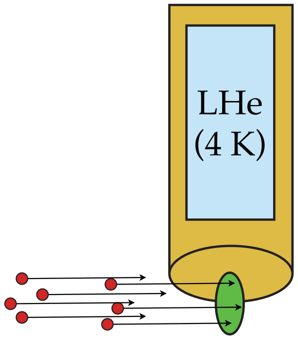
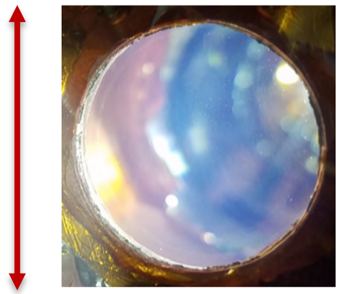
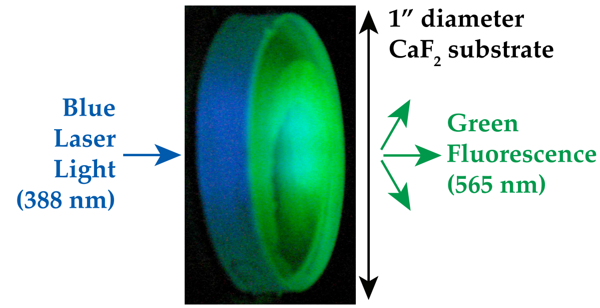
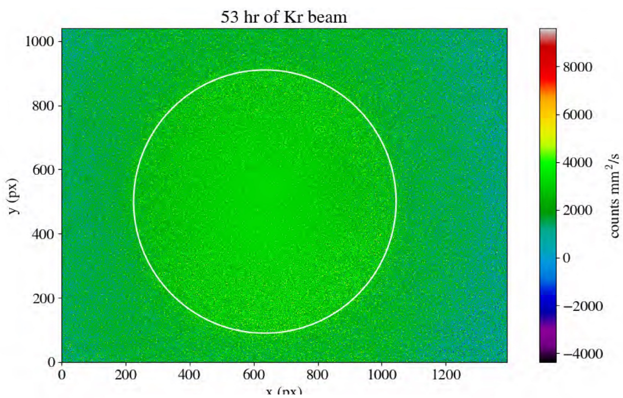
Using Lasers to Count Atoms to Explain the Stellar Origin of Copper and Silver



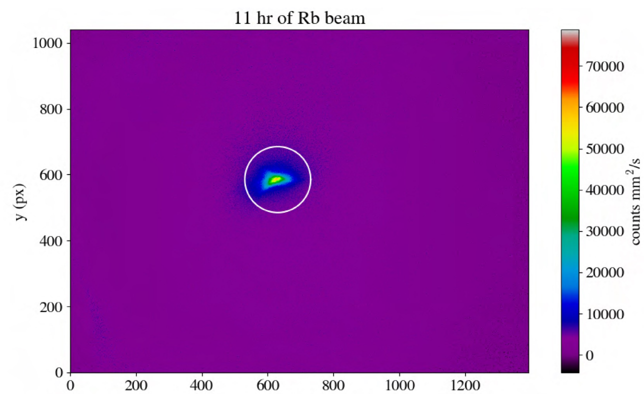
1 inch diameter sapphire





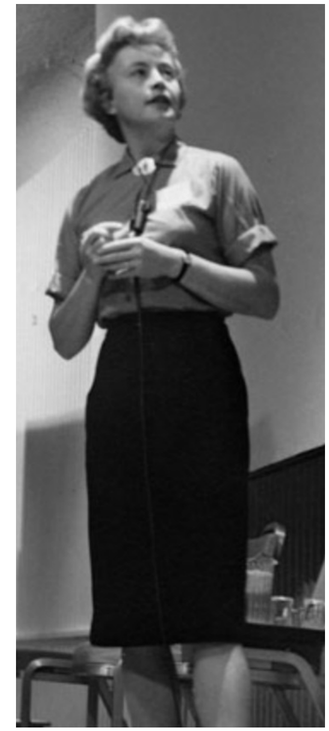


10^{11} Kr atoms



10^{10} Rb atoms

https://skyandtelescope.org/astronomy-news/happy-birthday-margaret-burbidge/



Margaret Burbidge

SCAN ME

Jaideep Taggart Singh

Facility for Rare Isotope Beams

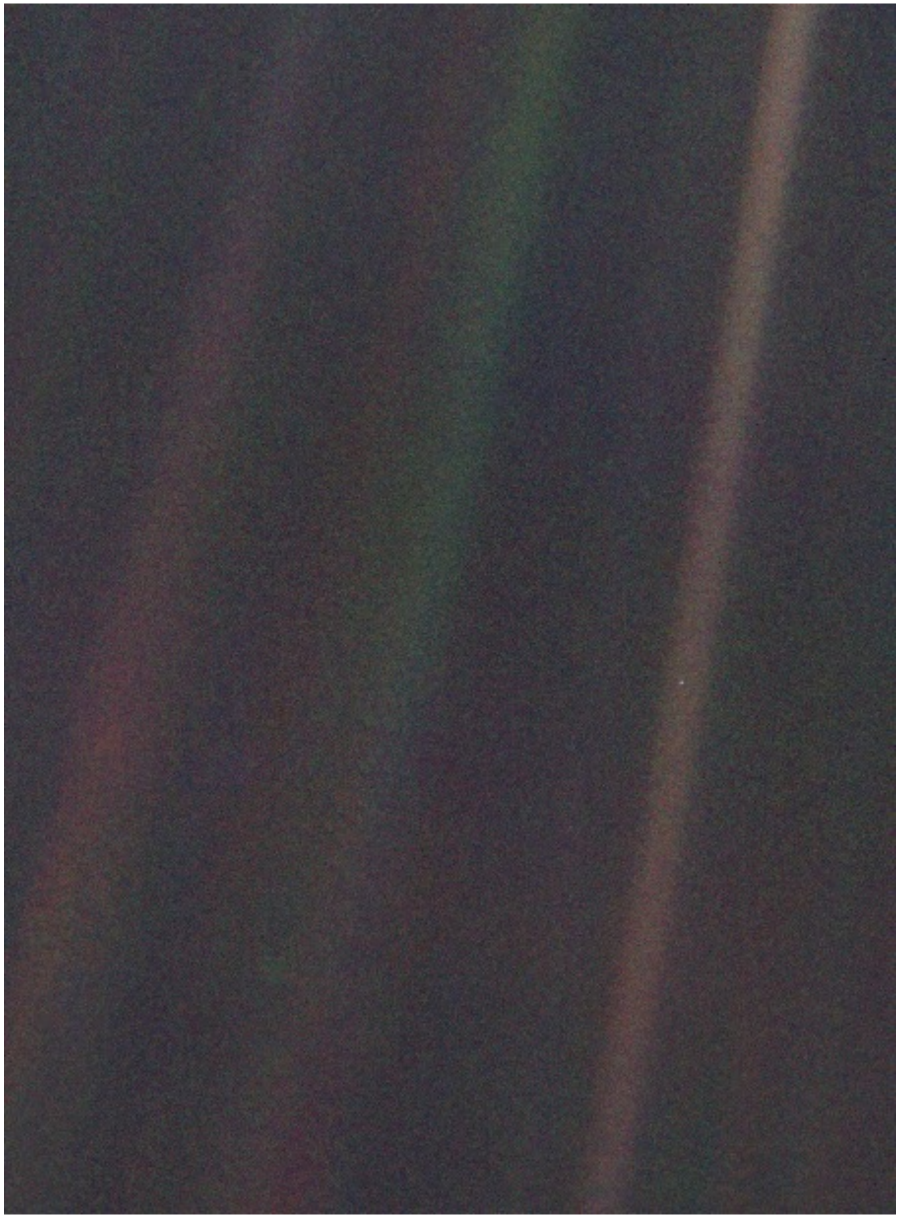
Michigan State University

18:00-19:00, September 23, 2024 @ BPS 1400

MSU Society of Physics Students - Pizza Talk

FRIB

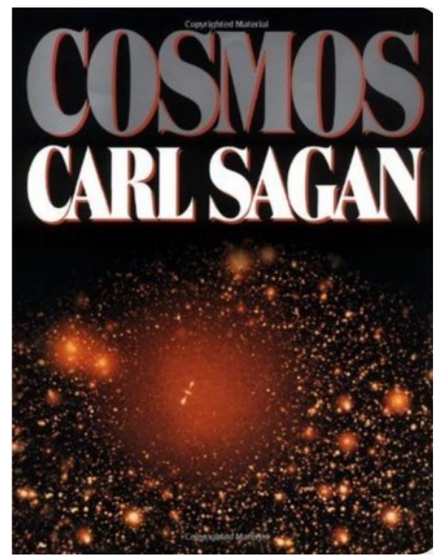
We are all made of dead stars!



1990

https://en.wikipedia.org/wiki/Pale_Blue_Dot

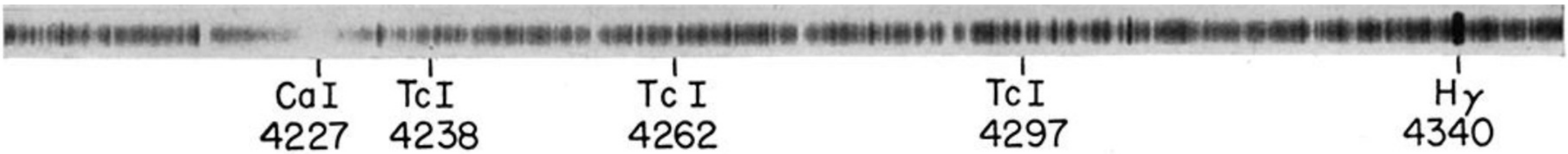
"The **nitrogen** in our DNA,
the **calcium** in our teeth,
the **iron** in our blood,
the **carbon** in our apple pies
were made in the interiors
of collapsing stars.
We are made of starstuff."



1980

https://www.goodreads.com/book/show/55030.Cosmos

“It is surprising to find an unstable element in the stars.”



Technetium in the Stars

Paul W. Merrill
Mount Wilson* and *Palomar Observatories

Technetium, the first ‘‘artificial’’ element, was identified in 1937 by Perrier and Segrè in a piece of molybdenum that had been bombarded with neutrons in the cyclotron at Berkeley. Technetium has also been detected among the products of fission of heavy atoms. No completely stable isotope is known; the most nearly stable has a half-life less than a million years.

The spectrum of technetium was thoroughly investigated in 1950 by Meggers and Scribner at the National Bureau of Standards. Their work has made astronomical investigations possible. In 1951 Charlotte E. Moore announced the possible presence of weak lines of ionized technetium in the solar spectrum.

It is surprising to find an unstable element in the stars. Either (1) a stable isotope actually exists although not yet found on earth; or (2) S-type stars somehow produce technetium as they go along; or (3) S-type stars represent a comparatively transient phase of stellar existence.

Star	Plate	Absorption				
		ZrO	*TiO*	*Ba* II	Low-Temp.	*Tc* I
R And....	Ce 3522	8	3	5	8	4
U Cas.....	Pc 127	7	7	5	6	3
HD 22649.	Pc 192	2	2	5	6	1
R Gem....	Pc 68	5	0	10	7	5
S UMa....	Pc 110	1	0	7	4	1
T Sgr.....	Pc 124	7	0	7	5	3
R Cyg....	Pc 137	10	0	10	5	3
AA Cyg...	Pc 115	8	7	7	8	4
Z Del.....	Pc 112	2	7	3	3	1
χ Cyg.....	Ce 3762	5	20	3	10	3
o Cet......	Ce 4109	1	15	1	7	2
	Ce 5925	1	10	2	6	1
R Hya....	Ce 3390	1	15	3	7	1
R Leo....	Pc 40	0	20	1	10	0

Science 115, 484 (1952) Rev. Mod. Phys. 29, 547 (1957) Astrophys. J. 116, 21 (1952)

B2FH (then) + AJP Resource Letter (now)

REVIEWS OF
MODERN PHYSICS

VOLUME 29, NUMBER 4 OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California

"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

but perhaps

"The fault, dear Brutus, is not in our stars, But in ourselves,"
(*Julius Caesar*, Act I, Scene 2)

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RESOURCE LETTERS | OCTOBER 01 2024

Resource Letter: Synthesis of the elements in stars

Artemis Spyrou

Check for updates

Am. J. Phys. 92, 731–736 (2024)
https://doi.org/10.1119/5.0209176 Article history

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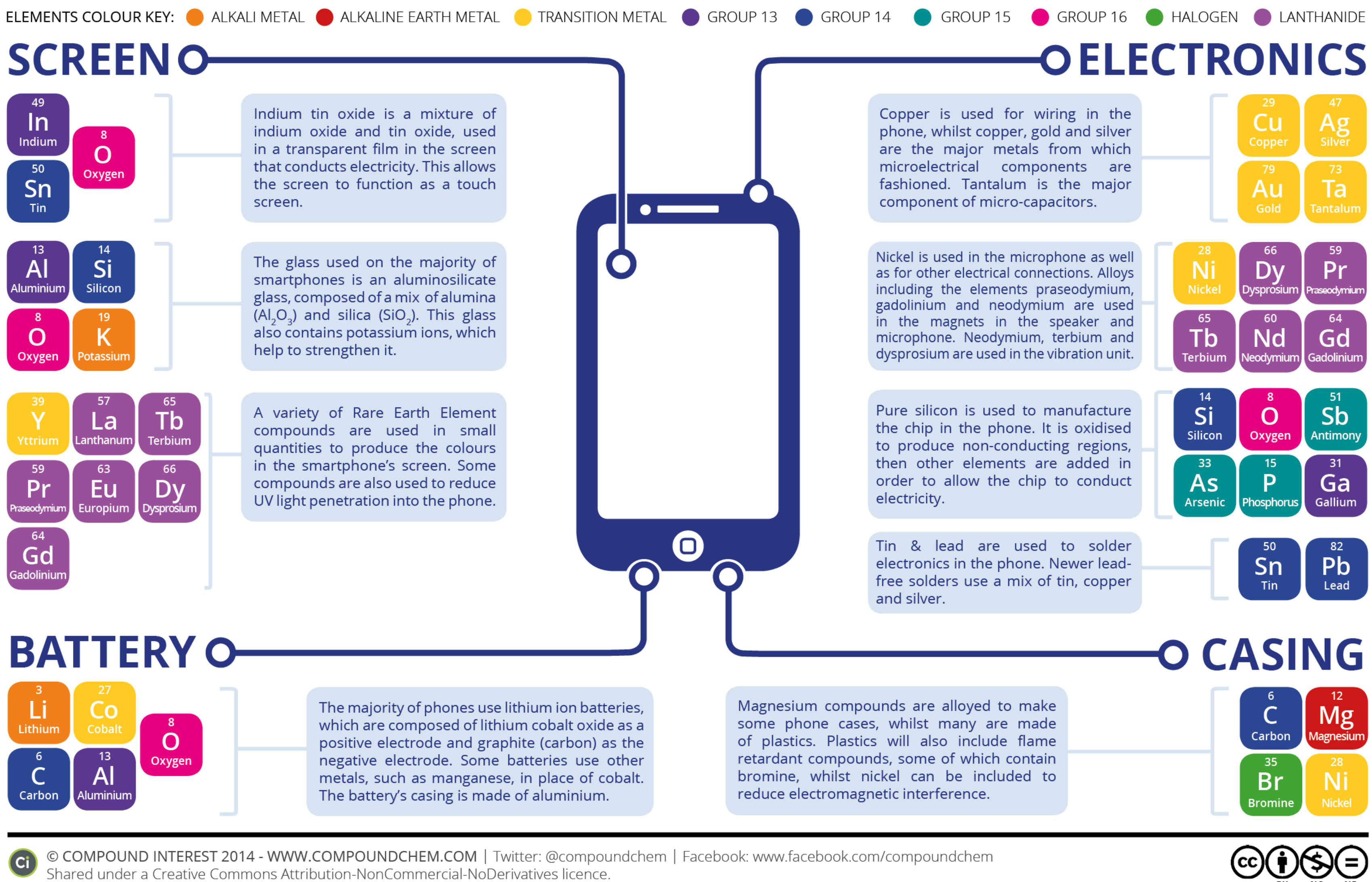
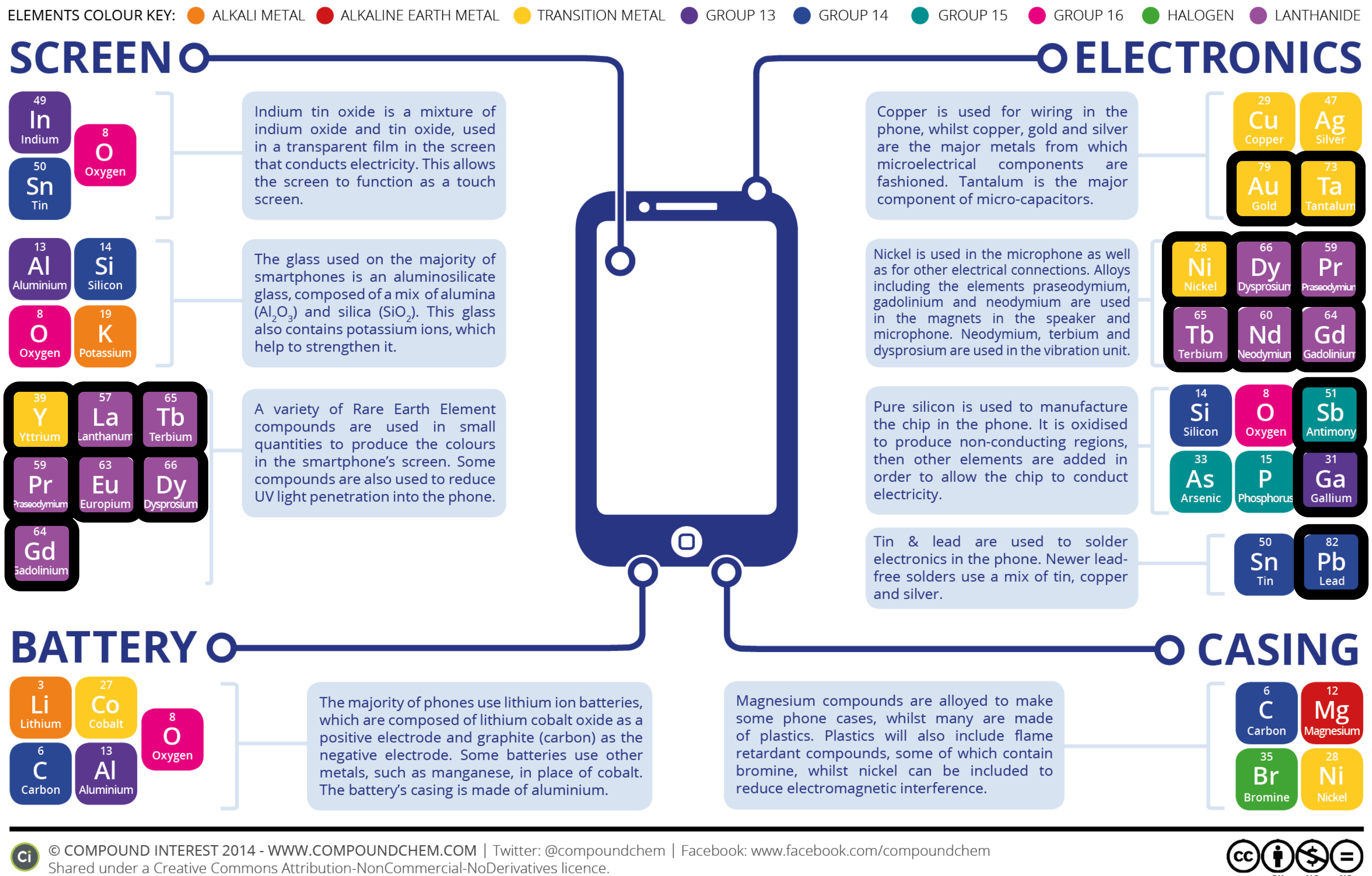
This Resource Letter provides a guide to the literature on the field of nuclear astrophysics, and particularly the origin of the elements. Nuclear astrophysics is a multidisciplinary field that aims at understanding where everything we see around us comes from and how it came to be. Astronomical observations, astrophysics modeling, and nuclear physics experiment and theory come together to answer important questions like: Where and how are the elements created? How do stars evolve? What drives the different types of stellar explosions? What is left behind after the cataclysmic death of a star? This Resource Letter presents our current understanding of the origin of the various chemical elements, together with modern research and new developments in the field, with a particular focus on the measurement of nuclear properties for astrophysical applications.

Where do the iPhone Elements Come From?



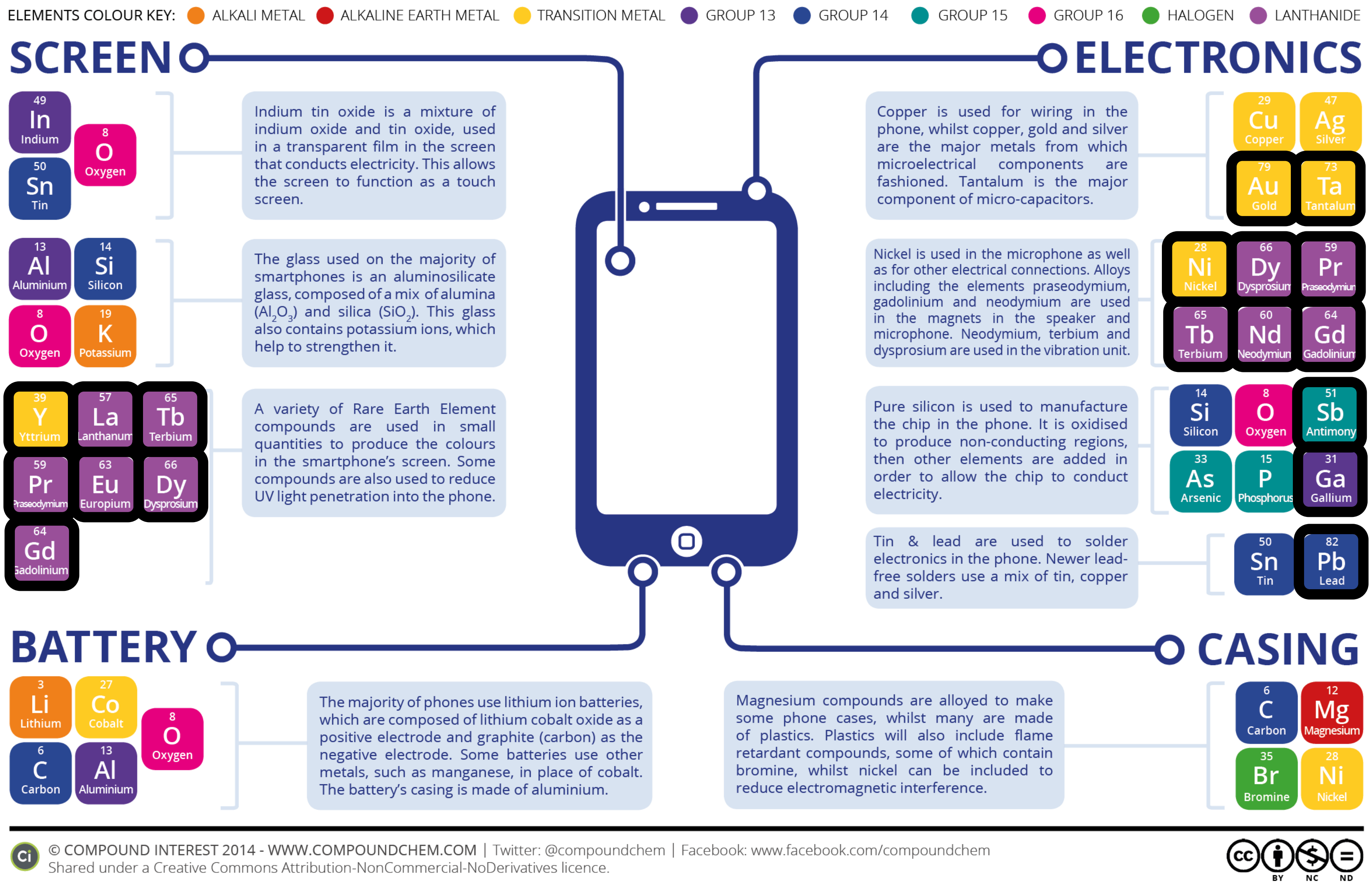
http://www.compoundchem.com/wp-content/uploads/2014/02/The-Chemical-Elements-of-a-Smartphone-v2.png

r-process ("rapid" neutron capture)



http://www.compoundchem.com/wp-content/uploads/2014/02/The-Chemical-Elements-of-a-Smartphone-v2.png

Neutron Capture Time < Radioactive Half-life



http://www.compoundchem.com/wp-content/uploads/2014/02/The-Chemical-Elements-of-a-Smartphone-v2.png

Neutron Star Mergers: Site of the r-process?

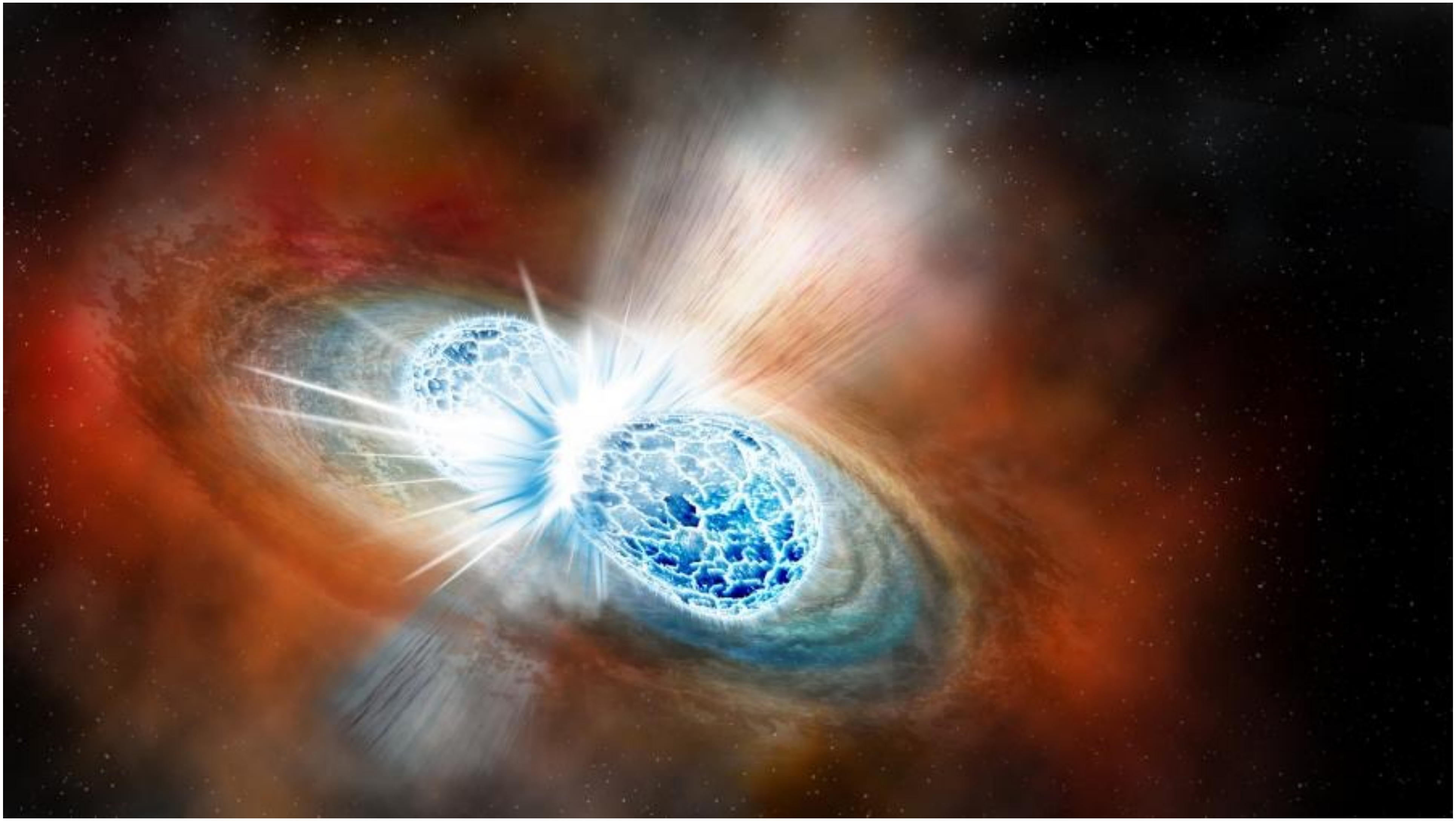
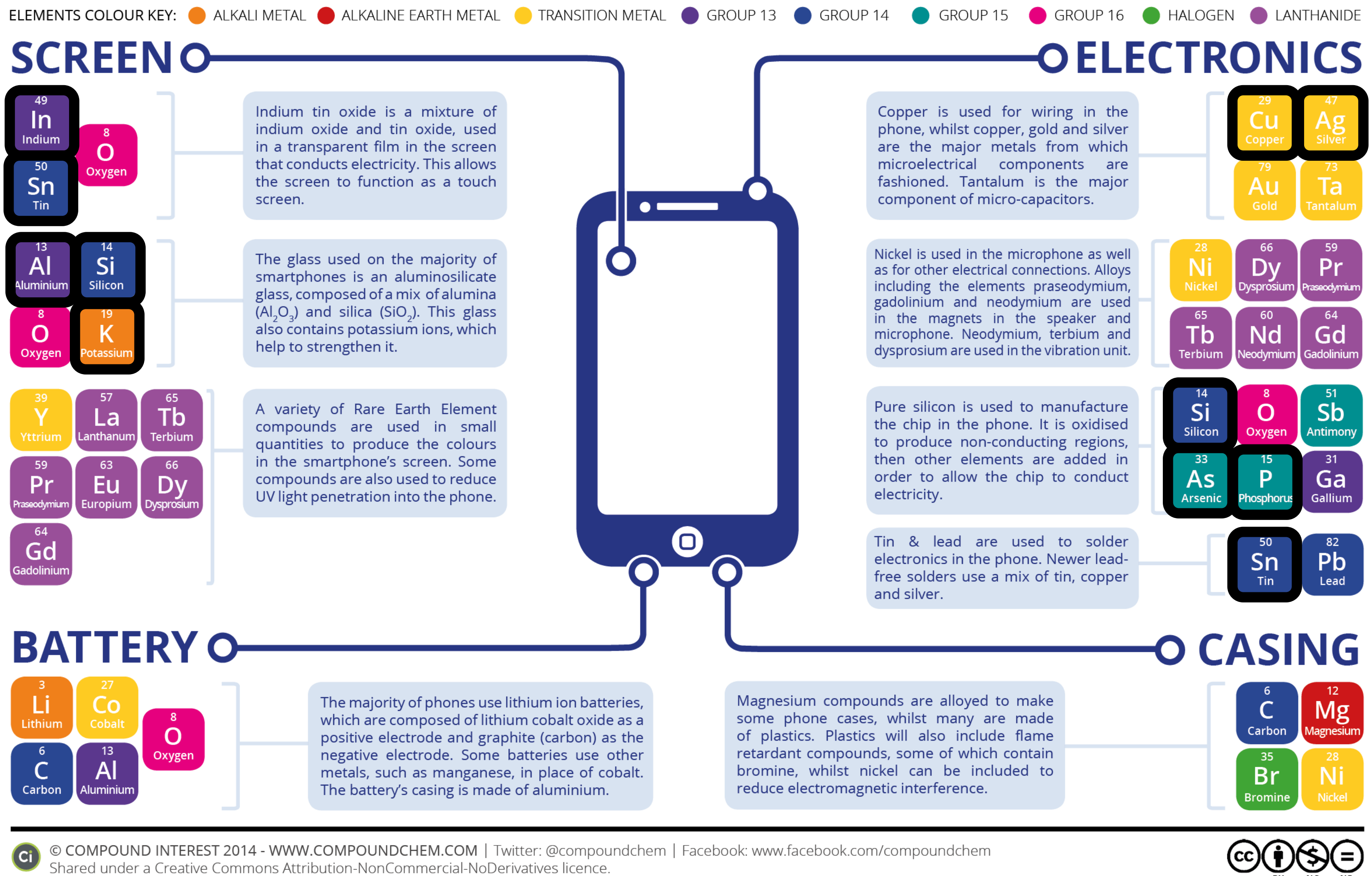


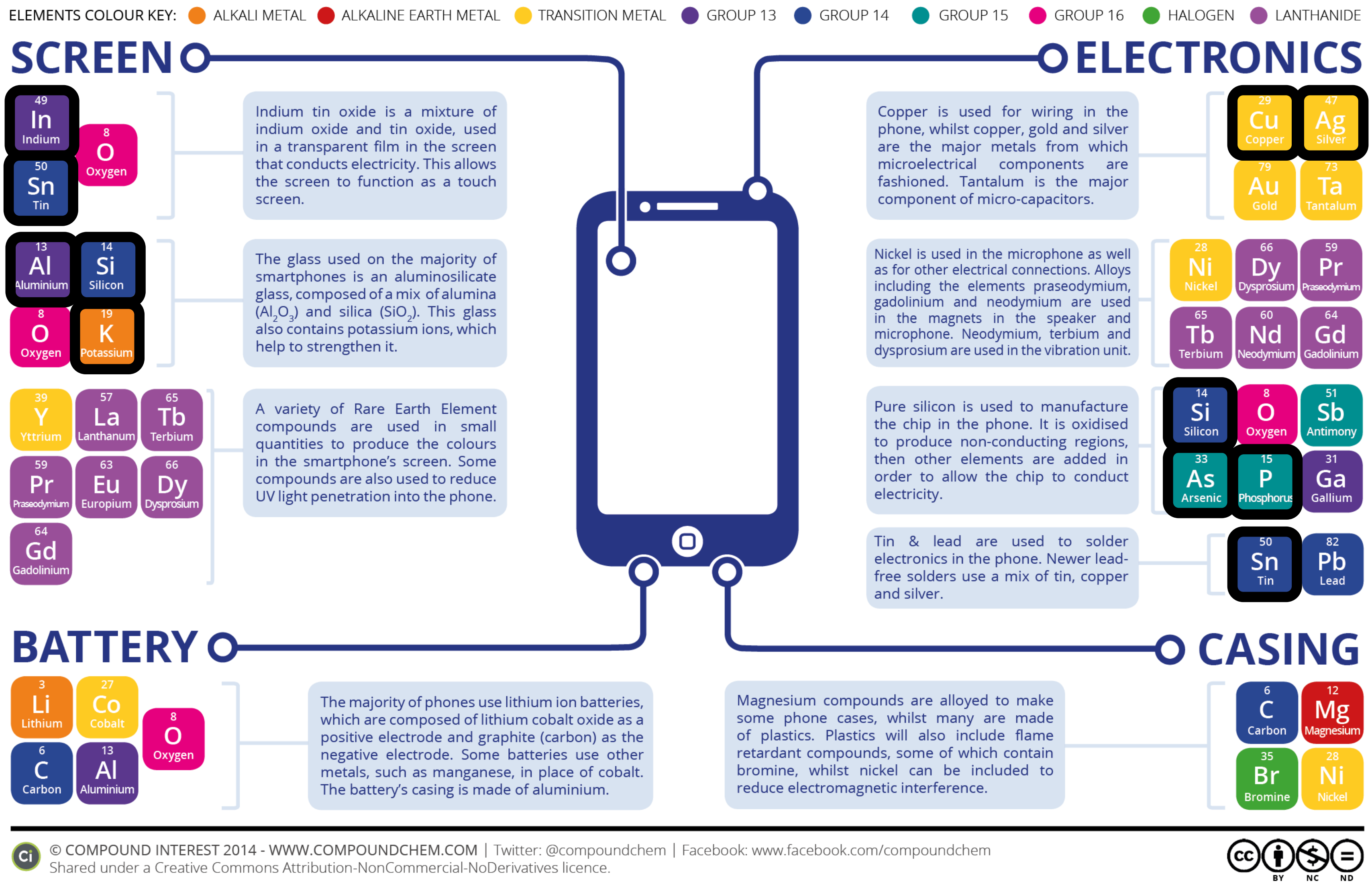
Illustration by Robin Dienel courtesy of the Carnegie Institution for Science.
https://carnegiescience.edu/news/new-era-astronomy-begins-first-ever-observation-two-neutron-stars-colliding

Neutron Capture Time > Radioactive Half-life



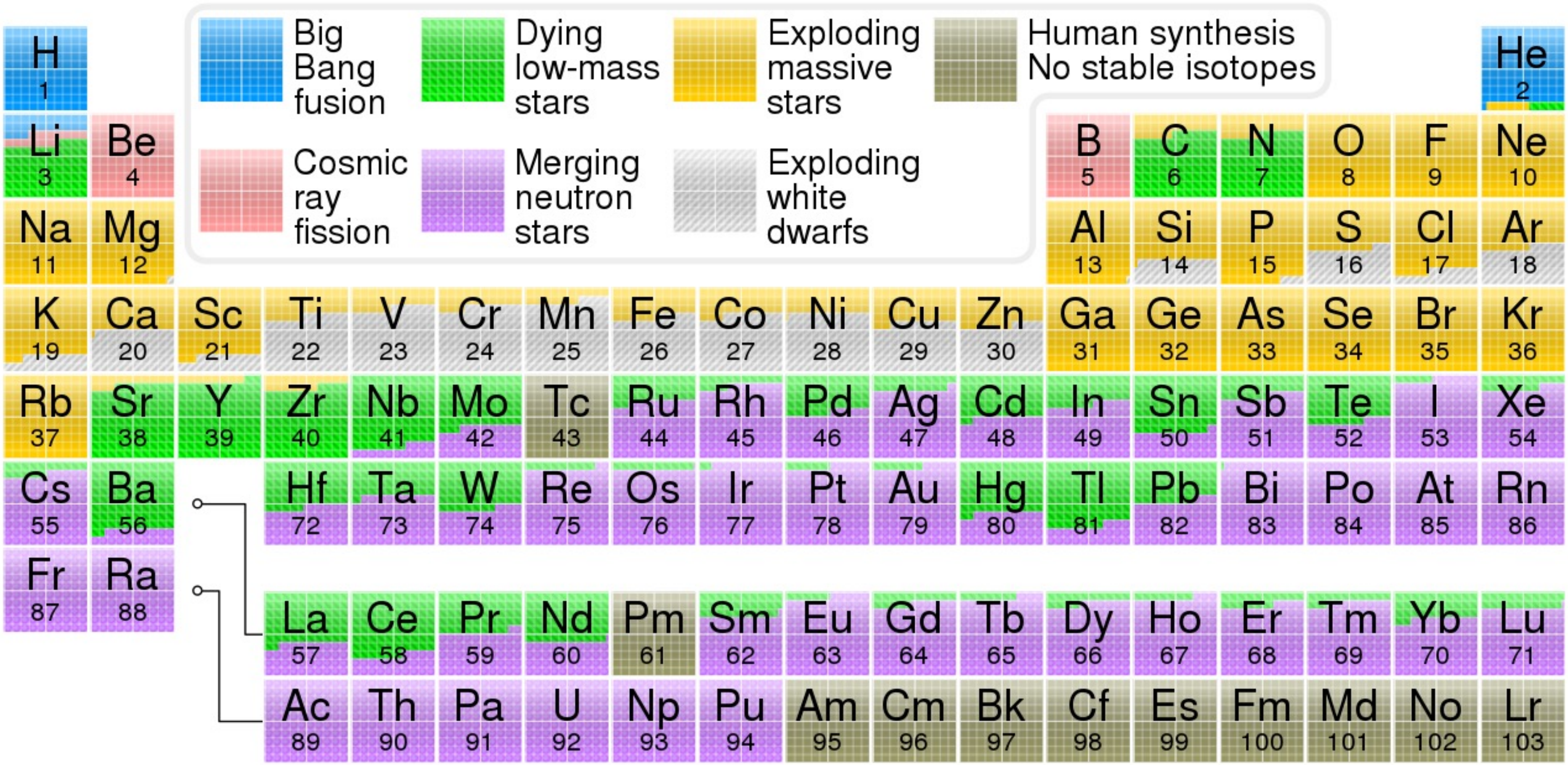
http://www.compoundchem.com/wp-content/uploads/2014/02/The-Chemical-Elements-of-a-Smartphone-v2.png

s-process (“slow” neutron capture)



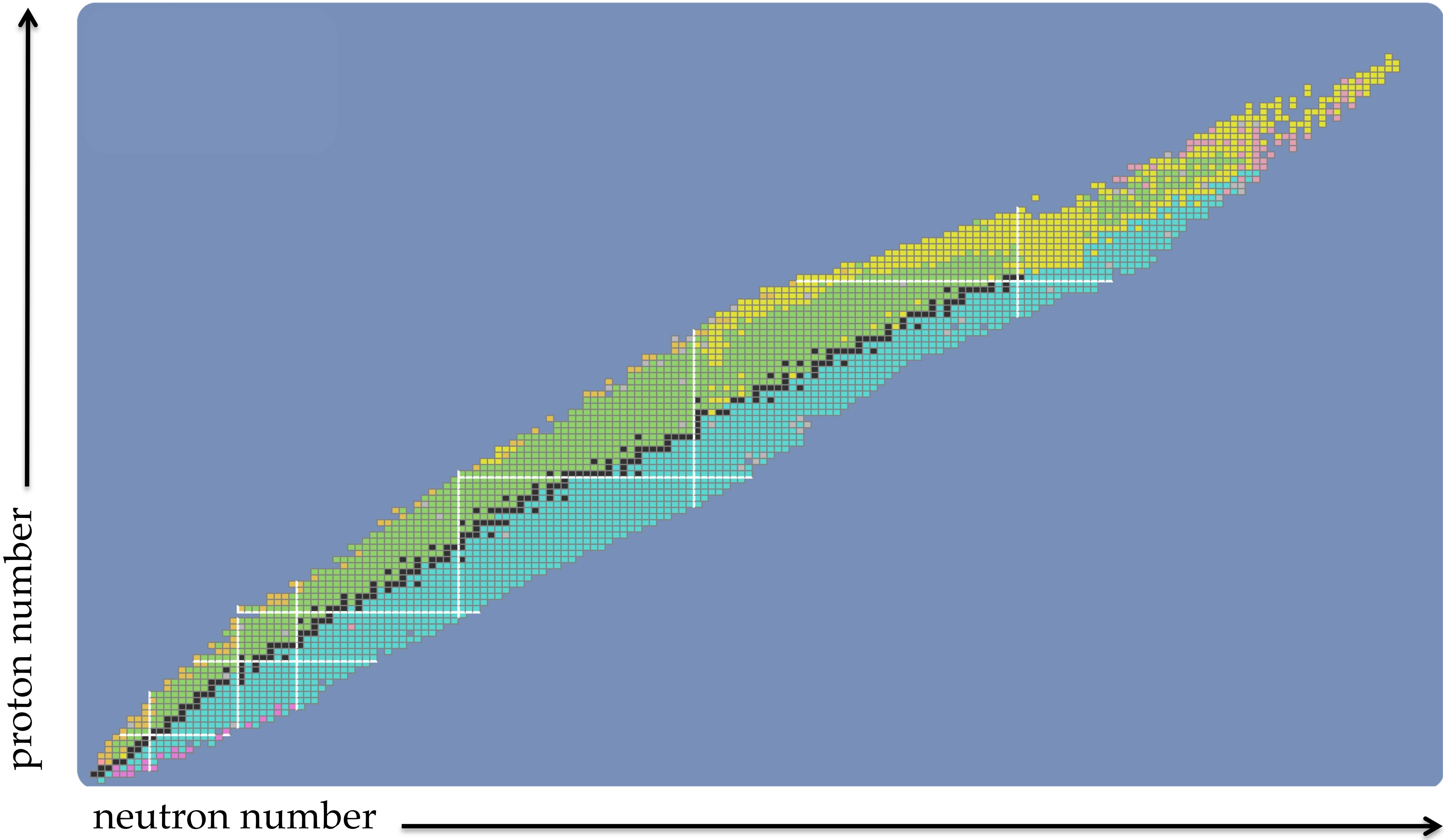
http://www.compoundchem.com/wp-content/uploads/2014/02/The-Chemical-Elements-of-a-Smartphone-v2.png

A Chemist's View of the Periodic Table



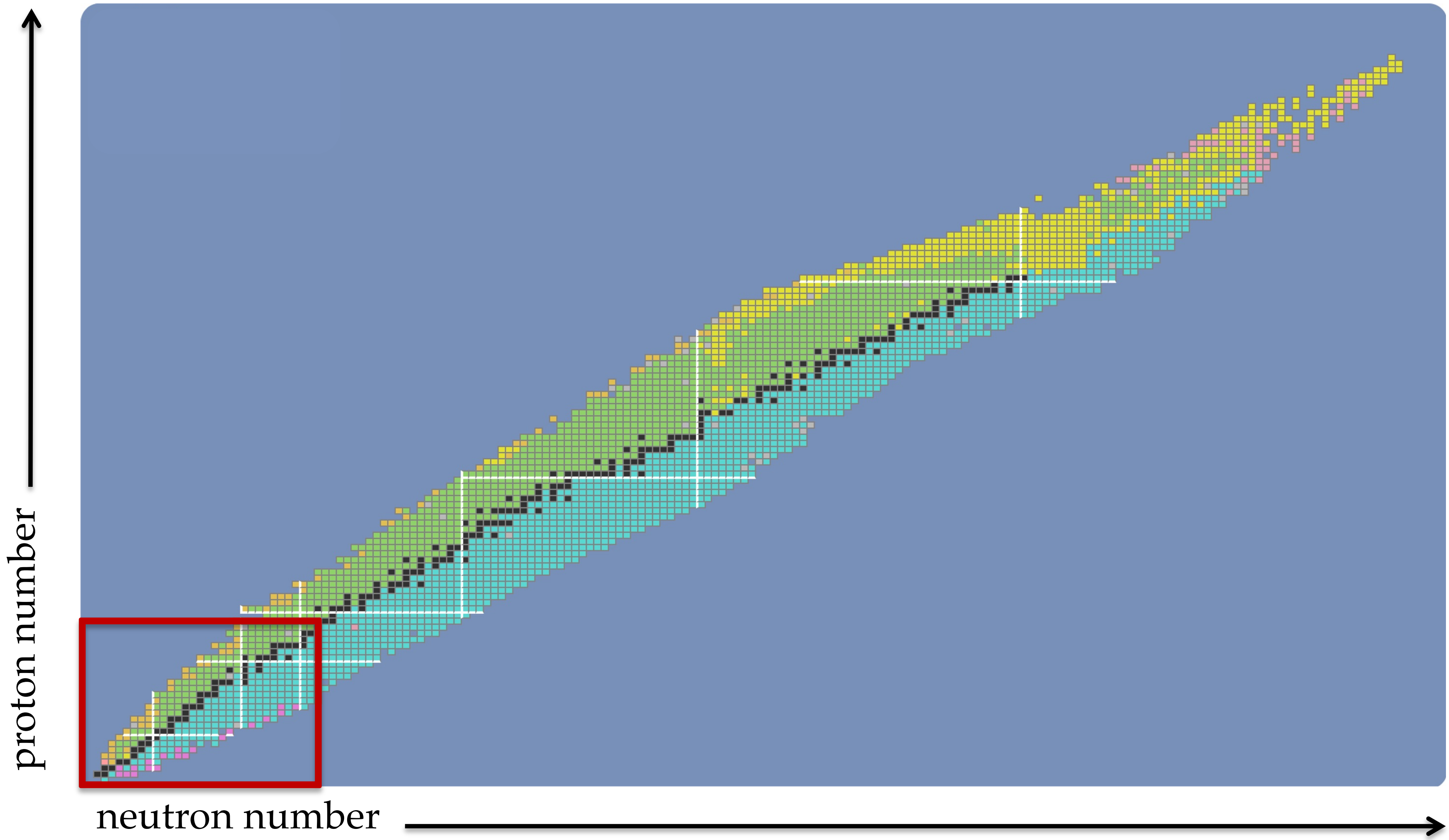
File:Nucleosynthesis periodic table.svg. (2020, March 7). Wikimedia Commons, the free media repository. Retrieved 16:41, May 24, 2020 from https://commons.wikimedia.org/w/index.php?title=File:Nucleosynthesis_periodic_table.svg&oldid=402170545.

A Nuclear Physicist's View of the "Periodic Table"



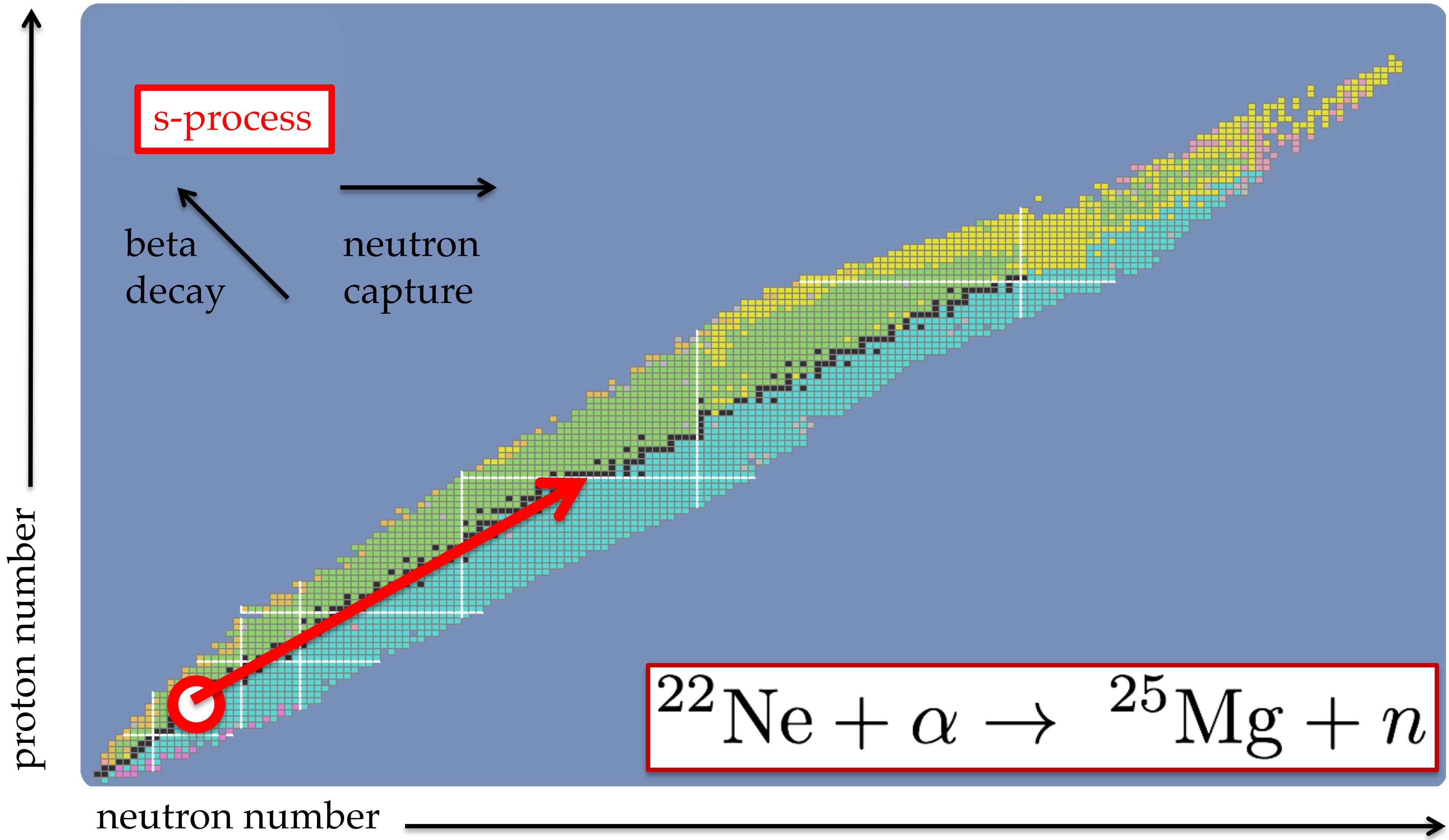
https://www-nds.iaea.org/relnsd/vcharthtml/VChartHTML.html

Nuclear Fusion Reactions Up To About ^{56}Fe



https://www-nds.iaea.org/relnsd/vcharthtml/VChartHTML.html

What is the source of neutrons that drives the "slow" neutron capture process?

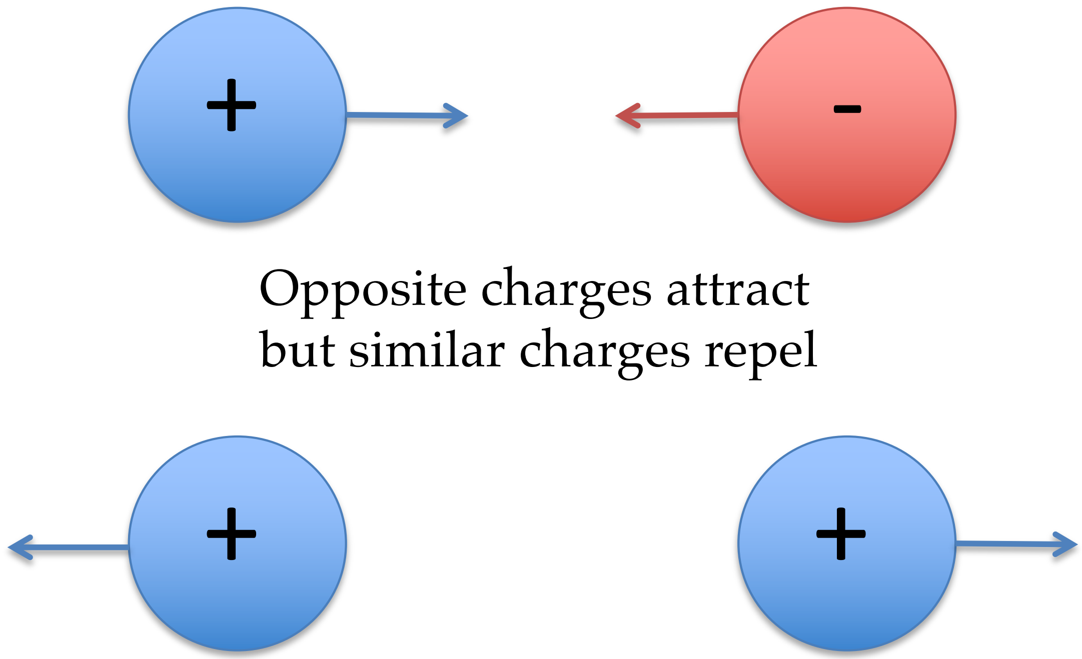


$$^{22}Ne + \alpha \rightarrow \ ^{25}Mg + n$$

https://www-nds.iaea.org/relnsd/vcharthtml/VChartHTML.html

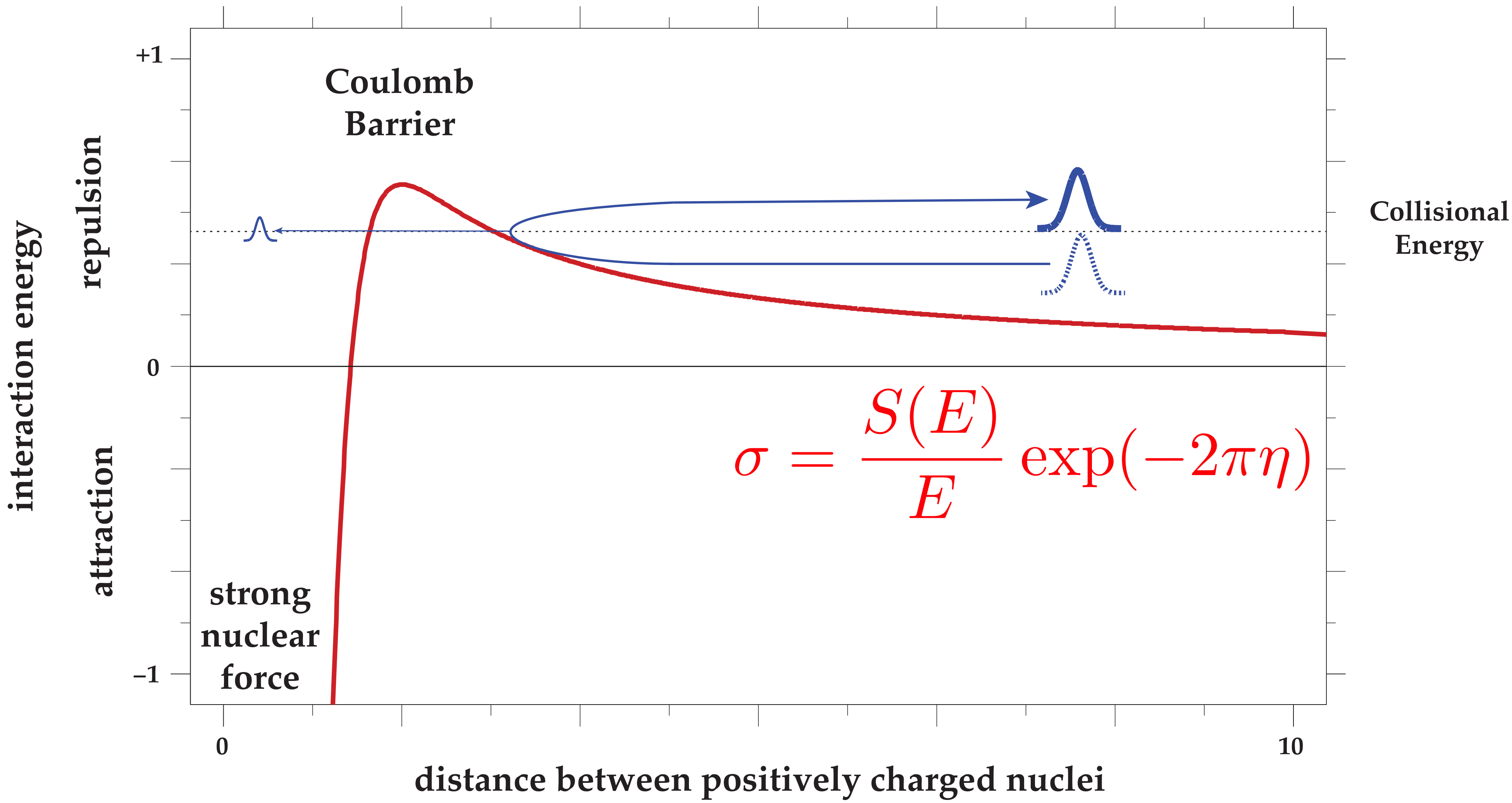
"Rate Determining Step"

$$^{22}\mathrm{Ne} + \alpha \rightarrow \ ^{25}\mathrm{Mg} + n$$



Opposite charges attract
but similar charges repel

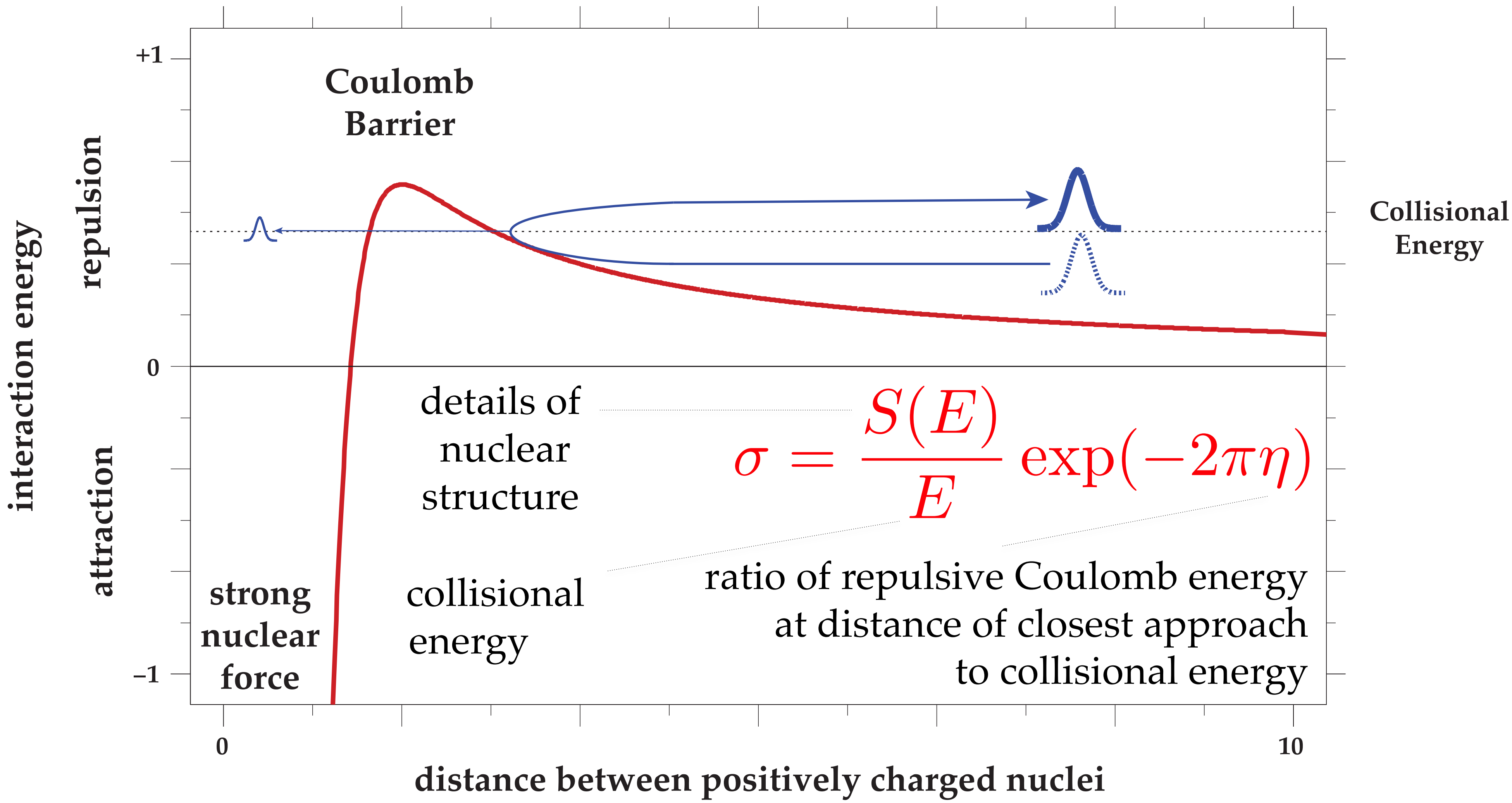
Fusion Reaction is Unlikely Due To “Coulomb Barrier”



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

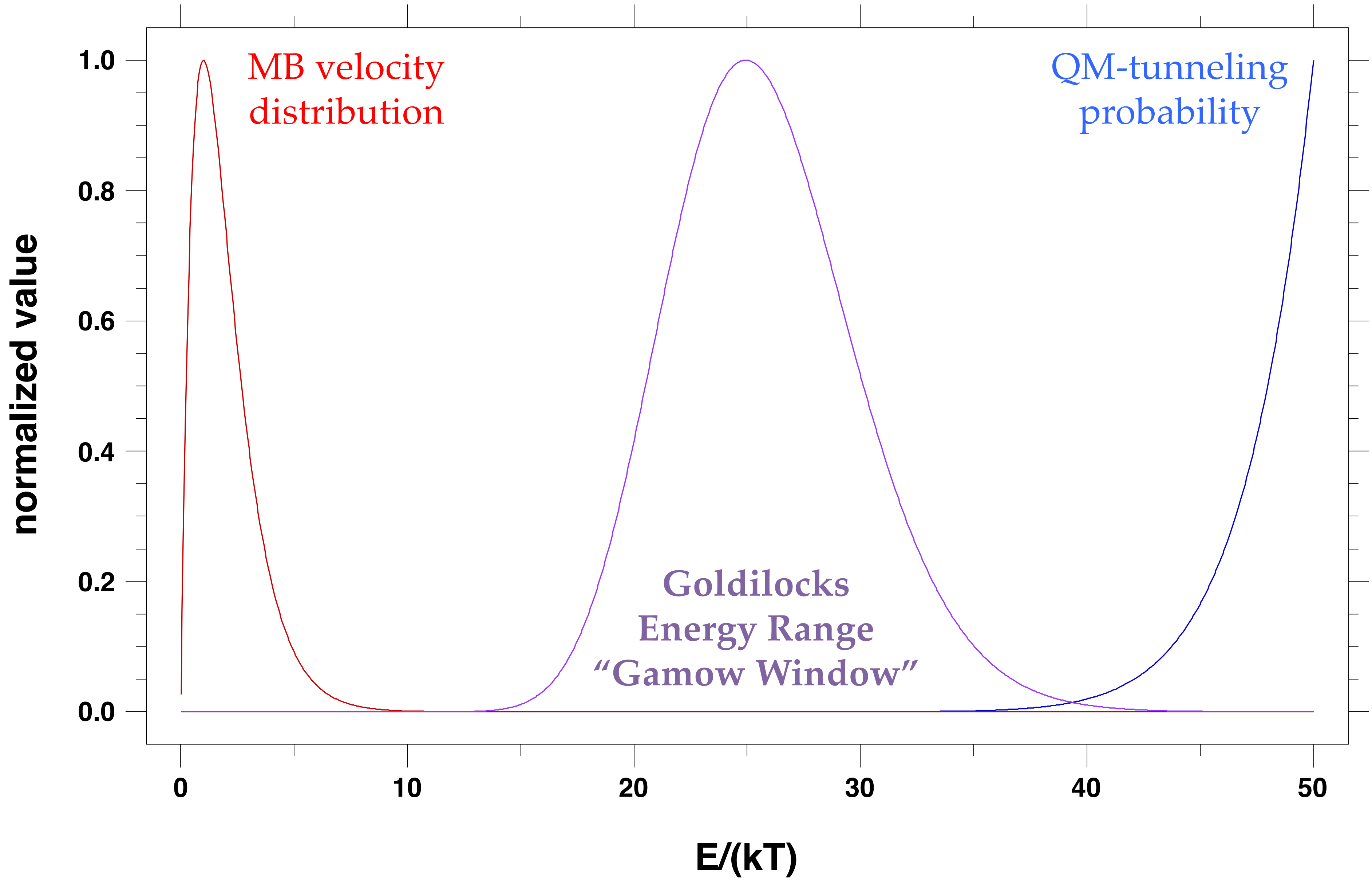
In the quantum mechanical picture, the positively charged nuclei repel each other but are able to interact via “Tunneling.”

Reaction is Unlikely Due To “Coulomb Barrier”

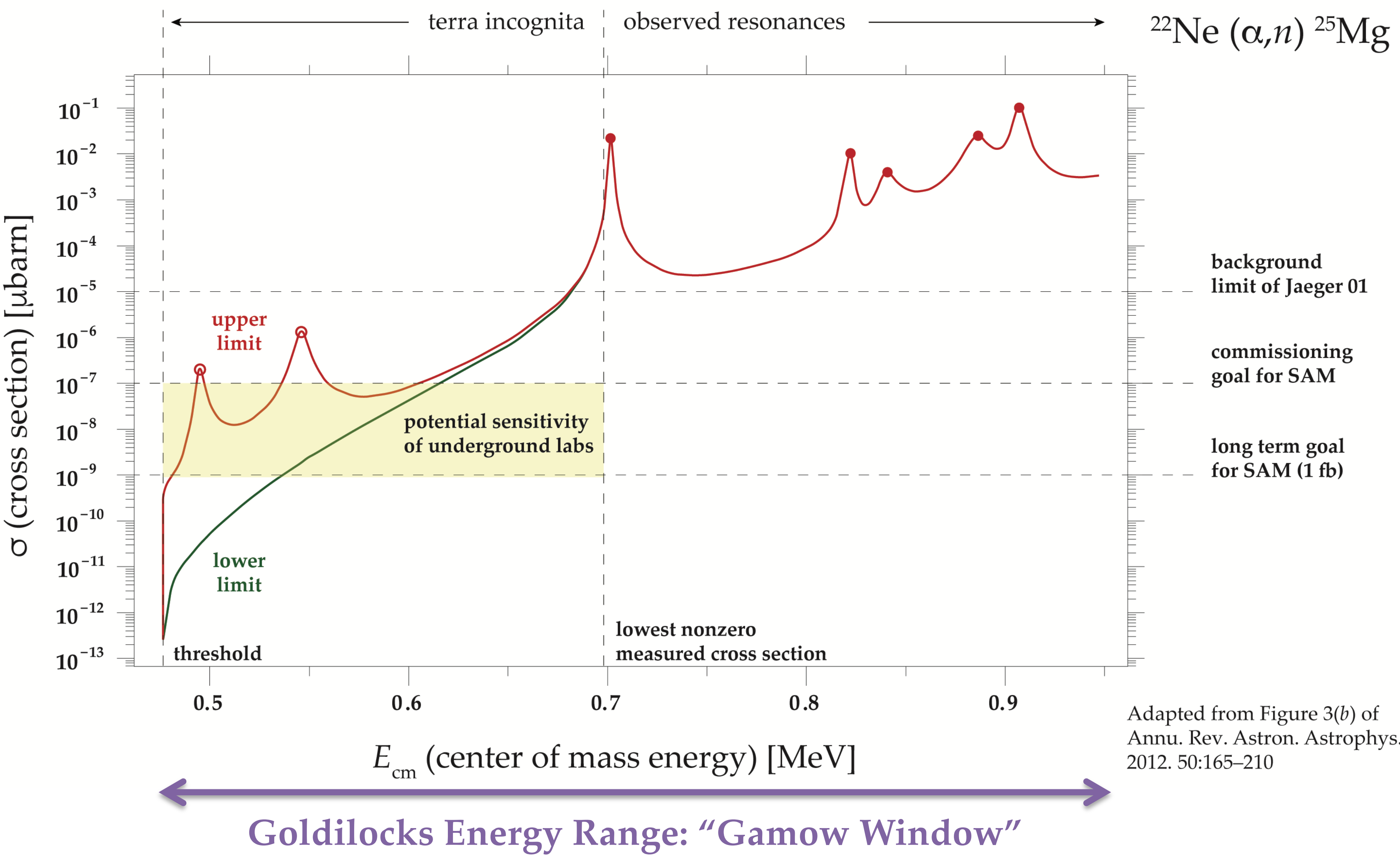


In the quantum mechanical picture, the positively charged nuclei repel each other but are able to interact via “Tunneling.”

Collisional Energy = Temperature of Star

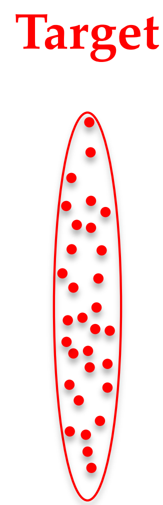


^{22}Ne+^{4}He: Key Source of Neutrons for s-Process



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

What do we mean by “measure”?



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

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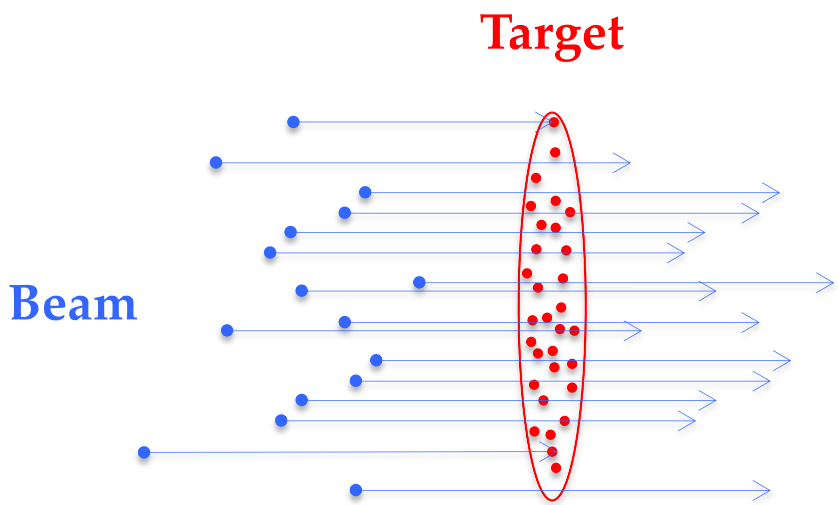

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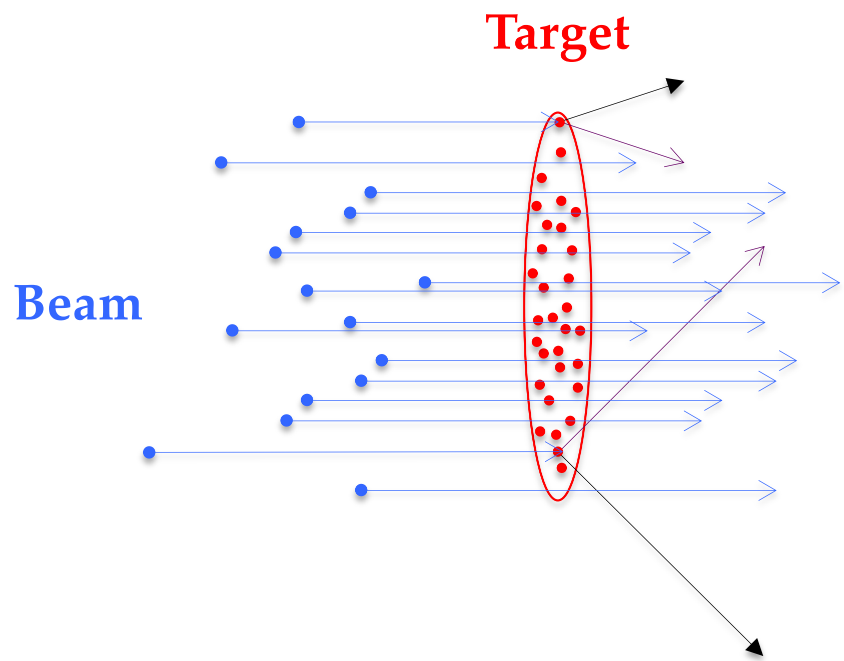

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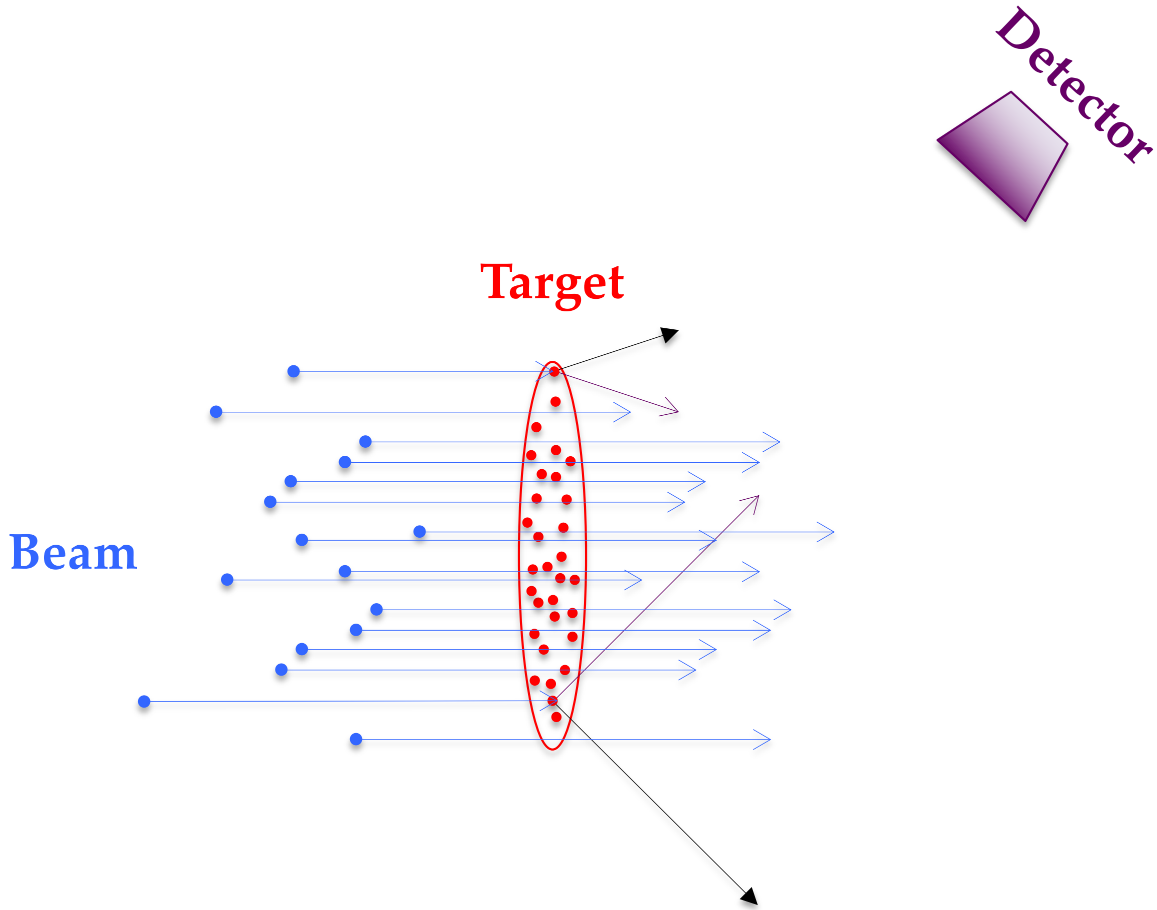

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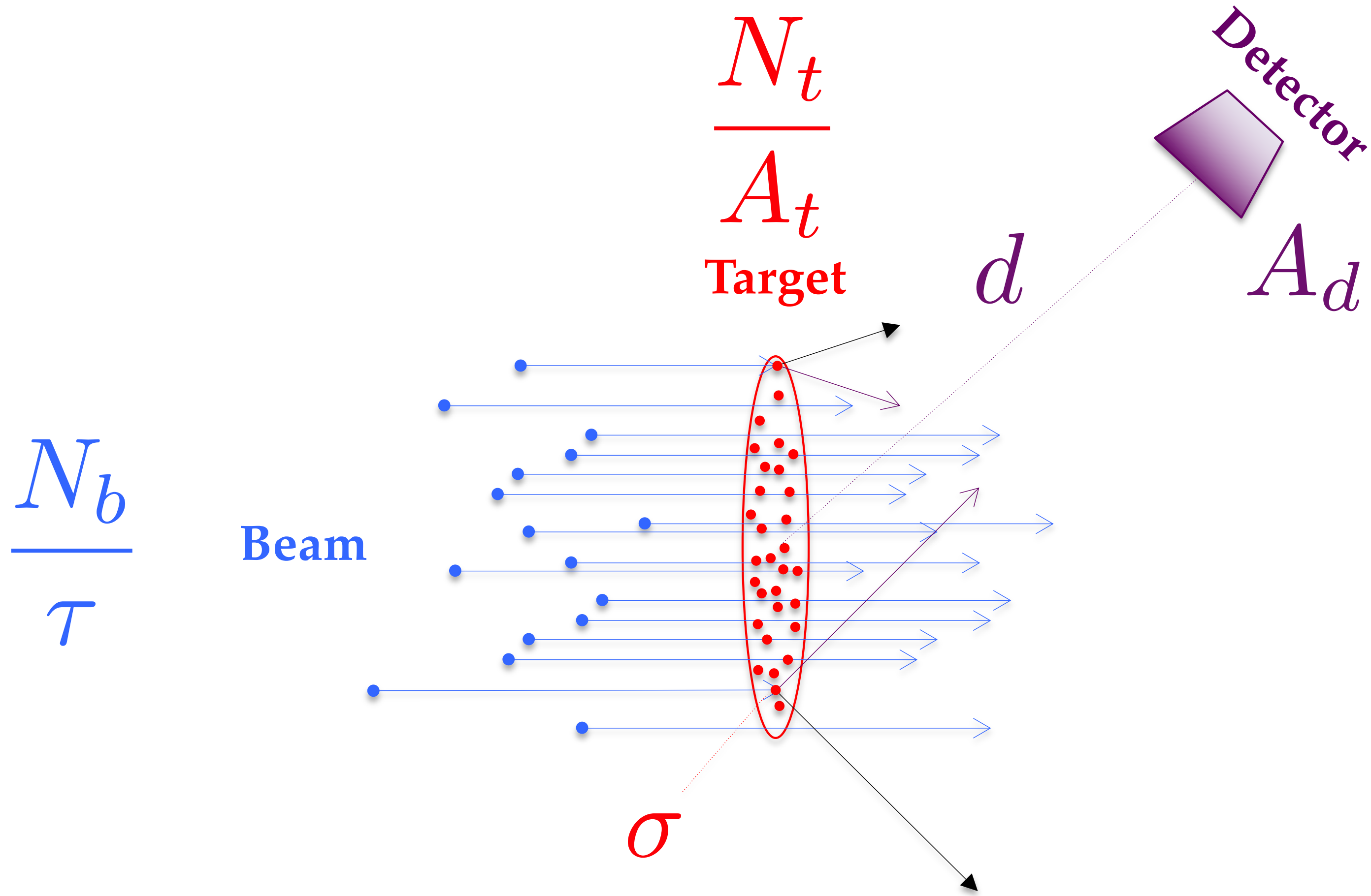
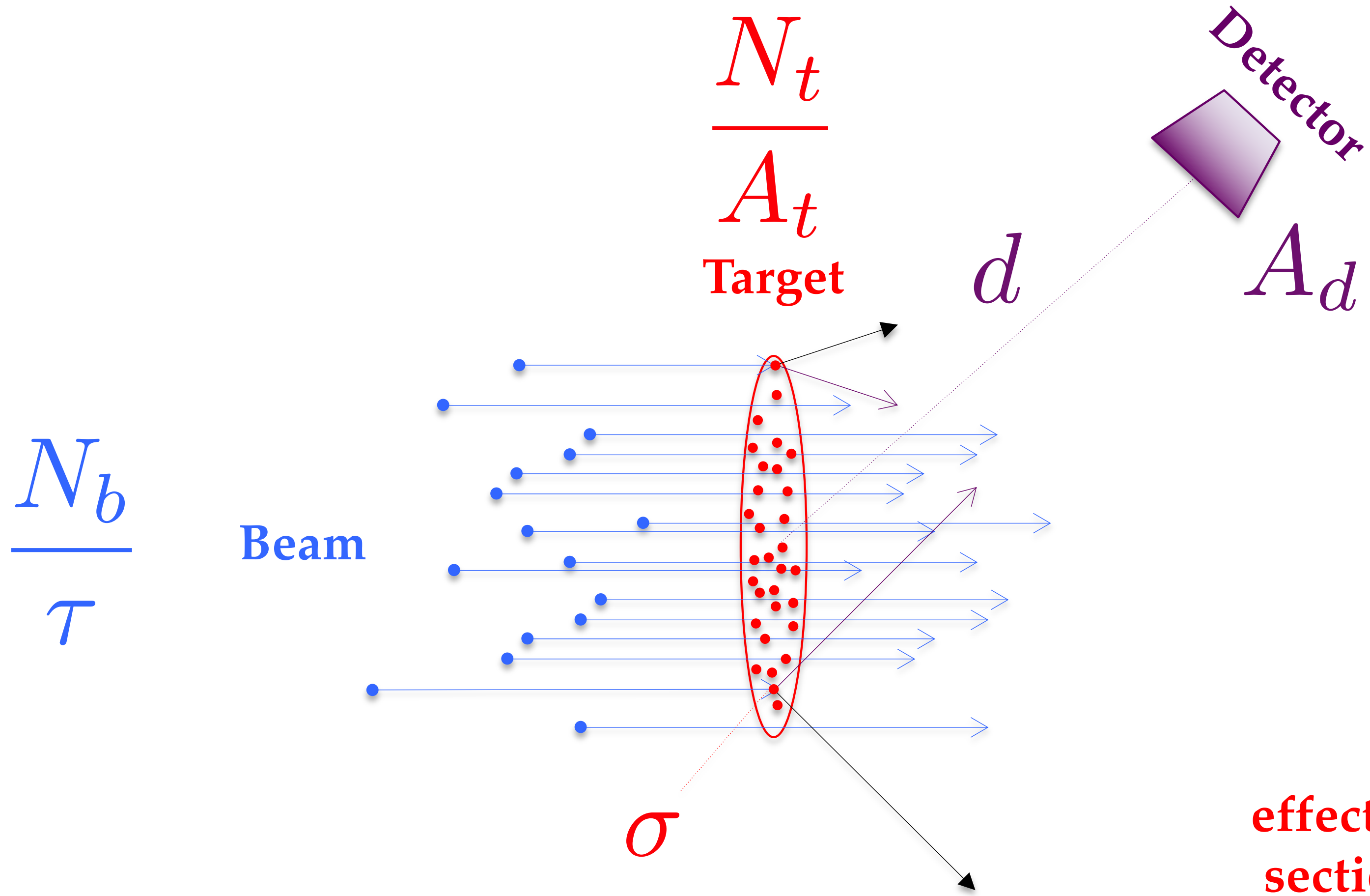


$$N_d = \tau \left(\frac{N_b}{\tau}\right)\left(\frac{N_t \sigma}{A_t}\right)\left(\frac{A_d}{4\pi d^2}\right)$$

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

What do we mean by “measure”?

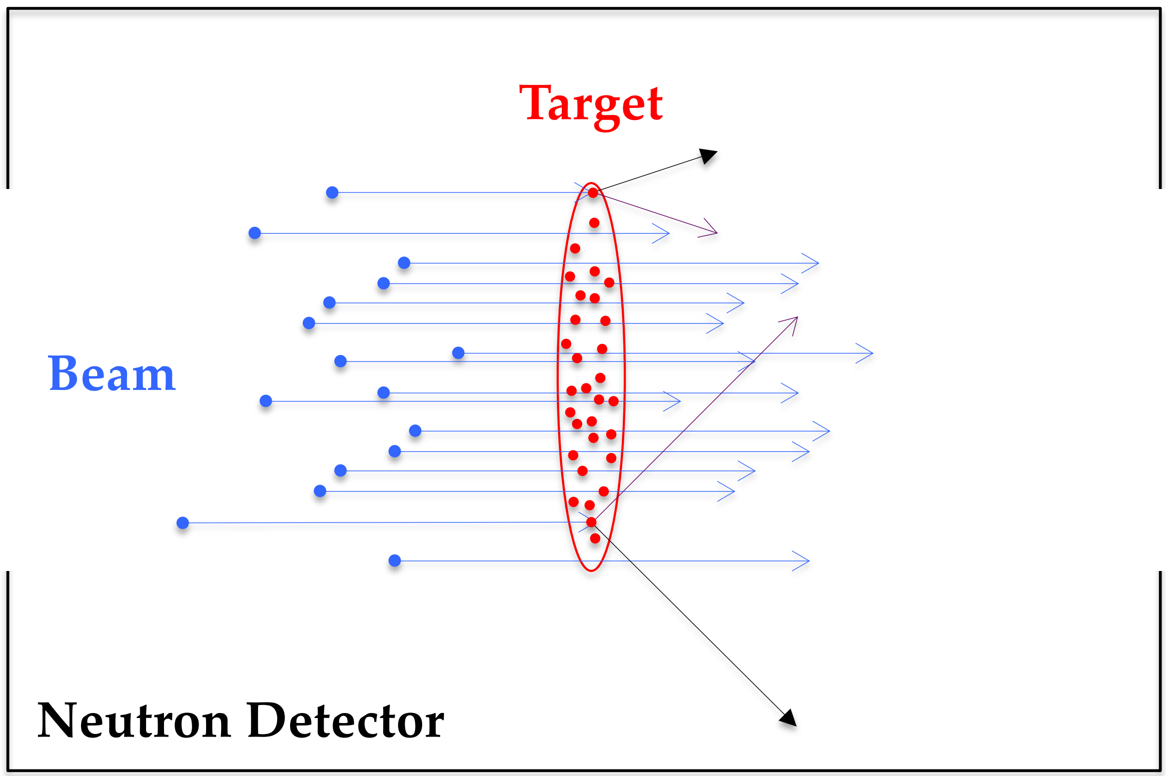


$$\sigma = \left(\frac{N_d}{N_b}\right)\left(\frac{A_t}{N_t}\right)\left(\frac{4\pi d^2}{A_d}\right) =$$

effective cross sectional area or scattering cross section

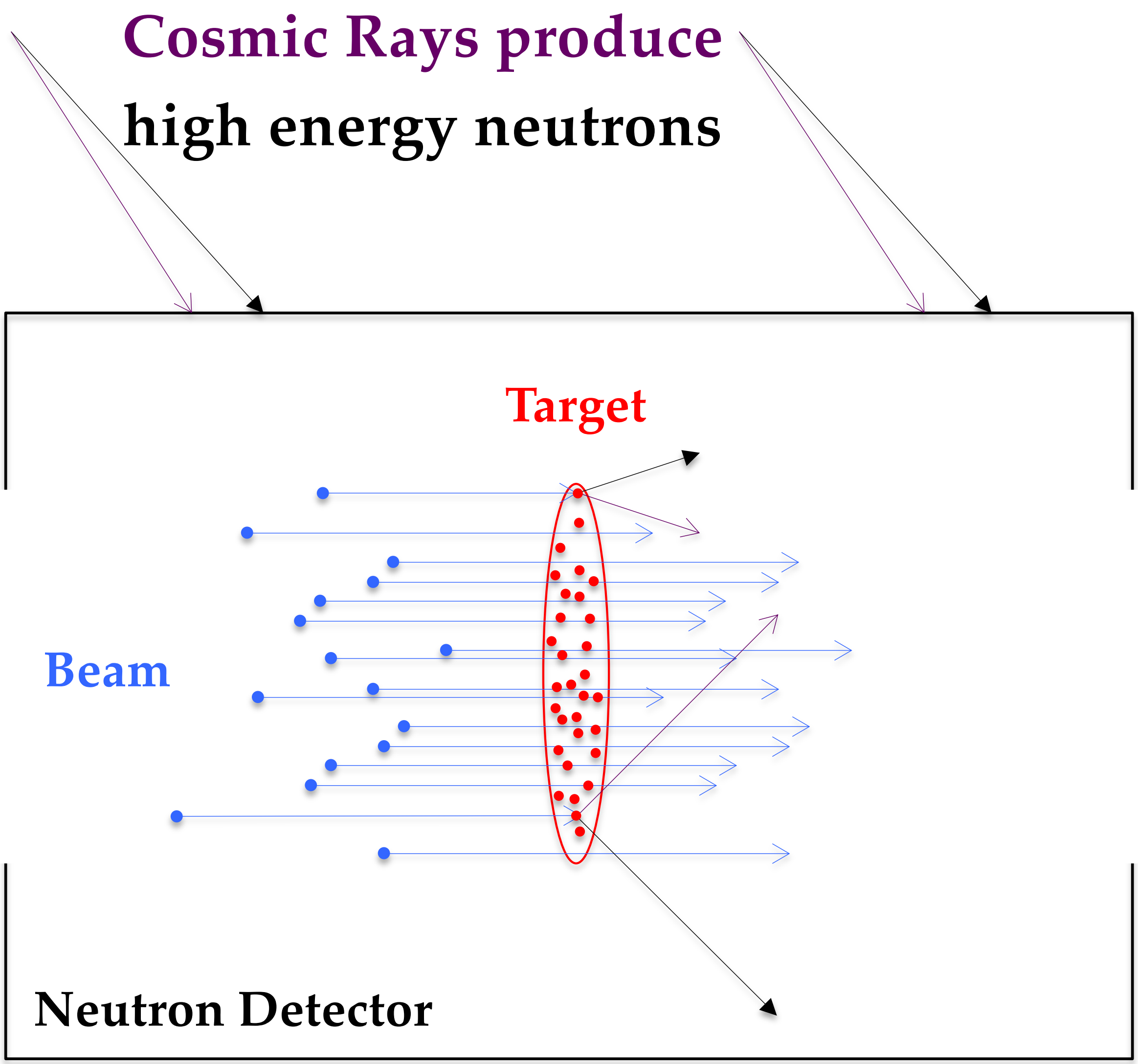
We want to measure the likelihood that the reaction will happen.

The Old Method: Count the Neutrons



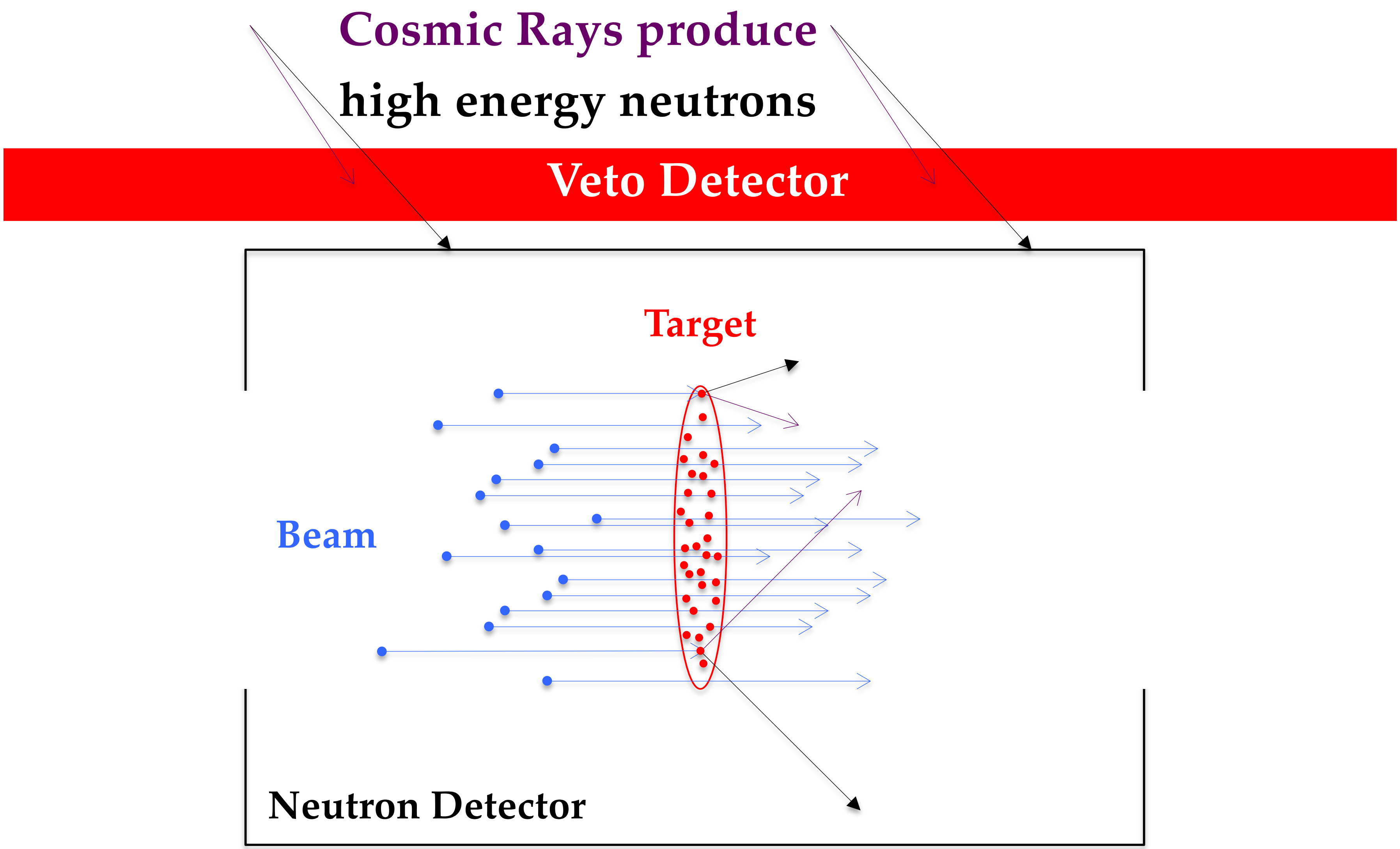
Detecting neutrons is very difficult – you lose all information about the energy of the neutron.

Bad: Cosmic Ray Induced Neutron Background



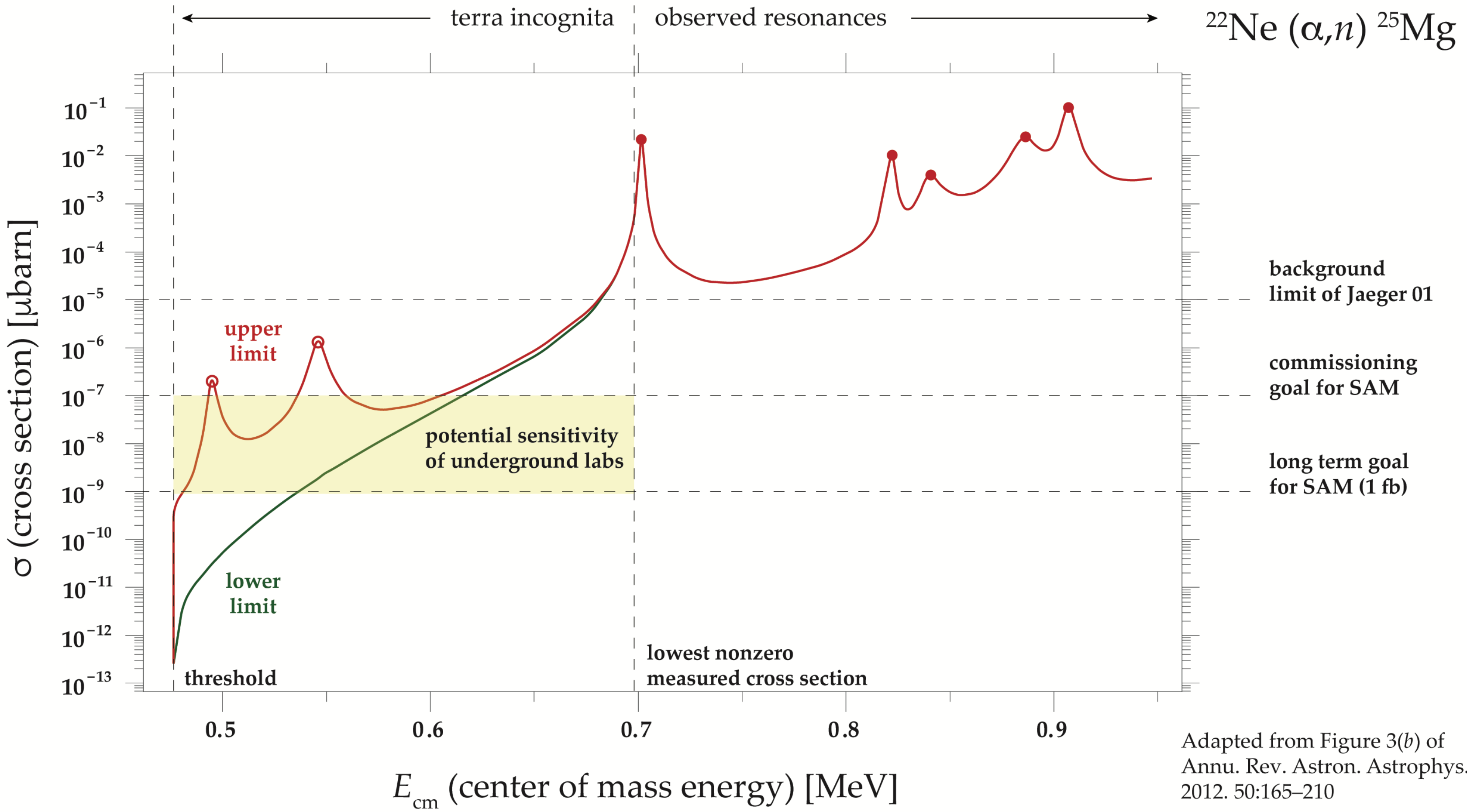
Detecting neutrons is very difficult – you lose all information about the energy of the neutron.

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



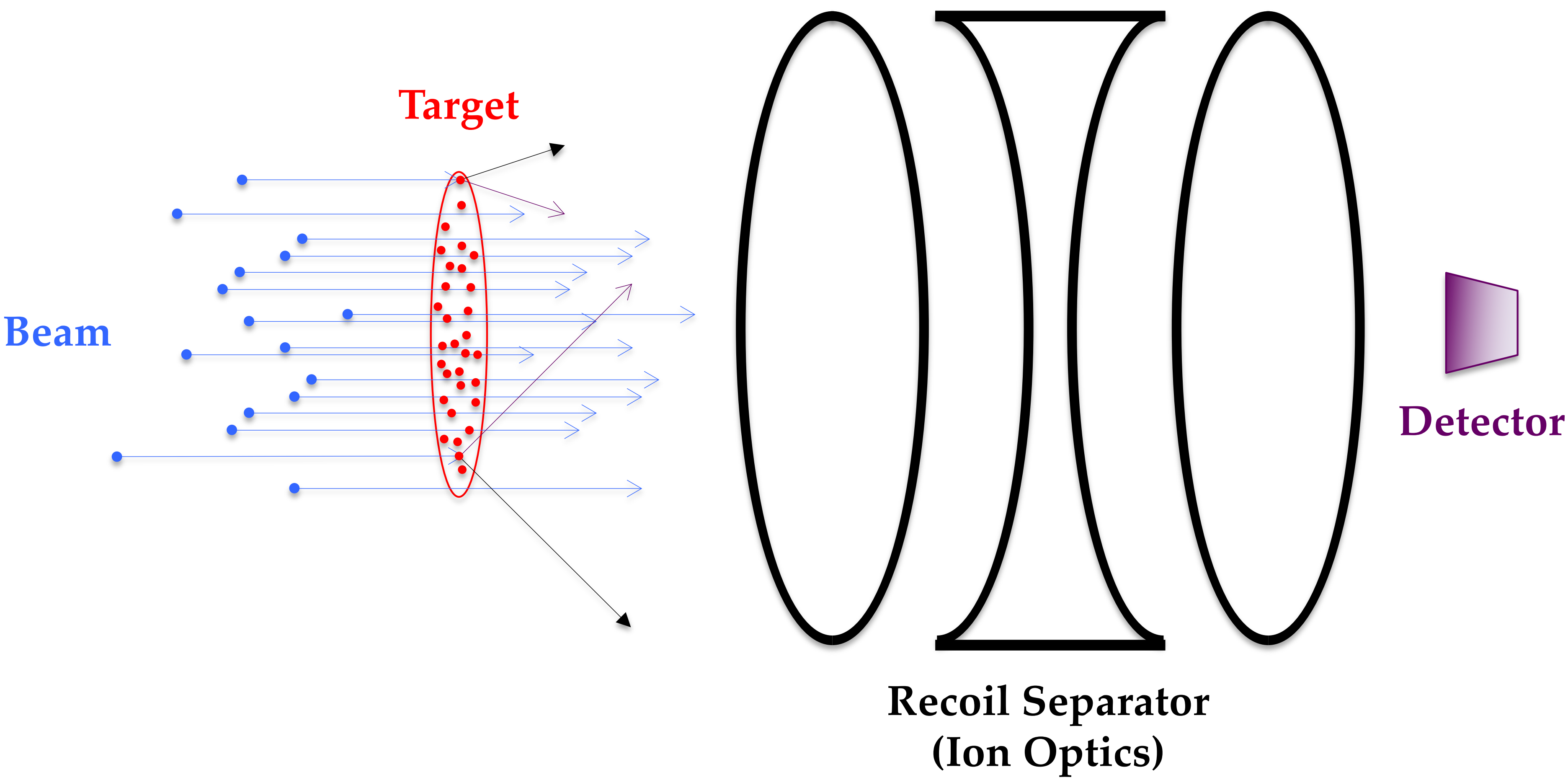
Adapted from Figure 3(*b*) of Annu. Rev. Astron. Astrophys. 2012. 50:165–210

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

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

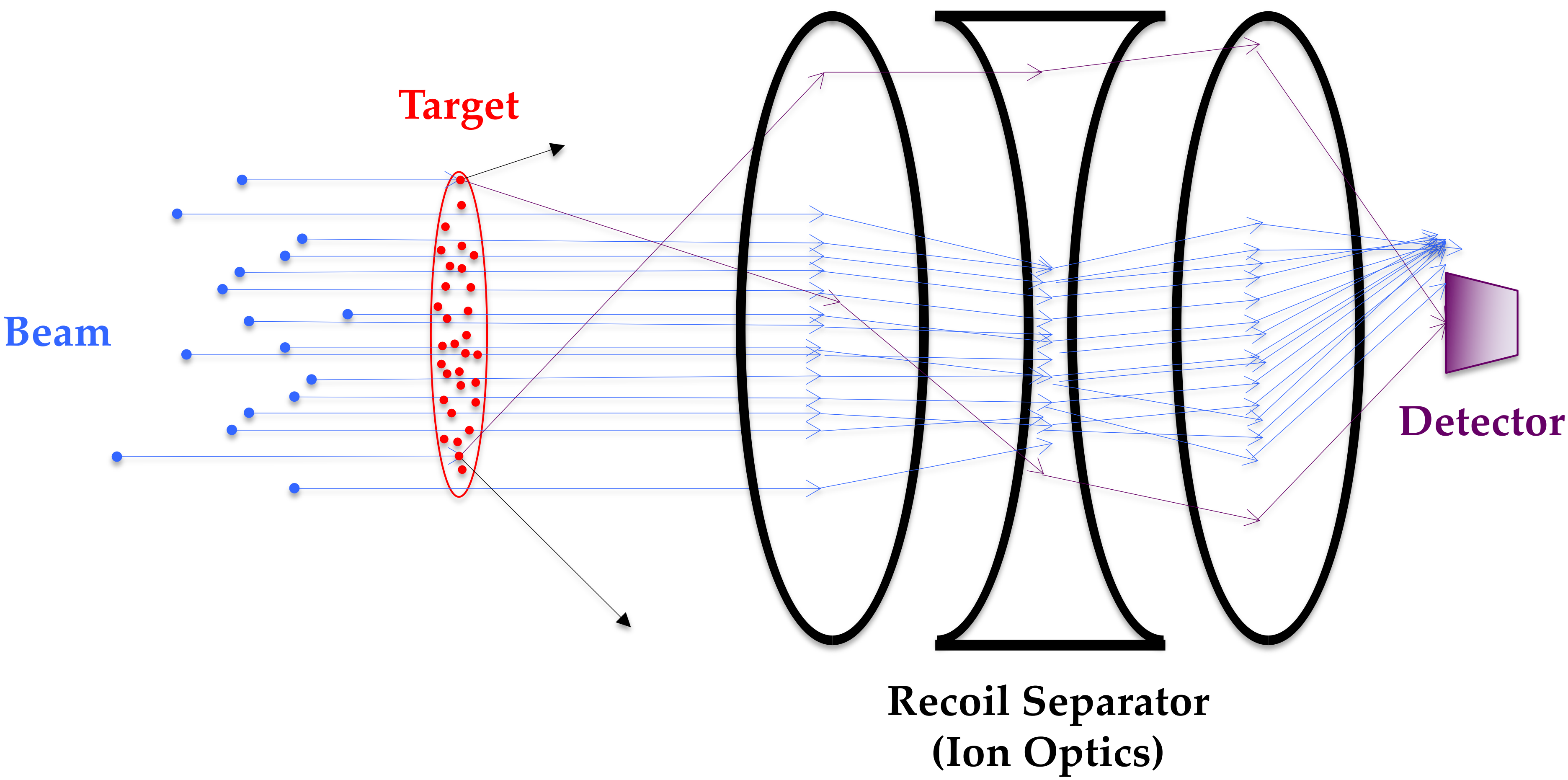
$$(1\ \text{fb})\left(10^{19}/\text{cm}^2\right)(2.1\ \text{mA}) = 7/\text{day}$$

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



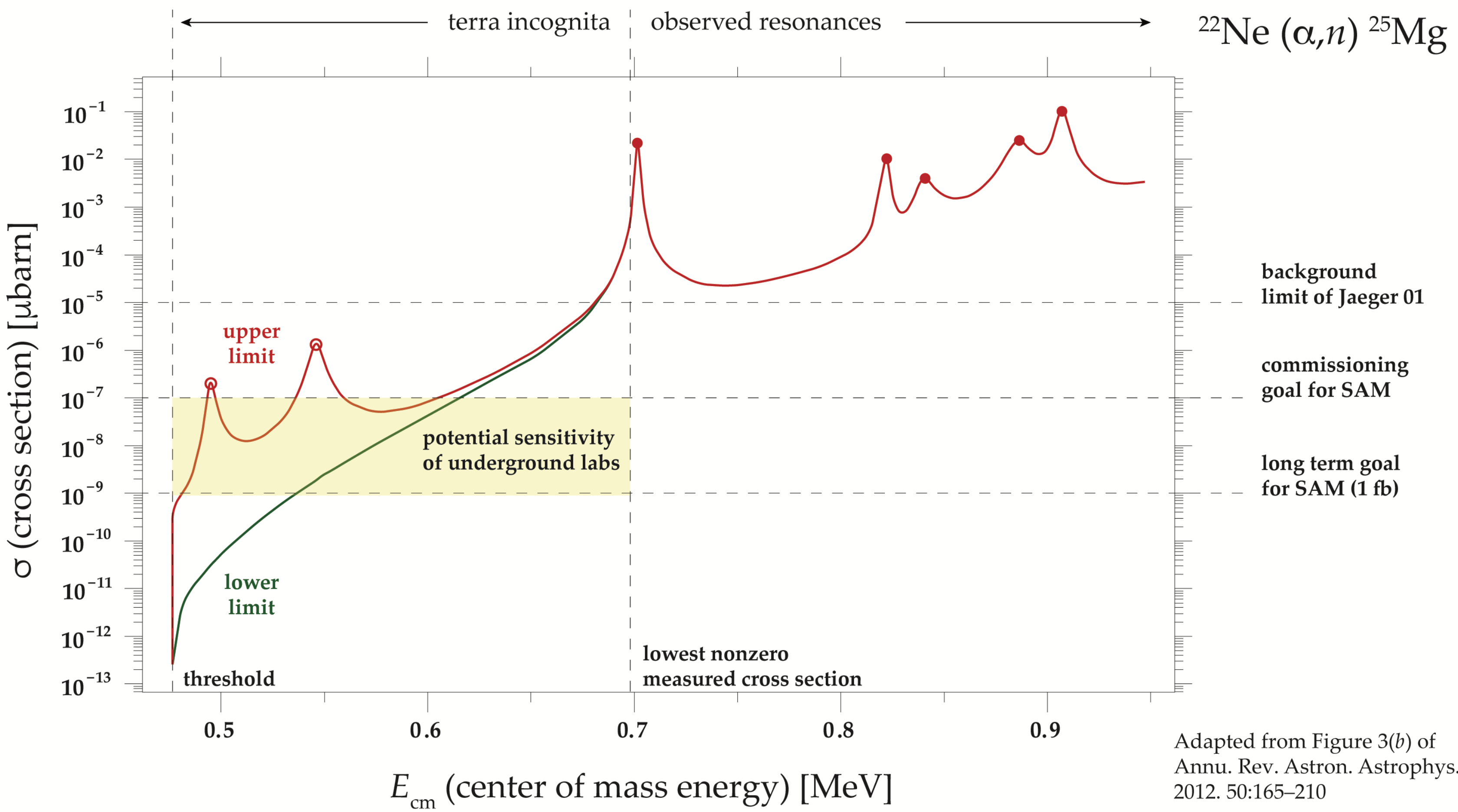
Electromagnetic recoil separator collects all of the products, separates them from the beam, and ***counts everything that makes it through***.

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!

Towards Sub-Picobarn Cross Section Sensitivity



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

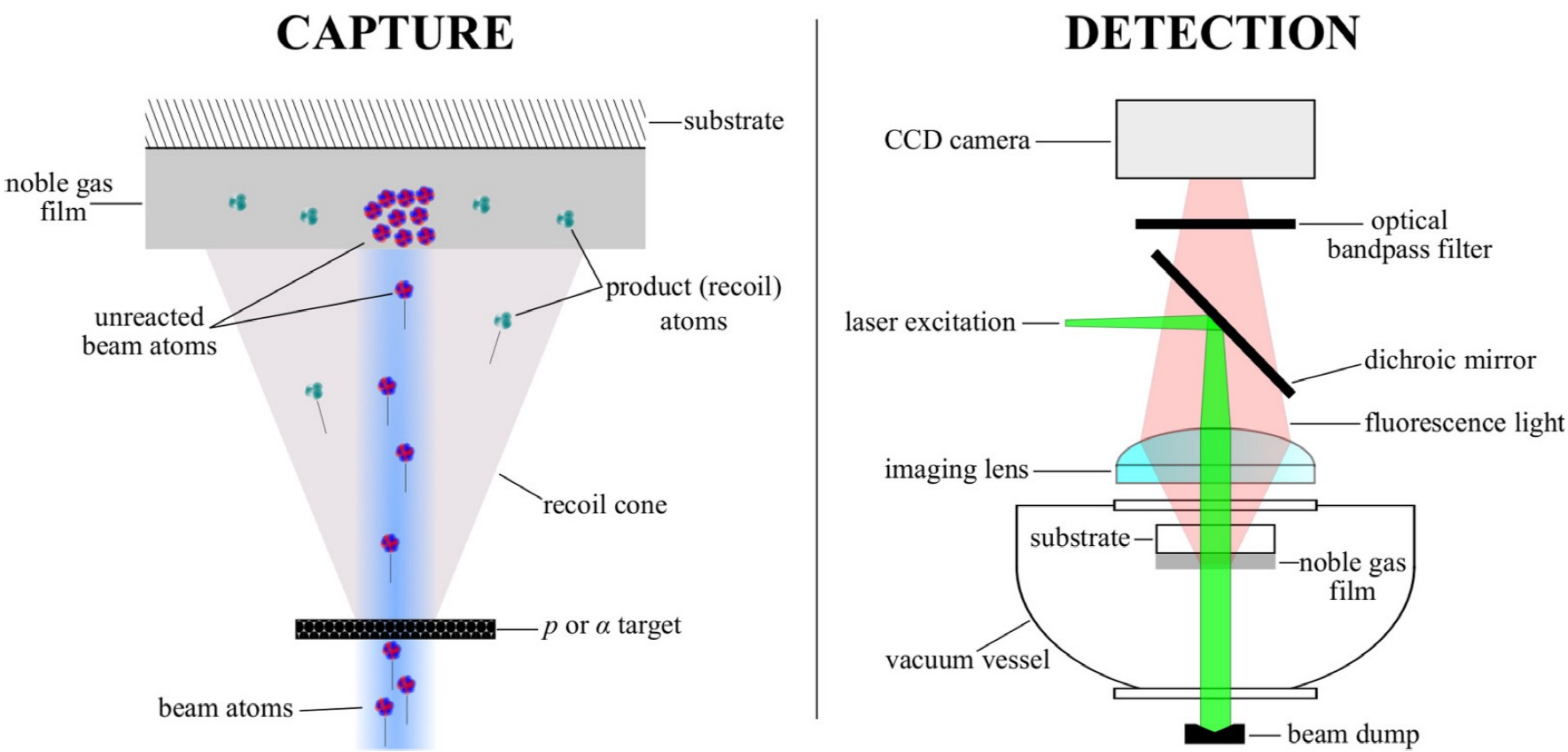
Underground labs are expected to have a factor of 100 or less background.

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

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

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

Single Atom Microscope Concept



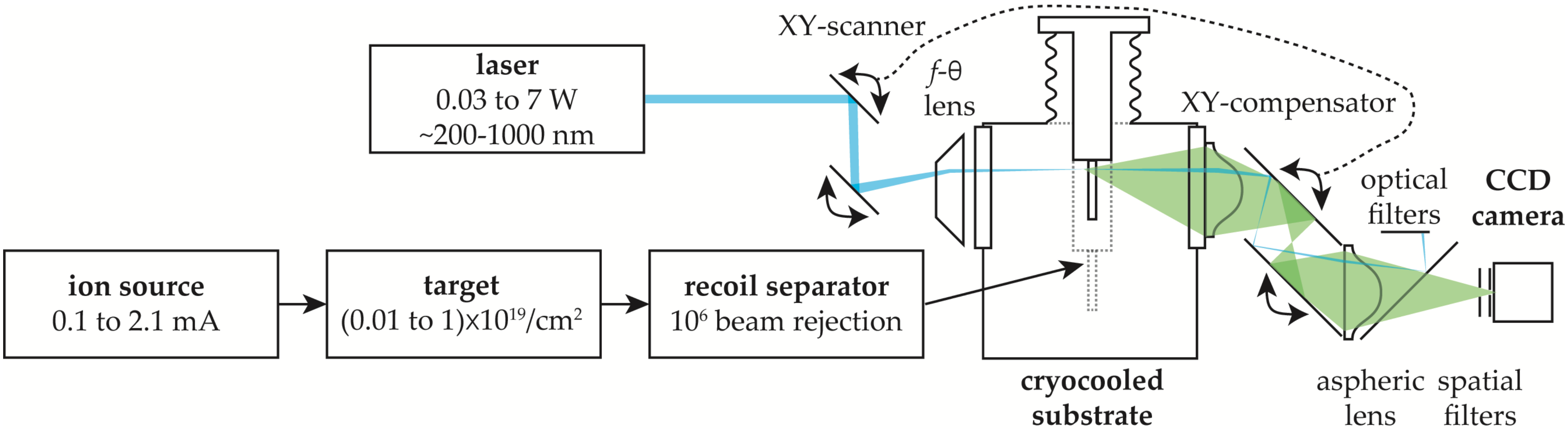
PRC 99, 065805 (2019)

Inspired directly from Ba-tagging concept for ν0ββ:

Moe PRC 44 R931(R) (1991)

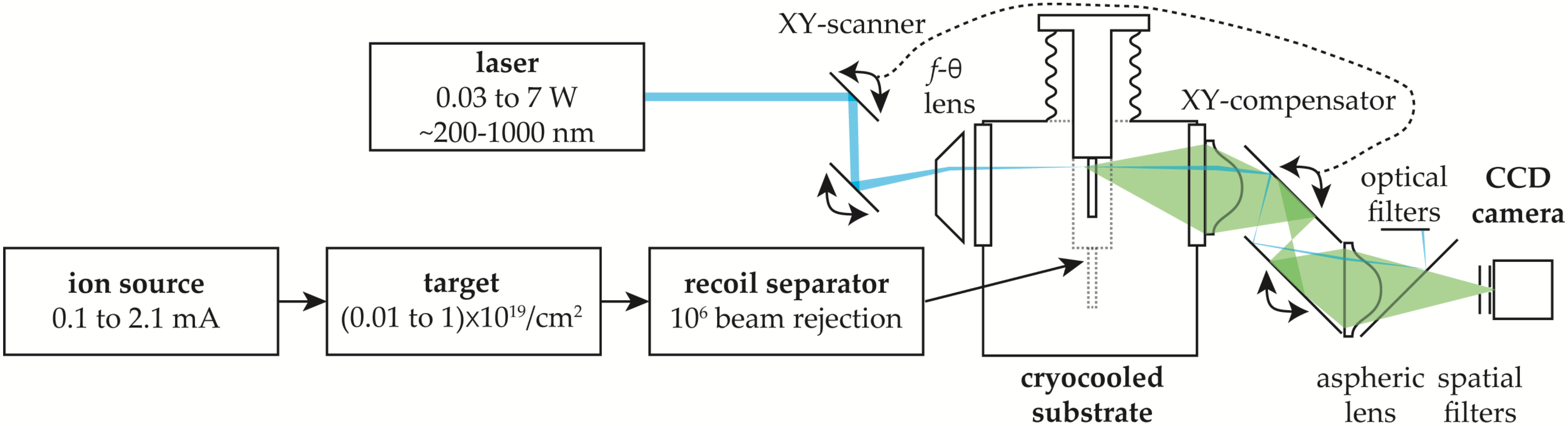
Chambers et al. Nature 569 p203 (2019)

Efficiency: Capture Every Product Atom



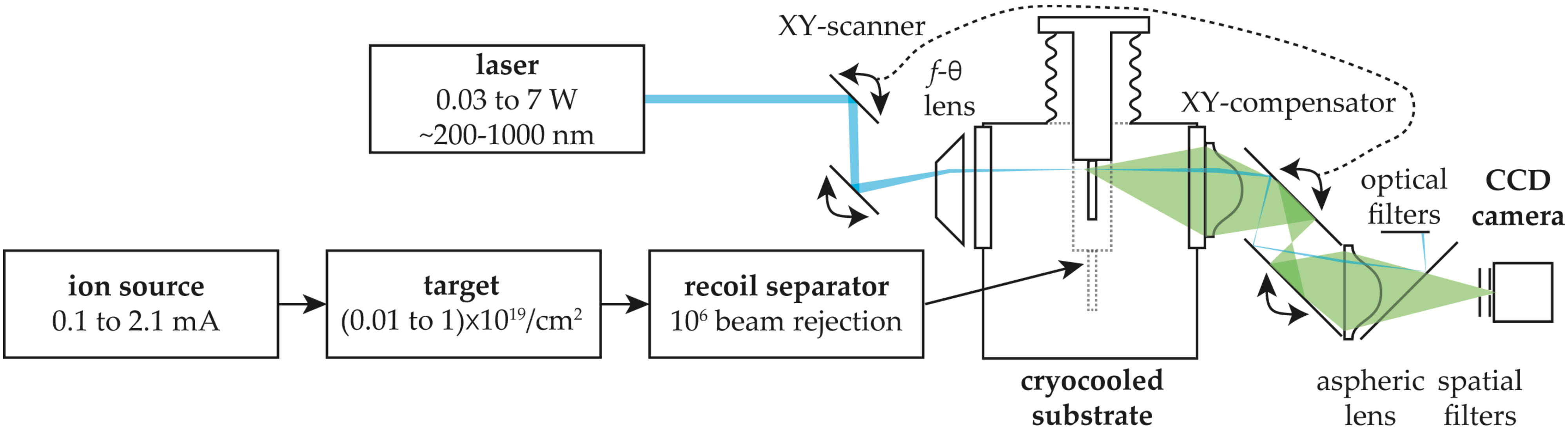
- Efficient: cryogenic film captures everything (both products and beam)

Selectivity: Count Only Product Atoms

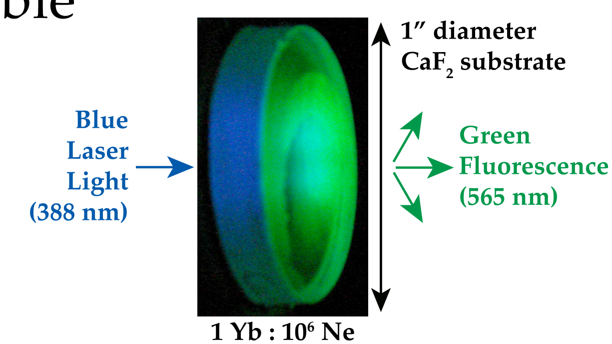


- Efficient: cryogenic film captures everything (both products and beam)
- Selective: product atoms identified by localized resonant laser excitation

Sensitivity (Key Challenge): Single Atom Sensitivity



- Efficient: cryogenic 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 film from beam
  - discriminate between isotopes

How do you take a picture of an atom?

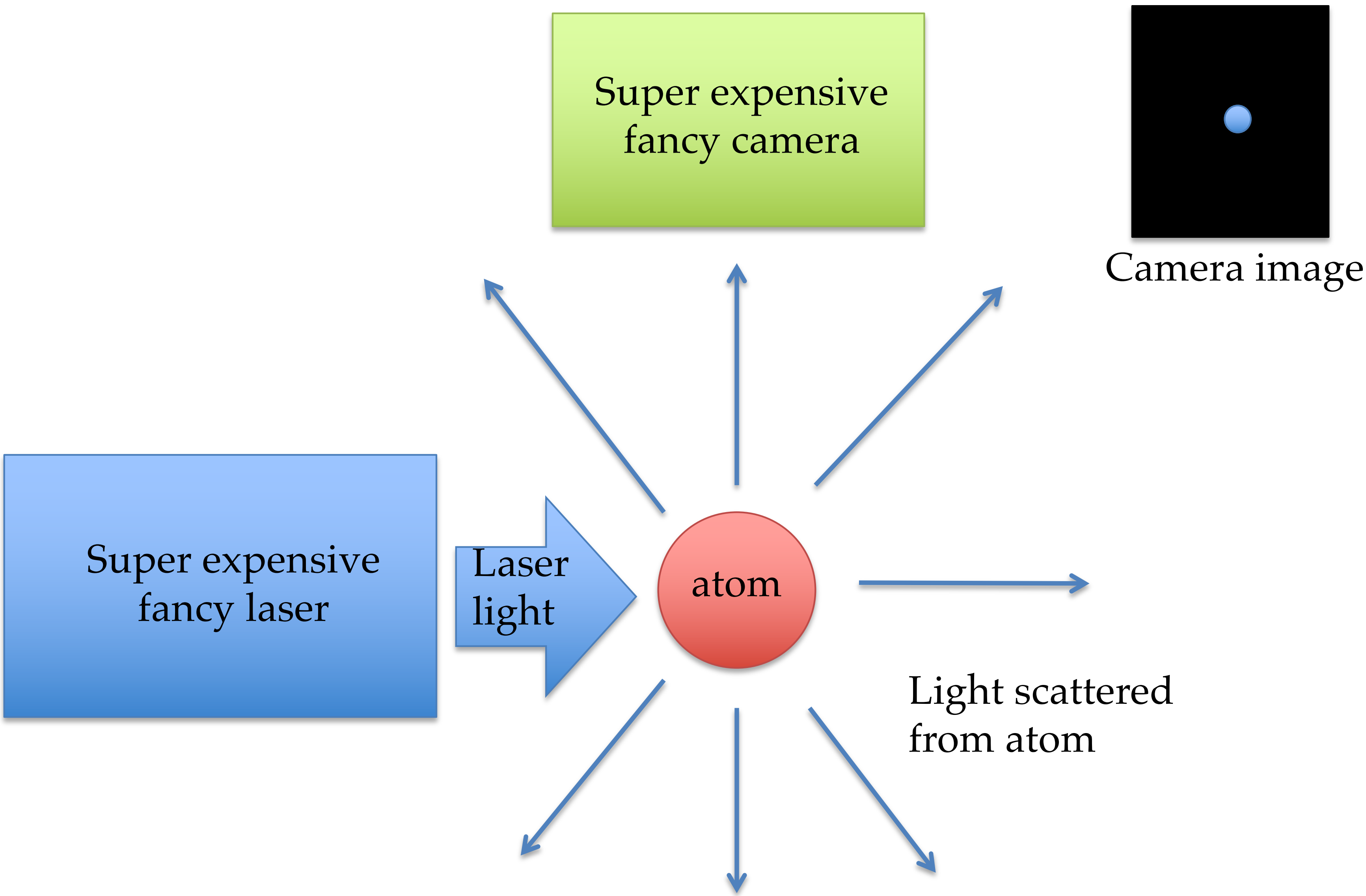
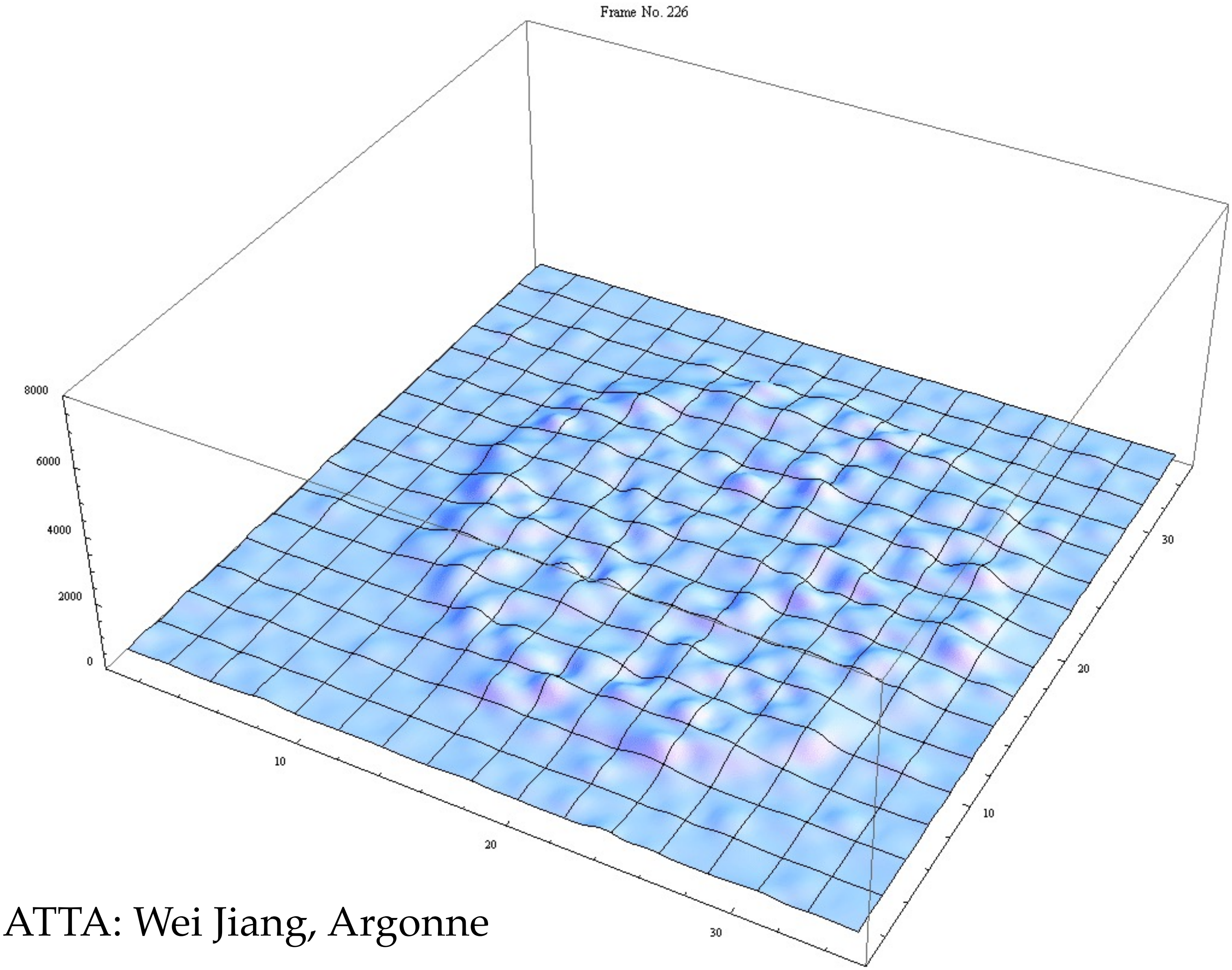
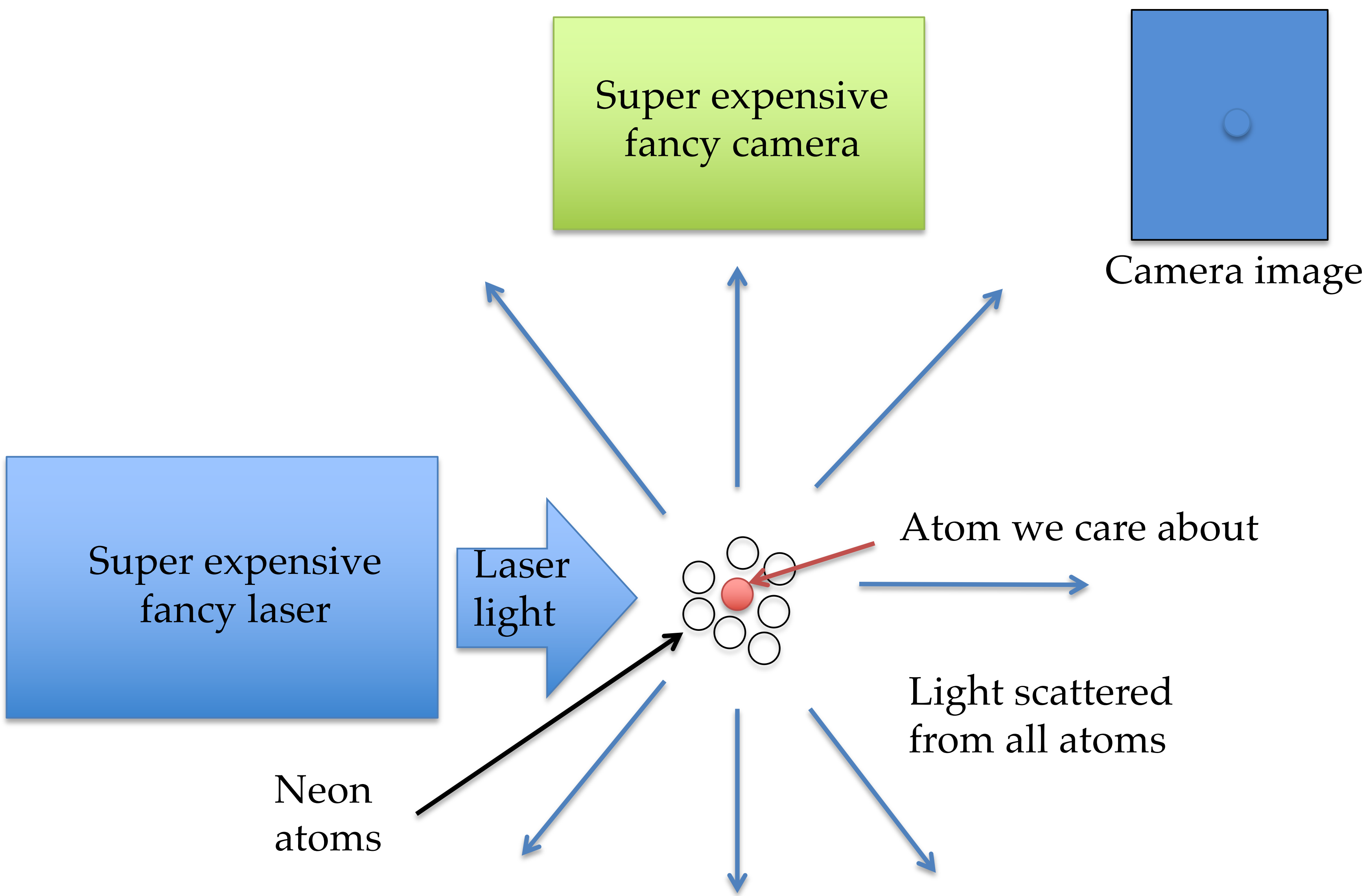


Image of Single Atom Suspended in Vacuum

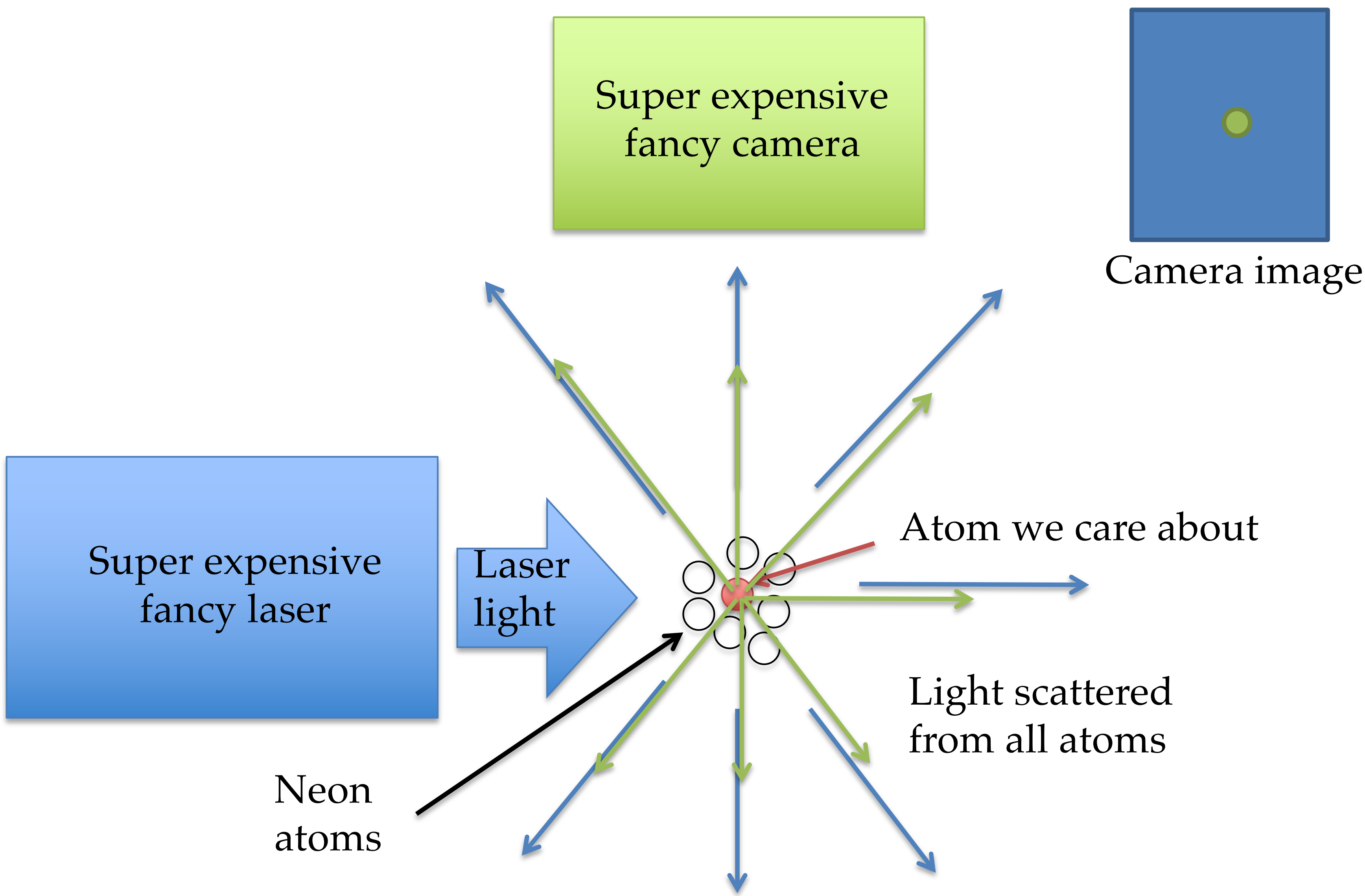


ATTA: Wei Jiang, Argonne

Taking a picture of an atom in solid is hard...



Taking a picture of an atom in solid is possible!



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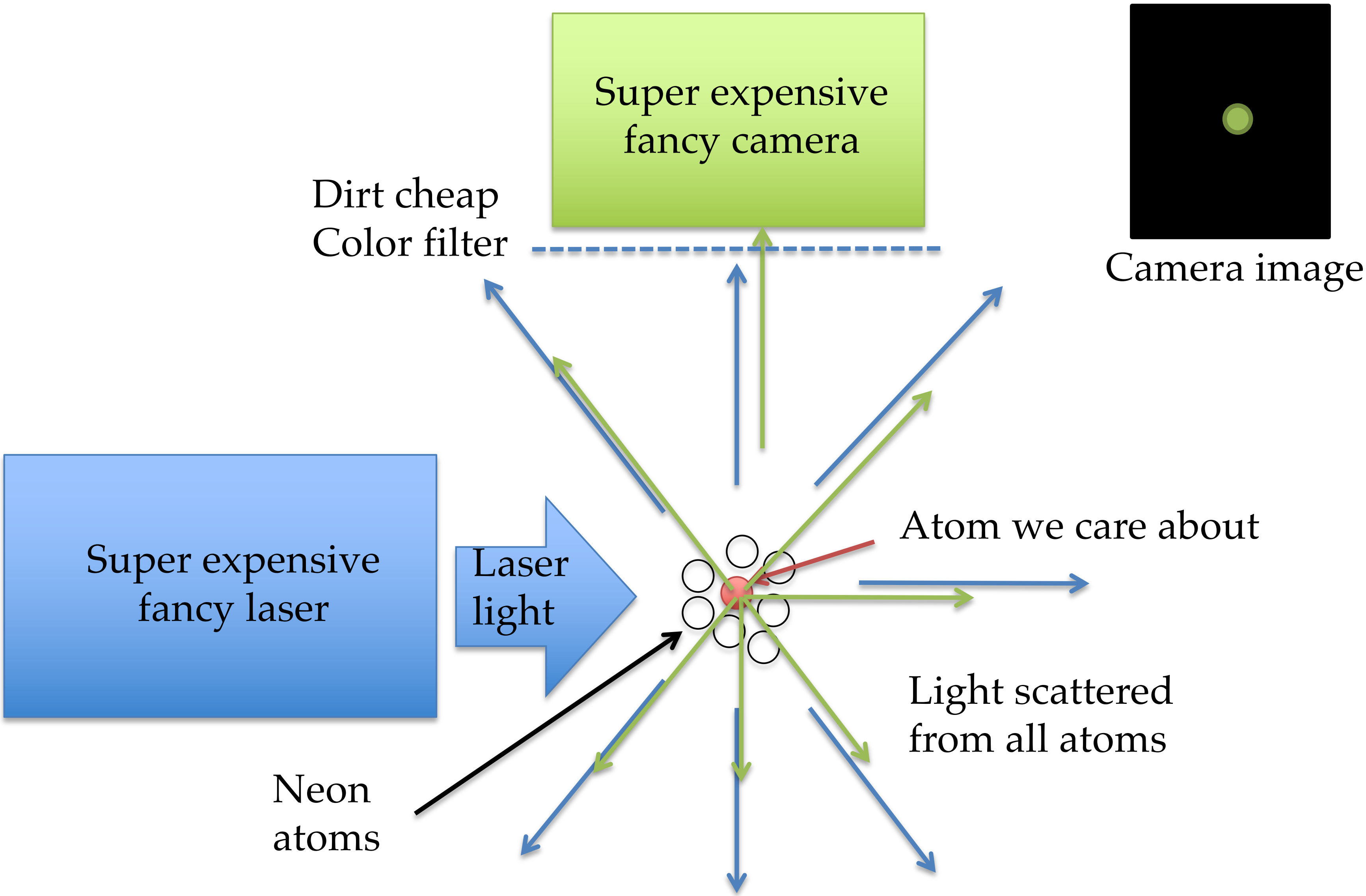
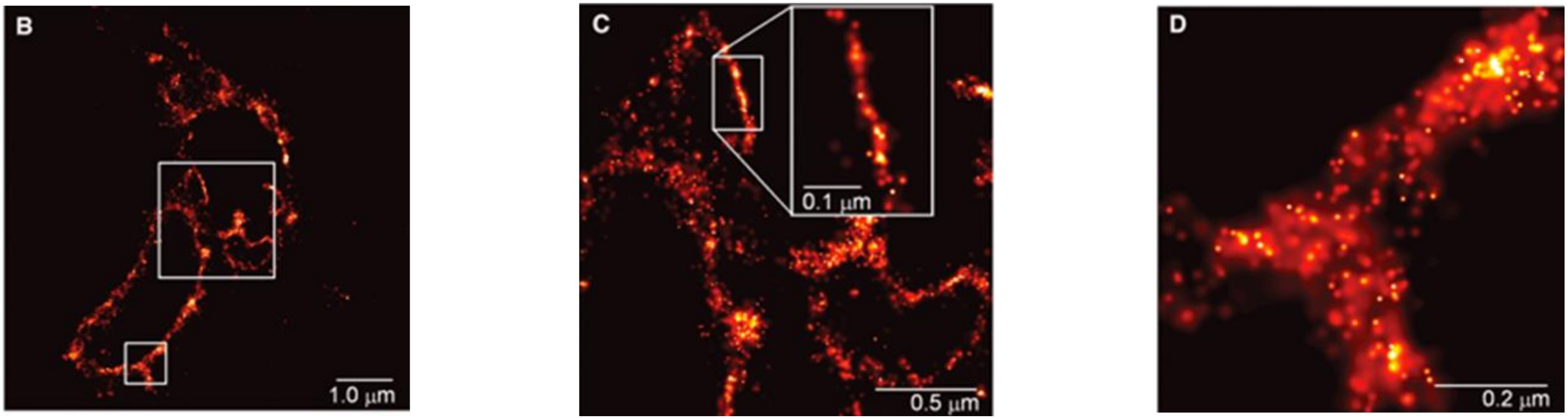


Single Emitter Imaging in Condensed Media



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

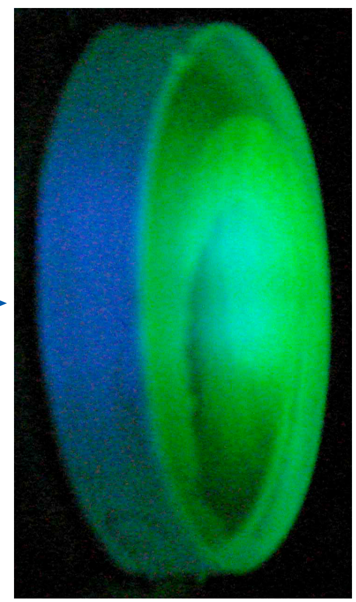
M. K. Moe PRC 44 R931 (1991)

W. Fairbank et al. @ Colorado State

Single Ba detection in s-Xe and laser scanning have been demonstrated!

Nature 569, 203 (2019)

Blue Laser Light (388 nm)



1 Yb : 10^6 Ne

1″ diameter CaF_2 substrate

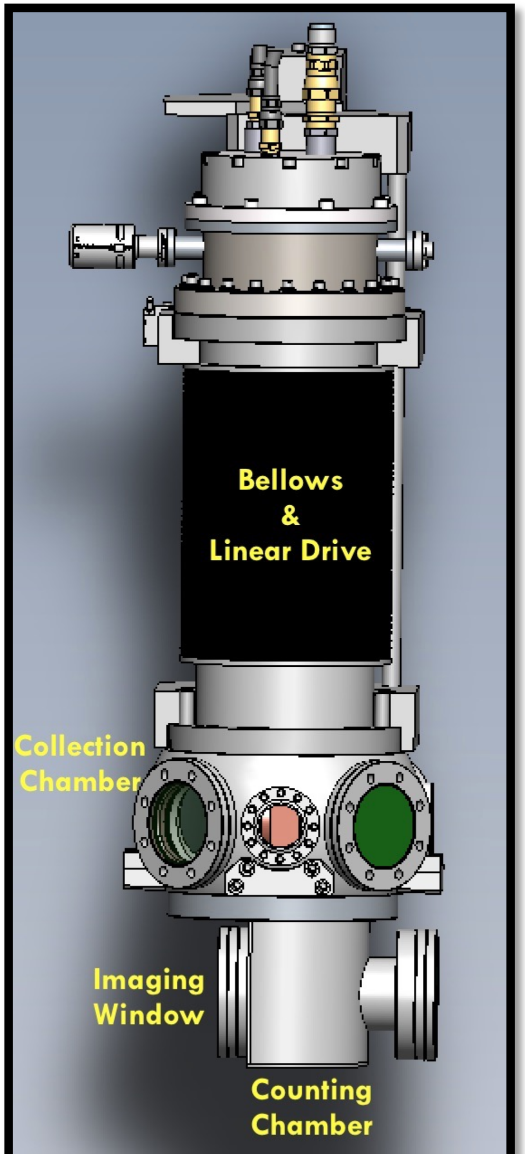
Green Fluorescence (565 nm)

Yb in s-Ne:

PRL 107, 093001

PRL 113, 033003

Prototype Single Atom Microscope

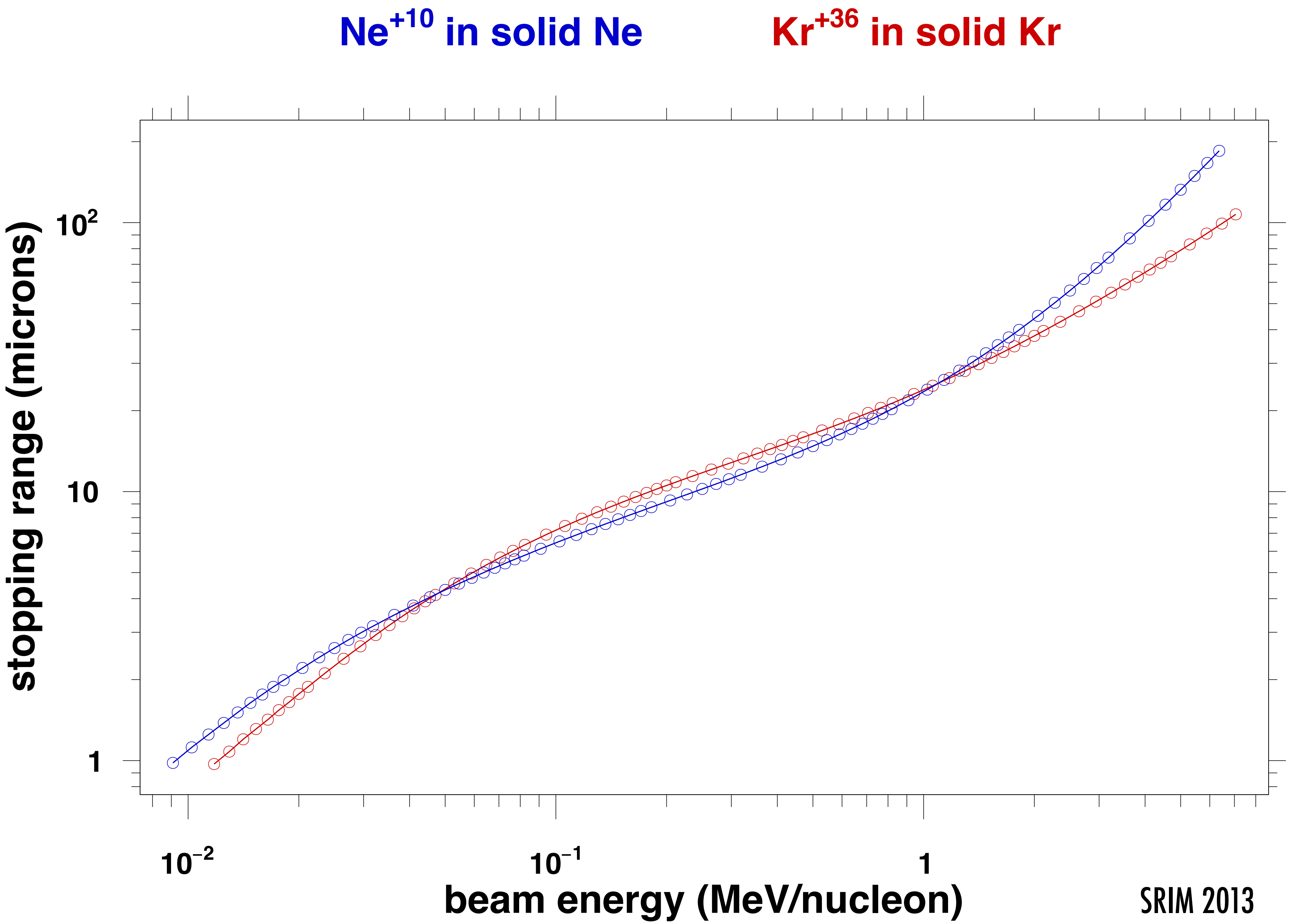


Pulsed Tube Cryocooler
- <10 micron amplitude vibrations
- 1.3 W cooling power

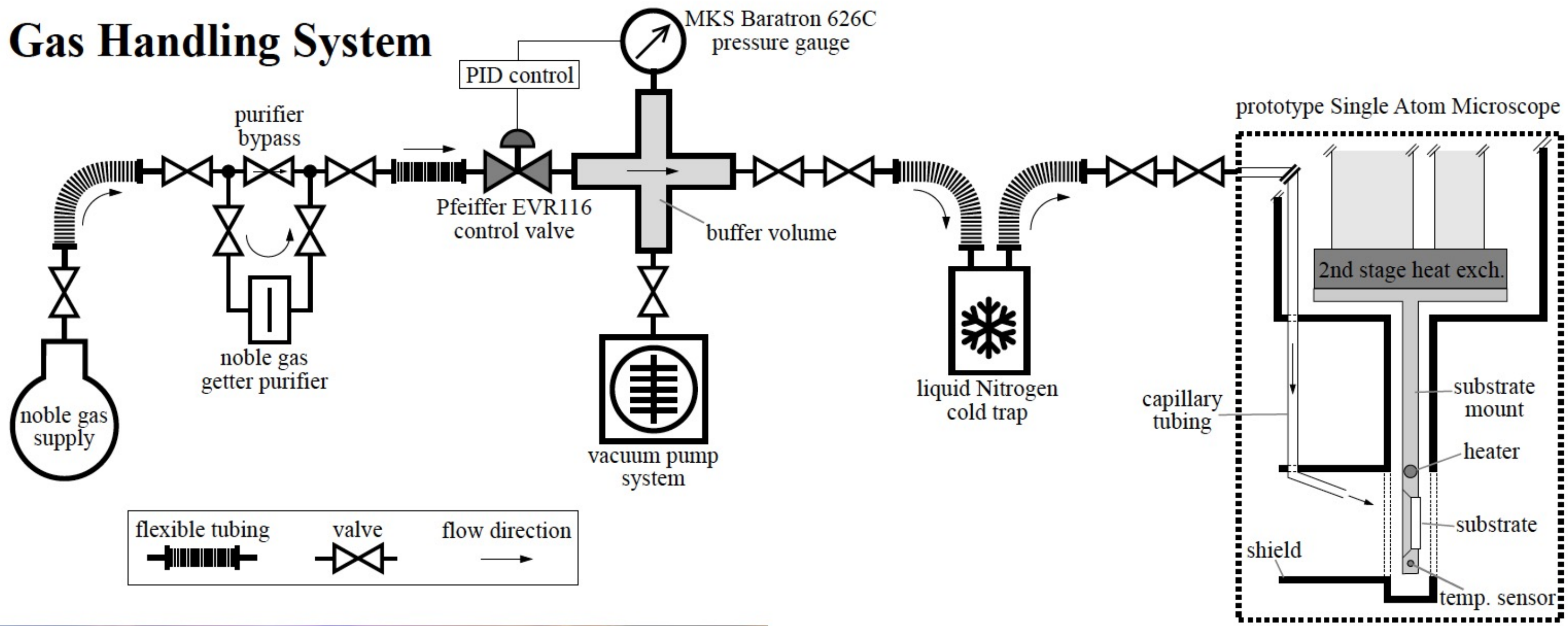
UHV compatible vertical linear drive
- up to 300 mm in travel
- <10 micron position repeatability

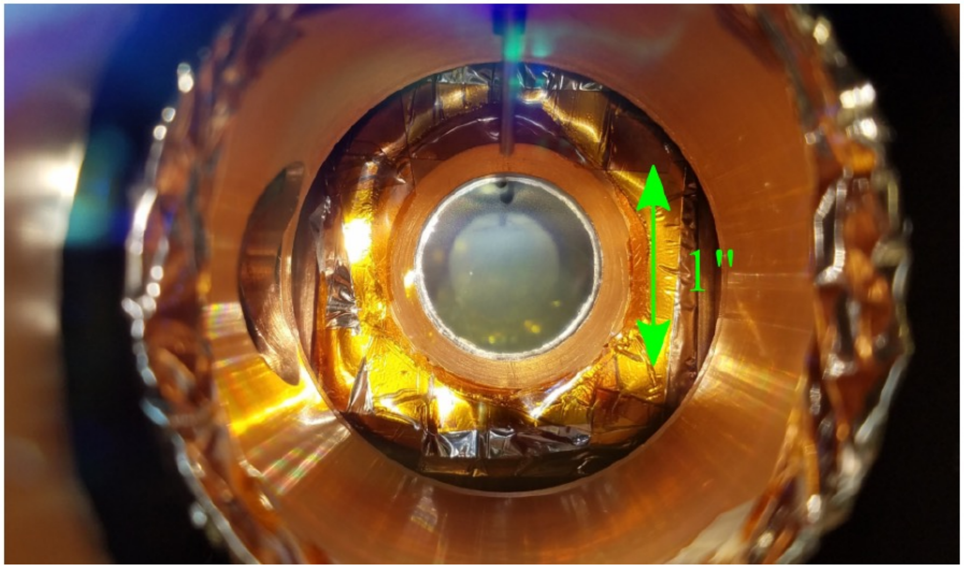
2.5” clear aperture
- 2% light collection w/ single aspheric lens
- DUV Fused Silica

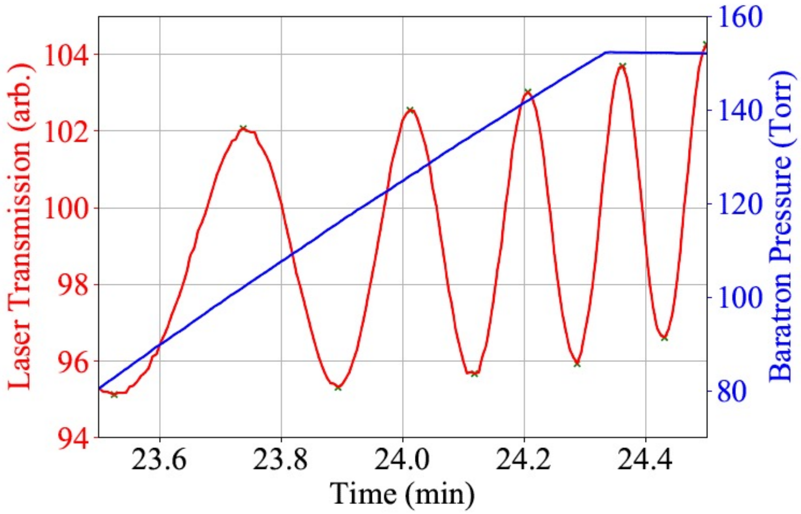
We need 100 μm thick films to fully stop ions.



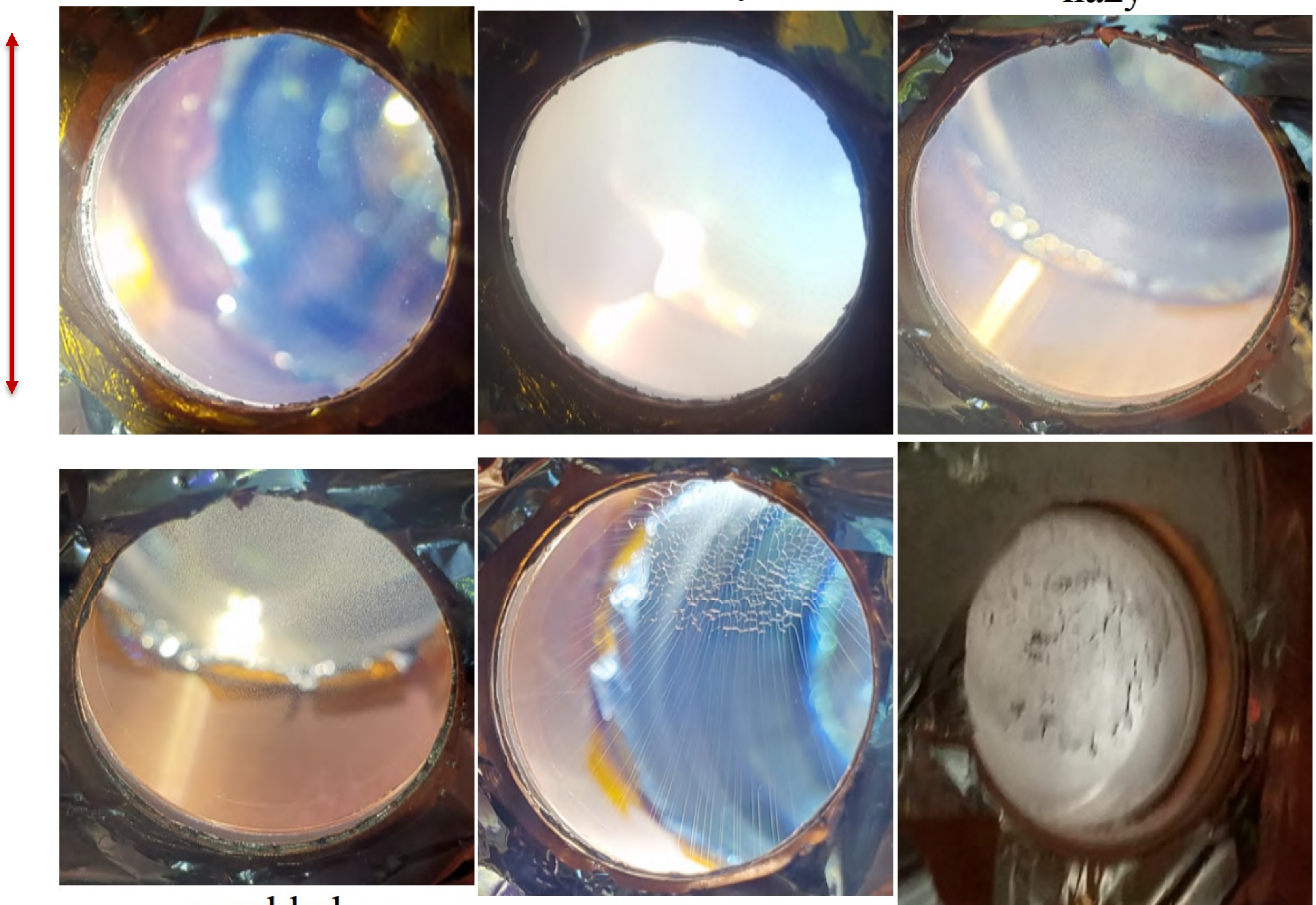
Growing Noble Gas Thin Films



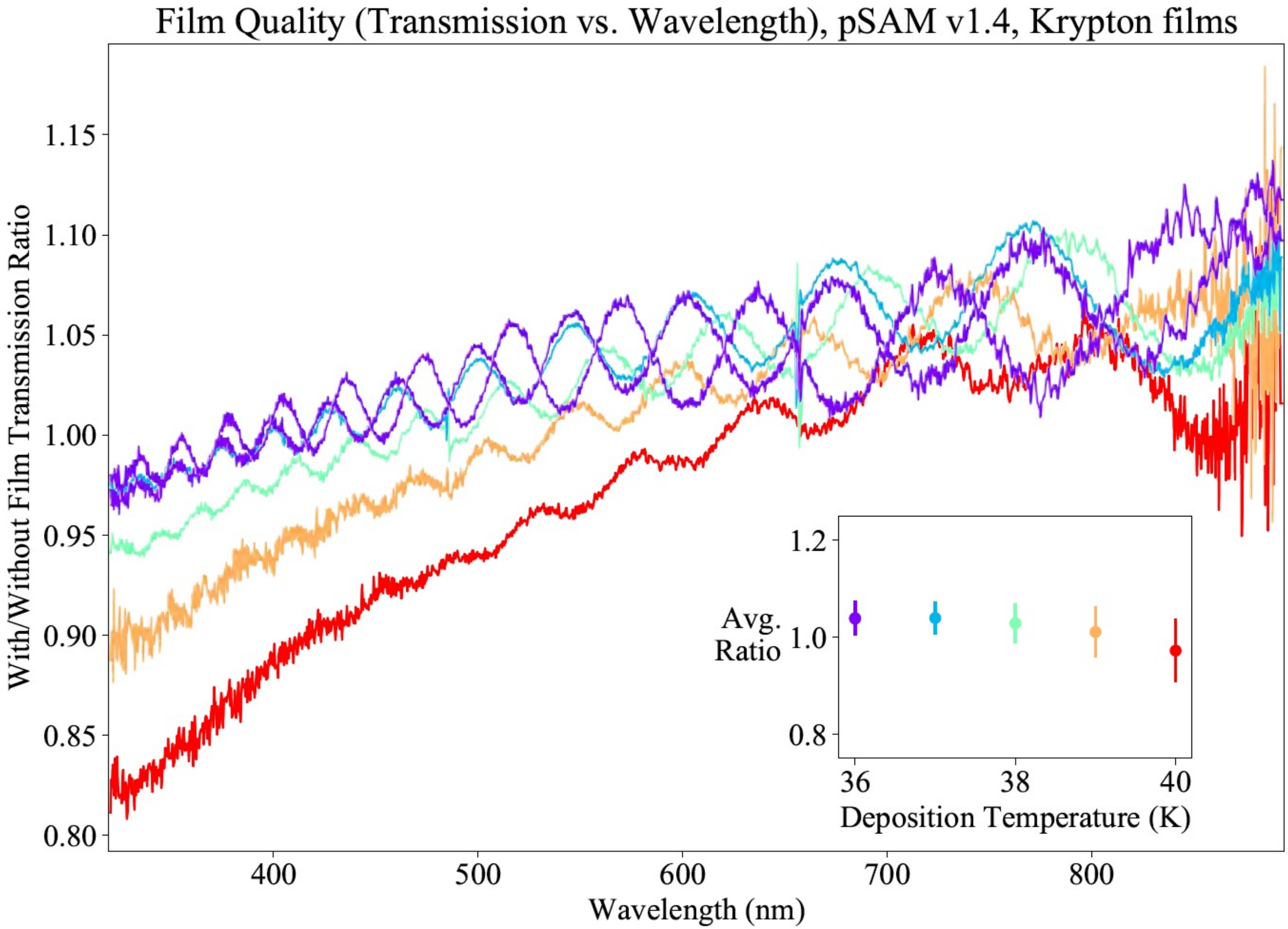




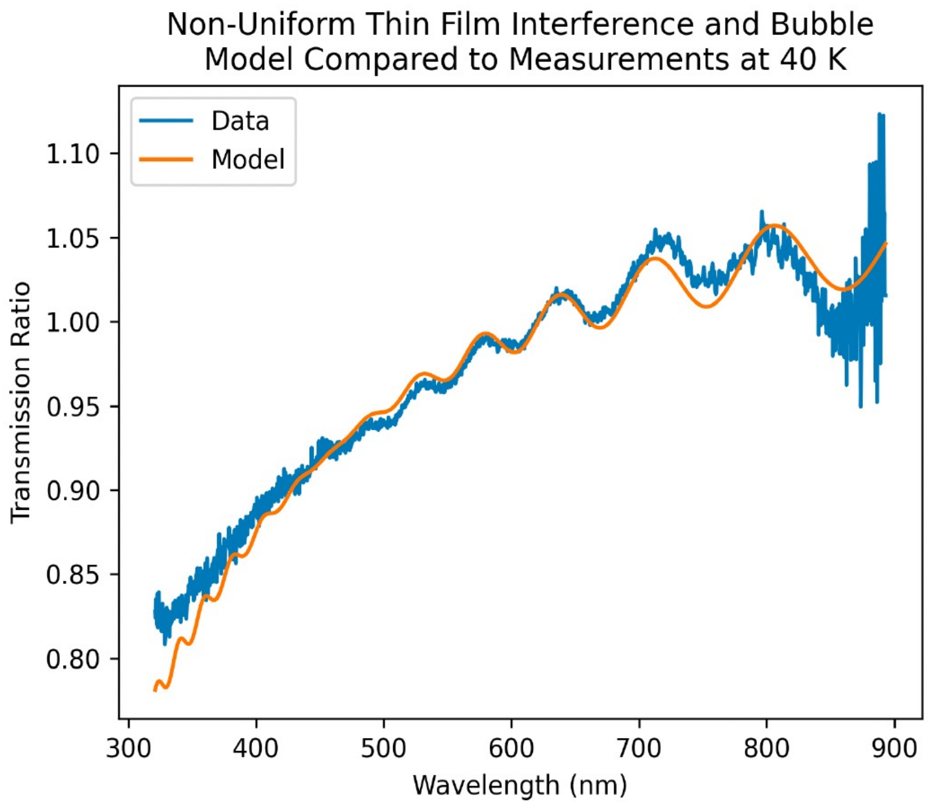
There is an art to growing transparent films.

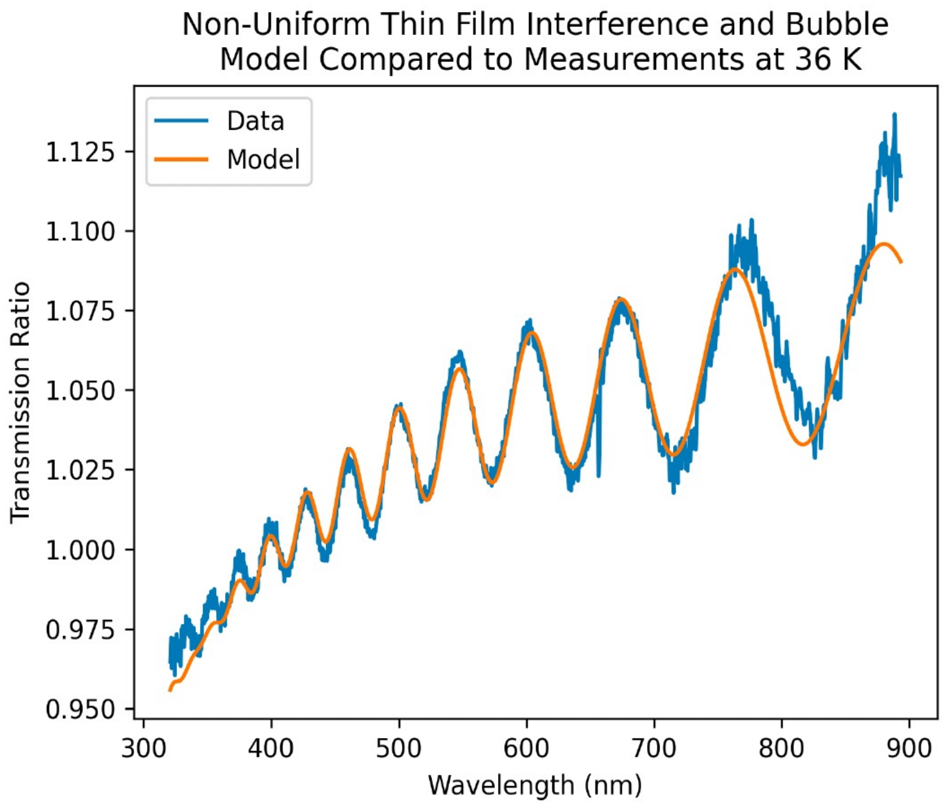


Film transparency is temperature dependent.



Mie Scattering From "Vacuum Bubbles" in Solid

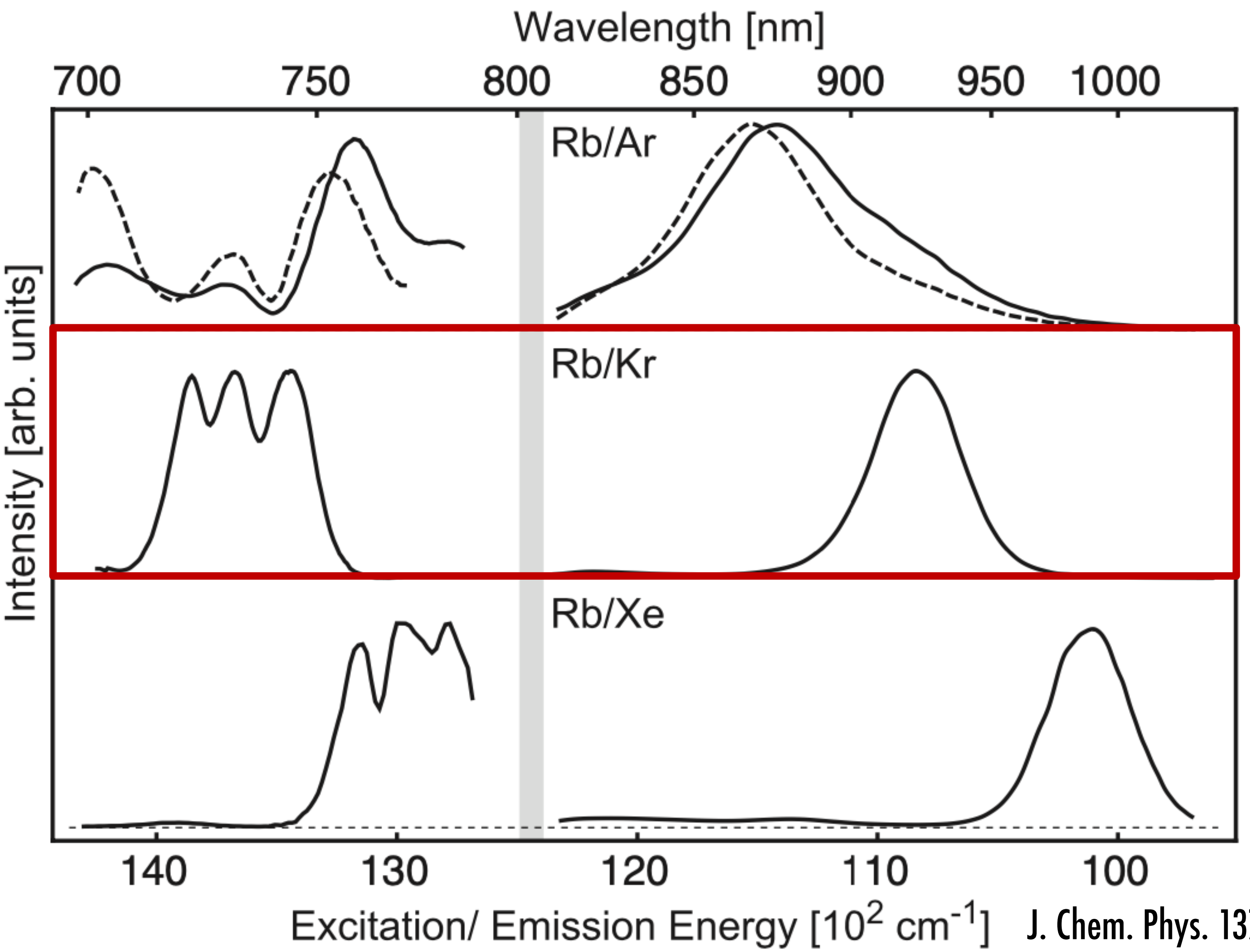




Oscillations due to an "anti-reflection coating" effect due to the presence of a nonuniform thin film on the back of the substrate

Start with Alkali Atoms!

Rb in solid Ar/Kr/Xe



J. Chem. Phys. 137, 014507 (2012)

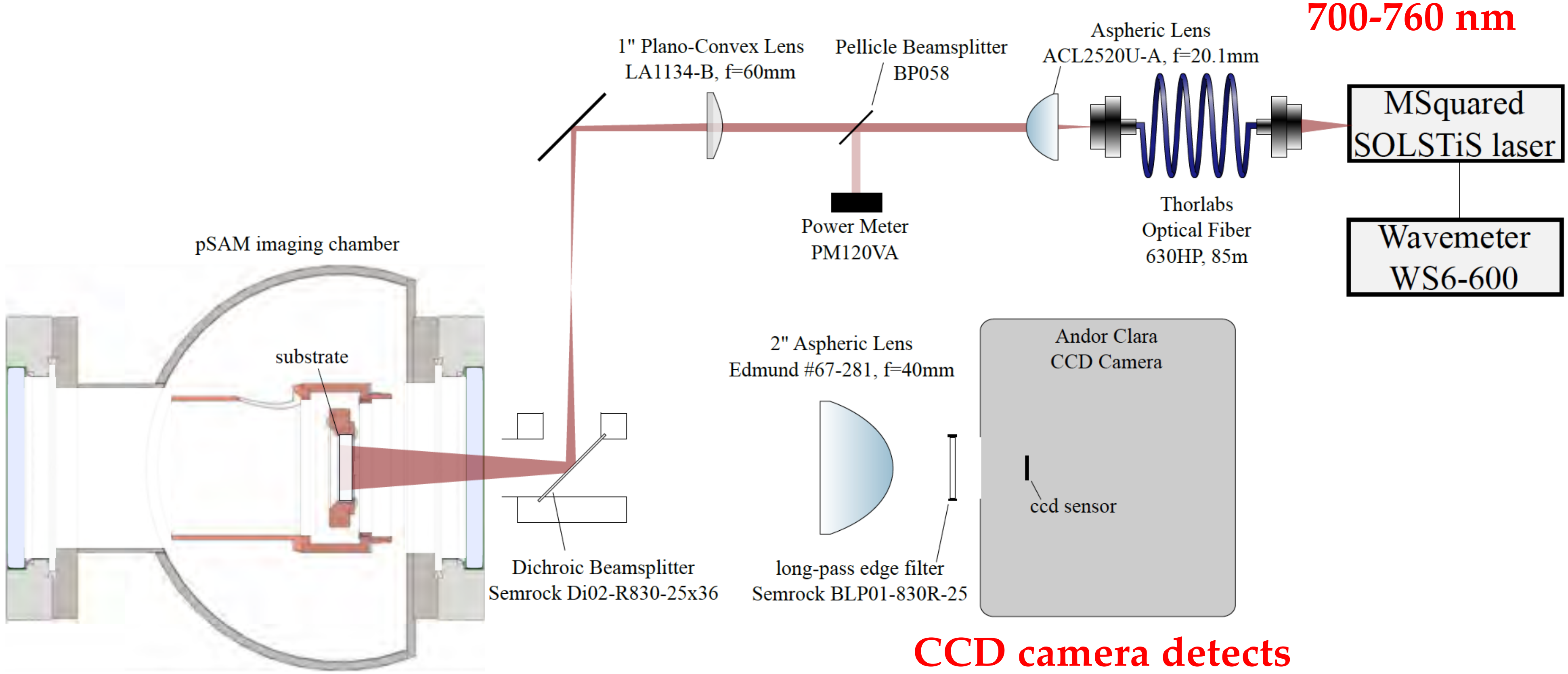
Rb in solid Ar

Absorption band (Å)	Emission peak (Å)
7980 (peak)	8300
7760 (peak)	8300
7550 (peak)	8300

J. Chem. Phys. 78, 592 (1983)

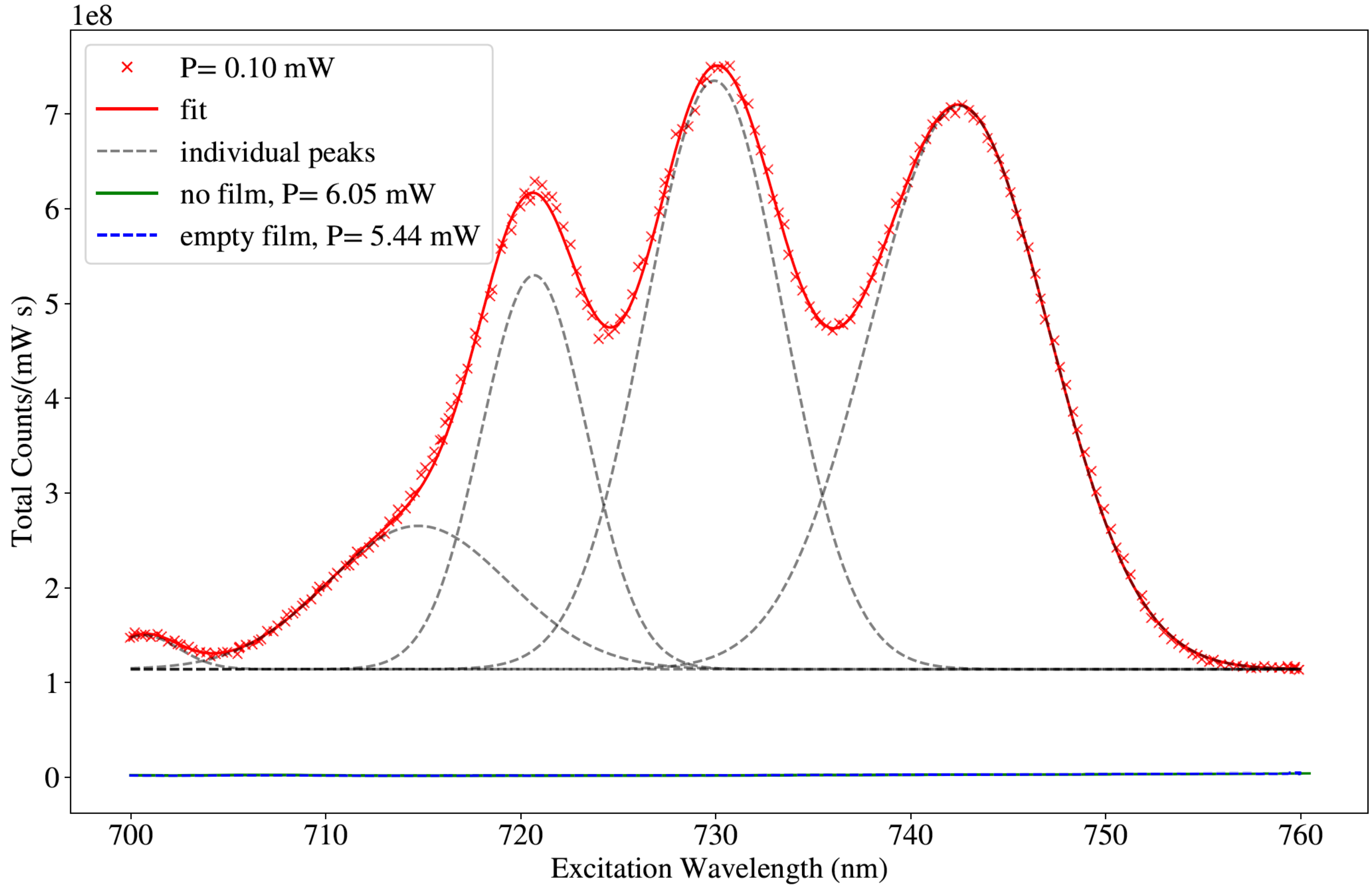
Neutral Rb Embedded into Kr From An "Effusive Oven"

~1 mW excitation from 700-760 nm

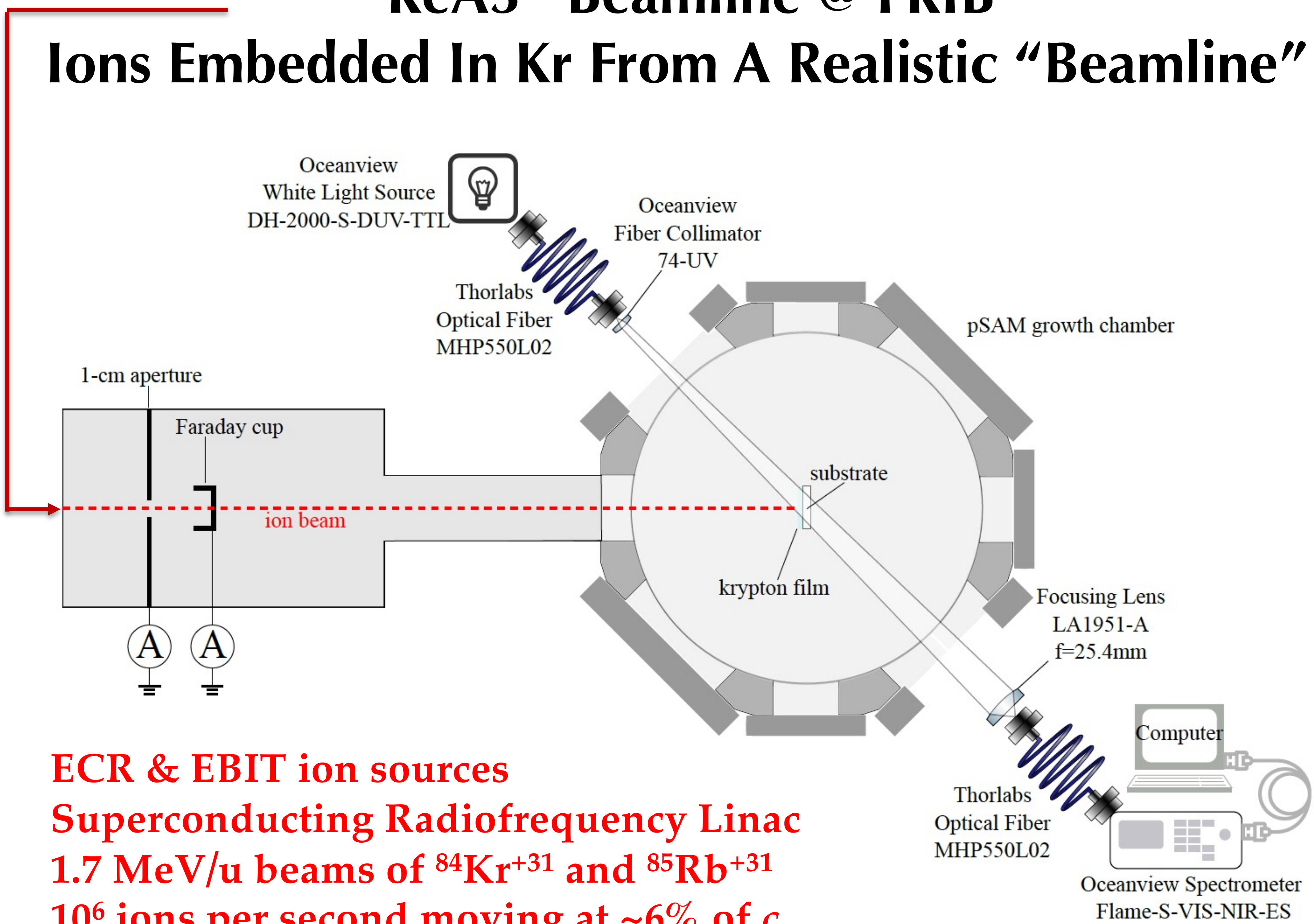


CCD camera detects fluorescence > 830 nm

Neutral Rb Fluorescence (>830 nm) in Solid Kr

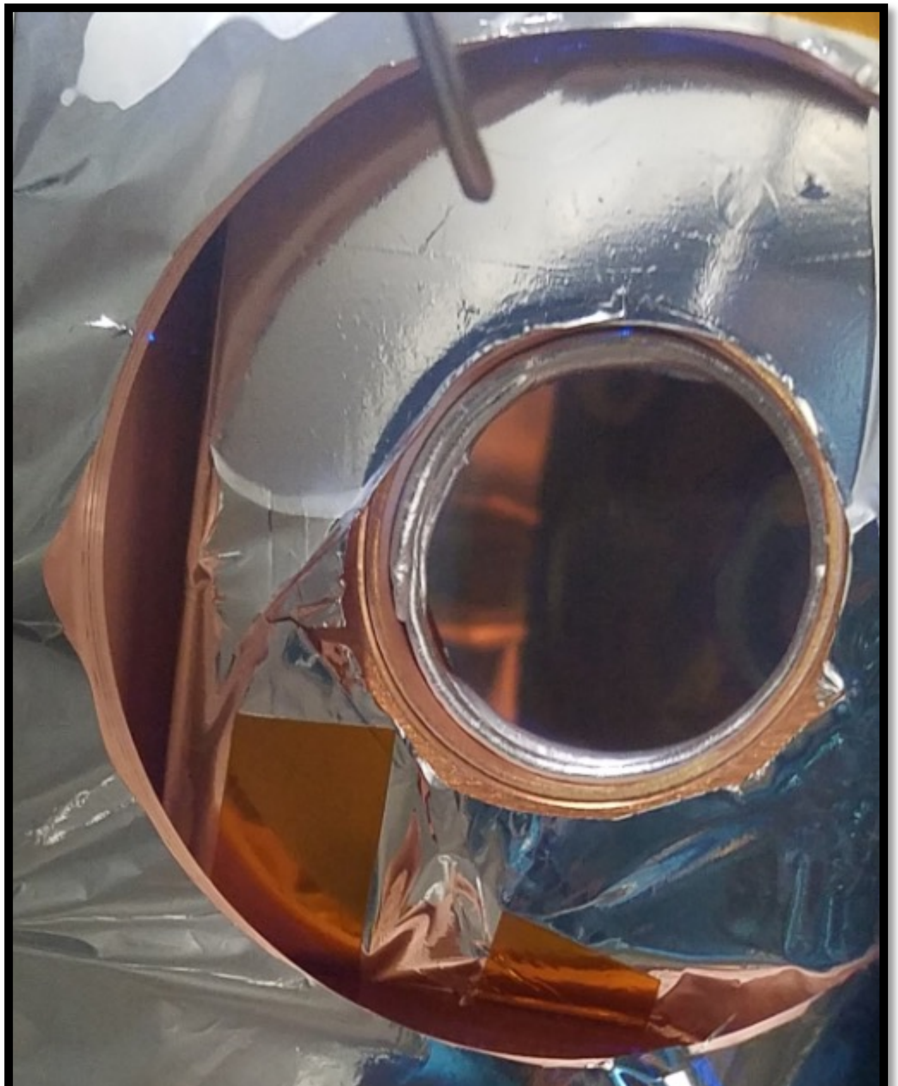


"ReA3" Beamline @ FRIB
Ions Embedded In Kr From A Realistic "Beamline"

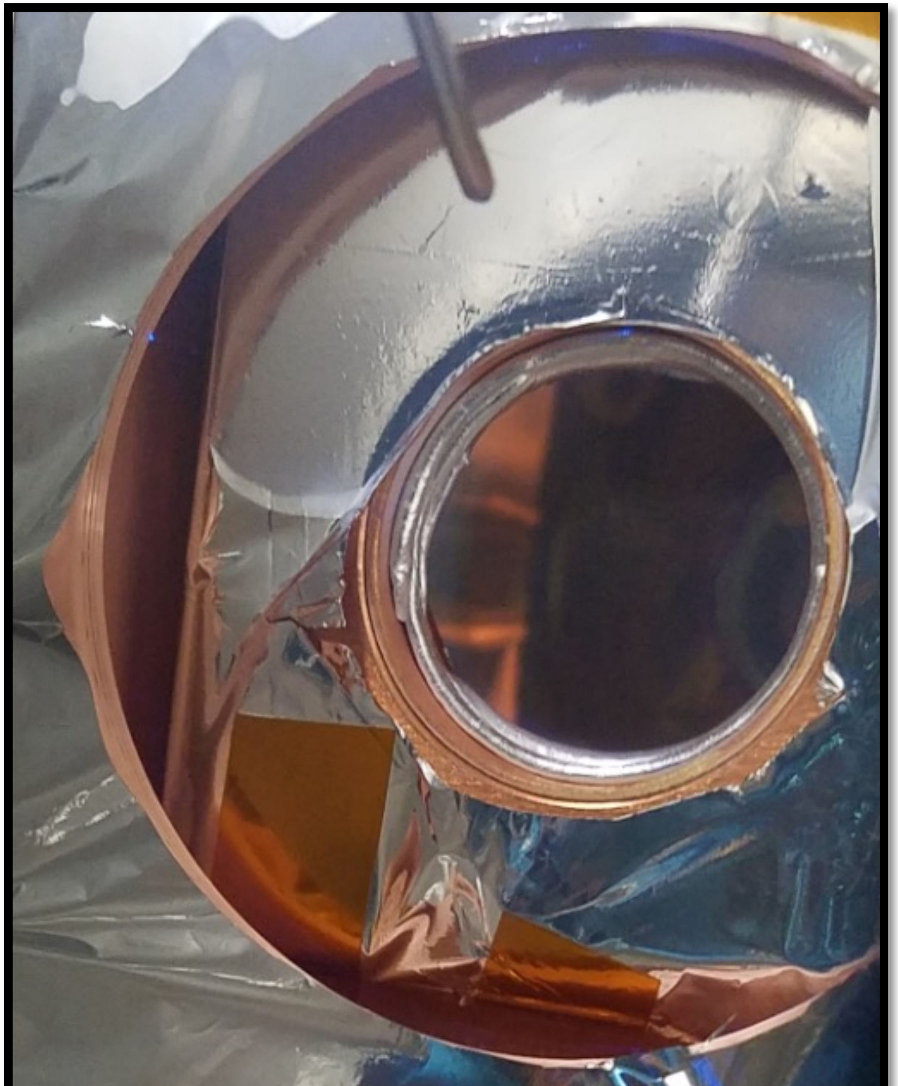


- ECR & EBIT ion sources
- Superconducting Radiofrequency Linac
- 1.7 MeV/u beams of $^{84}Kr^{+31}$ and $^{85}Rb^{+31}$
- 10^6 ions per second moving at ~6% of *c*

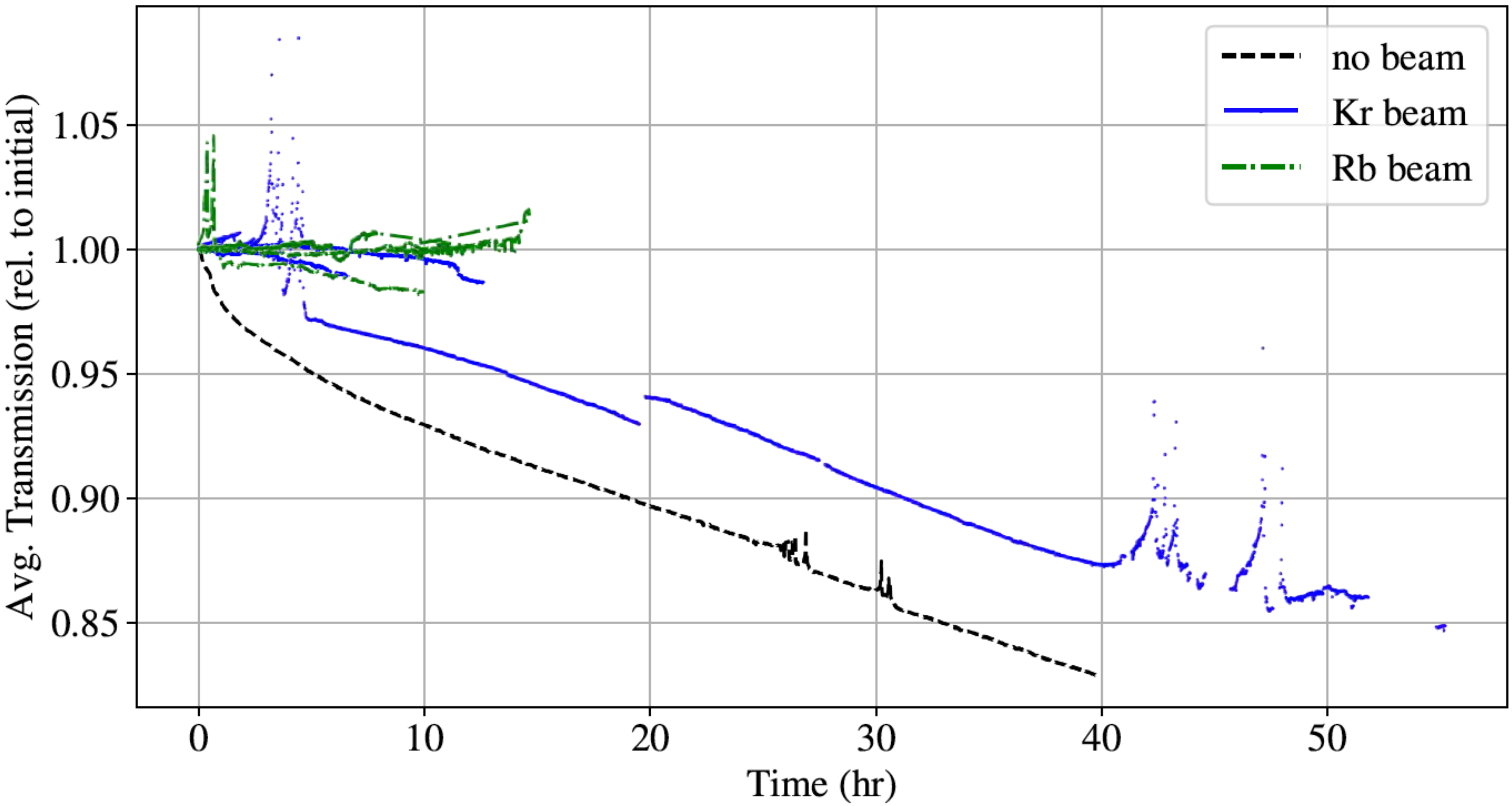
0.01 inch Film of Kr After 12 Hours



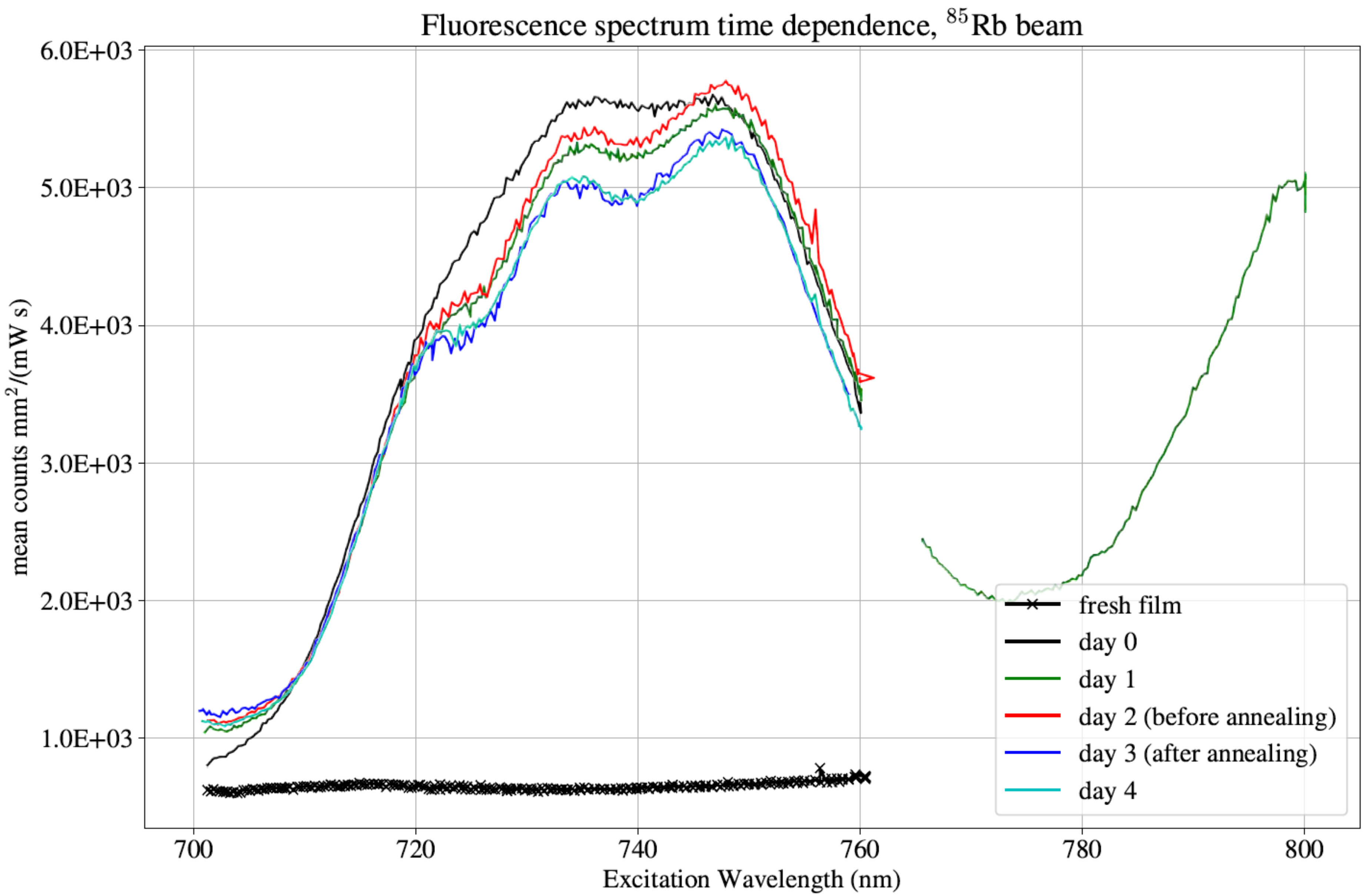
0.01 inch Film of Kr After Temperature Shock



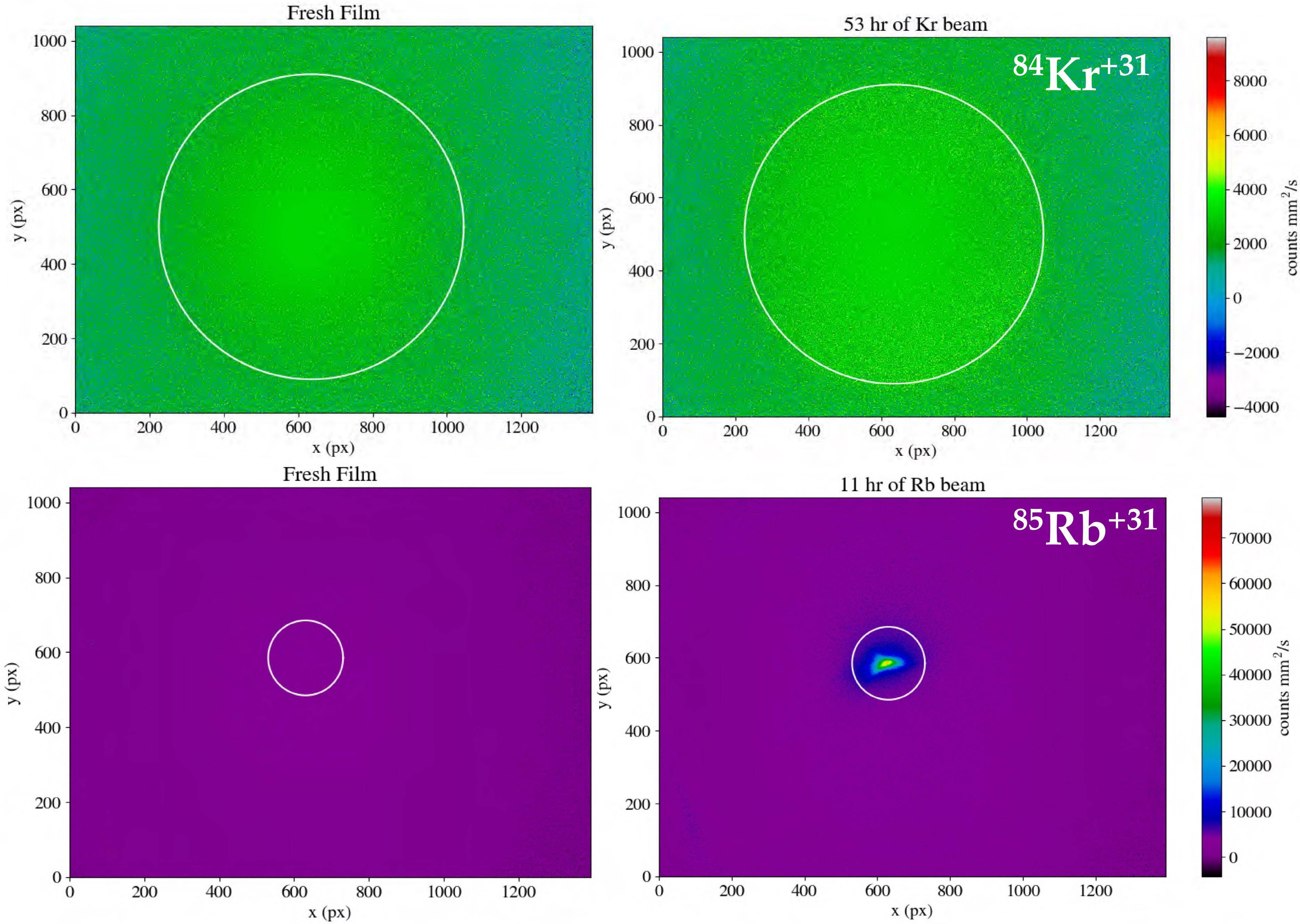
Film transparency is robust against damage.



Implanted Rb^{+31} spectrum resembles neutral Rb!



Fluorescence Light from 10^{11} Kr ions vs. 10^{10} Rb ions



Prospects of Single Atom Sensitivity

parameter	Neutral Rb from effusive oven	Implanted Rb^{+31} ions from ReA3	Barium in solid Xenon for nEXO	"Typical" Single Molecule Experiment
measured background rate	**100000×10^{3} cps/mW**		1×10^{3} cps/mW	0.4×10^{3} cps/mW
fluorescence cross section	**(2.3 +/- 1.7) $\times 10^{-16}$ cm²**	**>(9.2 +/- 2.8) $\times 10^{-16}$ cm²**	~0.1 $\times 10^{-16}$ cm²	~0.3 $\times 10^{-16}$ cm²
quantum efficiency	(3.1 +/- 0.8)%	>(12 +/- 8)%	>10%	>10%
Refs	this work		PRA 91, 022505 (2015) Nature 569 203 (2019)	ARPC 1997. 48:181 RSI 74 3597 (2003)

1. **Challenge: Background counts is 10^5 times more than successful single emitter experiments. Remedy: illuminate a smaller area of substrate + spatial filtering**
2. **Good: Most ions appear to be completely neutralized in medium.**
3. **Good: Rb fluorescence cross section appears to be comparable to other successful single emitter imaging experiments.**
4. **Next up: study LIF of Rb in solid Kr**

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

Some SAM-"Friendly" Atoms

Species	Excitation (nm)	Emission (nm)	Brightness (Hz)	Notes
Be	(225)	(455 & 332)	4.2E-1	(estimated)
Be	(225)	(245)	5.5E8	(estimated)
Mg	275	472 & 518	2.5E1	JCP 101, 10354-65, 1994
Mg	275	296	5.0E8	LTP 38, 679–87, 2012
Ca	(423)	(657 & 1953)	2.6E3	(estimated)
Sr	(461)	(689 & 2739)	4.7E4	(estimated)
Cd	(229)	(326 & 480)	4.1E5	(estimated)
Yb	388	(408)	1.9E8	(estimated)
Yb	388	546 & (1540)	1.1E6	PRL 107:093001, 2011
Li	670	890	~5E7	JCP 73, 3103-6, 1980
Na	587	720	4.6E7	JCP 69, 1670-5, 1978
K	762	900	~5E7	JCP 70, 2404-8, 1979
Rb	776	830	~5E7	JCP 78, 592-3, 1983
Cs	834	970	~5E7	JCP 78, 592-3, 1983

Thanks For Your Attention!

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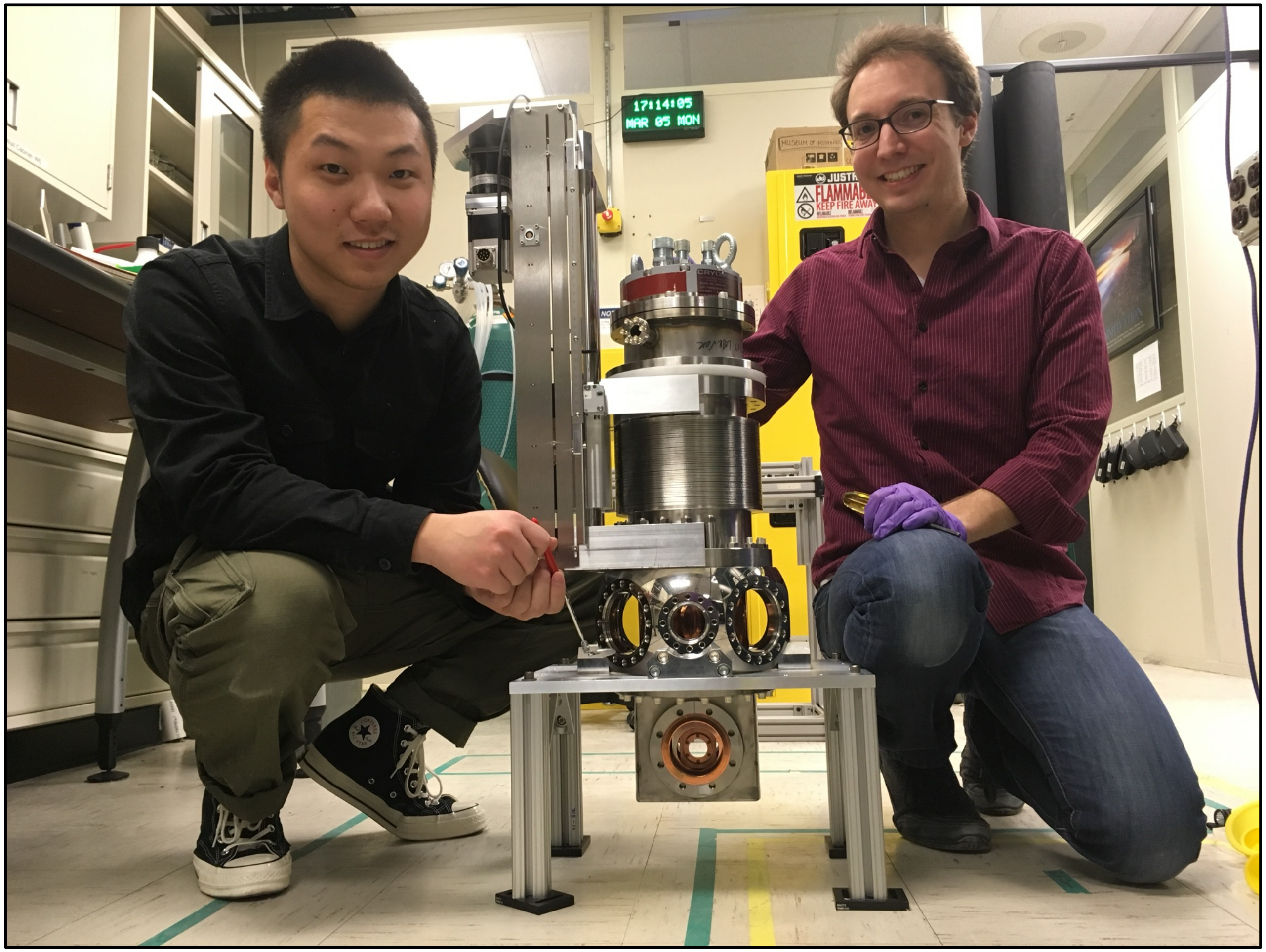

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Questions?
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