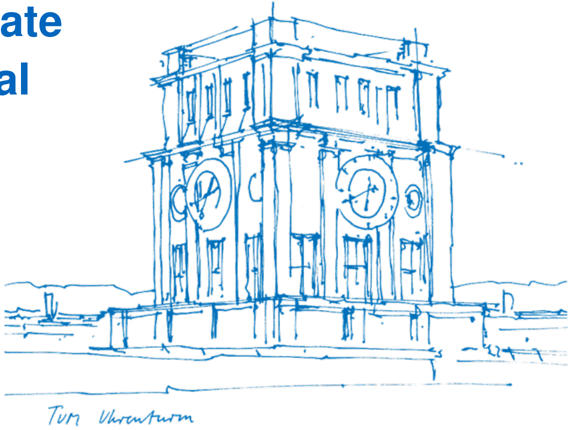
Chair of Computer Architecture and Parallel Systems
TUM School of Computation, Information and Technology
Technical University of Munich

Minimizing Readout and State Preparation Time for Neutral Atom Quantum Computing



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Outline

Neutral Atom Quantum Computing

Environment

MUNIQC-Atoms
Neutral Atom based Quantum Computing Demonstrator

Munich Quantum Valley

This work was funded by the German Federal Ministry of Education and Research (BMBF) under the funding program *Quantum Technologies - From Basic Research to Market* under contract numbers 13N16070, 13N16076, and 13N16087, as well as from the Munich Quantum Valley (MQV), which is supported by the Bavarian State Government with funds from the Hightech Agenda Bayern.

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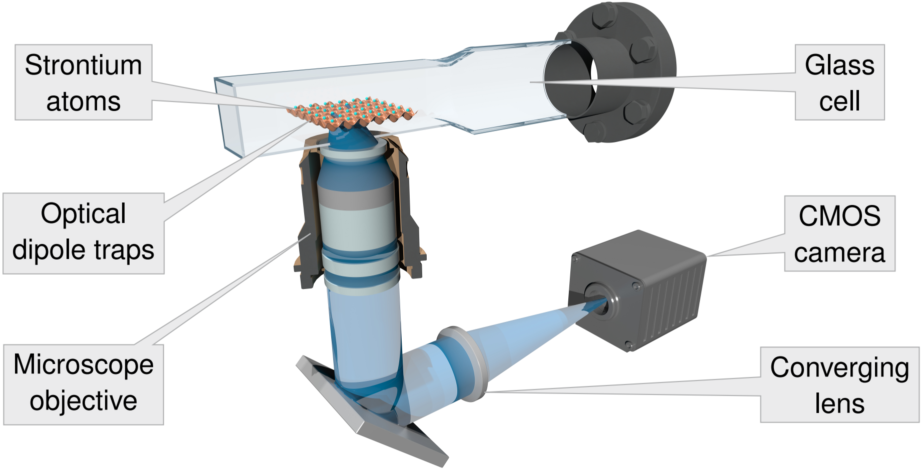
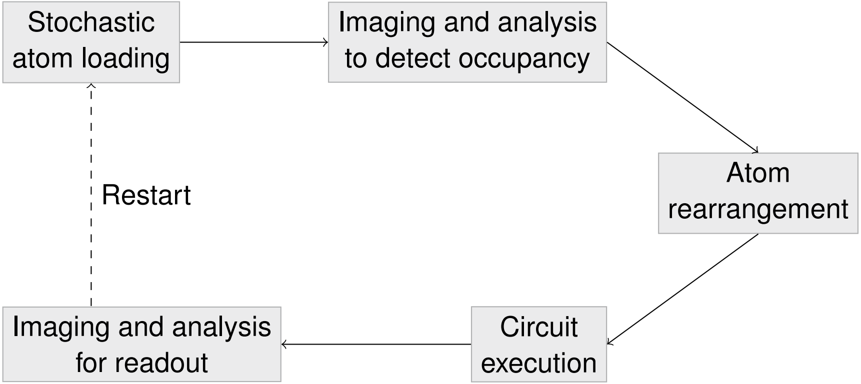
Neutral Atom Quantum Computing

Setup at MPQ



Neutral Atom Quantum Computing

Compute Cycle

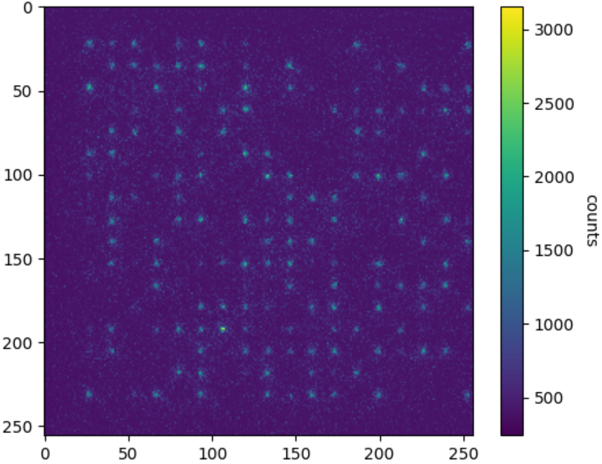


Neutral Atom Quantum Computing

Issue

Sum of exposure and image analysis time must be minimized because of

- Increased cycle time
- Atom heating



Neutral Atom Quantum Computing
Solution

Previous work: Image simulation

- Fast data generation
- Different parameters
- Labelled data

Realistic Neutral Atom Image Simulation

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Neutral Atom Quantum Computing

Solution

Previous work: Image simulation

- Fast data generation
- Different parameters
- Labelled data

⇒ Use simulated data to compare algorithms

⇒ Establish absolute precision bounds

Realistic Neutral Atom Image Simulation

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Outline

Cramér-Rao Bound
Introduction

Theoretical bound on best-possible precision of estimating a parameter

- Estimated parameter: Brightness of each atom site
- Measurements: Every pixel (up to a reasonable distance)

Based on likelihood function of pixel values, which depends on

- Each atom site’s brightness
- Background illumination
- Camera characteristics (Readout variance, offset, preamp gain)

Cramér-Rao Bound

Issues

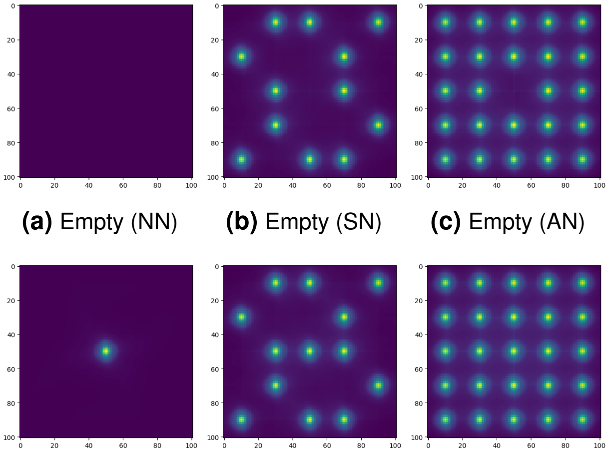
Bound depends on brightness and, therefore, occupancy

Solution:

⇒ Split into occupancy cases

⇒ Construct expected photon distributions

⇒ Calculate corresponding variances



(a) Empty (NN) **(b)** Empty (SN) **(c)** Empty (AN)

(d) Occupied (NN) **(e)** Occupied (SN) **(f)** Occupied (AN)

Cramér-Rao Bound

Calculation

Vector of each site's brightness: $\gamma \in \mathbb{R}^n$
Pixel likelihood function: $p(q, x, \gamma)$ for pixel x and value q

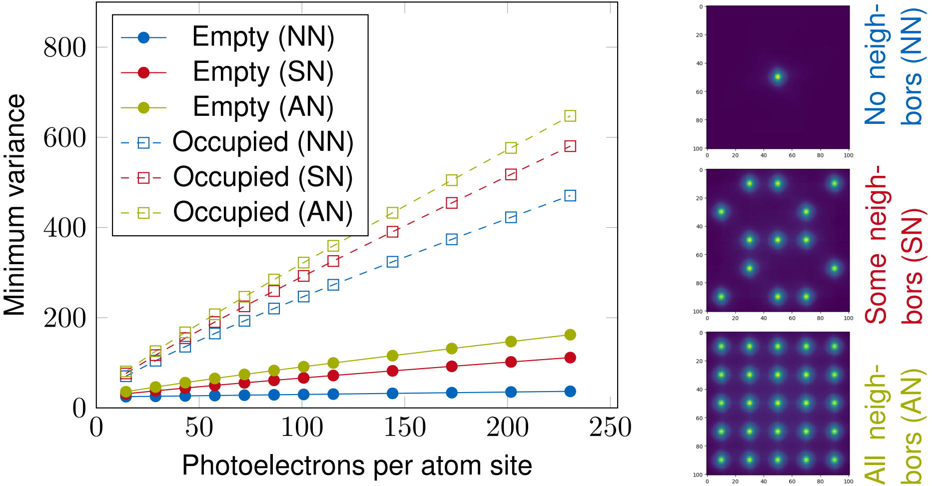
Integrate over all m pixels and all possible pixel values q

$$[I(\gamma)]_{i,j} = \sum_{x=0}^{m} \int_{\mathbb{R}} \frac{\frac{\partial}{\partial \gamma_i} p(q, x, \gamma) \cdot \frac{\partial}{\partial \gamma_j} p(q, x, \gamma)}{p(q, x, \gamma)} dq \tag{1}$$

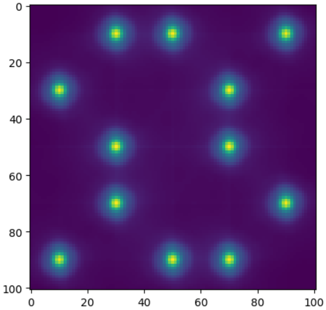
Any predictor T_i of atom site i's brightness must adhere to

$$var(T_i) \geq [I(\gamma)^{-1}]_{i,i} \tag{2}$$

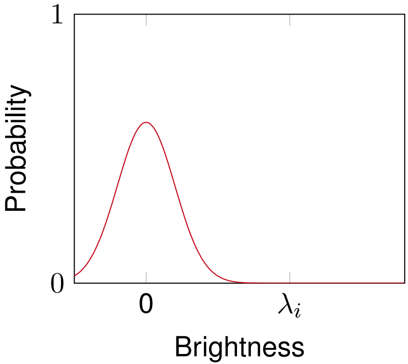
Cramér-Rao Bound
Results



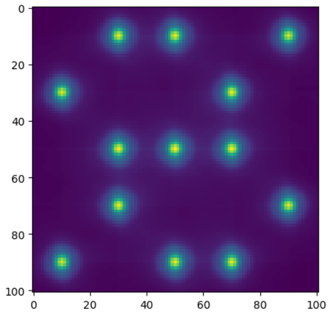
Cramér-Rao Bound
Results



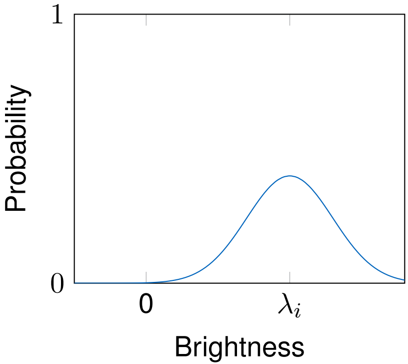
- Brightness of empty site: 0
- Minimal variance given by bound



Cramér-Rao Bound
Results



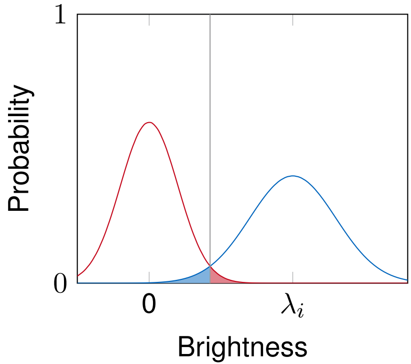
- Brightness of occupied site: λ_i
- Minimal variance given by bound



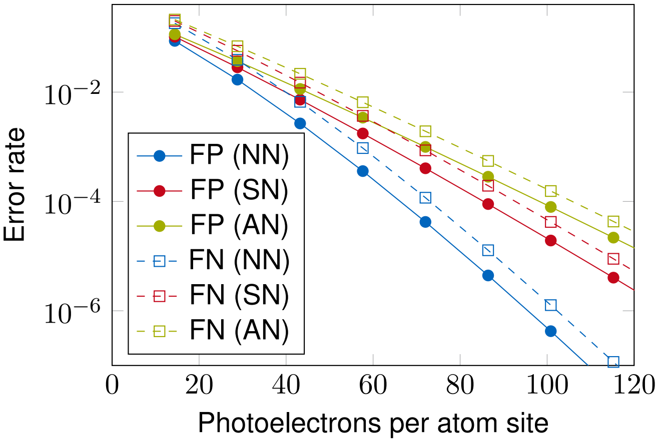
Cramér-Rao Bound
Results

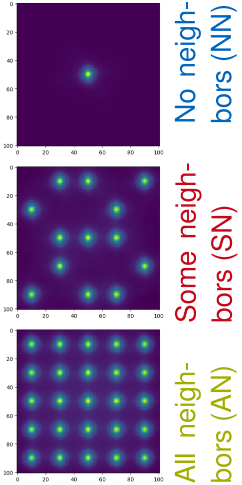
- Threshold at intersection
- Higher variance of occupied lobe leads to higher false negative rates

$\Rightarrow$ Skew towards measurements where most sites are not fluorescing?



Cramér-Rao Bound
Results

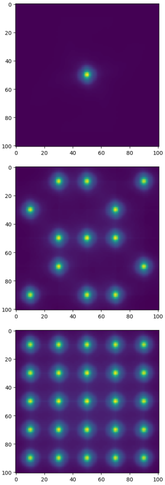




Outline

Detection Methods

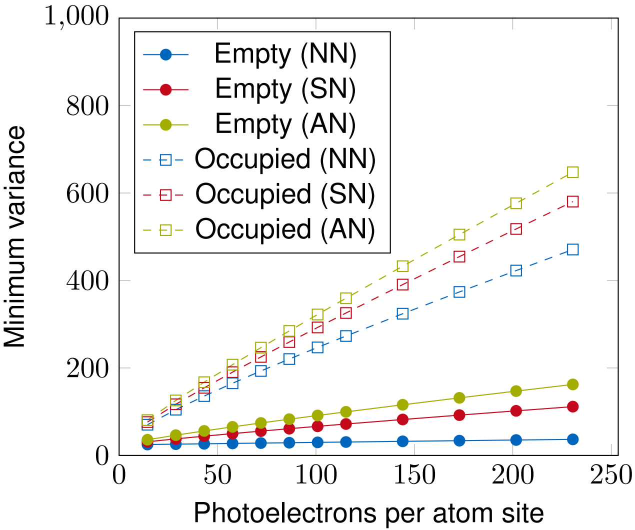
Visualization



No neighbors (NN)

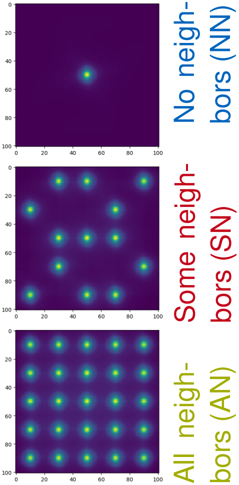
Some neighbors (SN)

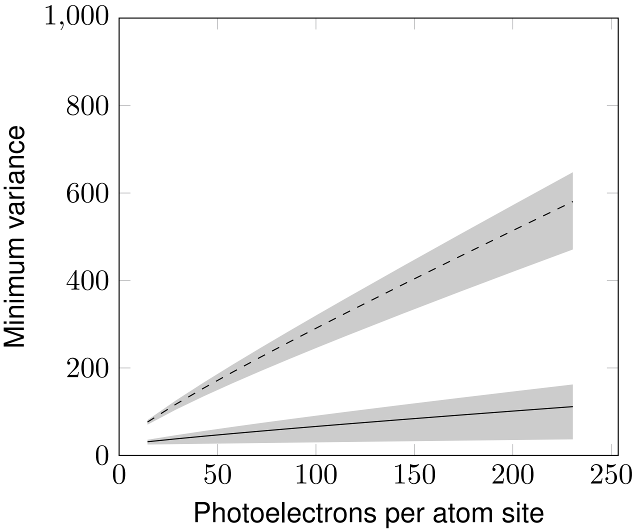
All neighbors (AN)



Detection Methods

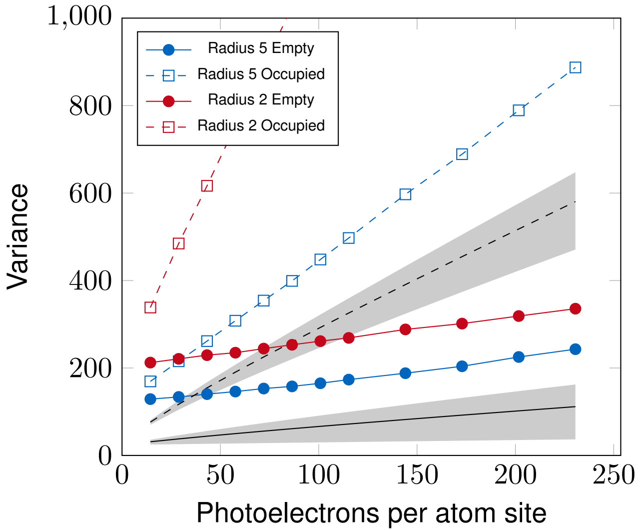
Visualization





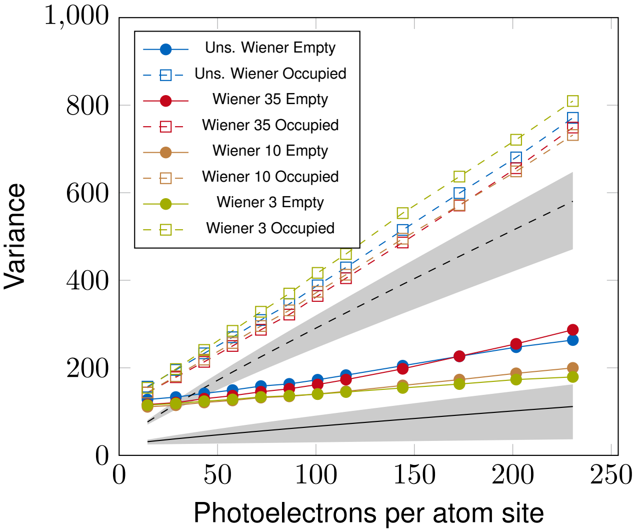
Detection Methods
ROI Integration

- Easiest and fastest
- Not very precise
- Wrong distance even worse



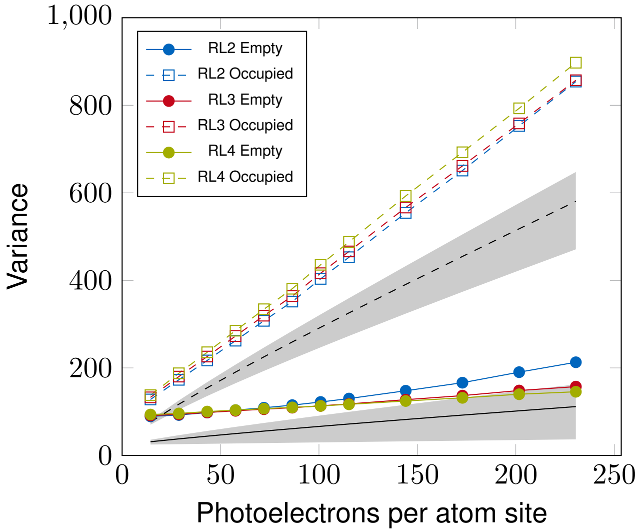
Detection Methods
Wiener

- Classic image processing tool
- Deconvolution in frequency domain with tunable balance factor
- Best balance parameter not universally the same



Detection Methods
Richardson-Lucy

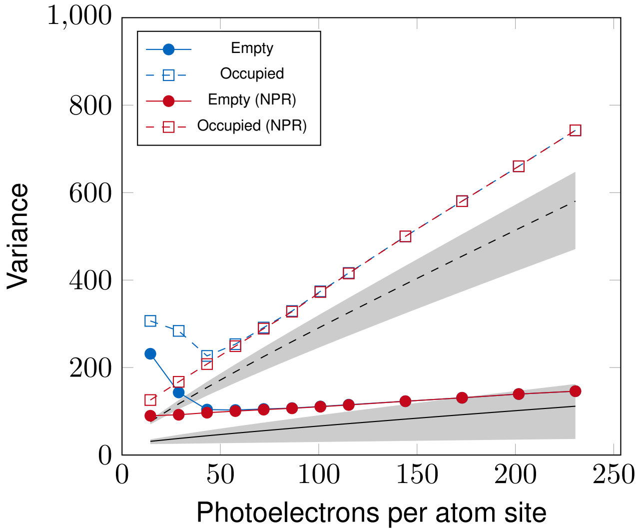
- Classic image processing tool
- Performs similar to Wiener
- Iterative algorithm



Detection Methods

Projection-Based Deconvolution

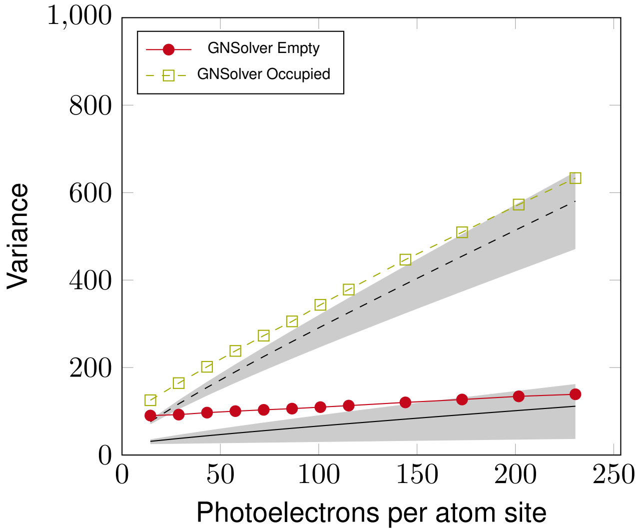
- Based on David Wei's state_reconstruction [github.com/david-wei/state_reconstruction]
- Originally for lattices
- Phase reconstruction not necessary here (NPR = No phase reconstruction)



Detection Methods

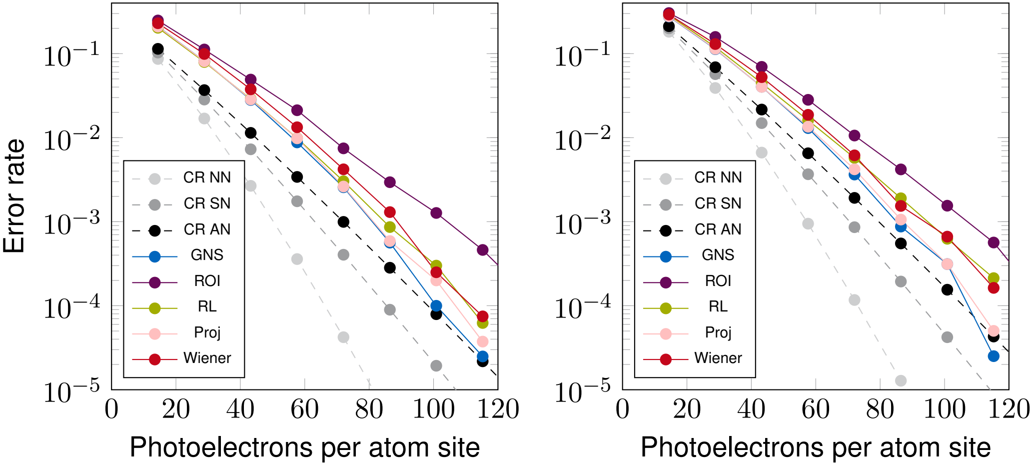
Non-Linear Least-Squares Solver

- Weighted global Gauss-Newton solver
- Produces global offset and brightness at each site from PSF, image, and image model function
- Very compute intensive
- Could deal with different PSFs for each site



Outline

Comparison



(a) False positive rates

(b) False negative rates

Comparison
Run time

Number of pixels per image m
Number of pixels in the PSF q
Number of atom sites n

Algorithm	Average run time	Run-time class
ROI Integration	$\approx 10ms$	$\mathcal{O}(n)$
Wiener unsupervised	$\approx 1.3s$	
Wiener	$\approx 40ms$	$\mathcal{O}(m \cdot log(m))$
Richardson-Lucy	$\approx 70ms$ per iteration	$\mathcal{O}(m \cdot q \cdot \#iter)$
Projection-Based	$\approx 60ms$ (opt.)	
Gauss-Newton solver	$\approx 4s$ (opt.)	$\mathcal{O}(n^{\frac{3}{2}} + n \cdot q^2)$

Outline

Conclusion

Problem:

- How to spend minimal time on atom detection?
- How to extract most information from given image?

⇒ ROI integration fast but imprecise

⇒ Gauss-Newton solver computationally complex

⇒ Projection-based solution conceptually complex

⇒ Classic image processing techniques in between

⇒ Best methods are not so far from theoretical bound

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Buffer

Lattice

- Cramér-Rao bound not trivial to calculate
- ROI Integration not viable