Reheating through inflaton & dark matter phenomenology

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AstroParticle Symposium 2024

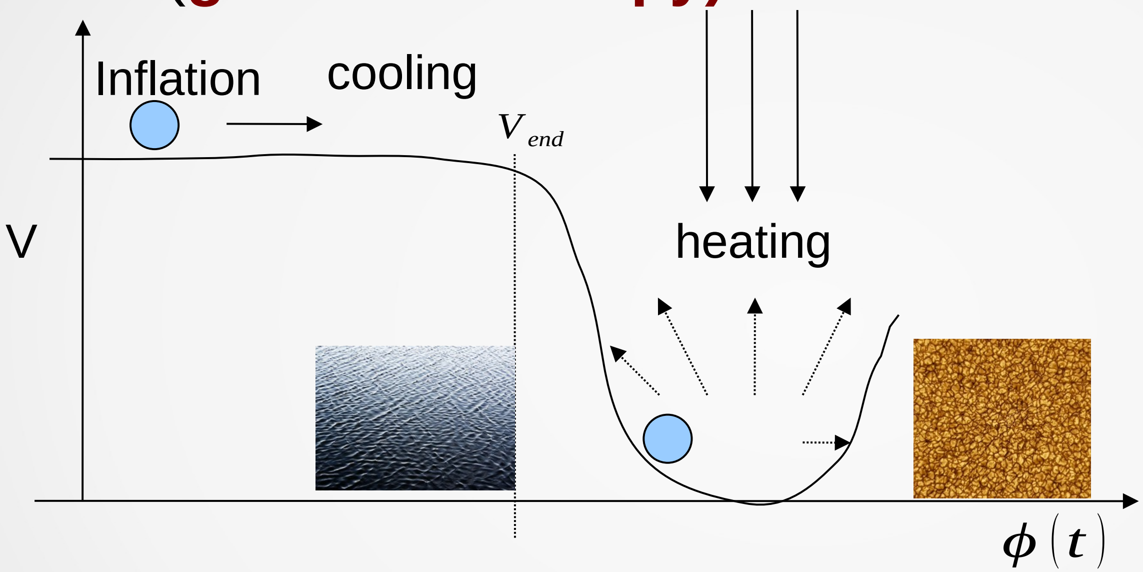
In Collaboration with: Rajesh, Riajul,

The place where I am from

What is reheating phase?

Lev Kofman, Andrei Linde, Alexei Starobinsky, Phys.Rev.D56:3258-3295,1997; Phys.Rev.Lett. 73 (1994) 3195-3198

- Inflation: creats huge empty space which needs to be filled with matters (**generate entropy)**.



Conventional Reheating mechansim: Non-perturbative, **Perturbative decay of inflaton**,

Reheating mechanisms: Different possibilities

Given the inflationary phase:
What do we expect right after?

Inflation

Non-gravitational

Universal (gravitational)

Background + Fluctutation

Stable massive particles(DM)

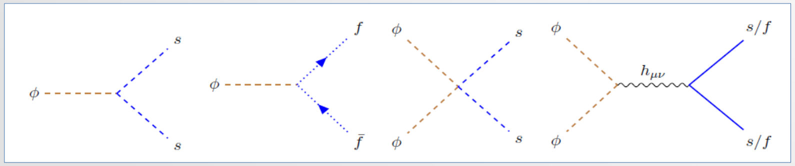
Massless particles (radiation)

Unstable massive particles or object (Right handed neutrino, PBH)

Gravitational wave

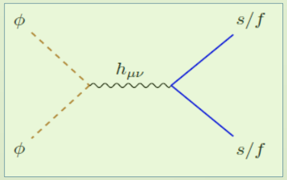
Non-Gravitational Reheating

$$g_1 \phi s^2 , g_2 \phi^2 s^2 , h \phi \bar{f} f \dots$$



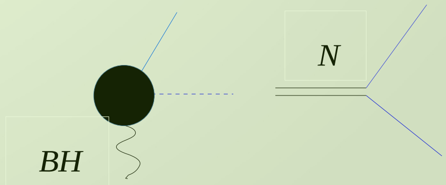
Gravitational Reheating

$$\sim \frac{1}{M_P} h_{\mu\nu} T_i^{\mu\nu}, i = s, f, DM, \phi$$



PBH Reheating, Neutrino reheating

$$\beta , M$$



Given the inflationary phase:

What do we observe long after (today)?

Inflation

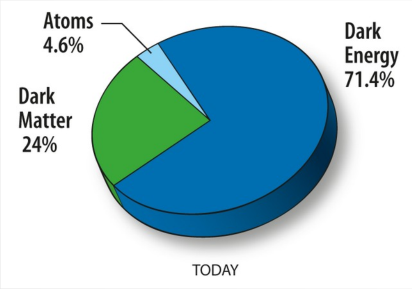
Reheating

Stable massive particles/objects (DM, PBH+all)

Massless particles (radiation), Large scale magnetic field

Gravitational wave

Today: Background + Fluctutations

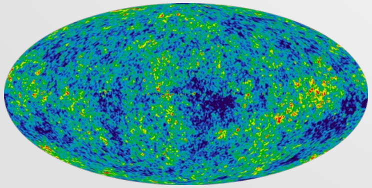


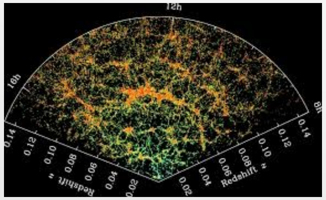
Extremely homogeneous Universe

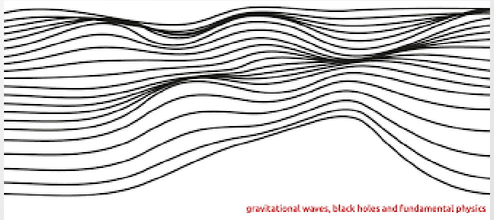
Many more...

Visible and Dark Matter

GW







Set up: Bosonic Reheating

Self interaction $V(\phi) = \Lambda^4 \left[1 - e^{-\sqrt{\frac{2}{3\,\alpha}}\phi/M_p}\right]^{2n}$

$$\Gamma^{gr}_{\phi\phi\to ss} = \frac{\rho_\phi m_\phi}{1024\pi M_p^4}(1 + 2 f_B(m_\phi/T)),$$

$$\Gamma^{gr}_{\phi\phi\to ff} = \frac{\rho_\phi m_f^2}{4096\pi M_p^4 m_\phi}(1 - 2 f_F(m_\phi/T))$$

Gravitational interaction $\sim \frac{1}{M_P} h_{\mu\nu} T_i^{\mu\nu}, i = s, f, \phi$

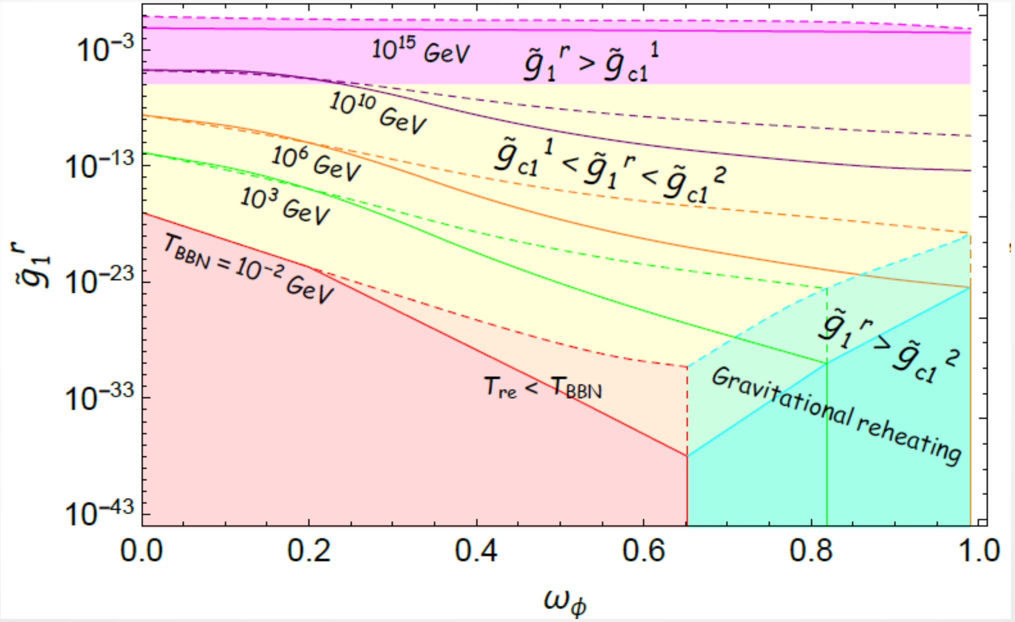
non-gravitational interaction $\sim g_1^r \phi s^2, g_2^r \phi^2 s^2, h^r \phi \bar{f} f$

$$\Gamma_{s/f} = \begin{cases} \Gamma_{\phi\to ss} &= \frac{(g_1^r)^2}{8\pi m_\phi(t)}(1 + 2 f_B(m_\phi/2T)), & \text{for } g_1^r \phi s^2 \\ \Gamma_{\phi\phi\to ss} &= \frac{(g_2^r)^2 \rho_\phi(t)}{8\pi m_\phi^3(t)}(1 + 2 f_B(m_\phi/T)), & \text{for } g_2^r \phi^2 s^2 \\ \Gamma_{\phi\to \bar{f} f} &= \frac{(h^r)^2}{8\pi} m_\phi(t)(1 - 2 f_F(m_\phi/2T)), & \text{for } h^r \phi \bar{f} f \end{cases}$$

R. Haque, DM, Rajesh Mondal, JHEP 09, 012 (2023)

Scanning the parameters

$$\omega_\phi = \frac{(n-1)}{(n+1)}$$



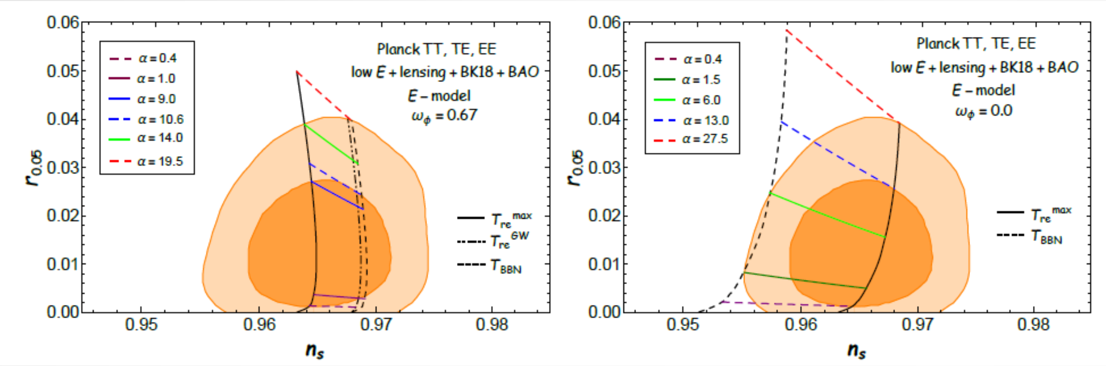
Y. Mambrini and K. A. Olive, PRD 103, 115009 (2021); A. Ahmed, B. Grzadkowski, A Socha, 2207.11218

R. Haque, DM, PRD 107 (2023) 4, 043531; PRD 106 (2022) 2, 023506

Inflaton phenomenology in light of PLANCK

Relating inflationary and Reheating parameters

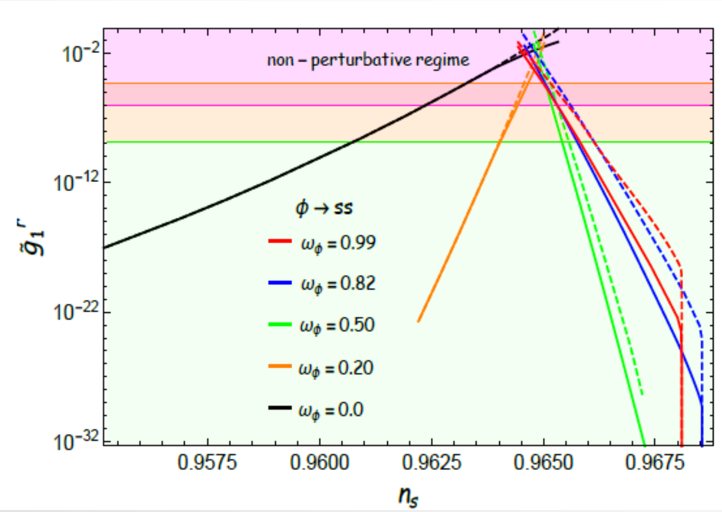
L. Dai, M. Kamionkowski and J. Wang, PRL. 113, 041302 (2014), J. L. Cook, etal JCAP 1504 (2015) 047; J. Ellis etal, JCAP 1507 (2015,, 050; Y. Ueno and K. Yamamoto, PRD 93 (2016), 083524; M. Eshaghi etal, PRD 93 (2016), 123517, A. Di Marco, etal, PRD 95 (2017),, 103502, S. Bhattacharya etal, PRD 96 (2017), 083522, DM, arXiv:1709.00251; DM, P. Saha, PRD 2018, …

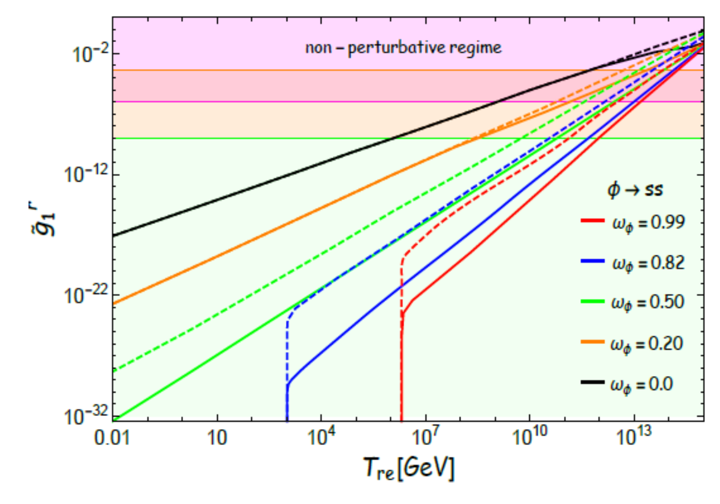


$$T_{re} = \left(\frac{43}{11\, g_*^{re}}\right)^{1/3} \left(\frac{a_0\, H_{end}}{k}\right) e^{-(N_k+N_{re})}\, T_0\,,$$

Entropy conservation

$$T_0 = 2.725^0\ \mathrm{K}$$





$$V(\phi) = \Lambda^4 \left[1 - e^{-\sqrt{\frac{2}{3\alpha}}\phi/M_p}\right]^{2n}$$

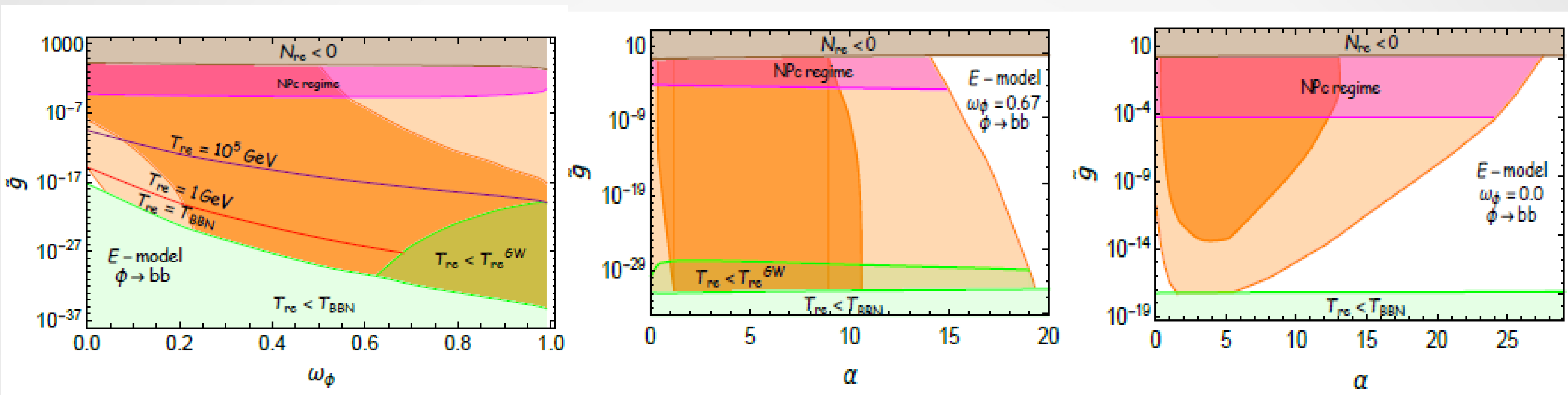
$$H_{end}^{max} > \pi M_p \sqrt{r A_s/2} \sim 5\times 10^{13}\, GeV$$

$$T_{re} > T_{BBN} \sim 10\, MeV$$

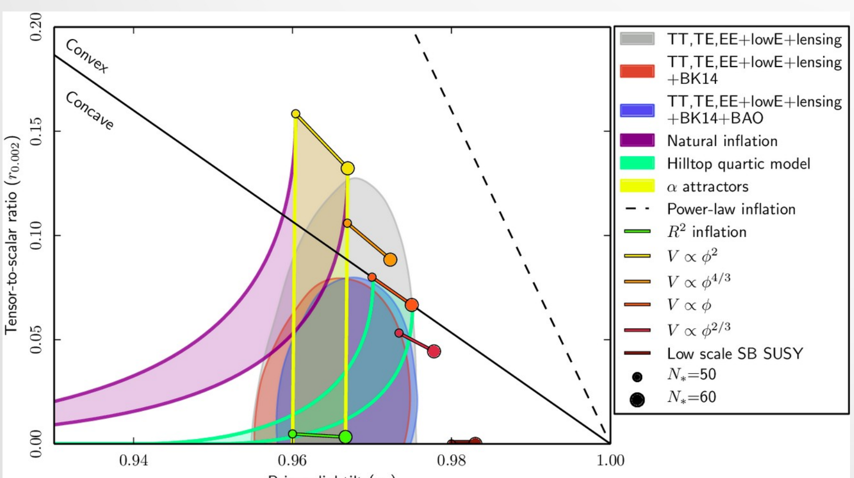
Inflation Phenomenology in light of PLANCK

R. Haque, DM, PRD 107 (2023) 4, 043531;
PRD 106 (2022) 2, 023506

R. Haque, DM, Rajesh Mondal, JHEP 09, 012 (2023)

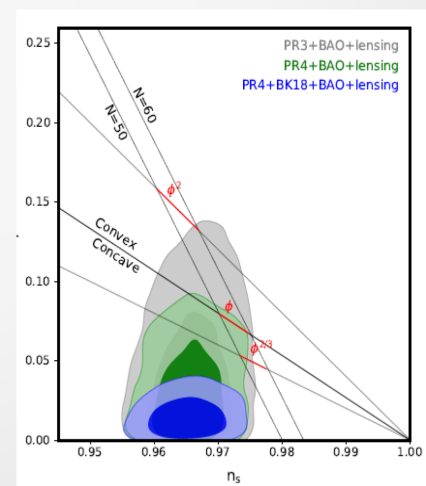


Planck 2018 results. X. Constraints on inflation@arXiv :1807.0621



$$V(\phi) = \Lambda^4 \left[1 - e^{-\sqrt{\frac{2}{3\alpha}}\phi/M_p}\right]^{2n}$$

$$\omega_\phi = \frac{(n-1)}{(n+1)} \quad ; \quad V(\phi) \sim \phi^{2n}$$

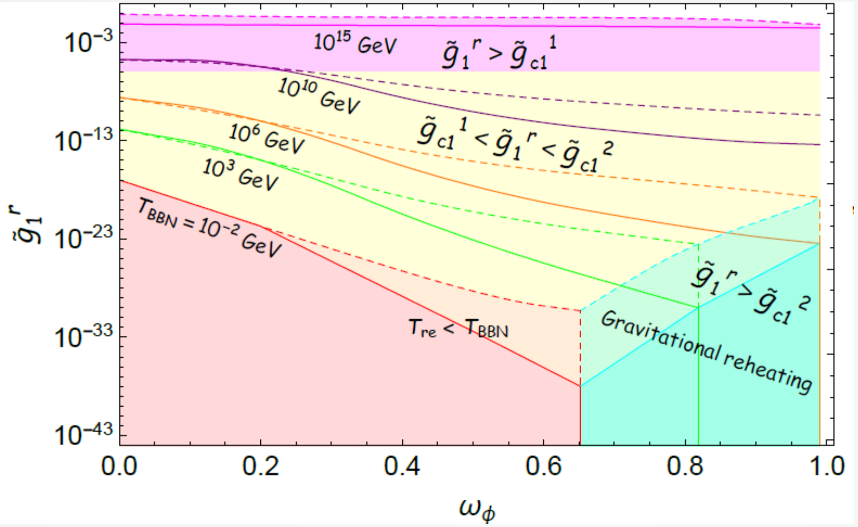


M. Tristram et al, Phys.Rev.D 105 (2022) 8, 083524

Bosonic Reheating: DM Phenomenology

R. Haque, DM, PRD 107 (2023) 4, 043531;
PRD 106 (2022) 2, 023506

R. Haque, DM, Rajesh Mondal, JHEP 09, 012 (2023)



Gravitational
+

$g_1^r \phi s^2, g_2^r \phi^2 s^2, h^r \phi \bar{f} f$

No DM-inflaton coupling,
Production from thermal bath

TABLE I: The evolution of bath temperature for bosonic reheating:

Channel	$T \ll m_\phi(t)$ (Without thermal effect)		$T \gg m_\phi(t)$ (With thermal effect)	
	Non-gravitational	Gravitational	Non-gravitational	Gravitational
$\phi \to ss$	$A^{-\frac{3(1-w_\phi)}{8}}$	A^{-1}	$A^{-\frac{(1-3w_\phi)}{2}}$	A^{-1}
$\phi\phi \to ss$	$A^{-\frac{9(1-w_\phi)}{8}}$ $(w_\phi > 1/9)$	A^{-1}	$A^{-\frac{(3-5w_\phi)}{2}}$ $(w_\phi > 3/5)$	A^{-1}

Case-I: Entire reheating by direct non-gravitational coupling $g^i > g^i_{c1}$

Case-II: Initially gravitational followed by non-gravitational $g^i_{c1} > g^i > g^i_{c2}$

Case-II: Gravitational $g^i_{c2} > g^i$

WIMP(scalar DM)

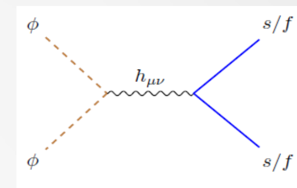
$$\dot{\rho}^r_{tot} + 4H\rho^r_{tot} - \Gamma^r_\phi(1+w_\phi)\rho_\phi - 2\langle\sigma v\rangle\langle E_x\rangle^r\left[(n^r_x)^2-(n^r_{x,eq})^2\right]=0,$$

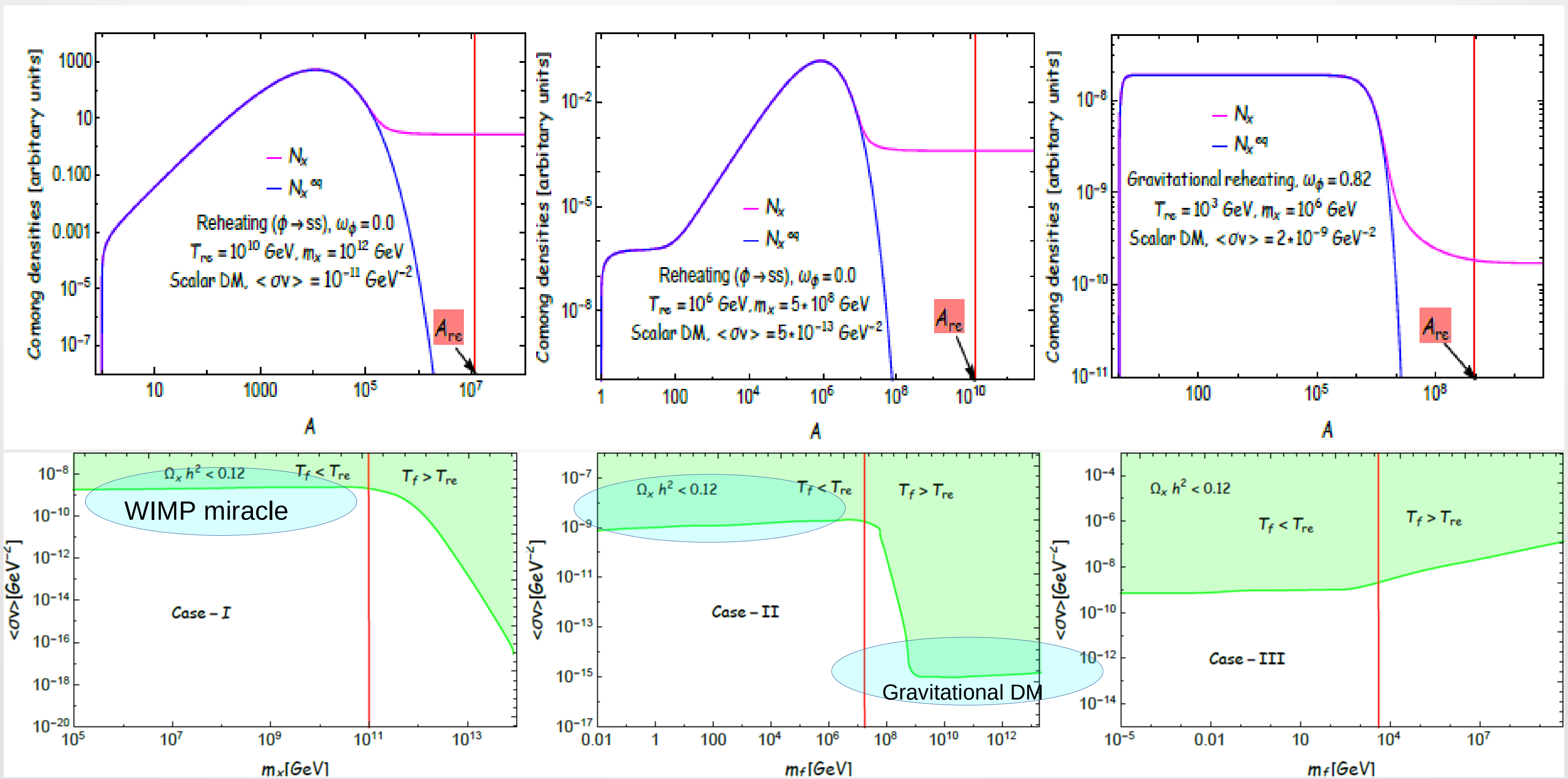
$$\dot{n}^r_x + 3Hn^r_x + \langle\sigma v\rangle\left[(n^r_x)^2-(n^r_{x,eq})^2\right] - \frac{\Gamma_{\phi\phi\to SS/FF}\,\rho_\phi}{m_\phi(t)} - \frac{\gamma_{S/F}T^8_{rad}}{M_p^4} = 0.$$

Thermal

Gravitational

Inflaton injecting entropy: reduced DM crossection





FIMP (Scalar DM)

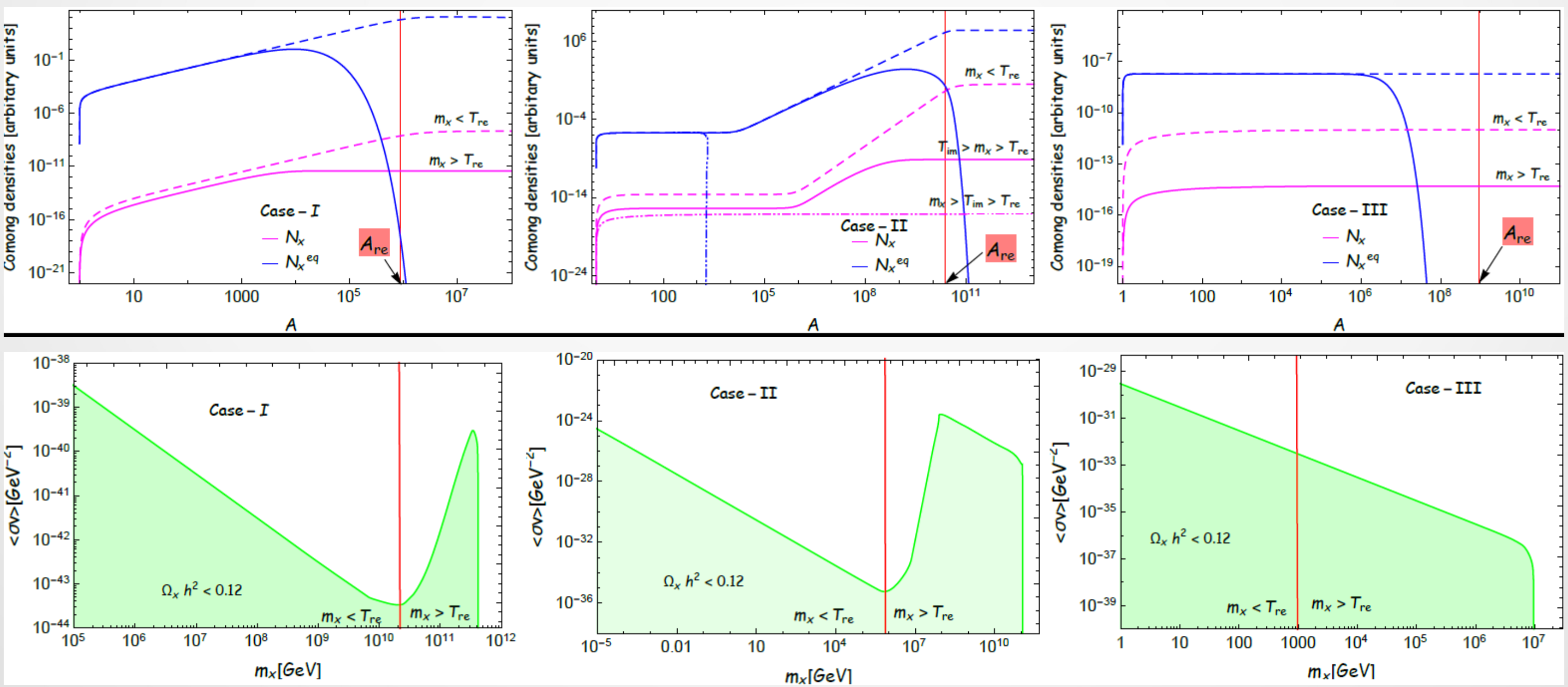
$$\dot{\rho}^r_{tot} + 4H\rho^r_{tot} - \Gamma^r_\phi(1+w_\phi)\rho_\phi - 2\langle\sigma v\rangle\langle E_x\rangle^r\left[(n^r_x)^2 - (n^r_{x,eq})^2\right] = 0,$$

$$\dot{n}^r_x + 3Hn^r_x + \langle\sigma v\rangle\left[(n^r_x)^2 - (n^r_{x,eq})^2\right] - \frac{\Gamma_{\phi\phi\to SS/FF}\,\rho_\phi}{m_\phi(t)} - \frac{\gamma_{S/F}T^8_{rad}}{M_p^4} = 0.$$

Thermal

Gravitational DM

Inflaton injecting entropy:
Larger DM crossection



Combined parameter space with PLANCK

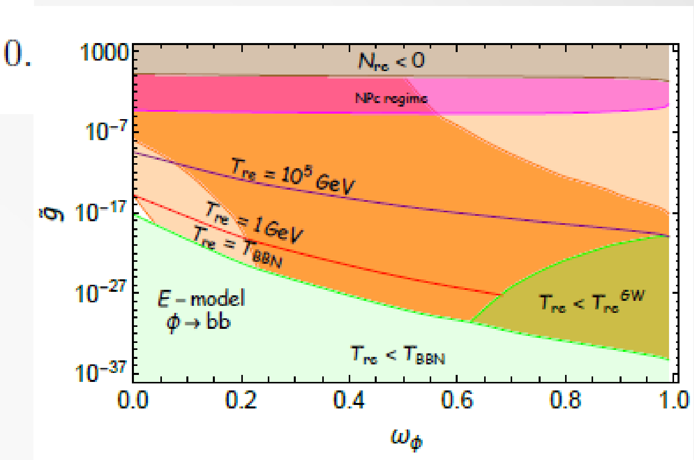
$$\dot{\rho}^r_{tot} + 4H\rho^r_{tot} - \Gamma^r_\phi(1+w_\phi)\rho_\phi - 2\langle\sigma v\rangle\langle E_x\rangle^r\left[(n^r_x)^2 - (n^r_{x,eq})^2\right] = 0,$$

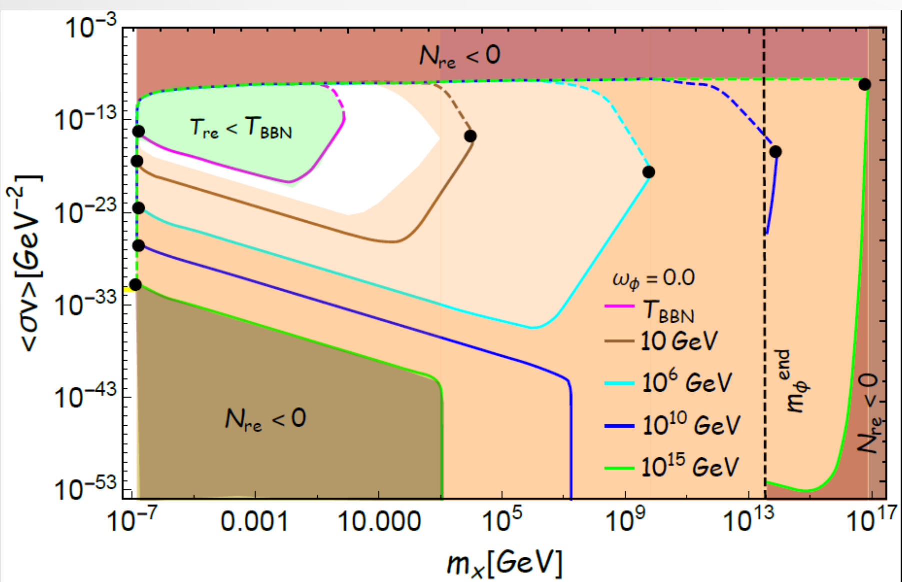
$$\dot{n}^r_x + 3Hn^r_x + \langle\sigma v\rangle\left[(n^r_x)^2 - (n^r_{x,eq})^2\right] - \frac{\Gamma_{\phi\phi\to SS/FF}\rho_\phi}{m_\phi(t)} - \frac{\gamma_{S/F}T^8_{rad}}{M^4_p} = 0.$$

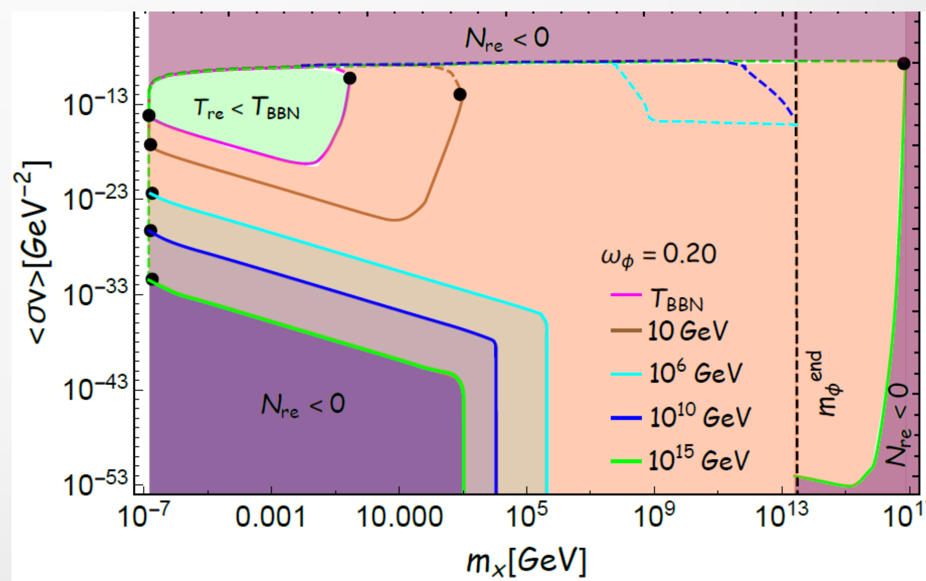
Thermal

Gravitational

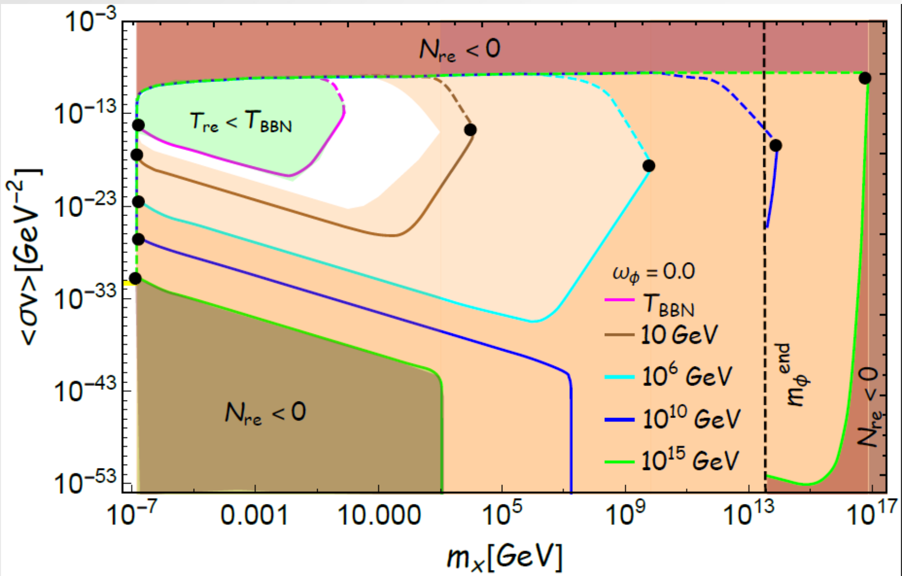
Inflaton injecting entropy: reduced DM crossection

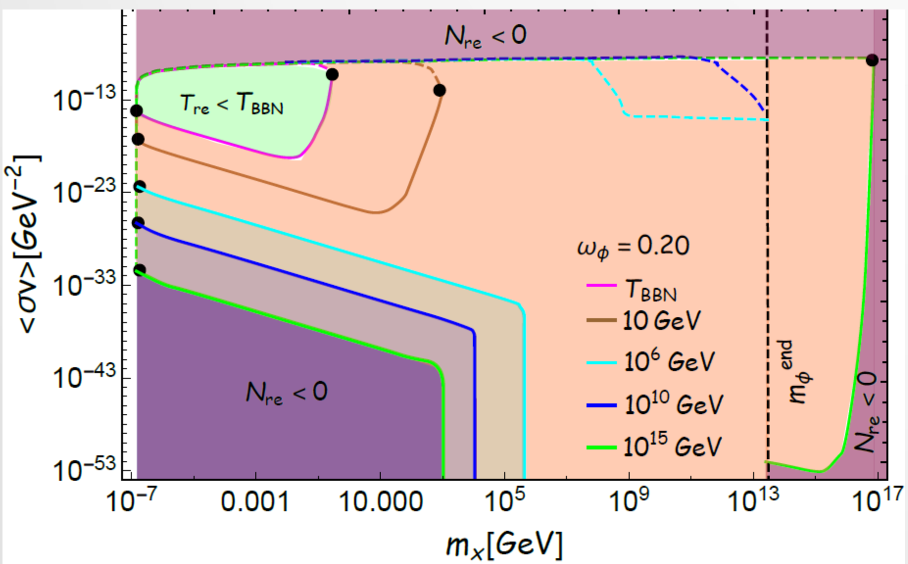


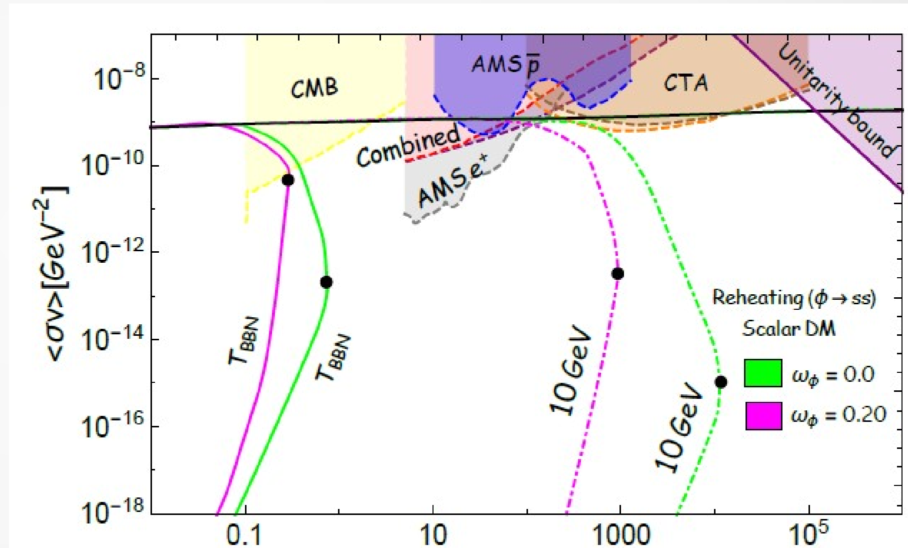




Though the Lens of PLANCK+DM searches







Facts, Questions and Conclusions

1. Reheating happens, Inflaton energy transfered into all the visible fields such that we obtain present state of the universe

2. Such information must be imprinted into Back ground+fluctuation that we see today in some way.

Questions: Where and how such information are imprinted?

How do we proceed to identify that?

- Inflaton and DM sector turns out be deeply connected with the physics of reheating even if they do not talk to each other directly
- **Pinponiting the value of spectral index can probably give important clue on the real nature of both DM and inflaton**

Talk by Nicolas, Riajul ...

Conclusions and future directions

Reheating:

- It is BSM physics which heppens at very high energy scale beyond the scope of laboratory experiments
- Cosmology behaves as laboratoy system where experiments has already been performed, observables need to be defined, explained.
- **Distinguish different reheating histories using DM phenomenology**
- **Inclusioni of more observables: baryogenesis and active neutrino mass also taking part in reheating.**

- Secondary GW, thermalization, evolution of small scale perturbations,

Combined parameter space

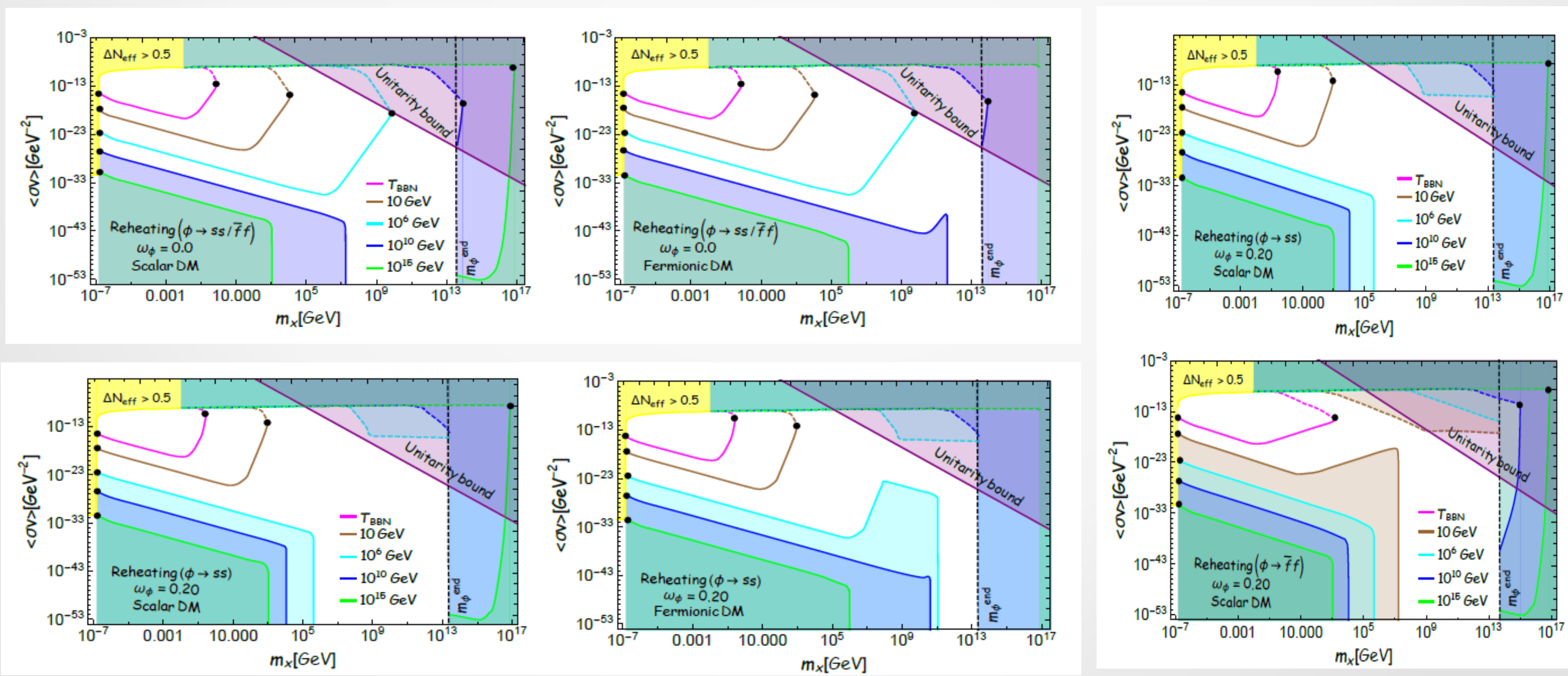
$$\dot{\rho}^r_{tot} + 4H\rho^r_{tot} - \Gamma^r_\phi(1+w_\phi)\rho_\phi - 2\langle\sigma v\rangle\langle E_x\rangle^r\left[(n^r_x)^2 - (n^r_{x,eq})^2\right] = 0,$$

$$\dot{n}^r_x + 3Hn^r_x + \langle\sigma v\rangle\left[(n^r_x)^2 - (n^r_{x,eq})^2\right] - \frac{\Gamma_{\phi\phi\to SS/FF}\,\rho_\phi}{m_\phi(t)} - \frac{\gamma_{S/F}T^8_{rad}}{M^4_p} = 0.$$

Thermal

Gravitational

Inflaton injecting entropy: reduced DM crossection



Fermionic Reheating Histories: Parameter space

R. Haque, DM, PRD 107 (2023) 4, 043531;
PRD 106 (2022) 2, 023506

R. Haque, DM, Rajesh Mondal, JHEP 09, 012 (2023)

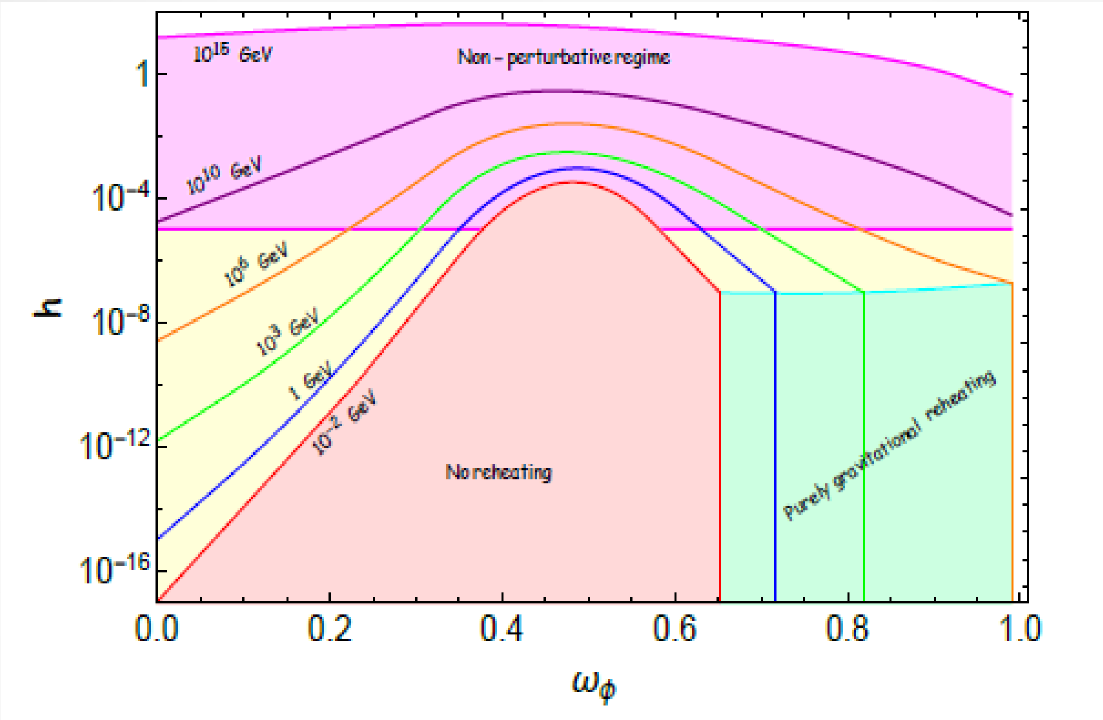


TABLE III: The temperature evolution for fermionic reheating

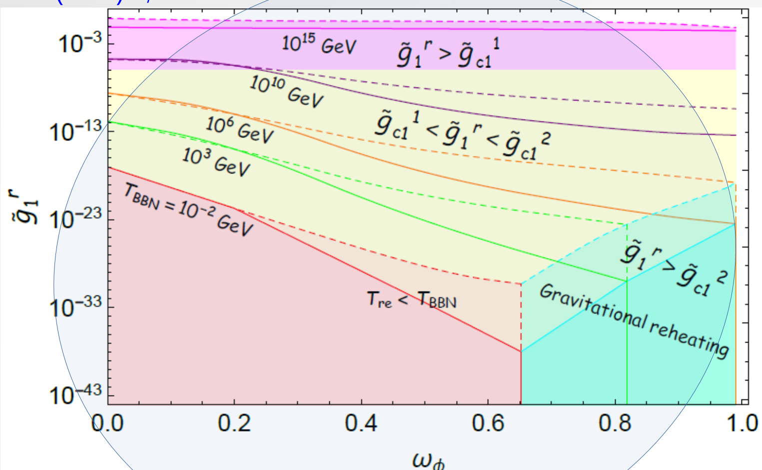
Channel	$T \ll m_\phi(t)$ (Without thermal effect)		$T \gg m_\phi(t)$ (With thermal effect)	
	Non-gravitational	Gravitational	Non-gravitational	Gravitational
$\phi \to \bar{f}f$	$A^{-\frac{3(1+3w_\phi)}{8}}(A^{-1})$ for $w_\phi < 5/9(> 5/9)$	A^{-1}	$A^{-\frac{3(1+5w_\phi)}{10}}(A^{-1})$ for $w_\phi < \frac{7}{15}(> \frac{7}{15})$	A^{-1}

$\phi \bar{f} f$

Bosonic Reheating Histories: Refined Parameter space

R. Haque, DM, PRD 107 (2023) 4, 043531;
PRD 106 (2022) 2, 023506

R. Haque, DM, Rajesh Mondal, JHEP 09, 012 (2023)



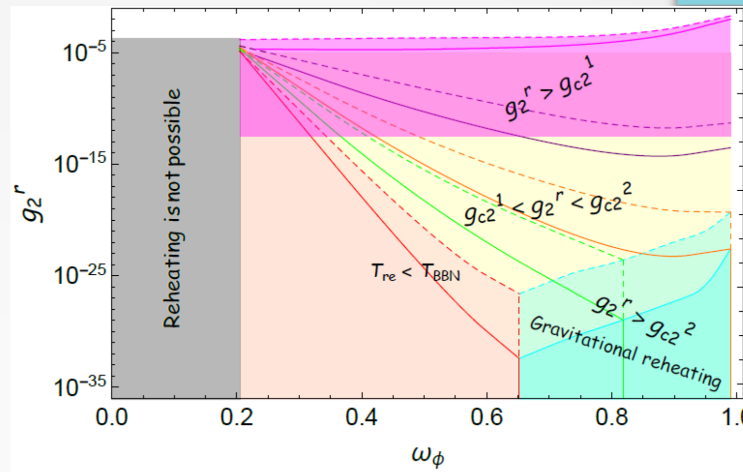


TABLE I: The evolution of bath temperature for bosonic reheating:

Channel	$T \ll m_\phi(t)$ (Without thermal effect)		$T \gg m_\phi(t)$ (With thermal effect)	
	Non-gravitational	Gravitational	Non-gravitational	Gravitational
$\phi \to ss$	$A^{-\frac{3(1-w_\phi)}{8}}$	A^{-1}	$A^{-\frac{(1-3w_\phi)}{2}}$	A^{-1}
$\phi\phi \to ss$	$A^{-\frac{9(1-w_\phi)}{8}}$ ($w_\phi > 1/9$)	A^{-1}	$A^{-\frac{(3-5w_\phi)}{2}}$ ($w_\phi > 3/5$)	A^{-1}

Case-I: Entire reheating by direct non-gravitational coupling $g^i > g^i_{c1}$

Case-II: Initially gravitational followed by non-gravitational $g^i_{c1} > g^i > g^i_{c2}$

Case-II: Gravitational $g^i_{c2} > g^i$

Due to thermal effect, decay width is enhanced -> low bosonic couplings to reheat

Different Reheating Histories: Inflaton parameters

Self interaction $V(\phi) = \Lambda^4 \left[1 - e^{-\sqrt{\frac{2}{3\alpha}}\phi/M_p}\right]^{2n}$

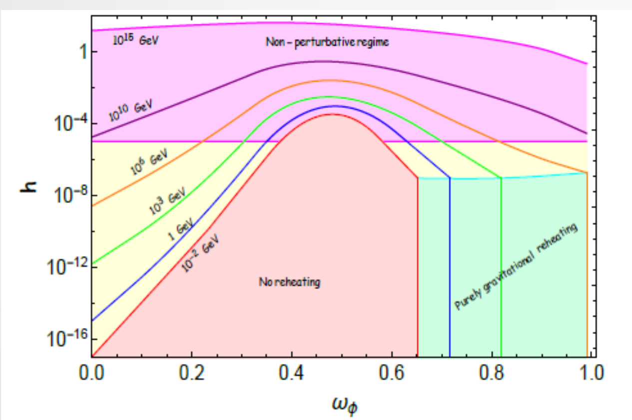
$$\Gamma^{gr}_{\phi\phi\to ss} = \frac{\rho_\phi m_\phi}{1024\pi M_p^4}(1 + 2f_B(m_\phi/T)),$$
$$\Gamma^{gr}_{\phi\phi\to ff} = \frac{\rho_\phi m_f^2}{4096\pi M_p^4 m_\phi}(1 - 2f_F(m_\phi/T))$$

Gravitational interaction $\sim \frac{1}{M_P} h_{\mu\nu} T_i^{\mu\nu}, i = s, f, \phi$

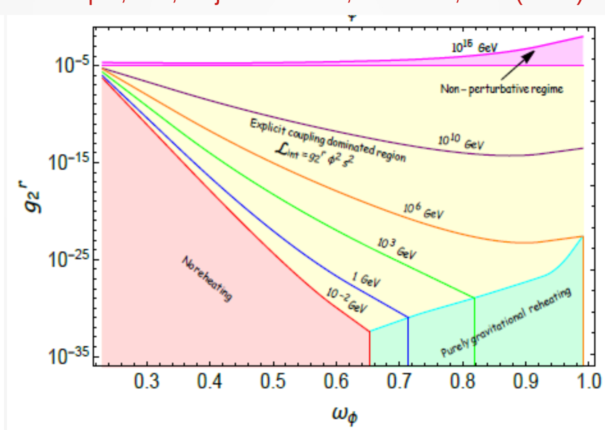
non-gravitational interaction $\sim$ $g_1^r \phi s^2, g_2^r \phi^2 s^2, h^r \phi \bar{f} f$

$$\Gamma_{s/f} = \begin{cases} \Gamma_{\phi\to ss} = \frac{(g_1^r)^2}{8\pi m_\phi(t)}(1 + 2f_B(m_\phi/2T)), & \text{for } g_1^r\phi s^2 \\ \Gamma_{\phi\phi\to ss} = \frac{(g_2^r)^2\rho_\phi(t)}{8\pi m_\phi^3(t)}(1 + 2f_B(m_\phi/T)), & \text{for } g_2^r\phi^2 s^2 \\ \Gamma_{\phi\to \bar{f}f} = \frac{(h^r)^2}{8\pi} m_\phi(t)(1 - 2f_F(m_\phi/2T)), & \text{for } h^r\phi\bar{f}f \end{cases}$$

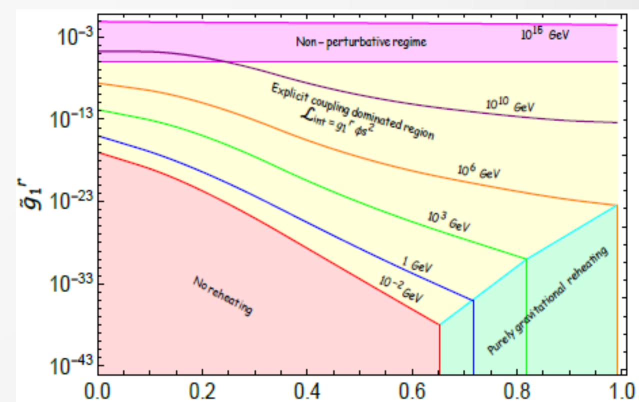
R. Haque, DM, Rajesh Mondal, JHEP 09, 012 (2023)



$\phi \bar{f} f$

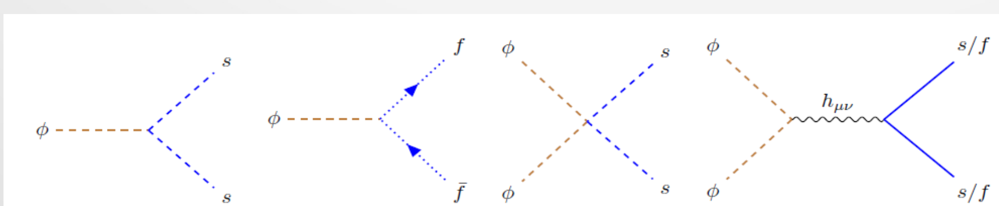


$\phi^2 S^2$



ϕS^2

Inflaton decay channels



Y. Mambrini and K. A. Olive, PRD 103, 115009 (2021); A. Ahmed, B. Grzadkowski, A Socha, 2207.11218

R. Haque, DM, PRD 107 (2023) 4, 043531; PRD 106 (2022) 2, 023506

Universal Contribution: Gravitational DM (scalar/fermion)

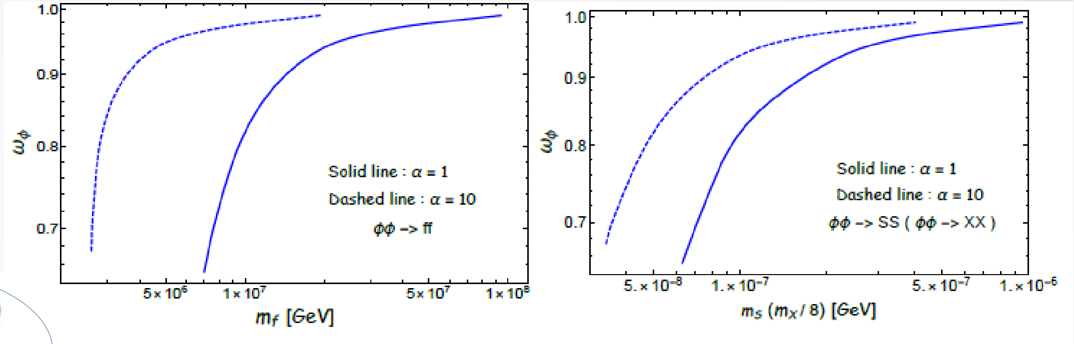
Gravitational Reheating: **DM** Produced through gravitatioal interaction only

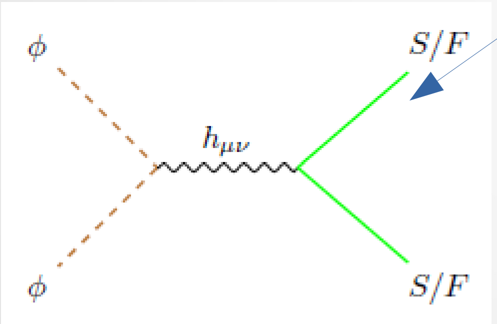
M_{DM}

Riajul Haque, DM, 2201.02348; Phys.Rev.D 106 (2022) 2, 023506

$$\dot{n}_x + 3Hn_x = \frac{\Gamma_x^\phi \rho_\phi}{\langle E_x \rangle^\phi}$$

$$\Gamma_x^\phi = \begin{cases} \frac{\rho_\phi m_\phi}{1024\pi M_p^4}\left(1+\frac{m_x^2}{2m_\phi^2}\right)^2\sqrt{1-\frac{m_x^2}{m_\phi^2}} & \text{for} \quad h_{\mu\nu}(T_S^{\mu\nu}+T_\phi^{\mu\nu}) \\ \frac{\rho_\phi m_f^2}{4096\pi M_p^4 m_\phi}\left(1-\frac{m_x^2}{m_\phi^2}\right)^{3/2} & \text{for} \quad h_{\mu\nu}(T_F^{\mu\nu}+T_\phi^{\mu\nu}). \end{cases}$$





$\alpha = 1$

$7\times10^6 < m_f < 9\times10^7 \ GeV$

$60 < (m_S, (1/8) m_X) < 1000 \ eV$

$\alpha = 10$

$3\times10^6 < m_f < 2\times10^7 \ GeV$

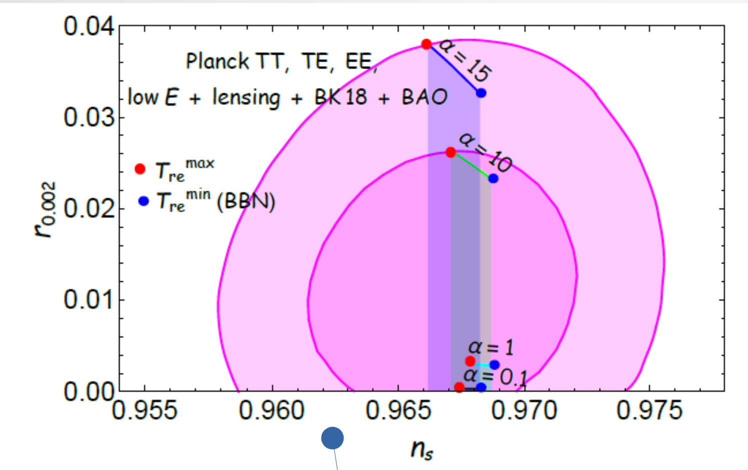
$30 < (m_S, (1/8) m_X) < 400 \ eV$

$$\omega_\phi = \frac{(n-1)}{(n+1)} \; ; \; V(\phi) \sim \phi^{2n}$$

$$V(\phi) = \Lambda^4 \left[1 - e^{-\sqrt{\frac{2}{3\alpha}}\phi/M_p}\right]^{2n}$$

GRe: Where are we in $n_s - r$ plane?

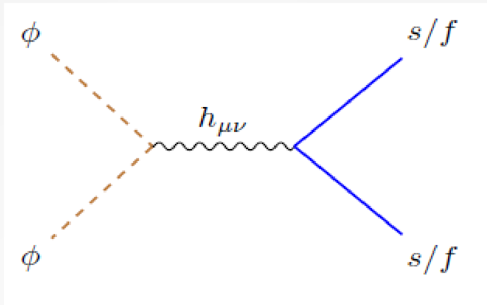
R. Haque, DM, PRD 107 (2023) 4, 043531



Large scale scalar & tensor fluctuation

$\alpha = 1 \rightarrow 0.9681 \leq n_s \leq 0.9687$

$w_\phi \geq 0.6$; $N_{inf} \sim 64$



Dominatinng chennel

$$V(\phi) = \Lambda^4 \left[1 - e^{-\sqrt{\frac{2}{3\,\alpha}}\phi/M_p}\right]^{2n}$$

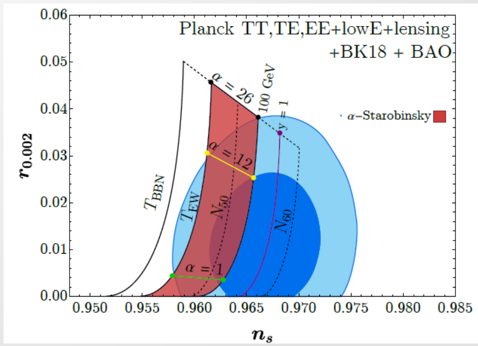
Important Point

No extra reheating parameter!

$$T_{re} = \left(\frac{43}{11\, g_*^{re}}\right)^{1/3} \left(\frac{a_0\, H_{end}}{k}\right) e^{-(N_k + N_{re})}\, T_0\,,$$

$$T_{re} = \left(\frac{9\,(1+\gamma)\, H_{end}^3\, m_\phi^{end}\,(1+\omega_\phi)}{512\,\beta\,\pi\,(1+15\omega_\phi)}\, e^{-4\,N_{re}}\right)^{1/4}$$

John Ellis etal, PRD 105, 4 (2022): 2112.04466



Important Result

Reheating tempreature completely fixed by the inflationary parameter

$H_{end} \sim 5 \times 10^{13}\, GeV \rightarrow T_{re} < 10^{6}\, GeV$