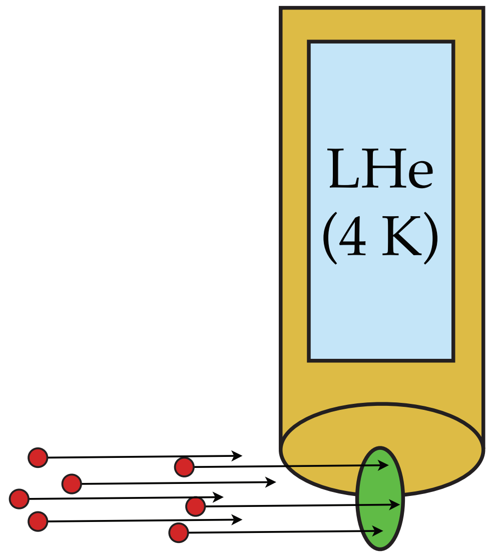
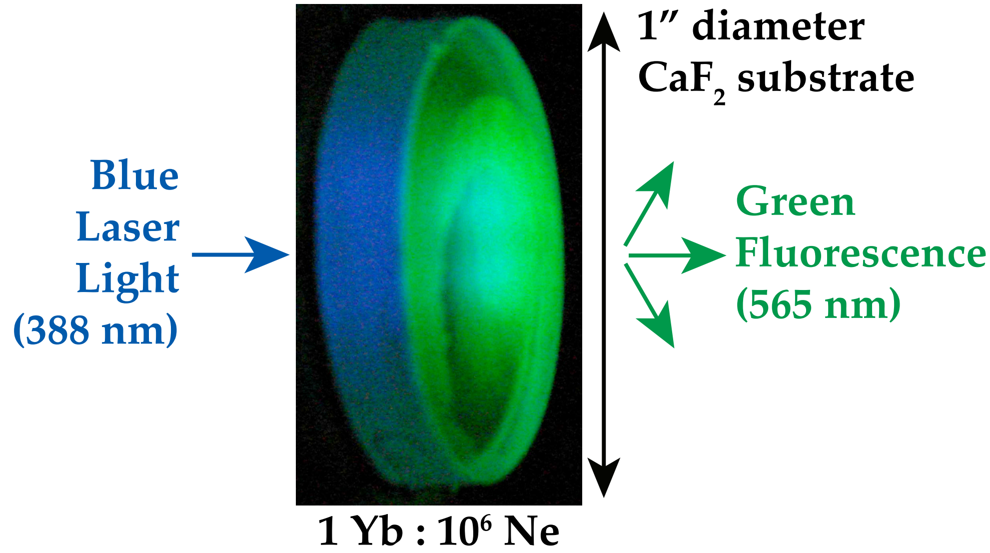
Progress Towards Optical Single Atom Detection for Nuclear Astrophysics



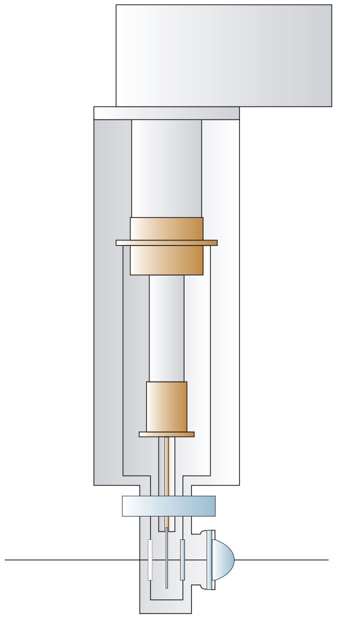


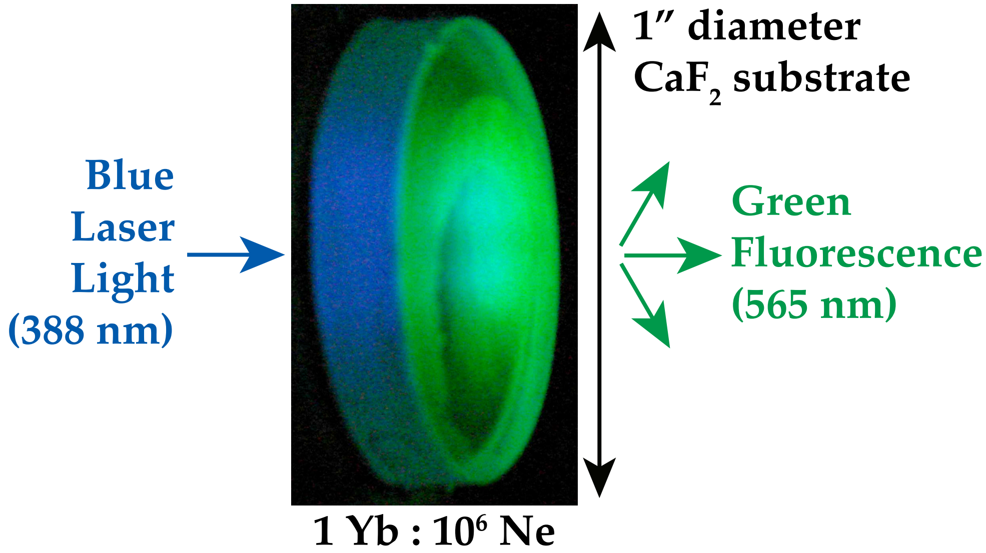
Jaideep Taggart Singh (NSCL/Michigan State)

DNP 2016 – Vancouver, BC, CA

00PC.01: 1030-1042, Junior Ballroom B, Sunday Oct. 16, 2016

Progress Towards A **Single Atom Microscope (SAM)** for Nuclear Astrophysics





Jaideep Taggart Singh (NSCL/Michigan State)

DNP 2016 – Vancouver, BC, CA

00PC.01: 1030-1042, Junior Ballroom B, Sunday Oct. 16, 2016

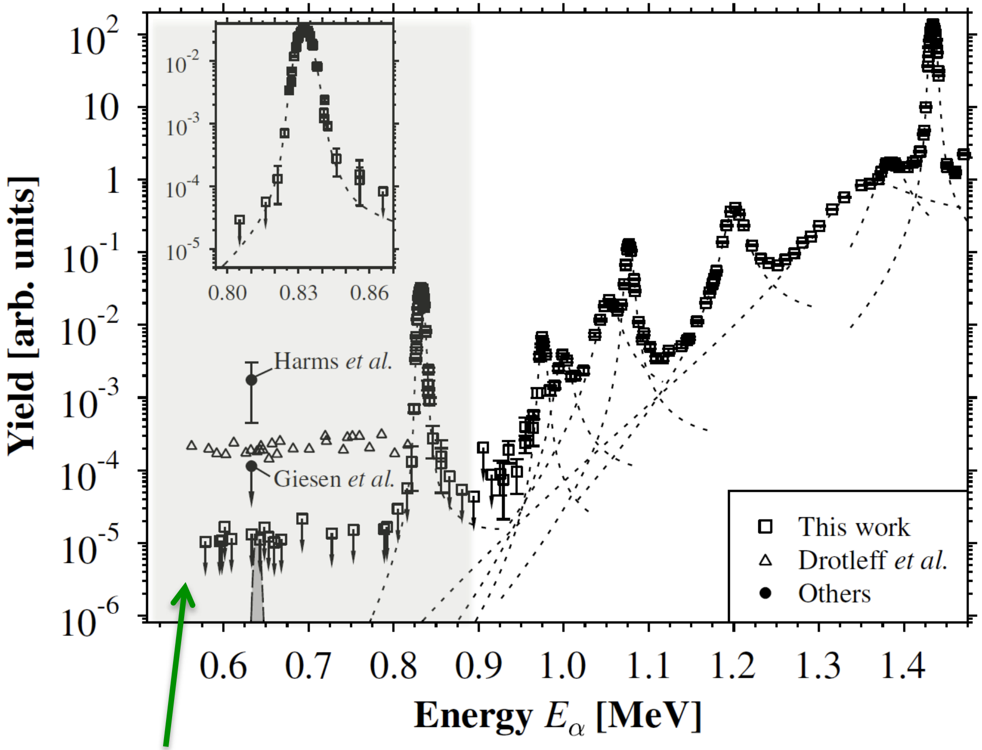
Motivation

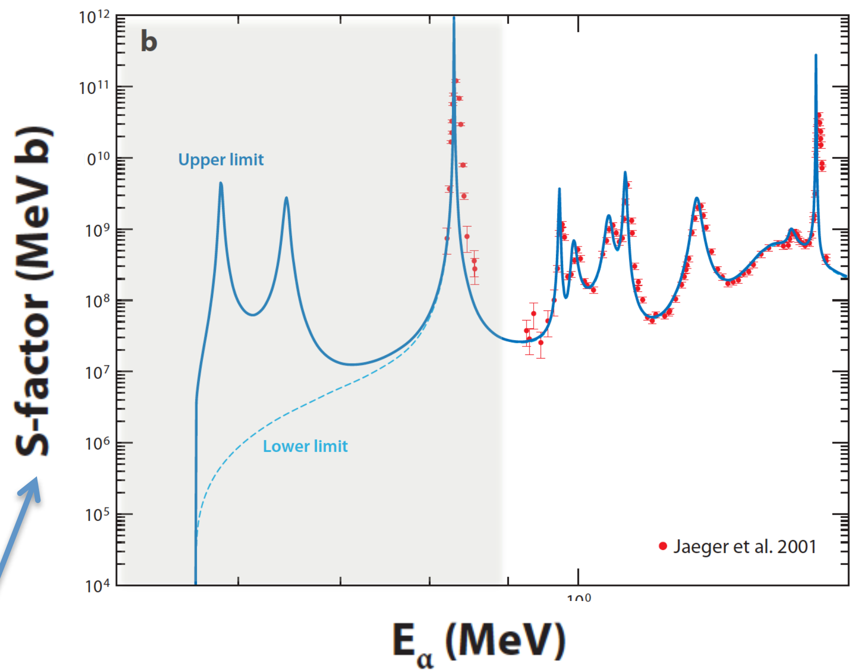
A key source of neutrons for the *s*-process…

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

Jaeger et al. *PRL* **87** 202501 (2001)

Wiescher, Käppeler, & Langanke, *Ann. Rev. Astro. Astrophys.* **50** 165 (2012)



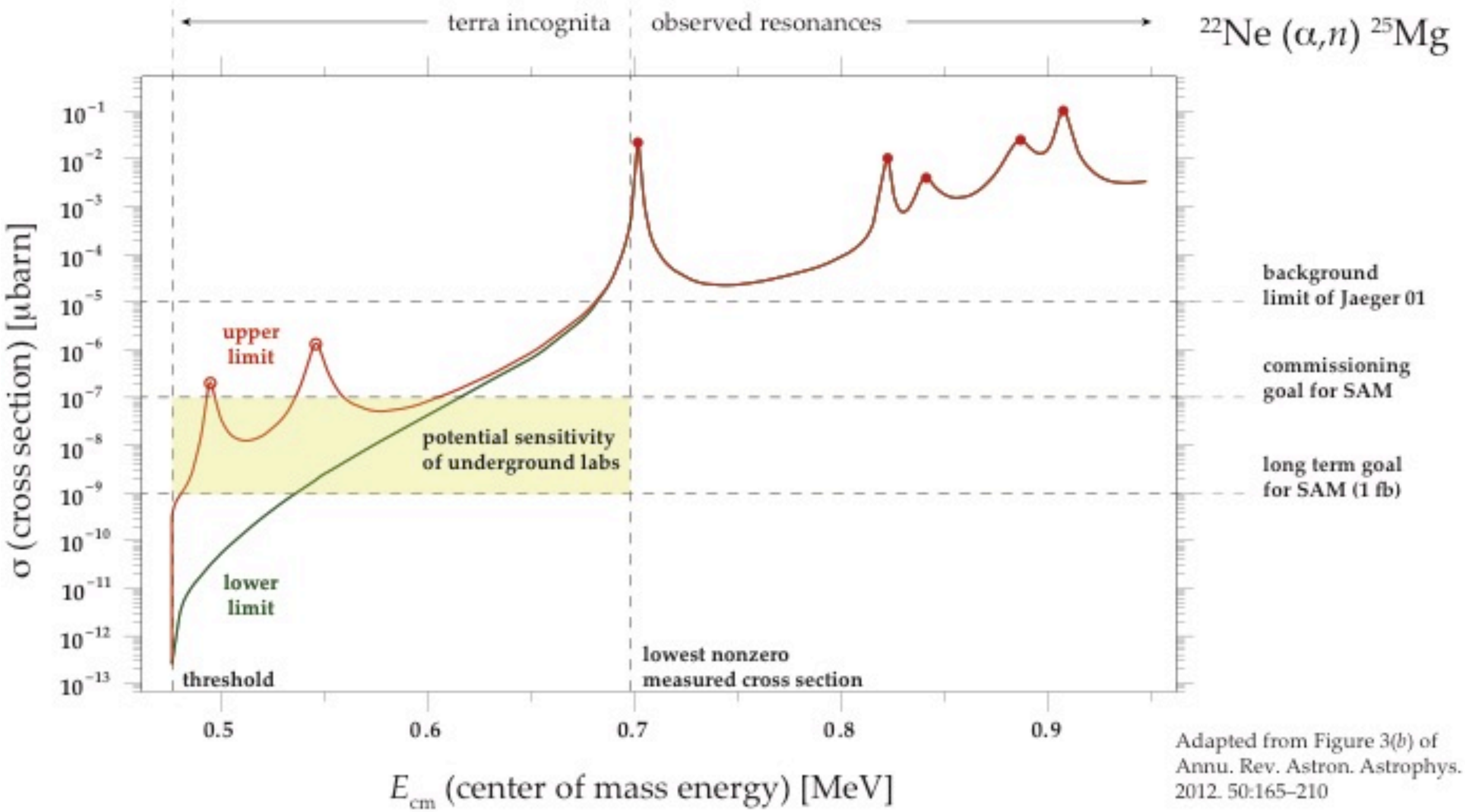


Gamow Window (600±300) keV

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

Coulomb Barrier

Towards Sub-Picobarn Cross Section Sensitivity



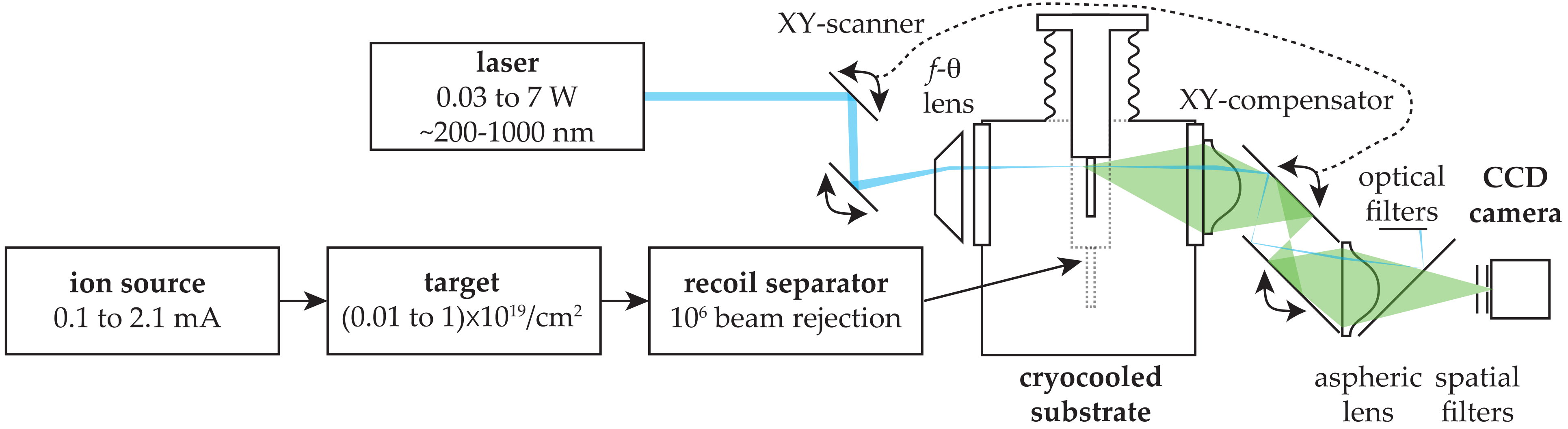
Underground labs are expected to have a factor of 100 or less background.

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

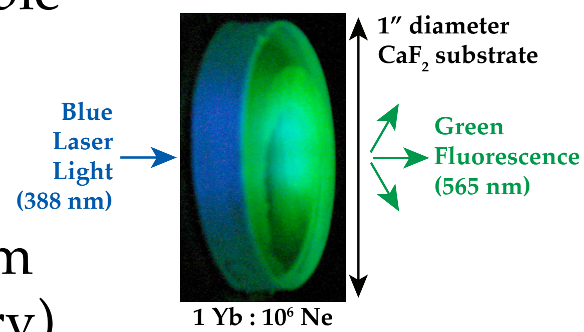
$$(1\ \text{pb})\left(10^{17}/\text{cm}^2\right)(150\ \mu\text{A}) = 5/\text{day}$$

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

Opportunities!



- 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
- Borrow off-the-shelf tools & existing techniques from Single Molecule Spectroscopy (2014 Nobel Chemistry)



Challenges…

- Excitation lines broadened & shifted in medium by nm
  - need high power and tunable lasers

- Potentially low brightness atoms:
  - fluorescence rate limited by atomic lifetimes (ns to seconds)
  - need very low noise detectors for long integration times
  - need large optical access for high photon capture efficiency
  - at present, technique is most suitable for stable or long-lived products

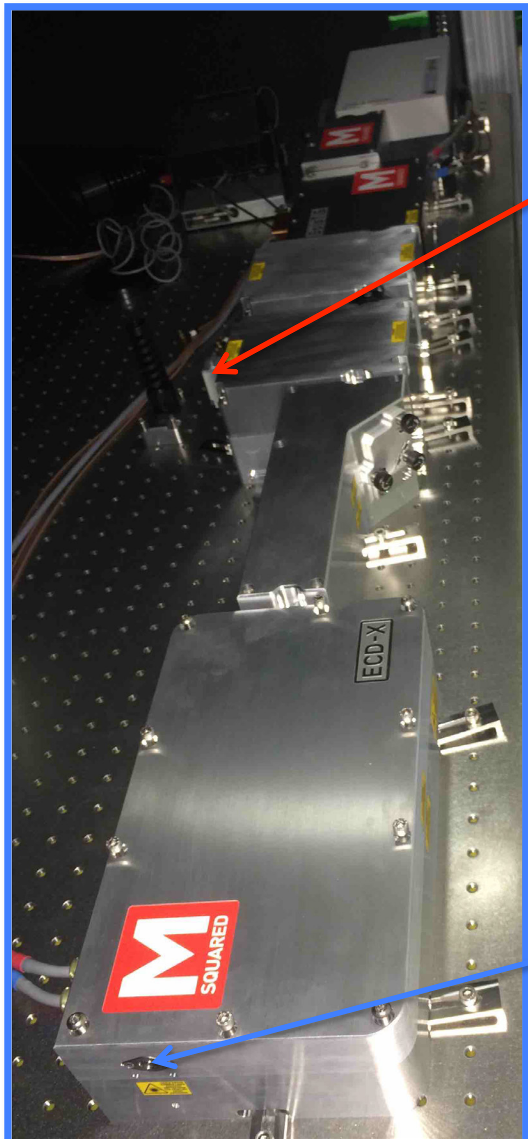
- Photo-bleaching: atoms may stop emitting light
  - need to understand atomic excitation and decay dynamics in medium
  - may need additional lasers to recover atoms from metastable states

- Backgrounds from impurities in:
  - solid Ne
  - substrate
  - vacuum windows
  - optical components

Behavior of Ytterbium (Mg-like atom) in solid Ne has been extensively studied:

Xu, Hu, **Singh**, *et al*. PRL 107, 093001 (2011)
Xu, **Singh**, *et al*. PRL 113, 033003 (2014)

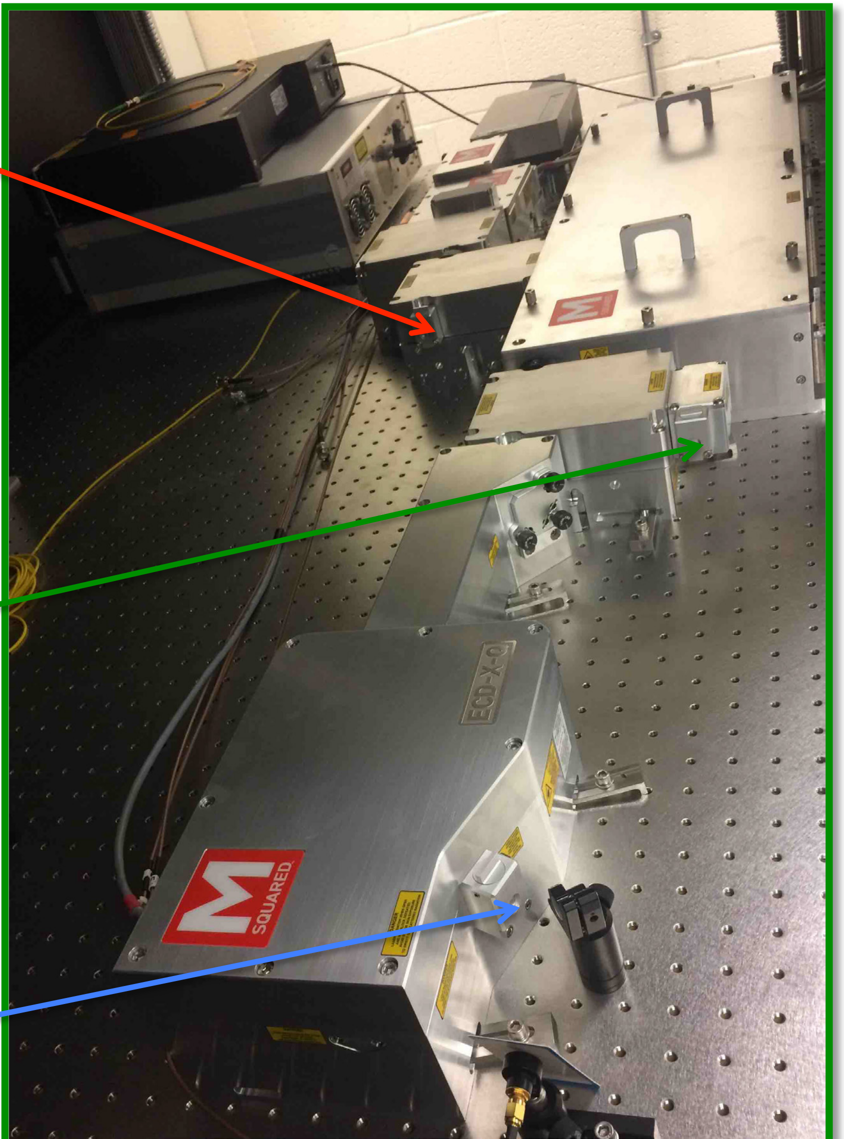
High Power and Tunable Lasers Installed!



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

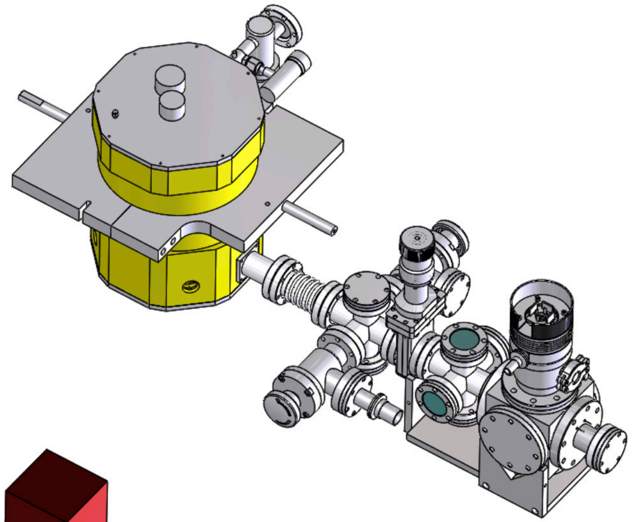
Sum Frequency
Mixing Module
1 W @ 500-600 nm
computer tunable

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

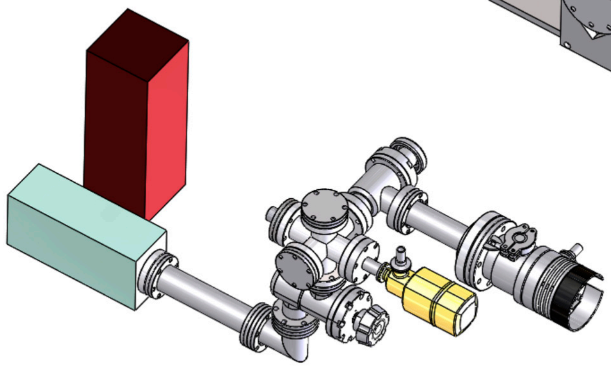


Other Equipment Installed in SPINLAB

LHe cryostat
for sample
preparation



Atomic
Beam
Source



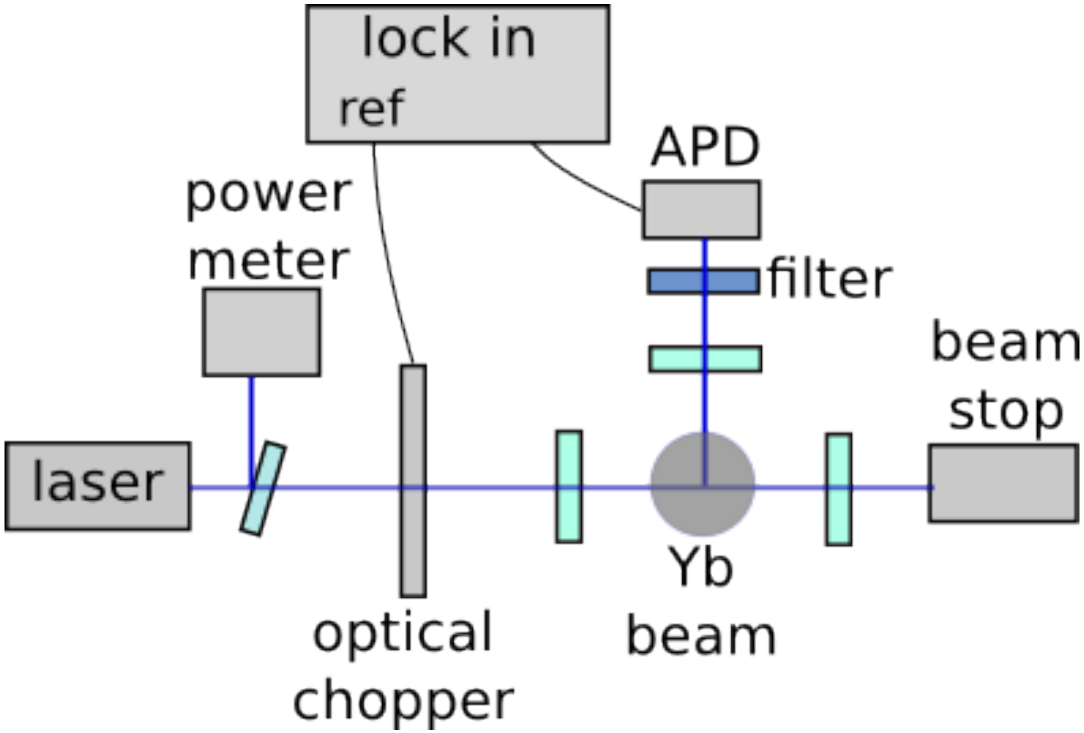
Neon Purification
Gas Handling

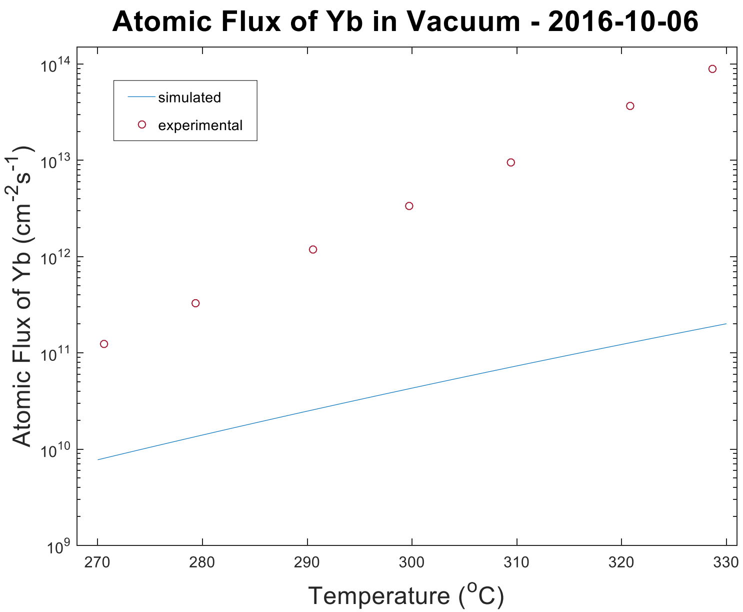
Andor Clara CCD Camera
operating temperature: -55 ^{o}C
dark noise: 2.3 “photons”/hr/pixel
read noise: 5.2 “photons”
quantum efficiency: 0.65 @ 550 nm
6.45x6.45 micron pixels
1392x1040 pixels
8.98x6.71 mm active area

Preliminary Study of Atomic Beam Flux

How many **green** photons are produced per atom per **blue** excitation?

1. Measurement of atomic beam flux from oven to substrate
   Kristen Parzuchowksi's poster (00EA.116 Friday 10/14 @ 1400)
2. Measurement of fluorescence yield from embedded atoms
3. Measurement of laser beam properties (power, size, shape, spectrum)



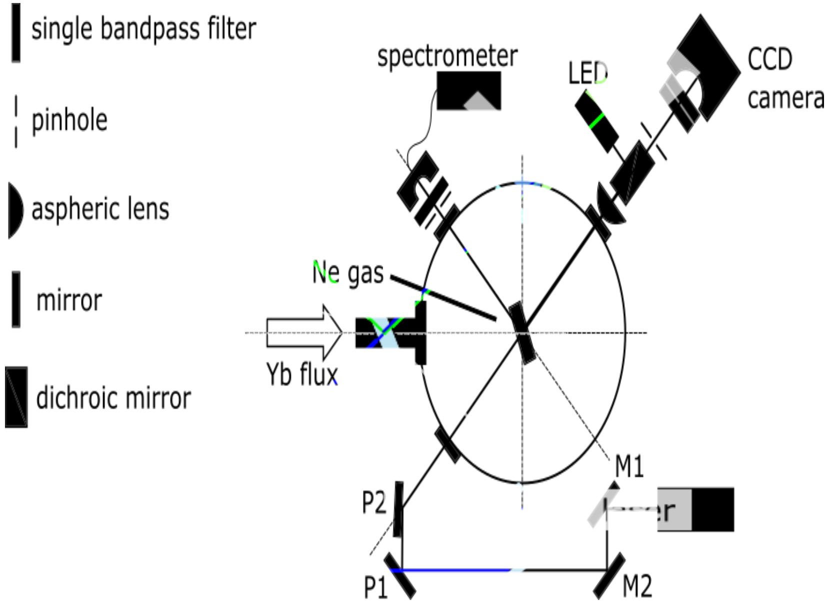


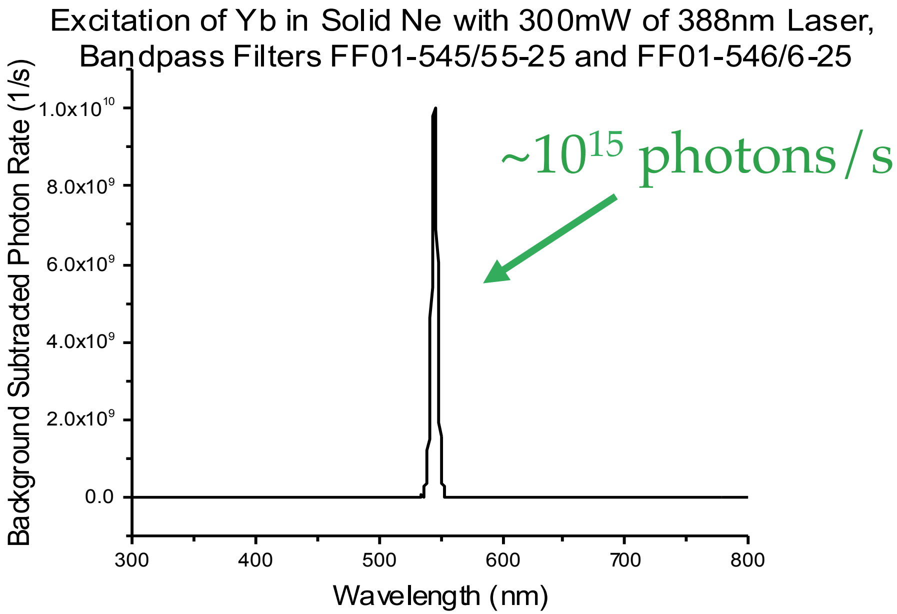
Very preliminary result:
(10^{11} to 10^{14})/cm^2/sec @ 327 ^{o}C

Preliminary Study of Yb-sNe Brightness

How many **green** photons are produced per atom per **blue** excitation?

1. Measurement of atomic beam flux from oven to substrate
   Kristen Parzuchowksi's poster (00EA.116 Friday 10/14 @ 1400)
2. Measurement of fluorescence yield from embedded atoms
3. Measurement of laser beam properties (power, size, shape, spectrum)



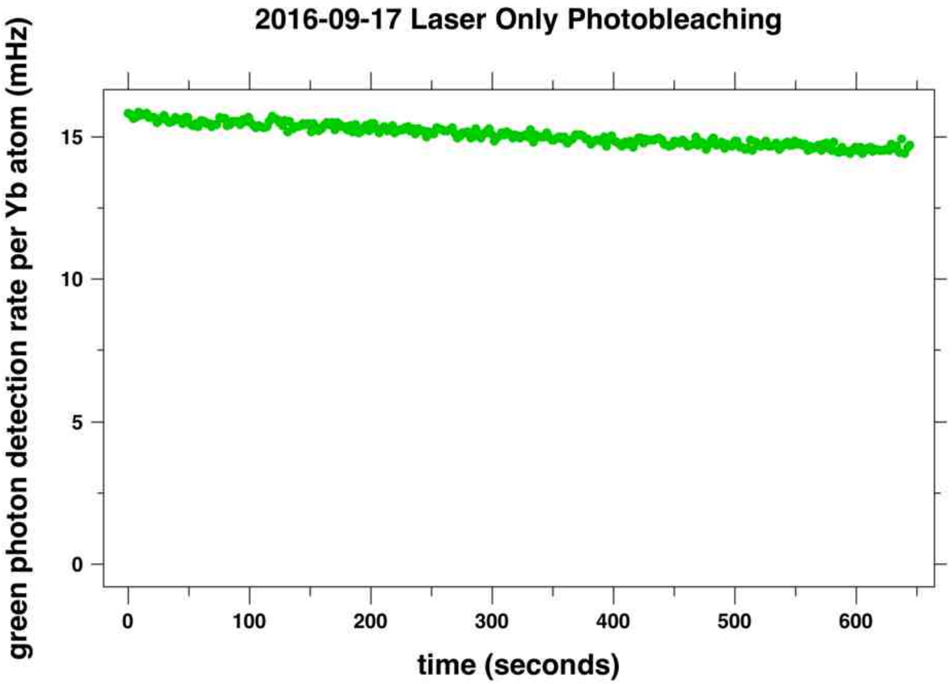


Very preliminary result:
Yb-sNe green-blue conversion efficiency = 10^{-5} to 10^{-2}

Preliminary Study of Photo-bleaching

How many **green** photons are produced per atom per **blue** excitation?

1. Measurement of atomic beam flux from oven to substrate
   Kristen Parzuchowksi's poster (00EA.116 Friday 10/14 @ 1400)
2. Measurement of fluorescence yield from embedded atoms
3. Measurement of laser beam properties (power, size, shape, spectrum)



Very preliminary results:

15 mHz rate (blue-green efficiency=10^{-4})

54 photons per atom per hour

dark noise = 2.3 per hour per pixel
read noise = 5.2

Potential Sources of Background

Background	Source	Wavelength	Notes
Scattered Light	excitation light	blue	optical filter
Nitrogen	residual gas	< 200 nm	too far off resonance
Oxygen	residual gas	< 245 nm	too far off resonance
Ozone	residual gas	< 350 nm	too far off resonance
Water	residual gas	< 210 nm	too far off resonance
UVFS	**windows**	**?**	**needs more study**
Cr^{3+}	**sapphire substrate**	**~700 nm + green tail**	**see below**
Apiezon N	**cryostat**	**broadband green**	**don't use this**

Impurities in sapphire substrate seem to have a very weak but broadband green emission spectrum

Plans to mitigate this:

- confocal optics
- higher quality sapphire substrates (Guild Optical)
- try CaF_2 substrates

Outlook and Conclusions

- Preliminary studies are underway!
- If backgrounds can be controlled, then single atom detection of Yb is possible with existing equipment!
- Next steps:
  - background studies
  - precision measurement of atomic beam flux
  - basic spectroscopy of Mg and alkalis
  - attempt single Yb detection in solid Ne

MSU Team:
Jennifer Wenzl (postdoc)
Dustin Frisbie (PhD Student)
Kristen Parzuchowski (undergrad)