CONSTRAINTS ON REHEATING TO SM PARTICLES DUE TO LARGE EFFECTIVE HIGGS BOSON MASS DURING INFLATION

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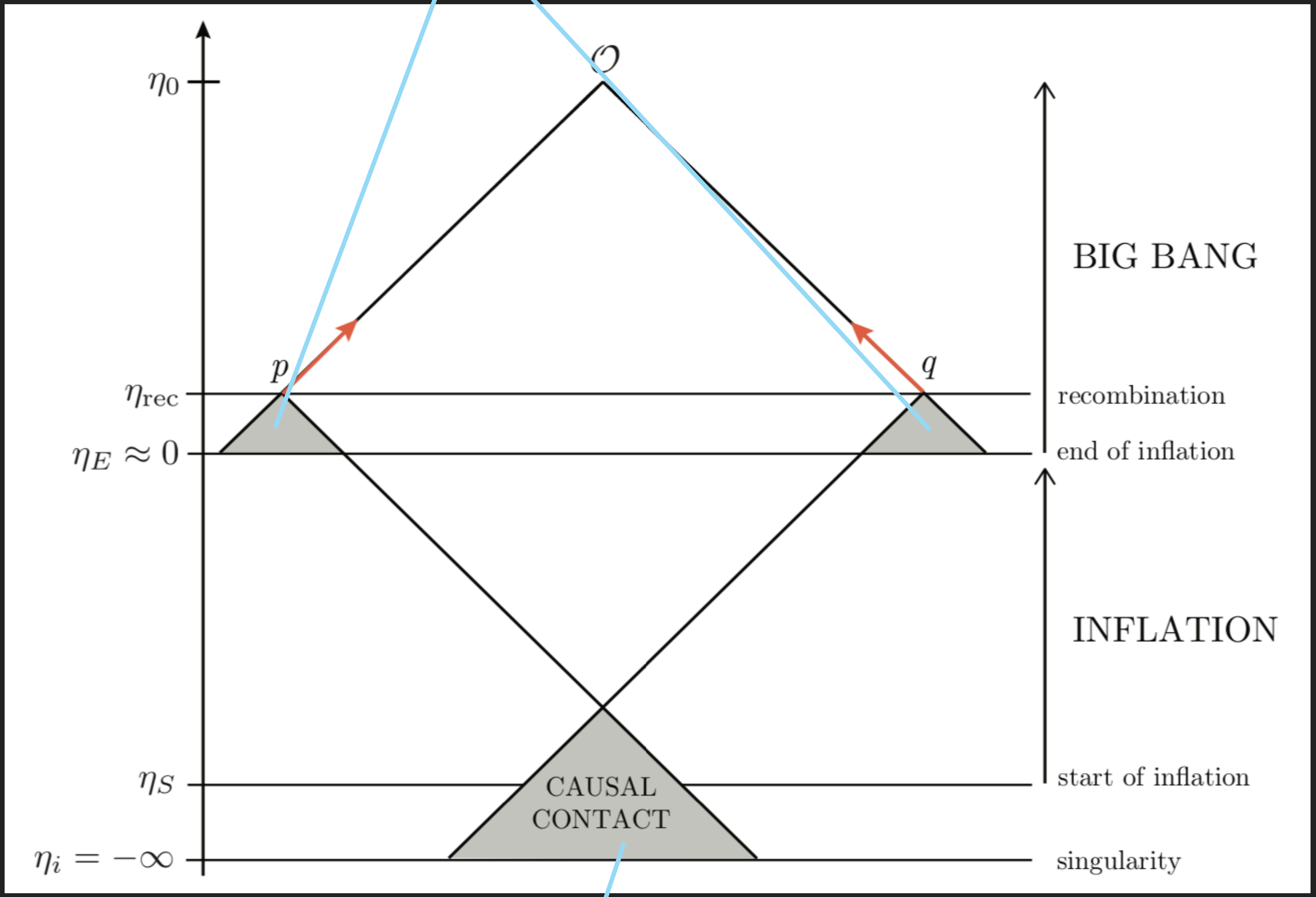
CONTENTS

WHY DO WE NEED INFLATION?

- A period of accelerated expansion in the Early Universe
- Solution to the horizon, flatness and monopole problems
- Seeds the observed CMB temperature fluctuations

Causally disconnected patches at CMB decoupling

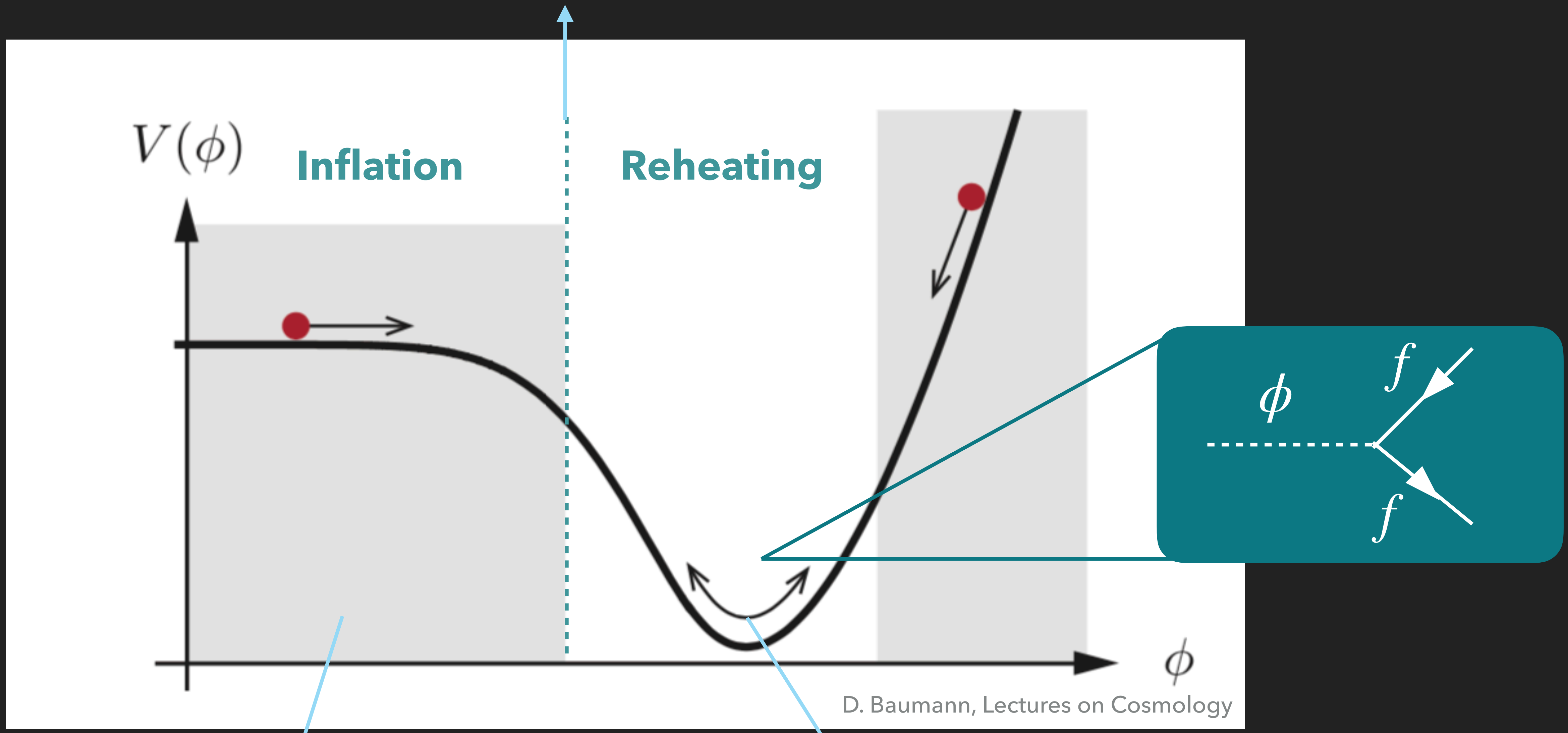


D. Baumann, Lectures on Cosmology

All Hubble patches initially in causal contact

SLOW-ROLL INFLATION

End of accelerated expansion



The inflaton slowly-rolls along its potential

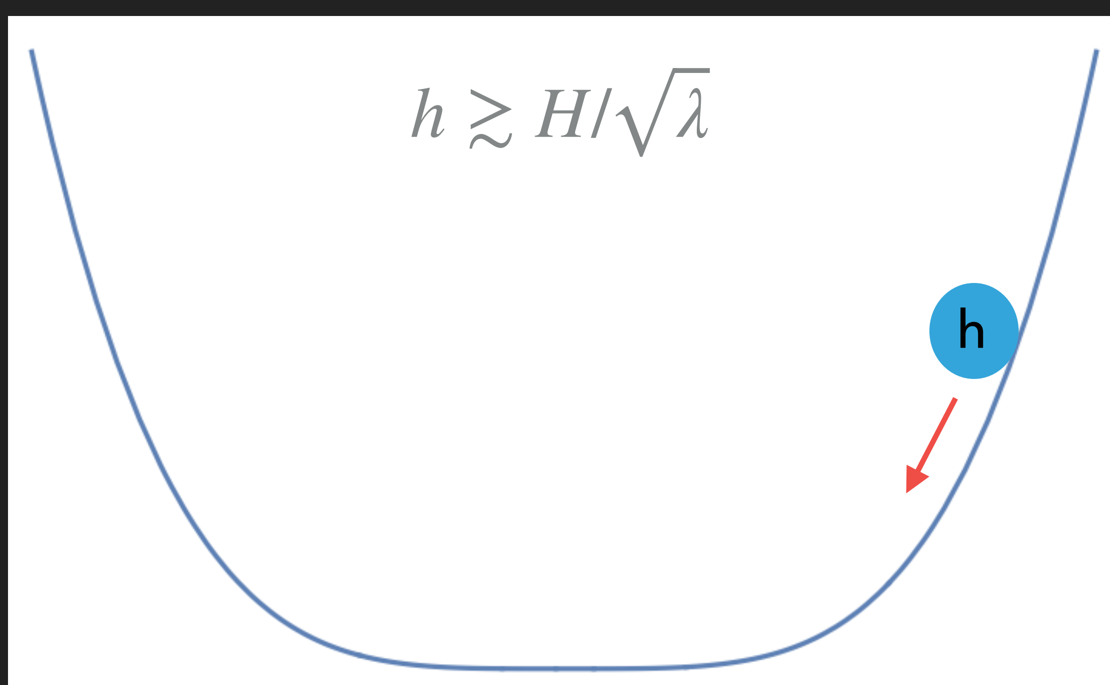
Inflaton begins oscillating and decaying to SM particles

DURING INFLATION

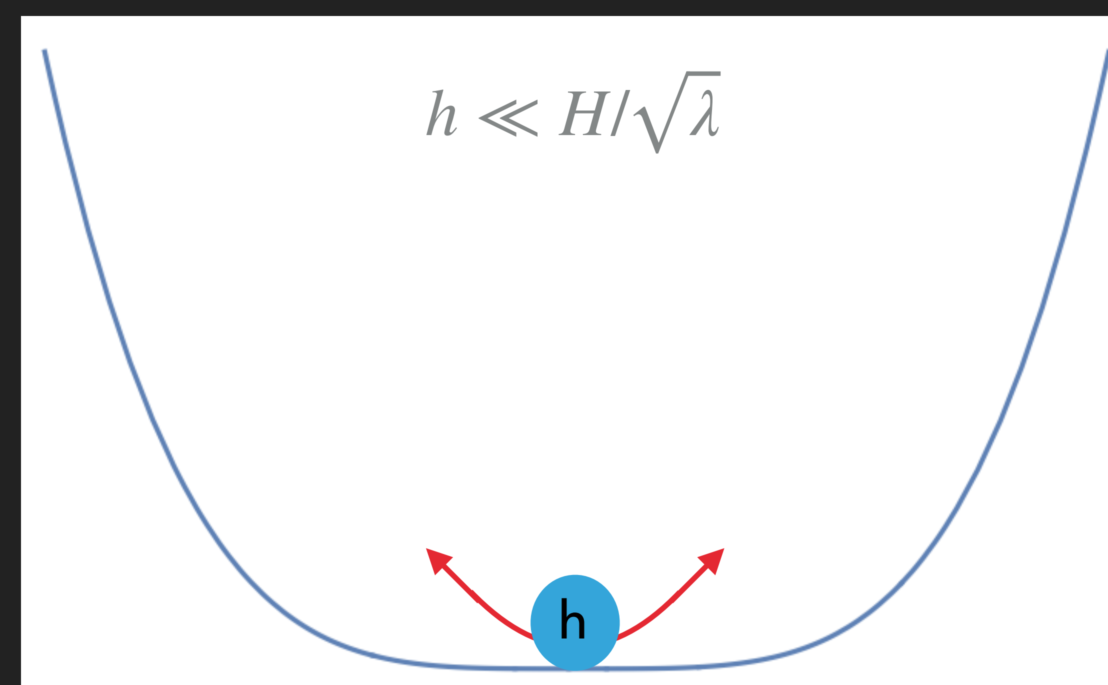
- Potential of the Higgs field for $h \gg v_{\rm EW} \approx 246$ GeV :

$$V(h) = \lambda \left(v_{\rm EW}^2 h^2 + v_{\rm EW} h^3 + h^4\right)/4 \approx \lambda h^4/4$$

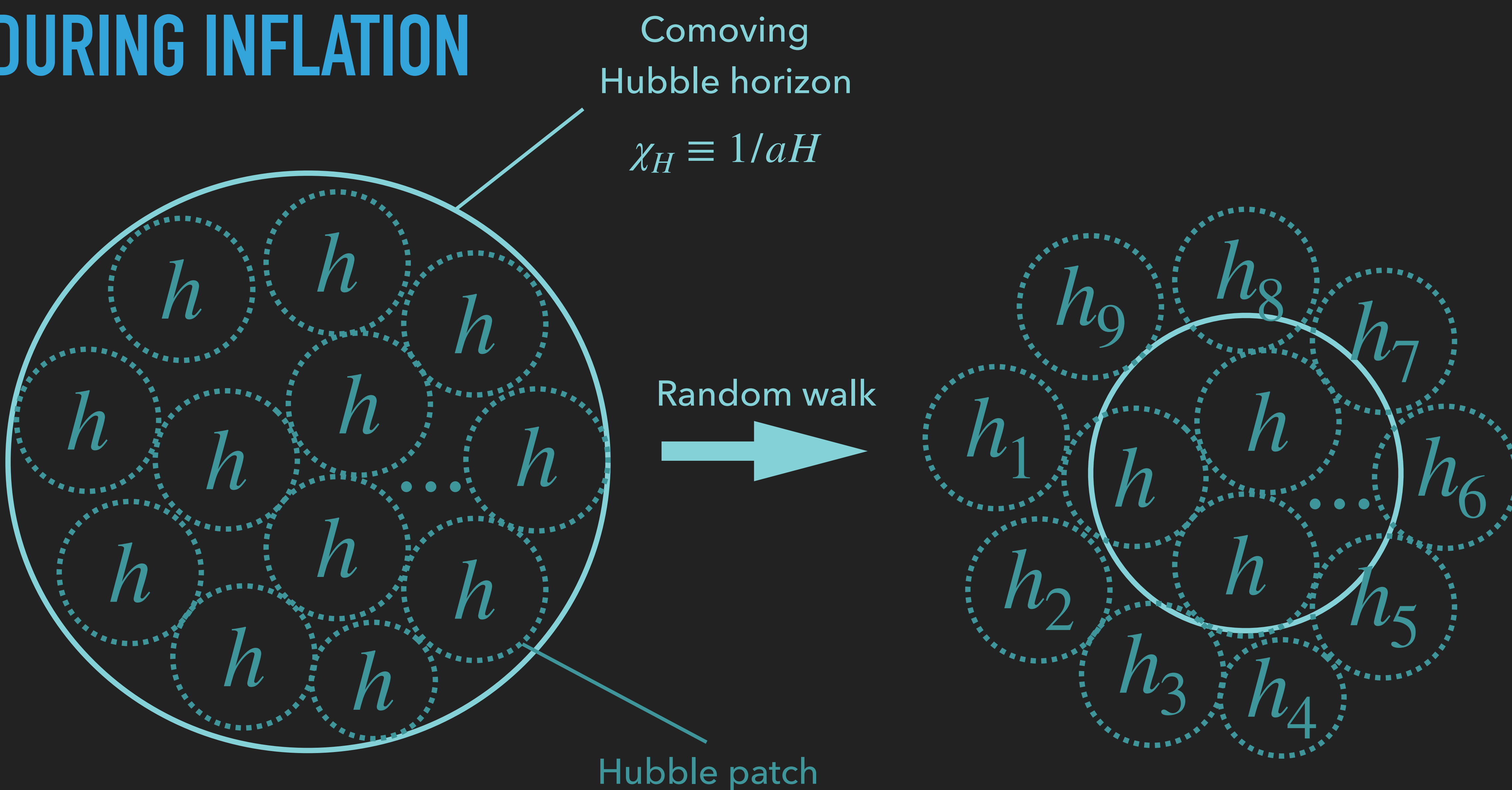
Initially, the Higgs field is rolling down its potential V(h)



Quantum fluctuations of the Higgs condensate take over



DURING INFLATION



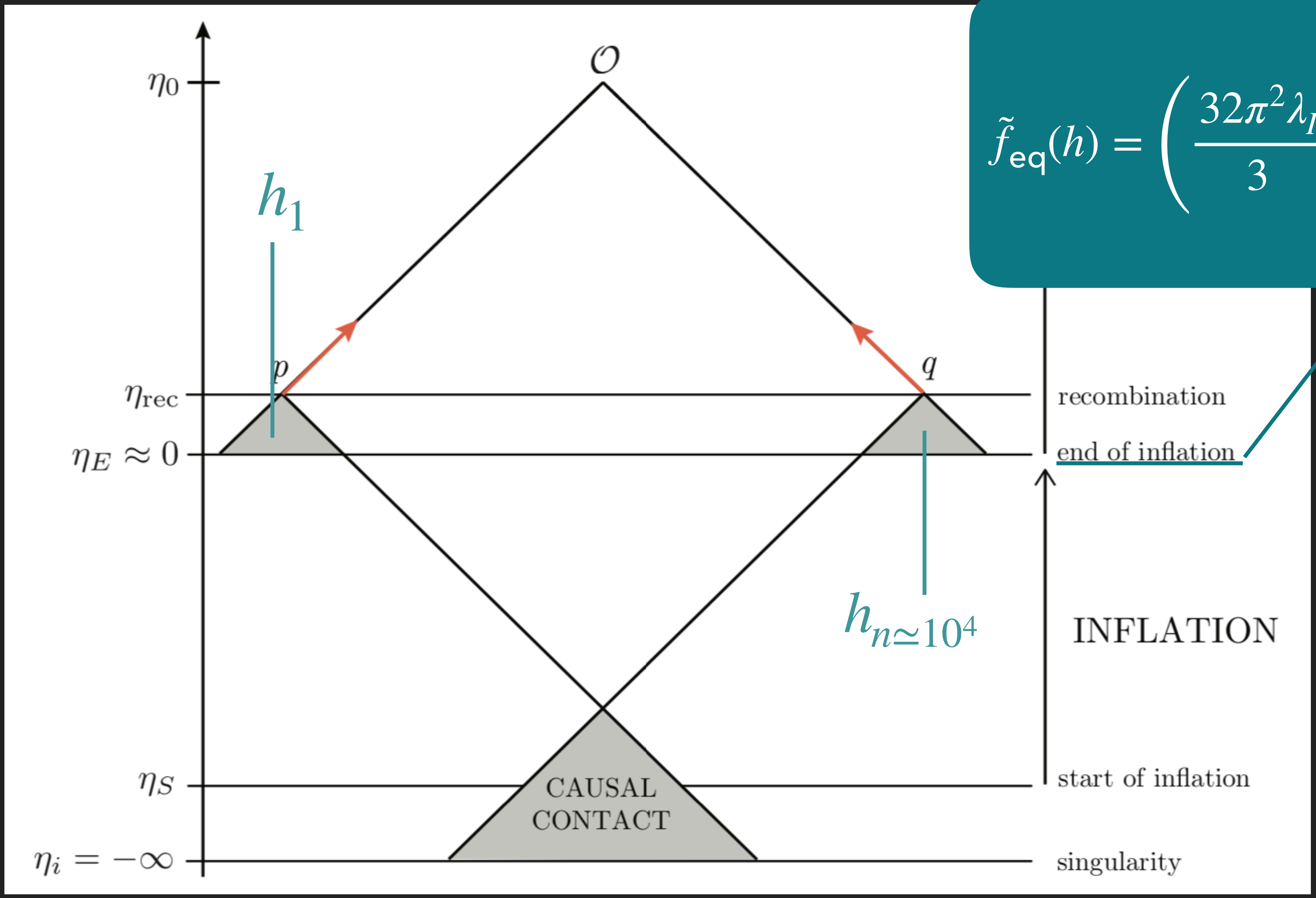
<u>Beginning of inflation:</u>
All patches inside the horizon
and in causal contact, same
Higgs VEV everywhere

<u>During inflation:</u>
Horizon shrinks, no causal contact,
different Higgs VEV in each super-horizon patch

AFTER INFLATION

- Every causally disconnected Hubble patch i, for $i \in \{1,\ldots,n\}$, has a different value of the Higgs h_i, which obeys the the equilibrium PDF at the end of inflation

$$\tilde{f}_{\rm eq}(h) = \left(\frac{32\pi^2\lambda_I}{3}\right)^{1/4} \frac{1}{\Gamma(1/4)H_I} \exp\left(-\frac{2\pi^2\lambda_I h^4}{3H_I^4}\right)$$

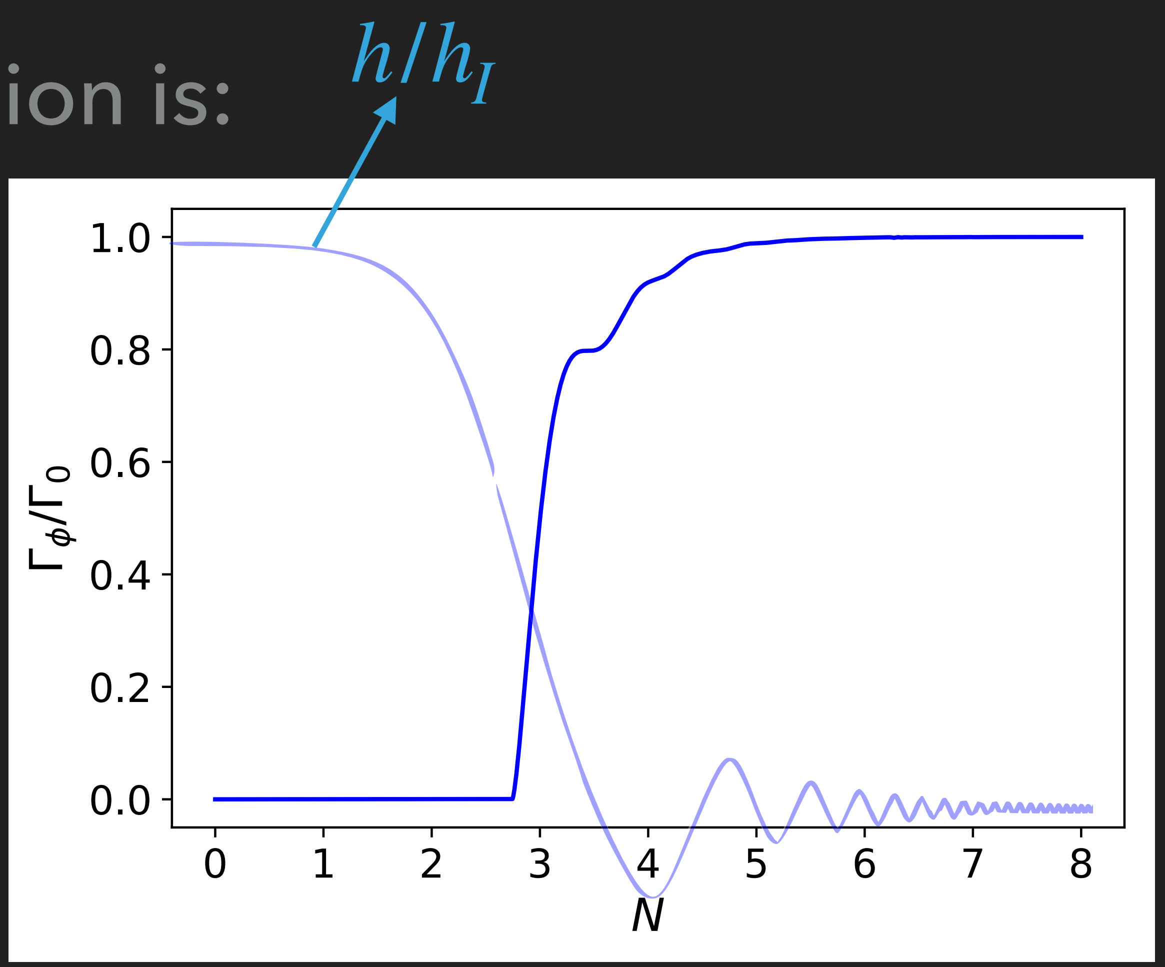


Adapted from D. Baumann, Lectures on Cosmology

HIGGS MODULATION/BLOCKING

- We assume a Yukawa-type coupling of the inflaton to SM fermions $\propto \phi f \bar{f}$
- The fermion mass at a patch i, is given by Yukawa couplings y to the Higgs as $m_f^{i\,2} = y^2 h_i^2/2$
- The inflaton decay rate to the fermion is:

$$\Gamma_\phi^i = \Gamma_0 \left(1 - \frac{4 m_f^{i\,2}}{m_\phi^2}\right)^{3/2} \Theta\left(m_\phi^2 - 4 m_f^{i\,2}\right)$$



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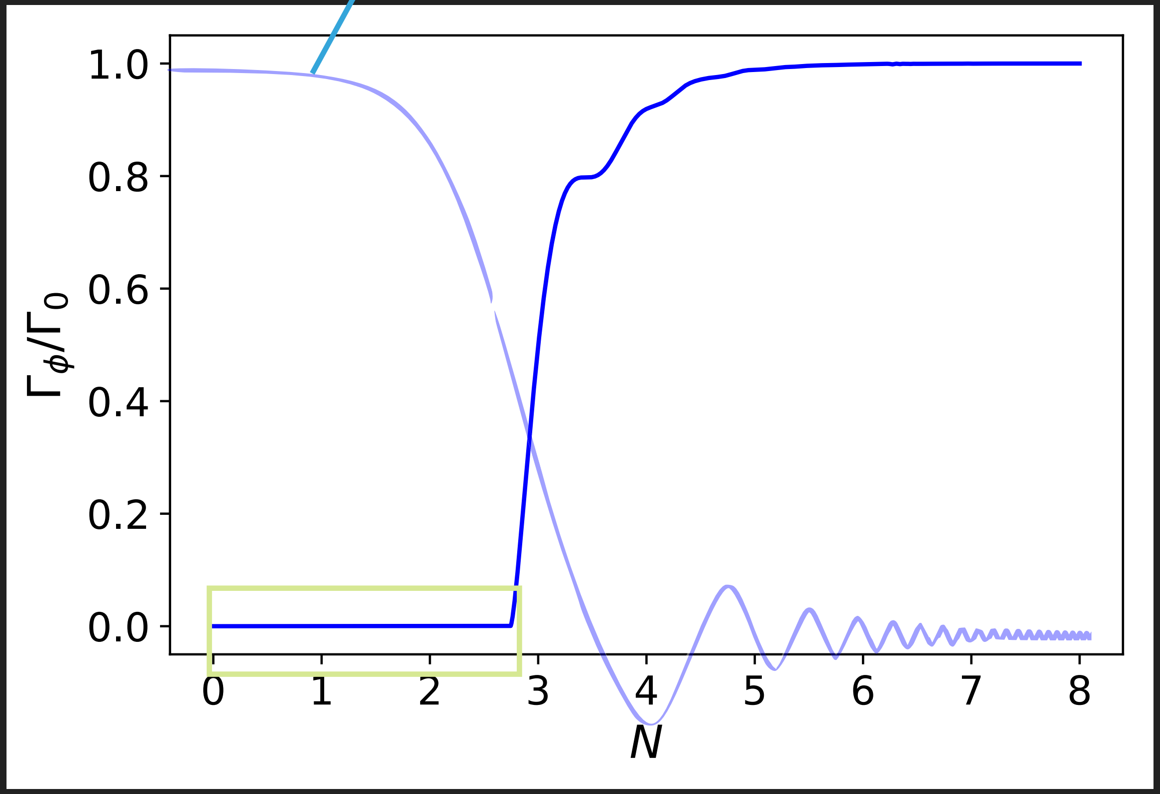
Higgs blocking of decay for $m_\phi < 2m_f^i$

h/h_I



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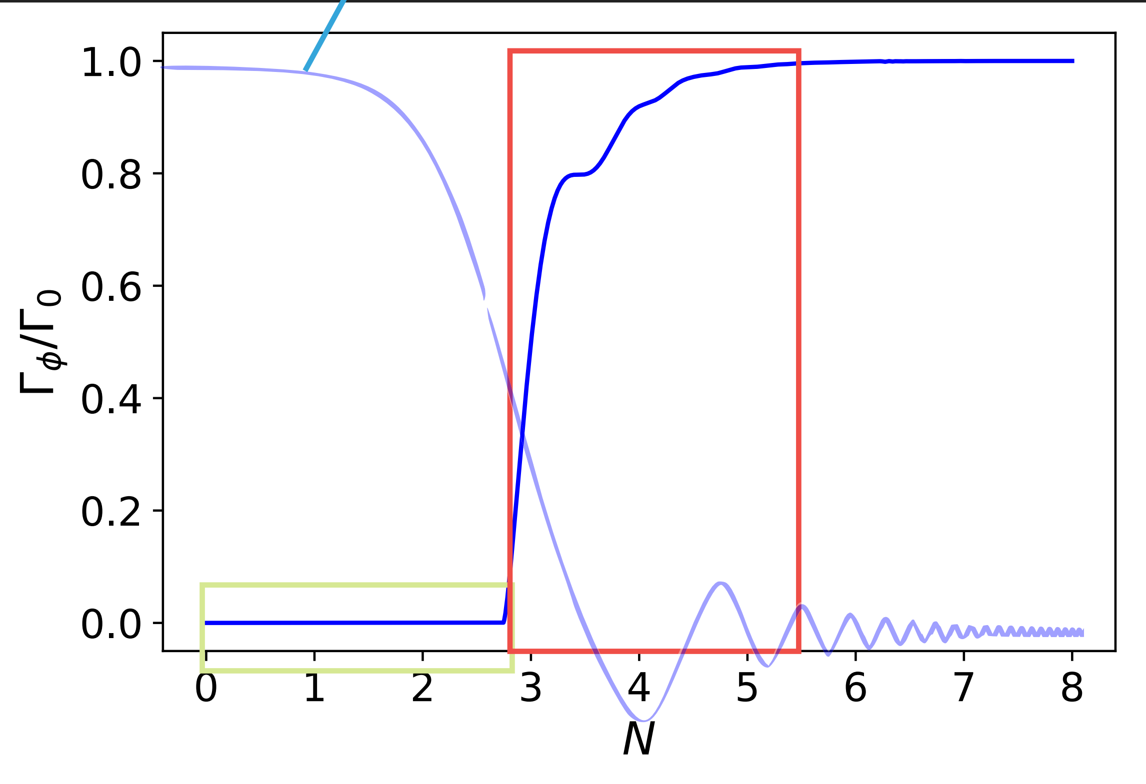

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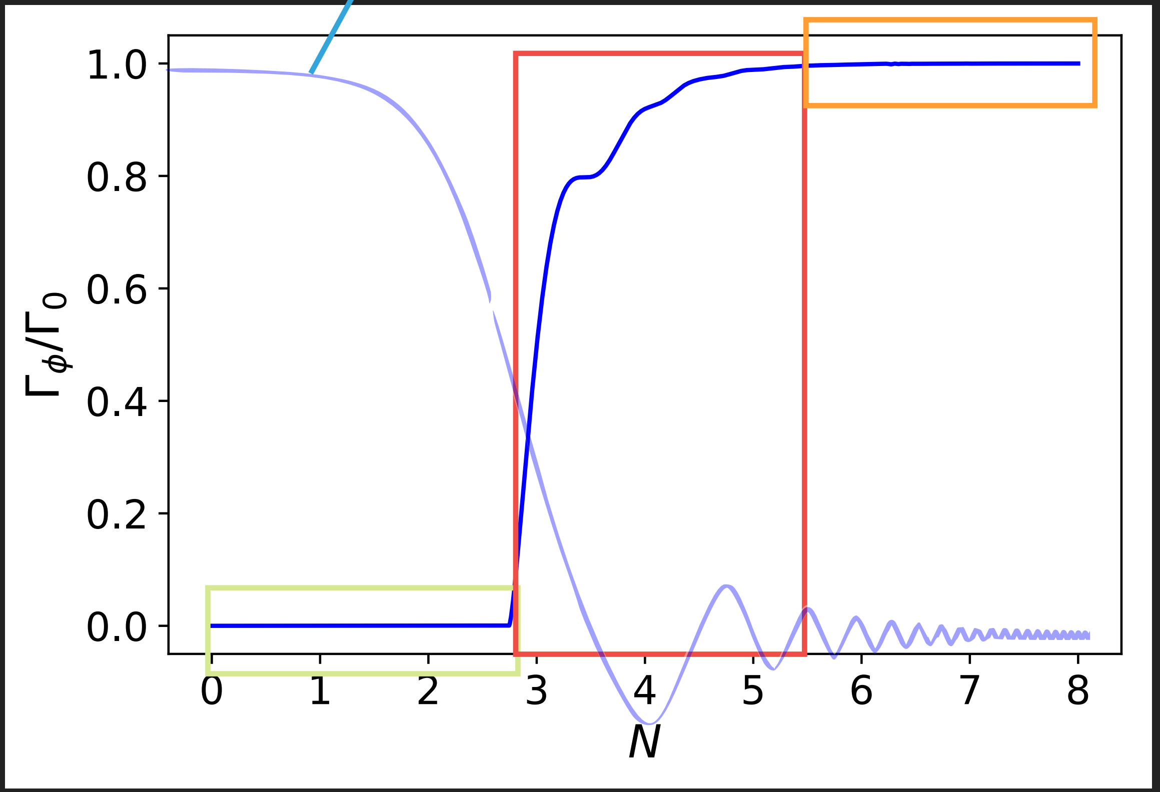
Unblocked decay rate (Γ_0)

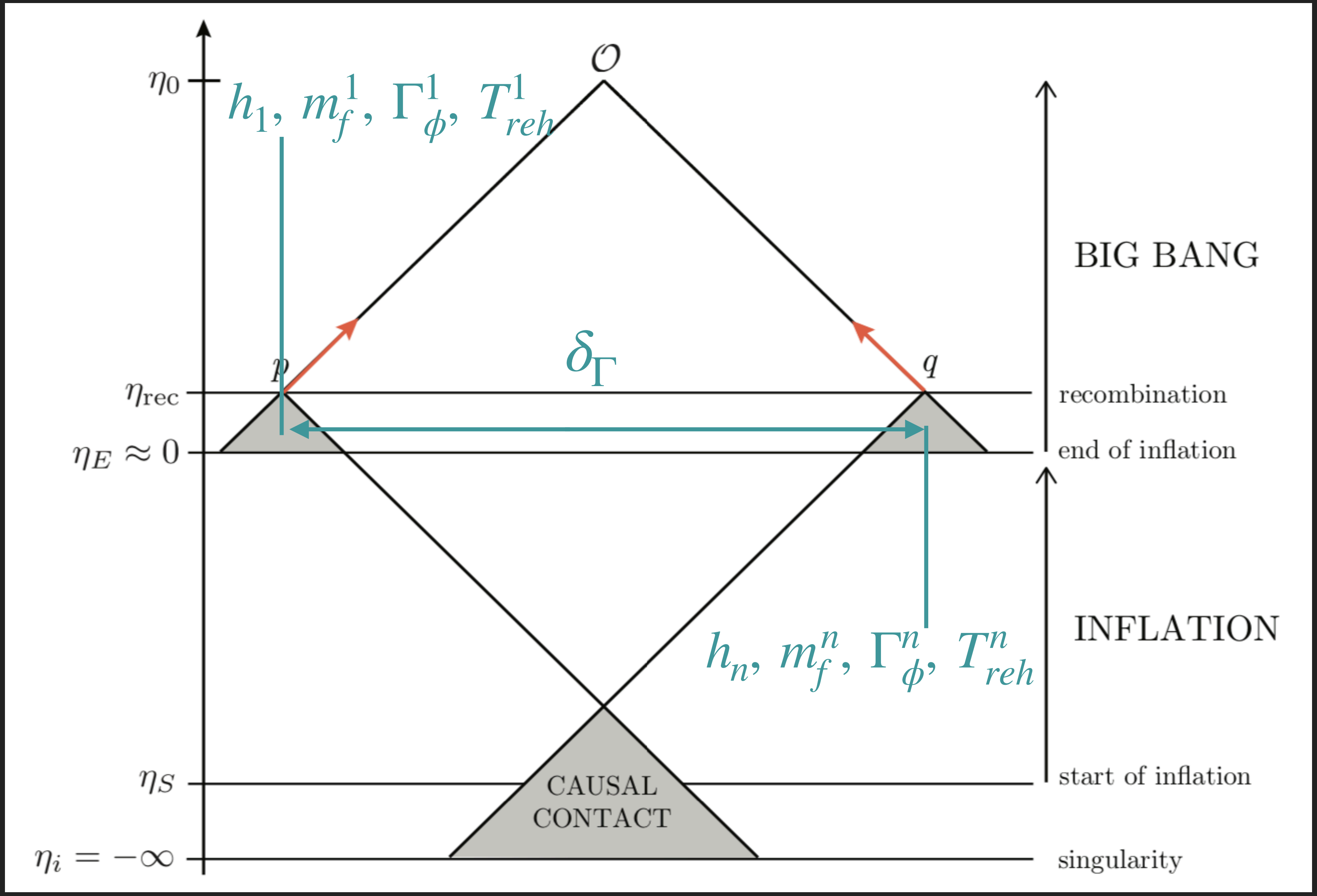
Higgs modulation of decay ($\frac{4m_f^{i\,2}}{m_\phi^2}$)

Higgs blocking of decay for $m_\phi < 2m_f^i$ (Θ)



SPACE-DEPENDENT REHEAT TEMPERATURE

- Reheating at each Hubble patch happens at a different temperature T^i_{reh}



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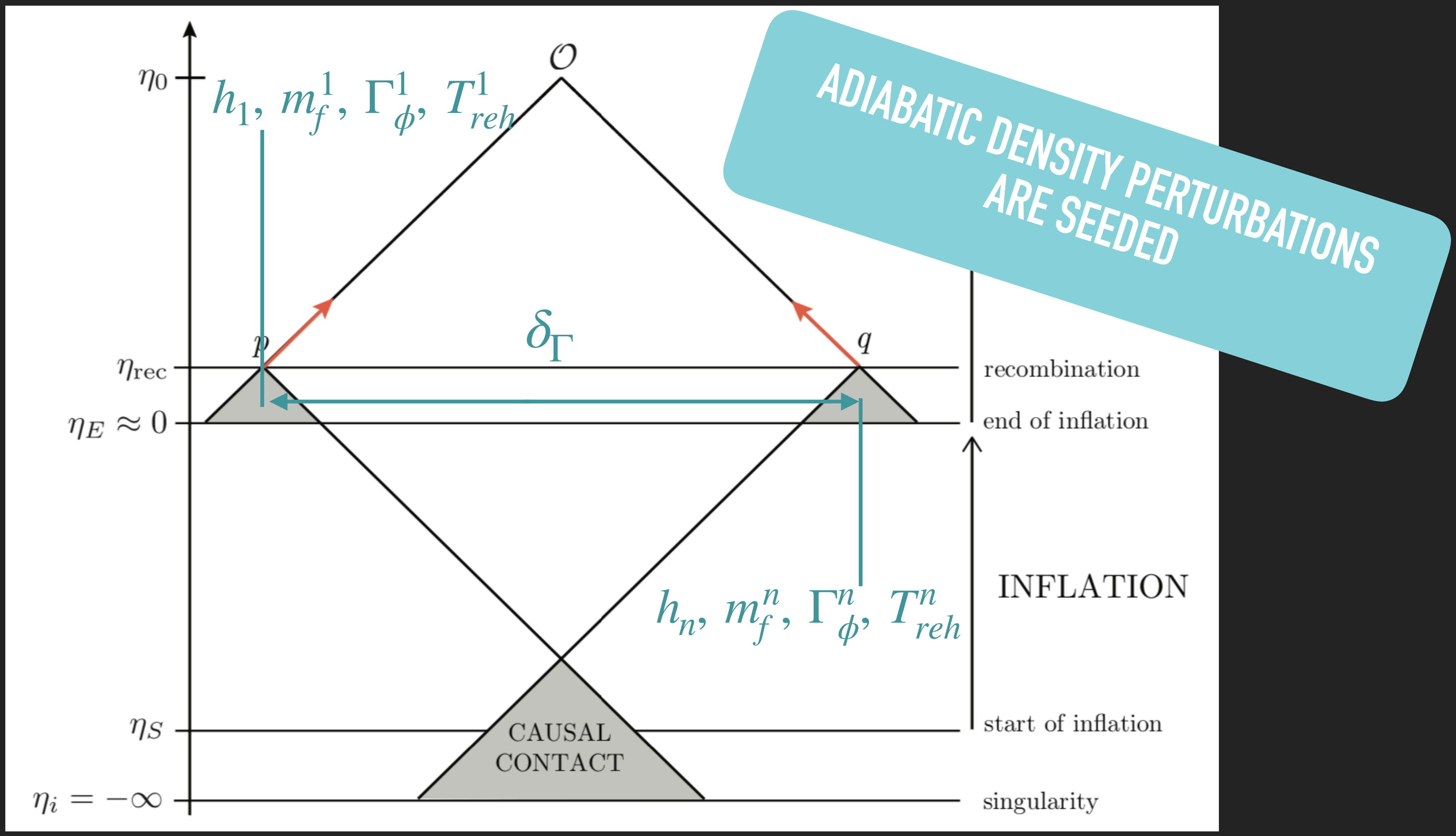

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UNPERTURBED EQUATIONS

$\tilde{f}_{\text{eq}}(h; N = 0)$

h_1^I

h_2^I

$\vdots$

h_i^I

$\vdots$

h_n^I

End of inflation

Evolve with time...

Energy density equations

$$d\rho_\phi^i/dN = -3\rho_\phi^i - (\Gamma_\phi^i/H^i)\rho_\phi^i$$

$$d\rho_r^i/dN = -4\rho_r^i + (\Gamma_\phi^i/H^i)\rho_\phi^i$$

Higgs EoM

$$\frac{d^2 h_i}{dN^2} + \left(3 + \frac{1}{H^i}\frac{dH^i}{dN}\right)\dot{h}_i + \frac{\lambda_I}{\left(H^i\right)^2} h_i^3 = 0$$

Expansion dynamics

$$\left(H^i\right)^2 = \frac{8\pi G}{3}\left(\rho_\phi^i + \rho_r^i\right)$$

$$\frac{dH^i}{dN} = \sqrt{\frac{4\pi G}{3\left(\rho_\phi^i + \rho_r^i\right)}}\left(\frac{d\rho_\phi^i}{dN} + \frac{d\rho_r^i}{dN}\right)$$

$\tilde{f}(h; N)$

$h_1(N)$

$h_2(N)$

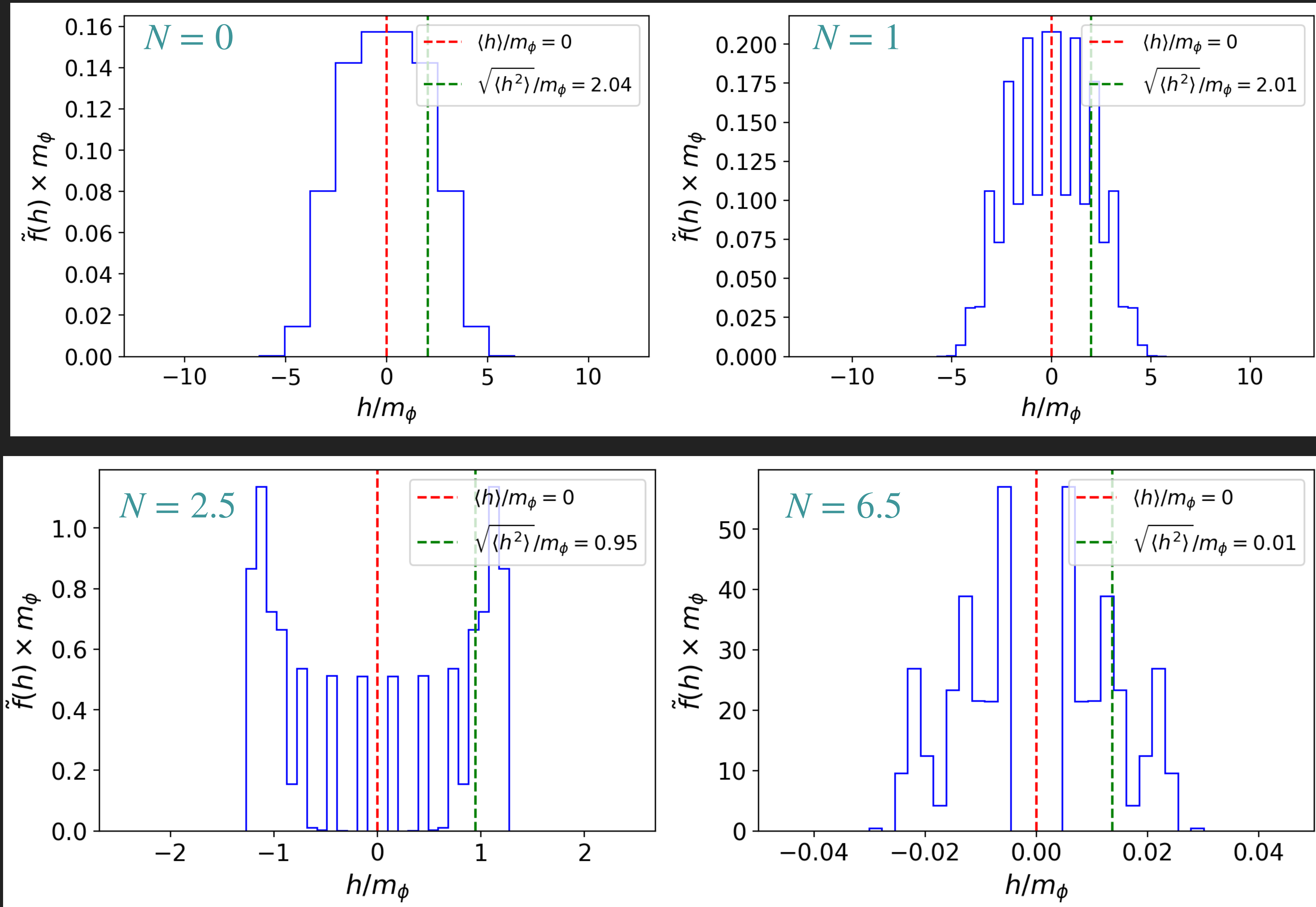
$\vdots$

$h_i(N)$

$\vdots$

$h_n(N)$

N e-folds after inflation



$y = 1,\ \Gamma_0 = 10^{-1} \times m_\phi,\ \lambda_I = 10^{-3},\ H_I = m_\phi$

DECAY RATE PERTURBATION

- We define a characteristic value of the Higgs VEV over all Hubble patches $\tilde{h}(N) \equiv \left(\int h^2 \tilde{f}(h;N) dh \right)^{1/2}$
- We define the average decay rate over all patches at the characteristic value $\tilde{h}$ as

$$\bar{\Gamma}_\phi = \Gamma_0 \left(1 - \frac{2y^2\tilde{h}^2}{m_\phi^2} \right)^{3/2} \Theta\left(m_\phi^2 - 2y^2\tilde{h}^2 \right)$$

- The characteristic decay rate perturbation, then, is

$$\delta_\Gamma \equiv \frac{\delta\Gamma_\phi}{\bar{\Gamma}_\phi} = \begin{cases} -\frac{6y^2h\,\delta h}{m_\phi^2}\left(1 - \frac{2y^2h^2}{m_\phi^2}\right)^{-1} \to -\frac{6y^2\tilde{h}^2}{m_\phi^2}\left(1 - \frac{2y^2\tilde{h}^2}{m_\phi^2}\right)^{-1} & \text{for } m_\phi^2 > 4m_f^2 \\ 0 & \text{for } m_\phi^2 \leq 4m_f^2 \end{cases}$$

PERTURBED EQUATIONS (DVALI ET. AL 2003)

- The perturbations in the inflation and radiation energy densities:

$$\frac{d\delta_\phi}{dN} = 3\frac{d\Phi}{dN} - \frac{\bar{\Gamma}_\phi}{H}\left(\delta_\Gamma + \Phi\right) \qquad \frac{d\delta_r}{dN} = 4\frac{d\Phi}{dN} + \frac{\bar{\rho}_\phi}{\bar{\rho}_r}\frac{\bar{\Gamma}_\phi}{H}\left(\delta_\Gamma + \Phi + \delta_\phi - \delta_r\right)$$

- The background equations:

$$d\bar{\rho}_\phi/dN = -3\bar{\rho}_\phi - (\bar{\Gamma}_\phi/H)\bar{\rho}_\phi \qquad d\bar{\rho}_r/dN = -4\bar{\rho}_r + (\bar{\Gamma}_\phi/H)\bar{\rho}_\phi$$

- The gravitational potential perturbation:

$$\frac{d\Phi}{dN} = -\Phi - \frac{4\pi G}{3H^2}\left(\bar{\rho}_\phi\delta_\phi + \bar{\rho}_r\delta_r\right)$$

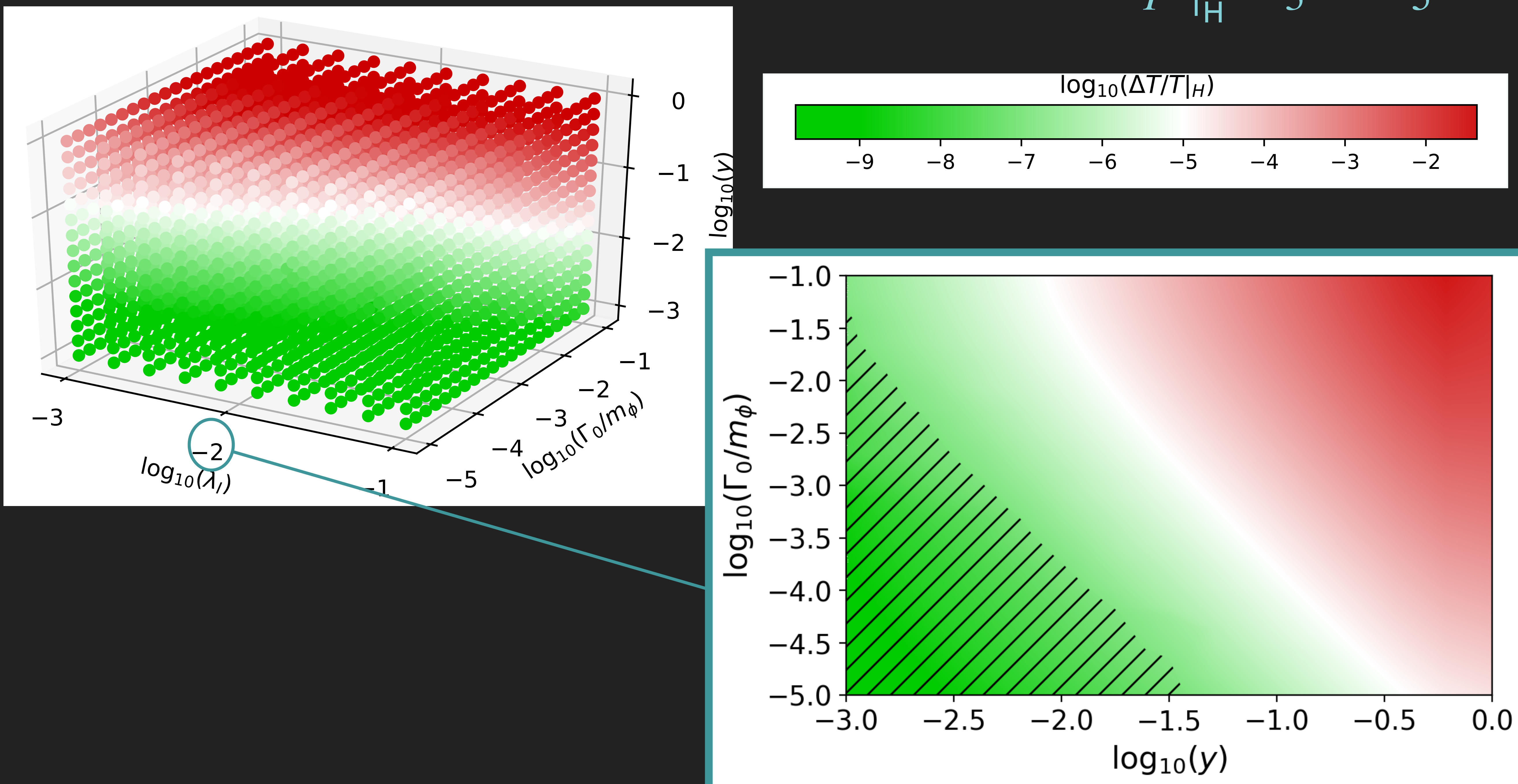
- The Bardeen parameter perturbation:

$$\zeta = -\Phi + \frac{\bar{\rho}_\phi\delta_\phi + \bar{\rho}_r\delta_r}{3\bar{\rho}_\phi + 4\bar{\rho}_r}$$

- We plug the $\bar{\Gamma}_\phi(N)$ and $\delta_\Gamma(N)$ calculated earlier and find $\zeta(N)$

CMB BOUNDS - TEMPERATURE FLUCTUATIONS

- The temperature fluctuations are given by $\left.\frac{\Delta T}{T}\right|_{\mathrm{H}} = \frac{1}{3}\Phi_f = \frac{1}{5}\zeta_f$



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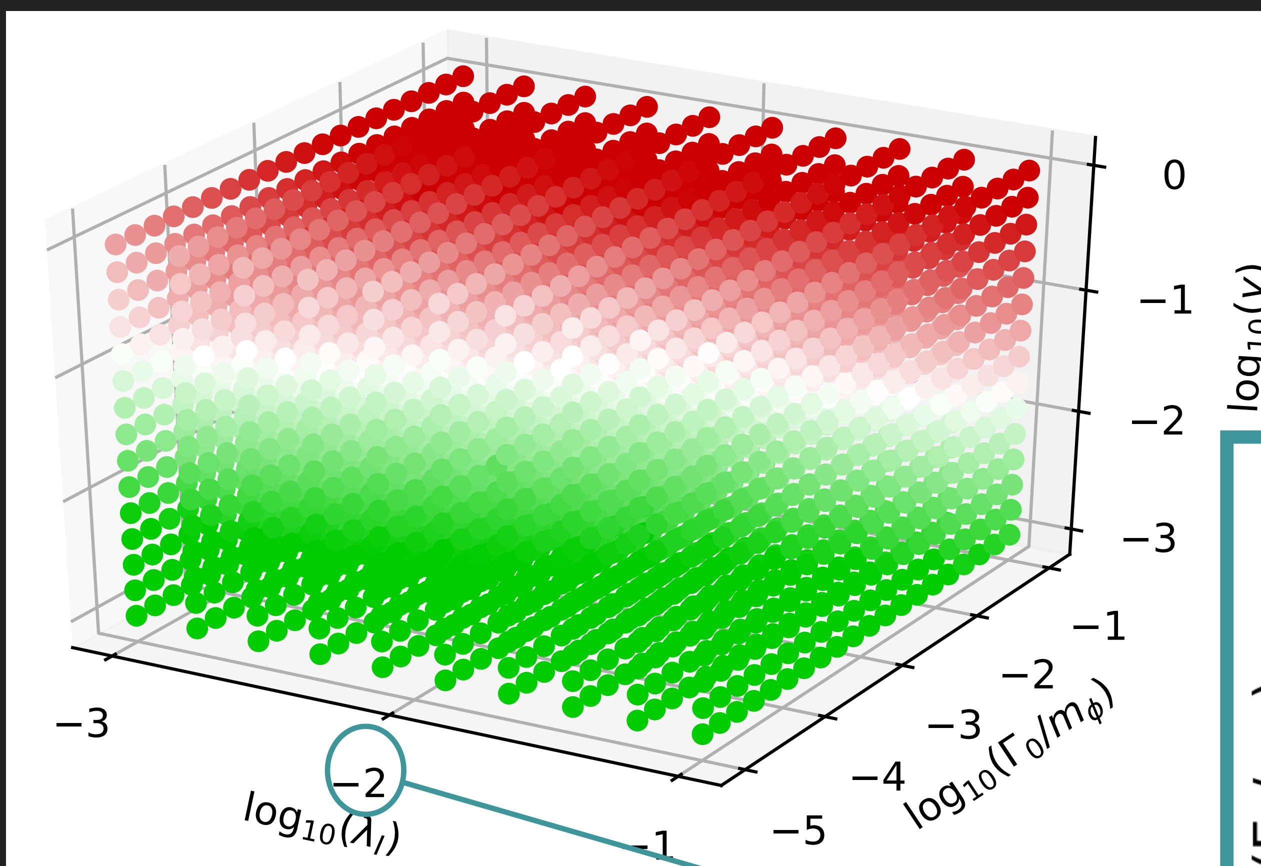

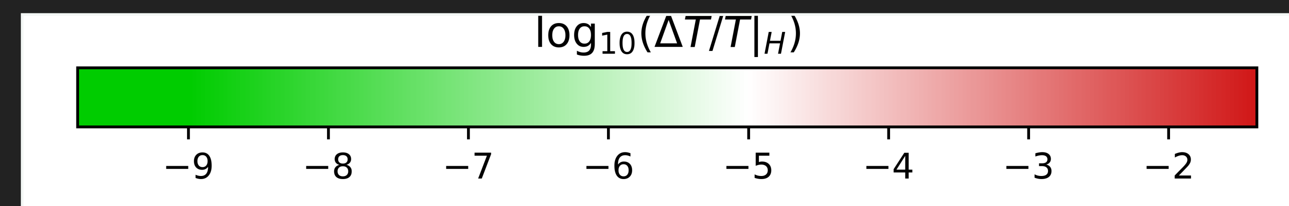

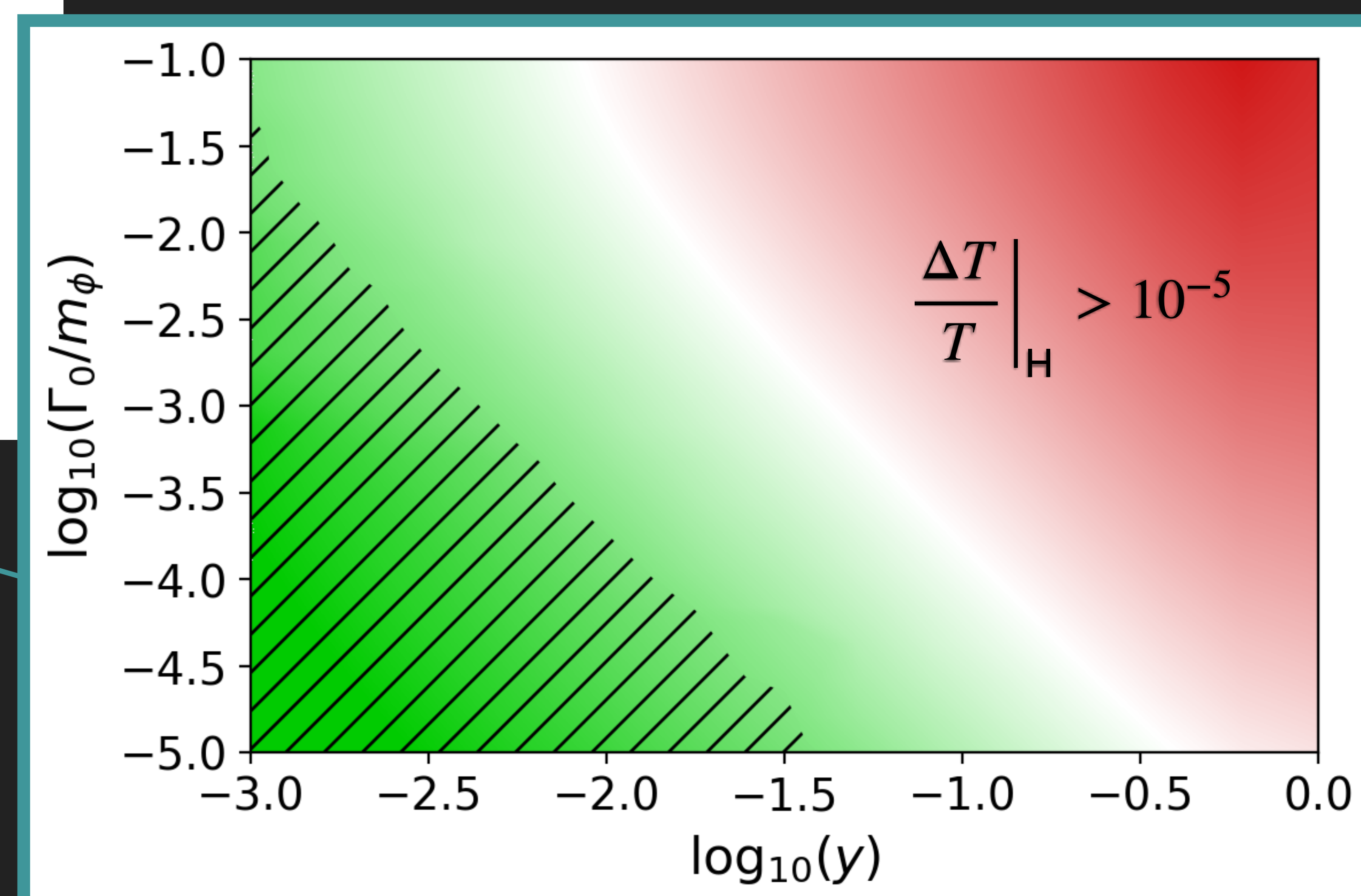

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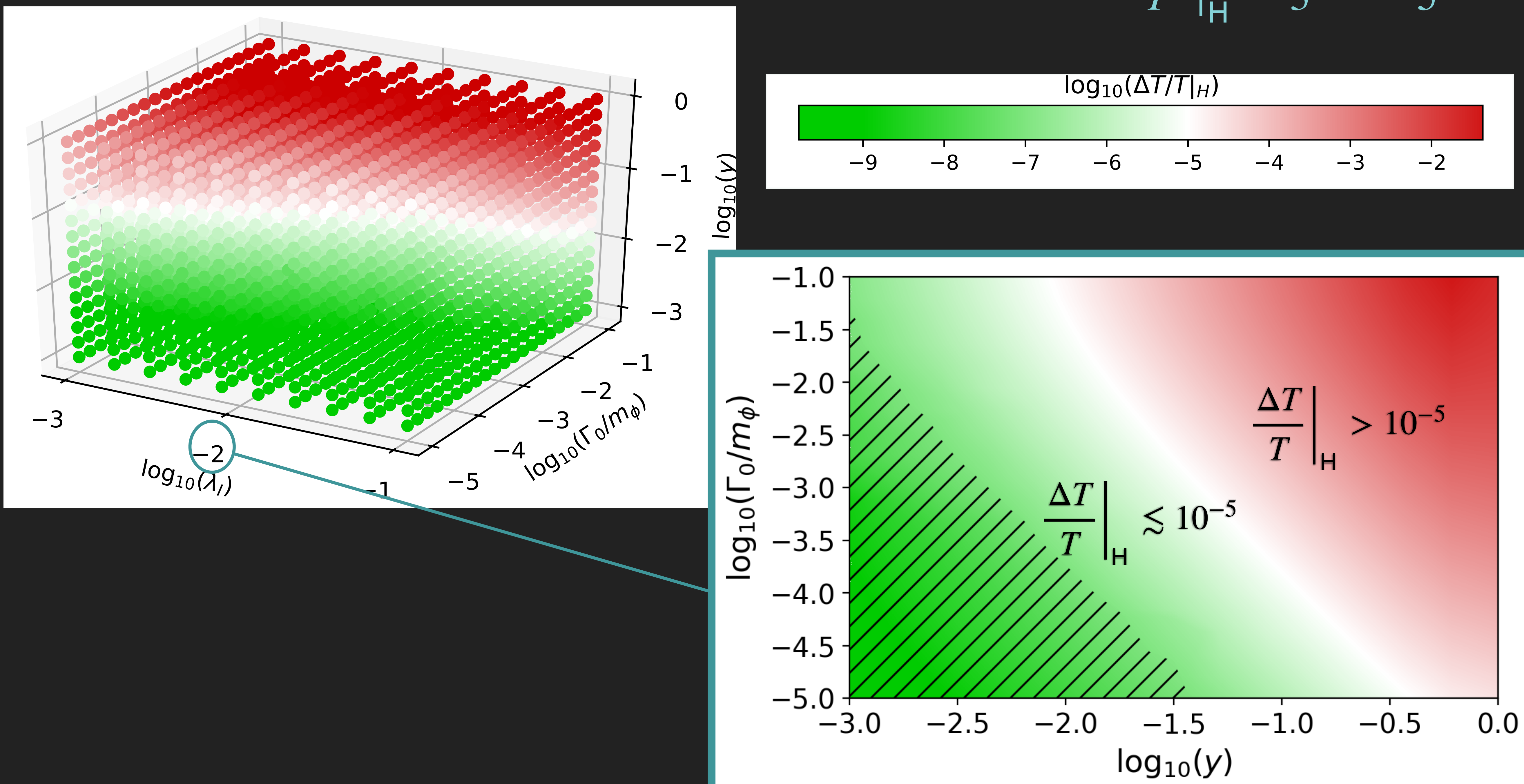

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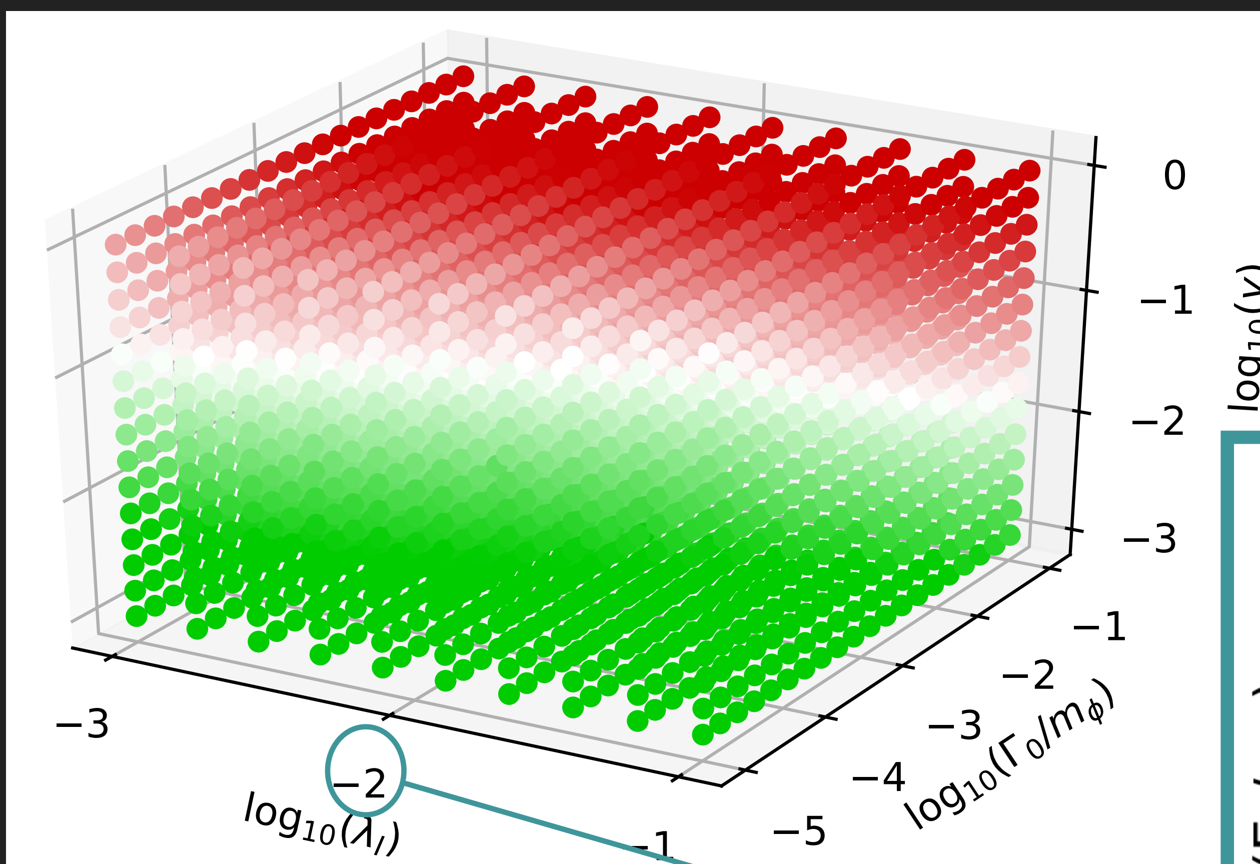
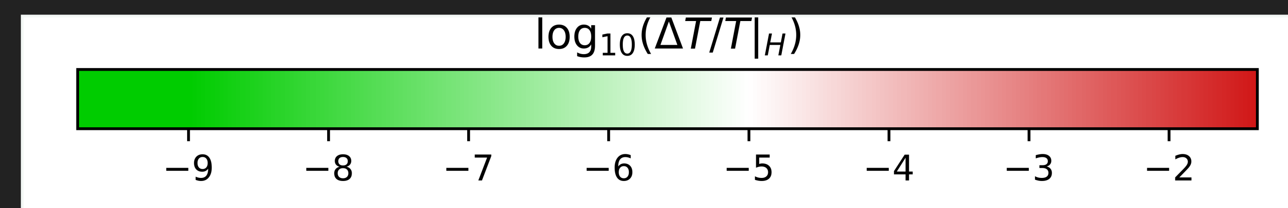
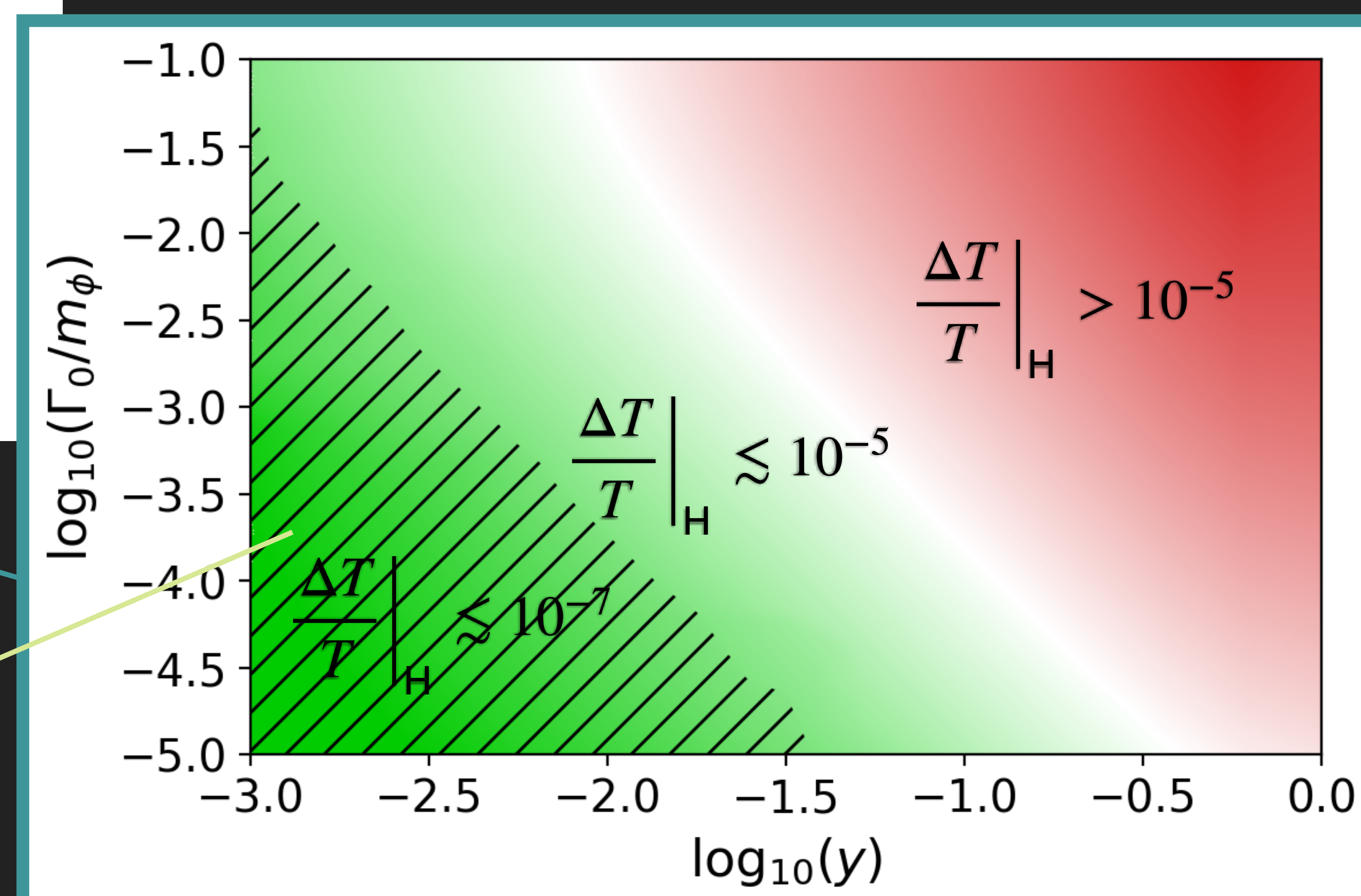






Region observations are not sensitive to

THEORY

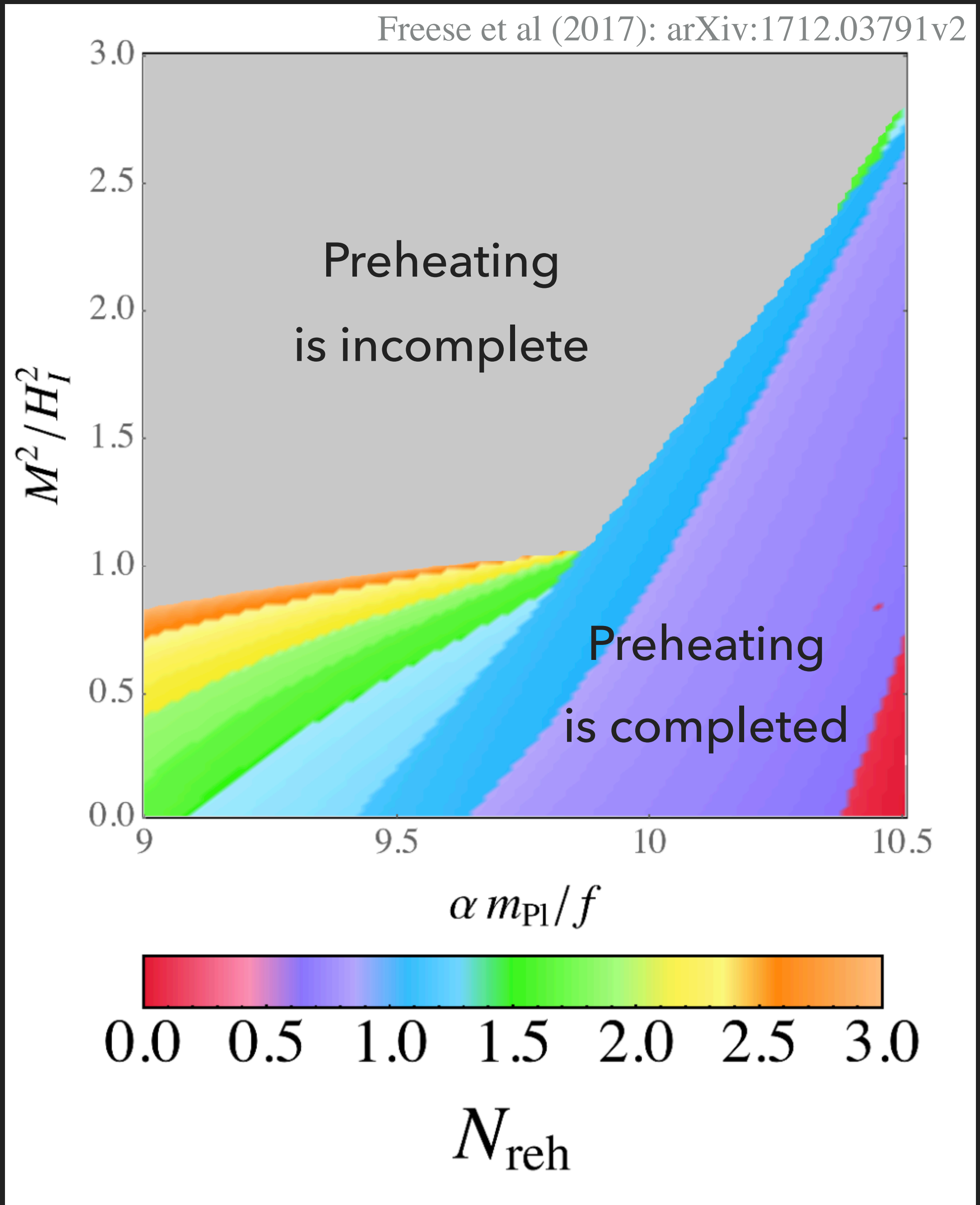
- Preheating via tachyonic resonant decays of the inflaton to gauge bosons
- The inflaton couples to U(1) gauge bosons via a Chern-Simons coupling

$$\propto \phi F^{\mu\nu}\tilde{F}_{\mu\nu}/4f$$

- The gauge boson gets its mass via a gauge coupling g to the Higgs:

$$M = g|h|/2$$

- We *cannot define a decay rate* like in the perturbative case!



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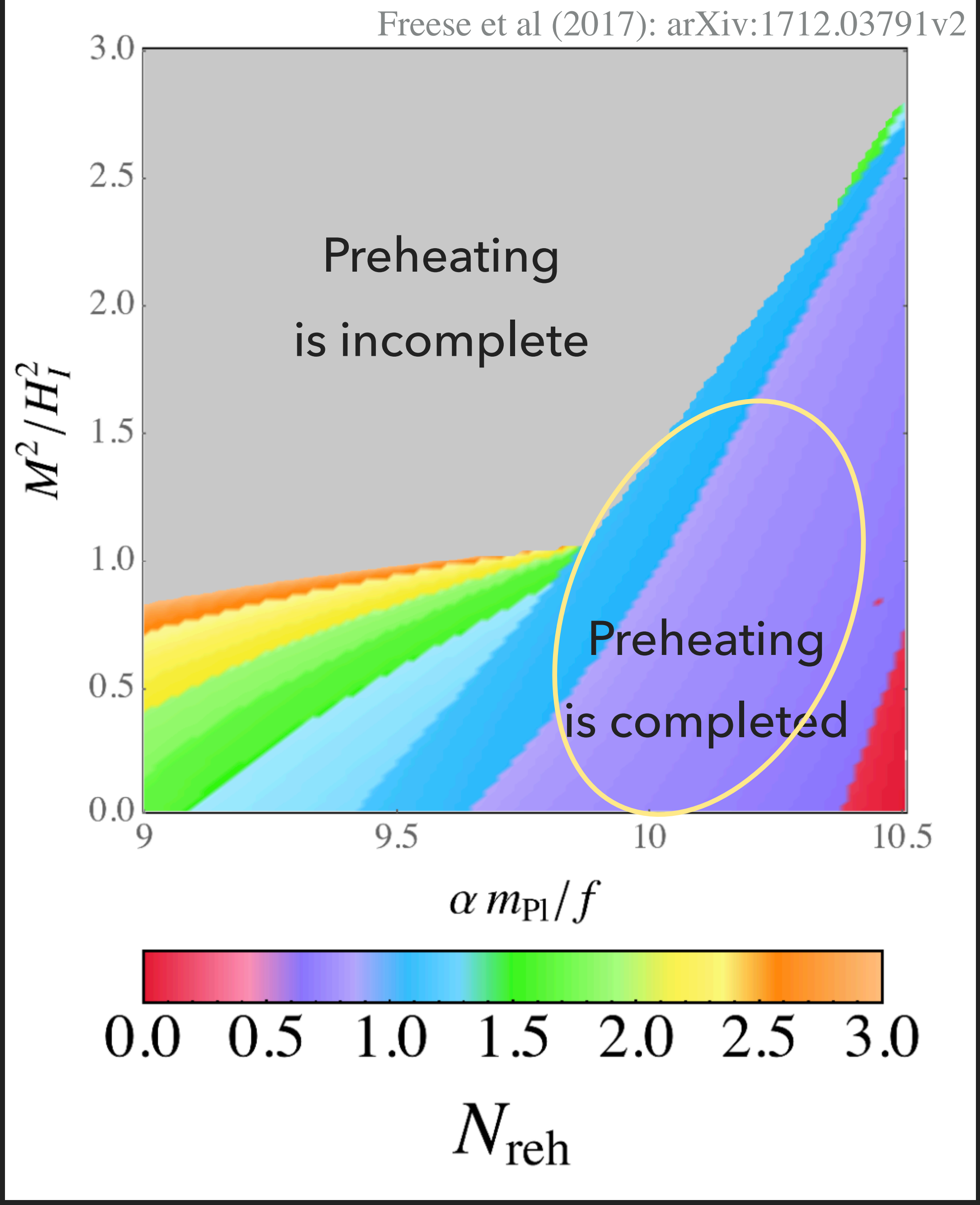


* We choose $f = 0.1\, m_{\rm Pl}$

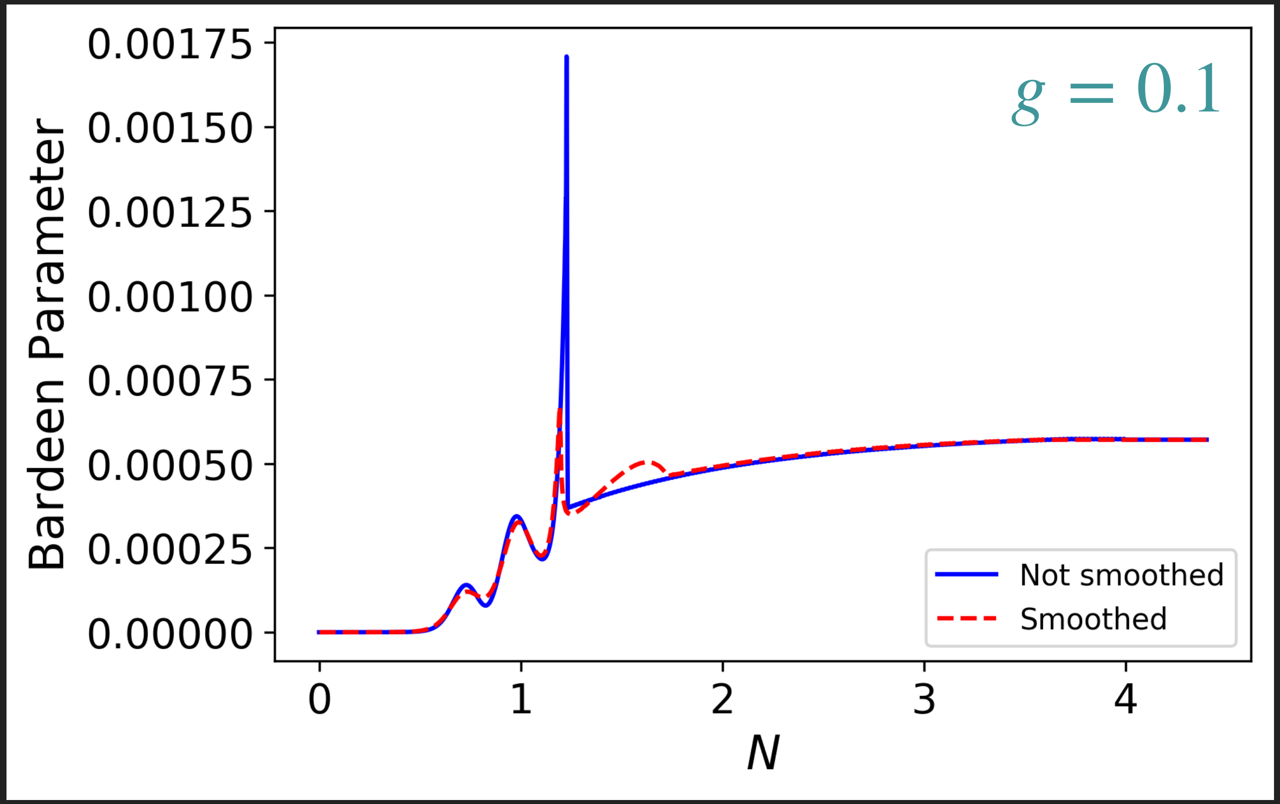
METHOD

- We again start from a distribution of n Higgs values h_i across n different Hubble patches
- Each Hubble patch, then, is characterized by a different gauge boson mass M_i
- We solve the EoM of the gauge field at each patch and derive the inflaton an radiation energy densities at each patch, at every point in time $\rho^i_\phi(N),\ \rho^i_r(N)$
- The energy density background and perturbations can then be defined as:

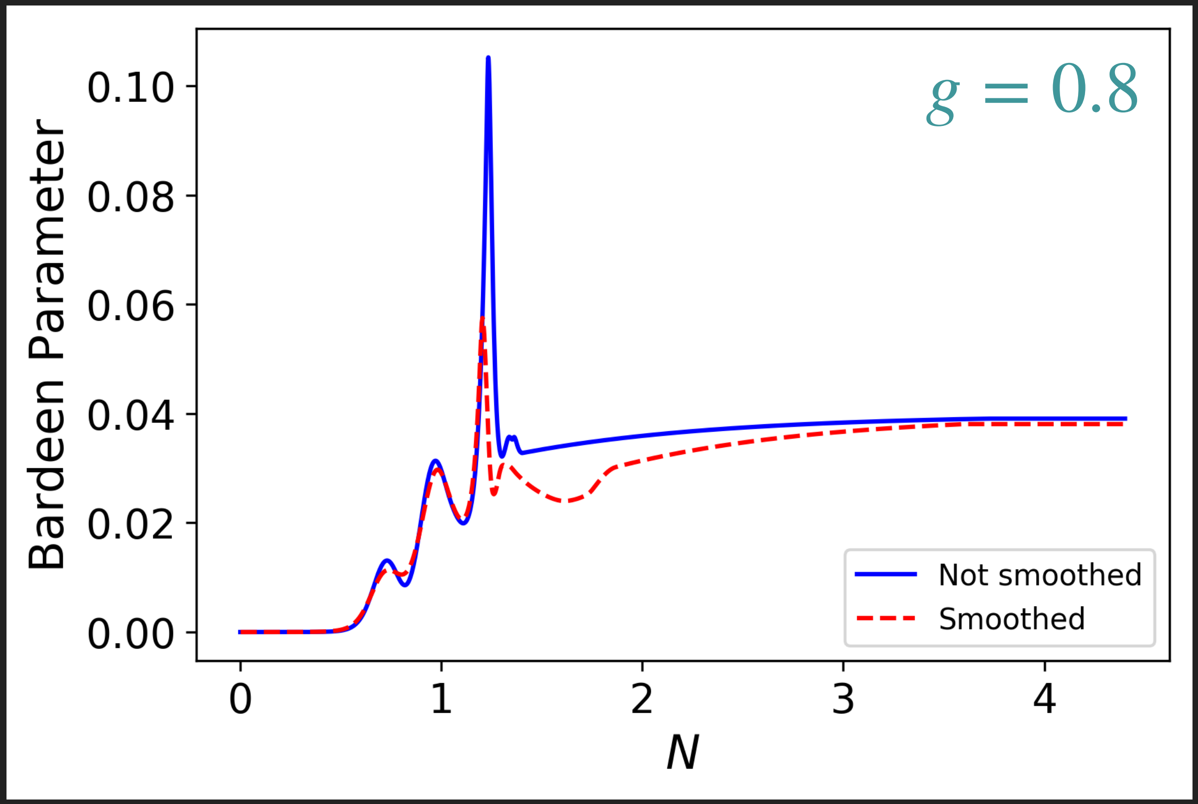
$$\bar{\rho}_{\phi/r}(N) \equiv \langle \rho_{\phi/r}(N) \rangle \qquad \delta_{\phi/r} \equiv \sqrt{\langle \rho^2_{\phi/r}(N) \rangle} / \bar{\rho}_{\phi/r}(N)$$

RESULTS

- We plug the background and perturbation functions into the gravitational potential and Bardeen parameter equations for $f = 0.1\, m_{\rm Pl}$



$$\left.\frac{\Delta T}{T}\right|_{\rm H} \simeq 10^{-4}$$



$$\left.\frac{\Delta T}{T}\right|_{\rm H} \simeq 8 \times 10^{-3}$$

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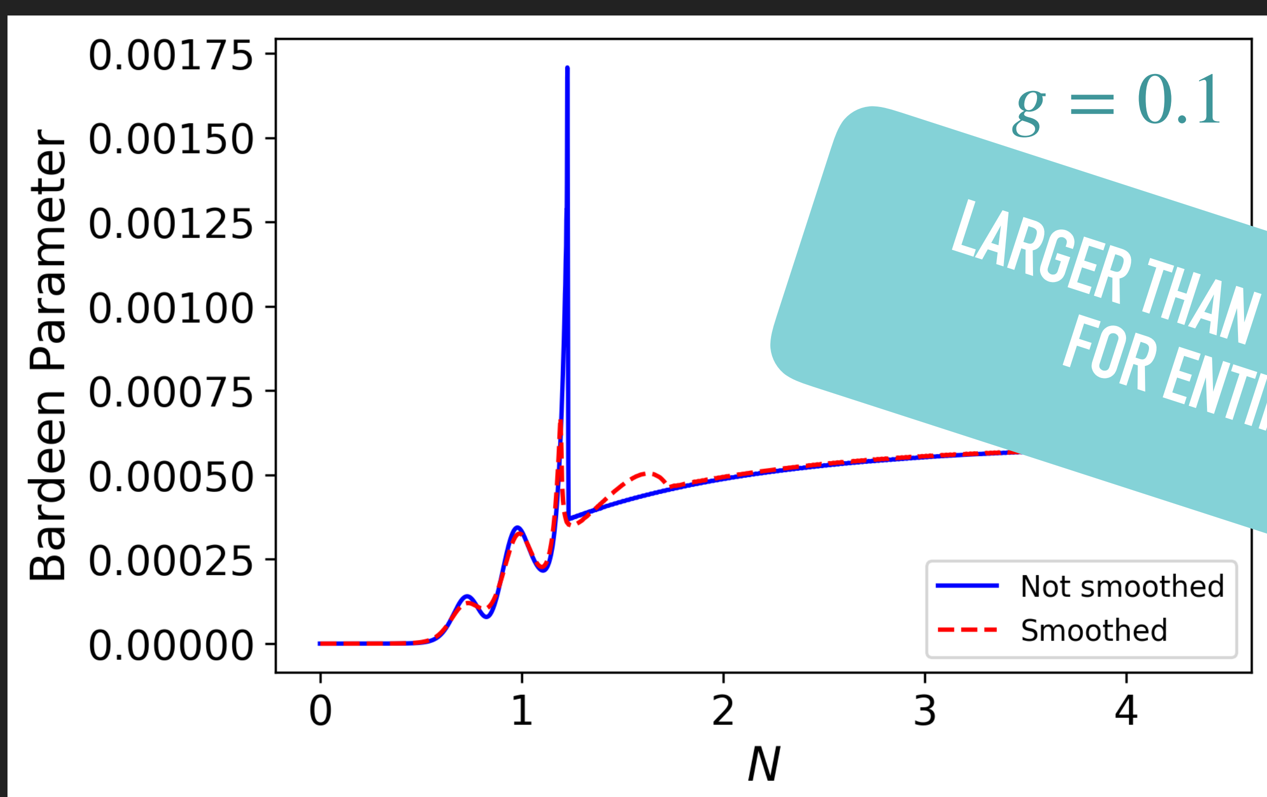

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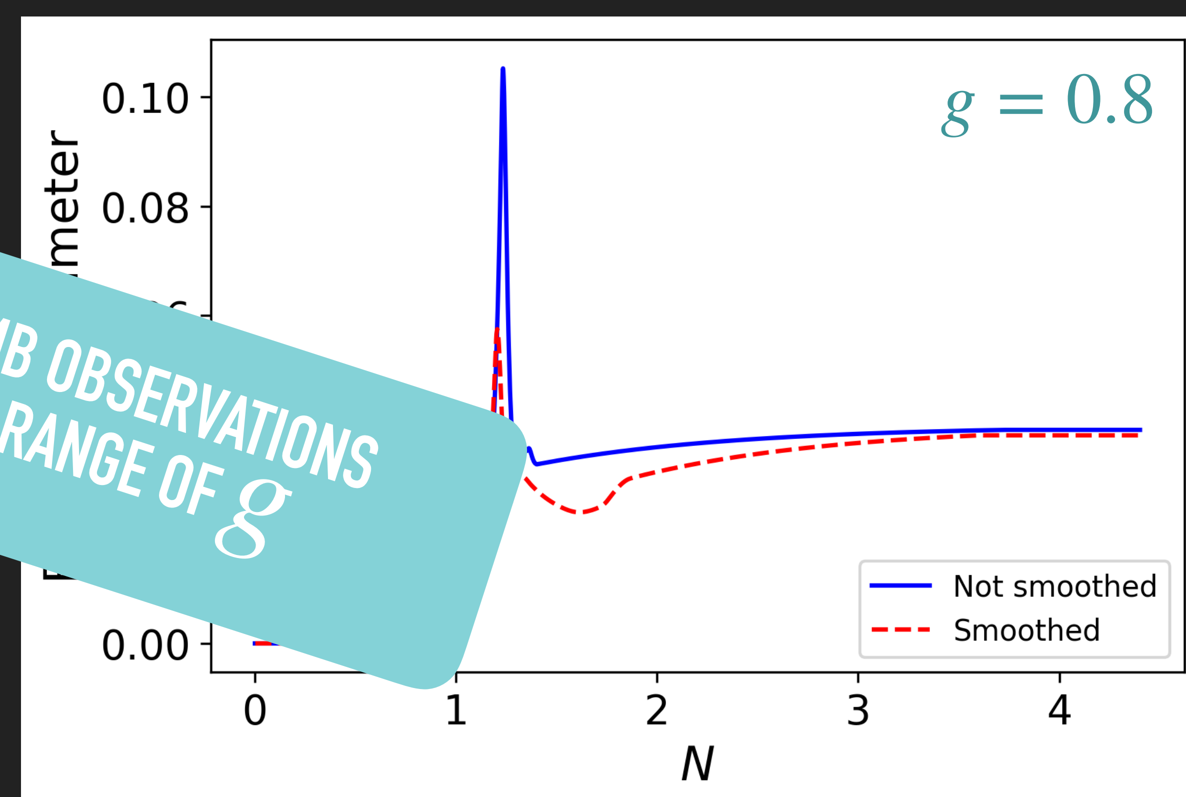

$$\left.\frac{\Delta T}{T}\right|_{\rm H} \simeq 8 \times 10^{-3}$$

LARGER THAN CMB OBSERVATIONS FOR ENTIRE RANGE OF g

PATCH-BY-PATCH METHOD

$\tilde{f}_{\rm eq}(h; N=0)$

h_1^I, h_2^I, ..., h_i^I, ..., h_n^I

Evolve with time....

Energy density equations

$$d\rho_\phi^i/dN = -3\rho_\phi^i - (\Gamma_\phi^i/H^i)\rho_\phi^i$$

$$d\rho_r^i/dN = -4\rho_r^i + (\Gamma_\phi^i/H^i)\rho_\phi^i$$

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$$\frac{d^2h_i}{dN^2} + \left(3 + \frac{1}{H^i}\frac{dH^i}{dN}\right)\dot{h}_i + \frac{\lambda_I}{\left(H^i\right)^2}h_i^3 = 0$$

Expansion dynamics

$$\left(H^i\right)^2 = \frac{8\pi G}{3}\left(\rho_\phi^i + \rho_r^i\right)$$

$$\frac{dH^i}{dN} = \sqrt{\frac{4\pi G}{3\left(\rho_\phi^i + \rho_r^i\right)}}\left(\frac{d\rho_\phi^i}{dN} + \frac{d\rho_r^i}{dN}\right)$$

$\tilde{g}(\rho_\phi; N)$ $\tilde{g}(\rho_r; N)$

$\rho_\phi^1(N)$ $\rho_r^1(N)$

$\rho_\phi^2(N)$ $\rho_r^2(N)$

...

$\rho_\phi^i(N)$ $\rho_r^i(N)$

...

$\rho_\phi^n(N)$ $\rho_r^n(N)$

End of inflation

N e-folds after inflation

PATCH-BY-PATCH METHOD

Perturbation PDFs with time

$\tilde{g}(\rho_{\phi/r}; N)$

$\rho^1_{\phi/r}(N)$, $\rho^2_{\phi/r}(N)$, …, $\rho^i_{\phi/r}(N)$, …, $\rho^n_{\phi/r}(N)$

We use the definitions of the energy density background and perturbations

$$\bar{\rho}_{\phi/r}(N) \equiv \langle \rho_{\phi/r}(N) \rangle$$

$$\delta^i_{\phi/r} \equiv \left(\rho^i_{\phi/r}(N) - \bar{\rho}_{\phi/r}(N) \right) / \bar{\rho}_{\phi/r}(N)$$

$\tilde{g}(\delta_{\phi/r}; N)$

$\delta^1_{\phi/r}(N)$, $\delta^2_{\phi/r}(N)$, …, $\delta^i_{\phi/r}(N)$, …, $\delta^n_{\phi/r}(N)$

$\tilde{g}(\Phi; N)$

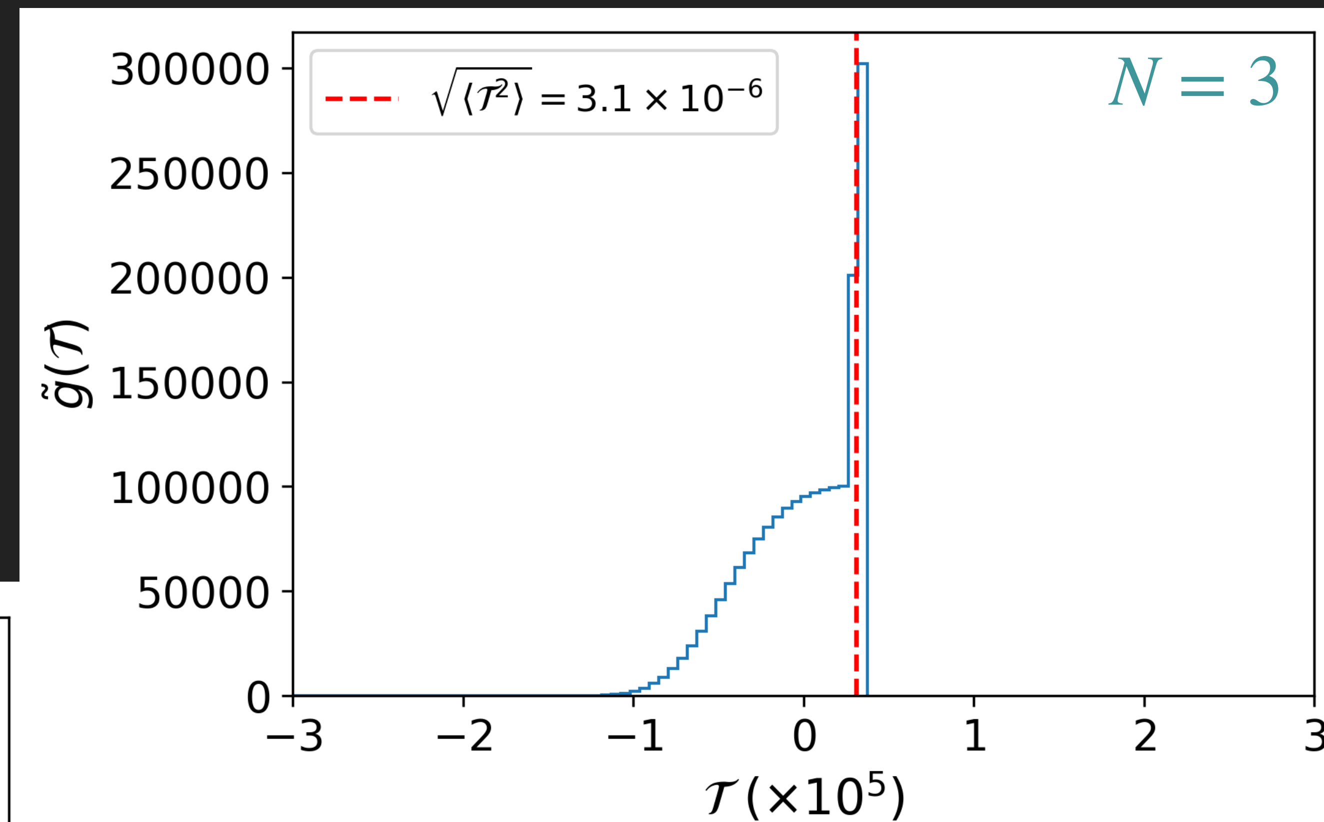
$\Phi^1(N)$, $\Phi^2(N)$, …, $\Phi^i(N)$, …, $\Phi^n(N)$

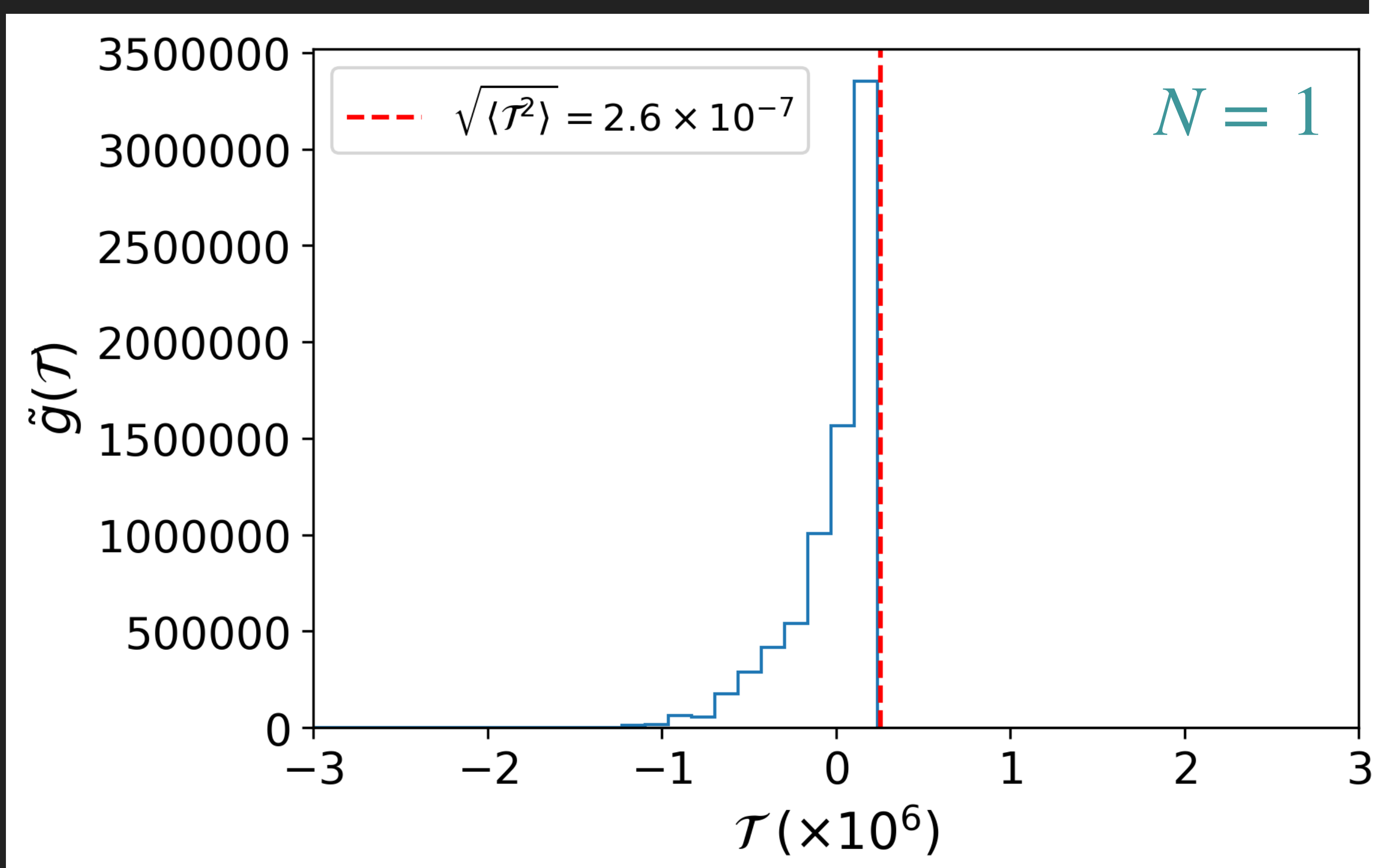
$\tilde{g}(\zeta; N)$

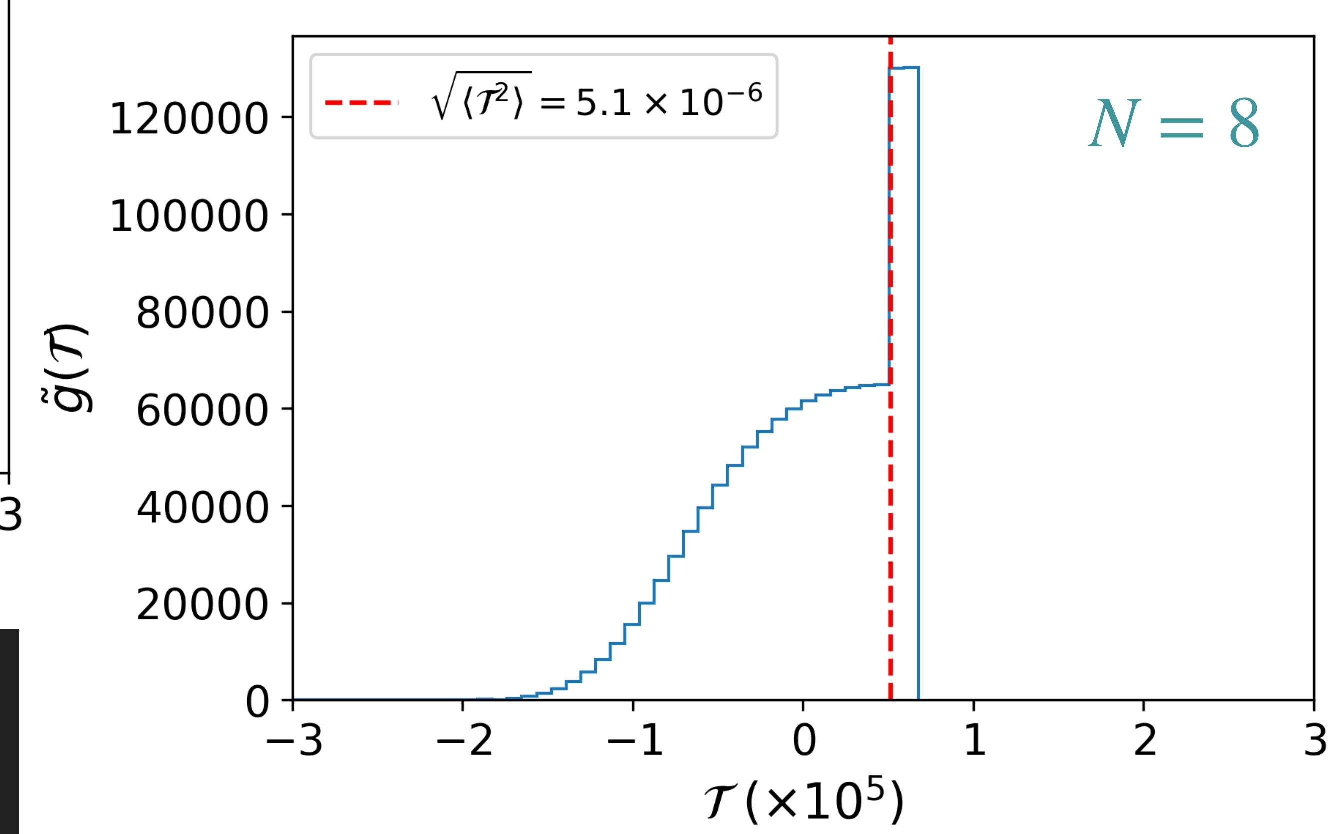
$\zeta^1(N)$, $\zeta^2(N)$, …, $\zeta^i(N)$, …, $\zeta^n(N)$

PATCH-BY-PATCH METHOD

$$\mathscr{T}^i \equiv \left.\frac{\Delta T}{T}\right|^i = \frac{\zeta^i}{5}$$







$$y = 10^{-2},\ \Gamma_0 = 10^{-2} \times m_\phi,\ \lambda_I = 10^{-2},\ H_I = m_\phi$$

f_{NL} CALCULATION

- Planck defines non-gaussianity as:

$$\tilde{g}(\mathcal{T}) = \tilde{g}_G(\mathcal{T}) + f_{NL}\left(\tilde{g}_G^2(\mathcal{T}) - \langle \tilde{g}_G^2(\mathcal{T}) \rangle\right)$$

- The skewness of the temperature fluctuations spectrum is:

$$\mathcal{S}_H = \langle \tilde{g}^3\left(\mathcal{T}\right)\rangle$$

- Non-gaussianity in terms of the skewness is:

$$f_{NL} \approx \frac{\mathcal{S}_\mathrm{H}}{6\left(\Delta T/T|_\mathrm{CMB}\right)^4}$$

- We assume that NG is dominated by reheating rather than SR dynamics
- We calculate NG in the green parameter space which is allowed based on temperature fluctuations. According to Planck $\left.\frac{\Delta T}{T}\right|_\mathrm{CMB} \approx 10^{-5}$.

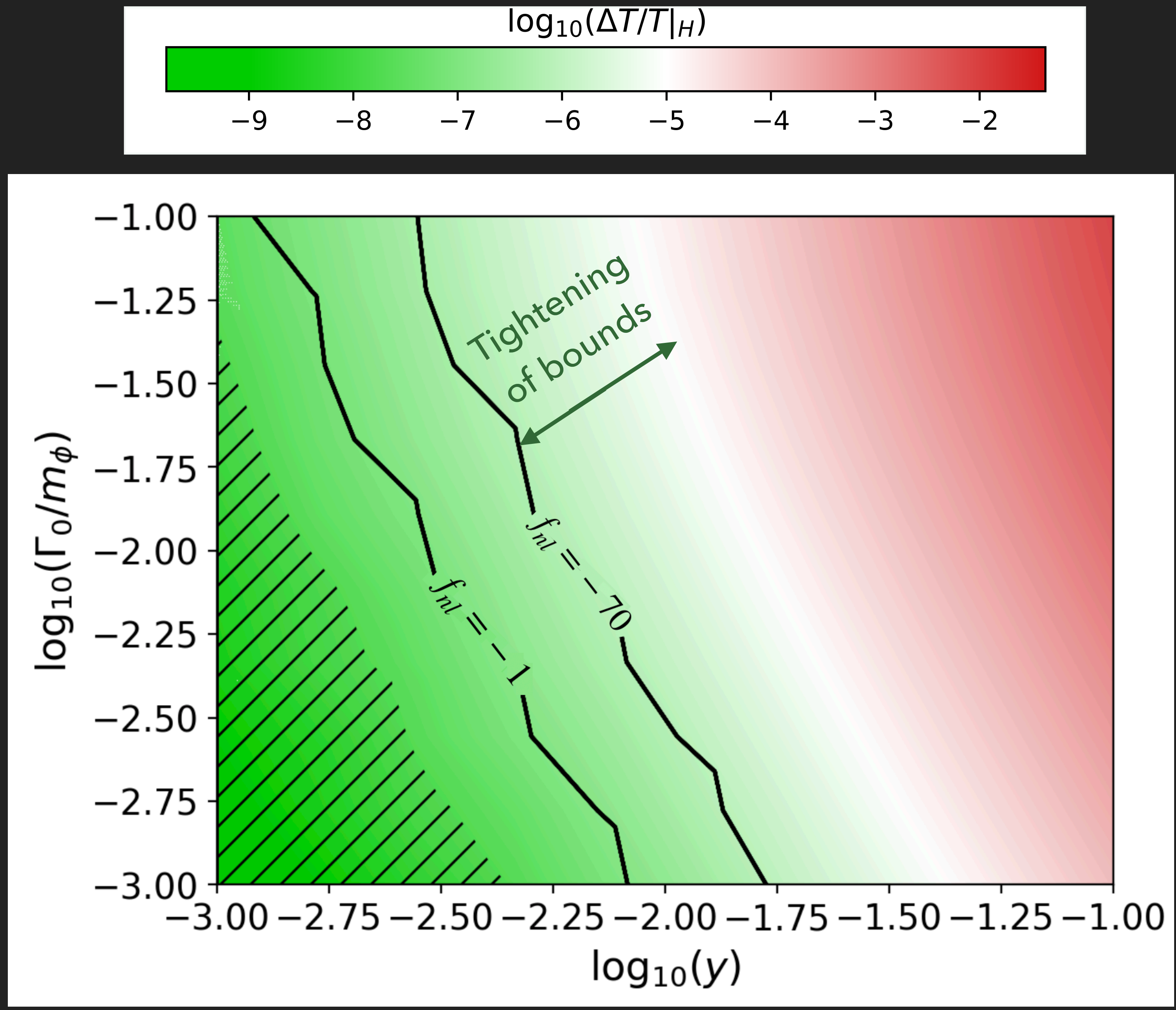
CMB BOUNDS

- Planck's bounds on non-gaussianity are:

$$-6 \leq f_{NL} \leq 5.1$$

- Since our approach does not take smaller scales into account, the bounds will ease by a factor of ~ 10 to:

$$|f_{NL}| \leq 70$$



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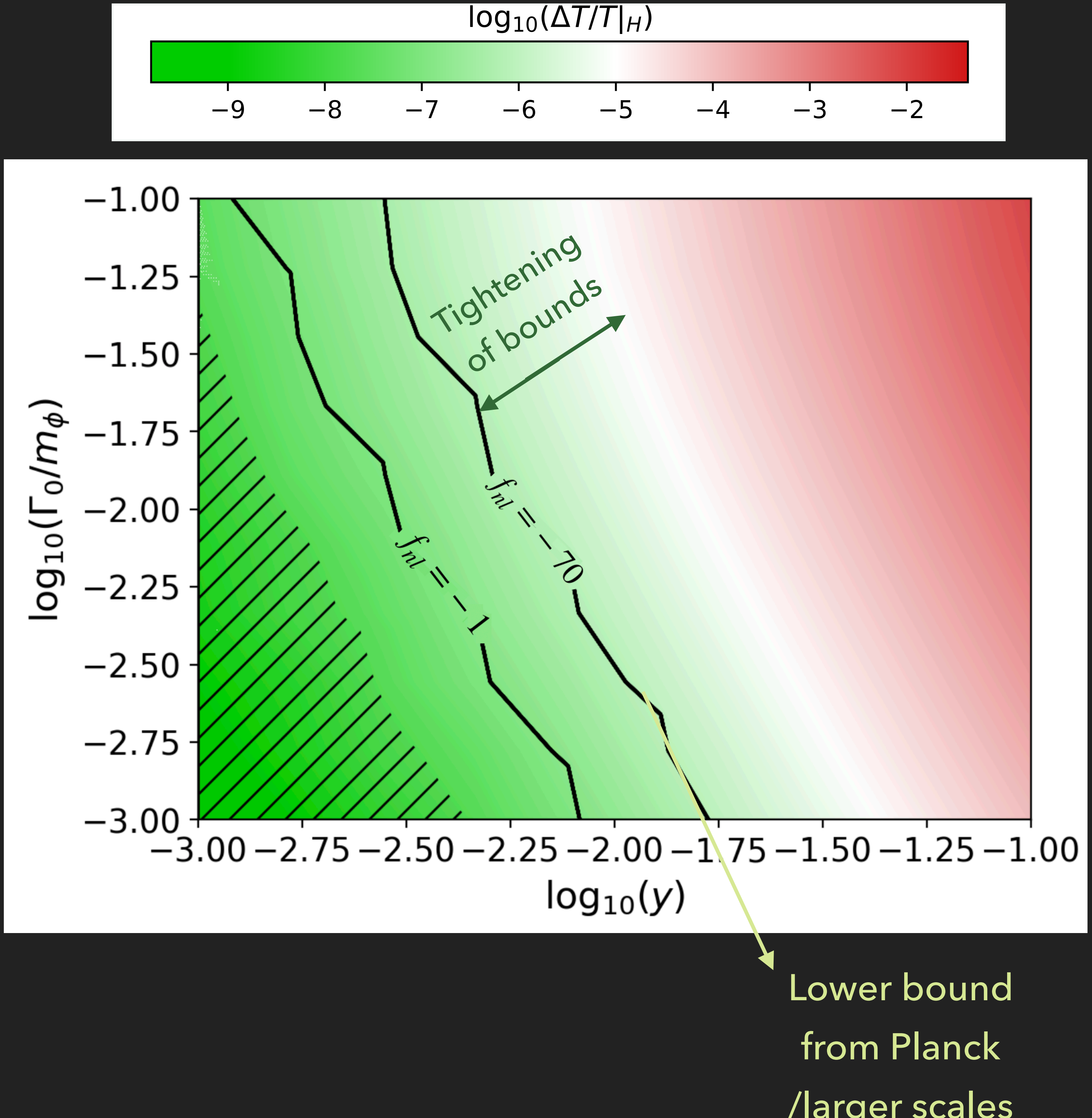

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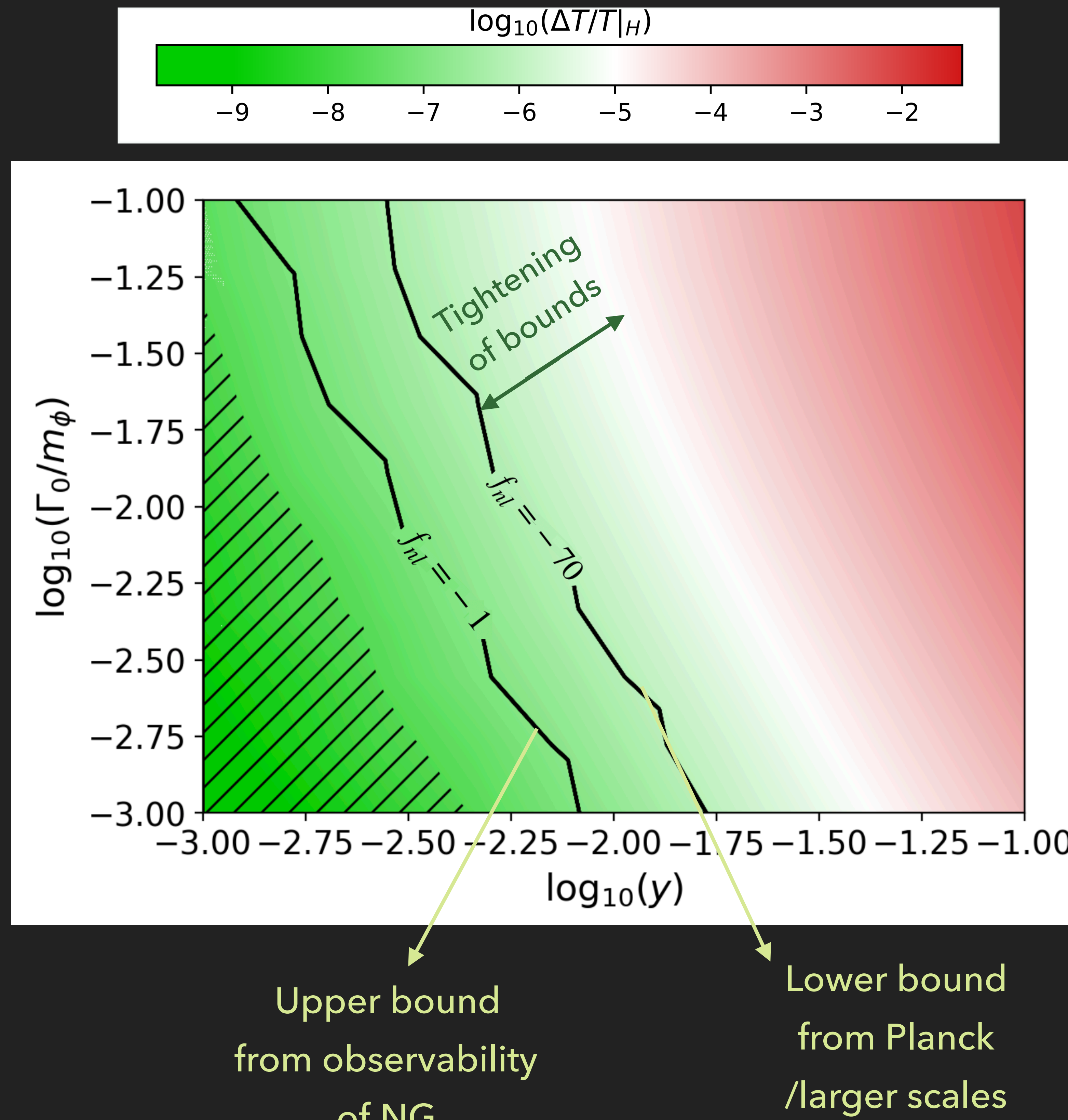
- Since our approach does not take smaller scales into account, the bounds will ease by a factor of ~ 10 to:

$$|f_{NL}| \leq 70$$



CONCLUSIONS

- The Higgs as a light spectator field during inflation can cause reheating to SM particles to be space-dependent
- This space-dependence results in large Higgs-induced temperature fluctuations and non-gaussianity
- By comparing with Planck observations we can constrain the SM parameter space
- The bounds placed on the reheat temperatures of SM particles are tighter for reheating to heavier particles
- We exclude resonant decays (preheating) of the inflaton to SM Higgsed gauge bosons
- Future study of scale-dependencies can provide more accurate results

THANK YOU