Feasibility of OTIMA interferometry for antihydrogen gravity measurement

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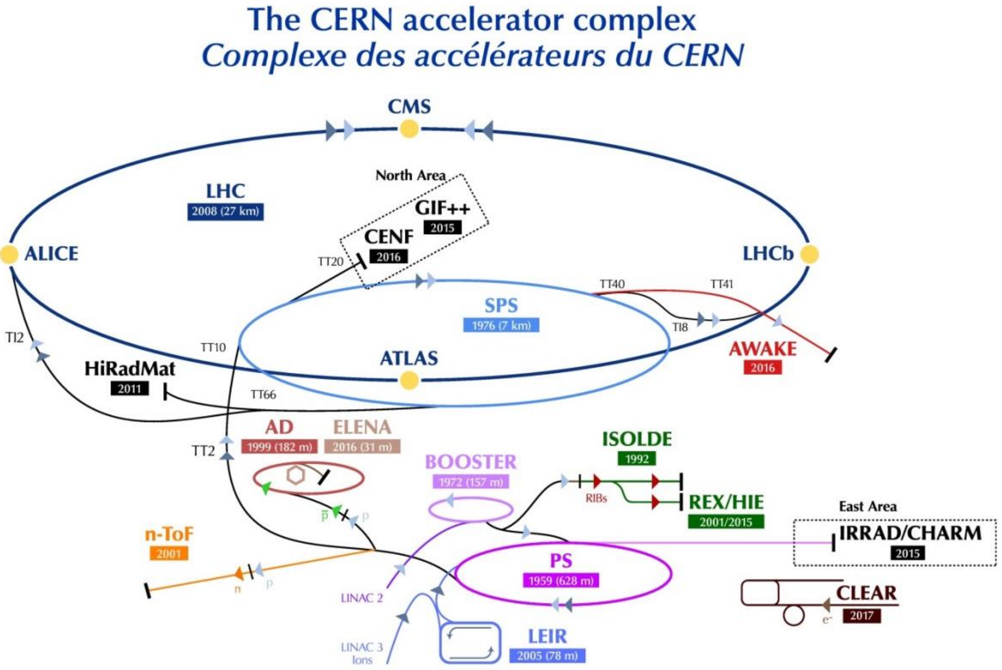
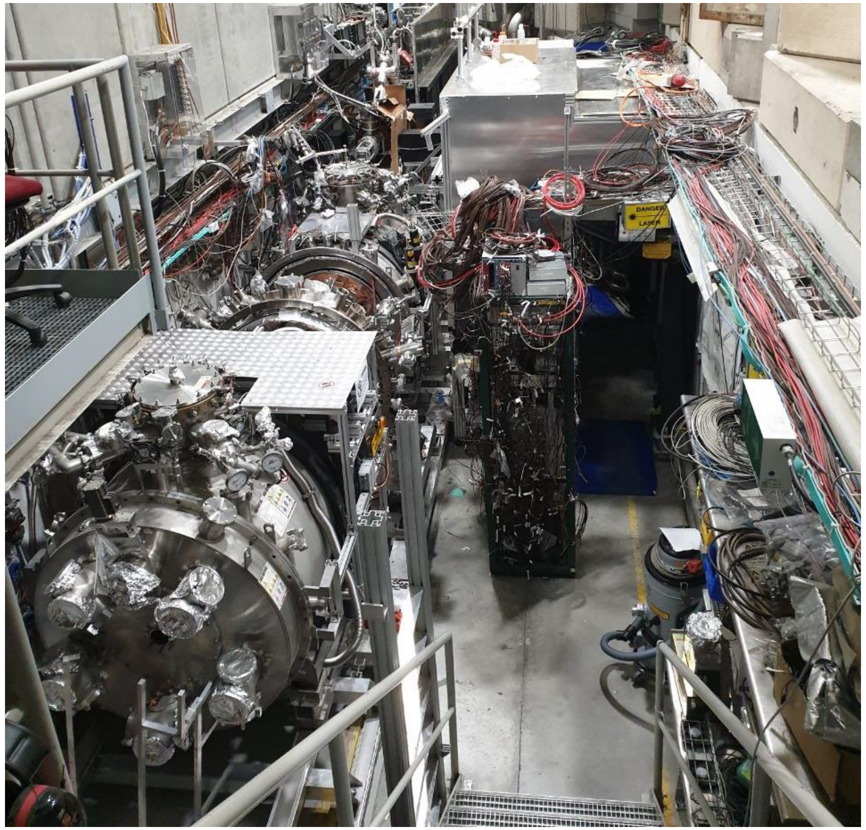
Introduction to AEgIS

- Antimatter Experiment: gravity, interferometry, spectroscopy
- Goal to measure free fall of antihydrogen

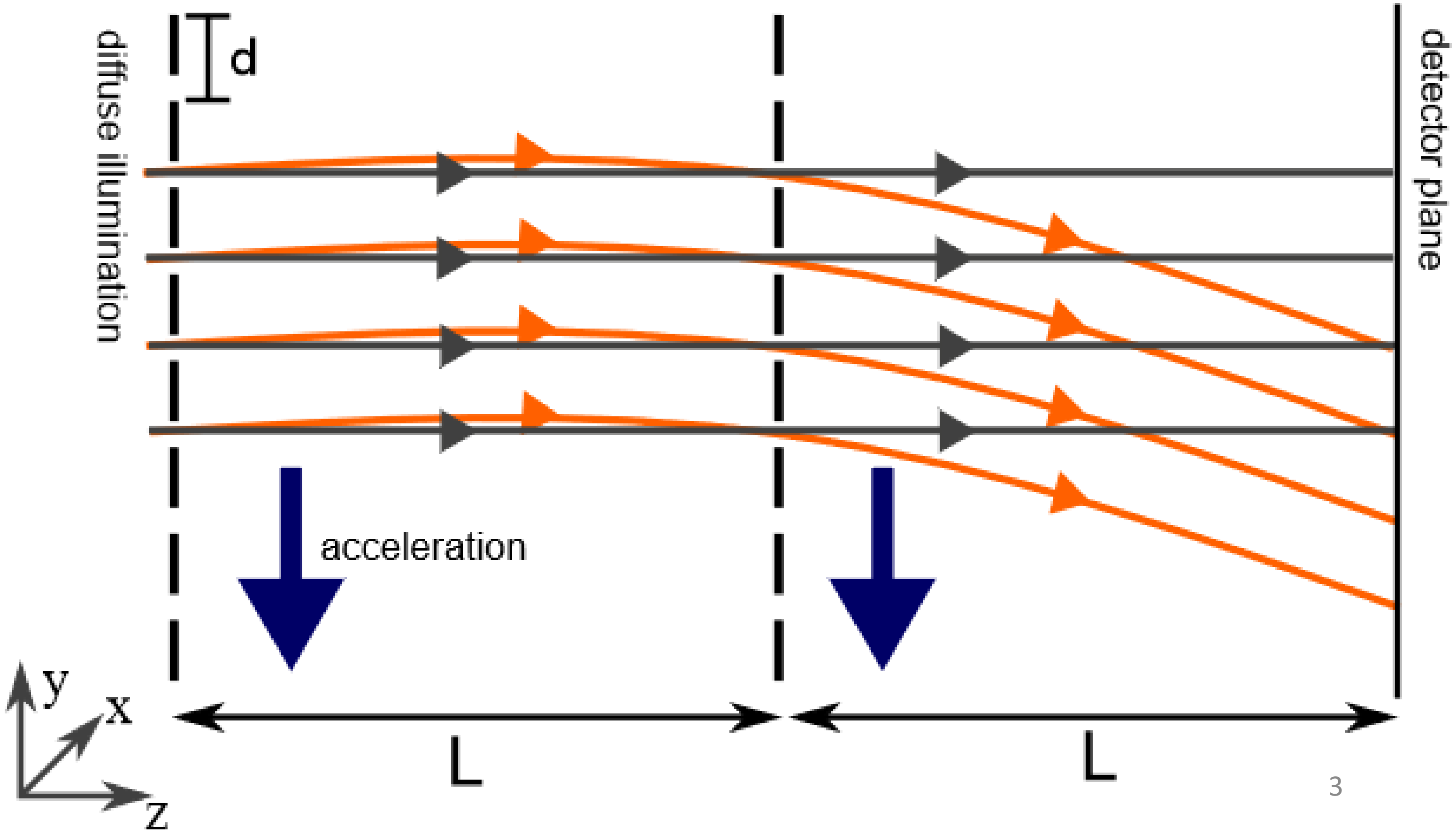


The CERN accelerator complex
Complexe des accélérateurs du CERN



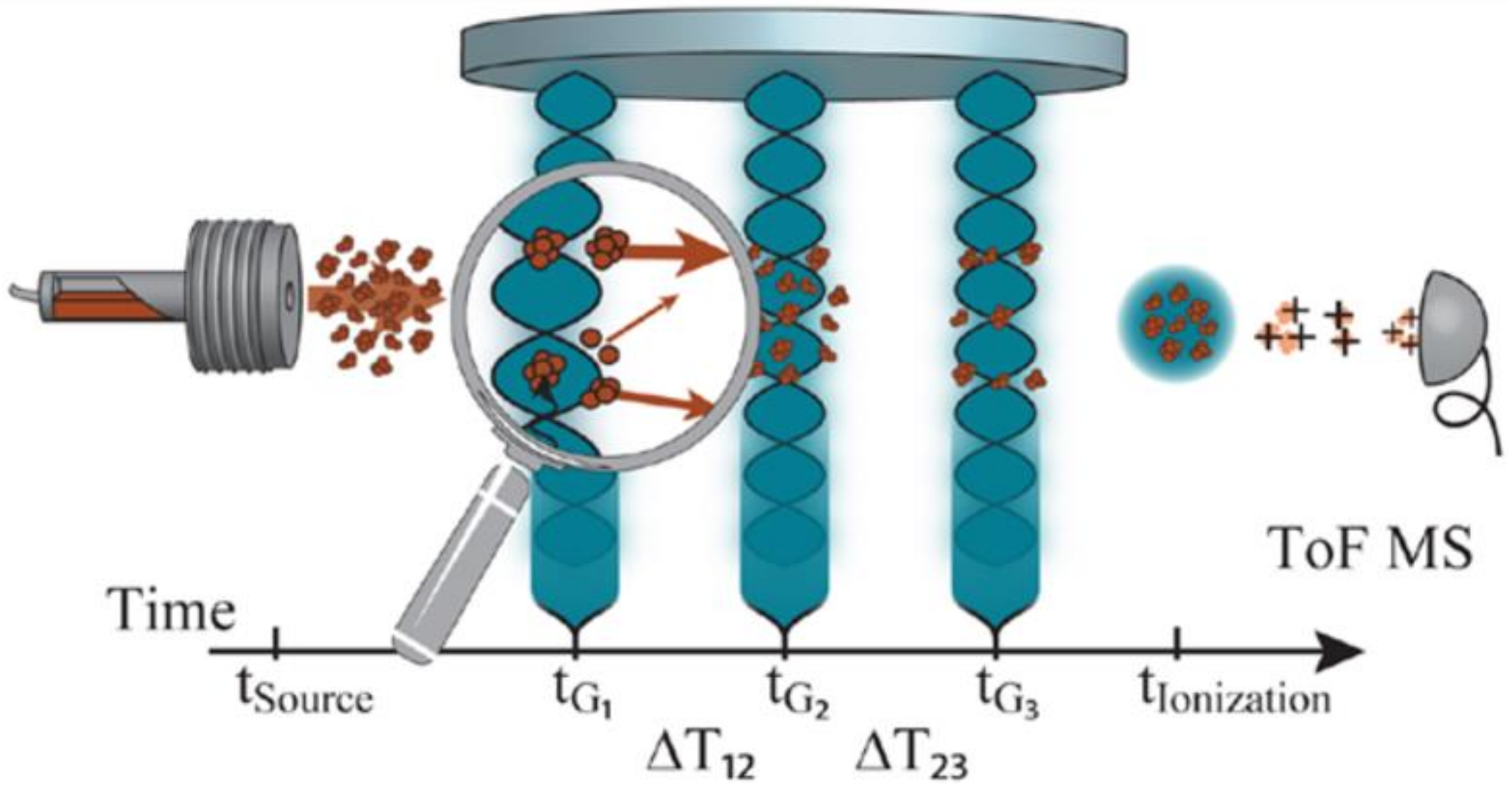
Moiré deflectometer

- Gravity measurement scheme using 2 matter gratings and position sensitive detector



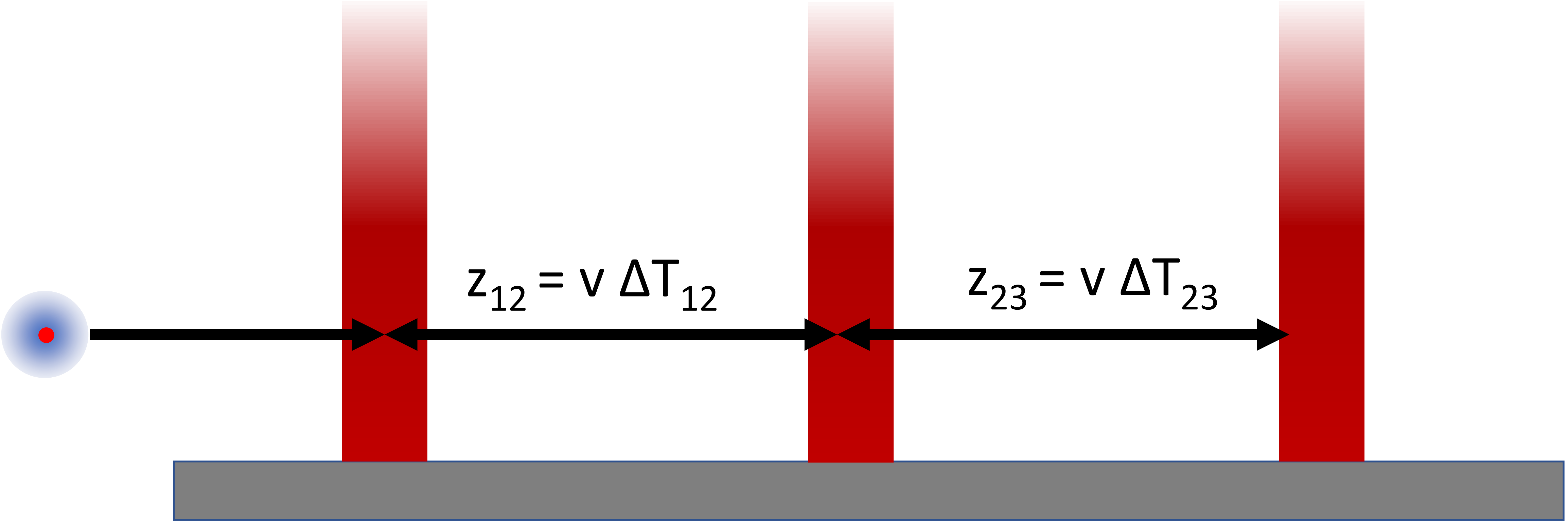
Optical time-domain ionizing matter-wave (OTIMA) interferometer

- Gratings are created by 3 pulsed lasers reflected of a common mirror



Optical time-domain ionizing matter-wave (OTIMA) interferometer

- Gratings are time domain which simplifies the alignment



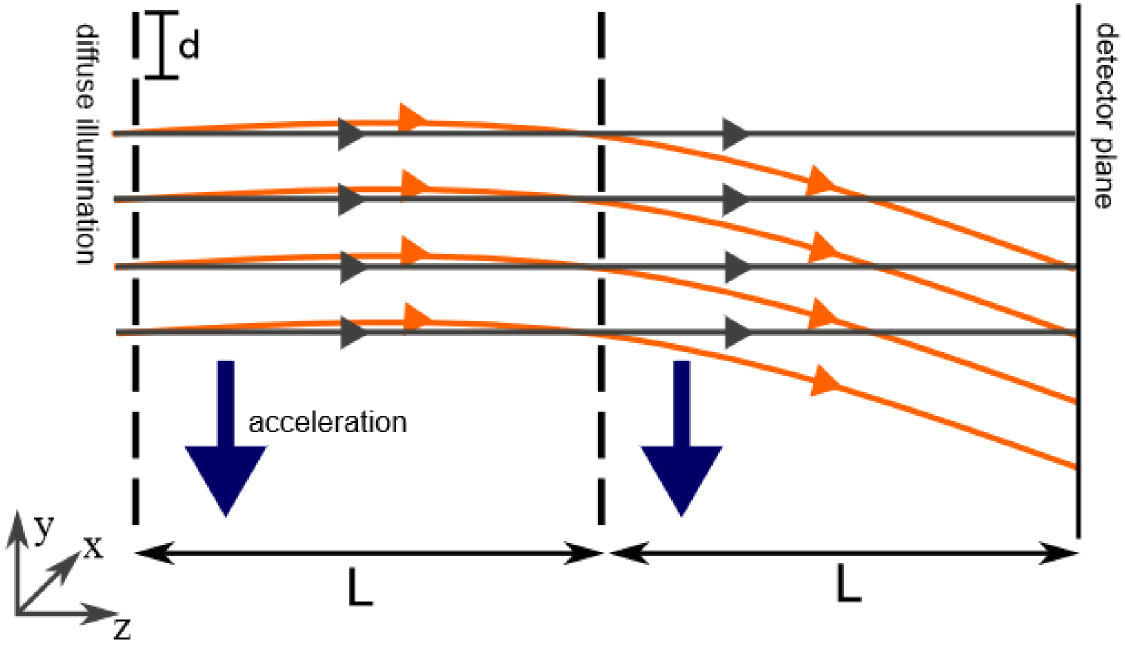
$z_{12} = v\ \Delta T_{12}$

$z_{23} = v\ \Delta T_{23}$

Optical vs matter gratings

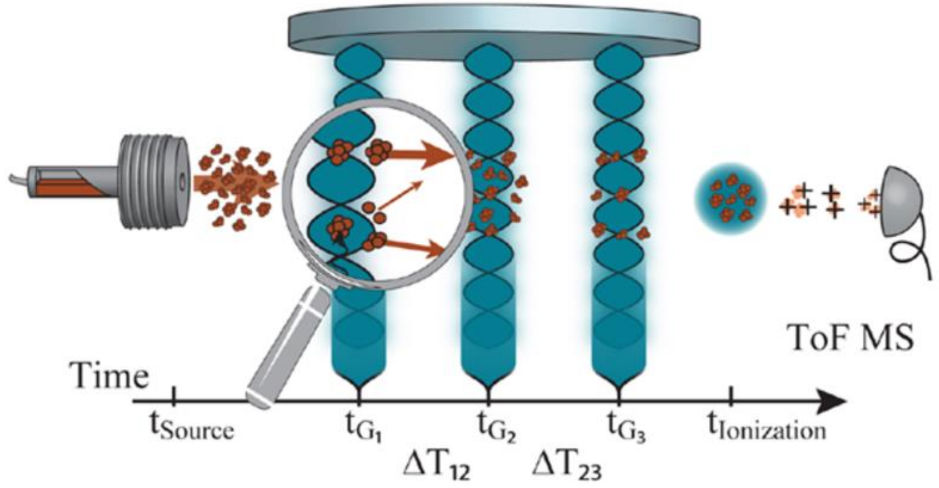
Moiré deflectometer

- Grating periodicity: >40µm
- Flux only depends on solid angle



OTIMA interferometer

- Grating periodicity: 532nm (if 1064nm laser is used)
- Flux depends both on solid angle and limits imposed by time



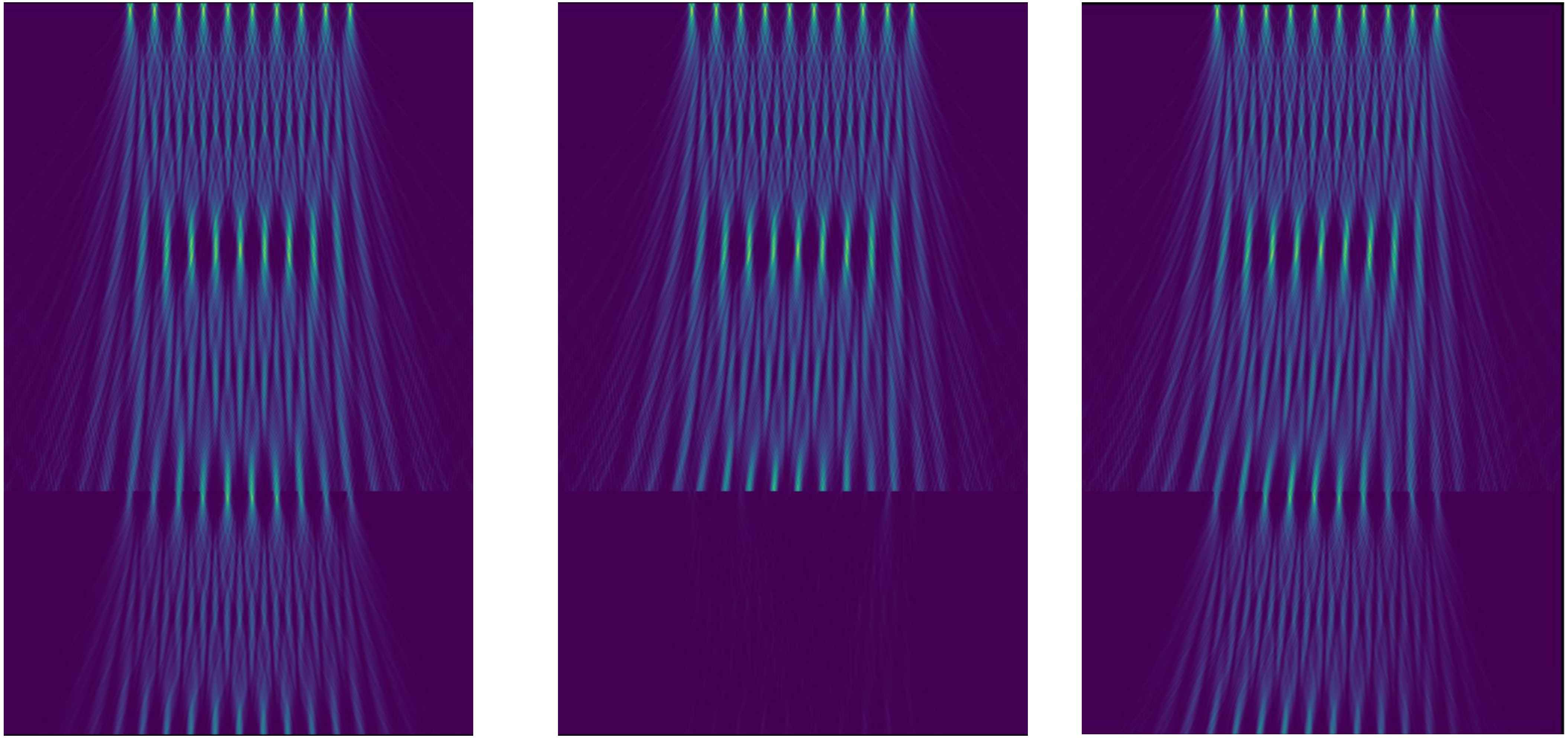
What we need to find out?

- What antihydrogen source parameters necessary?
- What laser parameters are necessary?

Interaction with light gratings

- Grating can be described by:
- $T(x) = \exp\left[\left(\cos\frac{\pi x}{d}\right)^2\left(-\frac{n}{2} + i\phi\right)\right]$
- Where $n = \frac{4\sigma(\lambda)E\lambda}{hcA}$ is number of absorbed photons
- And $\phi = \frac{16\pi^2 E\alpha(\lambda)}{hcA}$ is phase shift (negligible)
- Need to know ionization cross section $\sigma(\lambda)$, laser energy E and laser beam spot size A

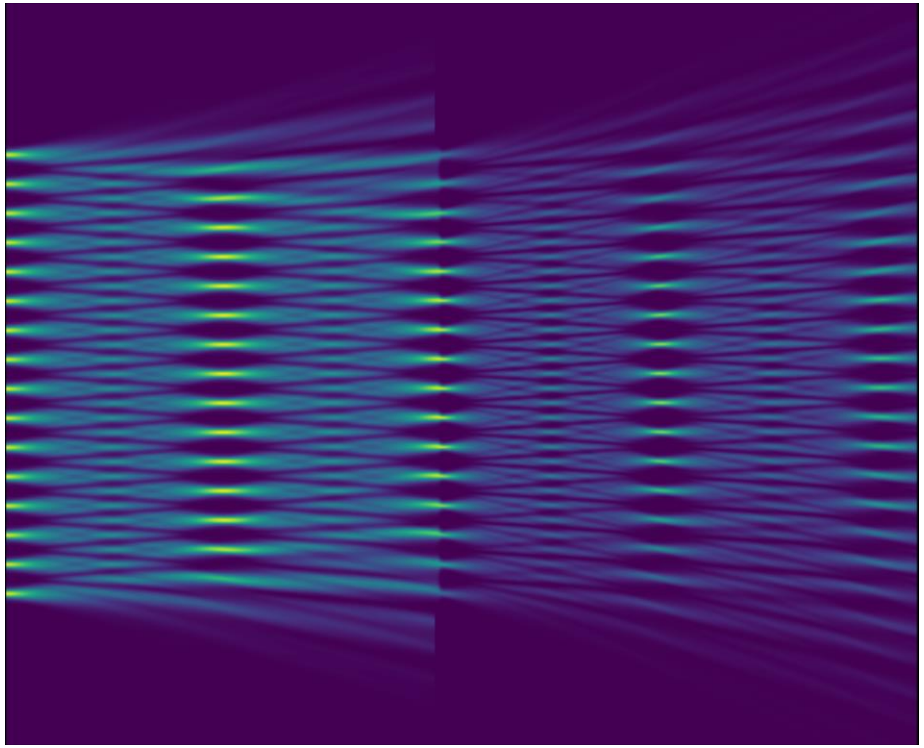
Plane wave simulation



Plane wave simulation

- Start with spherical wave from antihydrogen production site
- Multiply complex wave by grating function
- $T(x) = \exp\left[\left(\cos\frac{\pi x}{d}\right)^2\left(-\frac{n}{2} + i\phi\right)\right]$
- Calculate propagation in Fourier space
- $u(y,z) = \mathcal{F}_{k_y}^{-1}\{\mathcal{F}_y\{u(y,0)\}\mathcal{P}_{k_y}(z)\}$

where $\mathcal{P}_{k_y}(z) = e^{iz\sqrt{(2\pi/\lambda)^2 - k_y^2}}$

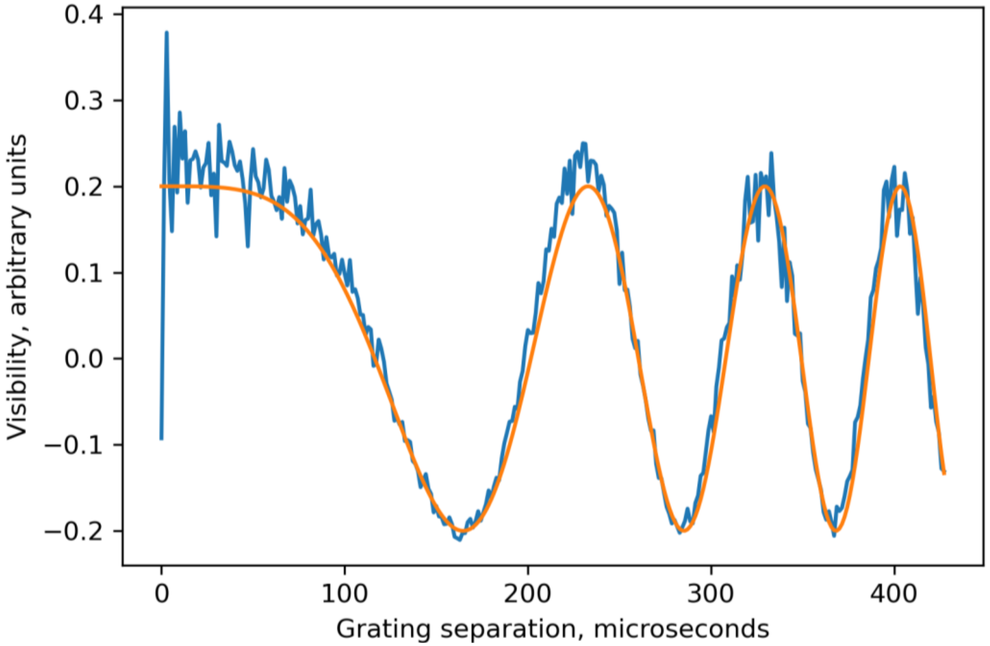


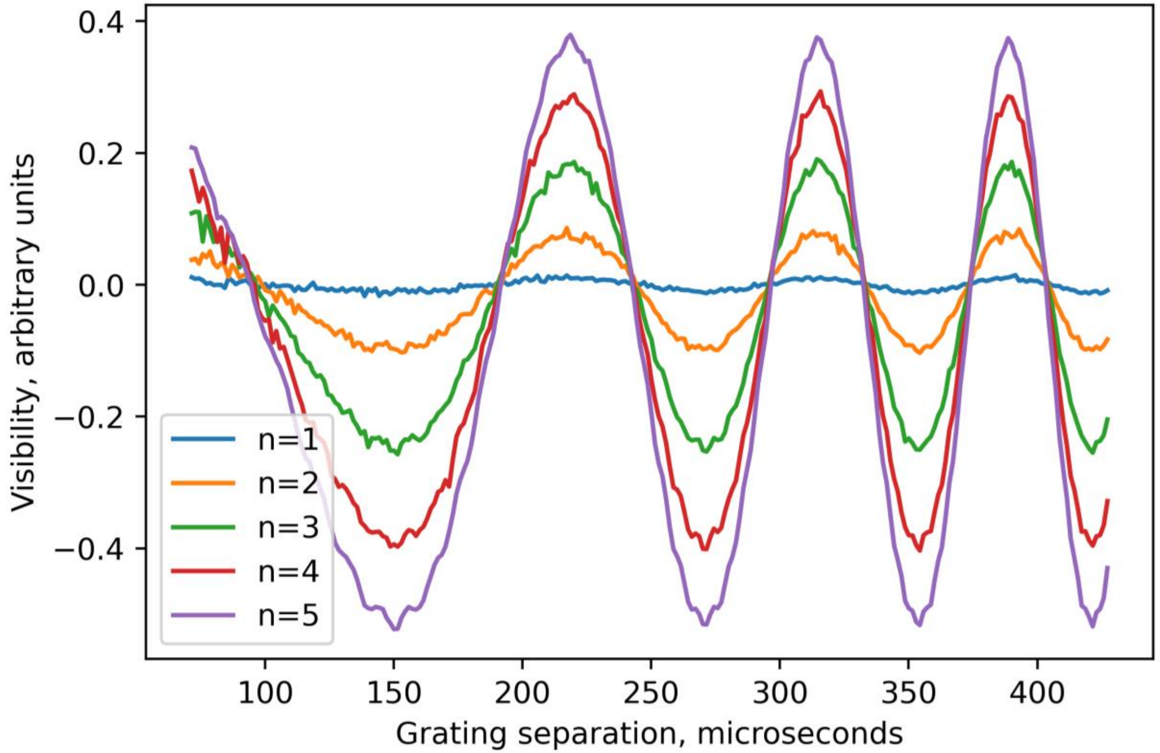
Plane wave simulation

- Repeat 10 times with different initial conditions, sum all signals
- Calculate $S_N = \frac{S_{ON} - S_{OFF}}{S_{OFF}}$ where

S_{ON} is resonant case and S_{OFF} is with 3rd grating delayed

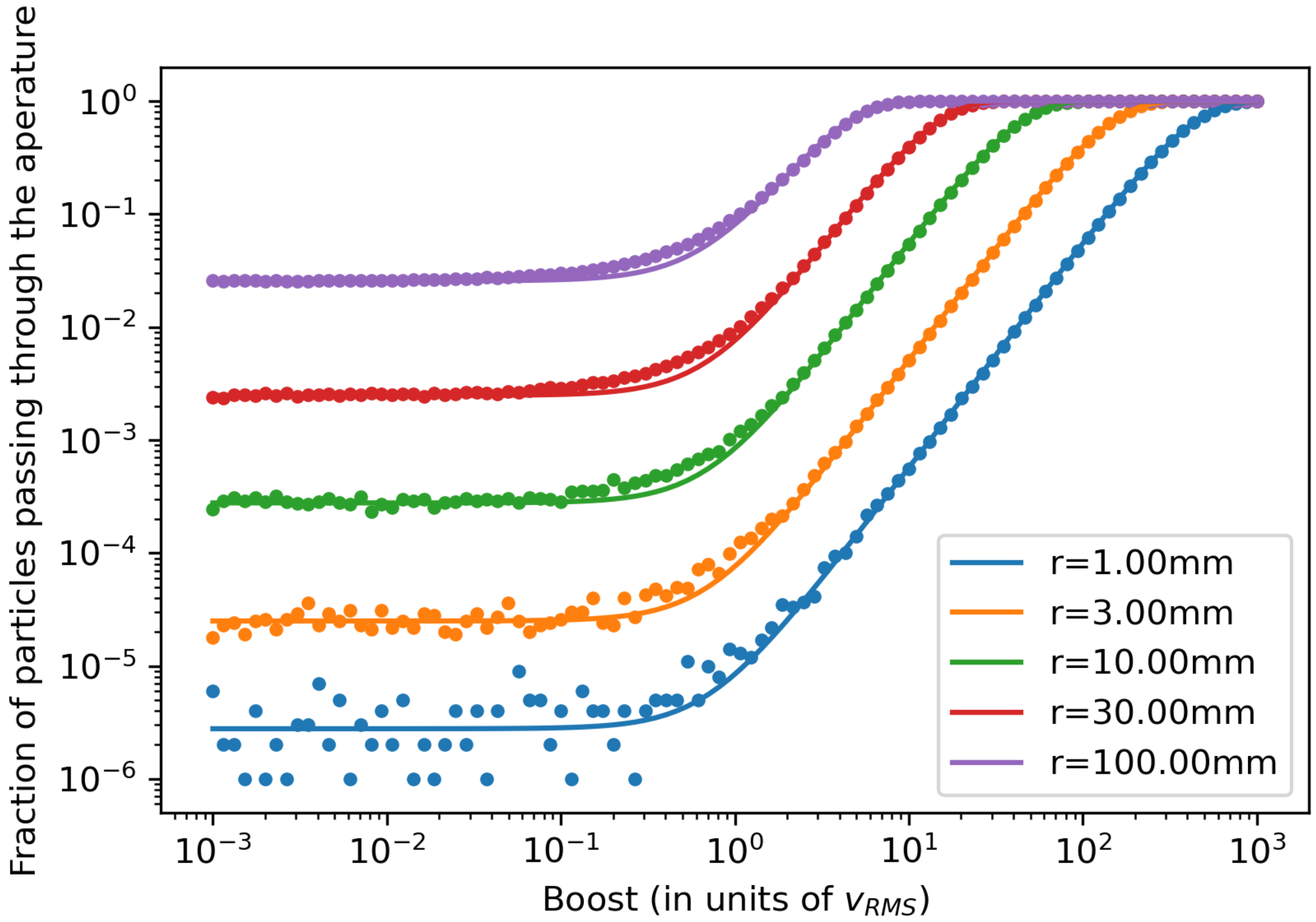
- $S_N = V_0 \cos\left[\frac{2\pi}{d}\left(b - g(\Delta T)^2\right)\right]$





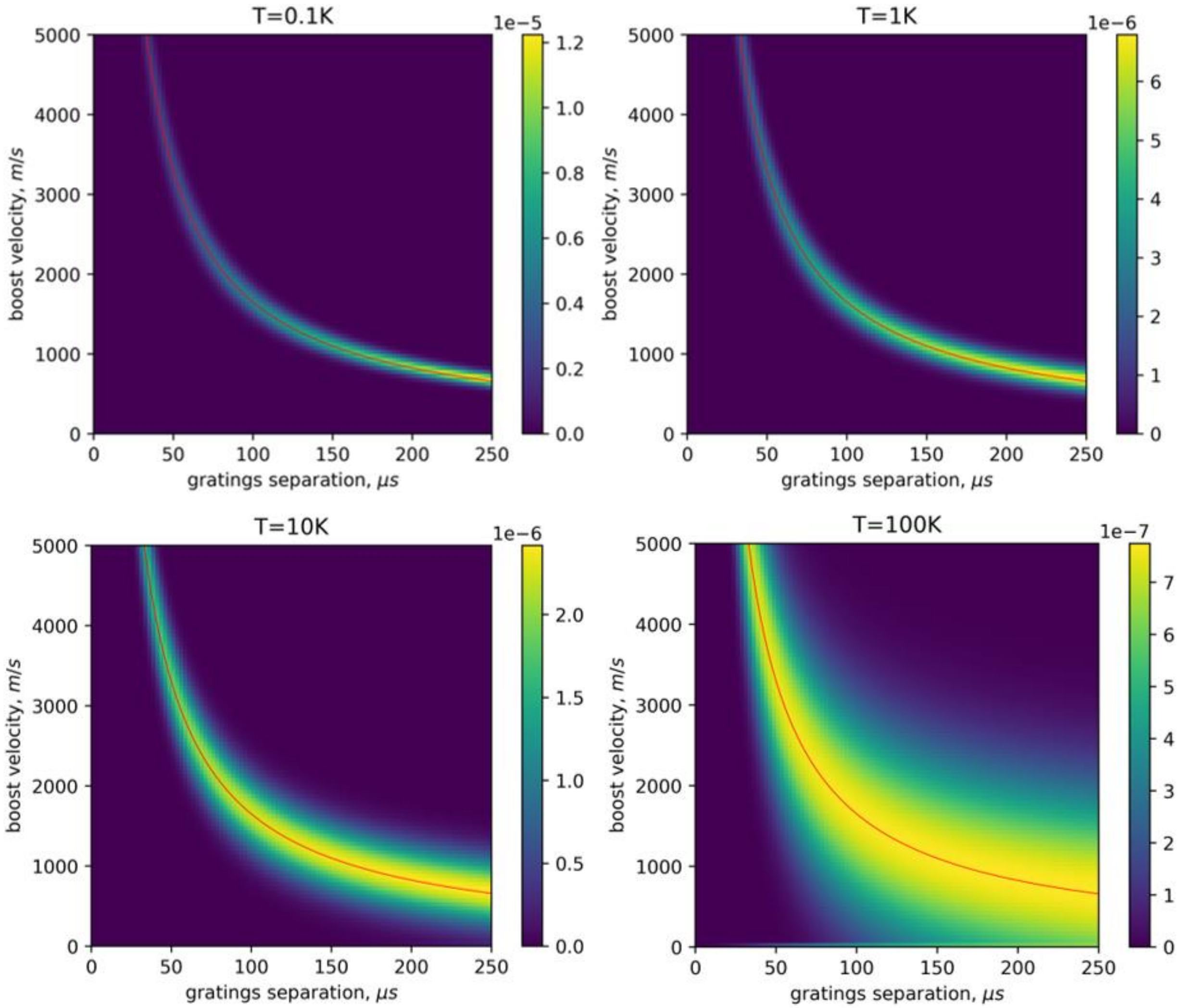
Flux limitations due to the solid angle

- Fraction of atoms passing through the grating depends on the grating size and the boost

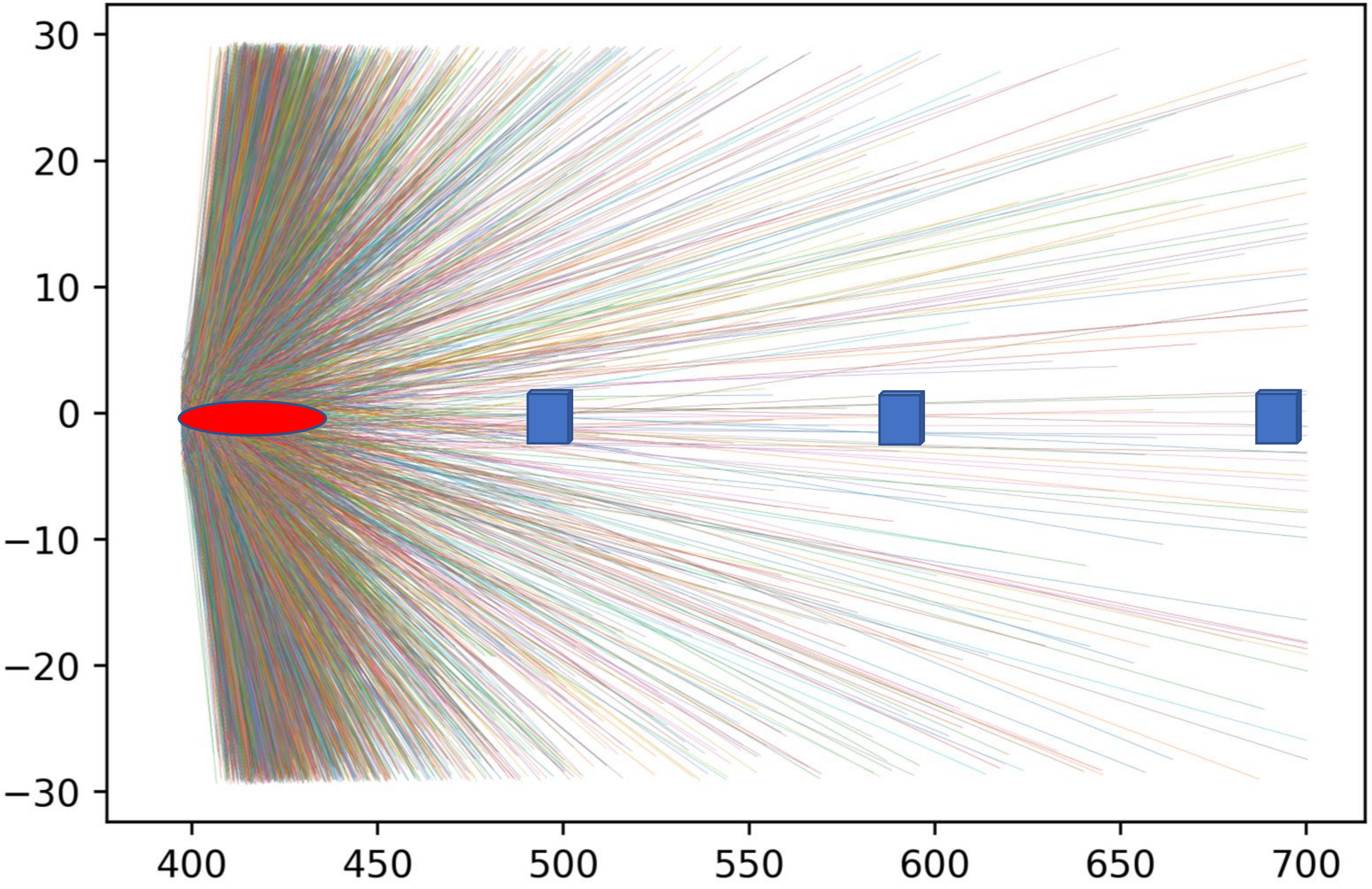


Flux limitations due to the timing

- Fraction of atoms that can interact with a grating of 1 mm
- Decreasing temperature from 100K to 1K would increase the usable flux from less than 1 atom out of million to almost 10 out of million



Expected flux from Monte-Carlo

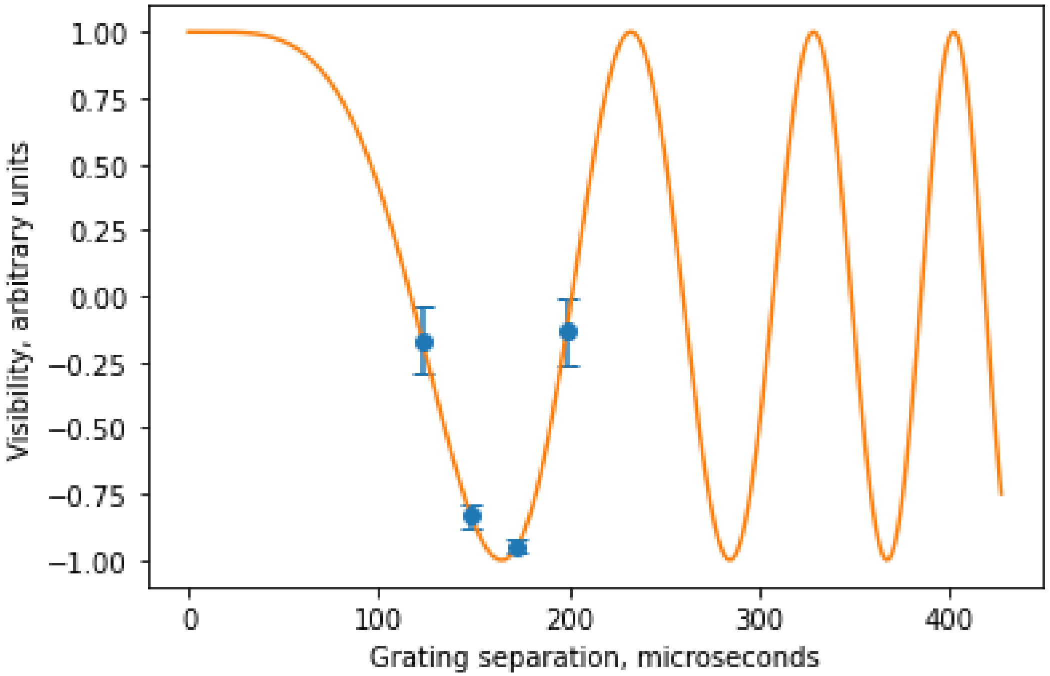


Number of particles out of million which interacted with all gratings

Boost, k_BT	0.1	1	10	100
T=100K	0	0	19	5853
T=10K	0	0	16	6797
T=1K	0	0	21	5872
T=0.1K	0	0	7	6391

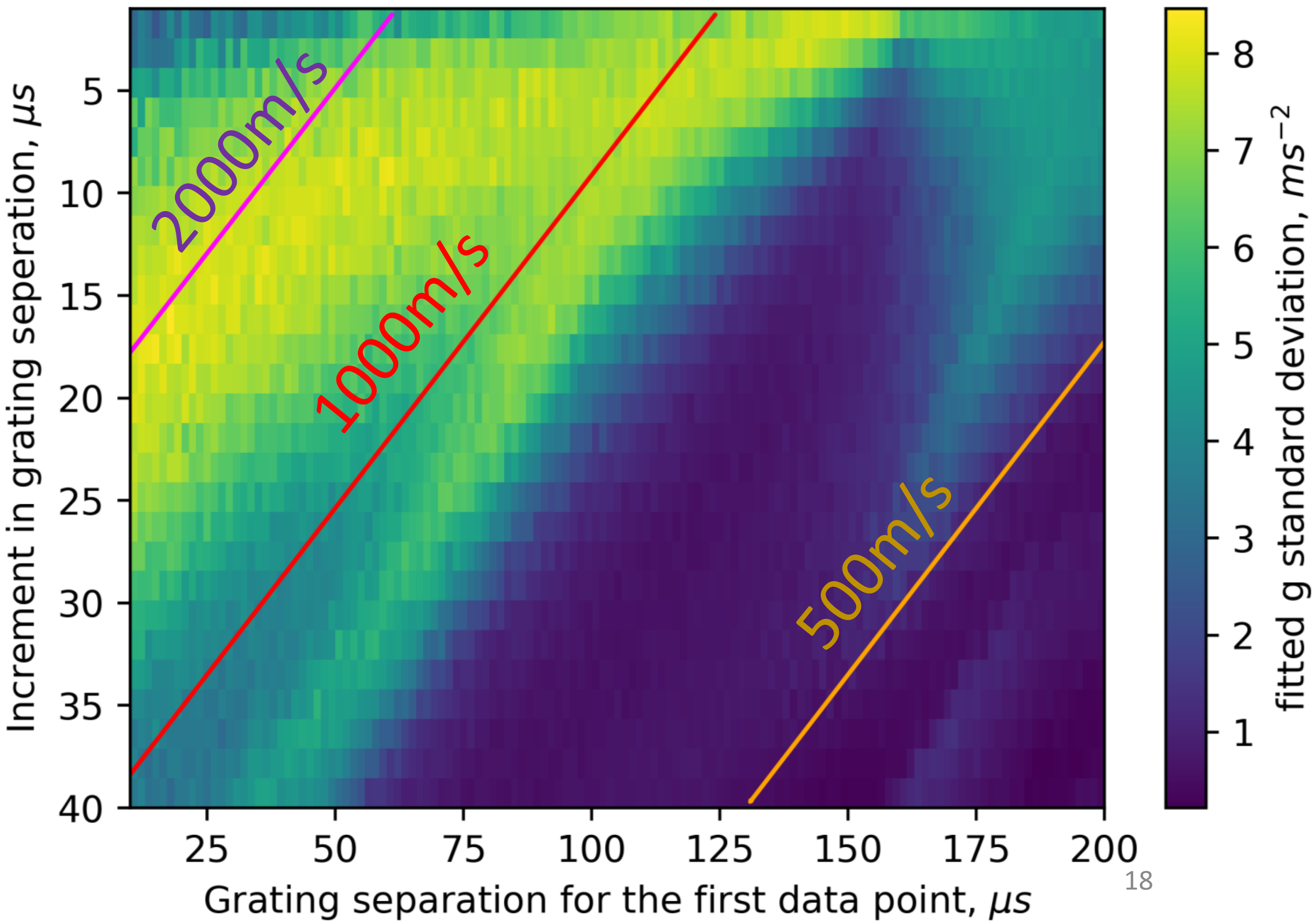
Expected sensitivity

- Generate 4 points according to Poissonian distribution (for expected value of 100) and do a fit with
- $S_N = V_0 \cos\left[\frac{2\pi}{d}\left(b - g(\Delta T)^2\right)\right]$
- Repeat and calculate standard deviation of the fitted g



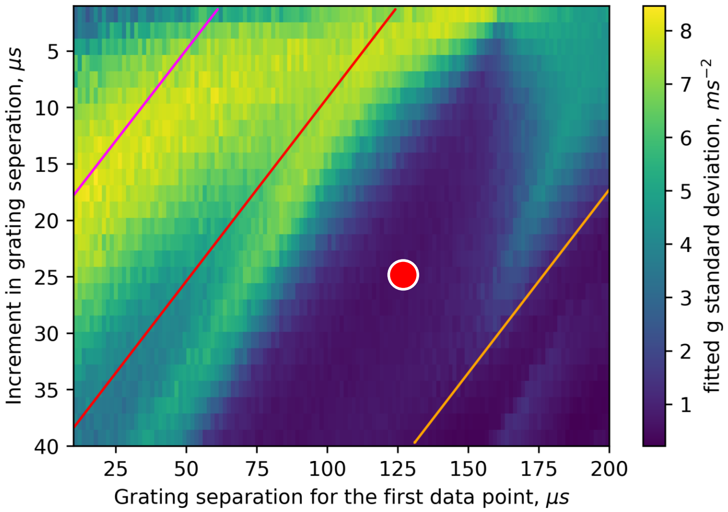
Expected sensitivity

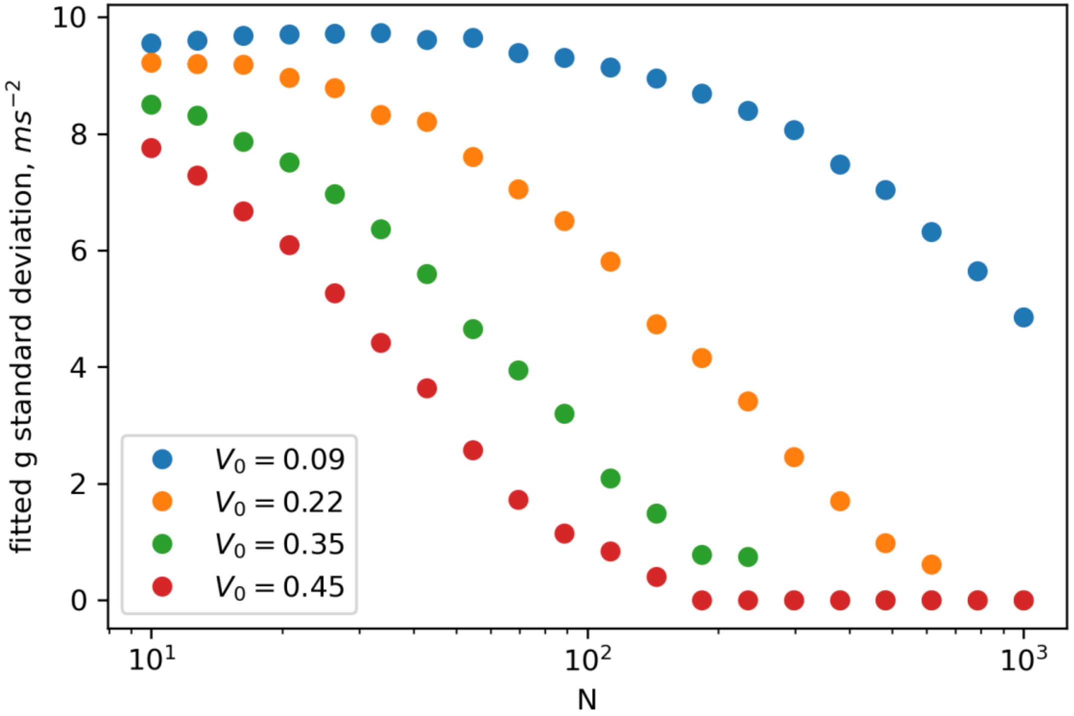
- Colored lines indicate limits imposed by 25 cm mirror for different boost velocities
- To achieve 10% sensitivity boost cannot be over 1000 m/s
- Boosts above 2000 m/s are completely unusable



The n influence on sensitivity

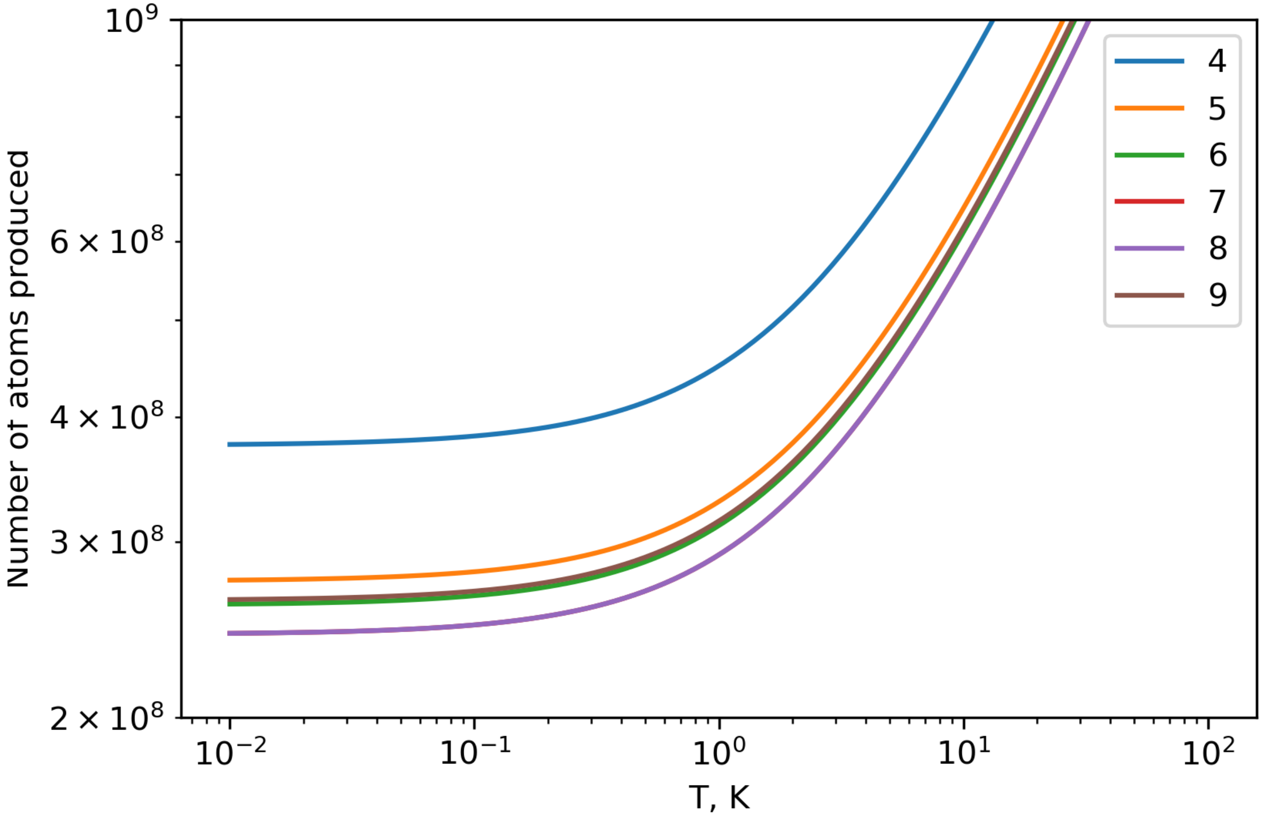
- Increasing n, decreases number of atoms necessary to detect
- Trade off – increasing n decreases solid angle





Dependence on n and temperature

- The optimal n is between 7 and 8
- Even in the best case it is necessary to produce more than 100 million antihydrogen atoms

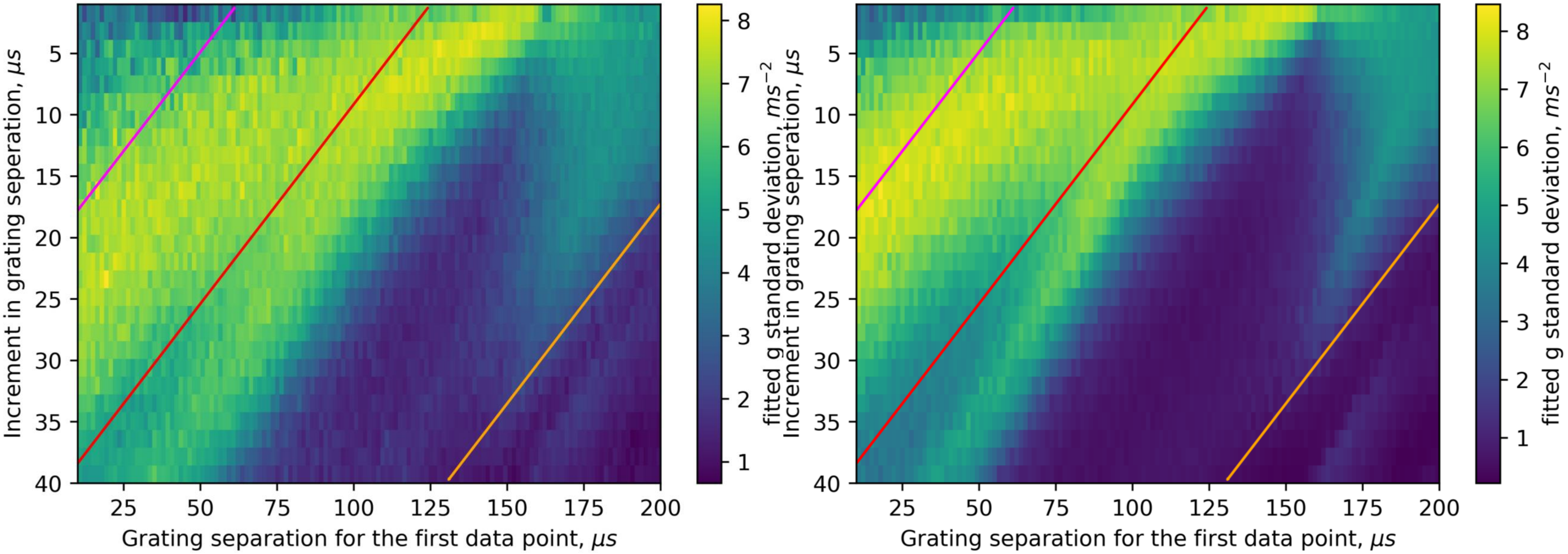


Conclusion

- To achieve a measurement in 6 months, it would be necessary to produce 2000 antihydrogen atoms in a production cycle at 1K
- That would be 40’000 times more atoms than AEgIS achieved in 2018. and at a significantly colder temperature

Questions?

20 vs 100 atoms



Expected flux from Monte-Carlo with better laser

- Grating is assumed to be 5x3x30 mm
- Number of particles that interacted with grating out of million

Boost, k_BT	0.1	1	10	100
T=10K	0	2	240	27710
T=1K		1	280	26370
T=0.1K			270	27380

Acceleration due to magnetic field gradient

- n=30