Connecting CMB and dark matter through reheating: Minimal plateau inflation

Debaprasad Maity@IIT Guwahati, India

Rencontres du Vietnam: Cosmology 2019

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DM, Pankaj Saha, PRD98, 103525 (2018)
Phy.Dark.Univ. 25, 100317(2019)
CQG 36 (2019) 045010
JCAP 1907, 018 (2019)

Tornedo

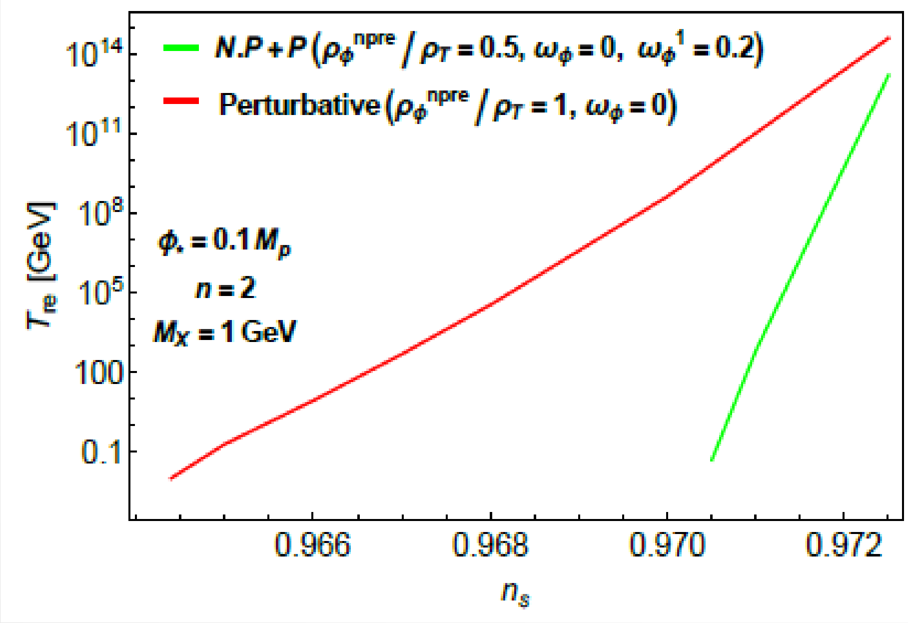
CMB, dark matter through reheating

$$n_s - 1 \equiv \frac{d \ln \Delta_s^2}{d \ln k}$$

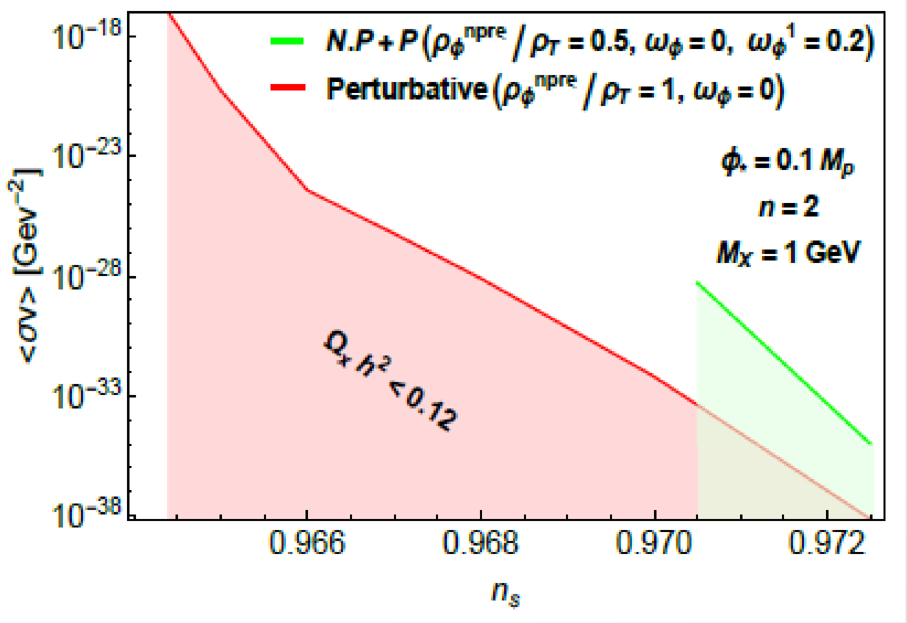
$$\Delta_s^2(k) \equiv \frac{k^3}{2\pi^2} P_\zeta(k)$$

$$C_\ell^{TT} = \frac{2}{\pi} \int k^2 \mathrm{d}k \underbrace{P_\zeta(k)}_{\text{Inflation}} \underbrace{\Delta_{T\ell}(k)\Delta_{T\ell}(k)}_{\text{Anisotropies}}$$

CMB-reheating

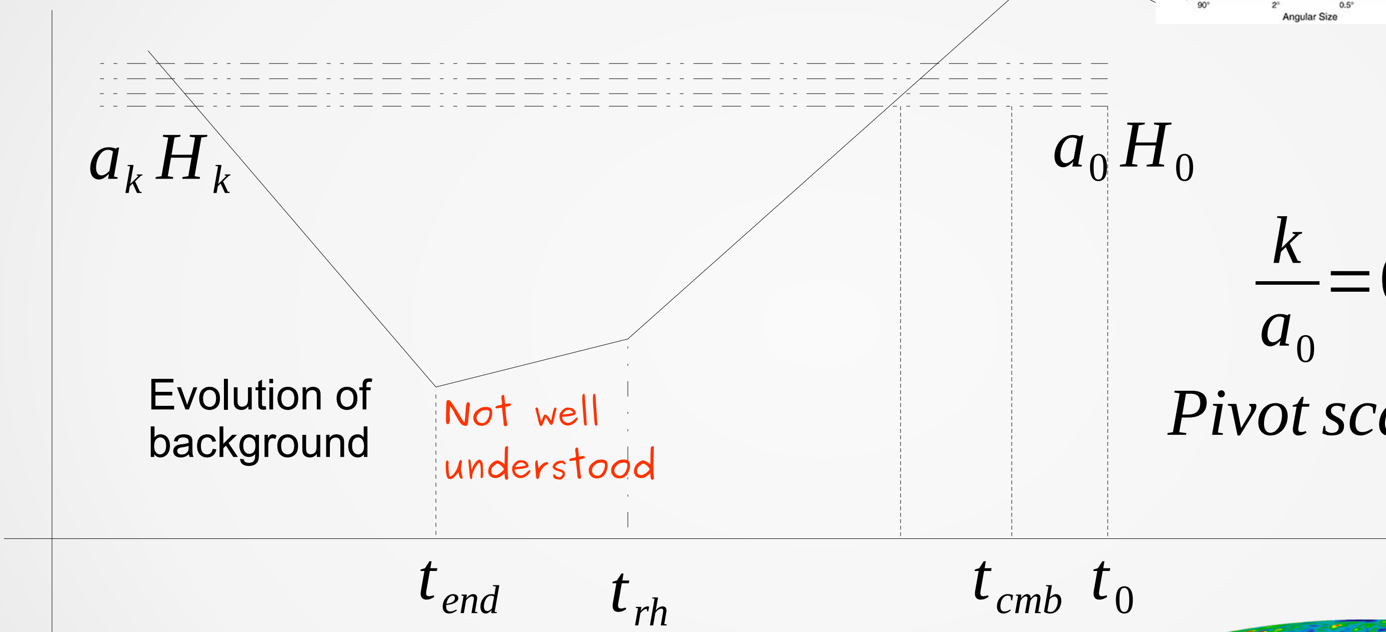


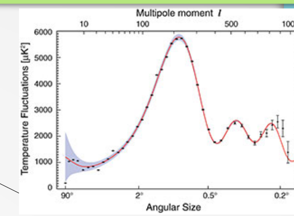
CMB-dark matter



Assuming the following Background+fluctuation

Evolution of fluctuation scale



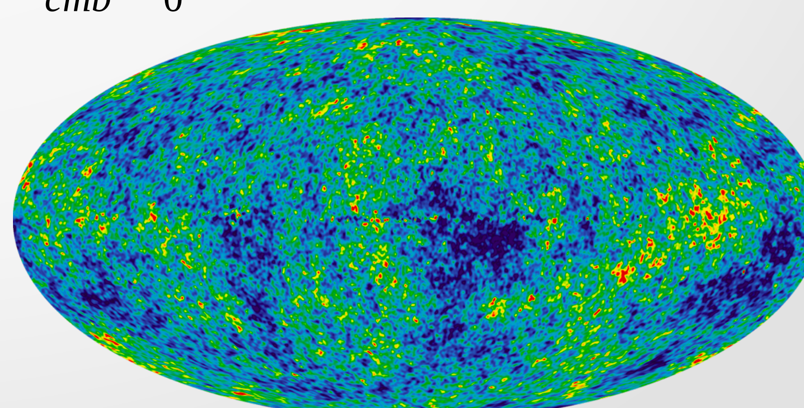


$$<\delta T \, \delta T>$$

$$\frac{k}{a_0} = 0.002 \, Mpc^{-1}$$

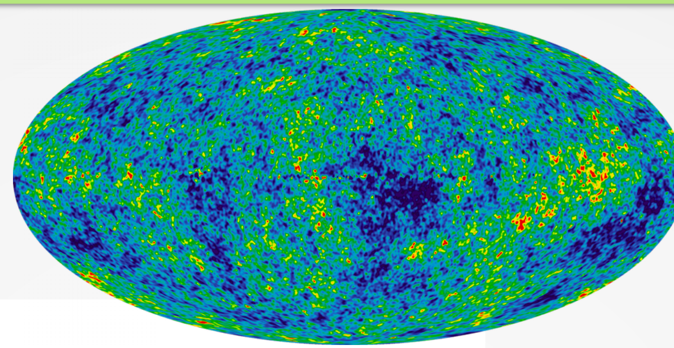
Pivot scale of PLANCK

$$\frac{\delta T}{T_0} \sim 10^{-5}$$

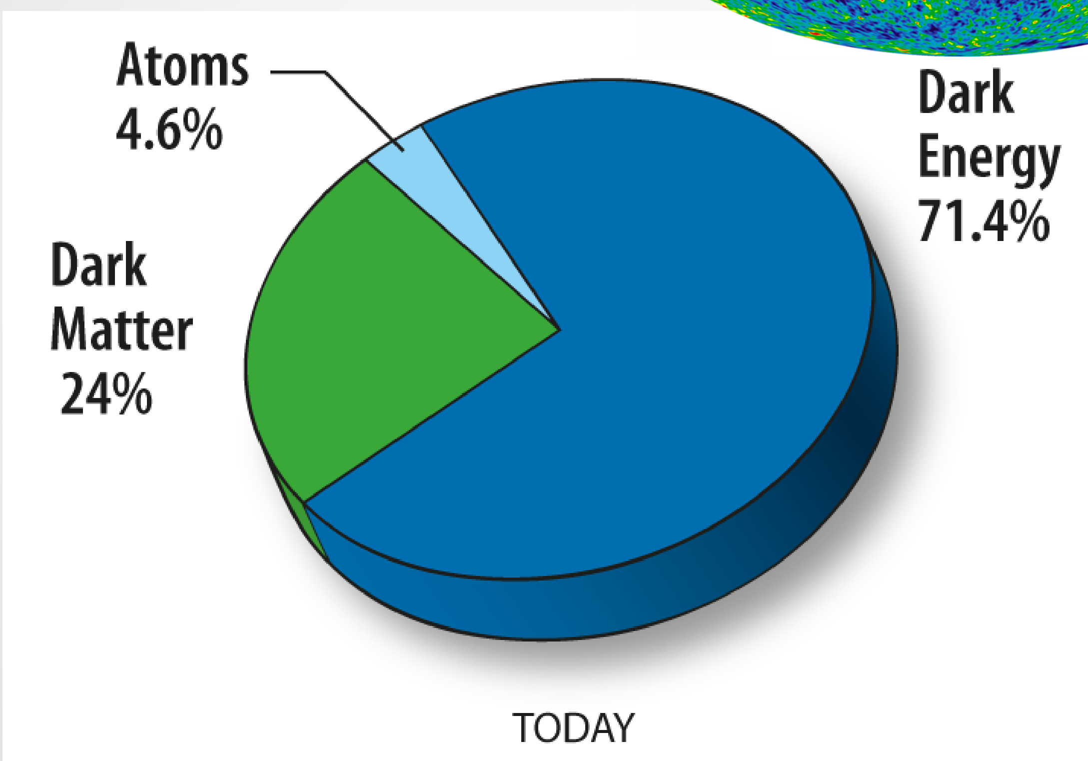


Given the inflationary background what do we observe today?

Extremely homogeneous CMB
Many more...



P.A.R Ade et. al.
ArXiv:1502:01589



No understanding of dark energy
(Cosmological constant,
Quintessence ...)

No understanding of Dark matter
(WIMP, axion...

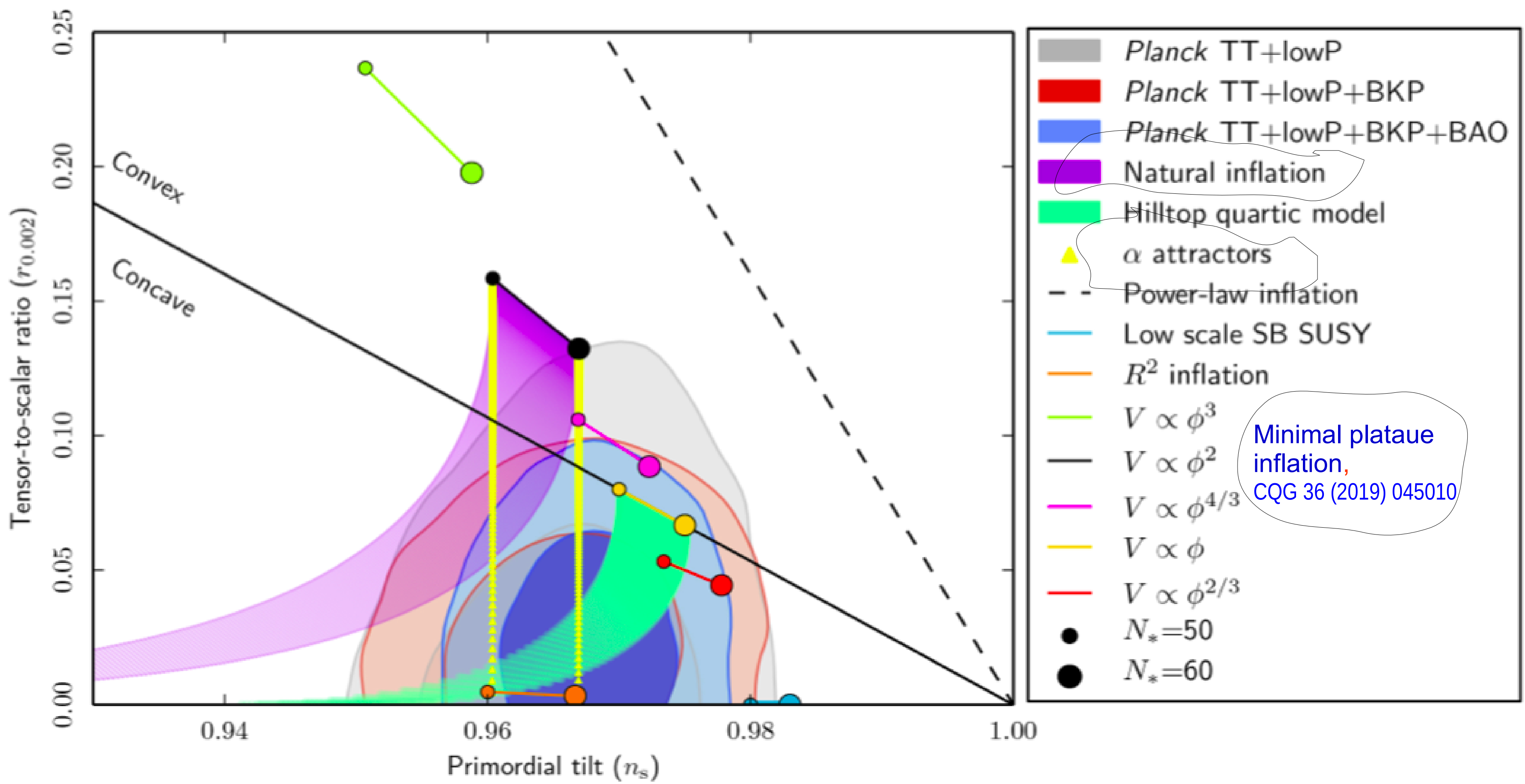
Talks on CMB observation:
T. Ghosh, K. Ichiki, O. Tajima, T. Hoang

emptyness

What inflation models

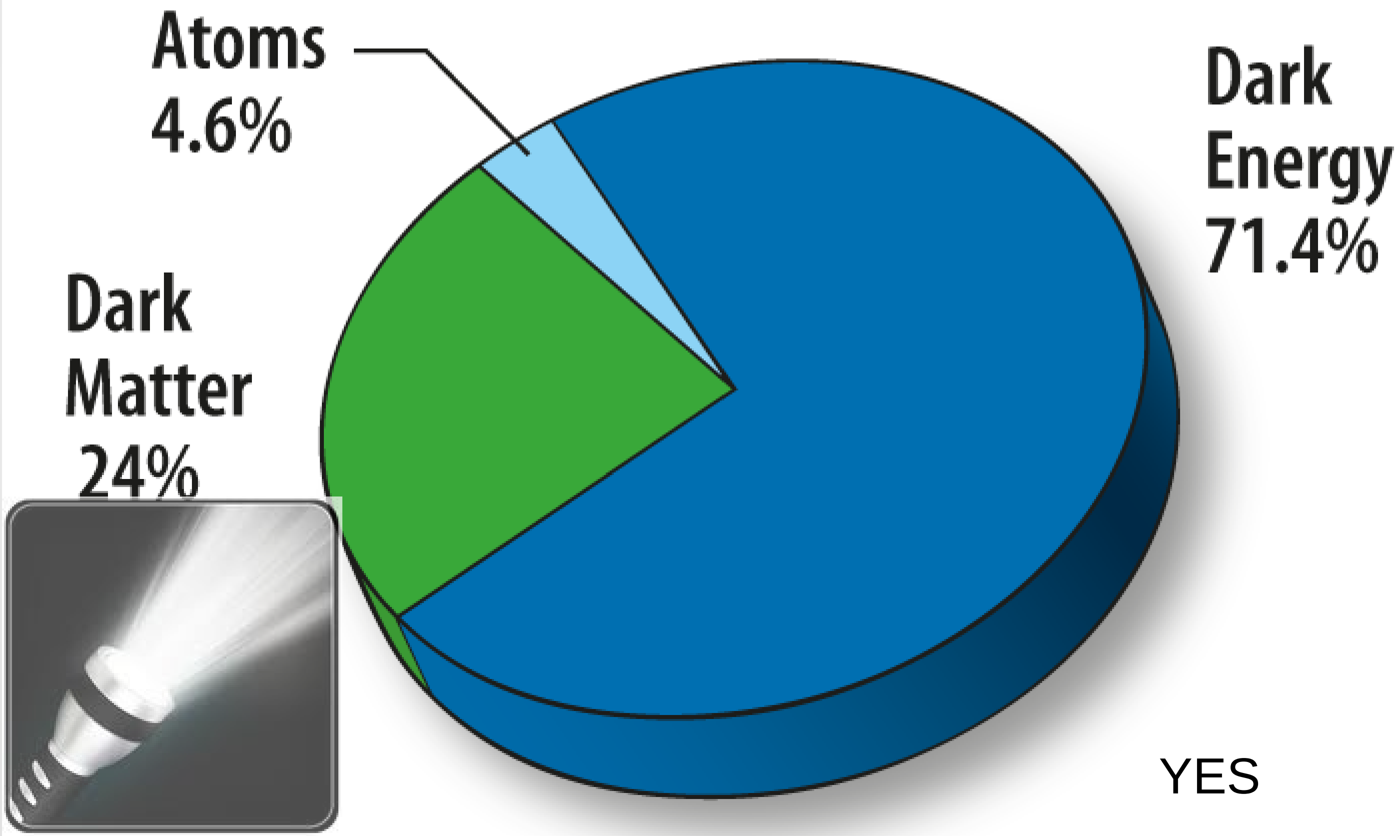
Planck-2015: Where do we stand?

P. A. R Ade et. al. ArXiv:1502:01589



Given the inflationary background

Does CMB have any role to play in understanding the dark matter phenomenology?



TODAY

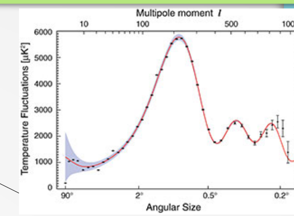
YES

Spectral distortion,
Axion-photon conversion,
R Khatri,
P Trivedi

Gravitational wave: PBH
M Sasaki, T Suyama,
A Escrivà

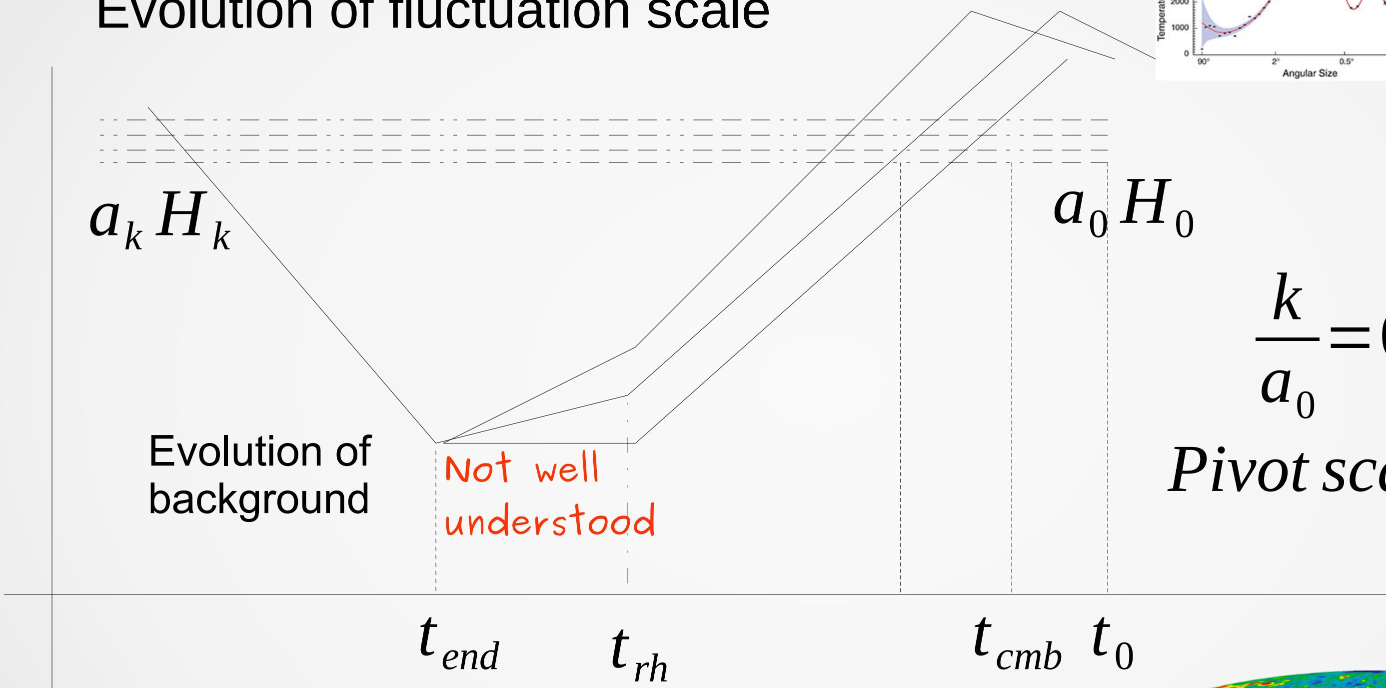
Let us go step by step

Play with reheating era



$$<\delta T \, \delta T>$$

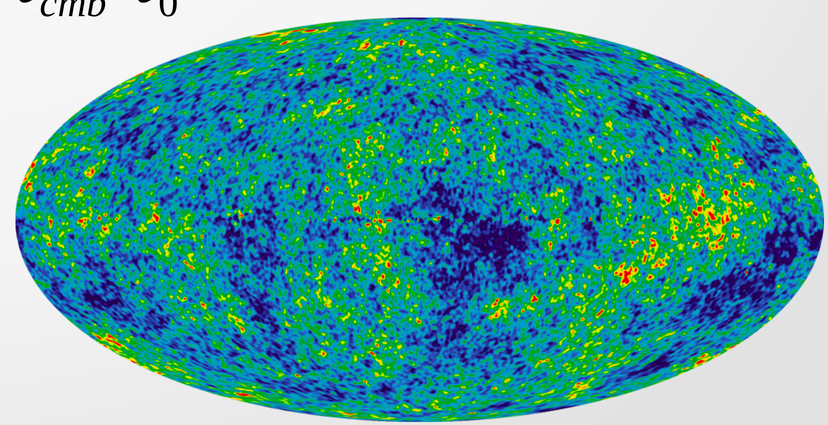
Evolution of fluctuation scale



$$\frac{k}{a_0} = 0.002 \, Mpc^{-1}$$

Pivot scale of PLANCK

$$\frac{\delta T}{T_0} \sim 10^{-5}$$



Plan

- Formalism

  CMB vs reheating temperature

  CMB, reheating and dark matter

- Particular model

  Minimal plateau inflation, Results

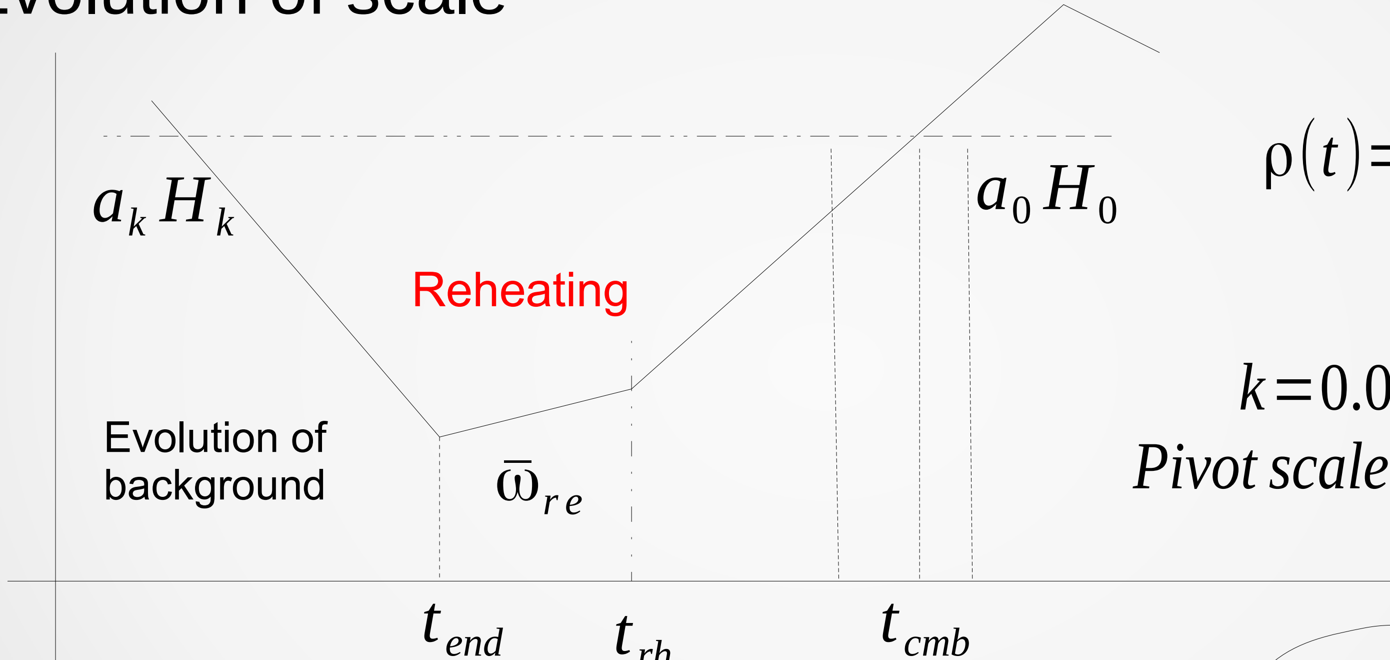
- Further generalisation
- conclusions

CMB and reheating

n_s vs T_{re}

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, …

- Evolution of scale



$$\rho(t)=\rho_\phi^i a^{3(1+\bar{\omega}_{re})}$$

$$k=0.02\,Mpc^{-1}$$

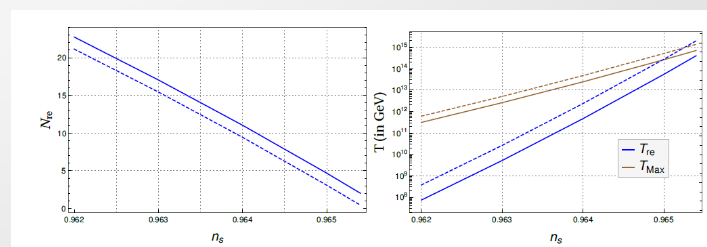
Pivot scale of PLANCK

$N_{re}, T_{re}, \bar{\omega}_{re}$

$$ln\left(\frac{a_k H_k}{a_0 H_0}\right) = -N_k - N_{re} - ln\left(\frac{a_{re} H_k}{a_0 H_0}\right)$$

$$g_{re} T_{rad}^3 = \left(\frac{a_0}{a_{re}}\right)^3 \left(2T_0^3 + 6 \times \frac{7}{8} T_{\nu 0}^3\right)$$

$$T_{re} = \left(\frac{43}{11 g_{re}}\right)^{\frac{1}{3}} \left(\frac{a_0 T_0}{k}\right) H_k e^{-N_k} e^{-N_r e}$$



CMB and reheating- Decying inflaton

L. Dai, M. Kamionkowski and J. Wang, PRL. 113, 041302 (2014)
DM, arXiv:1709.00251

- Rheating is model dependent: Inflaton → radiation

$$\ddot{n}_{re} = -2\dot{n}_{re}^2 + \frac{1-3w}{6M_P^2}\rho_\phi$$

$$\frac{\rho^f_{rad}}{\rho^i_\phi} = e^{-4N_{re}} - \frac{\rho^f_\phi}{\rho^i_\phi} + (1-3w)e^{-4N_{re}}\int_i^f \dot{n}_r\left(\frac{\rho_\phi}{\rho^i_\phi}\right)e^{4n_r}dt$$

$$n_{re} = \ln\left(\frac{a(t)}{a(t_i)}\right)$$

$$N_{re} = \ln\left(\frac{a(t_f)}{a(t_i)}\right)$$

$$\rho^f_{rad} = \pi^2(g_{re}/30)T^4_{rad}$$

$$\rho_{rad}(t_i) = 0 \;\; ; \;\; \dot{n}_{re}(t_i) = \sqrt{\frac{\rho^i_\phi}{3M_p^2}}.$$

$$\rho_\phi(t) = \rho^i_\phi e^{-3(1+w)n_{re}}e^{-\Gamma(t-t_i)}$$

At $t = t_f$

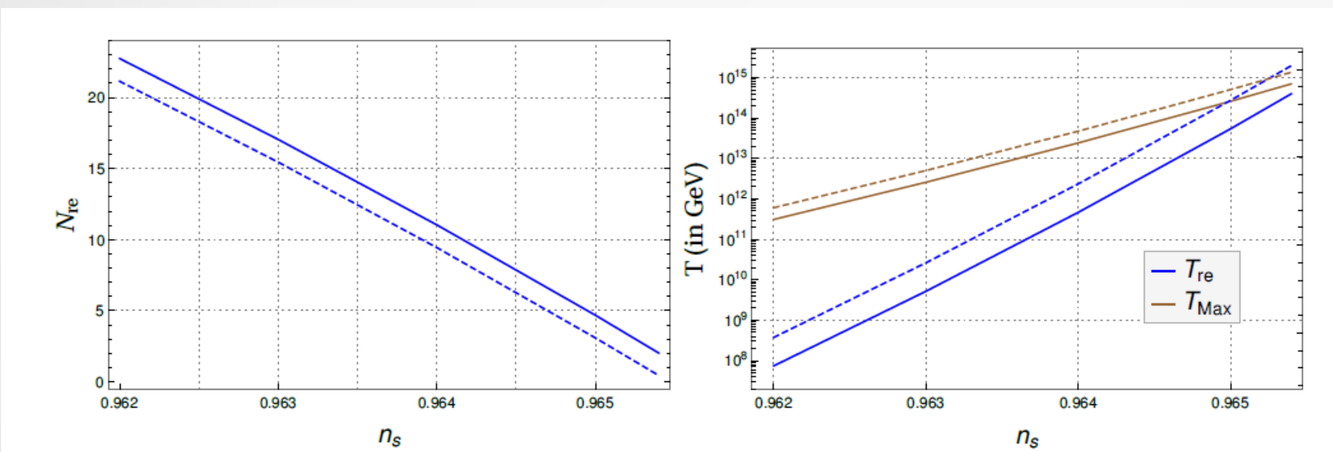
$$\Gamma = \dot{n}_{re}(t_f) = H_{re}$$

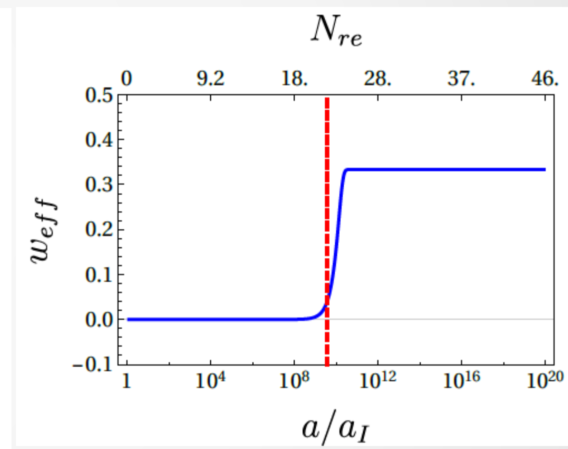
$$T_{re} = \left(\frac{43}{11g_{re}}\right)^{\frac{1}{3}}\left(\frac{a_0T_0}{k}\right)H_k e^{-N_k}e^{-N_re}$$

n_s vs T_{re} with inflaton decay

- Radiation is deaying into radiation filed (For chaotic inflation)
- $\rho_\phi(t) = \rho_\phi^i e^{-3(1+w)n_{re}} e^{-\Gamma(t-t_i)}$ (Solid lines) DM, arXiv:1709.00251

Chaotic inflation





$$w_{eff} = \left\langle \frac{3p_\phi + \rho_{rad}}{3(\rho_\phi + \rho_{rad})} \right\rangle$$

$\omega \to \bar{\omega}_{re}$

Dotted lines: complete conversion, inflaton energy → radiation

L. Dai, M. Kamionkowski and J. Wang, PRL. 113, 041302 (2014)

$$\rho_\phi(t) = \rho_\phi^i e^{-3(1+w)n_{re}} e^{-\Gamma(t-t_i)}$$

Going beyond: dark matter (perturbative)

- Assumption: Dark matter coupled to radiation field
- Inflaton → radiation → (radiation + dark matter)

$$\Phi = \frac{\rho_\phi a^{3(1+w_\phi)}}{m_\phi^{(1-3w_\phi)}}; \qquad R = \rho_R a^4; \qquad X = n_X a^3. \quad A = a/a_I$$

$$\frac{d\Phi}{dA} = -c_1(1+w_\phi)\frac{A^{1/2}\Phi}{\mathbb{H}}; \; \mathbb{H} = \left(\Phi/A^{3w_\phi} + R/A + X\langle E_X\rangle/m_\phi\right)^{1/2}$$

$$\frac{dR}{dA} = c_1(1+w_\phi)\frac{A^{3(1-2w_\phi)/2}}{\mathbb{H}}\Phi + c_2\frac{A^{-3/2}2\langle E_X\rangle\langle\sigma v\rangle M_{pl}}{\mathbb{H}}\left(X^2 - X_{eq}^2\right)$$

$$\frac{dX}{dA} = -c_2\frac{A^{-5/2}2\langle E_X\rangle\langle\sigma v\rangle M_{pl}}{\mathbb{H}}\left(X^2 - X_{eq}^2\right);$$

Unitarity limit

$$\langle\sigma v\rangle_{MAX} = 8\pi/M_X^2$$

Parameters

$T_{re} = \Gamma, M_X, <\sigma v>$

$$\Omega_X h^2 = \frac{\rho_X(T_F)}{\rho_R(T_F)}\frac{T_F}{T_{now}}\Omega_R h^2, \quad = \langle E_X\rangle\frac{X(T_F)}{R(T_F)}\frac{T_F}{T_{now}}\frac{A_F}{m_\phi}\Omega_R h^2$$

Parameter counting

Unique Initial conditions:

$$\Phi(1) = \frac{3}{8\pi}\frac{M_{pl}^2 H_I^2}{m_\phi^4}; \qquad R(1) = X(1) = 0.$$

Boundary conditions:

$$\Omega_X h^2 = 0.12$$

$$T_{re} = \left(\frac{43}{11 g_{re}}\right)^{\frac{1}{3}} \left(\frac{a_0 T_0}{k}\right) H_k e^{-N_k} e^{-N_{re}}$$

$$3 \quad Parameters$$
$$T_{re} \approx \Gamma, M_X, <\sigma v>$$

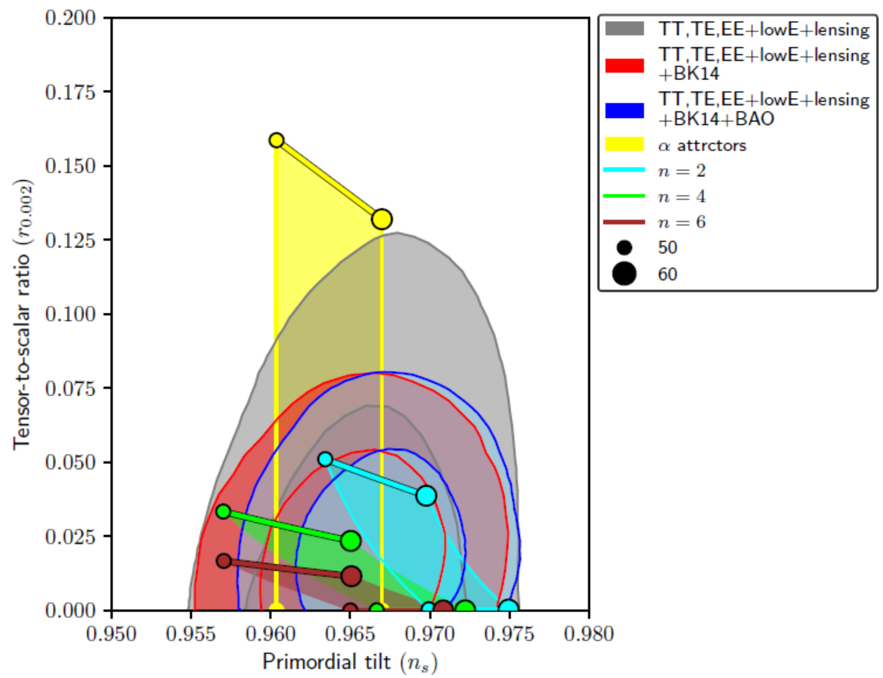
$$T_{\rm re} \equiv T_{\rm rad}^{\rm end} = \left[30/\pi^2 g_*(T)\right]^{1/4} \rho_R(\Gamma, n_s, M_X)^{1/4}.$$

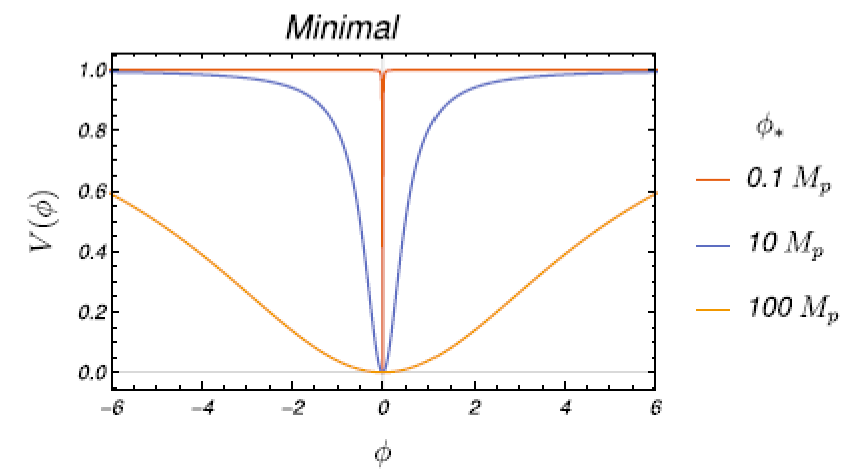
Therefore GIVEN a dark matter mass, all other parameters are uniquely fixed: Therefoe, we can successfully establish the connection we were looking for.

Model: Minimal Plateau Inflation

CQG 36 (2019) 045010

$$V_{\min}(\phi) = \frac{m^{4-n}\phi^n}{1+\left(\frac{\phi}{\phi_*}\right)^n}.$$





$\frac{\phi_*}{M_p}$	n	n_s	r	dn_s^k	$\Delta\phi$
0.01	2	0.969	4×10^{-5}	−0.000 66	0.39
	4	0.966	2×10^{-6}	−0.000 66	0.12
	6	0.965	3×10^{-7}	−0.000 69	0.06
1.00	2	0.969	4×10^{-3}	−0.0006	3.53
	4	0.966	9.6×10^{-4}	−0.0007	2.13
	6	0.964	3.5×10^{-4}	−0.0007	1.47

The spectral quantities for different values of n for 50 efolding.

All these prediction are for $\phi_* = 0.01M_\mathrm{p}$.

n	n_s	T_{re} (GeV)	N_{re}	N_k
2	0.9723	1×10^{15}	0.4	54
	0.9702	1×10^{3}	32	50
6	0.9670	1×10^{14}	00	53
	0.9679	2×10^{3}	23	55
8	0.9659	7×10^{13}	0.6	53
	0.9673	1×10^{3}	23	55

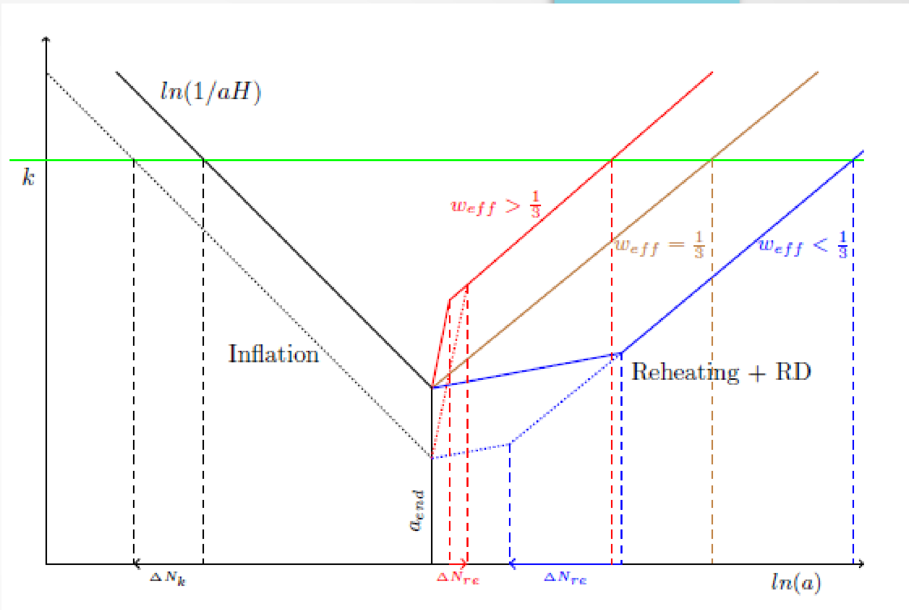
$$w_\phi \equiv \frac{P_\phi}{\rho_\phi} \simeq \frac{\langle\phi V'(\phi)\rangle - \langle 2V\rangle}{\langle\phi V'(\phi)\rangle + \langle 2V\rangle} = \frac{n-2}{n+2}.$$

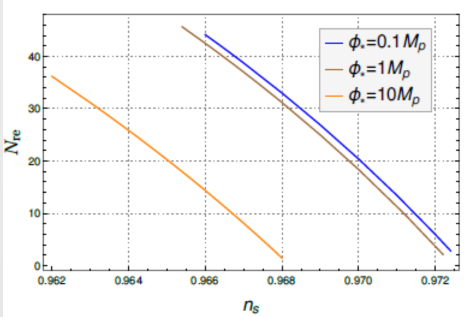
Minimal Plateau inflation: Perturbative reheating

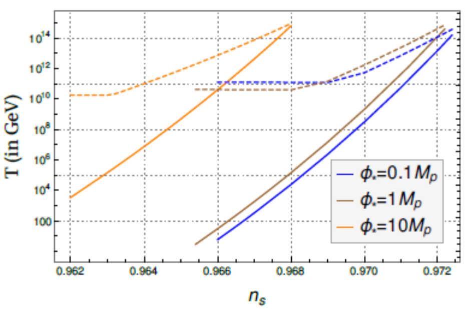
PRD98, 103525 (2018)
Phy.Dark.Univ. 25, 100317(2019)

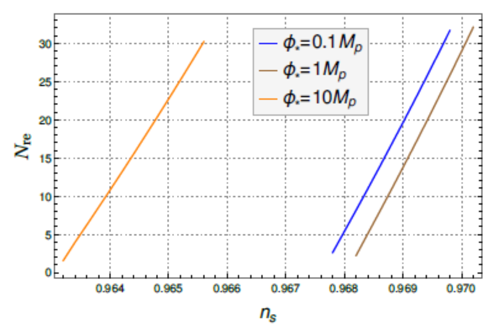
$$w_\phi \equiv \frac{P_\phi}{\rho_\phi} \simeq \frac{\langle \phi V'(\phi) \rangle - \langle 2V \rangle}{\langle \phi V'(\phi) \rangle + \langle 2V \rangle} = \frac{n-2}{n+2}.$$

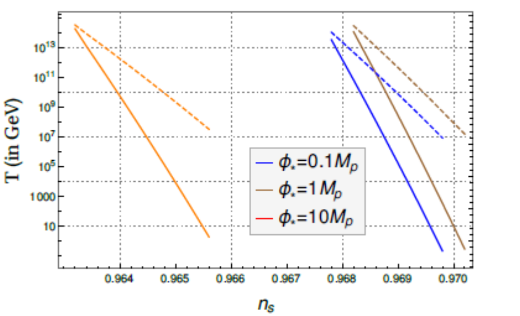
Effect of different inflaton equation of state during reheating







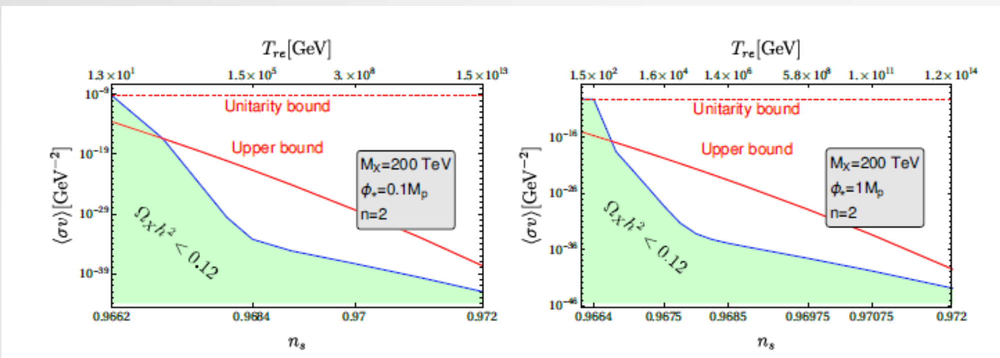


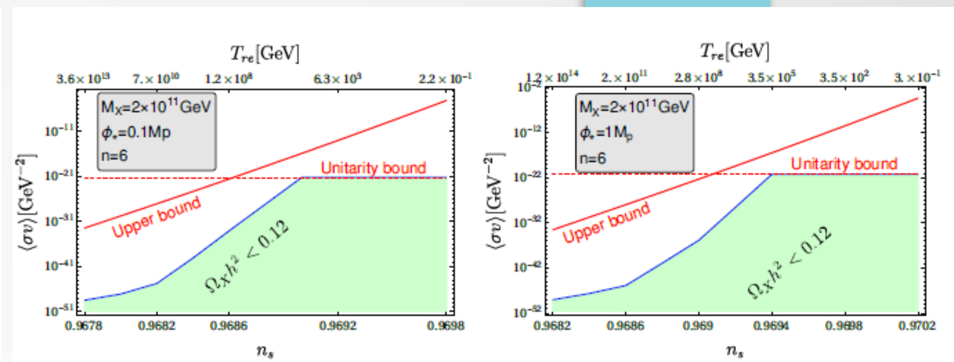


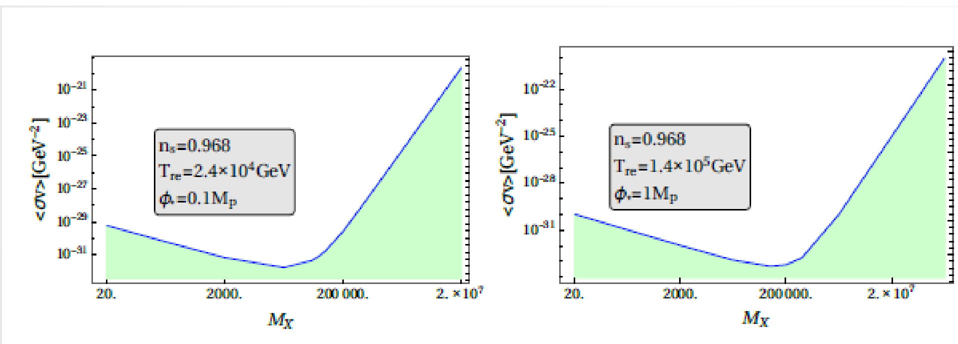
All these prediction are for $\phi_* = 0.01M_p$.

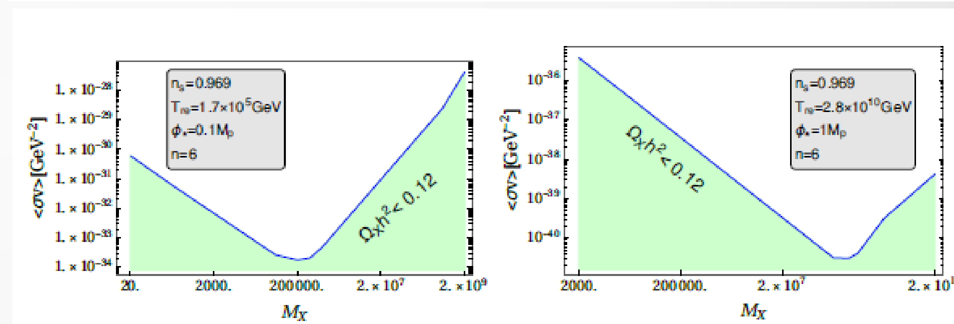
n	n_s	T_{re} (GeV)	N_{re}	N_k
2	0.9723	1×10^{15}	0.4	54
	0.9702	1×10^{3}	32	50
6	0.9670	1×10^{14}	00	53
	0.9679	2×10^{3}	23	55
8	0.9659	7×10^{13}	0.6	53
	0.9673	1×10^{3}	23	55

Constraining dark matter parameter space









$$\Omega_X h^2 \propto \langle\sigma|v|\rangle\, M_X^4 \exp\left[-\frac{(17+w)M_X}{(1+w)T_{\max}}\right] \quad \text{for } M_X \gtrsim T_{\max}$$

$$\Omega_X h^2 \propto \langle\sigma v\rangle \frac{T_{re}^{\frac{7+3w_\phi}{1+w_\phi}}}{M_X^{\frac{9-7w_\phi}{2(1+w_\phi)}}} \propto \frac{\langle\sigma v\rangle}{M_X^{\frac{9-7w_\phi}{2(1+w_\phi)}}}\left[\left(\frac{a_0T_0}{k}\right)H_k e^{-N_k} e^{-N_{re}}\right]^{\frac{7+3w_\phi}{1+w_\phi}} \quad \text{for } T_{\max} > M_X > T_{re}$$

$$\Omega_X h^2 \propto \langle\sigma v\rangle\, M_X\, T_{re} \propto \langle\sigma v\rangle\, M_X \left(\frac{a_0T_0}{k}\right) H_k e^{-N_k} e^{-N_{re}} \quad \text{When } M_X < T_{re}. \tag{24}$$

TABLE X: $\phi_* = 0.1M_p$

n	N_{re}	$T_{re}(GeV)$	$\langle\sigma v\rangle GeV^{-2}$ $M_X(200TeV)$
2	33	2.4×10^4	3×10^{-30}
4	-	-	-
6	5	1.6×10^{12}	7×10^{-42}
8	-	-	-

TABLE XI: $\phi_* = 1M_p$

n_s	N_{re}	$T_{re}(GeV)$	$\langle\sigma v\rangle GeV^{-2}$ $M_X(200TeV)$
2	31	1.4×10^5	6×10^{-34}
4	-	-	-
6	13	1.3×10^8	7×10^{-38}
8	8	6×10^{10}	2×10^{-40}

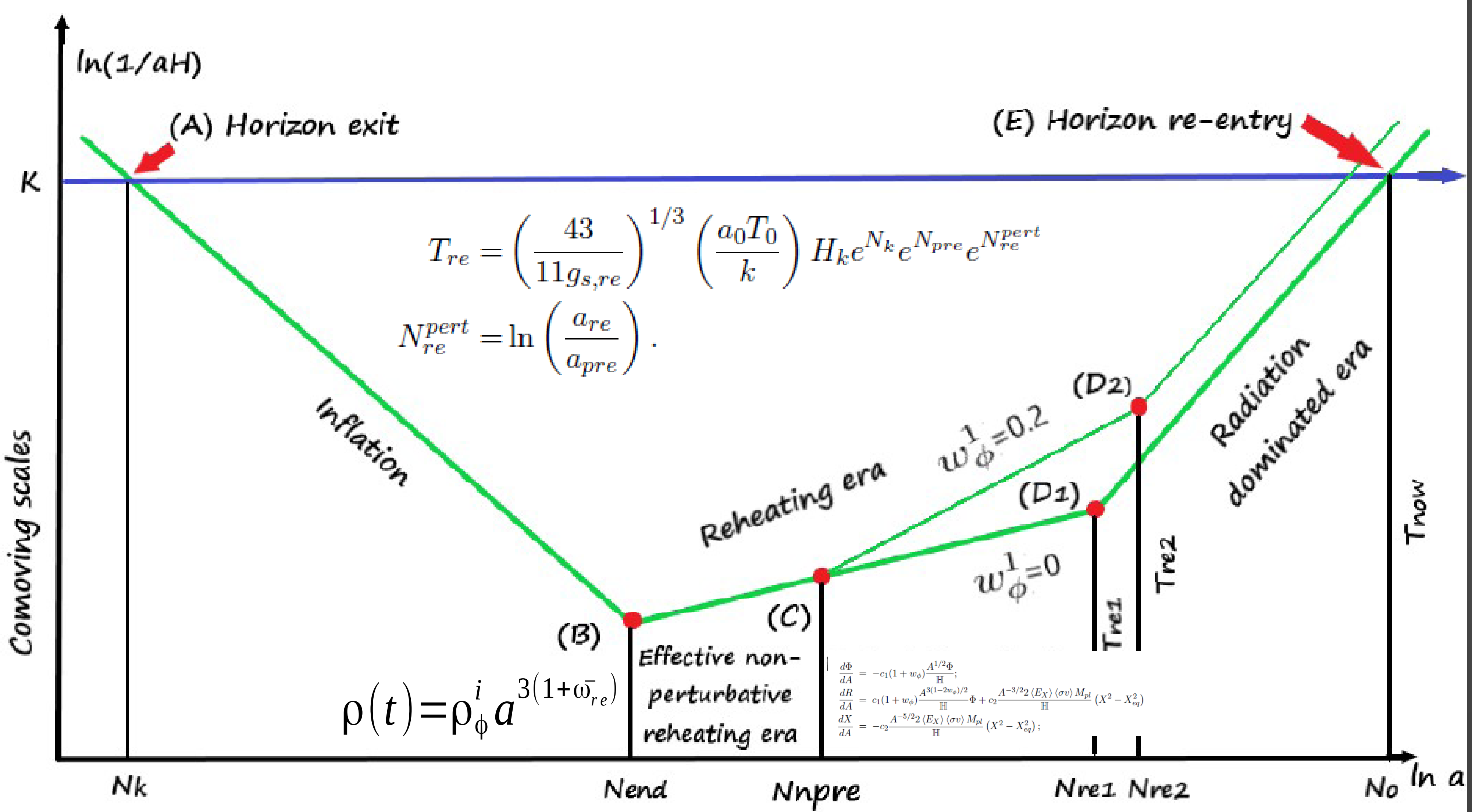
TABLE XII: $\phi_* = 10M_p$

n	N_{re}	$T_{re}(GeV)$	$\langle\sigma v\rangle GeV^{-2}$ $M_X(200TeV)$
2	1.5	6×10^{14}	3×10^{-44}
4	-	-	-
6	-	-	-
8	-	-	-

$$\log_{10}(T_{\rm re}\ {\rm GeV}) \simeq Q_p\left[A + B(n_s-0.962) + C(n_s-0.962)^2\right]$$

$$n_s = 0.968$$

Non perturbative effects: Boltzmann framework

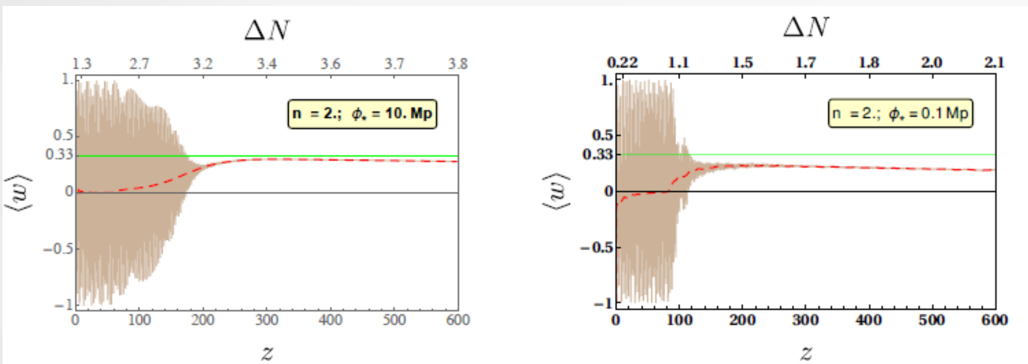


Nonperturbative aspects(Lattice result)

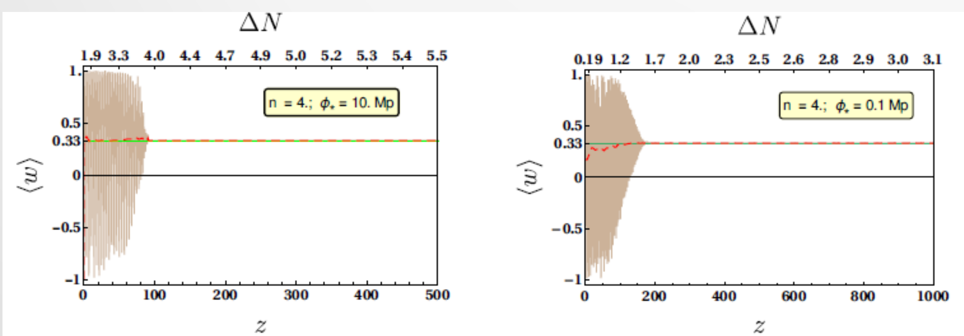
JCAP 1907 (2019) no.07, 018

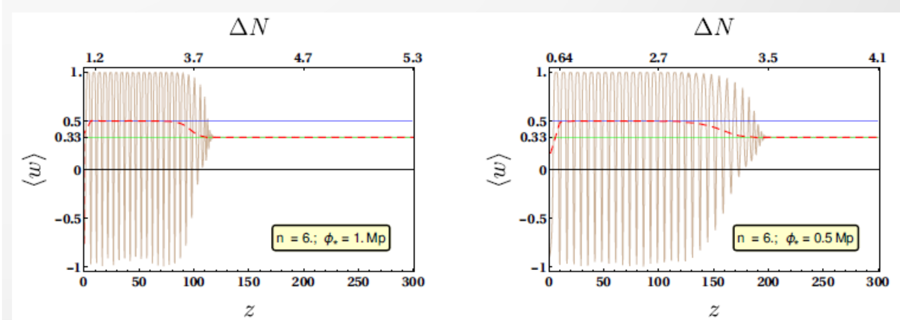
$$V(\phi,\chi) = \frac{1}{n}\frac{\lambda\, m^{4-n}\, \phi^n}{\left[1+\left(\frac{\phi}{\phi_*}\right)^n\right]} + \frac{1}{2}g^2\phi^2\chi^2.$$

$$\omega_\phi^1 \approx 0.22 \quad for \quad n=2$$
$$\omega_\phi^1 \approx 0.33 \quad for \quad n=4,6,$$



$$T_{re} = \left(\frac{43}{11 g_{s,re}}\right)^{1/3} \left(\frac{a_0 T_0}{k}\right) H_k e^{N_k} e^{N_{pre}} e^{N_{re}^{pert}}$$
$$N_{re}^{pert} = \ln\left(\frac{a_{re}}{a_{pre}}\right).$$



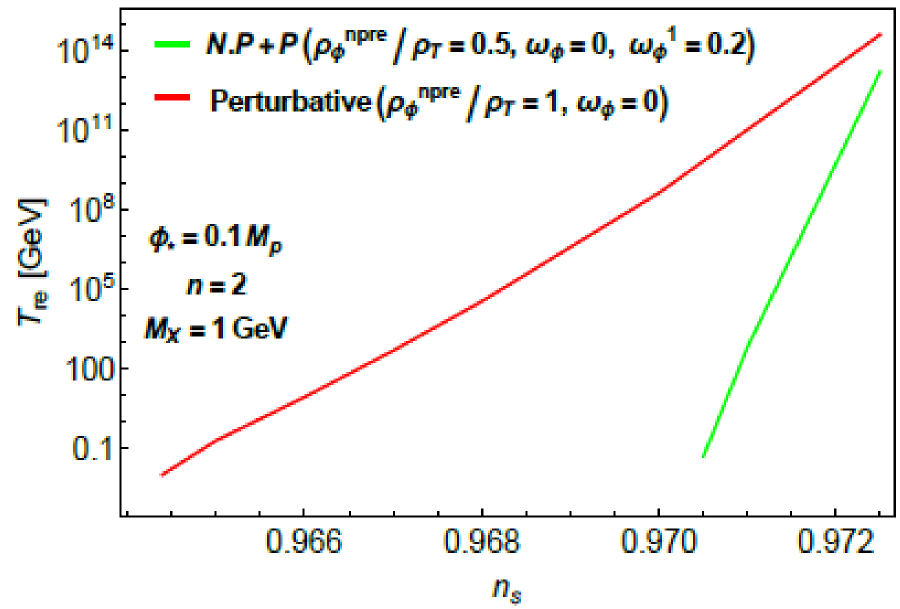


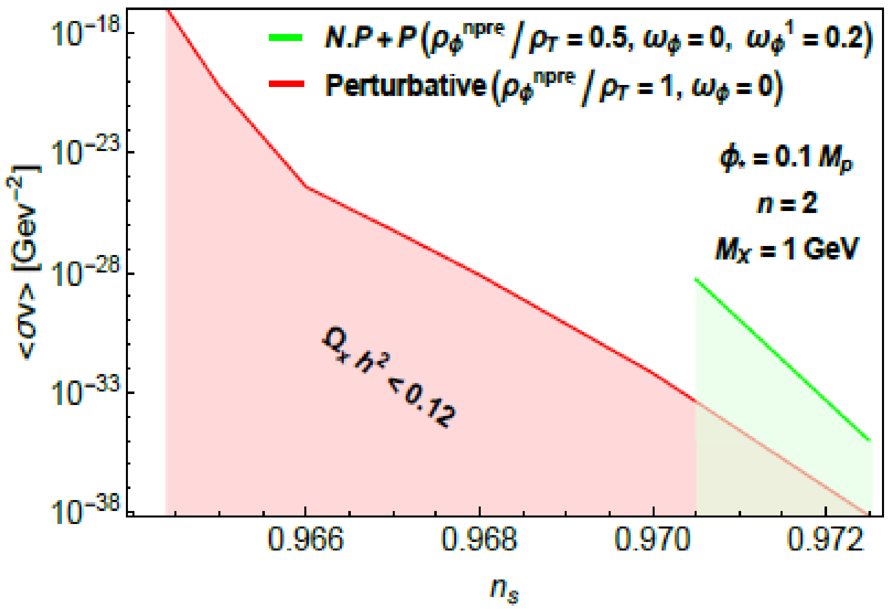
Non-perturbative: n=2 case

$$T_{re} = \left(\frac{43}{11 g_{s,re}}\right)^{1/3} \left(\frac{a_0 T_0}{k}\right) H_k e^{N_k} e^{N_{pre}} e^{N_{re}^{pert}}$$

$$N_{re}^{pert} = \ln\left(\frac{a_{re}}{a_{pre}}\right).$$

$$T_{\rm re} \equiv T_{\rm rad}^{\rm end} = \left[30/\pi^2 g_*(T)\right]^{1/4} \rho_R(\Gamma, n_s, M_X)^{1/4}.$$





Conclusions and future directions

- Assuming the perturbative reheating scenario, CMB can constrain the dark matter phenomenology.
- Pin pointing the value of scalar spectral index is very important
- Full non-linear evolution: Effect of non-perturbative dynamics will be necessary
- Inflaton-dark matter model construction

Thank you