Is Sgr A* a Black Hole of General Relativity or of a Modified Gravity Theory?

– Search for the Gravity Theory –

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+ **Collaborators in Subaru Proposal/Kakenhi**

- Subaru Users Meeting, 2022FY 2023/01/31 - 02/02
- 特異点研究会（名駅前会議室） 2022/12/28-30

- Members in Subaru proposals and Grants

data analysis & instrumentation	theory & data fitting
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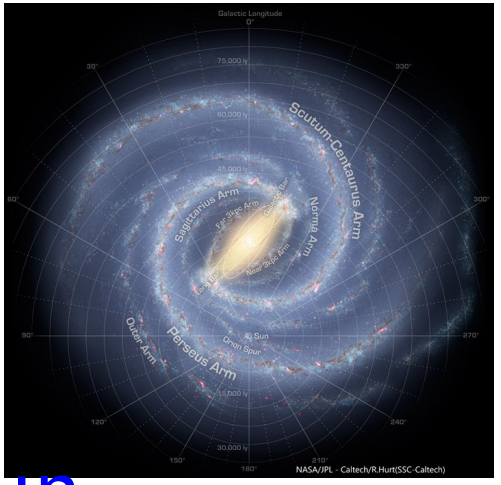
1. Sgr A* and GR

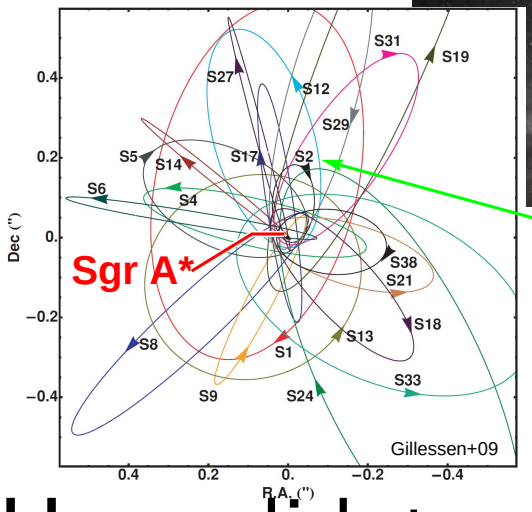
1.1 S-stars in GC

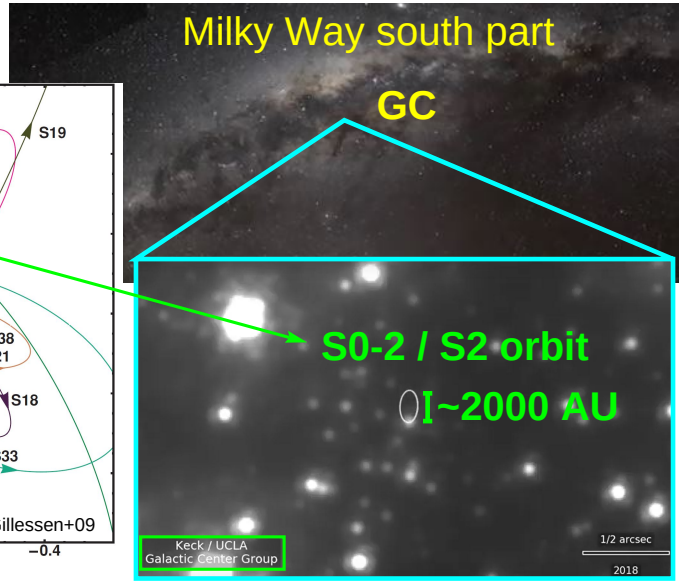


- Galactic center (GC) $\simeq$ 8 kpc from Sun

  Sagittarius A* (Sgr A*) + S-stars (↓)

- S-stars : Test Particles probing grav. of Sgr A*.





$\rightarrow$ Newtonian fitting

$\rightarrow$ $M_{\rm BH} \simeq 4 \times 10^6\, M_\odot$

$\rightarrow$ Sgr A* as a Massive BH candidate

- **Test of grav. theor. at MBH has just begun**
  S0-2, S24 have Short Periapse Distance ($r_{\rm p}$)

◇ For S0-2: 16yr/orbit

$r_{\rm p.S0\text{-}2} = 113\,{\rm AU}$

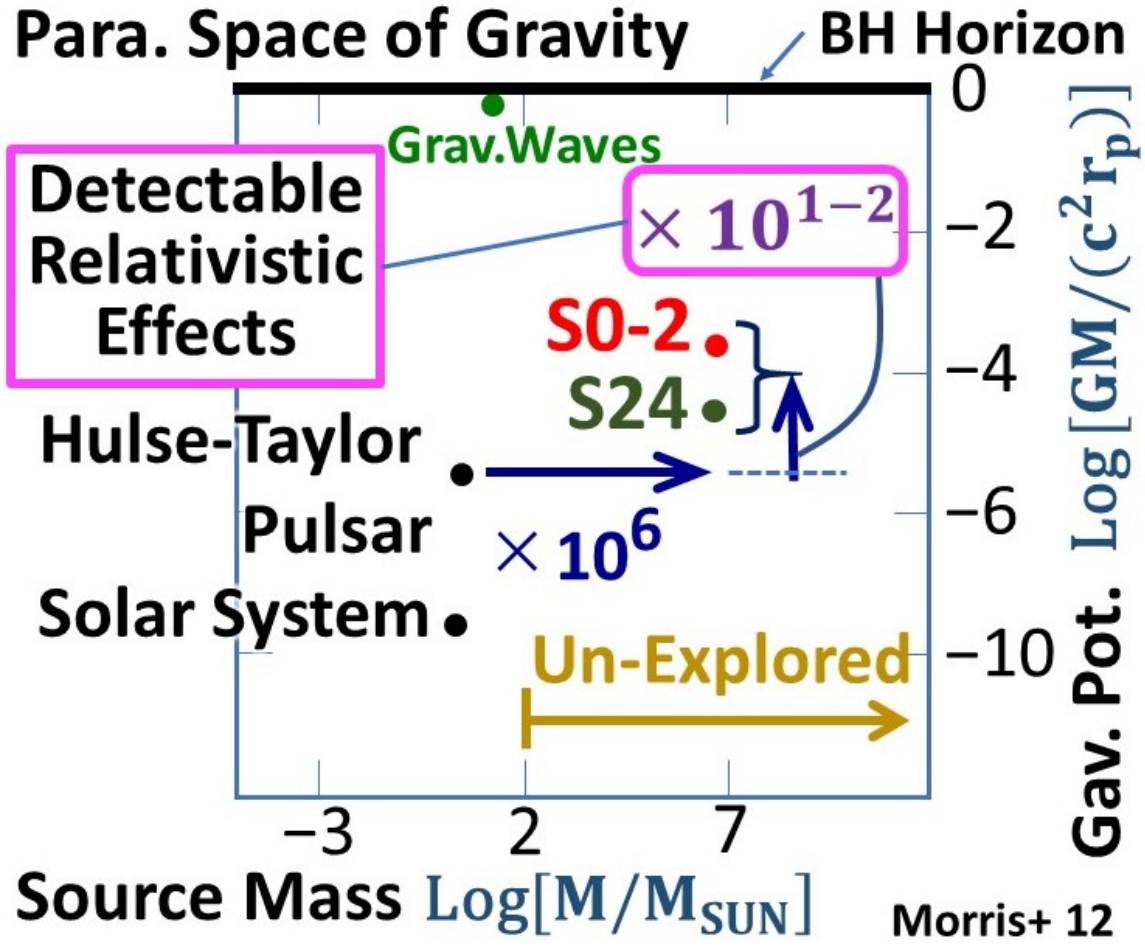
$t_{\rm p.S0\text{-}2} = \underline{2018.39}\,{\rm yr}$

◇ For S24: 300yr/orbit

$r_{\rm p.S24} \sim 800\,{\rm AU}$

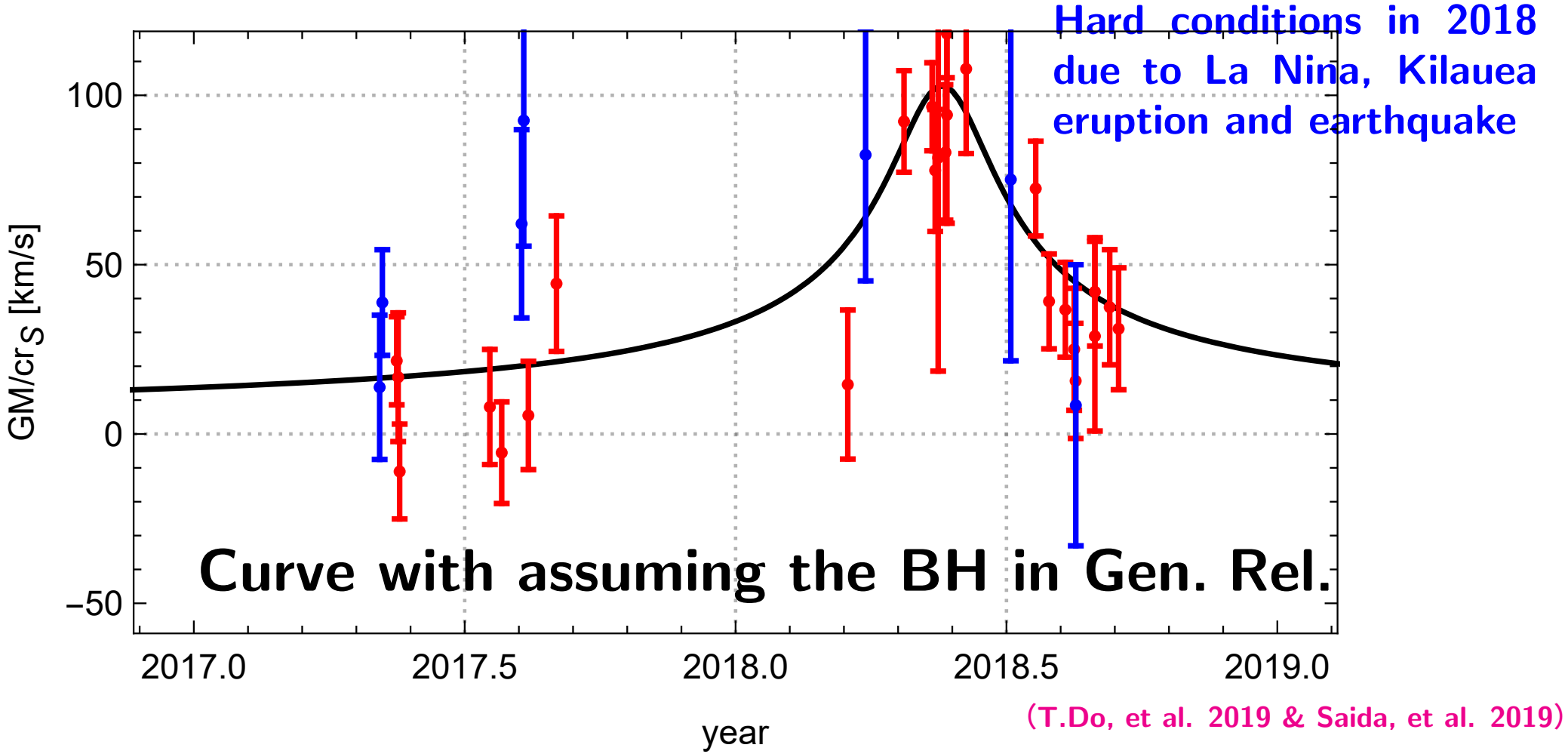
$t_{\rm p.S24} \sim \underline{2024.28}\,{\rm yr}$

◇ BH: $R_{\rm SgrA} \simeq 0.1\,{\rm AU}$



S0-2 data in 2018 contain Non-Newtonian Effects.

- Grav. Doppler effect (Red=Keck , Blue=Subaru)



(T.Do, et al. 2019 & Saida, et al. 2019)

◇ If Newton is true, then these data remain at 0

→ **Rejection of Newton Grav.** in 2018

1.2 Our aims, using Subaru/TMT

- NOTE : Many grav. theor. have been proposed.
  (General Relativity is NOT completley confirmed.)
- Fact: Rejection of Newton Gravity
  (GRAVITY collab. A&A 2018 ; Do et al. 2019 Science ; Saida et al. 2019 PASJ)
- Our aim: Which of gravity theories predicts
  the curve best-fitting with the data?

$\longrightarrow$ Method (explained from the next page)
Parametrized Post-Newtonian (PPN) formalism

- Other aims:
  - ◇ Invisible Mass Distribution around Sgr A*
  - ◇ Origin of stars in GC (Co-evolution of SMBH and galaxy ?)

2. Study of Gravity Theory

2.1 Taylor expansion of grav. pot.

- Post-Newtonian (PN) parameter $(V_{\rm p} \simeq 0.03c)$

$$\varepsilon \sim \frac{GM_{\rm BH}}{c^2 r_{\rm p}} \approx \left(\frac{V_{\rm p}}{c}\right)^2 \sim 10^{-3} \in \boxed{\text{Un-explored region in } (M_{\rm BH}\,,\,\varepsilon) \text{ space}}$$

- PN expansion: Taylor expansion of Grav. Pot. of Kerr BH (BH in GR) $g_{\mu\nu}^{\rm Kerr}$ by ε
- Parametrized PN formalism : Introduce some artificial parameters in the PN expansion of $g_{\mu\nu}^{\rm Kerr}$

2.2 PPN expansion and parameters

- BH's metric tensor (multi-comp. grav. pot.)

$$g_{tt} = -1 + \frac{2m}{r} + A\frac{m^2}{r^2} + [\text{higher}] \quad , \; m = \frac{GM_{\rm BH}}{c^2}$$

$$g_{tx} = +2\chi\frac{x}{r}\frac{m^2}{r^2} + [\text{higher}] \quad , \; \chi = \frac{cJ_{\rm BH}}{GM_{\rm BH}^2} \qquad \boxed{\varepsilon = \frac{m}{r}}$$

$$g_{ty} = -2\chi\frac{y}{r}\frac{m^2}{r^2} + [\text{higher}]$$

$$g_{tz} = +2\chi C_z\frac{z}{r}\frac{m^2}{r^2} + [\text{higher}]$$

$$g_{ij} = \delta_{ij} + 2B\frac{x^i x^j}{r^2}\frac{m}{r} + [\text{higher}]$$

This is a simplest PPN formulation with A, B, C_z for measuring the deviation from GR.

- Kerr (BH in GR) case $\Rightarrow$ $\boxed{A = C_z = 0\,,\ B = 1}$

Observational determination of $\{A, B, C_z\}$ can be regarded as a selection of gravity theories.

- PPN parameters $\{A, B, C_z\}$ modify the E.O.M. of stars and photons.

$\rightarrow$ Time evolution of Dec., R.A. and z (redshift) depend on $\{A, B, C_z\}$.

$\rightarrow$ By monitoring observation of S0-2 and S24, the best-fitting search of $\{A, B, C_z\}$ is possible.

S24 obs. needs IR AO (our kakenhi A is contributing)

2.3 Science targets with Subaru/TMT

- One science target with Subaru

  A and B are the effects of Sgr A* mass $M_{\rm BH}$

$\rightarrow$ A is 1PN order, and B is 1.5PN order.

(B is detectable with Subaru if $B > O(10)$)

- One science target with TMT

  C_z is the effects of Sgr A* spin $J_{\rm BH}$

$\rightarrow$ C_z is 1.5PN order (not detectable with Subaru)

- Currently we consider A and B without C.

3. Current Status

- Fact: Time evolution of obs. quantities (E.O.M. of stars and photons) depend on not only $\{A, B\}$ but also all parameters in grav. potential $g_{\mu\nu}$ and the choice of astrometric origin ($\because$ BH is invisible).
- Searching the value of 19 + 2PPN parameters by fitting PPN from of grav. pot. with obs. data of S0-2's motion.
- 19 parameters, except for $\{A, B\}$ are $\cdots$

- 19 parameters, except for $\{A, B\}$

$M_{\rm BH}$: Mass of Sgr A* (massive BH)

$R_{\rm SgrA}$: Distance to Sgr A*

$\left(\vec{a}_{\rm BH}\right.$: BH spin (magnitude and direction) $\leq$ 1.5PN$\left.\right)$

$\vec{x}_{\rm apo}\,,\vec{v}_{\rm apo}$: S0-2's initial conditions (6 components)

$\vec{v}_{\rm E}$: Our velocity w.r.t. Sgr A*(3 comp.)

$(X,Y)_{\rm Keck}$: Astro. reference point for Keck

$(\dot{X},\dot{Y})_{\rm Keck}$: Velocity of the ref. point for Keck

$(X,Y)_{\rm VLT}$: Astro. reference point for VLT

$(\dot{X},\dot{Y})_{\rm VLT}$: Velocity of the ref. point for VLT

$\uparrow$

$(X,Y) =$ (R.A. , Dec.)

NOTE: { Our coordinate origin is at Sgr A*
Assume $\vec{v}_{\rm E}$ and $(\dot{X},\dot{Y})$ are constant

- We have performed χ^2-fitting. (NG = Newtonian Gravity)

◇ NG and GR $(A = 0,\ B = 1)$ cases

Saida et al. PASJ 2019 + Preliminary incl. new data

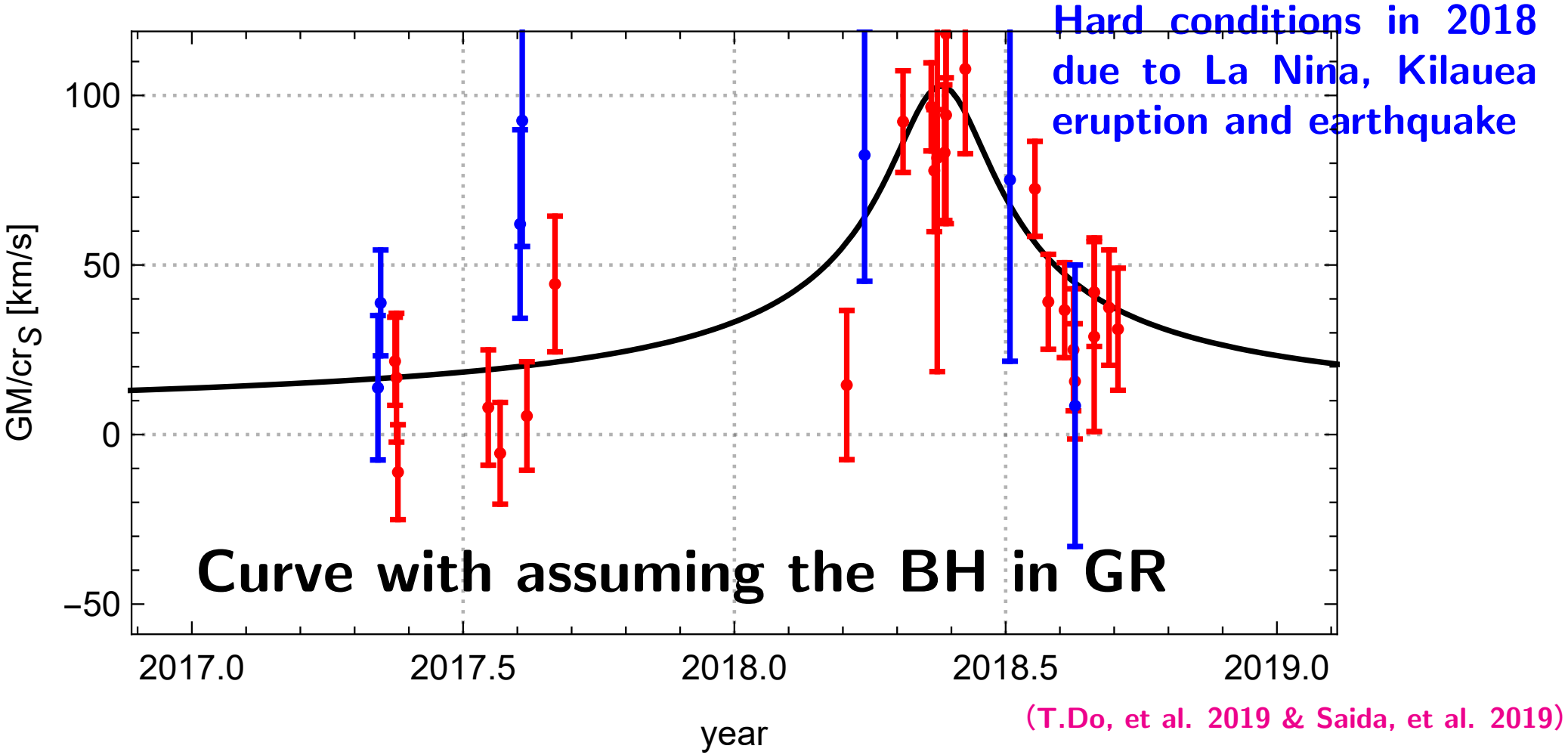
◦ $\chi^2_{\rm red} = \begin{cases} 1.3425 & \text{for Newton Grav. (NG)} \\ 1.3296 & \text{for Einstein Grav. (GR)} \end{cases}$

◦ Best-fitting values of some parameters:

	$M_{\rm BH}\,[10^6 M_\odot]$	$R_{\rm SgrA}$ [kpc]	$T_{\rm S0\text{-}2}$ [yr]	$v_{\rm E//}$ [km/s]
NG :	4.217 ± 0.538	8.201 ± 0.349	16.0485 ± 0.0009	5.9 ± 1.7
GR :	4.001 ± 0.010	7.987 ± 0.010	16.0486 ± 0.0004	-11.0 ± 1.1

$\rightarrow$ Non-Newton can be favored by t-z plots, not χ^2.

◦ Grav. Doppler effect (Red=Keck , Blue=Subaru)



(T.Do, et al. 2019 & Saida, et al. 2019)

◦ If Newton is true, then these data remain at 0

→ **Rejection of Newton Grav.** in 2018

◇ PPN case (without C_z): $\chi^2_{\rm red} = 1.3016$ **Preliminary**

○ Best-fitting values of some parameters:

$M_{\rm BH}\,[10^6 M_\odot]$	:	3.996 ± 0.005
$R_{\rm SgrA}\,[\rm kpc]$	:	7.988 ± 0.004
$T_{\rm S0\text{-}2}\,[\rm yr]$	:	16.0606 ± 0.0003
$v_{\rm E//}\,[\rm km/s]$	:	-9.6 ± 0.5
$A\,[\rm no.dim.]$	:	22.7 ± 1.3
$B\,[\rm no.dim.]$	:	-6.9 ± 0.9

○ Inconsistent with Schwarzschild (BH in GR),

$A \neq 0\,,\ B \neq 1$ within several σ

◇ Although $\Delta\chi^2_{\rm red} = 1.33(\text{GR}) - 1.30(\text{PPN}) = 0.03$, if PPN is true, there are two possibilities:

- ○ the assumption "2-body-system in vacuum BH spacetime" is not good ?
- ○ a "modified gravity theory" is favored ?

NOTE

Difference of $\chi^2_{\rm red}$ between GR and PPN is NOT statistically significant. We are planning to perform the **Hierarchical Bayesian Estimation**.

$\longrightarrow$ this is on going, I have no result to report here.

4. Summary

- Using the data of S-stars, Gravity/BH is tested.
- BH's mass effects are in our detection capability.
- Geodesic (Free fall) motion is the good model.
- Preliminary PPN χ^2-fitting is inconsistent with Schwarzschild (BH in GR) case:

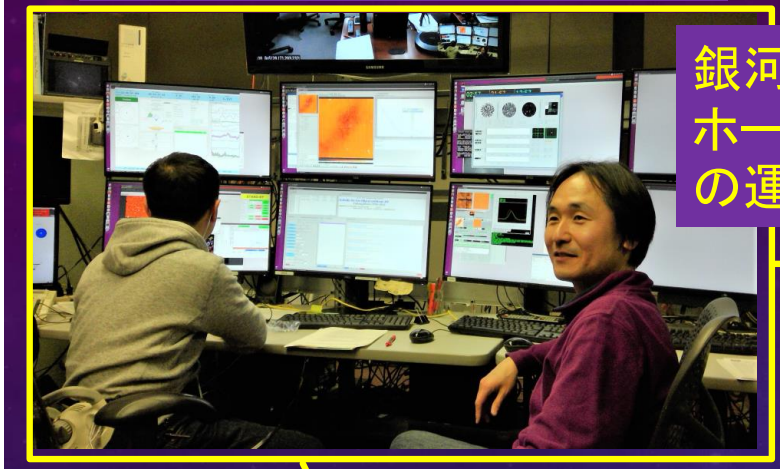
$$A = 22.7 \pm 1.3 \ , \ B = -6.9 \pm 0.9$$

- Hierarchical Bayesian code is under construction.

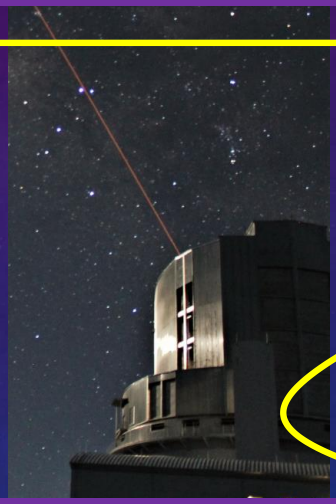
$\rightarrow$ with Takeuchi (竹内さん) and Matsui (松井さん)
(Nagoya Univ. Ω-Lab.)

- Subaru GC research beyond GR has just begun.

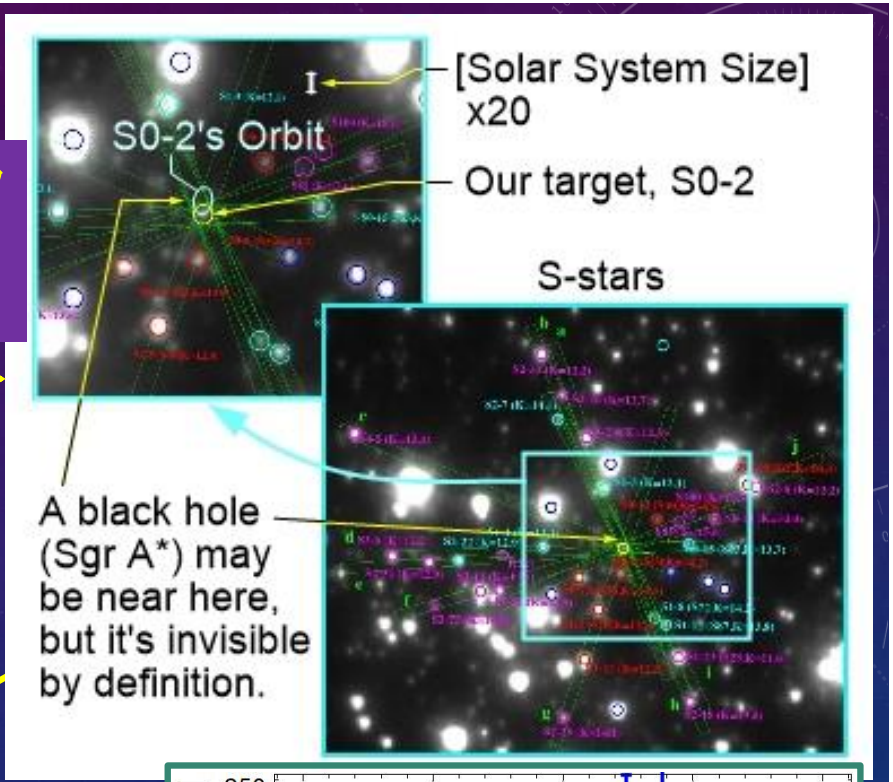
すばる望遠鏡コントロール室



銀河系中心のブラックホールを周回する星の運動の測定



ハワイ島マウナケア山（機内から撮影）



測定データと理論予測を比べて，星の速度の時間発展に現れる一般相対論の効果を抽出。