TWO SECTOR REHEATING

- PRANJAL RALEGANKAR, UIUC

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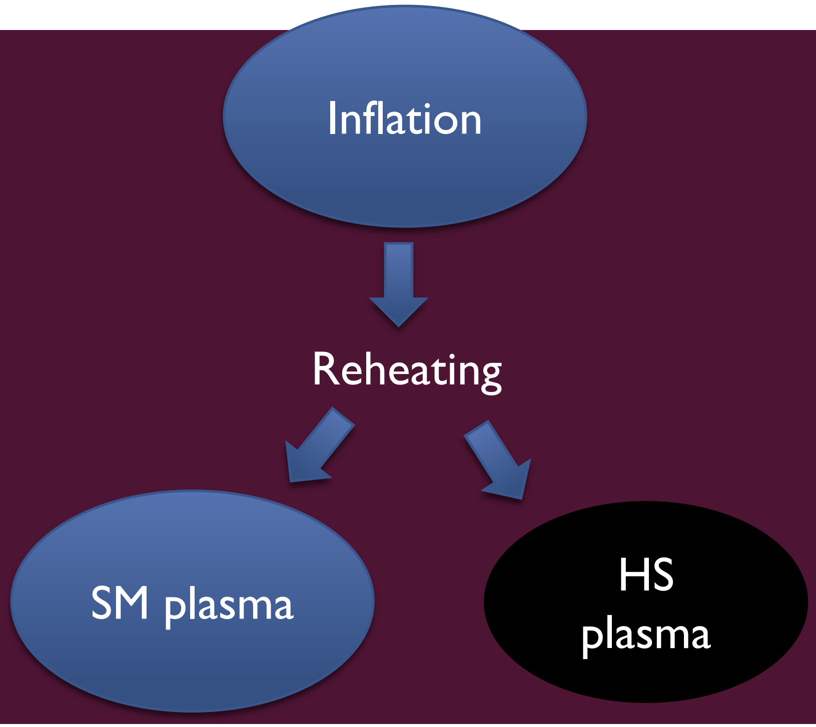
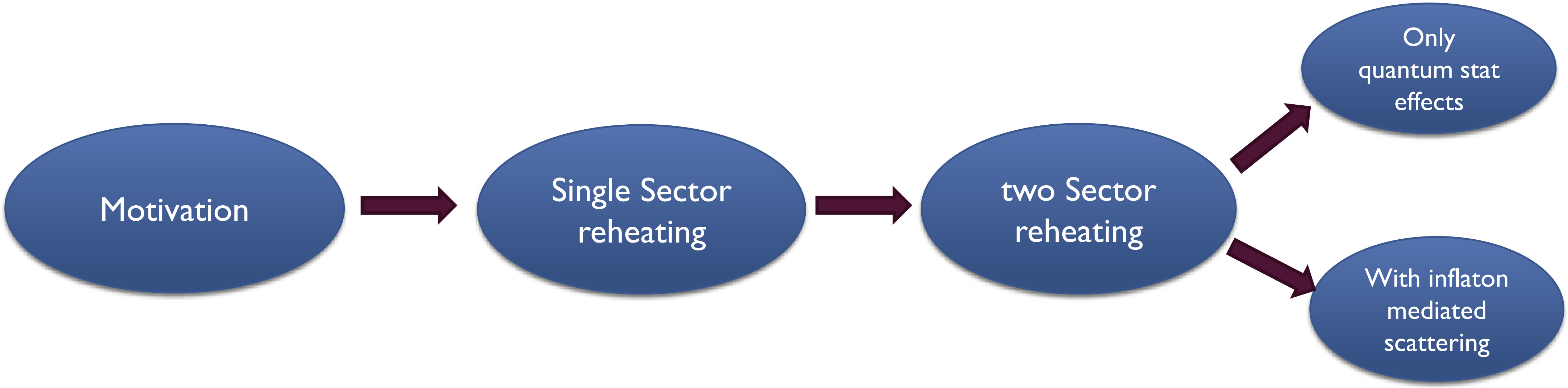
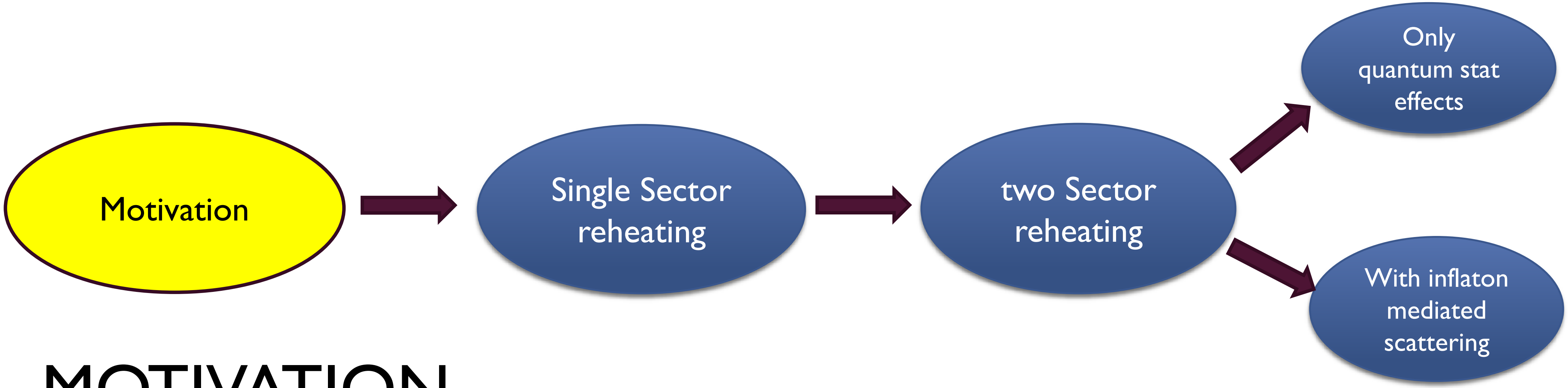


CONTENTS

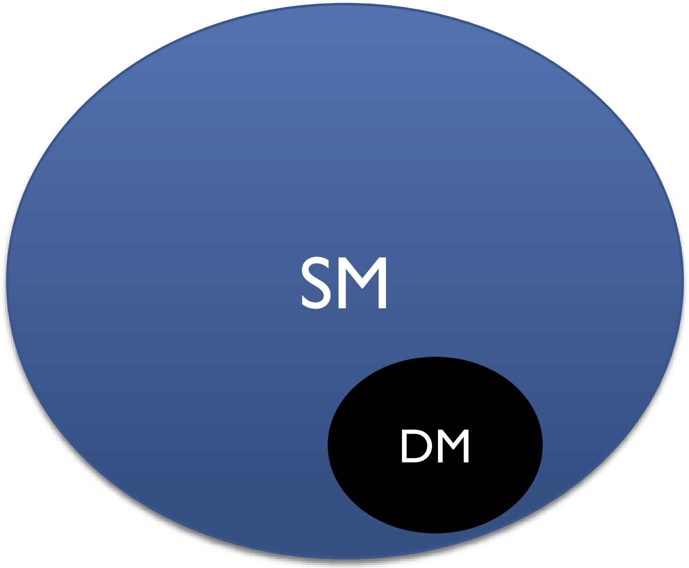

Motivation
Single Sector reheating
two Sector reheating
Only quantum stat effects
With inflaton mediated scattering



MOTIVATION

- WHY DO WE NEED A HIDDEN SECTOR (HS)?
- WHY TWO SECTOR REHEATING?

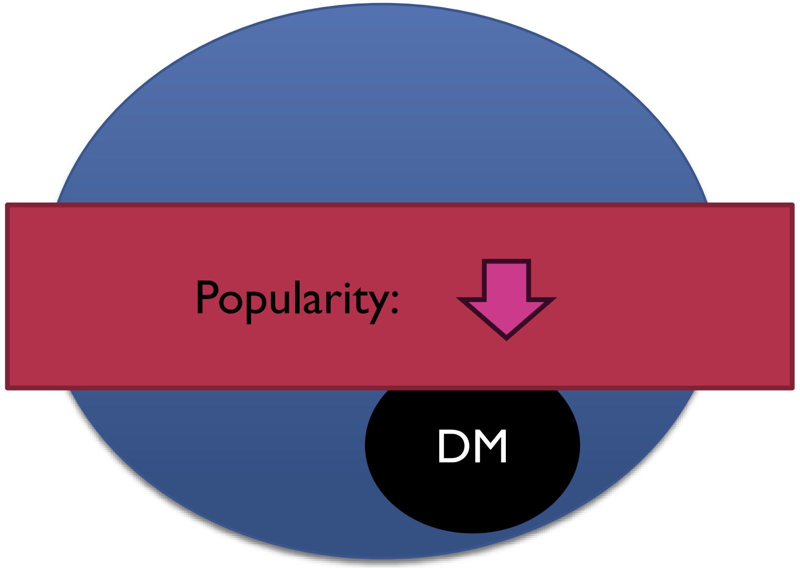
NEED FOR A HIDDEN SECTOR: Traditional DM scenario



WIMP scenario

NEED FOR A HIDDEN SECTOR: Traditional DM scenario

- Dearth of signals in collider, direct and indirect detection experiments reducing the parameters space for traditional WIMP scenario

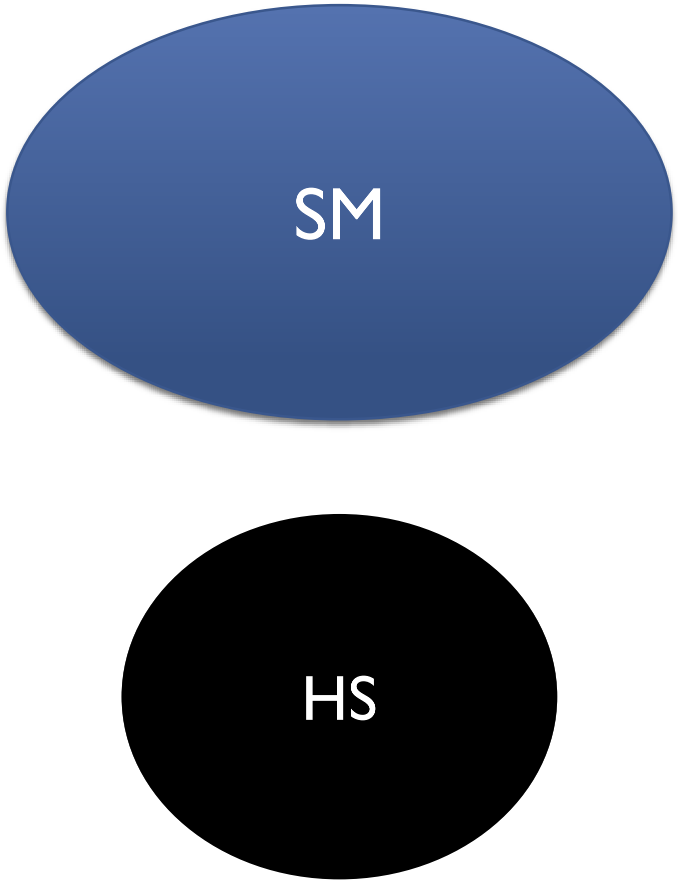


WIMP scenario

NEED FOR A HIDDEN SECTOR: HS as an alternative

- Dearth of signals in collider, direct and indirect detection experiments reducing the parameters space for traditional WIMP scenario

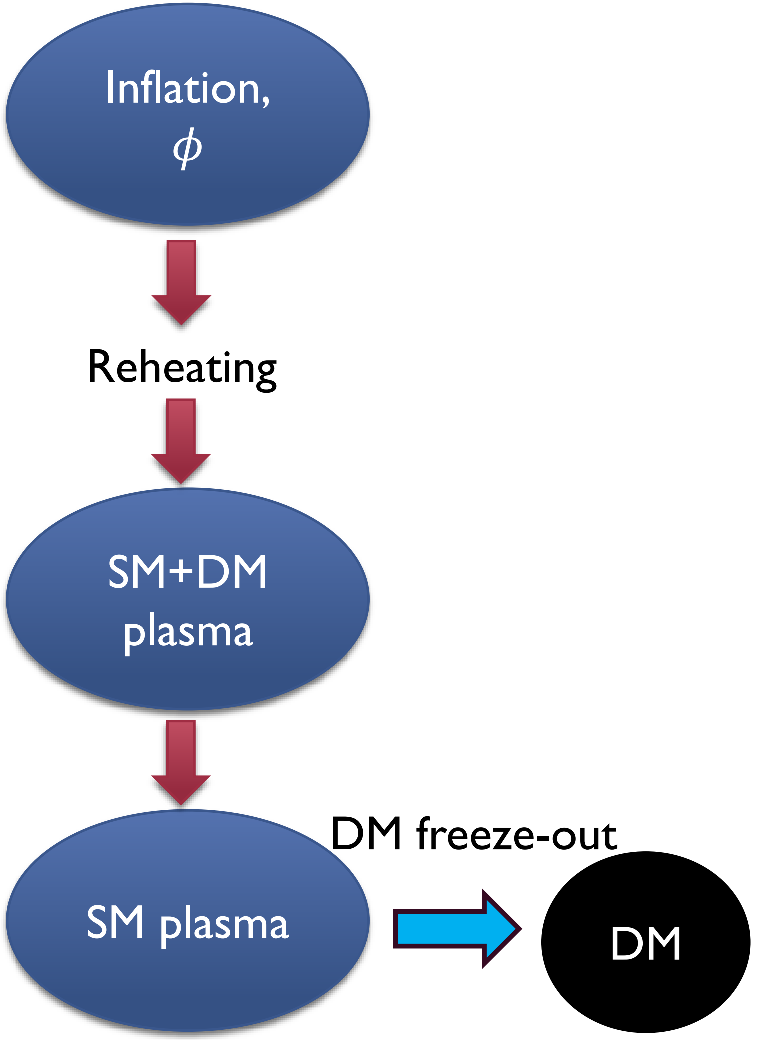
- A complete sector with its own host of particles decoupled from SM as a possible alternative



POPULATING THE HIDDEN SECTOR: How?

POPULATING THE HIDDEN SECTOR: Traditional DM production

- WIMP DM populated by freeze out mechanism



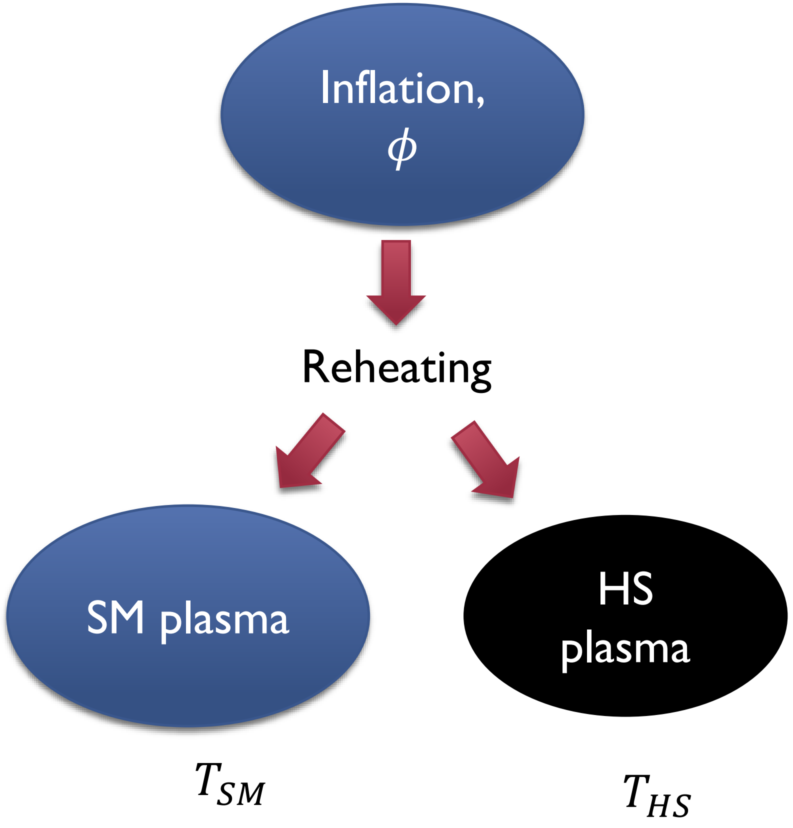
POPULATING THE HIDDEN SECTOR: Asymmetric reheating

- One straightforward way to populate the HS is directly during reheating

- Asymmetric reheating helps in avoiding the stringent N_{eff} constraints

$$\Delta N_{eff} = g_{HS}\left(\frac{T_{HS}}{T_{DM}}\right)^4 \leq 0.46$$

Relativistic degrees of freedom



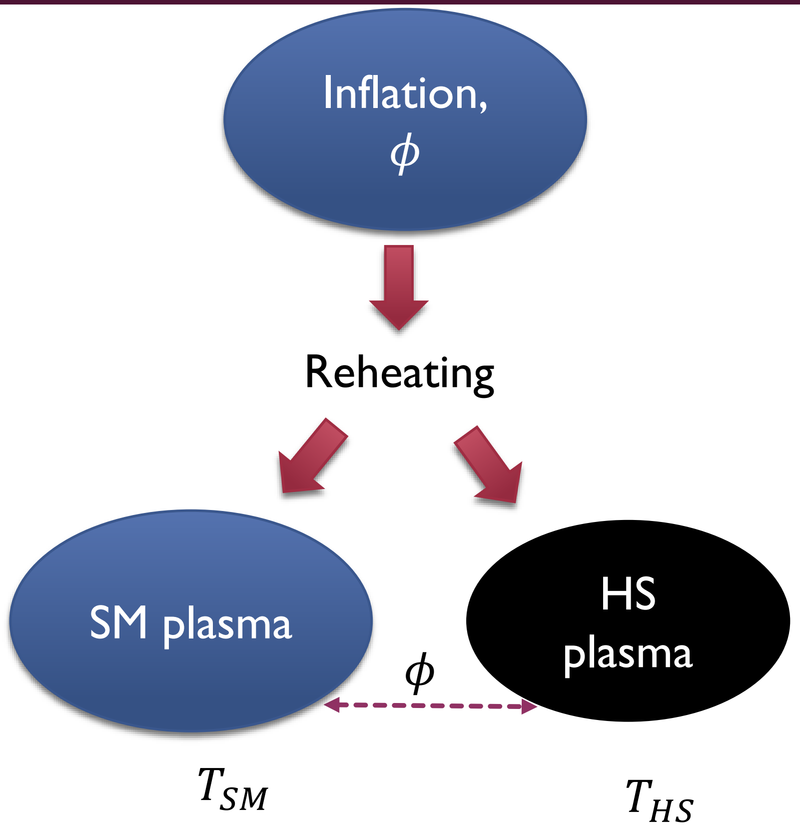
Two sector reheating

PRIMARY GOAL: Finding temperature asymmetry

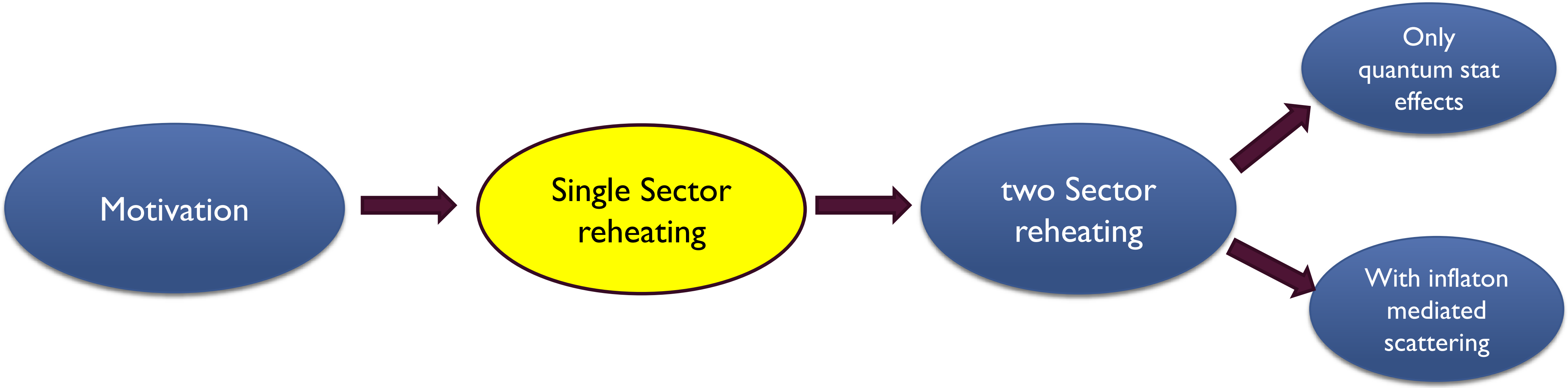
- Inflaton mediated interactions can thermalize the two sectors
  Adshead, Cui and Shelton (2016).

- Primary aim to determine the temperature ratio $x = \frac{T_{HS}}{T_{SM}}$

- A first step towards this goal.
  Limit to simple perturbative reheating scenario…



Two sector reheating



REVIEW OF SINGLE SECTOR PERTURBATIVE REHEATING

- UNDERSTAND PERTURBATIVE REHEATING PROCESS
- DEMONSTRATE MODIFICATION DUE TO QUANTUM STATISTICS

SINGLE SECTOR REHEATING: Boltzmann equations and assumptions

Post inflation Boltzmann Equations:

Inflaton density

$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi = -\Gamma_\phi \rho_\phi$$

Inflaton decay width

radiation density

$$\frac{d\rho}{dt} + 4H\rho = \Gamma_\phi \rho_\phi$$

Hubble rate

$$H = \frac{1}{\sqrt{3}M_{pl}} \sqrt{\rho_\phi + \rho}$$

- Generic model independent scenario in perturbative limit
- Post inflaton, inflaton condensate evolves like a cold matter.
- Assume instantaneous thermalization in matter sector $\rho = \alpha T^4$

SINGLE SECTOR REHEATING: Reheating conditions

Post inflation, reheating Boltzmann Equations:

Inflaton density

$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi \approx 0$$

Inflaton decay width

radiation density

$$\frac{d\rho}{dt} + 4H\rho = \Gamma_\phi \rho_\phi$$

Hubble rate

$$H \approx \frac{1}{\sqrt{3}M_{pl}} \sqrt{\rho_{\phi,I}} a^{-3/2}$$

- Initial conditions: $\rho_{\phi,I}$ large non zero value; $\rho_I = 0.$
- Perturbative reheating era:
  $$H \gg \Gamma_\phi$$
- Reheating ends when
  $$H \sim \Gamma_\phi$$

SINGLE SECTOR REHEATING: Inflaton condensate evolves like cold matter

Post inflation, reheating Boltzmann Equations:

$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi \approx 0$$

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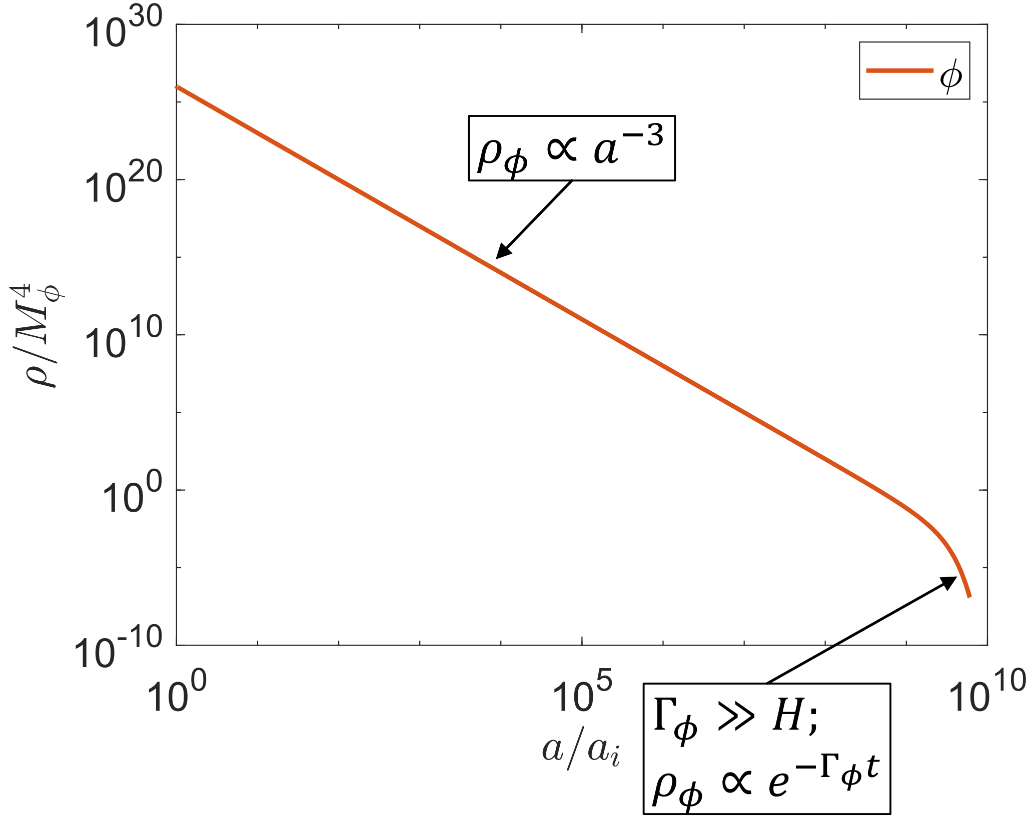

SINGLE SECTOR REHEATING: Radiation evolution non-adiabatic

Post inflation, reheating Boltzmann Equations:

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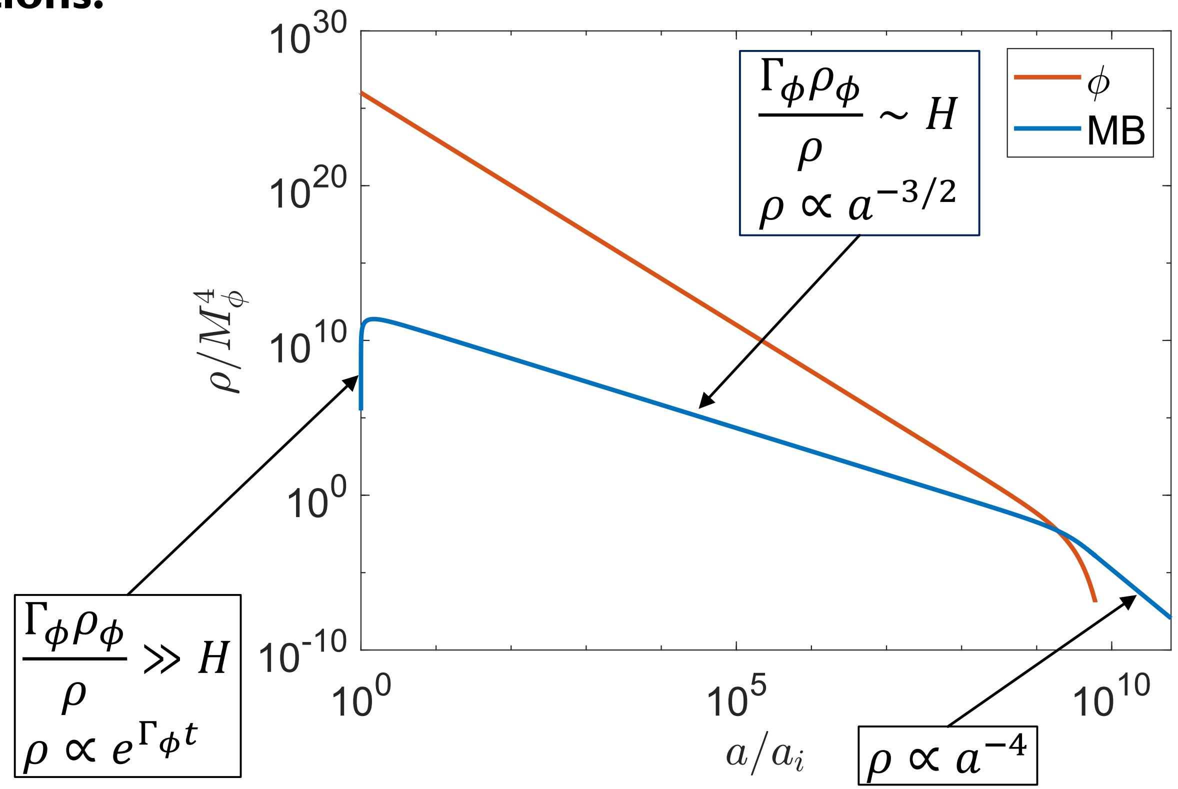

SINGLE SECTOR REHEATING: Attractor solution!

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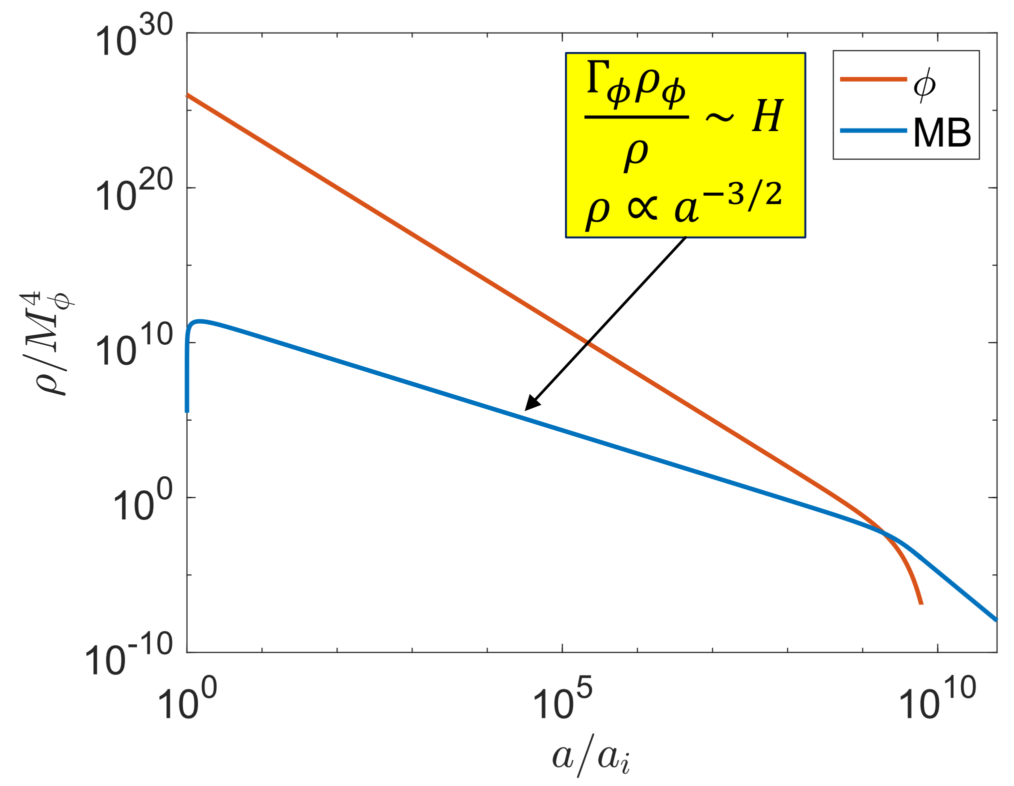

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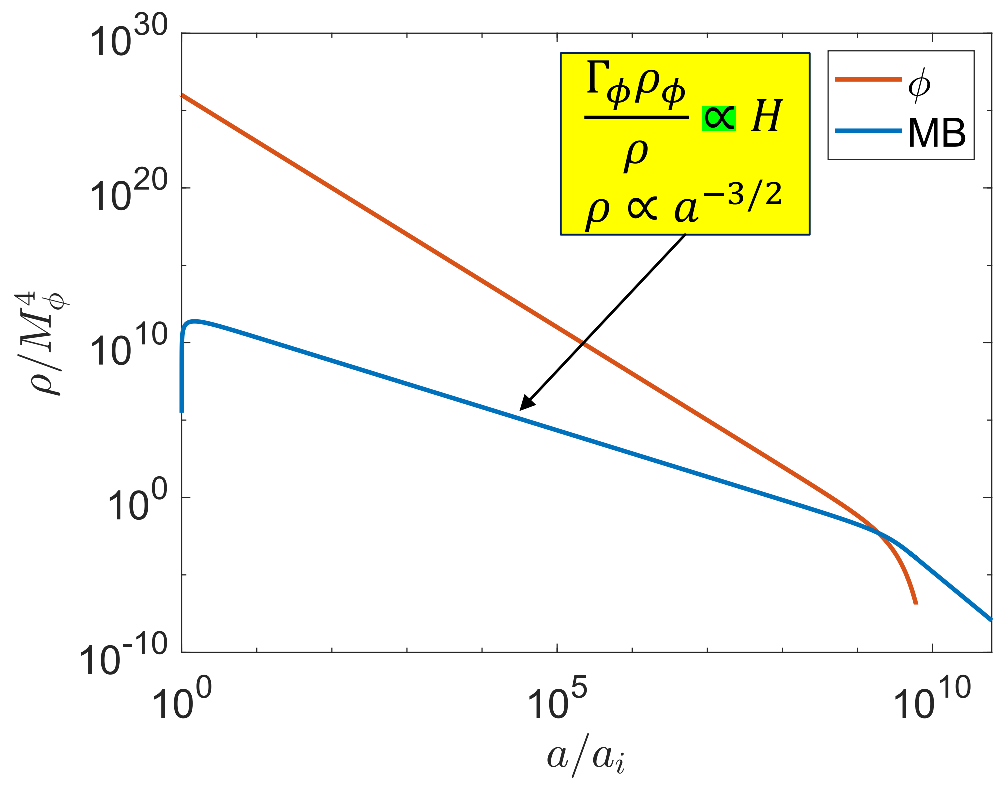

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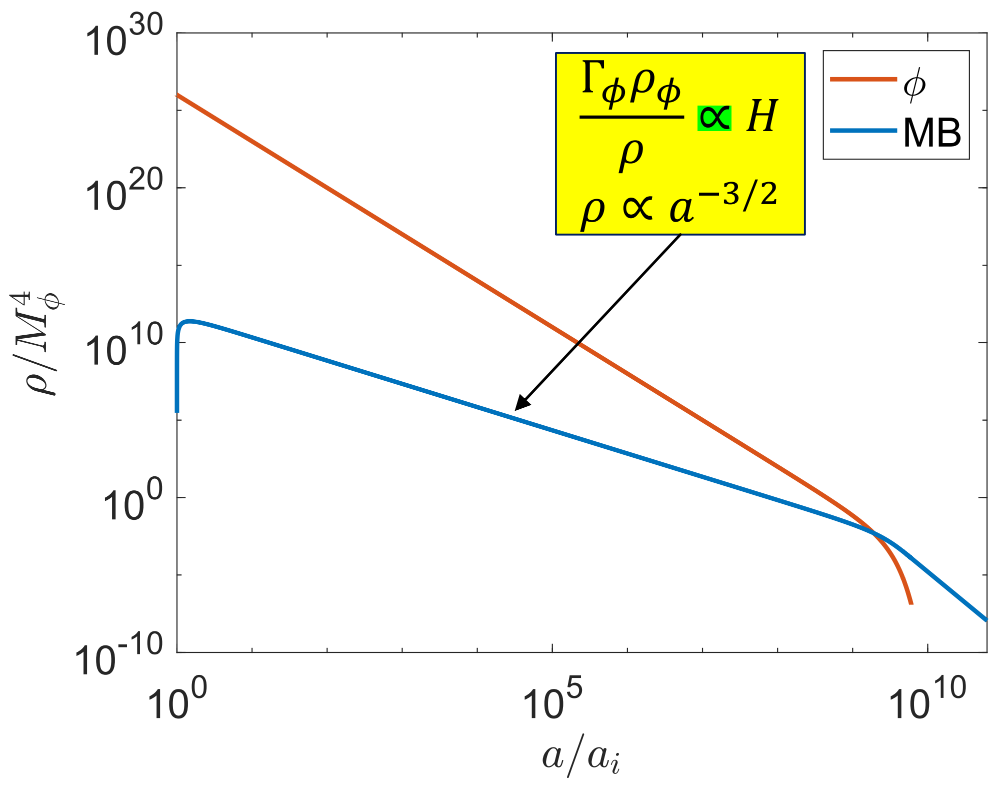
$$H \approx \frac{1}{\sqrt{3}M_{pl}} \sqrt{\rho_{\phi,I}}\, a^{-3/2}$$

$$T = \frac{2\sqrt{3}}{5\alpha} \frac{M_{pl}}{M_\phi} \Gamma_\phi \sqrt{\rho_{\phi,I}} \left(\frac{a}{a_I}\right)^{-3/8}$$

No dependence on temperature history



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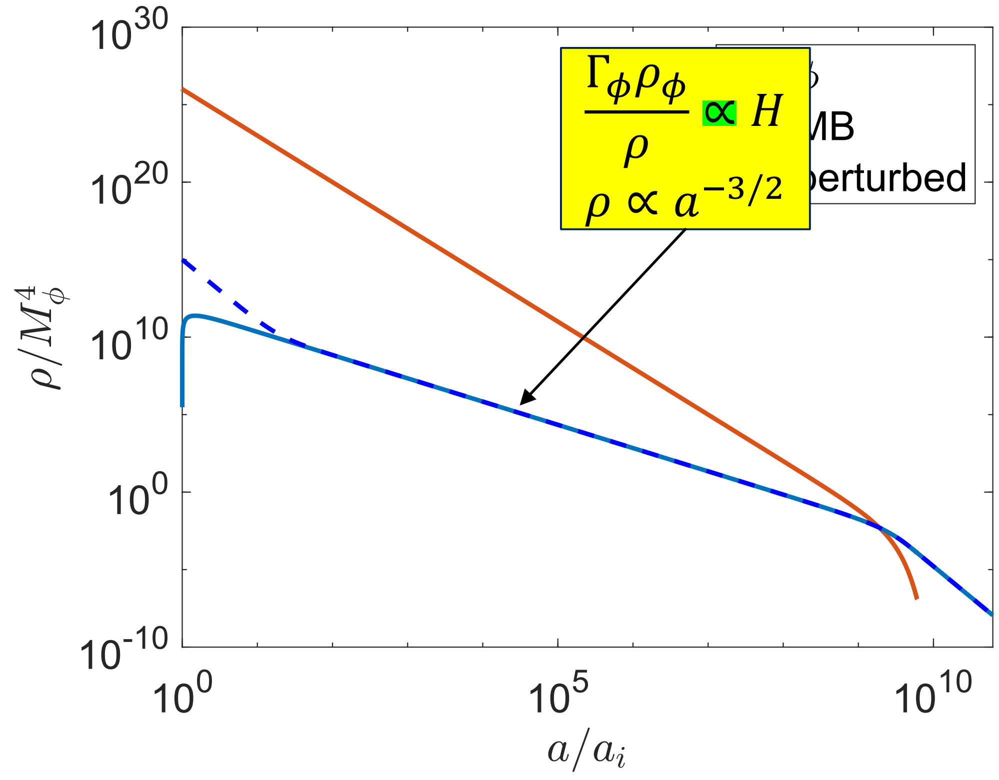

SINGLE SECTOR REHEATING: Reheat temperature independent of initial conditions

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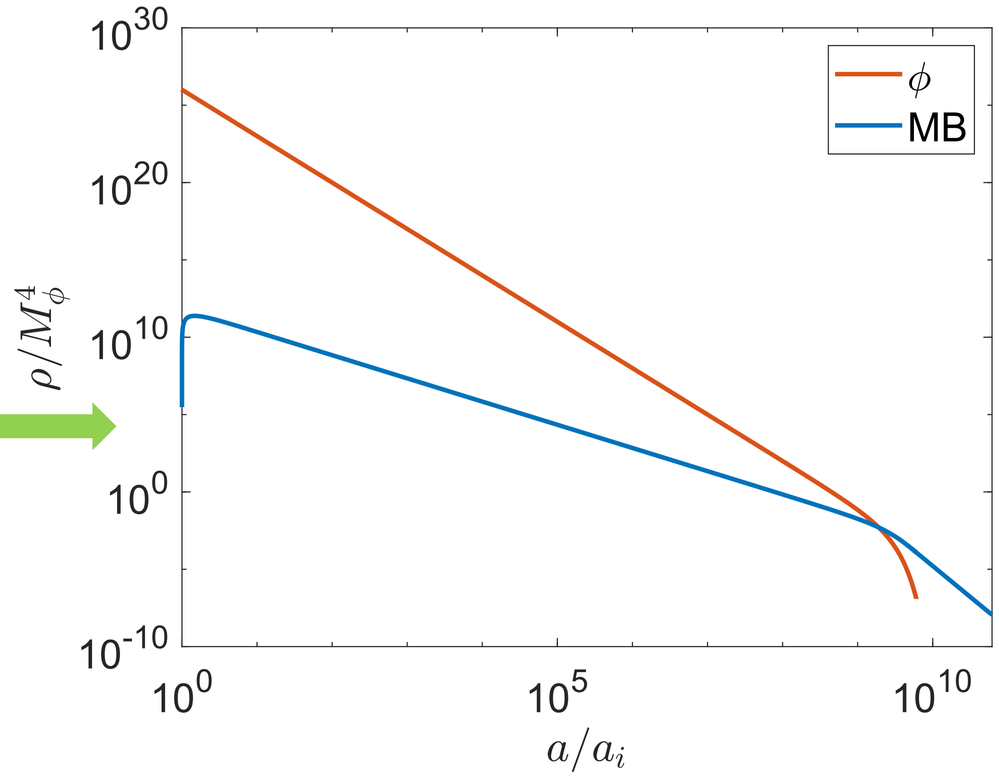
Input arbitrary initial condition of inflaton and radiation bath



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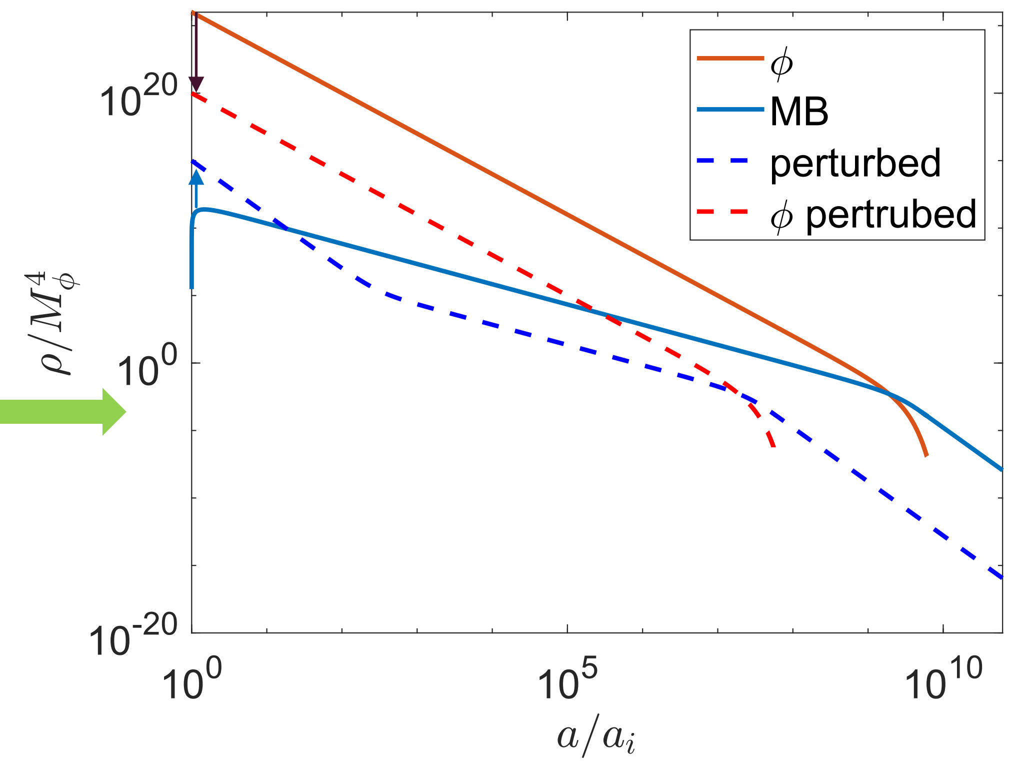

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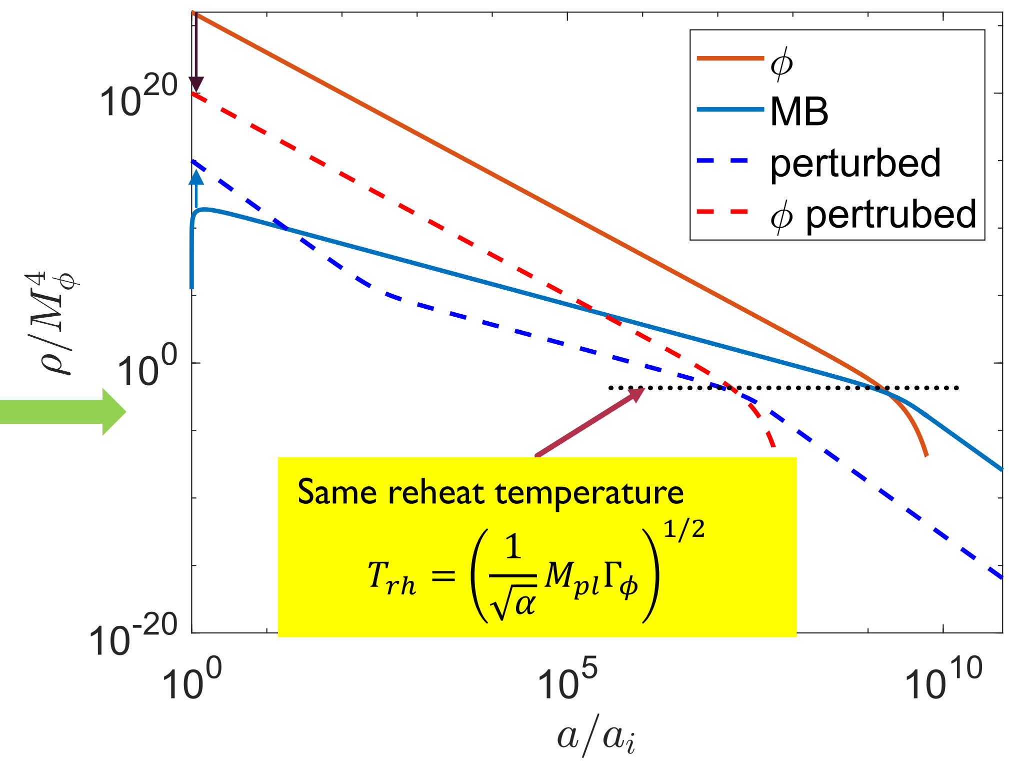
Input arbitrary initial condition of inflaton and radiation bath

Chung, Kolb and Riotto, (1999)



SINGLE SECTOR REHEATING: Temperature dependence in Γ_ϕ

$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi \approx 0$$

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- Feedback from Bose enhancement or Pauli Blocking alters inflaton decay width

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Bosons

$$\Gamma_\phi(T) = \Gamma_0 \frac{e^{M_\phi/2T} + 1}{e^{M_\phi/2T} - 1}$$

Fermions

$$\Gamma_\phi(T) = \Gamma_0 \frac{e^{M_\phi/2T} - 1}{e^{M_\phi/2T} + 1}$$

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$T \gg M_\phi$: $\Gamma_\phi(T) \approx 4\Gamma_0 T/M_\phi$

$T \ll M_\phi$: $\Gamma_\phi(T) \approx \Gamma_0$

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SINGLE SECTOR REHEATING: Temperature dependence in Γ_ϕ

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Bose-enhancement

$T \ll M_\phi$: $\Gamma_\phi(T) \approx \Gamma_0$

Fermions

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$T \gg M_\phi$: $\Gamma_\phi(T) \approx \Gamma_0 M_\phi/4T$

Pauli-blocking

$T \ll M_\phi$: $\Gamma_\phi(T) \approx \Gamma_0$

SINGLE SECTOR REHEATING: Modified attractor curves by quantum statistics

$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi \approx 0$$

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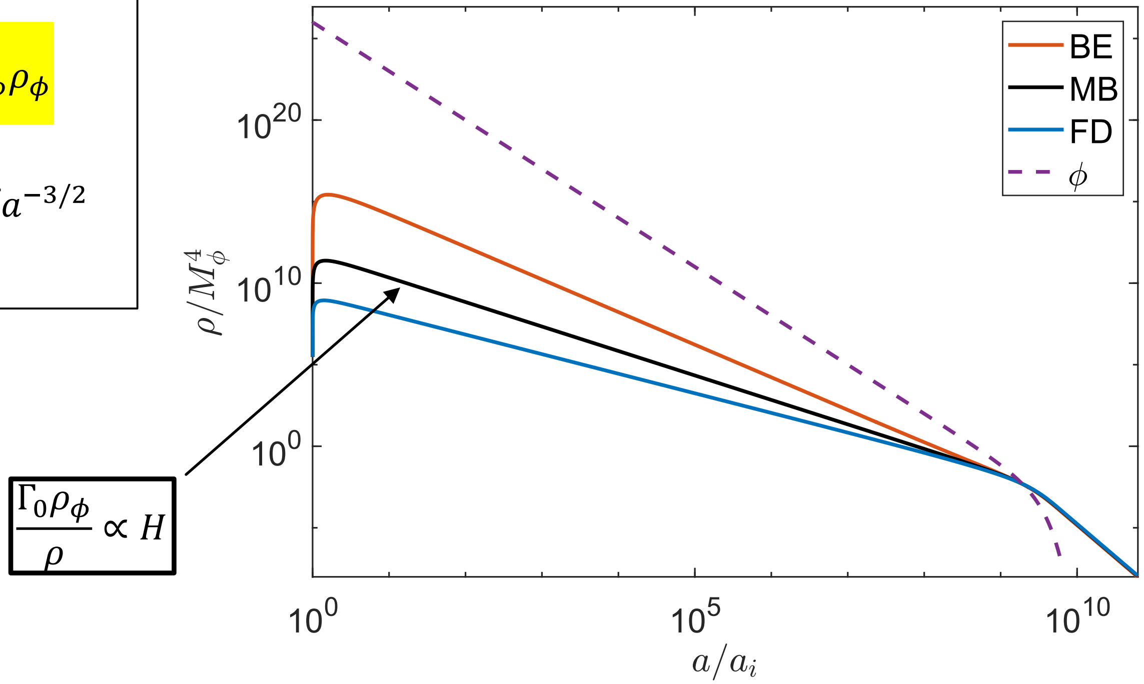

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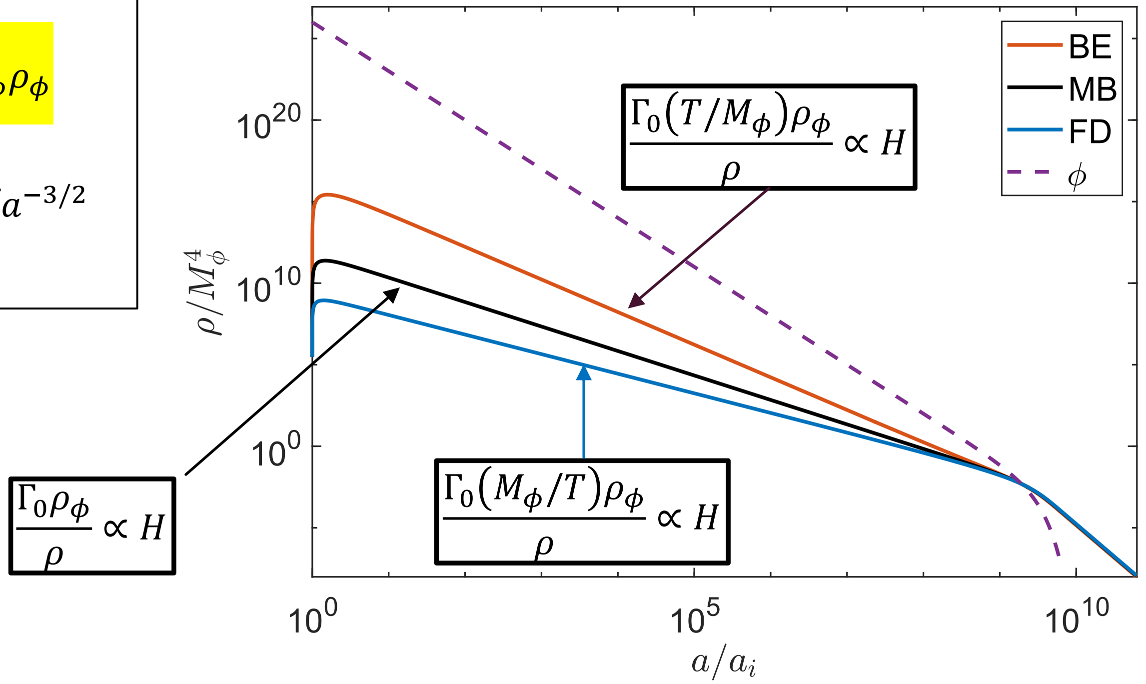

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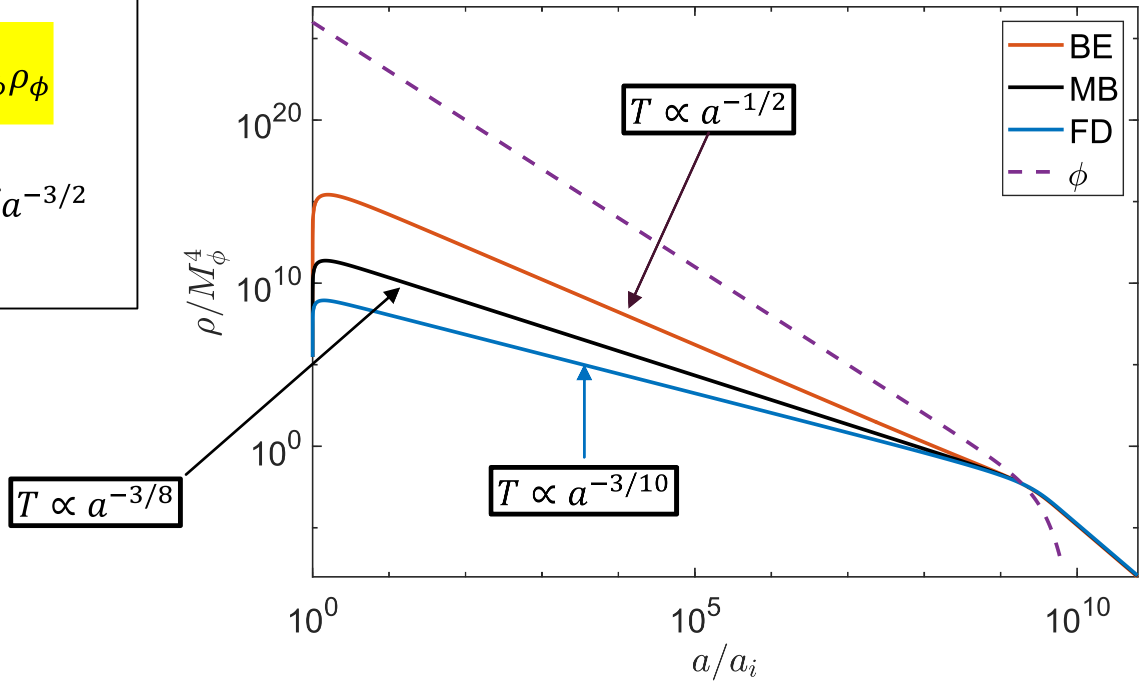

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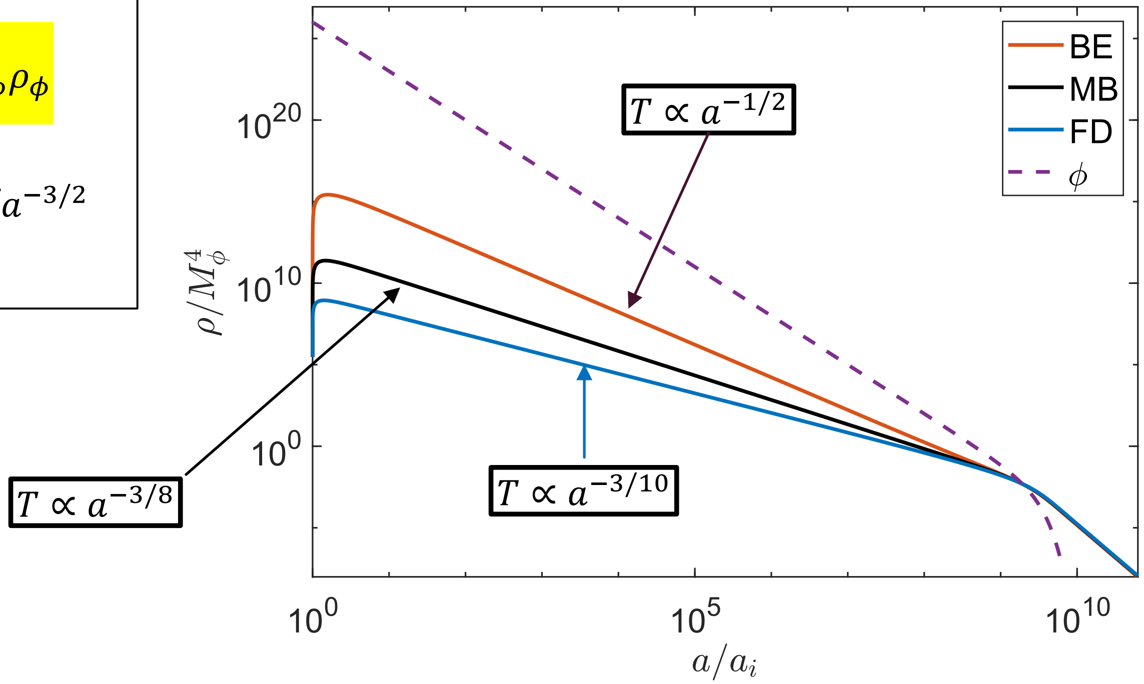

This is for $T_{rh} < M_\phi$

SINGLE SECTOR REHEATING: Modified attractor curves by quantum statistics

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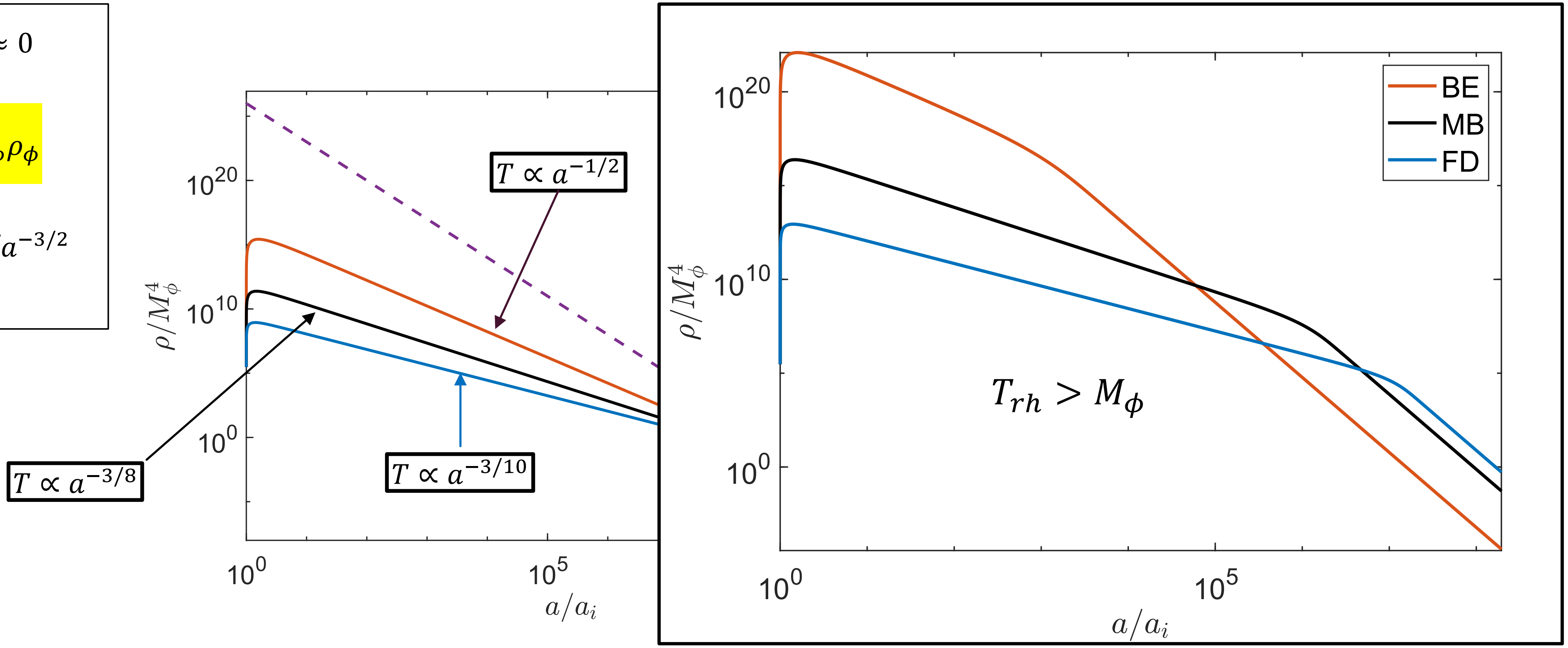

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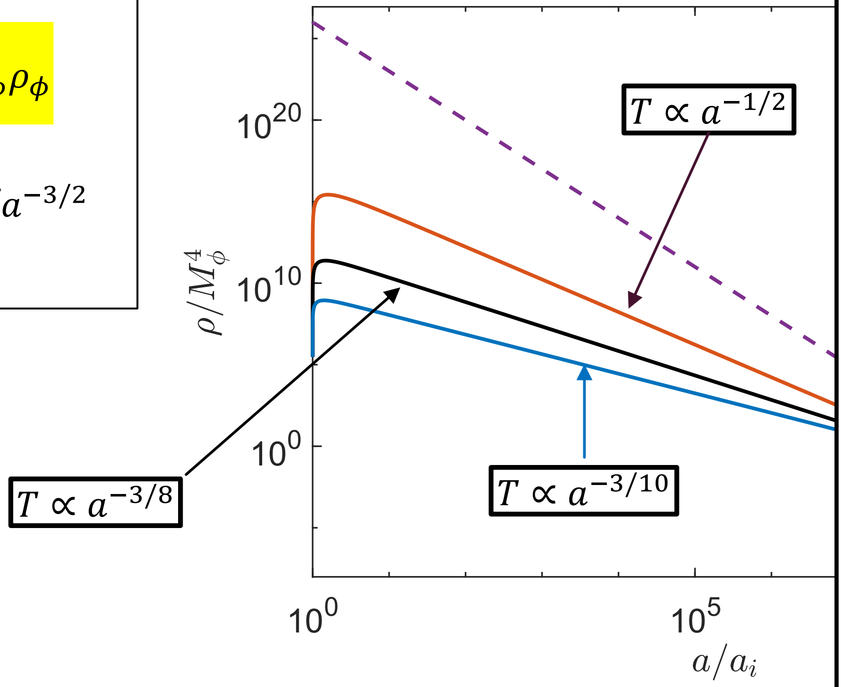
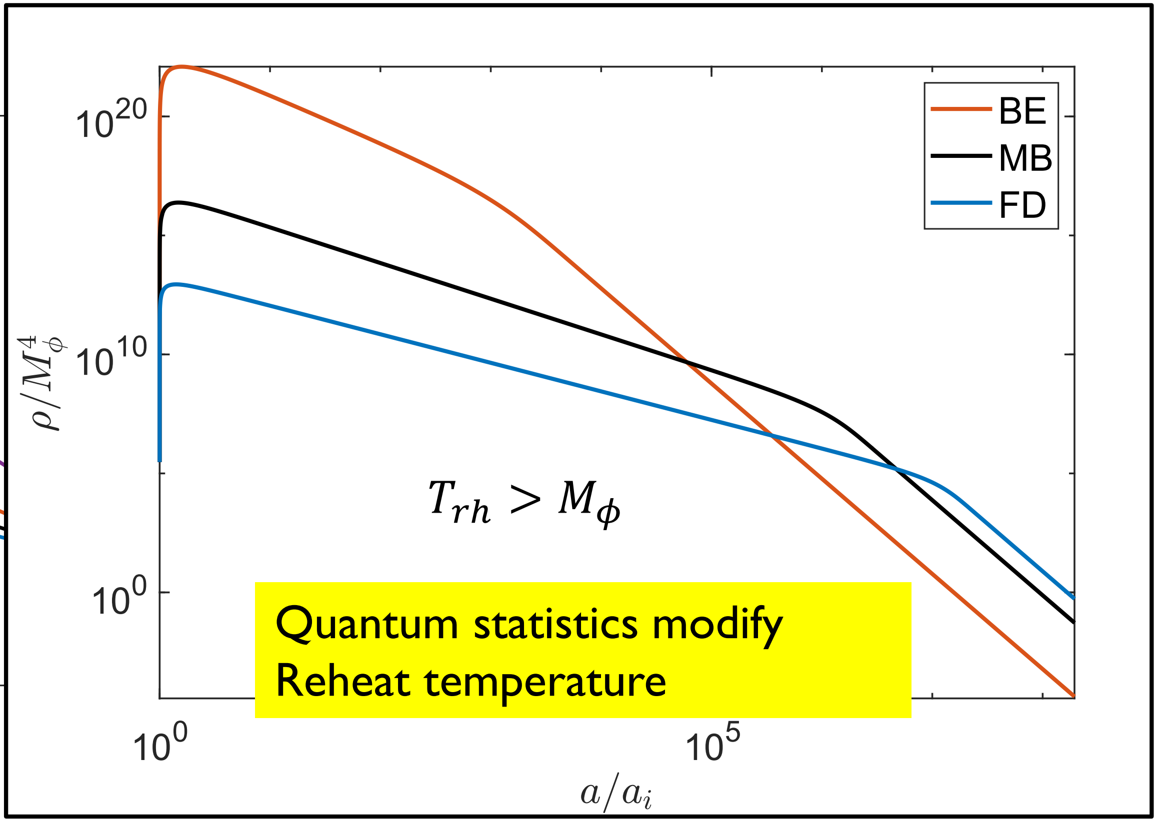
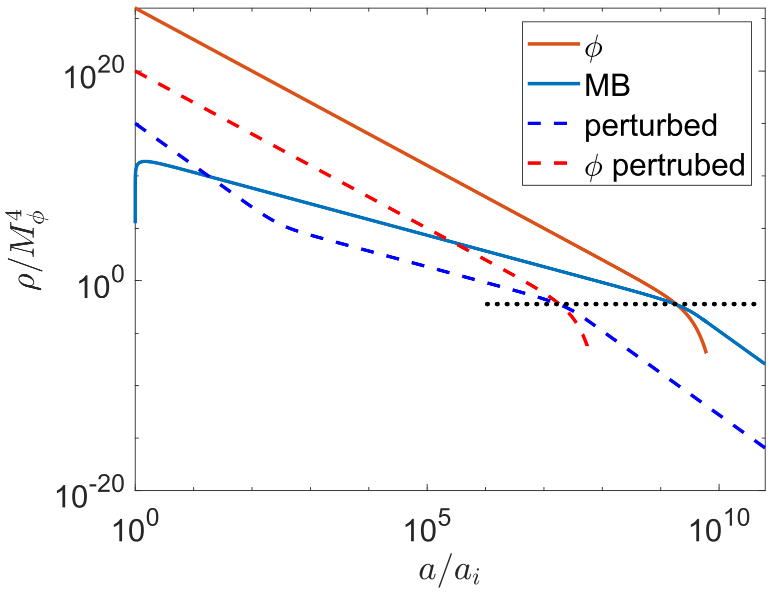
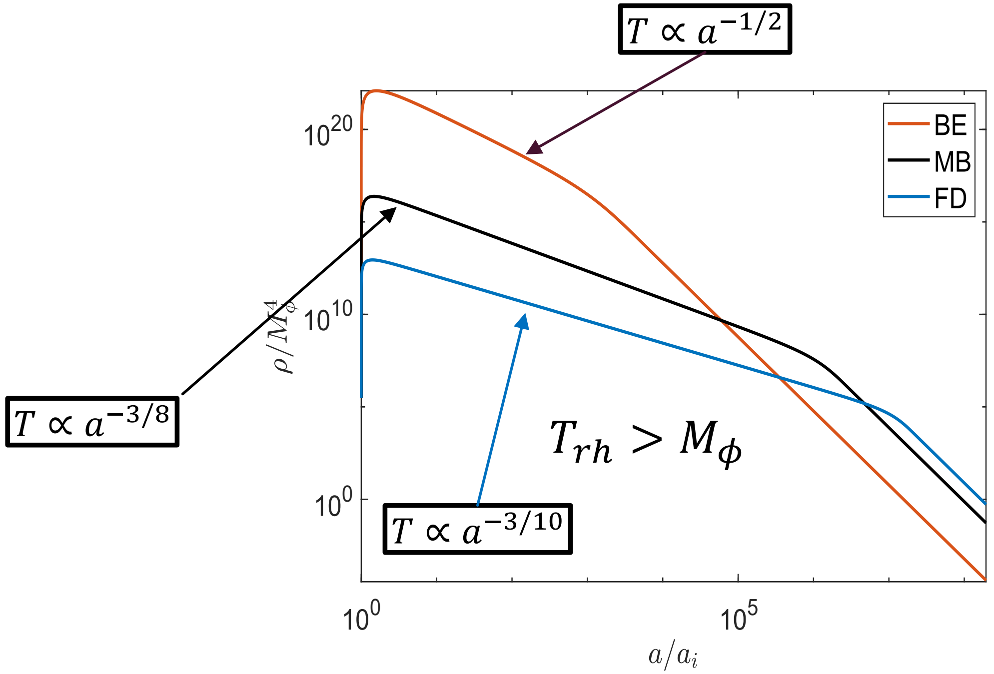




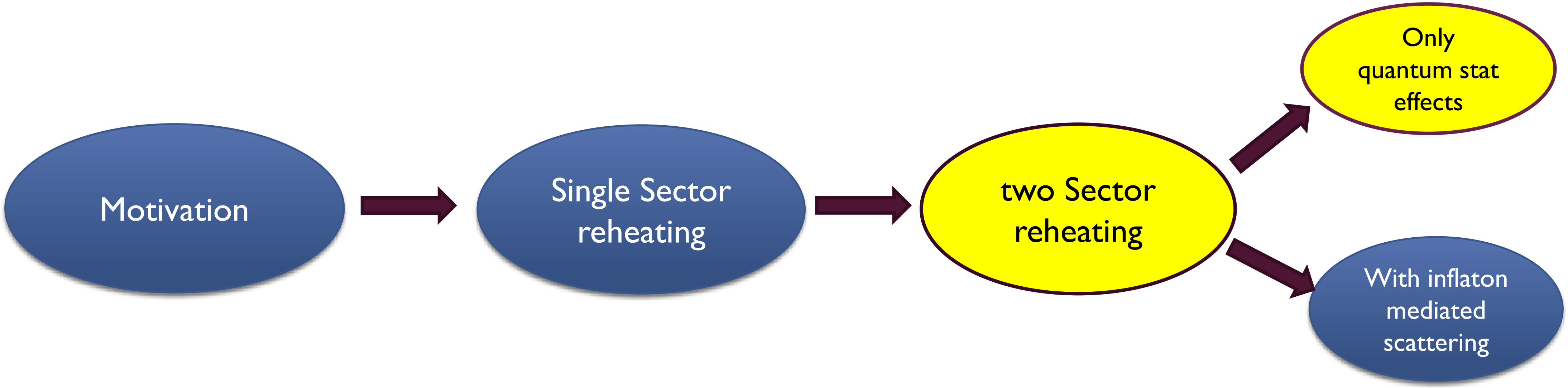
SINGLE SECTOR REHEATING: Summary



Reheat temperature independent of initial conditions



Quantum statistics can modify reheat temperature



TWO SECTOR REHEATING

- EFFECTS FROM QUANTUM STATISTICS- NEGLECT INFLATON MEDIATED INTERACTIONS
- EFFECTS FROM INFLATON MEDIATED INTERACTIONS
- REVIEW OF ASSUMPTIONS

NON INTERACTING SECTORS: Boltzmann equations

Post inflation, reheating Boltzmann Equations:

$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi \approx 0$$

$$\frac{d\rho_a}{dt} + 4H\rho_a = \Gamma_{\phi,a}\rho_\phi$$

$$\frac{d\rho_b}{dt} + 4H\rho_b = \Gamma_{\phi,b}\rho_\phi$$

$$H \approx \frac{1}{\sqrt{3}M_{pl}}\sqrt{\rho_{\phi,I}}\,a^{-3/2}$$

NON INTERACTING SECTORS: Final temperature ratio fixed after reheating

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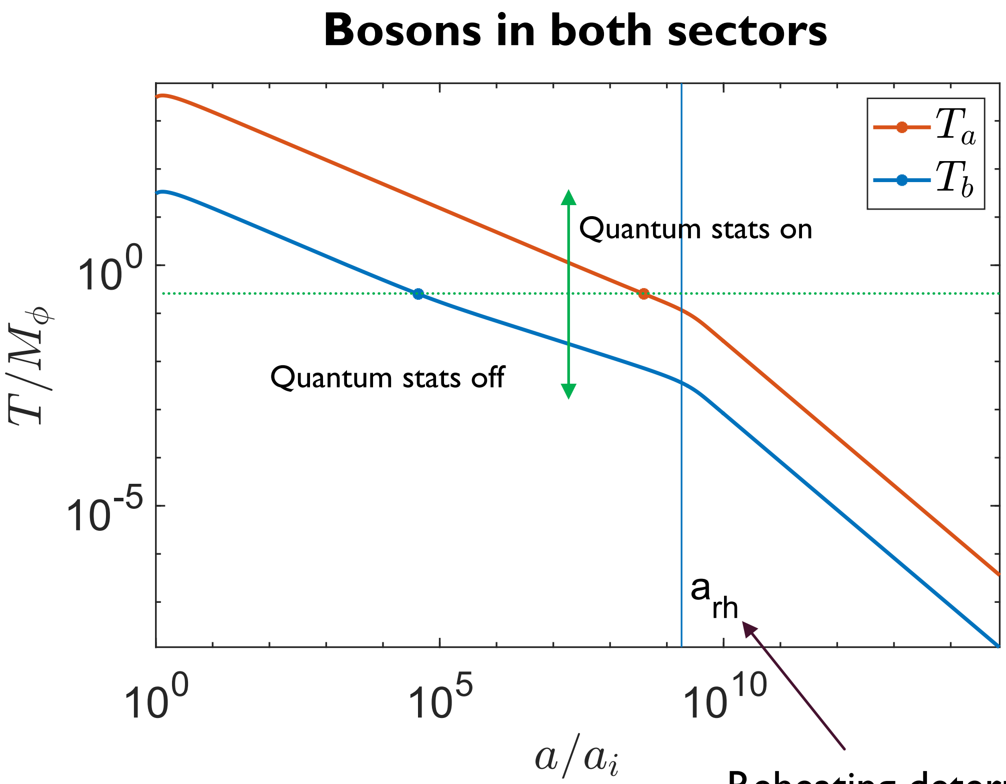

Reheating determined by hotter sector

NON INTERACTING SECTORS: Final temperature ratio fixed after reheating

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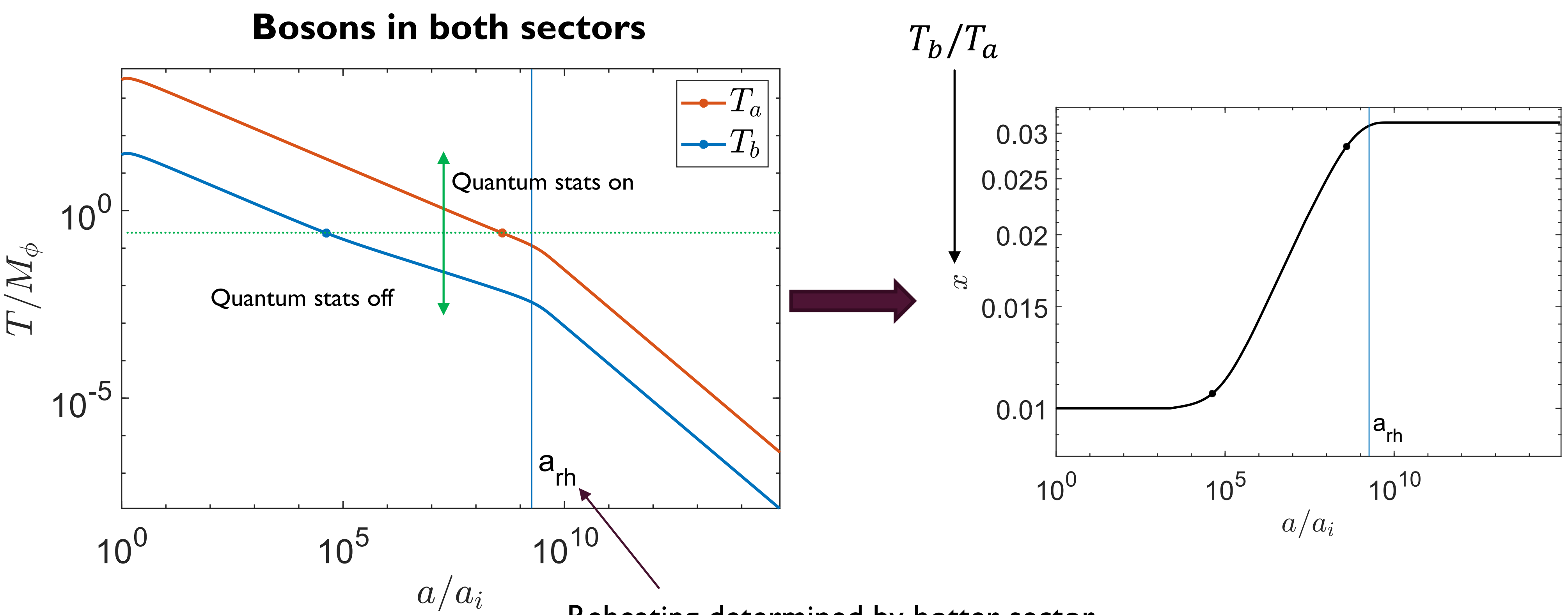

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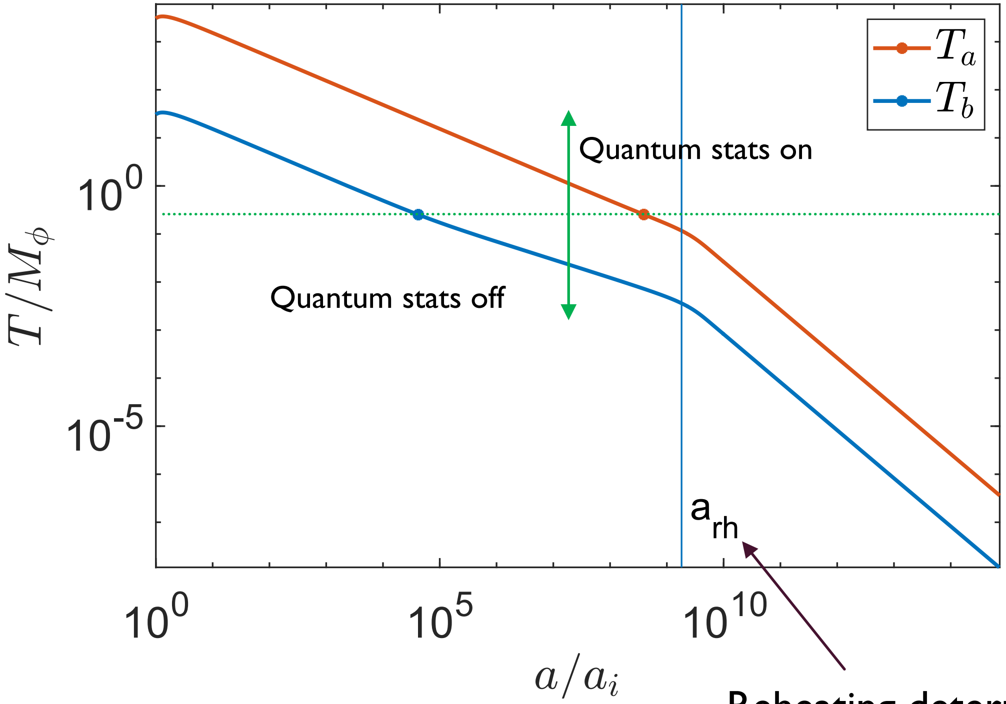
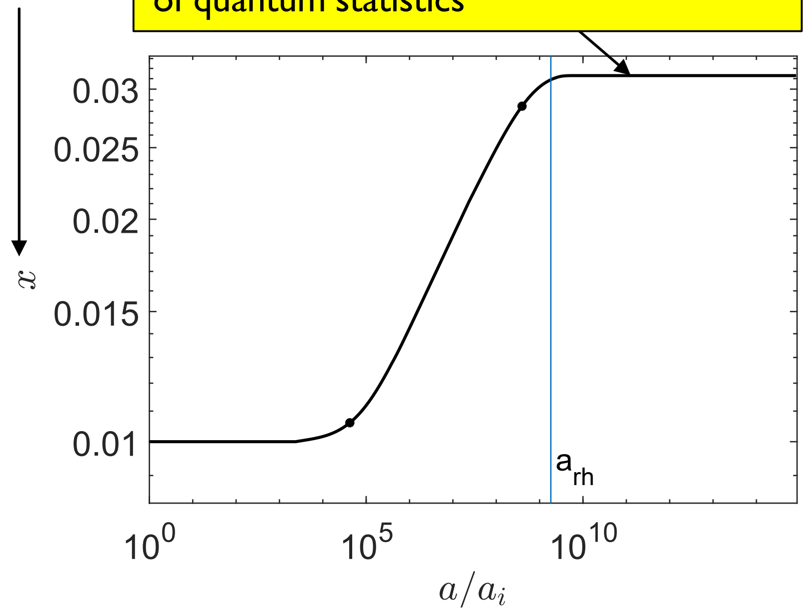
Bosons in both sectors



Reheating determined by hotter sector

T_b/T_a



Inflaton decay ends;
temperature ratio fixed regardless
of quantum statistics

NON INTERACTING SECTORS: Final temperature ratio fixed after reheating

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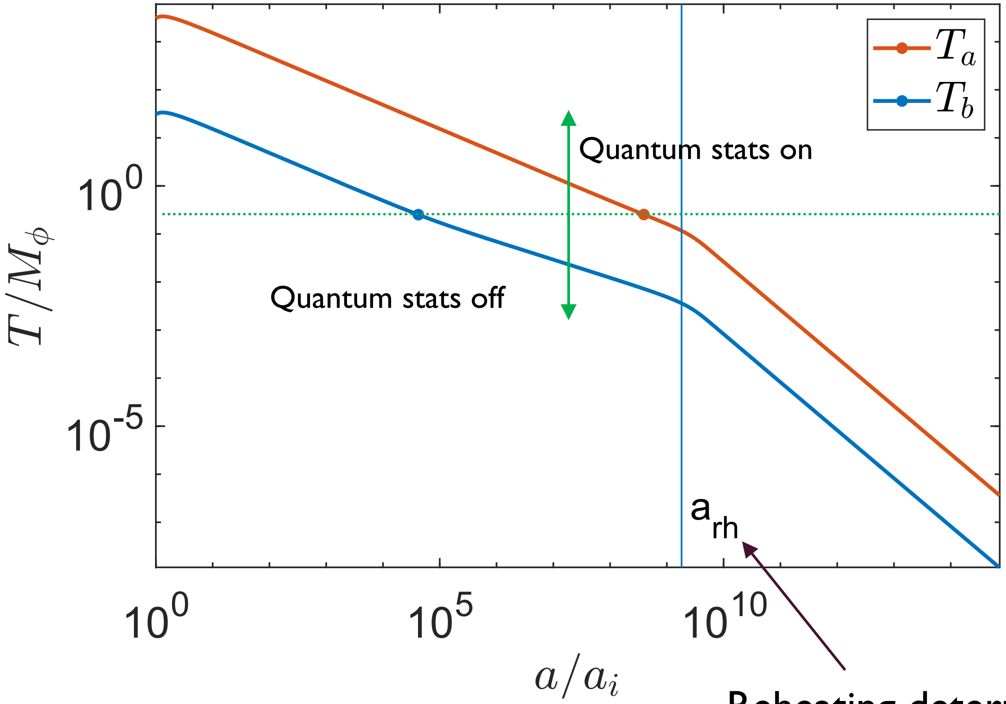
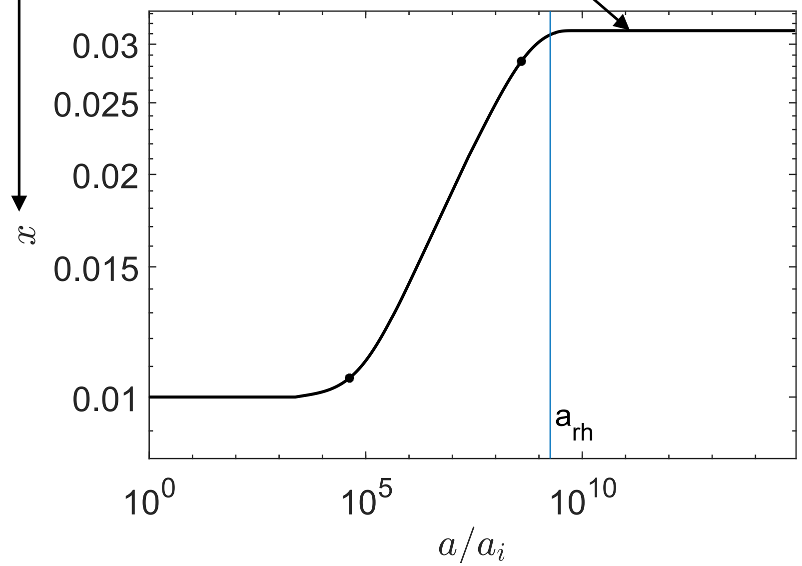


Reheating determined by hotter sector

T_b/T_a

x

Inflaton decay ends;
temperature ratio fixed regardless
of quantum statistics



$$x_{final}^4 \propto \frac{\Gamma_{\phi,a}(T_{a,rh})}{\Gamma_{\phi,b}(T_{b,rh})}$$

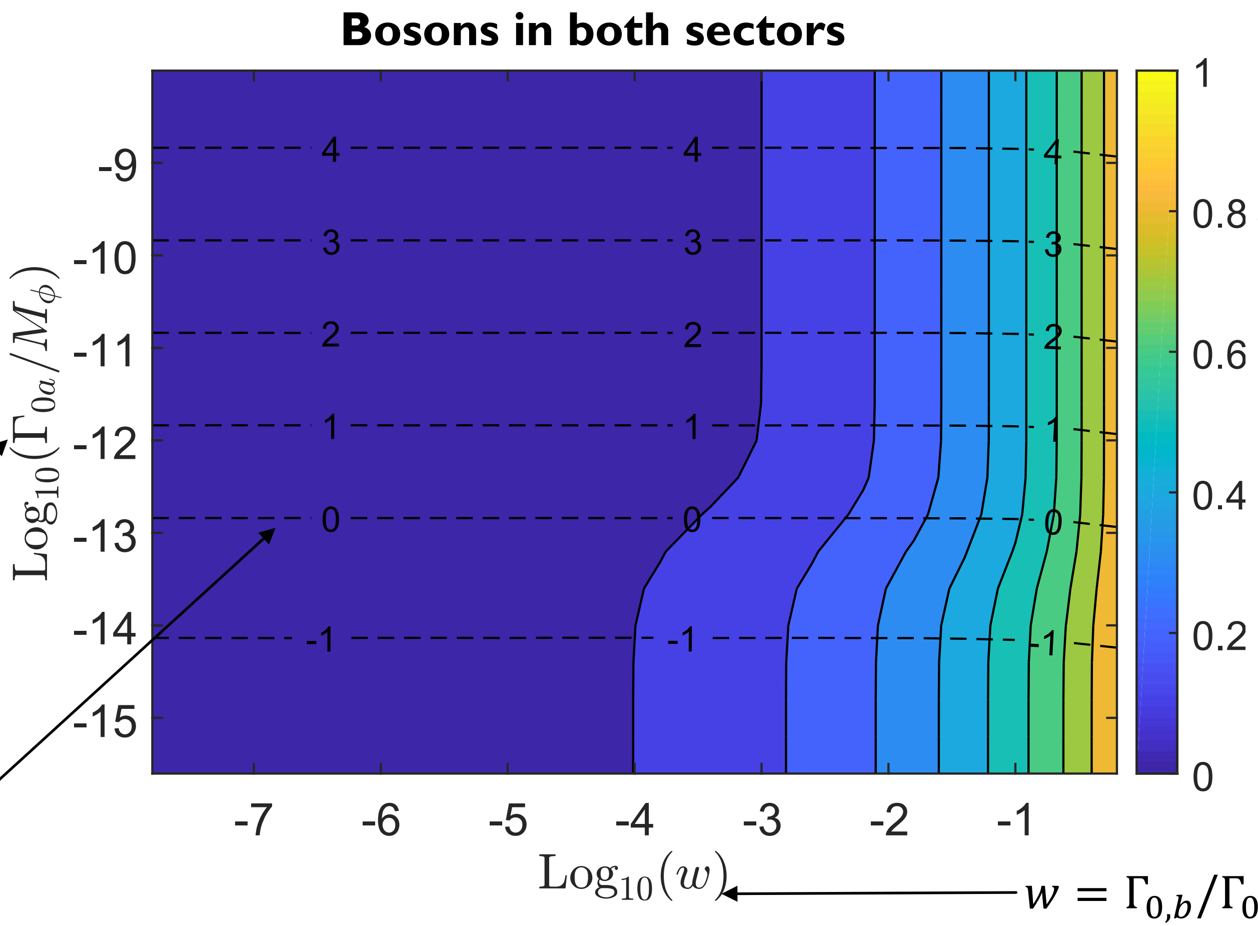
NON INTERACTING SECTORS: Quantum statistics shift final temperature ratio

$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi \approx 0$$

$$\frac{d\rho_a}{dt} + 4H\rho_a = \Gamma_{\phi,a}\rho_\phi$$

$$\frac{d\rho_b}{dt} + 4H\rho_b = \Gamma_{\phi,b}\rho_\phi$$

$$H \approx \frac{1}{\sqrt{3}M_{pl}}\sqrt{\rho_{\phi,I}}a^{-3/2}$$



Final $x = T_b/T_a$

Zero temperature decay width of hotter sector

$Log_{10}(T_{rh}/M_\phi)$

$w = \Gamma_{0,b}/\Gamma_{0,a}$

$$x^4_{final} \propto \frac{\Gamma_{\phi,a}(T_{a,rh})}{\Gamma_{\phi,b}(T_{b,rh})}$$

NON INTERACTING SECTORS: Quantum statistics shift final temperature ratio

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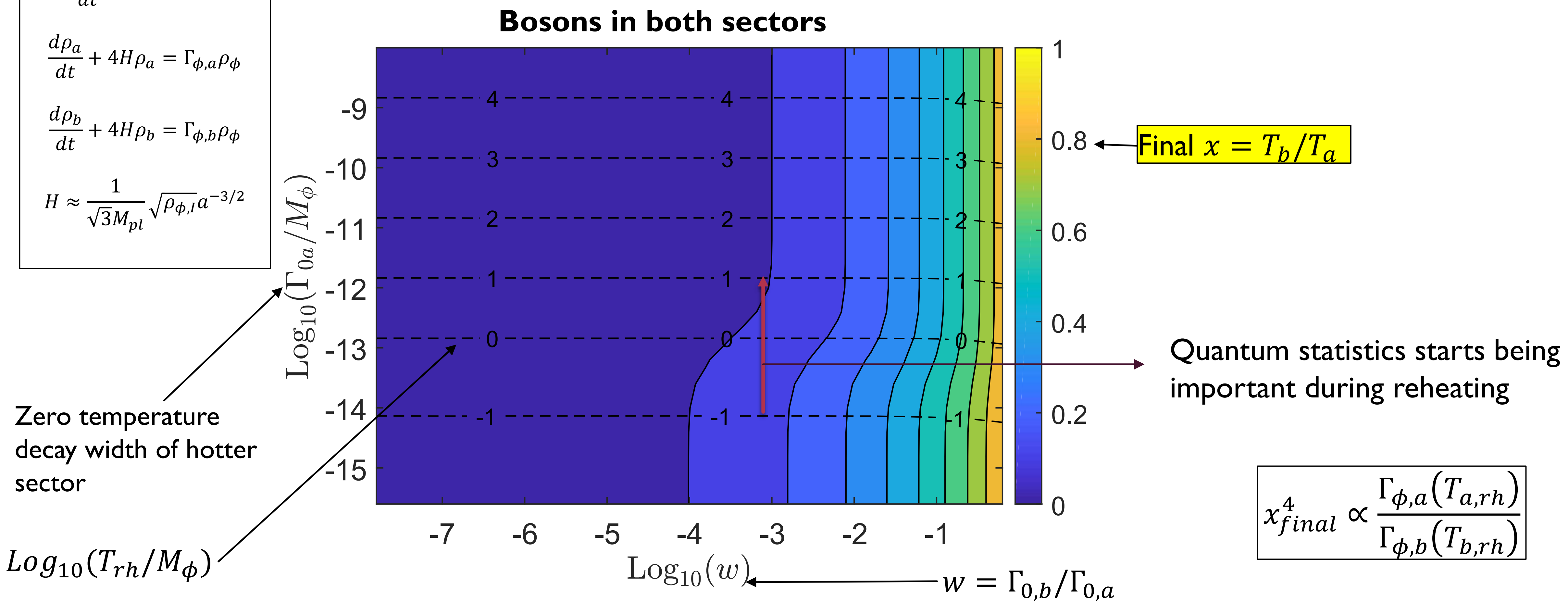

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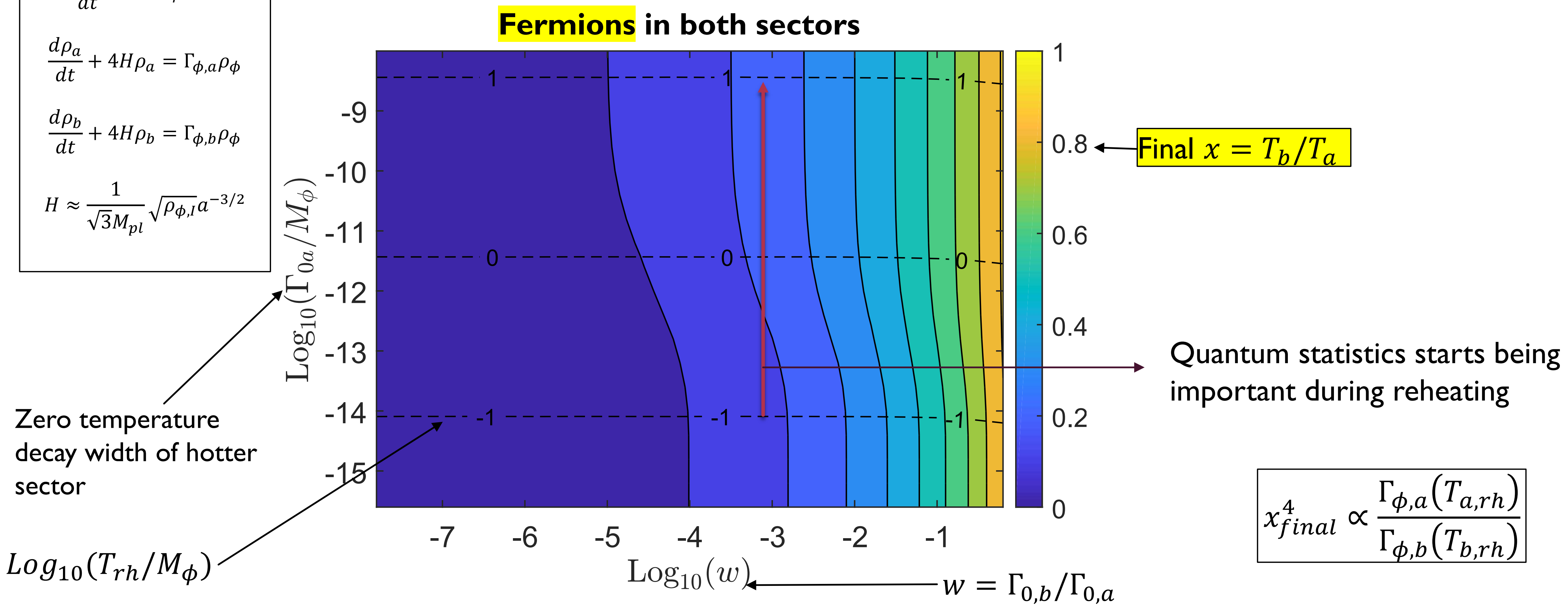

$$x_{final}^4 \propto \frac{\Gamma_{\phi,a}(T_{a,rh})}{\Gamma_{\phi,b}(T_{b,rh})}$$

NON INTERACTING SECTORS: Non trivial structure when different quantum statistics

$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi \approx 0$$

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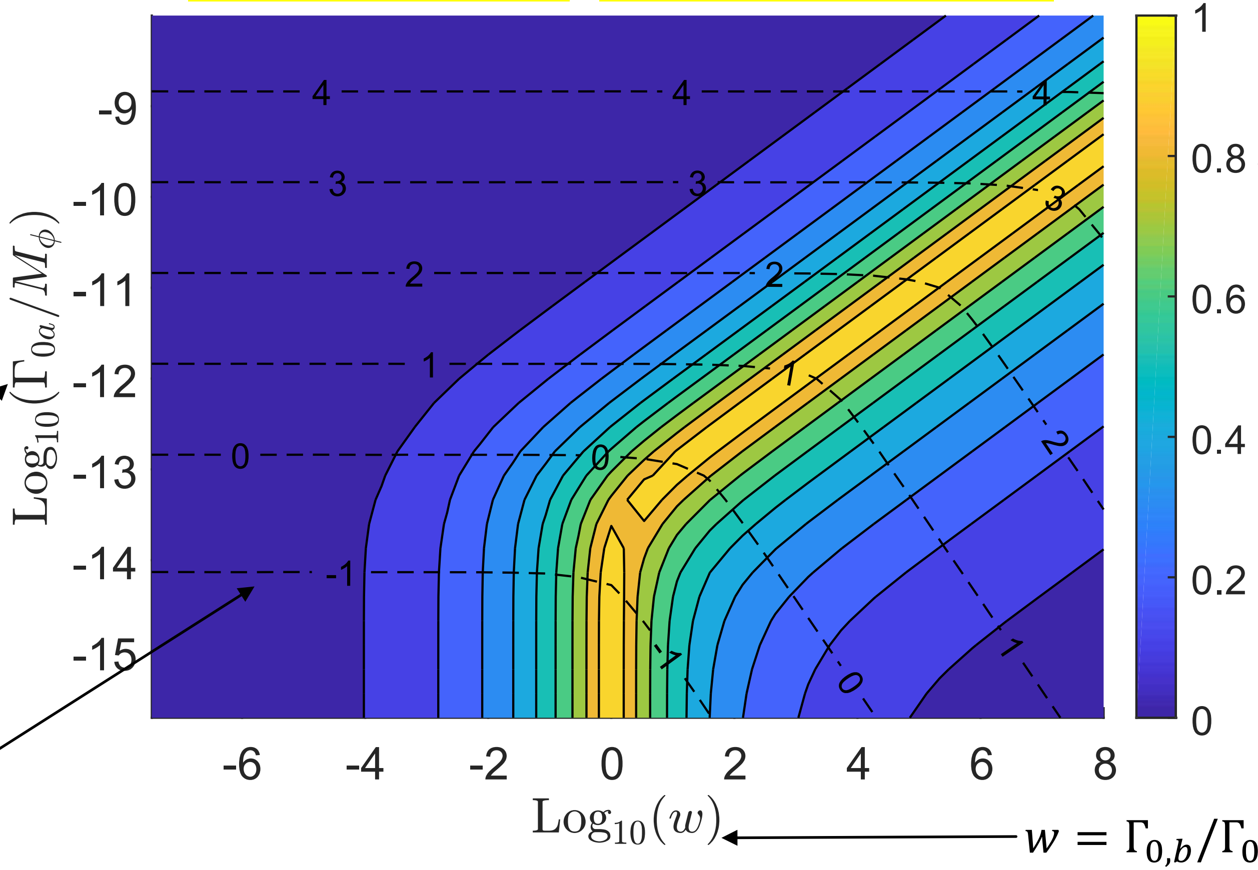
Bosons in sector a, Fermions in sector b



Final $x = T_{cold}/T_{hot}$

Zero temperature decay width of boson sector

$Log_{10}(T_{rh}/M_\phi)$

$w = \Gamma_{0,b}/\Gamma_{0,a}$

$$x_{final}^4 \propto \frac{\Gamma_{\phi,a}(T_{a,rh})}{\Gamma_{\phi,b}(T_{b,rh})}$$

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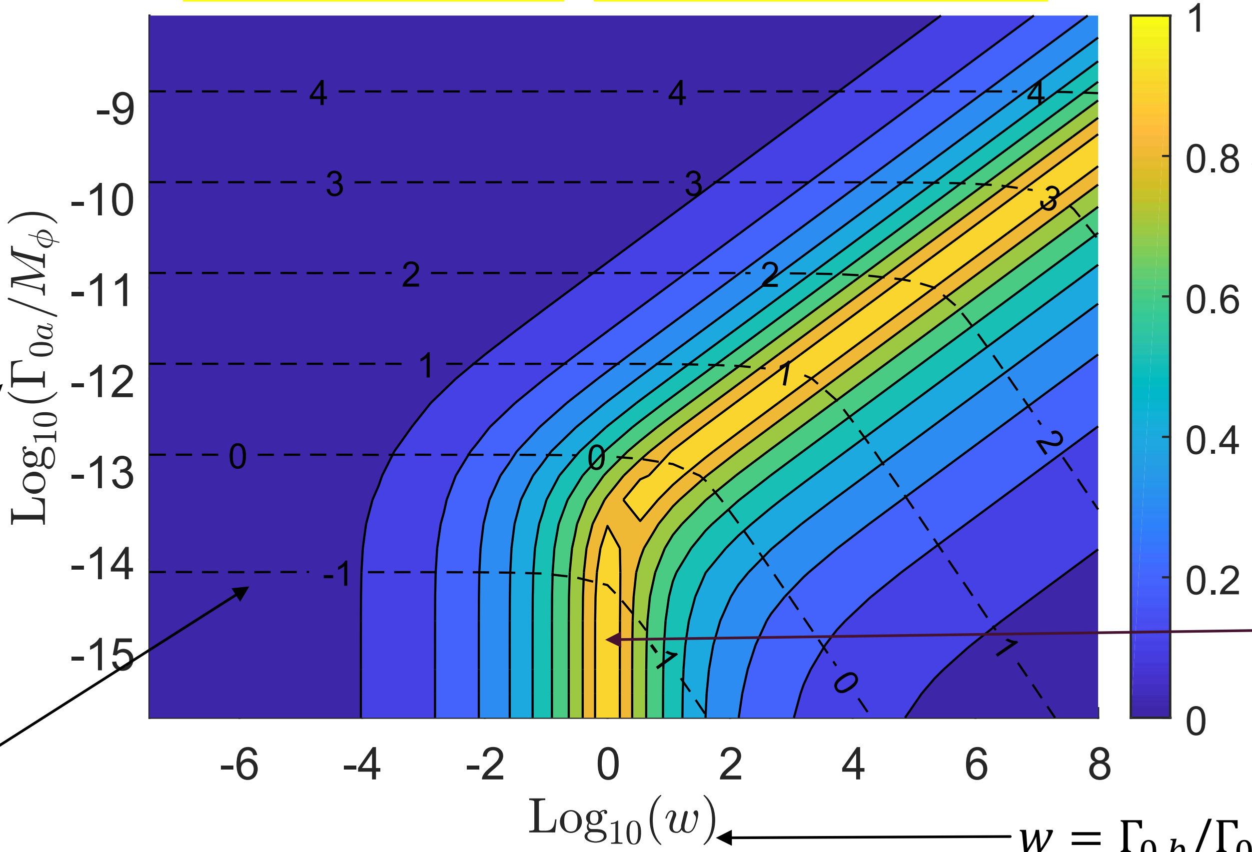

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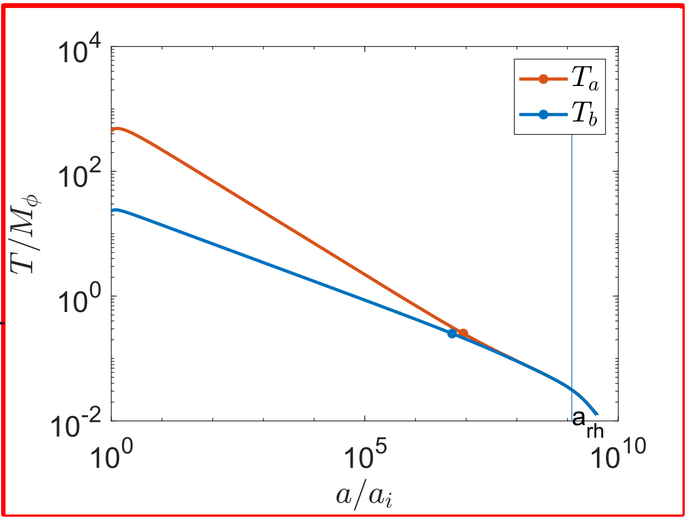

NON INTERACTING SECTORS: Non trivial structure when different quantum statistics

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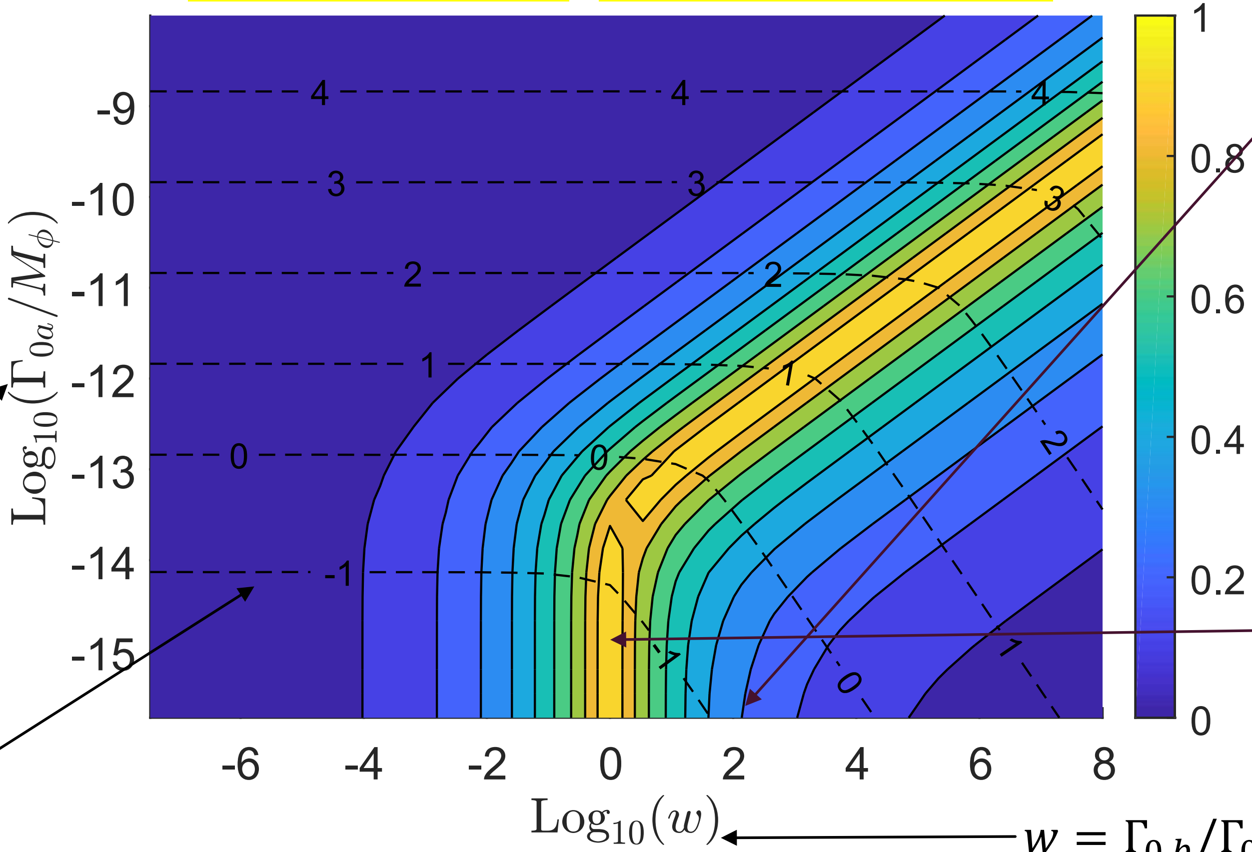
Bosons in sector a, Fermions in sector b



Zero temperature decay width of boson sector

$Log_{10}(T_{rh}/M_\phi)$

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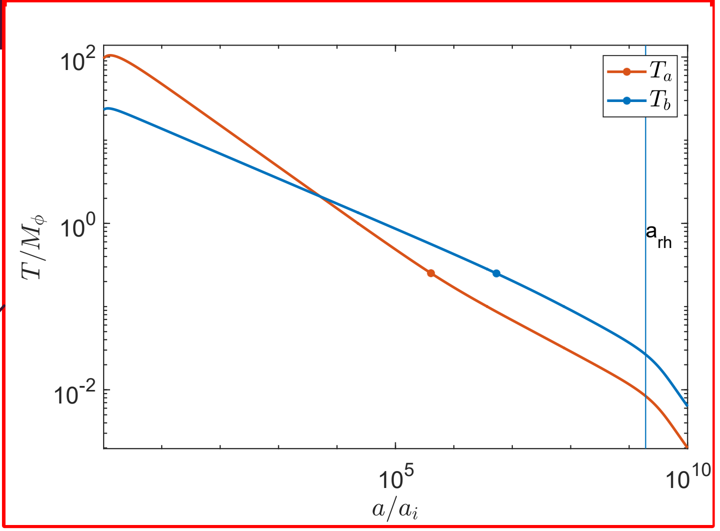

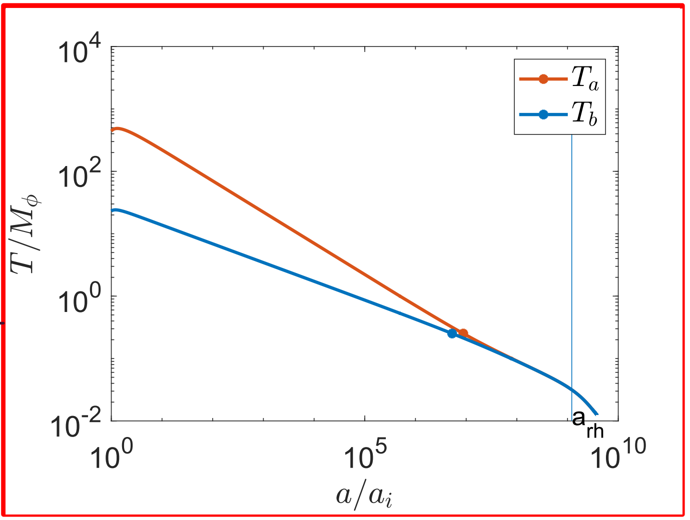

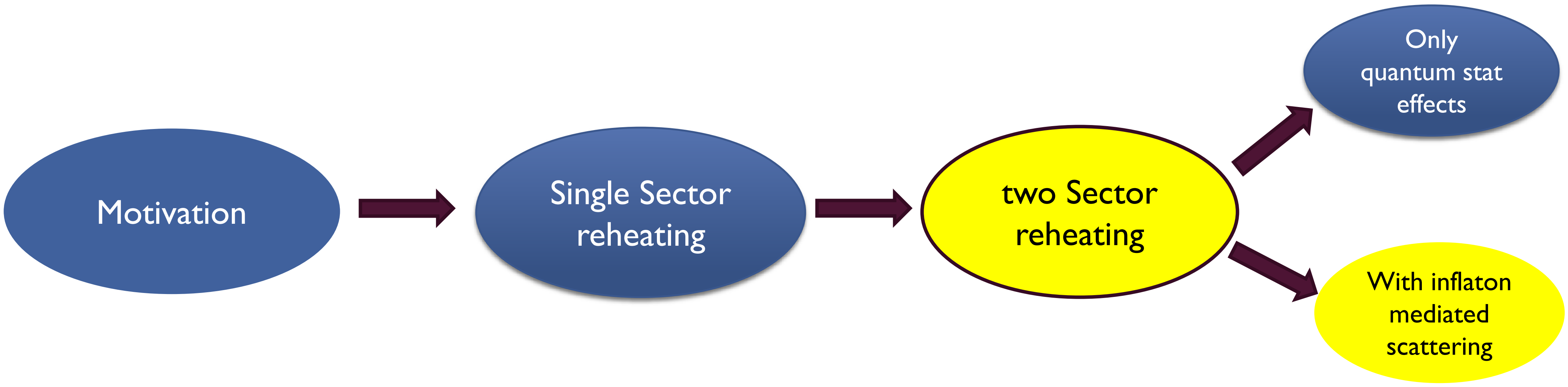
Motivation
Single Sector reheating
two Sector reheating
Only quantum stat effects
With inflaton mediated scattering

INFLATON MEDIATED SCATTERING BETWEEN SECTORS: Boltzmann equations

Post inflation, reheating Boltzmann Equations:

$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi = \left(\Gamma_{\phi,a} + \Gamma_{\phi,b}\right)\rho_\phi$$

$$\frac{d\rho_a}{dt} + 4H\rho_a = \Gamma_{\phi,a}\rho_\phi - C_E$$

$$\frac{d\rho_b}{dt} + 4H\rho_b = \Gamma_{\phi,b}\rho_\phi + C_E$$

$$H \approx \frac{1}{\sqrt{3}M_{pl}}\sqrt{\rho_\phi + \rho_a + \rho_b}$$

INFLATON MEDIATED SCATTERING BETWEEN SECTORS: Analytic form for collision term

$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi = (\Gamma_{\phi,a} + \Gamma_{\phi,b})\rho_\phi$$

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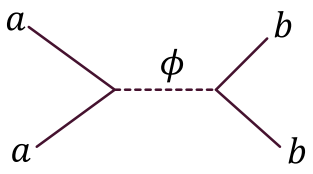

INFLATON MEDIATED SCATTERING BETWEEN SECTORS: Analytic form for collision term

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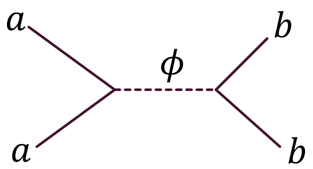

$$\mathcal{C}_E = \int \frac{d^3p_1}{2E_1(2\pi)^3}\frac{d^3p_2}{2E_2(2\pi)^3}\frac{d^3p_3}{2E_3(2\pi)^3}\frac{d^3p_4}{2E_4(2\pi)^3}(2\pi)^4\delta^4(p_1+p_2-p_3+p_4)|\mathcal{M}|^2\hat{S}$$
$$\times (E_1+E_2)[f_1(p_1)f_2(p_2)(1\pm f_3(p_3))(1\pm f_4(p_4)) - f_3(p_3)f_4(p_4)(1\pm f_1(p_1))(1\pm f_2(p_2))].$$

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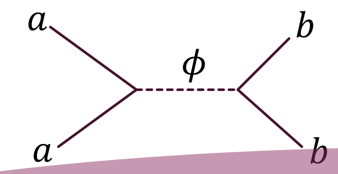

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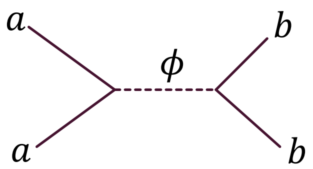
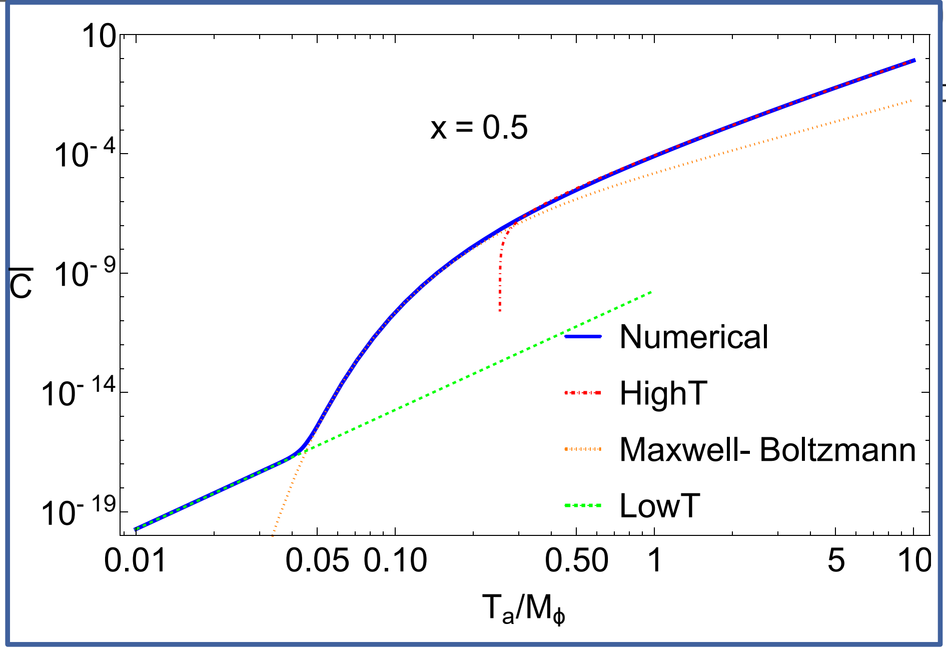
$$H \approx \frac{1}{\sqrt{3}M_{pl}}\sqrt{\rho_{\phi,I} + \rho_a + \rho_b}$$



$$\mathcal{C}_E = \int \frac{d^3p_1}{\ldots}\frac{d^3p_2}{\ldots}\frac{d^3p_3}{\ldots}\frac{d^3p_4}{\ldots}(2\pi)^4\delta^4(p_1+p_2-p_3+p_4)|\mathcal{M}|^2\hat{S}$$

$$\ldots \pm f_4(p_4)) - f_3(p_3)f_4(p_4)(1 \pm f_1(p_1))(1 \pm f_2(p_2))].$$



Derived analytic expression for non-equilibrium energy transfer between two sectors at different temperatures including quantum statistics.

INFLATON MEDIATED SCATTERING BETWEEN SECTORS: Analytic form for collision term

$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi = (\Gamma_{\phi,a} + \Gamma_{\phi,b})\rho_\phi$$

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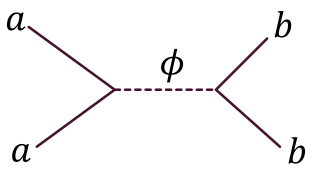

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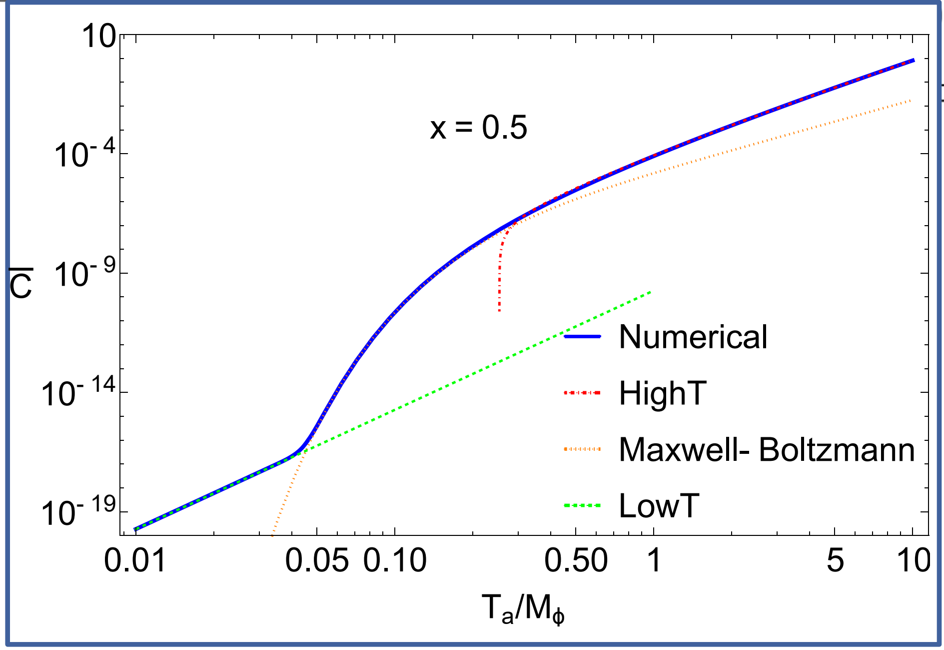

Derived analytic expression for non-equilibrium energy transfer between two sectors at different temperatures including quantum statistics.

Birell, Yang and Rafelski (2014)

INFLATON MEDIATED SCATTERING BETWEEN SECTORS: Collision term for scalar trilinear coupling with inflaton

$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi = (\Gamma_{\phi,a} + \Gamma_{\phi,b})\rho_\phi$$

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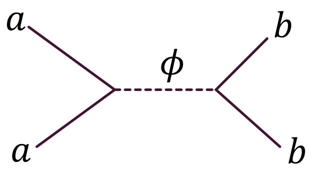
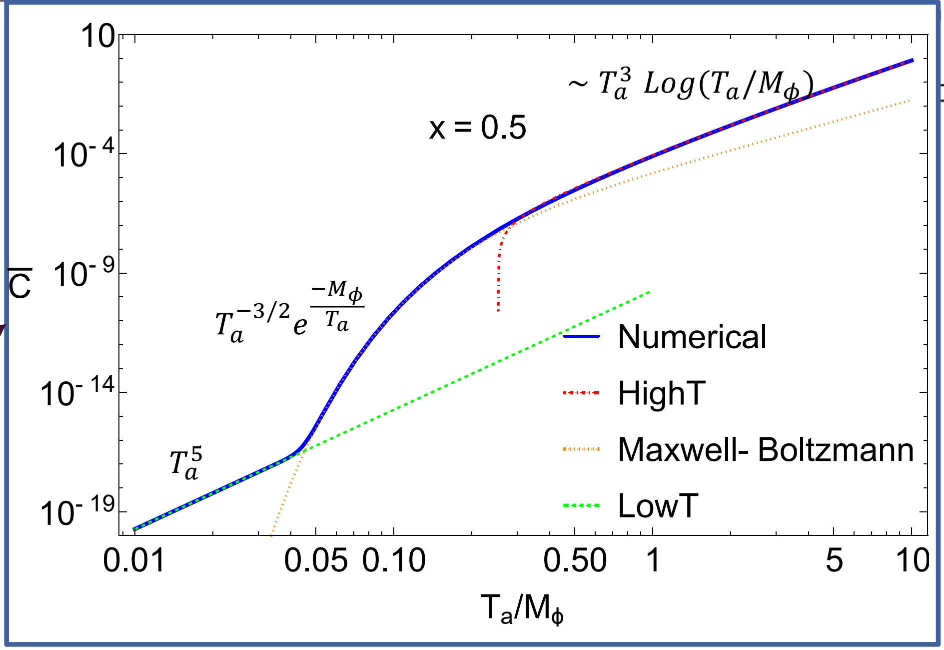


$$\mathcal{C}_E = \int \frac{d^3p_1}{\cdots}\frac{d^3p_2}{\cdots}\frac{d^3p_3}{\cdots}\frac{d^3p_4}{\cdots(2\pi)^3}(2\pi)^4\delta^4(p_1+p_2-p_3+p_4)|\mathcal{M}|^2\hat{S}$$

$$\cdots \pm f_4(p_4)) - f_3(p_3)f_4(p_4)(1 \pm f_1(p_1))(1 \pm f_2(p_2))].$$



s-channel collision term for scalar trilinear couplings of inflaton in both sectors

Derived analytic expression for non-equilibrium energy transfer between two sectors at different temperatures including quantum statistics.

INFLATON MEDIATED SCATTERING BETWEEN SECTORS: Collision term for scalar trilinear coupling with inflaton

$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi = (\Gamma_{\phi,a} + \Gamma_{\phi,b})\rho_\phi$$

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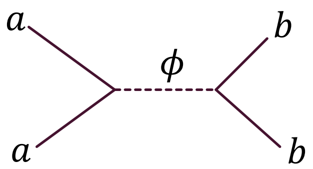
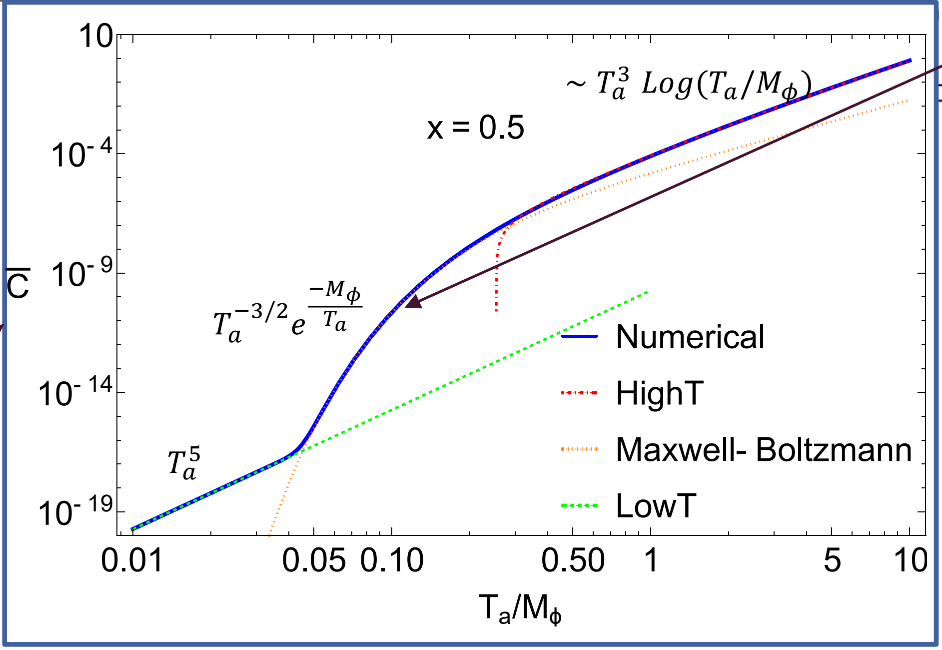
$$H \approx \frac{1}{\sqrt{3}M_{pl}}\sqrt{\rho_{\phi,I} + \rho_a + \rho_b}$$



$$\mathcal{C}_E = \int \frac{d^3p_1}{\ldots}\frac{d^3p_2}{\ldots}\frac{d^3p_3}{\ldots}\frac{d^3p_4}{\ldots{}^3}(2\pi)\ldots|^2\hat{S}$$

$$\ldots \pm f_4(p_4)) - f_3(p_3)f_4(p_4)(1 \pm f_1(p_1))(1 \pm f_2(p_2))].$$

Resonance boost in s-channel



s-channel collision term for scalar trilinear couplings of inflaton in both sectors

Derived analytic expression for non-equilibrium energy transfer between two sectors at different temperatures including quantum statistics.

INFLATON MEDIATED SCATTERING BETWEEN SECTORS: Scattering becomes effective after reheating

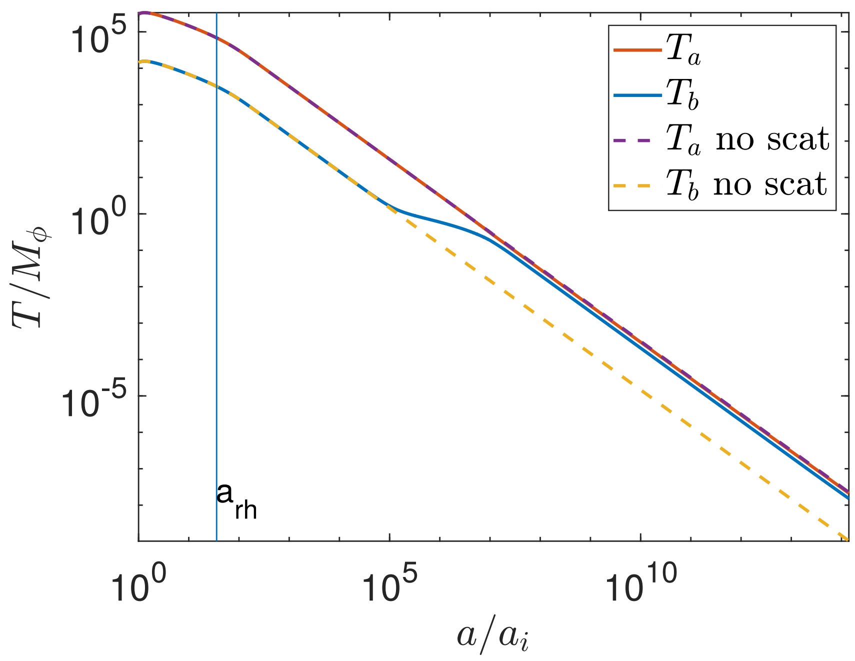
$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi = (\Gamma_{\phi,a} + \Gamma_{\phi,b})\rho_\phi$$

$$\frac{d\rho_a}{dt} + 4H\rho_a = \Gamma_{\phi,a}\rho_\phi - C_E$$

$$\frac{d\rho_b}{dt} + 4H\rho_b = \Gamma_{\phi,b}\rho_\phi + C_E$$

$$H \approx \frac{1}{\sqrt{3}M_{pl}}\sqrt{\rho_{\phi,I} + \rho_a + \rho_b}$$

Inflaton with trilinear coupling to relativistic scalars in both sectors



For $\alpha_a \sim \alpha_b$, inflaton mediated scattering is usually never strong enough to overcome the Hubble rate before reheating for the interaction theories we consider.

INFLATON MEDIATED SCATTERING BETWEEN SECTORS: C_E attractor curve

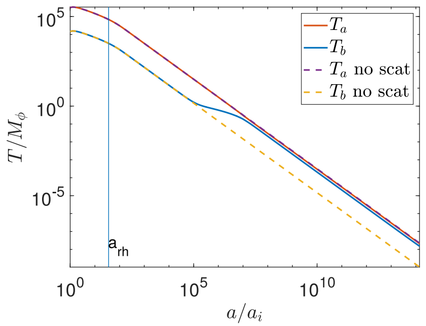
$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi = (\Gamma_{\phi,a} + \Gamma_{\phi,b})\rho_\phi$$

$$\frac{d\rho_a}{dt} + 4H\rho_a = \Gamma_{\phi,a}\rho_\phi - C_E$$

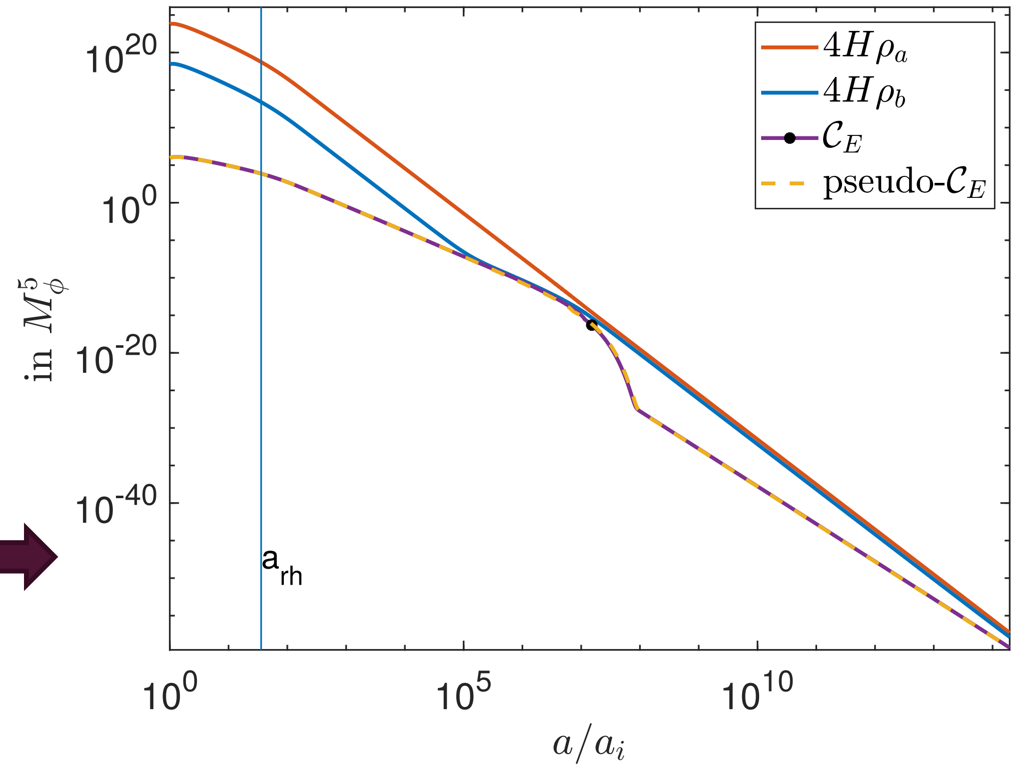
$$\frac{d\rho_b}{dt} + 4H\rho_b = \Gamma_{\phi,b}\rho_\phi + C_E$$

$$H \approx \frac{1}{\sqrt{3}M_{pl}}\sqrt{\rho_{\phi,I} + \rho_a + \rho_b}$$

Inflaton with trilinear coupling to relativistic scalars in both sectors



A better representation of thermalization process



INFLATON MEDIATED SCATTERING BETWEEN SECTORS: C_E attractor curve

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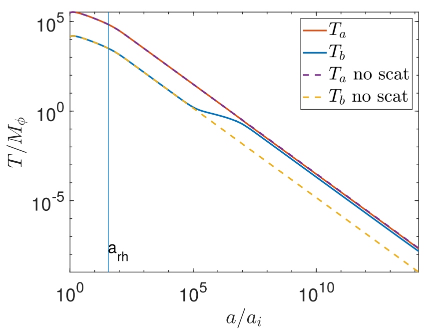
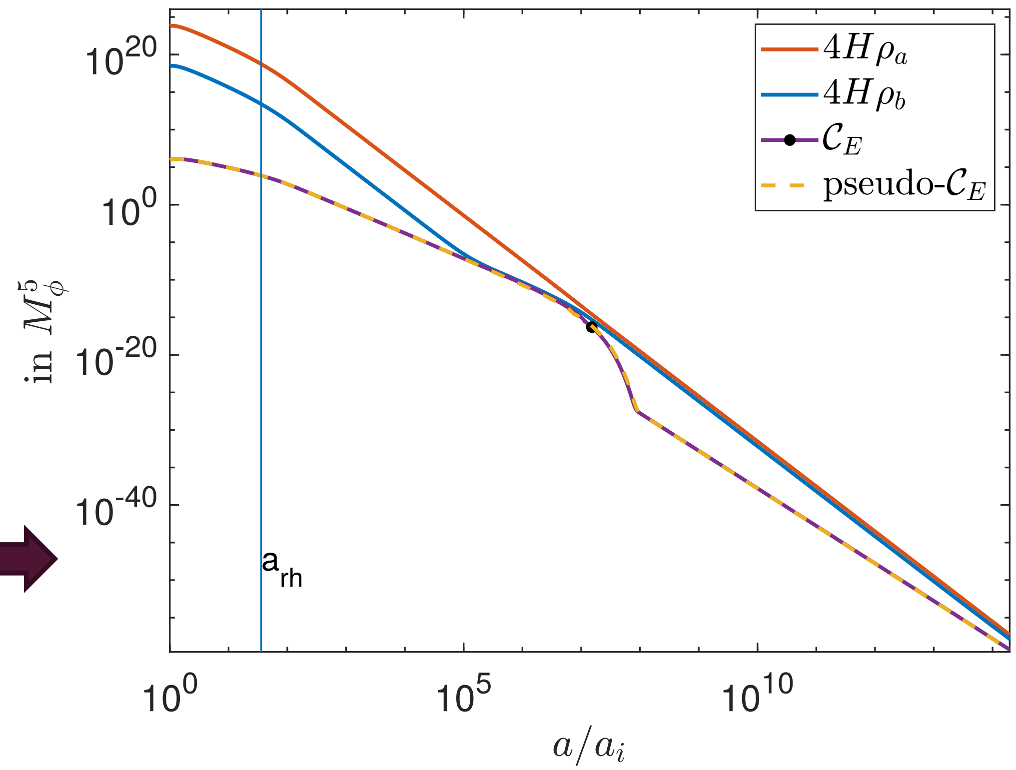
$$H \approx \frac{1}{\sqrt{3}M_{pl}}\sqrt{\rho_{\phi,I} + \rho_a + \rho_b}$$

Inflaton with trilinear coupling to relativistic scalars in both sectors

$$x^4 \sim \frac{4H\rho_b}{4H\rho_a}$$



A better representation of thermalization process



INFLATON MEDIATED SCATTERING BETWEEN SECTORS: C_E attractor curve

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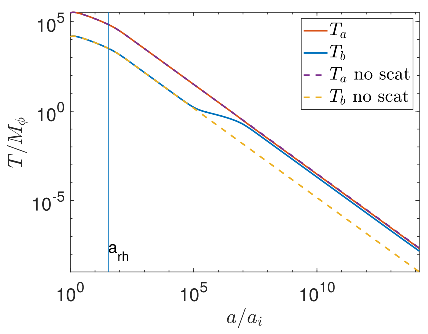
$$\frac{d\rho_b}{dt} + 4H\rho_b = \Gamma_{\phi,b}\rho_\phi + C_E$$

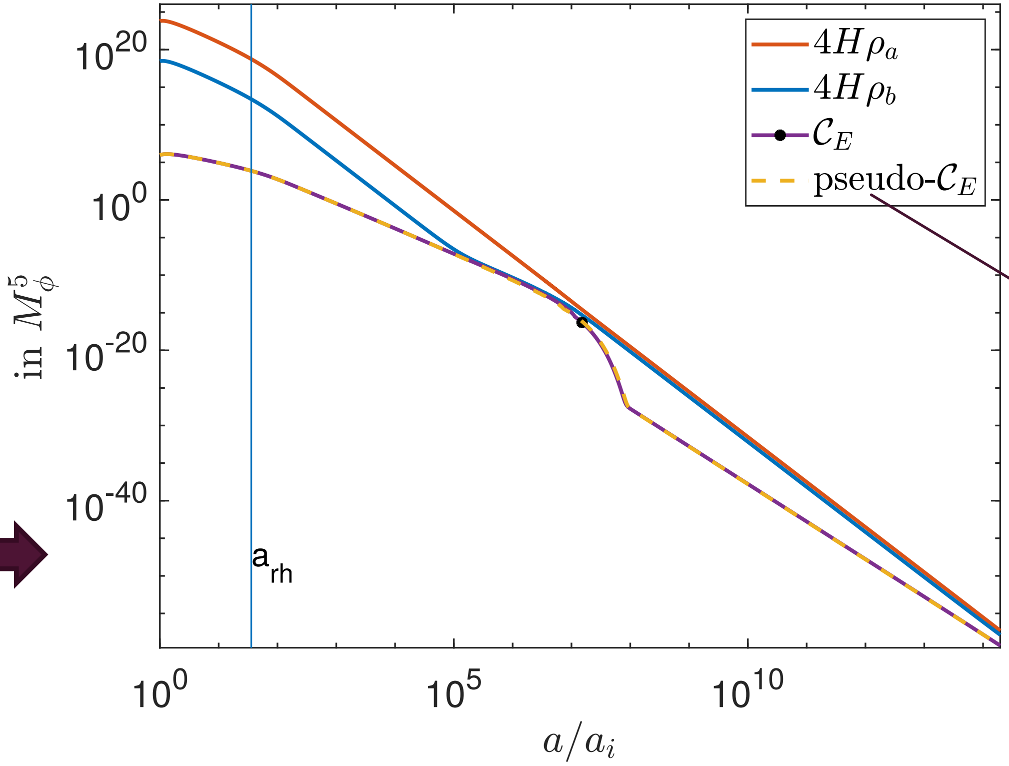
$$H \approx \frac{1}{\sqrt{3}M_{pl}}\sqrt{\rho_{\phi,I} + \rho_a + \rho_b}$$

Inflaton with trilinear coupling to relativistic scalars in both sectors

$$x^4 \sim \frac{4H\rho_b}{4H\rho_a}$$



A better representation of thermalization process



Collision term neglecting feedback from colder sector during thermalization process

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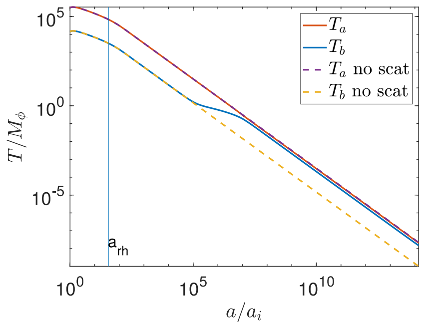
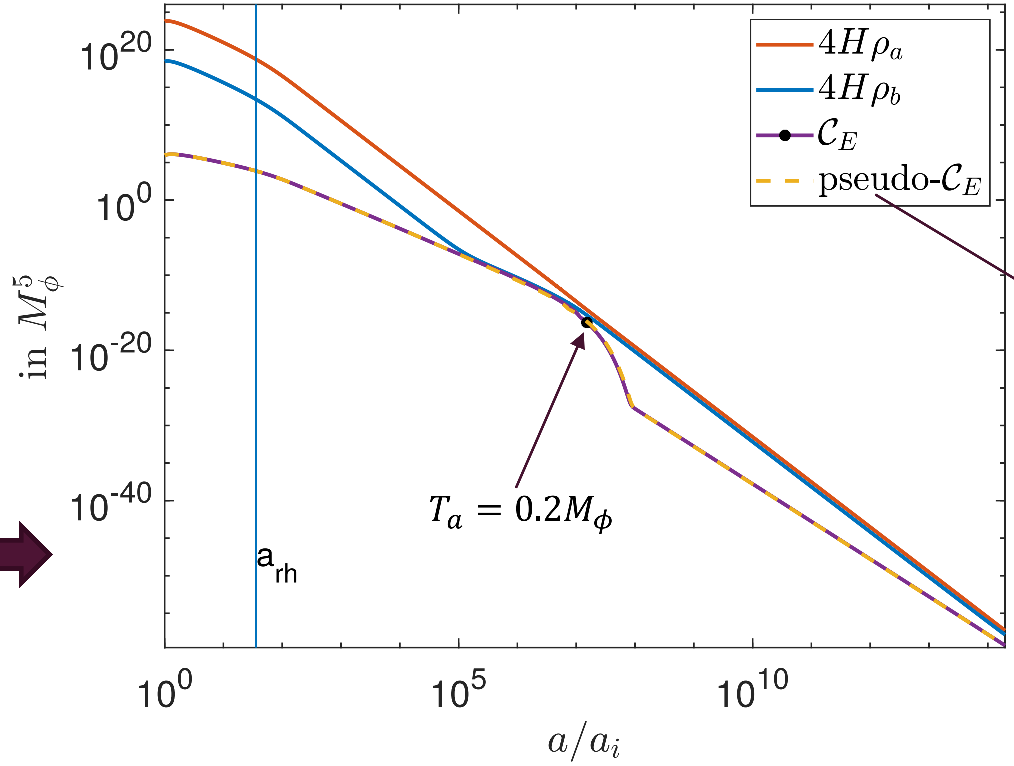
$$H \approx \frac{1}{\sqrt{3}M_{pl}}\sqrt{\rho_{\phi,I} + \rho_a + \rho_b}$$

Inflaton with trilinear coupling to relativistic scalars in both sectors

$$x^4 \sim \frac{4H\rho_b}{4H\rho_a}$$



A better representation of thermalization process



Collision term neglecting feedback from colder sector during thermalization process

INFLATON MEDIATED SCATTERING BETWEEN SECTORS: C_E attractor curve

$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi = (\Gamma_{\phi,a} + \Gamma_{\phi,b})\rho_\phi$$

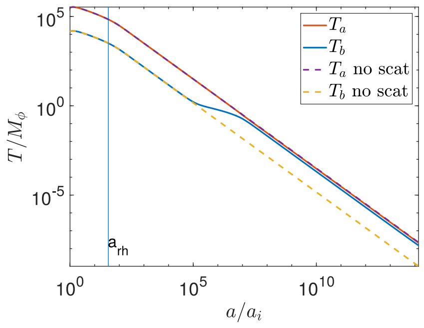
$$\frac{d\rho_a}{dt} + 4H\rho_a = \Gamma_{\phi,a}\rho_\phi - C_E$$

$$\frac{d\rho_b}{dt} + 4H\rho_b = \Gamma_{\phi,b}\rho_\phi + C_E$$

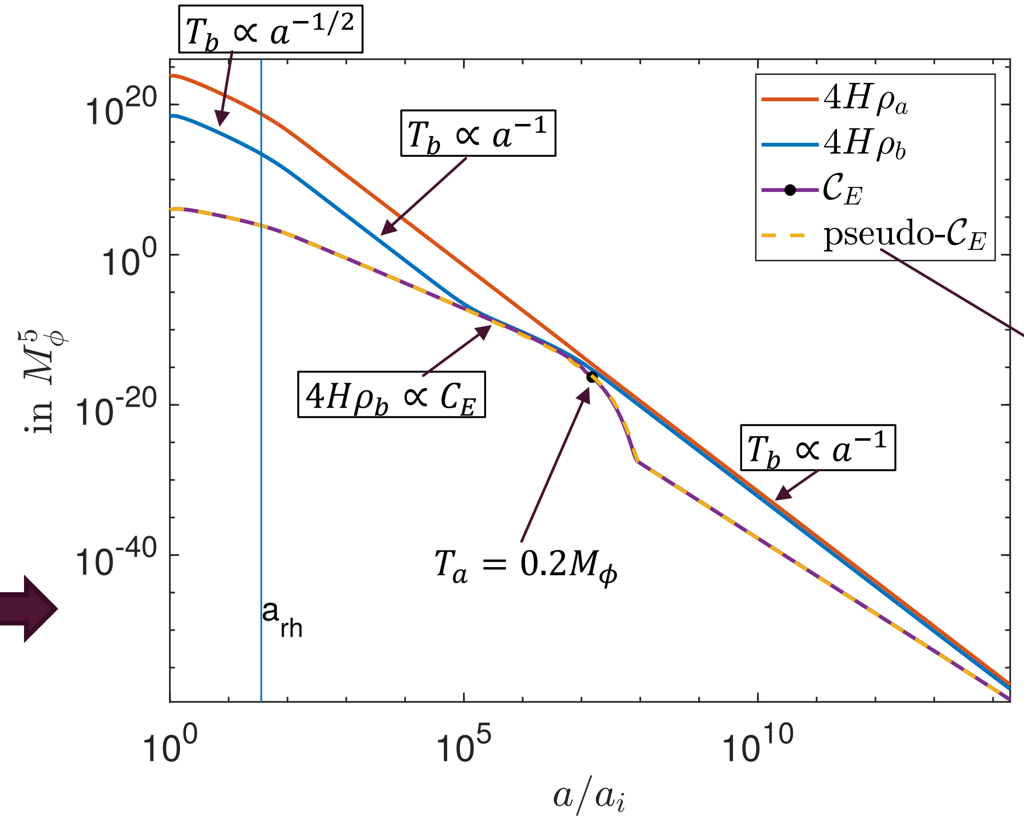
$$H \approx \frac{1}{\sqrt{3}M_{pl}}\sqrt{\rho_{\phi,I} + \rho_a + \rho_b}$$

Inflaton with trilinear coupling to relativistic scalars in both sectors

$$x^4 \sim \frac{4H\rho_b}{4H\rho_a}$$



A better representation of thermalization process



Collision term neglecting feedback from colder sector during thermalization process

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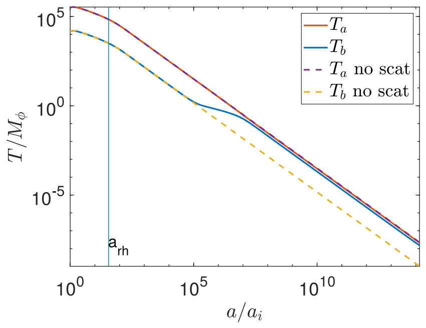
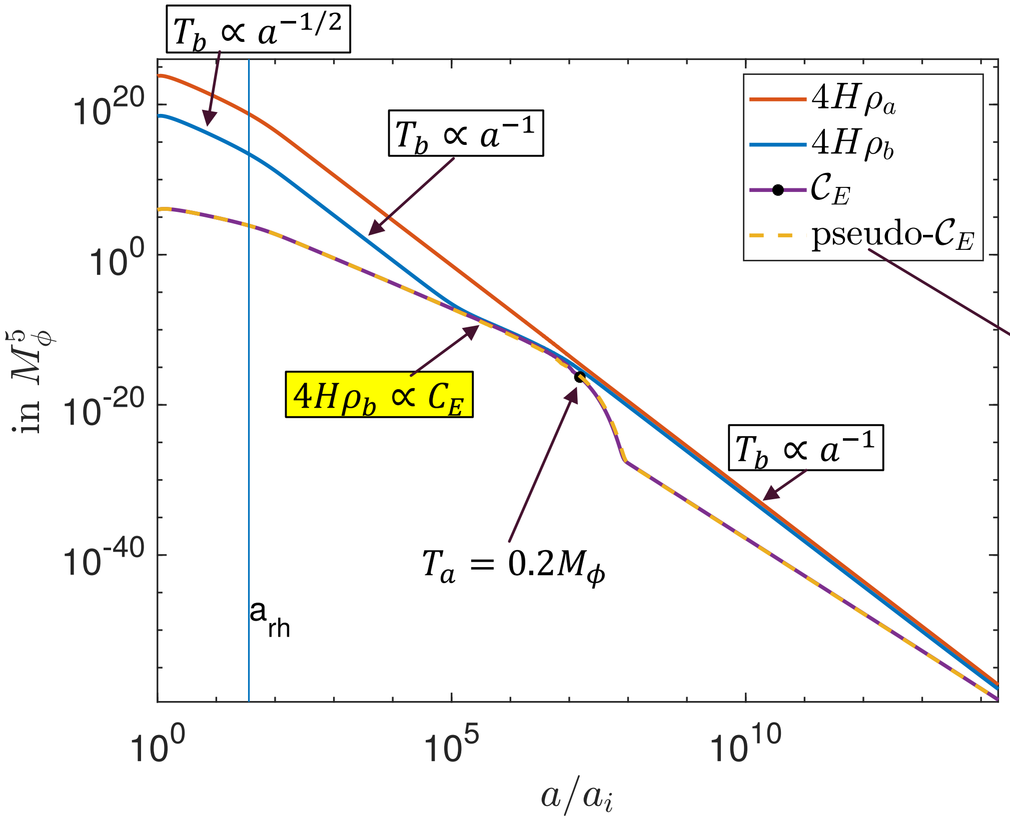
Inflaton with trilinear coupling to relativistic scalars in both sectors

$$x^4 \sim \frac{4H\rho_b}{4H\rho_a}$$





Collision term neglecting feedback from colder sector during thermalization process

Energy injection from the hotter sector imposes another attractor solution!

INFLATON MEDIATED SCATTERING BETWEEN SECTORS: x independent of initial history

$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi = (\Gamma_{\phi,a} + \Gamma_{\phi,b})\rho_\phi$$

$$\frac{d\rho_a}{dt} + 4H\rho_a = \Gamma_{\phi,a}\rho_\phi - C_E$$

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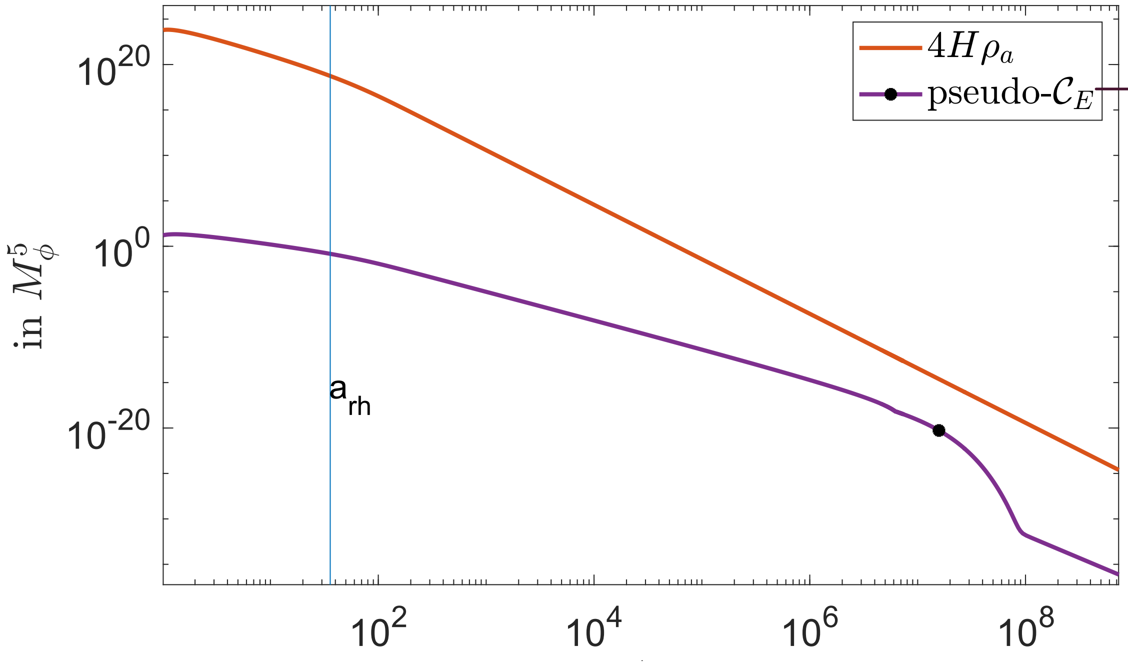
$$H \approx \frac{1}{\sqrt{3}M_{pl}}\sqrt{\rho_{\phi,I} + \rho_a + \rho_b}$$

Inflaton with trilinear coupling to relativistic scalars in both sectors

$$x^4 \sim \frac{4H\rho_b}{4H\rho_a}$$



Determined completely by hotter sector

INFLATON MEDIATED SCATTERING BETWEEN SECTORS: x independent of initial history

$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi = (\Gamma_{\phi,a} + \Gamma_{\phi,b})\rho_\phi$$

$$\frac{d\rho_a}{dt} + 4H\rho_a = \Gamma_{\phi,a}\rho_\phi - C_E$$

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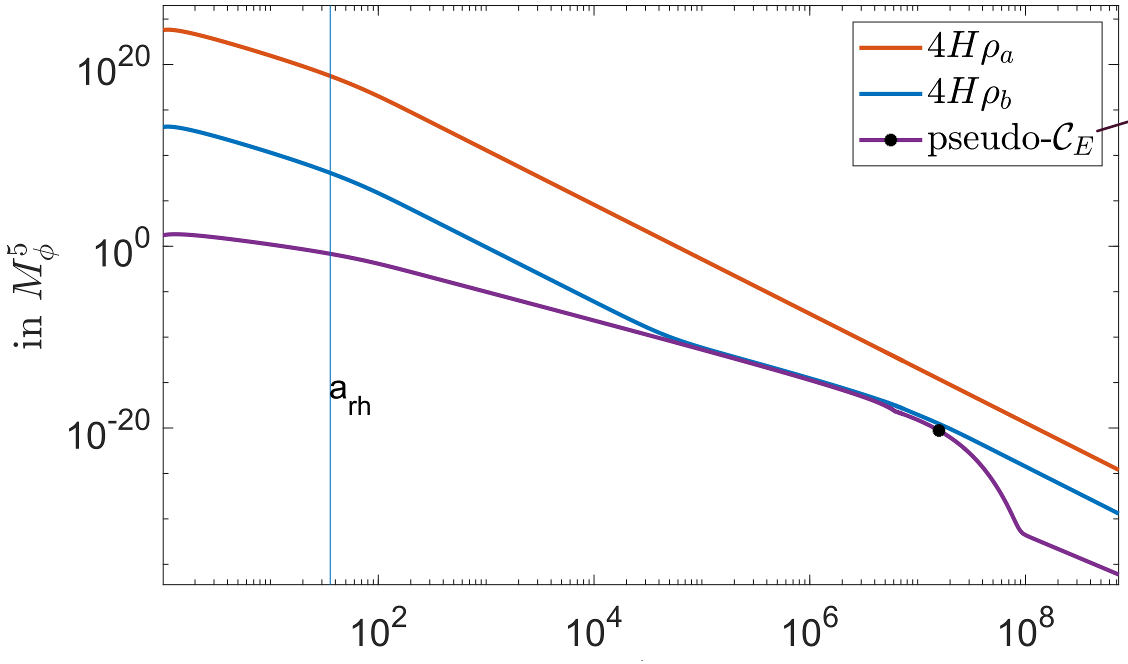
Inflaton with trilinear coupling to relativistic scalars in both sectors

$$x^4 \sim \frac{4H\rho_b}{4H\rho_a}$$



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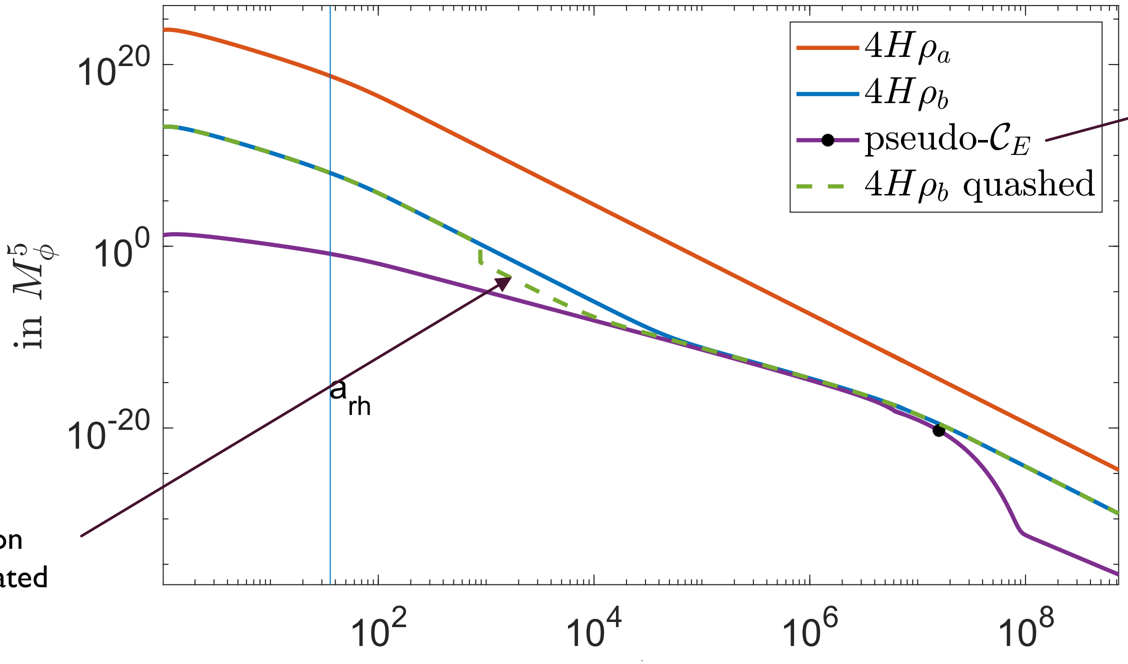
Inflaton with trilinear coupling to relativistic scalars in both sectors

$$x^4 \sim \frac{4H\rho_b}{4H\rho_a}$$



Determined completely by hotter sector

Quashed colder sector gets on the attractor curve and is heated to same temperature

INFLATON MEDIATED SCATTERING BETWEEN SECTORS: x independent of initial history

$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi = (\Gamma_{\phi,a} + \Gamma_{\phi,b})\rho_\phi$$

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Inflaton with trilinear coupling to relativistic scalars in both sectors

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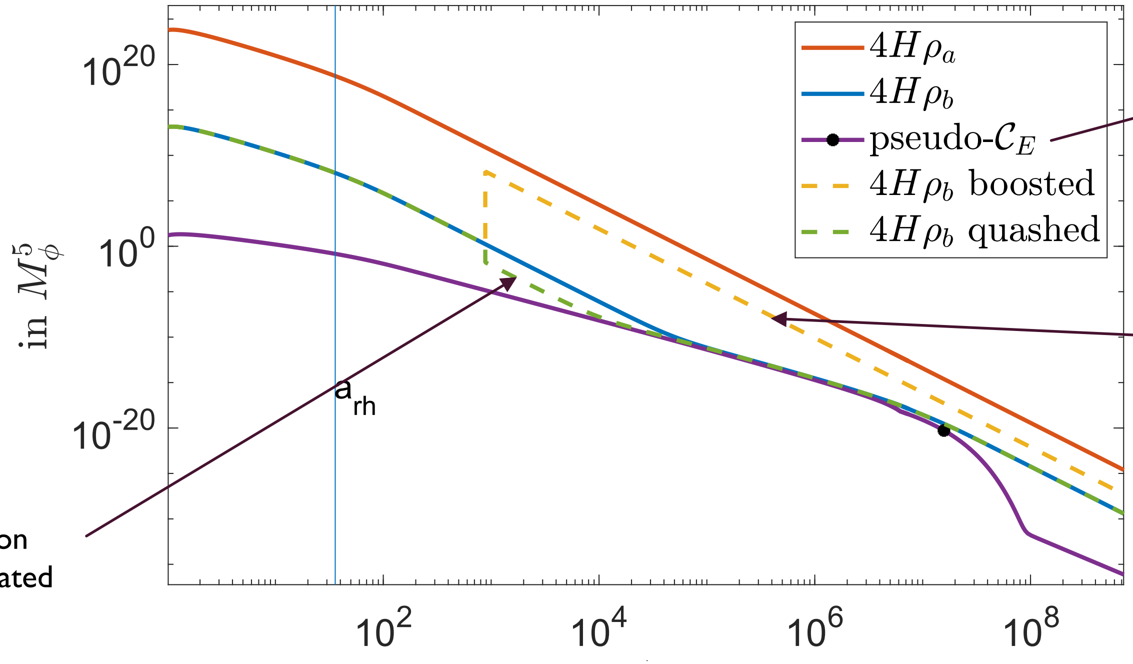


Determined completely by hotter sector

Boosted colder sector is unable to get on the attractor curve before $T_a \sim 0.2M_\phi$

Quashed colder sector gets on the attractor curve and is heated to same temperature

INFLATON MEDIATED SCATTERING BETWEEN SECTORS: x (almost) independent of initial history

$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi = (\Gamma_{\phi,a} + \Gamma_{\phi,b})\rho_\phi$$

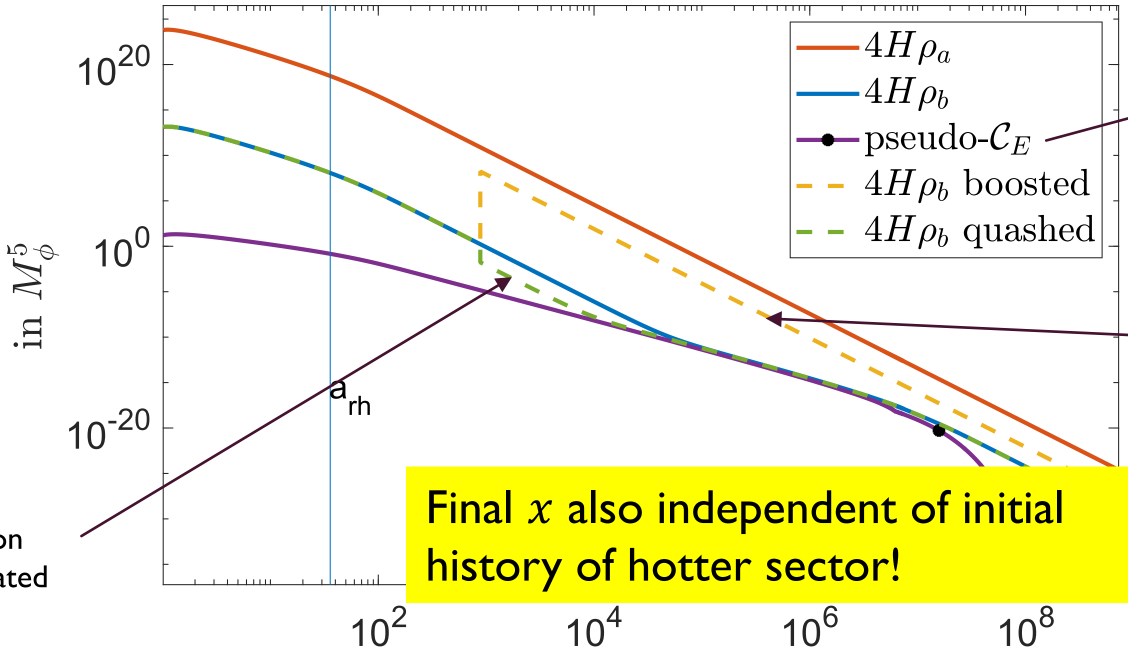
$$\frac{d\rho_a}{dt} + 4H\rho_a = \Gamma_{\phi,a}\rho_\phi - C_E$$

$$\frac{d\rho_b}{dt} + 4H\rho_b = \Gamma_{\phi,b}\rho_\phi + C_E$$

$$H \approx \frac{1}{\sqrt{3}M_{pl}}\sqrt{\rho_{\phi,I} + \rho_a + \rho_b}$$

Inflaton with trilinear coupling to relativistic scalars in both sectors

$$x^4 \sim \frac{4H\rho_b}{4H\rho_a}$$



Determined completely by hotter sector

Boosted colder sector is unable to get on the attractor curve before $T_a \sim 0.2 M_\phi$

Quashed colder sector gets on the attractor curve and is heated to same temperature

Final x also independent of initial history of hotter sector!

INFLATON MEDIATED SCATTERING BETWEEN SECTORS: Finding x analytically

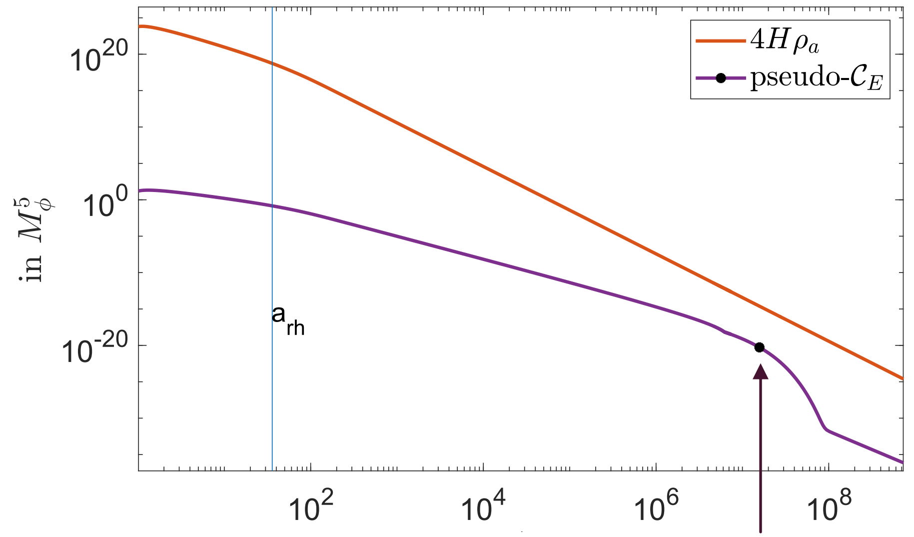
$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi = (\Gamma_{\phi,a} + \Gamma_{\phi,b})\rho_\phi$$

$$\frac{d\rho_a}{dt} + 4H\rho_a = \Gamma_{\phi,a}\rho_\phi - C_E$$

$$\frac{d\rho_b}{dt} + 4H\rho_b = \Gamma_{\phi,b}\rho_\phi + C_E$$

$$H \approx \frac{1}{\sqrt{3}M_{pl}}\sqrt{\rho_{\phi,I} + \rho_a + \rho_b}$$

Inflaton with trilinear coupling to relativistic scalars in both sectors



Integrate around $T_a \sim 0.2M_\phi$ to find x_{sc} assuming colder sector gets on the attractor curve.

$x = x_{sc}$ only when $x_{rh} < x_{sc} < 1$.

$$x_{sc}^4 \sim \frac{4H\rho_b}{4H\rho_a} \sim \left[\frac{C_E}{4H\rho_a}\right]_{T_a \sim 0.2M_\phi}$$

INFLATON MEDIATED SCATTERING BETWEEN SECTORS: Numerical final x contour plot

$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi = (\Gamma_{\phi,a} + \Gamma_{\phi,b})\rho_\phi$$

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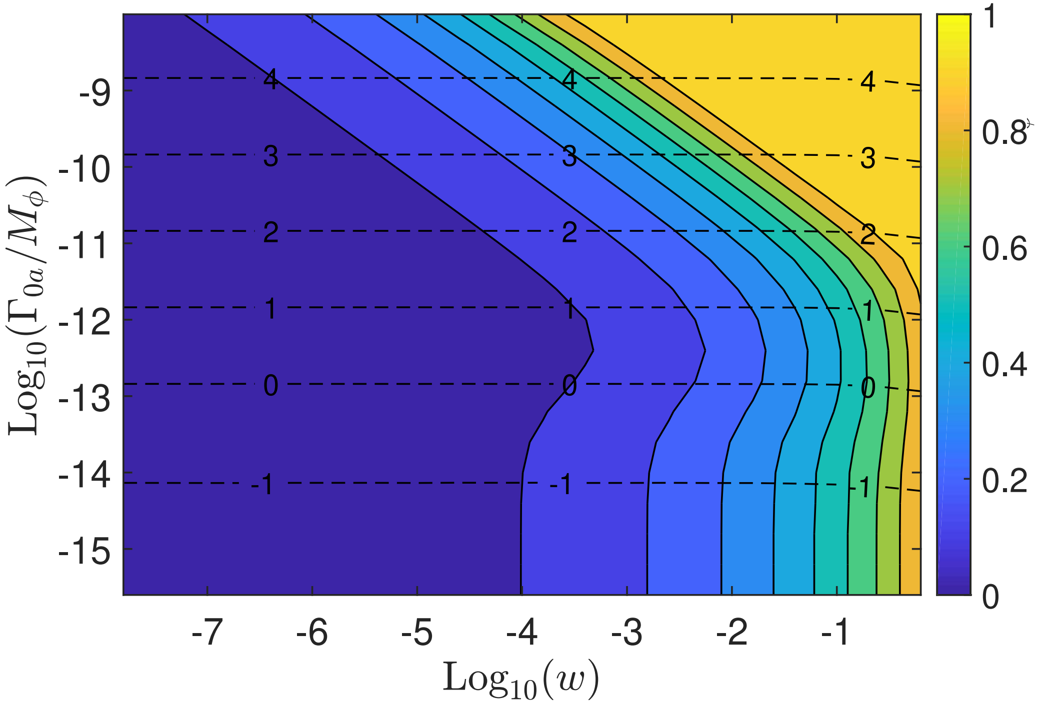
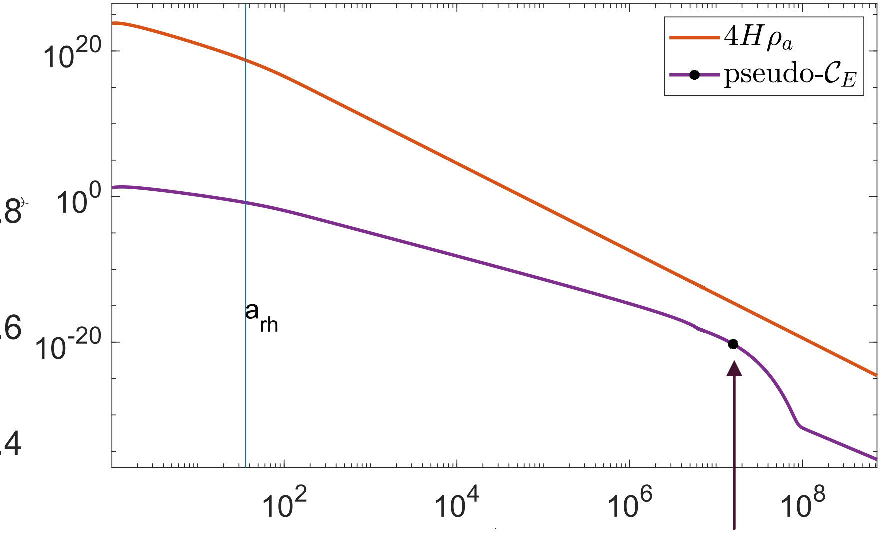
Inflaton with trilinear coupling to relativistic scalars in both sectors





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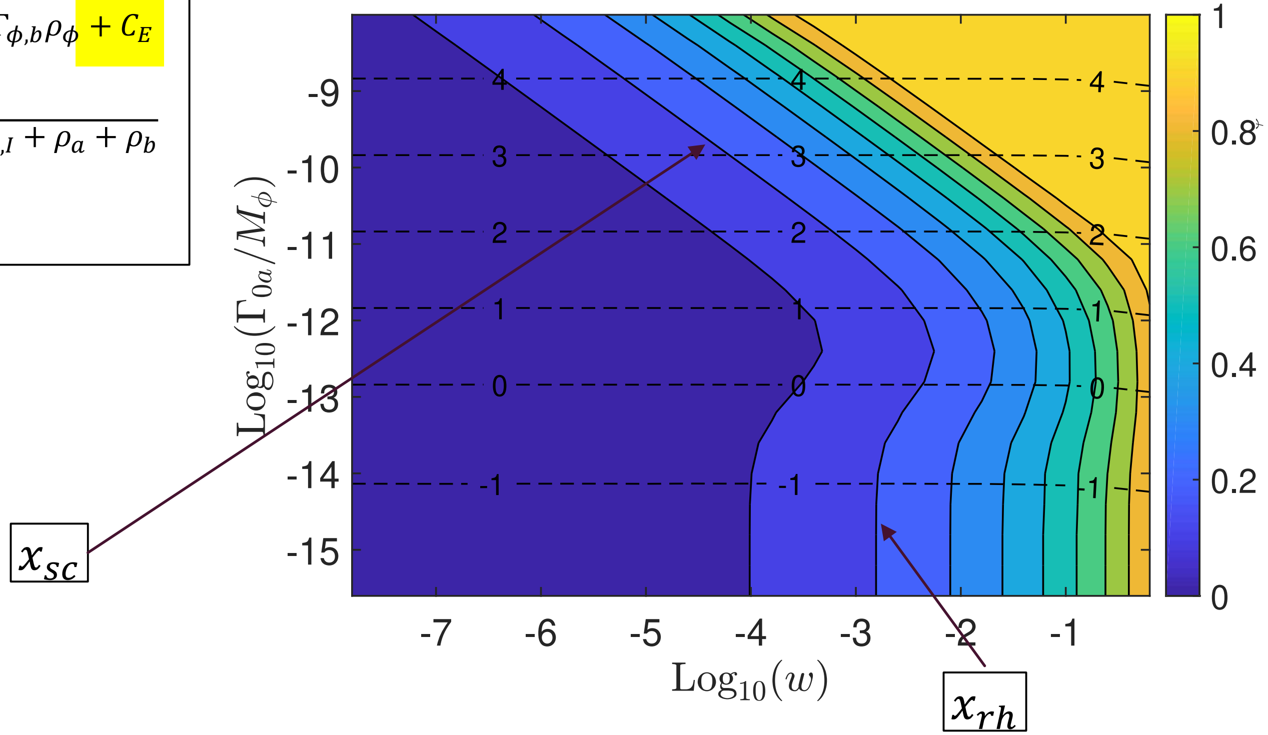

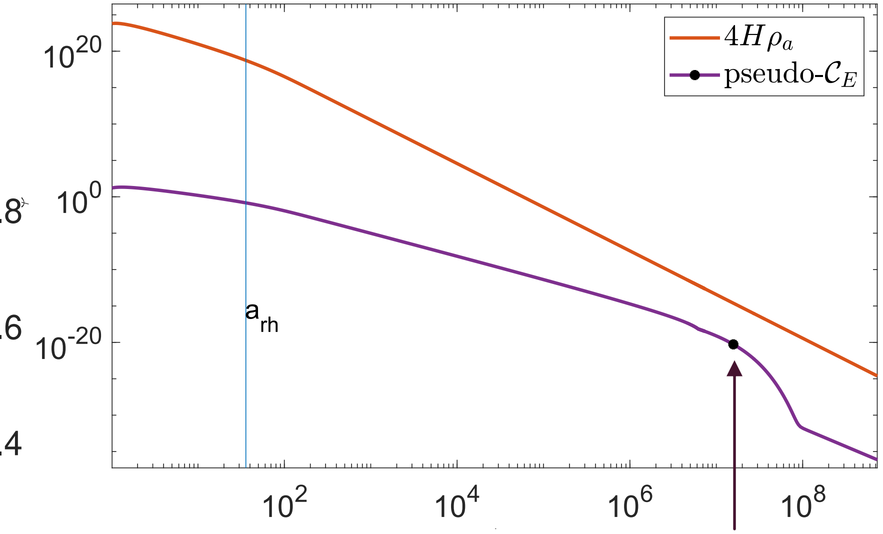

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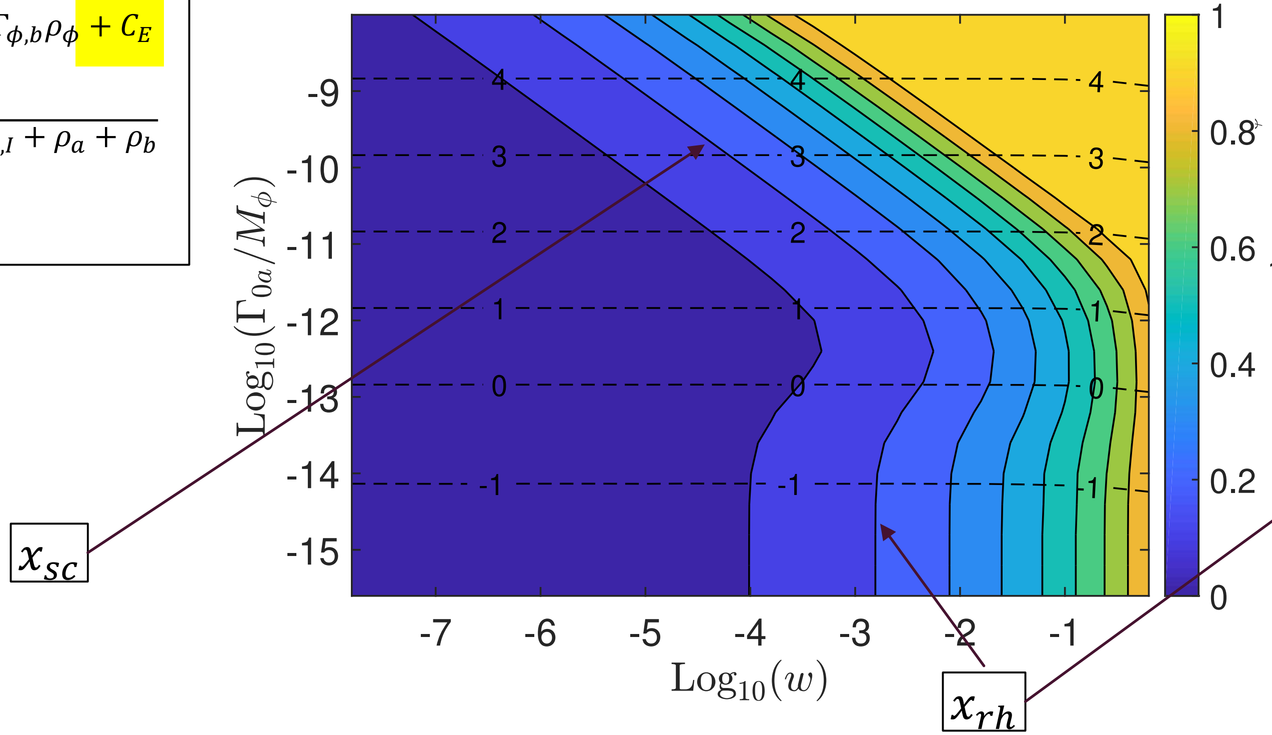

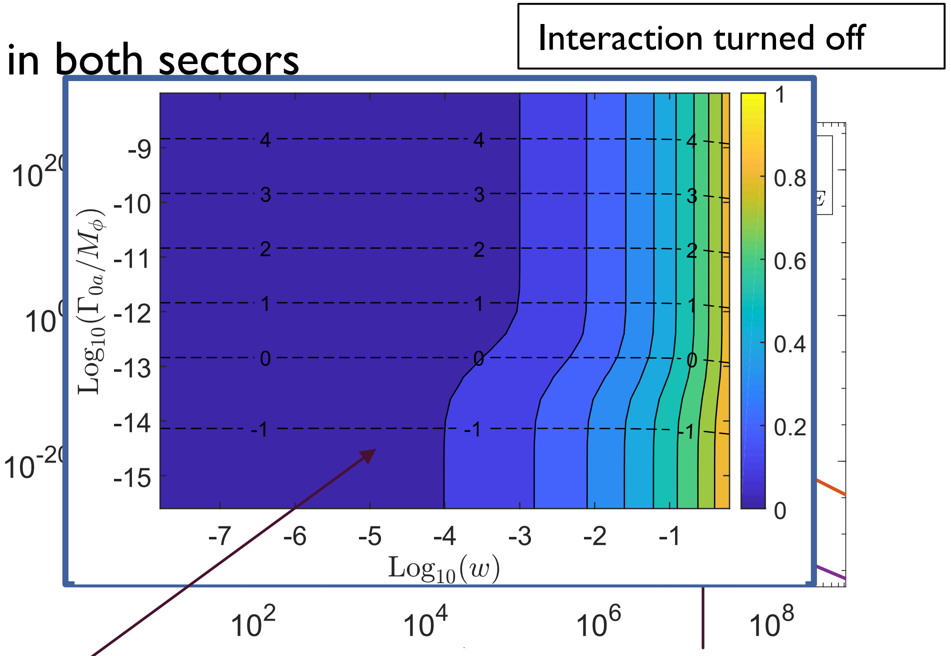

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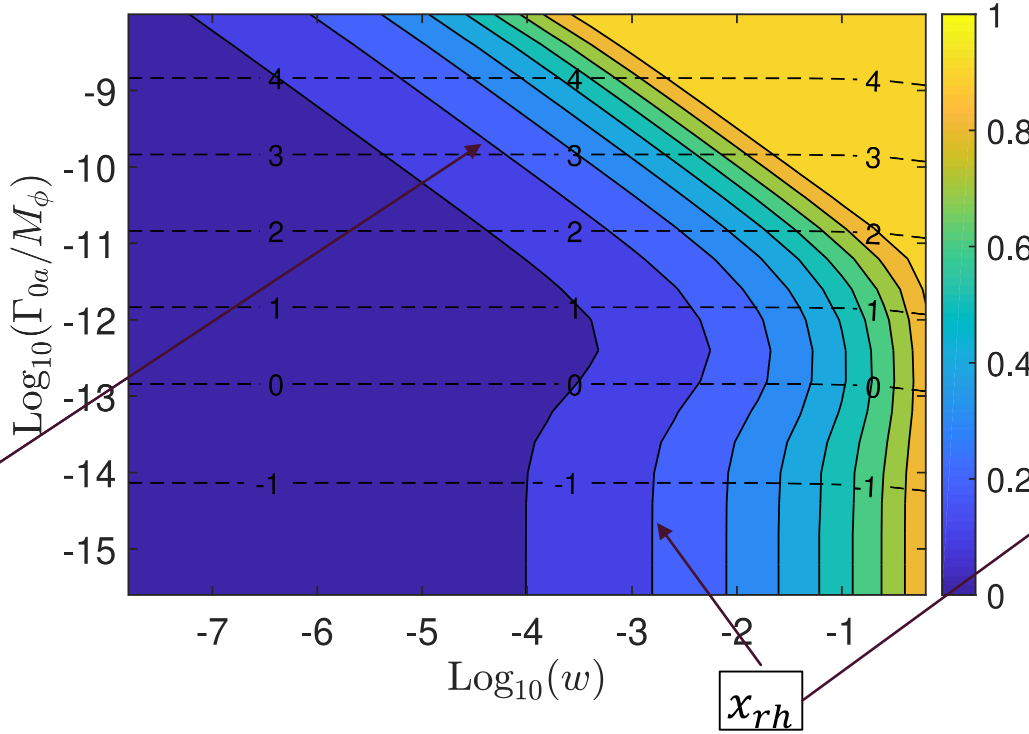
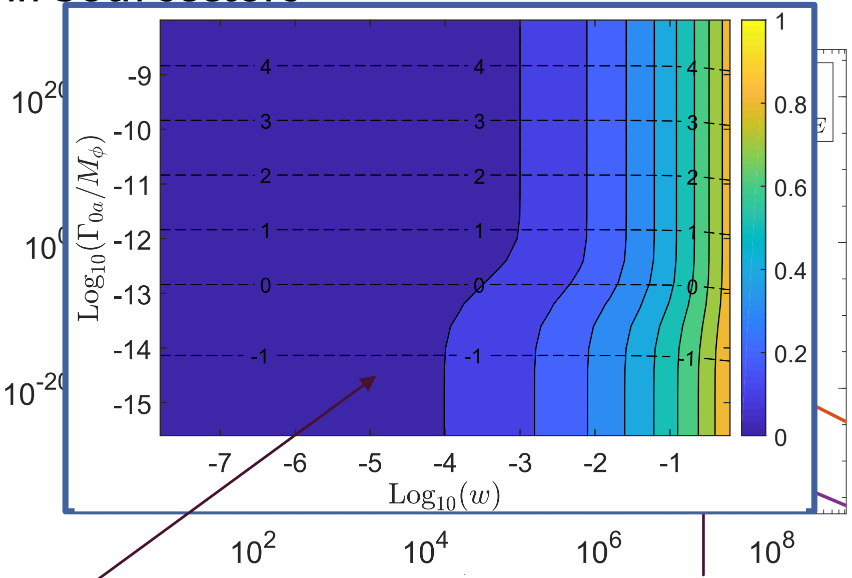
Inflaton with trilinear coupling to relativistic scalars in both sectors



Interaction turned off



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$$x_{sc}^4 \sim \frac{4H\rho_b}{4H\rho_a} \sim \left[\frac{C_E}{4H\rho_a}\right]_{T_a \sim 0.2M_\phi}$$

REVIEW OF MAJOR ASSUMPTIONS

- Instantaneous thermalization
- Neglected preheating
- Neglected thermal effects in plasma

REVIEW OF MAJOR ASSUMPTIONS: Robust lower bound on temperature ratio

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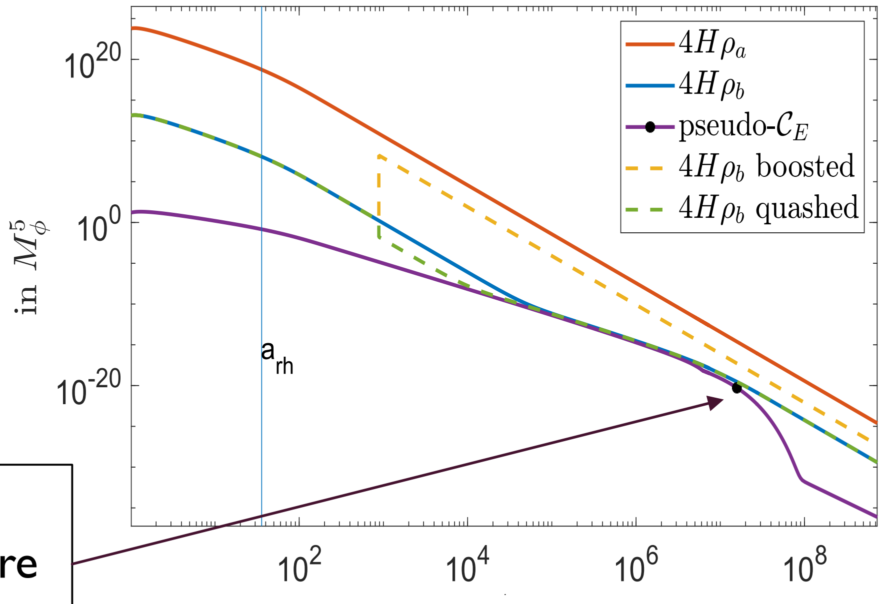
- Neglected thermal effects in plasma



Inflaton mediated scattering provides a robust floor for temperature ratio at $T_a \sim 0.2M_\phi$ given above effects end before this temperature scale.

$$x^4 \geq \left[\frac{C_E}{4H\rho_a}\right]_{T_a \sim 0.2M_\phi}$$

REVIEW OF MAJOR ASSUMPTIONS: Robust lower bound on temperature ratio

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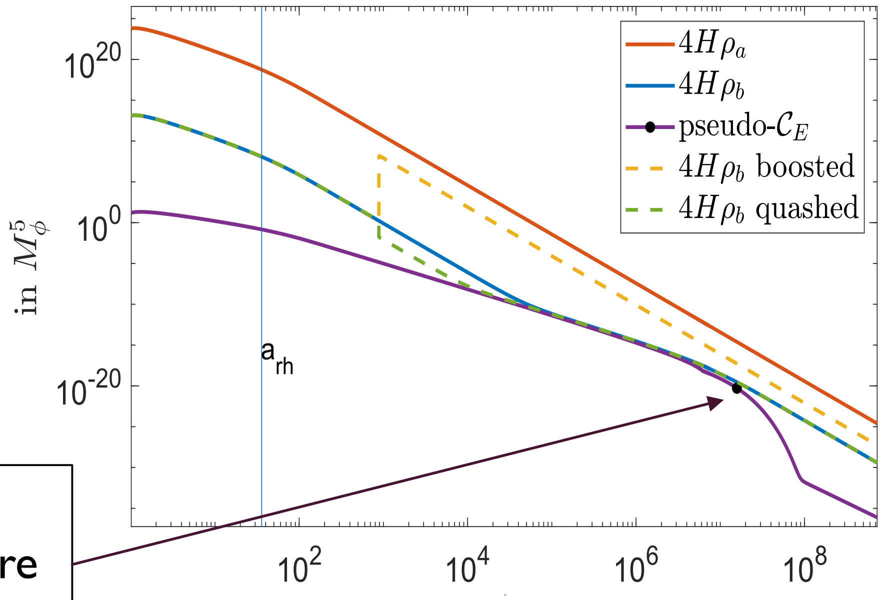


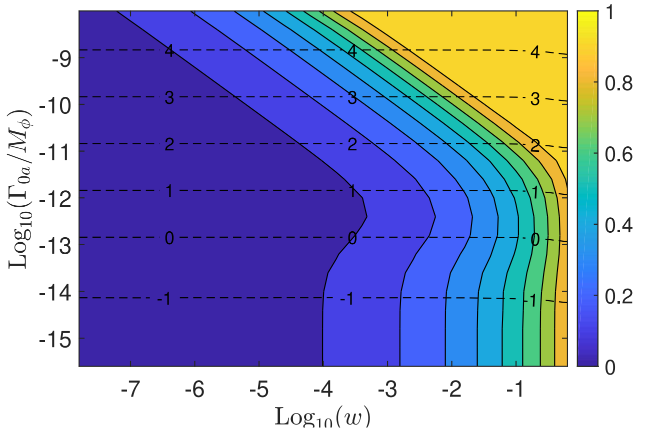
Inflaton mediated scattering provides a robust floor for temperature ratio at $T_a \sim 0.2M_\phi$ given above effects end before this temperature scale.

$T_{rh} > 0.2M_\phi$ necessary condition!

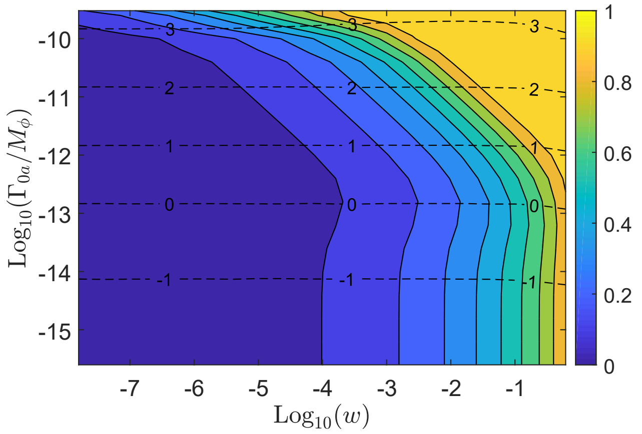
$$x^4 \geq \left[\frac{C_E}{4H\rho_a}\right]_{T_a \sim 0.2M_\phi}$$

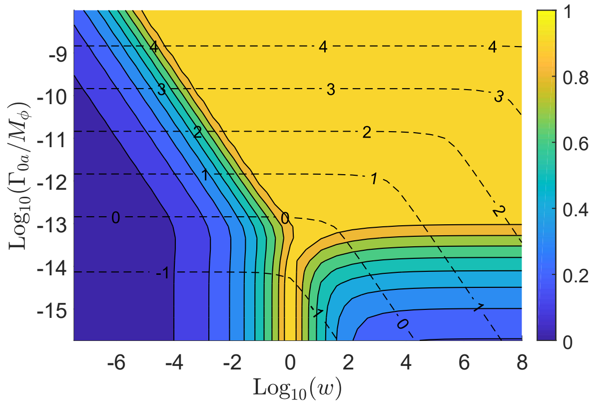
TWO SECTOR REHEATING: Final temperature ratio in other theories

Scalar bosons

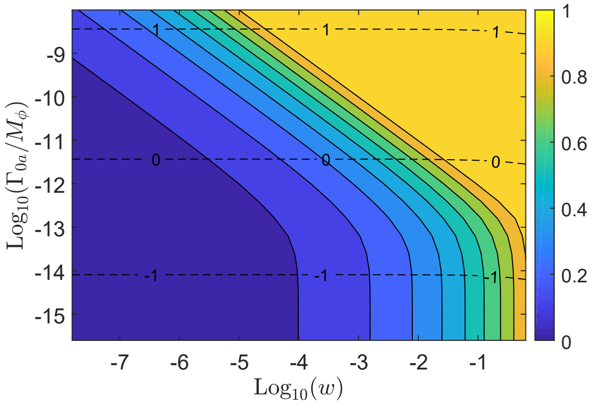


Gauge bosons



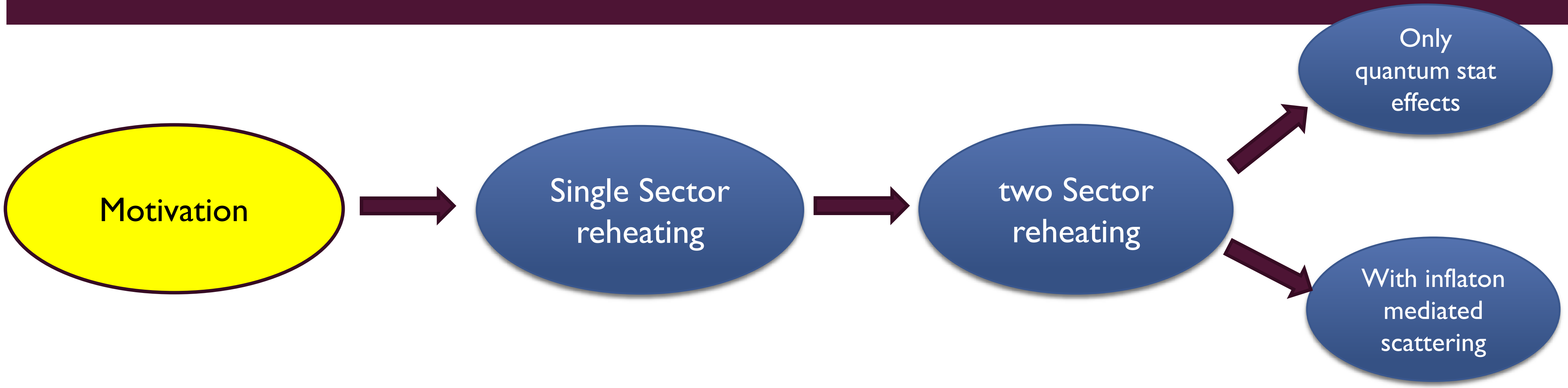


Fermions and scalar bosons



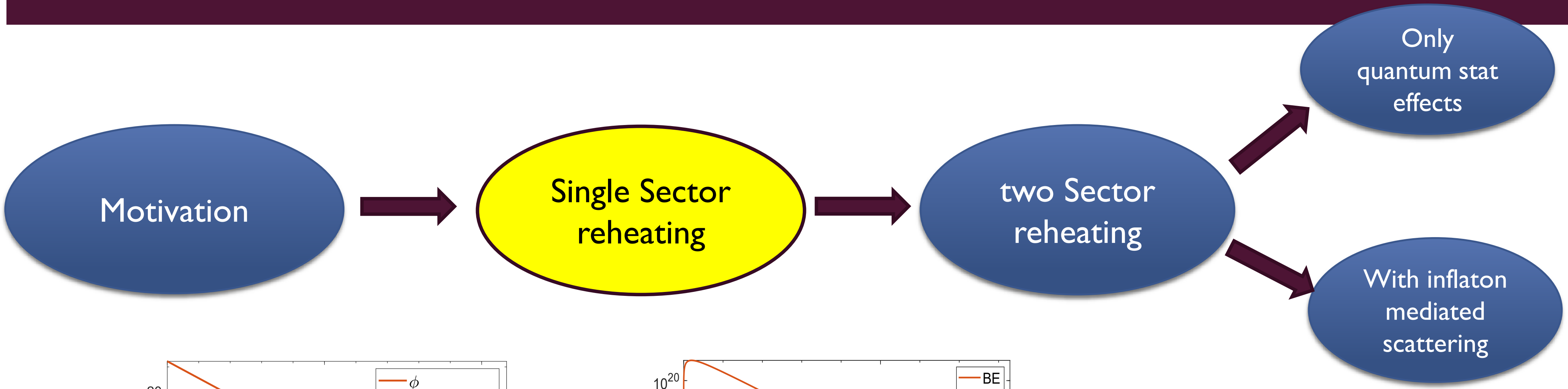
Fermions

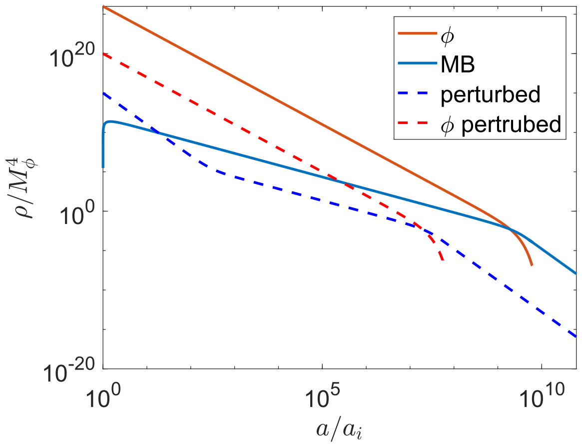
SUMMARY



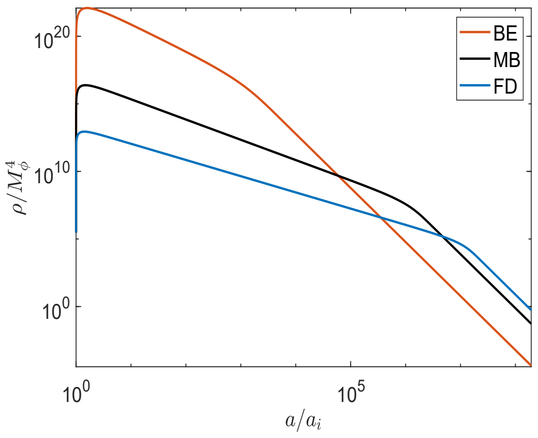
- WIMP searches null result
- Two sector reheating allows large temperature asymmetry

SUMMARY



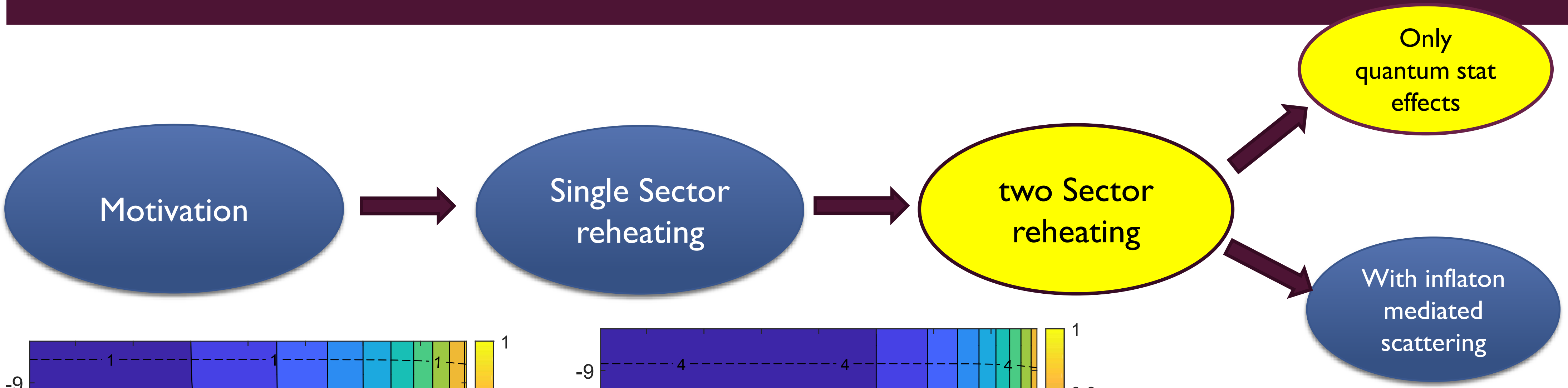


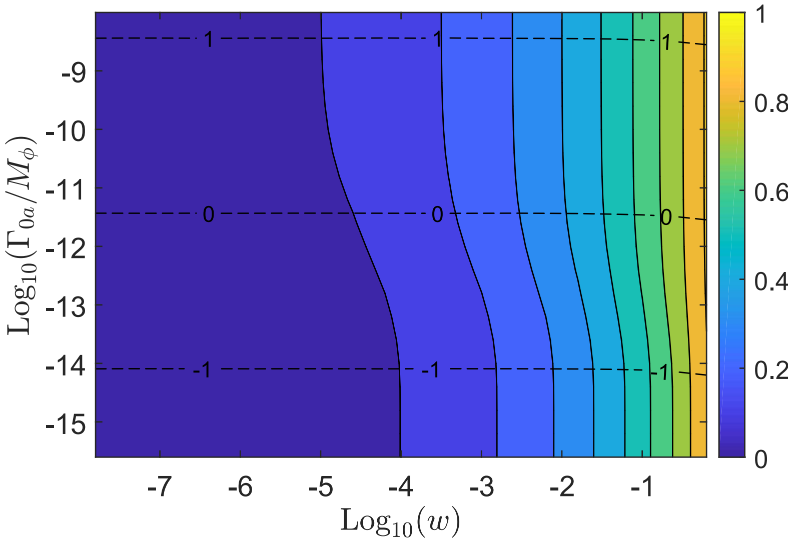
Reheat temperature independent of initial conditions



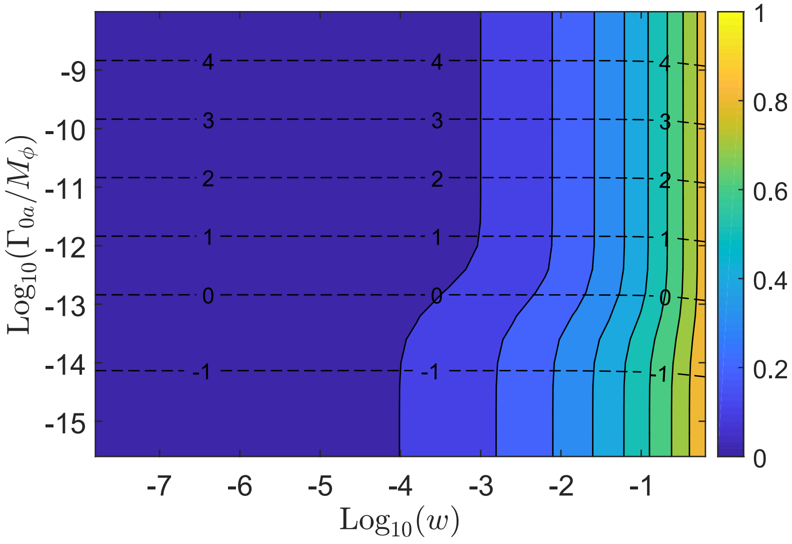
Quantum statistics can modify reheat temperature

SUMMARY

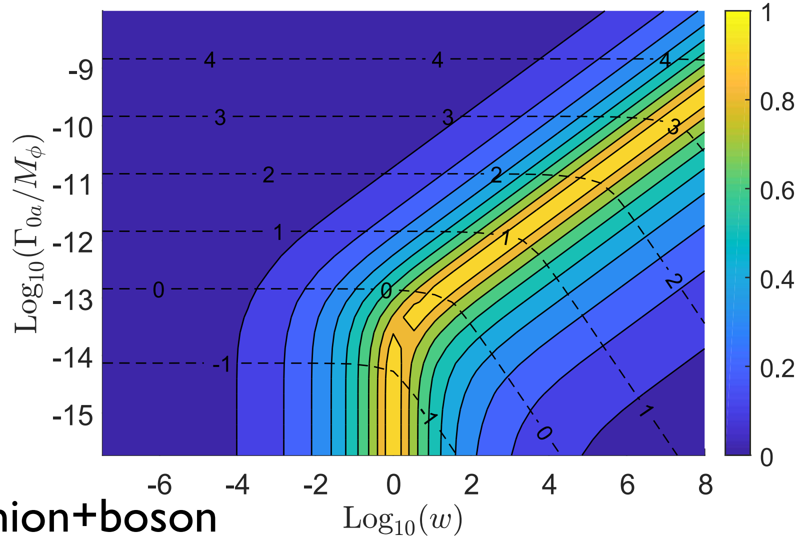




bosons

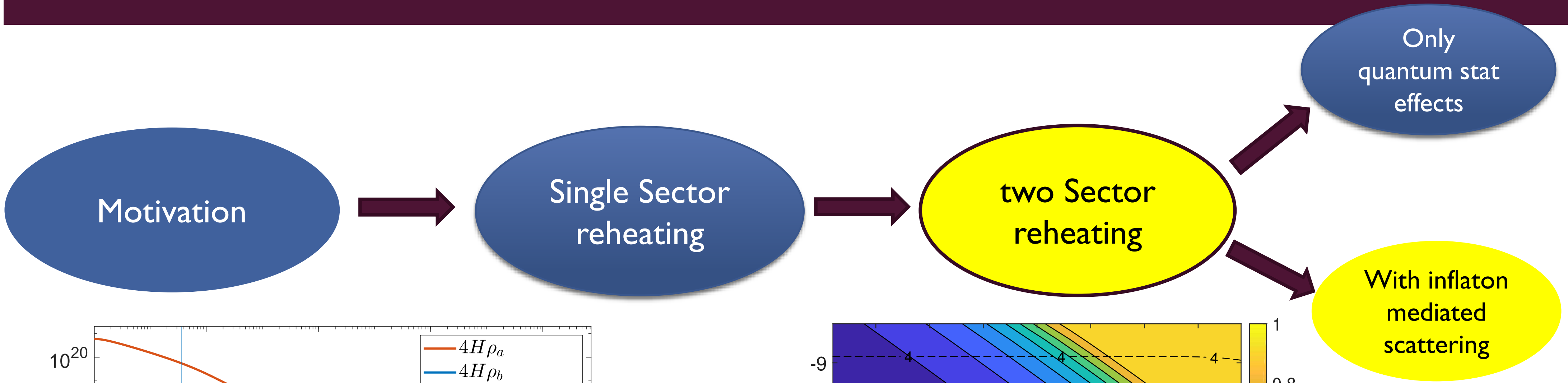


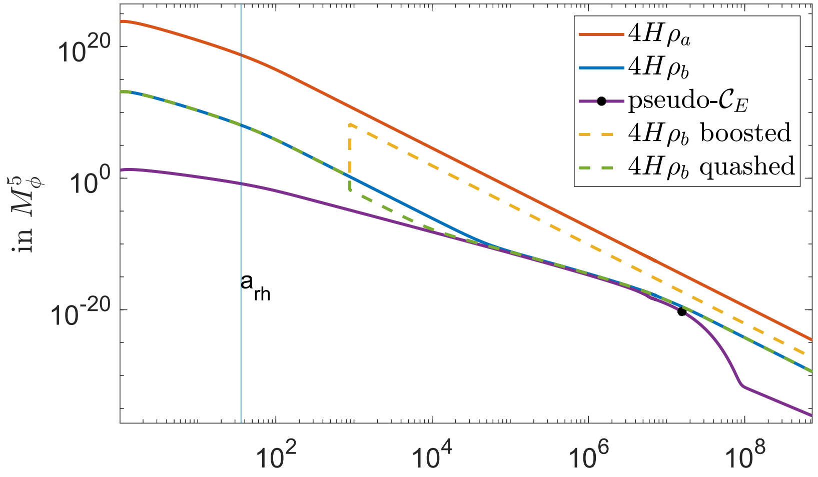
fermions



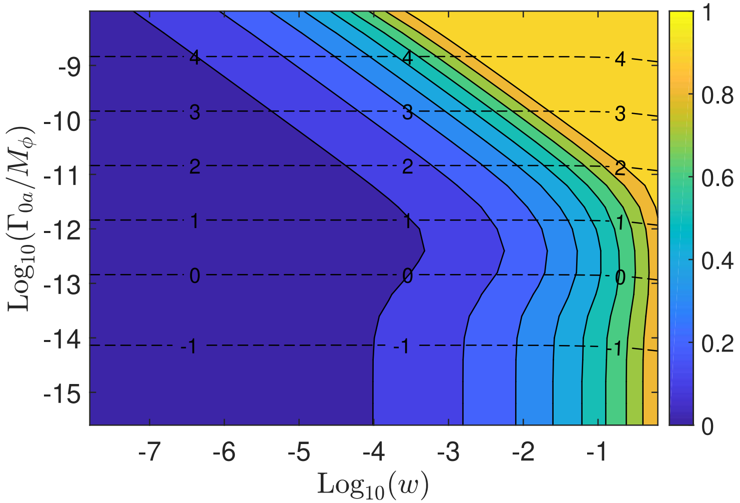
fermion+boson

SUMMARY



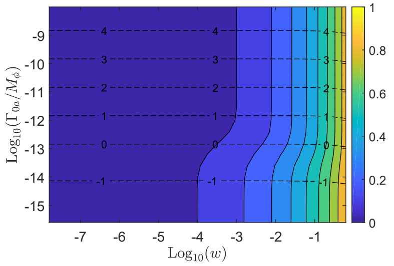


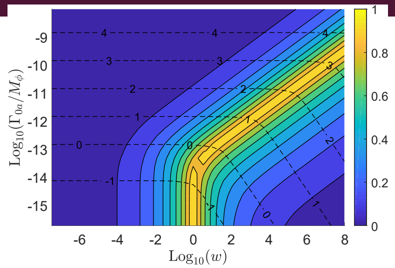
C_E establishes another attractor curve;
Final temperature ratio (almost) independent of history before $T_a \sim 0.2 M_\phi$

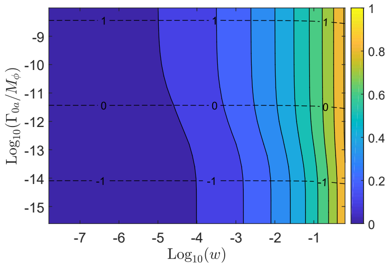


C_E affects temperature ratio at large reheat temperatures

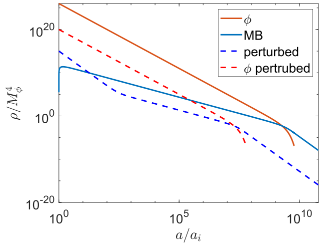
SUMMARY: QUESTIONS?

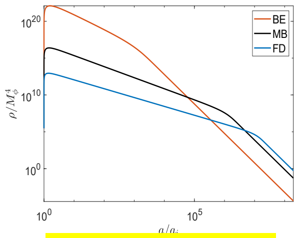






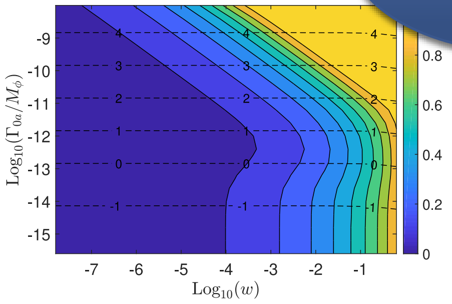
Motivation → Single Sector reheating → two Sector reheating → Only quantum stat effects / With inflaton mediated scattering

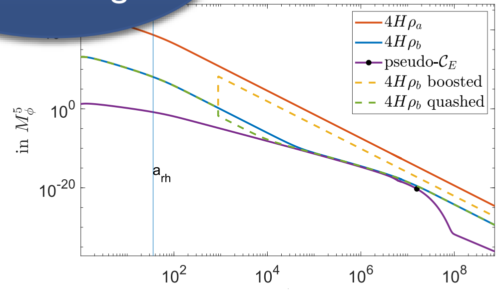




Reheat temperature (almost) independent of history before reheating.

Quantum statistics can modify reheat temperature





Final temperature ratio (almost) independent of history before $T_a \sim 0.2M$