Sloppy and Genetic Algorithms for Low-Emittance Tuning at CESR

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Acknowledgements: David Rubin, Jim Sethna
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Cornell University

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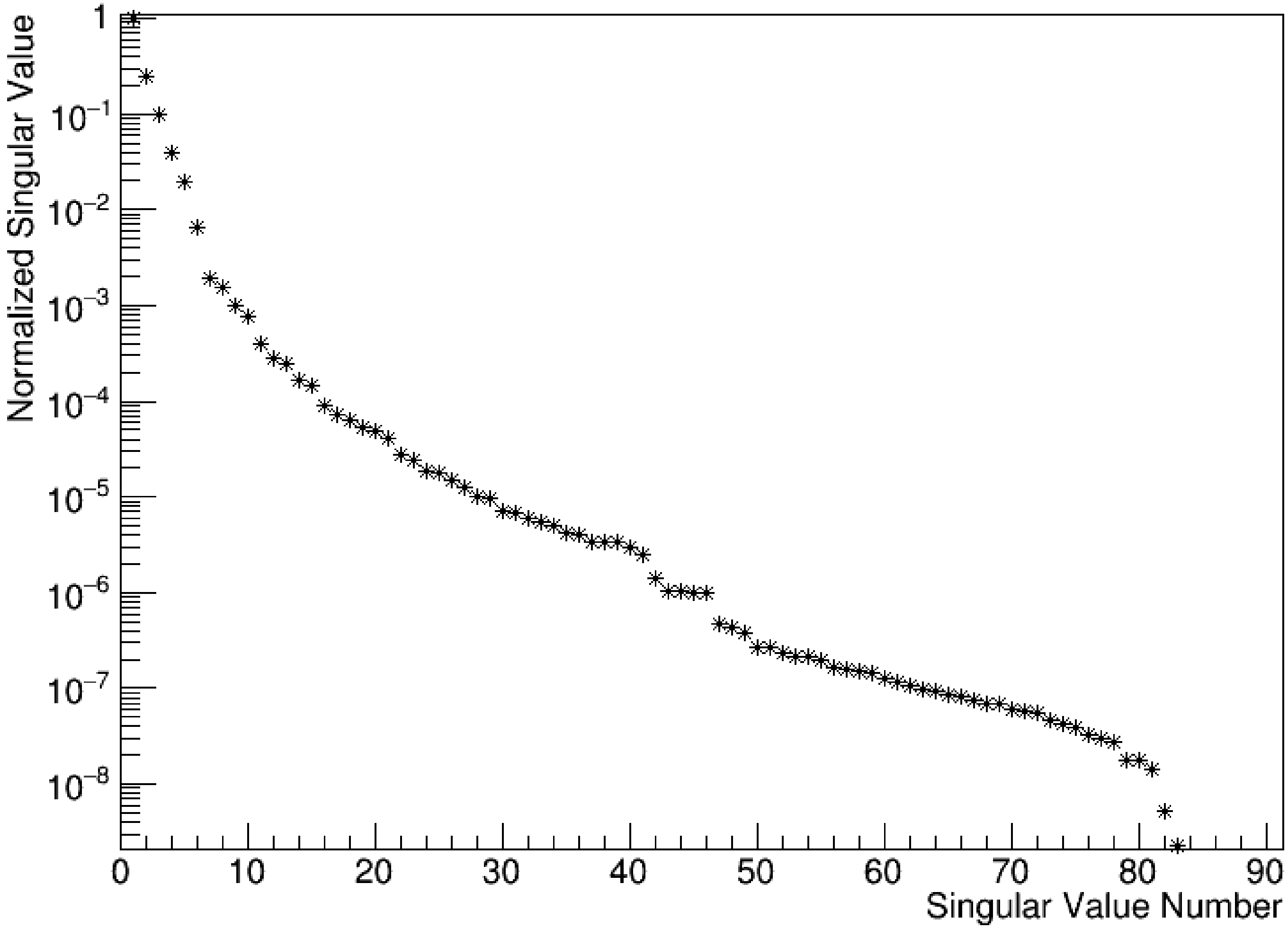
CESR

Sloppy Models
Problem Statement

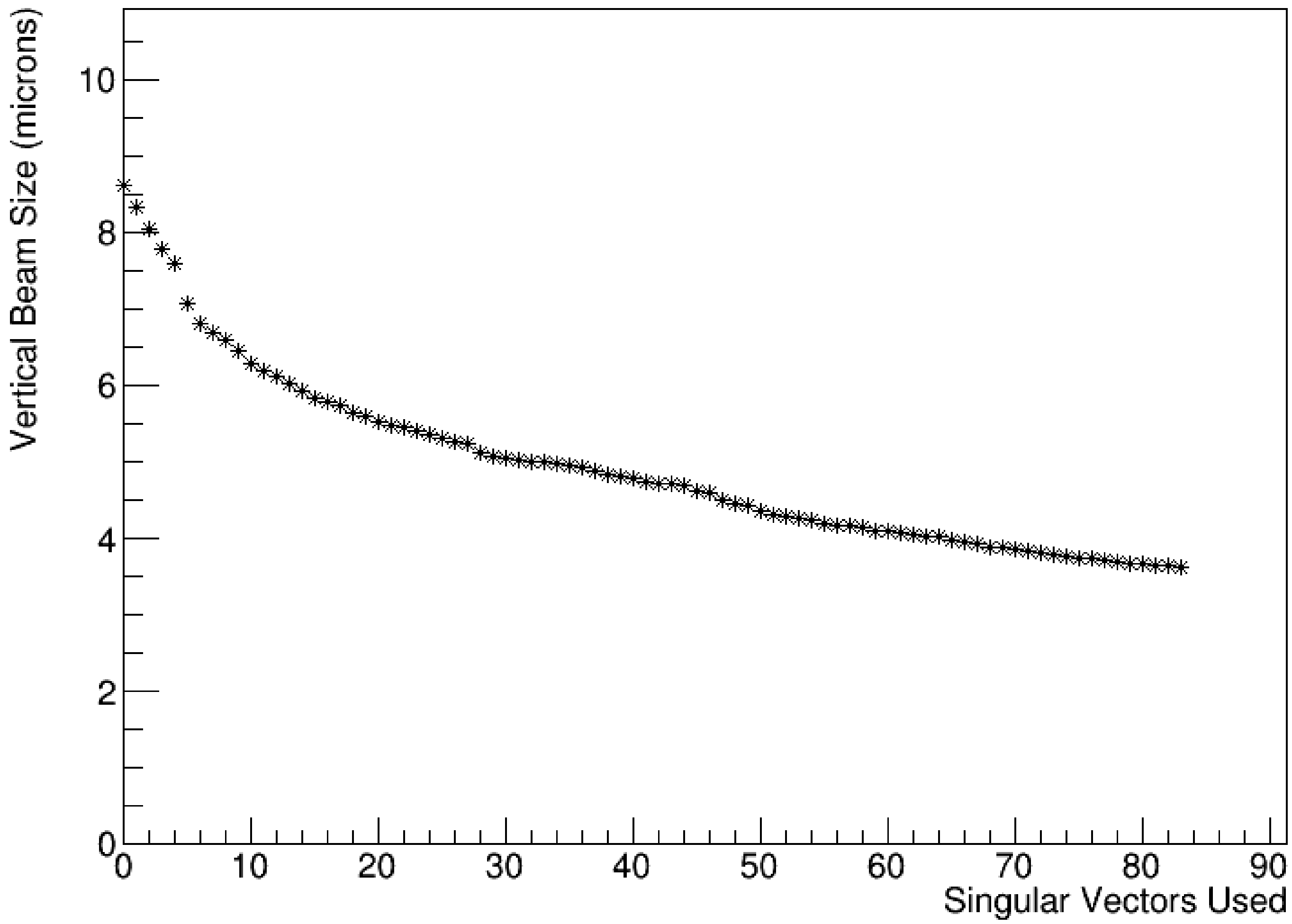
- Minimize one objective (vertical emittance/beam size)
- Large number of decision variables (independent magnets)
- No reliable auxiliary information (dispersion, coupling)
- Reliable model of machine responses (BMAD simulation)

Sloppy Models



Phys. Rev. E 68 (2003) 021904.

Simulated Results



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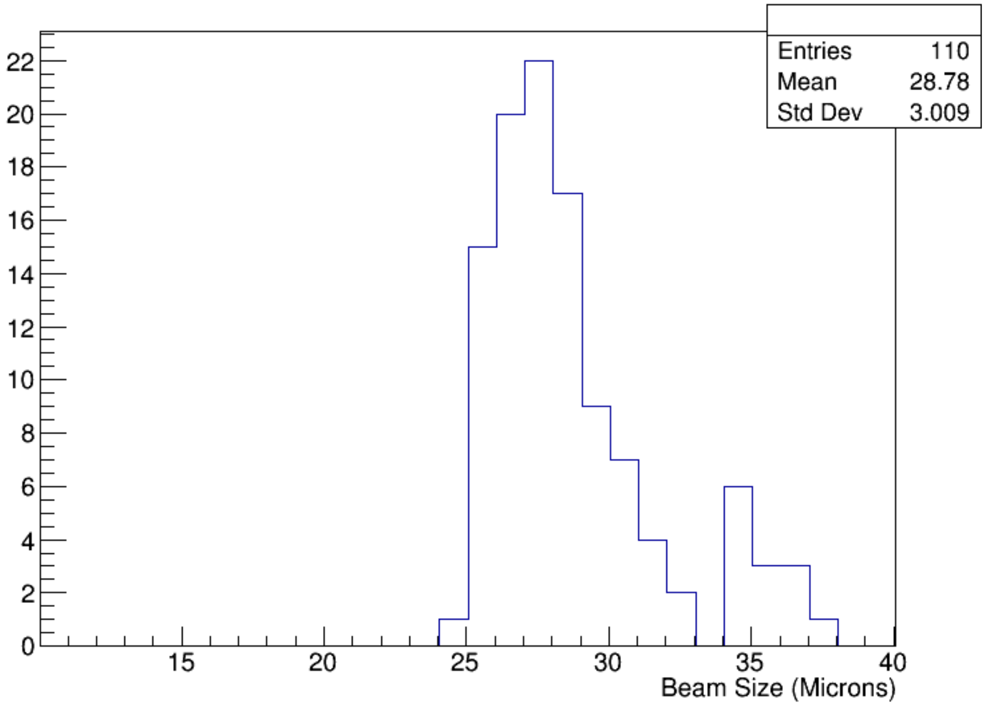
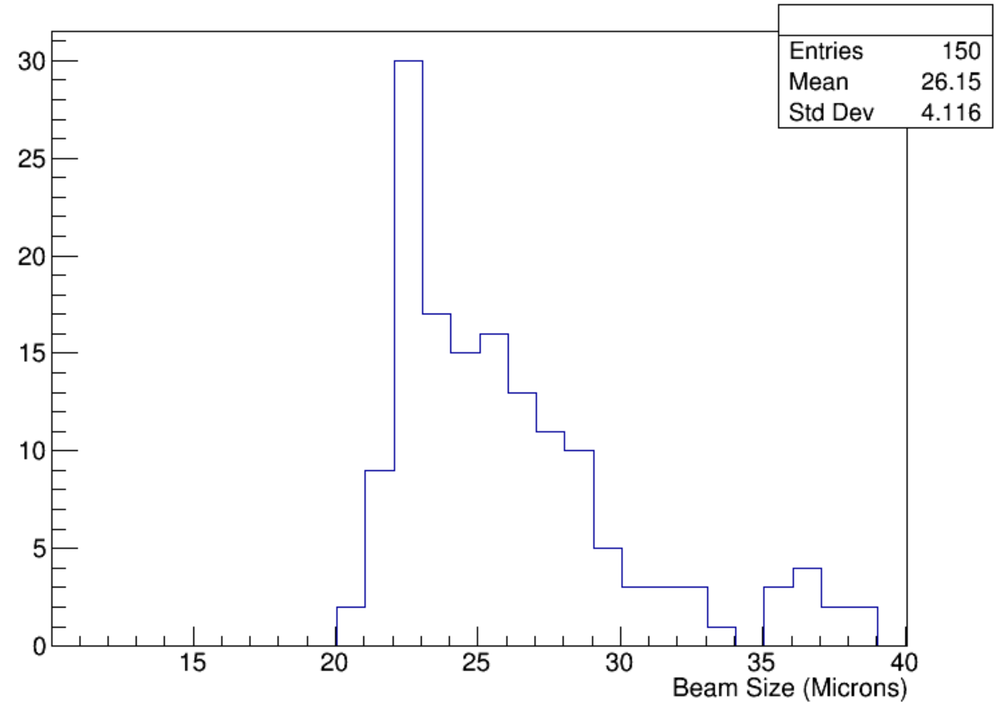
Experimental Results





RCDS - Nucl. Instr. Meth. 726 (2013) 77.

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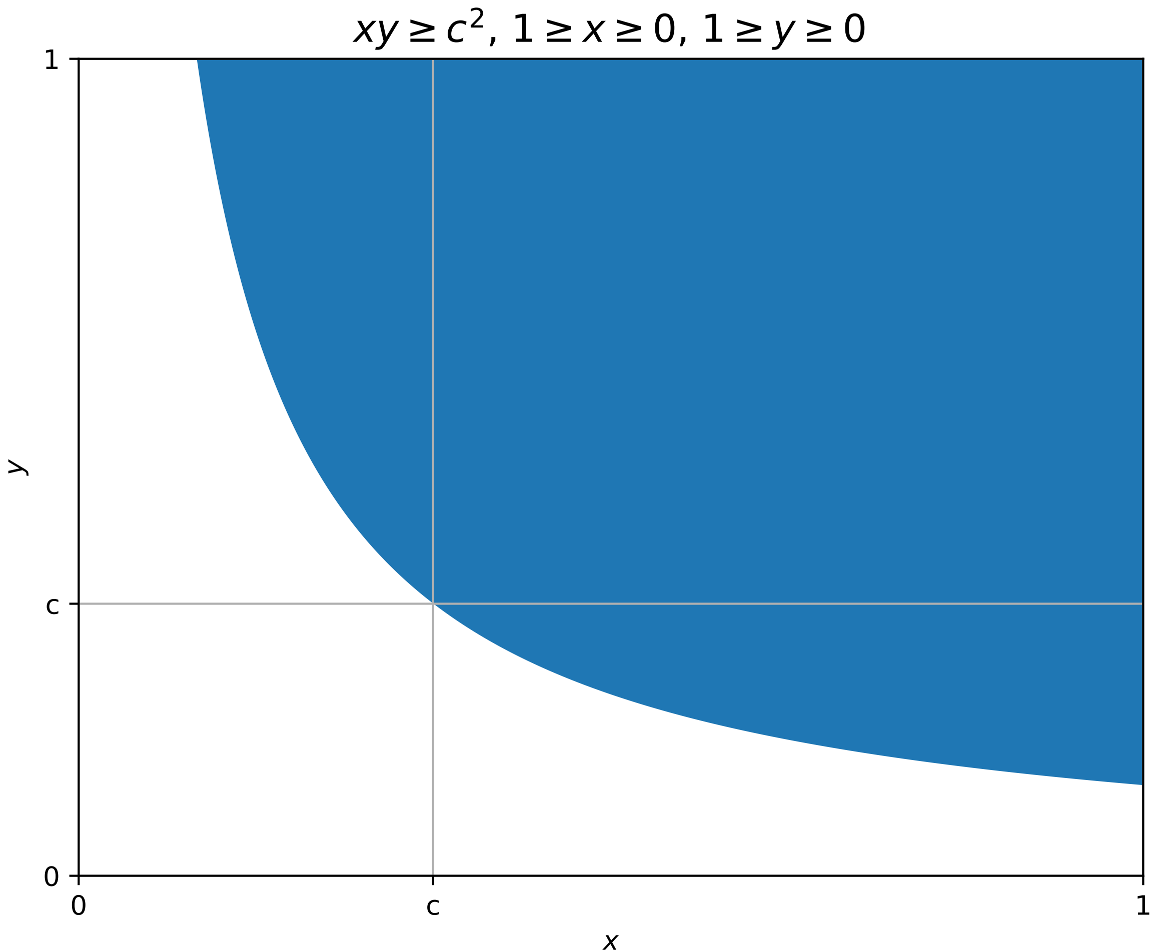
Conclusions

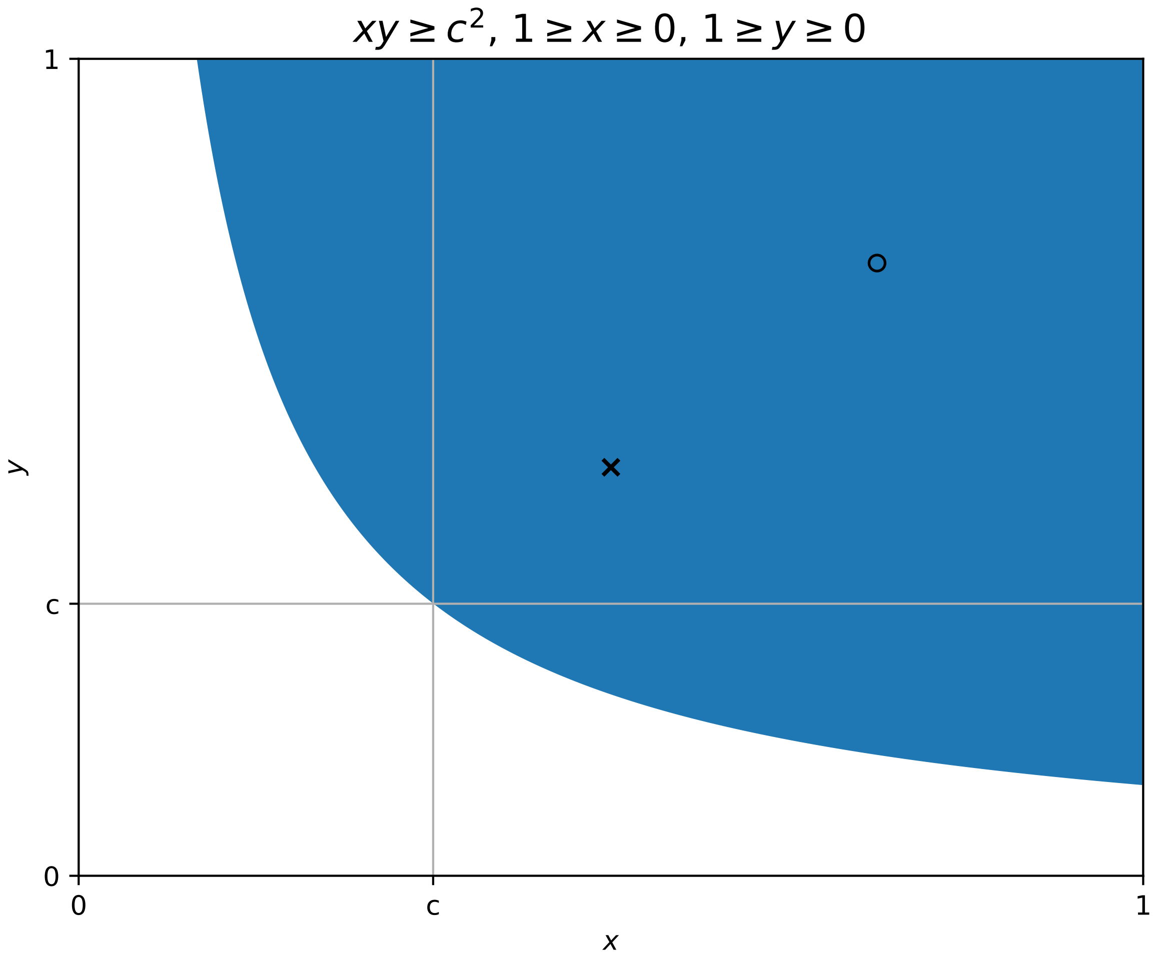
- Knobs provide some improvements
- Still far from quantum limit
- Something missing from models?

Multi-Objective Genetic Algorithm Problem Statement

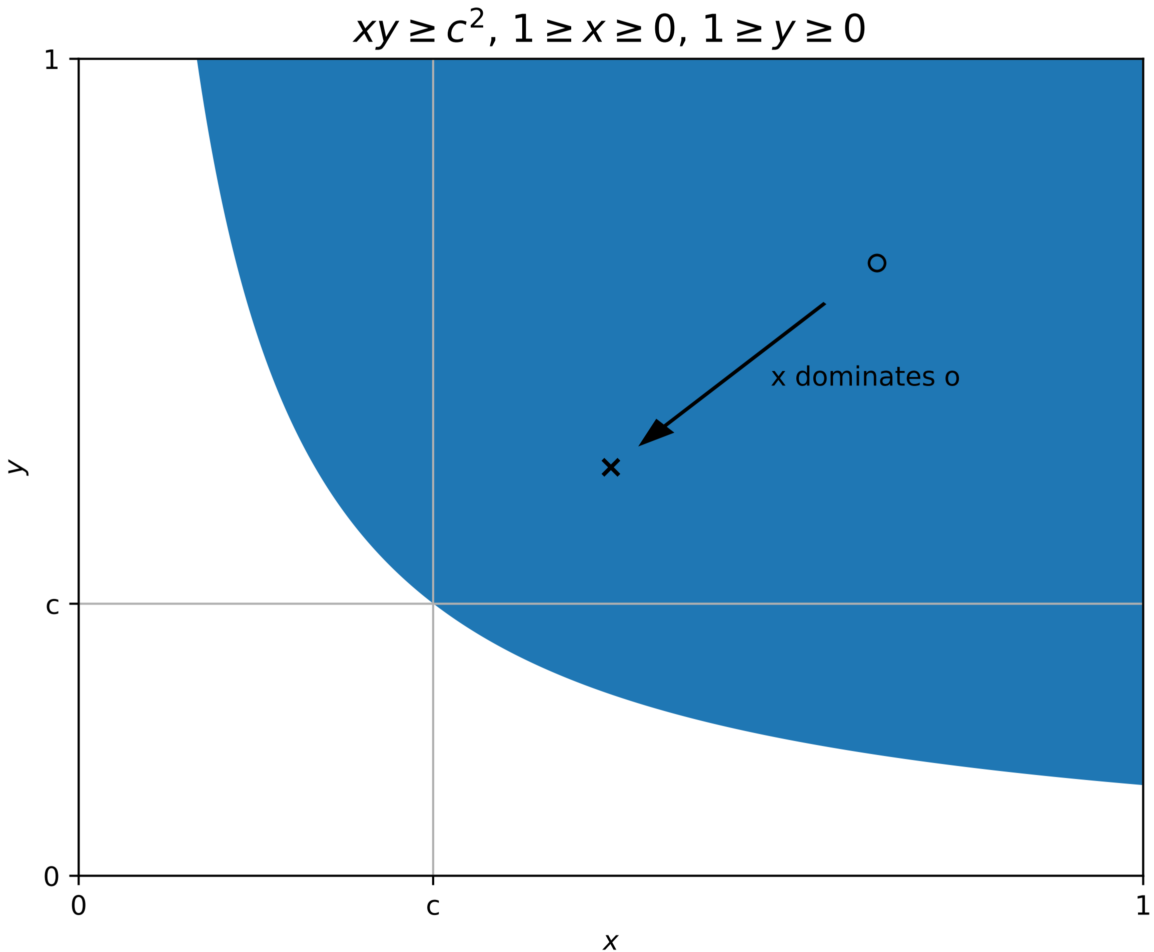
- What if:
  - Competing criteria of optimal machine performance
  - In regime where model of machine responses is unreliable
- Needed: a model-agnostic search for optimal performance *trade-offs*



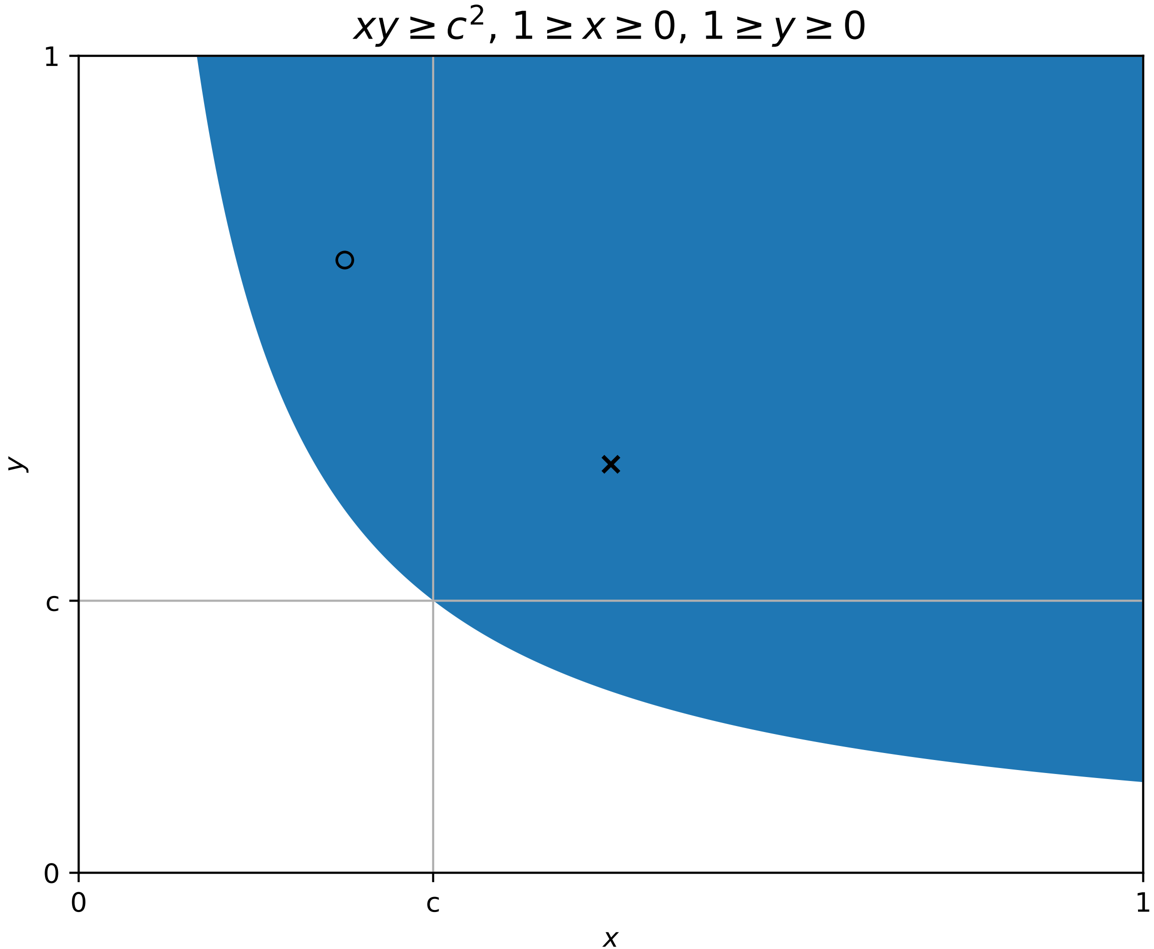
$xy \geq c^2$, $1 \geq x \geq 0$, $1 \geq y \geq 0$
1
c
0
0
c
1
x
y

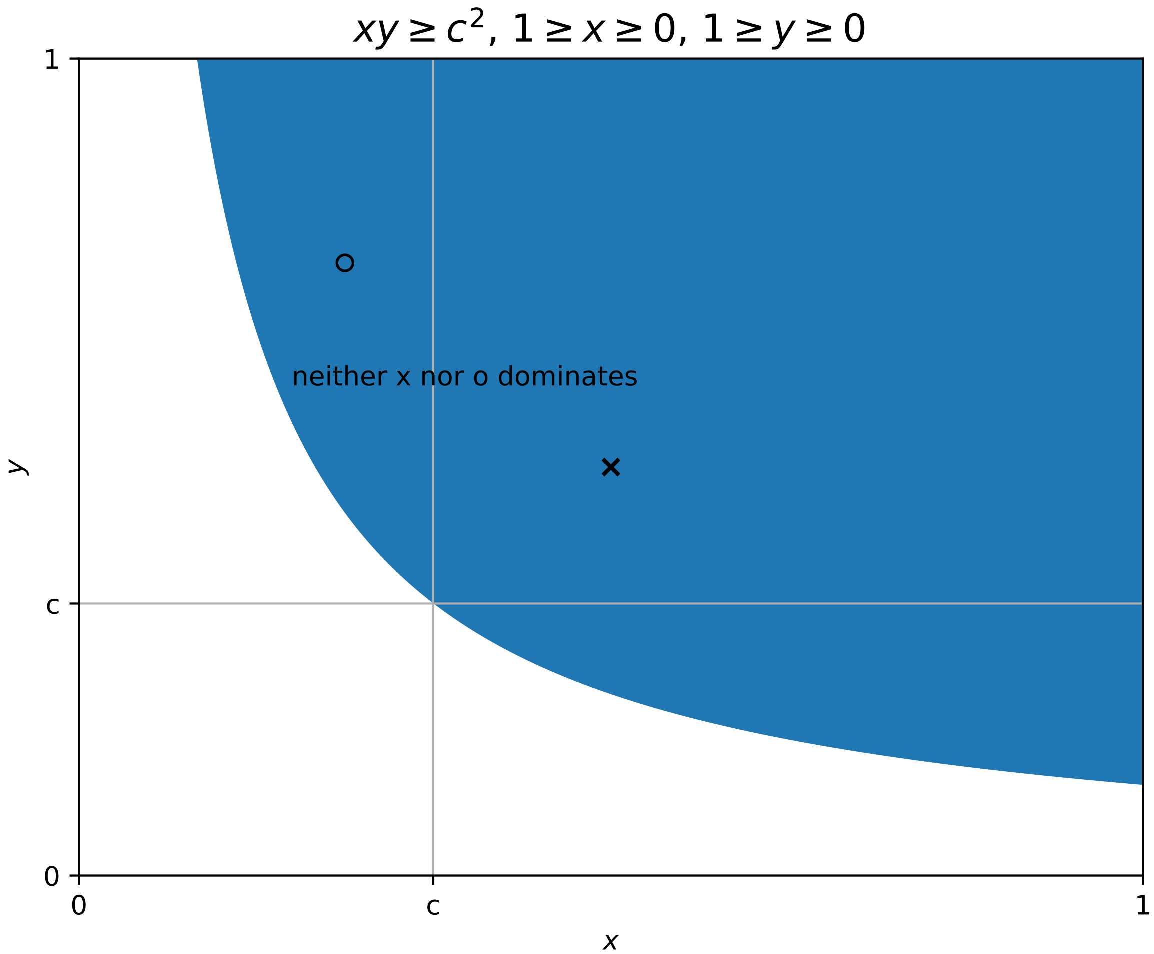


$xy \geq c^2$, $1 \geq x \geq 0$, $1 \geq y \geq 0$
1
c
0
0
c
1
x
y

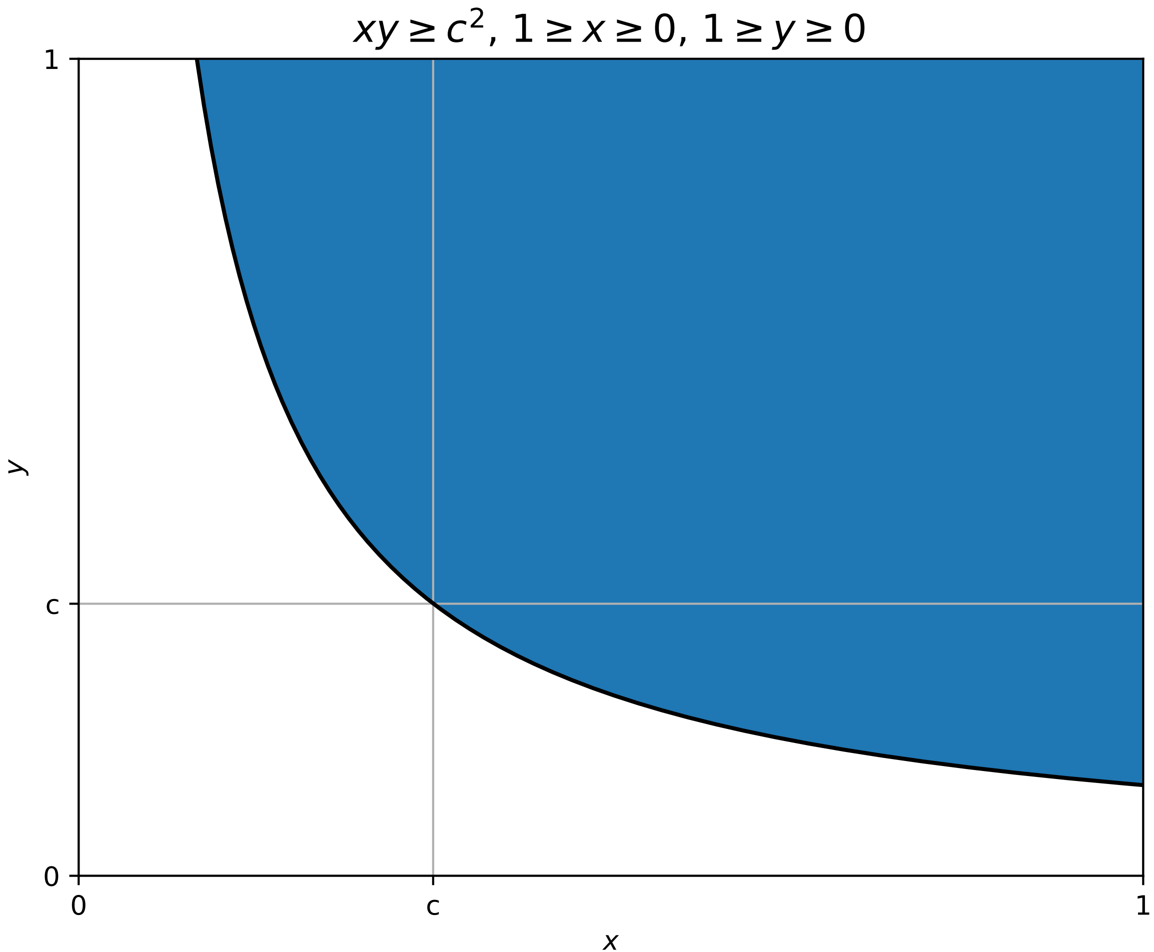


$xy \geq c^2$, $1 \geq x \geq 0$, $1 \geq y \geq 0$
1
c
0
0
c
1
x
y
x dominates o

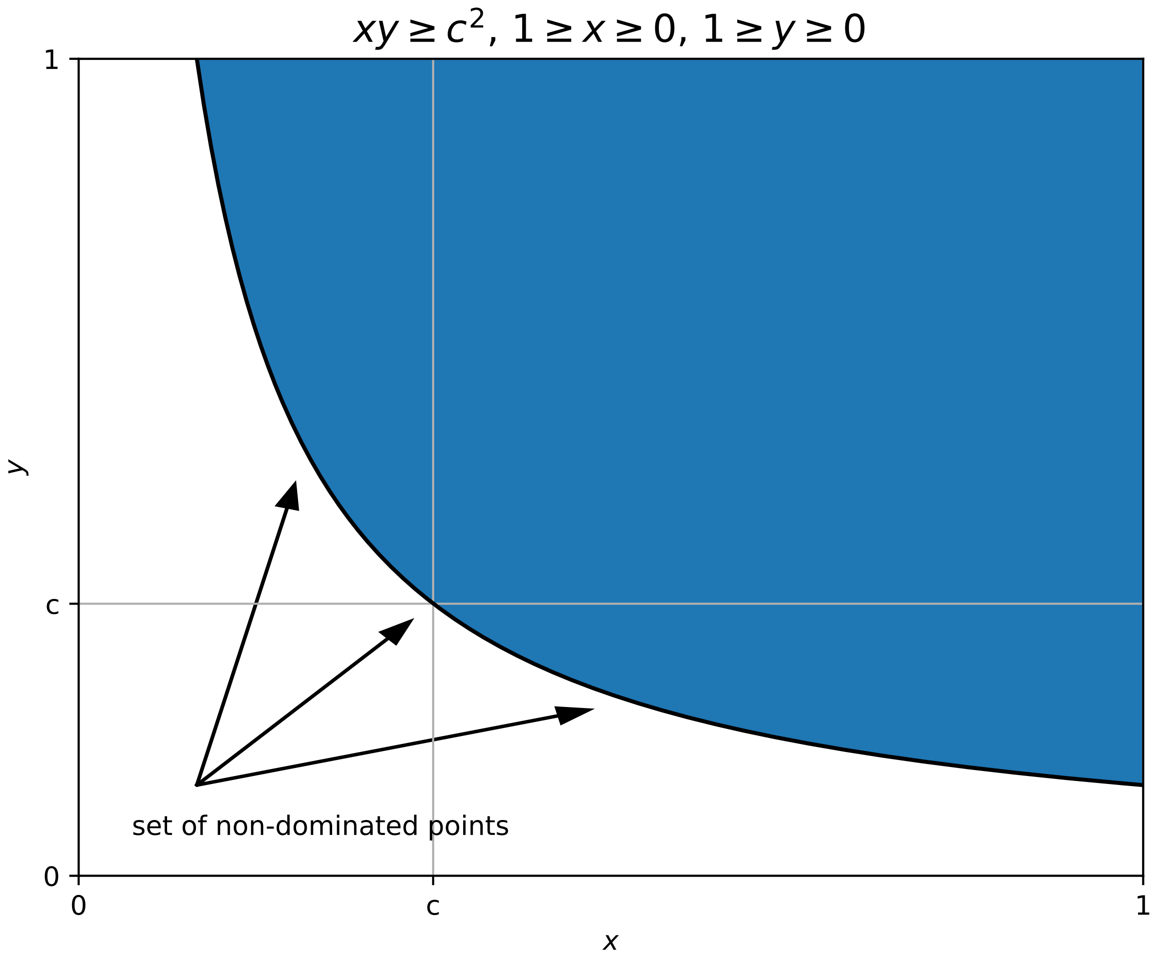

$xy \geq c^2$, $1 \geq x \geq 0$, $1 \geq y \geq 0$
1
c
0
0
c
1
x
y

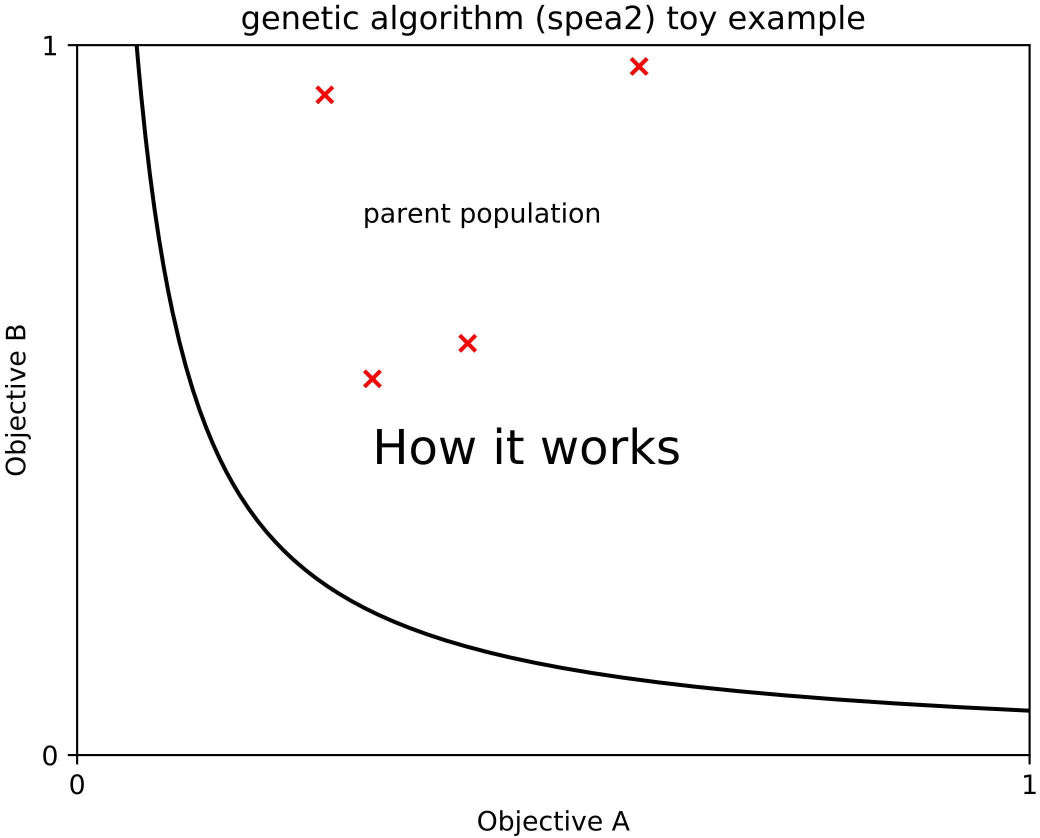


$xy \geq c^2$, $1 \geq x \geq 0$, $1 \geq y \geq 0$
neither x nor o dominates
1
c
0
0
c
1
x
y

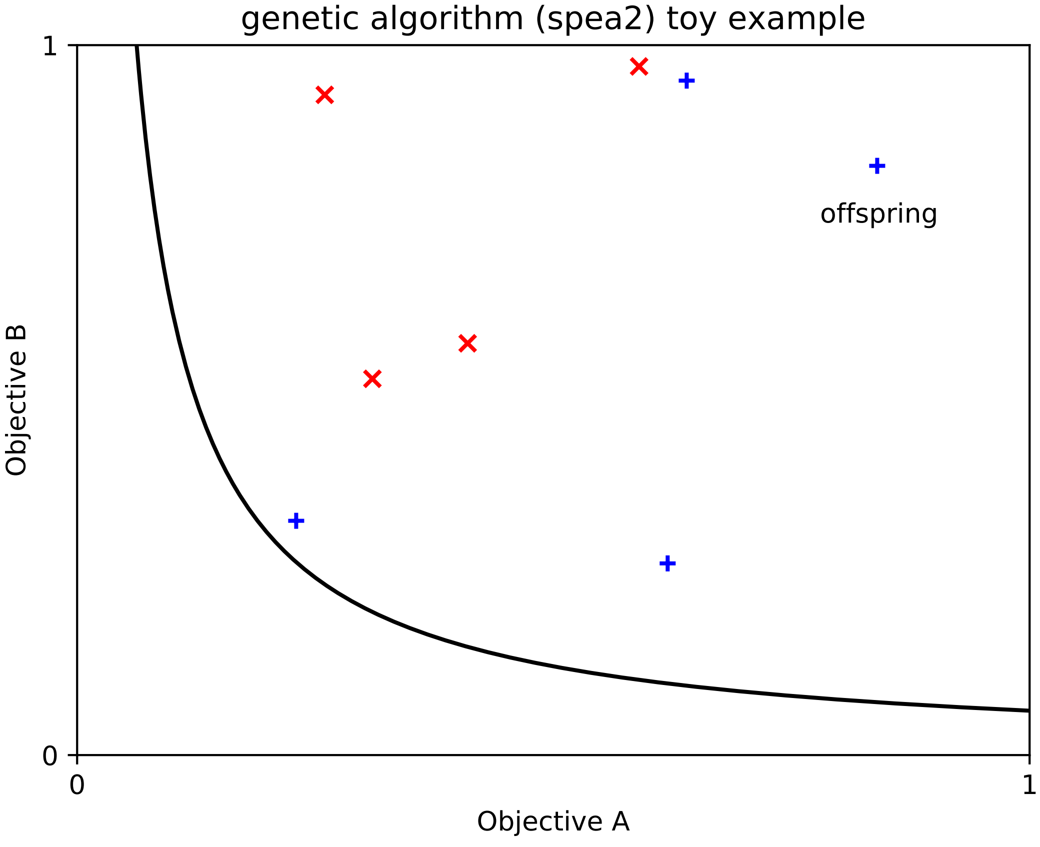


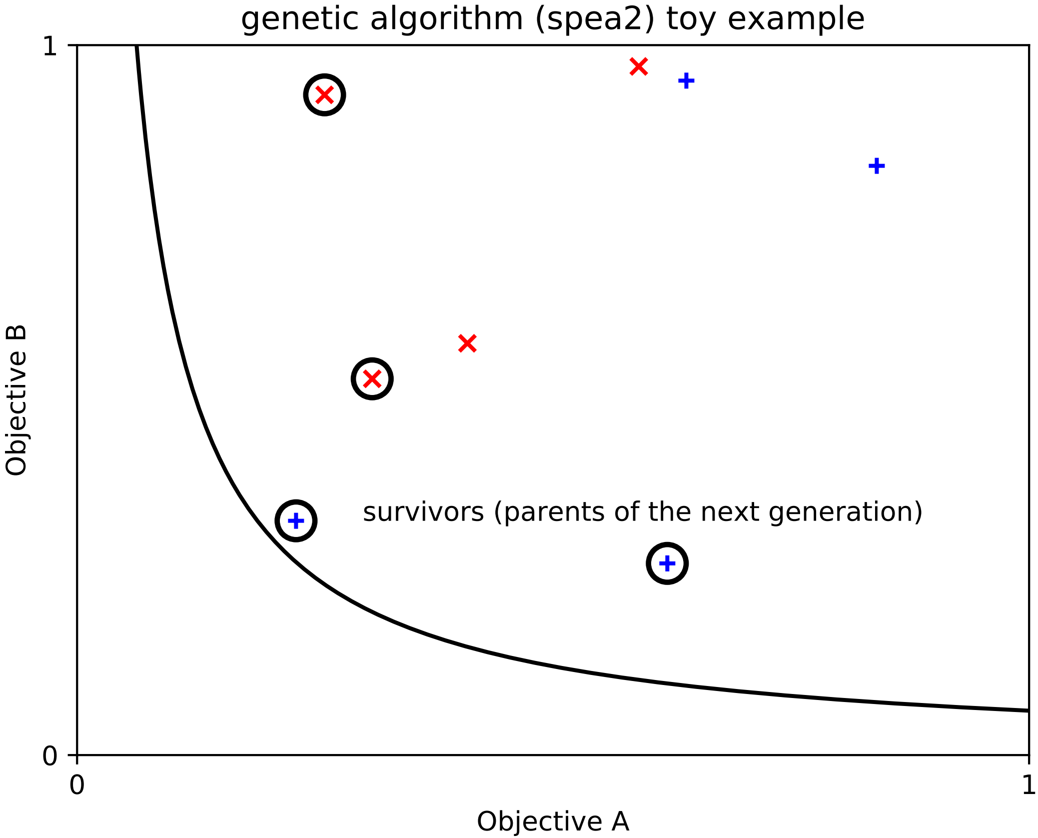
$xy \geq c^2$, $1 \geq x \geq 0$, $1 \geq y \geq 0$
1
c
0
y
0
c
1
x


$xy \geq c^2$, $1 \geq x \geq 0$, $1 \geq y \geq 0$
1
c
0
y
0
c
1
x
set of non-dominated points

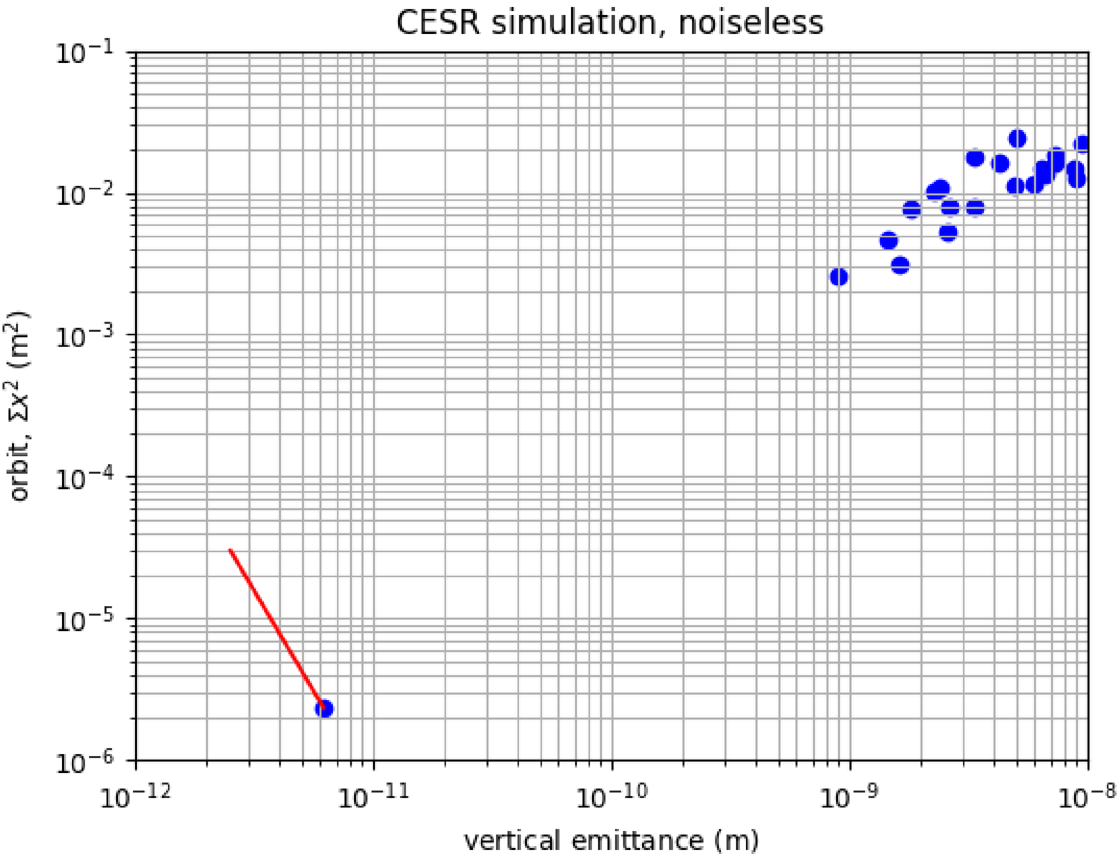


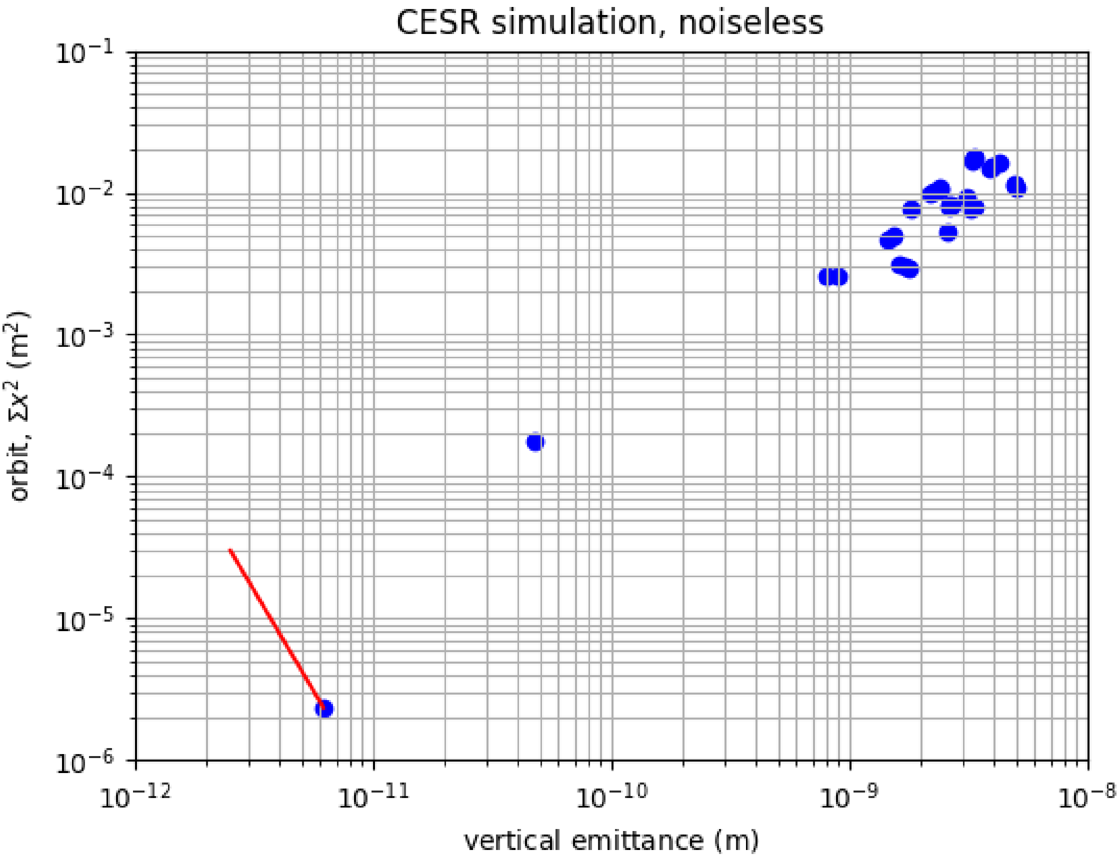
genetic algorithm (spea2) toy example
parent population
How it works
Objective B
Objective A
1
0
0
1


genetic algorithm (spea2) toy example
1
0
0
1
Objective B
Objective A
offspring



genetic algorithm (spea2) toy example
1
0
0
1
Objective B
Objective A
survivors (parents of the next generation)


CESR simulation, noiseless
orbit, Σx^2 (m^2)
vertical emittance (m)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-12}
10^{-11}
10^{-10}
10^{-9}
10^{-8}



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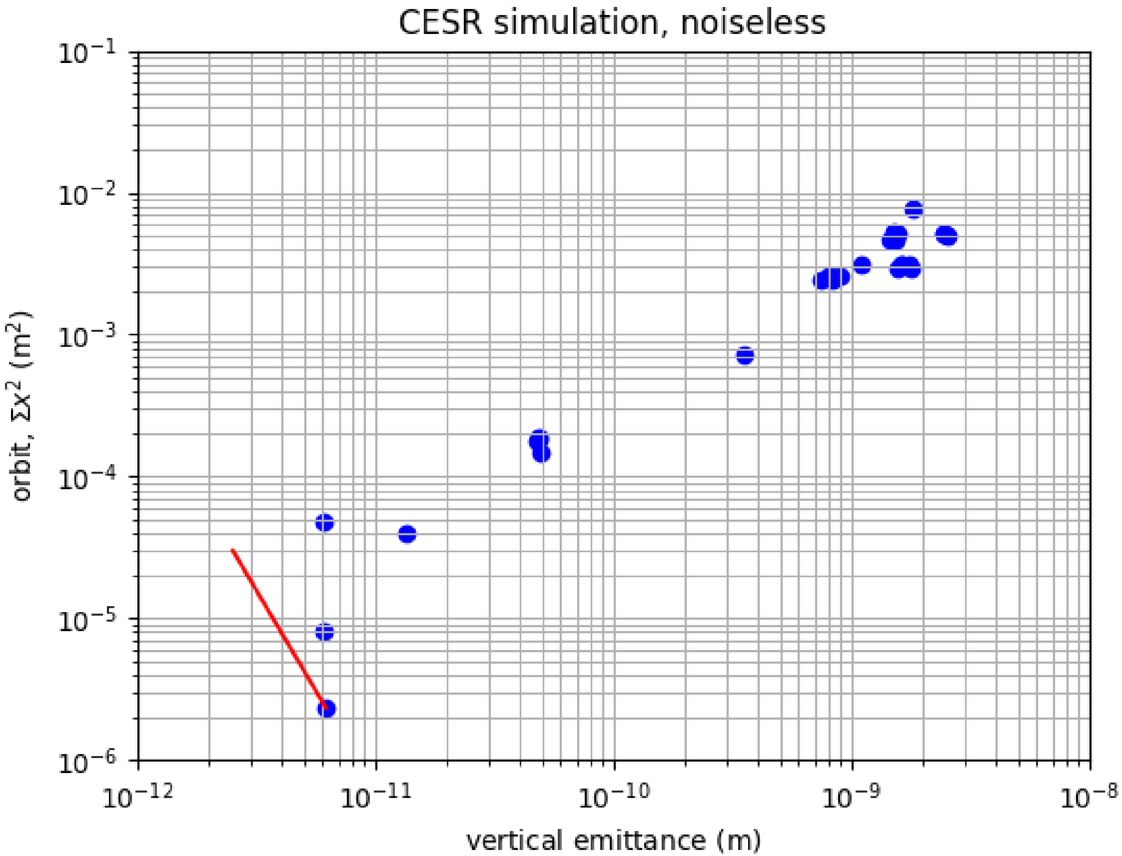

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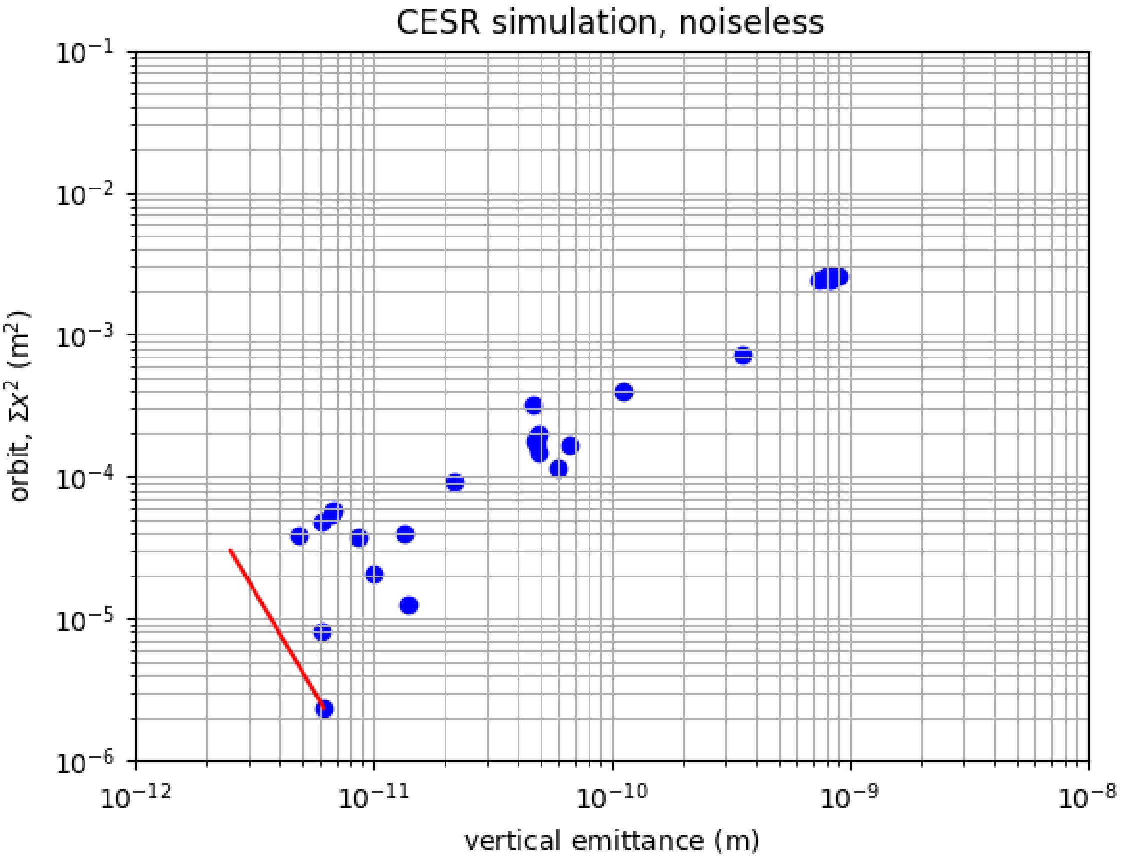

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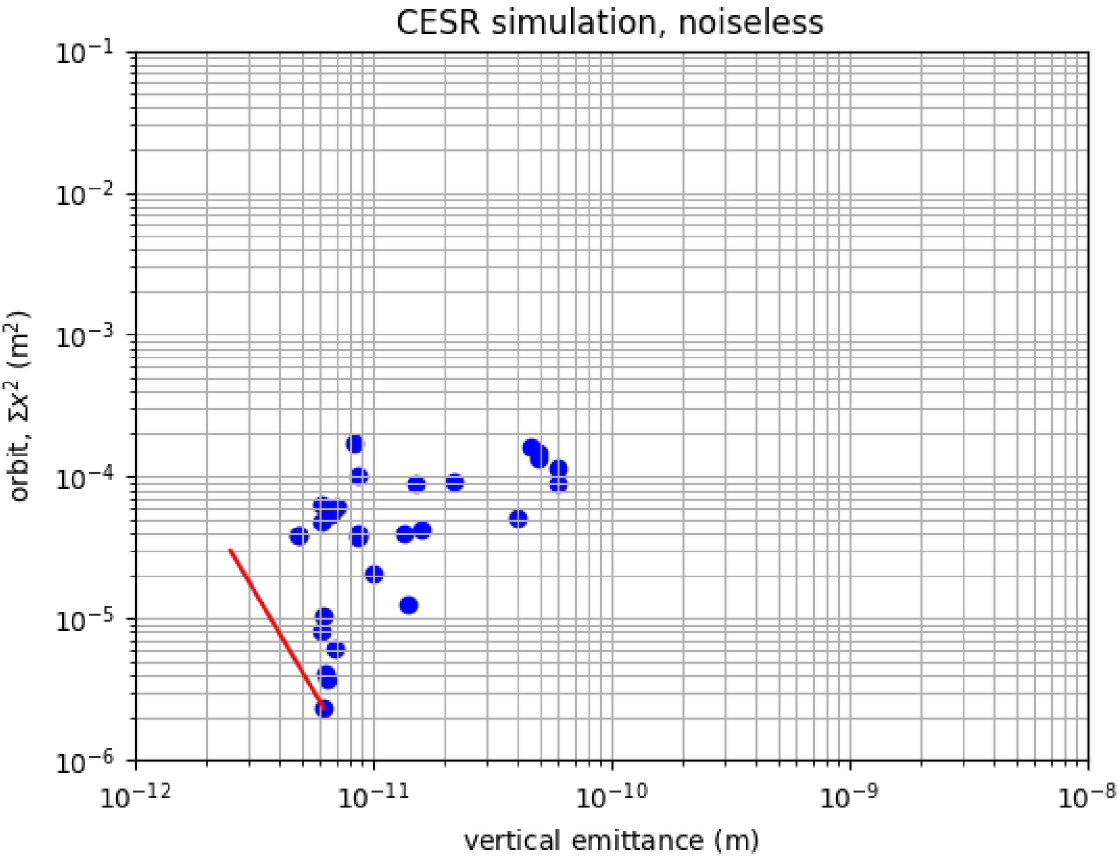
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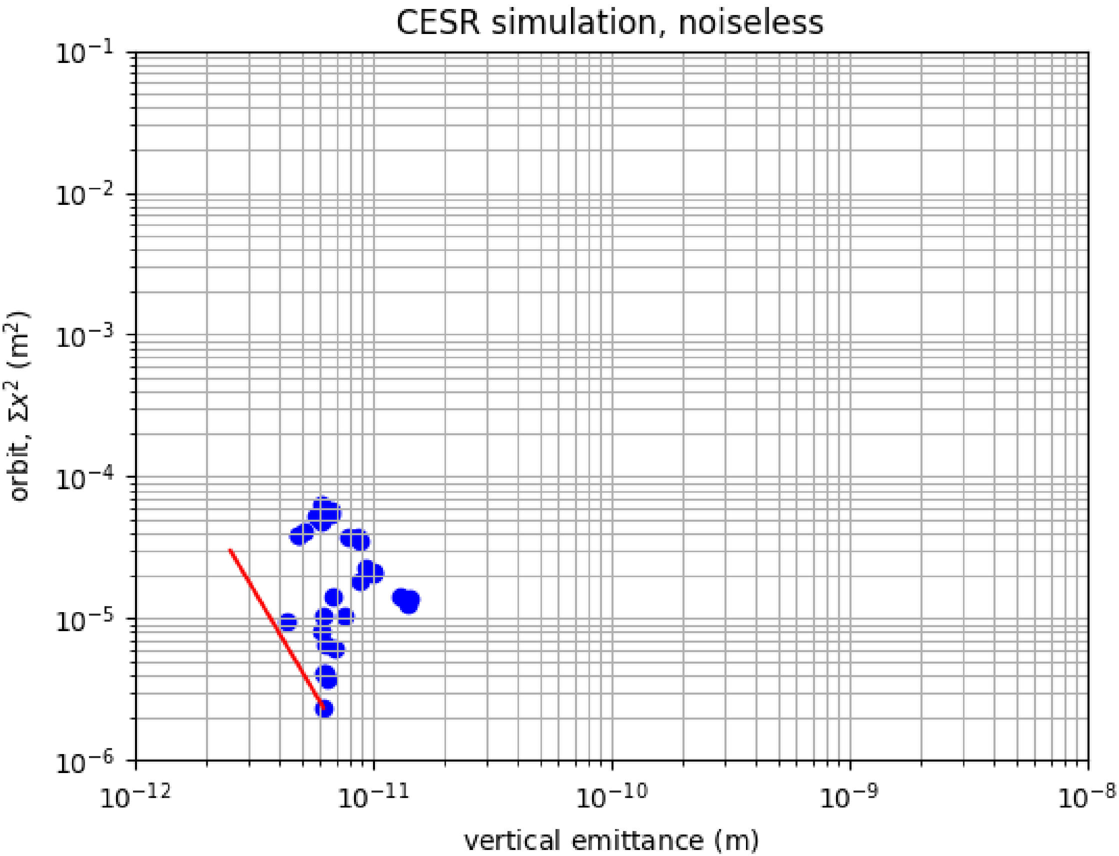

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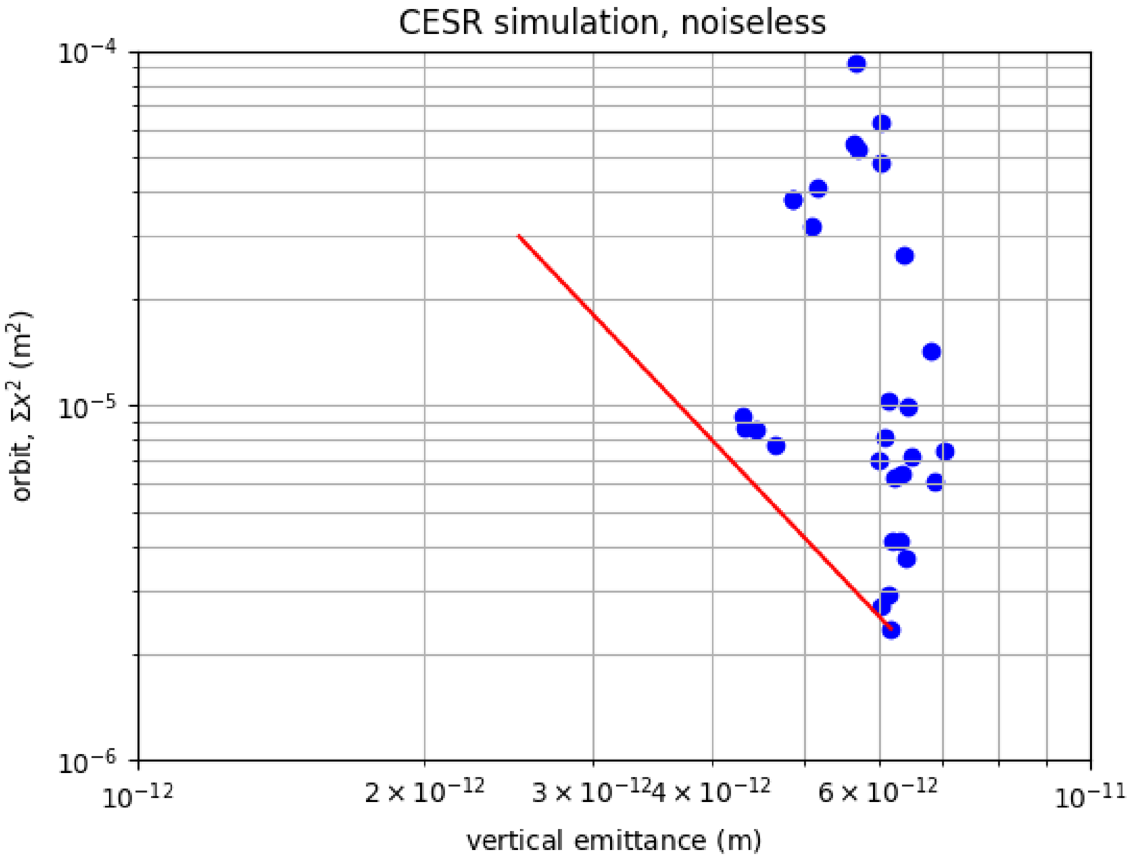

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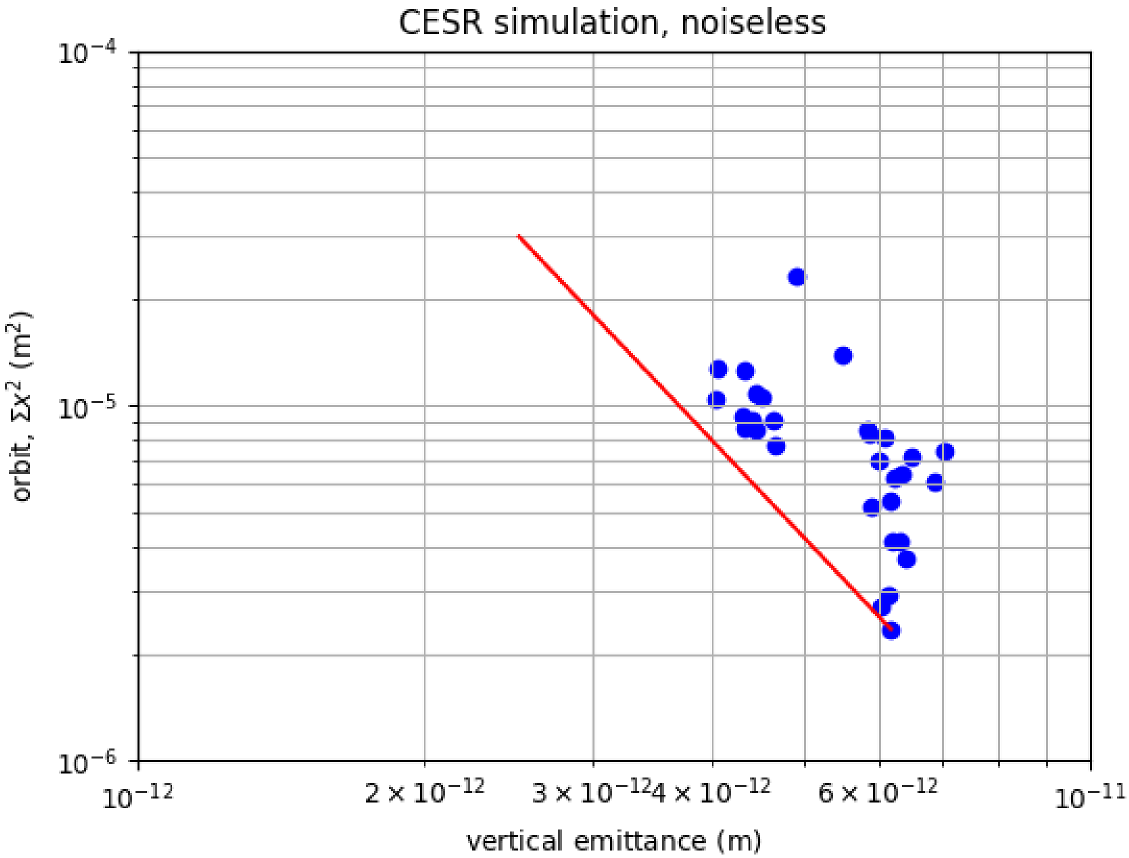
vertical emittance (m)



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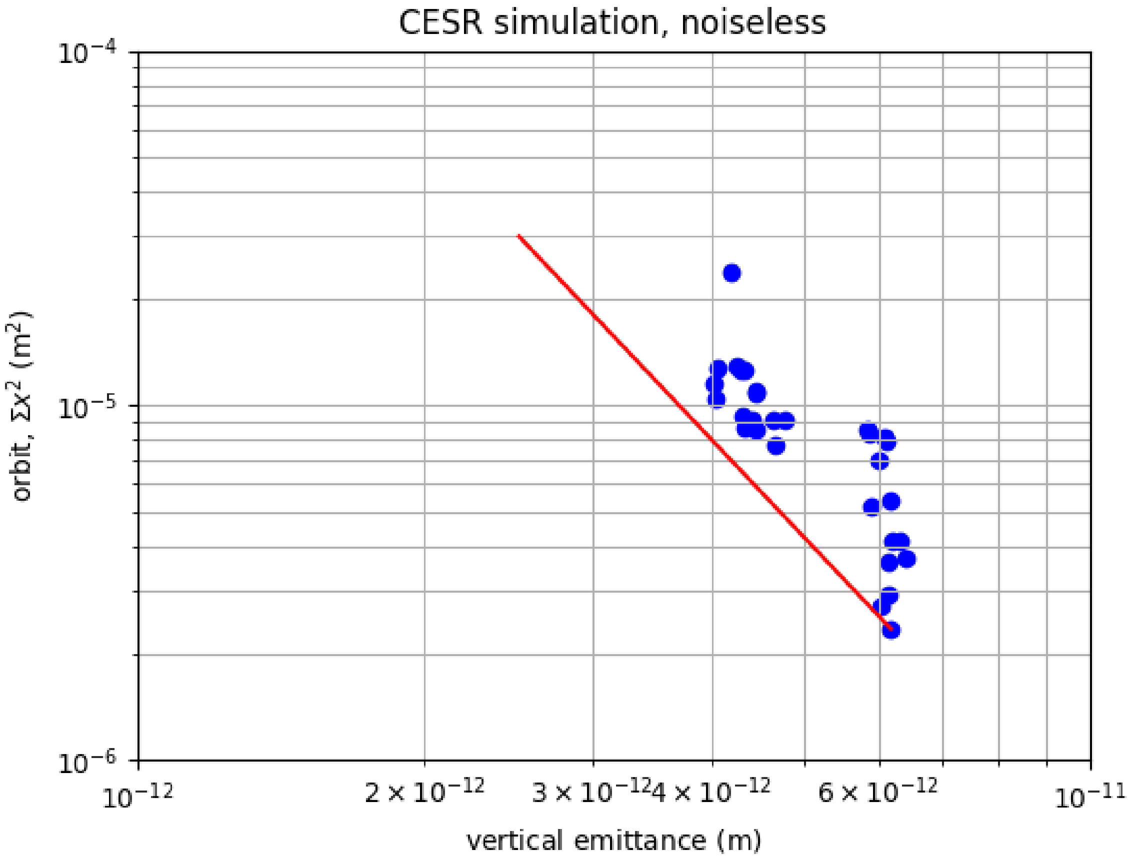

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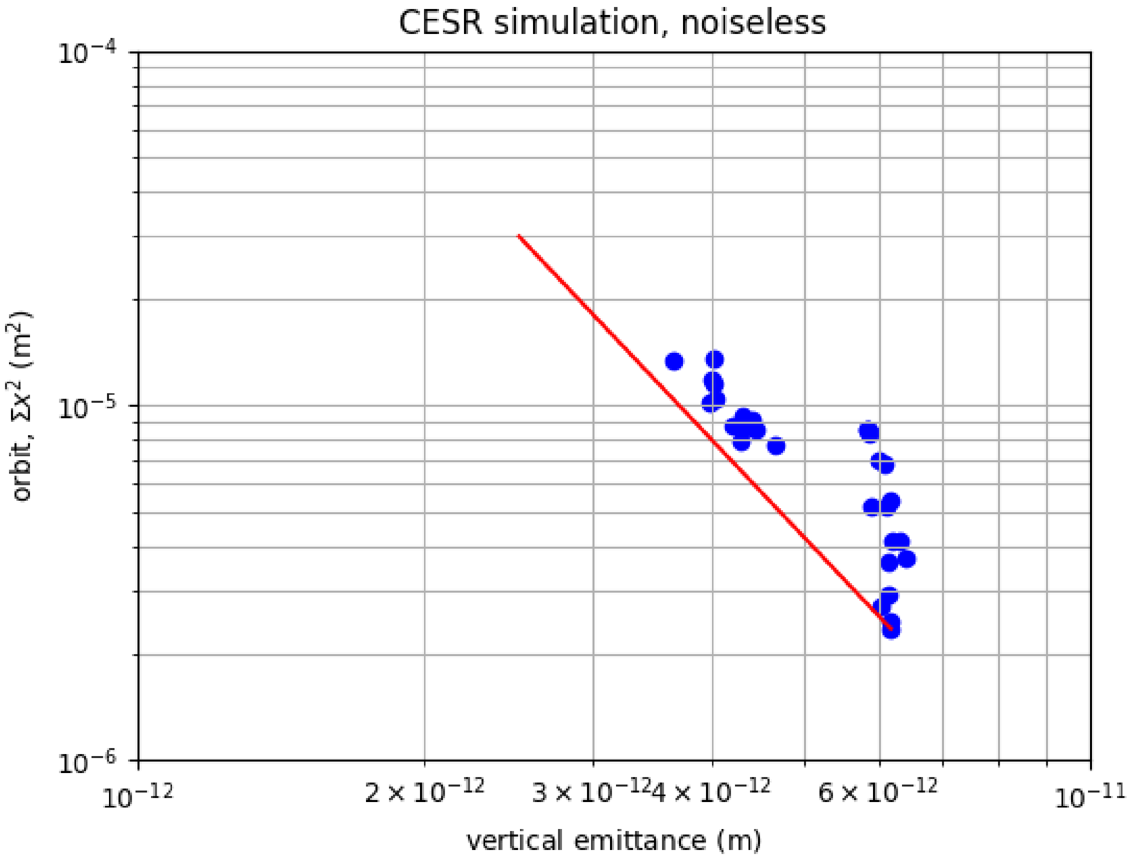

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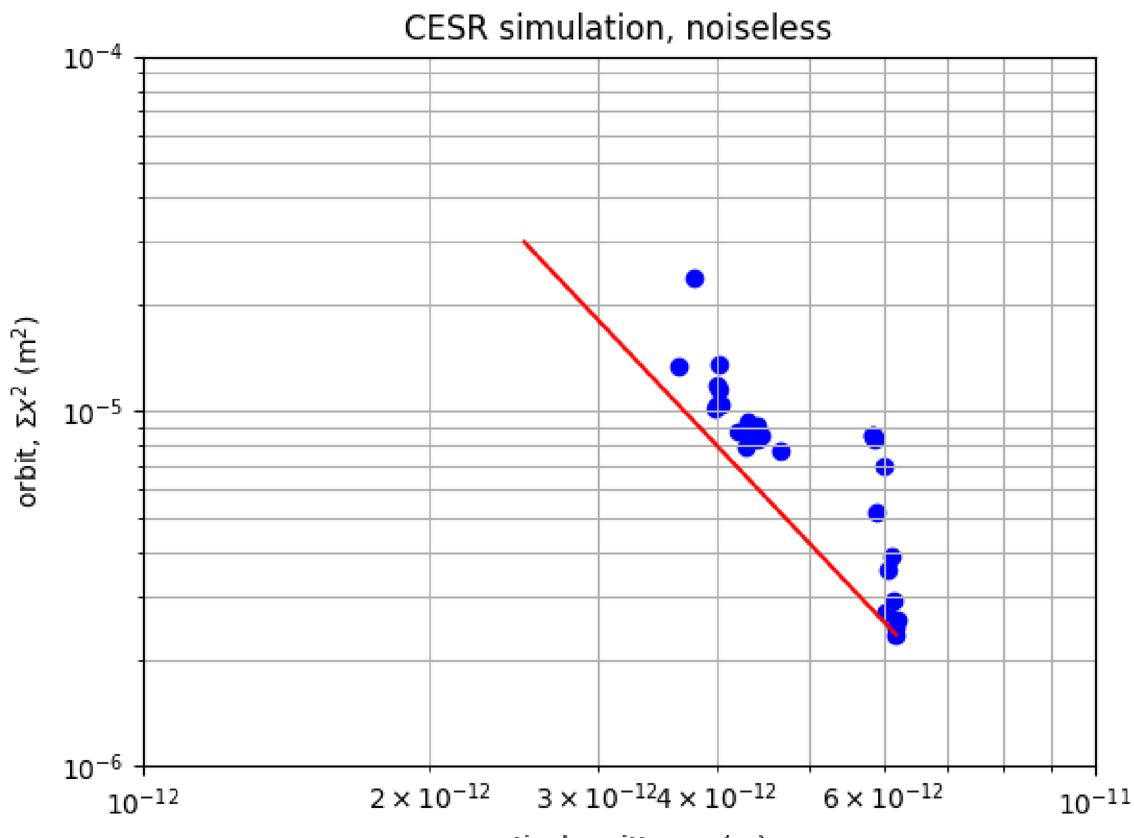

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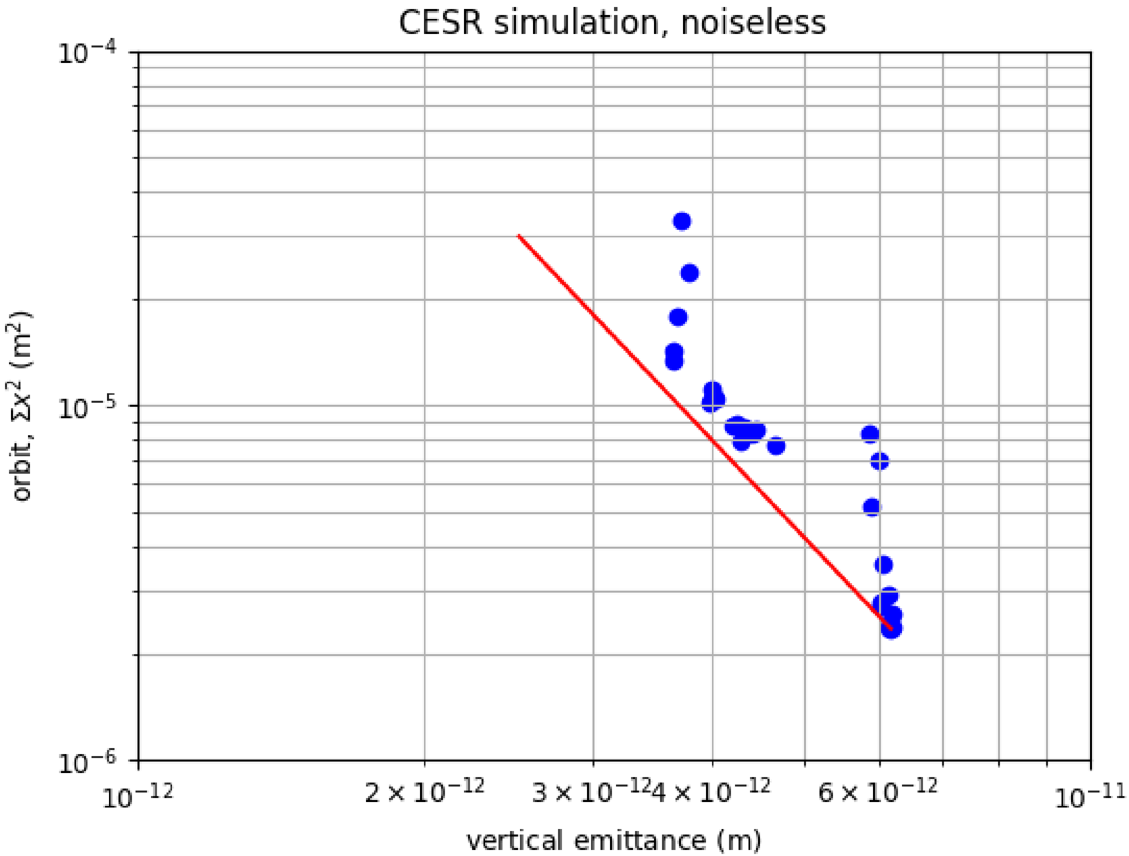

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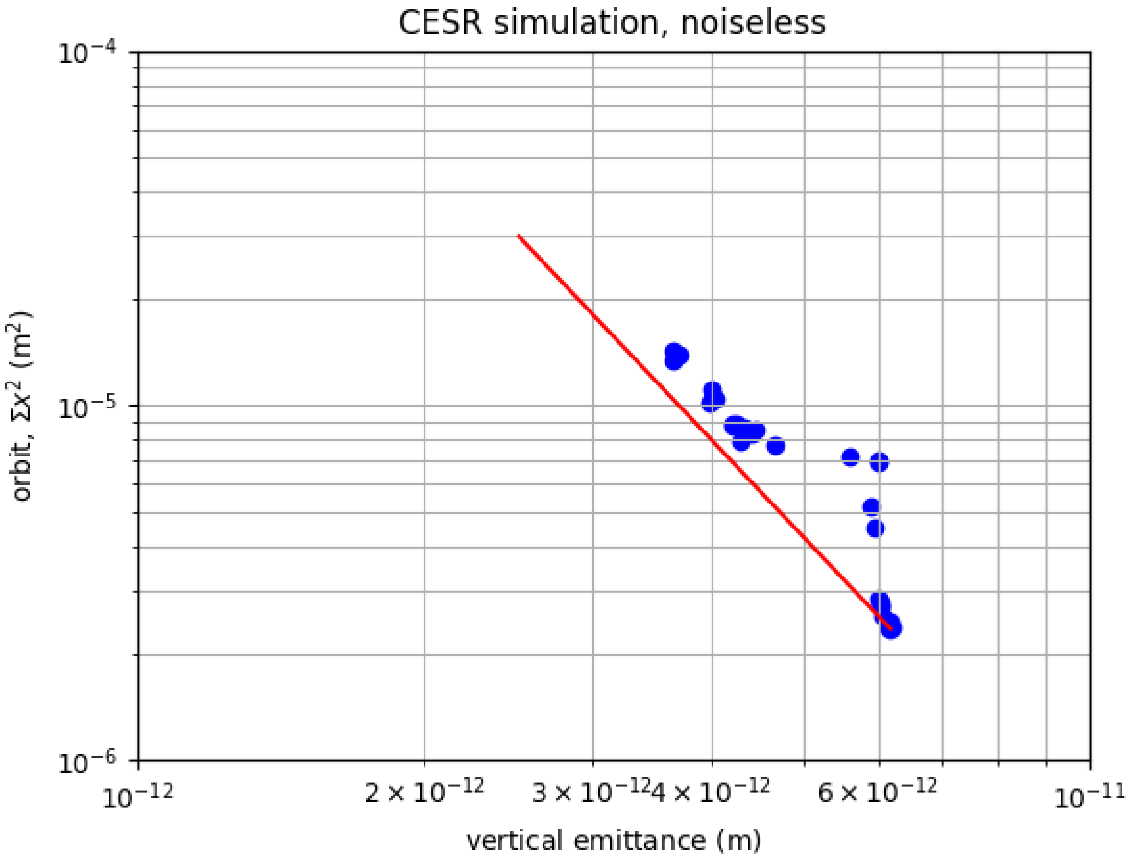

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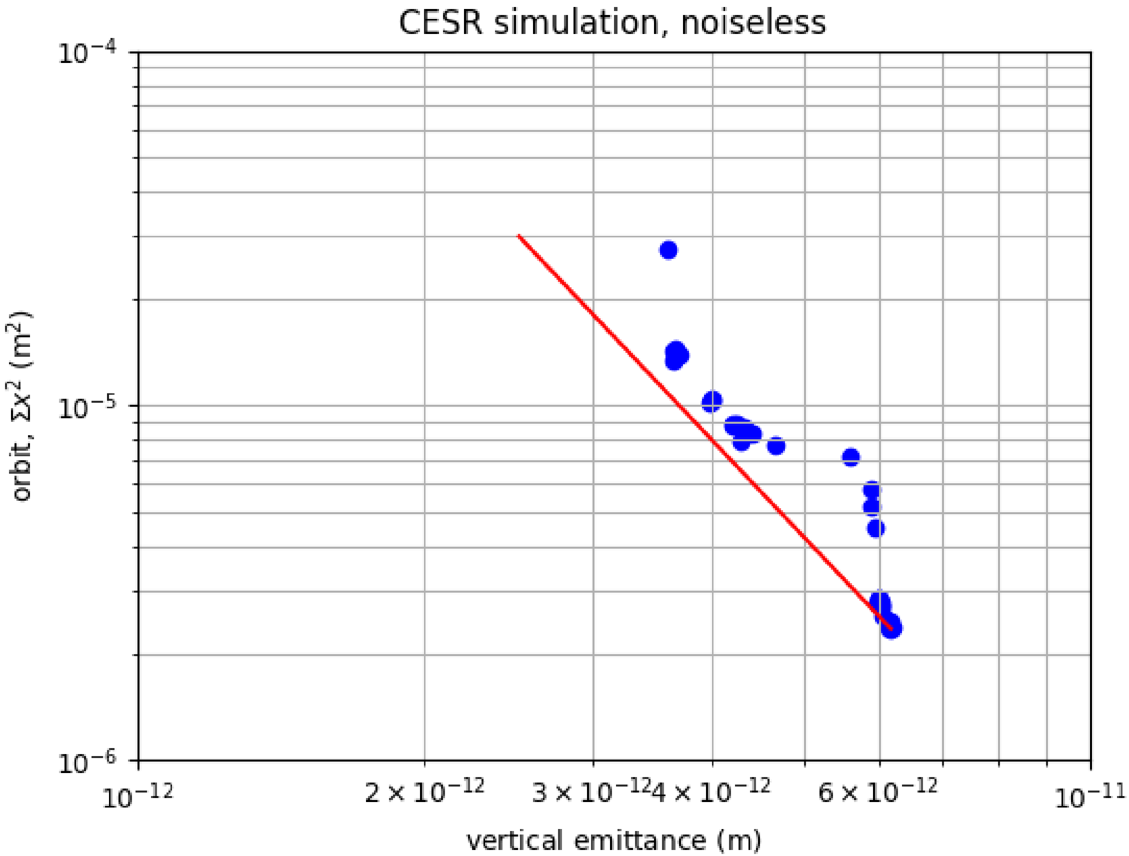

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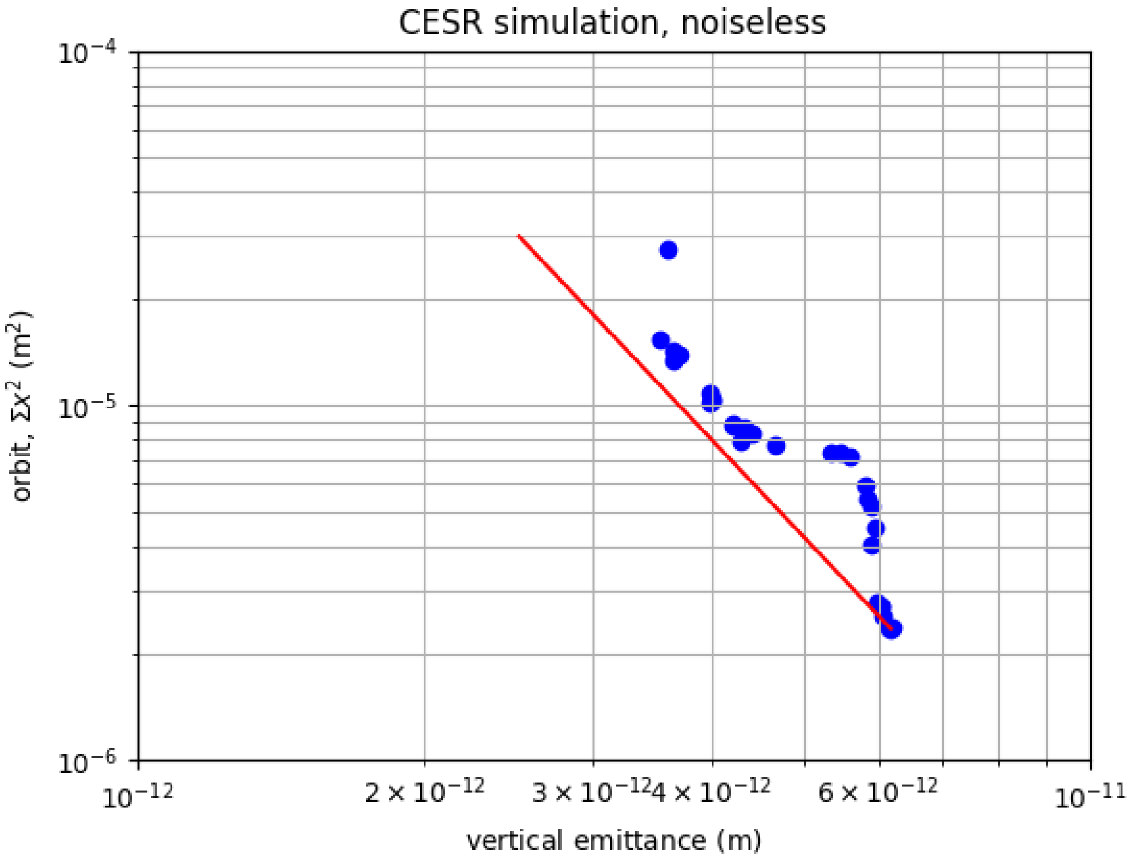
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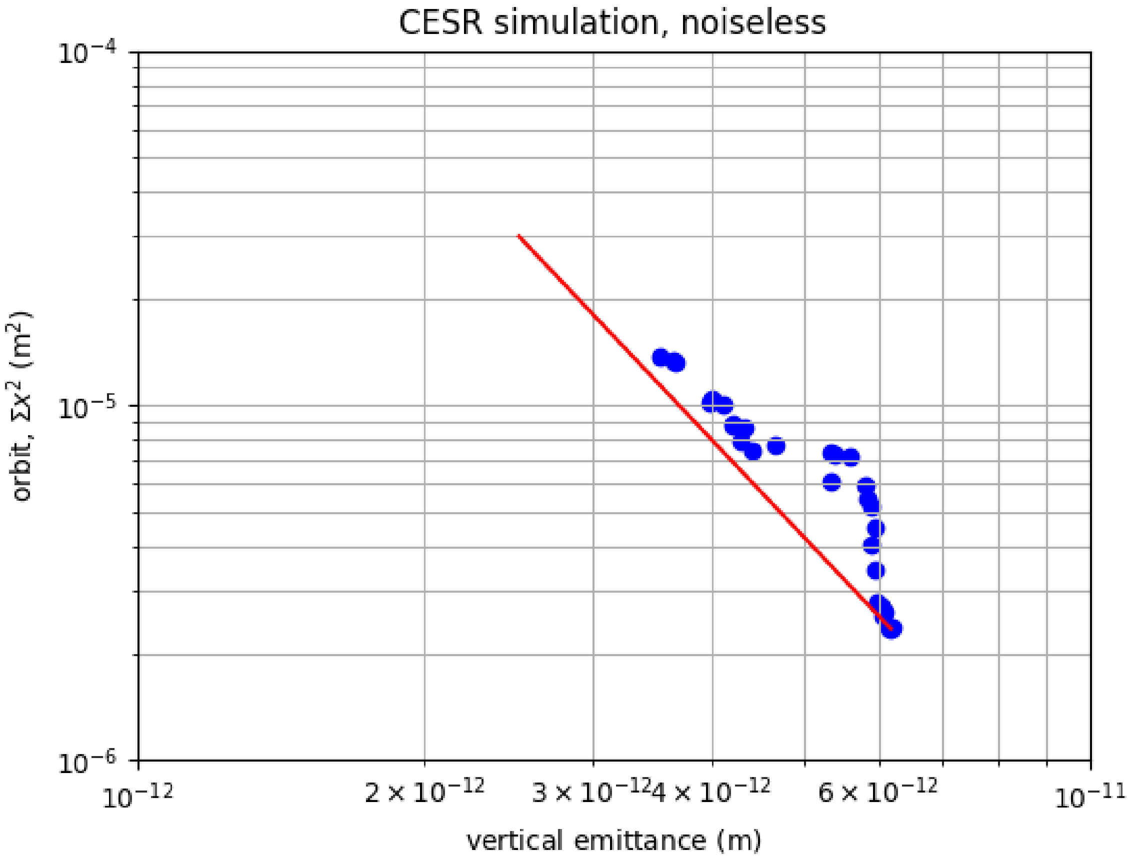
vertical emittance (m)



CESR simulation, noiseless
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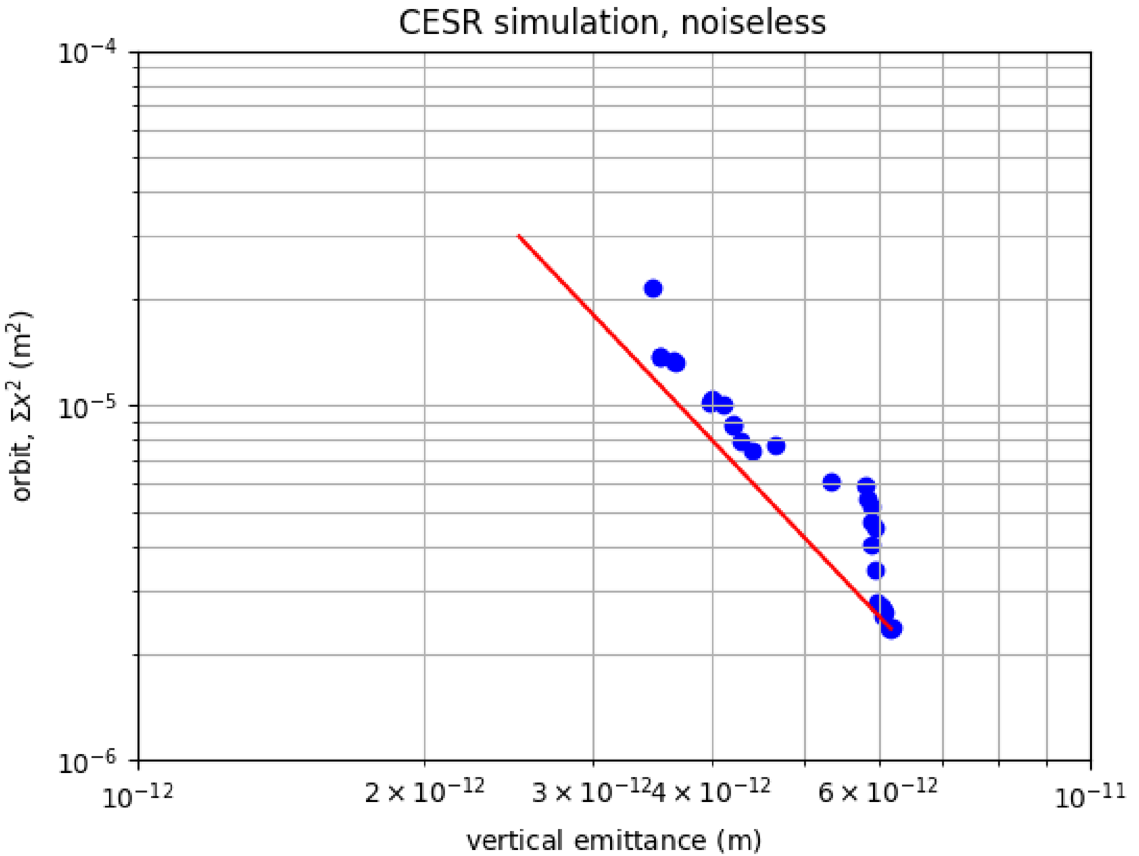

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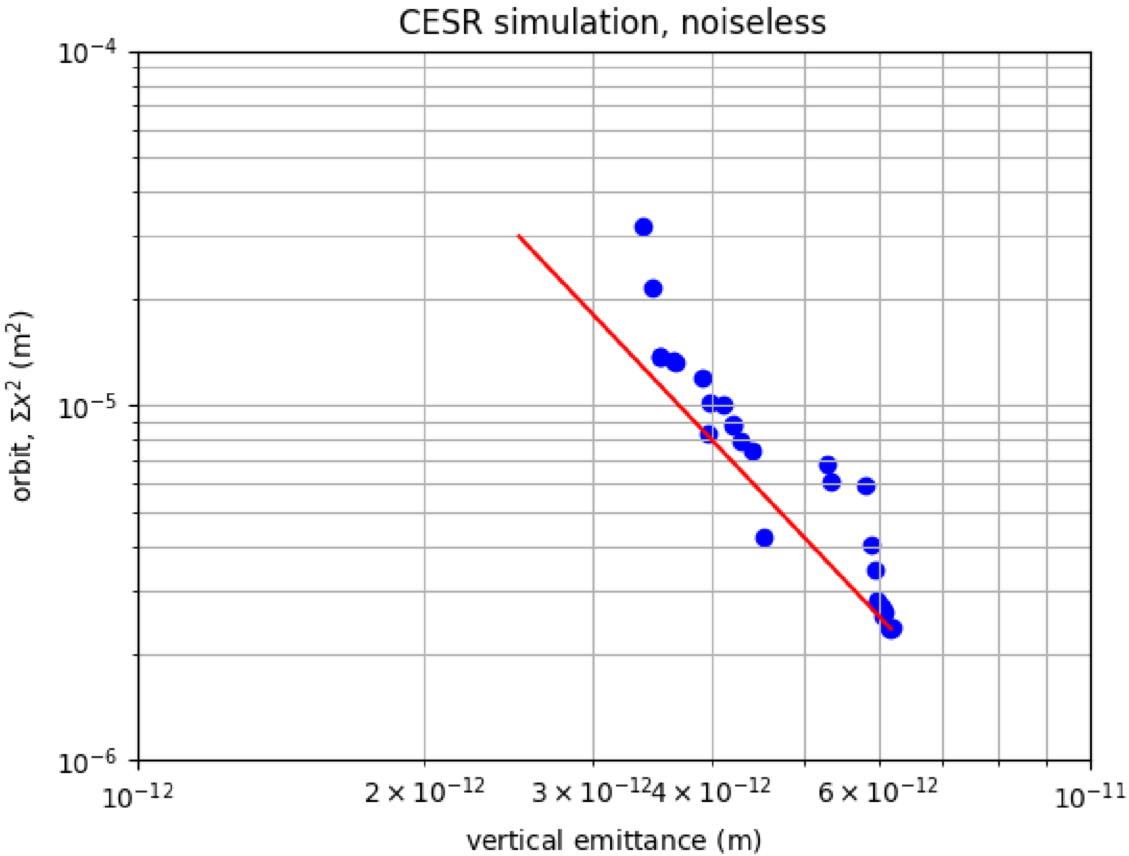

CESR simulation, noiseless
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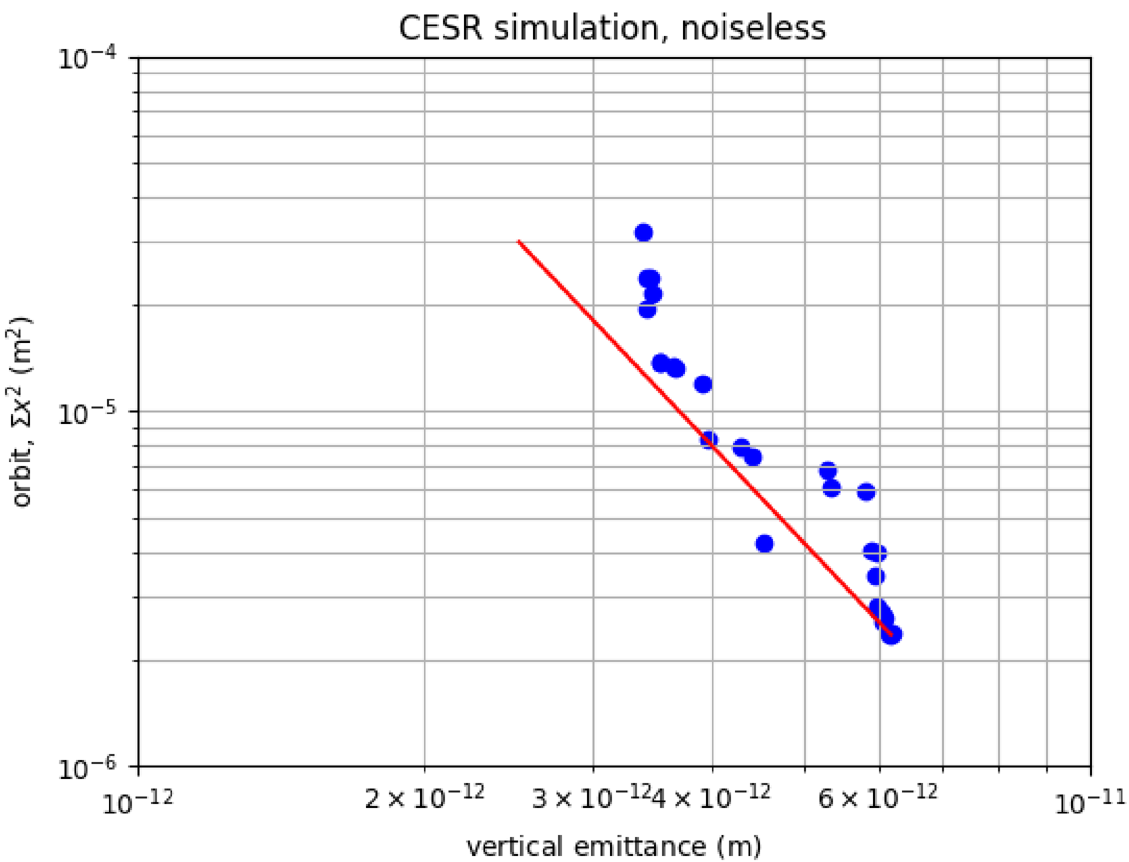
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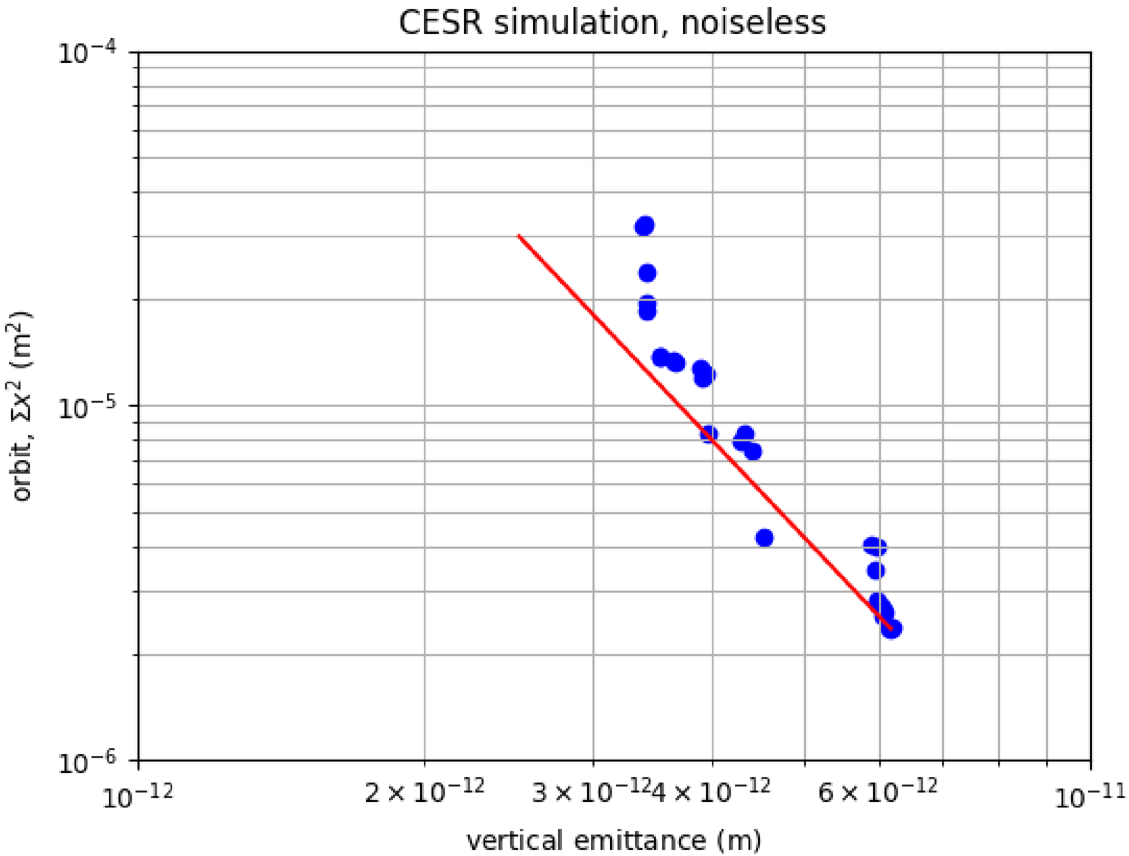
vertical emittance (m)



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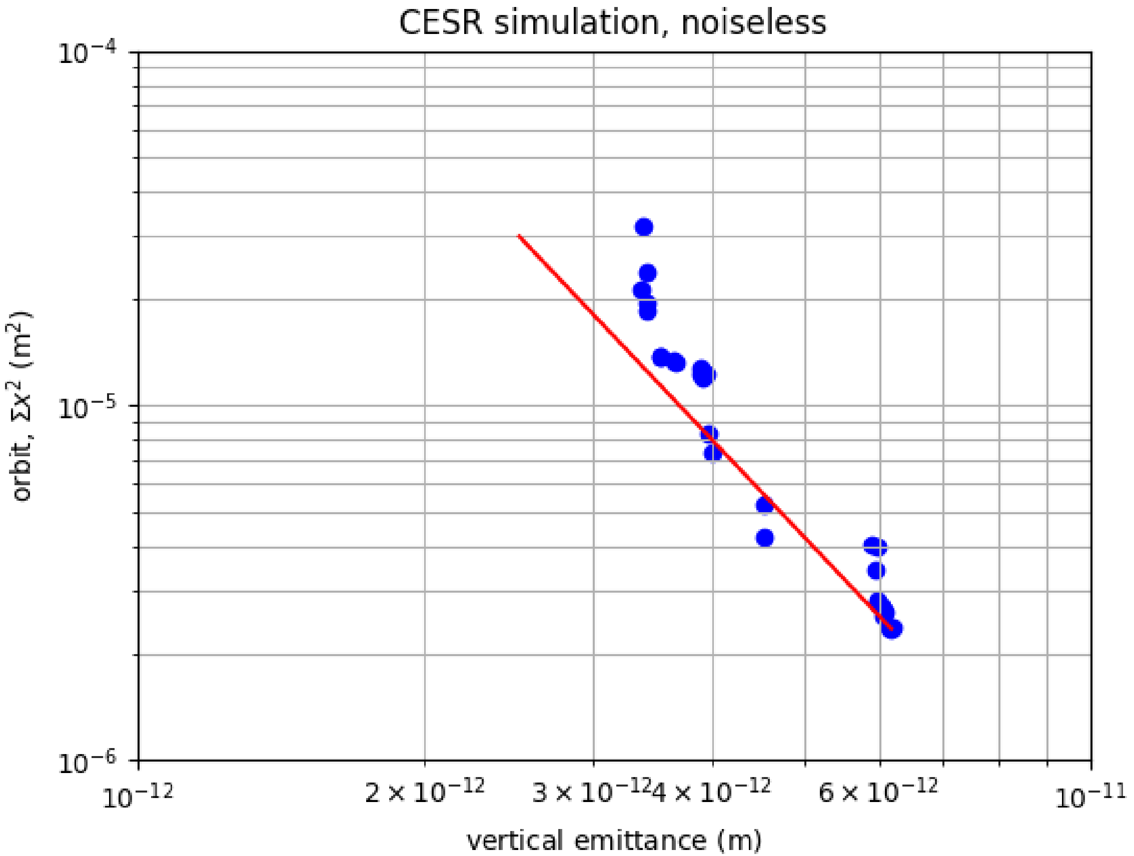
CESR simulation, noiseless
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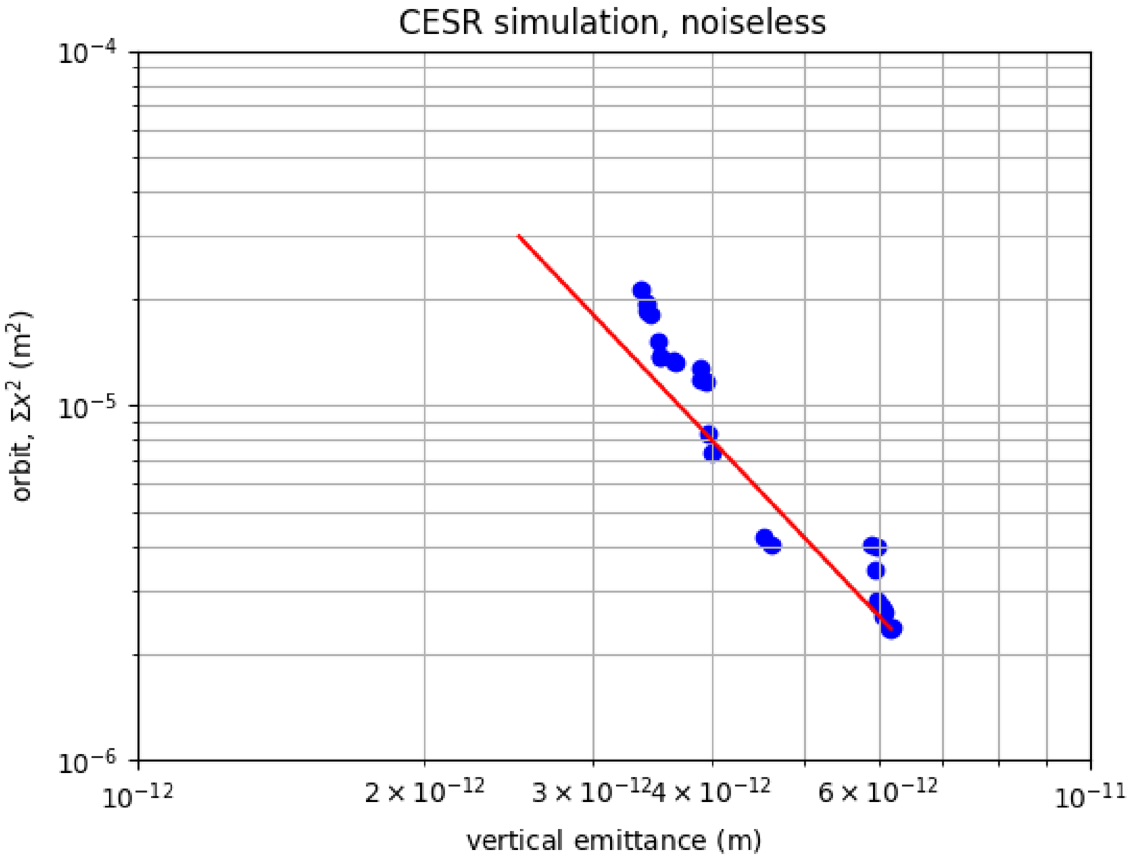
vertical emittance (m)



CESR simulation, noiseless
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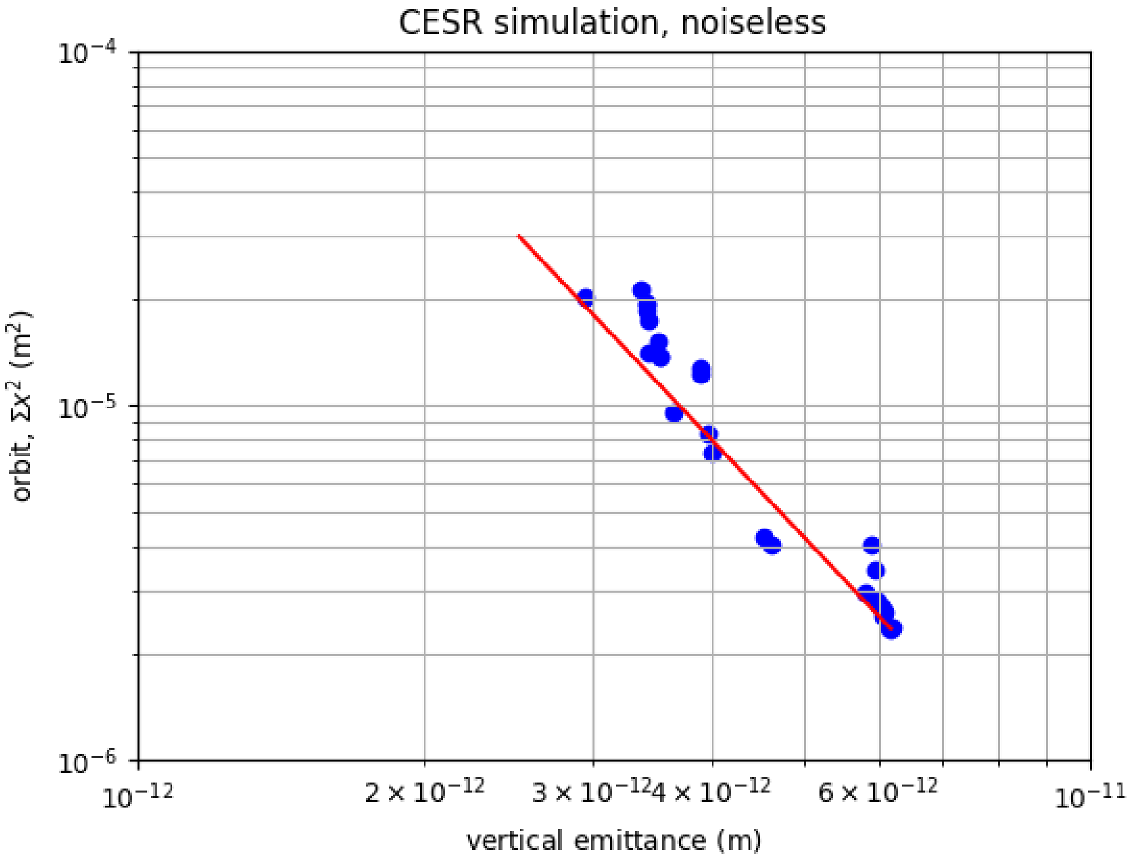
vertical emittance (m)



CESR simulation, noiseless
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10^{-6}
orbit, Σx^2 (m^2)
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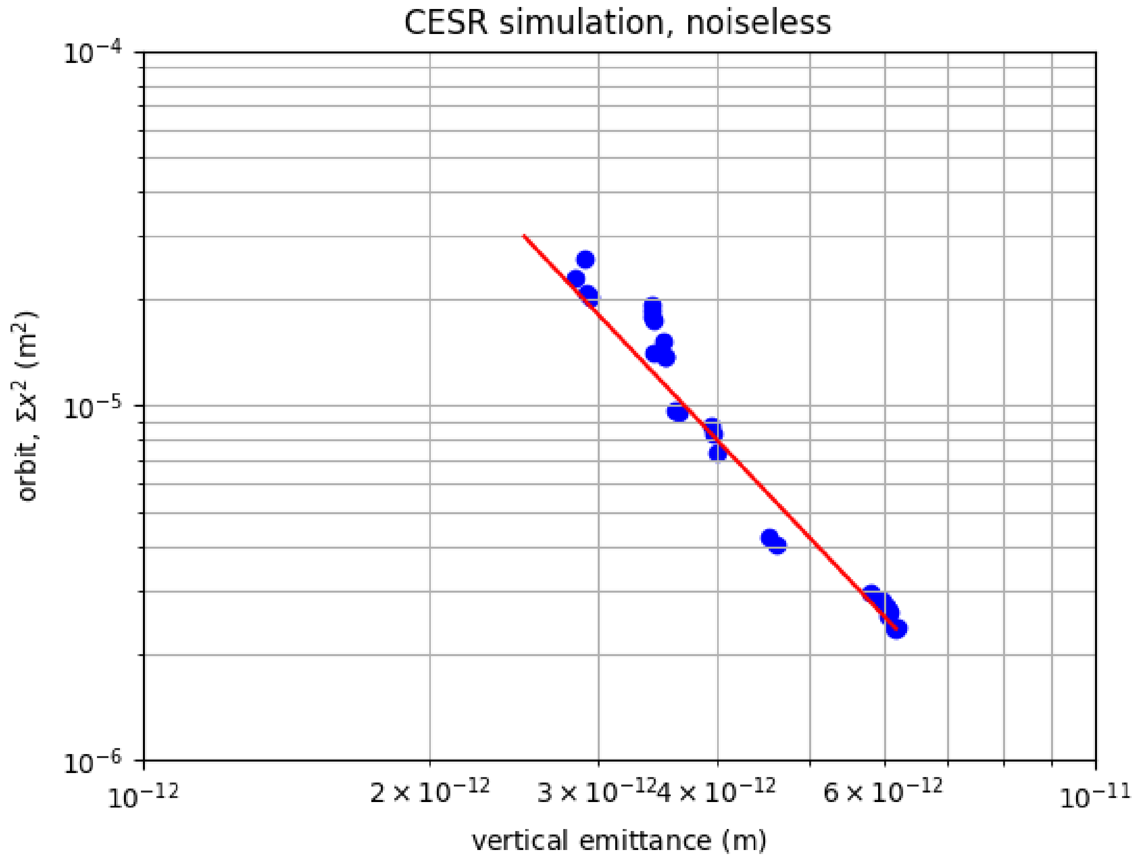
vertical emittance (m)



CESR simulation, noiseless
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orbit, Σx^2 (m^2)
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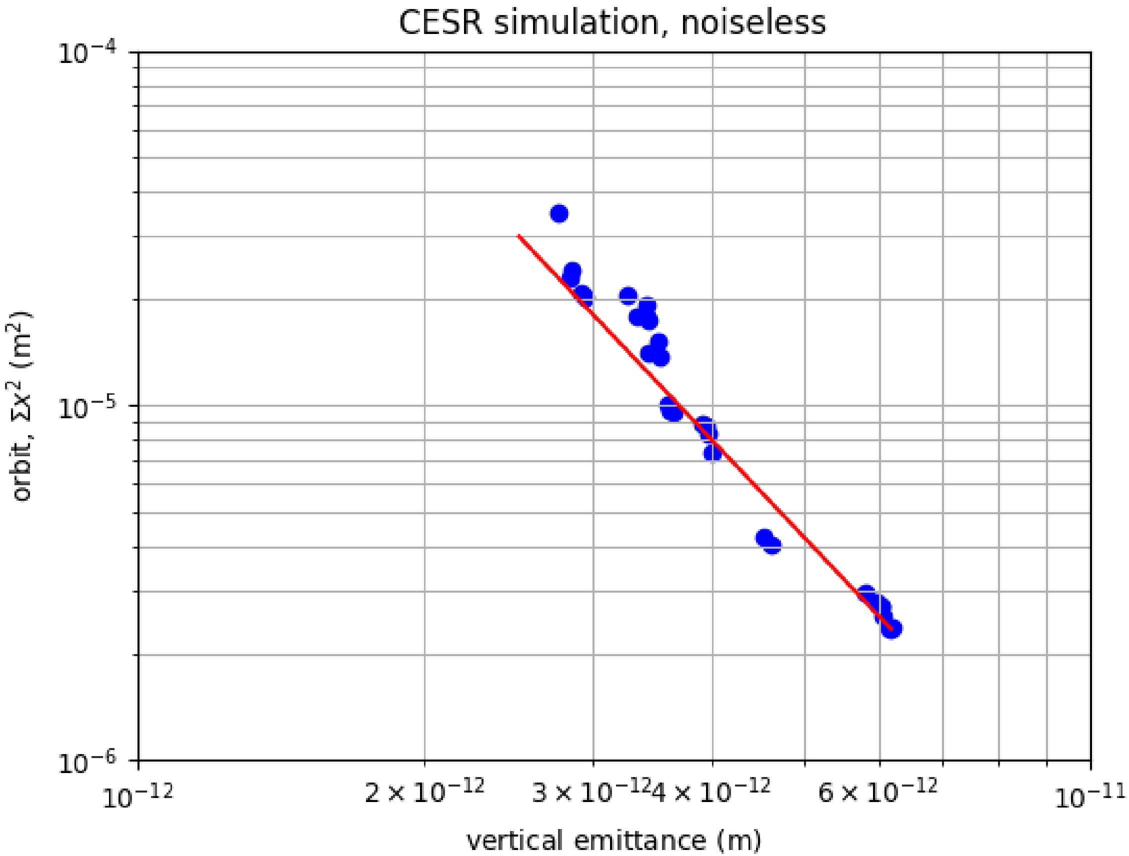
vertical emittance (m)



CESR simulation, noiseless
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orbit, Σx^2 (m^2)
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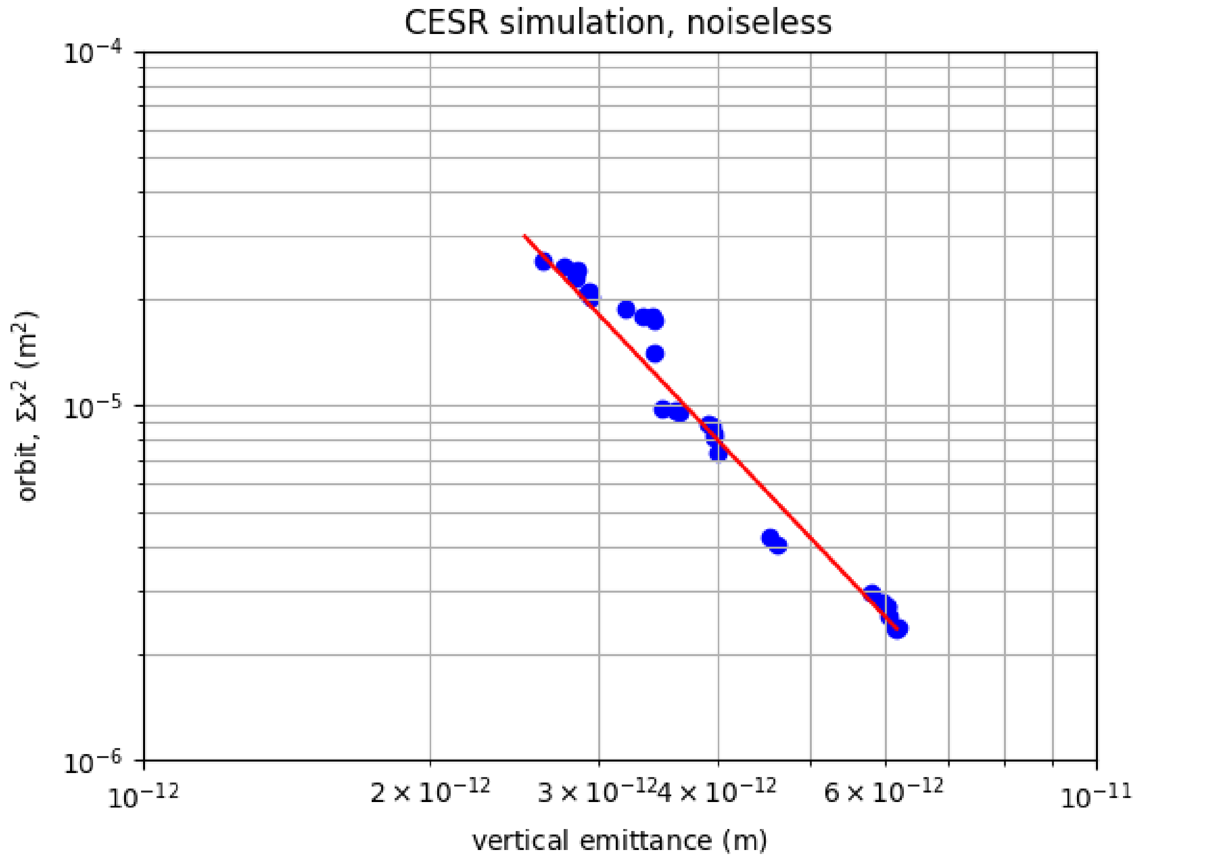
vertical emittance (m)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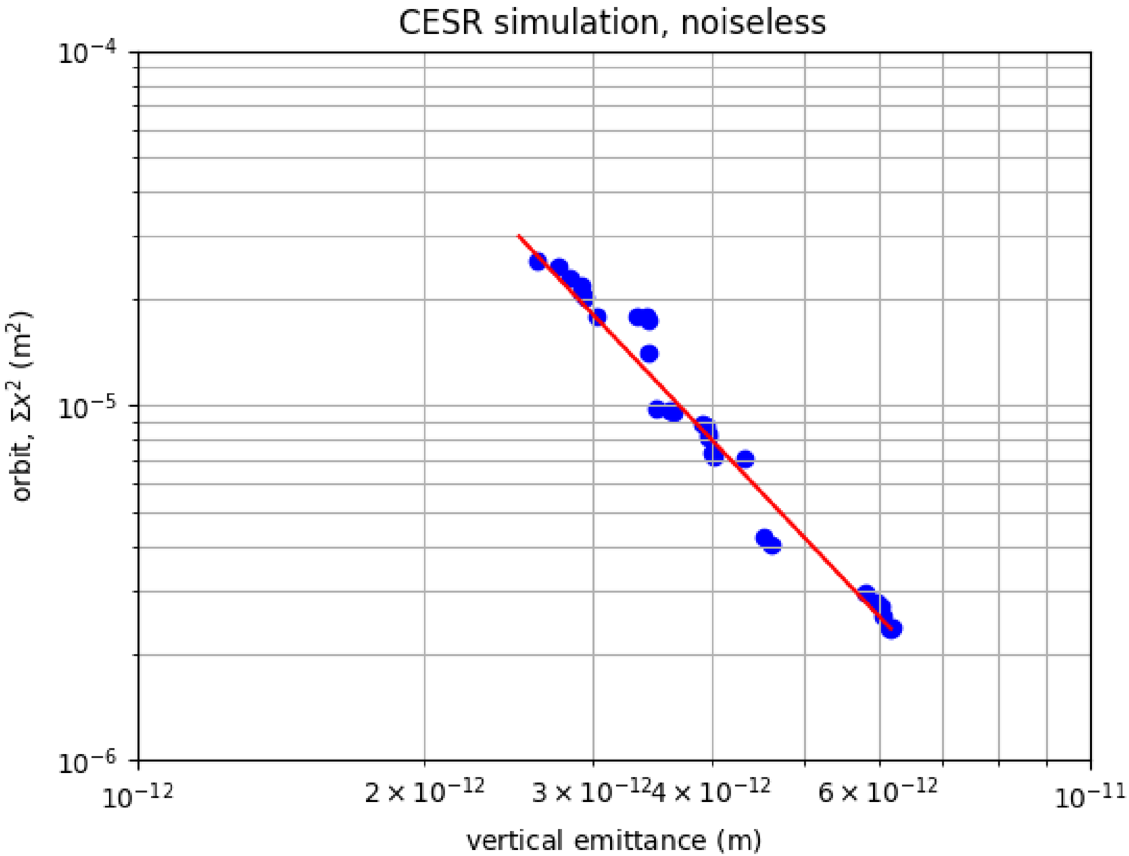
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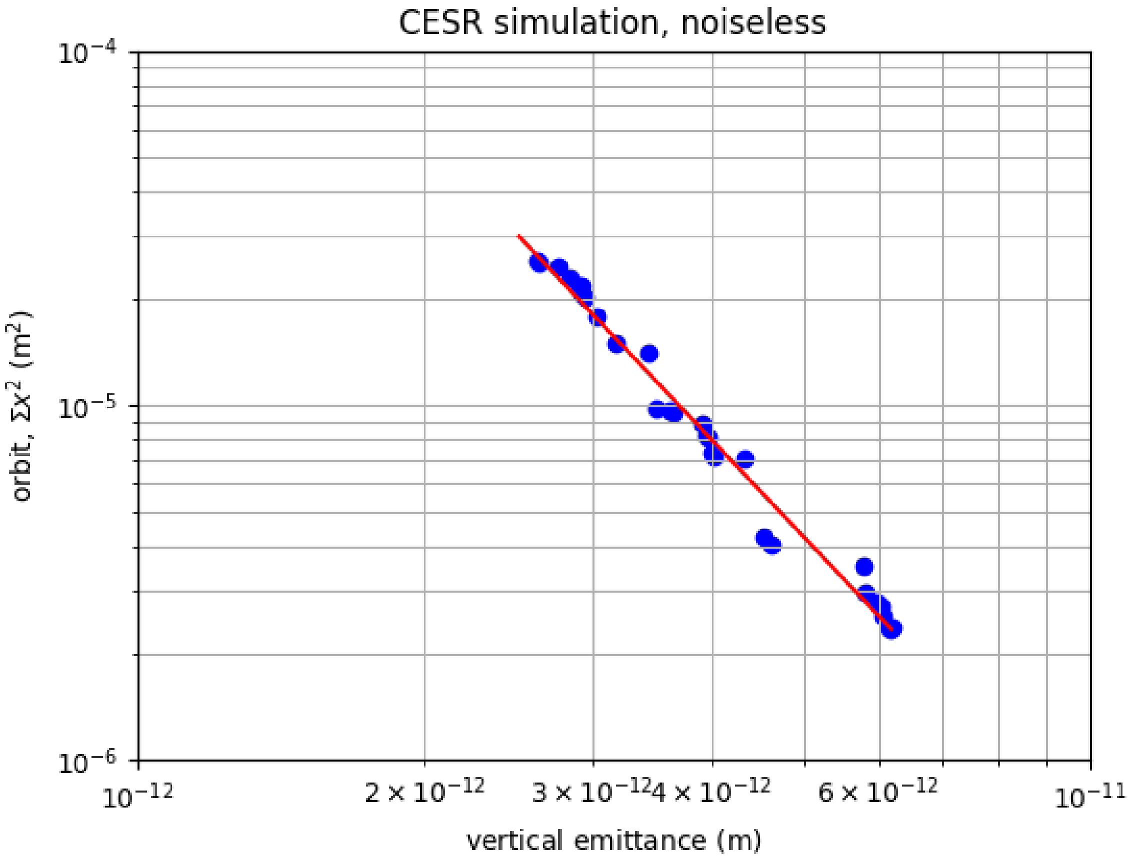
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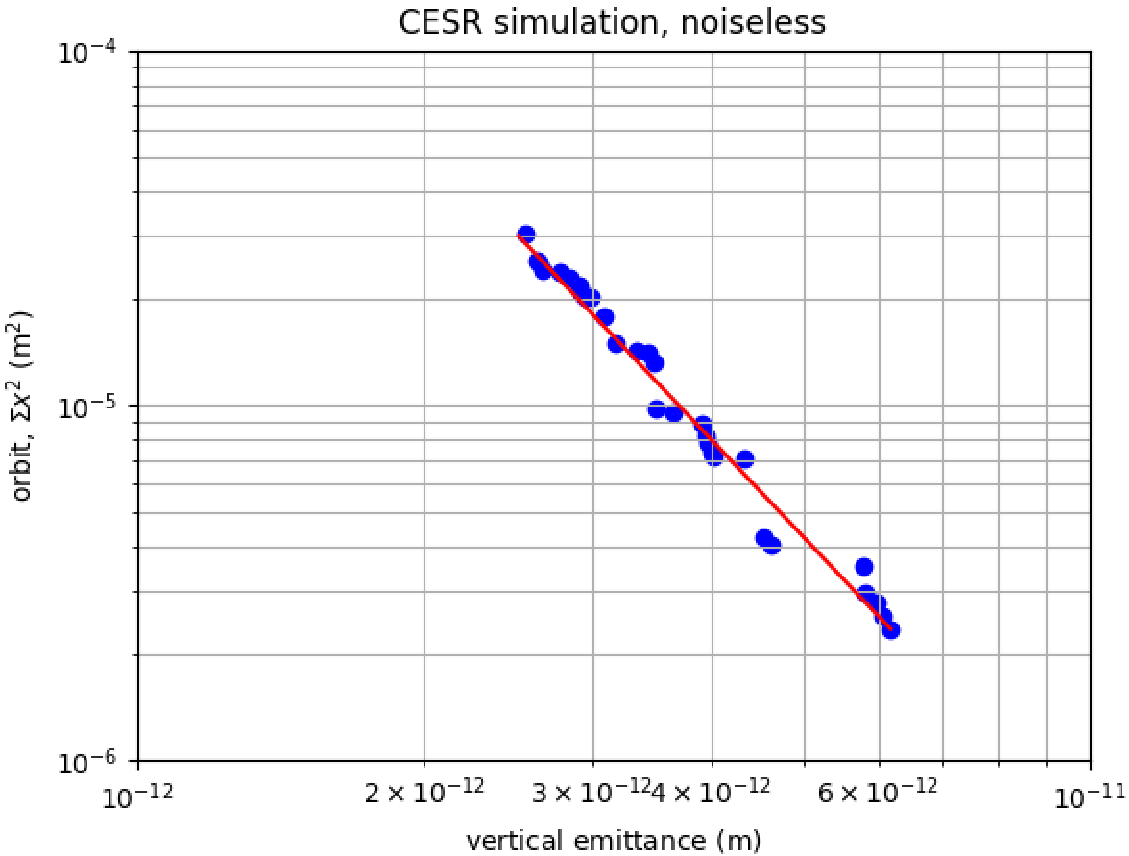
CESR simulation, noiseless
orbit, Σx^2 (m^2)
vertical emittance (m)
10^{-4}
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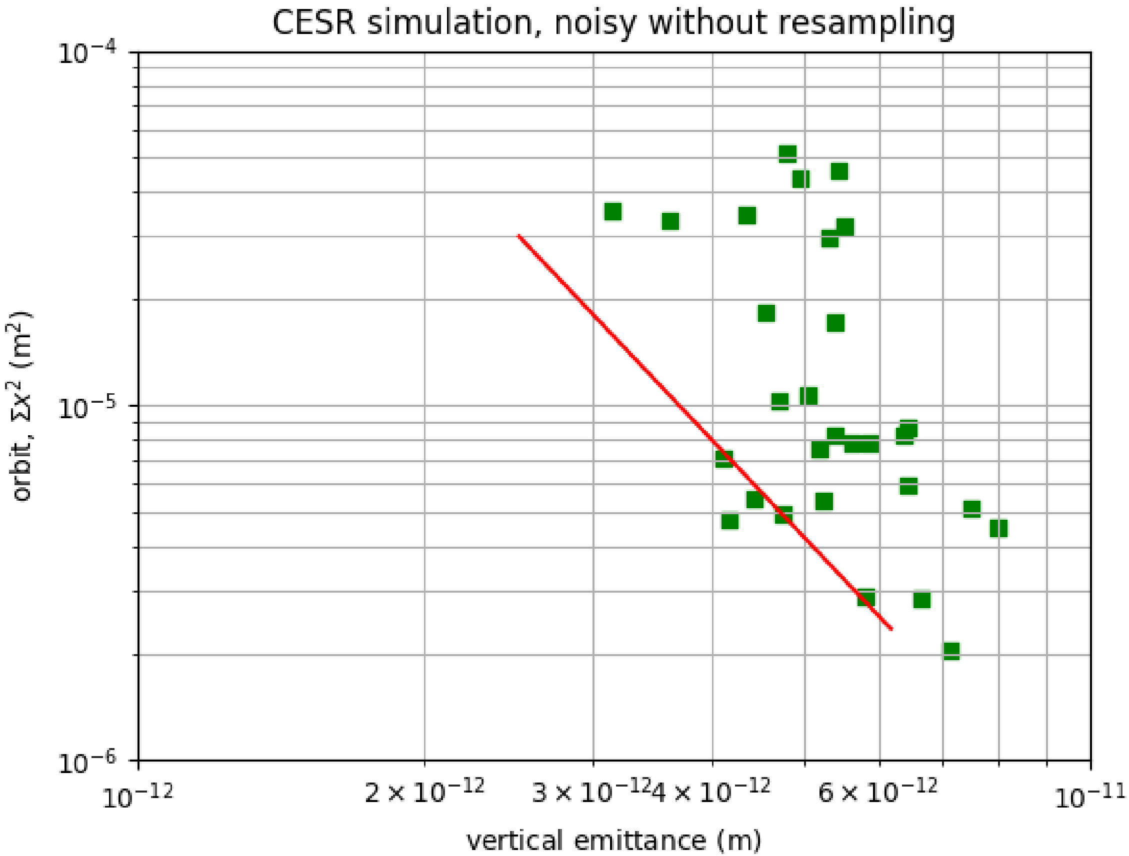
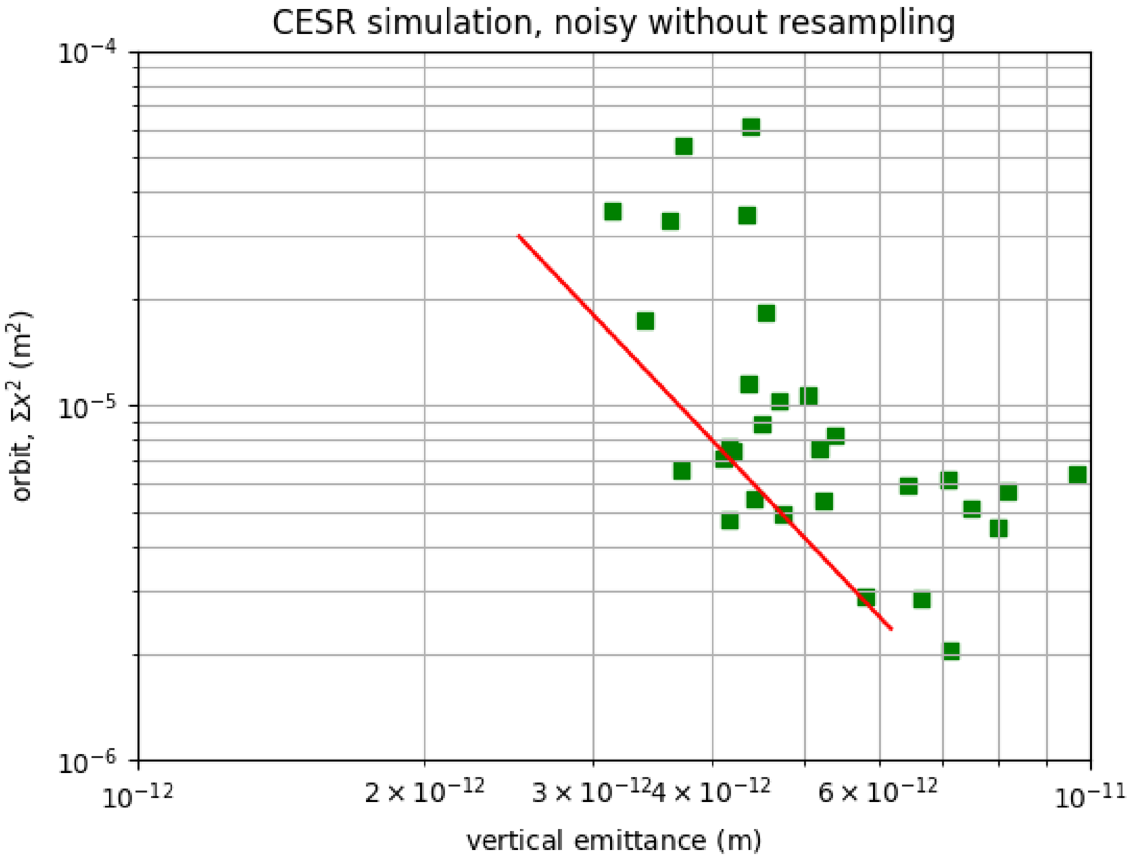
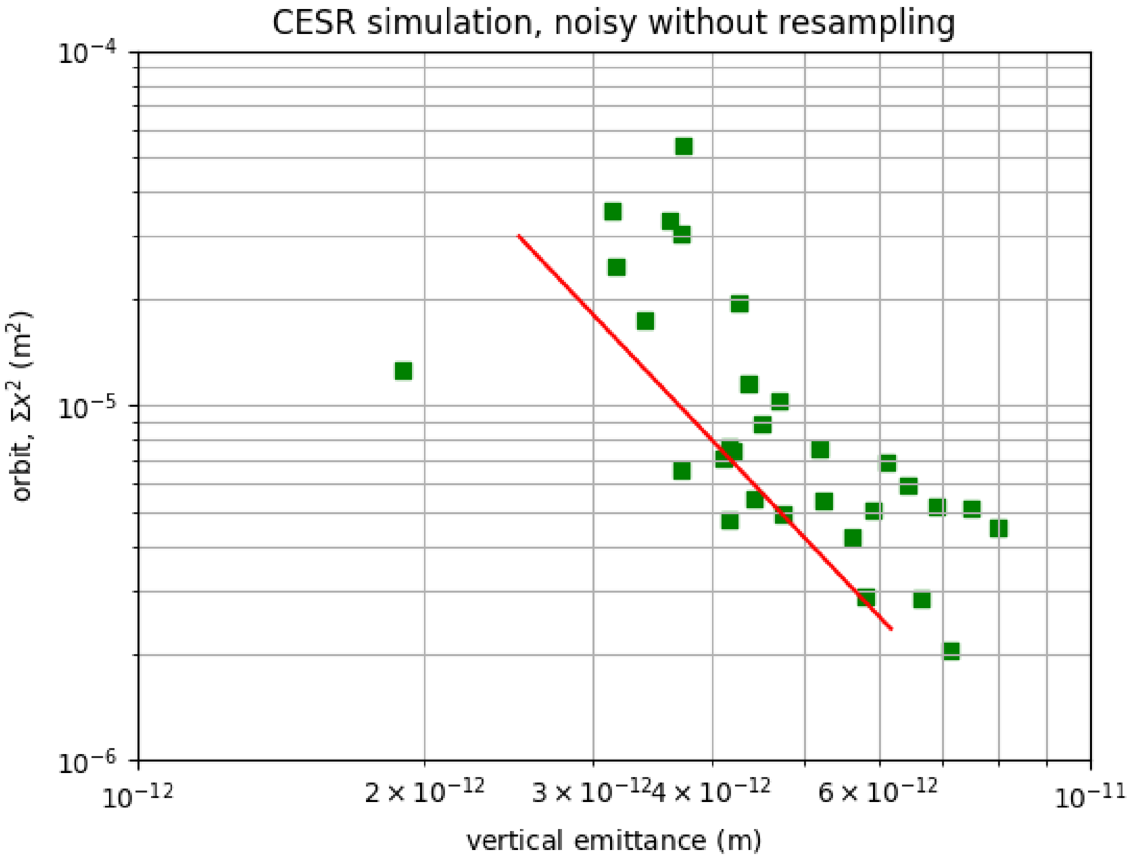


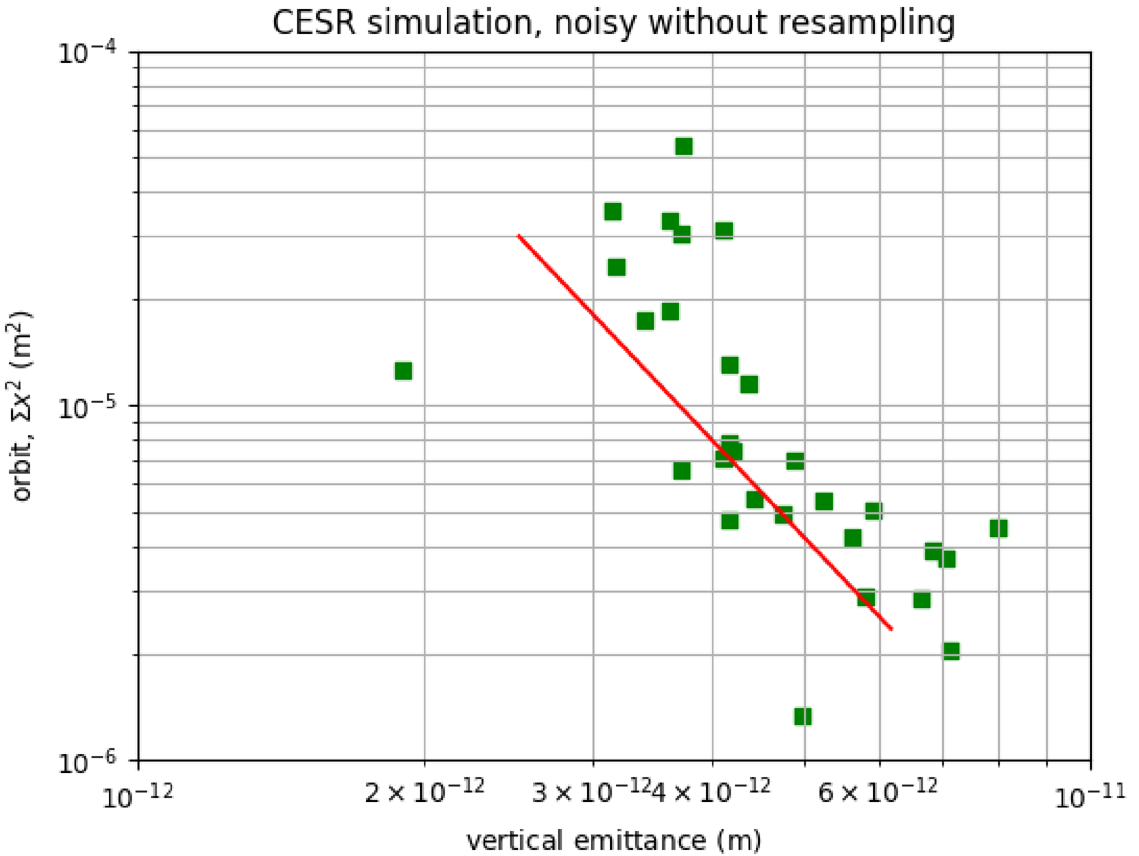
CESR simulation, noisy without resampling
10^{-4}
10^{-5}
10^{-6}
orbit, Σx^2 (m^2)
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)



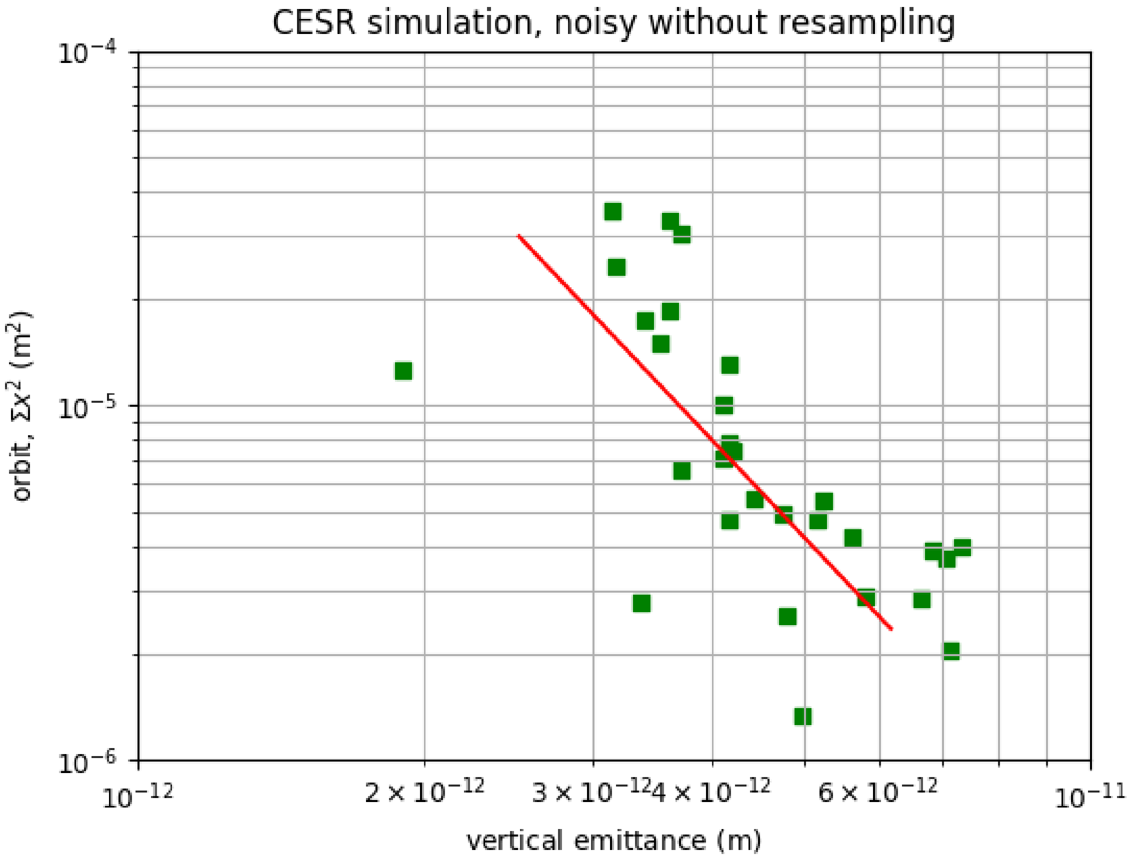
CESR simulation, noisy without resampling
orbit, Σx^2 (m^2)
10^{-4}
10^{-5}
10^{-6}
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)

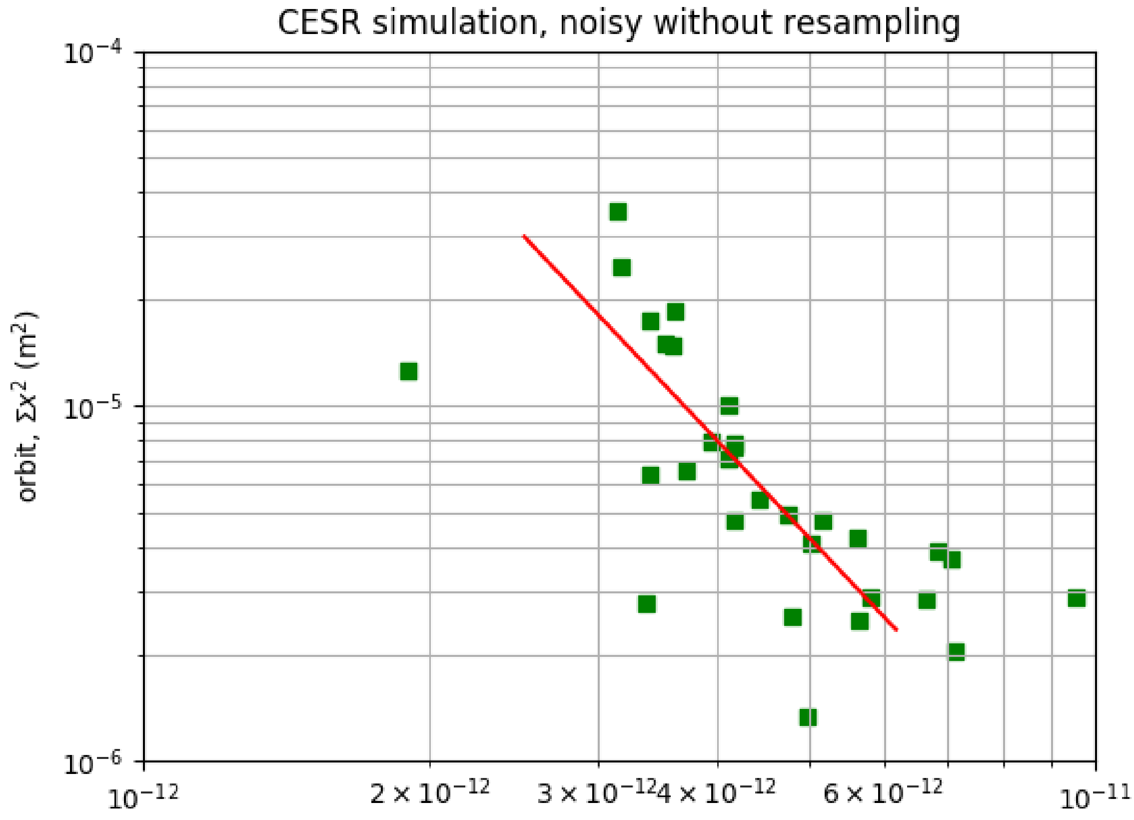


CESR simulation, noisy without resampling
orbit, Σx^2 (m^2)
10^{-4}
10^{-5}
10^{-6}
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)

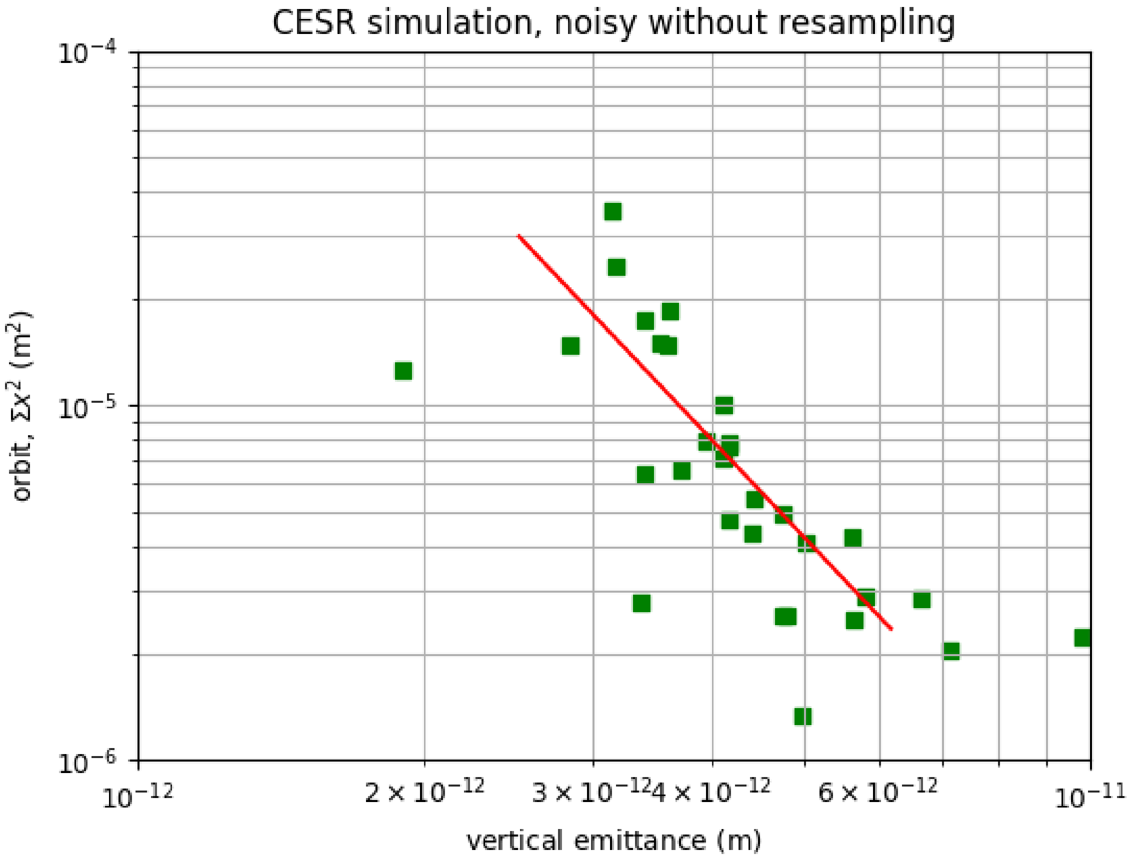


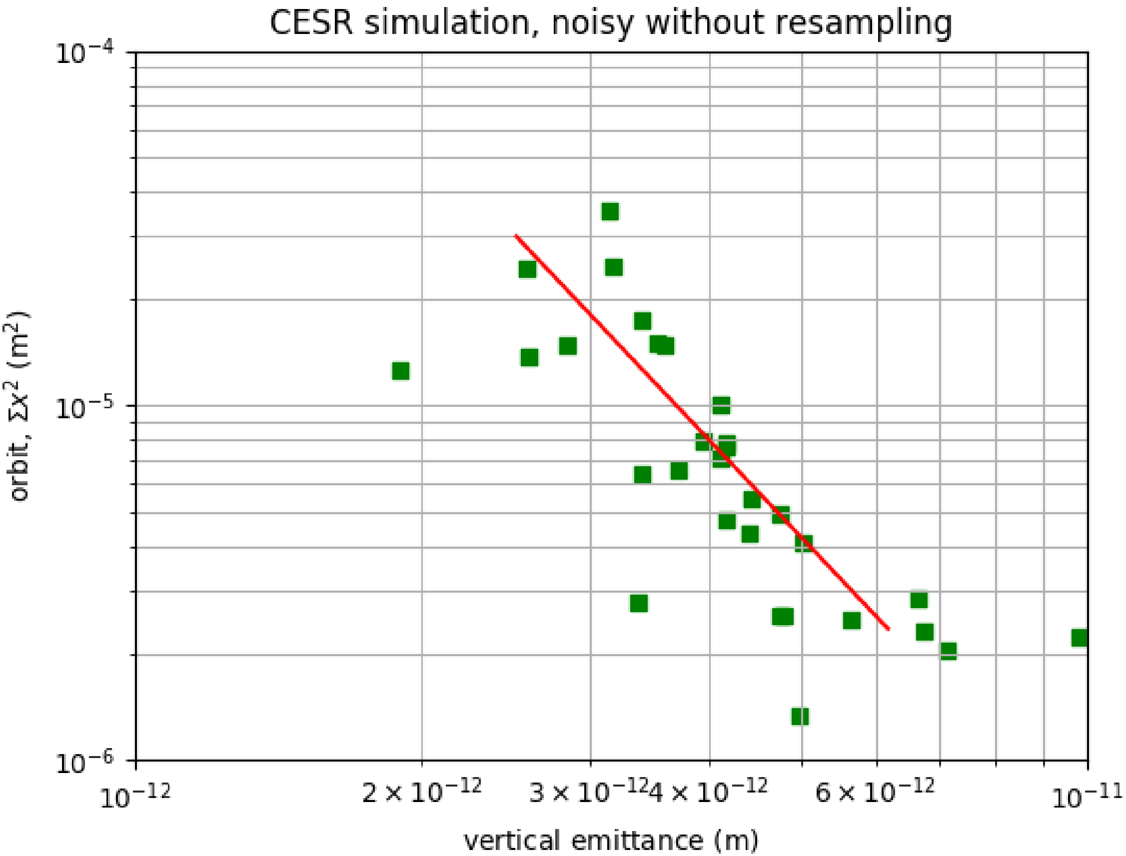
CESR simulation, noisy without resampling
10^{-4}
10^{-5}
10^{-6}
orbit, Σx^2 (m^2)
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)


CESR simulation, noisy without resampling
10^{-4}
10^{-5}
10^{-6}
orbit, Σx^2 (m^2)
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)

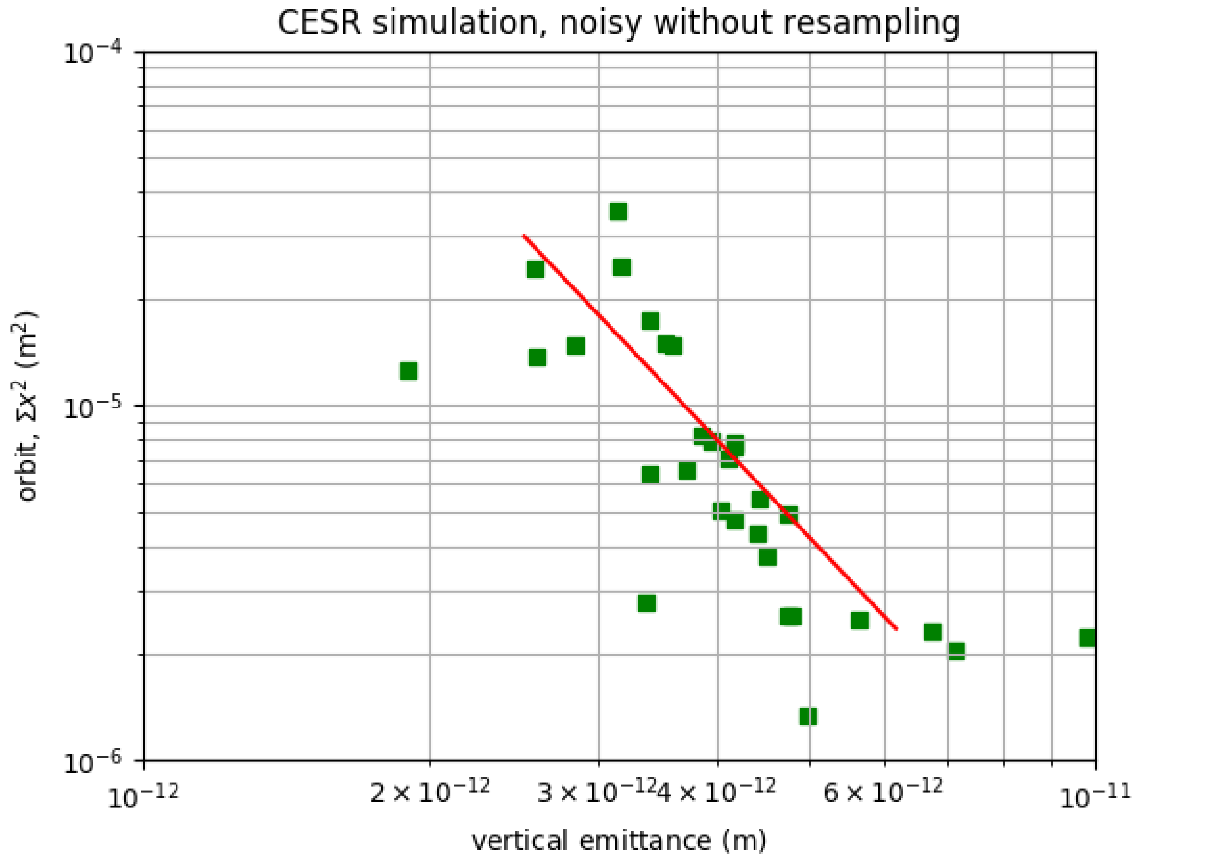


CESR simulation, noisy without resampling
10^{-4}
10^{-5}
10^{-6}
orbit, Σx^2 (m^2)
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)

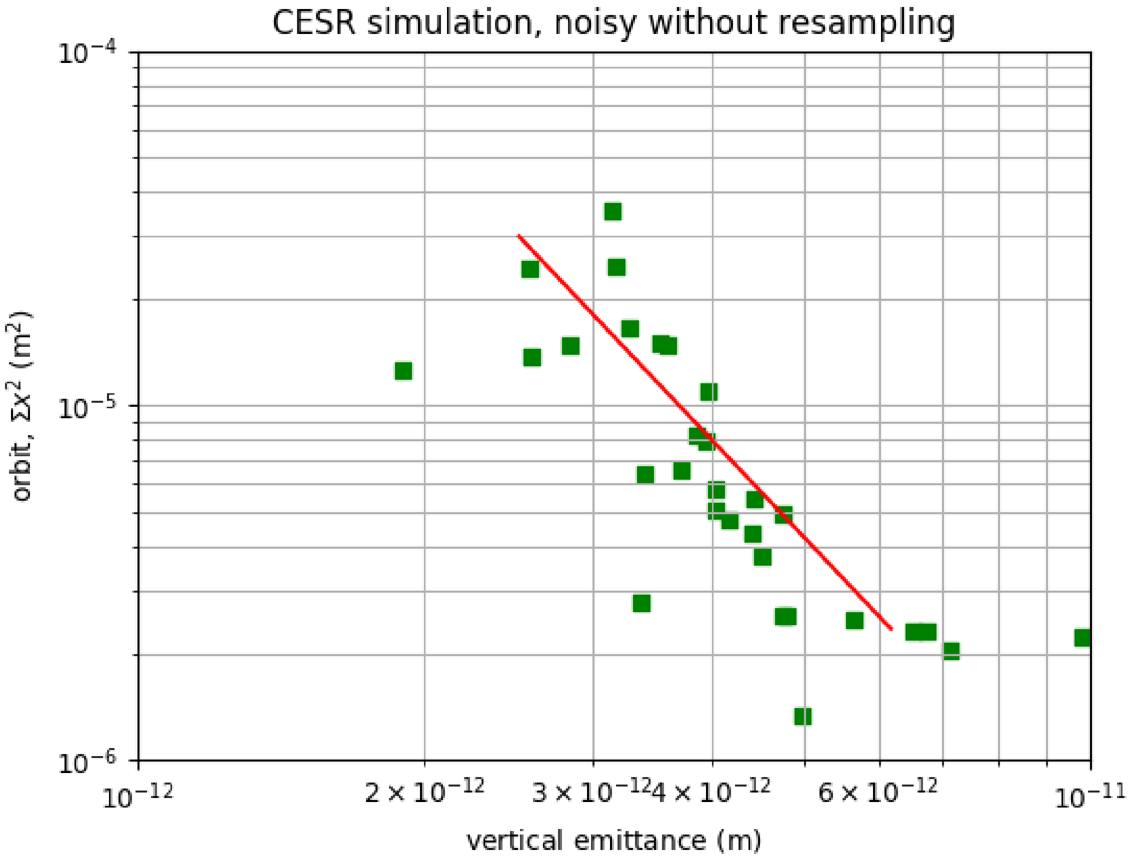

CESR simulation, noisy without resampling
orbit, Σx^2 (m^2)
10^{-4}
10^{-5}
10^{-6}
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)



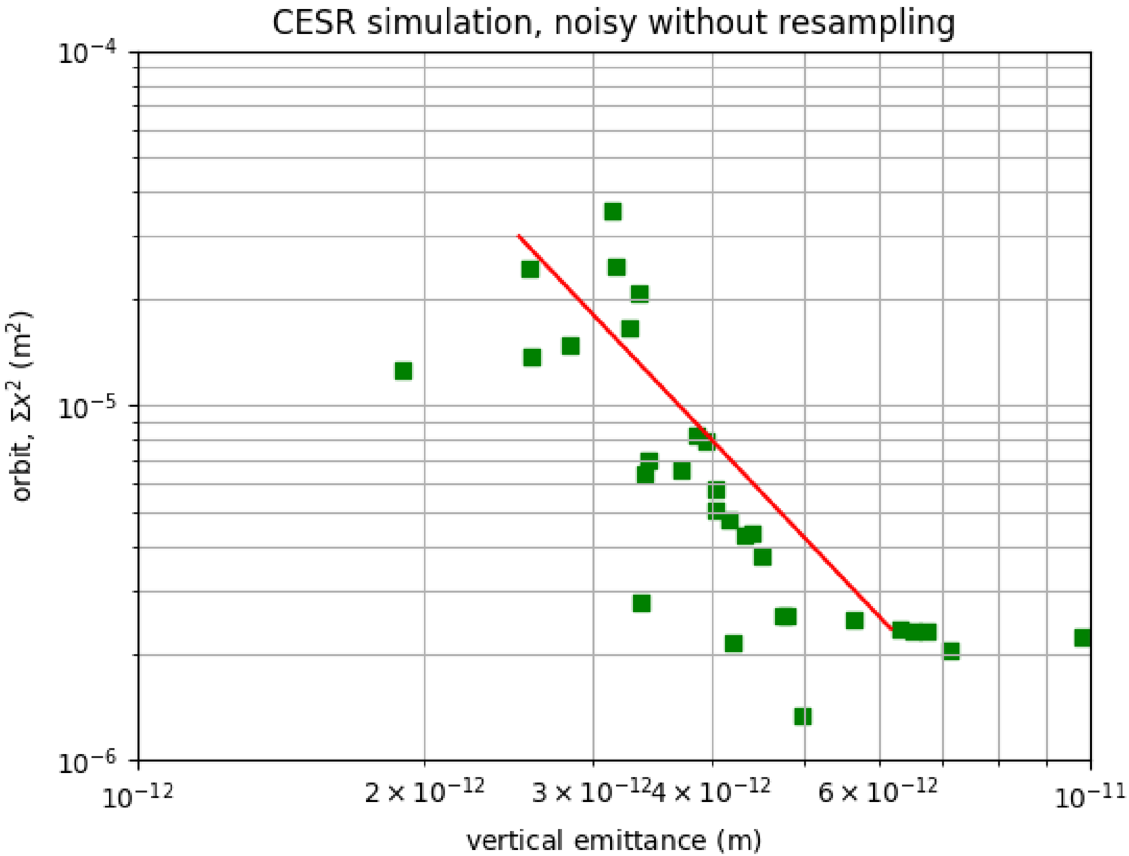
CESR simulation, noisy without resampling
10^{-4}
10^{-5}
10^{-6}
orbit, Σx^2 (m^2)
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)

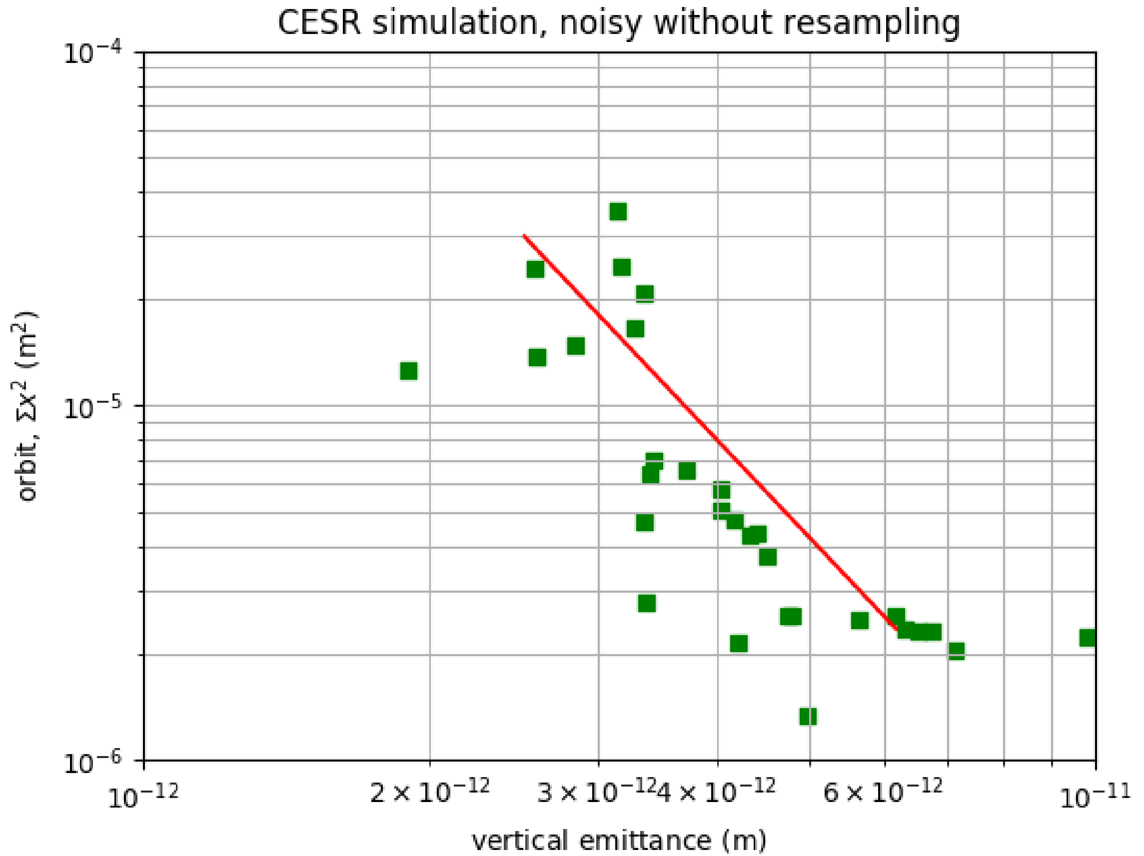


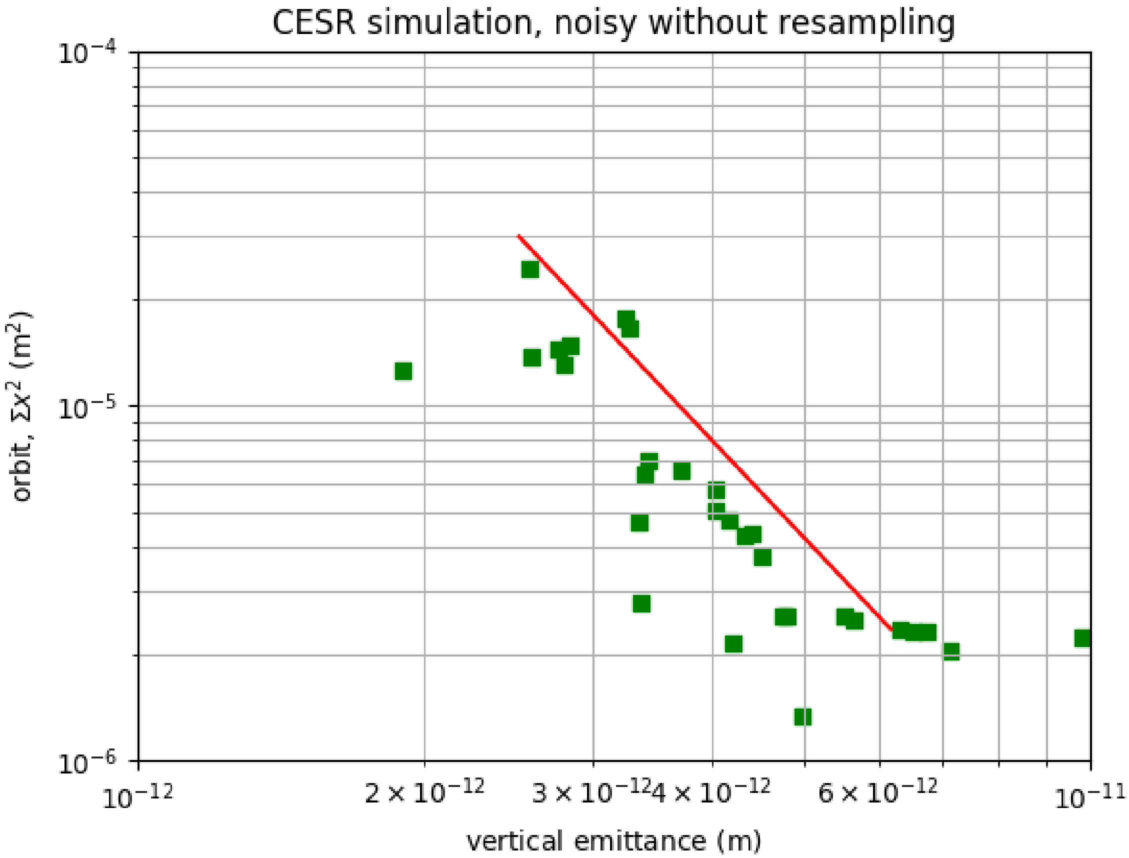
CESR simulation, noisy without resampling
10^{-4}
10^{-5}
10^{-6}
orbit, Σx^2 (m^2)
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)



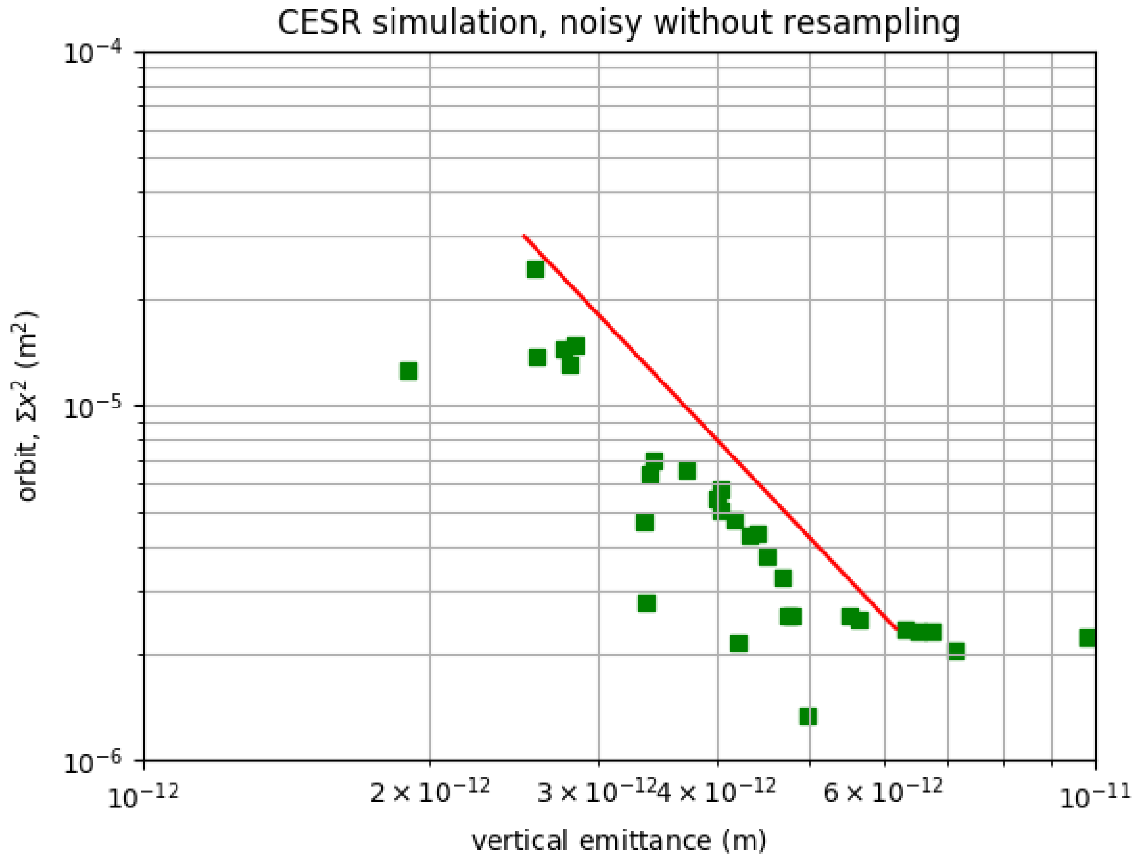
CESR simulation, noisy without resampling
10^{-4}
10^{-5}
10^{-6}
orbit, Σx^2 (m^2)
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)

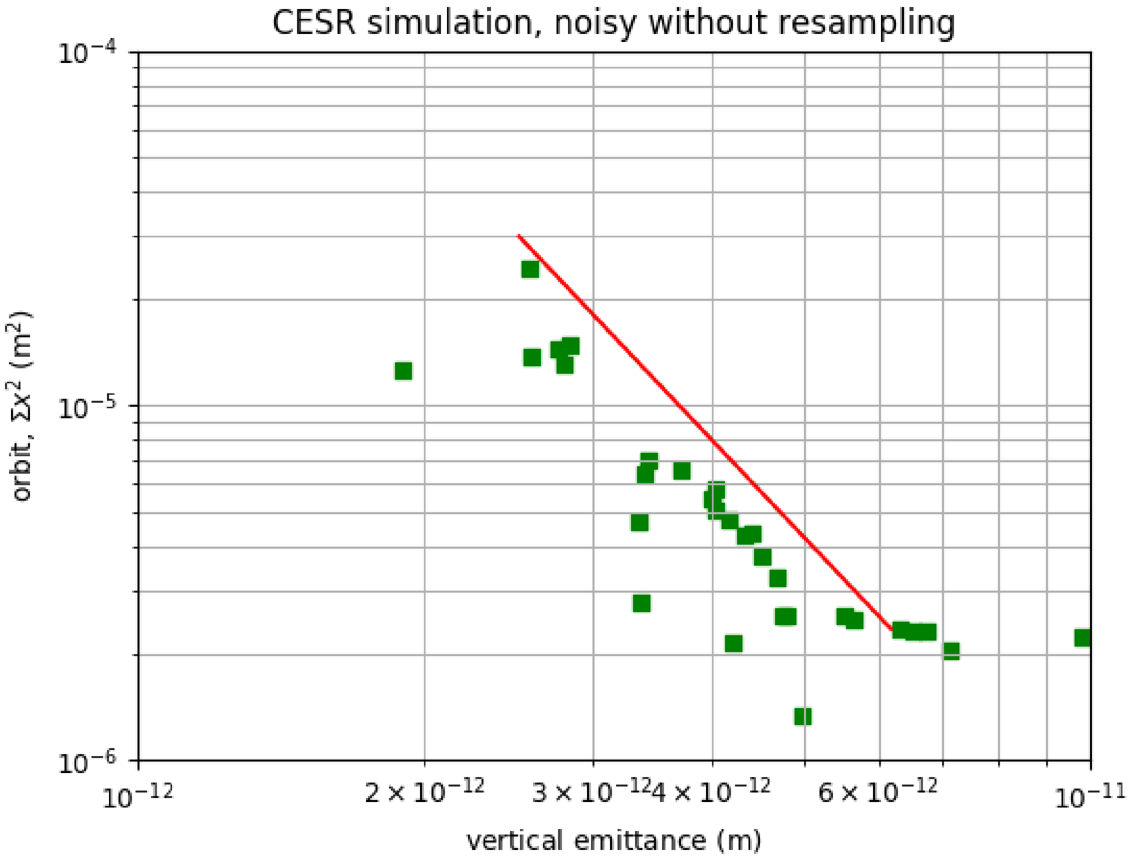

CESR simulation, noisy without resampling
10^{-4}
10^{-5}
10^{-6}
orbit, Σx^2 (m^2)
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)

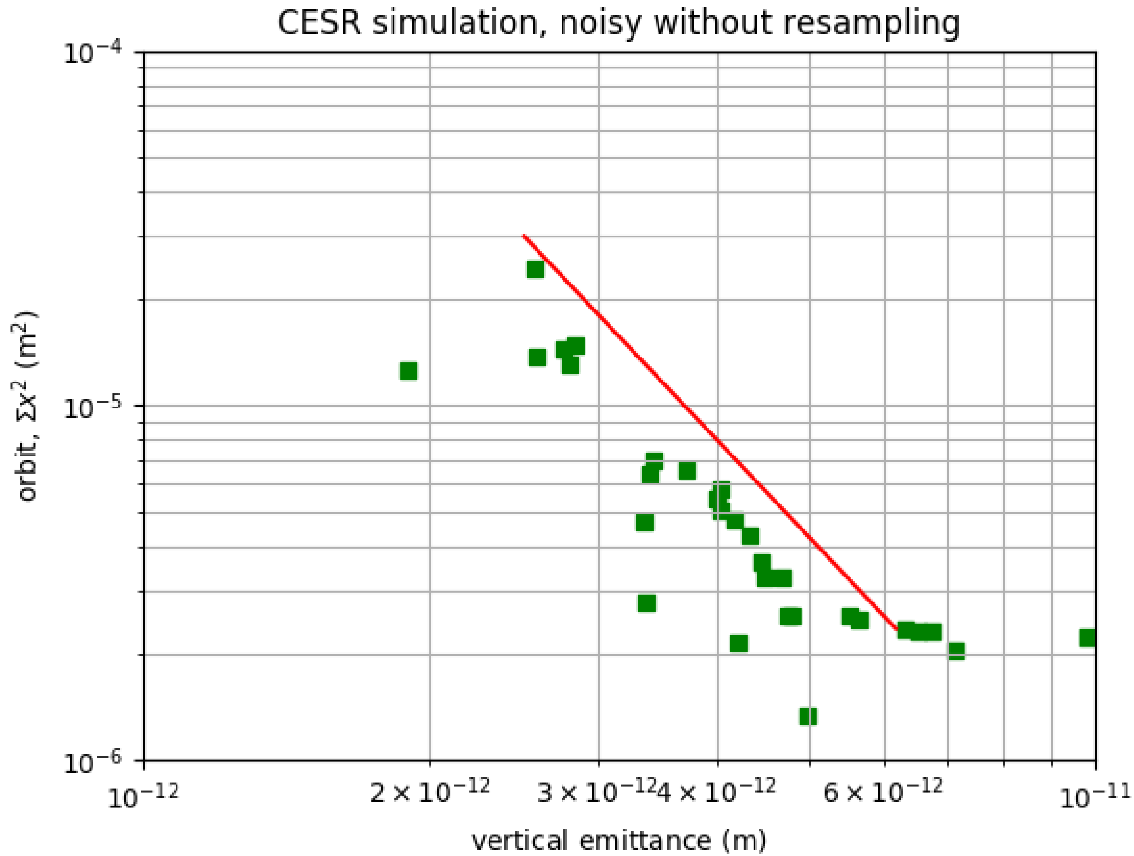

CESR simulation, noisy without resampling
10^{-4}
10^{-5}
10^{-6}
orbit, Σx^2 (m^2)
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)



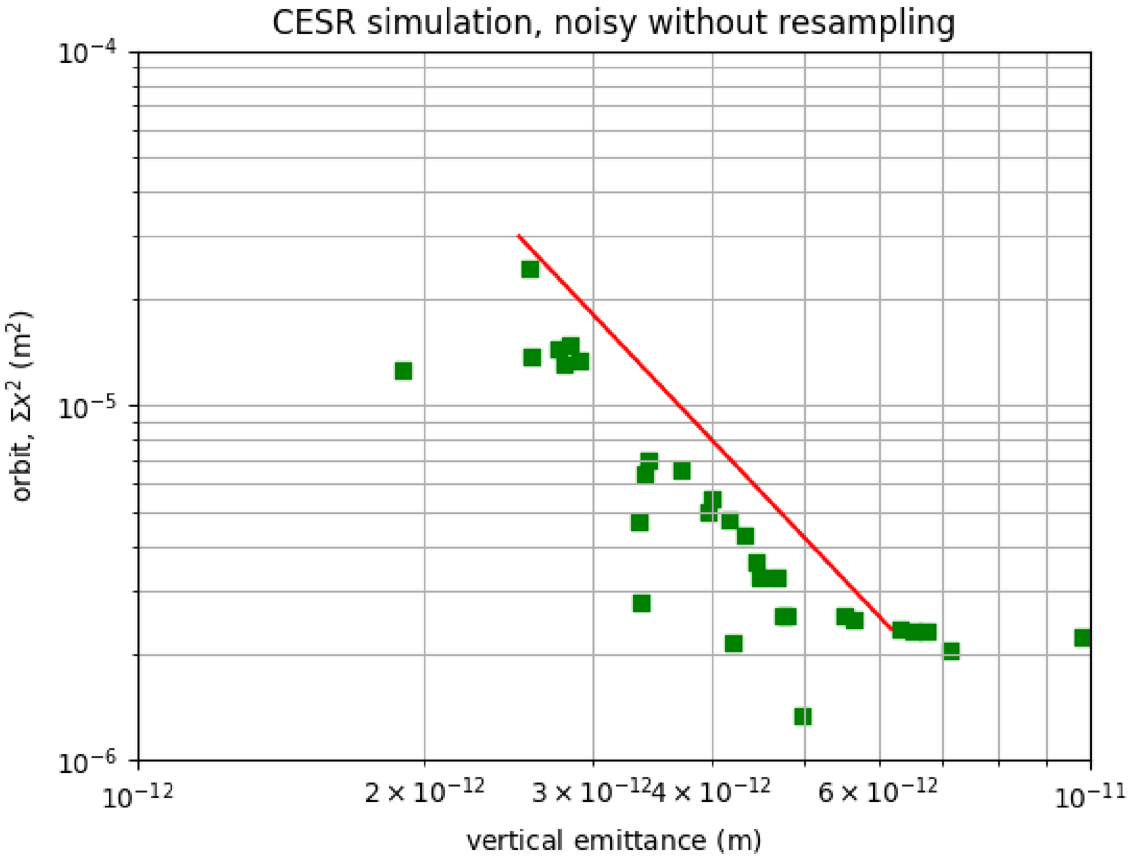
CESR simulation, noisy without resampling
10^{-4}
10^{-5}
10^{-6}
orbit, Σx^2 (m^2)
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)


CESR simulation, noisy without resampling
orbit, Σx^2 (m^2)
10^{-4}
10^{-5}
10^{-6}
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)

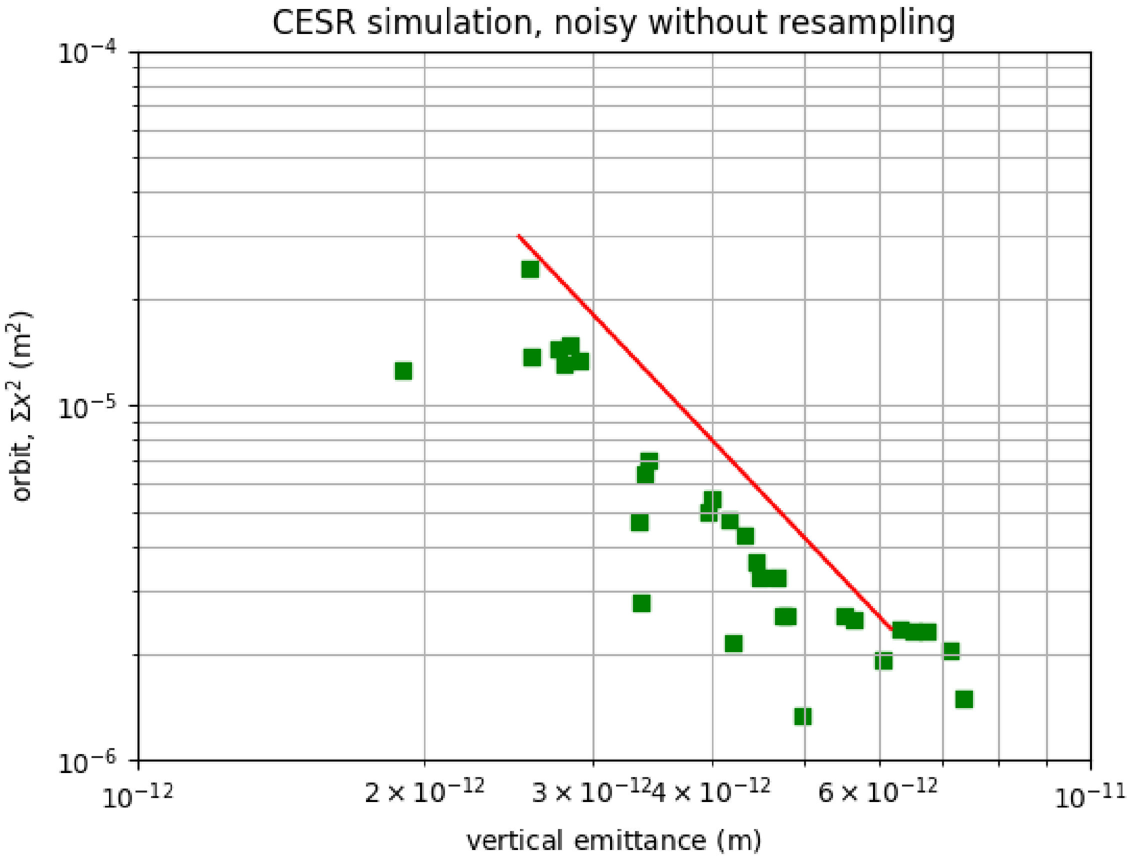

CESR simulation, noisy without resampling
orbit, Σx^2 (m^2)
vertical emittance (m)
10^{-4}
10^{-5}
10^{-6}
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}



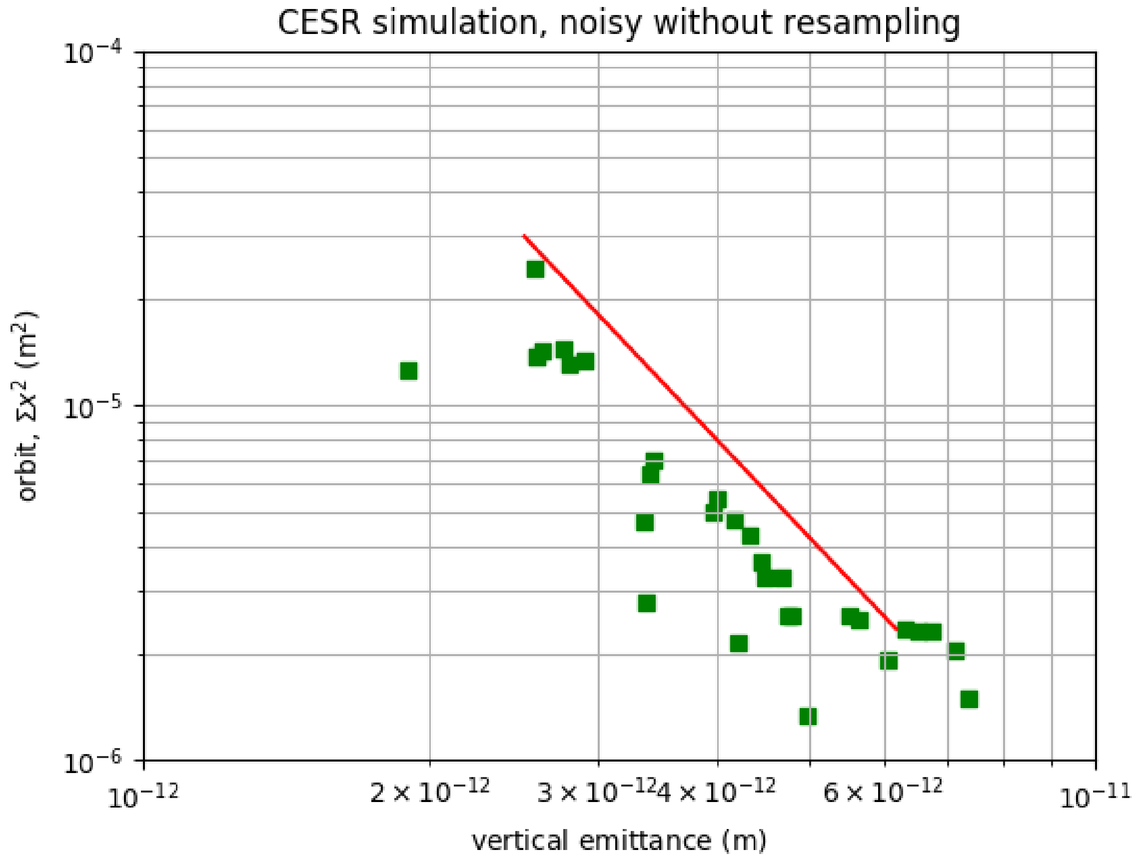
CESR simulation, noisy without resampling
10^{-4}
10^{-5}
10^{-6}
orbit, Σx^2 (m^2)
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)



CESR simulation, noisy without resampling
10^{-4}
10^{-5}
10^{-6}
orbit, Σx^2 (m^2)
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)



CESR simulation, noisy without resampling
10^{-4}
10^{-5}
10^{-6}
orbit, Σx^2 (m^2)
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)


CESR simulation, noisy without resampling
10^{-4}
10^{-5}
10^{-6}
orbit, Σx^2 (m^2)
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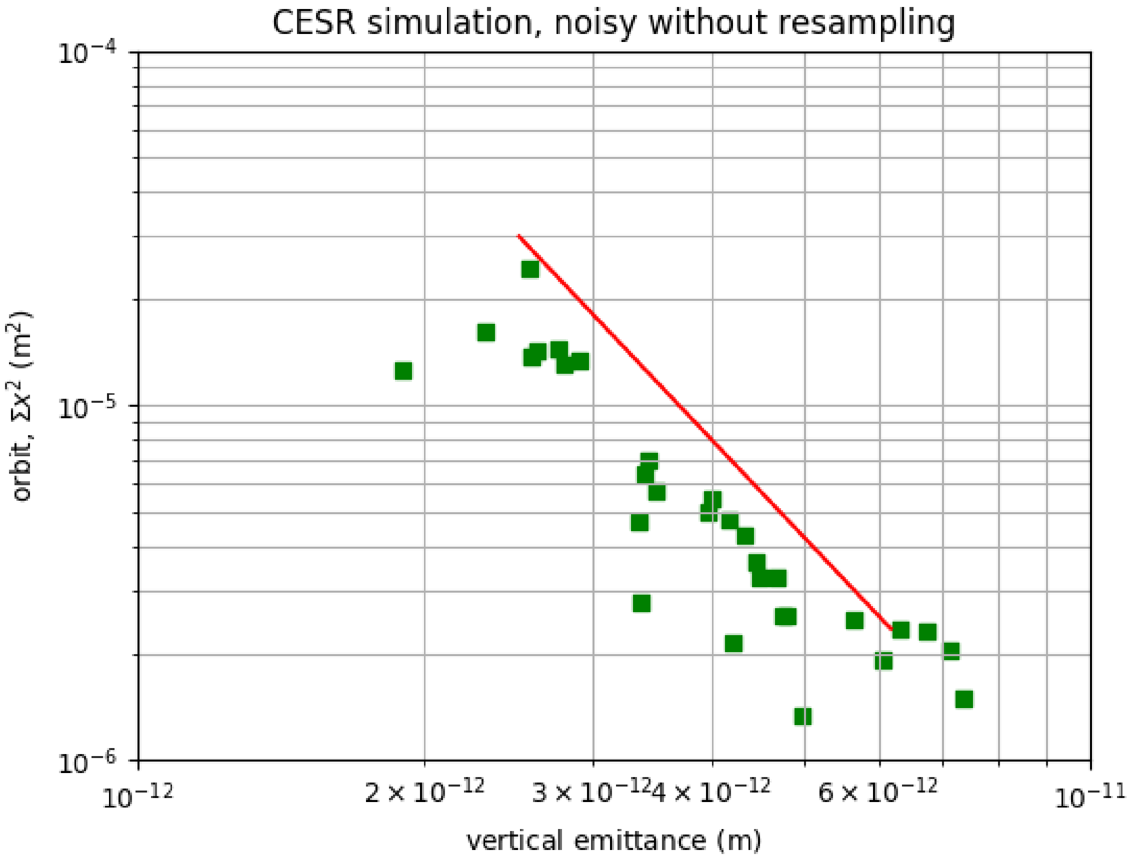
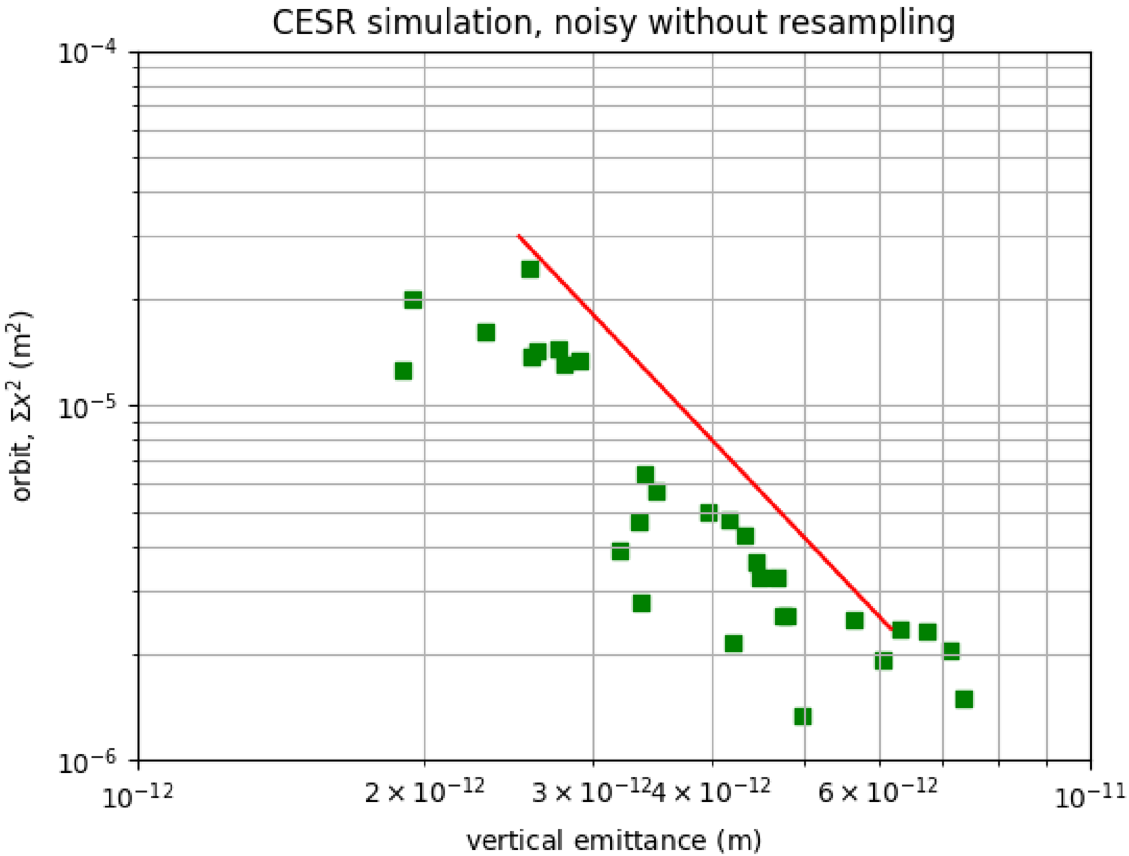
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)



CESR simulation, noisy without resampling
10^{-4}
10^{-5}
10^{-6}
orbit, Σx^2 (m^2)
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)



CESR simulation, noisy without resampling
10^{-4}
10^{-5}
10^{-6}
orbit, Σx^2 (m^2)
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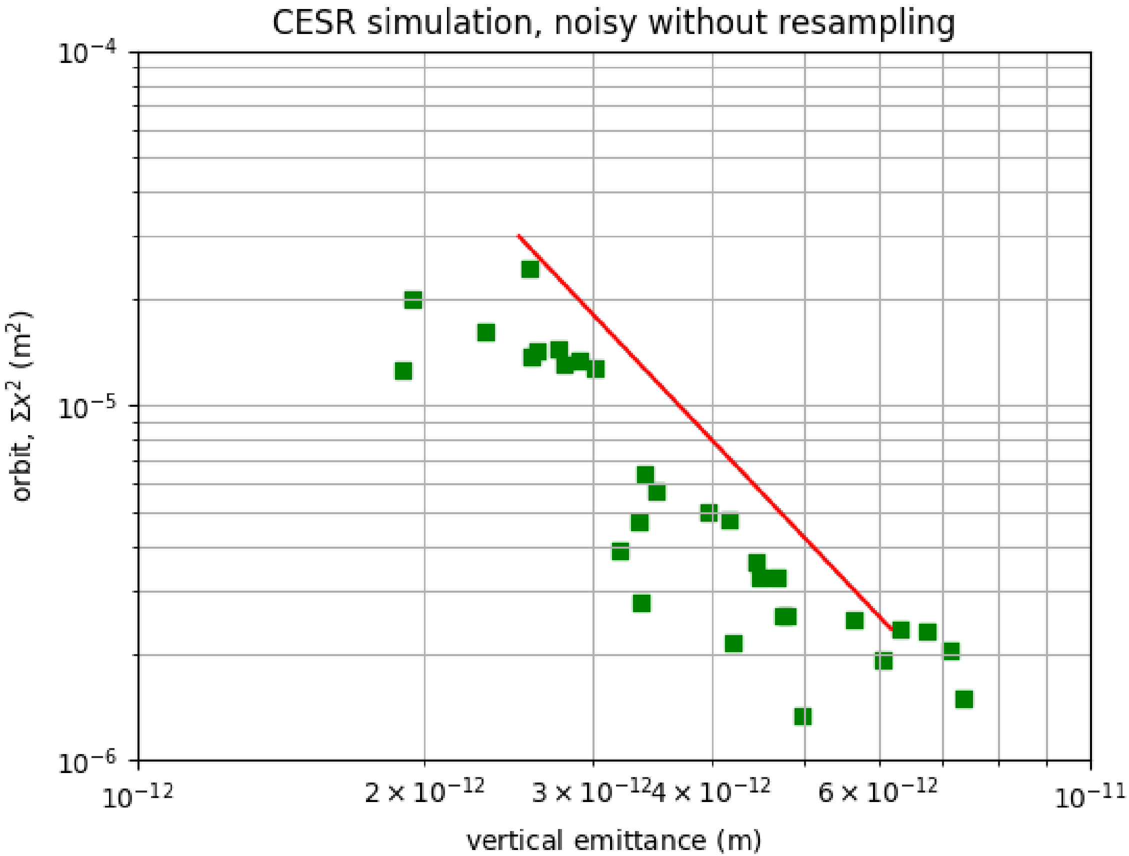
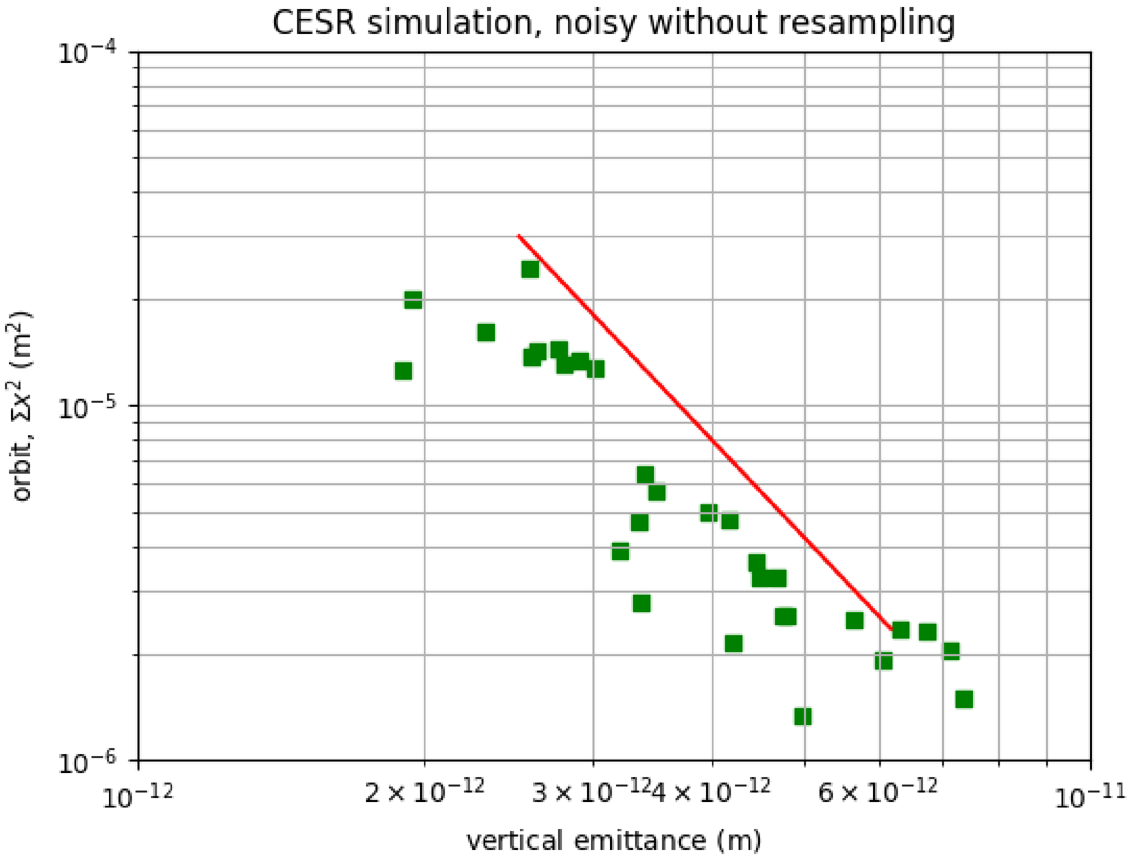
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)



CESR simulation, noisy without resampling
orbit, Σx^2 (m^2)
10^{-4}
10^{-5}
10^{-6}
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)



CESR simulation, noisy without resampling
10^{-4}
10^{-5}
10^{-6}
orbit, Σx^2 (m^2)
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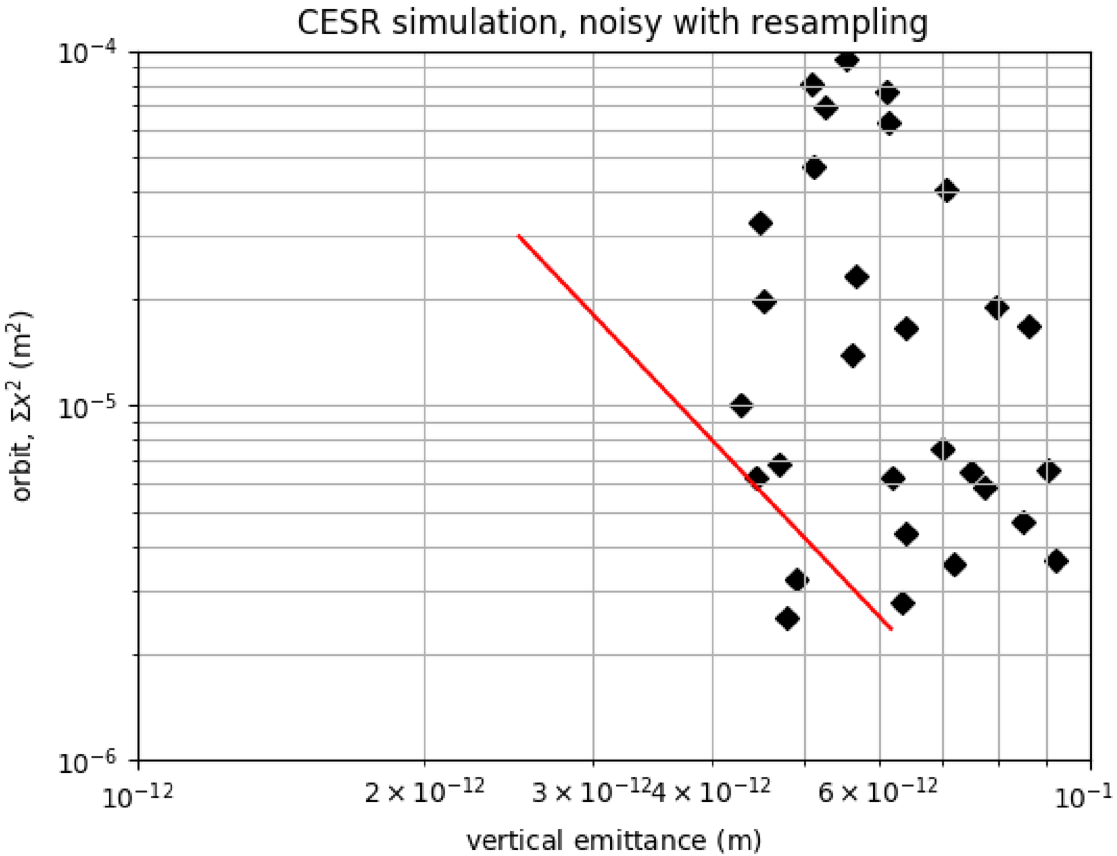
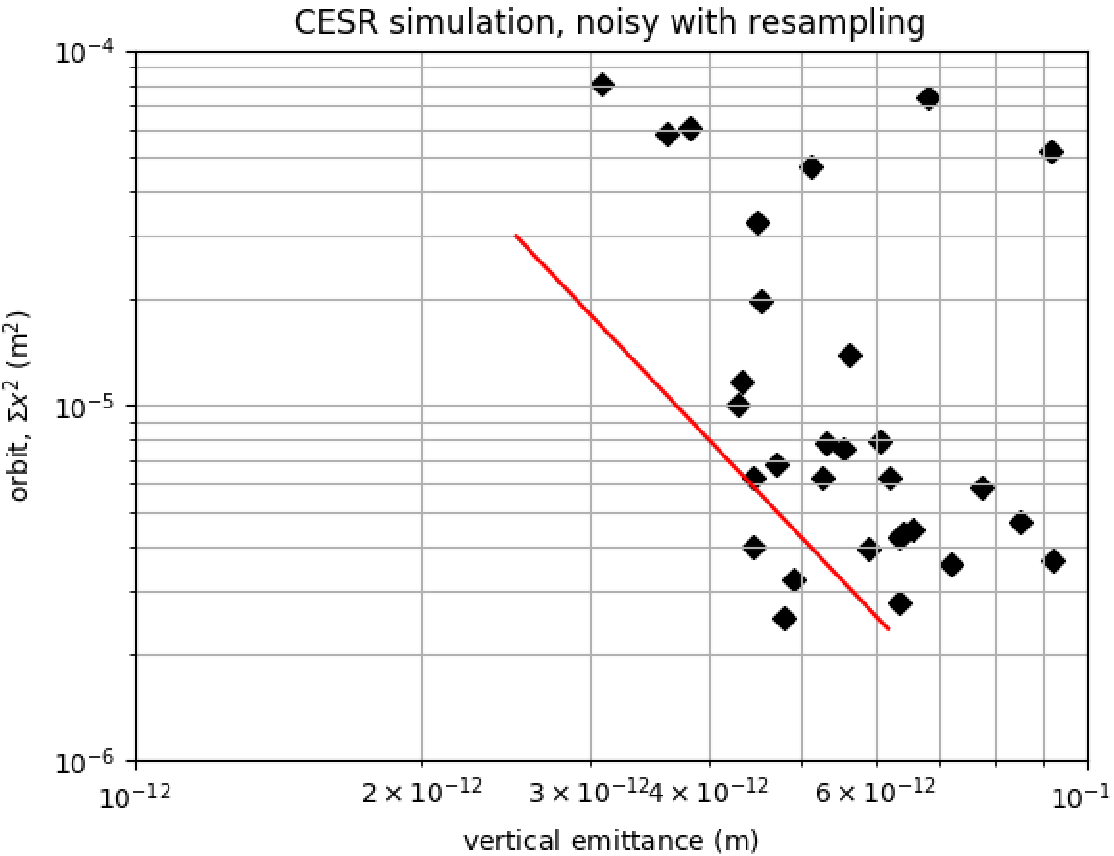
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)



CESR simulation, noisy with resampling
10^{-4}
10^{-5}
10^{-6}
orbit, Σx^2 (m^2)
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)


CESR simulation, noisy with resampling
10^{-4}
10^{-5}
10^{-6}
orbit, Σx^2 (m^2)
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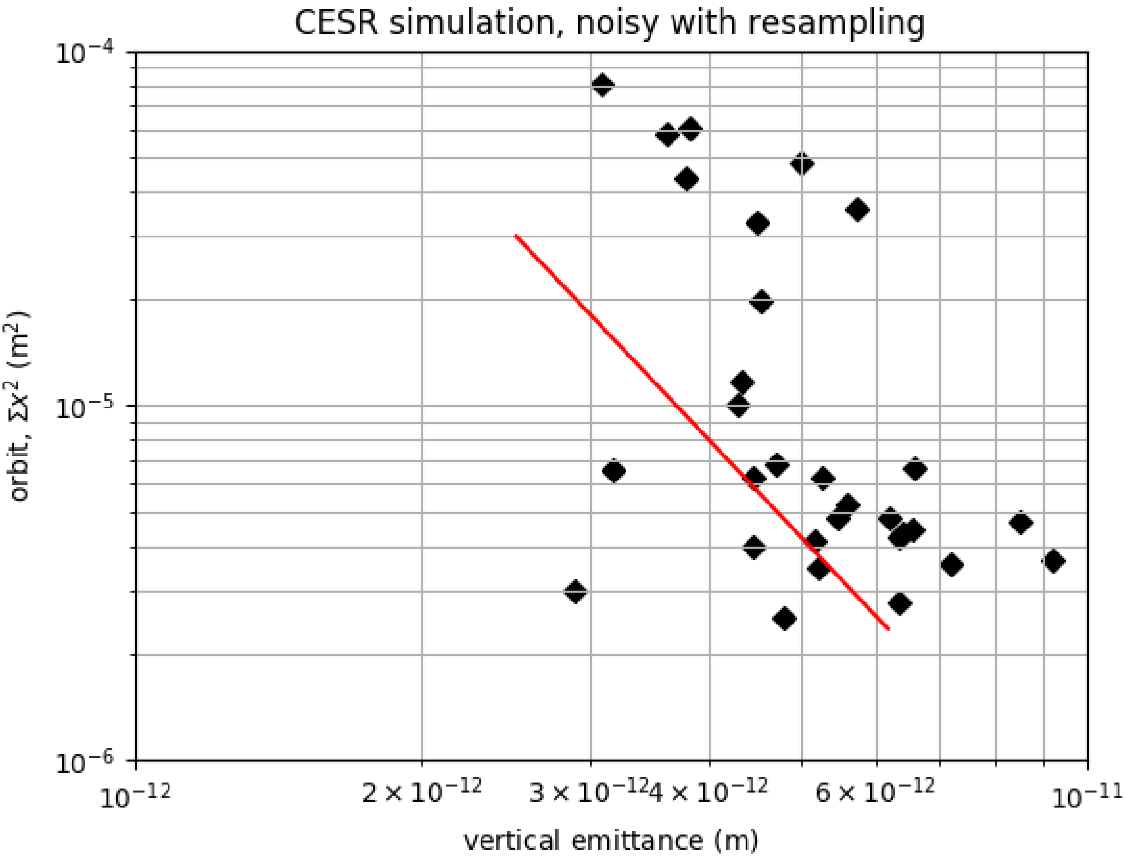
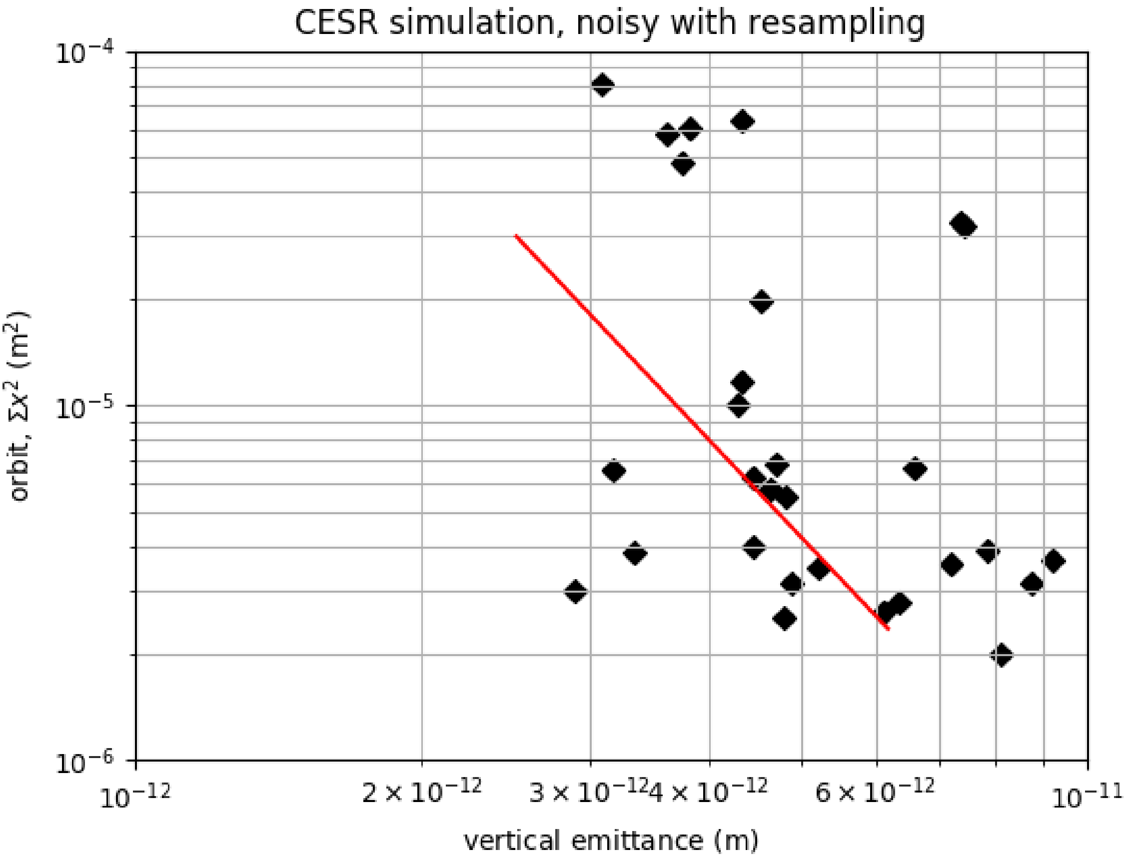
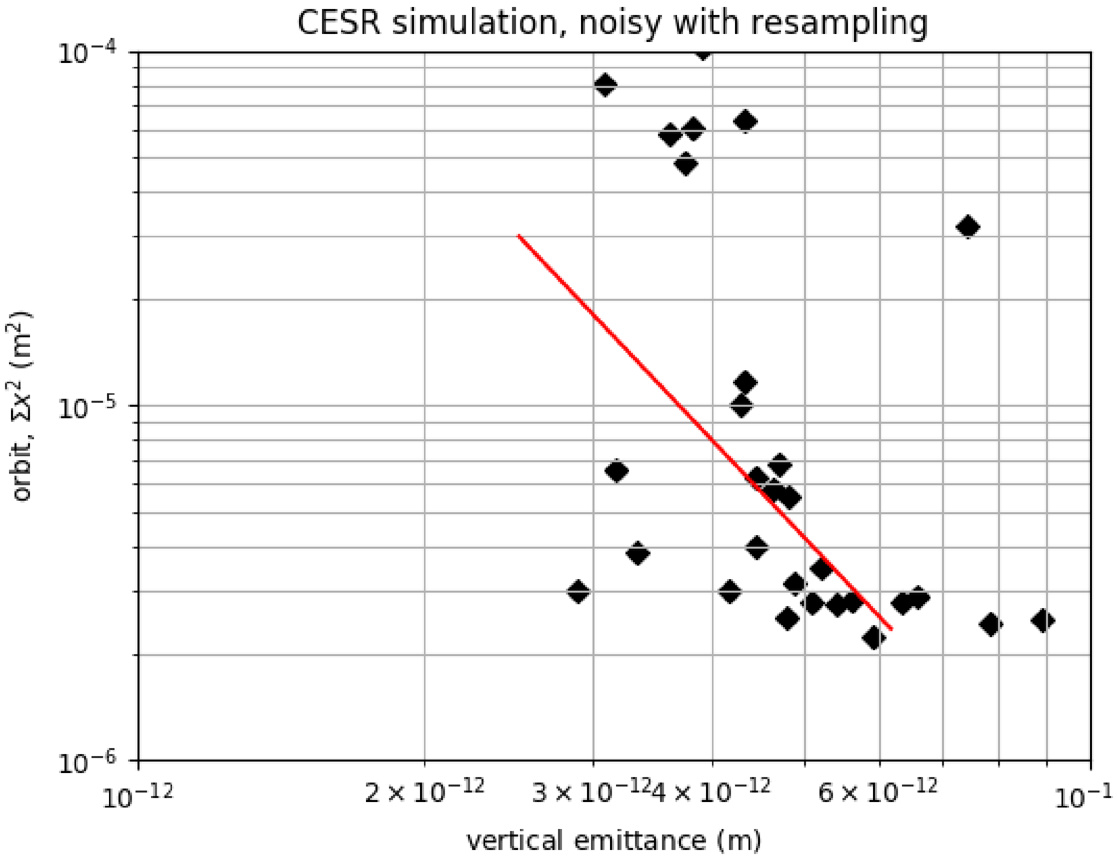
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)



CESR simulation, noisy with resampling
10^{-4}
10^{-5}
10^{-6}
orbit, Σx^2 (m^2)
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)



CESR simulation, noisy with resampling
10^{-4}
10^{-5}
10^{-6}
orbit, Σx^2 (m^2)
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)



CESR simulation, noisy with resampling
10^{-4}
10^{-5}
10^{-6}
orbit, Σx^2 (m^2)
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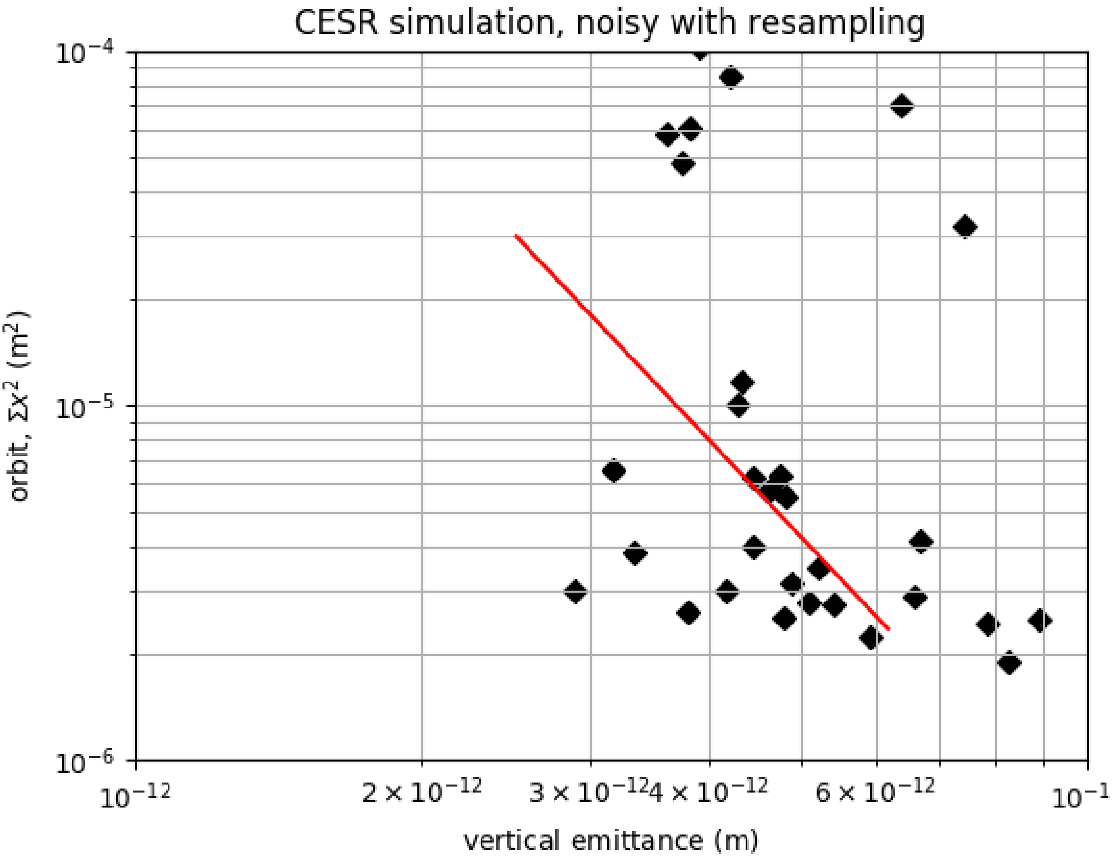
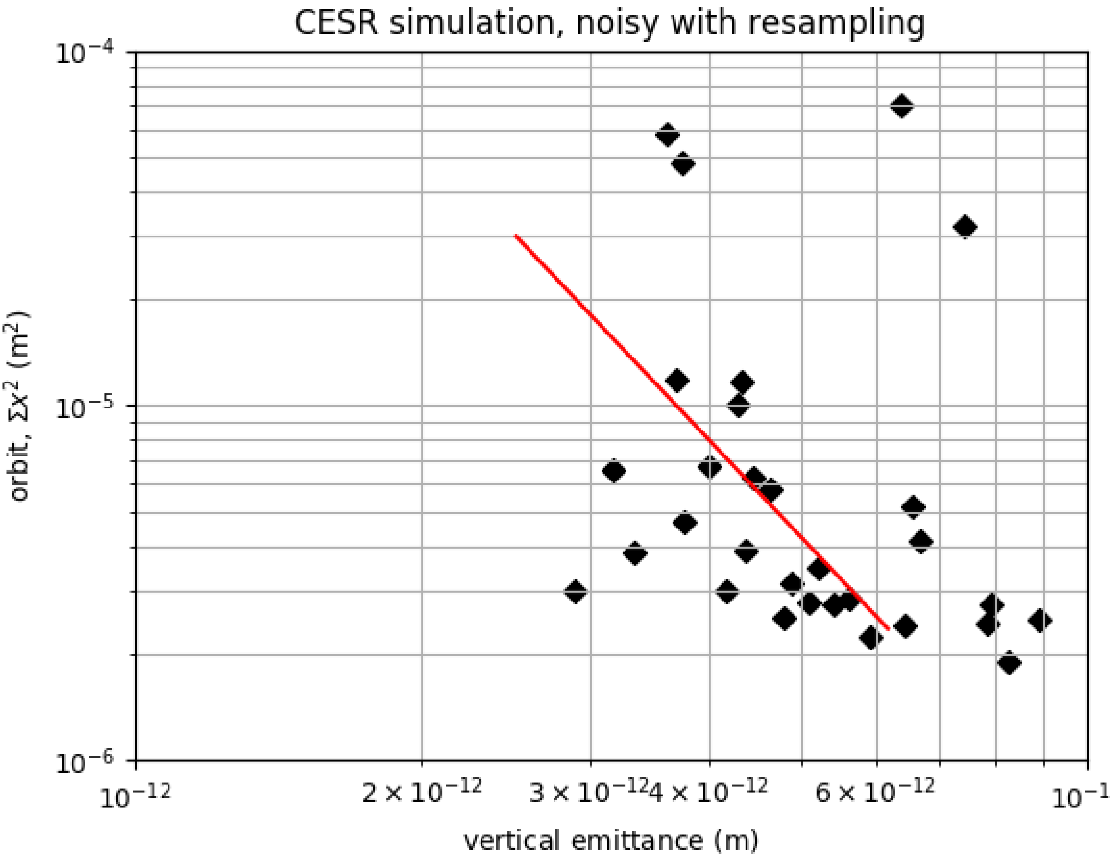
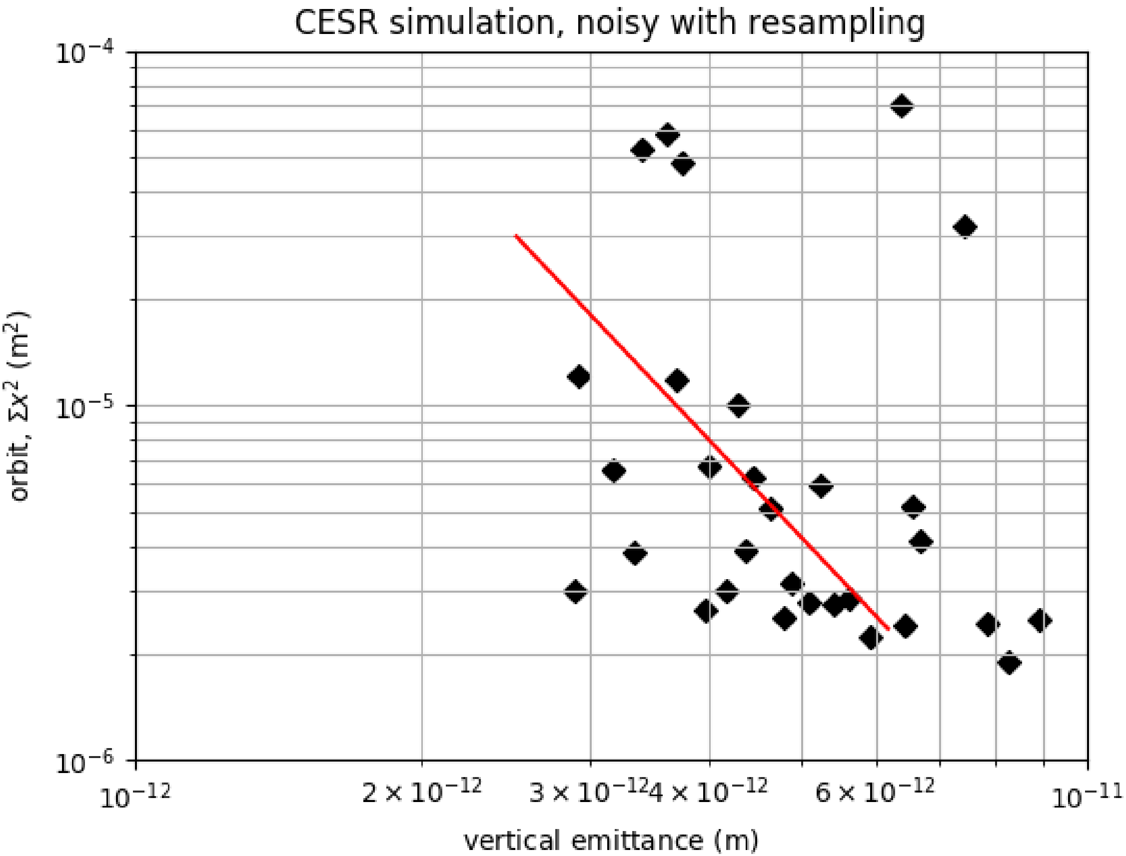
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)



CESR simulation, noisy with resampling
10^{-4}
10^{-5}
10^{-6}
orbit, Σx^2 (m^2)
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)



CESR simulation, noisy with resampling
orbit, Σx^2 (m^2)
10^{-4}
10^{-5}
10^{-6}
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)



CESR simulation, noisy with resampling
10^{-4}
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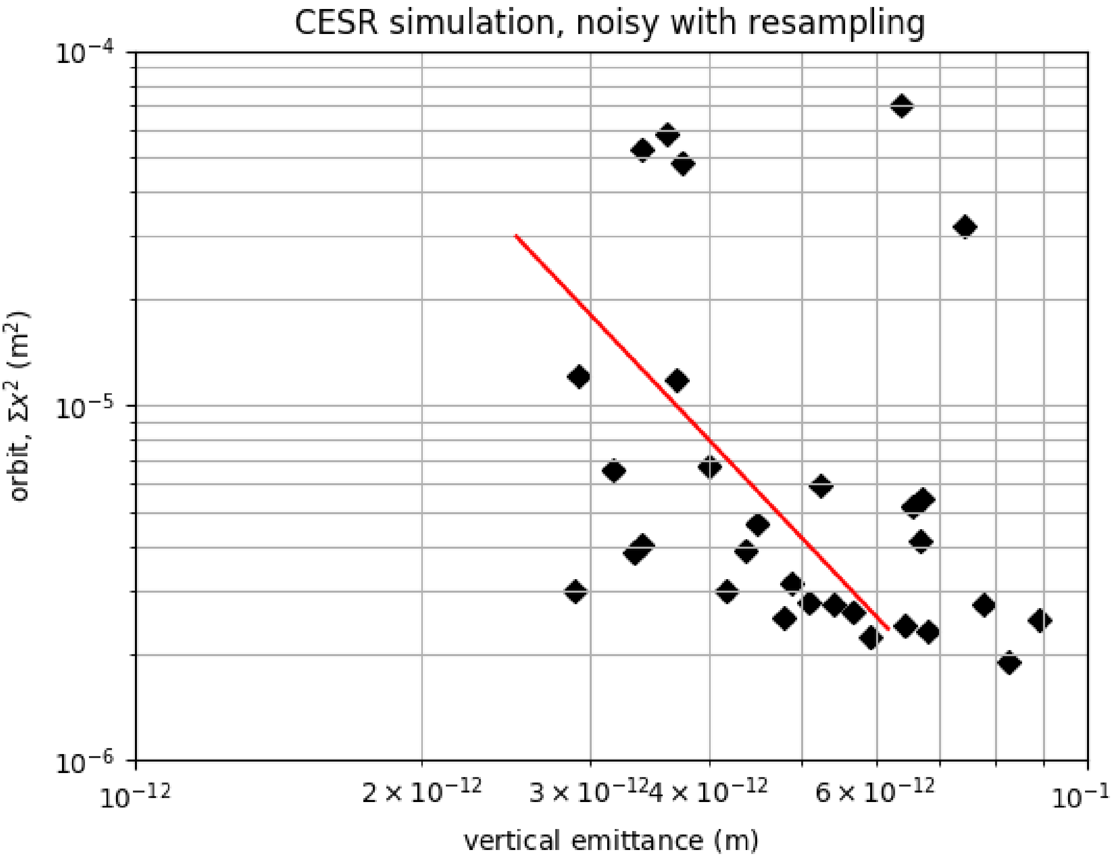
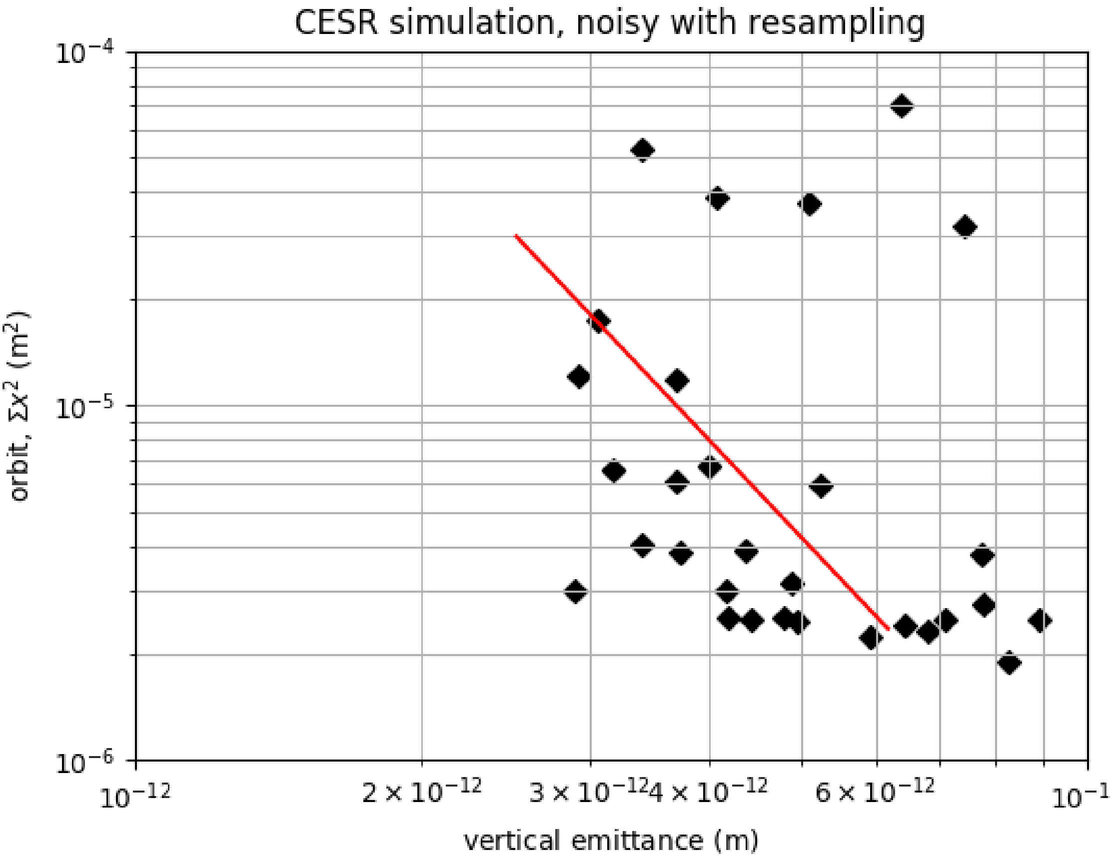
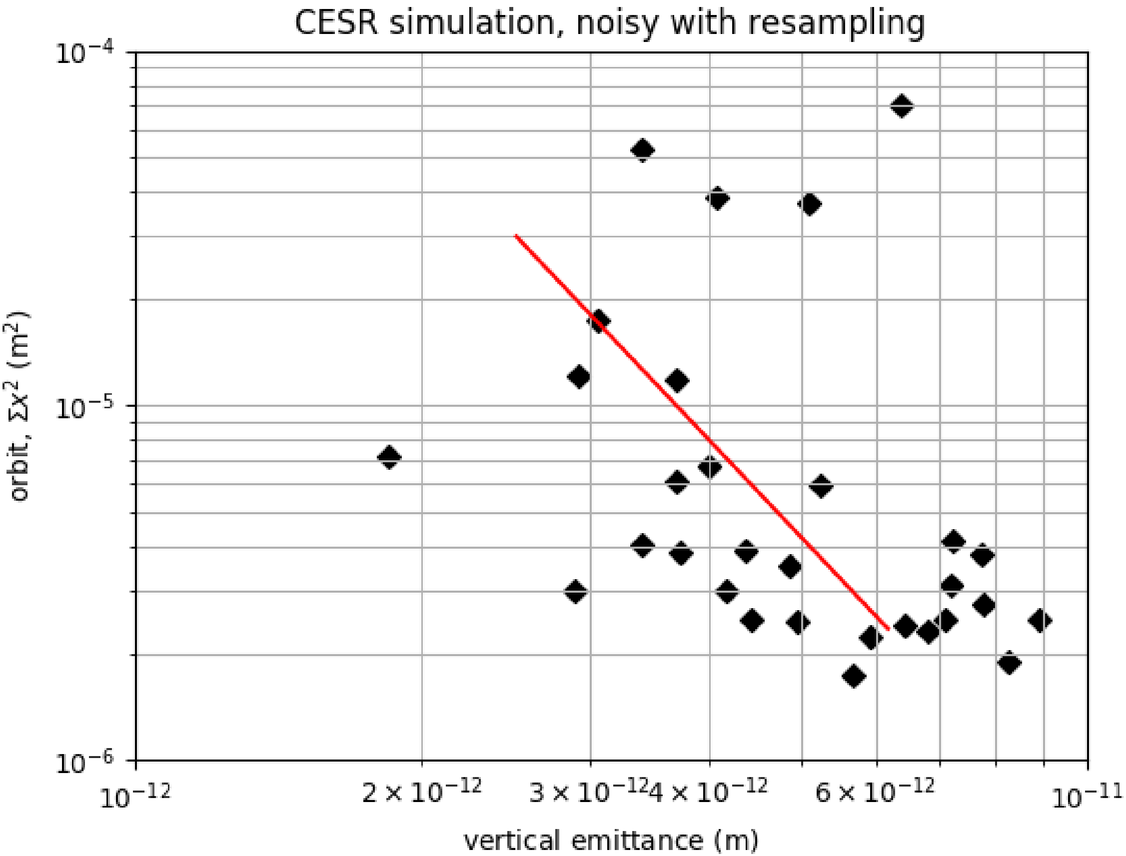
10^{-6}
orbit, Σx^2 (m^2)
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)



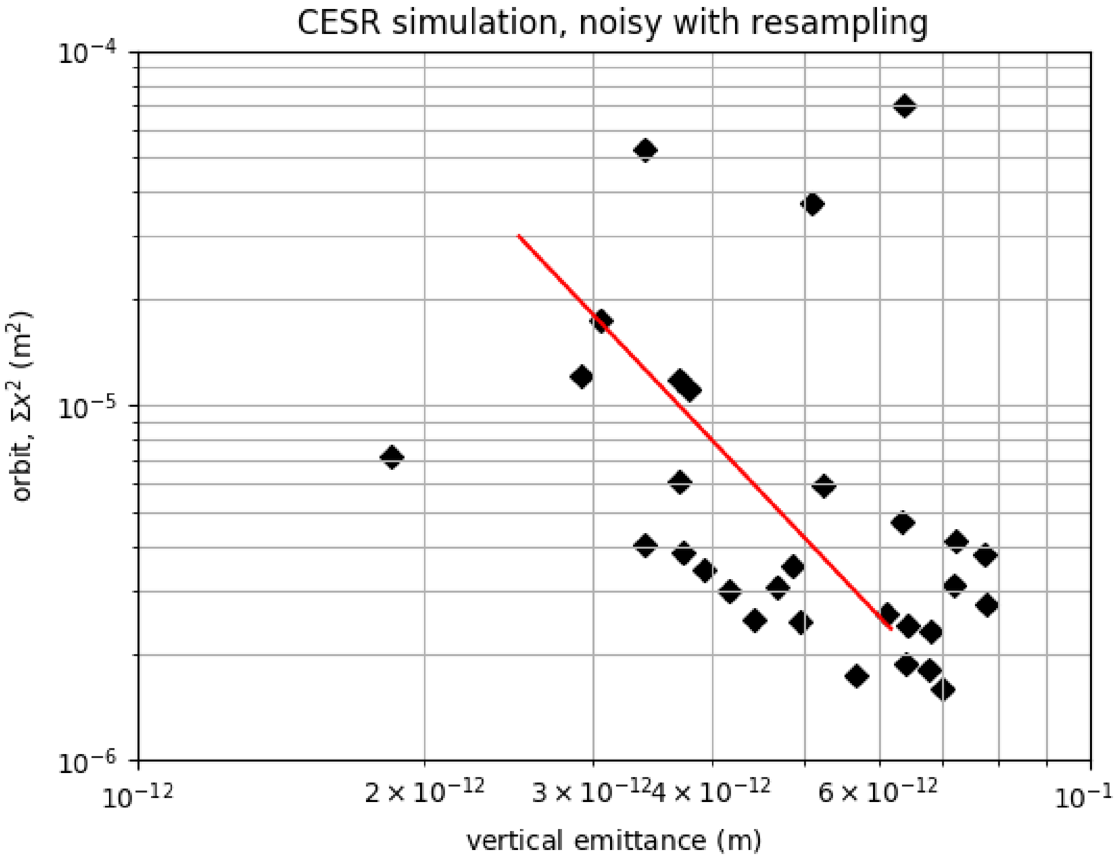
CESR simulation, noisy with resampling
10^{-4}
10^{-5}
10^{-6}
orbit, Σx^2 (m^2)
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)



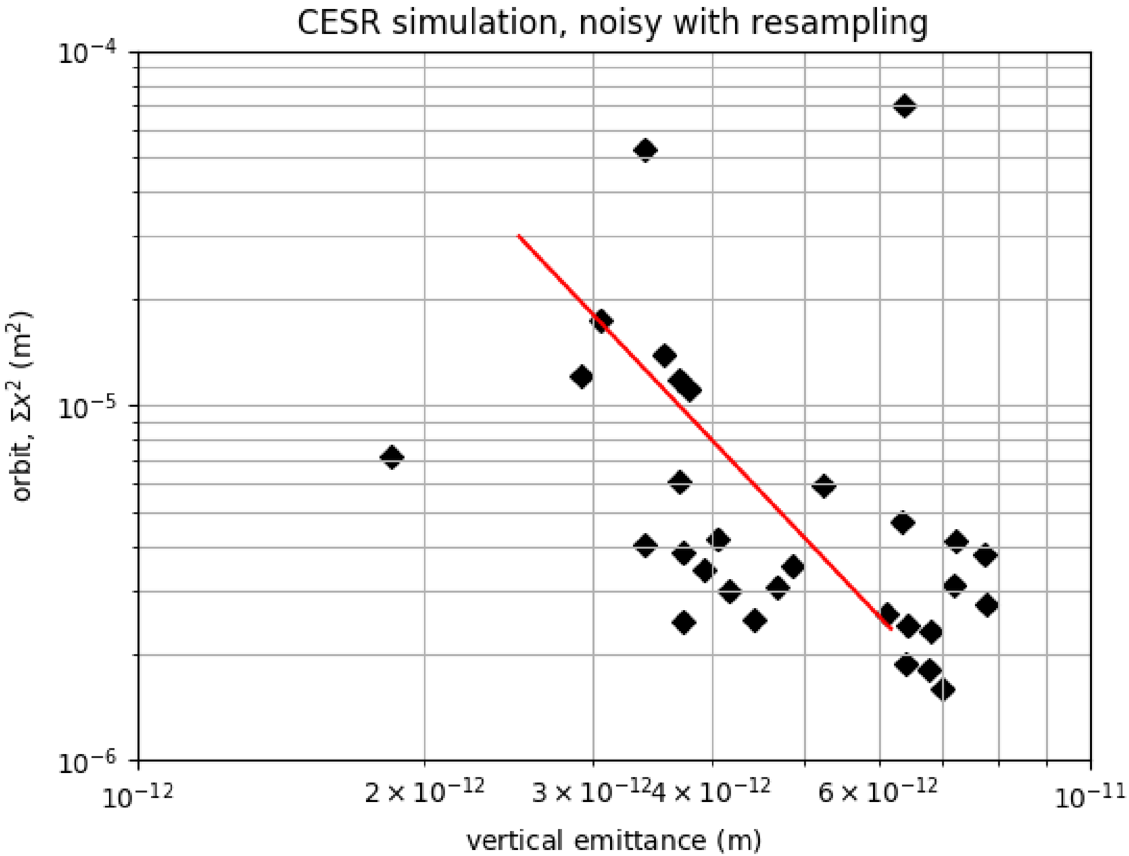
CESR simulation, noisy with resampling
10^{-4}
10^{-5}
10^{-6}
orbit, Σx^2 (m^2)
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)



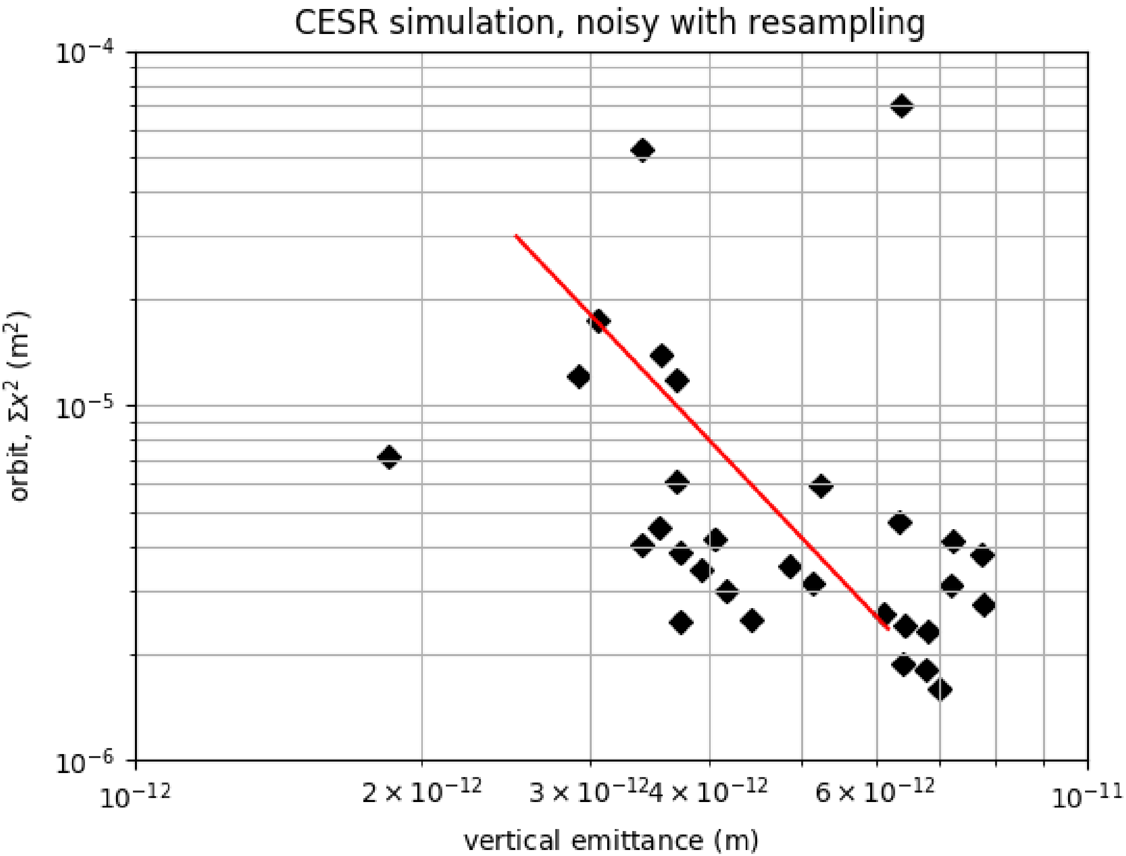
CESR simulation, noisy with resampling
orbit, Σx^2 (m^2)
10^{-4}
10^{-5}
10^{-6}
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)



CESR simulation, noisy with resampling
10^{-4}
10^{-5}
10^{-6}
orbit, Σx^2 (m^2)
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)



CESR simulation, noisy with resampling
orbit, Σx^2 (m^2)
10^{-4}
10^{-5}
10^{-6}
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)



CESR simulation, noisy with resampling
10^{-4}
10^{-5}
10^{-6}
orbit, Σx^2 (m^2)
10^{-12}
2×10^{-12}
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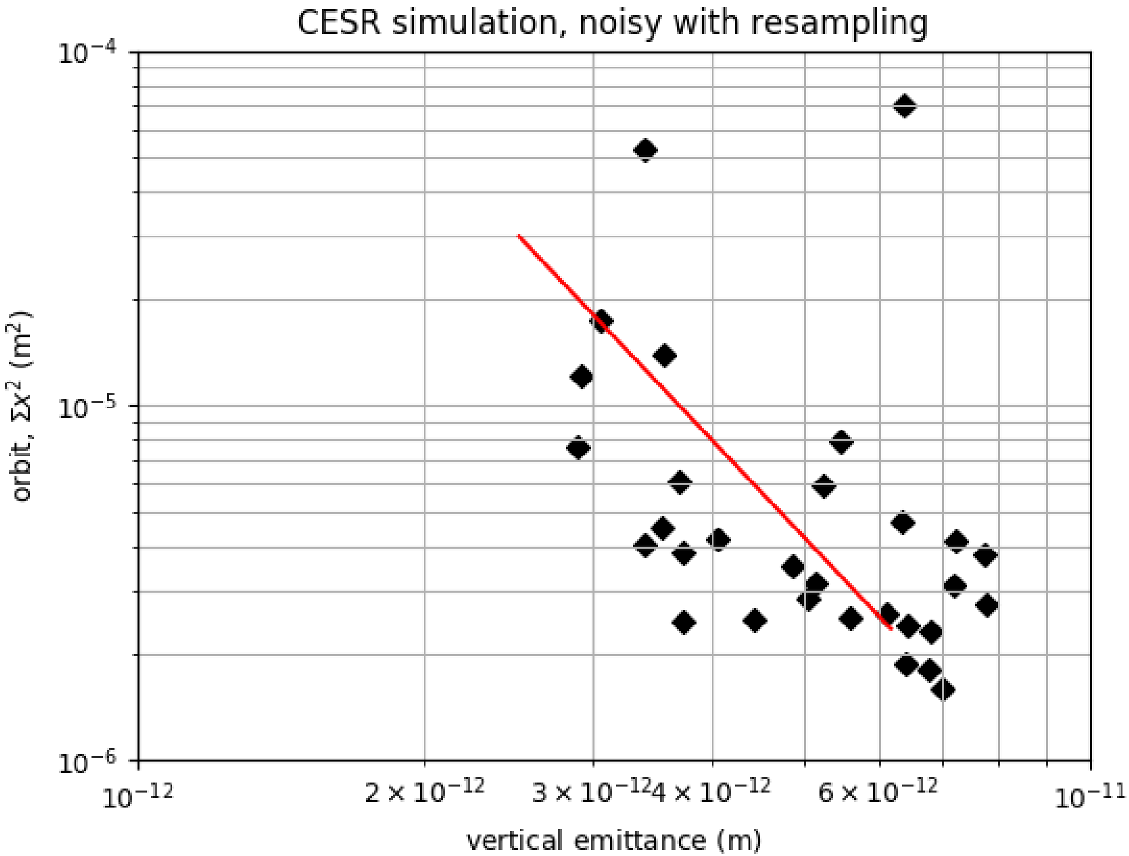
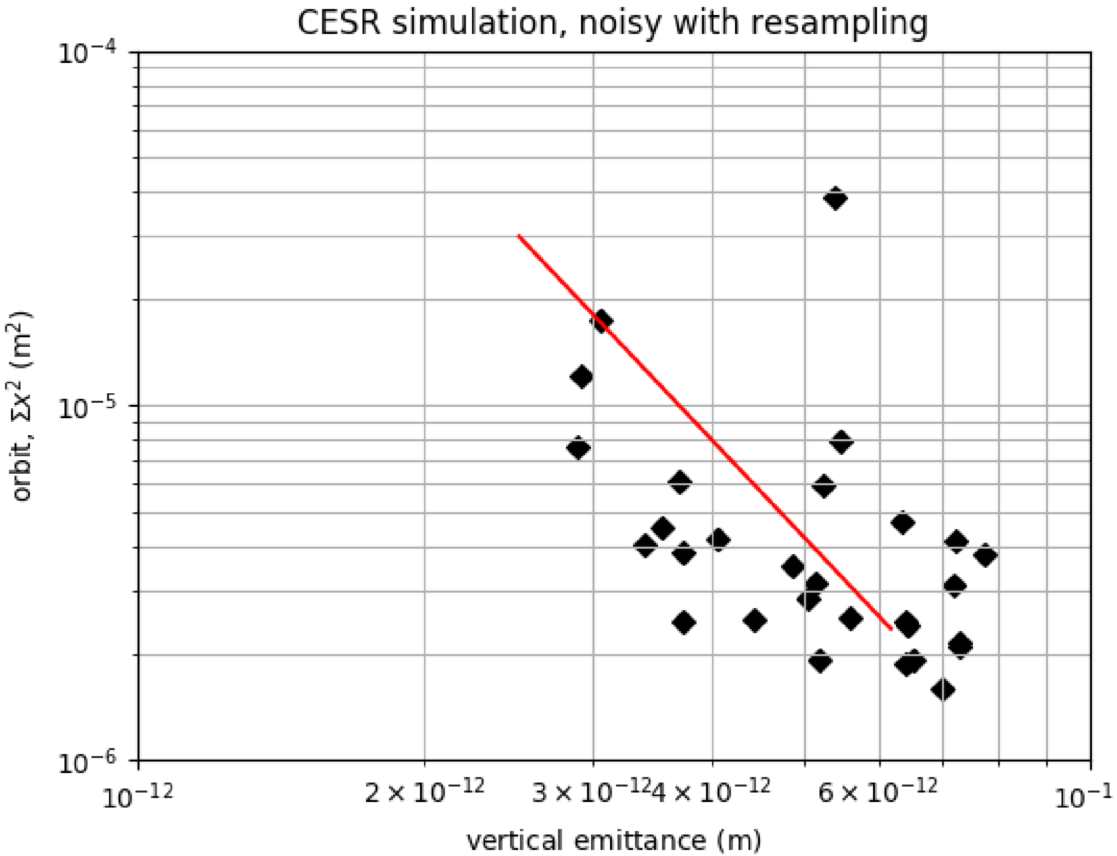
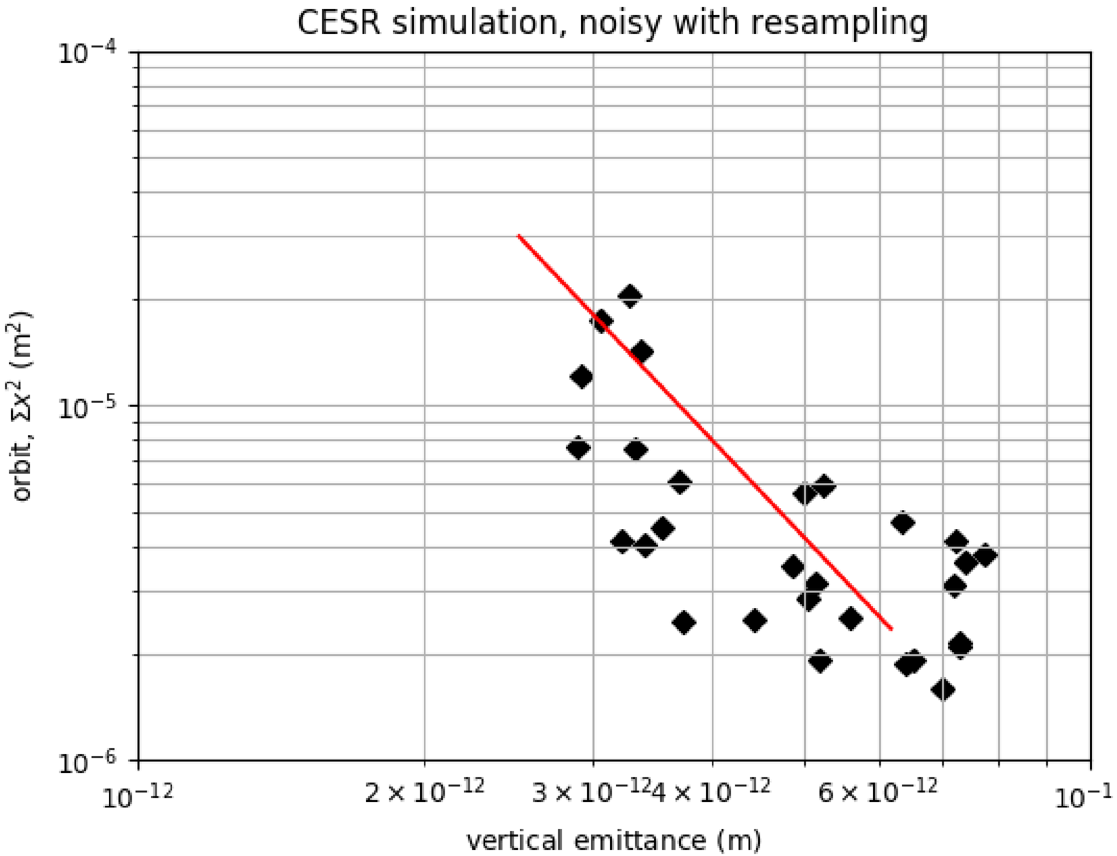
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)



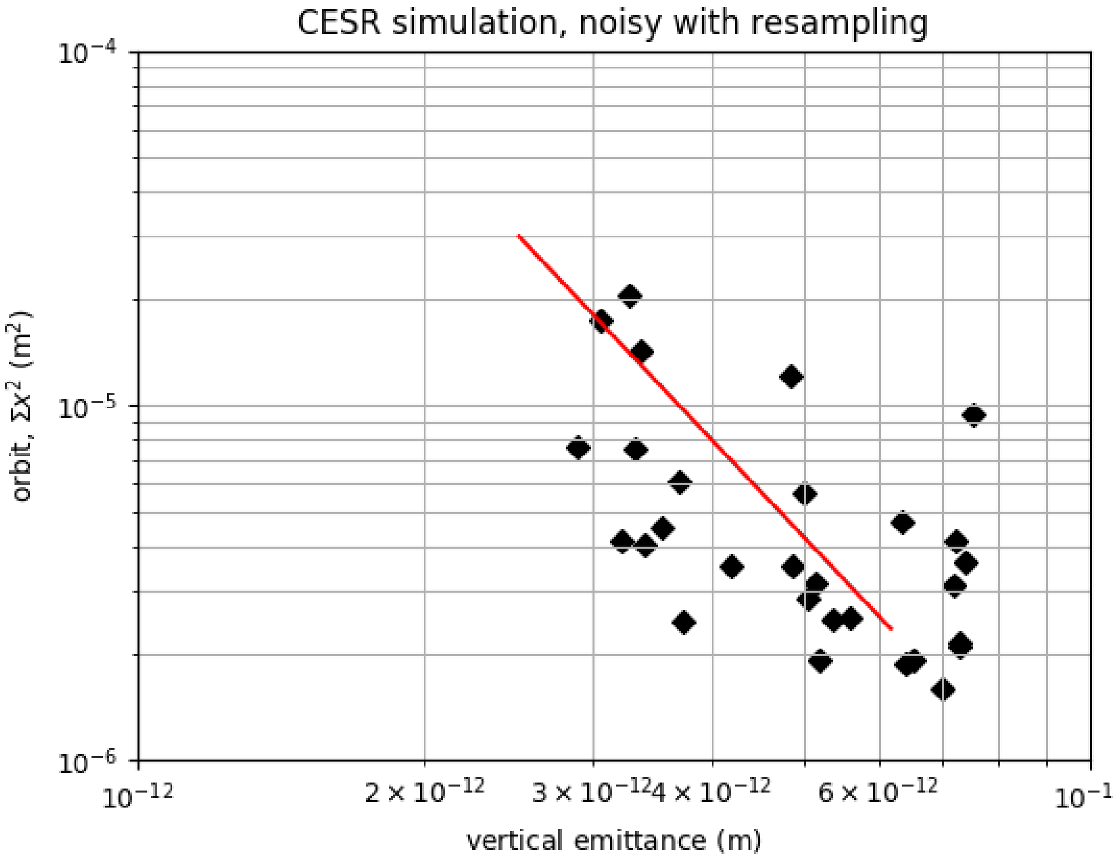
CESR simulation, noisy with resampling
orbit, Σx^2 (m^2)
10^{-4}
10^{-5}
10^{-6}
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)



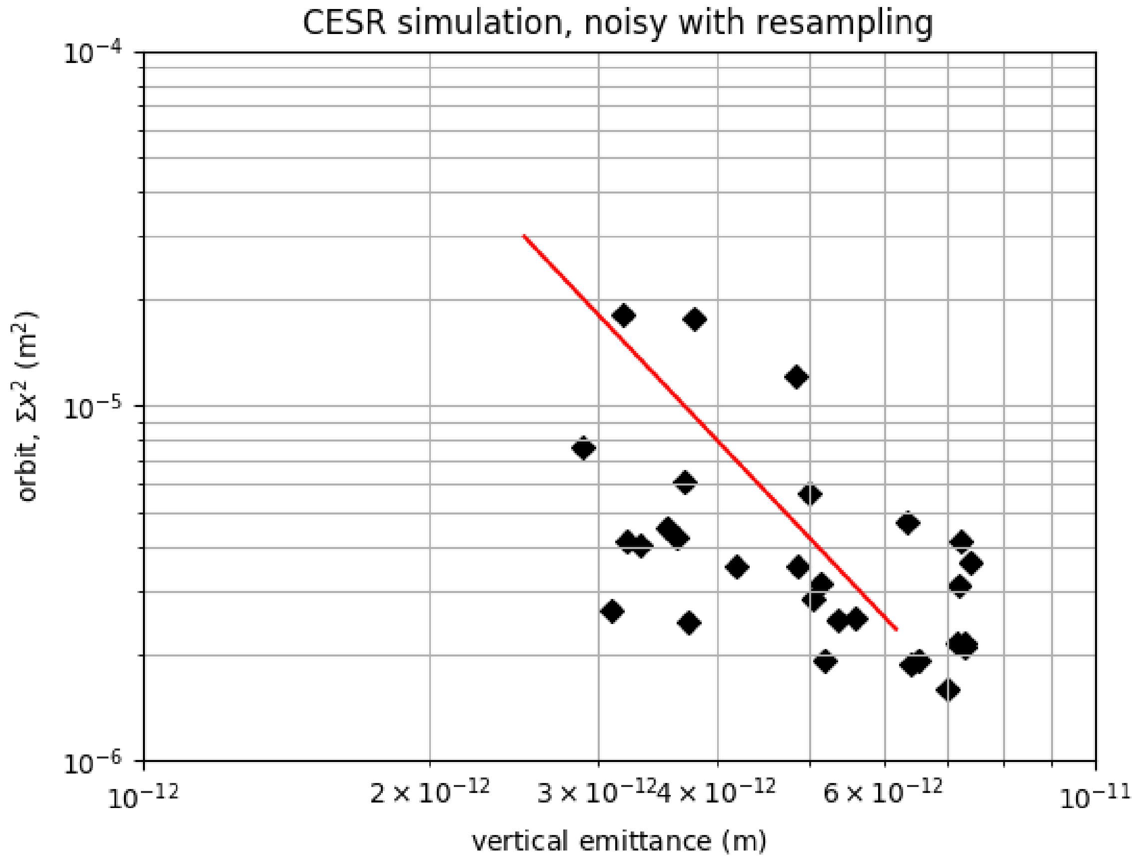
CESR simulation, noisy with resampling
orbit, Σx^2 (m^2)
10^{-4}
10^{-5}
10^{-6}
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)



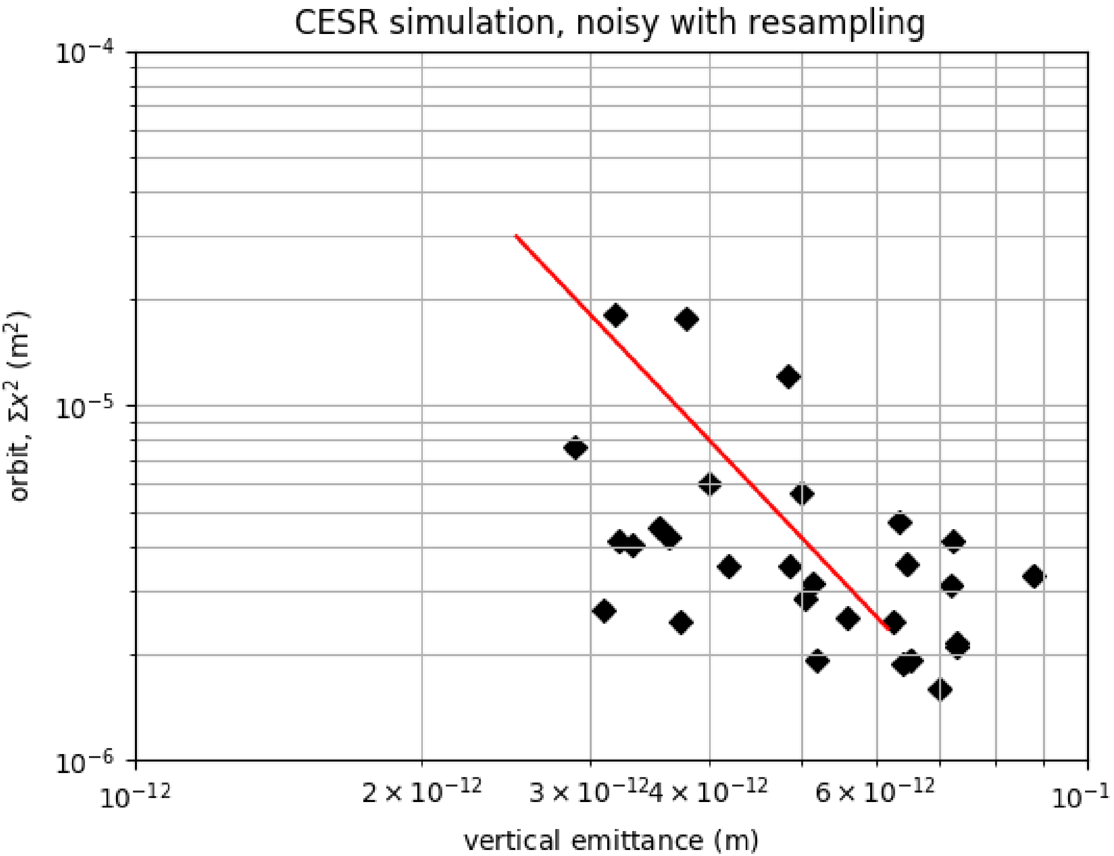
CESR simulation, noisy with resampling
10^{-4}
10^{-5}
10^{-6}
orbit, Σx^2 (m^2)
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)

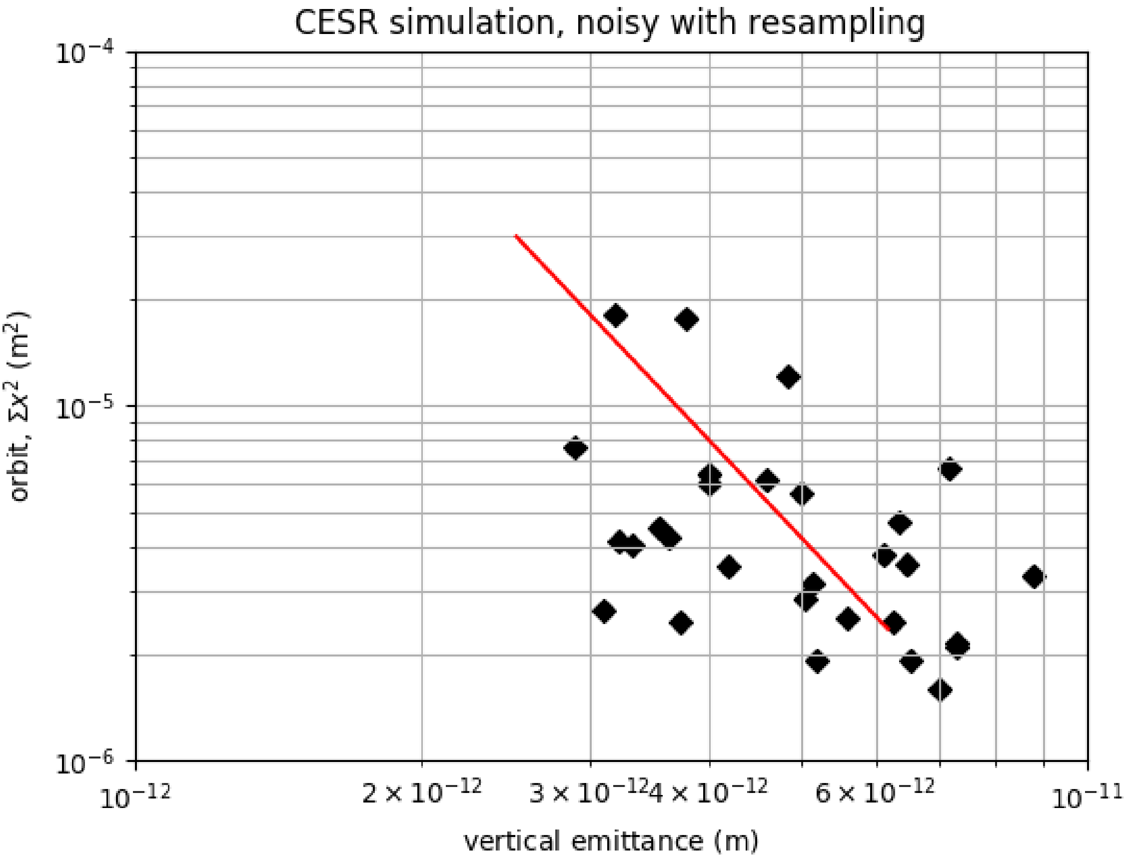


CESR simulation, noisy with resampling
10^{-4}
10^{-5}
10^{-6}
orbit, Σx^2 (m^2)
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)

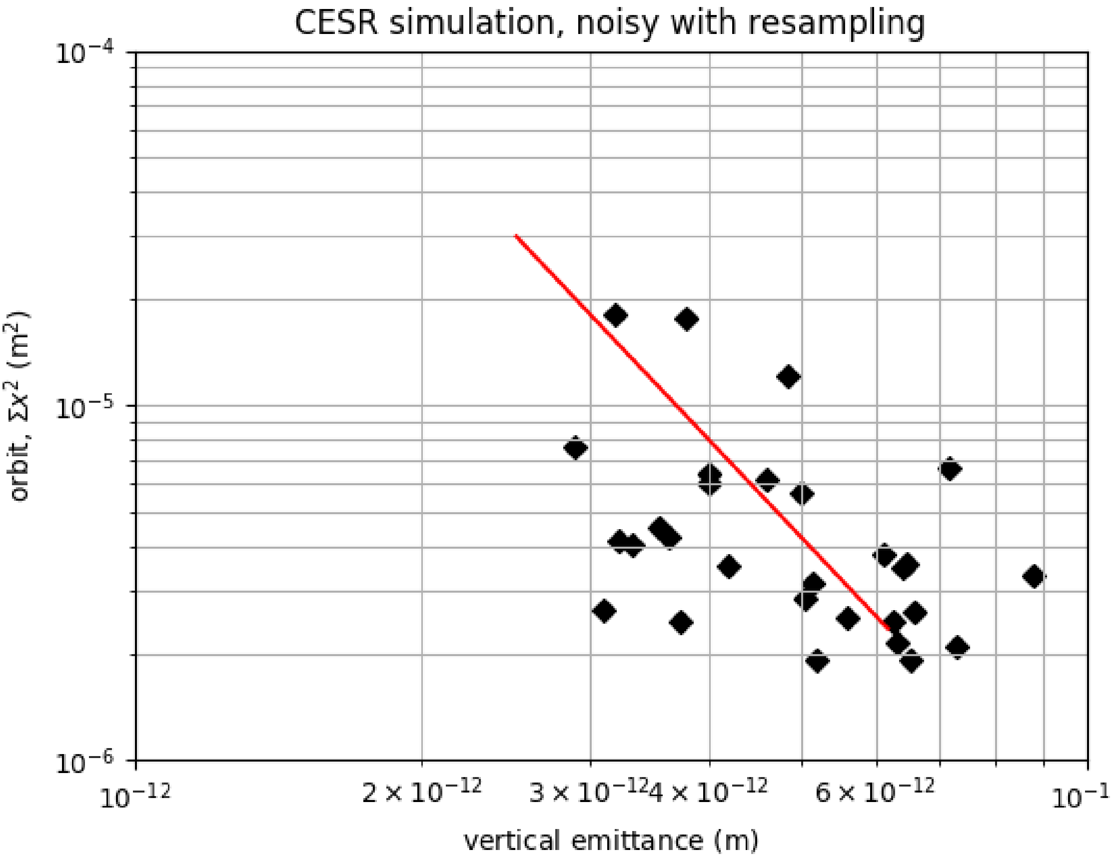


CESR simulation, noisy with resampling
orbit, Σx² (m²)
vertical emittance (m)
10⁻⁴
10⁻⁵
10⁻⁶
10⁻¹²
2 × 10⁻¹²
3 × 10⁻¹²
4 × 10⁻¹²
6 × 10⁻¹²
10⁻¹¹

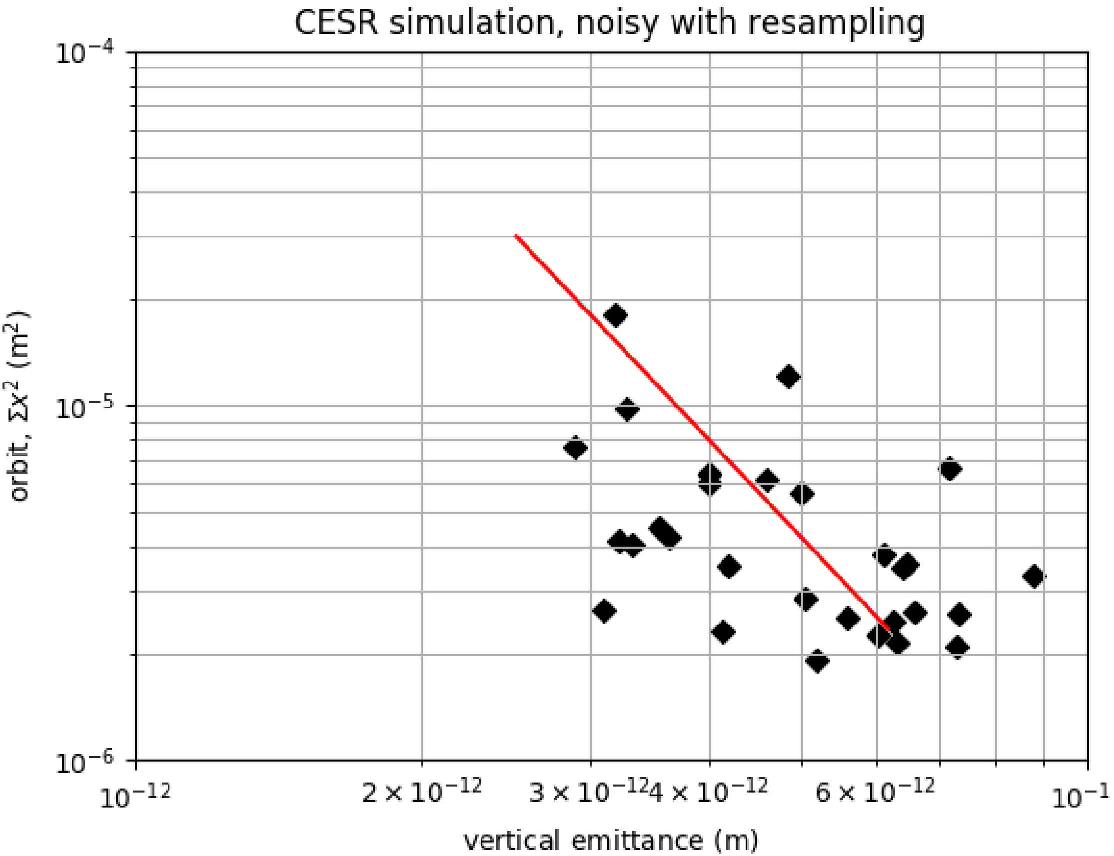

CESR simulation, noisy with resampling
10^{-4}
10^{-5}
10^{-6}
orbit, Σx^2 (m^2)
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)



CESR simulation, noisy with resampling
orbit, Σx^2 (m^2)
10^{-4}
10^{-5}
10^{-6}
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)



CESR simulation, noisy with resampling
10^{-4}
10^{-5}
10^{-6}
orbit, Σx^2 (m^2)
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)

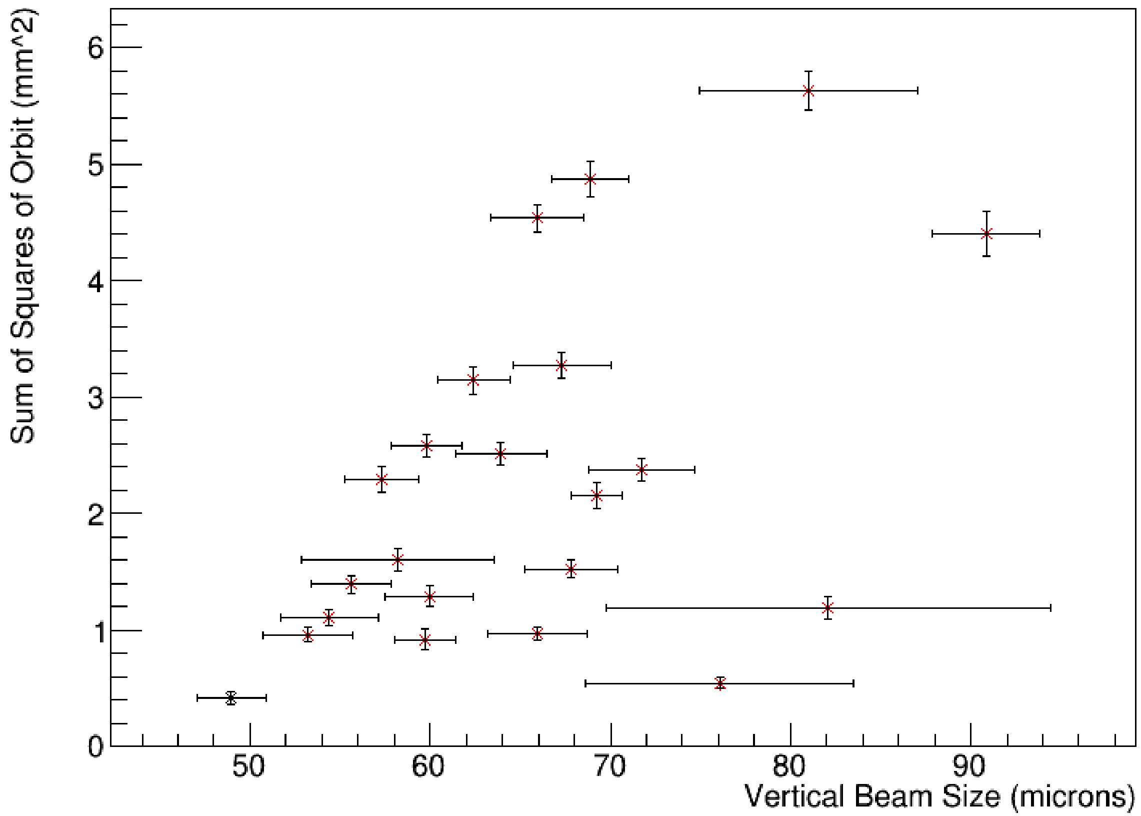


CESR simulation, noisy with resampling
orbit, Σx^2 (m^2)
10^{-4}
10^{-5}
10^{-6}
10^{-12}
2×10^{-12}
3×10^{-12}
4×10^{-12}
6×10^{-12}
10^{-11}
vertical emittance (m)

- Needed: a model-agnostic search for optimal performance *trade-offs*

- We tested an elitist genetic algorithm with re-sampling on bdad simulations of CESR
- Solution set shows randomness but converges in statistics
- Numerical evidence that power-law fit to solution set is an unbiased estimate of trade-off front

Preliminary Results



Final Thoughts

- Any real-life online optimization *metaheuristic* is likely to be a combination of model-cognizant and model-agnostic parts;
- Machine safety needs to “filter” trial solutions preventing them from adopting forbidden states;
- Noise handling and maximizing throughput are always key issues;
- CESR is an ideal platform to deploy new kinds of online optimization strategies, including AI and stochastic algorithms.