Nuclear physics for Astrophysics - experiment

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NUSYS, July 27 – Aug. 2, 2024, Zhuhai, China

Premises

- Nuclear astrophysics is an important part of all nuclear labs' scientific programs
- **Nuclear astrophysics** now consists or *is close to*
  - Nuclear physics for astrophysics
  - Stellar dynamics
  - Nucleosynthesis modelling
  - (specific) astronomy observations: X-ray and Gamma-ray space telescopes, cosmochemistry …
  - *Cosmology* (?!)

and there is need for closer interaction among specialists in these fields! This process has started.

Nuclear Physics for Astrophysics

Doing experiments in the nuclear laboratory to understand stars

Big Problems: Stars are cold! E_p=10s-100s keV

There are many reactions occurring in stars

a) Direct measurements – reactions at the low energies the reactions occur in stars, or close to, followed by extrapolations

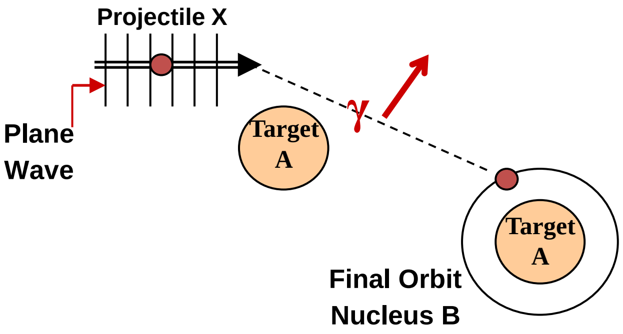
- Difficult because of extremely low cross sections
- Limited combinations of stable beams – targets
- Special accelerators (low energies, but high intensities) + targets + detection conditions (very low signals & high noise (backgr))

b) Indirect methods

- At higher (x10-1000), more convenient laboratory energies, extract relevant information
- Select quantities we measure → NA reaction rates
- Use radioactive beams (RIB) to reach wider ranges of reactions
- Several methods

Radiative capture reactions

Vocabulary



- Radiative capture reactions A(p,γ)B, A(α,γ), A(n,γ)
- **Non-resonant** or **resonant** reactions.
- At low energy, the probability that the incoming **charged particle** penetrates the Coulomb barrier:

$$P = \exp(-2\pi\eta), where \quad \eta(E) = \frac{Z_1 Z_2 e^2}{\hbar\nu}$$

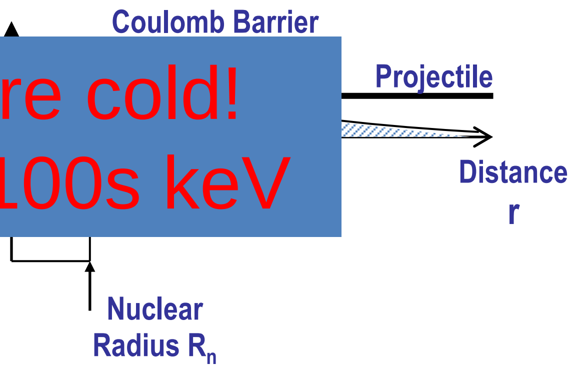
- The cross section – astrophysical S-facto

$$\sigma(E) = \frac{1}{E}\exp(-2\pi\eta) S(E)$$

- Reaction rate per particle pair (i distr):

to determine

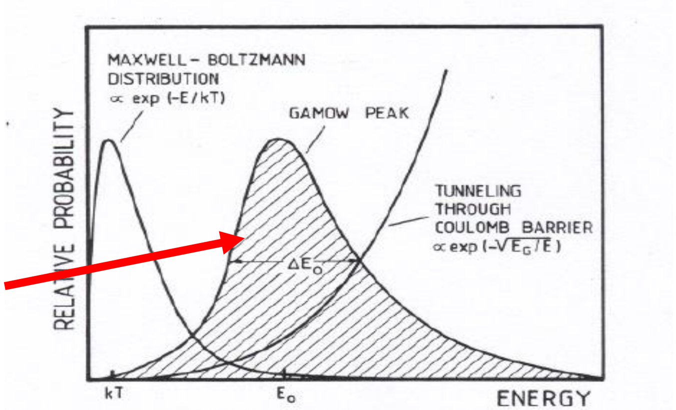
$$\langle\sigma\upsilon\rangle = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty S(E) \exp\left(-\frac{E}{kT} - \frac{b}{E^{1/2}}\right) dE$$



Stars are cold!

E_p=10s-100s keV

- Reactions (that matter) take place in the **Gamow energy window**.
- Direct, or non-resonant part



* C. Rolfs and W. Rodney, “Cauldrons in the Cosmos”.

Resonant Reaction Rates

* **Resonant** reaction is a two-step process.

$$\sigma_\gamma \propto \left|\langle E_f | H_\gamma | E_r \rangle\right|^2 \left|\langle E_r | H_f | A + p \rangle\right|^2$$

* The cross section (Breit-Wigner):

$$\sigma(E) = \frac{\lambda}{4\pi} \frac{2J+1}{(2J_1+1)(2J_2+1)} \frac{\Gamma_p \Gamma_\gamma}{(E-E_r)^2 + \left(\frac{\Gamma}{2}\right)^2}$$

* The contribution to the reaction rate:

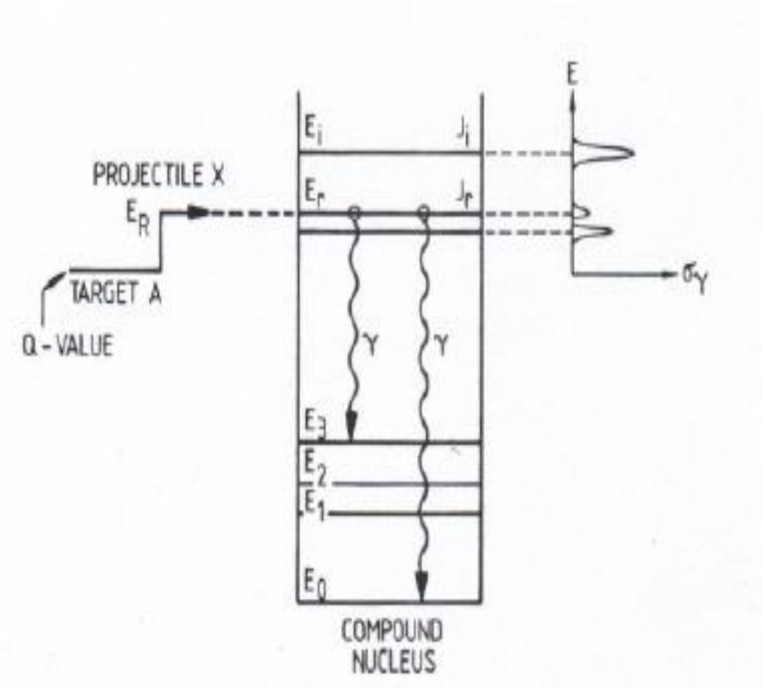
$$\langle \sigma v \rangle_{res} = \left(\frac{2\pi}{\mu k T}\right)^{3/2} \hbar^2 \omega\gamma \exp\left(-\boxed{\frac{E_r}{kT}}\right)$$

where

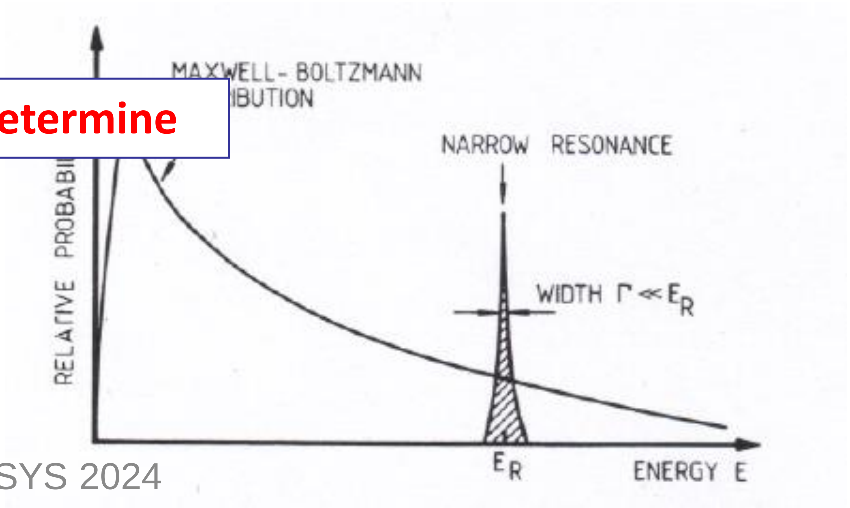
$$\omega\gamma = \frac{2J_r + 1}{(2J_p+1)(2J_t+1)} \boxed{\frac{\Gamma_p \Gamma_\gamma}{\Gamma_{tot}}}$$

to determine

ωγ= resonance strength

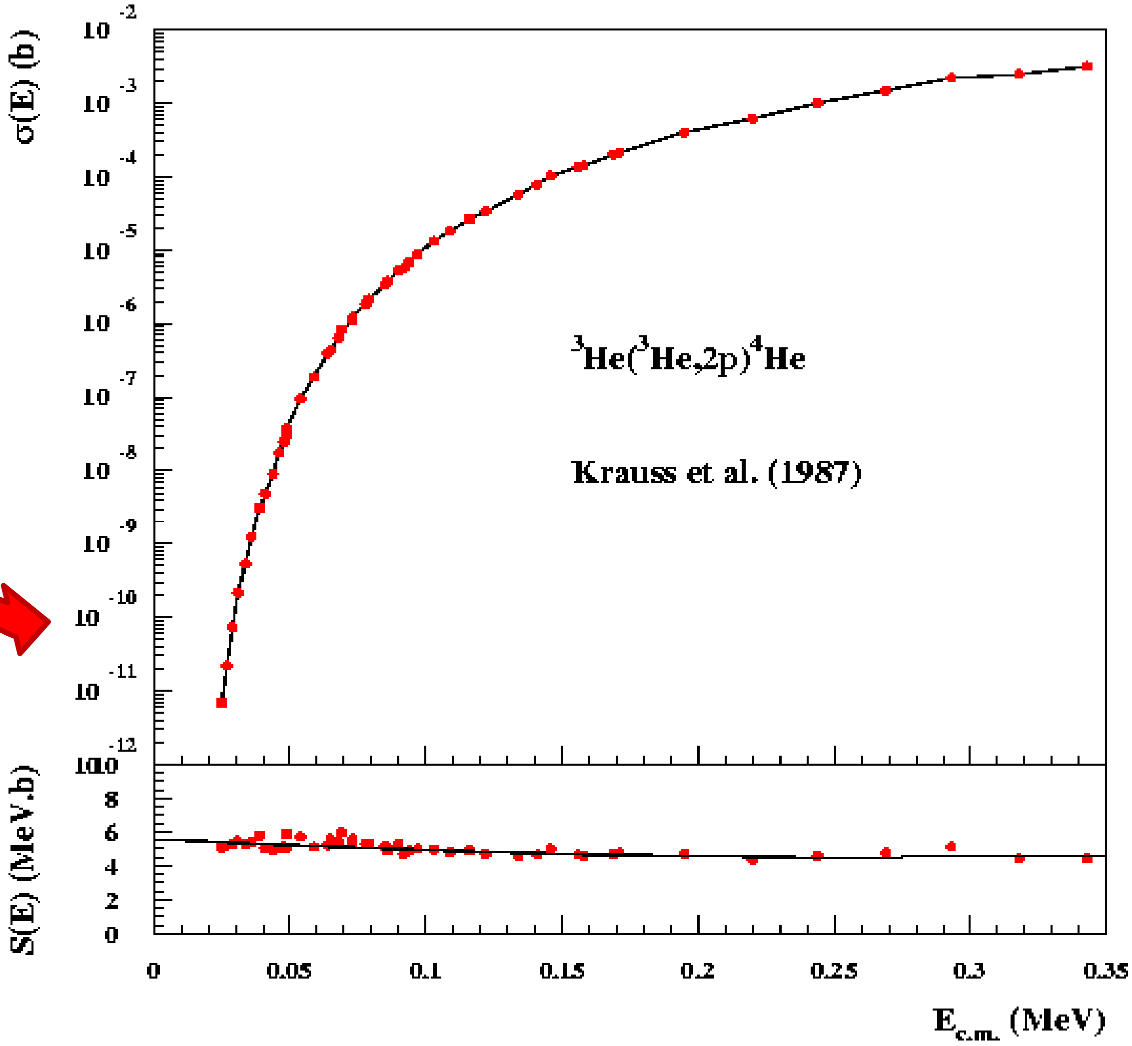


* C. Rolfs and W. Rodney, “Cauldrons in the Cosmos”.



Warning:

- we plot and say “we determine the astrophysical S-factor”
- but we measure cross sections

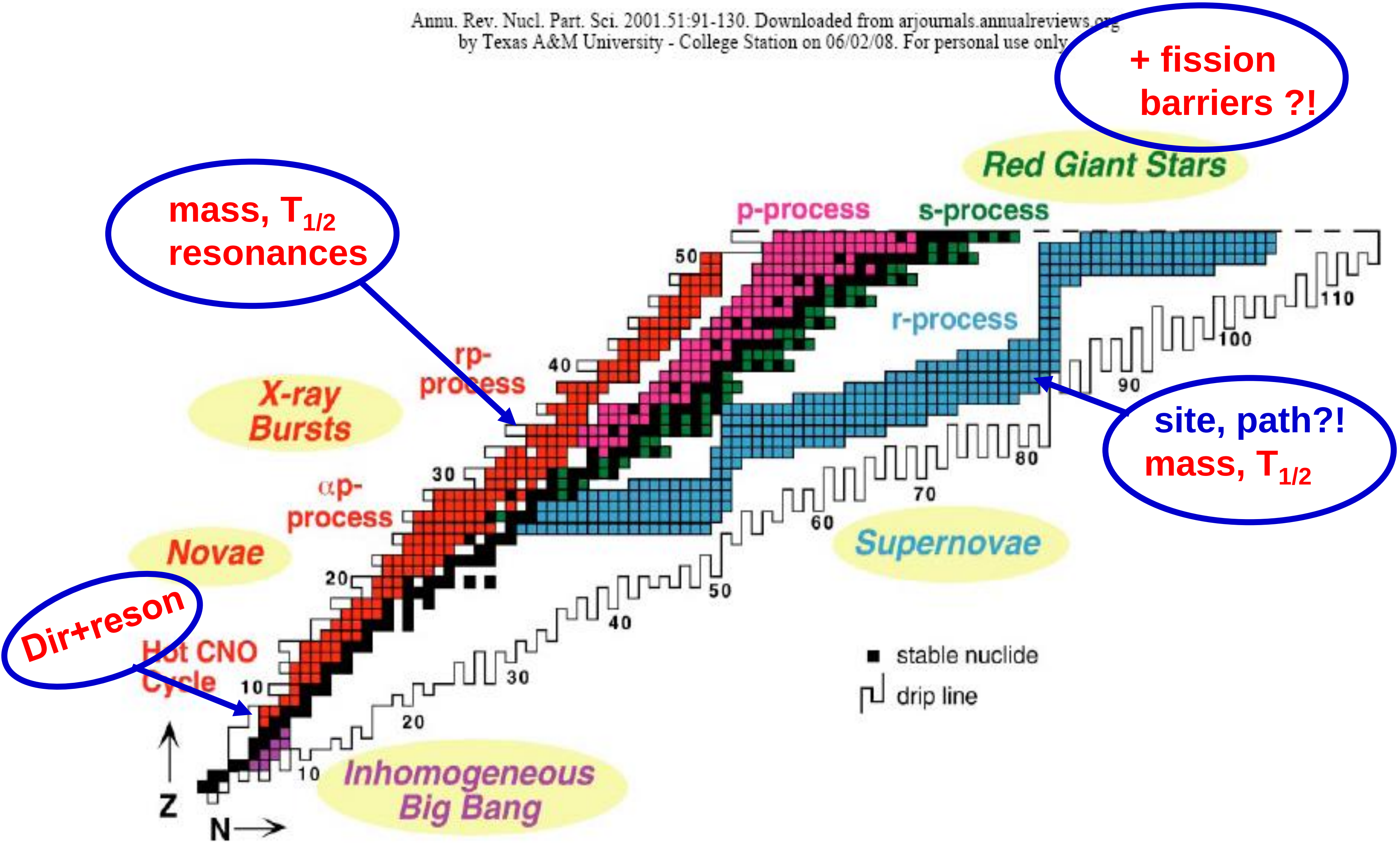


Energies and cross sections for some direct measurements (pp and CNO reactions)

Reaction	E_c/keV	E_0/keV	σ (E_0)/barn	E_{min}/keV
^{3}He(^{3}He,2p) ^{4}He	1540	21	$7\ 10^{-13}$	16.5
^{3}He(α,γ) ^{7}Be	1540	22	$9\ 10^{-18}$	107
^{14}N(p,γ) ^{15}O	2270	26	$4\ 10^{-21}$	200

…. how "easy" is their measurement in the Lab ?

M. Smith & E. Rehm



+ fission barriers ?!

mass, $T_{1/2}$ resonances

site, path?! mass, $T_{1/2}$

Dir+reson

Two big problems:

1. - very small energies and very small cross sections ⇒indirect methods
2. - reactions in stars involve(d) radioactive nuclei ⇒ use RNB

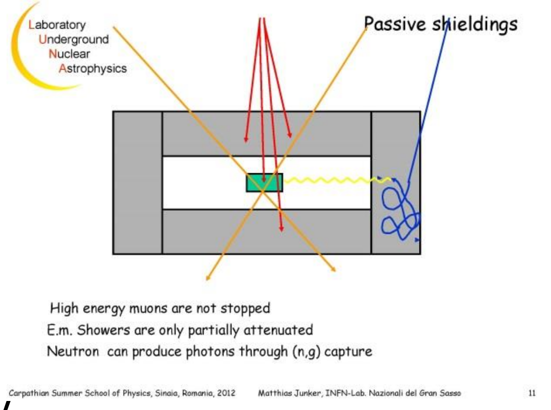
Nuclear physics for Astrophysics - experiment

2. Direct Measurements in Nuclear Astrophysics

NUSYS, July 27 – Aug. 2, 2024, Zhuhai, China

Old = direct measurements – problems and solutions

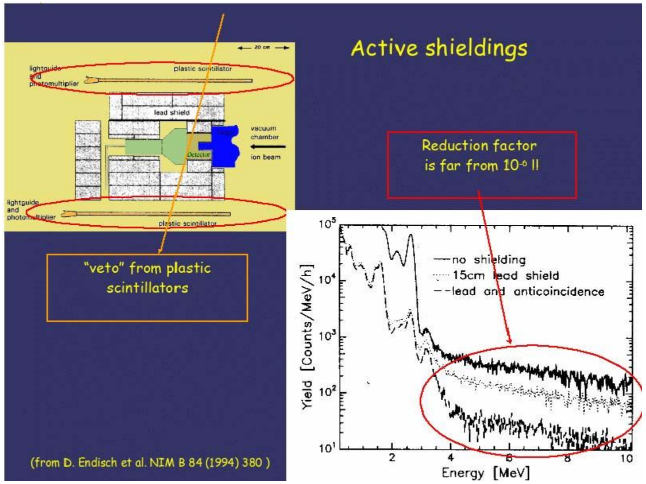
- low cross sections →
- measure longer?!
- **No, bc background issues!**
- Background from
    - Cosmic rays
    - Environment radioactivity
- Solution: **shielding**
    - Passive
    - Active
    - **Underground**
- **Low cross sections**
    - High current accelerators
    - Targets …
- Detect what?!



Passive shieldings

High energy muons are not stopped
E.m. Showers are only partially attenuated
Neutron can produce photons through (n,g) capture

Carpathian Summer School of Physics, Sinaia, Romania, 2012 Matthias Junker, INFN-Lab. Nazionali del Gran Sasso 11

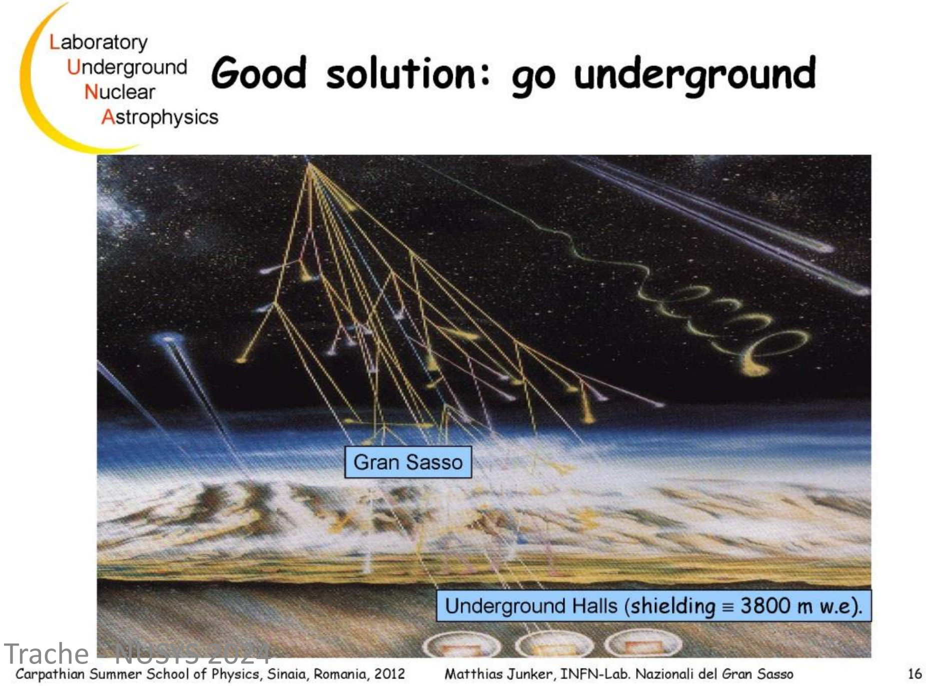


Active shieldings

Reduction factor is far from 10^{-6} !!

“veto” from plastic scintillators

(from D. Endisch et al. NIM B 84 (1994) 380)



Good solution: go underground

Underground Halls (shielding ≡ 3800 m w.e).

Carpathian Summer School of Physics, Sinaia, Romania, 2012 Matthias Junker, INFN-Lab. Nazionali del Gran Sasso 16

Direct measurements - facilities

Several small accelerators worldwide: Europe (Germany, Romania, Italy, Hungary …), US, China, India, etc…

Big improvement: underground labs

- LUNA1, LUNA2, LUNA MV (now Boletti Lab) at LN Gran Sasso, Italy
- Canfranco, Spain
- US: Notre Dame’s Diana ?!
- LEAF @ IMP, JUNA
- Romania: activation measurements facility in a salt mine

Detection improved:

  - increased efficiency – multi detectors
  - coincidences

EXPERIMENTAL SOLUTIONS
Direct measurements

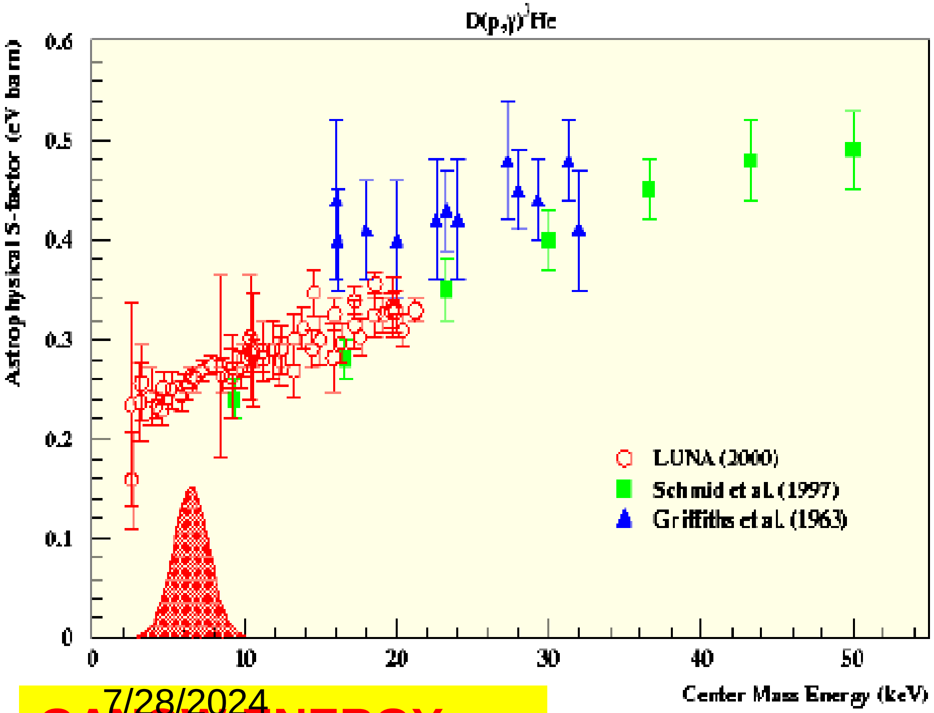
IMPROVEMENTS TO REDUCE THE BACKGROUND

-(UNDERGROUND LABORATORY)

Use of laboratory with natural shield

(underground physics-for instance **LUNA experiment at LNGS-Italy**)

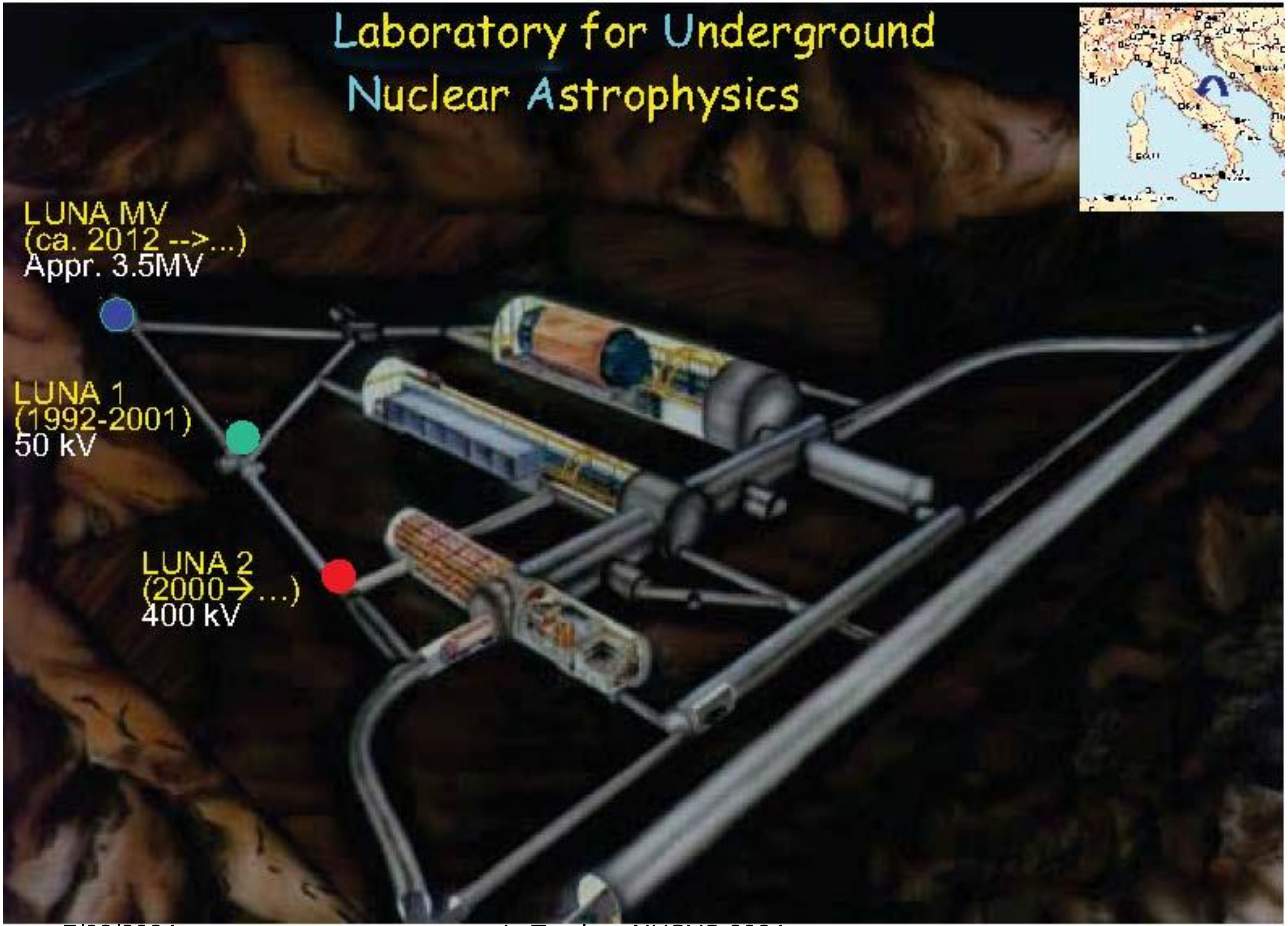
$^{2}H(p,\gamma)^{3}He$



GANOW ENERGY

NO EXTRAPOLATION needed

Laboratory for Underground Nuclear Astrophysics



LUNA MV
(ca. 2012 -->...)
Appr. 3.5MV

LUNA 1
(1992-2001)
50 kV

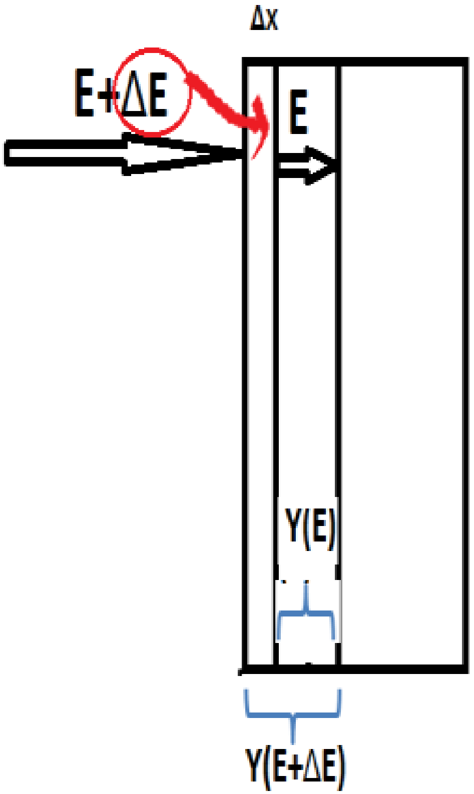
LUNA 2
(2000→…)
400 kV

Steps

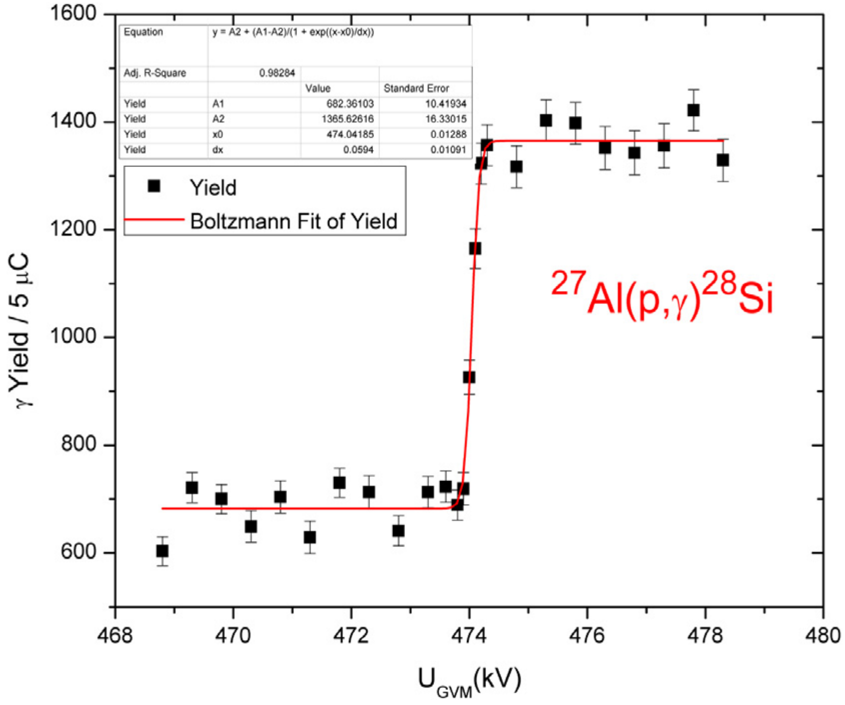
- Reaction ?!
- Targets – thin or thick, need to stand high currents
- Calibration of accelerator energies – need precision
- Detection and detectors
- Analysis – data
- Interpretation
- Extrapolation ?! Most of the time. “Theory guided” is best

Targets for NA

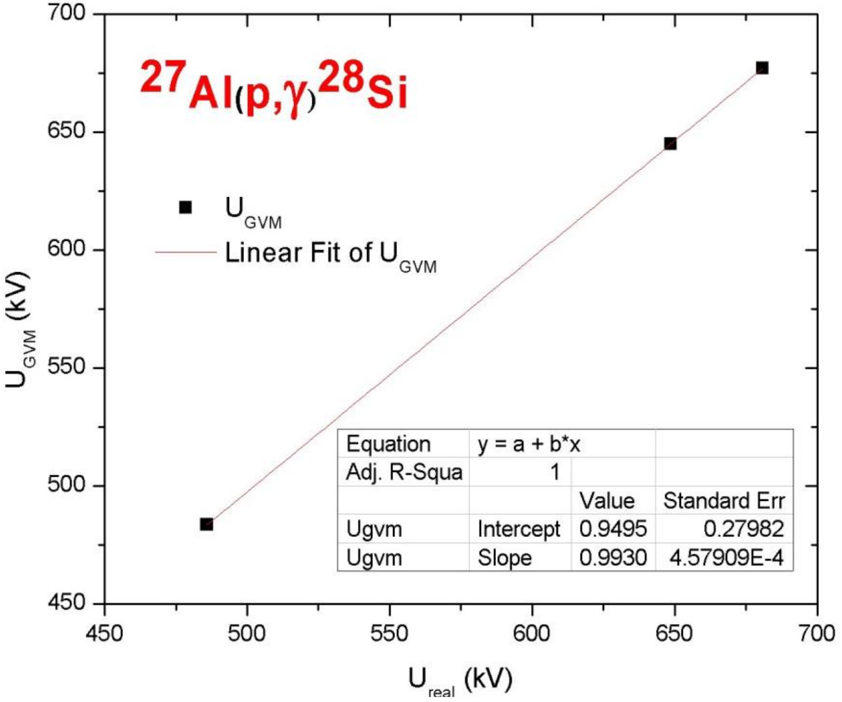
- May be difficult or very difficult
- Solid targets?! Gas targets ?! Composite targets ?!
- Thin targets may be difficult to make and handle – may not take high currents
- Thick target method
  - Advantage of being more resistant
  - Could be easier to cool



Accelerators’calibration
very important – done using known resonances



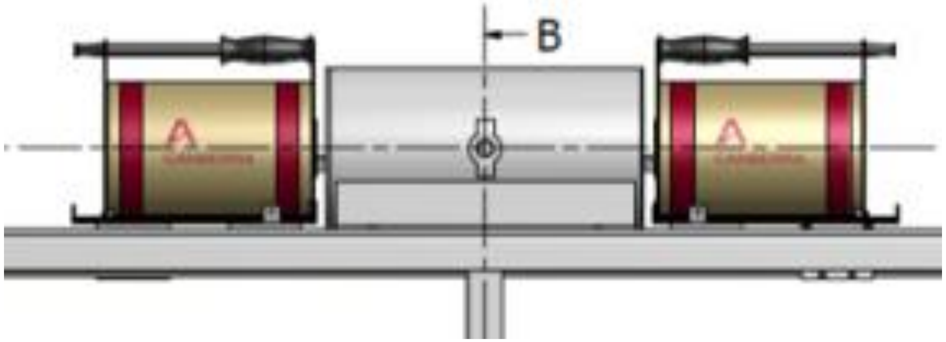
Equation	y = A2 + (A1-A2)/(1 + exp((x-x0)/dx))		
Adj. R-Square	0.98284		
		Value	Standard Error
Yield	A1	682.36103	10.41934
Yield	A2	1365.62616	16.33015
Yield	x0	474.04185	0.01288
Yield	dx	0.0594	0.01091



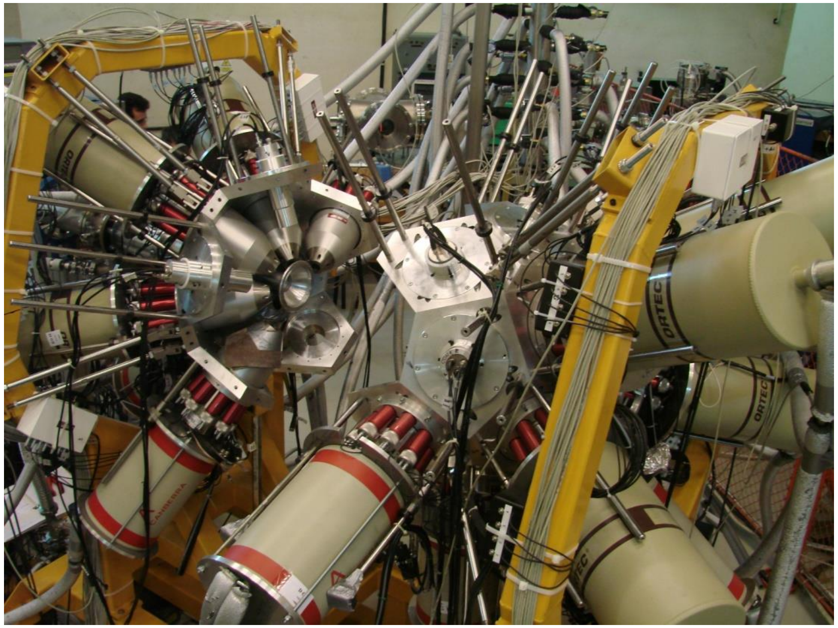
Equation	y = a + b*x		
Adj. R-Squa	1		
		Value	Standard Err
Ugvm	Intercept	0.9495	0.27982
Ugvm	Slope	0.9930	4.57909E-4

Detectors and detection systems

Simple: uni- or bi-, because can get close to target/probe



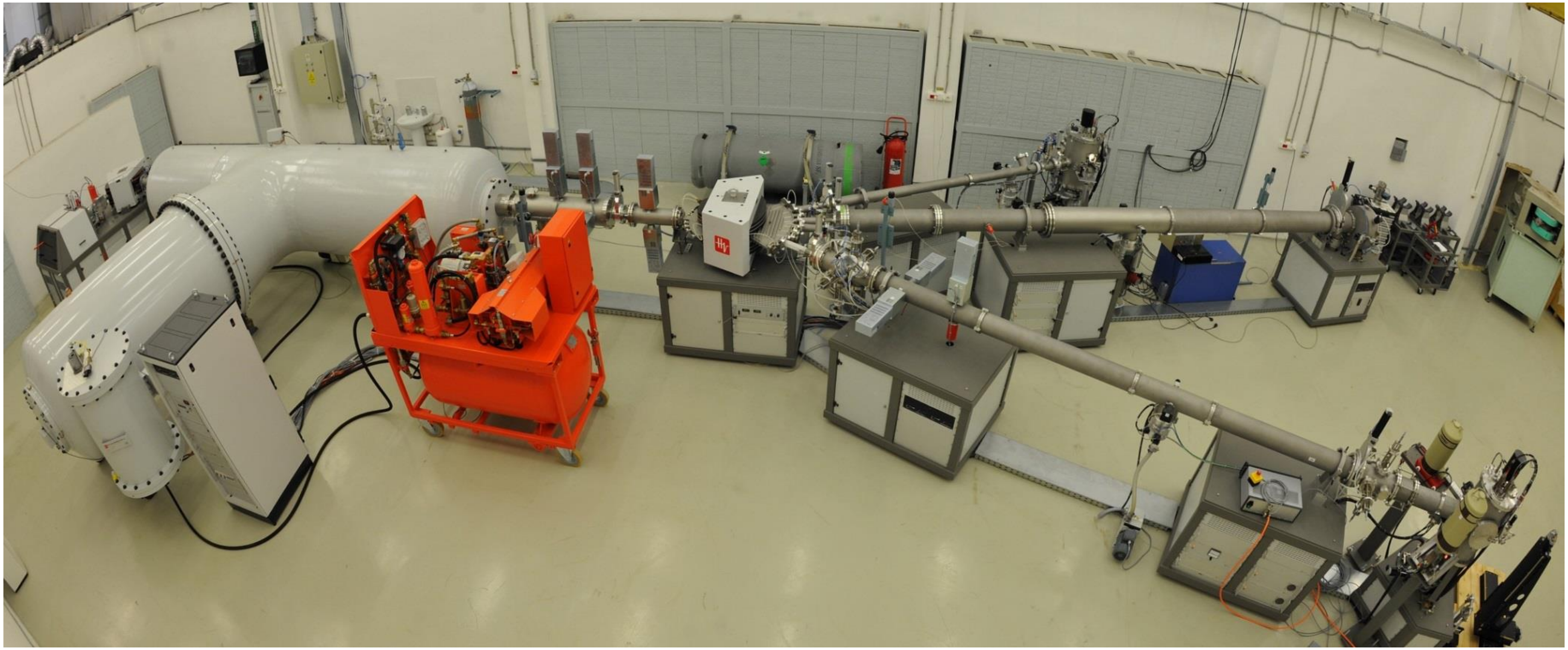
Detector arrays: more complex, more efficient (?!), better info …



At IFIN-HH

- At IFIN-HH we have a 3 MV tandetron accelerator
- an ultralow background laboratory in a salt mine, Slanic-Prahova, 125 km away
- Ultralow gamma-ray background due to pure salt and compact walls (no cracks for Radon to migrate in)
- Established that activation is the most sensitive method
- Could go into the salt mine, but only when activity has long half-lifes

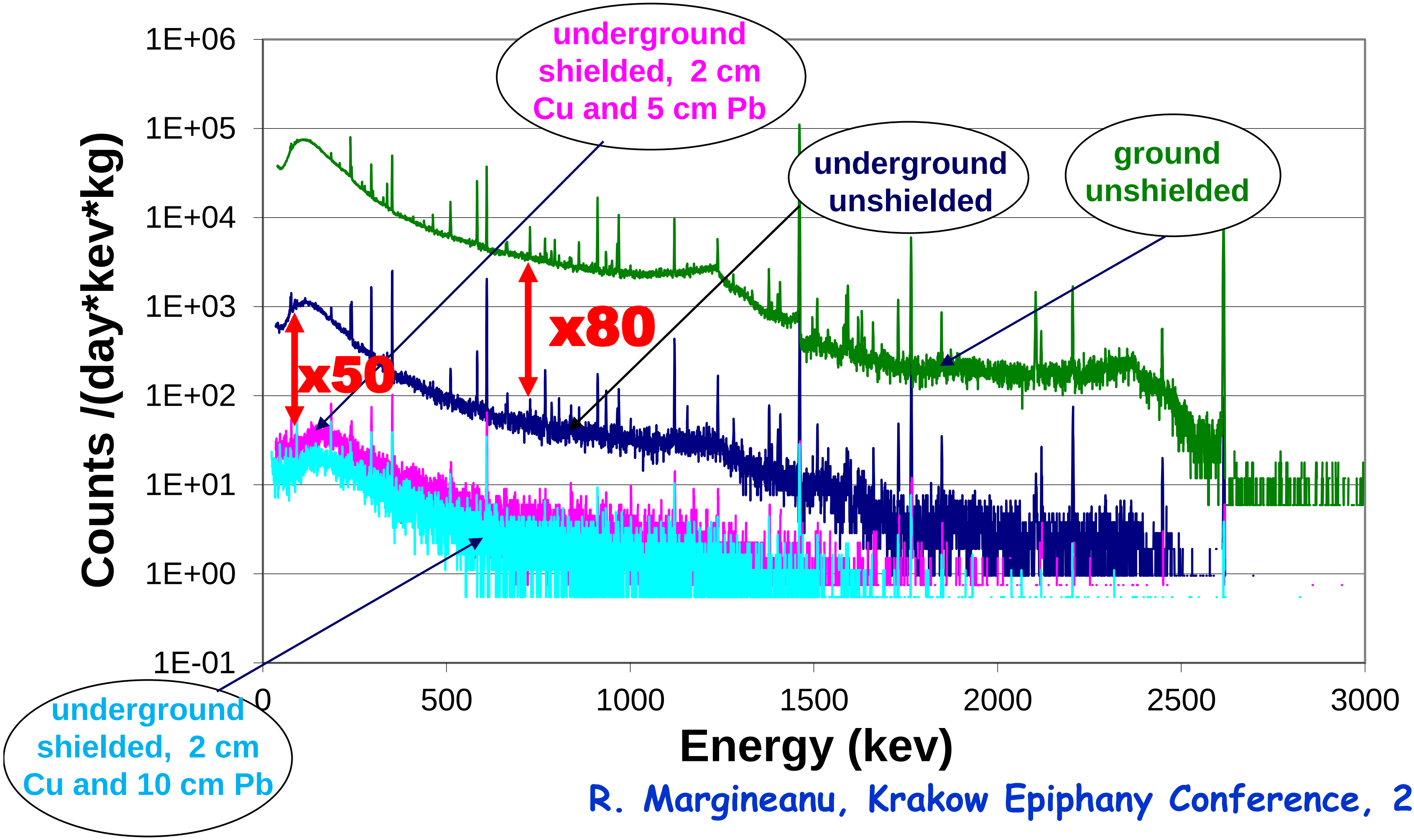
3 MV Tandetron™



I. Burducea et al., NIM B, vol. 359, 15: 12–19, 2015

“microBq” Lab

Background spectra collected with a CANBERRA HPGe detector with 100% relative efficiency

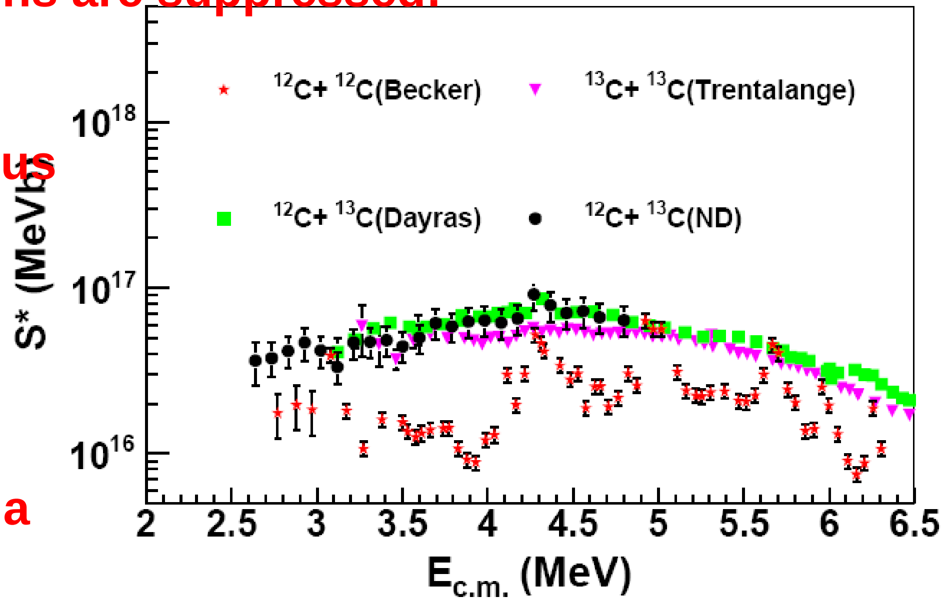


R. Margineanu, Krakow Epiphany Conference, 2010

^{13}C+^{12}C Exp Bucharest – Lanzhou

- **Motivation: important reaction in nuclear astrophysics: ^{12}C+^{12}C (Supernovae, massive stars evolution …)**
- **very difficult to measure, fluctuating due to resonances!**

- **No resonances observed in ^{13}C+^{12}C! Obs: for most energies, the ^{12}C+^{12}C cross sections are suppressed!**

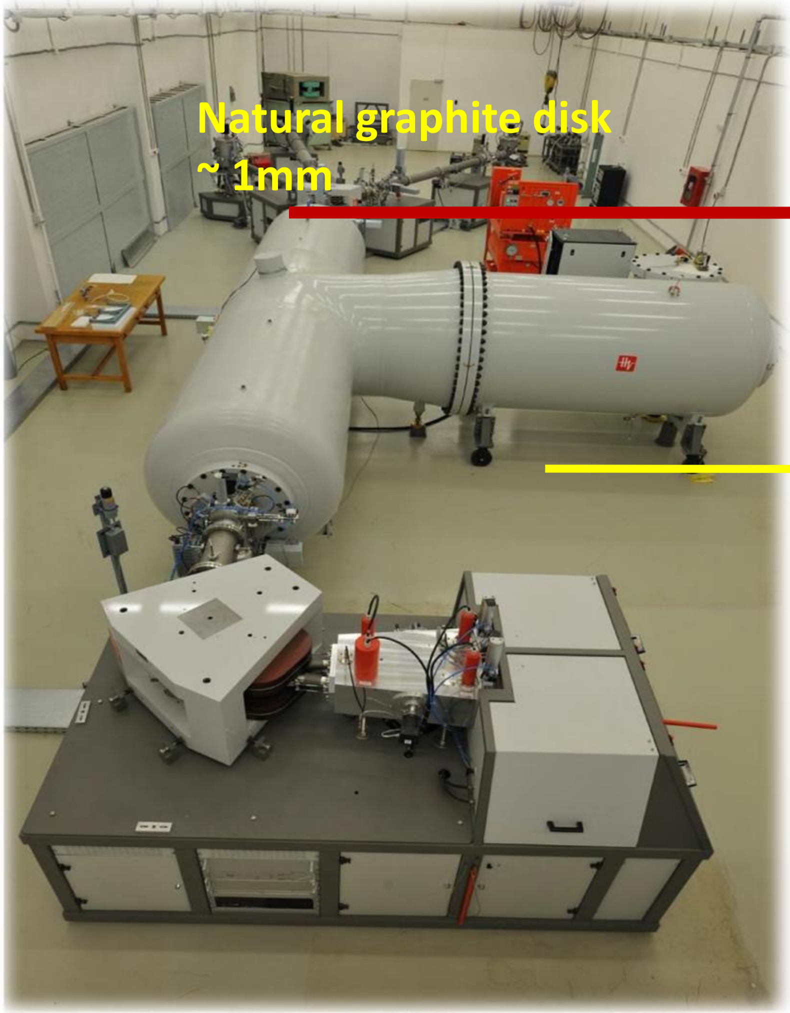


- **proposed tests of nucleus-nucleus models using ^{13}C+^{12}C, measured in the Gamow window**
Test react mech below barrier

- **Collaboration with group of prof. X. Tang – IMP Lanzhou, China**

The $^{13}C+^{12}C$ Experiment: prompt and activation

In beam irradiation, thick targets



$^{12}C(^{13}C,p)\ ^{24}Na$

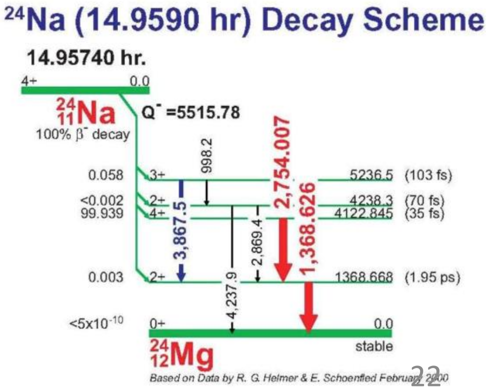
^{24}Na: $T_{1/2}$ =15 hr

E_{γ}=1369, 2754 keV

$^{13}C^{2+}$ beam

2-16 eμA

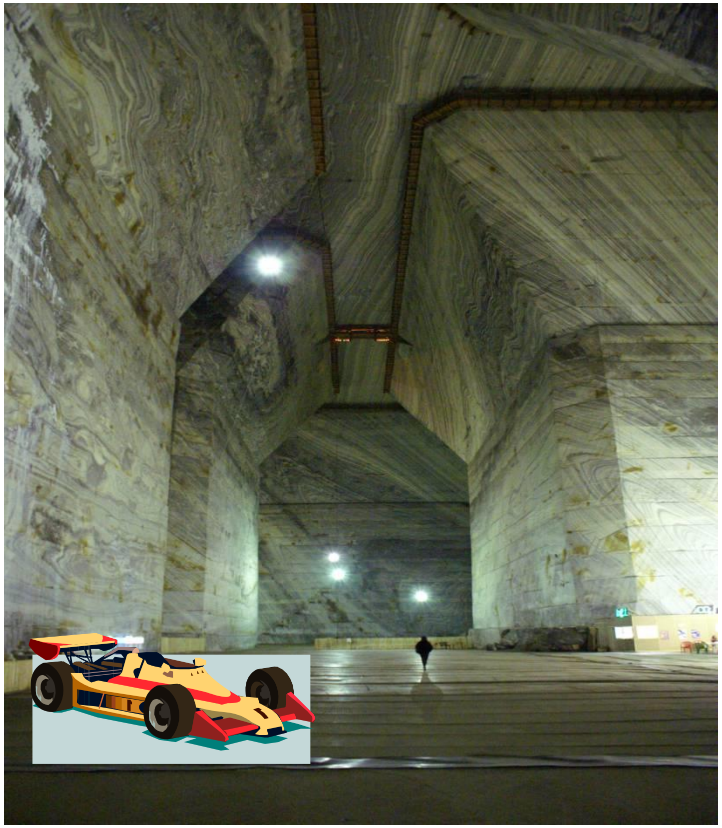
- ^{13}C beam energy 4.6 – 11. MeV (E_{cm}=2.3 – 5.4 MeV), in steps of 0.2 MeV



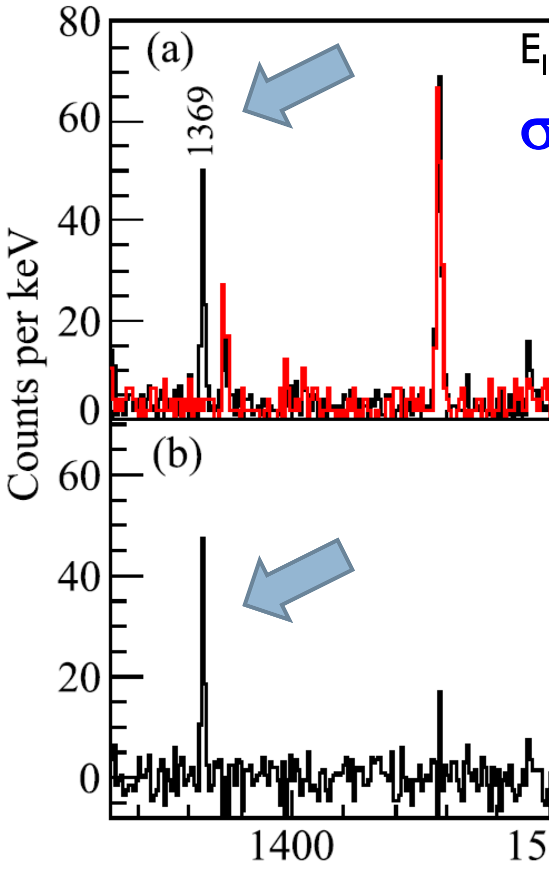
Activation and measurements in environments with ultralow background: salt mine

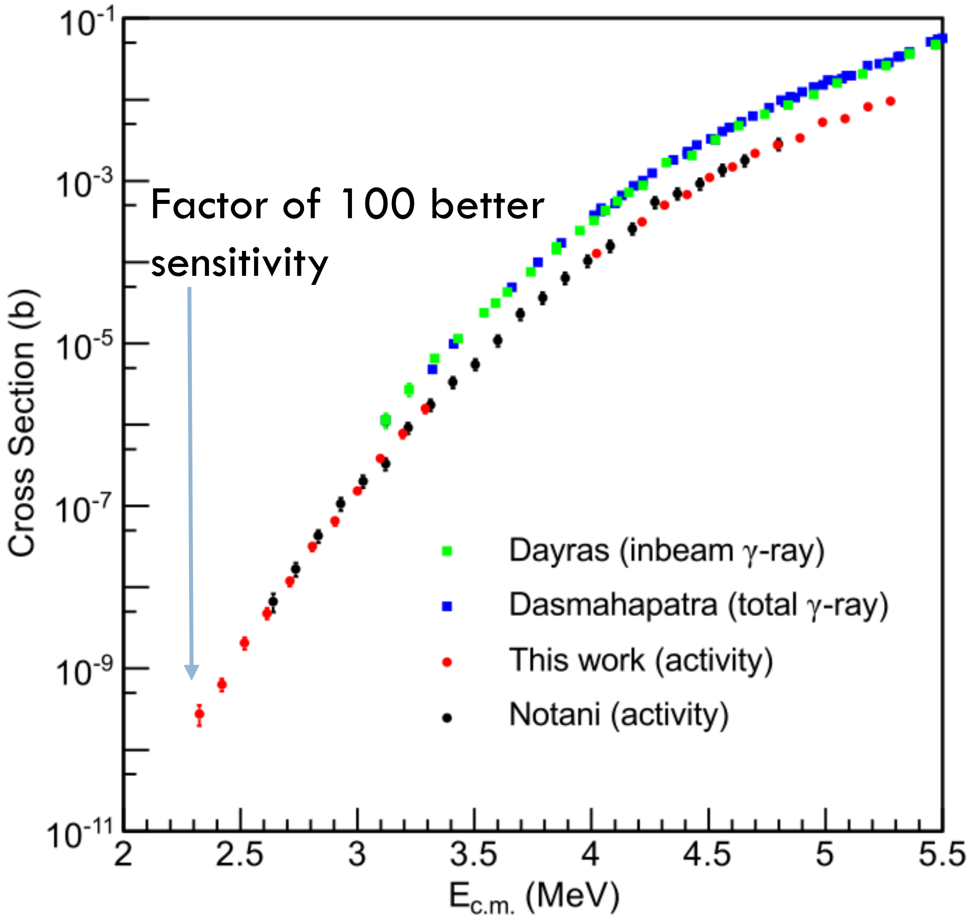
Activation in nuclear laboratory (this is the 3 MV tandetron)

Measurement in salt mine Slanic Prahova (2.5 hrs from Bucharest - very low gamma-ray background)



Low level background counting

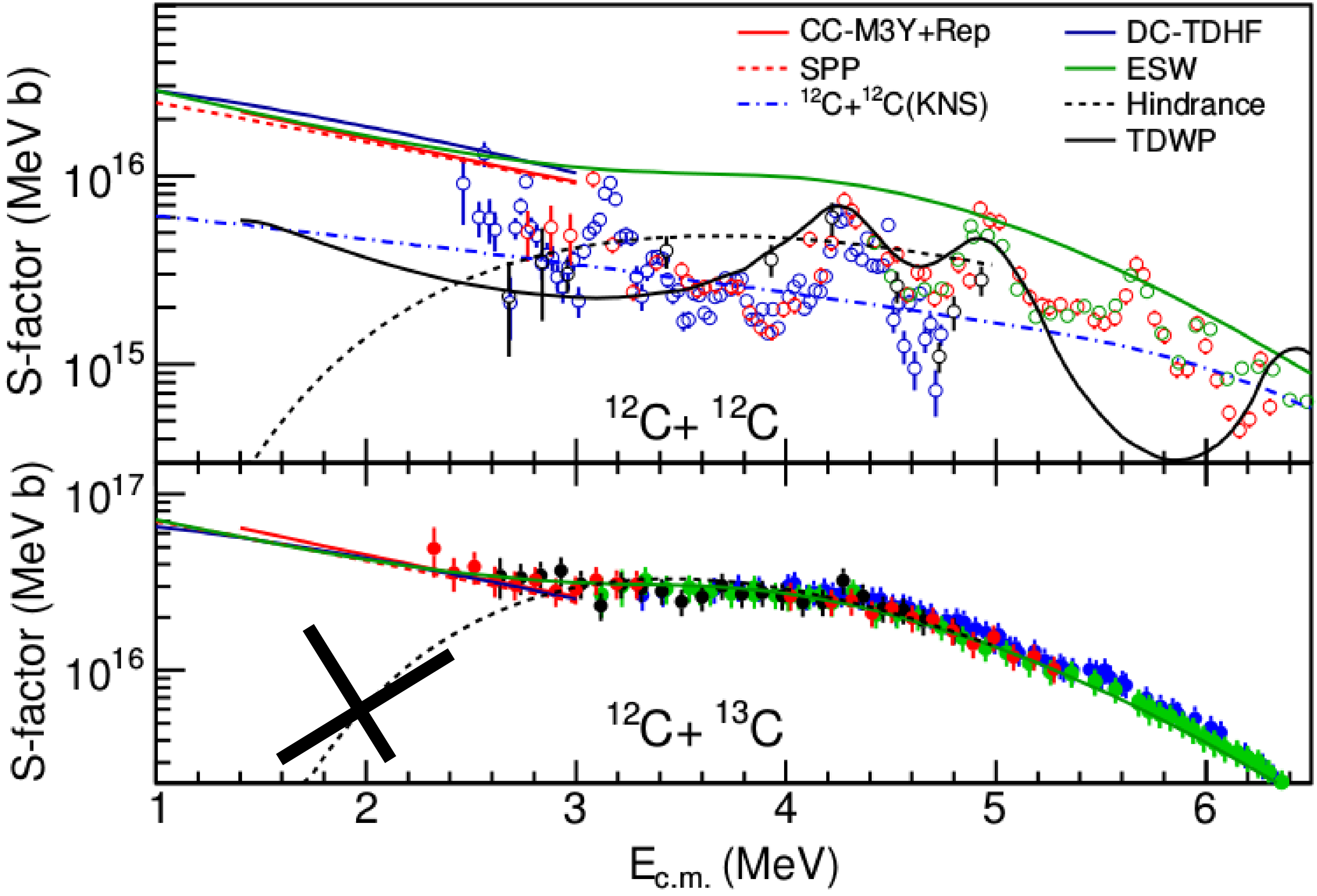




Factor of 100 better sensitivity

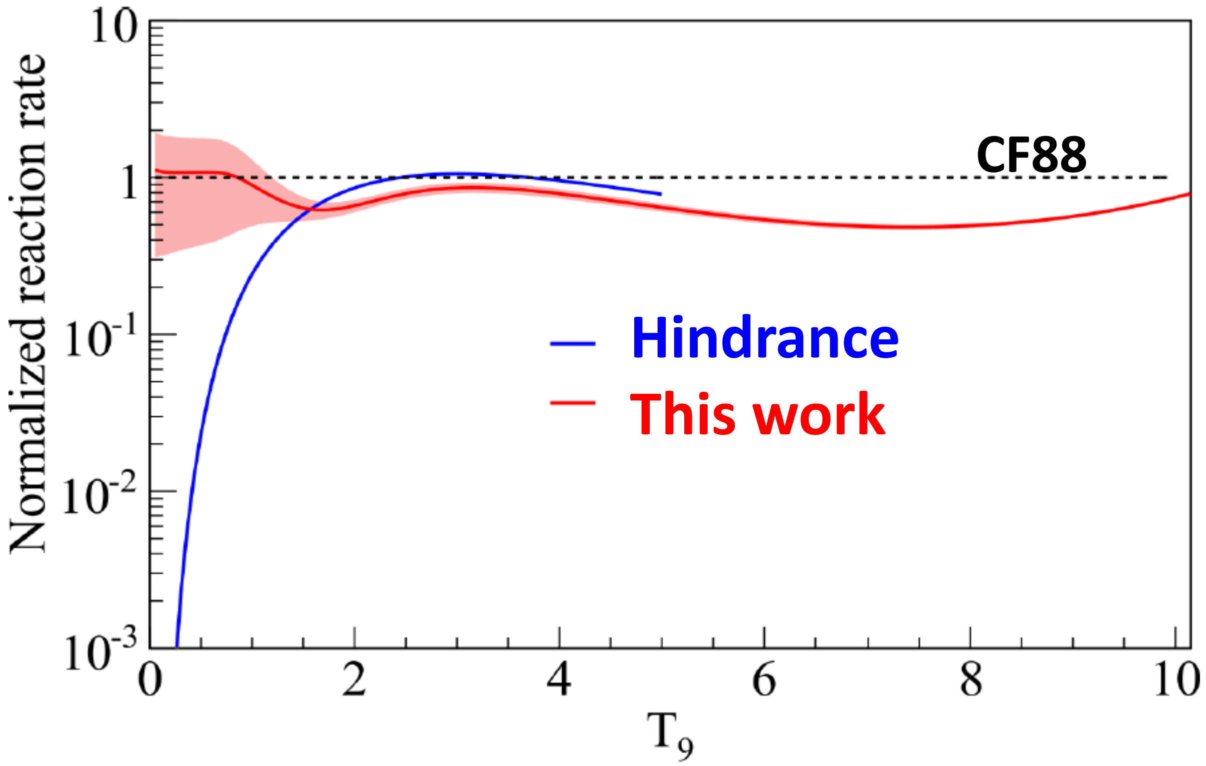
Thick target method activation: 3 targets, 3.4 days; measurements: 3.9 days

$^{12}C + ^{12}C$

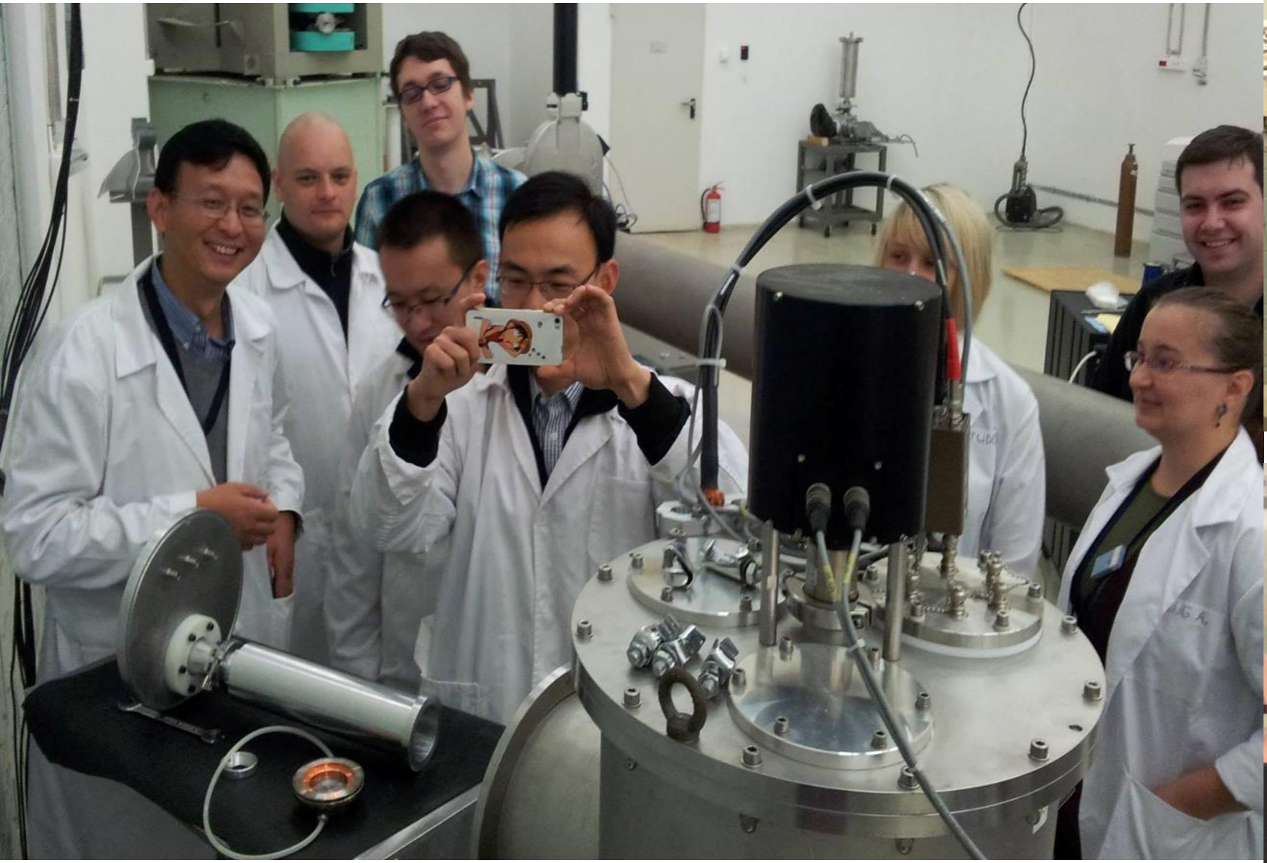


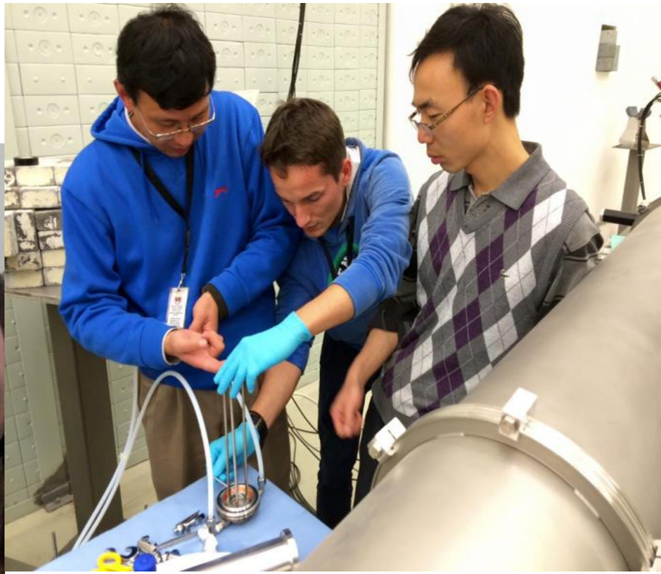
Zhang et al., *Phys. Letters B* **801** (2020)

Reaction rate recommendation



N.T. Zhang (IMP), D. Tudor (NAG) e.a., **Phys Lett B 801** (2020)





A. Tumino et al., Nature 2018

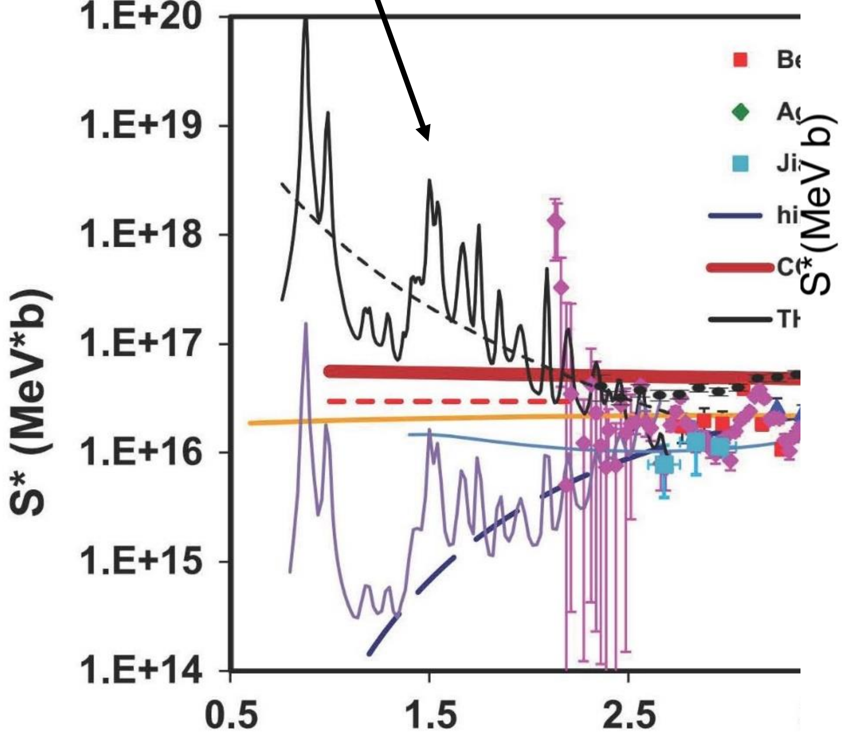
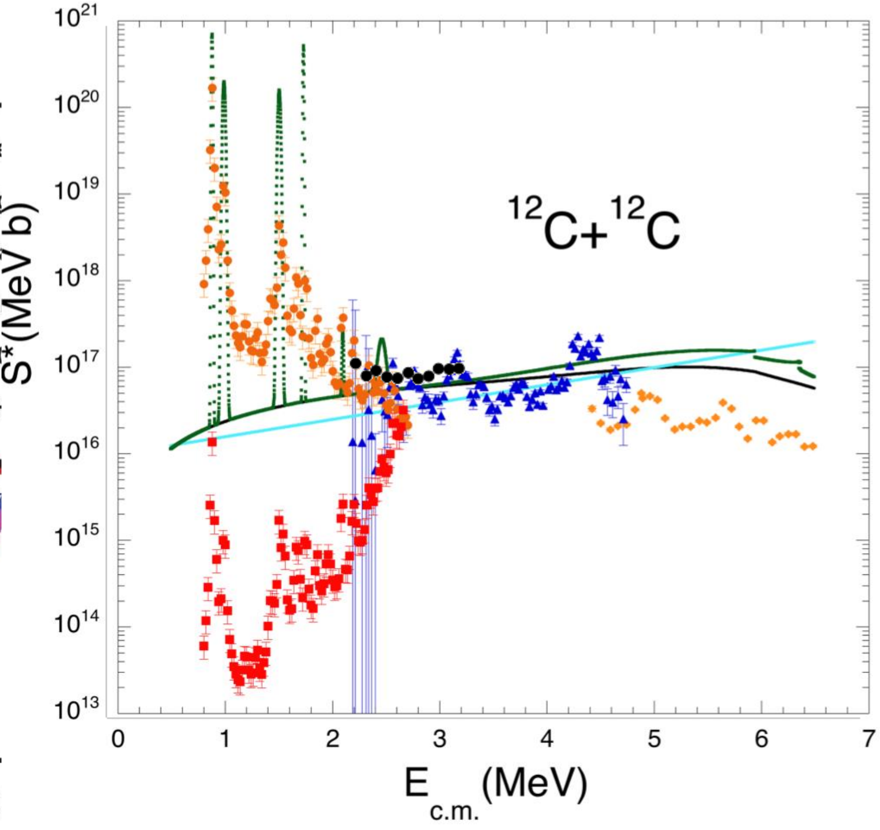


Figure from Beck et al, **Eur. Phys. J. A** (2020)



Green calc - Bonasera A., Natowitz J.B, **Phys Rev C 102** (2020)

Other cases

- Program to study light ion-ion fusion mechanisms at sub-barrier energies - dr. Alexandra Spiridon in charge
- $^{12}C+^{12}C$, $^{12}C+^{16}O$, $^{16}O+^{16}O$ – all do not produce activation!
- Try to use neighboring isotopes: $^{13}C+^{16}O$, $^{19}F+^{12,13}C$… most lead to short lived activities => no salt mine!
- Invent something else: clean spectra with coincidences in our lab
- Beta-gamma coincidences station BEGA: two HPGe detectors and a plastic scintilator
  - background reduction factor ~100
  - down to $T_{1/2}$ ~2 min
- Future: fast changing target system

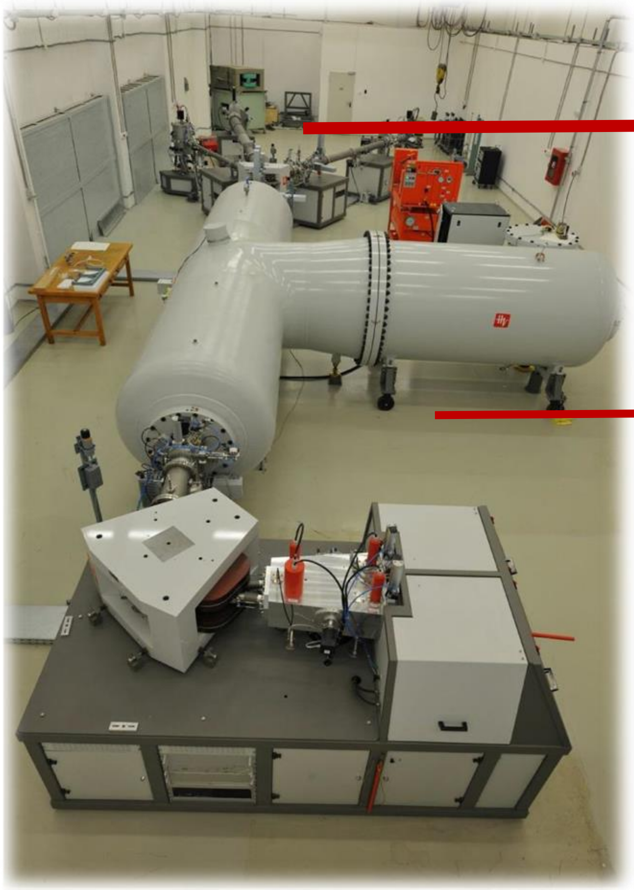
The $^{12}C+^{16}O$ Reaction

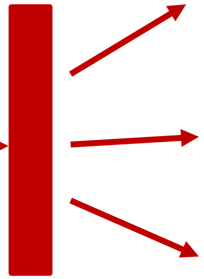
Problem: $^{12}C+^{16}O$ leads to stable residuals only

Solution: try $^{13}C+^{16}O$

Problem: ^{16}O target? Try oxide CeO_2

In beam irradiation, thick targets (CeO_2)





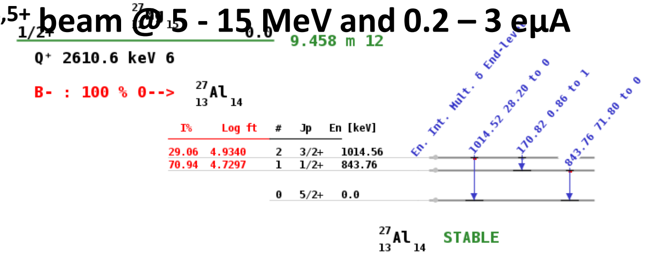
$^{16}O(^{13}C,p)\,^{28}Al$ - $T_{1/2}$ =2.2 min

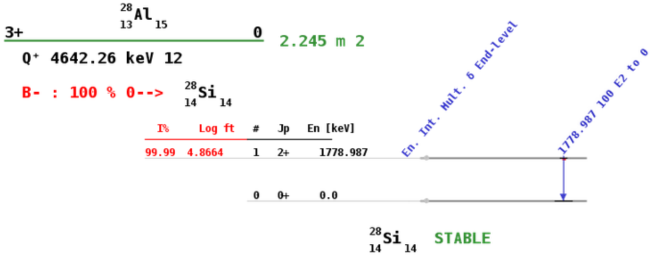
E_γ= 1779 keV

$^{16}O(^{13}C,2p)\,^{27}Mg$ - $T_{1/2}$ =9.5 min

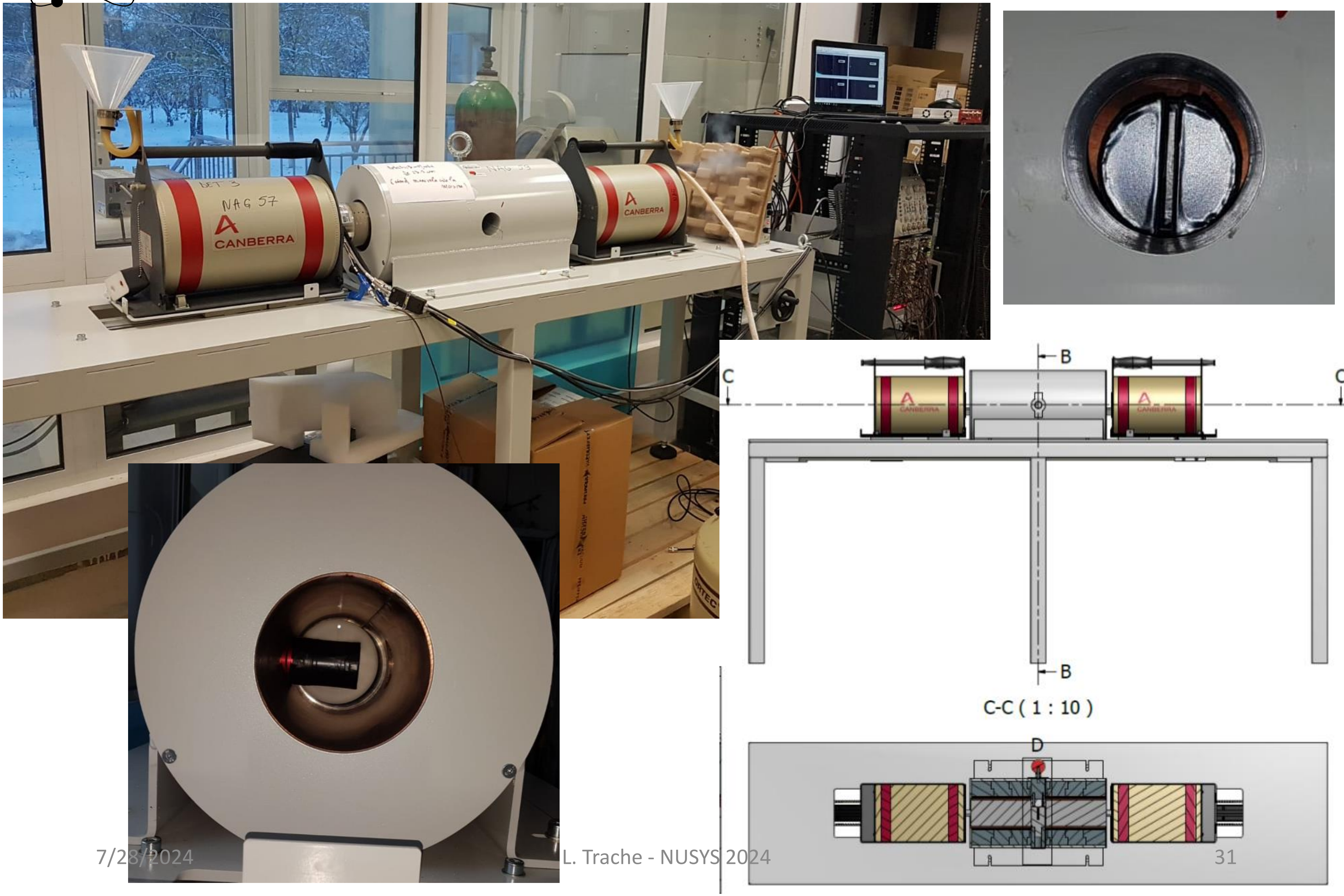
E_γ= 843.76 keV, 1014.52 keV

$^{13}C^{3,4,5+}$ beam @ 5 - 15 MeV and 0.2 – 3 eμA

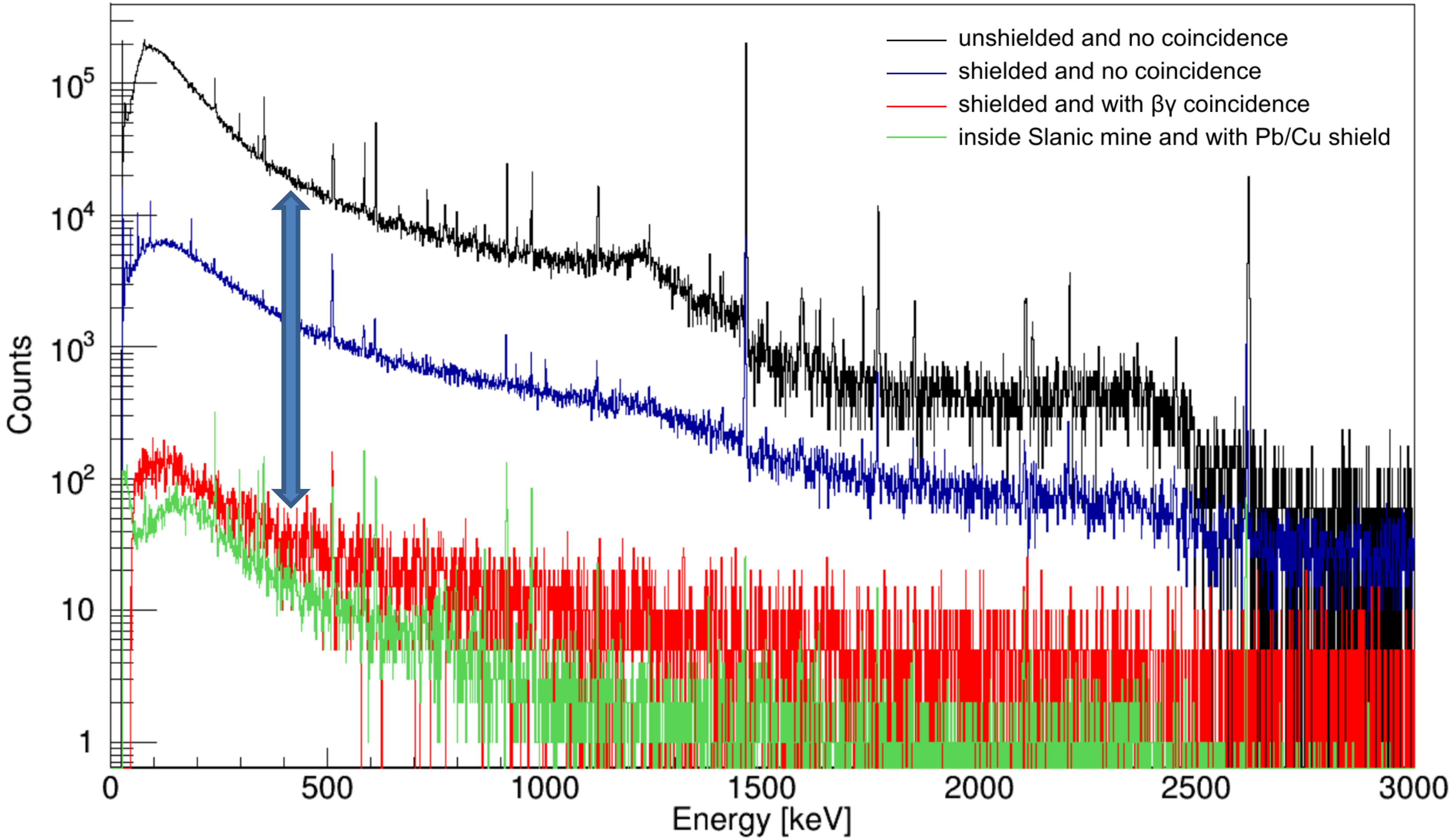




BeGa station (WIP)

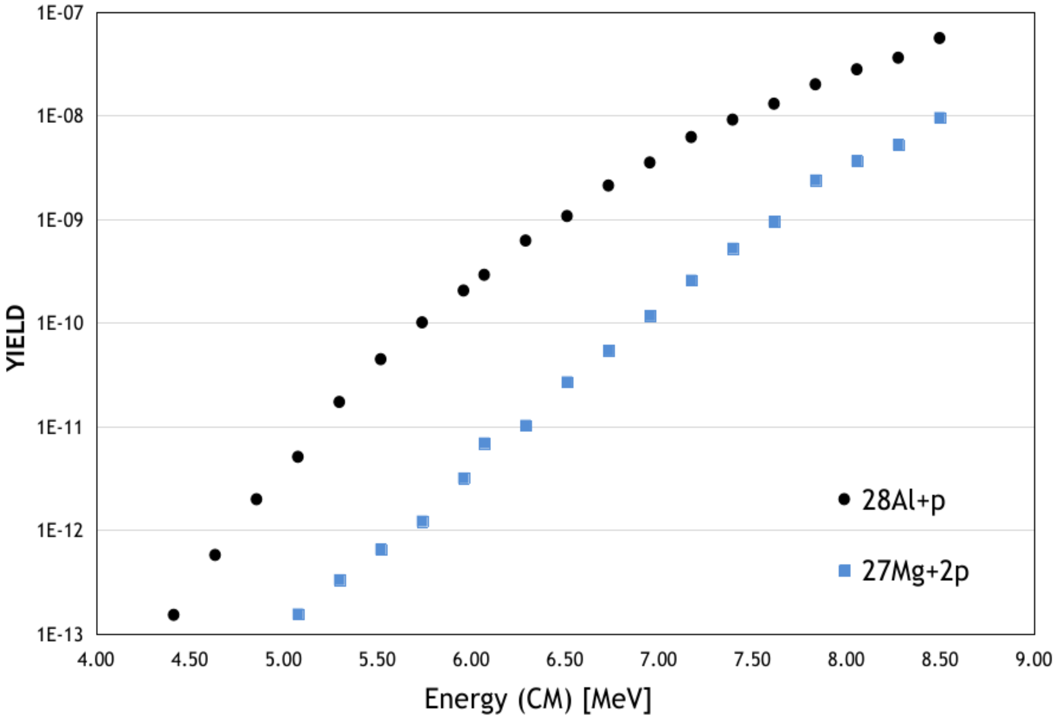


Background reduction ~ 1000 (red spectrum)



Further problems - targets
The $^{13}C+^{16}O$ Reaction – Preliminary results

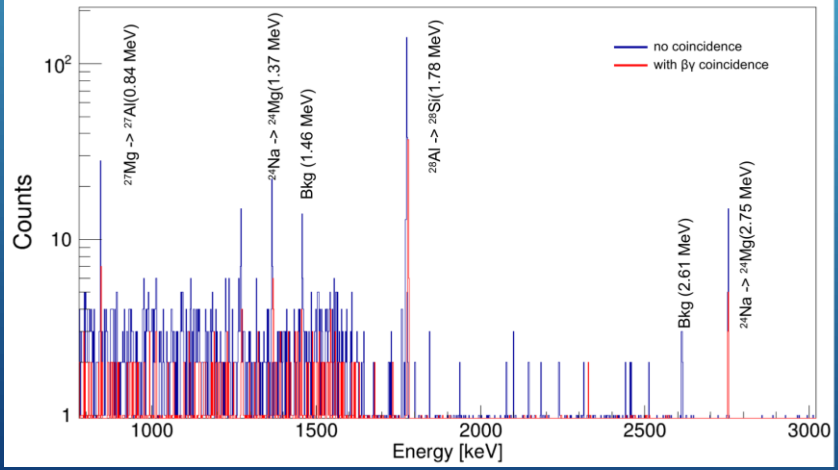
CeO_2 targets



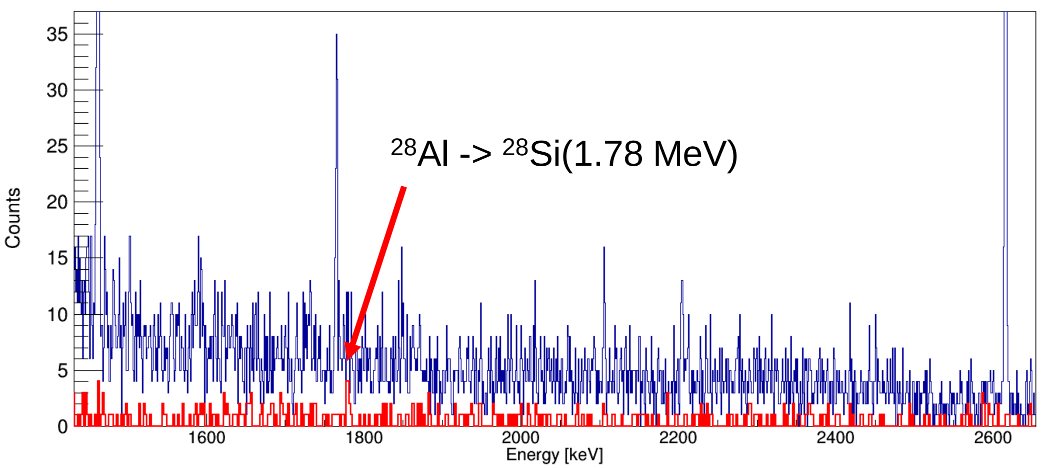
Alex Spiridon, PD grant (PN-III-P1-1.1-PD-2019-0234)

$^{13}C + ^{16}O$ – preliminary results

E_{Lab} = 11 MeV
t_{irr} = 1 hr and t_{decay} = 25 min

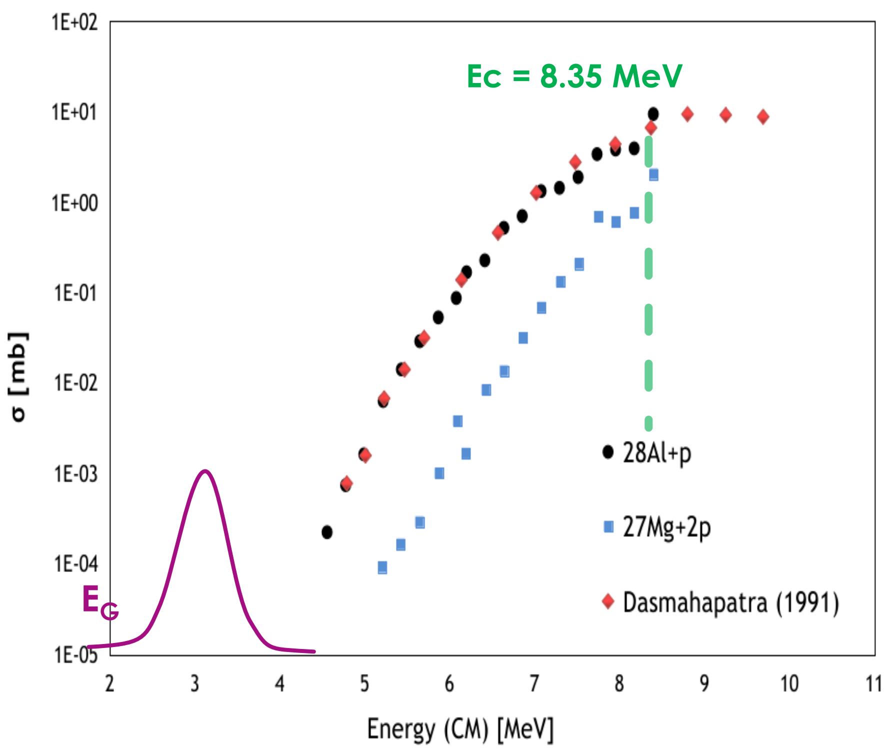


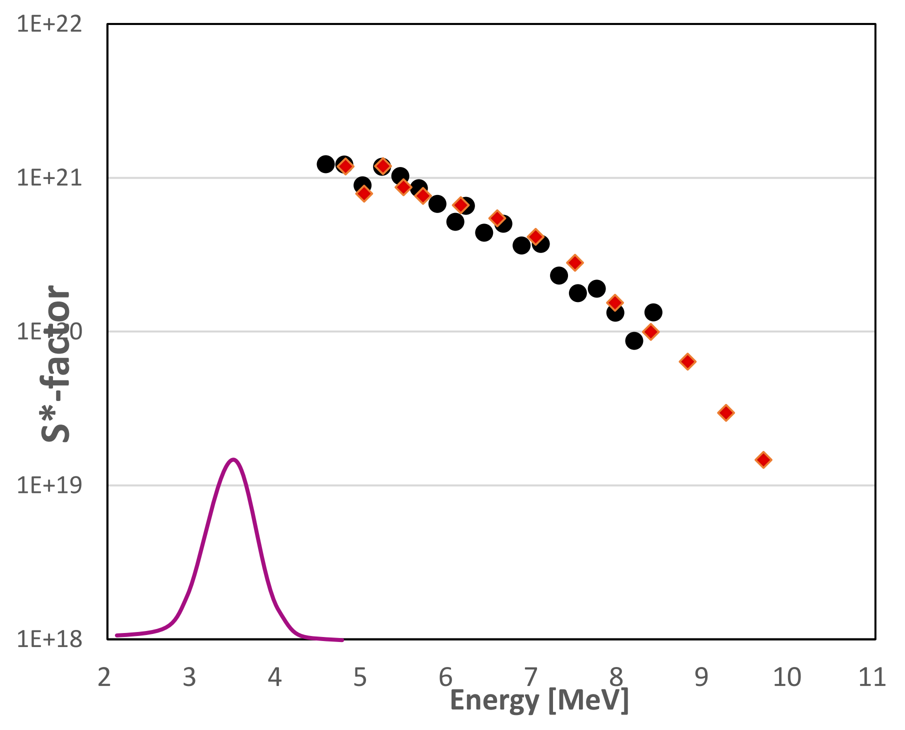
E_{Lab} = 8.4 MeV
t_{irr} = 1 hr and t_{decay} = 10 min
3 measurements



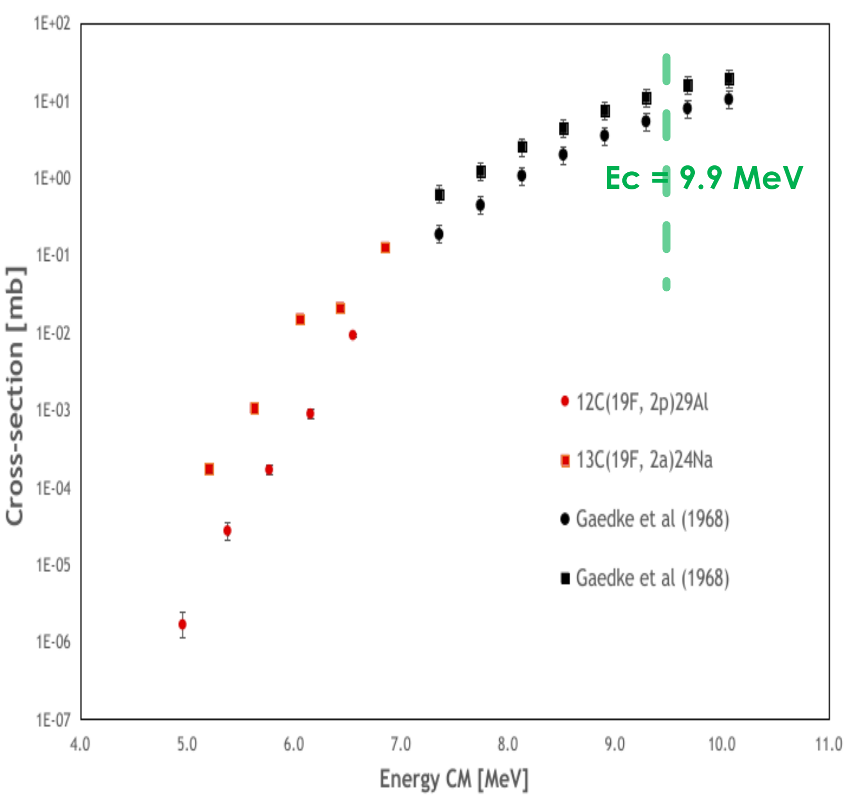
$^{28}Al \rightarrow ^{28}Si(1.78\ MeV)$

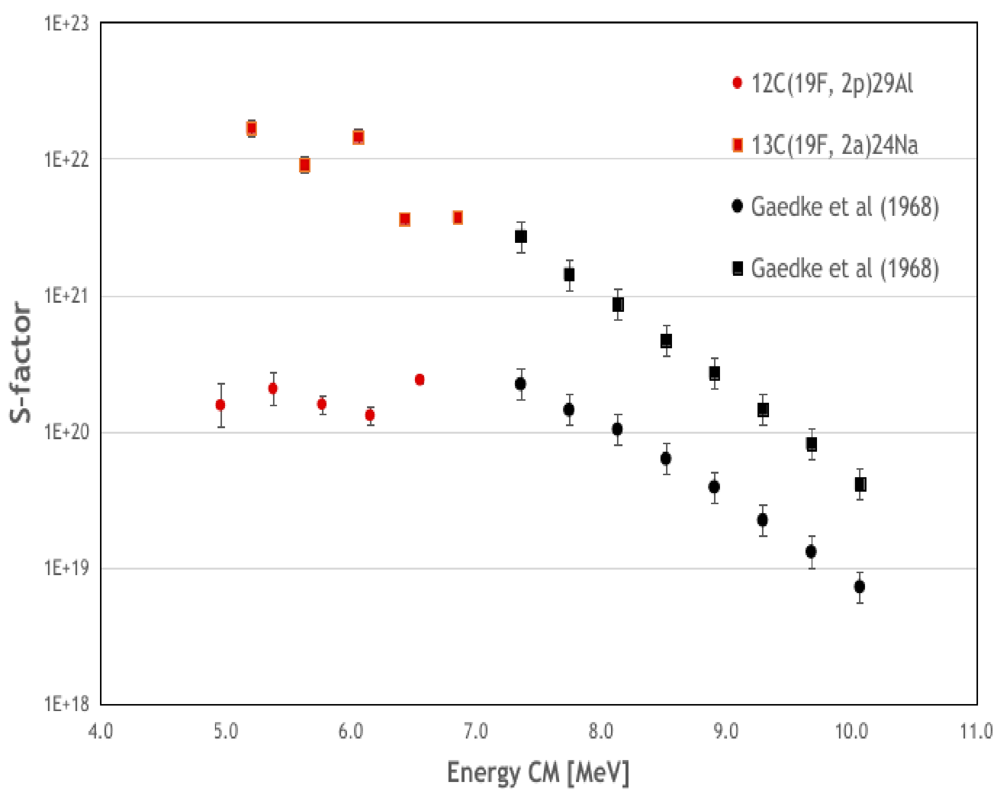
^{13}C +^{16}O – preliminary results



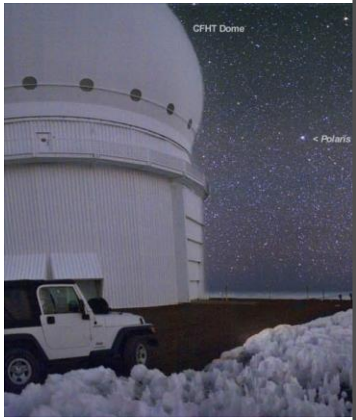


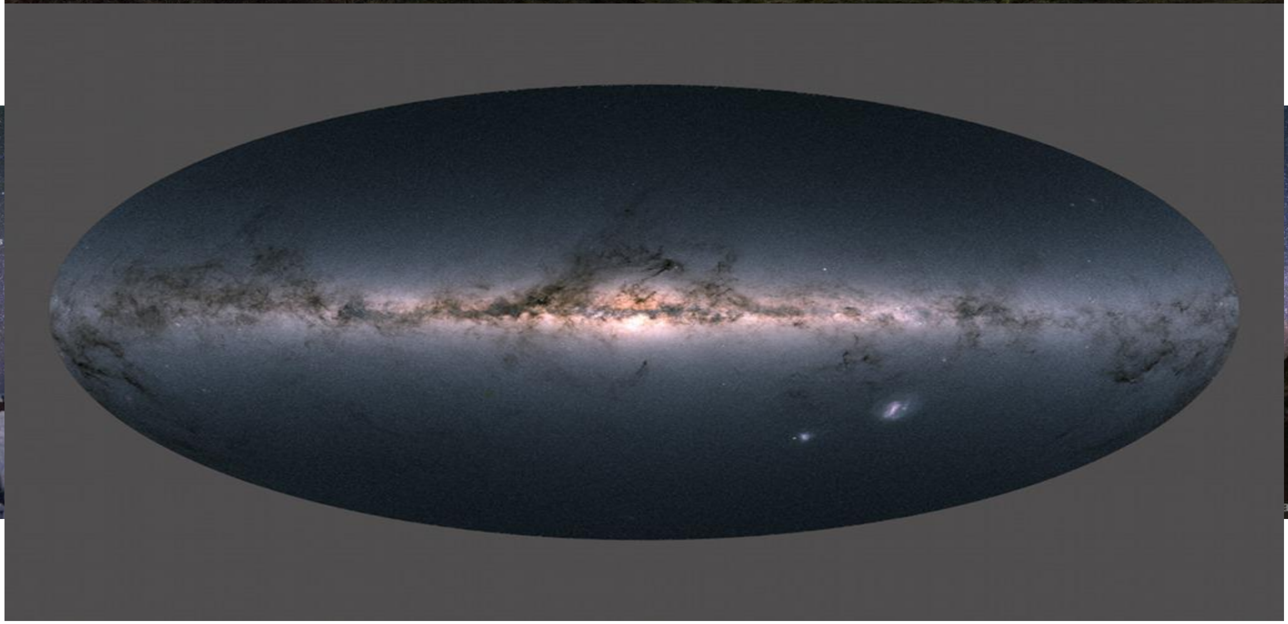
^{19}F +^{12,13}C – preliminary results





What astronomers show us





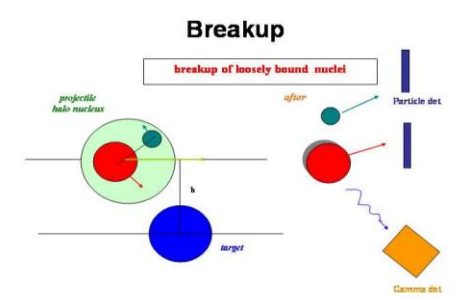
What astronomers show us

Impresive?! Vedeti zilnic pe:

https://apod.nasa.gov/apod/astropix.html

What we, Nuclear Physicists show !

Nuclear breakup



RIBF PAC15

$$\sigma^{\mathrm{th}}_{-1p} = \sum \mathrm{SF}(c;nlj)\left[\sigma^{\mathrm{stripp}}_{\mathrm{sp}}(nlj) + \sigma^{\mathrm{diff}}_{\mathrm{sp}}(nlj) + \sigma^{C}_{\mathrm{sp}}(nlj)\right],$$

For ^{9}C case:

$$\sigma_{-1p} = [S(1p_{3/2}) + S(1p_{1/2})]\sigma_{sp}(1p_j)$$
$$= (C^2_{p_{3/2}} + C^2_{p_{1/2}})\sigma_{sp}(1p_j)/b_p^2$$

L. Trache et al., PRL 2001,
PRC 66, 035801 (2002)

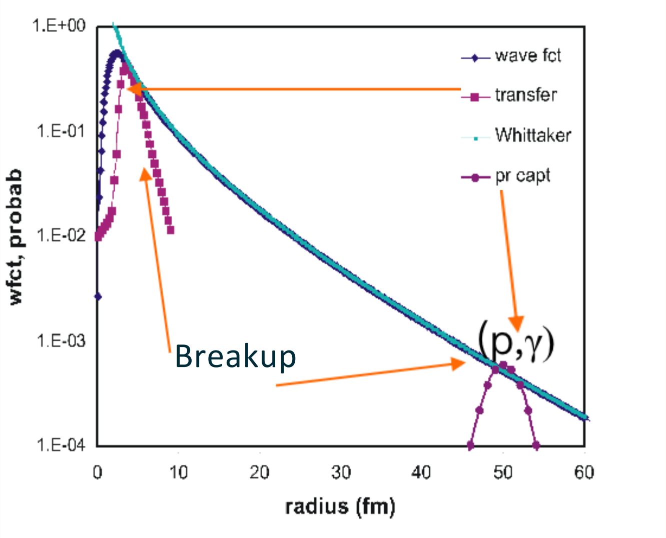
C(c,nlj) = the ANC of the system $^{9}\mathrm{C}\rightarrow{}^{8}\mathrm{B}+p$

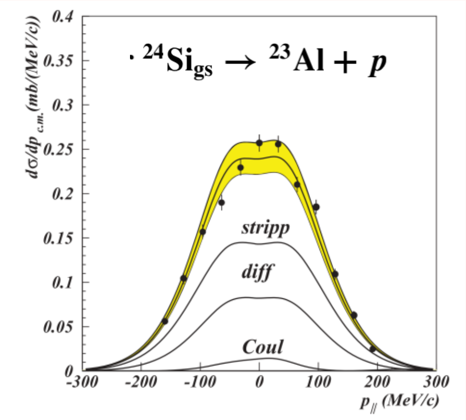
b_p = the single-particle ANC

$$C_l^2 = \frac{\sigma_{\exp}}{\sigma^{\mathrm{th}}_{\mathrm{sp}}}\left(\frac{r_L R_l(r_L)}{W_{-\eta,l+1/2}(2\kappa r_L)}\right)^2,$$

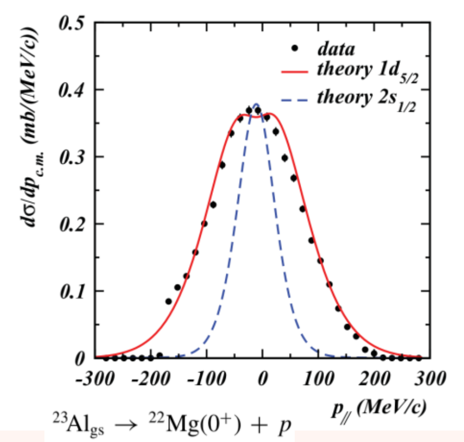
A. Banu et al.,
PRC 86, 015806 (2012)

L. Trache, Exotic Beam Summer School 2012





A. Banu et al., PRC 86, 015806 (2012)



A. Banu et al., PRC 84, 015803 (2011)