Gravitational Neutrino Reheating

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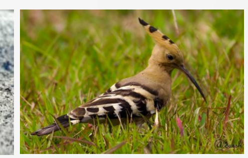
AstroParticle Symposium 2023

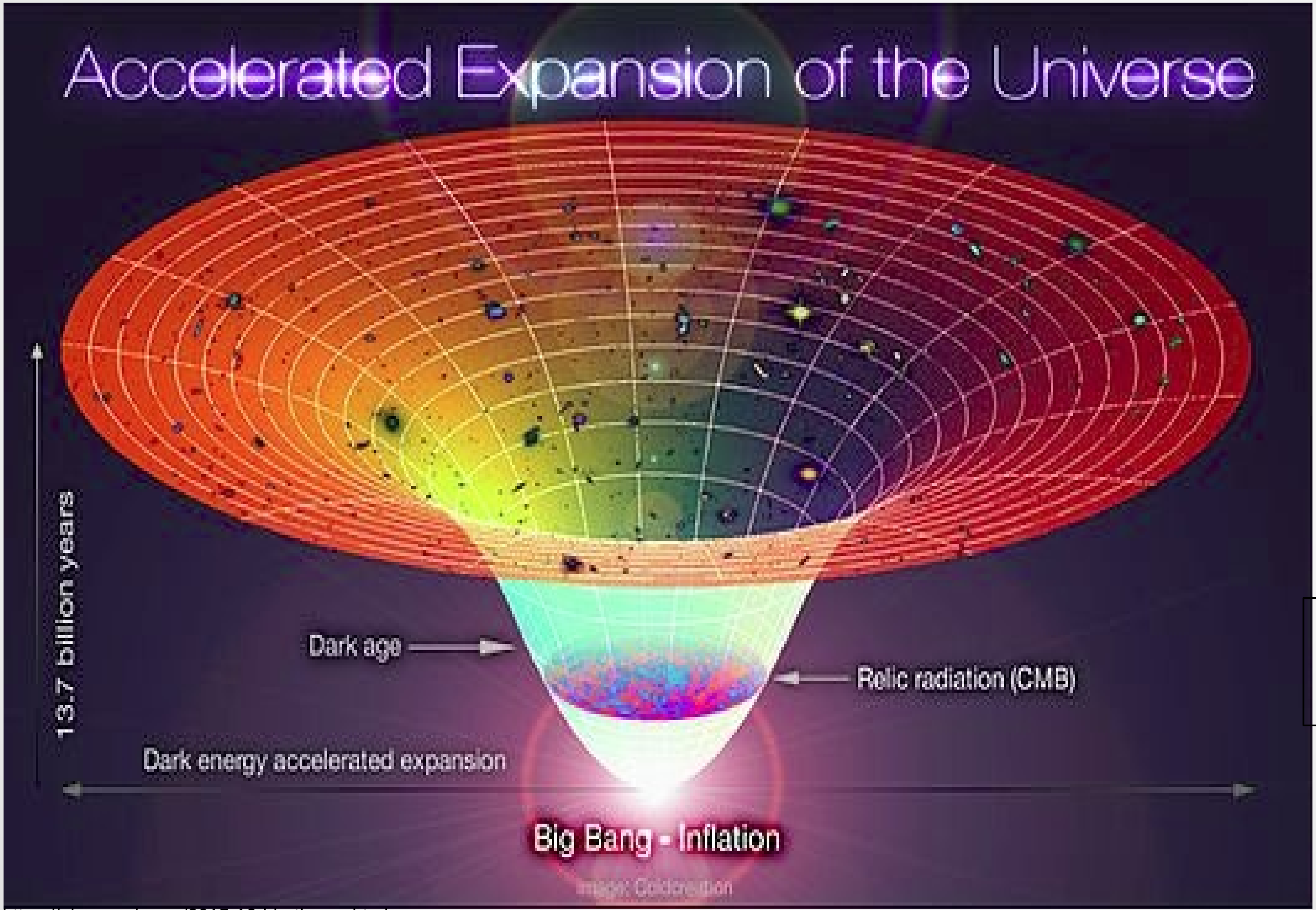
In Collaboration with: Rajesh, Riajul,

How does the present state of our universe arise?



Time evolving cosmos

Based on large number of observations



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

Cosmological constant

Matter

Radiation

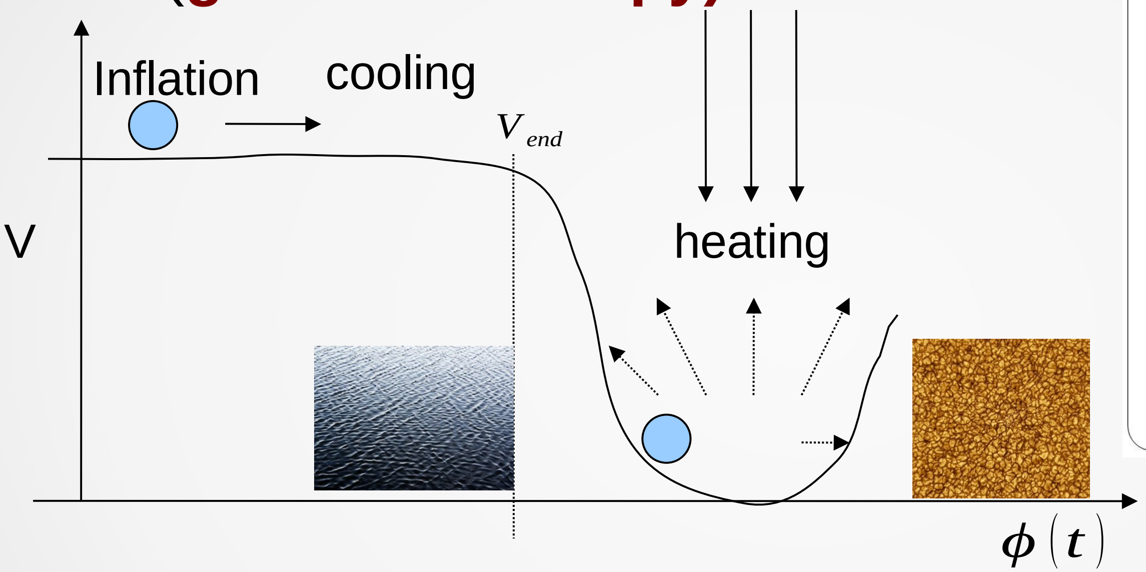
Reheating

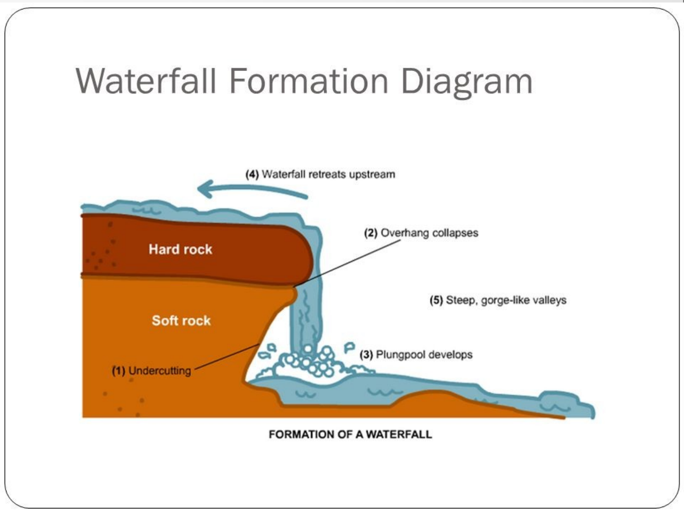
Inflation

What 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**).



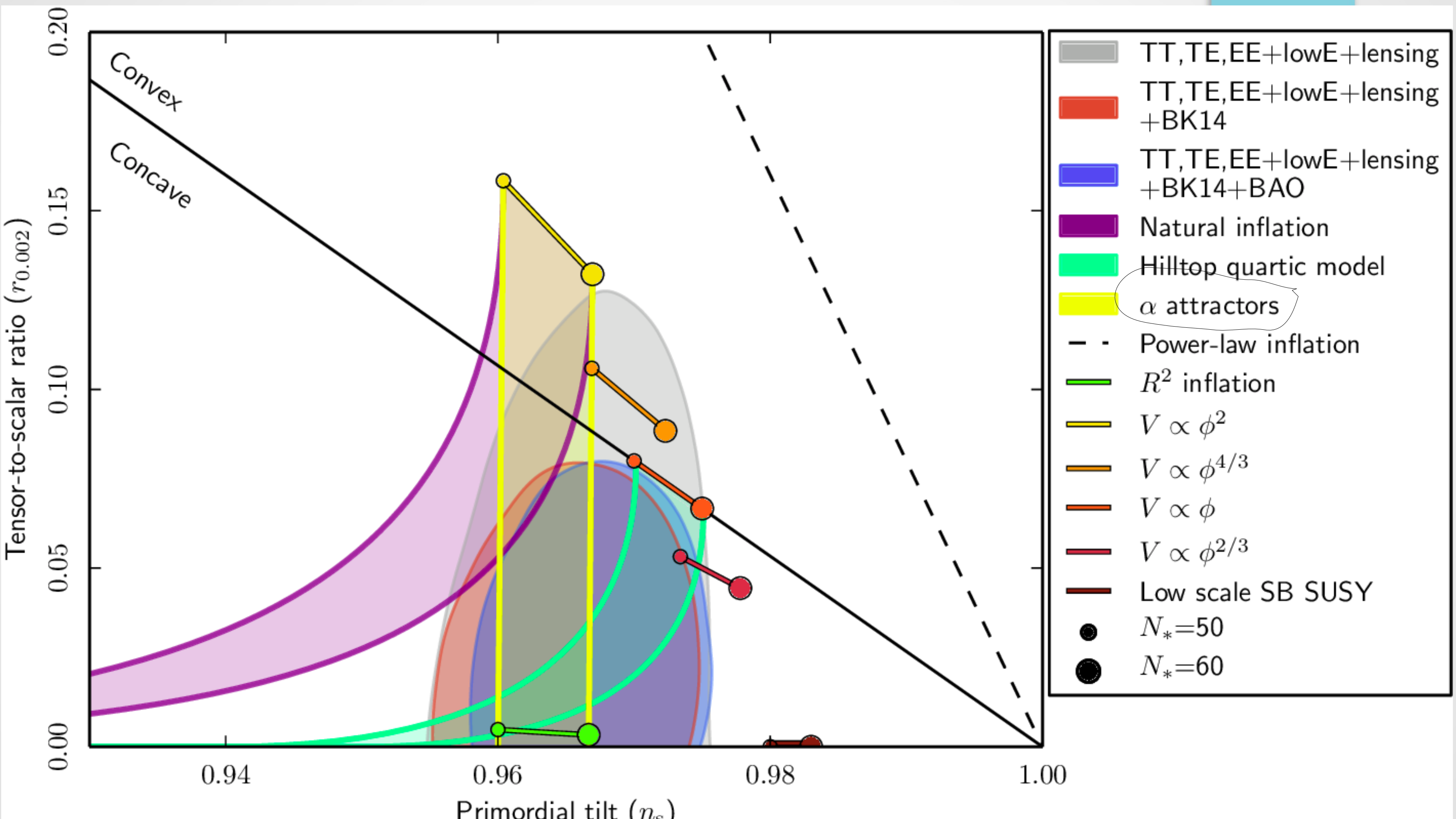


Conventional Reheating mechansim: Non-perturbative,
Perturbative decay of inflaton,

From the observational perspective:
Difficulties: Direct observation, equilibriation processes assumed to erase information, large possibilities of inflaton decay channels (unknown physics), difficult to identify observables

Where do we stand in terms of inflation?

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



Planck-2018

Facts, 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?

May help us understand inflation models, DM puzzle, Baryogenesis …

- Reheating phenomenology: Identifying parameter spce of reheating
- Universal reheating, pedictions and constraints
- Rehating though unstable particles/objects: Neutrino, PBH
- Conclusions

Talk by Riajul

Reheating phenomenology: Different possibilities

Inflaton

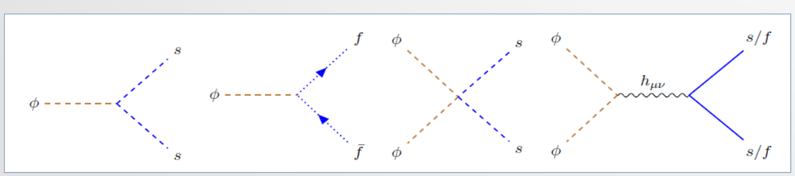
Model dependent | Universal (gravitational)

Fundamental particles + PBH + Oscillons

- Stable massive particles(DM)
- Massless particles (radiation)
- Unstable massive particles or object (Right handed neutrino, PBH)
- Gravitational wave

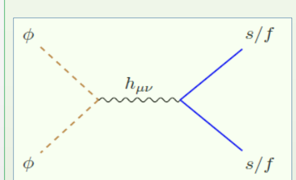
Non-Gravitational Reheating

$$g_1 \phi s^3, g_2 \phi^2 s^2, h \phi \bar{f} f \dots$$



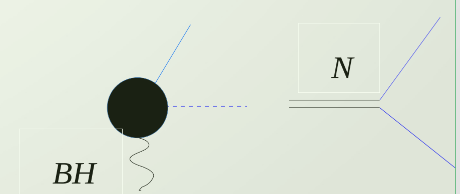
Gravitational Reheating

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



PBH Reheating, Neutrino reheating

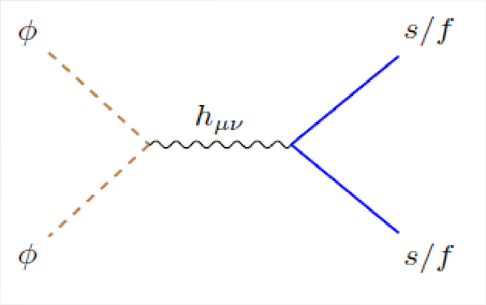
$$\beta, M$$



Gravitional Rheating (GRe) in brief

Gravitational decay

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



No unstable object
or particles

- Gravitational decay channel was always ignored because of obvious reason. Actually, such a possibility was never looked at!!

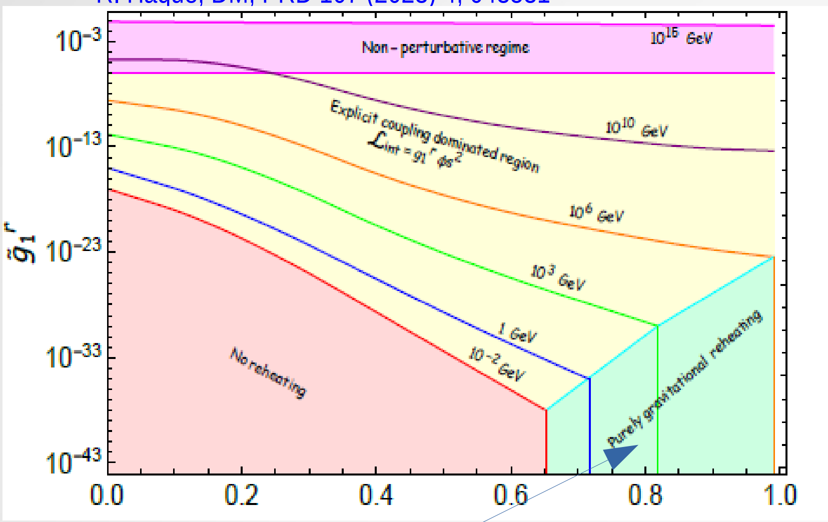
Important to remember that at the time of reheating typtical energy scale of the problem is

$$\sim 10^{13} - 10^{15}\, GeV$$

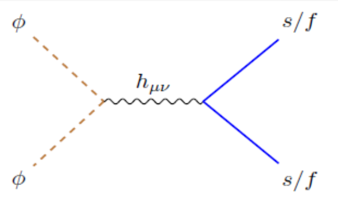
Y. Mambrini and K. A. Olive, PRD 103, 115009 (2021); Riajul Haque, DM, 2201.02348;
S. Clery, et al, Phys.Rev.D 105 (2022) 7, 075005

Greeze zone: GRe

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



Dominating chennel



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

$$\Gamma_{\phi\phi\to SS} = \frac{\rho_\phi m_\phi}{1024\pi M_p^4}\left(1 + \frac{m_S^2}{2m_\phi^2}\right)\sqrt{1 - \frac{m_S^2}{m_\phi^2}},$$

$$\Gamma_{\phi\phi\to ff} = \frac{\rho_\phi m_f^2}{4096\pi M_p^4 m_\phi}\left(1 - \frac{m_f^2}{m_\phi^2}\right)^{\frac{3}{2}}, \qquad (0.1)$$

$$\Gamma_{\phi\phi\to XX} = \frac{\rho_\phi m_\phi}{32768\pi M_p^4}\left(4 + 4\frac{m_X^2}{m_\phi^2} + 19\frac{m_X^4}{m_\phi^4}\right)\sqrt{1 - \frac{m_X^2}{m_\phi^2}}.$$

$$S^{(2)}_{\beta\alpha} = \frac{(-i)^2}{2!}\frac{1}{M_{\rm Pl}^2}\int d^4x\int d^4y \left\langle\beta_0\middle|T\left[h^{\mu\nu}(x)h^{\alpha\beta}(y)\left(T^{\phi}_{\mu\nu}(x)T^{F}_{\alpha\beta}(y) + T^{F}_{\mu\nu}(x)T^{\phi}_{\alpha\beta}(y)\right)\right]\middle|\alpha_0\right\rangle$$

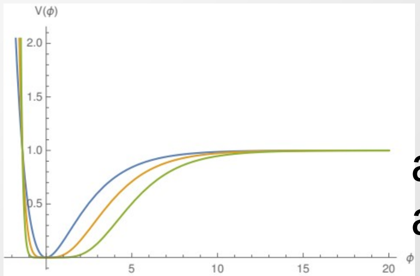
Universal reheating scenario

$$\sim g_1\phi s^3, g_2\phi^2 s^2, h\phi\bar{f}f\ldots$$

Negligible

$\alpha, \omega_\phi, g, h$

Y. Mambrini and K. A. Olive, PRD 103, 115009 (2021); Riajul Haque, DM, 2201.02348;



alpha-attractor

Important Point

No extra reheating parameter!

$$\dot{\rho}_\phi + 3H(1+\omega_\phi)\rho_\phi + \Gamma^T_\phi\rho_\phi(1+\omega_\phi) = 0,$$

$$\dot{\rho}_R + 4H\rho_R - \Gamma^{Rad}_{\phi\phi\to RR}\rho_\phi(1+\omega_\phi) = 0,$$

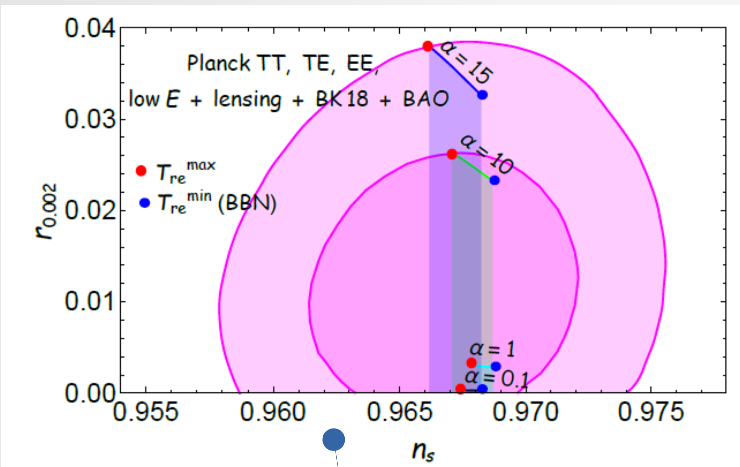
$$\dot{n}_Y + 3Hn_Y - \frac{\Gamma^{DM}_{\phi\phi\to YY}}{m_\phi}\rho_\phi(1+\omega_\phi) = 0$$

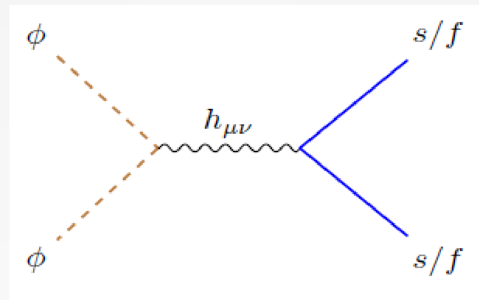
$$\omega_\phi = \frac{(n-1)}{(n+1)} \quad ; \quad V(\phi)\sim\phi^{2n}$$

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

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

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





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!

Large scale scalar & tensor fluctuation

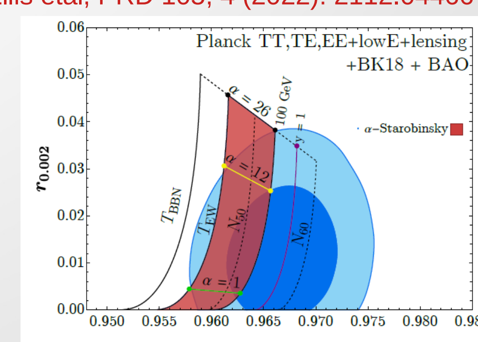
$$T_{re} = \left(\frac{43}{11\, g_*^{re}}\right)^{1/3} \left(\frac{a_0\, H_{end}}{k}\right) e^{-(N_k + N_{re})}\, T_0\,,$$

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

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

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

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



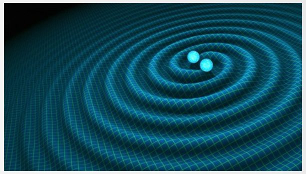
Important Result

Reheating tempreature completely fixed by the inflationary parameter

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

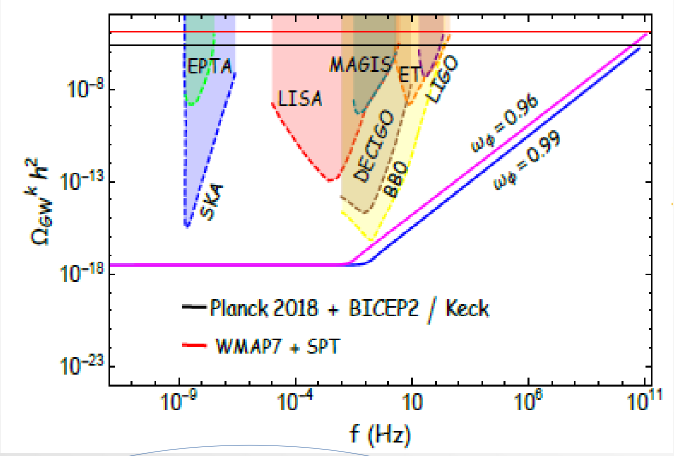
Probing GRe: Small scale tensor fluctuations(PGW)

1. Gratational wave is one of the best known probes
2. Large scale Tensor fluctuation provides the upper limit on "r"
3. Strongest constraints come from small scale tensor fluctuations

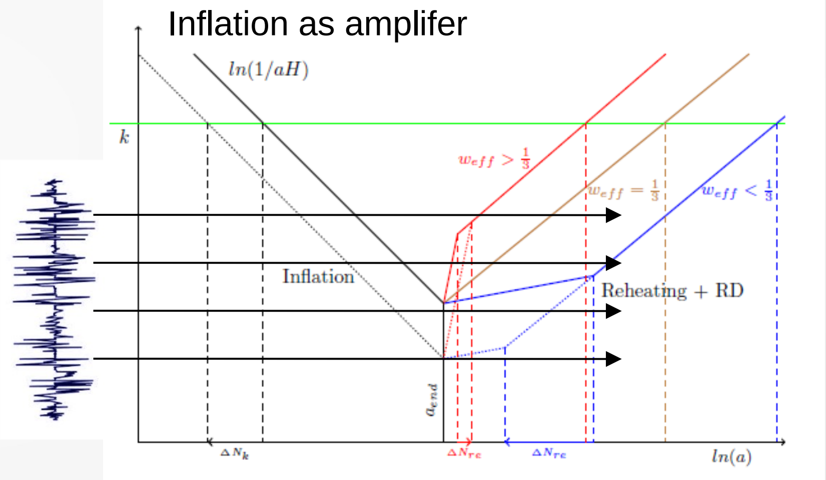


$$\Omega_{Gw} h^2 \propto \left(\frac{k}{k_{re}}\right)^{n_w}$$

GW spectrum



Quantum GW noise



Final Conclusion

Rule out almost all except

$\alpha = 1, \omega_\phi \rightarrow 1$ **Kinetion**

The existence of primordial gravitational waves (GWs) is one of the profound predictions of inflation. Originated from Quantum vacuum

Type-I extension:

νGRe

Inflaton sector

Strong coupling

Guiding principle:

Model depdendence

SM sector

Baryongenesis, ν- mass
Dark matter

Observations and unresolved issues

Assumption: a) Inflaton couples only gravitationaly

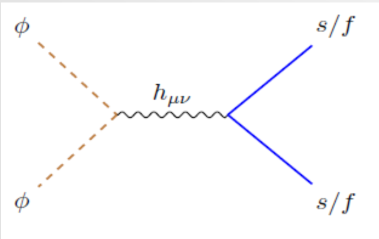
b) Three right handed neutrinos + SM (Type-I sea saw)

Produce Baryogenesis, active neutrino mass

All are unstable: Injecting additional entropy

$$\mathcal{L} = \mathcal{L}_\phi + \mathcal{L}_{\mathrm{SM}} - \frac{1}{2} M_{\mathrm{ij}} \bar{\nu}_{\mathrm{R}}^{\mathrm{ci}} \nu_{\mathrm{R}}^{\mathrm{j}} - y_{ij} \bar{\nu}_{\mathrm{R}}^{\mathrm{i}} \tilde{H}^\dagger L_{\mathrm{j}} + h.c.$$

$$\alpha, \omega_\phi, m_N, \beta \propto \sqrt{(y^\dagger y)_{33}}$$



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

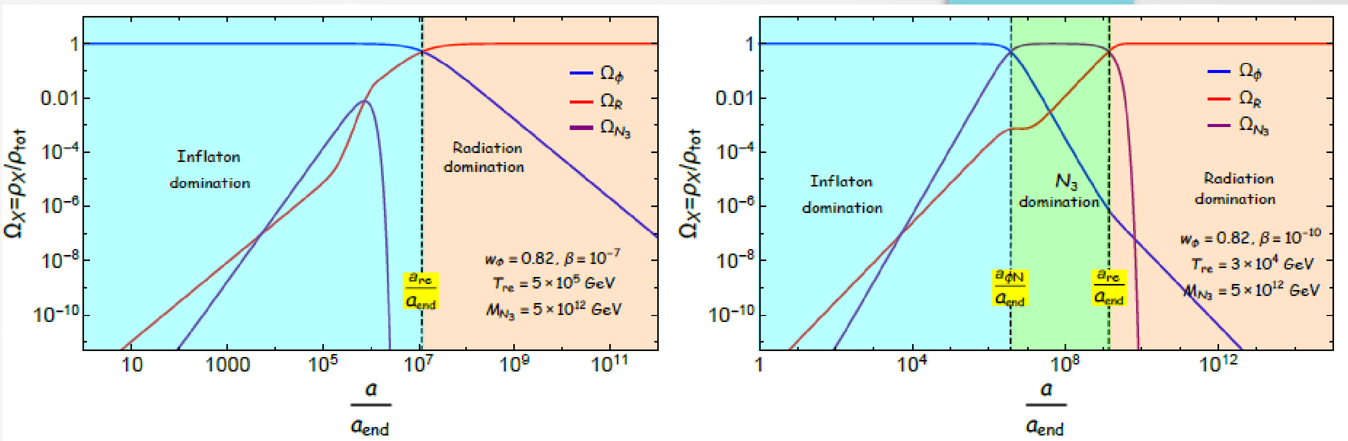
Can enhence the reheating temperature for a given EoS, and reduces

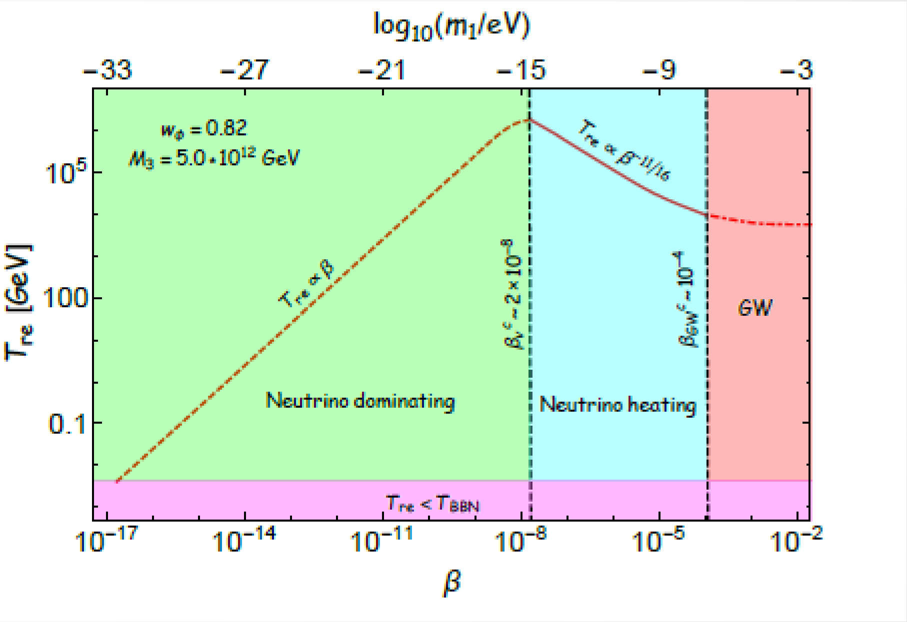
$$\Omega_{Gw} h^2 \propto \left(\frac{k}{k_{re}}\right)^{n_w} \downarrow$$

νGRe : Evolution of different energy components

Neutrinos: behave as matter, decays to radiation

$$\rho_\phi \propto a^{-3(1+w_\phi)}$$
$$\rho_\nu \propto a^{-3}$$
$$\rho_R \propto a^{-3(1-w)/2}$$





$$\dot\rho_\phi + 3H(1+w_\phi)\rho_\phi + \Gamma_\phi^T(1+w_\phi)\rho_\phi = 0,$$
$$\dot\rho_r + 4H\rho_r - \Gamma^{gr}_{\phi\phi\to hh}(1+w_\phi)\rho_\phi - \Gamma_3 E_3 n_3 = 0,$$
$$\dot n_1 + 3Hn_1 - R^1_\phi + \Gamma_1 n_1 = 0,$$
$$\dot n_3 + 3Hn_3 - R^3_\phi + \Gamma_3 n_3 = 0,$$
$$\dot n_{B-L} + 3Hn_{B-L} - \epsilon\Gamma_1 n_1 + \Gamma_{ID} n_{B-L} = 0,$$

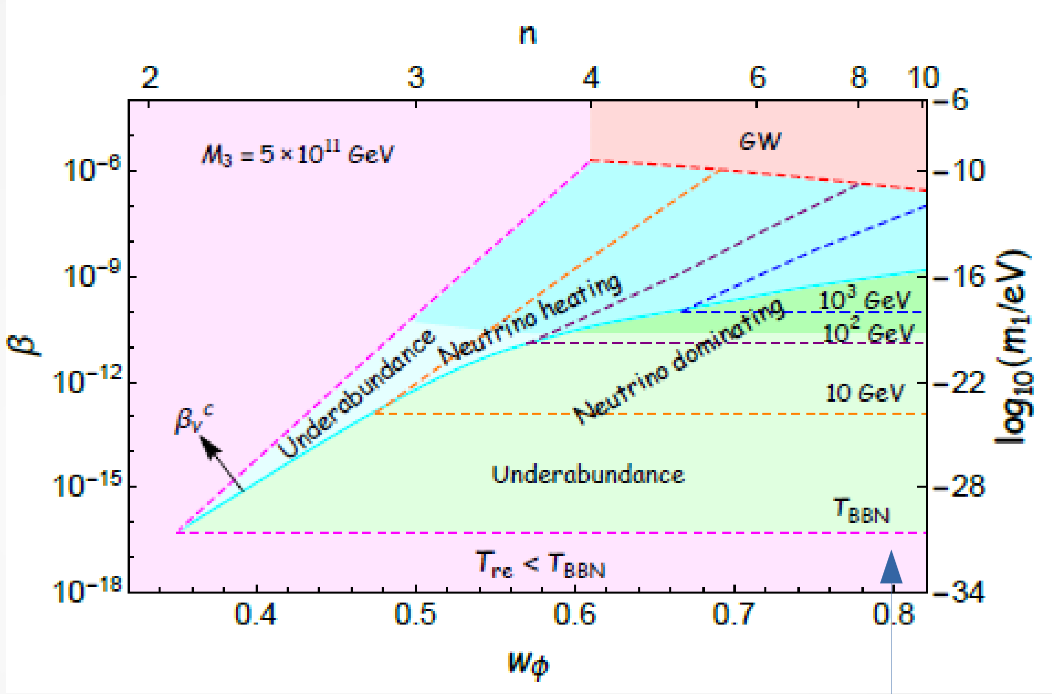
Lightest active neutrino mass $m_1 \sim \dfrac{\beta^2 v^2}{M_3}$

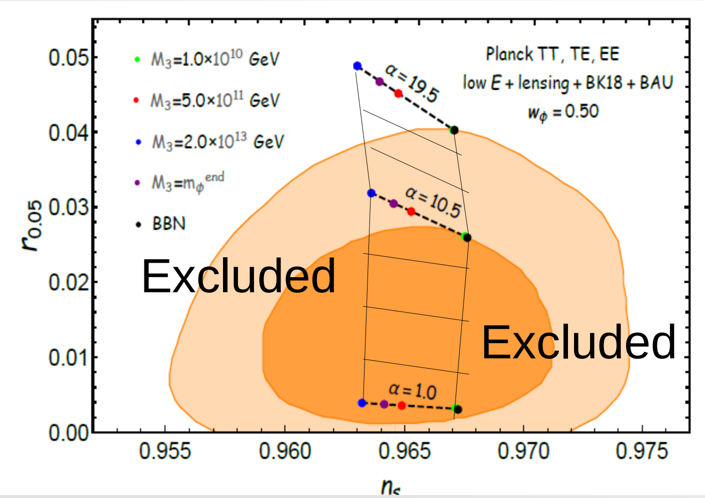
νGRe: Parameter space

Where are we in $n_s - r$ plane?

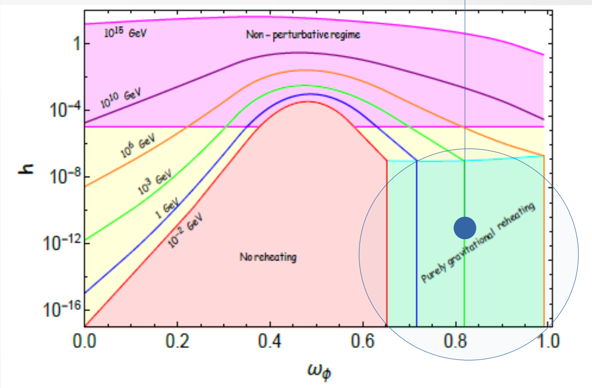
$$Y_B = \frac{n_B}{s} = \frac{28}{79}\epsilon_{\Delta L}\frac{n_1(T_{re})}{s(T_{re})}$$

$$\sim 8.7\times10^{-11}$$



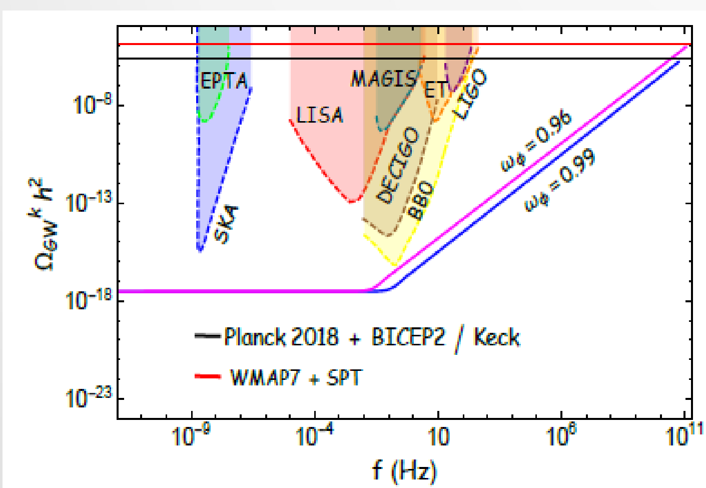


$M_\nu^1 \sim 10^{13}\, GeV$
$M_\nu^3 \sim 10^{10} - 10^{13}\, GeV$
$w_\phi \sim 0.5 - 1$
$m_\nu^{low} < 10^{-6}\, eV$

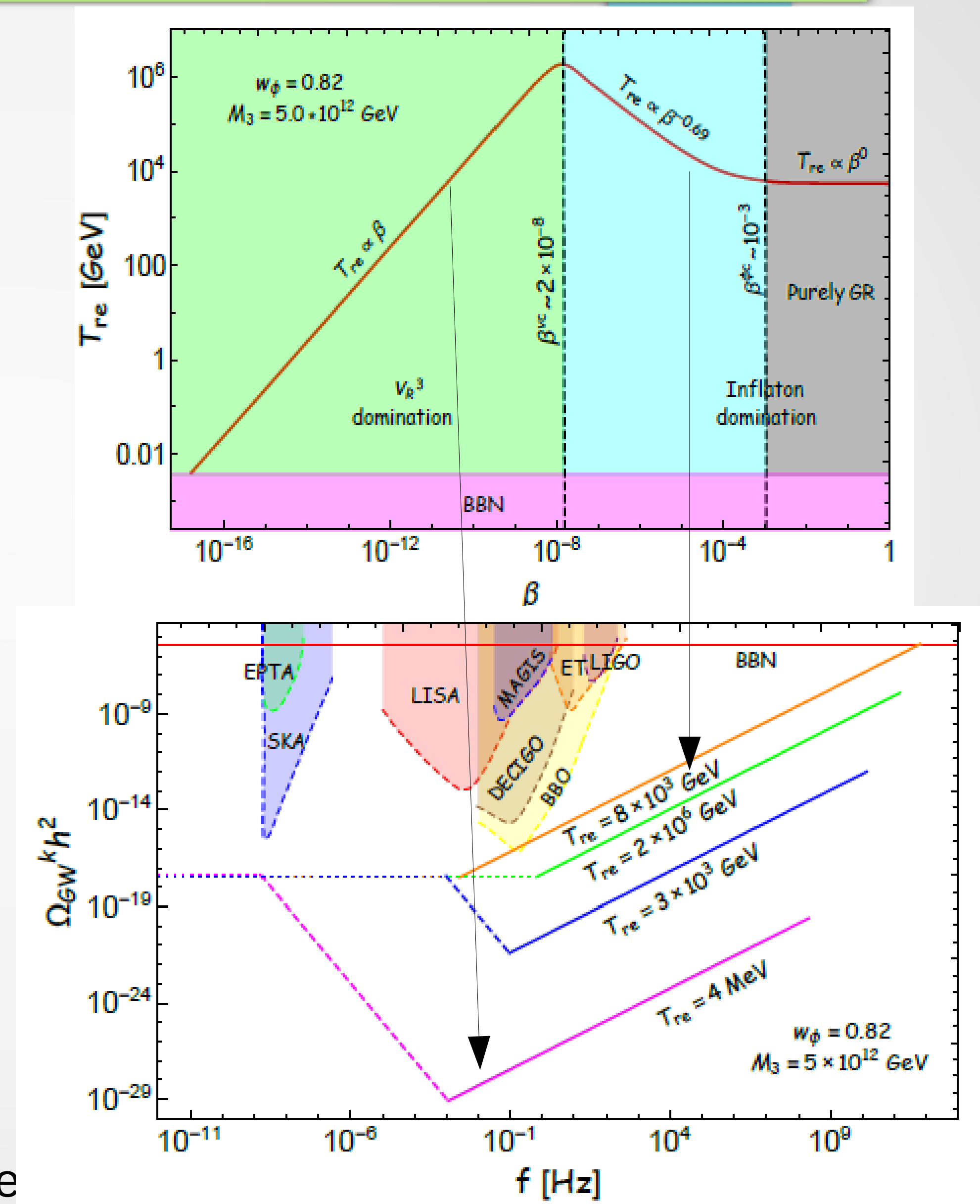


νGRe : Gravitational wave (Primary)

$$\rho_\phi \propto a^{-3(1+w_\phi)}$$
$$\rho_\nu \propto a^{-3}$$
$$\rho_R \propto a^{-4}$$



GRe



νGRe

Conclusions and future directions

Reheating:

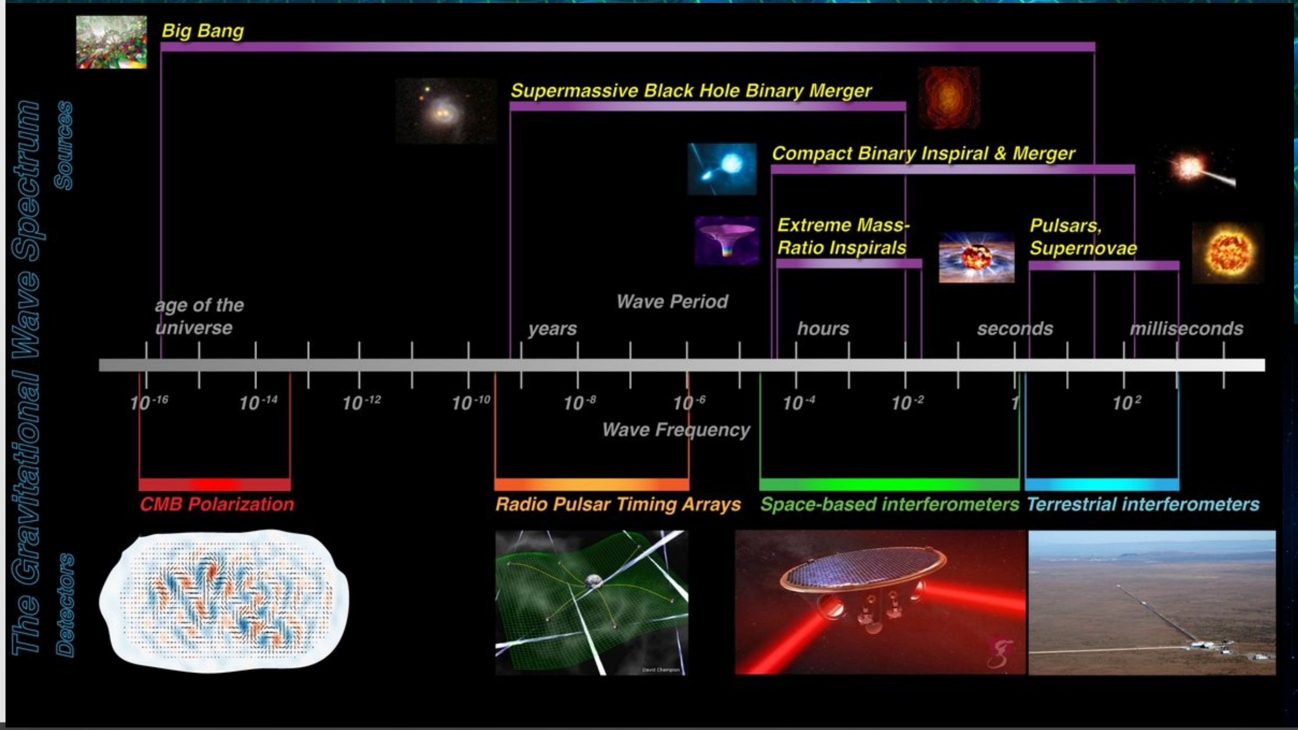
- It is BSM physics which heppens at very high energy scale beyond the scope of laboratory experiments
- Cosmology behaves as laboratoy system where experiments has already been performed, observables need to be defined, explained.
- **We identified Gravitational reheating scenario with definite predictions**

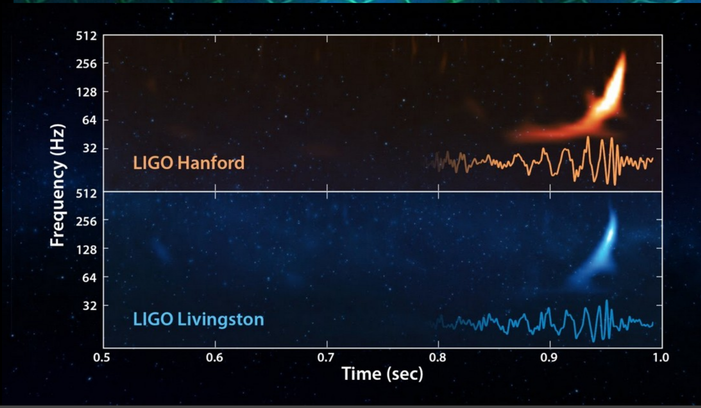
i) Selects limited class of inflaton models with efolding number within 62-63, and narrow range of ns value, unique GW spectrum leading Kination

ii) Generalization to Neutrino reheating is an extremely interesting possibility. Particle responsible for baryogenesis and active neutrino mass also taking part in reheating.

- Secondary GW, thermalization, evolution of small scale perturbations, Ripples in the spacetime can travel maximum path without getting disturbed

Thank you





Probing GRe: Small scale tensor fluctuation(PGW)

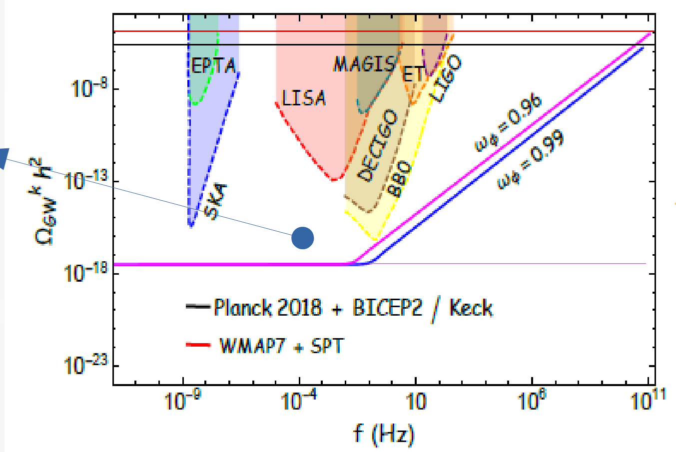
R. Haque, DM, S. T. Paul, L. Sriramkumar, Phys.Rev.D 104 (2021) 6, 063513, Riajul Haque, DM, 2201.02348

Reheating phase leads to significant effect on the gravitational waves (GWs)

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

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

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



Index of the GW spctrum:

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

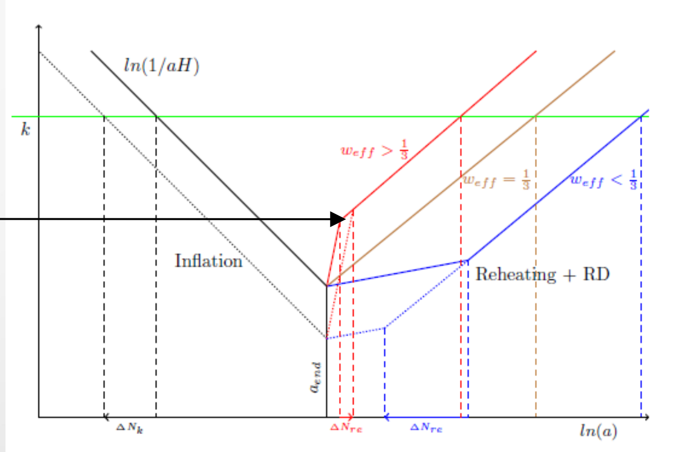
If GRe is ture: prediction of the Tensor sector,

Smaller the reheating temperature

Smaller k_{re}

Larger the value of $\Omega^k_{GW} h^2$

k_{re}

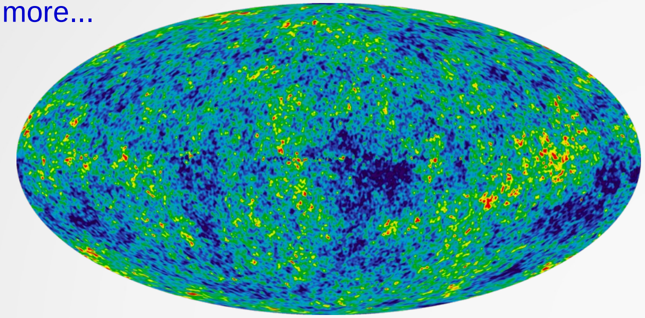


Given the inflationary phase:
What do we observe today?

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

Extremely homogeneous Universe

Many more...

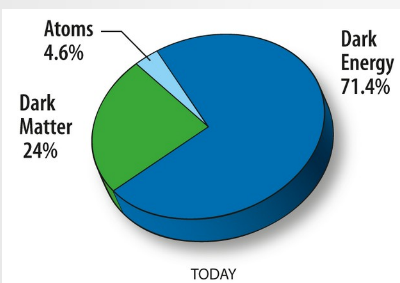


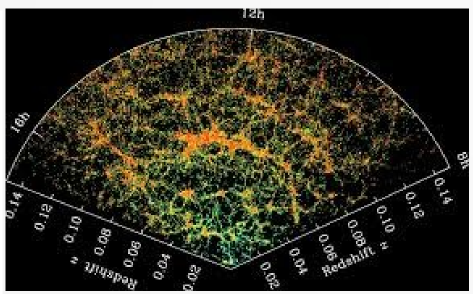
Background + Fluctuations of all fundamental fields

CMB

Scalar type

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





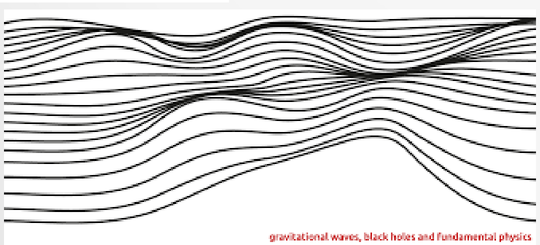
DM

FermionType

Baryonic Matter, Dark matter ?

Vector type

Large/small scale magnetic field, EM radiation...



PGW

Tensor type

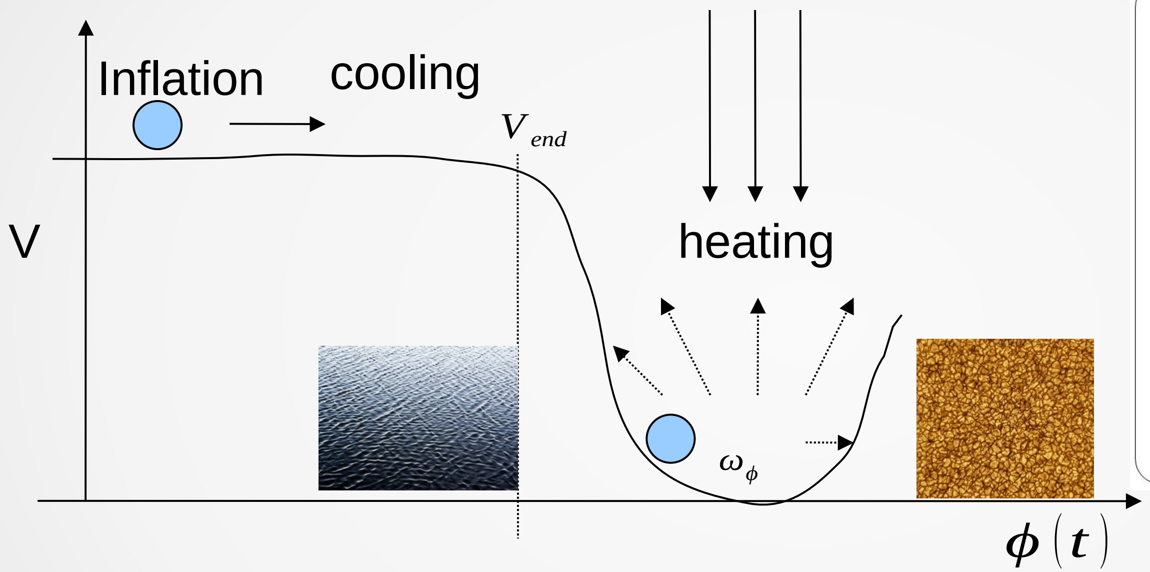
Primodial Graviational wave(PGW), Higher spin, Kalb Ramond...

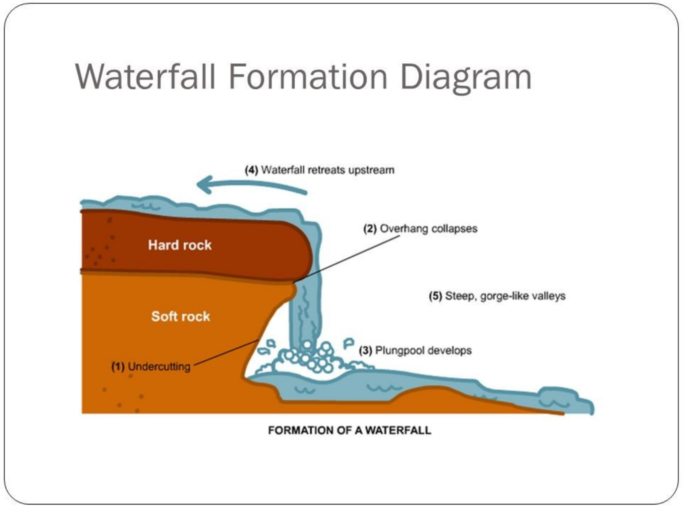
Reheating gives us right proportion of all these and this information must be imprinted into Background+fluctuation that we see today in some way

Reheating phenomenology: Conventional starting point

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

- The process of Inflaton energy tranferring into any other fields.





Quantum inflaton coupled with all the fundamental fields, tunning the couplings and get successful reheating.

Standard approach: Introduce effective theory operators

$$g_1\phi s^3, g_2\phi^2 s^2, h\phi\bar{f}f\ldots$$

Non-perturbative (resonance) + **Perturbative decay**

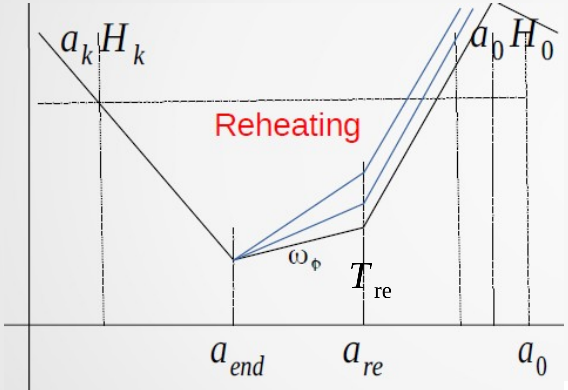
Set up: Reheating (perturbative)

Dynamical eqs + Boundary conds + 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: $\rho_\phi^{in} = 3 M_p^2 H_{end}^2, \quad \rho_R = \rho_{DM} = 0$

Constraints:



$$\dot\rho_\phi + 3H(1+w_\phi)\rho_\phi + (\Gamma_{s/f} + \Gamma^{gr}_{\phi\phi\to RR})(1+w_\phi)\rho_\phi = 0,$$
$$\dot\rho^r_{s/f} + 4H\rho^r_{s/f} - \Gamma_{s/f}(1+w_\phi)\rho_\phi = 0$$
$$\dot\rho^r_{gr} + 4H\rho^r_{gr} - \Gamma^{gr}_{\phi\phi\to RR}(1+w_\phi)\rho_\phi = 0.$$

$$\Gamma_{s/f} = \begin{cases} \Gamma_{\phi\to ss} &= \frac{(g_1^r)^2}{8\pi m_\phi(t)}(1+2f_B(m_\phi/2T)), \quad \text{for } g_1^r\phi s^2 \\ \Gamma_{\phi\phi\to ss} &= \frac{(g_2^r)^2\rho_\phi(t)}{8\pi m_\phi^3(t)}(1+2f_B(m_\phi/T)), \quad \text{for } g_2^r\phi^2 s^2 \\ \Gamma_{\phi\to\bar f f} &= \frac{(h^r)^2}{8\pi} m_\phi(t)(1-2f_F(m_\phi/2T)), \quad \text{for } h^r\phi\bar f f \end{cases}$$
$$\Gamma^{gr}_{\phi\phi\to ss} = \frac{\rho_\phi m_\phi}{1024\pi M_p^4}(1+2f_B(m_\phi/T)),$$
$$\Gamma^{gr}_{\phi\phi\to ff} = \frac{\rho_\phi m_f^2}{4096\pi M_p^4 m_\phi}(1-2f_F(m_\phi/T)),$$

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 $\Omega_Y h^2 = 0.12$

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 $H_{end}, \omega_\phi, M_{DM}, g, h$

Boltzmann dynamics + Boundary conds + 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: $\rho_\phi^{in} = 3\, M_p^2\, H_{end}^2, \quad \rho_R = \rho_{DM} = 0$

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

Constraint conditions: 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 $\Omega_Y h^2 = 0.12$

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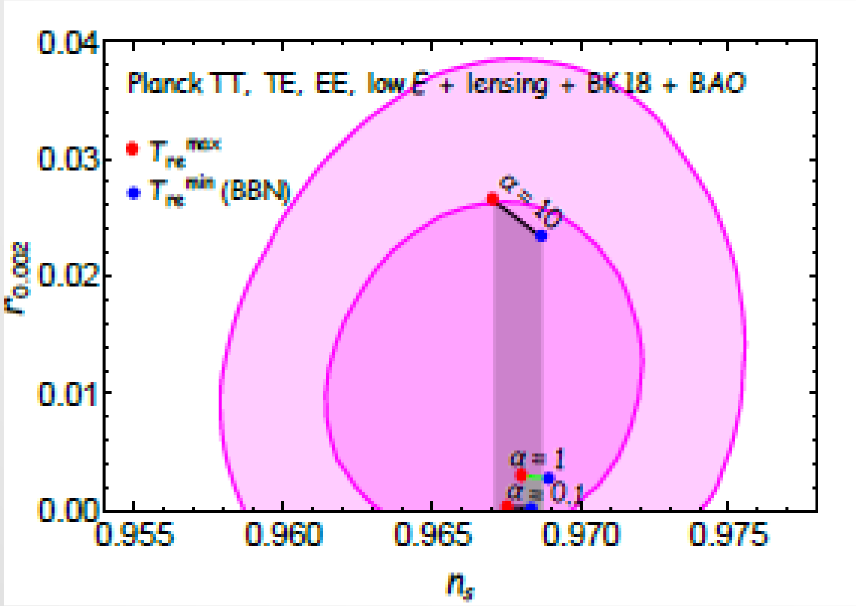
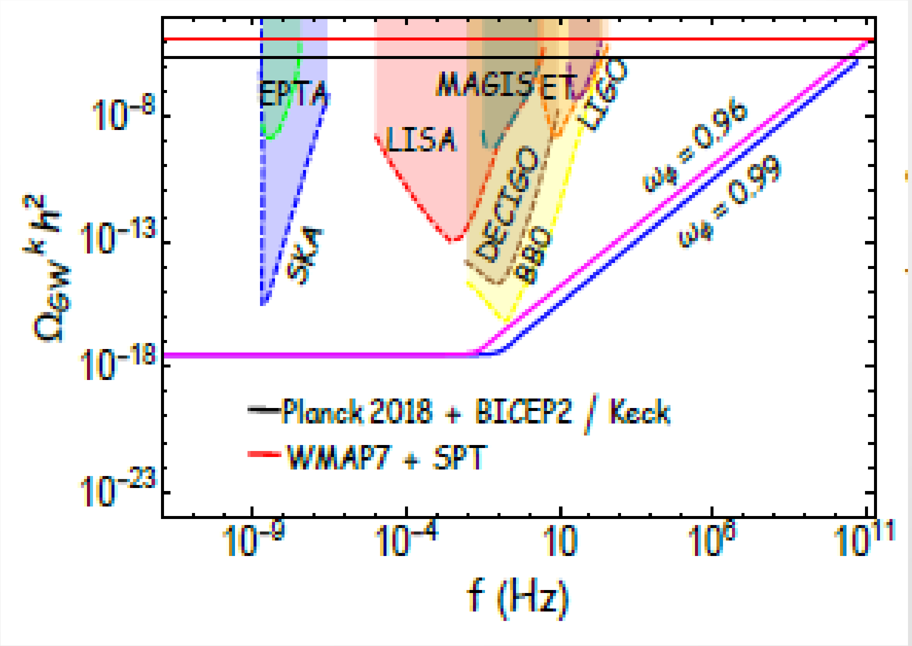
Present state of the universe is completely fixed by $H_{end}, \omega_\phi, M_{DM}$

GRe:Conclusions

- **Selects limited class of inflaton models which must provide efolding number within 62-63, Very narrow range of n_s value.**
- **Predicts: Low reheating temperature, Stiff reheating equation of state (w~1), unique GW spectrum.**

Riajul Haque, DM, 2201.02348,
R. Haque, DM, Rajesh Mondal, 2301.01641





Can we ralax such tight constraint on w, being in the framework of GRe?

Brief account on Type-I seasaw

Minkowski; Yanagida; Gell-Mann, Ramond, Slansky; Glashow; Senjanovic, Mohapatra.

1. Standard Model: Neutrinos are massless
2. Obvservation of Neutrino oscillation: massive Neutrinos
3. Simple Dirac Mass requires

$$\mathcal{L} = \mathcal{L}_\phi + \mathcal{L}_{\rm SM} - \frac{1}{2} M_{\rm ij} \bar{\nu}_{\rm R}^{\rm ci} \nu_{\rm R}^{\rm j} - y_{ij} \bar{\nu}_{\rm R}^{\rm i} \tilde{H}^\dagger L_{\rm j} + h.c.$$

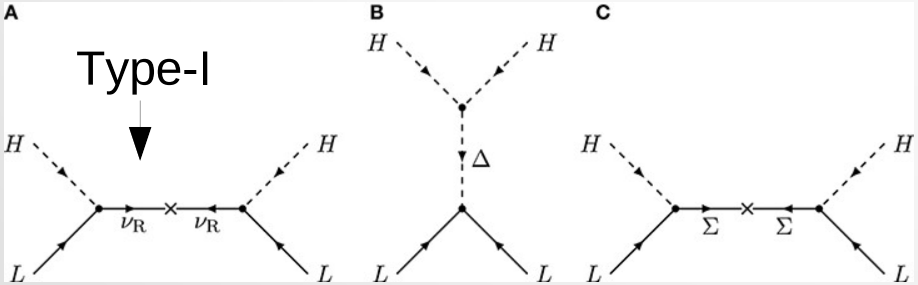
Assumed to be unnatural compared to other Yukowa couplings

$=0$ $\qquad y \sim 10^{-12}$

4. Suppression may be due to new physics(Majorana mass)

Weinberg Operator: $\frac{d^{ij}}{M} (H . \bar{L}_i^c)(L_j . H) + h.c$

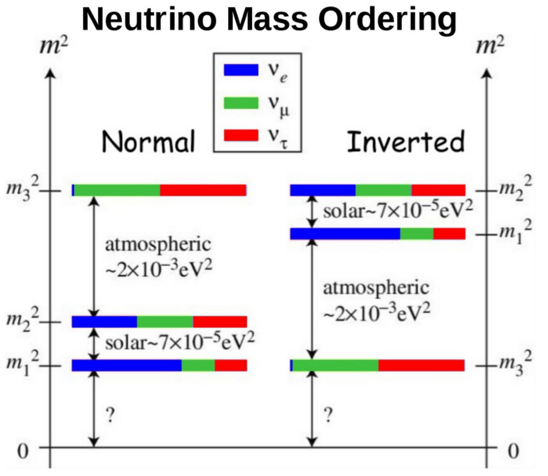
Opening up the above operator :



Example

$m_\nu \sim 0.1\, eV, \langle H \rangle \sim 10^2 GeV$

$M \sim 10^{14} Gev$

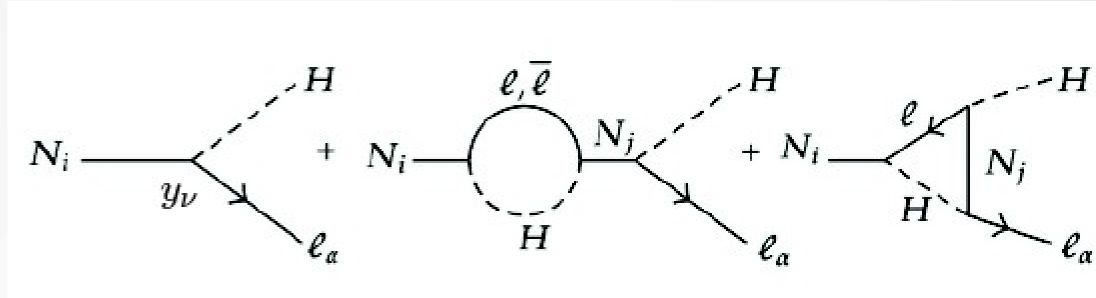


Mediator is heavy right handed SM singlet Neutrinos

Leptogenesis/Baryogenesis

L, C, CP violation:

$$\Gamma(N \to \ell H) \neq \Gamma(N \to \bar{\ell} H^*)$$

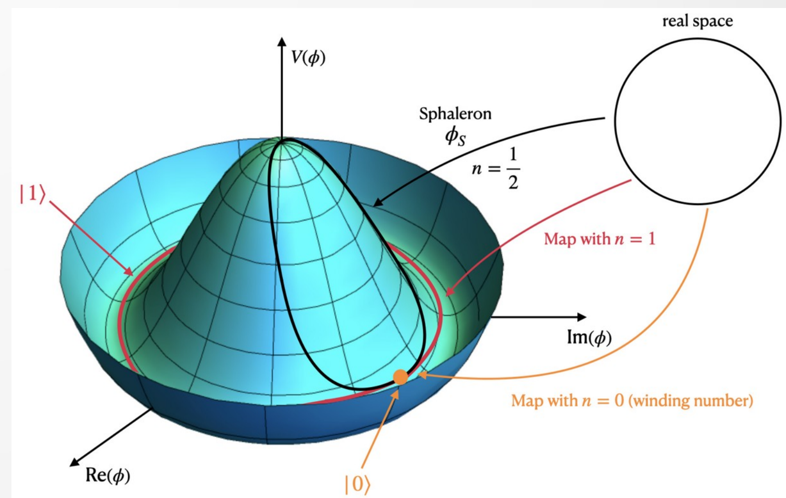


Our of equilibrium decay of neutrinos leading to non-zero (**Sakharov Condtions**)

$$\epsilon = \frac{\sum_j [\Gamma(N_1 \to l_j H) - \Gamma(N_1 \to \bar{l}_j H^\star)]}{\sum_j [\Gamma(N_1 \to l_j H) + \Gamma(N_1 \to \bar{l}_j H^\star)]}$$

Non-perturbative process: called Spheleron

$$Y_{B-L} \sim \epsilon \eta Y^{eq} \sim 8.7 \times 10^{-11}$$



Taken from, Galaxies 2022, 10(6), 116
https://doi.org/10.3390/galaxies10060116

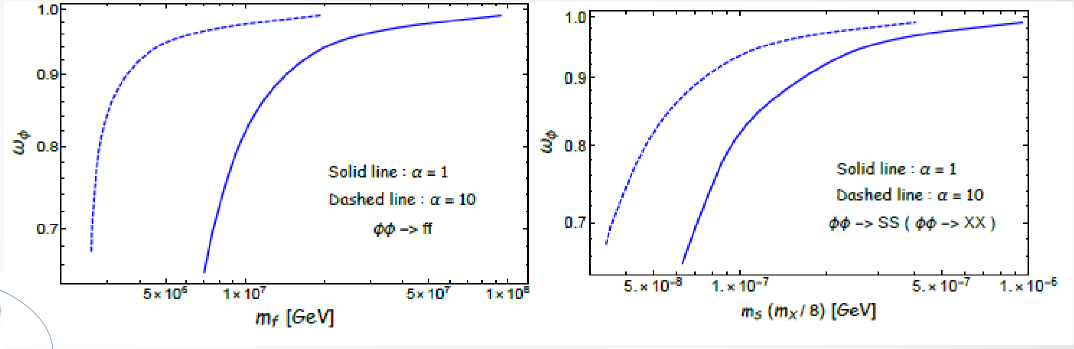
GRe: Gravitational DM (scalar/fermion)

Gravitational DM: Produced through gravitatioal interaction only

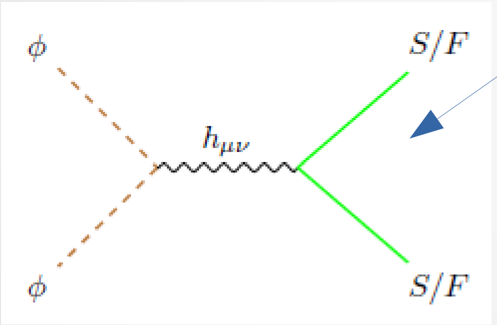
M_{DM}

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

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



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



$\alpha = 1$

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

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

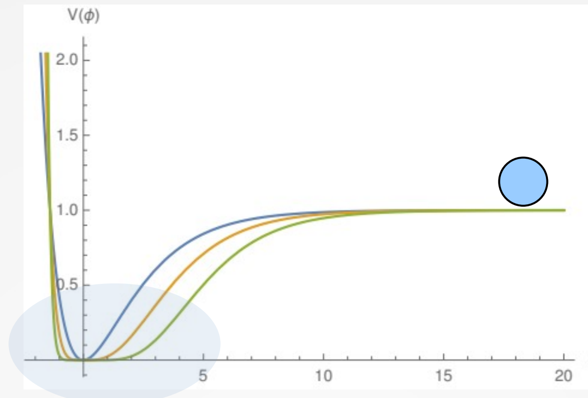
$$\Gamma^{gr}_{\phi\phi\to ff} = \frac{\rho_\phi m_f^2}{4096\pi\pi M_p^4 m_\phi}(1-2f_F(m_\phi/T))$$

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

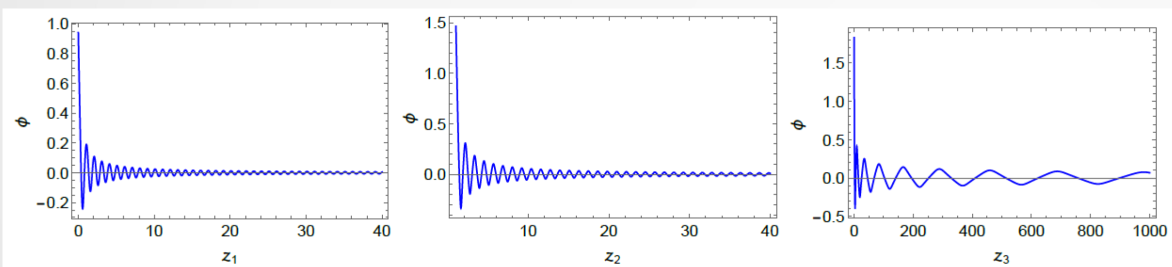
Set up: Inflation (Alpha-attactor model)

Linde etal ; JHEP 11 (2013) 198

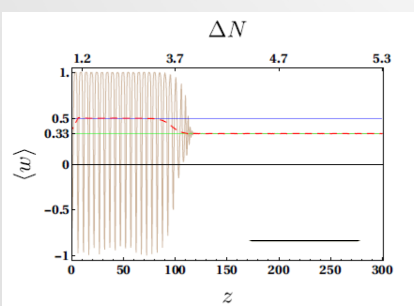
$$V(\phi) = \Lambda^4 \left[1 - e^{-\sqrt{\frac{2}{3\,\alpha}}\phi/M_p}\right]^{2n}$$



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

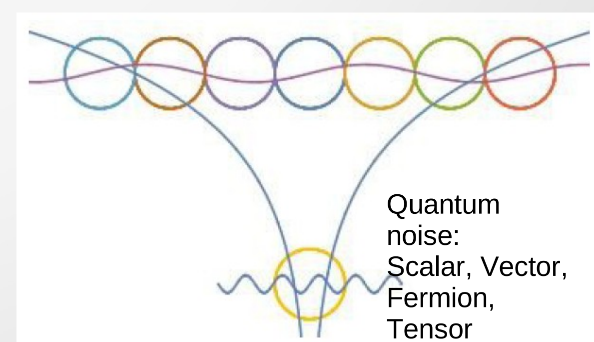


Reheating can distinguish Λ, α, n



Distinguishing parameter

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



Quantum noise: Scalar, Vector, Fermion, Tensor (GW),...