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）

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Tomohiro Harada	Rikkyo Univ.
Sachiko Kuroyanagi	Nagoya Univ. / IFT Madrid
Alexander Kusenko	Kavli IPMU / UCLA
Misao Sasaki	Kavli IPMU

Why PBH as Dark Matter?

Black Hole

◎Invisible spacetime region from far even in far future.

◎Final fate of unstoppable gravitational collapse [R. Penrose (1965, 1969)]

⇒ trapped region ⇒ singularity in the future

⇒ existence of an invisible region from far (without naked singularity) ⇒ **BH**

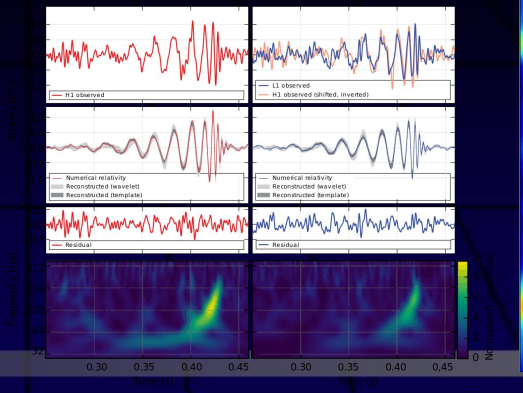
◎If a mass gets compacted into a small enough region, BH will form.

◎Such objects have been observed!

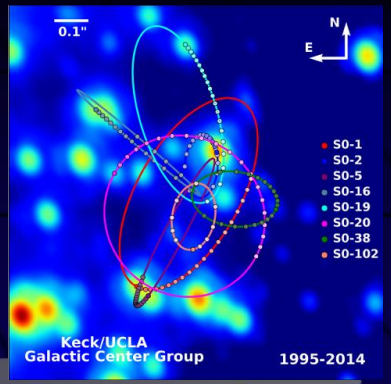
◎Black holes “exist” in our universe

◎Black holes behave as **DM** in a cosmological scale

Nobel Prize(2017)
R. Weiss, K. S. Thorne, B. C. Barish



Nobel Prize(2020)
R.Genzel, A. Ghez



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 PBHs can account for?

To answer this, we need

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

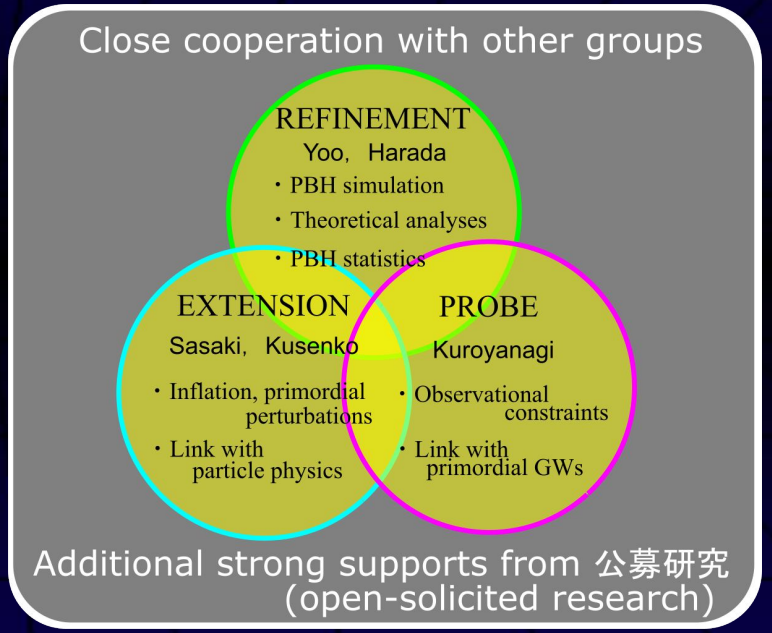
◎What are distinct characters of PBH DM?

For the prediction, we need

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

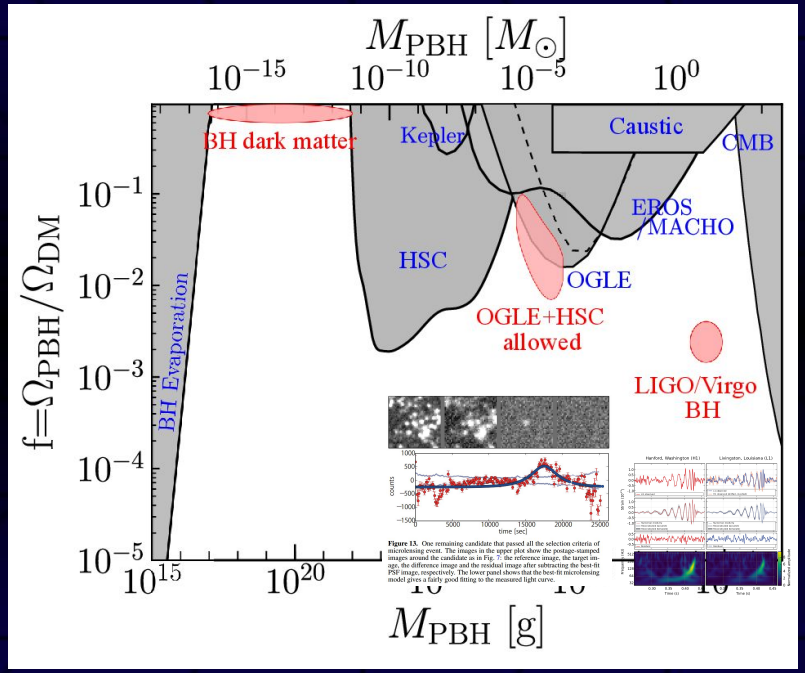
◎Possible other macroscopic DM?

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



Progress and hot topics in PBH research

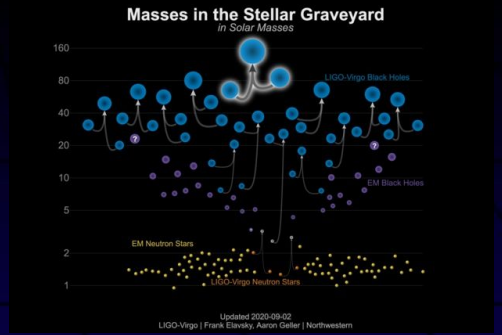
Observational constraints and PBH candidates



◎Active updates on observational constraints

◎3 particularly attractive PBH candidates

- DM
- Microlensing event in OGLE+HSC (1701.02151, 1901.07120)
- Binary BHs

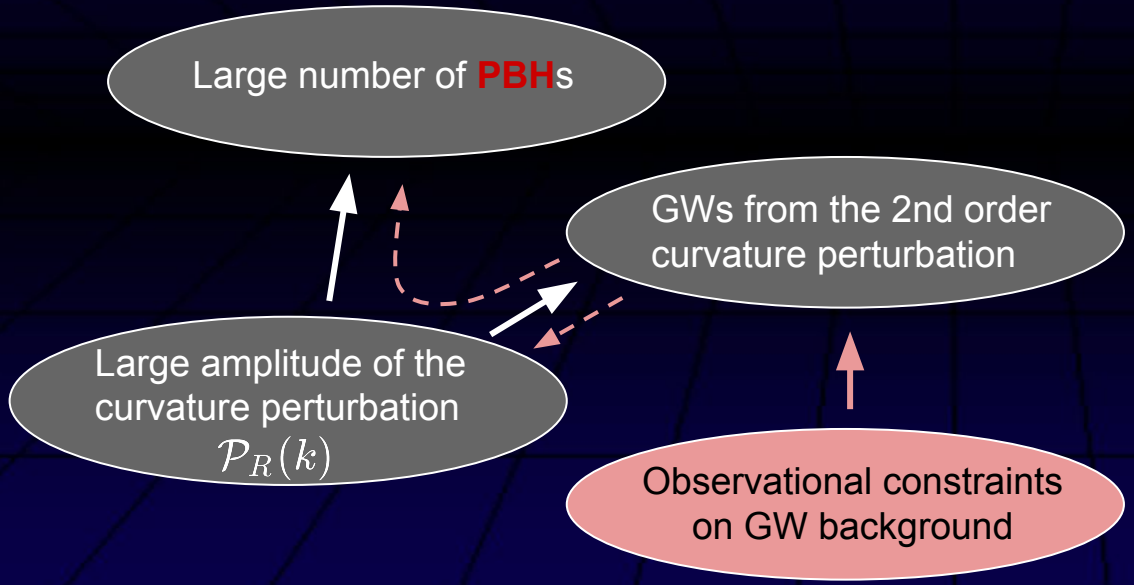


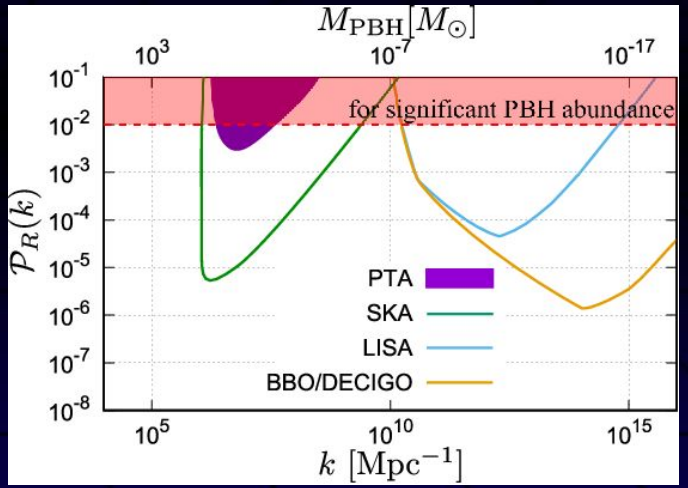
It is very exciting to ask “Are they really PBHs?”

Gravitational wave astronomy to probe PBH DM

◎ PBHs as origin of BH binaries observed by LIGO/Virgo

◎ A substantial number of PBHs has to be associated with an observable GW background



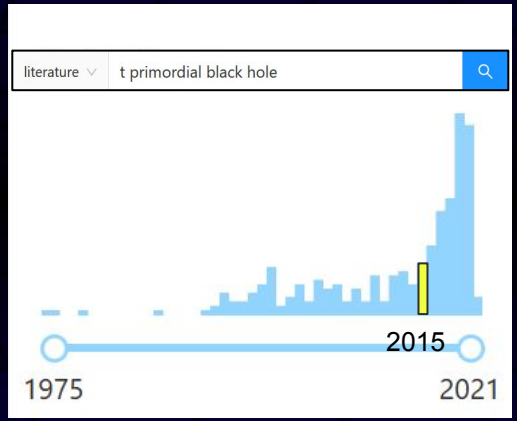


Progress in the theoretical study of PBH

◎ Detection of GWs from binary black holes triggered number of PBH papers

◎ Progress in the theoretical study has been accelerated

- attractive models which produce a number of PBHs
- better understanding of PBH formation criterion
- finer prediction of PBH abundance
- PBH statistics by use of the peak theory
- effects of primordial non-Gaussianity on PBH statistics
- estimation of spin distribution of PBHs
- non-spherical numerical simulation of PBH formation
- PBH formation in matter-dominated era
- ...



◎ Having these new technologies,
we aim to develop the PBH study further and clarify the possibility of PBH DM

A03 Research proposal and group members

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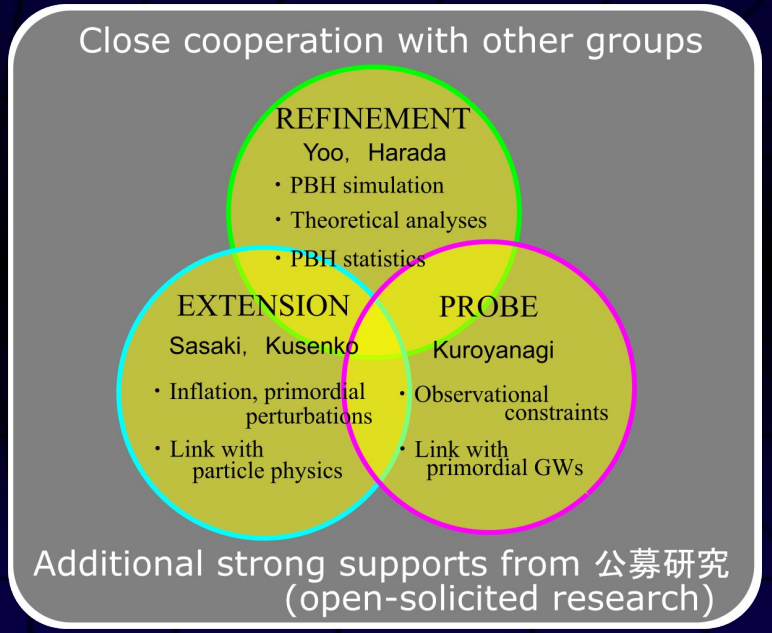


Sachiko Kuroyanagi (Nagoya U./IFT)

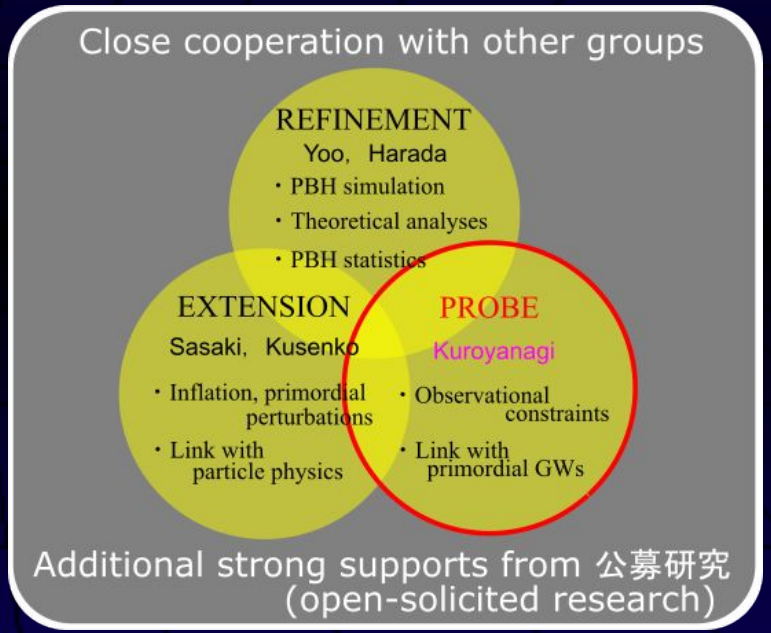
◎Expert in observational tests by use of GW background

◎Recent related research

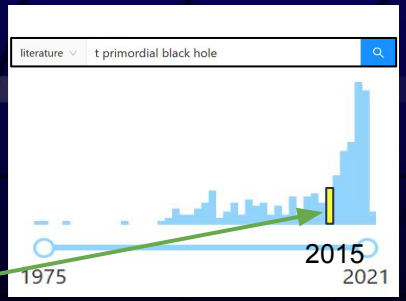
- 1807.00786 Kuroyanagi, Chiba, Takahashi
  Probing the Universe through the Stochastic Gravitational Wave Background
- 2101.12130 LIGO, Virgo, KAGRA Collaboration
  Upper Limits on the Isotropic Gravitational-Wave Background from Advanced LIGO's and Advanced Virgo's Third Observing Run
  *contributed as an internal reviewer

◎Fills a crucial piece of observational tests

- Contribution of **PBH**s to GW background
- Constraints from GW observations
- Other possible observational tests



Misao Sasaki (Kavli IPMU)



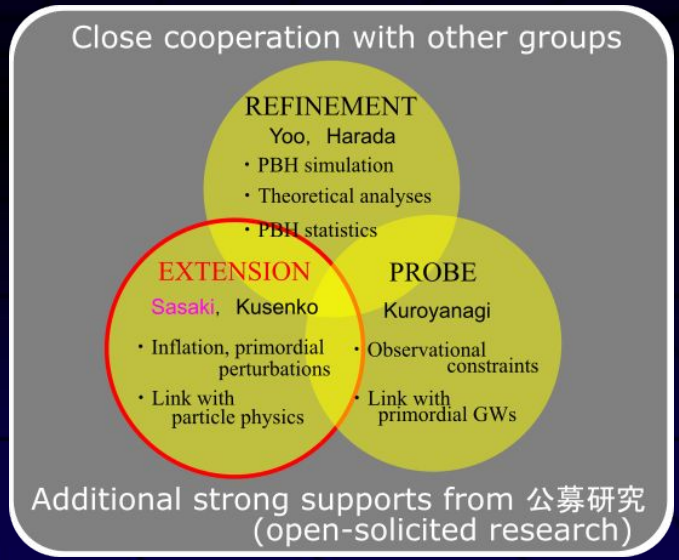
◎Expert in cosmology and gravity

◎Recent related research

- 1603.08338 Sasaki, Suyama, Tanaka, Yokoyama
  Primordial Black Hole Scenario for the Gravitational-Wave Event GW150914
- 2010.03537 Zhou, Jiang, Cai, Sasaki, Pi
  Primordial Black Holes and Gravitational Waves from Resonant Amplification during Inflation
- 2012.08151 Domènech, Lin, Sasaki
  Gravitational Wave Constraints on the Primordial Black Hole Dominated Early Universe

◎Construction and analyses of attractive models

- Construction of inflationary models generating **PBH**s
- Effects of primordial non-Gaussianity in **PBH** statistics
- Adviser in every field

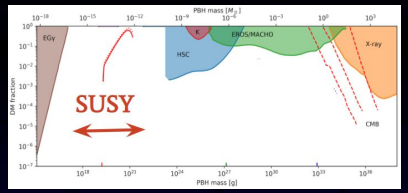


Alexander Kusenko (Kavli IPMU / UCLA)

◎Leading researcher on the origin of **DM** in particle phys, high-energy astro. and cosmology

◎Recent related research

- 1612.02529, 1706.09003, 1801.03321, 1907.10613
  Cotner, Kusenko, Sasaki, et al.
  PBH formation mechanism: scalar fragmentation in SUSY

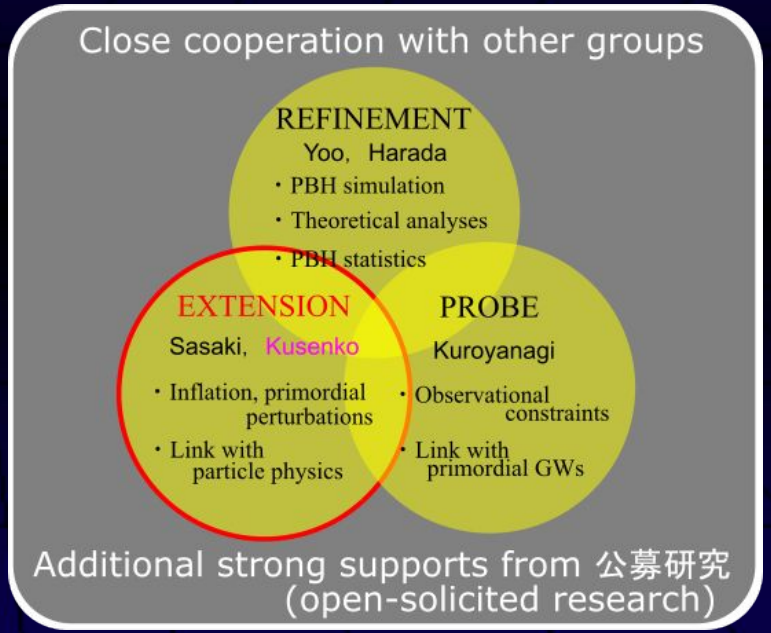


SUSY breaking terms determine the scale

- 2008.12456 Flores, Kusenko
  Primordial Black Holes from Long-range Scalar Forces and Scalar Radiative Cooling

◎Construction and analyses of attractive models

- Particle physics models generating **PBH**s
- Other macroscopic **DM** models, e.g. Q-ball, boson star,...



Tomohiro Harada (Rikkyo U.)

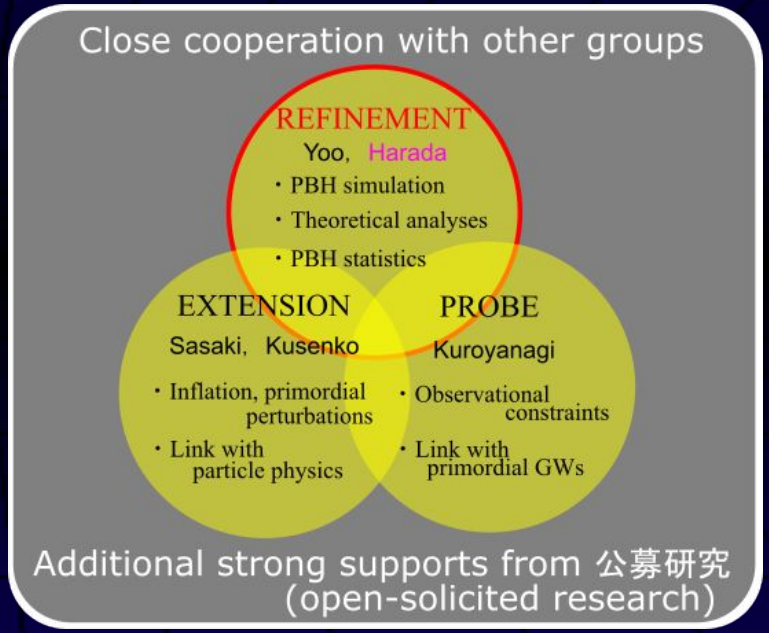
◎Expert in physics of **PBH** formation

◎Recent related research

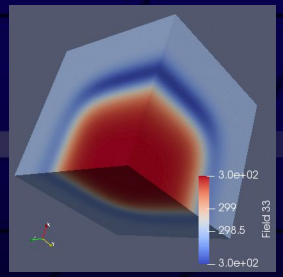
- 1309.4201, 1503.03934 Harada, Yoo, et al.
  Fundamental research on **PBH** formation process
- 1609.01588, 1707.03595, 1810.03490 Harada, Yoo, et al.
  PBH formation in the matter-dominated phase of the Universe
- 2011.00710 Harada, Yoo, Kohri, Koga, Monobe
  *Spins of **P**rimordial **B**lack **H**oles Formed in the Radiation-dominated Phase of the Universe: First-Order Effect*

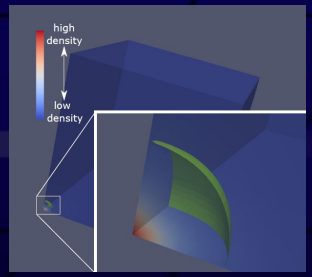
◎Deeper understanding of general **PBH** formation

- Reanalyses of **PBH** formation in the radiation/matter dominated era taking recent progress into account
- Prediction of Spins of **PBH**s
- Refinement of **PBH** statistics



Chulmoon Yoo (Nagoya U.)





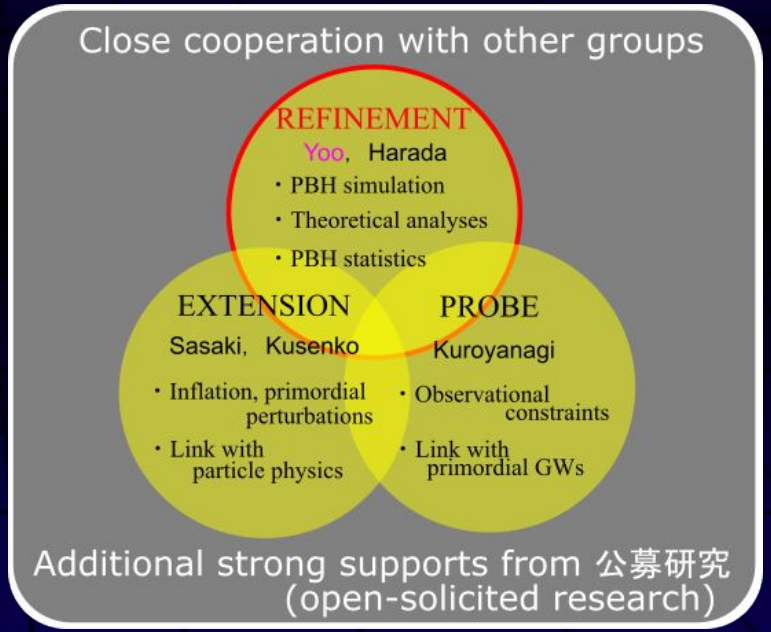
◎PI of **A03** group

◎Recent related research

- 1906.06790 Yoo, Gong, Yokoyama
  Abundance of Primordial Black Holes with Local Non-Gaussianity in Peak Theory
- 2004.01042 Yoo, Harada, Okawa
  Threshold of Primordial Black Hole Formation in Nonspherical Collapse
- 2008.02425 Yoo, Harada, Hirano, Kohri,
  Abundance of Primordial Black Holes in Peak Theory for an Arbitrary Power Spectrum

◎Simulation of **PBH** formation and **PBH** statistics

- Simulation of spinning **PBH** formation
- Non-spherical **PBH** formation in matter dominated era
- Refinement of **PBH** statistics combining the results of numerical simulation



Specific topics of our research proposal

◎Deeper understanding of **PBH** physics and refinement of theoretical predictions

- ➢ Numerical simulation of nonspherical and spinning **PBH** formation
- ➢ Improvement of **PBH** abundance prediction
- ➢ Providing procedure to get precise mass and spin distribution of **PBH**

◎Looking for attractive extended PBH formation scenario ↔ other theory groups (**A0x**, **C0x**)

- ➢ Models naturally explain the **PBH** candidates
- ➢ Models associated with exciting predictions of observation(e.g., GW background)
- ➢ Effects of primordial non-Gaussianities and those observational tests (abundance, clustering)
- ➢ **PBH**s from gravitational collapse of topological defects
- ➢ Attractive macroscopic **DM** models

◎Observational tests with generalized and improved theoretical predictions ↔ **B0x** groups

- ➢ GW background spectrum
- ➢ GWs from BH mergers
- ➢ Effects of **PBH** clustering in small scale structures

And more!

Young Active Postdocs will join us!

★ Albert Escrivà (from May)

➢ Cosmology and numerical simulation of PBH formation

★ Shin'ichi Hirano (from April)

➢ Cosmology and modified gravity

★ Yasutaka Koga (from April)

➢ General relativity, PBH formation

It's time to study Primordial Black Hole!

◎Primordial Black Hole is a plausible Dark Matter candidate

◎There are 3 attractive observational candidates of PBHs

◎PBH is a very active and exciting research topic

◎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.