Status report of A03
Investigation of Primordial Black Holes and Macroscopic Dark Matter
（原始ブラックホール・巨視的ダークマターの探求）

Chulmoon Yoo	Nagoya U.
Tomohiro Harada	Rikkyo U.
Sachiko Kuroyanagi	Nagoya U. / IFT Madrid
Alexander Kusenko	KIPMU / UCLA
Misao Sasaki	KIPMU
Shin'ichi Hirano	Nagoya U → TITech
Yasutaka Koga	Nagoya U.
Takafumi Kokubu	KIPMU

Primordial Black Hole

◎Remnants of primordial non-linear inhomogeneity

◎BHs not produced by late time stellar collapse

◎Reliable formation scenario:

collapse of rarely dense regions generated by quantum fluctuation during inflation

It's rare, but has a finite probability!!

◎If you accept inflation, you should be able to accept the **PBH formation**

◎**PBH** is a plausible and appealing **DM** candidate

- BHs "exist" in our universe
- BHs behave as **DM** in a cosmological scale
- Reliable scenario of **PBH** formation

How many PBHs in our universe?

◎They could provide a substantial part of **DM**

◎How large fraction of **DM PBH**s can account for?

To answer this, we need

- ➢ precise theoretical estimation of abundance
- ➢ realistic and attractive models
- ➢ tests through observational constraints

◎What are distinct characters of **PBH DM**?

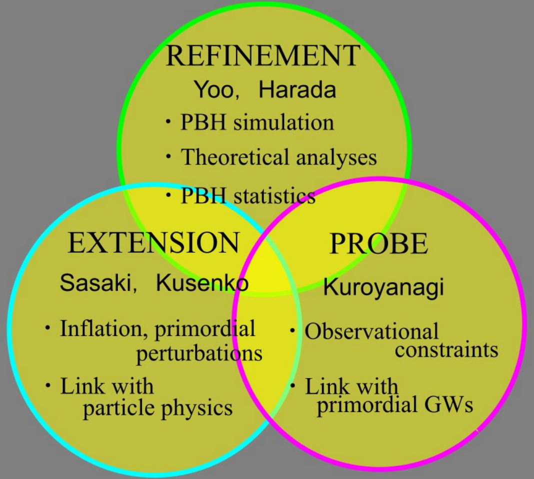
For the prediction, we need

- ➢ deeper understanding of formation process
- ➢ finding model dependent features
- ➢ proposal of specific observables to probe it

◎Possible other macroscopic **DM**?

- ➢ Exotic stars (gravastar, soliton star, Q-balls...)

Close cooperation with other groups



Additional strong supports from 公募研究 (open-solicited research)

Activities of A03 in the fiscal year 2021

- 2104.05271 *Cosmology of strongly interacting fermions in the early universe*
  Domenech, **Sasaki**
- 2105.05581 *Backreaction of Mass and Angular Momentum Accretion on Black Holes: General Formulation of the Metric Perturbations and Application to the Blandford-Znajek Process*
  Kimura, **Harada**, **Naruko**, Toma
- 2105.06099 *Interstellar Gas Heating by Primordial Black Holes*
  Takhitov, Lu, Gelmini, Hayashi, Inoue, **Kusenko**
- 2105.06816 *Exploring Evaporating Primordial Black Holes with Gravitational Waves*
  Domenech, Takhistov, **Sasaki**
- 2105.12554 *Beating the Lyth bound by parametric resonance during inflation*
  Cai, Jiang, **Sasaki**, Vardanyan, Zhou
- 2106.03786 *Probing pre-Recombination Physics by the Cross-Correlation of Stochastic Gravitational Waves and CMB Anisotropies*
  Braglia, **Kuroyanagi**
- 2106.03237 *Spins of primordial black holes formed in different cosmological scenarios*
  Flores, **Kusenko**
- 2106.06651 *Thakurta metric does not describe a cosmological black hole*
  Harada, Maeda, Sato
- 2107.05260 Robustness of particle creation in the formation of a compact object
  Okabayashi, **Harada**, Nakao
- 2108.08416 *Primordial black holes as a dark matter candidate in theories with supersymmetry and inflation*
  Flores, **Kusenko**
- 2108.13026 *Testing the Non-circularity of the Spacetime around Sagittarius A* with Orbiting Pulsars*
  Takamori, **Naruko**, Sakurai, Takahashi, Yamauchi, **Yoo**

A03 A02 A01 collaboration

Activities of A03 in the fiscal year 2021

A03 A02 A01
collaboration

- 2109.00791 *Primordial black holes in peak theory with a non-Gaussian tail*
  Kitajima, Tada, Yokoyama, **Yoo**
- 2109.04051 *False Vacuum Decay in Rotating BTZ Spacetimes*
  Saito, **Yoo**
- 2109.11376 *The stochastic gravitational wave background from close hyperbolic encounters of primordial blackholes in dense clusters*
  Garcia-Bellido, Jaraba, **Kuroyanagi**
- 2109.12824 *Primordial Black Holes from CDM Isocurvature*
  Passaglia, **Sasaki**
- 2110.13421 *Complete conformal classification of the Friedmann-Lemaitre-Robertson-Walker solutions with a linear equation of state II*
  Harada, Igata, Sato, Carr
- 2110.07488 *Testing Primordial Black Holes with multi-band observations of the stochastic gravitational wave background*
  Braglia, Garcia-Bellido, **Kuroyanagi**
- 2111.01005 *Solving information loss paradox via Euclidean path integral*
  Chen, **Sasaki**, Yeom, Yoon
- 2111.09509 *Establishing the Non-Primordial Origin of Black Hole-Neutron Star Mergers*
  Sasaki, Takhistov, Vardanyan, Zhang
- 2112.12335 *Primordial black hole formation from massless scalar isocurvature*
  Yoo, **Harada**, **Hirano**, Okawa, **Sasaki**
- 2112.12680 *Primordial Black Hole Formation in Non-Minimal Curvaton Scenario*
  Pi, **Sasaki**
- 2112.13836 *One Small Step for an Inflation, One Giant Leap for Inflation: a novel non-Gaussian tail and primordial black holes*
  Cai, Ma, **Sasaki**, Wang, Zhou
- 2201.13414 *Tracking the origin of black holes with the stochastic gravitational wave background popcorn signal*
  Braglia, Garcia-Bellido, **Kuroyanagi**

Activities of A03 in the fiscal year 2021

A03 A02 A01 collaboration

- 2202.01028 *Simulation of Primordial Black Holes with large negative non-Gaussianity*
  Escriva, Tada, Yokoyama, **Yoo**
- 2202.00201 *Dynamical photon sphere and time evolving shadow around black holes with temporal accretion*
  Koga, Asaka, Kimura, Okabayashi
- 2202.00202 *Periapsis shift in dark matter distribution around a black hole*
  Igata, **Harada**, Saida, Takamori
- 2203.10740 *Gravothermal catastrophe and critical dimension in a D-dimensional asymptotically AdS spacetime*
  Asami, **Yoo**

◎Today's talks

- **Alexander Kusenko**
  Primordial black holes: a generic DM candidate in supersymmetry and other extensions of the Standard Model
- **Yuichiro Tada**
  Primordial black holes and induced gravitational waves in light of the non-Gaussian tail
- **Sachiko Kuroyanagi**
  Probing primordial black holes through the stochastic gravitational wave background

◎Other activities

New PBH formation scenarios

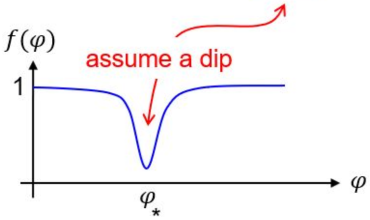
2112.12680 *Primordial Black Hole Formation in Non-Minimal Curvaton Scenario*
Pi, **Sasaki**
2112.13836 *One Small Step for an Inflation, One Giant Leap for Inflation: a novel non-Gaussian tail and primordial black holes*
Cai, Ma, **Sasaki**, Wang, Zhou

New PBH formation scenarios-1

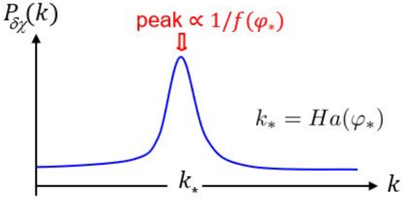
PBH formation in non-minimal curvaton scenario

Pi & MS, 2112.12680

$$\mathscr{L} = -\frac{1}{2}(\partial\varphi)^2 - V(\varphi) - \frac{1}{2}f(\varphi)^2(\partial\chi)^2 - \frac{1}{2}m_\chi^2\chi^2 \quad (m_\chi^2 \ll H^2)$$



vacuum fluctuation: $f(\varphi)\delta x = \frac{H}{2\pi}$ ➡ $\delta x = \frac{H}{2\pi f}$



- highly non-Gaussian curvature perturbation

$$e^{4\zeta} - \left[\frac{4r}{3+r}\left(1+\frac{\delta\chi}{\chi}\right)^2\right]e^{\zeta} + \left[\frac{3r-3}{3+r}\right] = 0$$

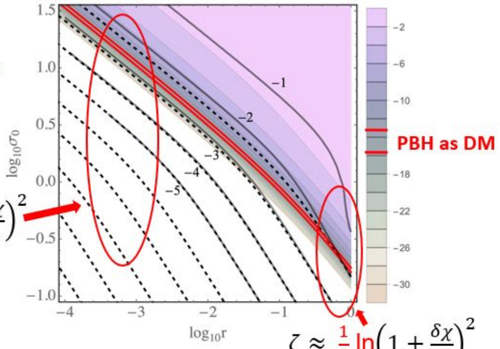
MS, Valiviita & Wands, astro-ph/0607627

ζ = curvature perturbation on uniform density slices

$r = \rho_\chi/\rho_{tot}$ at epoch of curvaton decay

- yet curvature pert spectrum is well approximated by that of chi[2]

$$\zeta \approx \frac{\delta\chi}{\chi} + \frac{3}{4r}\left(\frac{\delta\chi}{\chi}\right)^2$$



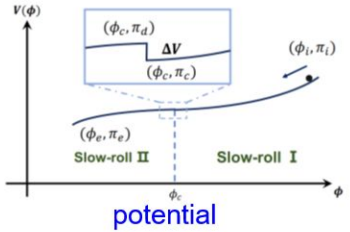
$$\zeta \approx \frac{1}{3}\ln\left(1+\frac{\delta\chi}{\chi}\right)^2$$

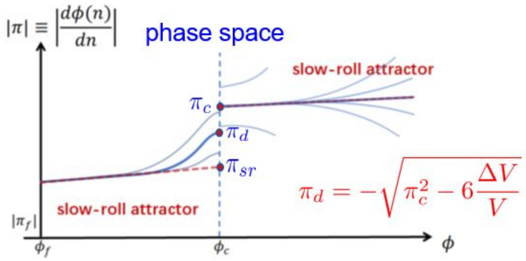
LISA will detect iGWs if PBH=CDM

New PBH formation scenarios-2

a new model for PBH formation: Inflation with an upward step

Cai, Ma, MS, Wang & Zhou, 2112.13836

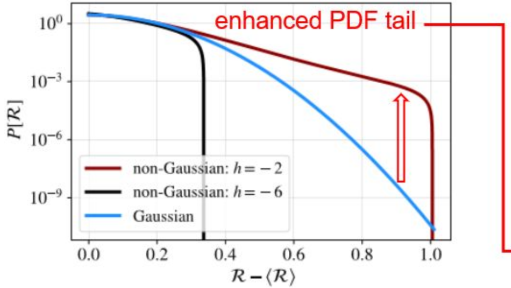


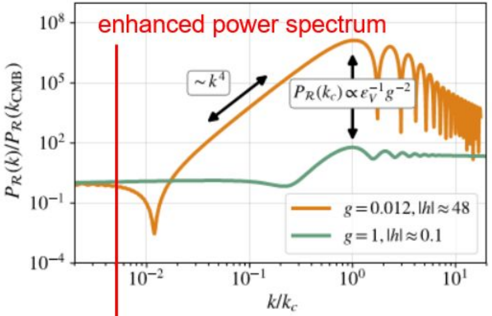


- highly non-Gaussian curvature perturbation

$$\mathcal{R}_c \simeq \frac{2}{|h|}\left(1-\sqrt{1-|h|\mathcal{R}_G}\right) \text{ for } g \equiv \frac{\pi_d}{\pi_c} \ll 1$$

$$|h| = 6\frac{\pi_{sr}}{\pi_d}$$





abundant PBH formation

Simulation of PBH formation from iso-curvature perturbation

2112.12335 *Primordial black hole formation from massless scalar isocurvature*

Yoo, **Harada**, **Hirano**, Okawa, **Sasaki**

Simulation of PBH formation from iso-curvature

◎**PBH can be formed from the isocurvature of a massless scalar field**

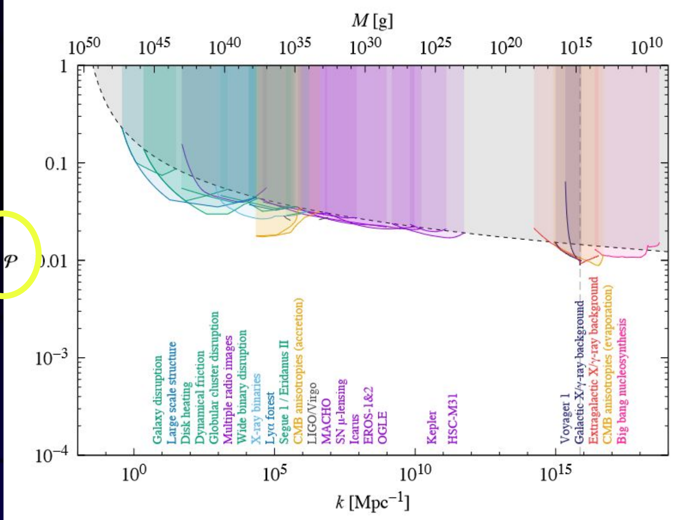
2112.12335 **CY**, **Harada**, **Hirano**, Okawa, **Sasaki**

◎The formation and accretion process are similar to those in the RD dominated universe

◎Constraints on the massless scalar isocurvature would be given by observational constraints of the PBH abundance similarly to those for the curvature perturbation.

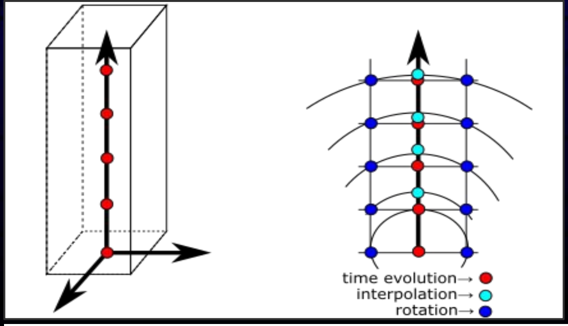
Can be replaced by the power spectrum of the massless scalar isocurvature

2002.12778 Carr, Kohri, Sendouda, Yokoyama



Technically significant progress

◎We solve standard 3+1 dimensional equations on z-axis with CARTOON method

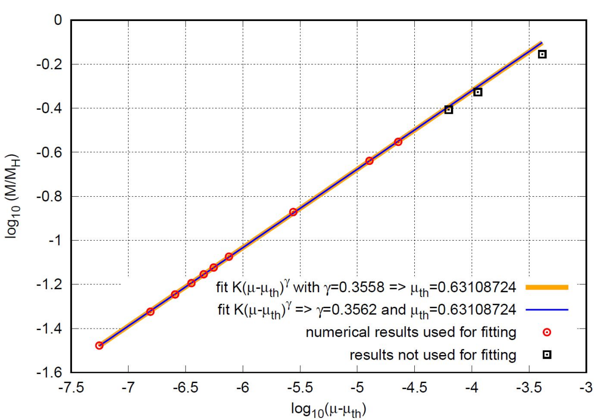


◎Critical behavior for the radiation fluid

$$M \propto (\mu - \mu_{\rm th})^{\gamma} \text{ with } \gamma \simeq 0.3558$$

◎To resolve the small black hole

- ➢ **Fixed mesh refinement**
- ➢ **Inhomogeneous coordinates**



◎Technically important step (to me) for the simulation of non-spherical PBH formation and evaluating the PBH spin

Ongoing works by young PDs

Hirano's work

- **PBH**

[1] C. M. Yoo, T. Harada, **SH**, H. Okawa, and M. Sasaki, ``Primordial black hole formation from massless scalar isocurvature,'' [arXiv:2112.12335 [gr-qc]].

[2] C. M. Yoo, T. Harada, **SH**, and K. Kohri, ``Abundance of Primordial Black Holes in Peak Theory for an Arbitrary Power Spectrum,'' PTEP 2021 (2021) no.1, 013E02 [arXiv:2008.02425 [astro-ph.CO]].

- **EFT beyond GR**

[3] **SH**, M. Kimura, M. Yamaguchi, "Black holes in effective field theory extension of GR with scalar and parity violation", in preparation

- **Modified gravity**

[4] **SH**, T. Fujita, "Effective field theory of large scale structure in modified gravity", in preparation

A03 B01 collaboration

[5] S. Akama, **SH**, "Strong coupling problem in extended generalized galilean genesis and non-gaussianity", in preparation

[6] **SH**, T. Kobayashi, D. Yamauchi, and S. Yokoyama, ``UV sensitive one-loop matter power spectrum in degenerate higher-order scalar-tensor theories,'' Phys. Rev. D102 (2020) no.10, 103505 [arXiv:2008.02798 [gr-qc]].

[7] J. Tokuda, K. Aoki, and **SH**,``Gravitational positivity bounds,'' JHEP **11** (2020), 054 [arXiv:2007.15009 [hep-th]].

Ongoing work by Koga-kun -1

PBH binary distribution with the effect of critical phenomena

Y. Koga, T. Harada, Y. Tada, S. Yokoyama, & C-M. Yoo, (paper in preparation).

Data analysis of GWTC-2 [Callister+ (2021)]

- BH-BH binaries are distributed in $-0.2 \lesssim \chi_{\rm eff} \lesssim 0.4$ & $0.2 \lesssim q < 1$.

  Effective spin of binary ↗ Mass ratio ↗
- Apparent anti-correlation between $\chi_{\rm eff}$ & q.
- Unexpected from astrophysical models.

➡ Investigation of PBH-PBH binary distribution is interesting.

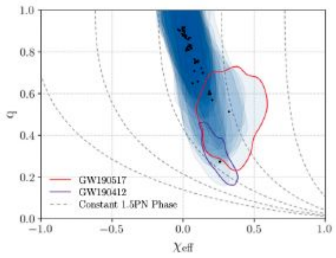


Figure 5. Effective spin and mass ratio posteriors for BBHs

This work

- We investigate PBH binary distribution.
- Consider a simplest model as the first step.
- Include the effect of critical phenomena.

Interesting to investigate this effect on $\chi_{\rm eff}$.

Average of PBH spins [Harada+ (2021)]

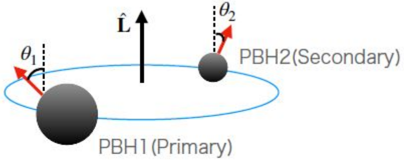
- Ordinary PBH formation: $M \sim M_H \Rightarrow \sqrt{< a_*^2 >} = \mathcal{O}(10^{-3})$
- Critical collapse: $M \ll M_H \Rightarrow \sqrt{< a_*^2 >} \leq 1$

M_H: total mass in Hubble horizon

Ongoing work by Koga-kun -2

Assumptions

- Each PBH is formed by gravitational collapse of an overdense region, with the density perturbation amplitude $\delta > \delta_{\rm th}$, of the radiation-dominated universe & has the parameters:



Mass M, Kerr parameter a, & spin direction (θ, ϕ).

- The density contrast δ obeys the Gaussian distribution:

$$P_{\rm G}(\nu) = \frac{1}{\sqrt{2\pi}} e^{-\nu^2/2}, \qquad \nu := \delta/\sigma_0$$

- The narrow power spectrum of δ:

$$\mathcal{P}_\delta(k) \approx \sigma_0^2 k_0 \delta_{\rm D}(k - k_0)$$

- The mass scaling law (critical phenomena):

$$M(\nu) = K M_H (\sigma_0 \nu - \sigma_0 \nu_{\rm th})^\beta, \quad K = 3.3, \quad \beta = 0.36.$$

[Evans & Coleman (1994)]

- The binary is formed by randomly choosing two PBHs.

Ongoing work by Koga-kun -3

Single PBH distribution

c.f [Harada + (2021)]

$$P(a, M, \theta, \phi) da dM d\theta d\phi = \frac{1}{4\pi} P(a \mid M(\nu), \nu) P_\nu(\nu) da d\nu d(\cos\theta) d\phi$$

$$P(a \mid M, \nu) = \frac{P_h(a/C(M,\nu))}{C(M,\nu) N_a(M,\nu)}, \qquad P_h(h) = 563 h^2 \exp[-2.37 - 4.12 \ln h - 1.53 (\ln h)^2 - 0.13 (\ln h)^3],$$

$$C(M,\nu) = 6.24 \times 10^{-3} \sqrt{1-\gamma^2} \left(\frac{M}{M_{k_0}}\right)^{-1/3} \left(\frac{\nu}{10}\right)^{-2}, \qquad N_a(M,\nu) := \int_0^{1/C(M,\nu)} P_h(h) dh, \qquad \gamma := \sigma_1^2/(\sigma_0 \sigma_2), \qquad \sigma_j^2 := \int d\ln k \, k^{2j} \mathcal{P}_\delta(k)$$

PBH binary distribution

$$P(\mathcal{M}, q, \chi_{\rm eff}) = \frac{1+q}{2\mathcal{M} q^2 \beta^2 \sigma_0^2} \left(\frac{(1+q)^{2/5} \mathcal{M}^2}{q^{1/5} K^2 M_{k_0}^2} \right)^{1/\beta} \int_0^1 da_1 \int_0^1 da_2 \Theta \left(L(a_1, a_2, \chi_{\rm eff}, q) \right) L(a_1, a_2, \chi_{\rm eff}, q) \times \frac{1}{a_1 a_2} \prod_{i=1}^{2} P\left(a_i \mid M_i(\mathcal{M}, q), \nu\left(M_i(\mathcal{M}, q)\right)\right) P\left(\nu\left(M_i(\mathcal{M}, q)\right)\right)$$

$$M_1(\mathcal{M}, q) = q^{-3/5} (1+q)^{1/5} \mathcal{M}, \qquad M_2(\mathcal{M}, q) = q^{2/5} (1+q)^{1/5} \mathcal{M}, \qquad \nu(M) = \sigma_0^{-1} \left(M/(K M_{k_0}) \right)^{1/\beta} + \nu_{\rm th},$$

$$L(a_1, a_2, \chi, q) = \min\left[a_1, q a_2 + (1+q)\chi\right] + \min\left[a_1, q a_2 - (1+q)\chi\right]$$

effective spin

$$\chi_{\rm eff} = \frac{M_1 a_1 \cos\theta_1 + M_2 a_2 \cos\theta_2}{M_1 + M_2}$$

mass ratio

$$q = m_2/m_1$$

chirp mass

$$\mathcal{M} = \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}}$$

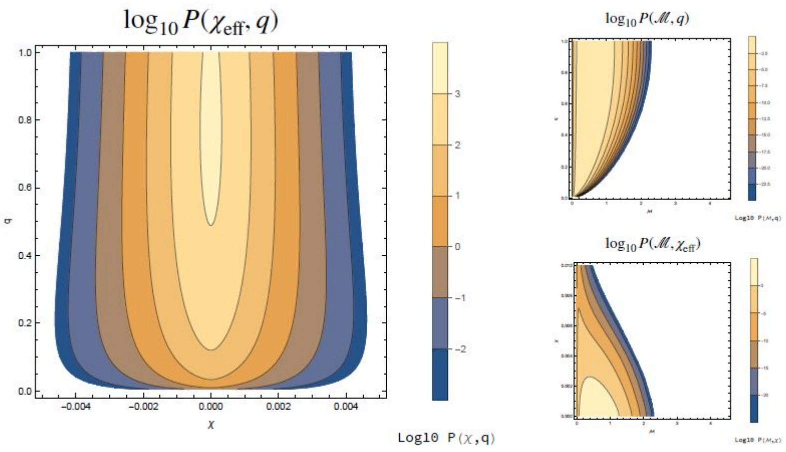
Ongoing work by Koga-kun -4

Numerical result of $P(\chi_{\rm eff}, q)$

- $|\chi_{\rm eff}| \lesssim 0.001$ in 90% CL.
- $0 \lesssim q \leq 1.$
- Symmetric about $\chi_{\rm eff} = 0.$
- No (anti-)correlation between $\chi_{\rm eff}$ & q.

$\gamma = 0.85,\ \ \delta_{\rm peak,th} = 1.92,\ \ \sigma_0 = 0.192$ (PS approximation),

$\nu_{\rm th} = 10$, Normalization with $M_{k_0} = 1.$



Conclusion

- The central values of $\chi_{\rm eff}$ & q seem to be well inside the observational data.
- Necessary to incorporate other effects, such as accretion, non-linear evolution during binary formation, etc⋯, to explain the anti-correlation.

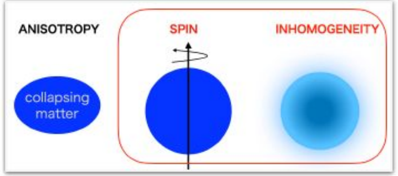
Ongoing work by Kokubu-kun-1

PBH formation from dynamical Einstein cluster

Takafumi Kokubu

Motivation & Model

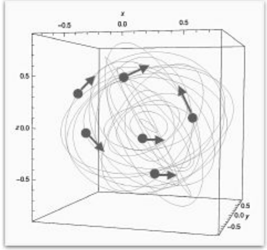
- Primordial BHs (PBH): a possible dark matter candidate
- Detailed **gravitational** dynamics of PBH formation is a fundamental issue
- We estimate the probability of PBH formation in matter dominated era



- PBHs form by 3 effects
- But, difficult to the all affects
- Thus, adopt 2 of them (spin & inhomogeneity)

↓

Dynamical Einstein Cluster



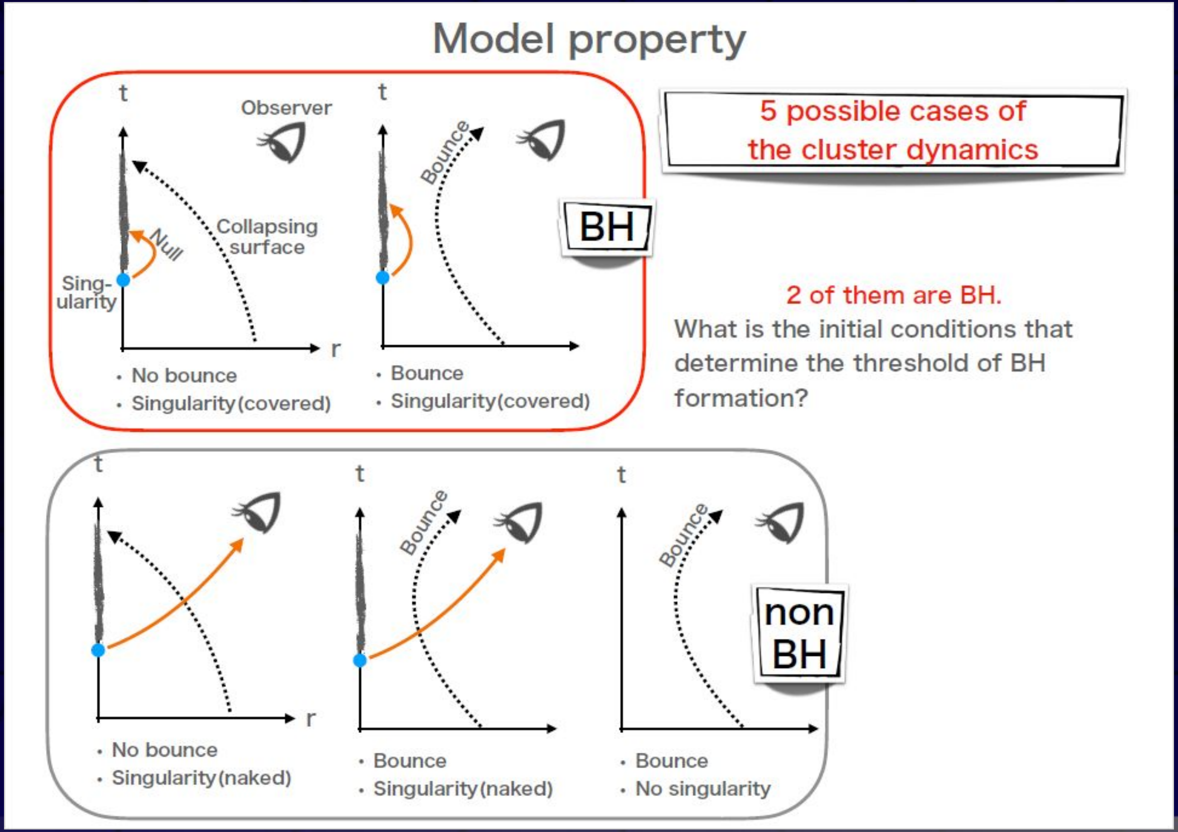
- INHOMOGENEOUS cloud of counter-rotating particles
- Many particles with angular momentum = ROTATION
- Total angular momentum = 0
- Allowed to move radially

↓

$T^{\mu}_{\nu} = \mathrm{diag}(-\epsilon, 0, \Pi, \Pi)$, Π : tangential pressure

($\Pi = 0$: Tolman-Bondi sol.)

Ongoing work by Kokubu-kun-2

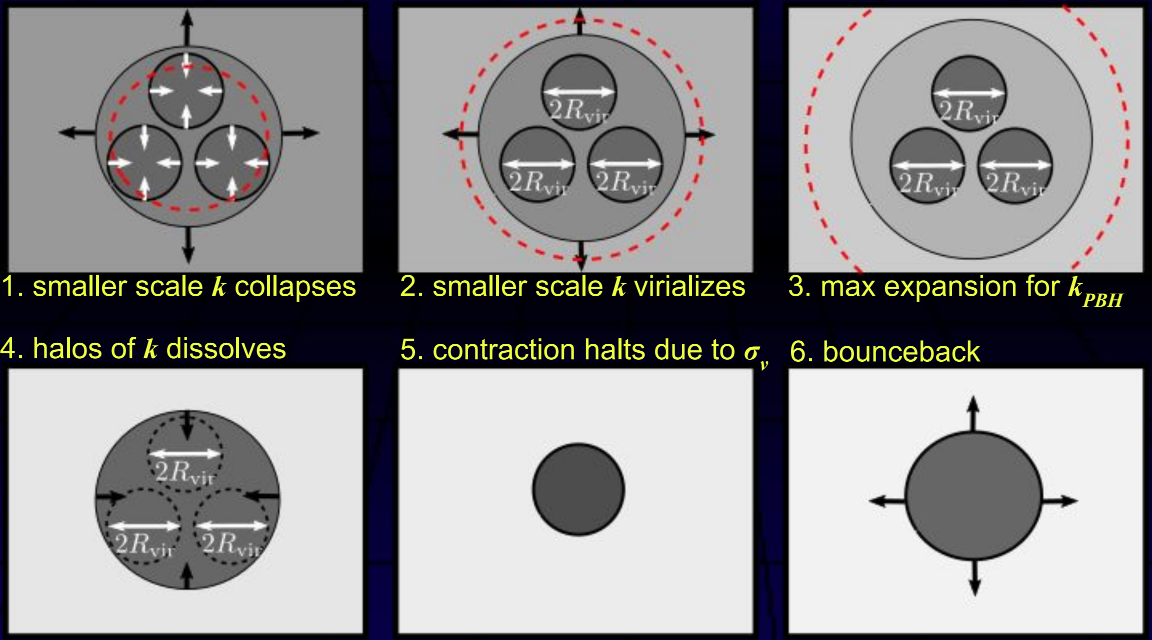


Ongoing work by seniors

Effect of velocity dispersion in PBH in MD

in preparation Harada, Kohri, Sasaki, Terada, CY

◎Let us consider two separated scales k and $k_{\mathrm{PBH}} < k$



1. smaller scale k collapses
2. smaller scale k virializes
3. max expansion for k_{PBH}
4. halos of k dissolves
5. contraction halts due to σ_v
6. bounceback

◎What is the condition for the velocity dispersion to halt the collapse?

Today's talks

- **Alexander Kusenko**
  Primordial black holes: a generic DM candidate in supersymmetry and other extensions of the Standard Model
- **Yuichiro Tada**
  Primordial black holes and induced gravitational waves in light of the non-Gaussian tail
- **Sachiko Kuroyanagi**
  Probing primordial black holes through the stochastic gravitational wave background

It's time to study Primordial Black Hole!

◎We aim to develop the PBH study further and clarify the possibility of PBH DM

◎The field is broad and still many possibilities to extend and think of

◎Anybody is welcome to join us. Please contact me if you are interested in our activity.

Let's enjoy PBH research with us!
Thank you for your attention.