Unveiling brown dwarf's atmosphere from observations with REACH/Subaru

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Outline

1. Introduction
2. First Scientific Demonstration of REACH:
   Atmospheric Retrieval Analysis of HR 7672B
3. Report on Periodic Noise in REACH Spectra of Faint Targets
4. Summary and Conclusions

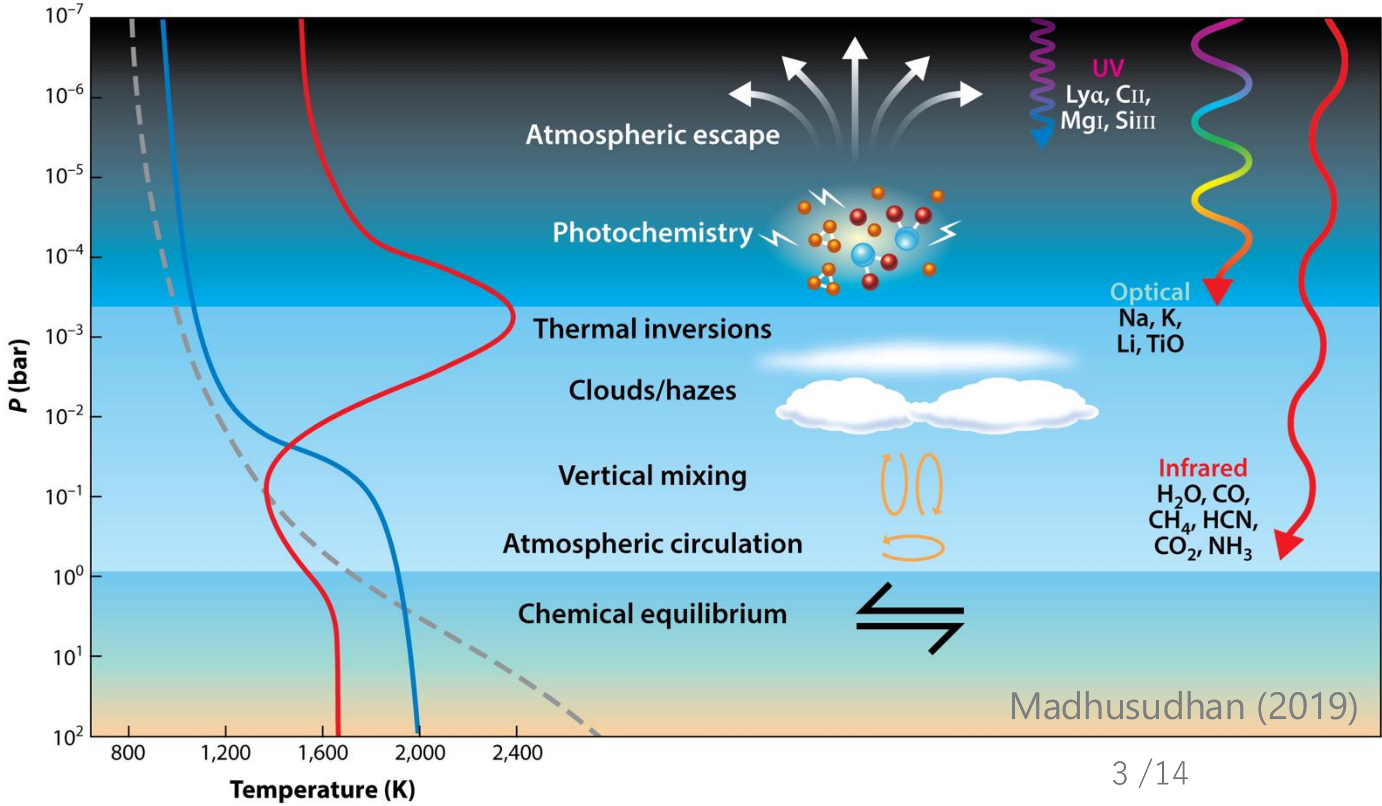
Atmospheric Characterization of Substellar Objects

- <u>Understand Atmospheric Conditions</u>
  - **Chemical and physical processes** in the atmosphere
    (Chemical reactions, cloud formation, temperature structure, etc...)
  - Search for evidence of life (Biosignatures)

- <u>Formation and Migration History</u>
  - From compositions,
    ratio of elements (e.g., C/O)

Current targets: hydrogen-rich atmospheres
(e.g., Hot-Jupiters and Brown dwarfs)

→ Toward advancing characterization of
smaller planet atmospheres

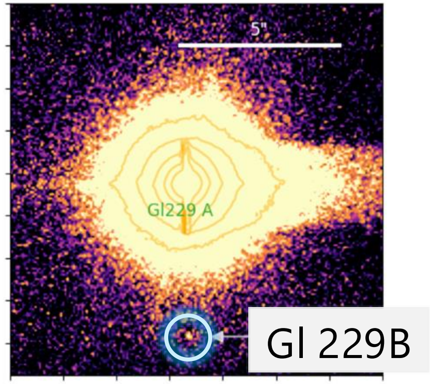


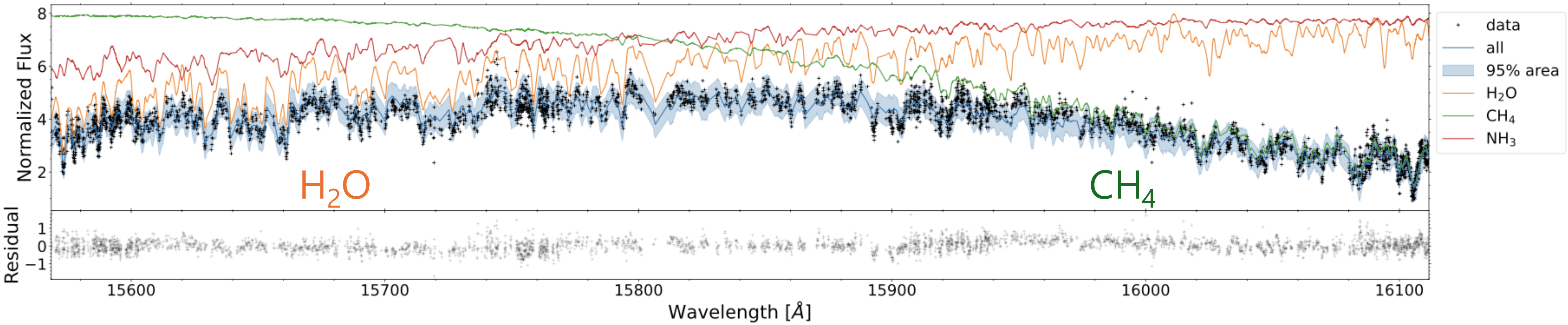
Madhusudhan (2019)

Atmospheric Retrievals Using High-Resolution Spectra

Find a model by exploring a wide parameter space w/ Bayesian inference

High-resolution spectrum observed with IRD+AO188 (Kawashima et al. 2024)





High-resolution spectra → Detailed understanding of atmospheric properties

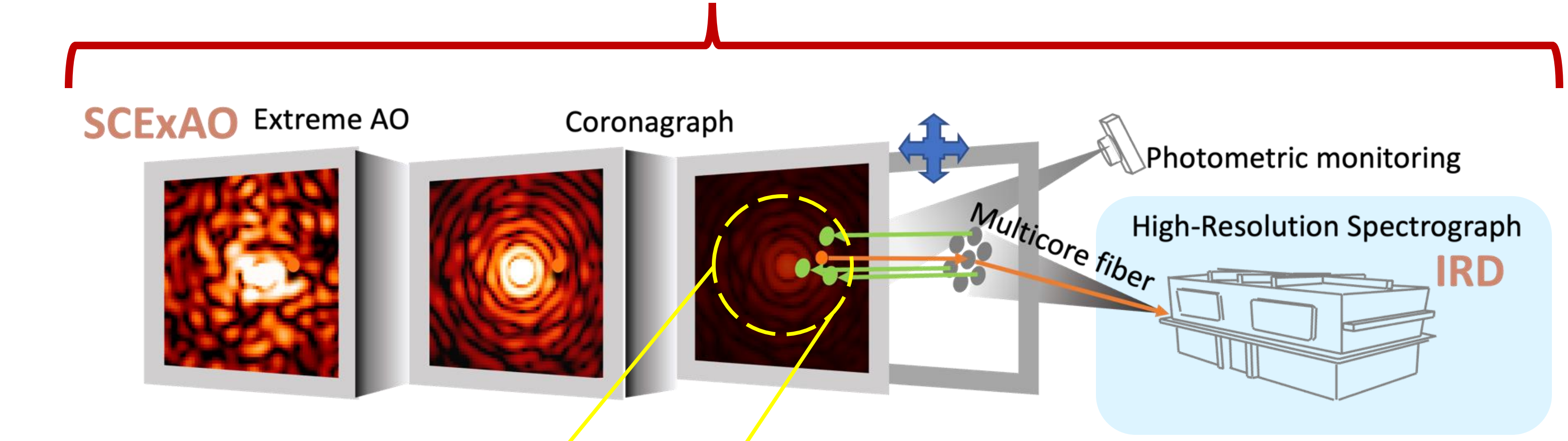
- ✓ Detection of molecules and atoms
  → Chemical composition, Physical processes
- ✓ Pressure broadening/intensity ratio of absorption lines
  → Temperature-Pressure profile
- ✓ Additional opacity → Presence of clouds

Observations of Close Companions with REACH/Subaru

REACH (**R**igorous **E**xoplanetary **A**tmosphere **C**haracterization with **H**igh dispersion coronagraphy)

(Kotani et al. 2020)

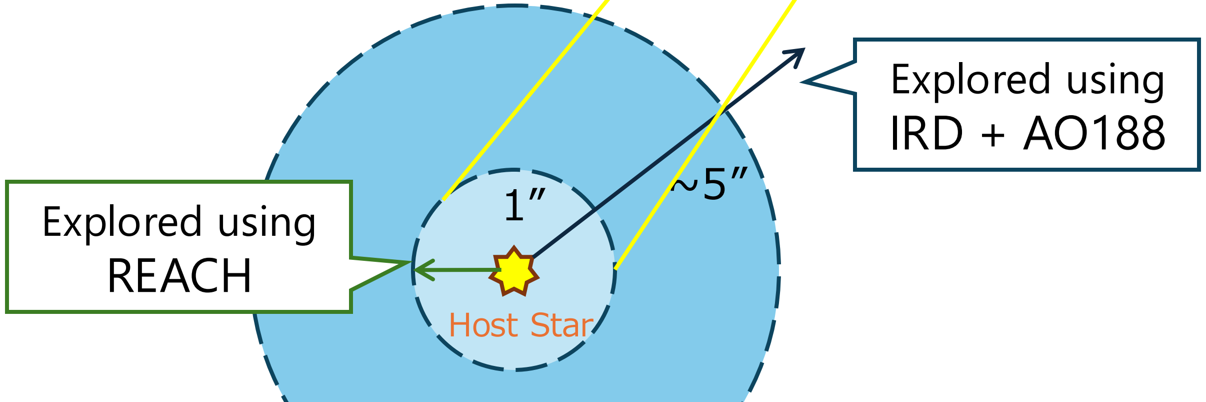
- Y, J, H band
- R~100,000
- Single-mode fiber (ϕ 0.04″)



IRD (**I**nfra**R**ed **D**oppler)

(Tamura et al. 2012, Kotani et al. 2018)

- Y, J, H band
- R~70,000
- Multi-mode fiber (ϕ 0.48″)



Instrumental effects of REACH on faint target spectra have not been well understood…

→ Investigated in this study besides the retrieval analysis

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Target for Retrieval Analysis

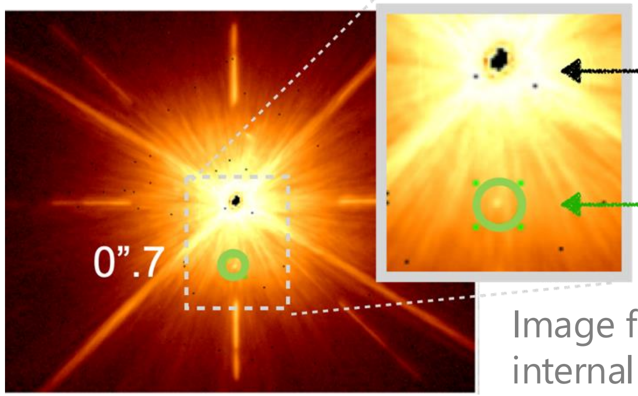


Image from SCExAO internal fast IR detector (Cred2)

	HR 7672A	**HR 7672B**
SpT	G0V	L4.5
Mass	$0.96^{+0.04}_{-0.05} M_{\odot}$	$72.7 \pm 0.8 M_{\mathrm{Jup}}$
Age	$\sim 2 - 4\mathrm{Gyr}$	
J mag	4.689 ± 0.206	14.39 ± 0.20
H mag	4.430 ± 0.204	14.04 ± 0.14

Dynamical mass (Brandt et al. 2019)

- **Observations** (PI: H. Kawahara)
- HR 7672B
  - June 6, 2021
  - exp. time: 1500s x2 (S/N~27)
- HR 7672A
  - June 24, 2021
  - exp. time: 60s x2

- **Data Reduction**
- PyIRD ver. 1.0.0 (Kasagi et al., in prep.)

  (ver. 1.1.0 will be released soon!)

Modeling Method for Brown Dwarf Atmosphere

<u>**Brown Dwarf spectrum** calculated by *ExoJAX*</u> (Kawahara et al., 2022, 2024)

- Volume Mixing Ratios of H_2O & FeH,
- T-P profile (power-law),
- Mass,
- Surface gravity,
- Vsini, ...

→ Sampling the posterior distributions of parameters using the Hamiltonian Monte Carlo (HMC) with No-U-Turn Sampler (NUTS) (1000 samples, NVIDIA A100 GPU @ CfCA)

\+ <u>Absorption lines of Earth's Atmosphere (telluric)</u>

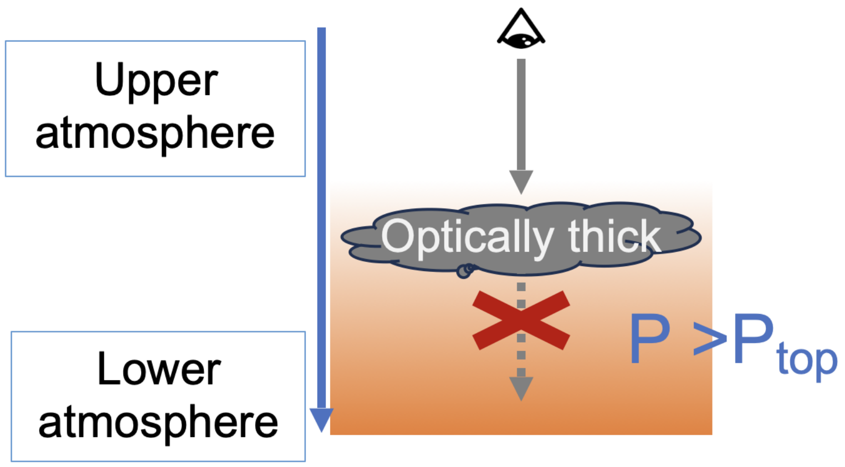
simultaneously modeling by applying ExoJAX

\+ <u>Light leakage from the host star</u>

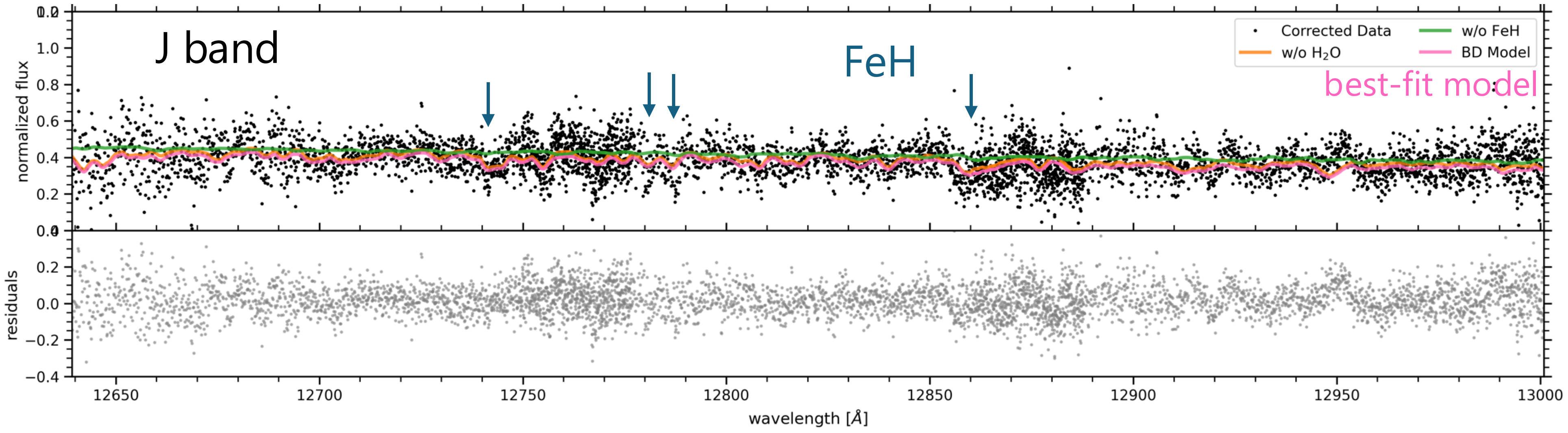
subtract the scaled HR 7672A's spectrum

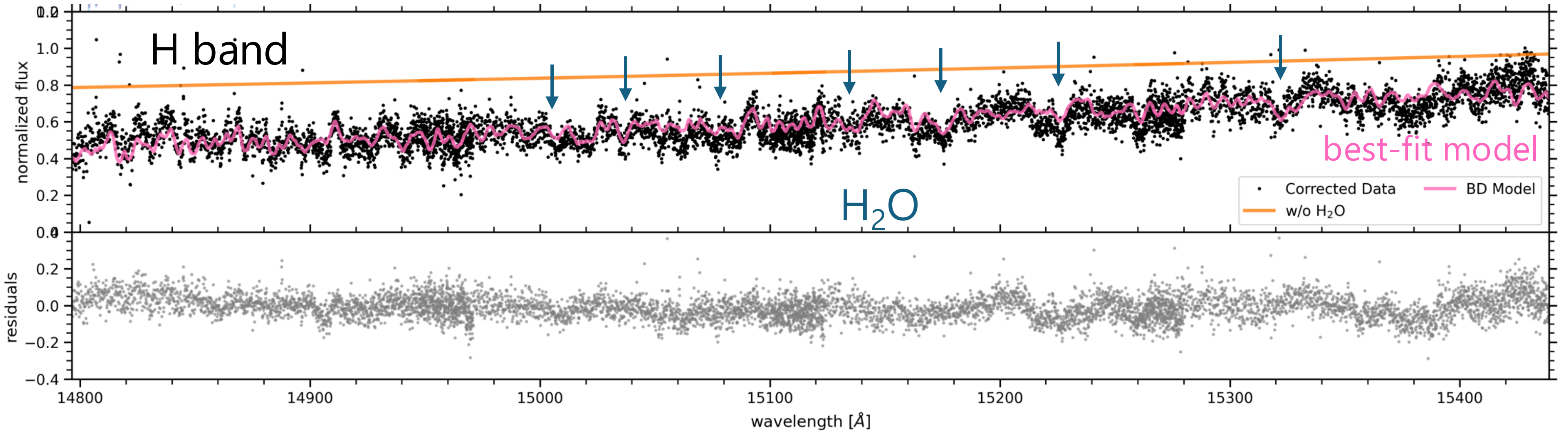
\+ <u>**Clouds (simple model)**</u>

- Cloud-top Pressure (P_{top})



Results





* only fit a portion of J- and H-band spectra & J mag, in this study

Cloud Opacity and CIA: Roles in Spectral Continuum Modeling

- Clouds are located at a specific altitude

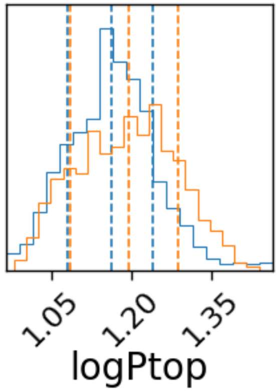
  ← Different wavelength dependencies of the spectral continuum were observed:

  - J-band: Wavelength-independent continuum by cloud opacity
  - H-band: Wavelength-dependent continuum by CIA

Pressure of cloud top

$\log P_{\rm top} = \mathbf{1.16^{+0.08}_{-0.08}}$

$(1.20^{+0.09}_{-0.11})$

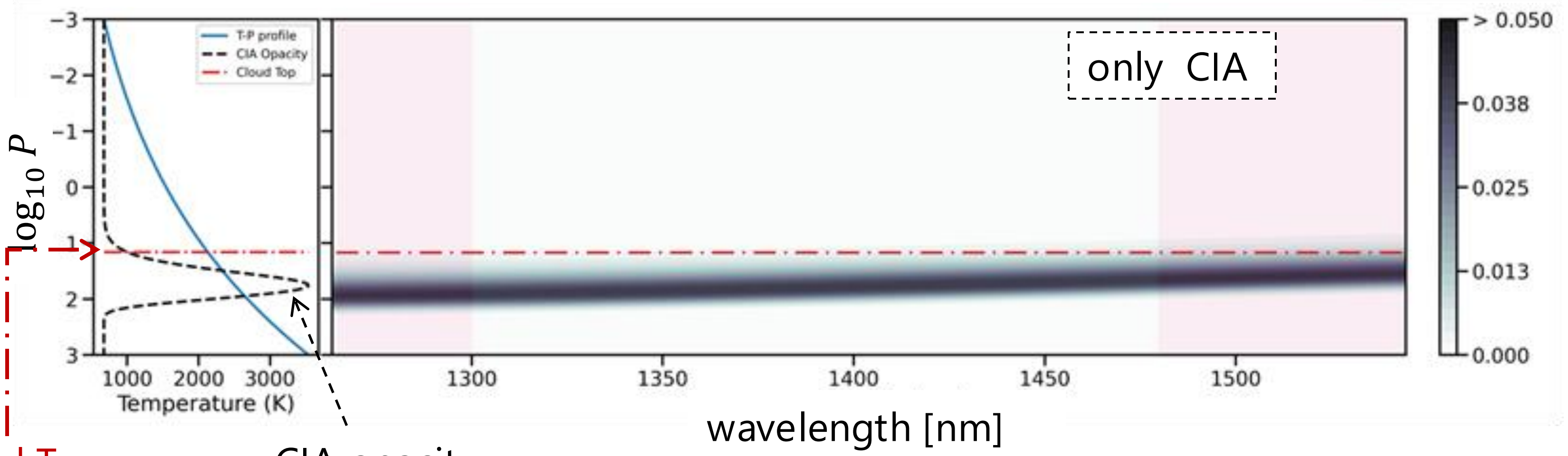


– Mass-Constrained (prior: $\mathcal{N}(72.7,0.8)$)

– Mass-Free (prior: $U(1,150)$)

Spectral averaged contributions

Line opacities (H_2O, FeH) + Cloud opacity + CIA



Cloud Top

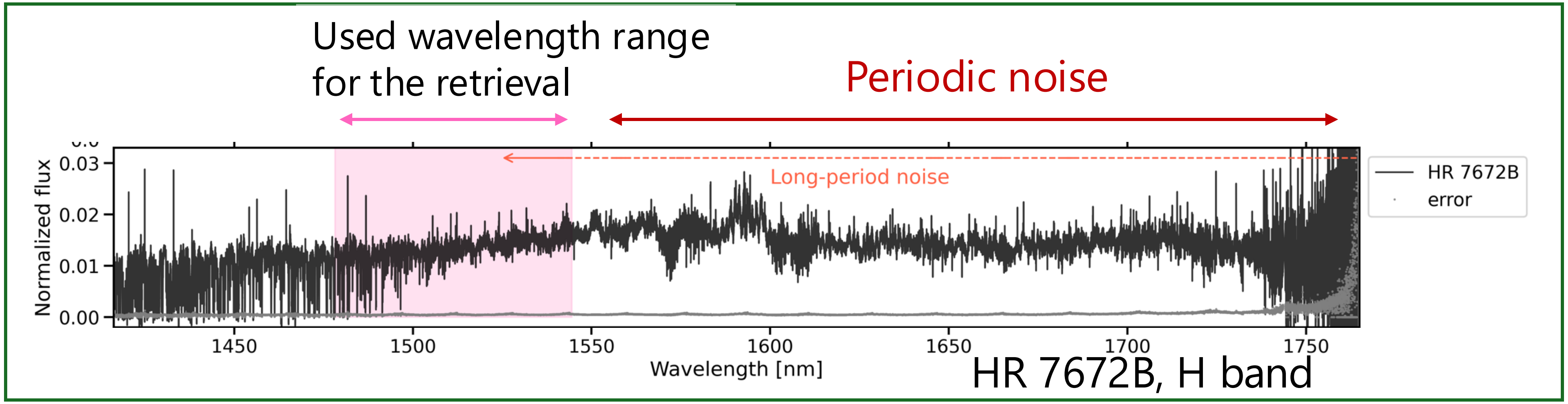
CIA opacity

(Collision Induced Absorption; H_2-H_2, H_2-He)

Outline

1.

2.



3. Report on Periodic Noise in REACH Spectra of Faint Targets

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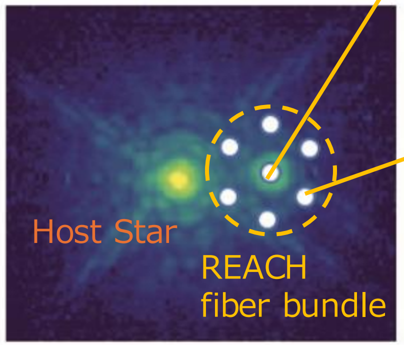
Properties of Periodic Noise

- We found an unknown periodic noise in REACH spectra.
  - ➢ Short-period noise: ~0.18 nm
  - ➢ Long-period noise: ~1.2 nm
- It affects a wide wavelength range in the spectra, with a particularly strong impact on the H-band.

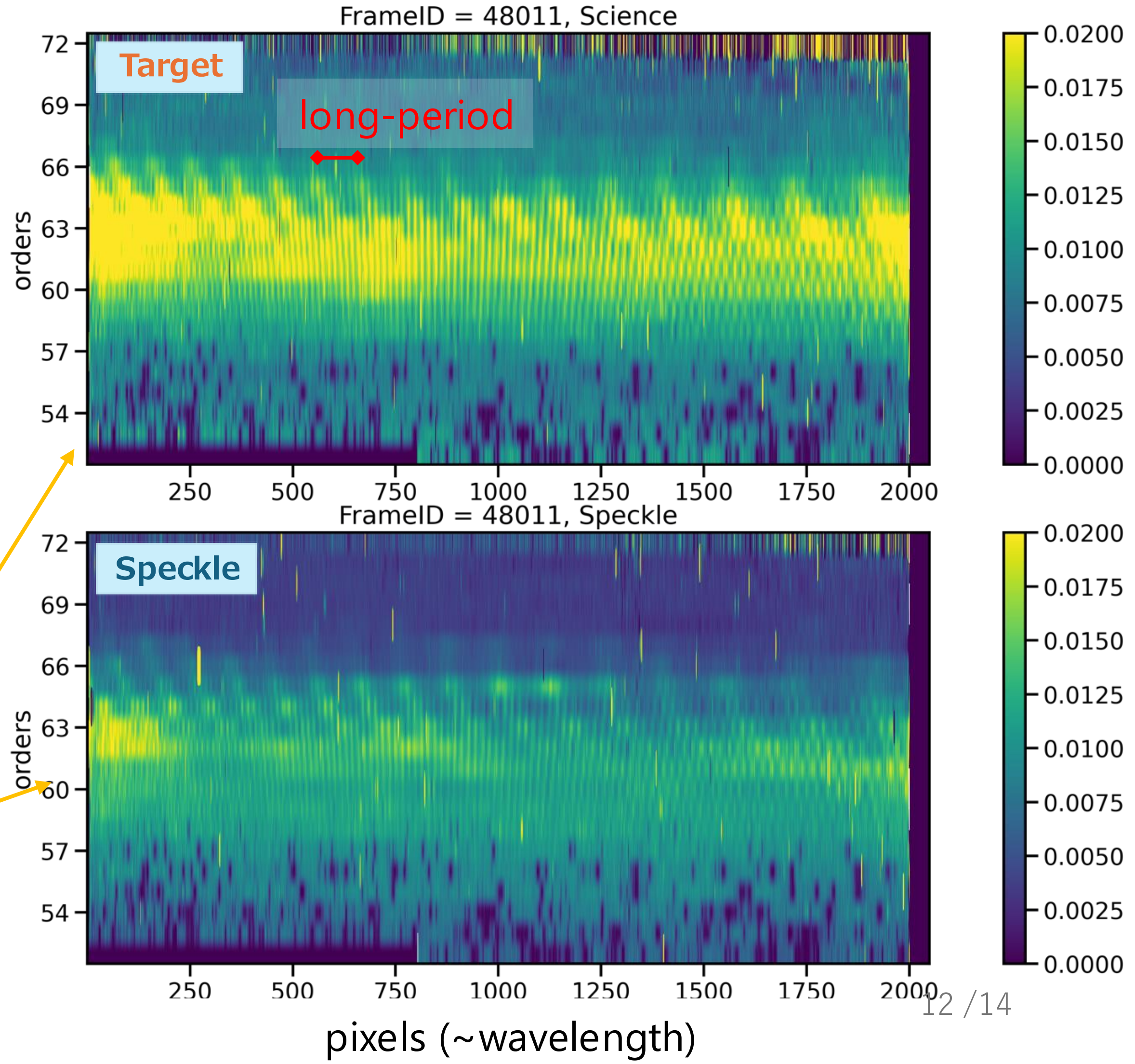
- The exact cause is unknown, but it needs to be mitigated for further analysis, including atmospheric characterization.

✓ Related to single-mode fibers?

✓ Periodic noise was NOT observed in IRD observations (IRD uses multi-mode fibers)



H-band Normalized Flux (color map)



Mitigation Strategies for Periodic Noise

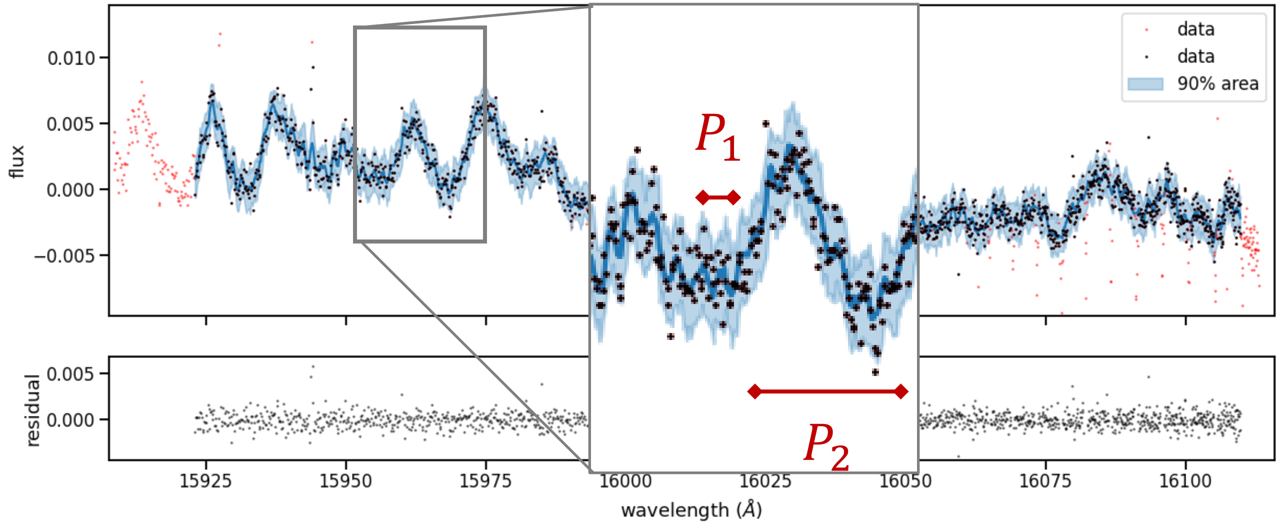
- **A simultaneous modeling with brown dwarf spectra is necessary** because it is challenging to distinguish between noise and absorption lines

1. Kernel Parameter Estimation:
   Gaussian Process (GP) is applied to speckle spectra

Periodic kernels RBF kernel

$$kernel(x, x') = A \exp\left[-\Gamma_1 \sin^2\left(\pi \frac{(x-x')}{P_1}\right) - \Gamma_2 \sin^2\left(\pi \frac{(x-x')}{P_2}\right) - \frac{(x-x')^2}{2l^2}\right]$$

speckle light from host star ← periodic noise is dominant



2. Apply to Target Spectra:
   Using the derived P_1 and P_2,
   GP is applied to simultaneously model both BD spectrum & noise

Validation of this method has not completed yet…
→ In our retrieval analysis, we focus only on wavelength regions that are less affected by periodic noise.

Summary

Demonstrated the Capability of REACH/Subaru to Unveil Atmospheres of Faint Substellar Objects

■ Atmospheric Retrieval Analysis of L-dwarf HR 7672B

- Spectra modeled using ExoJAX, with additional models for telluric absorption, host star light leakage, and clouds
- Retrieval results suggest clouds are located at a specific altitude
  - Cloud opacity acts as a wavelength-independent continuum in the J-band
  - CIA acts as a wavelength-dependent continuum in the H-band

■ High-Resolution Spectroscopy of Faint Targets Using REACH

- Periodic noise (short-period & long-period) detected in faint spectra
- Exact cause of the noise remains unknown (possibly related to single-mode fibers)
- Applying Gaussian Process to both speckle and target spectra helps distinguish between noise and scientific signals