QED with cooperative atom arrays

Susanne Yelin

Harvard University

SPICE workshop, June 18, 2024

Cooperative 2D arrays

Goals

- Use 2D array…

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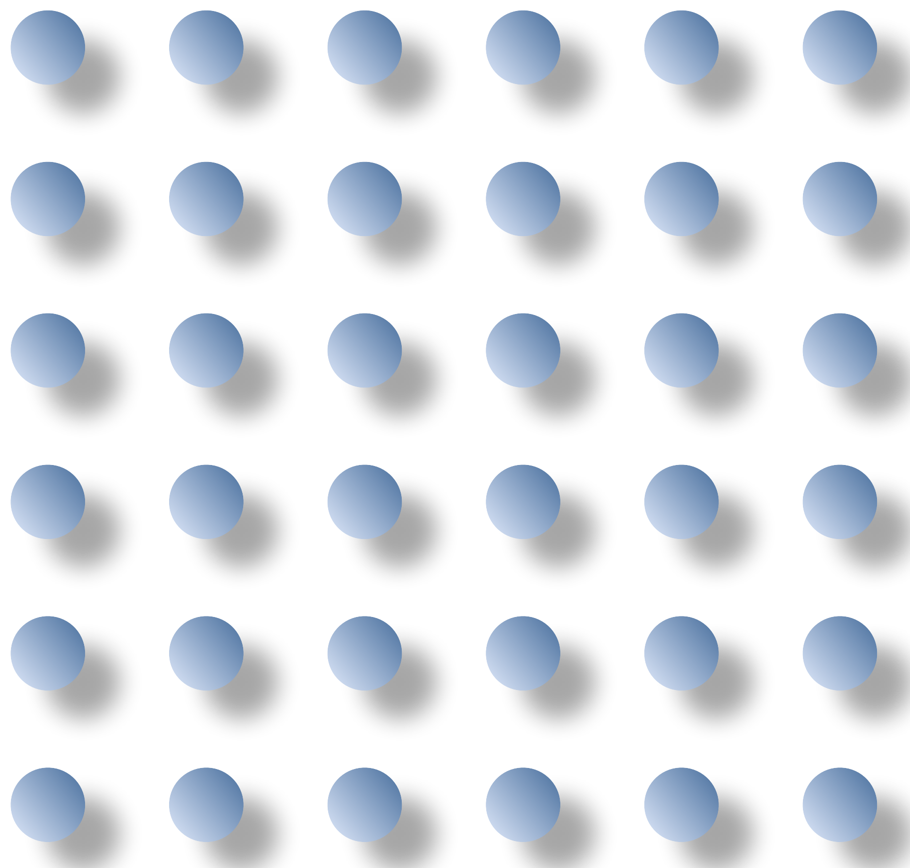
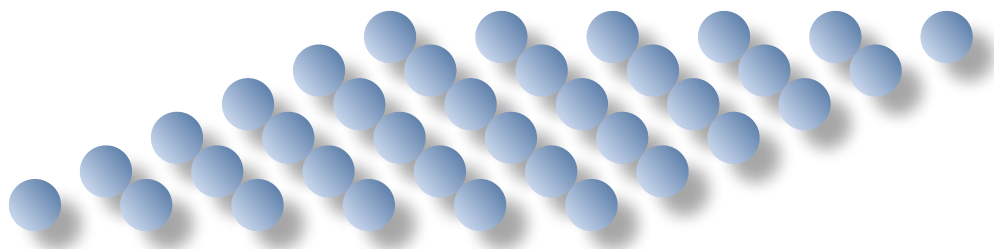
- Use 2D array…



Quantum optics with atomically thin materials

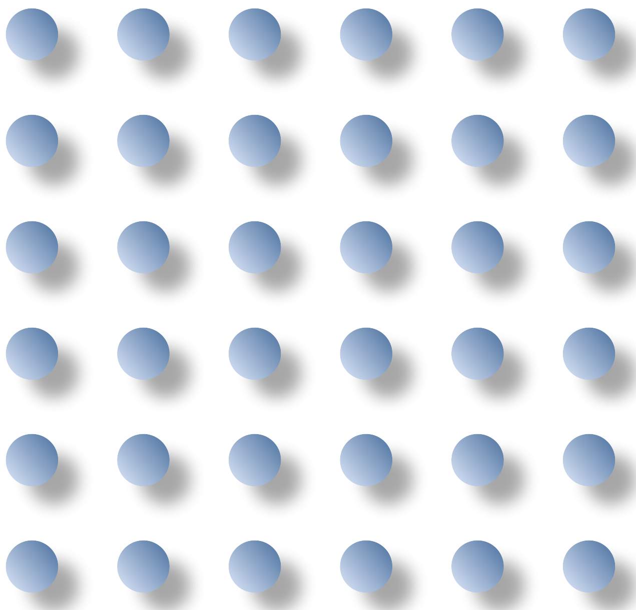


➡ can have very strong optical response

➡ optical response can be engineered

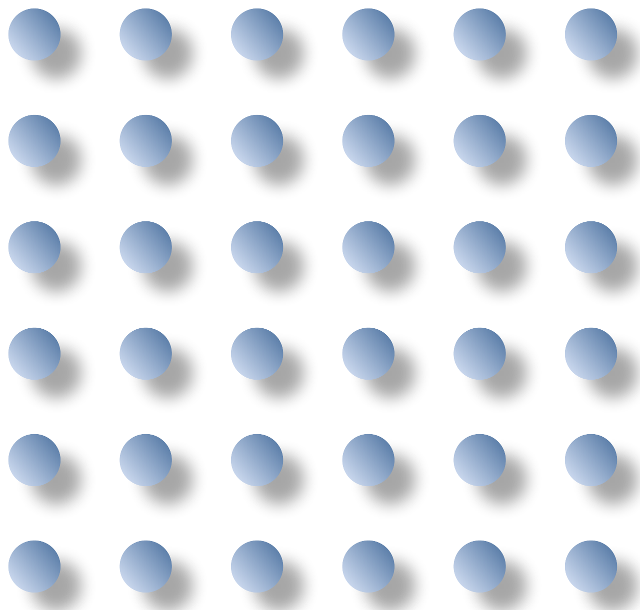
"atomic metasurfaces"

Simple example: Reflectivity



Simple example: Reflectivity

array of atoms



Shahmoon, Wild, Lukin, Yelin, PRL **118**, 113601 (2017)
cf. Bettles, Gardiner, Adams, PRL **116**, 103602

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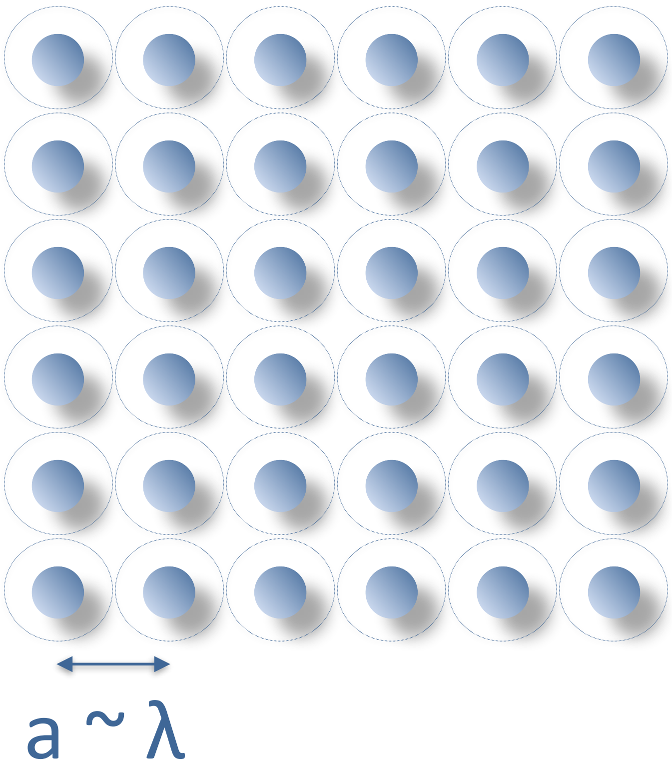

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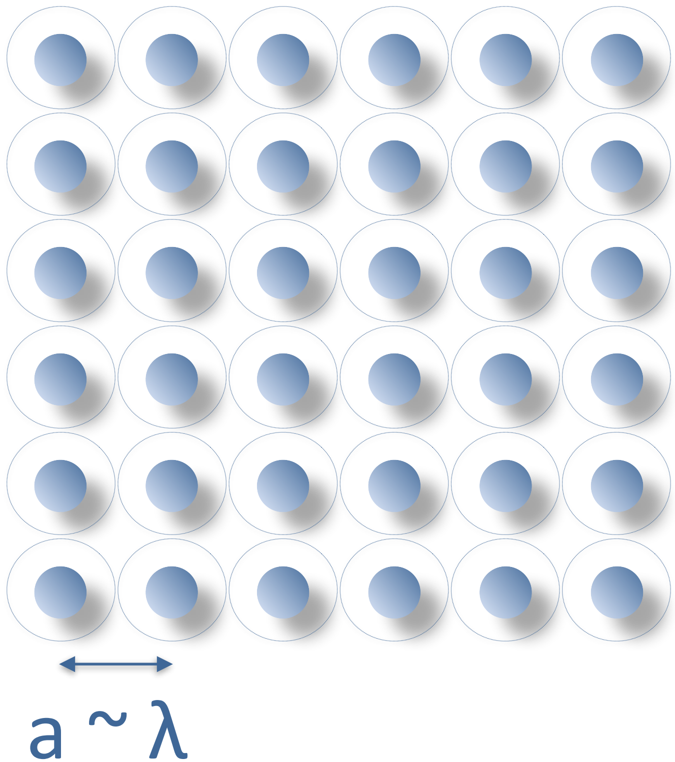

Complete Reflection!

for $a/\lambda = 0.2$

and $a/\lambda = 0.8$

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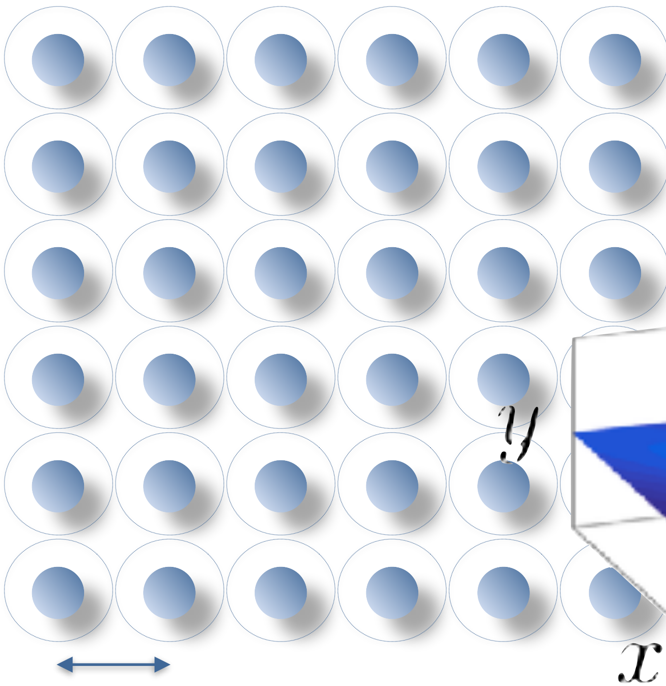
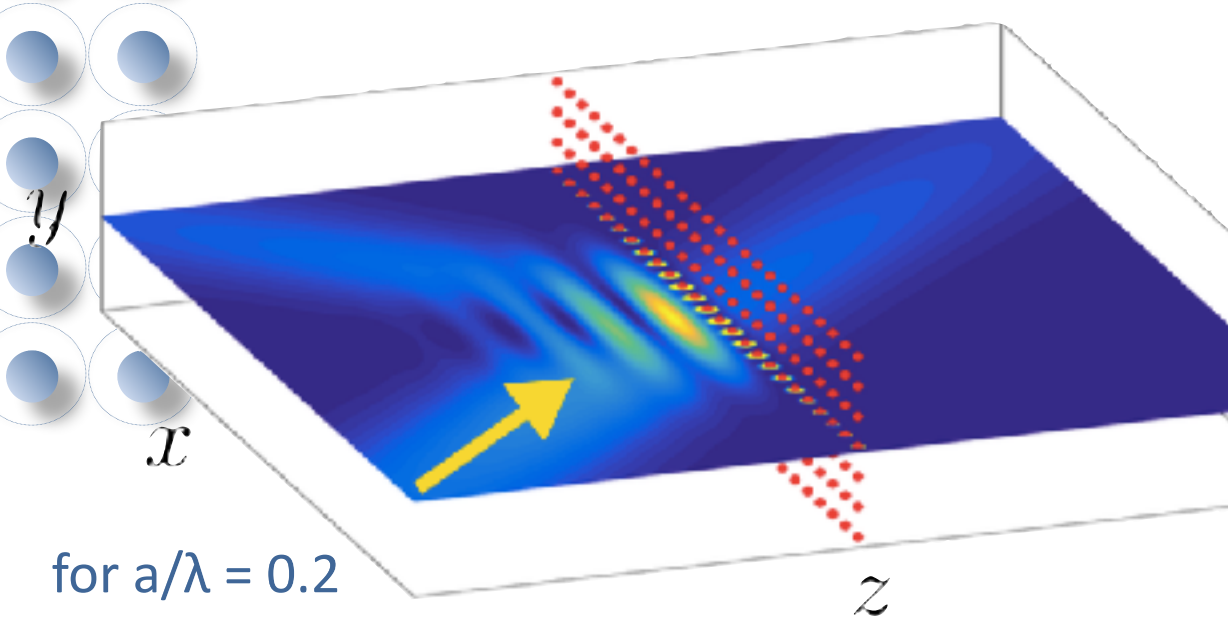


a ~ λ

Complete Reflection!



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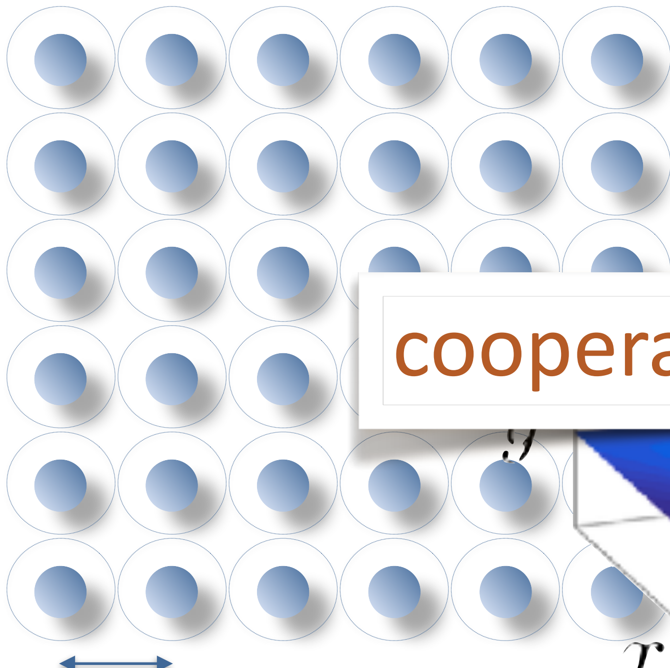
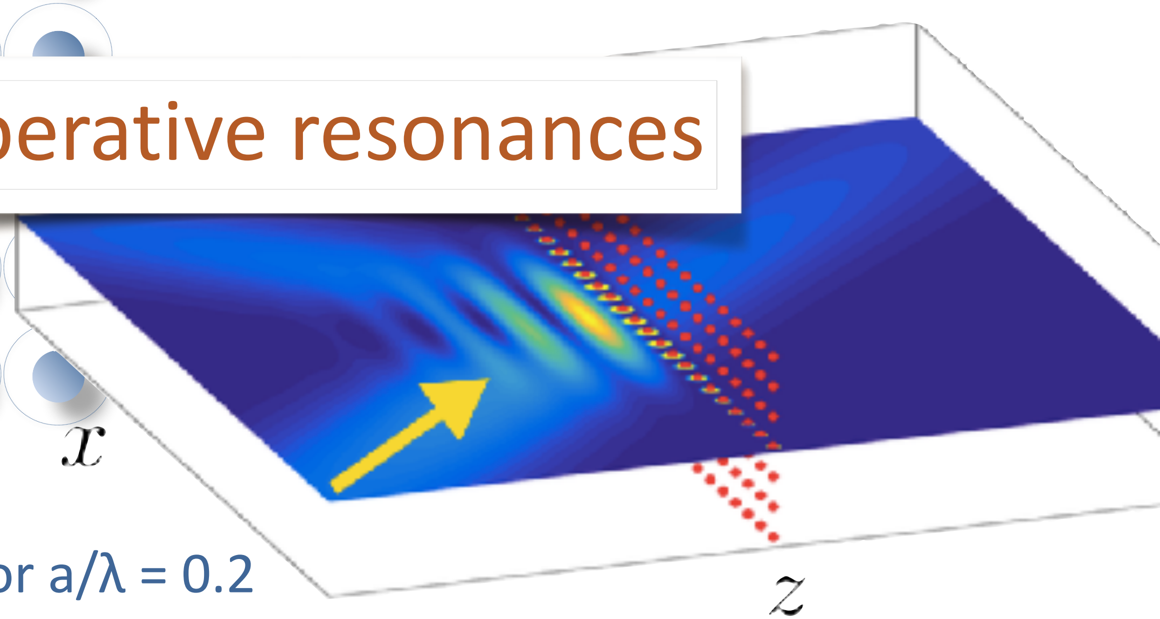


$a \sim \lambda$

Complete Reflection!

cooperative resonances



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Perfect Reflection

$$E_{\text{out}} = E_0 \left(e^{ik_z z} + S e^{ik_z |z|} \right)$$

Shahmoon, Wild, Lukin, Yelin, PRL **118**, 113601 (2017)

Perfect Reflection

outgoing

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Perfect Reflection

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incoming

Shahmoon, Wild, Lukin, Yelin, PRL **118**, 113601 (2017)

Perfect Reflection

outgoing

scattered

$$E_{out} = E_0 \left(e^{ik_z z} + S e^{ik_z |z|} \right)$$

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Perfect Reflection

$$E_{out} = E_0 \left(e^{ik_z z} + S e^{ik_z |z|} \right)$$

scattered

incoming

$$S = -1$$

Shahmoon, Wild, Lukin, Yelin, PRL **118**, 113601 (2017)

Perfect Reflection

$$E_{out} = E_0 \left(e^{ik_z z} + S e^{ik_z |z|} \right)$$

$$S = -\frac{i}{2} \frac{\gamma + \Gamma_{coll}}{\delta + \Delta_{coll} + \frac{i}{2}(\gamma + \Gamma_{coll})}$$

where $\Delta_{coll} - \frac{i}{2}\Gamma_{coll} =$ dipolar interaction between all atoms

Shahmoon, Wild, Lukin, Yelin, PRL **118**, 113601 (2017)

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cooperative effects !

where $\Delta_{coll} - \frac{i}{2}\Gamma_{coll} = \;\cdots$ ...action
...een all atoms

Shahmoon, Wild, Lukin, Yelin, PRL **118**, 113601 (2017)

Perfect Reflection

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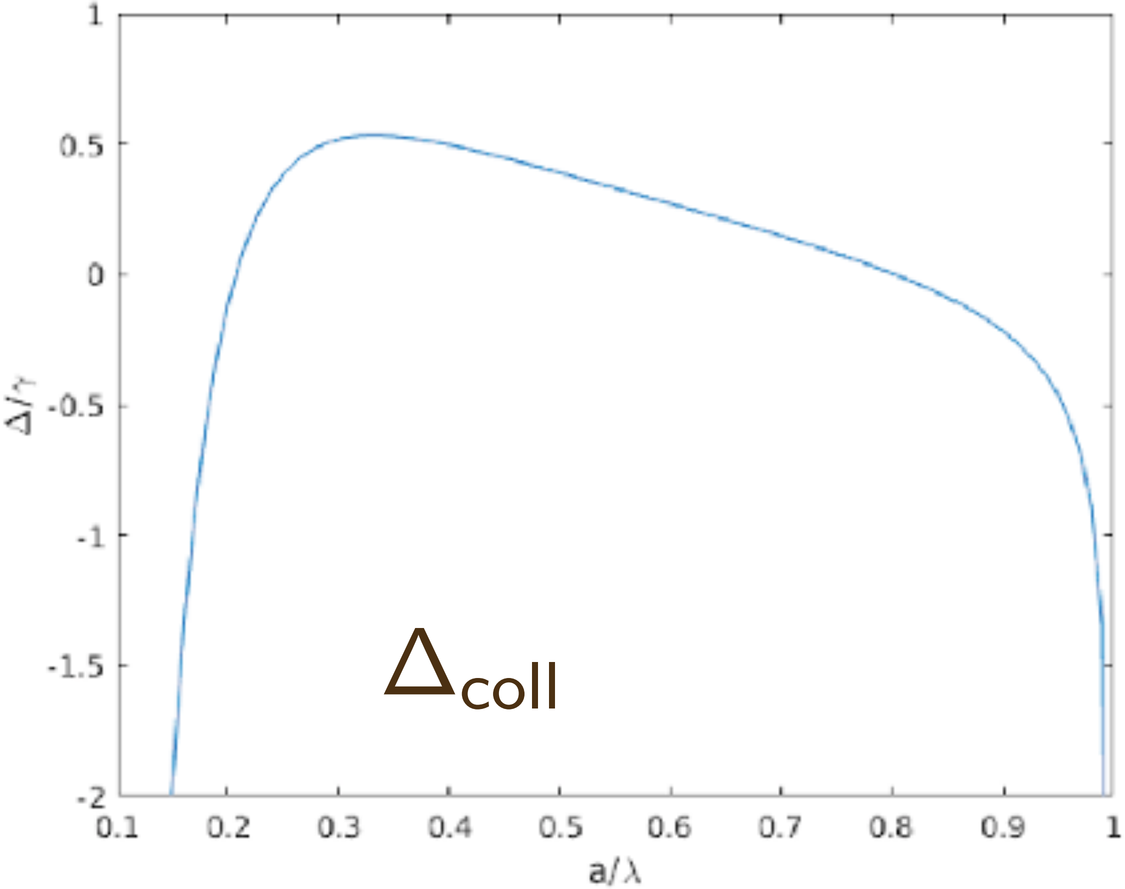
$$S = -\frac{i}{2} \frac{\gamma + \Gamma_{coll}}{\delta + \Delta_{coll} + \frac{i}{2}(\gamma + \Gamma_{coll})}$$

$$\Rightarrow S = -1 \quad \text{for} \quad \delta + \Delta_{coll} = 0$$

where $\Delta_{coll} - \frac{i}{2}\Gamma_{coll} =$ dipolar interaction between all atoms

Shahmoon, Wild, Lukin, Yelin, PRL **118**, 113601 (2017)

ion



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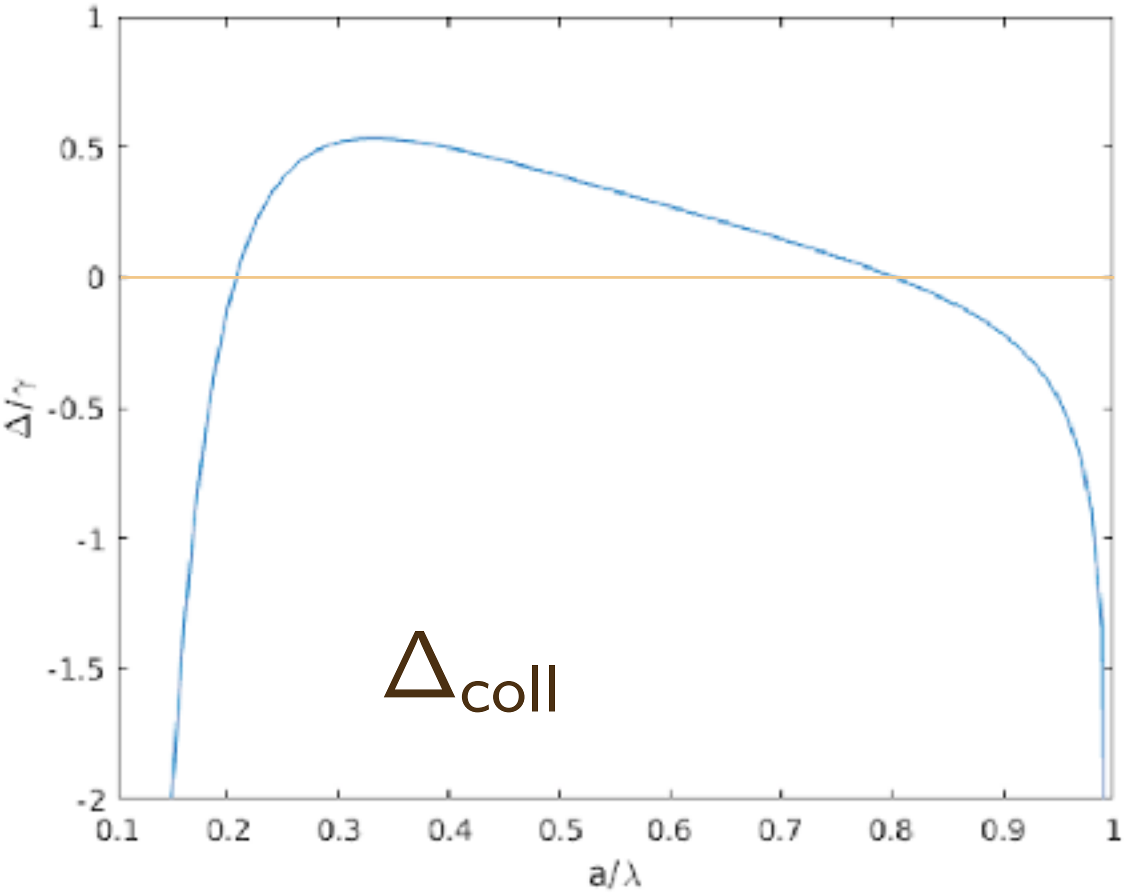

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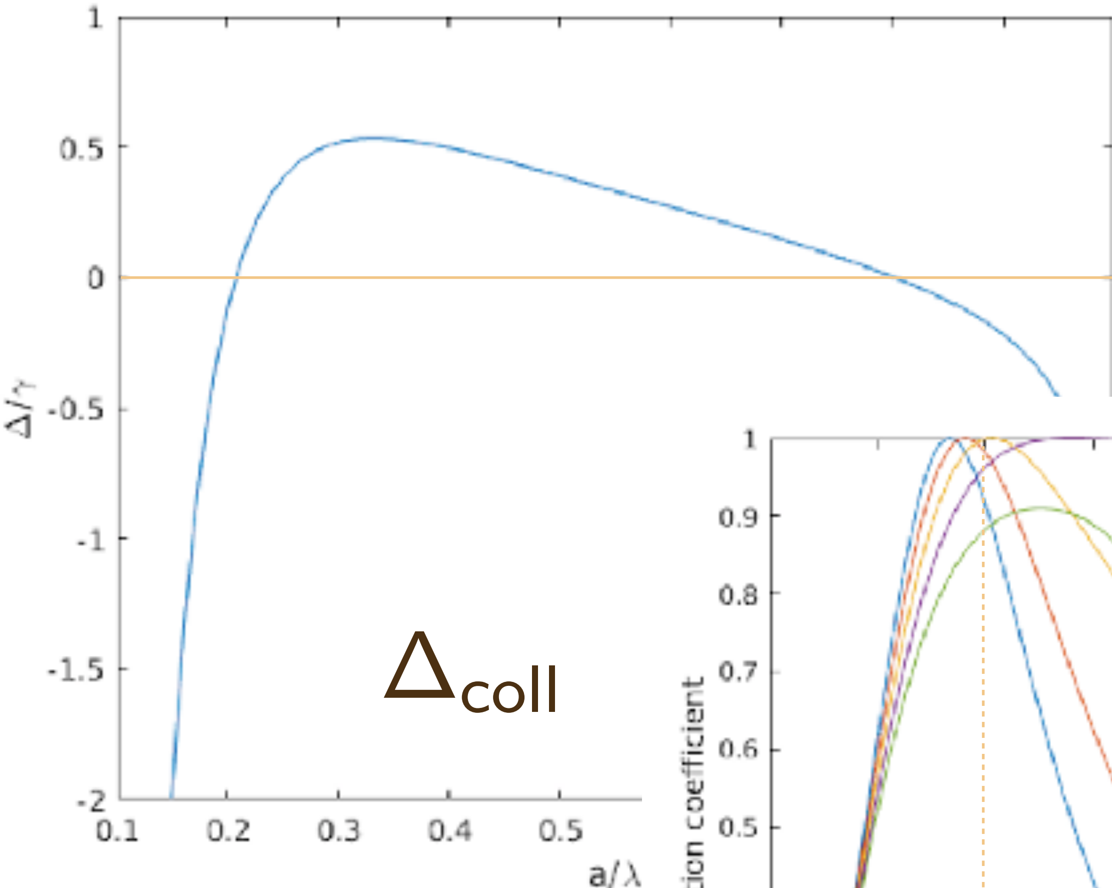
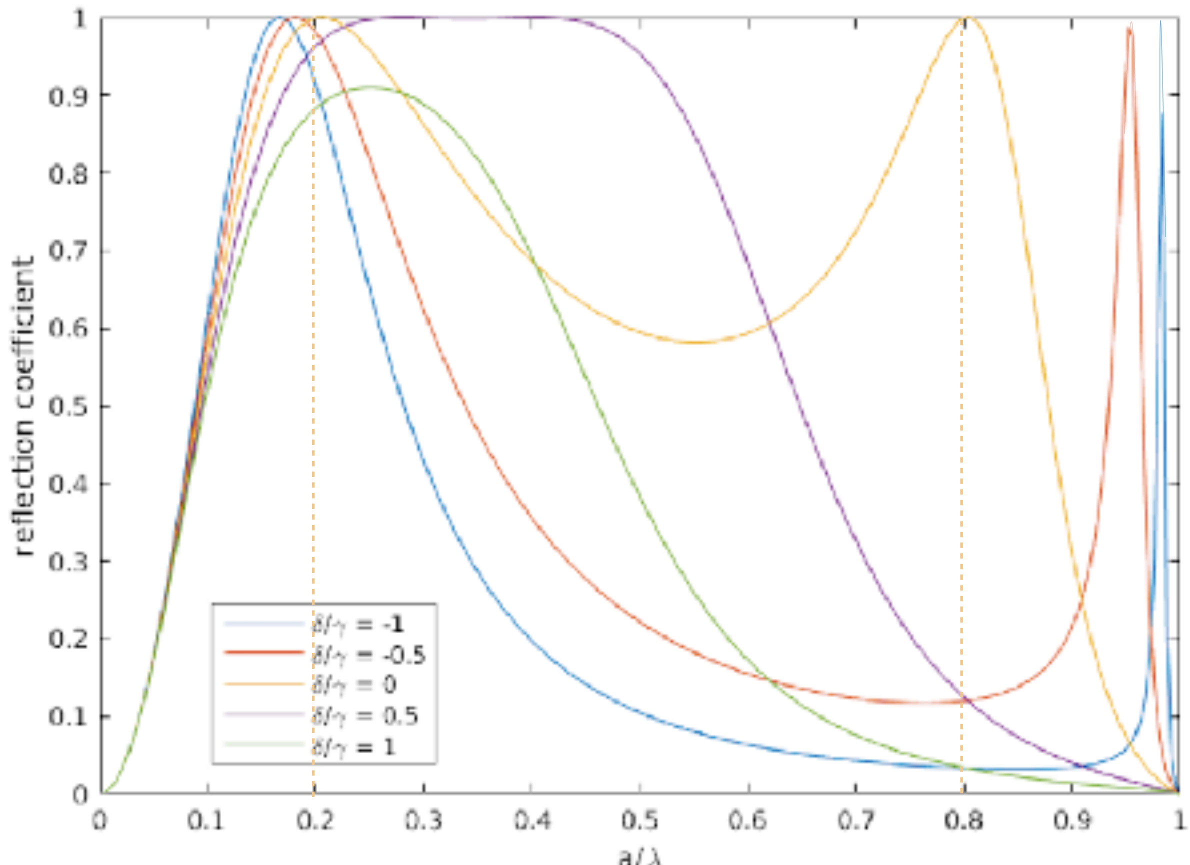
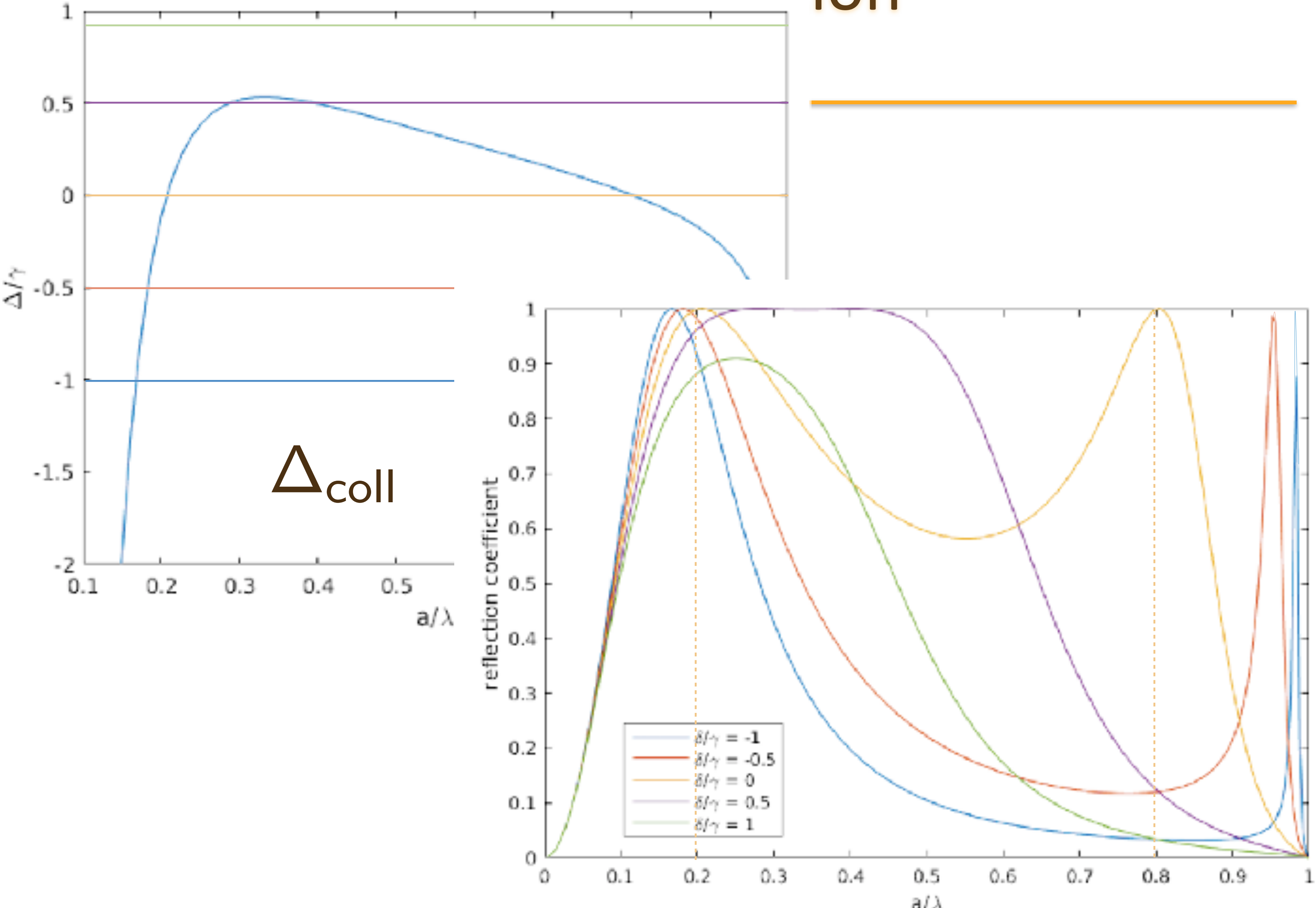

Δ/γ
a/λ
Δ_{coll}


reflection coefficient
a/λ
δ/γ = -1
δ/γ = -0.5
δ/γ = 0
δ/γ = 0.5
δ/γ = 1

ion



Δ/γ
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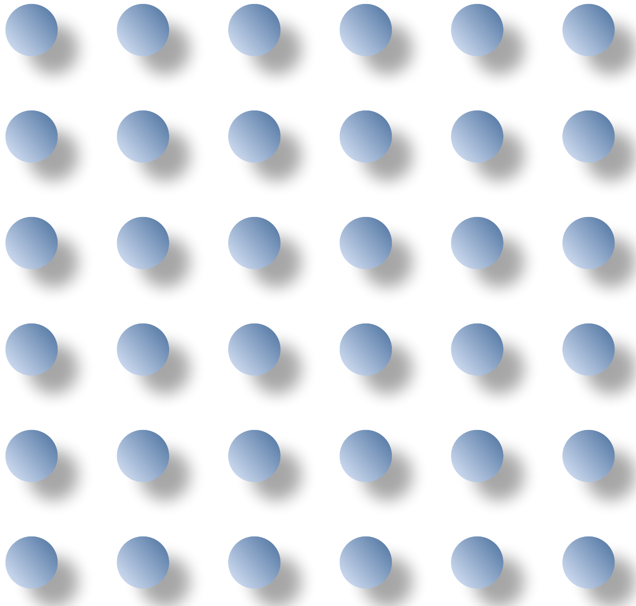
Works for other lattices



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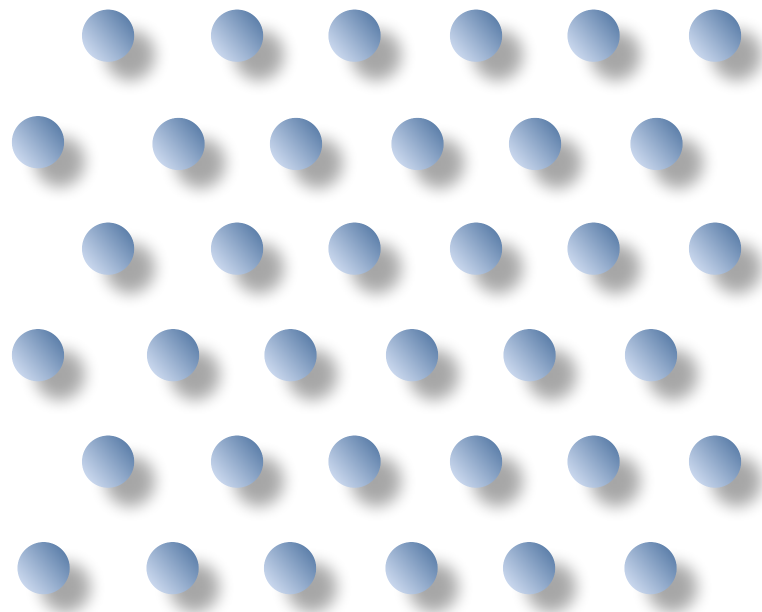

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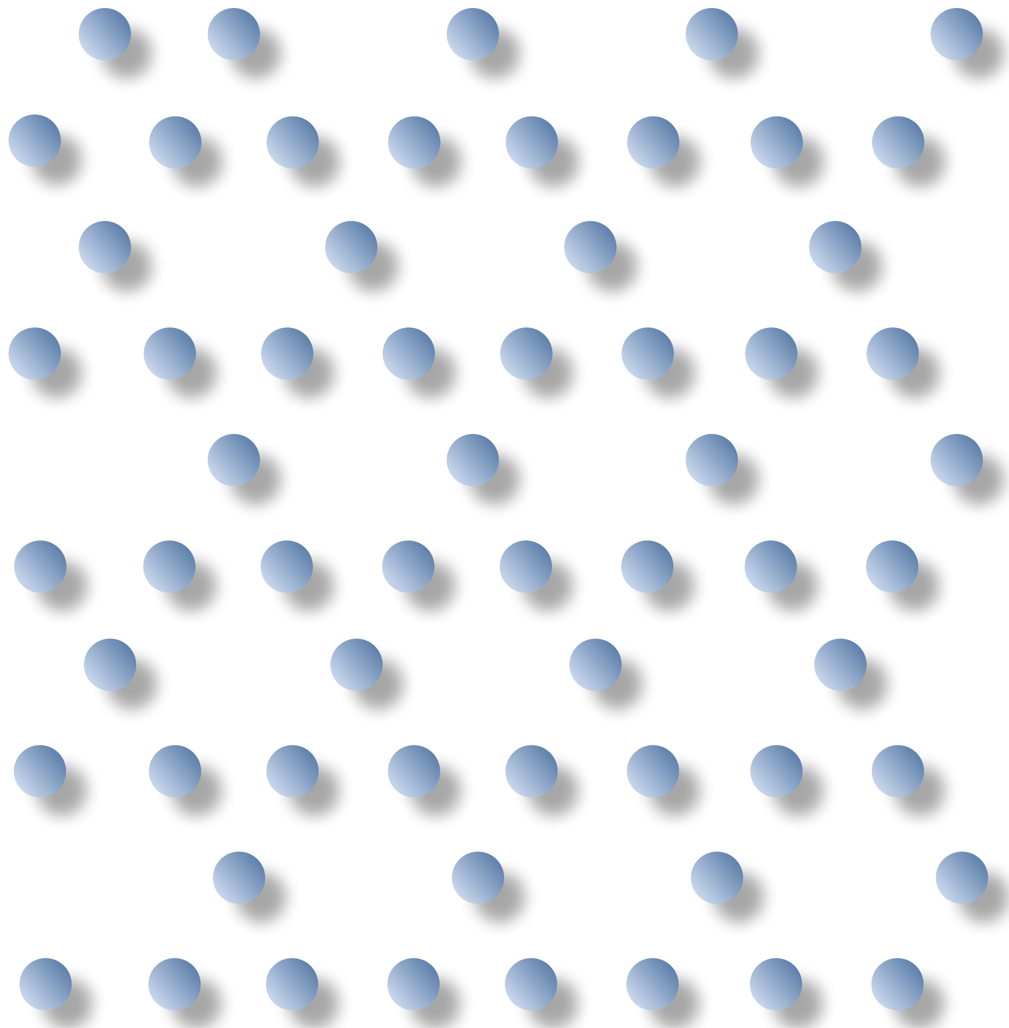

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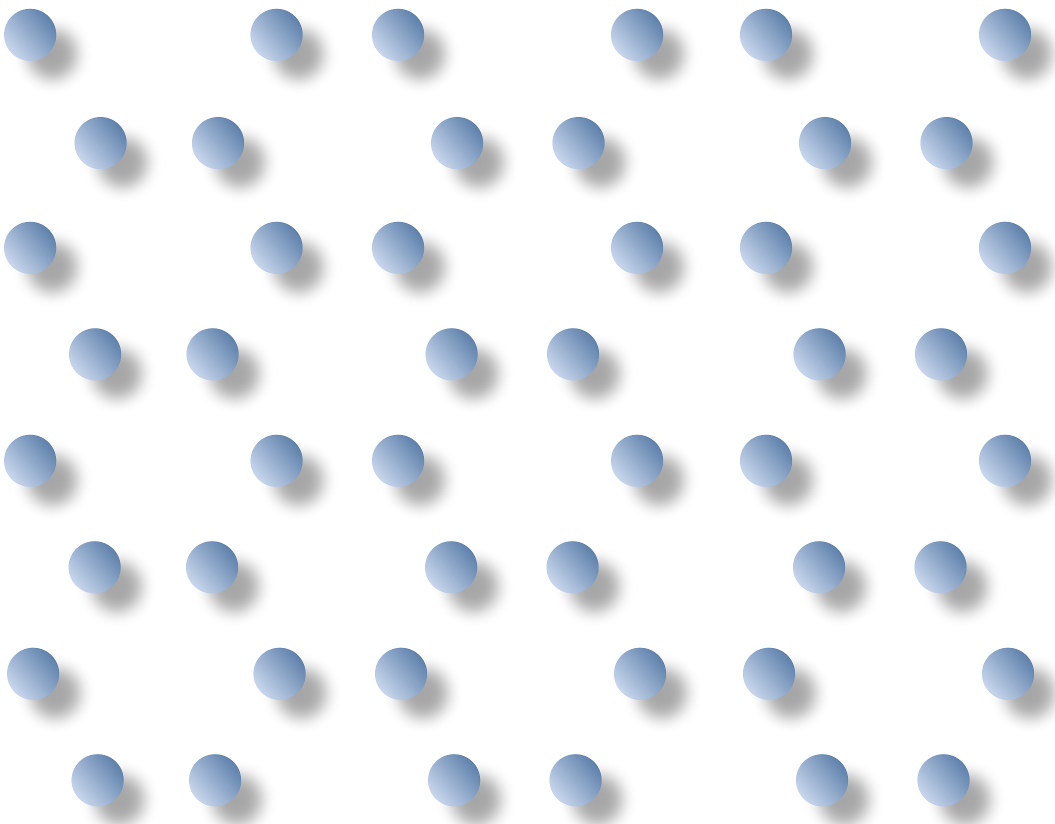

3D setup

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"Inside lightcone": volume where $\sqrt{k_x^2 + k_y^2} \leq k_{vacuum}$

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lattice constant $a < \lambda \;\; \Rightarrow$
lightcone is smaller than
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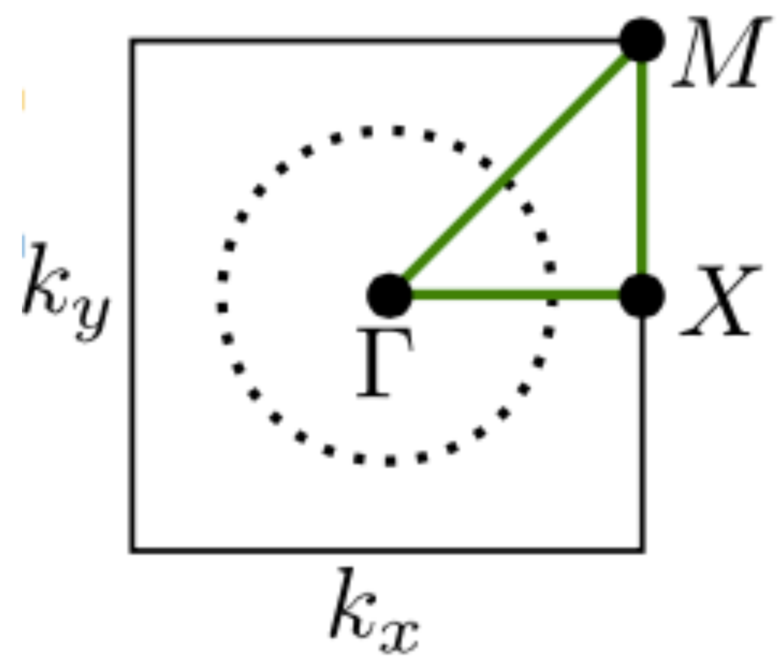
3D setup

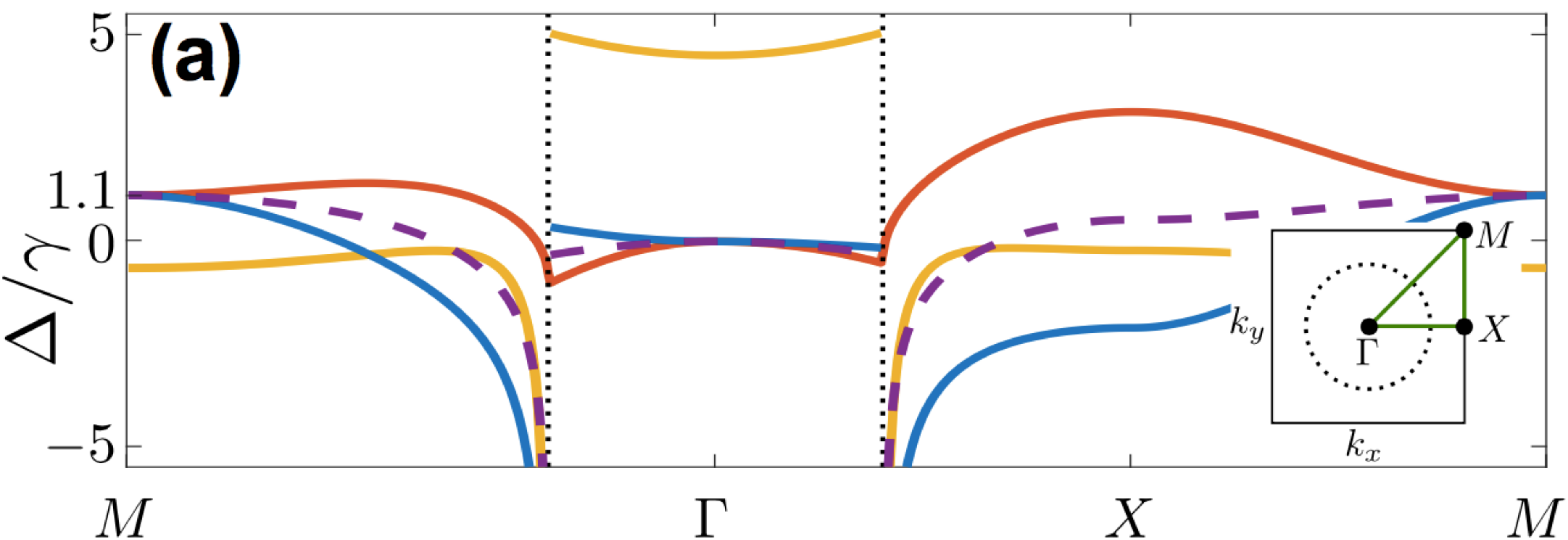
“Inside lightcone”: volume where $\sqrt{k_x^2 + k_y^2} \leq k_{vacuum}$

lattice constant a $< \lambda \Rightarrow$ lightcone is smaller than Brillouin zone

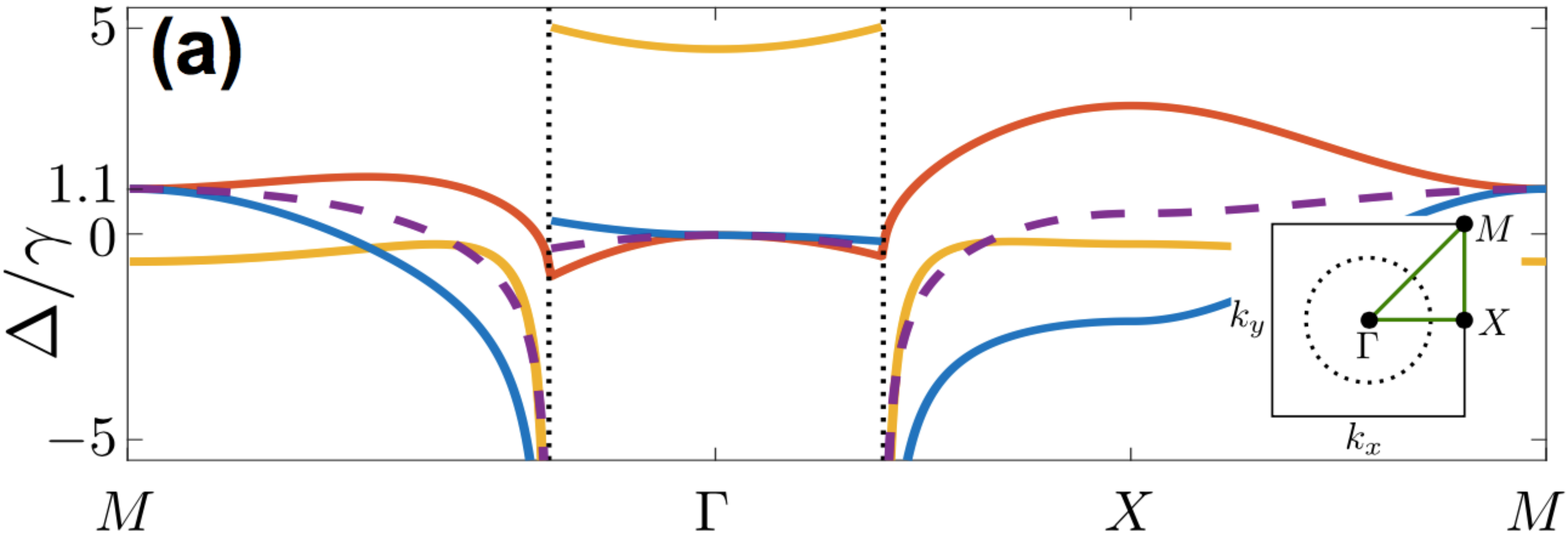


3D setup

Dispersion relation of collective surface dipole excitations



3D setup



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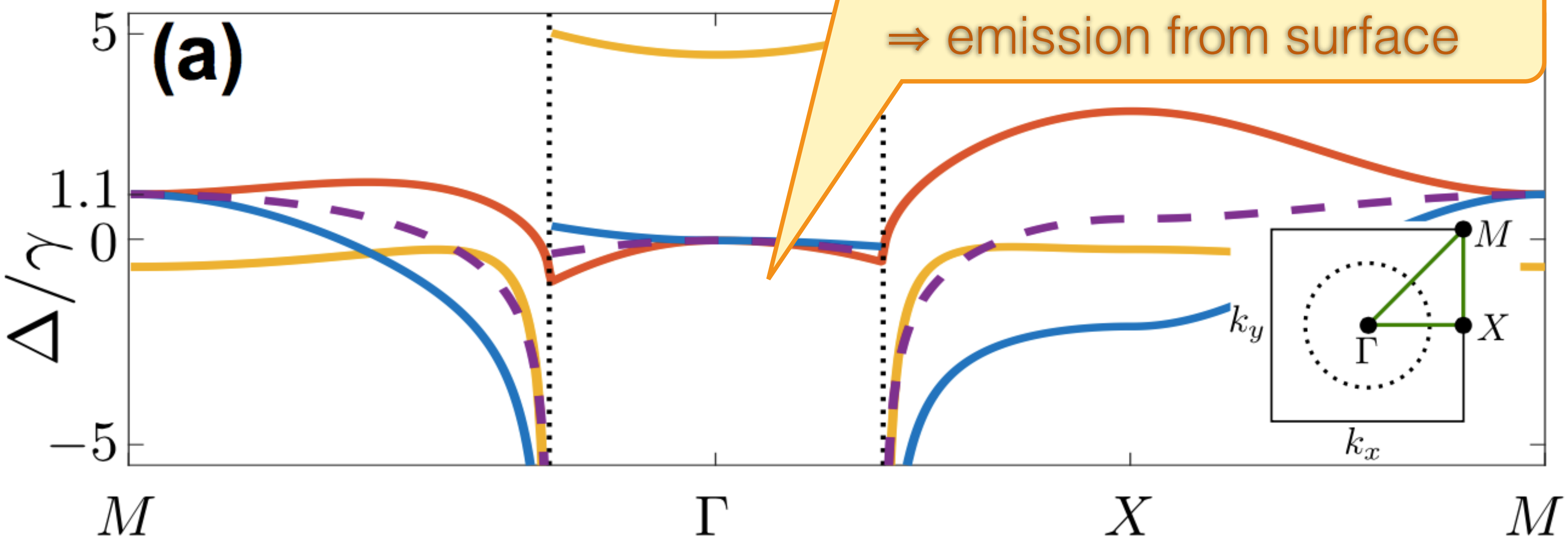
3D setup

within light cone: couples to far-field (perpendicular) radiation
⇒ emission from surface



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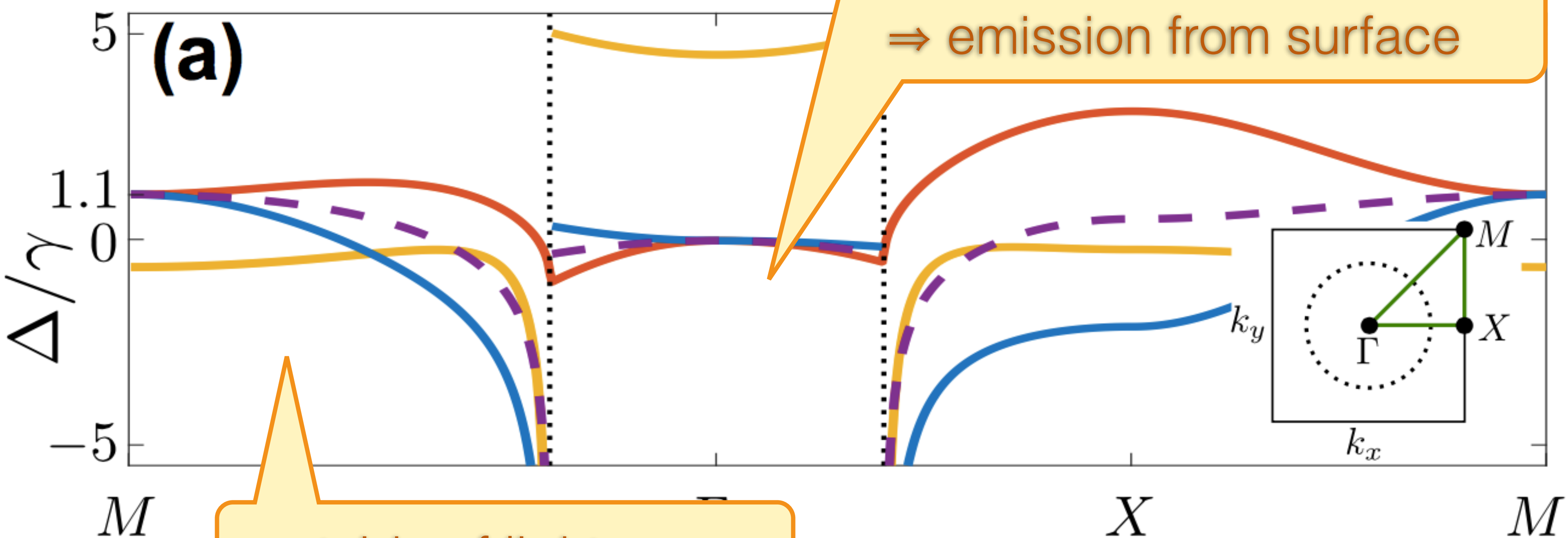
3D setup



within light cone: couples to far-field (perpendicular) radiation
⇒ emission from surface

outside of light cone
⇒ surface waves only

Implementations

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Examples:

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Examples:

- atoms in optical lattice

Implementations

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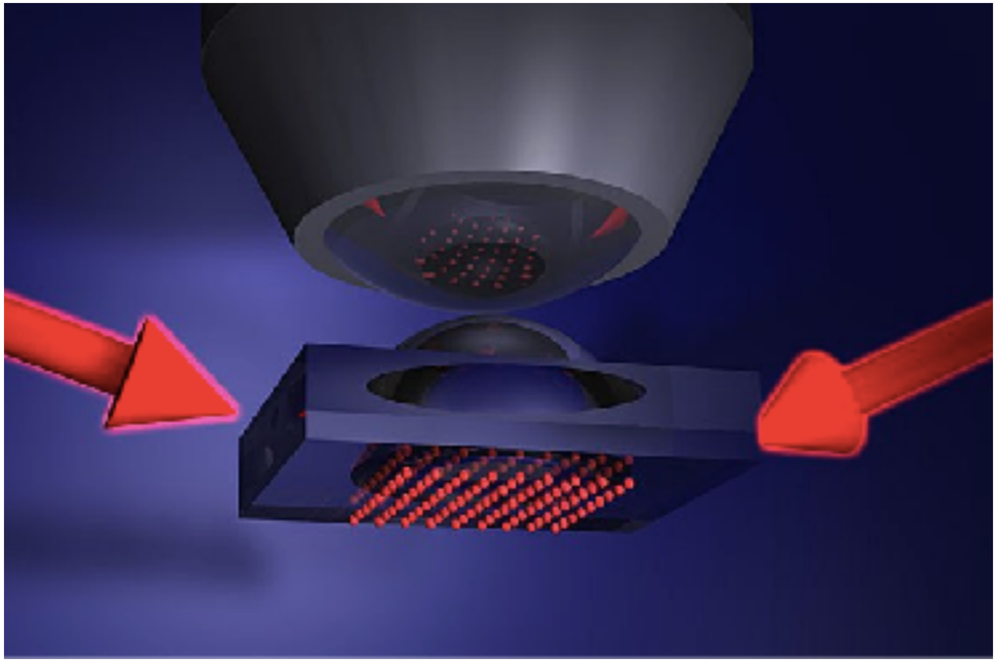
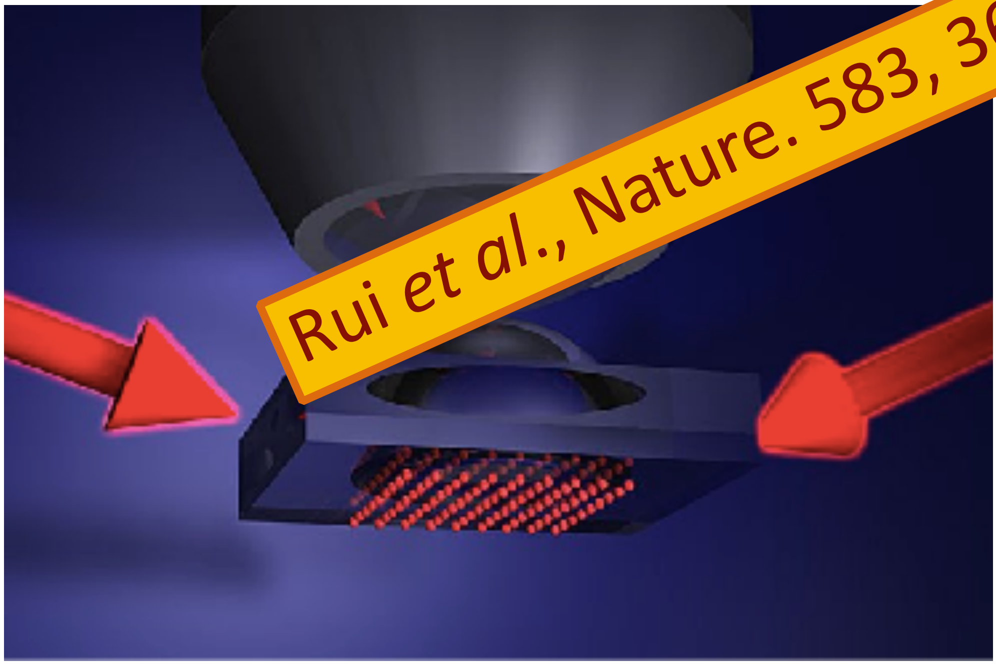


Implementations

Examples:

- atoms in optical lattice



Rui *et al.*, Nature. 583, 369 (2020)

Implementations

Examples:

- atoms in optical lattice

- solid state 2D semiconductors

Implementation in solid state 2D

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Excitons in transition metal dichalcogenides (MoS_2, WSe_2, …)

Implementation in solid state 2D

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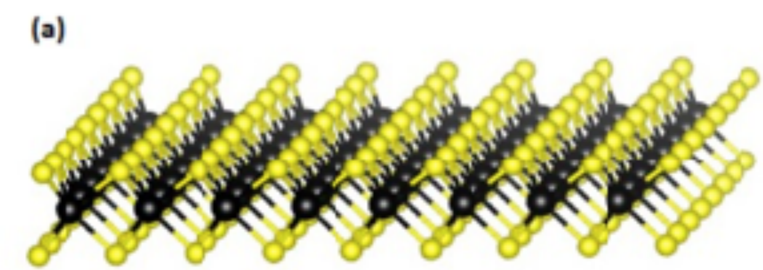
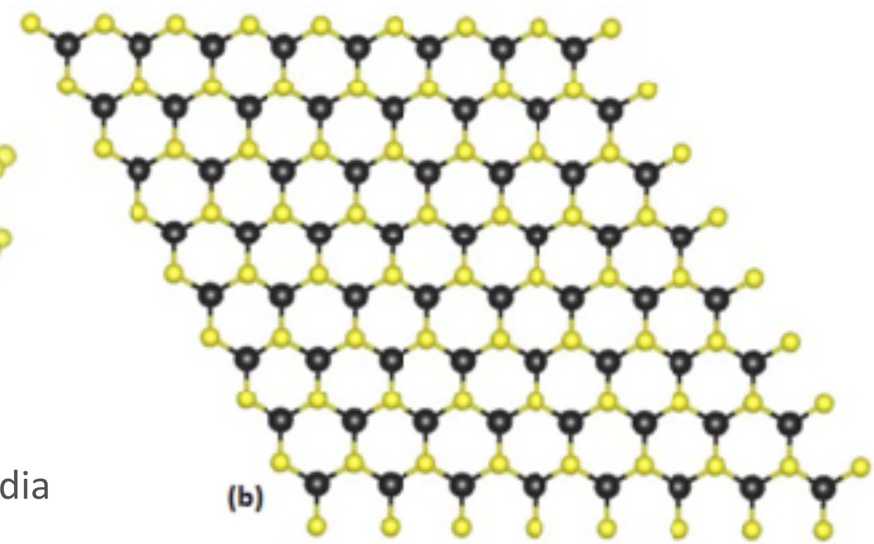
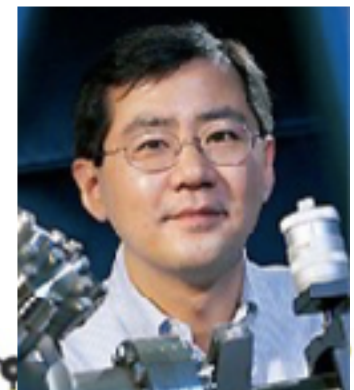




wikipedia

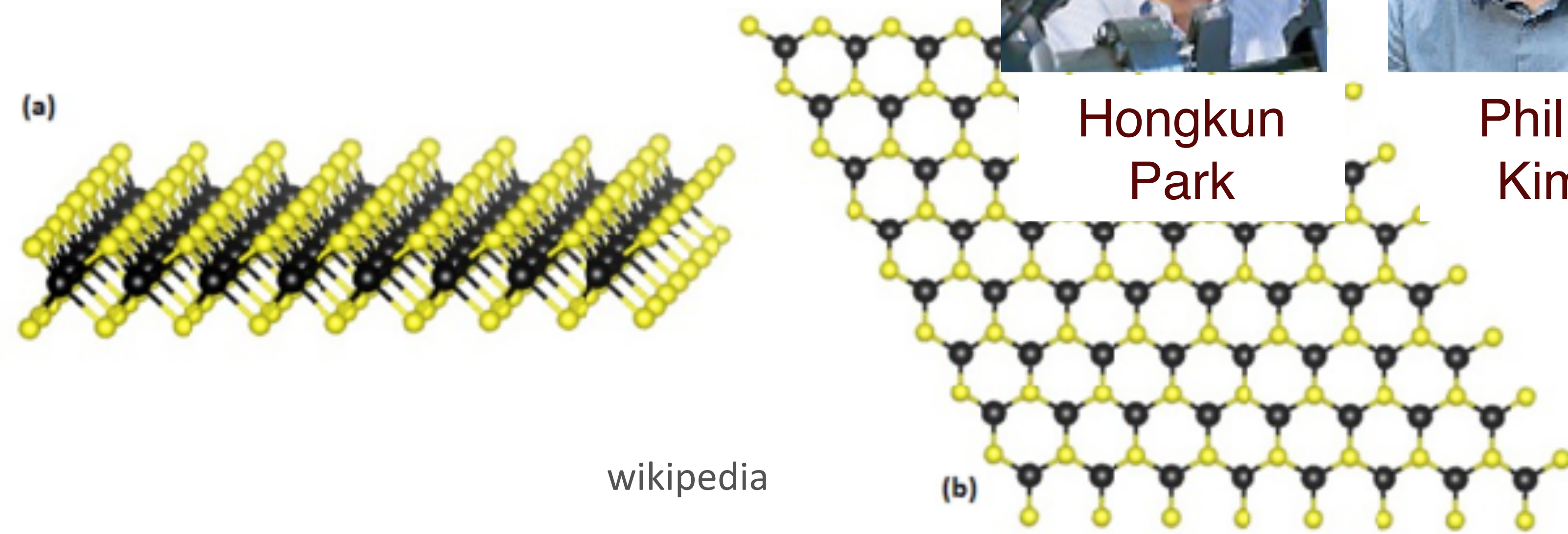
Implementation in solid state 2D

Excitons in transition metal dichalcogenides (MoS_2, WSe_2, …)



Hongkun Park

Philip Kim



wikipedia

Application: Impurities and array QED

Increase (impurity) cross section?

Patti, Wild, Shahmoon, Lukin, Yelin, PRL, **126**, 223602 (2021)

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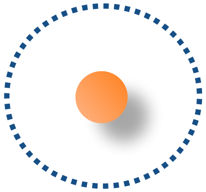

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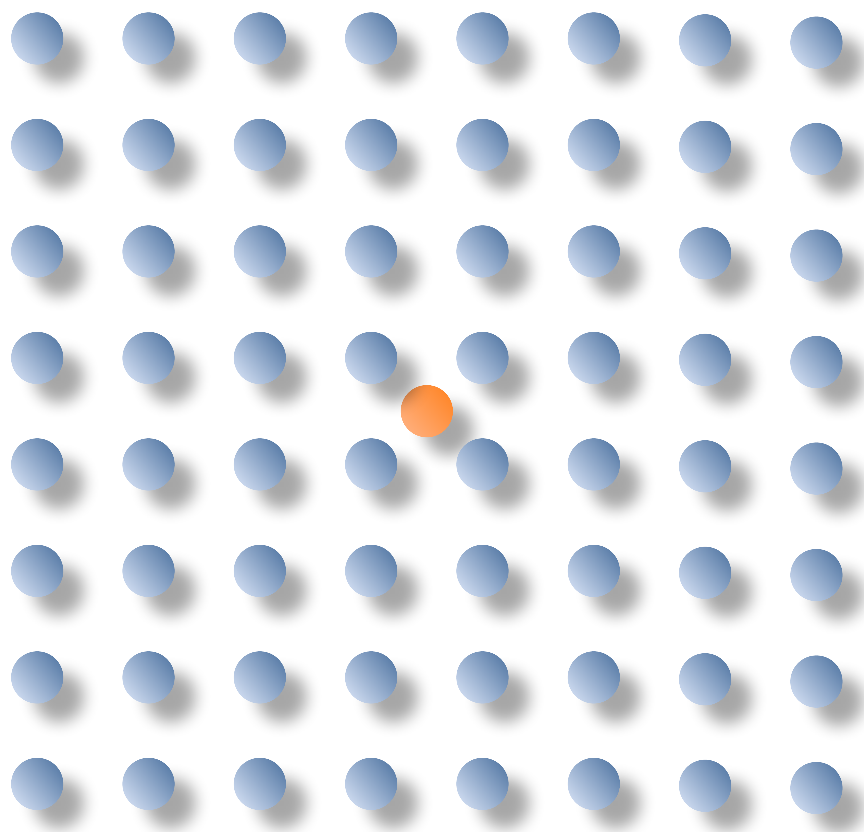

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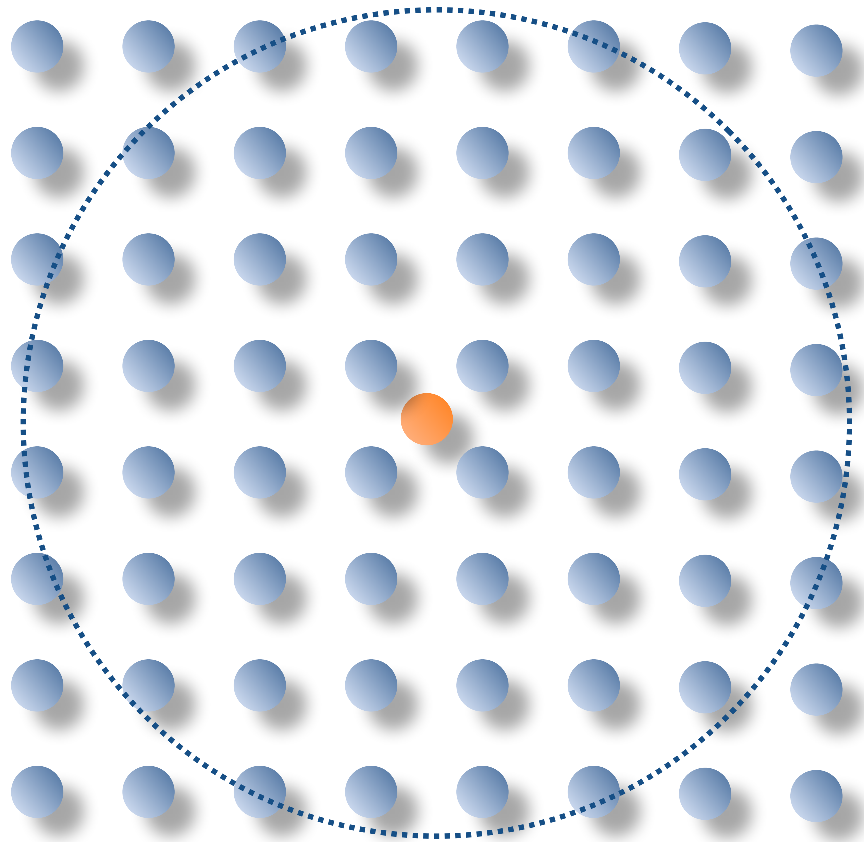

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Impurity + Array Scattering

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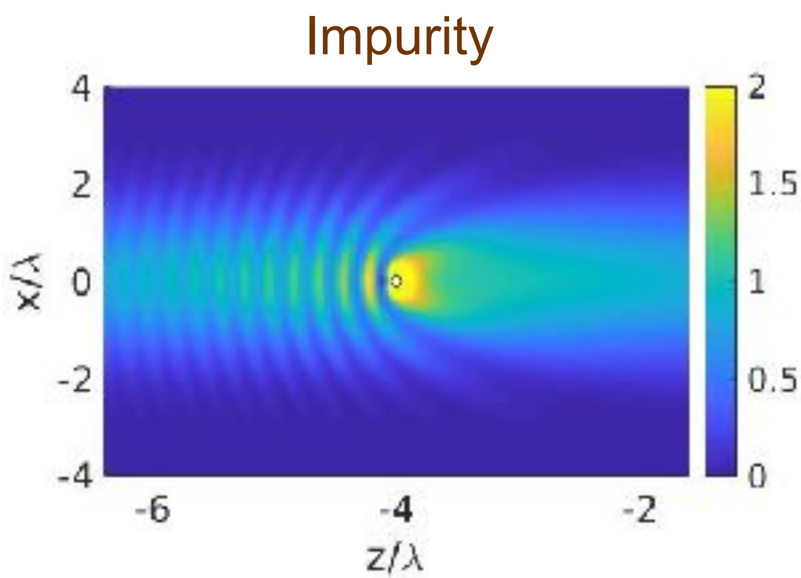

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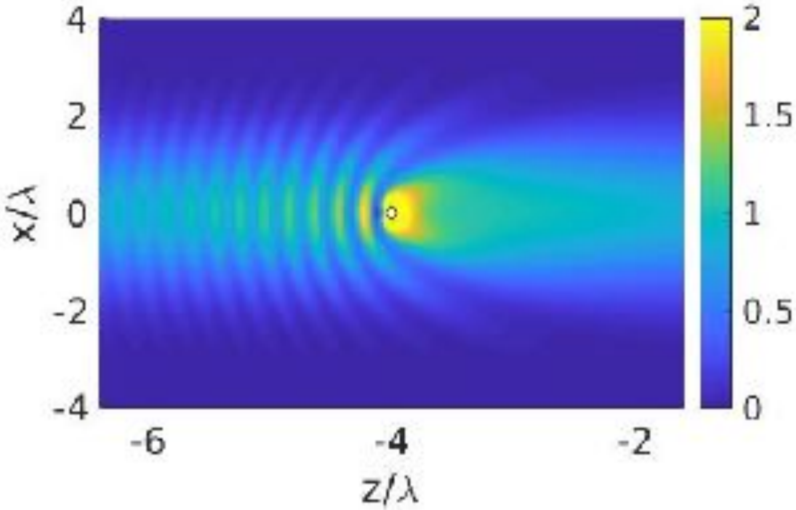
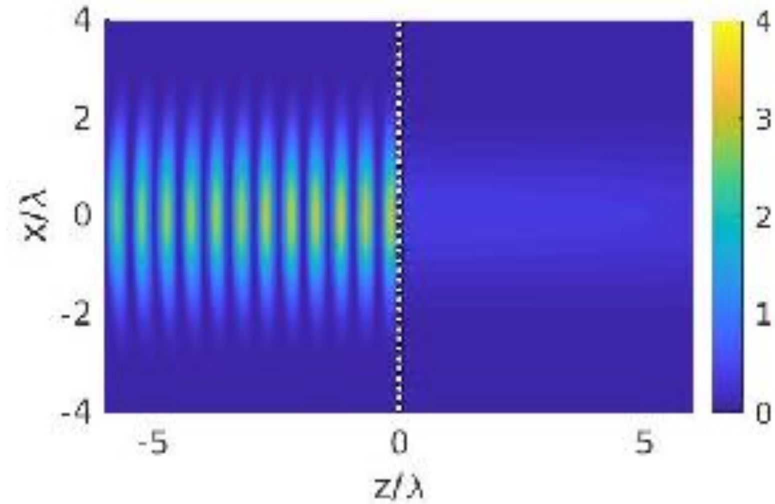
Impurity + Array Scattering

Impurity



Array



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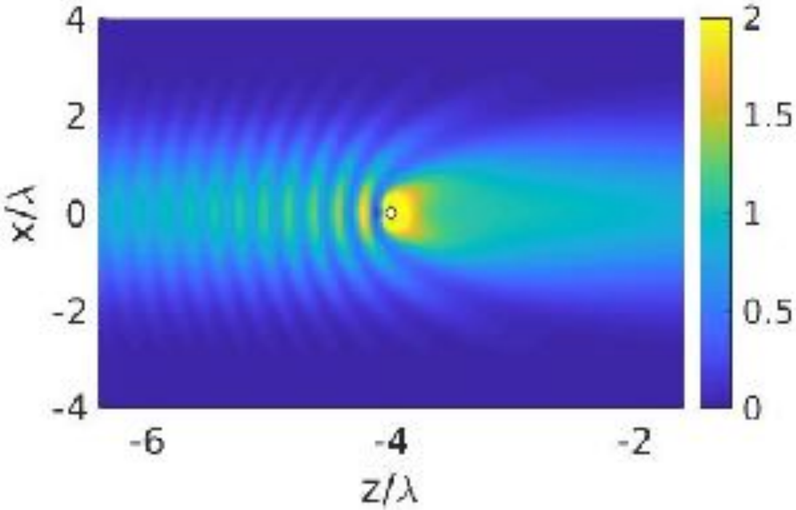

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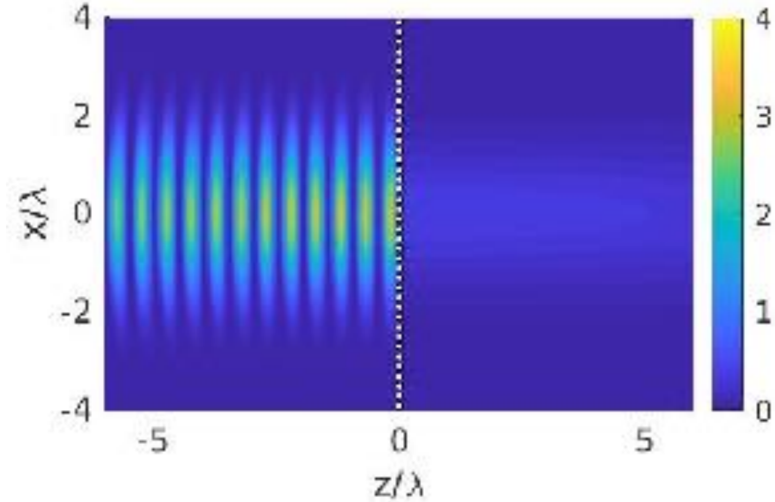

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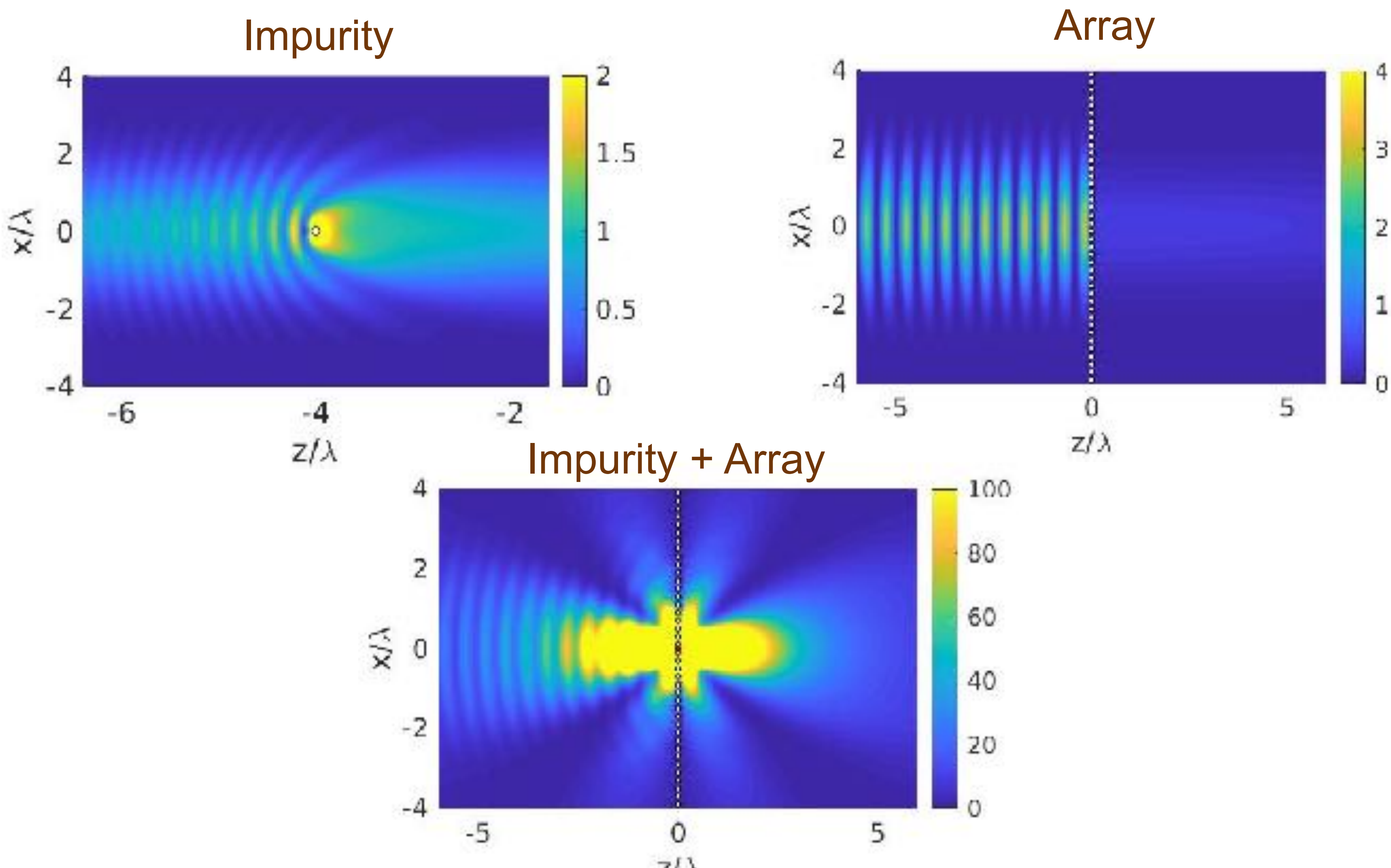
Impurity + Array Scattering



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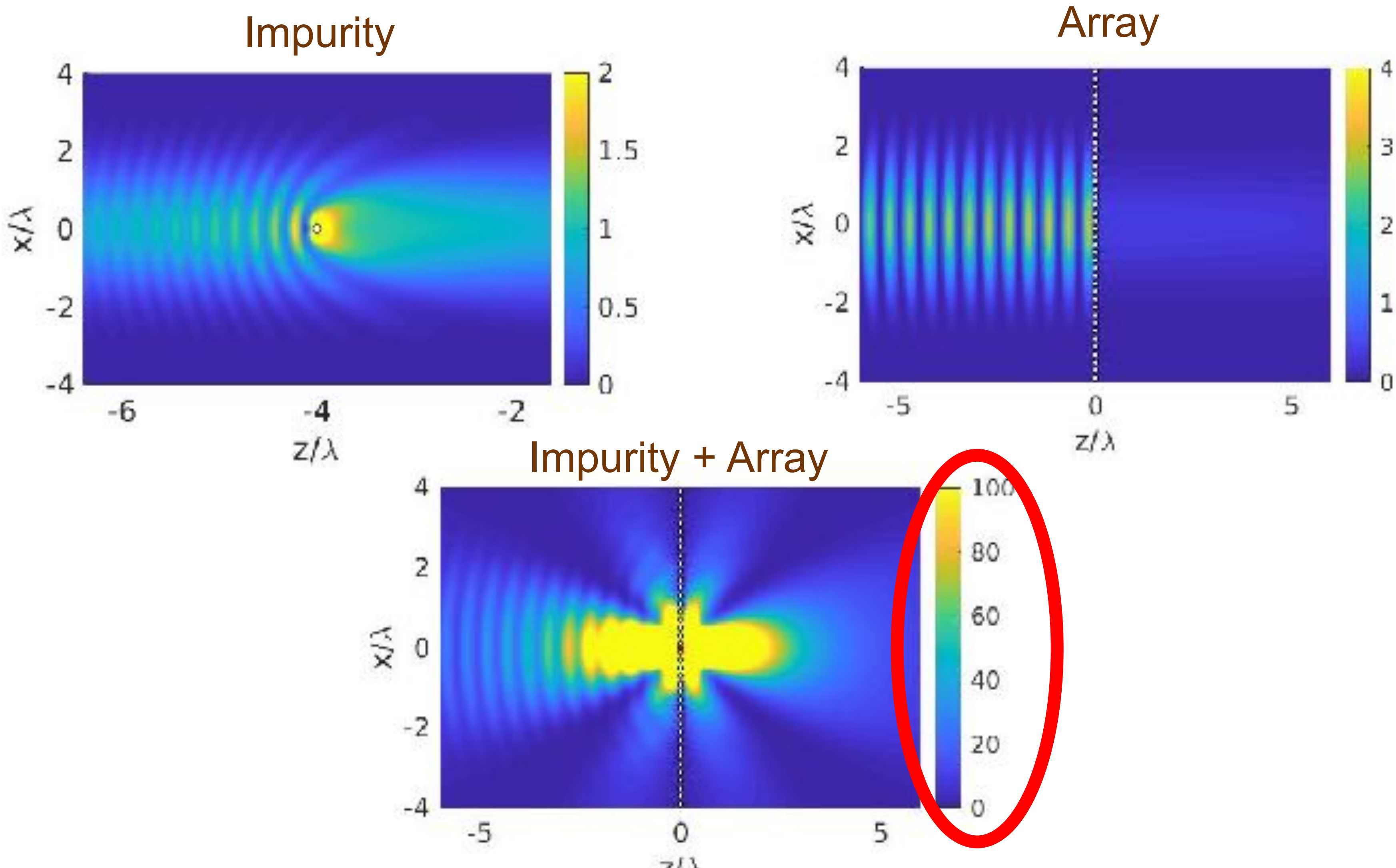

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Impurity + Array Scattering

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Why?

Impurity + Array Scattering

Why?

- **classical intuition**: dipoles act like antenna arrays
- **quantum explanation:** impurity transition (slightly) outside of array resonance window ⇒ only virtual excitation of array atoms possible ⇒ excitation collects on impurity

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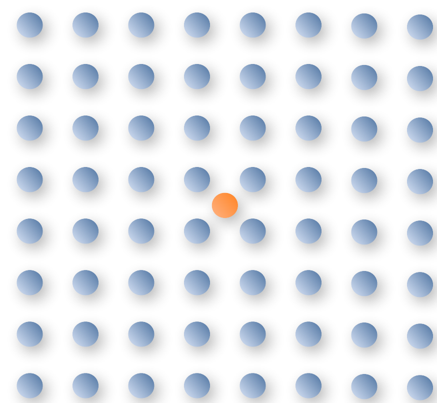

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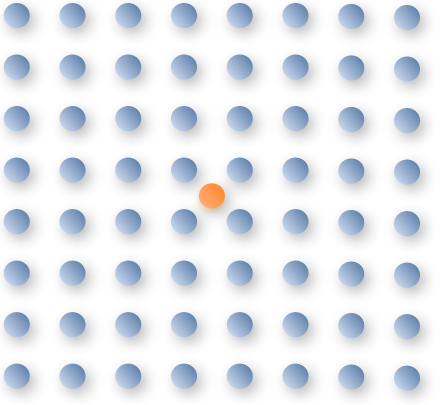

Two interacting qubits?

Patti, Wild, Shahmoon, Lukin, Yelin, PRL, **126**, 223602 (2021)

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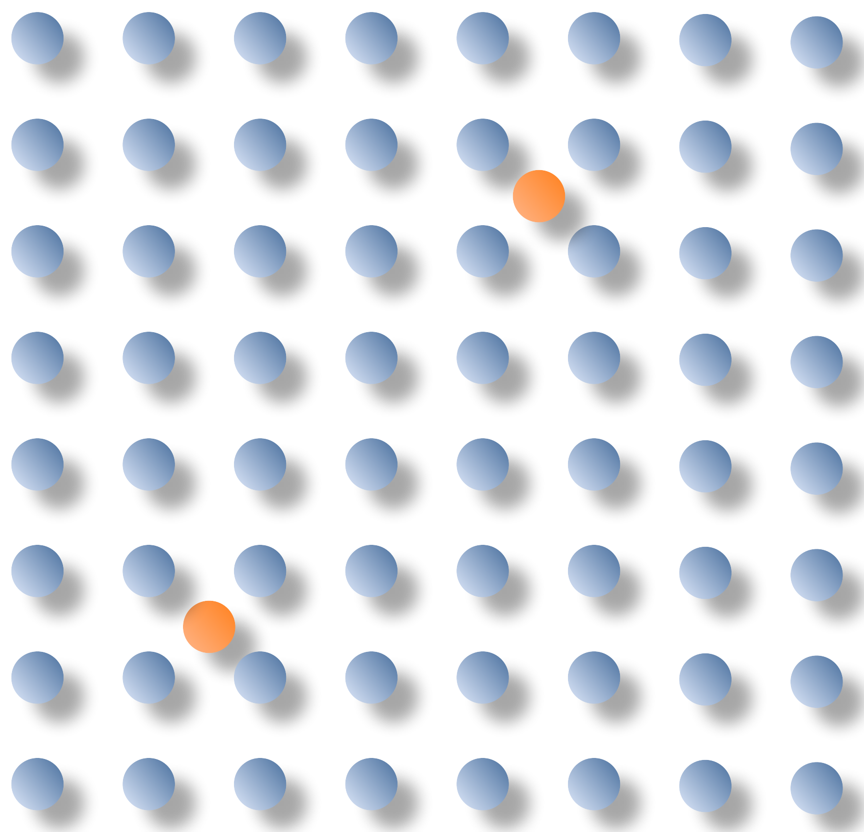

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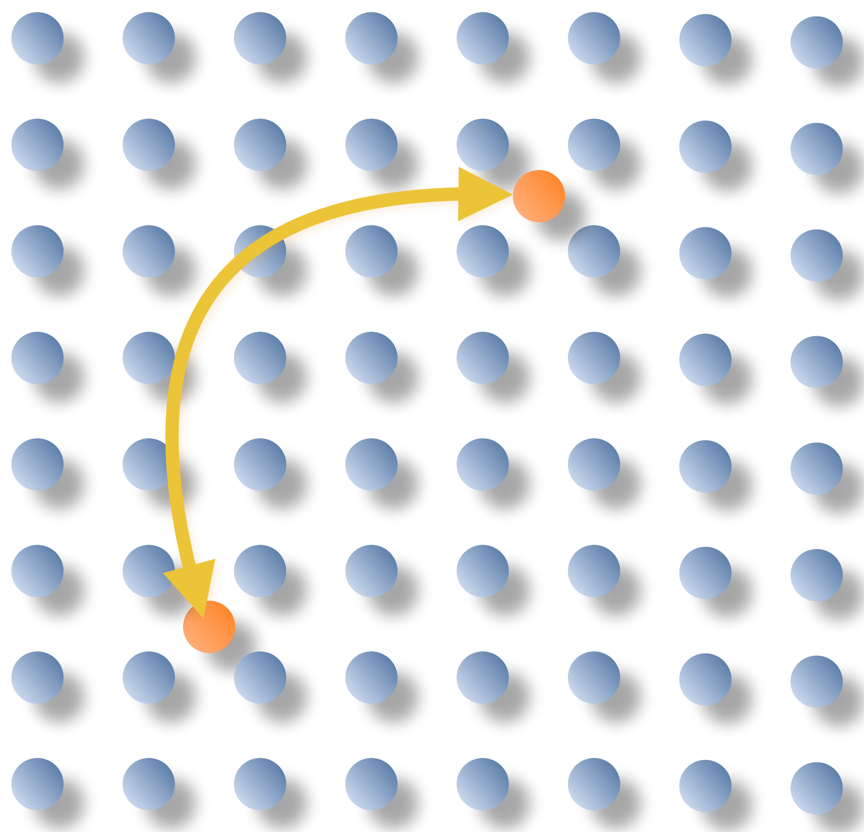

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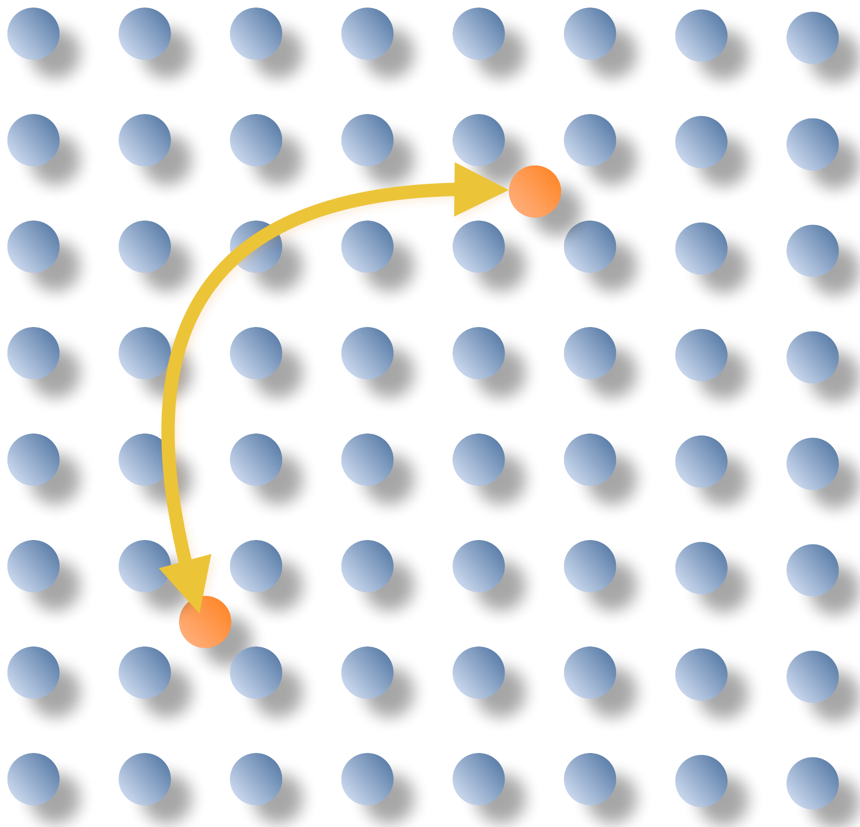

Exchange population (coherently)

Patti, Wild, Shahmoon, Lukin, Yelin, PRL, **126**, 223602 (2021)

Excitation exchange: Quality factor

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Question:

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How good is coupling between impurities

vs

decay into space?

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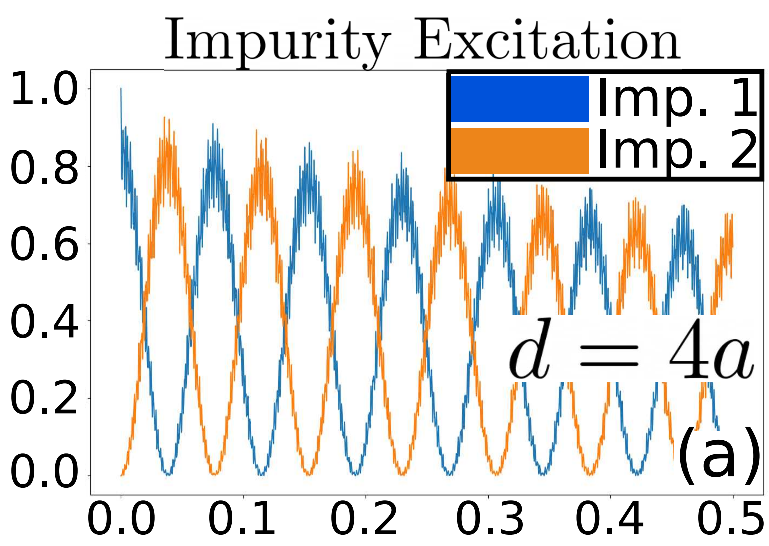


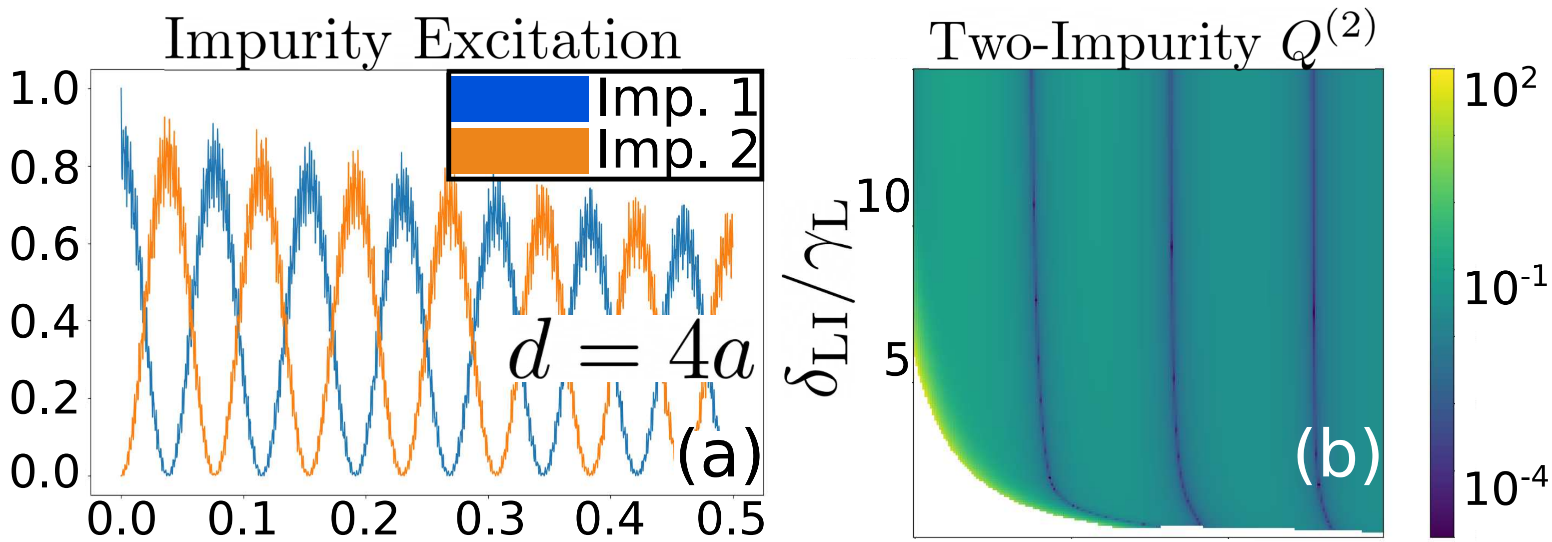
Excitation exchange: Quality factor

Question:

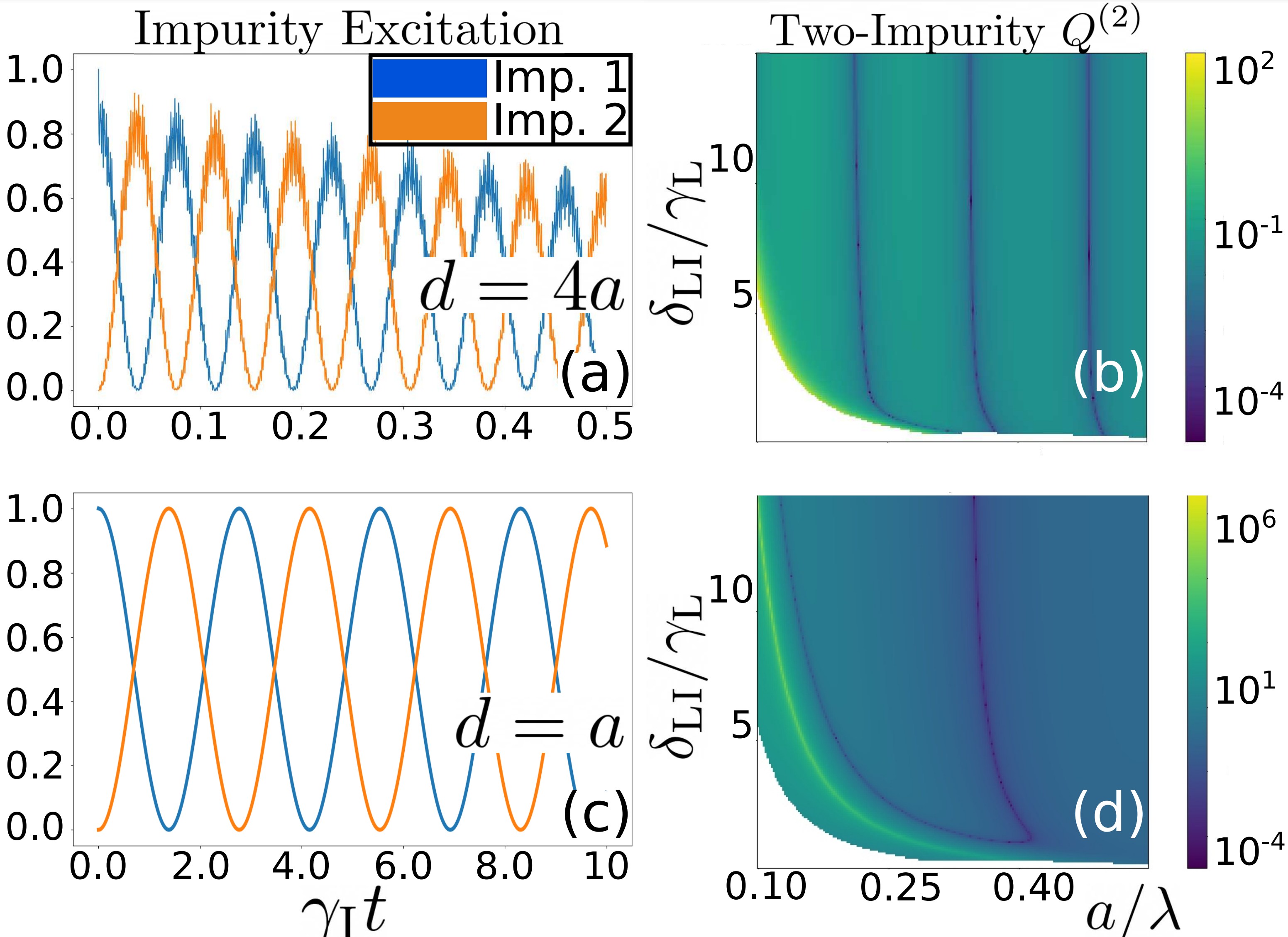
How good is coupling between impurities

vs

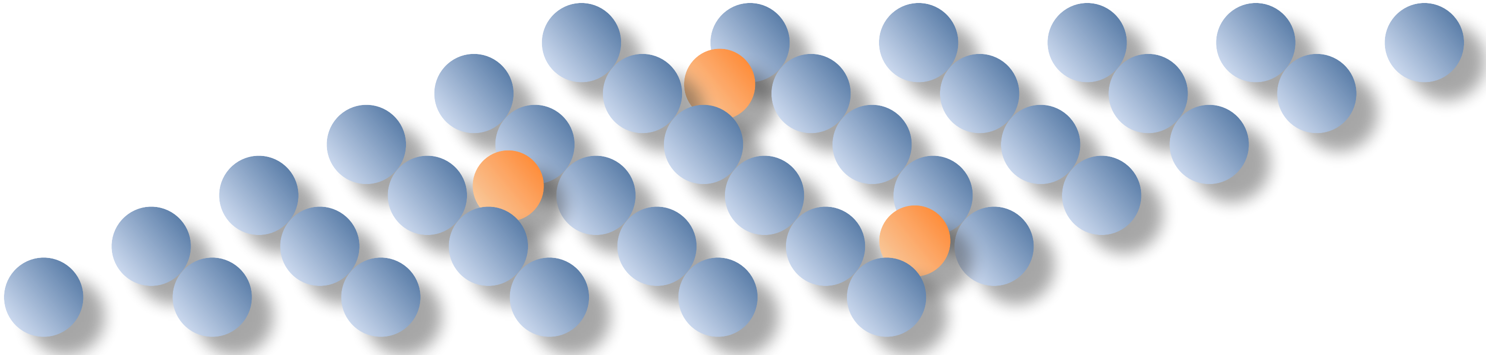
decay into space?



Excitation exchange: Quality factor



On-array quantum computer…



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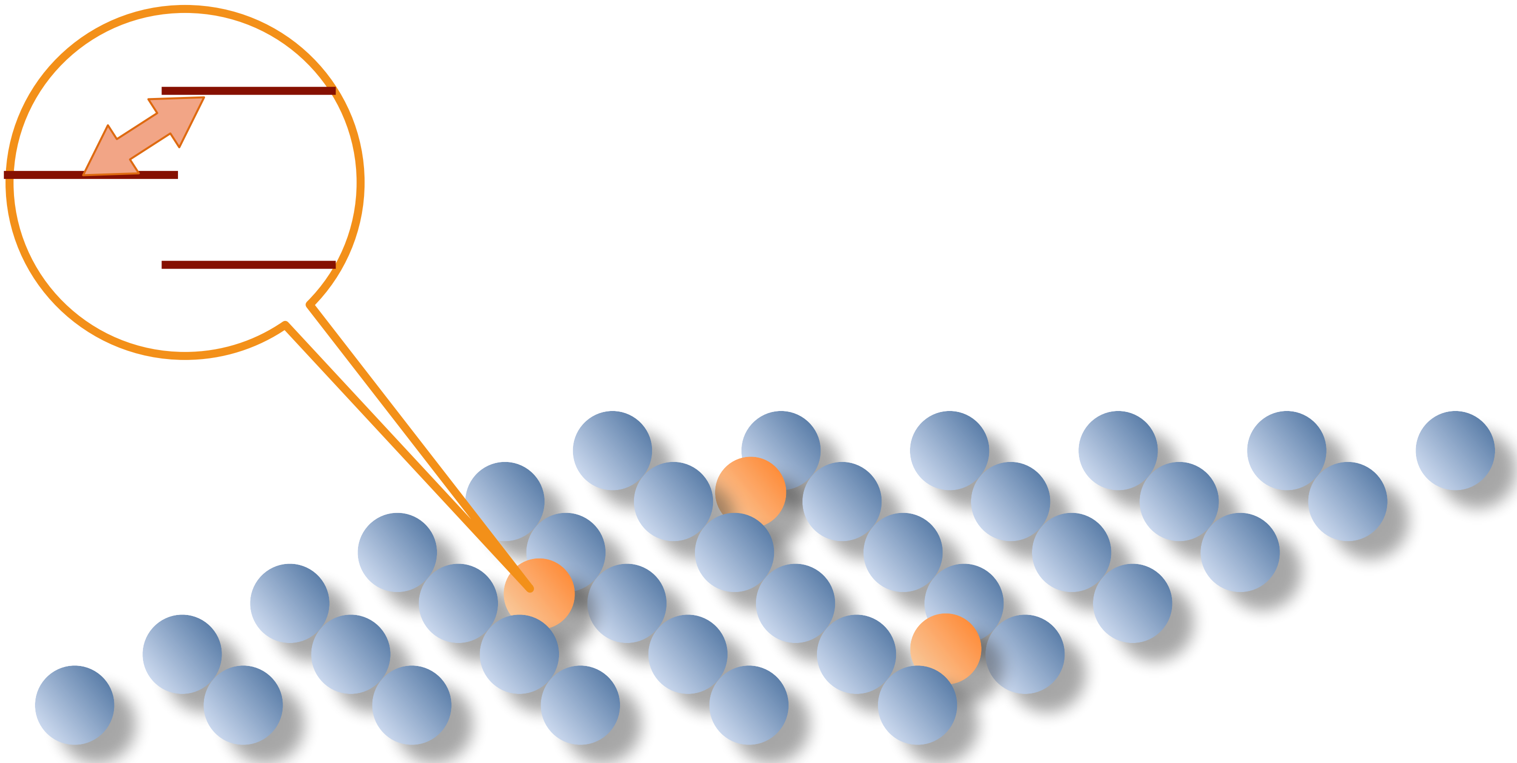
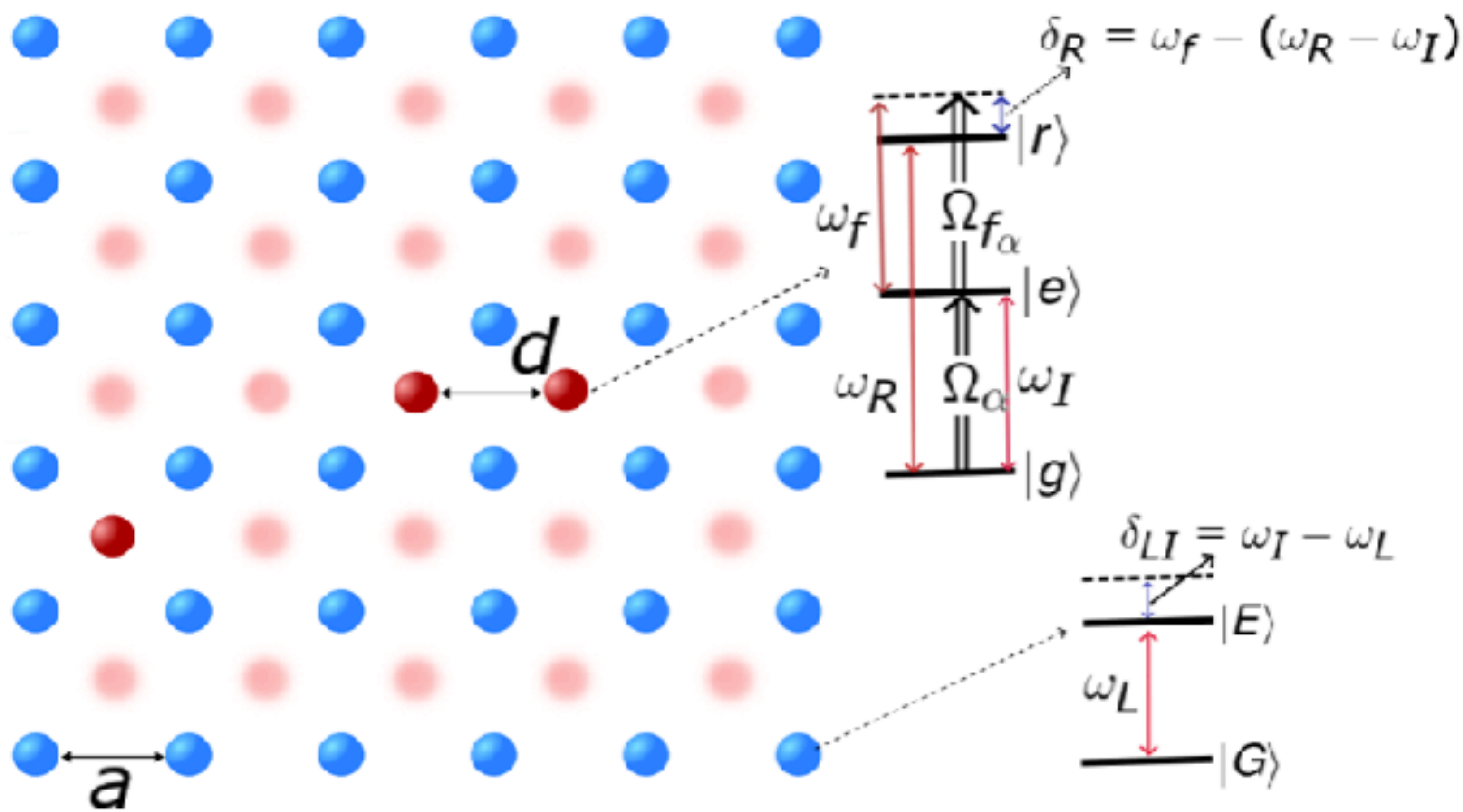
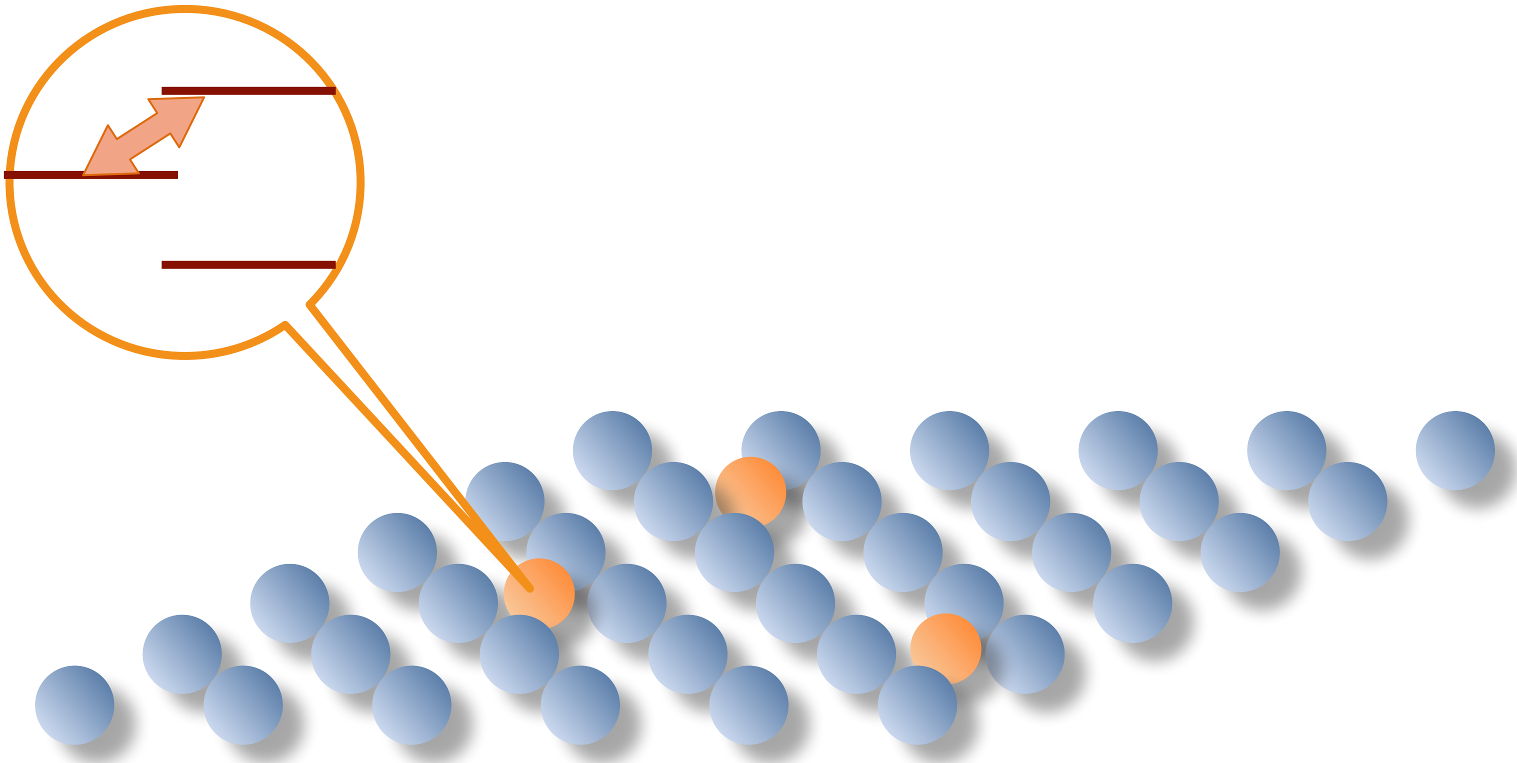


Control using 3 levels/EIT



On-array quantum computer…



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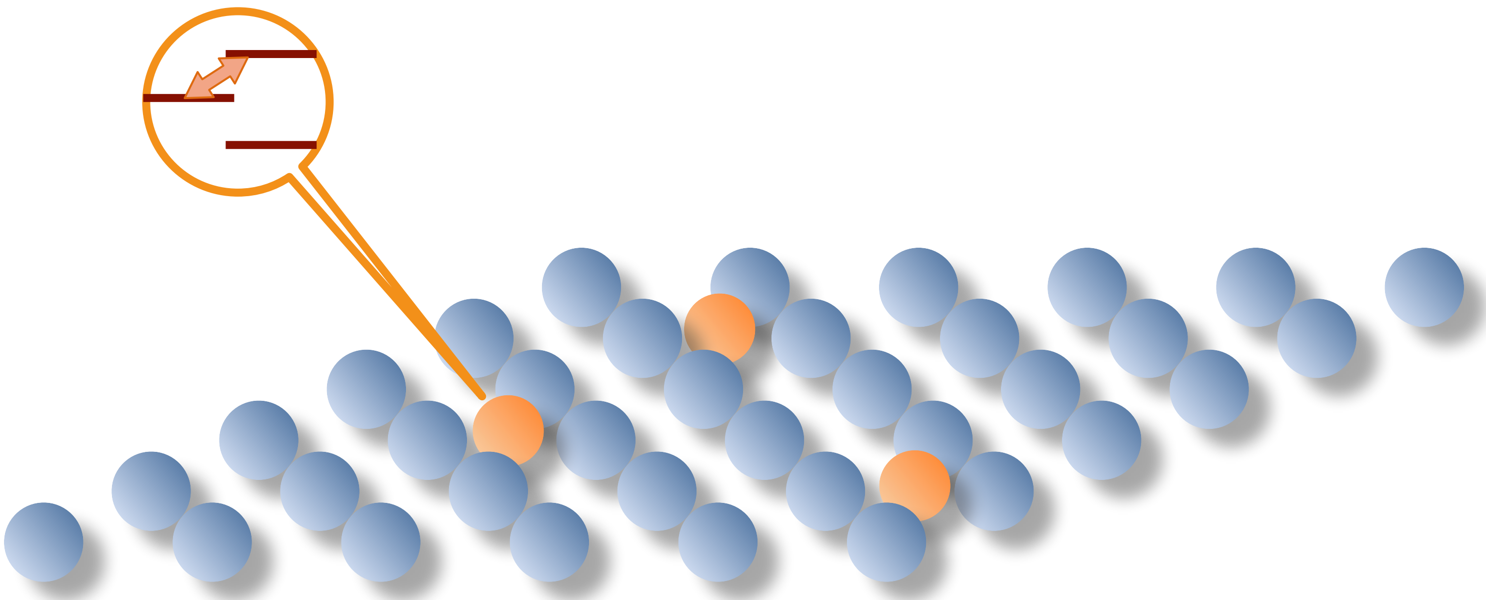

Shah, Rubies Bigorda, Patti, Yelin, PRA 109, 012613 (2024)

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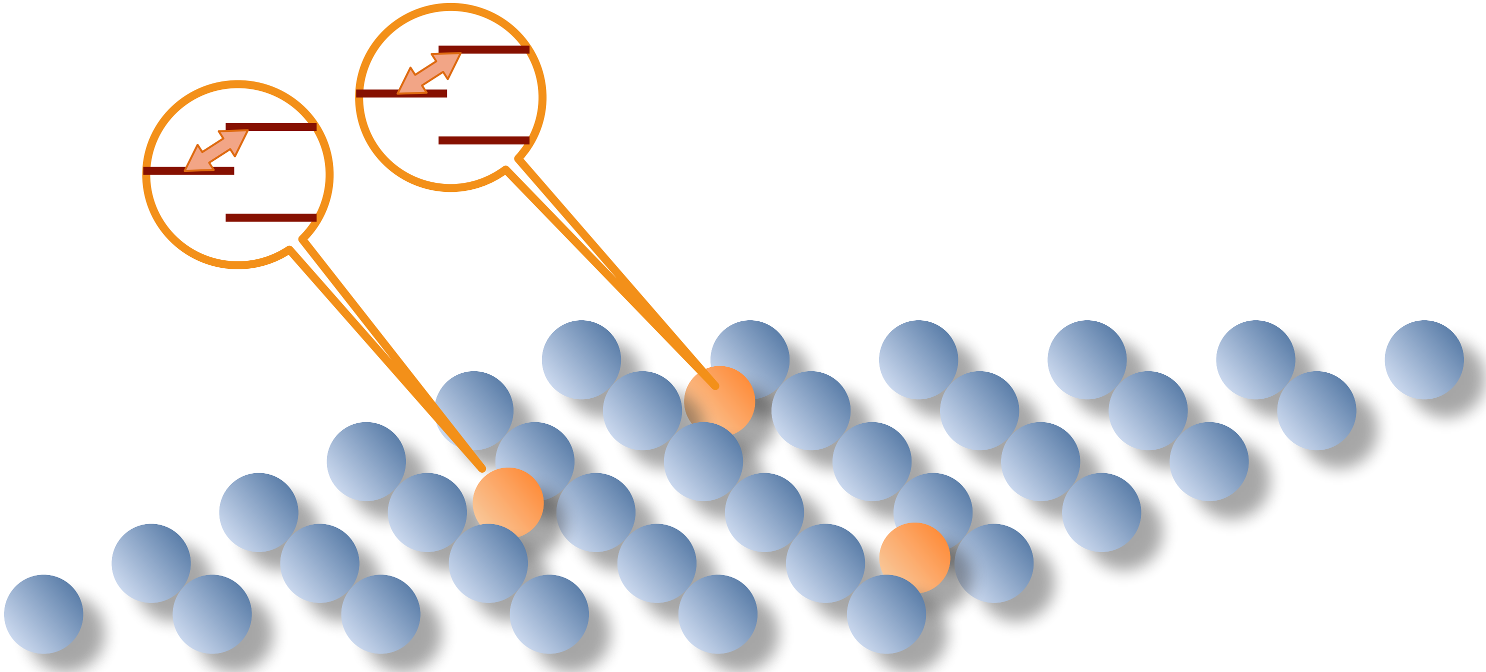

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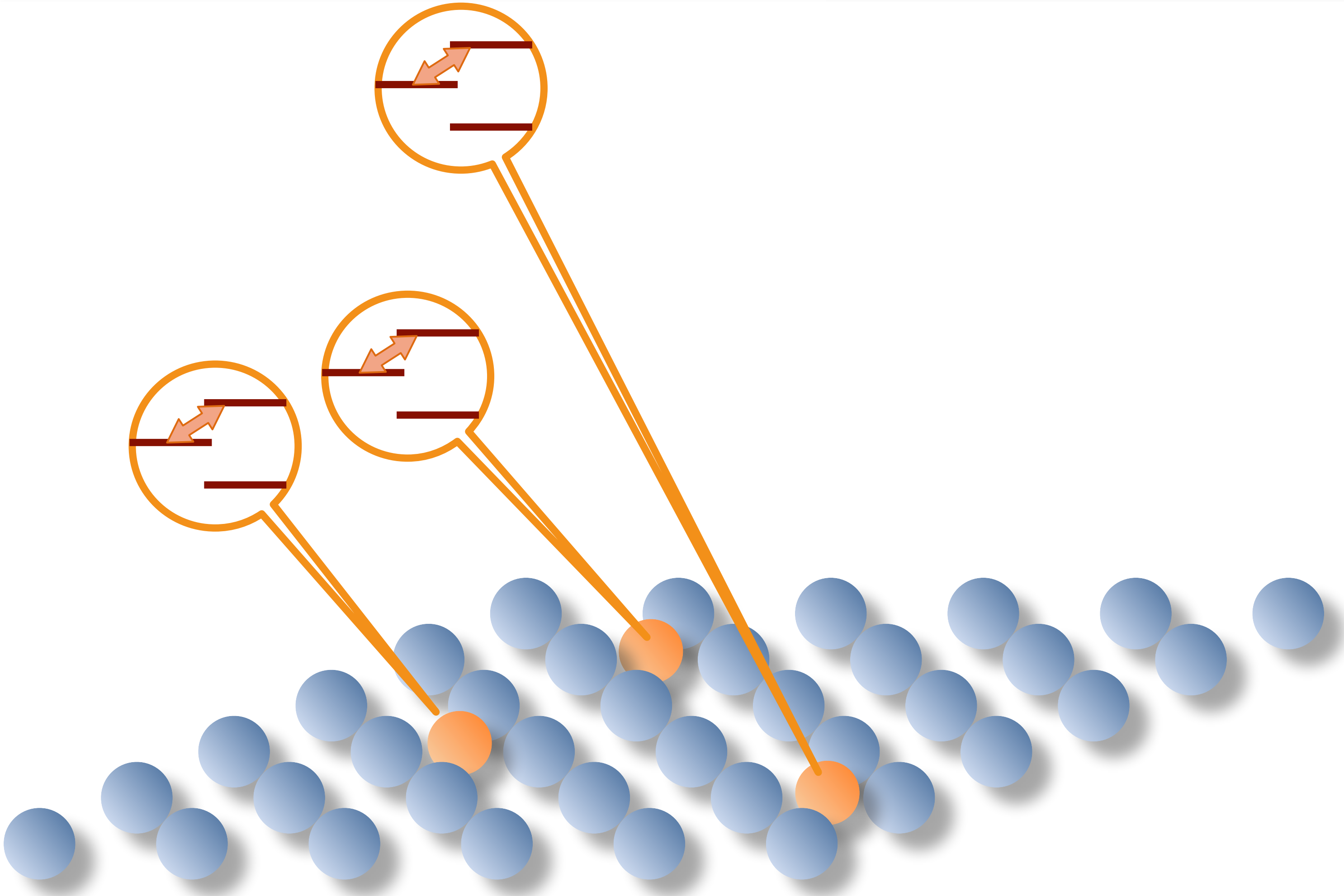

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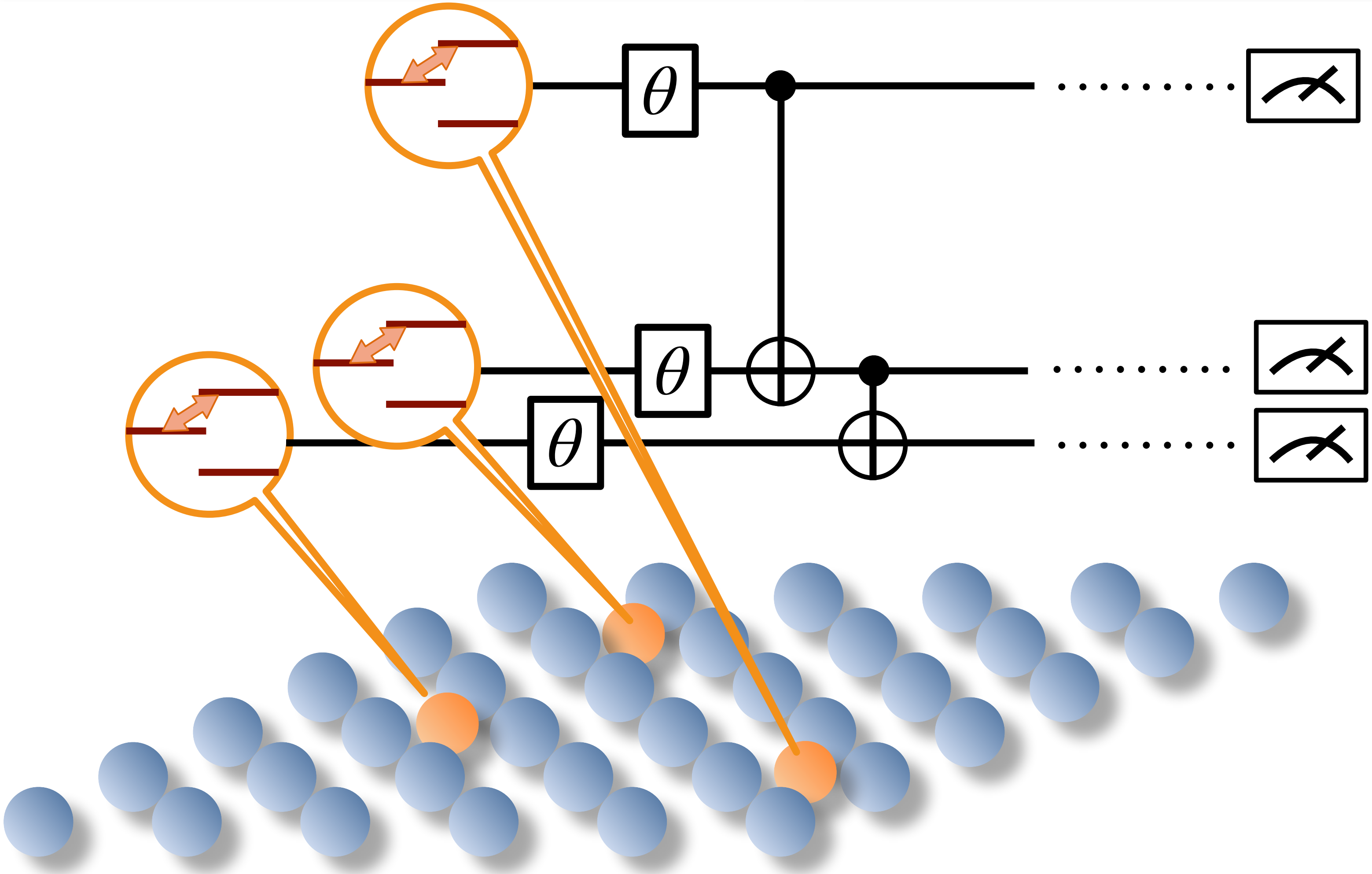

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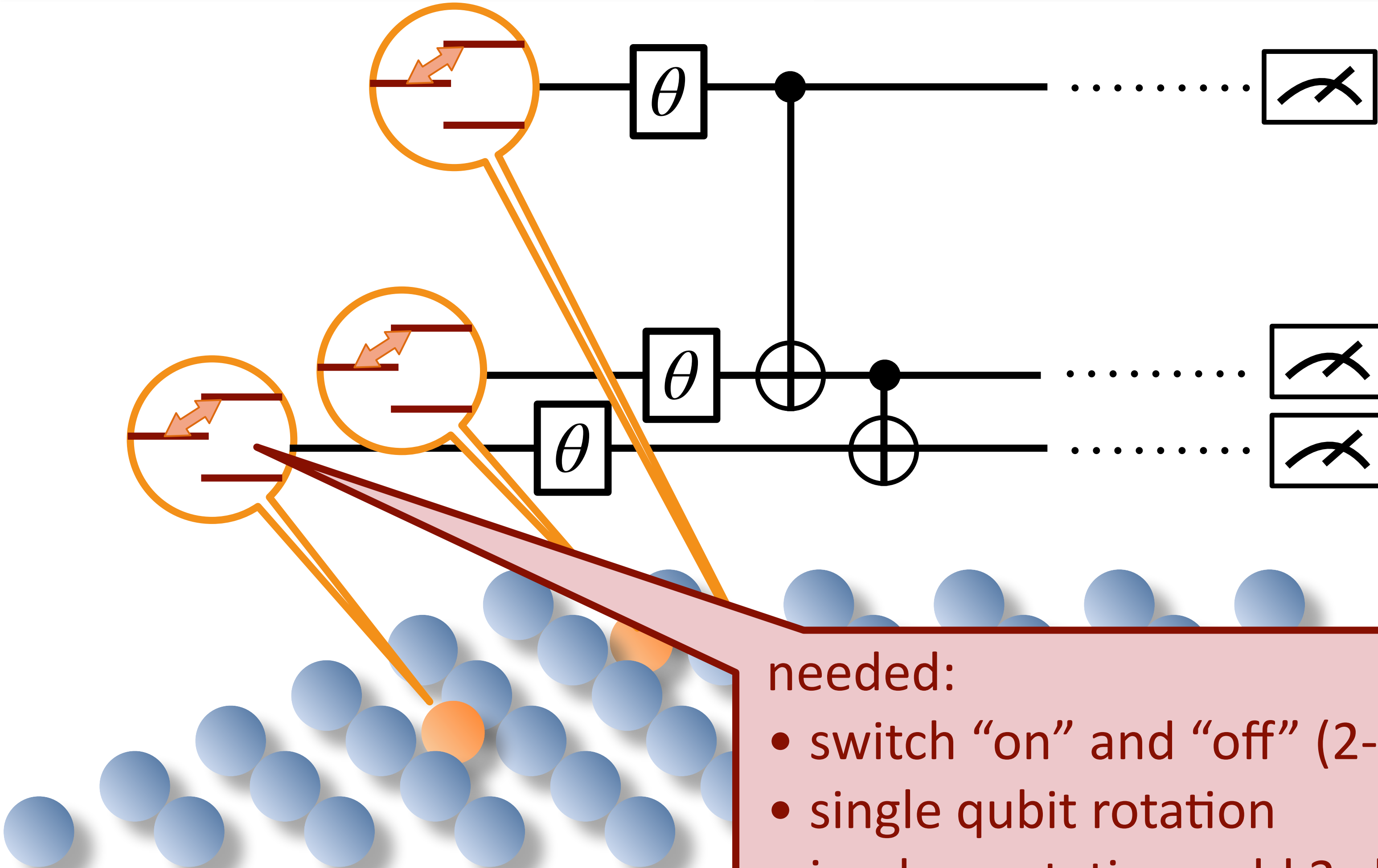
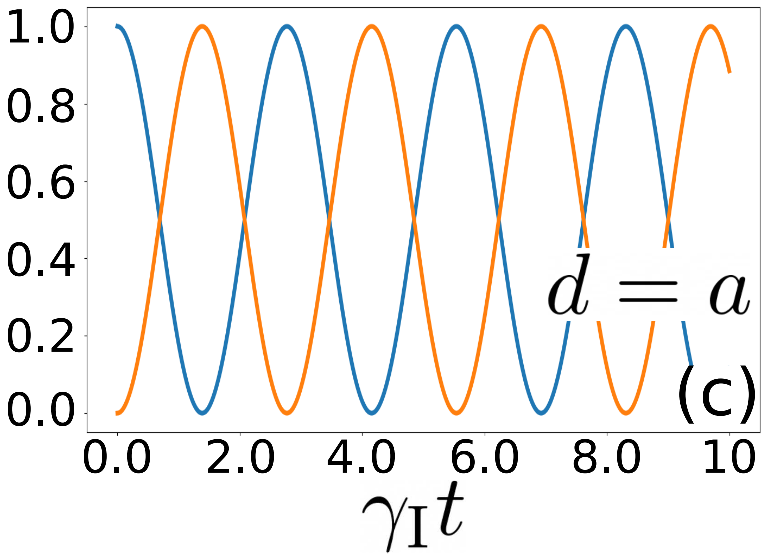


needed:

- switch "on" and "off" (2-qubit gate)
- single qubit rotation
- implementation: add 3rd level (EIT)

Shah, Rubies Bigorda, Patti, Yelin, PRA 109, 012613 (2024)

Excitation exchange: Quality factor



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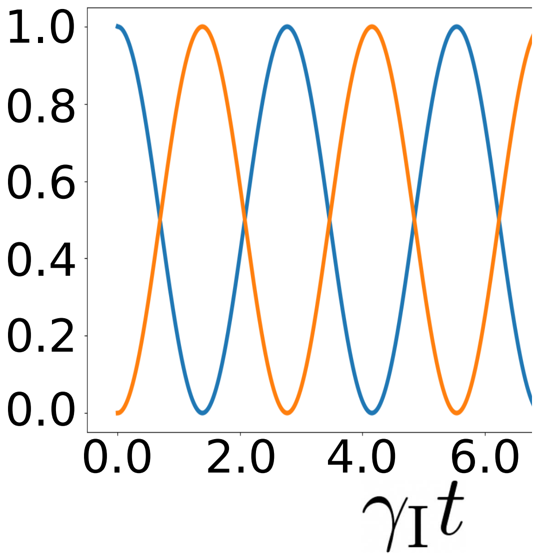
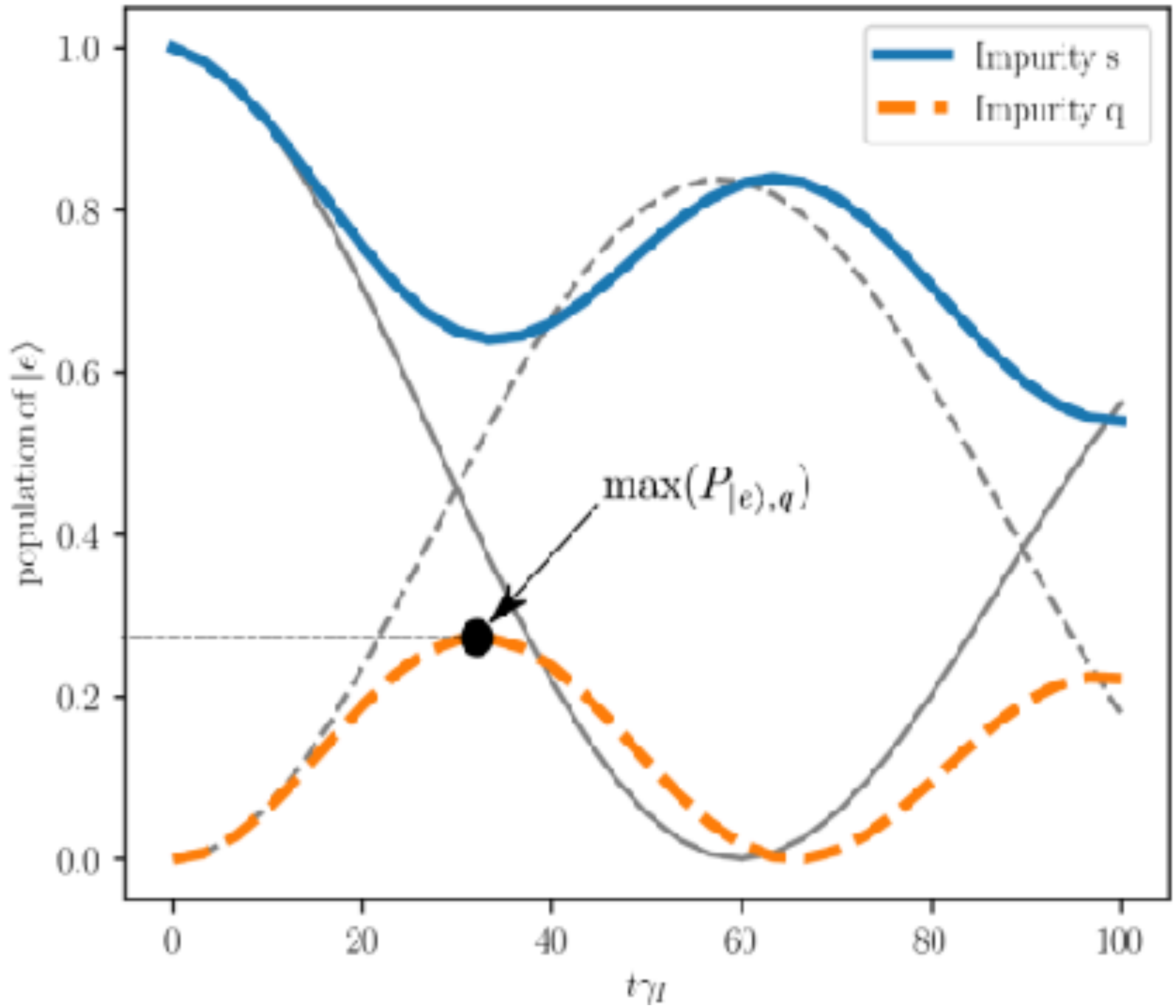
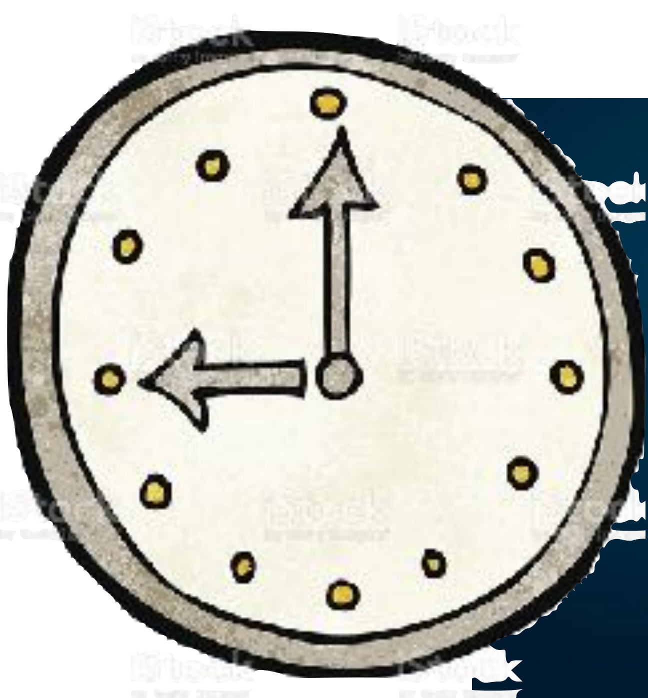




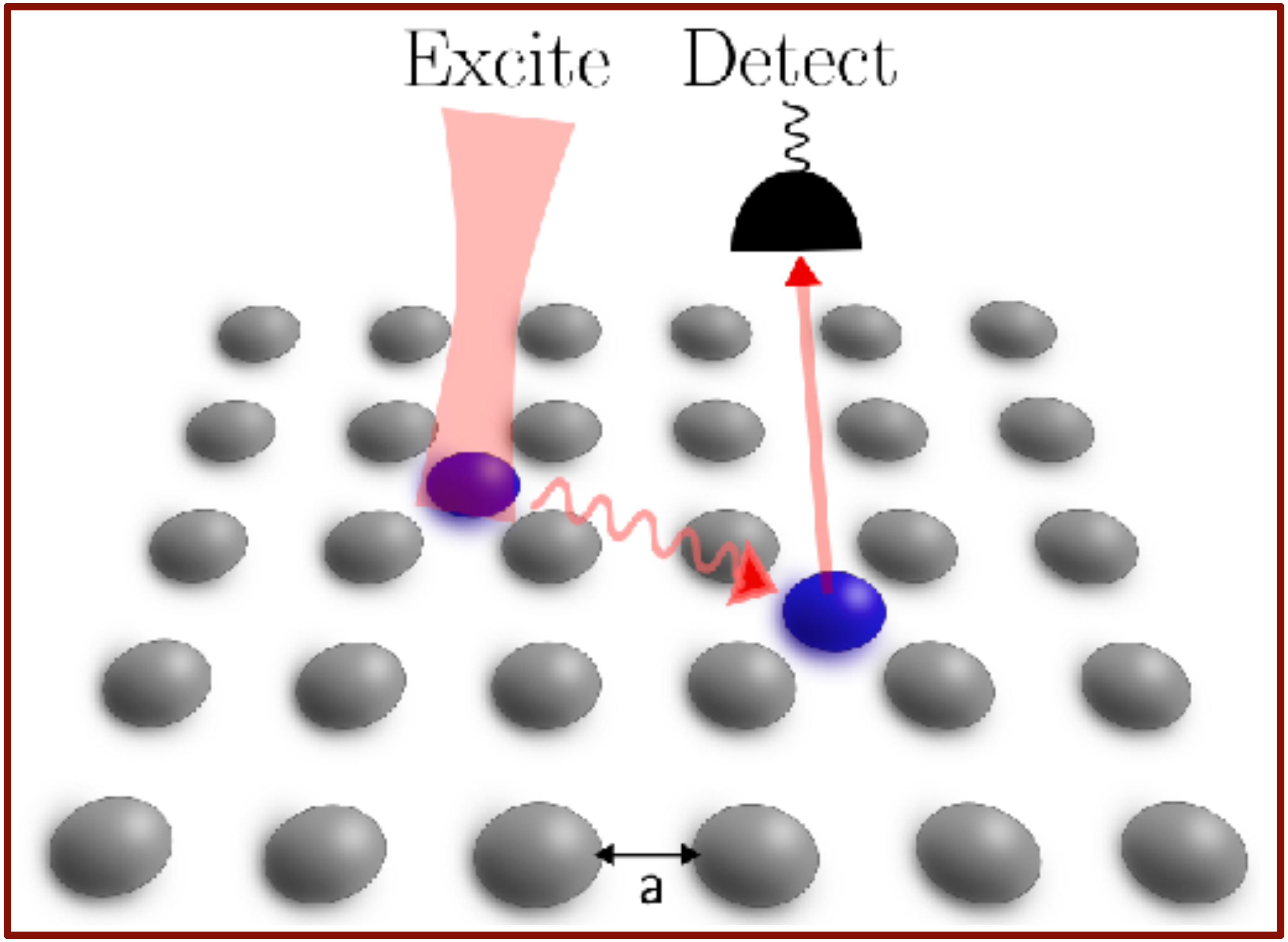
Application: Metrology

Sandberg, Ostermann, Patti, Yelin arXiv:2406.07619

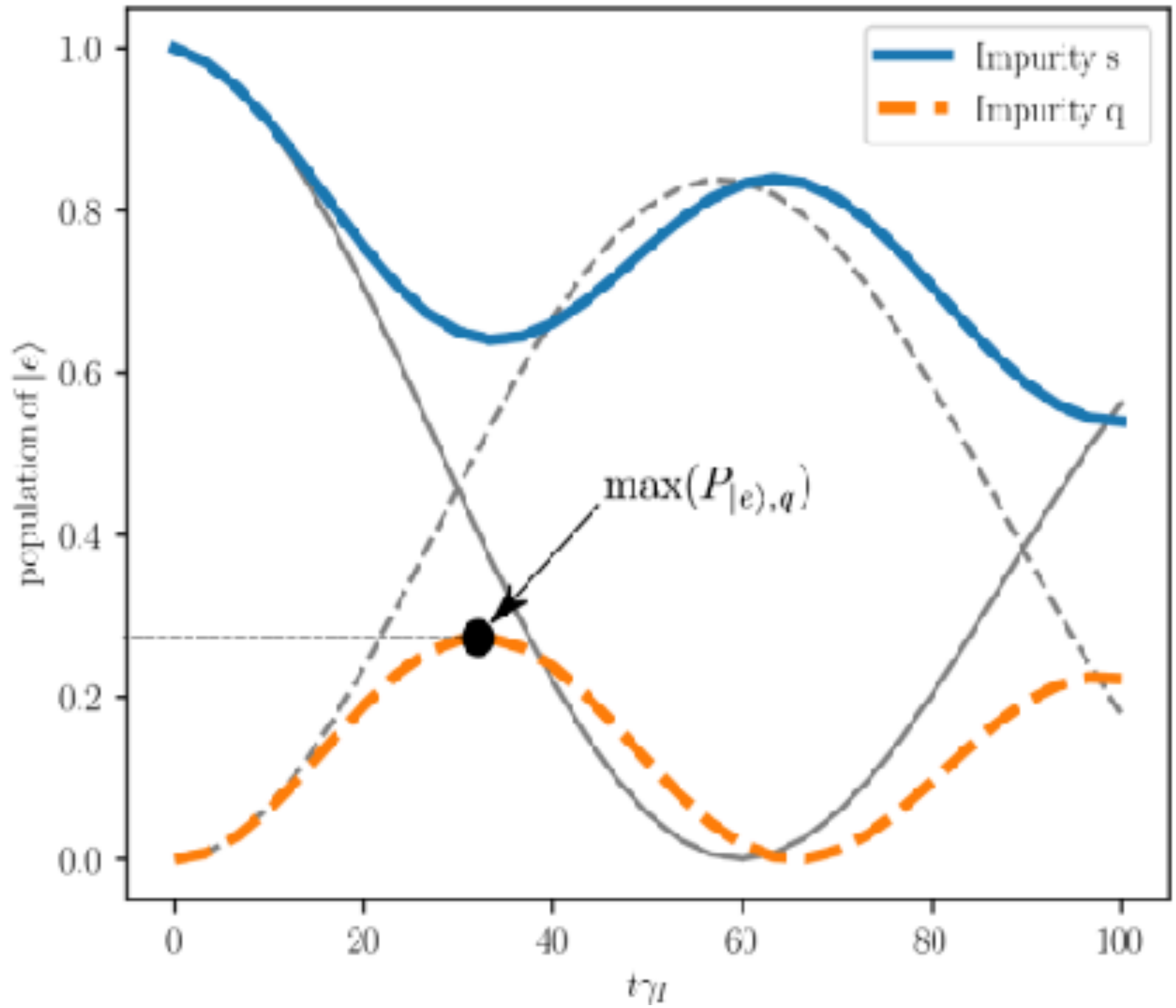


Sandberg, Ostermann, Patti, Yelin arXiv:2406.07619

Metrology with array QED



Measurement Protocol



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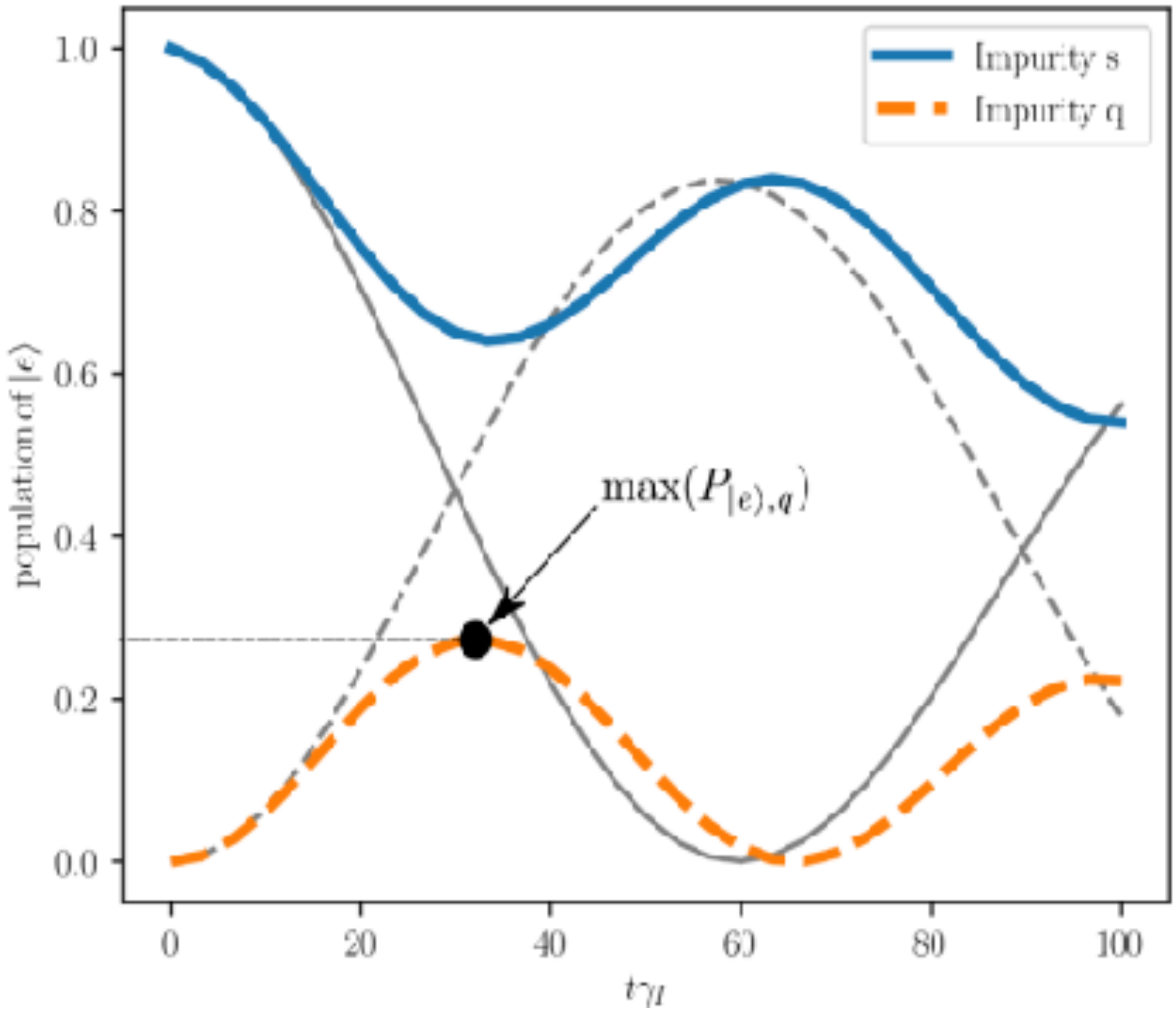

Mechanism: Nonlinearity

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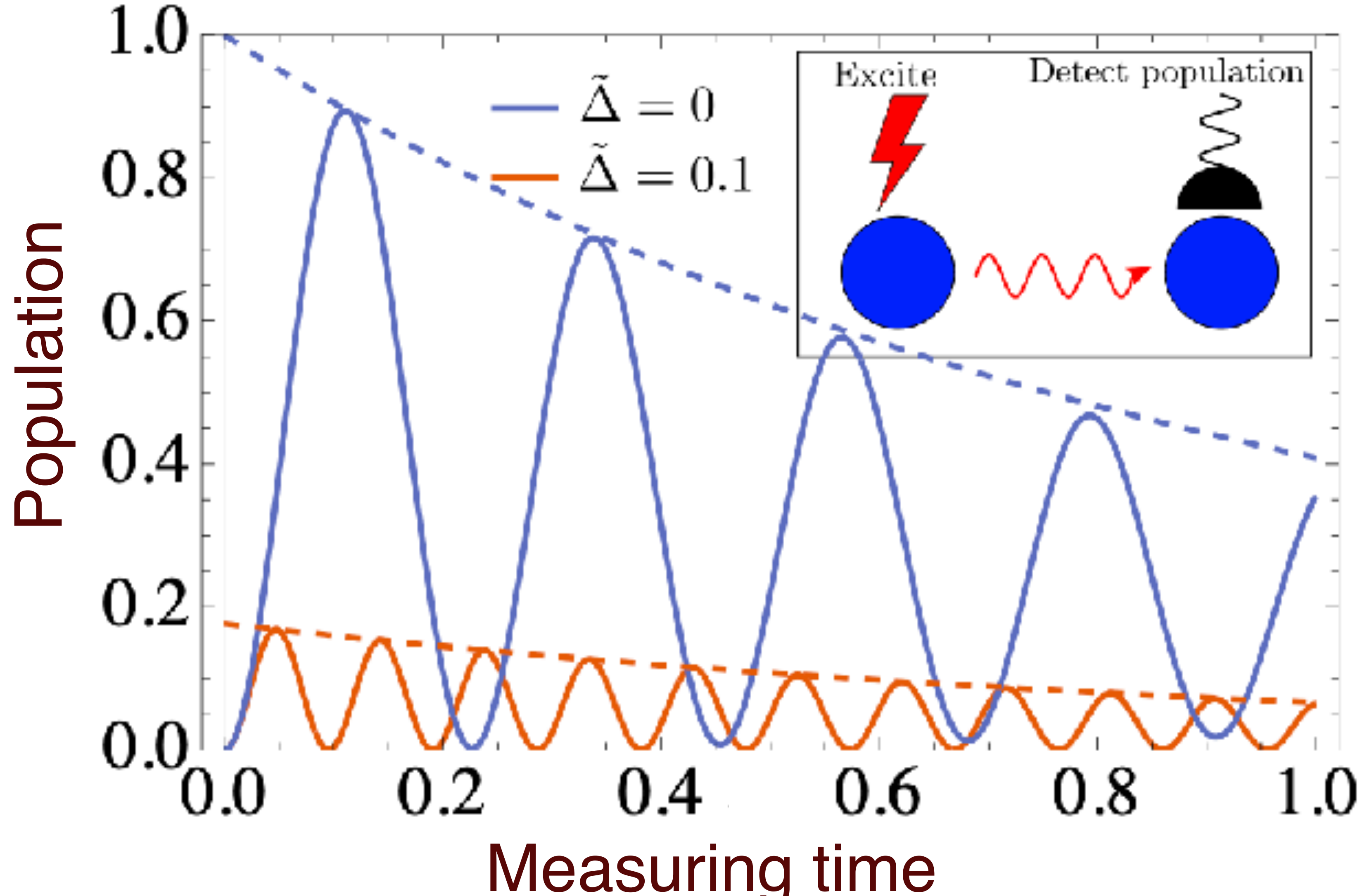
$$\sigma_{\Delta_{\mathrm{signal}}} = \frac{\sigma_{|c_1|^2}}{\left|\frac{\partial |c_1|^2}{\partial \Delta}\right|}$$

Variance

Measurement Protocol



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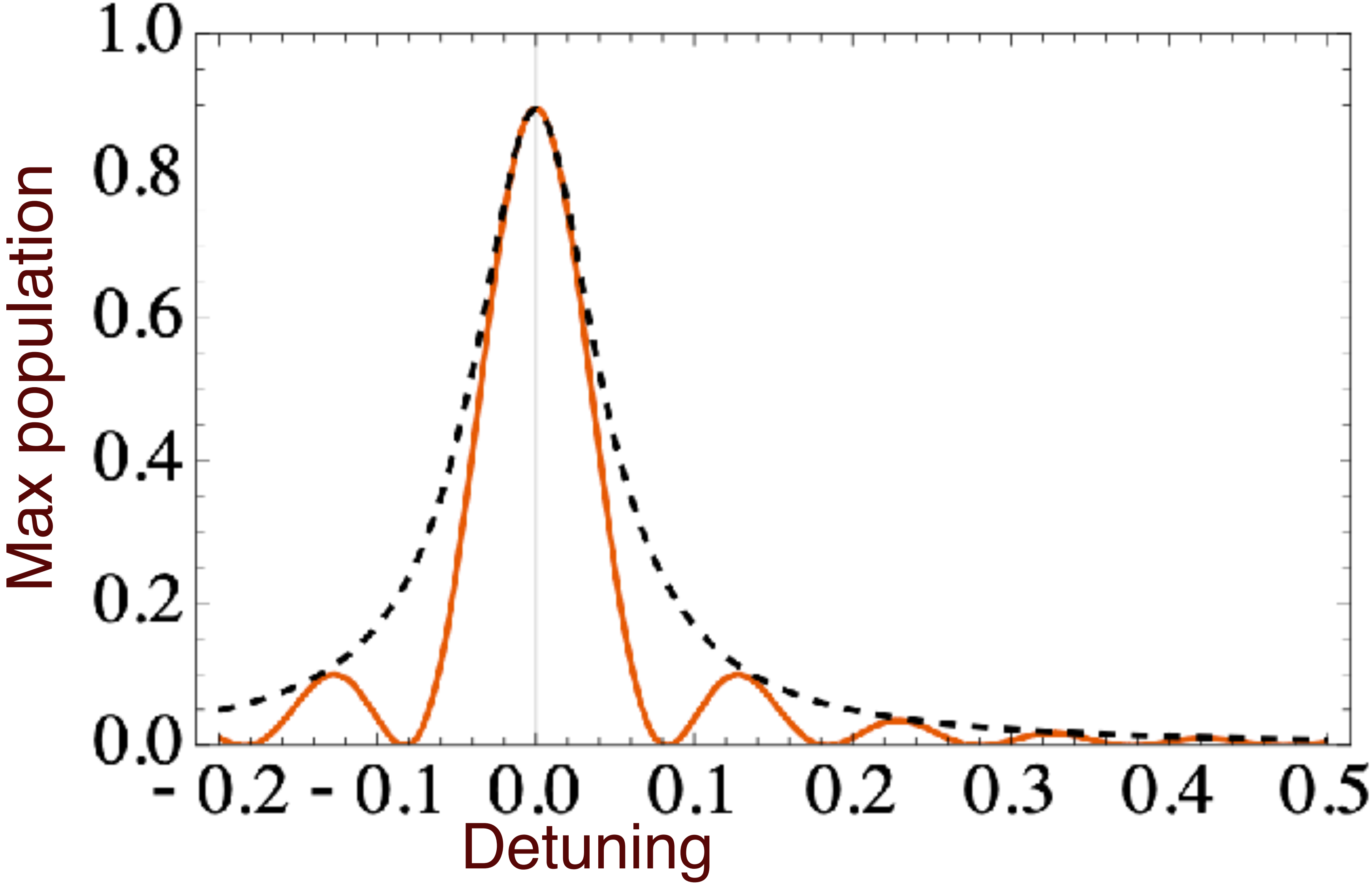

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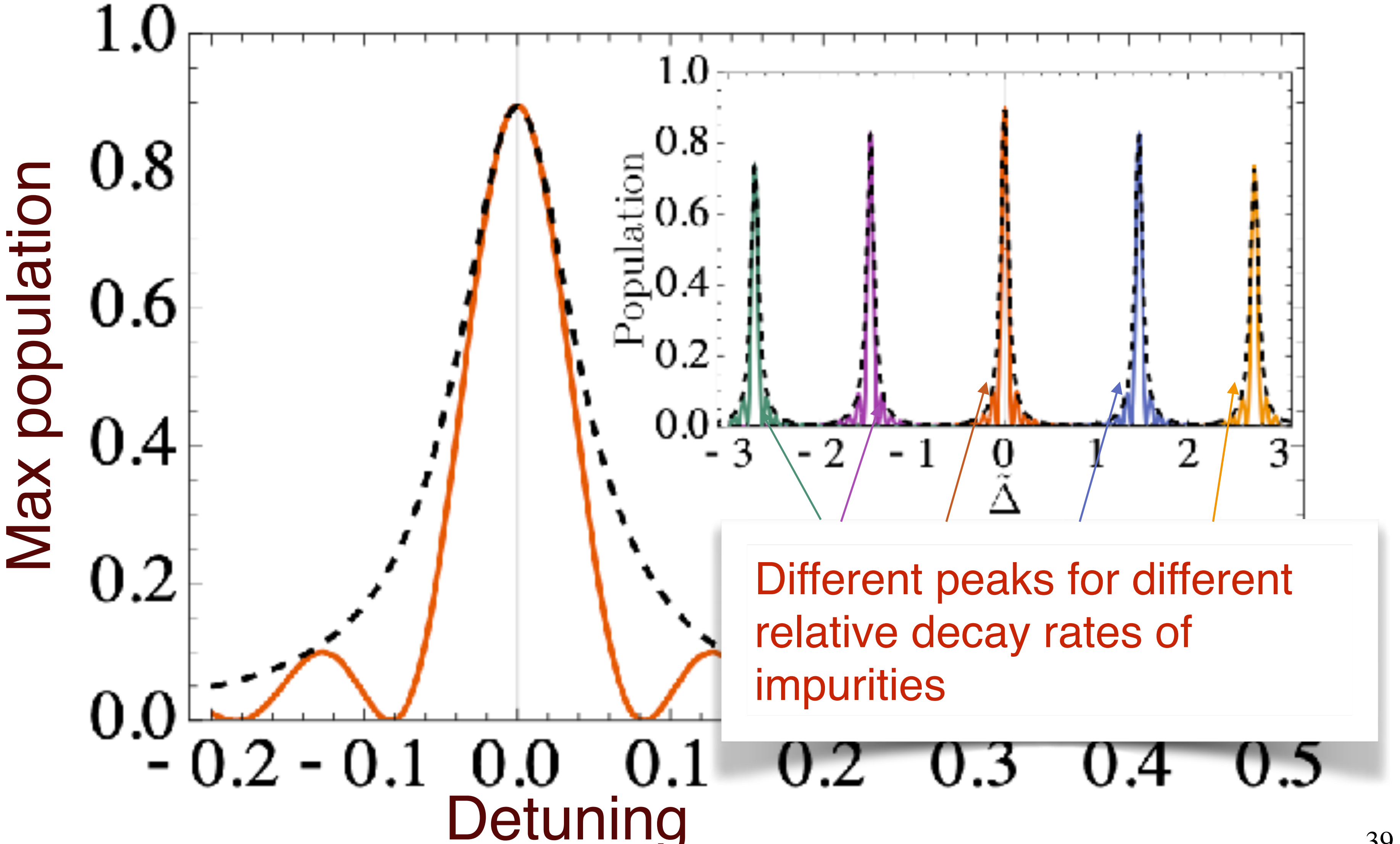

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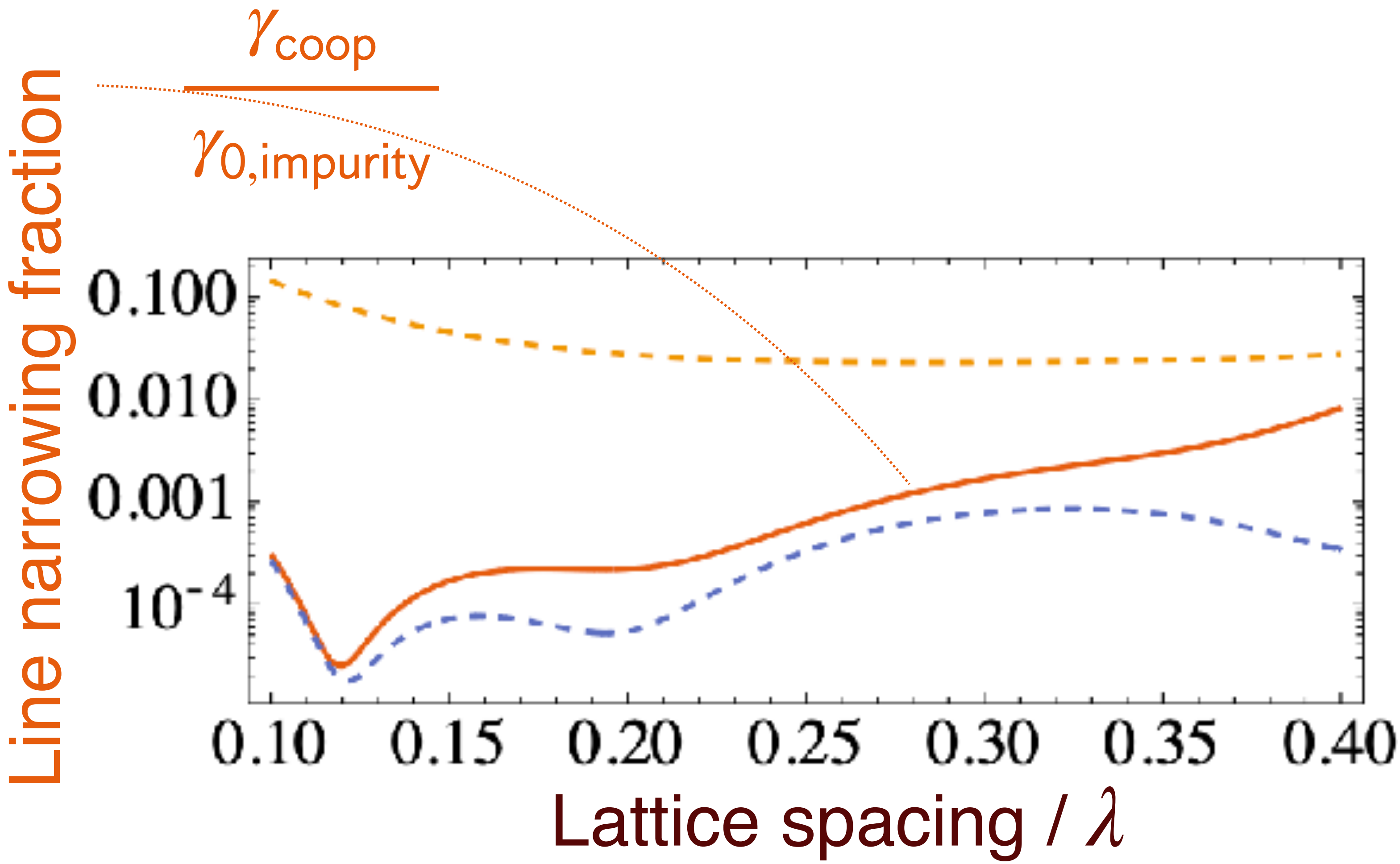
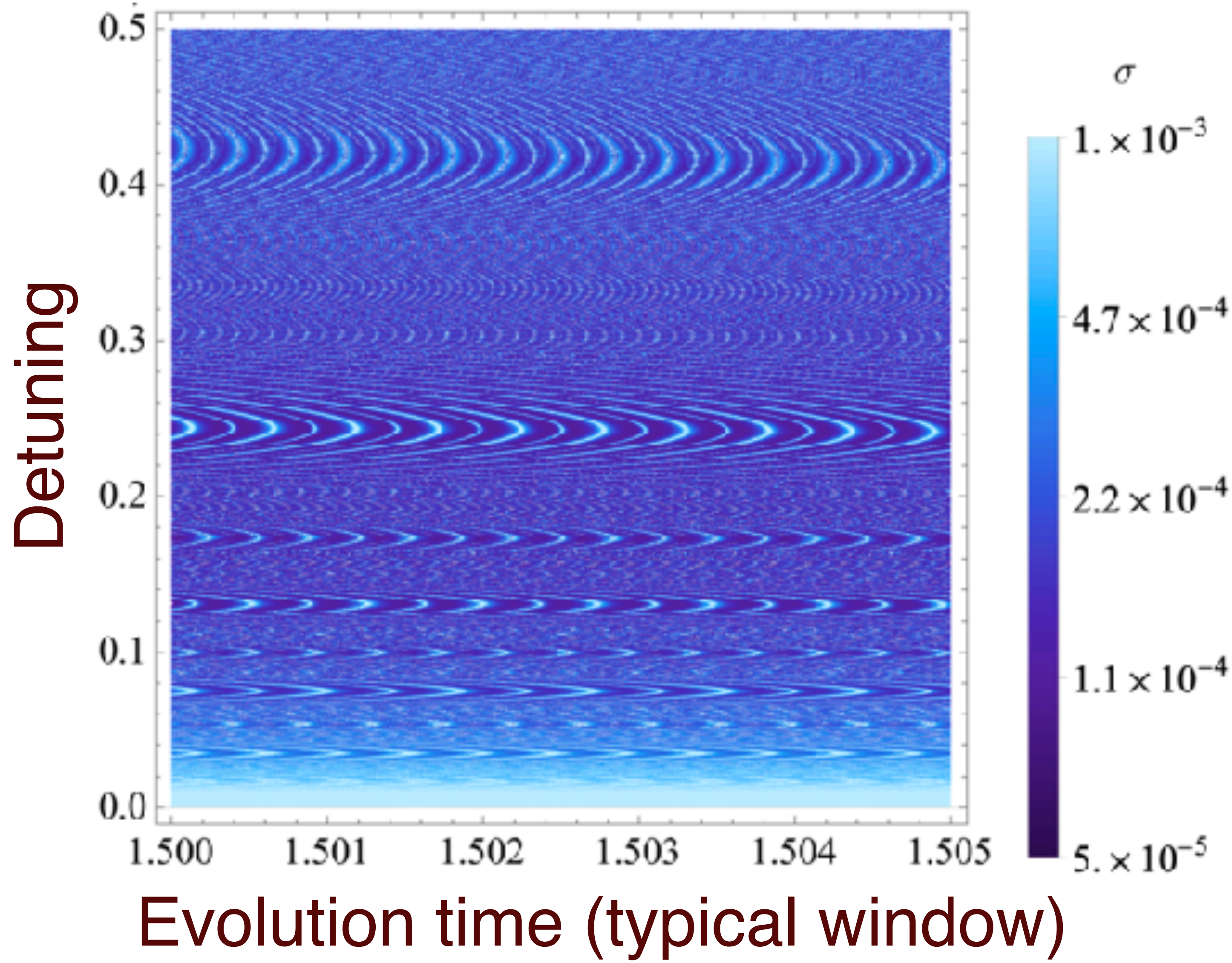


Standard deviation of measurement



What about noise and errors?

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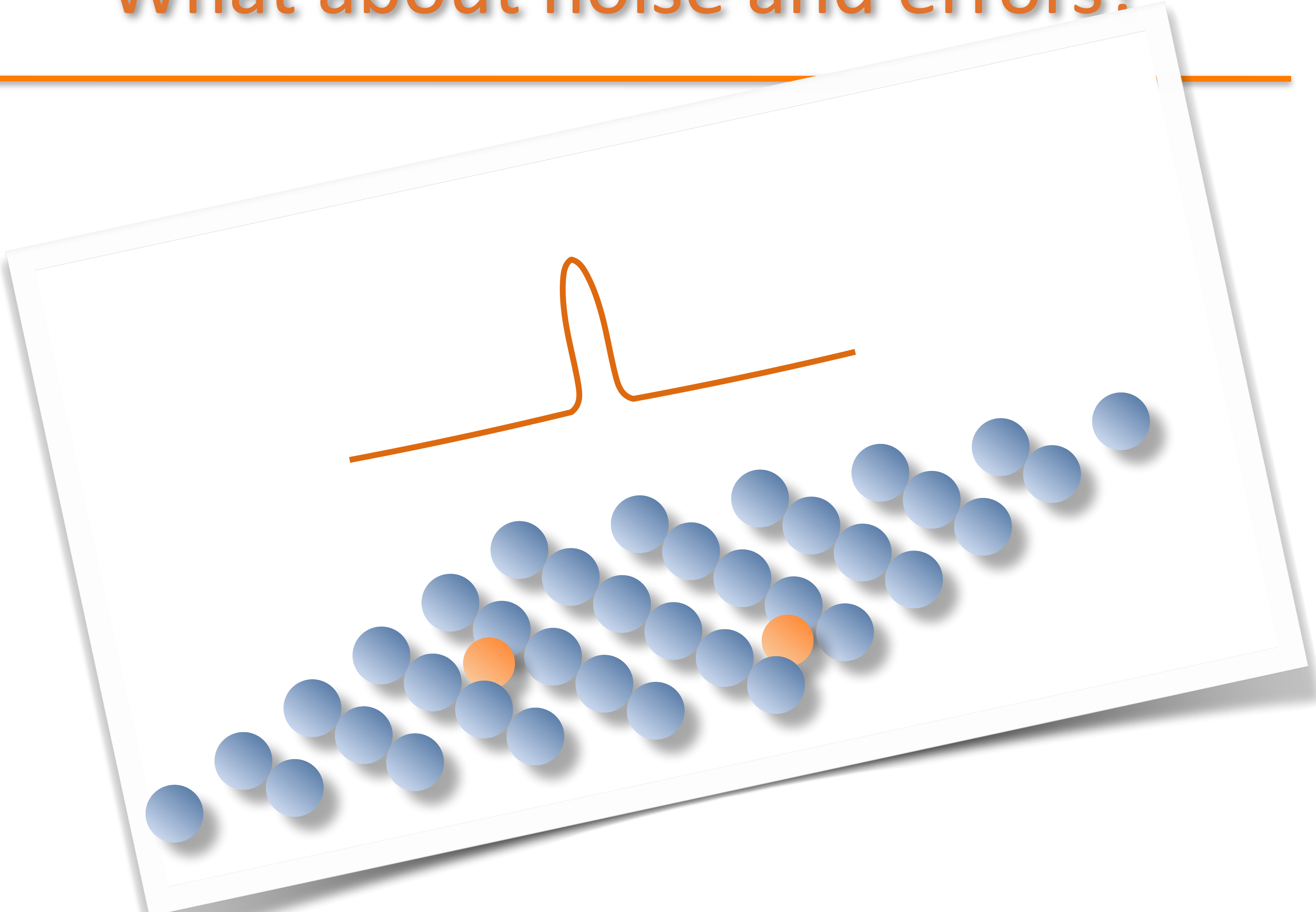

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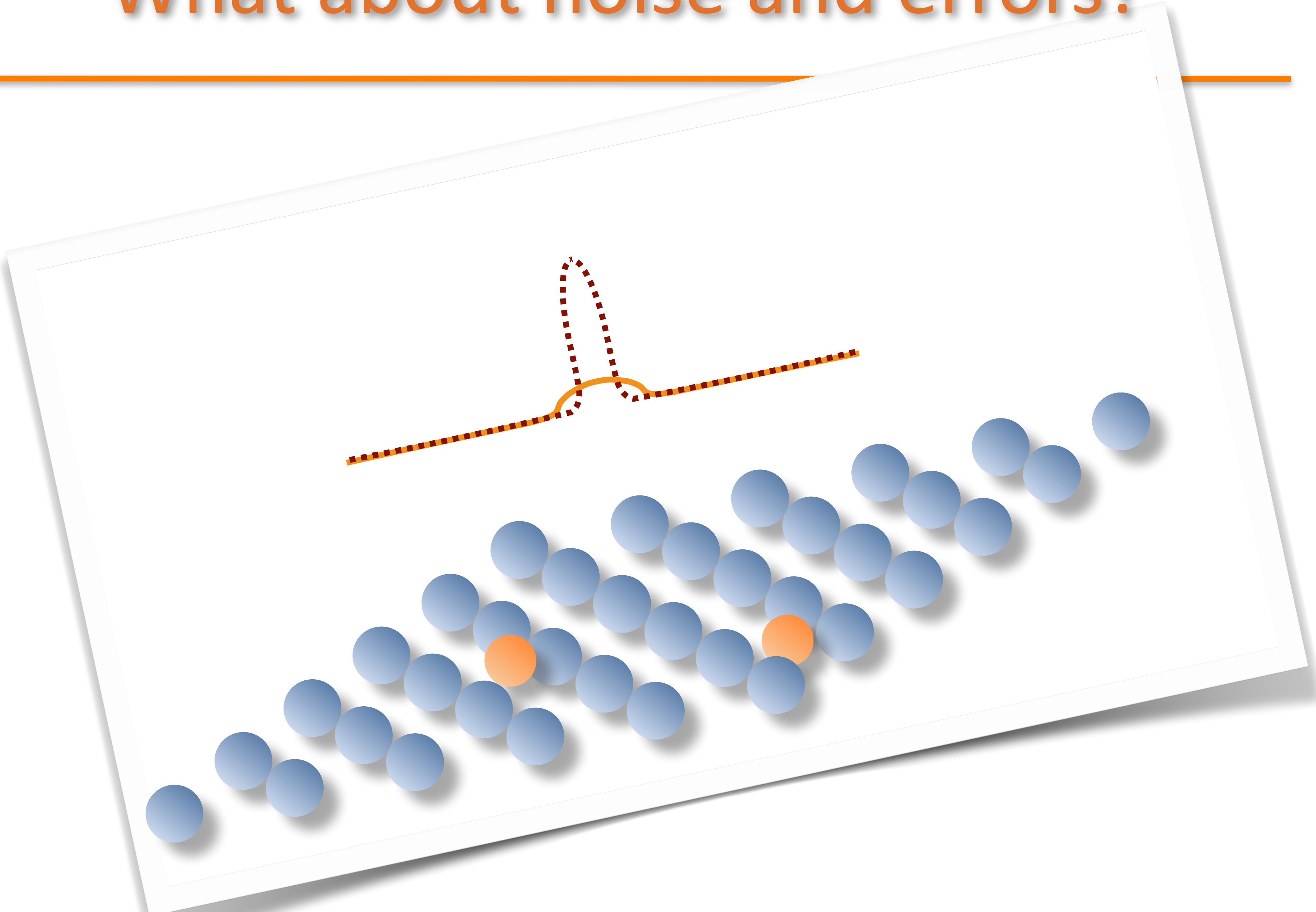

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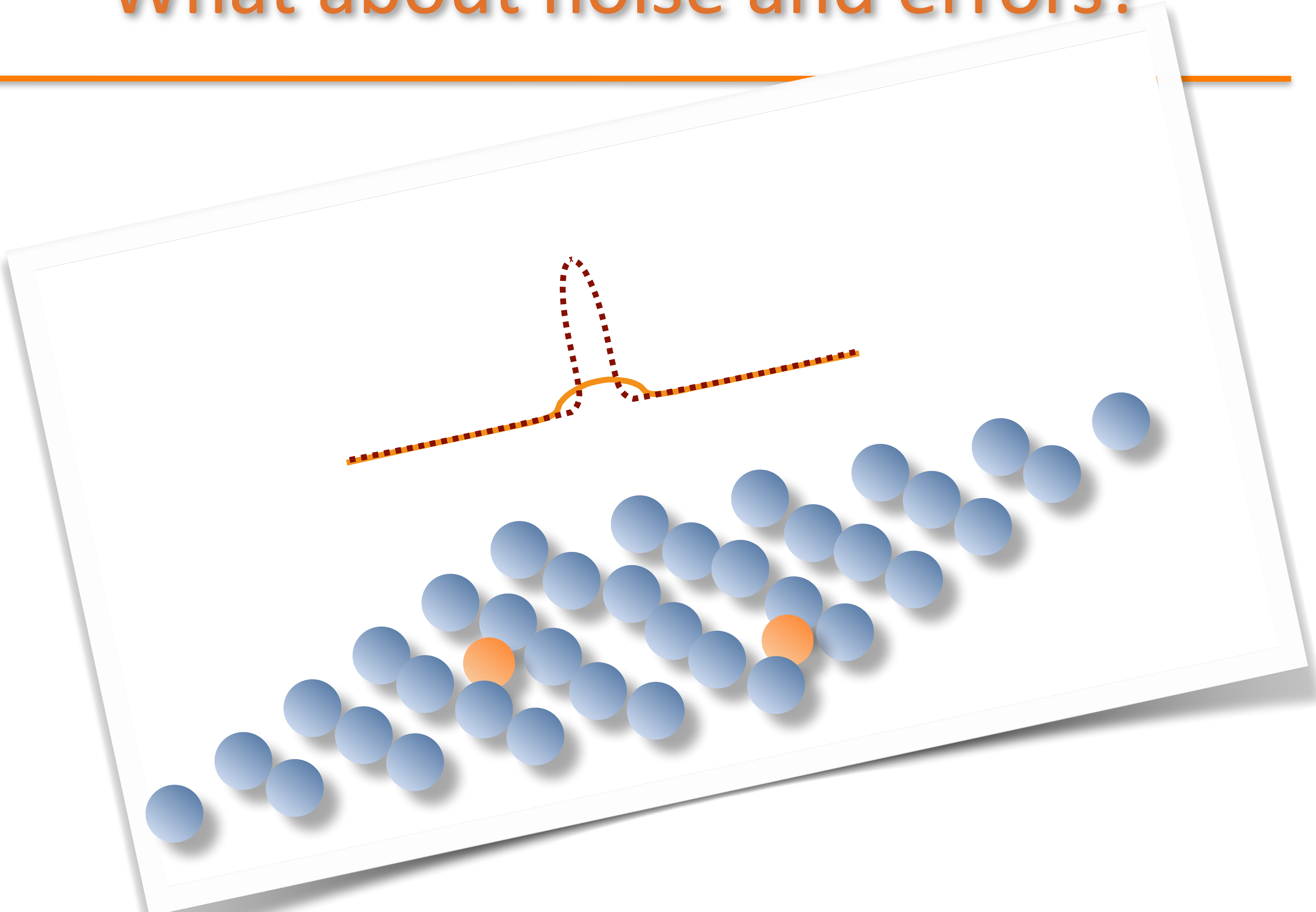

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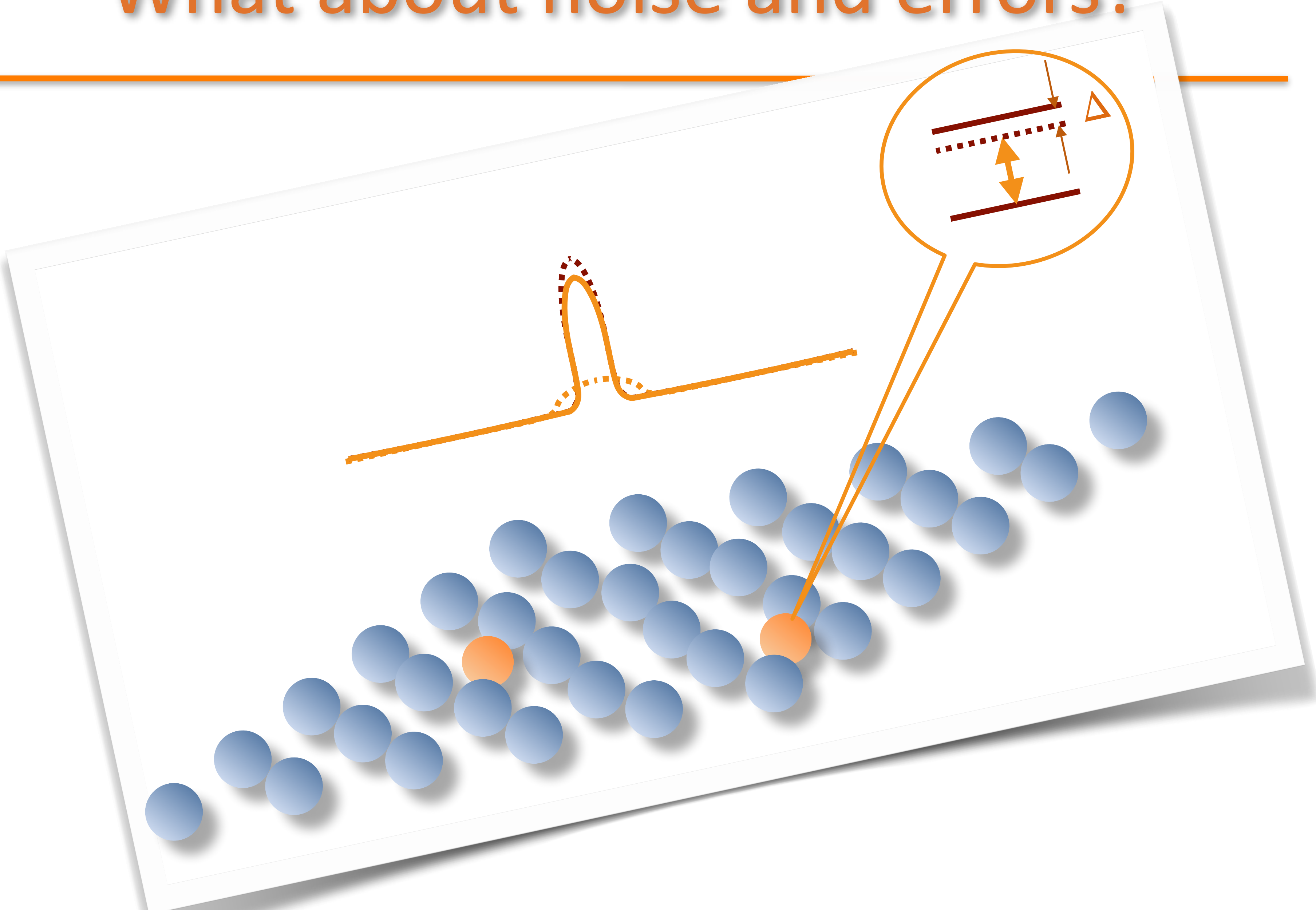

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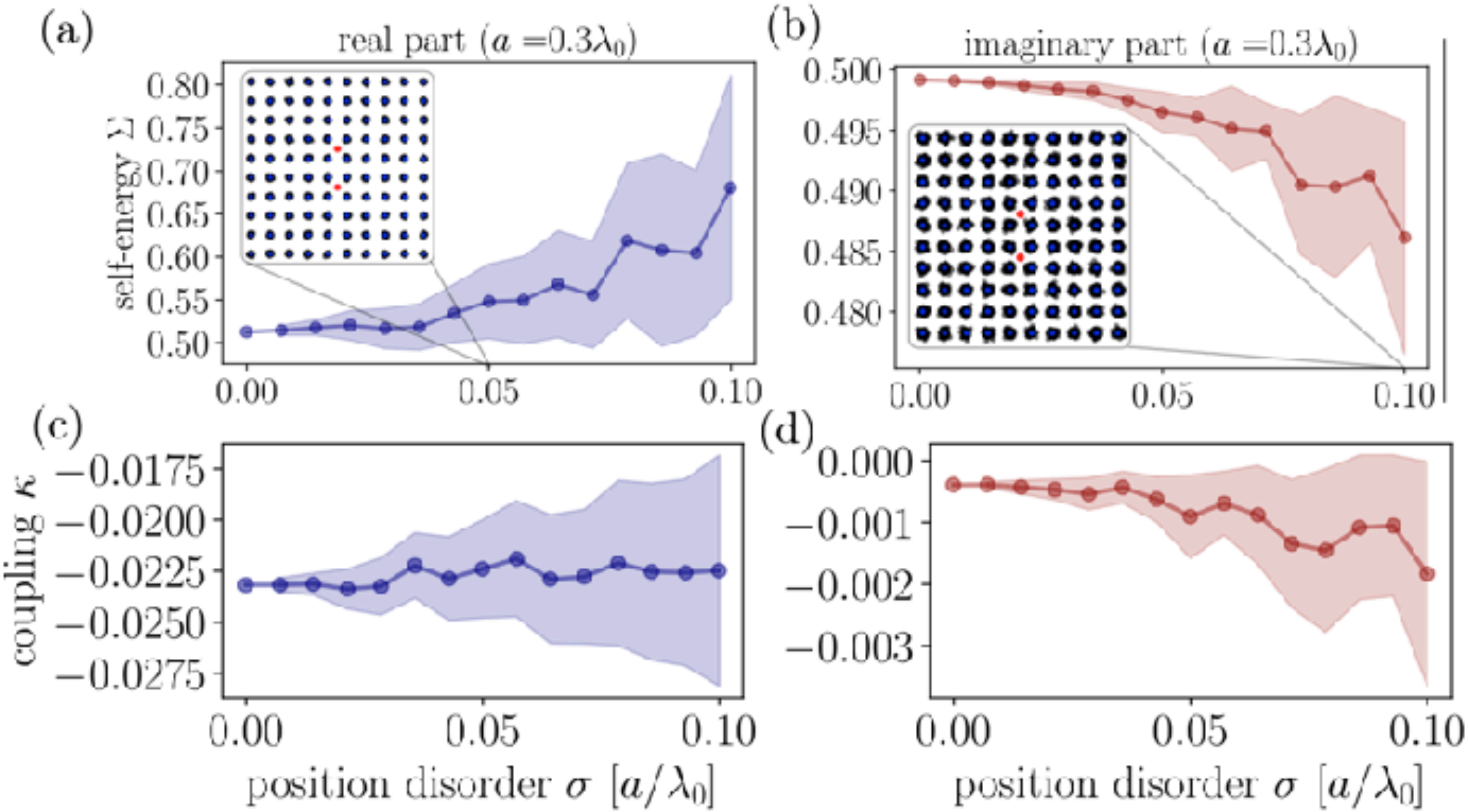

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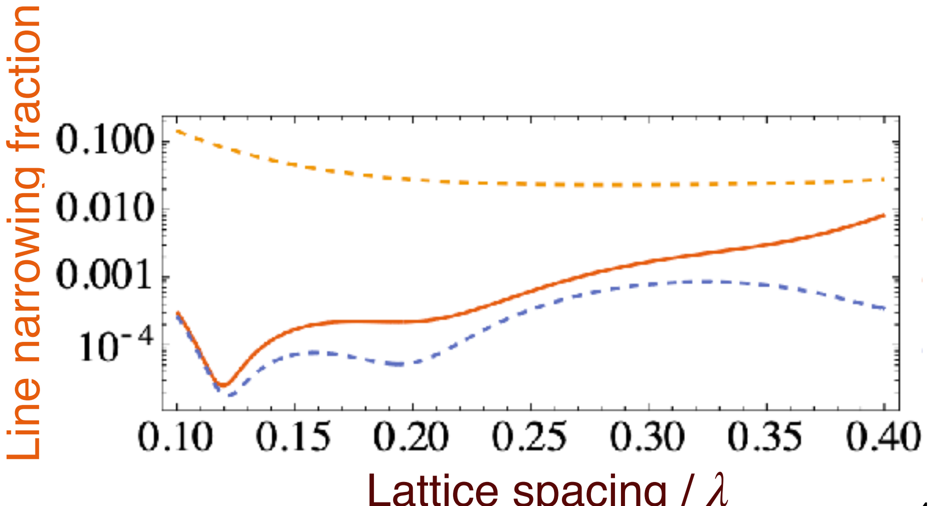

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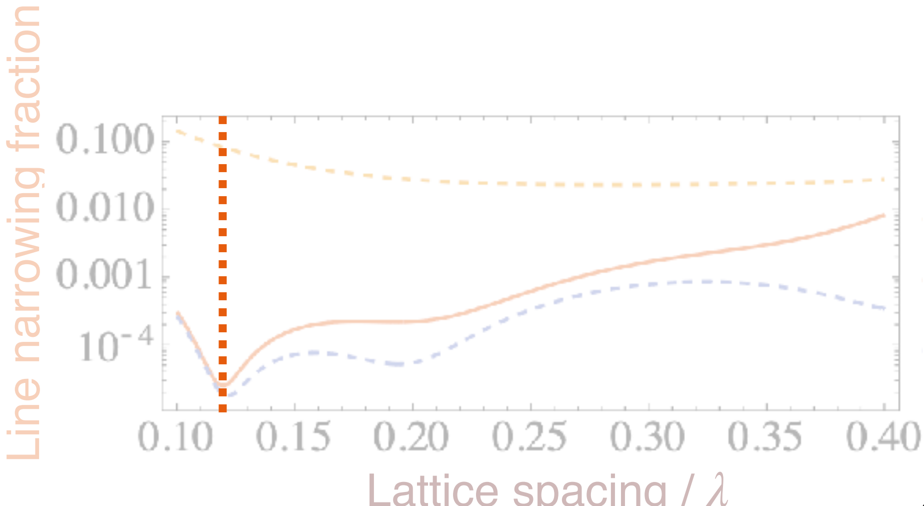

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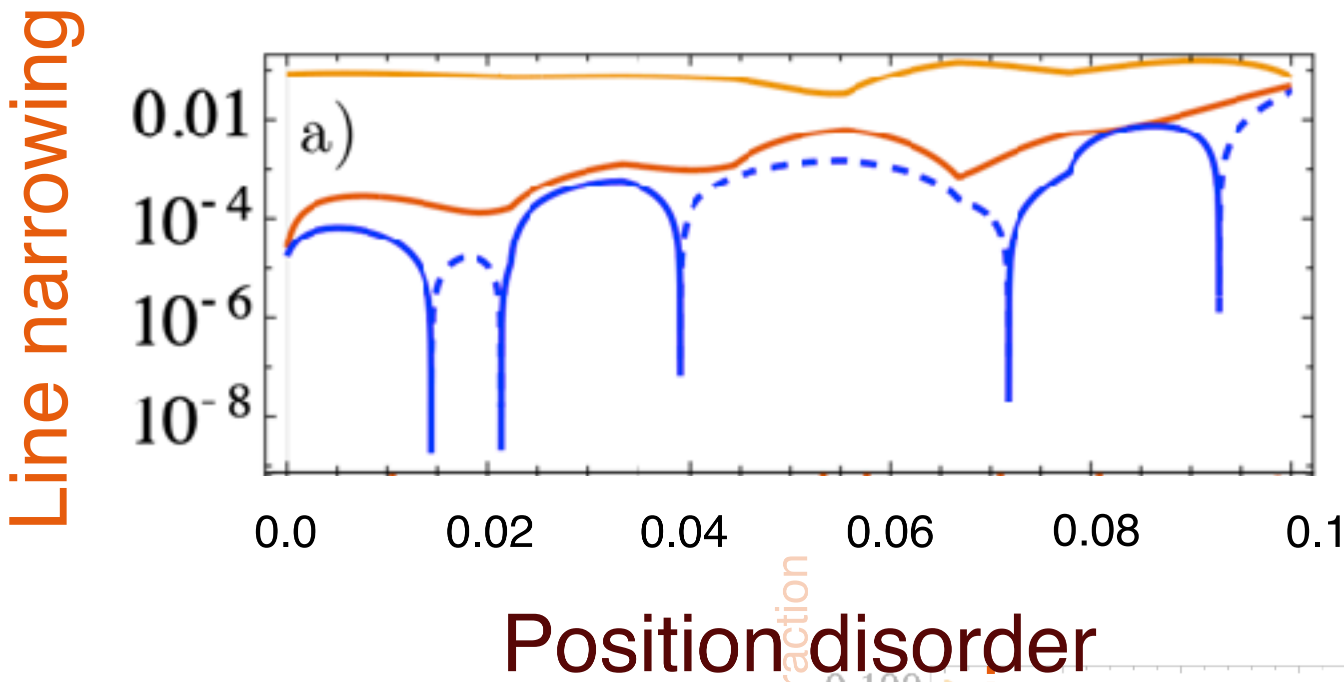

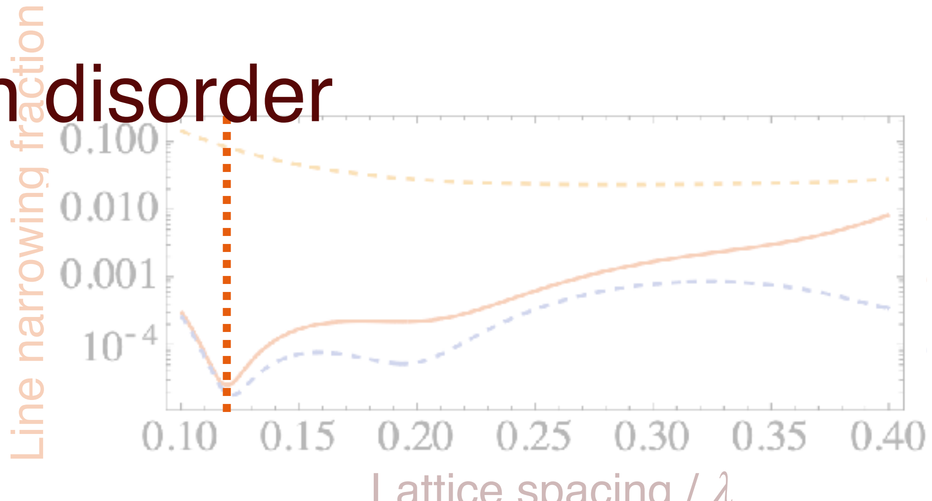

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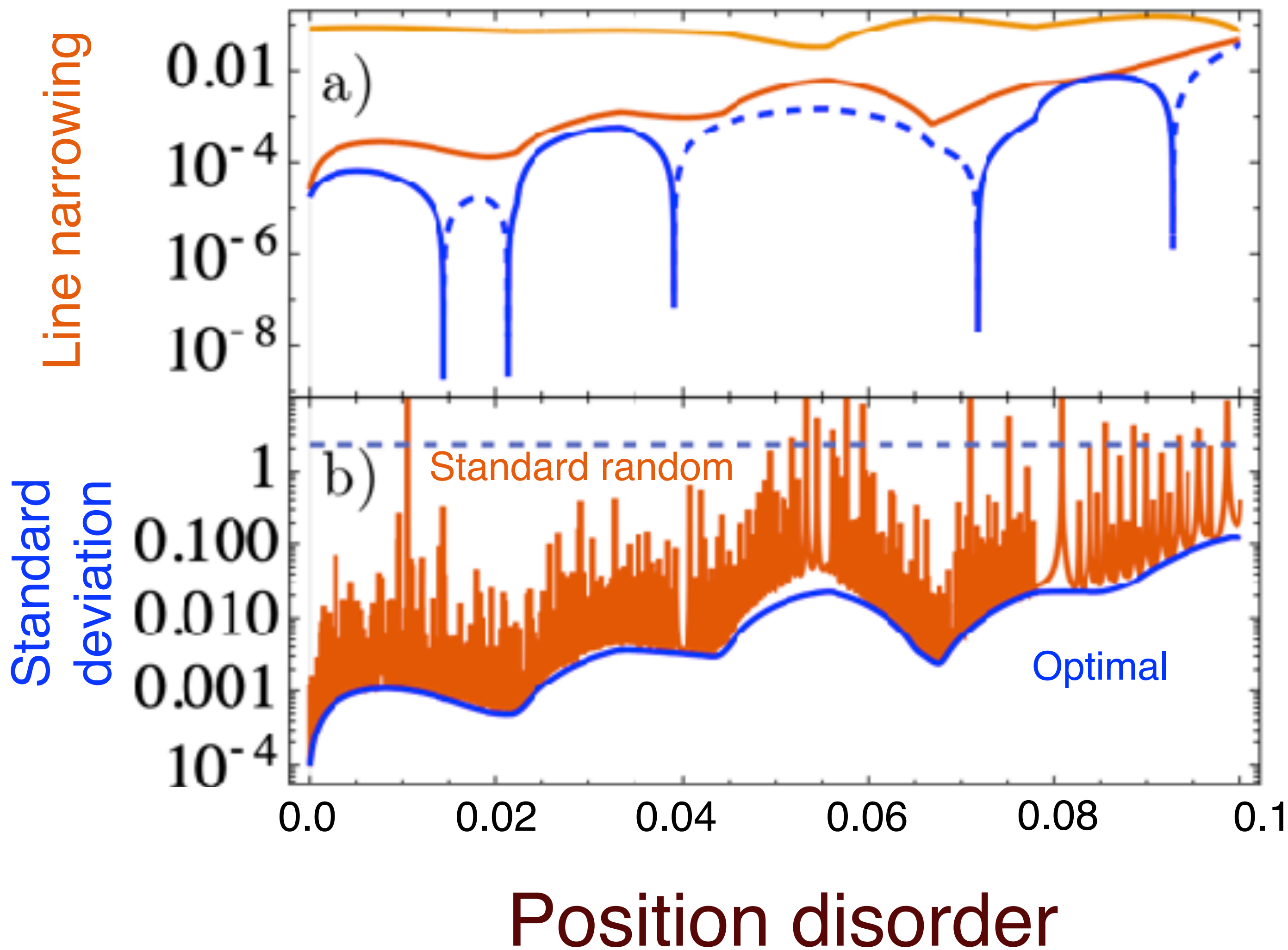

Narrowing Linewidths

Sandberg, Ostermann, Patti, Yelin arXiv:2406.07619

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Outlook:

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- Direct comparison to cavity qed?

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Collaborators

Stefan Ostermann

Taylor Patti

Hanzhen Ma

Oriol Rubies Bigorda

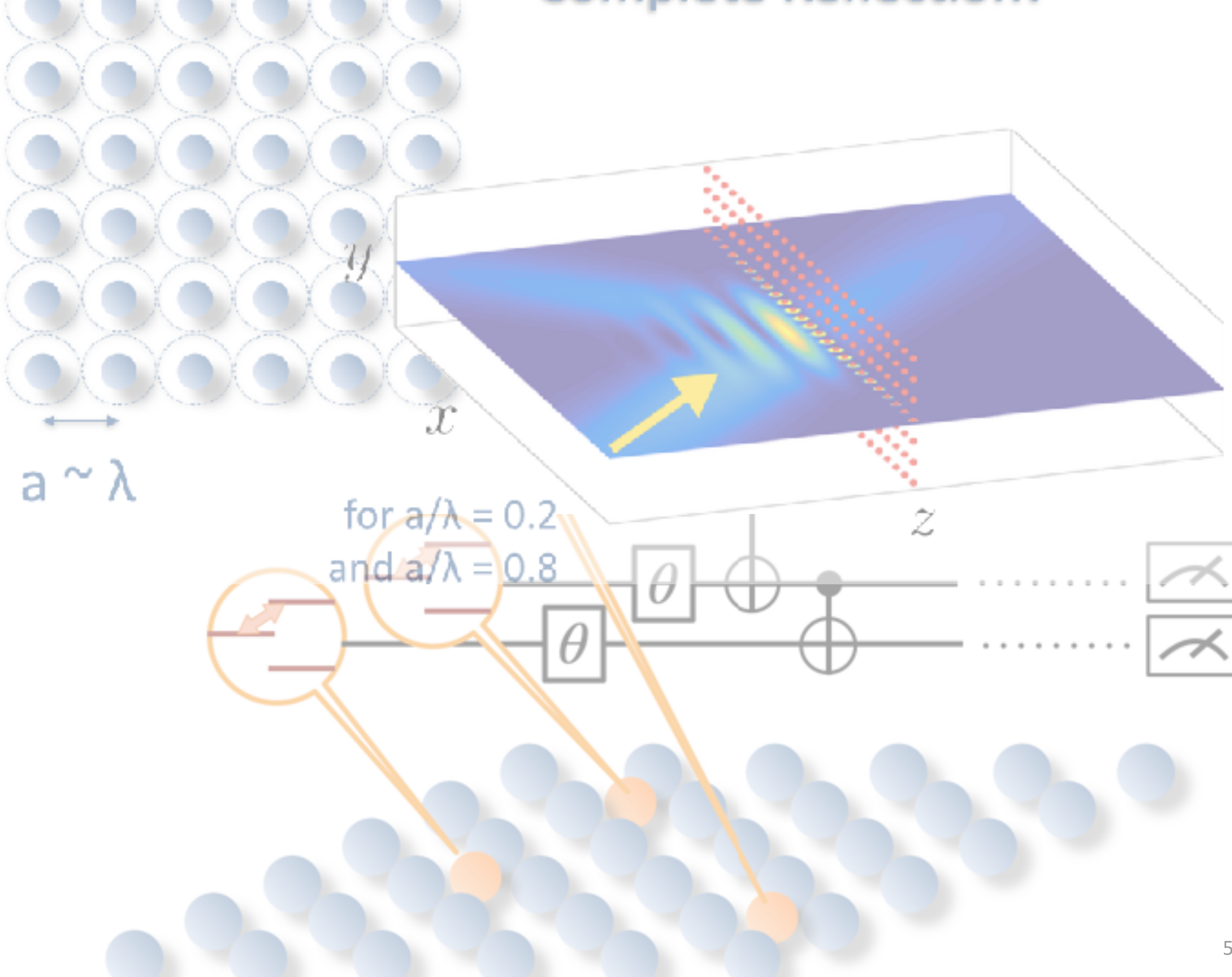
Abigail McClain Gomez

Yidan Wang

Oliver Sandberg

Raphael Holzinger

$$$: NSF (CUA, Q-SEnSE)), AFOSR, WellcomeLEAP


y
x
z
a ~ λ
for a/λ = 0.2
and a/λ = 0.8
θ
θ

Thank you!