Primordial black holes

November 5,2024
Saga-Yonsei Joint Workshop

Saga University　Kikuko Sato

Academic Advisor
Motoi Tachibana

Content

1:Discoveries from observed gravitational wave sources

2:PBH Generation

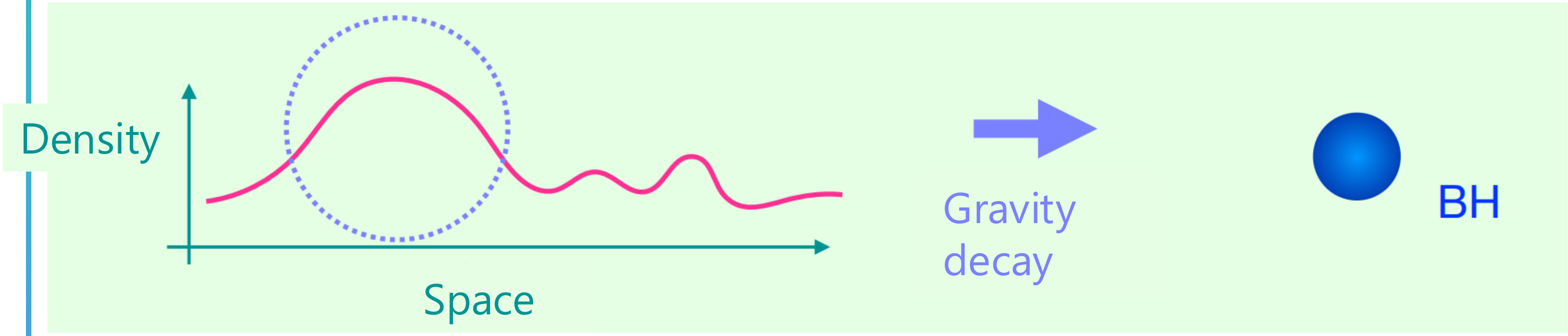
3:Summary

4:Future

1:Discoveries from observed gravitational wave sources

Primordial Black Holes=PBH

- Black holes formed in the early universe



Cited from https://www.icrr.u-tokyo.ac.jp/prwps/wp-content/uploads/2019/07/PBH.pdf

- Initially pointed out by Hawking in 1971
- It can have a variety of masses from 10^{-5}g to several hundred solar masses

LIGO=(Laser Interferometer Gravitational-Wave Observatory)

- On September 14, 2015, the gravitational wave detector LIGO observed gravitational waves caused by the merger of black hole binaries for the first time in history with two detectors.
- The gravitational wave source is the result of the merger of two black holes with approximately 30 times the mass of the Sun → It is difficult for a black hole, which is 30 times the mass of the Sun, to form in the end

Is it a primordial black hole?

gravitational wave

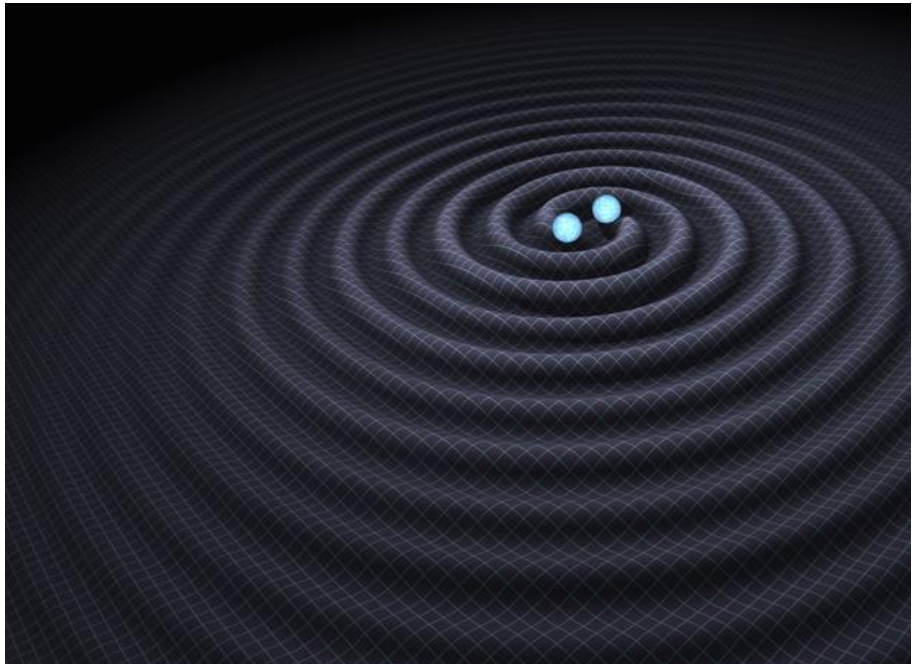
- A phenomenon in which space-time distortion caused by the motion of a huge celestial body propagates at the speed of light

Black hole binaries

- A binary star system in which two black holes orbit each other by their gravitational pull
- The black holes that make up the binary star shrink their orbital radius due to gravitational wave emissions, and eventually merge into a single black hole.

Merger of two black holes →
This diagram shows the merger of two black holes
The image shows gravitational waves that ripple outward when black holes spiral to each other

Cited from
https://www.ligo.caltech.edu/image/ligo20160211f



LIGO(Hanford)

LIGO(Livingston)

Cited from
https://www.ligo.caltech.edu/image/ligo20150731a

Cited from
https://www.ligo.caltech.edu/image/ligo20150731d

VIRGO(Italia)

Cited from
https://astro-dic.jp/virgo-interferometer/

KAGRA(Japan)

Cited from
https://gwcenter.icrr.u-tokyo.ac.jp/aboutkagra/summary

2:PBH Generation

Density fluctuations to produce PBH

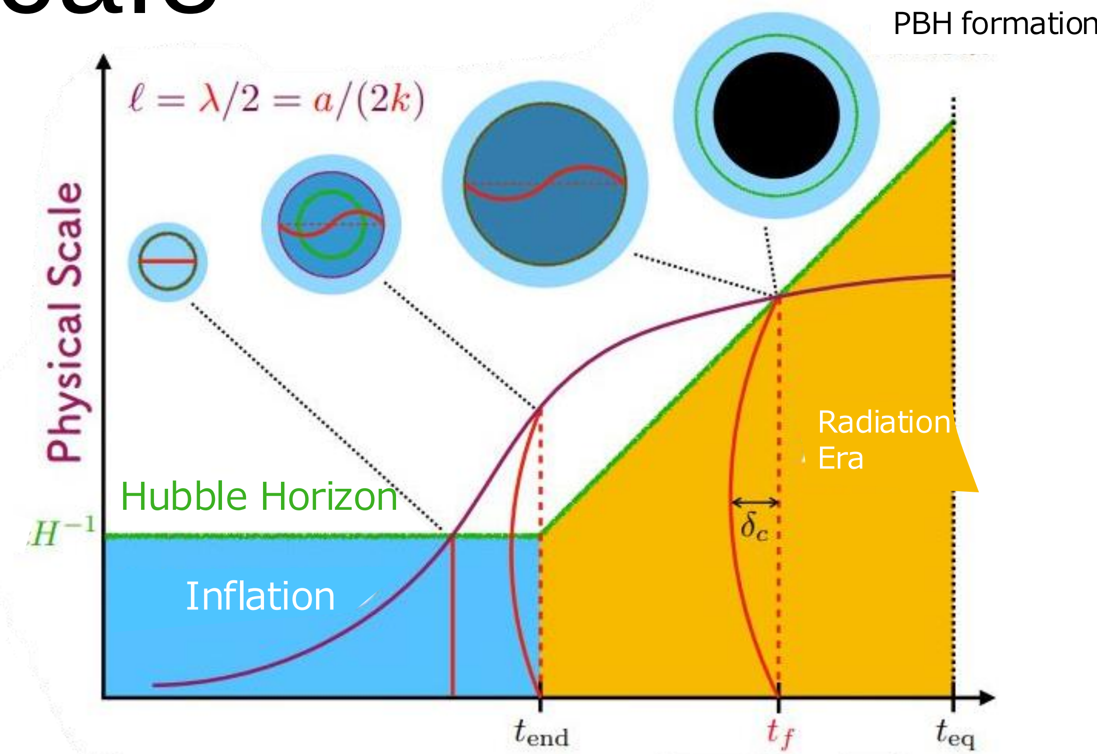
- In the area of scale beyond the horizon during inflation,

→ Primordial density fluctuations are generated

- After inflation

→ PBH is generated

Evolution of physical scale



- The extent of the formation of primordial black holes

  = Radius below Hubble Horizon

- Inflationary period

The physical scale of the area grows exponentially

= During this period, the physical scale can exceed the horizon

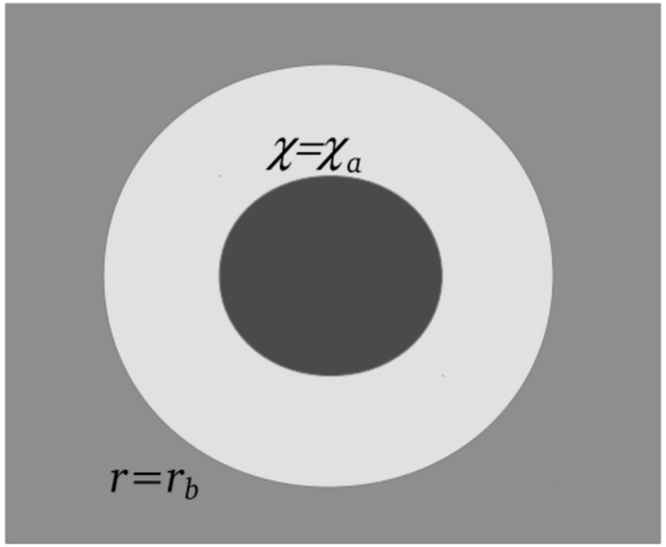
Three zone model

- Metric of the background space-time

$$\mathrm{d}\bar{a}^2 = -dt^2 + \bar{a}^2(t)(dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta d\varphi^2)$$

- Freedman equations for background space-time

$$\bar{H}^2 = \left(\frac{\dot{\bar{a}}}{\bar{a}}\right)^2 = \frac{\bar{\rho}}{3M_{\mathrm{Pl}}^2}$$



- Metric of locally closed space-time

$$ds^2 = -dt^2 + a^2(t)\left[\frac{dR^2}{1 - K(R)R^2} + R^2 d\theta^2 + R^2 \sin^2\theta d^2\varphi\right]$$

Threshold of primordial black hole formation

Arxiv 1309.4201

$$R = K^{-1/2}\sin(\sqrt{K}\,\chi) \;\; (0 < \chi < \chi_a)$$

$$ds^2 = -dt^2 + a^2(t)\left[d\chi^2 + \frac{\sin^2(\sqrt{K}\,\chi)}{K}\left(d\theta^2 + \sin^2\theta\, d\varphi^2\right)\right]$$

- Freedman equation of the locally closed space-time

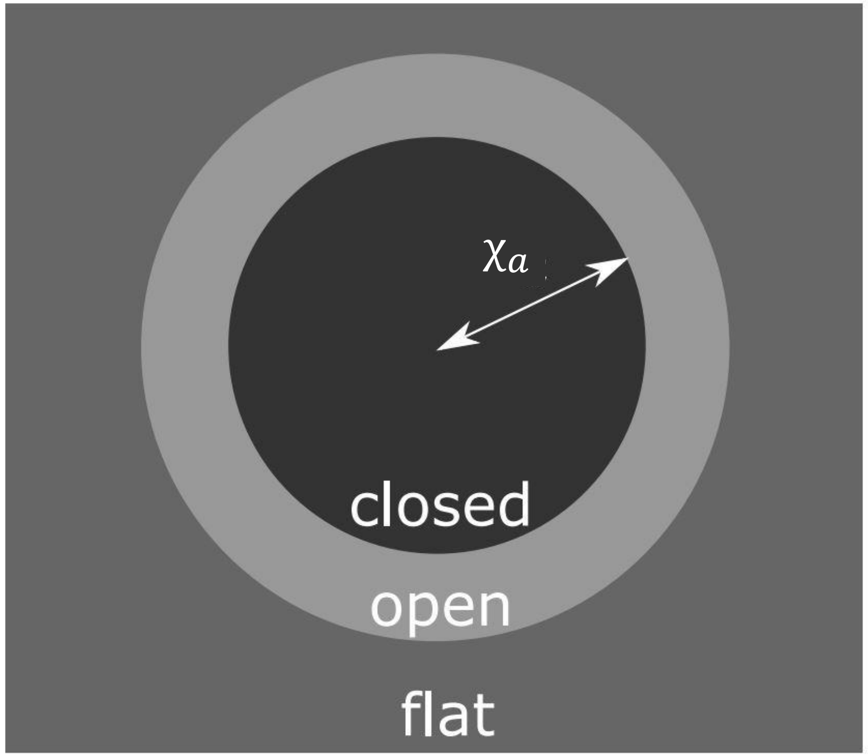
$$H^2 = \left(\frac{\dot{\bar{a}}}{\bar{a}}\right)^2 = \frac{\rho}{3M_{\rm Pl}^2} - \frac{K}{a^2}\,.$$

- Background space-time and the local region expand in the same way until the time of decay, so

$$\bar{H} = H$$

- Density parameters in the local region

$$\Omega \equiv \frac{\rho}{3M_{\rm Pl}^2 H^2} = 1 + \frac{K}{a^2H^2} \quad \cdots ★$$



- Density fluctuations in the overcrowded area (Horizon-closing)

$$\delta \equiv \frac{\rho - \bar{\rho}}{\bar{\rho}}$$

Three zone model
The basics of primordial black hole formation and abundance estimation Chul-Moon Yoo
Arxiv 2211.13512v1

- Defining the Hubble horizon radius $R_H = H^{-1}$ in the overcrowded region, Eq. ★ can be transformed to

$$(\Omega - 1)\left(\frac{R_a}{R_H}\right)^2 = \sin^2 \chi_a .$$

- The density parameter Ω can then be related to δ according to

$$\Omega = (1+\delta)(\frac{\bar{H}}{H})^2$$

- Density fluctuations at the time (t_{HC}) when the overcrowded area was generated

$$\delta_{\mathrm{HC}}=\left(\frac{H\left(t_{\mathrm{HC}}\right)}{\bar{H}\left(t_{\mathrm{HC}}\right)}\right)^{2}-\cos^{2}\left(\sqrt{K}\chi_{a}\right)$$

- From the condition $\bar{H}=H$,then

$$\delta_{\mathrm{HC}}^{\mathrm{UH}}\equiv\delta^{\mathrm{UH}}\left(t_{\mathrm{HC}}\right)=\sin^{2}\left(\sqrt{K}\chi_{a}\right)$$

- If we rewrite the metric of the local region using conformal time $d\tau = dt/a$,

$$ds^2 = a^2(\tau)\left[-d\tau^2 + d\chi^2 + \frac{\sin^2(\sqrt{K}\,\chi)}{K}\,d\Omega^2\right]$$

$$\left(\frac{d\ln a}{d\tau}\right)^2 = K\left[\left(\frac{a}{a_{\max}}\right)^{-(1+3w)} - 1\right]$$

- Possible range of conformal time τ is defined by

$$0 \le \tau \le \tau_{\max} \equiv \frac{\pi}{\sqrt{K}\,(1+3w)}$$

Critical condition in which gravitational collapse occurs

$$\chi_J \equiv \chi_a = c_s \tau_{\max}$$

Then,

$$\delta_{\rm th}^{\rm UH} = \sin^2\left(\frac{\sqrt{w}\pi}{1+3w}\right) \overset{w=1/3}{\simeq} 0.62$$

3:Summary

- The threshold of density fluctuations that generate PBH was found
- In addition, the exact value of the threshold value needs to be simulated
- In the future, we would like to further conduct calculations to clarify the existence of PBH and consider other PBHs produced during the radiation dominant phase

4.Future

Primordial Black Hole Formation during the QCD Epoch

Karsten Jedamzik

Physics Research Program

Institute for Geophysics and Planetary Physics

University of California

Lawrence Livermore National Laboratory

Livermore, CA 94550

We consider the formation of horizon-size primordial black holes (PBH's) from pre-existing density fluctuations during cosmic phase transitions. It is pointed out that the formation of PBH's should be particularly efficient during the QCD epoch due to a substantial reduction of pressure forces during adiabatic collapse, or equivalently, a significant decrease in the effective speed of sound during the color-confinement transition. Our considerations imply that for generic initial density perturbation spectra PBH mass functions are expected to exhibit a pronounced peak on the QCD-horizon mass scale $\sim 1M_{\odot}$. This mass scale is roughly coincident with the estimated masses for compact objects recently observed in our galactic halo by the MACHO collaboration. Black holes formed during the QCD epoch may offer an attractive explanation for the origin of halo dark matter evading possibly problematic nucleosynthesis and luminosity bounds on baryonic halo dark matter.

PACS number(s): 97.60.LF, 98.35.+d, 12.38.AW, 98.35.Gi

- Black holes formed during the QCD epoch may offer an attractive explanation for the origin of halo dark matter evading possibly problematic nucleosynthesis and luminosity bounds on baryonic halo dark matter.

Thank you for your patience.