Measurement of astrophysical reaction rates with a bubble chamber and inverse Compton scattering beams

Superheated Target for Astrophysics Research (STAR)

STAR

Claudio Ugalde, for the **STAR** collaboration.

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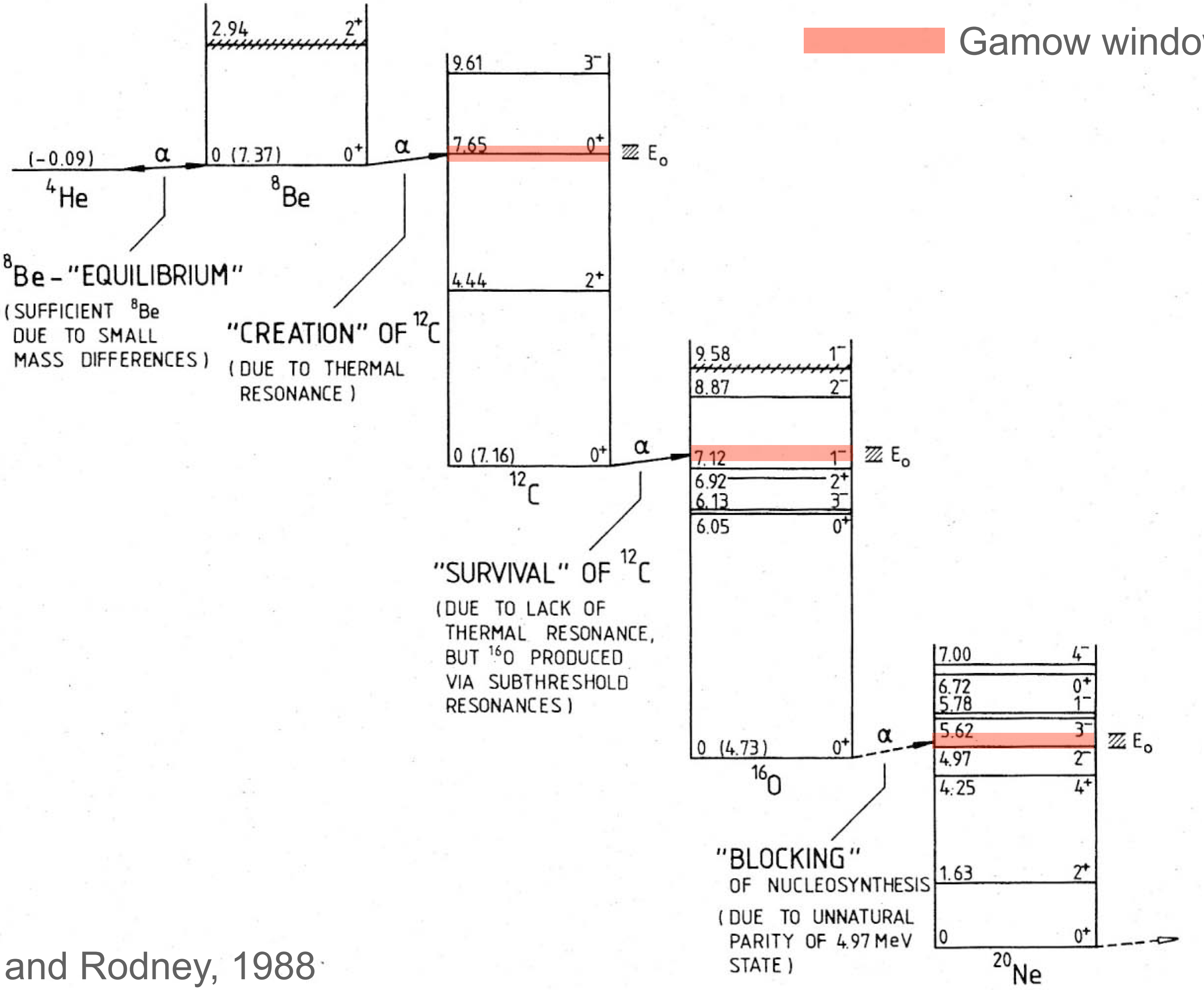
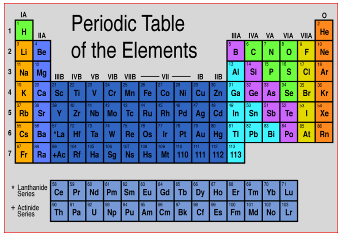


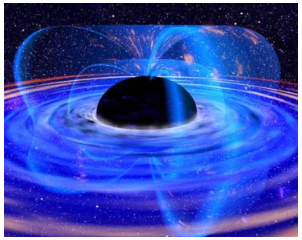
Rolfs and Rodney, 1988

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

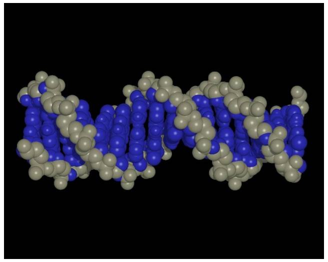
Key reaction for nucleosynthesis in massive stars, progenitors of Type Ia Supernovae, White Dwarf ages.



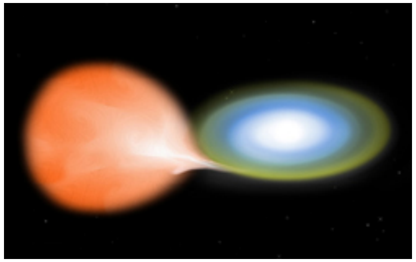
Affects the synthesis of most of the elements of the periodic table



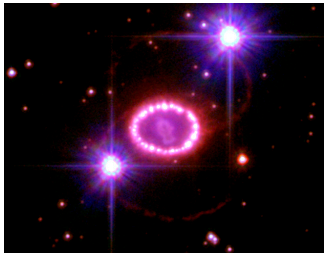
Determines whether for a given initial mass, a star will become a black hole or a neutron star



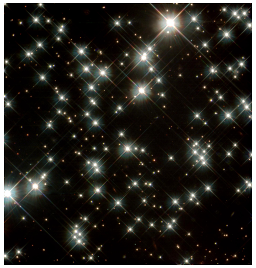
Sets the C to O ratio in the universe



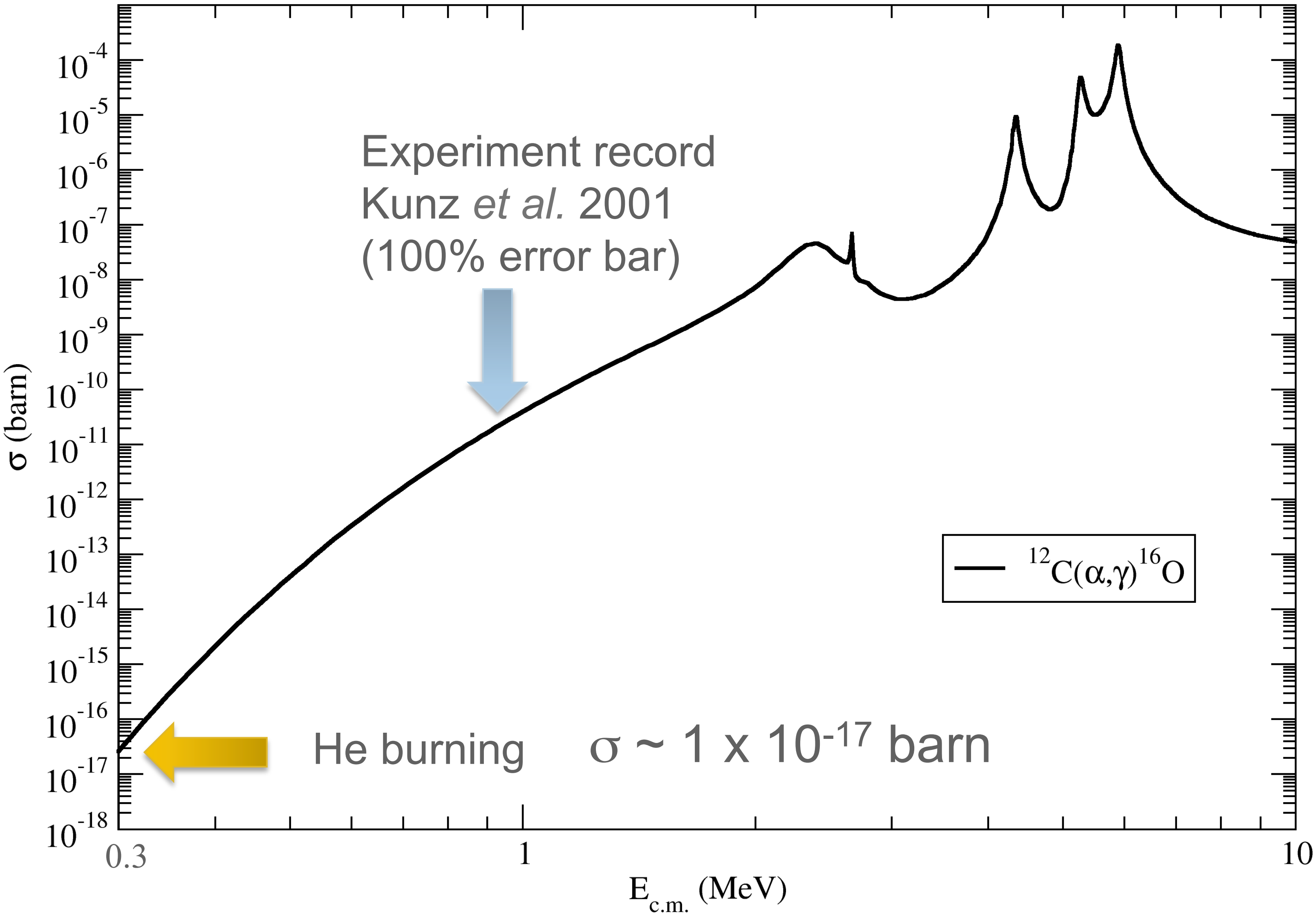
The variation of the C/O ratio in the progenitor might be a cause of the variation of SNIa brightness



Determines the minimum mass a star requires to become a core collapse supernova

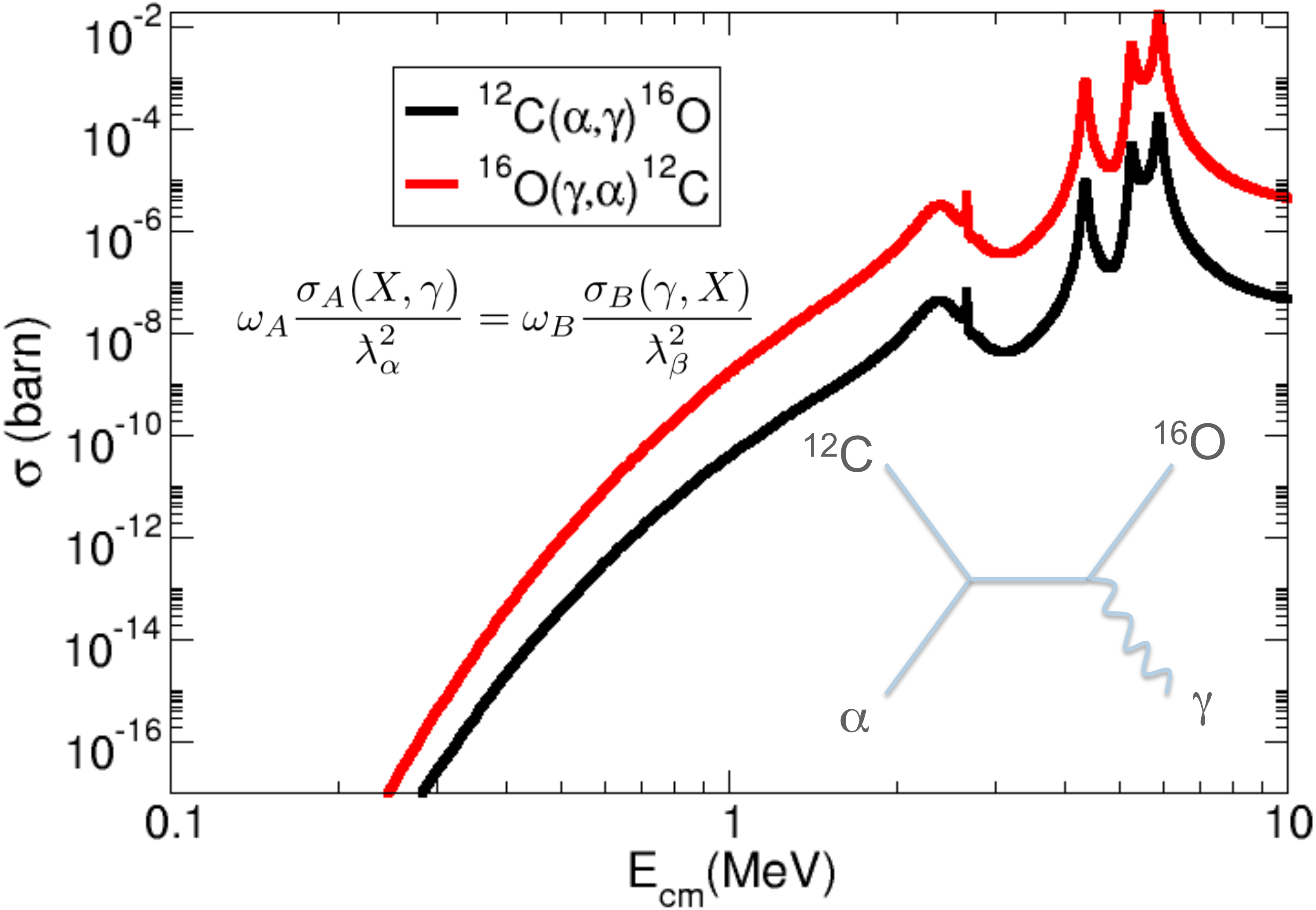


Affects the constraints on the age of stellar populations from White Dwarfs



$$N_A\langle\sigma\upsilon\rangle = N_A\sqrt{\frac{8}{\pi\mu(kT)^3}}\int_0^\infty \sigma(E)E\exp\left(-\frac{E}{kT}\right)dE$$

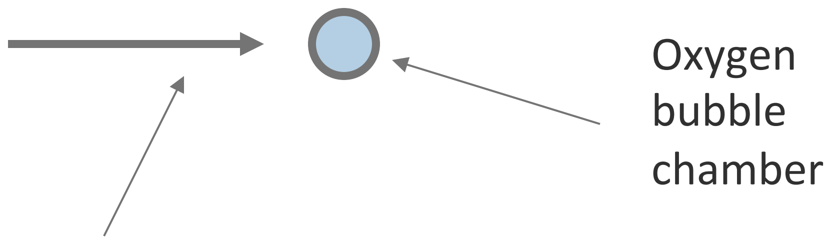
Time reversal symmetry: x100 gain in cross section



New approach:
Inverse reaction + Liquid target + ICS beam

beam   target   signal

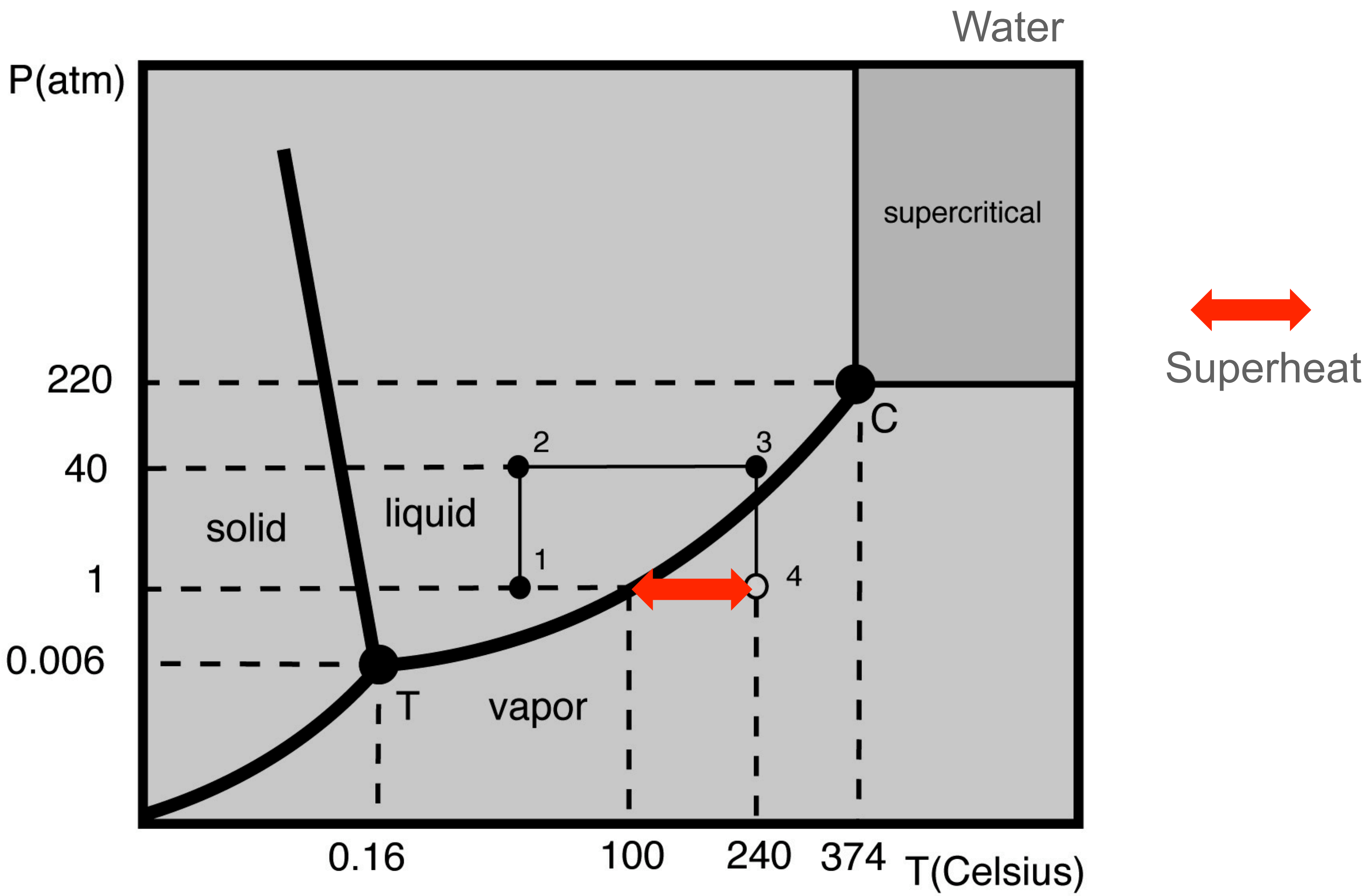
$$\gamma + {}^{16}O \dashrightarrow {}^{12}C + \alpha$$



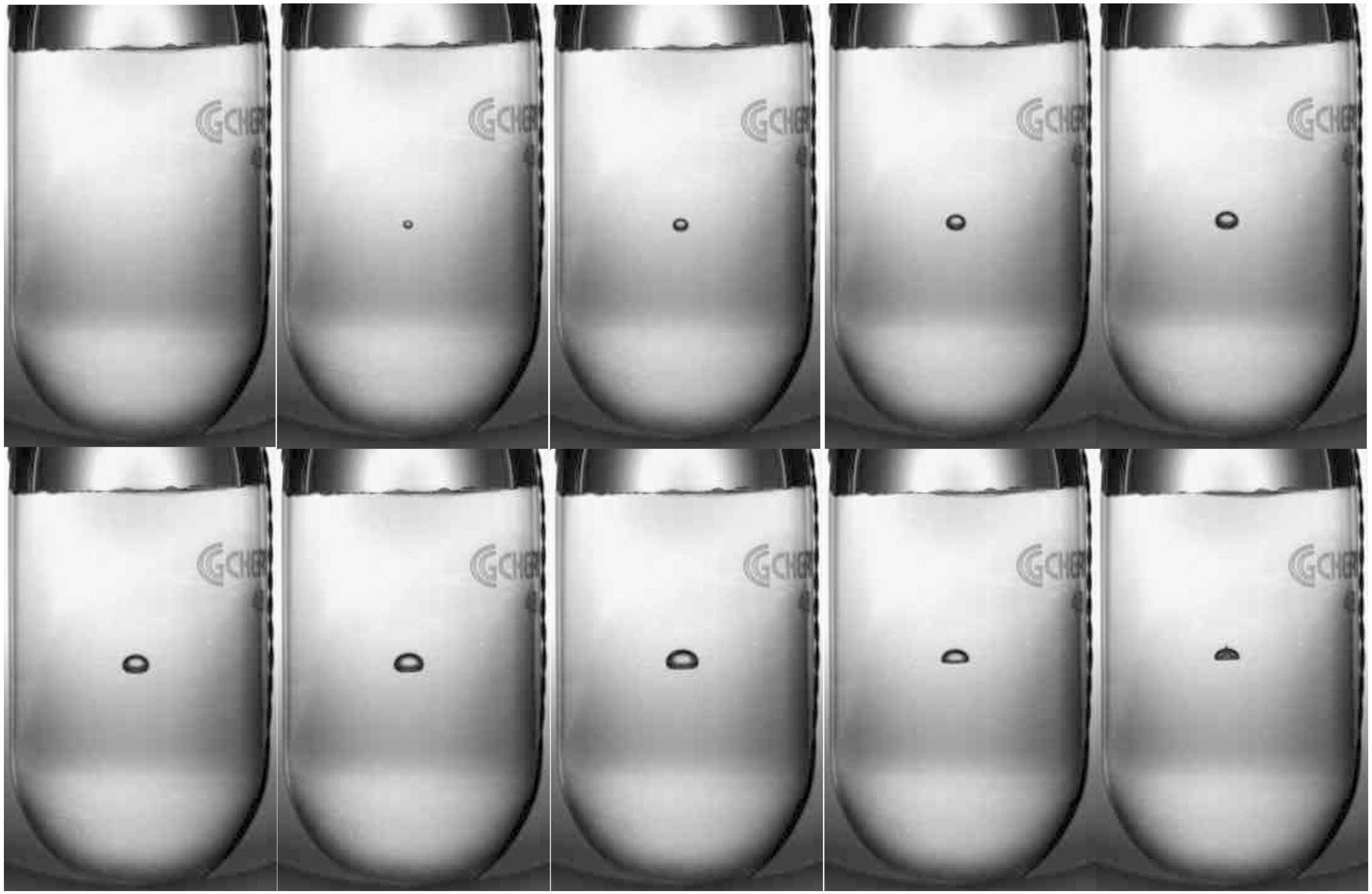
Monochromatic γ beam from HIγS
~ $10^{7\text{-}8}$ γ/s
ELI-NP~ 1×10^{13} γ/s, ASTA…

- Extra gain (x100) by measuring time inverse reaction
- Target density up to $\times10^{6}$ higher than conventional targets.
- Superheated water will nucleate from α and ^{12}C recoils
- Electromagnetic debris (degraded electrons and gammas, or positrons) that escape the collimator/electron beam do NOT trigger nucleation (The detector is insensitive to γ-rays by at least 1 part in 10^{11}).
- Idea tested at HIγS

Superheating of liquids

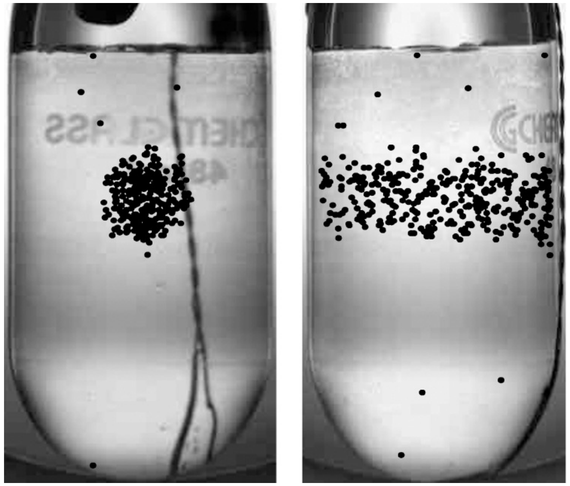


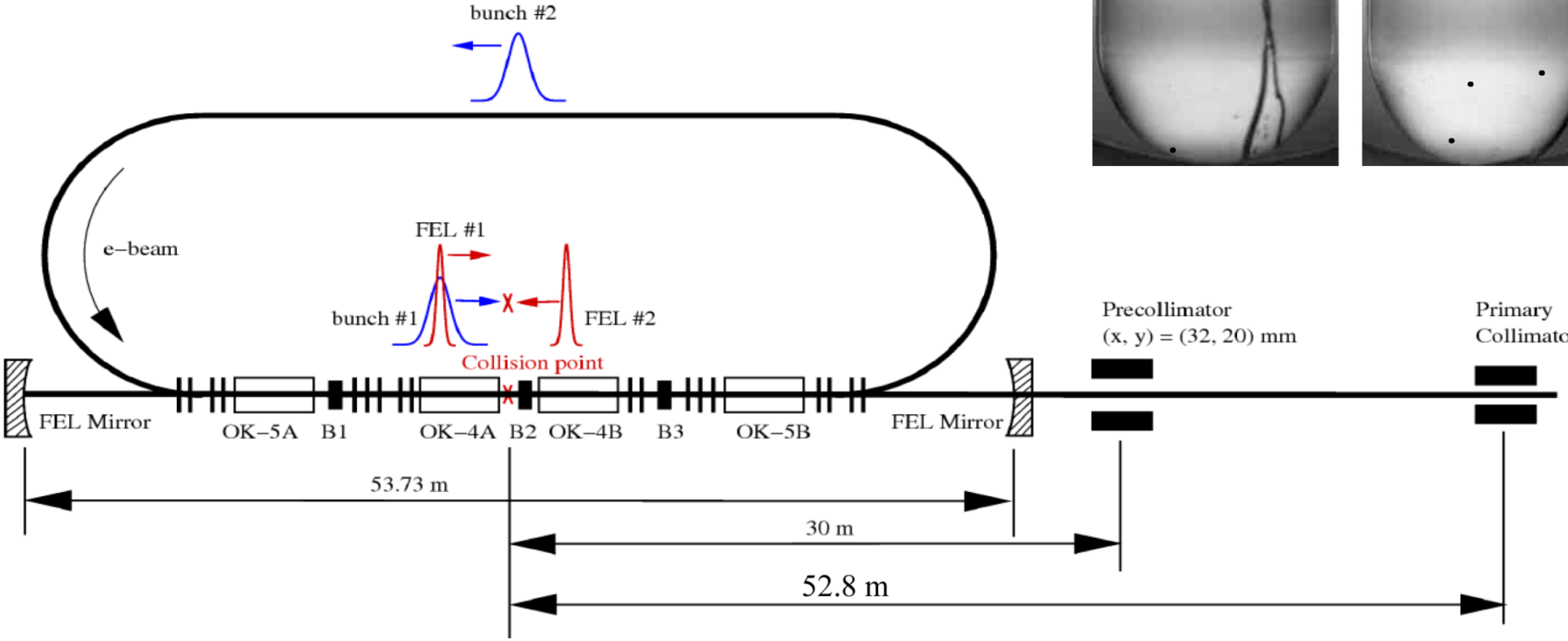
Bubble growth and quenching. $^{19}F(\gamma,\alpha)^{15}N$ in R134a



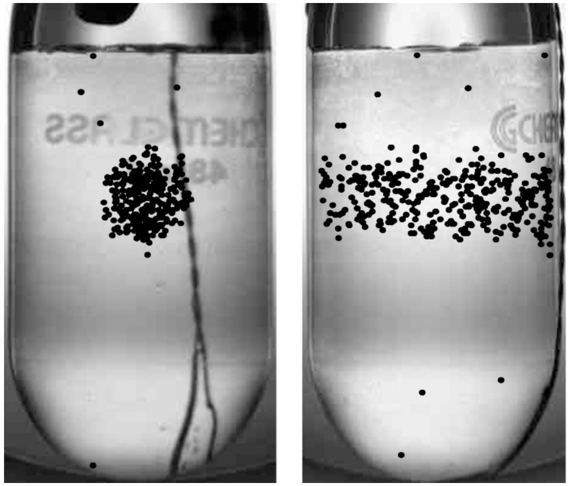
Δt = 10 ms

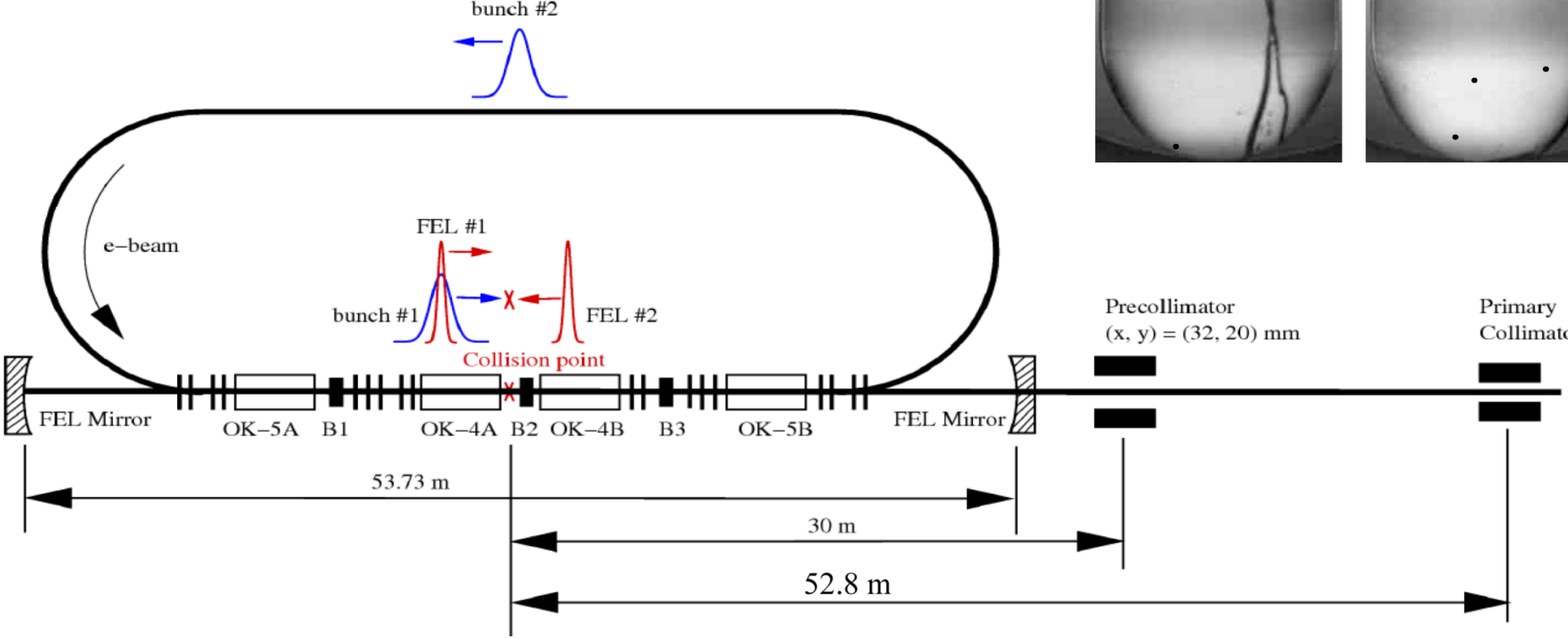
HIγS Photon Beam





HIγS Photon Beam





E (electron) ~ 500 MeV, I_e=50mA
+
2 x10^{-10} torr vacuum

Strong bremsstrahlung background component

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Physics Letters B

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

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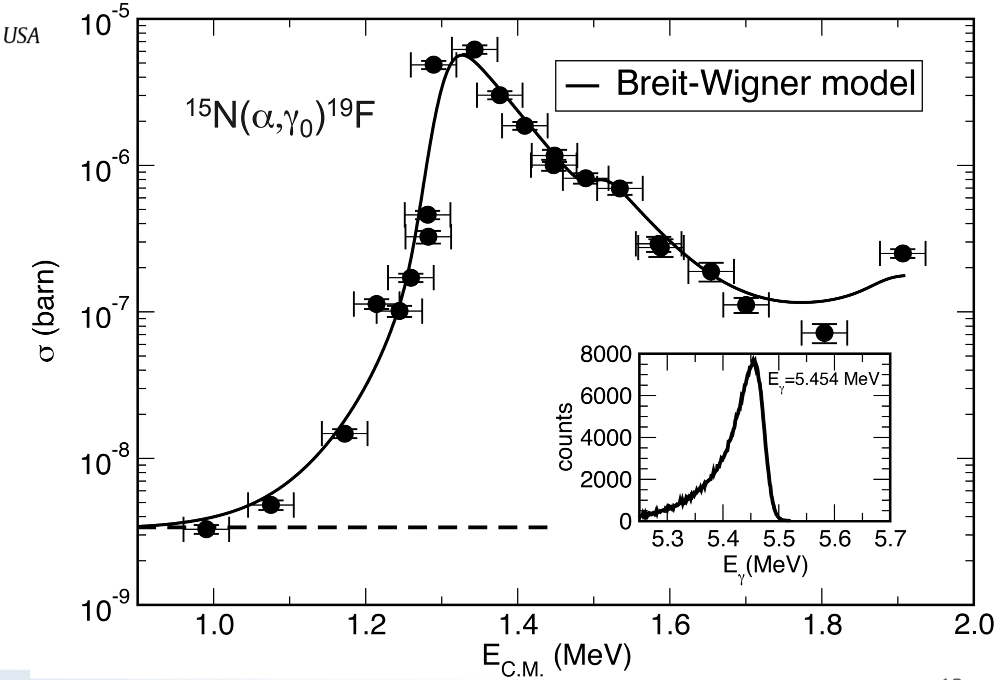
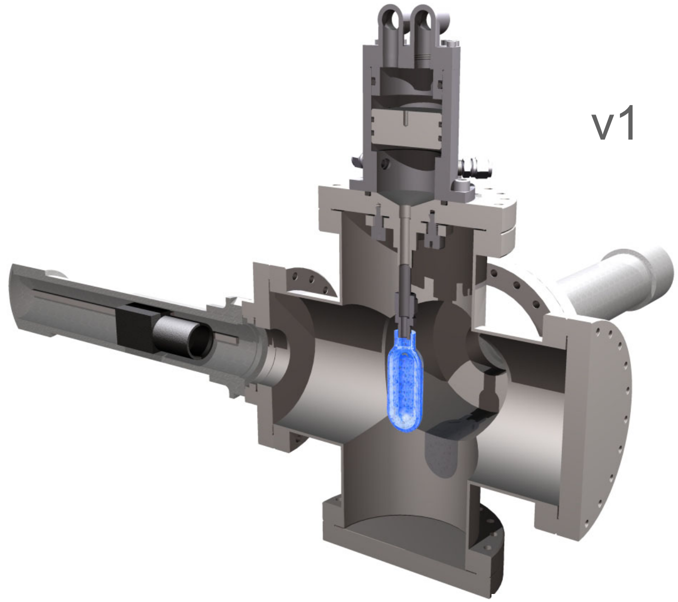


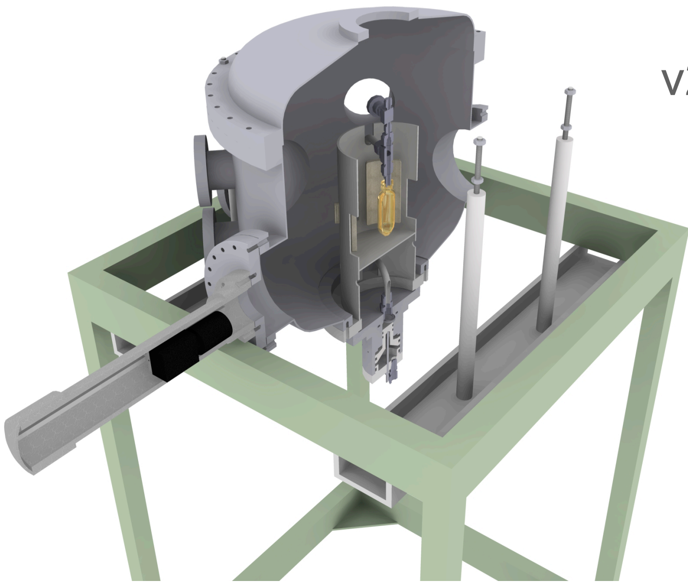
C_4F_{10}

Liquids tested

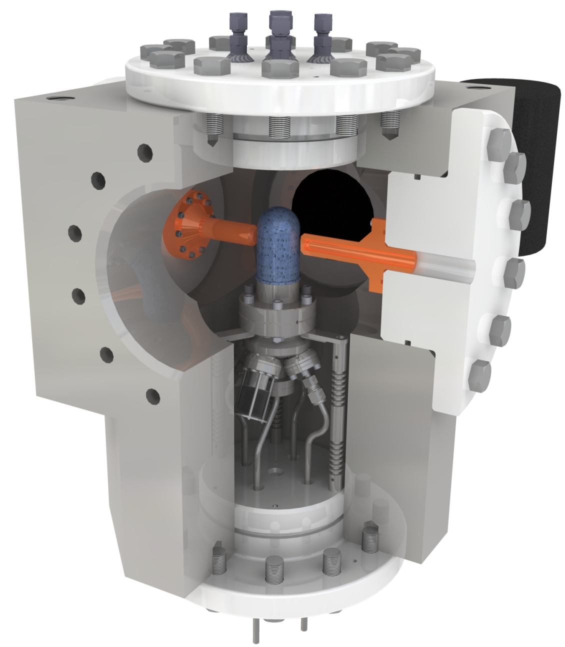
- CH_2FCF_3
- C_4F_{10}
- H_2O
- N_2O
- CO_2



v1



v2



v3

Outlook 10 years

Kunz 2001

N1= 2×10^{18} Carbon implanted particles
N2= 0.5 mA = 3.12×10^{15} α-particles/s

in 1 year
N1 N2 = 1.97×10^{41}
Yield = 2 events in one year

DIANA + JENSA (DUSEL)

N1= 1×10^{19} helium particles gas target
N2= 10 mA =6.24×10^{16} carbon part/s

in 1 year
N1 N2 = 1.97×10^{43}
Yield = 200 events in one year

LUNA-MV (Gran Sasso)

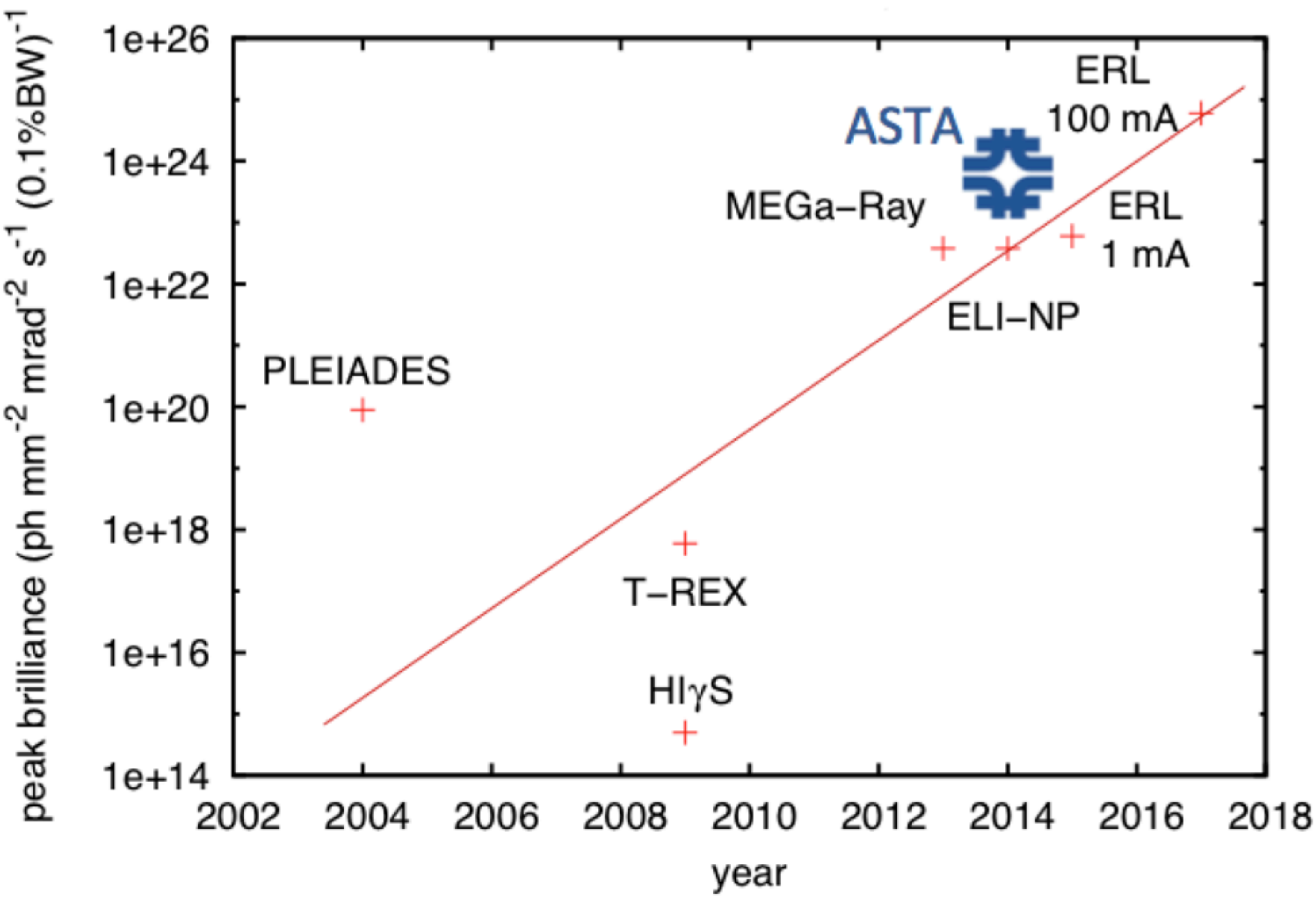
N1= 2×10^{18} Carbon implanted particles
N2= 0.5 mA = 3.12×10^{15} α-particles/s

in 1 year
N1 N2 = 1.97×10^{41}
Yield = 2 events in one year

Bubble + ELI-NP (Phase 1)

N1= 3.35×10^{23} particles in liquid target
N2= 1×10^{13} γ/s

in 1 year
N1 N2 = 2.11×10^{44}
Reciprocity -> x100
Yield = 200,000 events in one year


peak brilliance (ph mm^{-2} mrad^{-2} s^{-1} (0.1%BW)$^{-1}$
1e+26
1e+24
1e+22
1e+20
1e+18
1e+16
1e+14
2002
2004
2006
2008
2010
2012
2014
2016
2018
year
ERL
100 mA
ASTA
MEGa–Ray
ERL
1 mA
ELI–NP
PLEIADES
T–REX
HIγS

Conclusions

STAR @ ASTA

We have provided a proof of principle of operation of the bubble chamber as a low rate counter. This is ideal for nuclear astrophysics applications.

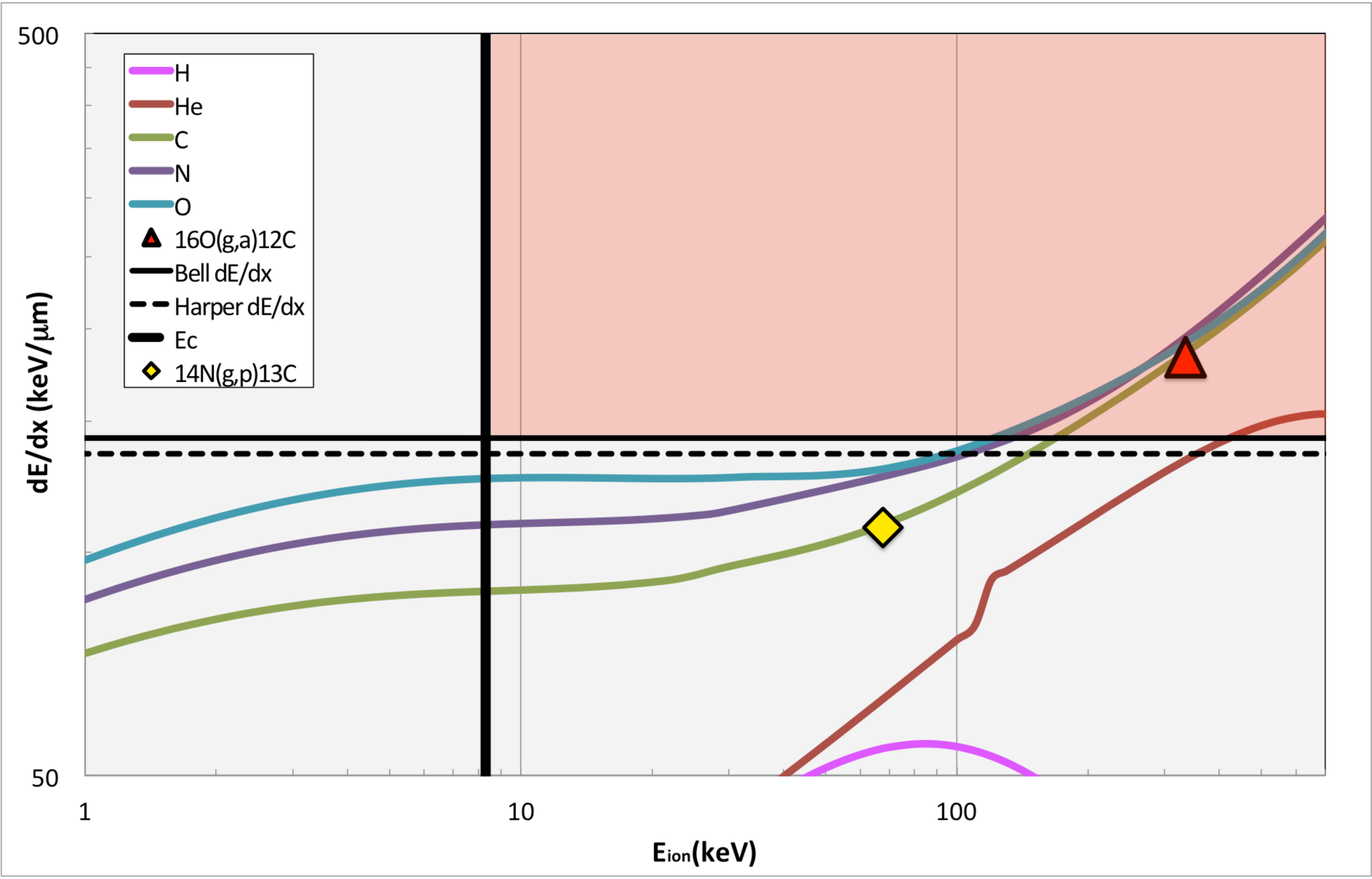
Bremsstrahlung from the electrons in the beam line manifests mainly as neutrons. Particle ID would help separating these events from the α-particle + heavy ion signal.

Main challenges:

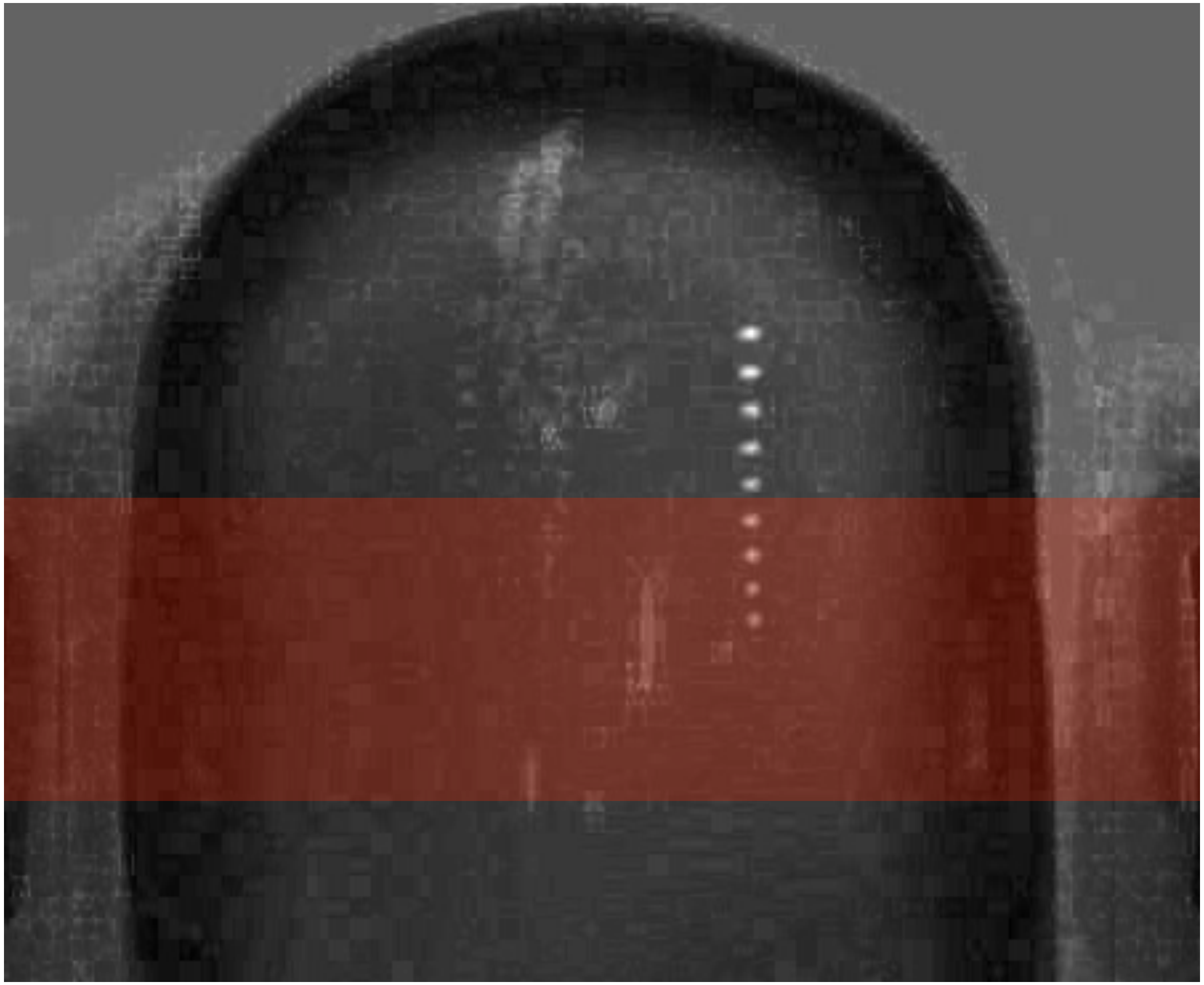
- Maximize beam intensity
- Minimize beam bandwidth
- Maximize level of depletion of heavy oxygen in liquid

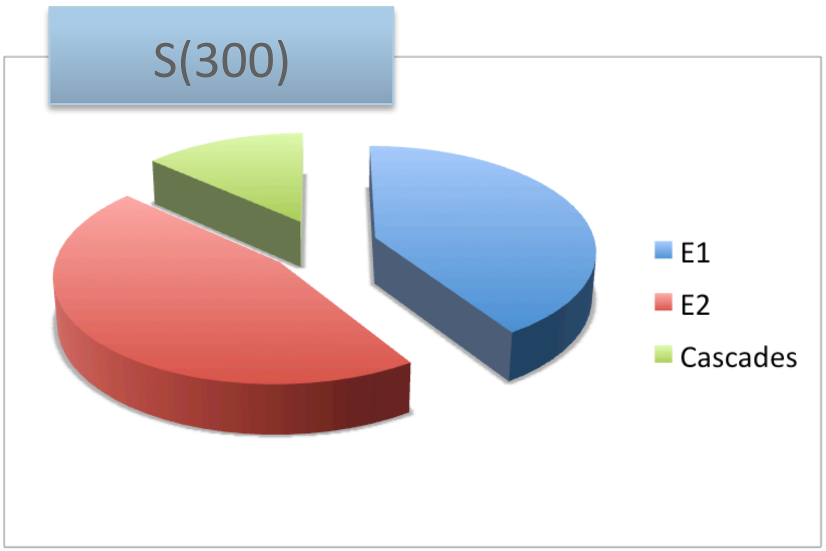
- Need excellent characterization of γ-ray beam properties
- Minimize high energy bremsstrahlung photons

N_2O thresholds, Superheat = 3.3 ^{O}C, $E\gamma$=8.5 MeV



N_2O
First γ + oxygen -> alpha + carbon bubble
April 2013





Kunz 2001, Matei 2006

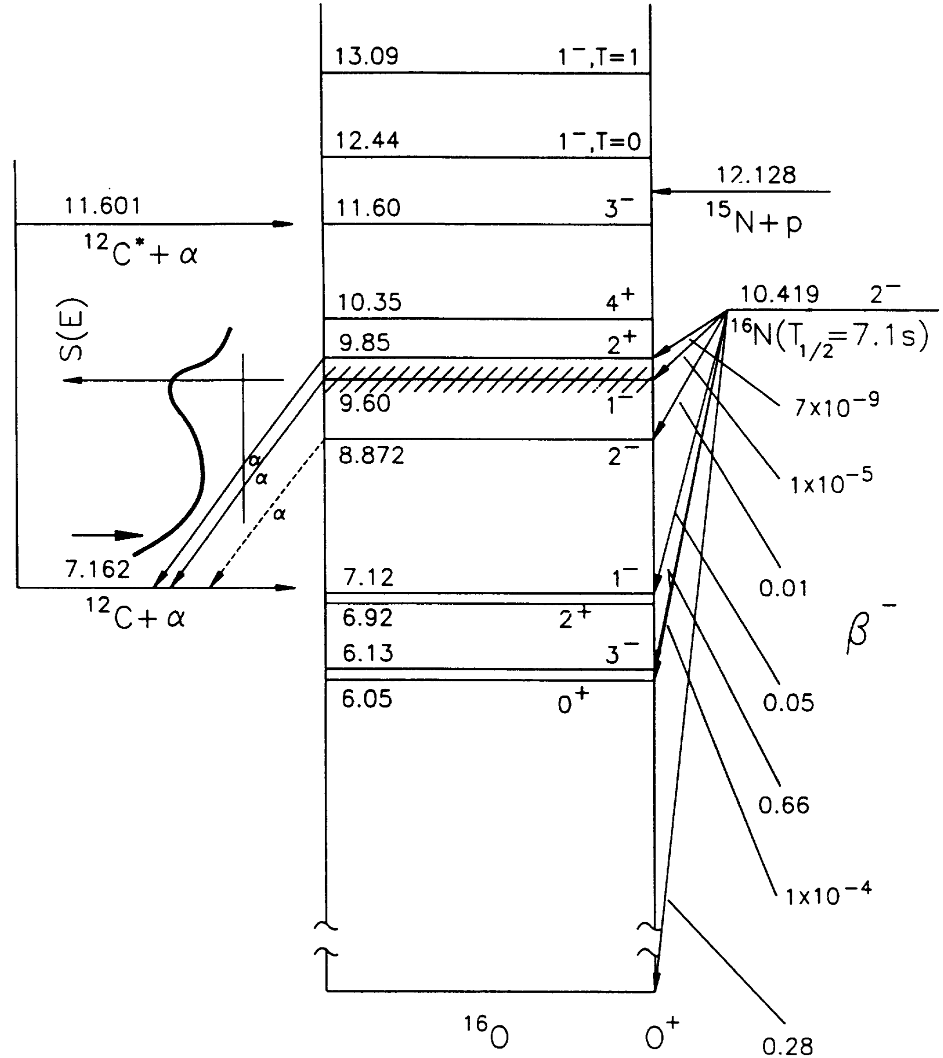
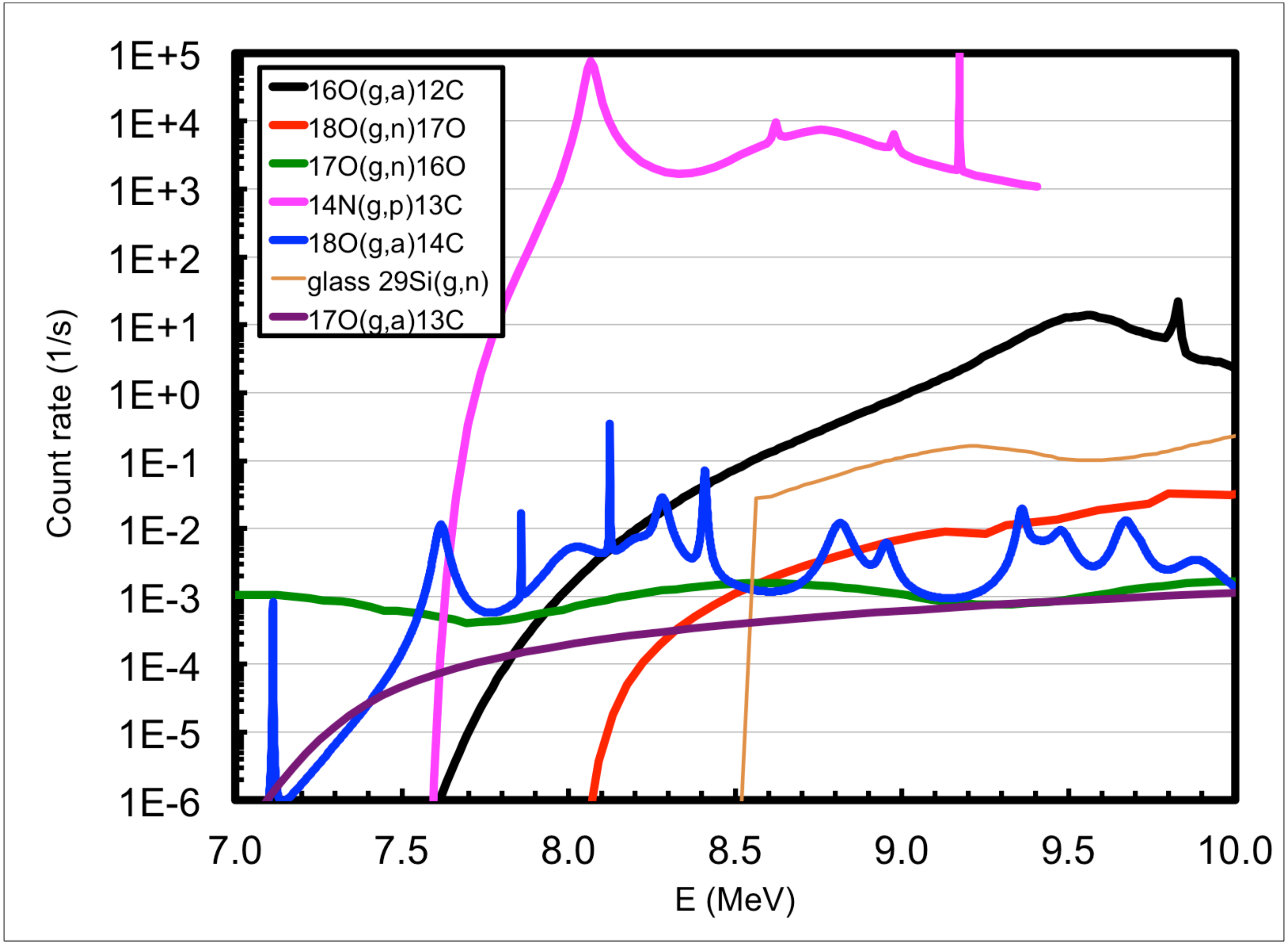
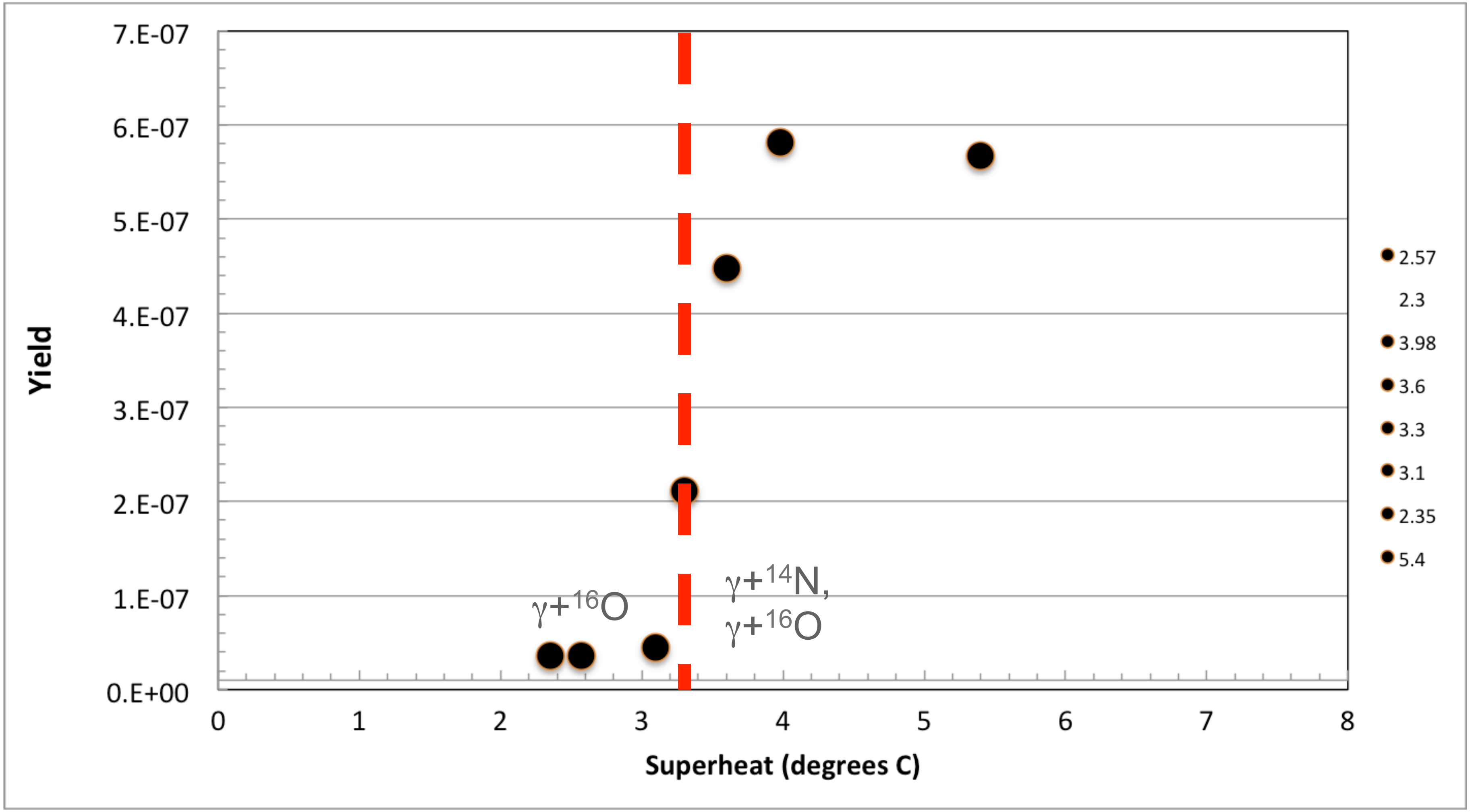


FIG. 1. Partial energy-level diagram for ^{16}O (adapted from [4]).

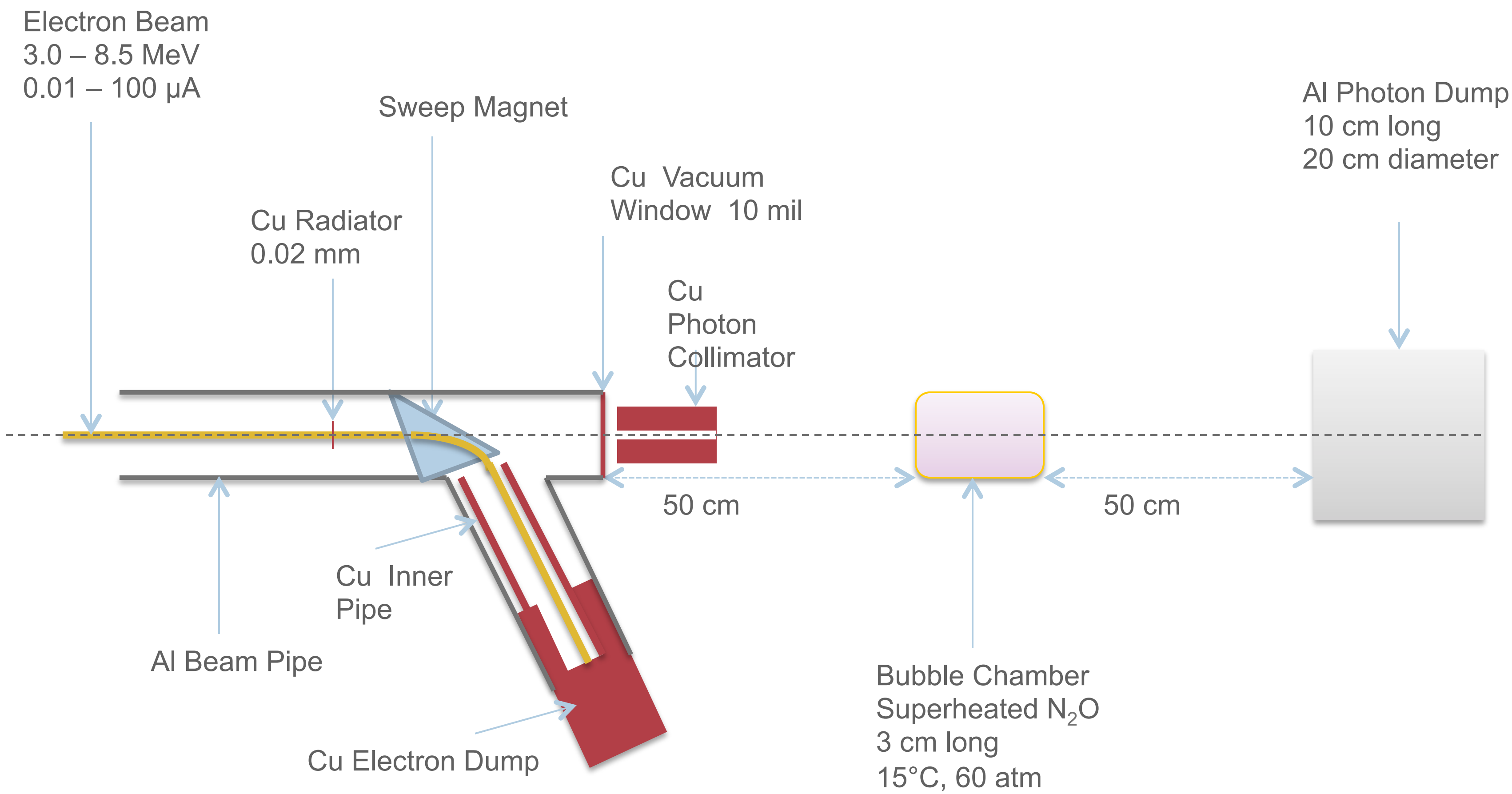
N_2O count rate contributions, $I\gamma = 1 \times 10^8$ γ/s
L = 3.6 cm, x1000 depleted liquid



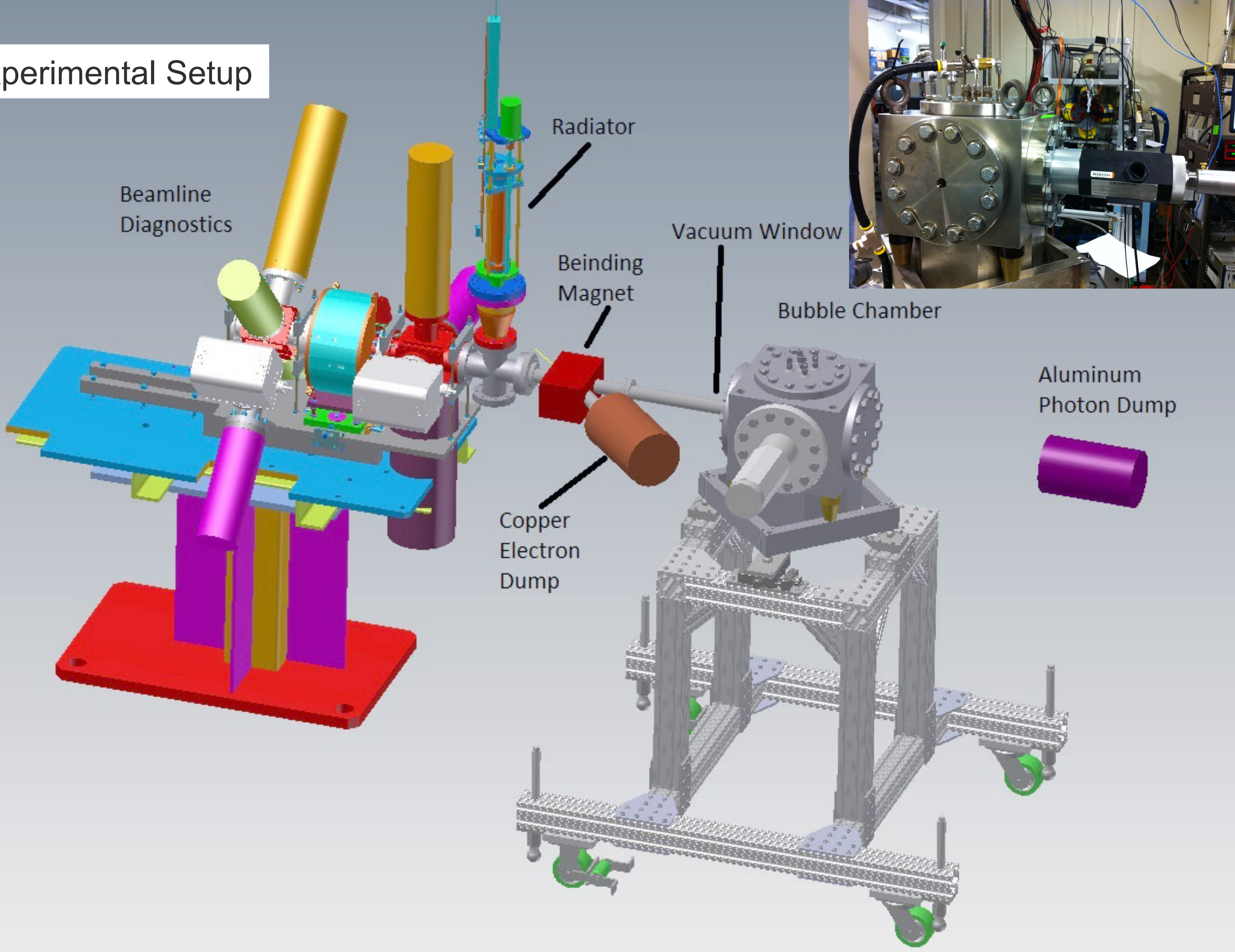
N_2O efficiency curve, HIγS April 2013. Eγ = 9.7MeV



Experimental setup

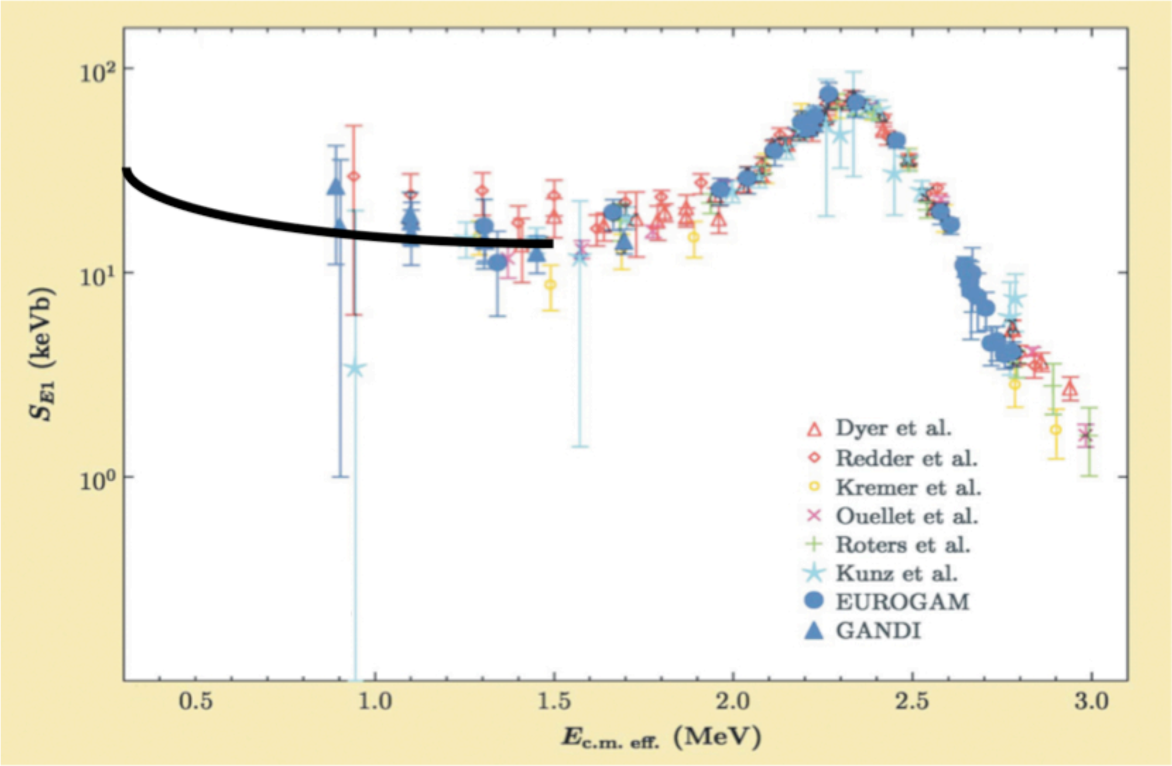


Experimental Setup



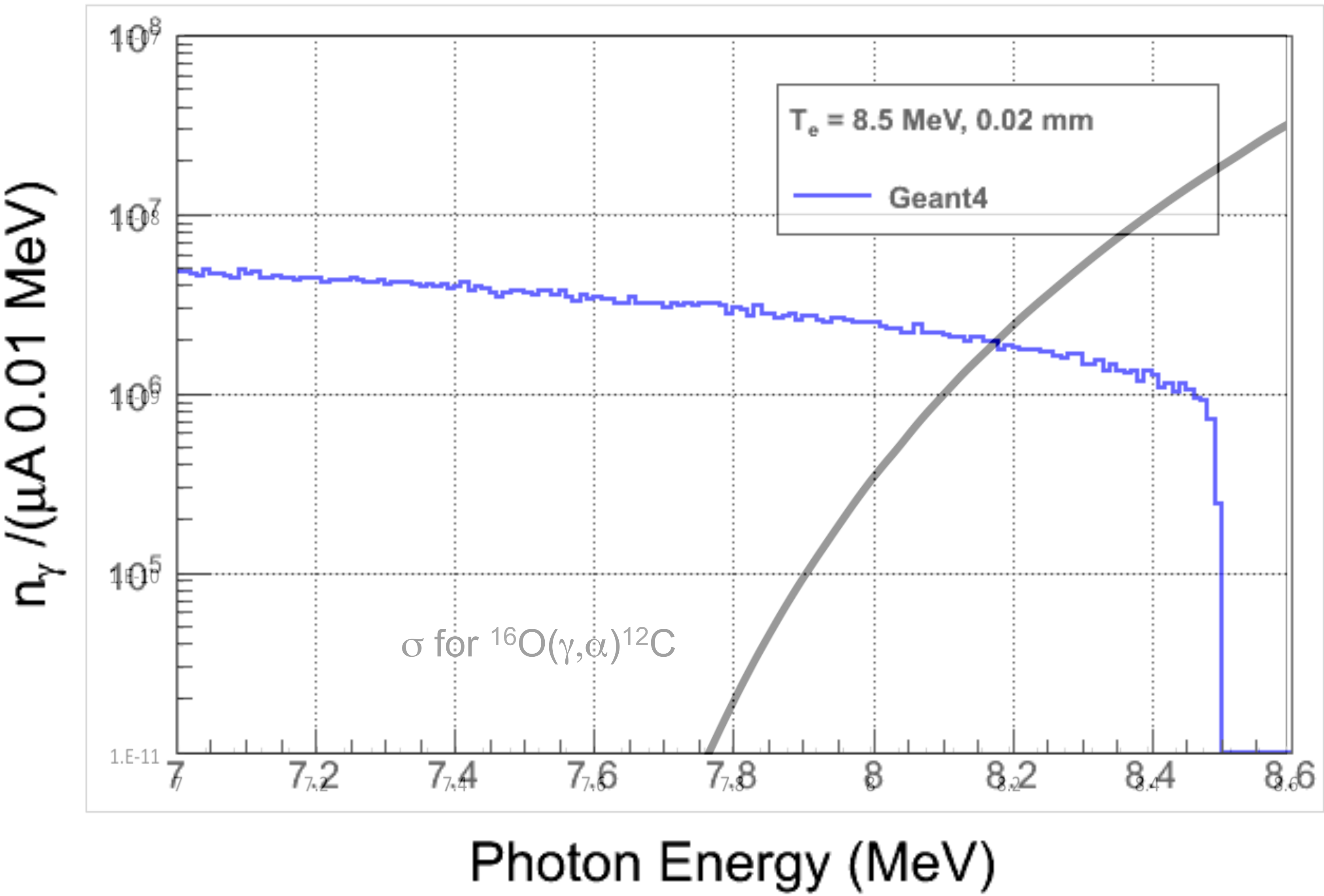
Astrophysical S-factor for $^{12}C(\alpha,\gamma)^{16}O$

$$S = E\,\sigma\,\exp(2\pi\eta)$$

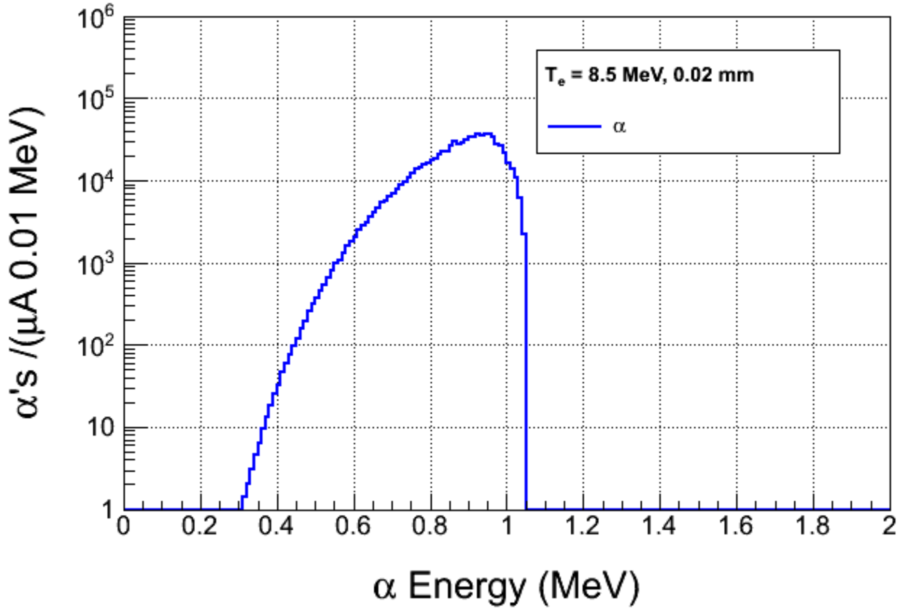


Stellar helium burning at E=300 keV

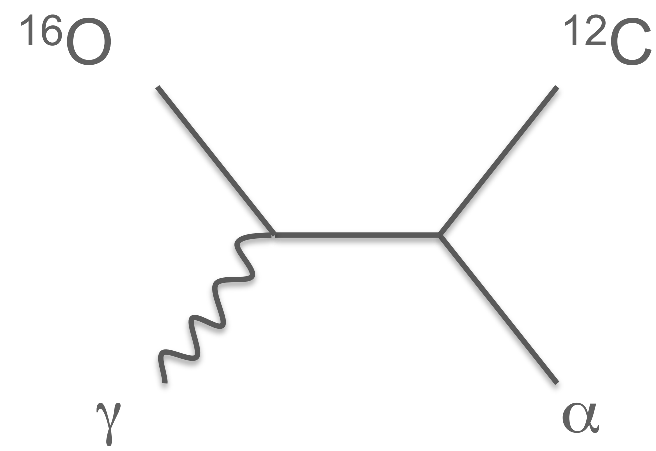
Author	S(300keV) (keV-b)
Buchmann (2005)	102-198
Caughlan and Fowler (1988)	120-220
Hammer (2005)	162+-39



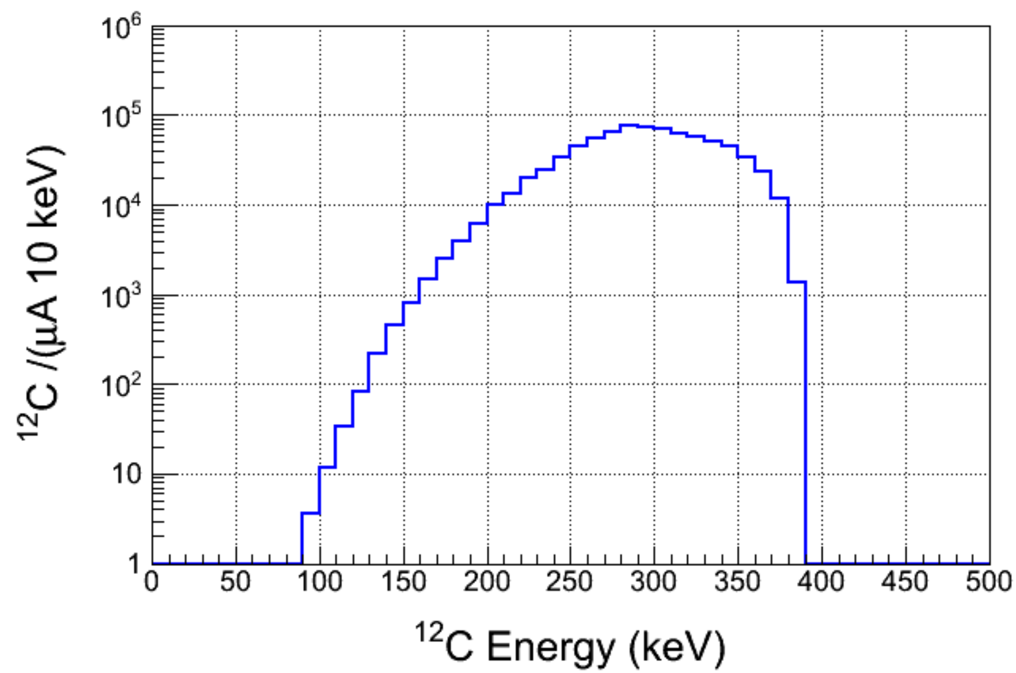
T_e = 8.5 MeV, 0.02 mm
Geant4
σ for $^{16}O(\gamma,\alpha)^{12}C$
10^8
10^7
10^6
10^5
7
7.2
7.4
7.6
7.8
8
8.2
8.4
8.6
n_γ /(μA 0.01 MeV)
Photon Energy (MeV)



T_e = 8.5 MeV, 0.02 mm
α
α's /(μA 0.01 MeV)
α Energy (MeV)



^{16}O
^{12}C
γ
α



^{12}C /(μA 10 keV)
^{12}C Energy (keV)

Non-resonant charged particle reactions (The Gamow peak)

Let's write the cross section as $\sigma(E) = \frac{1}{E}\exp(-2\pi\eta)S(E)$

and substitute in $<\sigma v> = (\frac{8}{\pi\mu})^{1/2}\frac{1}{(kT)^{3/2}}\int_0^\infty \sigma(E)E\exp(-\frac{E}{kT})dE$

If no resonances are present S(E) = S(Eo) = constant, so

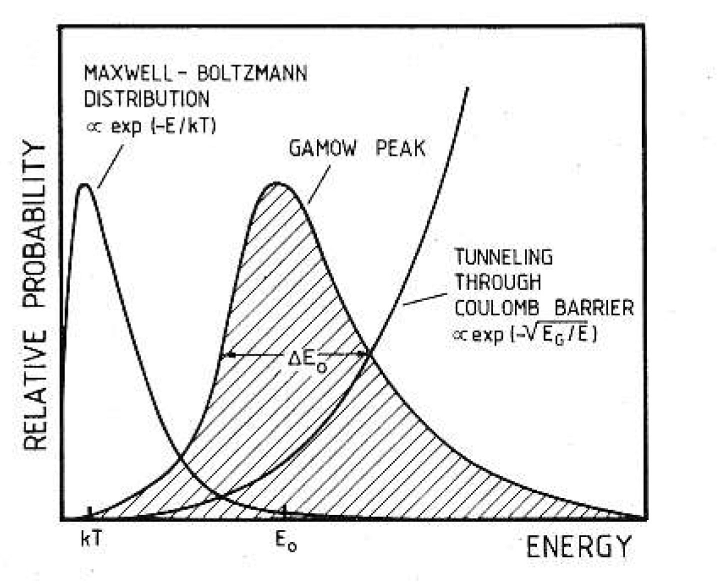
$$<\sigma v> = (\frac{8}{\pi\mu})^{1/2}\frac{1}{(kT)^{3/2}}S(E_0)\int_0^\infty \exp(-\frac{E}{kT}-\frac{b}{E^{1/2}})dE \qquad b = (\frac{2\mu}{\hbar^2})^{1/2}\pi Z_1 Z_2 e^2$$

Gamow peak

* The rate has a peak shape product of two negative exponentials: Maxwell-Boltzmann distribution at low energy and tunneling through the Coulomb barrier for higher E.

* It represents the region in energy where reactions are more likely to occur.

* The concept can be extended to a general S(E)



Neutron event in water.