Gravitational reheating and its observable effects

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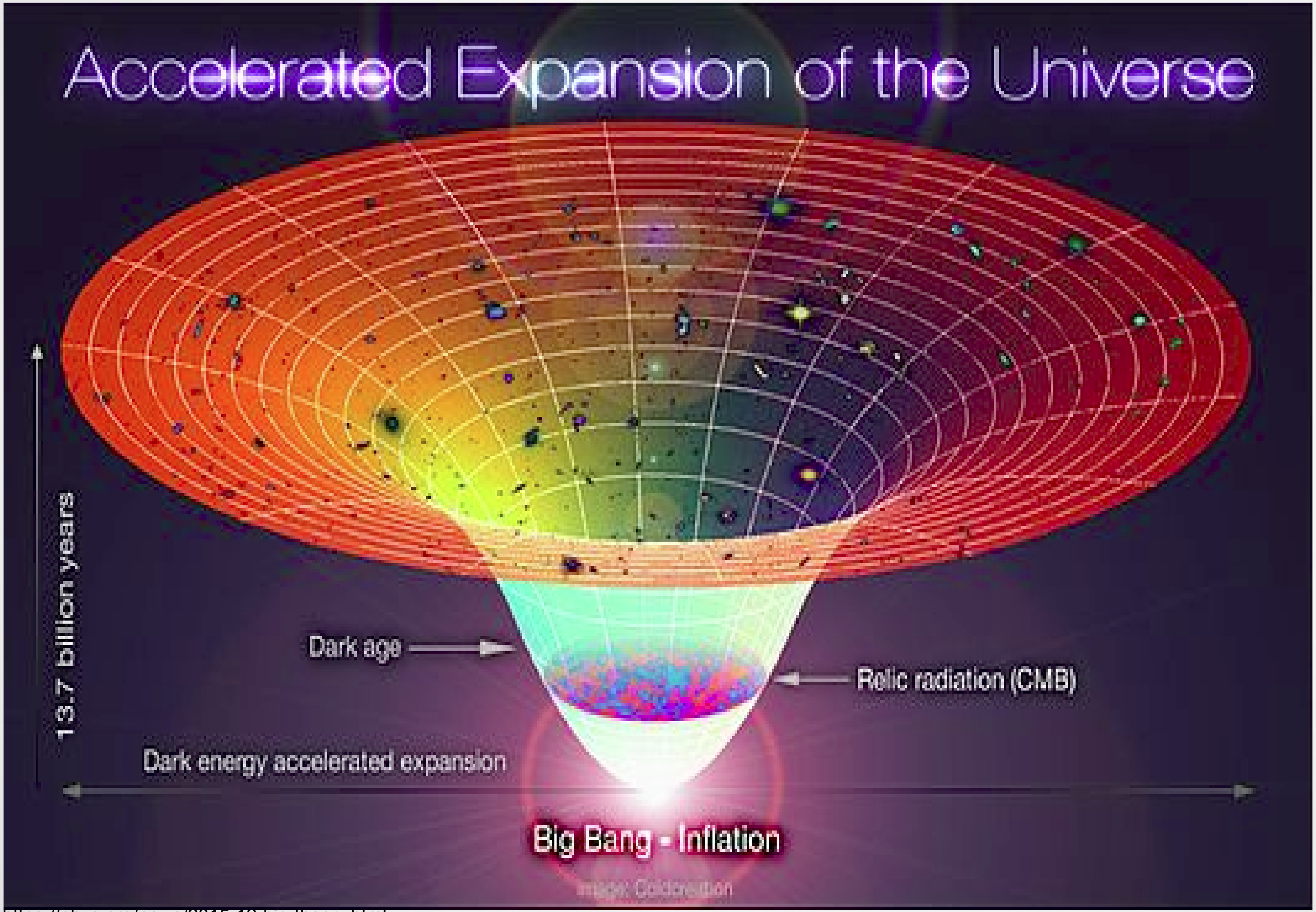
How the present state of our universe has been created?

Time evolving cosmos

Based on large number of observations



https://phys.org/news/2015-12-big-theory.html

Cosmological constant

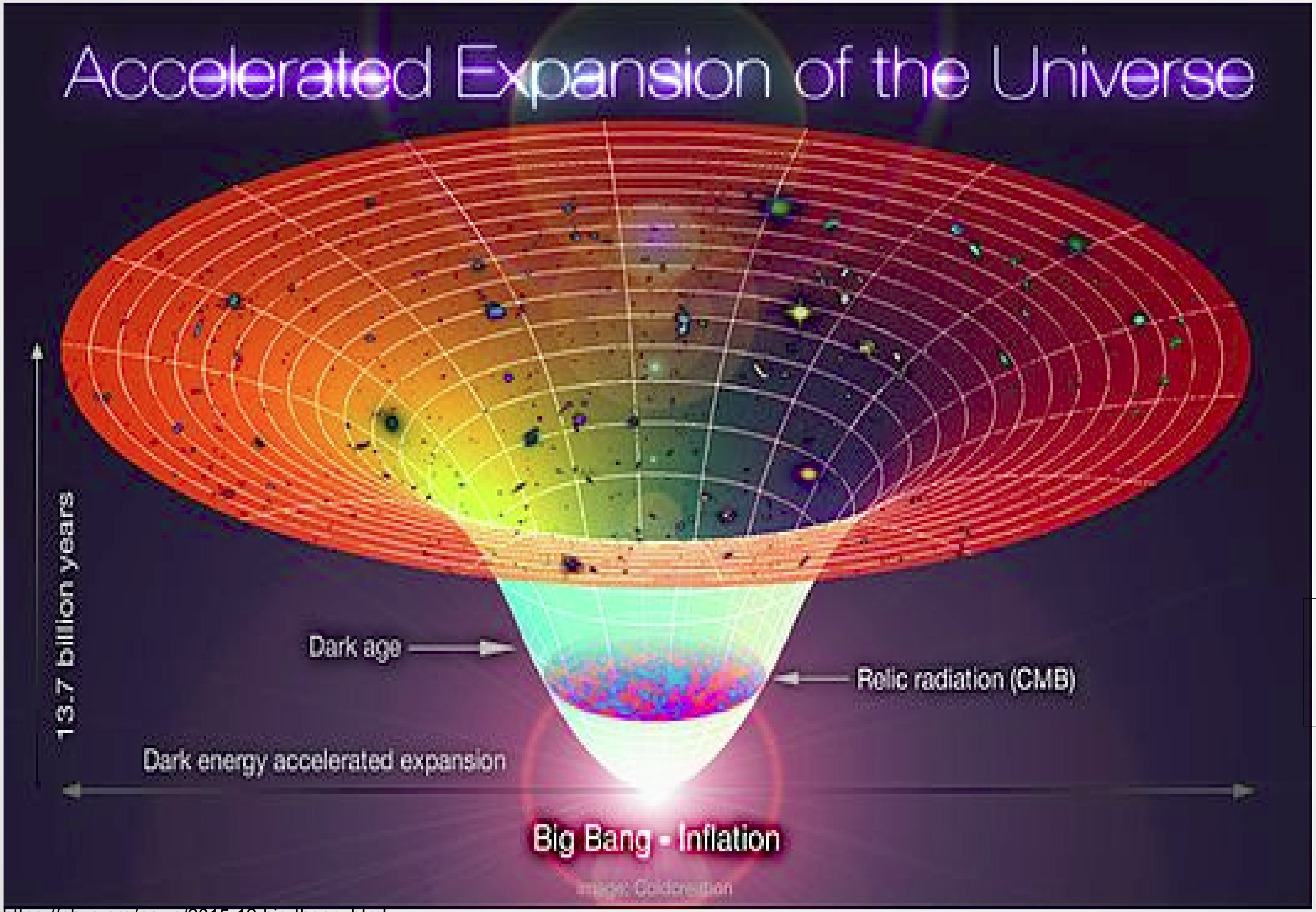
Matter

Radiation

Inflation

Time evolving cosmos

Based on large number of observations



https://phys.org/news/2015-12-big-theory.html

Cosmological constant

Matter

Radiation

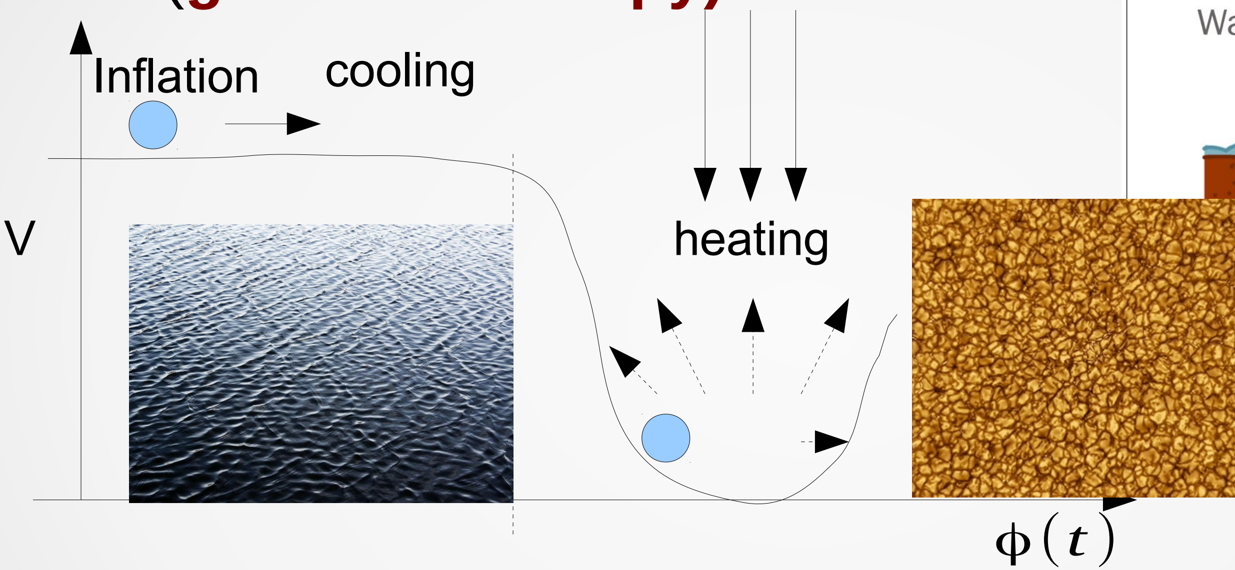
Reheating

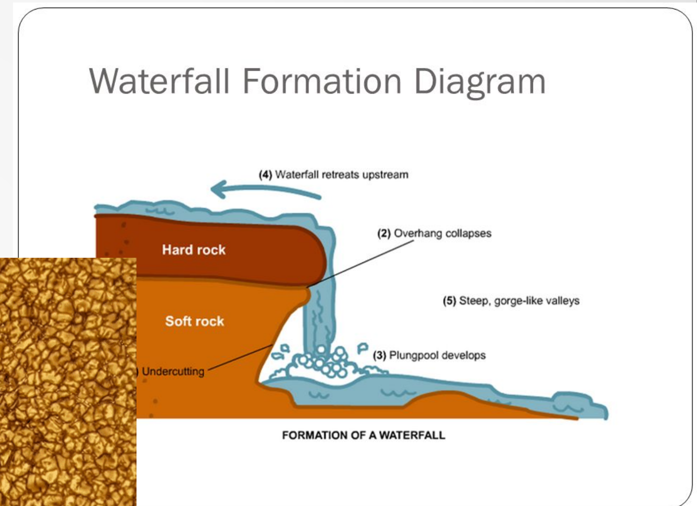
Inflation

What does it do?

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,

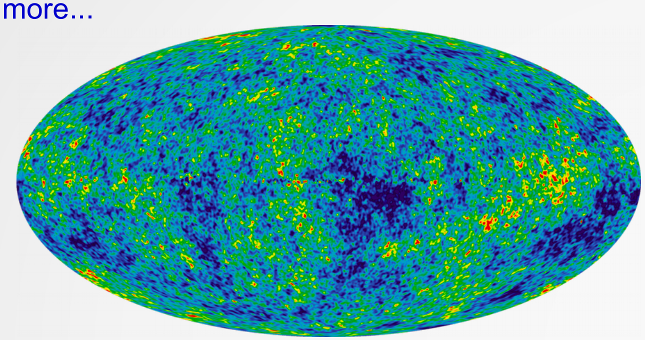
From the observational perspective little attention has been paid: Difficulties: Equilibriation processes assumed to erase information, large possibilities of inflaton decay channels, difficult to identify observables and observe the phase

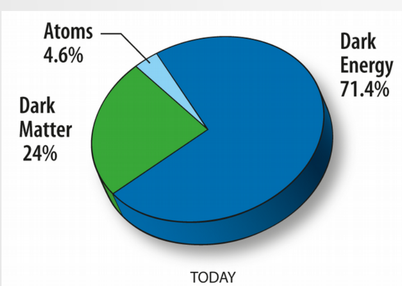
Given the inflationary phase:
What do we observe today?

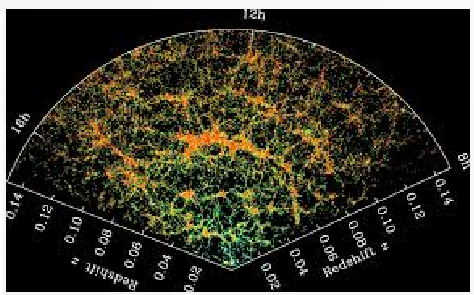
P.A.R Ade et. al. ArXiv:1502:01589

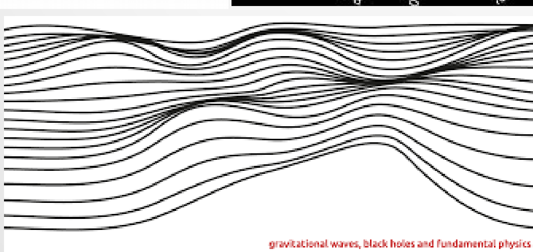
Extremely homogeneous Universe

Many more...









Reheating gives us right proportion of all these and this information must be imprinted into Background+fluctuation that we see today in some way

Background + Fluctuations of all fundamental fields but not inflaton

CMB

Scalar type

Density(curavature) fluctuations, Dark Matter, Dark energy...

FermionType

Baryonic Matter, Dark matter ?

DM

Vector type

Primordial Large scale Magnetic field, EM radiation...

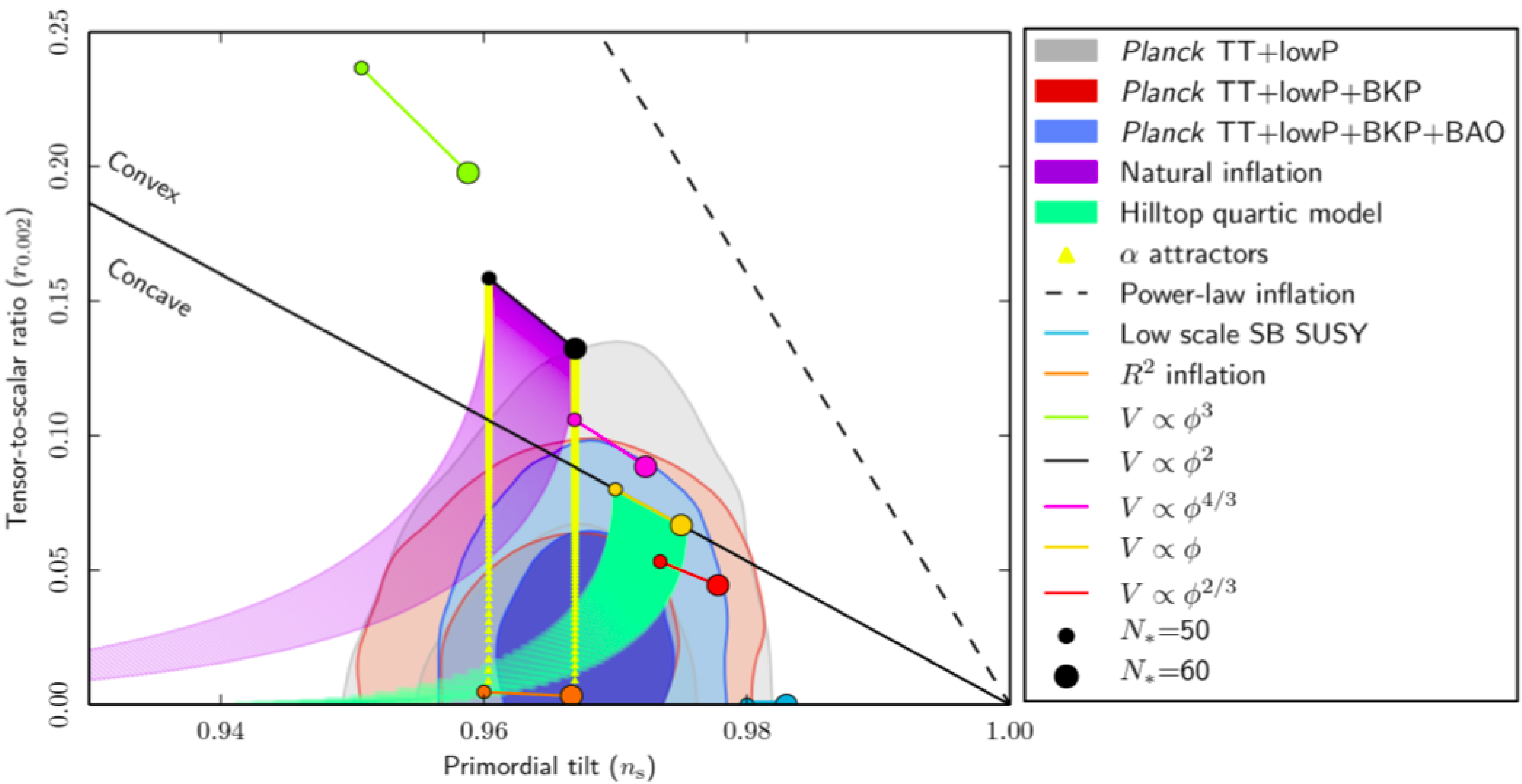
PGW

Tensor type

Primodial Graviational wave(PGW), Higher spin, Kalb Ramond...

Where do we stand?

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



Planck-2015

Questions and Plan

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?

This will help us resolve DM puzzle, Baryogenesis …

- Gravitational reheating set up
- Predictions and constraints
- Conclusions

Reheating phenomenology

- Usual approach:(preheating) Through parametric resonance +

  Perturbative decay $\sim \alpha_1 \phi S^3, \alpha_2 \phi^2 S^2, \alpha_3 \phi \bar{f} f \ldots$

Many parameters to look for observables

- Gravitational decay $\sim \frac{1}{M_P} h_{\mu\nu} T_i^{\mu\nu}, i = S, f, X, \phi$

Universal in nature

- Gravitational decay channel was always ignored because of obvious reason. Actually no body has studied it before!!

Can gravitational decay reheat the universe?

How do we realise such scenario and why?

Why?

$\sim \alpha_1 \phi S^3, \alpha_2 \phi^2 S^2, \alpha_3 \phi \bar{f} f, \alpha_4 \phi^3 S \ldots$

Too many unknown parameters to look for observables

Universal reheating dynamics: $\sim \frac{1}{M_P} h_{\mu\nu} T_i^{\mu\nu}, i = S, f, X, \phi$

$\alpha_i = 0$

How?

- Z_2 Symmetry : $Z\phi = -\phi \quad ; \quad Z\psi_{visible} = \psi_{visible} \qquad \alpha_2 \phi^2 S^2$
- Shift symmetry, (inflation is guided by shift symmetry): $\frac{\beta_5}{M_P} \partial_\mu \phi \partial^\mu S S$
- Assuming: Z_2 and shift symmetry $\frac{1}{M_p^2} S^2 \partial_\mu \phi \partial^\mu \phi$

Gravitational reheating

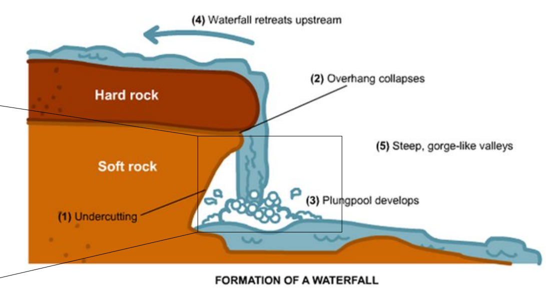
Riajul Haque, DM, 2201.02348

Inflaton gravitationally decaying into
Radiation (massless) + Dark matter (massive)

$$\dot{\rho}_\phi + 3H(1+\omega_\phi)\rho_\phi + \Gamma^T_\phi \rho_\phi (1+\omega_\phi) = 0\,,$$
$$\dot{\rho}_R + 4H\rho_R - \Gamma^{Rad}_{\phi\phi\to RR}\,\rho_\phi(1+\omega_\phi) = 0\,,$$
$$\dot{n}_Y + 3Hn_Y - \frac{\Gamma^{DM}_{\phi\phi\to YY}}{m_\phi}\rho_\phi(1+\omega_\phi) = 0$$

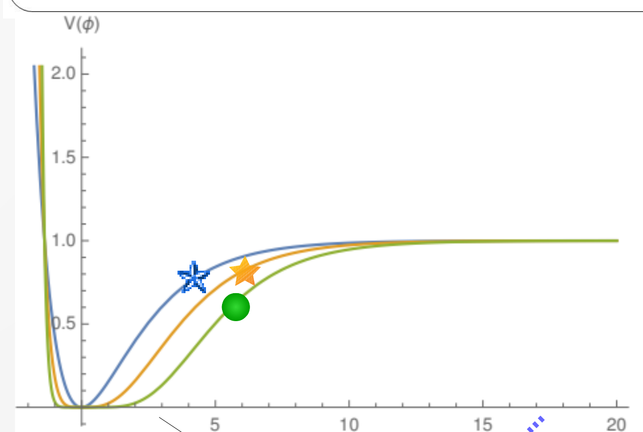
parametric resonance channel subdominant,
Y. Ema, et al, JHEP07(2019)060

Waterfall Formation Diagram



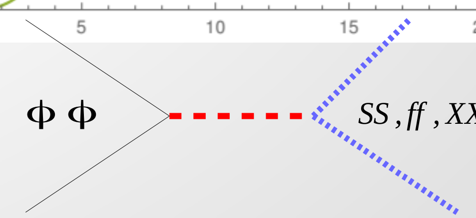
$$\Gamma_{\phi\phi\to SS} = \frac{\rho_\phi m_\phi}{1024\pi M_p^4}\left(1+\frac{m_S^2}{2m_\phi^2}\right)\sqrt{1-\frac{m_S^2}{m_\phi^2}}\,,$$
$$\Gamma_{\phi\phi\to ff} = \frac{\rho_\phi m_f^2}{4096\pi M_p^4 m_\phi}\left(1-\frac{m_f^2}{m_\phi^2}\right)^{\frac{3}{2}}\,, \qquad (0.1)$$
$$\Gamma_{\phi\phi\to XX} = \frac{\rho_\phi m_\phi}{32768\pi M_p^4}\left(4+4\frac{m_X^2}{m_\phi^2}+19\frac{m_X^4}{m_\phi^4}\right)\sqrt{1-\frac{m_X^2}{m_\phi^2}}.$$

Parameters:
$\rho_\phi^{in}, \omega_\phi, M_{DM}$



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

$$\Gamma^T_\phi = (\Gamma^{Rad} + \Gamma^{DM})$$
$$\Gamma^{Rad} = (\Gamma^S + \Gamma^f + \Gamma^X)$$



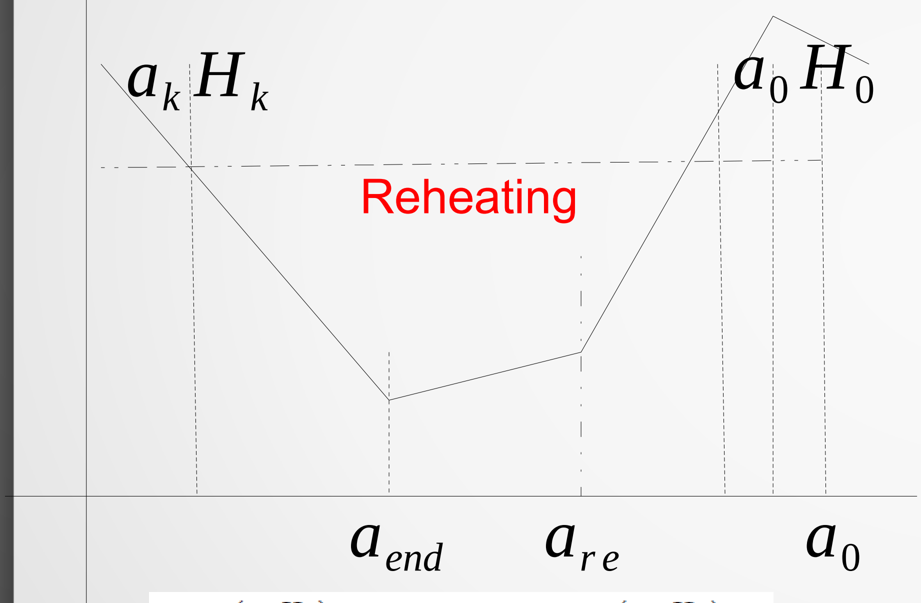
s-channel dominating process

Initial conditions and constraints

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, …

Unique Initial conditions: $\rho_\phi^{in} = 3 M_p^2 H_{end}^2, \quad \rho_R = \rho_{DM} = 0$

Constraint conditions:



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

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

Present state of our universe

1. Entropy conservation

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

With $k/a_0 = 0.05\ \mathrm{Mpc}^{-1}$ and $T_0 = 2.725^0\ \mathrm{K}$

2. Present DM abundance $\Omega_X h^2 = 0.12$

3. Universe must be radiation dominated for $T_{re} > T_{BBN} \sim 10\ MeV$

4. Upper limit on Inflationary energy scale $H_{end}^{max} > \pi M_p \sqrt{r A_s/2} \sim 5 \times 10^{13}\ GeV$

Present state of the universe is completely fixed by $H_{end}, \omega_\phi, M_{DM}$

Model independent predictions:

- **Assume slow roll inflation scenario (no specific model)**

$$m_\phi^{end} \simeq \sqrt{(1+\omega_\phi)(4+12\omega_\phi)/(1-\omega_\phi)^2}\, H_{end}$$

$$N_{re} = \frac{1}{3\omega_\phi - 1} \ln\left(\frac{512\,\pi\; M_p^2\,(1+15\,\omega_\phi)}{3\,(1+\gamma)H_{end}\, m_\phi^{end}\,(1+\omega_\phi)}\right)$$

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

$$n_f^{com} \simeq \frac{3H_{end}^3}{2048\pi}\frac{1+\omega_\phi}{1-\omega_\phi}\left(\frac{m_f}{m_\phi^{end}}\right)^2\left(1-e^{-\frac{3N_{re}}{2}(1-\omega_\phi)}\right),$$

$$n_S^{com} = 8n_X^{com} = \frac{3H_{end}^3\,(1+\omega_\phi)}{512(\pi+3\pi\omega_\phi)}, \qquad (0.12)$$

$$\Omega_Y\, h^2 = \frac{m_Y\, n_Y(A_{re})A_{re}^3}{\rho_R(A_{re})A_{re}^4}\,\frac{A_{re}T_{re}}{T_0}\,\Omega_R\, h^2 \;= 0.12$$

$$m_\phi^{end} \simeq \sqrt{(1+\omega_\phi)(4+12\omega_\phi)/(1-\omega_\phi)^2}\, H_{end}$$

3. Universe must be radiation dominated for

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

4. Upper limit on Inflationary energy scale

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

$$H_{end} = (1\times 10^9, 5\times 10^{13})\,GeV \rightarrow T_{re} = (10^8, 10^{-3})\,GeV$$

$$\omega_\phi = (0.6, 0.99)$$

Reheating phase dominated by stiff matter

1. Entropy conservation
2. Present DM abundance

$$62 < N_{efold} < 63$$

$$2\times 10^5 < m_f < 3\times 10^8\;\; GeV$$

$$50 < (m_S, (1/8)\, m_X) < 1000\;\; eV$$

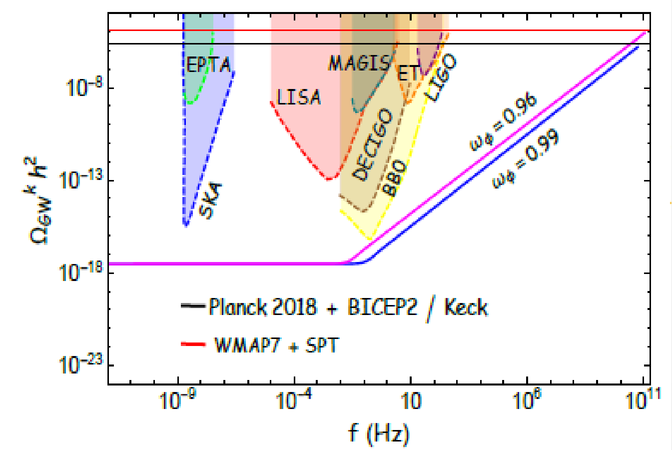
Imprints on Primordial GW

R. Haque, DM, S. T. Paul, L. Sriramkumar, Phys.Rev.D 104 (2021) 6, 063513, Riajul Haque, DM, 2201.02348

- The existence of primordial gravitational waves (GWs) is one of the profound predictions of inflation

$$\Omega^{k}_{GW} h^2 \simeq \Omega_R h^2 P_T(k) \frac{4\mu^2}{\pi}\Gamma^2 \left(\frac{5+3\omega_\phi}{2+6\omega_\phi}\right)\left(\frac{k}{2\mu k_{re}}\right)^{n_{GW}}$$

$$\mu = \frac{1}{2}(1+3\omega_\phi) \qquad P_T(k) = H^2_{end}/12\pi^2 M_p^2.$$



- Index of the GW spctrum:

$$n_{GW} = \frac{(6\,\omega_\phi - 2)}{(3\,\omega_\phi + 1)} \quad \Rightarrow \quad 0.57 \le n_{GW} \le 0.99$$

$$\omega_\phi = (0.6\,,0.99)$$

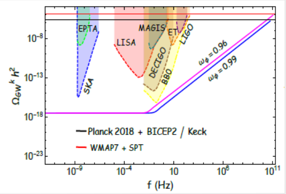
Summary of model independent predictions and constraints

Gravitational Reheating predicts

- Fermionic dark matter: $2\times10^{5} < m_f < 3\times10^{8}\ GeV$
- Bosonic dark matter: $50 < (m_S, (1/8)m_X) < 1000\ eV$
- GW spectral index: $0.57 \leq n_{GW} \leq 0.99$

Visible sector

$T_{re} = (10^{8}, 10^{-3})\, GeV$



- Inflaton equation of state $\omega_{\phi} = (0.6, 0.99)$
- Energy scale of inflation $H_{end} = (1\times10^{9}, 5\times10^{13})\ GeV$
- Inflationary e-folding number $62 < N_{efold} < 63$

Inflaton sector

Important conclusion: Not all inflation models are consistent with Gravitational Reheating mechanism!

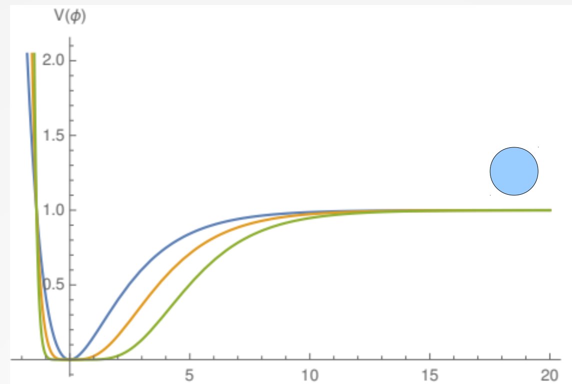
Constraining specific models

Linde etal ; JHEP 11 (2013) 198

Riajul Haque, DM, 2201.02348

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

$$1 - n_s \simeq 2/N_k,\; r \simeq 12\,\alpha/N_k^2$$



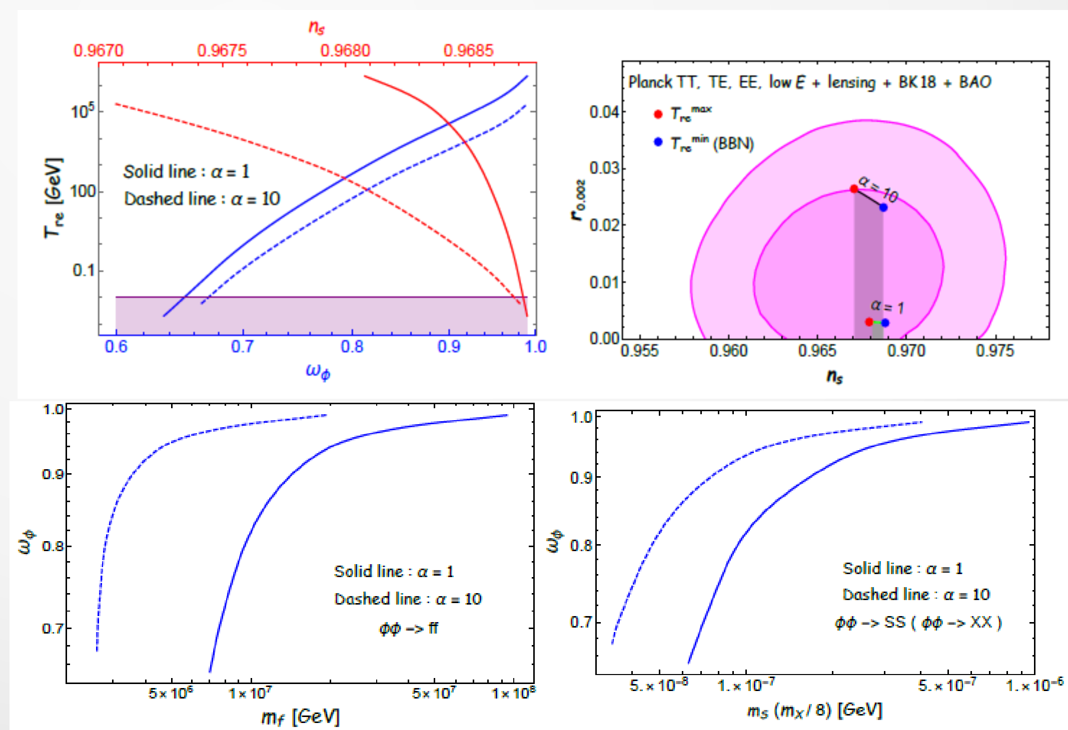
$\alpha=10$ → $0.9611 \leq n_s \leq 0.9687$

$n \geq 5.15$

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

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

$$\omega_\phi = \frac{P_\phi}{\rho_\phi} = \frac{\langle \phi v'(\phi)\rangle - \langle 2V\rangle}{\langle \phi v'(\phi)\rangle + \langle 2V\rangle} = \frac{(n-1)}{(n+1)}$$



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

$n \geq 4.75$

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

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

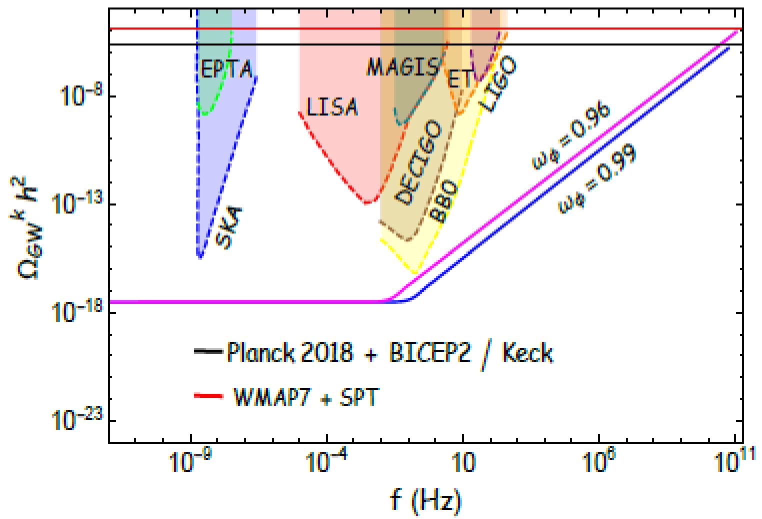
Conclusions and future directions

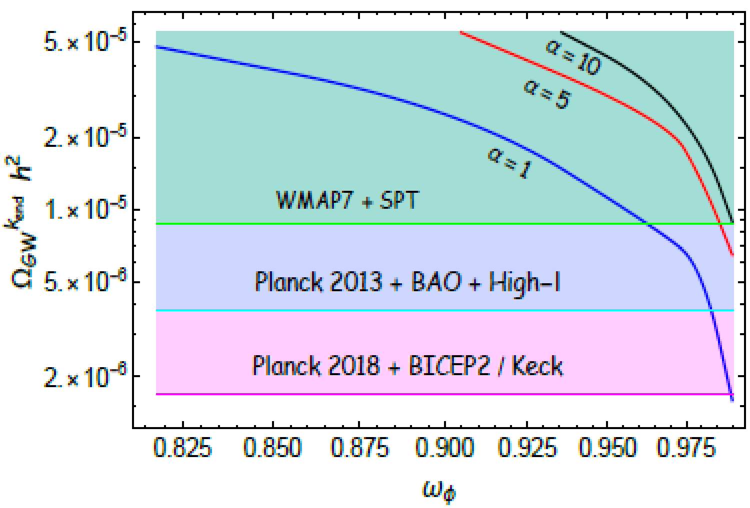
- Reheating is a poorly understood phase
- It can give a new physics which heppens at very high energy scale beyond the scope of laboratory experiments
- Cosmology behaves as laboratoy system where experiments has already been performed, observables need to be explained.
- **We propose Gravitational reheating scenario with definite predictions**
- **Selects limited class of inflaton models which must provide efolding number within 62-63, narrow range of ns value.**

  Predicts: Very narrow range of DM mass, low reheating temperature, unique GW spectrum, Stiff reheating equation of state.
- **Non-detection of any one of those will rule out such scenario.**
- Systematic inclusion of interaction is imoprtant direction to study

Thank you

BBN constraint





Adding DM-Radiation coupling