Focus Week on Primordial Black Holes
@Kavli-IPMU   Dec. 2-6 2019

Particle Physics Models for Primordial Black Hole Formation

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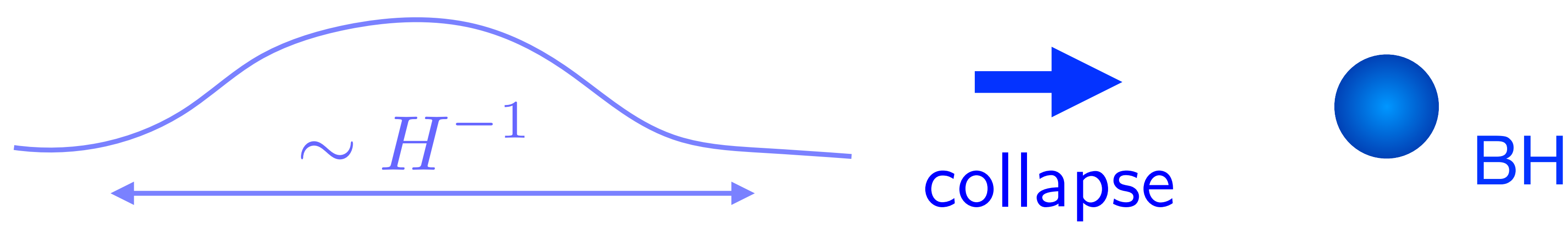
1. Introduction

- Primordial Black Holes (PBHs) Zeldovich-Novikov (1967) Hawking (1971)
- PBHs have attracted much attention because they could
  - Give a significant contribution to dark matter $\sim 10^{17-22}\mathrm{g}$
  - Account for GW events detected by LIGO-Virgo $\sim 30 M_\odot$
  - Account for seeds of supermassive BHs $\sim 10^{4-5} M_\odot$
- PBHs can be formed by gravitational collapse of over-density regions with Hubble radius in the early universe



- Such over-density regions may be produced by inflation but large density fluctuations δ with O(0.01) are required

- It is not easy to build such inflation models
- Many sophisticated models are proposed

Garcia-Belliido Linde Wands (1996)
MK, Sugiyama, Yanagida (1998)
MK Kusenko Tada Yanagida (2016)
. . . . . .

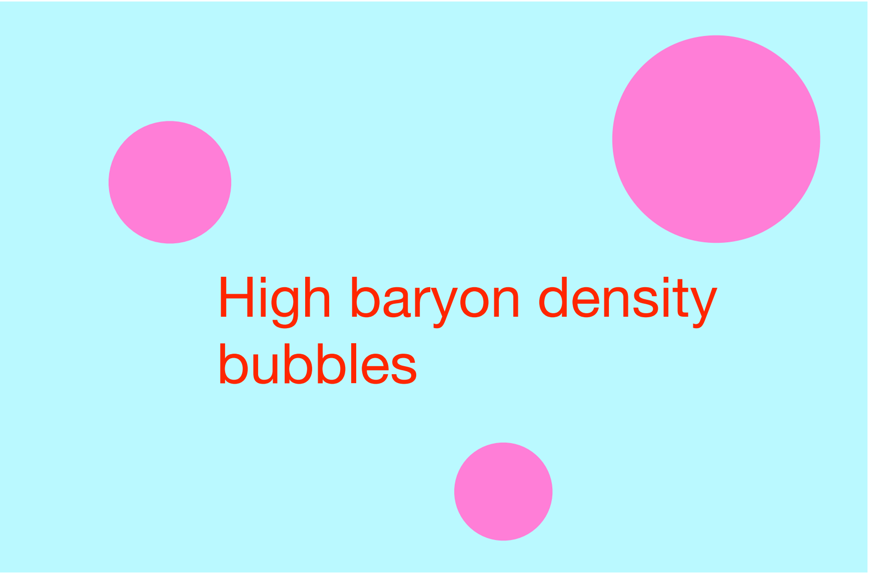
- We present two models
- PBH formation by Affleck-Dine mechanism

Dolgov, Silk (1993)
Dogov MK Kevlishvili (2009)
Hsegawa, MK (2018)

  - High-baryon bubbles are formed

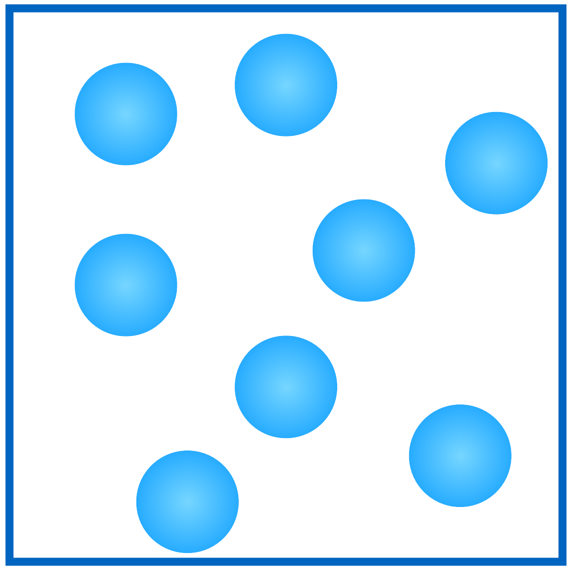
    → LIGO PBHs or SMBHs

  - Evades constrains from pulsar timing and CMB mu-distortion



- PBH formation from non-topological solitons
  - Oscillons (or Q-balls) produce large density fluctuations

Cotner, Kusenko (2016)
Cotner, Kusenko, Takhistov (2018)
Cotner, MK, Kusenko, Sonomoto, Takhistov (2019)



Contents

2.1 PBH formation in Affleck-Dine mechanism

- Affleck-Dine mechanism
  - Flat directions in scalar potential of MSSM $\ni (\tilde{q},\ \tilde{\ell},\ H)$
- One of flat directions = AD field ϕ

$$V(\phi) = (m_\phi^2 + c_H H^2)|\phi|^2 + \lambda^2 \frac{|\phi|^{2(n-1)}}{M_p^{2(n-3)}} + A\frac{\phi^n}{M_p^{(n-3)}} + h.c.$$

SUSY breaking mass term

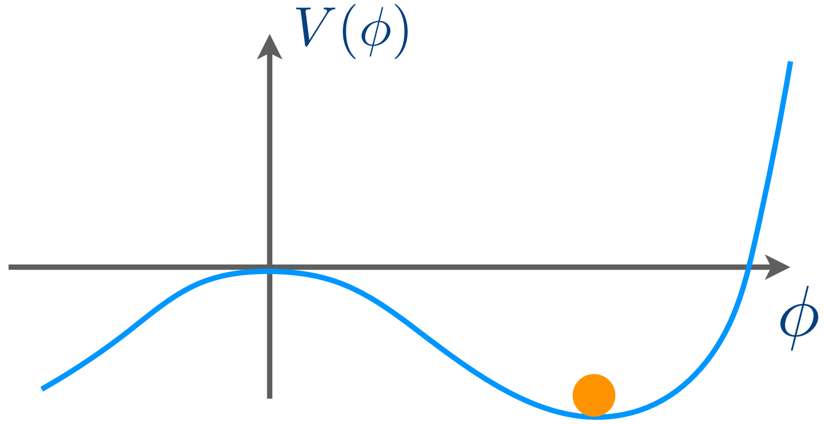
Hubble induced mass term

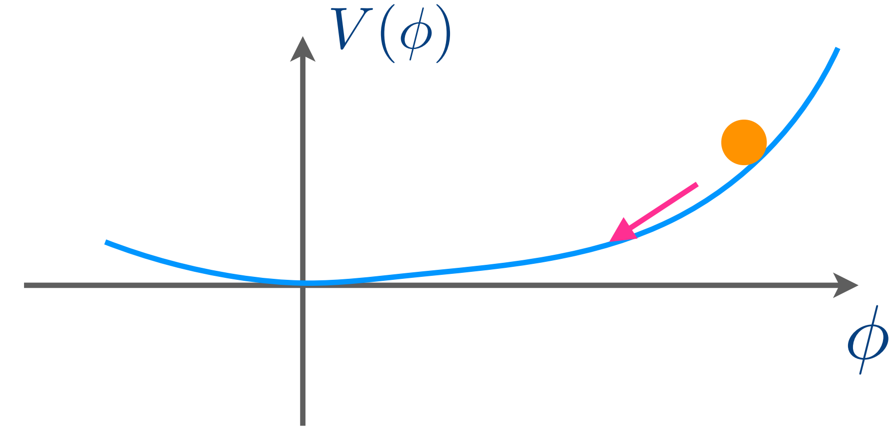
V_{NR} : Non-renormalizable term (n≥4)

V_A : A-term

$$A = \lambda a_M m_{3/2} \quad (m_{3/2} : \text{gravitino mass})$$

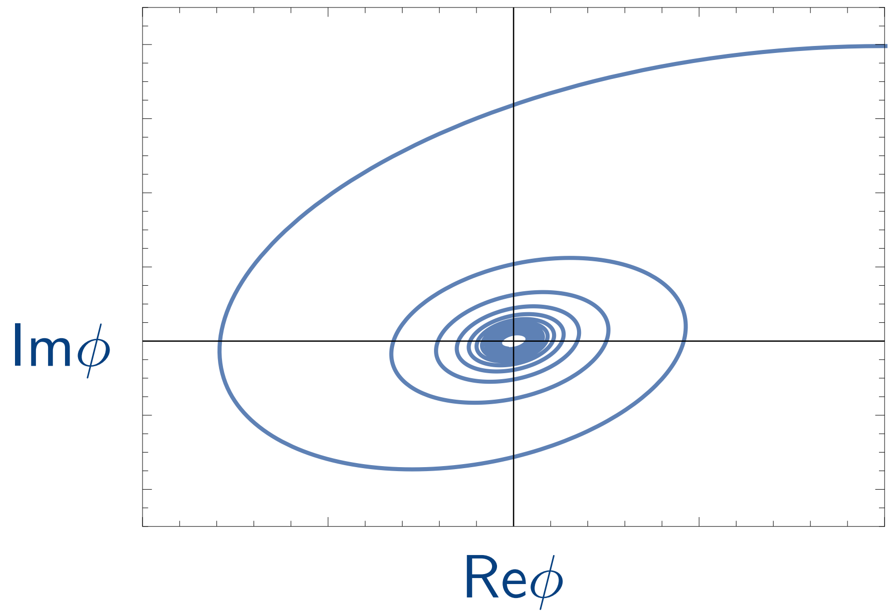
- During inflation ϕ has a large value if $c_H < 0$
- After inflation, when $m_\phi \simeq H$ ϕ starts to oscillate





2.1 PBH formation in Affleck-Dine baryogenesis

- AD field is kicked in phase direction due to A-term



$$n_B \sim |\phi|^2\dot{\theta}$$

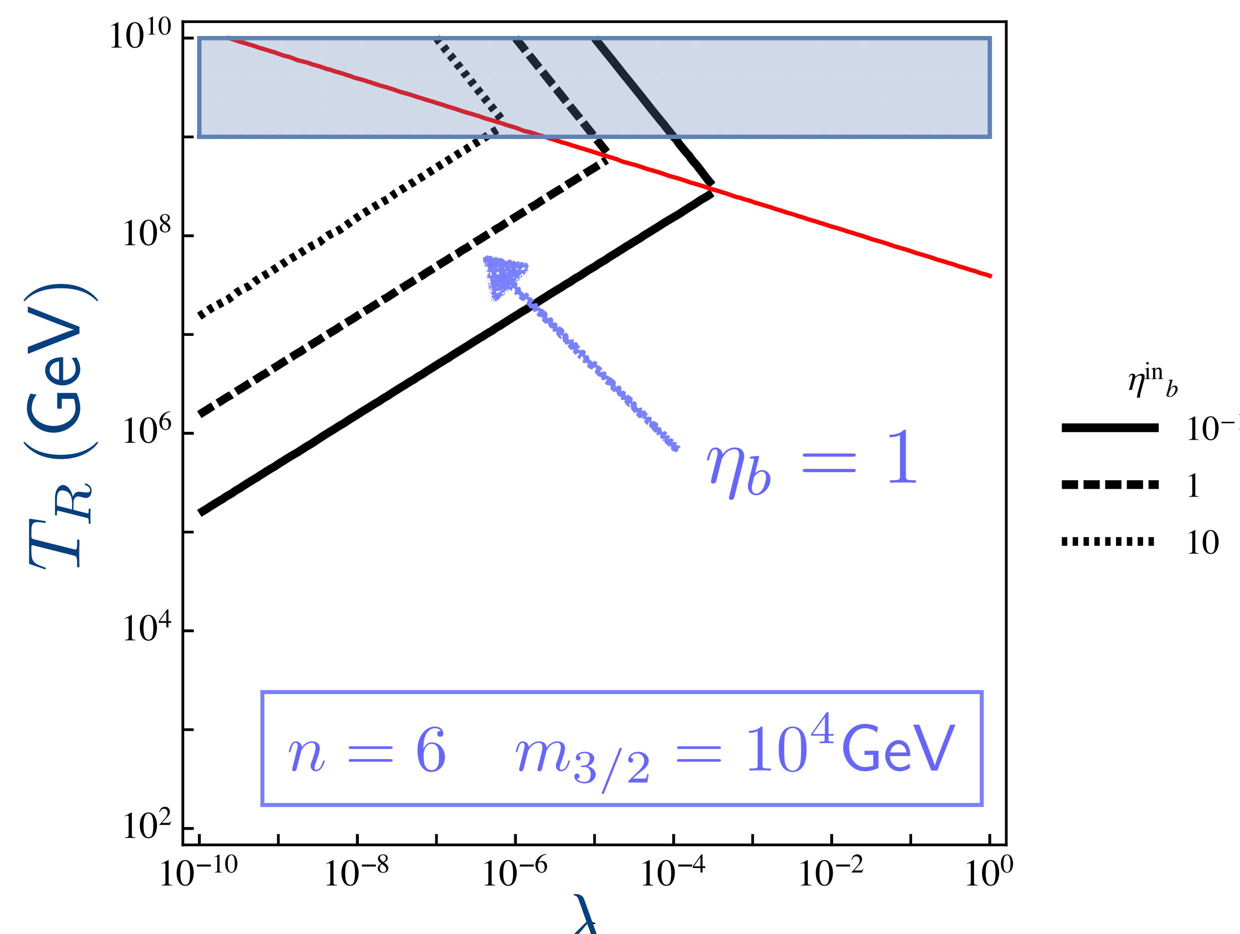
Baryon number generation

AD baryogenesis

- AD mechanism can generate baryon number efficiently

$$\eta_b = \frac{n_b}{s} \sim \frac{T_R m_{3/2}}{H_{\rm osc}^2}\left(\frac{\phi_{\rm osc}}{M_p}\right)^2$$

▷ large baryon asymmetry $\eta_b \sim 1$ is realized



2.2 High-baryon bubble formation

- Two unconventional assumptions:
  - Hubble mass is positive during inflation and becomes negative after inflation
  - Thermal mass overcomes Hubble mass after inflation
- Potential for AD field

$$V = \begin{cases} (m_\phi^2 + c_I H^2)|\phi|^2 + V_{\rm NR} + V_{\rm A} & \text{(during inflation)} \\ (m_\phi^2 - c_M H^2)|\phi|^2 + V_{\rm NR} + V_{\rm A} + V_{\rm T} & \text{(after inflation)} \end{cases}$$

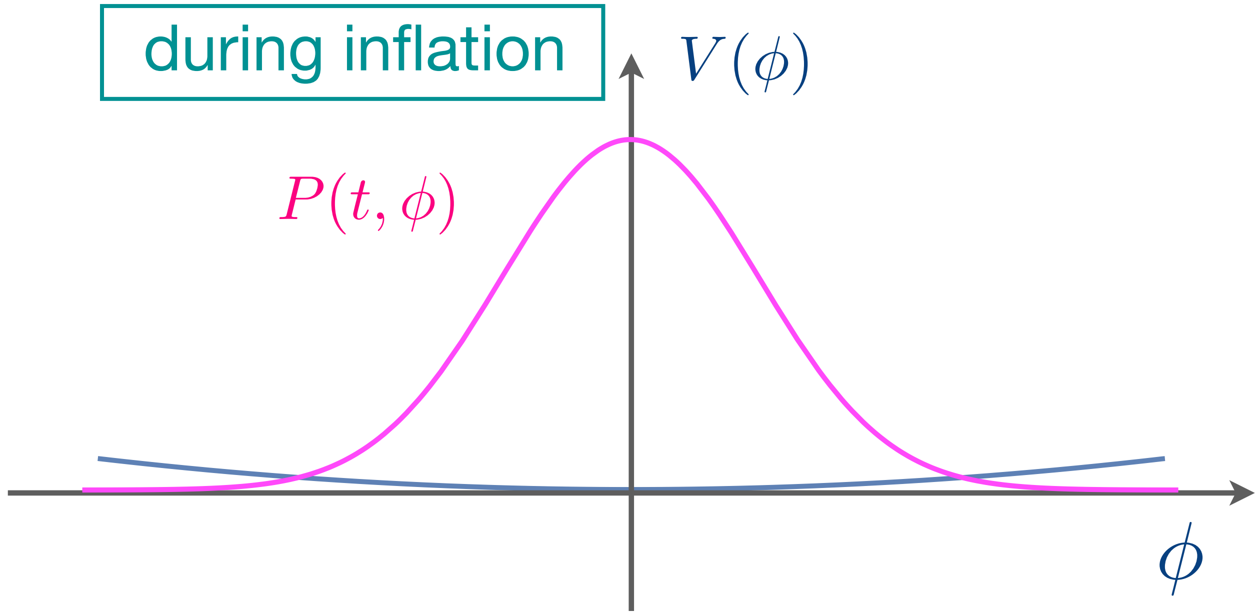
$$V_T = \begin{cases} c_1 T^2 |\phi|^2 & |\phi| \lesssim T \\ c_2 T^4 \ln(|\phi|^2/T^2) & |\phi| \gtrsim T \end{cases}$$

2.2 High-baryon bubble formation

- During inflation
  - $c_H > 0$ (positive Hubble mass)
  - Flat potential $c_H << 1$
- Quantum fluctuations of AD field
  - Gaussian distribution

$$P(t,\phi) = \frac{1}{2\pi\sigma(t)^2}\exp\left[-\frac{|\phi|^2}{2\sigma(t)^2}\right]$$

$$\sigma^2 = \left(\frac{H_I}{2\pi}\right)^2\left(\frac{2}{3c_H}\right)\left[1 - e^{-(2c_H/3)H_I t}\right]$$



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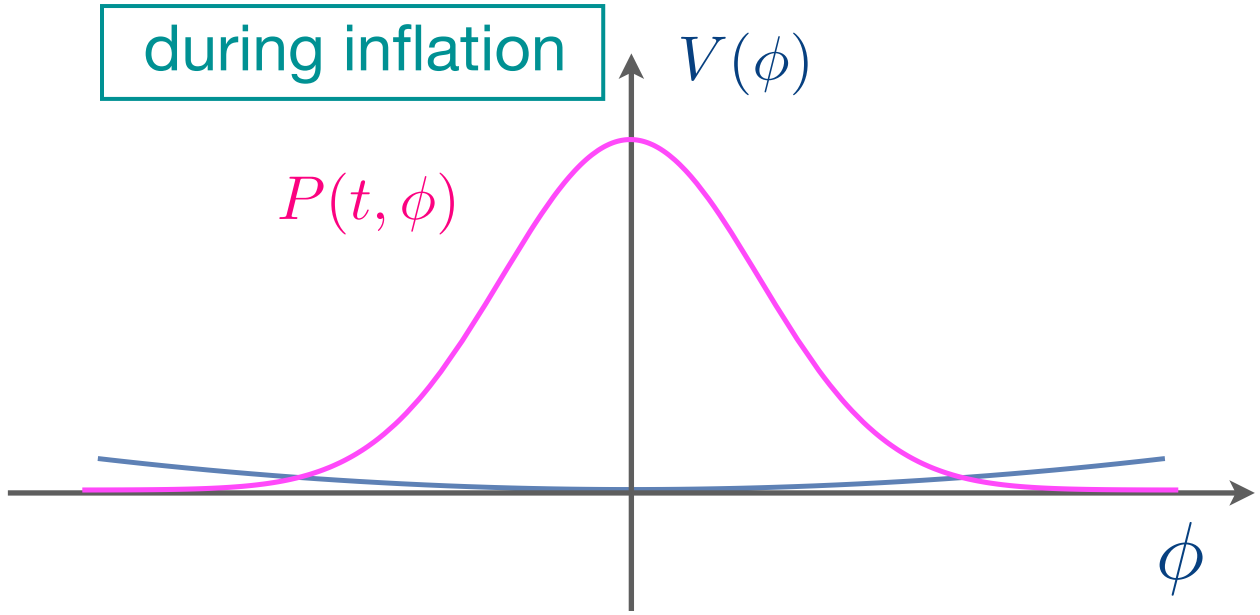
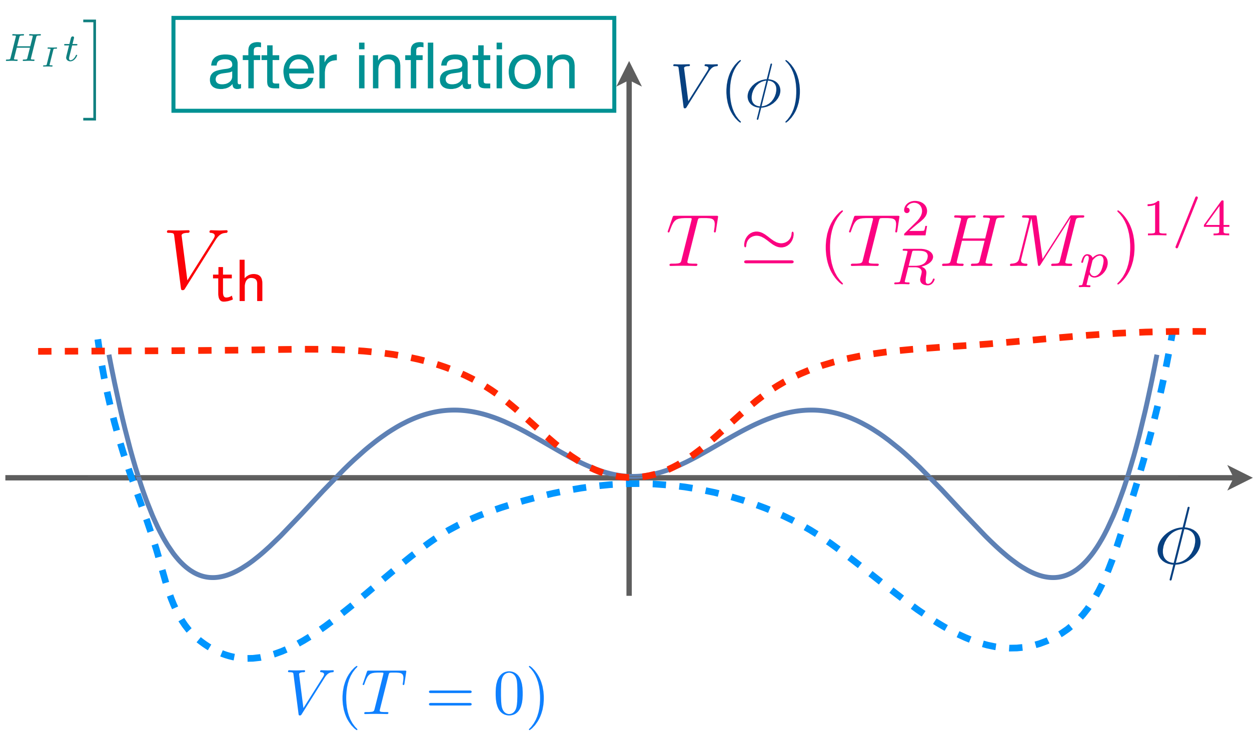
- After inflation
  - $c_H < 0$ (negative Hubble mass)
  - Thermal effect due to inflaton decay

→ multi-vacua

$$\Delta \equiv \frac{T_R^2 M_p}{H_I^3} \gtrsim 1$$





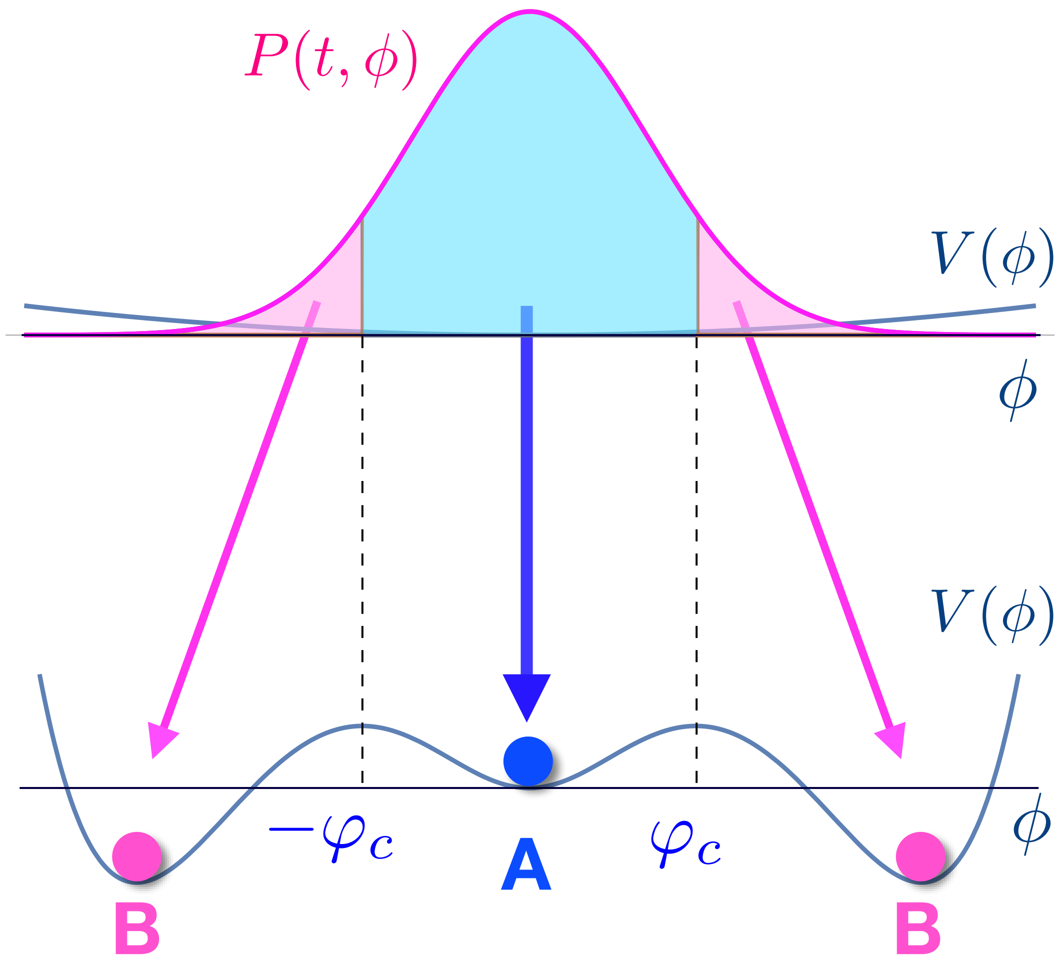
2.2 High-baryon bubble formation

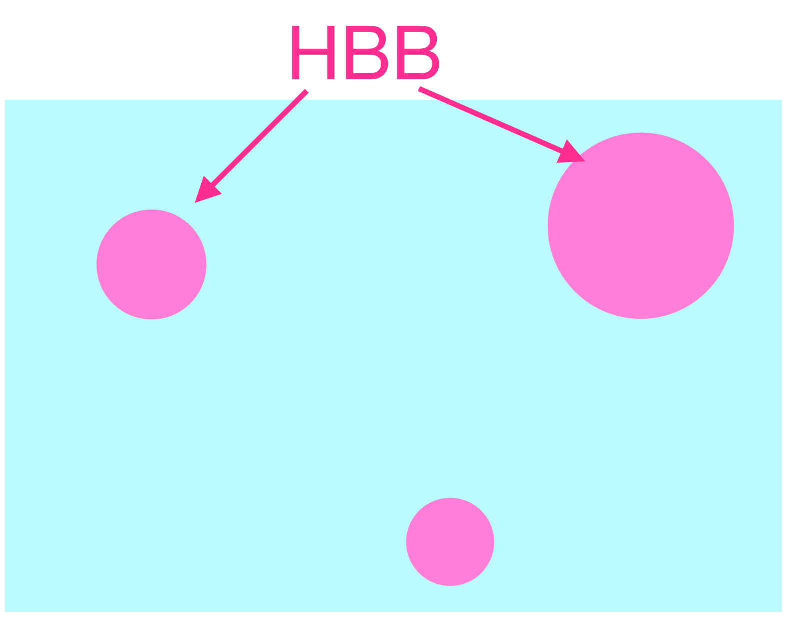
- Regions with $|\phi| < \varphi_c$ go to A-vacuum

$$\varphi_c = \Delta^{1/2} H_I \qquad \Delta = \frac{T_R^2 M_p}{H^3}$$

  - no baryon generation
- Regions with $|\phi| > \varphi_c$ go to B-vacuum
  - baryon generation takes place (same way as the standard AD)
  - Efficient AD baryogenesis

  → Formation of high-baryon bubble





- Fraction of volume which will go to B-vacuum

$$f_B(N) = \int_{\varphi > \varphi_c} d\phi\, P(N,\phi) \qquad N \propto \ln a$$

- Formation rate of HBB with scale k(N)=k* exp(N-N*)

$$\beta_B(N) = \frac{d}{dN} f_B(N)$$

2.3 PBH formation from high-baryon bubbles

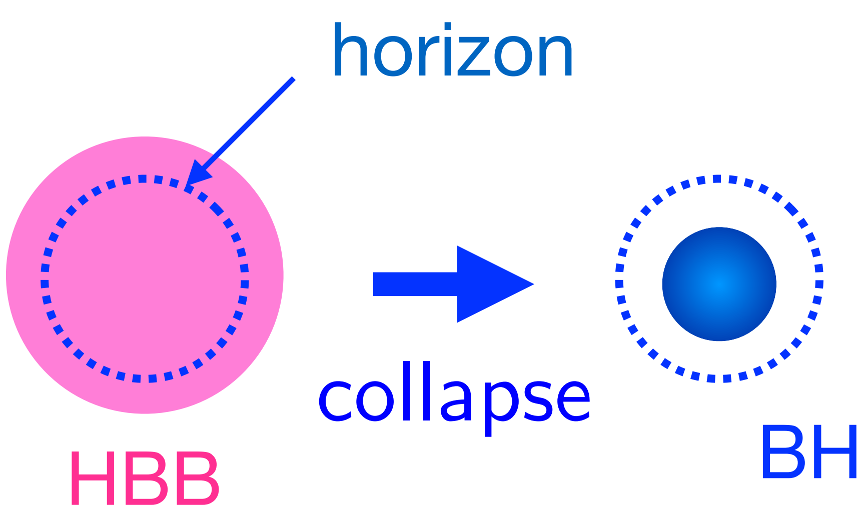
- After QCD phase transition quarks ➡ non-relativistic nucleons
- Density contrast between inside and outside of HBBs

$$\delta = \frac{\rho^{\text{in}} - \rho^{\text{out}}}{\rho^{\text{out}}} \simeq 0.3\eta_b^{\text{in}} \left(\frac{T}{200\text{MeV}}\right)^{-1}$$

$$\Rightarrow \quad \delta \gtrsim \delta_c \text{ for } T \lesssim T_c \simeq 200\eta_b^{\text{in}}\text{MeV}$$

- When HBBs enter the horizon after T_c

➡ PBH formation



- PBH mass has a lower cutoff

$M_c \simeq 18M_\odot$ for $\eta_b^{\text{in}} \simeq 1$ $\quad$ $M_c \simeq 14M_\odot(\eta_b^{\text{in}})^{-2}$ for $\eta_b^{\text{in}} \lesssim 1$

- PBH mass fraction at formation

$$\beta_{\text{PBH}}(M_{\text{PBH}}) = \beta_B(M_{\text{PBH}})\theta(M_{\text{PBH}} - M_c)$$

- This explains LIGO events $\quad \Omega_{\text{PBH}}/\Omega_c \sim 10^{-3} - 10^{-2}$

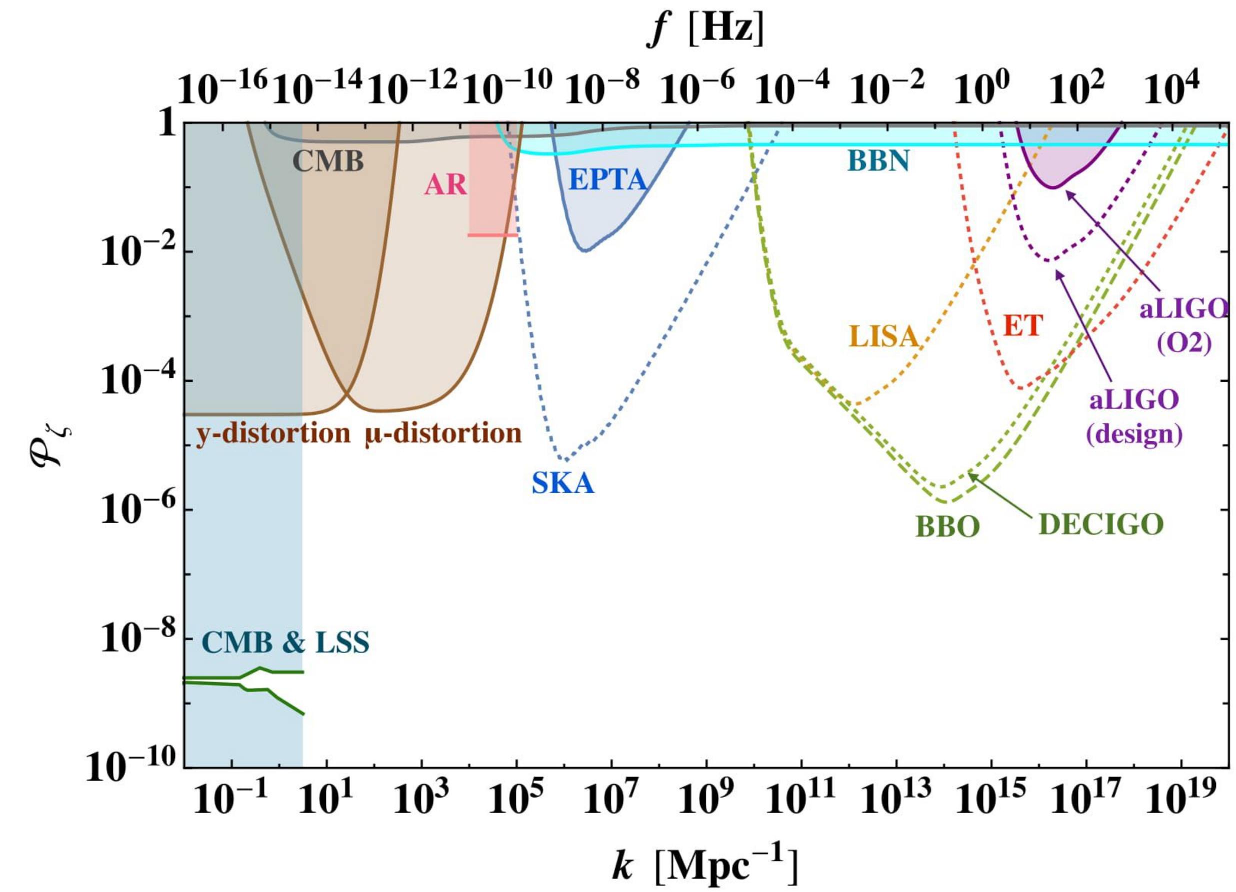
Constraints on Gaussian fluctuations

- Gaussian density fluctuations produced by inflation suffer from stringent constraints
  - from CMB spectral distortion which excludes

    $$400 M_\odot \lesssim M_{\rm PBH} \lesssim 10^{13} M_\odot$$

  - from pulsar timing array exp. which excludes

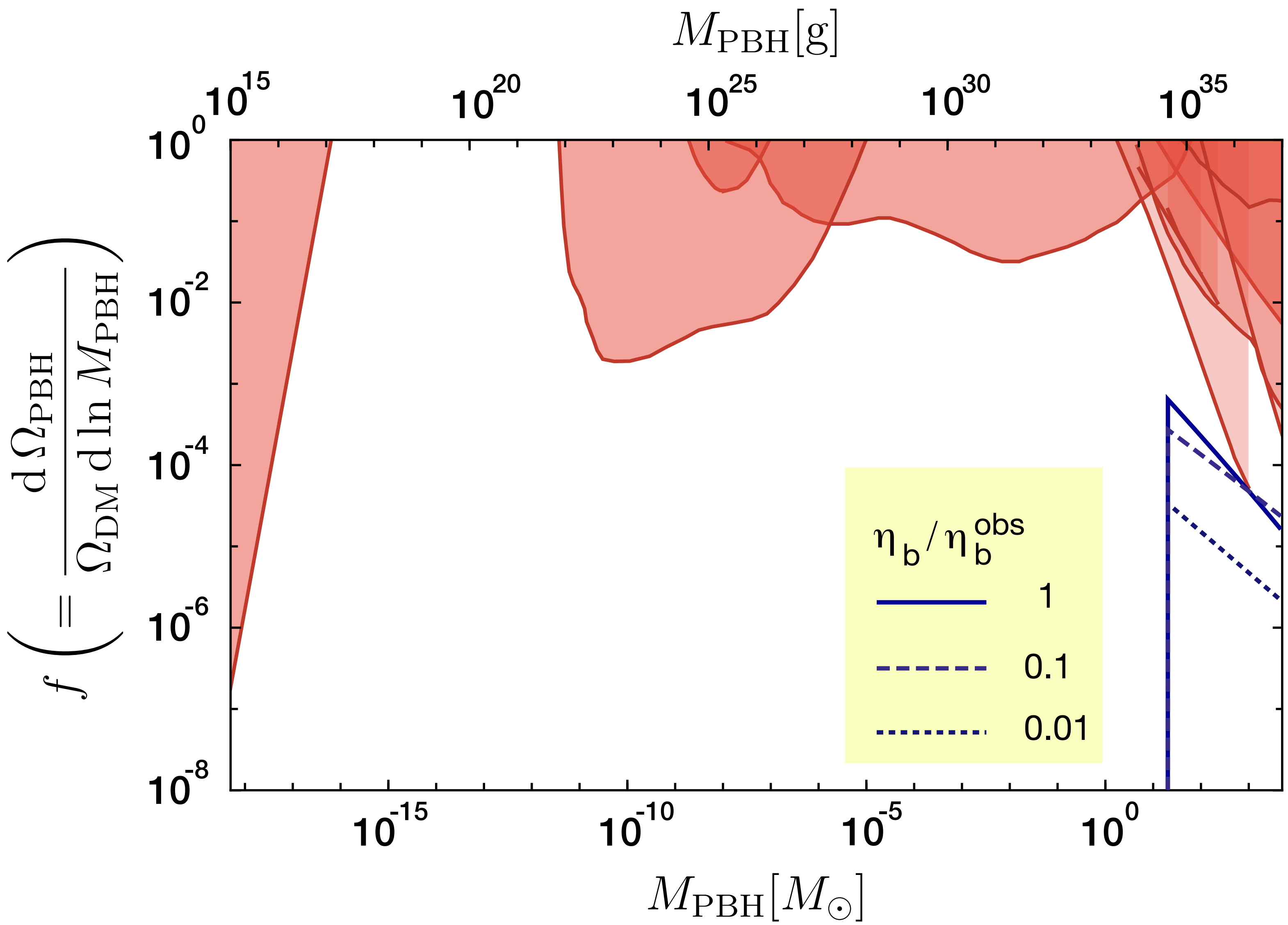
    $$0.1 M_\odot \lesssim M_{\rm PBH} \lesssim 10 M_\odot$$



Inomata, Nakama (2019)

- Difficulty to explain LIGO events
- SMB seeds cannot be produced
- HBBs produced Affleck-Dine mechanism evades those constraints

2.3 PBH formation from high-baryon bubbles



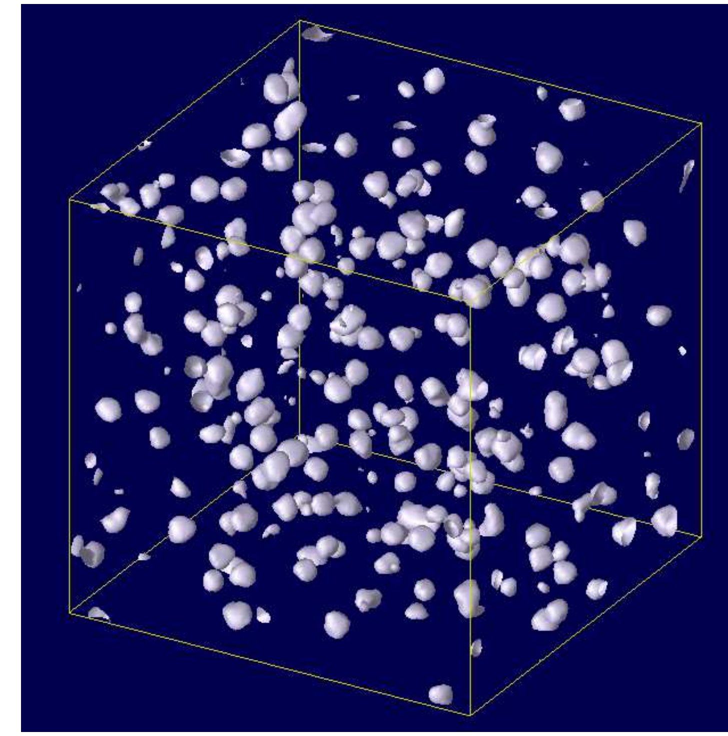
- HBBs with M < Mc contribute to baryon asym of the universe
- inhomogeneous baryons spoil success of standard BBN

$\Rightarrow \eta_b^{\rm HBB} \ll \eta_b^{\rm obs}$

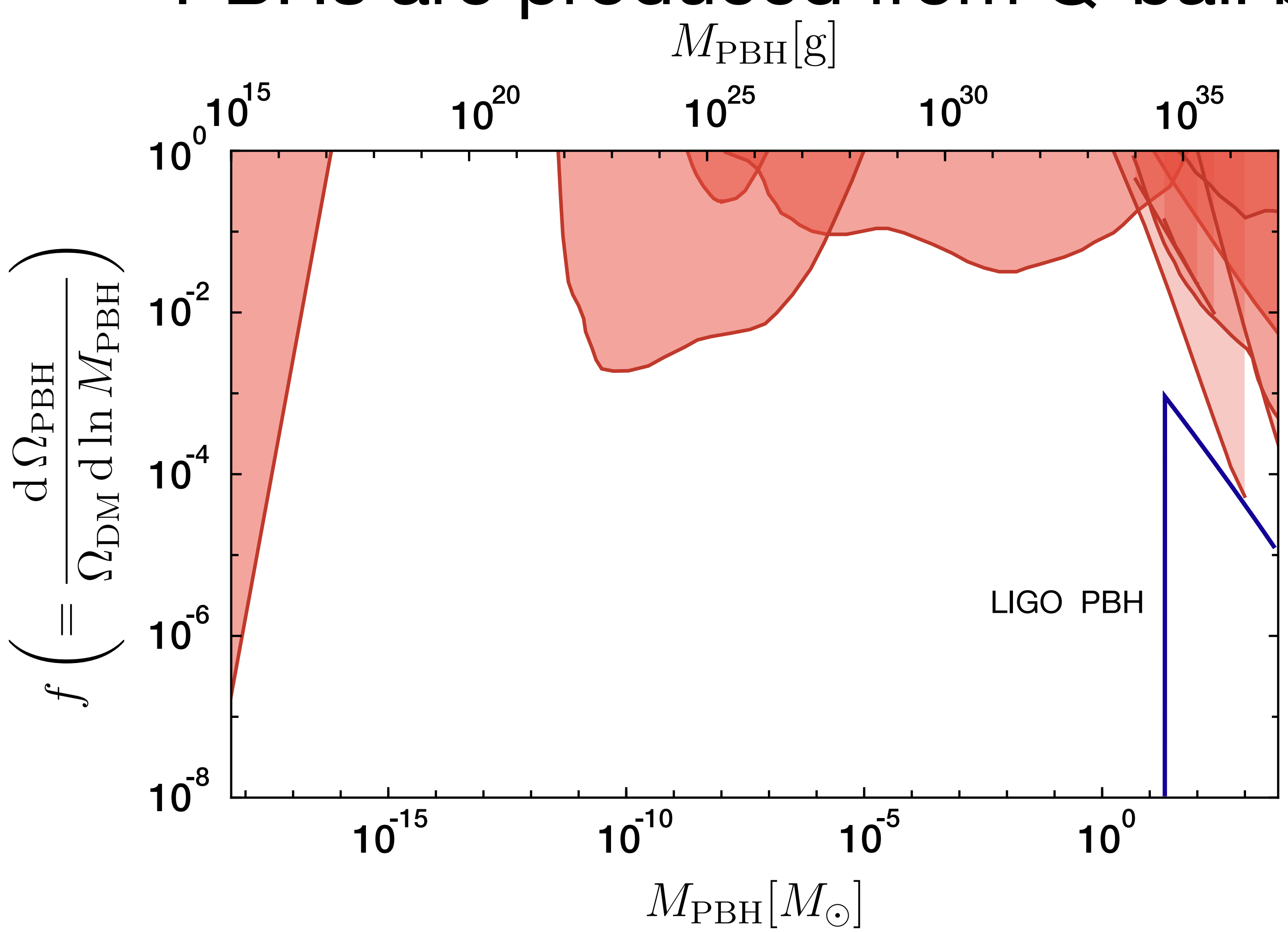
- This can be satisfied by considering Q-ball formation

2.3 PBH formation from high-baryon bubbles

- AD mechanism also produces Q-balls
- If Q-balls are stable they carry produced baryon number
- High -baryon bubbles → Q-ball bubbles
  - Q-balls are non-relativistic
- PBHs are produced from Q-ball bubbles



Hiramatsu MK Takahashi (2010)



- PBH mass has a lower cutoff

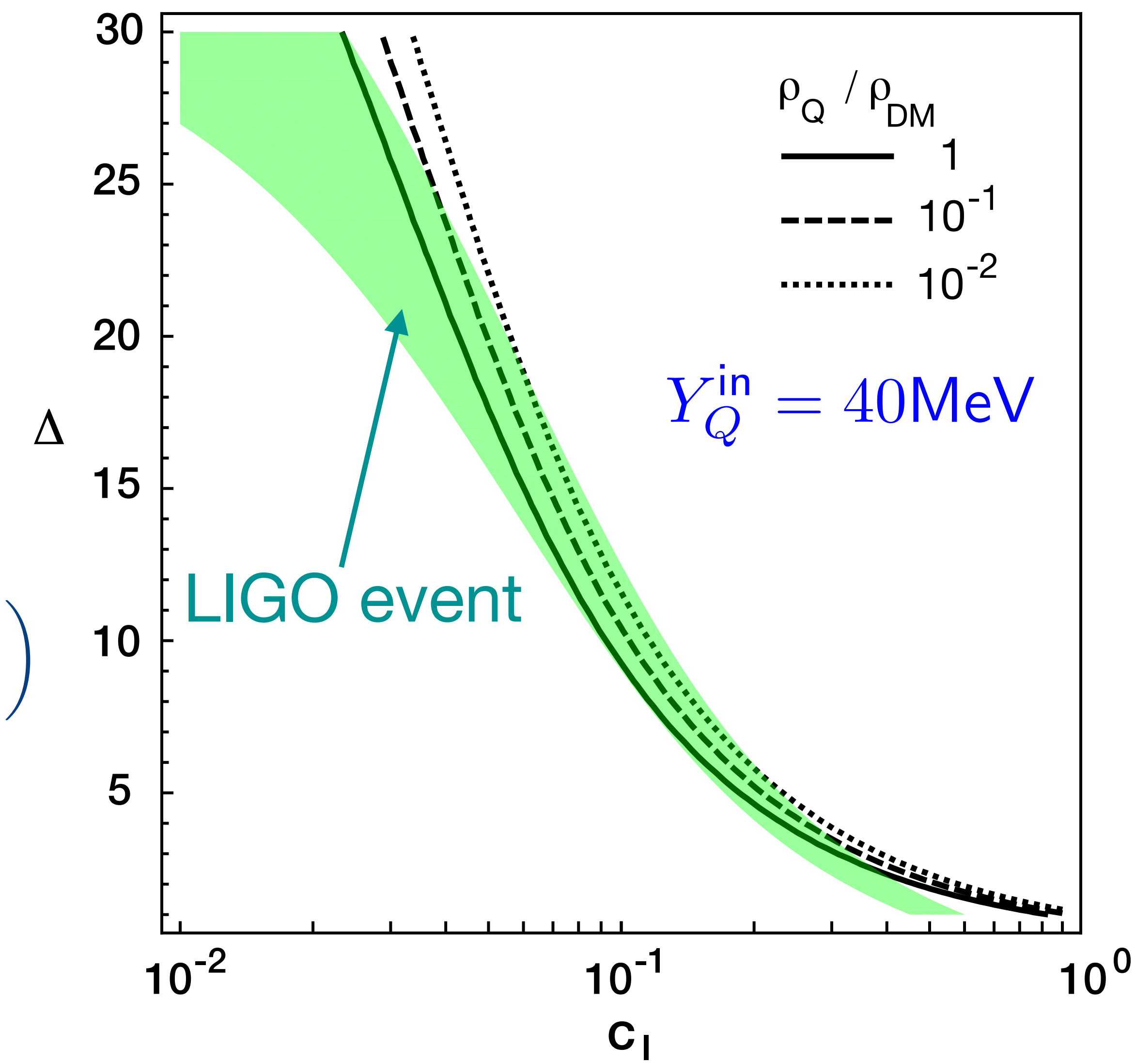
$$M_c \simeq 18 M_\odot \left(\frac{Y_Q^{\rm in}}{40{\rm MeV}}\right)^{-2}$$

$$Y_Q^{\rm in} = \rho_Q/s \simeq m_{3/2}\eta_b^{\rm in}$$

2.3 PBH formation from high-baryon bubbles

- Q-balls in HBBs with M < Mc contribute to DM
- This scenario can explain both LIGO events and DM simultaneously

$$\left(\Delta = \frac{T_R^2 M_p}{H_I^3}\right)$$



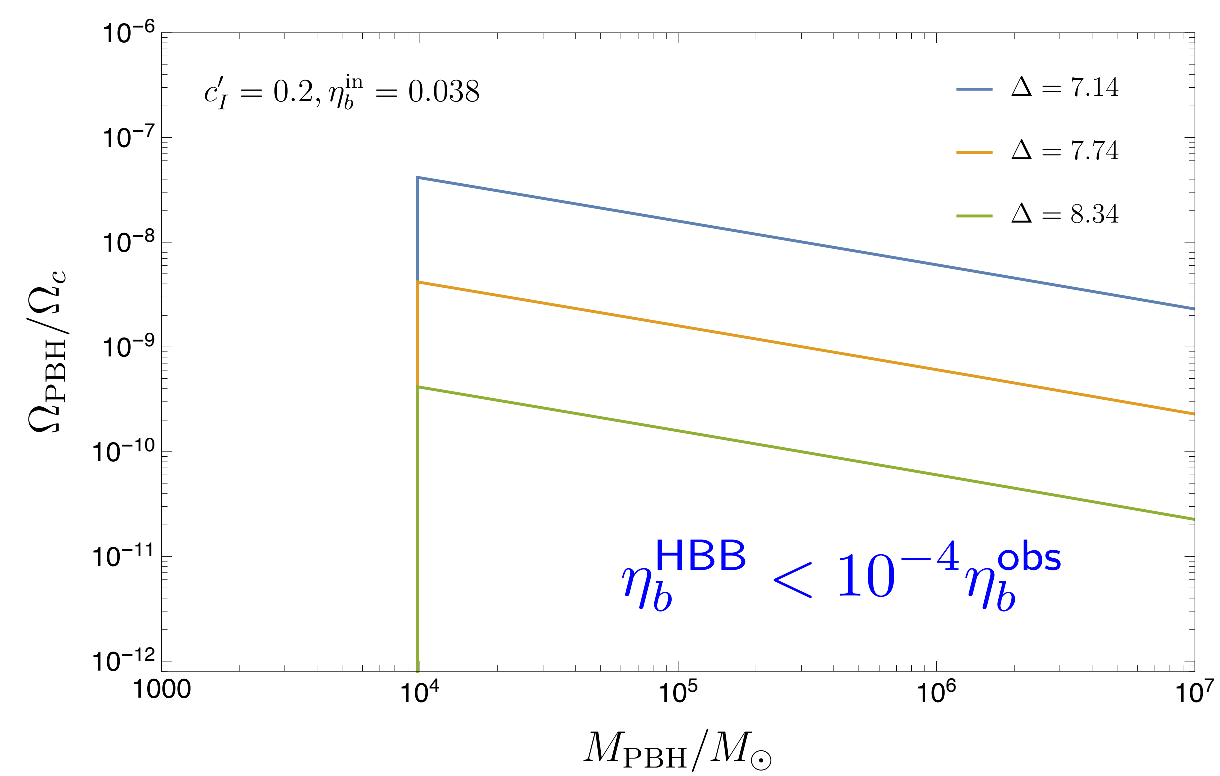
$$V \simeq c_I H^2 |\phi|^2 \quad \text{(during inflation)}$$

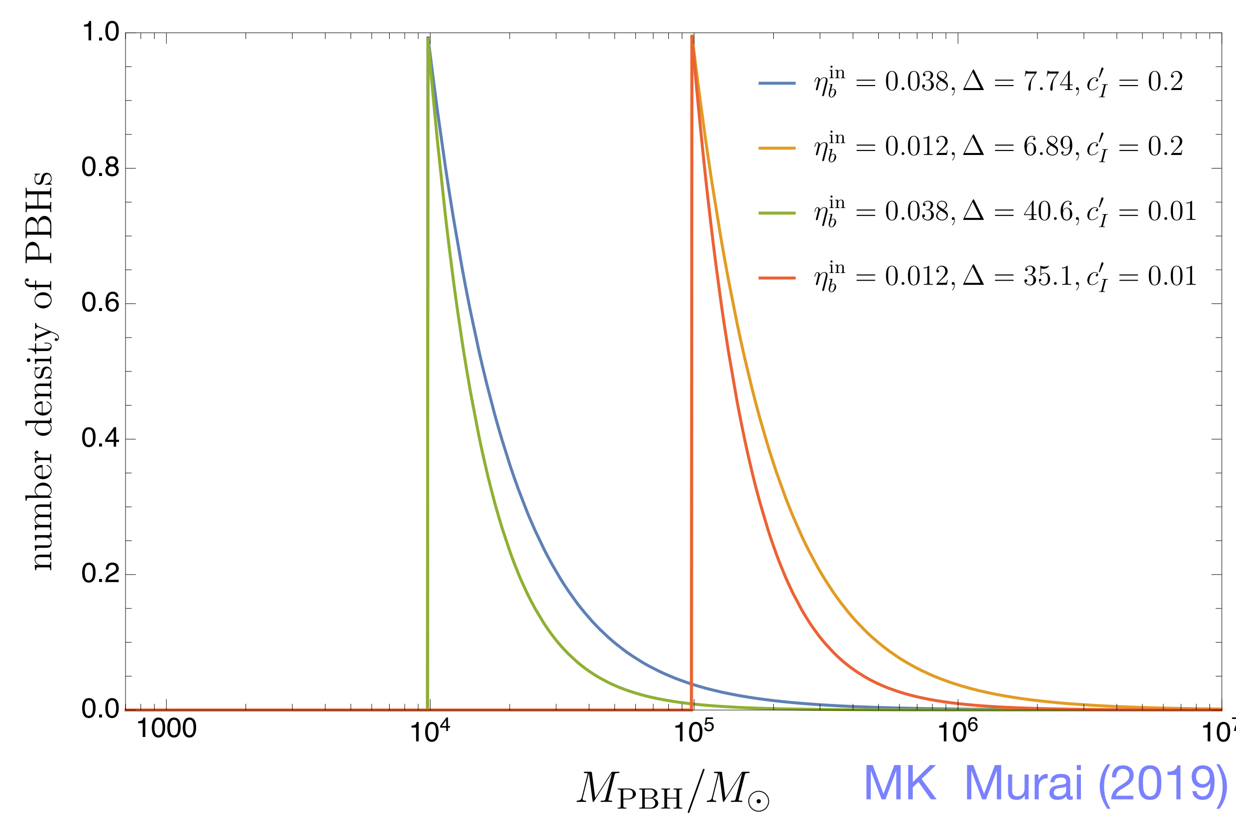
2.4 Formation of supermassive black holes (SMBHs)

- SMBHs are observed in the center of galaxies

$$M_{\mathrm{SMBH}} \simeq 10^6 - 10^{9.5}\, M_\odot$$

- Seed BHs with mass $10^{4-5} M_\odot$ already existed at z > 10
- Seed BHs are PBHs?
    - But stringent constraint from CMB spectral distortion
- AD mechanism can produce such seed BHs



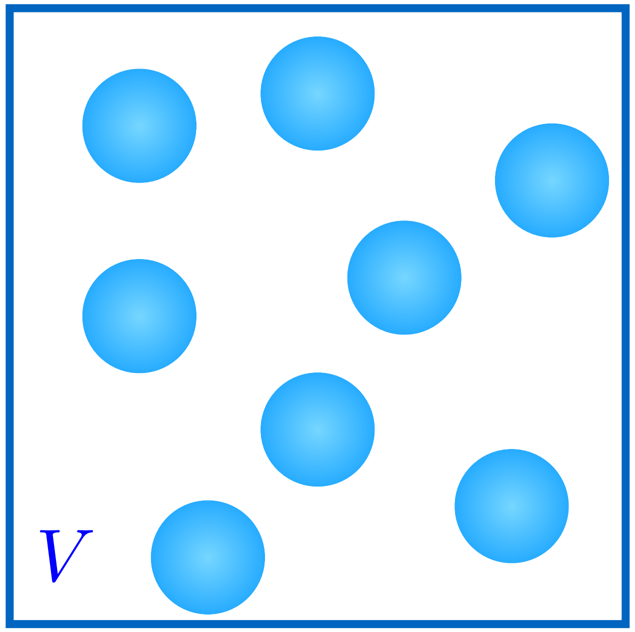


MK Murai (2019)

3. PBHs from non-topological solitons

Cotner, Kusenko (2016)
Cotner, Kusenko, Takhistov (2018)
Cotner, Kusenko, Sasaki, Takhistov (2019)

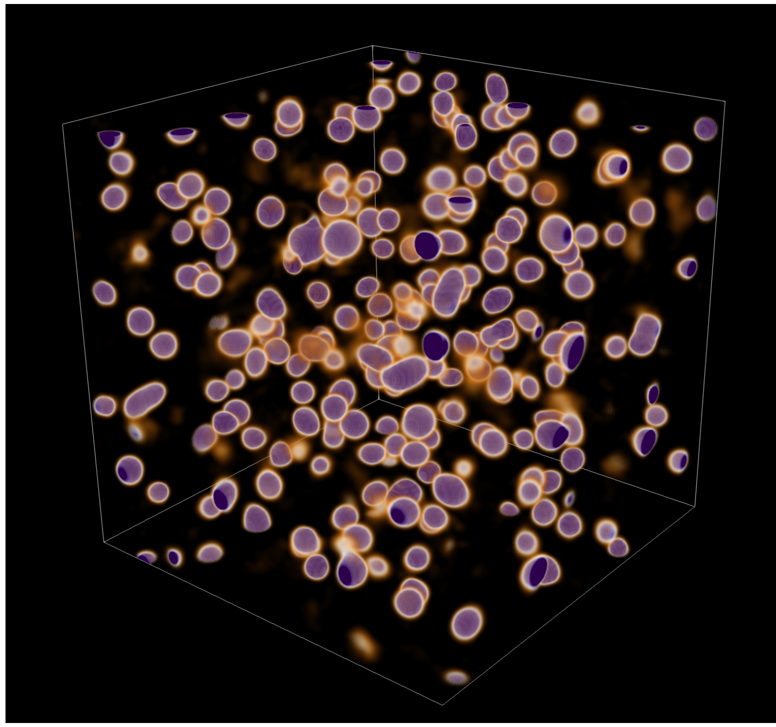
- Oscillon and Q-ball : non-topological solitons in scalar field theory
- Formed during oscillation of a scalar field in the early universe
- Suppose N solitons in a volume V
  - If N follows Poisson statistics



$$\frac{\delta N}{N} \simeq \frac{1}{\sqrt{N}}$$

$$\frac{\delta \rho}{\rho} \simeq \frac{1}{\sqrt{N}}$$

← large for small N



- After solitons dominated the universe $\delta\rho/\rho$ increases as a

→ PBH

3.1 PBH abundance

- Suppose solitons dominate Universe (e.g. scalar field = inflation)
  - PBH fraction (PBH formation matter dominated era)

$$\beta(M) = 0.56\,\sigma(M)^5 \left(\frac{M}{M_H}\right)^{10/3}$$

Harada, Yoo, K. Kohri, Nakao, Jhingan (2016)

$\sigma(M)^2$: variance of density fluctuation at scale R $\Leftarrow$ $M = \frac{4\pi}{3}\rho R^3$

- Let us consider fraction of PBHs with the horizon scale at oscillon (Q-ball) formation

$$\beta(M_H) = 0.56\,\sigma_f(M_H)^5$$

- The present PBH abundance

$$f_{\rm PBH}(M_H) = \frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}} = \frac{a_{\rm eq}}{a_R}\beta(M) \sim \frac{T_R}{T_{\rm eq}}\beta(M)$$

$$\sim \left(\frac{\sigma(M_H)}{10^{-2}}\right)^5 \left(\frac{T_R}{10^3\,{\rm GeV}}\right)$$

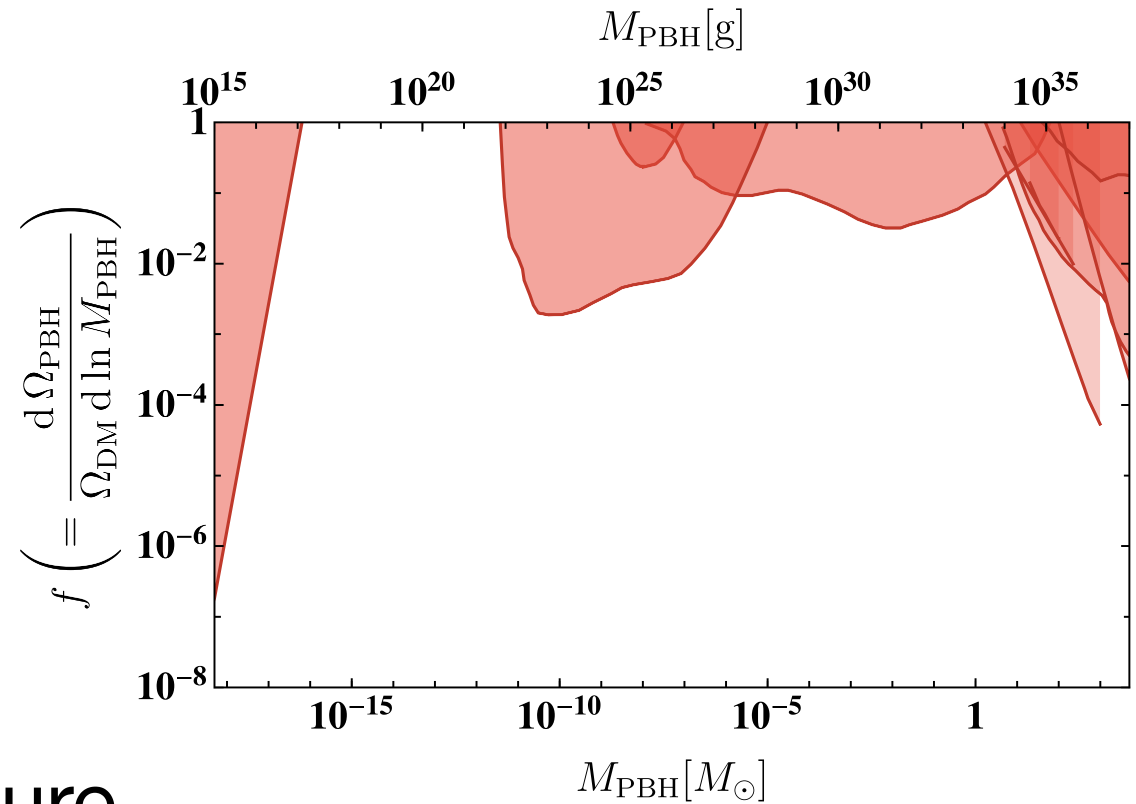
T_R : reheating temp.

$T_{\rm eq}$: temp. at matter-radiation equality

3.1 PBH abundance

- PBH mass

$$M_{\rm PBH} = \frac{4\pi}{3}\rho H_f^3 \simeq 10^{17}{\rm g}\left(\frac{H_f}{10^{-3}{\rm GeV}}\right)^{-1}$$



- Upper bound of reheating temperature
  - collapse over-density region $\sigma(t_{\rm coll}) = \sigma(t_f)(a_{\rm coll}/a_f) \sim 1$
  - Reheating must take place after collapse

$$a(t_R) \gtrsim a(t_{\rm coll}) \Rightarrow H_R = H(t_R) \lesssim H(t_{\rm coll}) = H_f(a_{\rm coll}/a_f)^{-3/2} = H_f\sigma_f^{3/2}$$

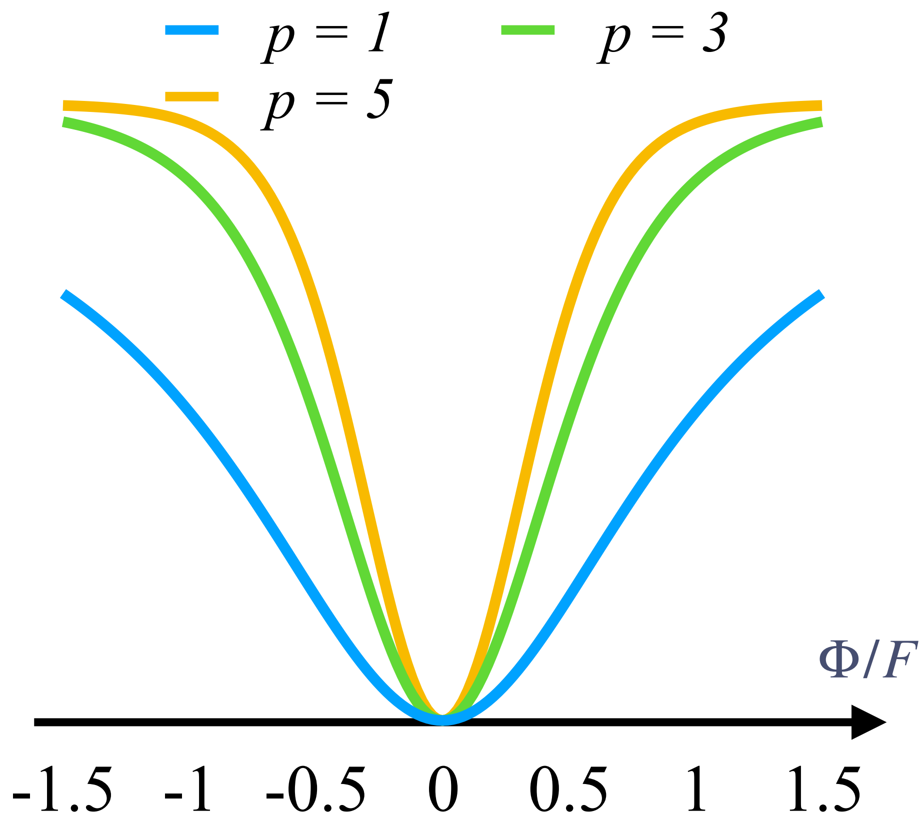
$$\Rightarrow \quad T_R \lesssim \sqrt{3H_f\sigma_f^{3/2}M_p} \sim 10^6{\rm GeV}\left(\frac{\sigma_f}{10^{-2}}\right)^{3/4}\left(\frac{H_f}{10^{-3}{\rm GeV}}\right)^{1/2}$$

- Dark matter PBHs with smaller mass

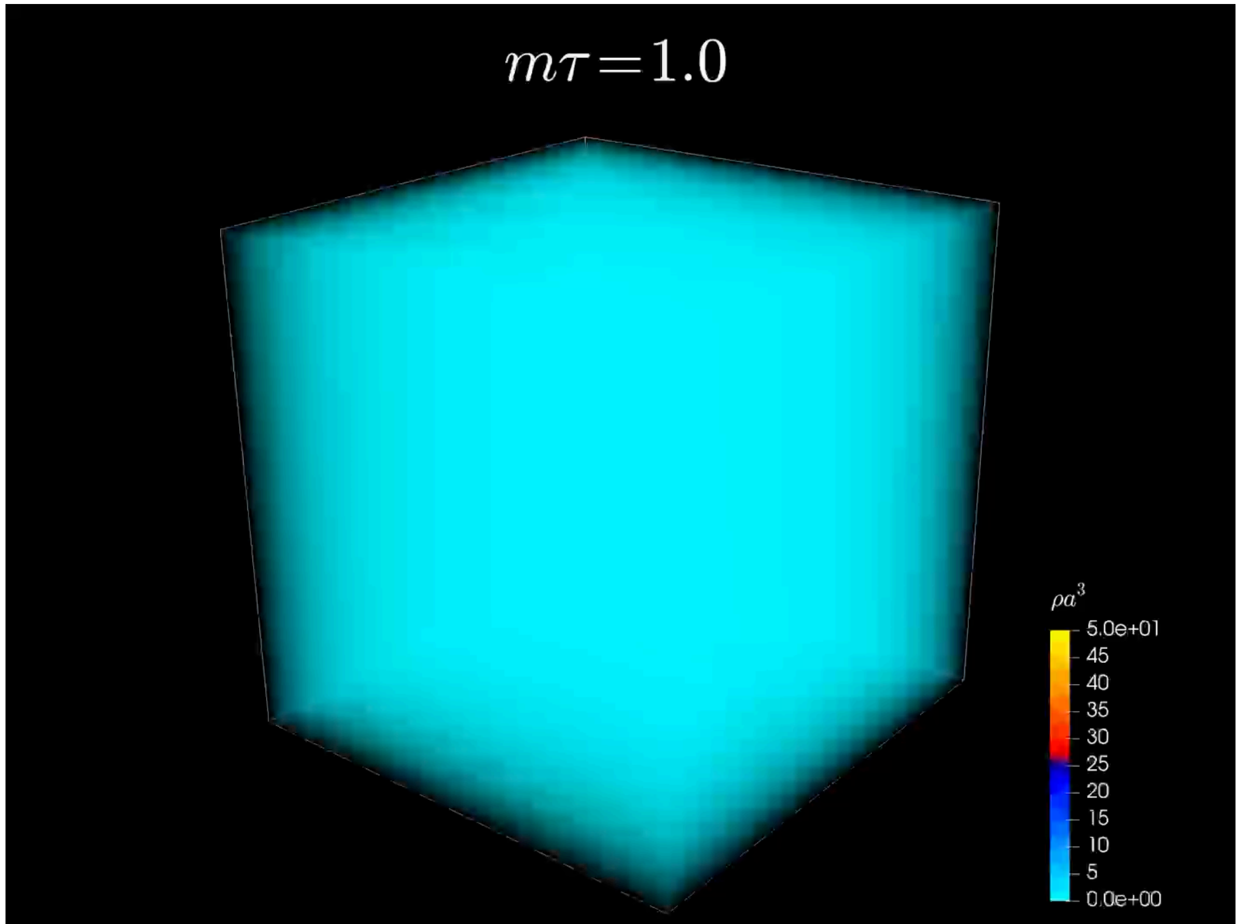
3.2 PBHs from Oscillons

- Oscillons are non-topological solitons in a real scalar field theory
- Oscilon solution exists if the potential is shallower than quadratic
  - e.g. potential for pure natural inflation Nomura Watari Yamazaki (2017)

$$V(\phi) = \frac{m^2 F^2}{2p}\left[1 - \left(1 + \frac{\phi^2}{F^2}\right)^{-p}\right]$$



- Oscilons are formed when the scalar field starts to oscillate



Sonomoto (2019)

3.3 Lattice simulation of oscillon

- We estimate the variance $\sigma(R)$ by performing lattice simulations

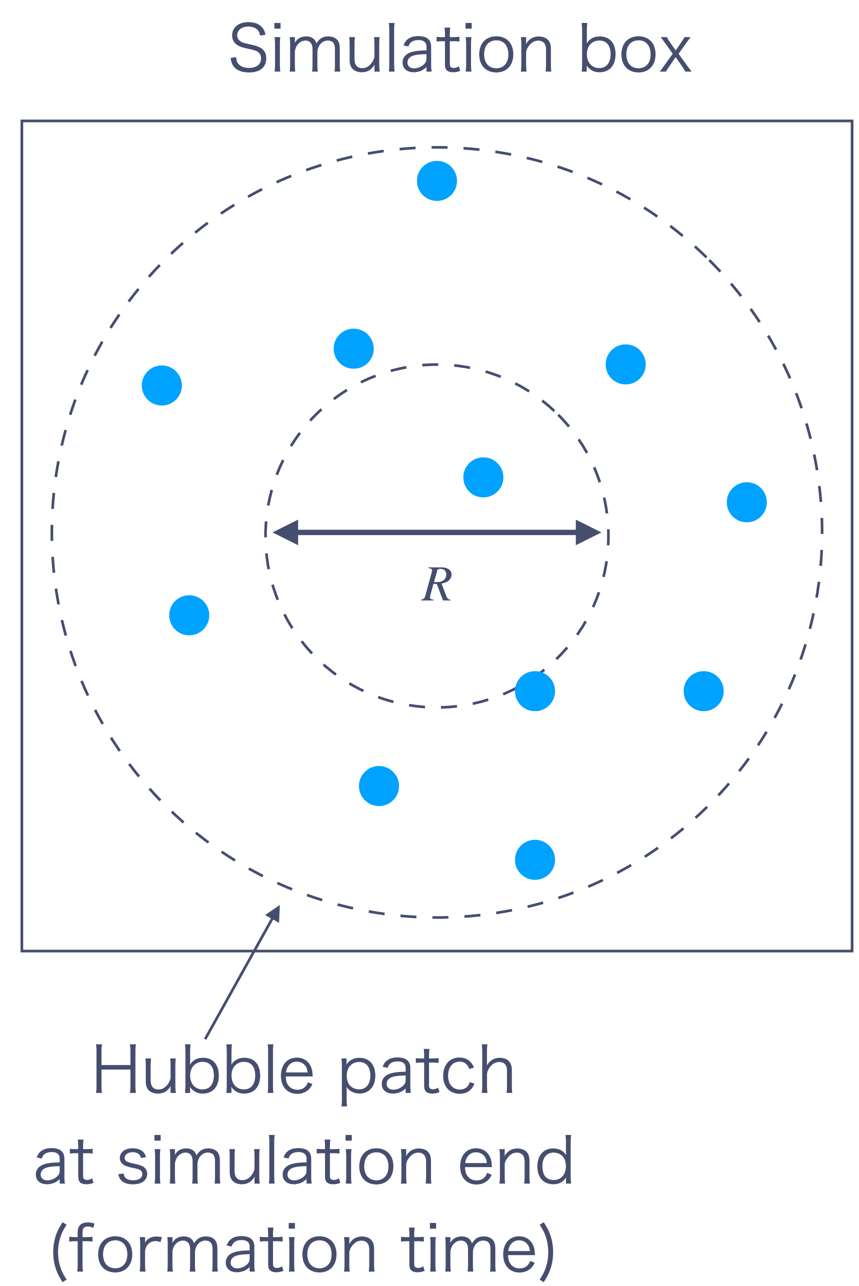
- Simulation setup
  - 2-dimensional simulation (grid 1023^2)
  - calculate the energy in sub-horizon scale R
  - 500 realizations
  - potential

$$V(\phi) = \frac{m^2 F^2}{2p}\left[1 - \left(1 + \frac{\phi^2}{F^2}\right)^{-p}\right]$$

$$p = 4 \qquad F/M_p = 0.09$$

Pure natural inflation model

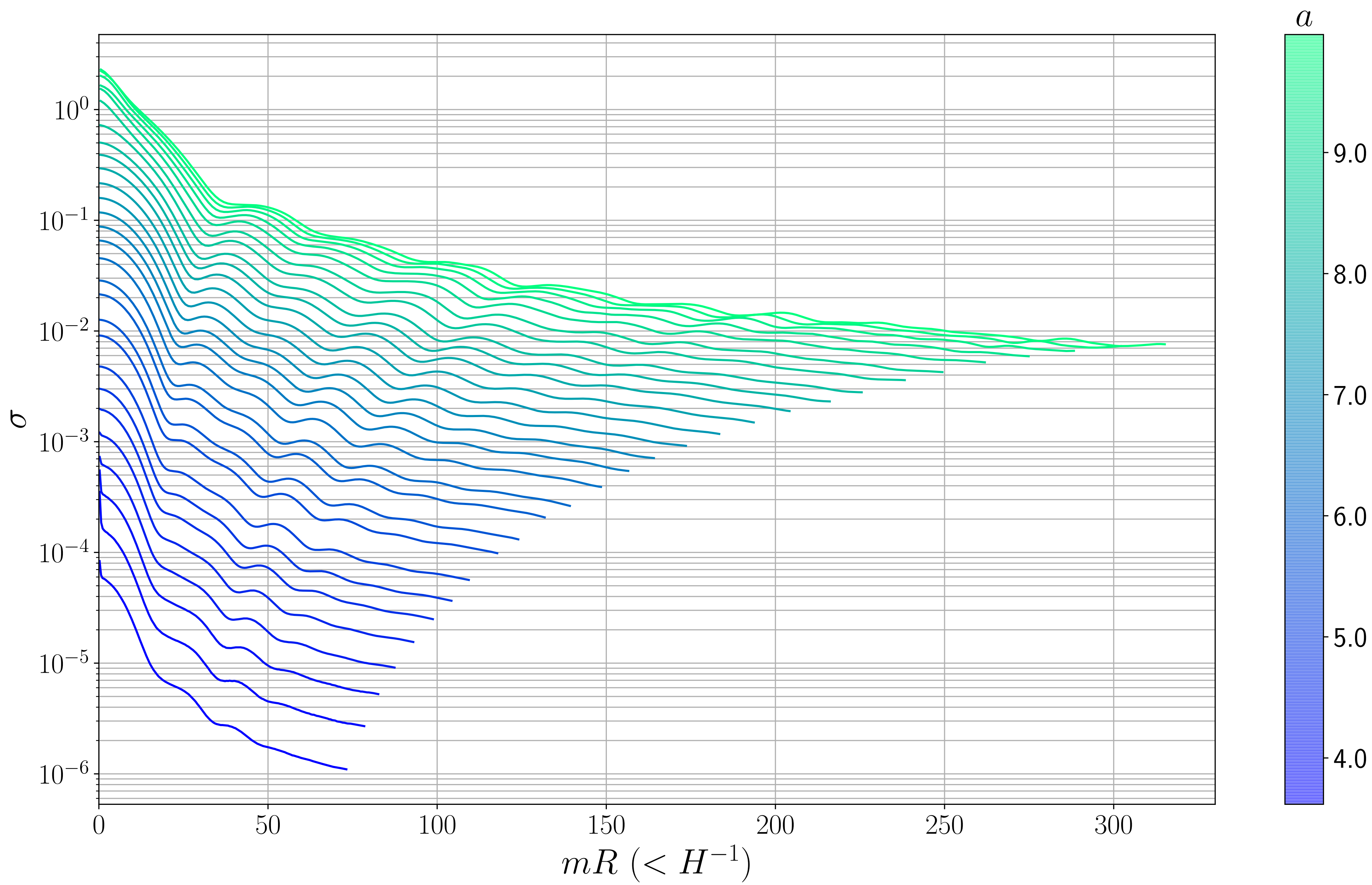
Nomura Watari Yamazaki (2017)



3.4 Result of lattice simulation

- The energy variance of the horizon scale at the oscillon formation time

$$\sigma_f^{2D} = \sigma(H_f^{-1}) \simeq 10^{-2}$$



3.5 PBH formation from oscillons

- We have estimated energy variance in 2D simulations

$$\sigma_f^{2D} = \sigma(H_f^{-1}) \simeq 10^{-2}$$

- If $\sigma_f^{3D} \sim \sigma_f^{2D}$ PBHs can be all dark matter of the universe
- If the number of oscillons follows Poisson statistics, 3D variance would be smaller
    - Naive estimation $N \propto V \quad \Rightarrow \quad N^{3D} = (N^{2D})^{3/2}$

$$\rightarrow \quad \sigma_f^{3D} \sim \frac{1}{\sqrt{N^{3D}}} \sim \frac{1}{\left(\sqrt{N^{2D}}\right)^{3/2}} \sim \left(\sigma_f^{2D}\right)^{3/2}$$

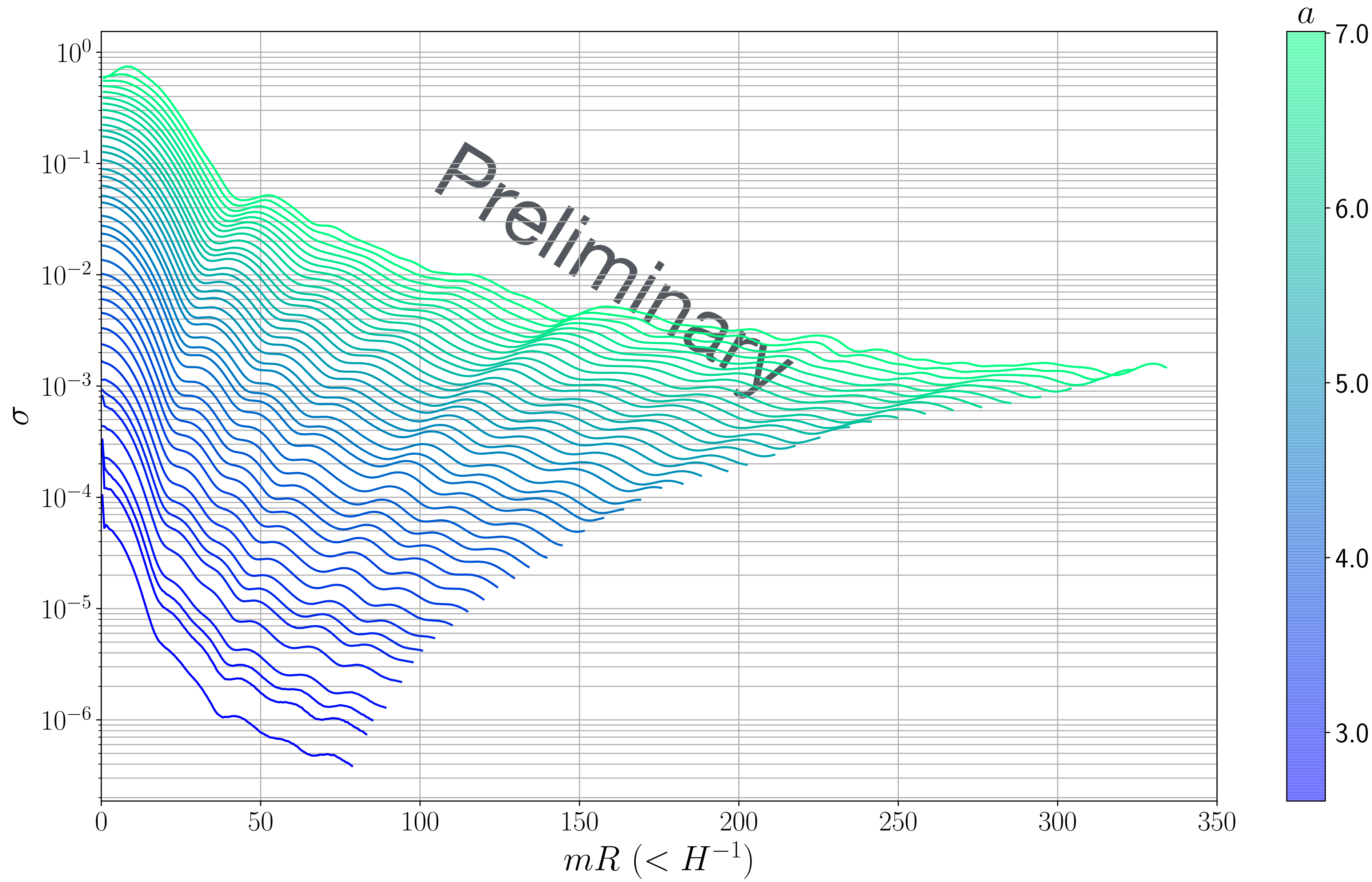
- PBH abundance

$$f_{\text{PBH}}(M_H) = \frac{\Omega_{\text{PBH}}}{\Omega_{\text{DM}}} \sim 0.01 \left(\frac{\sigma_f^{2D}}{10^{-2}}\right)^{15/2} \left(\frac{T_R}{10^6\,\text{GeV}}\right)$$

- There may be uncertainty in estimation of 3D variance

3.5 PBH formation from oscillons

- 3D simulation $\sigma_f^{3D} = \sigma(H_f^{-1}) \simeq 2 \times 10^{-3}$



$$f_{\mathrm{PBH}}(M_H) \sim 0.6 \left(\frac{\sigma^{3D}(M_H)}{2 \times 10^{-3}} \right)^5 \left(\frac{T_R}{10^6 \mathrm{GeV}} \right)$$

- PBHs can account for a significant fraction of dark matter

7. Conclusion

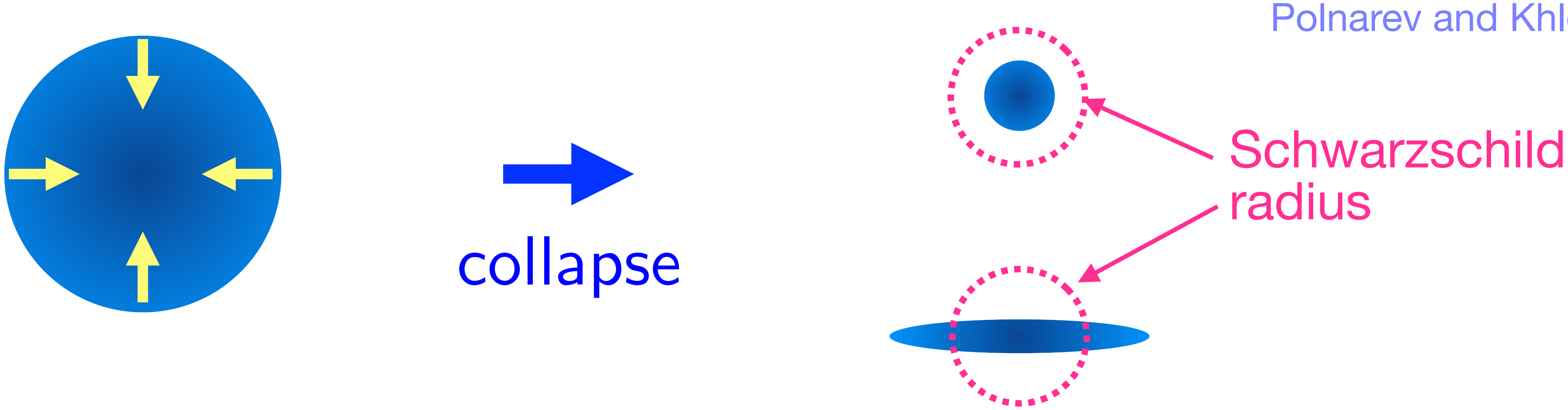
- Affleck-Dine mechanism produces HBBs which form PBHs with > O(10) solar mass
- The model can account for LIGO events or Supermassive BHs evading the constraints from CMB spectral distortion and pulsar timing
- Lattice simulations suggest that non-topological solitons could produce density fluctuations which collapse into PBHs

Backup slides

2.2 PBH formation in matter dominated era

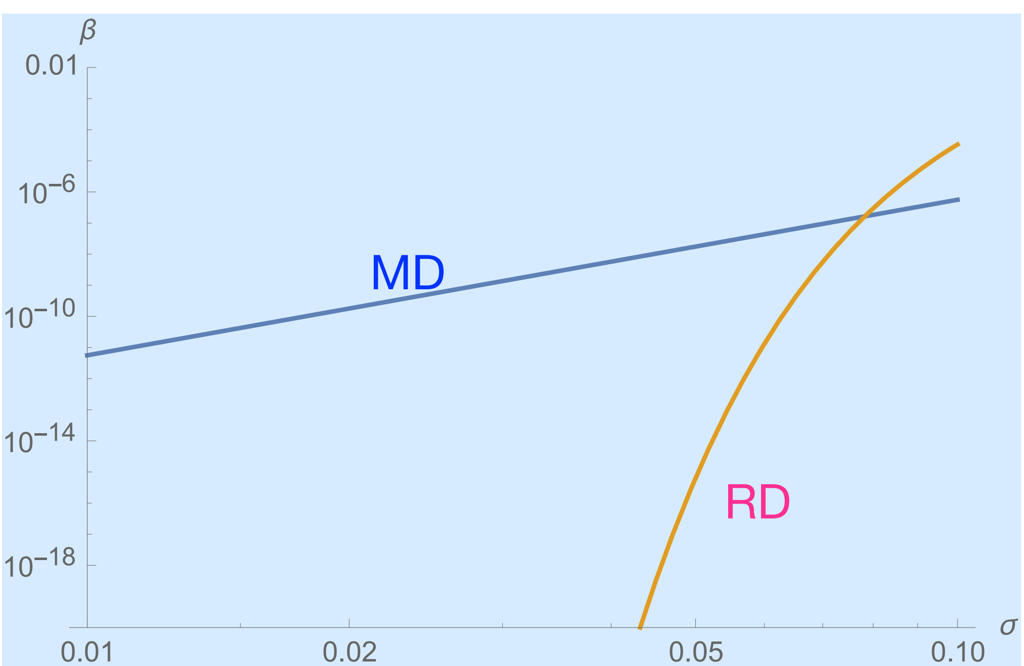
- Density perturbations grow and gravitationally collapse in MD
  - PBHs are more easily produced?
  - Collapse should be spherical to form a PBH

Polnarev and Khlopov (1985)



- Recent analysis Harada, Yoo, K. Kohri, Nakao, Jhingan (2016)

$$\beta(M) = 0.056\sigma(M)^5 \left(\frac{M}{M_H}\right)^{-2}$$



3.2 Constraint from CMB spectral distortion

- Photon diffusion erases small-scale curvature perturbations

→ Silk damping $k_d \sim 4 \times 10^{-6} \text{Mpc}^{-1} (1+z)^{3/2}$

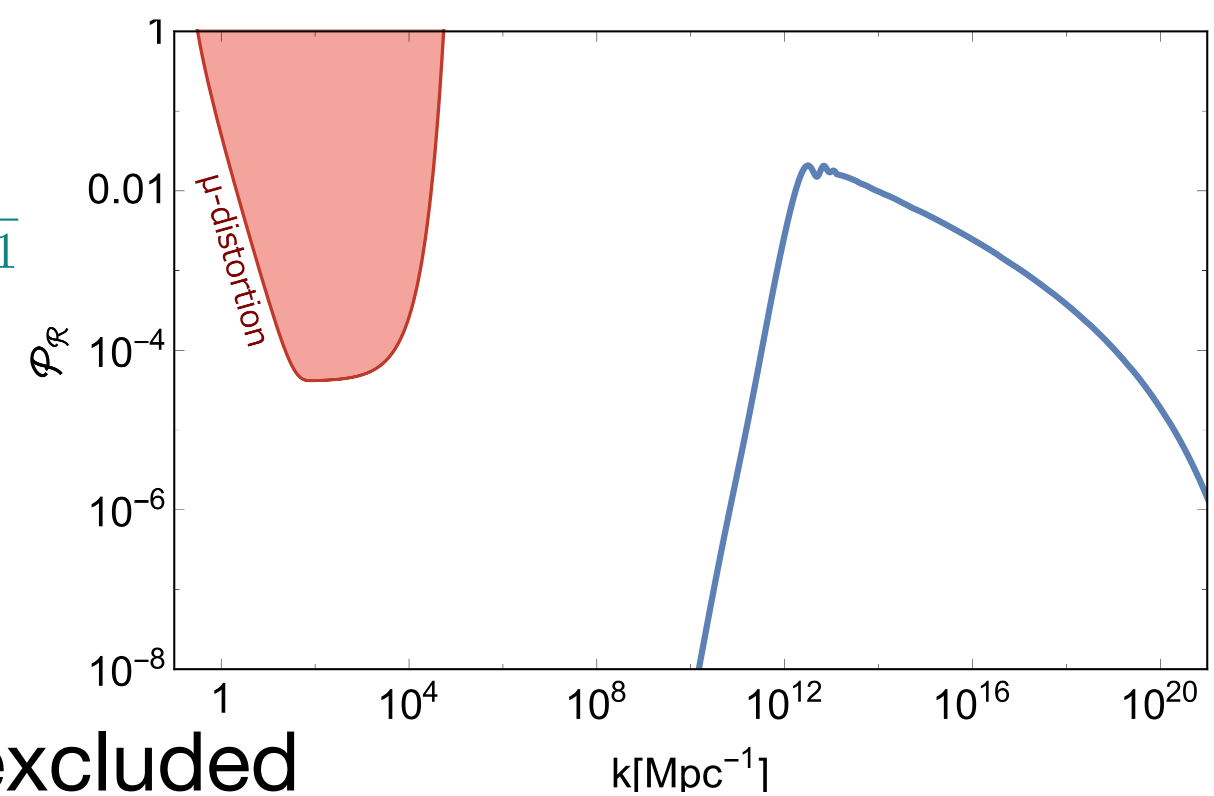
- Diffusion injects energy of perturbations into background
  - Planck distribution is re-established at $z \gtrsim 2 \times 10^6$ by double Compton scattering $(e^- + \gamma \to e^- + \gamma + \gamma)$

→ CMB spectral distortion (mu distortion) at $z \lesssim 2 \times 10^6$

- CMB observation (COBE/FIRAS)

$|\mu| < 9 \times 10^{-5}$ $\quad f(p) = \frac{1}{\exp(p/T + \mu) - 1}$

  - Stringent constraint on curvature perturbations



- PBH with mass

$400 M_\odot \lesssim M_{\text{PBH}} \lesssim 10^{13} M_\odot$ is excluded

3.3 Constraint from pulsar timing

- Large curvature perturbations required for PBH induce tensor perturbations (gravitational waves) through 2nd order effect

Saito Yokoyama (2009) Bugaev Kulimai (2010)

$$h''_{\vec{k}} + 2\mathcal{H}h'_{\vec{k}} + k^2 h_{\vec{k}} = \mathcal{S}(\vec{k}, t)$$

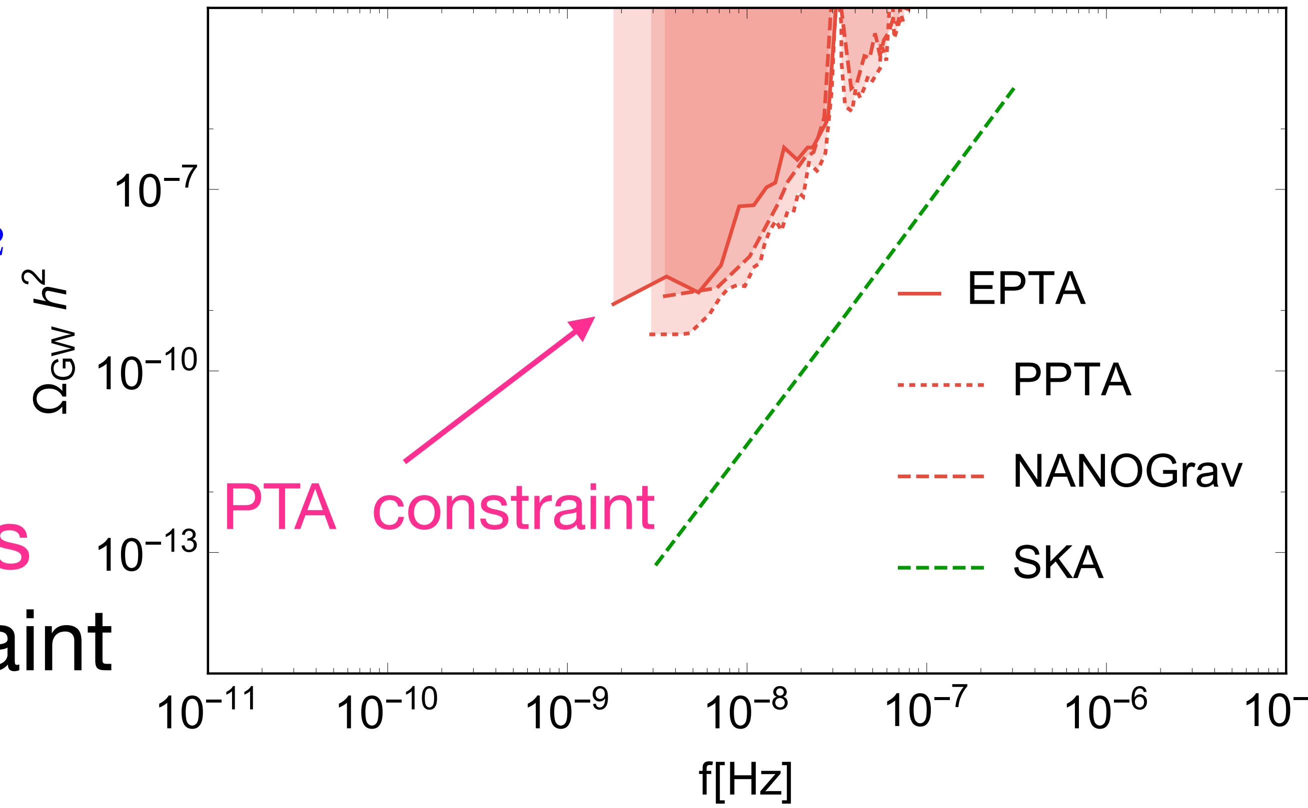
$O(\zeta_{\vec{k}}\zeta_{\vec{k}-\vec{k}'})$

h_k : tensor perturbation

$$\rightarrow \quad \Omega_{\rm GW} h^2 \sim 10^{-8} (\mathcal{P}_\zeta / 10^{-2})^2$$

$$f_{\rm GW} \sim 2 \times 10^{-9} {\rm Hz} \left(\frac{\gamma}{0.2}\right)^{1/2} \left(\frac{M_{\rm PBH}}{M_\odot}\right)^{-1/2}$$

- Pulsar timing array experiments already give a stringent constraint



- PBH with mass

$$0.1 M_\odot \lesssim M_{\rm PBH} \lesssim 10 M_\odot$$ is excluded

5.1 Hawking radiation

- Hawing radiation

$$T_{\rm H} = \frac{1}{8\pi G M_{\rm PBH}} \sim 10^{-7}{\rm K}\left(\frac{M_{\rm PBH}}{M_\odot}\right)^{-1} \sim 1{\rm TeV}\left(\frac{M_{\rm PBH}}{10^{10}{\rm g}}\right)^{-1}$$

$$\frac{dM_{\rm PBH}}{dt} \simeq -5\times 10^5{\rm g\ s^{-1}} f(M_{\rm PBH})\left(\frac{M_{\rm PBH}}{10^{10}{\rm g}}\right)^{-2}$$

$$\tau \simeq 6\times 10^3{\rm s} f^{-1}(M_{\rm PBH})\left(\frac{M_{\rm PBH}}{10^{10}{\rm g}}\right)^{3}$$

$dM/dt \sim (\sigma T_{\rm H}^4)(4\pi r_s^2) \propto M_{\rm PBH}^{-2}$

$f(M_{\rm PBH}) \simeq 1 - 15$

- PBHs with mass > 10^{15} g survive today
- PBHs with mass ~ 10^{15} g are evaporating today
  - extra-galactic gamma rays
- PBHs with mass < 10^{15} g have evaporated by now
  - effects on processes in the early universe (BBN, CMB,….)