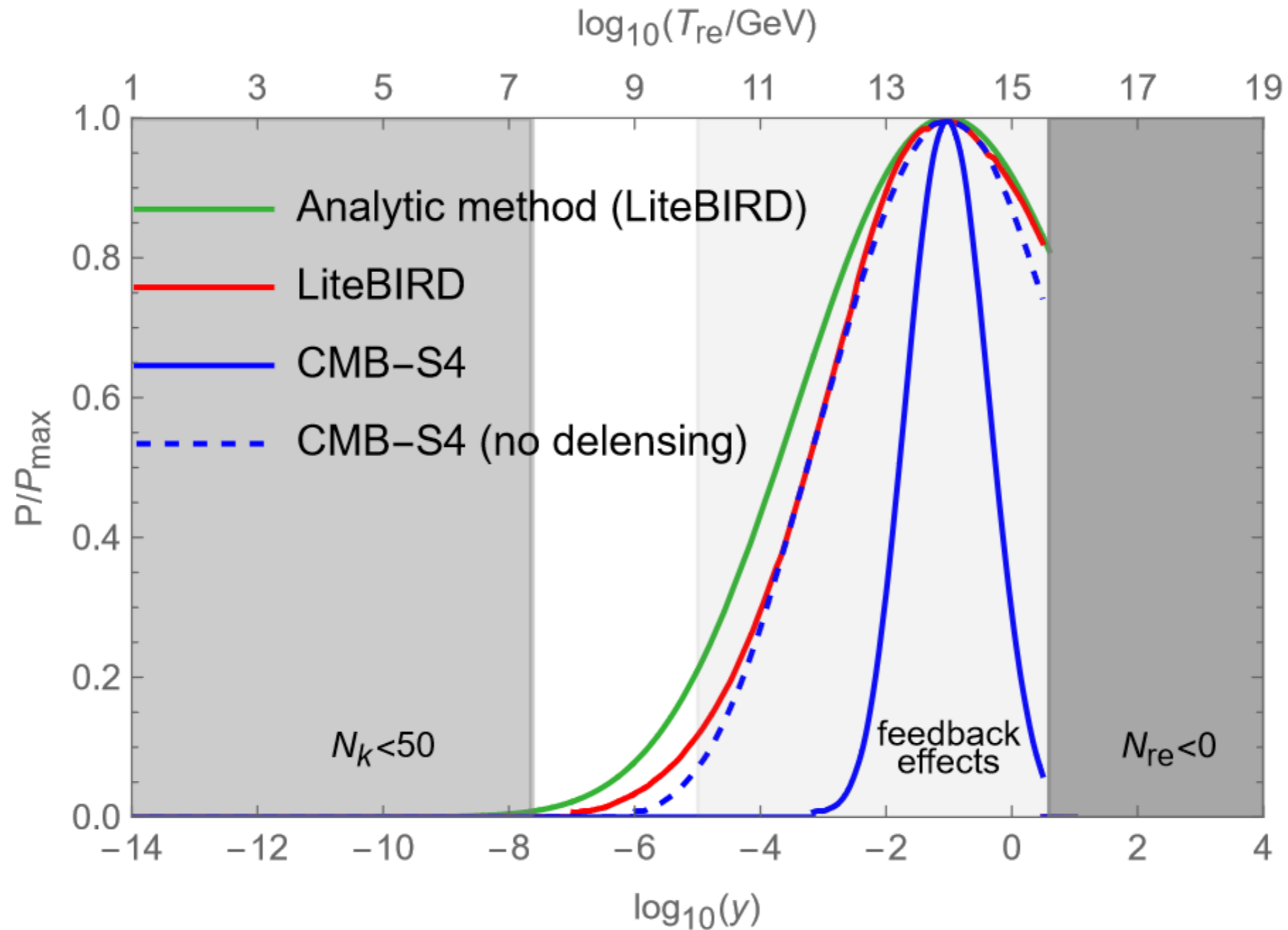
Forecast Method: RGI



Forecast Method: MHI



Forecast Method: α -T



Forecast Method: Summary

LiteBIRD

model	$\log_{10}(y)$	$M[M_{\text{pl}}]$	$\log_{10}(T_{\text{re}}[\text{GeV}])$
MHI	-5.39 ± 1.52	0.00516 ± 0.00005	9.49 ± 1.51
RGI	-5.56 ± 1.44	0.00526 ± 0.00005	9.34 ± 1.44
α -T	-1.70 ± 1.43	0.00521 ± 0.00005	13.13 ± 1.43

CMB-S4

model	$\log_{10}(y)$	$M[M_{\text{pl}}]$	$\log_{10}(T_{\text{re}}[\text{GeV}])$
MHI	-6.28 ± 0.63 (-5.80 ± 1.19)	0.00519 ± 0.00002 (0.00518 ± 0.00004)	8.59 ± 0.63 (9.08 ± 1.19)
RGI	-6.67 ± 0.57 (-5.97 ± 1.14)	0.00529 ± 0.00002 (0.00527 ± 0.00004)	8.23 ± 0.57 (8.93 ± 1.14)
α -T	-1.03 ± 0.62 (-1.62 ± 1.32)	0.00518 ± 0.00002 (0.00520 ± 0.00005)	13.80 ± 0.62 (13.20 ± 1.32)

Summary II

- The inflaton coupling can in practice be “measured” in the CMB if by next generation experiments
- More precisely: In the plateau models considered here, one can simultaneously constrain the scale of inflation and the inflaton coupling (and the reheating temperature)
- Adding information from optical and 21cm surveys will further reduce the error
- One parameter that relates the scale of inflation to the inflaton mass has to be fixed by hand (because the error bar on the spectral index is too large)
- Additional information (e.g. running of the spectral index, non-Gaussianities) may help to break this degeneracy
- Either way, this opens up a new window to probe the connection between inflation and particle physics at very high energies
- Analytic method gives reasonably accurate sensitivity forecasts very quickly

Backup Slides

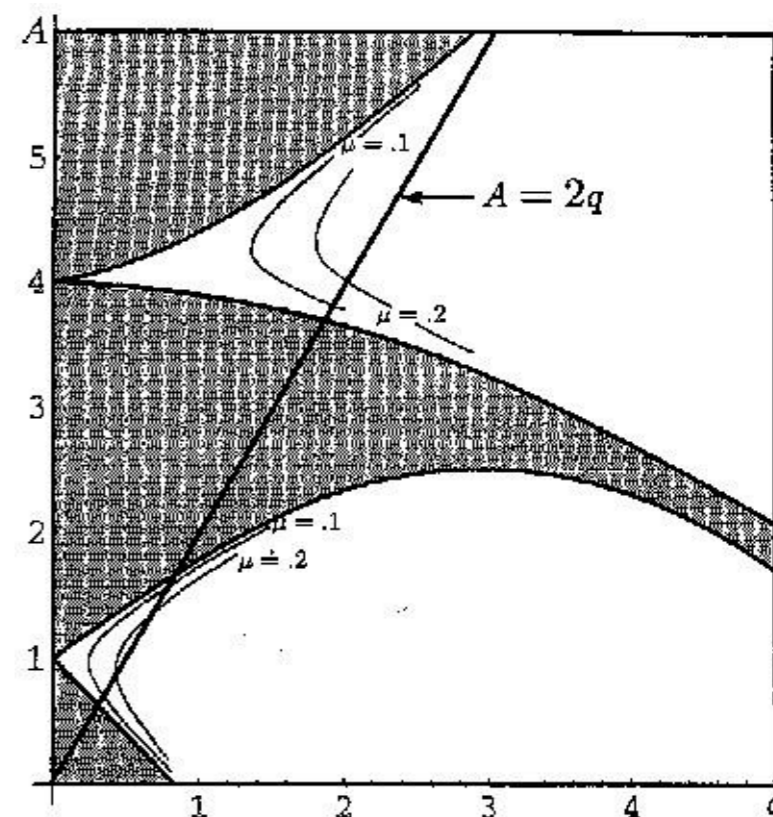
Parametric Resonance

Mode equation for produced particles during harmonic oscillations $\varphi(t) = \Phi \cos(\omega t)$ can be rewritten as **Mathieu equation** with $z \sim \omega t$ Kofman/Linde/Starobinski

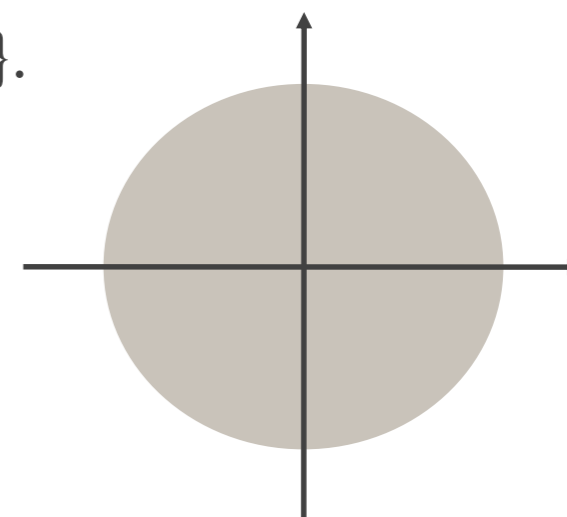
$$\mathcal{X}_k''(z) + [A_k - 2q \cos(2z)] \mathcal{X}_k(z) = 0$$

We demand

- I) $q < 1$ to avoid “broad resonance”
- II) $q^2 m < H$ to make sure that redshifting avoids “narrow resonance”



Note that redshifting depends only on the model of inflation $\{v_i\}$ because φ dominates during reheating. Avoiding the narrow resonance by rescattering would introduce a dependence on $\{a_i\}$.



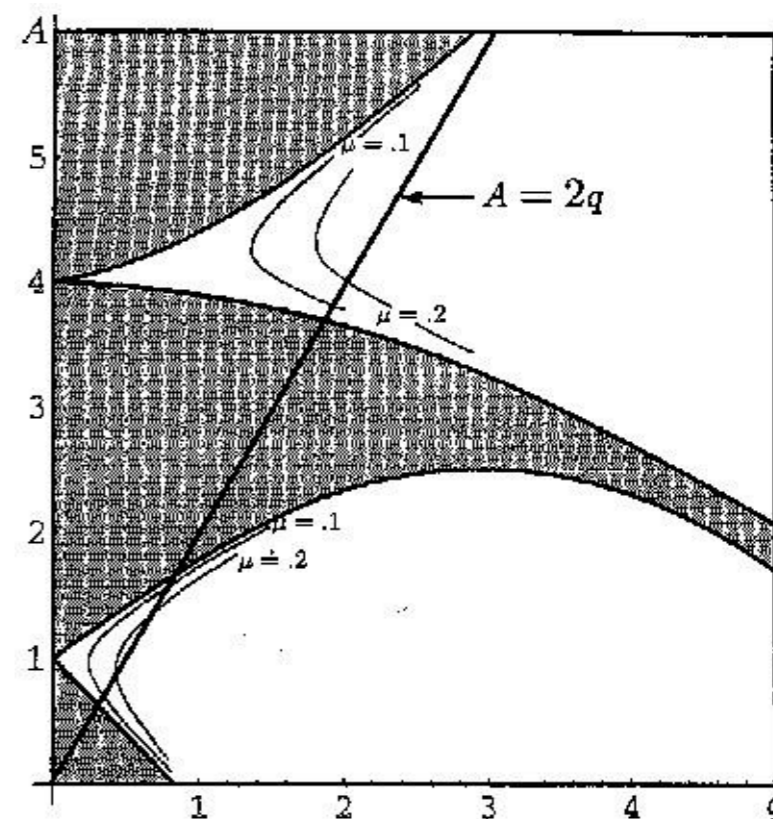
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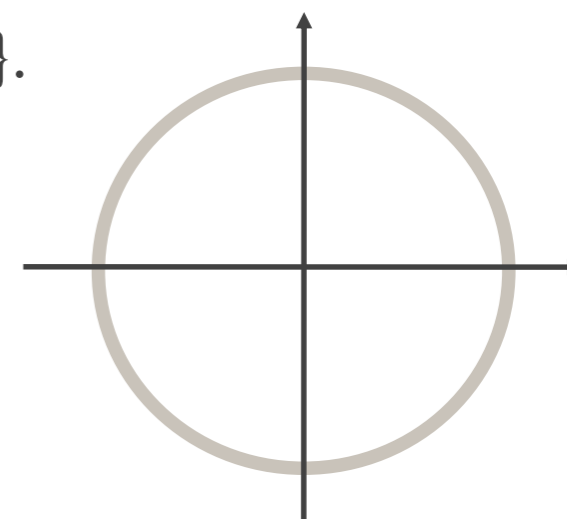
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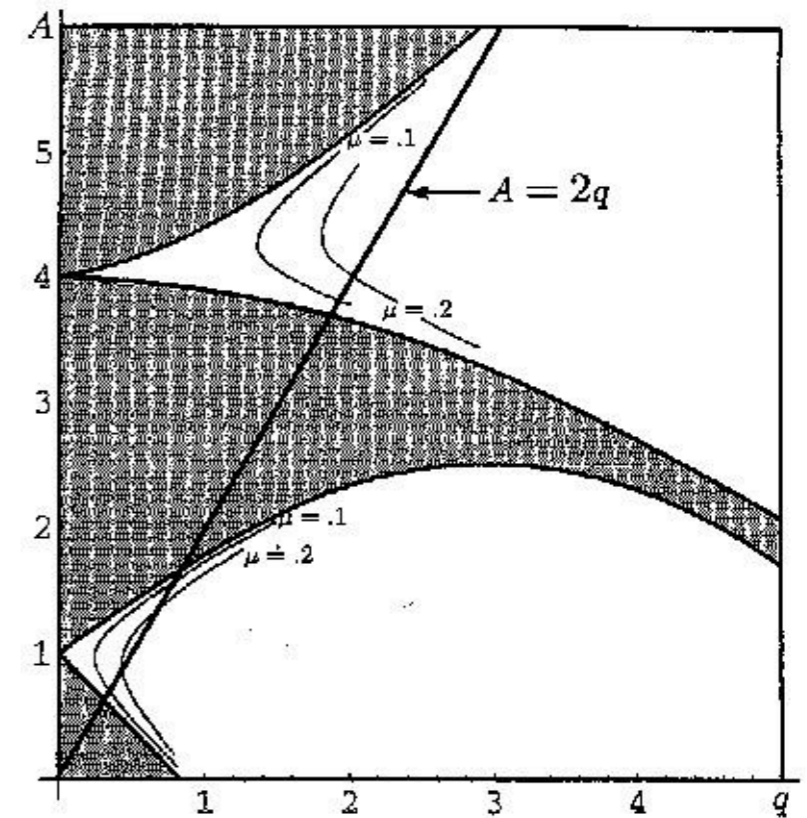
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For self-interaction terms this leads to

$$|v_j| \ll \left(\frac{\omega}{\varphi}\right)^{j-\frac{5}{2}} \min\left(\sqrt{\frac{\omega}{M_{pl}}}, \sqrt{\frac{\omega}{\varphi}}\right) \left(\frac{\omega}{\Lambda}\right)^{4-j},$$

And for couplings to other fields via operator $g\Phi^j \Lambda^{4-D} \mathcal{O}[\{\mathcal{X}_i\}]$

$$|g| \ll \left(\frac{m_\phi}{\varphi_{\text{end}}}\right)^{j-\frac{1}{2}} \min\left(\sqrt{\frac{m_\phi}{M_{pl}}}, \sqrt{\frac{m_\phi}{\varphi_{\text{end}}}}\right) \left(\frac{m_\phi}{\Lambda}\right)^{4-D}$$

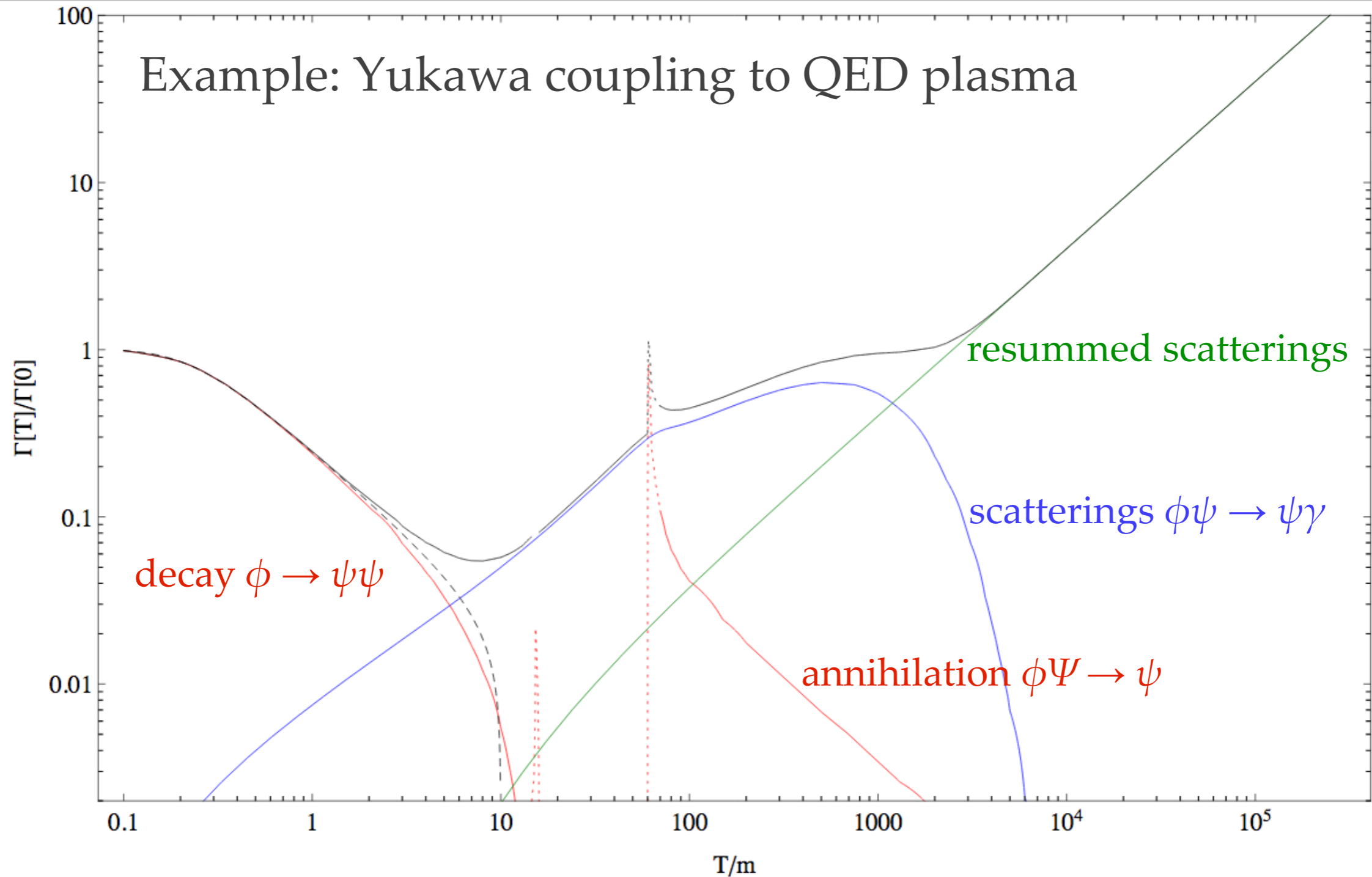
What about thermal feedback?

- Even if there is no resonance, thermal effects can potentially modify Γ

interaction	process	contribution to Γ		
$g\Phi\chi^2$	$\varphi \rightarrow \chi\chi$	$\frac{g^2}{8\pi M_\phi}$	$(1 - 2M_\chi/M_\phi)^{1/2}$	$(1 + 2f_B(M_\phi/2))\theta(M_\phi - 2M_\chi)$
$\frac{\kappa}{4}\Phi^2\chi^2$	$\varphi\varphi \rightarrow \chi\chi$	$\frac{h^2\varphi^2}{256\pi M_\phi}$	$(1 - M_\chi/M_\phi)^{1/2}$	$(1 + 2f_B(M_\phi))\theta(M_\phi - M_\chi)$
$\frac{\sigma}{\Lambda}\Phi F_{\mu\nu}\tilde{F}^{\mu\nu}$	$\varphi \rightarrow \gamma\gamma$	$\frac{\sigma^2}{4\pi}\frac{M_\phi^3}{\Lambda^2}$	$(1 - 2M_\gamma/M_\phi)^{1/2}$	$(1 + 2f_B(M_\phi/2))\theta(M_\phi - 2M_\gamma)$
$y\Phi\bar{\psi}\psi$	$\varphi \rightarrow \psi\bar{\psi},$ $M_\psi \simeq m_\psi$	$\frac{y^2}{8\pi}M_\phi$	$(1 - 2m_\psi/M_\phi)^{3/2}$	$(1 - 2f_F(M_\phi/2))\theta(M_\phi - 2m_\psi)$
	$\varphi \rightarrow \psi\bar{\psi},$ $M_\psi \gg m_\psi$	$\frac{y^2}{8\pi}M_\phi$	$(1 - 2M_\psi/M_\phi)^{1/2}$	$(1 - 2f_F(M_\phi/2))\theta(M_\phi - 2M_\psi)$

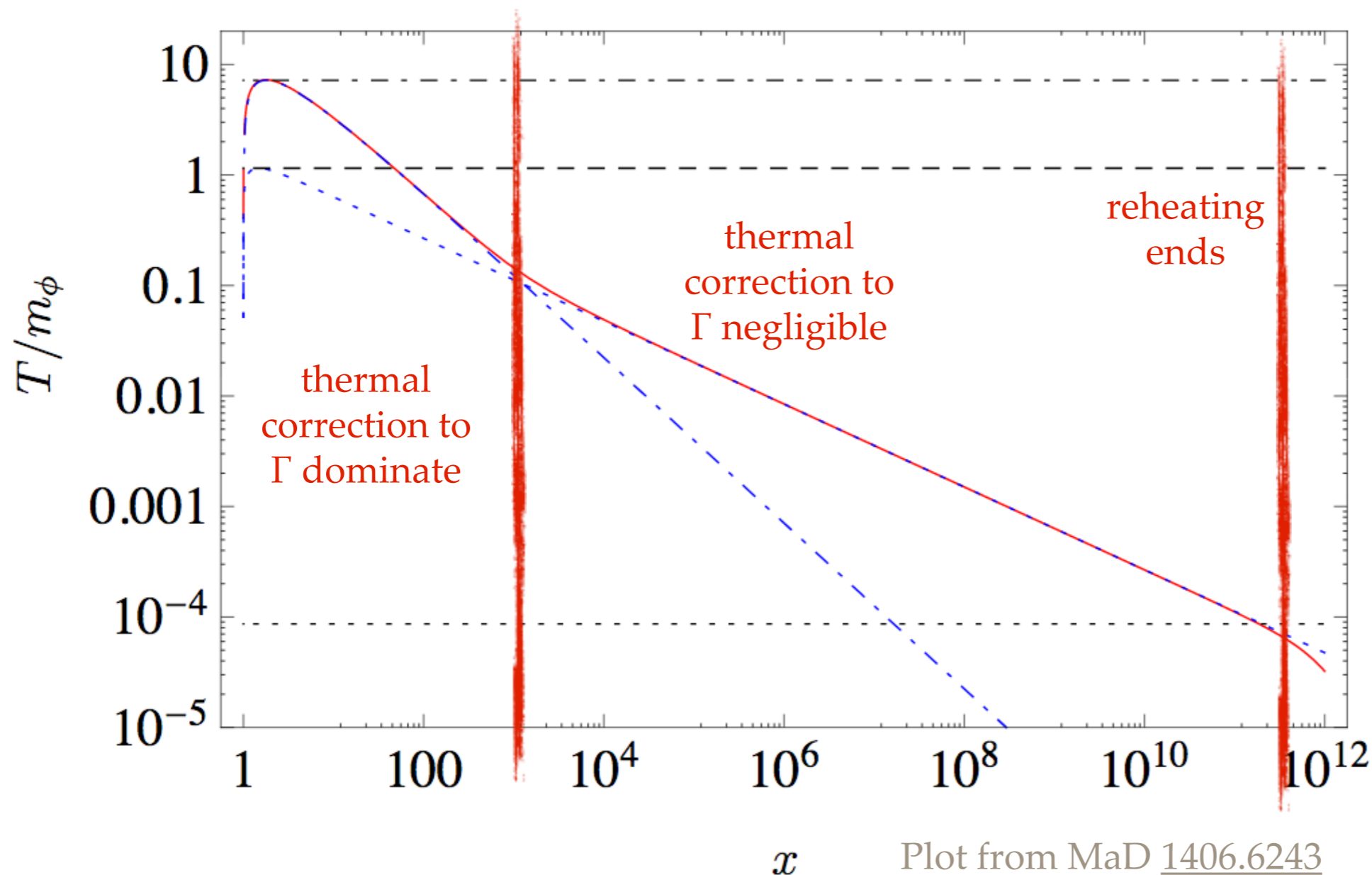
- Prefactor typically depends on a single coupling constant $\in \{ g_i \}$
- Phase space given by “thermal masses” depends on the $\{ \alpha_i \}$, becomes relevant when $T > m\varphi/\alpha_i$
- Quantum statistical effects are relevant for occupation numbers $O[1]$ ($T > m\varphi$ for equilibrium distributions), depends on $\{ \alpha_i \}$ because rescatterings determine distribution functions

What about thermal feedback?



What about thermal feedback?

Thermal corrections modify the thermal history during reheating, but the effect on the expansion history is subdominant within the regime where the previous conditions are fulfilled. [MaD 1903.09599](#)



**No visible
effect in CMB!**