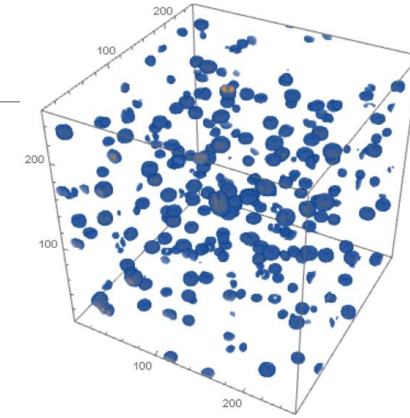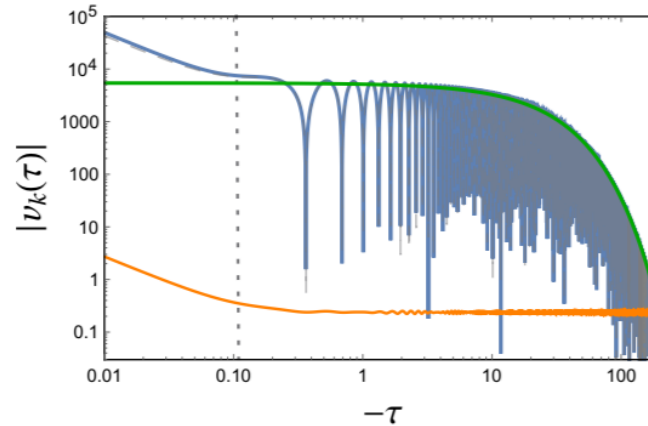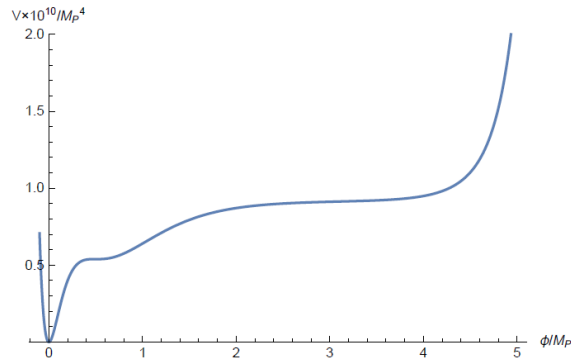# PBHs from cosmic domain walls

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THE 2019 CCNU-USTC JUNIOR COSMOLOGY SYMPOSIUM   WUHAN, APRIL 28, 2019

Amplification of scalar perturbation comes from

1.ultra slow-roll inflation   2.resonance due to oscillatory sound speed   3. early dust stage

Regions where the average energy density in a Hubble horizon exceeds a threshold δ_c will collapse into primordia black hole(PBH)

Energy stored in topological defects

shrink into PBHs

# Content

1.Introduction to topological defects: cosmic domain walls

2.Quantum creation of topological defects during inflation

3.Dynamics of domain walls after inflation

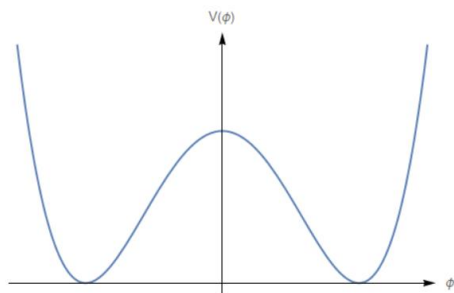3.Inflation model and the mass function of PBHs

4.Conclusion and discussion

Topological defects: domain wall

Domain walls are sheet-like objects which are formed in the early universe when a discrete symmetry is spontaneously broken
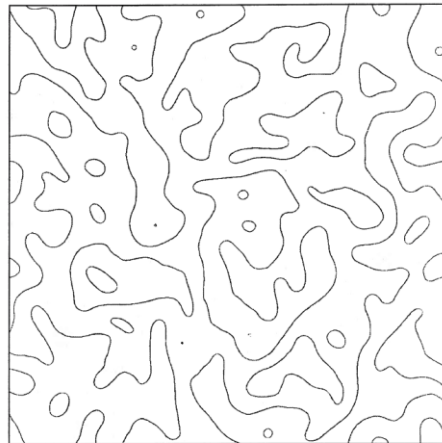
$$V(\phi) = \frac{m^2 v^2}{N^2}\left[1 - \cos\left(N\frac{a}{v}\right)\right]$$
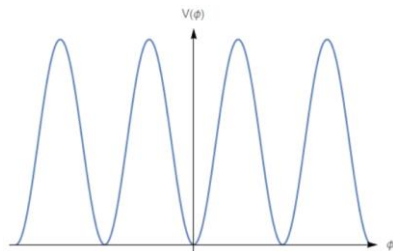
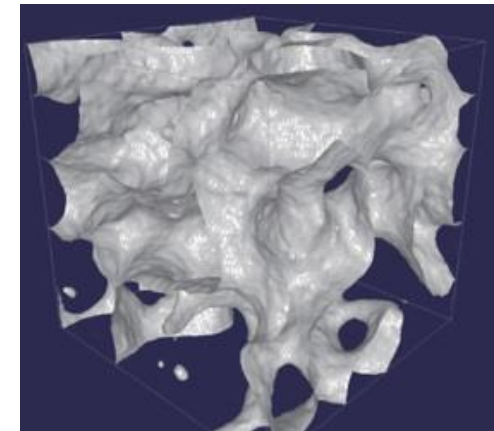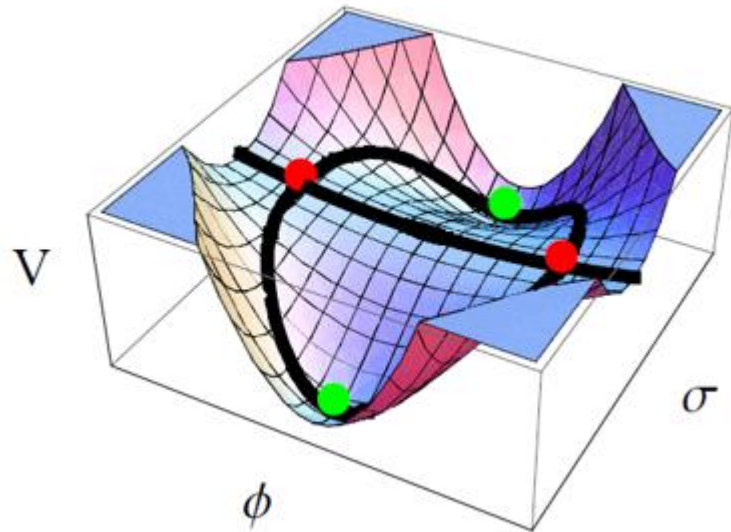$$V(\phi) = \frac{\lambda}{4}\left(\phi^2 - v^2\right)^2$$
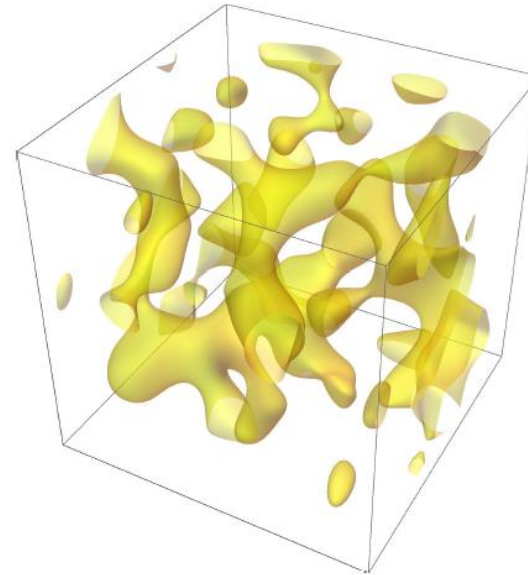
2-dimensional domain walls

3-dimensional domain walls

FIG. 1c

Topological defects: domain wall

The initial value of scalar field in on the potential barrier, then fall in different vacuum.

On each side of the wall the scalar field settles in different vacuum. On the wall the field should clime up the barrier and energy is stored in the walls.

Static domain wall

1. Lagrangian and effective potential

$$\mathcal{L} = -\frac{1}{2}\partial^{\mu}\phi\partial_{\mu}\phi - V(\phi)$$

$$V(\phi) = \frac{\lambda}{4}\left(\phi^2 - v^2\right)^2$$

2. Static solution perpendicular to the z-axis

$$\phi(z) = v\tanh\left[\sqrt{\frac{\lambda}{2}}vz\right]$$

3. Typical length scale of the spatial variation

$$\delta \simeq \left(\sqrt{\frac{\lambda}{2}}v\right)^{-1}$$

4. The surface energy density (also the tension)

$$\sigma = \frac{4}{3}\sqrt{\frac{\lambda}{2}}v^3$$

Quantum creation of topological defects during inflation

R. Basu, A. H. Guth and A. Vilenkin, Phys. Rev. D 44, 340 (1991).
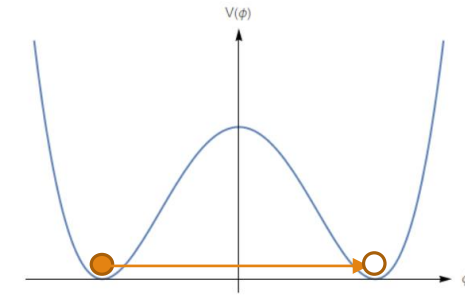
1.De Sitter space can be described as

$$-\tau^2 + \omega^2 + \Sigma_{i=1}^{n-2}\zeta_i^2 = H^{-2}$$

2. The nucleation can be described using the instanton language. The domain wall described

above is a three-sphere of maximal radius and the tunneling probability

is proportional to $\exp(-S_E)$.

$$\zeta_1^2 + \zeta_2^2 + \zeta_3^2 + \tau^2 = H^{-2}, \quad w = 0$$

$$dN = \lambda e^{3Ht_0} d^3\mathbf{x}dt_0 \qquad \lambda \approx H^4 e^{-S_E} \qquad S_E = 2\pi^2\sigma H^{-3}$$

Dynamics of domain walls after inflation

arxiv:1512.01819 J. Garriga, A. Vilenkin and J. Zhang

arxiv:1612.03753 H. Deng, J. Garriga and A. Vilenkin

1.The domain wall is subcritical or supercritical depends on whether the energy of the domain wall is dominant in the local universe.

2.If the domain wall is subcritical, its gravitational field can be safely neglected before horizon crossing.

The initial mass can be expressed by

$$M_{BHi} = 4\pi\sigma C R_H^2$$

$$C_{dust} \approx 0.15 \text{ and } C_{radiation} \approx 0.62$$

Where R_H is the radius of the domain wall when the Hubble horizon exceeds the domain wall.

Dynamics of domain walls after inflation

3.In radiation dominant era, due to accretion the final mass is 2 times the initial mass according to numerical simulation. In matter dominant era, accretion effect is negligible.

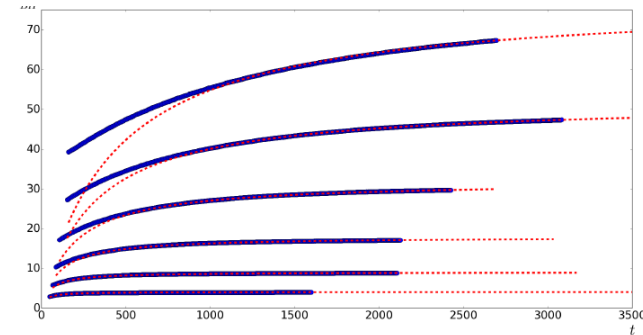$$M_{f,RD} = 2M_{i,RD}$$
$$M_{f,MD} = M_{i,MD}$$

Figure 4: M_{BH} as a function of time for six subcritical walls in the background of radiation with the same surface tension ($t_\sigma \approx 300$) but different radii. $r_i = 5, 6, 7, 8, 9$ and 10 from the bottom. Blue curves are from simulations, and dashed red curves are from Eq. (35). For $r_i = 5$, $\frac{M_{BHf}}{M_{BHi}} \approx 1.5$; for $r_i = 6$, $\frac{M_{BHf}}{M_{BHi}} \approx 1.6$; for $r_i = 7$, $\frac{M_{BHf}}{M_{BHi}} \approx 1.8$; for $r_i = 8$, $\frac{M_{BHf}}{M_{BHi}} \approx 1.9$; for $r_i = 9$, $\frac{M_{BHf}}{M_{BHi}} \approx 2.0$; for $r_i = 10$, $\frac{M_{BHf}}{M_{BHi}} \approx 2.0$. The ratio increases to ~ 2 as we approach the critical regime.

Dynamics of domain walls after inflation

1. As for the supercritical case, the initial black hole mass has an upper bound which is the total mass enclosed by the horizon crossing

radius of the unperturbed FRW region.

$$M_{i,RD} = \frac{1}{2} \times 5.6 (RH_i)^2 \qquad M_{i,MD} = \frac{1}{2} \times (RH_i)^3$$

Where R is the radius of the domain wall at the end of

inflation

2.The subsequent process is similar as the

subcritical case.

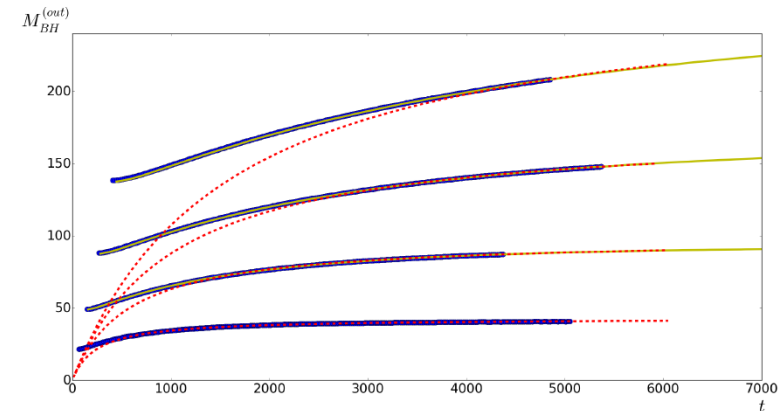$$M_{f,RD} = 5.6 (RH_i)^2 \qquad M_{f,MD} = \frac{1}{2} \times (RH_i)^3$$

Figure 18: This graph shows $M_{BH}^{(out)}$ as a function of time for four supercritical walls in the background of radiation with $r_i = 4, 6, 8$ and 10 respectively (the same walls as those in Fig. 15). Blue curves are from simulations, dashed red curves from Eq. (35), and solid yellow curves are from Eq. (39) relative to the wall with $r_i = 4$. For $r_i = 6$, $K = 1.512^2 \approx \left(\frac{6}{4}\right)^2$; For $r_i = 8$, $K = 2.022^2 \approx \left(\frac{8}{4}\right)^2$; For $r_i = 10$, $K = 2.533^2 \approx \left(\frac{10}{4}\right)^2$.

The model of inflation

1.The potential of inflation can be written as

$$V(\phi, \chi) = \frac{\lambda_\phi}{p}\phi^p + \frac{\lambda_\chi}{4}\left(\chi^2 - m^2 - \alpha^2(\phi - \phi_0)^2\right)^2$$

2.The initial value of χ is in one of the minima. The mass of χ is large at the beginning or end of inflation.

3.The tension of domain wall is a time dependent variable At the time $\alpha^2(\phi - \phi_0)^2$ vanishes, tunneling possibility reaches the maximum.

4.The comoving radius of domain walls and thus the PBH mass is sensitive to ϕ_0 . By tuning ϕ_0 we can get a large mass range.
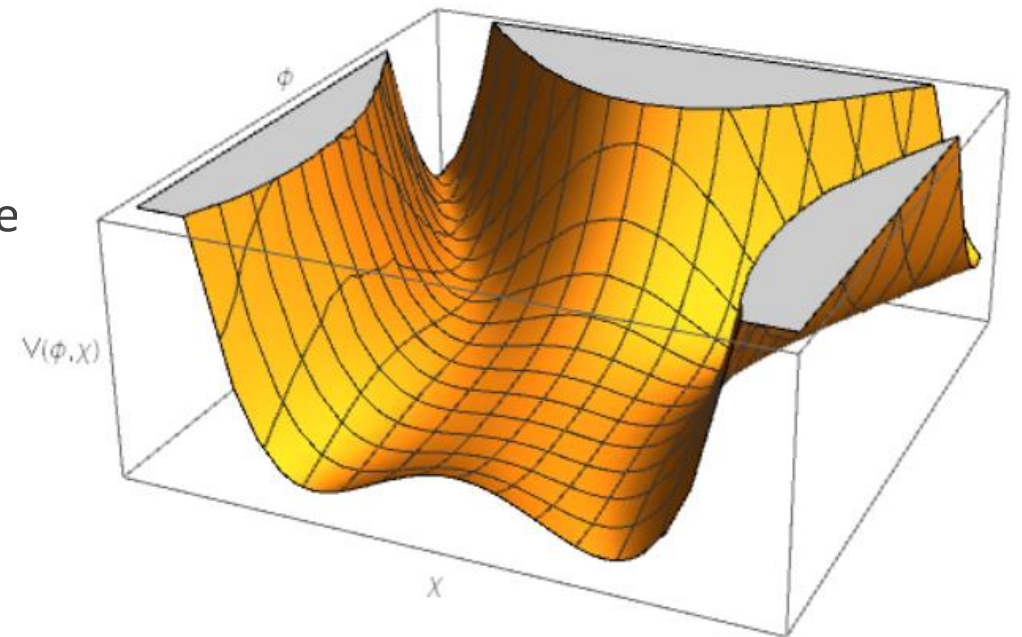
PBH mass function

For subcritical case, given the comoving radius of the domain walls, we need to know the time it enters the horizon and evaluate the mass. The number in an interval dt_0 is changed to that in an interval dM

$$\frac{1}{a(t_0)H(t_0)} = \frac{1}{a(t_H)H(t_H)} = \frac{2t}{(t/t_e)^{1/2}} = \sqrt{2R_H t_e}$$

$$\frac{dH}{dt}(t_0)a(t_0) \ll \frac{da}{dt}(t_0)H(t_0) \qquad \left|\frac{dt_0}{dR_H}\right| = t_e H(t_0)a^2(t_0) \qquad M \approx 4\pi\sigma R_H^2$$

$$\rho_{cri,0}\Omega_{DM}f(M) = \frac{d\rho}{d\ln M} = \frac{M^2 dN}{dV_{\mathsf{phy}}(t_*)dM} = \frac{H^4(t_0)e^{-S(t_0)}M^2}{8\pi R_H \sigma}\frac{dV_{\mathsf{phy}}(t_0)}{dV_{\mathsf{phy}}(t_*)}\left|\frac{dt_0}{dR_H}\right|$$

$$\rho_{cri,0}\Omega_{DM}f(M) = H^5(t_0)e^{-2\pi^2\sigma(t_0)H^{-3}(t_0)}\pi\left(\frac{M}{4\pi\sigma(t_0)}\right)^{3/2}\sigma\sqrt{\frac{24\pi Gp}{\lambda_\phi}}a^2(t_0)\left(\frac{a(t_0)}{a(t_*)}\right)^3$$

Where $a(t_*)$ is the scale factor at present.

PBH mass function

For supercritical case, the radius of domain walls at the end of inflation should be determined to relate dt_0 to dM. The horizon mass at the radiation matter equality is about 10^{50}g, much larger than the supermassive black hole so we only consider PBHs formed in radiation dominant era.

$$M = 5.6 \left(RH_i \right)^2 \qquad R = \frac{1}{H_0} \frac{a(t_e)}{a(t_0)}$$

$$\frac{dH}{dt}(t_0)a(t_0) \ll \frac{da}{dt}(t_0)H(t_0) \qquad \left| \frac{dt_0}{dR_H} \right| = \frac{a(t_0)}{a(t_e)} \frac{\sqrt{G}}{11.2RH(t_e)}$$

$$\rho_{cri,0}\Omega_{DM}f(M) = \frac{M^{5/2}e^{-S_E(t_0)}a^4(t_0)H(t_e)}{2Ga^3(t_*)}$$

Primordial black holes as dark matter and current constrains
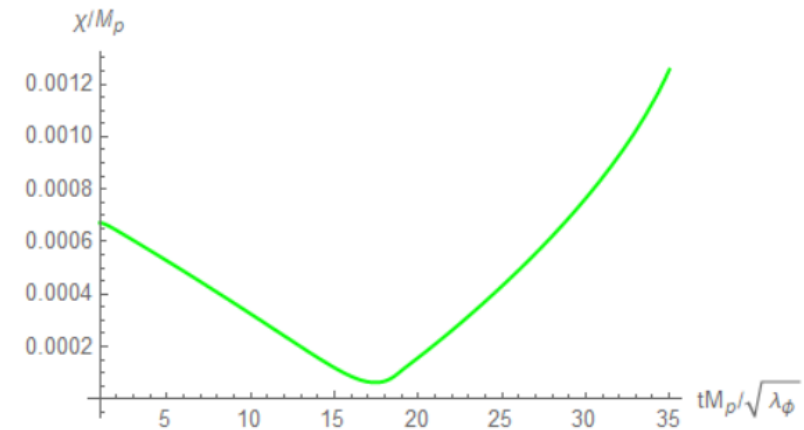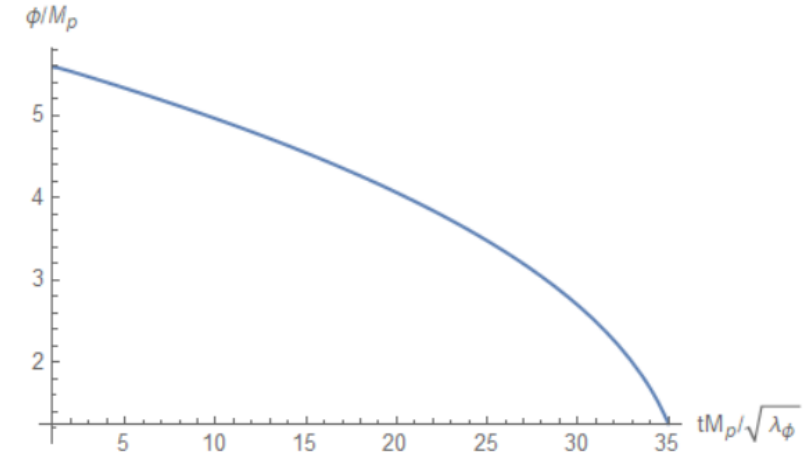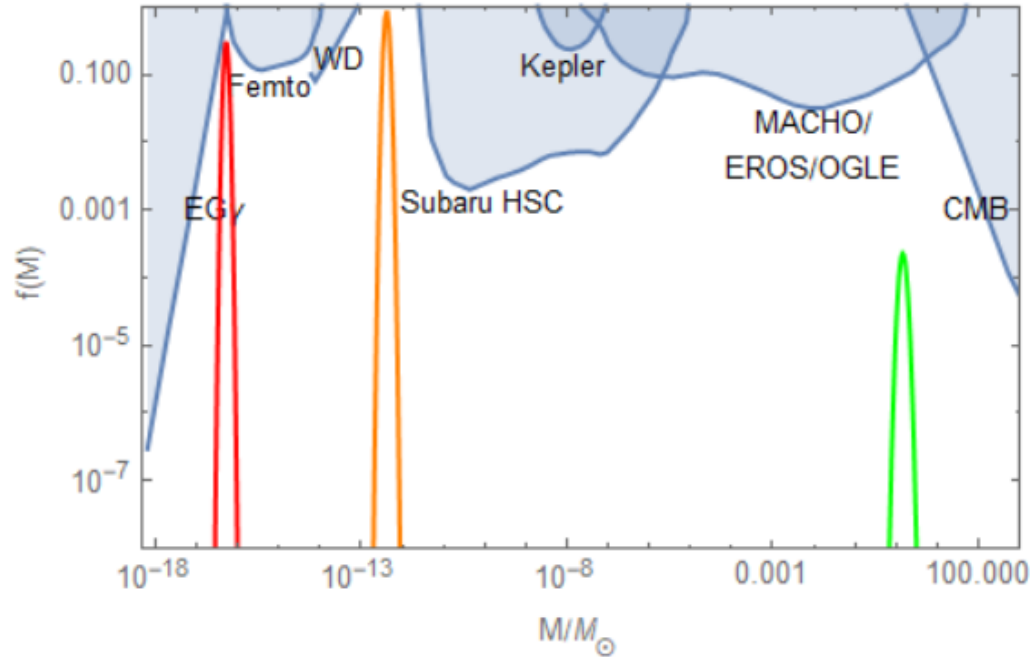
$\phi_{ini}/M_{\mathrm{P}}$	λ_ϕ	λ_χ	α	p
7.18	3×10^{-10}	0.3	3×10^{-4}	2/3

ϕ_0/M_{P}	5.52	4.95	7.05
m/M_{P}	6.40×10^{-5}	6.66×10^{-5}	7.40×10^{-5}

Conclusion and discussion

1. Domain walls from quantum creation during inflation can collapse into PBHs with a large mass range avoiding cosmic domain wall problem.

2. In some multi-field inflation models the PBHs from cosmic domain walls can be the candidates of a part or all of the dark matter. The seed of super massive black hole can be provided through this mechanism.

3. The PBH mass is not directly relevant to the Hubble mass and the sensitivity of δ_c in gravitational collapse models can be avoided.

4. PBHs from domain walls do not require large scalar perturbation, the induced GWs can not give constraint to the mass function.

5. Tuning possibility exponentially depends the action and fine tuning of this model is still large.

Thanks for your attention