Measurement of rare nuclear reactions of astrophysical interest: status and prospects

[a biased and limited overview]

Antonino Di Leva - Università di Napoli "Federico II" and INFN Sezione di Napoli

Recent Developments In Neutrino Physics And Astrophysics - 5 September 2017

Outline

- a very short introduction to Nuclear Astrophysics
- from experimental data to astrophysical rates
- few selected examples

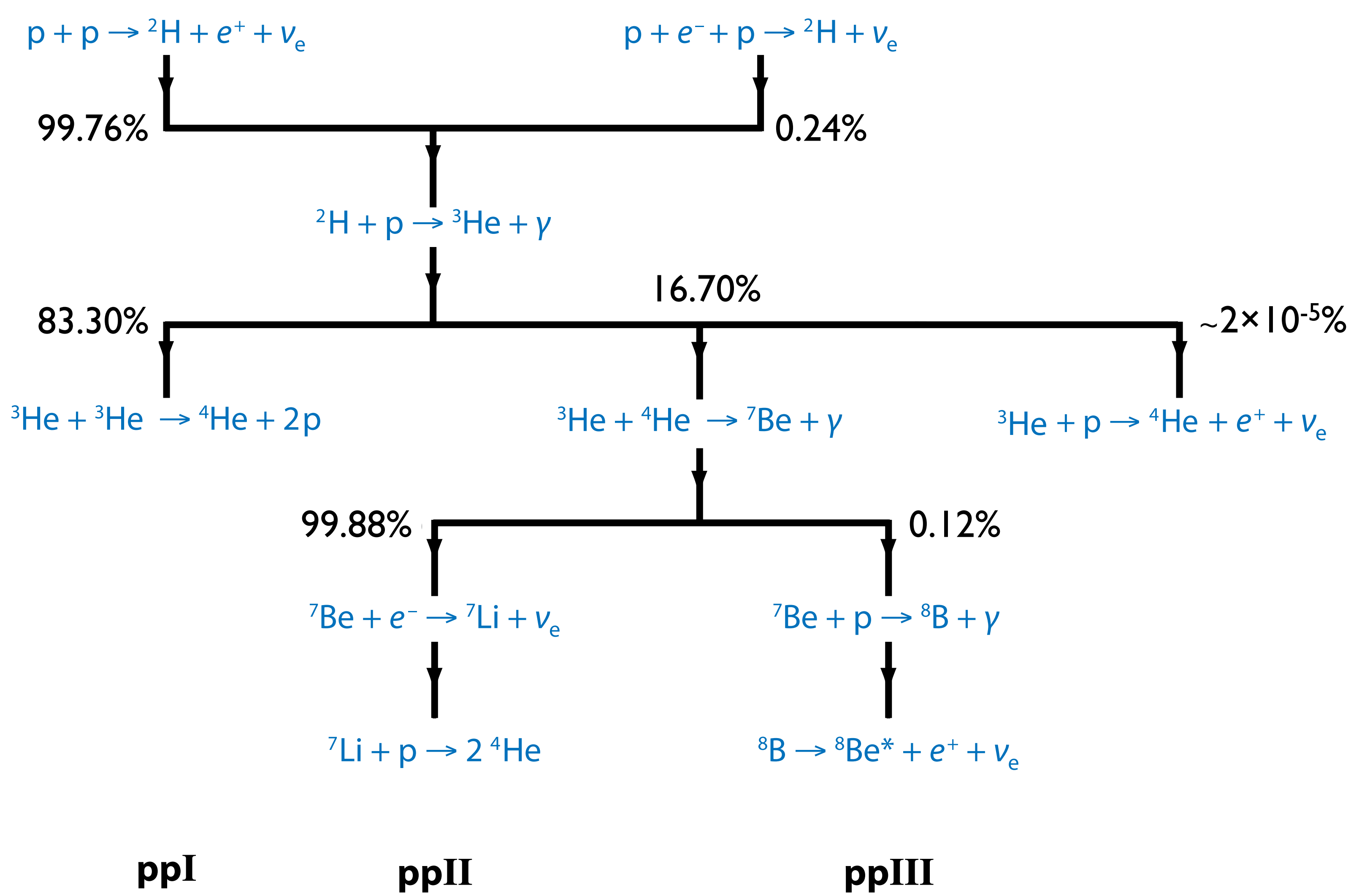
  $^{3}He(\alpha,\gamma)^{7}Be$

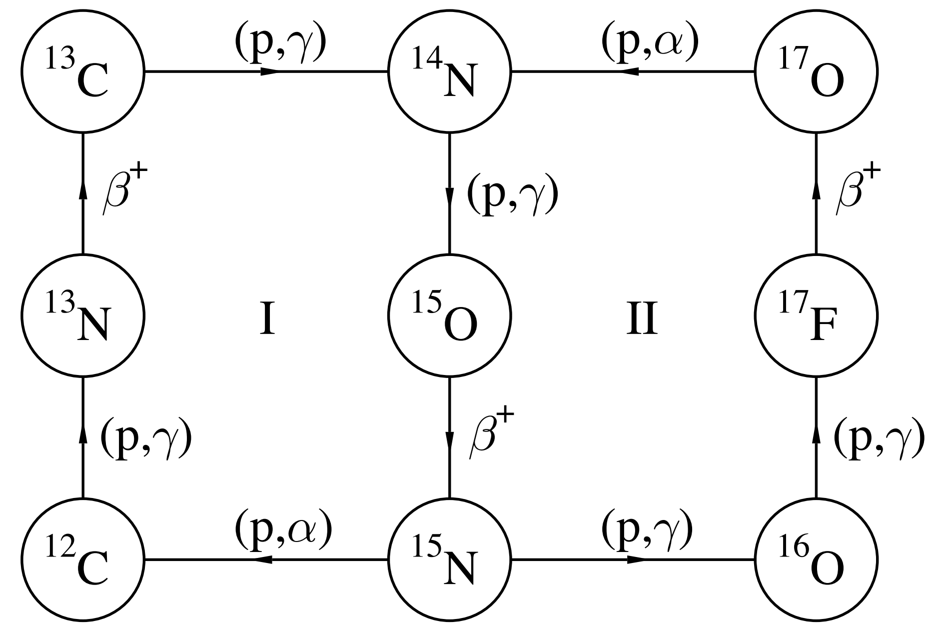
  $^{7}Be(p,\gamma)^{8}B$

  $^{14}N(p,\gamma)^{15}O$

- near future developments

H burning

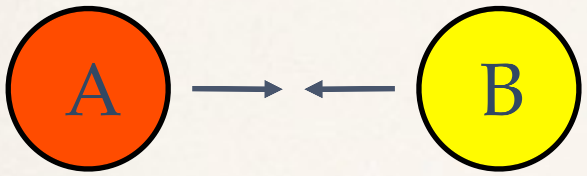




Adelberger et al. Rev.Mod.Phys.83(2011)

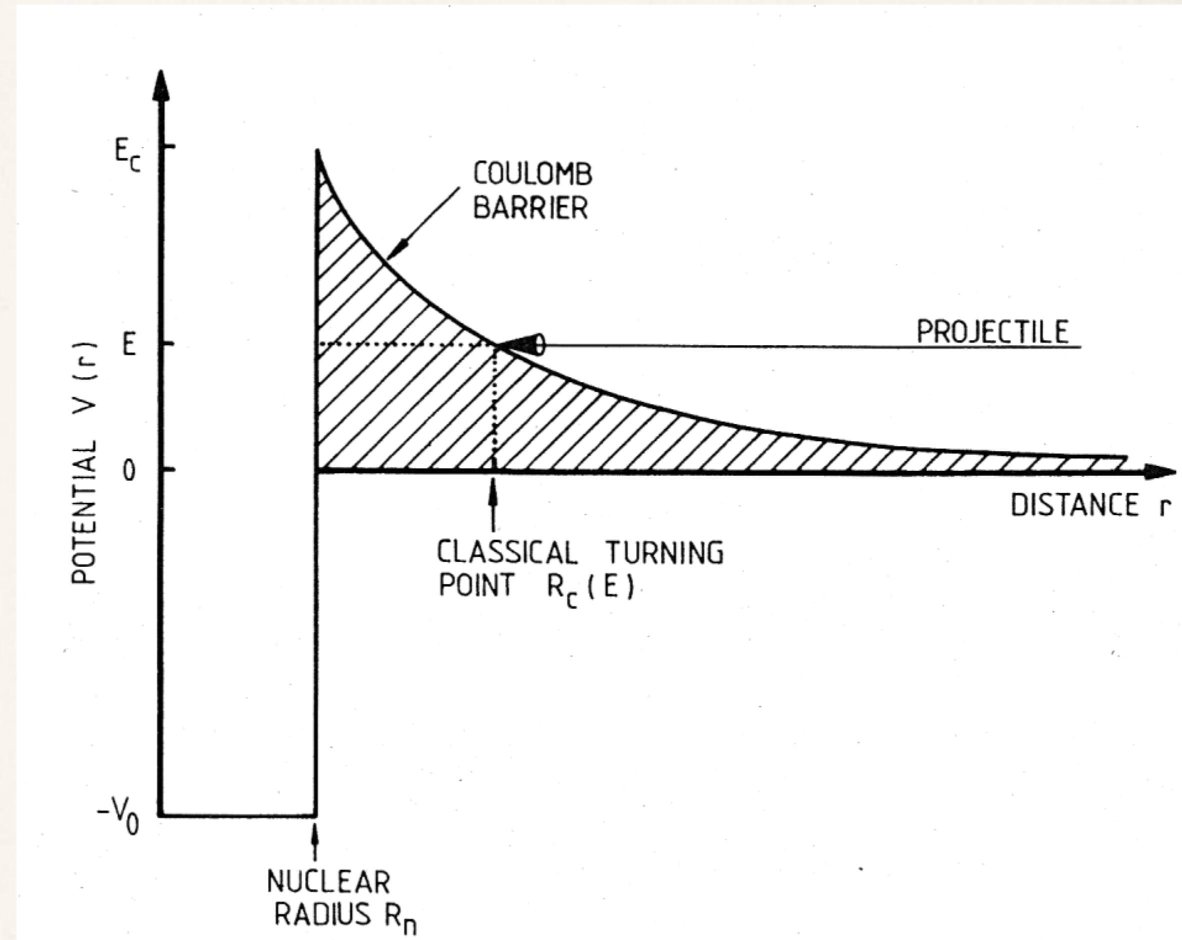
Nuclear reactions in stars

A(B,C)D



$T_6 \sim 15\ ^\circ K \quad \Rightarrow \quad E \sim k_B T \sim keV$

$E_c \sim Z_A Z_B / r_0 \sim MeV$



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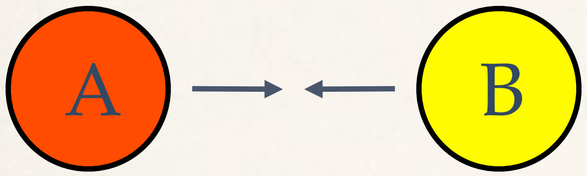


T_6~15 °K ⇒ $E \sim k_B T \sim$ keV

$E_c \sim Z_A Z_B / r_0 \sim$ MeV

⇓

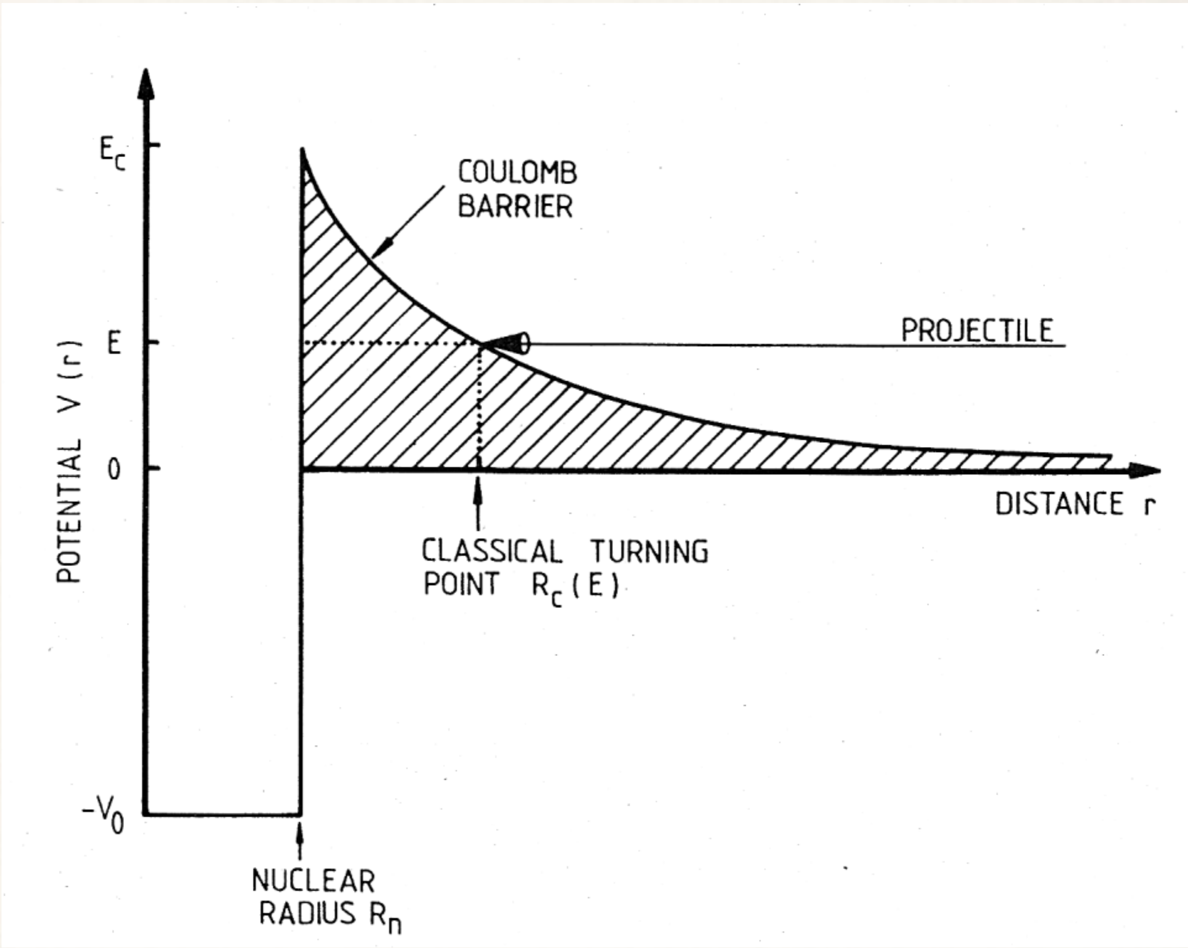
extremely low cross sections

⇓

measurements at higher energies

⇓

need of models to extrapolate to relevant energies



$^3He(\alpha,\gamma)^7Be$ $\sigma \sim 3 \times 10^{-5}$pb

N_p ~1000pμA ~ 6×10^{15}/s

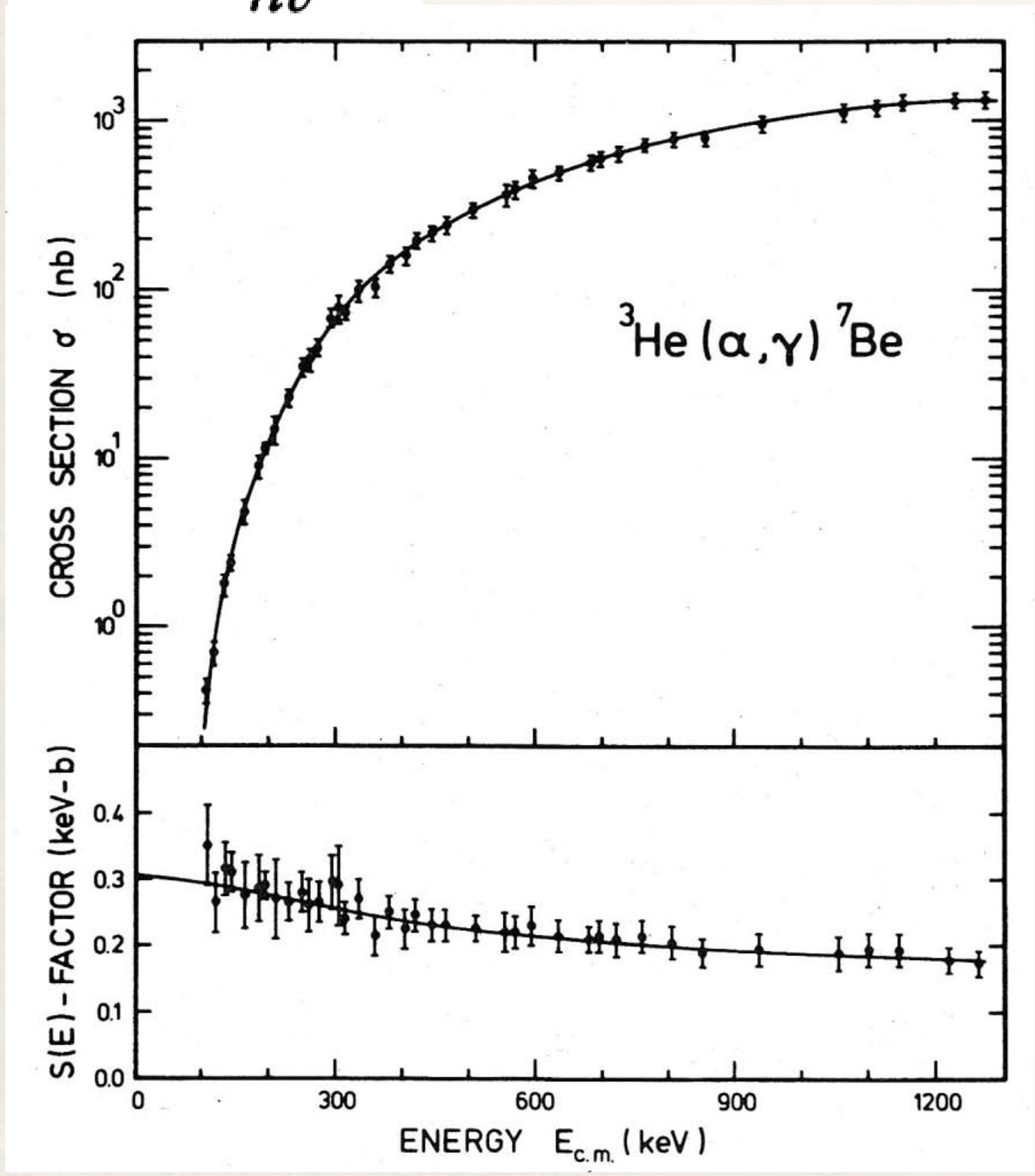
N_t ~1^{18}/cm^2

$N(^7Be) = \sigma N_p N_t \sim 1.5 \times 10^{-7}$/s ~ 6/year

S-factor & Reaction rate

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

$$\eta = \frac{Z_1 Z_2 e^2}{\hbar v}$$

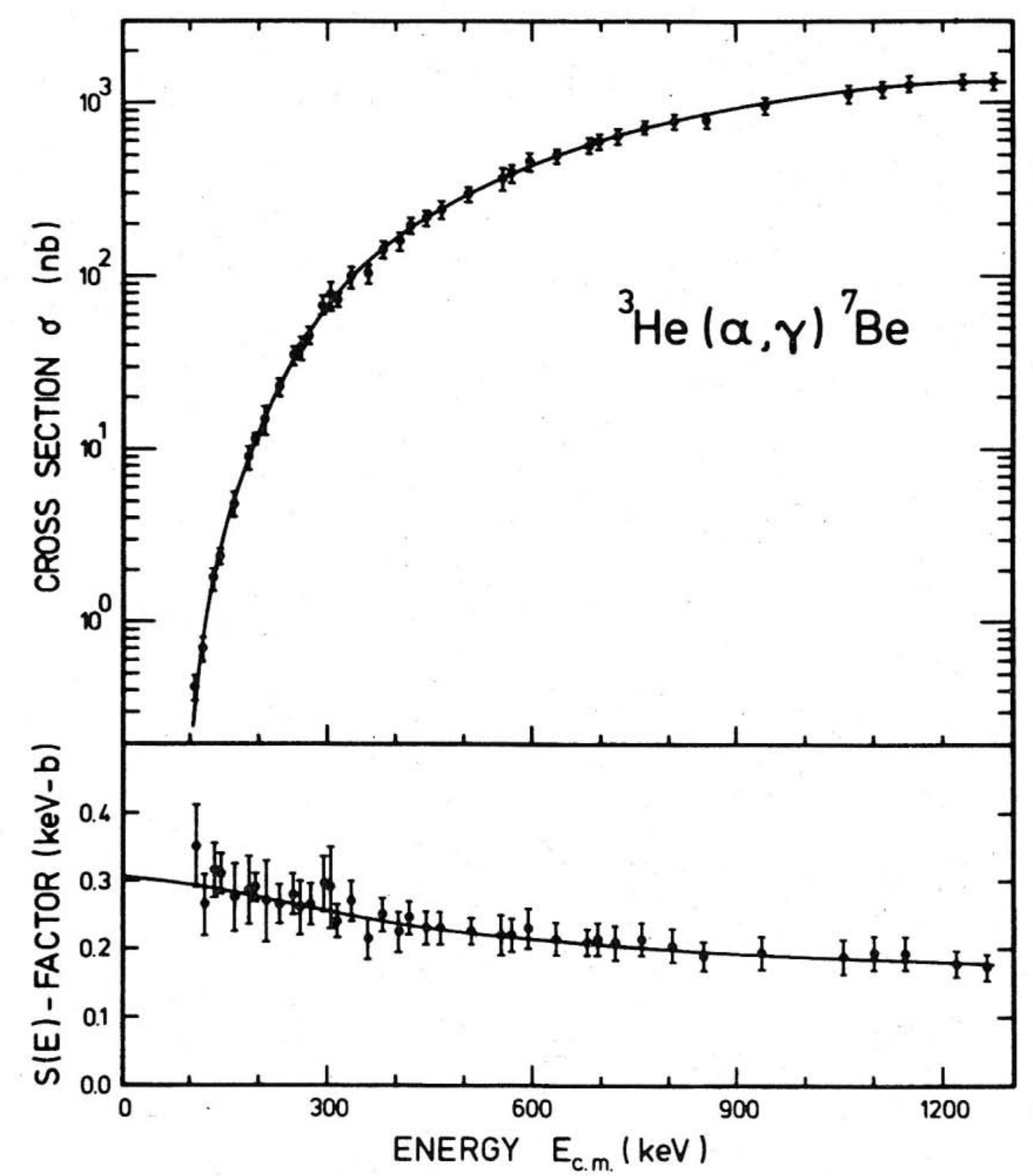


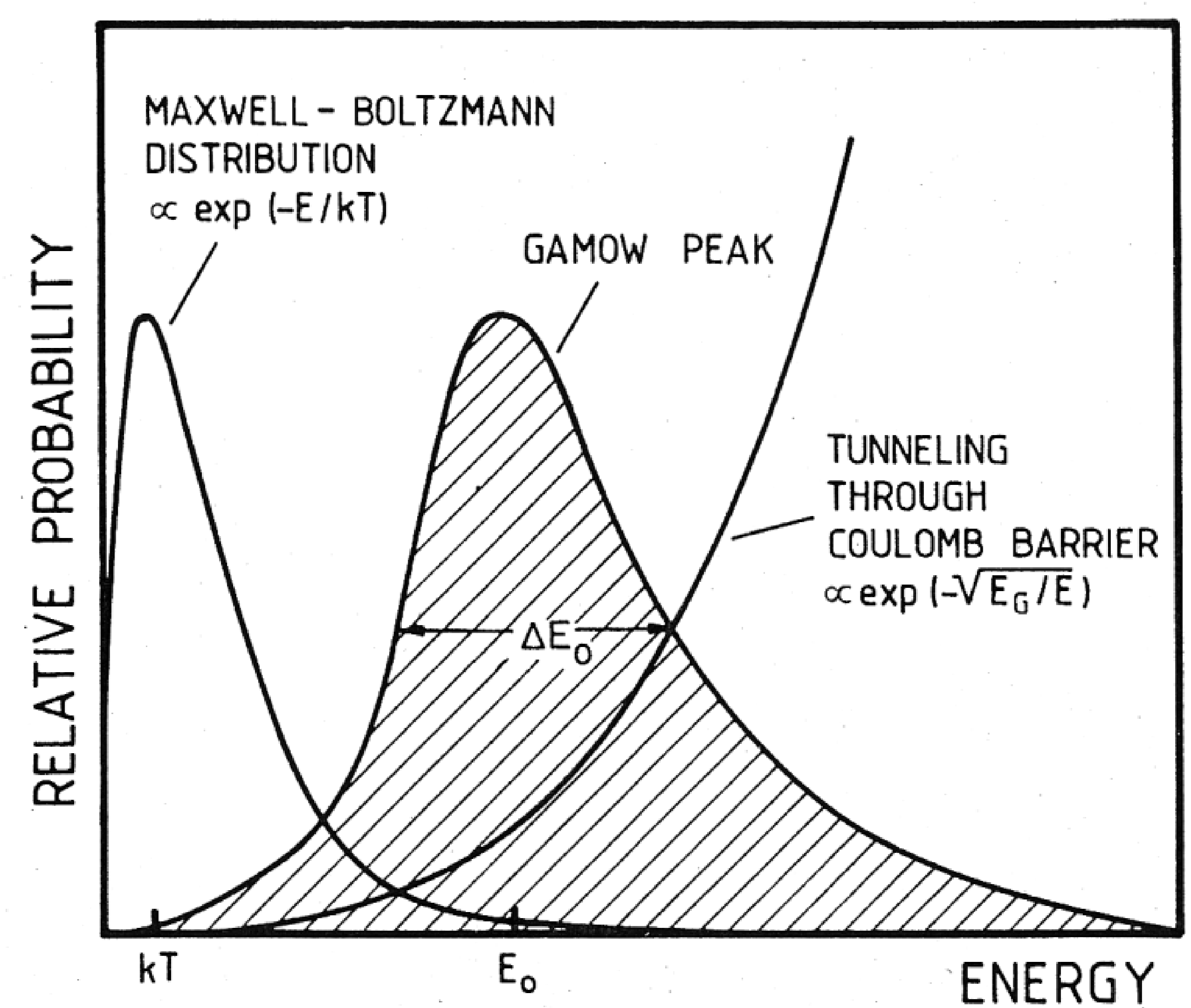
S-factor & Reaction rate

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

$$\eta = \frac{Z_1 Z_2 e^2}{\hbar v}$$

$$\langle \sigma v \rangle = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(kT)^{3/2}} S(E_0) \int_0^\infty \exp\left(-\frac{E}{kT} - \frac{b}{E^{1/2}}\right) dE$$





How to determine reaction rates

measurements of cross section at selected energies (with proper error determination)

$\Updownarrow$

fit model to data to obtain cross section (and uncertainty) at (any) relevant energy

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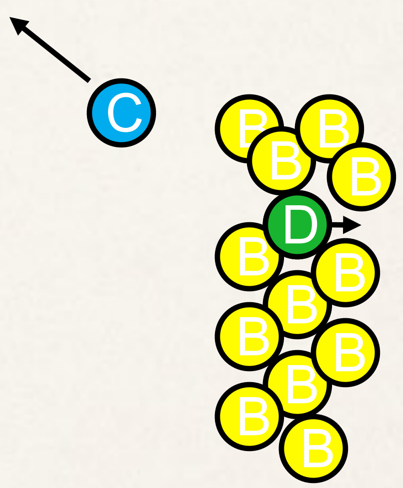
calculate rate (and its uncertainty)

$\Downarrow$

evaluate consequences, check against observations

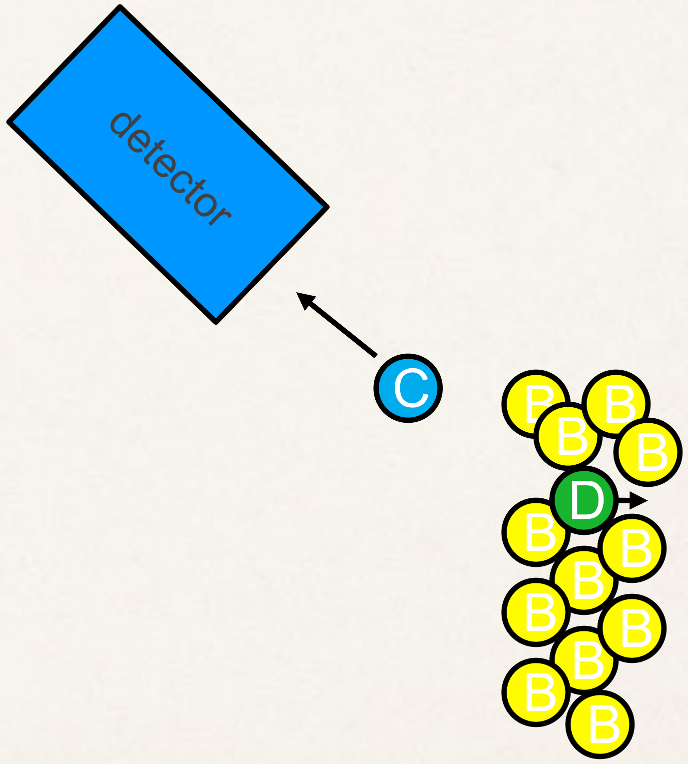
Laboratory measurements

Laboratory measurements



Laboratory measurements

$$N_C = \sigma(E) N_{\text{target}} N_{\text{projectiles}} \varepsilon$$



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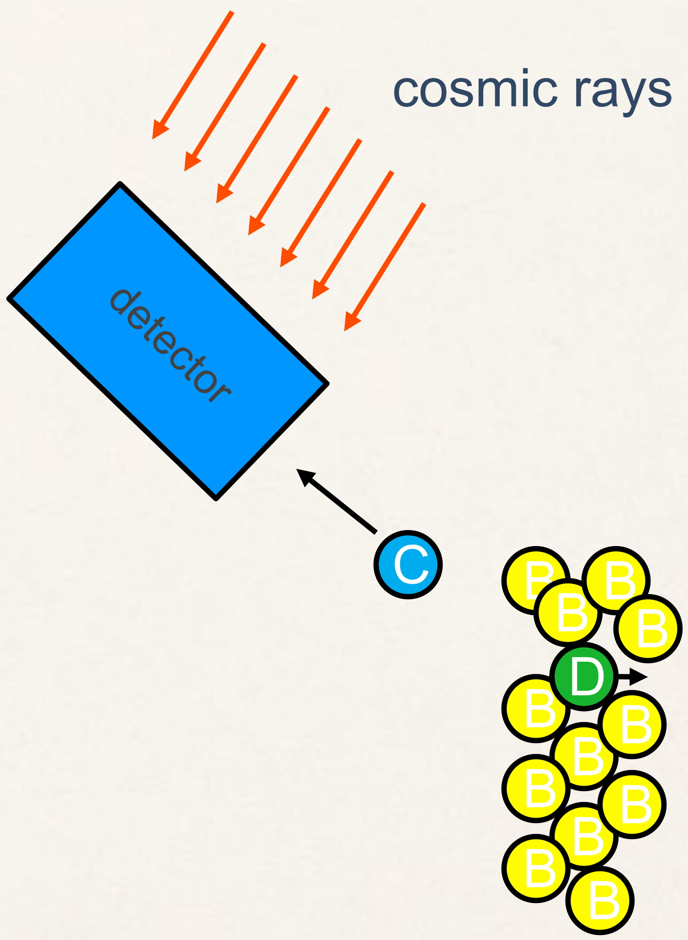
$$N_{Det} = N_C + N_{Bkg}$$



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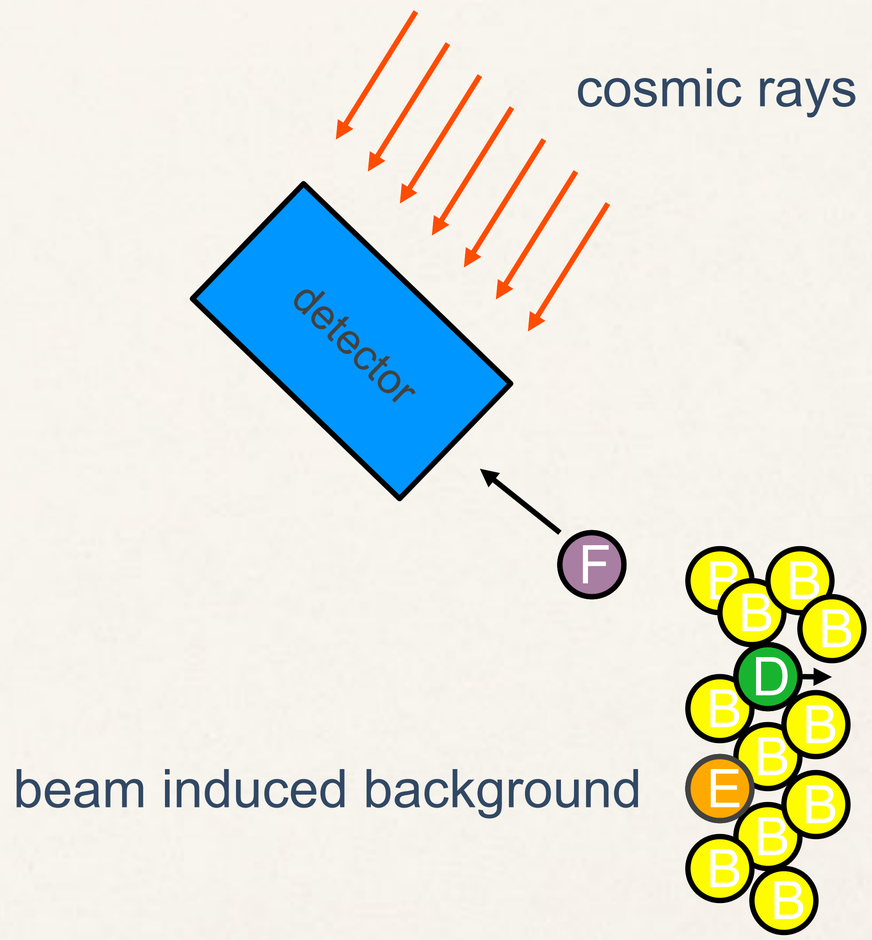

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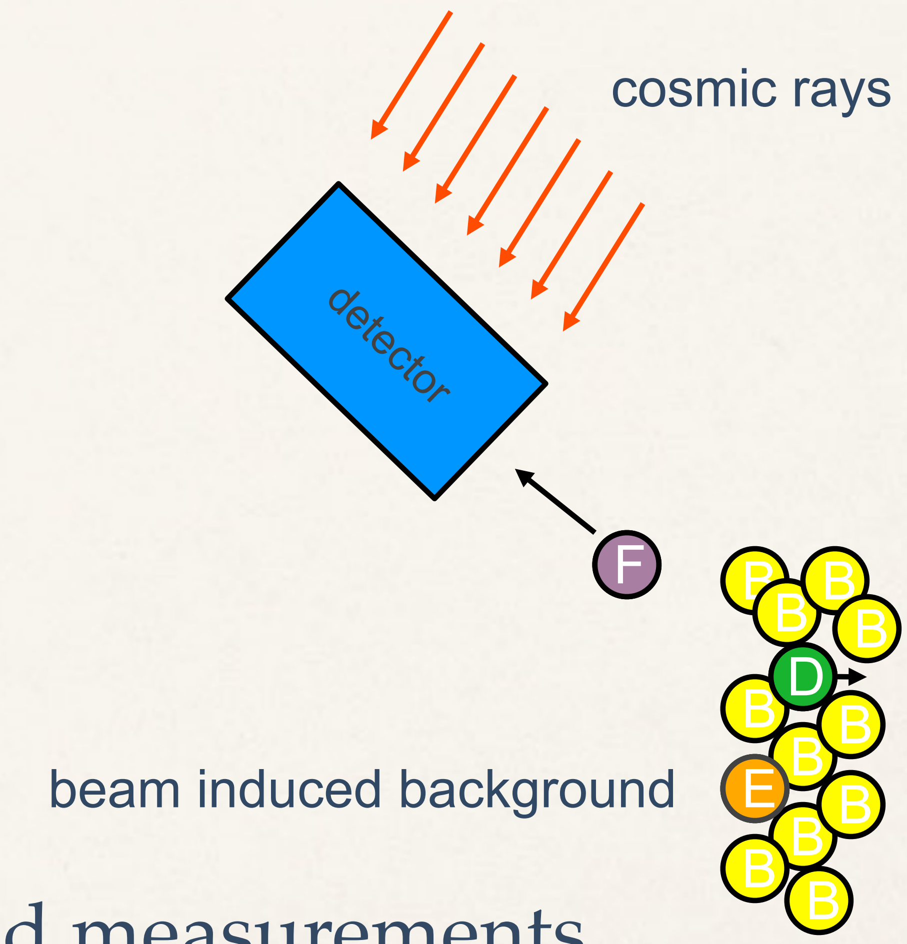

Minimize background: underground measurements

Laboratory measurements

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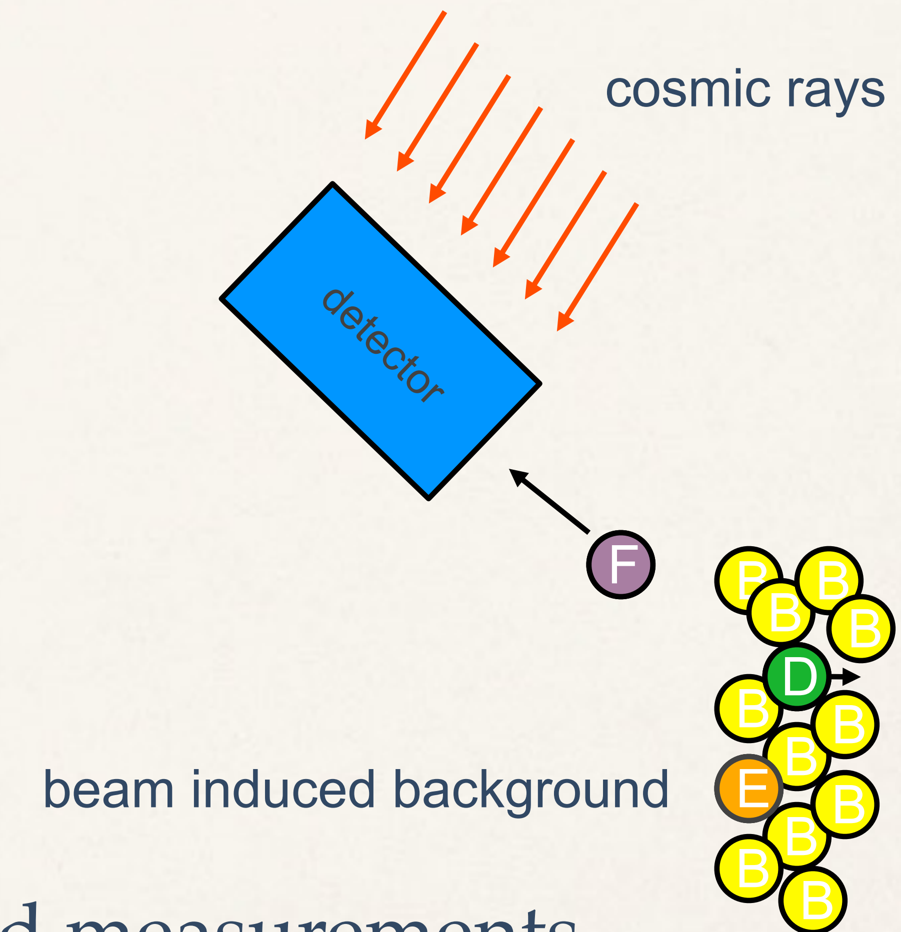


Minimize background: underground measurements

Maximise signal: recoil separators, indirect methods, …

Two ways towards improved experiments

Nuclear Astrophysics is a very active and productive field. Several groups around the world devote their efforts to cross section measurements, continuously developing interesting new techniques to overcome experimental difficulties.
However over the years two strategies have proven to be very effective

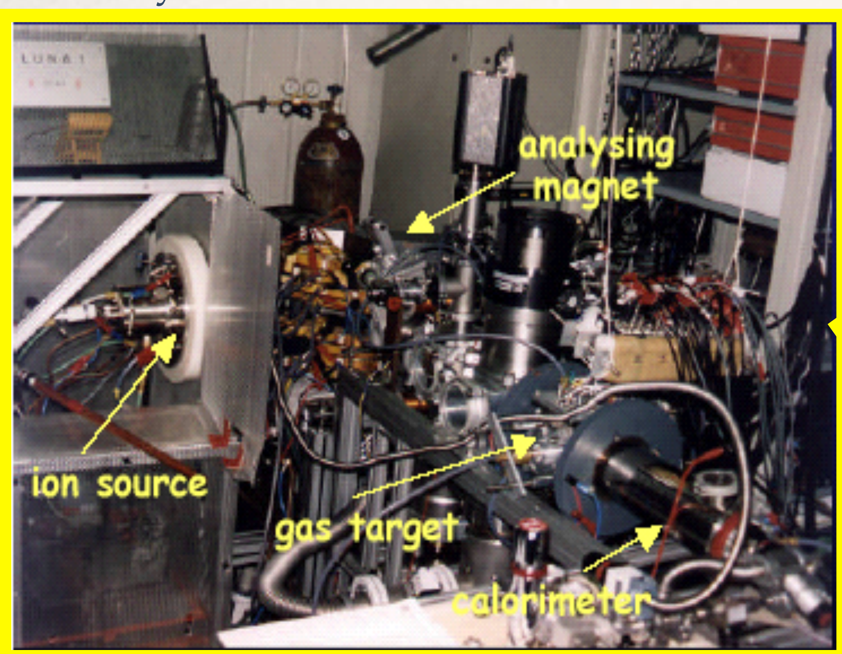
- Background reduction by moving to cosmic ray free underground environments
  LUNA@LNGS-Italy
  CASPAR@SURF-USA
  JUNA@CJPL-China

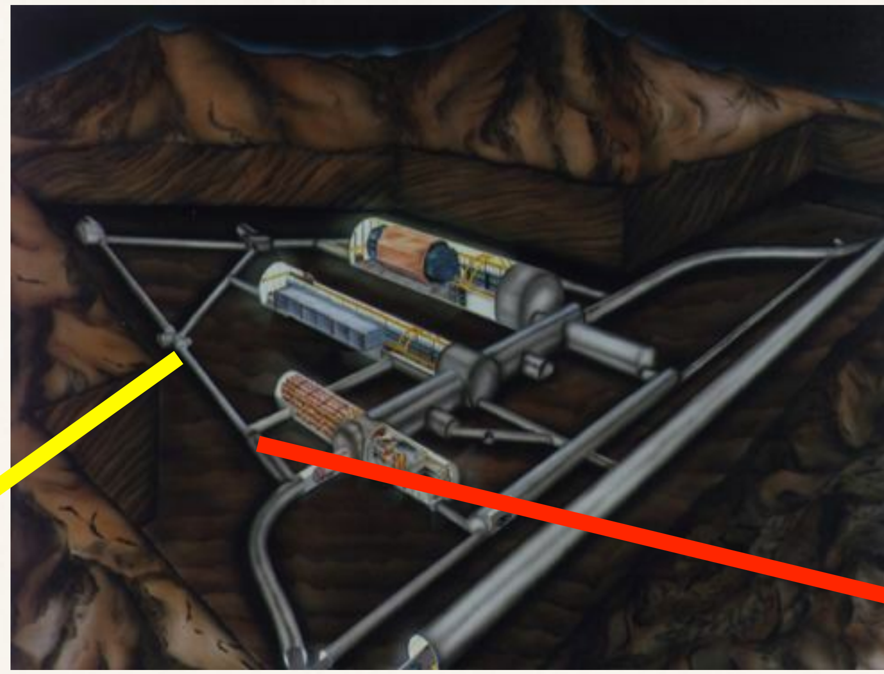
- Inverse kinematics techniques with recoil separators
  DRAGON@TRIUMF-Canada
  St. GEORGE@NotreDame-USA
  ERNA@CIRCE-Italy

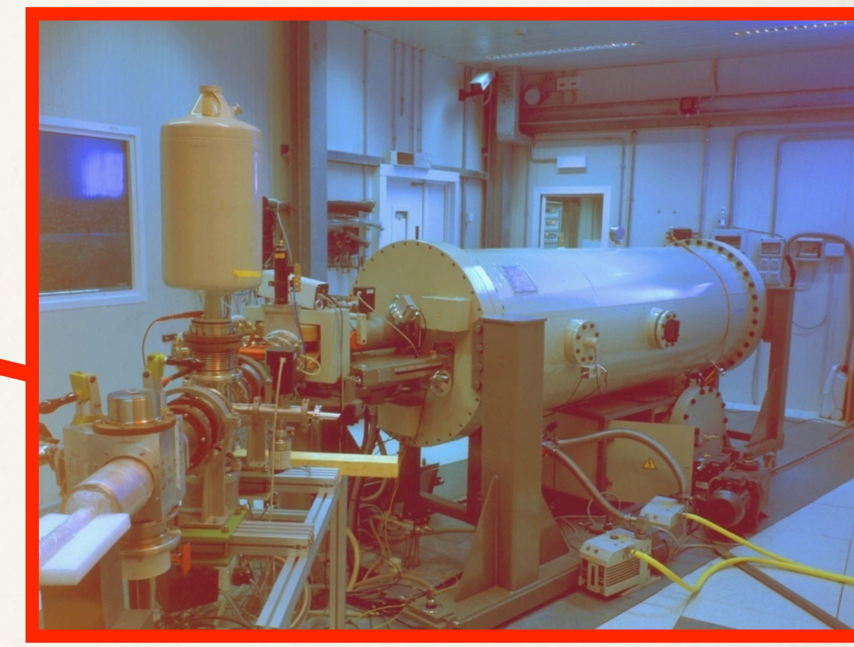
Underground labs

LUNA at Laboratori Nazionali del Gran Sasso

Courtesy of LUNA Collaboration





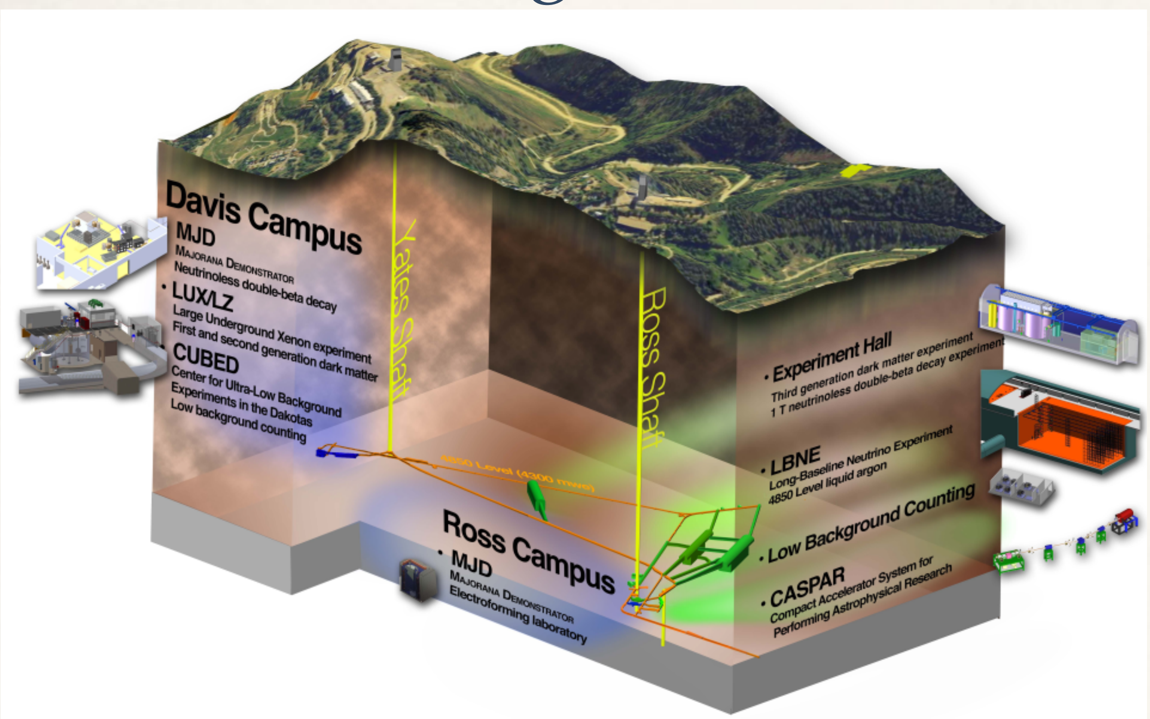


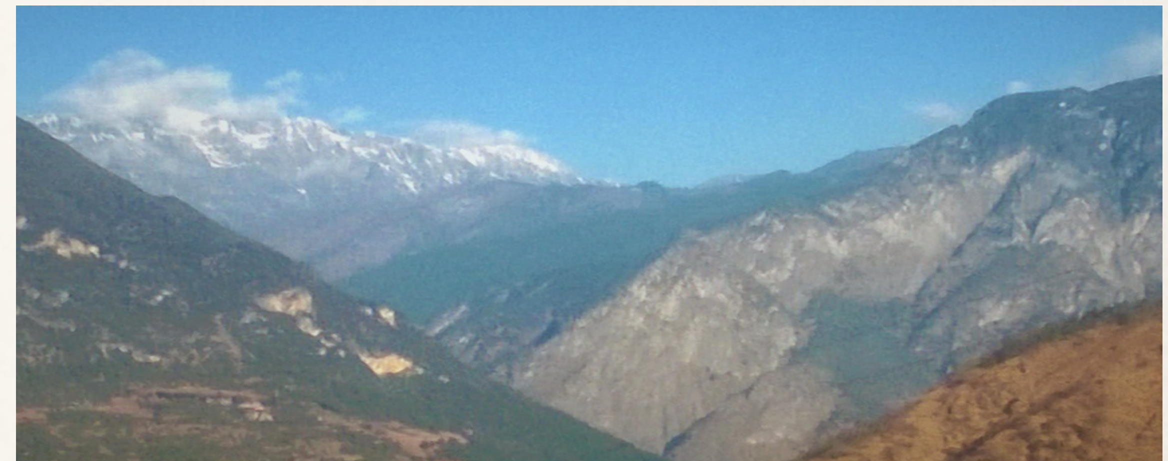
- BBN and H-burning in the Sun and solar neutrinos: p(d,γ)^{3}He, d(α,γ)^{6}Li, ^{3}He(^{3}He,2p)^{4}He, ^{3}He(α,γ)^{7}Be and ^{14}N(p,γ)^{15}O

- AGB nucleosynthesis – light nuclei abundances: ^{15}N(p,γ)^{16}O, ^{17}O(p,γ)^{18}F, ^{17}O(p,α)^{14}N, ^{18}O(p,γ)^{19}F, ^{18}O(p,α)^{15}N, ^{22}Ne(p,γ)^{23}Na, ^{23}Na(p,γ)^{24}Mg, ^{24}Mg(p,γ)^{25}Al, ^{25}Mg(p,γ)^{26}Al, ^{26}Mg(p,γ)^{27}Al

Underground labs

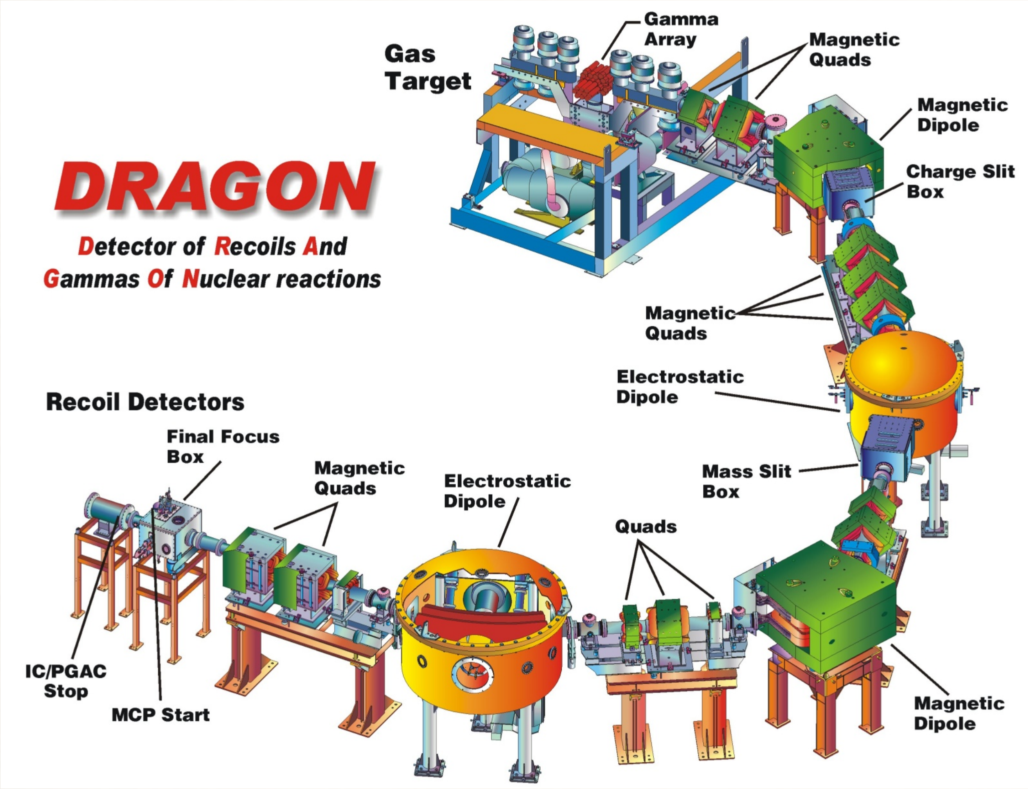
CASPAR at
Sanford Underground Research Facility

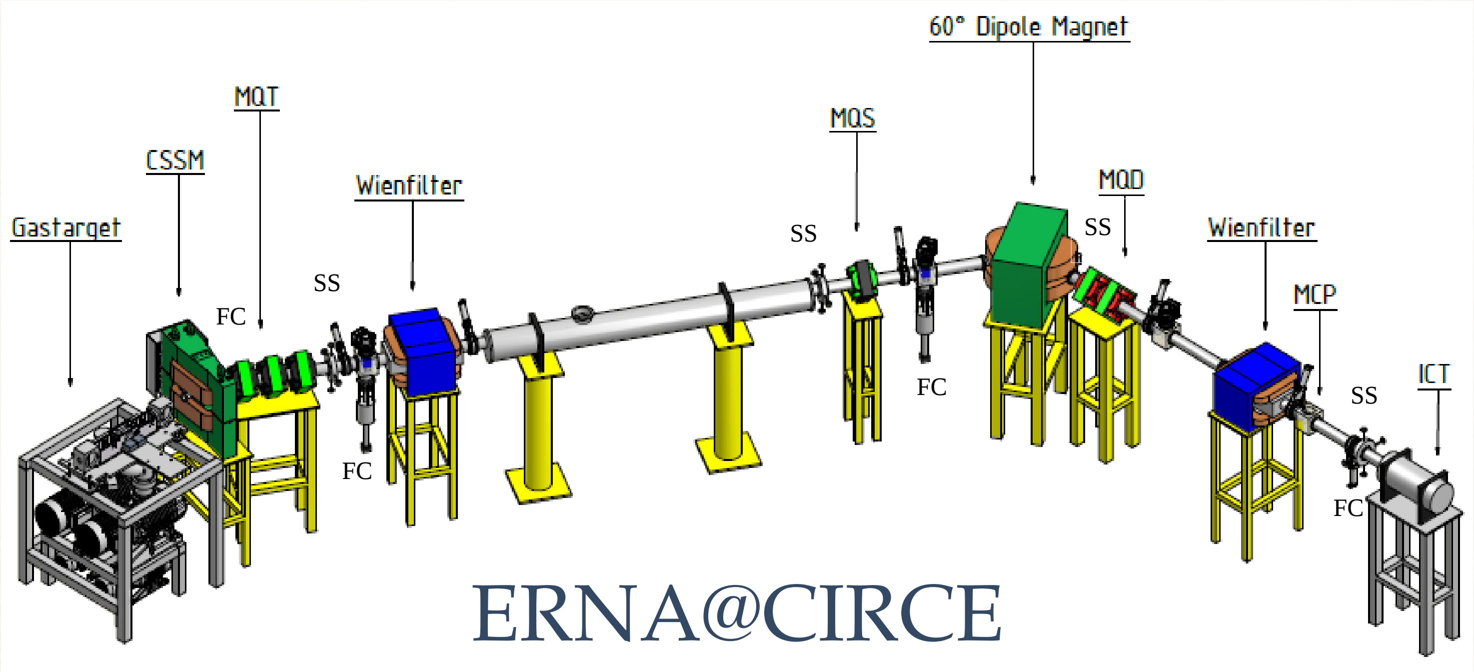


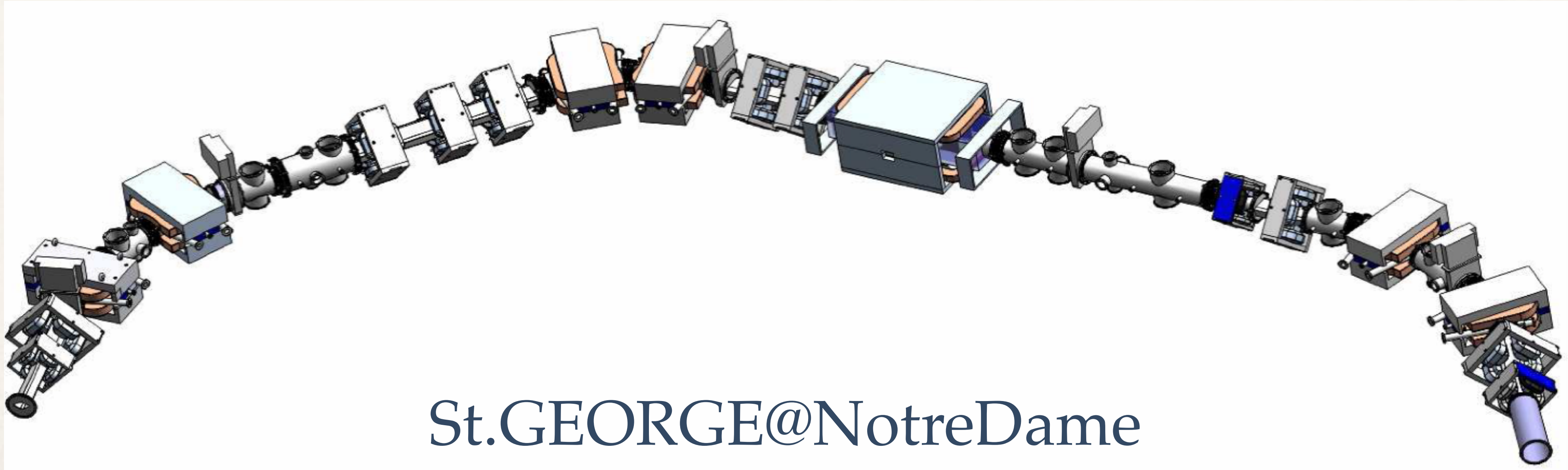


JUNA at
China Jinping Underground Laboratory

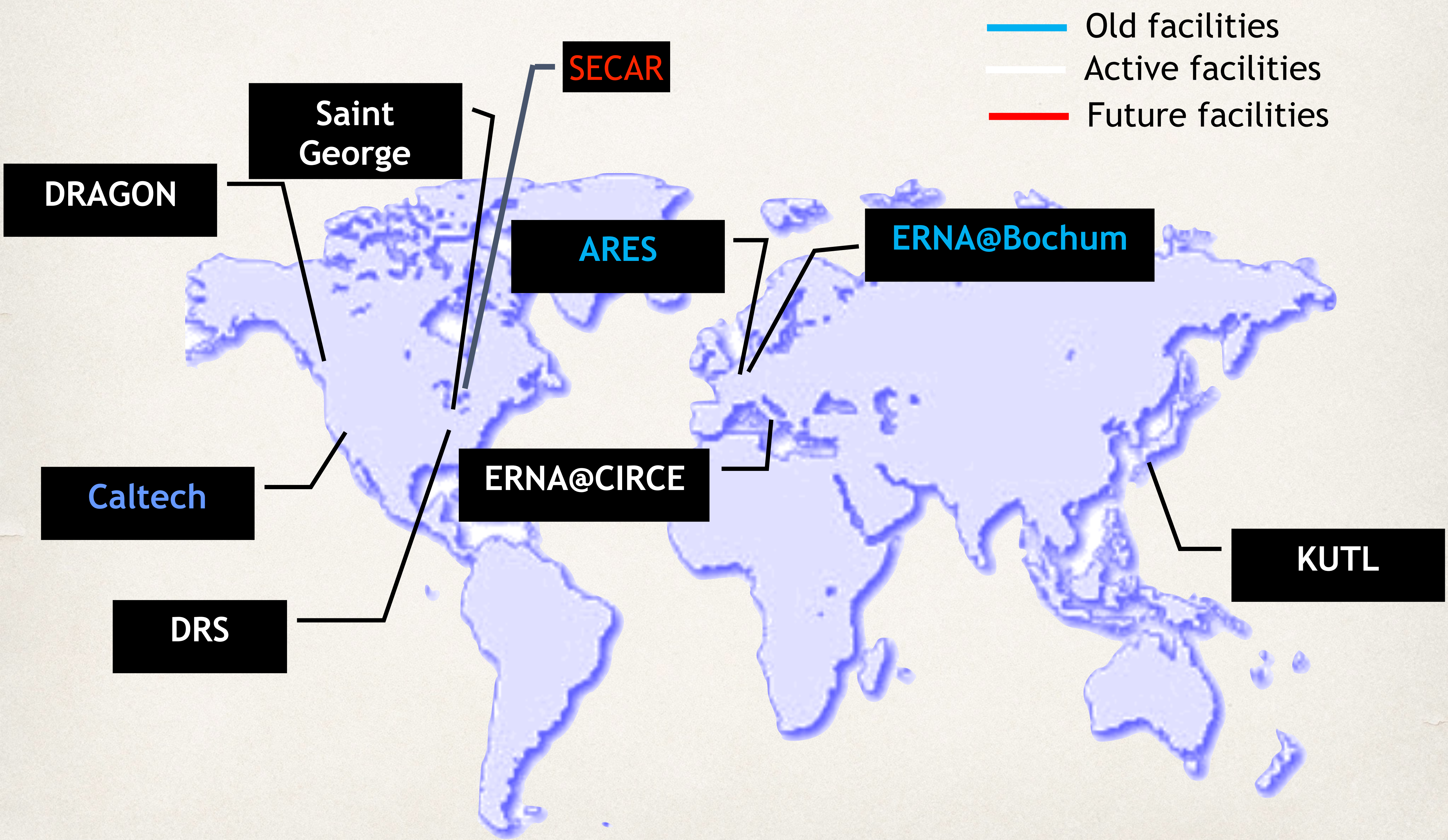
Recoil separators







Recoil separators for Nuclear Astrophysics



Other valuable tools

* Reaction rates are nuclear physics. Nuclear structure and reaction theory is necessary for providing guidance and setting limits.

* Indirect techniques are essential tools to probe low energy nuclear structure and reaction features

* Single particle or alpha transfer can be used used as surrogates, THM/ANC methods, alpha scattering, lifetime measurements, Coulomb dissociation studies, all provide a scale for low energy extrapolation. However direct measurements close to the stellar energy range are needed for high precision predictions

How to determine reaction rates

measurements of cross section at selected energies
(with proper error determination)

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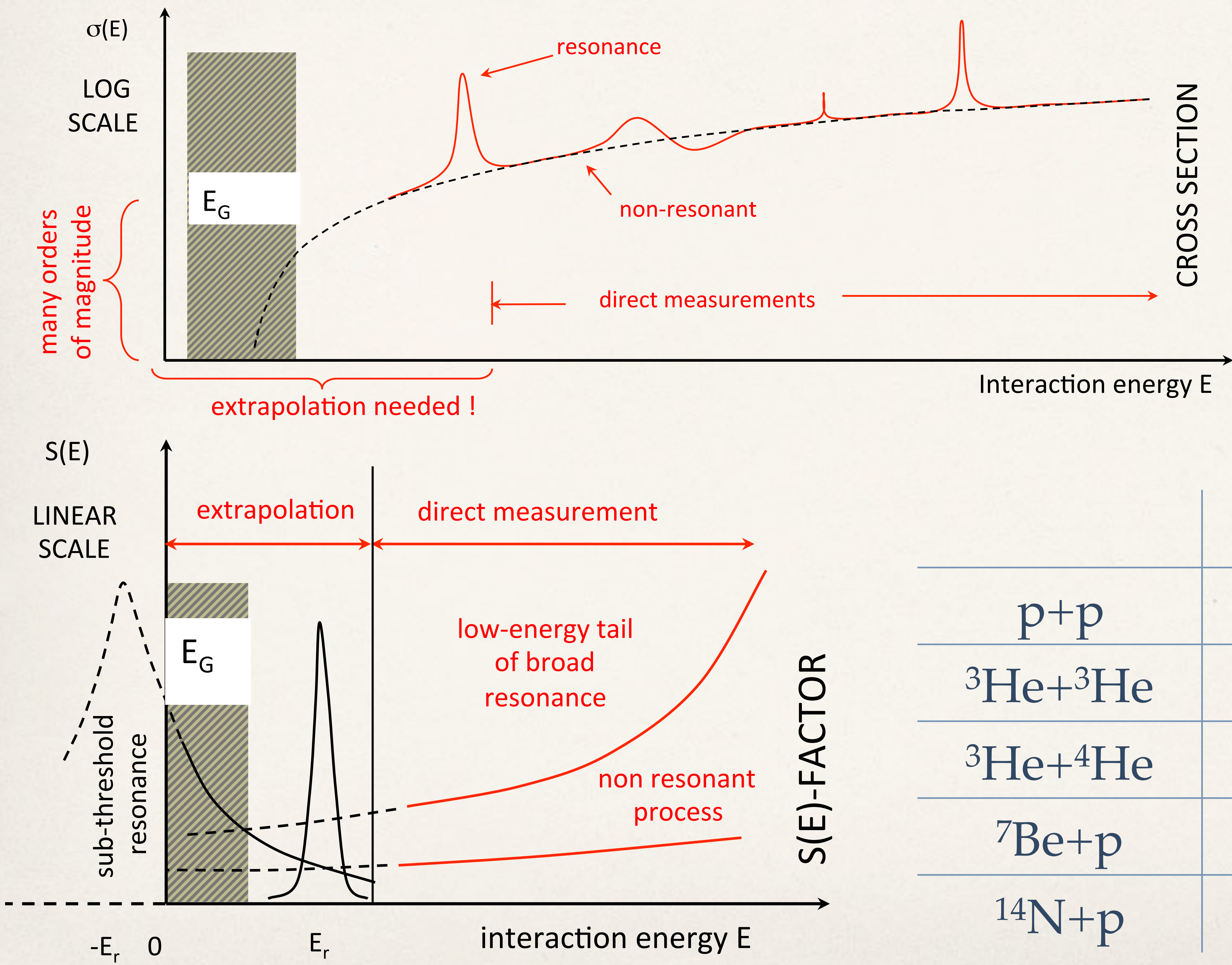
Extrapolation & role of the models



	E_G [keV]
p+p	6
^{3}He+^{3}He	22
^{3}He+^{4}He	23
^{7}Be+p	18
^{14}N+p	27

Model fit to the data

- Use as much of experimental information as possible
- Choose the model that best describes simultaneously all of the datasets
- Treat data in statistical robust way (no arbitrary inflation of errors, if possible)
- Take into account (probably combined) systematic errors
- Determine best estimate of $S_{ij}(0)$

A paradigmatic case: $^{3}He(\alpha,\gamma)^{7}Be$

- Potential models (global scaling parameter): Tombrello & Parker, Descouvemont (R-matrix based), Mohr
- Microscopic models (no global scaling parameter): Neff, Csótó & Langanke, Kajino et al., Nollett, etc...
- Usually claimed to be valid up to E_{cm}~2.0MeV

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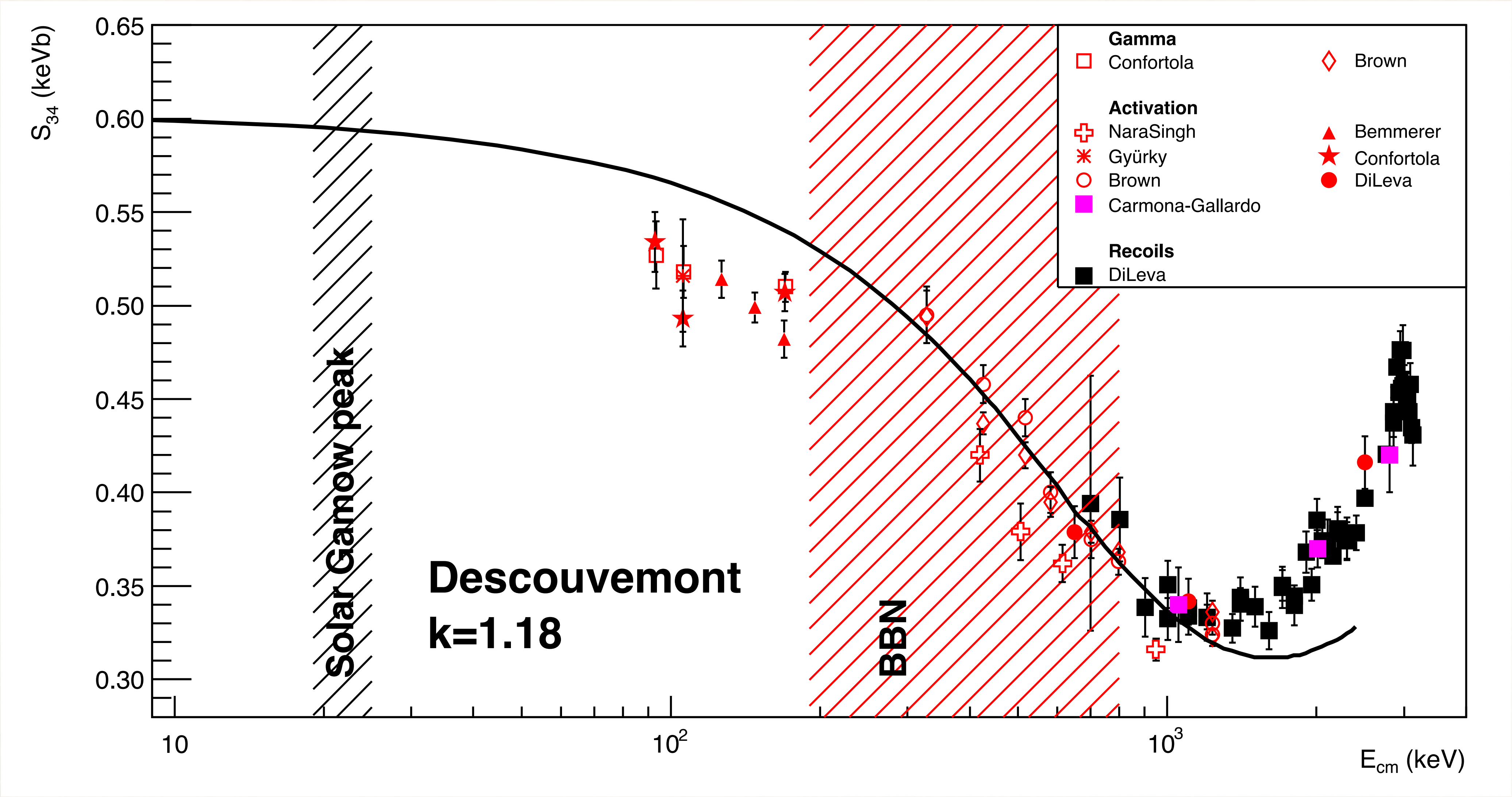

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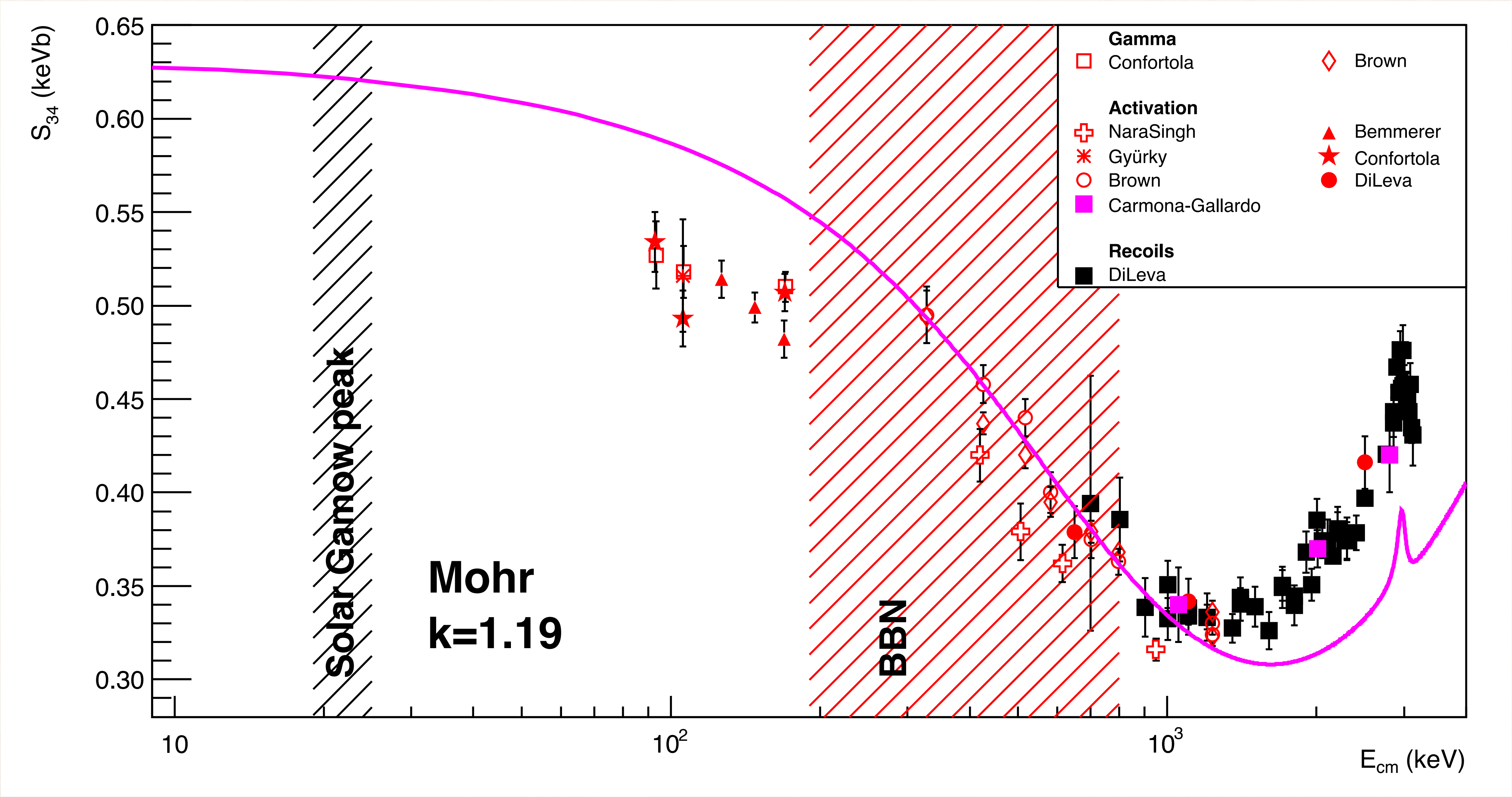

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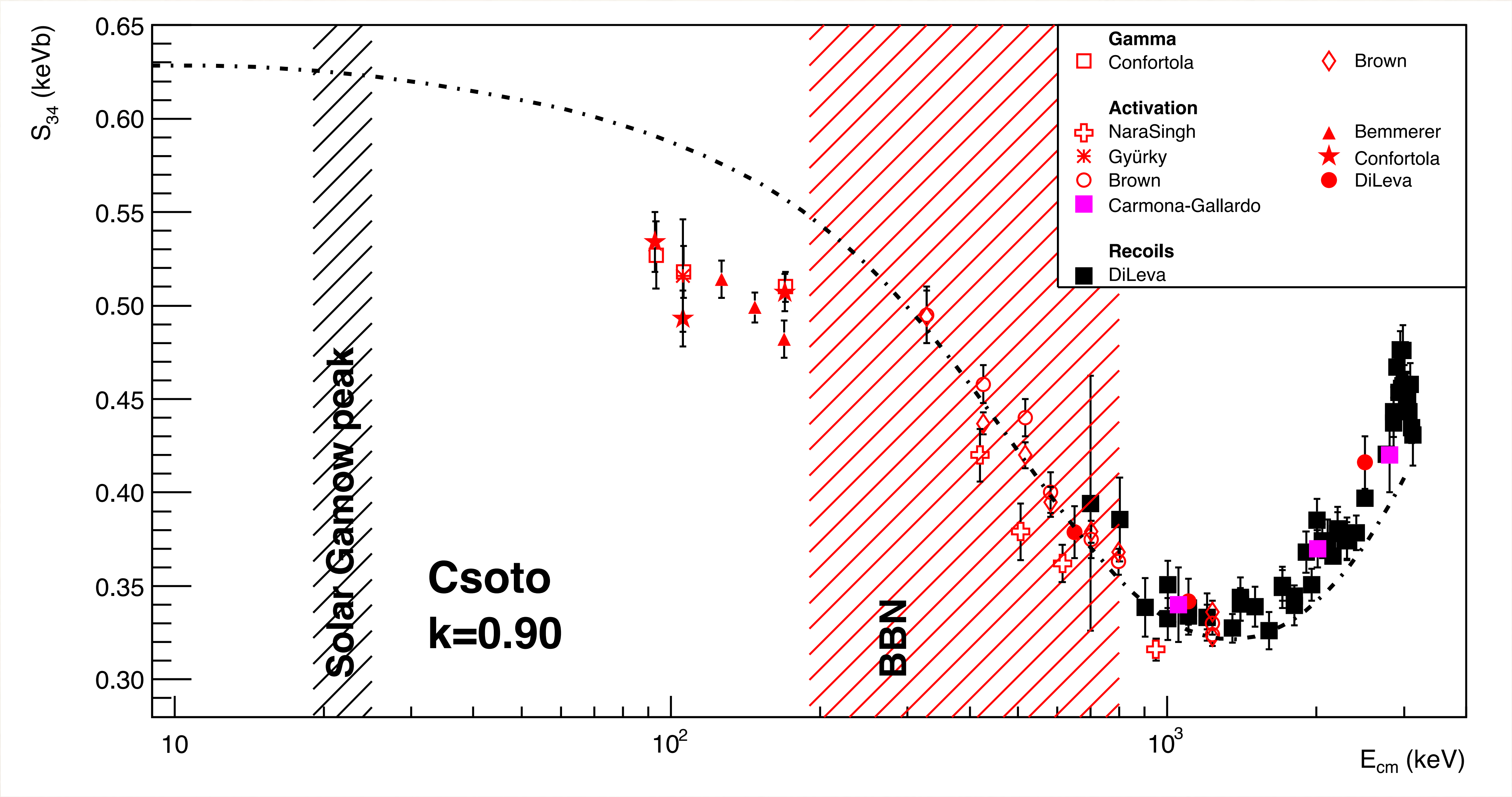

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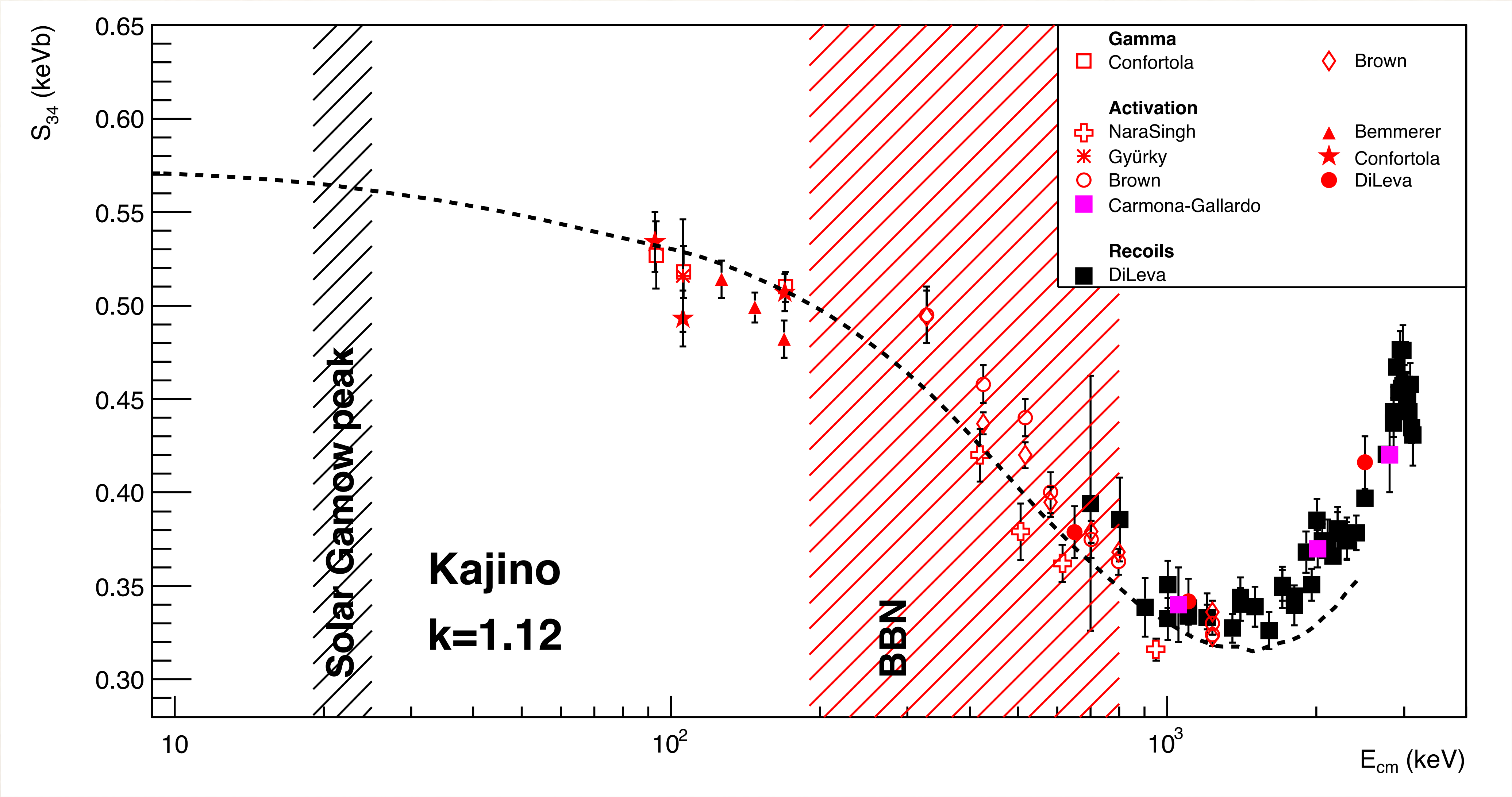

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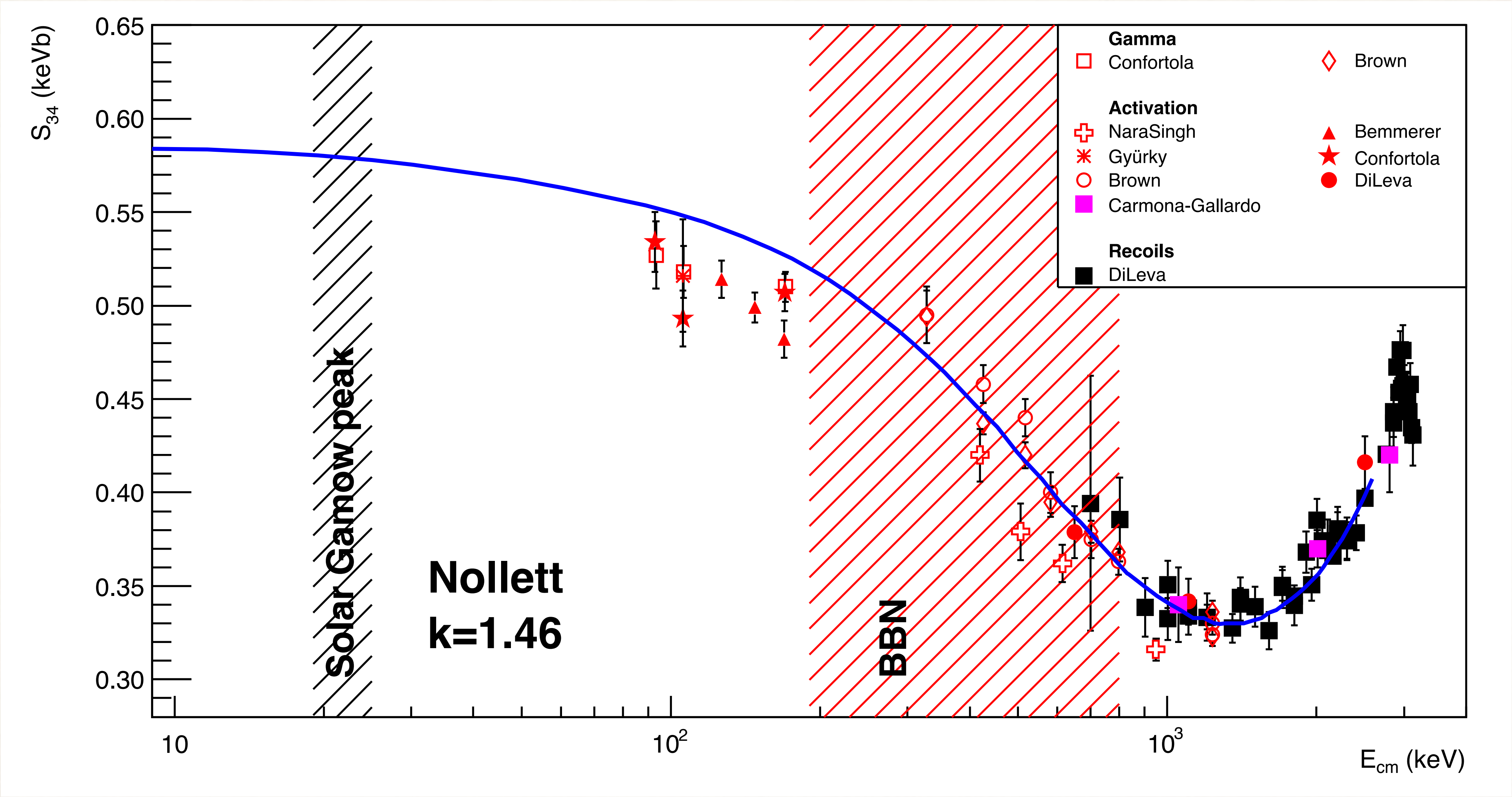

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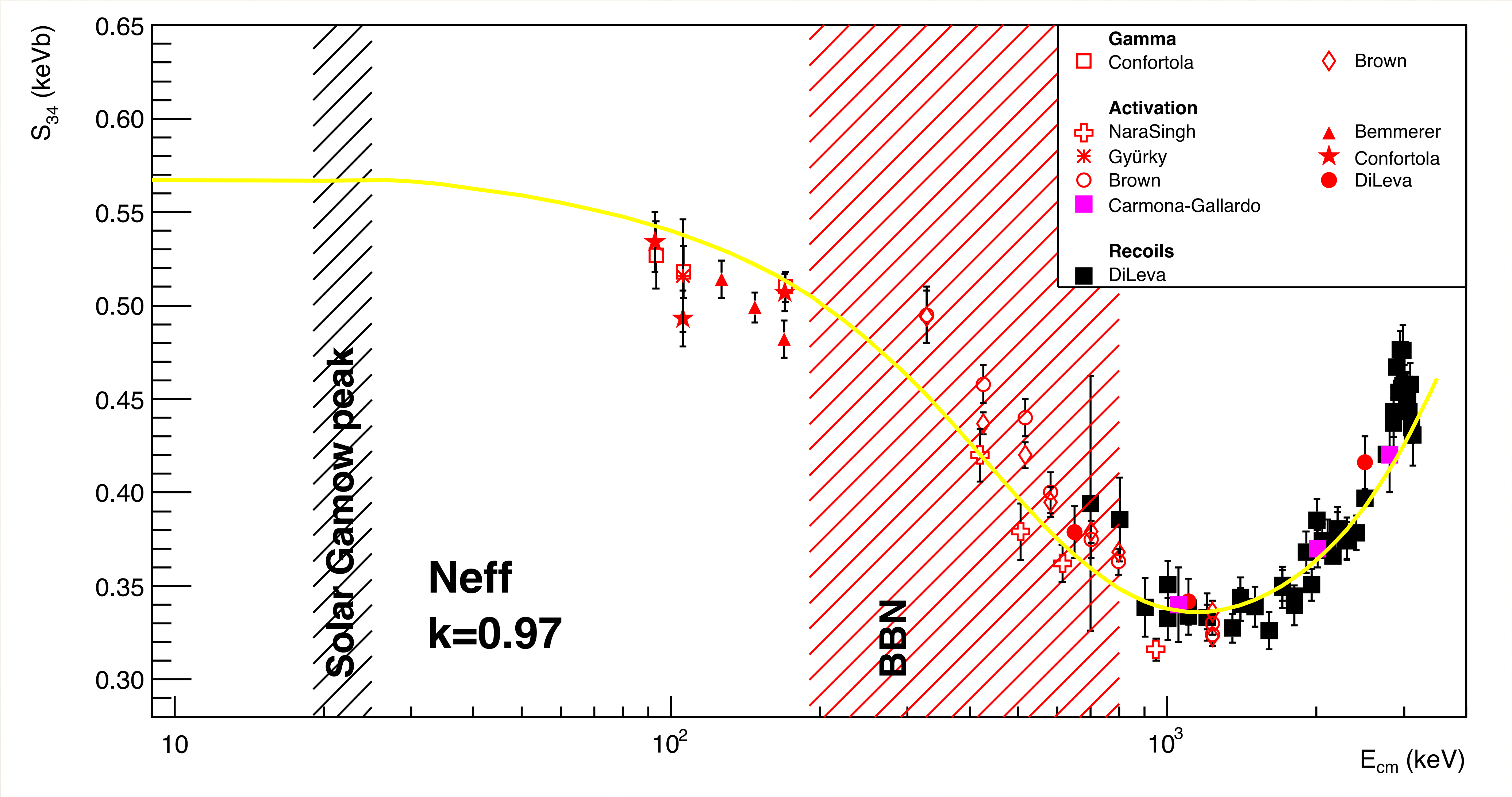

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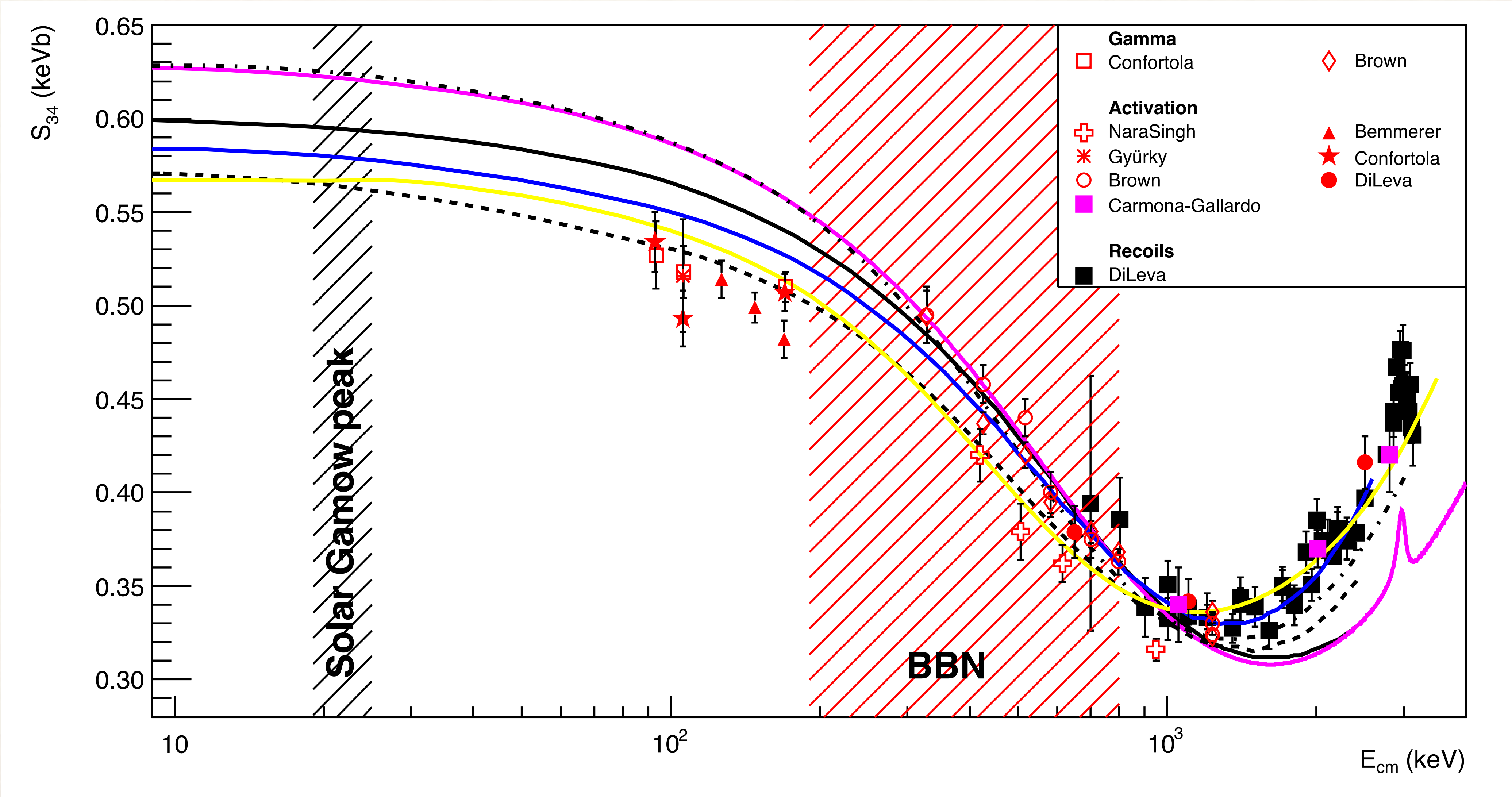

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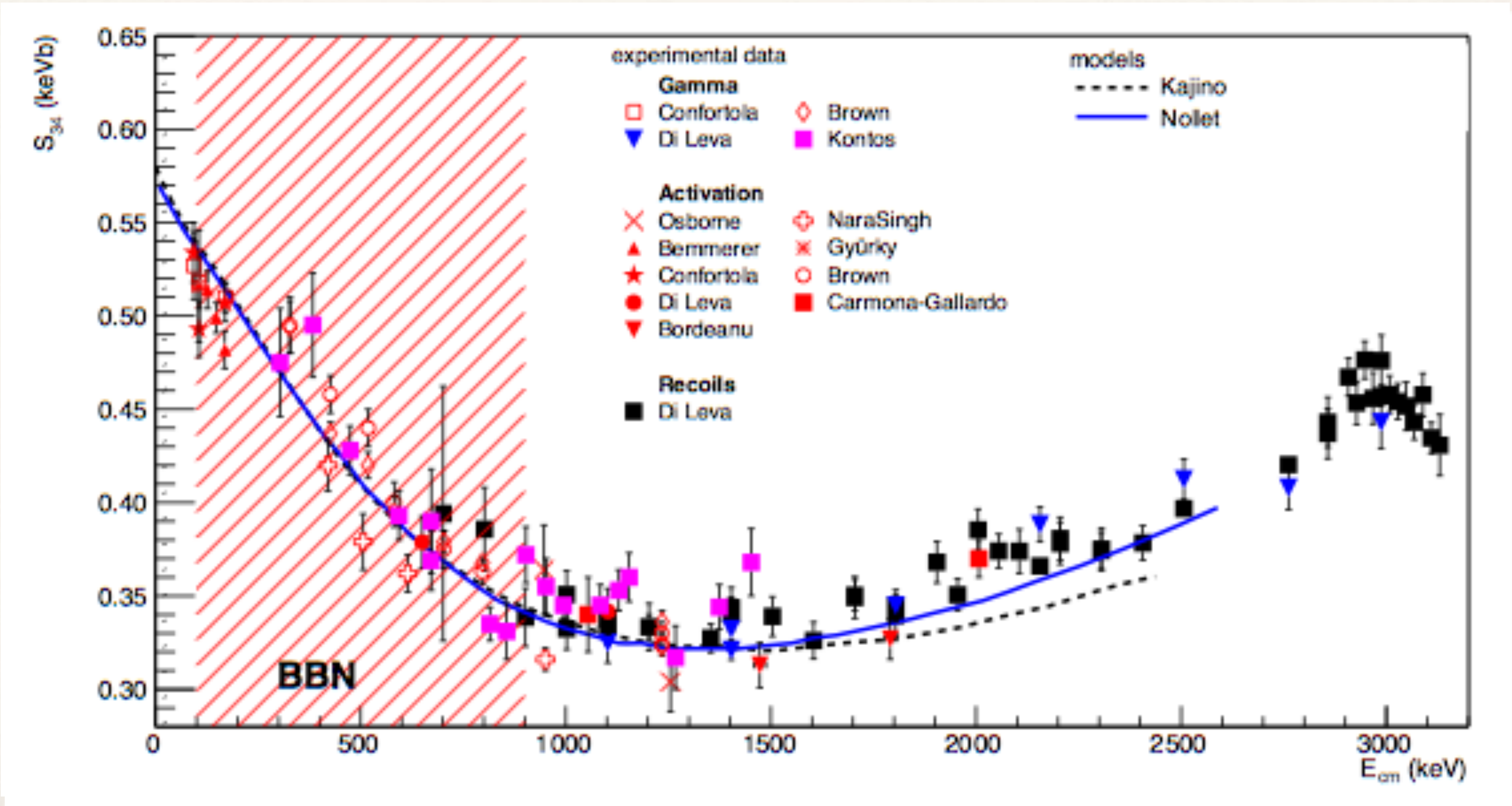
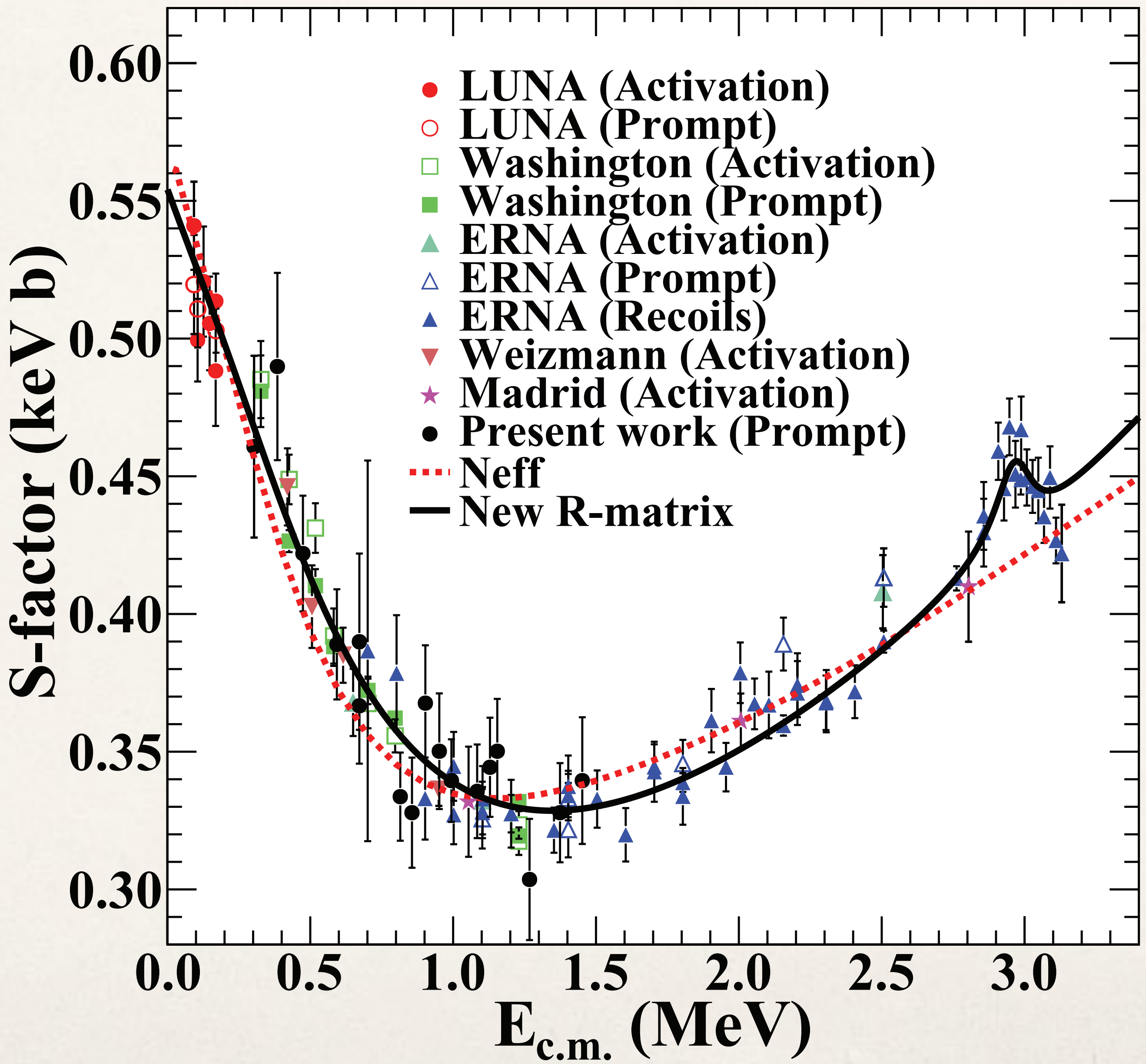


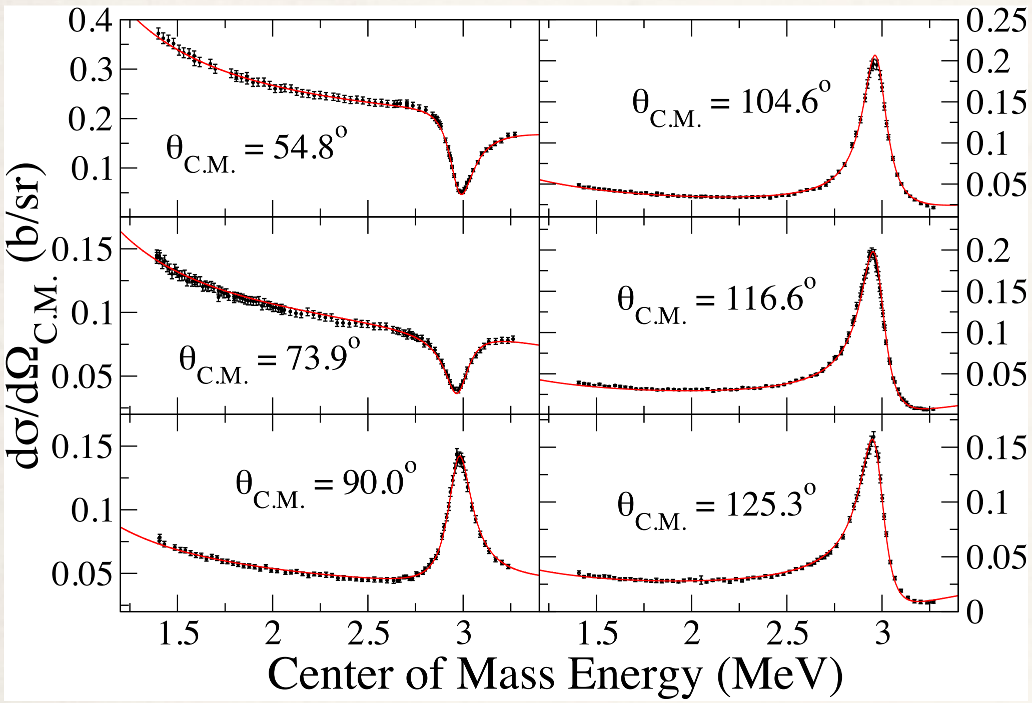
R-matrix fit to the data

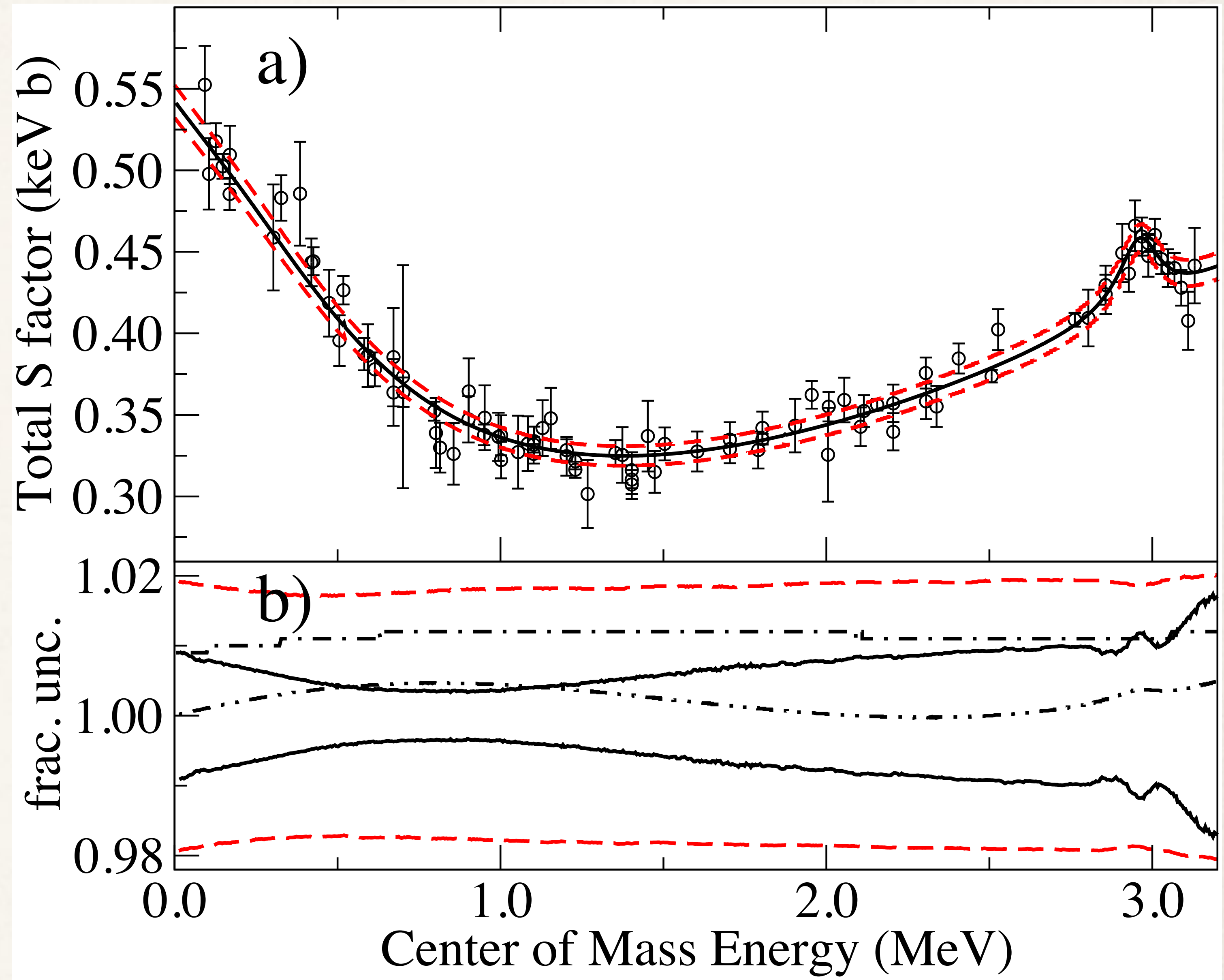
R-matrix is a phenomenological model that can possibly fit simultaneously all data available, through all reaction channels possible for the same compound nucleus



Kontos et al. Phys.Rev. C 87 (2013) 065804

R-matrix fit to the data





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S34(0) = 0.542±0.011(MC fit)±0.006(model)$^{+0.009}_{-0.011}$(phase shifts) keV b

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SFII

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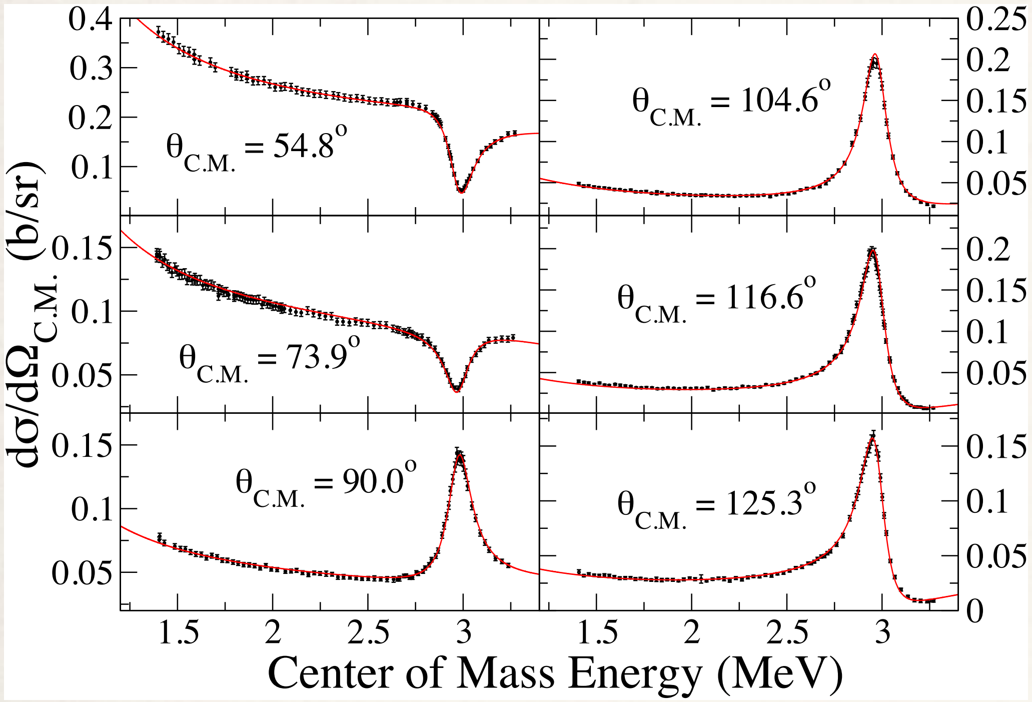

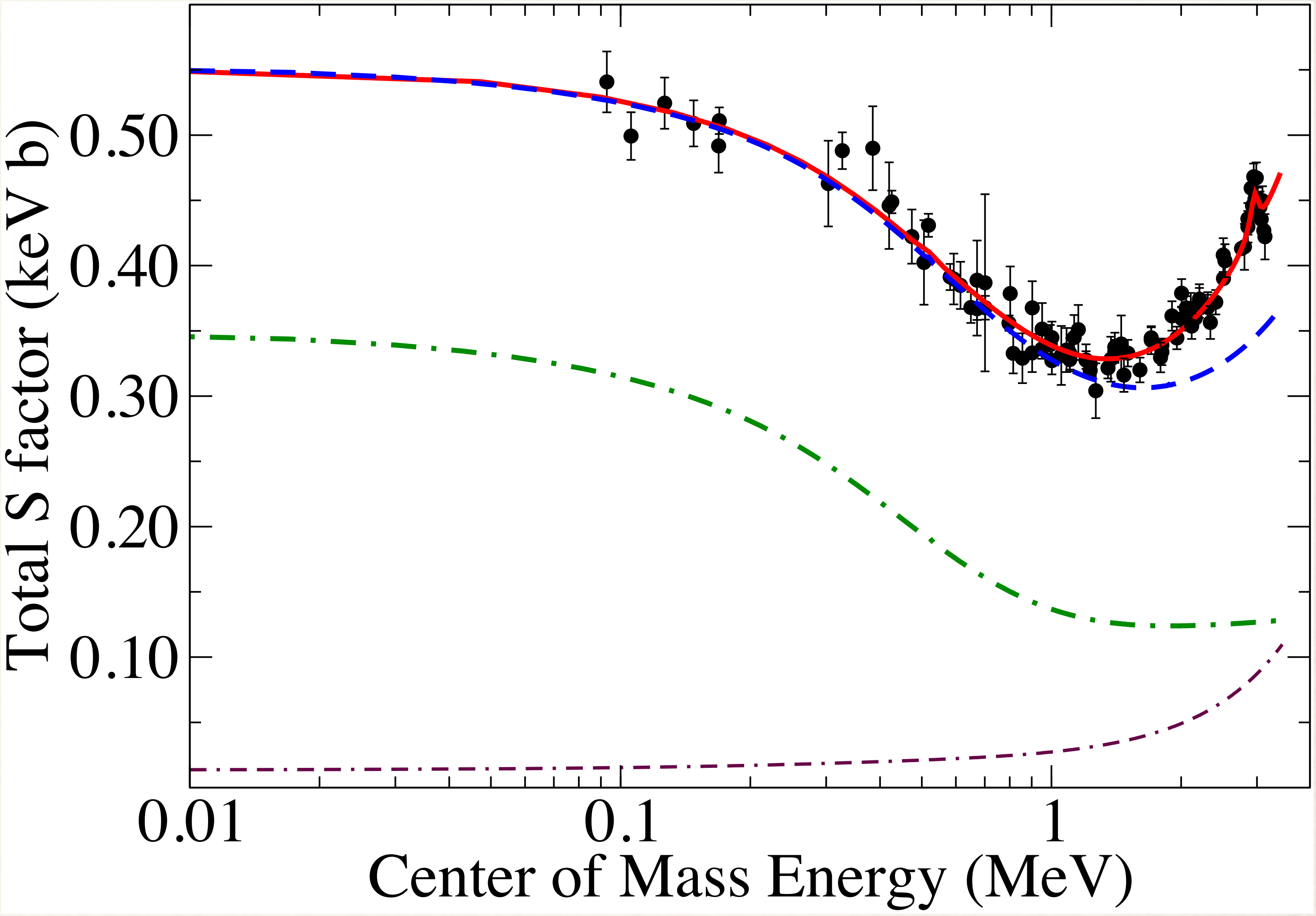

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SFII

Something went wrong...

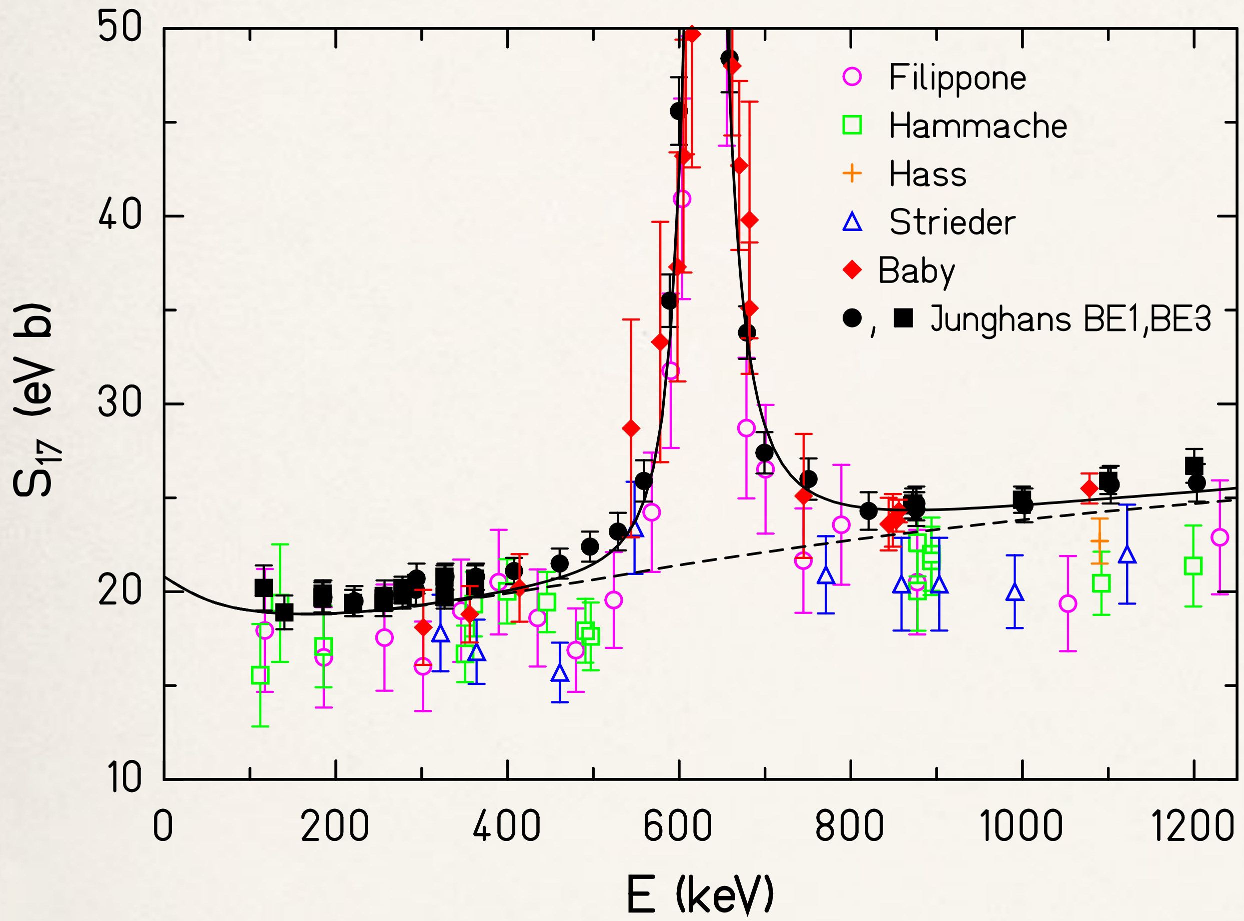
We were not able to deliver the message:

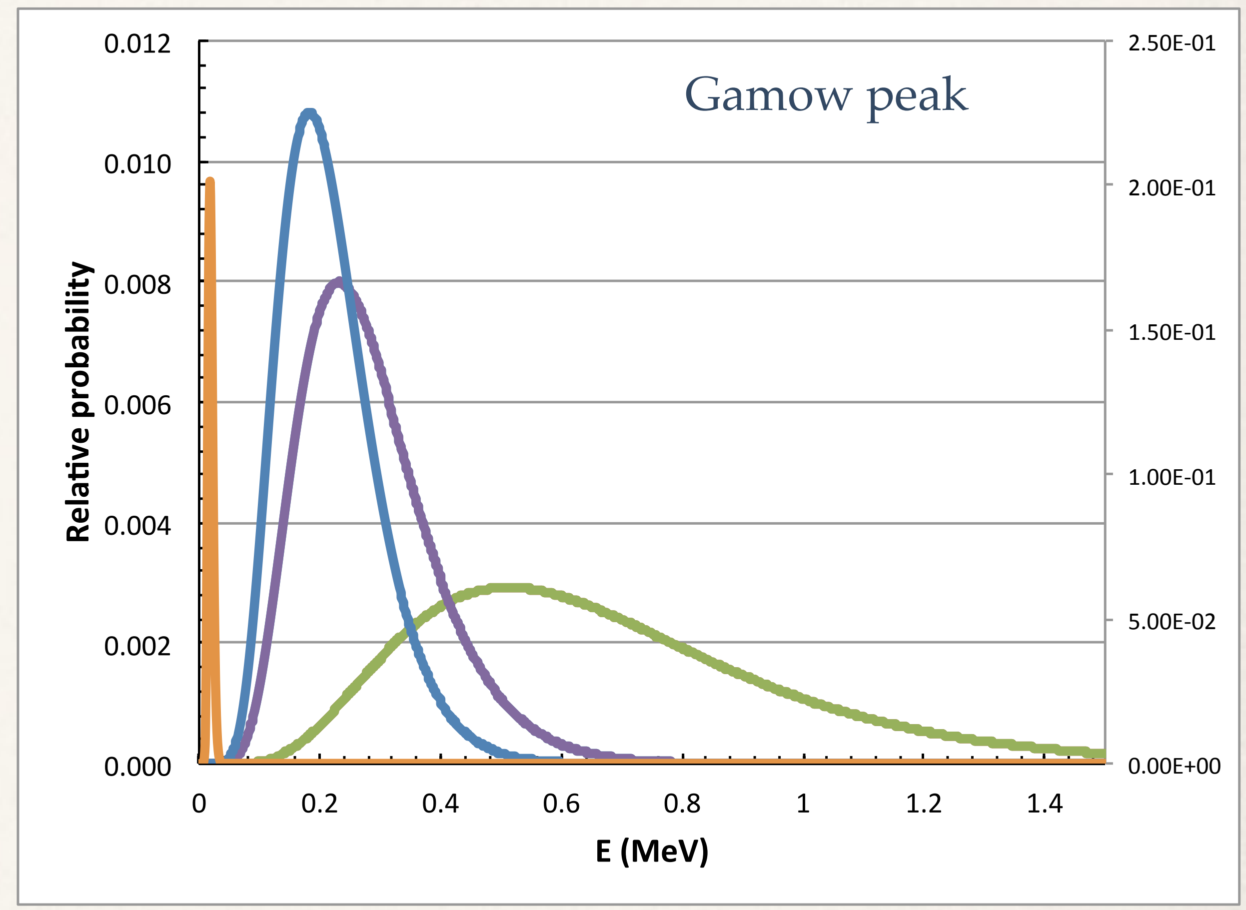
"The central value is ~3% lower than the previous A11 recommended value. […] The underlying reasons for these differences are not discussed in deBoer et al. (2014).
[…]
We point out, however, that a reduction in S34(0) such as that claimed by deBoer et al. (2014) would have an impact in the comparison between solar neutrino data and SSMs built with the GS98 or AGSS09met compositions for the Φ(8B) and Φ(7Be) fluxes."

Vinyoles et al. ApJ 835 (2017)

$^7Be(p,\gamma)^8B$

Solar Fusion II - Adelberger et al. Rev. Mod. Phys. 83(2011)

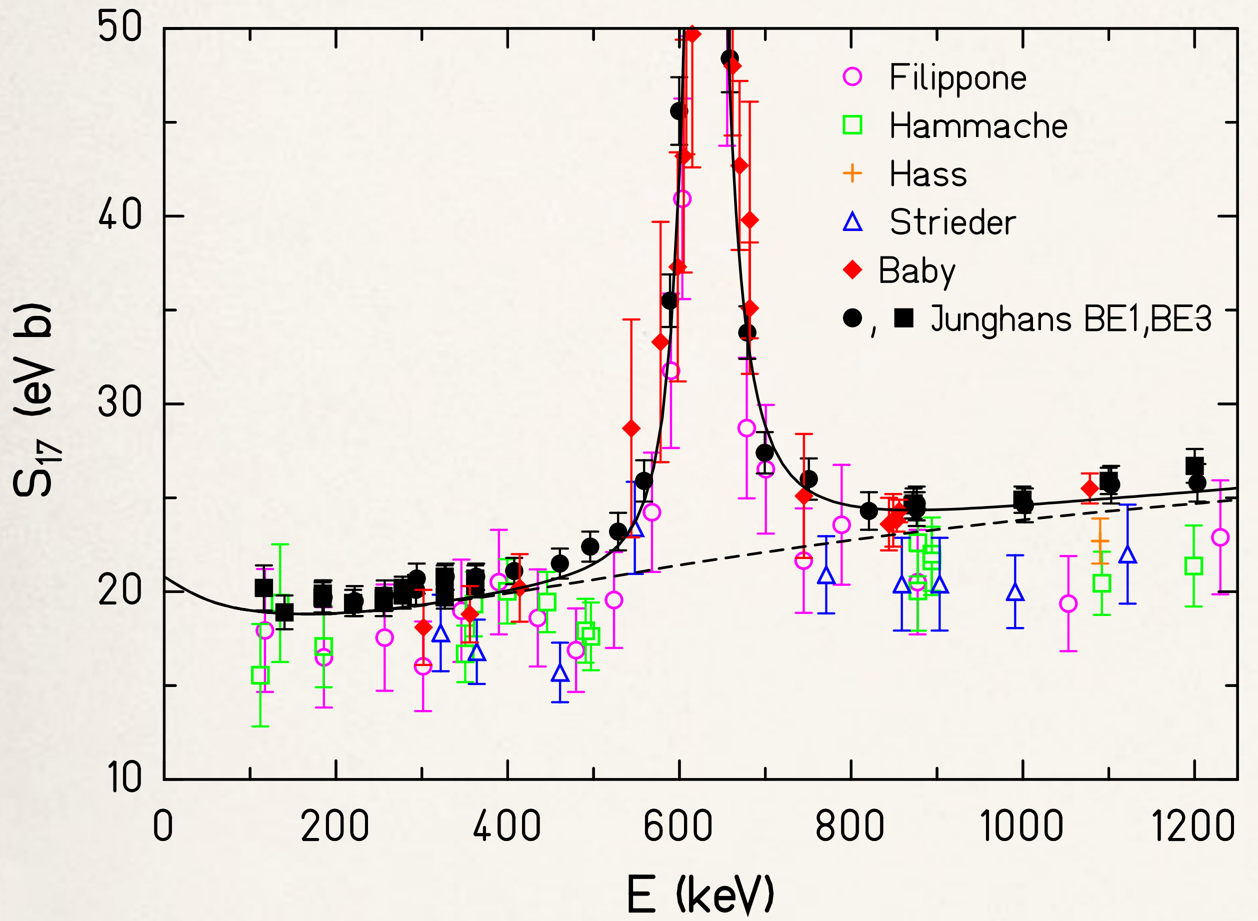


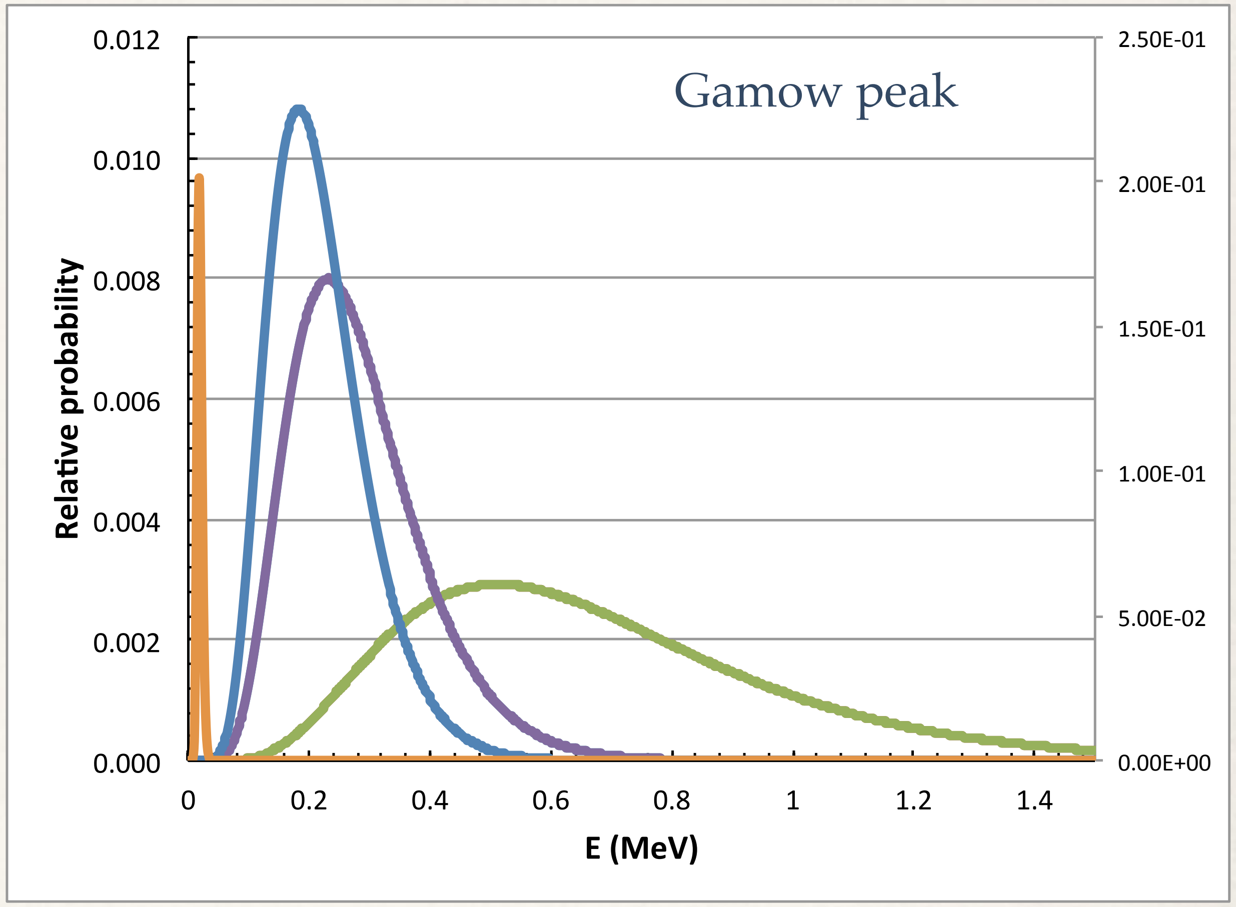


Sun - $T_9 = 0.015$, $E_0 = 18$ keV

$^{7}Be(p,\gamma)^{8}B$

Solar Fusion II - Adelberger et al. Rev. Mod. Phys. 83(2011)





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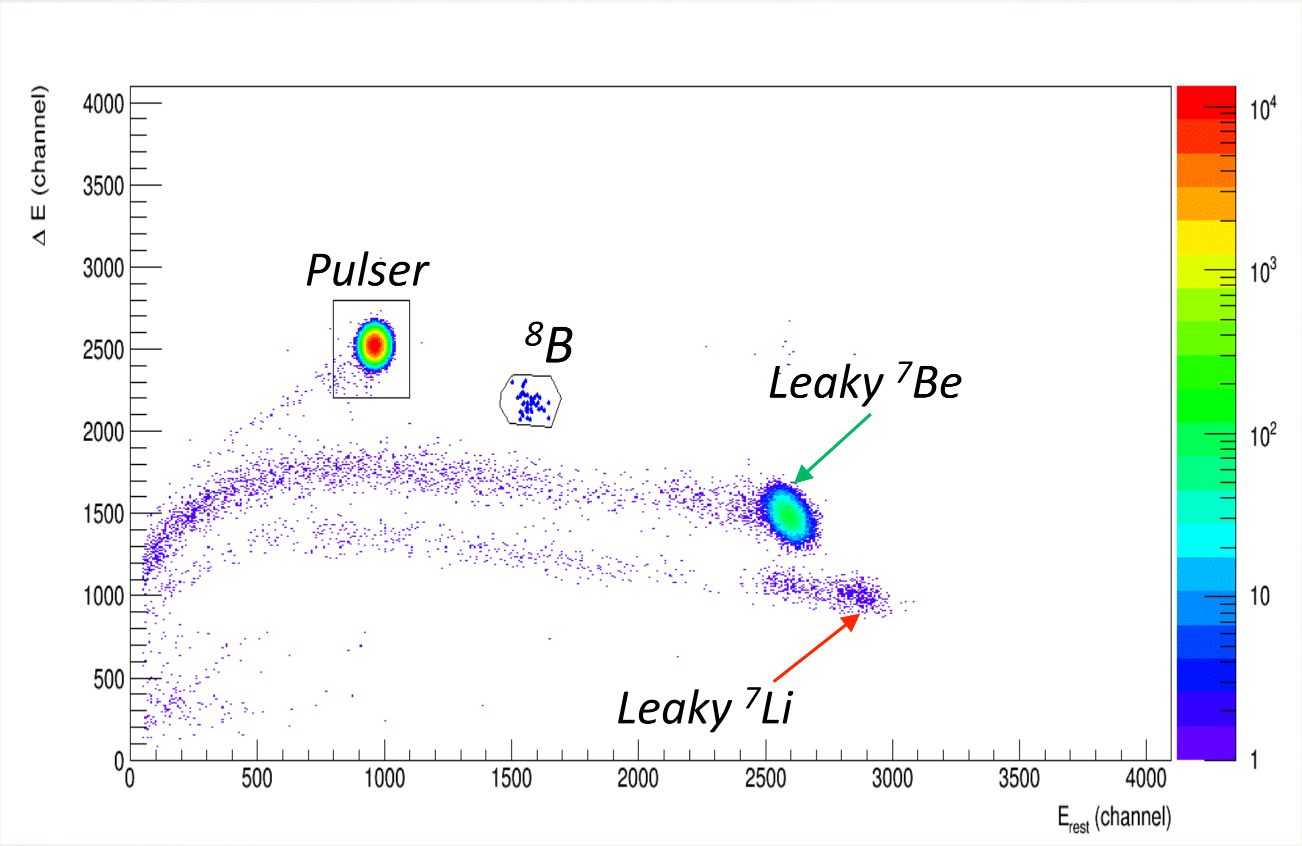
Direct Measurements		Indirect Measurements	
Strieder et al. NuPhA 696(2001) – Bochum	S(0) = 18.4 ± 1.6 eVb	Azhari et al. PRL 82 (1999) - ANC	S(0) = 17.8 ± 2.8 eVb
Hammache et al. PRL 86(2001) – Orsay	S(0) = 18.8 ± 1.7 eVb	Tabacaru et al. PRC 73(2006) - ANC	S(0) = 18.0 ± 1.8 eVb
Jumgans et al. PRC 68(2003) – Seattle	S(0) = 21.4 ± 0.6 ± 0.6 eVb	Schumann et al. PRC 73(2006) - CD	S(0) = 20.6 ± 0.8 ± 1.2 eVb
Baby et al. PRC 67 (2003) – Weizmann	S(0) = 21.2 ± 0.6 eVb		

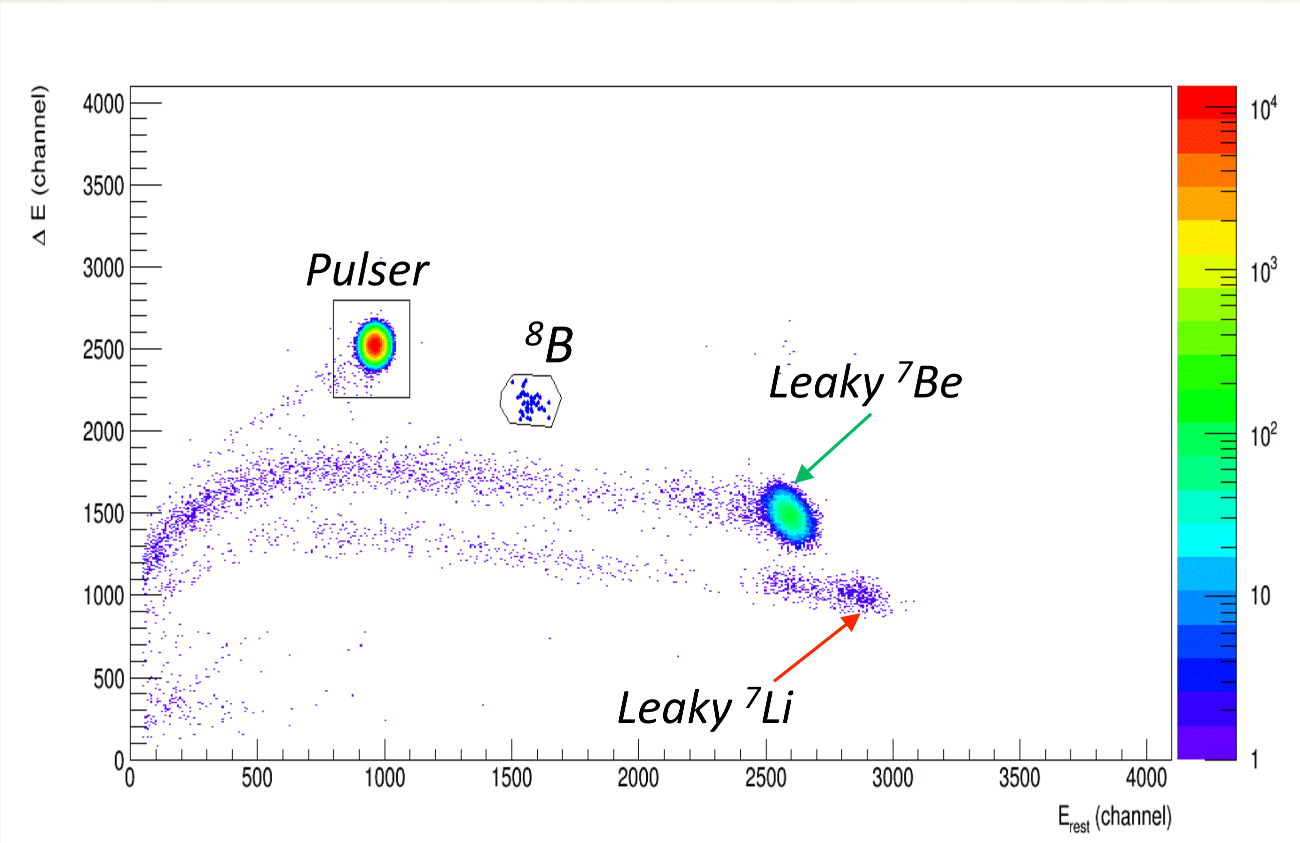
$$S_{34}(0) = 20.8\pm(0.7)_{exp}\pm(1.4)_{model}\ \text{eVb}$$

$^7Be(p,\gamma)^8B$ with ERNA

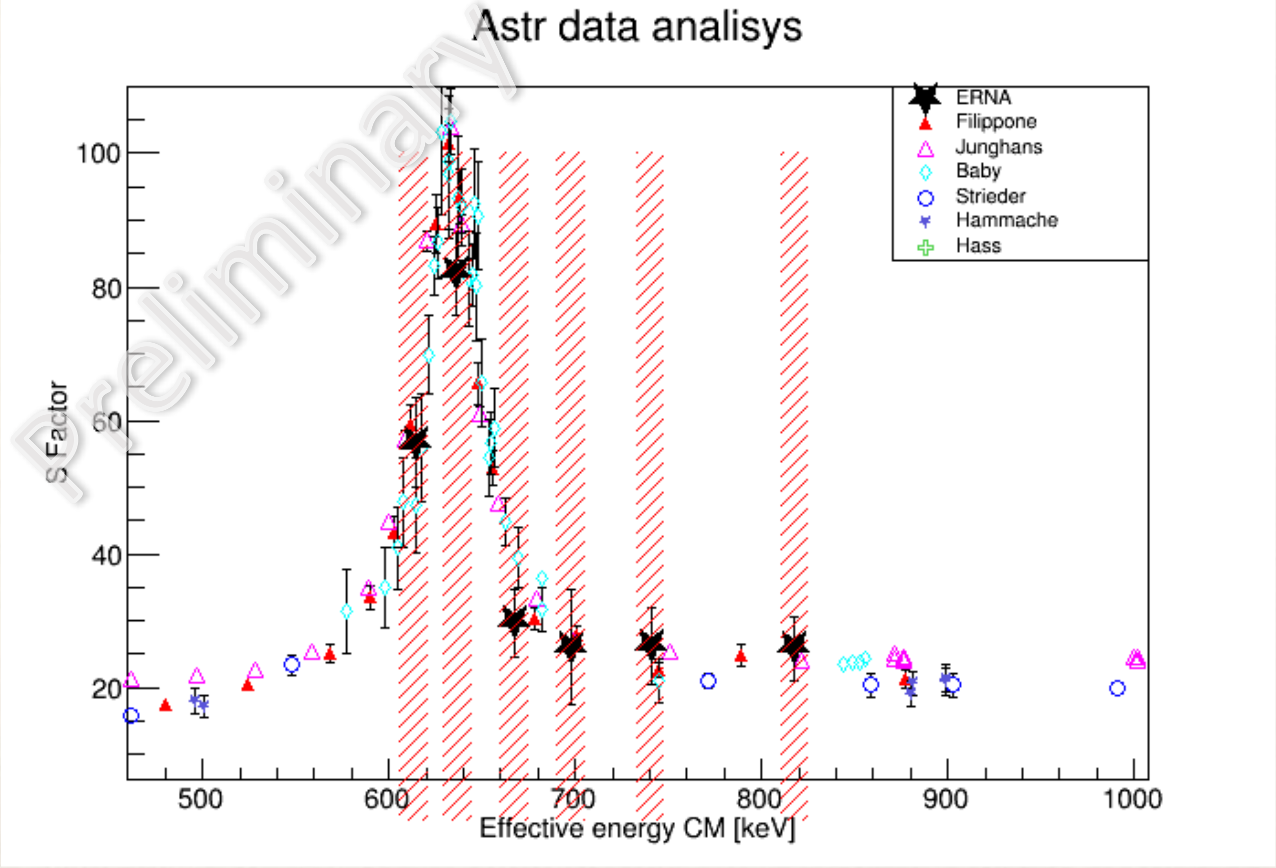


Typical E-ΔE spectrum with ionization chamber telescope. The ^8B recoil are well separated from the primary beam residue.

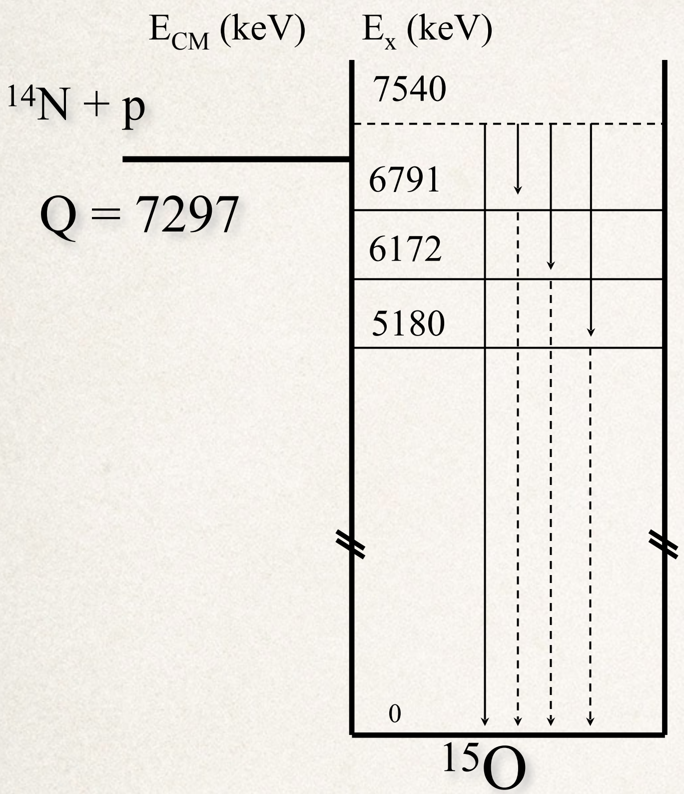
$^{7}Be(p,\gamma)^{8}B$ with ERNA

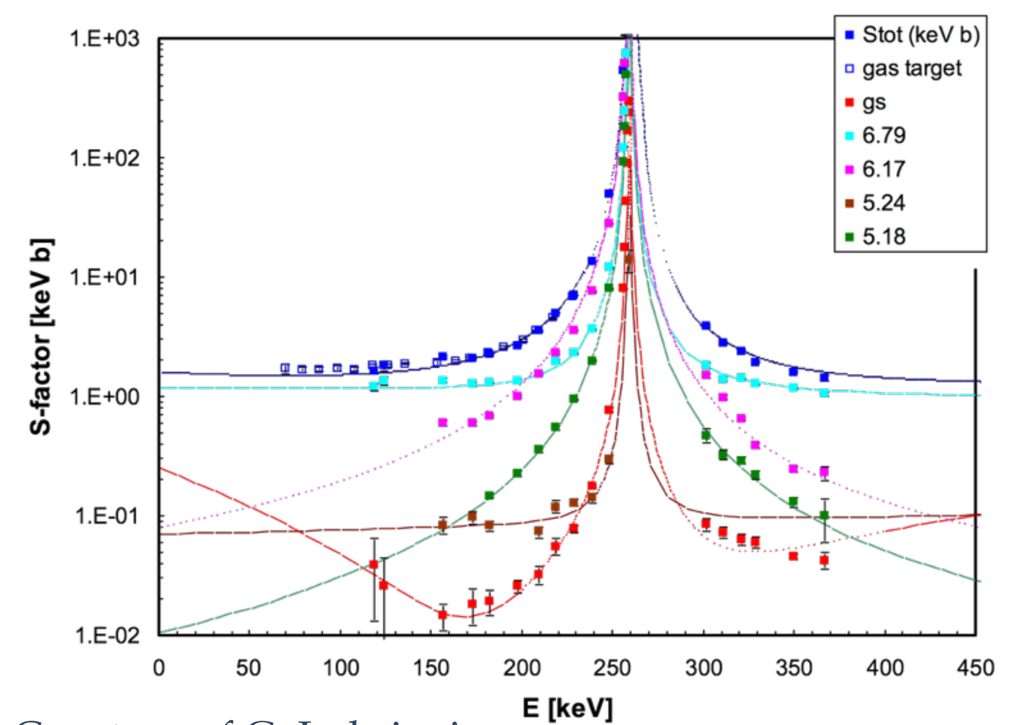


Typical E-ΔE spectrum with ionization chamber telescope. The ^{8}B recoil are well separated from the primary beam residue.

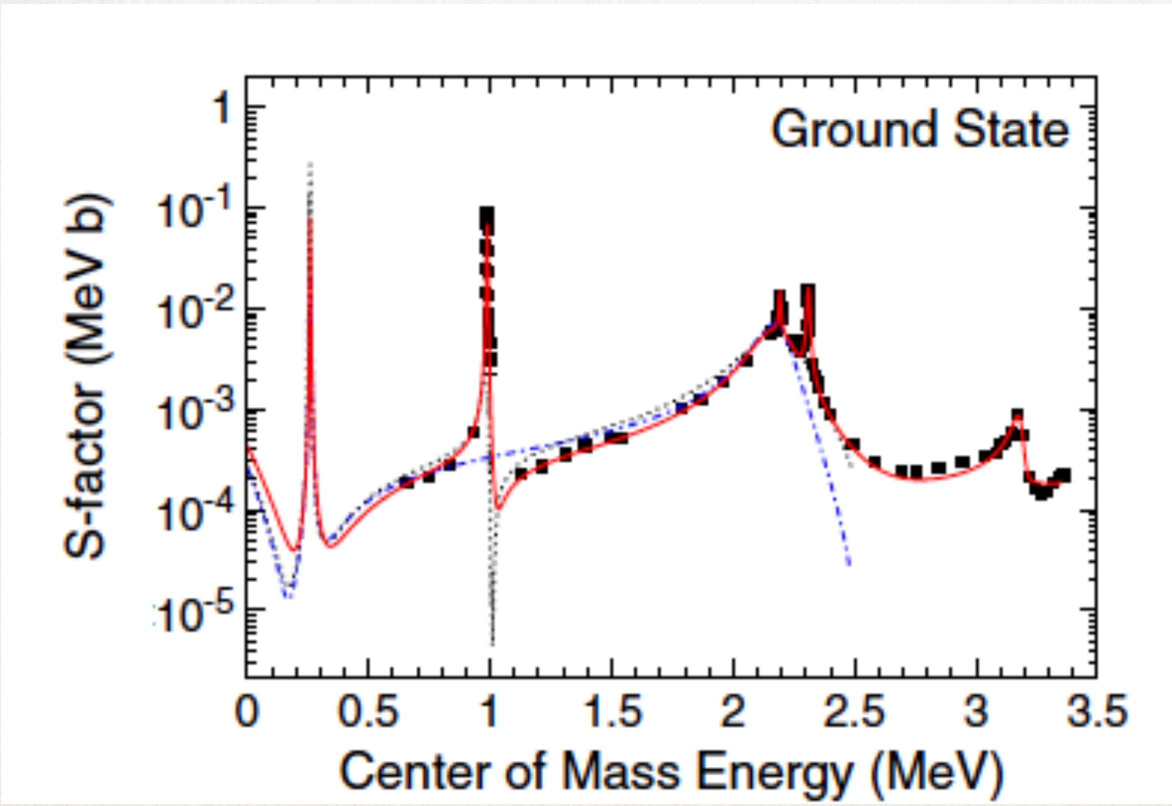


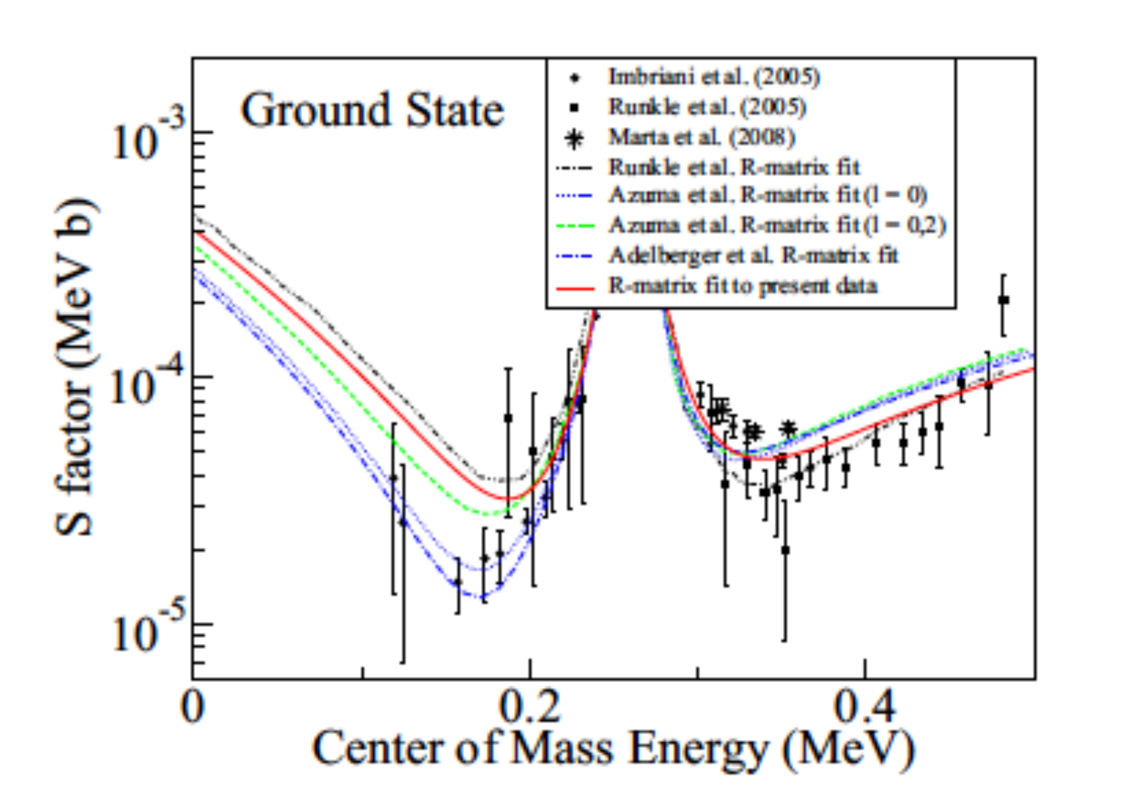
$^{14}N(p,\gamma)^{15}O$





Courtesy of G. Imbriani





Q. Li et al. Phys.Rev. C 93 (2016)055806

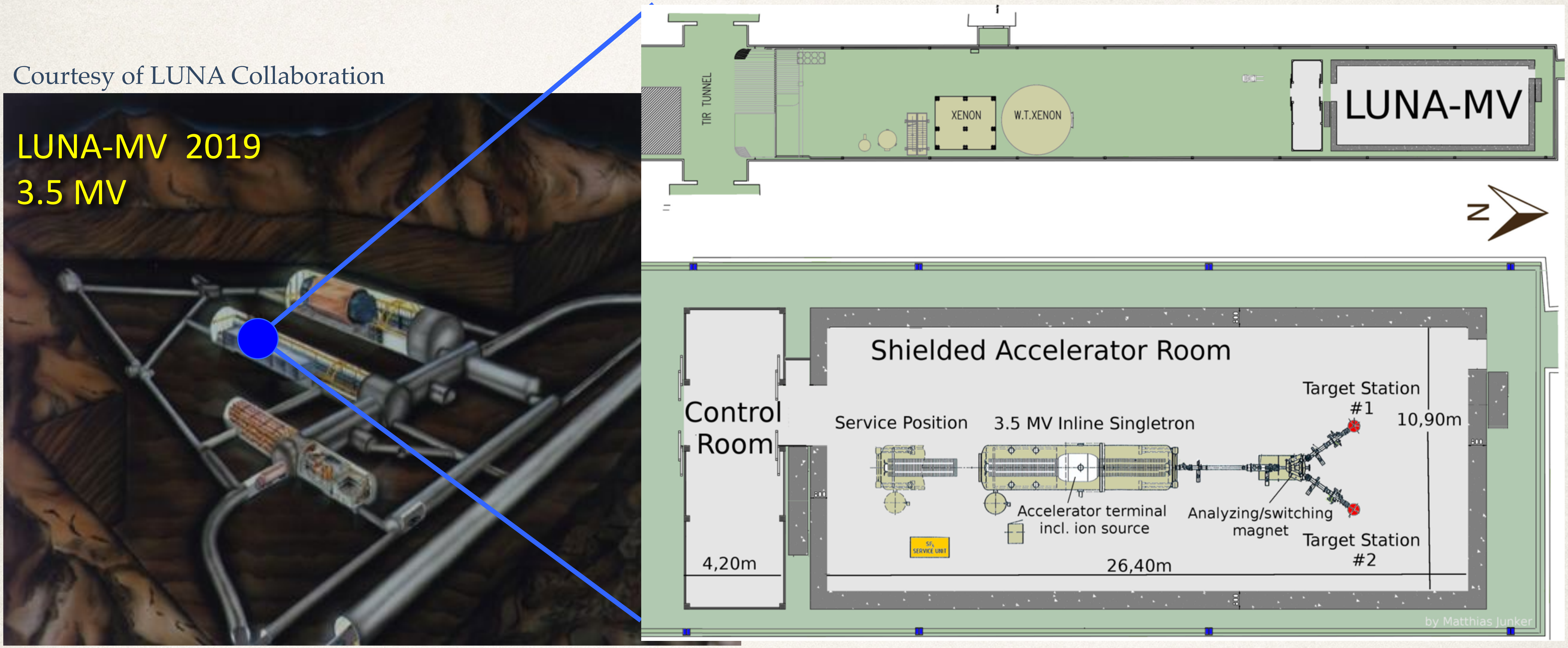
Exciting perspectives

Four scenario, among others, that in my opinion can bring significant advances in Nuclear Astrophysics in the years to come

- The LUNA_MV accelerator at LNGS
- New experimental techniques with lasers
- Next generation RIB facilities
- Neutron induced reactions

LUNA_MV

Courtesy of LUNA Collaboration



A new 3.5MV accelerator to be hosted in hall B of LNGS

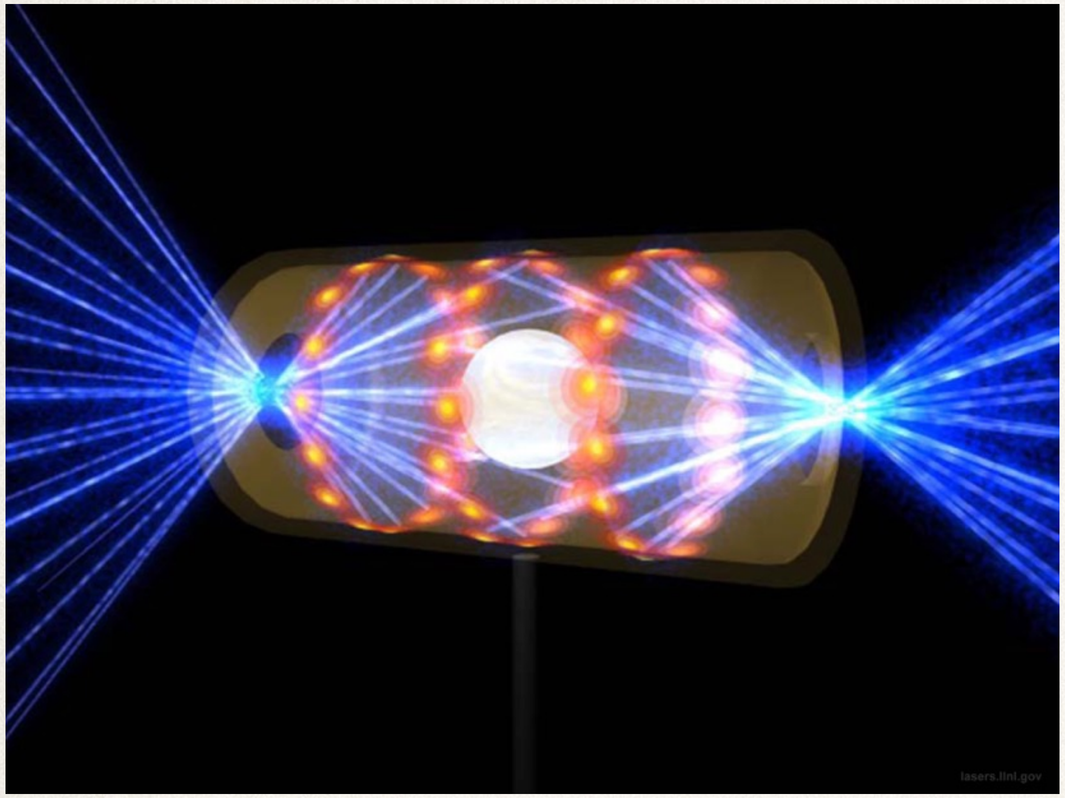
High intensity beams:

^{1}H up to 1mA

^{4}He up to 500μA

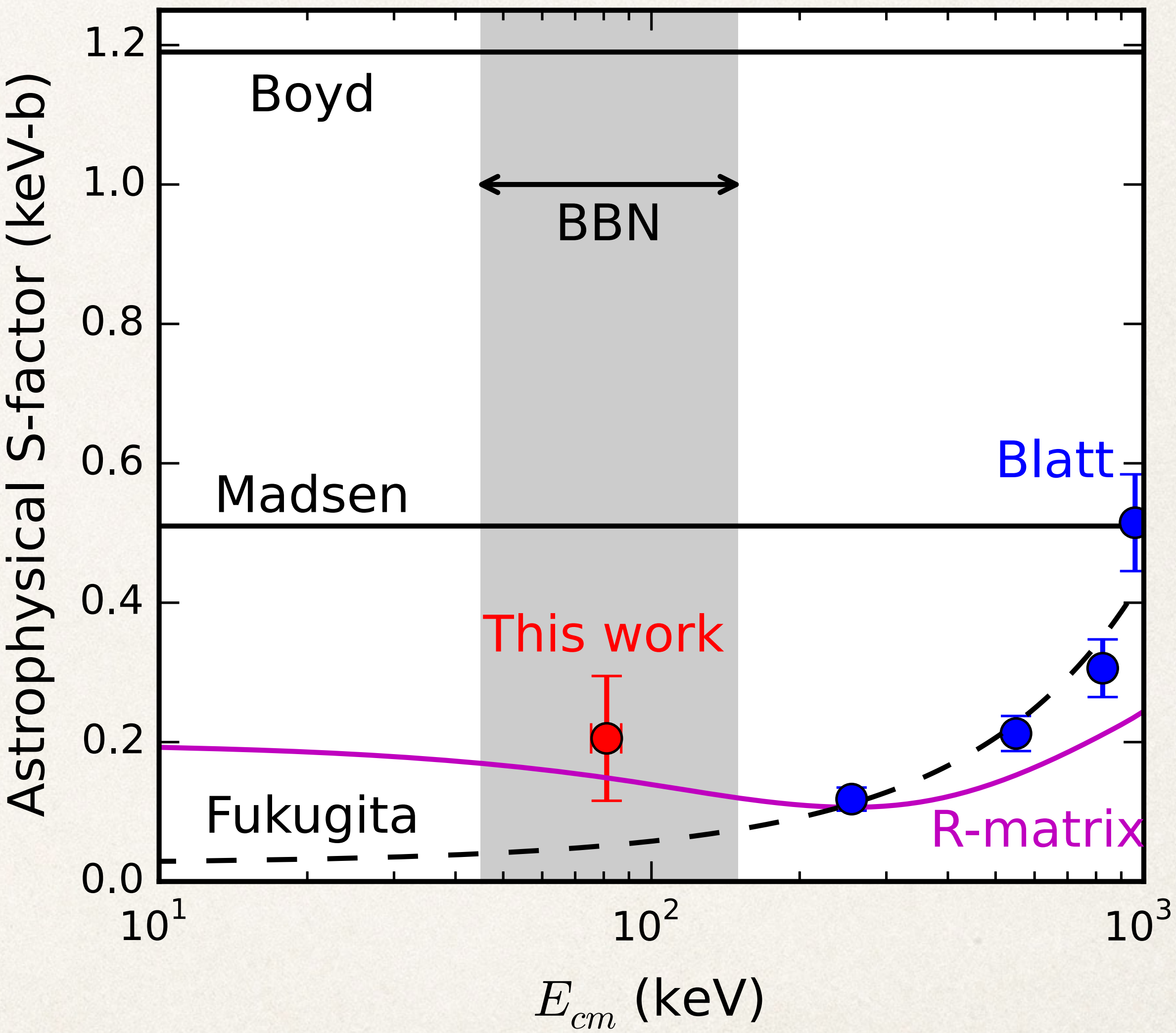
^{12}C up to 150μA

Inertial confinement fusion



https://lasers.llnl.gov/media/photo-gallery

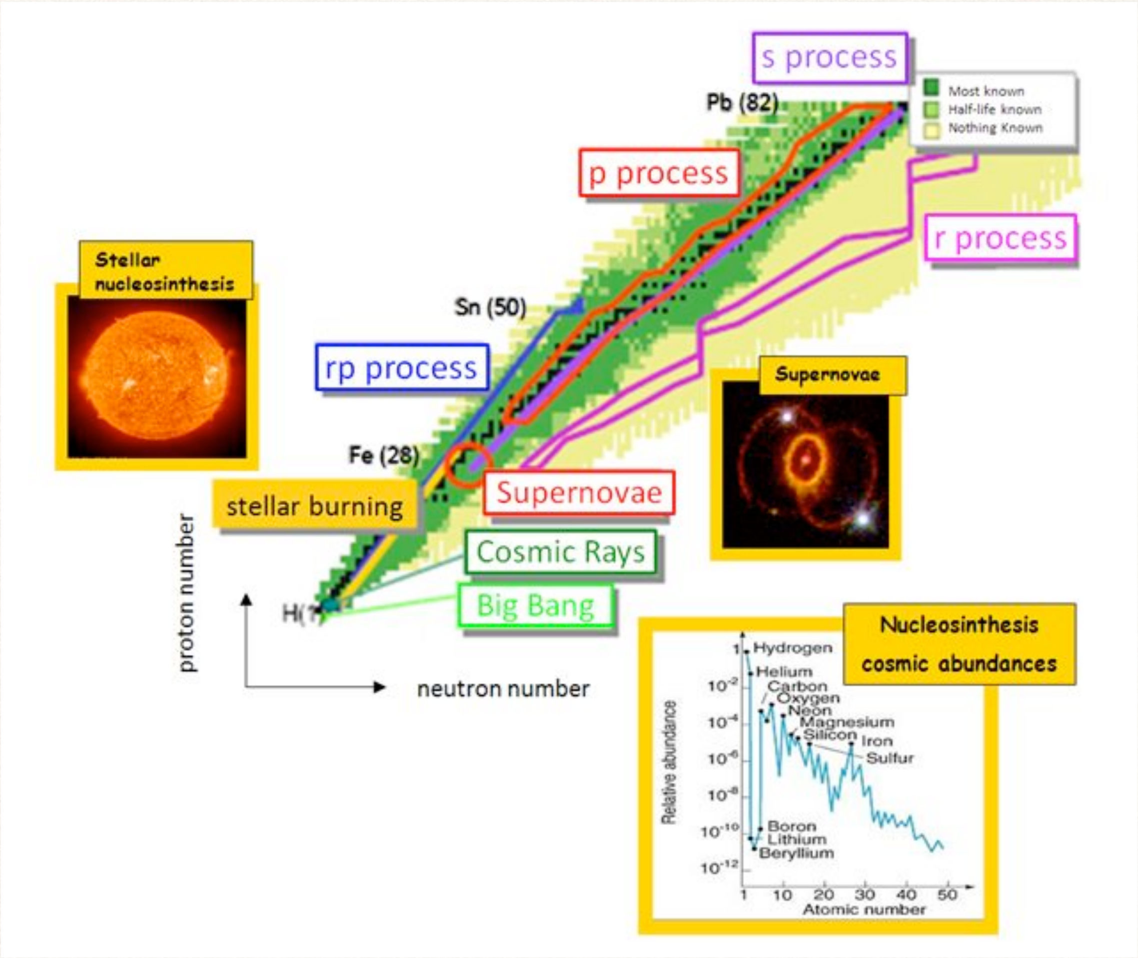
National Ignition Facility at LLNL and the Omega facility at Rochester University, USA



Zylstra et al., "Using Inertial Fusion Implosions to Measure the T + He-3 Fusion Cross Section at Nucleosynthesis-Relevant Energies." Phys. Rev. Lett., v. 117, 035002 (2016)

Next generation RIB facilities

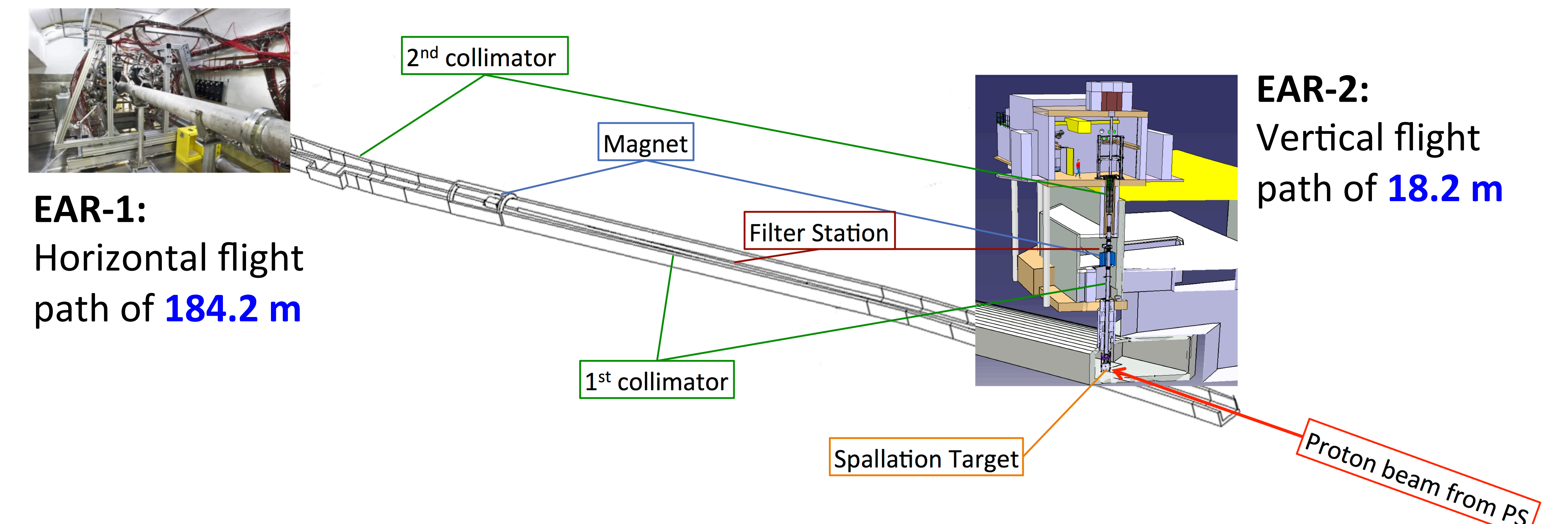
Nuclear processes occurring in extreme environments can be studied with radioactive beams.



New facilities, with a focus on Nuclear Astrophysics, are currently being built e.g. FAIR at GSI, FRIB at Michigan State University, USA or under commissioning e.g. SPES at INFN’s Laboratori Nazionali di Legnaro

Neutron induced reactions

The n_TOF facility at CERN was recently upgraded with a second experimental area



Courtesy of n_TOF Collaboration

The challenging $^{7}Be(n,\alpha)^{4}He$ relevant for BBN was measured Barbagallo et al. Phys. Rev. Lett 117 (2016) 152701

Thank you for your attention

15th International Symposium on Nuclei in the Cosmos,
June 24-29, 2018
Laboratori Nazionali del Gran Sasso
http://nic2018.lngs.infn.it