December 27, 2023 at the CAU HEP
Center Workshop, konjiam Resort

2023 Progress Report on Astrophysics Lab.

Gungwon Kang

Outline

I. Introduction to Astrophysics Lab.

II. Research works in 2023

III. Outlook in 2024

I. Introduction to Astrophysics Lab.

Rm. 203 in Bld. 209

- **Group leader:**
  - Gungwon Kang
- **Members:**
  - Yeong-Bok Bae (Dr. to be joined)

  - Jiyoon Sun (Ms, 2nd)
  - YeongIl Kim (Ms, 1st)

  - Dongchan Kim (Ms, 0th)
  - Hyungwook Son (Ms, 0th)

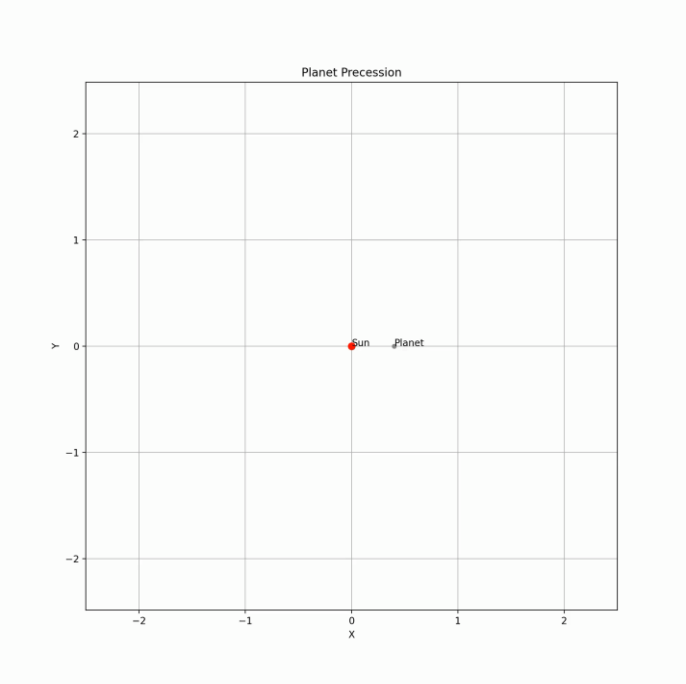
  - Yejun Han (U, 3rd)

- **Topics:**
  - Numerical relativity
  - Gravitational wave physics
  - Quantum gravity
  - Etc.
- **Grant:**
  - 보호연구(PI, ~1.3억/년)
  - 중견연구(공동연구원, ~1.x억/년)

II. Research works in 2023

- **Jiyoon Sun**
  - GW data analysis: cWB+GMM
- **Dongchan Kim**
  - Numerical relativity: BH simulation
- **Kim Hyungwook Son**
  - General relativity: Light bending

- **YeongIl Kim:** Numerical studies on geodesic motions



Schwarzchild Metric

$$ds^2 = -\left(1-\frac{2M}{r}\right)dt^2 + \left(1-\frac{2M}{r}\right)^{-1}dr^2 + r^2(d\theta^2 + \sin^2\theta\, d\varphi^2)$$

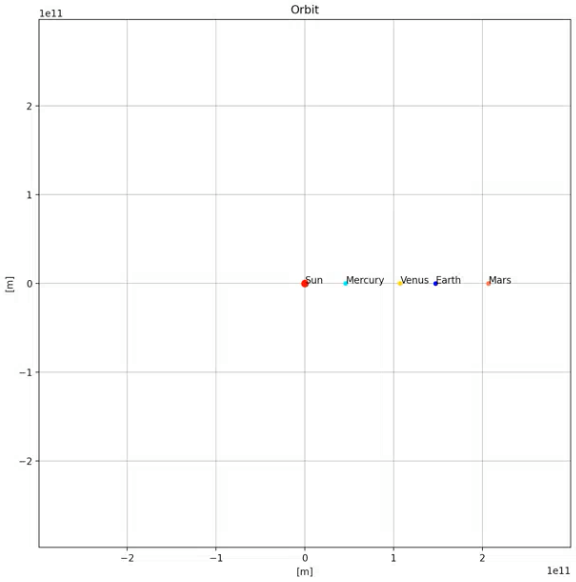
Newtonian Gravity

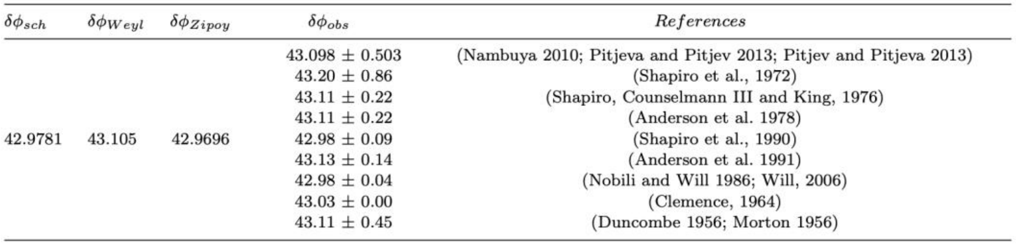
$$V_{eff} = -\frac{M}{r} + \frac{L^2}{2r^2}$$

G.R. effect

General Relativity

$$V_{eff} = -\frac{M}{r} + \frac{\tilde{L}^2}{2r^2} \boxed{-\frac{M\tilde{L}^2}{r^3}}$$





$\delta\phi_{sch}$	$\delta\phi_{Weyl}$	$\delta\phi_{Zipoy}$	$\delta\phi_{obs}$	*References*
42.9781	43.105	42.9696	43.098 ± 0.503	(Nambuya 2010; Pitjeva and Pitjev 2013; Pitjev and Pitjeva 2013)
			43.20 ± 0.86	(Shapiro et al., 1972)
			43.11 ± 0.22	(Shapiro, Counselmann III and King, 1976)
			43.11 ± 0.22	(Anderson et al. 1978)
			42.98 ± 0.09	(Shapiro et al., 1990)
			43.13 ± 0.14	(Anderson et al. 1991)
			42.98 ± 0.04	(Nobili and Will 1986; Will, 2006)
			43.03 ± 0.00	(Clemence, 1964)
			43.11 ± 0.45	(Duncombe 1956; Morton 1956)

Effective Apsidal Precession in Oblate Coordinates 2018 Abraao J. S. Capistrano

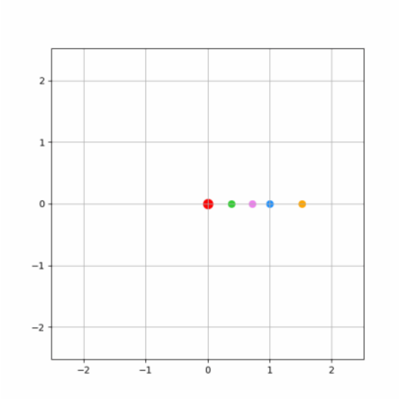
Precession ["/century]	Observed ["/century]	Analytic Sol ["/century]	RK4 Sol ["/century]	Error [Analytic & RK4]
Mercury	42.9799	42.9900	43.0025	0.0291 %
Venus	8.6247	8.6265	8.6983	0.8323 %
Earth	3.8387	3.8395	3.8222	0.4506 %
Mars	1.3624	1.3512	1.3549	0.2738 %

- **Yejoon Han:** Numerical construction for orbital motions in the solar system

2-Body Simulation

$$\mu = \frac{m_1 m_2}{m_1 + m_2} \qquad M = m_1 + m_2$$

$$\vec{F} = \frac{M\mu}{r^2}\hat{r} = \mu\vec{a} \quad \rightarrow \quad \vec{a} = \frac{\vec{F}}{\mu}$$



Runge-Kutta 4th order :

$$\frac{dx}{dt} = f(t,x), \qquad x(t_0) = x_0, \qquad x_{n+1} = x_n + \frac{h}{6}(k_1 + 2k_2 + 2k_3 + k_4), \qquad \mathrm{t}_{\mathrm{n}+1} = \mathrm{t}_\mathrm{n} + \mathrm{h}$$

$$where \quad k_1 = f(t_n, y_n)$$

$$k_2 = f(t_n + \frac{h}{2}, y_n + \frac{k_1}{2}h)$$

$$k_3 = f(t_n + \frac{h}{2}, y_n + \frac{k_2}{2}h)$$

$$k_4 = f(t_n + h, y_n + hk_3)$$

$h : time\ step = 0.001$

$f : velocity, \quad x : (x,y)$

$$\frac{d^2x}{dt^2} = f'(t,x), \qquad v(t_0) = v_0, \qquad v_{n+1} = v_n + \frac{h}{6}(k_1{}' + 2k_2{}' + 2k_3{}' + k_4{}'), \qquad \mathrm{t}_{\mathrm{n}+1} = \mathrm{t}_\mathrm{n} + \mathrm{h}$$

$$where \quad k_1{}' = f'(t_n, x_n)$$

$$k_2{}' = f'(t_n + \frac{h}{2}, x_n + \frac{k_1}{2}h)$$

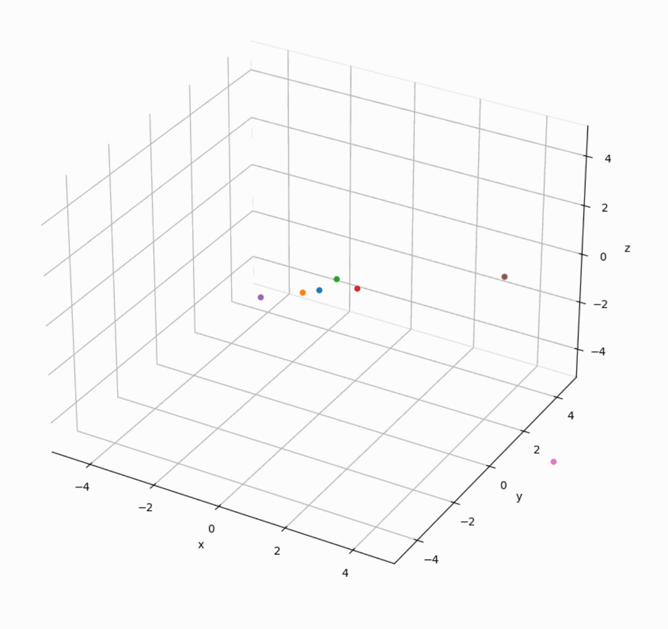
$$k_3{}' = f'(t_n + \frac{h}{2}, x_n + \frac{k_2}{2}h)$$

$$k_4{}' = f'(t_n + h, x_n + hk_3)$$

$h : time\ step = 0.001$

$f\,' : acceleration, \quad x : (x,y)$

N-Body Simulation in 3-Dimensional Space

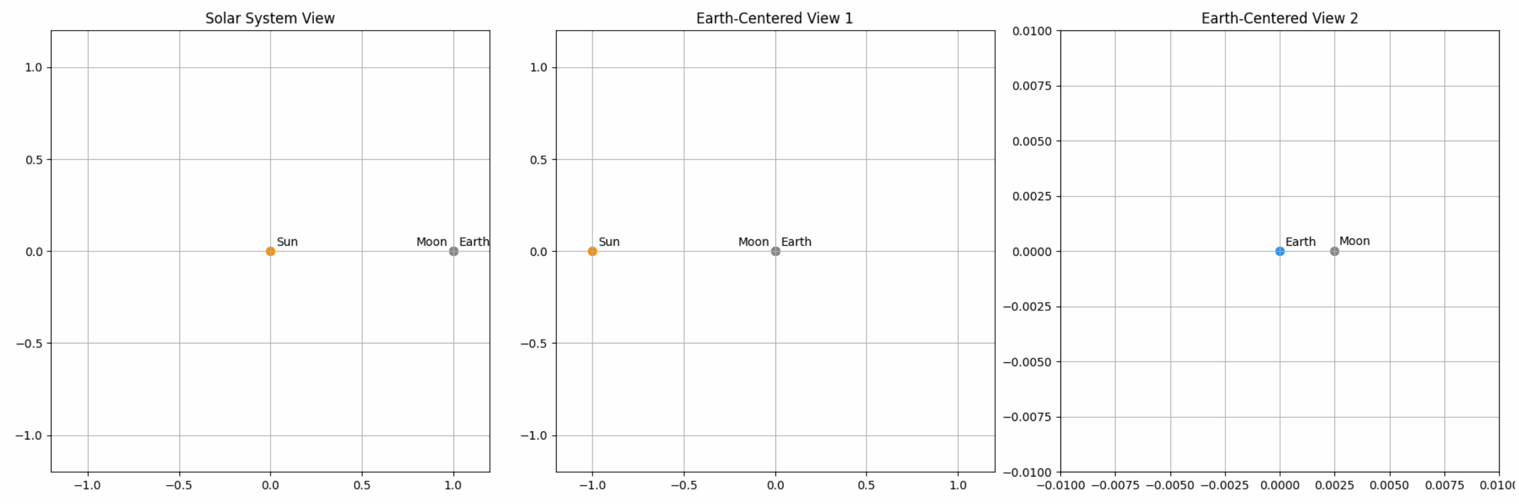


$$(x, y) \quad \rightarrow \quad (x, y, z)$$

$$\overrightarrow{a_i} = \frac{1}{m_i} \sum_{k \neq i} \overrightarrow{F_k}$$

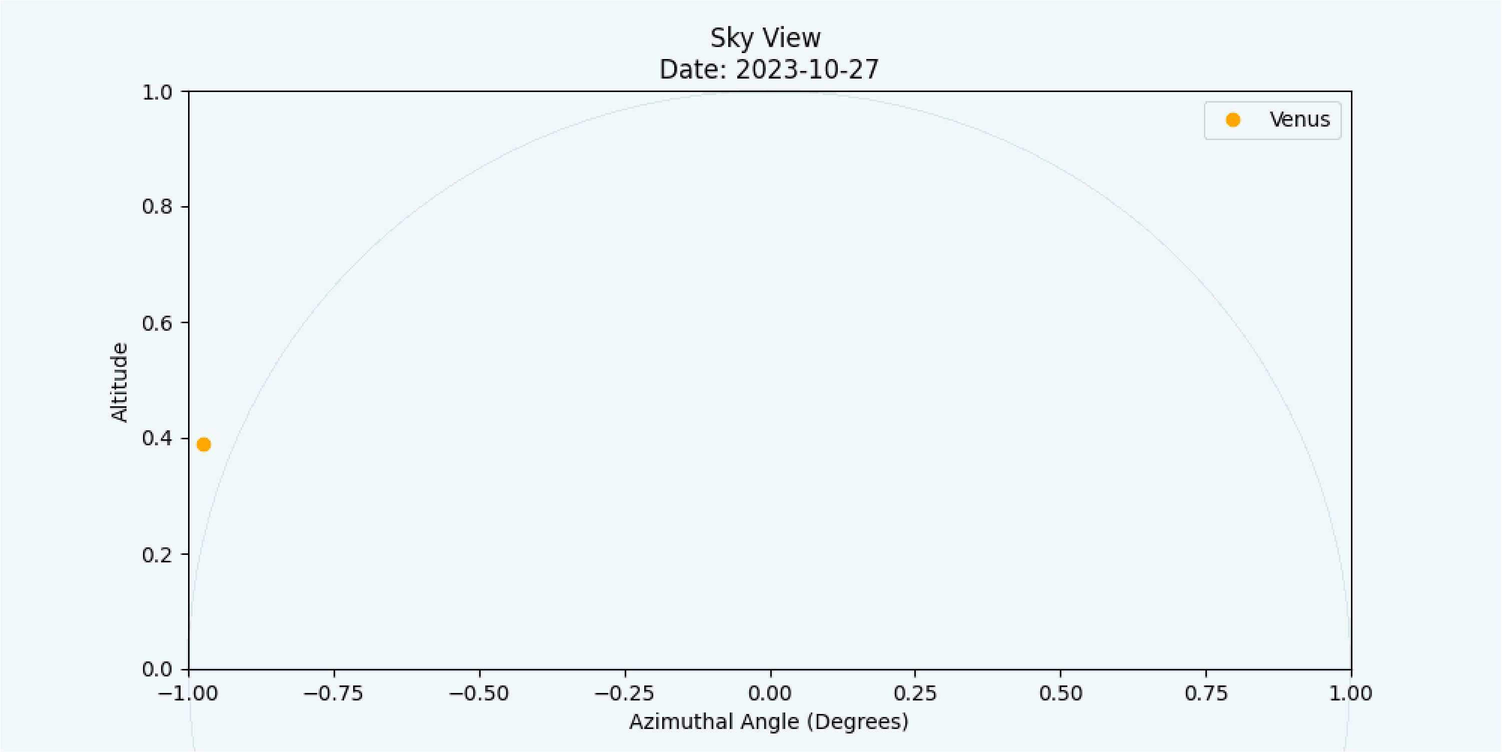
Github link : https://github.com/Cat-yejun/numerical_simulation_on_Solar_System.git

N-Body Simulation in 3-Dimensional Space



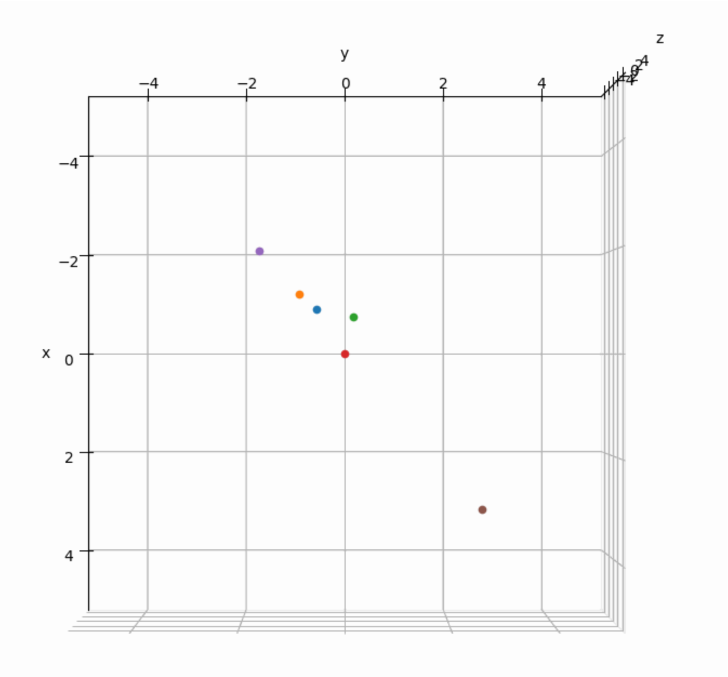
Sun, Earth, Moon Simulation

N-Body Simulation in 3-Dimensional Space



Apparent Retrograde Motion(겉보기 역행 운동) Simulation

N-Body Simulation in 3-Dimensional Space

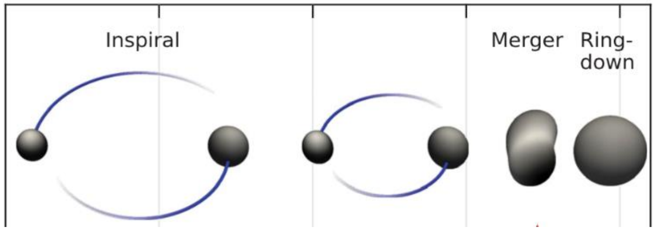


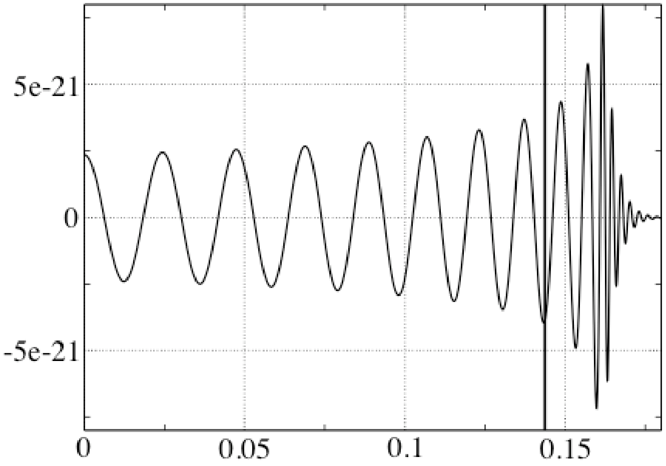
Geocentric Motion (Red : Earth, Blue : Sun)

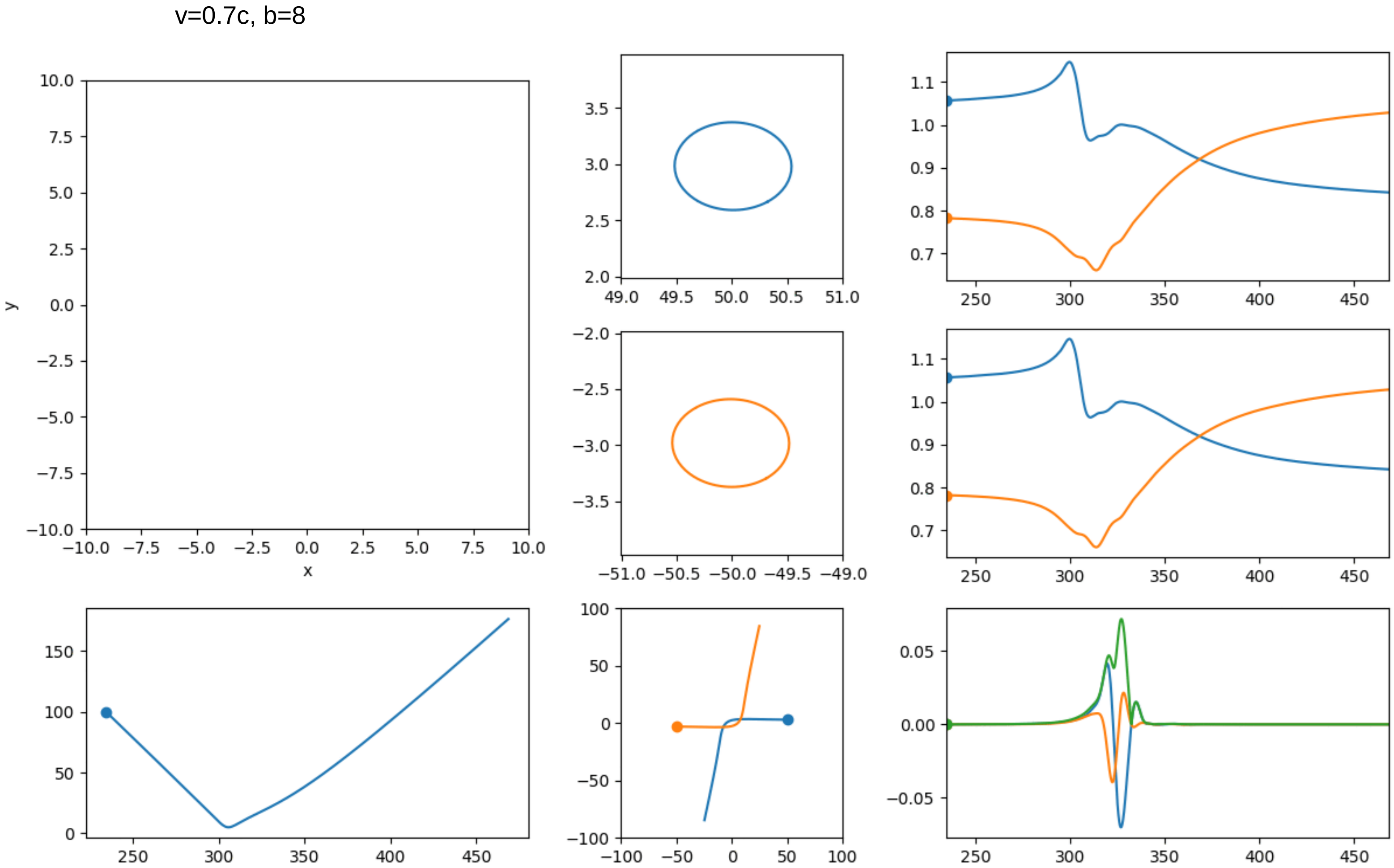
• Main works

- **Waveform modeling:**
  - Arbitrary eccentricity
  - 3PM EOB Hamiltonian
- **Black hole encounters:**
  - BH captures: Formation of BBHs
  - Hyperbolic encounters: Scattering angles
  - Close encounters
- **SOGRO**
- **Others**

- ✓ Ringdown radiation has been known well in binary black hole mergers:



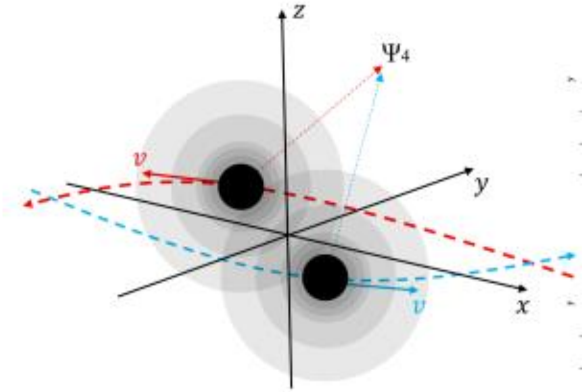


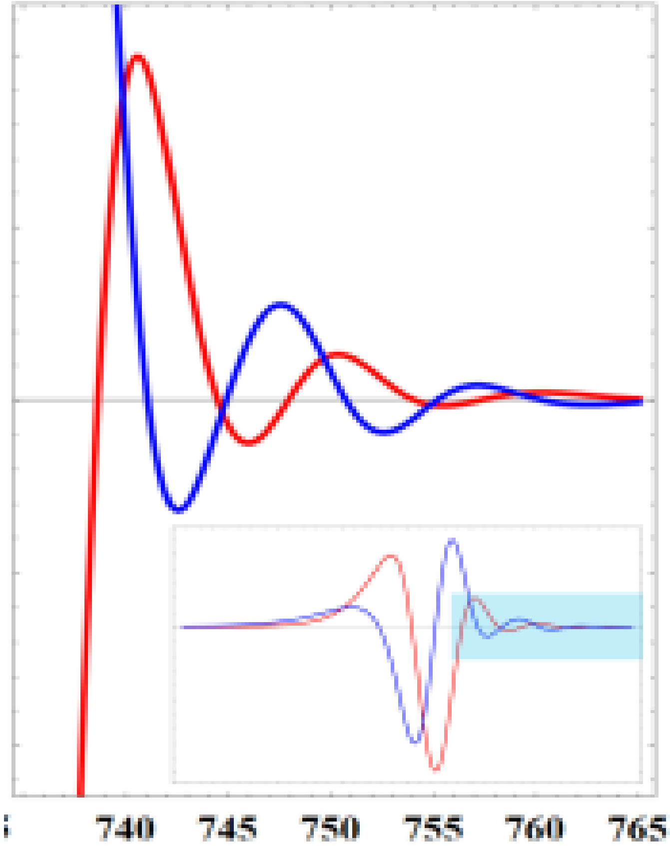

v=0.7c, b=8
10.0
7.5
5.0
2.5
0.0
−2.5
−5.0
−7.5
−10.0
y
−10.0
−7.5
−5.0
−2.5
0.0
2.5
5.0
7.5
10.0
x
3.5
3.0
2.5
2.0
49.0
49.5
50.0
50.5
51.0
1.1
1.0
0.9
0.8
0.7
250
300
350
400
450
−2.0
−2.5
−3.0
−3.5
−51.0
−50.5
−50.0
−49.5
−49.0
1.1
1.0
0.9
0.8
0.7
250
300
350
400
450
150
100
50
0
250
300
350
400
450
100
50
0
−50
−100
−100
−50
0
50
100
0.05
0.00
−0.05
250
300
350
400
450

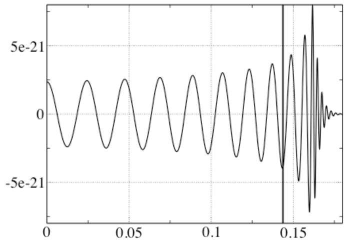
✓ Tidal-driven ringdown GWs and Quasi-normal modes:

$$\Psi_4(t,r,\theta,\varphi) \approx \sum_{l=2}^{8} \sum_{m=-l}^{l} \Psi_4^{lm}(t,r)\,{}_{-2}Y_{lm}(\theta,\varphi)$$

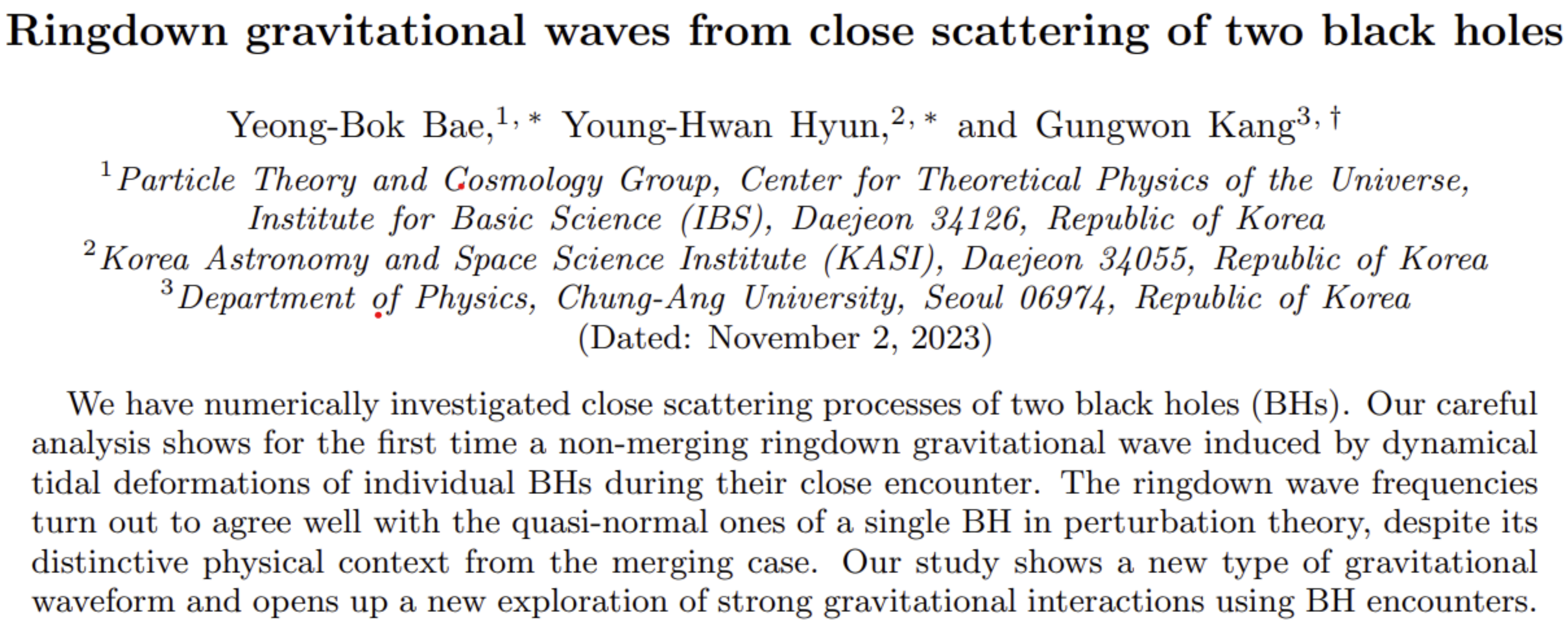
$$\Psi_4^{NP} = \Psi_4(t, r_{ext}, \theta = 0)$$







"Ringdown wave" without merger!!



Ringdown gravitational waves from close scattering of two black holes

Yeong-Bok Bae,[1,*] Young-Hwan Hyun,[2,*] and Gungwon Kang[3,†]

[1] *Particle Theory and Cosmology Group, Center for Theoretical Physics of the Universe,*
Institute for Basic Science (IBS), Daejeon 34126, Republic of Korea
[2] *Korea Astronomy and Space Science Institute (KASI), Daejeon 34055, Republic of Korea*
[3] *Department of Physics, Chung-Ang University, Seoul 06974, Republic of Korea*

(Dated: November 2, 2023)

We have numerically investigated close scattering processes of two black holes (BHs). Our careful analysis shows for the first time a non-merging ringdown gravitational wave induced by dynamical tidal deformations of individual BHs during their close encounter. The ringdown wave frequencies turn out to agree well with the quasi-normal ones of a single BH in perturbation theory, despite its distinctive physical context from the merging case. Our study shows a new type of gravitational waveform and opens up a new exploration of strong gravitational interactions using BH encounters.

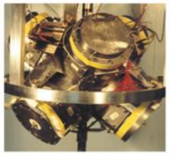
arXiv: 2310.18686 **In review at PRL**

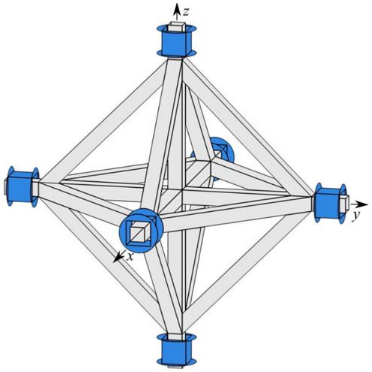
$$\widetilde{\Psi}_4 = \sum_i A_i e^{-\omega_{\mathrm{I}}^{(i)}(t-\Delta t_i)} \cos(\omega_{\mathrm{R}}^{(i)}(t-\Delta t_i)) + \frac{B}{(t-\Delta t_{\mathrm{T}})^p} + C\,,$$

RD Frequencies		$\boldsymbol{M\omega_{\mathrm{R}}^{(l=2)}}$	$\boldsymbol{M\omega_{\mathrm{I}}^{(l=2)}}$	$\boldsymbol{M\omega_{\mathrm{R}}^{(l=3)}}$	$\boldsymbol{M\omega_{\mathrm{I}}^{(l=3)}}$
Perturbation Theory		0.3737	0.0890	0.5994	0.0927
NR $(b=8)$	*single-mode*	0.3915(91) (+4.8 %)	0.0906(45) (+1.8 %)	–	–
	double-mode	0.3798(11) (+1.6 %)	0.0894(4) (+0.5 %)	0.5965(234) (−0.5 %)	0.0617(234) (−33.4 %)
NR $(b=10)$	*single-mode*	0.3738(14) (+0.0 %)	0.0737(68) (−17.2 %)	–	–
	double-mode	0.3741(25) (+0.1 %)	0.0826(31) (−7.2 %)	0.6498(541) (+8.4 %)	0.0549(778) (−40.7 %)

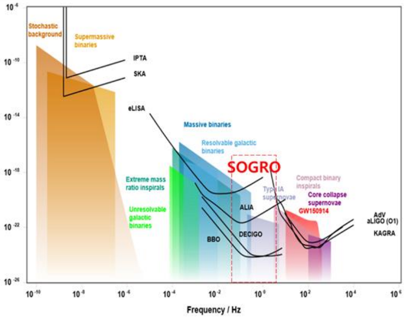
✓ SOGRO:

- **SOGRO:** **Superconducting Omni-directional Gravitational Radiation Observatory**
- 초전도 상태에 있는 테스트 질량의 미세한 움직임을 스퀴드 양자센서를 이용해 측정하여 중력파를 검출
- $(0.1\sim10)Hz$ 사이의 주파수를 갖는 중력파 관측
- 중력파의 모든 성분을 측정할 수 있는 텐서 검출기

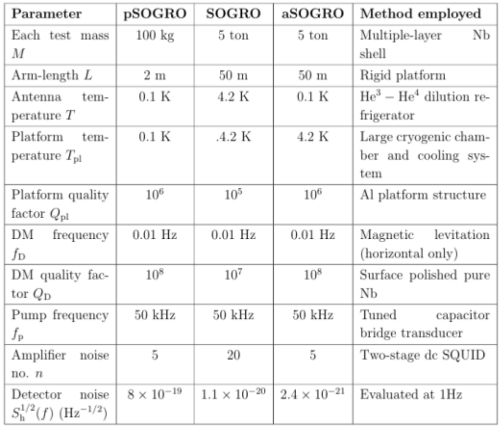




중력파 스펙트럼: 파원과 검출기

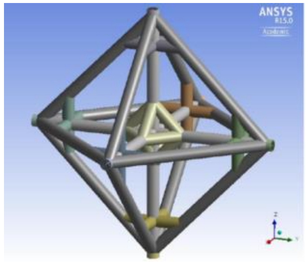


Based on http://rhcole.com/apps/GWplotter/
by Moore, Cole & Berry

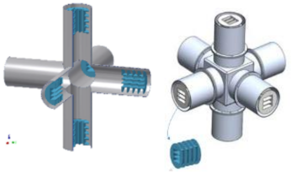


Parameter	pSOGRO	SOGRO	aSOGRO	Method employed
Each test mass M	100 kg	5 ton	5 ton	Multiple-layer Nb shell
Arm-length L	2 m	50 m	50 m	Rigid platform
Antenna temperature T	0.1 K	4.2 K	0.1 K	$He^3 - He^4$ dilution refrigerator
Platform temperature T_{pl}	0.1 K	.4.2 K	4.2 K	Large cryogenic chamber and cooling system
Platform quality factor Q_{pl}	10^6	10^5	10^6	Al platform structure
DM frequency f_D	0.01 Hz	0.01 Hz	0.01 Hz	Magnetic levitation (horizontal only)
DM quality factor Q_D	10^8	10^7	10^8	Surface polished pure Nb
Pump frequency f_p	50 kHz	50 kHz	50 kHz	Tuned capacitor bridge transducer
Amplifier noise no. n	5	20	5	Two-stage dc SQUID
Detector noise $S_h^{1/2}(f)$ ($Hz^{-1/2}$)	8×10^{-19}	1.1×10^{-20}	2.4×10^{-21}	Evaluated at 1Hz

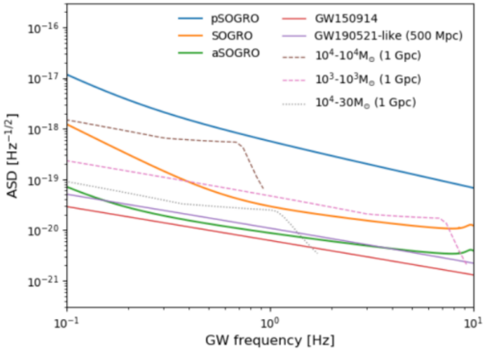
소그로 디자인 파라미터



Advanced SOGRO: 50 m



프로토타입 소그로: 2 m



소그로 감도 및 중력파 파원 강도

A superconducting tensor detector for mid-frequency gravitational waves: its multi-channel nature and main astrophysical targets

Yeong-Bok Bae[†1], Chan Park[†1], Edwin J. Son[†2], Sang-Hyeon Ahn[3], Minjoong Jeong[4], Gungwon Kang[‡5], Chunglee Kim[‡6], Dong Lak Kim[7], Jaewan Kim[8], Whansun Kim[2], Hyung Mok Lee[9], Yong-Ho Lee[10], Ronald S. Norton[11], John J. Oh[2], Sang Hoon Oh[2], and Ho Jung Paik[11]

Mid-frequency band gravitational-wave detectors will be complementary for the existing Earth-based detectors (sensitive above 10 Hz or so) and the future space-based detectors such as LISA, which will be sensitive below around 10 mHz. A ground-based superconducting omni-directional gravitational radiation observatory (SOGRO) has recently been proposed along with several design variations for the frequency band of 0.1 to 10 Hz. For three conceptual designs of SOGRO (*e.g.*, pSOGRO, SOGRO and aSOGRO), we examine their multi-channel natures, sensitivities and science cases. One of the key characteristics of the SOGRO concept is its six detection channels. The response functions of each channel are calculated for all possible gravitational wave polarizations including scalar and vector modes. Combining these response functions, we also confirm the omnidirectional nature of SOGRO. Hence, even a single SOGRO detector will be able to determine the position of a source and polarizations of gravitational waves, if detected. Taking into account SOGRO's sensitivity and technical requirements, two main targets are most plausible: gravitational waves from compact binaries and stochastic backgrounds. Based on assumptions we consider in this work, detection rates for intermediate-mass binary black holes (in the mass range of hundreds up to 10^4 $M_\odot$) are expected to be $0.0014 - 2.5$ yr^{-1}. In order to detect stochastic gravitational wave background, multiple detectors are required. Two aSOGRO detector networks may be able to put limits on the stochastic background beyond the indirect limit from cosmological observations.

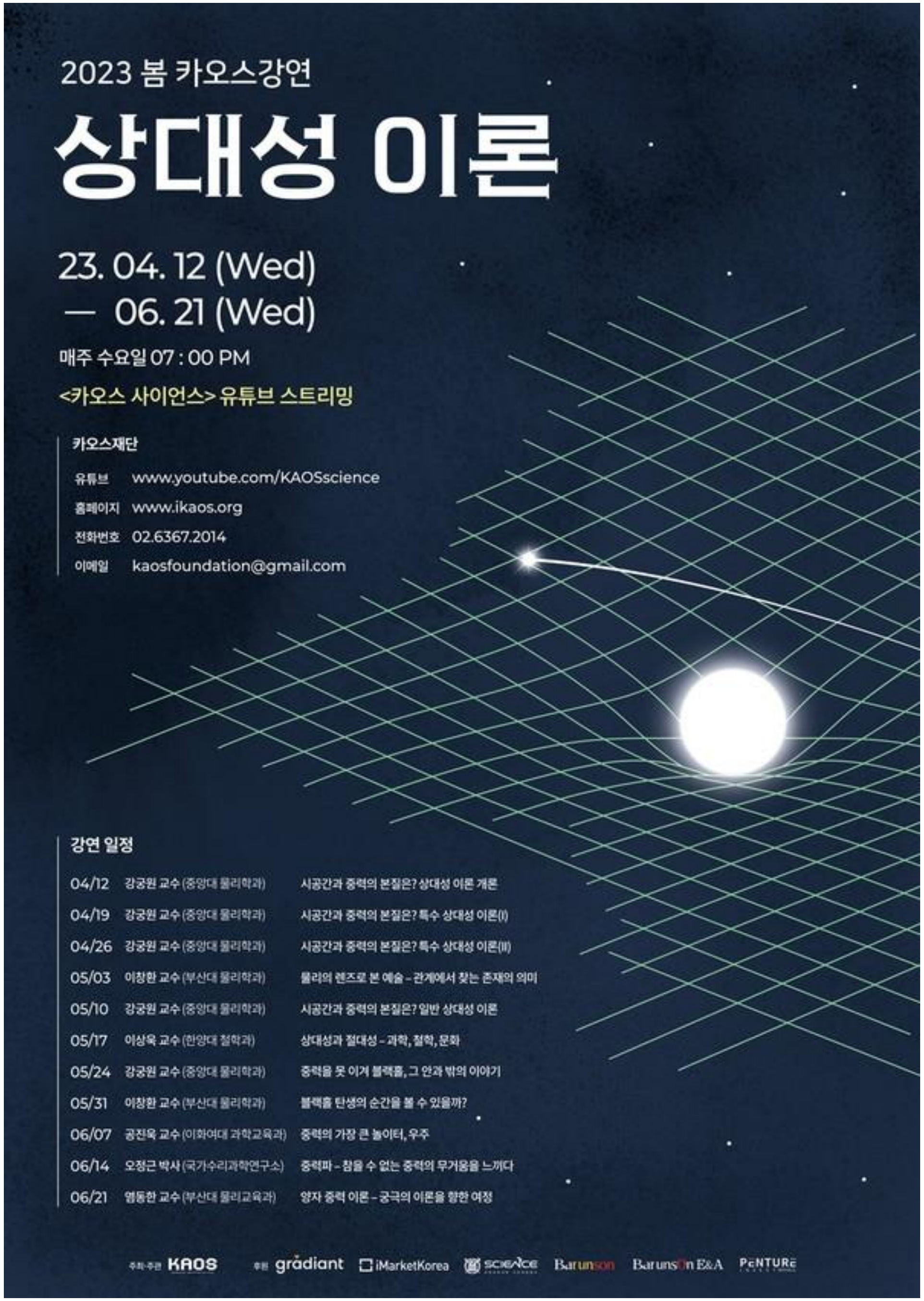
Subject Index Gravitational waves, Observational astronomy, Black holes, Superconducting, Cryogenic

arXiv: 5263785

In review at PTEP

✓ Outreach:

- Lecture series on General Relativity at the KAOS Foundation
- https://www.youtube.com/watch?v=mtHOUsdyxSY&t=5s



2023 봄 카오스강연

상대성 이론

23. 04. 12 (Wed)
— 06. 21 (Wed)

매주 수요일 07 : 00 PM

<카오스 사이언스> 유튜브 스트리밍

카오스재단

유튜브 www.youtube.com/KAOSscience
홈페이지 www.ikaos.org
전화번호 02.6367.2014
이메일 kaosfoundation@gmail.com

강연 일정

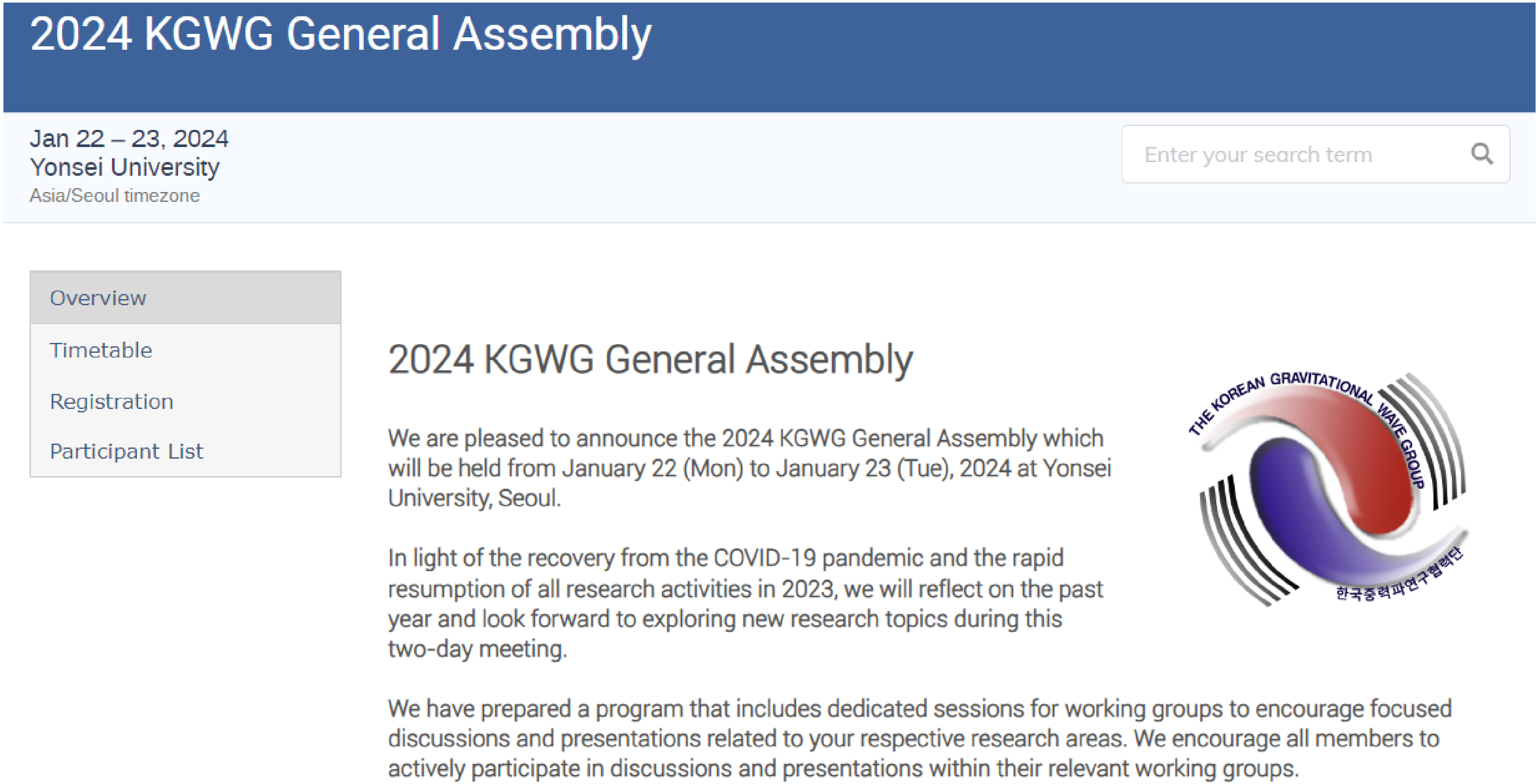
04/12	강궁원 교수 (중앙대 물리학과)	시공간과 중력의 본질은? 상대성 이론 개론
04/19	강궁원 교수 (중앙대 물리학과)	시공간과 중력의 본질은? 특수 상대성 이론(I)
04/26	강궁원 교수 (중앙대 물리학과)	시공간과 중력의 본질은? 특수 상대성 이론(II)
05/03	이창환 교수 (부산대 물리학과)	물리의 렌즈로 본 예술 – 관계에서 찾는 존재의 의미
05/10	강궁원 교수 (중앙대 물리학과)	시공간과 중력의 본질은? 일반 상대성 이론
05/17	이상욱 교수 (한양대 철학과)	상대성과 절대성 – 과학, 철학, 문화
05/24	강궁원 교수 (중앙대 물리학과)	중력을 못 이겨 블랙홀, 그 안과 밖의 이야기
05/31	이창환 교수 (부산대 물리학과)	블랙홀 탄생의 순간을 볼 수 있을까?
06/07	공진욱 교수 (이화여대 과학교육과)	중력의 가장 큰 놀이터, 우주
06/14	오정근 박사 (국가수리과학연구소)	중력파 – 참을 수 없는 중력의 무거움을 느끼다
06/21	염동한 교수 (부산대 물리교육과)	양자 중력 이론 – 궁극의 이론을 향한 여정

주최·주관 KAOS 후원 gradiant iMarketKorea SCIENCE Barunson BarunsOn E&A PENTURE

III. Outlook in 2024

- Many interesting topics associated with the tidal-driven ringdown radiation.
- Develop further the collaboration with Glasgow group on S231123.
- Educate and train the students

- Work hard……(?)



2024 KGWG General Assembly

Jan 22 – 23, 2024
Yonsei University
Asia/Seoul timezone

2024 KGWG General Assembly

We are pleased to announce the 2024 KGWG General Assembly which will be held from January 22 (Mon) to January 23 (Tue), 2024 at Yonsei University, Seoul.

In light of the recovery from the COVID-19 pandemic and the rapid resumption of all research activities in 2023, we will reflect on the past year and look forward to exploring new research topics during this two-day meeting.

We have prepared a program that includes dedicated sessions for working groups to encourage focused discussions and presentations related to your respective research areas. We encourage all members to actively participate in discussions and presentations within their relevant working groups.

https://indico.kgwg.org/event/58/

THANKS!