An Evidence of Dark Matter Accumulation at Sgr A* from S0-2 Star Observational Data

SAIDA Hiromi (Daido Univ.) / 斉田浩見 (talk)
UCHIDA Shun-ya (Naogya Univ.) / 内田舜也
NISHIYAMA Shogo (Miyagi U. Edu.) / 西山正吾

+ Members in Subaru Proposal/Kakenhi Grants/Bayesian Team

- Subaru Users Meeting 2026FY (NAOJ, Mitaka) 2026/06/17 - 19
- Traversing the Galactic Center in Space and Time 2026/05/18 - 22
  (Brno Planetarium & Observatory. Czech)
- Subaru Users Meeting 2025FY (NAOJ, Mitaka) 2025/10/29 - 31

Authors of this report/paper (in preparation)

UCHIDA Shun-ya (Nagoya U.) / 内田舜也 名古屋大学

SAIDA Hiromi (Daido U.) / 斉田浩見 大同大学

MATSUI Sena (Nagoya U.) / 松井瀬奈 名古屋大学

TAKEUCHI T. Tsutomu (Nagoya U.) / 竹内努 名古屋大学

NISHIYAMA Shogo (Miyagi U. of Edu.) / 西山正吾 宮城教育大学

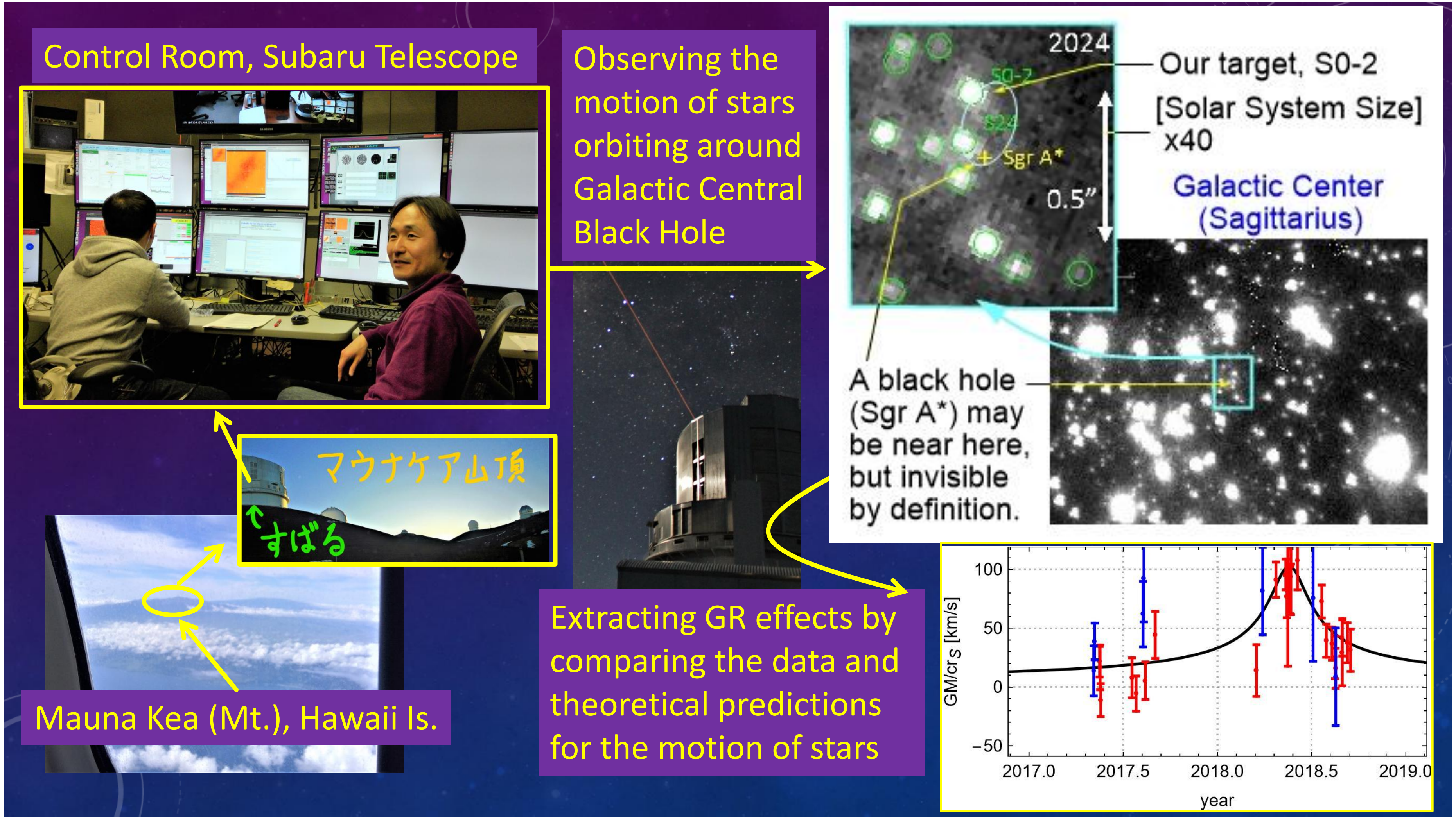
TAKAMORI Yohsuke (Wakayama NITC) / 孝森洋介 和歌山高専

TAKAHASHI Masaaki (Aichi U. of Edu.) / 高橋真聡 愛知教育大学

1. Sgr A* and GR

GR = General Relativity

- Subaru GC research **beyond GR** is launched



- S0-2 is a little bit bright and near to Sgr A*,
  enough to detect GR effect with AO.
- Fact

  Rejection of Newton Gravity compared to
  General Relativistic Black Hole in vacuum

  (GRAVITY collab. A&A 2018 ; Do et al. 2019 Science ;Saida et al. 2019 PASJ)
- Note
  - ◇ Some "modified gravity theories" are alive for some issues:

    Cosmic censorship, Global hyperbolicity,
    Dark matter, Dark energy, H_0/S_8 tension, and so on.
  - ◇ Environment of Sgr A* is not exactly vacuum.

- Our aims/key questions

Is a Modified Gravity Theory favored?
Is Dark Matter accumulating at Sgr A^*?

→ Method (explained from the next page)

Parametrized Post-Newtonian (PPN) formalism

Saida et al. 2024 Prog.Ther.Exp.Phys (talk in last year)

- Other aim: Origin of stars in GC
  → Poster by S.Nishiyama

Nshiyama et al. 2024 Proc.Jpn.Acad. & 2025 Universe

2. Theoretical Framework

2.1 Taylor expansion of grav. field

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

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

- 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 / stationary axialsymmetric

$$g_{tt} = -1 + 2\varepsilon(r) + \boldsymbol{A}\,\varepsilon(r)^2 + O(\varepsilon^3) \quad , \; m = GM_{\rm BH}/c^2$$

$$g_{tx} = +2q\frac{x}{r}\,\varepsilon(r)^2 + O(\varepsilon^3) \quad , \; q = \frac{cJ_{\rm BH}}{GM_{\rm BH}^2} \qquad \boxed{\varepsilon(r) = \frac{m}{r}}$$

$$g_{ty} = -2q\frac{y}{r}\,\varepsilon(r)^2 + O(\varepsilon^3)$$

$$g_{tz} = +2q\,\boldsymbol{C_z}\,\frac{z}{r}\,\varepsilon(r)^2 + O(\varepsilon^3)$$

$$g_{ij} = \delta_{ij} + 2\boldsymbol{B}\,\frac{x^i x^j}{r^2}\,\varepsilon(r) + O(\varepsilon^2)$$

The simplest PPN form with A, B, C_z for measuring deviation from GR.

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

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, B are 1PN order, in Dec., R.A. and z

- One science target with TMT (Thirty-Meter-Telescope)

  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_z.

- Important note for A and B $\cdots$

- Important note for A and B:

If $|A| > O(10)$ and/or $|B| > O(10)$,
then the gravitational lens effect (due to BH mass) becomes detectable with Subaru.

Difference from other groups

In our PPN model, the grav. lens effect is icluded, while the grav. lens effect has not been considered in reports by Keck and VLT/GRAVITY groups.

3. Bayesian fitting

- Search the value of 19 + 2PPN parameters:
  - theoretical prediction of S0-2's motion in the PPN from of grav. pot.
  - fitting the theoretical prediction 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)
$R_{\rm GC}$	:	Distance to Sgr A*(Galactic Center)
($\vec{a}_{\rm BH}$	:	BH spin (magnitude and direction) $\leq$ 1.5PN)
$\vec{x}_{\rm apo}$, $\vec{v}_{\rm apo}$	:	S0-2's initial conditions (6 components)
$\vec{V}_{\rm obs}$	:	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

↑

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

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

- Data set used in this report: $\simeq 500$ data points
  - VLT's open data, 1992–2016
  - Keck's open data, 1995–2018
  - Our Subaru data, 2014–2018

Subaru Data taken with NIR-Wave Front Sensor + AO3k

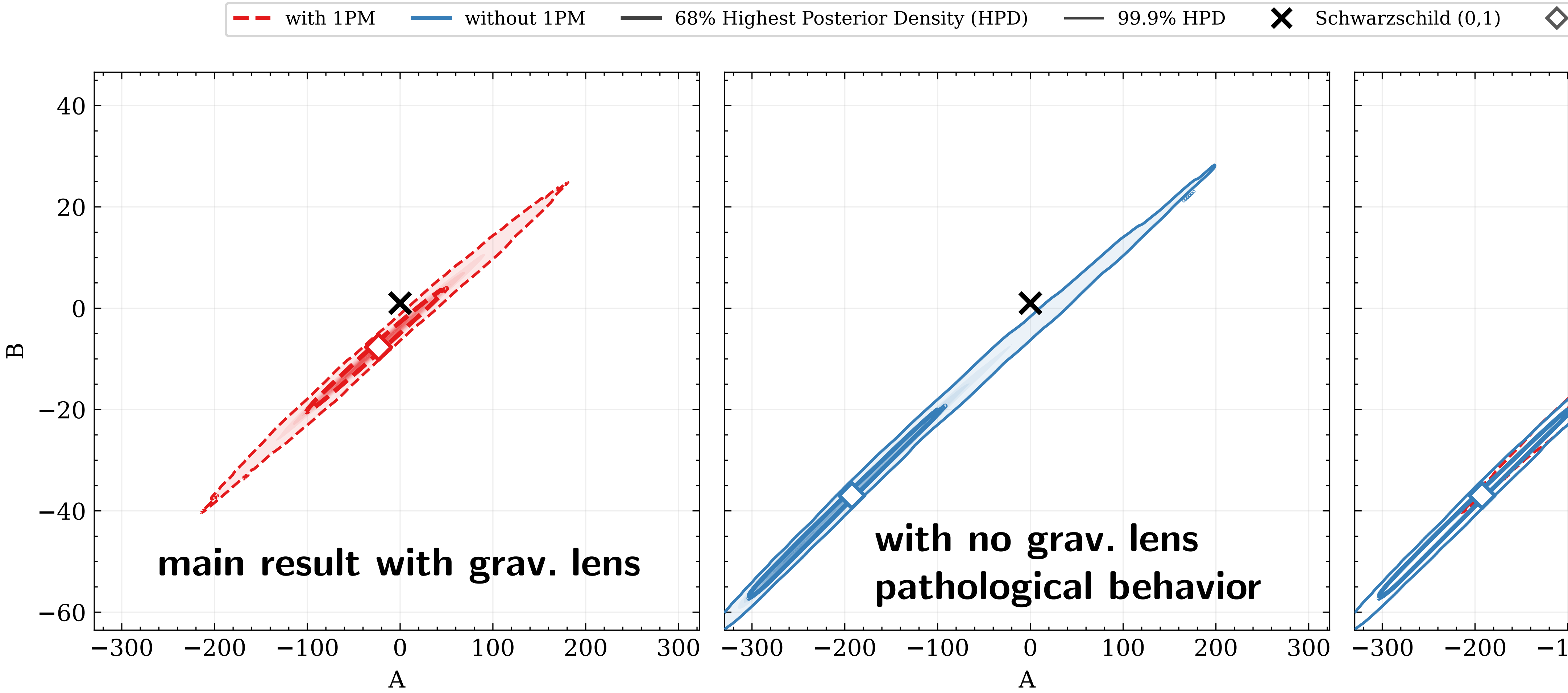
◇ have been used for "origin of stars at GC".
$\rightarrow$ see poster by Shogo Nishiyam

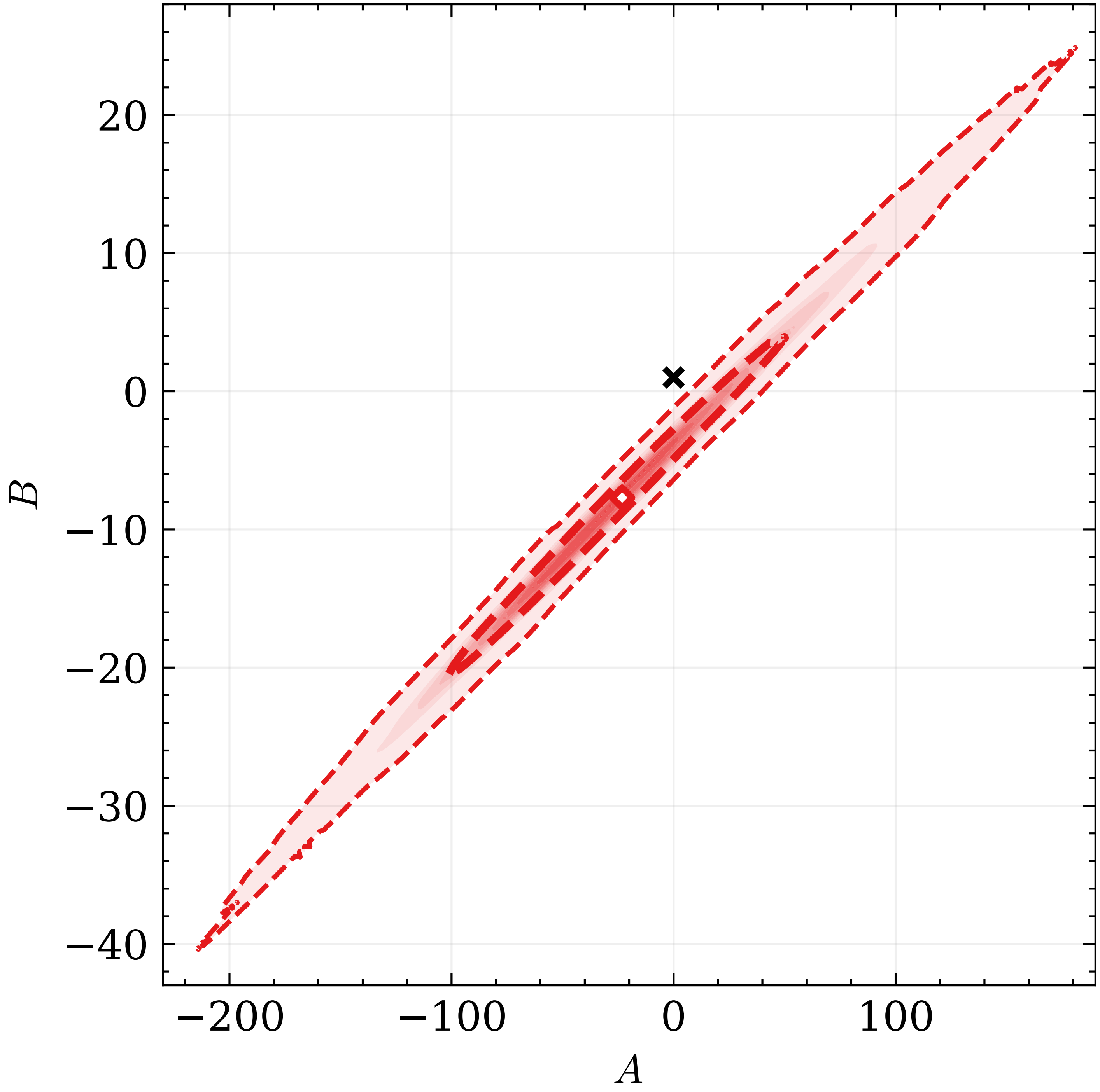
◇ are left to be analyzed for S0-2's motion.
You are welcome, having interests in analyzing those data!

• We are doing Bayesian-fitting — **Preliminary**

with flat prior probability distribution

◇ Posterior probab. distr. of the PPN para. (A, B)





Preliminary

GR BH in vac. is exluded from 99.9% region of Highest Posterior Density

◇ **Preliminary** result of all parameter values

Parameter		Median, central 68%	HPD 68% interval
$M_{\rm BH}$	$[10^6\ M_\odot]$	$4.009^{+0.042}_{-0.041}$	$[3.969,\ 4.052]$
A		$-24.9^{+51.8}_{-48.1}$	$[-77.5,\ 22.0]$
B		$-7.9^{+8.4}_{-8.0}$	$[-16.0,\ 0.4]$
$R_{\rm GC}$	[kpc]	$7.9865^{+0.0411}_{-0.0409}$	$[7.944,\ 8.026]$
$V^{\rm X}_{\rm obs}$	$[{\rm arcsec\,yr^{-1}}]$	$(-0.18^{+6.75}_{-6.77}) \times 10^{-3}$	$[-4.5,\ 9.0] \times 10^{-3}$
$V^{\rm Y}_{\rm obs}$	$[{\rm arcsec\,yr^{-1}}]$	$(-0.03^{+6.96}_{-6.82}) \times 10^{-3}$	$[-3.8,\ 9.9] \times 10^{-3}$
$V^{\rm Z}_{\rm obs}$	$[{\rm km\,s^{-1}}]$	$-10.30^{+2.57}_{-2.44}$	$[-12.89,\ -7.89]$
${\rm Dec}_{\rm Keck}$	[arcsec]	$(-1.442^{+0.221}_{-0.223}) \times 10^{-3}$	$[-1.658,\ -1.215] \times 10^{-3}$
${\rm RA}_{\rm Keck}$	[arcsec]	$(9.15^{+1.28}_{-1.33}) \times 10^{-4}$	$[7.89,\ 10.49] \times 10^{-4}$
$V^{\rm Dec}_{\rm Keck}$	$[{\rm arcsec\,yr^{-1}}]$	$(-0.05^{+6.77}_{-6.76}) \times 10^{-3}$	$[-9.2,\ 4.2] \times 10^{-3}$
$V^{\rm Ra}_{\rm Keck}$	$[{\rm arcsec\,yr^{-1}}]$	$(-0.10^{+6.82}_{-6.95}) \times 10^{-3}$	$[-9.9,\ 3.7] \times 10^{-3}$
${\rm Dec}_{\rm VLT}$	[arcsec]	$(1.21^{+2.27}_{-2.29}) \times 10^{-4}$	$[-0.96,\ 3.59] \times 10^{-4}$
${\rm RA}_{\rm VLT}$	[arcsec]	$(-7.42^{+1.25}_{-1.32}) \times 10^{-4}$	$[-8.66,\ -6.10] \times 10^{-4}$
$V^{\rm Dec}_{\rm VLT}$	$[{\rm arcsec\,yr^{-1}}]$	$(-0.01^{+6.76}_{-6.77}) \times 10^{-3}$	$[-9.2,\ 4.3] \times 10^{-3}$
$V^{\rm Ra}_{\rm VLT}$	$[{\rm arcsec\,yr^{-1}}]$	$(-0.11^{+6.82}_{-6.95}) \times 10^{-3}$	$[-10.0,\ 3.7] \times 10^{-3}$
$t_{\rm apo}$	[yr (AD)]	$2010.3346^{+0.0008}_{-0.0008}$	$[2010.3338,\ 2010.3353]$
$I_{\rm star}$	[deg]	$133.869^{+0.147}_{-0.146}$	$[133.719,\ 134.012]$
$\Omega_{\rm star}$	[deg]	$227.684^{+0.128}_{-0.121}$	$[227.563,\ 227.813]$
$\omega_{\rm star}$	[deg]	$66.272^{+0.112}_{-0.107}$	$[66.159,\ 66.376]$
$e_{\rm star}$		$0.88519^{+0.00083}_{-0.00080}$	$[0.88441,\ 0.88603]$
$T_{\rm star}$	[yr]	$16.0501^{+0.0069}_{-0.0065}$	$[16.0432,\ 16.0566]$

◇ Pick up some parameters — **Preliminary**

◦ Median & 68% Highest Posterior Density:

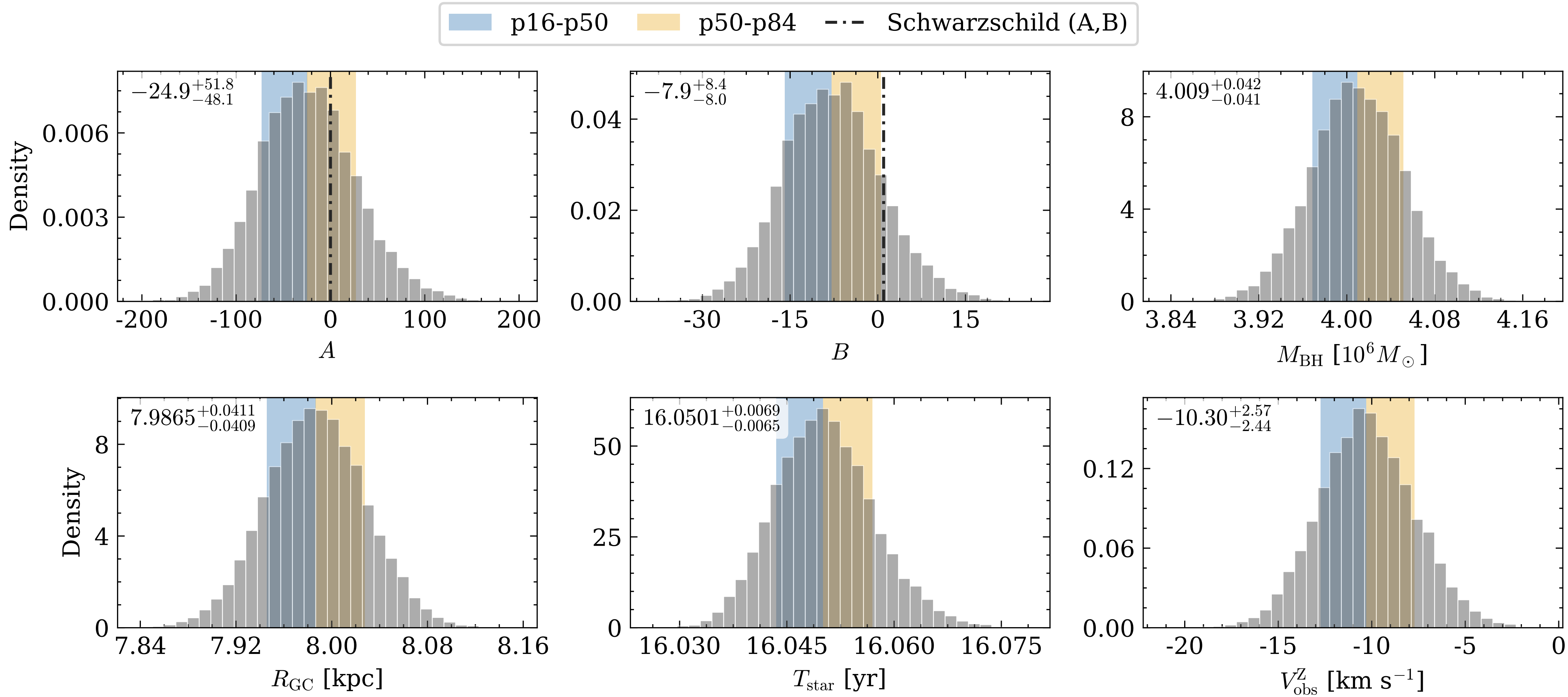
$M_{\rm BH}$ [$10^6 M_\odot$]	:	4.009	$+0.0042/-0.041$
$R_{\rm GC}$ [kpc]	:	7.9865	$+0.0411/-0.0409$
$T_{\rm star}$ [yr]	:	16.0501	$+0.0069/-0.0065$
$V^{\rm Z}_{\rm obs}$ [km/s]	:	-10.3	$+2.57/-2.44$
A [no.dim.]	:	-24.9	$+51.8/-48.1$
B [no.dim.]	:	-7.9	$+8.4/-8.0$

◦ Inconsistent with Schwarzschild (GR BH in vac.),

$A \neq 0\,,\; B \neq 1$ with $>$ 99.9% credibility

Preliminary

○ Marginal plots of some parameters



◇ Our result indicates two+1 possibilities:

- If GR is correct, then the modelling of 2-body-system in "vacuum BH spacetime" is not good.

  → **Dark Matters accumulate at Sgr A*!?**

- If the vac. BH environment is the good model, then a "modified gravity theory" is favored.

- Hybrid of the above possibilities.

4. Summary and Discussions

- Using the data of S-stars, Gravity/BH is tested.
- BH's mass effects are in our detection capability.
- Are "BH in vacuum" and/or "GR" credible?
- Bayesian-fitting of PPN BH with given data set

GR BH in vacuum (Schwarzschild) is ruled out with more than 99.9% credibility.

◇ **Dark Matter Accumlation around Sgr A***

◇ **Violation of GR**

- Three discussions $\cdots$

◇ Quantitative estimate of

- Amount of Dark Matters
- Modified Gravity Parameters

→ Under calculation using exact solutions of GR hairy BH and DHOST BH

◇ Comparison with GRAVITY group's result

→ They are doing a similar PPN analysis with

- very different data set
- different policy of parameter treatments
- NO gravitational lens effect

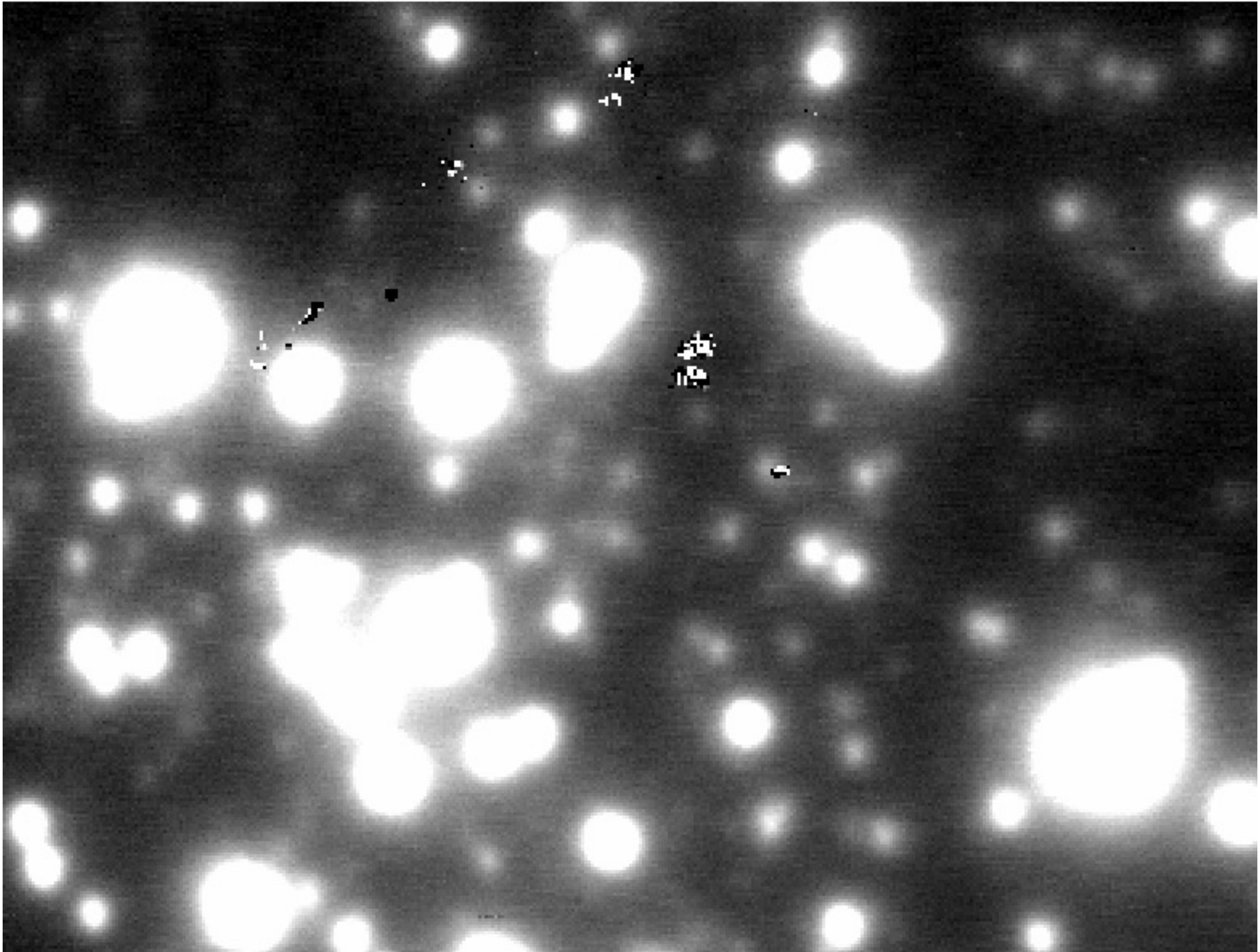
◇ Analysis of our data taken with NIR-WFS/AO3k

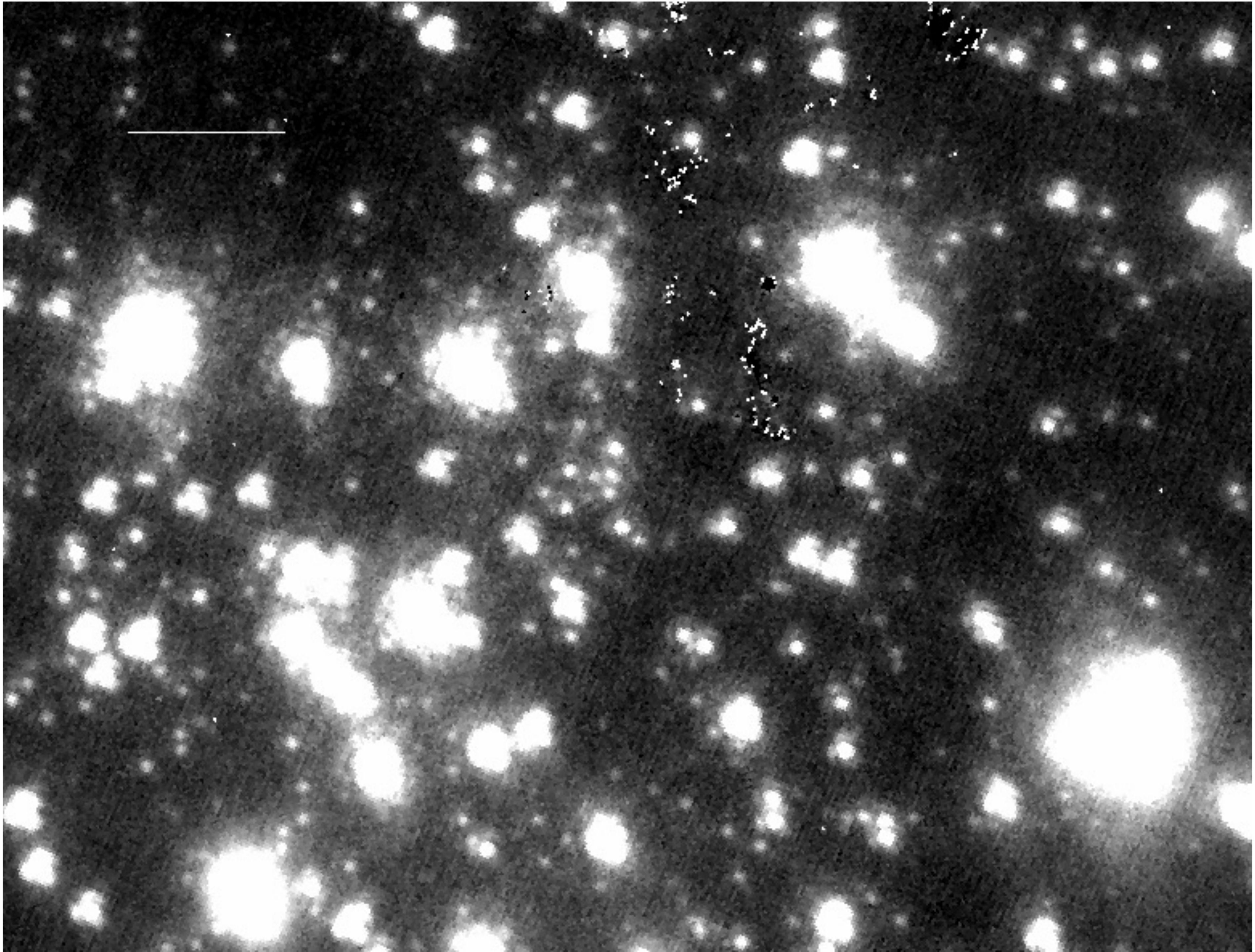
— Supplement: NIR-WFS/AO3k Data —

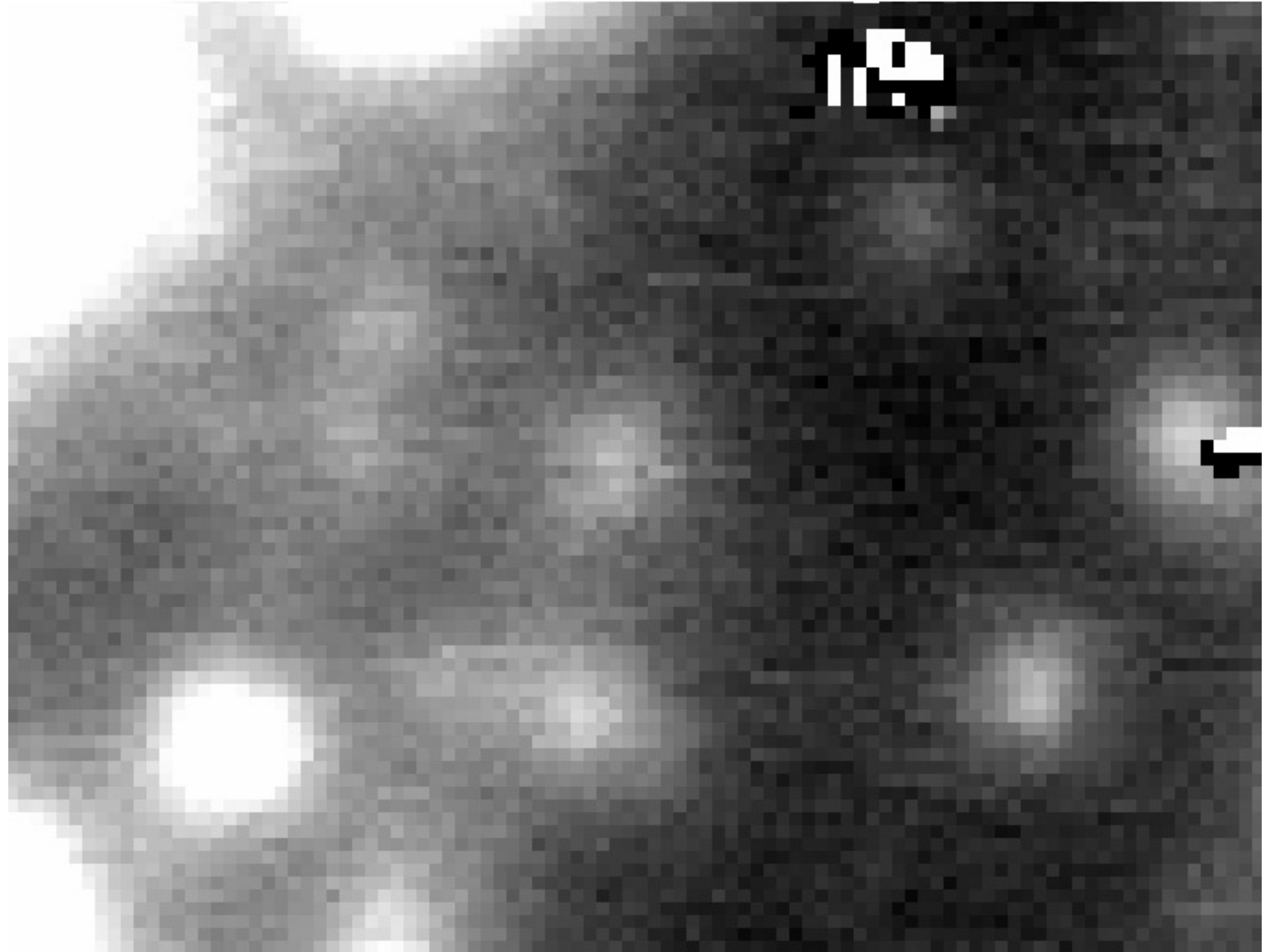
Comparison of

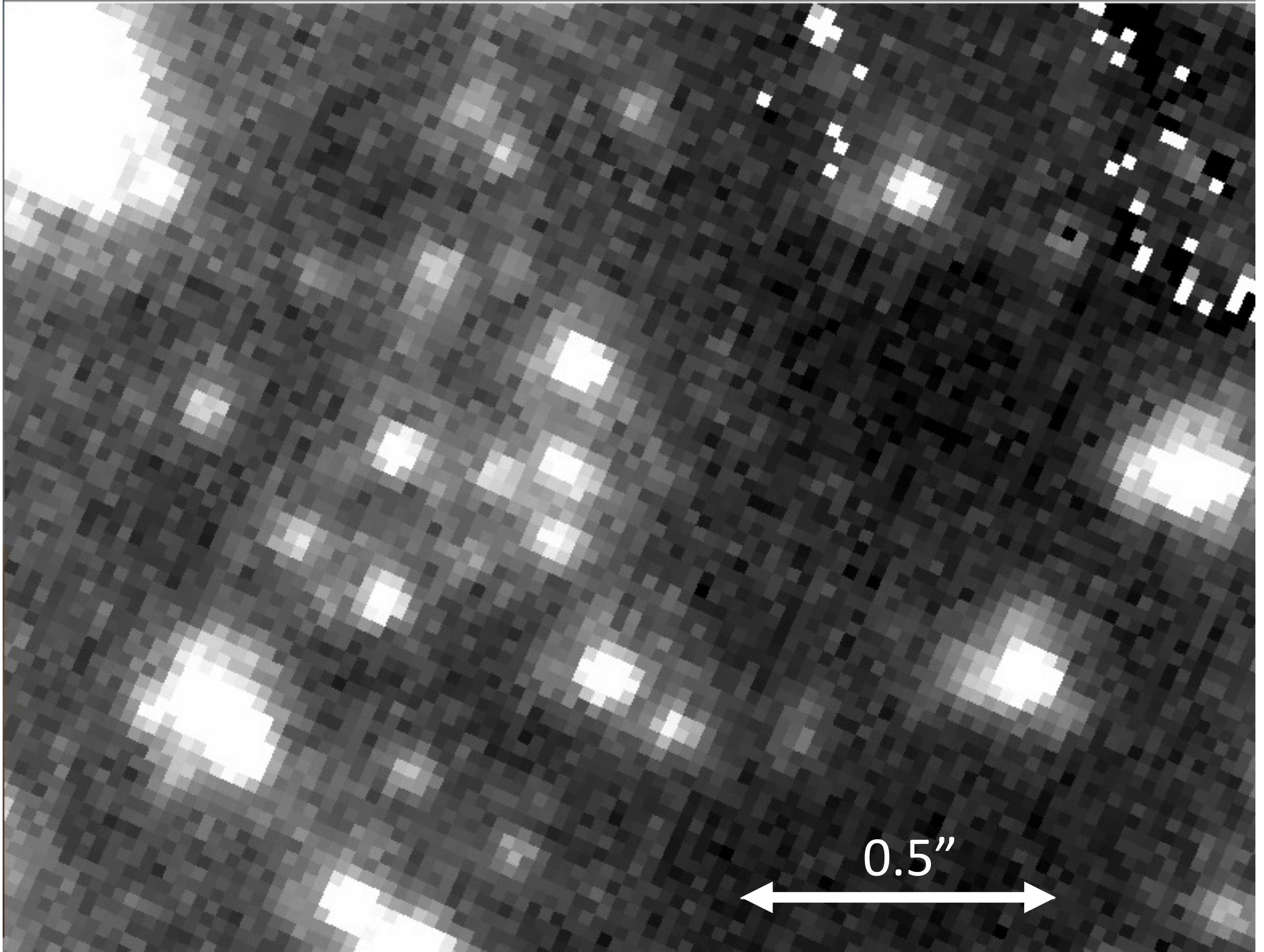
IRCS/AO188 with IRCS/NIR-WFS/AO3k

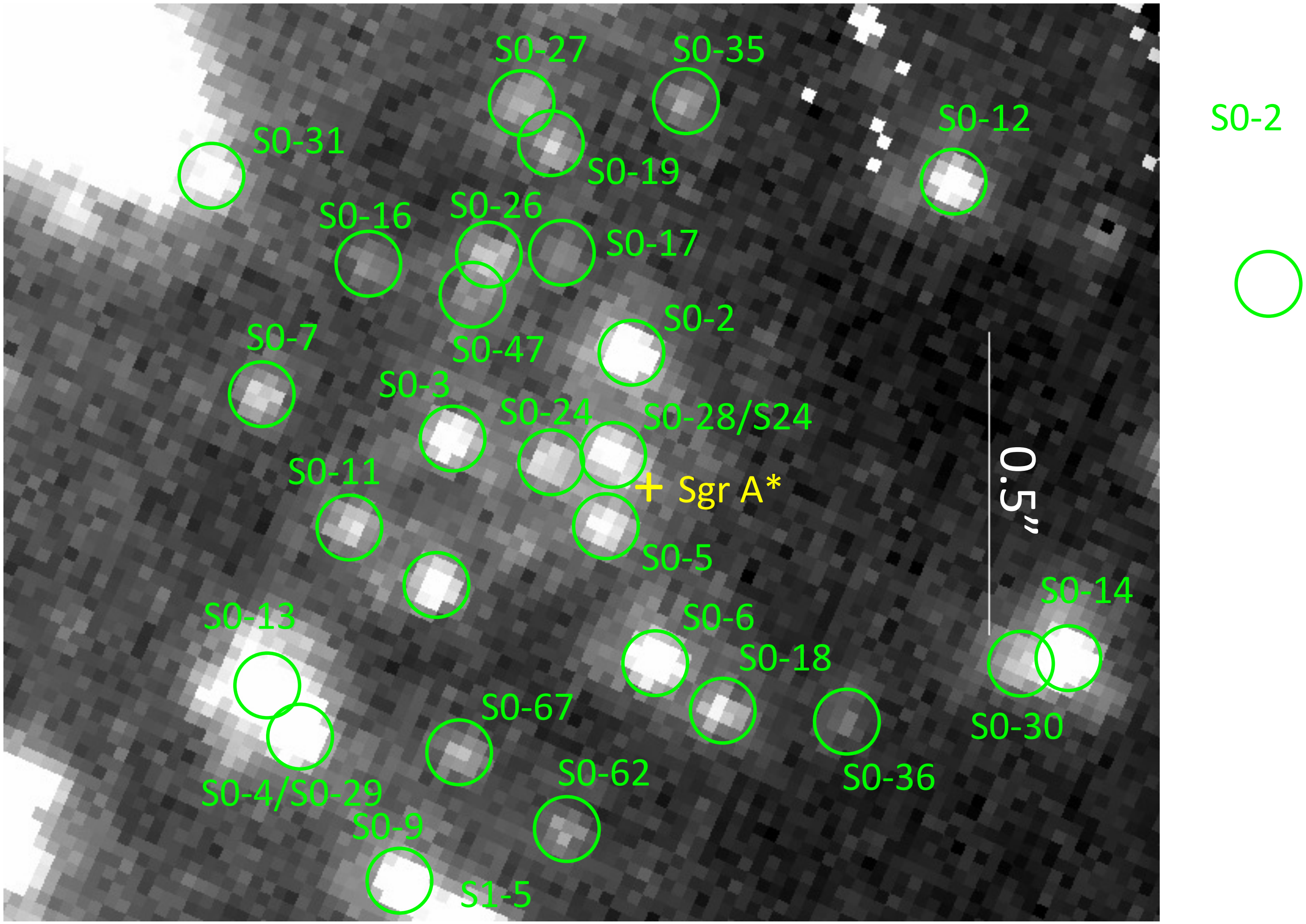
for NIR observaion of S-stars

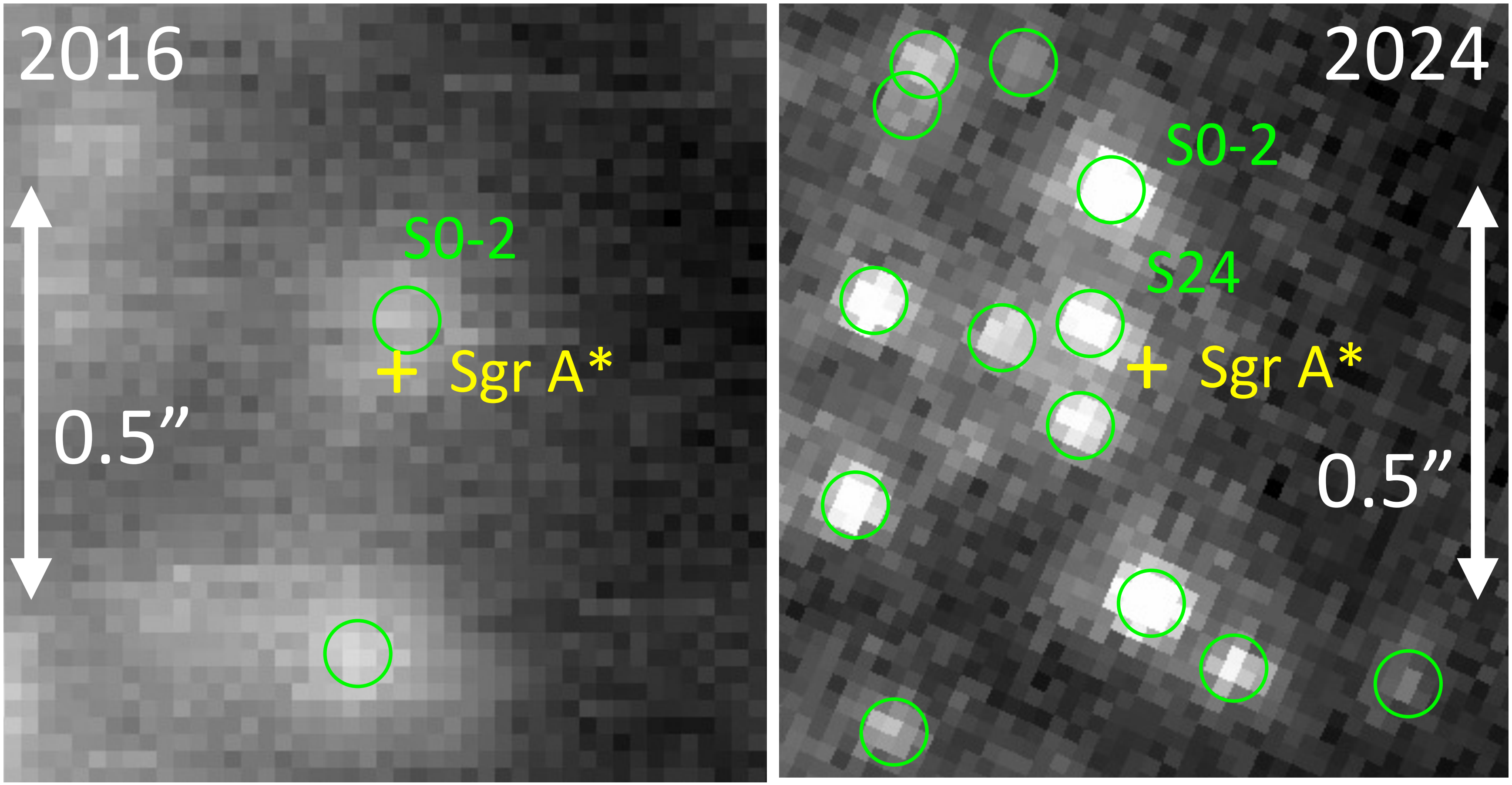







0.5”


S0-27
S0-35
S0-2
S0-31
S0-12
S0-19
S0-16
S0-26
S0-17
S0-2
S0-7
S0-47
S0-3
S0-24
S0-28/S24
Sgr A*
0.5”
S0-11
S0-5
S0-14
S0-13
S0-6
S0-18
S0-30
S0-67
S0-36
S0-62
S0-4/S0-29
S0-9
S1-5



2016
S0-2
Sgr A*
0.5”
2024
S0-2
S24
Sgr A*
0.5”