

Focusing of light energy inside a scattering medium by controlling the time-gated multiple light scattering



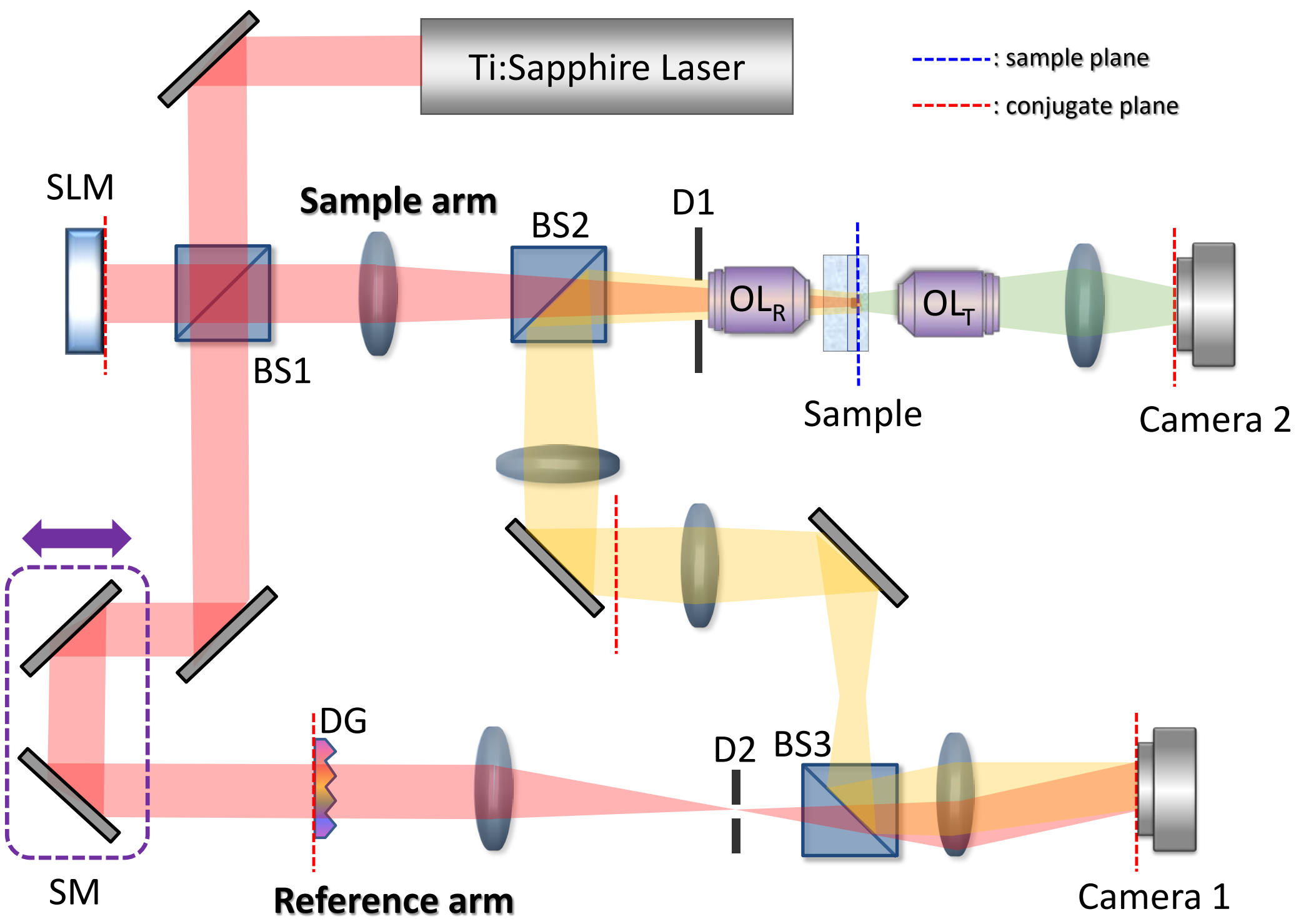
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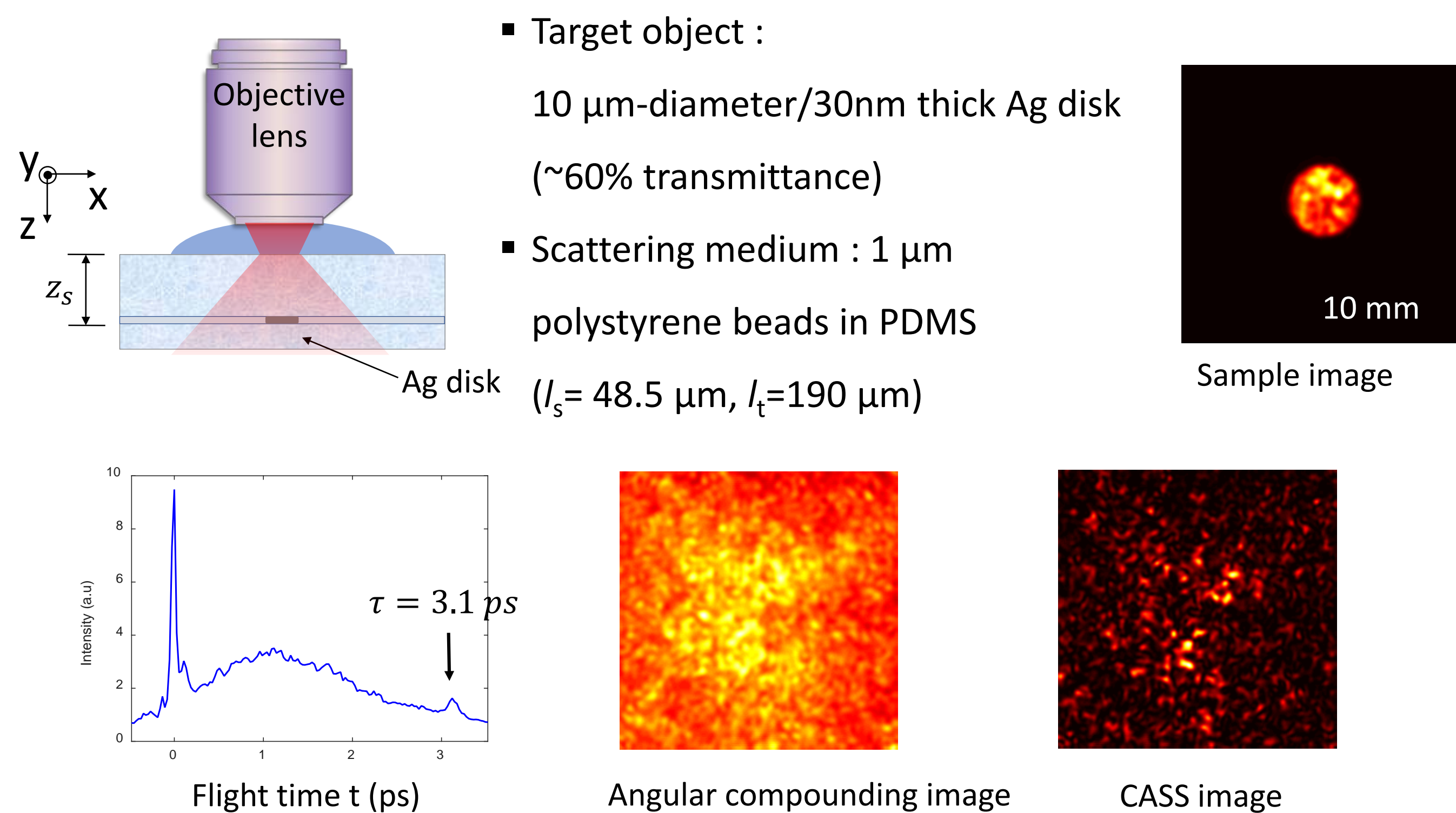
Experimental Procedure

1. Setup



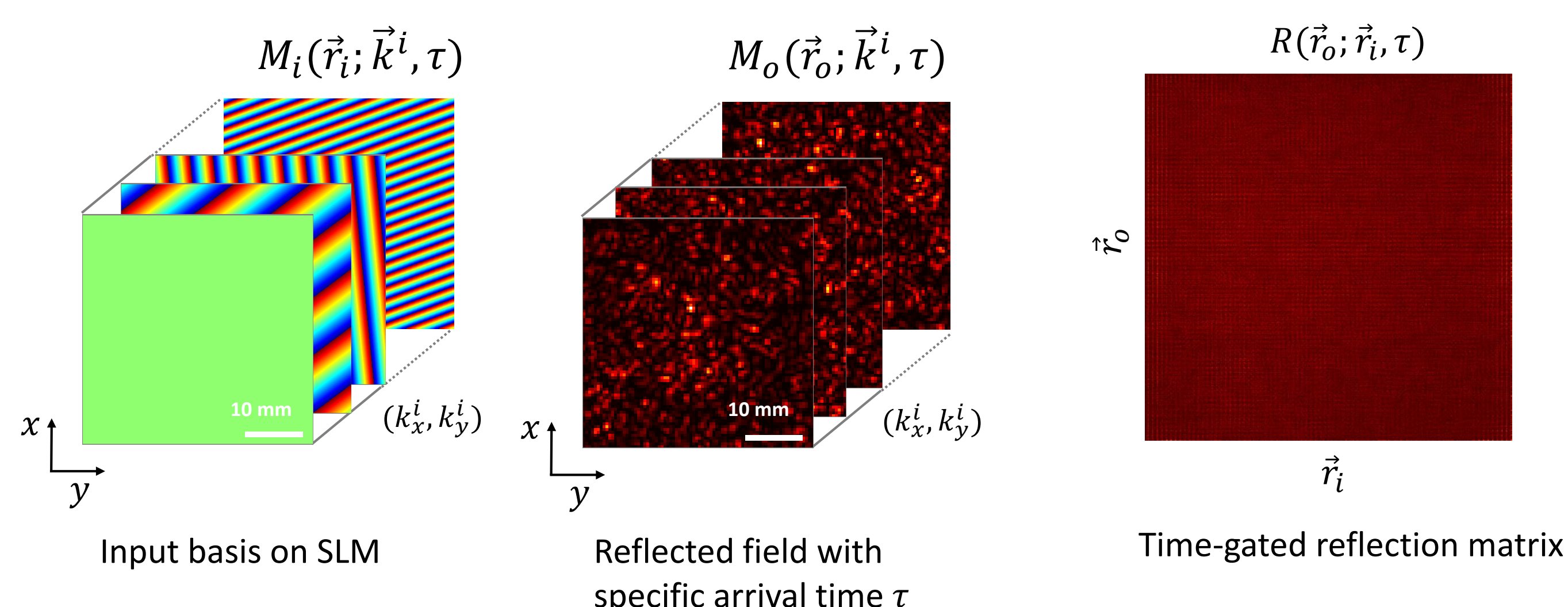
- ✓ Time-gated detection by using low-coherence light source (Ti:Sa ; pulse width ~ 52 fs)
- ✓ Wide-field detection by off-axis holographic microscopy (FOV : $40 \times 40 \mu\text{m}^2$)
- ✓ Wave front shaping to control the incidence angle and couple input eigenchannel
- ✓ Transmission measurement (FOV : $180 \times 180 \mu\text{m}^2$)

2. Sample



- ✓ The silver disk was deeply embedded within scattering media, so that the target was not resolved even via CASS microscopy.
- S. Kang et al., Nature Photonics 9, 583 (2015)

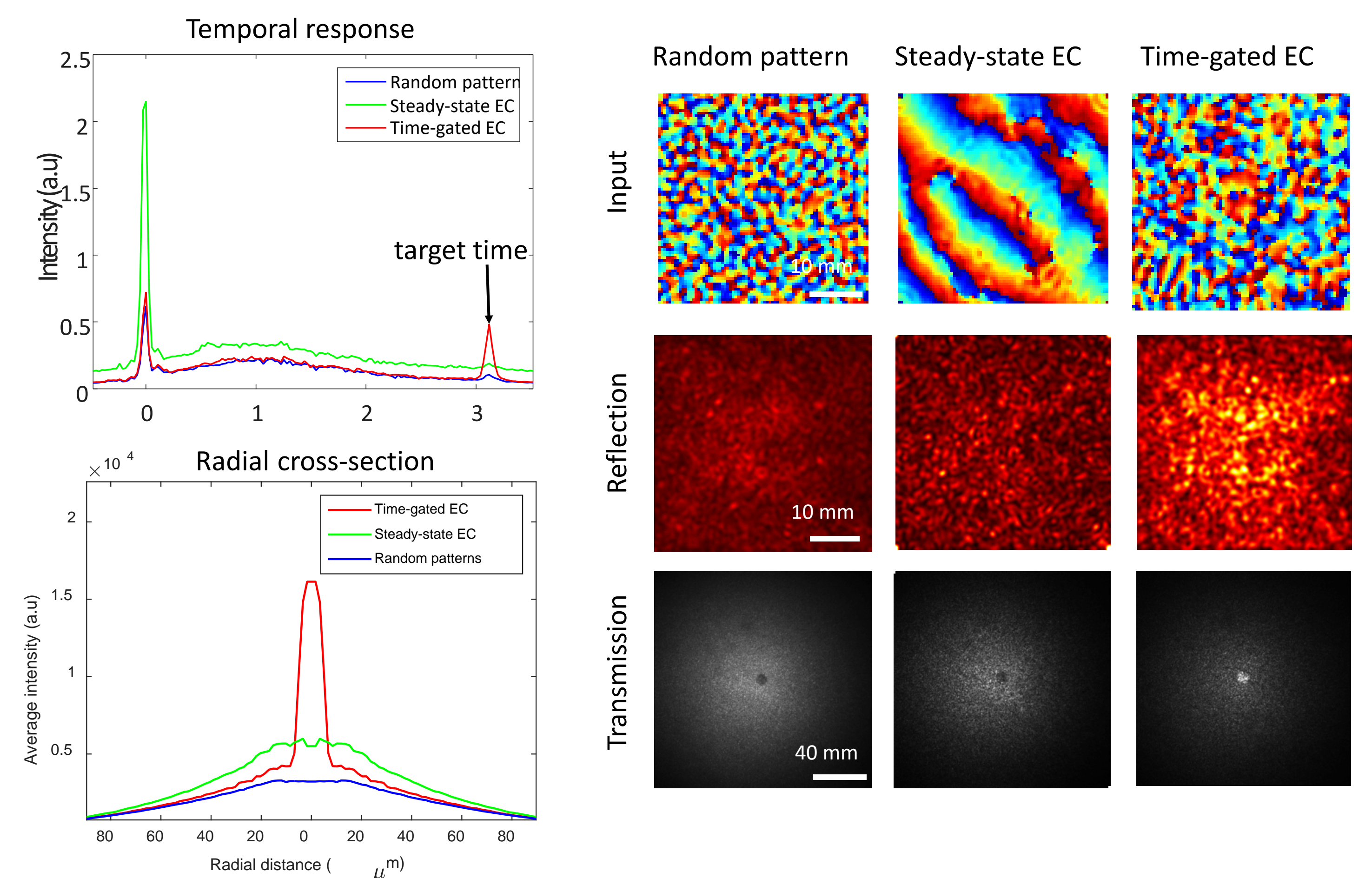
3. Matrix measurement



- ✓ Time-gating was matched to the depth of target object.
 - ✓ We used 1,600 phase ramp pattern within 0.4 NA to cover orthogonal basis for $40 \times 40 \mu\text{m}^2$ FOV.
 - ✓ We measured reflected image as each input incident angles.
 - ✓ Time-gated reflection matrix was matrix multiplication,
- $$R(\vec{r}_o; \vec{r}_i, \tau) = M_o(\vec{r}_o; \vec{k}^i, \tau) M_i(\vec{r}_i; \vec{k}^i, \tau)^{-1}.$$

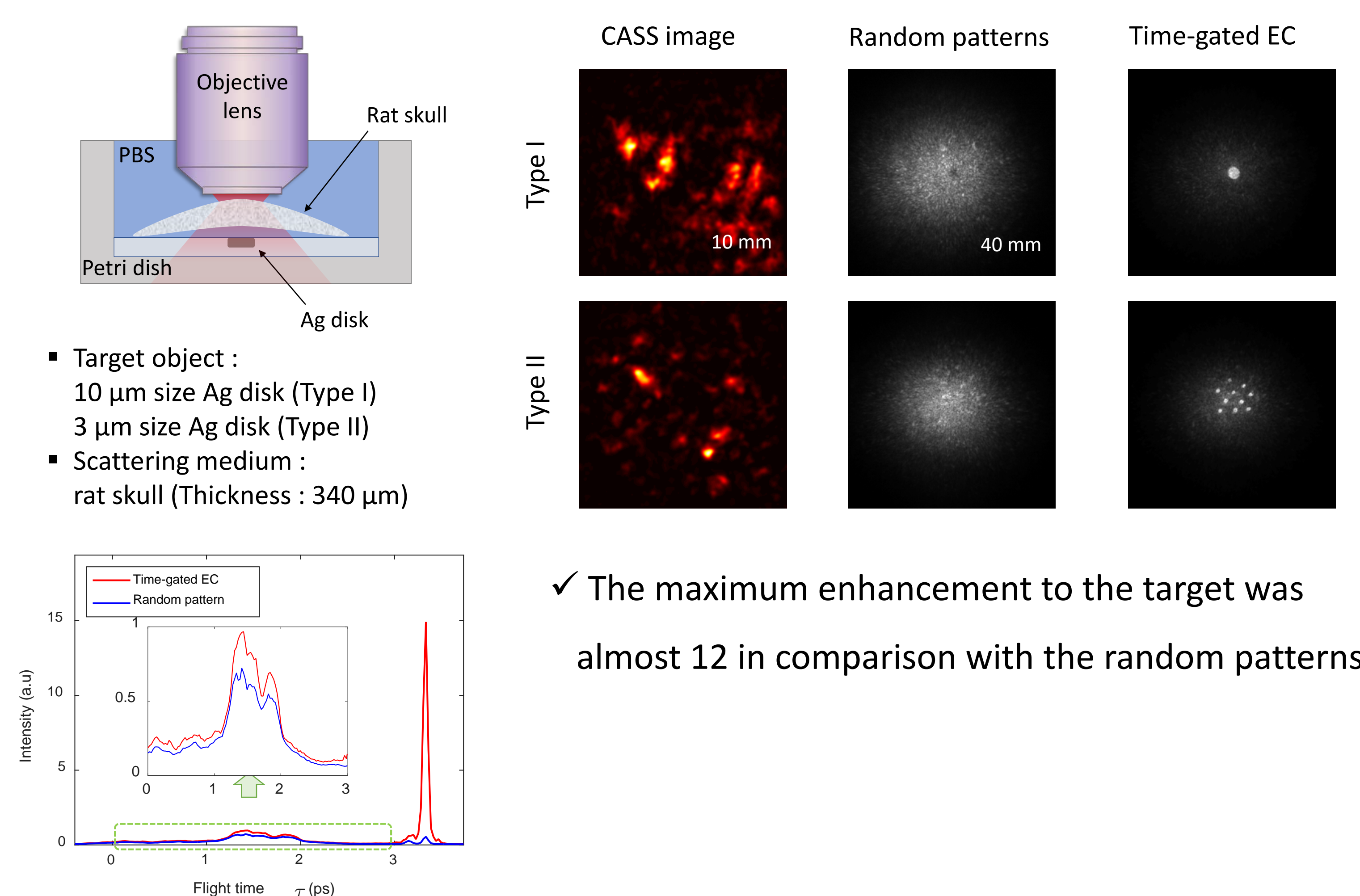
Results

1. Enhanced light energy delivery to the target



- ✓ For the unambiguous proof that the incident light was focused to the target in the case of time-gated eigenchannel, we measured the transmission images.
- ✓ 4 times enhancement of reflection and transmission for the target at 1.7 It in comparison with the random patterns.

2. Light energy delivery through rat skull



- ✓ The maximum enhancement to the target was almost 12 in comparison with the random patterns.

Conclusion

- ✓ We presented the first experimental implementation of the time-gated reflection eigenchannels.
- ✓ The presented method enables controlling multiple-scattered waves for the targets embedded in a scattering medium, which is particularly important for *in vivo* and *in situ* applications.
- ✓ We could enhance the light energy that reaches the target by a factor of more than 10 in comparison with the random input.
- ✓ This work will lay a foundation for enhancing the working depth of imaging, sensing, and light stimulation.