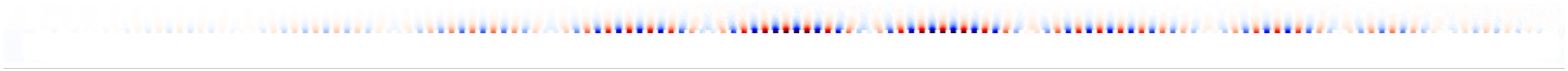
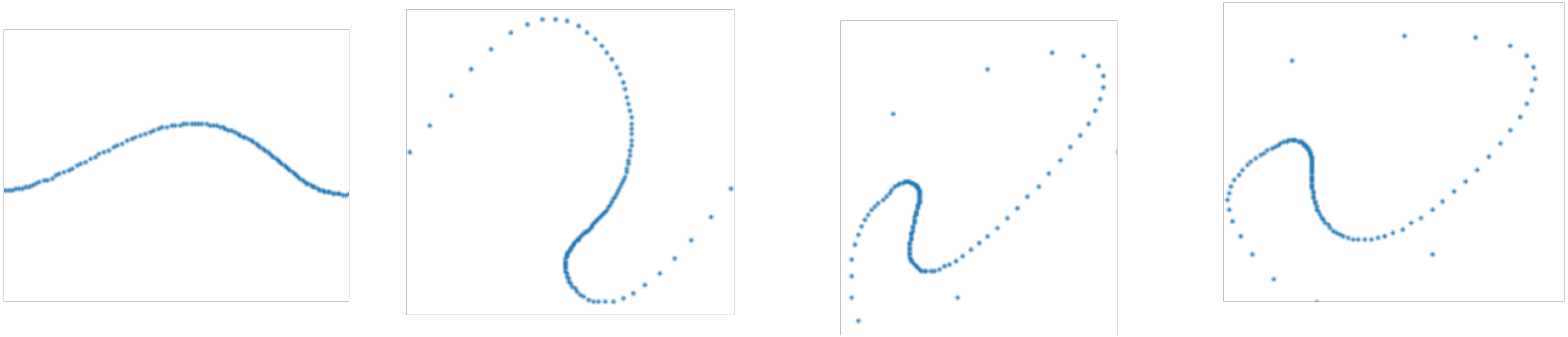
Nanophotonic free-electron lasers





Nick Rivera (MIT), Charles Roques-Carmes (MIT),
Ido Kaminer (Technion) & Marin Soljačić (MIT)

http://nrivera.scripts.mit.edu/nhr/

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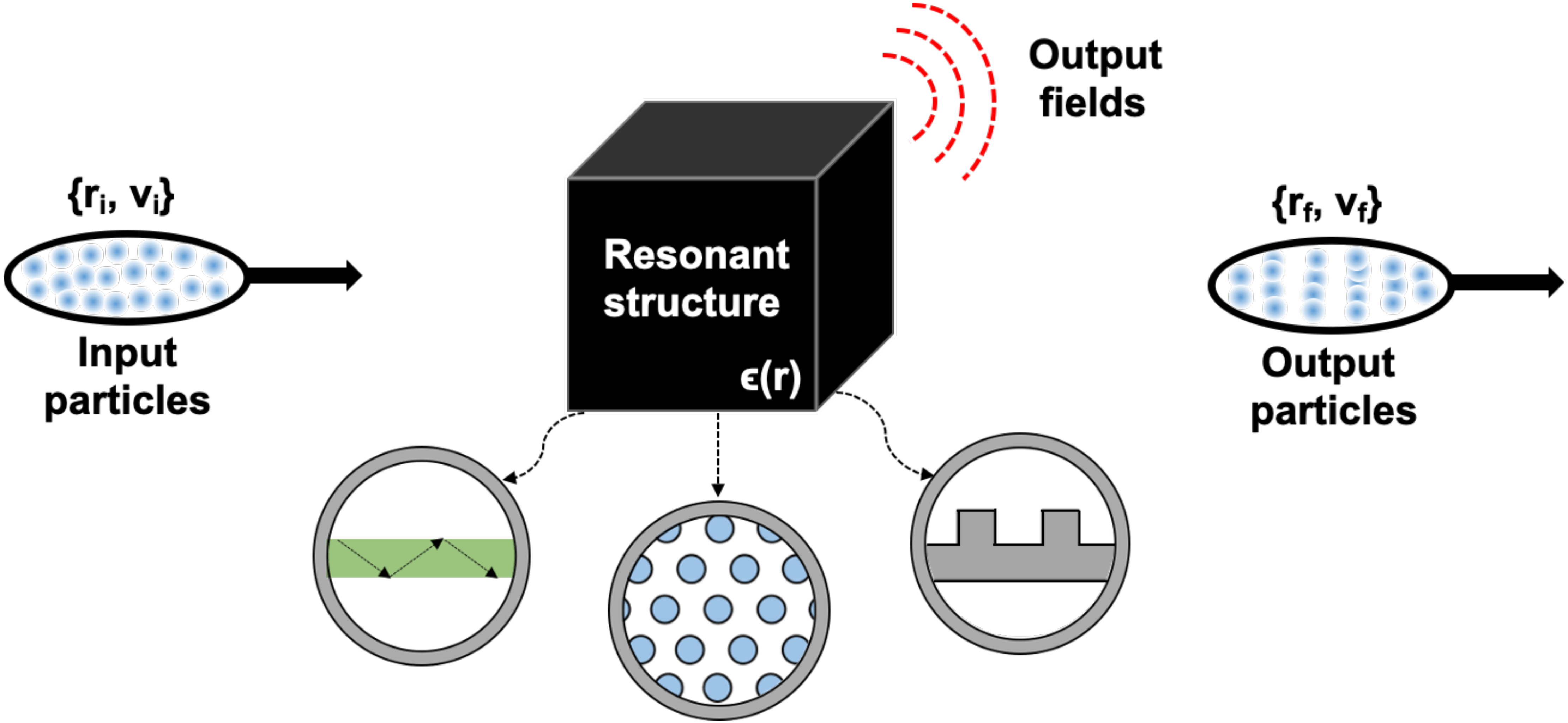
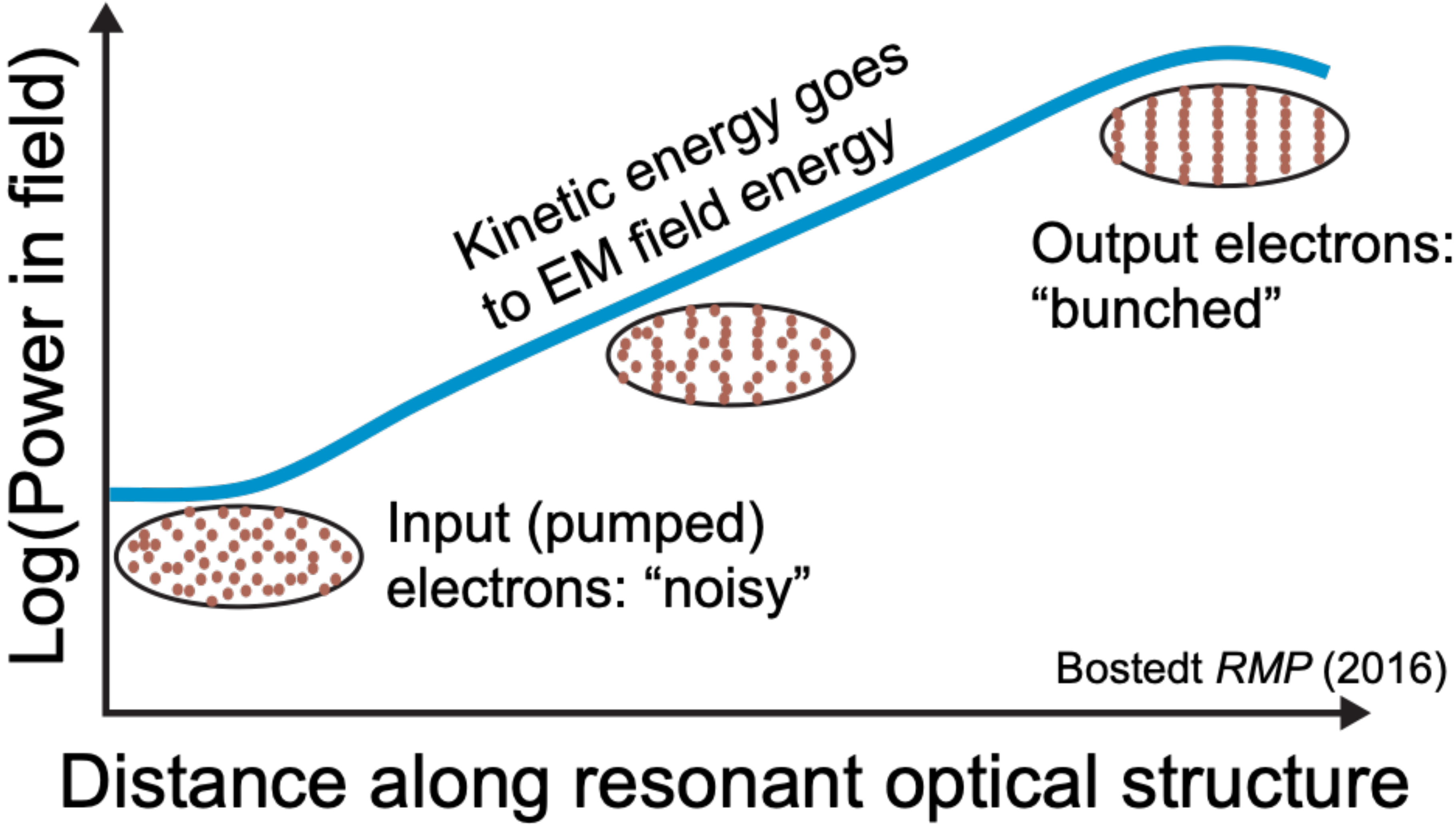
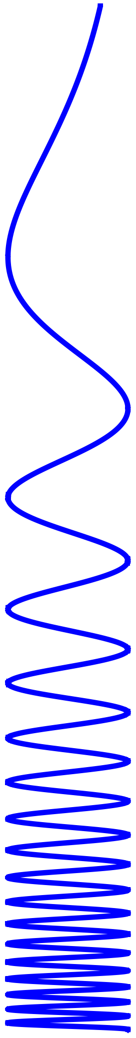


FEL: resonant optical structure + free electron *gain medium & pump*

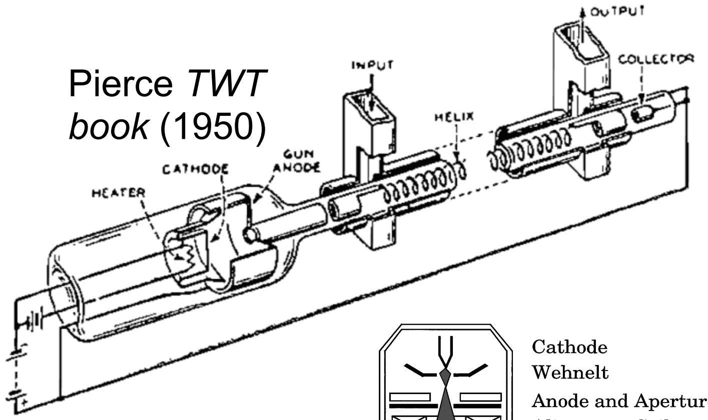


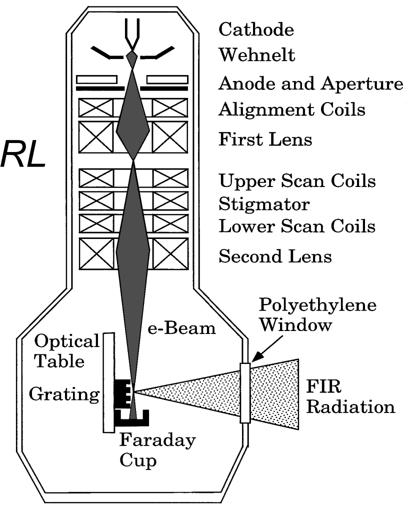
Bostedt *RMP* (2016)

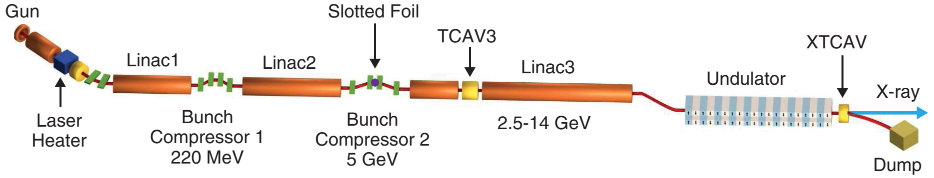
FEL principle: applicable through the full electromagnetic spectrum



Microwave	Traveling wave tubes	Pierce *TWT book* (1950)
THz	Smith-Purcell lasers	Urata *PRL* (1998)
IR		
Vis	**?**	**?**
UV		
X-ray	X-FEL	Bostedt *RMP* (2016)







General (semi-analytical) description of nanophotonic FELs

Field expandable in terms of a few modes:

$$\mathbf{E}(\mathbf{r}, t) = \sum_{\text{resonances } m} \alpha_m(z - v_g t, t)\mathbf{E}_m(\mathbf{r})e^{-i\omega_m t}$$

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Slowly-varying envelope → scale separation and coarse-graining:

$$\left(\partial_t + v_{gm}\partial_z + \tau_m^{-1}\right)\alpha_m = \frac{qL}{2i\omega_m \epsilon_0 \Delta z} \sum_{i \in \text{vol}(z)} \mathbf{v}_i(t) \cdot \nabla \mathbf{E}^*(\mathbf{r}_i(t)) \cdot \mathbf{v}_i(t) e^{i\omega_m t}$$

group velocity

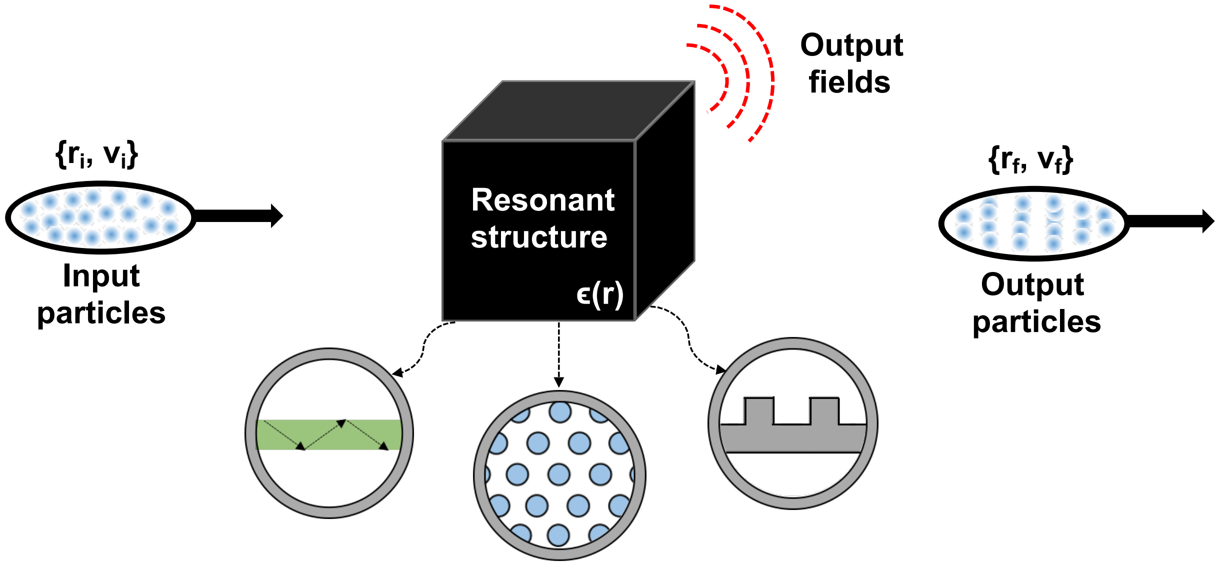
loss rate

coarse-grained scale

volume in the coarse-grained cell

Ab initio free electron laser physics

What constitutes an *ab initio* description?



$\{r_i, v_i\}$

Input particles

Resonant structure

$\epsilon(r)$

Output fields

$\{r_f, v_f\}$

Output particles

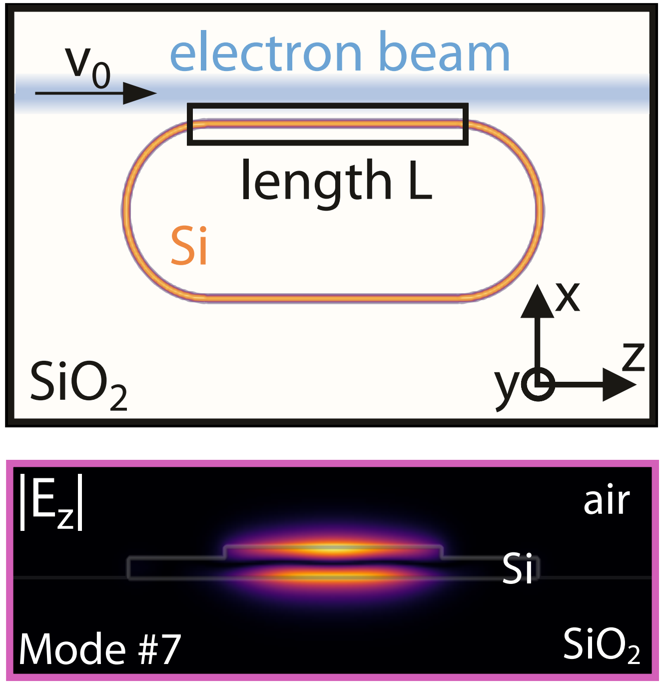
Implementation:

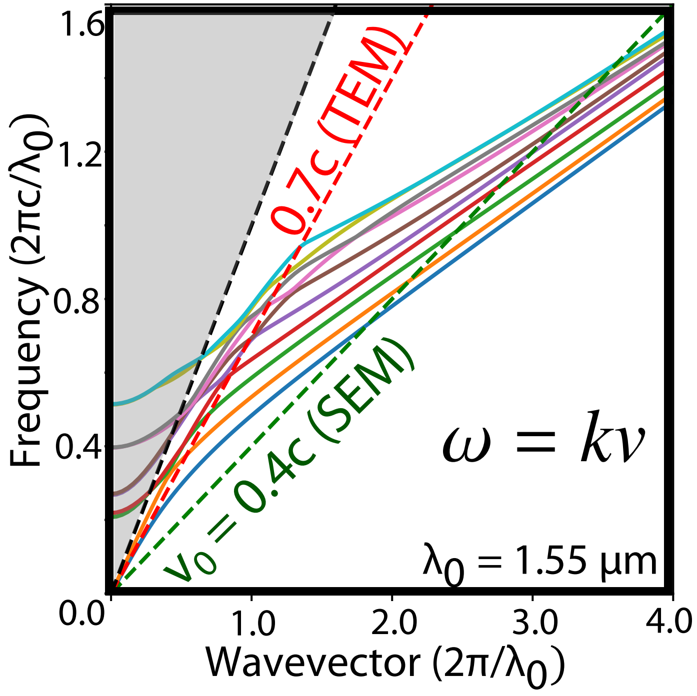
Oskooi, *et al*.
Comp. Phys. Comm. (2010)

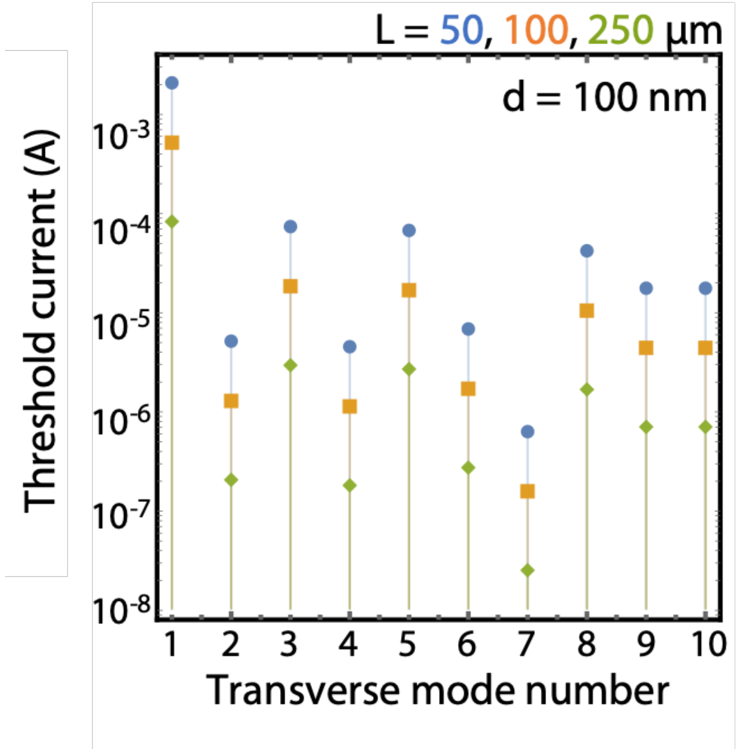
Benefits?

- Pulsed systems: highest intensities
- Surprising modes can lase
- Fundamental insights into nonlinear regime
- **Emergent phenomena?**

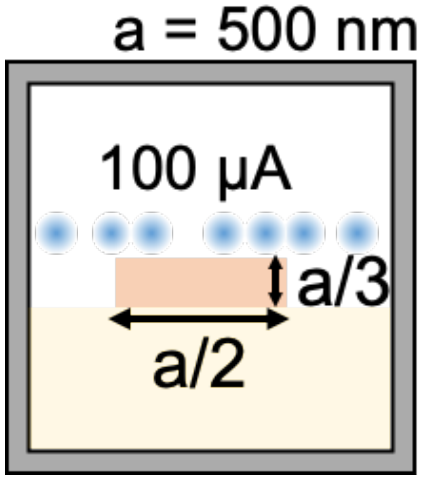
An ultra-low threshold FEL based on a silicon racetrack resonator

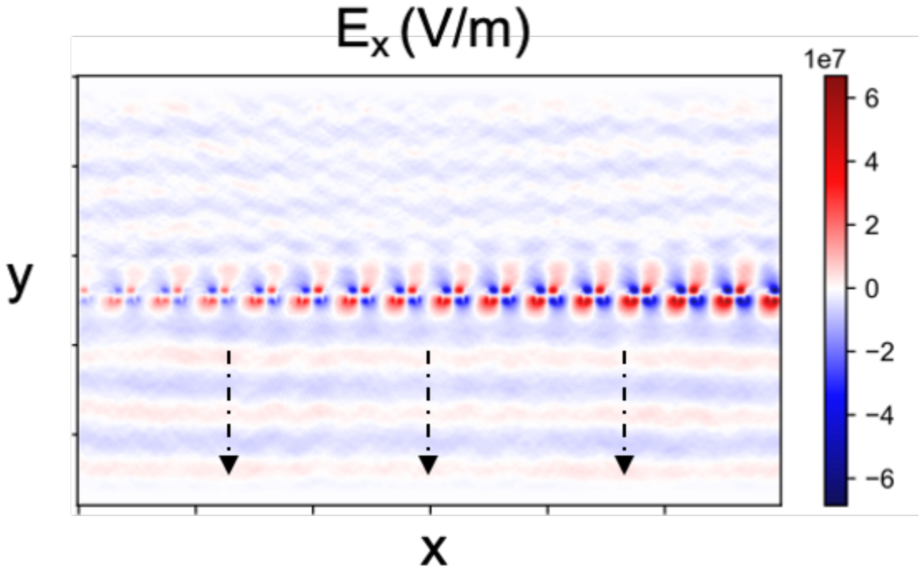


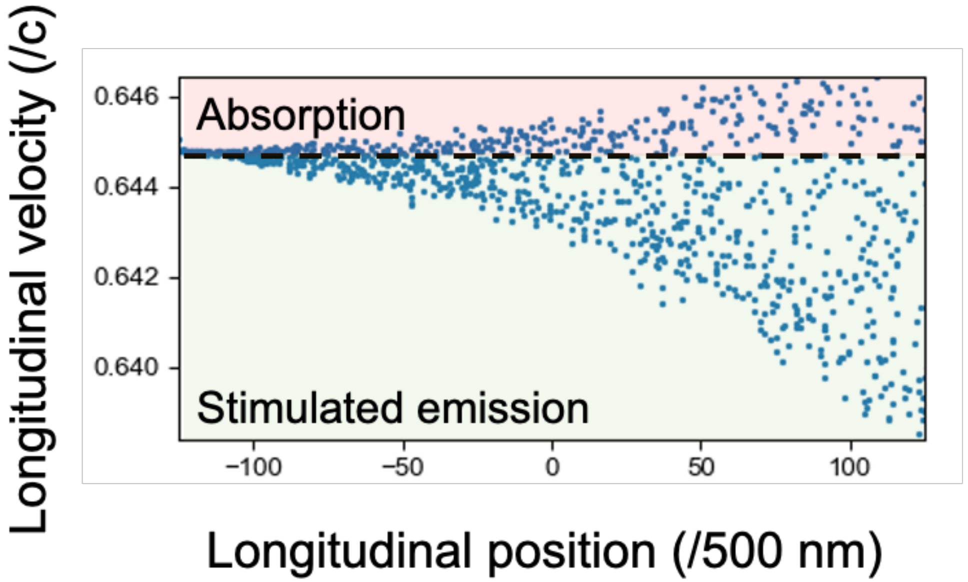


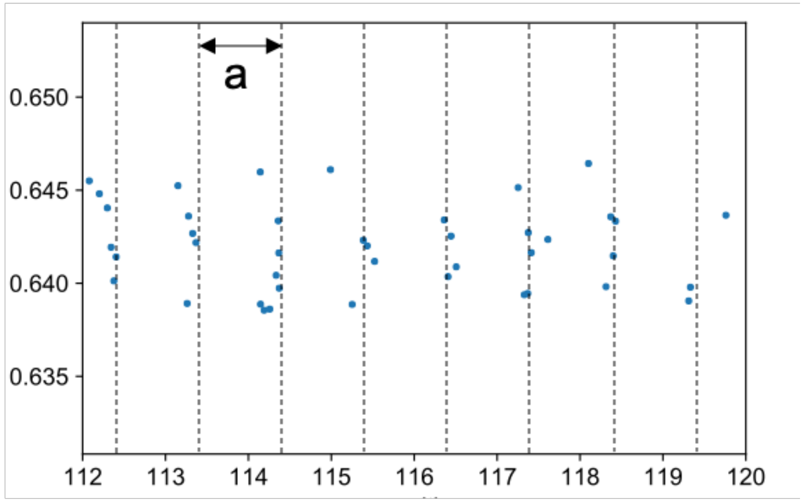


An FEL based on an high-Q photonic crystal resonance









Potential realizations

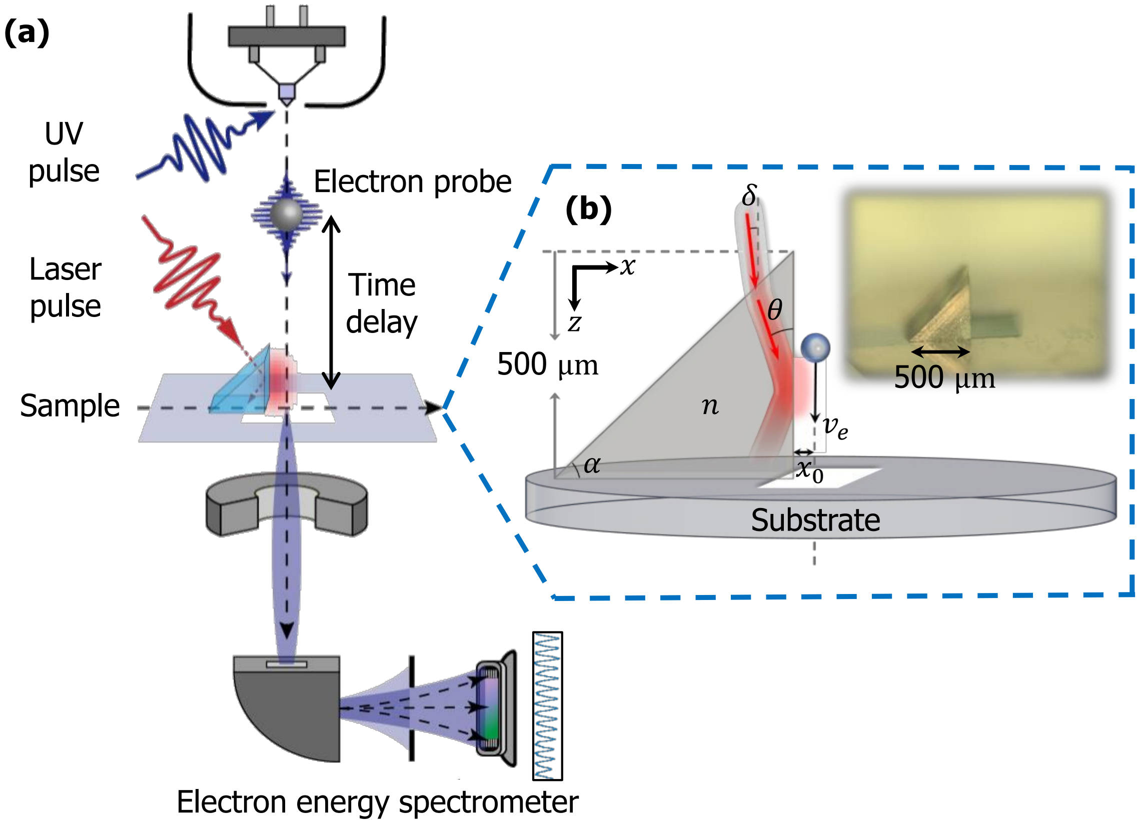
Parameters realizable:

- Schottky field emission sources,
- Racetrack resonators, photonic crystals with high-Q BICs

Major difficulty: long enough interaction

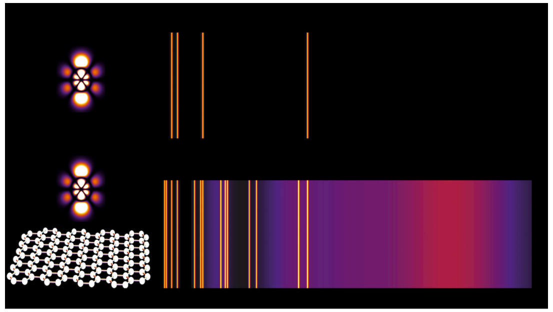
Promising work: grazing angle in ultrafast TEMs (at lower currents)

Nehemia*, Dahan* *et al.* arXiv: 1909.00757



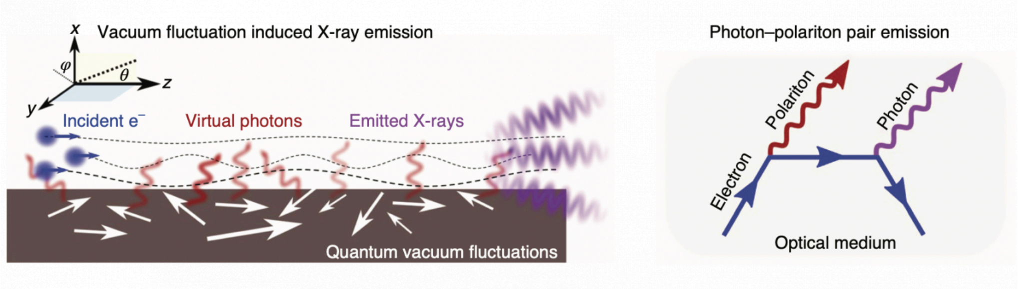
Shameless advertising…

Light-matter interactions in 2D materials



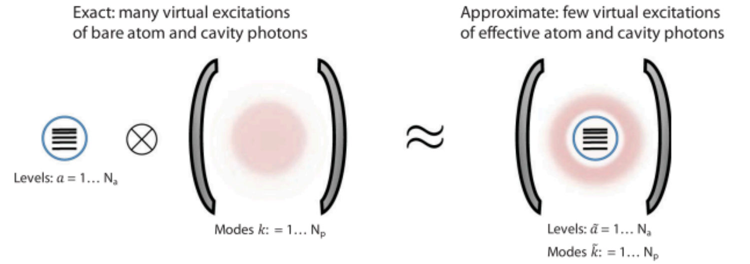
Rivera*, Kaminer*, Zhen, Joannopoulos & Soljačić. *Science* (2016).

Quantum free-electron radiation sources



Rivera, Wong, Joannopoulos, Soljačić & Kaminer. *Nature Physics* (2019).

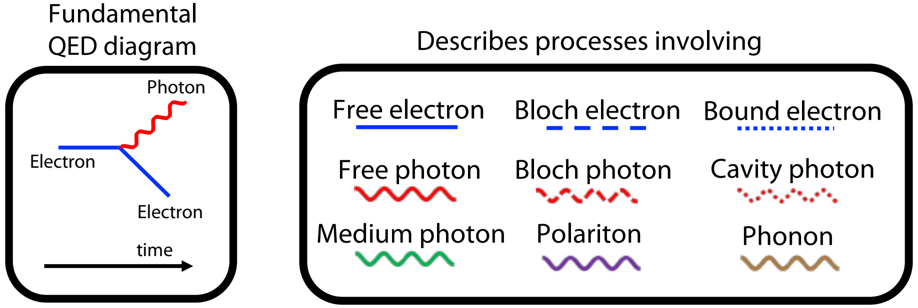
New methods in strong quantum light-matter interaction



$$|\Psi\rangle = \sum_{a=0}^{N_a} \sum_{n_1 \cdots n_{N_p}=0}^{\infty} c_{a;n_1 \cdots n_{N_p}} |a\rangle \otimes |n_1 \cdots n_N\rangle \qquad |\Psi\rangle \approx |\tilde{g}\rangle \otimes |\tilde{0}\rangle + \sum_{\tilde{a}=1}^{N_a} \sum_{\tilde{k}=1}^{N_p} c_{\tilde{a};\tilde{k}} |\tilde{a}\rangle \otimes |\tilde{1}_{\tilde{k}}\rangle$$

Rivera, Flick & Narang. *Phys. Rev. Lett.* (2019).

Unifying light-matter interactions



Rivera & Kaminer. In press at *Nature Reviews Physics* (2020).