新学術領域研究「なぜ宇宙は加速するのか？ - 徹底的究明と将来への挑戦 -」
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Primordial Black Holes and Dark Matter

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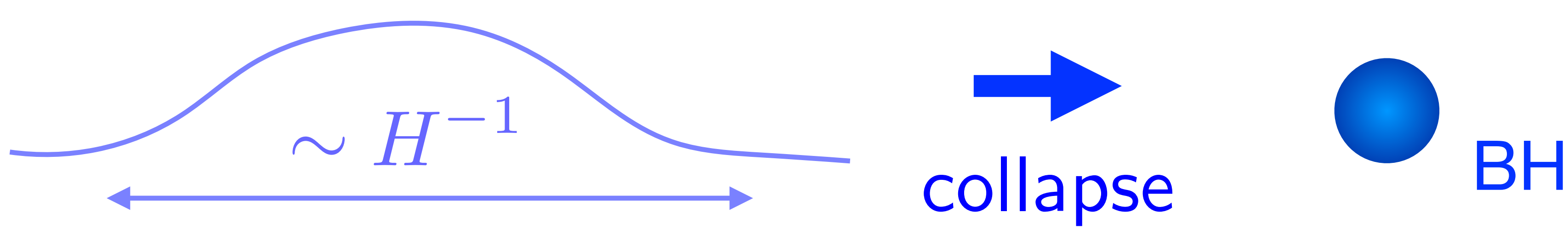
Based on MK Mukaida Yanagida, arXiv:1605.04974
MK Kusenko Tada Yanagida arXiv:1606.07631
Inomate MK Mukaida Tada Yanagida, arXiv:1611.06130, 1701.02544, 1711.06129
Hasegawa MK arXiv:1711.00990

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 detected by LIGO-Virgo recently
- 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

- We consider the following two models for PBH formation
  - Double inflation (preinflation+new inflation)

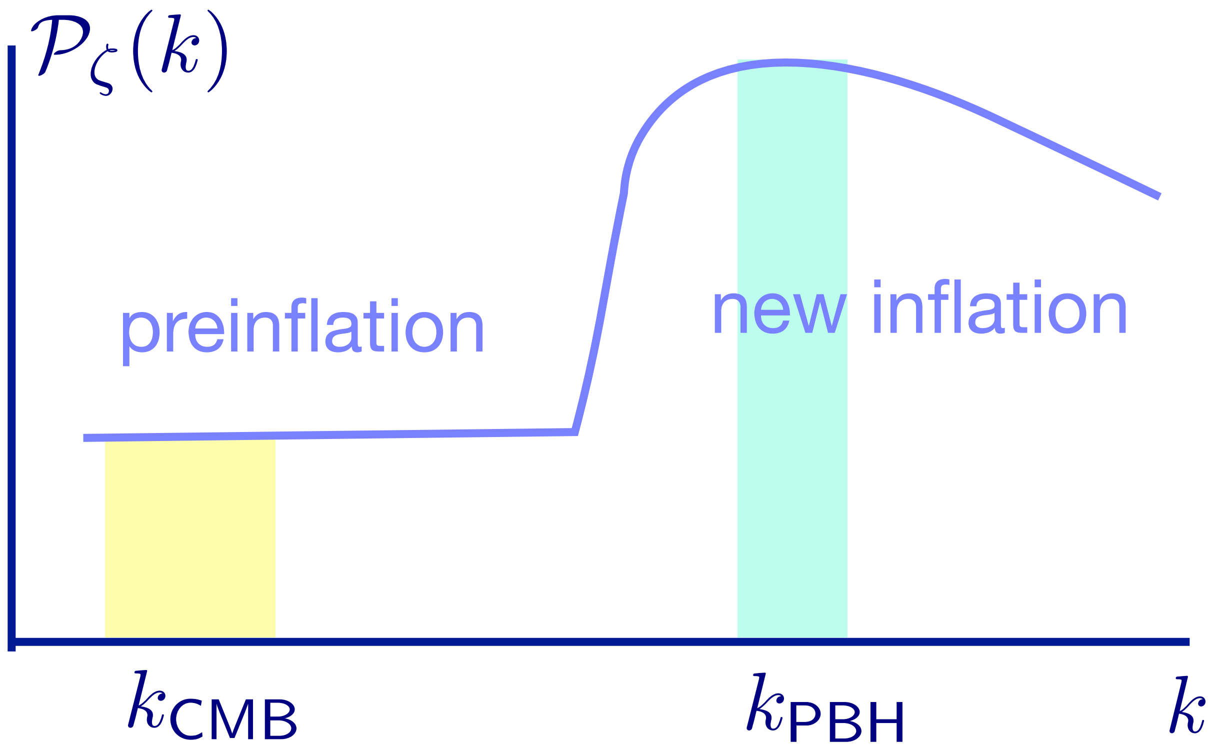
    → DM PBHs and LIGO PBHs

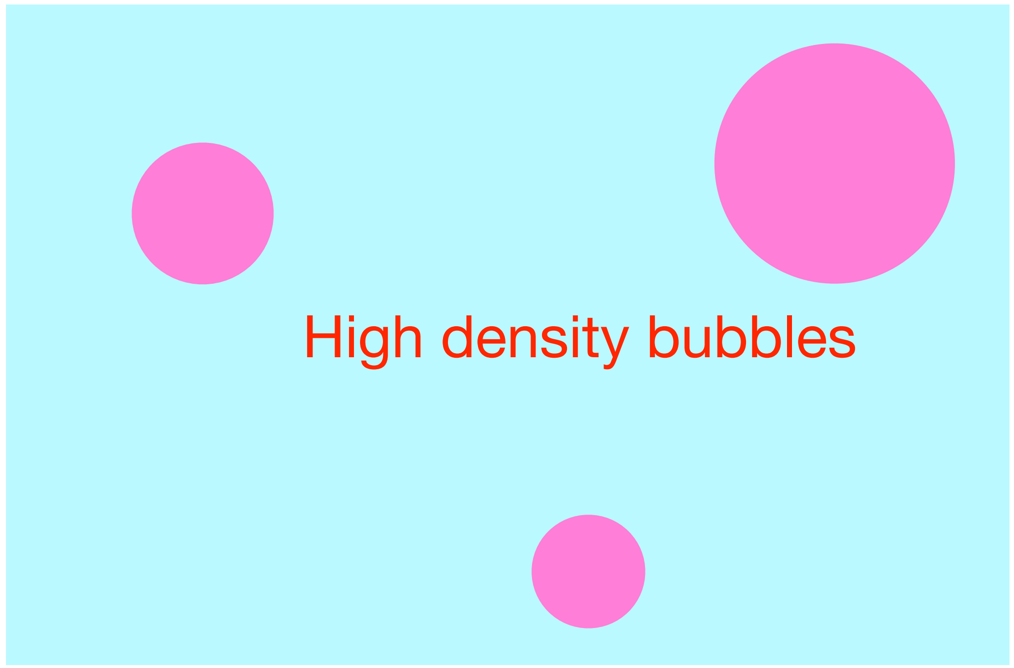
    MK, Sugiyama, Yanagida (1998)
  - Non-standard Affleck-Dine mechanism

    (Formation of high density bubbles)

    → LIGO PBHs

    Hsegawa, MK (2017)
    Dogov MK Kevlishvili (2009)
    Nakama Suyama Yokoyama (2016)

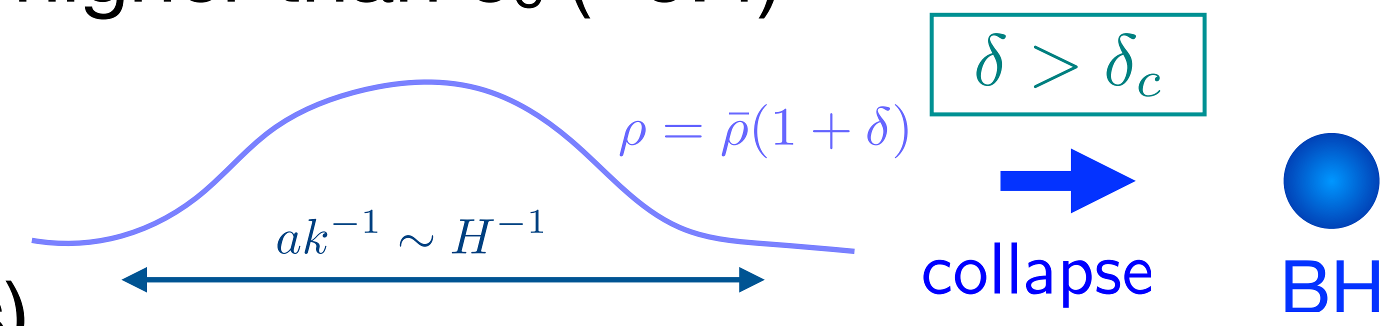




Contents

2. PBH formation in radiation dominated universe

- When density fluctuations reenter the horizon, a PBH is formed if its over-density is higher than δ_c (≈0.4)



- PBH mass (~ Horizon mass)

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

$M_{\mathrm{PBH}} = \gamma M_H$ (horizon mass)   [$\gamma = 0.2$ Carr (1975)]

- PBH abundance is estimated by Press-Schechter formalism

$\mathcal{P}_\zeta(k)$ → PBH mass fraction $\beta = \rho_{\mathrm{PBH}}(M)/\rho$

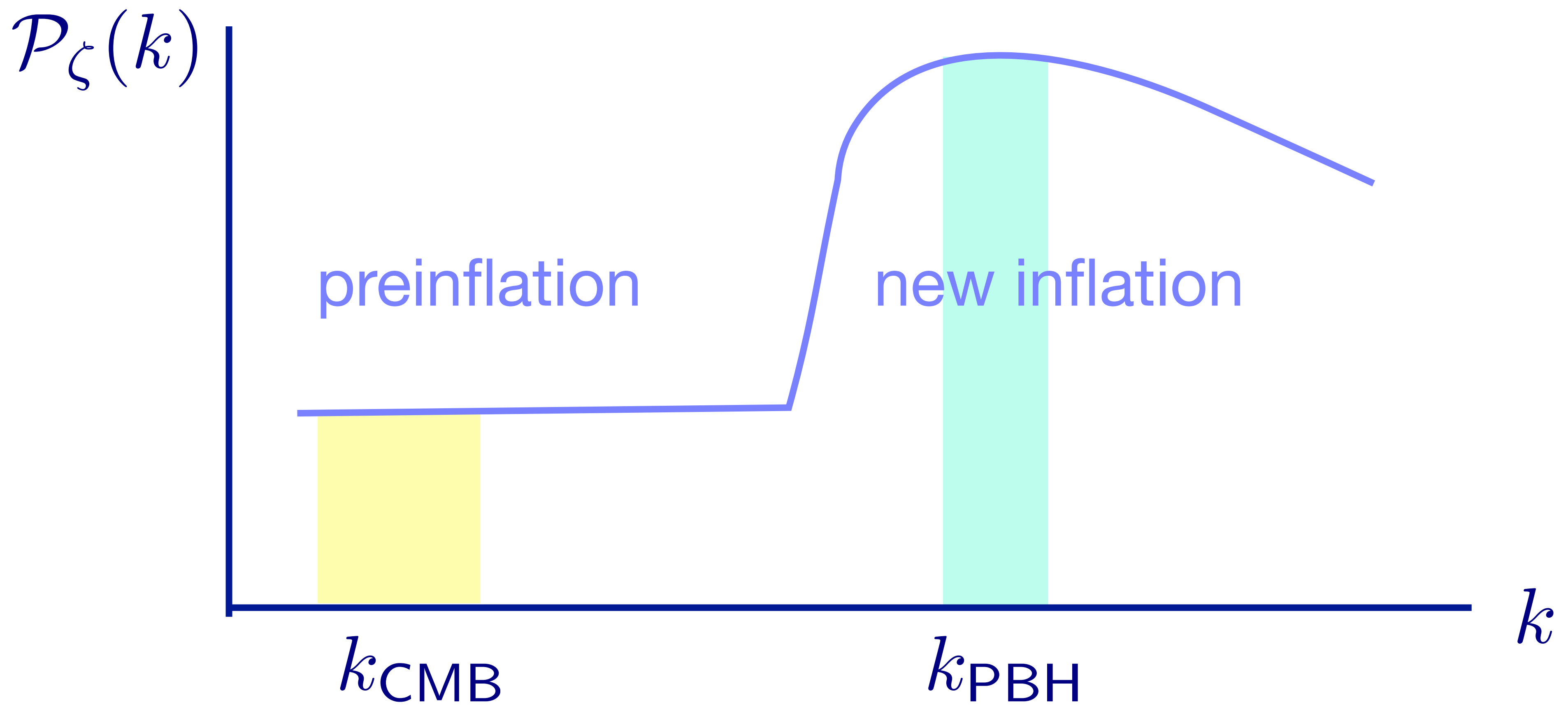
$\mathcal{P}_\zeta(k) \sim O(10^{-2})$ for PBH formation

- Present PBH fraction to DM

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

3. Double inflation model

- Preinflation (no specific model is required) accounts for perturbations on large scales observed by Planck
- New inflation (after preinflation) with e-fold $N_{new} < 50$ produces large curvature perturbations on small scales



- New inflation is important to produce PBHs

3. Double inflation model

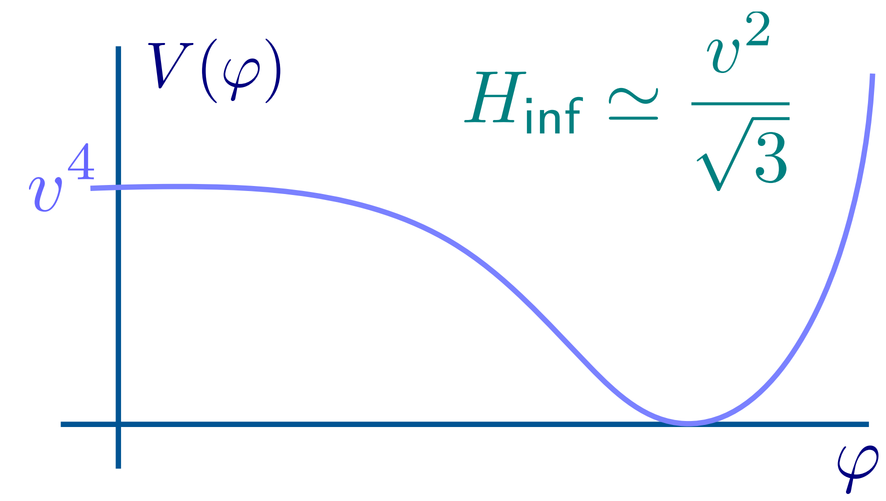
- Potential for new inflation

$$V(\varphi) = (v^2 - g\varphi^n)^2 - \varepsilon v^4 \varphi - \frac{1}{2}\kappa v^4 \varphi^2$$

Hubble mass before new inf.

$$+ cH^2\varphi^2$$

$n = 3, 4, \cdots$ $\quad M_p = 1$

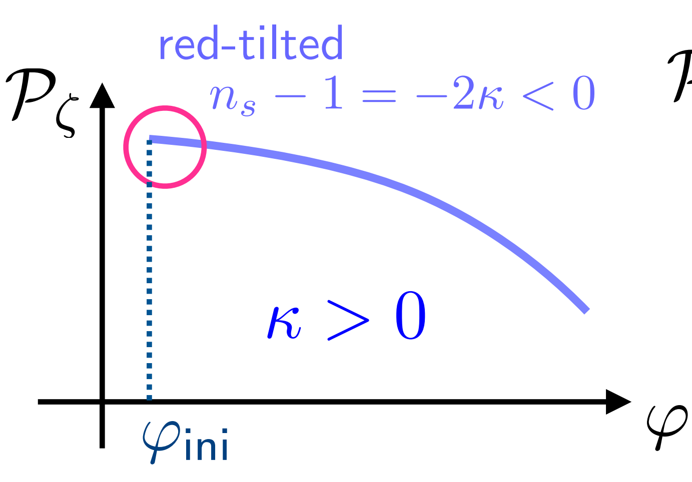


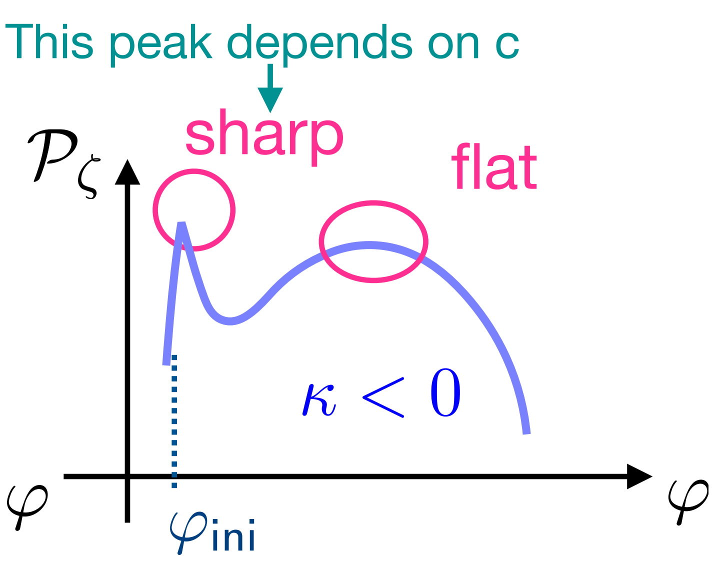
- Linear term $\quad \varepsilon \ll 1$
  - determining initial value $\quad \varphi_{\rm ini} \sim \varepsilon$
  - amplitude of curvature perturbations

$$\mathcal{P}_\zeta^{1/2} = \frac{H_{\rm inf}}{2\pi}\frac{1}{\sqrt{2\epsilon}} \simeq \frac{1}{2\sqrt{3}\pi}\frac{v^2}{\varepsilon + \kappa\varphi} \sim \frac{1}{2\sqrt{3}\pi}\frac{v^2}{\varepsilon} \qquad (\varphi \lesssim \varepsilon)$$

$\mathcal{P}_\zeta \sim O(0.01)$ for $\varepsilon \sim v^2$ → PBH formation

- Quadratic term $\quad \kappa \sim O(0.1)$
  - spectrum index (shape of power spectrum)

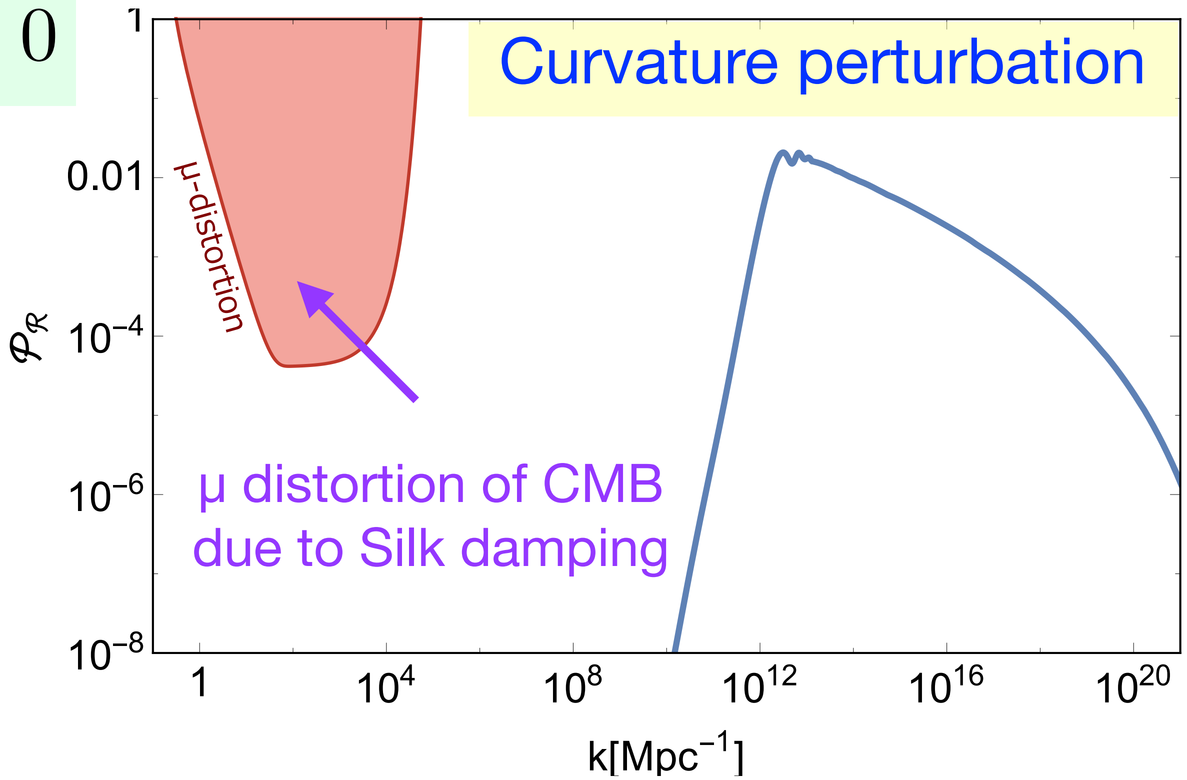


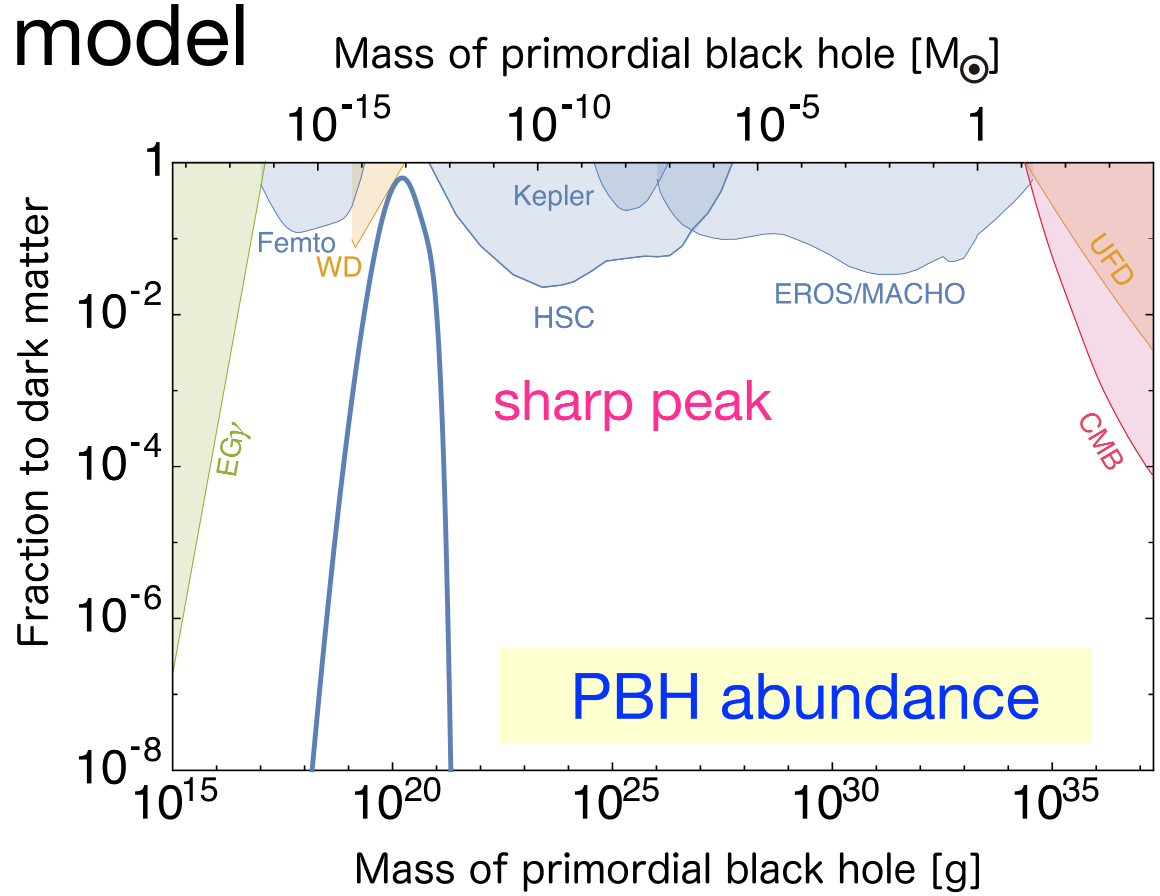


Power spectrum and PBH mass function

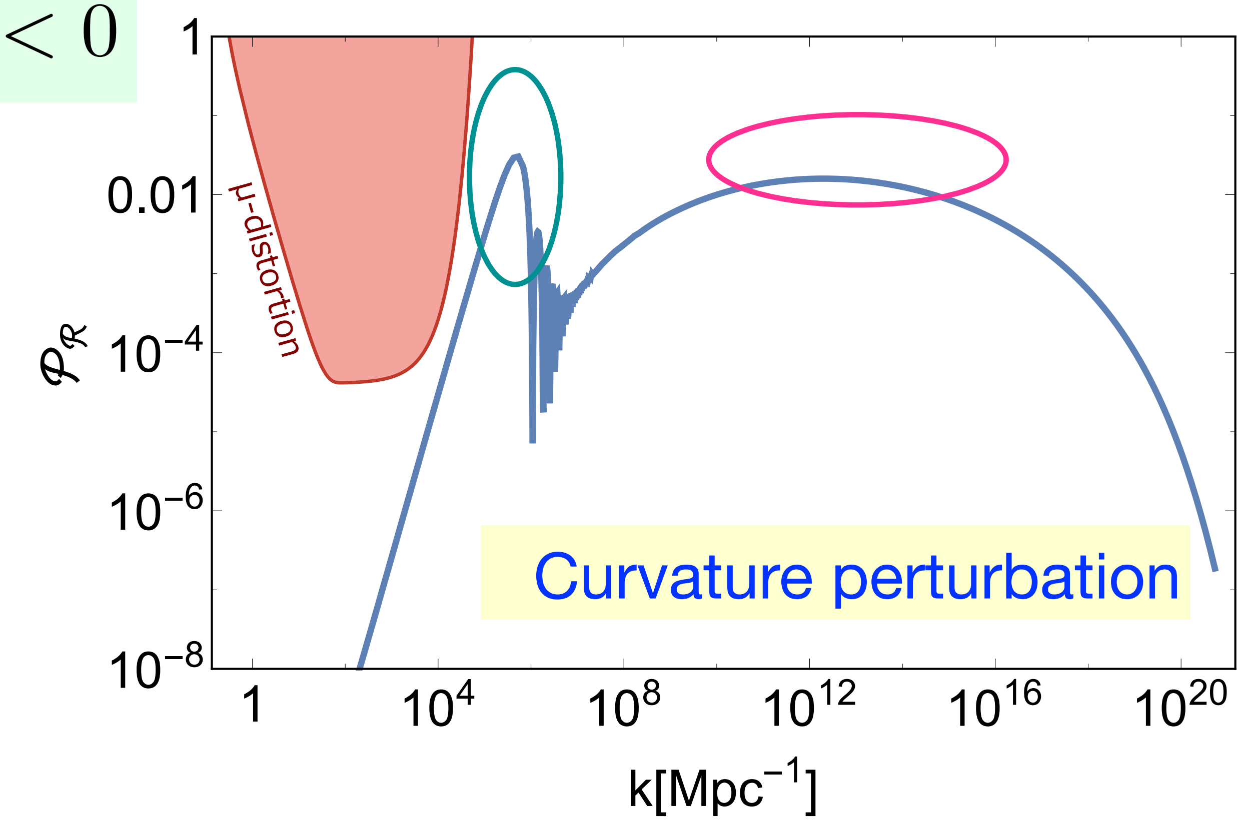
- Double inflation (chaotic+new) model

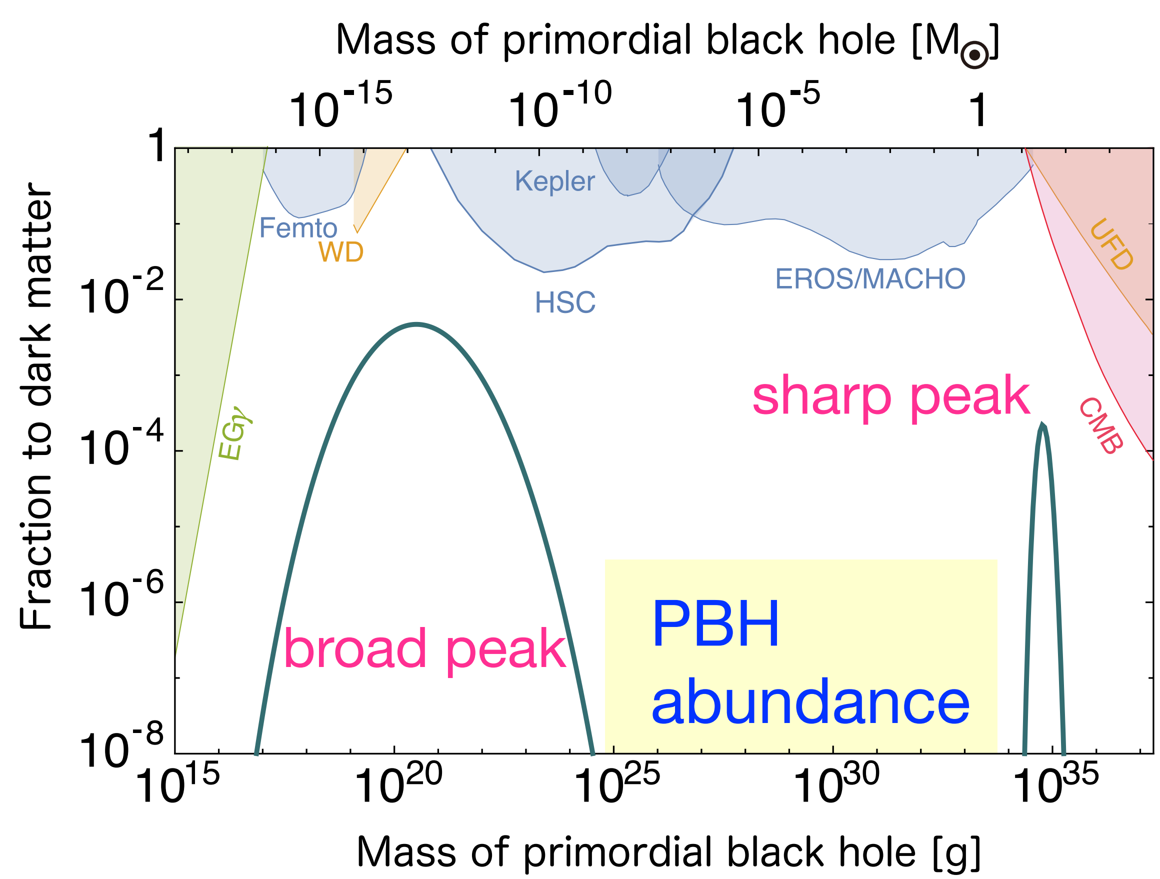
$\kappa > 0$





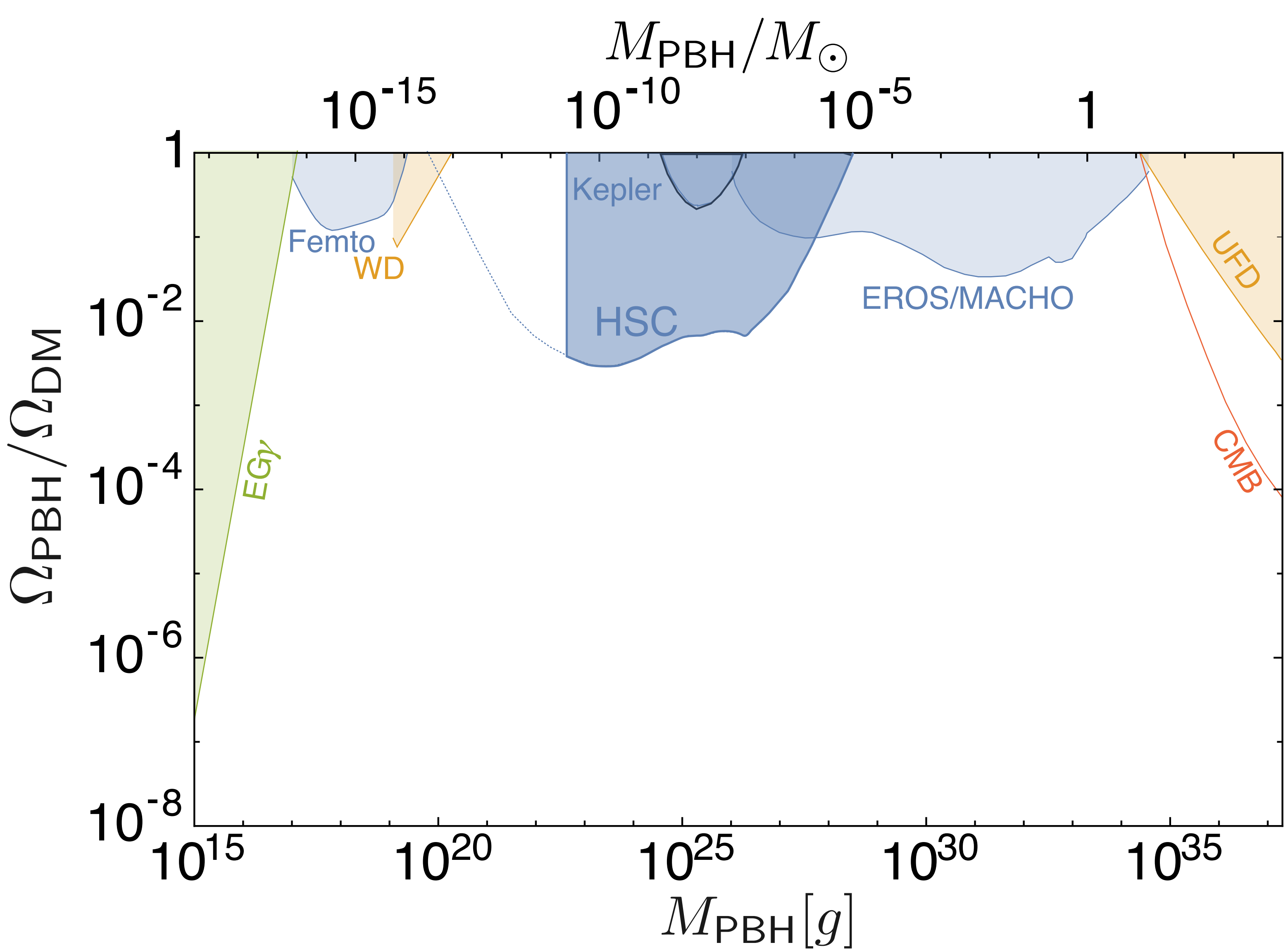
$\kappa < 0$





4. Black Hole as Dark Matter

- PBHs can account for all dark matter of the universe?
- Observational constraints on wide range of PBH mass
- However there is a window around mass~ 10^{20}g
- Double inflation (e.g.chaotic + new) can produce such DM PBHs



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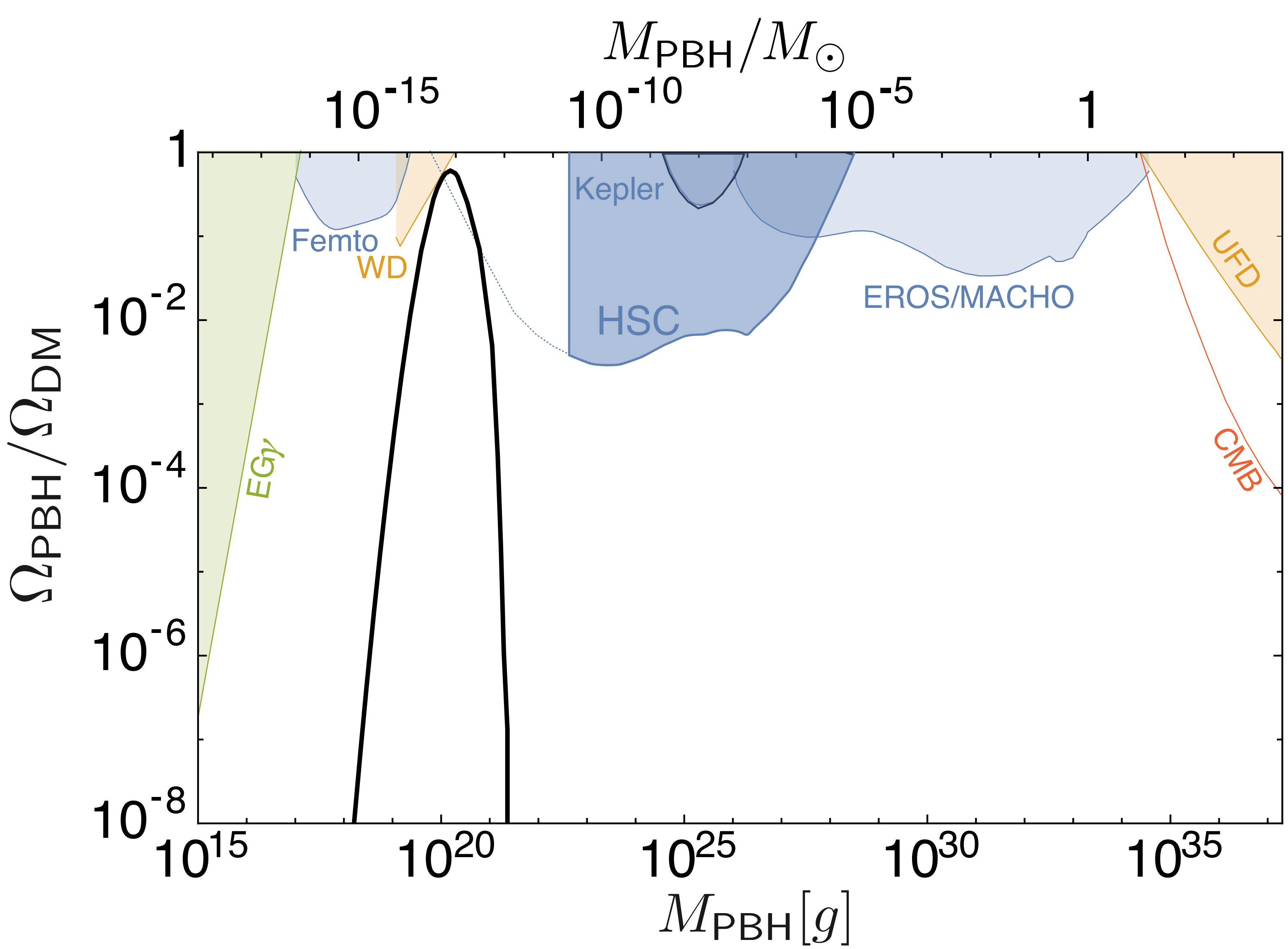


Inomata MK Mukaida
Tada Yanagida (2017)

$v = 10^{-3}$ $c_{\rm pot} = 1$

$\kappa = 0.13$

5. LIGO-Virgo gravitational wave events and dark matter

- GW events by LIGO

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

- Origin of BHs

  ➡ PBHs are one of candidates

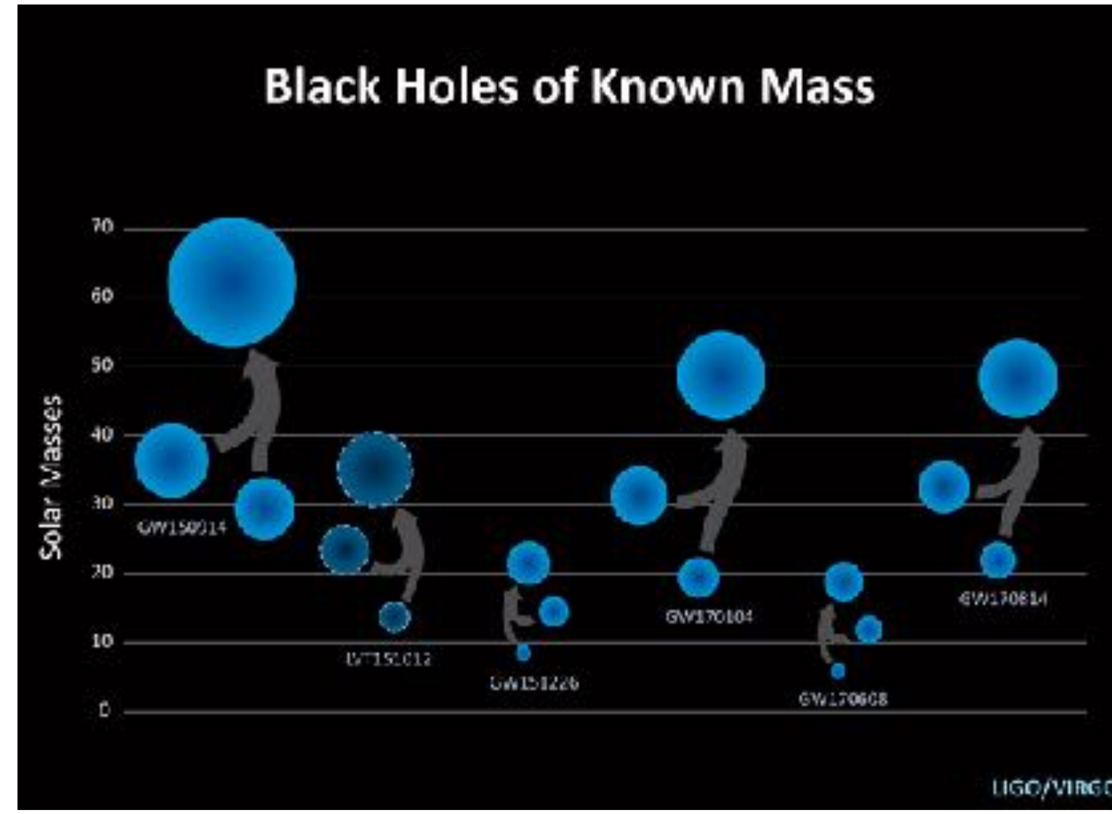
- Required fraction of PBHs

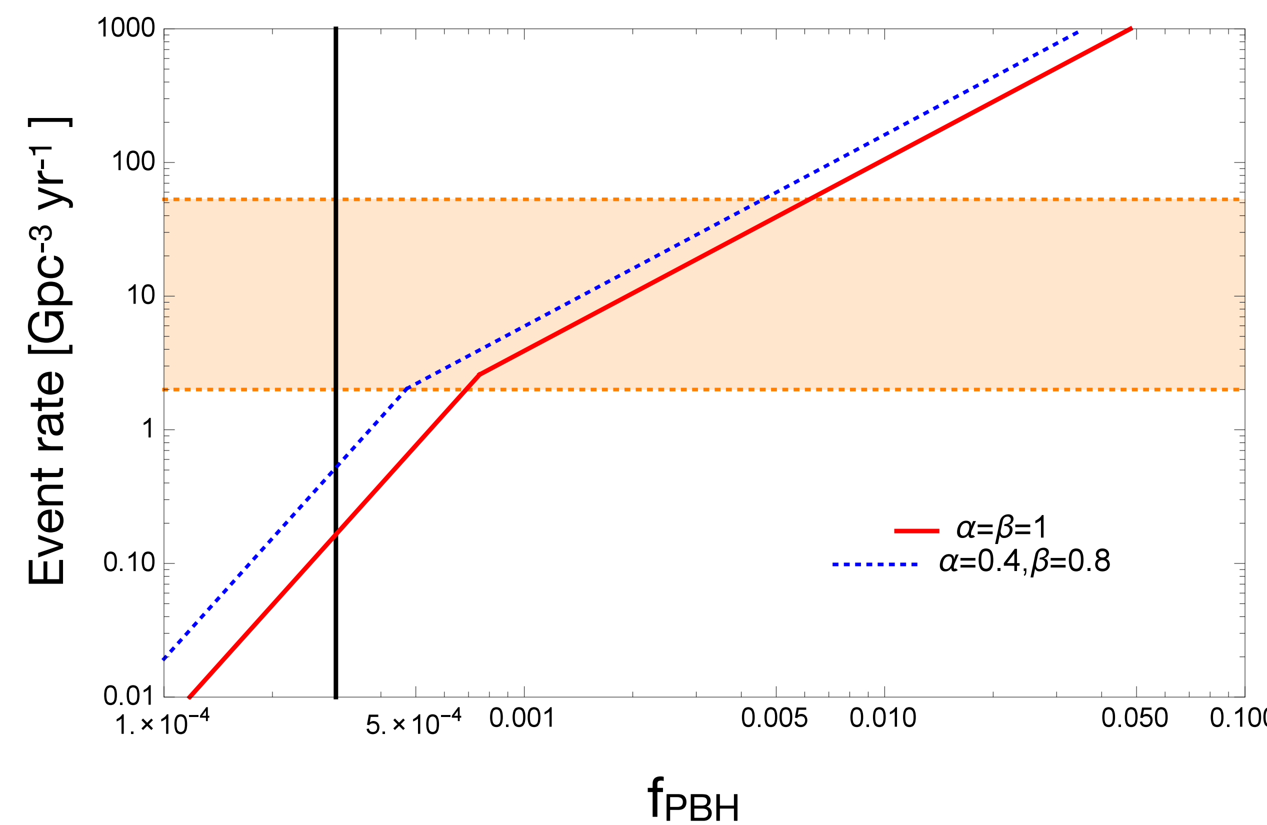
$$\Omega_{\rm PBH}/\Omega_c \sim 10^{-3} - 10^{-2}$$

Sasaki Suyama Tanaka Yokoyama (2016)

- If PBHs account for LIGO events WIMP DM is constrained

Large density perturbations produce Urtra Compact Mini Halos (UCMHs)

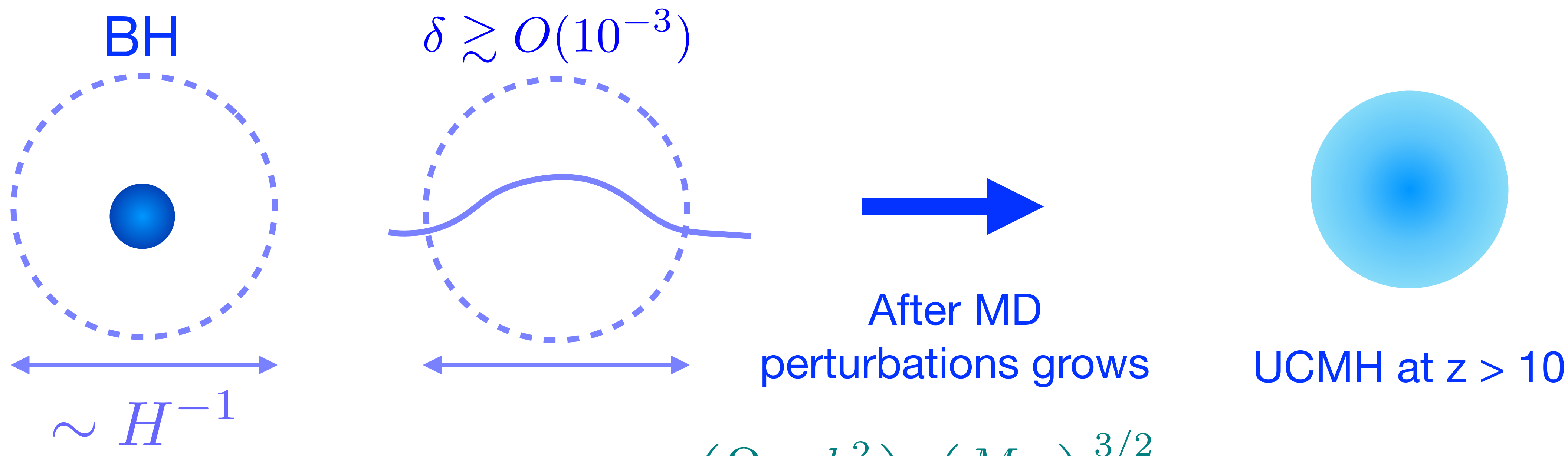




5.1 Ultra-Compact Mini Halos (UCMHs)

Ricotti Gould (2009)
Scott Sivertsson (2009)

- PBHs and large density fluctuations produce UCMHs



$$M^0_{\mathrm{UCMH}} \simeq 3 \times 10^{-7} \left(\frac{\Omega_{\mathrm{DM}} h^2}{0.11}\right) \left(\frac{M_H}{M_\odot}\right)^{3/2} M_\odot$$

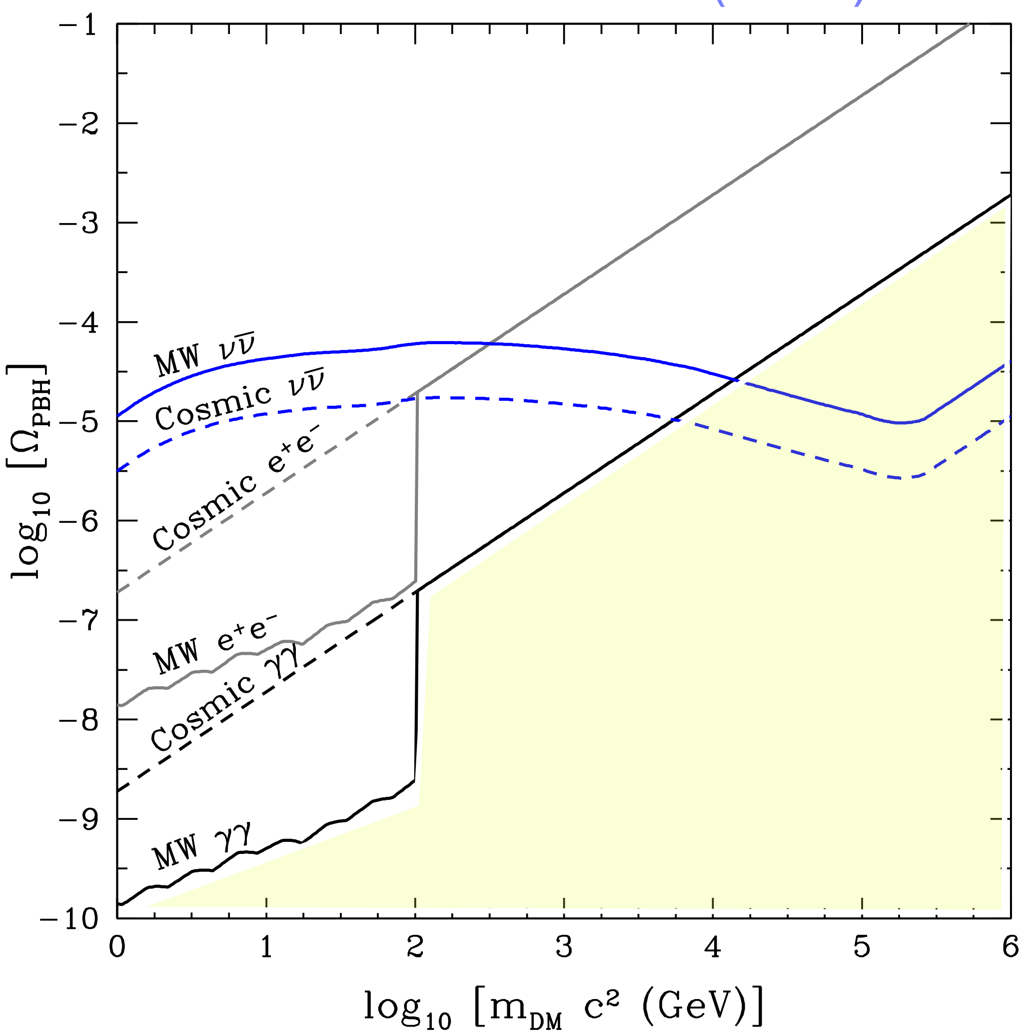
- Radial infall of DM produces a steep profile $\rho_{\mathrm{UCMH}} \propto r^{-9/4}$
- Annihilations of DM particles are drastically enhanced
  - Produce gamma rays
  - Affect CMB by changing the ionization history

→ Stringent constraint on WIMP DM

5.1 Ultra-Compact Mini Halos (UCMHs)

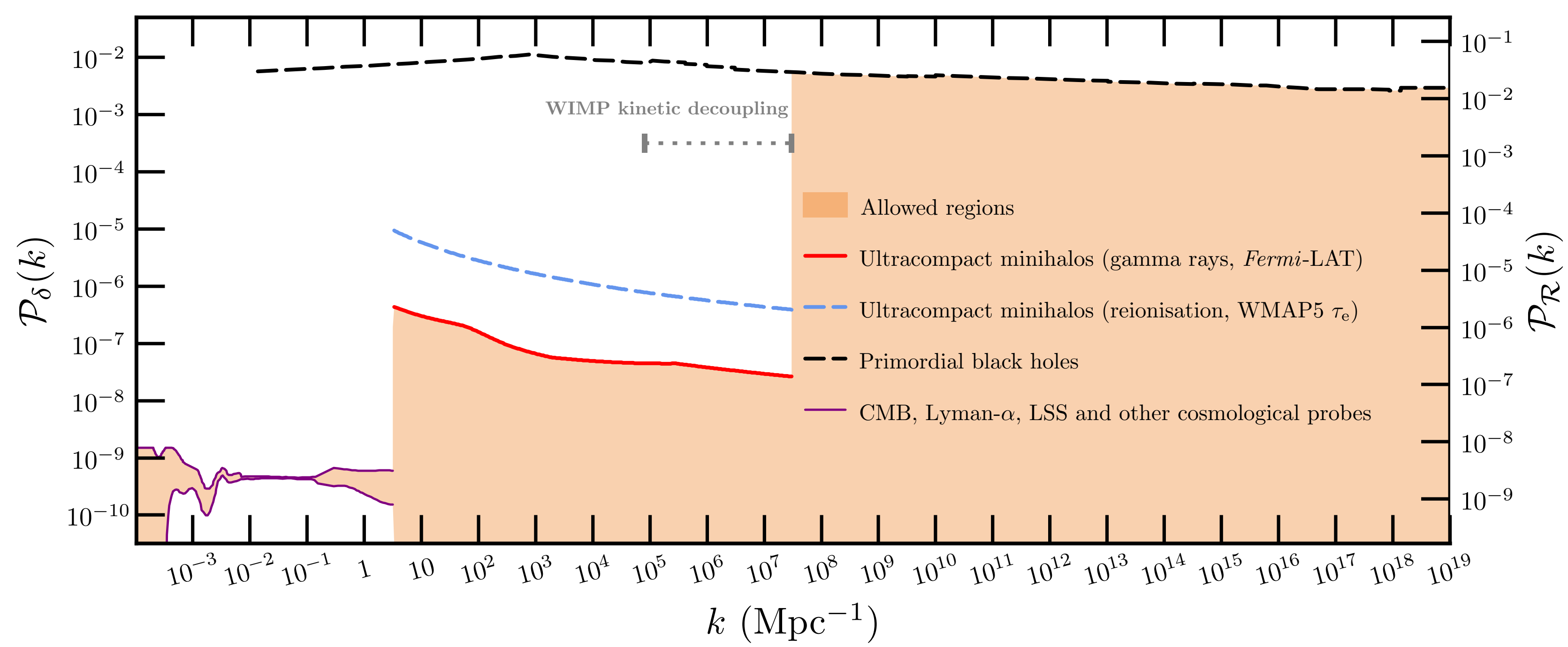
- Assume thermal relic DM $\langle \sigma v \rangle = 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$
- Constraint on PBH abundance and density perturbations

Lacki Beacom (2010)



$\Omega_{\mathrm{PBH}} \lesssim 10^{-4}$

Bringmann Scott Akrami (2011)



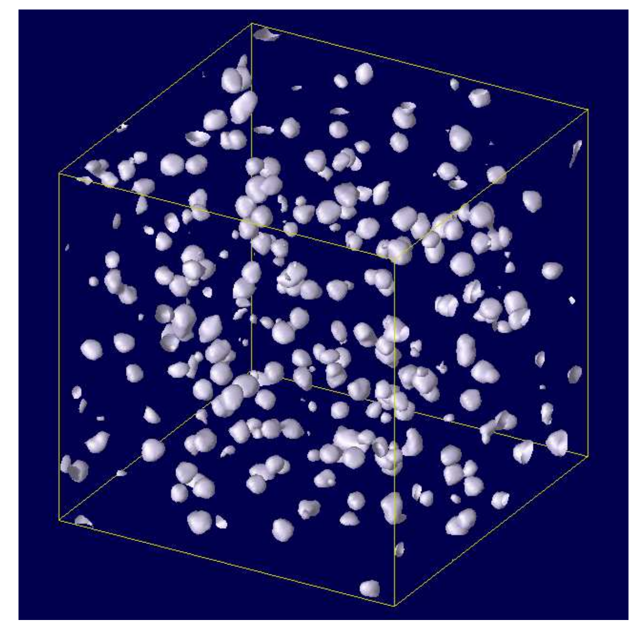
$\mathcal{P}_\zeta \lesssim 10^{-6}$

5.2 LIGO-Virgo GW events and dark matter

- If PBHs account for LIGO GW events, dark matter cannot be WIMPs
- Other dark matter candidates?
  - PBH : PBHs with $O(10)M_{\odot}$ cannot be DM ← various obs. constraints

    10^{20} g PBH can be DM
  - Axion : no UCMH constraint
  - Q ball : no UCMH constraint

    because it is heavy and rare



Hiramatsu MK Takahashi (2010)

- Double inflation can account for both LIGO and DM PBHs
- Affleck-Dine mechanism can account for LIGO PBHs and Q-ball DM

5.3 PBHs formation in double inflation

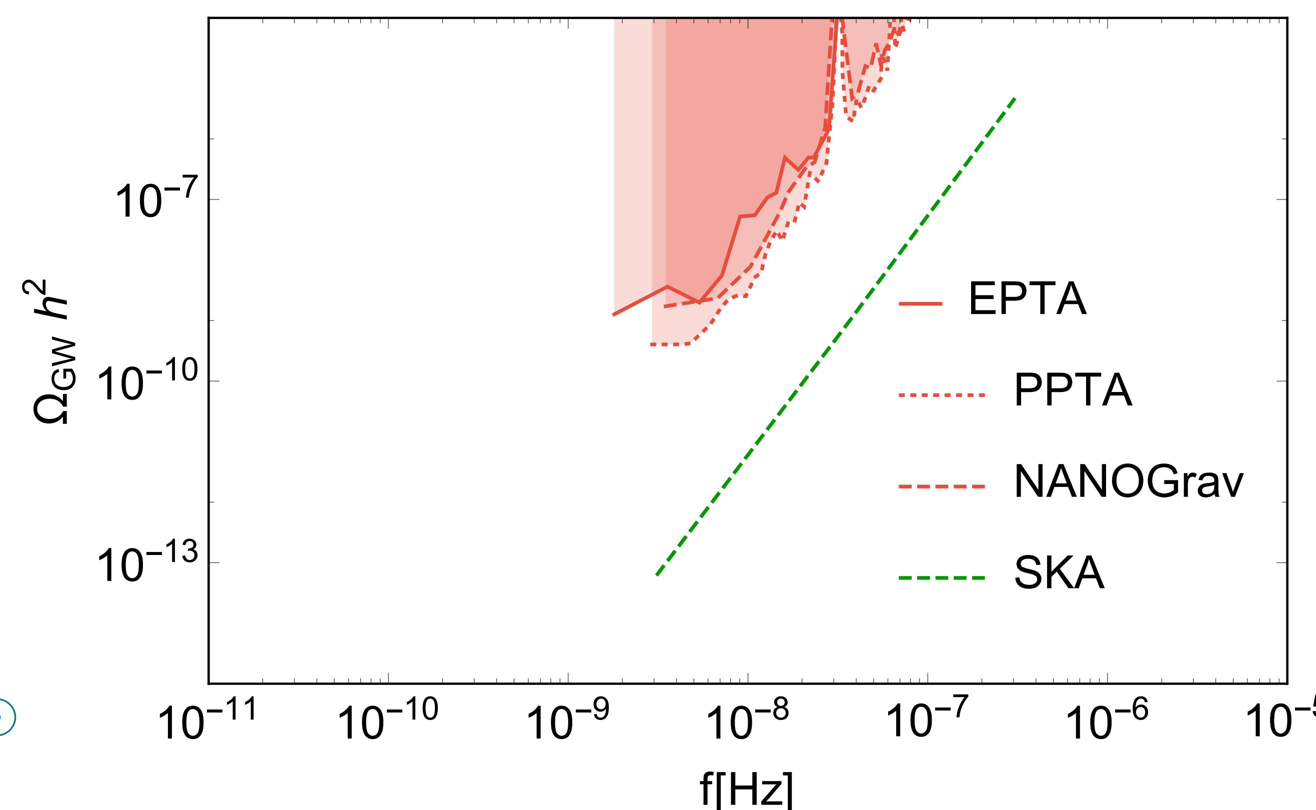
- LIGO PBHs can be produced in the double inflation model
- However, stringent constraint from pulsar timing experiment
- In PBH scenario 2nd order perturbations
  ~ $O(\zeta_{\vec{k}}\zeta_{\vec{k}-\vec{k}'})$ induce a source term of tensor perturbations

Saito Yokoyama (2009)
Bugaev Kulimai (2010)

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

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

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



- mu-distortion constraint

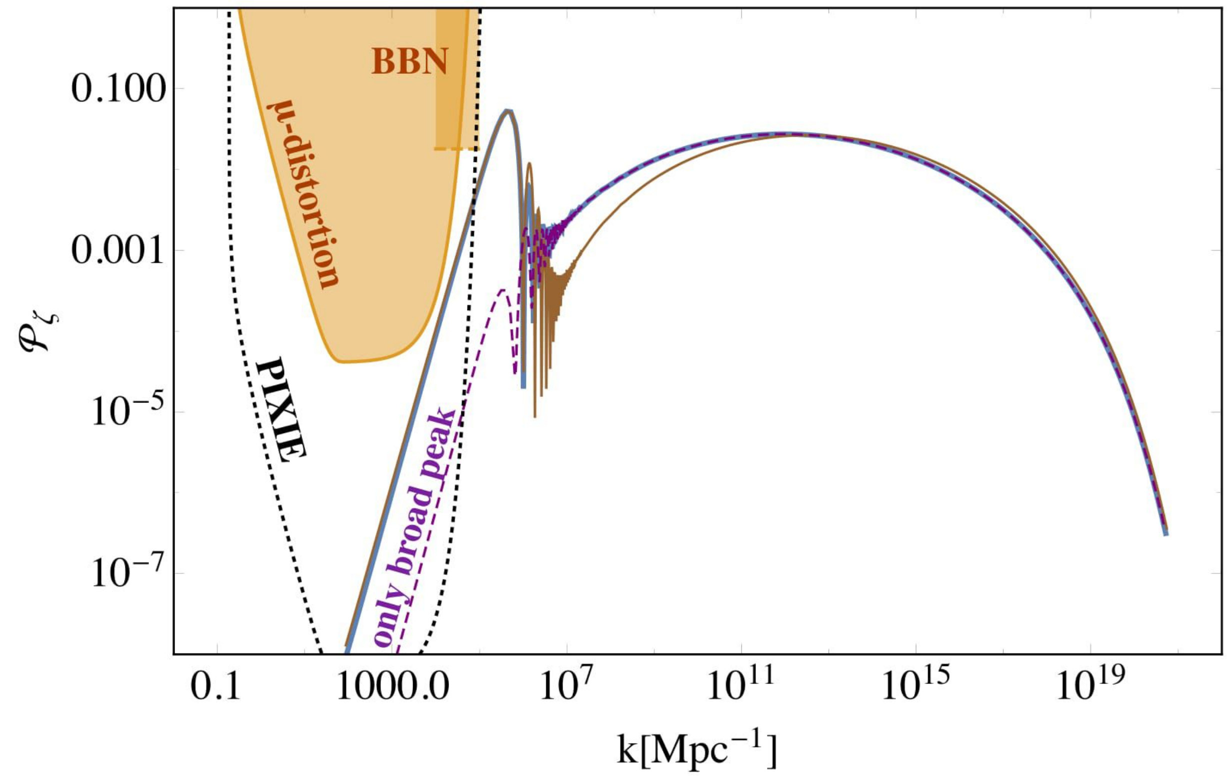
→ $400M_\odot \lesssim M_{\rm PBH} \lesssim 10^{13}M_\odot$

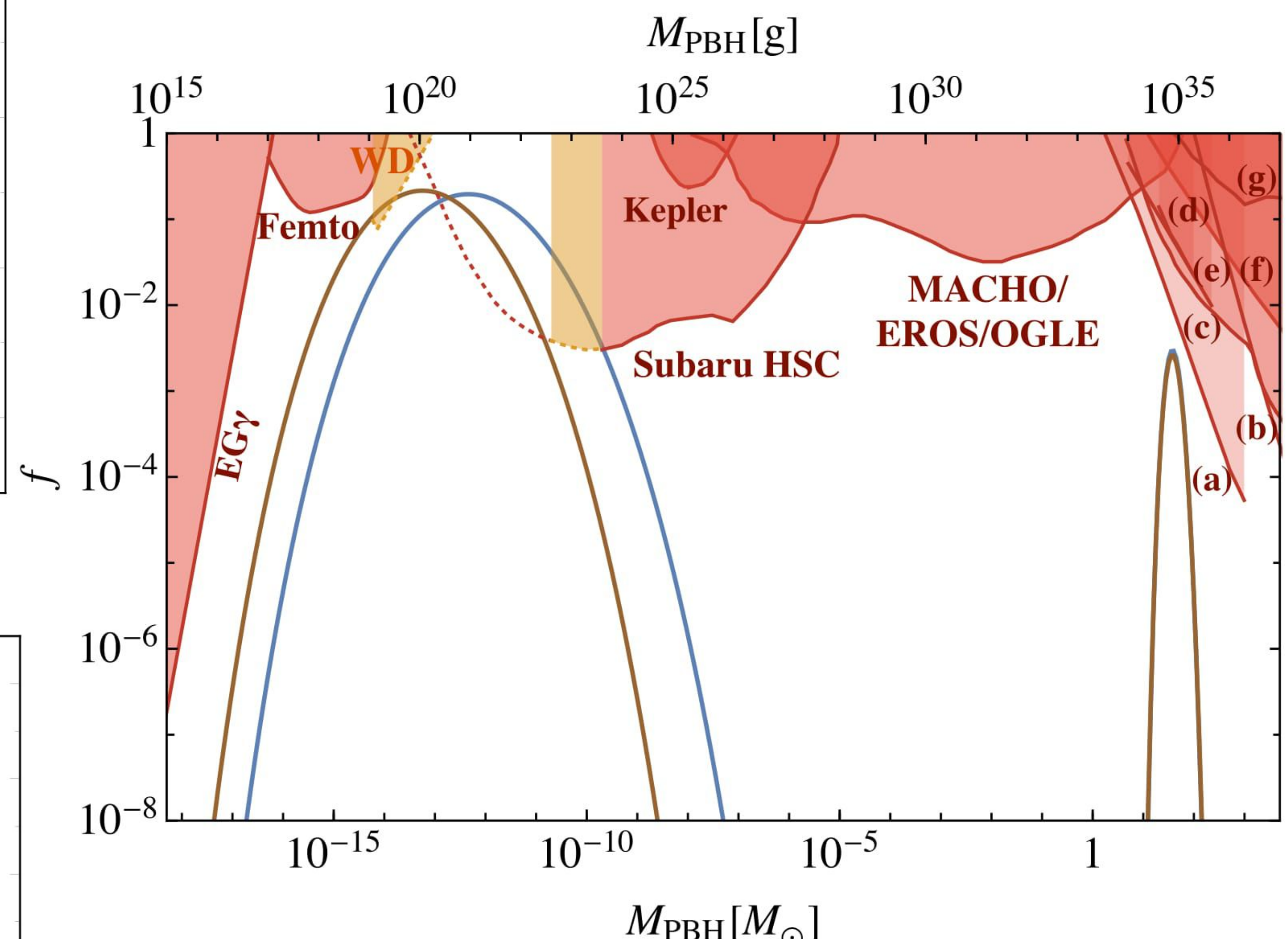
→ Sharp mass function around $M_{\rm PBH} \sim O(10)M_\odot$

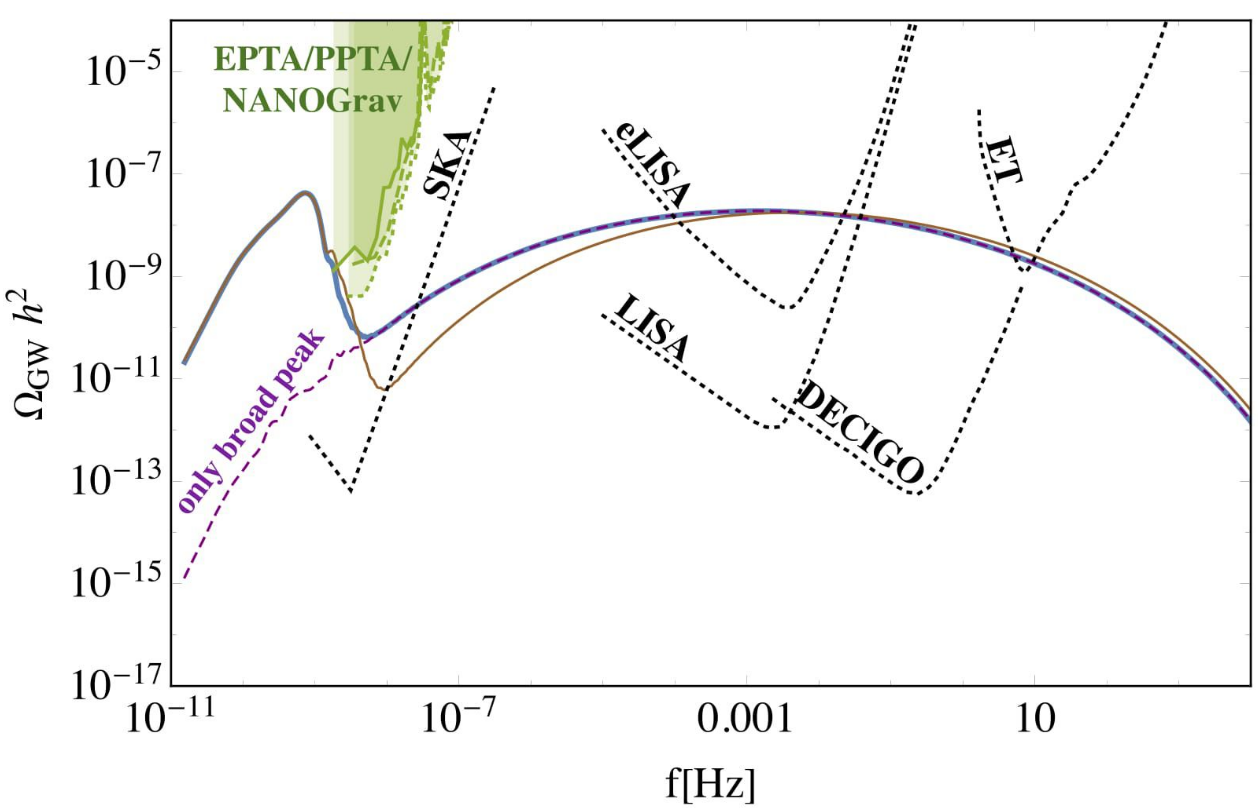
Double inflation as a single origin of PBHs for DM and LIGO

Inomata MK MukaidaYanagida (2017)

- Curvature perturbation spectrum can have two peaks
  - Large (small) k peak from $\delta\varphi$ produced during new (pre-) inflation





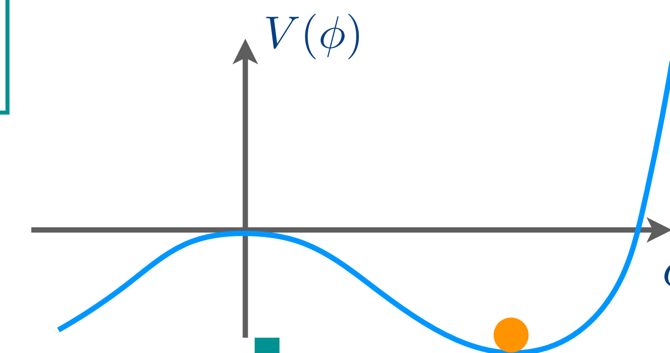


5.4 PBH formation in Affleck-Dine baryogenesis

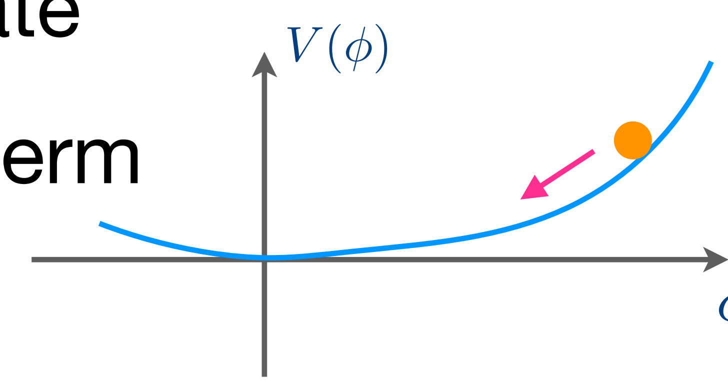
- Affleck-Dine mechanism
  - Flat directions in scalar potential of MSSM $\ni (\tilde{q},\ \tilde{\ell},\ H)$
- One of flat directions = AD field ϕ

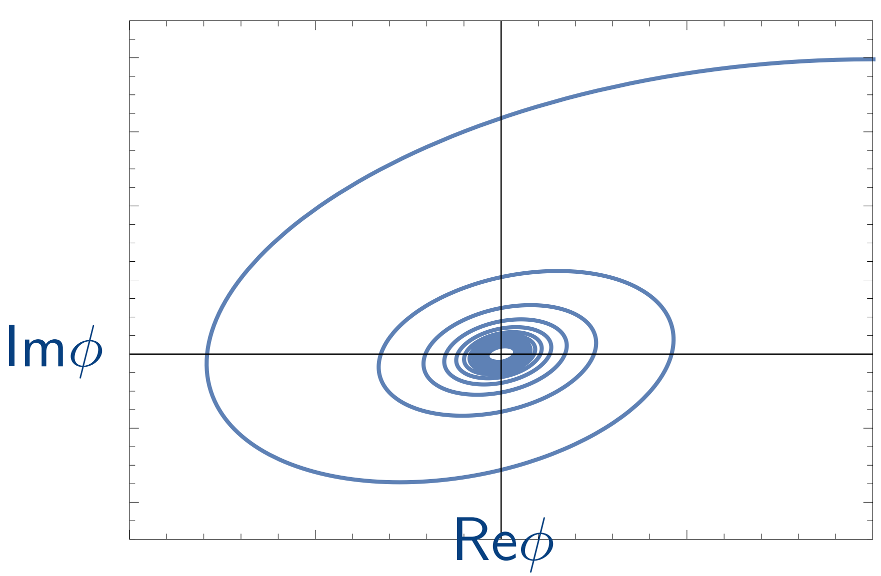
$$V(\phi) = (m_\phi^2 + c_H H^2)|\phi|^2 + \lambda^2 \frac{|\phi|^{2(n-1)}}{M_p^{2(n-3)}} + A\frac{\phi^n}{M_p^{(n-3)}} + h.c.$$

SUSY breaking mass term — Hubble induced mass term — Non-renormalizable term (n≥1) — A-term



- During inflation ϕ has a large value if c_H <0
- After inflation, when $m_\phi \simeq H$ ϕ starts to oscillate
- AD field is kicked in phase direction due to A-term





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

Baryon number generation

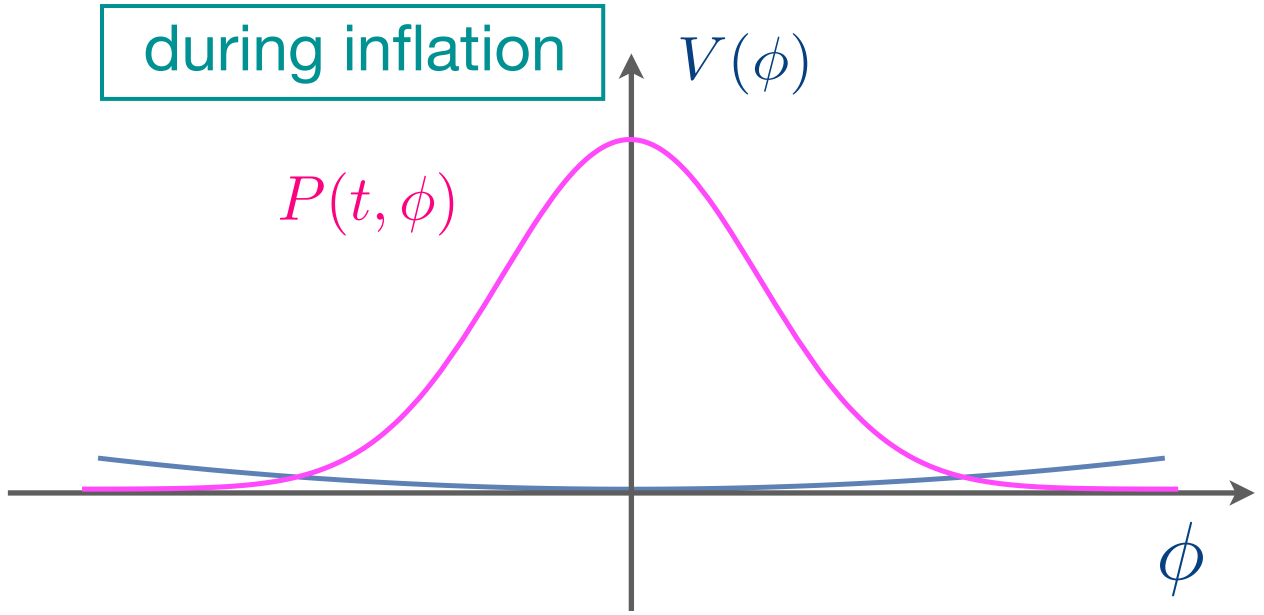
AD baryogenesis

High-baryon bubble formation

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

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

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



High-baryon bubble formation

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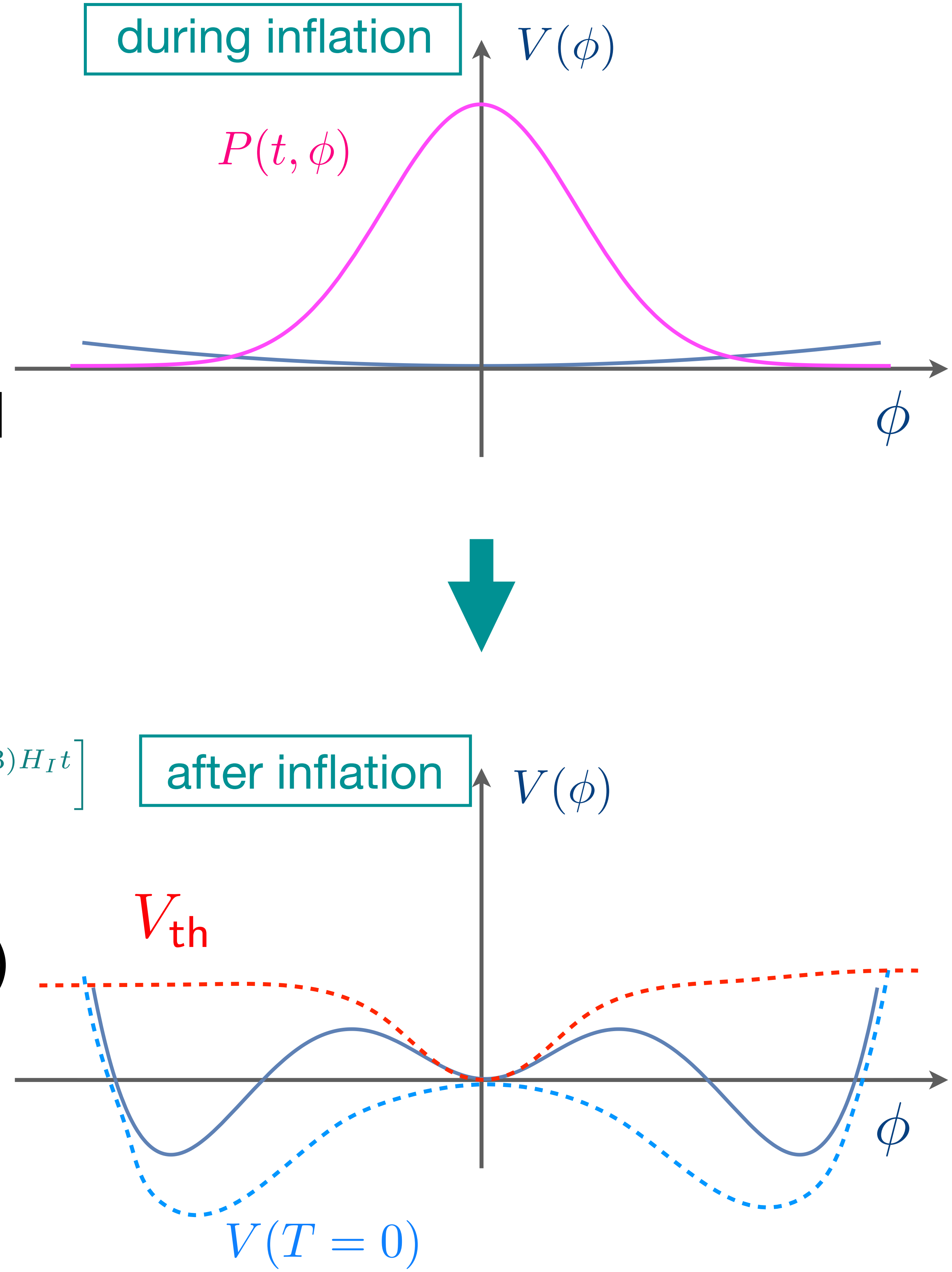
- After inflation
  - $c_H < 0$ (negative Hubble mass)
  - Thermal effect due to inflaton decay

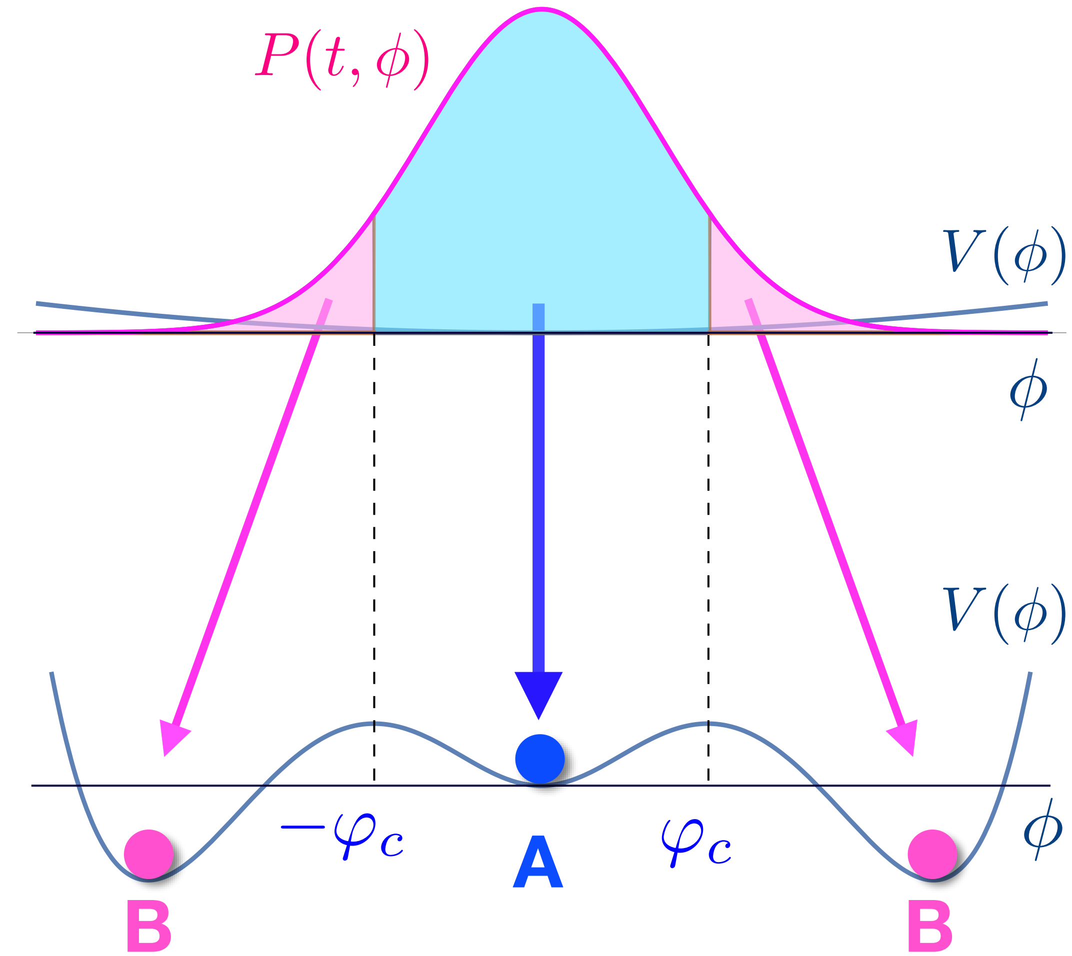
➡ multi-vacua

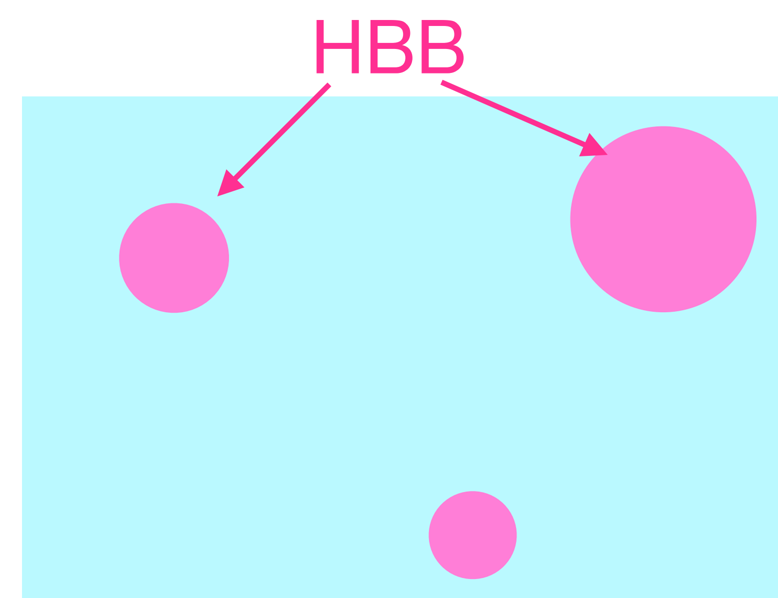


High-baryon bubble formation

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





- Oscillation of AD field forms Q-balls
  - Here we assume Q-balls are stable
  - Q-balls behave like matter

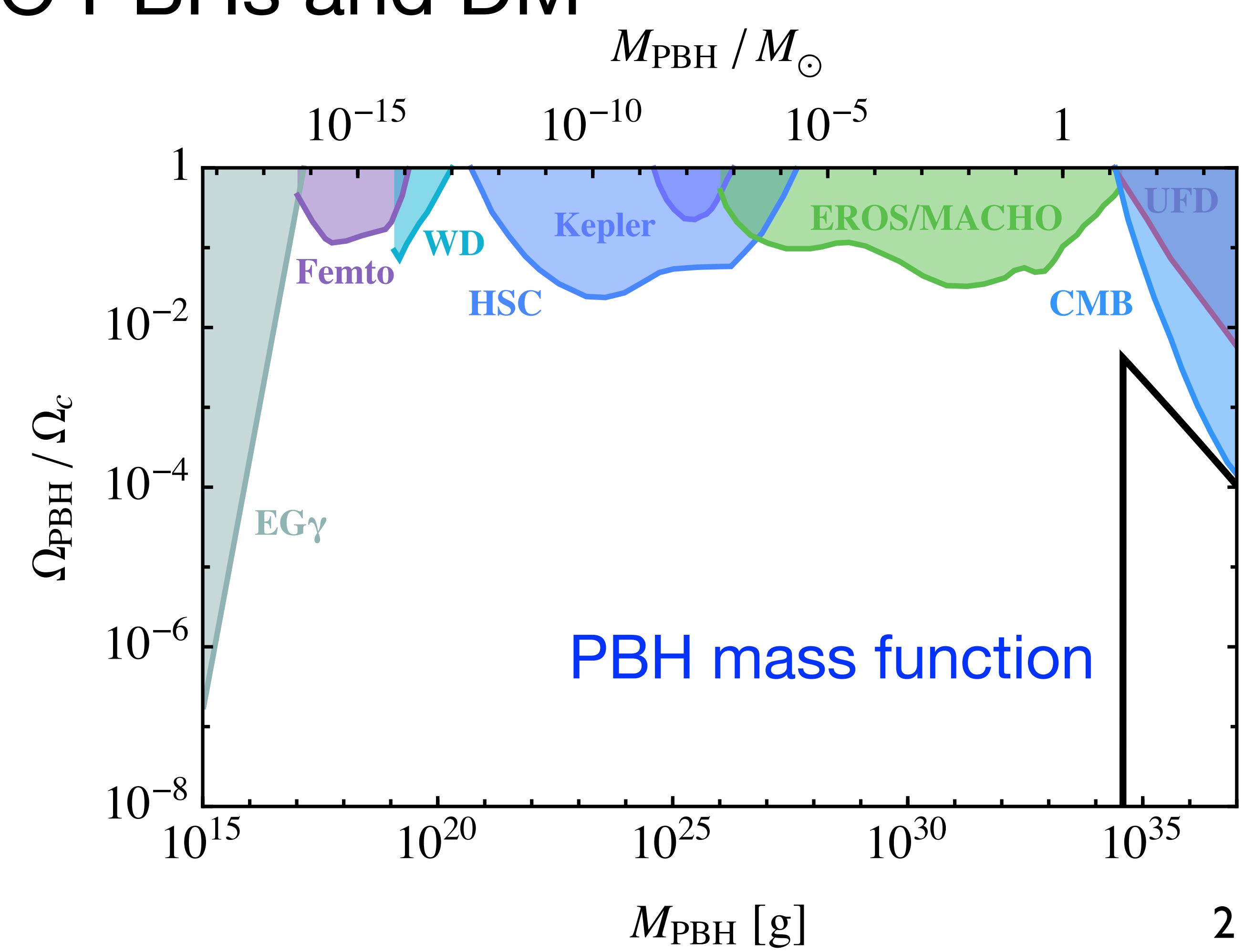
→ $$\delta \equiv \frac{\rho_{\rm HBB} - \bar{\rho}}{\bar{\rho}} \sim \frac{1}{T}\left(\frac{\rho_Q}{s}\right)_{\rm HBB}$$ →

PBH formation when HBB reenter the horizon

LIGO PBHs and dark matter

- Cosmic temperature T_c when $\delta \sim 1$
  - HBBs reenter the horizon after T_c → PBHs
  - HBBs reenter the horizon before T_c hardly form PBHs due to un-sphericity → Q-balls in HBBs can be dark matter
  - PBH mass function has a cut off M_c =(horizon mass at T_c)
- Model can account for both LIGO PBHs and DM

  for $T_c \simeq 200$ MeV
- Constraints from mu-distortion and pulsar timing are avoided because $\langle\delta^2\rangle$ is small
- Supermassive BHs are also produced



6. Conclusion

- Although observational constraints are stringent, double inflation model can produce PBHs that account for all DM of the universe
- The model also can produce PBHs for LIGO events and evade constraints from PTA experiments on gravitational waves
- High baryon bubbles produced in Affleck-Dine mechanism form PBHs which account for LIGO events
- High baryon bubbles also produce Q-ball DM