General Relativistic Measurement of Mass of the Galactic Massive Black Hole

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Introduction

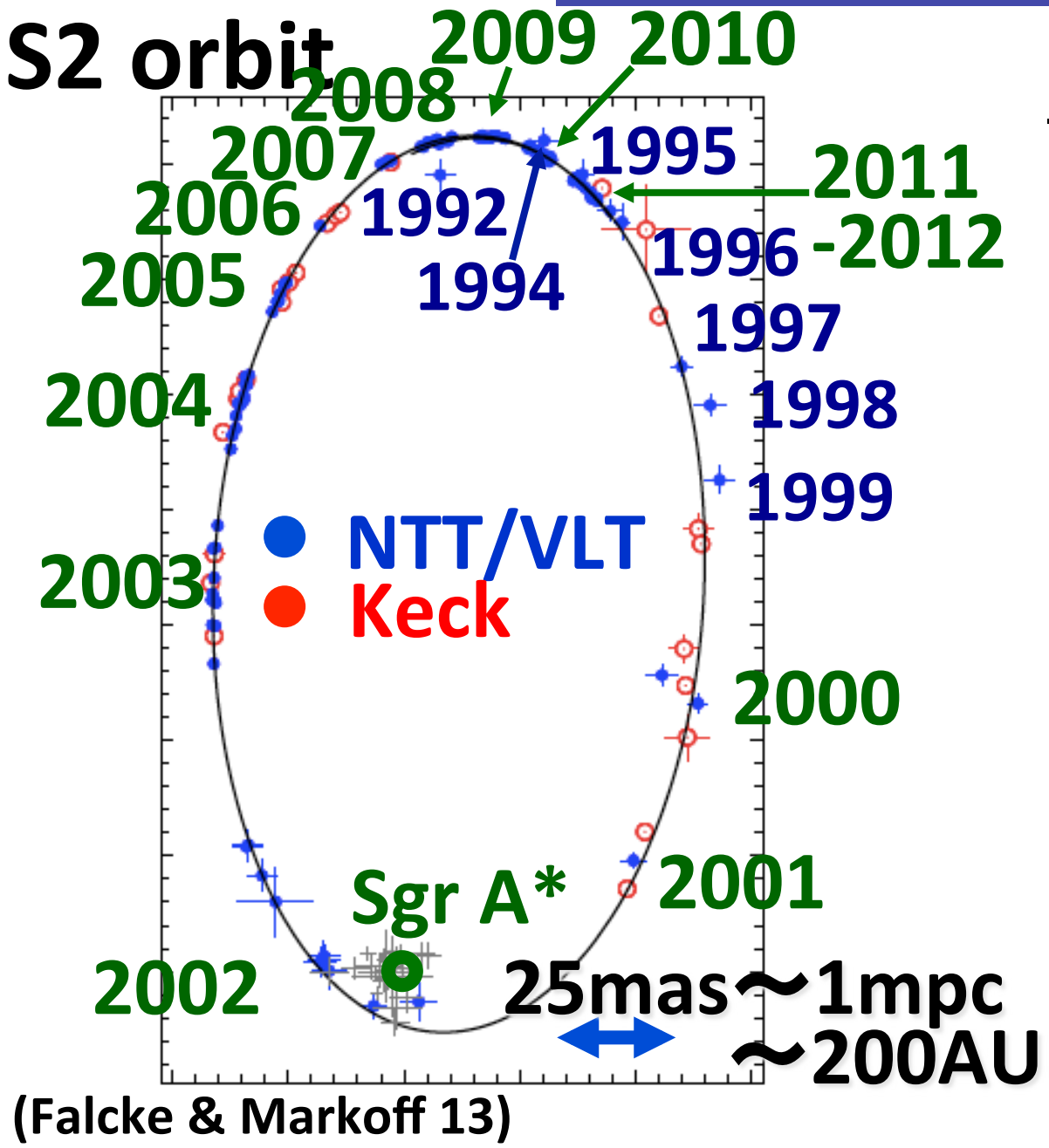
"Direct" observation of BH (*our* definition)

1. **Detection of General Relativity (GR) effects from a black hole (BH)**
2. **Measurements of the mass and spin of the BH through the GR effects (in the case of no electric charge)**

1st case: GW detection by aLIGO

***No* example by EM wave observations**

Sgr A* & S2



(Falcke & Markoff 13)

S2 (S0-2)

- O8-B0V
- H = 16, K = 14
- Orbital Period: ~16 yr
- Next pericenter: 2018
- Pericenter Dist.: ~1,400 R_S

Sgr A* & S2

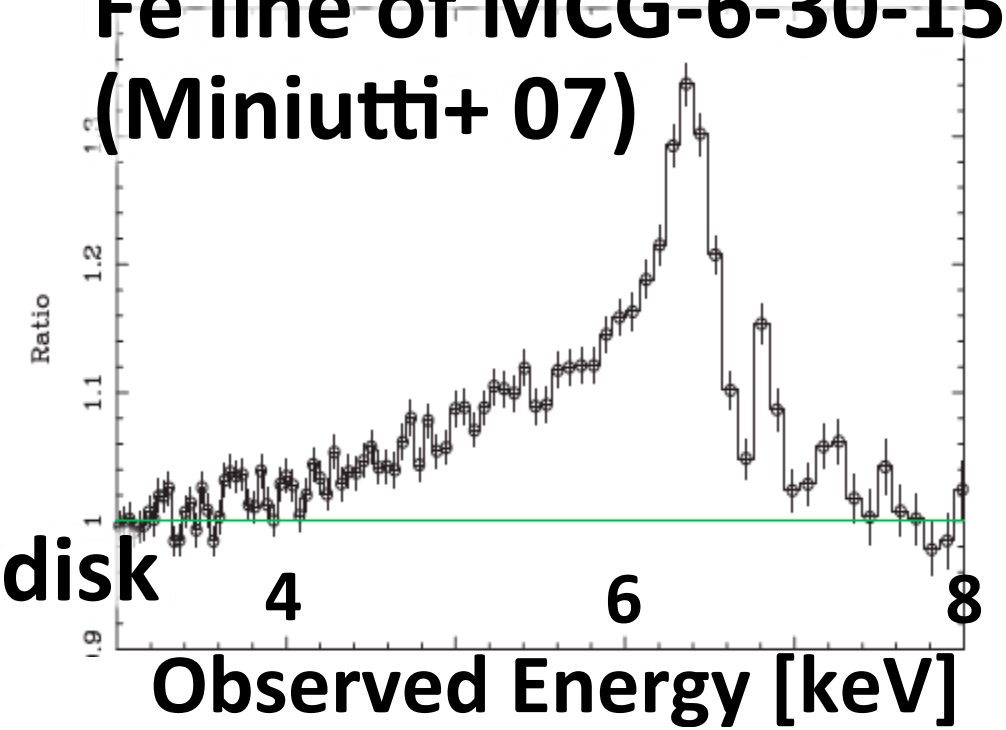
Direct observation of BH (Saida)

1. **Detection of GR effects from a BH**
2. **Measurements of the mass and spin of the BH through the GR effects**

Why Sgr A* & S2?

1. **Strongest grav. field in EM wave observations**
2. **Free from complex physics in accretion disk**

Fe line of MCG-6-30-15 (Miniutti+ 07)

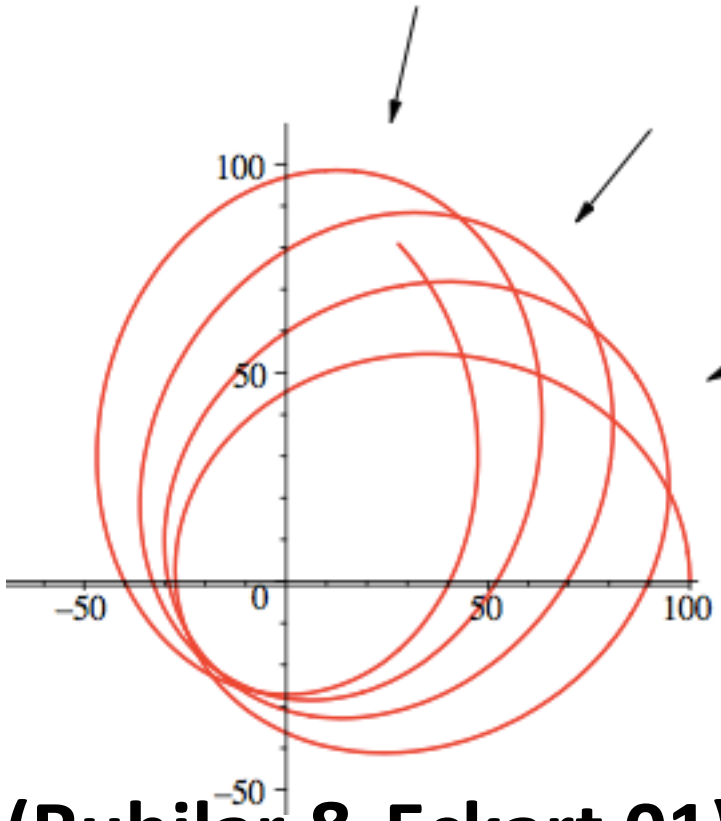


Orbiting Stars: Astrometry

Observations of General Relativistic effects

1. Astrometry

Precession



(Rubilar & Eckart 01)

S2

Shift ~ 1 mas/orbit @apocenter

cf. current accuracy ~ 0.1 mas (Yelda+11)

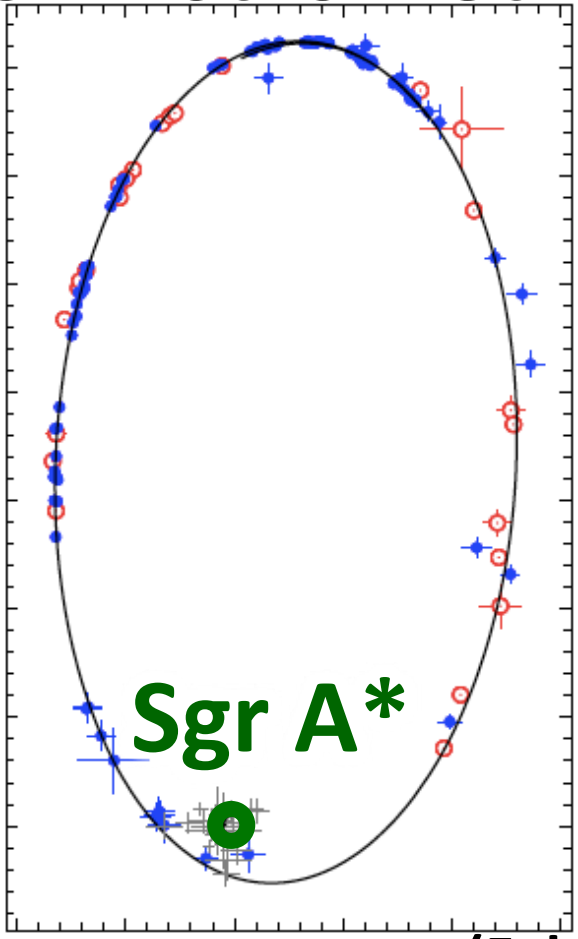
- small shift @pericenter
- confusion with Sgr A*
- next apocent.: 2025

Orbiting Stars: Radial Velocity

Observations of General Relativistic effects

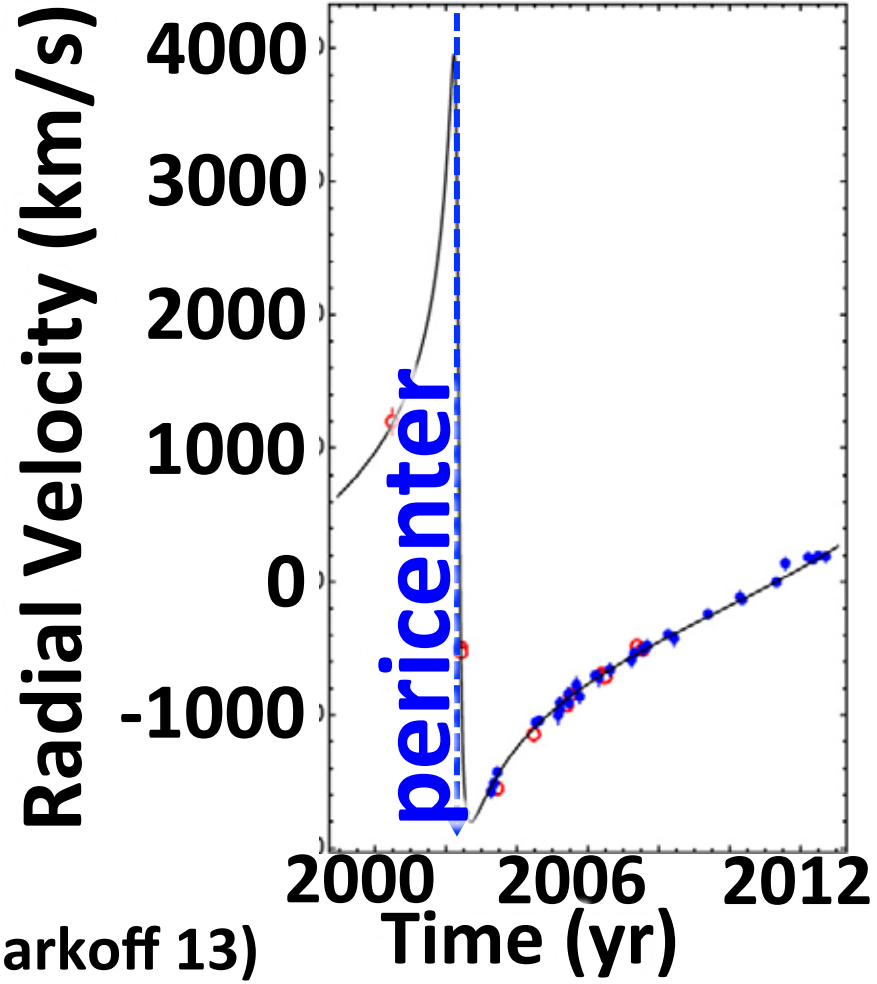
2. Radial Velocity (RV)

S2 Astrometry

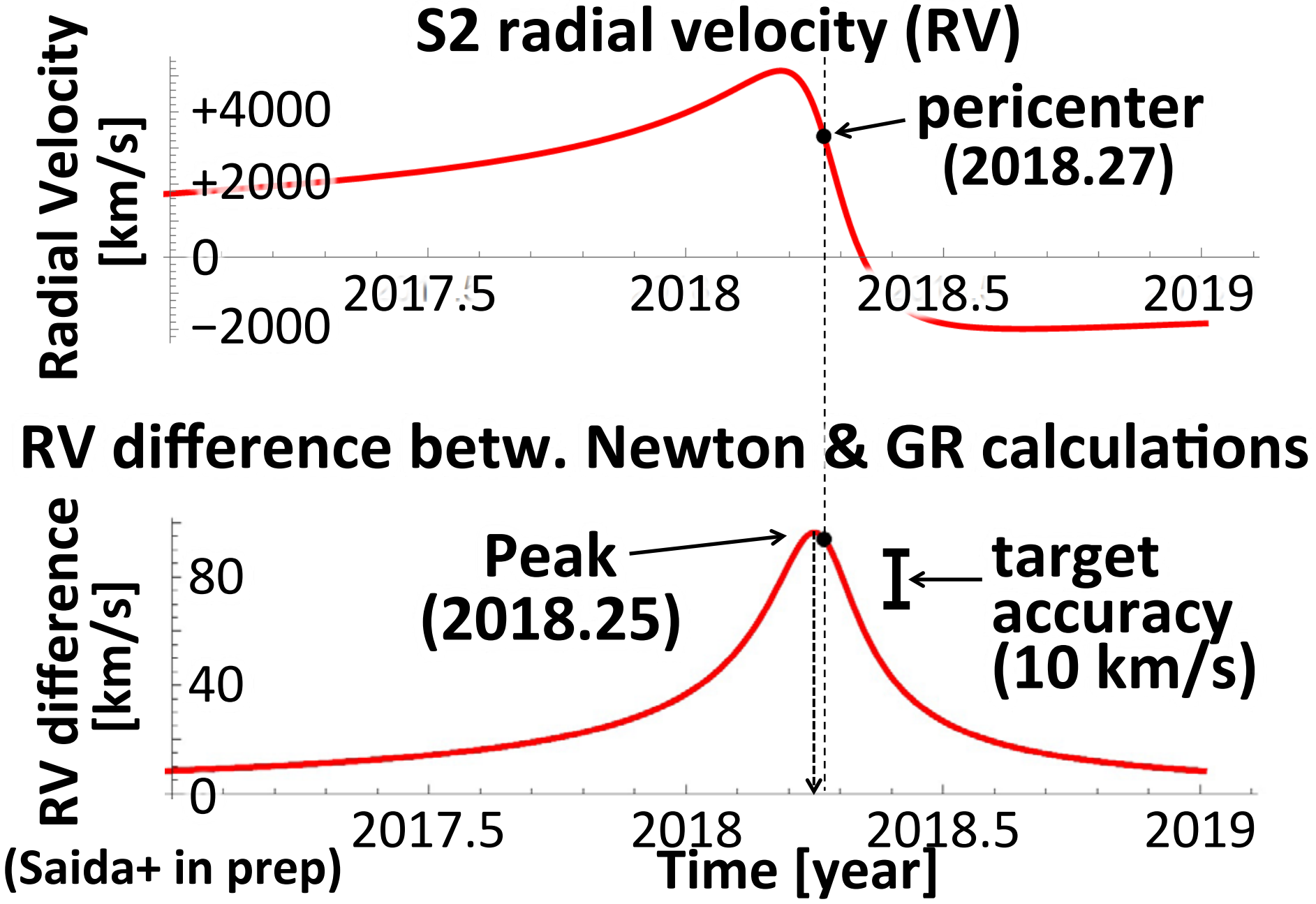


(Falcke & Markoff 13)

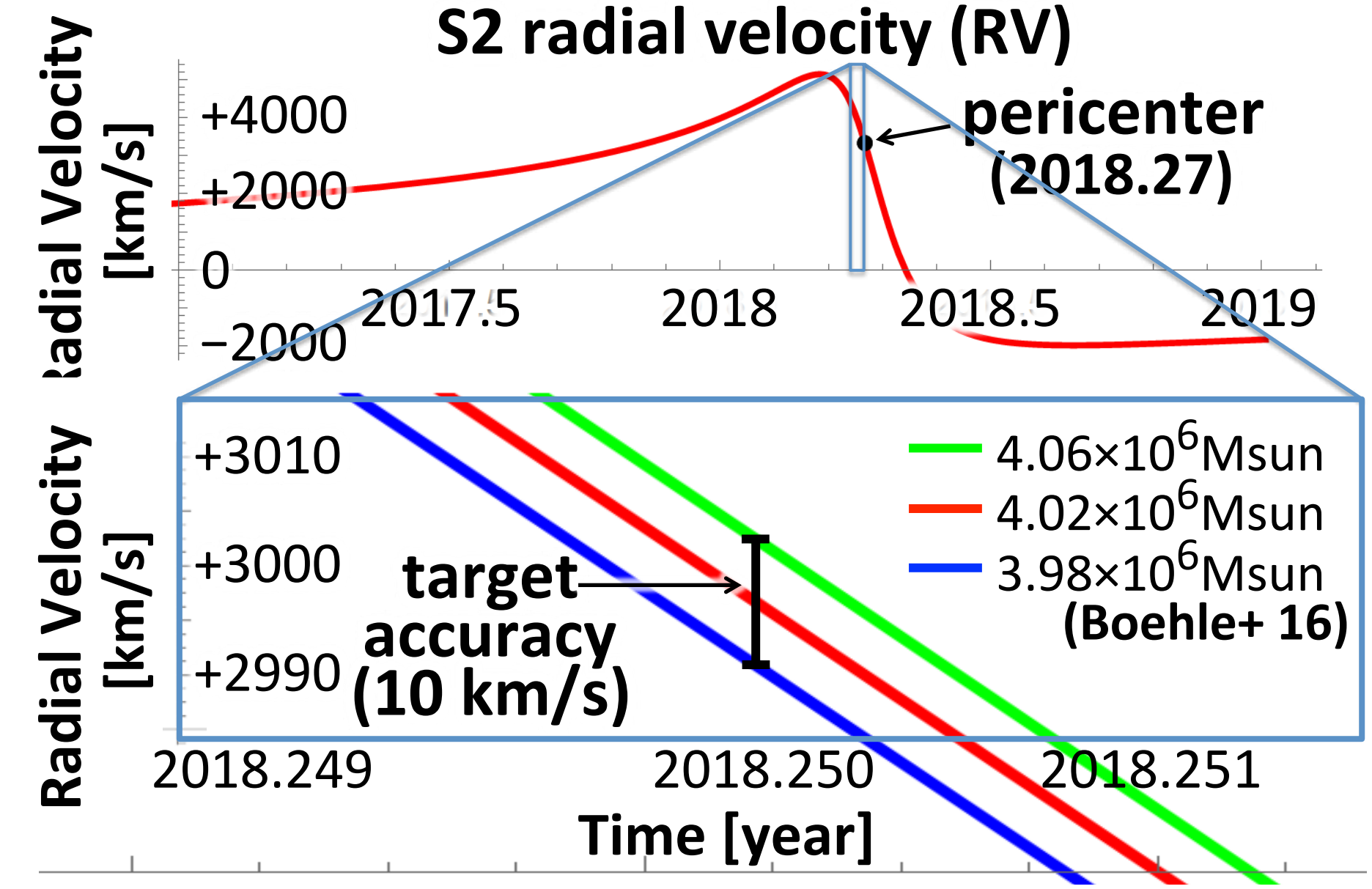
S2 Radial Velocity



S2 Radial Velocity



S2 Radial Velocity



(Saida+ in prep)

S2 Observations with Subaru

2014/5 1st obs, 2-half night

2015/8 ~~2nd obs~~, 2-half night

LGS unavailable, bad weather

2016/5,7 3rd obs, 4-half nights

2: good, 2: bad weather

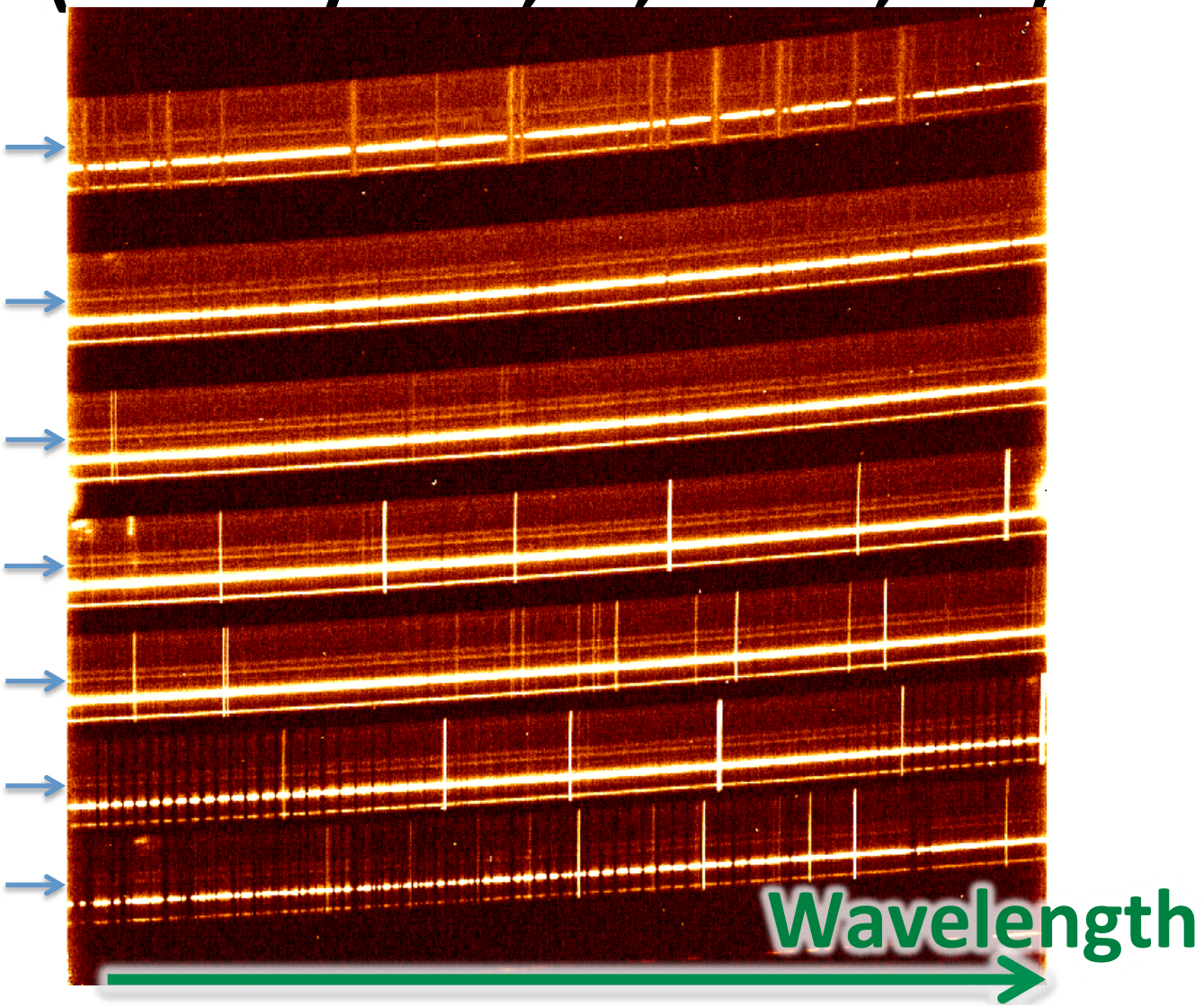
The shuttle to Hilo did not come

My flight to Japan cancelled

Credit: Sean Goebel/NAOJ

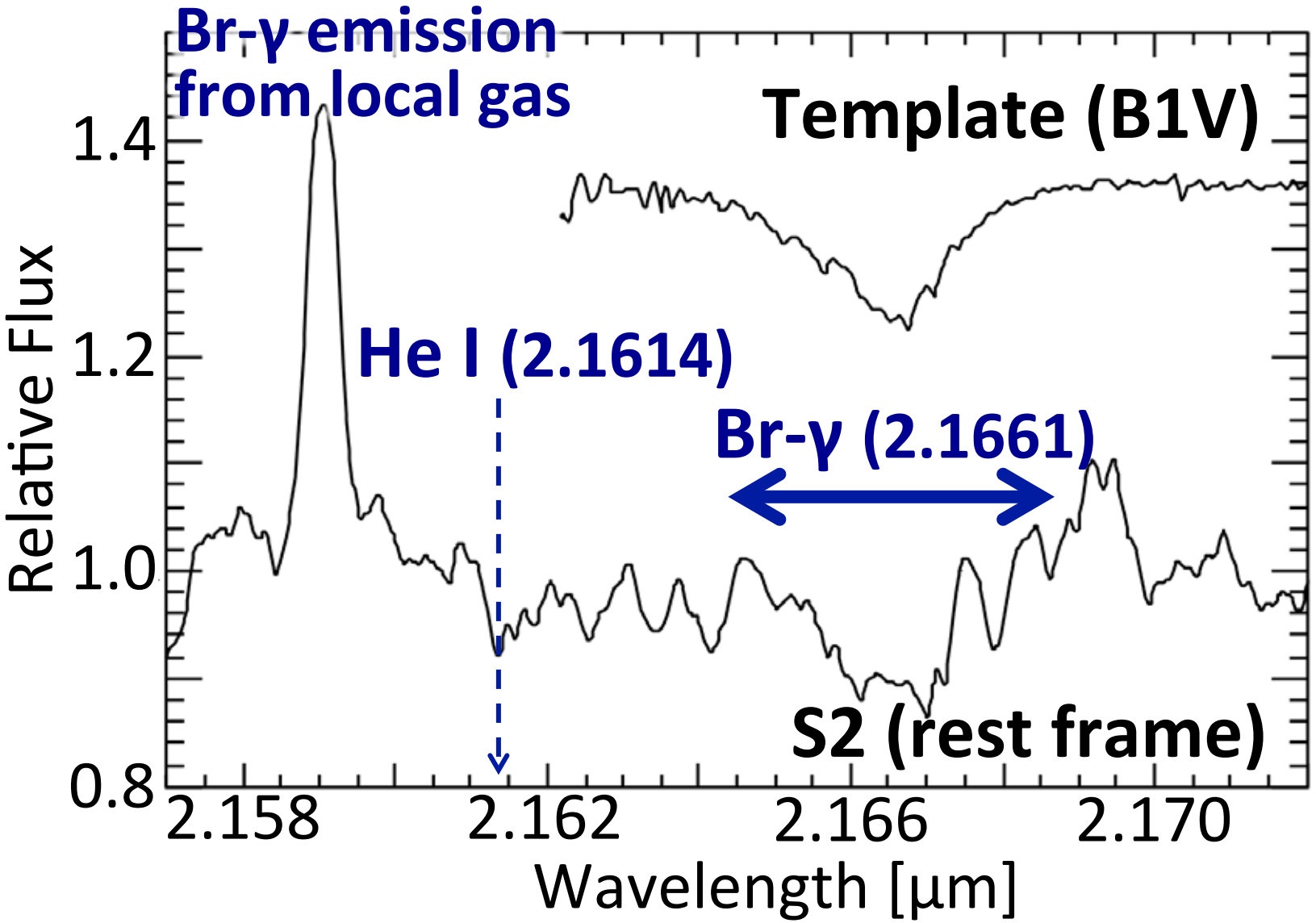
S2 Observations with Subaru

S2 Spectrum
(Subaru/IRCS,*K*+, *R* ~20,000)



S2 Observations with Subaru

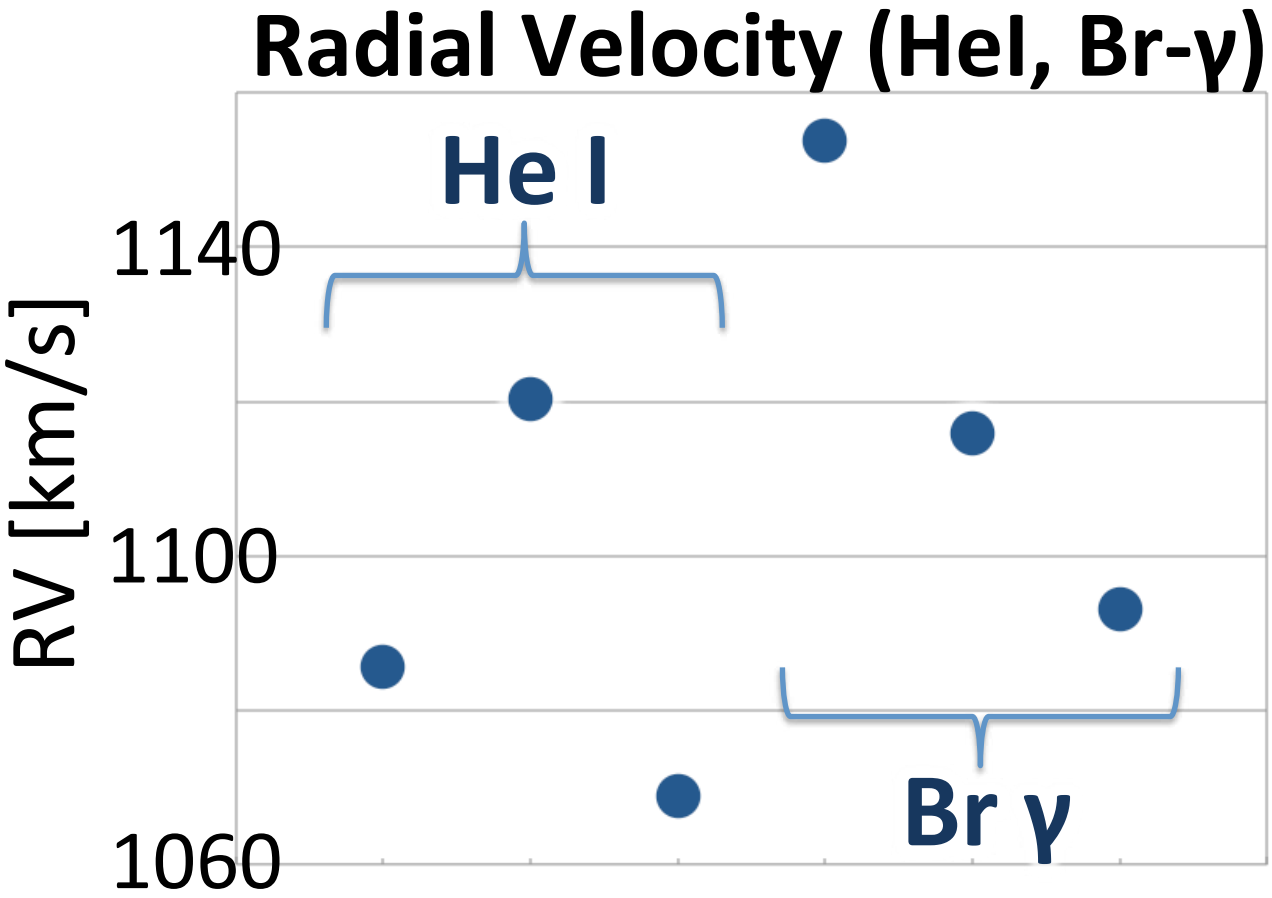
S2 Spectrum (2.16-2.22μm, 4hr, May2016)



S2 Observations with Subaru

RV uncertainty for Br-γ absorption (May/2016)

S2: 300 sec × 32 sets → (300×12 or 10) × 3 sets



STD error

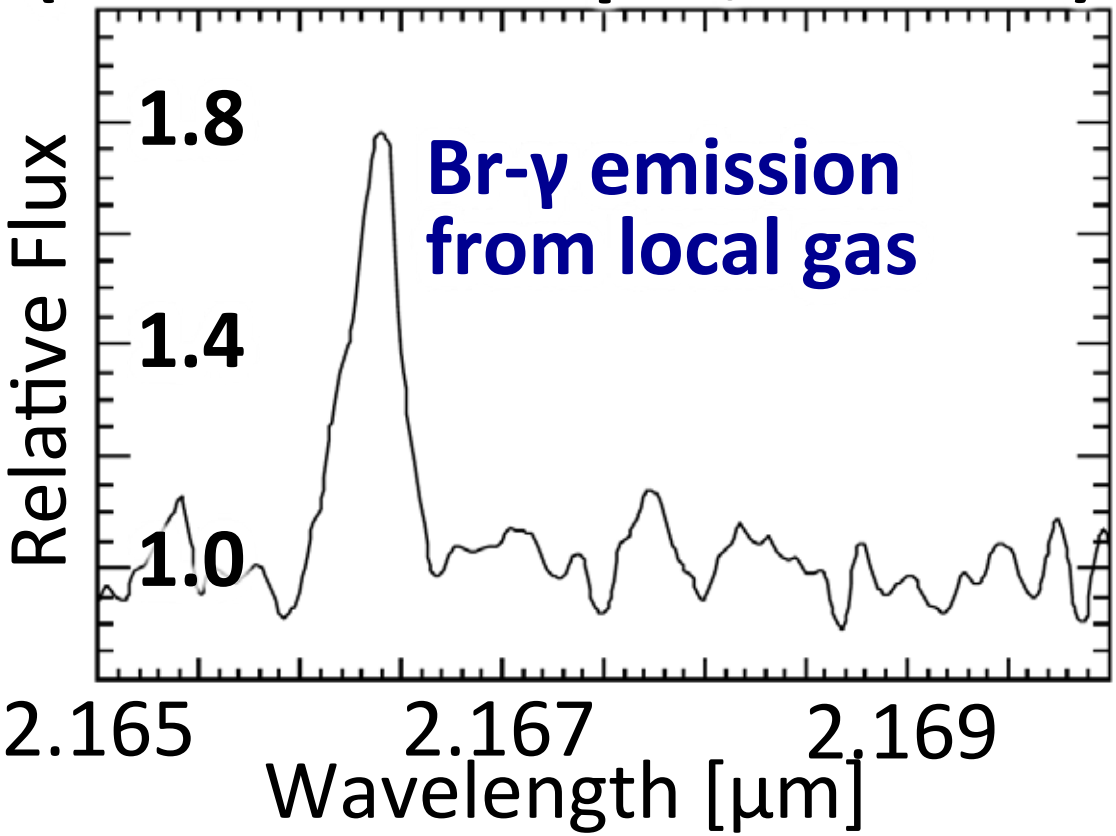
= 30.1/√6

= 12.3 km/s

S2 Observations with Subaru

Internal systematic uncertainty

S2 Spectrum
(2.165 - 2.170 μm, 160min)



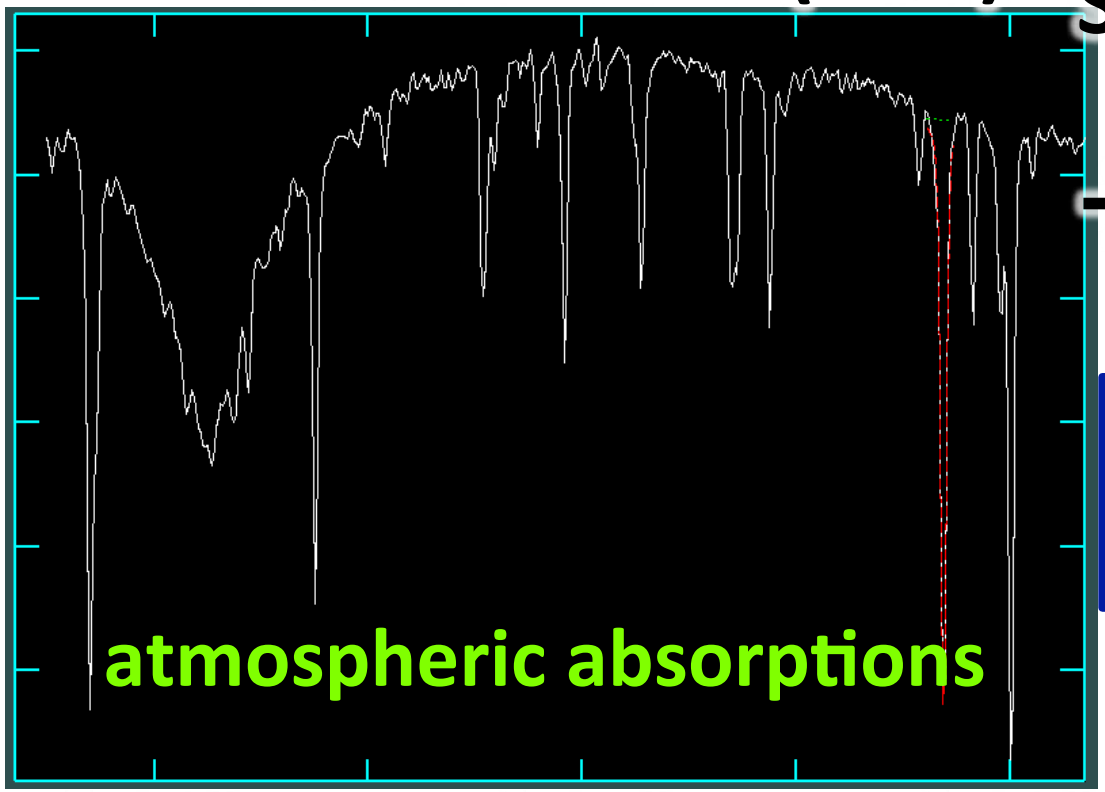
Stability of λ of Br-γ emission → internal uncertainty

STDDEV of 3 sets = 25 nm → 3.5 km/s

S2 Observations with Subaru

long-term stability (additional systematic error)

Telluric standard (A0V)

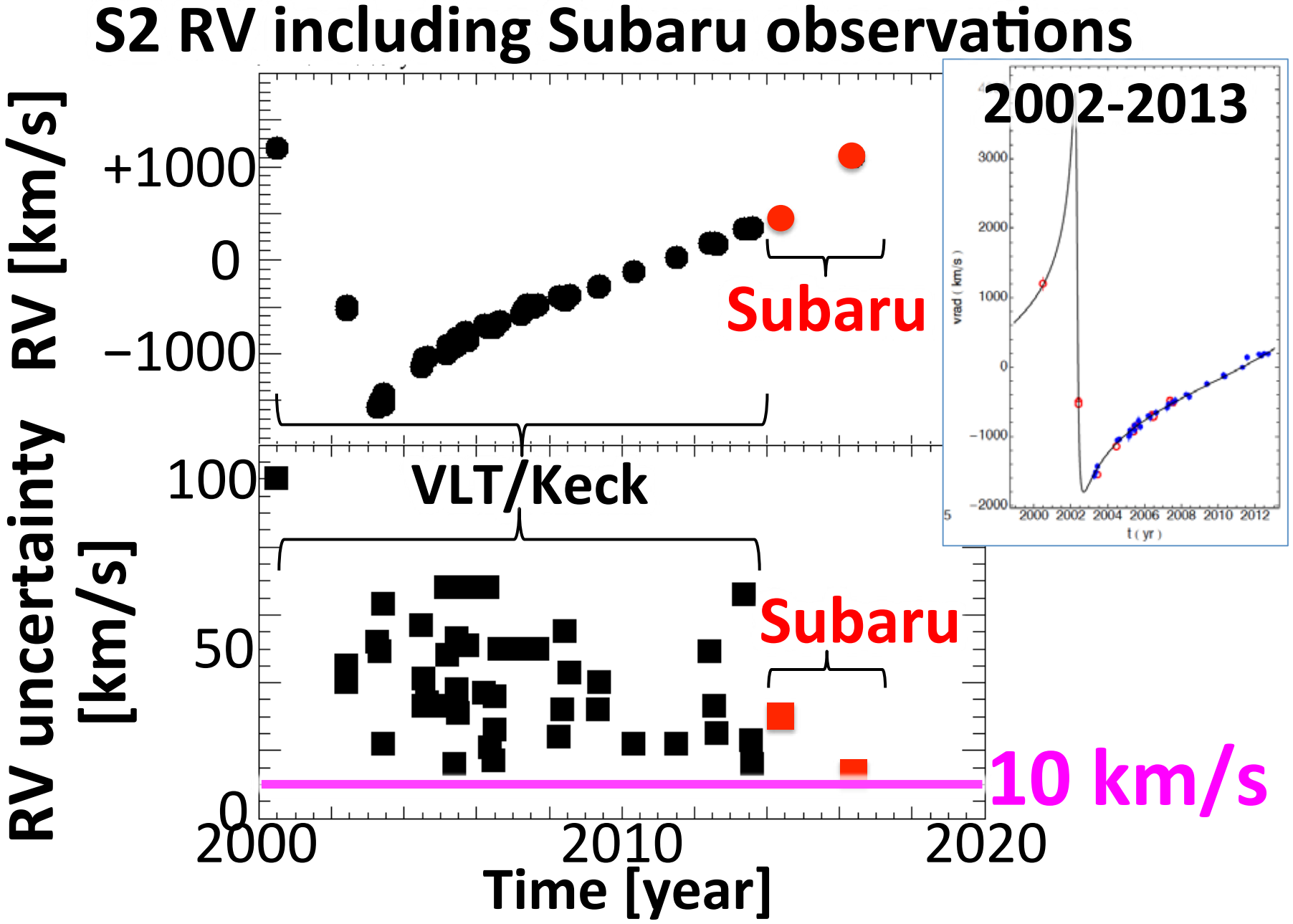


Same reduction and λ-calibration

→ stability of atmos. absorption lines

→ σ ~5 km/s in RV (2014 - 2016)

S2 Observations with Subaru



Summary & Future Works

Aims: Detection of GR effects from Sgr A*

Measurement of the mass through GR effe

Results: σ ~13 km/s (2016)

→ 10 km/s (longer *t*, more lines)

Observations:

2014/5 1st obs, 2-half night

2015/8 ~~2nd obs~~, 2-half night

2016/5,7 3rd obs, 4-half nights

☆2017/5 4th obs, 4-half nights (in GW)