Workshop: Inflation and the dark sector — Current challenges and future perspectives June 3-7 (2019) @Jyväskylä

Primordial Black Hole Formation in Affleck-Dine Mechanism

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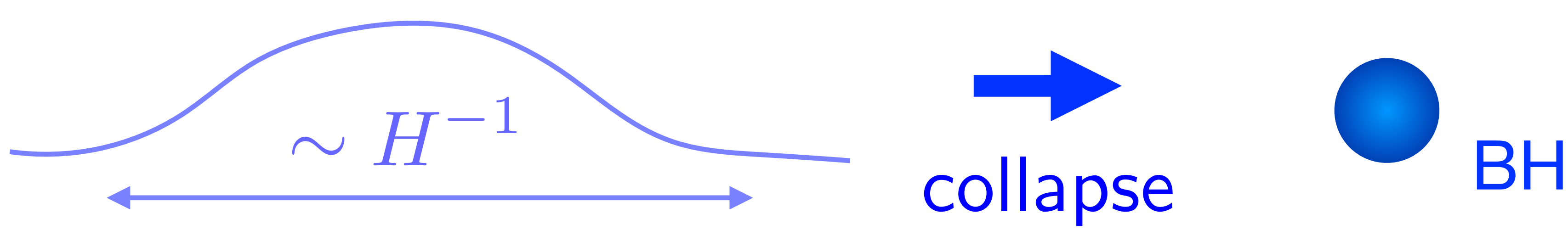
Based on Hasegawa MK arXiv:1711.00990 PRD98 043514 (2018)
arXiv:1807.00463 JCAP 01 027 (2019)

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 (>10^{15} g)
  - Account for GW events recently detected by LIGO-Virgo
- PBHs can be formed by gravitational collapse of over-density region with Hubble radius in the early universe



- Large density fluctuations δ with O(0.1) are required for PBH formation but δ ~ O(10^{-5}) on CMB scale

→ need to break scale invariance of spectrum of density fluctuations

- It is difficult to realize large density fluctuations in a single-field inflation

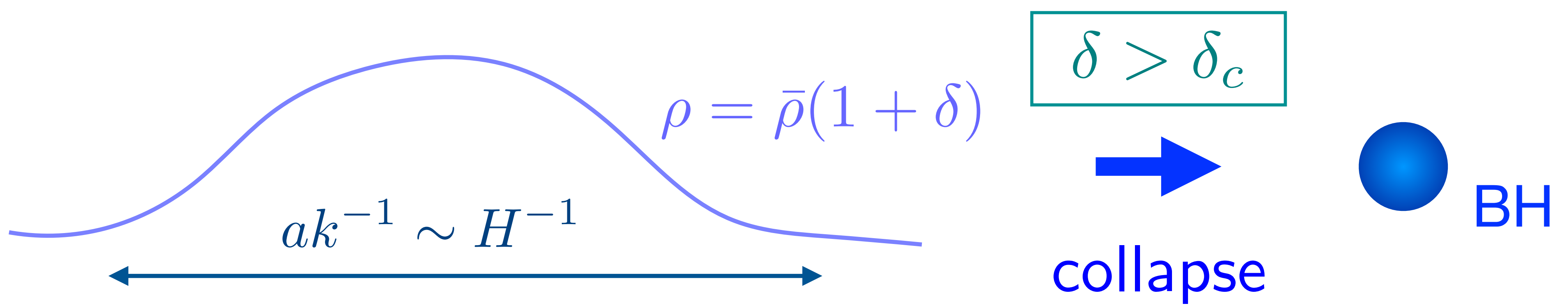
- Sophisticated models are proposed
  - Multi-stage inflation
    Garcia-Belliido Linde Wands (1996)
    MK, Sugiyama, Yanagida (1998)
    MK Kusenko Tada Yanagida (2016) . . . . .
  - Axion-like curvaton model
    MK, Kitajima, Yanagida (2012)
    Ando, Inomata, MK, Mukaida, Yanagida (2017)
  - . . . .

- PBH formation by Affleck-Dine mechanism
  Dolgov, Silk (1993)
  Dogov MK Kevlishvili (2009)
  Hsegawa, MK (2018)
  - High-baryon bubbles are formed
    → LIGO PBHs
  - Evades constrains from pulsar timing and CMB mu-distortion which are severe for PBH formation from inflation

Contents

2. Conventional PBH formation from inflation

- After inflation, when density fluctuations reenter the horizon, region with Hubble radius collapses to form a PBH if its over-density is higher than δ_c (≈0.4)



- PBH mass (~ Horizon mass)

$$M_{\rm PBH} \simeq 3.6 M_\odot \left(\frac{\gamma}{0.2}\right)\left(\frac{k}{10^6{\rm Mpc}^{-1}}\right)^{-2} \simeq 4.5 M_\odot \left(\frac{\gamma}{0.2}\right)\left(\frac{T}{0.1{\rm GeV}}\right)^{-2}$$

$M_{\rm PBH} = \gamma M_H$ (horizon mass)

[$\gamma = 0.2$ Carr (1975)]

2. Conventional PBH formation from inflation

- PBH abundance is estimated by Press-Schechter formalism assuming density fluctuations follow Gaussian statistics

- PBH mass fraction $\beta = \rho_{\rm PBH}(M)/\rho$

$$\beta(M) = \int_{\delta_c} d\delta \frac{1}{\sqrt{2\pi\sigma^2(k)}} \exp\left(-\frac{\delta^2}{2\sigma^2(k)}\right)$$

$$\mathcal{P}_\zeta(k)$$

$$\sigma^2(k) = \int d\log k' \, W^2(k'/k) \frac{16}{81} (k'/k)^4 \mathcal{P}_\zeta(k')$$

$\sigma^2(k)$: variance of the comoving density perturbation coarse-grained on k^{-1}

→ $\mathcal{P}_\zeta(k) \sim O(10^{-2})$ for PBH formation

- Present PBH fraction to DM

$$f_{\rm PBH}(M) = \frac{\Omega_{\rm PBH}(M)}{\Omega_{\rm DM}} \simeq 1.3 \times 10^8 \, \beta(M) \left(\frac{M_{\rm PBH}}{M_\odot}\right)^{-1/2}$$

[fraction per log M]

3.1 Constraint from CMB spectral distortion

- Photon diffusion erases small-scale curvature perturbations

  → Silk damping

- Diffusion injects energy of perturbations into background

  → CMB spectral distortion (mu distortion)

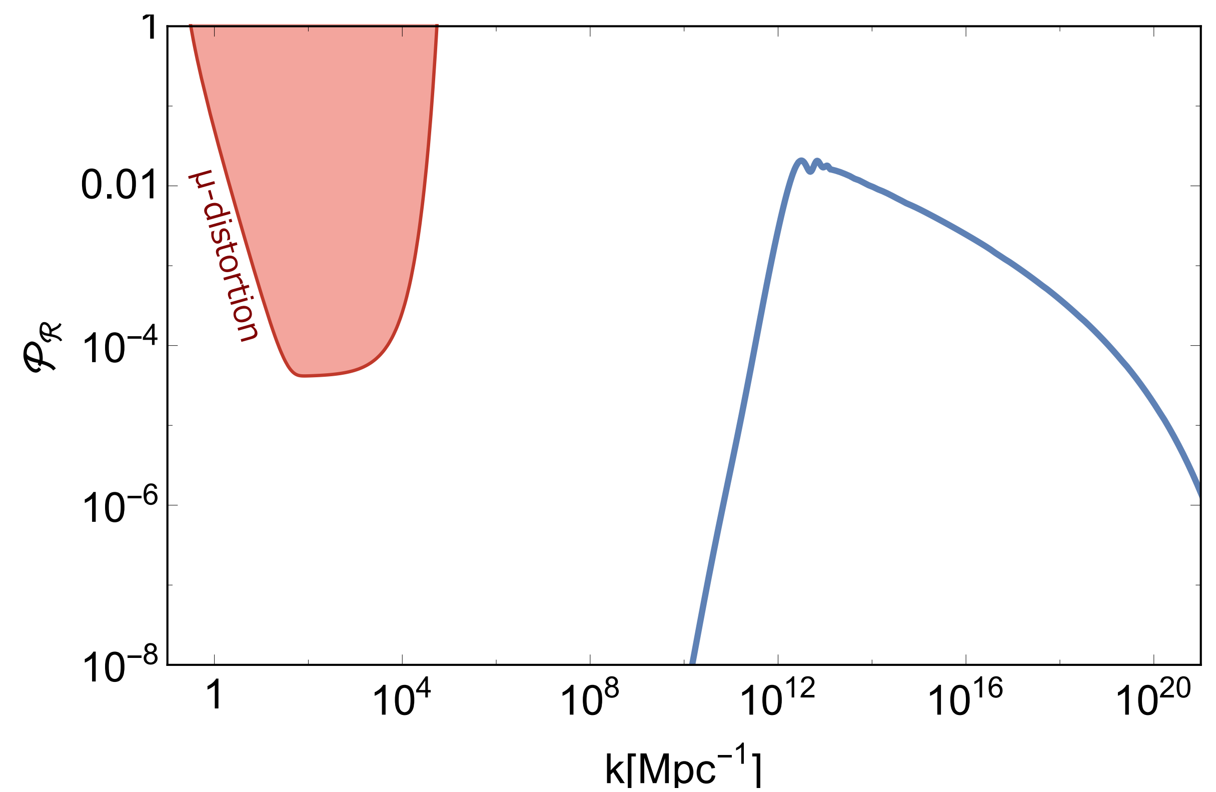
$$f(p) = \frac{1}{\exp(p/T + \mu) - 1}$$

- CMB observation (COBE/FIRAS)

$$|\mu| < 9 \times 10^{-5}$$

▷ Stringent constraint on curvature perturbations

↓



- PBH with mass

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

3.2 Constraint from pulsar timing

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

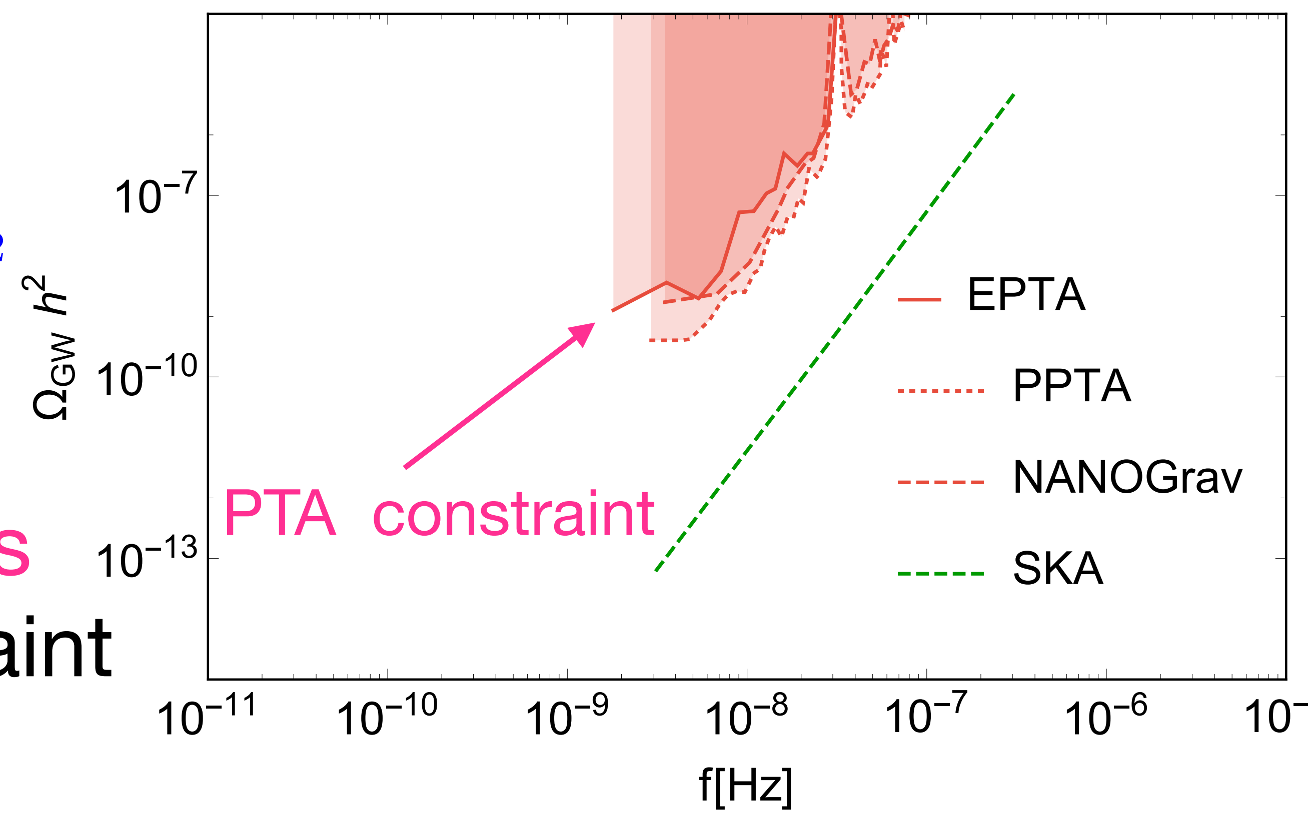
Saito Yokoyama (2009) Bugaev Kulimai (2010) $O(\zeta_{\vec{k}}\zeta_{\vec{k}-\vec{k}'})$

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

h_k : tensor perturbation

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

$$f_{\rm GW} \sim 2\times10^{-9}{\rm Hz}\left(\frac{\gamma}{0.2}\right)^{1/2}\left(\frac{M_{\rm PBH}}{M_\odot}\right)^{-1/2}$$



- Pulsar timing array experiments already give a stringent constraint

- PBH with mass

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

3.3. LIGO-Virgo gravitational wave events

- GW events by LIGO   Abbott et al (2016, 2017)

  ➡ BH-BH binaries with ~ 30 $M_{\odot}$

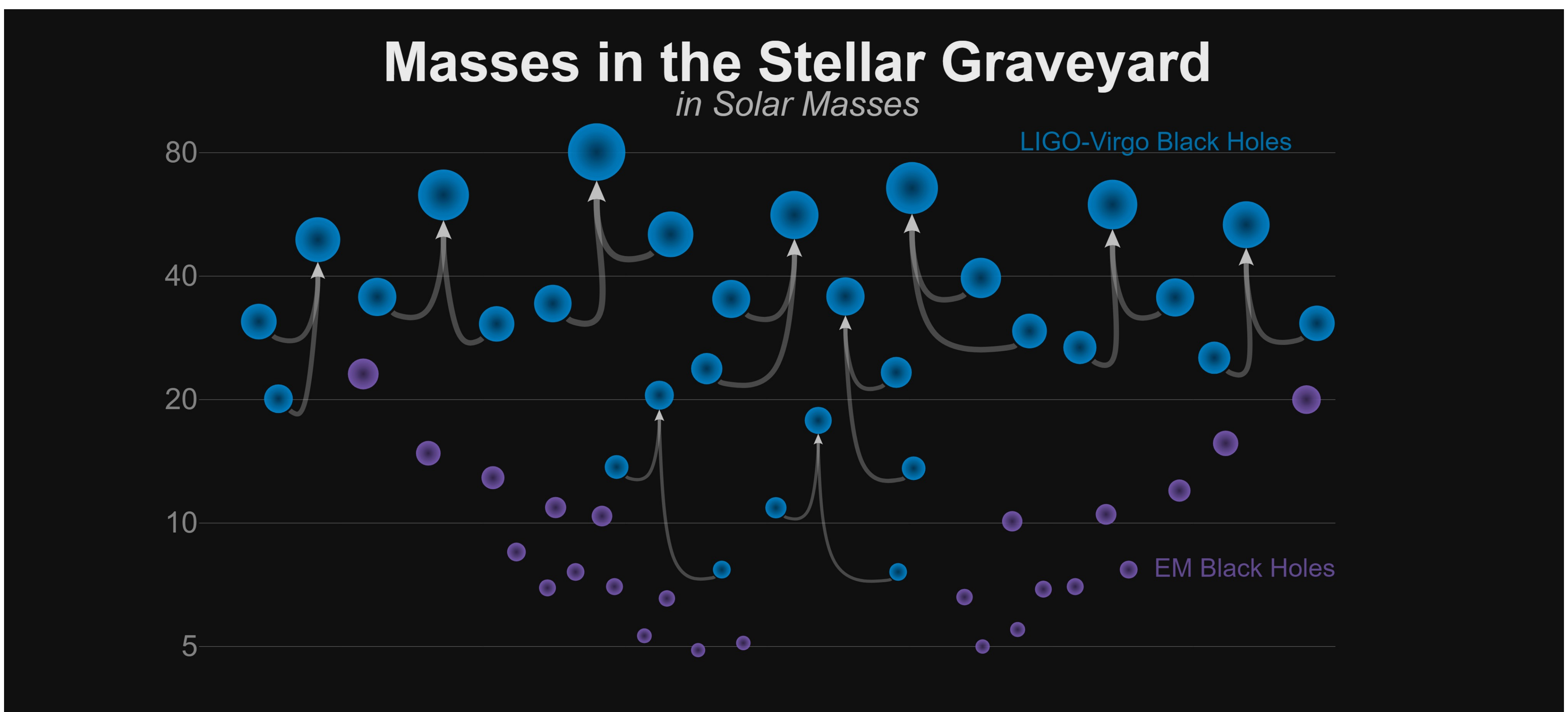
- Origin of BHs

  ➡ PBHs are one of candidates

- Required fraction of PBHs

  Sasaki Suyama Tanaka Yokoyama (2016)

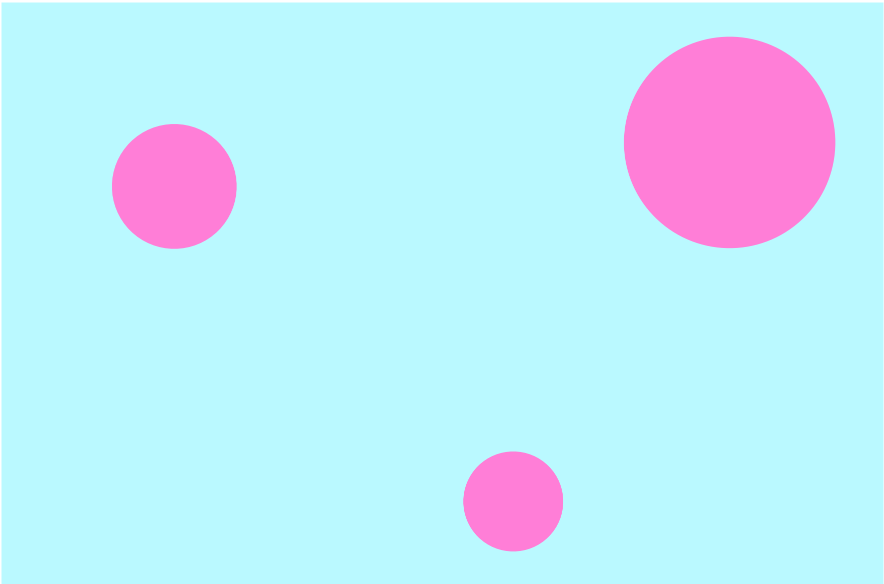
$$\Omega_{\mathrm{PBH}}/\Omega_c \sim 10^{-3} - 10^{-2}$$



3.3 Gaussian fluctuations

- In order to account LIGO events PBH mass spectrum has a sharp peak around $M_{\mathrm{PBH}} \sim O(10) M_\odot$
- PBH with mass $> \mathrm{O}(100) M_\odot$ cannot be produced

- Highly non-gaussian model evades those constraints
  - Rare high density regions
  - small density fluctuation outside the regions



4.1 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

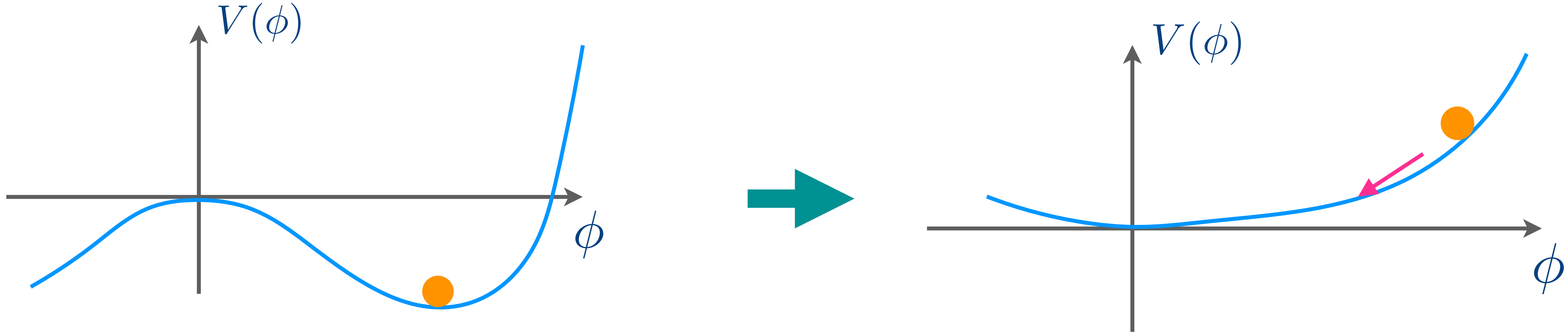
Hubble induced mass term

V_{NR} : Non-renormalizable term (n≥1)

V_A : A-term

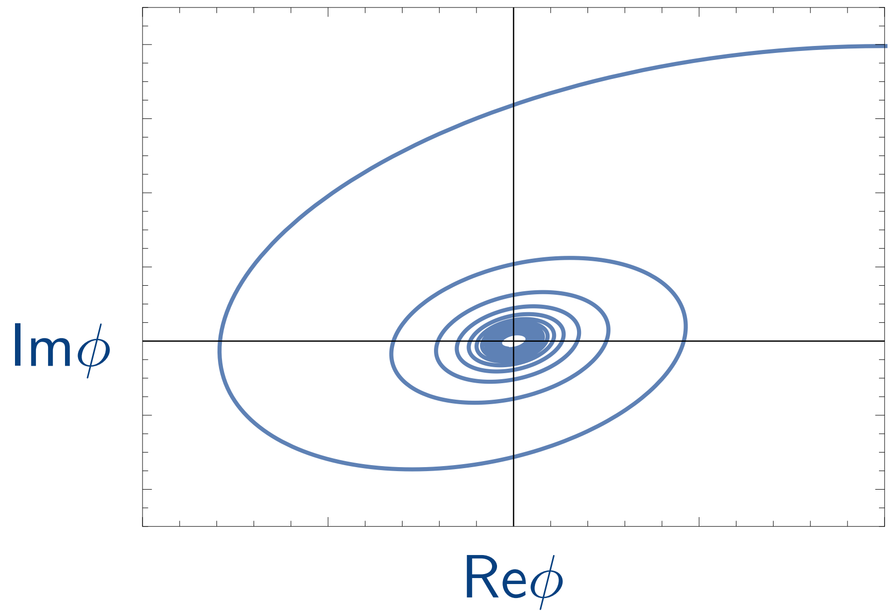
$$A = \lambda a_M m_{3/2} \quad (m_{3/2} : \text{gravitino mass})$$

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



4.1 PBH formation in Affleck-Dine baryogenesis

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



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

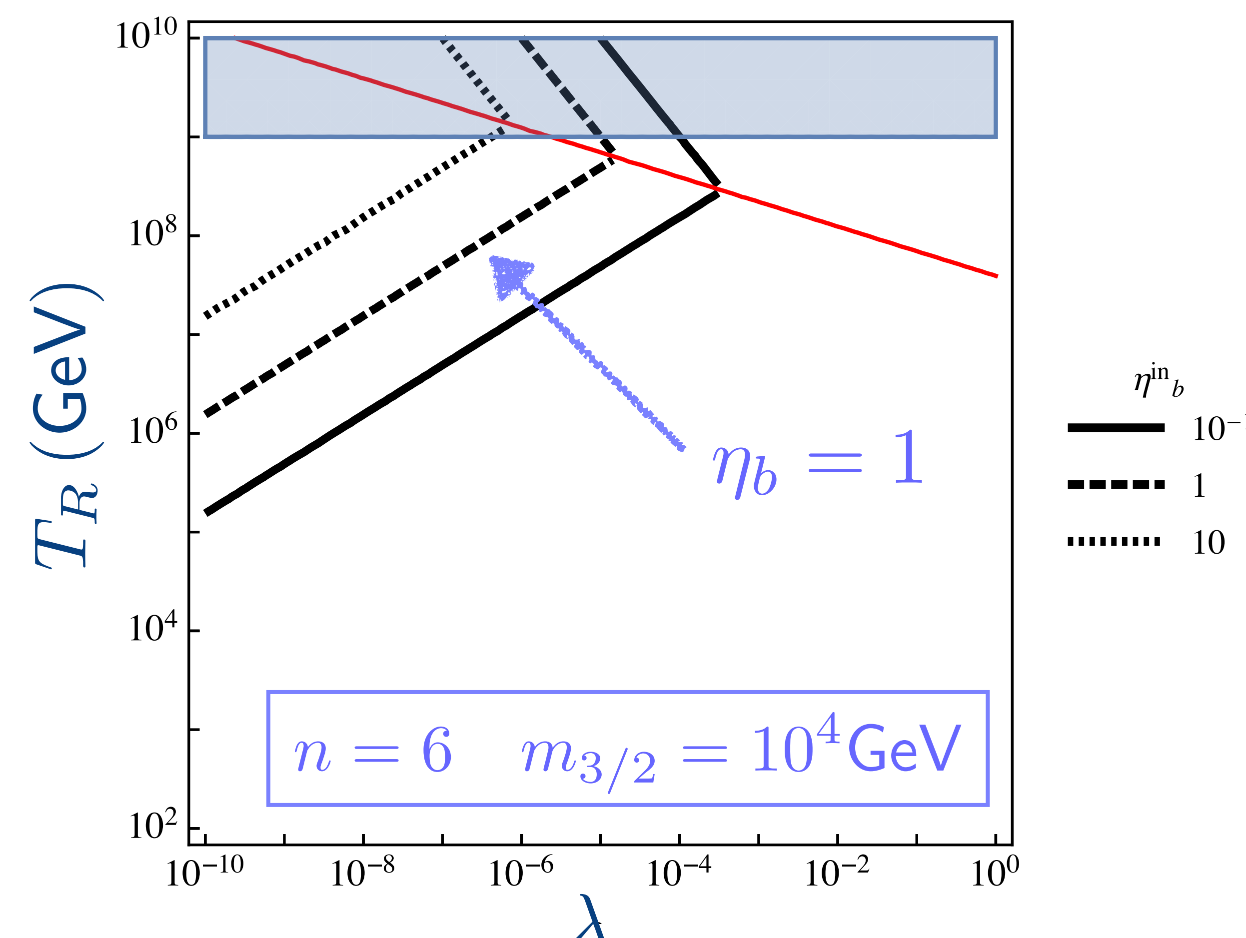
Baryon number generation

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



4.2 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

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

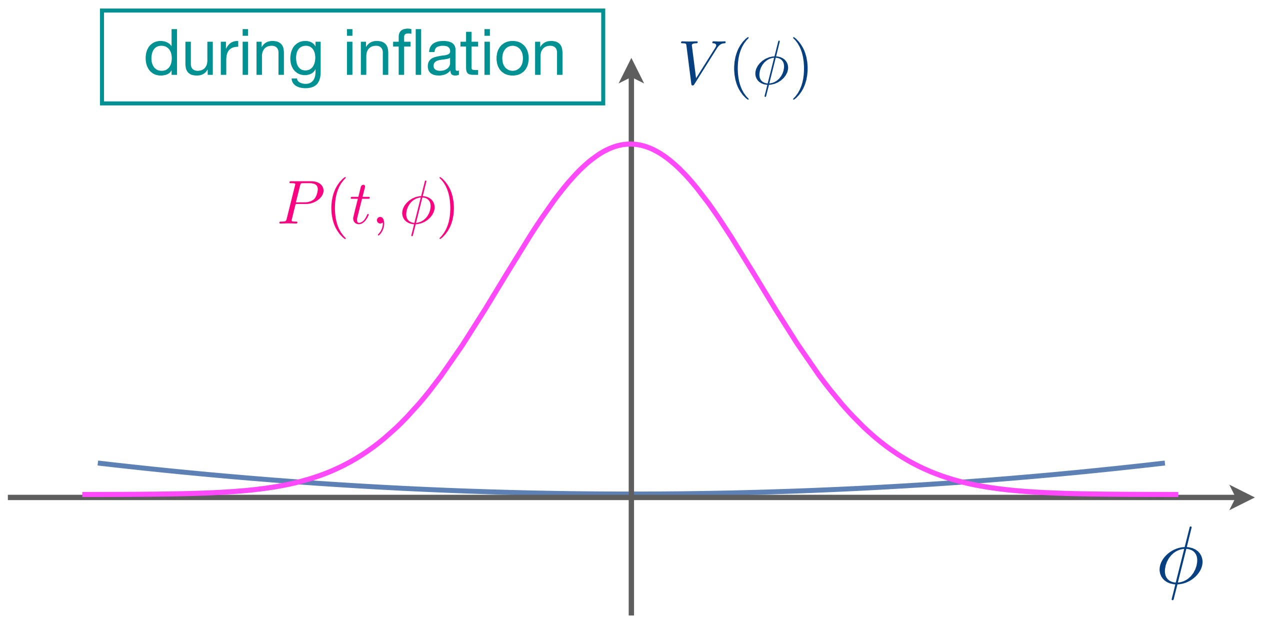
$$V_T = \begin{cases} c_1 T^2 |\phi|^2 & |\phi| \lesssim T \\ c_2 T^4 \ln(|\phi|^2/T^2) & |\phi| \gtrsim T \end{cases}$$

4.2 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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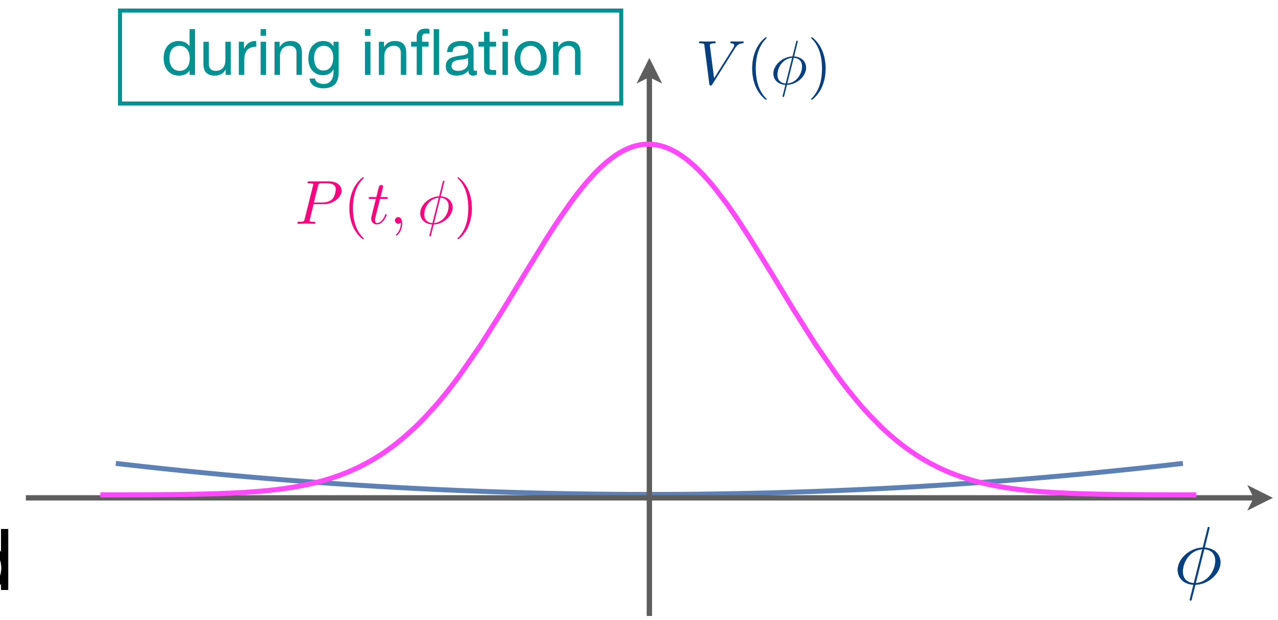
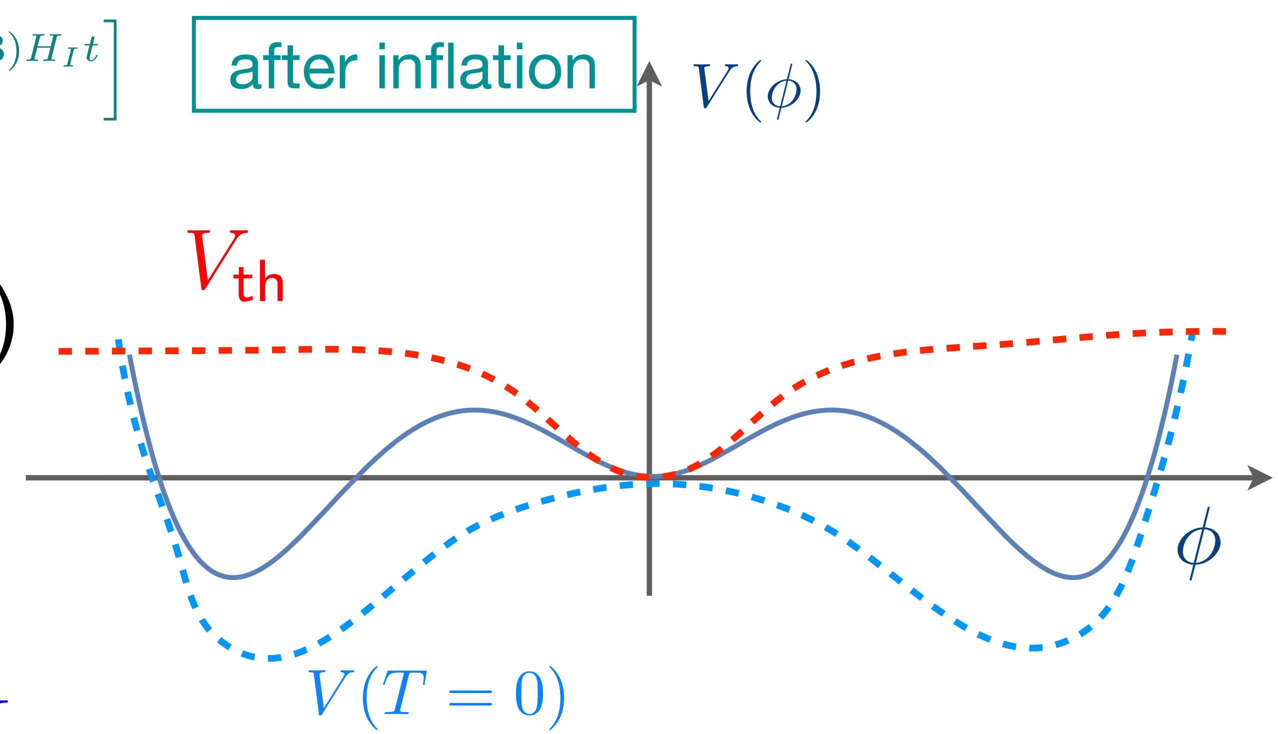


- After inflation
  - $c_H < 0$ (negative Hubble mass)
  - Thermal effect due to inflaton decay $T \simeq (T_R^2 H M_p)^{1/4}$



→ multi-vacua $\quad \Delta \equiv \frac{T_R^2 M_p}{H_I^3} \gtrsim 1$

4.2 High-baryon bubble formation

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

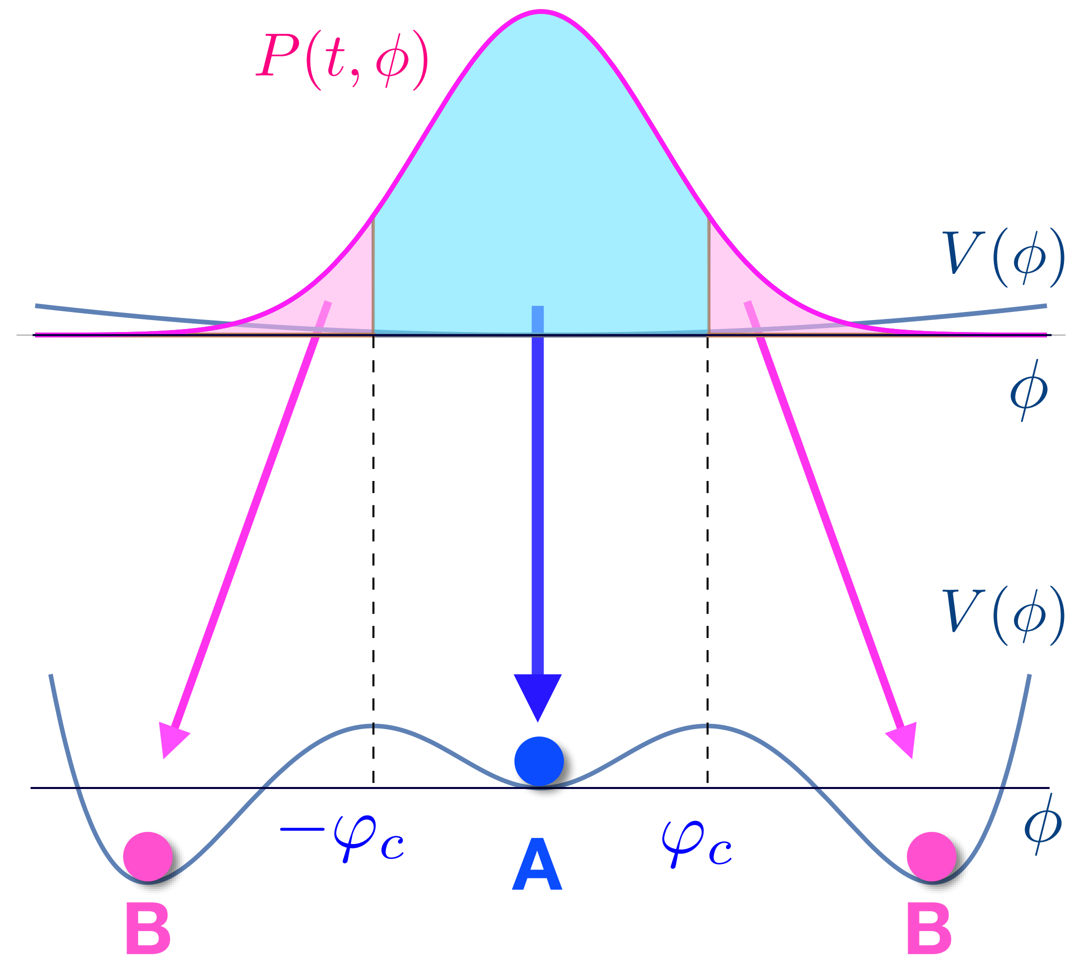
$$\varphi_c = \Delta^{1/2} H_I \qquad \Delta = \frac{T_R^2 M_p}{H^3}$$

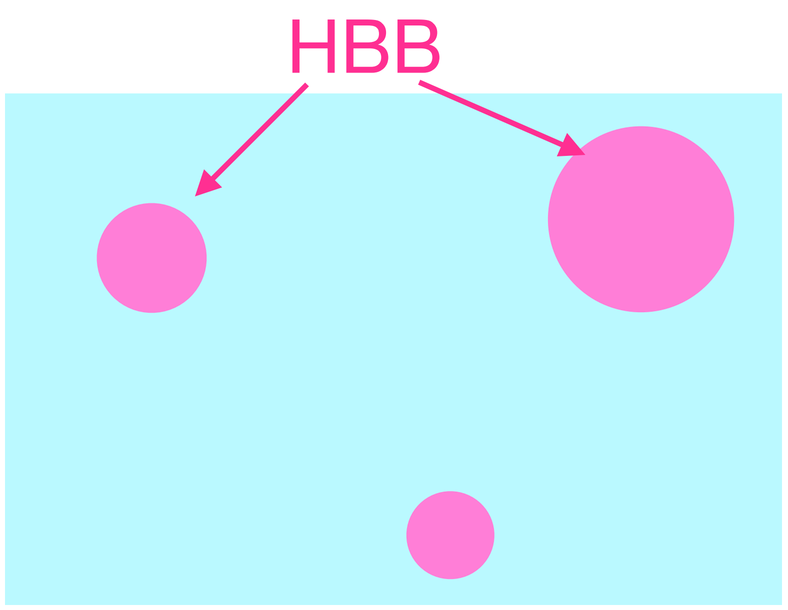
  - no baryon generation

- 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

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

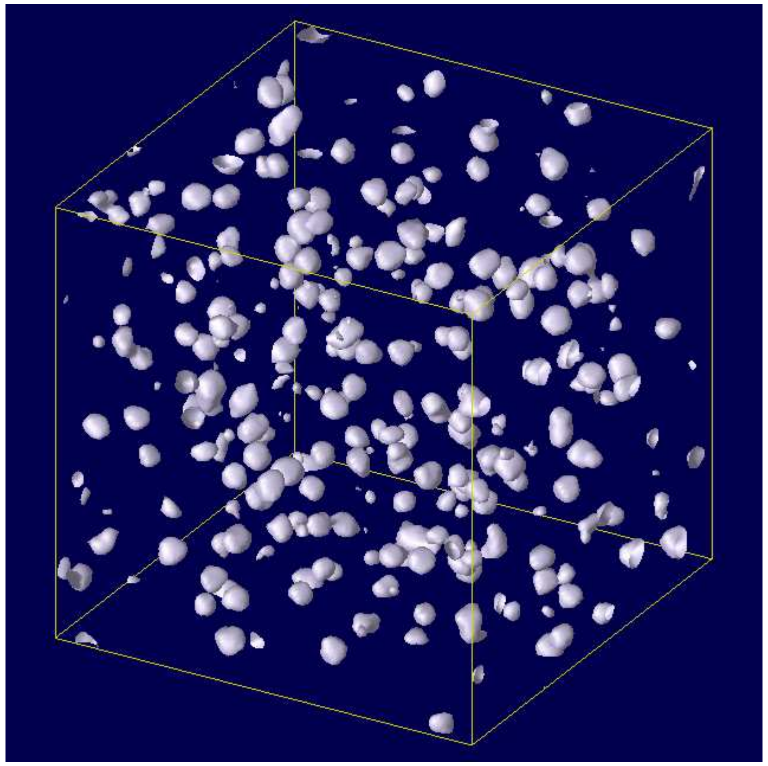
- Formation rate of HBB with scale k(N)=k* exp(N-N*)

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

4.3 Q-ball formation

- In AD mechanism, AD field oscillation generally form Q-balls
  - non-topological soliton solution in a scalar theory with U(1)
- Q-ball properties depend on SUSY breaking scheme
- Gravity-mediated SUSY breaking scenario

$$V \simeq m_\phi^2 |\phi|^2 \left[1 + K \ln\left(\frac{|\phi|^2}{M_*^2}\right)\right] \qquad m_\phi \sim \mathcal{O}(1)\text{TeV}$$



Hiramatsu MK Takahashi (2010)

  - $K < 0$ Q-balls are formed but they are unstable
  - No effect on HBB bubble formation
- Gauge-mediated SUSY breaking scenario

$$V \simeq M_F^4 \left(\ln \frac{|\phi|^2}{M_{\rm mess}^2}\right)^2 + m_{3/2}^2 |\phi|^2 \left[1 + K \ln\left(\frac{|\phi|^2}{M_*^2}\right)\right] \qquad m_{3/2} < 1\text{GeV}$$

  - Q-balls are formed and they are stable
  - Baryons are confined inside Q-balls

4.4 PBH formation in gravity-mediated SUSY breaking

- For simplicity we assume $\eta_b = 1$ inside HBBs
- After QCD phase transition baryon number is carried by non-relativistic nucleons
- Density contrast between inside and outside of HBBs

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

$$\Rightarrow \quad \delta \gtrsim \delta_c \quad \text{for} \quad T \lesssim 200\text{MeV}$$

PBH formation

- PBH mass has a lower cutoff $M_c \simeq 18 M_\odot$
- PBH mass fraction at formation

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

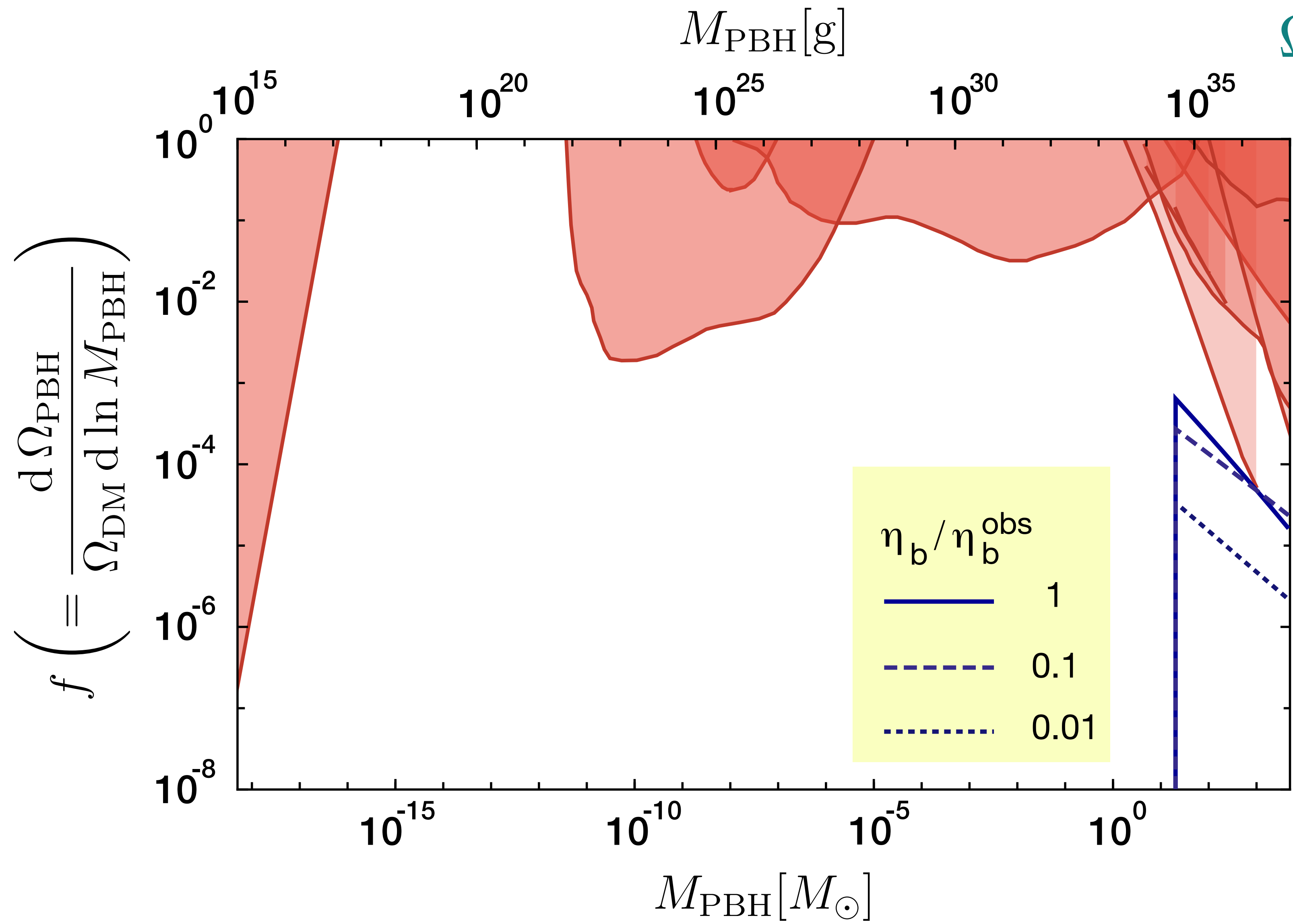
- PBH mass distribution

$$\Omega_{\text{PBH}}(M_{\text{PBH}})/\Omega_c \simeq \left(\frac{\beta_{\text{PBH}}}{1.6 \times 10^{-9}}\right)\left(\frac{M_{\text{PBH}}}{M_\odot}\right)^{1/2}$$

4.4 PBH formation in gravity-mediated SUSY breaking

- Predicted mass spectrum can account for LIGO events

$\Omega_{\rm PBH}/\Omega_c \sim 10^{-3} - 10^{-2}$



- HBBs with M < Mc contribute to baryon asym. of the universe
- baryons are highly inhomogeneous, which spoils success of standard BBN → $\eta_b^{\rm HBB} \ll \eta_b^{\rm obs}$
- This can be satisfied by modifying the model

4.5 PBH formation in gauge-mediated SUSY breaking

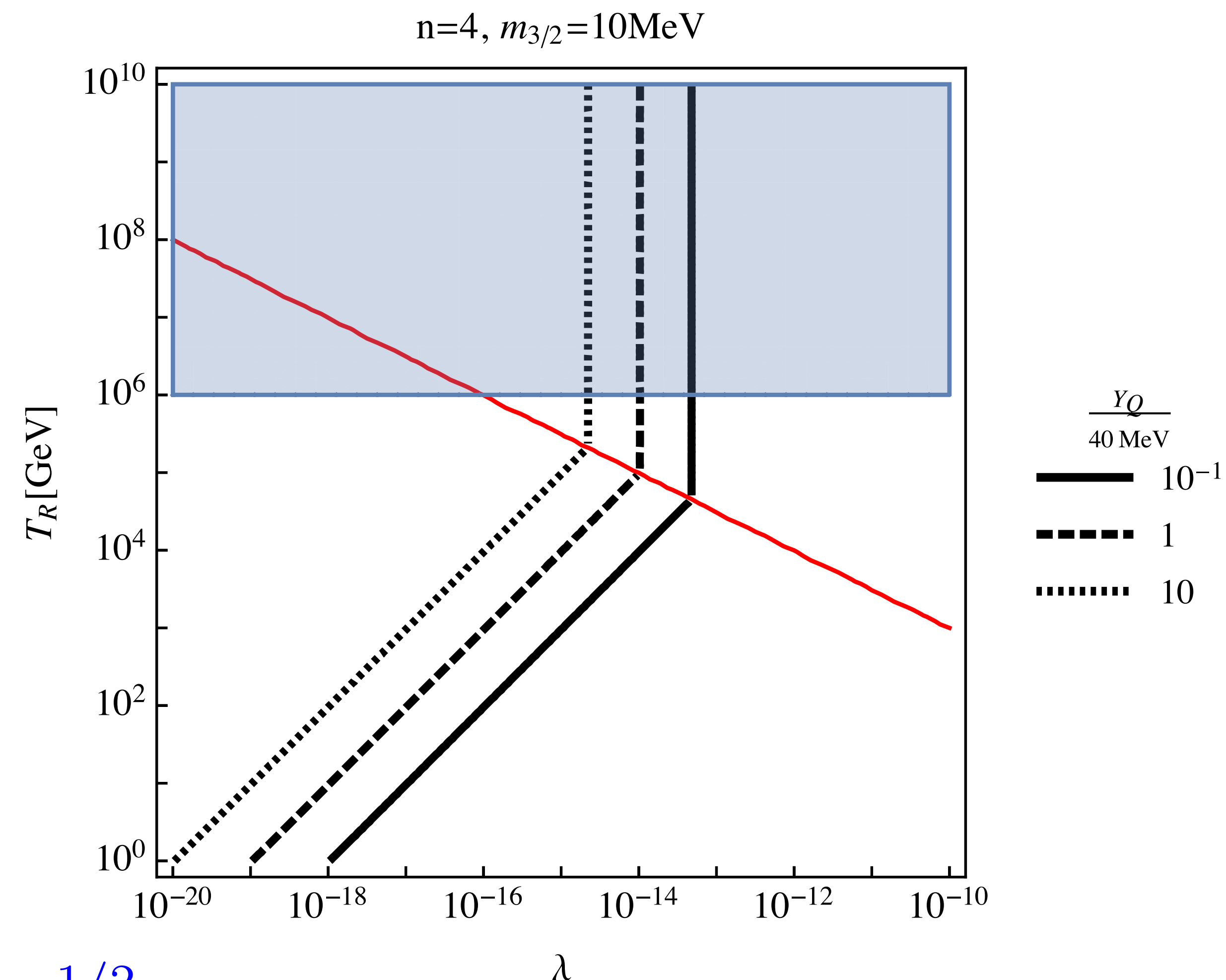
- Q-balls are formed and they behave like matter
- Density contrast between inside and outside of HBBs

$$\delta = \frac{\rho^{\text{in}} - \rho^{\text{out}}}{\rho^{\text{out}}} \simeq \frac{4}{3}\frac{Y_Q^{\text{in}}}{T}$$

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

$$\Rightarrow \quad \delta \gtrsim \delta_c \quad \text{for} \quad T \lesssim 5\,Y_Q^{\text{in}}$$

➡ PBH formation



- PBH mass has a lower cutoff

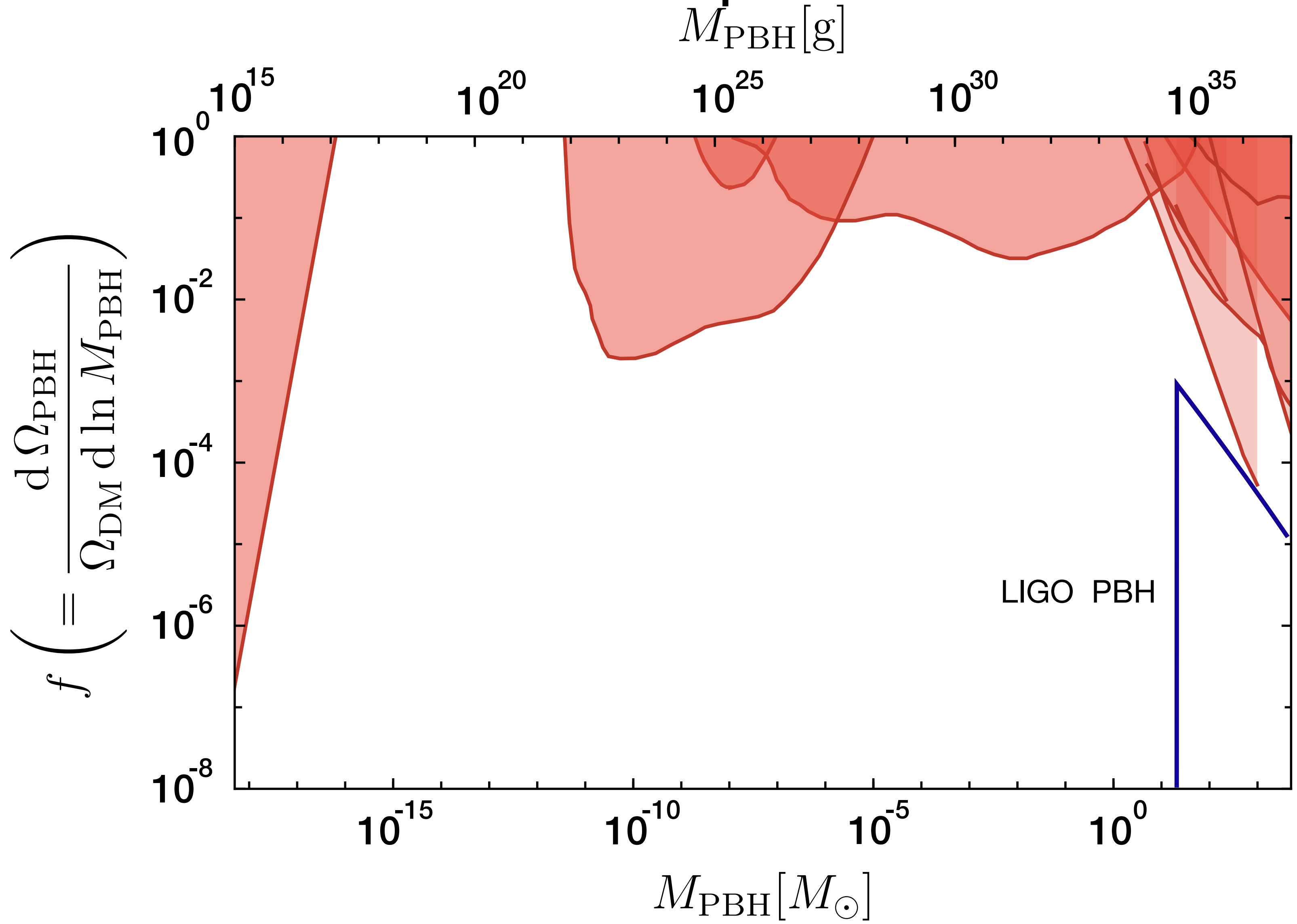
$$M_c \simeq 18 M_\odot \left(\frac{Y_Q^{\text{in}}}{40\text{MeV}}\right)^{-2}$$

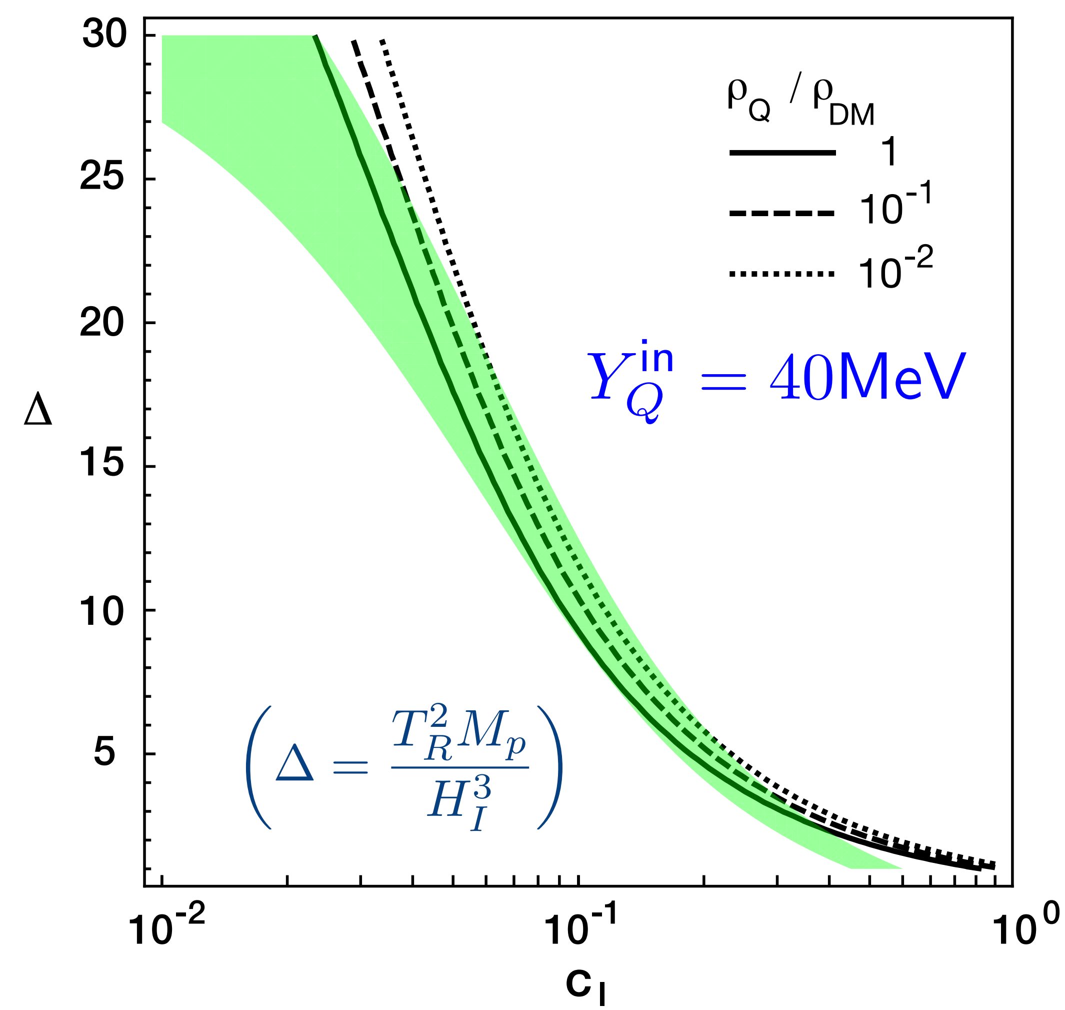
- PBH mass distribution

$$\Omega_{\text{PBH}}(M_{\text{PBH}})/\Omega_c \simeq \left(\frac{\beta_{\text{PBH}}}{1.6\times 10^{-9}}\right)\left(\frac{M_{\text{PBH}}}{M_\odot}\right)^{1/2}$$

4.4 PBH formation in gauge-mediated SUSY breaking

- Predicted mass spectrum can account for LIGO events





- Q-balls in HBBs with M < Mc contribute to DM
- This scenario can explain both LIGO events and DM simultaneously
- Possible to form supermassive PBH $M_{\rm PBH} \gg 100 M_\odot$

5. Conclusion

- Affleck-Dine mechanism produces HBBs which form PBHs with > O(10) solar mass
- The model can account LIGO events evading the constraints from CMB spectral distortion and pulsar timing
- High baryon bubbles also produce Q-ball DM
- Supermassive BH can be produced in this mechanism