

## **Decoding the early universe through primordial black hole abundance, dark matter, and gravitational waves**

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In collaboration with Suvashis Maity, Dr. Essodjolo Kpatcha, Dr. Nilanjandev Bhaumik, Prof. Yann Mambrini, Prof. L. Sriramkumar, Prof. Debaprasad Maity, Prof. Rajiv Kumar Jain and Prof. Marek Lewicki.

> Md Riajul Haque, Postdoctoral Fellow, Physics and applied Mathematics Unit, Indian Statistical Institute, Kolkata, India

## **Outline of the talk**

### **Motivation:**

Observational difficulty in the early Universe and introduction to the reheating phase

## **Goal:**

- $\bullet$  Constraining the reheating phase through scalar-induced secondary gravitational waves with NANOGrav 15-year data.
- **◆ Possibilities of PBH reheating**
- Doubly peak-induced GWs associated with ultralight PBHs.

#### **Conclusions**

# **Why do we need reheating phase?**

### $\Box$  The end point of inflation

- **❖** The universe is cold, dark, and dominated by the homogeneous inflaton field.
- How does the Universe transition to a the hot, thermalized, radiationdominated state after inflation, which is required for nucleosynthesis.

Reheating!



 $\Box$  Natural consequence after inflation: fill the empty space with matter (**generate entropy)**

## **PBH formation during reheating : possibilities**

**Q** The production of PBHs from inflation usually requires the existence of a short period of *ultra-slowroll* that produces a peak in the primordial power spectrum of scalar curvature perturbations.

 $\Box$  Perturbations that were generated during the late inflationary era can get resonantly amplified and collapse into black holes before the Universe is reheated. Depending on the reheating temperature, the PBH mass fraction can peak at different masses.

 $\Box$  Bubble collision during phase transition and in principle that can happen during reheating.

## **Formation of primordial black holes (PBHs) during reheating/radiation domination**



A schematic representation of the standard PBH formation scenario. The green line indicates the comoving scale of perturbations generated during inflation responsible for the PBH formation, much smaller than the CMB scales indicated in blue.

## **Amplitude of the perturbation required to form PBHs**



v In order to form significant number of black holes, the amplitude of the perturbations on In order to form significant number of black holes, the amplitude of the perturbations on small scales has to be large enough such that the dimensionless amplitude of the scalar perturbation is close to unity 13Figure credit G. Franciolini.

#### **Formation of the PBHs during reheating that the power spectrum rises as a conduction of the peak and, beyond the peak and, beyond the peak and, it fa** as *kn*<sup>0</sup> with *n*<sup>0</sup> *<* 0. We should point out that such power spectra arise in single-field models nearly scale invariant, as is the companies, as is required to fit the CMB data. On small scales, we shall assume the companies, we shall assume that  $\mathbb{R}^2$ **that the power spectrum rises as** *k***<sub>4</sub> as** *k***<sub>4</sub> as** *k***<sub>4</sub> as** *k***<sub>4</sub> and, beyond the peak and, it falls the peak, it falls the p** as *kn*<sup>0</sup> with *n*<sup>0</sup> *<* 0. We should point out that such power spectra arise in single-field models Inflation of the **pperiod of the period of united period**  $\mathbf{r}$ power spectrum that with the south with ingelering that the power spectrum rises as *karmation* of the pRHs during reheating as **k**<sup>n</sup>0 matron of the *r* Dris auring reneating

nearly scale invariant, as is required to fit the CMB data. On small scales, we shall scales, we shall assume

We assume that the inflationary scalar power spectrum with a broken power law is given by power spectrum that with intervals with intervals with intervals with intervals  $\mathbf{r}$ ◆ We assume that the inflationary scalar power spectrum with a broken pow<br>  $\left( \begin{array}{ccc} k & \lambda^4 & k & k \end{array} \right)$ of inflation that permit a brief period of ultra slow roll  $\mathcal{I}$  is complete form of the scalar slow roll  $\mathcal{I}$  $\bullet$  we assume that the initiationally scalar pow

*,* (2.8)

*,* (2.9)

$$
\mathcal{P}_{\mathcal{R}}(k) = A_{\text{s}} \left(\frac{k}{k_*}\right)^{n_{\text{s}}-1} + A_0 \left\{ \frac{\left(\frac{k}{k_{\text{peak}}}\right)^4}{\left(\frac{k}{k_{\text{peak}}}\right)^{n_0}} \right\} \quad k \le k_{\text{peak}}
$$

where  $A_{\rm s}$  and  $n_{\rm s}$  are the amplitude and spectral index of the power spectrum at the CMB pivot scale of  $k_* = 0.05 \text{ Mpc}^{-1}$ . ale of  $k_*=0.05\,\text{Mpc}^{-1}$ . is located and *A*<sup>0</sup> represents the extent of enhancement of the power spectrum at the location where  $A_s$  and  $n_s$  are the amplitude and spectral index of the power spectrum at the CMB pivot

• We shall assume that the threshold value of the density contrast for the formation of PBHs is given by following analytical expression  $W_{\alpha}$  abell example that the thus hald value of the density contrast for the formation of  $\overline{\text{DI}}$ we shall assume that the threshold value of the density contrast for the formation of  $\Gamma$  is given by following analytical expression ↓<br>• We shall assume that the threshold value of the density contrast for the formation of PBHs is given by following analytical expression generated, we shall assume the values of *A*<sup>S</sup> and *n*<sup>S</sup> to be as suggested by the recent Planck

$$
\delta_c^{\rm an} = \frac{3(1+w_{\rm re})}{5+3 w_{\rm re}} \sin^2\left(\frac{\pi \sqrt{w_{\rm re}}}{1+3 w_{\rm re}}\right)
$$

is located and *A*<sup>0</sup> represents the extent of enhancement of the power spectrum at the location

the critical value of the density contrast above which the overdense regions collapse to form

domination, the power spectrum, say, *P*(*k*), associated with the density contrast is related to

where, in arriving at the final expression, we have assumed that the probability distribution, we have assumed that the probability distribution, we have assumed that the probability distribution *P*() is a Gaussian function. During the phase of reheating or the epoch of radiation

where, in arriving at the final expression, we have assumed that the final expression, we have a stributed that the probability of the probability

cold dark matter, i.e. *f*PBH = ⌦PBH */*⌦c. Note that the energy density of PBHs ⇢PBH always

epoch of radiation domination which follows reheating, since total energy density varies as

◆ Fraction of the dark matter contributed from PBH today  $\bullet$  P<sub>B</sub>  $\bullet$  fraction of the density that collapses to form PBHs (often referred to as the PBHs (often referred to as the PBHs (of  $\bullet$ **₩** Fraction of the dark matter contributed from PDH tod ◆ Fraction of the dark matter contributed from PBH today It is important to recognize that di↵erent models for the collapse of PBHs lead to di↵erent

<u>range</u>

$$
f_{\rm PBH}(M)=\beta(M)\,\frac{\Omega_{\rm m}\,h^2}{\Omega_{\rm c}\,h^2}\,\left(\frac{g_{\rm s,eq}}{g_{\rm s,re}}\right)\,\left(\frac{g_{\rm re}}{g_{\rm eq}}\right)^{\frac{1}{1+w_{\rm re}}}\,\left(\frac{T_{\rm re}}{T_{\rm eq}}\right)^{\frac{1-3\,w_{\rm re}}{1+w_{\rm re}}}\,\left(\frac{M}{\gamma\,M_{\rm eq}}\right)^{-\frac{2\,w_{\rm re}}{1+w_{\rm re}}}
$$

<sup>p</sup><sup>2</sup> (*M*)

T. Harada, C.-M. Yoo, and K. Kohri, Phys. Rev. D 88, 084051 (2013). T. Harada, C.-M. Yoo, and K. Kohri, Phys. Rev. D 88, 084051 (2013).  $\frac{13}{2}$ . tion **P**() is a Gaussian function. During the phase of reduced or the phase of reduced or the epoch of radiation. During the epoch of radiation. The epoch of radiation of reduced or the epoch or the epoch or the epoch of r T Harada, C<sub>N</sub> Voo and K Kohri Phys Rey D 88 084051 (2013) <sup>1</sup>/<sub>1</sub> (*a*) (*a* 

data (10).<br>1970 - Paris Barbara, prima pendang pangangan pangangan pangangan pangangan pangangan pangangan pangang panga<br>1970 - Paris Barbara, pangangan pangangan pangangan pangangan pangang pangang pangang pangang pangang

 $\frac{1}{2}$ 

## **Generation of scalar induced secondary GWs during the epoch of reheating**



The dimensionless spectral energy density of primary and secondary GWs today have been plotted for a given reheating temperature and different values of the parameter describing the equation of state during reheating

8

## **Best-fit values**



The best-fit values arrived upon comparison with the NANOGrav 15-year data.

L. Sriramkumar (CSGC, IIT Madras, Chennai, India) Decoding the physics of the early universe through GWs March 19, 2024 35 / 58

S. Maity, N. Bhaumik, M. R. Haque, D. Maity and L. Sriramkumar, arXiv 2403.16963.

## **Constraints on the epoch of reheating and secondary constraints on the spoch of reheating reduced by a**



 $\bullet$  we have plotted the marginalized posterior distributions of the parameters that have been arrived at upon comparing our model with the NANOGrav 15-year data.

28S. Maity, N. Bhaumik, Md. R. Haque, D. Maity and L. Sriramkumar, in preparation.

## **Spectrum of the secondary GWs and the formation of the PBHs with the best-fit values**



**Example Strate Secondary Strategy ↓** density of the secondary GWs today  $\Omega_{\rm GW}$  $(f)$  is plotted for a given reheating temperature and the best-fit values of the L. Sriramkumar (CSGC, IIT Madras, Chennai, India) Decoding the physics of the early universe through GWs March 19, 2024 37 / 58 parameters in the different models.



- v The fraction of PBHs that constitute the dark matter density today is plotted for a given reheating temperature  $T_{re} = 50$  MeV and the best-fit values of the parameters in the different models.
- S. Maity, N. Bhaumik, M. R. Haque, D. Maity and L. Sriramkumar, arXiv 2403.16963.

## **Bayesian evidence**



- We obtain the marginalized likelihood in support of model Y and utilize it to evaluate the Bayesian factor against a reference model X. source of the stochastic GW background observed by the NANOGrav 15-year data, when  $\bullet$  we obtain the marginalized included in
- $\cdot$  When  $\delta_c = \delta_c$ <sup>an</sup> and  $\delta_c = 1.5 \delta_c$ <sup>an</sup>, our comparison with the NANOGrav's 15-year data finds strong Bayesian evidence in favor of the scenario wherein PBHs are formed during reheating, resulting<br>contract the CLEAR of t in the generation of secondary GWs rather than the SMBHB model.

Bayesian evidence<br>Bayesian evidence<br>Bayesian evidence de la provincia evidence

## **Overview of PBH Reheating**



 $\Box$  Boltzmann equations :

$$
\dot{\rho}_{\phi} + 3H(1 + w_{\phi})\rho_{\phi} = -\Gamma_{\phi}\rho_{\phi}(1 + w_{\phi})
$$
  
\n
$$
\dot{\rho}_{R} + 4H\rho_{R} = \Gamma_{\phi}\rho_{\phi}(1 + w_{\phi}) - \frac{\rho_{BH}}{M_{BH}} \frac{dM_{BH}}{dt} \theta(t - t_{\rm in}) \theta(t_{\rm ev} - t)
$$
  
\n
$$
\dot{\rho}_{BH} + 3H\rho_{BH} = \frac{\rho_{BH}}{M_{BH}} \frac{dM_{BH}}{dt} \theta(t - t_{\rm in}) \theta(t_{\rm ev} - t)
$$
  
\nMass reduction:  
\n
$$
\frac{dM_{BH}}{dt} = -\epsilon \frac{M_{P}^{4}}{M_{BH}^{2}}
$$
  
\n
$$
\frac{dM_{BH}}{dt} = -\epsilon \frac{M_{P}^{4}}{M_{BH}^{2}}
$$
  
\n
$$
\frac{M_{BH}}{dt} = \frac{M_{BH}}{M_{BH}} \frac{M_{BH} = M_{\rm in} (1 - \Gamma_{BH}(t - t_{\rm in}))^{\frac{1}{3}}}{M_{BH} = M_{\rm in} (1 - \Gamma_{BH}(t - t_{\rm in}))^{\frac{1}{3}}}
$$
  
\n
$$
\Phi
$$
 Evaporation coefficient as function  
\n
$$
\sigma_{R} = m_{j}/T_{BH}
$$

13 M. R. Haque, E. Kpatcha, D. Maity and Y. Mambrini, Phys. Rev. D 108, 063523 (2023).

## **Overview of my previous work: Background dynamics of reheating: PBH Reheating**



Condition for the PBH domination :

$$
\beta_c = \left(\frac{\epsilon}{(1+w_{\phi})2\pi\gamma}\right)^{\frac{2w_{\phi}}{1+w_{\phi}}} \left(\frac{M_P}{M_{\text{in}}}\right)^{\frac{4w_{\phi}}{1+w_{\phi}}}
$$
  

$$
\Box \text{ Reheating temperature } \boxed{T_{\text{RH}} = M_P \left(\frac{3\epsilon^2}{\alpha_T}\right)^{\frac{1}{4}} \left(\frac{M_P}{M_{\text{in}}}\right)^{\frac{3}{2}}}
$$

#### $\Box$  Reheating temperature

$$
T_{\rm RH} \sim M_P \beta^{\frac{3}{4} \frac{1+w_{\phi}}{3w_{\phi}-1}} \left(\frac{M_{\rm in}}{M_P}\right)^{\frac{3}{2} \frac{1-w_{\phi}}{3w_{\phi}-1}}
$$

14 M. R. Haque, E. Kpatcha, D. Maity and Y. Mambrini, Phys. Rev. D **108**, 063523 (2023).

## **Reheating and DM parameter space from PBH evaporation**



#### Inflaton reheating Vs PBH reheating **DM** parameter space from evaporating PBHs

M. R. Haque, E. Kpatcha, D. Maity and Y. Mambrini, Phys. Rev. D 108, 063523 (2023). M. R. Haque, E. Kpatcha, D. Maity and Y. Mambrini, Phys. Rev. D **109**, 023521 (2024).

## **Doubly peaked GWs for PBH reheating scenario**



16 N. Bhaumik, M. R. Haque, R.K. Jain, and M. Lewicki, JHEP 10 (2024) 142.

## **Conclusions**

- $\Box$  We assume a specific functional form for the primordial scalar power spectrum and examine the production of PBHs and the scalar-induced secondary GWs during the reheating phase. Specifically, we account for the uncertainties in the conditions for the formation of PBHs and ensure that the extent of PBHs produced remains within the observational bounds. We find that the scalar-induced SGWB generated during a phase of reheating with a steeper equation of state (than that of radiation) fit the NANOGrav 15 year data with stronger Bayesian evidence than the astrophysical scenario involving GWs produced by merging supermassive binary black holes.
- $\Box$  I have discussed the reheating and DM parameter space in the background of the reheating phase dynamically obtained from two chief systems in the early Universe: the inflaton  $\phi$ and the primordial black holes. The DM is assumed to be produced purely gravitationally from the PBH decay, not interacting with the thermal bath and the inflaton.
- $\Box$  Ultra-low mass primordial black holes (PBH), briefly dominating the expansion of the universe, would leave detectable imprints in the secondary stochastic gravitational wave background (SGWB). Such a scenario leads to a characteristic doubly peaked spectrum of SGWB and strongly depends on the background where the ultra-light PBHs form.

# **Thank You**