Direct measurement of (*α*,*p*) cross sections for the CENS *αp*-explorer project

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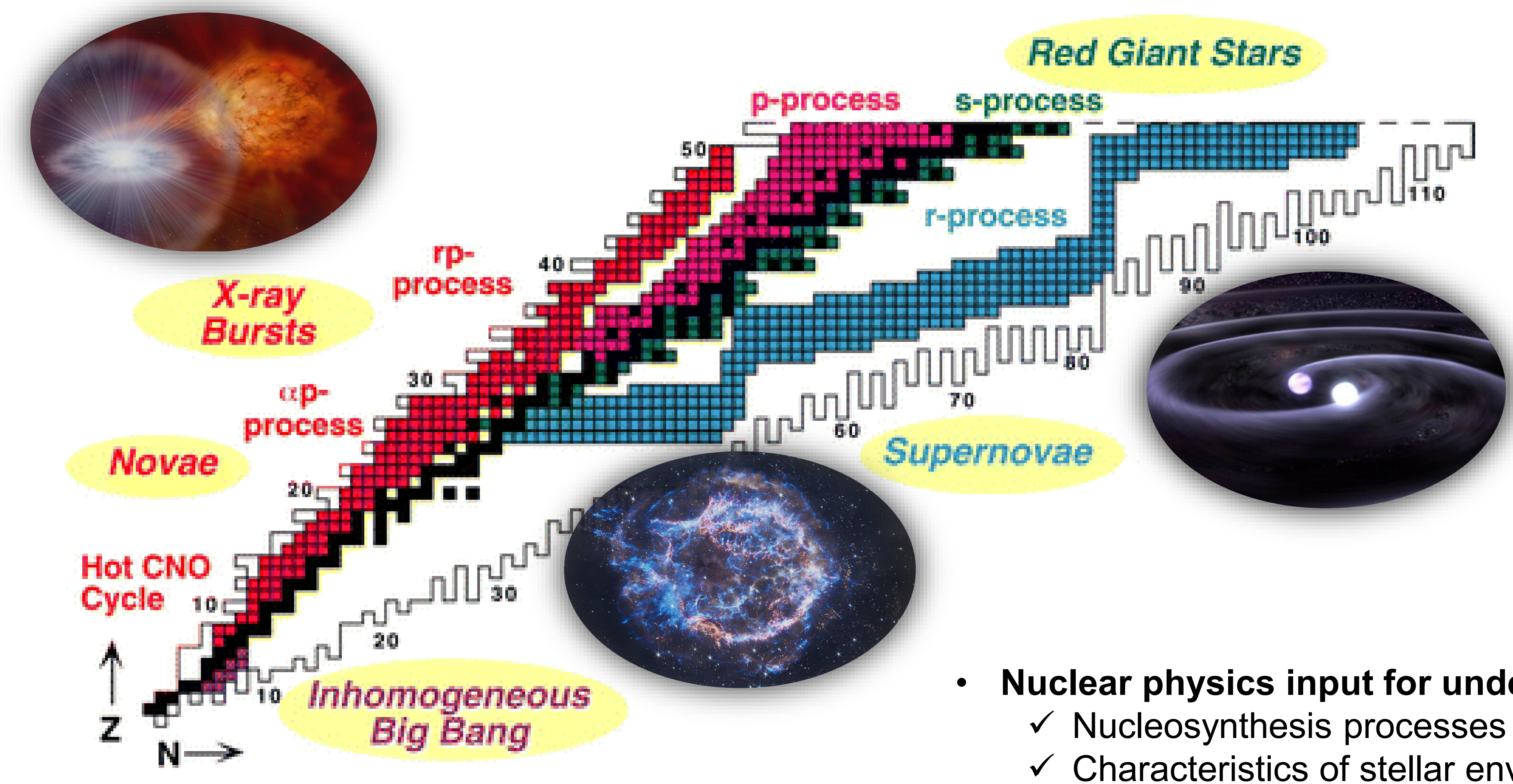
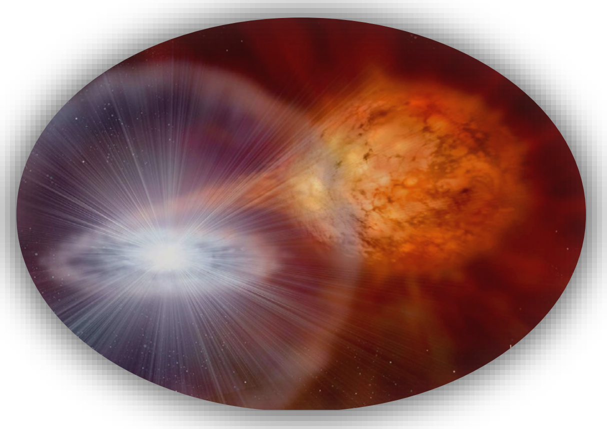
Origin of Elements: Nucleosynthesis during the stellar evolution

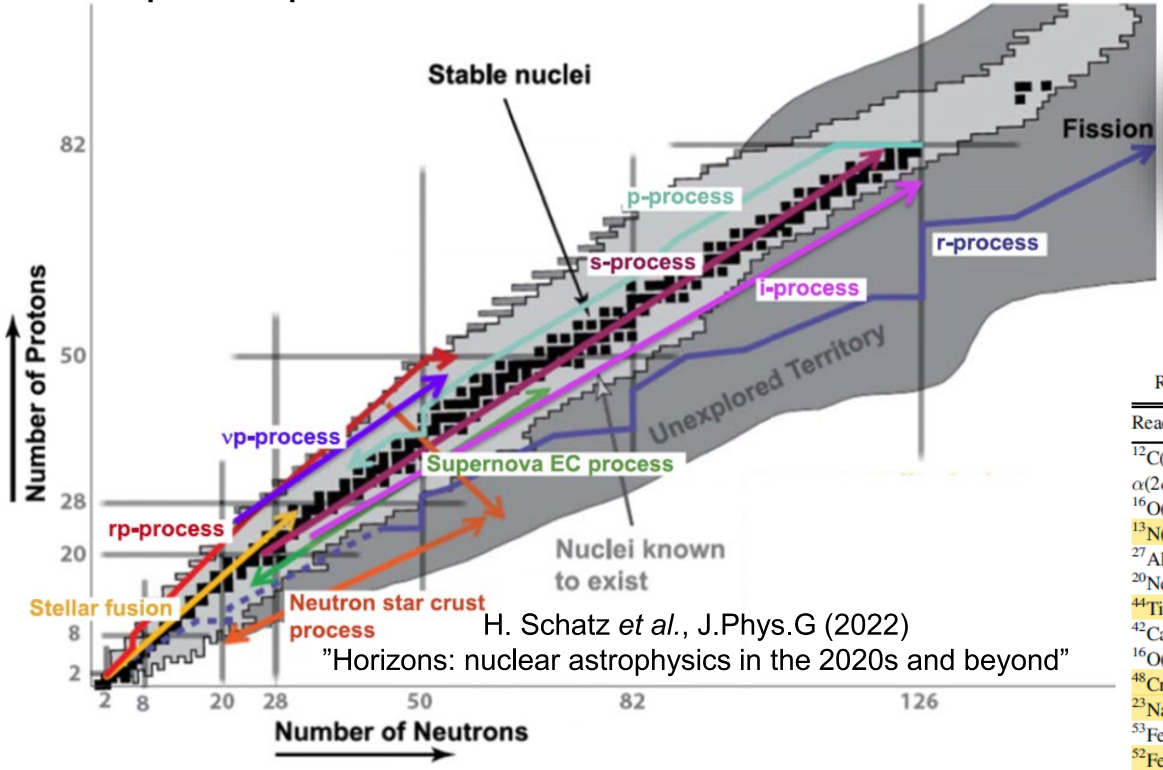


- **Nuclear physics input for understanding:**
  - ✓ Nucleosynthesis processes
  - ✓ Characteristics of stellar environments
- Mass, Lifetime, Level structure, Reaction rate, …

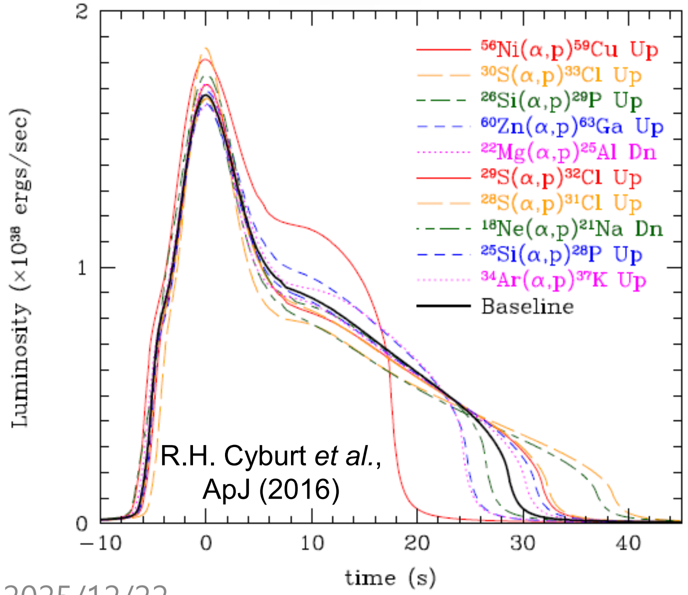
Importance of (*α,p*) reactions for astrophysics

- **(*α,p*) reaction rates play an important role in understanding:**
  - ✓ Light curve, burst ashes of the X-ray burst
  - ✓ Nucleosynthesis in the core-collapse supernovae





H. Schatz *et al.*, J.Phys.G (2022)
"Horizons: nuclear astrophysics in the 2020s and beyond"



R.H. Cyburt *et al.*, ApJ (2016)

Very small reaction cross sections
→ Challenging experiments!

Reaction Rate Variations that Affect Three or More Isotopes of Interest

Reaction	Number of Isotopes Affected
^{12}C(α,γ)^{16}O	8
α(2α,γ)^{12}C	8
^{16}O(^{12}C,p)^{27}Al	8
^{13}N(α,p)^{16}O	7
^{27}Al(α,n)^{30}P	6
^{20}Ne(α,γ)^{24}Mg	6
^{44}Ti(α,p)^{47}V	5
^{42}Ca(α,γ)^{46}Ti	5
^{16}O(^{12}C,α)^{24}Mg	5
^{48}Cr(α,p)^{51}Mn	4
^{23}Na(α,p)^{26}Mg	4
^{53}Fe(n,p)^{53}Mn	3
^{52}Fe(α,p)^{55}Co	3
^{33}S(n,α)^{30}Si	3
^{30}Si(p,γ)^{31}P	3
^{28}Si(n,γ)^{29}Si	3
^{28}Al(p,α)^{25}Mg	3
^{27}Si(n,^{12}C)^{16}O	3
^{27}Al(α,p)^{30}Si	3
^{26}Mg(α,n)^{29}Si	3
^{25}Mg(p,γ)^{26}Al	3
^{25}Mg(n,γ)^{26}Mg	3
^{25}Mg(α,n)^{28}Si	3

K. Hermansen *et al.*, ApJ (2020)

CENS *αp*- explore project

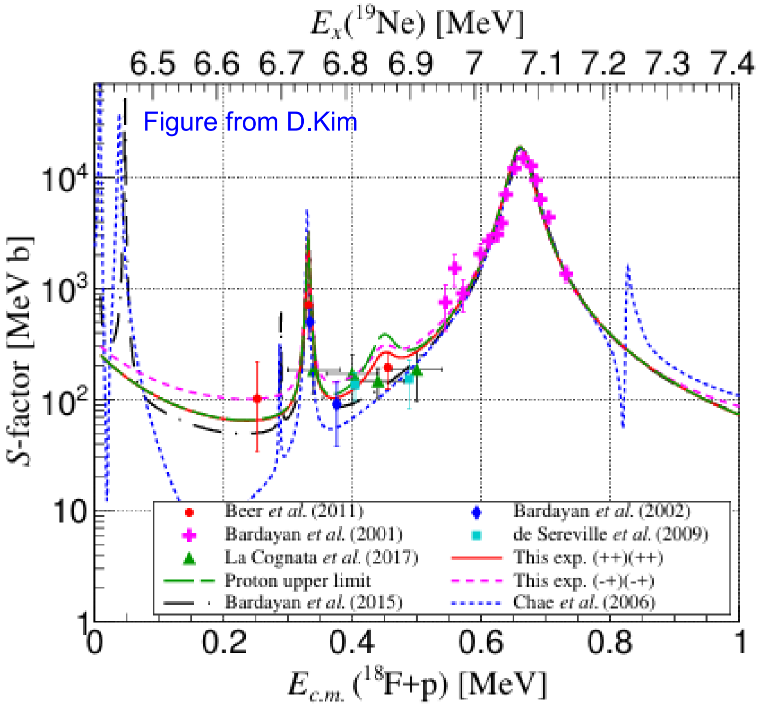
- **Key Research Question:**
  - ✓ Measurements of key nuclear reaction cross sections which are important for *αp*- and *rp*-processes.

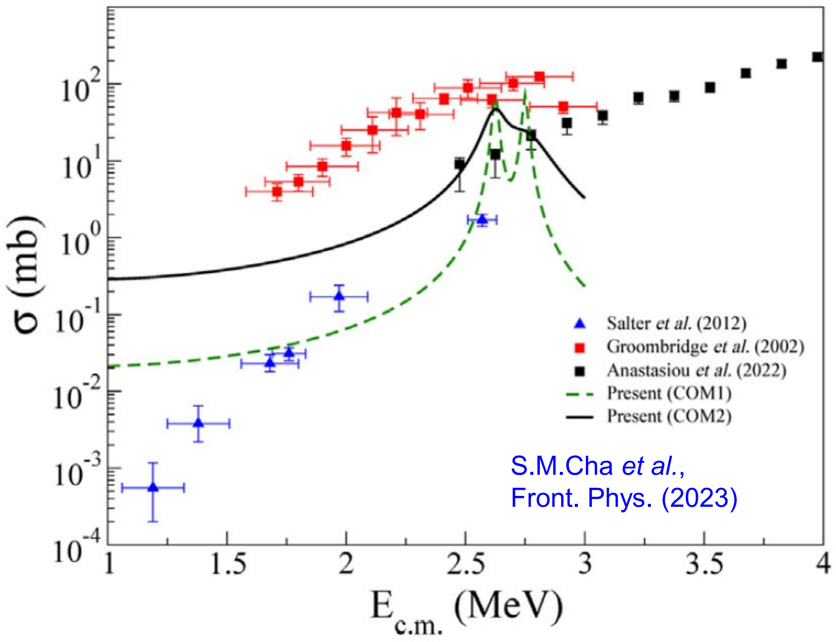
- **Methods:**
  - ✓ Indirect measurements of key reactions
    - Elastic resonant scatterings: ^{15}O+α, ^{18}Ne+α and ^{26}Si+α at CRIB
    - Transfer reactions: ^{27}Al(p,t)^{25}Al and ^{19}F(p,t)^{17}F at JAEA
    - Charged-particle decay: ^{20}Mg($\beta p\alpha$)^{15}O, ^{60}Ga($\beta^{+}p$)^{59}Cu & ^{60}Ga($\beta^{+}\alpha$)^{56}Ni at FRIB

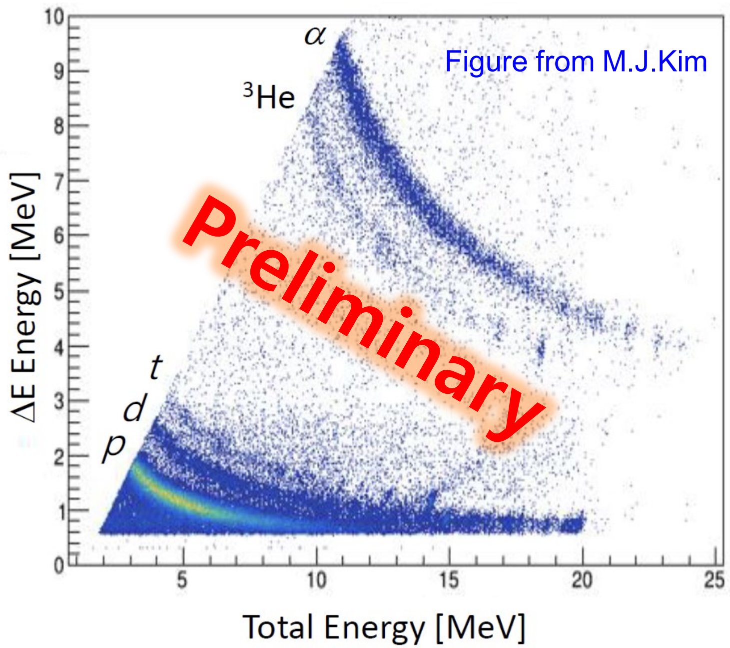
D.Kim *et al.*, submitted to PLB
S.M.Cha *et al.*, Front. Phys. (2023)
M.J.Kim *et al.*, in preparation

M.J.Kim *et al.*, in preparation
S.H.Kim *et al.*, in preparation

T.Wheeler *et al.*, NIMA (2025)
C.Wrede *et al.*, in preparation





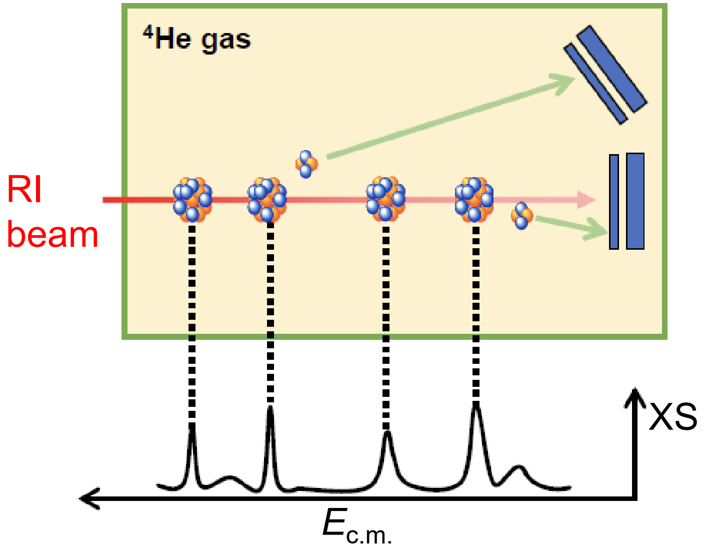


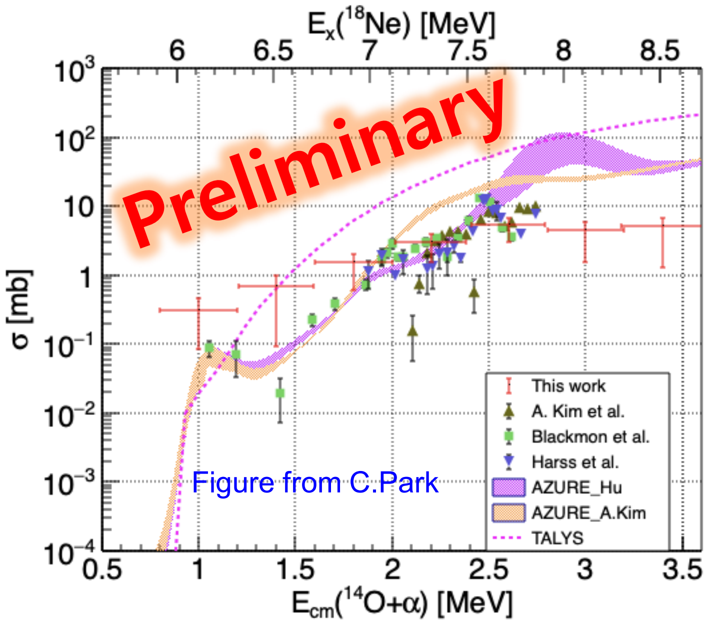
CENS *αp*- explore project

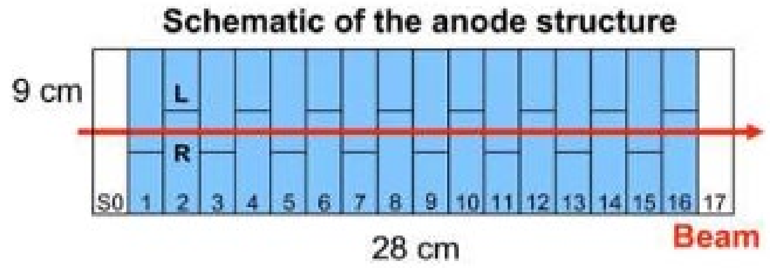
- **Key Research Question:**
  - ✓ Measurements of key nuclear reaction cross sections which are important for *αp*- and *rp*-processes.

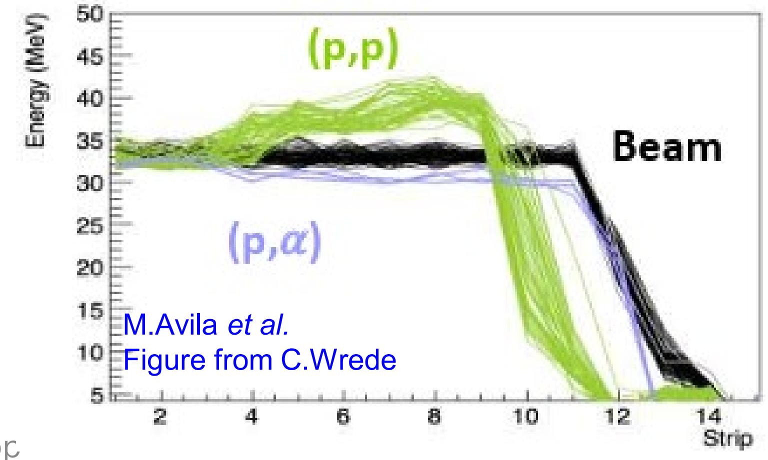
- **Methods:**
  - ✓ Direct measurements of important (*α,p*) and (*p,α*) reactions by the thick target method in inverse kinematics
    - ^{13}N(*α,p*)^{16}O, ^{14}O(*α,p*)^{17}F, ^{34}Ar(*α,p*)^{37}K, and ^{17}F(*α,p*)^{20}Ne at CRIB
    - ^{59}Cu(p,*α*)^{56}Ni at FRIB

A.Psaltis *et al.*, in preparation
C.Park *et al.*, in preparation
A.Kim *et al.*, approved
S.M.Cha *et al.*, approved
E.S. Lopez *et al.*, submit to PRL









Device for CENS *αp*- explore project

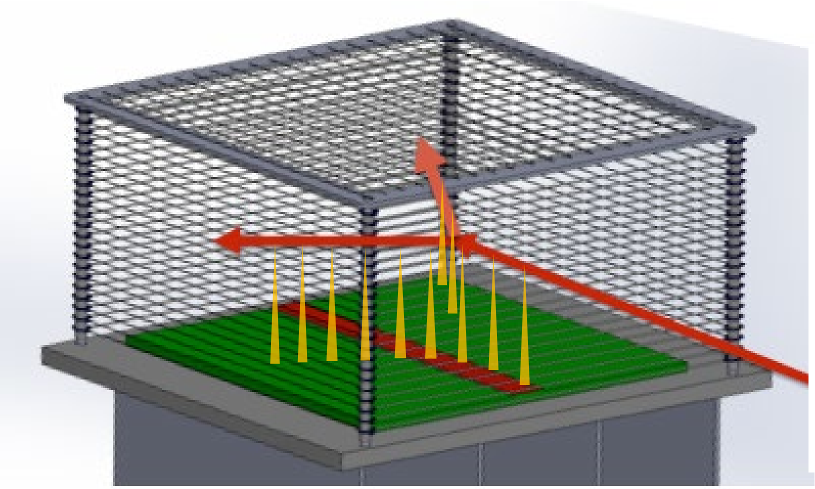
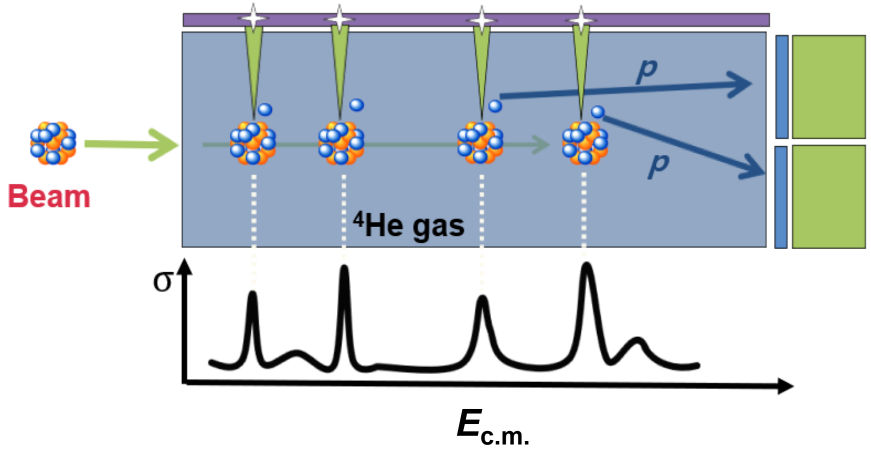
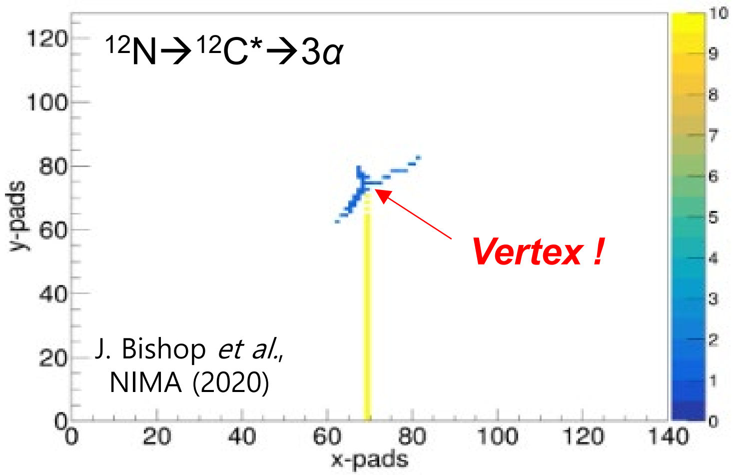


Figure from G.V. Rogachev





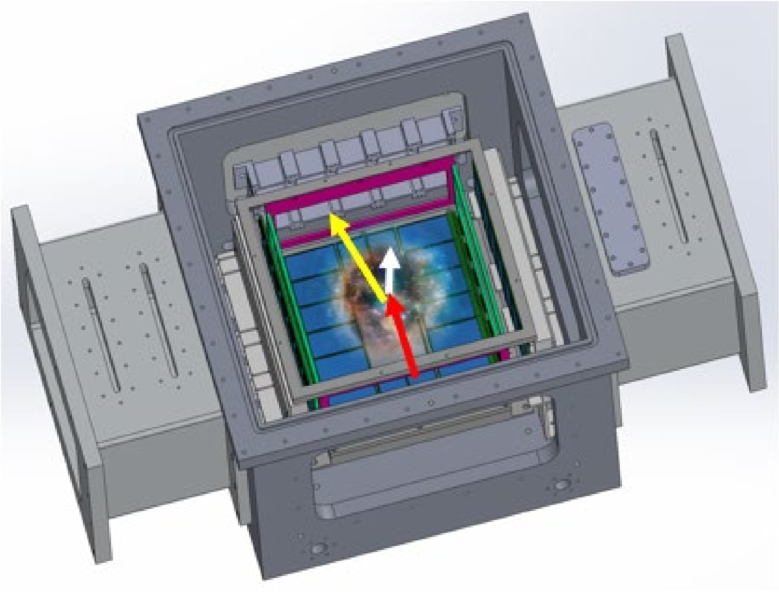
- **Active target Time Projection Chamber**
  - ✓ Detection gas plays as a reaction target
  - ✓ 3D tracking of charged particles (like 3D camera) → reaction vertex measurement available

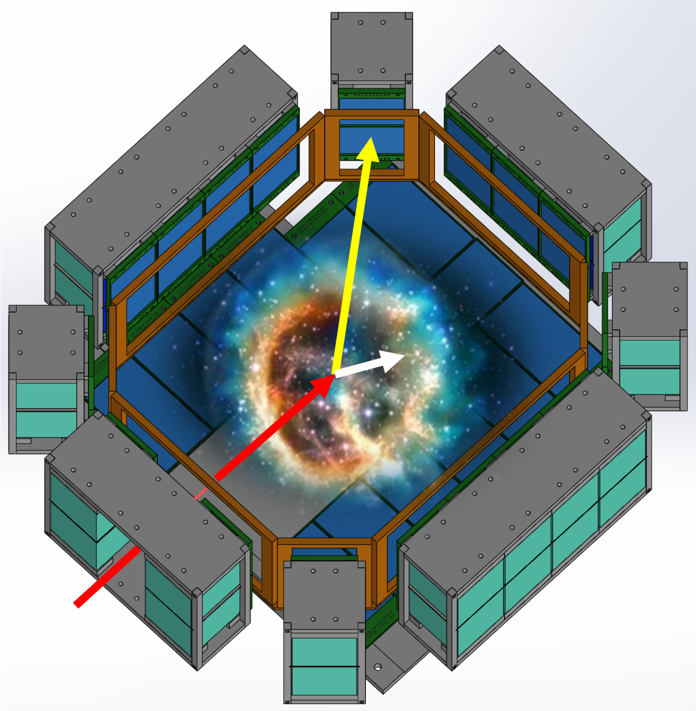
  → state-of-the-art device for experiments adopting the thick target method in inverse kinematics

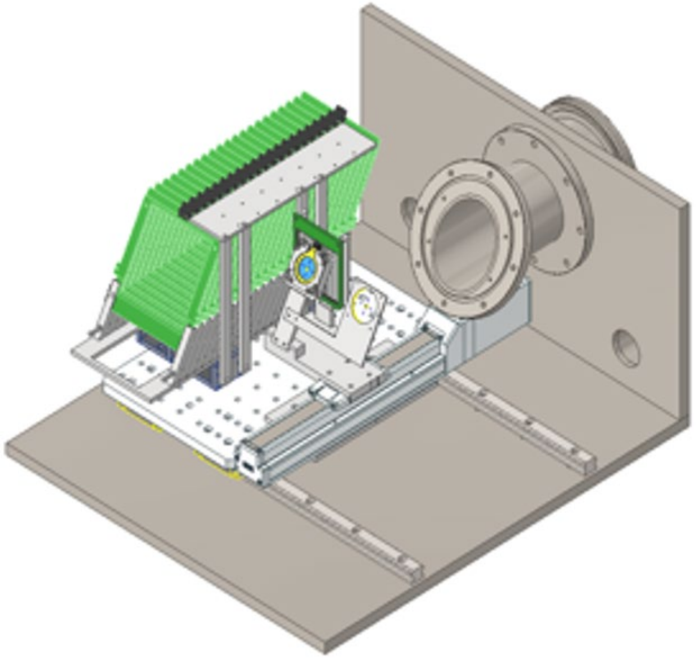
- **Challenges for direct (*α,p*) measurements**
  - ✓ High detection efficiency
  - ✓ High beam rate endurable (~10^5 pps)
  - ✓ Good enough position and energy resolution

Advanced AT-TPC Required !

Active Target detectors at CENS







TexAT_v2

- ✓ Upgraded Texas Active Target TPC (TexAT)
- ✓ Successfully used for the $^{14}O(\alpha,p)^{17}F$ measurement at CRIB

AToM-X

New device under the development!

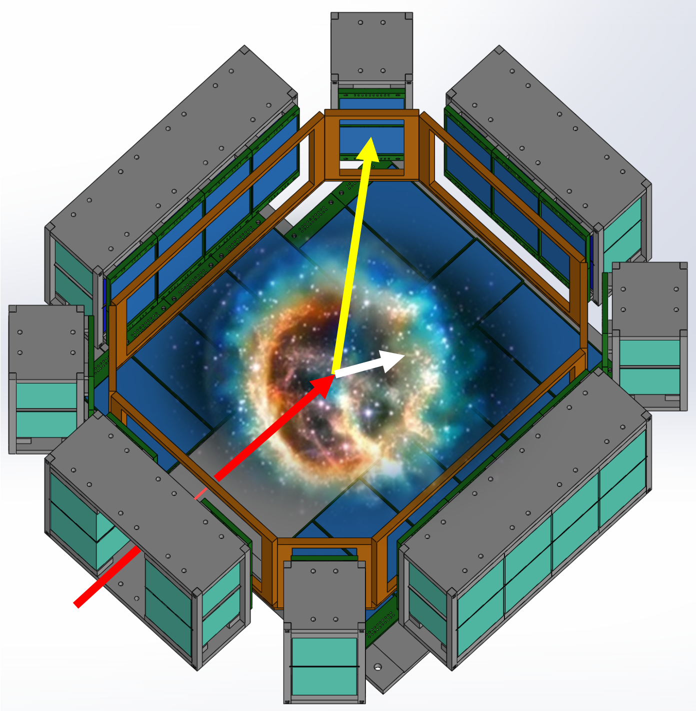
VOICE

New device
under the development

Active Target detectors at CENS

TexAT_v2

- ✓ Upgraded Texas Active Target TPC (TexAT)
- ✓ Successfully used for the $^{14}O(\alpha,p)^{17}F$ measurement at CRIB



AToM-X

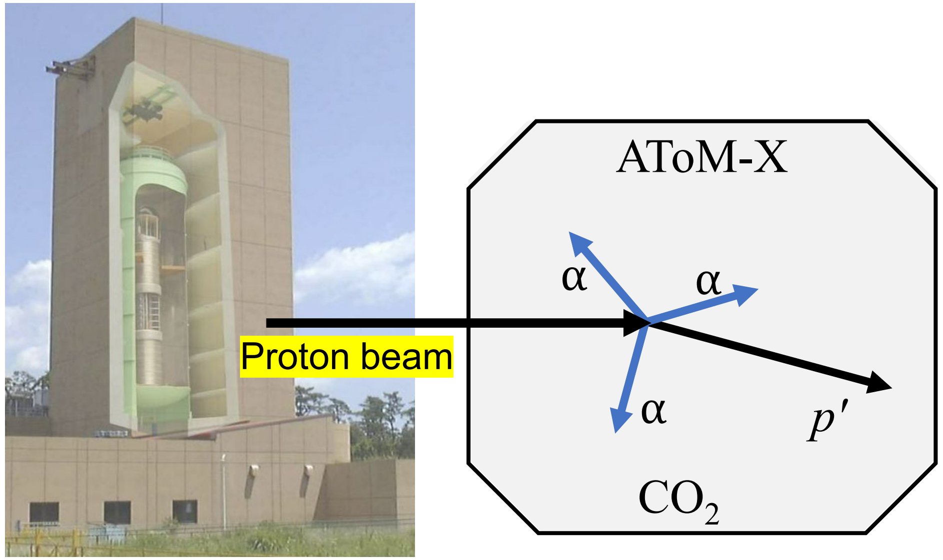
New device
under the development!

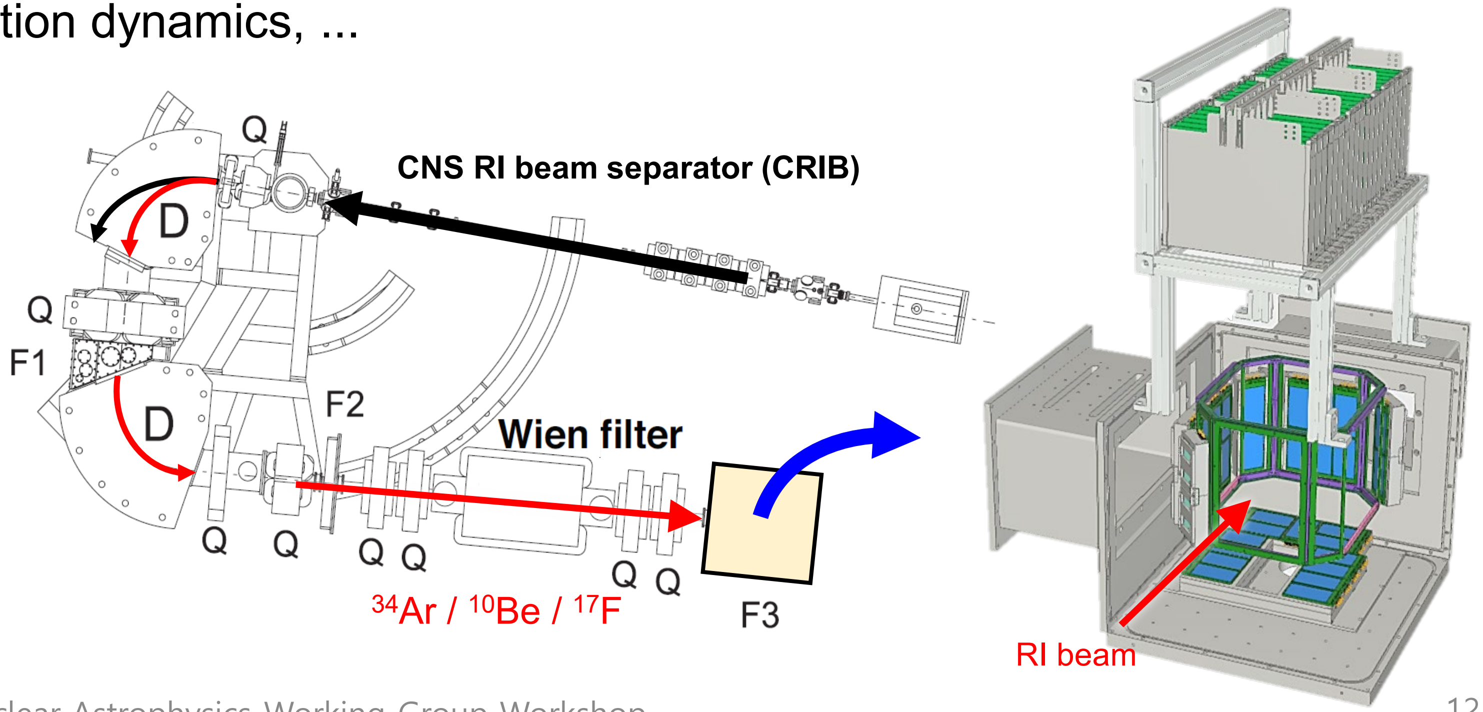
VOICE

New device
under the development

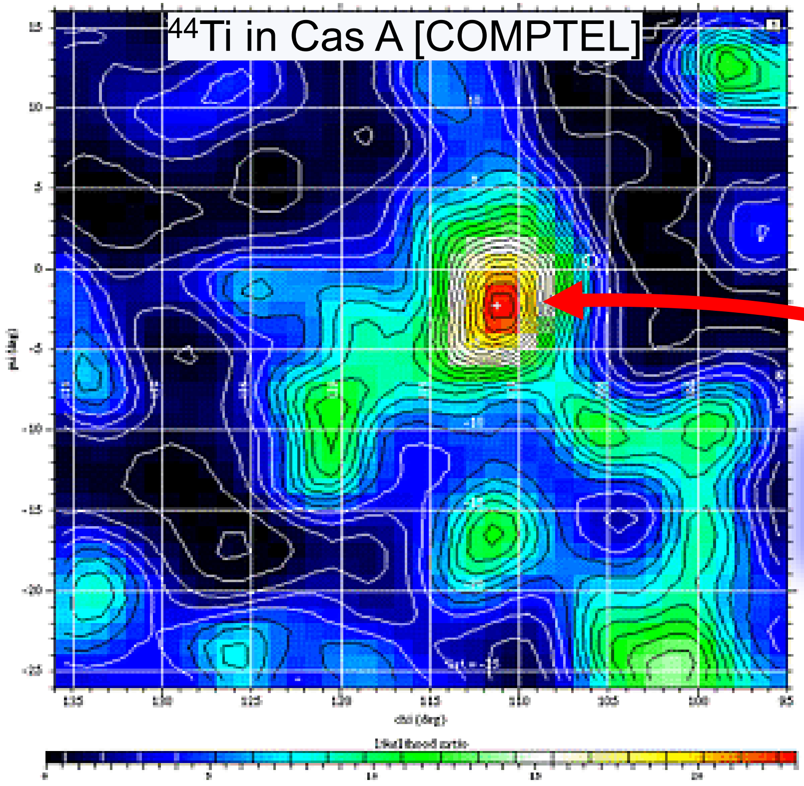
Physics plans with AToM-X

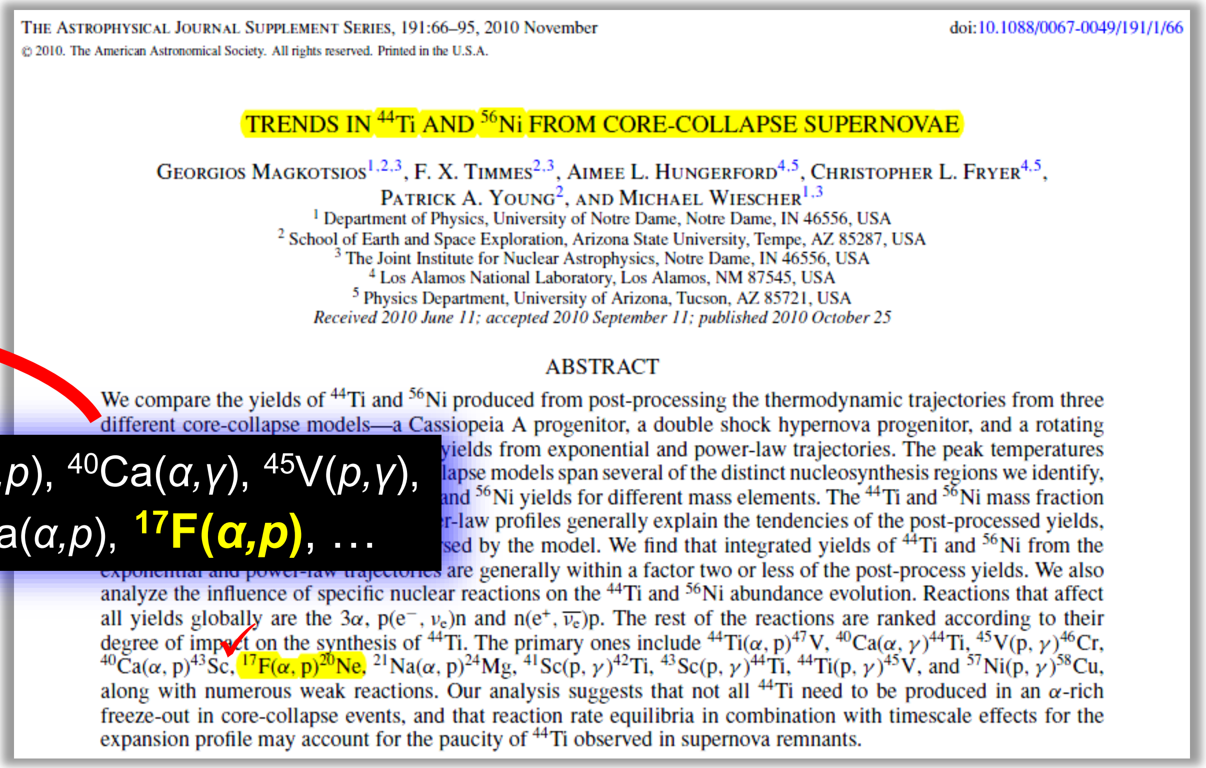
- **(α,p) reactions impact on XRB / Reactions for the *rp*- and *αp*-process**
  - ✓ ^{17}F(α,p)^{20}Ne ✓**Approved** (S.M.Cha *et al.*, CRIB+AToM-X)
  - ✓ ^{34}Ar(α,p)^{37}K ✓**Approved** (A.Kim *et al.*, CRIB+AToM-X)
- **Other astrophysically important reactions**
  - ✓ ^{10}Be(p,α)^{7}Li ✓**Approved** (M.J.Kim *et al.*, CRIB+AToM-X)
  - ✓ ^{12}C(p,p')3α ✓**Approved** (J.W. Lee *et al.*, JAEA+AToM-X)
  - ✓ Indirect measurements : resonant scatterings, transfer reactions, ...
- **And various nuclear reactions!**
  - ✓ fusion reactions for understanding reaction dynamics, ...





Production of ^{44}Ti in the core-collapse supernovae




THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 191:66–95, 2010 November doi:10.1088/0067-0049/191/1/66

TRENDS IN ^{44}Ti AND ^{56}Ni FROM CORE-COLLAPSE SUPERNOVAE

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ABSTRACT

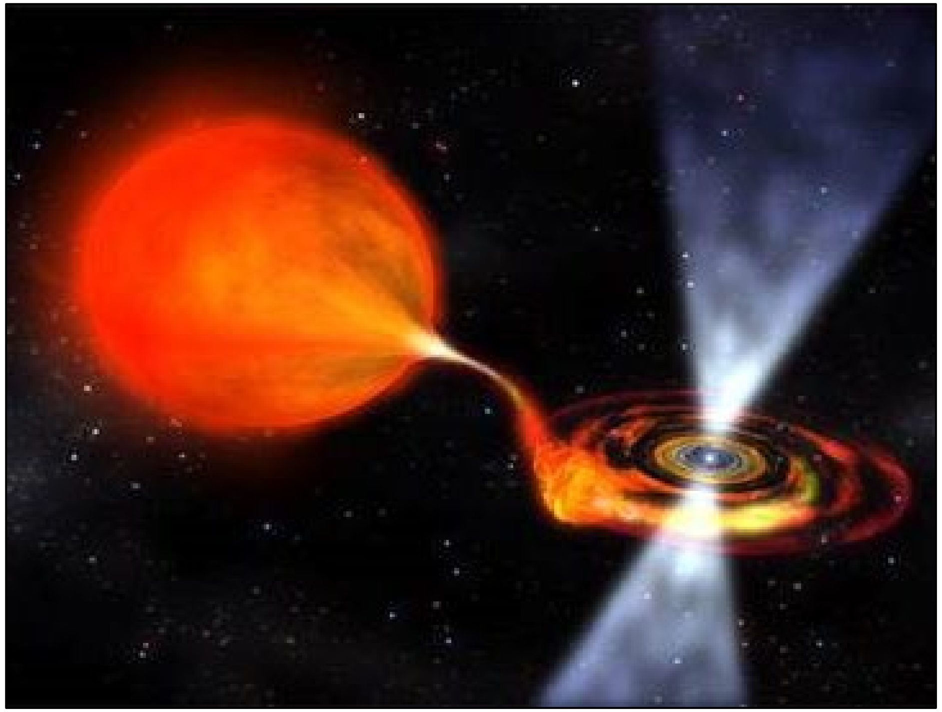
We compare the yields of ^{44}Ti and ^{56}Ni produced from post-processing the thermodynamic trajectories from three different core-collapse models—a Cassiopeia A progenitor, a double shock hypernova progenitor, and a rotating ... yields from exponential and power-law trajectories. The peak temperatures ... lapse models span several of the distinct nucleosynthesis regions we identify, ... and ^{56}Ni yields for different mass elements. The ^{44}Ti and ^{56}Ni mass fraction ... r-law profiles generally explain the tendencies of the post-processed yields, ... sed by the model. We find that integrated yields of ^{44}Ti and ^{56}Ni from the exponential and power-law trajectories are generally within a factor two or less of the post-process yields. We also analyze the influence of specific nuclear reactions on the ^{44}Ti and ^{56}Ni abundance evolution. Reactions that affect all yields globally are the 3α, p(e$^-$, ν_e)n and n(e$^+$, $\overline{\nu_e}$)p. The rest of the reactions are ranked according to their degree of impact on the synthesis of ^{44}Ti. The primary ones include ^{44}Ti(α, p)^{47}V, ^{40}Ca(α, γ)^{44}Ti, ^{45}V(p, γ)^{46}Cr, ^{40}Ca(α, p)^{43}Sc, ^{17}F(α, p)^{20}Ne, ^{21}Na(α, p)^{24}Mg, ^{41}Sc(p, γ)^{42}Ti, ^{43}Sc(p, γ)^{44}Ti, ^{44}Ti(p, γ)^{45}V, and ^{57}Ni(p, γ)^{58}Cu, along with numerous weak reactions. Our analysis suggests that not all ^{44}Ti need to be produced in an α-rich freeze-out in core-collapse events, and that reaction rate equilibria in combination with timescale effects for the expansion profile may account for the paucity of ^{44}Ti observed in supernova remnants.

^{44}Ti(α,p), ^{40}Ca(α,γ), ^{45}V(p,γ), ^{40}Ca(α,p), **^{17}F(α,p)**, …

- ^{44}Ti : ideal probe for constraining the explosion mechanism (T, ρ, mass cut…)
- 1.157 MeV γ-ray emitter ($t_{1/2}$ = 59.1 y) → can be observed.
- synthesized amount : observations > model prediction P. A. Young *et al.*, ApJ (2006)
- Sensitivity study shows that ^{17}F(α,p)^{20}Ne reaction rate significantly impacts the ^{44}Ti abundance.

G. Magkotsios *et al.*, ApJS (2010)

X-ray burst light curves and burst ashes



Rank	Reaction
1	^{15}O(α, γ)^{19}Ne
2	^{56}Ni(α, p)^{59}Cu
3	^{59}Cu(p, γ)^{60}Zn
4	^{61}Ga(p, γ)^{62}Ge
5	^{22}Mg(α, p)^{25}Al
6	^{14}O(α, p)^{17}F
7	^{23}Al(p, γ)^{24}Si
8	^{18}Ne(α, p)^{21}Na
9	^{63}Ga(p, γ)^{64}Ge
10	^{19}F(p, α)^{16}O
11	^{12}C(α, γ)^{16}O
12	^{26}Si(α, p)^{29}P
13	^{17}F(α, p)^{20}Ne ✓
14	^{24}Mg(α, γ)^{28}Si
15	^{57}Cu(p, γ)^{58}Zn
16	^{60}Zn(α, p)^{63}Ga
17	^{17}F(p, γ)^{18}Ne
18	^{40}Sc(p, γ)^{41}Ti
19	^{48}Cr(p, γ)^{49}Mn

Count	Reaction
1	^{12}C(p, γ)^{13}N
2	^{15}O(α, γ)^{19}Ne[a]
3	^{16}O(α, γ)^{20}Ne[a]
4	^{17}F(α, p)^{20}Ne[a] ✓
5	^{17}F(p, γ)^{18}Ne[a]
6	^{18}F(α, p)^{21}Ne[a]
7	^{18}Ne(α, p)^{21}Na[a]
8	^{20}Ne(α, γ)^{24}Mg[a]
9	^{22}Na(α, p)^{25}Mg[a]
10	^{22}Na(p, γ)^{23}Mg[a]
11	^{22}Mg(α, p)^{25}Al[a]
12	^{23}Mg(p, γ)^{24}Al
13	^{23}Al(p, γ)^{24}Si[a]
14	^{24}Al(p, γ)^{25}Si
15	^{26}Al(p, γ)^{27}Si[a]
16	^{26}Si(α, p)^{29}P[a]
17	^{27}Si(p, γ)^{28}P[a]
18	^{28}Si(p, γ)^{29}P
19	^{27}P(p, γ)^{28}S[a]

Count	Reaction
1	^{8}Be(α, γ)^{12}C
2	^{12}C(α, γ)^{16}O
3	^{14}O(α, p)^{17}F
4	^{15}O(α, γ)^{19}Ne
5	^{16}O(α, p)^{19}F
6	^{17}F(α, p)^{20}Ne ✓
7	^{18}Ne(α, p)^{21}Na
8	^{22}Mg(α, p)^{25}Al
9	^{23}Mg(α, p)^{26}Al
10	^{24}Mg(α, γ)^{28}Si
11	^{23}Al(p, γ)^{24}Si
12	^{26}Al(α, p)^{29}Si
13	^{29}P(p, γ)^{30}S
14	^{40}Sc(p, γ)^{41}Ti
15	^{45}V(p, γ)^{46}Cr
16	^{47}Cr(p, γ)^{48}Mn
17	^{48}Cr(p, γ)^{49}Mn
18	^{49}Cr(p, γ)^{50}Mn
19	^{47}Mn(p, γ)^{48}Fe

- Sensitivity study to find important reaction rates that affect the characteristics of X-ray bursts
  - ✓ By changing a set of 1931 reaction rates by a factor of 10
  - ✓ Ranked the most influential nuclear reactions

R. H. Cyburt *et al.*, ApJ (2016)

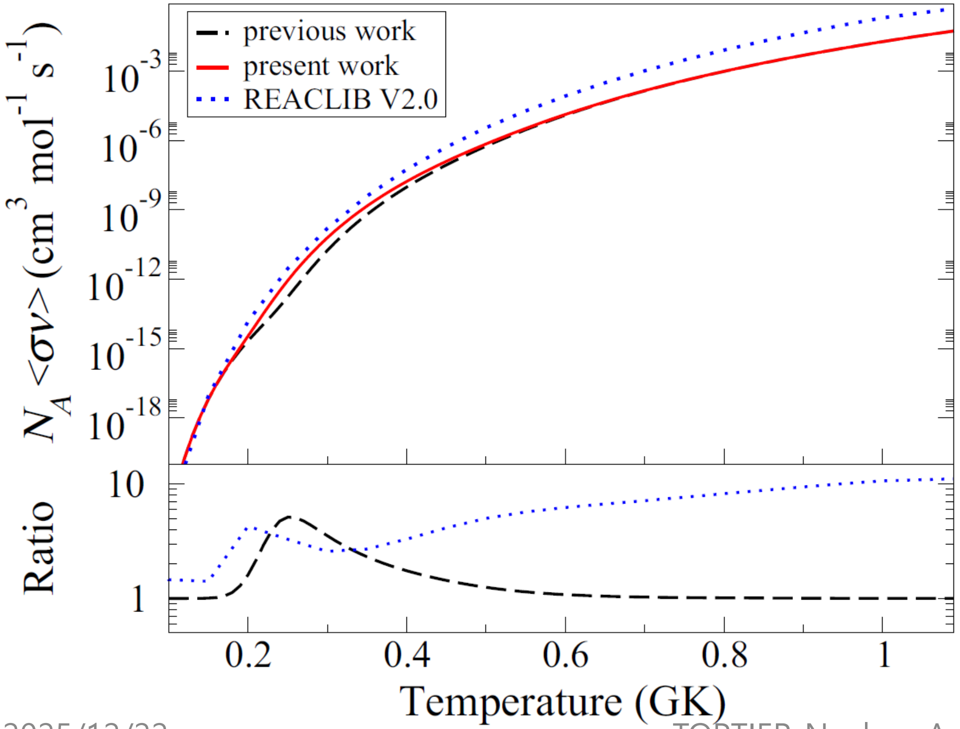
- ^{17}F(α,p)^{20}Ne reaction can lead to a significant effect both on the light curve and nucleosynthesis.

Previous indirect studies on $^{17}F(\alpha,p)^{20}Ne$ reaction

- $^{24}Mg(p,\alpha)^{21}Na$ measurement at ORNL
- $^{17}F(\alpha,p)^{20}Ne$ reaction rate obtained from ^{21}Na level properties
- Many resonance parameters estimated by theory

  → direct measurement required.

S. M. Cha *et al.*, PRC (2017)



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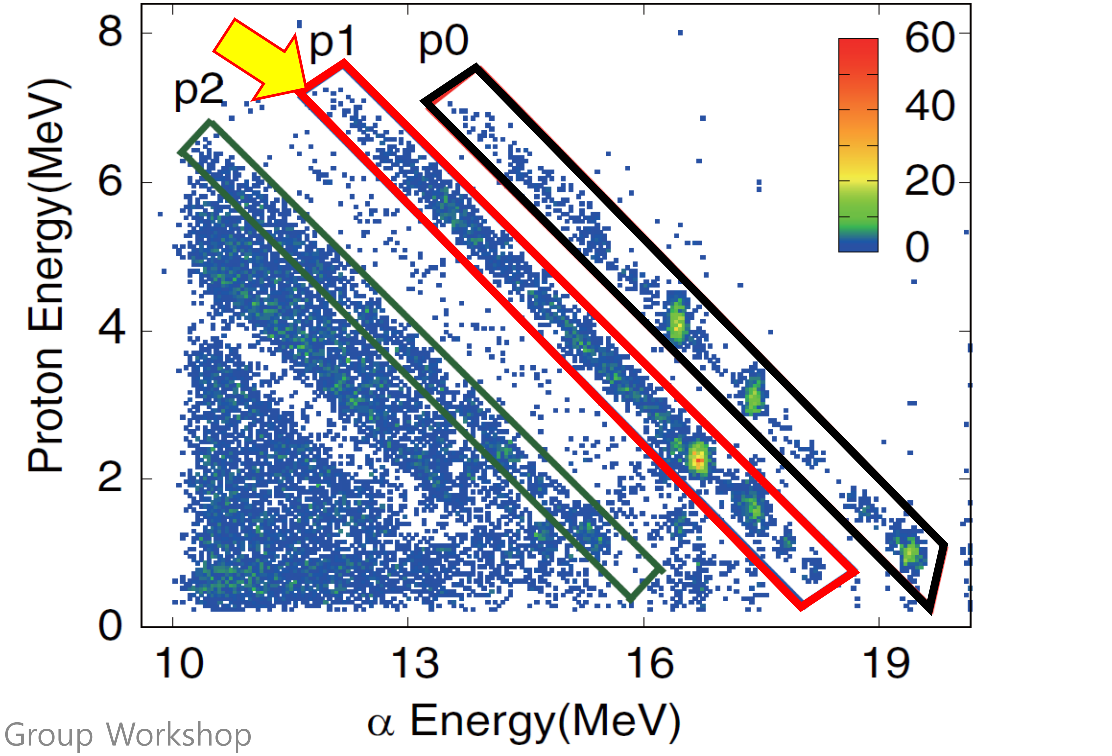
S. M. Cha *et al.*, PRC (2017)

- Follow-up study: ^{21}Na*(p)^{20}Ne* decay
- Large contributions from p_1 decay channels

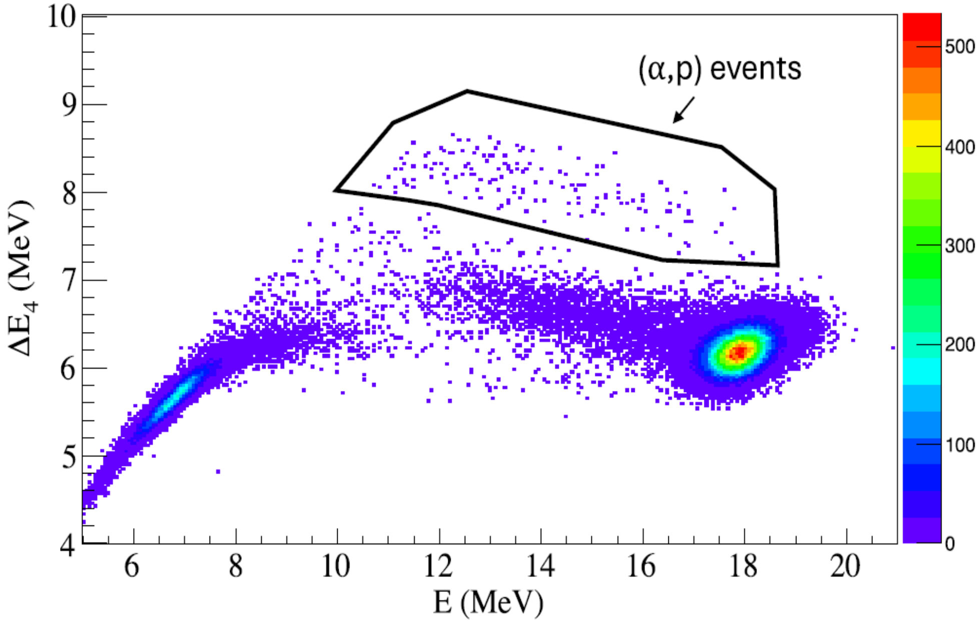
  Ex) $B_{p1} \sim 8B_{p0}$ for E_x = 7.132 MeV level in ^{21}Na
- However, p_1 channels not considered in previous sensitivity studies → underestimated !

M. J. Kim, S.M. Cha *et al.*, PRC (2021)



Direct measurement of $^{17}F(\alpha,p)^{20}Ne$ reaction cross section

- Previous study at ANL M. Avila *et al.*, NPA (2025)
  - ✓ ^{17}F beam rate only ~ 3000 cps
  - ✓ using MUSIC active target detector
  - ✓ Demonstrated the feasibility,
    but limited statistics
  - ✓ No cross section, No reaction rate obtained



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  - ✓ No cross section, No reaction rate obtained

- Our proposal
  - ✓ More Beam: ^{17}F beam at CRIB ~ 3×10^5 pps
  - ✓ Advanced active target detector (AToM-X)

Direct measurement of ^{17}F(α,p)^{20}Ne reaction cross section

- Previous study at ANL M. Avila *et al.*, NPA (2025)
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- Our proposal
  - ✓ More Beam: ^{17}F beam at CRIB ~ 3x10^5 pps
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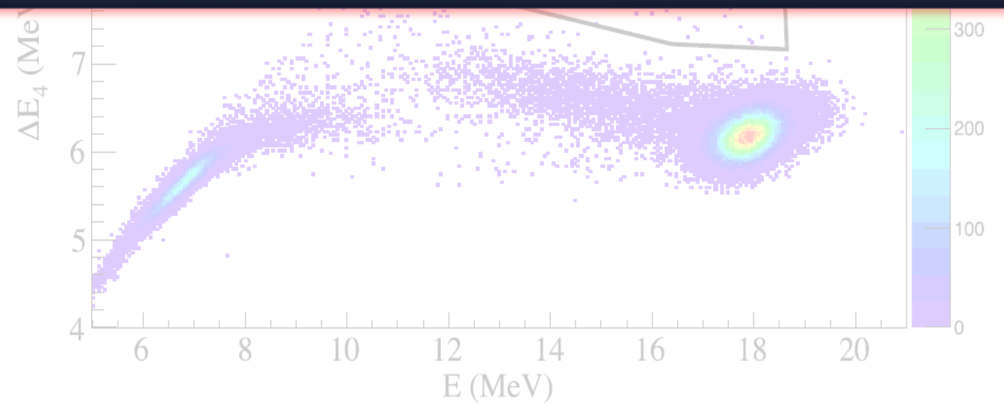
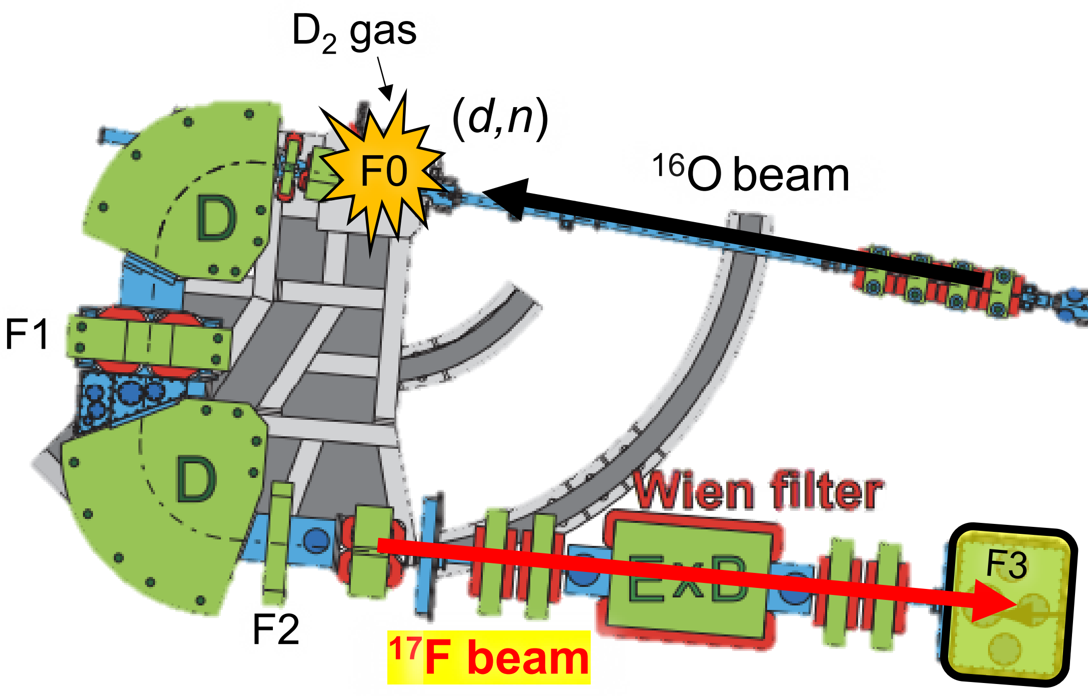
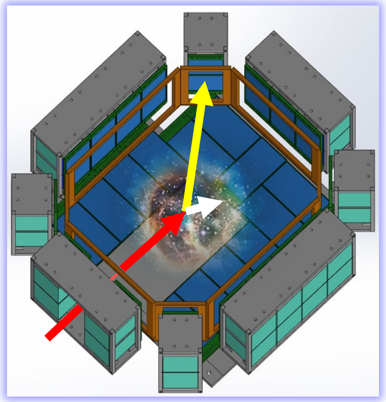
Direct experimental constraints on the ^{17}F(α,p)^{20}Ne reaction rate including the contribution from the p_1 reaction channel at $1 < T < 4$ GK region ($1.5 < E_{c.m.} < 4.5$ MeV)



^{17}F beam production



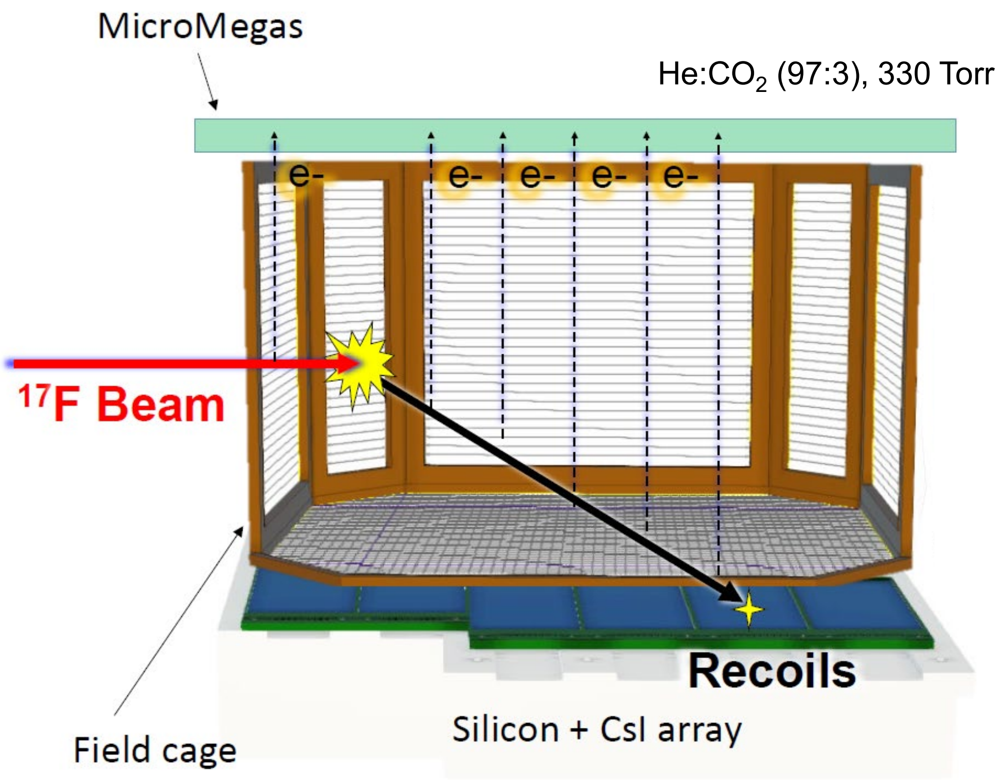


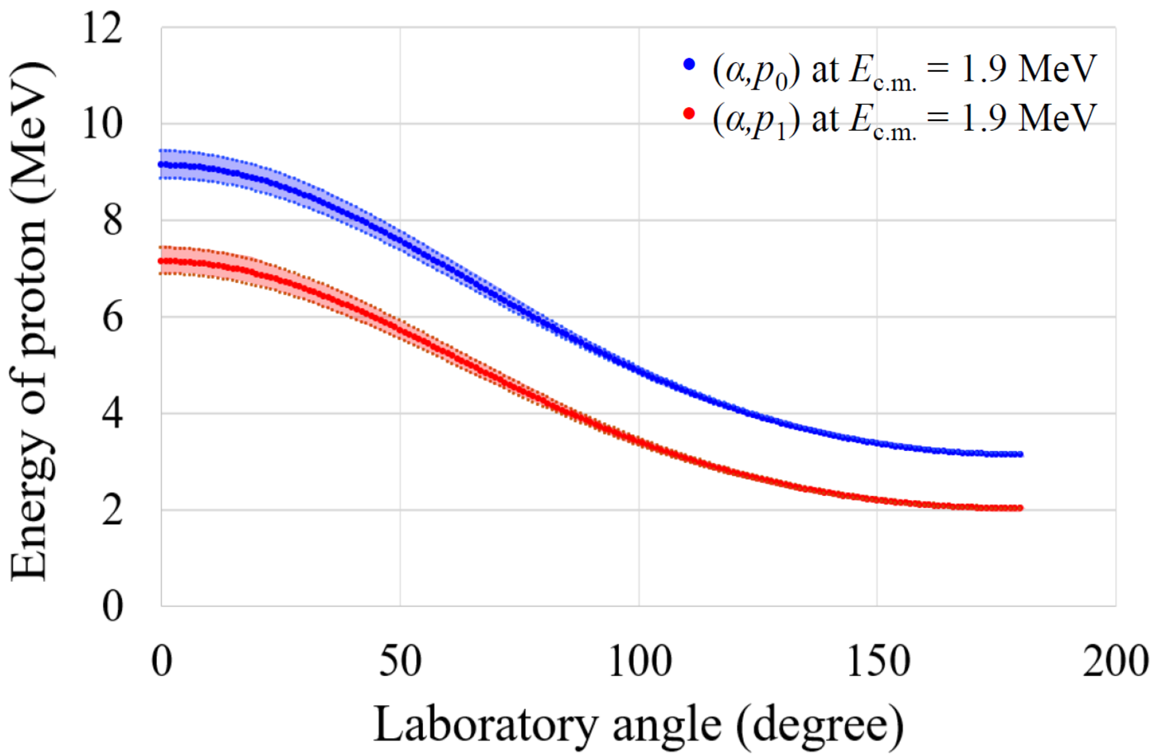
- via the ^{2}H(^{16}O,^{17}F)n reaction
- F3 PPACs for beam monitoring
  - ✓ intensity and purity of ^{17}F beam
  - ✓ separation of events available
- CRIB has produced high quality ^{17}F beams with similar conditions:
  - ✓ ^{17}F+^{58}Ni : PLB (2020), EPJA (2019)
  - ✓ ^{17}F(p,p)^{17}F : PRC (2014)
  - ✓ ^{17}F(^{12}C,^{12}C)^{17}F: EPJA (2012)

Primary beam	Energy	Intensity	Target
$^{16}O^{5+}$	6.27 MeV/u	330 pnA	D_2 (300 Torr, ~90K)
Secondary beam	**Energy**	**Intensity @ F3**	**Purity @ F3**
$^{17}F^{9+}$	2.8 MeV/u	~3 x 10^5 pps	> 80%

well-established !

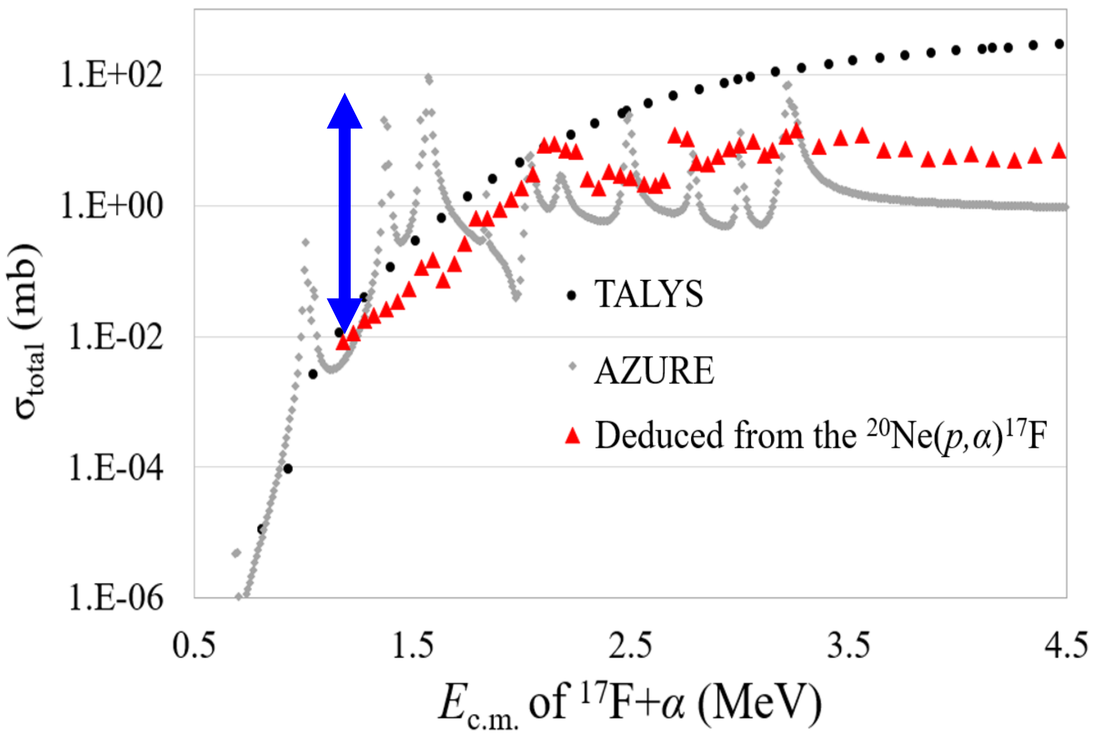
Experimental setup





- Active Target TPC for Multiple nuclear experiments (AToM-X) installed at F3
  - ✓ 3-dim. track reconstruction by the field cage + Micromegas
  - ✓ recoiling light charged particles (energy, position) measured by the Si+CsI array
  - ✓ Similar with two approved experiments by the RIBF NP-PAC : ^{34}Ar(α,p)^{37}K and ^{10}Be(p,α)^{7}Li
- p_0 and p_1 channel separation by the reaction vertex (angle) and energy information

Yield estimation



$E_{c.m.}$ (MeV)	σ (mb)	Expected Counts (/100keV)	Statistical Error (%)
1.5	0.15	23	21
1.9	1.26	180	9.1
2.7	3.6	540	4.3
4.3	5.9	820	3.5

*Estimated 14 days of production run

- Expected proton yields from ^{17}F(α,p_0)^{20}Ne taken from the ^{20}Ne(p,α)^{17}F cross sections
  - ✓ Reciprocity theorem & the fraction of the ^{20}Ne(p,α_1)^{17}F* for more reliable estimation

Need precise data!

- Estimation using TALYS and AZURE → XS at $E_{c.m}$~1.5 MeV could be factor of 10 – 10^4 different.
- High statistics of p_1 decay channels → anticipate comparable proton yields from ^{17}F(α,p_1)^{20}Ne* channel

Beam time request and Readiness

^{17}F beam production and AToM-X optimization ✓ 1 day for the beam production (Technical review) ✓ 1 day for optimization: gas pressure, gating grid, DAQ, ...	2 days
Production run with He:CO_2 mixture gas	14 days
Background run with CO_2 gas	2 days
Total	**18 days**

Approved by RIBF PAC !

- Readiness
  - ✓ ^{17}F beam production at CRIB: already well established.
  - ✓ AToM-X construction: final stage of offline test using an α source
  - ✓ Commissioning experiment at JAEA scheduled early next year
  - ✓ Two approved experiments using AToM-X : NP2312-AVF76R1 and NP-2412-AVF81
    ^{34}Ar(α,p)^{37}K ^{10}Be(p,α)^{7}Li
  - ✓ Extensive experience with (α,p) measurement using ATTPC including ^{14}O(α,p)^{17}F at CRIB

List of Collaborators

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Background Image:
Courtesy of Paul Montague
“Neighbors”
Astronomy photographer of the year 2023