aluminum-26 nucleosynthesis with proton-rich exotic beams

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themes

rare isotopes in nuclear astrophysics: some examples

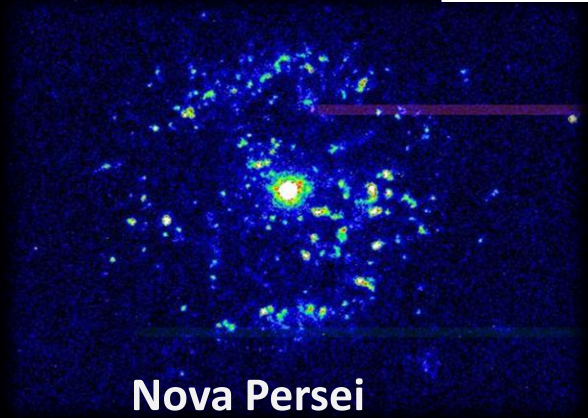
rare isotope beam production: ISOL and fragmentation

rare isotope beam facilities: TRIUMF and NSCL

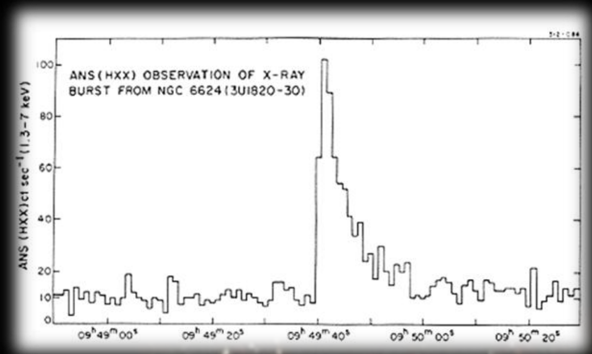
direct vs. indirect approaches

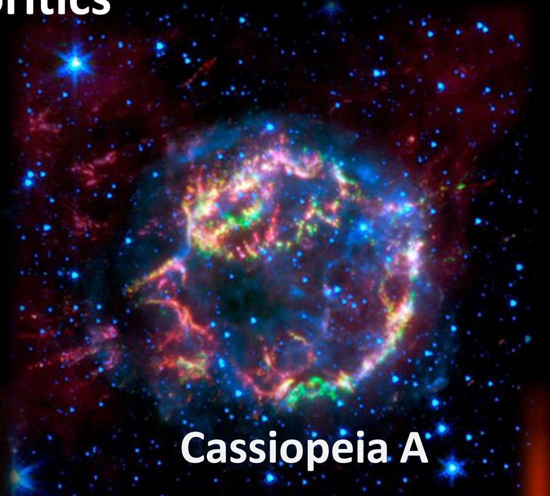
Explosive Stellar Nucleosynthesis

What: hydrogen/helium "burning", high temperature and density
Where: novae, x-ray bursts, supernovae
Tracers: abundances, gamma rays, meteoritics



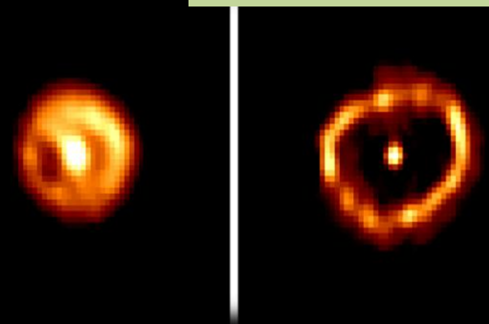
Nova Persei



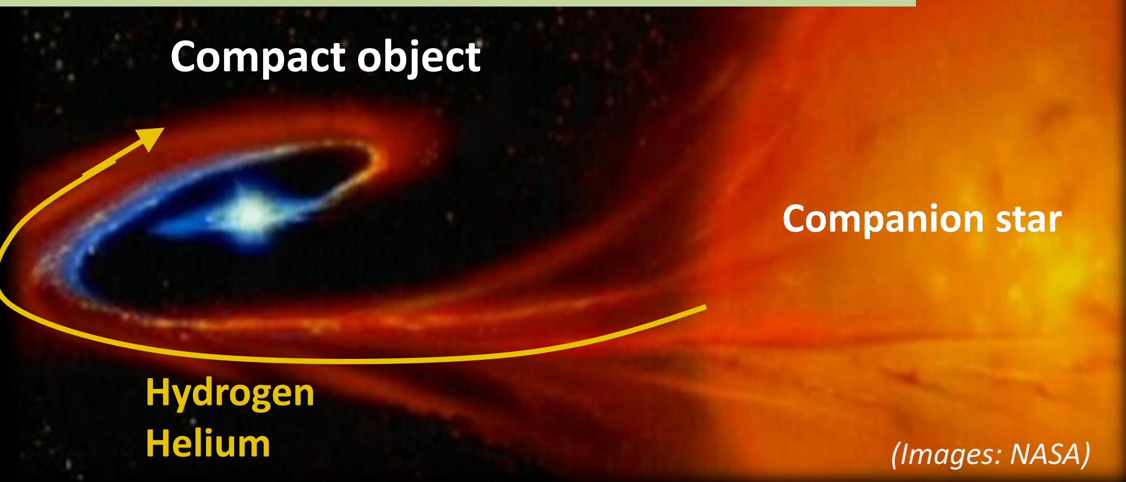


Cassiopeia A

Energy generation? Origin of the elements?

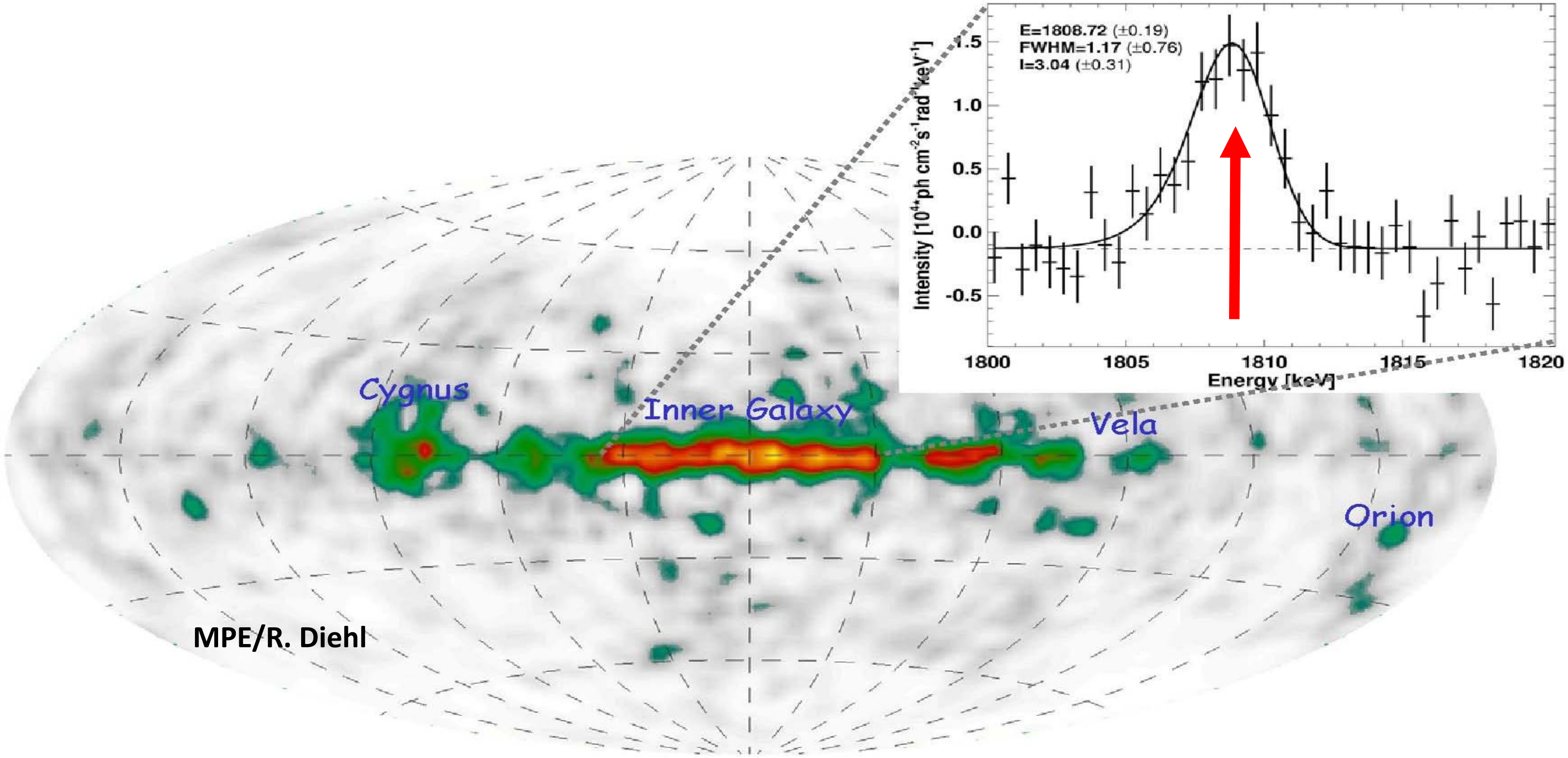


Nova Cygni



(Images: NASA)

^{26}Al in gamma-ray astronomy

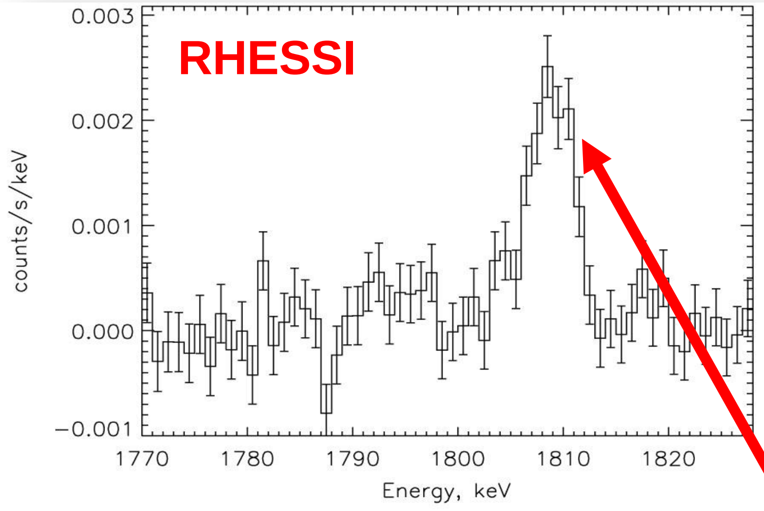


- evidence for recent stellar nucleosynthesis
- ~ 3 solar masses of ^{26}Al

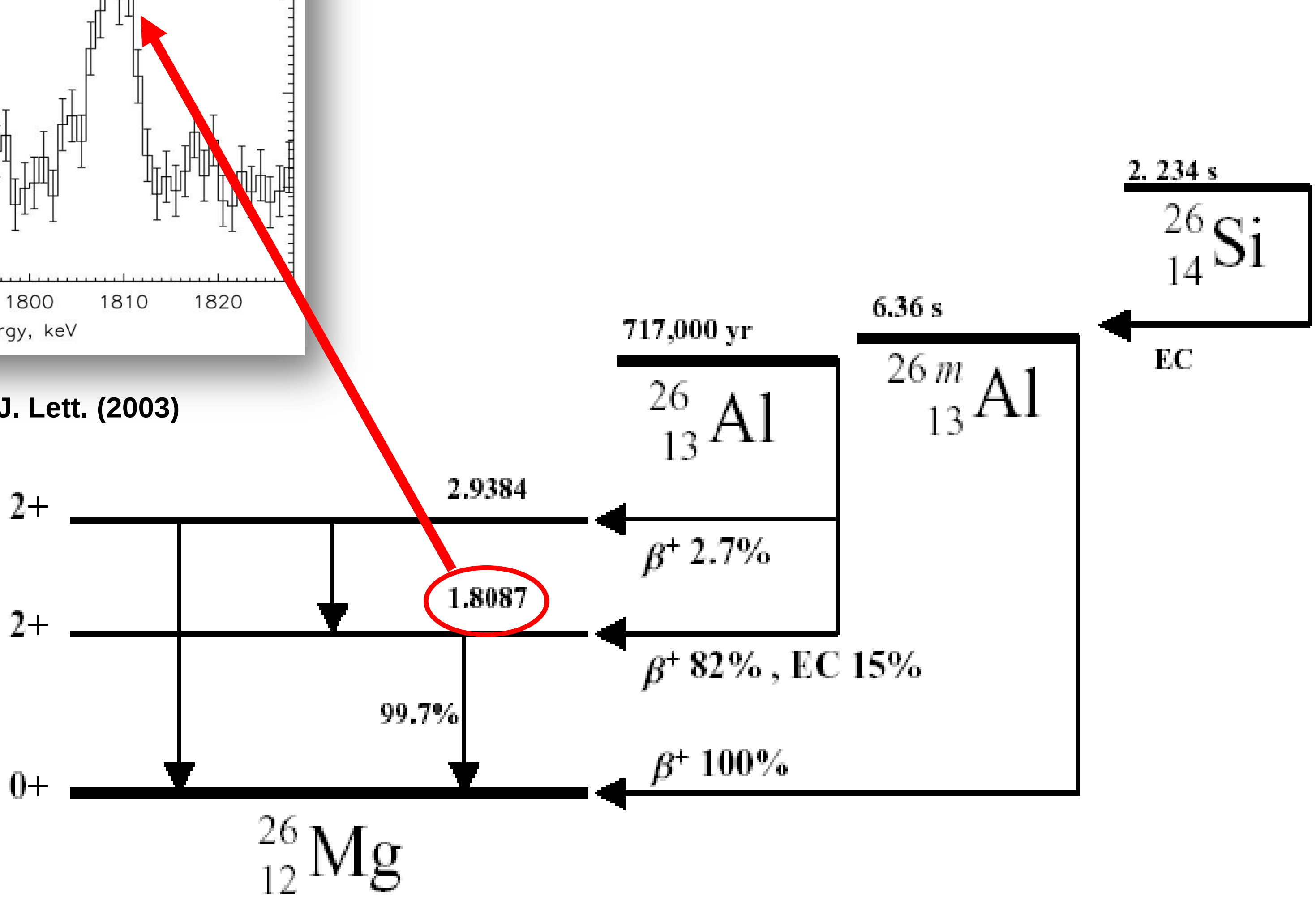
(R. Diehl et al., Nature 2006)

Stellar sources?

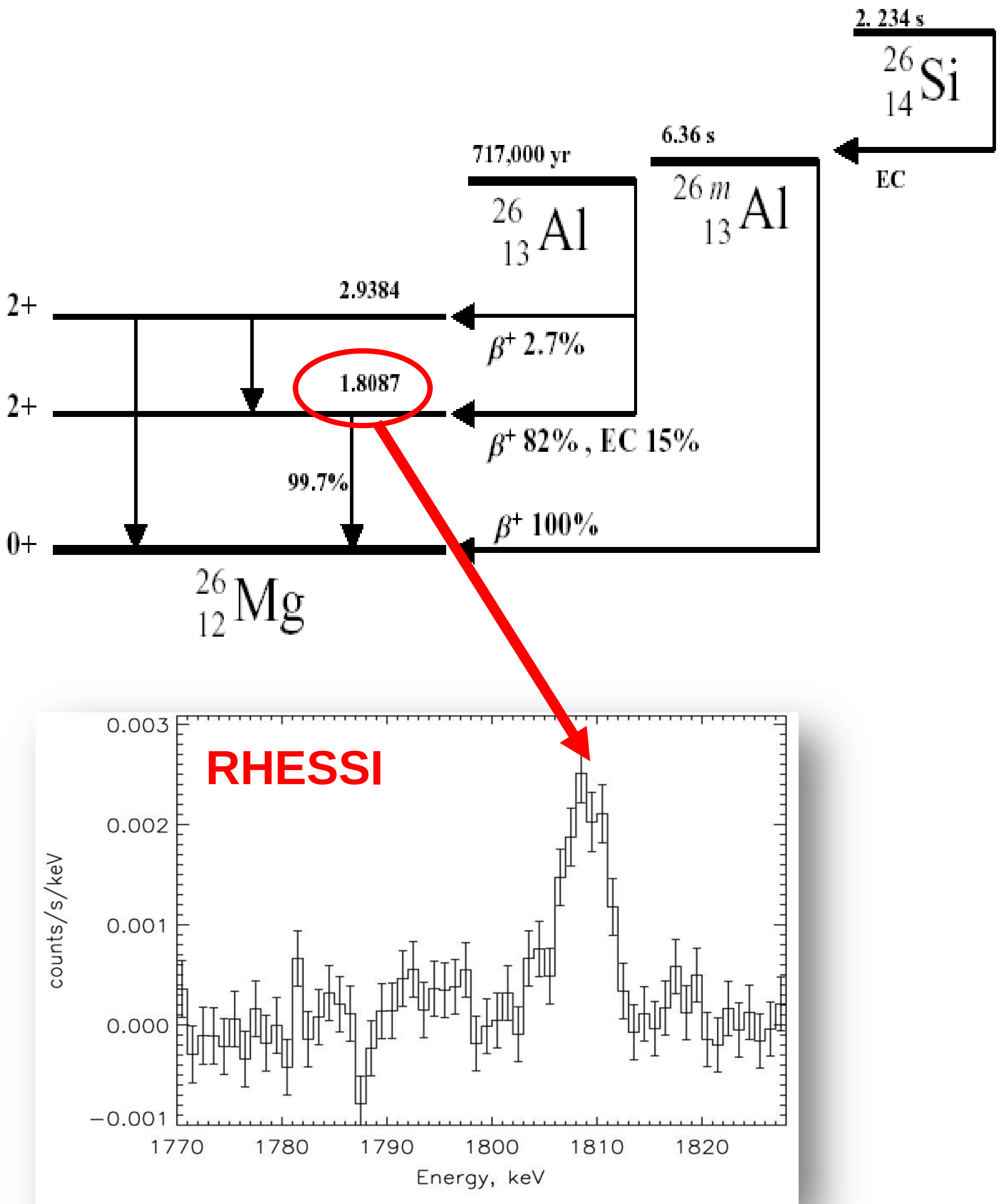
the nuclear origin of galactic ^{26}Al

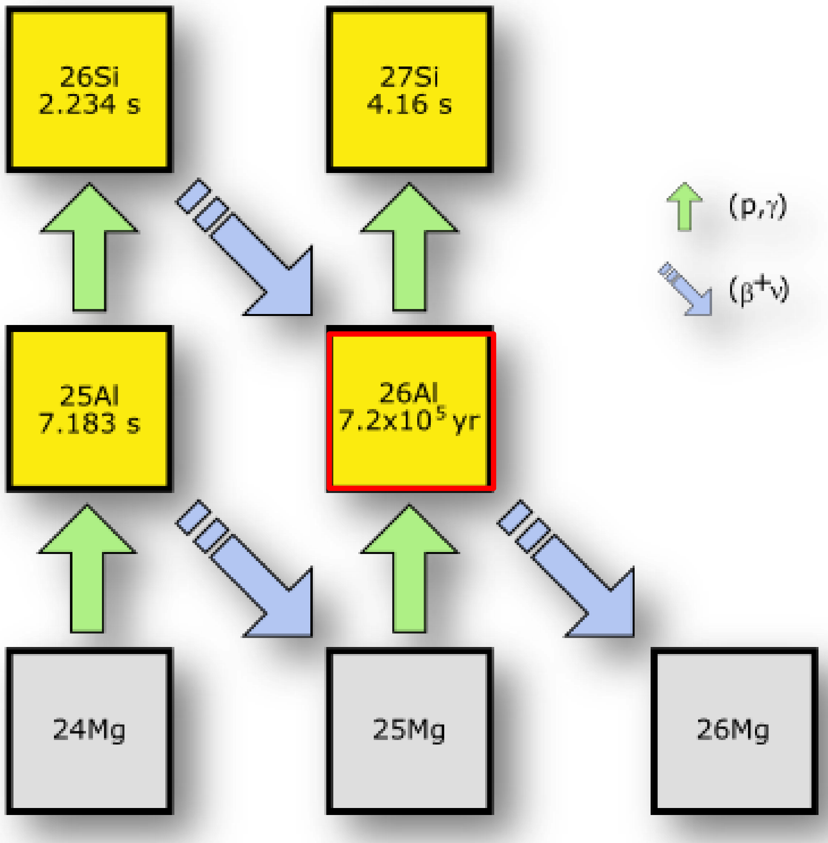


D.M. Smith, Ap. J. Lett. (2003)



the nuclear origin of galactic ^{26}Al





important reactions:

^{26}Al(p,γ)^{27}Si

^{25}Al(p,γ)^{26}Si

[Iliadis et al. Ap. J. (2002)]

nucleosynthesis in the lab

- **explosive hydrogen/helium burning:**

  $T \sim 0.1$ – few GK

  → $E_{cm} \sim$ keV – few MeV

- ***Unstable* nuclei are now important**

- **Goal: to determine the *reaction rates* from the nuclear *cross-sections***

resonant reaction rate

reaction rate per particle pair:

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

at temperatures of interest, cross-sections are dominated by contributions from resonances in the compound nucleus.

→ **rate ~ $T^{-3/2}$ ($\omega\gamma$) exp [- E_R / T]**

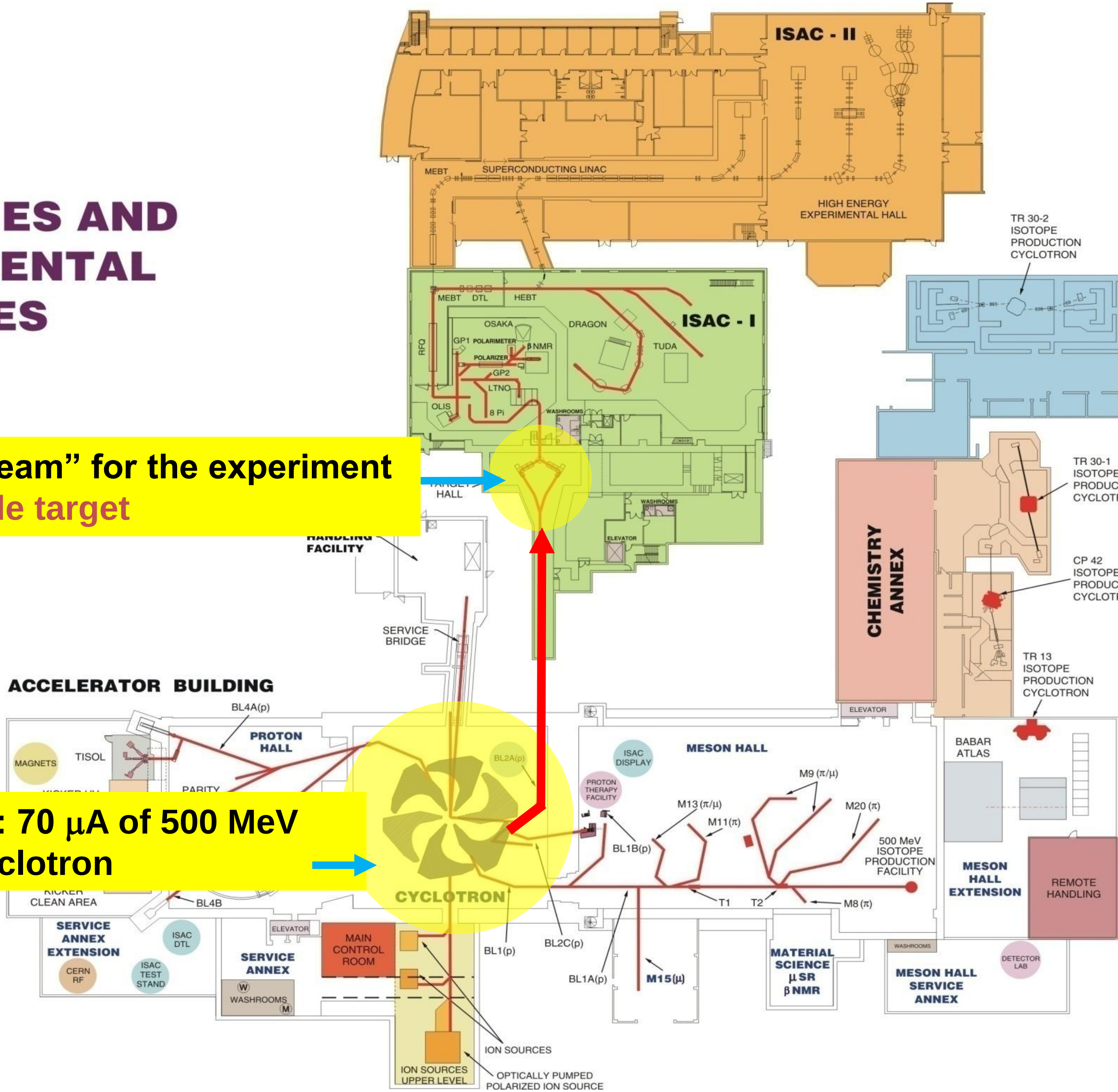
where E_R = resonance energy
$\omega\gamma$ = resonance "strength"

[$\omega\gamma$ ~ $\Gamma_p \Gamma_\gamma / \Gamma_{total}$ for (p,γ) reaction]

Measurement of $^{26}Al(p,\gamma)^{27}Si$ at TRIUMF-ISAC

- Goal: determine the (p,γ)-strength of the E_{cm} = 188 keV resonance
  - $E_{beam}(^{26}Al)$ ~ 200 keV/u
  - Need ISAC beam intensity > 10^9 ions per second

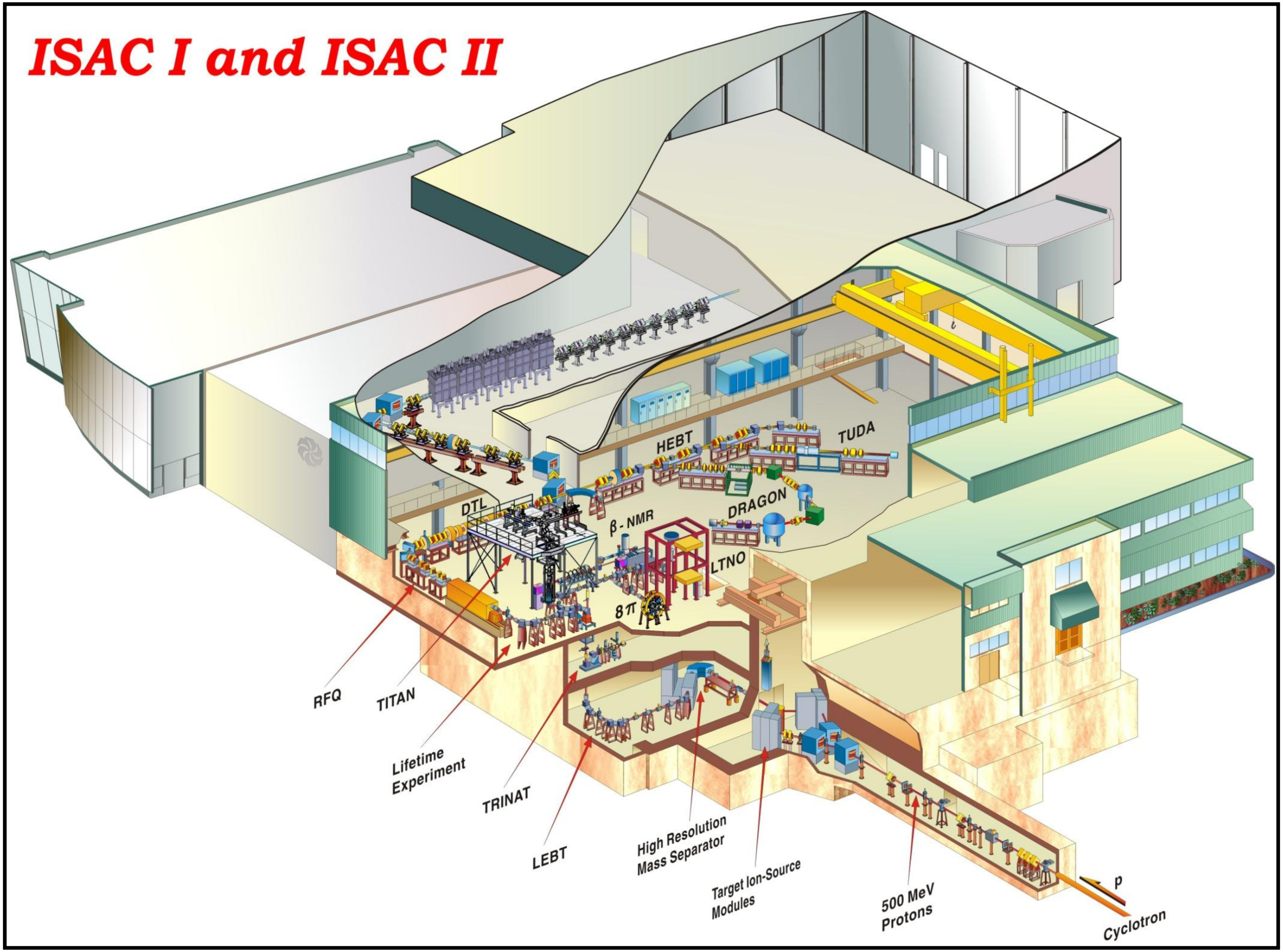
TRIUMF BEAMLINES AND EXPERIMENTAL FACILITIES



^{26}Al "secondary beam" for the experiment
Silicon Carbide target

"primary beam": 70 μA of 500 MeV protons from cyclotron

ISAC I and ISAC II



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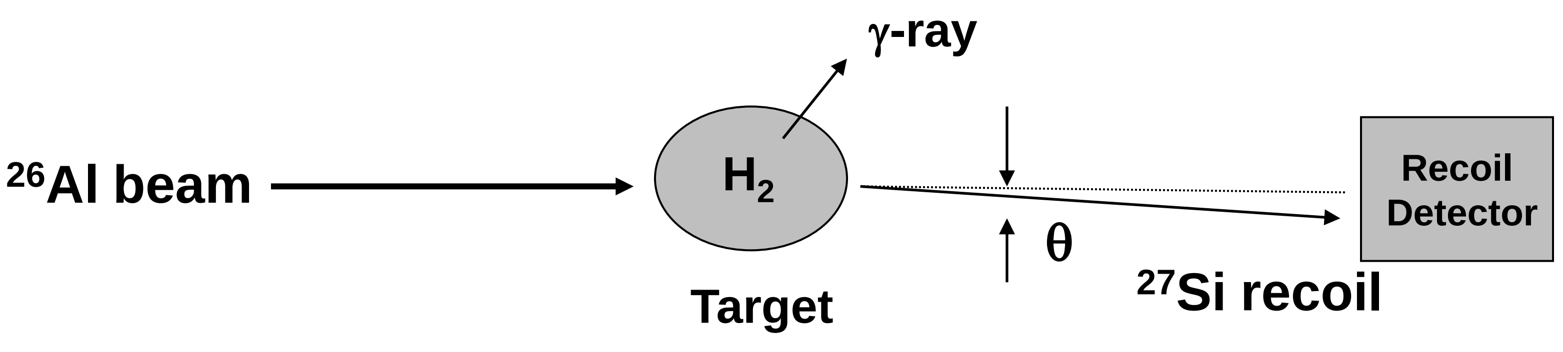
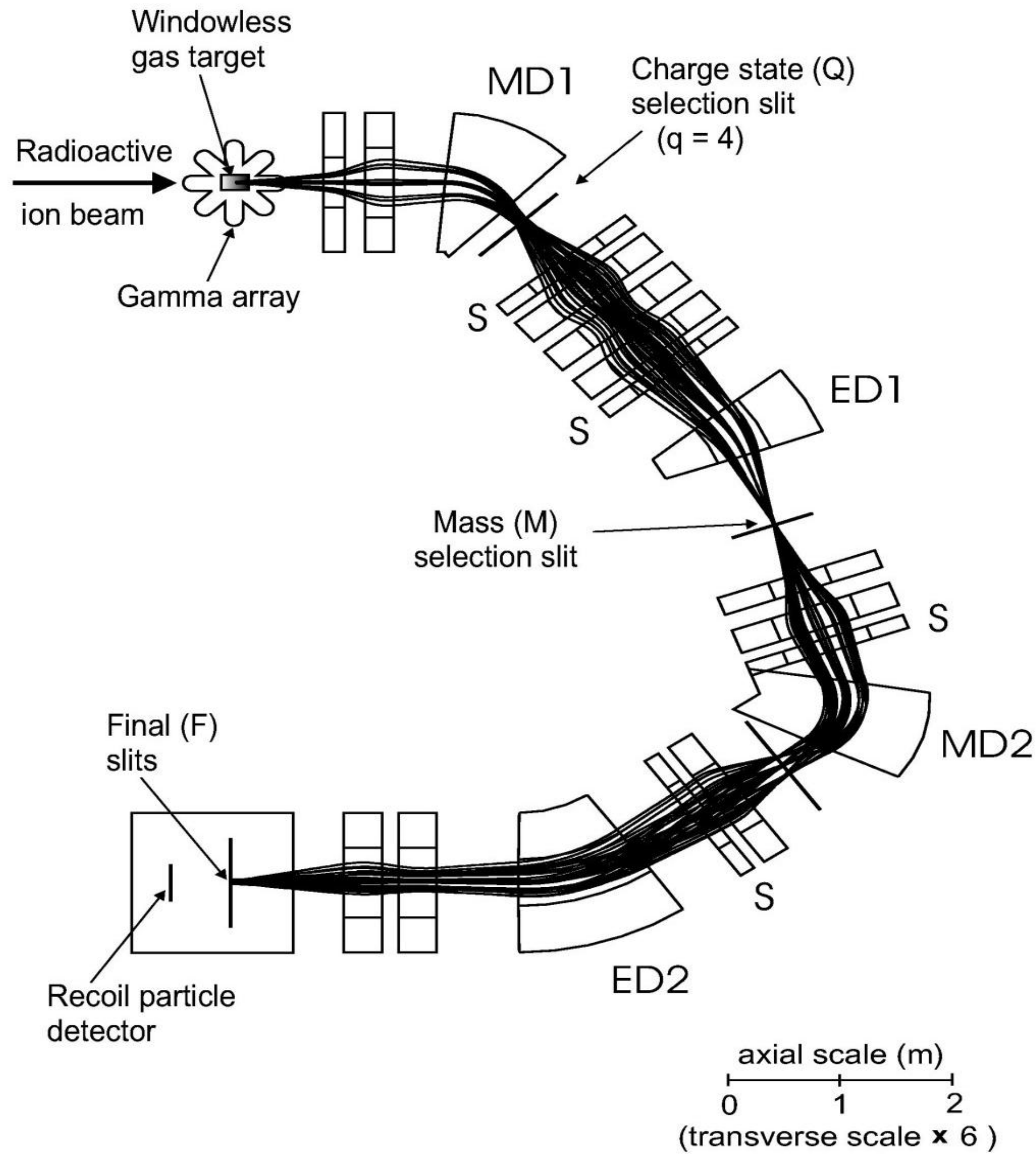
  - Measure the yield of ^{27}Si recoils with DRAGON recoil separator (coincidence with prompt gamma rays)

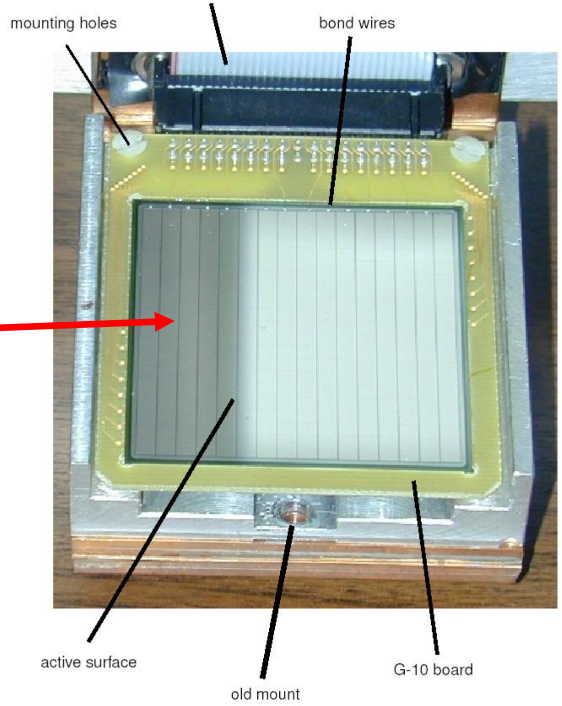


The DRAGON facility



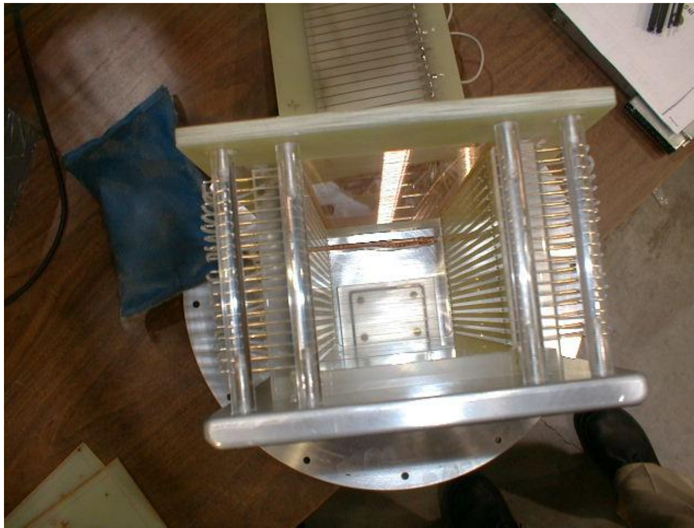

DRAGON
Detector of Recoils And
Gammas Of Nuclear reactions
Gas Target
Gamma Array
Magnetic Quads
Magnetic Dipole
Charge Slit Box
Magnetic Quads
Electrostatic Dipole
Mass Slit Box
Final Focus Box
Magnetic Quads
Electrostatic Dipole
Quads
Magnetic Dipole
IC/PGAC Stop
MCP Start
Recoil Detectors

DRAGON end-detectors



silicon strip detector (“DSSD”)

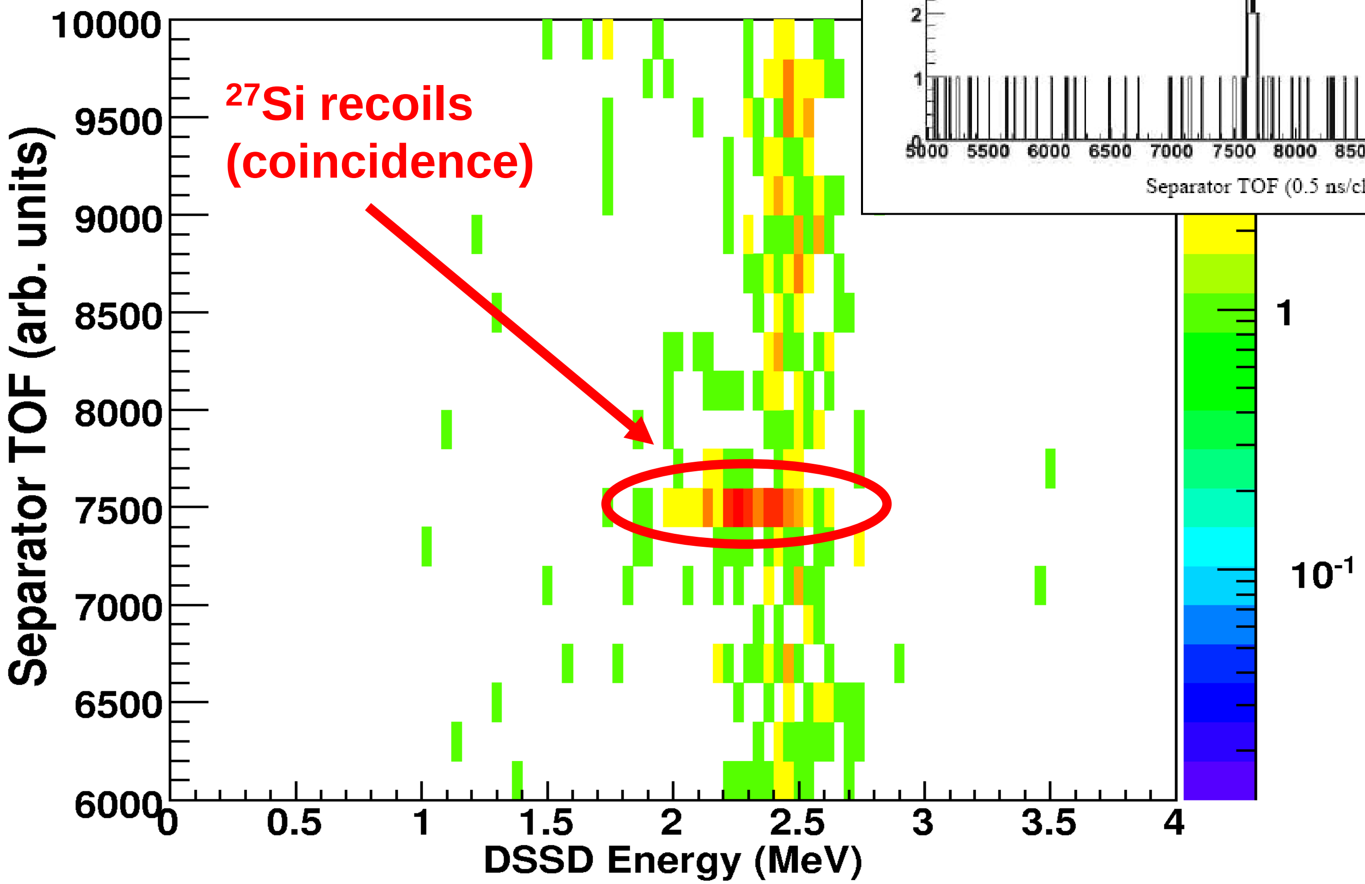
- **time, position, energy**
- **$^{26}Al(p,\gamma)^{27}Si$**

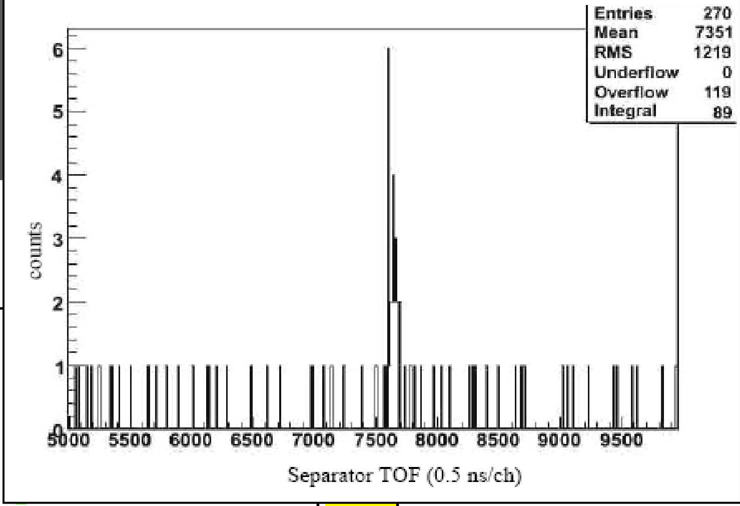


ionization chamber

- **energy for E-ΔE particle identification**
- **$^{40}Ca(\alpha,\gamma)^{44}Ti$**

^{26}Al(p,γ)^{27}Si with DRAGON: ^{27}Si yield





^{27}Si time-of-flight through DRAGON vs. ^{27}Si energy

[Ruiz et al. (2006) / PhD thesis: Anuj Parikh (Yale)]

ωγ = 35 ± 7 μeV

future plans with DRAGON

Reaction	Importance	Experiment
$^{33}S(p,\gamma)^{34}Cl$ *(Parikh et al.)*	abundances of sulphur isotopes in nova nucleosynthesis	stable beam from ISAC's offline ion source DONE: JUNE 2010
$^{17}F(p,\gamma)^{18}Ne$ *(Chen et al.)*	production of gamma-emitter ^{18}F in novae; break out from the Hot-CNO cycle in x-ray bursts	Need 10^{7-8} ions per sec.
$^{25}Al(p,\gamma)^{26}Si$ *(Chen et al.)*	production of gamma-emitter ^{26}Al in explosive hydrogen burning	Need 10^{8-9} ions per sec.

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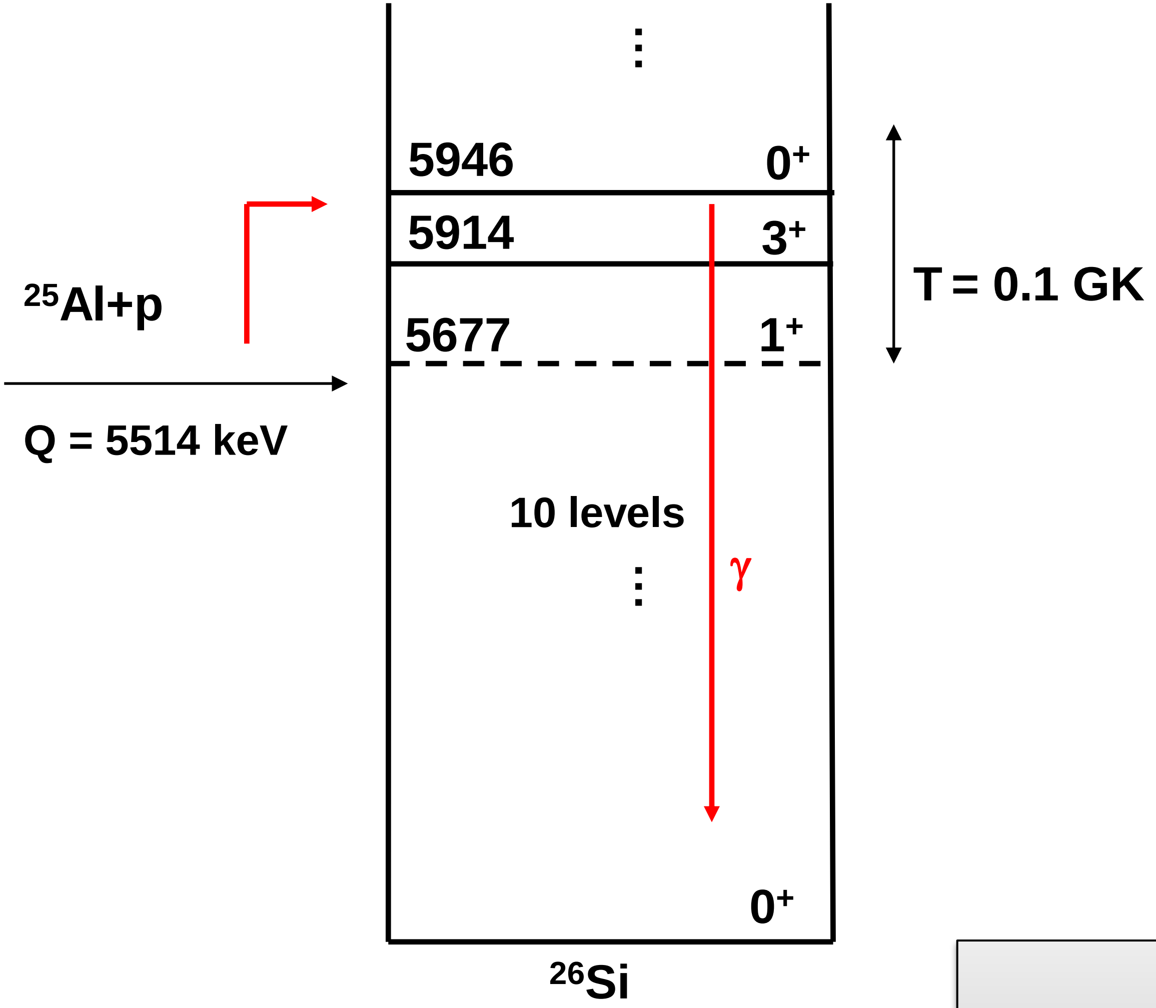
Good candidate for "indirect" approaches...

^{25}Al(p,γ)^{26}Si: levels of ^{26}Si



^{25}Al(p,γ)^{26}Si, indirectly:

in-beam γ-ray spectroscopy @ NSCL

resonant proton scattering @ CNS-CRIB

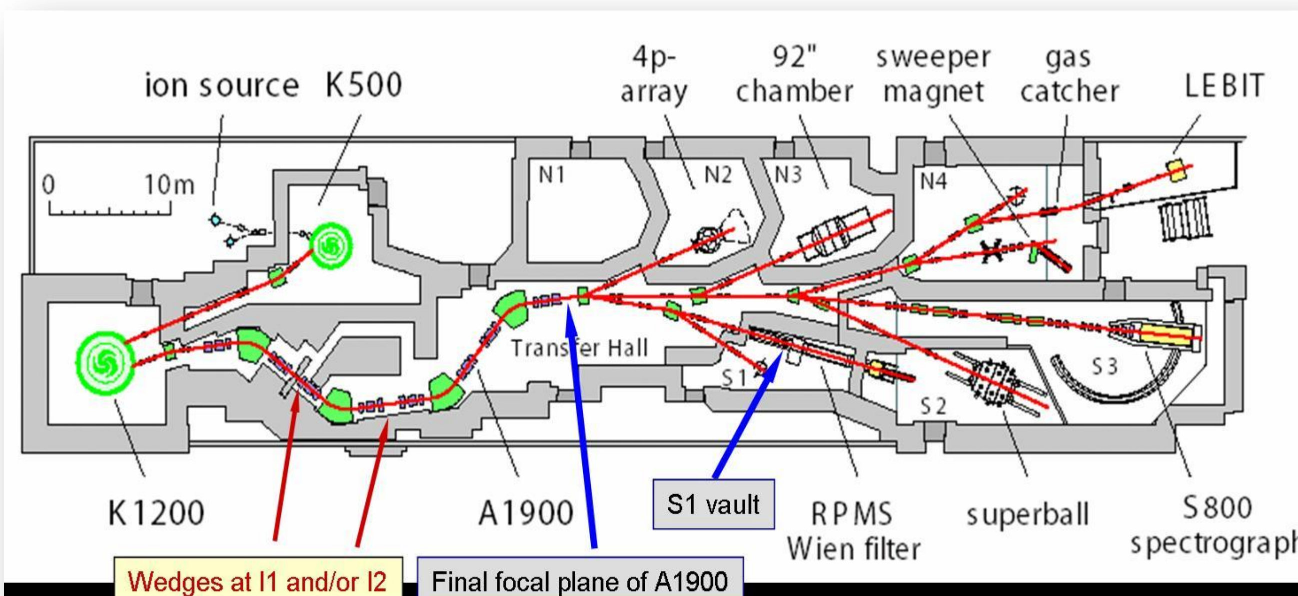
the $^{25}Al(p,\gamma)^{26}Si$ reaction: indirect approaches

- ***Direct measurement:***
  - need beam with more than 10^8 ions per second: ISAC? REX-ISOLDE?
- ***Indirect studies:***
  - (^{3}He,^{6}He) Caggiano *et al*. 2002
  - (^{3}He,n) Parpottas *et al*. 2004
  - ^{26}P decay Thomas *et al*. 2004
  - ^{26}Si mass Parikh *et al*. 2005 + Eronen *et al*. 2009 + Kwiatkowski *et al*. 2010
  - (^{4}He,^{6}He) Kwon *et al*. 2006
  - (p,t) Bardayan *et al*. 2006 + Matic *et al*. 2010 + Chipps *et al*. 2010
  - (^{16}O,2n) Seweryniak *et al*. 2007
  - (d,n) Peplowski *et al*. 2009
  - (^{3}He,nγ) Komatsubara *et al*. 2011 + de Séréville *et al*. 2011

McMaster: (*p,d*) with rare isotope beams at the NSCL

studying ^{26}Si at the NSCL with ^{27}Si(p,d)^{26}Si

Jun Chen
Ph.D. Thesis



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NSCL

p(^{27}Si,^{26}Si)d at NSCL: experiment details

- ***single neutron removal:*** easy beam intensity, large cross-section

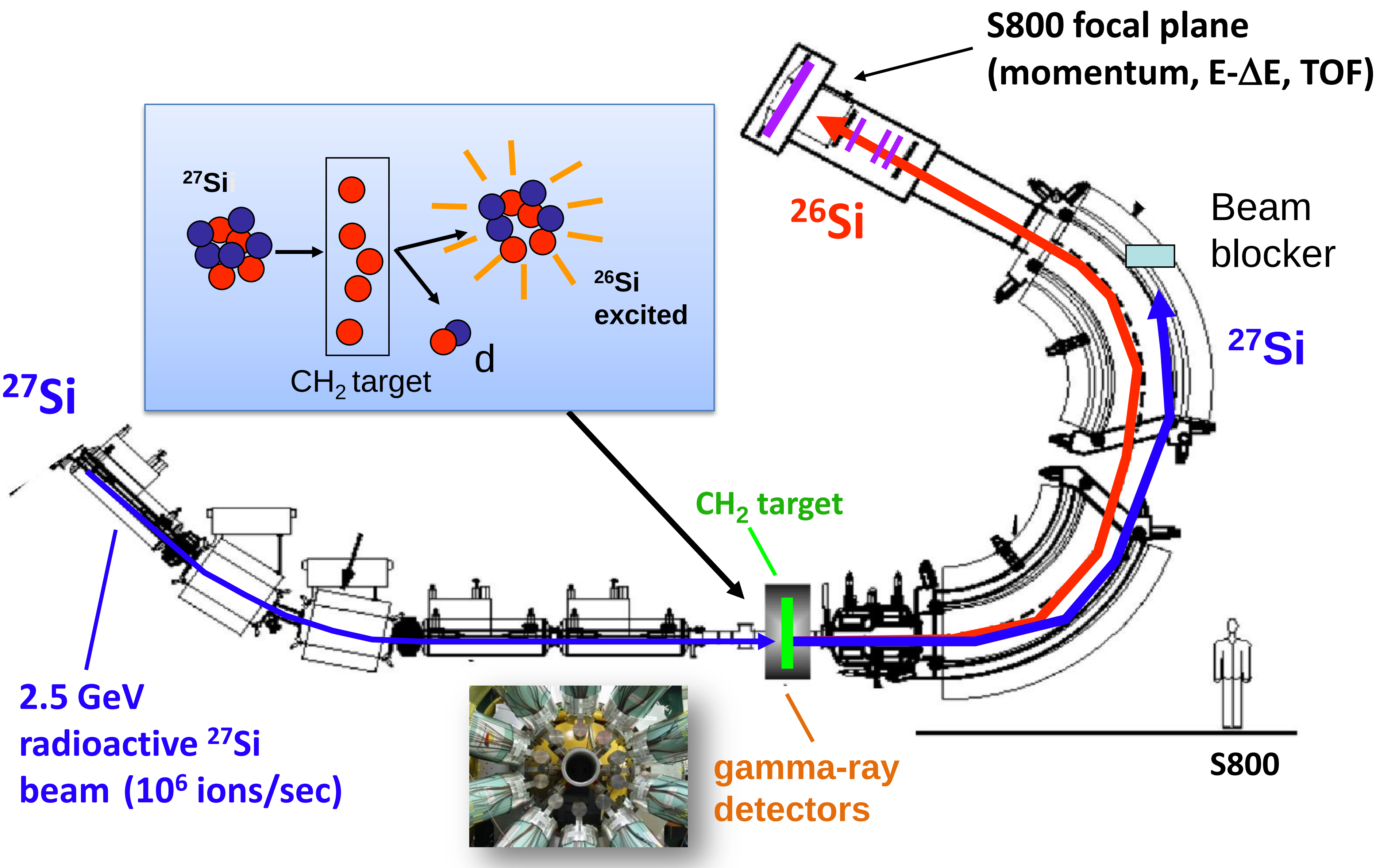
- ***^{27}Si beam*** ($T_{1/2}$ = 4.2 sec)
  - ^{34}Ar beam (150 MeV/u) + Be target → fragmentation
  - selection of ^{27}Si ions with the S1900 spectrometer

    → 10^6 ions/sec, 50% purity, 92 MeV/u

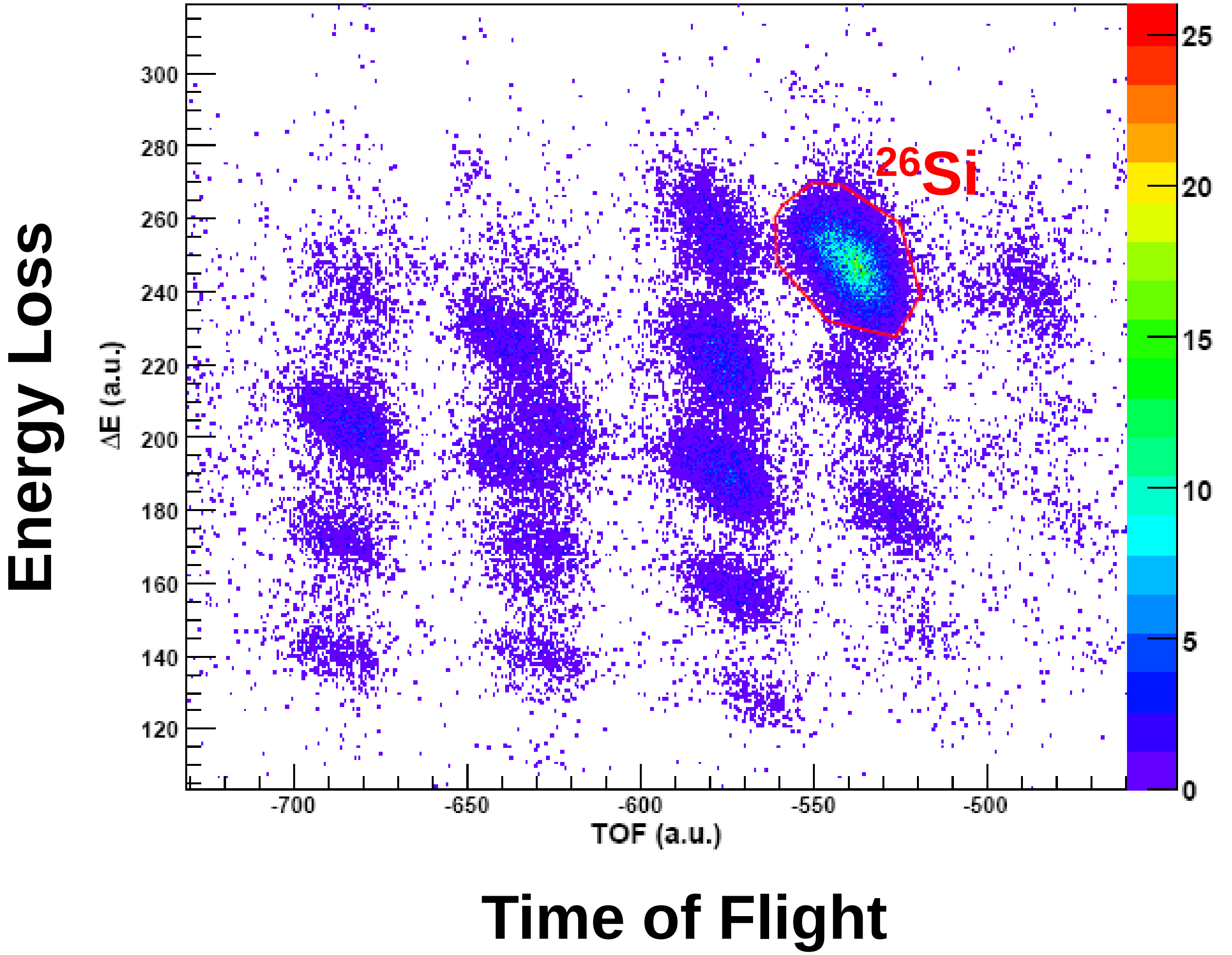
- ***proton target:*** CH_2 foil, ~ 2 mm thick, at the entrance to the S800 spectrometer

- ***goals:***
  - populate excited states of ^{26}Si
  - measure decay gamma rays
  - search for the 3^+ and 0^+ proton-unbound states

$^{27}Si(p,d)^{26}Si$: experiment setup

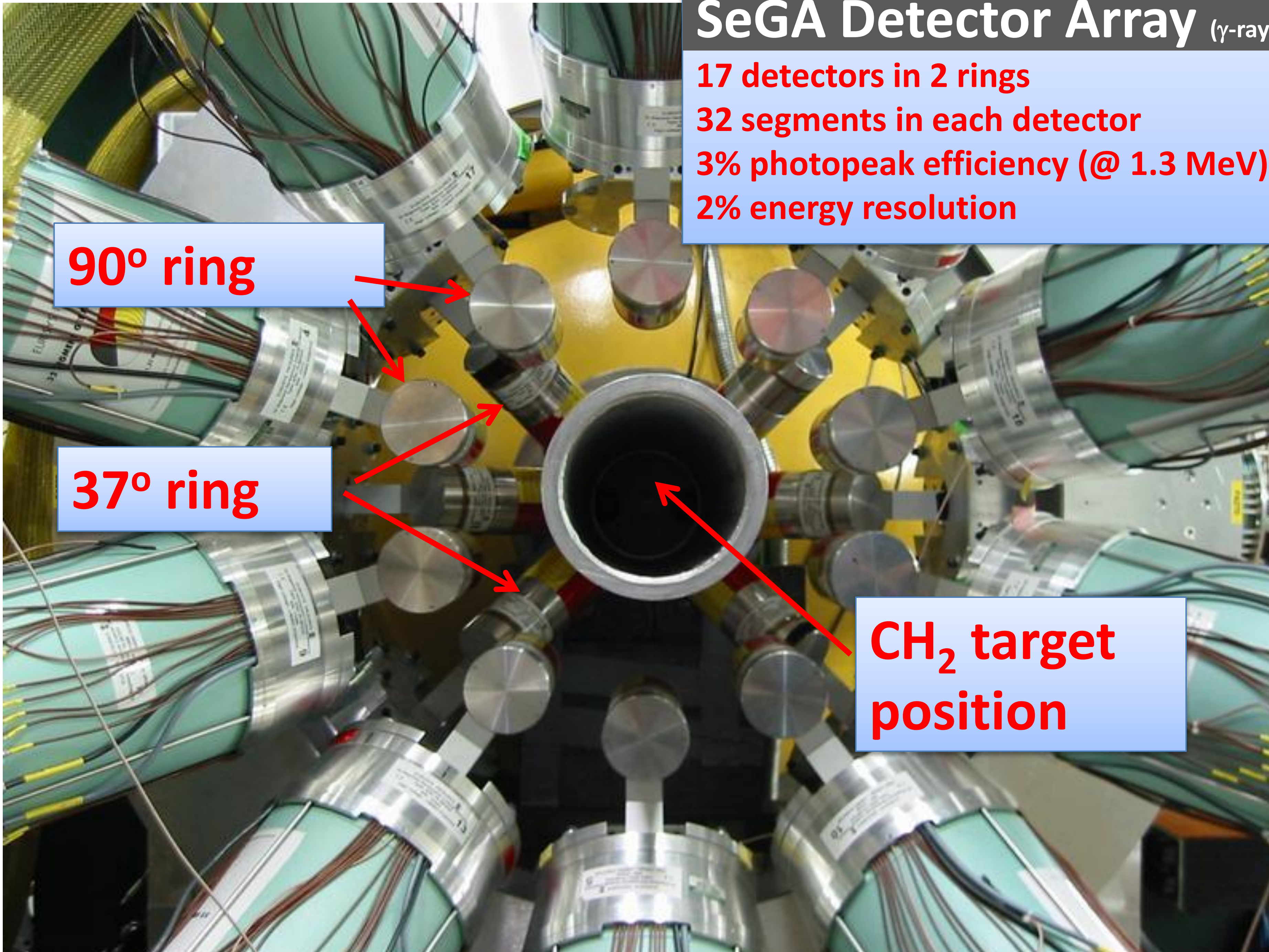


silicon-26 in the S800

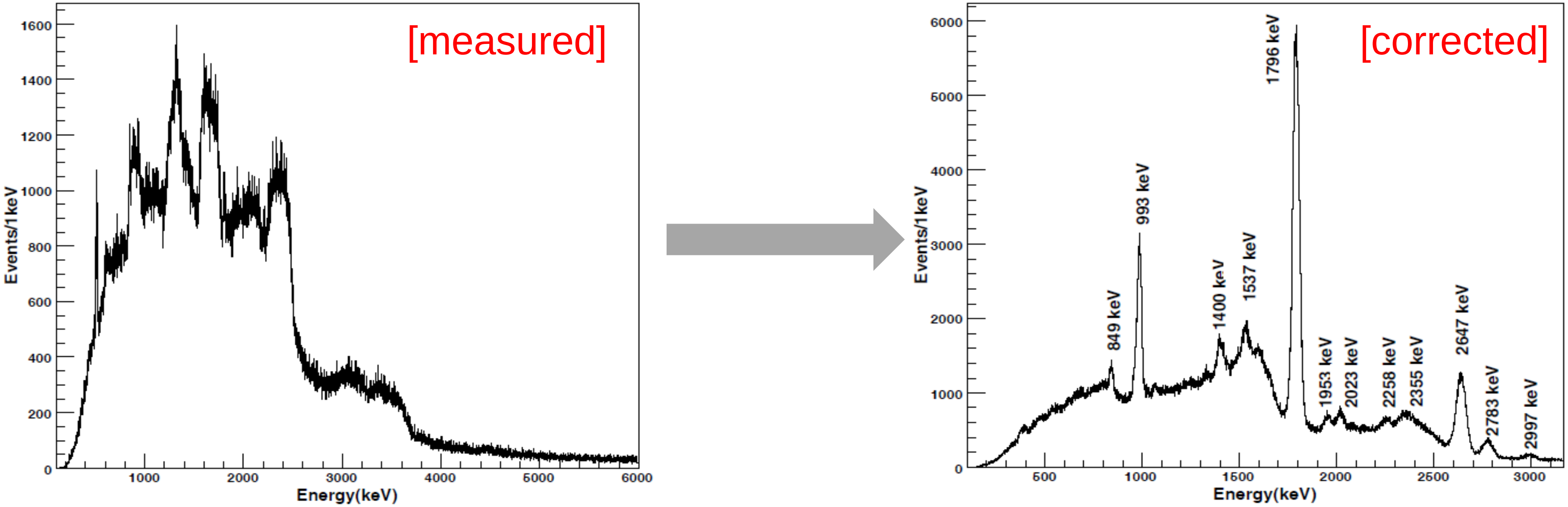


SeGA Detector Array (γ-rays)

17 detectors in 2 rings
32 segments in each detector
3% photopeak efficiency (@ 1.3 MeV)
2% energy resolution



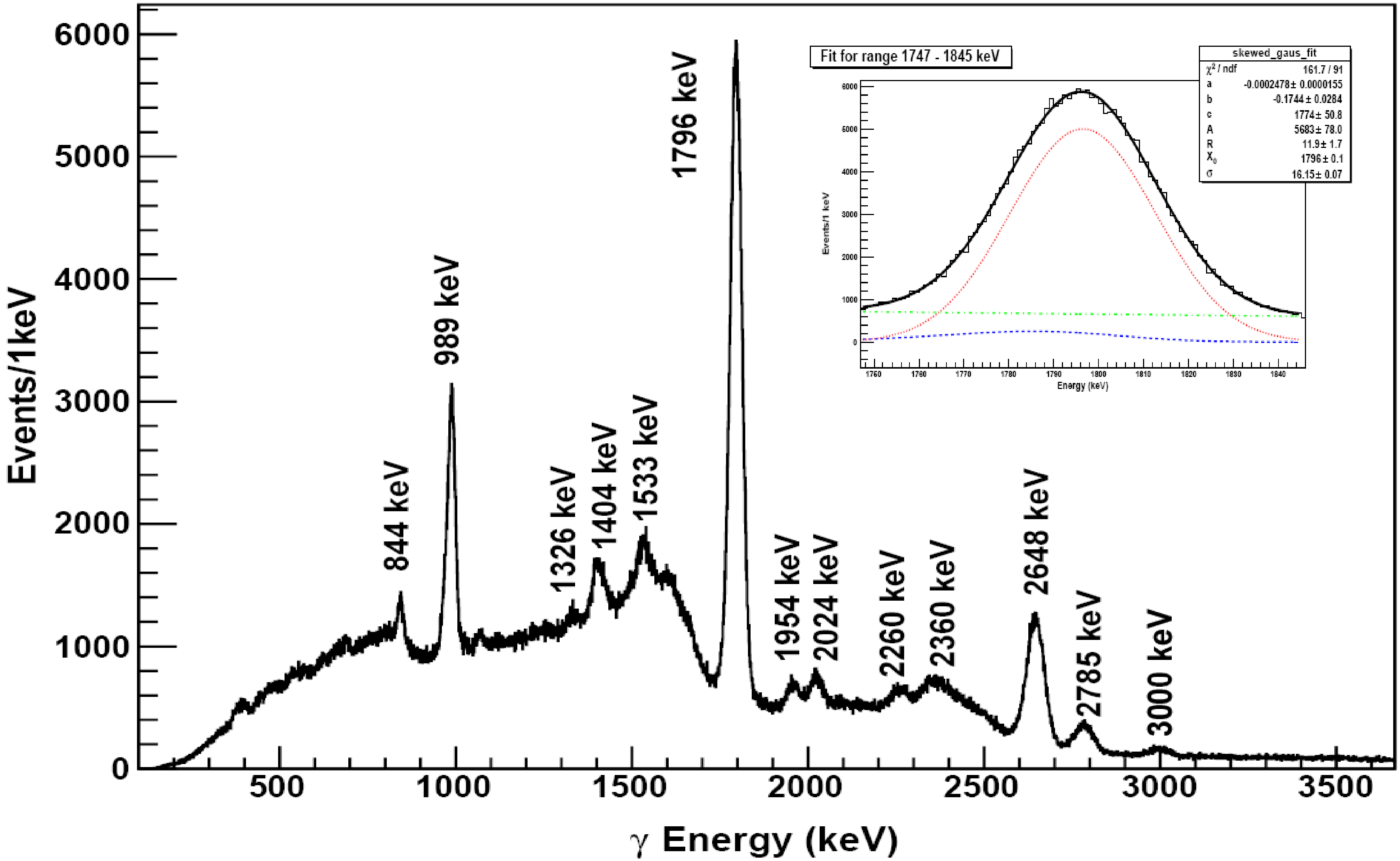
γ-rays in SeGA: doppler broadening correction



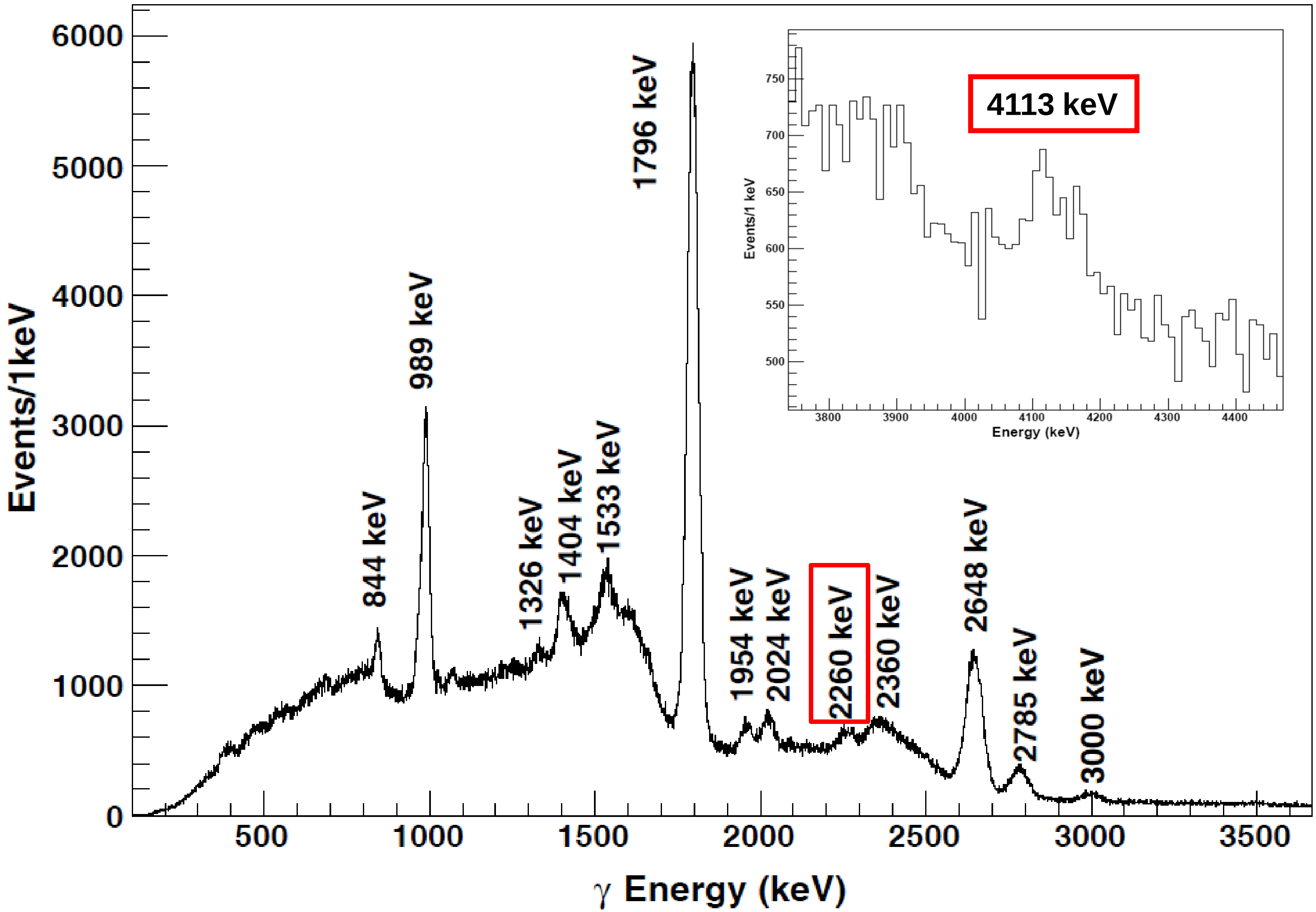
$$E_{corrected} = \frac{1-\beta\cos\theta}{\sqrt{1-\beta^2}} E_{measured}$$

$$\text{where } \beta = \frac{v}{c} \text{ and } v = \text{velocity of } {}^{26}\text{Si} (\sim 0.4\,\text{c})$$

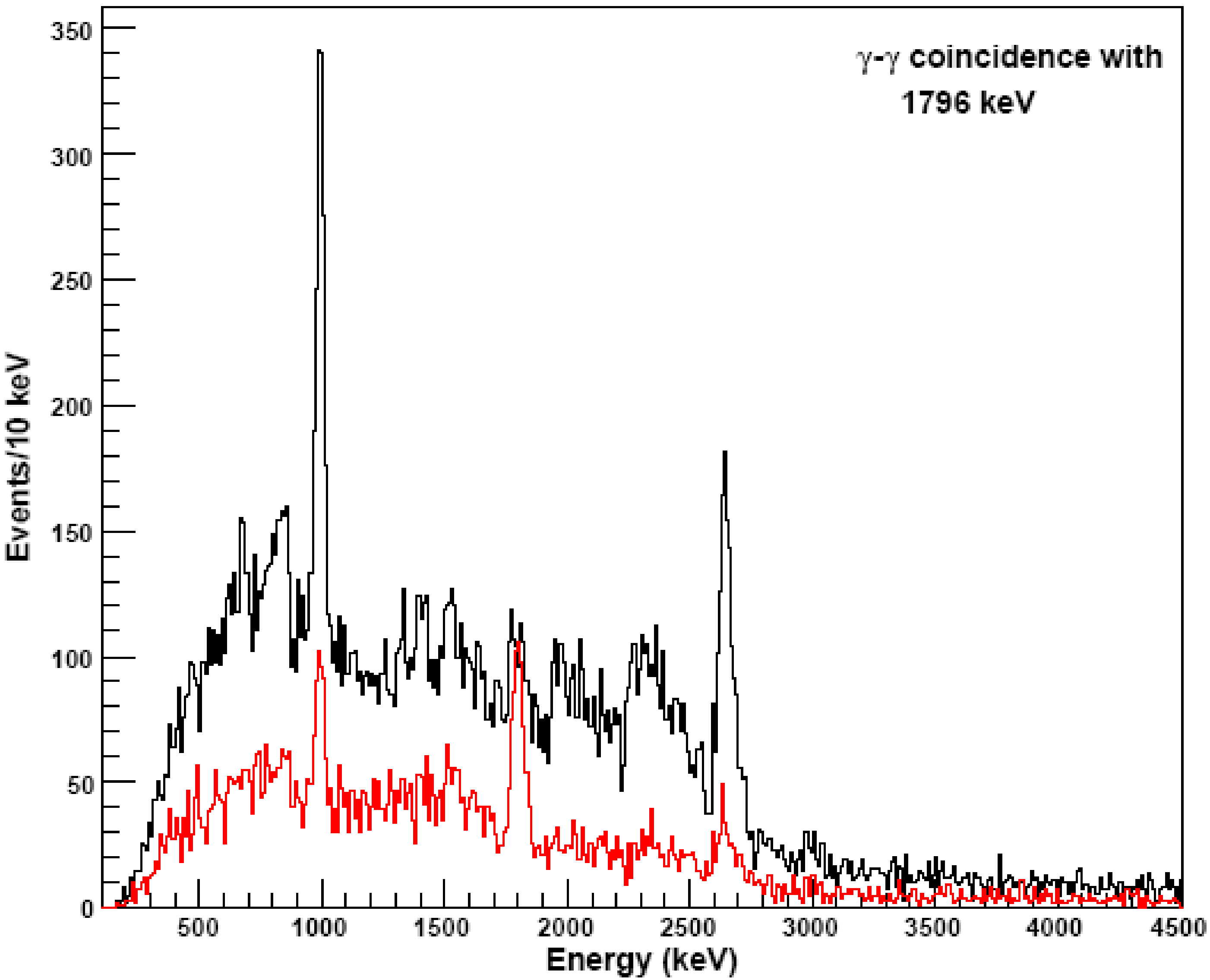
γ-rays from ^{26}Si excited nuclear states



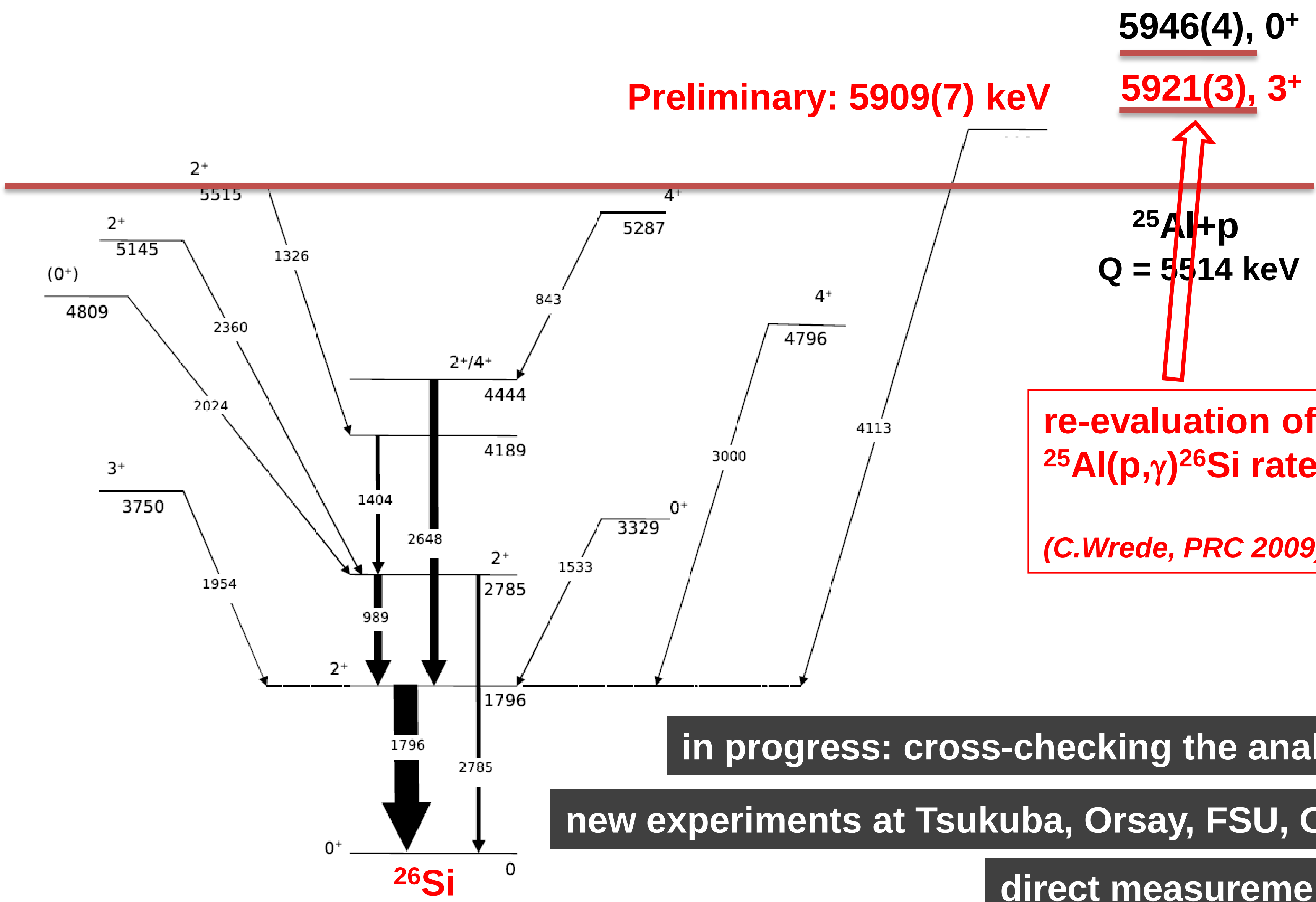
new γ-ray transitions (preliminary)



γ-γ coincidence analysis



^{26}Si level scheme



re-evaluation of $^{25}Al(p,\gamma)^{26}Si$ rate

(C.Wrede, PRC 2009)

in progress: cross-checking the analysis

new experiments at Tsukuba, Orsay, FSU, ORNL

direct measurements?

Conclusions

Small sample of experiments aimed at improving our understanding of stellar explosions
– benefiting from interactions with astronomers and theorists/modellers

Future: FAIR, FRIB, RIKEN, GANIL, TRIUMF, EURISOL

Experiments at smaller accelerator labs (e.g., TU-Munich):

> **these complement – and guide – those at bigger places**
>
> **pedagogically important**

Thanks to...

- **Collaborators:**
  - **DRAGON collaboration (TRIUMF)**
  - **Hendrik Schatz's group (NSCL – Michigan State University)**

- **Technical staff at these labs**

- **and :**

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