The $^{12}C(\alpha,\gamma)^{16}O$ Bubble Chamber Experiment

K. E. Rehm
Physics Division
Argonne National Laboratory

Elba XIV Lepton Nucleus Scattering
Marciana Marina, Isola d’Elba
June 30, 2016

NGC 7635 Bubble Nebula

Outline

1. Importance of $^{12}C(\alpha,\gamma)^{16}O$ in nuclear astrophysics

2. Previous experiments
   a) ^{12}C targets + α beams
   b) ^{4}He targets + ^{12}C beams
   c) Bubble chamber

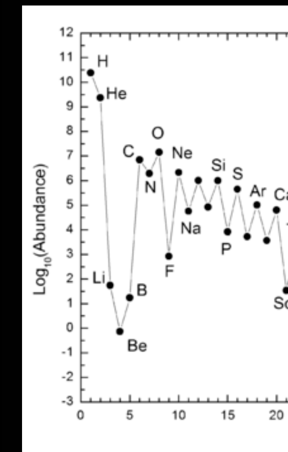
3. Measurements at HIγS

4. Experiments at JLAB

5. Outlook and future plans

NGC 7635 Bubble Nebula

Importance of the $^{12}C(\alpha,\gamma)^{16}O$ reaction



stars

Oxygen: 3rd most abundant element in the universe, the most abundant on the earth' s surface and in our body

Massive stars → Black hole / Neutron star

lighter stars → C/O ratio of white-dwarfs – type Ia SN

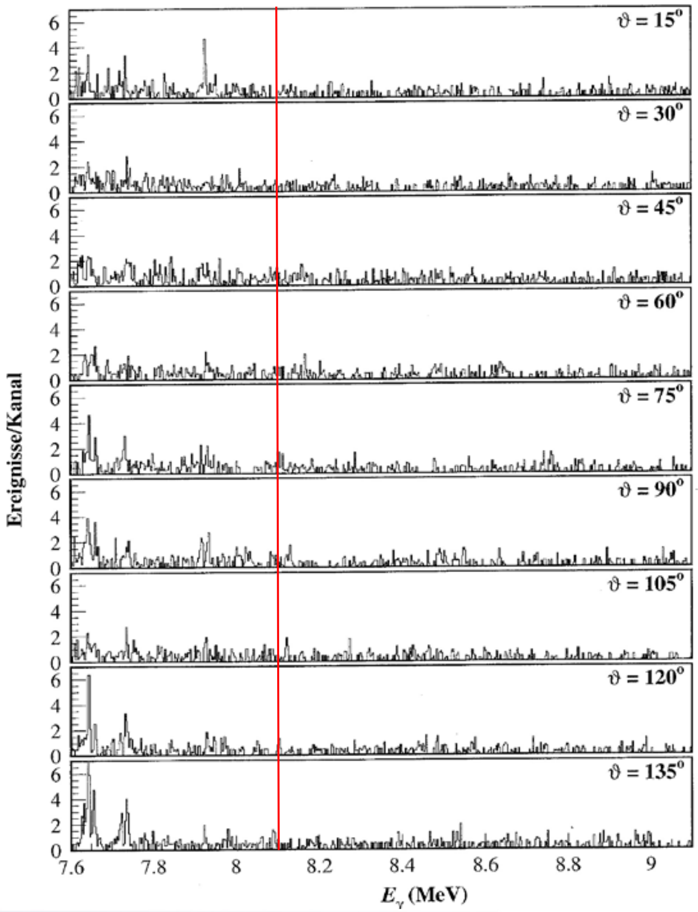
- $^{12}C(\alpha,\gamma)^{16}O$, ..a problem of paramount importance to nuclear astrophysics.
- ..the "holy grail" of nuclear astrophysics. W. Fowler

$^{12}C(\alpha,\gamma)^{16}O$ (1964 –)

Using EUROGAM detectors

R. Kunz et al. PRL 86, 3244 (2001)

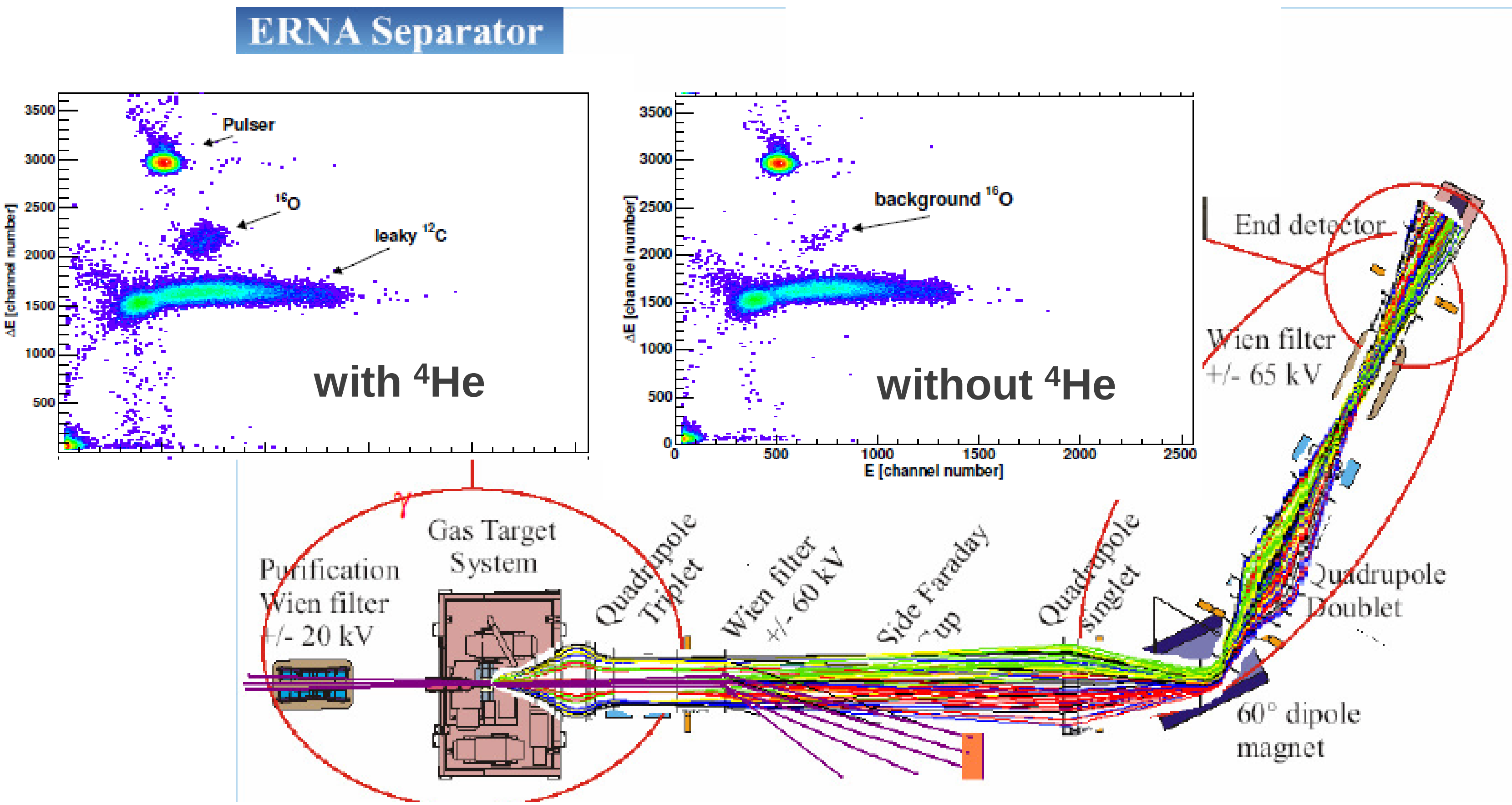
Lowest energy: E_{cm}=0.945 MeV



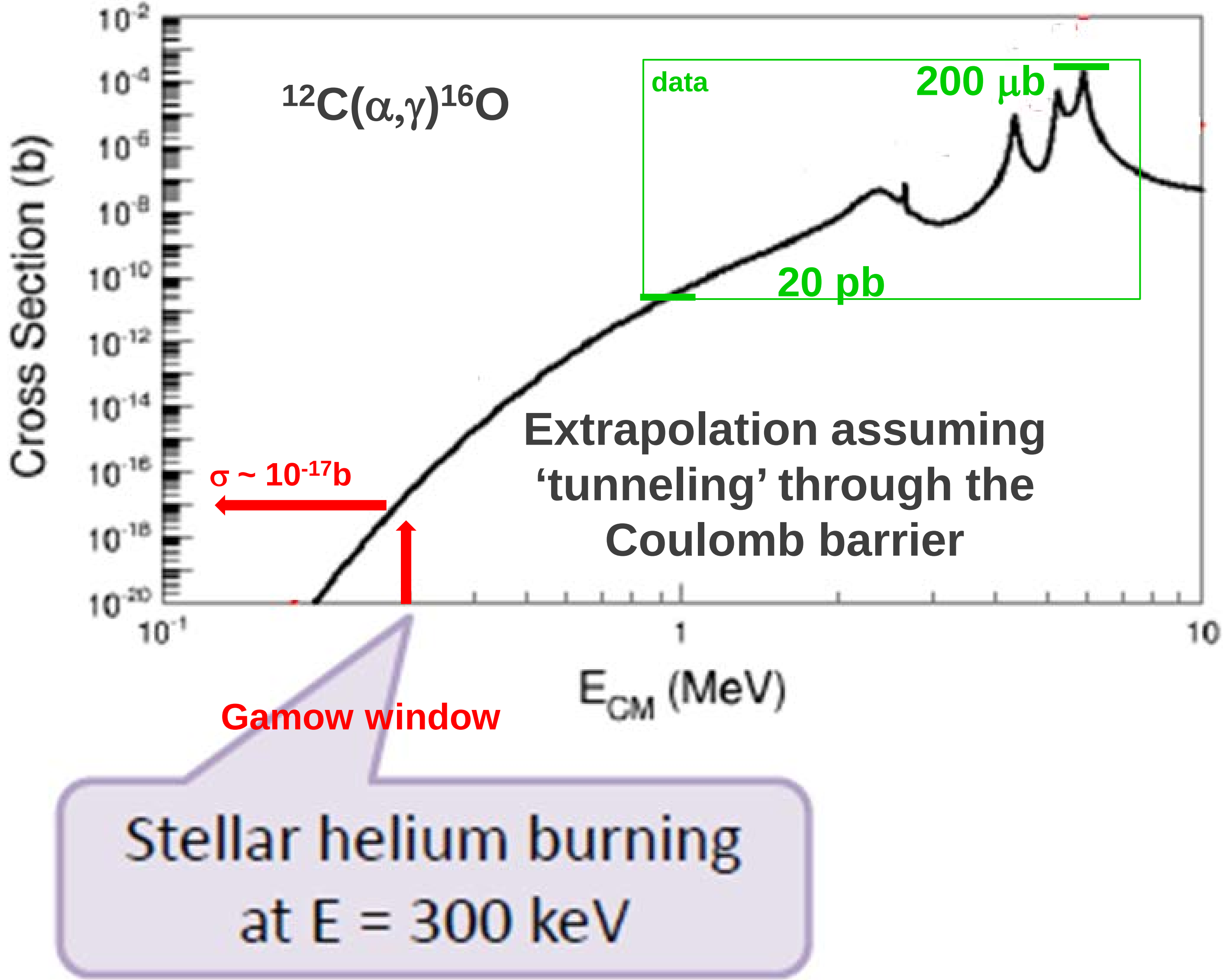
^{4}He(^{12}C,^{16}O)γ (2001–)

Using a Recoil Mass Separator

D. Schürmann et al. EPJA 26, 301 (2001)

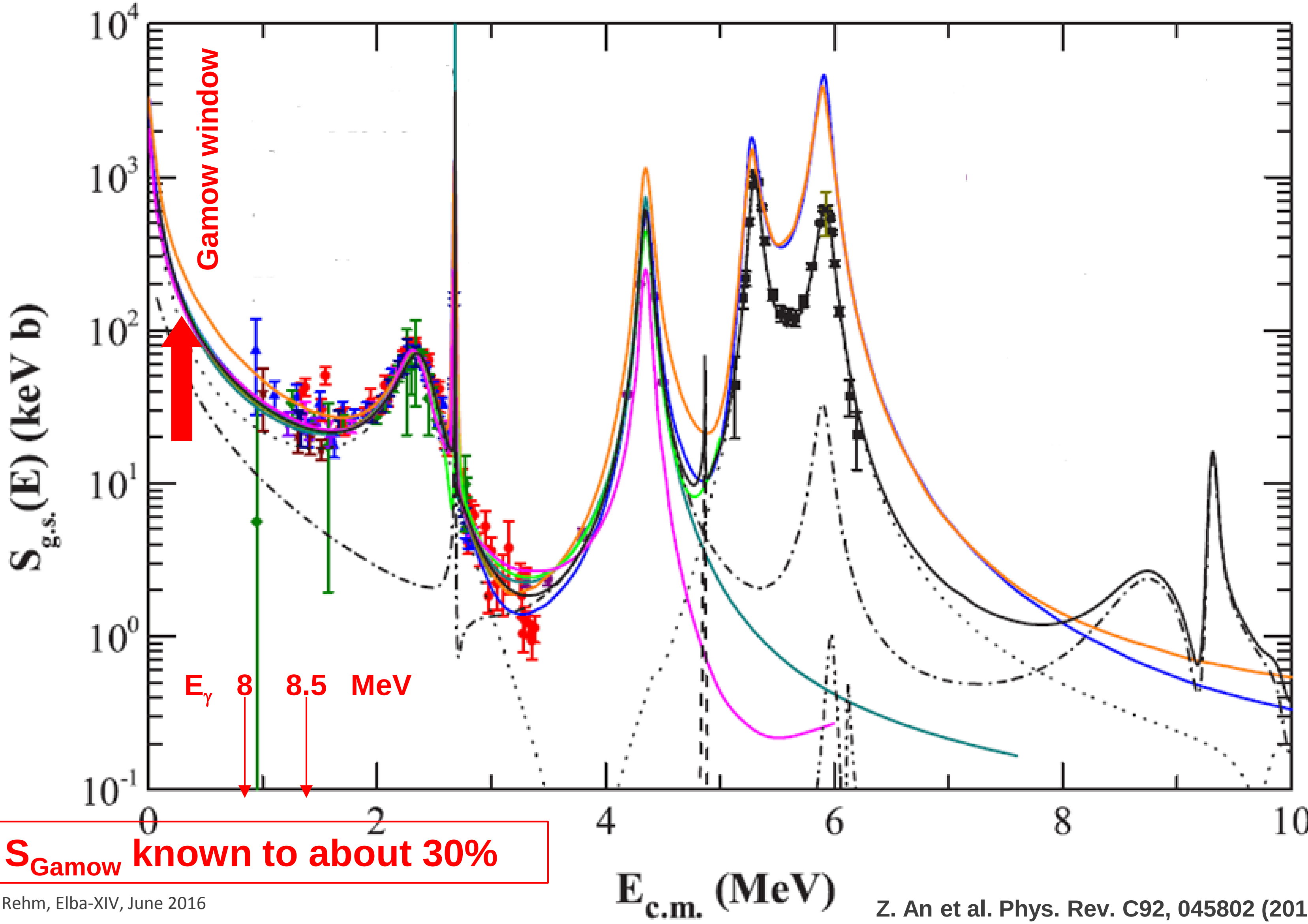


Lowest energy: E_{cm}=1.903 MeV



$^{12}C(\alpha,\gamma)^{16}O$
data
200 μb
20 pb
Extrapolation assuming 'tunneling' through the Coulomb barrier
σ ~ 10^{-17}b
Gamow window
Cross Section (b)
E_{CM} (MeV)
Stellar helium burning at E = 300 keV

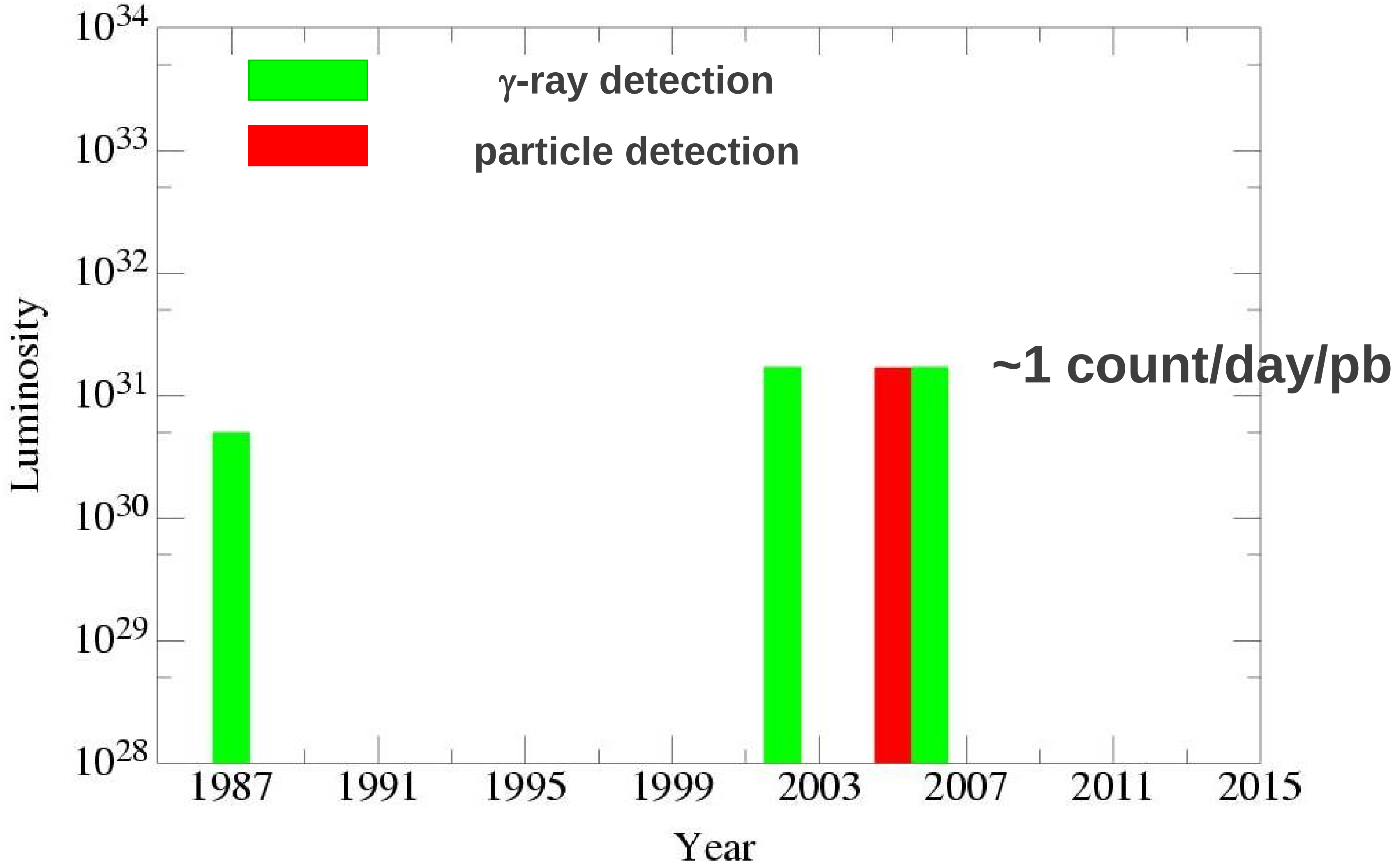
‘World’ data of $^{12}C(\alpha,\gamma)^{16}O$



S_{Gamow} known to about 30%

Z. An et al. Phys. Rev. C92, 045802 (2015)

luminosity of recent experiments



Measurement of the inverse $^{16}O(\gamma,\alpha)^{12}C$ reaction

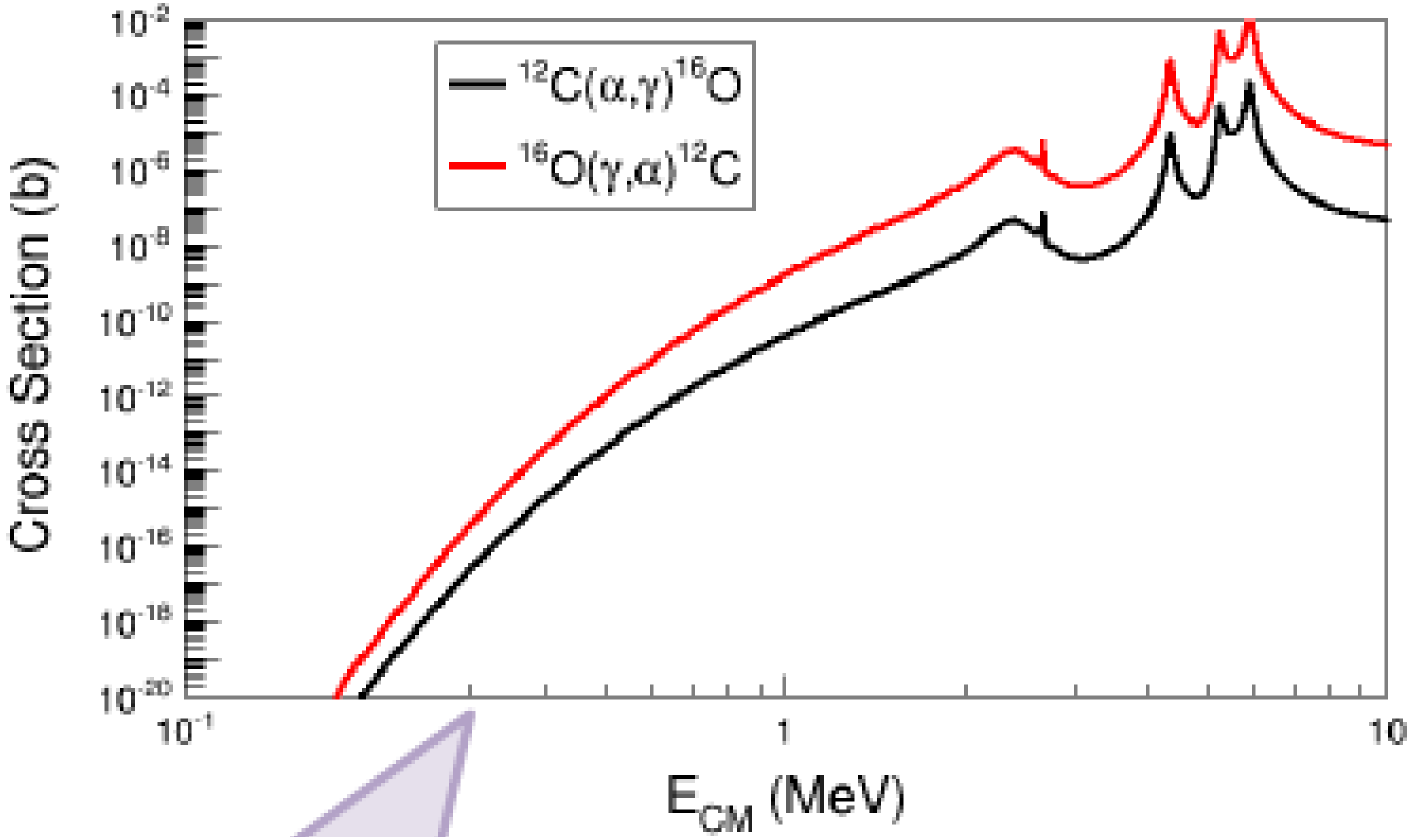
Advantages of inverse reactions (theorem of reciprocity)

[0(1,2)3 vs 3(2,1)0]

$$\frac{\sigma_{23\to01}}{\sigma_{01\to23}} = \frac{(2j_o+1)(2j_1+1)}{(2j_2+1)(2j_3+1)}\frac{k_{01}^2}{k_{23}^2}$$

For $^{12}C(\alpha,\gamma)^{16}O$ vs $^{16}O(\gamma,\alpha)^{12}C$

$$\frac{\sigma_{\gamma,\alpha}}{\sigma_{\alpha,\gamma}} = \frac{2\mu_{\alpha,\gamma}c^2E_{\alpha,\gamma}}{2E_\gamma^2} = \frac{2\cdot4\cdot12\cdot1000\cdot1}{2\cdot16\cdot8\cdot8}\approx 50$$



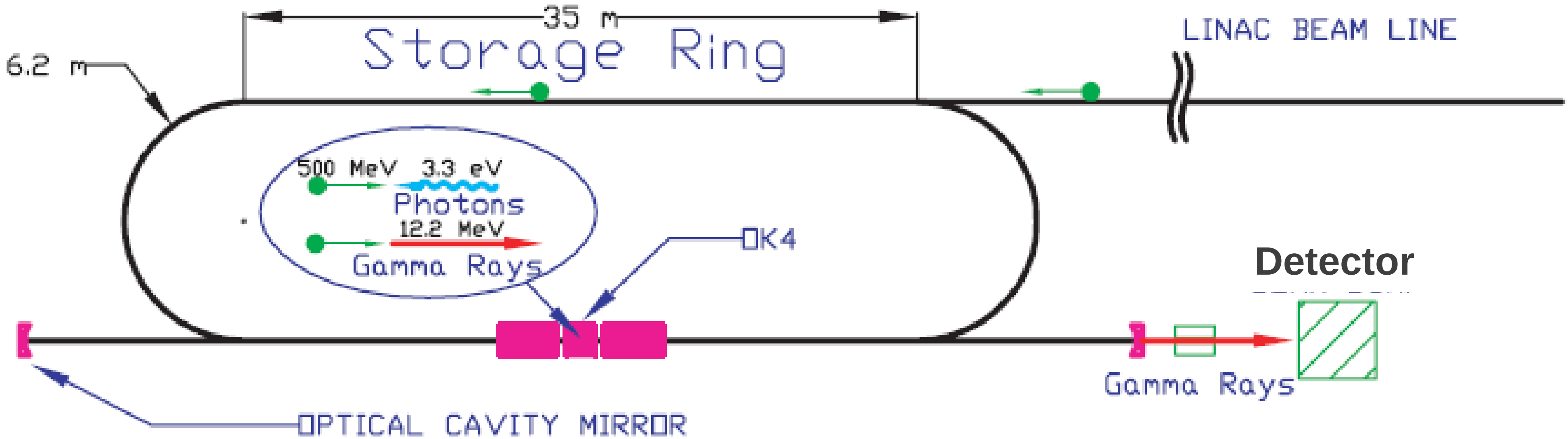
Stellar helium burning
at E = 300 keV

1. Need a source of 7-10 MeV γ's

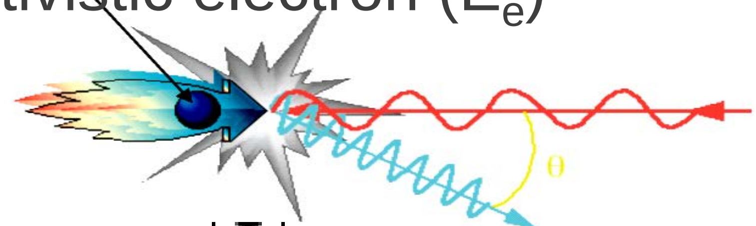
- High Intensity Gamma Source (HIγS) at Duke University
- Bremsstrahlung beam at Jefferson Lab in Virginia

2. Need an active target detector: $^{16}O(\gamma,\alpha)^{12}C$

Production of γ's at HIγS, inverse Compton effect

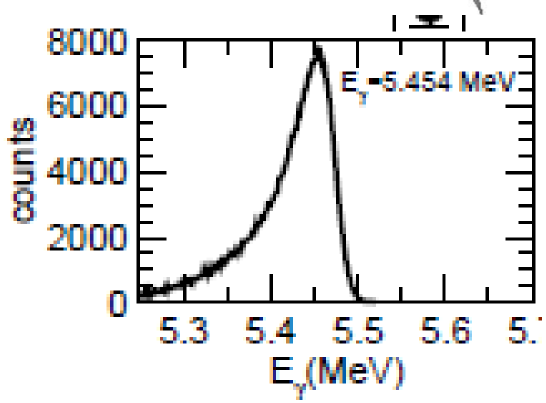


Relativistic electron (E_e)



Laser light (λ_L)

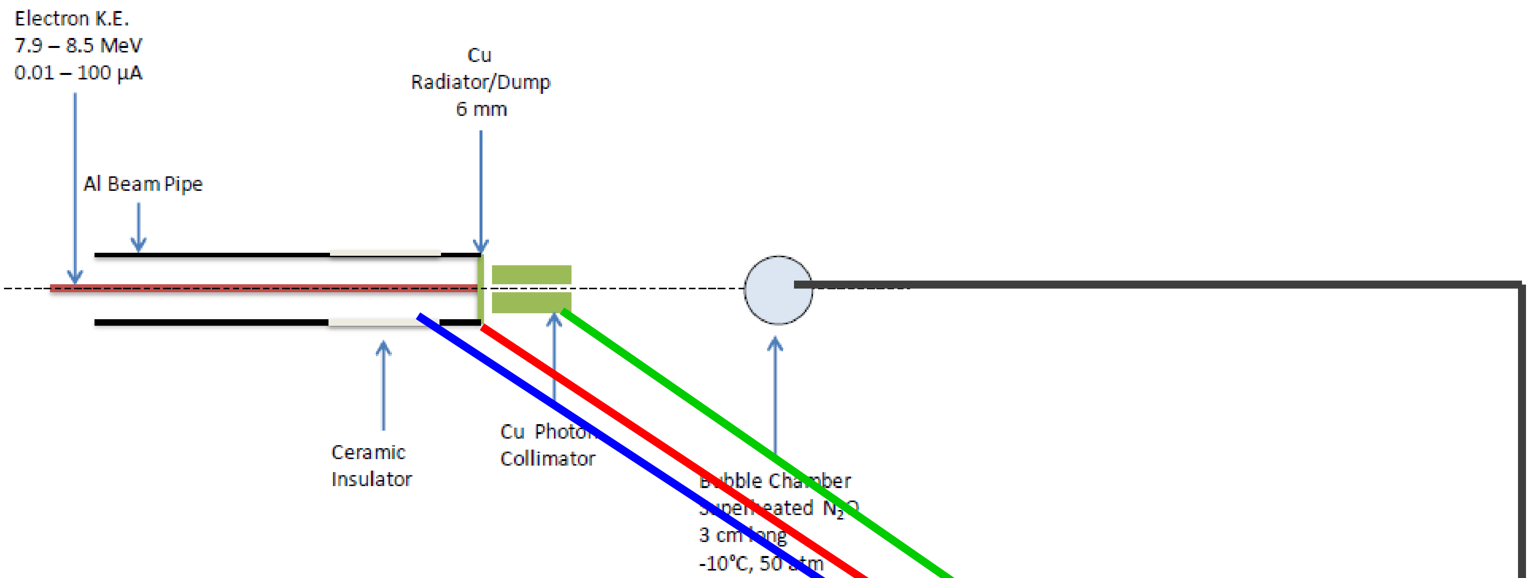
γ (E_γ) 'mono-energetic'

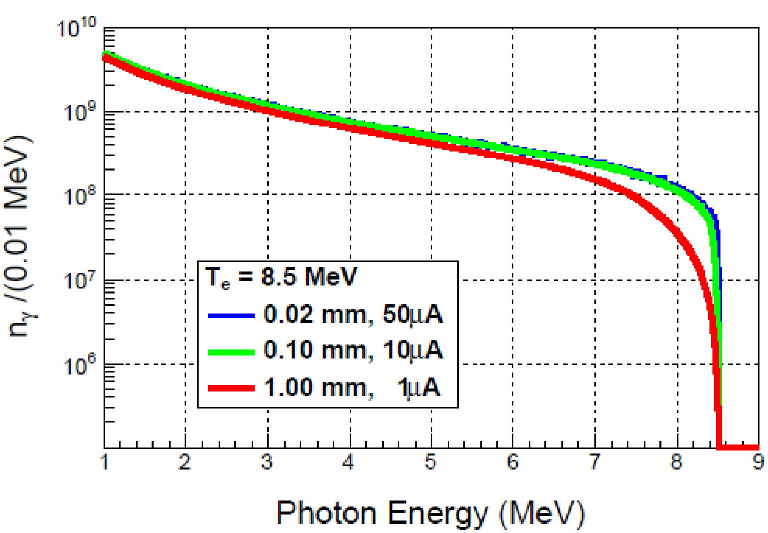


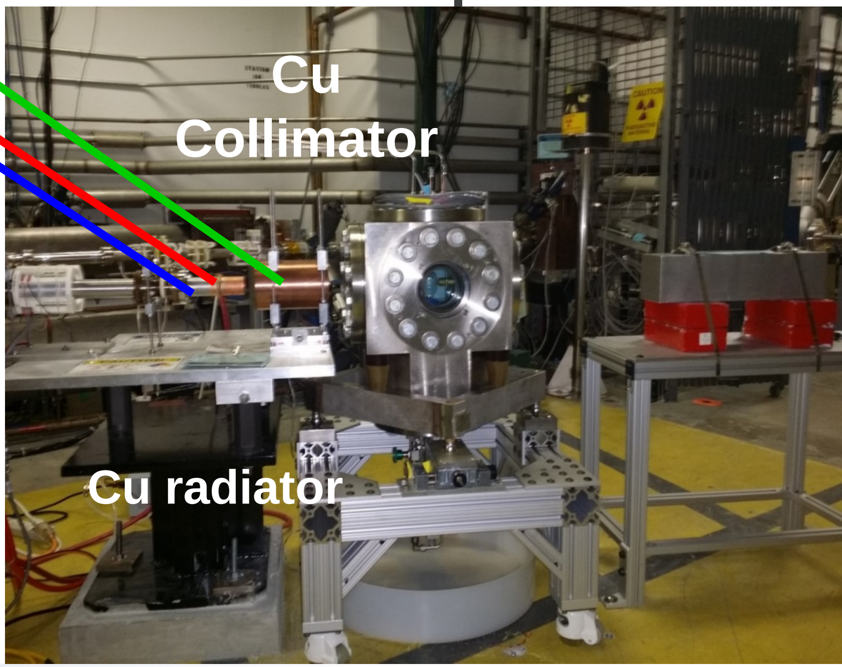
$\Phi \sim 10^8$ γ/sec, FWHM ~ 70 keV

<u>Other laboratories:</u>
NewSUBARU (JAPAN)
SLEGS (China)
ELI (Romania)

Production of γ's at JLAB, $\Phi \sim 10^{11}\gamma$/s Bremsstrahlung







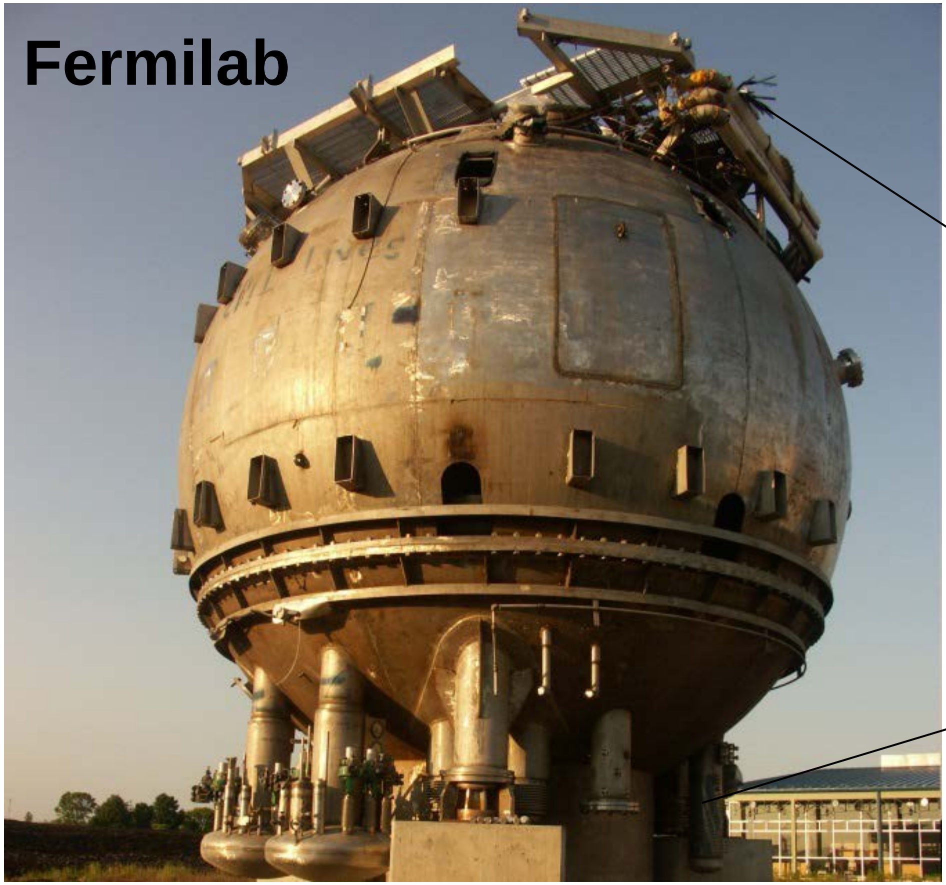
2. Need an active target detector: $^{16}O(\gamma,\alpha)^{12}C$

- Insensitive to gammas
- 100% sensitivity for charged particles (α,^{12}C)
- Works with an oxygen-containing material

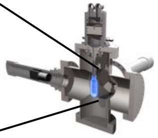
→Bubble chamber

- **Liquids in bubble chambers have thicknesses of ~10 g/cm^2 (compared to ~10 $\mu g/cm^2$ for (α,γ) studies)**

Bubble chambers



ANL



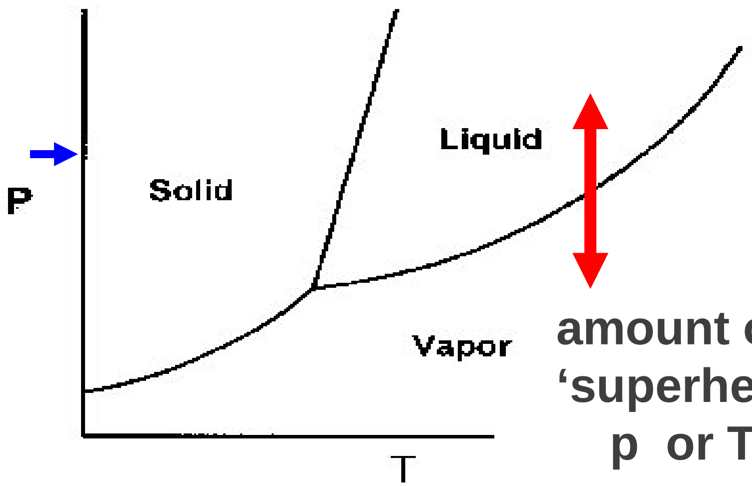
based on Dark Matter experiments (COUPP, Picasso at SNO-lab)

Pulsed

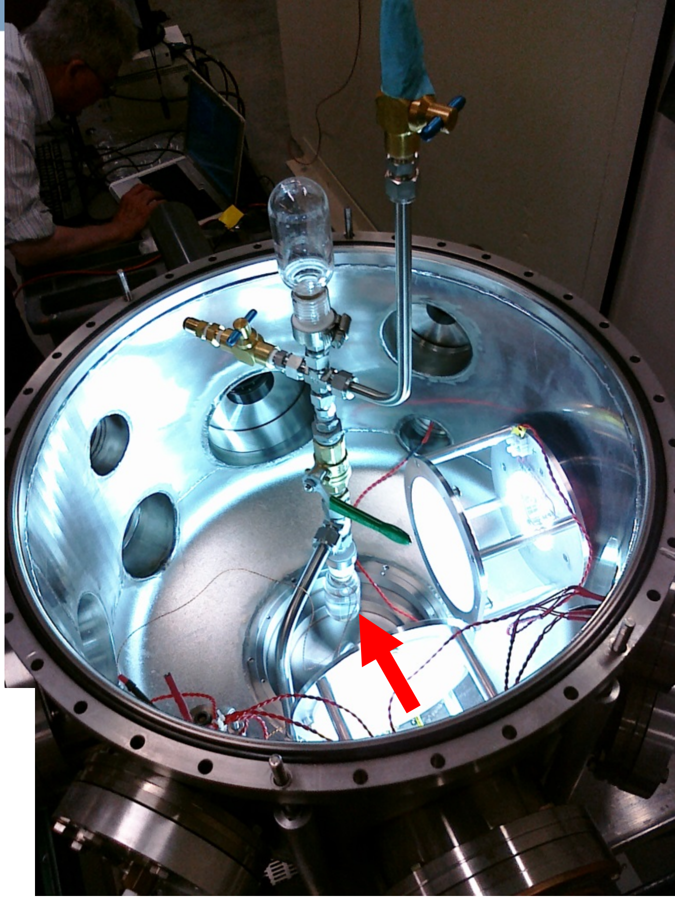
continuously operating

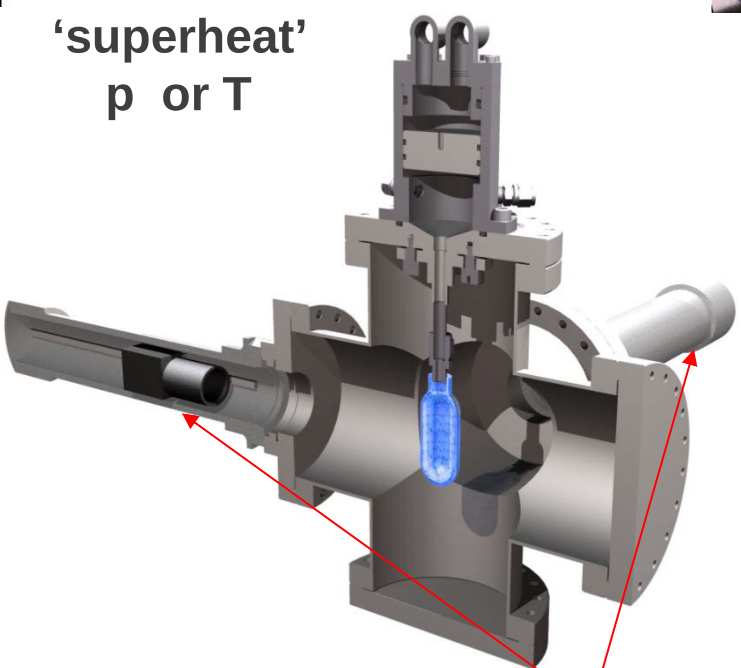
C. Amole et al. , PRL 114, 231302 (2015)

bubble chamber operating with C_4F_{10}



amount of
‘superheat’
p or T





2 fast cameras

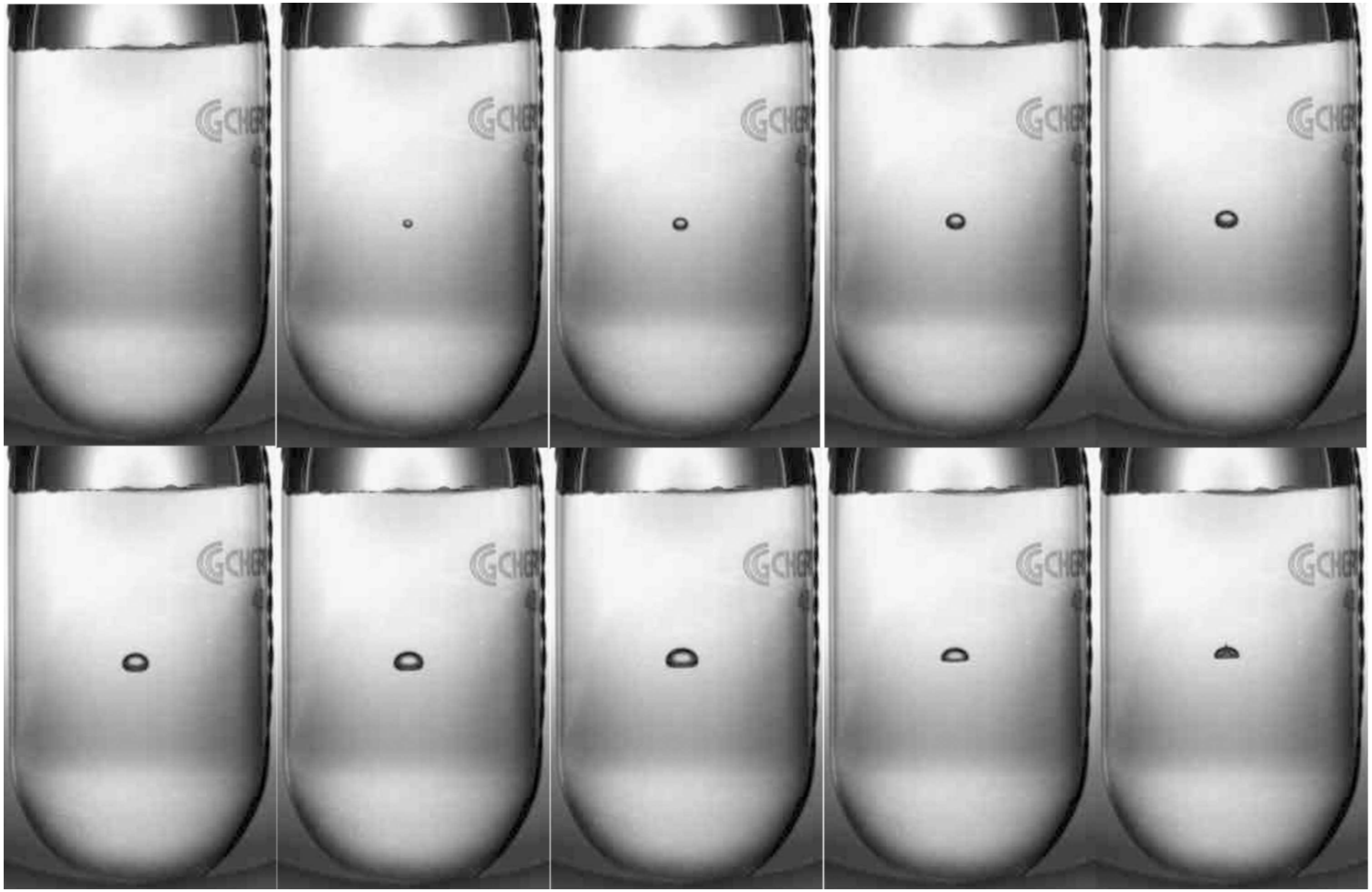
$^{19}F(\gamma,\alpha)^{15}N$

Fluorine is
mono-isotopic

A bubble chamber operating with C_4F_{10}

Δt=10 msec

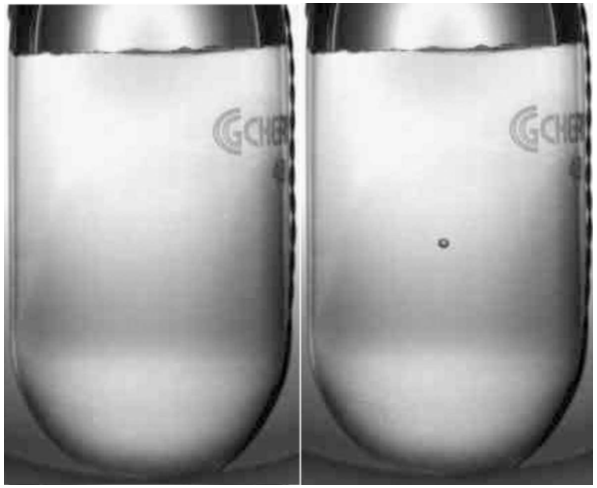
γ beam →

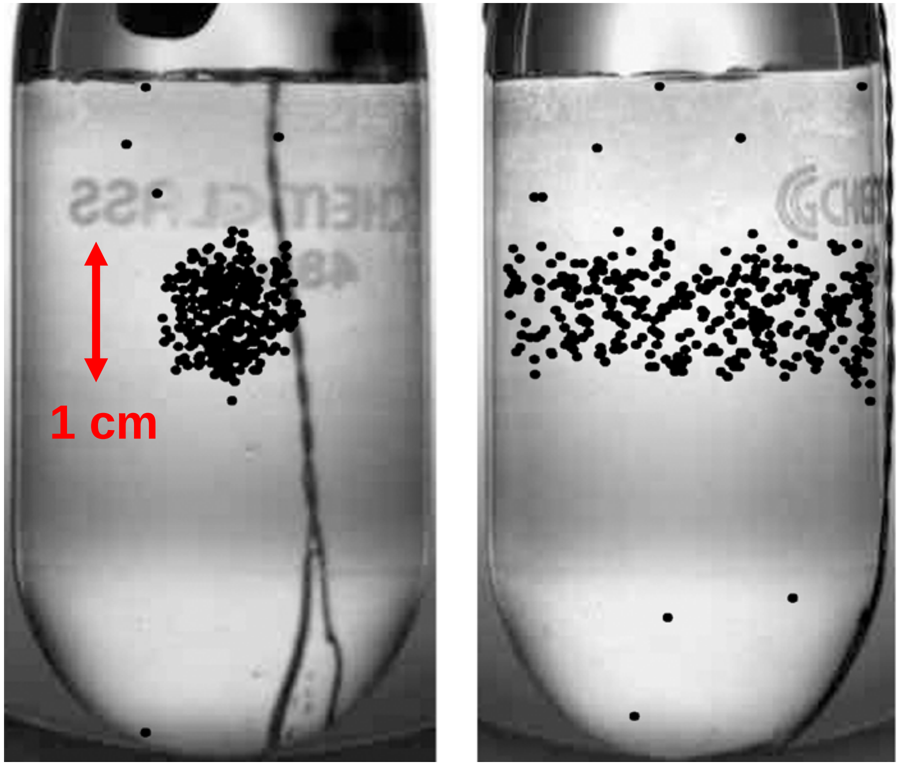


low count rate ~ 0.1- 0.5 Hz !

Δt=10 msec

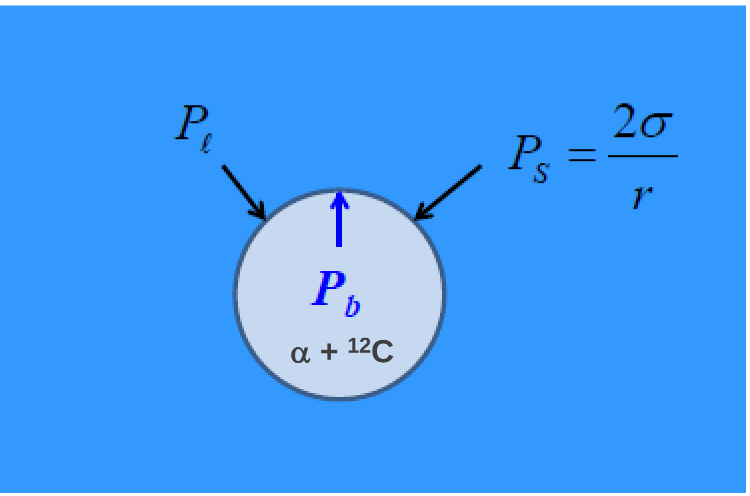
γ beam

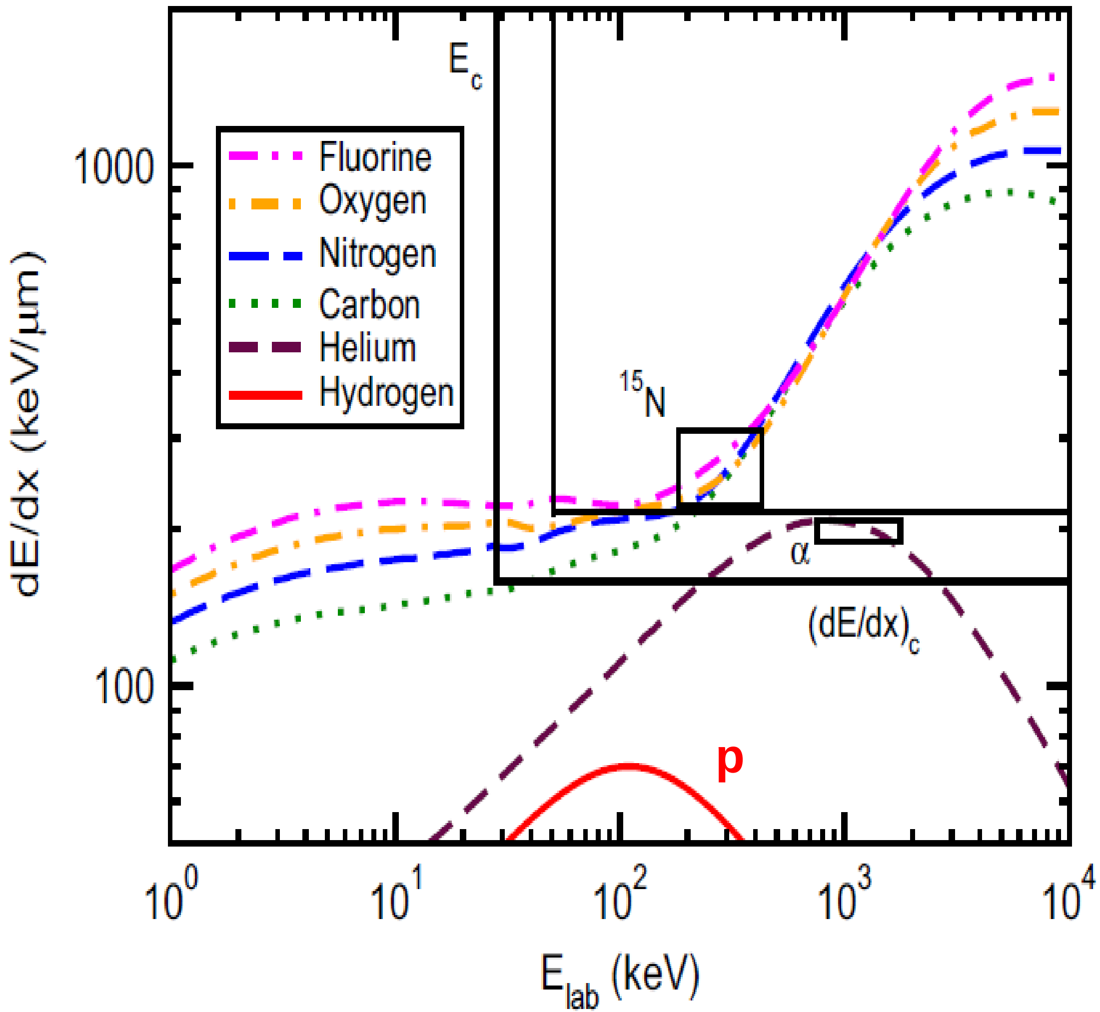




Principle of bubble chambers (threshold detector)

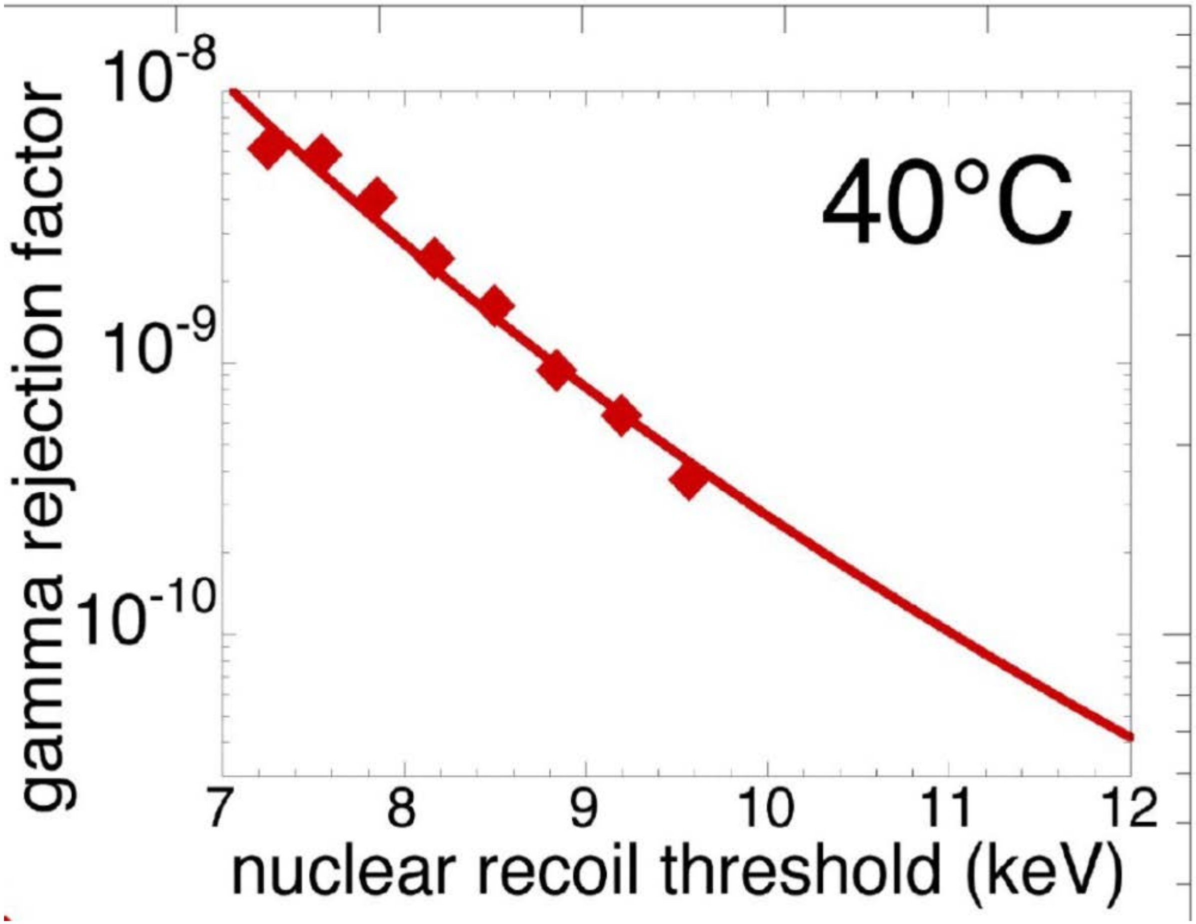
F. Seitz, Phys. Fluids 1,1(1958)





$$P_b > P_l + 2\sigma/r$$

Insensitivity to γ's (FNAL)



Contents lists available at SciVerse ScienceDirect
Physics Letters B
www.elsevier.com/locate/physletb

First determination of an astrophysical cross section with a bubble chamber: The $^{15}N(\alpha,\gamma)^{19}F$ reaction

C. Ugalde [a,*], B. DiGiovine [b], D. Henderson [b], R.J. Holt [b], K.E. Rehm [b], A. Sonnenschein [c], A. Robinson [d], R. Raut [e,f,1], G. Rusev [e,f,2], A.P. Tonchev [e,f,3]

[a] Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637, USA
[b] Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA
[c] Fermi National Accelerator Laboratory, Batavia, IL 60510, USA
[d] Department of Physics, University of Chicago, Chicago, IL 60637, USA
[e] Department of Physics, Duke University, Durham, NC 27708, USA
[f] Triangle Universities Nuclear Laboratory, Durham, NC 27708, USA

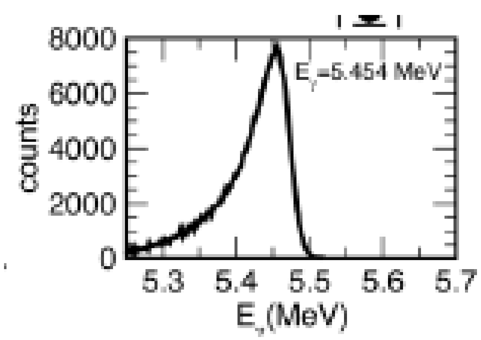
High luminosity

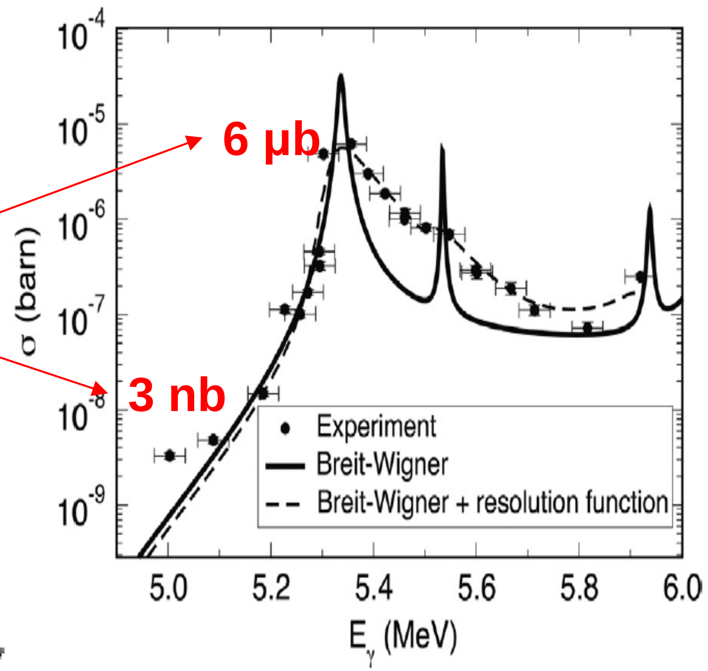
N_γ (6 μb) = 2 x 10^3 γ/sec

N_γ (3 nb) = 3 x 10^6 γ/sec

~ 400 events/hr

1 day of HIγS beam



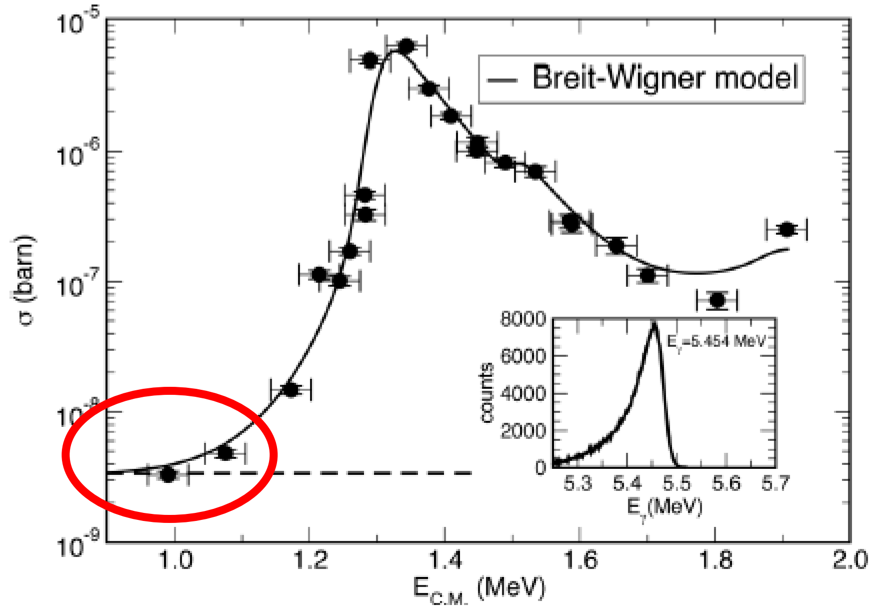


ELSEVIER
Contents lists available at SciVerse ScienceDirect
Physics Letters B
www.elsevier.com/locate/physletb

First determination of an astrophysical cross section with a bubble chamber: The $^{15}N(\alpha,\gamma)^{19}F$ reaction

C. Ugalde [a,*], B. DiGiovine [b], D. Henderson [b], R.J. Holt [b], K.E. Rehm [b], A. Sonnenschein [c], A. Robinson [d], R. Raut [e,f,1], G. Rusev [e,f,2], A.P. Tonchev [e,f,3]

[a] Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637, USA
[b] Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA
[c] Fermi National Accelerator Laboratory, Batavia, IL 60510, USA
[d] Department of Physics, University of Chicago, Chicago, IL 60637, USA
[e] Department of Physics, Duke University, Durham, NC 27708, USA
[f] Triangle Universities Nuclear Laboratory, Durham, NC 27708, USA



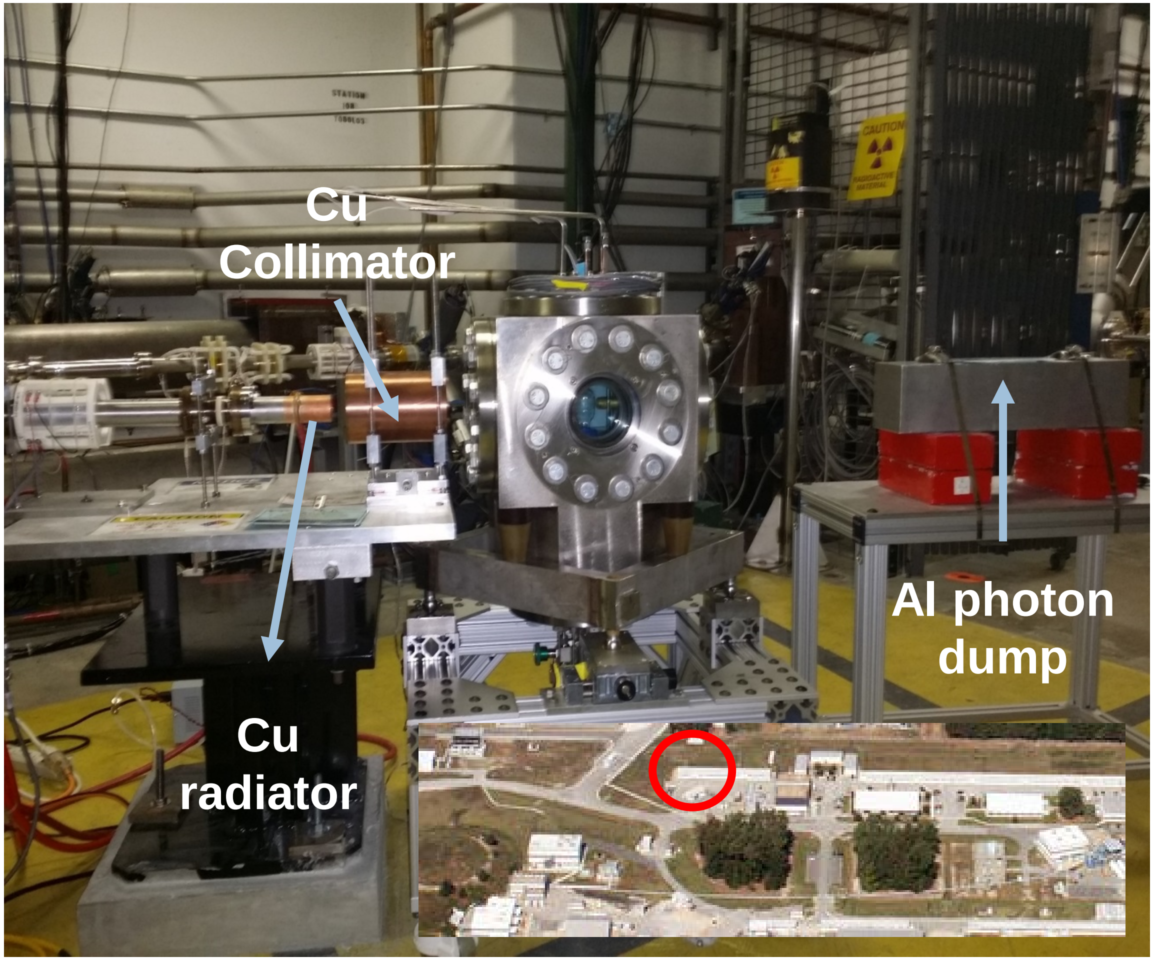
Problem: background from electron-residual gas interactions in the storage ring (σ ~ 3 nb)

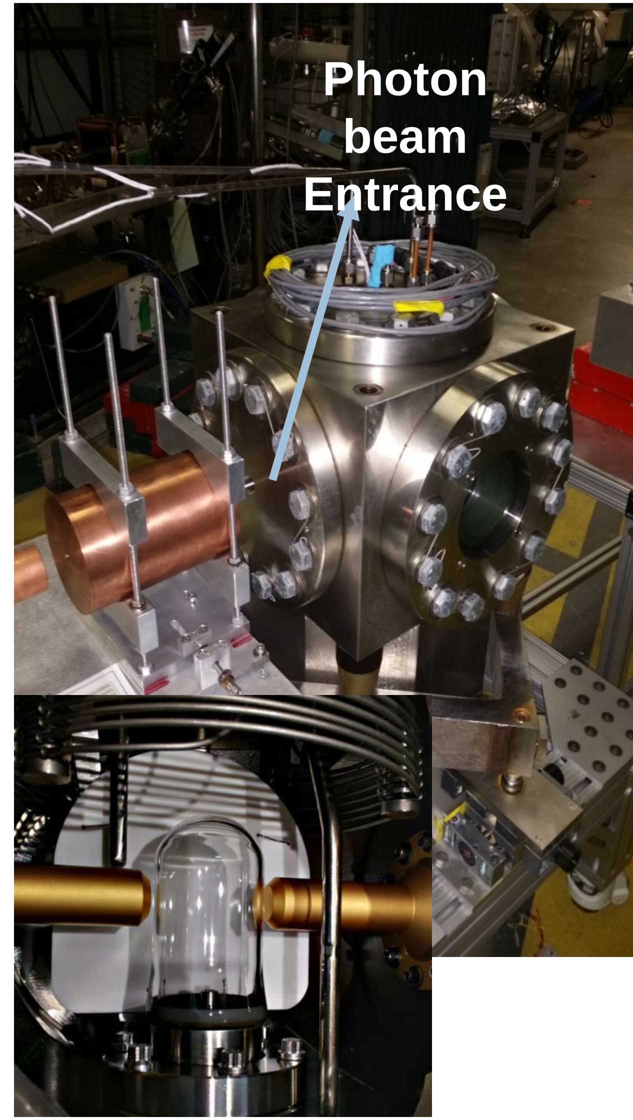
HIγS → JLAB

Choice of oxygen material ($Q(^{16}O(\gamma,\alpha)^{12}C = -7.164$ MeV):

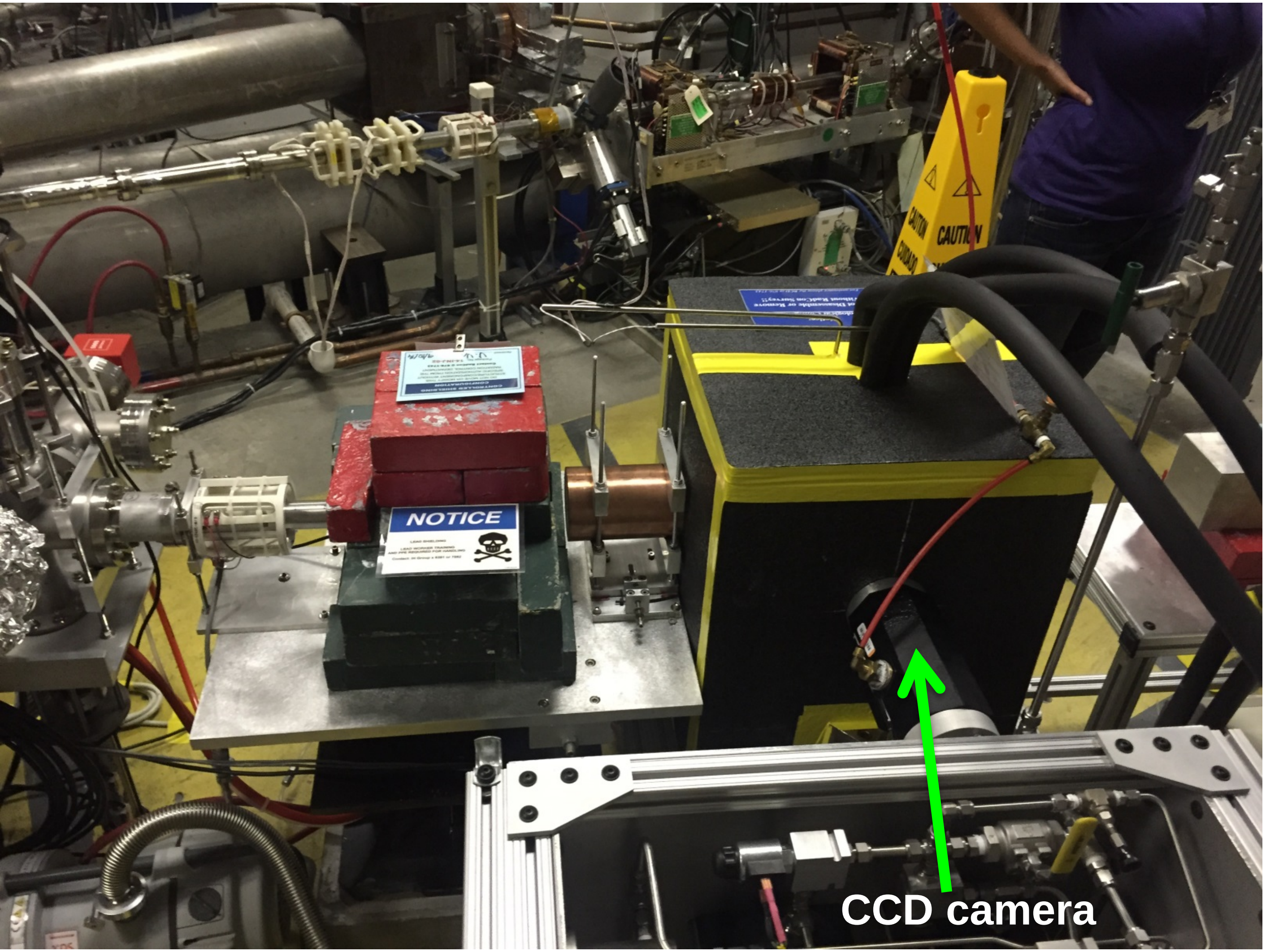
Fluid/buffer	Safety issues	Technical issues	Purity issues
H_2O/oil	no	high (T, p), mixing	^{2}H, $^{17,18}O$
CO_2/water	no	mixing	$^{12,13}C$, $^{17,18}O$
N_2O/water	yes	mixing	^{14}N, $^{17,18}O$
N_2O/Hg	yes	no	^{14}N, $^{17,18}O$

Set-Up for the Hg-N_2O engineering run at JLAB





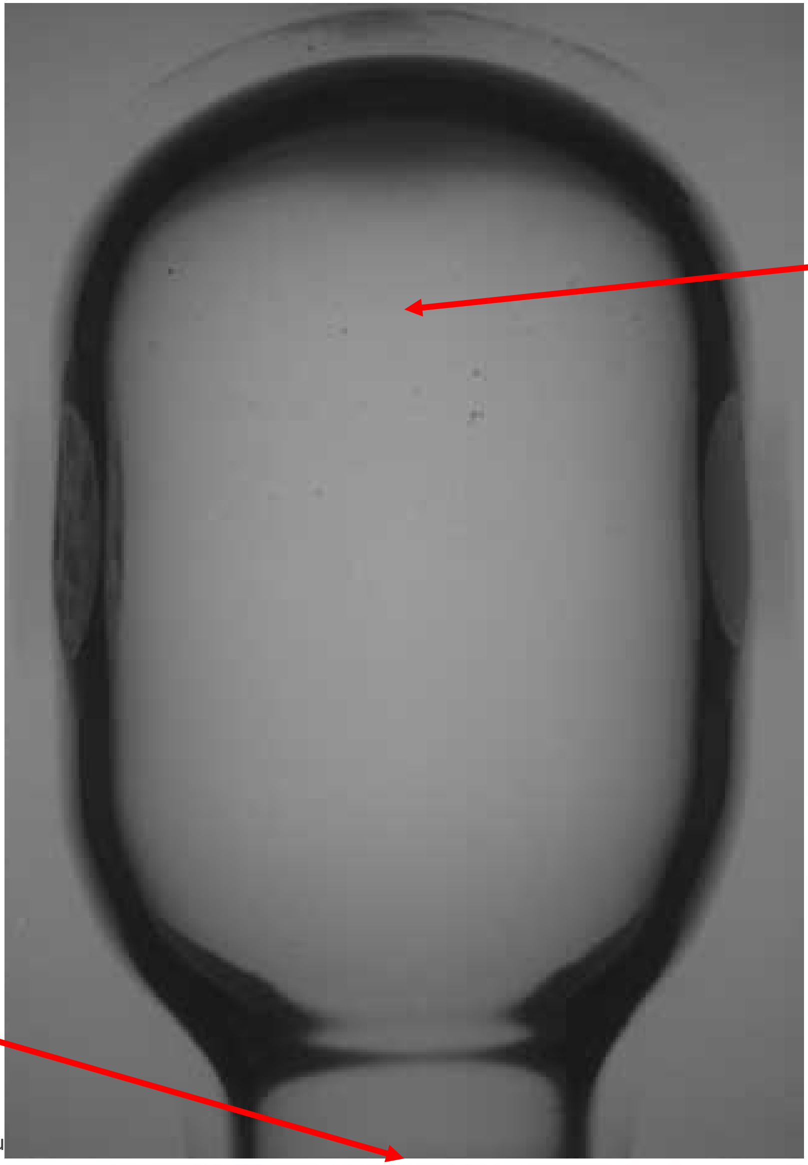
After installation of shielding



Goal of the engineering run:

- Test the performance of the bubble chamber with a Bremsstrahlung beam at JLAB
- Study the background level from cosmic ray neutrons
- Study the gamma suppression
- Measure the photodisintegration cross sections of the isotopes in the superheated N_2O liquid ($^{16,17,18}O$, $^{14,15}N$)

First photodisintegration event in bubble chamber with Bremsstrahlung from JLAB



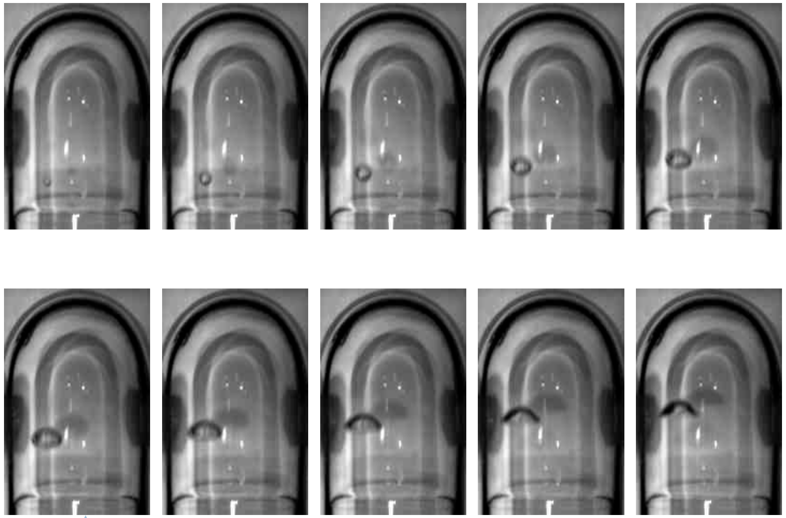
Liquid N_2O

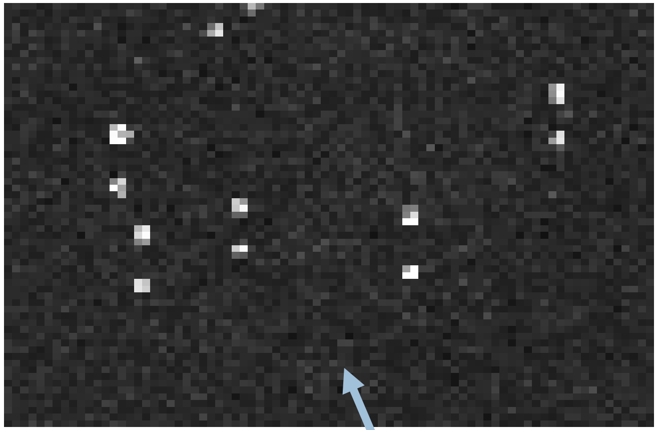
γ beam

Hg

September 10, 2015 19:40

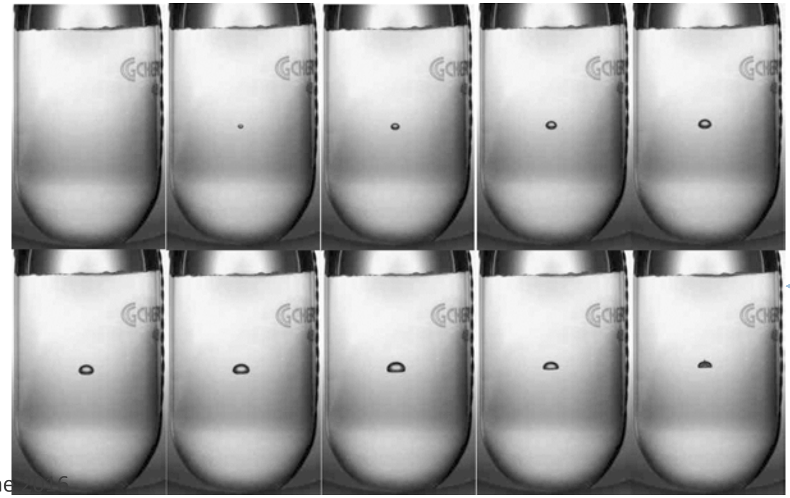
N_2O Bubble size small





N_2O bubbles
JLAB

H_2O bubble
n-source ANL

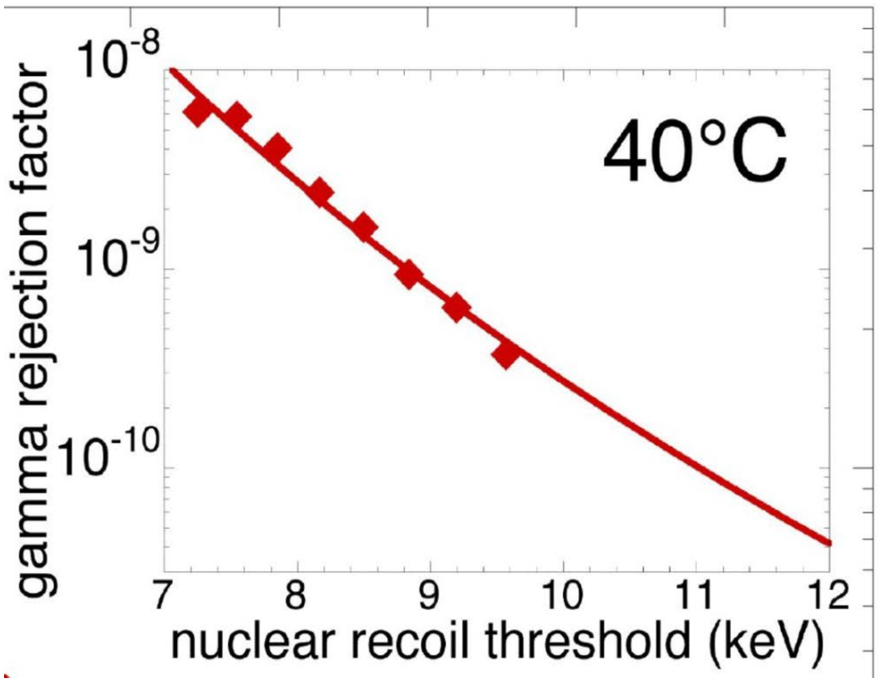


C_4F_{10} bubble HIγS

Test measurements, Sept 10-13

Cosmic background: JLAB injector is underground
cosmic neutron background is lower
(1 count in 17 min vs. 1 count in 2 min at HIγS)

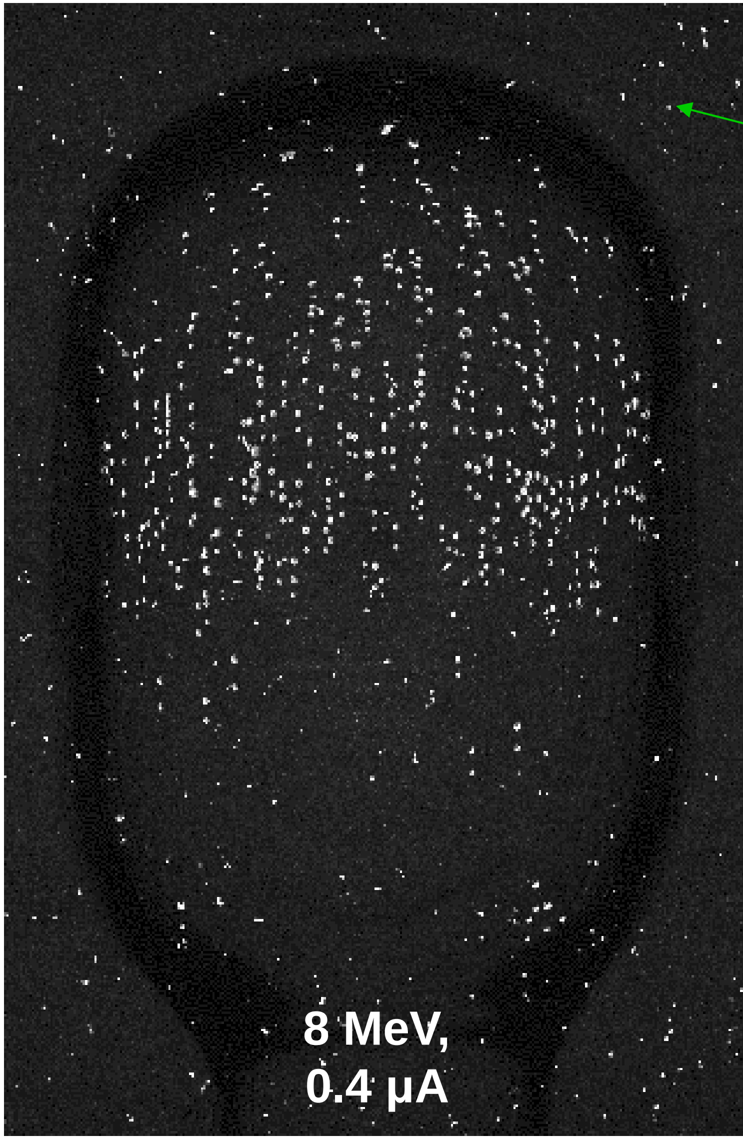
Gamma suppression: Excellent



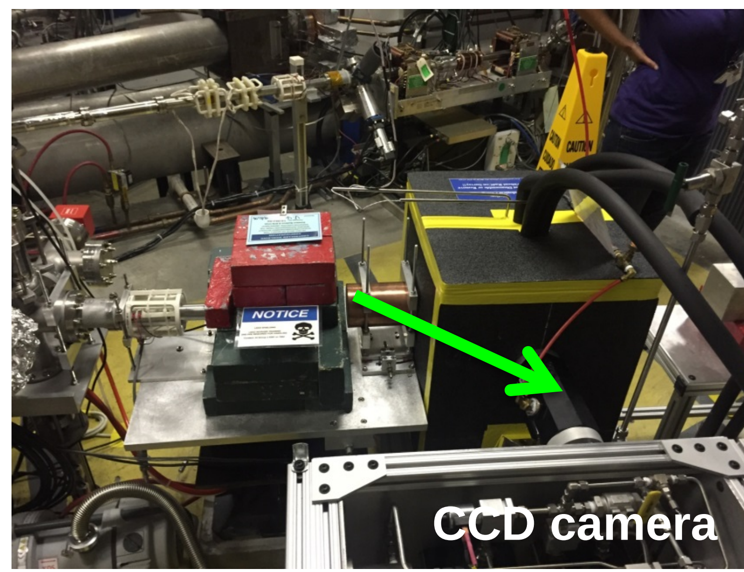
COUPP exp. FNAL ($3x10^{-10}$)

Data point from JLAB $< 10^{-12}$

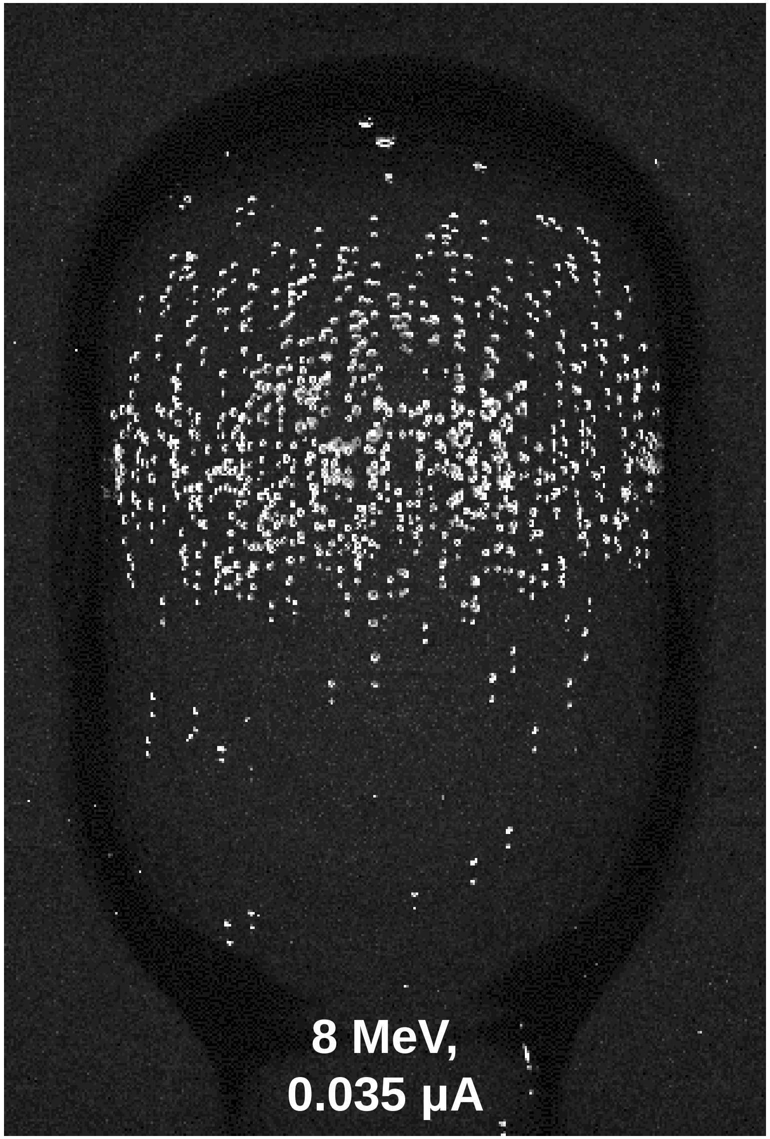
Background in CCD camera



Signals outside of the fiducial volume

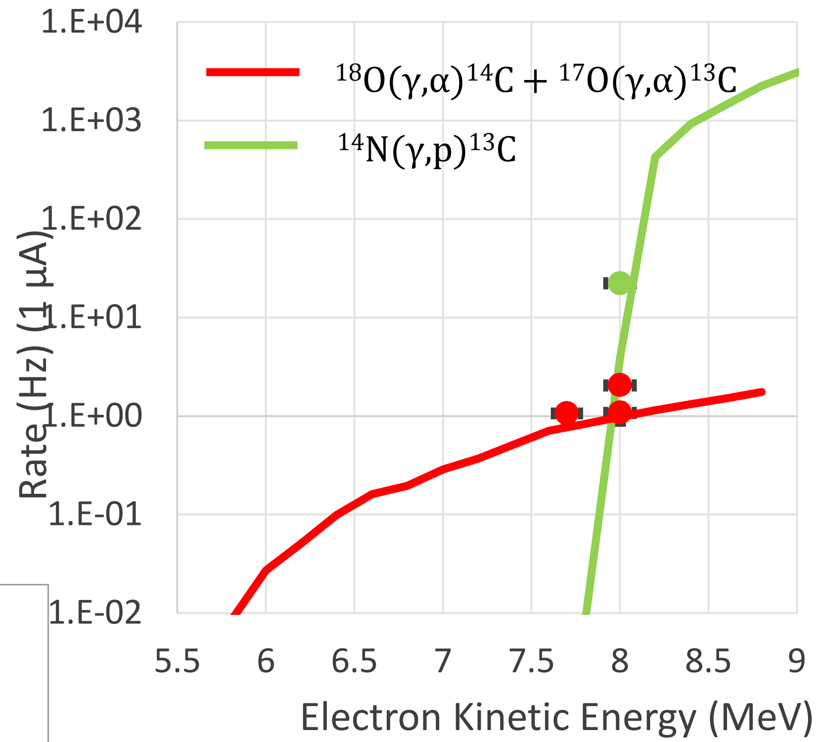


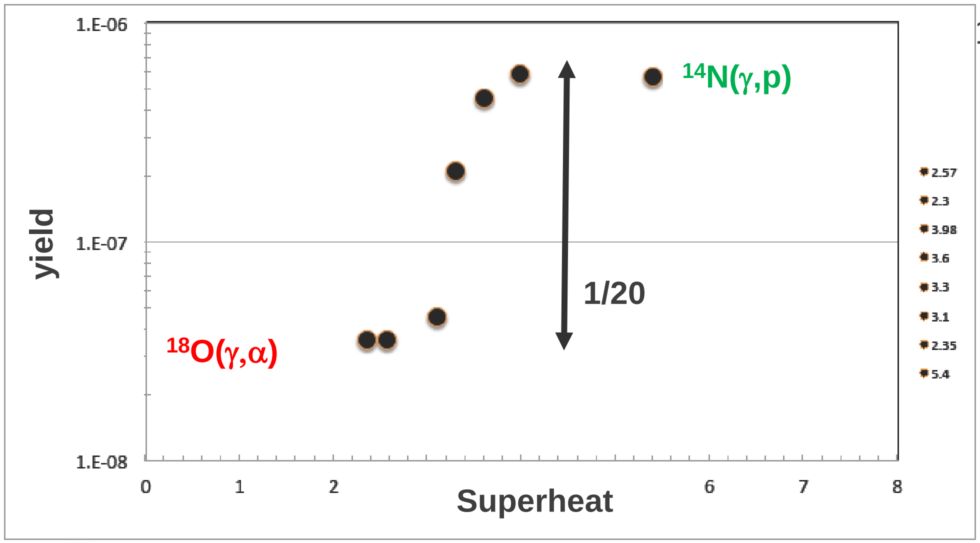
Reduce background with shielding and lower flux

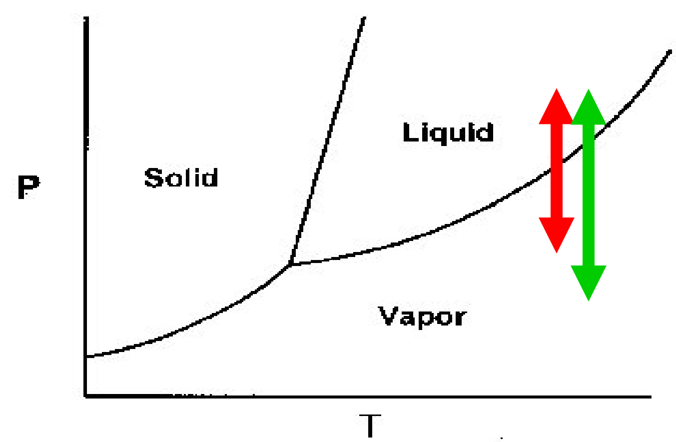


First Half of the Experiment (September 10-13, 2015)

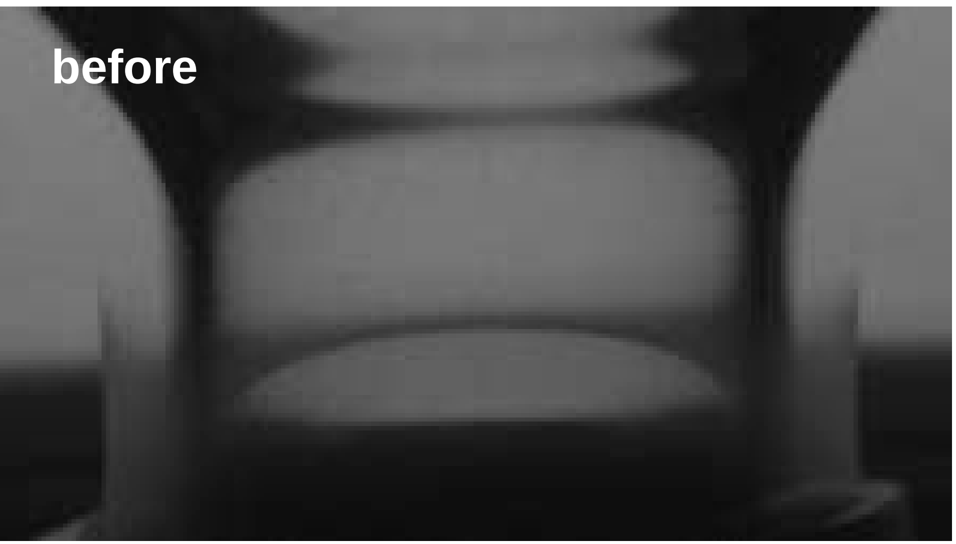
Energy Measured (MeV)	Superheat Pressure (psi)	Superheat Temperature (°C)	Beam Current (μA)
7.7	325	-8	0.4
8	325	-8	0.4
8	325	-8	0.04
8	310	-8	0.035

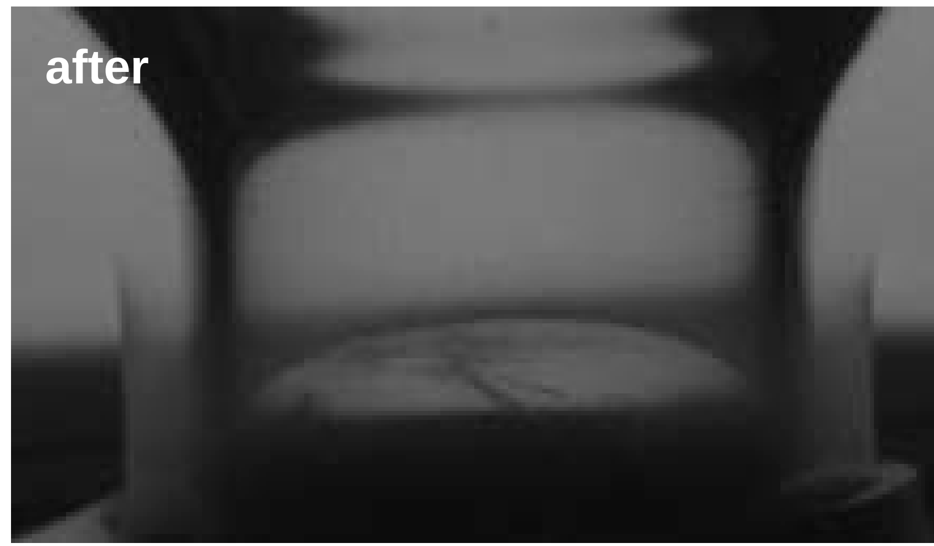






Second half of the experiment (September 14-18, 2015)

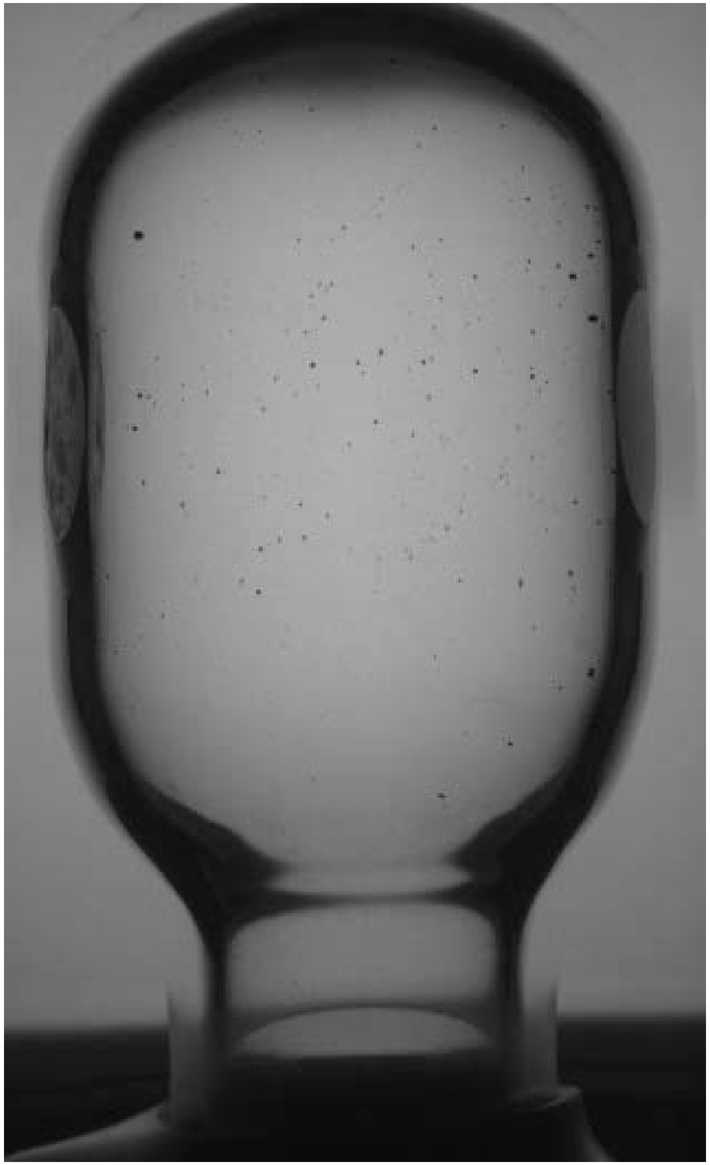


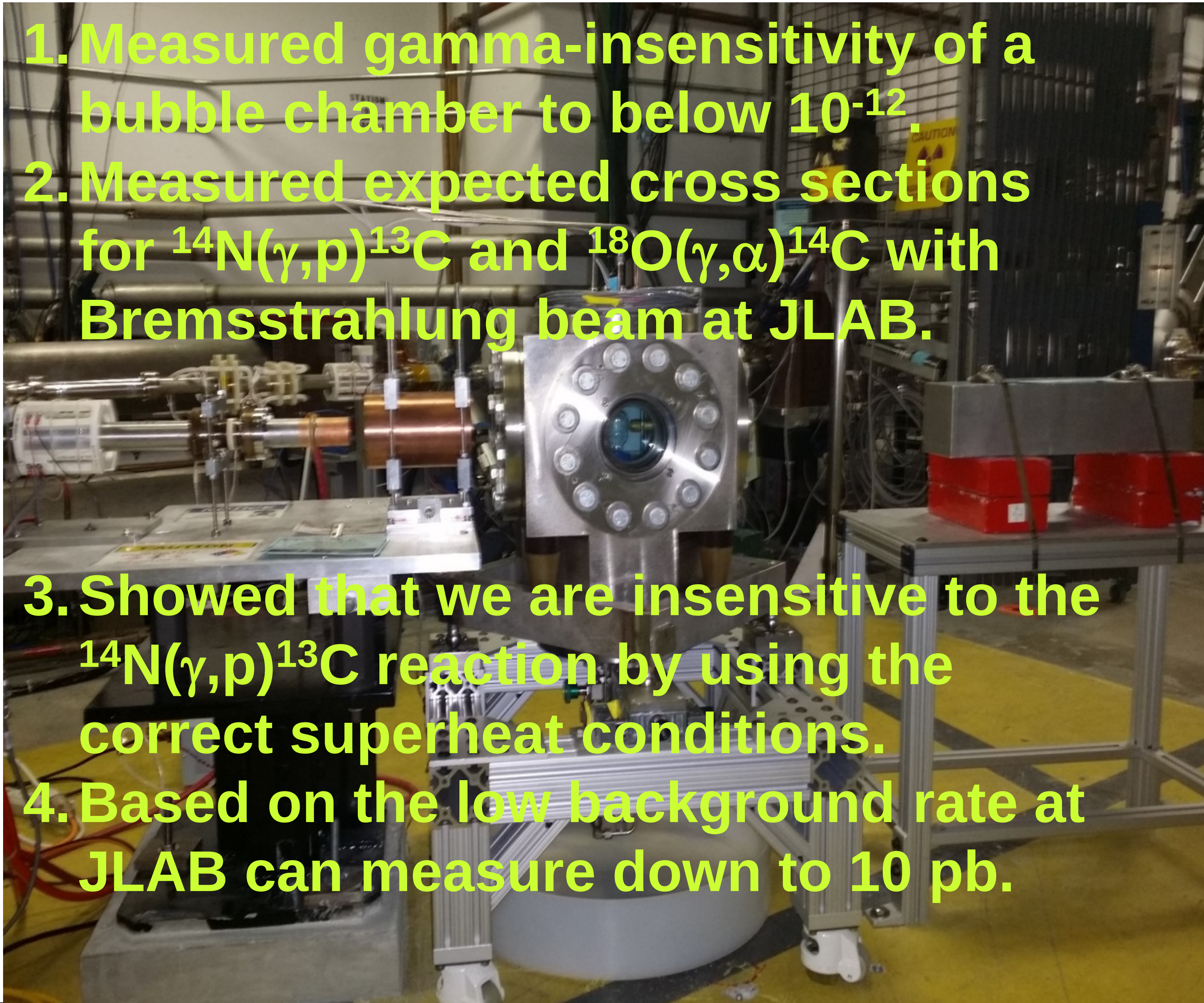


Photodissociation of N_2O ?

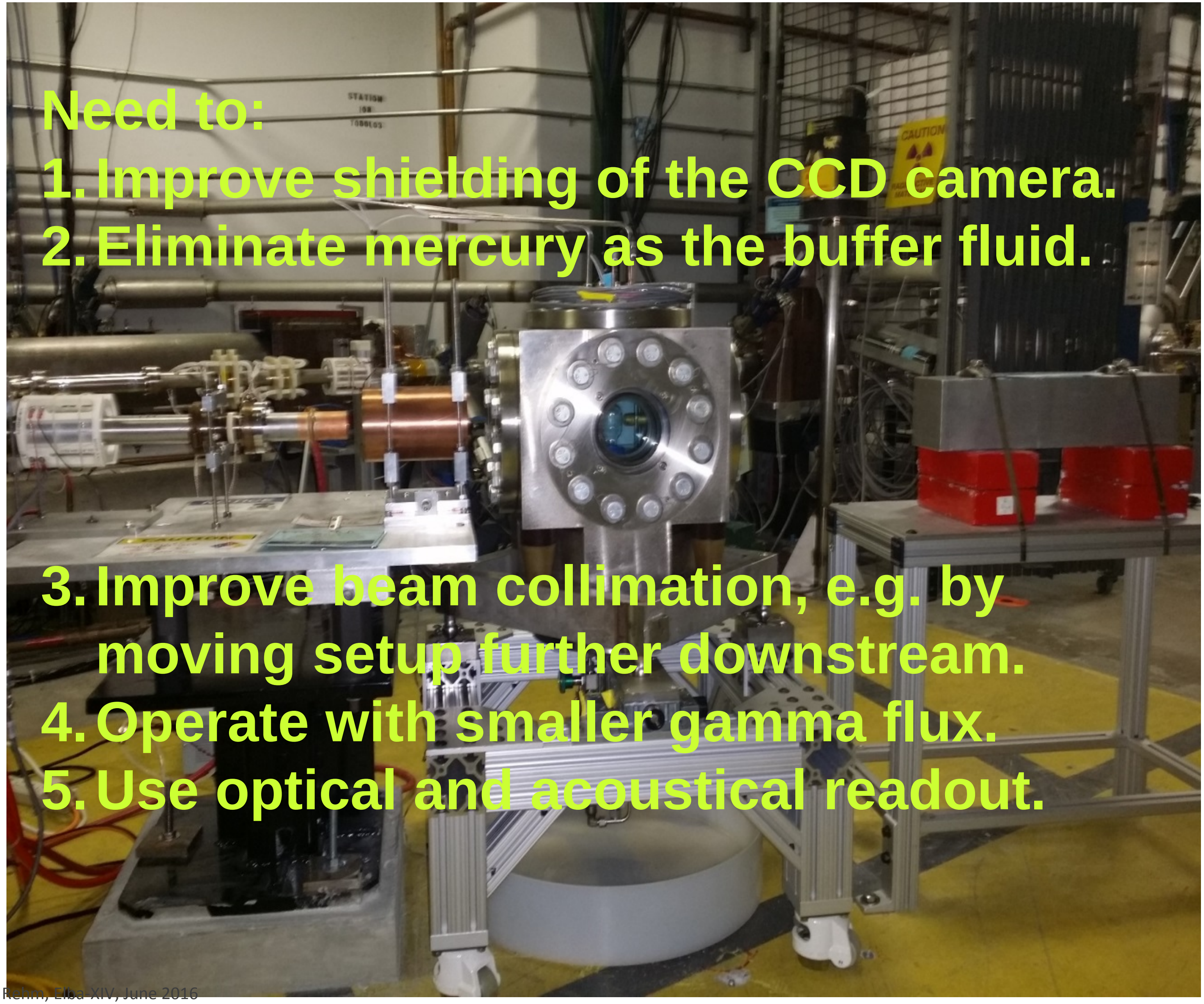
$\gamma + N_2O > O + 2N$

After refilling with fresh N_2O





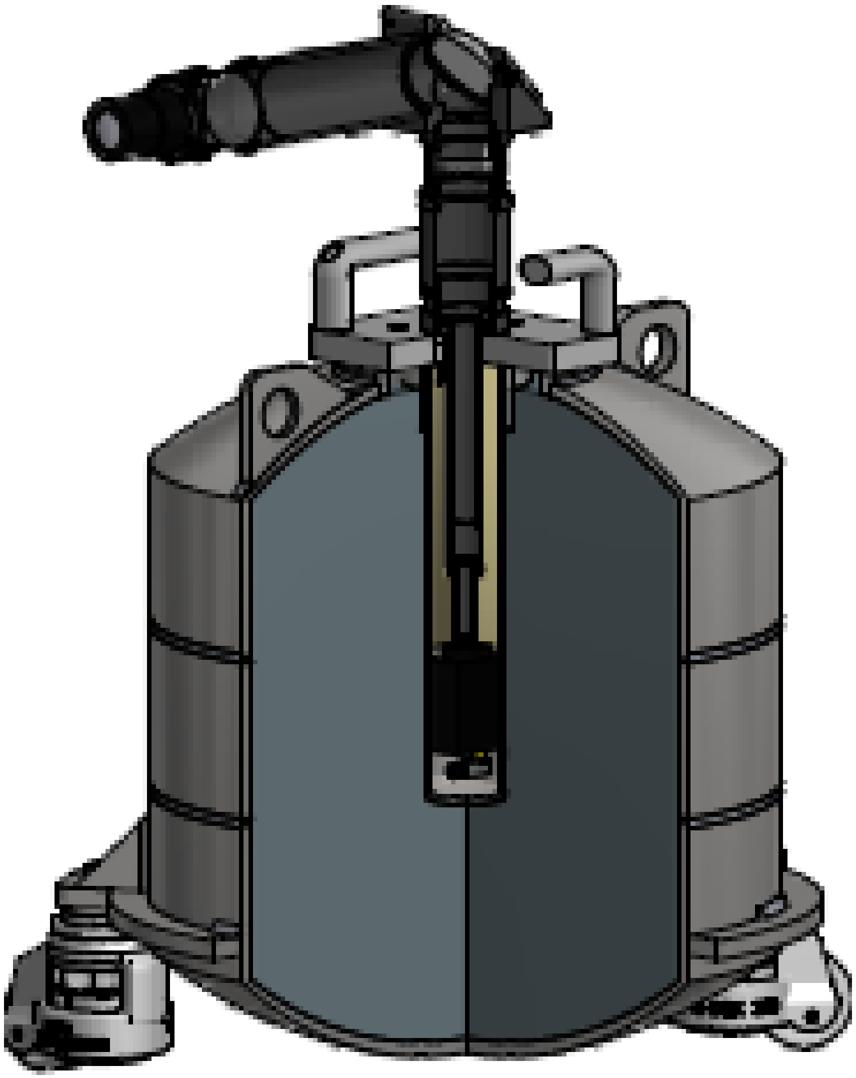
1. Measured gamma-insensitivity of a bubble chamber to below 10^{-12}.
2. Measured expected cross sections for $^{14}N(\gamma,p)^{13}C$ and $^{18}O(\gamma,\alpha)^{14}C$ with Bremsstrahlung beam at JLAB.
3. Showed that we are insensitive to the $^{14}N(\gamma,p)^{13}C$ reaction by using the correct superheat conditions.
4. Based on the low background rate at JLAB can measure down to 10 pb.



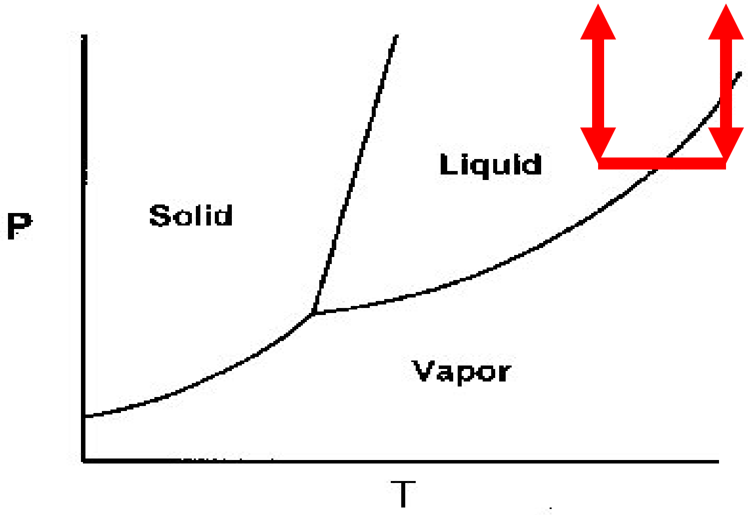
Need to:

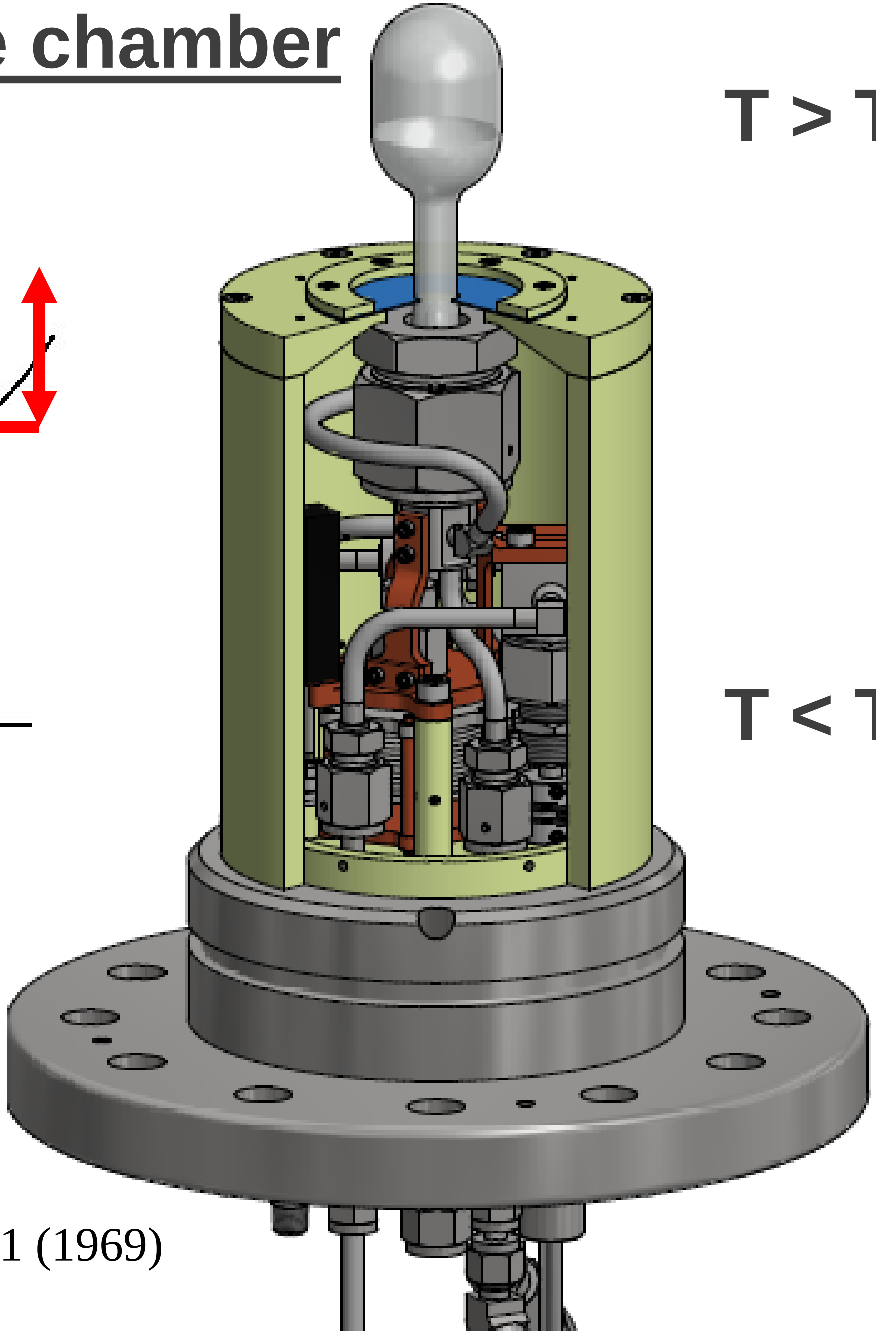
1. Improve shielding of the CCD camera.
2. Eliminate mercury as the buffer fluid.
3. Improve beam collimation, e.g. by moving setup further downstream.
4. Operate with smaller gamma flux.
5. Use optical and acoustical readout.

Improved camera shielding (R2D2)



Single-fluid bubble chamber





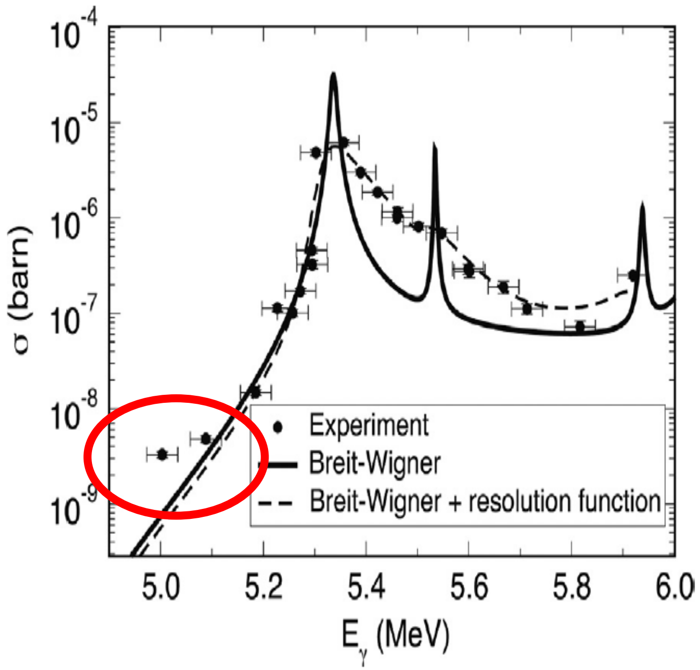
T > T_c

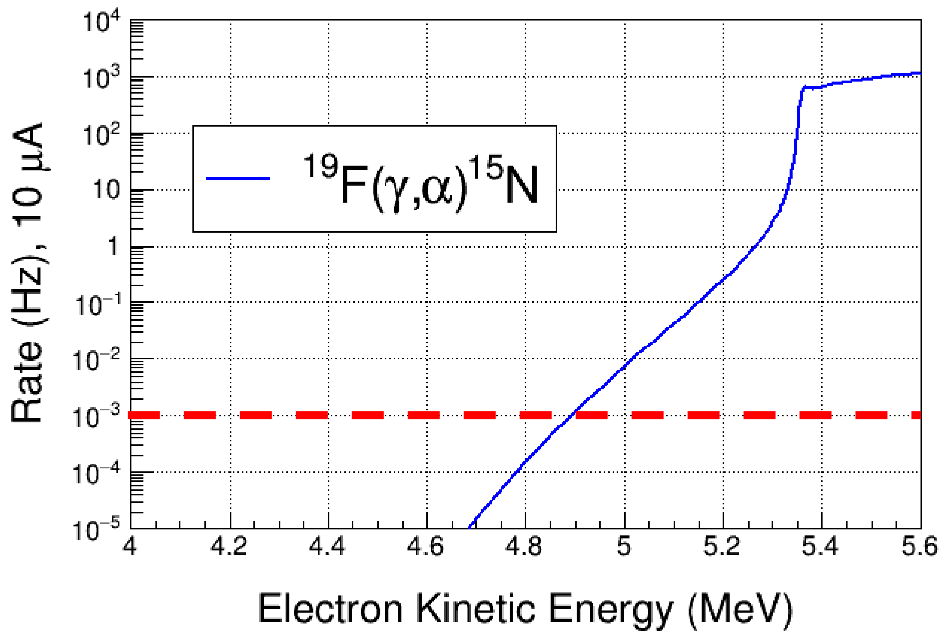
T < T_c

Waters, Petroff, and Koski,
IEEE Trans. Nuc. Sci. 16(1) 398-401 (1969)

Next steps:

1. Study $^{19}F(\gamma,\alpha)^{15}N$ down to cross sections of 50 pb

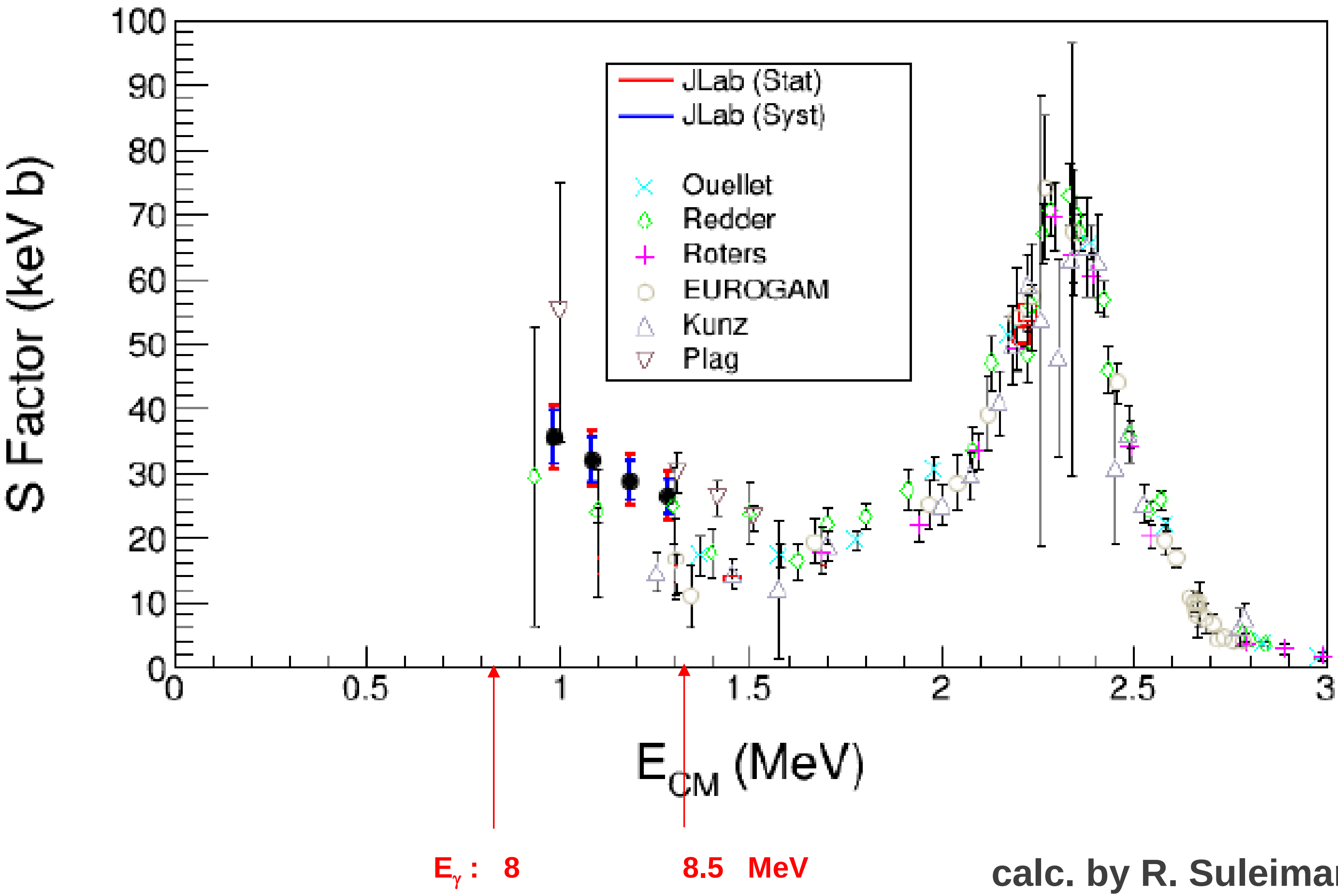




We have bought 5 l of water depleted to < 10^{-6} in $^{17,18}O$

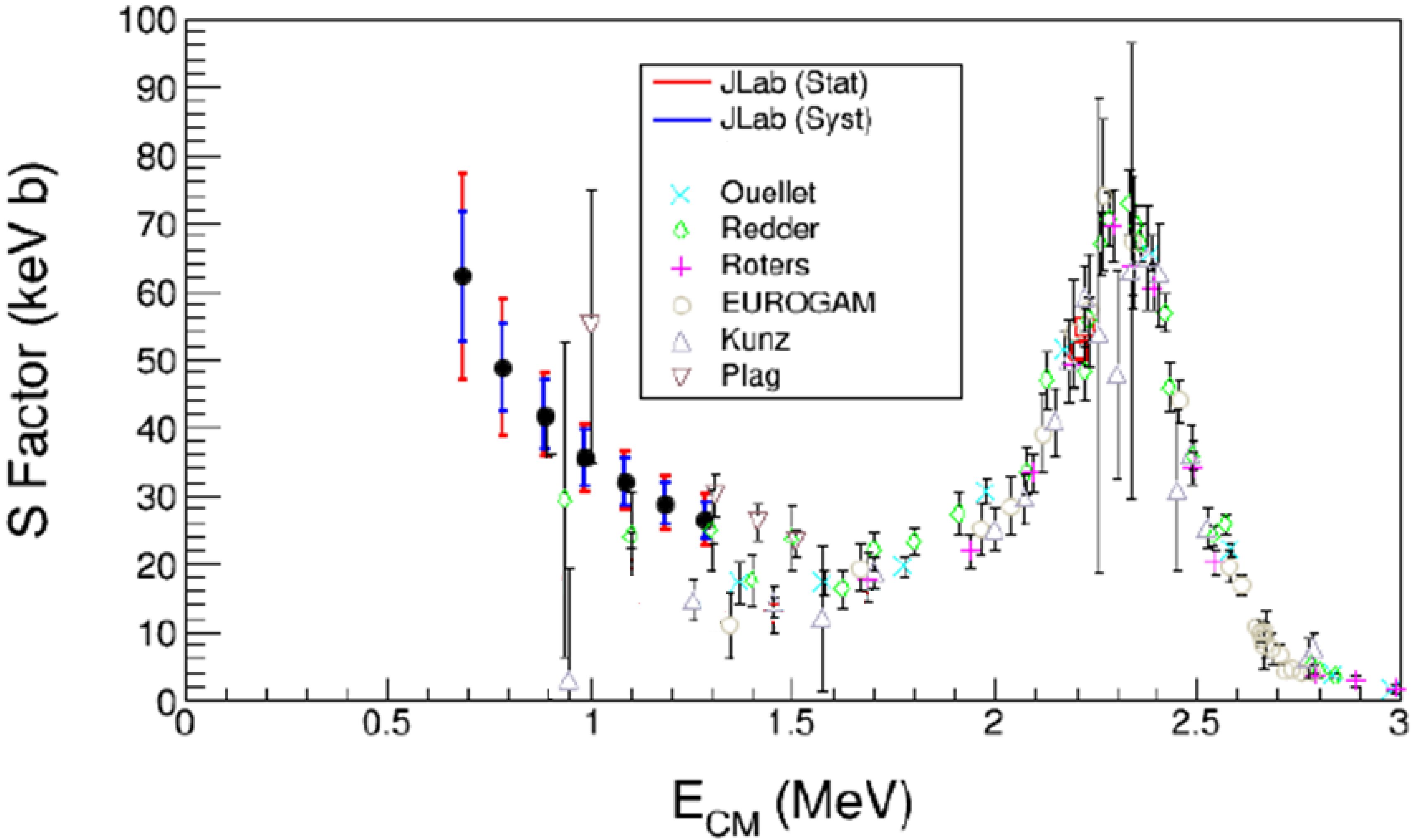
2. Measure actual enrichment and convert to N_2O

With 10^{-6} depleted water (2 days, < 20 μA)



calc. by R. Suleiman

With 10^{-7} depleted water (add. 5 days, < 100 μA)



calc. by R. Suleiman

$^{12}C(\alpha,\gamma)^{16}O$ – summary and outlook

- **Developed a technique that provides >100 times higher luminosities for measurements of inverse (γ,α) reactions. $^{19}F(\gamma,\alpha)$, $^{18}O(\gamma,\alpha)$ and $^{14}N(\gamma,p)$ agreed with literature values. Measure $^{19}F(\gamma,\alpha)$ and then $^{16}O(\gamma,\alpha)$ with enriched ^{16}O.**

- Status: measurements via γ – detection: go underground
  - LUNA (Italy)
  - Sanford underground laboratory (USA)
  - JUNO (China), (Romania, Spain, Korea?)
- Status: measurements via ^{16}O–detection: cleaner beams
  - ERNA (Naples)
  - Kyushu
  - Notre Dame
- Future possibilities
  - HIγS-II (10^{11} γ/sec)
  - ELI (Romania) (10^{12} γ/sec)
  - higher purity water

Collaborators:

Argonne NATIONAL LABORATORY

B. DiGiovine
D. Henderson
R. J. Holt
K. E. Rehm
R. Talwar

Fermilab

A. Robinson
A. Sonnenschein

Duke UNIVERSITY

R. Raut
G. Rusev
A. Tonchev

Jefferson Lab

J. Benesch
J. Grames
G. Kharashvili
D. Meekens
D. Moser
M. Poelker
M. Stutzman
R. Suleiman
C. Tennant

UIC UNIVERSITY OF ILLINOIS AT CHICAGO

C. Ugalde