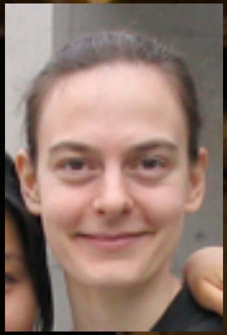
Part I : A cold atom based UHV pressure standard

Kirk W. Madison

University of British Columbia

March 29, 2013 - ENS, *Lutetia Parisiorum*



Janelle Van Dongen (PhD student)

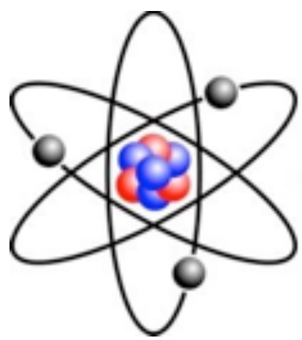
University of British Columbia

James L. Booth (Visiting Professor)

British Columbia Institute of Technology

Cold atoms : metrology and standards

stationary
atom



- internal degree of freedom: **high Q-resonator**
- external degree of freedom: **inertial reference**

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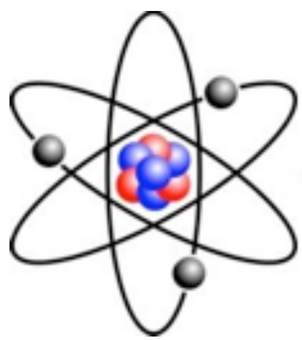

high Q-resonator

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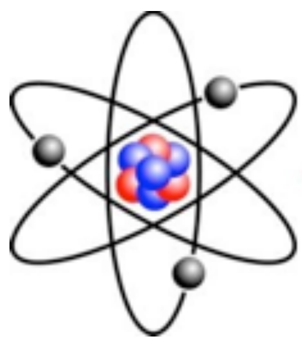
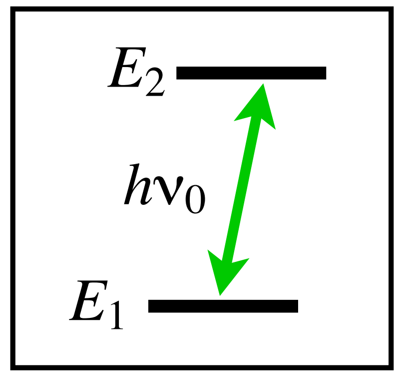


high Q-resonator

atomic clock



international time standard

Cold atoms : metrology and standards

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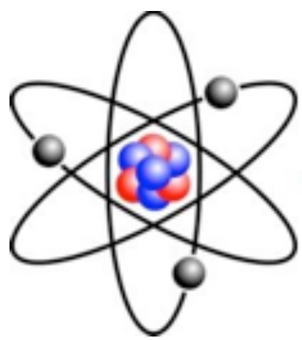
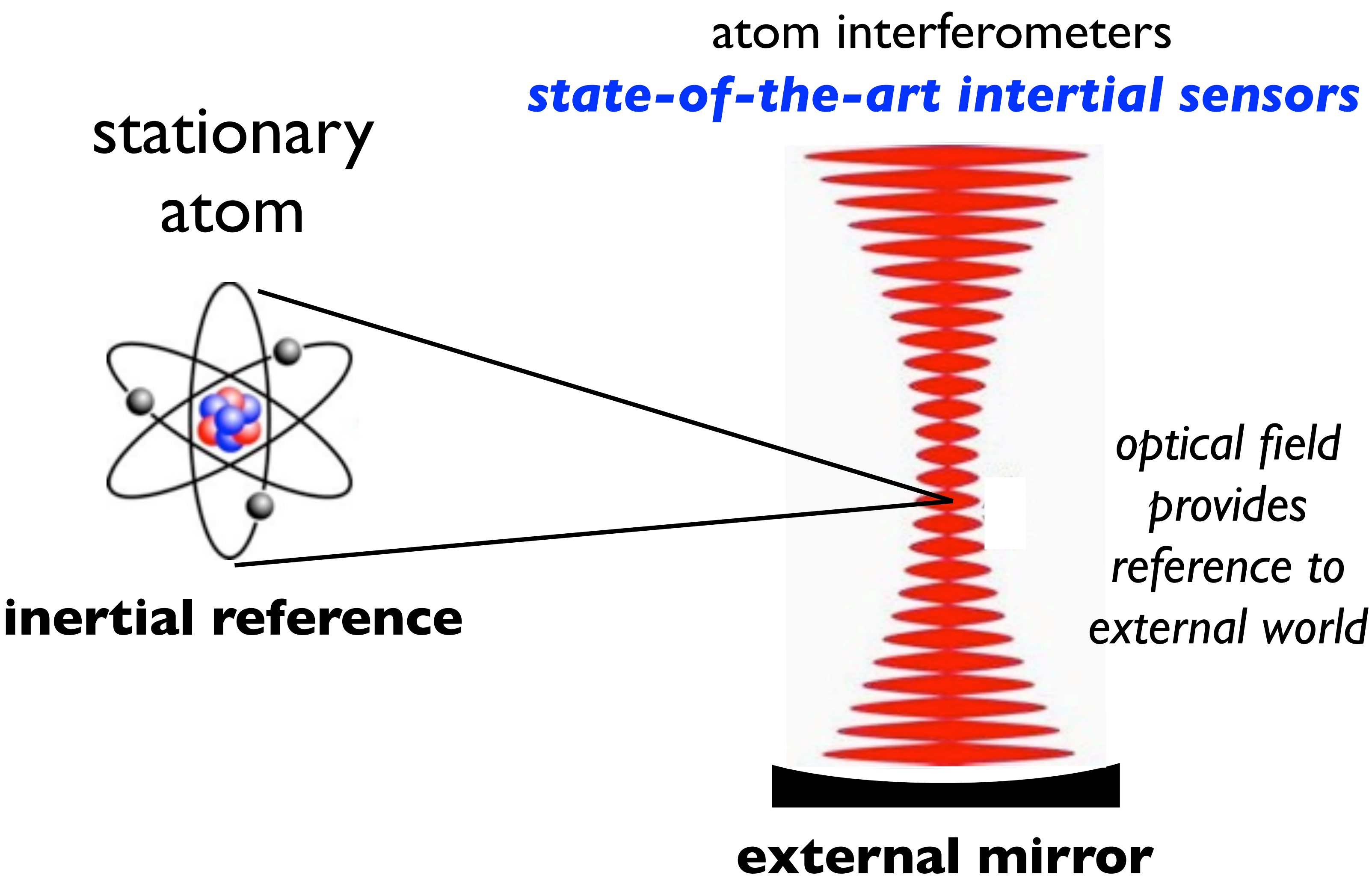


inertial reference

Cold atoms : metrology and standards



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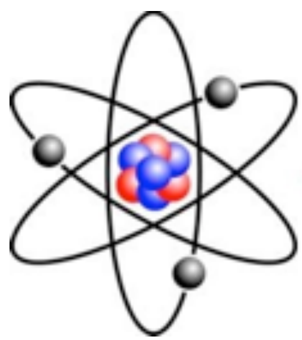

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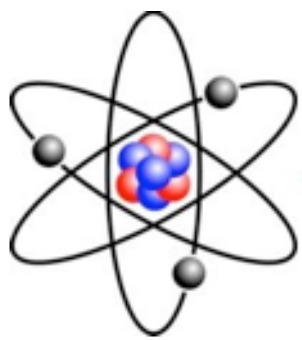
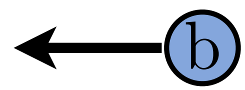
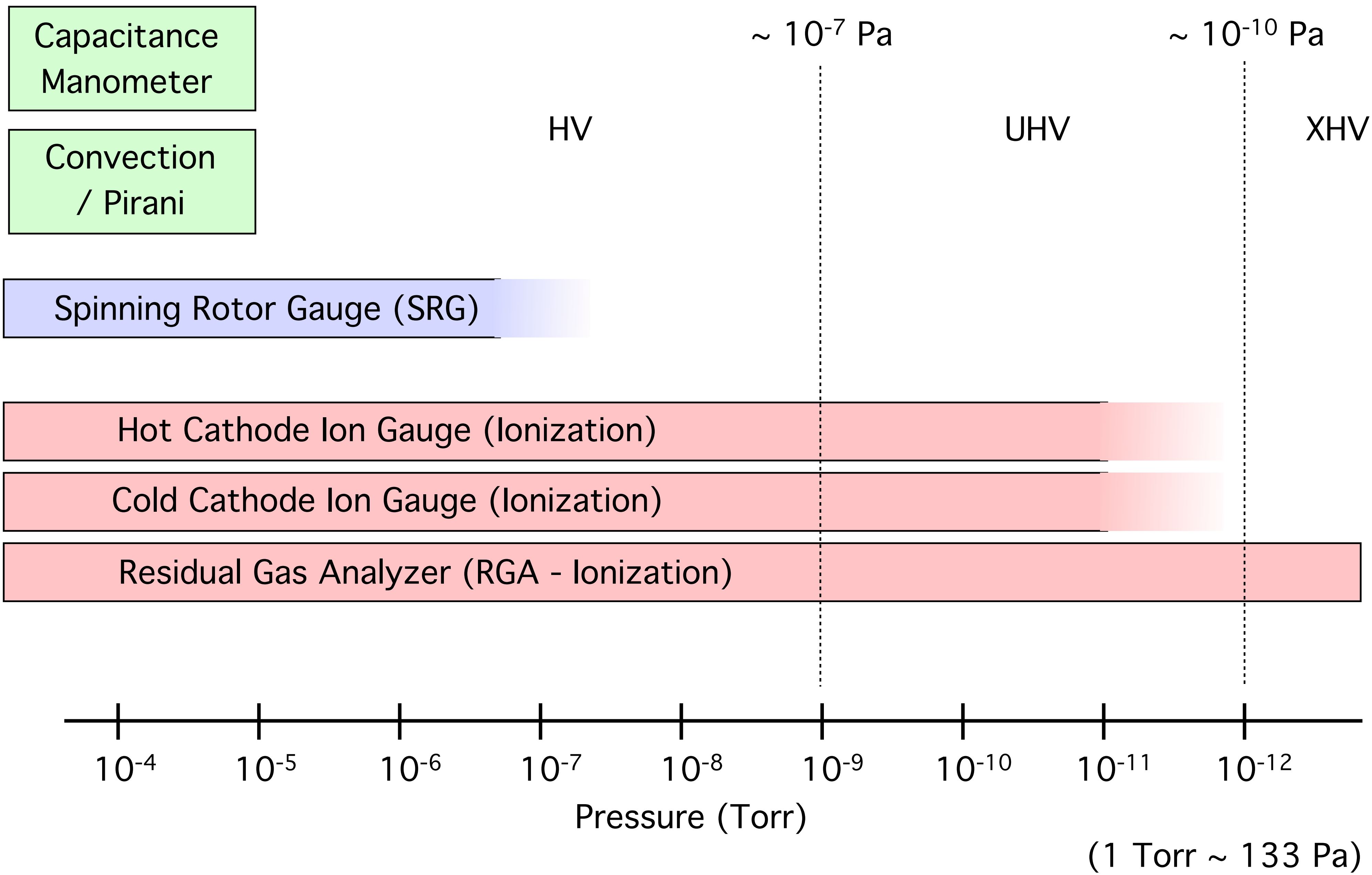


incident particle

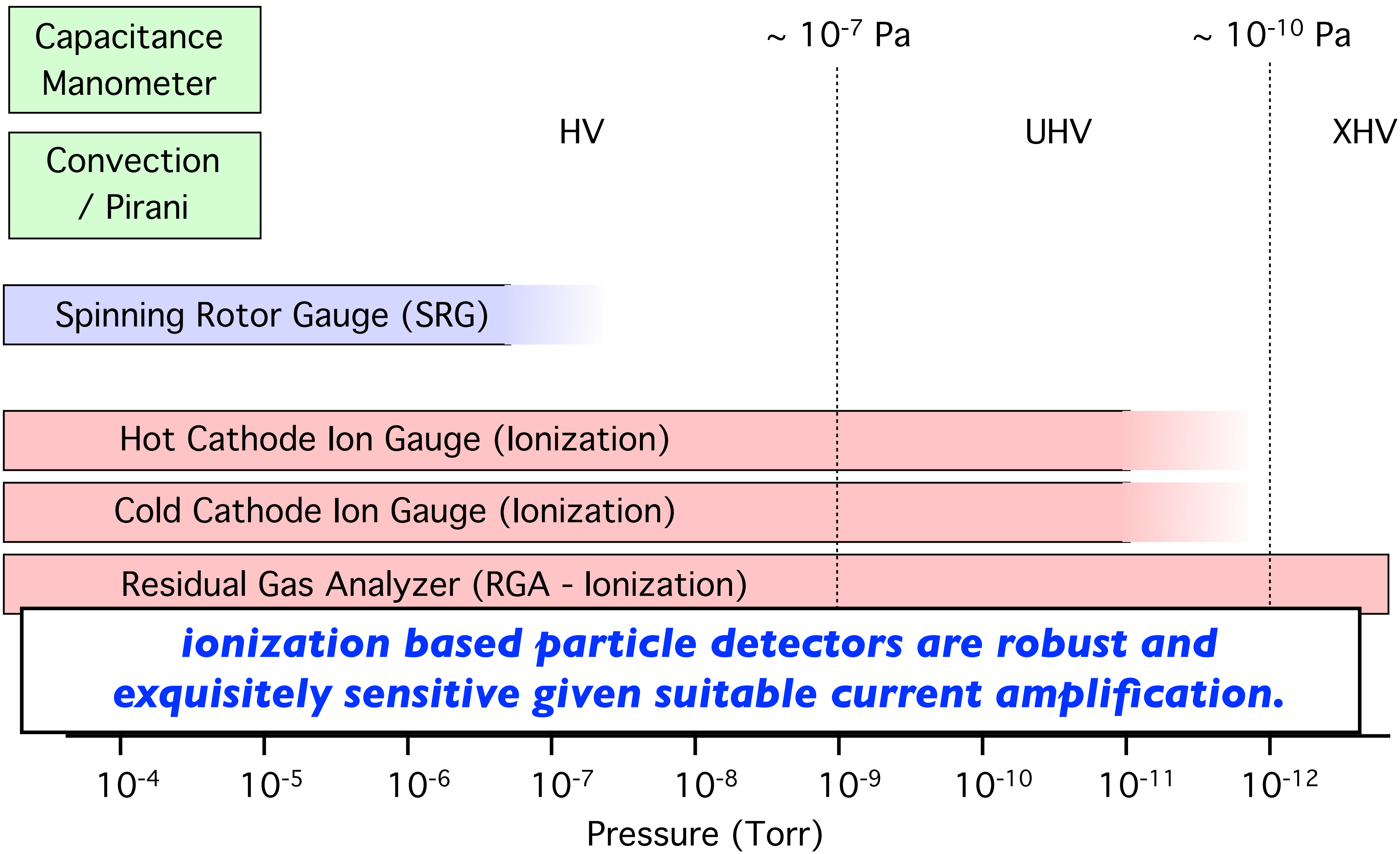


particle detector ?

High and Ultra-high vacuum metrology



High and Ultra-high vacuum metrology

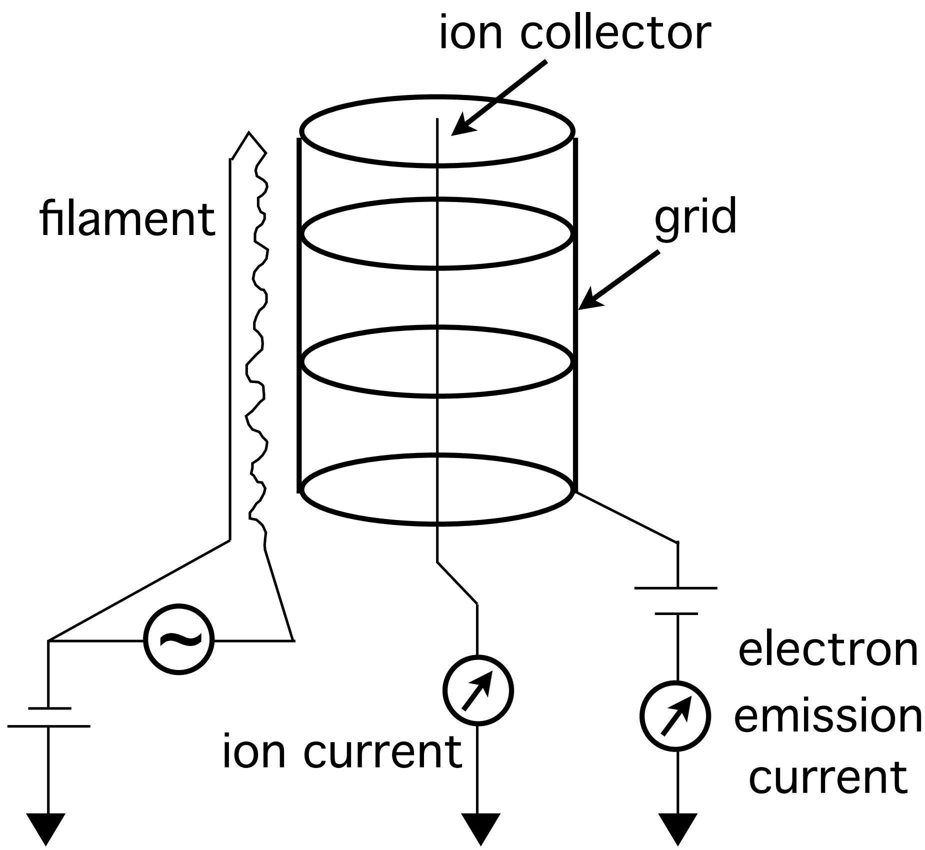


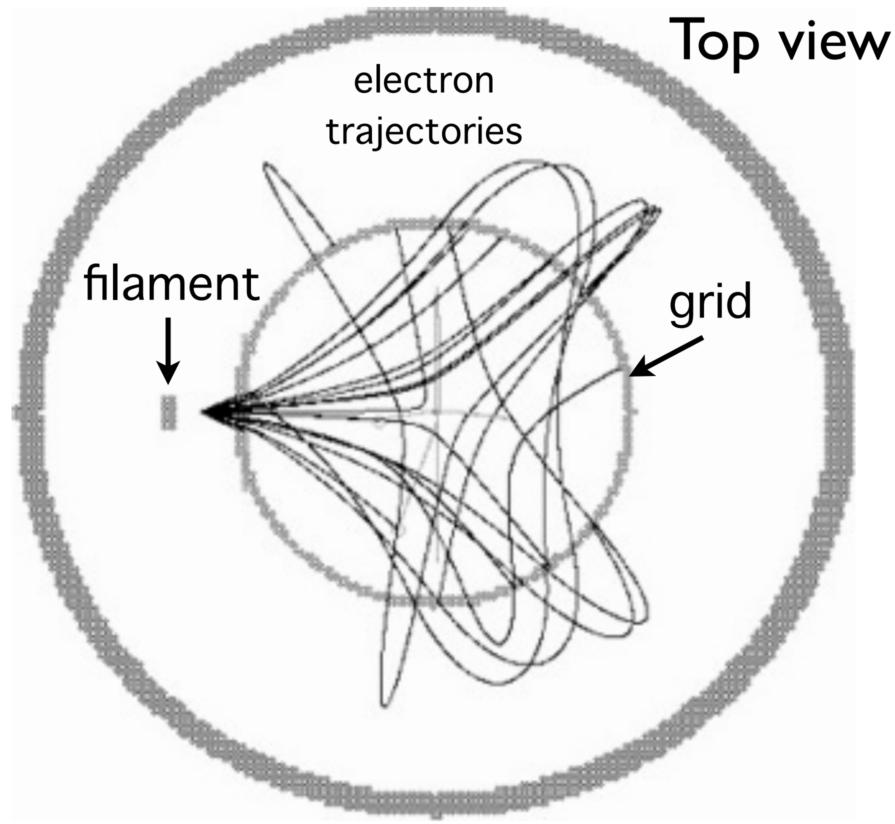
ionization based particle detectors are robust and exquisitely sensitive given suitable current amplification.

(1 Torr ~ 133 Pa)

High and Ultra-high vacuum metrology

What are the limitations of ionization based particle detectors?





Thermal motion of residual gas results in a flux of particles through sensor grid surface area and into detector

High and Ultra-high vacuum metrology

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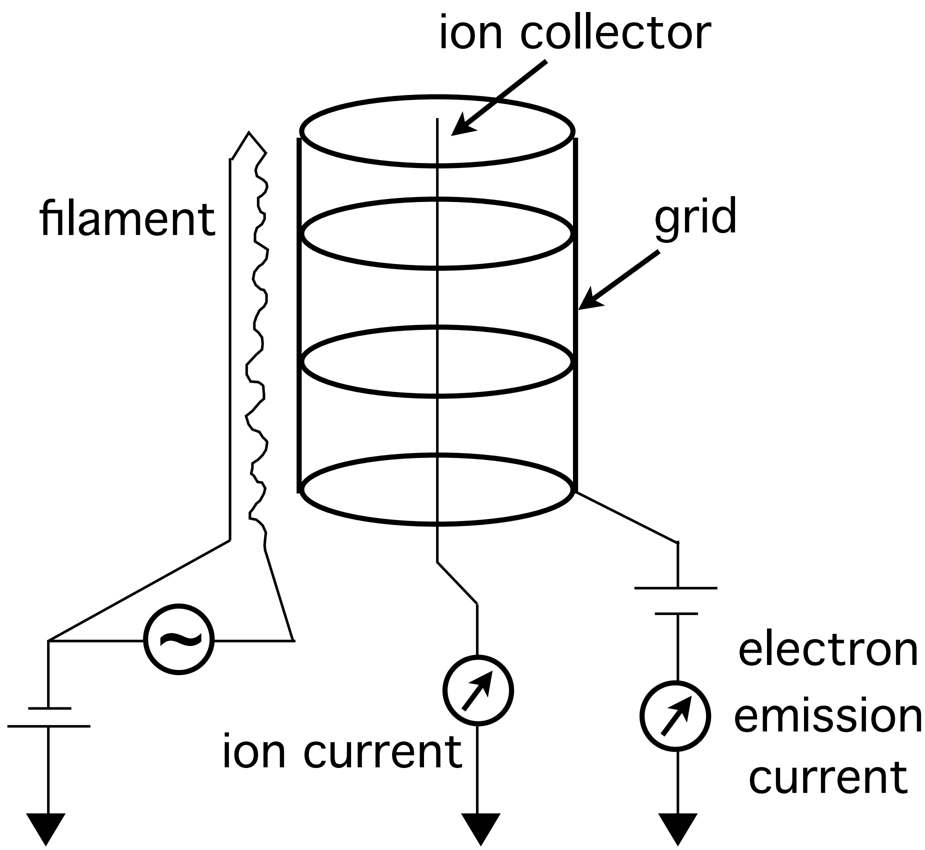
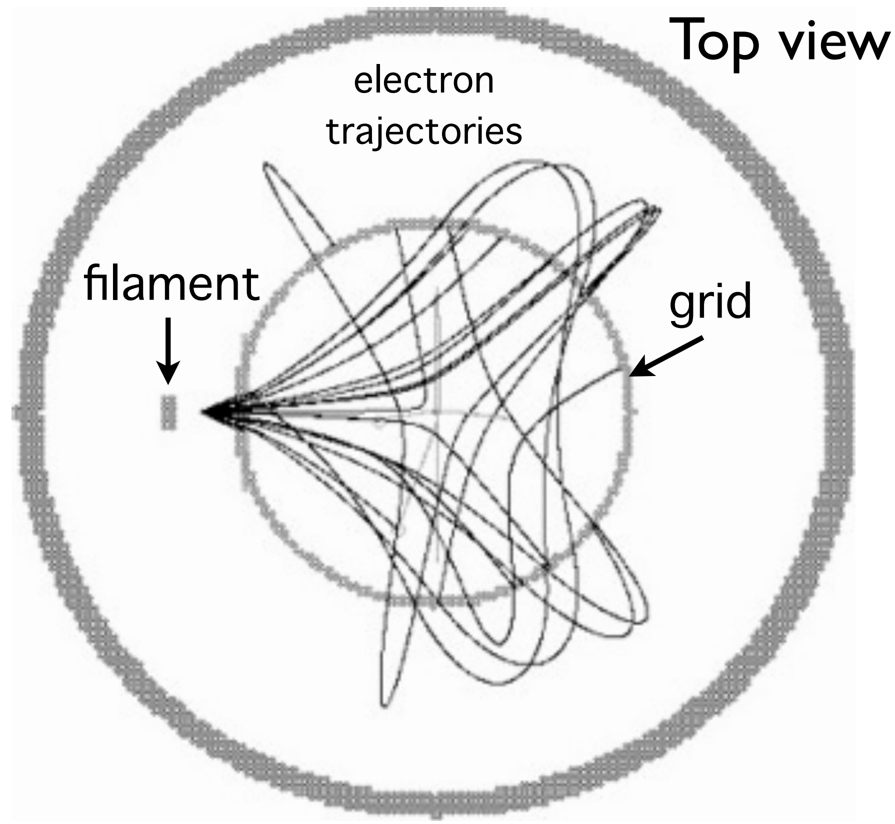
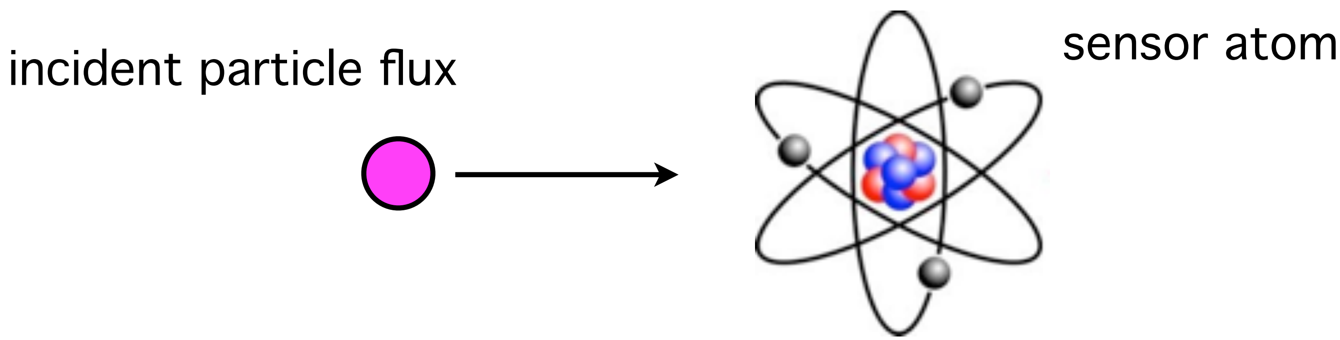




- ionization and detection efficiency depends on electric fields inside sensor. Mechanical changes cause calibration drift...

A cold atom based UHV pressure standard ?

what is the evidence of the incident particle's passage?



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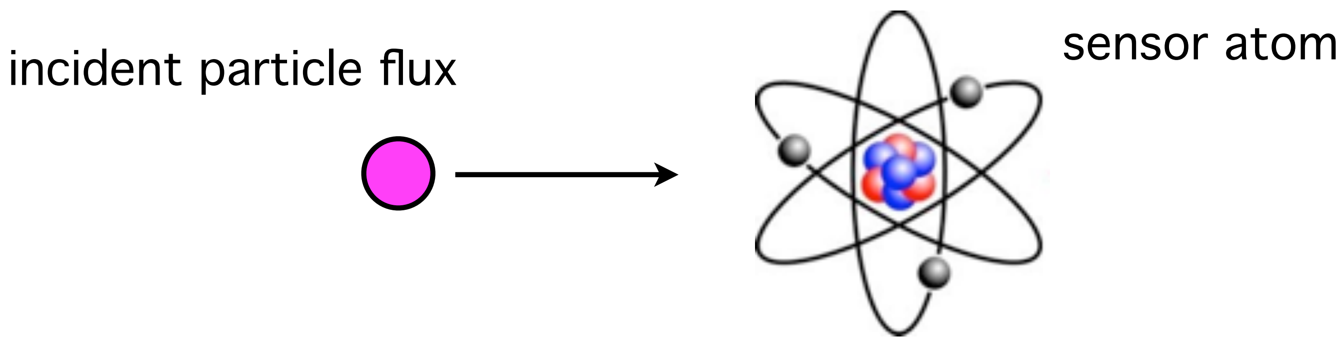

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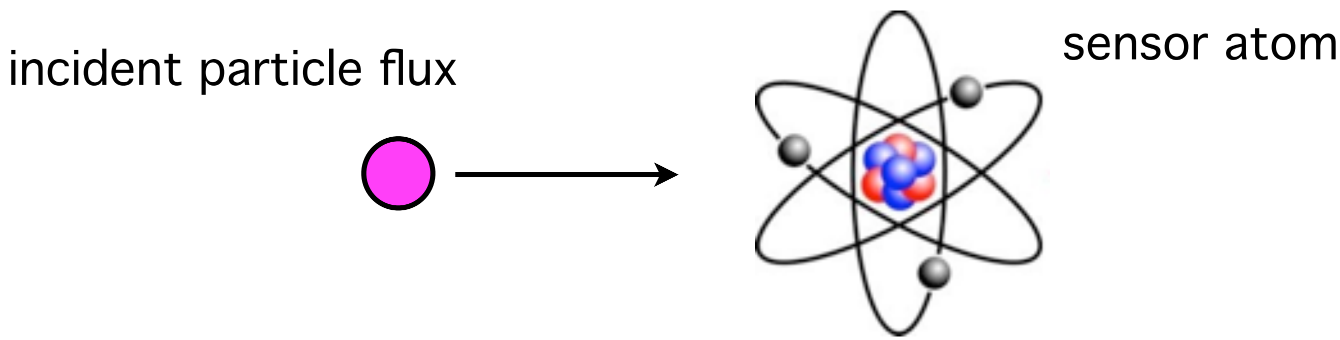

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Internal state:
- state population redistribution
- quantum decoherence ("clock shift")

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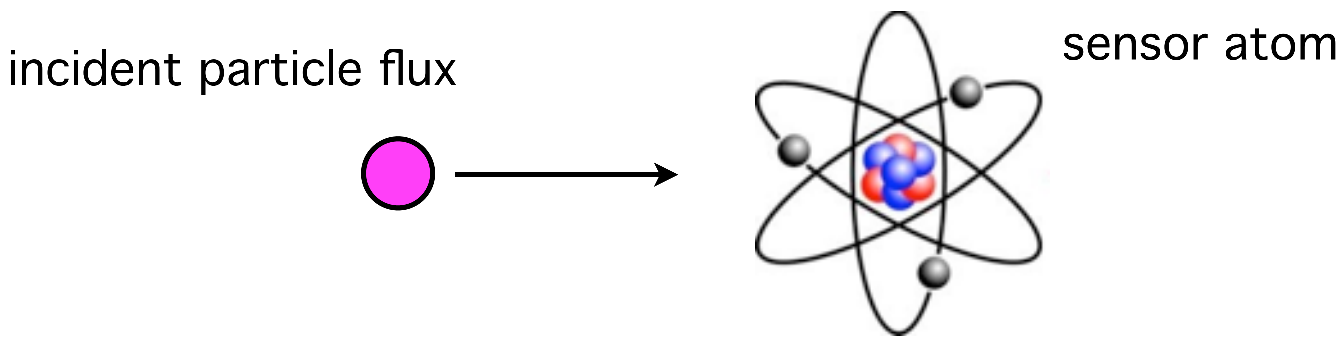

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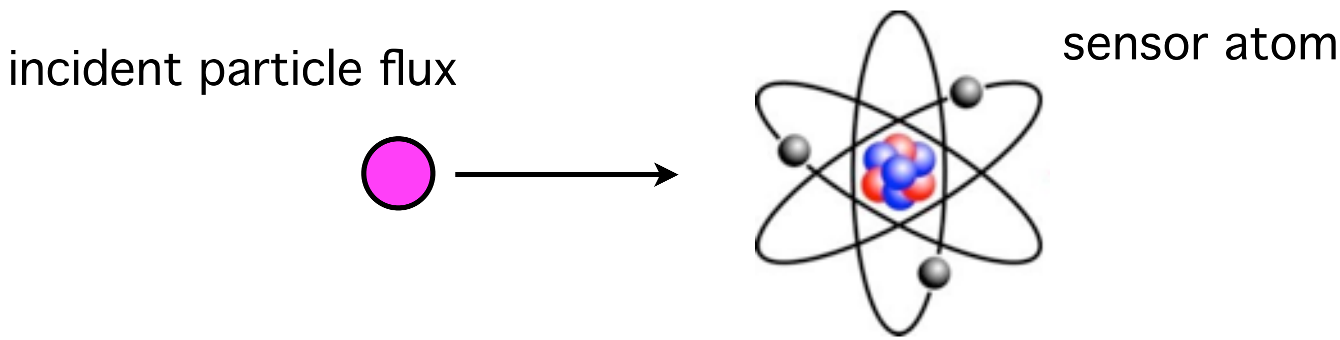

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both require knowing/preparing the sensor atom's initial state

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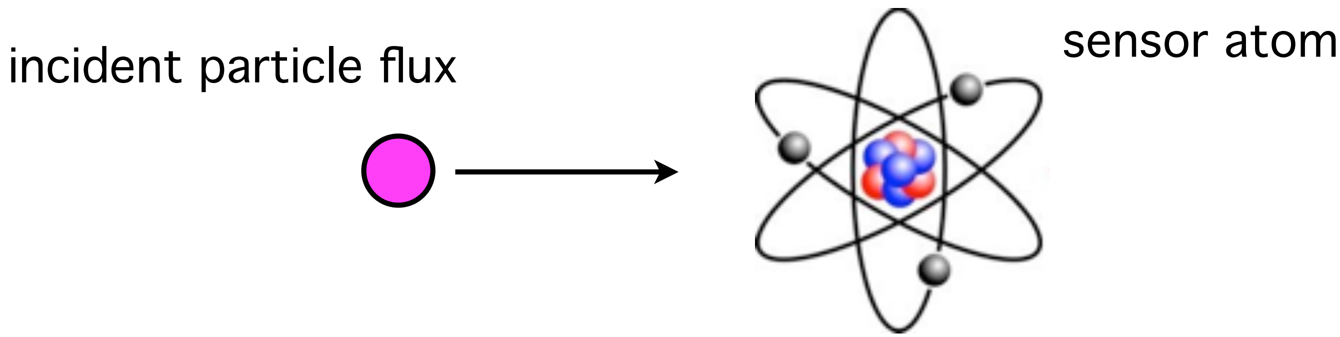

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momentum recoil particle detector

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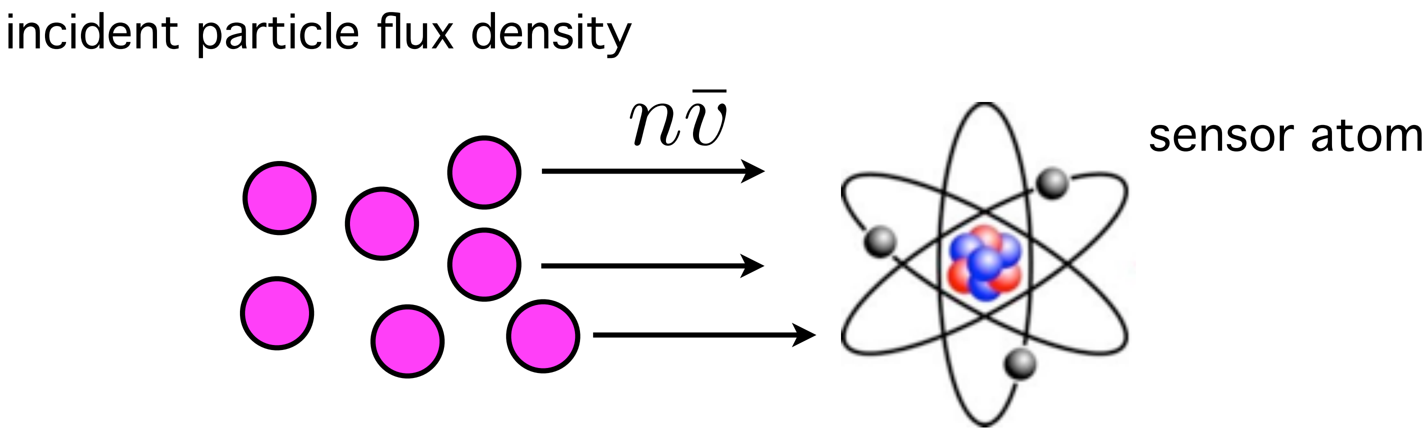
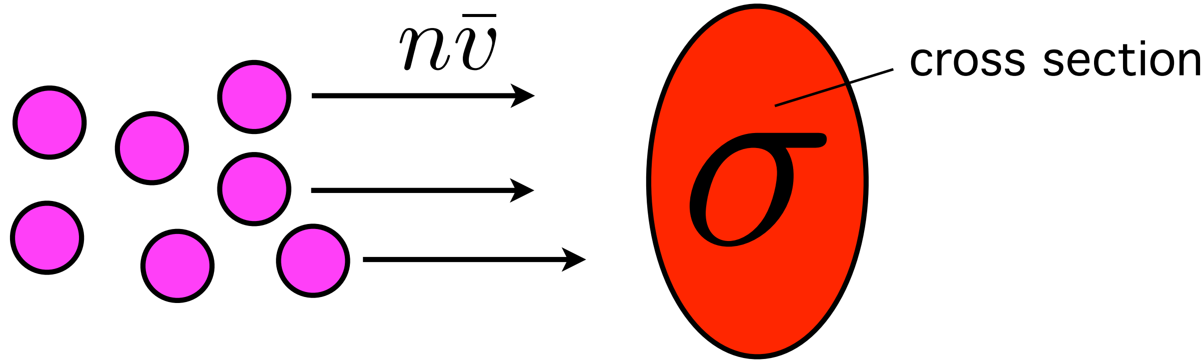


A cold atom based UHV pressure standard ?

incident particle flux density



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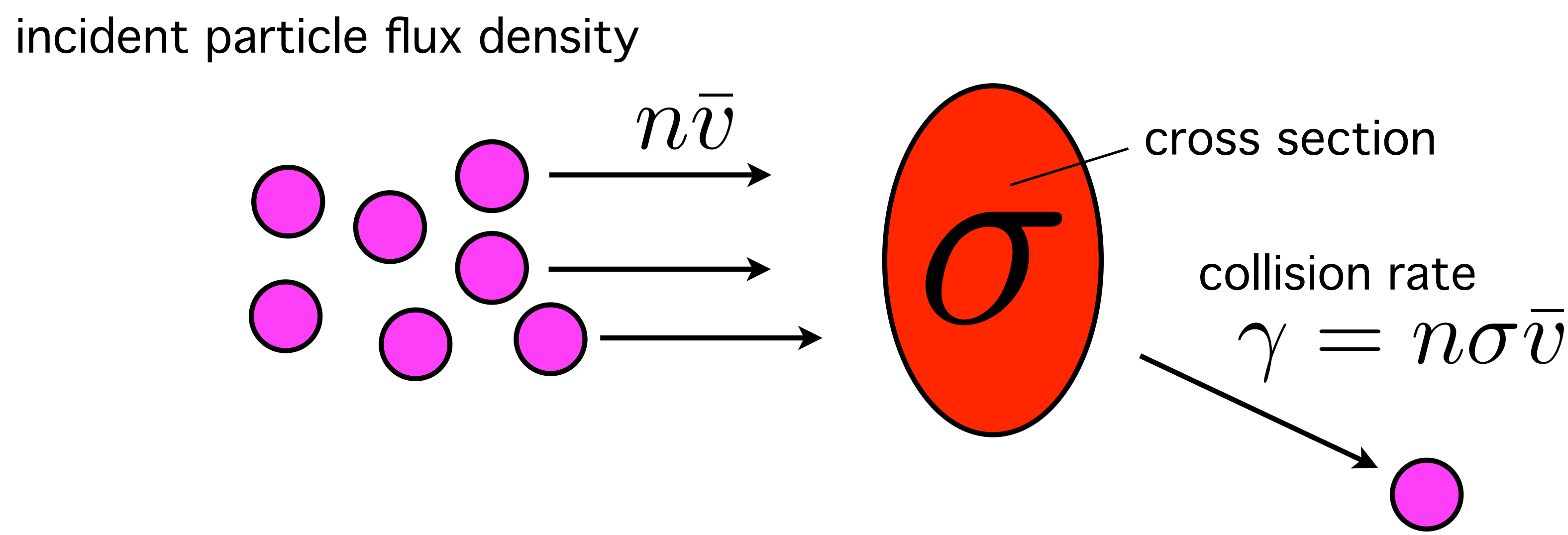

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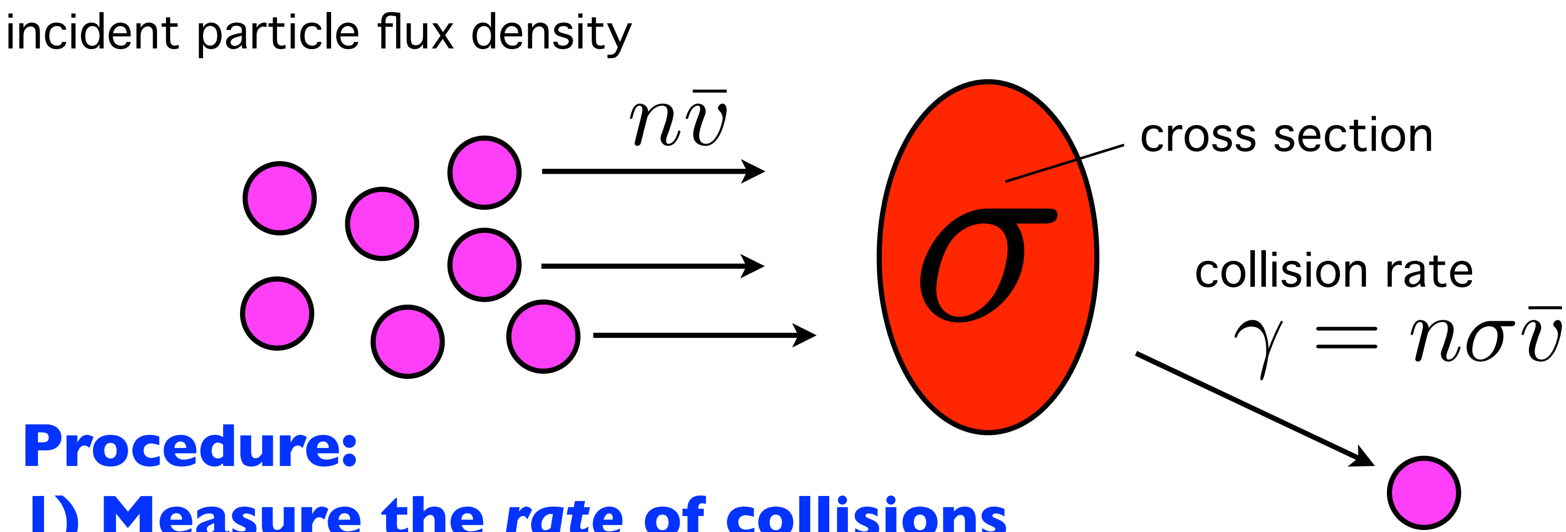


Procedure:

1) Measure the *rate* of collisions

(i.e. rate of sensor atom state changes)

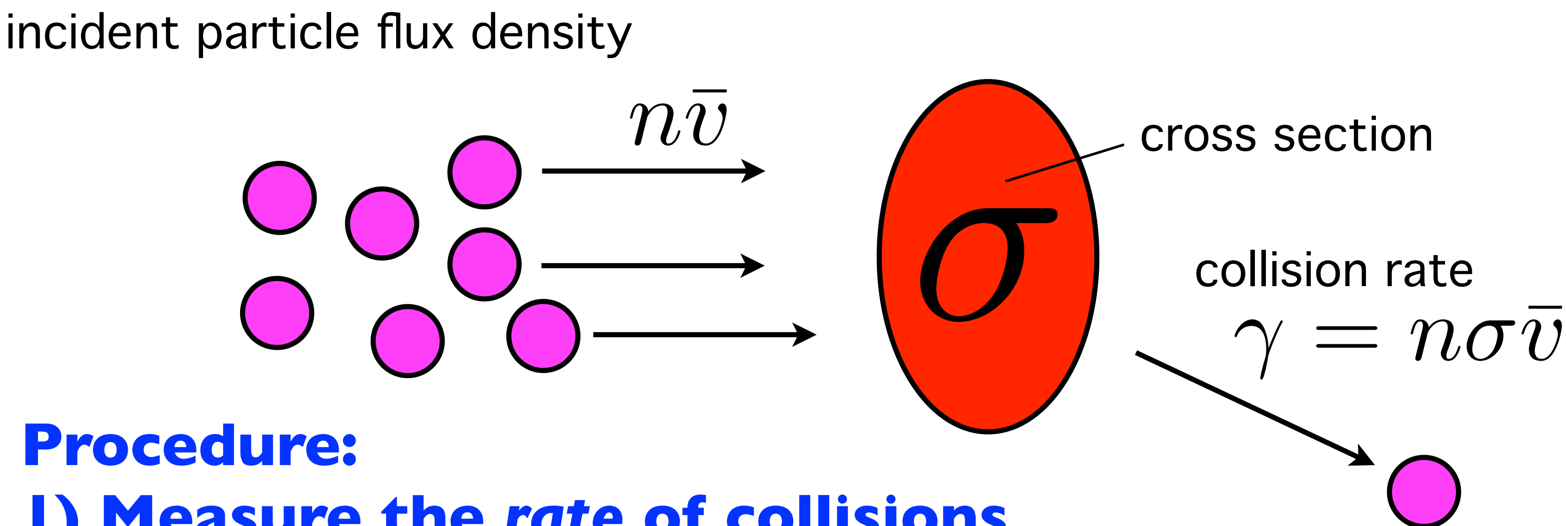
2) Solve for incident particle density

$$n = \frac{\gamma}{\langle \sigma v \rangle}$$

measurement of time

this is known

A cold atom based UHV pressure standard ?



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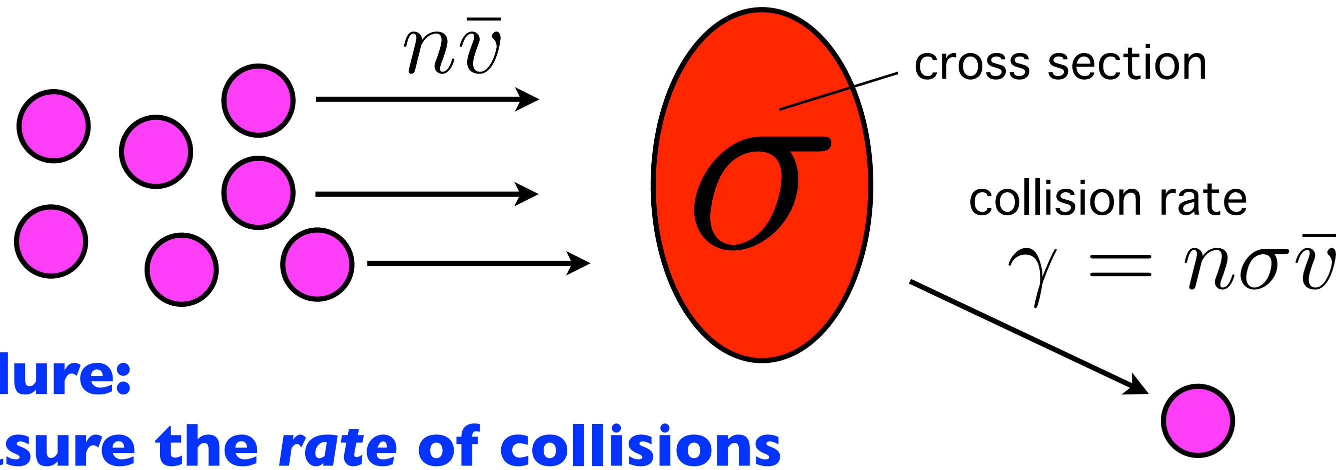
unique feature: atoms and their interaction potentials do not change

sensor never ages, and no calibration is necessary

A cold atom based UHV pressure standard ?



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1) Measure the *rate* of collisions
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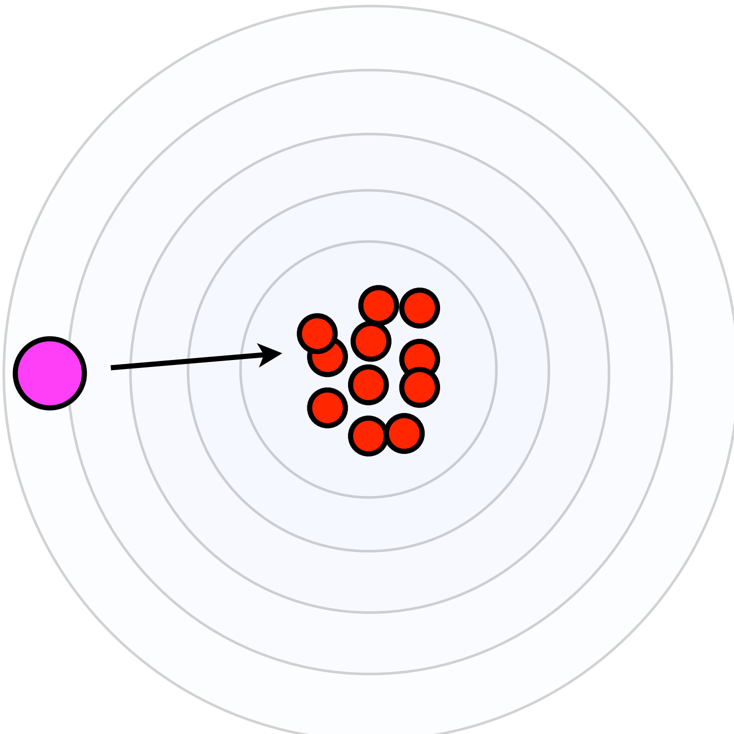
Our implementation: *momentum recoil particle detector*

- we detect changes of the sensor atom momentum because it's easy to measure

- we use argon gas because we understand the elastic collision physics between Ar and alkali atoms

detect particles via loss of sensor atoms



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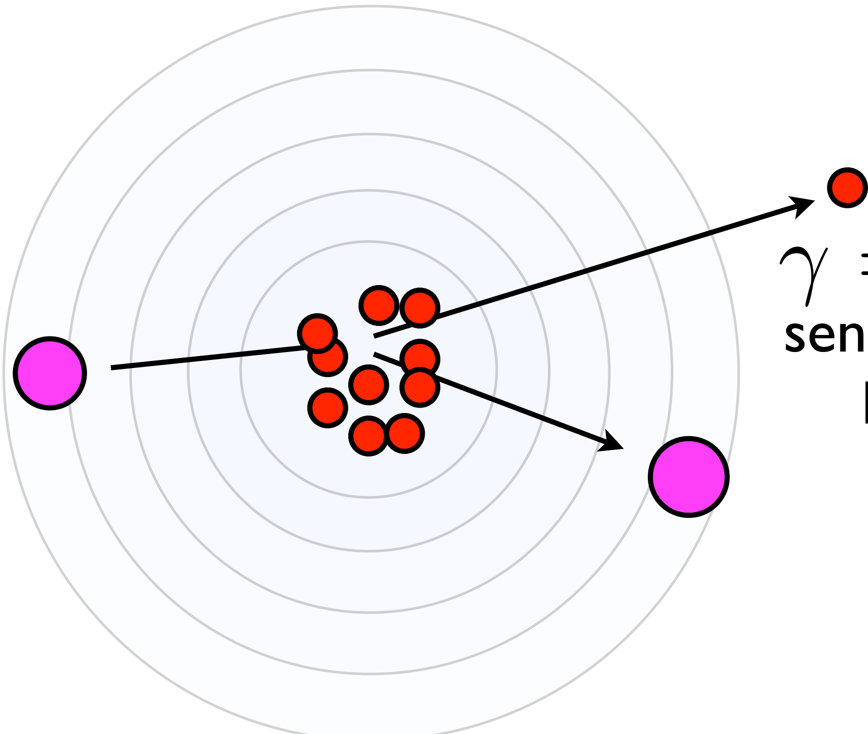
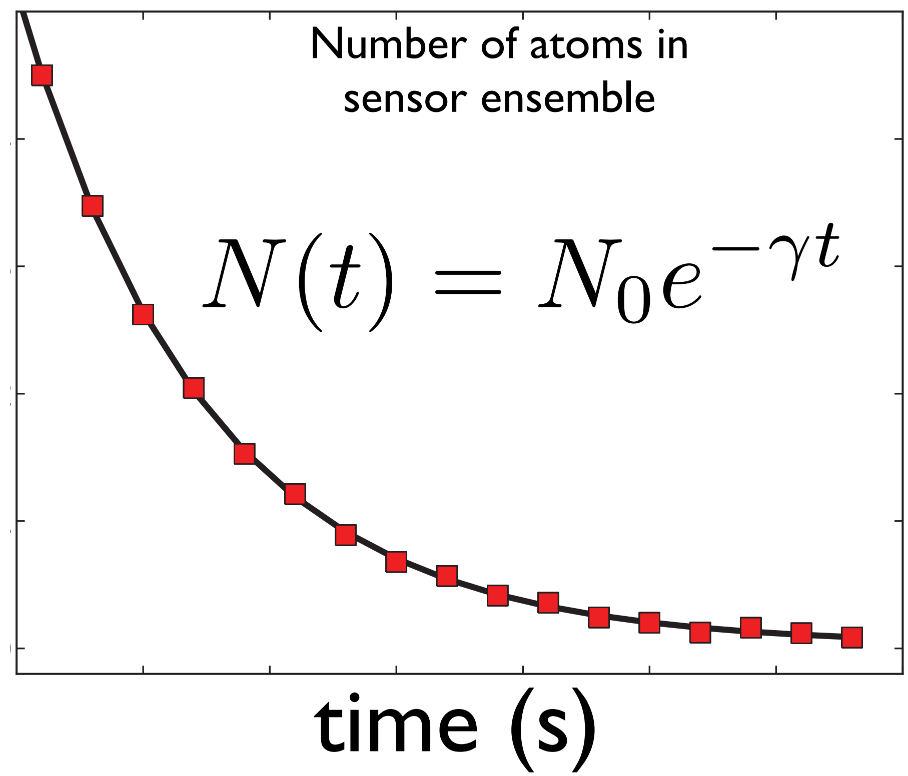


$$\gamma = n\sigma\bar{v}$$

sensor particle
loss rate



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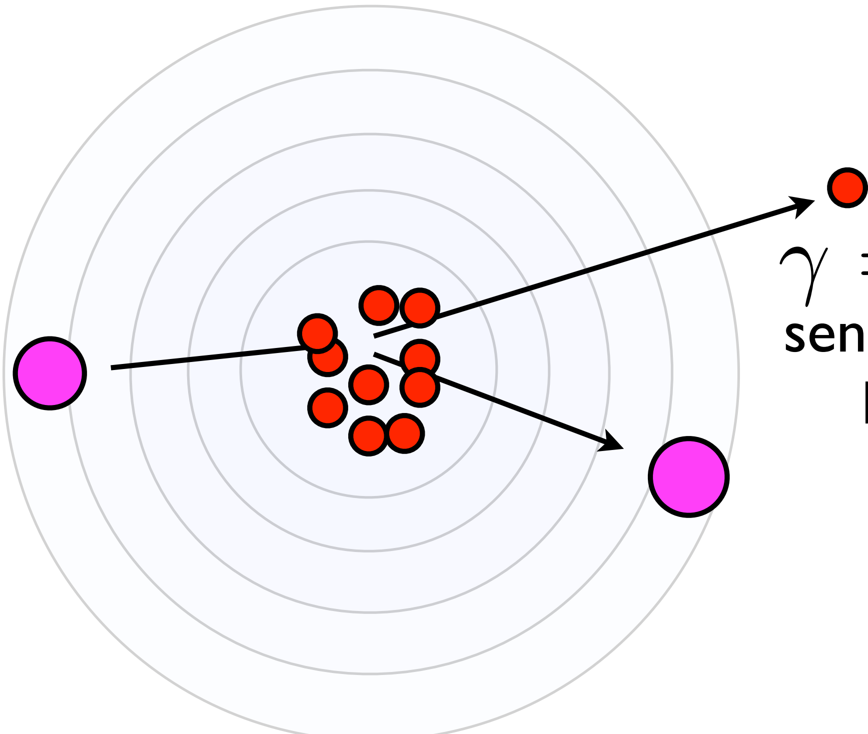

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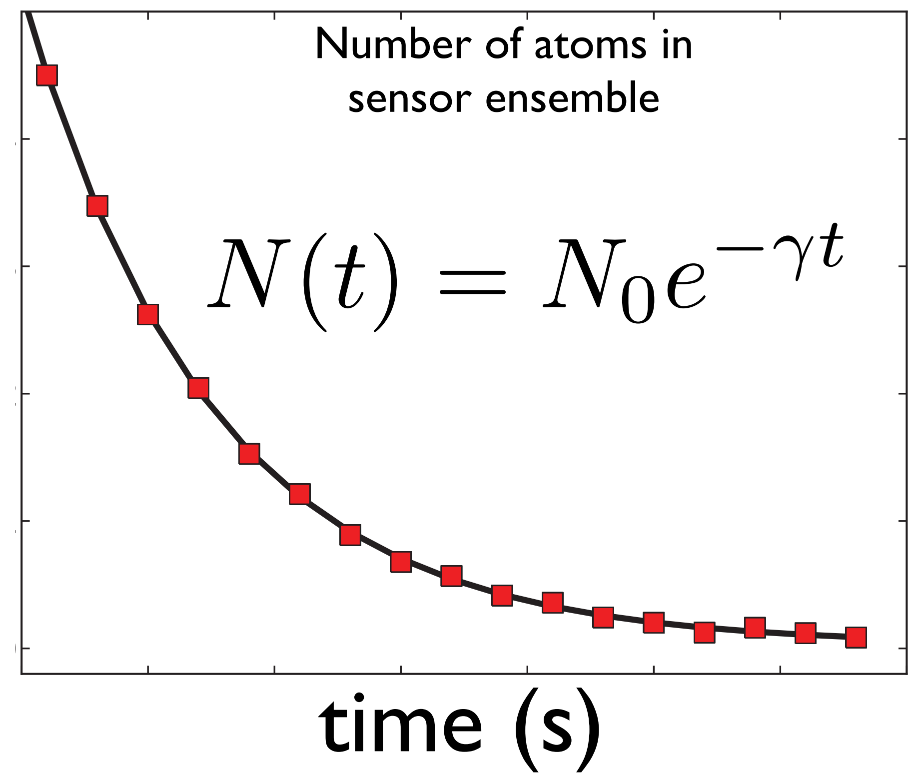
sensor particle loss rate

$$\gamma = \sum n_i \langle \sigma v \rangle_i$$

background vapor composed of multiple species



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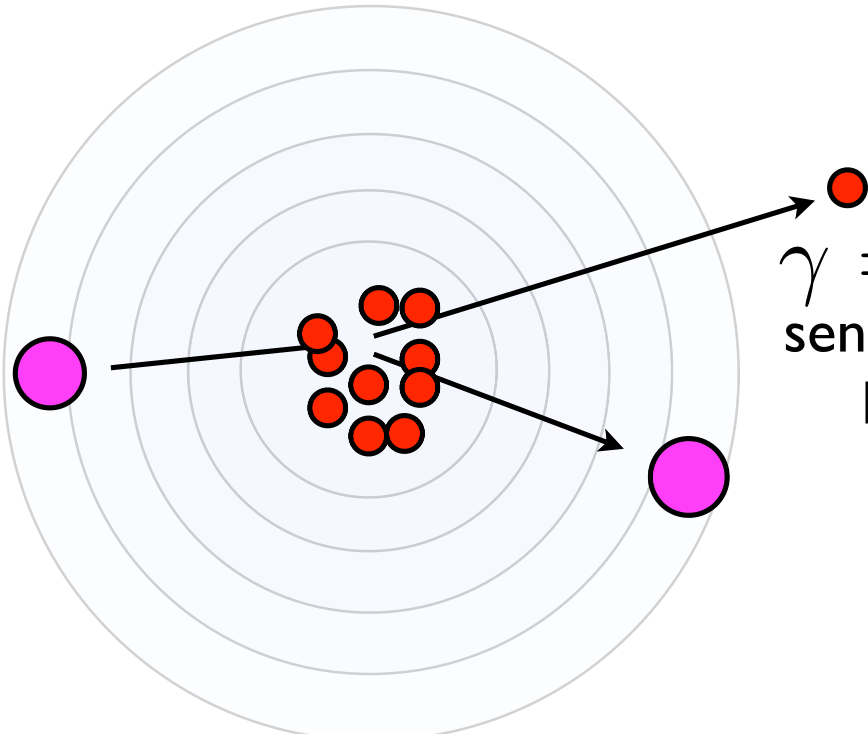

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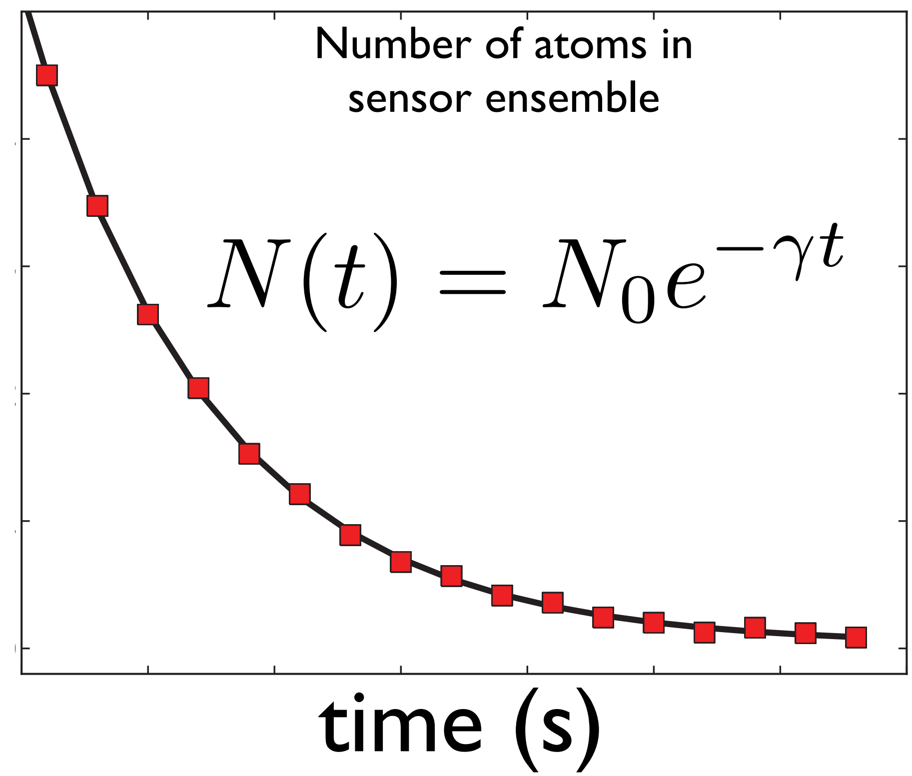
To provide long interaction times, the sensor particles are held in a trap



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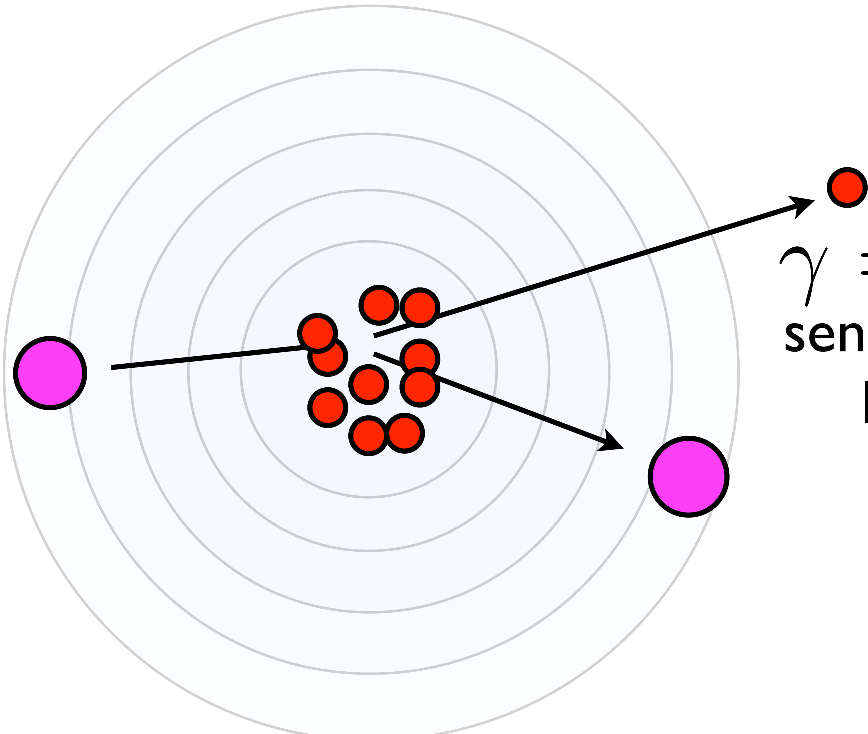

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sensor particle loss rate

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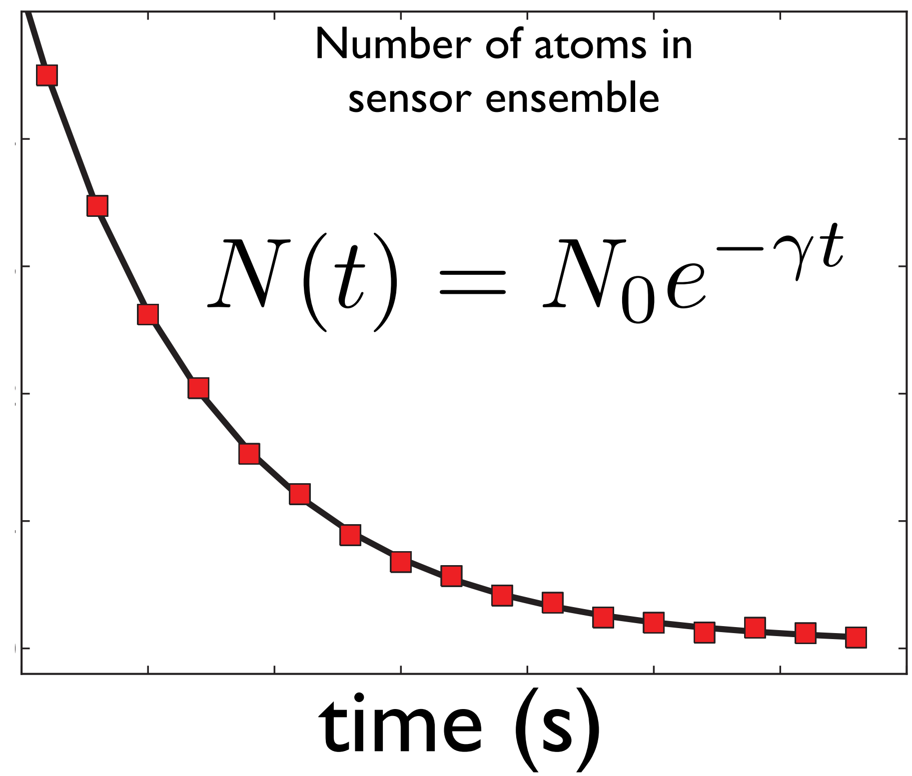
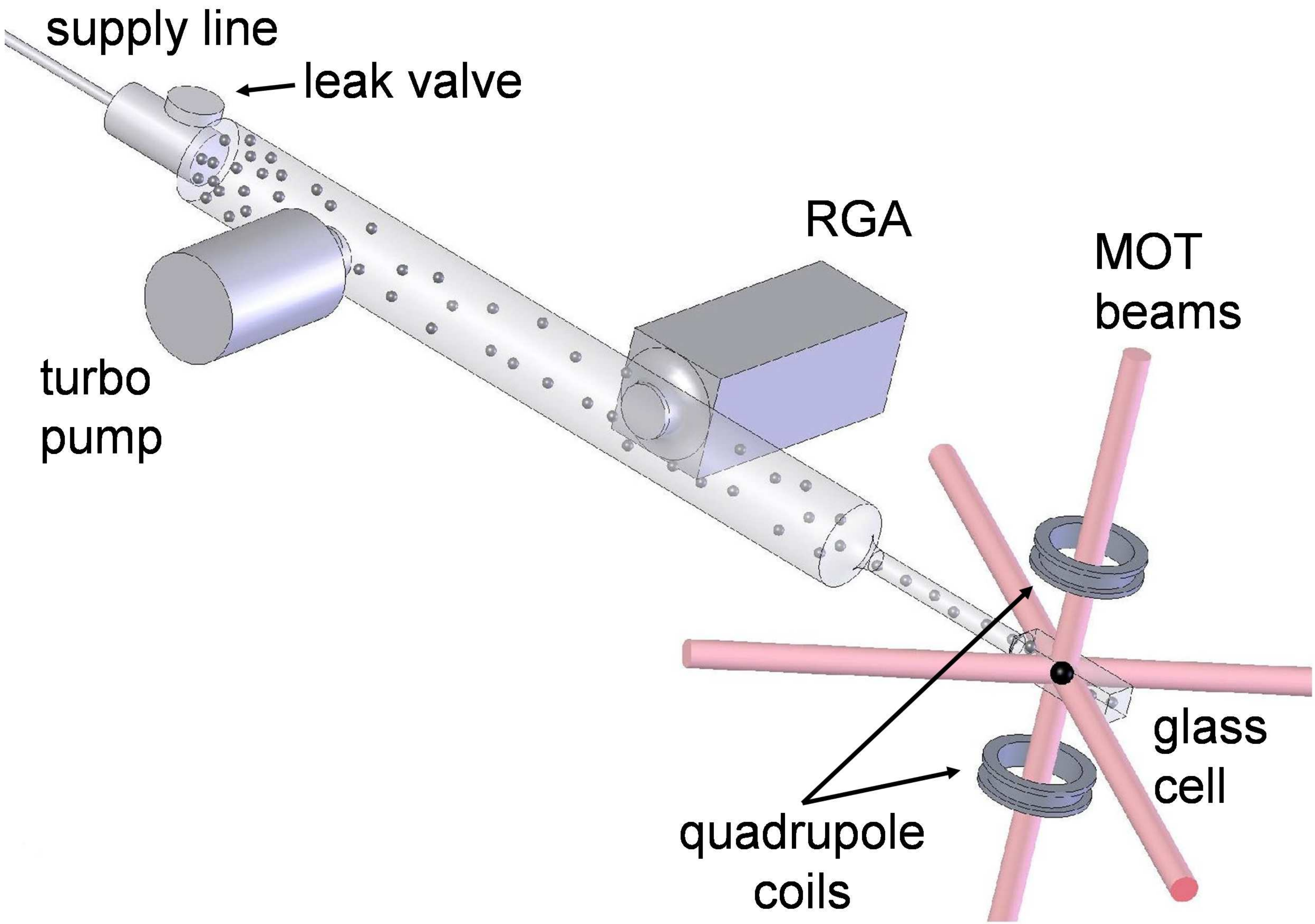
CAVEAT: For atoms in a trap, not every collision results in sensor particle loss !

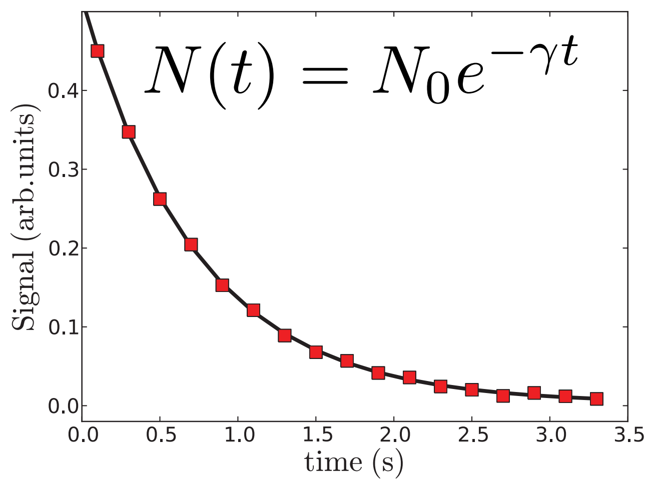


Proof of principle experiment



Proof of principle experiment

$$\gamma = \sum n_i \langle \sigma v \rangle_i = \gamma_0 + n_{\mathrm{Ar}} \langle \sigma v \rangle_{\mathrm{Ar}}$$



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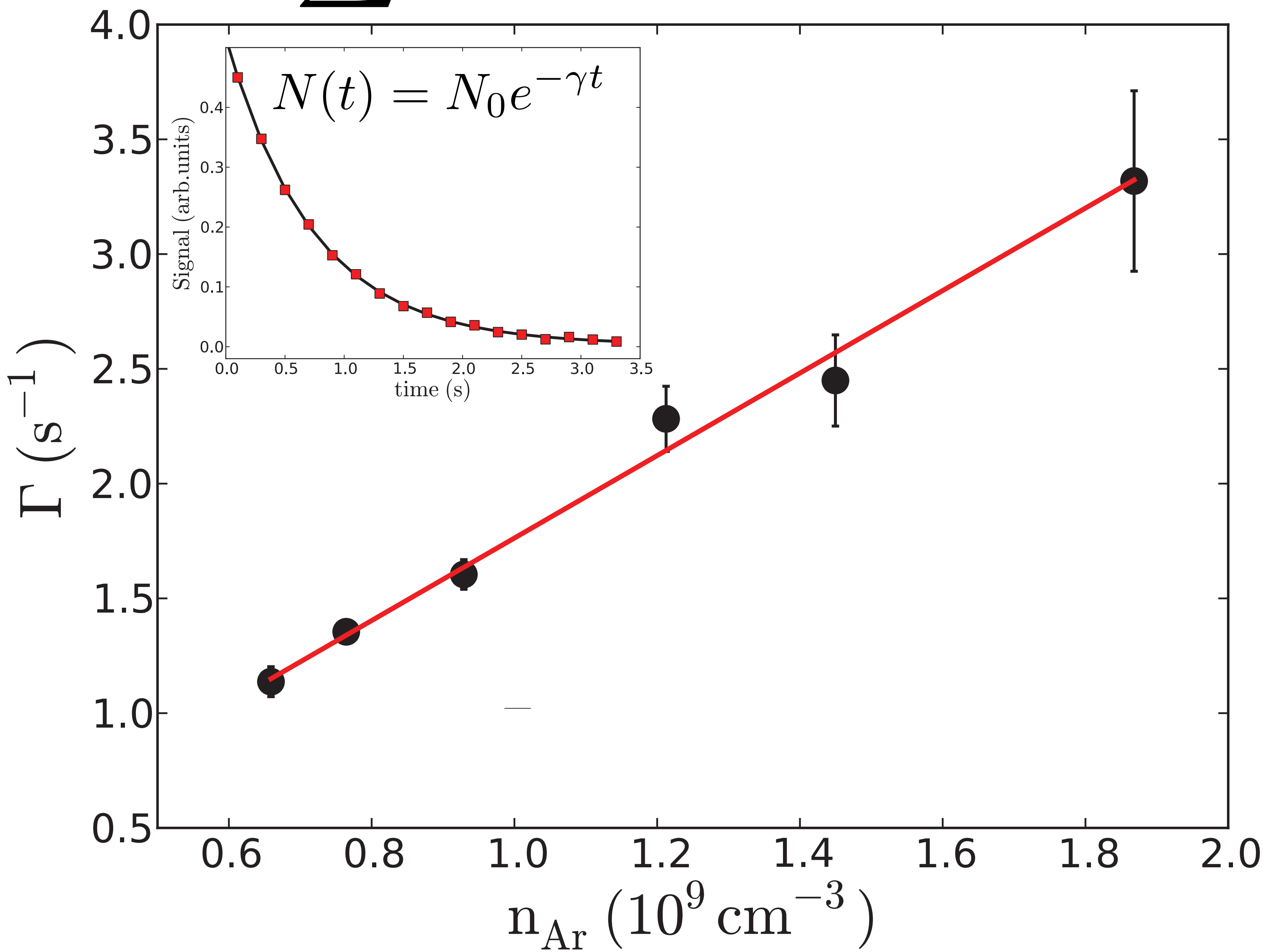

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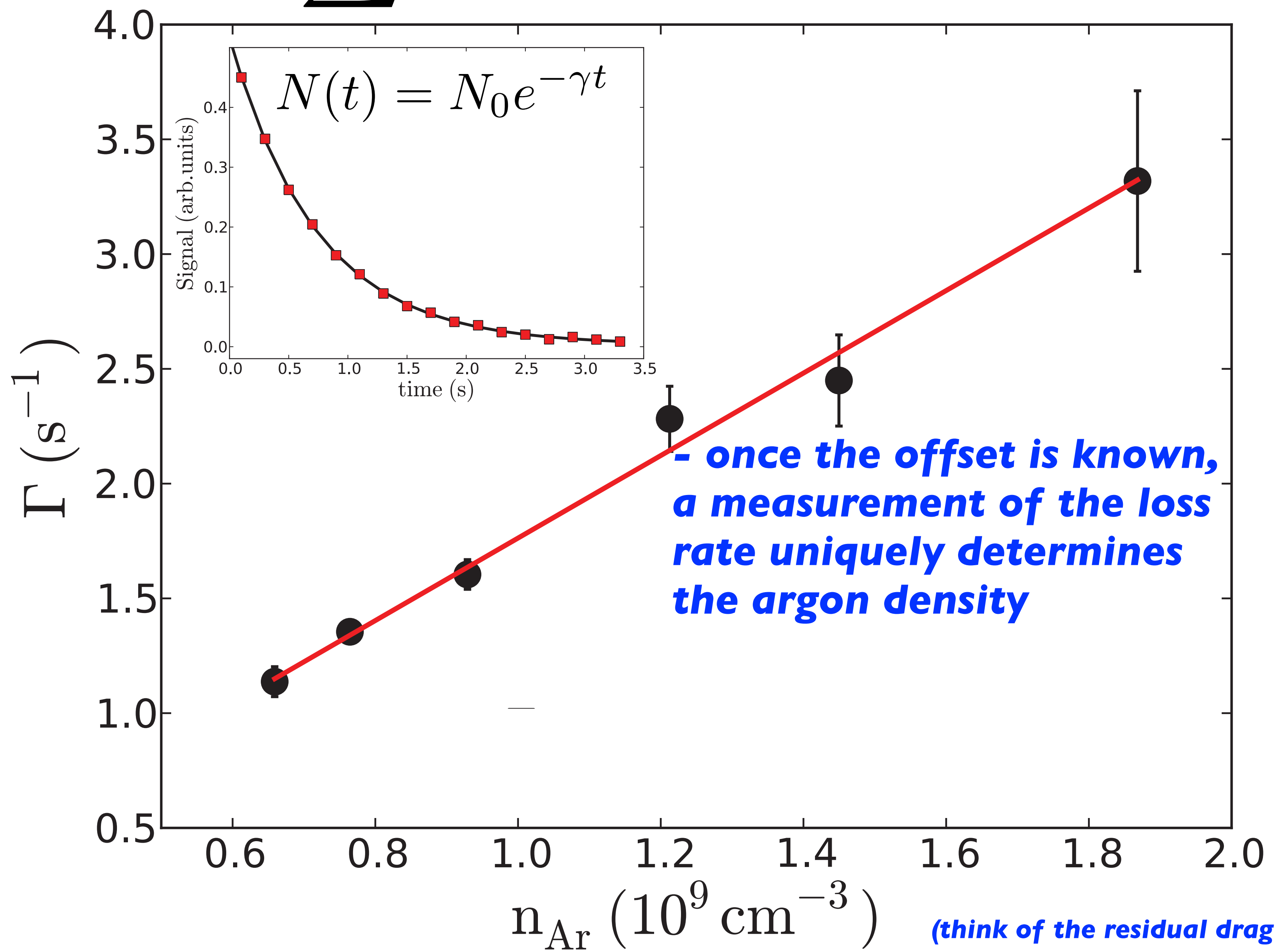

- once the offset is known, a measurement of the loss rate uniquely determines the argon density

(think of the residual drag of an SRG)

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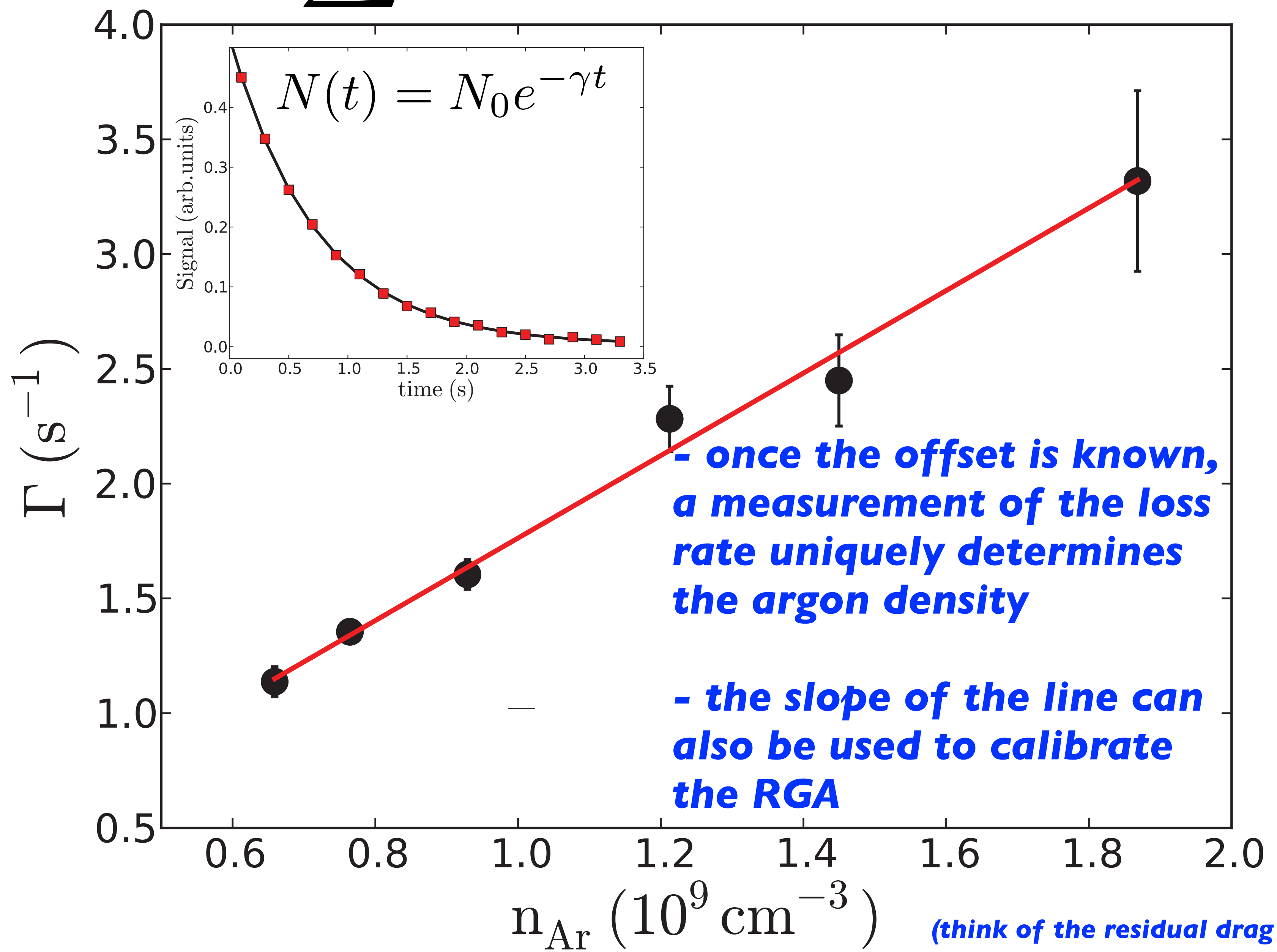

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- the slope of the line can also be used to calibrate the RGA

(think of the residual drag of an SRG)

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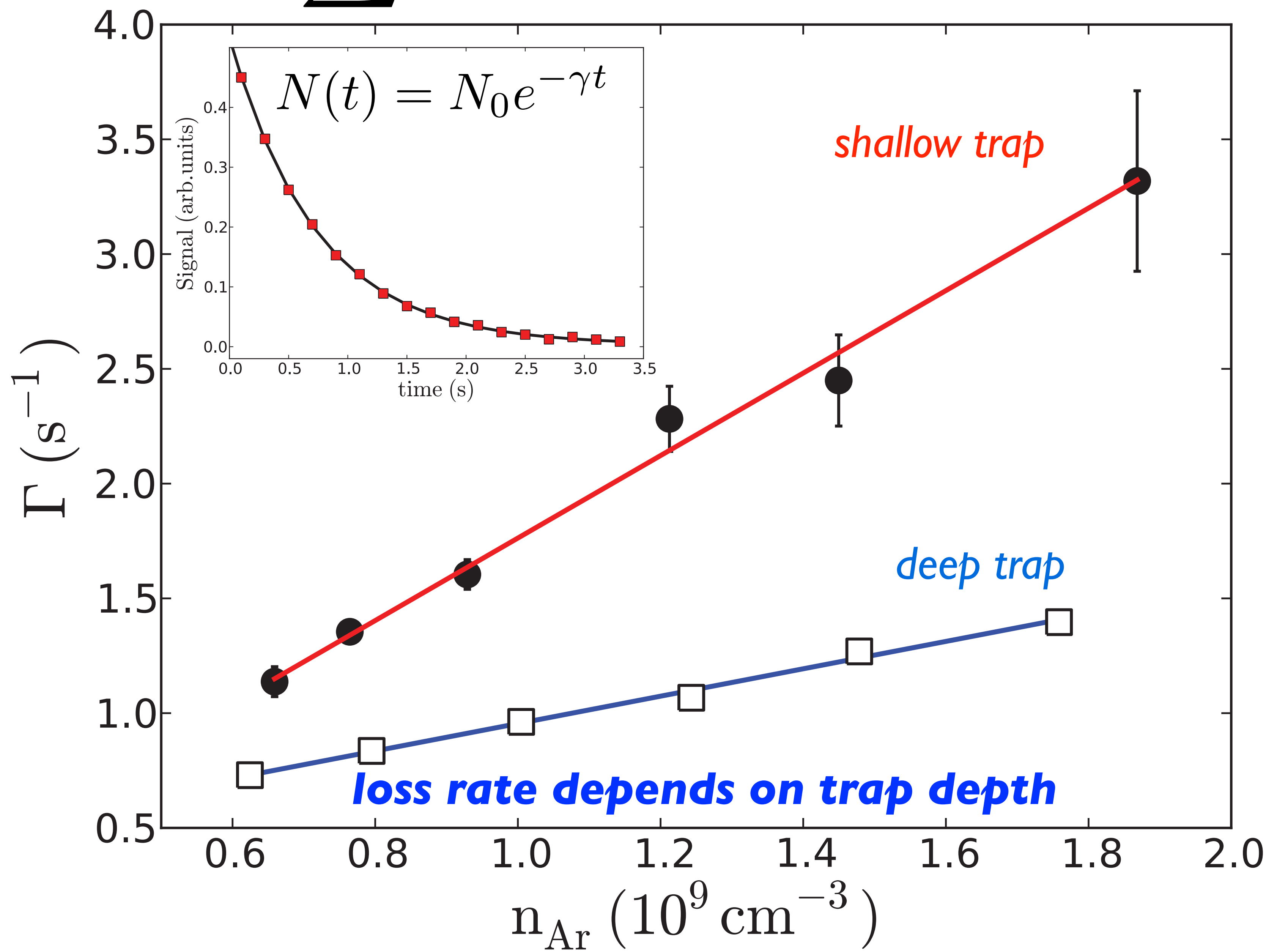
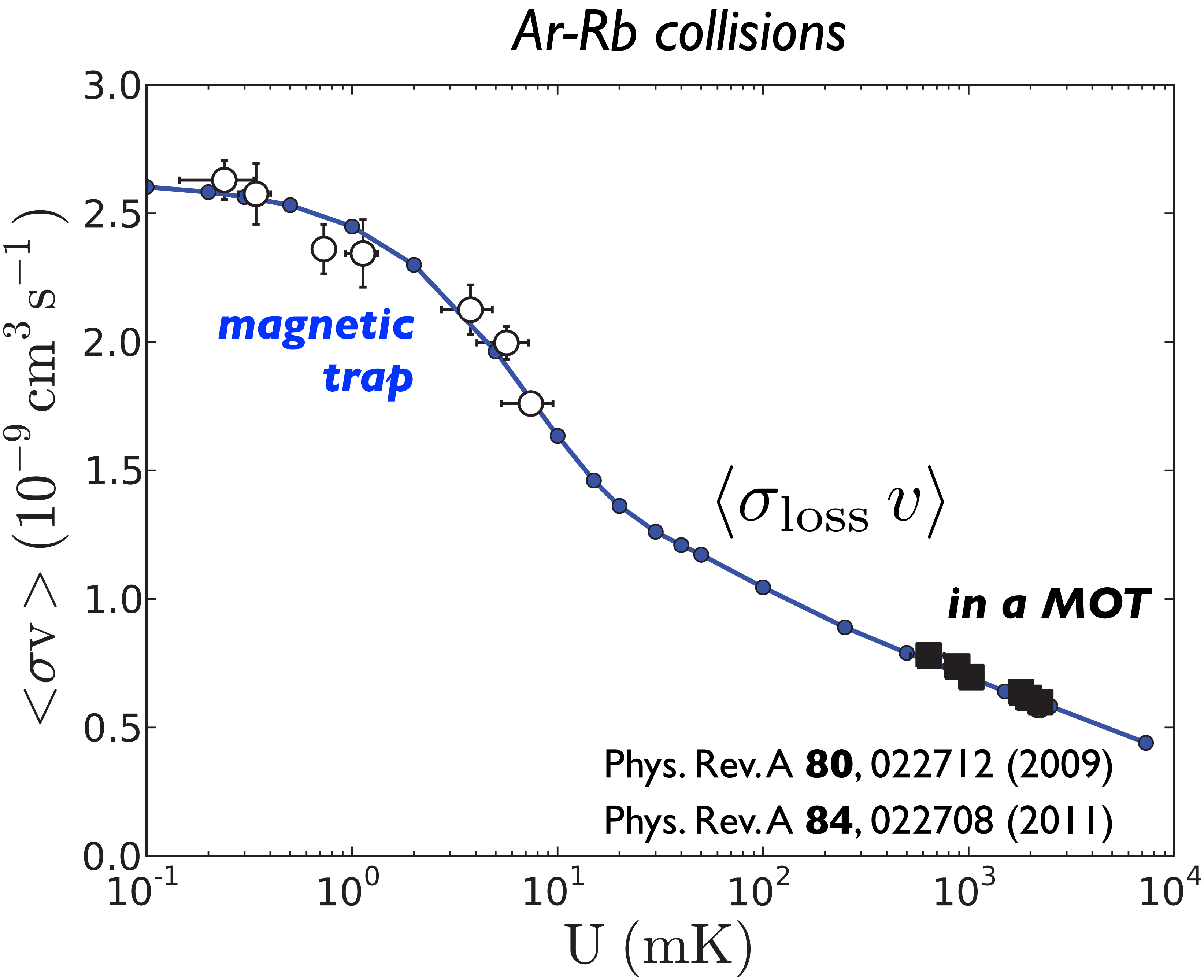


Loss cross section vs. trap depth



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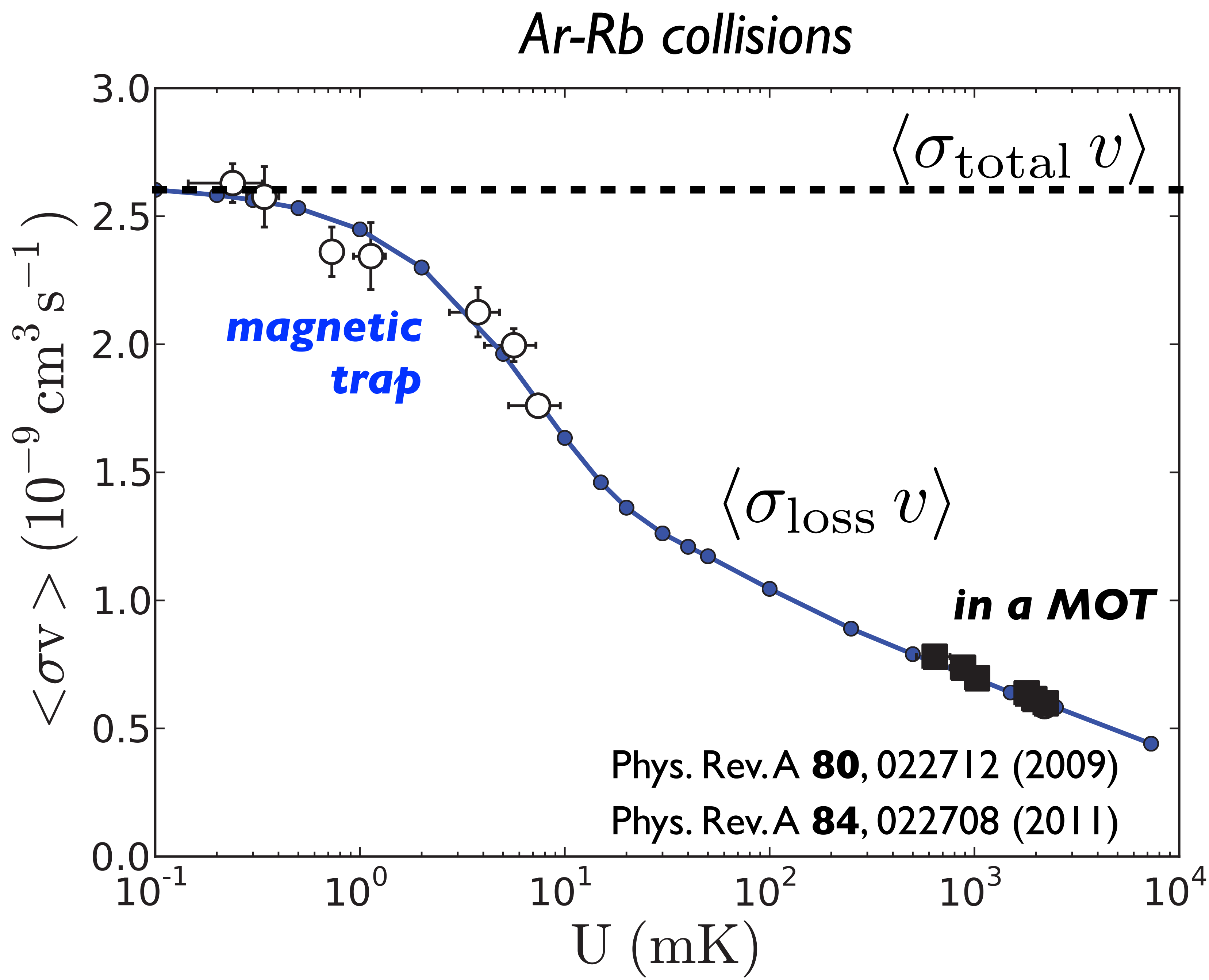

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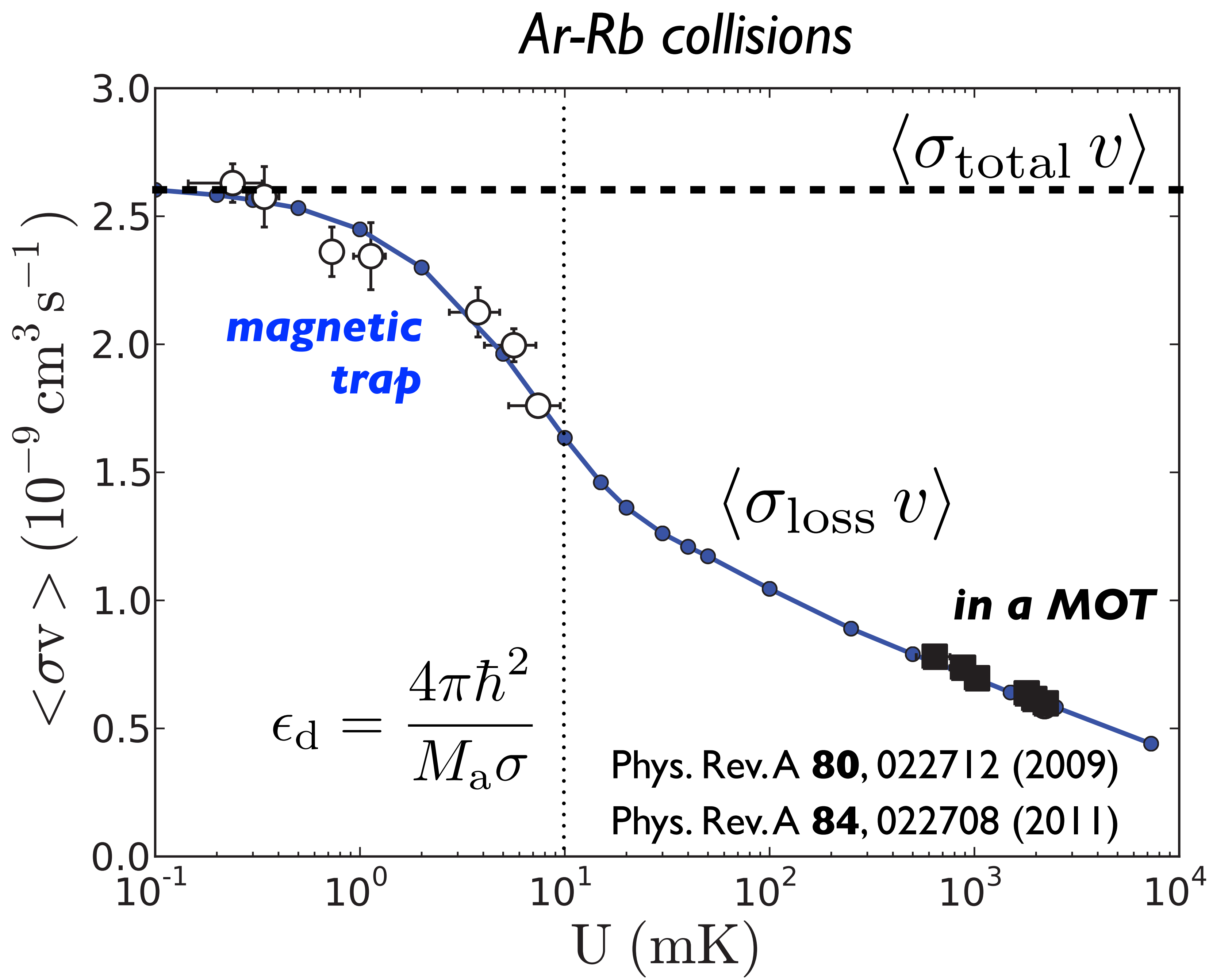
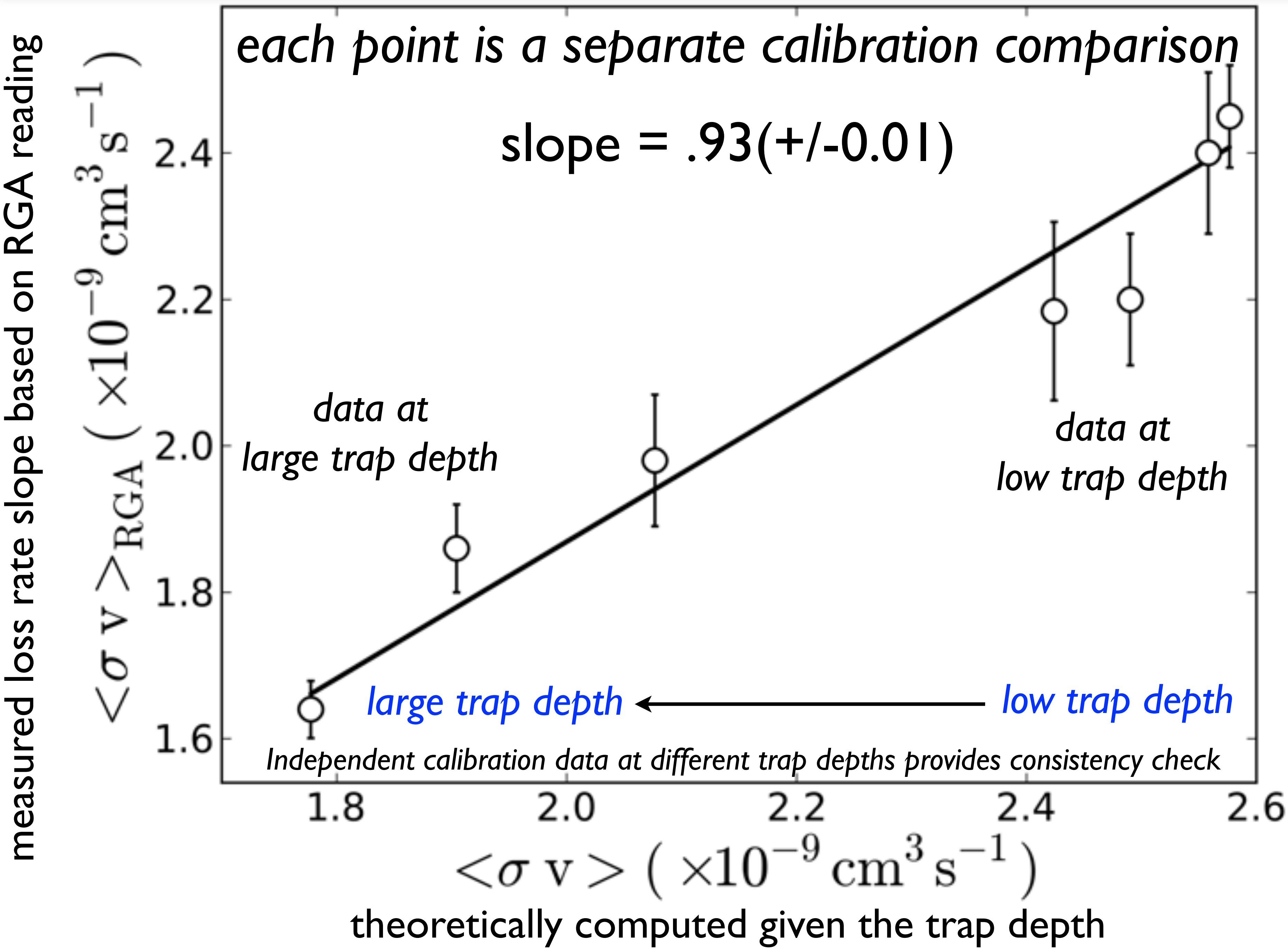
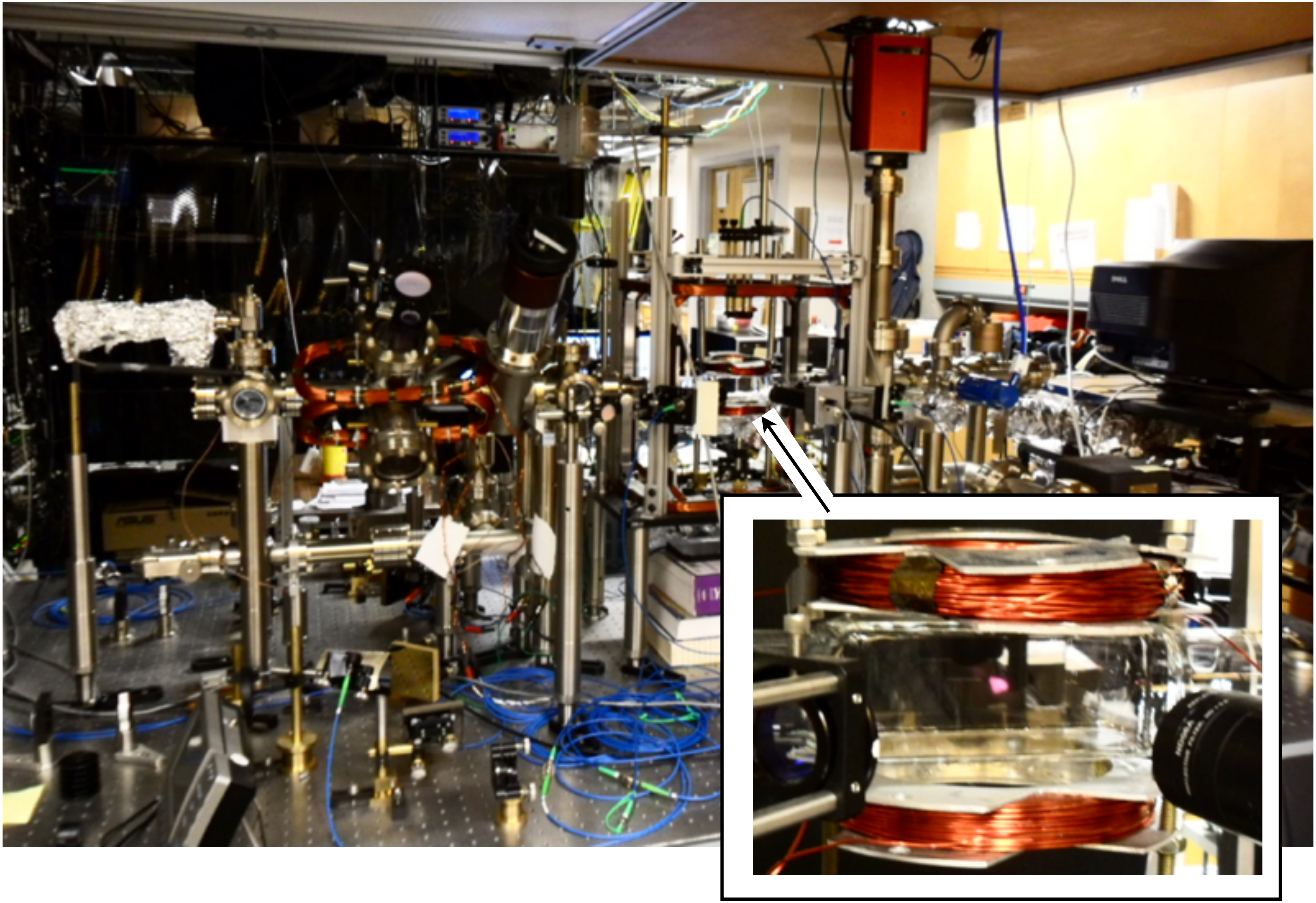


Proof of principle: RGA calibration



Next steps: benchmark atom gauge



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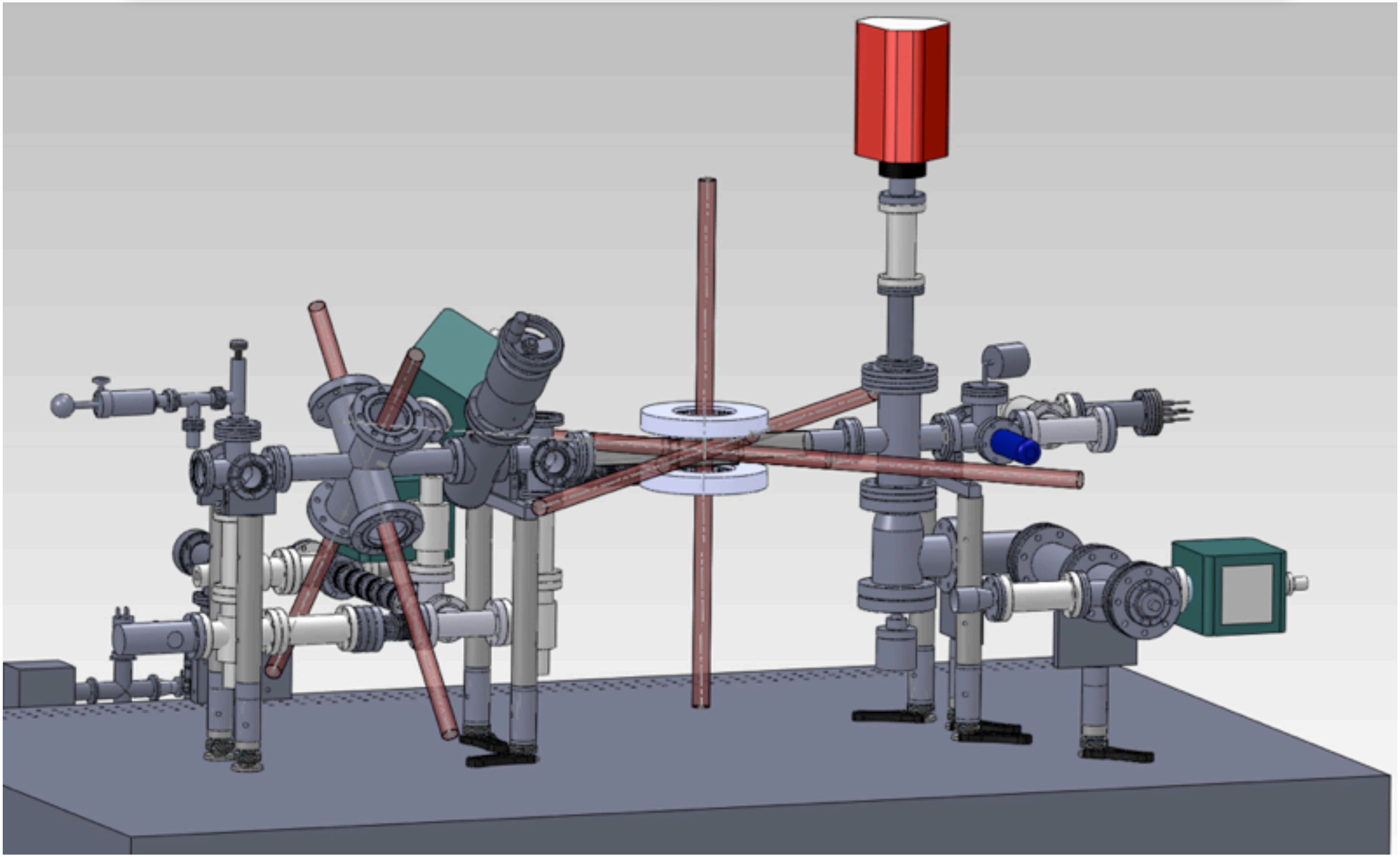

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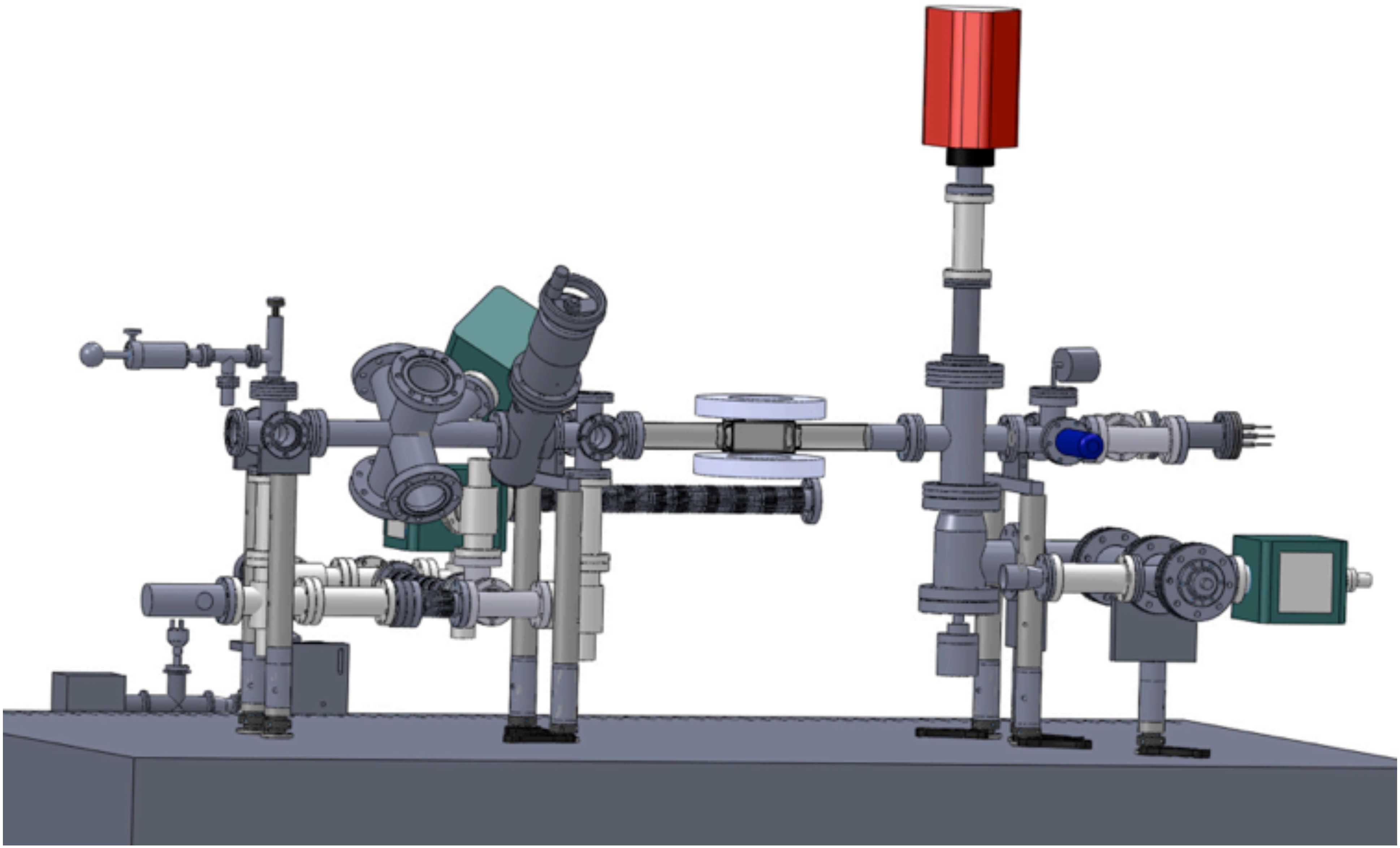

The complications of using loss rates from a MOT

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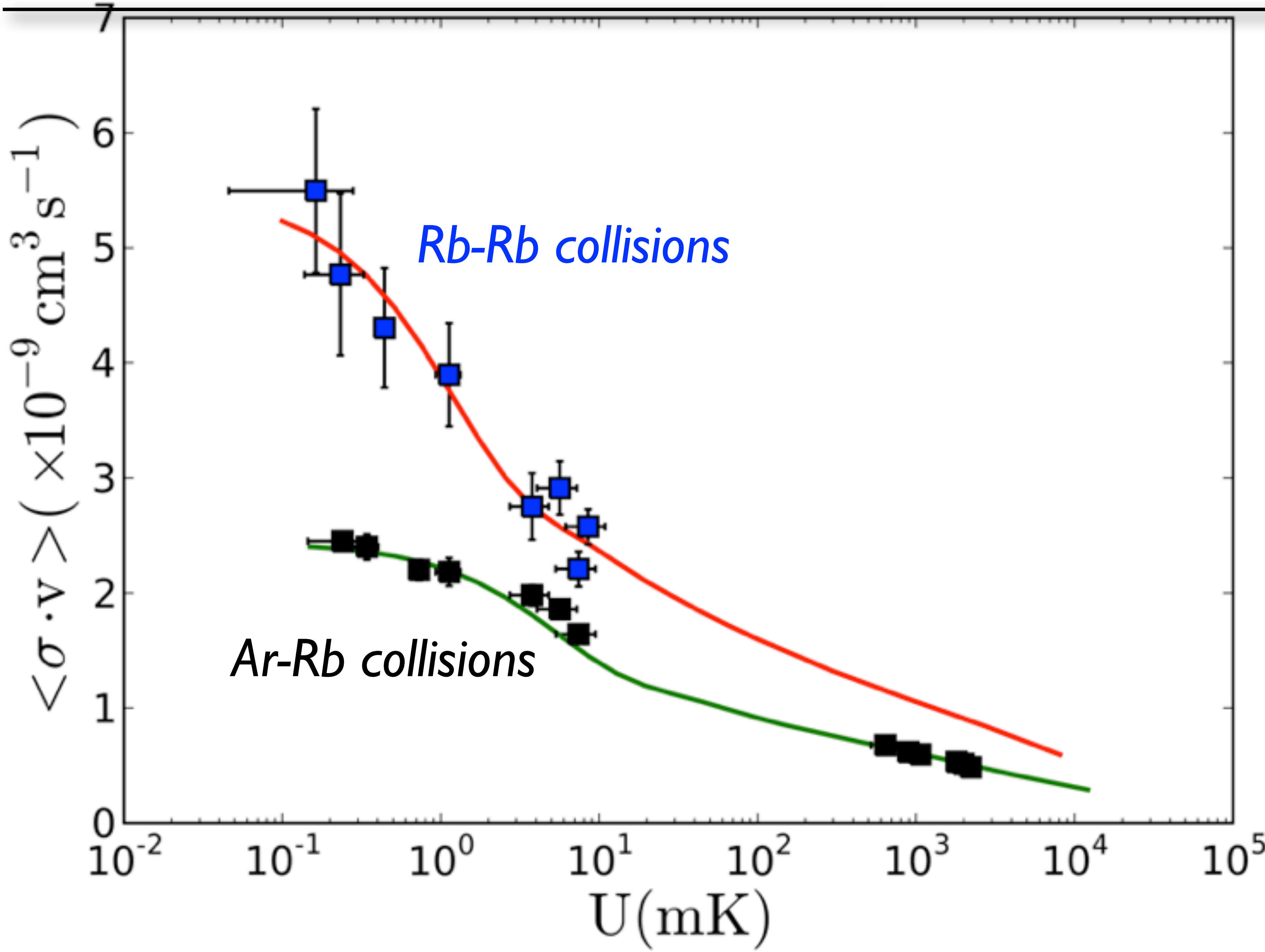
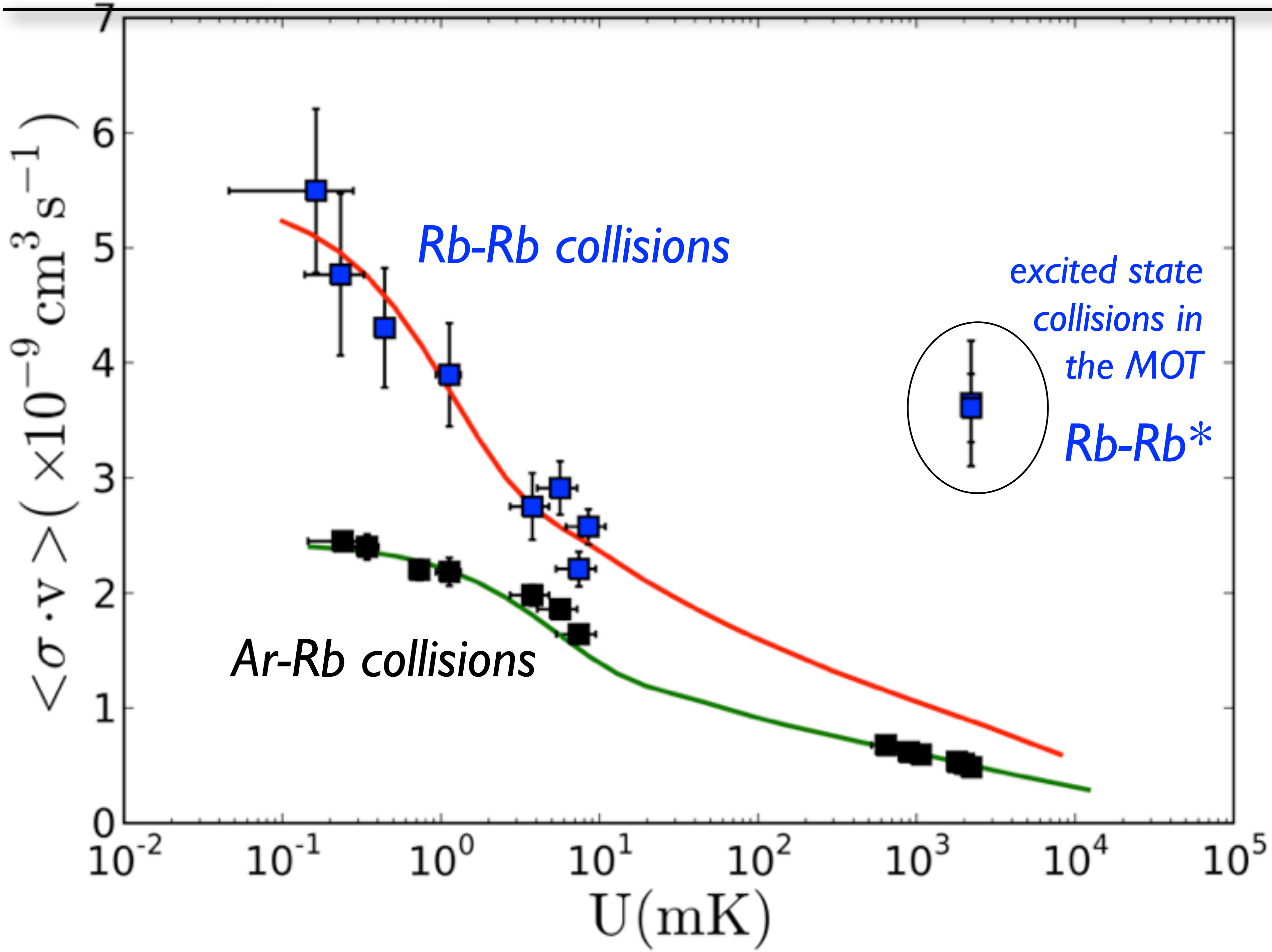
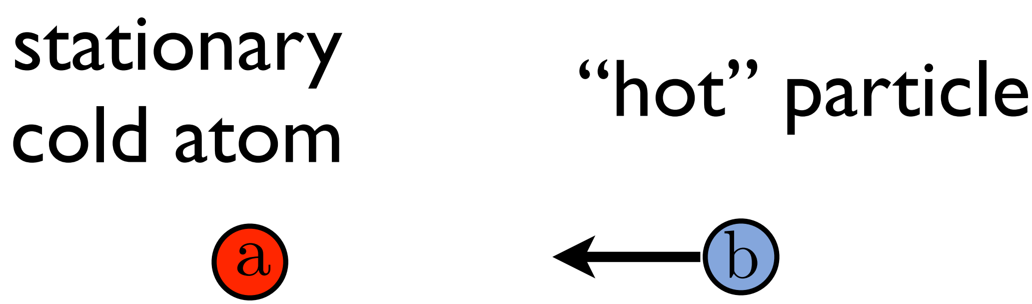


The complications of loss rates from a MOT



Theory of elastic scattering and trap loss

Scattering and trap loss



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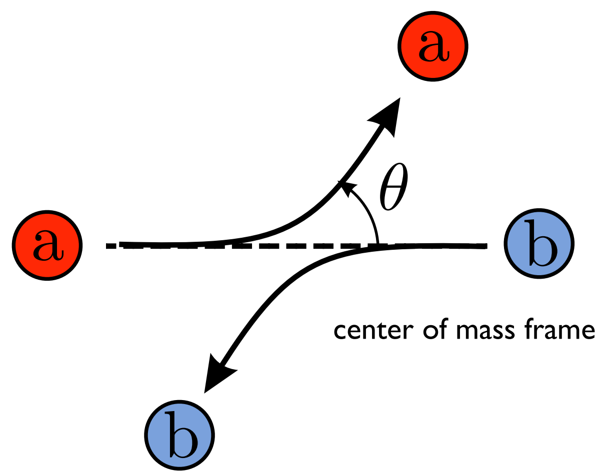
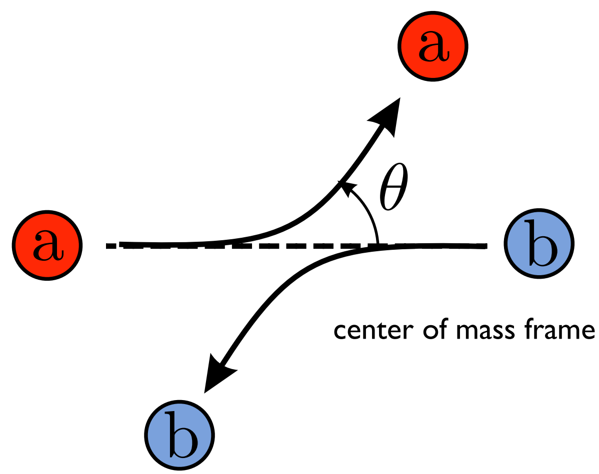


Scattering and trap loss

conservation of energy and momentum gives

$$\Delta E \simeq \frac{\mu^2}{M_{\mathrm{a}}} |\vec{v}_{\mathrm{r}}|^2 (1 - \cos\theta).$$

elastic collisions



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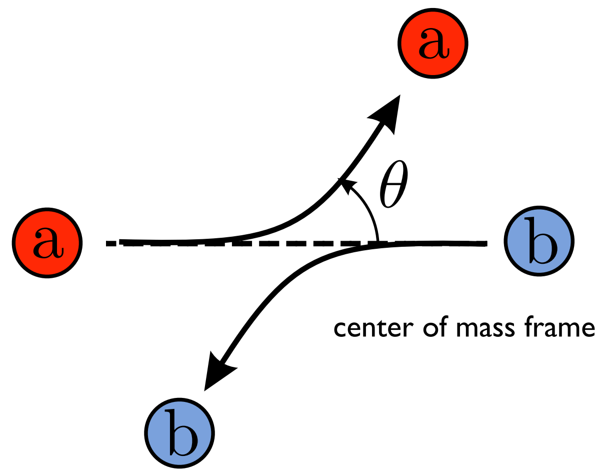

atom "a" is lost from trap if $\Delta E > U_0$

$$\theta > \theta_\mathrm{min}$$

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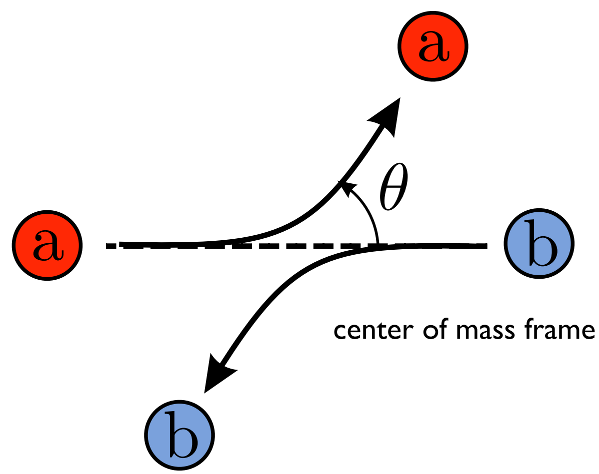

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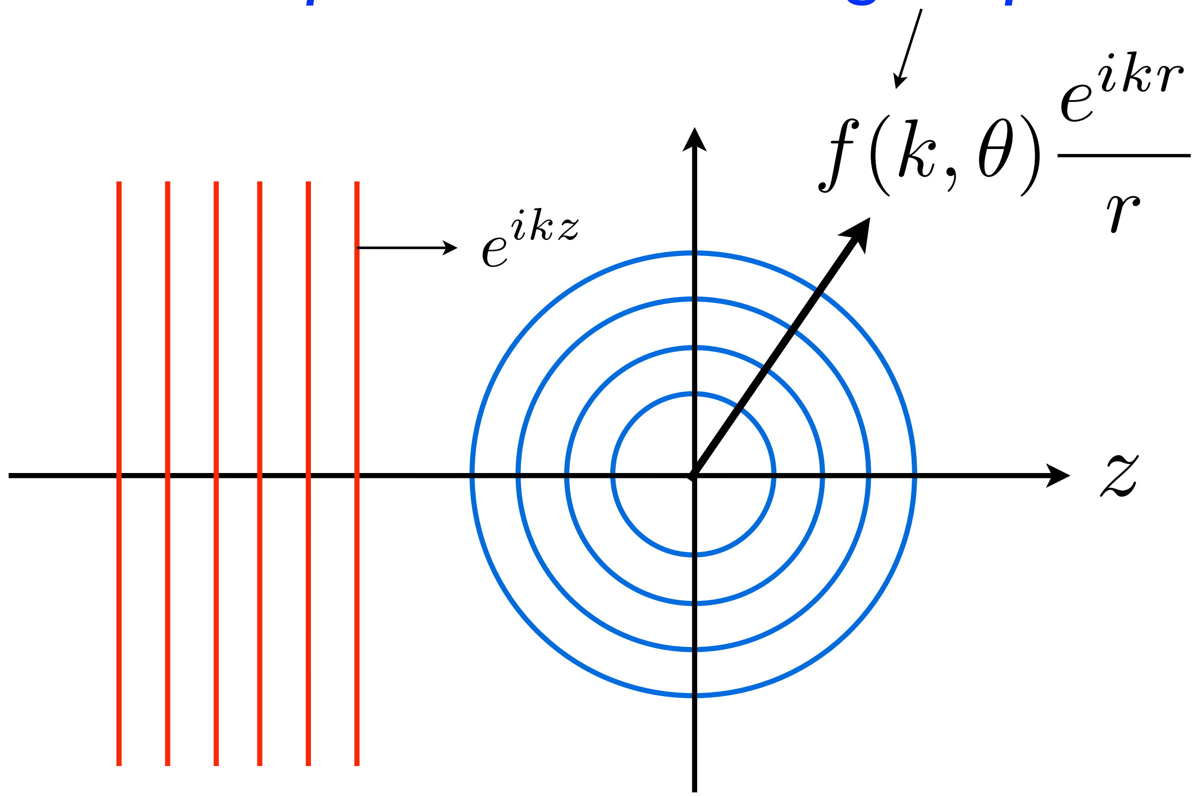
what is the distribution of scattering angles?

Quantum treatment of scattering

compute the scattering amplitude



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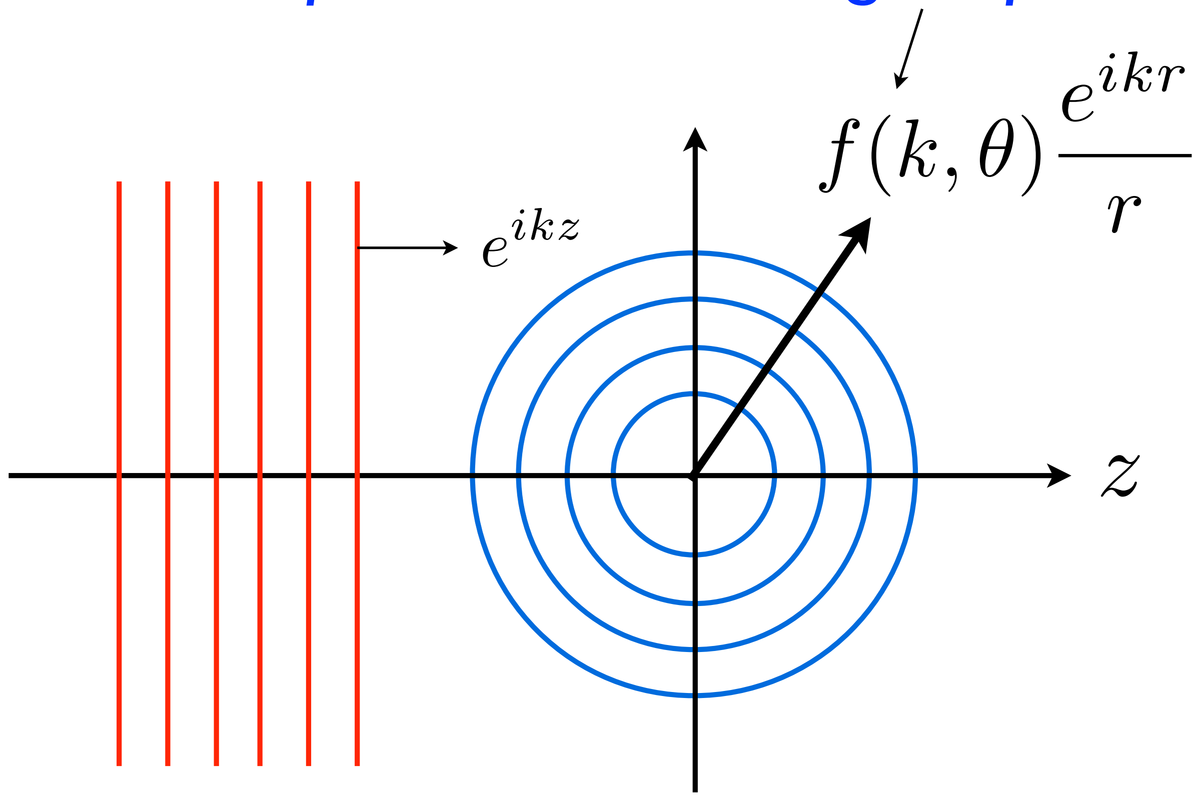
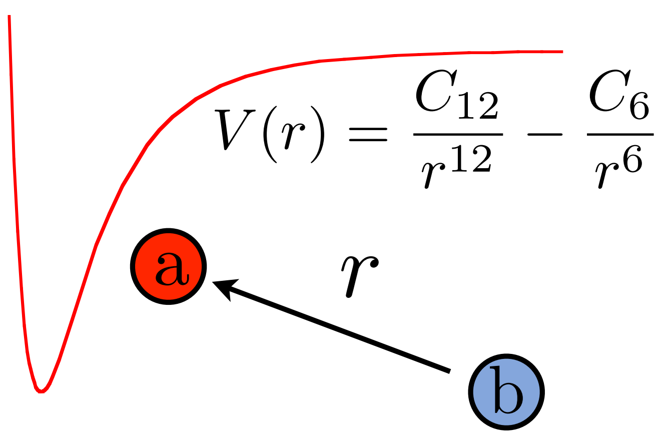
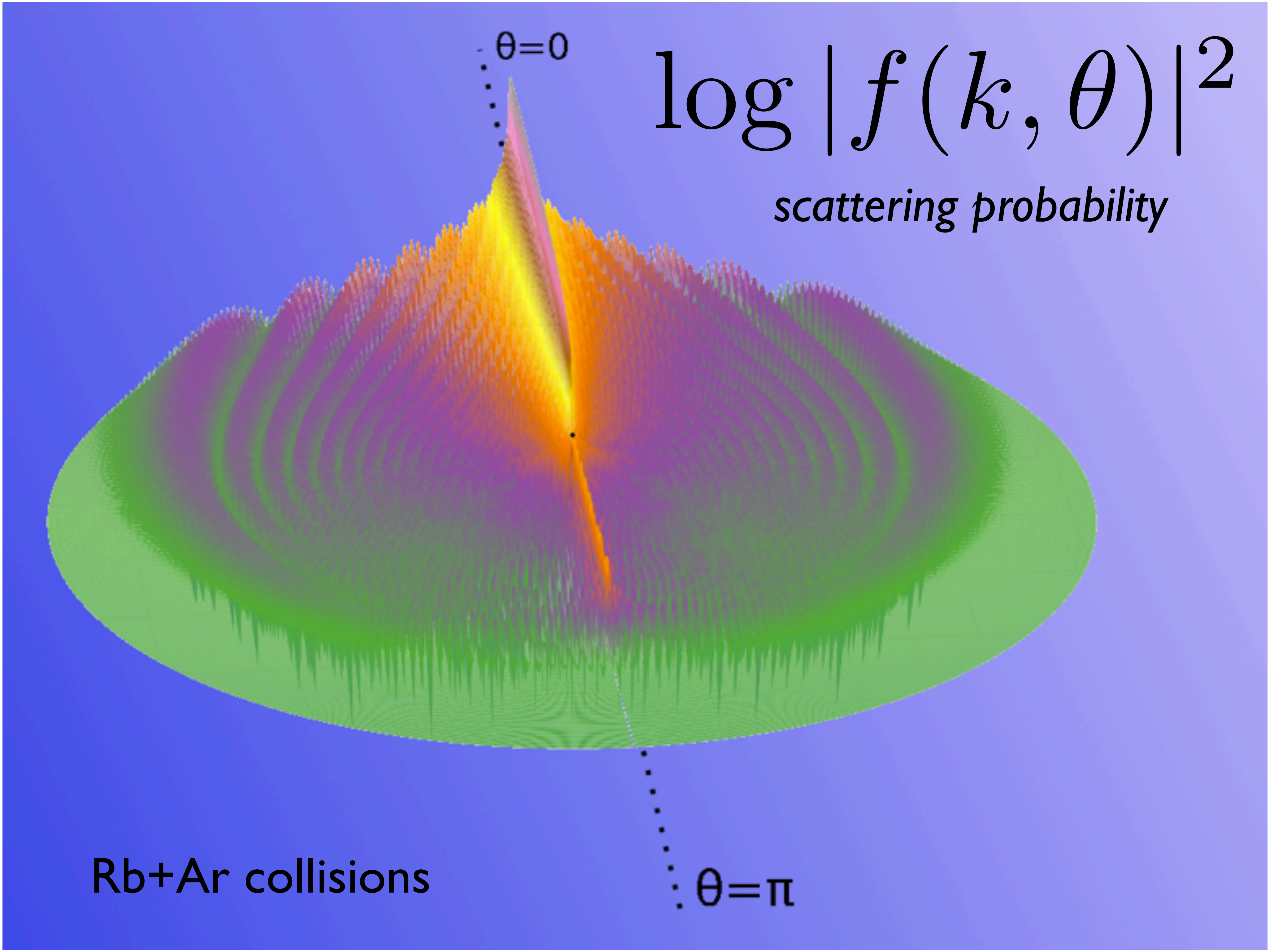
compute the scattering amplitude

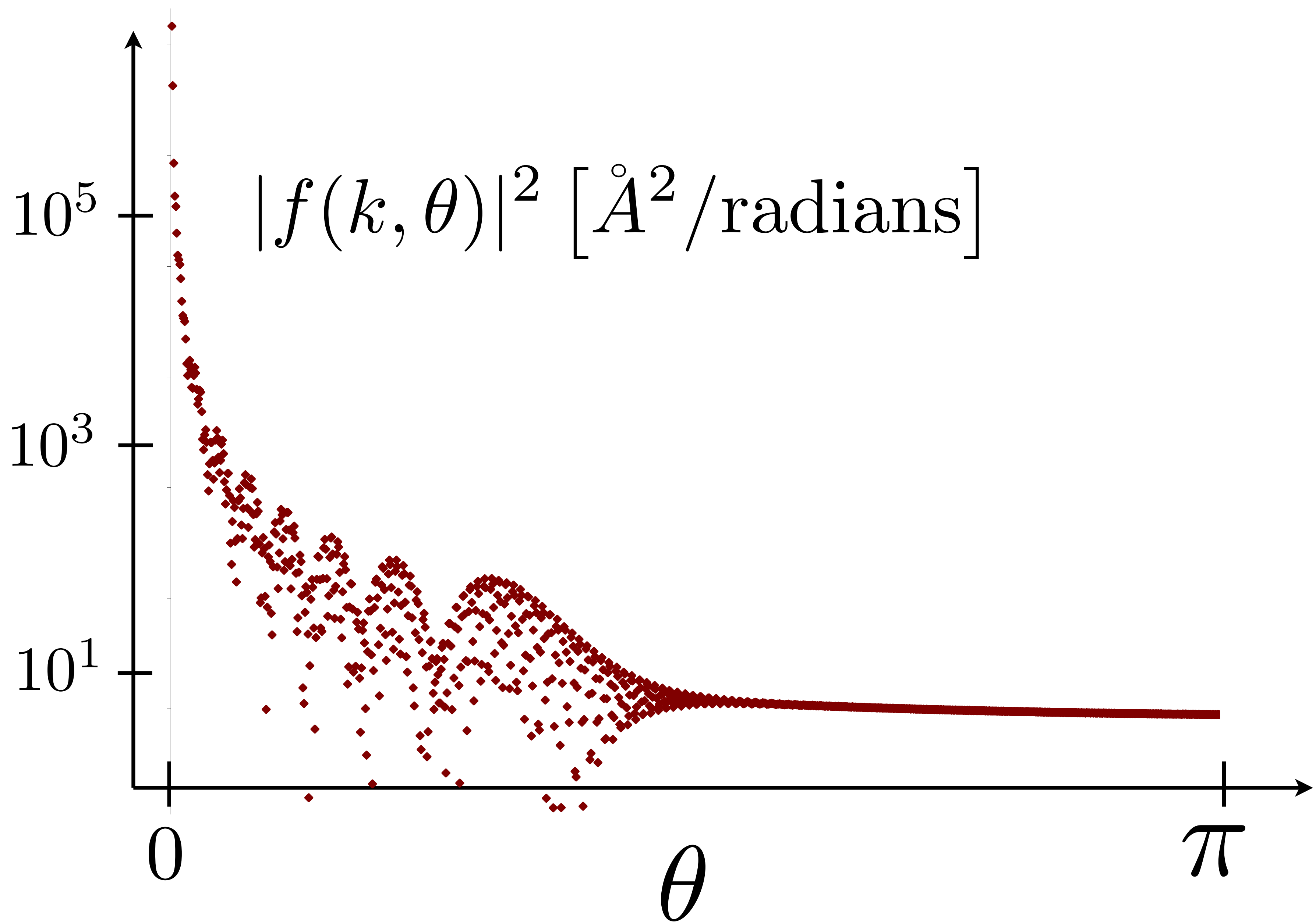


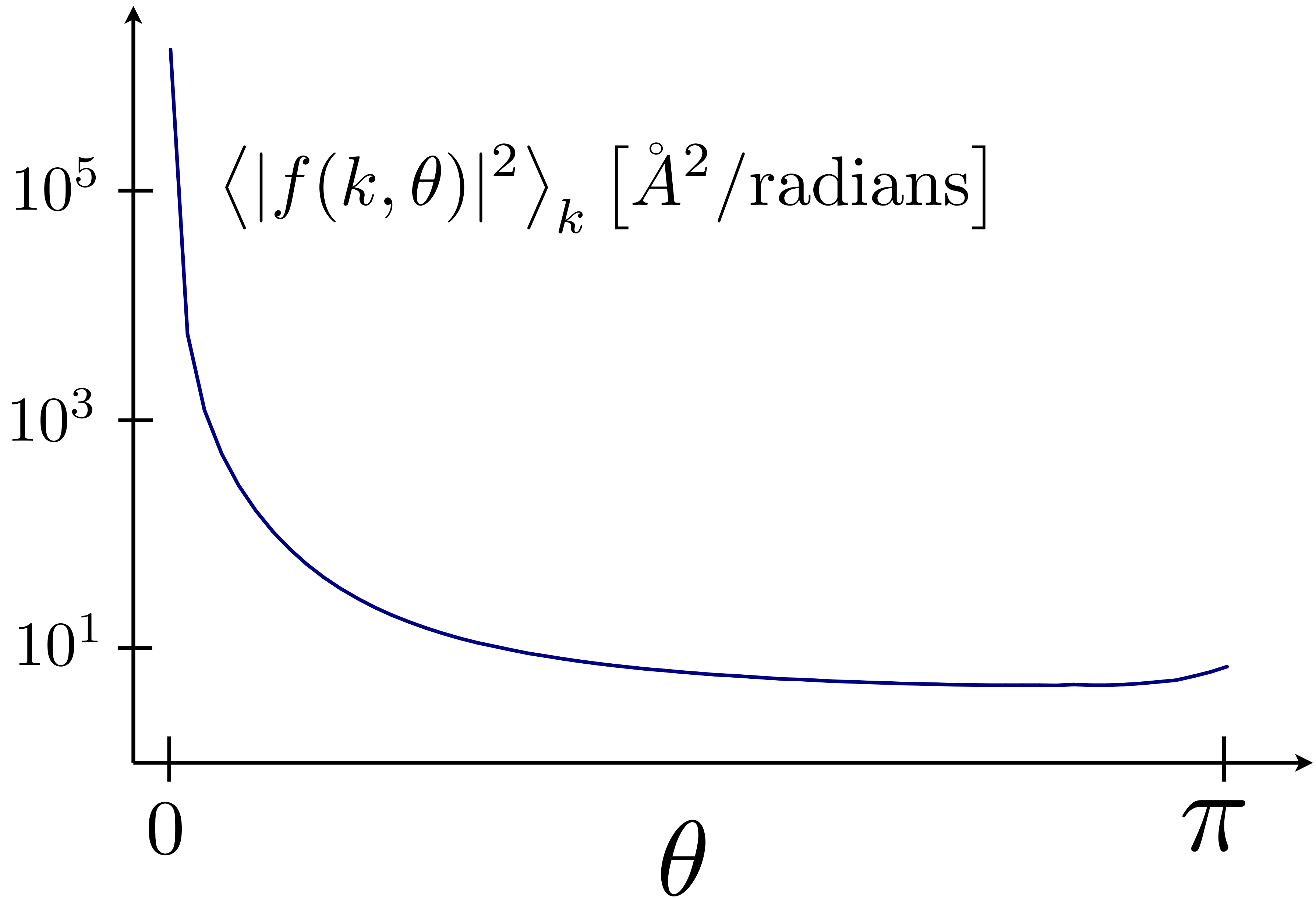


Solve Sch. eqn. and match to asymptotic form

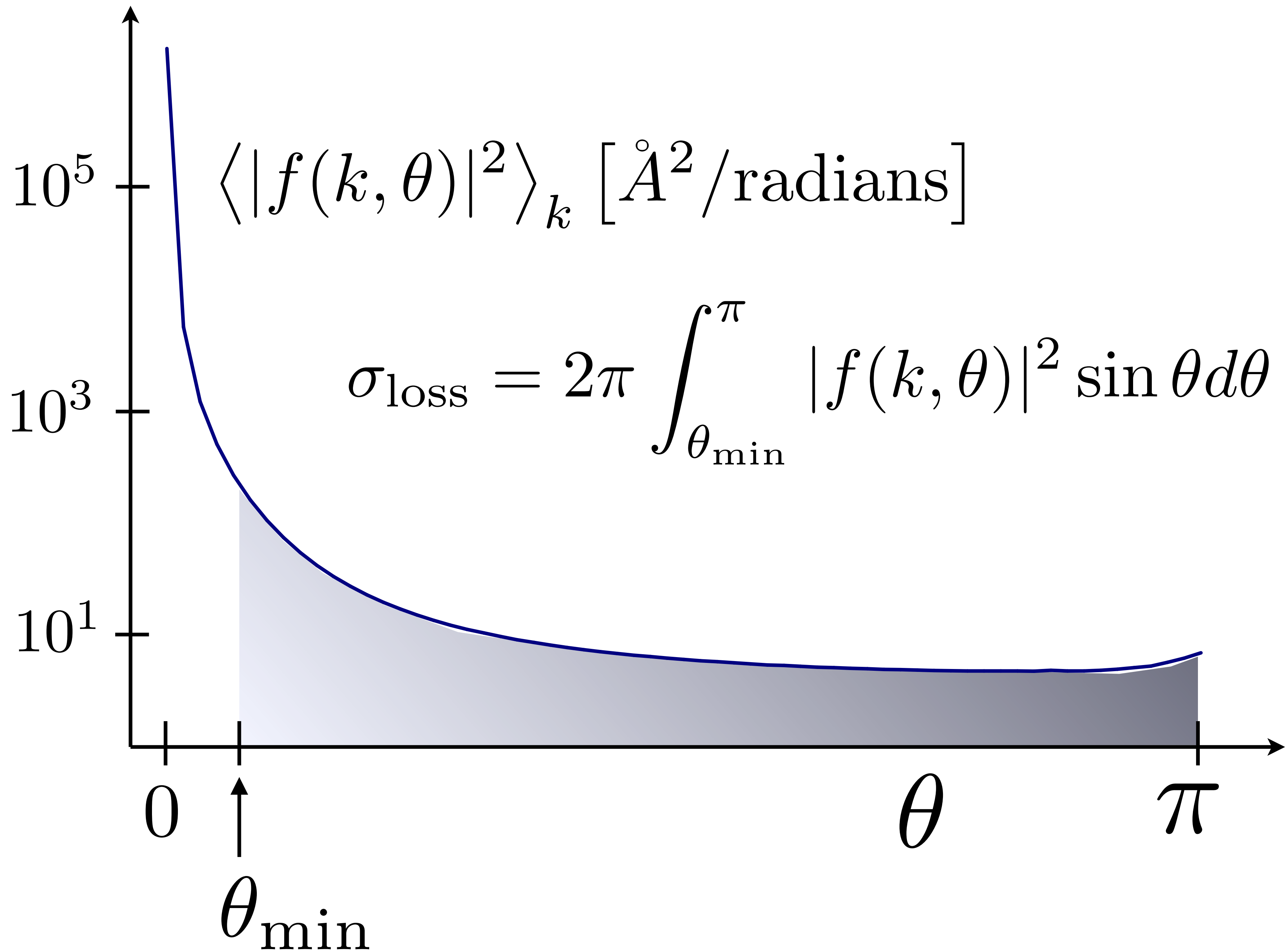
$$\psi(\mathbf{r})|_{r\to\infty} = A\left(e^{ikz} + f(k,\theta)\frac{e^{ikr}}{r}\right)$$


θ=0
$\log|f(k,\theta)|^2$
scattering probability
Rb+Ar collisions
θ=π

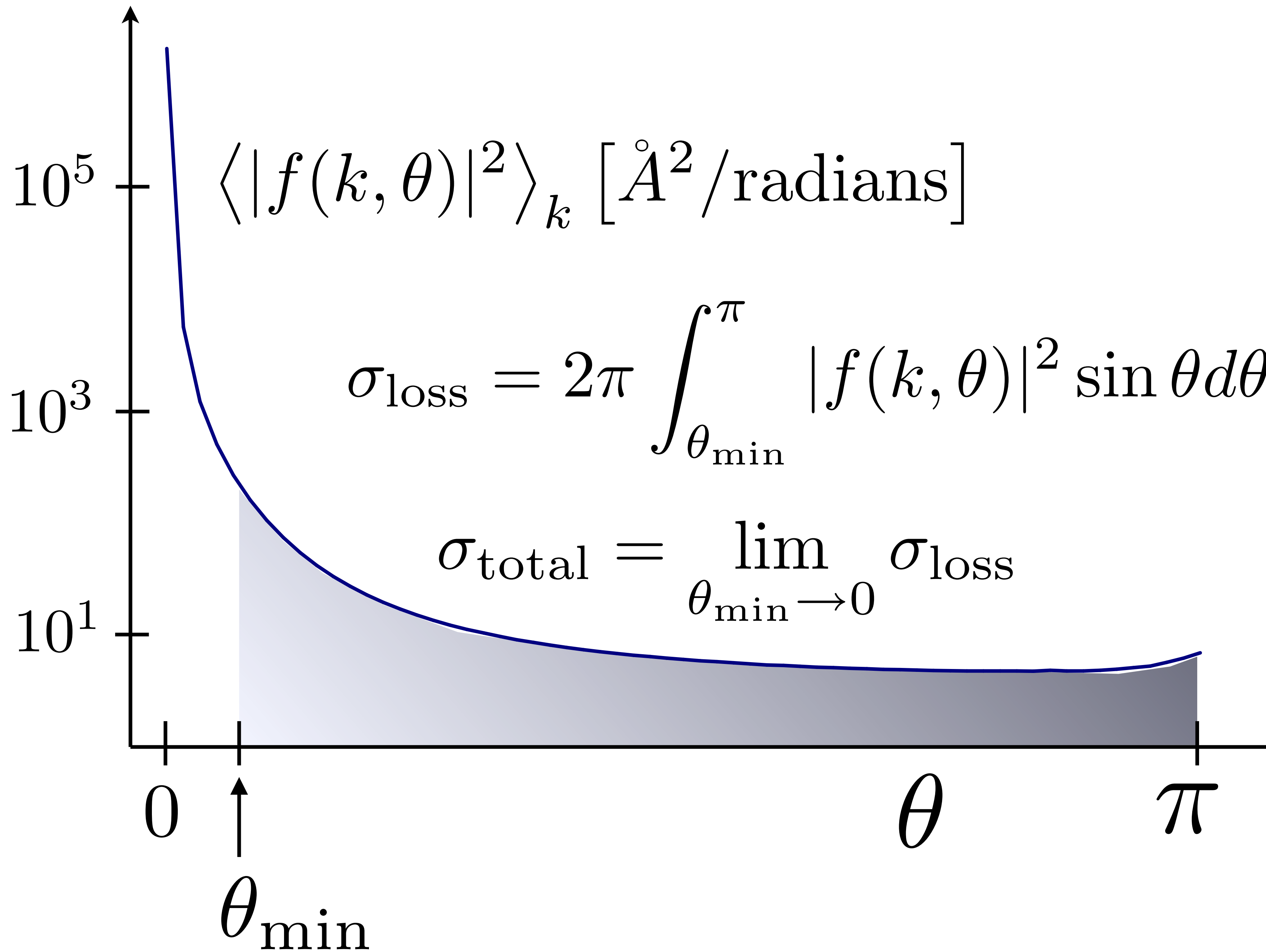

$|f(k,\theta)|^2$ [$\mathring{A}^2$/radians]
10^5
10^3
10^1
0
θ
π



$\langle |f(k,\theta)|^2 \rangle_k \; [\AA^2/\text{radians}]$
10^5
10^3
10^1
0
θ
π

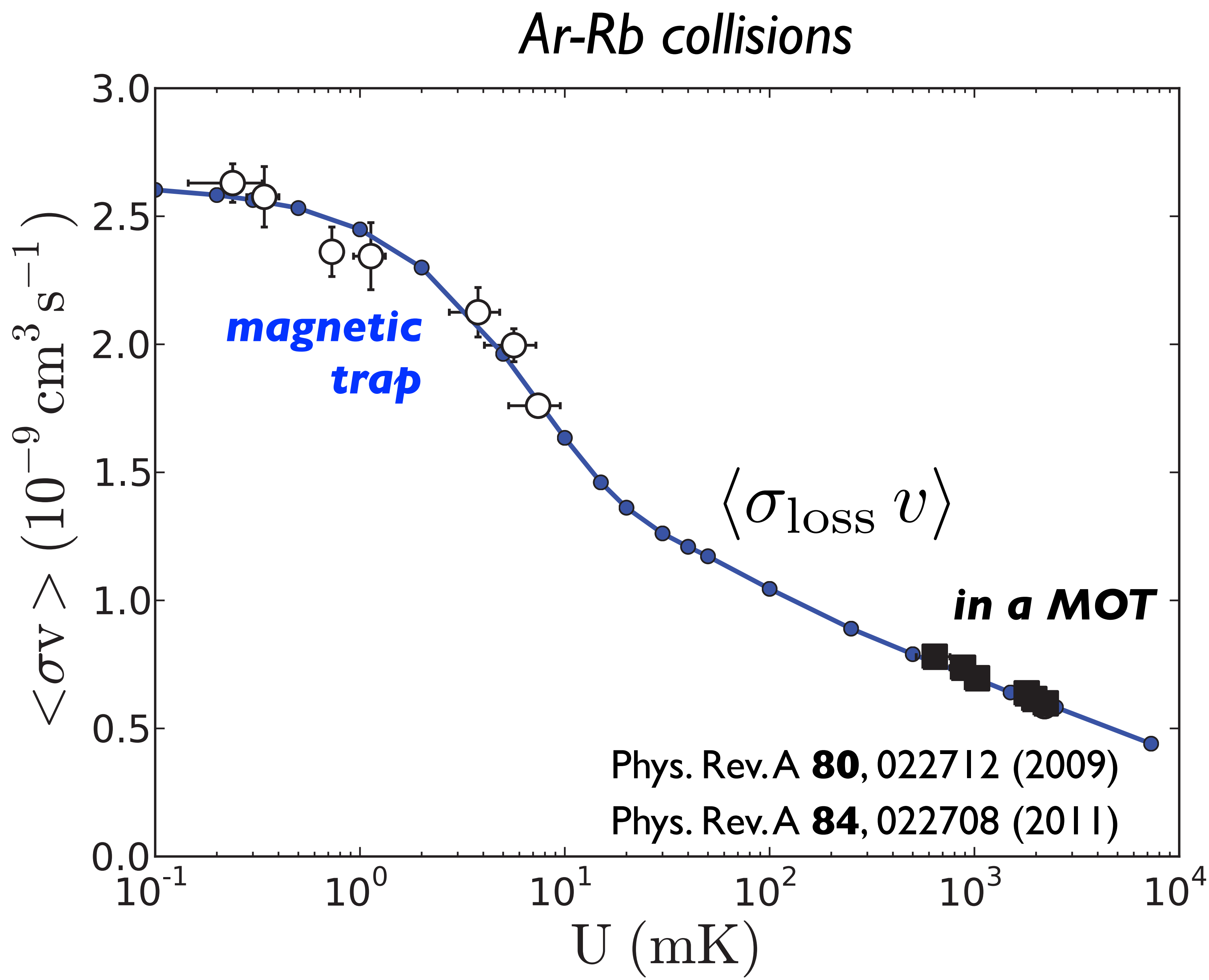


$\langle |f(k,\theta)|^2 \rangle_k$ [$\mathring{A}^2$/radians]
$\sigma_{\rm loss} = 2\pi \int_{\theta_{\rm min}}^{\pi} |f(k,\theta)|^2 \sin\theta d\theta$
10^5
10^3
10^1
0
$\theta_{\rm min}$
θ
π



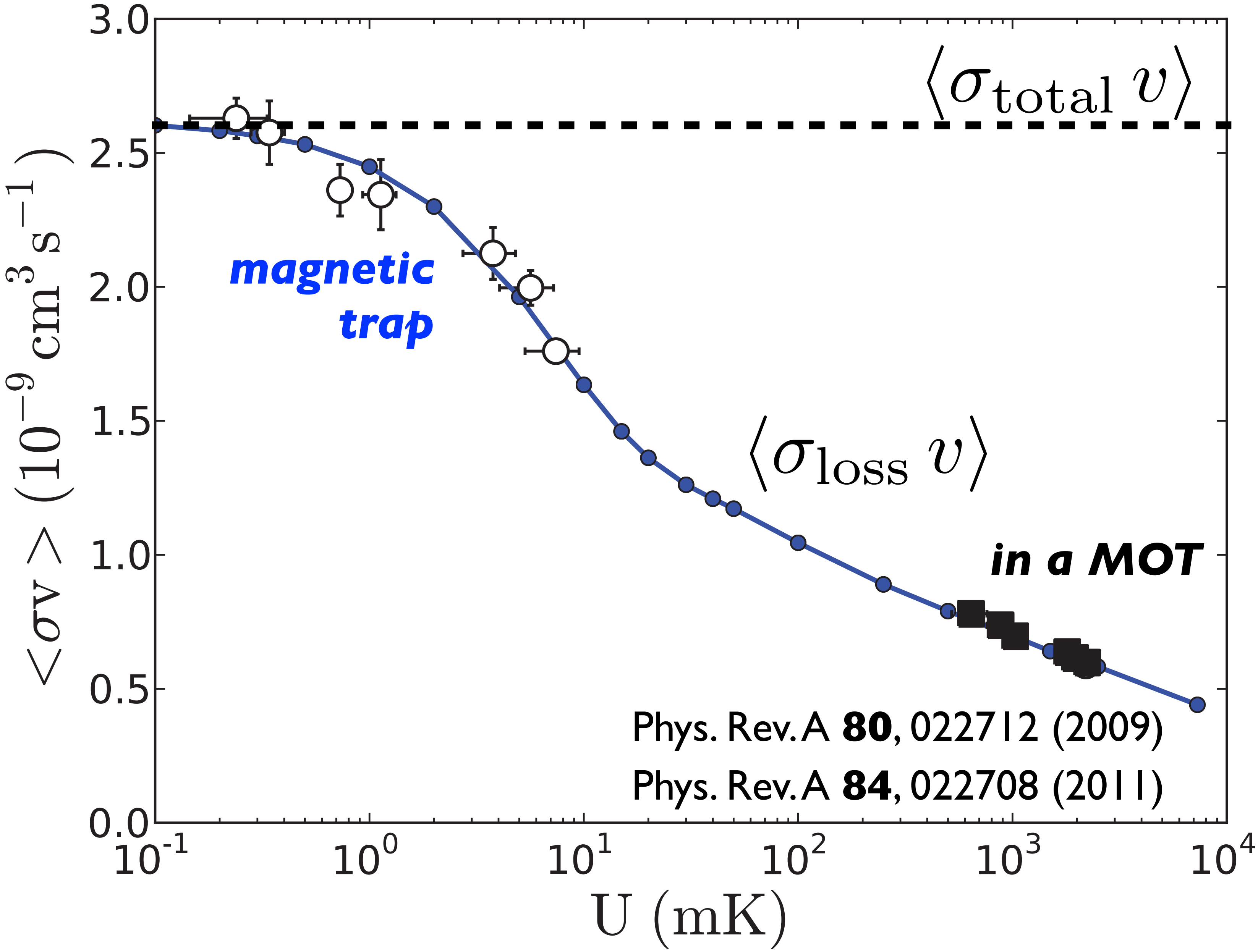
10^5
10^3
10^1
$\langle |f(k,\theta)|^2 \rangle_k \, [\mathring{A}^2/\text{radians}]$
$\sigma_{\text{loss}} = 2\pi \int_{\theta_{\min}}^{\pi} |f(k,\theta)|^2 \sin\theta d\theta$
$\sigma_{\text{total}} = \lim_{\theta_{\min}\to 0} \sigma_{\text{loss}}$
0
θ
π
$\theta_{\min}$

Loss cross section vs. trap depth

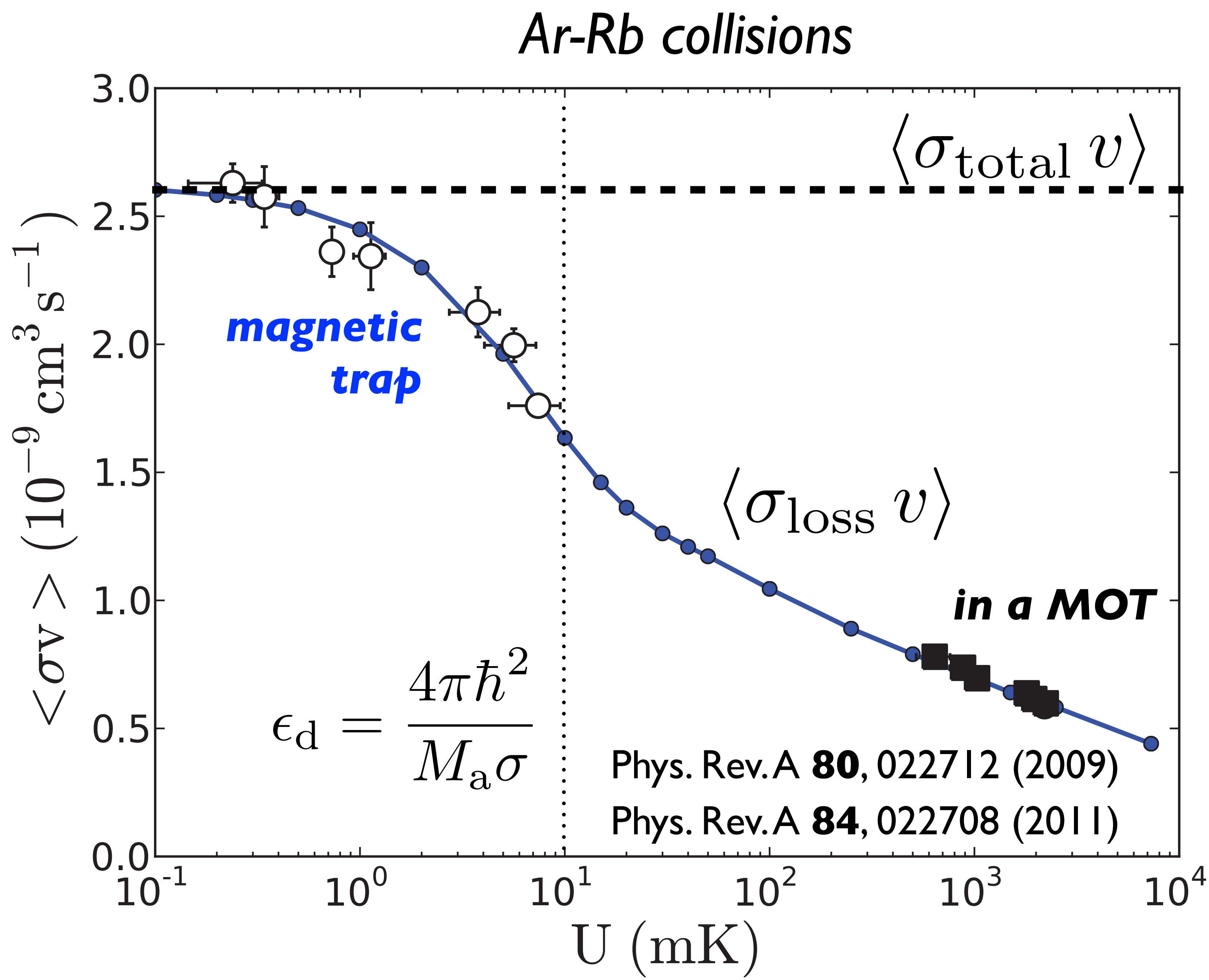


Loss cross section vs. trap depth

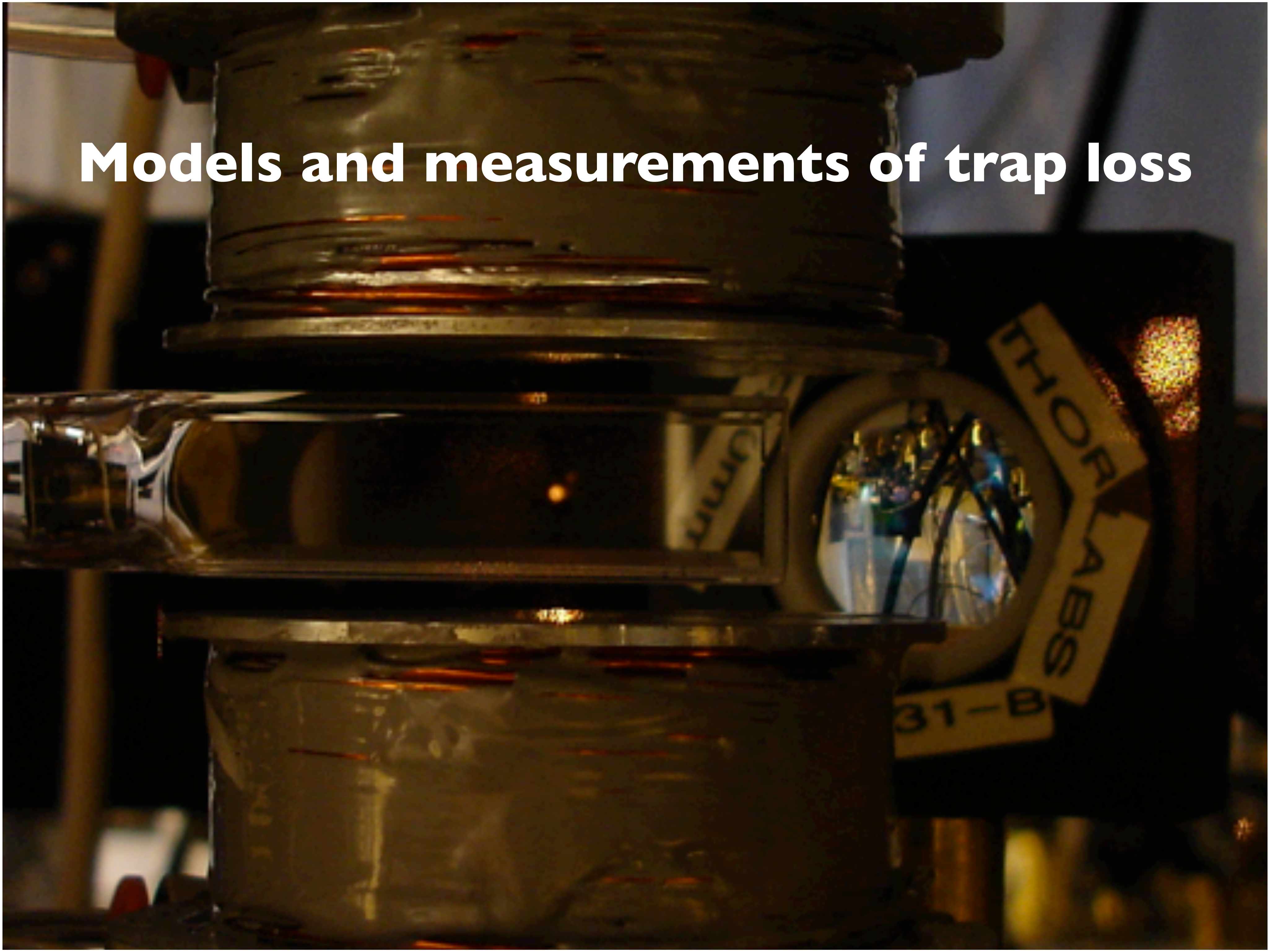
Ar-Rb collisions



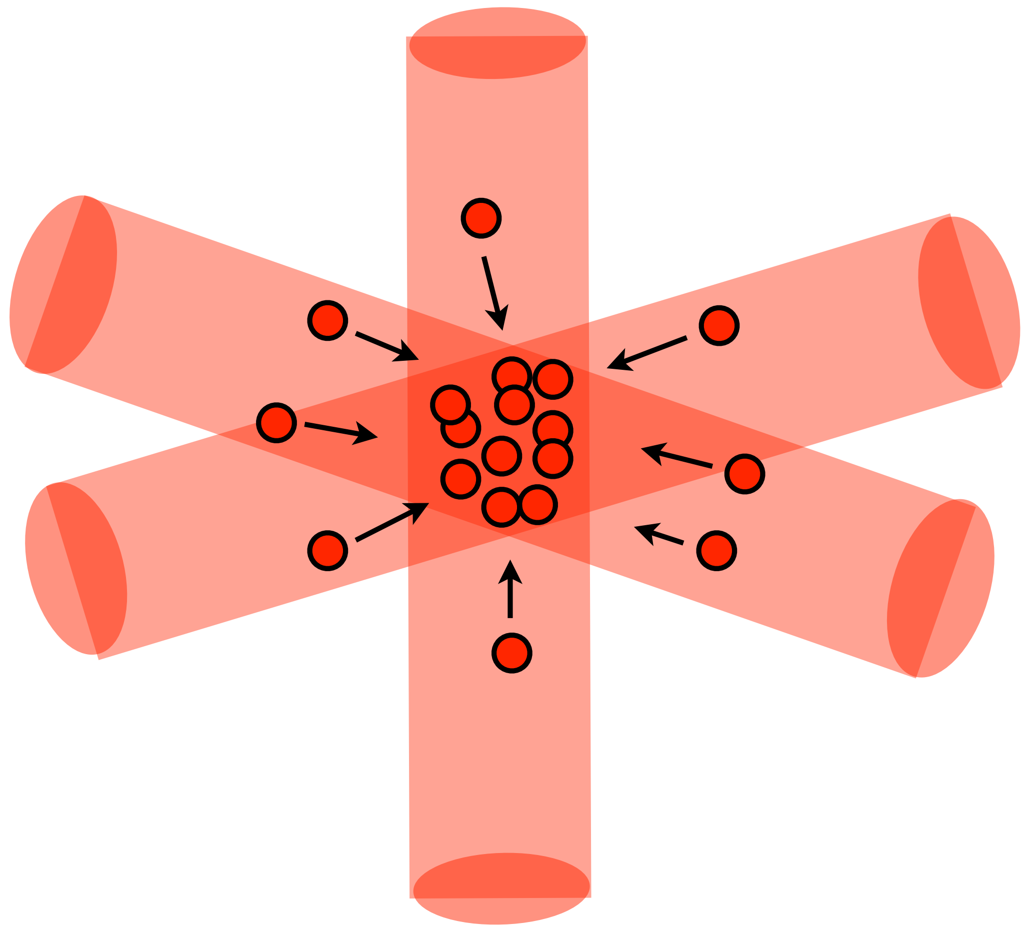
Loss cross section vs. trap depth



Models and measurements of trap loss



MOT loading: model

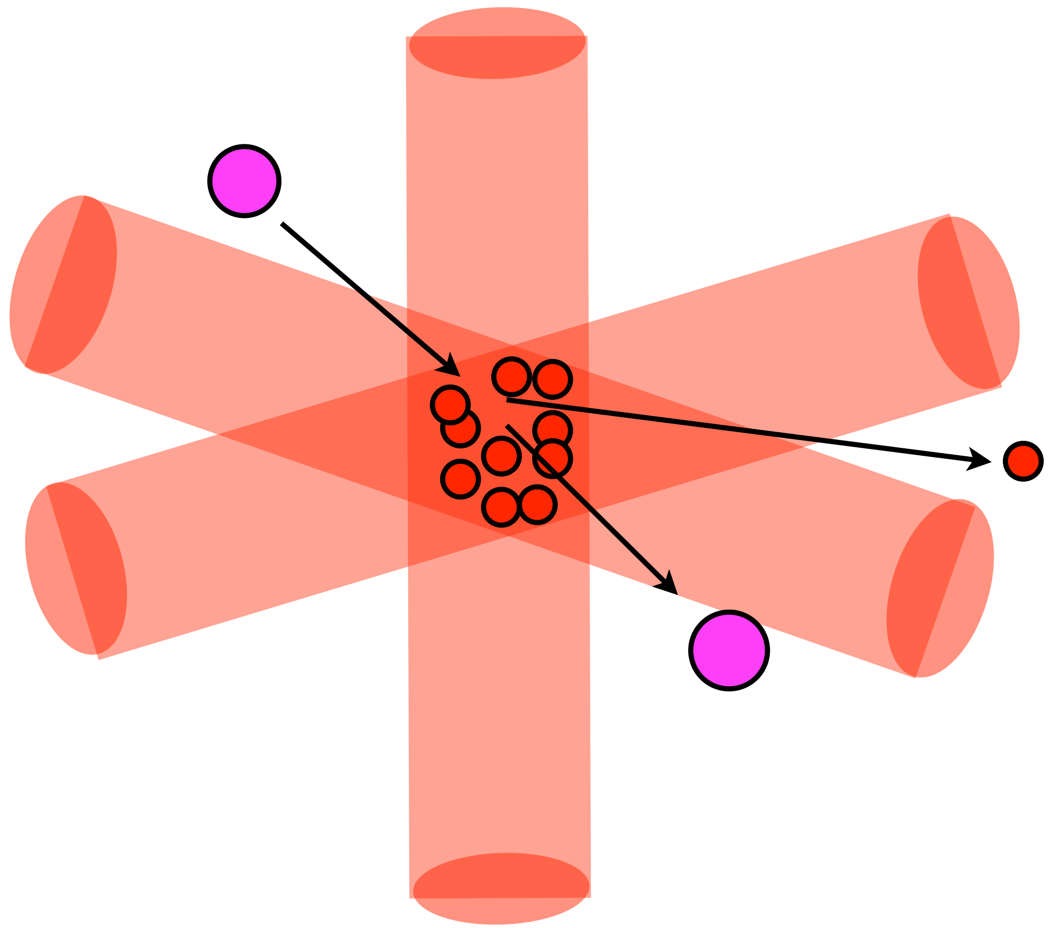


N = Number of atoms in trap

$$\dot{N} = R$$

load rate

MOT loading: model



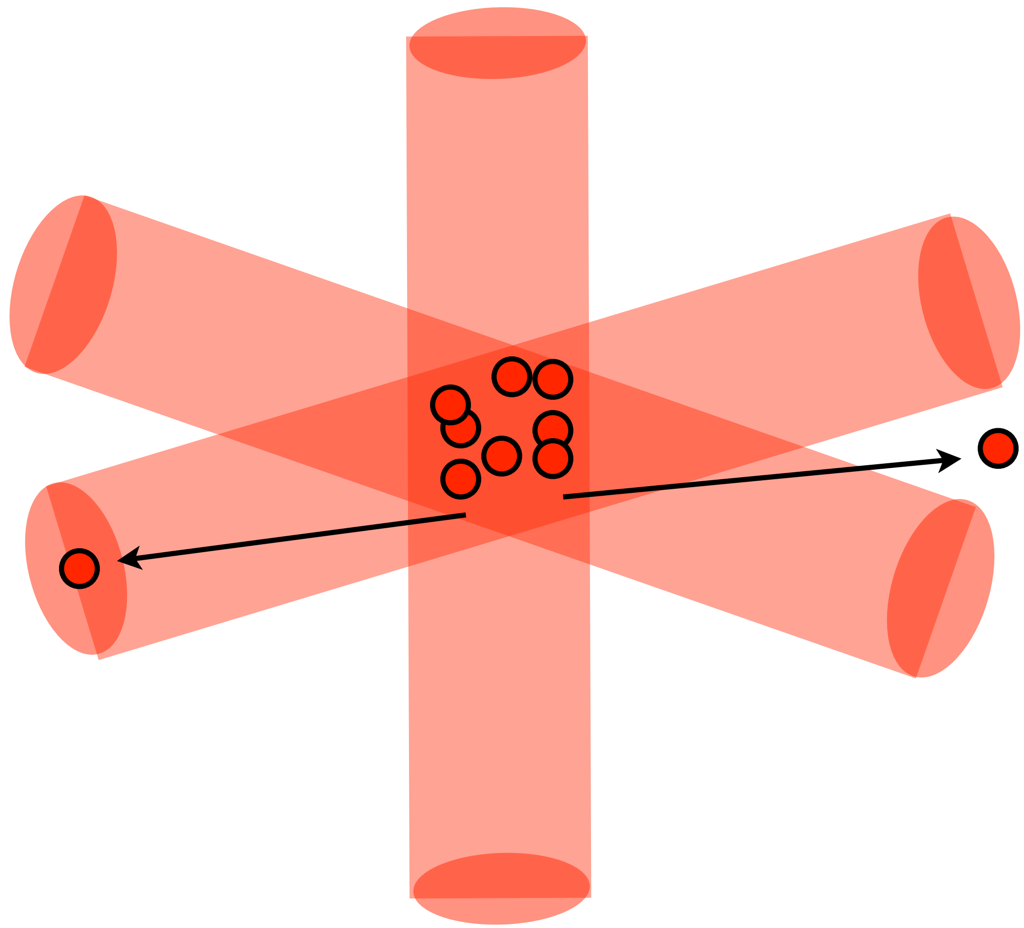
N = Number of atoms in trap

$$\dot{N} = R - \gamma N$$

load rate

single particle loss rate
rate of loss inducing collisions

MOT loading: model



N = Number of atoms in trap

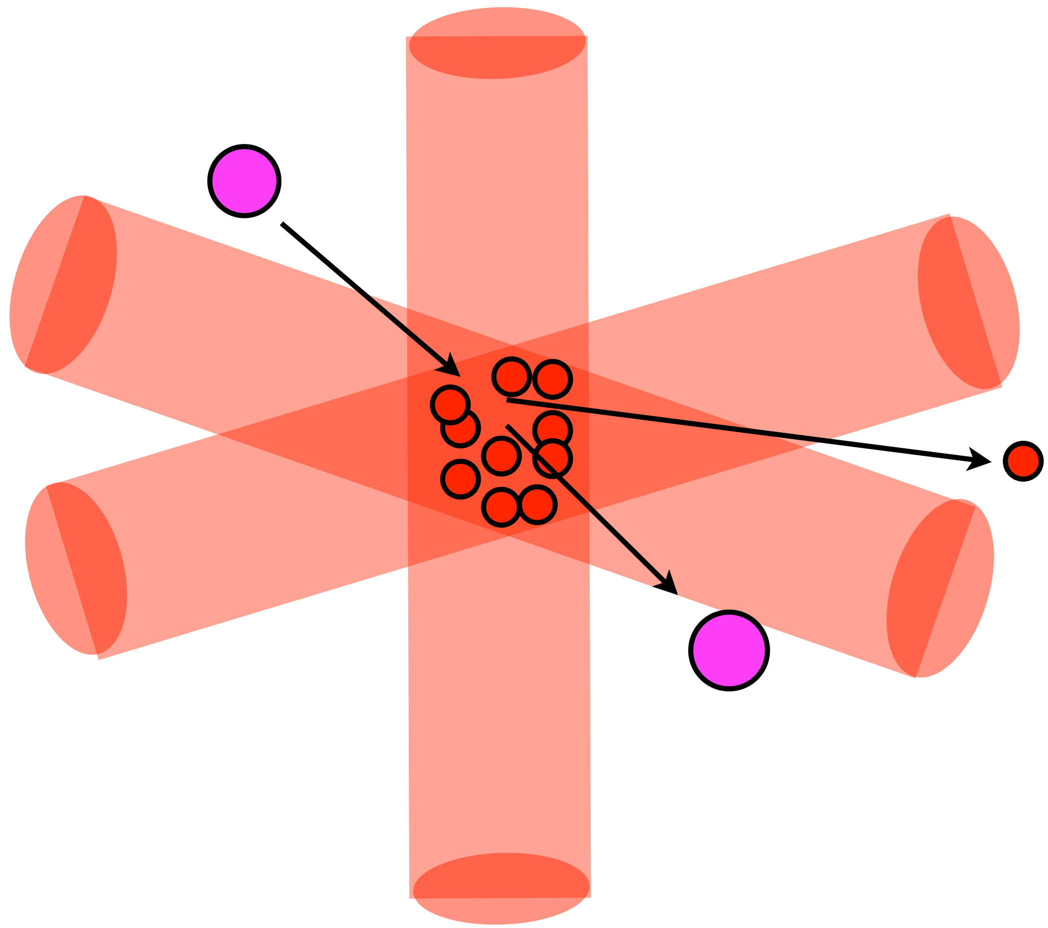
$$\dot{N} = R - \gamma N - \beta(n) N^2 \ldots$$

load rate

single particle loss rate
rate of loss inducing collisions

2-body collisions produce density dependent loss term

MOT loading: model



N = Number of atoms in trap

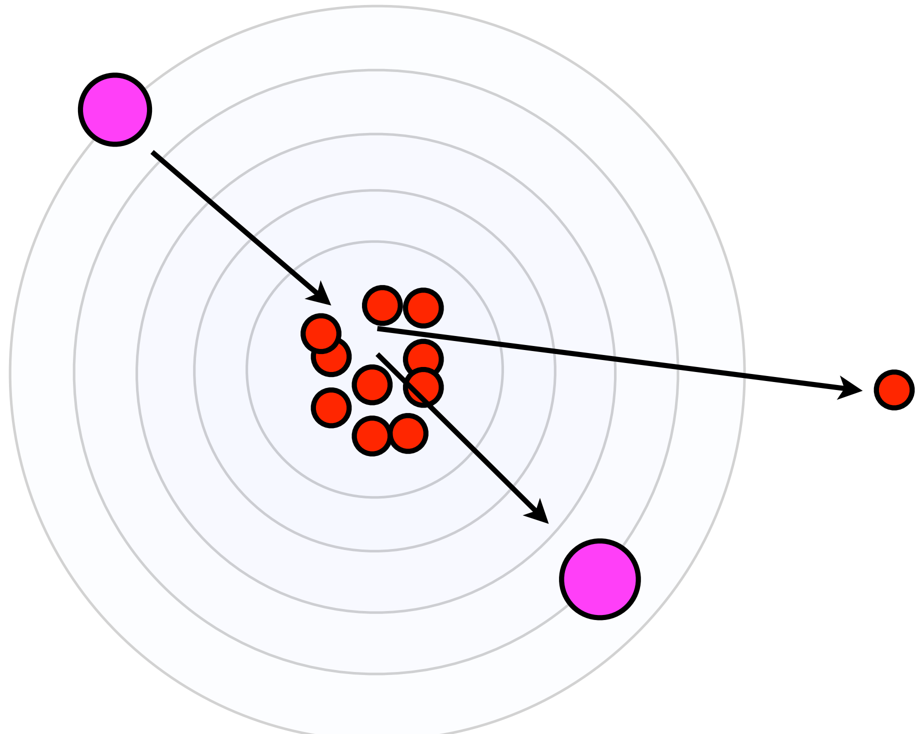
$$\dot{N} = R - \gamma N - \beta\cancel{(n)}N^2 \ldots$$

load rate

single particle loss rate
rate of loss inducing collisions

$$\boxed{N(t) = \frac{R}{\gamma}(1 - e^{\gamma t})}$$

Magnetic trap loss: model



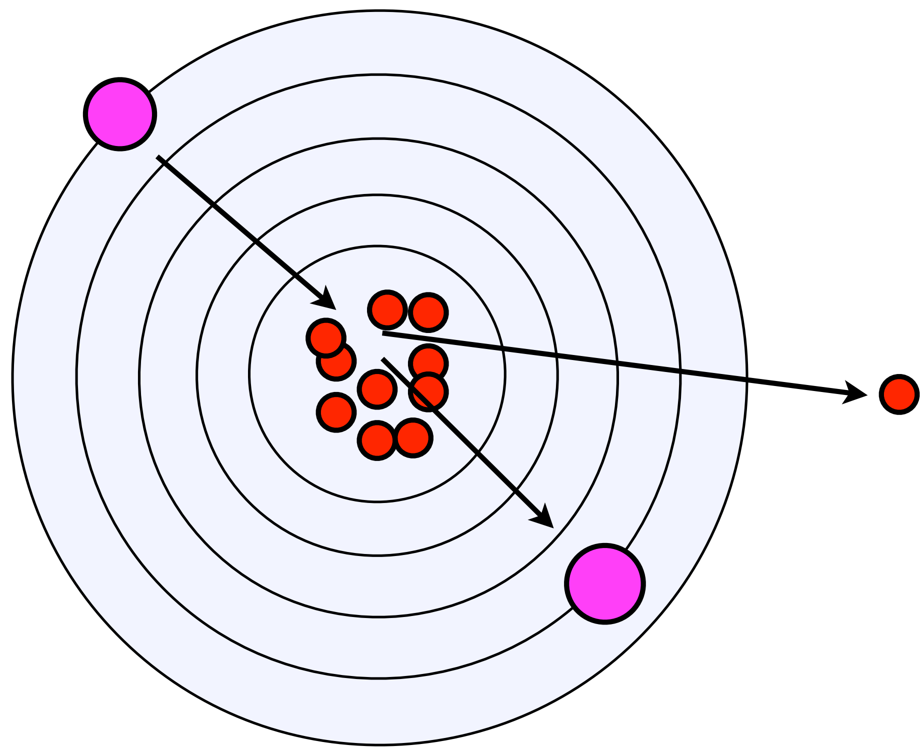
N = Number of atoms in trap

$$\dot{N} = \cancel{R} - \gamma N - \beta\cancel{(n)}N^2 \ldots$$

single particle loss rate
rate of loss inducing collisions

$$\boxed{N(t) = N_0 e^{-\gamma t}}$$

Magnetic trap loss: model



N = Number of atoms in trap

$$\dot{N} = \cancel{R} - \gamma N - \cancel{\beta(n) N^2}\ldots$$

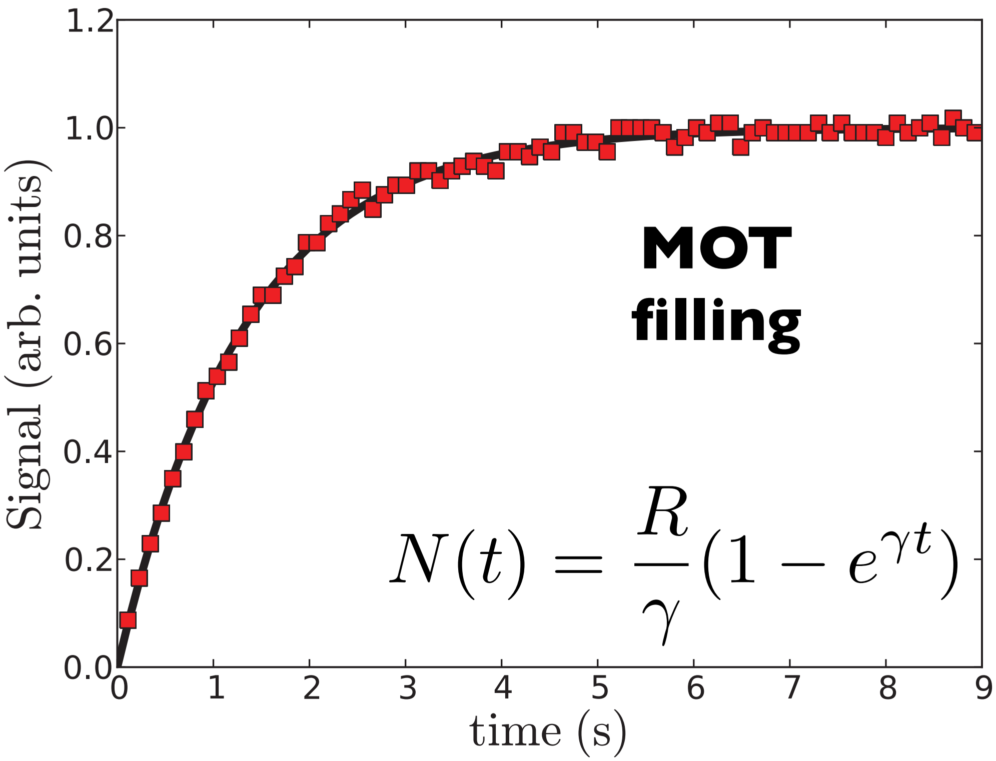
single particle loss rate
rate of loss inducing collisions

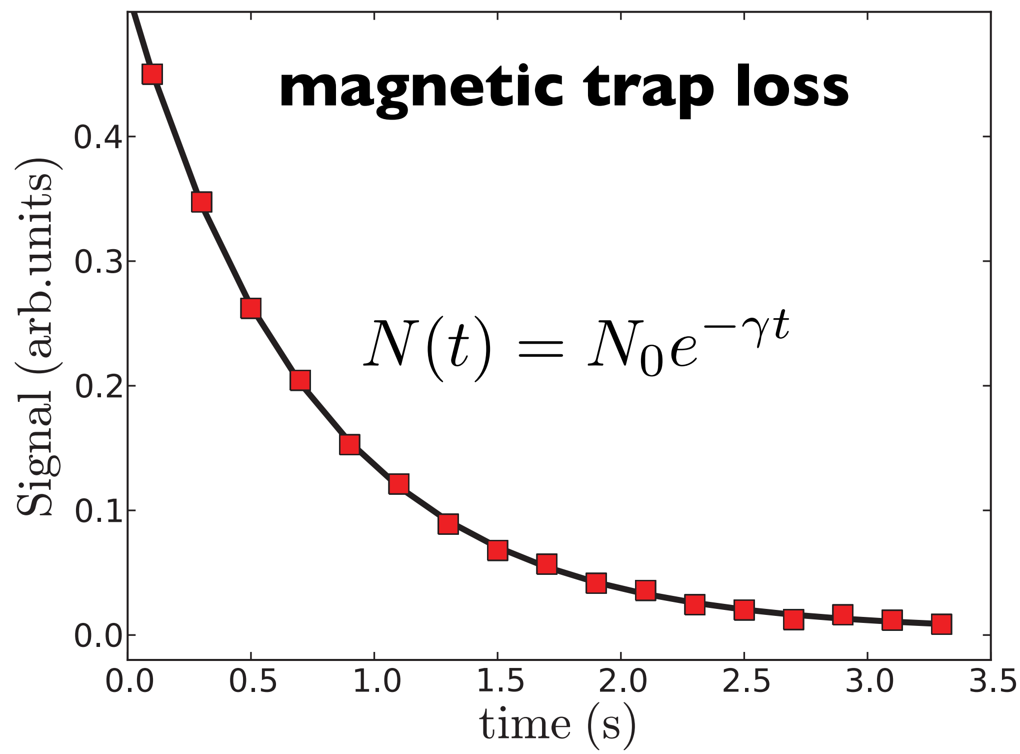
$$\boxed{N(t) = N_0 e^{-\gamma t}}$$

Single particle loss rates

$$\gamma = n\sigma\bar{v}$$ *(related to collision rate)*

N





Some more theoretical details