The Coherent Differential Imaging on Speckle Area Nulling (CDI-SAN) for direct detection of Earth-like exoplanets using ground-based telescopes

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1. Background

◆ **Detection of exoplanets**
- ➢ Goal: discovery of Earth-like exoplanets and detection of biosignatures
- ➢ Problem: brightness ratio (contrast) between a star and a planet
- ➔ Performance requirement: stellar suppression of 10^{-8} - 10^{-10} level

◆ **High-contrast imaging system**
- ➢ Suppressing only stellar light, enabling observation of exoplanets
  - ✓ **Coronagraph**: suppressing the light diffracted by a telescope aperture
  - ✓ **Wavefront control system**: suppressing the light scattered by wavefront aberrations (speckles)
- ➢ The speckles fluctuating faster than the control cannot be suppressed
  - ✓ Ground-based telescope ← Atmospheric turbulence
- ➔ **Coherent Differential Imaging on Speckle Area Nulling (CDI-SAN) method** [1]

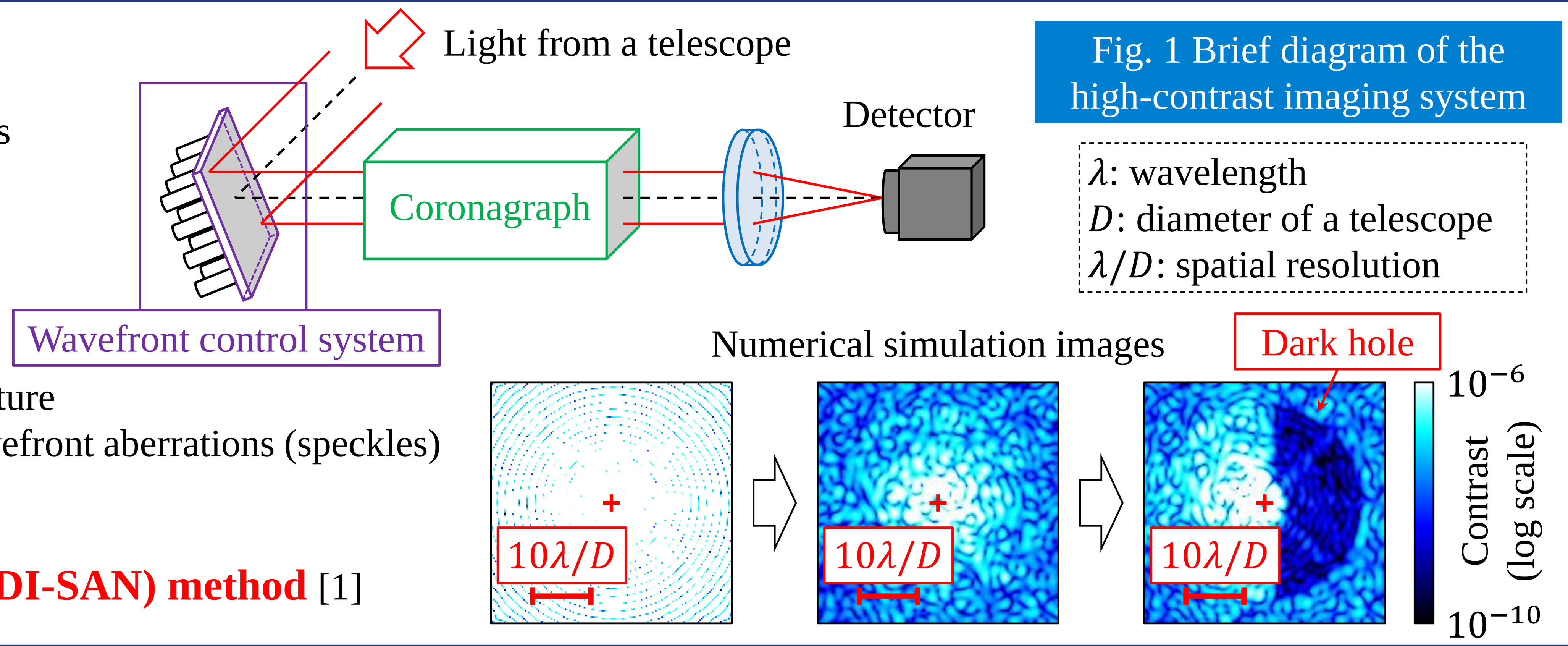

Fig. 1 Brief diagram of the high-contrast imaging system

2. Principle

◆ **Speckle Area Nulling (SAN)** [2]
- ➢ One of the wavefront control method that suppresses speckles in a target region
  - ✓ Synchronized focal plane intensity measurements with 5 wavefront modulations
    - $I_0 = I_s + I_p = |E_s|^2 + I_p$
      (I_s: intensity of stellar light, I_p: intensity of exoplanetary light)
    - $I_{1,2}^{\pm} = \left|E_s \pm \Delta E_{1,2}\right|^2 + I_p$
      ($\Delta E_1, \Delta E_2$: modulated electric field, $\Delta E_1 \cdot \Delta E_2 = 0, |\Delta E_1| = |\Delta E_2|$)
  - ✓ Generating a dark hole by calculating the optimal modulation from 5 intensities

◆ **Coherent Differential Imaging on Speckle Area Nulling (CDI-SAN)**
- ➢ Post-processing technique for subtracting fluctuating speckles from observed image
  - ✓ 5 modulations and measurements are performed repeatedly at high speed
  - ✓ Fluctuating speckles are subtracted using integral intensities of focal plane

$$I_{p1} = \langle I_0\rangle - \langle I_s\rangle = \langle I_0\rangle - \left[\frac{\langle (I_1^+ - I_1^-)^2\rangle}{8(\langle I_1^+\rangle + \langle I_1^-\rangle - 2\langle I_0\rangle)} + \frac{\langle (I_2^+ - I_2^-)^2\rangle}{8(\langle I_2^+\rangle + \langle I_2^-\rangle - 2\langle I_0\rangle)}\right]$$

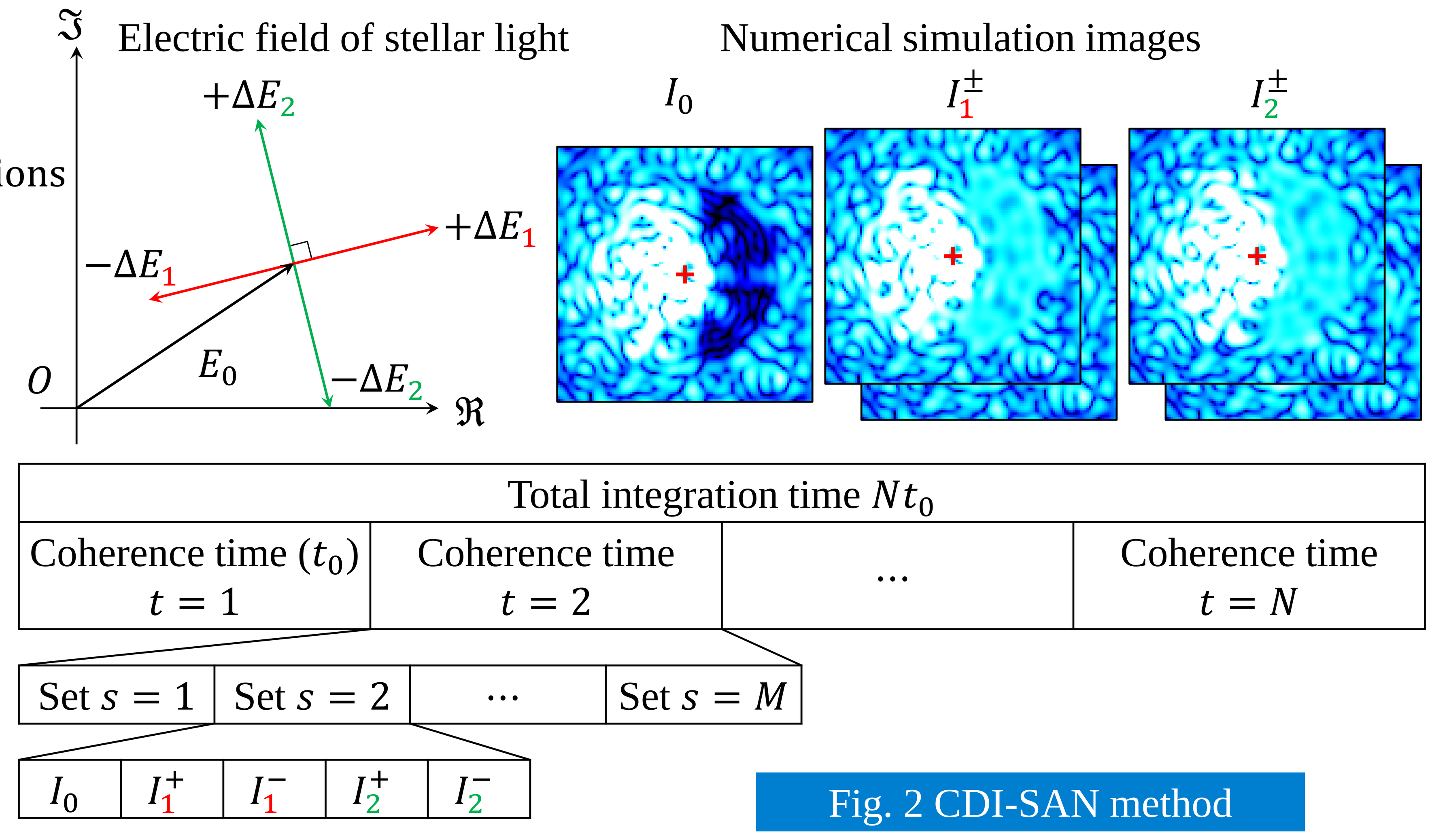

Fig. 2 CDI-SAN method

3. Laboratory Demonstration

◆ **Laboratory setup**
- ➢ Coronagraph: 8-Octant Phase Mask (8OPM) coronagraph
- ➢ Wavefront control device: deformable mirror (DM) with 492 actuators

◆ **Procedure of the laboratory demonstration**
- ➢ Diffracted stellar light was suppressed by the 8OPM coronagraph
- ➢ Static speckles were suppressed by the SAN method
- ➢ Residual speckles were suppressed by the CDI-SAN method
  - ✓ The DM and the focal plane camera were controlled by the PC1 or the FPGA

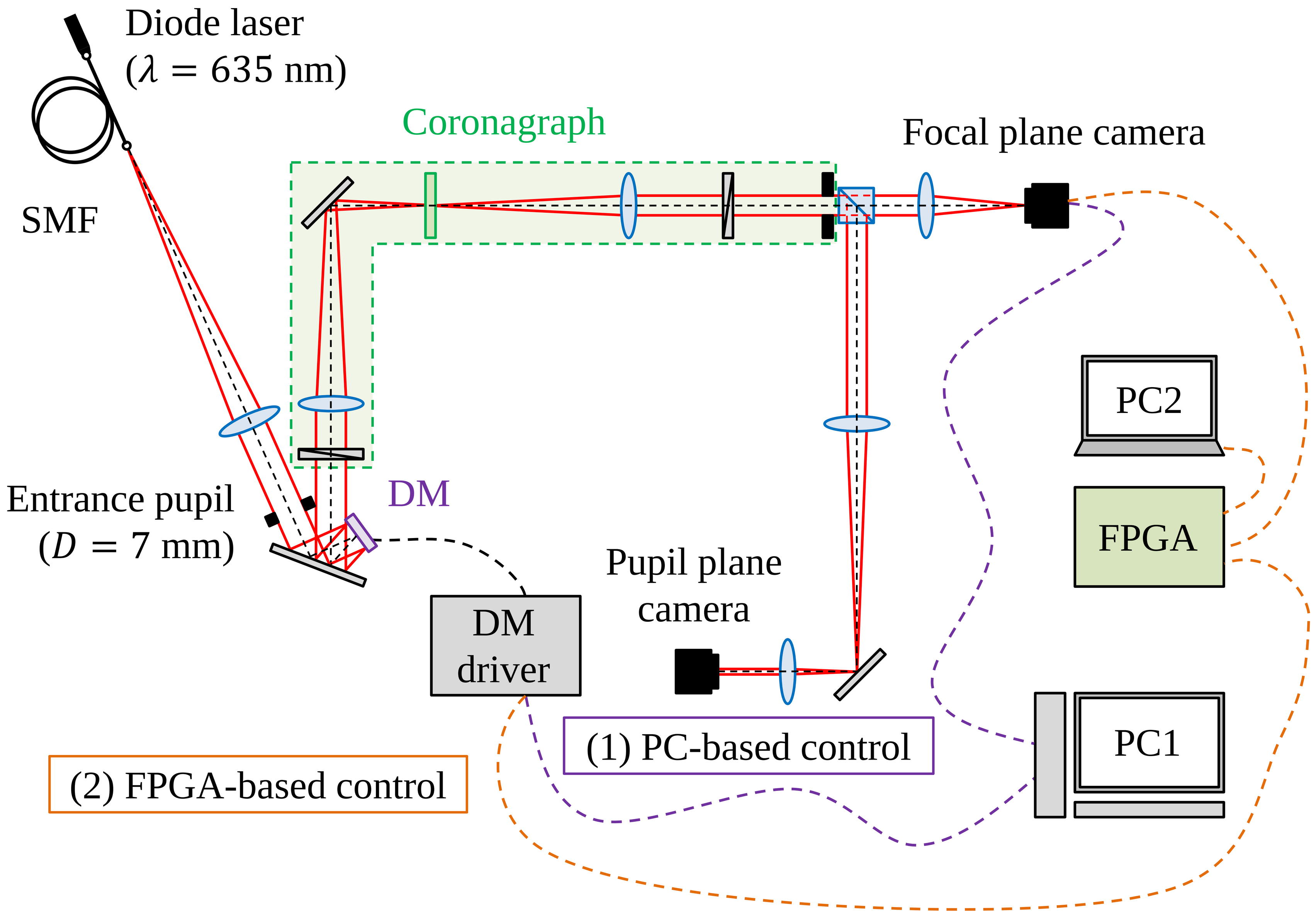

Fig. 3 Optical setup

◆ **Results of the laboratory demonstration**
- ➢ **The contrast was improved by the CDI-SAN method**
  - ✓ The contrast improvement by CDI-SAN in the target region
    - 0.15 (before the dark hole generation)
    - 0.62 (after the dark hole generation)
  - ✓ Same results were acquired by the PC-based and the FPGA-based control

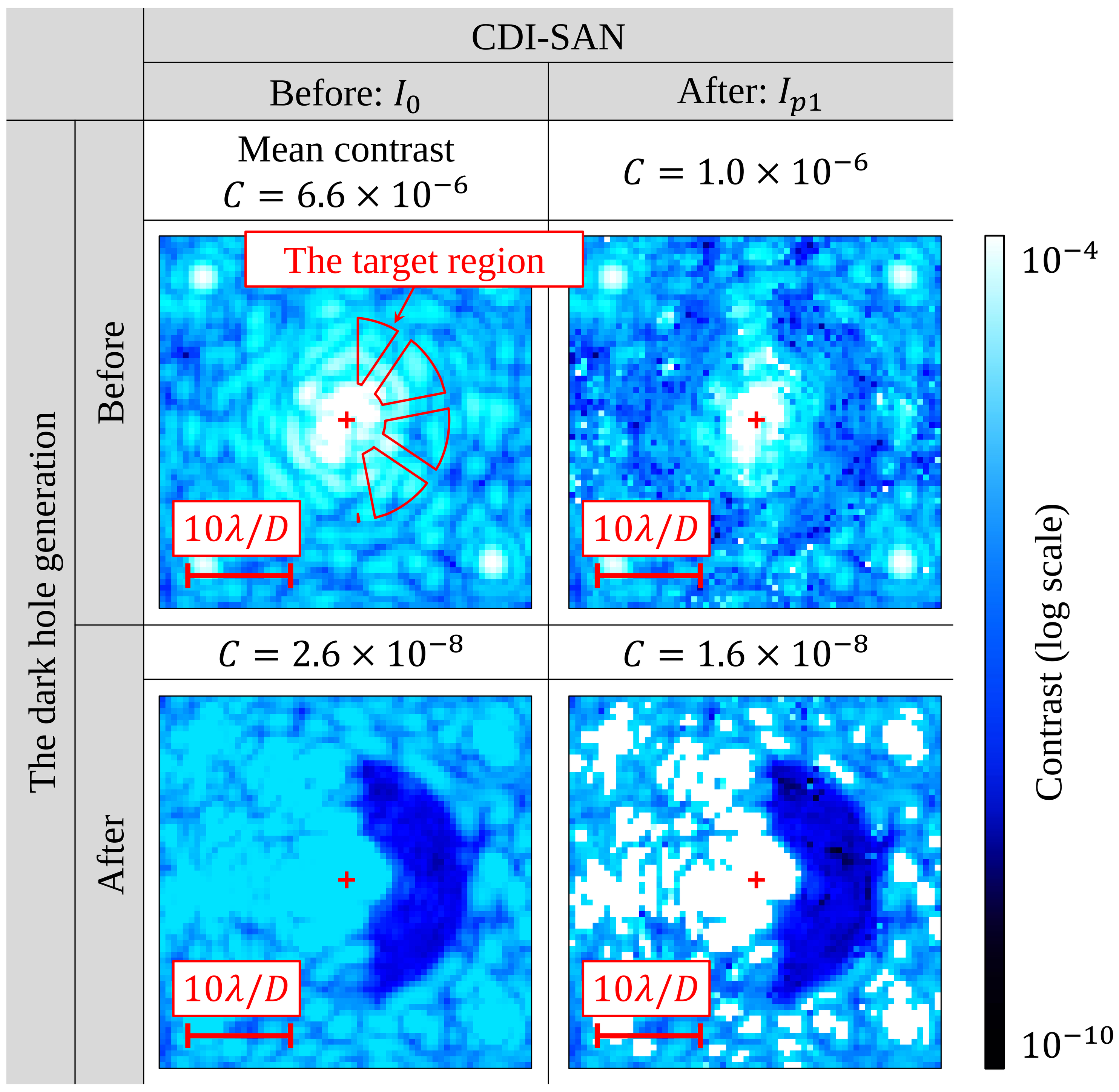

Fig. 4 Demonstration results of the PC-based control

4. Conclusion

◆ **The CDI-SAN method successfully suppressed residual speckles**

◆ **Future works**
- ➢ Investigating causes of limitation of the contrast improvement by the CDI-SAN method
- ➢ Developing the wide wavelength range CDI-SAN method

References

[1] J. Nishikawa, *Astrophys. J.*, **930**, 163 (2022).
[2] M. Oya et al., *Opt. Rev.*, **22**, 736 (2015).

Acknowledgement

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