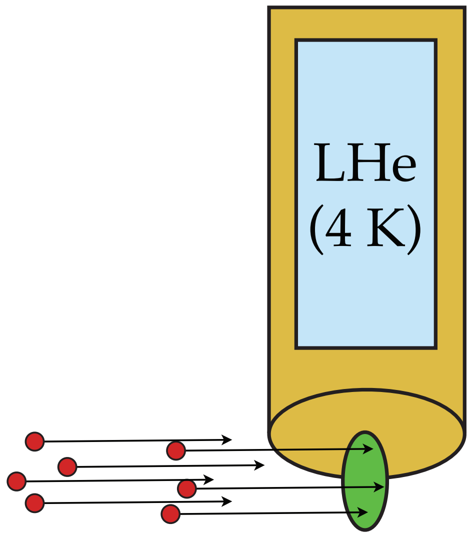
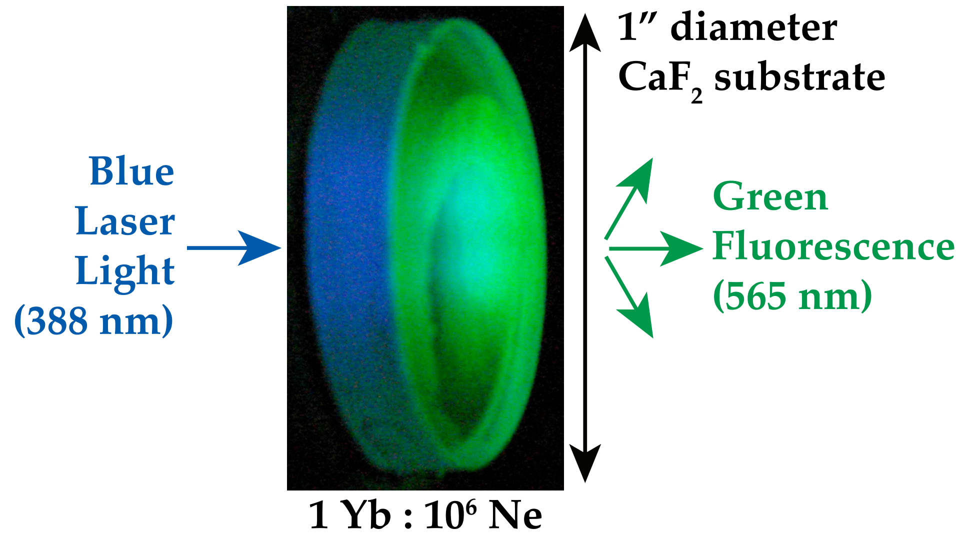
The Physics of Using Lasers to Count Atoms: Optical Single Atom Detection (OSAD) for Nuclear Astrophysics





Jaideep Taggart Singh (NSCL/Michigan State)

Tube on Internets: spinlab.me @spinlabmsu

July 28, 2017 – 0900 - Room 1309 – FRIB / NSCL

Physics of Atomic Nuclei, July 23-28, 2017, Michigan State University

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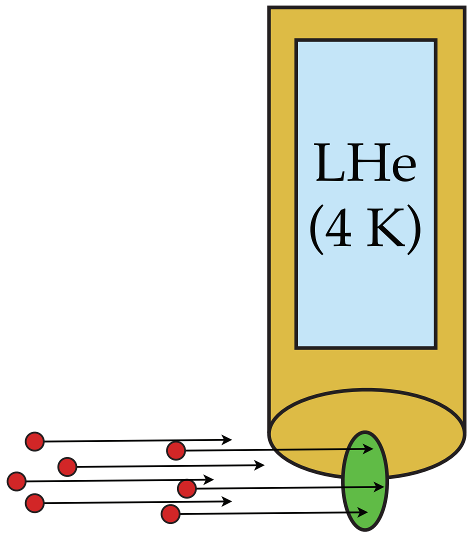

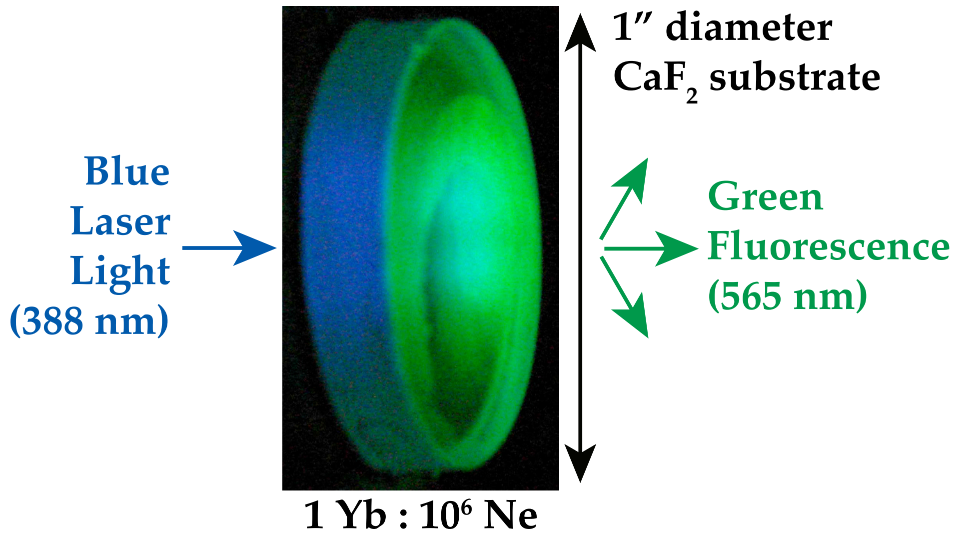

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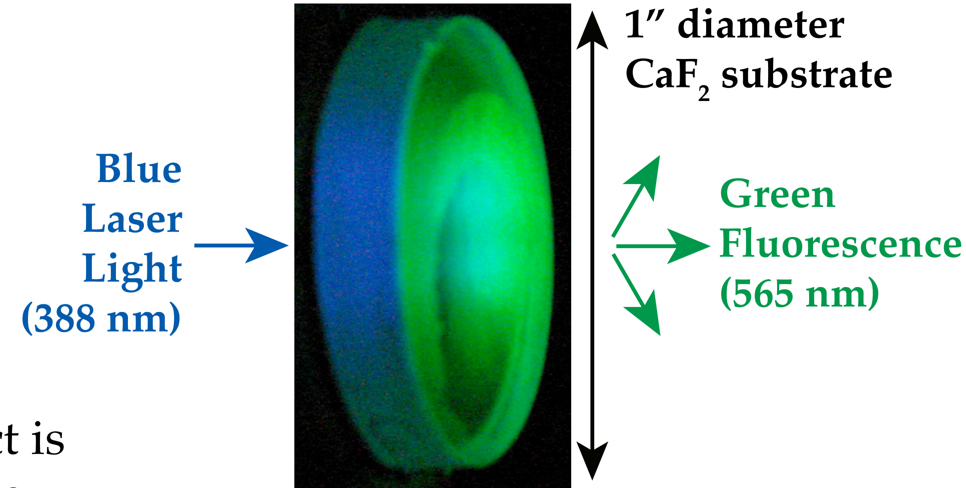
The Physics of Using Lasers to Count Atoms:
Single Atom Microscope (SAM)
for Nuclear Astrophysics

The \$ingle Atom Microscope Project is \$upported by the National \$cience Foundation under grant number #1654610.



1 Yb : 10^6 Ne

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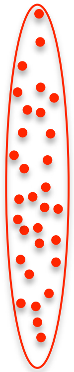
Overview of Nuclear Astrophysics – Thanks Luke!

1. Boom! **Big Bang**
2. Lighter elements (**H, He**) clump together to make ***stars***
3. *Nuclear reactions* occur inside of stars
   - source of energy that "powers" stars
   - results in the stepwise creation of **heavier chemical elements**
4. Elements such as **copper (Cu) & silver (Ag)** result from ***s*-process**
5. *Slow neutron capture***-process** – needs a source of **neutrons**
6. **Neutrons** are produced by one of two reactions:
   1. $^{13}C + {}^{4}He \rightarrow {}^{16}O + \mathbf{n}$
   2. $^{22}\mathbf{Ne} + {}^{4}\mathbf{He} \rightarrow {}^{25}\mathbf{Mg} + \mathbf{n}$
7. Need to "**measure**" the **2nd reaction** in order to "how" **Cu & Ag**!
   1. old method - **count the neutrons**
   2. new method – **count the ^{25}Mg atoms with *pew-pew-pew* lasers**

What do we mean by "measure"?



We want to measure the likelihood that the reaction will happen.

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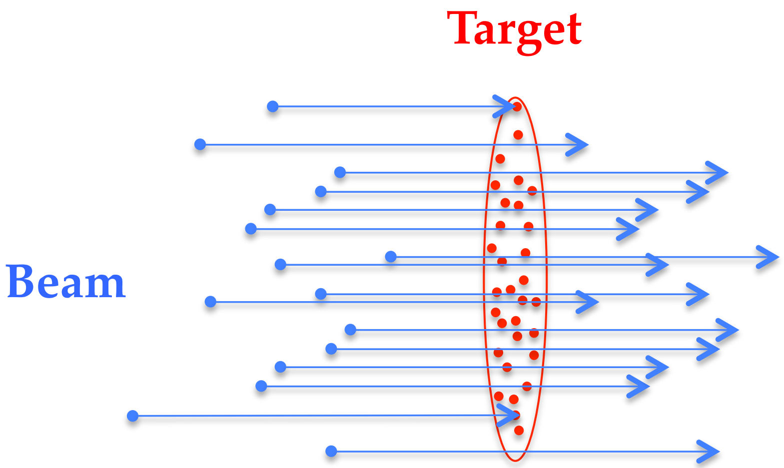

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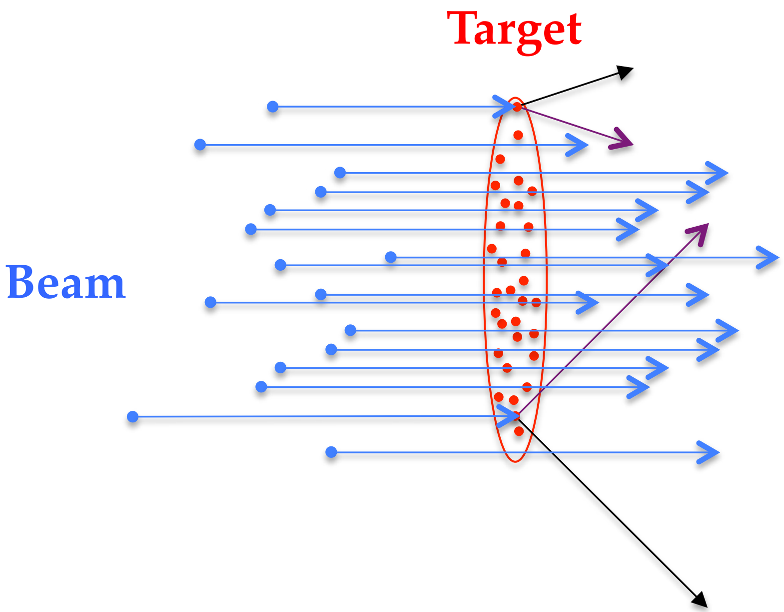

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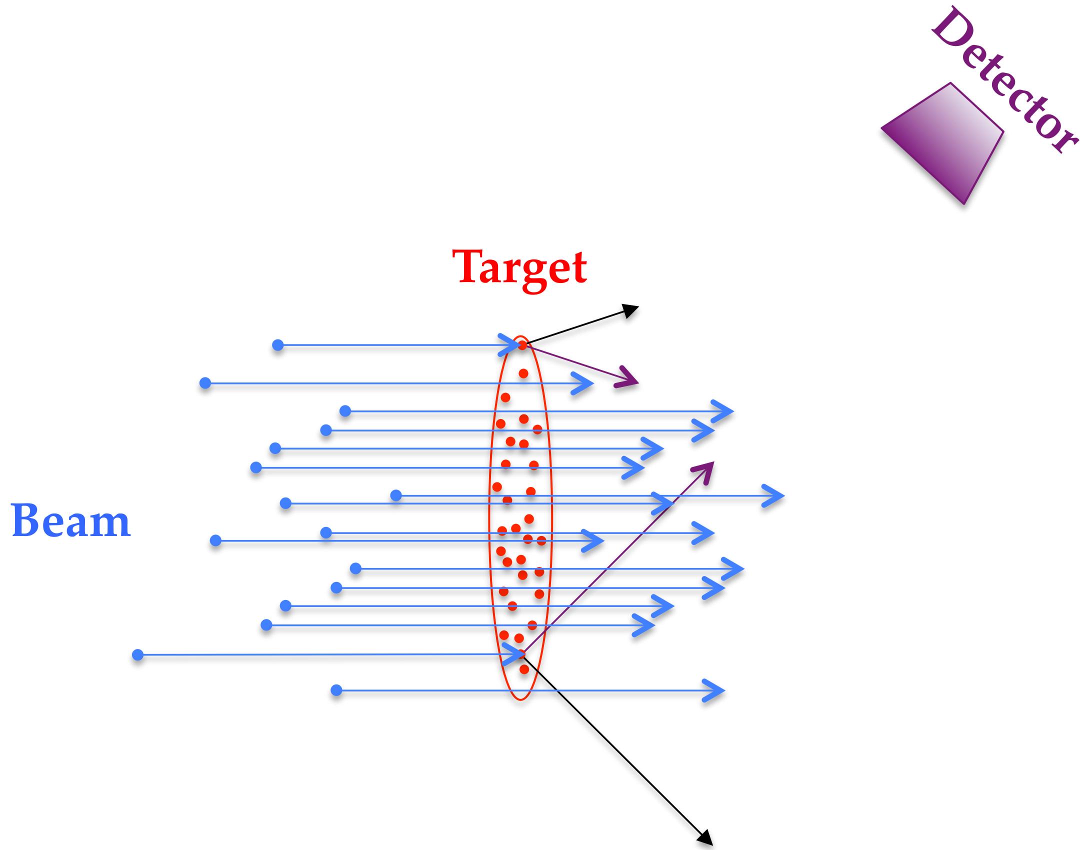

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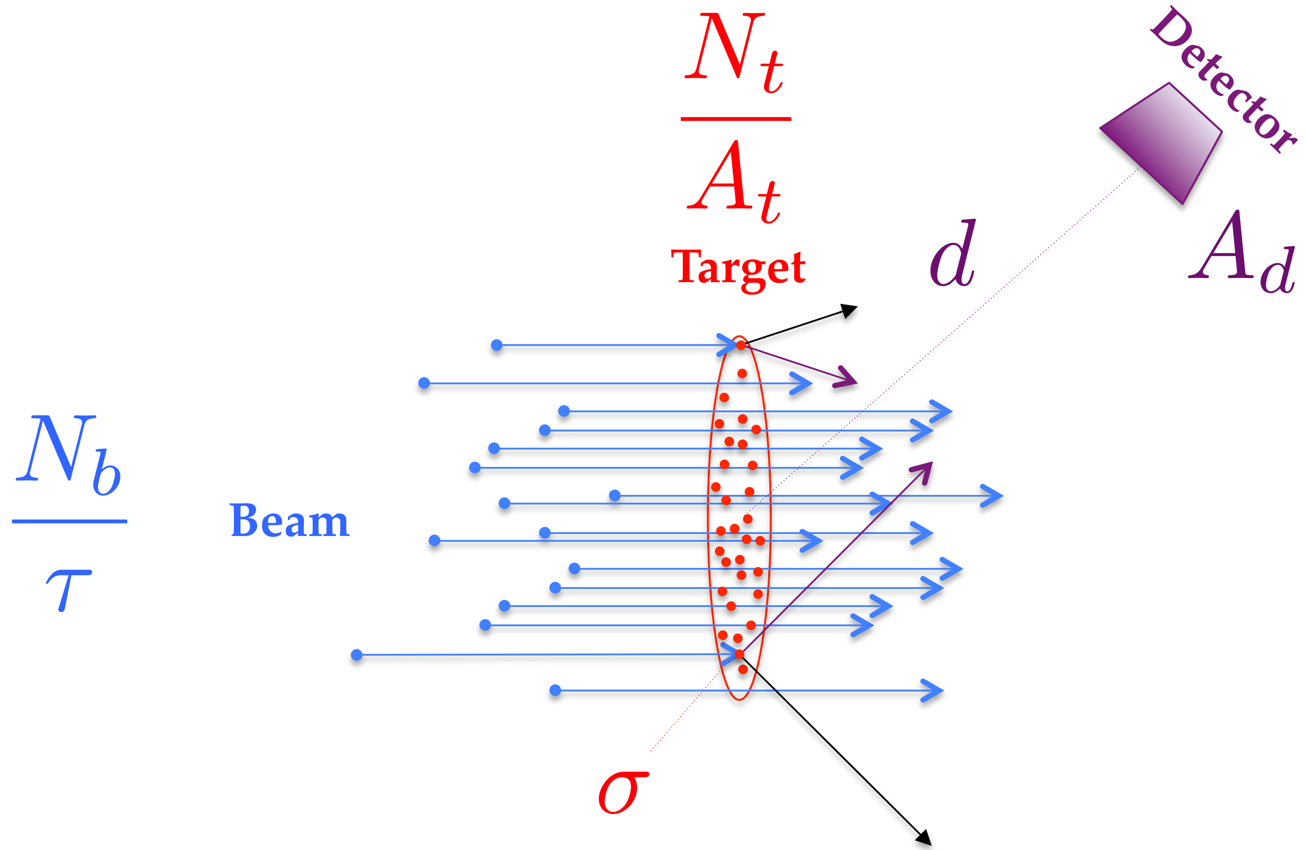

$$N_d = \tau \left(\frac{N_b}{\tau} \right) \left(\frac{N_t \sigma}{A_t} \right) \left(\frac{A_d}{4\pi d^2} \right)$$

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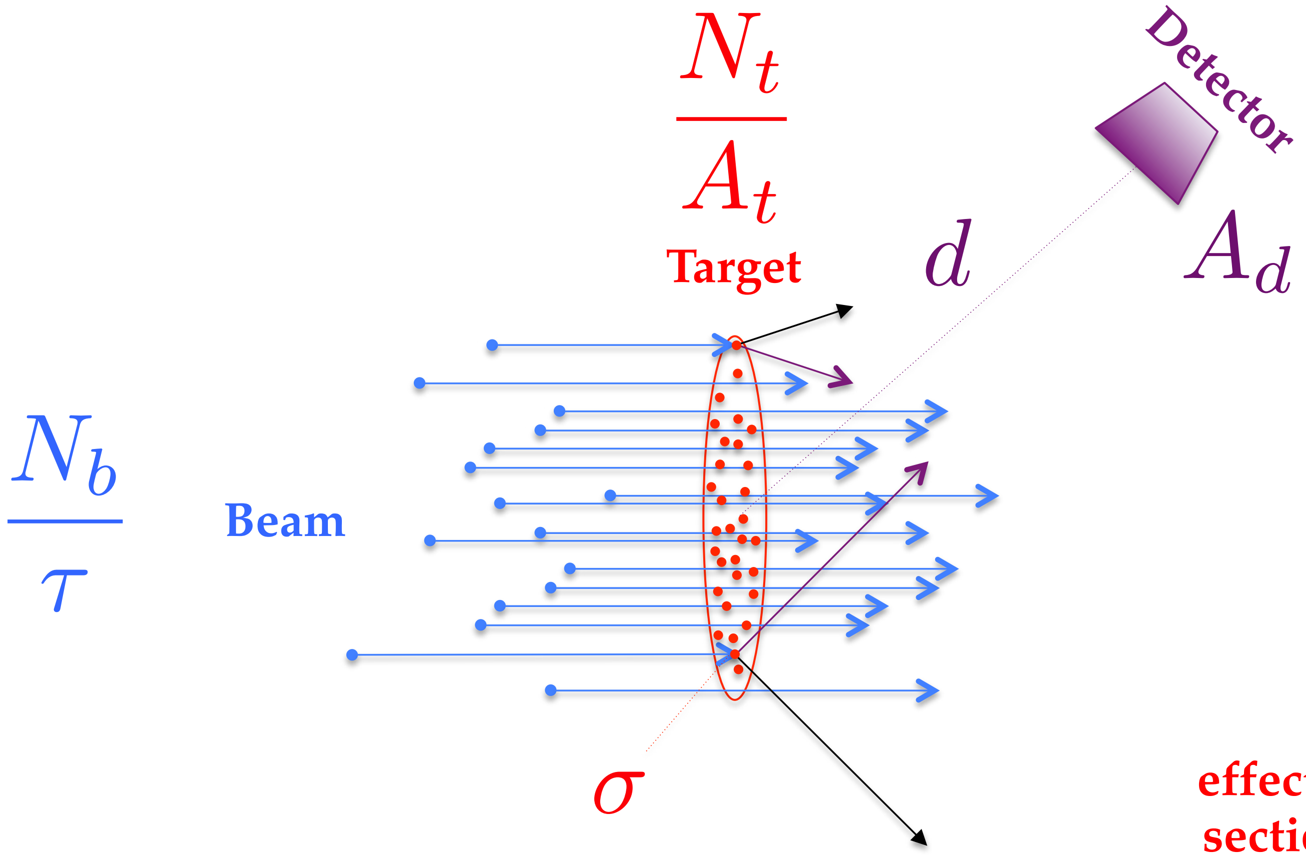
What do we mean by "**measure**"?

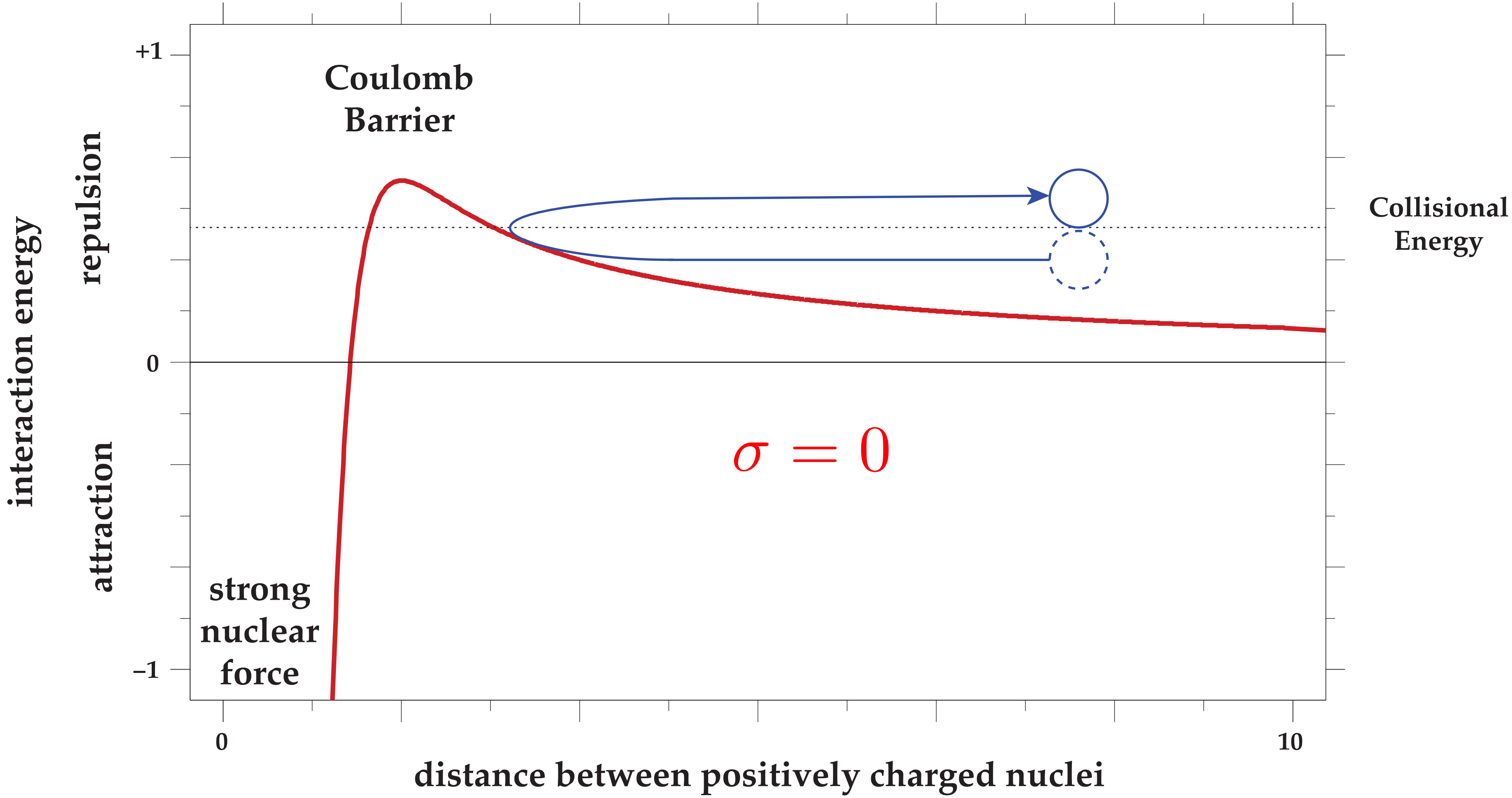


$$\sigma = \left(\frac{N_d}{N_b}\right)\left(\frac{A_t}{N_t}\right)\left(\frac{4\pi d^2}{A_d}\right) =$$

effective cross sectional area or scattering cross section

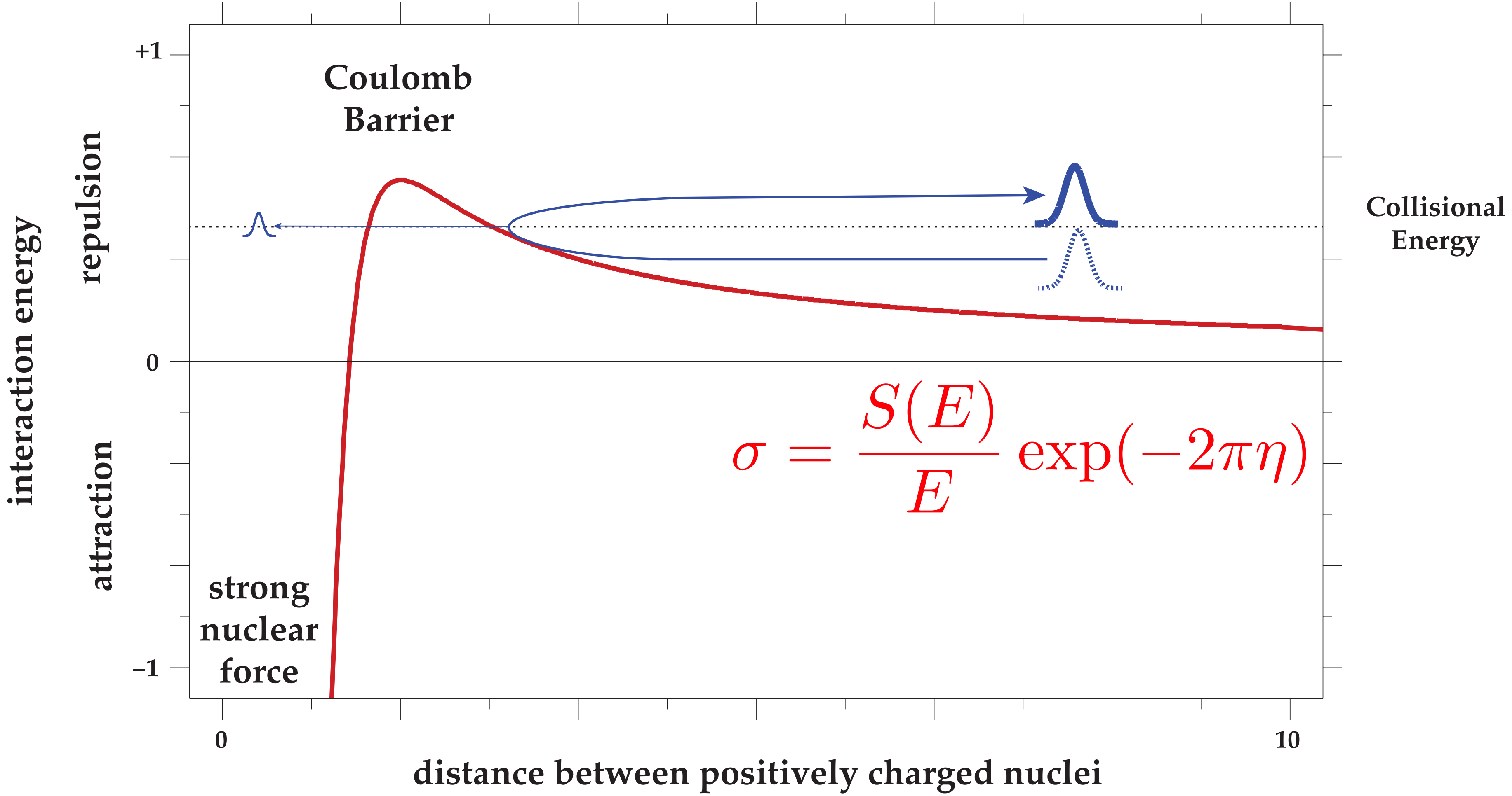
We want to measure the likelihood that the reaction will happen.

Reaction is Unlikely because "Coulomb Barrier"



In the classical picture, the positively charged nuclei repel each other and do not react at all.

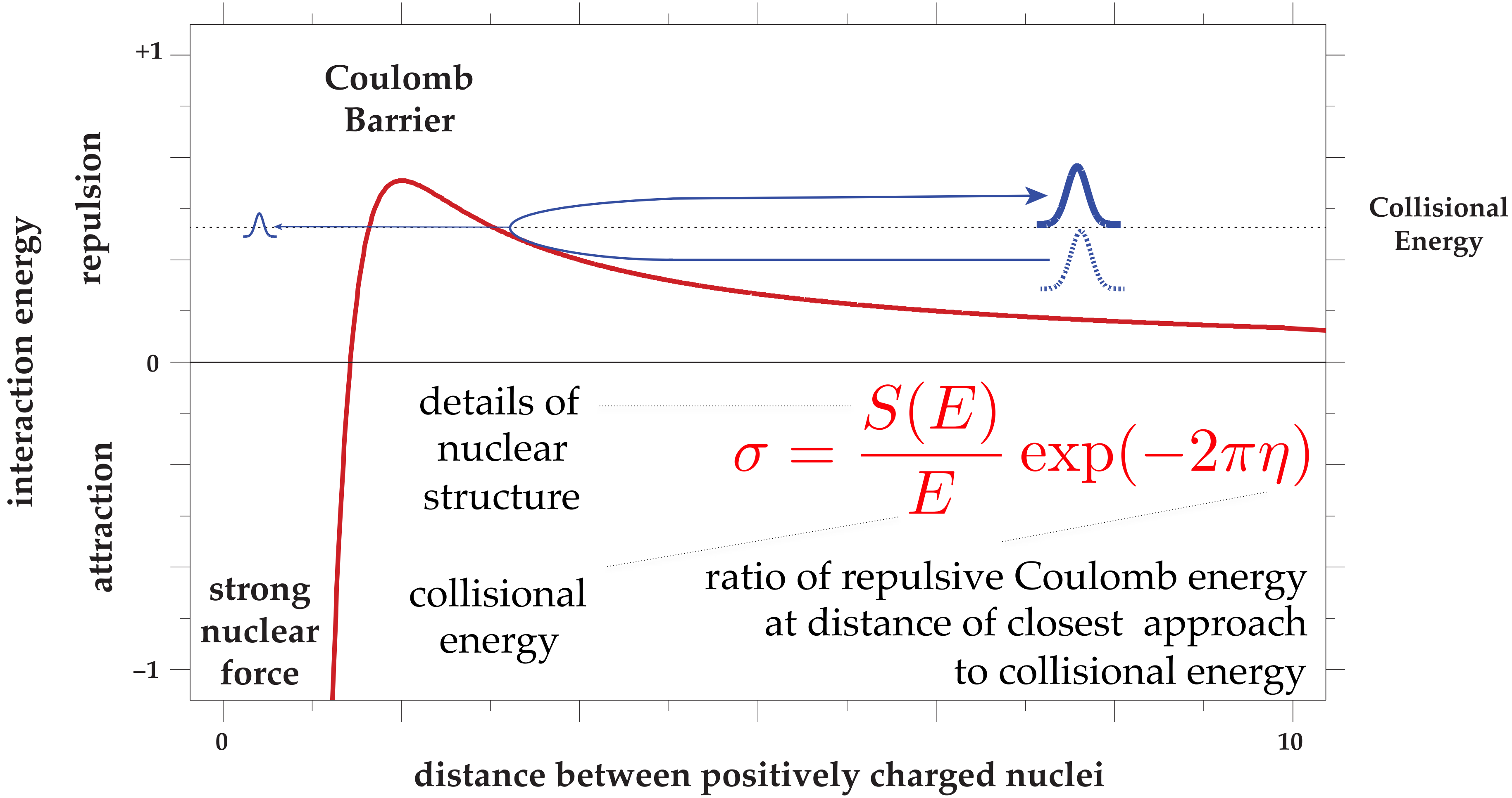
Reaction is Unlikely because “Coulomb Barrier”



$$\sigma = \frac{S(E)}{E}\exp(-2\pi\eta)$$

In the quantum mechanical picture, the positively charged nuclei repel each other but are able to interact via “Tunneling.”

Reaction is Unlikely because "Coulomb Barrier"



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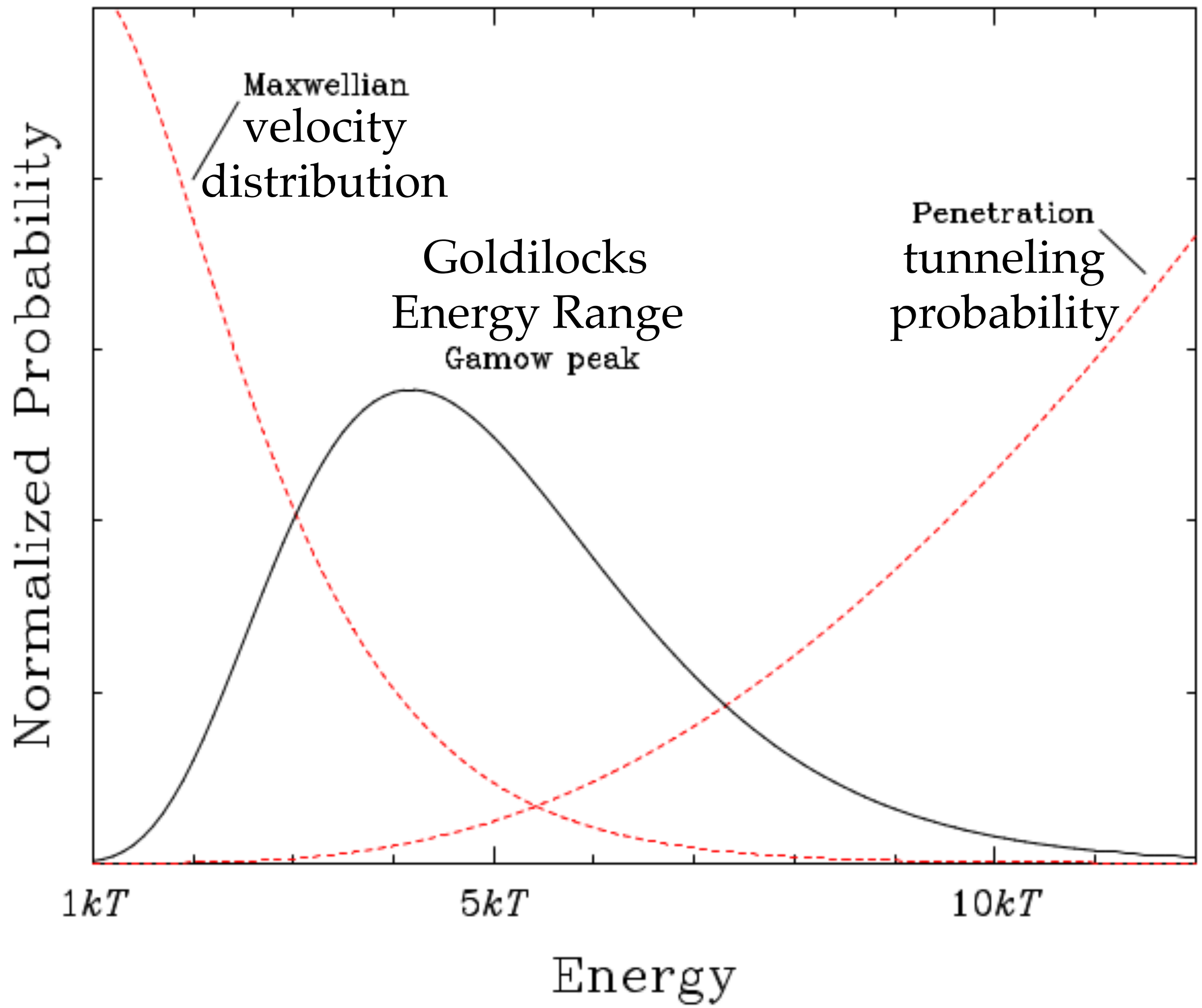
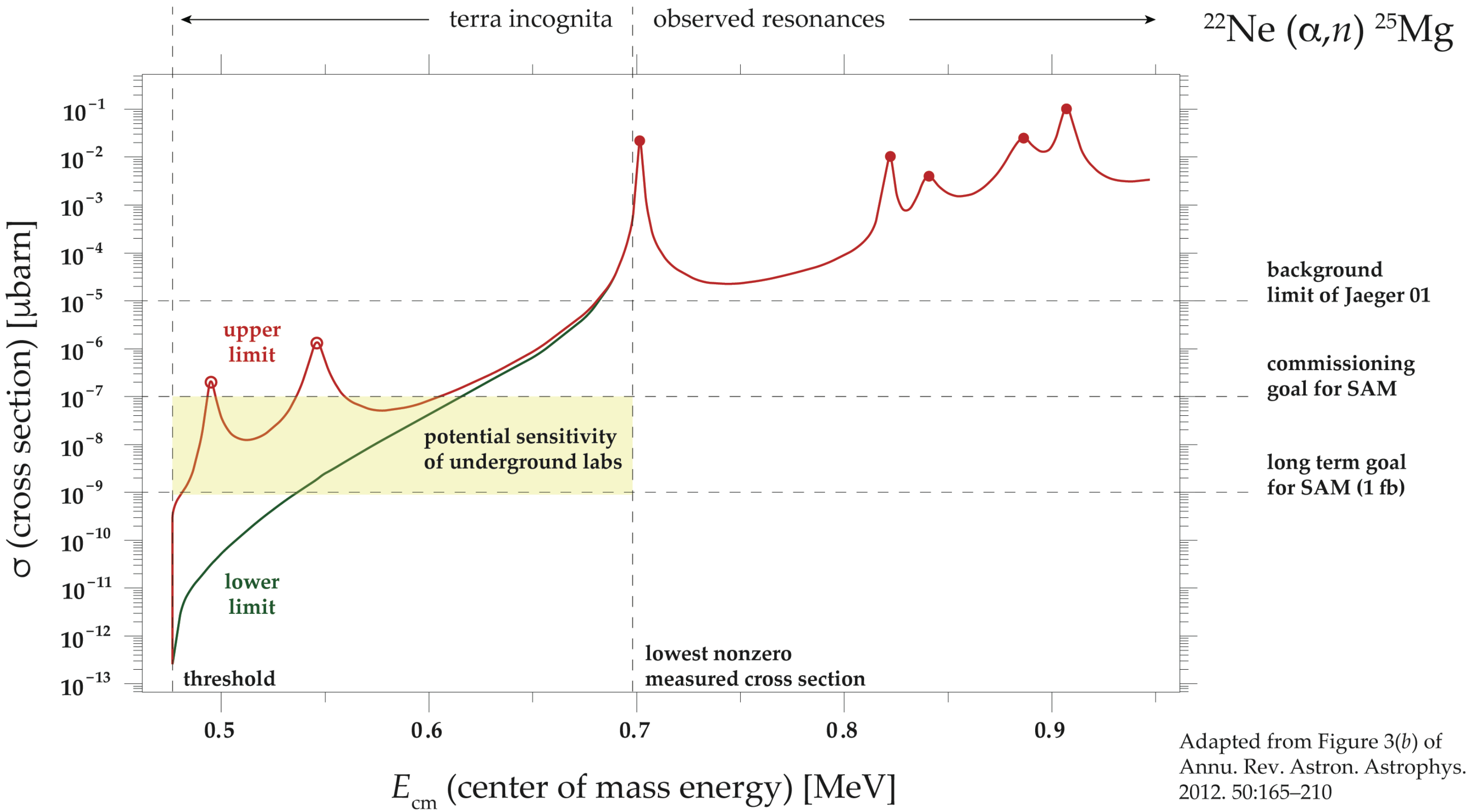
Temperature of Star → Collisional Energy



https://andromedageek.wordpress.com/2015/02/01/the-gamow-window/

^{22}Ne+^{4}He: Key Source of Neutrons for s-Process



Adapted from Figure 3(*b*) of Annu. Rev. Astron. Astrophys. 2012. 50:165–210

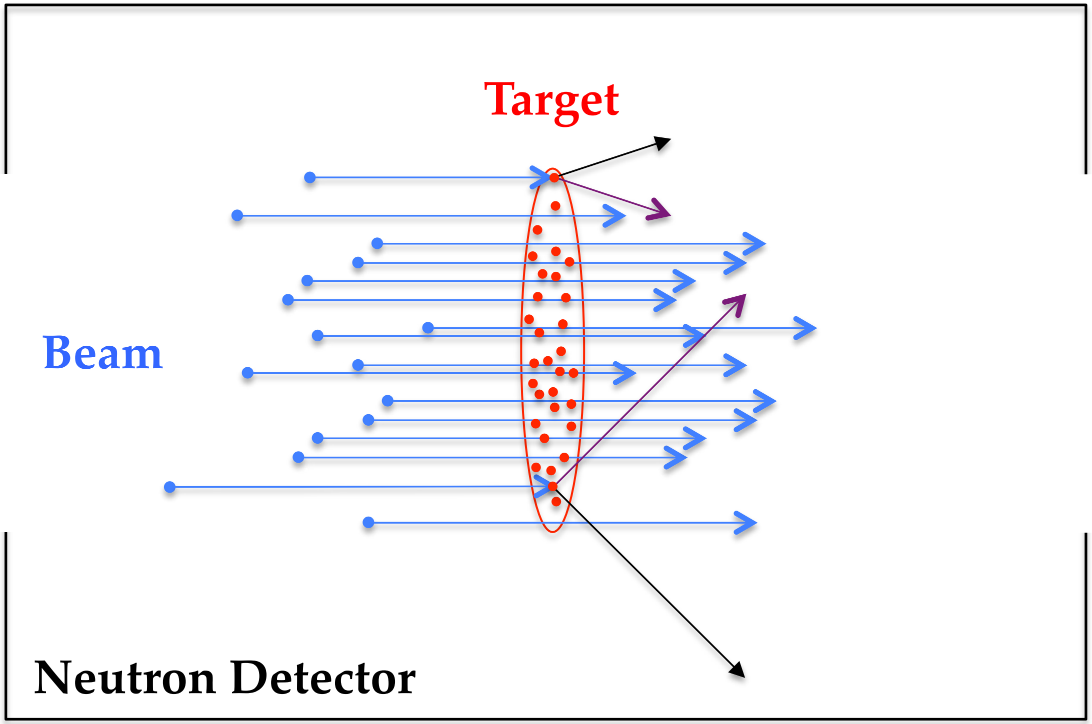
Underground labs are expected to have a factor of 100 or less background.

Recoils separators would need 10^{19}-10^{20} beam rejection ratios.

$$(1\ \text{pb})\left(10^{17}/\text{cm}^2\right)(150\ \mu\text{A}) = 5/\text{day}$$

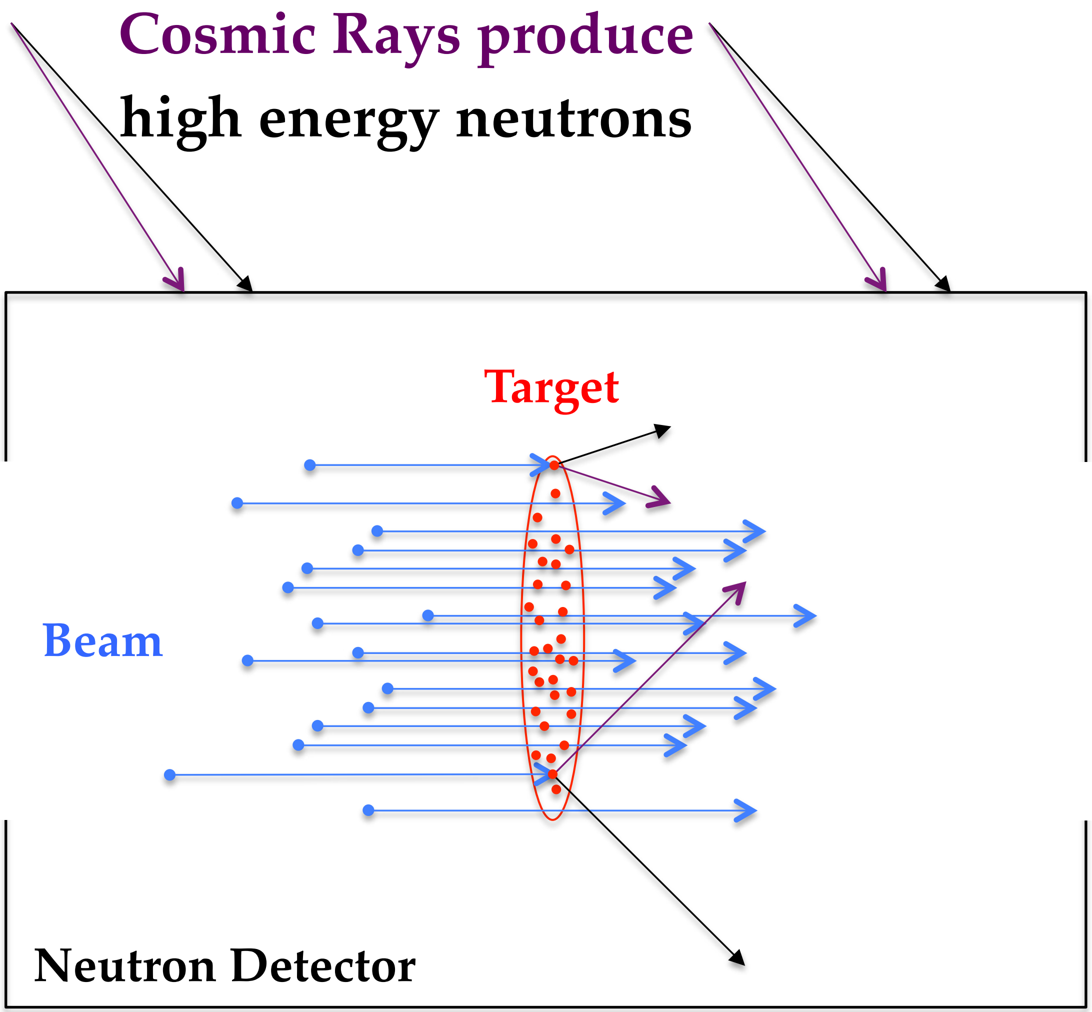
$$(1\ \text{fb})\left(10^{19}/\text{cm}^2\right)(2.1\ \text{mA}) = 7/\text{day}$$

The Old Method: Count the Neutrons



Detecting neutrons is very difficult – you lose all information about the energy of the neutron.

Bad: Cosmic Ray Induced Neutron Background



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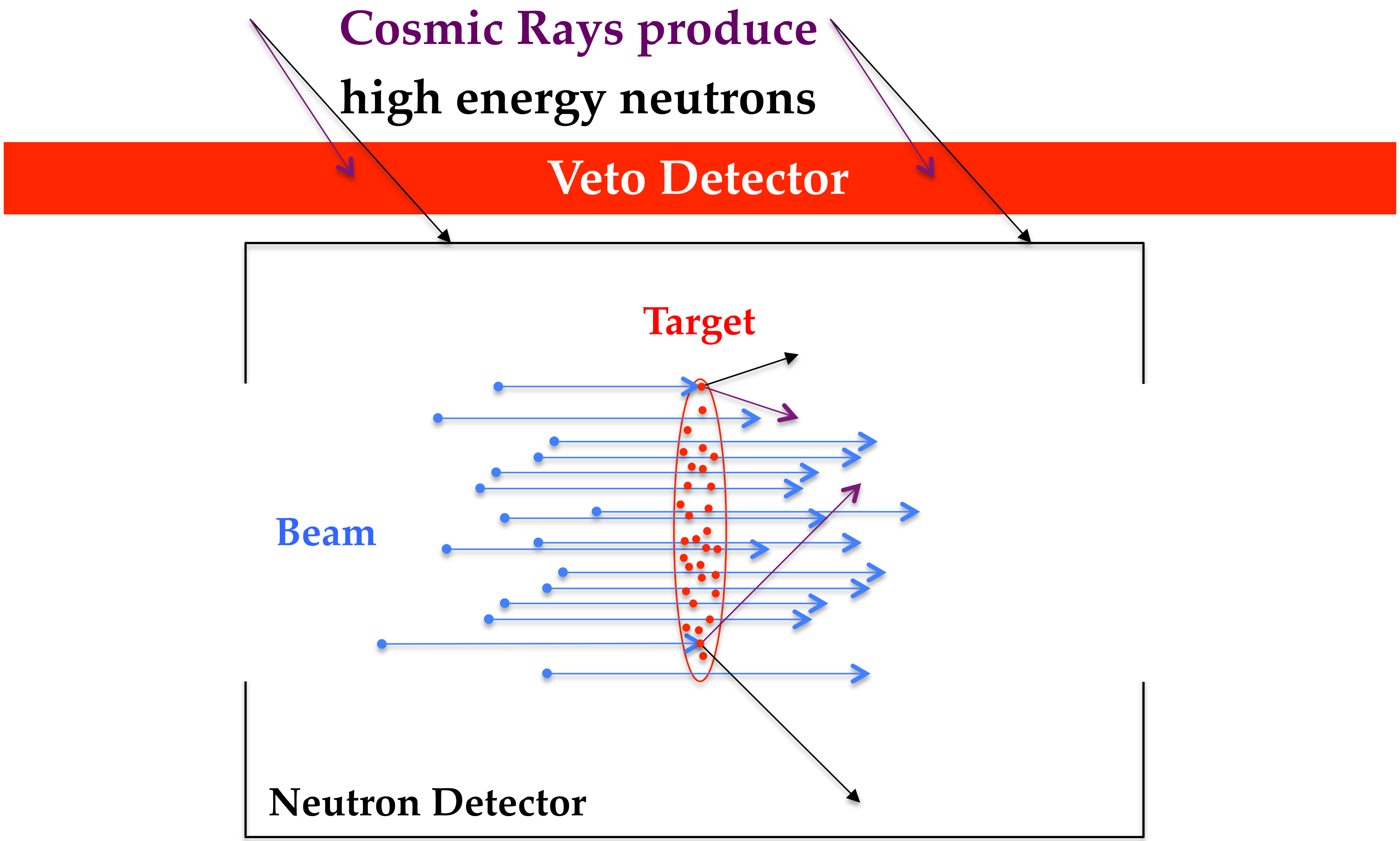
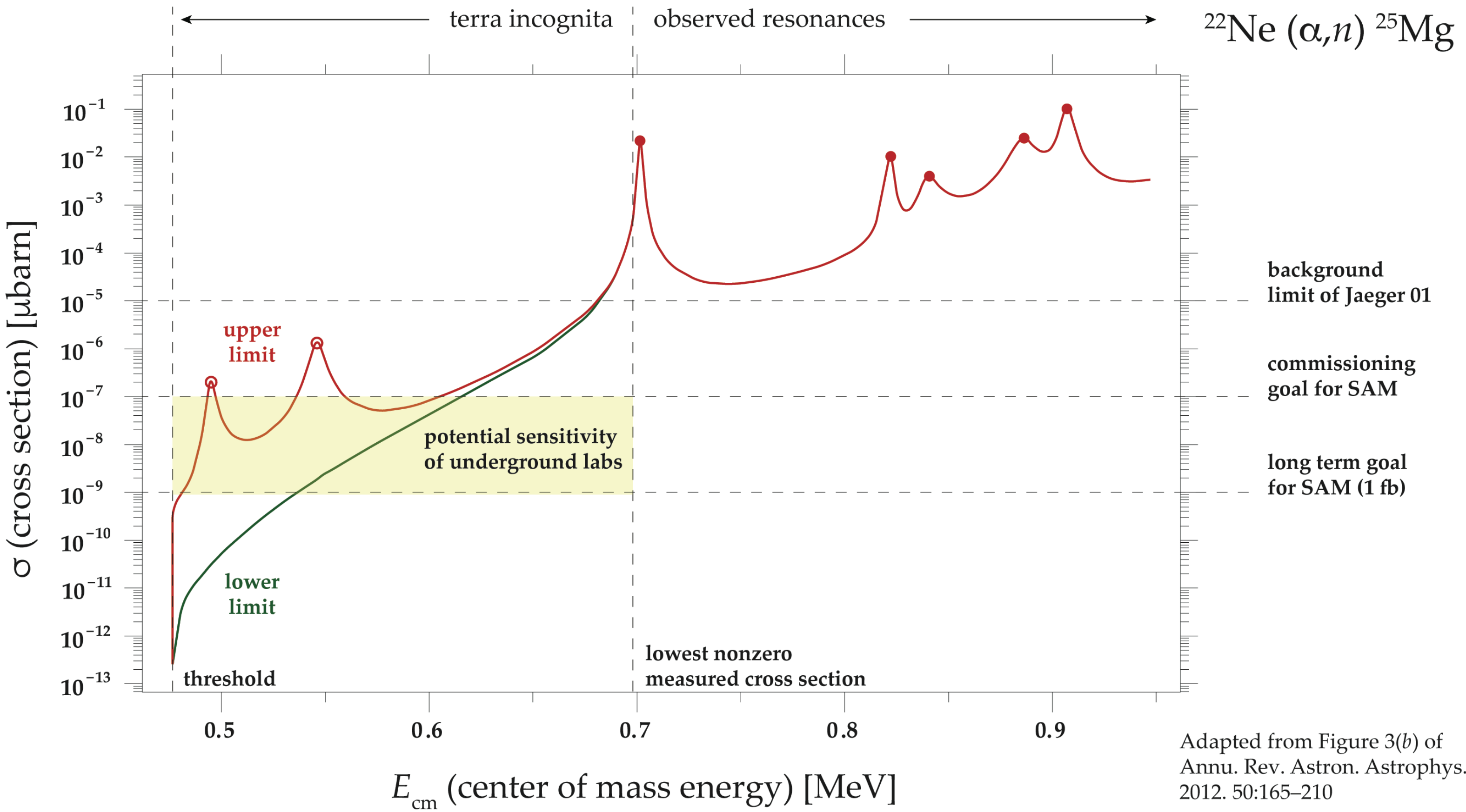
Good: The Beautiful Jaeger 2001 Experiment



Veto detector that registers a "hit" simultaneously as the neutron detector helps rule out background neutrons…great but not perfect.

^{22}Ne+^{4}He: Key Source of Neutrons for s-Process



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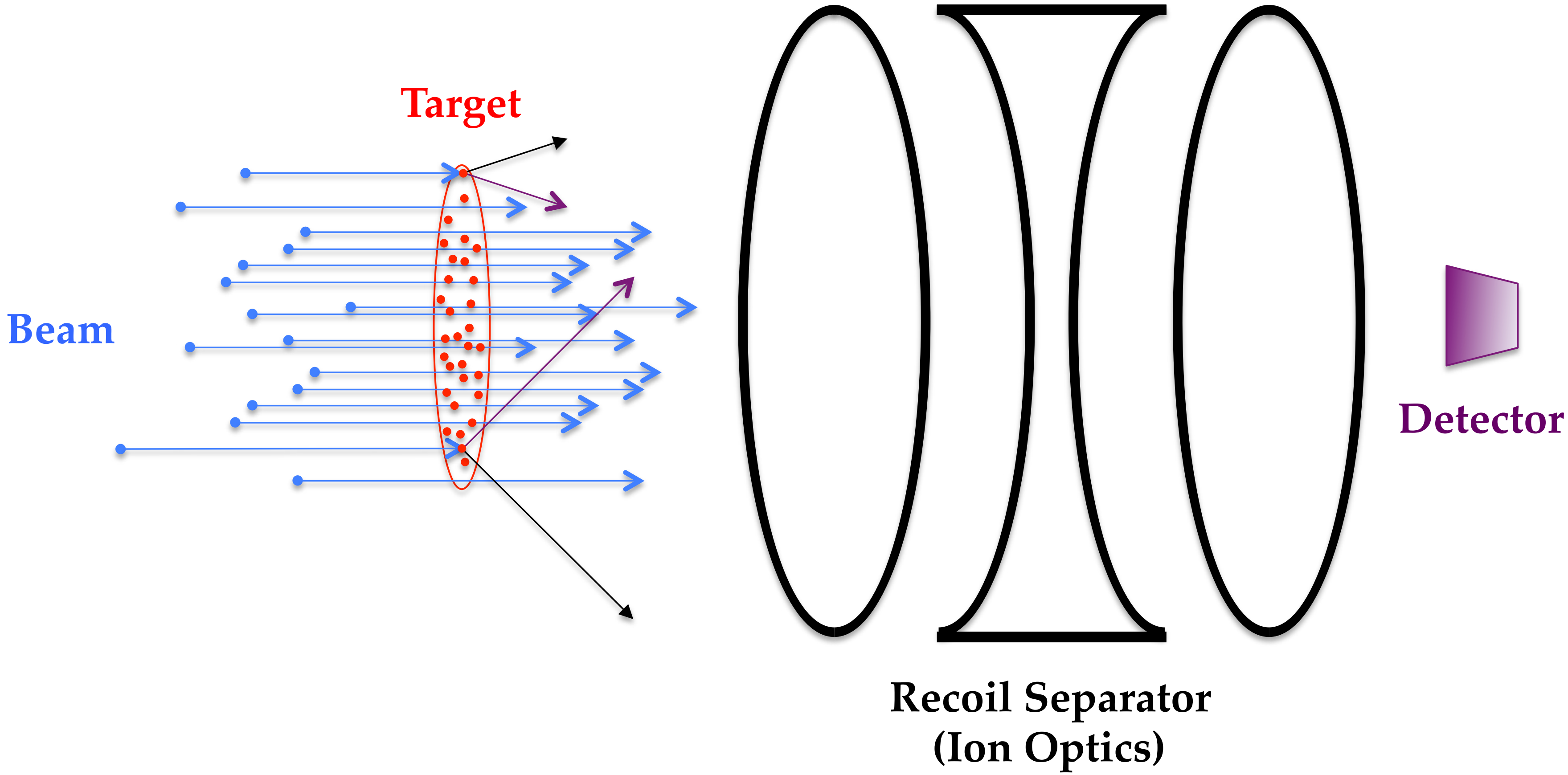
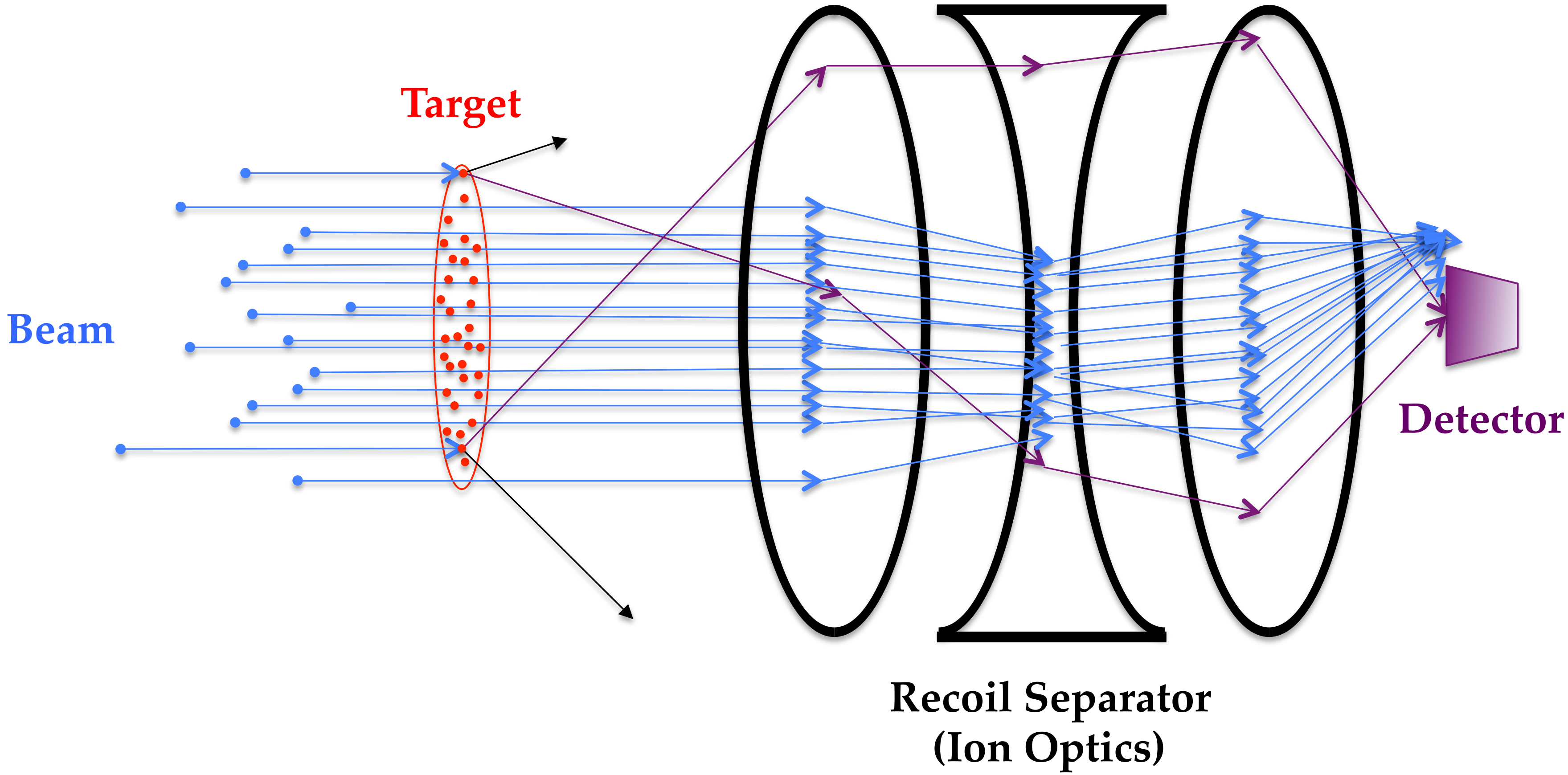
The New Method: Count the ^{25}Mg Atoms



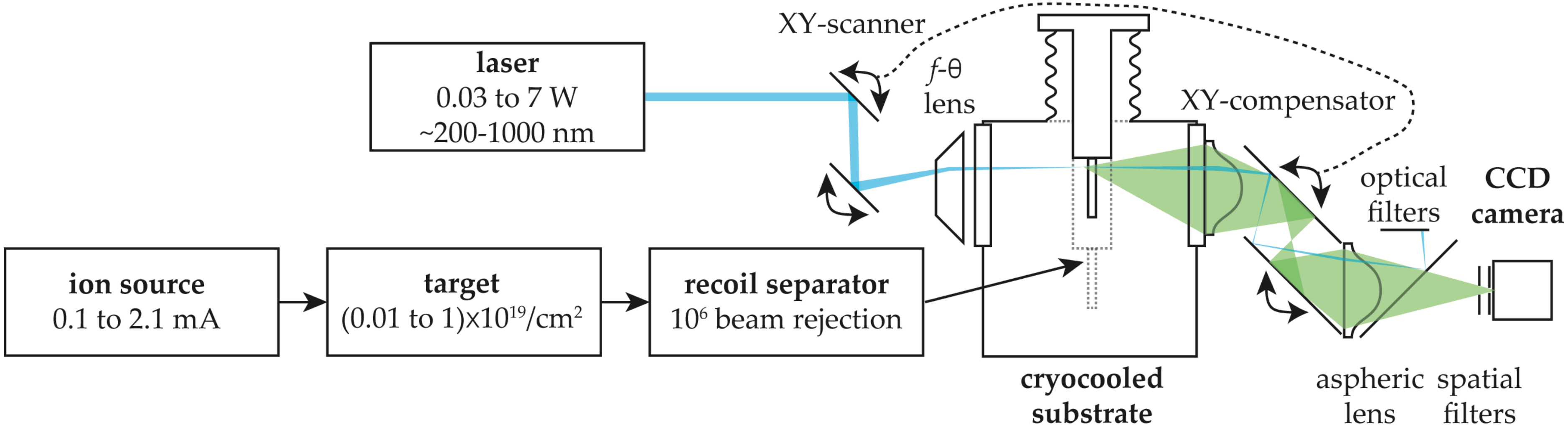
Electromagnetic recoil separator collects all of the products, separates them from the beam, and ***counts everything that makes it through***.

Recoil Separators Are Awesome But Not Perfect!



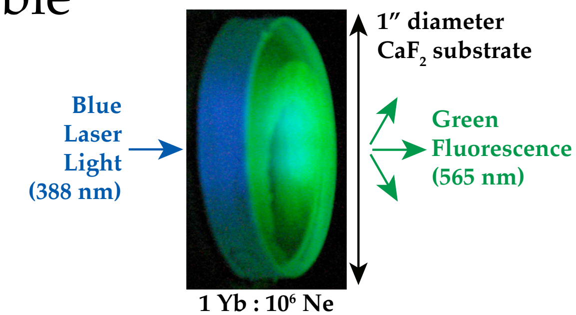
The best recoil separators only let 1 beam atom through out of 100,000,000, 000,000,000 or 10^{17} beam rejection efficiency, which is not quite good enough!

Basic Concept of Measurement Using SAM



- Efficient: cryogenic Ne film captures everything (both products and beam)
- Selective: product atoms identified by localized resonant laser excitation
- Sensitive: large shift (few nm to 100's of nm) between **excitation spectrum** and **emission spectrum** coupled with spatial & optical filtering makes optical single atom detection feasible

- **Recoil separator is needed to**:
  - minimize heat load on Ne film from beam
  - discriminate between isotopes



How do you take a picture of an atom?

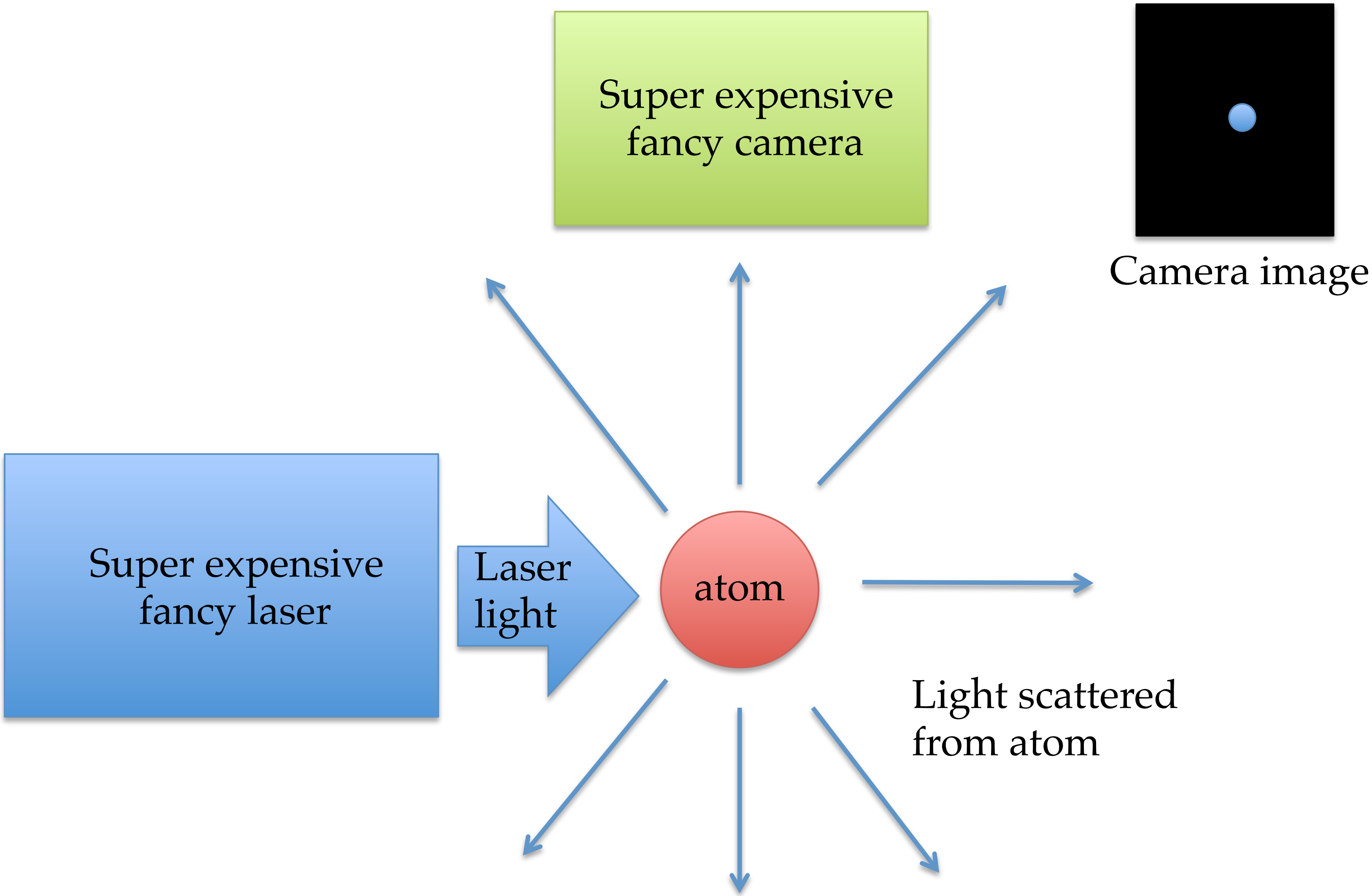
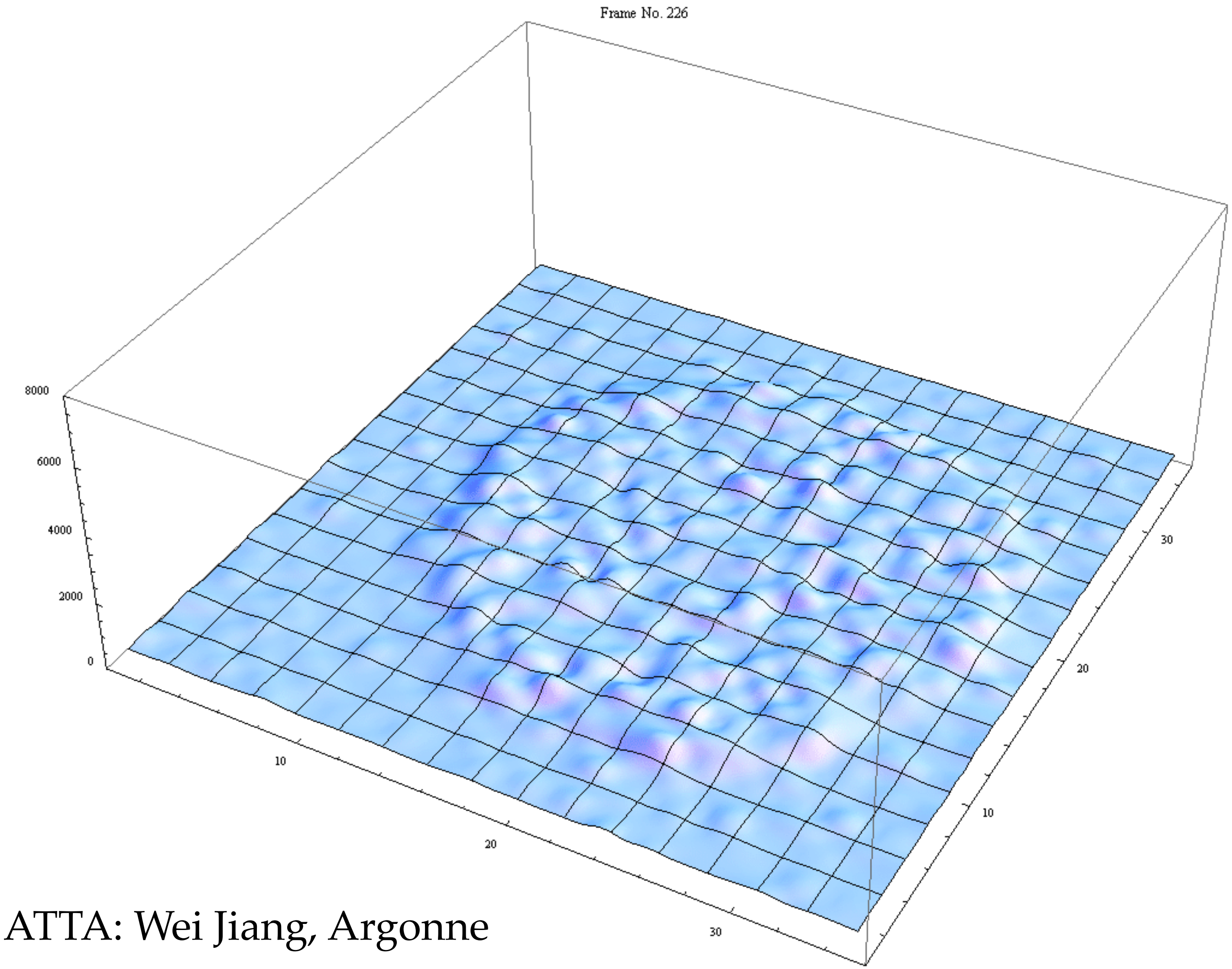
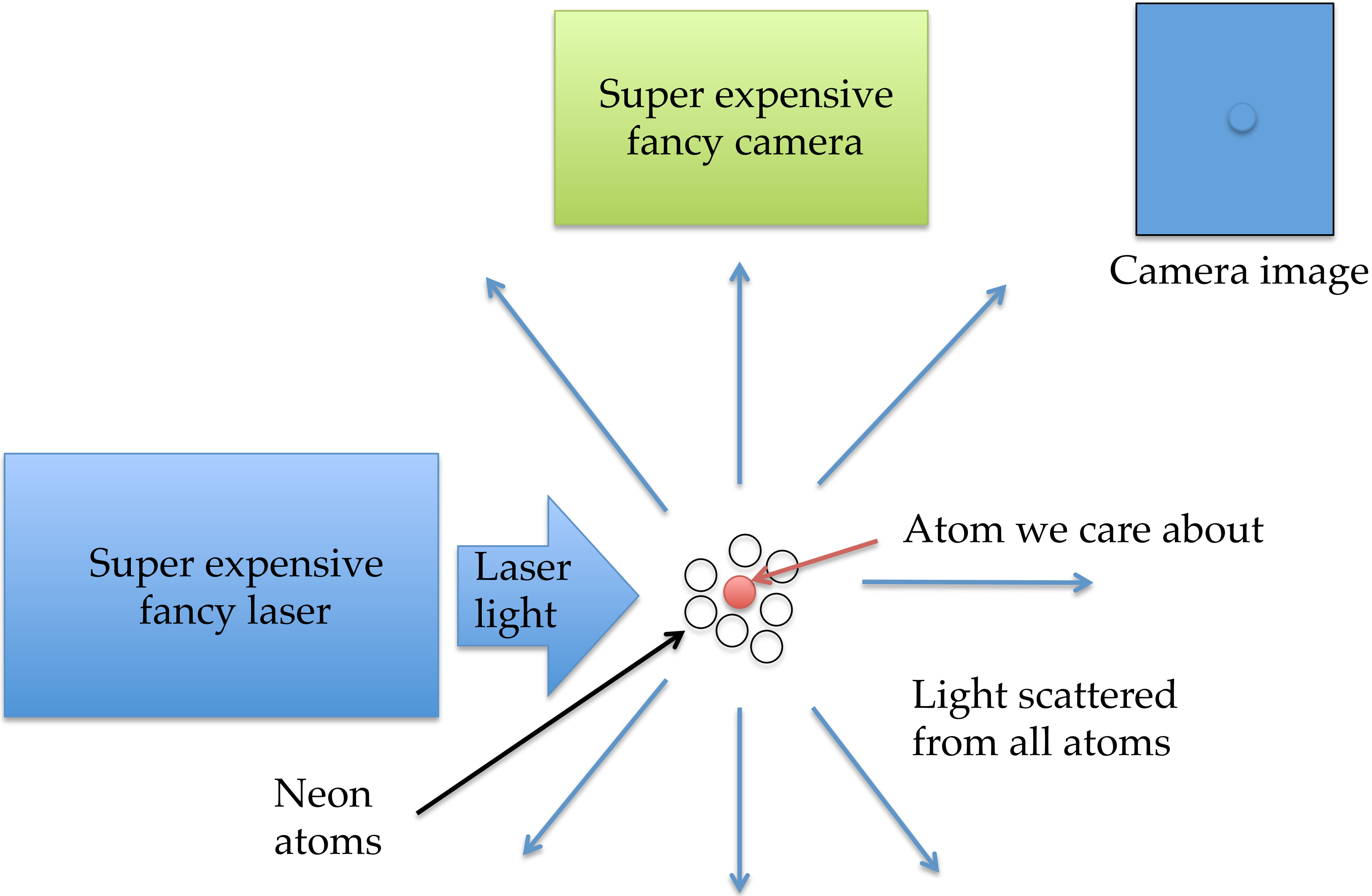


Image of single atom suspended in Vacuum

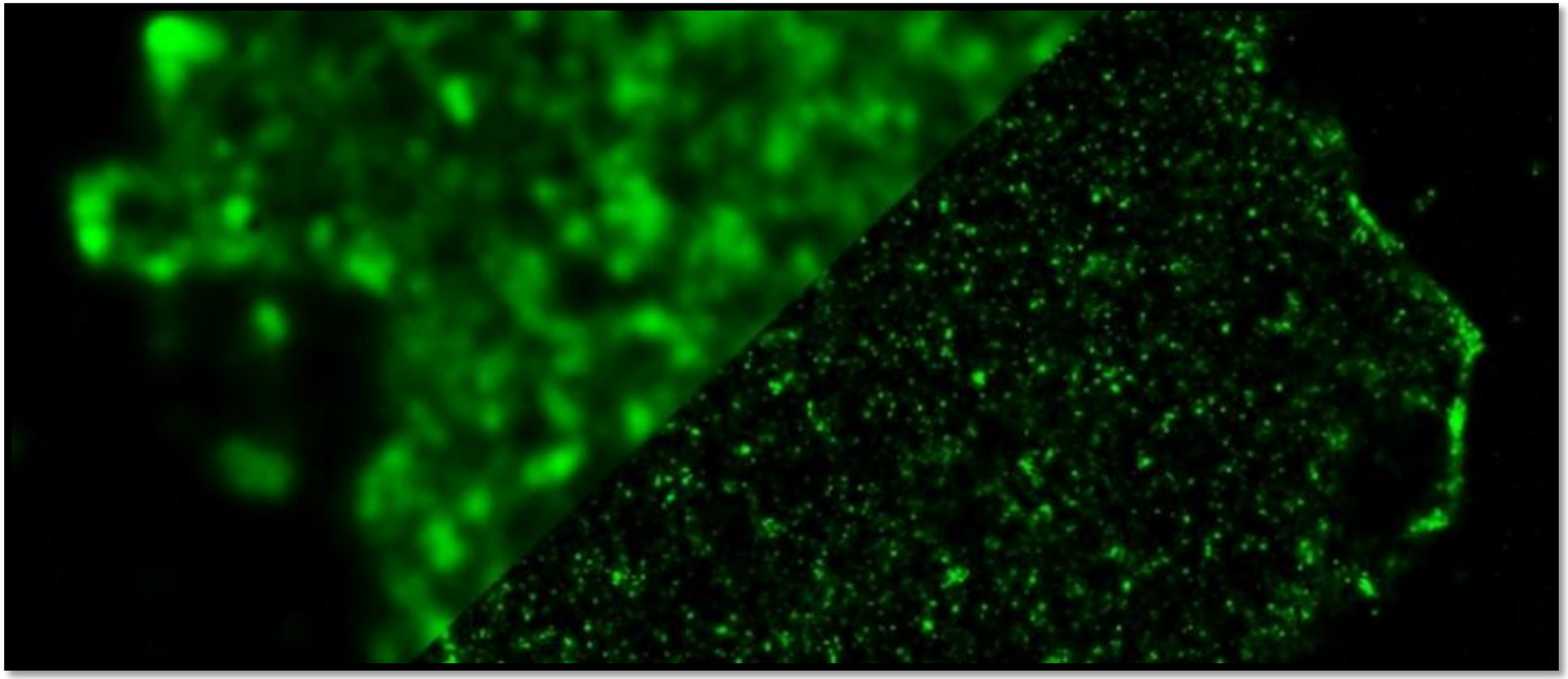


ATTA: Wei Jiang, Argonne

Taking a picture of an atom in solid is hard

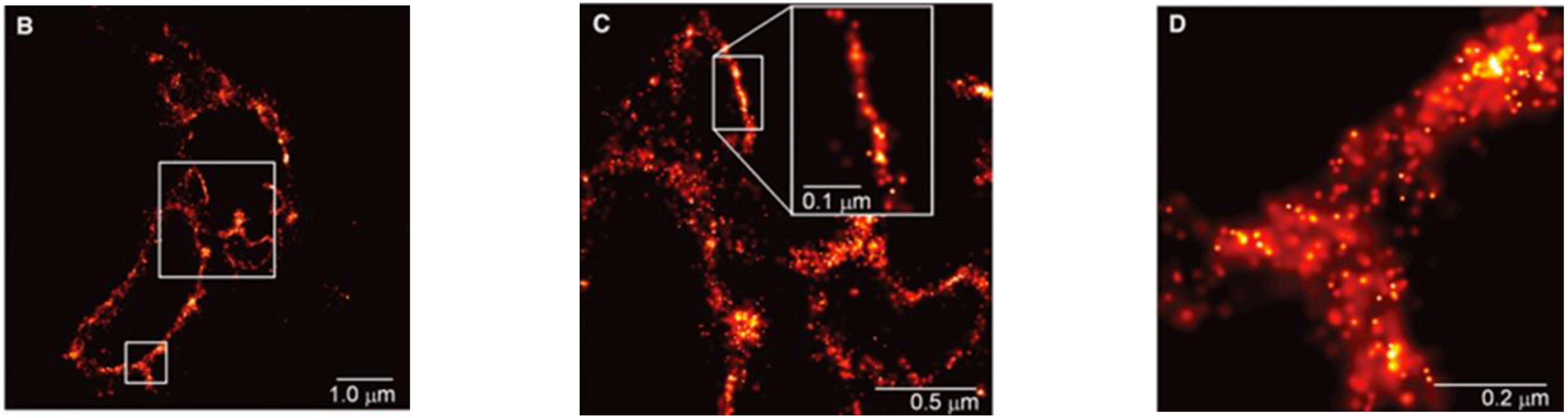


Example of individual emitters in solid images



https://sms.unsw.edu.au/what-sms

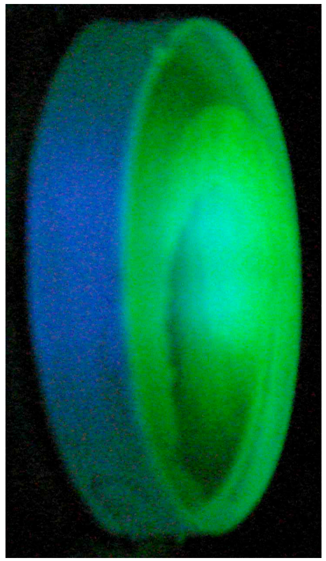
Single Atom Sensitivity is Feasible!



Betzig et al., Science, 2006, 313, 1642-1645
Nobel Prize Chemistry 2014
Mature tools & techniques can be borrowed from Single Molecule Biophysics!

Ba tagging for EXO
M. K. Moe PRC 44 R931 (1991)
T. Brunner
W. Fairbank et al. @ Colorado State
Single Ba detection in s-Xe and laser scanning have been demonstrated!

Blue Laser Light (388 nm)



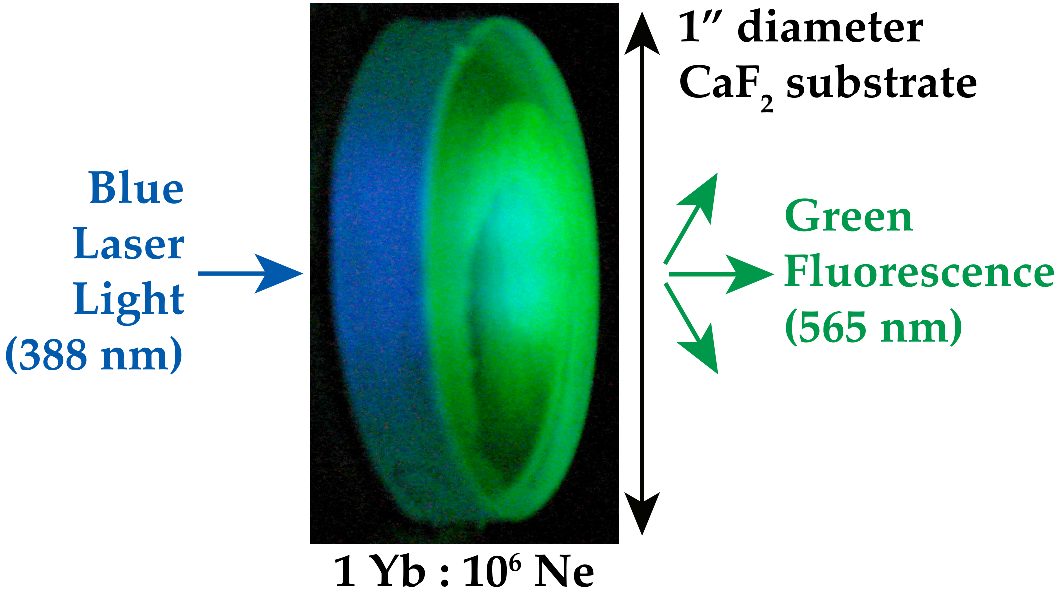
1 Yb : 10^6 Ne

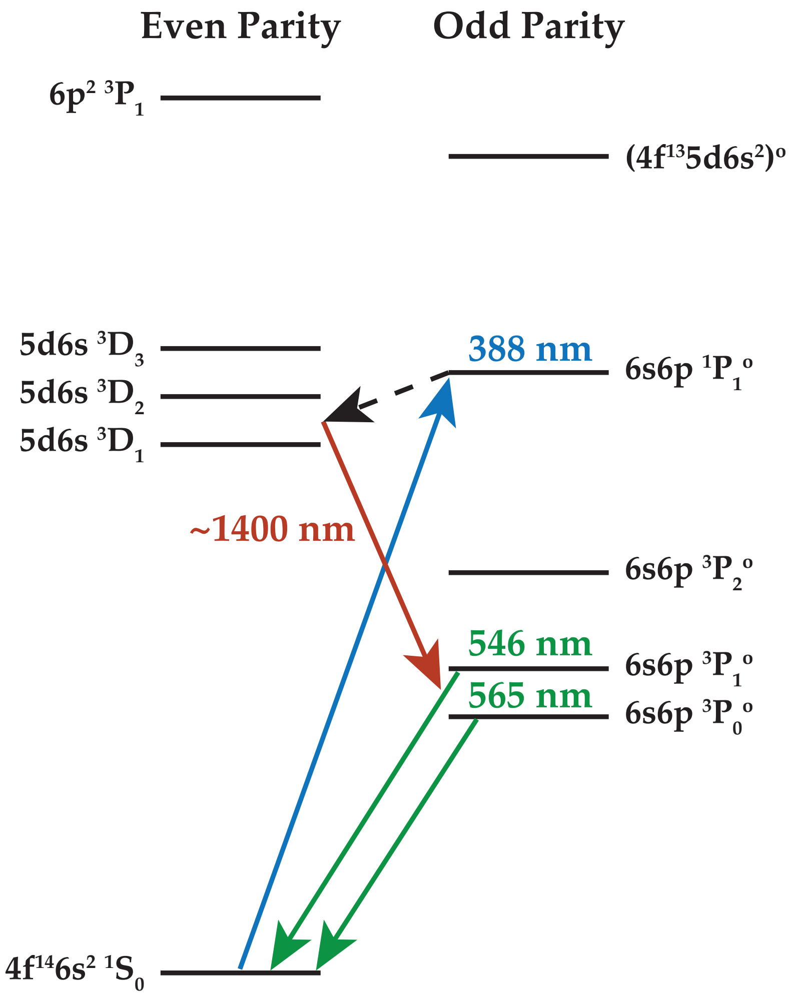
1″ diameter CaF_2 substrate

Green Fluorescence (565 nm)

Yb in s-Ne:
PRL 107, 093001
PRL 113, 033003

The Magic that should make this work

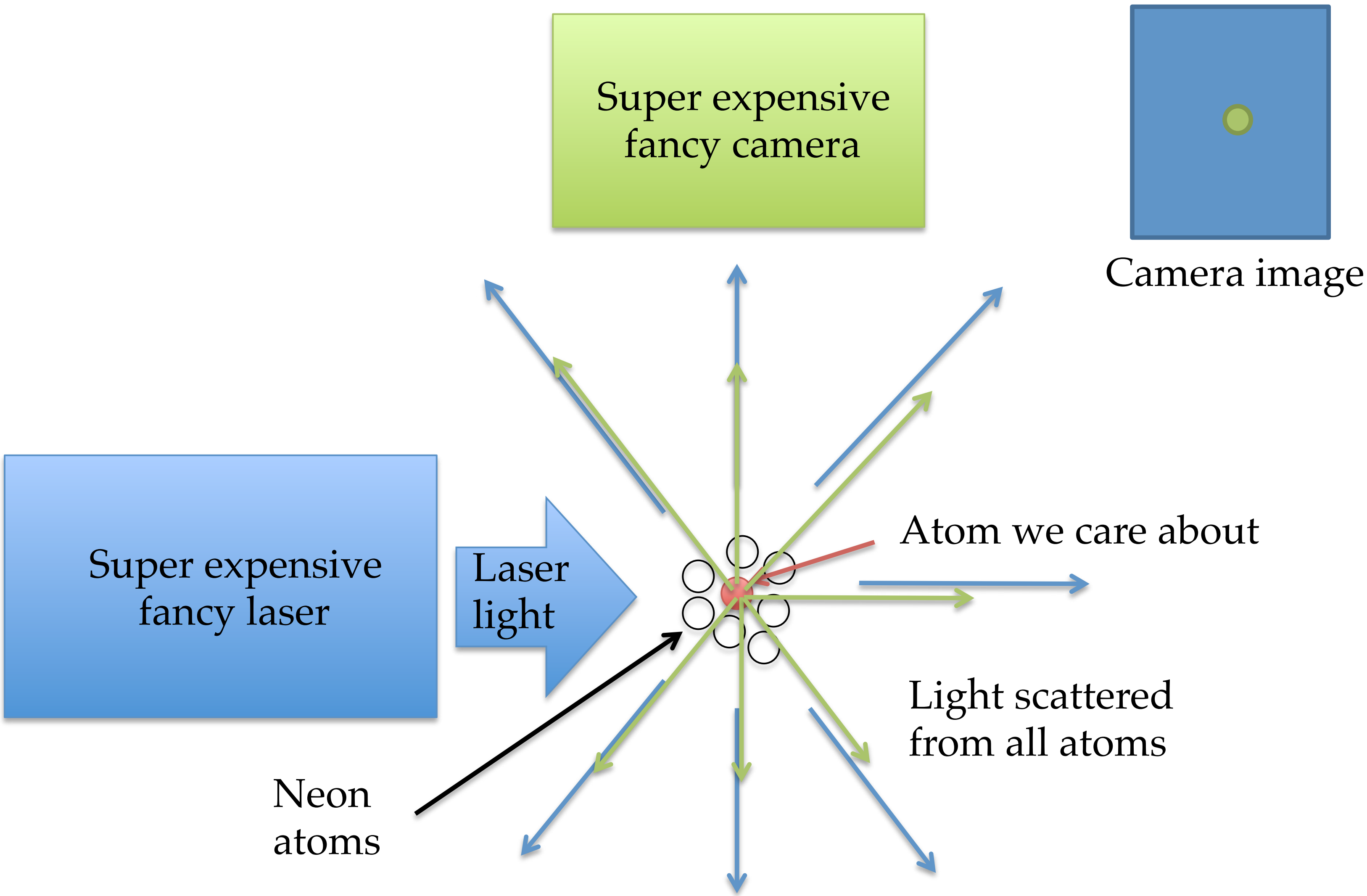




Xu, Hu, Singh, et al., *PRL* **109** 093001 (2011)

Xu, Singh, et al., *PRL* **113** 033003 (2014)

Taking a picture of an atom in solid is possible!



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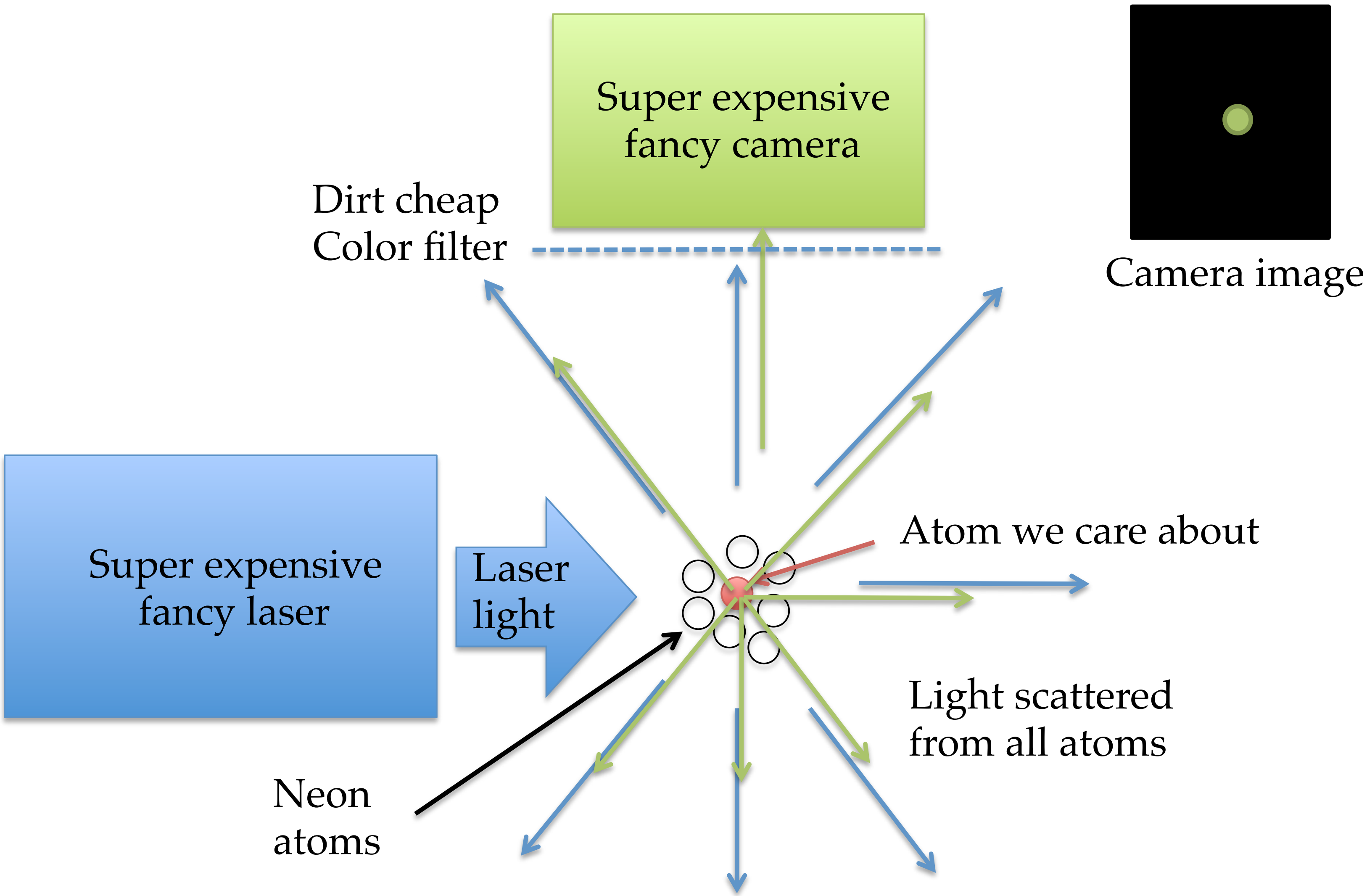
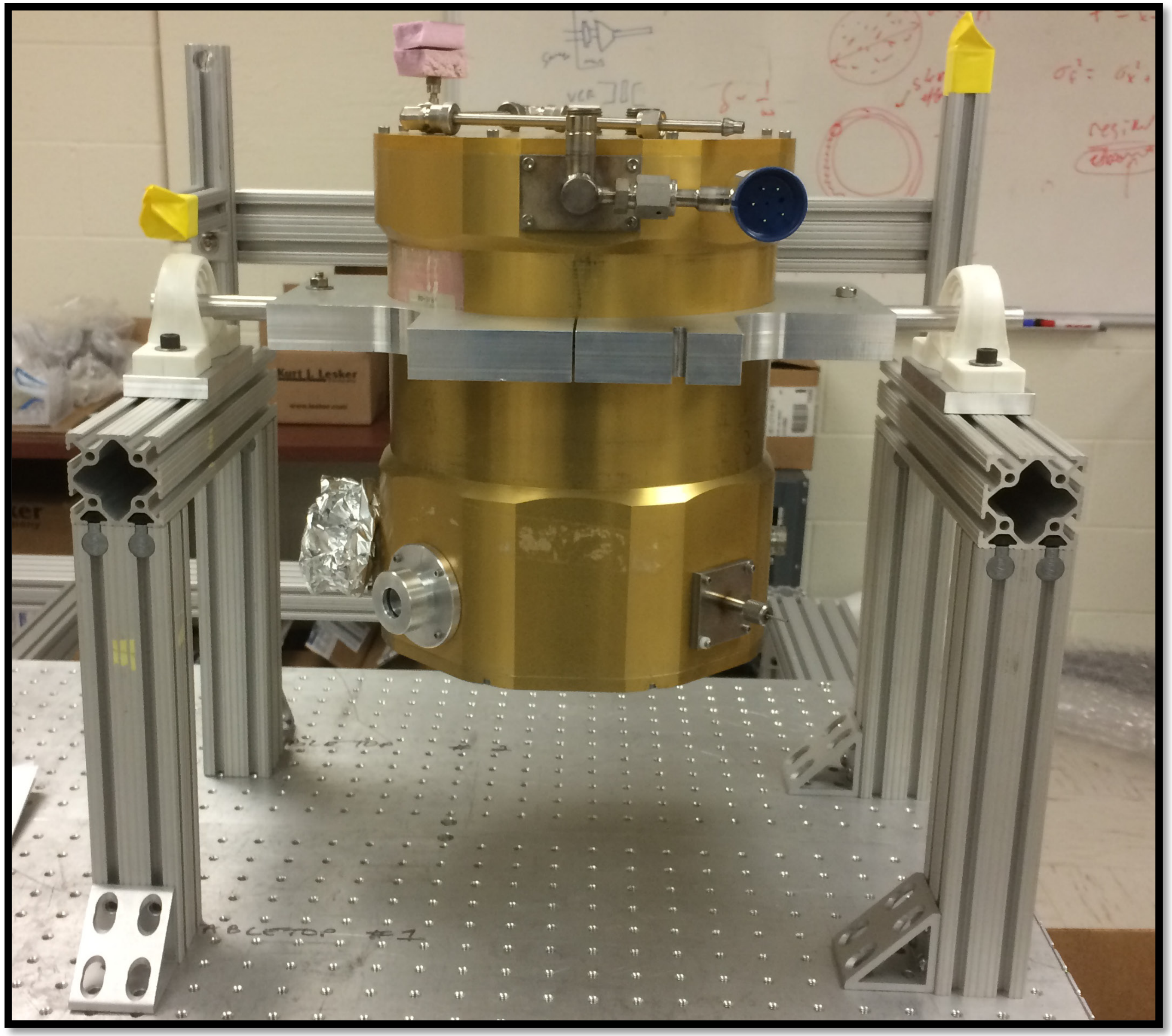
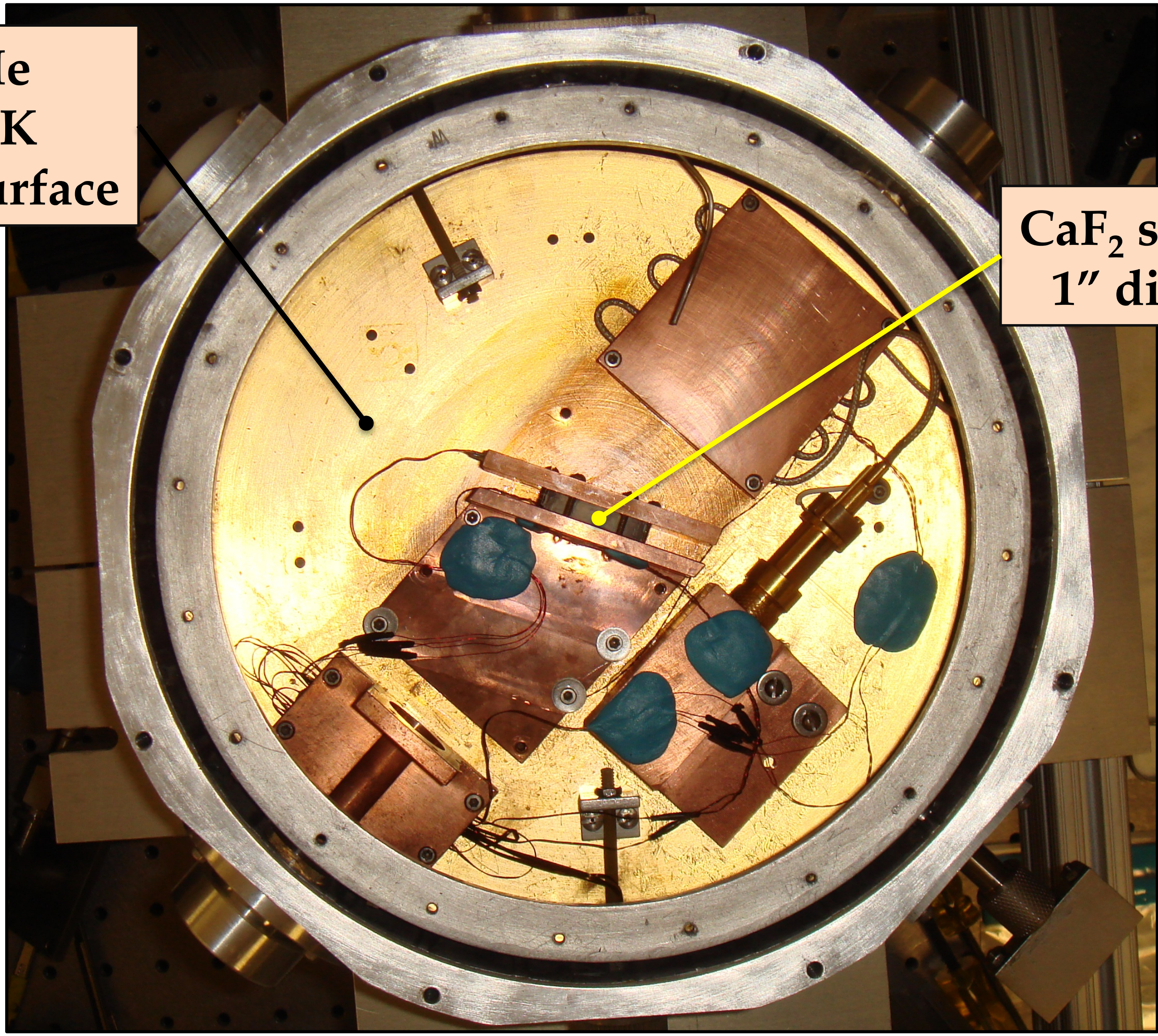


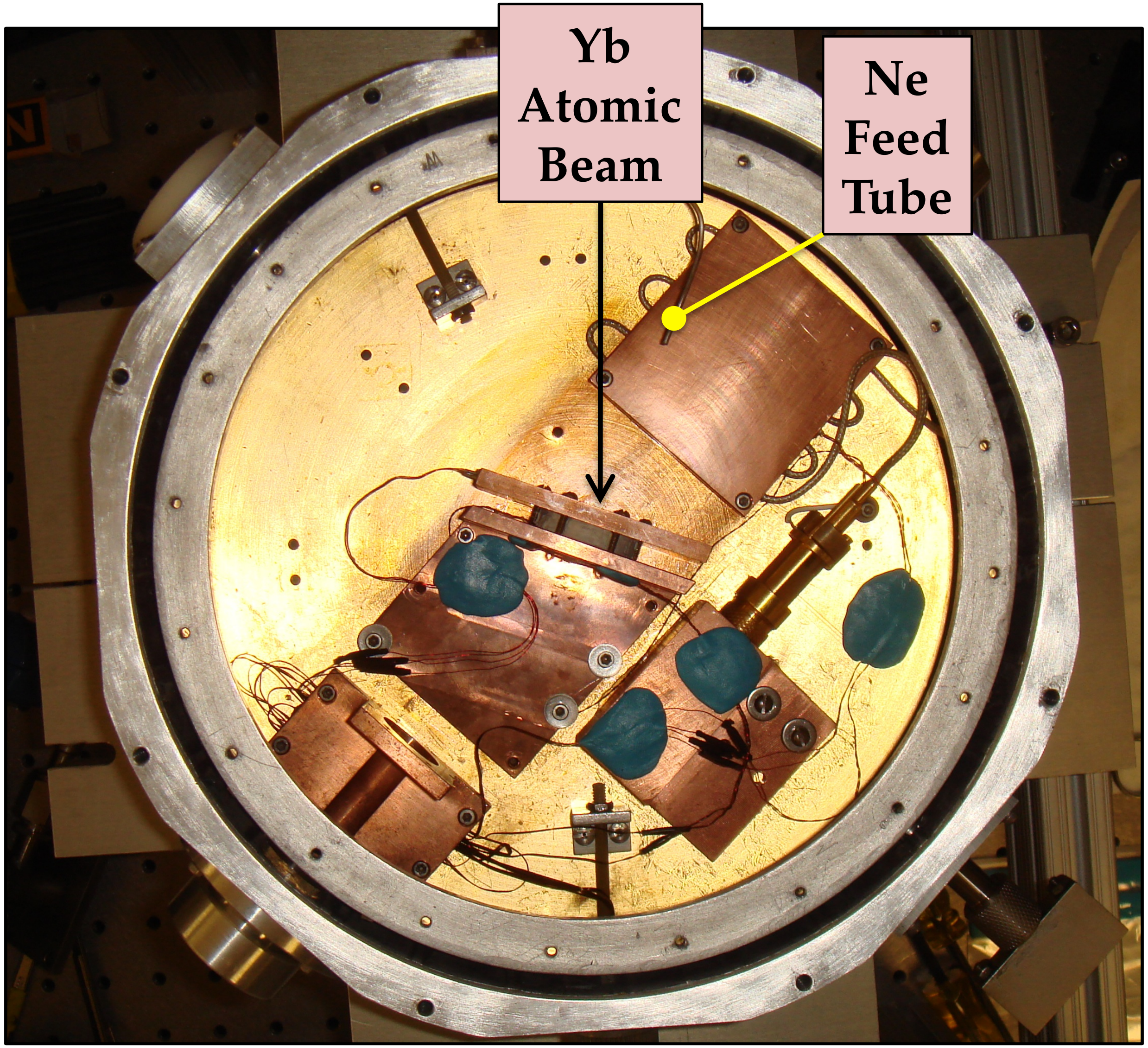
Liquid Helium Cryostat



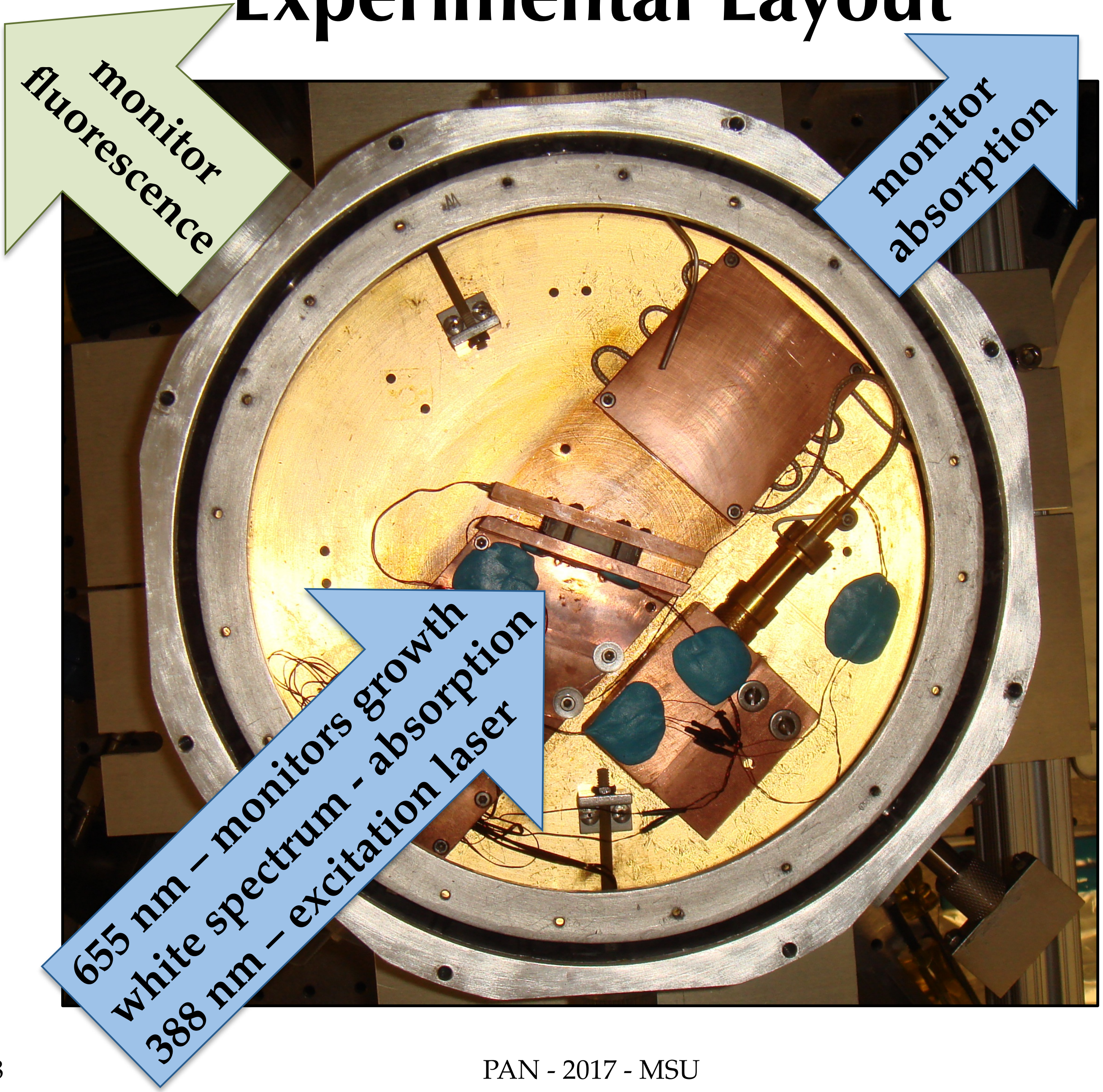
Making Solid Neon Catchers



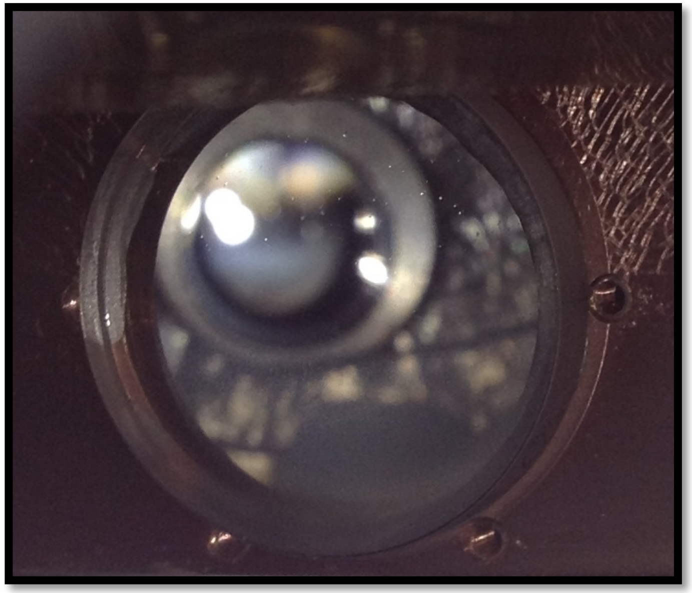
Freeze Neon gas into a cold surface



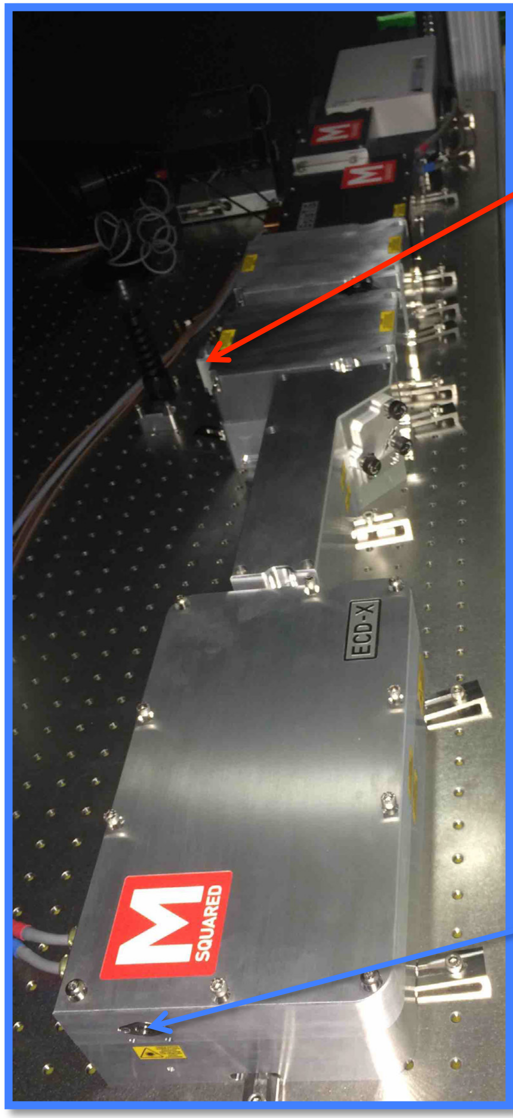
Experimental Layout



Good and Bad Solid Neon



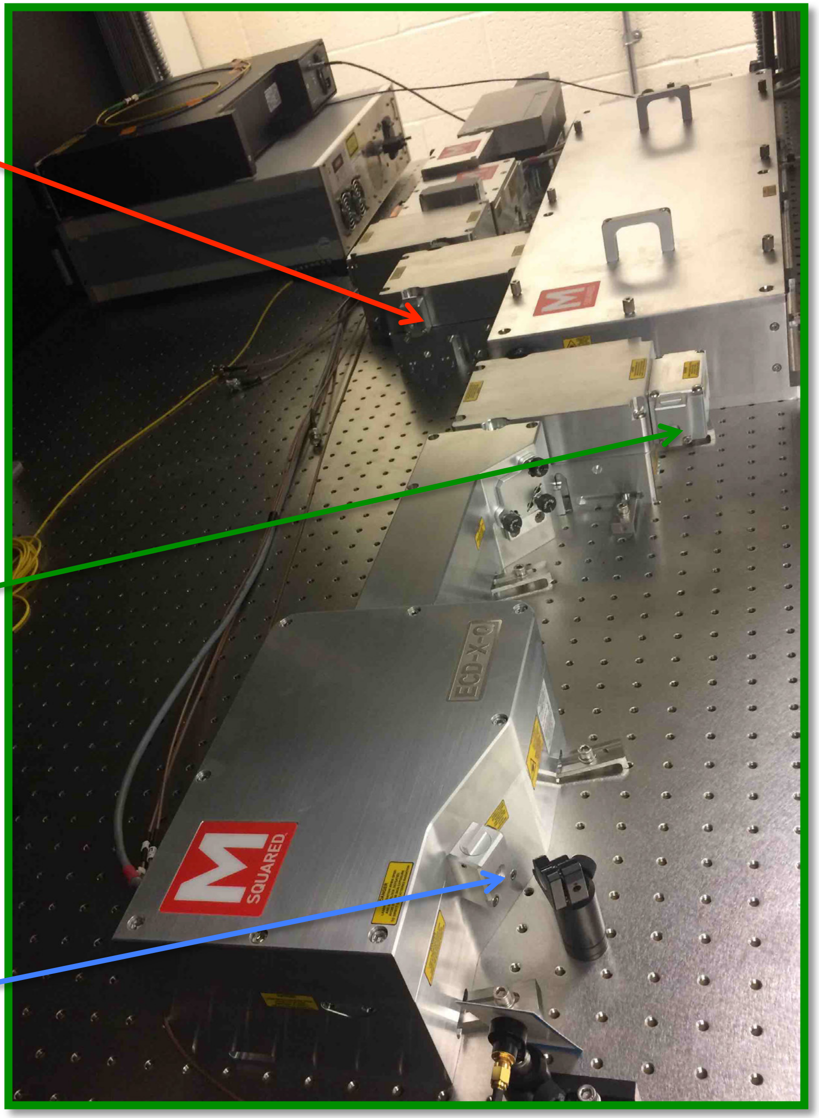
Fancy Lasers!



Ti:Sapphire Laser
7 W & 5 W
700-1000 nm
computer tunable

Sum Frequency
Mixing Module
1 W @ 500-600 nm
computer tunable

Frequency Doubling
3 W @ 350-500 nm
0.2 W @ 250-300 nm
computer scannable



Backgrounds From Impurity Atoms

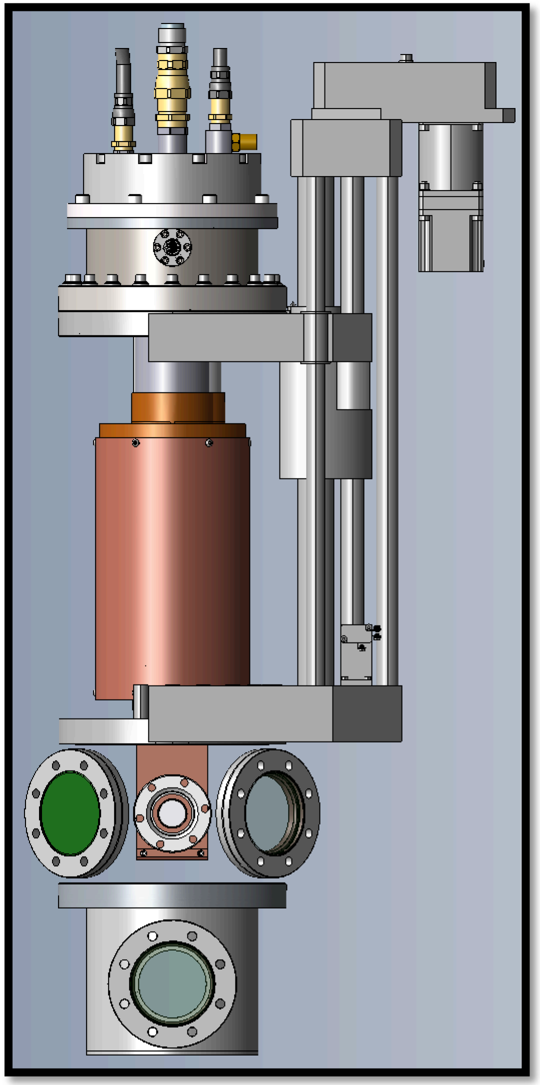
Main Technical Challenge: Suppressing Sources of Optical Background

Impurity	Source	Wavelength	Notes
all surfaces	excitation light	blue	optical filter
Nitrogen	vacuum residual gas	< 200 nm	too far off resonance
Oxygen	vacuum residual gas	< 245 nm	too far off resonance
Ozone	vacuum residual gas	< 350 nm	too far off resonance
Water	vacuum residual gas	< 210 nm	too far off resonance
"Stuff"	**UVFS viewports**	**~green**	**needs more study**
Cr^{3+}	**sapphire substrate**	**690 nm + broadband tail**	**needs more study**
Apiezon N	**inside cryostat**	**broadband green**	**don't use this**
"Stuff"	**surface of substrate**	**broadband green**	**needs more study**

Plans to mitigate this:

- pre-photobleaching of impurities before measurement
- confocal optics
- aggressive surface treatments
- low impurity substrate materials

Prototype SAM



Pulse Tube Cryocooler

- <10 micron amplitude vibrations
- 1.3 W cooling power

UHV compatible vertical linear drive

- up to 300 mm in travel
- <10 micron position repeatability

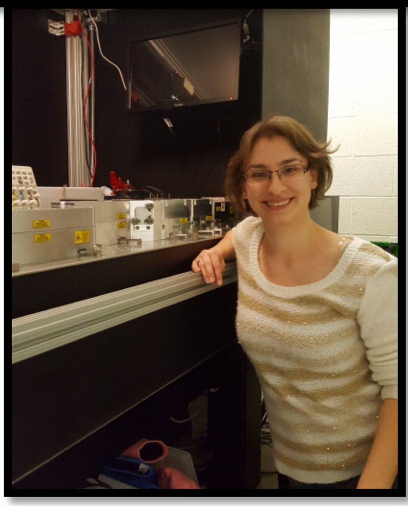
2.5″ clear aperture

- 2% light collection w/ single aspheric lens
- DUV Fused Silica

Assembly in November 2017

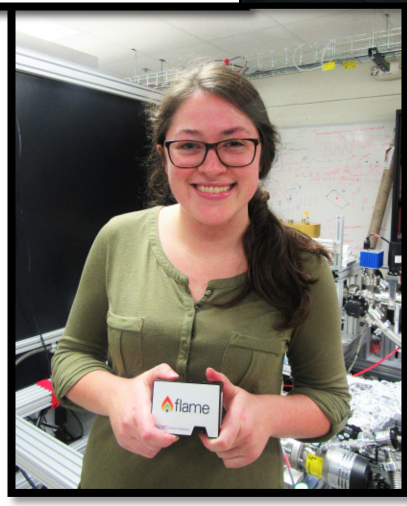
The SAM Team

Special Thanks:
Z.T. Lu & P. Mueller
C.-Y. Xu, J. Zappala,
and S.-M. Hu



Jennifer Wenzl (Postdoc)

Dustin Frisbie (G)



Kristen Parzuchowski (UG)