# Primordial Fluctuations and Rare Objects in the Universe

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refs: Huang, PRD, 2019; Bond, Frolov, Huang, Kofman, PRL, 2009

# Outline

# A remarkable concordance cosmology ($\Lambda$CDM with slow-roll single-field inflation)

| parameter | expected | measured |
|---|---|---|
| spatial curvature $\Omega_k$ | $\lesssim 10^{-4}$ | $0.0007 \pm 0.0019$ |
| scalar tilt $n_s$ | $0.9 \lesssim n_s < 1$ | $0.967 \pm 0.004$ |
| scalar running $n_{\rm run}$ | $\lesssim 10^{-3}$ | $-0.007^{+0.013}_{-0.014}$ |
| tensor $r$ | $\lesssim 1$ | $< 0.07$ |
| Non-Gaussianity $f_{\rm NL}^{\rm local}$ | $\lesssim 1$ | $2.5 \pm 5.7$ |
| iso-curvature component $\alpha$ | 0 | $0.00013 \pm 0.00037$ |
| neutrino species $N_{\rm eff}$ | 3.046 | $2.96^{+0.34}_{-0.33}$ |
| neutrino mass $\sum m_\nu$ | $0.06\mathrm{eV}$ or $0.1\mathrm{eV}$ | $< 0.12\mathrm{eV}$ |
| Helium abundance $Y_p$ | $\sim 0.25 \pm 0.01$ | $0.241^{+0.023}_{0.024}$ |

(numbers cited from Planck 2018 series of papers)

# Puzzles to be resolved

- The $H_0$ tension (HST + H0LiCOW SL, $\sim 5\sigma$)
- Lensing Anomaly ($\sim 2\sigma$, Planck 2018)
- $\sigma_8$ tension ($\sim 2.5\sigma$, Böhringer et al. 2014, 2017)
- CMB missing large-angular correlation; CMB cold spot; Lithium abundance; ISW-LSS over-correlation; origin of SMBH at $z > 6$; ...

# Some Trials

**Super-CMB fluctuations can resolve the Hubble tension**

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We study the covariance in the angular power spectrum estimates of CMB fluctuations when the primordial fluctuations are non-Gaussian. The non-Gaussian covariance comes from a nonzero connected four-point correlation function — or the trispectrum in Fourier space — and can be large when long-wavelength (super-CMB) modes are strongly coupled to short-wavelength modes. The effect of such non-Gaussian covariance can be modeled through additional freedom in the theoretical CMB angular power spectrum and can lead to different inferred values of the standard cosmological parameters relative to those in ΛCDM. Taking the collapsed limit of the primordial trispectrum in the quasi-single field inflation model as an example, we study how the six standard ΛCDM parameters shift when two additional parameters describing the trispectrum are allowed. We find that the combination of *Planck* temperature data along with type Ia supernovae from Panstarrs and the distance-ladder measurement of the Hubble constant shows strong evidence for a primordial trispectrum-induced non-Gaussian covariance, with a likelihood improvement of $\Delta\chi^2 \approx -15$ relative to ΛCDM. The improvement is driven by Planck data's preference for a higher lensing amplitude, which leads to an upward shift of the Planck-inferred Hubble constant.

resolves $H_0$ tension and lensing anomaly; but worsen $\sigma_8$ tension; polarization and tri-spectrum may be problematic

# Today's topic

- The $H_0$ tension (HST + H0LiCOW SL, $\sim 5\sigma$)
- Lensing Anomaly ($\sim 2\sigma$, Planck 2018)
- $\sigma_8$ tension ($\sim 2.5\sigma$, Böhringer et al. 2014, 2017)
- CMB missing large-angular correlation; CMB cold spot; Lithium abundance; ISW-LSS over-correlation; origin of SMBH at $z > 6$; . . .

# High-redshift SMBH Timing Problem

# Observed SMBH at high-$z$

- Luminous quasars (QSOs) at $z \gtrsim 6$. (Fan *et al* 2003, 2006; Willott *et al* 2003, 2007, 2010; Kurk *et al* 2007; Jiang *et al* 2007, 2008, 2009; Rosa *et al* 2011, 2014; Mortlock *et al* 2011; Wu *et al* 2015; Banados *et al* 2014, 2018)
- Powered by SMBHs (mass $\gtrsim$ a few $\times 10^9 M_\odot$). (Willott *et al* 2003; Wu *et al* 2015)
- Number density $\sim 1\,\mathrm{Gpc}^{-3}$.

# Timing Crisis and DCBH scenario

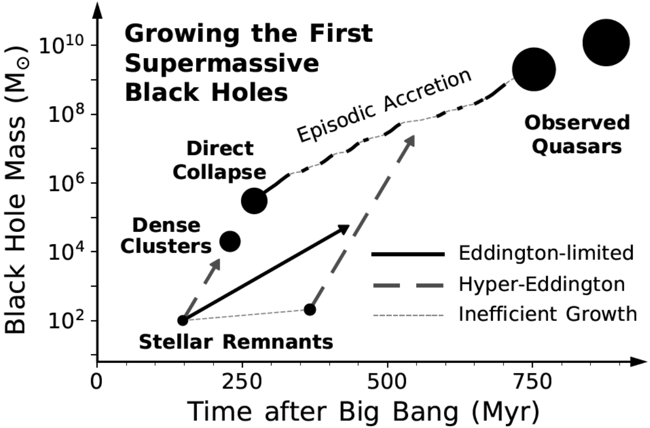



figure credit: Smith *et al.* 2017

# LW Flux dissociates $H_2 \rightarrow$ DCBH

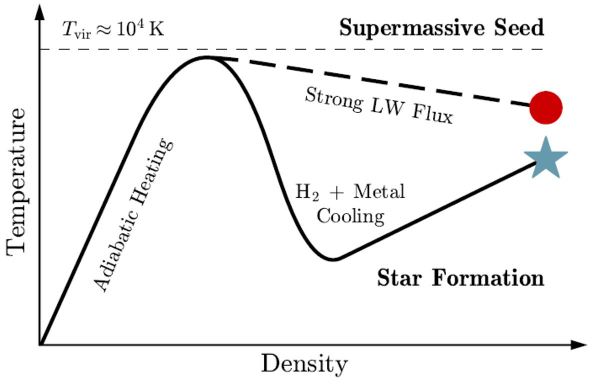



figure credit: Smith *et al.* 2017

# DCBH scenario vs Star accretion scenario

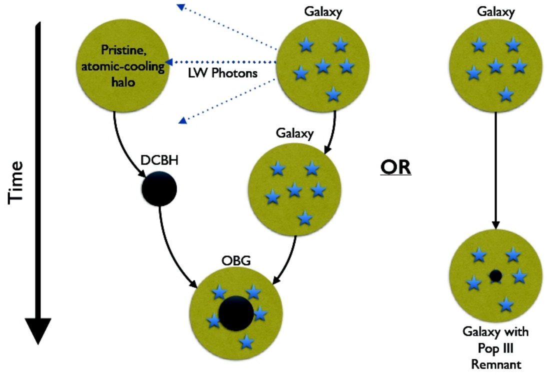



figure credit: Natarajan *et al.* 2007

# The problem with DCBH

Cosmological simulations $\rightarrow$ much fewer candidates than expected

(Habouzit *et al.* 2016, Agarwal *et al.* 2018)

# High-redshift SMBH Environment Problem

# Expected High-$z$ SMBH Environment

Cosmological simulations $\Rightarrow$ high-$z$ SMBH forms in dense regions extending to $\sim 10$ physical Mpc (Overzier *et al.* 2009; Muldrew *et al.* 2015)

# Observed High-$z$ SMBH Environment

No obvious overdensity around high-$z$ QSOs within $\sim$ a few physical Mpc around.

(Francis & Bland-Hawthorn 2004; Kashikawa*et al.* 2007; Kim*et al.* 2009; Banados*et al.* 2013; Simpson*et al.* 2014; Kikuta*et al.* 2017; Mazzucchelli*et al.* 2017; Uchiyama*et al.* 2018; Ota*et al.* 2018)

# Primordial Black Holes (PBH) as a Solution

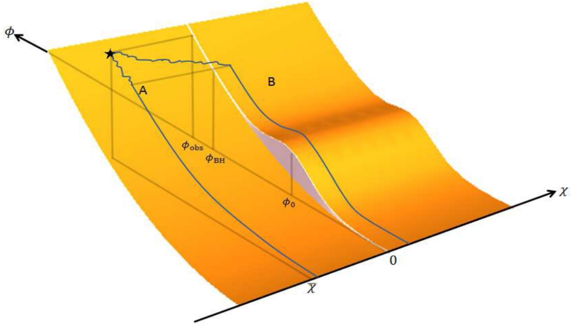
# PBH models

High-$z$ SMBHs are primordial ($\sim O(1)$ primordial metric fluctuations)?

- No timing problem.
- May or may not have environment problem (model-dependent).
- Most of the models produces too many small PBHs (ruled out by microlensing, wide binaries, CMB $\mu$ distortion etc.).

# A successful example

A two-field inflation model that works. (Nakama *et al.* 2016)



# Modulated Preheating (M. P.) as a Solution

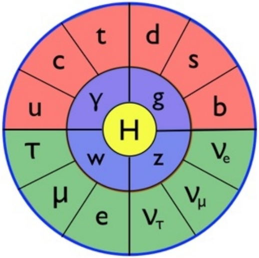
# Idea

Much larger (but still $\ll 1$) primordial fluctuations on scales $\lesssim 0.1h^{-1}\mathrm{Mpc}$

Key point: make this happen only in very rare regions.

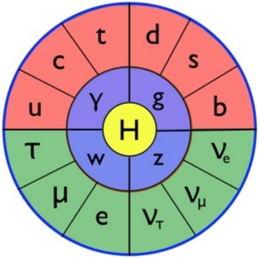
# Inflaton $\Rightarrow$ Standard Model Particles?


$\overset{?}{\Longrightarrow}$



# Reheating: Inflaton $\Rightarrow$ SM Particles


$\underset{\Longrightarrow}{\textit{reheating}}$



# Inflaton $\overset{\text{decay}}{\Rightarrow}$ SM Partialces?

reheating = perturbative decay?

Nothing wrong but too slow:

$$T_r \sim 10^9 \mathrm{GeV}$$

# Better scenarios: reheating begins with non-perturbative decay - preheating

Inflaton $\phi \overset{\text{para. reson.}}{\Longrightarrow}$ some field $\chi \overset{\text{decay}}{\Rightarrow}$ SM partialces

The first step ($\phi \overset{\text{para. reson.}}{\Longrightarrow} \chi$): preheating

# High school math

constant frequency

$$\ddot{\chi} + \omega^2 \chi = 0.$$

if $\omega^2 > 0$ ($\omega$ is real): $\chi$ oscillates;
if $\omega^2 < 0$ ($\omega$ is imaginary): $\chi$ exponentially grows;

# Parametric resonance

time-dependent frequency:

$$\ddot{\chi} + \omega^2(t)\chi = 0.$$

if $\omega(t)$ quickly varies, $|\dot{\omega}| \gtrsim \omega^2 > 0$ can also make $\chi$ exponentially grow.

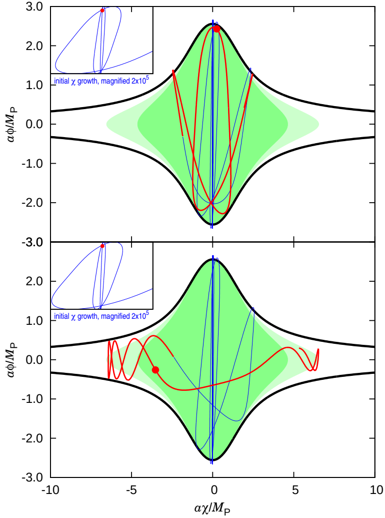
# Example of Parametric Resonance: Swing

# A toy model

$$V(\phi, \chi) = \frac{\lambda}{4}\phi^4 + \frac{g^2}{2}\phi^2\chi^2.$$

($\phi$: inflaton)

# Chaotic dynamics




$$V(\phi, \chi) = \frac{\lambda}{4}\phi^4 + \frac{g^2}{2}\phi^2\chi^2.$$

# Typical settings

Hubble horizon size $\sim$ 1 cm (comoving)

# Conjecture

causality $\Rightarrow$ uncorrelated on scales $\gg$cm?

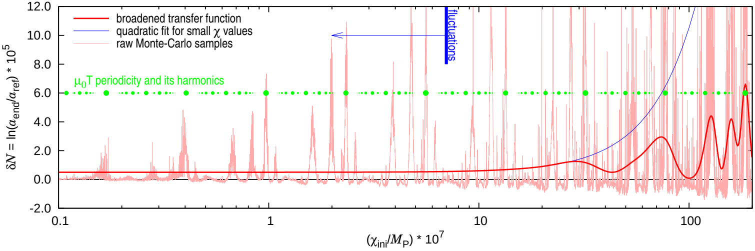
# Modulated preheating - basic idea

inflation prepares long wavelength $\chi$ fluctuations $\Rightarrow$ modulates preheating

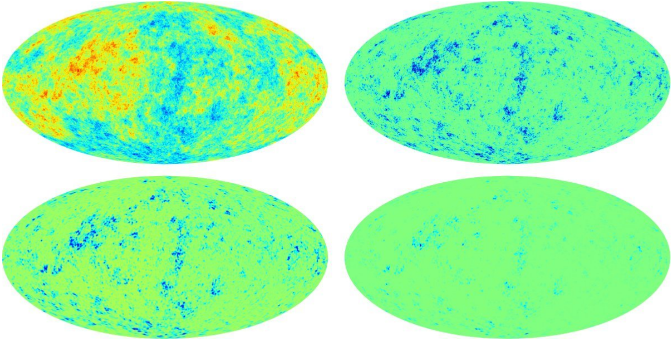
# The discovery of modulated preheating

- Propose the chicken and duck idea, wrong numeric result (Suyama and Yokoyama 2007)
- Tried again, wrong numeric result (Chambers and Rajantie 2008)
- New algorithm with 5 orders magnitude improvement of numeric accuracy, correct result (Bond, Frolov, Huang, Kofman, 2009)

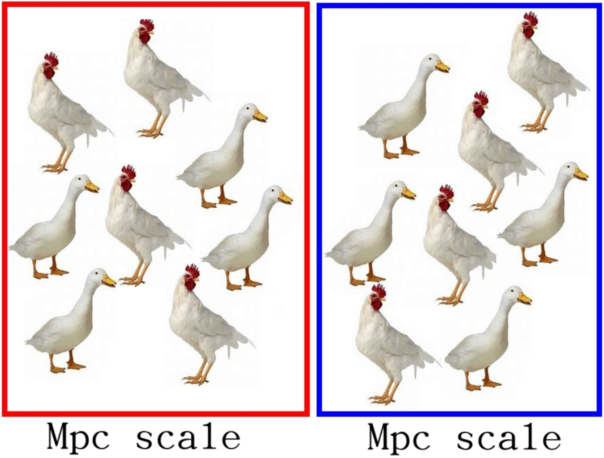
# The BFHK result



# Explaining the CMB cold spot



# Use modulated preheating to enhance fluctuations on $\sim 0.1\mathrm{Mpc}$ scales



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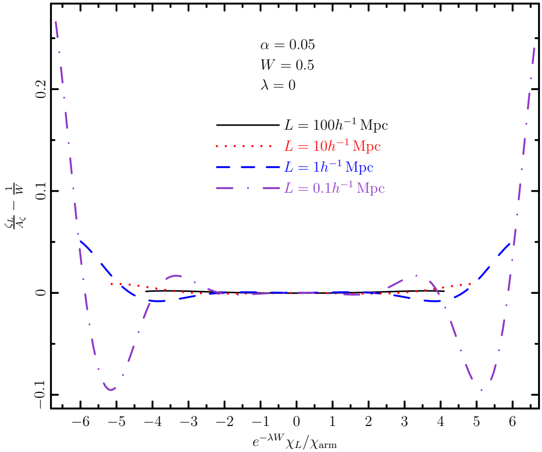
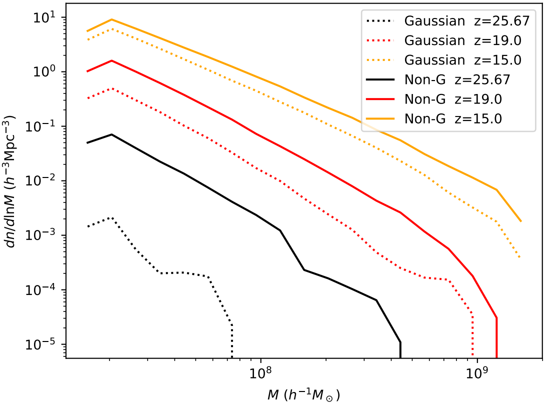


# Generating more $\gtrsim 10^8 M_\odot$ haloes



# Summary: modulated preheating as a solution

Pros.

 regions v.s.  regions (= standard)

- Much more halo pairs for DCBH formation.
- No overdense environment on $\gtrsim$ Mpc scales

Cons.

Need $\sim 1/60$ fine-tuning (increase $\chi$ mass when $aH \gtrsim 10h\mathrm{Mpc}^{-1}$ during inflation)

# Standard Model, M.P. or PBH?

| redshift | Standard | M. P. | PBH |
|---|---|---|---|
| $z \gtrsim 25$ | nothing | nothing | acretion |
| $15 \lesssim z \lesssim 25$ | nothing | $\gtrsim 10^5 M_\odot$ seeds merger & acretion | acretion |
| $6 \lesssim z \lesssim 15$ | $\gtrsim 10^5 M_\odot$ seeds merger & acretion | $\gtrsim 10^6 M_\odot$ seeds; merger & acretion | acretion |
| philosophy | 靠山吃山 | 早起的鸟儿有虫吃 | 存在即合理 |

# Conclusions

- High-$z$ SMBHs seem not fit well into cosmology: timing problem and environment problem.
- PBH (very nontrivial inflation potential) and M.P. (assymmetric preheating potential $+\sim 1/60$ tuning on modulator mass) can both resolve high-$z$ SMBH problems.
- Direct collapse and merger of $\gtrsim 10^5$ BH seeds at very high redshift (detectable GW signals?).