Primordial Black Holes from Affleck-Dine Mechanism

Fuminori Hasegawa
(ICRR, University of Tokyo)

based on: 1711.00990, 1807.00463 with **M. Kawasaki**

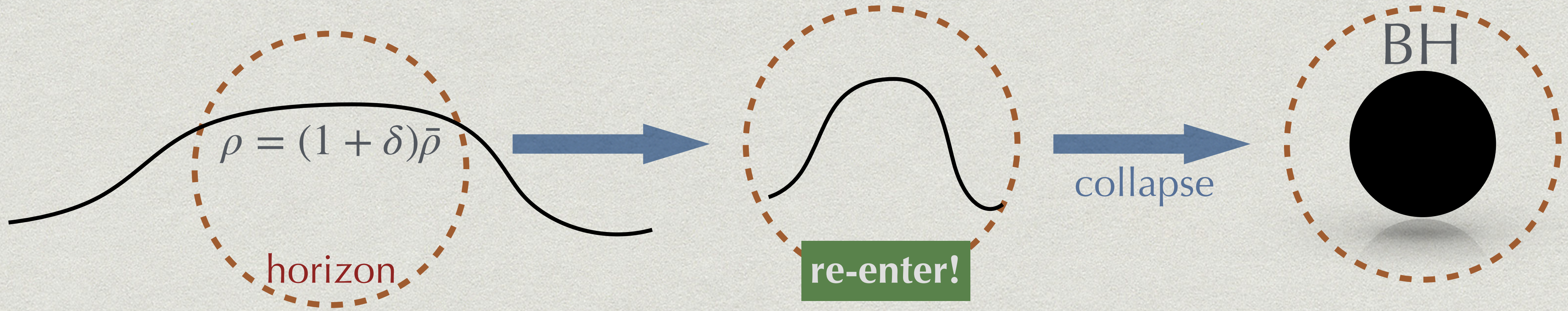
SUSY2018@Barcelona, July 25

Introduction

- **Primordial Black Holes** (PBH) are BHs formed in very early universe. [Zel'dovich+ '67, Hawking '71]
- They give a significant contribution to **dark matter**
- They (may) explain **Supermassive black holes** at the centre of galaxy
- explain the GW events detected by **LIGO collaboration**
    - PBHs can have a wide range of mass **including $30M_{\odot}$**
    - Their spin are **very small**

Formation of PBH

- PBHs are formed by the gravitational collapse of the over-dense regions in the early universe.
- If the density contrast δ is $\mathcal{O}(1)$ at the region re-enters the horizon, PBH is formed.

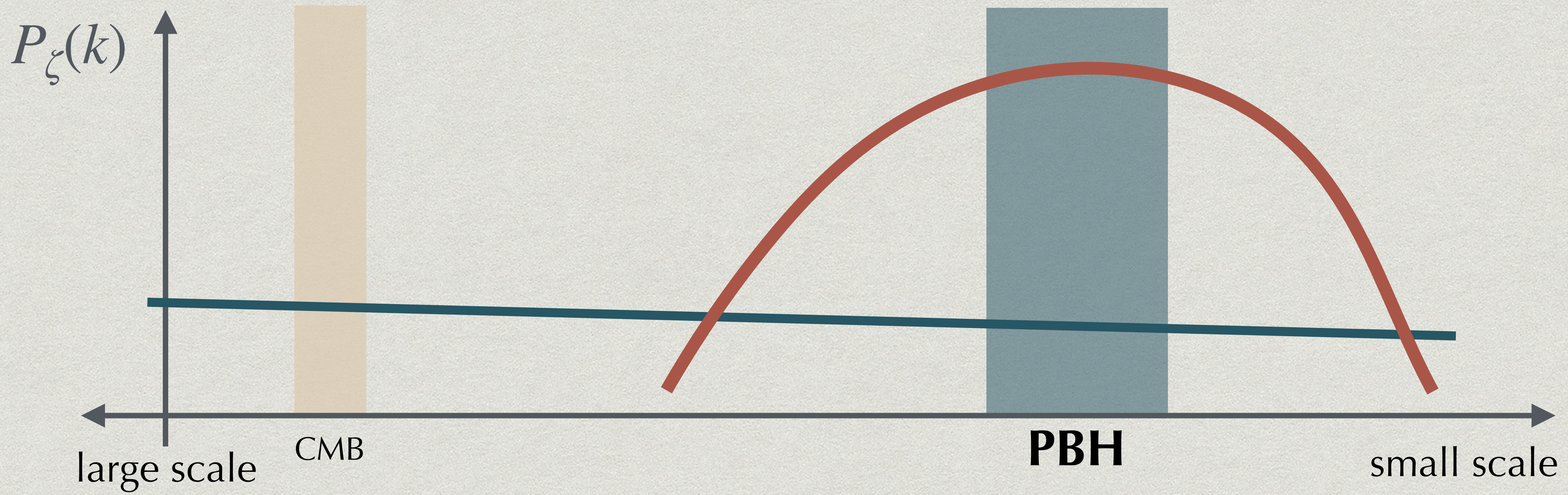


- The mass of the PBH is similar to the horizon mass at the horizon re-entry:

$$M_{\rm PBH} \sim \rho H^{-3} \sim 20 M_\odot \left(\frac{k}{1{\rm pc}^{-1}}\right) \sim 20 M_\odot \left(\frac{T}{200{\rm MeV}}\right)^{-2}$$

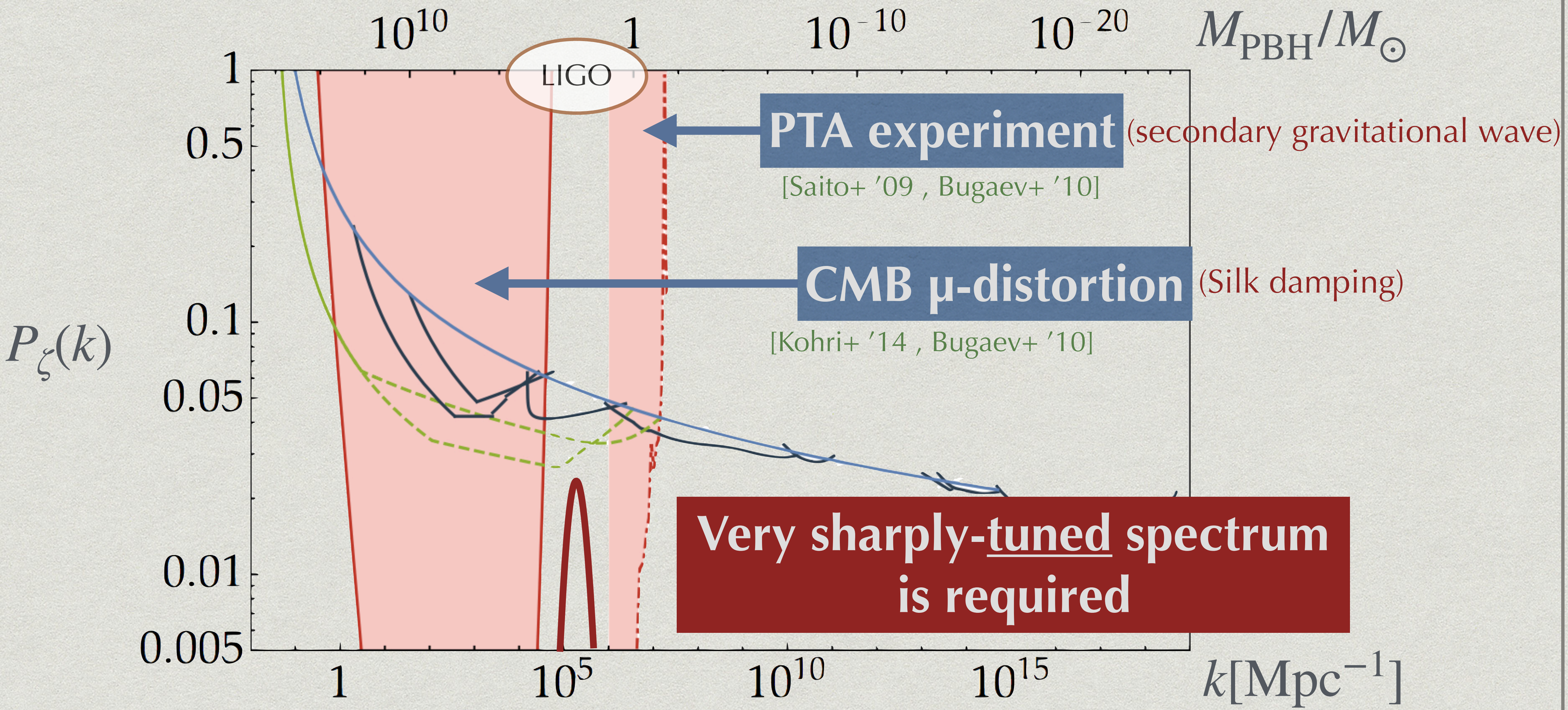
Inflationary PBH

- **Inflation** can generate such large density perturbations
- amplify the small-scale density perturbation
  - Double inflation [Kawasaki+ '98]
  - Saddle-point inflation [García-Bellido+ '96]



Constraints on inflationary PBH

- However, small-scale **adiabatic curvature perturbations** are constrained by cosmological observations.



How to evade the constraints

- Non-Gaussian density perturbation
  - multi-field inflation [García-Bellido+ '96]
  - curvaton model [Kawasaki+ '12]
- Non-inflationary density perturbation?
  - cosmic string? [Polnarev+ '91]
  - Phase transition? [Jedamzik+ '99]
  - **High Baryon Bubble [Dolgov+ '93]**
  - etc…

We naturally embedded the model in AD mechanism in MSSM

PBH from Affleck-Dine mechanism

* Affleck-Dine (AD) mechanism is a most efficient and well-motivated scenario of the baryogenesis in supersymmetric framework

* We find that special version of the AD mechanism naturally produces **High Baryon Bubbles** (HBBs), which collapse into PBHs

* Since the density contrast of HBBs is baryonic isocurvature perturbation, the constraint from PTA experiment and μ-distortion is **completely absent**

* Moreover, the peak at LIGO scale is **predicted** without tuning

Affleck-Dine mechanism (review)

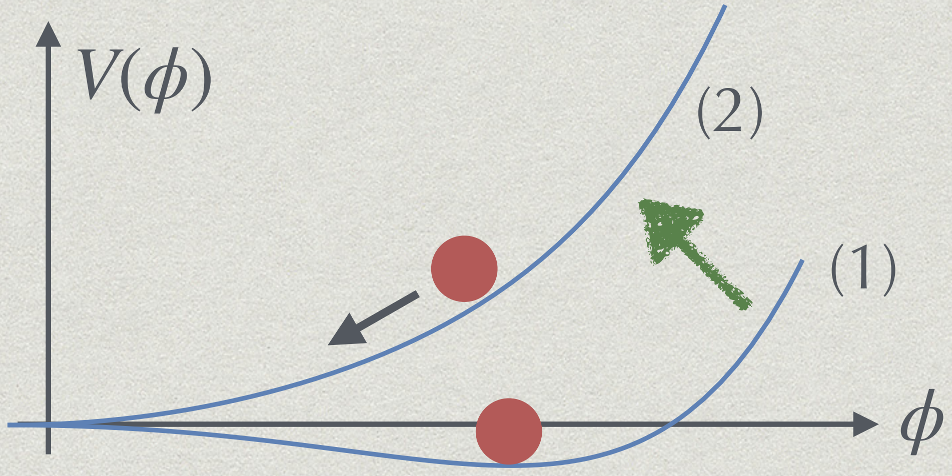
- AD mechanism is described by the dynamics of the flat direction with a baryon charge (=**AD field** ϕ)

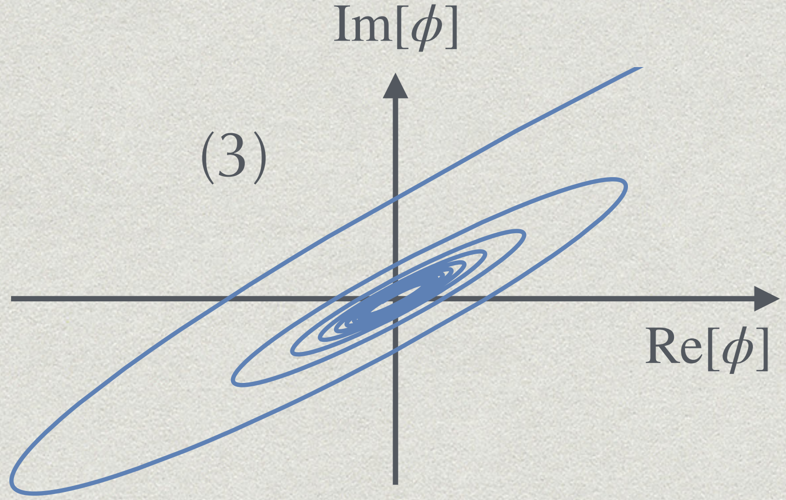
$$V_{\rm AD} = (\underbrace{m_\phi^2}_{\text{SUSY mass}} + \underbrace{cH^2}_{\text{Hubble-induced mass}})|\phi|^2 + \underbrace{\frac{\lambda^2|\phi|^{2n-2}}{M_p^{(2n-2)}}}_{\text{Non-renormalizable term}} + \underbrace{a_m \frac{\lambda m_{3/2}\phi^n}{nM_p^{(n-3)}}}_{\text{A-term}}$$

(1) During inflation, ϕ has a large VEV if c<0

(2) After inflation, when H~m_ϕ, ϕ starts to oscillate

(3) AD field is kicked in phase direction due to the A-term





Baryon # generation

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

HBB formation in AD baryogenesis

- We make two assumptions:
  - The sign of Hubble induced mass **flips**:

    + $H^2\phi^2$ during inf.

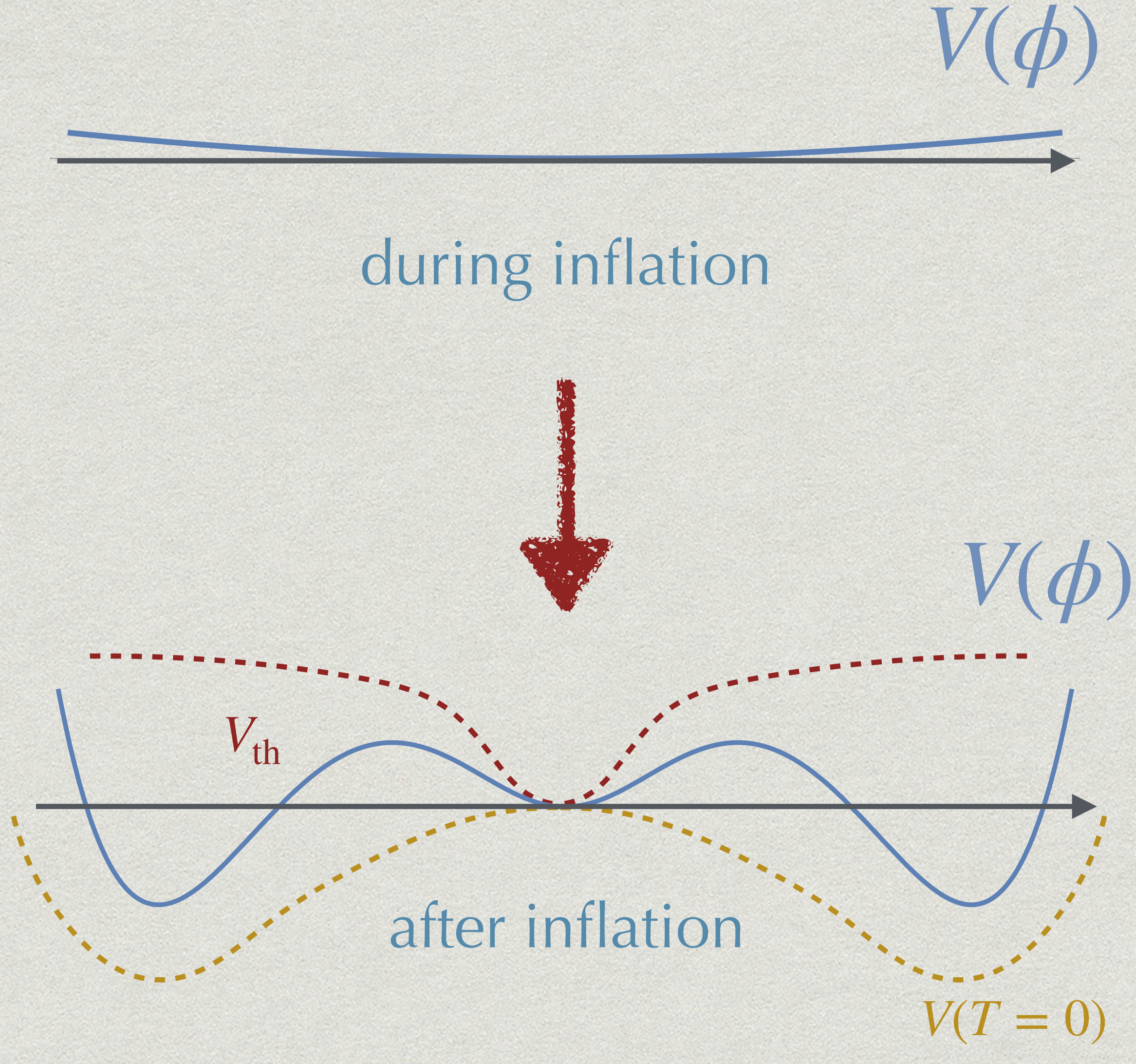
    flip!

    - $H^2\phi^2$ after inf.

    *It generally occurs in SUSY inflation model [Kamada+'14,15]

  - After inflation, the **thermal mass** overcomes the negative Hubble-induced mass

$$T \sim (T_{\mathrm{R}}^2 H_{\mathrm{inf}} M_p)^{1/4} > H_{\mathrm{inf}}$$



Multi vacua

Dynamics 1

$N = \ln(a/a_{\rm in})$

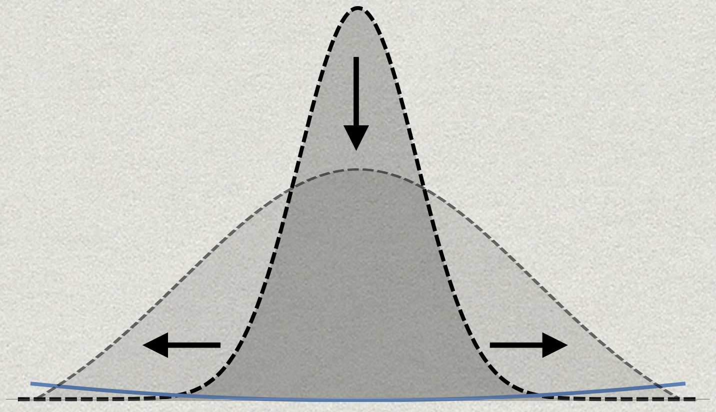
- During inflation: ϕ quantumly fluctuates around origin
  - ϕ takes different values in different patches

  - Distribution of ϕ obey the Fokker-Planck equation:

$$\frac{\partial P(N,\phi)}{\partial N} = \frac{\partial}{\partial \phi}\left[\frac{V'(\phi)}{3H^2} + \frac{H^2}{8\pi^2}\frac{\partial P(N,\phi)}{\partial \phi}\right]$$

drift by the scalar potential

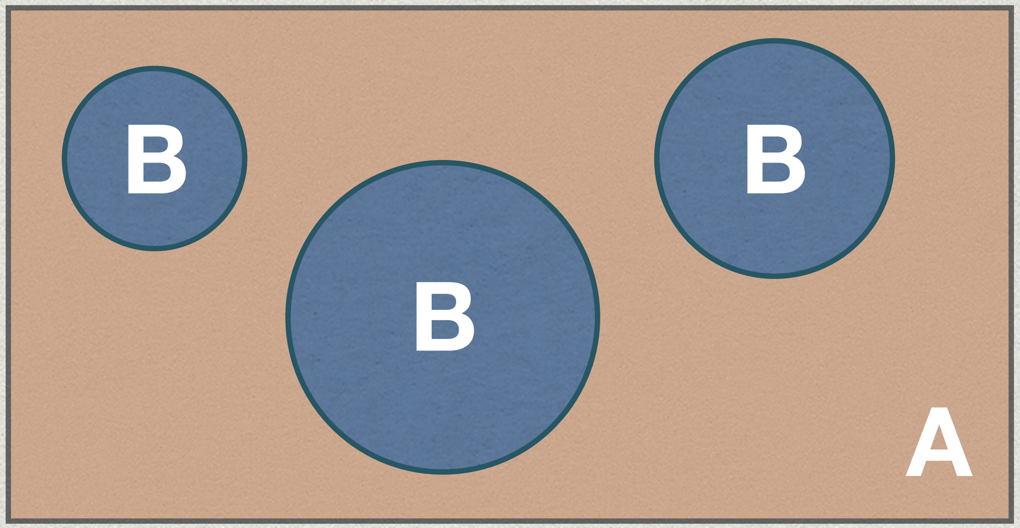
diffusion by quantum fluctuation

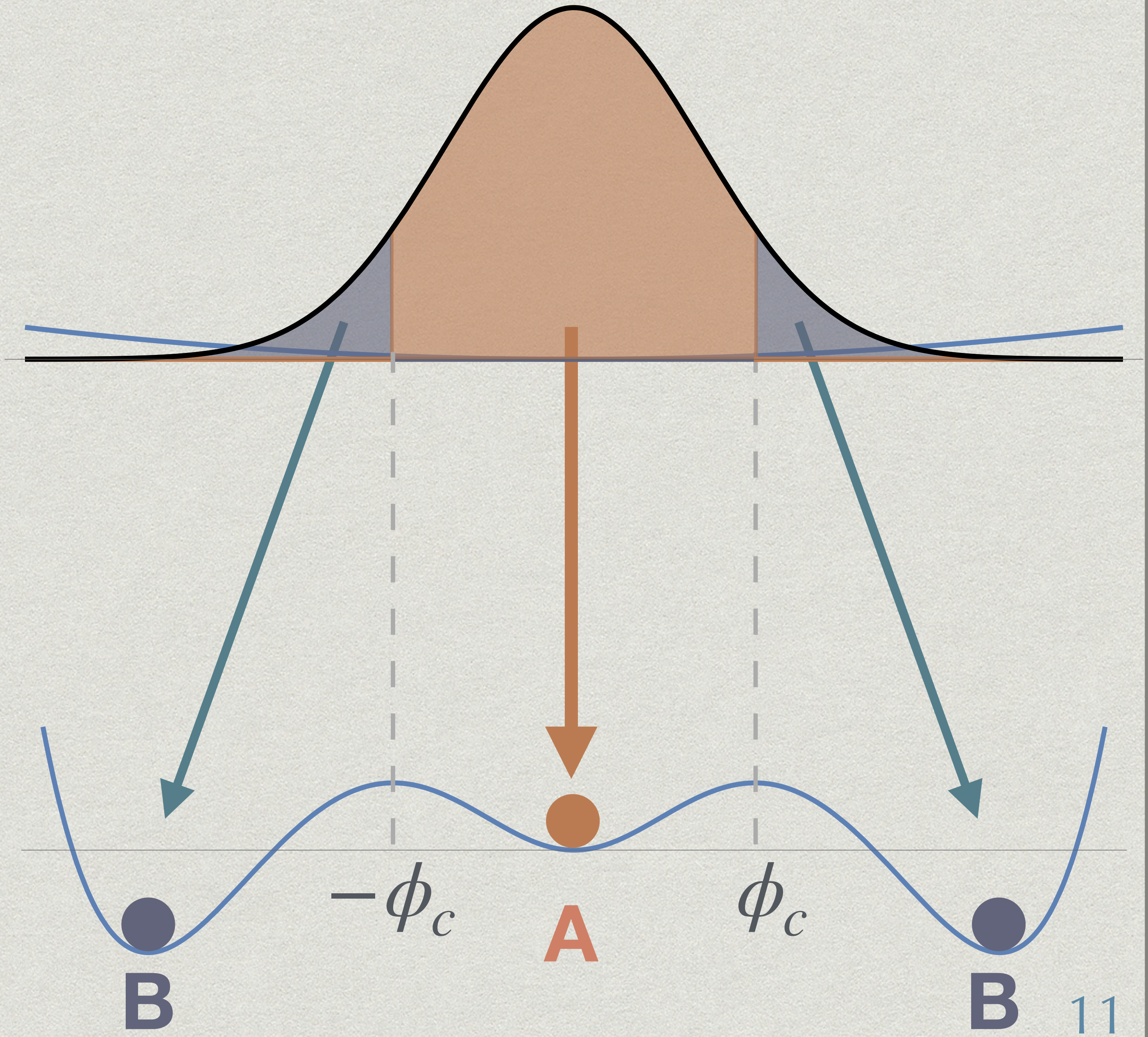


P(N, ϕ): Gaussian with $\sigma(N) = \langle \delta\phi^2(N) \rangle = \left(\frac{H^2}{2\pi}\right)\frac{1-e^{-cN}}{c}$

Dynamics 2

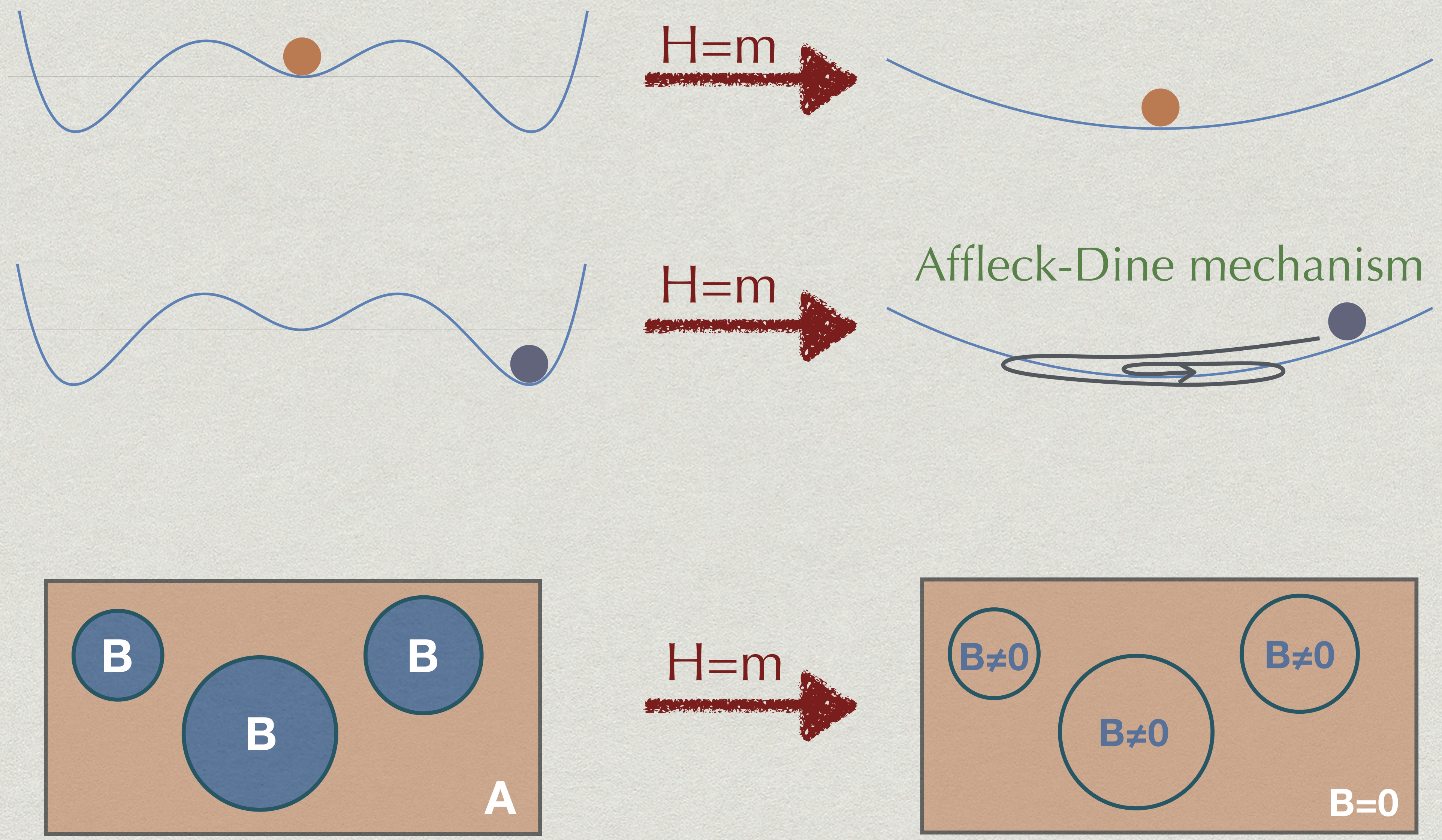
- After inflation: ϕ rolls down to either of the two vacua
  - the patch $|\phi|<\phi_c$
    → **vacuum A**
  - the patch $|\phi|>\phi_c$
    → **vacuum B**





Dynamics 3

- When H=m: baryon# generation only in B



no B#

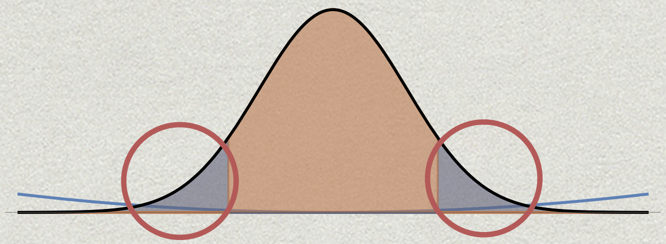
B# generation

inhomogeneous
baryon
asymmetry
=
Baryon Bubbles

Distribution of HBBs

- The distribution of HBBs is determined by the distribution of the patch $|\phi|>\phi_c$.
  - The fraction of the patch $|\phi|>\phi_c$ at N

$$f_B(N) = \int_{|\phi|>\phi_c} P(N,\phi)d\phi$$



  - The fraction of the patch $|\phi|>\phi_c$ created at N

$$\beta_B(N) = \frac{df_B}{dN} = \int_{|\phi|>\phi_c} \frac{dP(N,\phi)}{dN}d\phi$$

  - Scale of patches ≃ Hubble radius at their formation

Horizon mass at reentering

$$N(k) \simeq \ln\frac{k}{k_{\rm CMB}} + N_{\rm CMB} = -\frac{1}{2}\ln\frac{M_H}{M_\odot} + 21.5 + N_{\rm CMB}$$

Collapse of HBBs

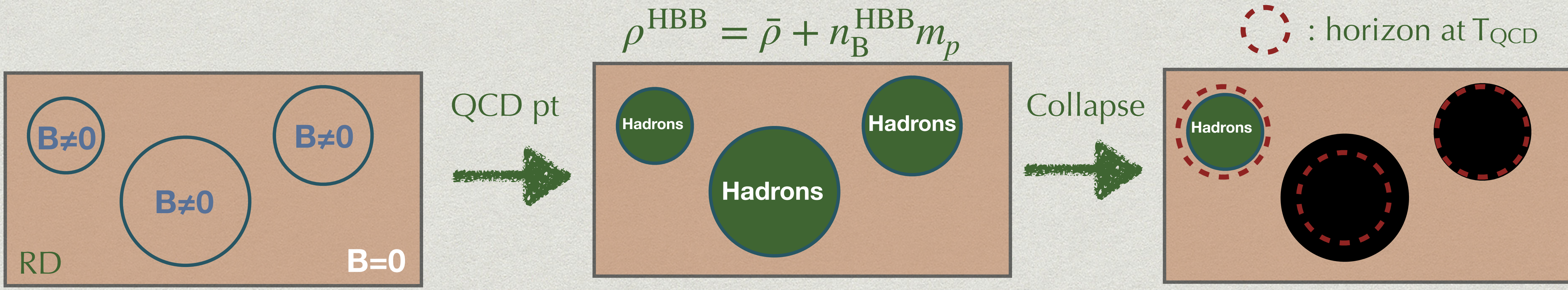
- Just after H=m, the density contrast of HBBs is negligible
  - By the QCD pt, baryons become **non-relativistic**

we assume inside the HBB is highly baryon asymmetric: $\eta^{\mathrm{HBB}} = n_{\mathrm{B}}^{\mathrm{HBB}}/s \sim 1$

$$\delta \simeq \frac{n_{\mathrm{B}}^{\mathrm{HBB}} m_p}{g_* T^4} \simeq 0.3\eta^{\mathrm{HBB}} \left(\frac{T}{200\mathrm{MeV}}\right)^{-1} :$$

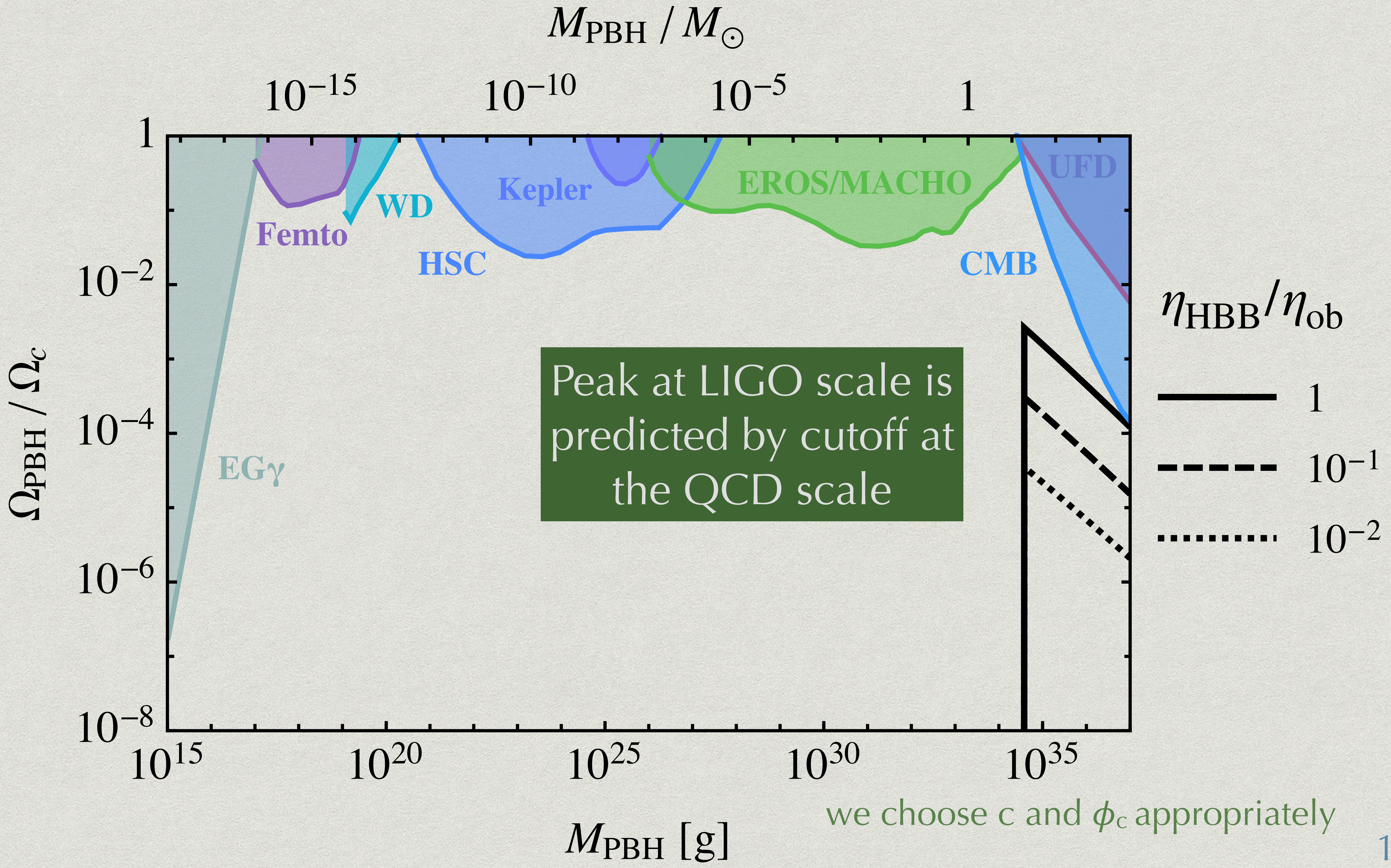
$\mathcal{O}(1)$ after QCD
→ **PBH formation**

$\rho^{\mathrm{HBB}} = \bar{\rho} + n_{\mathrm{B}}^{\mathrm{HBB}} m_p$



Only the HBBs reenter the horizon after QCD can collapse to PBH!
$\beta_{\mathrm{PBH}}(M) = \beta_{\mathrm{B}}(M)\theta(M - M_{\mathrm{QCD}})$

Abundance of PBHs



we choose c and ϕ_c appropriately

Conclusion

- PBHs are formed in AD mechanism in MSSM
- The PBHs with mass ~ $10M_{\odot}$ is predicted due to the QCD phase transition
- The stringent constraint from the μ-distortion and PTA experiment are completely absent because adiabatic curvature perturbation is not required

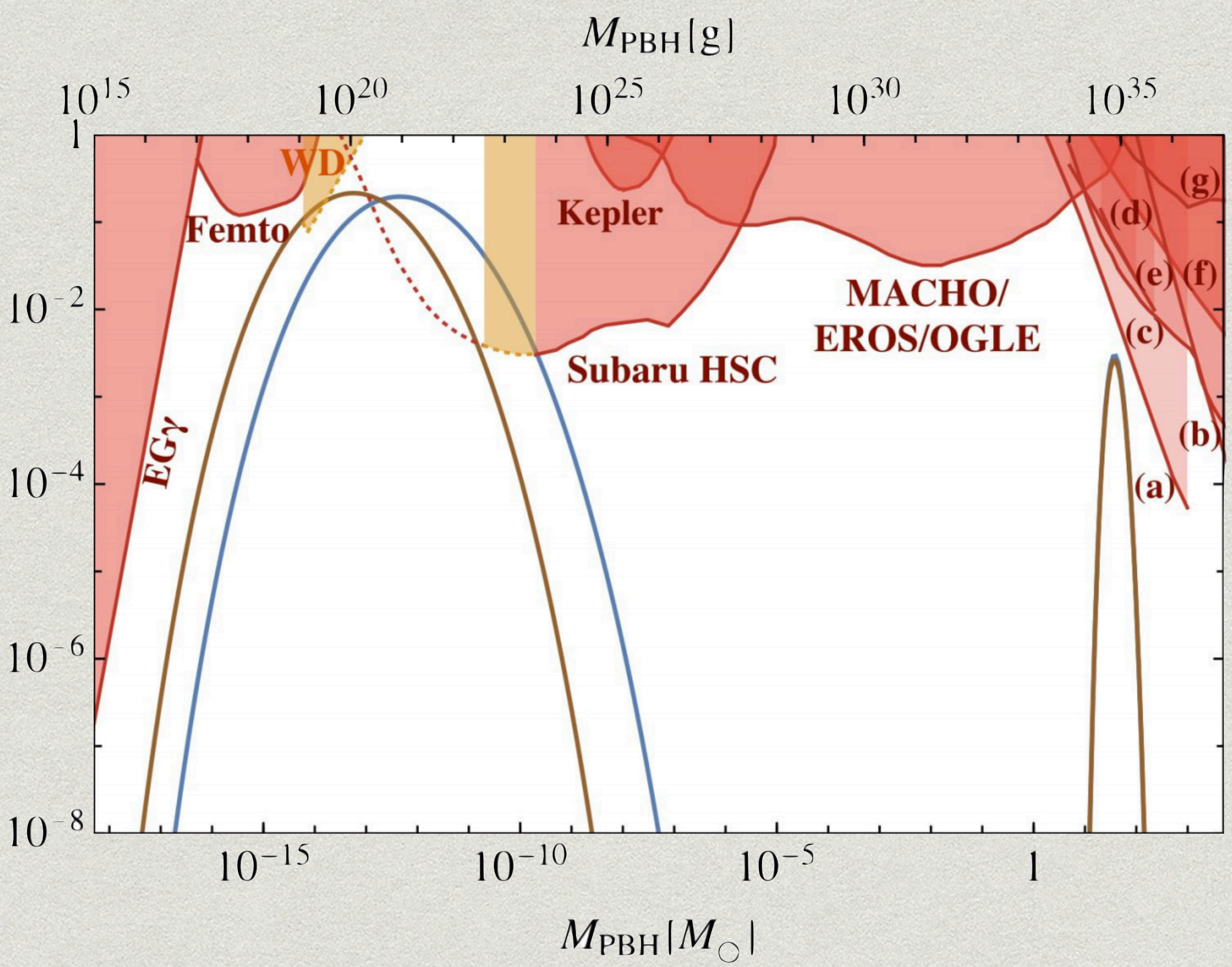
Backup

Successful example

- pre-inflation + new inflation [Inomata+ '17]
- produce the sufficient PBHs with mass ~30 $M_\odot$ evading all the constraints
- To explain the event rate of the LIGO, the PBH fraction must satisfy

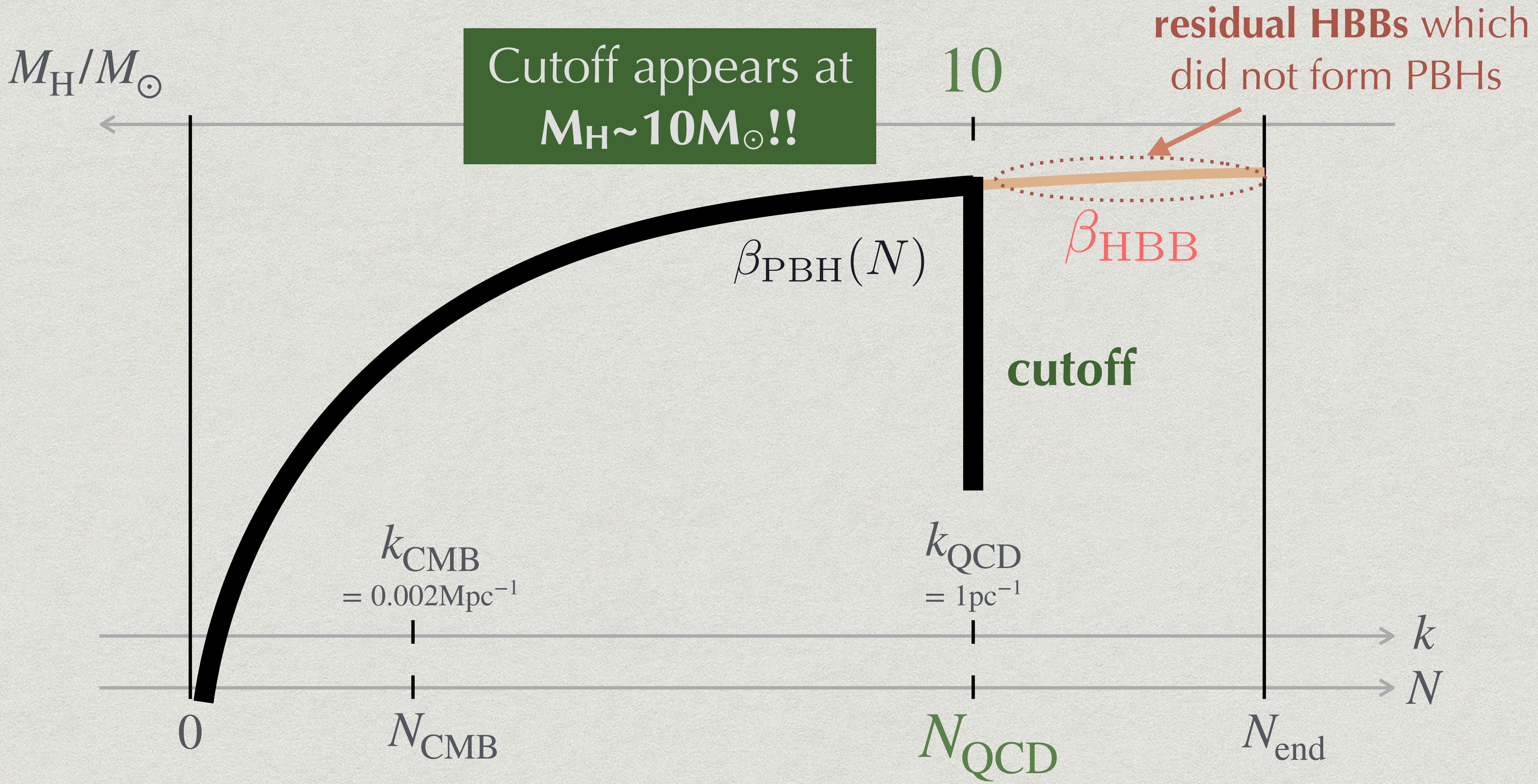
$$\boxed{\frac{\Omega_{\mathrm{PBH}}}{\Omega_{\mathrm{DM}}} \sim 10^{-3} - 10^{-2}}$$

[Sasaki+ '16]



Distribution of PBHs

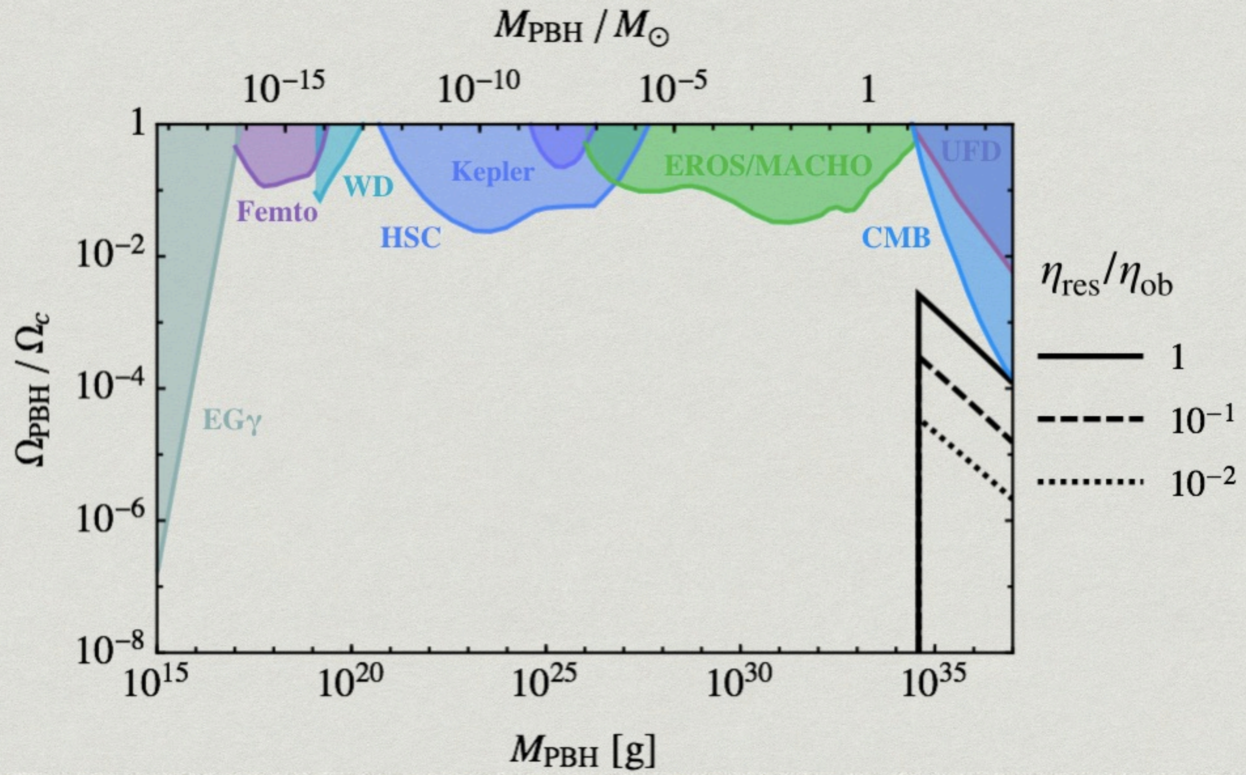
- HBBs larger then QCD scale collapse to PBHs



Abundance of PBHs

- PBHs at LIGO scale are predicted evading all the constraints
- The hight of peak is related to the abundance of the residual HBB:

$$\eta_{\rm res} = f_{\rm B}^{\rm residual} \eta^{\rm HBB}$$

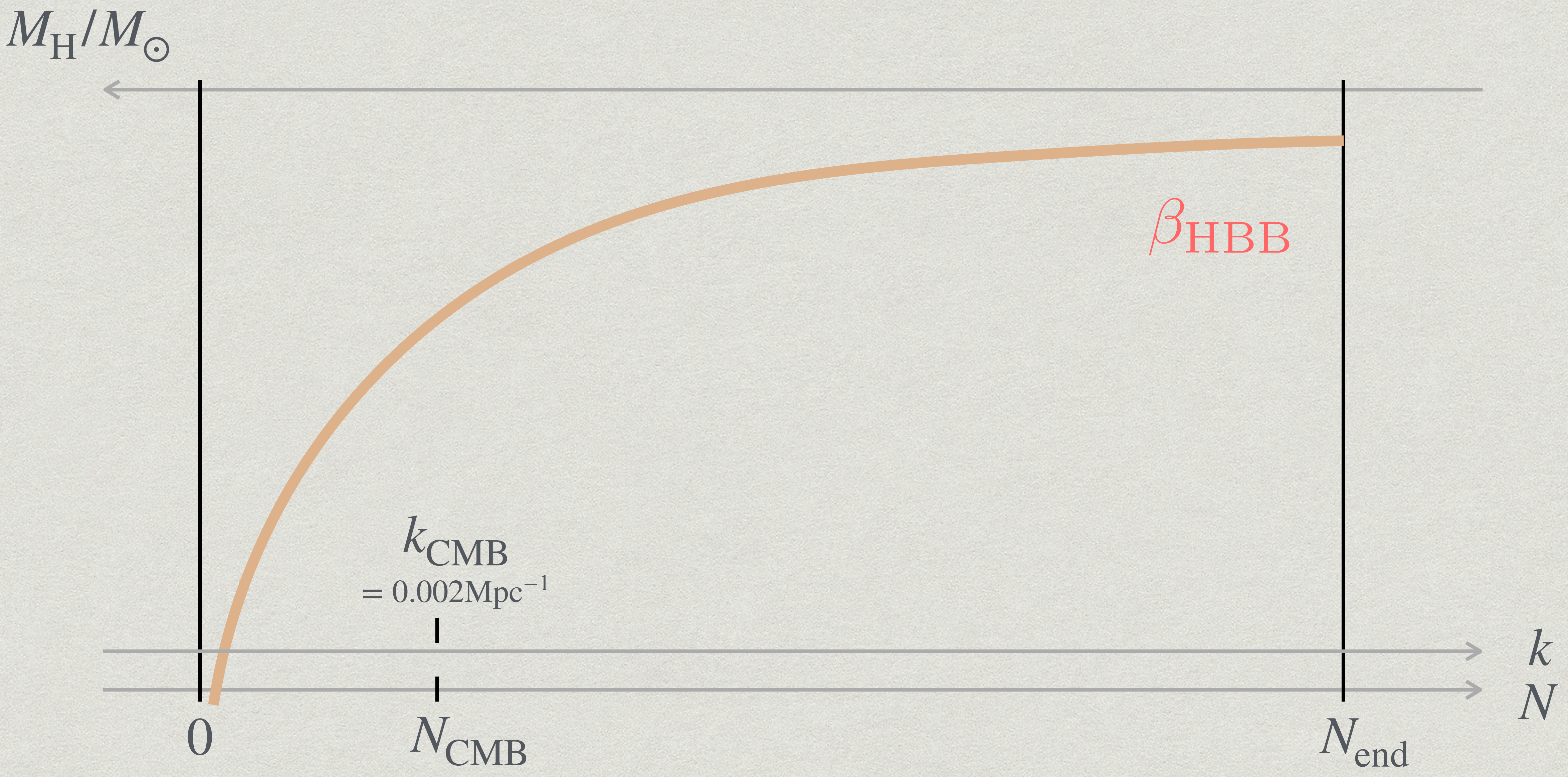


- to realize the LIGO event rate $\frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}} \sim 10^{-3} - 10^{-2}$, we need
  [Sasaki+ '16]

$$\eta_{\rm res} \sim (10 - 100)\,\%\,\eta_{\rm ob}$$

Distribution of HBBs

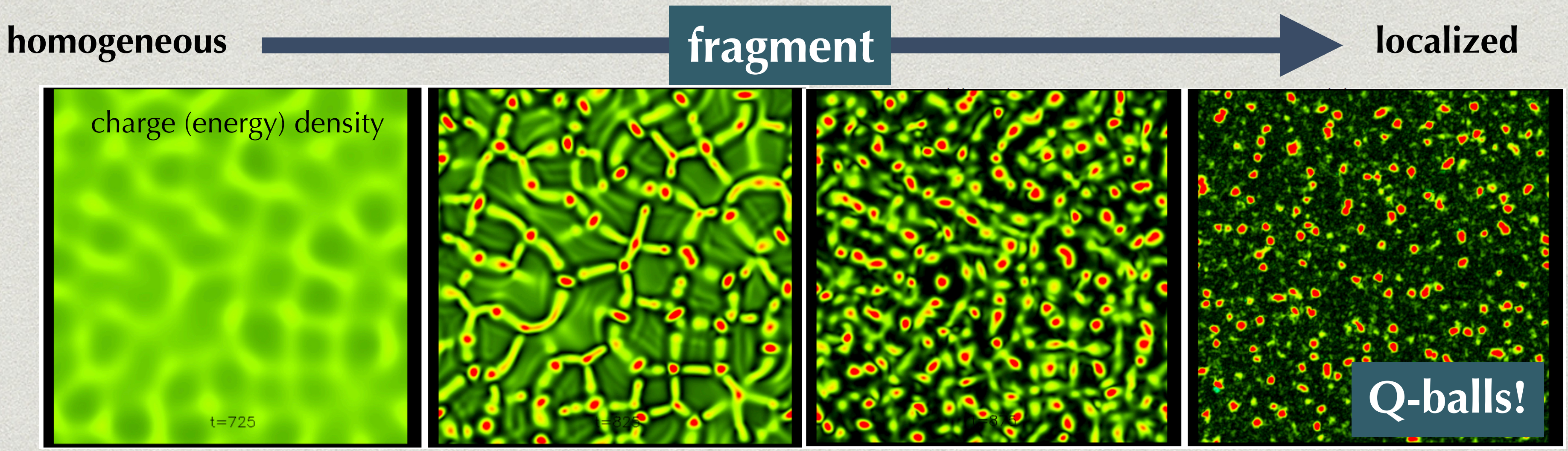
- The size distribution of HBBs (parameters: c, ϕ_c)



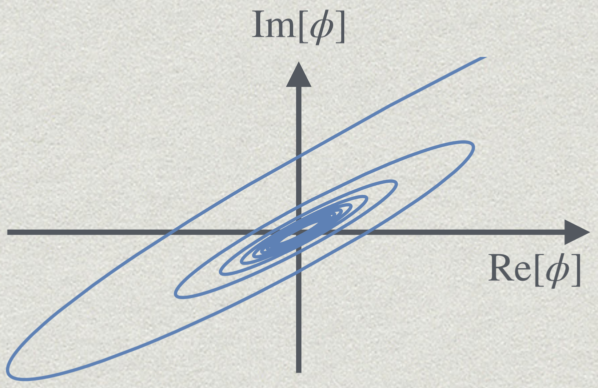
HBBs are created with very wide mass range

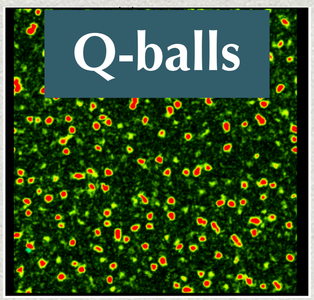
Q-ball formation

- In **gauge-mediation**, AD field form stable Q-balls
  - Q-balls are localized configuration of complex scalar under fixed U(1) charge



Simulation of Q-ball formation in 2D [Hiramatsu+ '03]





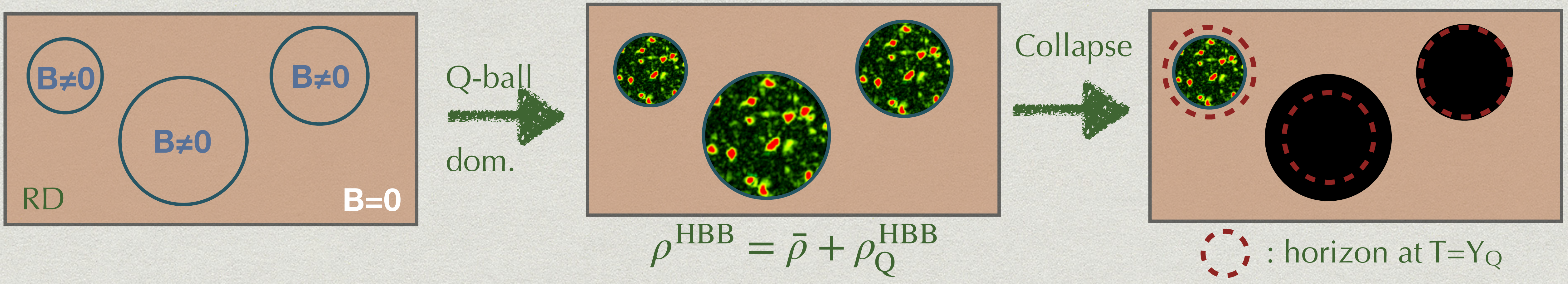
behave as **dark matter** and do not contribute to baryon asymmetry

Collapse of HBBs

- With the Q-ball formation, HBBs also form PBHs
  - Q-ball eventually dominate the energy density of HBBs

$$\delta \simeq \frac{4}{3T} Y_Q^{\rm HBB} \simeq 1.3 \left(\frac{T}{Y_Q^{\rm HBB}} \right)^{-1} :$$

$\mathcal{O}(1)$ for $T \lesssim Y_Q$
→ **PBH formation**

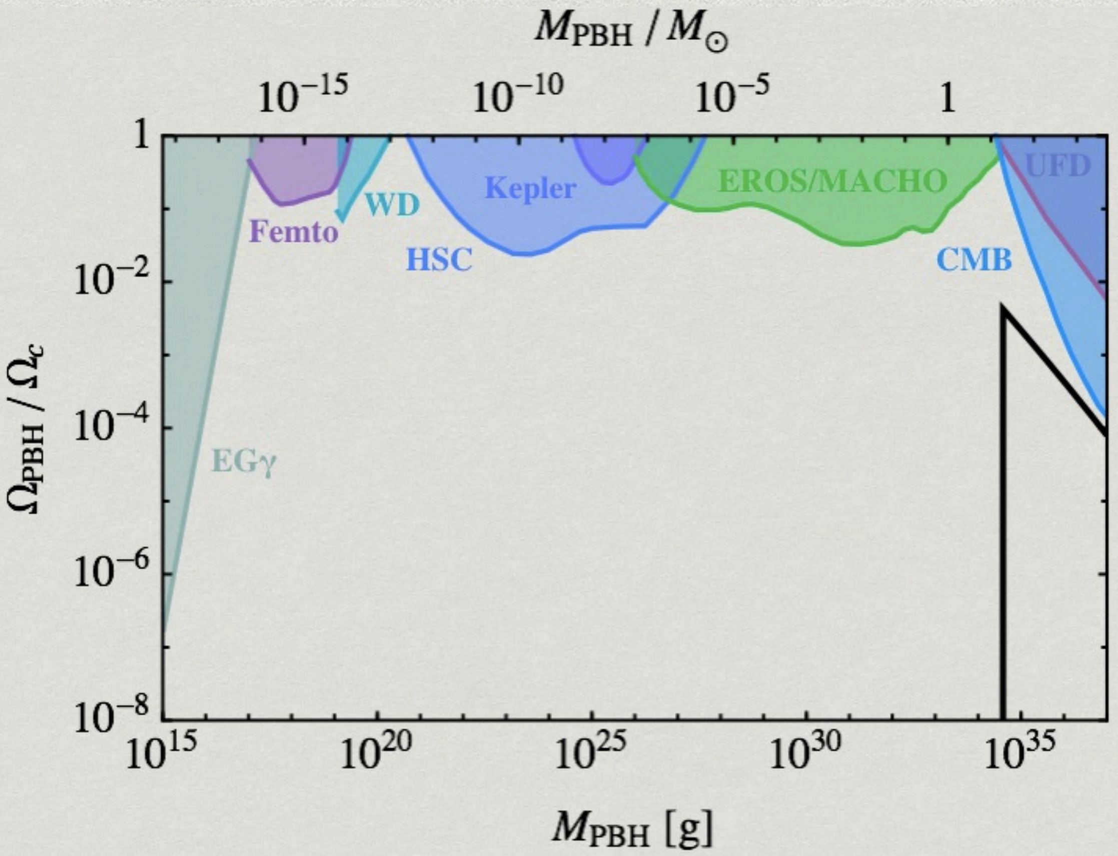


- To explain the $10M_\odot$ PBH, we set **Y_Q~10MeV**
- We assume Q-balls in residual HBBs account for the all DM: $Y_Q = Y_Q^{\rm HBB} f_B = Y_{\rm DM}$

Abundance of PBHs

- PBHs at LIGO scale are predicted evading all the constraints

- The hight of peak is related to the abundance of the residual HBB:



- to realize the LIGO event rate $\dfrac{\Omega_{\rm PBH}}{\Omega_{\rm DM}} \sim 10^{-3} - 10^{-2}$, we need

$$Y_{\rm Q} \sim (10 - 100)\,\%\, Y_{\rm DM}$$

LIGO PBHs and Q-ball DM are cogenerated!!

Summary

- PBHs is formed in AD mechanism in MSSM
- The PBHs with mass ~ $10M_\odot$ is predicted due to the QCD phase transition
- The stringent constraint from the μ-distortion and PTA experiment is completely absent because adiabatic curvature perturbation is not required
- In the case with Q-ball, LIGO PBHs and Q-ball DM are cogenerated

- Multi vacua condition

$$\Delta \equiv \frac{T_R^2 M_{\rm Pl}}{H(t_e)^3} \gtrsim 1,$$

- critical point between the vacua

$$\varphi_c(t_e) \equiv \varphi_c = \Delta^{1/2} H(t_e),$$

- critical value for the PBH formaiton

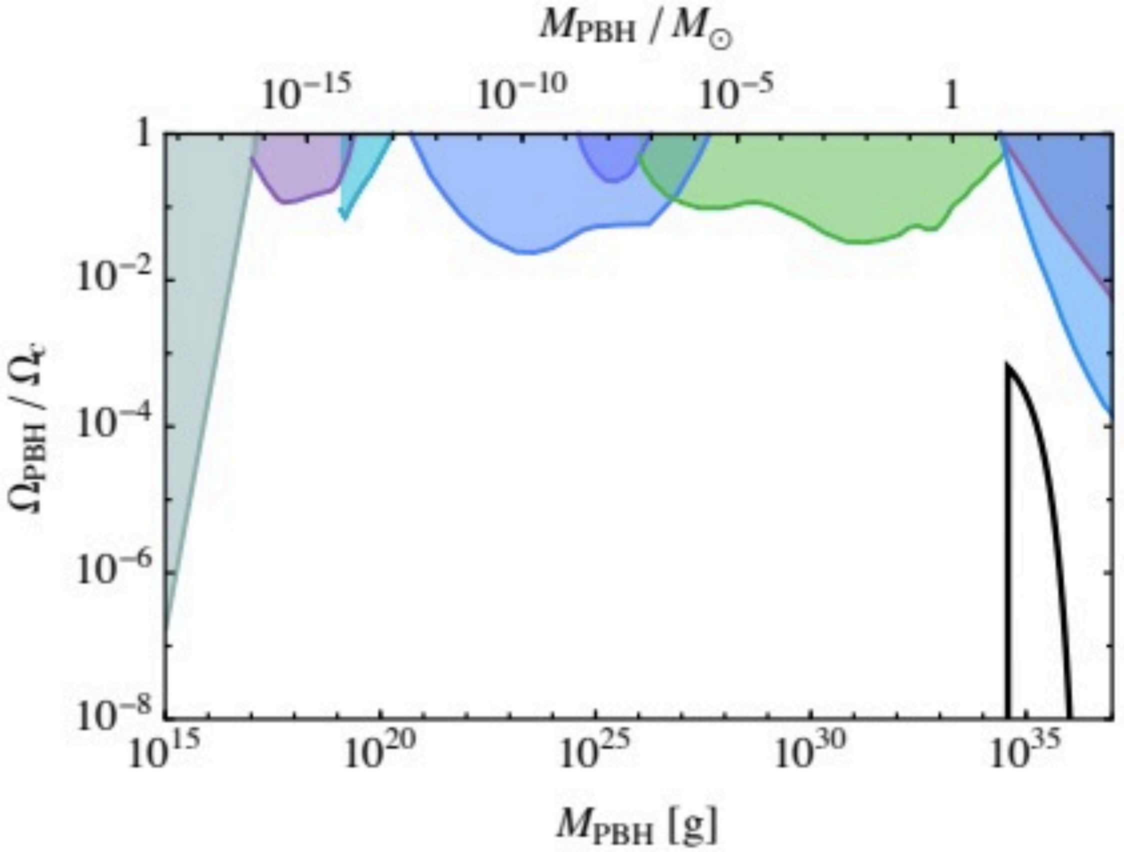
$$\delta(T) > \delta_c(T) \simeq w(T)$$

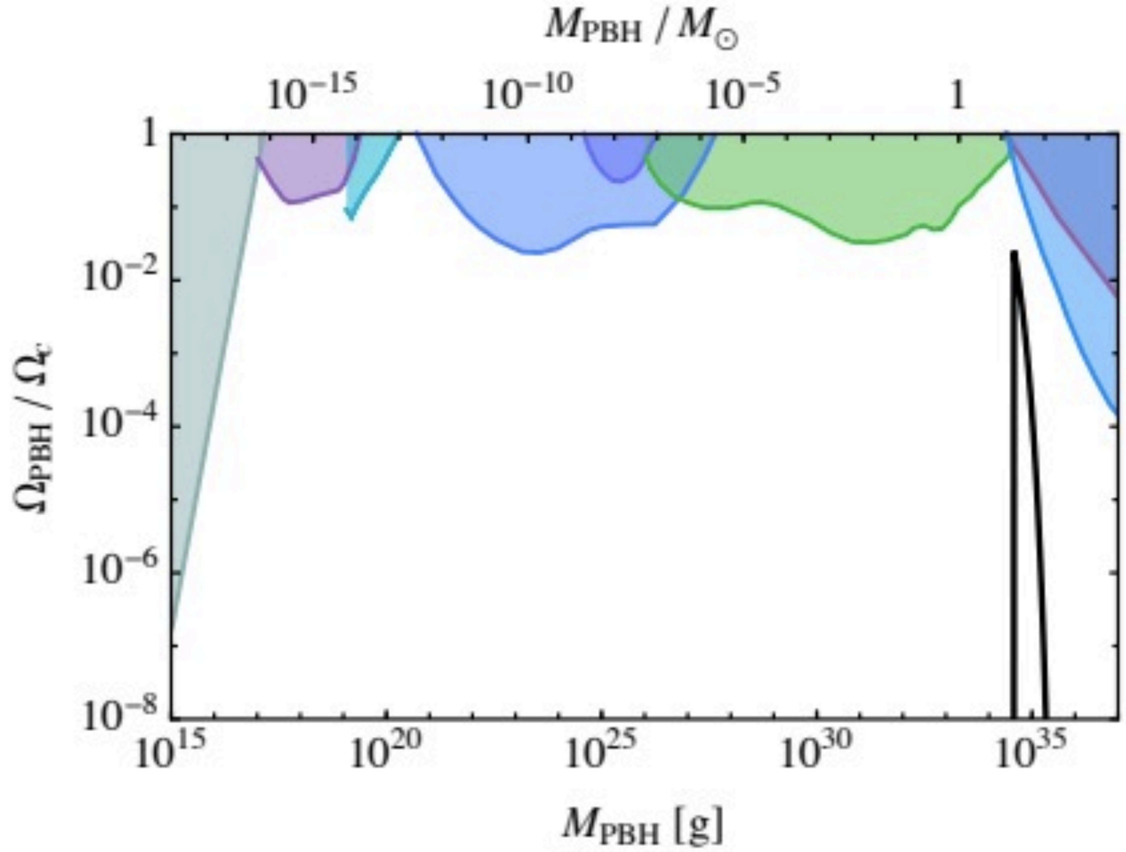
- Thermal potential in 1&2 loop order

$$V_{\rm T}(\phi) = \begin{cases} c_1 T^2 |\phi|^2, & f_k|\phi| \lesssim T, \\ c_2 T^4 \ln\left(\frac{|\phi|^2}{T^2}\right), & |\phi| \gtrsim T, \end{cases}$$

- Current abundance of the PBH

$$\frac{\Omega_{\rm PBH}(M_{\rm PBH})}{\Omega_c} \simeq \frac{\rho_{\rm PBH}}{\rho_m}\bigg|_{\rm eq} \frac{\Omega_m}{\Omega_c} = \frac{\Omega_m}{\Omega_c} \frac{T(M_{\rm PBH})}{T_{\rm eq}} \beta_{\rm PBH}(M_{\rm PBH})$$
$$\simeq \left(\frac{\beta_{\rm PBH}(M_{\rm PBH})}{1.6 \times 10^{-9}}\right) \left(\frac{\Omega_c h^2}{0.12}\right)^{-1} \left(\frac{M_{\rm PBH}}{M_\odot}\right)^{-1/2},$$


$M_{\rm PBH} / M_\odot$
10^{-15}
10^{-10}
10^{-5}
1
$\Omega_{\rm PBH} / \Omega_c$
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{15}
10^{20}
10^{25}
10^{30}
10^{35}
$M_{\rm PBH}$ [g]


$M_{\rm PBH} / M_\odot$
10^{-15}
10^{-10}
10^{-5}
1
$\Omega_{\rm PBH} / \Omega_c$
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{15}
10^{20}
10^{25}
10^{30}
10^{35}
$M_{\rm PBH}$ [g]