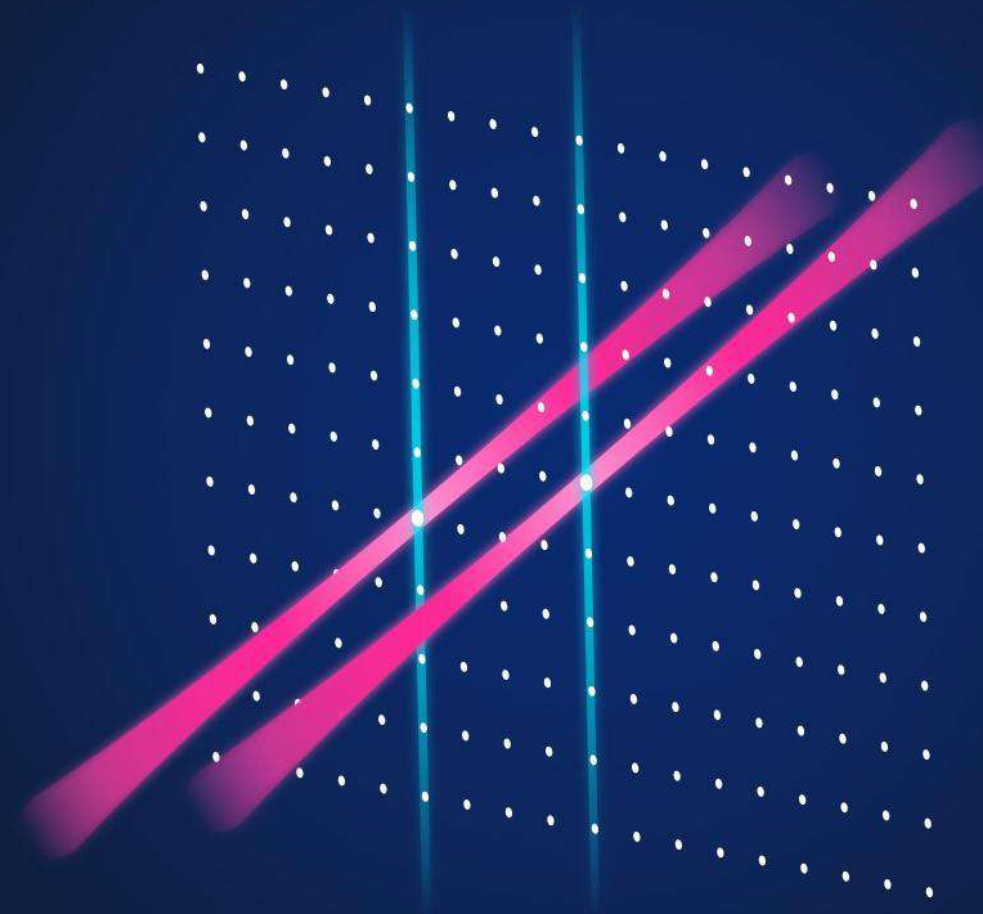
Goal 6
moonshot
大森 PM
大規模・高コヒーレンスな
動的原子アレー型・
誤り耐性量子コンピュータ

Development of a Tiny Integrated Picosecond Laser for Ultrafast Rydberg Excitation of Atomic Arrays toward Quantum Computing

Tirumalasetty Panduranga Mahesh

National Institute for Fusion Science (NIFS),
National Institutes of Natural Sciences, Okazaki, Japan



Sept 16th (Wed), 2026

TILA- consortium

Part 1: Motivation: Why single atoms and Rydberg atoms are interesting?

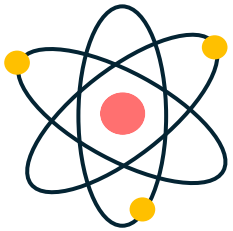
Part 2: Developed laser for QC and ultrafast quantum gates demonstration

Part 3: New laser development for scaling the number of qubits

Part 4: Current challenges for the laser development.

Motivation

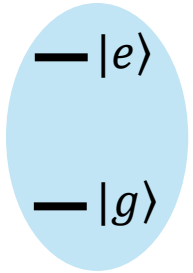
- Single quantum particles
- Development of new technologies using quantum properties.



Single atoms and ions

2012
Measuring and manipulating individual quantum system

D. Wineland S. Haroche



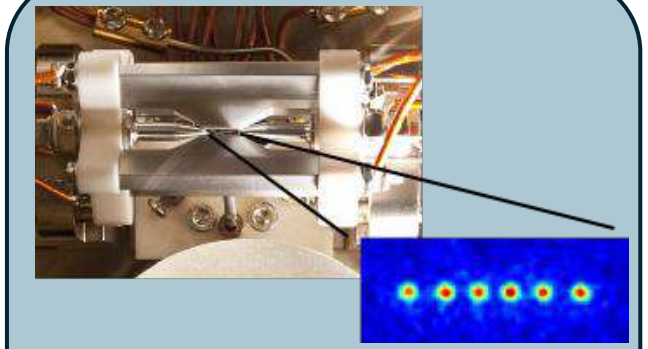
Superposition

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|g\rangle + |e\rangle)$$

Entanglement

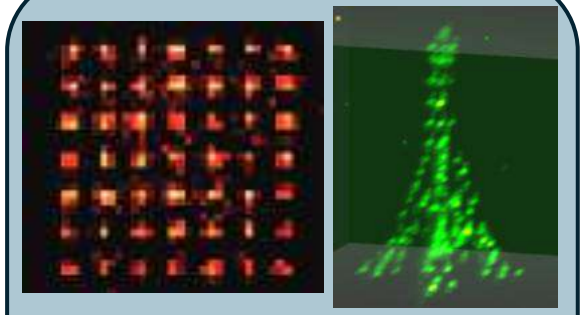
$$|\psi\rangle = \frac{1}{\sqrt{2}}(|gg\rangle + |ee\rangle)$$

Ion traps



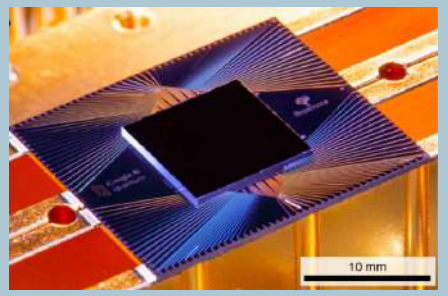
R. Blatt, Innsbruck

Neutral atoms



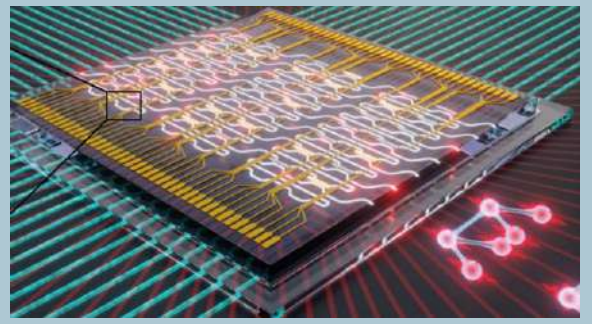
D. Barredo, S. de Léséleuc *et al.*, *Sci.* **354**, 1021 (2016)

Superconducting circuits



Google AI Quantum., *Nat.* **574**, 505-510 (2019)

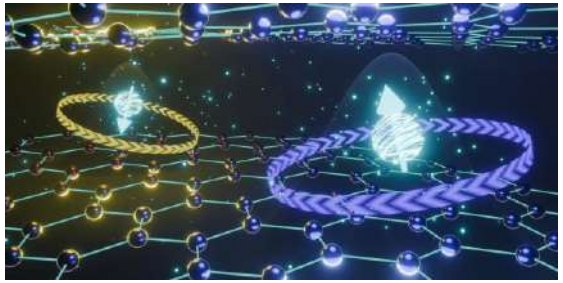
Photonic system



S. Paesani, Copenhagen

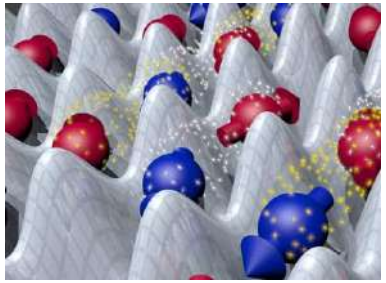
Motivation

Quantum computation



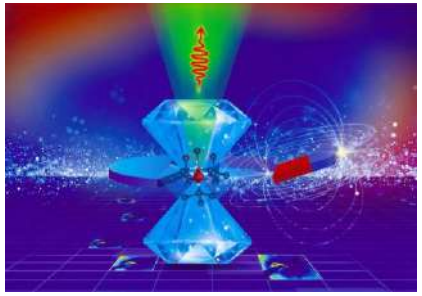
PC: Chuyao Tong, ETH Zürich

Quantum simulation



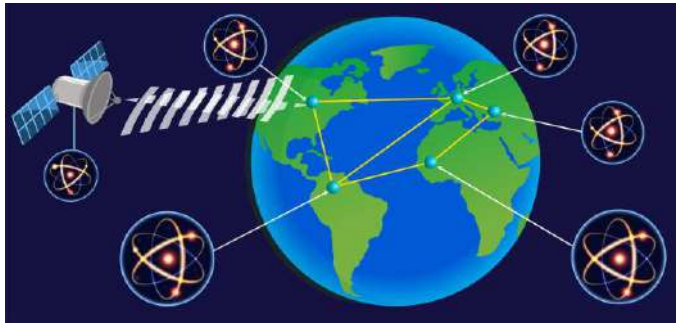
PC: Thomas Uehlinger, ETH Zürich

Quantum sensing



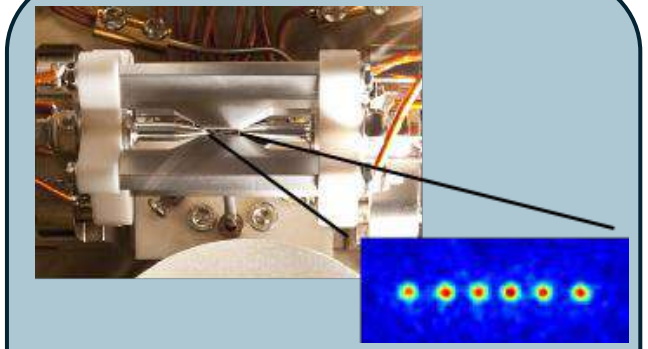
PC: Zhen Zhai, Chinese Academy of Sciences, Beijing

Quantum networking



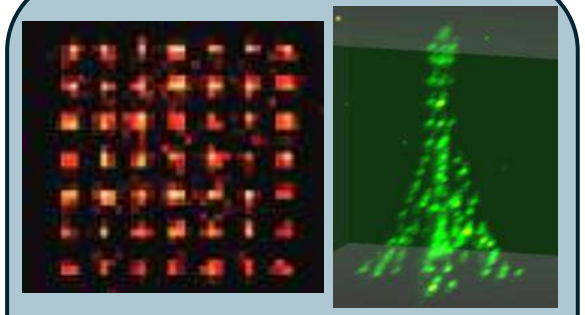
PC: K. Dill, NIST

Ion traps



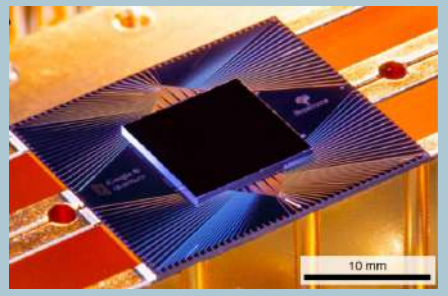
R. Blatt, Innsbruck

Neutral atoms



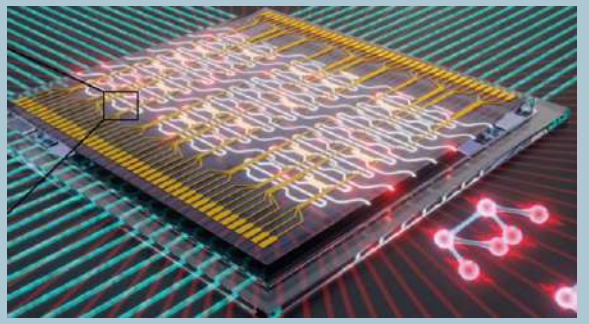
D. Barredo, S. de Léséleuc *et al.*, *Sci.* **354**, 1021 (2016)

Superconducting circuits



Google AI Quantum., *Nat.* **574**, 505-510 (2019)

Photonic system

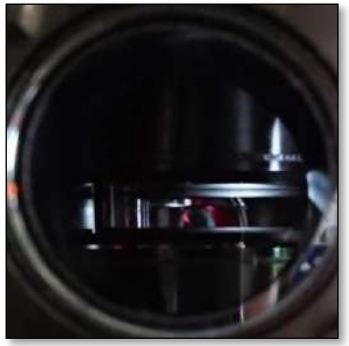


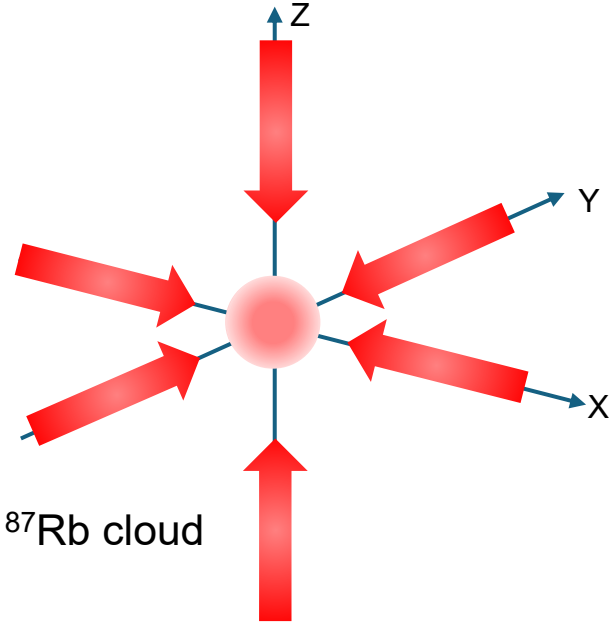
S. Paesani, Copenhagen

Trapping of single atom

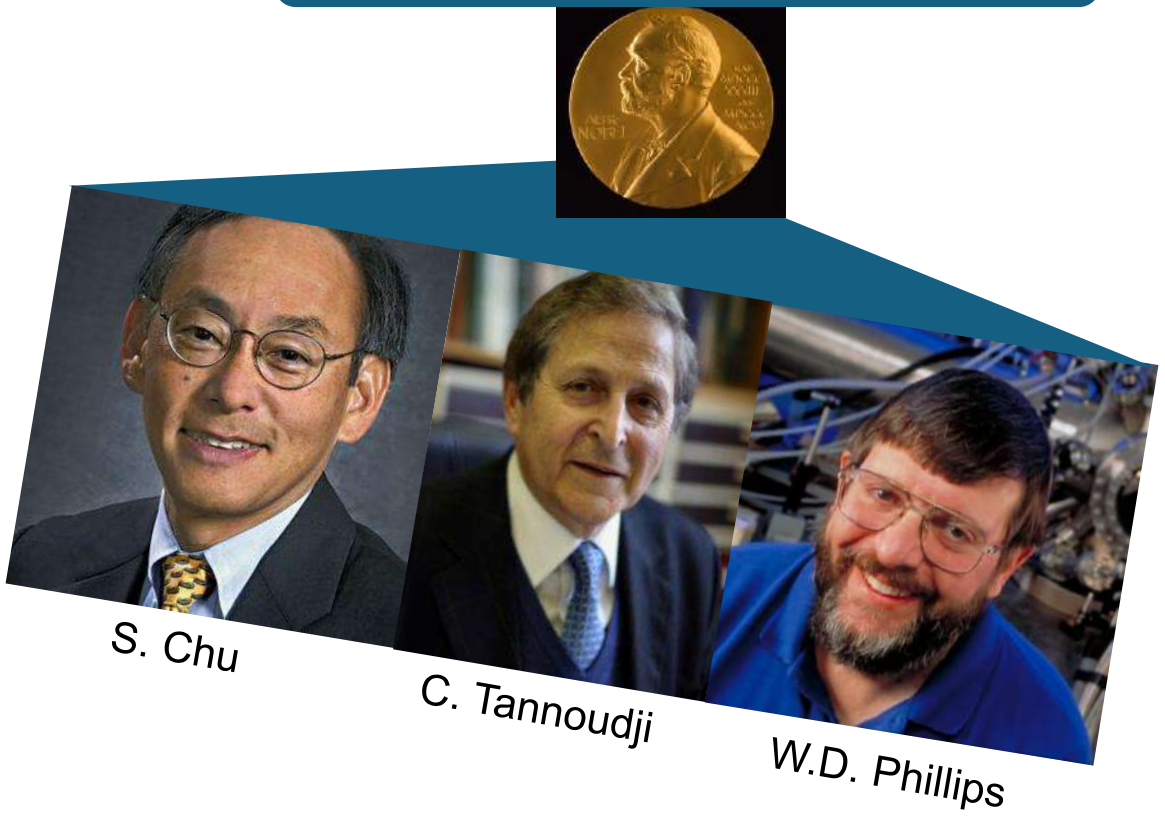
2019.09 — 2019.11 — 2020.01 — 2020.07 — 2020.09 — 2021.01

MOT





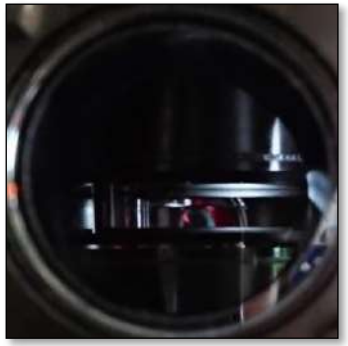
1997
Cool and trap atoms with laser light

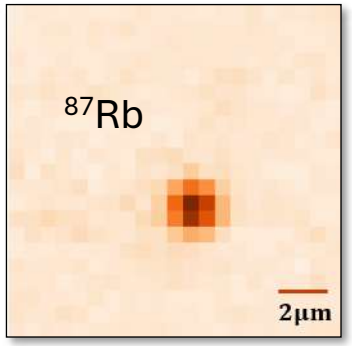


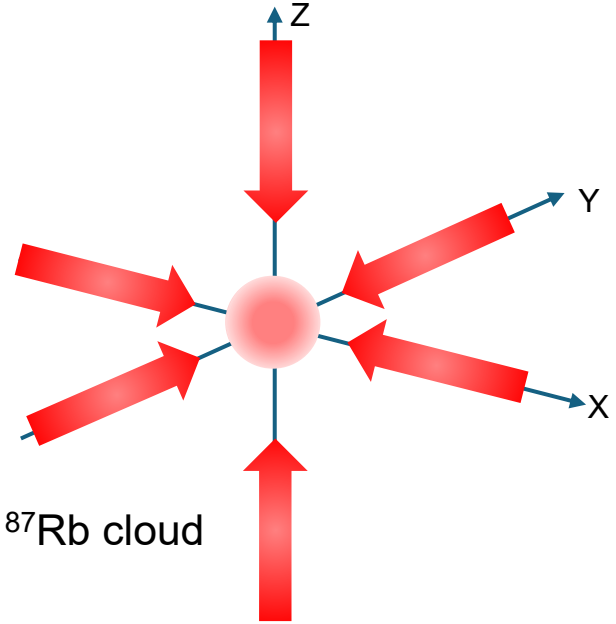
Trapping of single atom

2019.09 — 2019.11 — 2020.01 — 2020.07 — 2020.09 — 2021.01

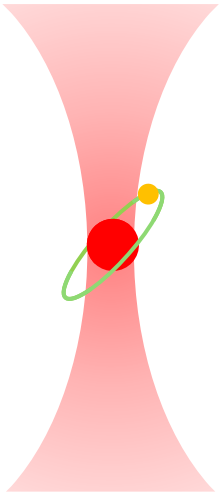
MOT — Single atom



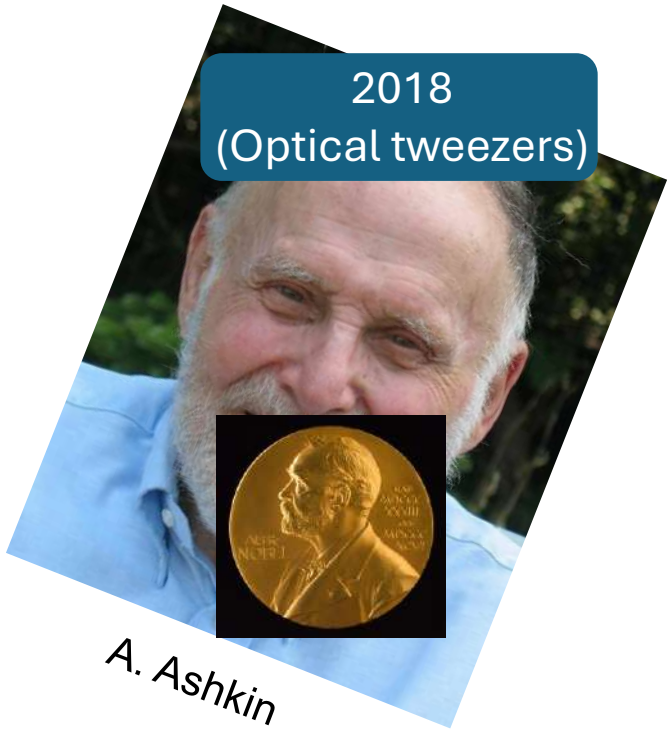




^{87}Rb cloud



Optical tweezer

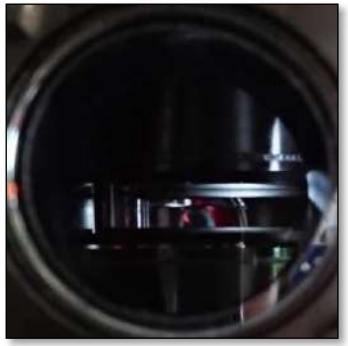


A. Ashkin

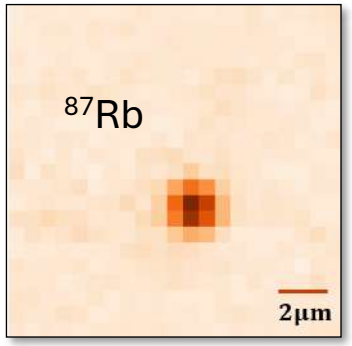
Trapping of single atom

2019.09 2019.11 2020.01 2020.07 2020.09 2021.01

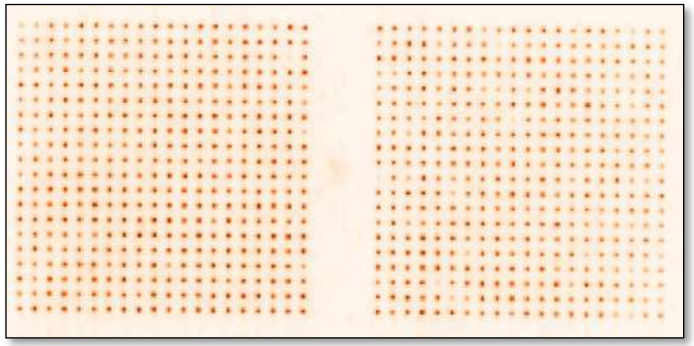
MOT

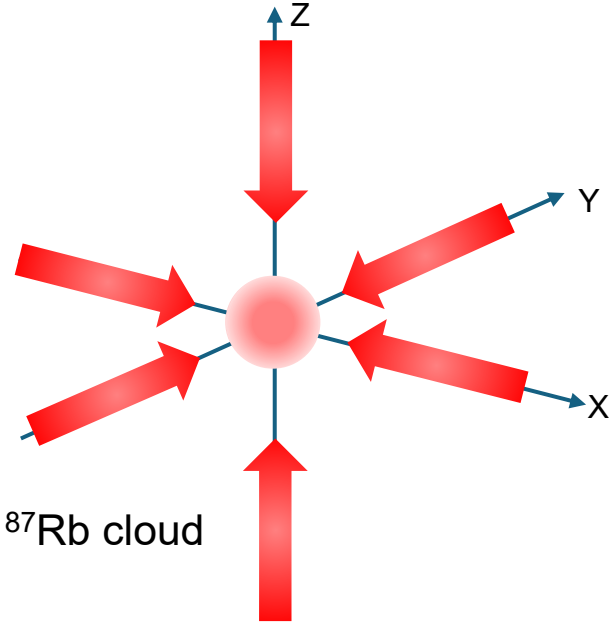


Single atom

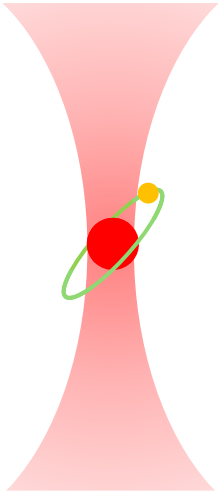


Array of 800 single Rb atoms

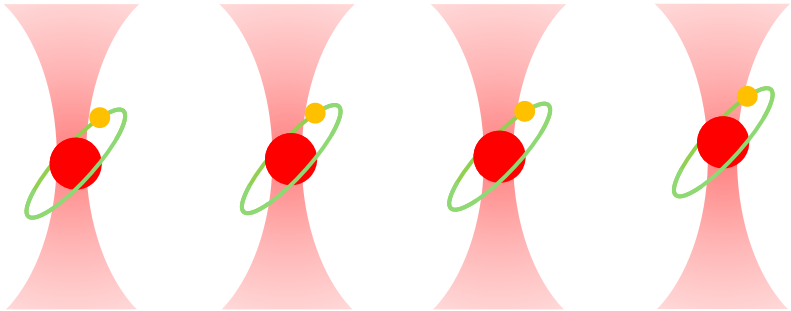




87Rb cloud

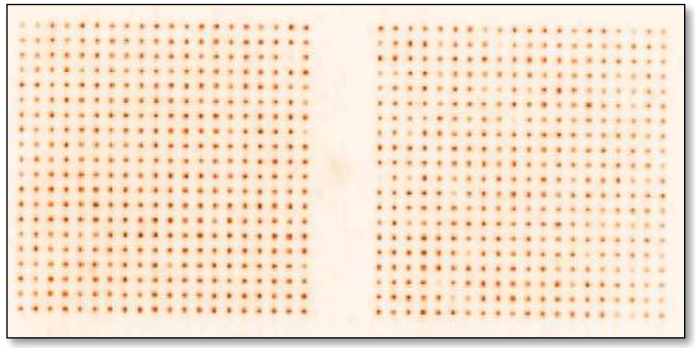


Optical tweezer



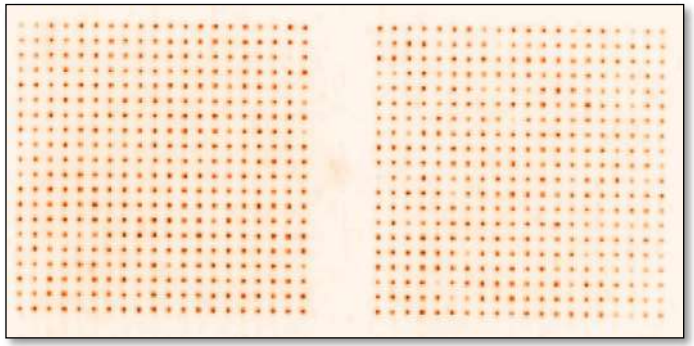
Why Rydberg?

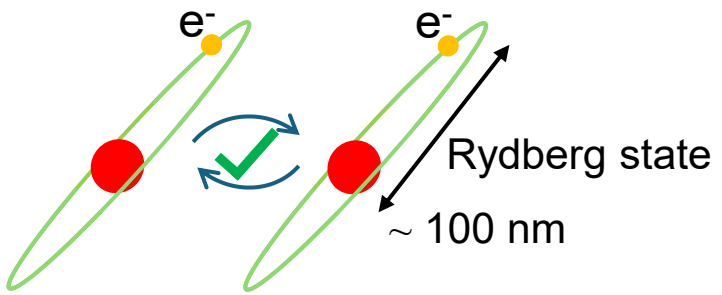
Array of 800 single Rb atoms



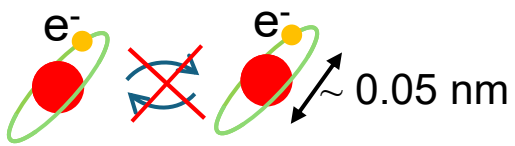
Why Rydberg?

Array of 800 single Rb atoms





Ground state

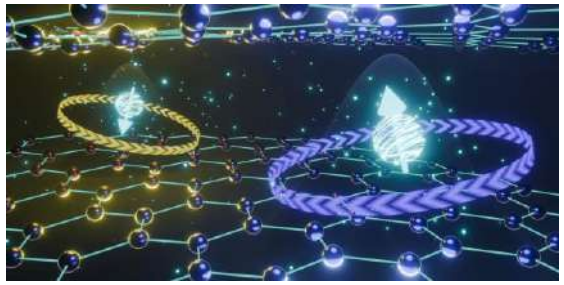


Why Rydberg?

Aim of Moonshot project:

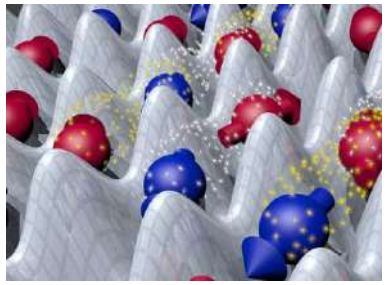
- Interaction between Rydberg atoms used for quantum computation[1] and quantum simulation[2]

Quantum computation



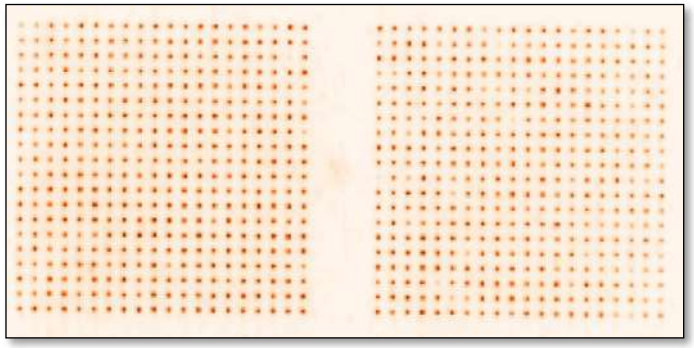
PC: Chuyao Tong, ETH Zürich

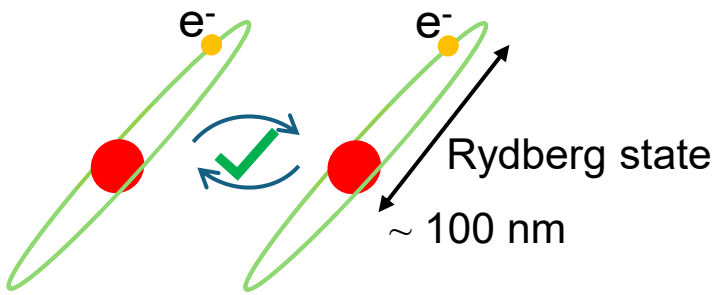
Quantum simulation



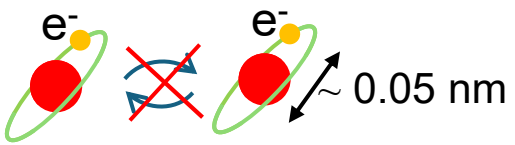
PC: Thomas Uehlinger, ETH Zürich

Array of 800 single Rb atoms





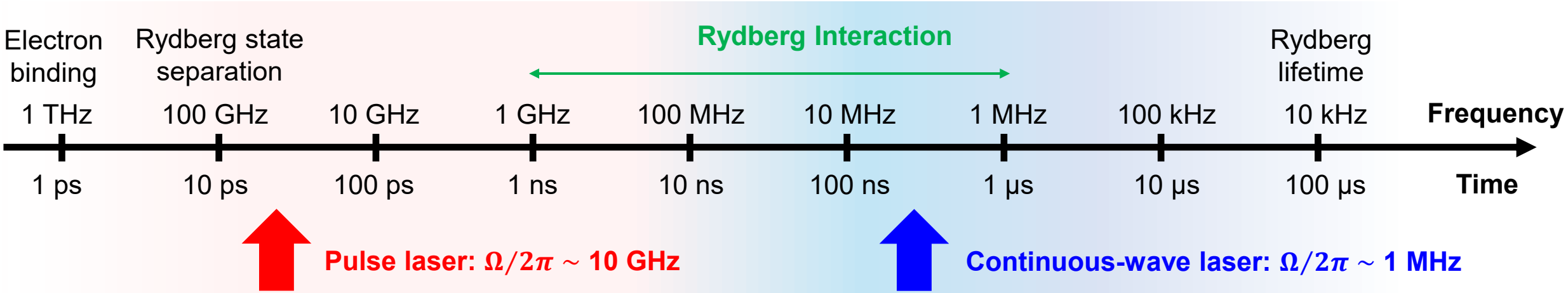
Ground state

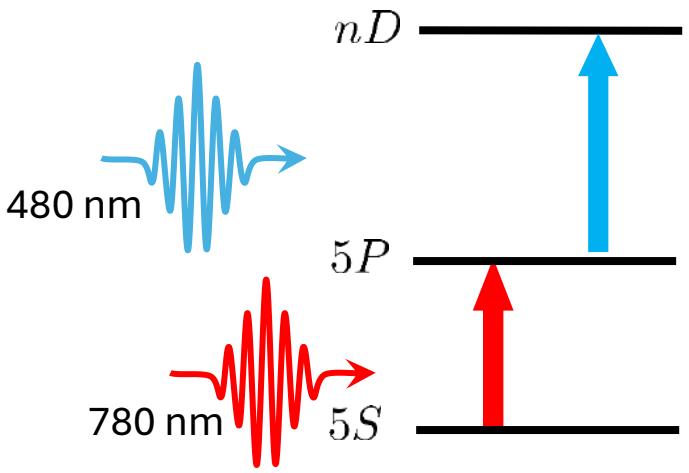


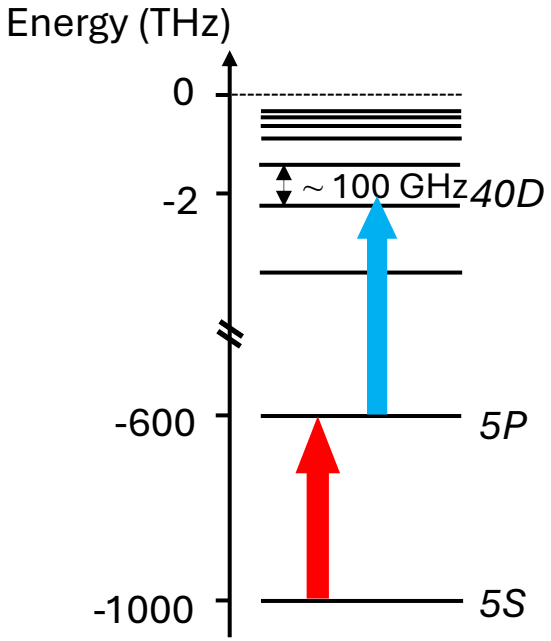
[1] Y. Chew et al., *Nature Photonics* **16**(10),724–729, (2022).

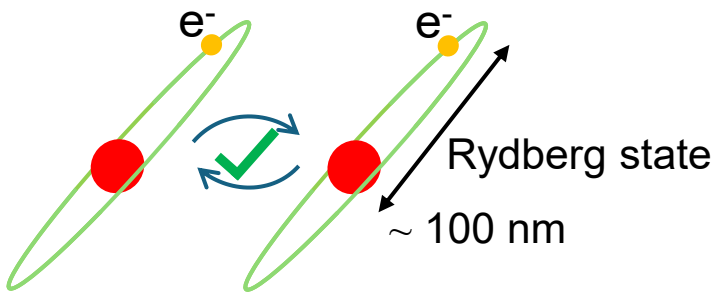
[2] V. Bharti et al., *Phys. Rev. Lett*. **133**, 093405, (2024)

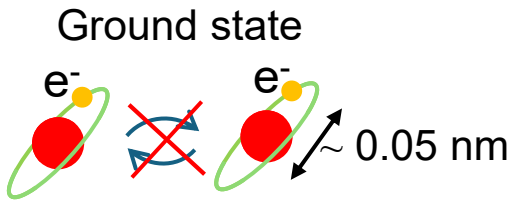
Time-scale in Rydberg physics



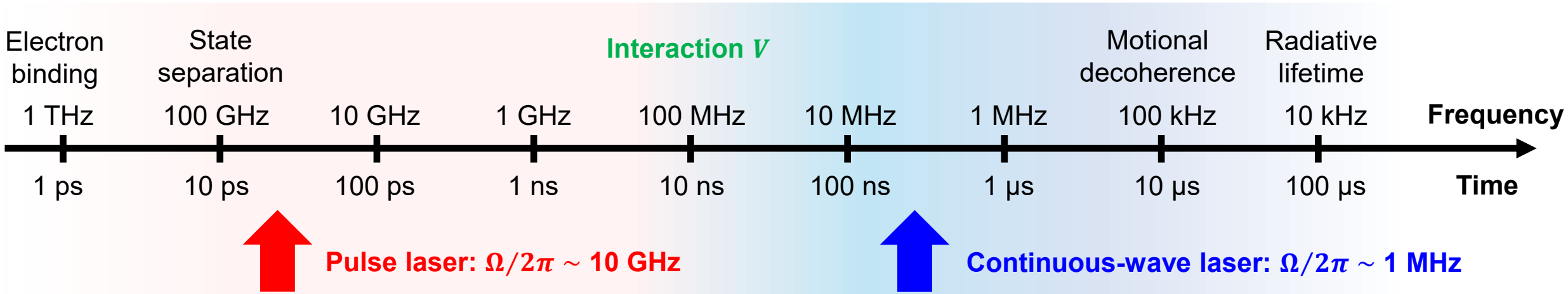


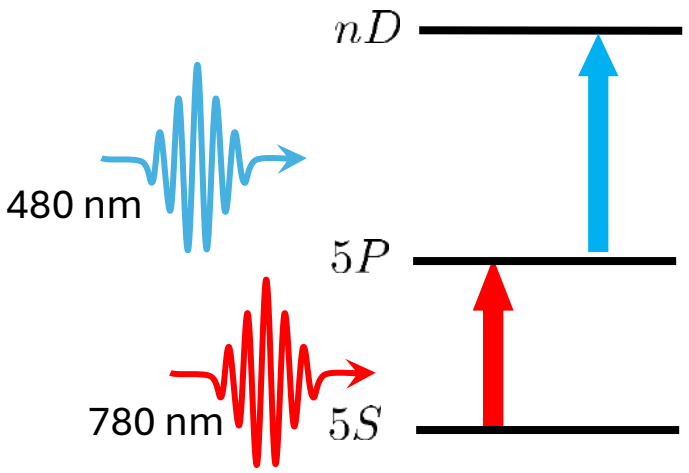






Pulse excitation





Advantages of picosecond excitation:

- to avoid the motion of atoms
- to stay further away from the finite Rydberg lifetime
- to overcome noisy environments (e.g., surfaces)
- Can explore the interaction in ns-timescale

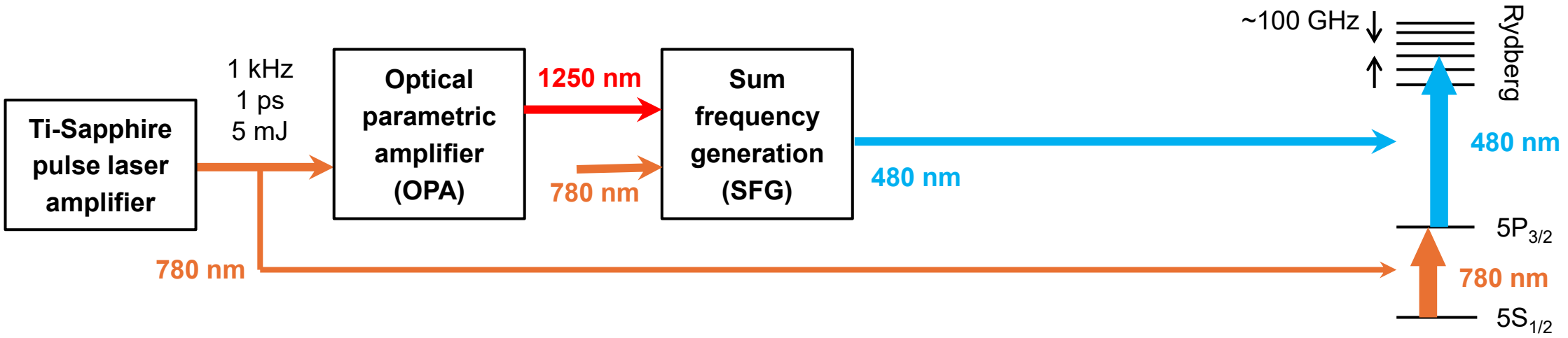
Part 1: Motivation: Why single atoms and Rydberg atoms are interesting?

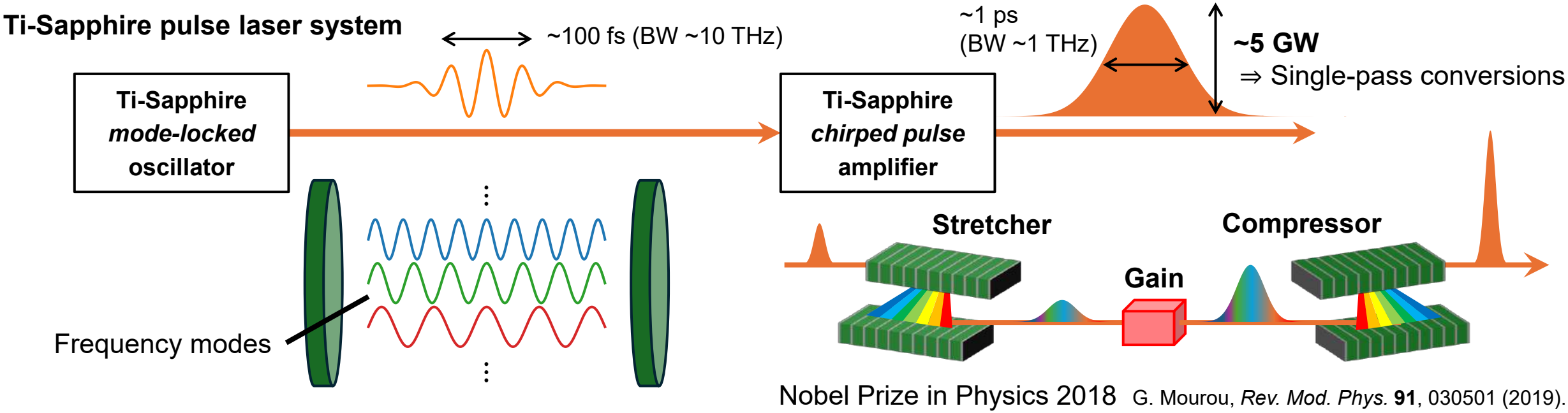
Part 2: Developed laser for QC and ultrafast quantum gates demonstration

Part 3: New laser development for scaling the number of qubits

Part 4: Current challenges for the laser development.

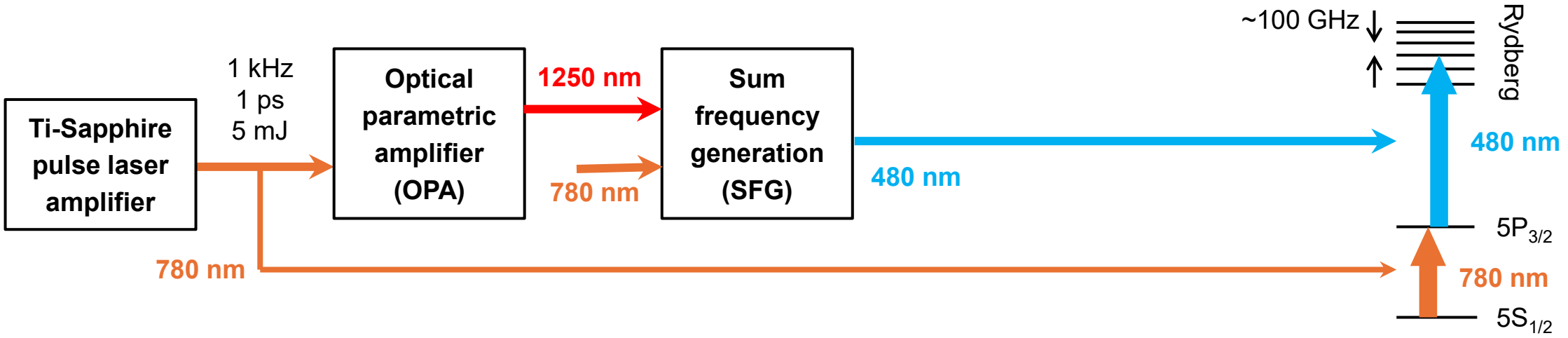
Picosecond pulse laser system





Nobel Prize in Physics 2018 G. Mourou, *Rev. Mod. Phys.* **91**, 030501 (2019).

Picosecond pulse laser system



Optical parametric amplification (OPA)

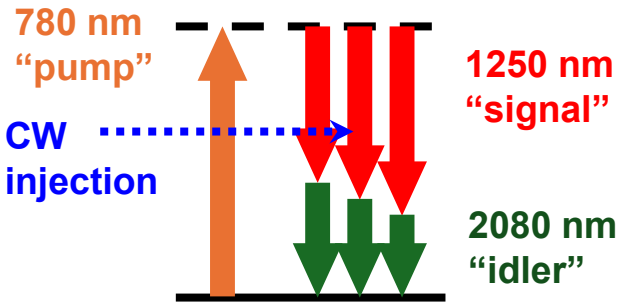
✓ Down-conversion to ***arbitrary frequency***

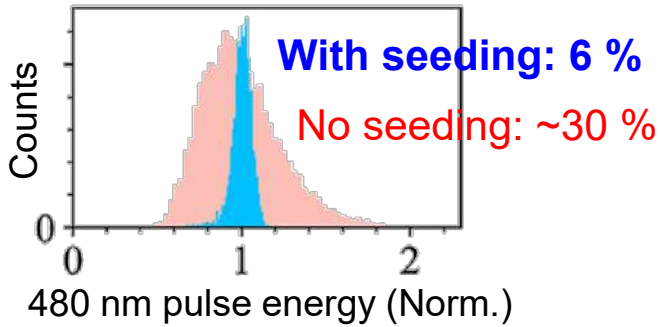
△ Stochastic: initiated by vacuum fluctuation

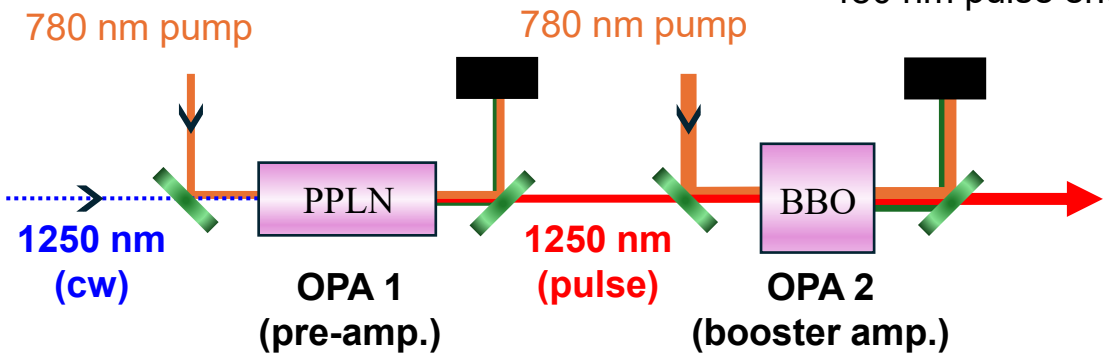
Large pulse-to-pulse energy fluctuation (~ 30 %)

⇒ ***<u>Continuous wave (CW) injection seeding</u>***

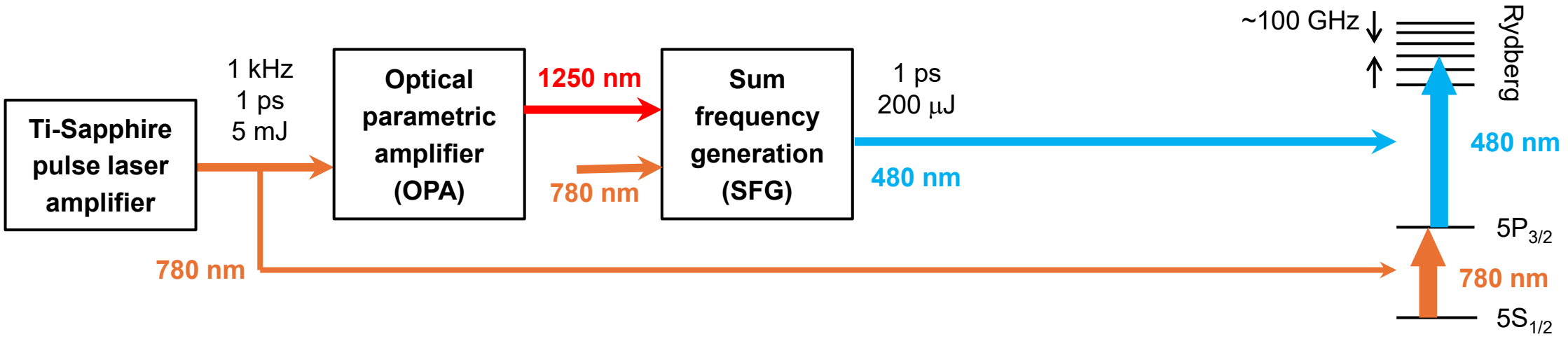
T. P. Mahesh *et al.*, *Opt. Lett.* **50**, 403 (2025).



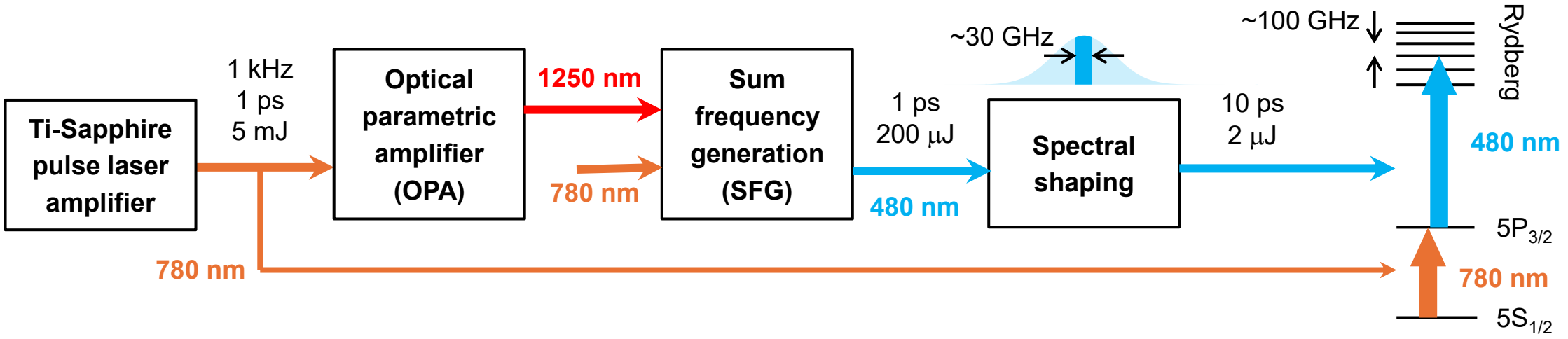


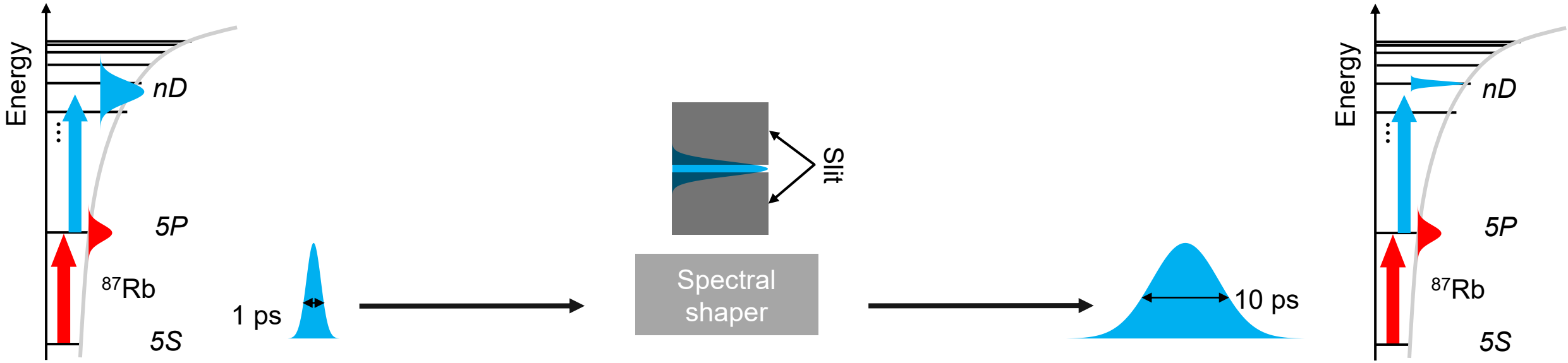


Picosecond pulse laser system

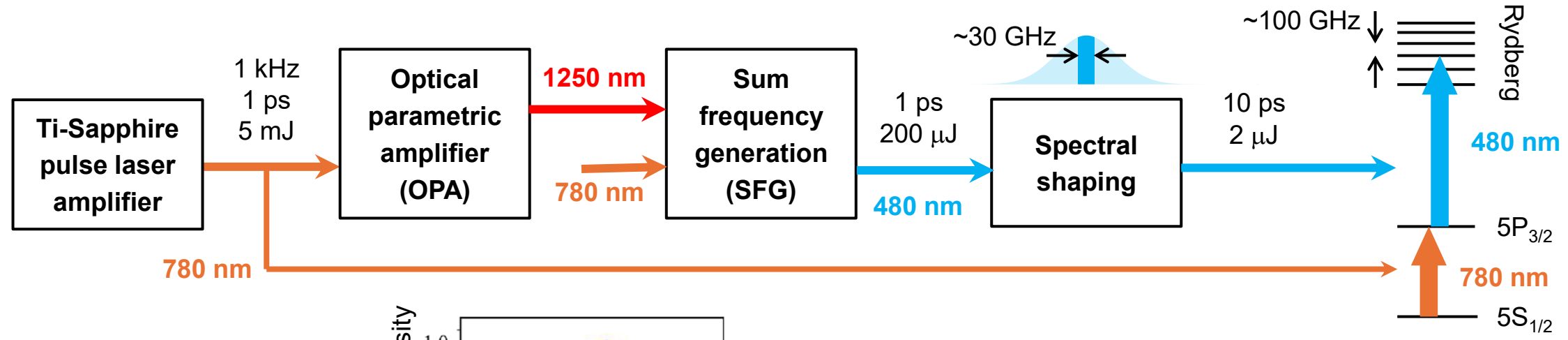


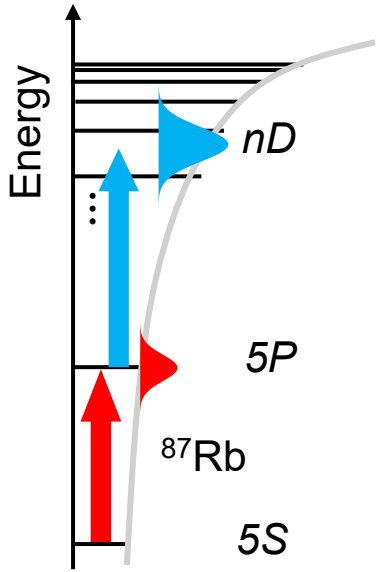
Picosecond pulse laser system

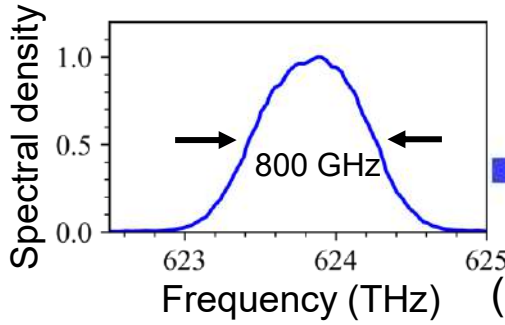


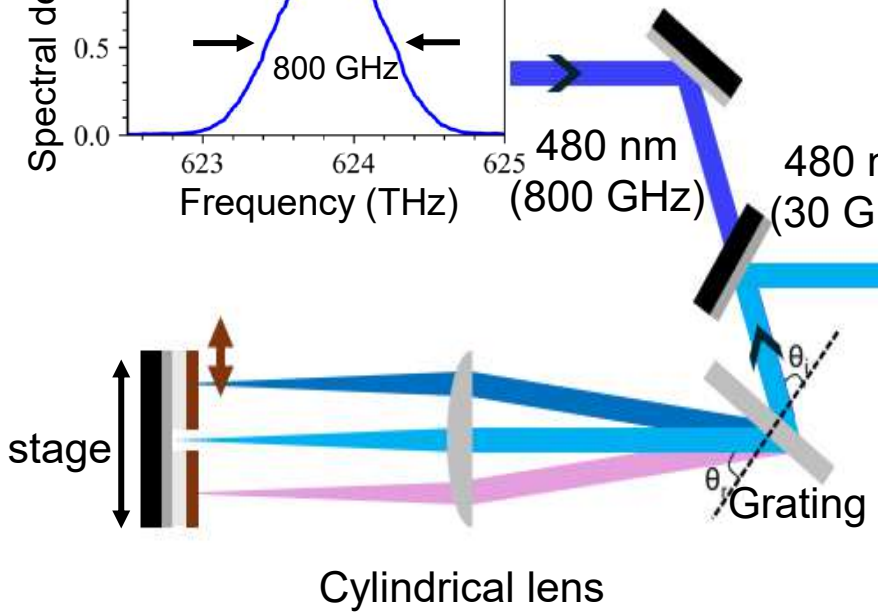


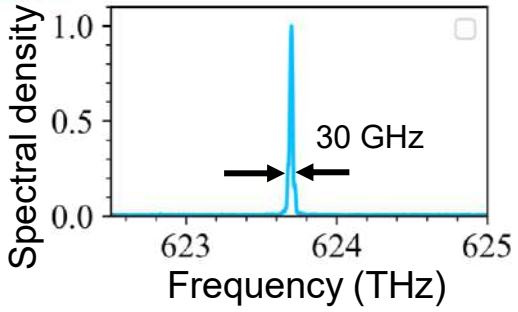
Picosecond pulse laser system

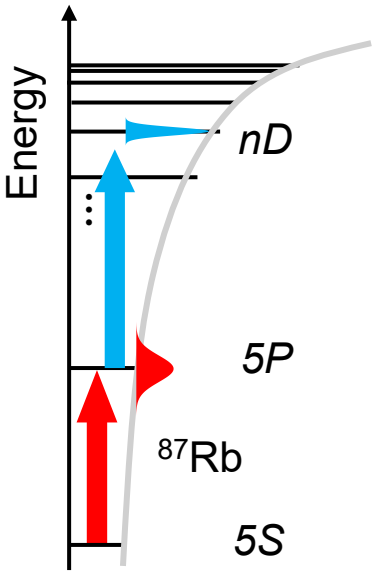




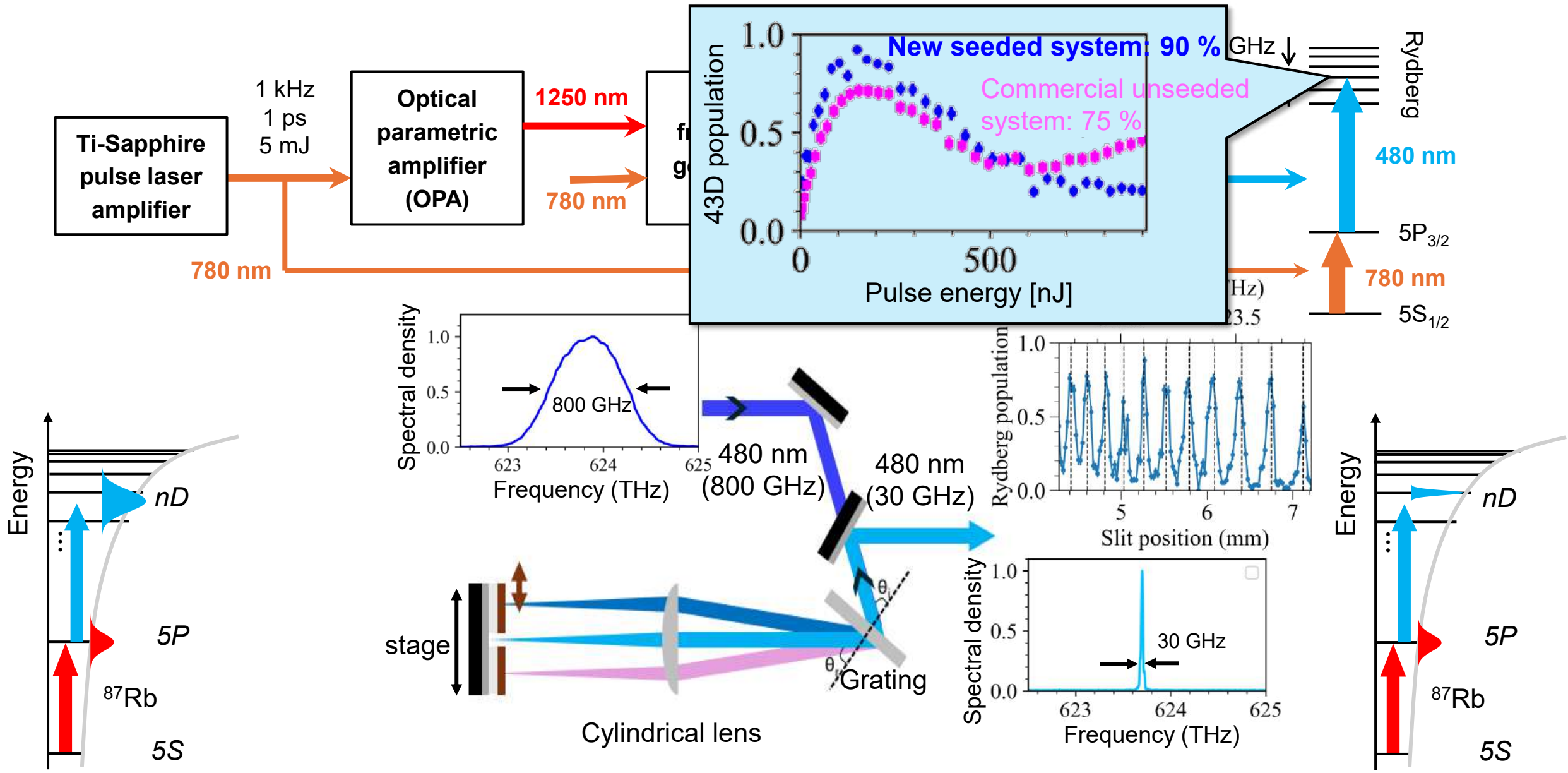




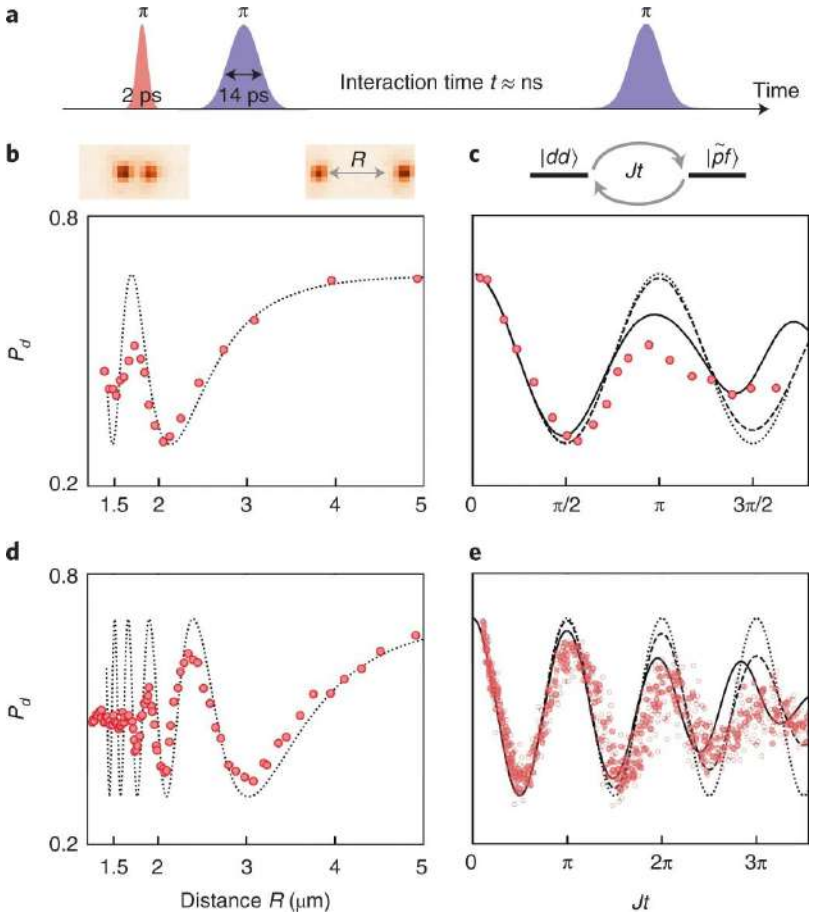


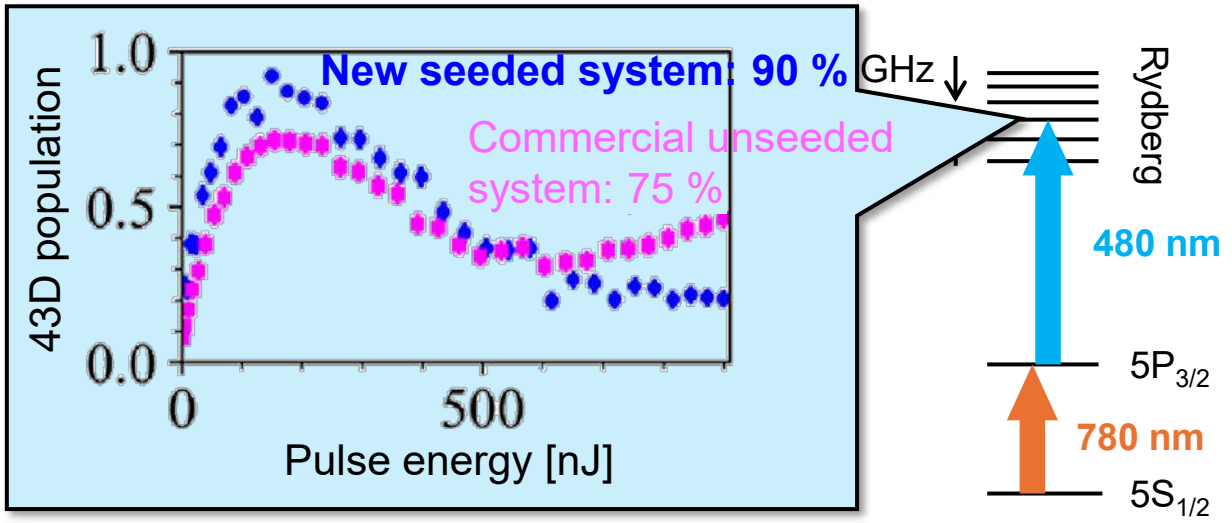


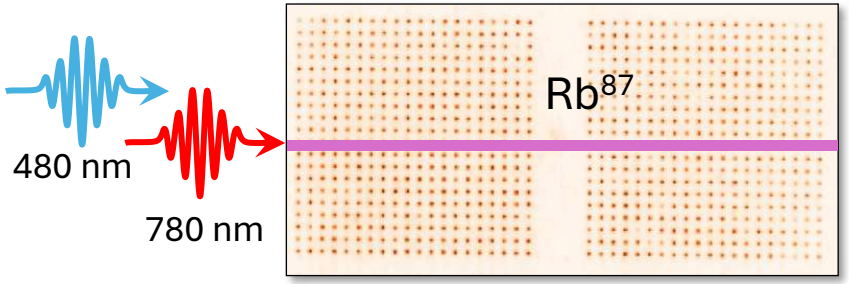
Ultrafast Rydberg excitation

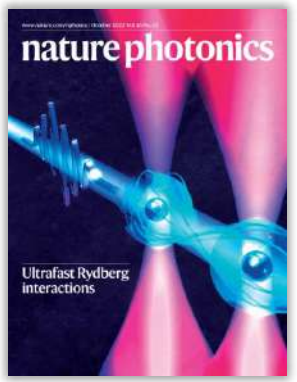


Ultrafast quantum gates



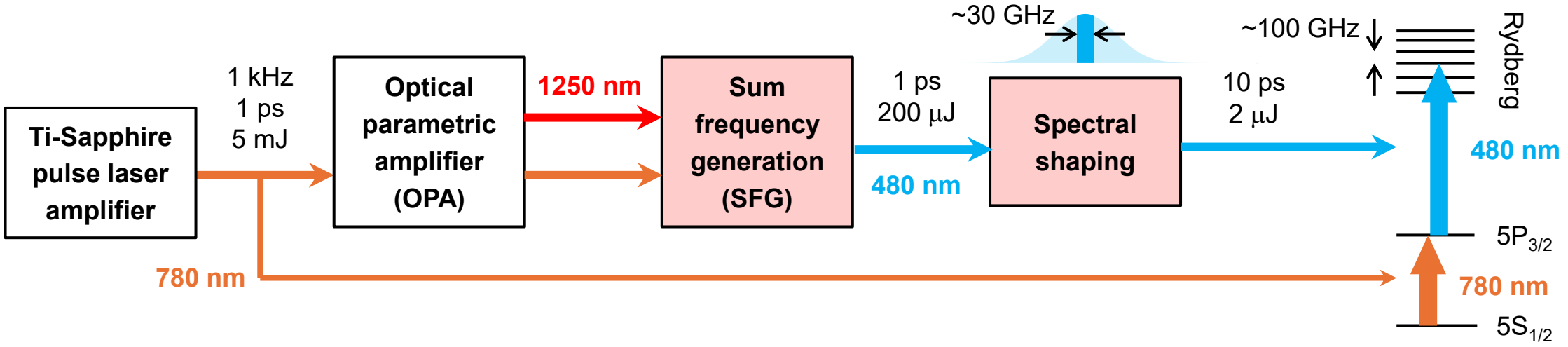




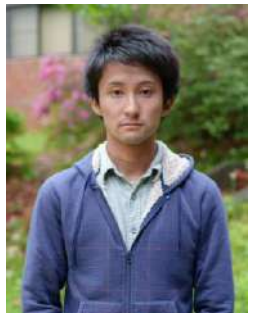


Y. Chew, T. Tomita, **T.P. Mahesh**, S. Sugawa, S. de Léséleuc, K. Ohmori, *Nat. Photonics* **16**, 724 (2022)

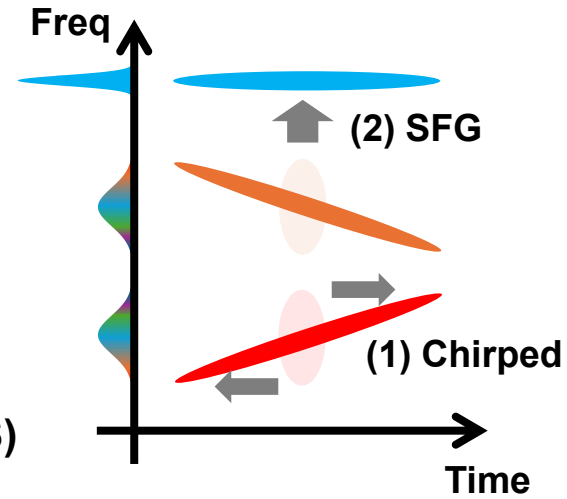
Picosecond pulse laser system

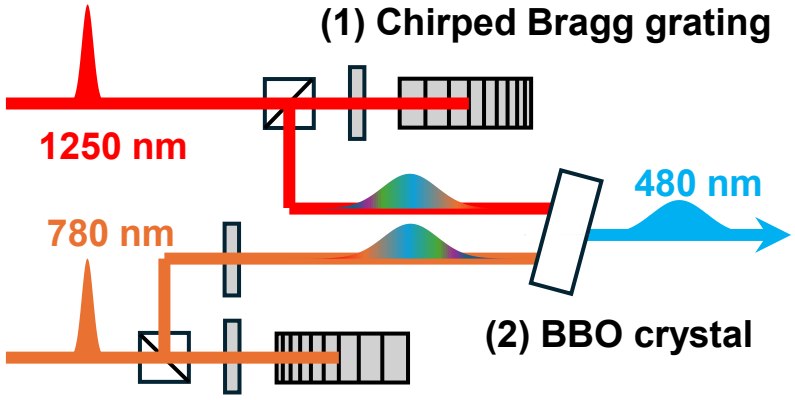


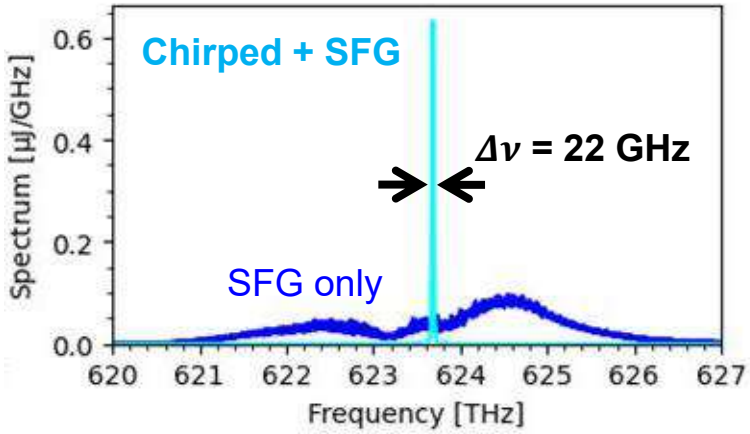
Sum-frequency bandwidth compression



T. Matsubara
(Ohmori G, IMS)







- Succeeded in generating 480 nm pulse of 22 GHz bandwidth.
- Currently 20 μJ pulse energy is generated. Further optimization required.

Part 1: Motivation: Why single atoms and Rydberg atoms are interesting?

Part 2: Developed laser for QC and ultrafast quantum gates demonstration

Part 3: New laser development for scaling the number of qubits

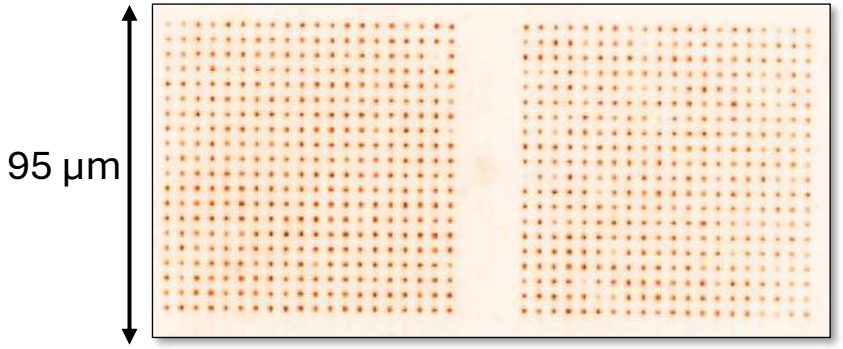
Part 4: Current challenges for the laser development.

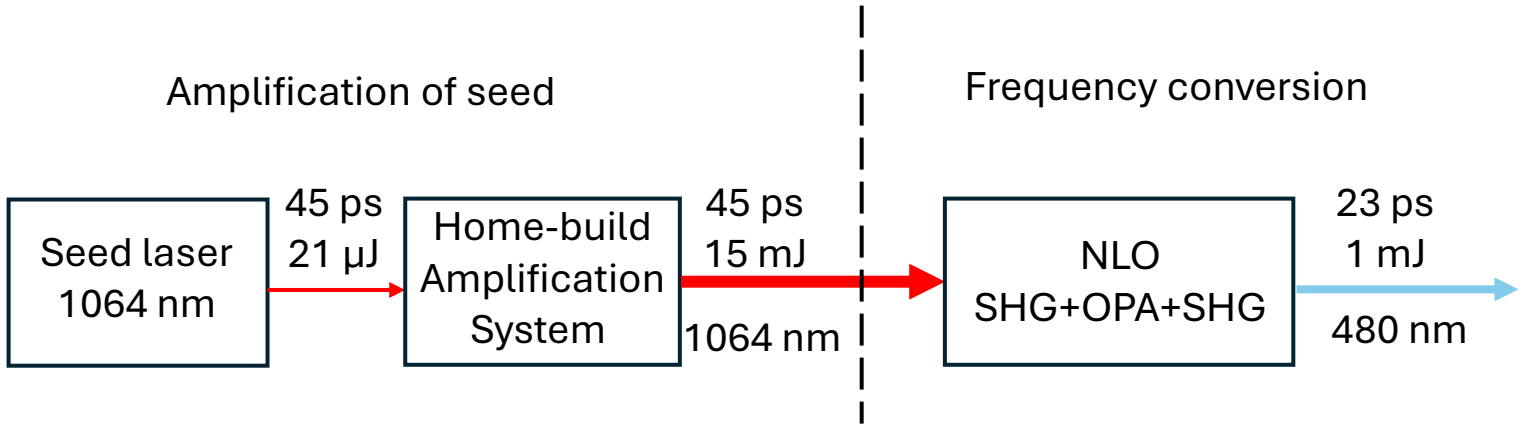
Picosecond pulse laser system

Requirements for 480 nm pulse to transfer atoms to single Rydberg state:

- Pulse width = 30 ps
- Pulse energy = ~1 mJ (1 mm beam diameter)

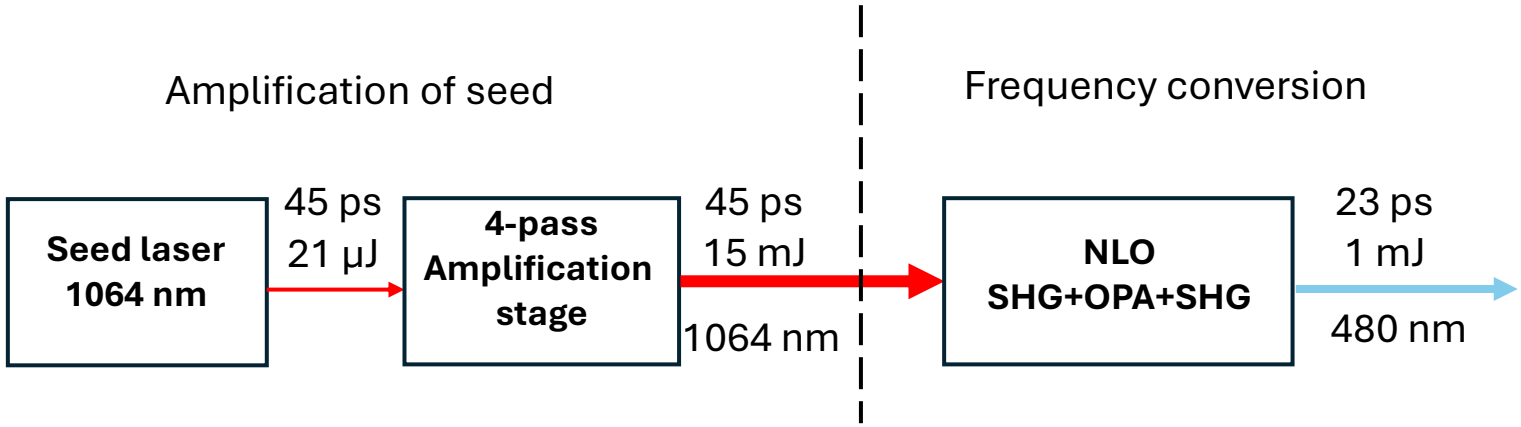
Array of Rb atoms in our lab

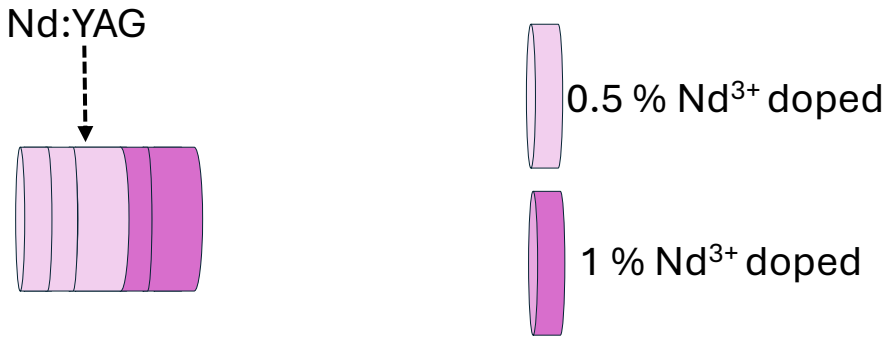


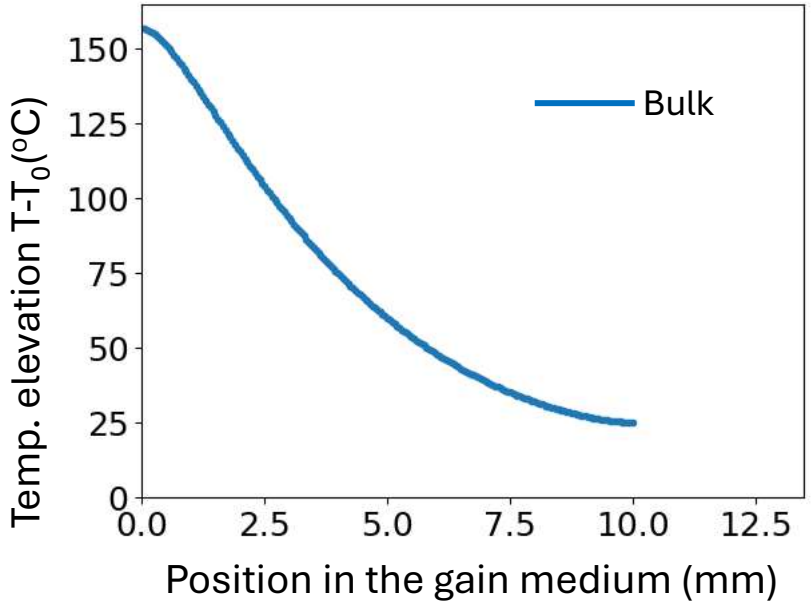


Wavelength (nm)	Target energy	Achieved energy
1064	15 mJ	3.6 mJ
532	10 mJ	320 µJ
960	2 mJ	12 µJ
480	1 mJ	Not yet

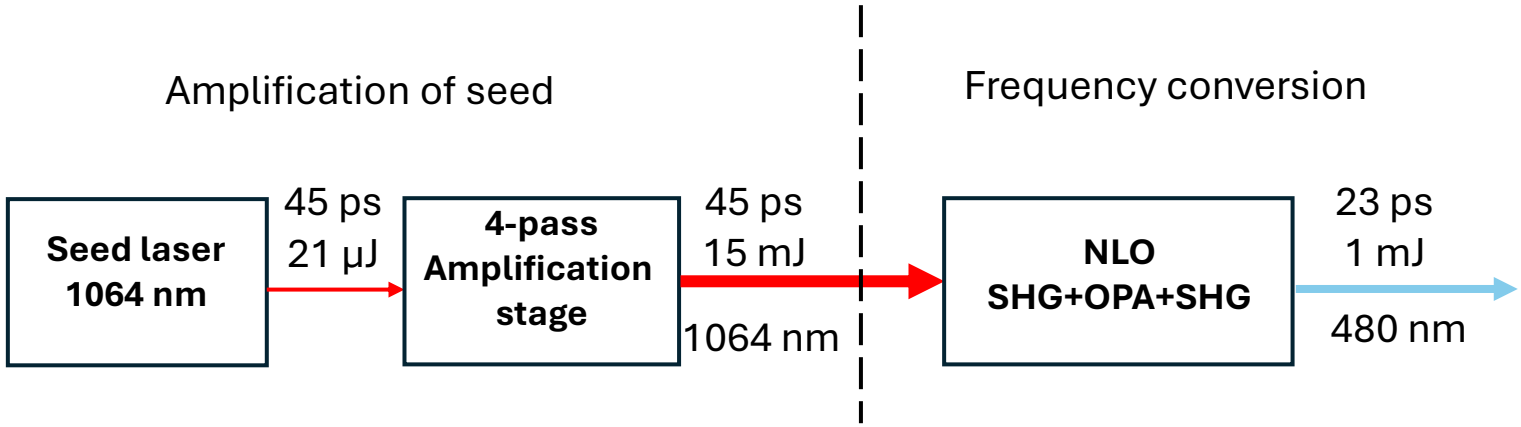
Picosecond pulse amplification

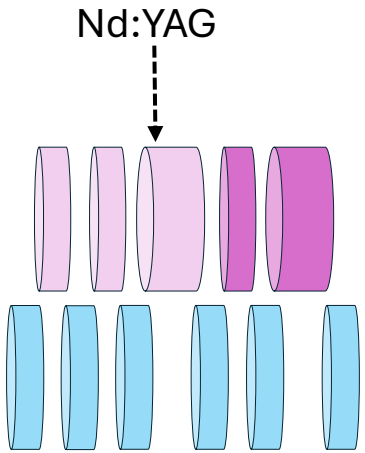


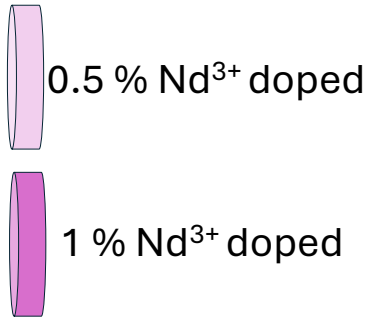


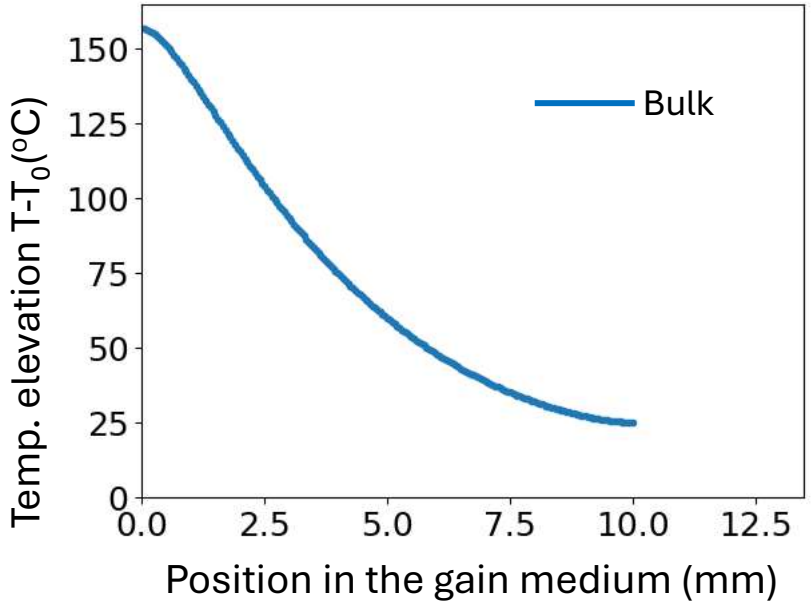


Picosecond pulse amplification

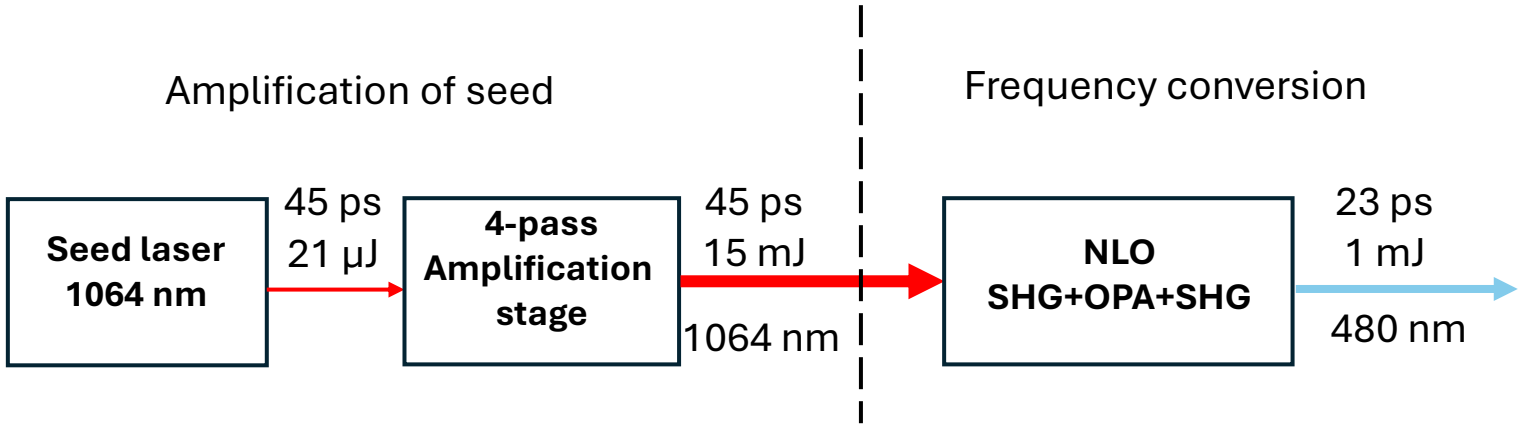




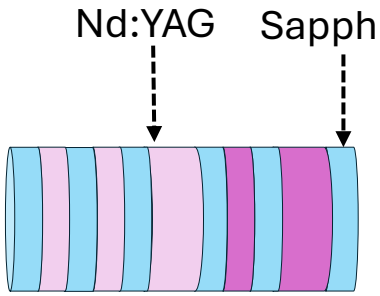


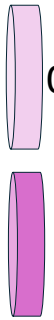


Picosecond pulse amplification



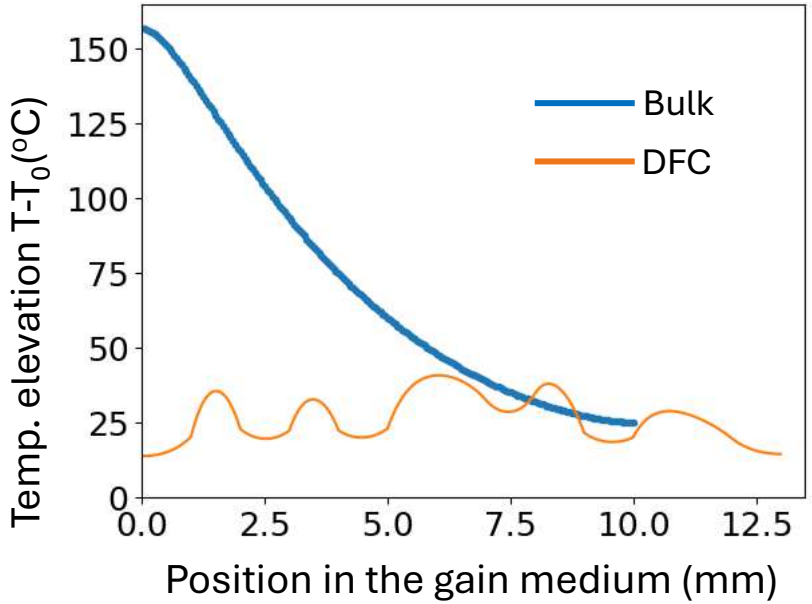
DFC chip





0.5 % Nd^{3+} doped

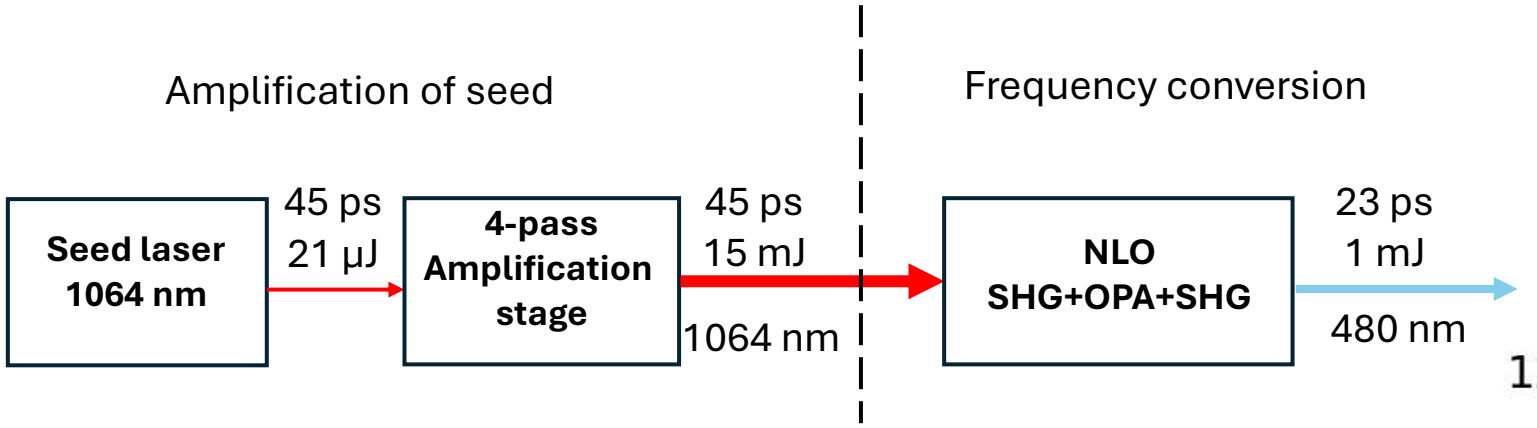
1 % Nd^{3+} doped

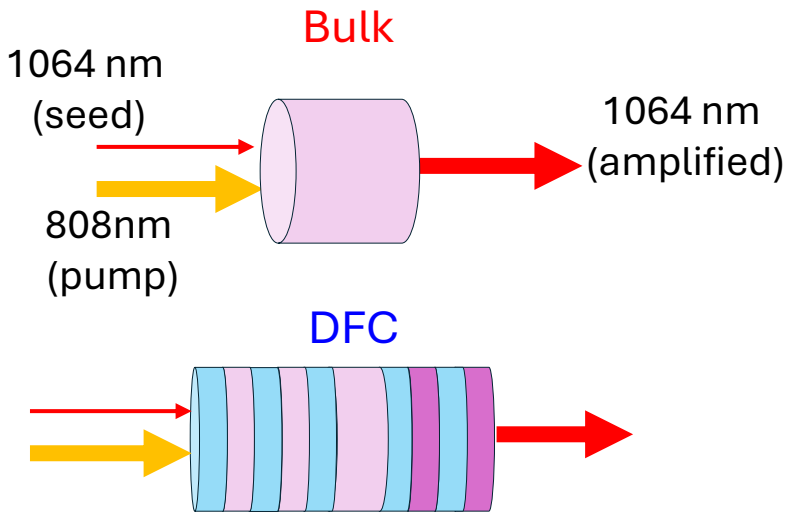


- Distributed face cooling (DFC) chip Bonded with YAG: Sapphire
- Drastic reduction of thermal effect [4,5]

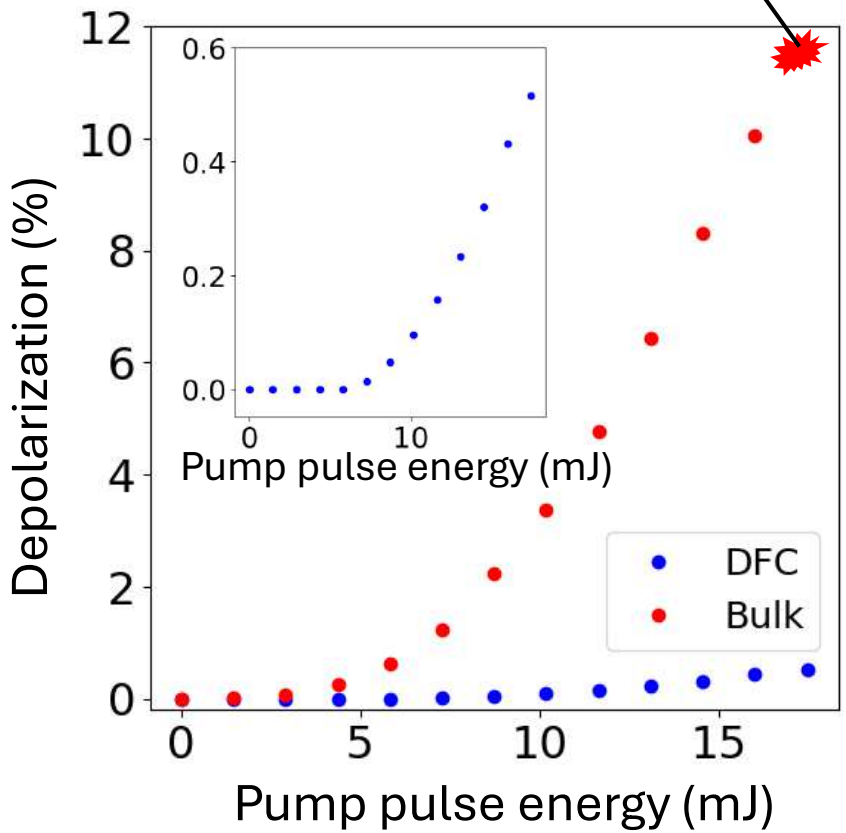
[4] L. Zheng et al., *Opt. Mater. Express* **7(9)**, 3214-3221 (2017).
[5] L. Zheng et al., Opt. Express **27(21)**, 30217-30224 (2019).

Picosecond pulse amplification



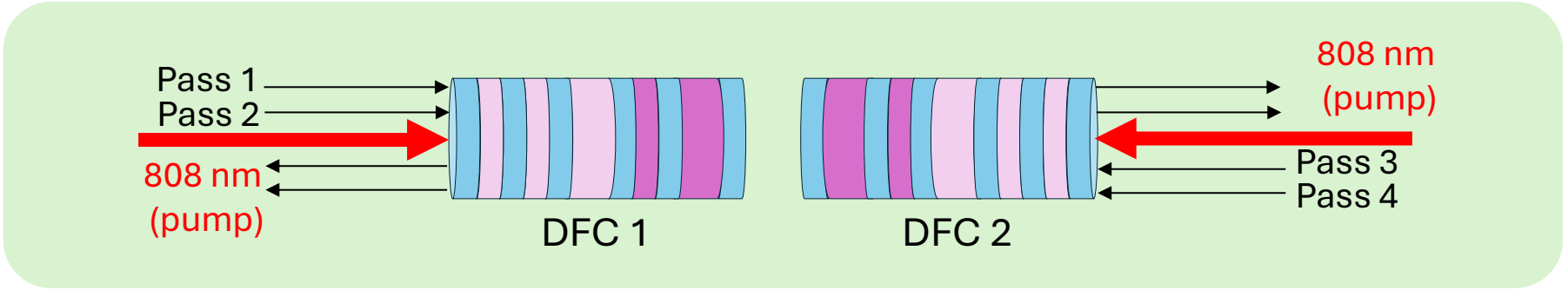


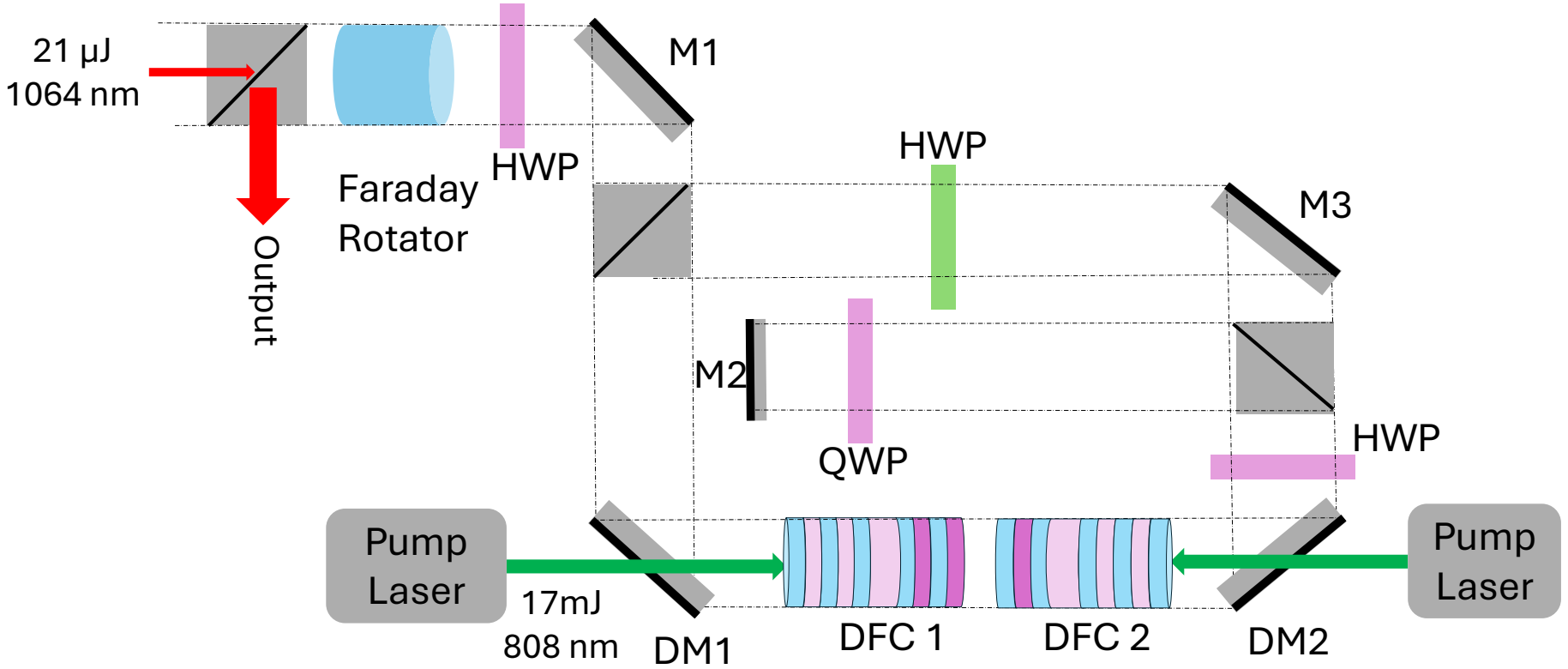
Damaged gain medium



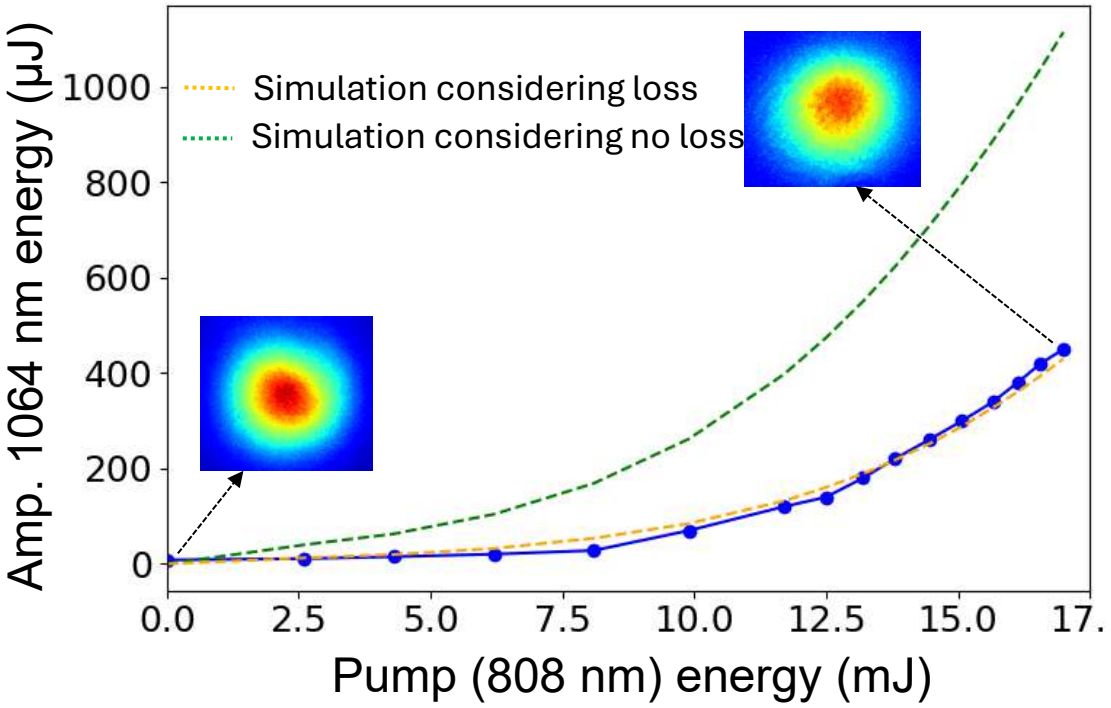
- DFC techniques solves depolarization and heating problem during amplification

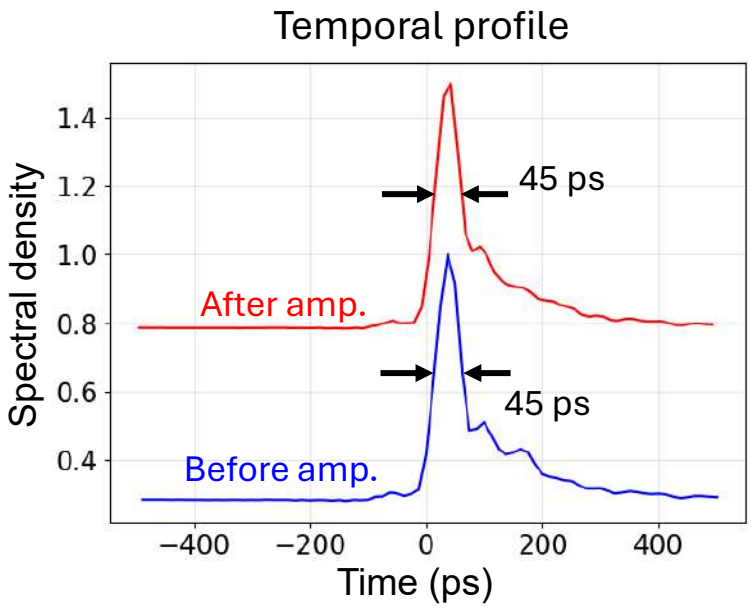
Picosecond pulse amplification

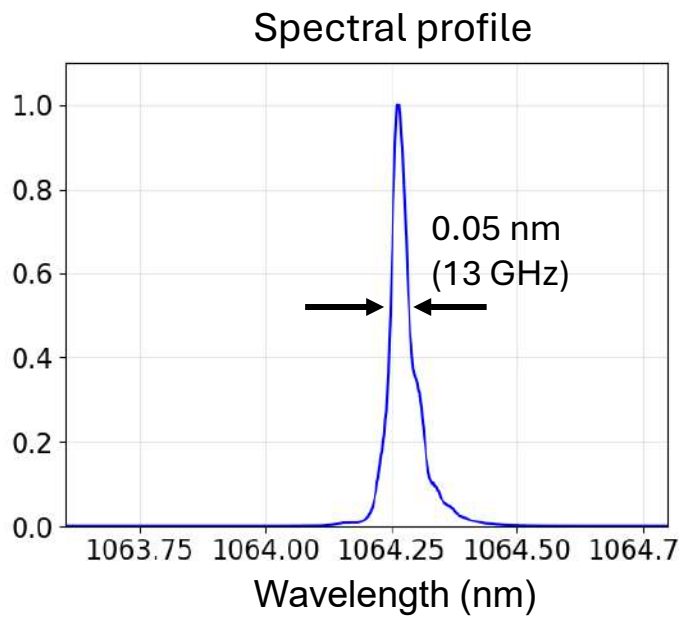




Picosecond pulse amplification

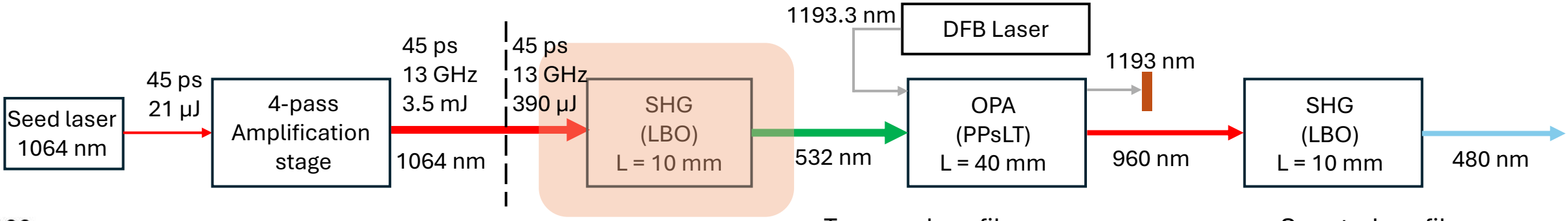


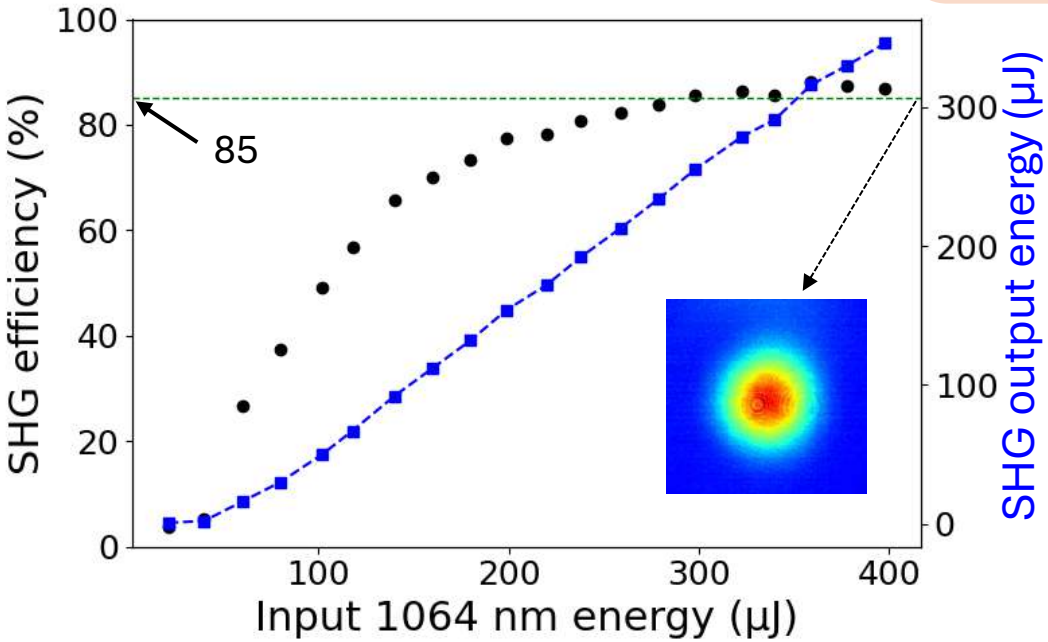


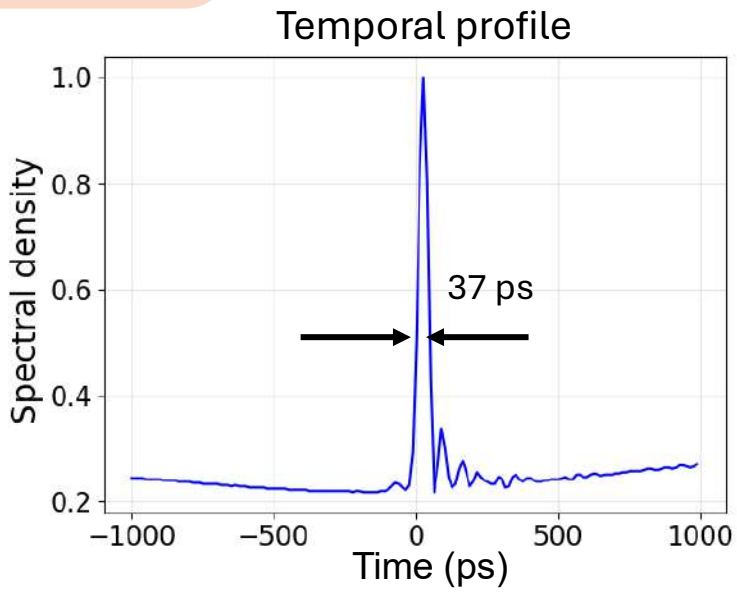


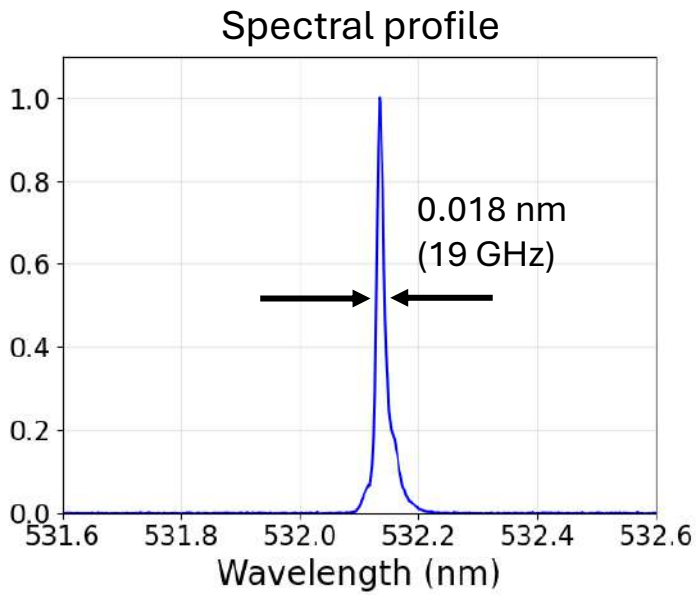
- We succeeded in generating 420 μJ pulse energy (10 MW peak power) of a 1064 nm pulse.
- Deviation from simulation due to improper beam overlap between pump and seed pulse.
- No change in pulse width before and after amplification.
- Spectral width of the amplified pulse is 13 GHz.
- The time bandwidth product gives 0.58, not too far from Gaussian (0.44).

Frequency conversion system



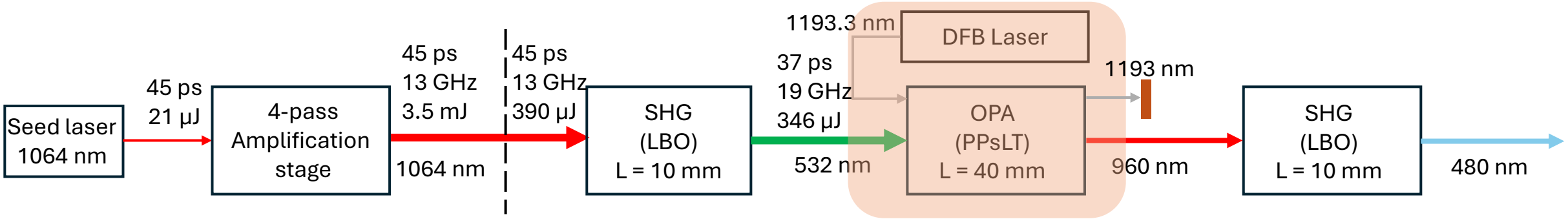




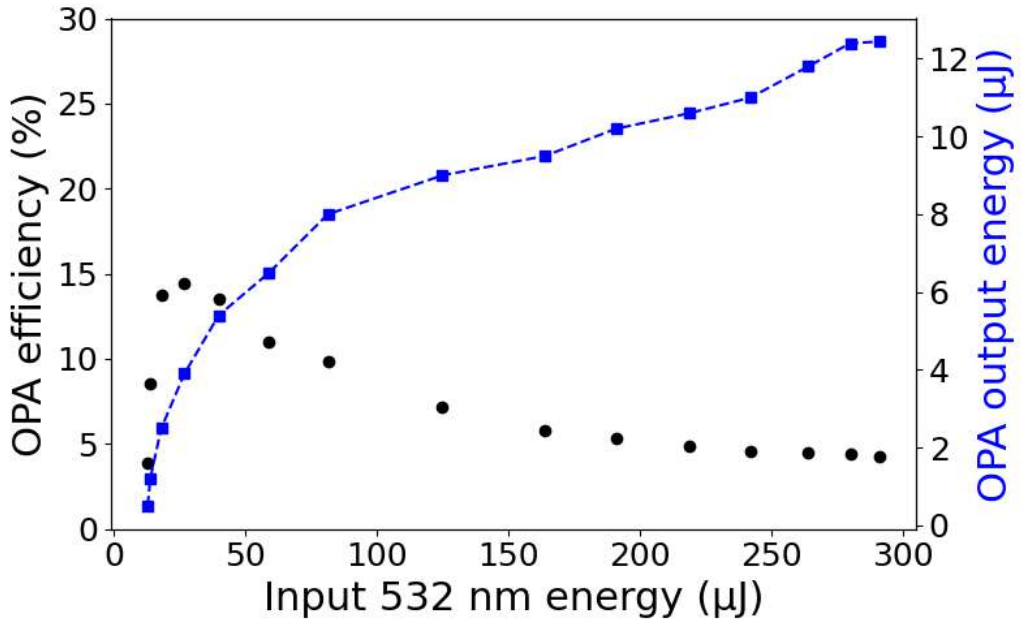


- We succeeded to get 88 % conversion efficiency (energy of 346 µJ) by using a 0.5 mm diameter 1064 nm input beam.
- The time bandwidth product is 0.70.
- Beam profile of 532 nm looks clean with M^2 = 1.2 .

Frequency conversion system

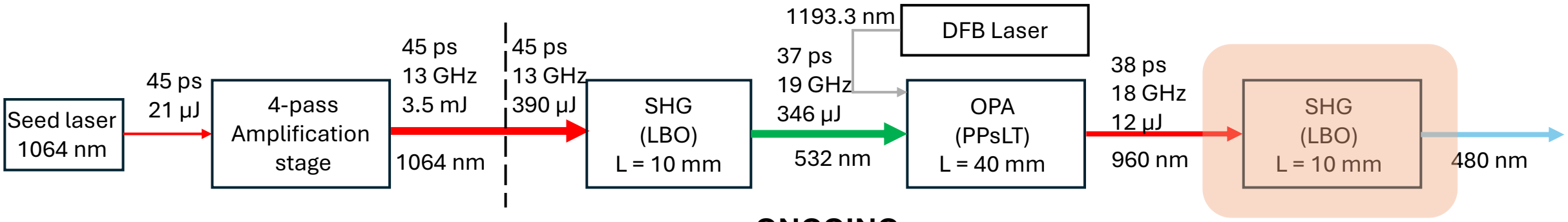


ONGOING
(Under progress)

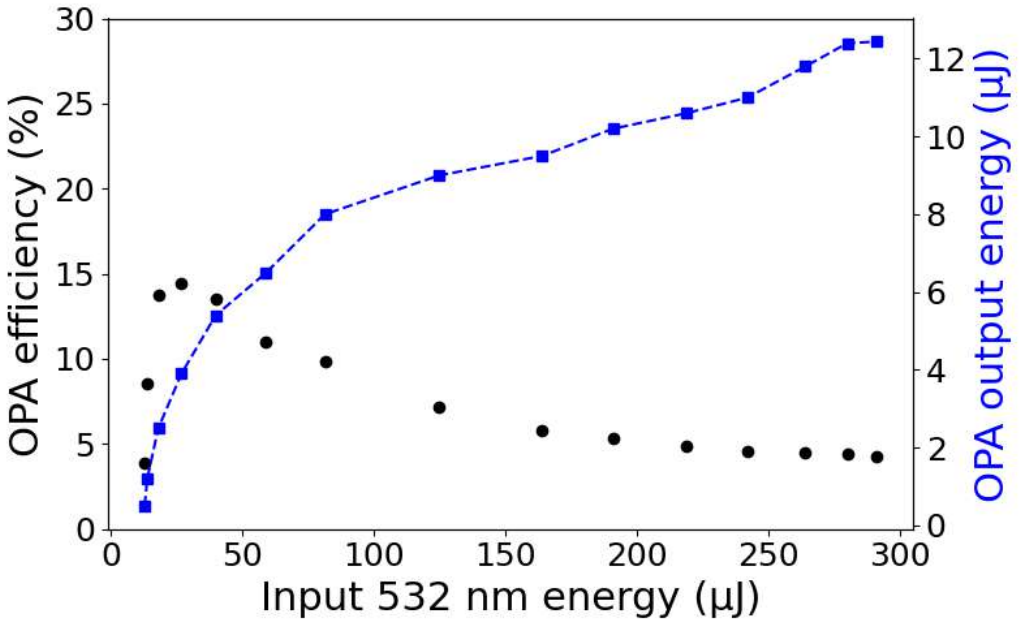


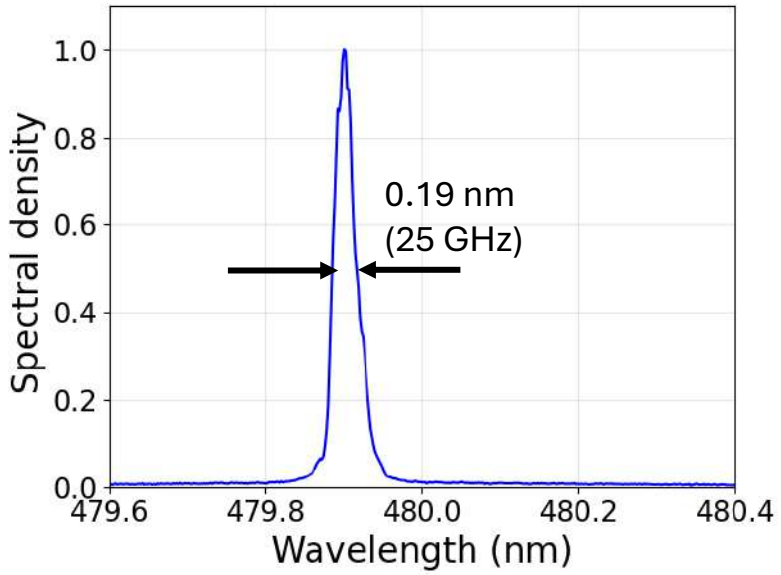
- For the OPA process, we generated 12 µJ of 960 nm pulse with conversion efficiency of 4 %.
- OPA efficiency starts decreasing after 25 µJ input energy.
- The time bandwidth product is 0.61.

Frequency conversion system



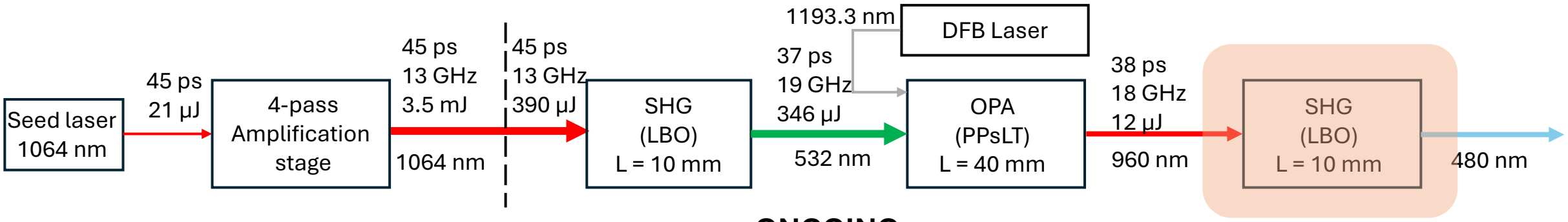
ONGOING
(Under progress)



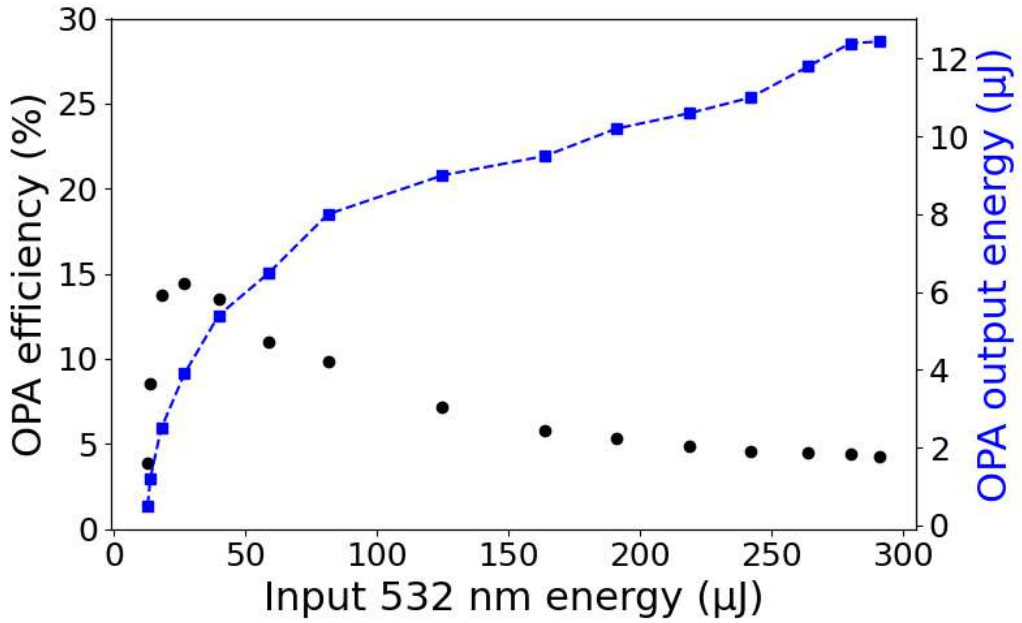


- For the OPA process, we generated 12 µJ of 960 nm pulse with conversion efficiency of 4 %.
- OPA efficiency starts decreasing after 25 µJ input energy.
- Bandwidth of 480 nm pulse is 25 GHz which is close to our expected value.

Frequency conversion system



ONGOING
(Under progress)



Wavelength (nm)	Target energy	Achieved energy
1064	15 mJ	420 mJ
532	10 mJ	320 µJ
960	2 mJ	12 µJ
480	1 mJ	Not yet

- For the OPA process, we generated 12 µJ of 960 nm pulse with conversion efficiency of 4 %.
- OPA efficiency starts decreasing after 25 µJ input energy.
- Bandwidth of 480 nm pulse is 25 GHz which is close to our expected value.

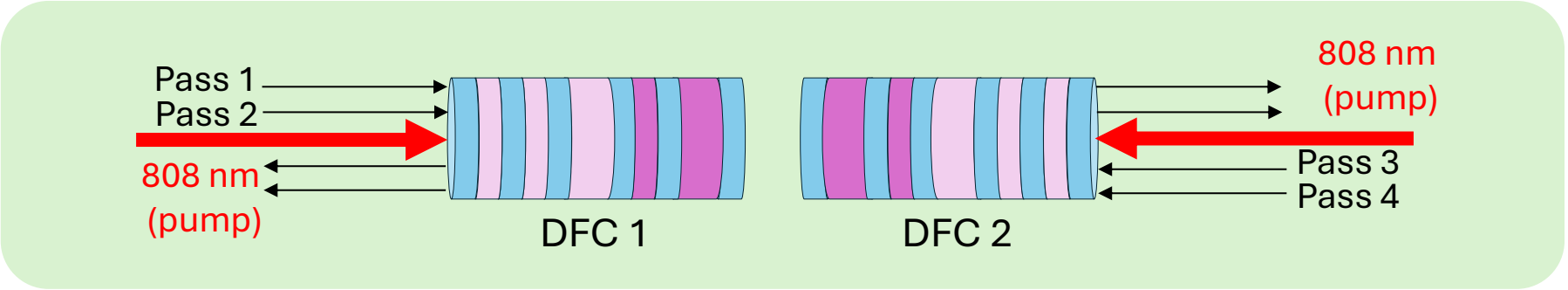
Part 1: Motivation: Why single atoms and Rydberg atoms are interesting?

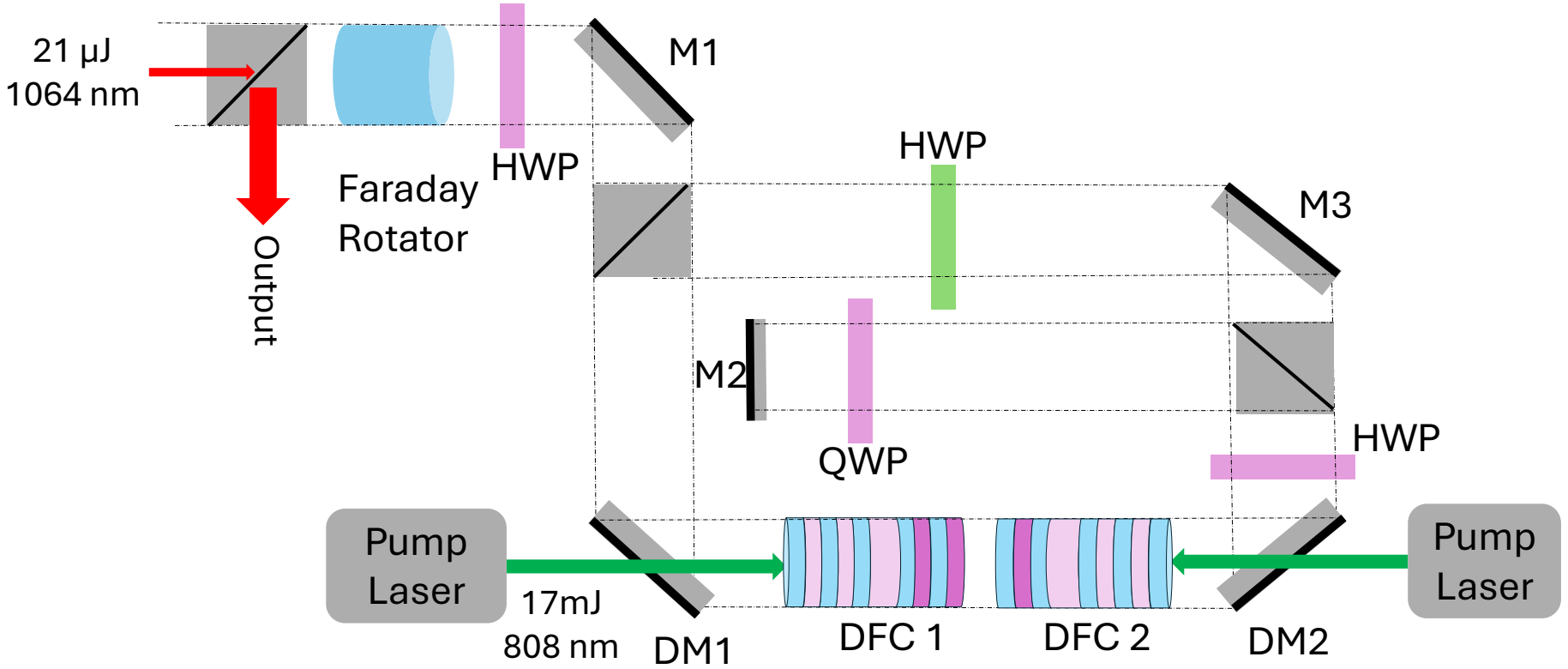
Part 2: Developed laser for QC and ultrafast quantum gates demonstration

Part 3: New laser development for scaling the number of qubits

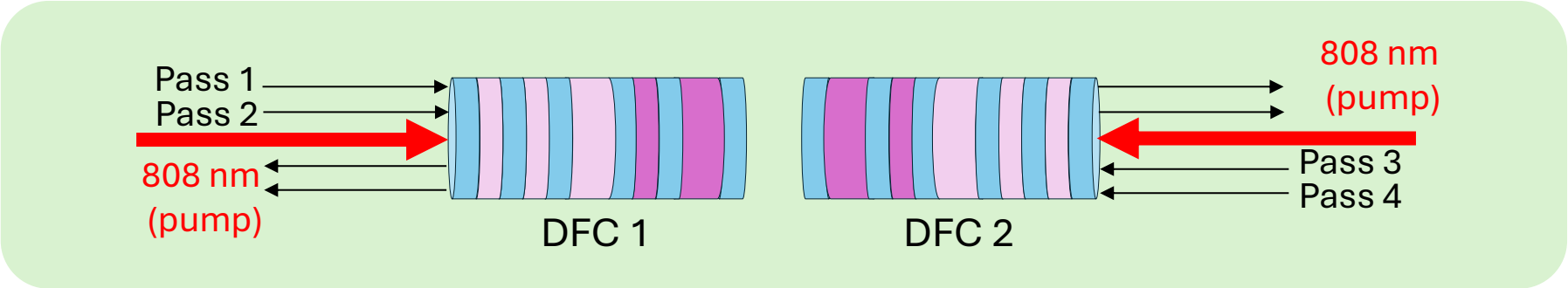
Part 4: Current challenges for the laser development.

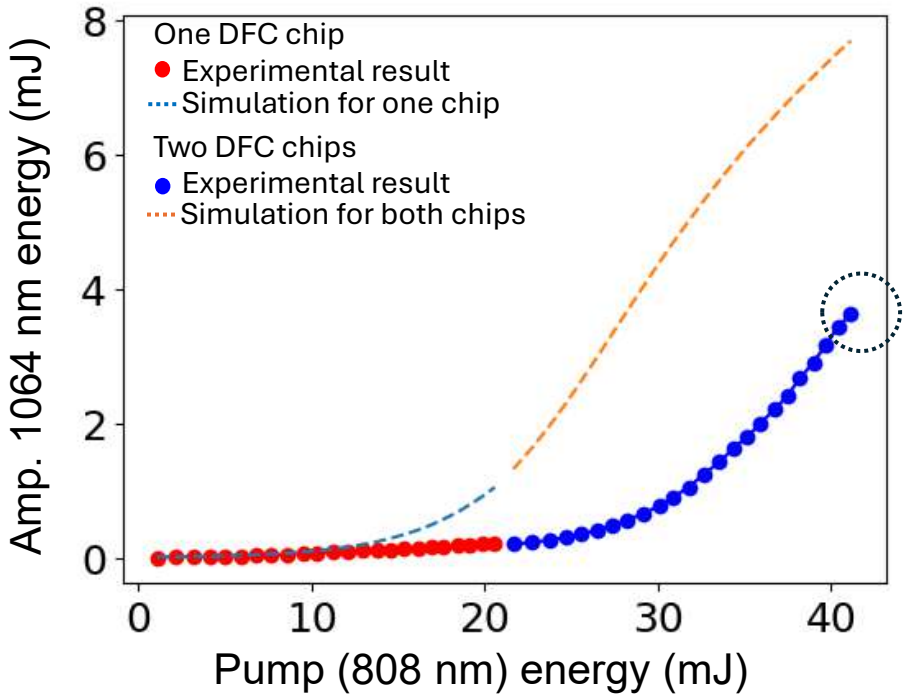
Picosecond pulse amplification

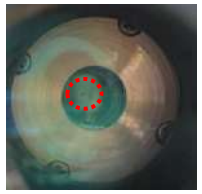




Picosecond pulse amplification







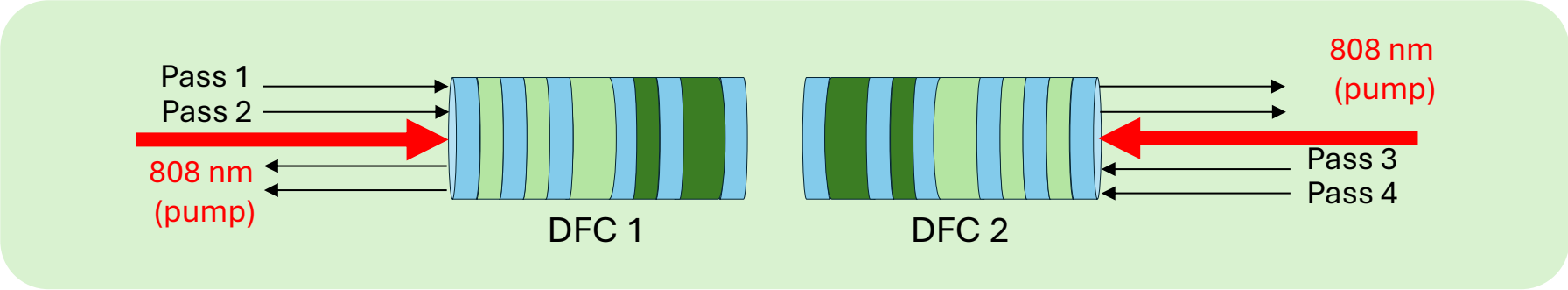
Damaged multiple optics

Solution:

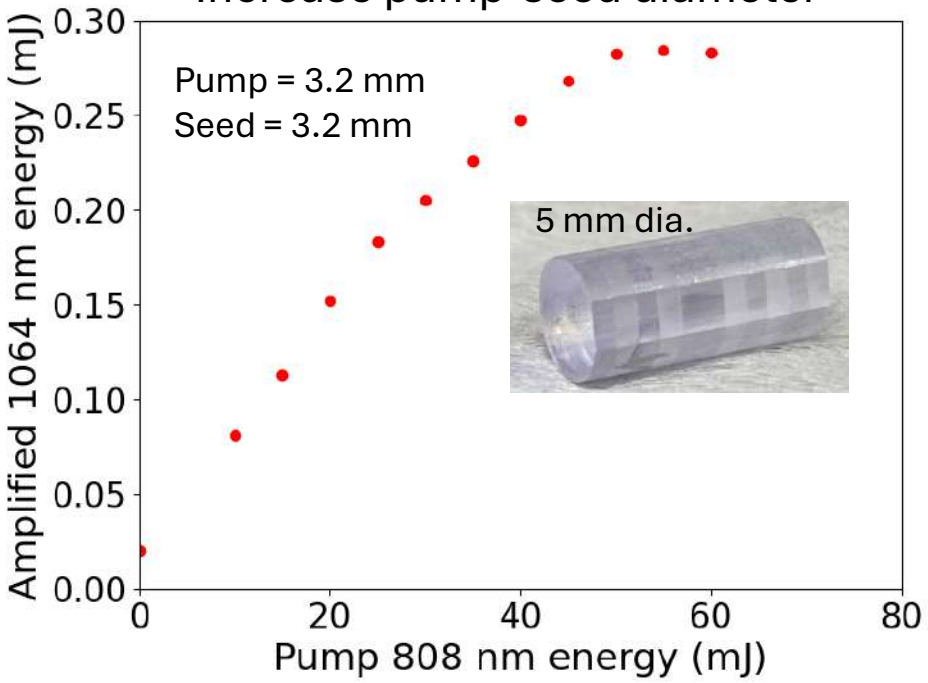
- Increase pump and seed beam size.
- Increase the pump energy to keep same gain.

- We succeeded in generating 3.5 mJ pulse energy (77 MW peak power) of a 1064 nm pulse.
- Deviation from simulation due to improper beam overlap between pump and seed pulse.
- Pump and seed beam diameter is 1.4 mm.

Picosecond pulse amplification

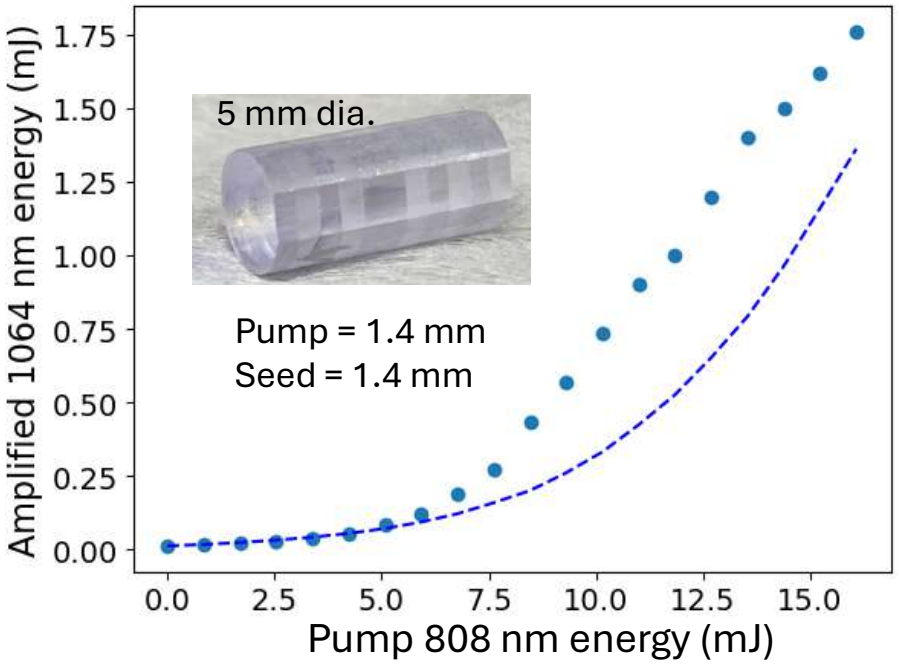


Increase pump-seed diameter



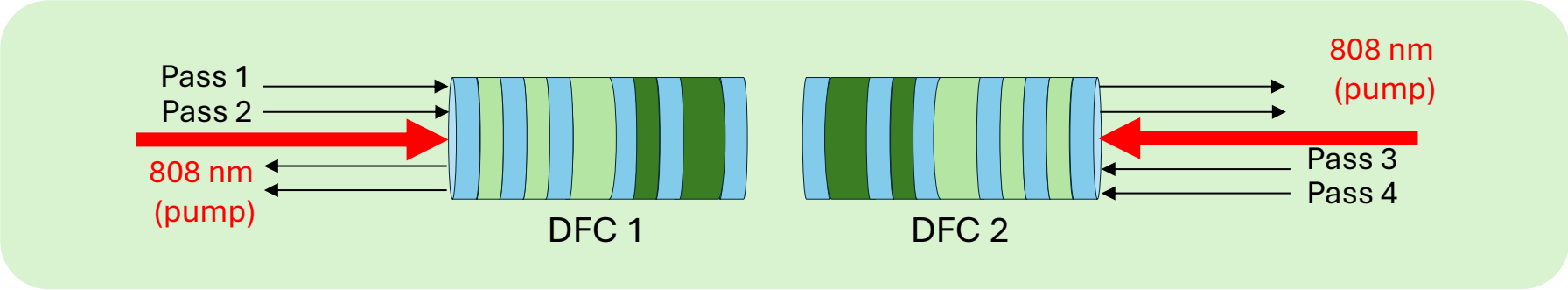
- ASE in the transverse direction start to dominate.

Current situation

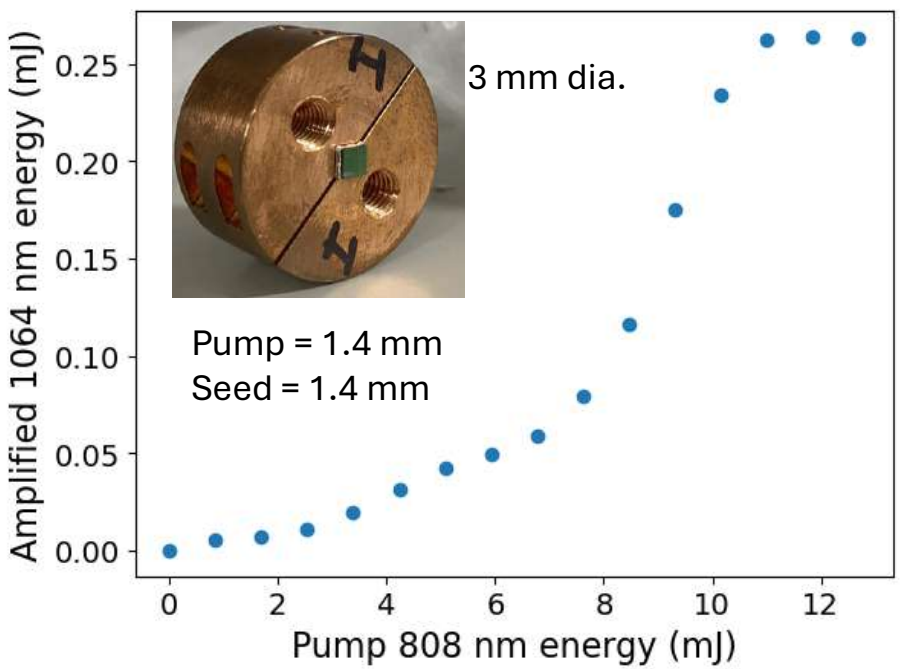


- ASE in transverse direction absorbed by Nd:YAG
- Strong gain along longitudinal direction.

Picosecond pulse amplification

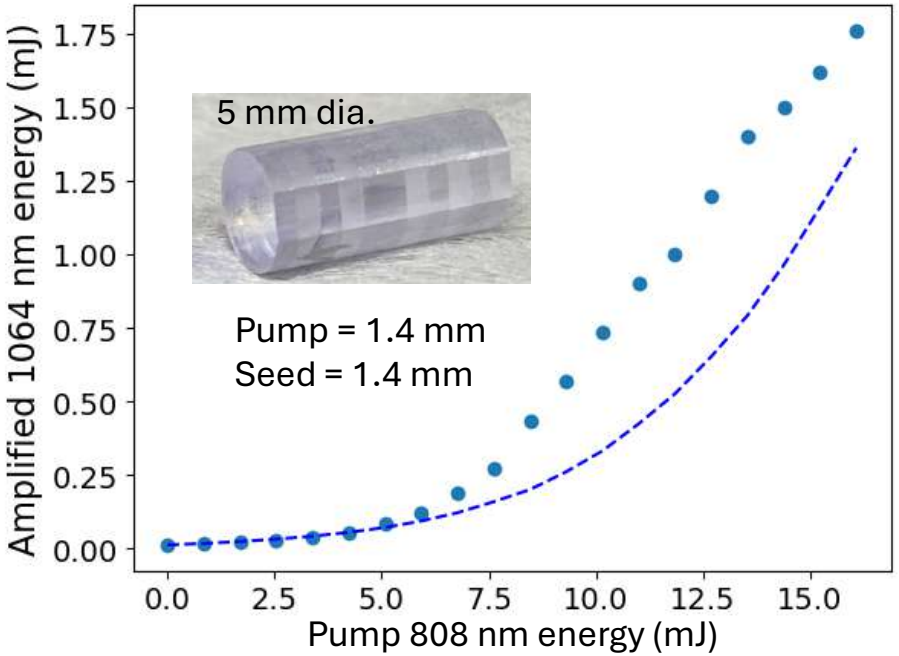


Decrease the aperture of DFC



- This conforms that ASE in transverse direction is strong.

Current situation



- ASE in transverse direction absorbed by Nd:YAG
- Strong gain along longitudinal direction.