A03 group highlights

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	APCTP / 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**?

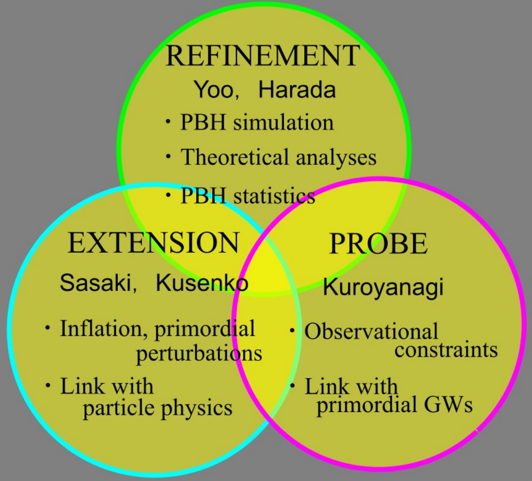
For the prediction, we need

- ➢ 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 2024

➢ Workshop: Dynamics of primordial black hole formation II (10/7 - 10)

	10/7 Mon.	10/8 Tue.	10/9 Wed.	10/10 Thu.
09:00 - 09:30	Reception and free discussion	Free discussion	Free discussion	Free discussion
09:30 - 10:00				
10:00 - 10:30		Invited talk3 Marcos Flores	Invited talk5 Juan Carlos Hidalgo	X.C. He
10:30 - 11:00	Opening (10:50-)			R. Inui
11:00 - 11:30	Invited talk1 Gabriele Franciolini	Buffer & break time	Buffer & break time	Buffer & break time
11:30 - 12:00		M. Tanaka	C. Yoo	Invited talk7 Kazunori Kohri
12:00 - 12:30	Y. Tada	T. Terada	I. Musco	
12:30 - 13:00	Lunch	Lunch	Lunch	Closing
13:00 - 13:30				
13:30 - 14:00				
14:00 - 14:30	X. Wang	D. Cruces	K. Uehara	
14:30 - 15:00	X.H. Ma	Y. Mizuguchi	M. Shimada	
15:00 - 15:30	Buffer & break time	Buffer & break time	Buffer & break time	
15:30 - 16:00	Invited talk2 Shi Pi	P.J.L. Martens	T. Harada	
16:00 - 16:30		A. Escrivà	D. Saito	
16:30 - 17:00		Buffer & break time	Buffer & break time	
17:00 - 17:30		Invited talk4 Eugene A. Lim	Invited talk6 Tom Giblin	
17:30 - 18:00				
18:00 - 18:30				
18:30 - 19:00		Free discussion		
19:00 -	Free discussion	Reception party	Free discussion	Free discussion

Activities of A03 in the fiscal year 2024

➢ Contribution to a textbook on PBH

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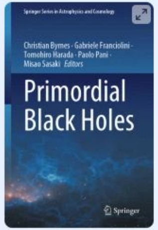

Primordial Black Holes

Book | May 2025

Overview

Editors: Christian Byrnes, Gabriele Franciolini, Tomohiro Harada, Paolo Pani, Misao Sasaki

- Covers contributions from key researchers in cosmology, particle physics, and numerical simulation
- Discusses a variety of topics, providing a unique resource for students and researchers interested in the subject
- Provides a reference for next-generation cosmologists, particle physicists, and gravitational-wave astrophysicists

Chapter 2

Overall picture: a beginner's guide to primordial black hole formation

Teruaki Suyama and Chul-Moon Yoo

Abstract The air seeking a founda passing their forn equations. It is ir striving to be self can be comprehe and cosmology, present quantitati for verification a foster a clear phy this chapter is ne associated equati

Chapter 26

LIGO-Virgo-KAGRA constraints on primordial black holes from stochastic gravitational-wave background searches

Alba Romero-Rodríguez and Sachiko Kuroyanagi

Abstract Primordi gravitational wave verse. This chapter those generated by hole formation in t tional waves emitte methods and a bri straints imposed b of the stochastic gr tions.

Chapter 9

New ideas on the formation and astrophysical detection of primordial black holes

Marcos M. Flores and Alexander Kusenko

Abstract Recently, a number of novel scenarios for primordial black hole (PBH) formation have been discovered. Some of them require very minimal new physics, some others require no new ingredients besides those already present in commonly

Activities of A03 in the fiscal year 2024

- 2401.02314 *Applying the Viterbi Algorithm to Planetary-Mass Black Hole Searches*
  George Alestas, Gonzalo Morras, Takahiro S. Yamamoto, Juan Garcia-Bellido, **Sachiko Kuroyanagi** et al.
- 2401.06329 *Numerical simulation of type II primordial black hole formation*
  Koichiro Uehara, Albert Escrivà, **Tomohiro Harada**, Daiki Saito, **Chul-Moon Yoo**
- 2402.13341 *Revisiting formation of primordial black holes in a supercooled first-order phase transition*
  Marcos M. Flores, **Alexander Kusenko, Misao Sasaki**
- 2403.00660 *New probe of non-Gaussianities with primordial black hole induced gravitational waves*
  Theodoros Papanikolaou, Xin-Chen He, Xiao-Han Ma, Yi-Fu Cai, Emmanuel N. Saridakis, **Misao Sasaki**
- 2403.11147 *Primordial black hole formation from a nonspherical density profile with a misaligned deformation tensor*
  Chul-Moon Yoo
- 2404.02492 *Enhanced Curvature Perturbation and Primordial Black Hole Formation in Two-stage Inflation with a break*
  Xinpeng Wang, Ying-li Zhang, **Misao Sasaki**
- 2404.03909 *Direct-collapse supermassive black holes from relic particle decay*
  Yifan Lu, Zachary S. C. Picker, **Alexander Kusenko**
- 2404.05430 *New ideas on the formation and astrophysical detection of primordial black holes*
  Marcos M. Flores, **Alexander Kusenko**
- 2404.12591 *The LISA forecast on a smooth crossover beyond the Standard Model through the scalar-induced gravitational waves*
  Albert Escrivà, Ryoto Inui, Yuichiro Tada, **Chul-Moon Yoo**
- 2405.01620 *JWST Lensed quasar dark matter survey II: Strongest gravitational lensing limit on the dark matter free streaming length to date*
  Ryan E. Keeley, Anna M. Nierenberg, Daniel Gilman, Charles Gannon, Simon Birrer, Tommaso Treu, Andrew J. Benson, Xiaolong Du, K. N. Abazajian, T. Anguita, V. N. Bennert, S. G. Djorgovski, K. K. Gupta, S. F. Hoenig, **A. Kusenko**, C. Lemon, M. Malkan, V. Motta, L. A. Moustakas, M. S. H. Oh, D. Sluse, D. Stern, R. H. Wechsler

Activities of A03 in the fiscal year 2024

- 2405.03740 *Gravitational waves from cosmic strings in LISA: reconstruction pipeline and physics interpretation*
  Jose J. Blanco-Pillado, Yanou Cui, **Sachiko Kuroyanagi**, Marek Lewicki, Germano Nardini, Mauro Pieroni, Ivan Yu. Rybak, Lara Sousa, Jeremy M. Wachter
- 2405.04210 *Extracting parity-violating gravitational waves from projected tidal force tensor in three dimensions*
  Teppei Okumura, **Misao Sasaki**
- 2405.05247 *Neutrinos and gamma rays from beta decays in an active galactic nucleus NGC 1068 jet*
  Koichiro Yasuda, Yoshiyuki Inoue, **Alexander Kusenko**
- 2405.05402 *The possibility of multi-TeV secondary gamma rays from GRB221009A*
  Oleg Kalashev, Felix Aharonian, Warren Essey, Yoshiyuki Inoue, **Alexander Kusenko**
- 2405.10201 *Investigating cosmic histories with a stiff era through Gravitational Waves*
  Hannah Duval, **Sachiko Kuroyanagi**, Alberto Mariotti, Alba Romero-Rodríguez, Mairi Sakellariadou
- 2405.11755 *Testing Gravity with Frequency-Dependent Overlap Reduction Function in Pulsar Timing Array*
  Qiuyue Liang, Ippei Obata, **Misao Sasaki**
- 2406.11742 *Detection Prospects of Gravitational Waves from SU(2) Axion Inflation*
  Charles Badger, Hannah Duval, Tomohiro Fujita, **Sachiko Kuroyanagi**, Alba Romero-Rodríguez, Mairi Sakellariadou
- 2407.00205 *LVK constraints on PBHs from stochastic gravitational wave background searches*
  Alba Romero-Rodríguez, **Sachiko Kuroyanagi**
- 2407.06066 *Revisiting the Ultraviolet Tail of the Primordial Gravitational Wave*
  Shi Pi, **Misao Sasaki**, Ao Wang, Jianing Wang
- 2408.12977 *New series expansion method for the periapsis shift*
  Akihito Katsumata, **Tomohiro Harada**, Kota Ogasawara, Hayami Iizuka
- 2409.00435 *Revisiting spins of primordial black holes in a matter-dominated era based on peak theory*
  Daiki Saito, **Tomohiro Harada**, Yasutaka Koga, **Chul-Moon Yoo**

Activities of A03 in the fiscal year 2024

- 2409.01934 *Primordial black holes: formation, spin and type II*
  Tomohiro Harada
- 2409.05544 *Geometrical origin for the compaction function for primordial black hole formation*
  Tomohiro Harada, Hayami Iizuka, Yasutaka Koga, **Chul-Moon Yoo**
- 2409.06494 *Spin of Primordial Black Holes from Broad Power Spectrum: Radiation Dominated Universe*
  Indra Kumar Banerjee, **Tomohiro Harada**
- 2409.09935 *New shape for cross-bispectra in Chern-Simons gravity*
  Perseas Christodoulidis, Jinn-Ouk Gong, Wei-Chen Lin, Maria Mylova, **Misao Sasaki**
- 2409.11333 *Gravitational waves from primordial black hole isocurvature: the effect of non-Gaussianities*
  Xin-Chen He, Yi-Fu Cai, Xiao-Han Ma, Theodoros Papanikolaou, Emmanuel N. Saridakis, **Misao Sasaki**
- 2410.00827 *DESI constraints on α-attractor inflationary models*
  George Alestas, Marienza Caldarola, **Sachiko Kuroyanagi**, Savvas Nesseris
- 2410.14414 *Black Holes Inside and Out 2024: visions for the future of black hole physics*
  Niayesh Afshordi, Abhay Ashtekar, Enrico Barausse, Emanuele Berti, Richard Brito, Luca Buoninfante, Raúl Carballo-Rubio, Vitor Cardoso, Gregorio Carullo, Mihalis Dafermos, Mariafelicia De Laurentis, Adrian del Rio, Francesco Di Filippo, Astrid Eichhorn, Roberto Emparan, Ruth Gregory, Carlos A. R. Herdeiro, Jutta Kunz, Luis Lehner, Stefano Liberati, Samir D. Mathur, Samaya Nissanke, Paolo Pani, Alessia Platania, Frans Pretorius, **Misao Sasaki**, Paul Tiede, William Unruh, Matt Visser, Robert M. Wald
- 2410.03451 *Non-spherical effects on the mass function of Primordial Black Holes*
  Albert Escrivà, **Chul-Moon Yoo**
- 2410.03452 *Simulations of Ellipsoidal Primordial Black Hole Formation*
  Albert Escrivà, **Chul-Moon Yoo**
- 2411.07648 *Primordial Black Hole Formation from Type II Fluctuations with Primordial Non-Gaussianity*
  Masaaki Shimada, Albert Escrivá, Daiki Saito, Koichiro Uehara, **Chul-Moon Yoo**

Activities of A03 in the fiscal year 2024

- 2411.07692 *Crunch from AdS bubble collapse in unbounded potentials*
  Kaloian D. Lozanov, **Misao Sasaki**
- 2411.11322 *Beyond Coleman's Instantons*
  Misao Sasaki, Vicharit Yingcharoenrat, Ying-li Zhang
- 2411.17074 *Black Holes from Fermi Ball Collapse*
  Yifan Lu, Zachary S. C. Picker, Stefano Profumo, **Alexander Kusenko**
- 2412.12975 *Comparative analysis of the NANOgrav Hellings-Downs as a window into new physics*
  Rubén Arjona, Savvas Nesseris, **Sachiko Kuroyanagi**
- 2412.15879 *Astrometric constraints on stochastic gravitational wave background with neural networks*
  Marienza Caldarola, Gonzalo Morrás, Santiago Jaraba, **Sachiko Kuroyanagi**, Savvas Nesseris, Juan García-Bellido
- 2412.16463 *A complete analysis of inflation with piecewise quadratic potential*
  Xinpeng Wang, Xiao-Han Ma, **Misao Sasaki**
- 2412.18318 *Search for a gravitational wave background from primordial black hole binaries using data from the first three LIGO-Virgo-KAGRA observing runs*
  Tore Boybeyi, Sebastien Clesse, **Sachiko Kuroyanagi**, Mairi Sakellariadou
- 2501.00295 *Primordial Black Hole Formation from Power Spectrum with Finite-width*
  Shi Pi, **Misao Sasaki**, Volodymyr Takhistov, Jianing Wang
- 2501.03444 *Dark matter from inflationary quantum fluctuations*
  Mohammad Ali Gorji, **Misao Sasaki**, Teruaki Suyama
- 2501.11040 *Super-critical primordial black hole formation via delayed first-order electroweak phase transition*
  Katsuya Hashino, Shinya Kanemura, Tomo Takahashi, Masanori Tanaka, **Chul-Moon Yoo**
- 2502.16787 *Singularity resolution and regular black hole formation in gravitational collapse in asymptotically safe gravity*
  Tomohiro Harada, Chiang-Mei Chen, Rituparna Mandal

Activities of A03 in the fiscal year 2024

- 2502.20138 *Fundamental Physics and Cosmology with TianQin*
  Jun Luo, Haipeng An, Ligong Bian, Rong-Gen Cai, Zhoujian Cao, Wenbiao Han, Jianhua He, Martin A. Hendry, Bin Hu, Yi-Ming Hu, Fa Peng Huang, Shun-Jia Huang, Sang Pyo Kim, En-Kun Li, Yu-Xiao Liu, Vadim Milyukov, Shi Pi, Konstantin Postnov, **Misao Sasaki**, Cheng-Gang Shao, Lijing Shao, Changfu Shi, Shuo Sun, Anzhong Wang, Pan-Pan Wang, Sai Wang, Shao-Jiang Wang, Zhong-Zhi Xianyu, Huan Yang, Tao Yang, Jian-dong Zhang, Xin Zhang, Wen Zhao, Liang-Gui Zhu, Jianwei Mei
- 2503.11401 *Shadow formation in gravitational collapse: redshift and blueshift by spacetime dynamics*
  Yasutaka Koga, Nobuyuki Asaka, Masashi Kimura, Kazumasa Okabayashi
- 2503.19744 *Dip and non-linearity in the curvature perturbation from inflation with a transient non-slow-roll stage*
  Tomohiro Fujita, Ryodai Kawaguchi, **Misao Sasaki**, Yuichiro Tada
- 2504.00449 *General relativistic effects on photon spectrum emitted from dark matter halos around primordial black holes*
  Toya Suzuki, Takahisa Igata, Kazunori Kohri, **Tomohiro Harada**

46 papers in FY2024

totally 137 papers from A03 group members

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◎How large fraction of DM PBHs can account for?

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

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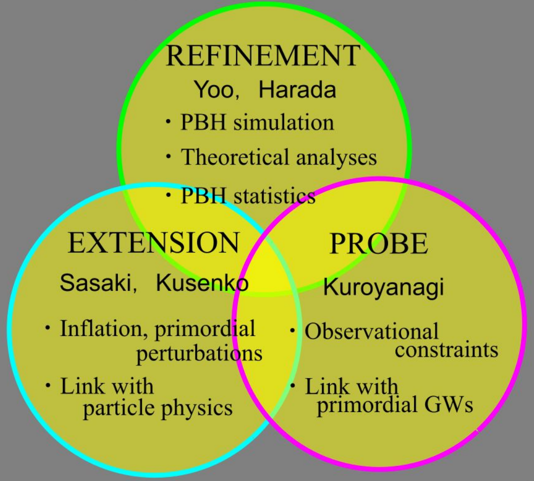
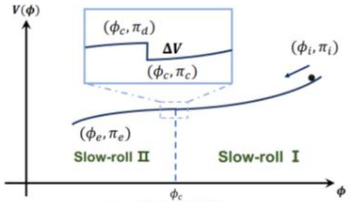


Additional strong supports from 公募研究 (open-solicited research)

Extension: inflation and primordial perturbations

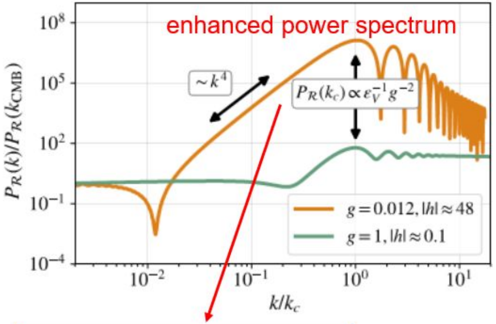
- a new model for PBH formation: Inflation with an upward step

Cai, Ma, MS, Wang & Zhou, 2112.13836; 2207.11910



potential

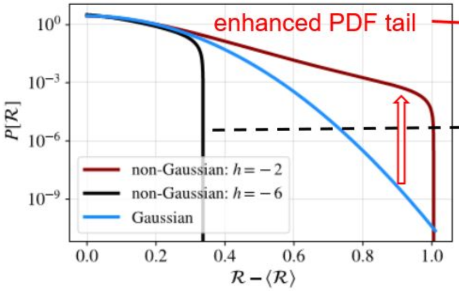
$$\pi_d = -\sqrt{\pi_c^2 - 6\frac{\Delta V}{V}}$$: energy conservation across the step



- highly non-Gaussian curvature perturbation

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

h: model parameter



abundant PBH formation

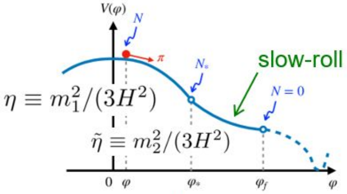
no PBH formation (of normal type)

Extension: inflation and primordial perturbations

➢ Logarithmic duality of the curvature perturbation

S. Pi & M. Sasaki, 2211.13932

- exponential tails in PDF commonly appear in inflation with featured potentials



example

- dual expression

$$\mathcal{R} \equiv \delta N = \frac{1}{\lambda_\pm} \ln\left[1 + \frac{\lambda_\mp \delta\varphi}{\pi + \lambda_\mp \varphi}\right] + \ldots$$

$$\lambda_\pm = \frac{3 \pm \sqrt{9 - 12\eta}}{2}$$

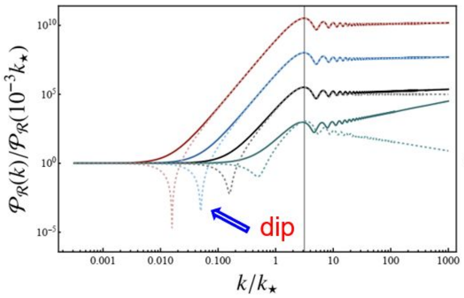
- Gaussian $\delta\phi$ leads to exponential tail in $\mathcal{R}$

$$P(\mathcal{R}) \sim \exp[-c\,\mathcal{R}]$$

- clarified the reason for the appearance of exponential tail

➢ A complete analysis of inflation with piecewise quadratic potential

X. Wang, X.-H. Ma & M. Sasaki, 2412.16463



- the reason for the spectrum with or without a dip is clarified
- the importance of non-linear evolution of $\delta\phi$ on superhorizon scales is clearly shown

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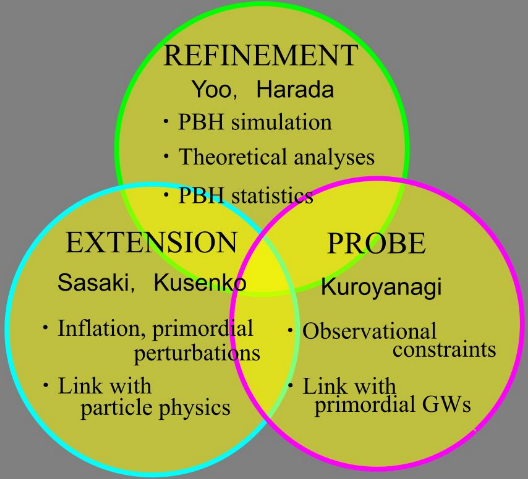

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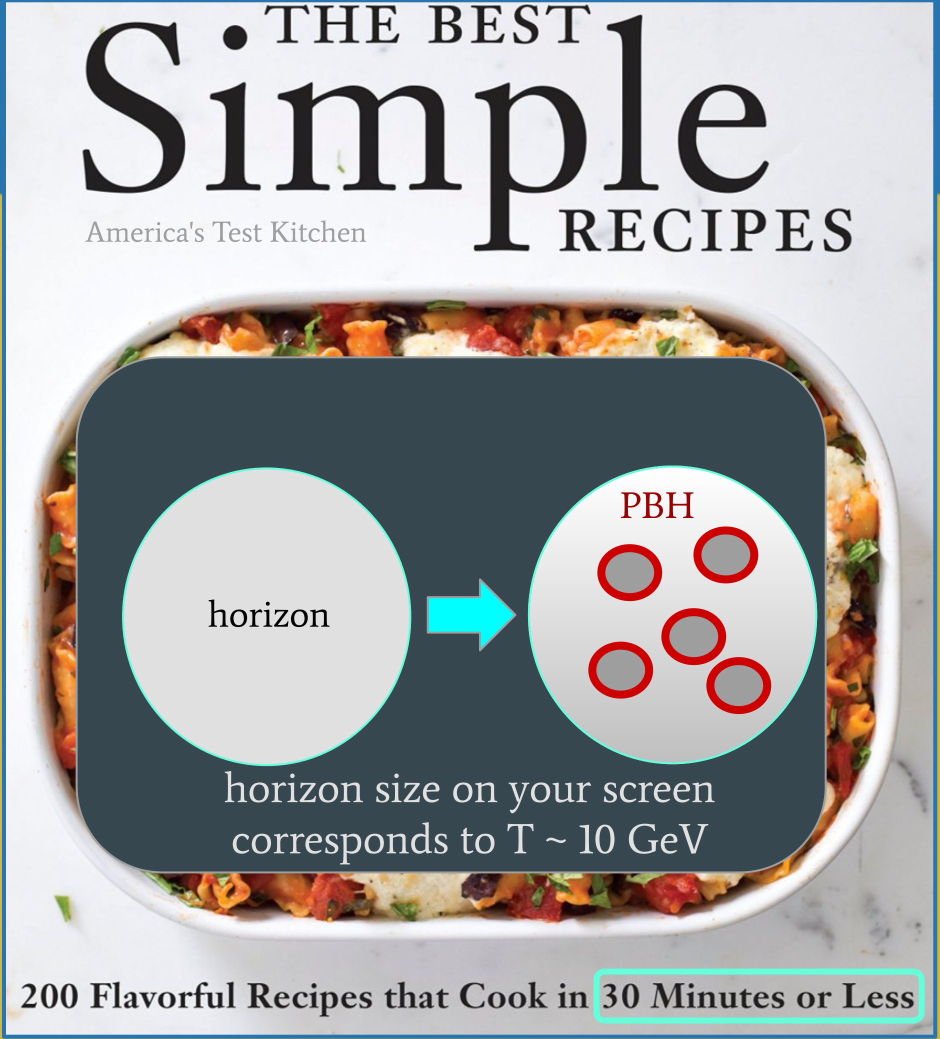
Extension: Link with particle physics

- Simple, generic formation scenarios in the early universe:
  PBH from scalar forces, PBH from a scalar field fragmentation, PBH from vacuum bubbles...
- PBH with masses 10^{-16} - 10^{-10} $M_\odot$, motivated by 1-100 TeV scale **supersymmetry**, can make up 100% (or less) of dark matter. **PBH is a generic dark matter candidate in SUSY**
- PBH from ~ 1-100 GeV scale particles can naturally explain DM abundance
- Microlensing (HSC, others) can detect the tail of DM mass function.
- PBH can contribute to r-process nucleosynthesis
- Signatures of PBH:
  - Kilonova without a GW counterpart, or with a weak/unusual GW signature
    Accompanied by an FRB
  - GW from early halo formation
  - An unexpected population of 1-2 $M_\odot$ black holes (GW)
  - Galactic positrons, FRB, etc.

Many ways to make PBHs

Need a ~30% or higher overdensity early enough in the history of the universe.

- Primordial fluctuations enhanced on small scales (inflation models)
- **Yukawa interactions, “long-range” forces, radiative cooling => PBH**
- Supersymmetry: Q-balls as building blocks of PBH
- Supersymmetry: Q-balls with long-range scalar forces
- Multiverse => PBHs
- ...



PBH formation mechanism: Yukawa "fifth force"

Yukawa interactions:

$$V(r) = \frac{y^2}{r} e^{-m_\chi r}$$

$$y\chi\bar{\psi}\psi$$

a heavy fermion interacting with a light scalar

A light scalar field $\Rightarrow$ long-range attractive force, stronger than gravity $\Rightarrow$ instability similar to gravitational instability, only stronger

$\Rightarrow$ **halos form** even in **radiation dominated universe**

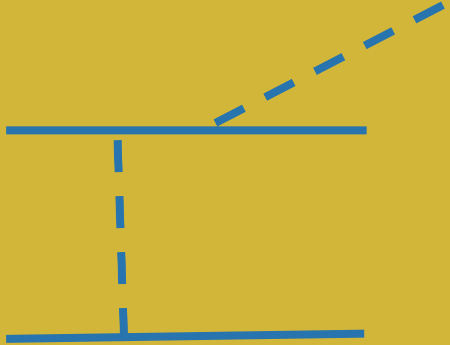
[Amendola et al., 1711.09915; Savastano et al., 1906.05300; Domenech, Sasaki, 2104.05271]

Same Yukawa coupling provides a source of **radiative cooling** by emission of gravitational radiation $\Rightarrow$ **halos collapse to black holes**

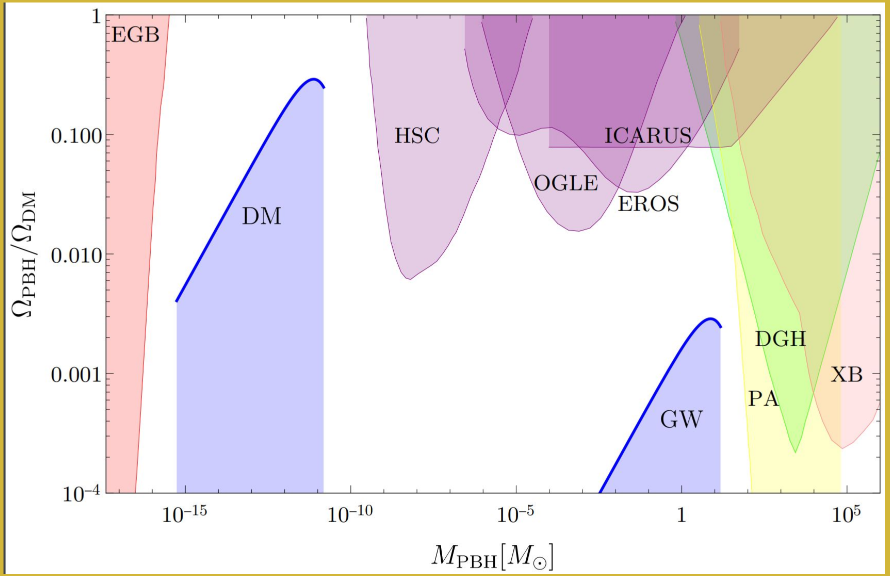
[Flores, Kusenko, PRL 126 (2021) 041101]

Rapid growth of structures... plus radiative cooling!

Same Yukawa fields allow particles moving with acceleration emit scalar waves



⇒ radiative cooling and collapse to black holes



Flores, Kusenko, Phys.Rev.Lett. 126 (2021) 4, 041101

PBH DM abundance natural for m_ψ~1-100 GeV

Asymmetric dark matter models: Asymmetry in the dark sector = baryon asymmetry

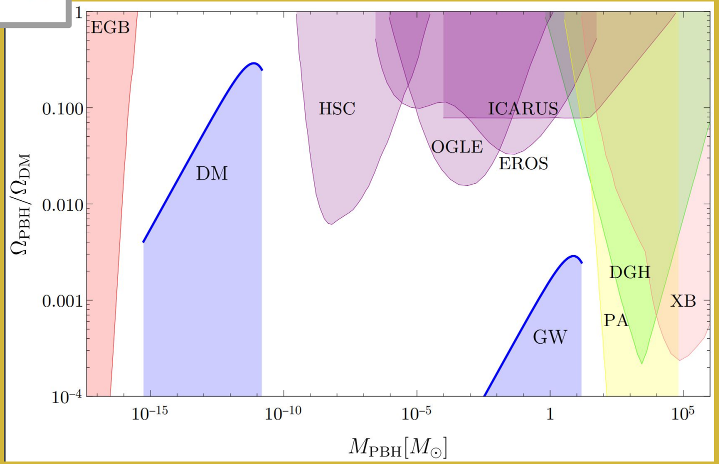
In our case, all these particles end up in black holes:

$$f_{\rm PBH} = \frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}} = 0.2 \frac{m_\psi}{m_p}\frac{\eta_\psi}{\eta_B} = \left(\frac{m_\psi}{5\,{\rm GeV}}\right)\left(\frac{\eta_\psi}{10^{-10}}\right)$$

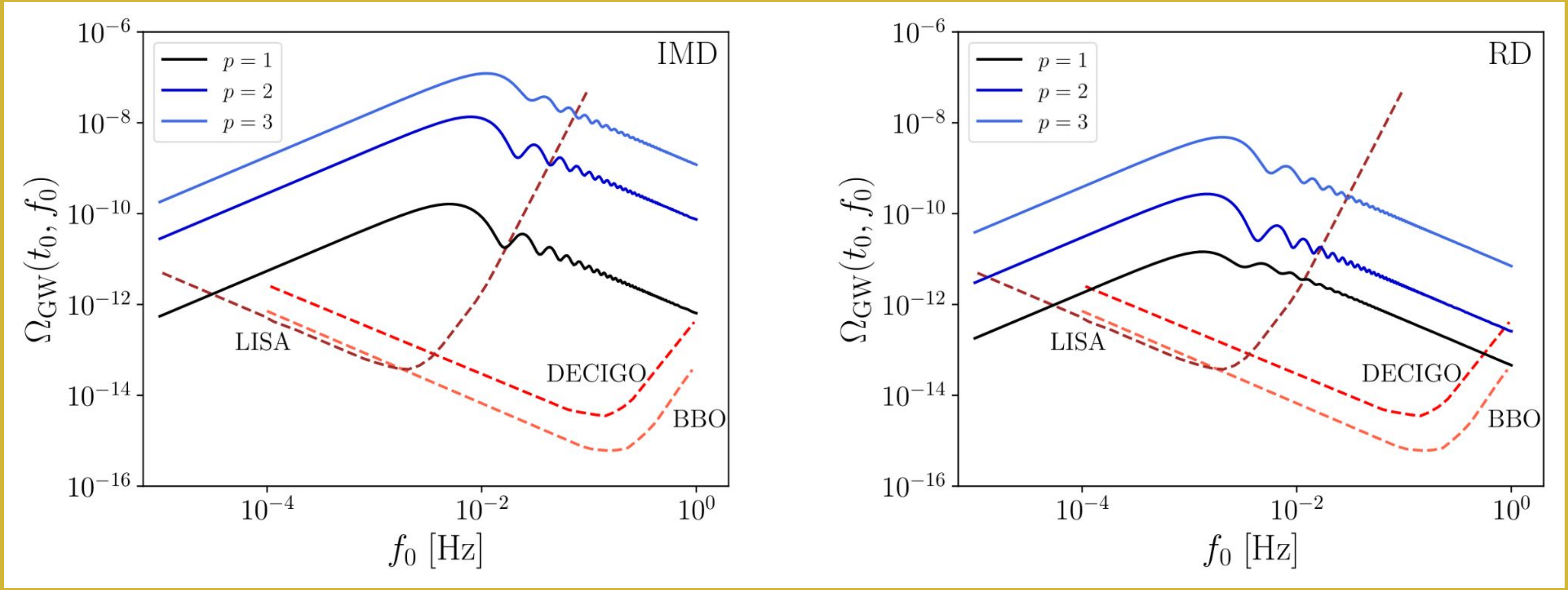
[Flores, Kusenko, PRL 126 (2021) 041101]

Natural explanation for the ratio

(dark matter density) / (ordinary matter density)
for ~1-100 GeV masses



Gravitational waves from early halo formation



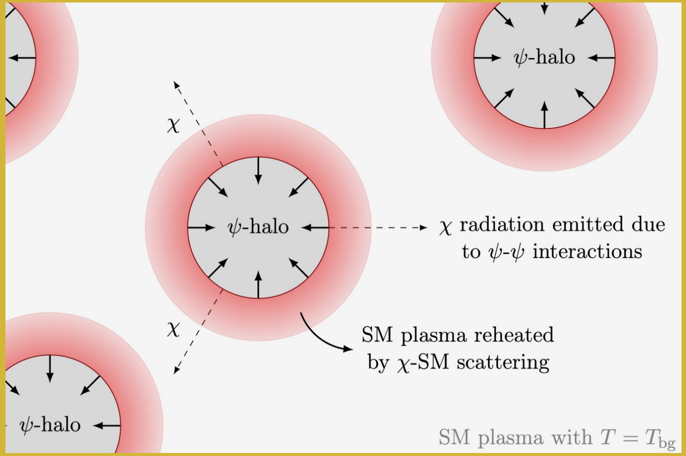
[Flores, Kusenko, Sasaki, Phys. Rev. Lett, 131 (2023) 1]

Possible consequences of early halo formation

Structure formation in RD era!

Many possible consequences

Inhomogeneous heating by collapsing halos



⇒ PBH dark matter [Flores, Kusenko, PRL 126 (2021) 041101]

⇒ Electroweak baryogenesis, even if the phase transition is second order!
[Flores et al., Phys.Rev.D 108 (2023) 9, 9]

⇒ Defrosting and Blast Freezing Dark Matter
[Flores et al., Phys.Rev.D 108 (2023) 10, 10]

⇒ Magnetogenesis
[Durrer, Kusenko, JCAP 11 (2023) 002]

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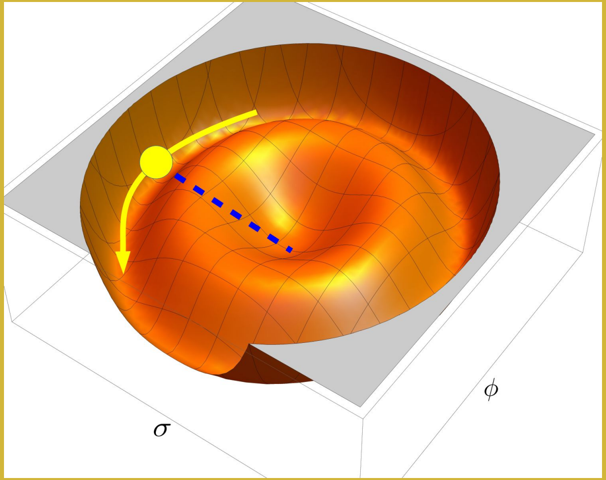
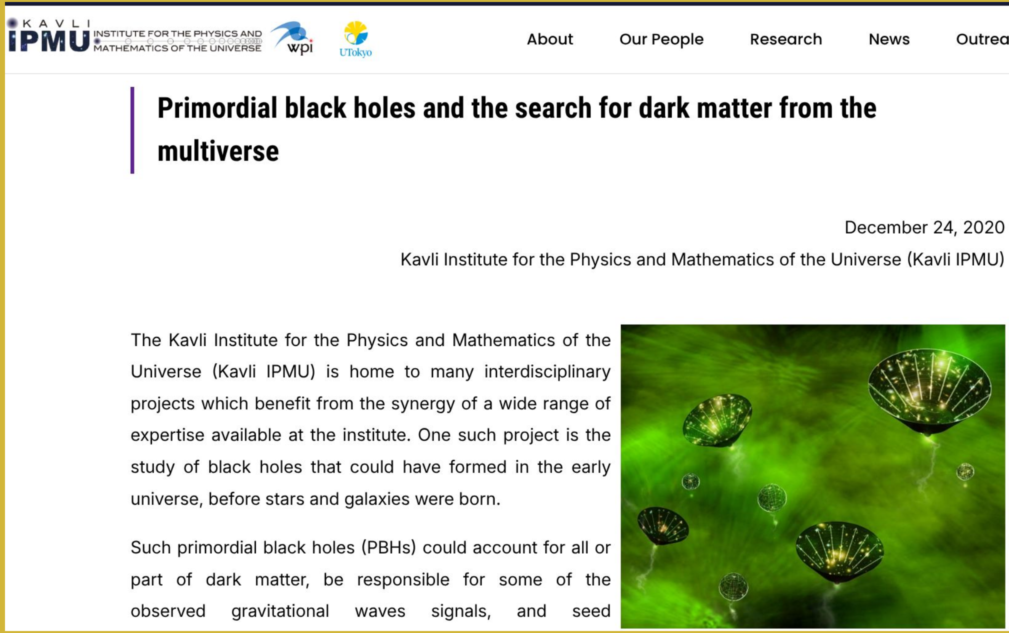
- Yukawa interactions, “long-range” forces, radiative cooling => PBH
- Supersymmetry: Q-balls as building blocks of PBH
- Supersymmetry: Q-balls with long-range scalar forces

- **Multiverse => PBHs**

And yet another mechanism: inflationary multiverse

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Primordial black holes and the search for dark matter from the multiverse

December 24, 2020

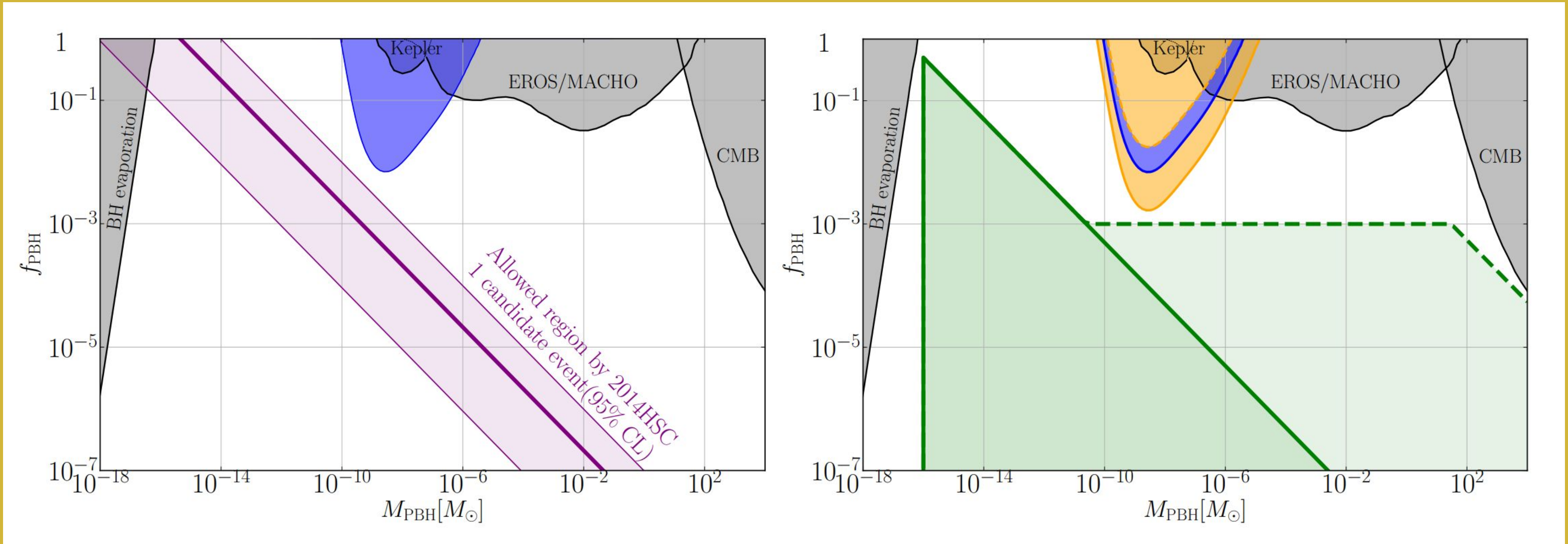
Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU)

The Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU) is home to many interdisciplinary projects which benefit from the synergy of a wide range of expertise available at the institute. One such project is the study of black holes that could have formed in the early universe, before stars and galaxies were born.

Such primordial black holes (PBHs) could account for all or part of dark matter, be responsible for some of the observed gravitational waves signals, and seed

Tunneling events lead to nucleation of baby universes, which appear to outside observer as black holes. [Deng, Vilenkin JCAP 12 (2017) 044; Kusenko, Sasaki, Sugiyama, Takada, Takhistov, Vitagliano, Phys Rev Lett 125 (2020) 181304]

Tail of the mass the function $\propto M^{-1/2}$, accessible to HSC

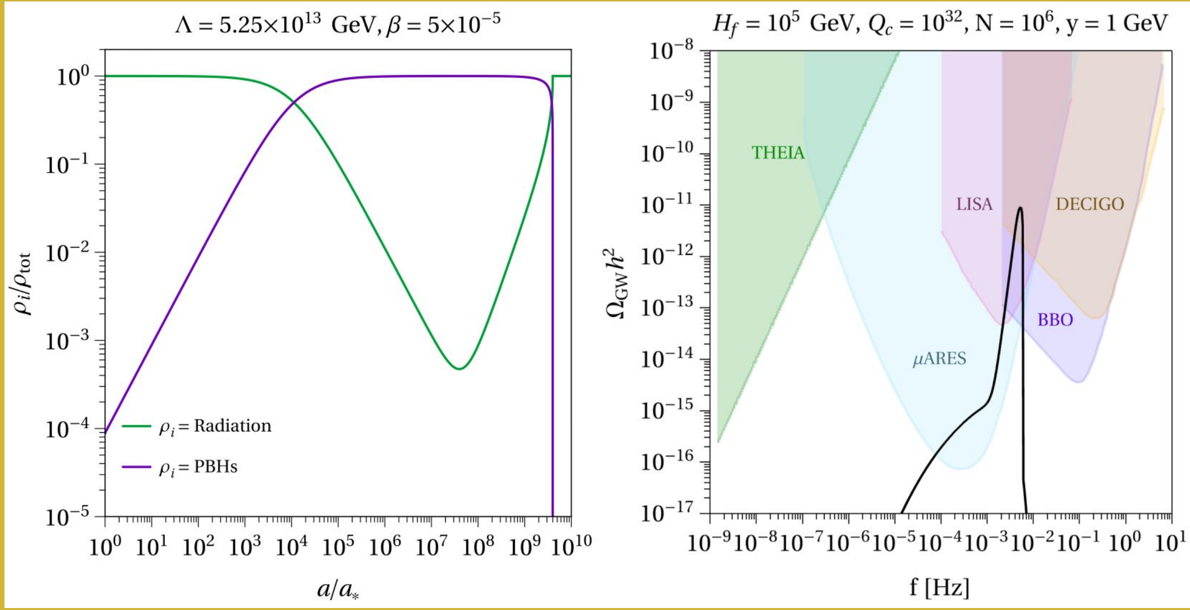


[Kusenko, Sasaki, Sugiyama, Takada, Takhistov, Vitagliano, Phys.Rev.Lett. 125 (2020) 181304]

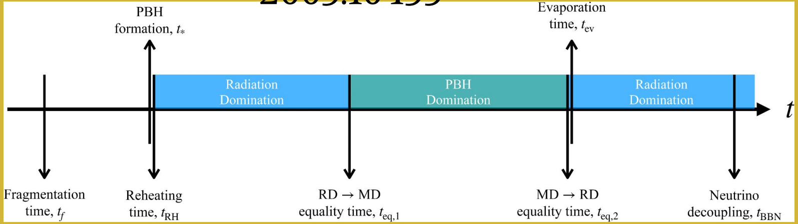
PBH masses, spins, and a *new window on the early universe*

Formation mechanism	Mass range	PBH spin
Inflationary perturbations [review: 2007.10722]	DM, LIGO, supermassive	small
Yukawa “fifth force” [2008.12456]	DM, LIGO, supermassive	small
Long-range forces between SUSY Q-balls [2108.08416]	DM (mass range: 10^{-16}-10^{-6} $M_\odot$)	small
Supersymmetry flat directions, Q-balls [1612.02529, 1706.09003, 1907.10613]	DM (mass range: 10^{-16}-10^{-6} $M_\odot$)	large
Light scalar field Q-balls (not SUSY) [1612.02529, 1706.09003, 1907.10613]	DM, LIGO, supermassive	large
Oscillons [1801.03321]	DM, LIGO, supermassive	large
Multiverse bubbles [1512.01819, 1710.02865, 2001.09160]	DM, LIGO, supermassive	small

Gravitational waves from SUSY flat directions, Q-balls, PBHs



Inomata et al.,1904.12879, 2003.10455



Flores, Kusenko, Pearce,
Perez-Gonzalez, White, 2308.15522

GW detectors can discover small PBH from NS⇨BH process

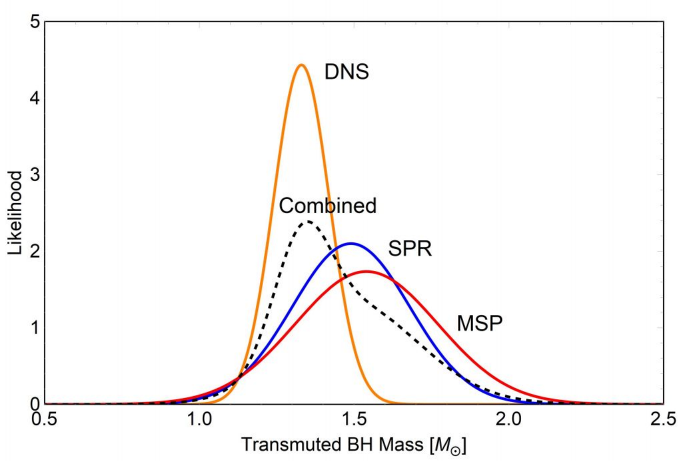
PBH + NS

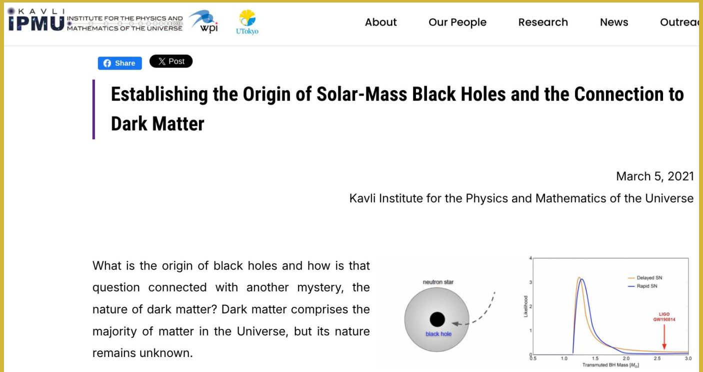
⇓

BH of 1-2 $M_\odot$

KAGRA may detect mergers of
1-2 $M_\odot$ black holes
(not expected from evolution of stars)

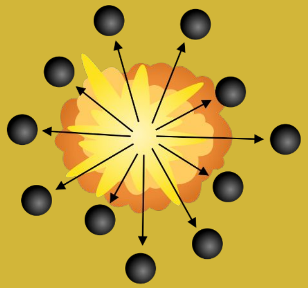
Fuller et al., PRL 119 (2017) 6, 061101 [1704.01129]
Takhistov et al., 1707.05849, 2008.12780



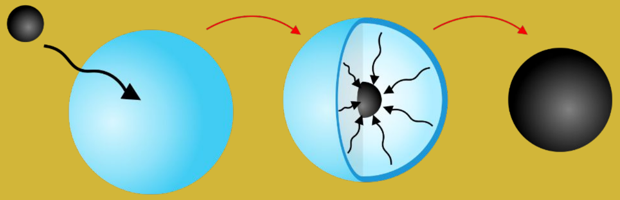


Observed G objects: remnants of NS to BH conversions by PBH?

1. Primordial black holes produced in Big Bang make up part or all of dark matter.



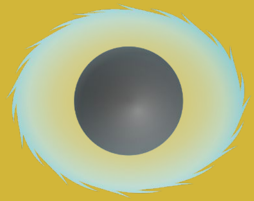
2. A microscopic black hole falls into a neutron star, eats it from the inside, and creates a 1-2 solar mass black hole



Flores, Kusenko, Ghez, Naoz,
Phys.Rev.D 108 (2023) 6, L061301 [2308.08623]

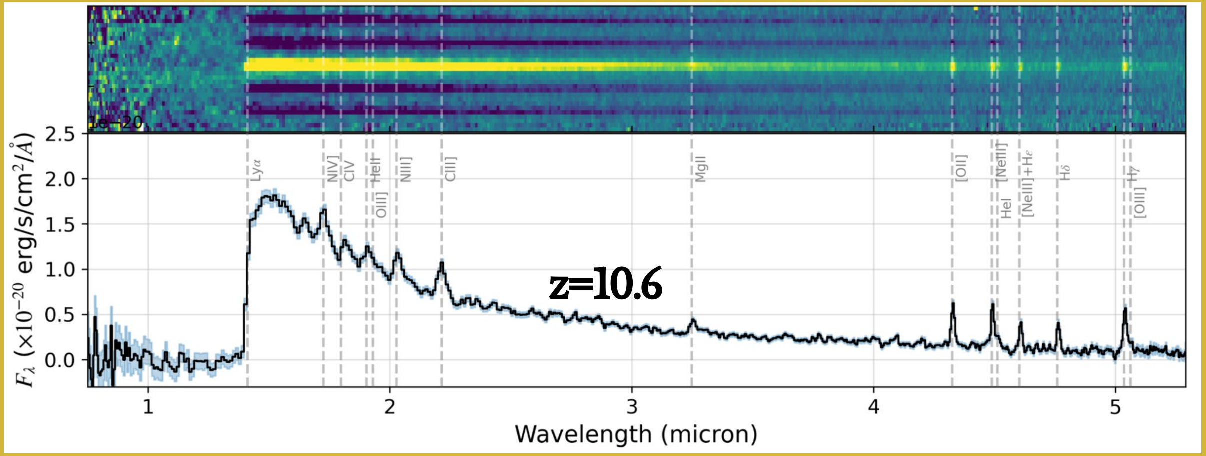
3. A 1-2 solar mass black hole, surrounded by a gaseous atmosphere, is observed in the vicinity of the supermassive black hole at the galactic center as a G-object. The small black hole's gravity holds the gas together and protects the G-object from being torn apart by the gravitational pull of the supermassive black hole.

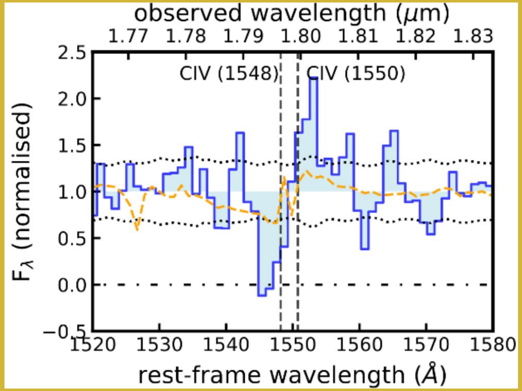
Supermassive black hole



Small black hole surrounded by gas

Supermassive black holes: observed less than 0.5 Gyr since the Big Bang!





Bunker et al., 2302.07256;

- A JWST observation suggests that a galaxy GN-z11 at **z=10.60** has a supermassive black hole – **only 430 Myr after the Big Bang!**
- Other SMBHs: **quasars** exist at very early times, such as J0313–1806 at redshift **z = 7.642**

Too early!

Direct collapse: need to reduce H_2, the cooling agent!

- Photodissociation & photodetachment require a LW radiation, need some additional sources!
  The additional radiation can come from
  - **PBH evaporation**
    Lu, Picker, Kusenko Phys.Rev.D 109 (2024) 12, 123016 [2312.15062]
  - **Dark matter particle decays**
    [Lu, Picker, Kusenko Phys. Rev. Lett. 133 (2024) 9, 091001 2404.03909]
    - Decaying particles can be a small part of dark matter
    - Decaying particles can be 100% dark matter, with a lifetime >> age of the universe

$$\mathrm{H} + e^- \rightarrow \mathrm{H}^- + \gamma,$$
$$\mathrm{H} + \mathrm{H}^- \rightarrow \mathrm{H}_2 + e^-.$$

Conclusion

- Simple, generic formation scenarios in the early universe:
  PBH from scalar forces, PBH from a scalar field fragmentation, PBH from vacuum bubbles...
- PBH with masses 10^{-16} - 10^{-10} $M_{\odot}$, motivated by 1-100 TeV scale **supersymmetry** ,
  can make up 100% (or less) of dark matter. **PBH is a generic dark matter candidate in SUSY**
- PBH from ~ 1-100 GeV scale particles can naturally explain DM abundance
- Microlensing (HSC, others) can detect the tail of DM mass function.
- PBH can contribute to r-process nucleosynthesis
- Signatures of PBH:
  - Kilonova without a GW counterpart, or with a weak/unusual GW signature
    Accompanied by an FRB
  - GW from early halo formation
  - An unexpected population of 1-2 $M_{\odot}$ black holes (GW)
  - Galactic positrons, FRB, etc.

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**?

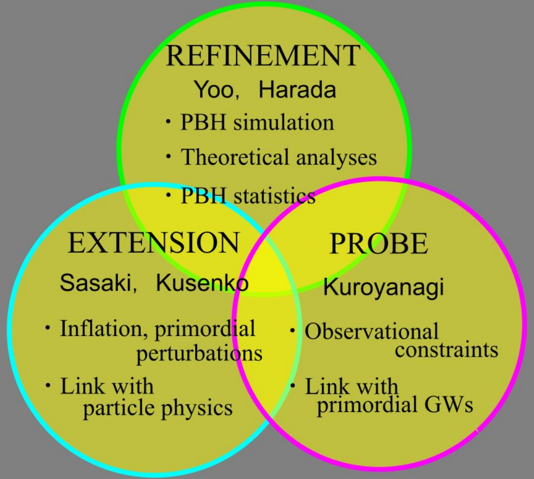
For the prediction, we need

- ➢ 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)

Probe: link with GW

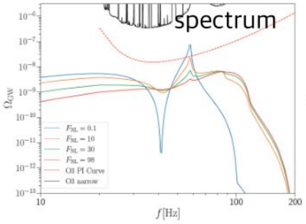
Gravitational wave constraints on PBH

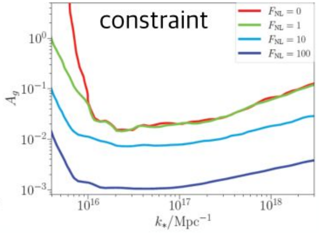
We have explored various ways to constrain PBHs using GWs

① Scalar-induced GWs (associated with PBH formation)

R. Inui, S. Jaraba, **S. Kuroyanagi**, S. Yokoyama, JCAP 05 082 (2024), arXiv:2311.05423

Constraints on scalar induced GW background using the latest LIGO-Virgo-KAGRA O3 data

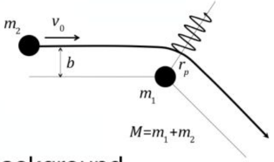




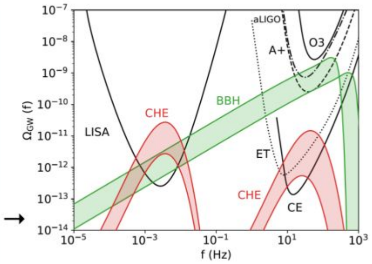
② GW background from PBH close hyperbolic encounters

J. Garcia-Bellido, S. Jaraba, **S. Kuroyanagi,** PDU 36 (2022) 101009, arXiv:2109.11376

GW burst is emitted by a BH encounter



Calculation of the stochastic background formed by ensemble of events assuming PBH clusters →



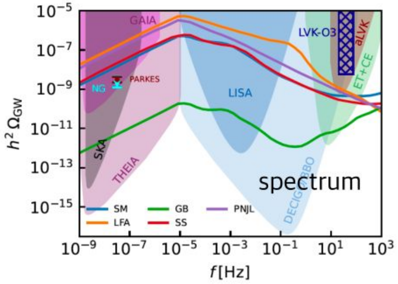
Probe: link with GW

③ GW background from PBH binaries

A. Calculation of GW spectrum for thermal history mass function

M. Braglia, J. Garcia-Bellido, **S. Kuroyanagi**, JCAP 2112 (2021) no. 12, 012, arXiv:2110.07488

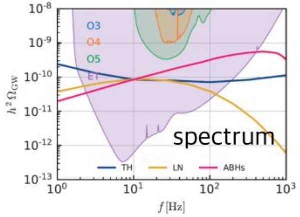
Calculation of the stochastic background formed by ensemble of PBH binaries, specifically assuming the characteristic mass function naturally predicted from a QCD phase transition

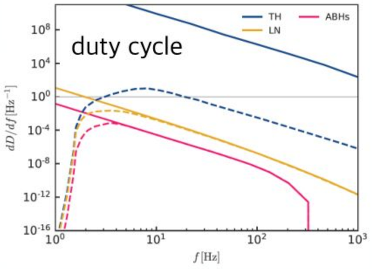


B. Prediction for a non-Gaussian background

M. Braglia, J. Garcia-Bellido, **S. Kuroyanagi**, MNRAS 519 (2023) 4, 6008-6019, arXiv:2201.13414

Predicting the level of non-Gaussianity (duty cycle) for the PBH binary GW background





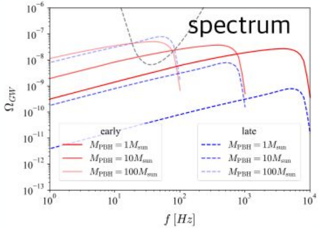
Probe: link with GW

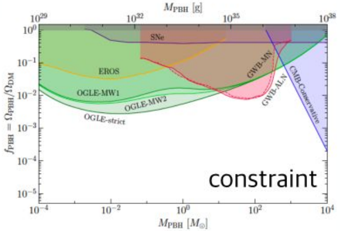
③ GW background from PBH binaries

C. Constraint from LIGO-Virgo-KAGRA O3 data

T. Boybeyi, S. Clesse, **S. Kuroyanagi**, M. Sakellariadou, arXiv:2412.18318

Constraints on the GW background from PBH binaries using the latest LIGO-Virgo-KAGRA O3 data



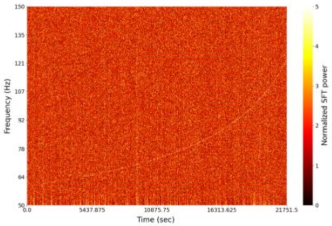


④ Planetary mass PBH binary search in the LVK data

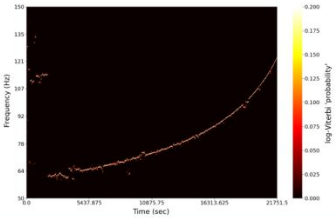
G. Alestas, G. Morras, T. S. Yamamoto, J. Garcia-Bellido, **S. Kuroyanagi**, S. Nesseris,
PRD 109, 12, 123516 (2024), arXiv:2401.02314

Formulating a agnostic detection method to search for planetary mass PBH binaries using Viterbi algorithm

injected



recovered



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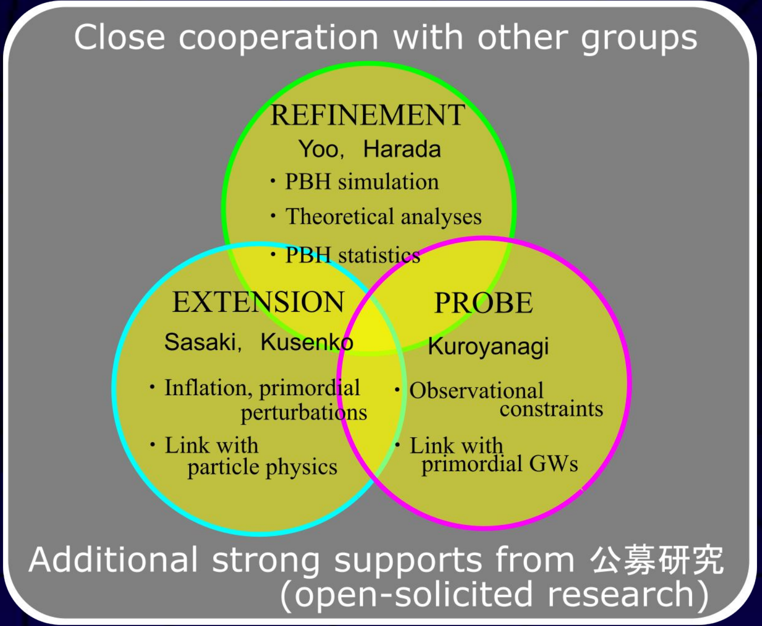


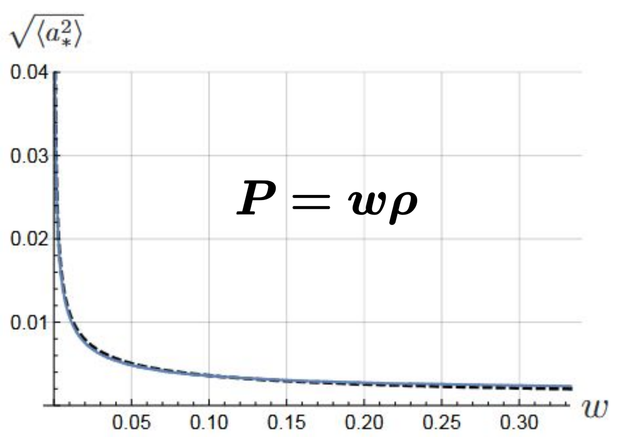
Refinement: PBH spin

- 2011.0010 *Spins of primordial black holes formed in the radiation-dominated phase of the universe: first-order effect*
  Tomohiro Harada, **Chul-Moon Yoo**, Kazunori Kohri, **Yasutaka Koga**, Takeru Monobe
- 2208.00696 *Effective Inspiral Spin Distribution of Primordial Black Hole Binaries*
  Yasutaka Koga, **Tomohiro Harada**, Yuichiro Tada, Shuichiro Yokoyama, **Chul-Moon Yoo**
- 2305.13830 *Spins of primordial black holes formed with a soft equation of state*
  Daiki Saito, **Tomohiro Harada**, **Yasutaka Koga**, **Chul-Moon Yoo**
- 2403.11147 *Primordial black hole formation from a nonspherical density profile with a misaligned deformation tensor*
  Chul-Moon Yoo
- 2409.00435 *Revisiting spins of primordial black holes in a matter-dominated era based on peak theory*
  Daiki Saito, **Tomohiro Harada**, **Yasutaka Koga**, **Chul-Moon Yoo**
- 2409.06494 *Spin of Primordial Black Holes from Broad Power Spectrum: Radiation Dominated Universe*
  Indra Kumar Banerjee, **Tomohiro Harada**

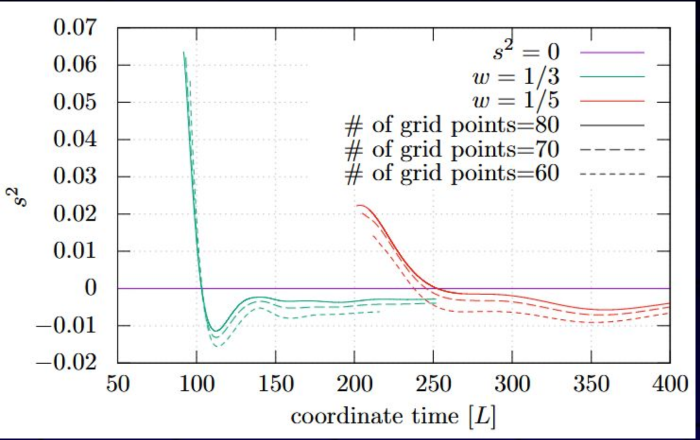
PBH spins are very small for standard formation in radiation domination or QCD crossover but can be large for formation in matter domination.

Refinement: PBH spin

- 2305.13830 *Spins of primordial black holes formed with a soft equation of state*
  Daiki Saito, **Tomohiro Harada**, **Yasutaka Koga**, **Chul-Moon Yoo**



- 2403.11147 *Primordial black hole formation from a nonspherical density profile with a misaligned deformation tensor*
  Chul-Moon Yoo



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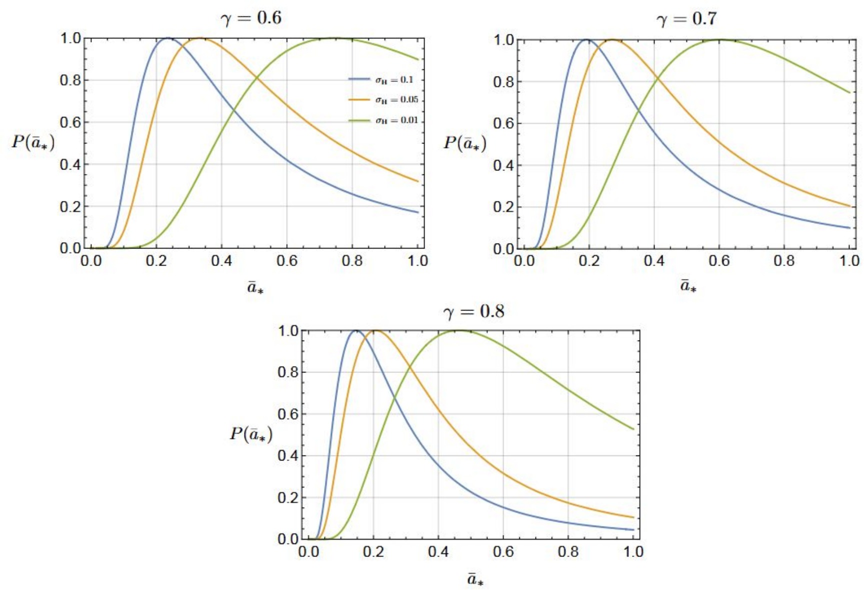
Refinement: PBH spin

➢ 2409.00435 *Revisiting spins of primordial black holes in a matter-dominated era based on peak theory*
Daiki Saito, **Tomohiro Harada**, **Yasutaka Koga**, **Chul-Moon Yoo**

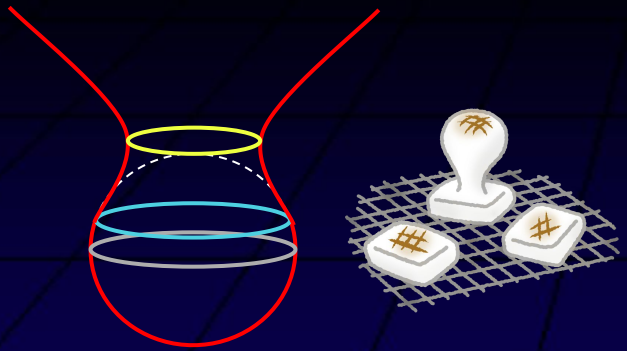


PBH spins can be large for formation in matter domination.

Refinement: Type II PBH formation

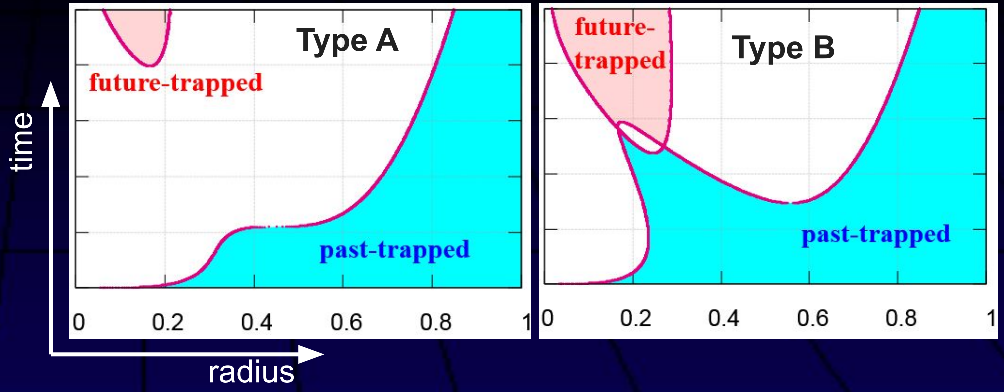
- ➢ 2401.06329 *Numerical simulation of type II primordial black hole formation*
  Koichiro Uehara, Albert Escrivà, **Tomohiro Harada**, Daiki Saito, **Chul-Moon Yoo**
- ➢ 2409.05544 *Geometrical origin for the compaction function for primordial black hole formation*
  Tomohiro Harada, Hayami Iizuka, **Yasutaka Koga**, **Chul-Moon Yoo**
- ➢ 2504.xxxxxx *Primordial black hole formation from a type II perturbation in the absence and presence of pressure*
  Koichiro Uehara, Albert Escrivà, **Tomohiro Harada**, Daiki Saito, **Chul-Moon Yoo**

◎Areal radius becomes non-monotonic in the initial time for a large amplitude of the curvature perturbation: Type II



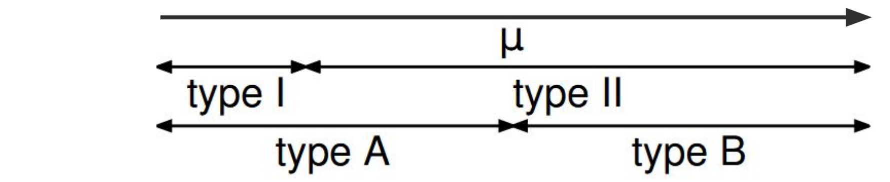
◎Spacetime structure becomes non-trivial for a larger amplitude of the curvature perturbation: Type B

Time evolution of horizon radius

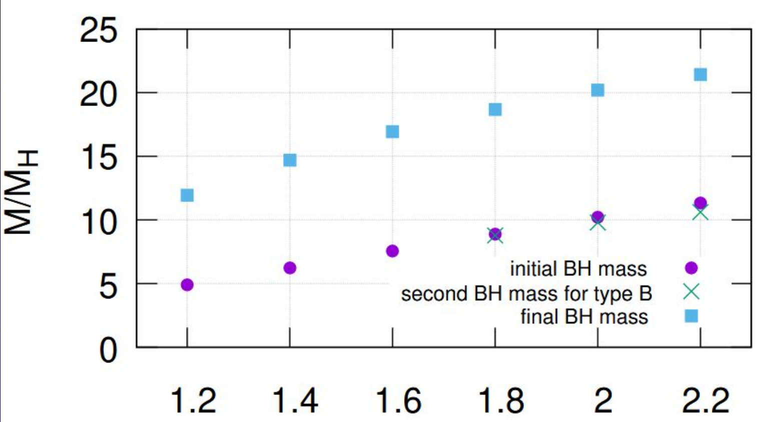


Refinement: Type II PBH formation

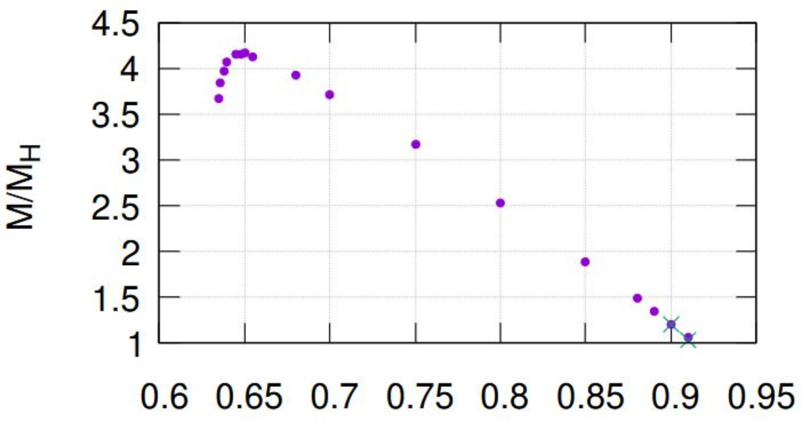
◎Threshold between Type I/II is smaller than that of Type A/B for p>0, while equivalent for p=0



◎For an initial amplitude well above the threshold value, the resulting PBH mass may either increase or decrease with the initial amplitude, depending on its specific profile rather than its fluctuation type



initial amplitude



initial amplitude

Refinement: Investigation through simulation

- 2004.01042 *Threshold of Primordial Black Hole Formation in Nonspherical Collapse*
  Chul-Moon Yoo, **Tomohiro Harada**, Hirotada Okawa

  The first paper of the non-spherical PBH formation with a standard initial setting
- 2112.12335 *Primordial black hole formation from massless scalar isocurvature*
  Chul-Moon Yoo, **Tomohiro Harada**, **Shin'ichi Hirano**, Hirotada Okawa, **Misao Sasaki**

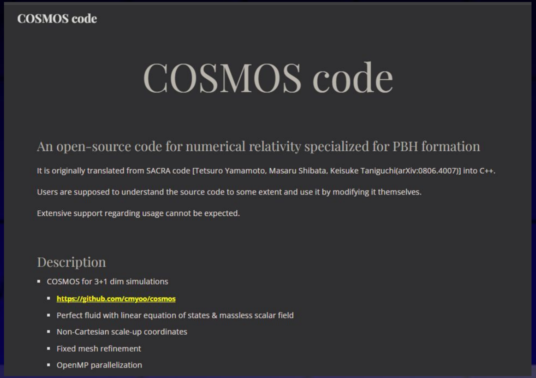
  The first paper (and probably still unique) of the simulation of iso-curvature PBH formation
- 2202.01028 *Simulation of primordial black holes with large negative non-Gaussianity*
  Albert Escrivà, Yuichiro Tada, Shuichiro Yokoyama, **Chul-Moon Yoo**
- 2310.16482 *Primordial Black hole formation from overlapping cosmological fluctuations*
  Albert Escrivà, **Chul-Moon Yoo**
- 2401.06329 *Numerical simulation of type II primordial black hole formation*
  Koichiro Uehara, Albert Escrivà, **Tomohiro Harada**, Daiki Saito, **Chul-Moon Yoo**

  The first paper of the simulation of type II PBH formation
- 2403.11147 *Primordial black hole formation from a nonspherical density profile with a misaligned deformation tensor*
  Chul-Moon Yoo
- 2410.03451 *Non-spherical effects on the mass function of Primordial Black Holes*
  Albert Escrivà, **Chul-Moon Yoo**
- 2410.03452 *Simulations of Ellipsoidal Primordial Black Hole Formation*
  Albert Escrivà, **Chul-Moon Yoo**
- 2411.07648 *Primordial Black Hole Formation from Type II Fluctuations with Primordial Non-Gaussianity*
  Masaaki Shimada, Albert Escrivá, Daiki Saito, Koichiro Uehara, **Chul-Moon Yoo**

COSMOS code

◎What is COSMOS

- Simple tools for the simulation of PBH formation
- C++ packages for the simulation in 3+1 dimensions and spherical symmetry
- Sufficient resolution due to non-Cartesian scale-up coordinates [4] and FMR [5]
- OpenMP parallelization
- No other packages are required and minimal functionality
- Easy use for beginners and various possible extensions



COSMOS code

COSMOS code

An open-source code for numerical relativity specialized for PBH formation

It is originally translated from SACRA code [Tetsuro Yamamoto, Masaru Shibata, Keisuke Taniguchi(arXiv:0806.4007)] into C++.

Users are supposed to understand the source code to some extent and use it by modifying it themselves.

Extensive support regarding usage cannot be expected.

Description

- COSMOS for 3+1 dim simulations
  - https://github.com/cmyoo/cosmos
  - Perfect fluid with linear equation of states & massless scalar field
  - Non-Cartesian scale-up coordinates
  - Fixed mesh refinement
  - OpenMP parallelization

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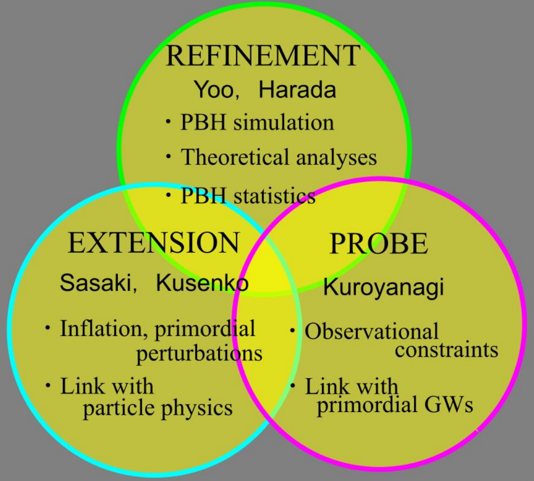
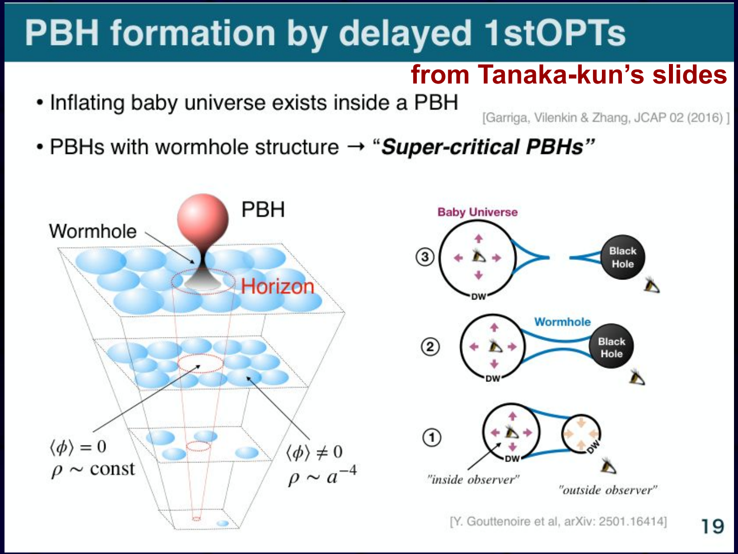
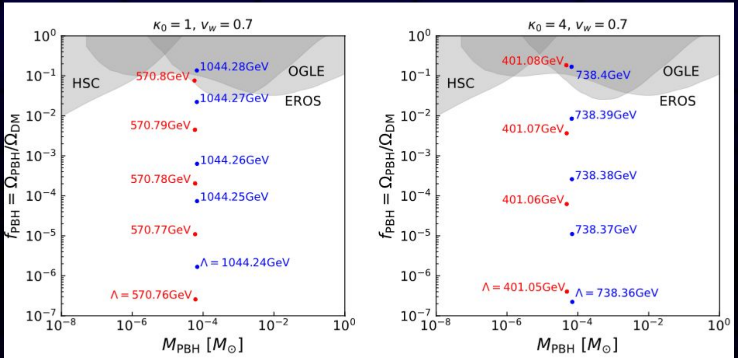


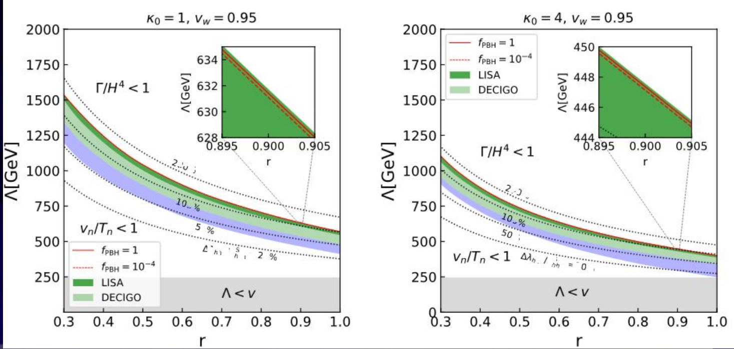
Additional strong supports from 公募研究 (open-solicited research)

Synergy：there is still much to be explored

➢ 2501.11040 *Super-critical primordial black hole formation via delayed first-order electroweak phase transition*
Katsuya Hashino, Shinya Kanemura, Tomo Takahashi, Masanori Tanaka, **Chul-Moon Yoo**







◎Numerically solve bubble wall dynamics assuming sph. sym.
⇒ criterion utilizing characteristic timescales is better

◎Parameters in EWPT can be probed by
PBH abundance and GW background observation

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.

It’s still time to study Primordial Black Hole!

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

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

Thank you for all your supports.
We look forward to working with you
in the future.