ASFIN: Nuclear Astrophysics

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Nuclear and Atomic input for quiescent burning

- Activities which may be performed as soon as the beam is delivered @LNS: stable beams
- Activities with Noble gas Tandem Source;
- Activities with Laser

Stable Beams:
Important physical cases can be studied with pre-upgrade accelerator conditions (e.g. Tandem):
ANC + THM measurements: physical cases NeNaAl cycles, or C-burning (e.g. **^{12}C+^{16}O reaction**);

Noble gas sources:
Potentially groundbreaking results may be achieved with Noble Gas Tandem Source, e.g. **^{16}O +^{16}O fusion**
Via THM after ^{20,22}Ne breakup with similar methodology of ^{12}C+^{12}C studies.

Tandem beams are very much needed for our research → back-log exps.

All those activities included in LNS MIDTERM paper as well as NUPECC LRP

Explosive nucleosynthesis

- BBN nucleosynthesis studied via Noble gas Tandem Source;
- BBN nucleosynthesis studied via Laser *induced plasma*
- Long-lived isotopes induced reactions at Tandem (batch mode)

Long-lived isotopes induced reactions at Tandem: e.g. $^{26}Al_{GS}(n,\alpha)$, *(n,p)* (p,γ) *while metastable state to be investigated at LNL – SPES*

s and r process

- S-process reactions studied at Tandem;
- R-process nucleosynthesis investigation with Polyfemo detector.

- *S process reactions may be investigated via indirect methods;*
- *R-process nucleosynthesis studied with Polyfemo.*

All those activities included in LNS MIDTERM paper as well as NUPECC LRP

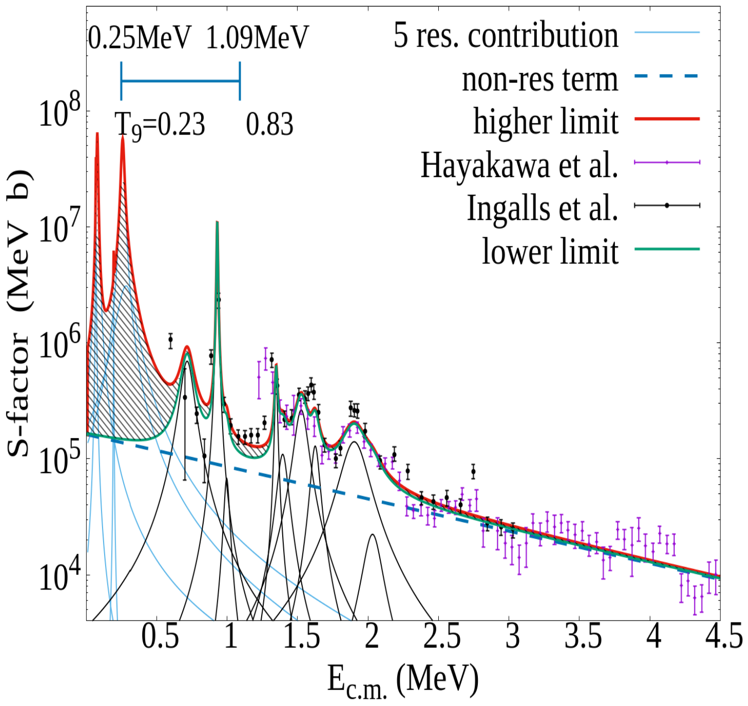
case1: The $^{11}C(\alpha,p)^{14}N$ cross section measurement

Models suggest that the $^{7}Li/^{11}B$ abundance ratio may reflect the information on the *neutrino mass hierarchy, "normal" or "inverted"* (Yoshida 2006, Mathews+ 2012).

Latest calculation (Kajino, Kusakabe, Yao) shows that much ^{11}C is produced in the ν-process and affects the **final ^{11}B abundance**. We need **a precise knowledge of the nuclear reactions around ^{11}C.**

$^{11}C(\alpha,p)^{14}N$ has a large uncertainty and possibly the most effective to the A=11 abundance among 91 reactions (Yao et al., NIC proceeding, 2022).

The present knowledge of the $^{11}C(\alpha,p)^{14}N$ S-factor is summarized in figure:



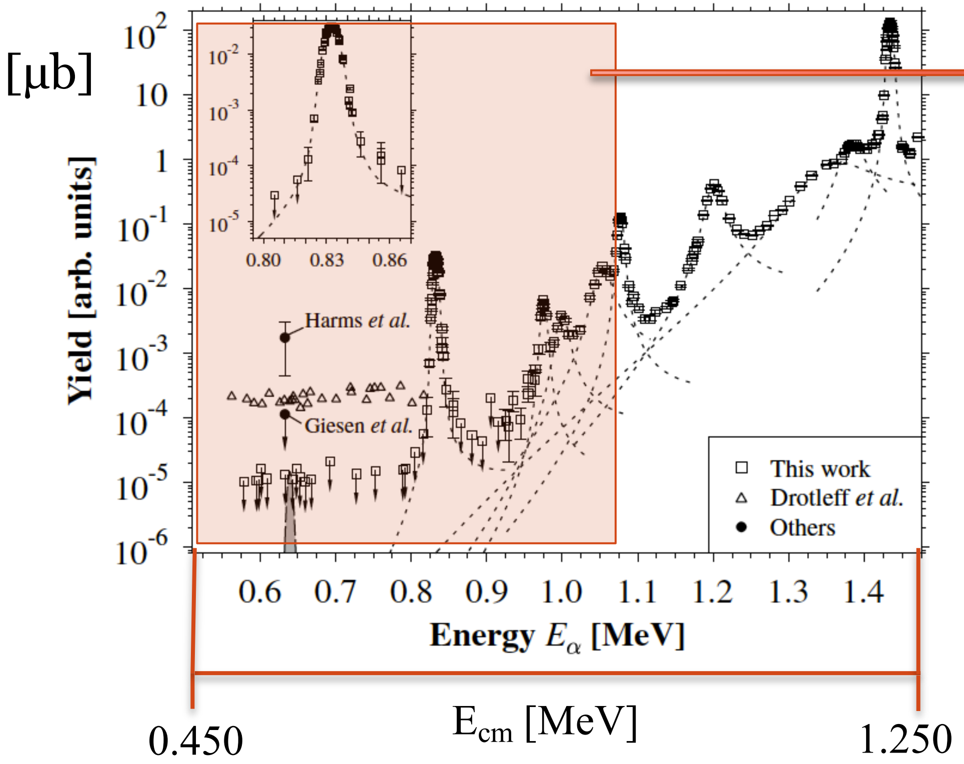
^{15}O excited levels (E_x=10.290-11.218 MeV) contribute to the cross section at Gamow energies.

5 resonances are known to exist below the direct measurement data points.
α widths are unknown and thus produce a **large uncertainty** (shaded area in the figure) **at the Gamow window (~0.25-1.1 MeV)**.

Hayakawa et al. 2016 found a **dominance of the p_o channel** with respect excited states.

Because of low cross section values (~nb), we aim at explore this low-energy region by using the **Trojan Horse Method (THM) for studying the reverse $^{14}N(p,\alpha)^{11}C$ reaction .**

Case 2: $^{22}Ne(a,n)^{25}Mg$



Region of interest for s-process E_{cm} = 600 ± 300 keV

[Jaeger et al. 2001]

- ✓ Magn-a: $^{25}Mg(n,\alpha)^{22}Ne$ + det.bal.princ. → $d(^{25}Mg,n\alpha)^{22}Ne$ THM (not worked, 23Na instead of 22Ne)

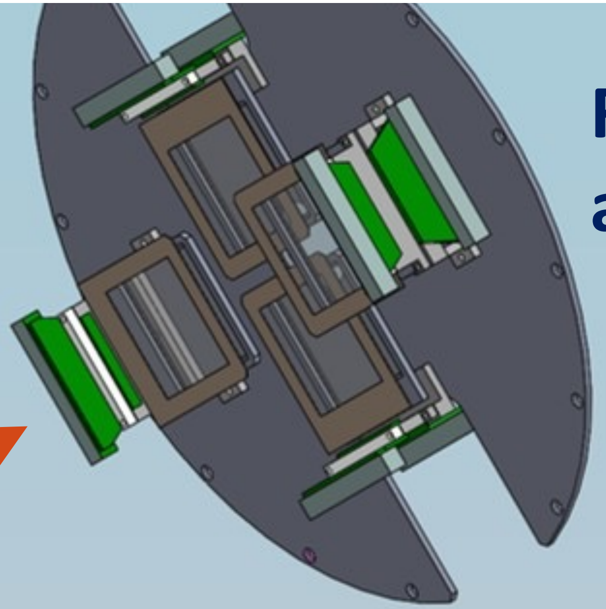
- **^{22}Ne beam by the (NobleElementsSource) + Tandem → $^{6}Li(^{22}Ne,dn)^{25}Mg$ THM + solid ^{6}LiF targets (^{6}Li= α+d) or other break-ups**

Below 1.2 MeV values are smaller than 1 μb
→ very difficult to perform direct measurements

Indirect measurement is needed @low energy
to cover the whole range and solve the discrepancy

ADONIS: Aluminum DestructiON in Stars

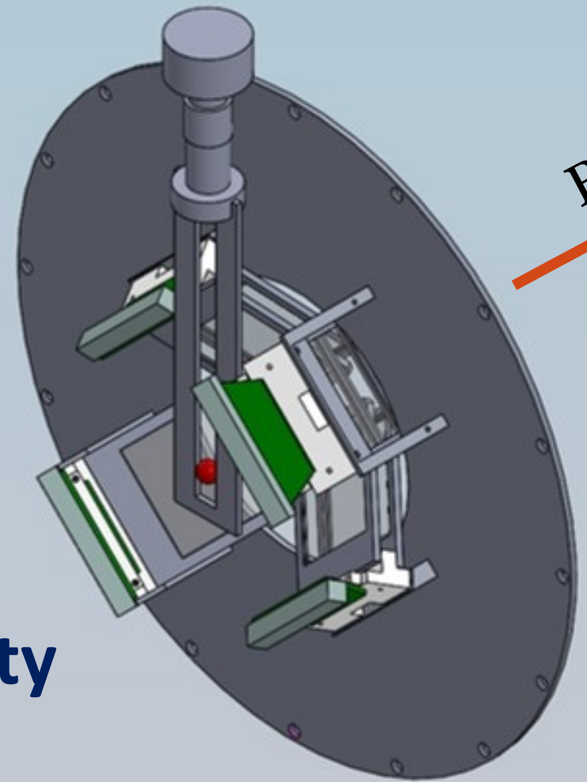
Introducing NEFASTA (NEar FAr Silicon Telescope Array)



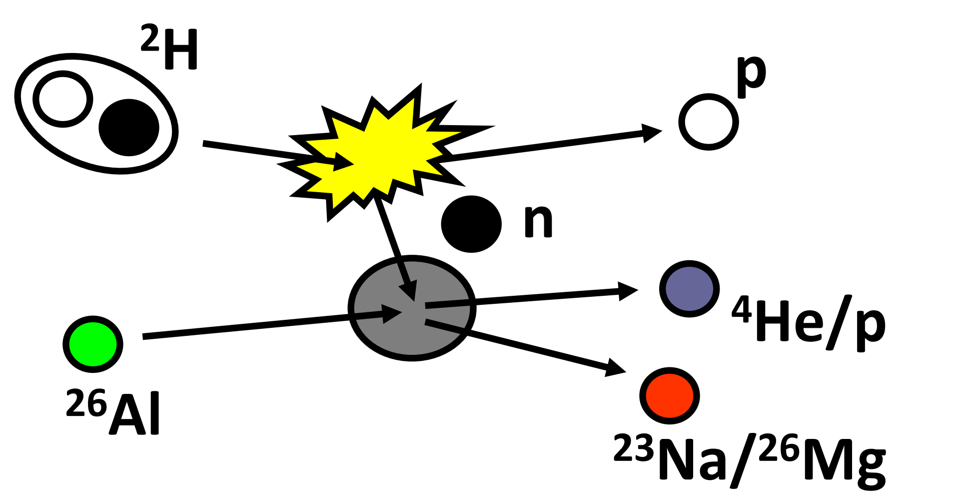
FAR: min. angle 2°

Use of *d* quasi-free breakup to induce reactions on ^{26}Al

BEAM DIRECTION



NEAR
High
granularity



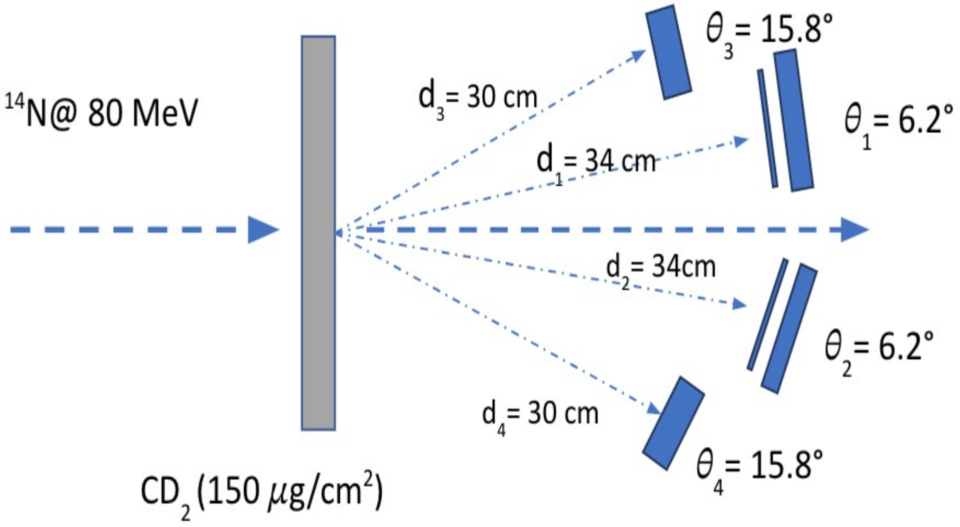
Trojan Horse Method: THM

LNS & the future of Nuclear Astrophysics:

- Up-to-date detector array → NEFASTA
- Radioactive ion source for long lived isotopes on the Tandem;
- Noble gas source for the Tandem;
- Laser induced measurements in plasma- Coulomb Explosion;

Necessity of a resident detector array for measurements @LNS Tandem –> dedicated facilities (dedicated testing and developing point)

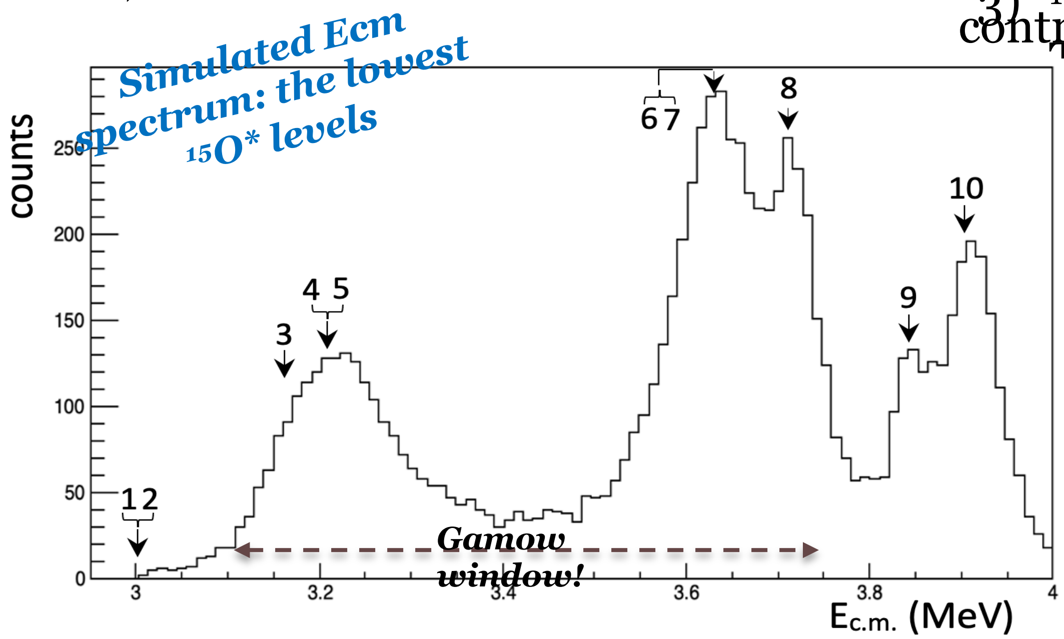
The $^{14}N(p,\alpha)^{11}C$ reaction via THM applied to the QF $^{2}H(^{14}N,\alpha\,^{11}C)n$



$T_{1(2)}$→ ΔE(20μm, SSD)+E(1000μm, DSSSD)

1) The two body reaction **$^{14}N(p,\alpha)^{11}C$** **(Q=-2.922 MeV)** will be studied by applying the THM to the reaction **$^{2}H(^{14}N,\alpha\,^{11}C)n$ (Q-value=-5.146 MeV)** by properly selecting the corresponding quasi-free contribution (QF) to the total reaction yield;
1) Deuteron "d" is used as **TH-nucleus;**
2) A 80 MeV ^{14}N is required
3) ^{11}C detection via telescopes T_1 and T_2

➢ At lower angles (~ 3°), maximum elastic contribution at ~1.5 KHz with 10^9 pps;



1) E_x= 10.290 MeV, Γ=3±1 keV
2) E_x= 10.300 MeV, Γ=11±2 keV
3) E_x= 10.461 MeV, Γ<2 keV
4) E_x= 10.480 MeV, Γ=25±5 keV
5) E_x= 10.506 MeV, Γ=140±40 keV
6) E_x= 10.917 MeV, Γ=90 keV
7) E_x= 10.938 MeV, Γ=99±5 keV
8) E_x= 11.025 MeV, Γ=25±2 keV
9) E_x= 11.151 MeV, Γ<10 keV
10) E_x= 11.218 MeV, Γ=40±4 keV

Nuclear Physics Mid Term Plan in Italy

[Courtesy of Dr. S. Palmerini]

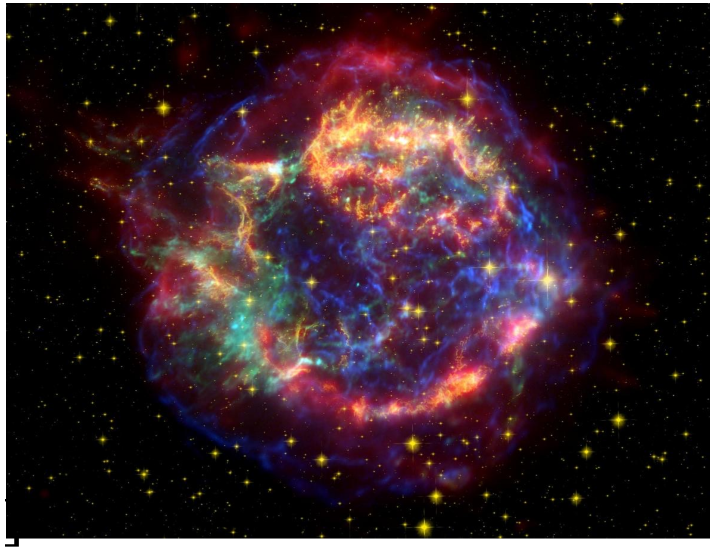
Case 2: ^{22}Ne(α,n)^{25}Mg Astrophysical scenario

- neutron source that feeds the s-process **weak component** (60<A<90) during central-^{4}He/shell-^{12}C burning stage in massive stars

- most intense n-source in AGB stars (provides n fluxes during thermal pulses up to 10^{10} n/cm^{3}) allowing competition between n-capture and β-decay → ^{86}Kr, ^{87}Rb and ^{96}Zr not only synthetized by r-process (and ^{86}Sr is s-only nucleus)

- **type II** supernova explosions

[Longland et al.]
^{60}Fe is mainly produced in massive stars by neutron captures during convective C-shell burning → its abundance depends strongly on the ^{22}Ne+α rates.

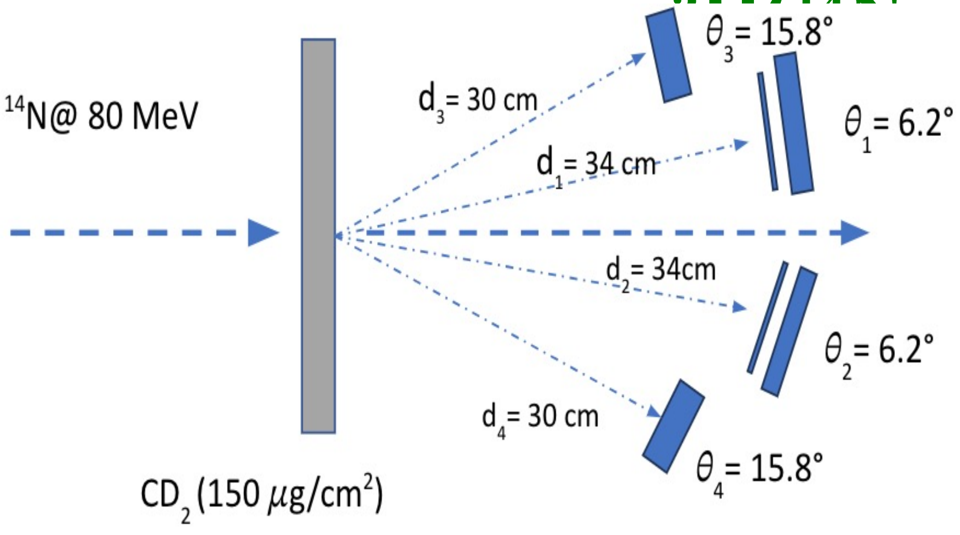


- **type Ia** supernovae

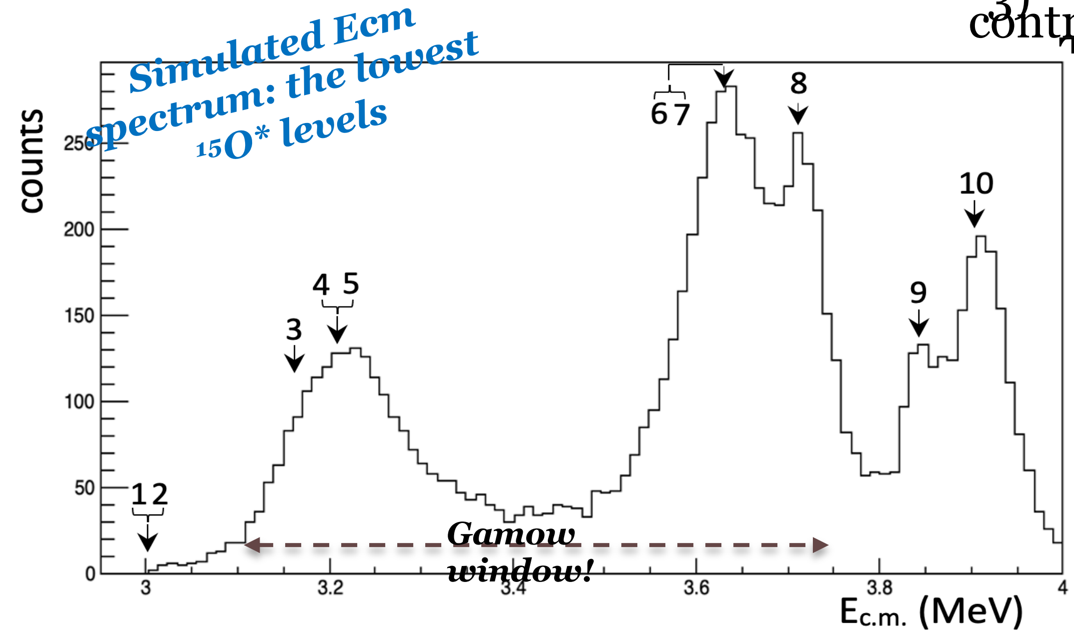
[Piro and Bildsten et al.]
"simmering" stage (1000 years prior to the explosion) n from ^{22}Ne(α,n)^{25}Mg affect C-abundance, thus altering the amount of ^{56}Ni produced (i.e., the **peak luminosity**) in the explosion.

[Timmes et al.]
during the explosion, n from ^{22}Ne(α,n)^{25}Mg affect the electron mole fraction, Ye → influencing the nature of the explosion.

The $^{14}N(p,\alpha)^{11}C$ reaction via THM applied to the QF $^{2}H(^{14}N,\alpha\,^{11}C)n$



$T_{1(2)}$→ ΔE(20μm, SSD)+E(1000μm, DSSSD)



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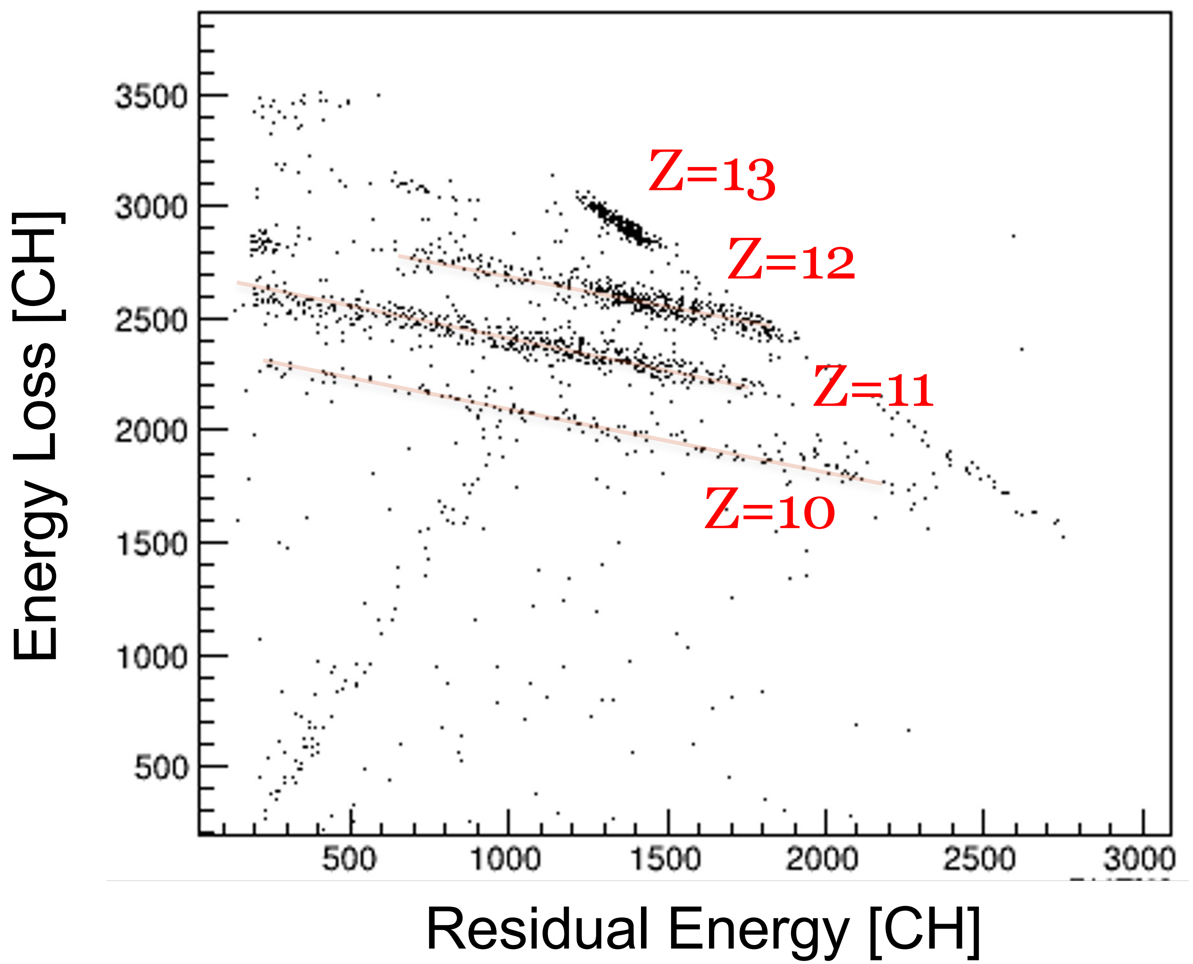
➢ At lower angles (~ 3°), maximum elastic contribution at ~1.5 KHz with 10^9 pps;

- We explore the energy region in which **^{15}O excited levels** influencing the $^{11}C(\alpha,p)^{14}N$ cross section are populated (E_x=10.290-11.218 MeV) at QF conditions.
- We have a pixel definition of 1.6x1.6mm² (32 strips DSSSD), an angular resolution of ~0.27° is expected

→ 40-60 keV's in E_{cm}.

ADONIS: Aluminum DestructiON in Stars

One pixel 3x3 mm², 24h statistics



Measurement of the neutron-induced reaction cross sections in core-collapse supernovae

Four channels:

^{26}Al(n,p)^{26}Mg gs and 1st excited

^{26}Al(n,α)^{23}Na gs and 1st excited

We use deuteron to transfer a neutron and induce the reaction of interest

We observe both the Mg and Na channels

Essentially no contamination in the beam (except 1/1000 ^{26}Al isomeric state)