A03 group updates

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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A03 Group

A03 group members

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Alexander Kusenko	KIPMU / UCLA
Misao Sasaki	KIPMU
Yasutaka Koga	Nagoya U.
Takafumi Kokubu	KIPMU

Collaborators participating regular meetings

Albert Escrivà	Nagoya U.
Shin-ichi Hirano	TITech
Kazunori Kohri	KEK
Yuichiro Tada	Nagoya U.
Takahiro S. Yamamoto	Nagoya U.
Shuichiro Yokoyama	KMI/Nagoya

Students participating regular meetings

Daiki Saito	Nagoya U.
Koichiro Uehara	Nagoya U.
Hayami Iizuka	Rikkyo U.
Akihito Katsumata	Rikkyo U.
Ryoto Inui	Nagoya U.
Katsuya Abe	Nagoya U.

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**?

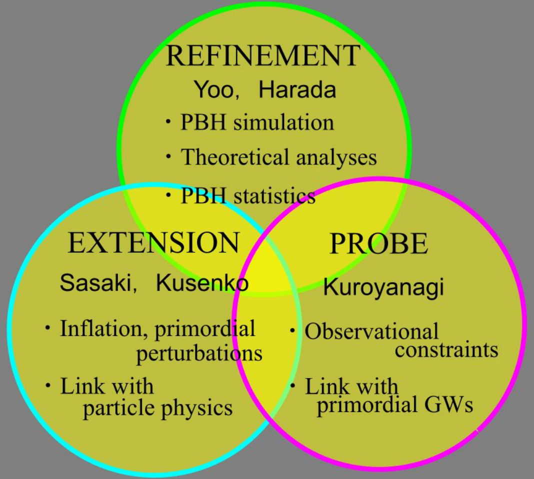
For the prediction, we need

- ➢ 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 2022

- 2205.05966 *Gravitational wave matched filtering by quantum Monte Carlo integration and quantum amplitude amplification*
  Miyamoto, Morrás, Yamamoto, **Kuroyanagi**, Nesseris
- 2206.03667 *Graviton non-gaussianity in α-vacuum*
  Kanno, **Sasaki**
- 2205.08320 *Resolving information loss paradox with Euclidean path integral*
  Chen, **Sasaki**, Yeom, Yoon
- 2203.14519 *Radiative gravastar with Gibbons-Hawking temperature*
  Nakao, Okabayashi, **Harada**
- 2205.12993 *Criteria for energy conditions*
  Maeda, **Harada**
- 2206.10251 *Tunneling between multiple histories as a solution to the information loss paradox*
  Chen, **Sasaki**, Yeom, Yoon
- 2206.10998 *Conformally Schwarzschild cosmological black holes*
  Sato, Maeda, **Harada**
- 2207.11910 *Highly non-Gaussian tails and primordial black holes from single-field inflation*
  Cai, Ma, **Sasaki**, Wang, Zhou
- 2208.00696 *Effective inspiral spin distribution of primordial black hole binaries*
  Koga, **Harada**, Tada, Yokoyama, **Yoo**
- 2208.02941 *Non-Gaussianity effects on the primordial black hole abundance for sharply-peaked primordial spectrum*
  Matsubara, **Sasaki**
- 2208.07504 *Stationary Vacuum Bubble in a Kerr-de Sitter Spacetime*
  Saito, **Yoo**

Activities of A03 in the fiscal year 2022

- 2208.13156 *Deep learning for intermittent gravitational wave signals*
  Yamamoto, **Kuroyanagi**, Liu
- 2209.12610 *Relativistic orbits of S2 star in the presence of scalar field*
  Bambhaniya, Joshi, Dey, Joshi, Mazumdar, **Harada**, Nakao
- 2210.07516 *Periapsis shift of a quasi-circular orbit in a general static spherically symmetric spacetime*
  Harada, Igata, Saida, Takamori
- 2210.17112 *Einstein-Vlasov system with equal-angular momenta in AdS5*
  Asami, **Yoo**, Kitaku, Uemichi
- 2211.13477 *Radiative gravastar with thermal spectrum; Sudden vacuum condensation without gravitational collapse*
  Nakao, Okabayashi, **Harada**
- 2211.13512 *The basics of primordial black hole formation and abundance estimation*
  Yoo
- 2211.13950 *Threshold of Primordial Black Hole Formation against Velocity Dispersion in Matter-Dominated Era*
  Harada, **Kohri**, **Sasaki**, Terada, **Yoo**
- 2209.02272 *Scale-invariant enhancement of gravitational waves during inflation*
  Ota, **Sasaki**, Wang
- 2210.07050 *Super-horizon resonant magnetogenesis during inflation*
  Sasaki, Vardanyan, Yingcharoenrat
- 2211.12766 *One-loop tensor power spectrum from an excited scalar field during inflation*
  Ota, **Sasaki**, Wang
- 2211.13932 *Logarithmic Duality of the Curvature Perturbation*
  Pi, **Sasaki**
- 2205.09777 *Constraints on sterile neutrino models from strong gravitational lensing, Milky Way satellites, and Lyman-α forest*
  lZelko, Treu, Abazajian, Gilman, Benson, Birrer, Nierenberg, **Kusenko**

Activities of A03 in the fiscal year 2022

- 2205.13557 *Generating Non-topological Solitons Via Thermal Corrections: Higgs Balls*
  Pearce, White, **Kusenko**
- 2208.09789 *Inhomogeneous cold electroweak baryogenesis from early structure formation due to Yukawa forces*
  Flores, **Kusenko**, Pearce, White
- 2209.04970 *Gravitational waves from rapid structure formation on microscopic scales before matter-radiation equality*
  Flores, **Kusenko**, **Sasaki**
- 2209.13313 *Magnetogenesis from early structure formation due to Yukawa forces*
  Durrer, **Kusenko**
- 2210.16462 *Late-Forming PBH: Beyond the CMB era*
  Lu, Kawana, **Kusenko**
- 2212.08793 *Strong Lensing of High-Energy Neutrinos*
  Taak, Treu, Inoue, **Kusenko**
- 2302.14419 *Quasi-periodic relativistic shells in reflecting boundaries: How likely are black holes to form?*
  Kokubu

◎Other activities

- Regular meetings (https://sites.google.com/view/pbhmacrodm/)

5th meeting 2022/06/09 online	10 mins short talks by Sasaki-san, Kusenko-san, Koga-san
6th meeting 2022/08/09 in-person	Brainstorming, 12 participants
7th meeting 2022/11/21 in-person	Brainstorming, with C01, about 20 participants

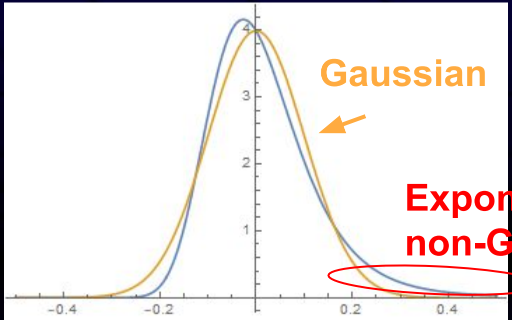
- Workshop: Dynamics of primordial black hole formation (3/9,10)

Inflationary dynamics causing exponential tails

2211.13932 *Logarithmic Duality of the Curvature Perturbation*
Pi, **Sasaki**

Inflationary dynamics causing exponential tails

◎Effect of exponential tail non-Gaussian



There are several models which predict
the exponential tail non-Gaussianity
⇒ the longer tail can cause large **PBH** abundance

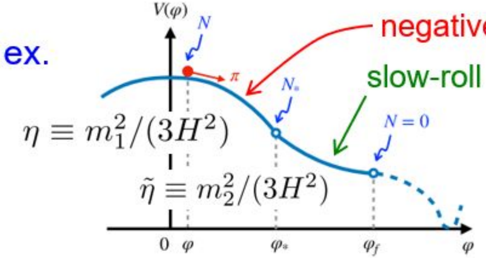
$$\beta = \int_{\Delta_{th}}^{\infty} P(\Delta) d\Delta$$

➢ Logarithmic duality of the curvature perturbation

S. Pi & M. Sasaki, arXiv: 2211.13932

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

ex.



- dual expression

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

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

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

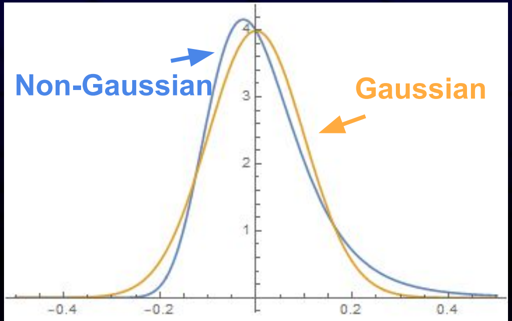
$$P(\mathcal{R}) \sim \exp[-c\,\mathcal{R}]$$

Non-Gaussian effects on PBH abundance

2208.02941 *Non-Gaussianity effects on the primordial black hole abundance for sharply-peaked primordial spectrum*
Matsubara, **Sasaki**

Non-Gaussian effects on PBH abundance

◎Effect of non-Gaussianity



The non-Gaussianity can significantly affect the **PBH** abundance

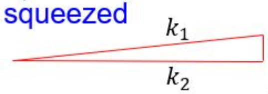
$$\beta = \int_{\Delta_{th}}^{\infty} P(\Delta) d\Delta$$

Non-Gaussian effects on the PBH abundance for sharply-peaked primordial spectrum

T. Matsubara & M. Sasaki, arXiv: 2208.02941

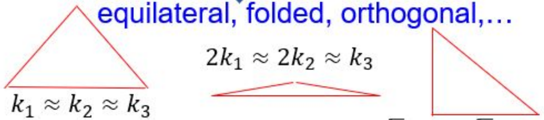
local NG effects have been well studies. How about other types of NG?

squeezed



$k_1 \approx k_2 \gg k_3$

equilateral, folded, orthogonal,…



$k_1 \approx k_2 \approx k_3$ $\quad 2k_1 \approx 2k_2 \approx k_3$ $\quad \sqrt{2}k_1 \approx \sqrt{2}k_2 \approx k_3$

- perturbatively, they can be concisely given by a multiplicative factor

PBH fraction: $\beta \approx \beta^{G} \exp\left[\nu^2 \Delta_c \left(\frac{S_3}{6} + \frac{\Delta_c S_4}{24}\right)\right]$

Gaussian case (β^G); $\nu \equiv \Delta_c/\sigma$ critical density contrast

S_3: skewness $\quad S_4$: kurtosis

$$S_3 \simeq \frac{6}{5}\left(f_{NL}^{loc} - 3f_{NL}^{eql} + 3f_{NL}^{fol} - 9f_{NL}^{ort}\right) S_3^{I}$$

Effective Inspiral Spin Distribution of **P**rimordial **B**lack **H**ole Binaries

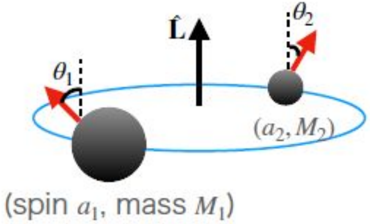
2208.00696 *Effective inspiral spin distribution of primordial black hole binaries*
Koga, **Harada**, Tada, Yokoyama, **Yoo**

Effective spin distribution of PBH binaries

PBH & PBH binary formation from density fluctuation

Key assumptions:

- -Gaussian distribution of the density contrast.
- -Almost monochromatic power spectrum.
- -The peaks higher than the threshold form PBHs in radiation era.
- -Two PBHs are randomly chosen and form a binary.



PBH binary distribution

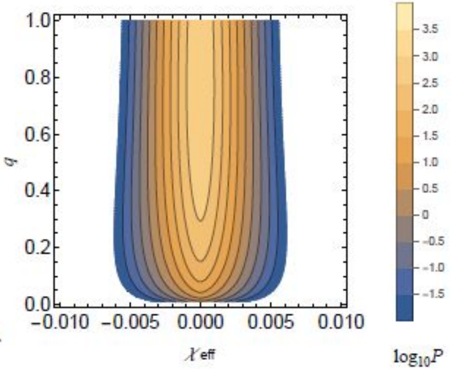
PDF of intrinsic param.: $P(\mathbf{x})d\mathbf{x} = 2\prod_{i=1,2} P(a_i, M_i, \theta_i, \phi_i)da_i dv_i d\theta_i d\phi_i$, $\mathbf{x} = (a_1, M_1, \theta_1, \phi_1, a_2, M_2, \theta_2, \phi_2)$. ← single PBH PDF

Binary parameters:

- -Effective inspiral spin: $\chi_{\rm eff}(a_i, M_i, \theta_i) = \dfrac{M_1 a_1 \cos\theta_1 + M_2 a_2 \cos\theta_2}{M_1 + M_2}$
- -Mass ratio: $q(M_i) = M_2/M_1$

Results of $P(\chi_{\rm eff}, q)$:

- -rms: $\sqrt{\langle \chi_{\rm eff}^2 \rangle} = 8.4 \times 10^{-4}$.
- -No correlation btwn $\chi_{\rm eff}$ & q (contribution of large a_2 is suppressed for $q \ll 1$).
- -Consistent with the O3 data analysis (cf. Callister+ '21).



Threshold of PBH formation against velocity dispersion in MD era

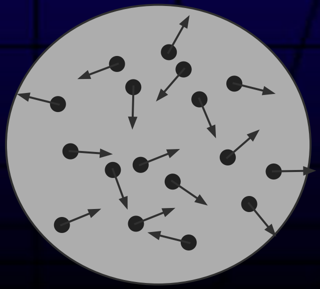
2211.13950 *Threshold of Primordial Black Hole Formation against Velocity Dispersion in Matter-Dominated Era*

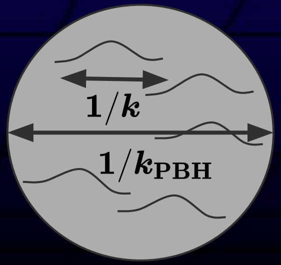
Harada, **Kohri**, **Sasaki**, Terada, **Yoo**

Threshold against velocity dispersion in ME era

◎Relevant process

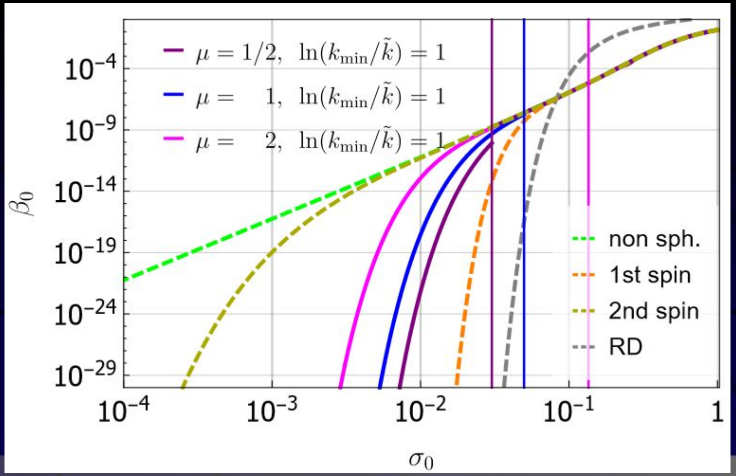
- ➢ No time for virialization of 1/k scale
- ➢ $\boldsymbol{\delta}$ **and** $\boldsymbol{v}$ **(velocity perturbation) grow**
- ➢ become non-linear
- ➢ velocity dispersion released and shared in the PBH scale





◎for Log-normal spectrum →

$$\ln \sigma_{\rm ent}(k) = -\mu (\ln k/k_{\rm PBH})^2 + \ln \sigma_0$$



◎Effect of velocity dispersion

$\delta_{\rm th} \sim \sigma^{2/5}$ with $\sigma = \langle\delta\rangle$

$$\beta \sim \sigma^{3/5} \exp[-\sigma^{-6/5}]$$

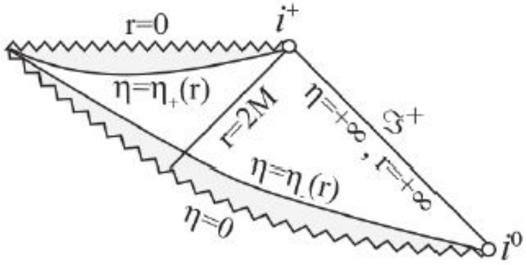
◎It may give a comparable contribution to the spin effect

Cosmological Black Hole Spacetime

2206.10998 *Conformally Schwarzschild cosmological black holes*
Sato, Maeda, **Harada**

Cosmological black hole spacetimes

- T. Sato, H. Maeda and T. Harada, "Conformally Schwarzschild cosmological black holes", CQG 39 (2022) 21, 215011, e-Print:2206.10998 [gr-qc]
  - Quest for an analytic cosmological black hole spacetime
  - We consider a metric tensor $g = a^2(\eta) g_{Sch}$ with some time coordinate η and the scale factor $a(\eta)$.



  - We find η and $a(\eta)$ so that the spacetime can be asymptotically FLRW universe with a regular event horizon but with serious breakdown of all standard energy conditions.

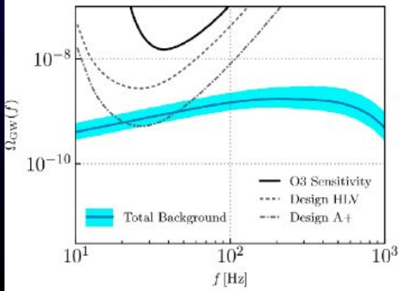
New data analysis method for a popcorn-like stochastic GWBG

2201.13414 *Tracking the origin of black holes with the stochastic gravitational wave background popcorn signal*
Braglia, Garcia-Bellido, **Kuroyanagi**

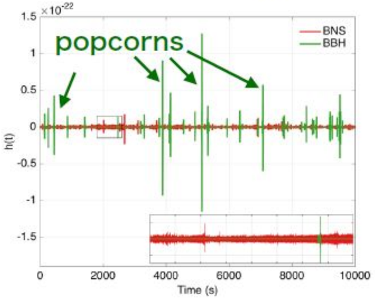
2208.13156 *Deep learning for intermittent gravitational wave signals*
Yamamoto, **Kuroyanagi**, Liu

New data analysis method for popcorn-like GWBG

SGWB spectrum from BBHs



SGWB in time-series

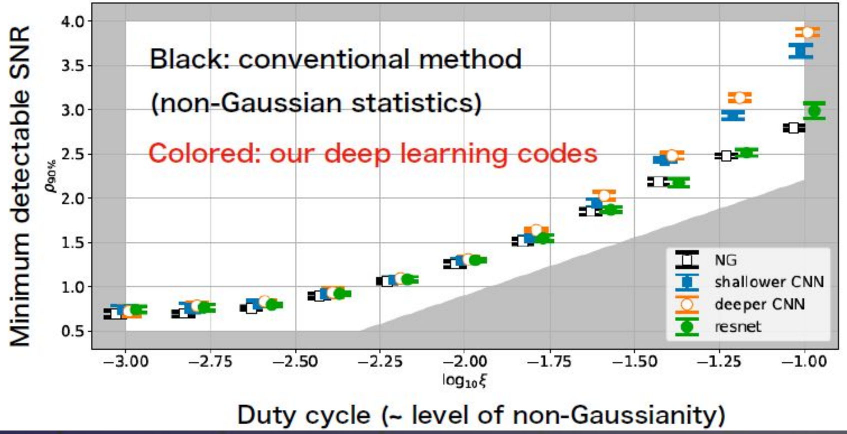


PBH binaries form a stochastic GW background and it could have popcorn feature

Braglia et al. (+SK), MNRAS 519, 4, 6008 (2023), arXiv:2201.13414

We developed **a deep learning code** to detect such background. It shows almost the same performance as the conventional method (and it's faster!)

Yamamoto et al. (+SK), accepted by PRD, arXiv:2208.13156



Simulation of spinning **PBH** formation

Ongoing by **CY**

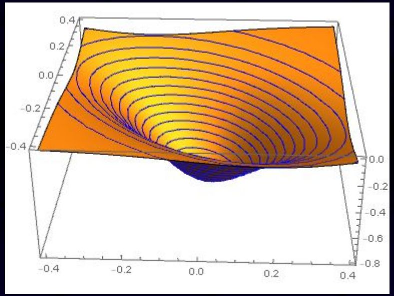
3+1 dimensional simulation of PBH formation

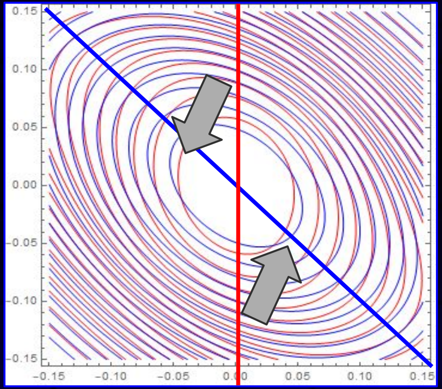
◎Initial curvature perturbation

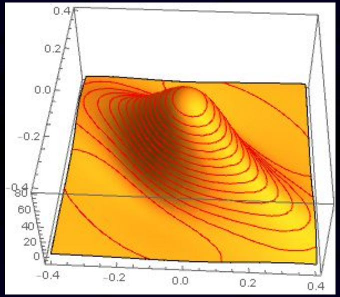
$$ds^2 \simeq -dt^2 + a(t)^2 e^{-2\zeta(x)} d\vec{x} \cdot d\vec{x}$$

ζ∼gravitational potential on (x,y) plane

Δζ∼energy density on (x,y) plane







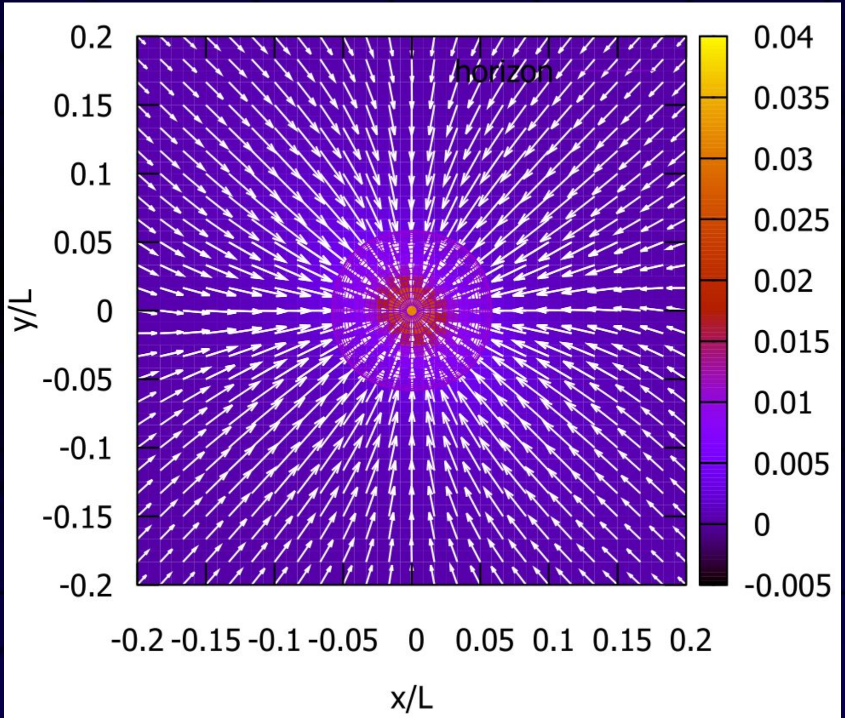
tidal torque ⇒ angular momentum transfer ⇒ spinning **PBH**

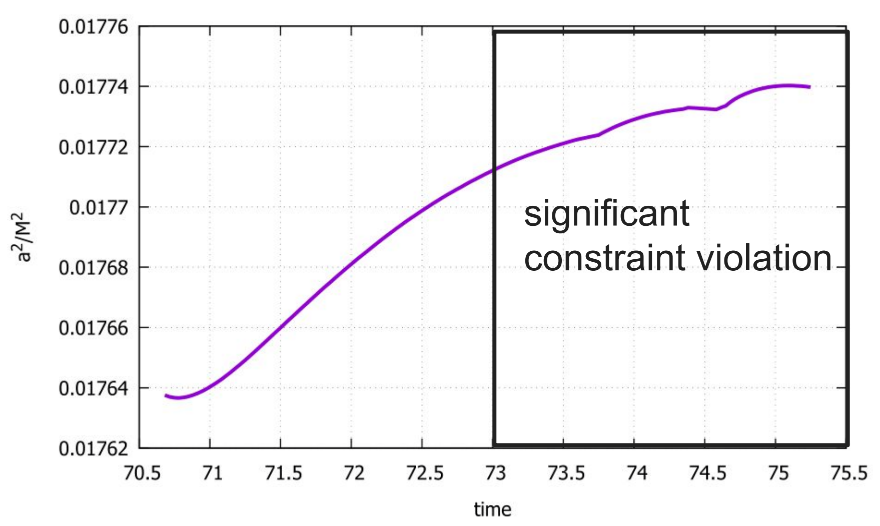
◎3+1 dimensional full GR numerical simulation with BSSN formalism

Spinning PBH formation…?

◎Non-zero spin parameter … ?

$$A_{\rm Kerr} = 8\pi(M^2 + \sqrt{M^4 - a^2 M^2})$$
$$l_{\rm Kerr} = 4\pi M$$
$$\Rightarrow \left(\frac{a^2}{M^2}\right)_{\rm eff} = \frac{4\pi A(l^2 - \pi A)}{l^4}$$





More effort is needed…

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.

End