^{68}Se rp-process waiting point and the ^{69}Kr β-delayed proton emission experiment

Marcelo Del Santo
Joint Institute for Nuclear Astrophysics
National Superconducting Cyclotron Laboratory

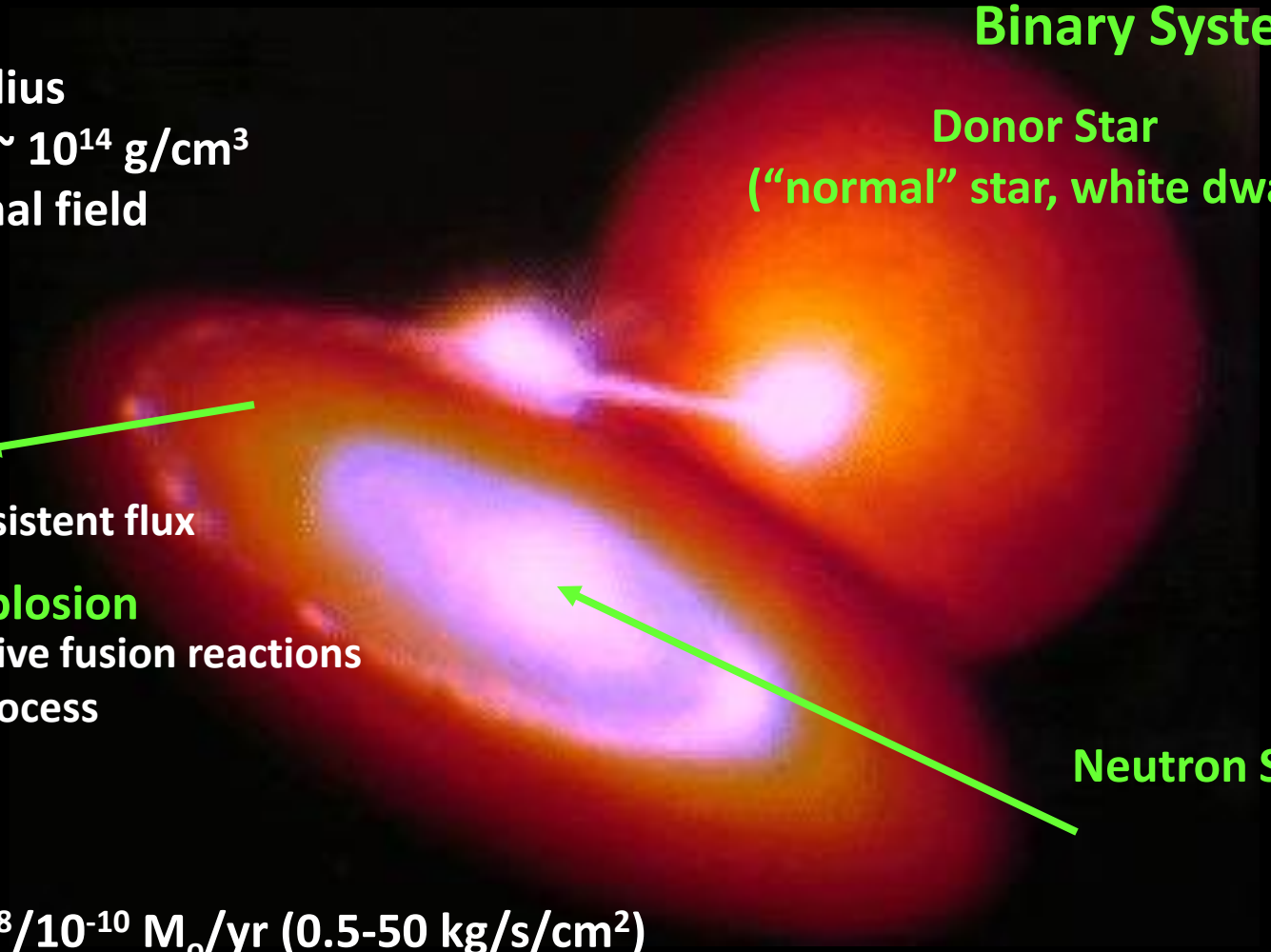
Frontiers 2010 Workshop on Nuclear Astrophysics
October 21-23,2010
Abbey Resort, Lake Geneva WI

Outline

- X-ray bursts and rp-process
- Waiting point nuclei in the rp-process
- Proton separation energy of ^{69}Br
- ^{69}Kr β-delayed proton emission experiment

X-ray bursts and rp-process scenario

Neutron stars:
- 1.4 M_o, 10 km radius
- average density: ~ 10^{14} g/cm^3
- strong gravitational field



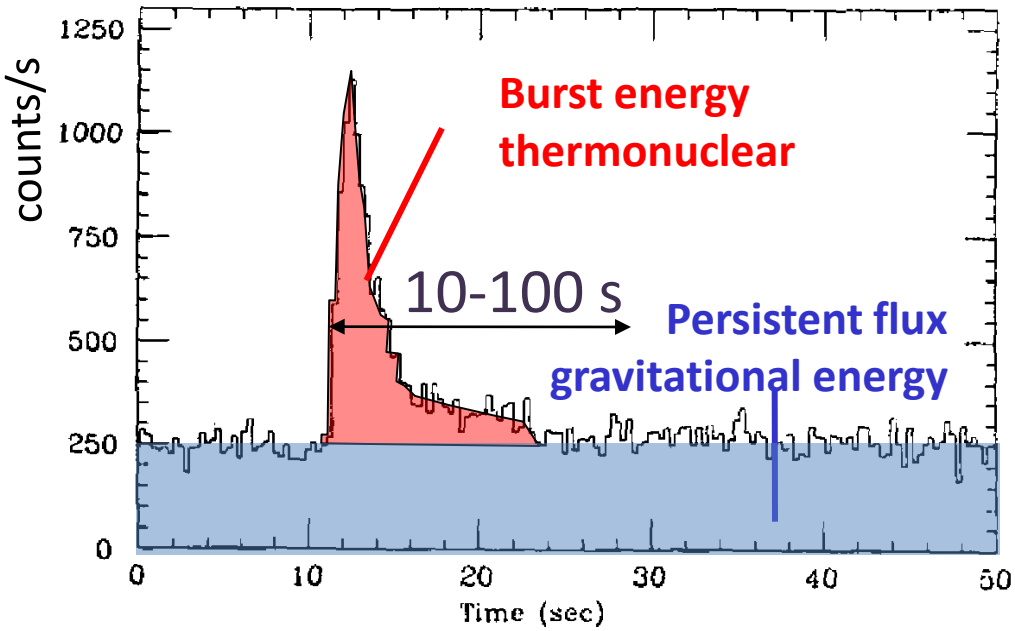
Typical systems:
- accretion rate $10^{-8}/10^{-10}$ M_o/yr (0.5-50 kg/s/cm^2)
- orbital periods 0.01-100 days
- orbital separations 0.001-1 AU's

X-Ray Burst characteristics and classification

Type I:

- Nuclear energy (rp-process)
- Energy proportional to preceding inactivity period

- Fast rise: 1-2s
- Exponential decay profile



Typical X-ray bursts:

- duration: 10s – 100s
- recurrence: hours-days
- regular or irregular
- energy: 10^{36}-10^{38} erg/s
  (stars 10^{33}-10^{35} erg/s)

To interpret quantitatively:
Need precise nuclear data to make full use of high quality observational data

- masses (proton separation energies)
- β-decay rates
- reaction rates (p-capture, α,p)

rp-process

rp-process

$^{41}Sc+p \rightarrow {}^{42}Ti$

$^{42}Ti+p \rightarrow {}^{43}V$

$^{43}V+p \rightarrow {}^{44}Cr$

$^{44}Cr \rightarrow {}^{44}V + e^{+} + \nu_e$

$^{44}V+p$ ...

Wallace & Woosley (1981)

Schatz et al. (1998)

SnSbTe cycle

Set the end point

Schatz et al. (2001)

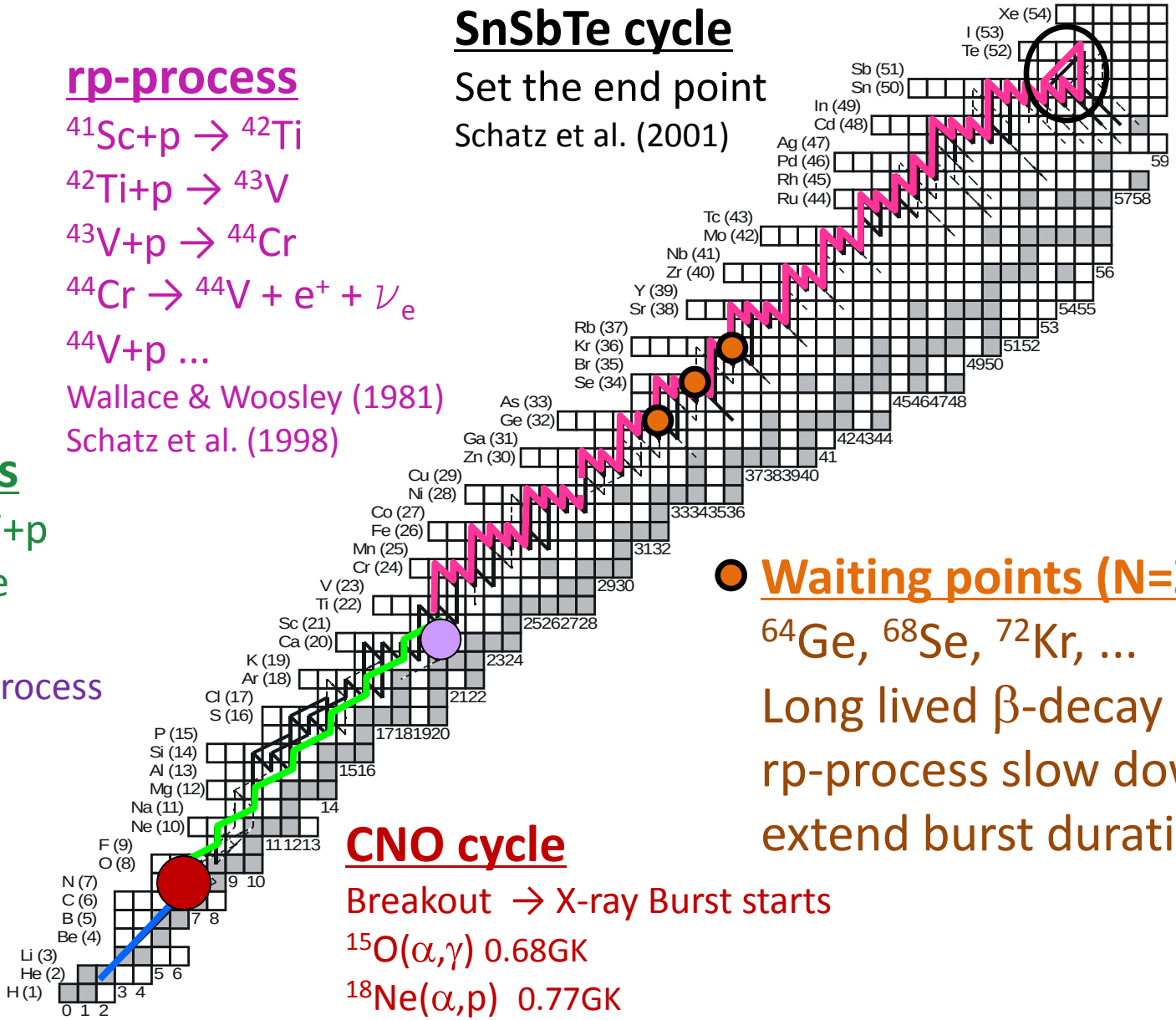
αp-process

$^{14}O+\alpha \rightarrow {}^{17}F+p$

$^{17}F+p \rightarrow {}^{18}Ne$

$^{18}Ne+\alpha$ ...

^{40}Ca end αp-process



Waiting points (N=Z)

^{64}Ge, ^{68}Se, ^{72}Kr, ...

Long lived β-decay

rp-process slow down

extend burst duration

3α reaction

$\alpha+\alpha+\alpha \rightarrow {}^{12}C$

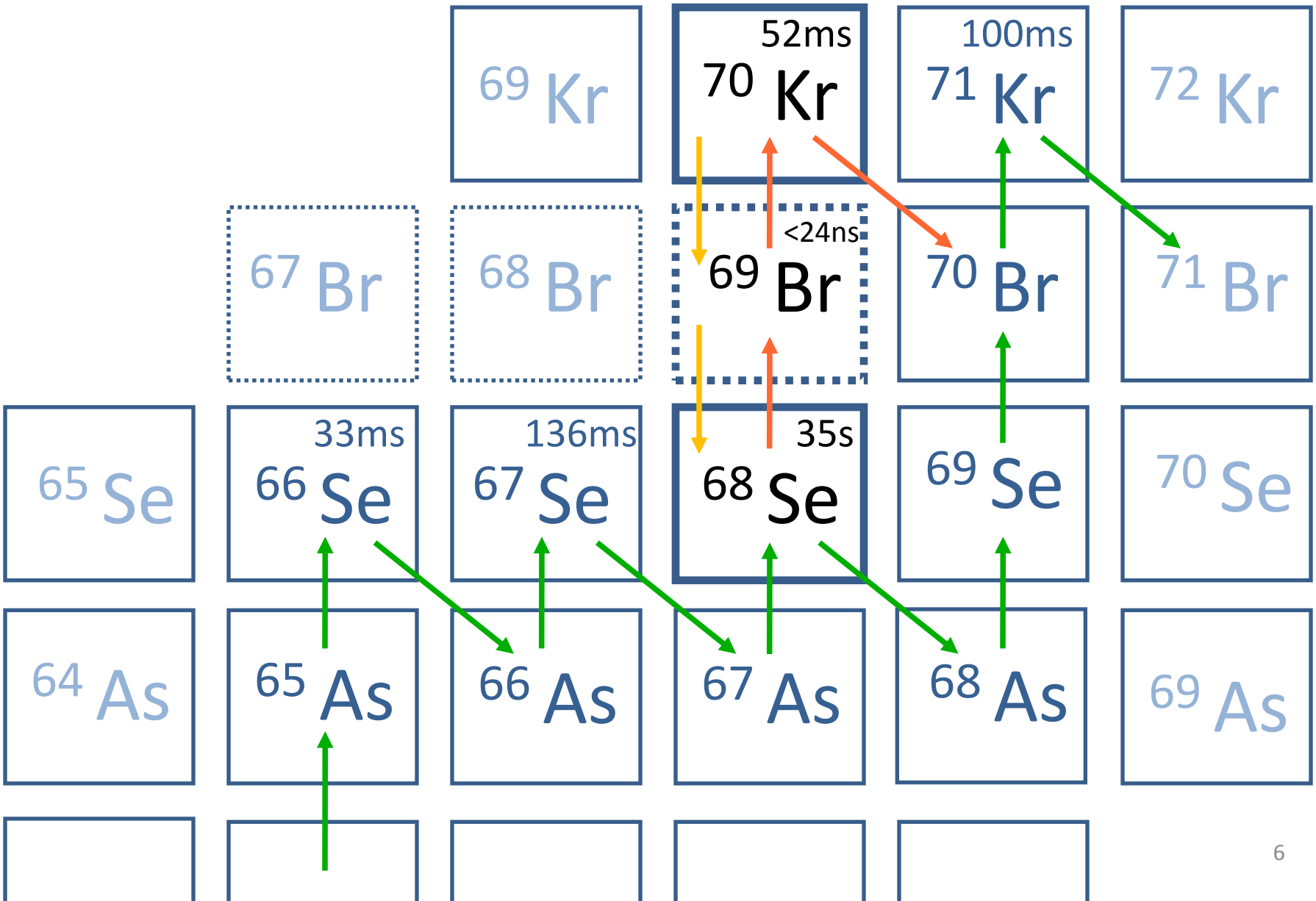
CNO cycle

Breakout → X-ray Burst starts

$^{15}O(\alpha,\gamma)$ 0.68GK

$^{18}Ne(\alpha,p)$ 0.77GK

^{68}Se Waiting point



Effective life time of the ^{68}Se waiting point

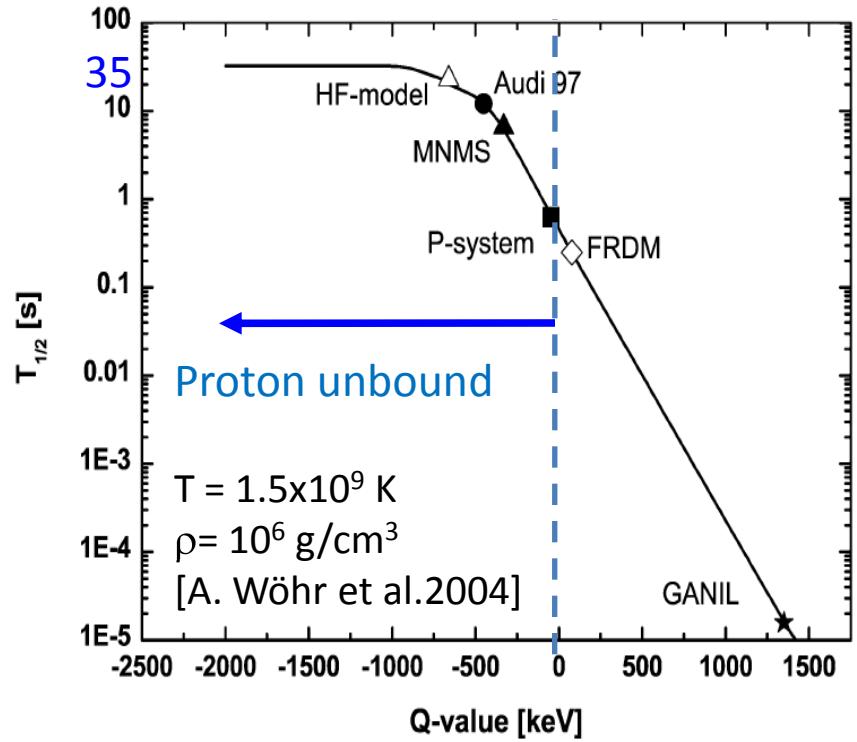
Saha equation:

decay rate:

$$\lambda_{\text{eff}} = \lambda_\beta + Y_p^2 \rho^2 N_A^2 \left(\frac{2\pi\hbar^2}{kT}\right)^{3/2} \frac{G_2(T)}{G_1(T)} \exp\left(\frac{Q_1}{kT}\right) \langle \sigma, v \rangle_{(p,\gamma)_2}$$

^{68}Se + p → ^{69}Br $Q_1 = S_p$

	Sp (keV)	Error (keV)
CPT [Clark et al. 2004] Penning trap, AW extrap. ^{69}Br mass	-809	130
[Wöhr et al. 2004] β-decay end point, AW extrap. ^{69}Br mass	-766	350
[Rogers et al. 2010] Measurement of ^{68}Se+p decay products	-785	40
	$T_{1/2}$eff (s)	Error (s)
[Savory et al. 2009] LEBIT ^{68}Se mass - Penning trap ^{69}Br mass - Coulomb displacement	17.4	4.5

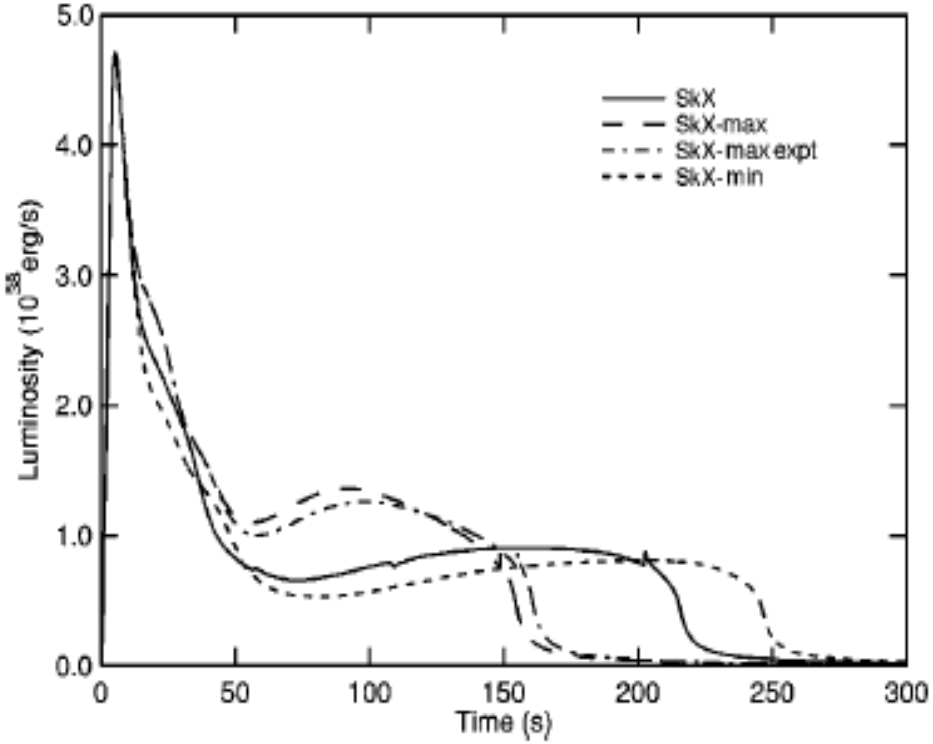


non-observation of ^{69}Br in projectile fragmentation experiments [Pfaff1996]

^{69}Br $T_{1/2}$ < 24 ns → Sp < -500 keV

Sensitivity studies of rp-process calculations

Influence of the proton capture Q-values on Type I X-ray burst models



[Brown et al. PRC (2002)]

-Coulomb displacement energy
-exp. masses from the neutron rich side

Wainting point	SkX	SkX_{min}-SkX_{max}
^{64}Ge	30 %	0.5 - 86%
^{68}Se	0.5 %	0.0 - 26%
^{72}Kr	0.0 %	0.0 - 8%

Branching for proton captures

- Large errors in 64Ge and 68Se masses provide the dominant uncertainty in the rp-process calculations.

- Improve underlying nuclear physics

Experiment carried out at NSCL (May 2010)

How unbound is ^{69}Br?
What's the proton separation energy ?

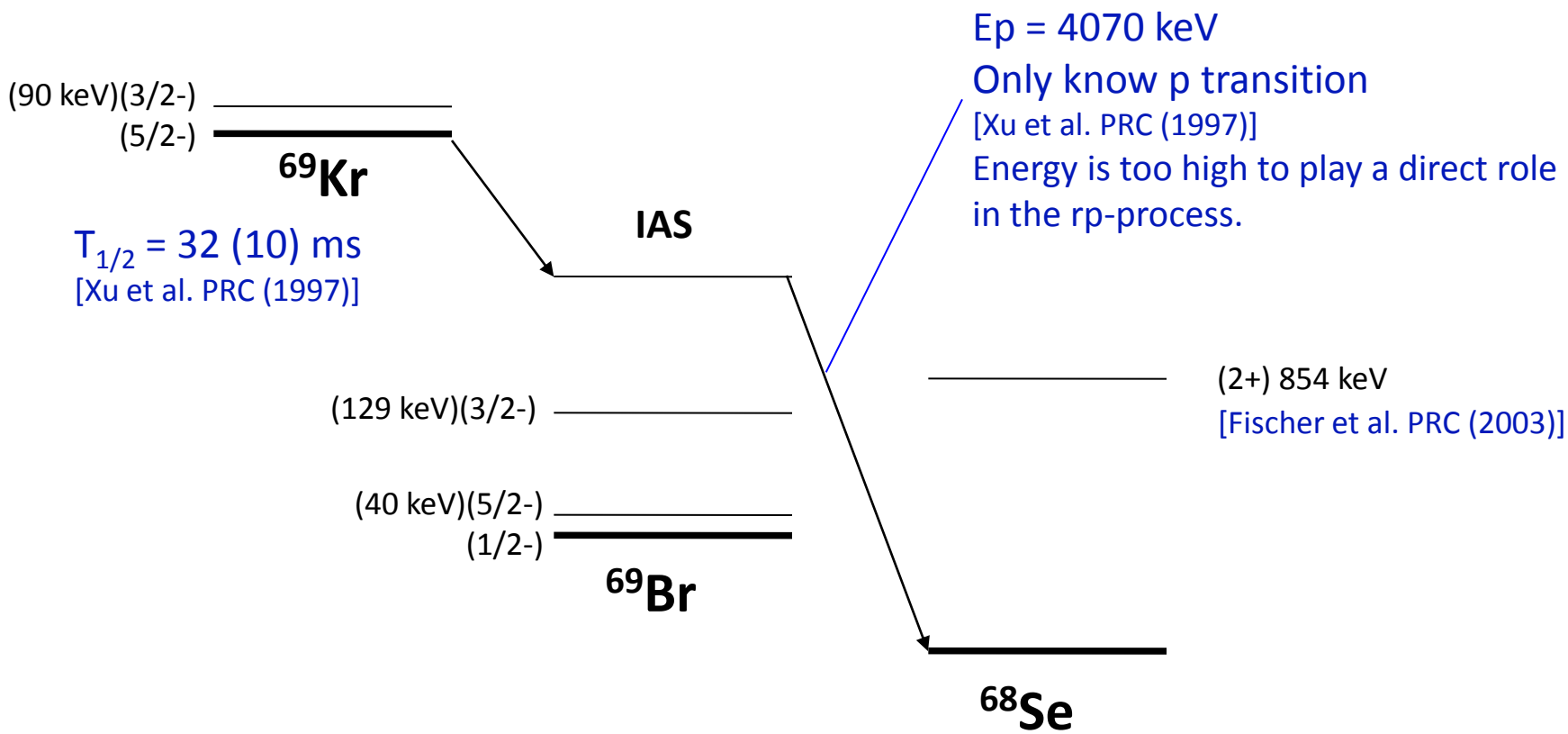
β delayed proton emission of ^{69}Kr

$$^{69}\mathrm{Kr} \longrightarrow e^{+} + \nu_e + {}^{69}\mathrm{Br}$$

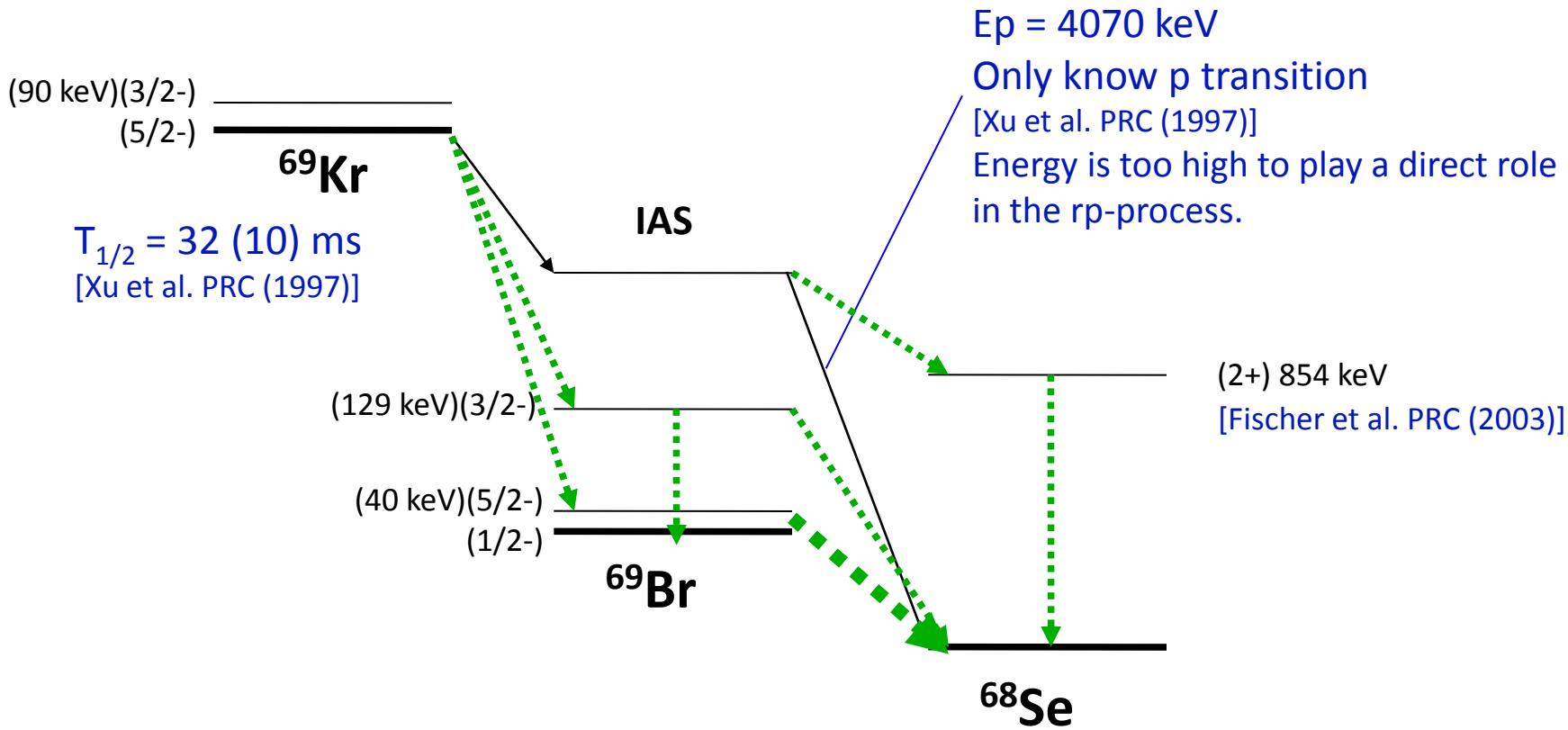
β decay (ms)

$$^{69}\mathrm{Br} \longrightarrow {}^{68}\mathrm{Se} + p$$

^{69}Kr β-delayed proton emission



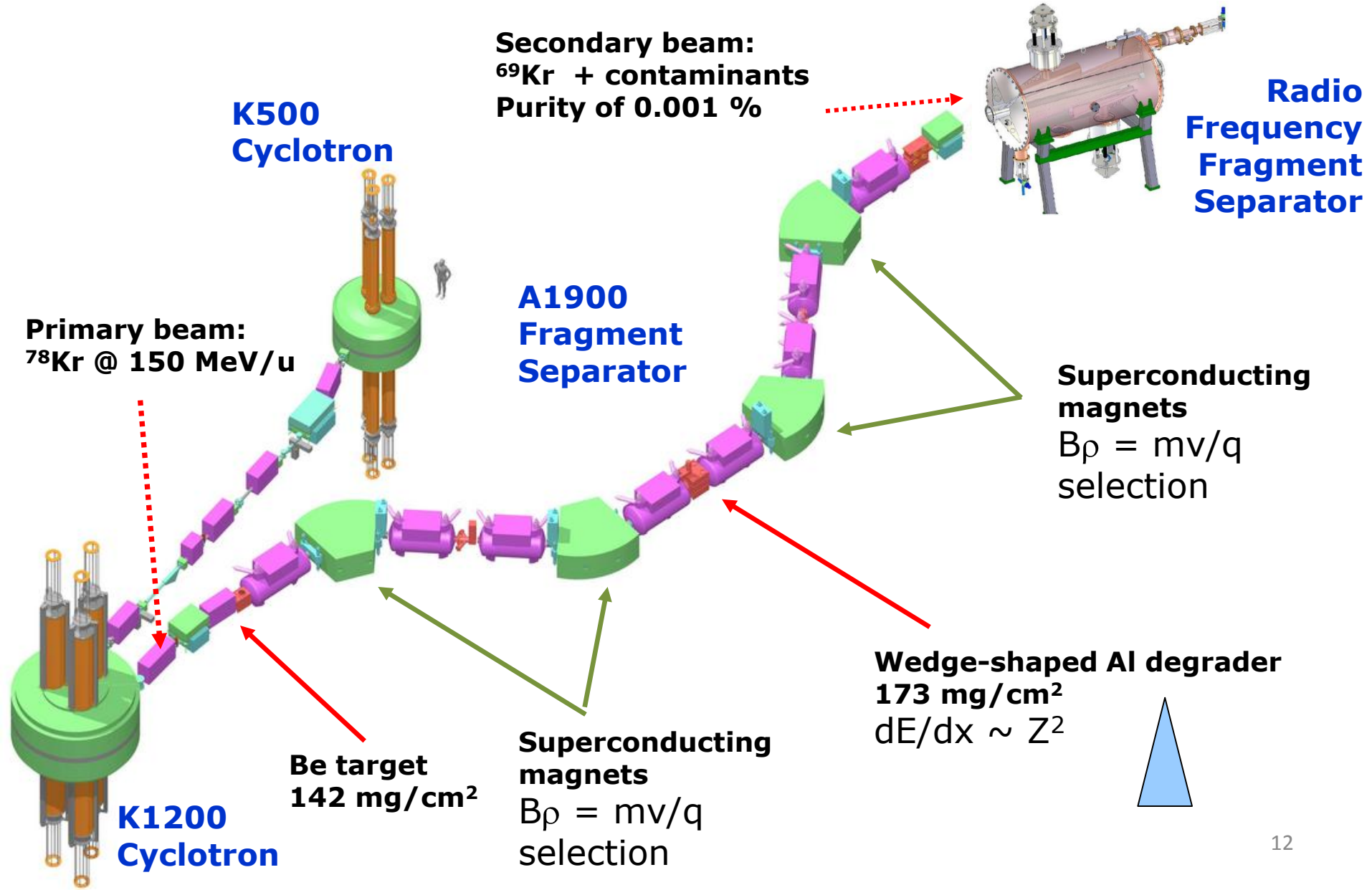
^{69}Kr β-delayed proton emission



Our Goal

Identify branches of β-delayed proton emission, particularly from the lower states in ^{69}Br to better constrain the proton separation energy

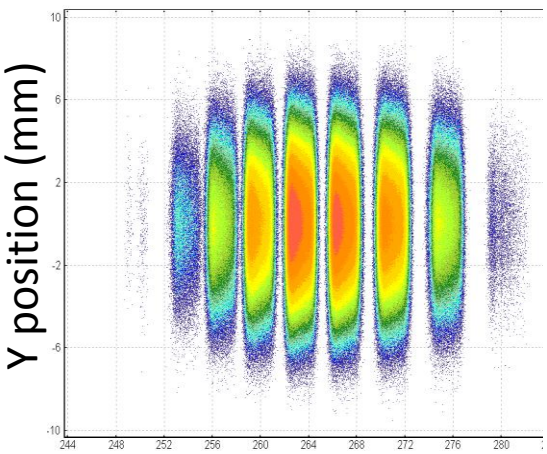
Beam production at NSCL

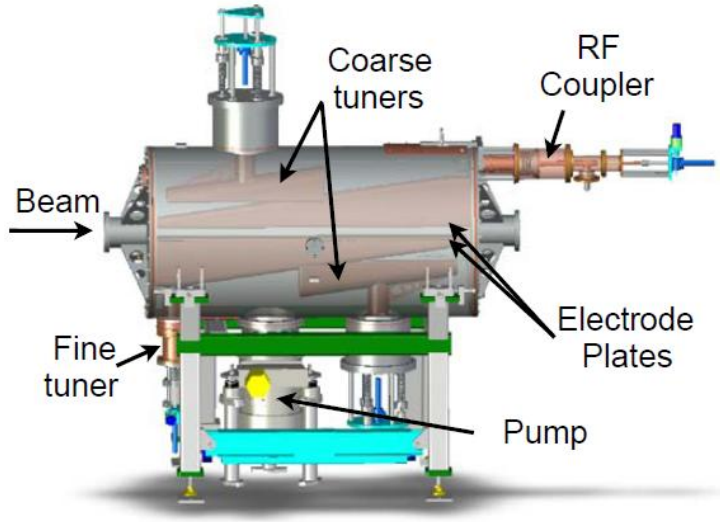


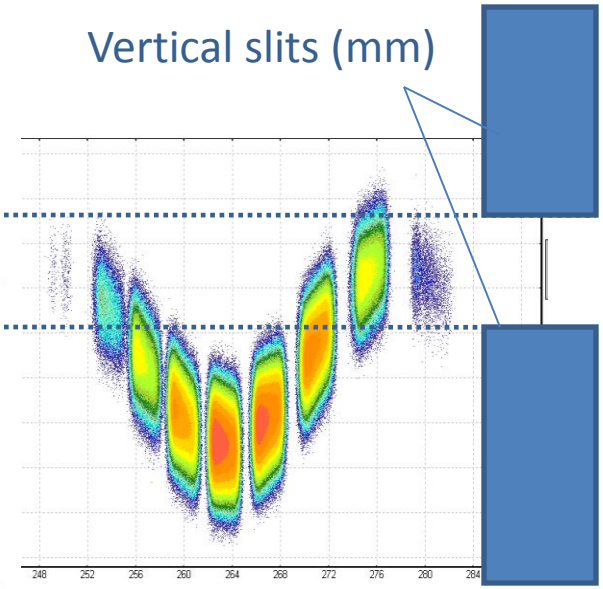
The Radio Frequency Fragment Separator at NSCL

RFFS

(^{69}Kr, ^{67}Se, ^{66}As, ^{62}Cu, ^{60}Ni, ^{59}Co, …)







RF electric field:
Frequency range: 17MHz to 27 MHz
Maximum peak voltage of 100 kV

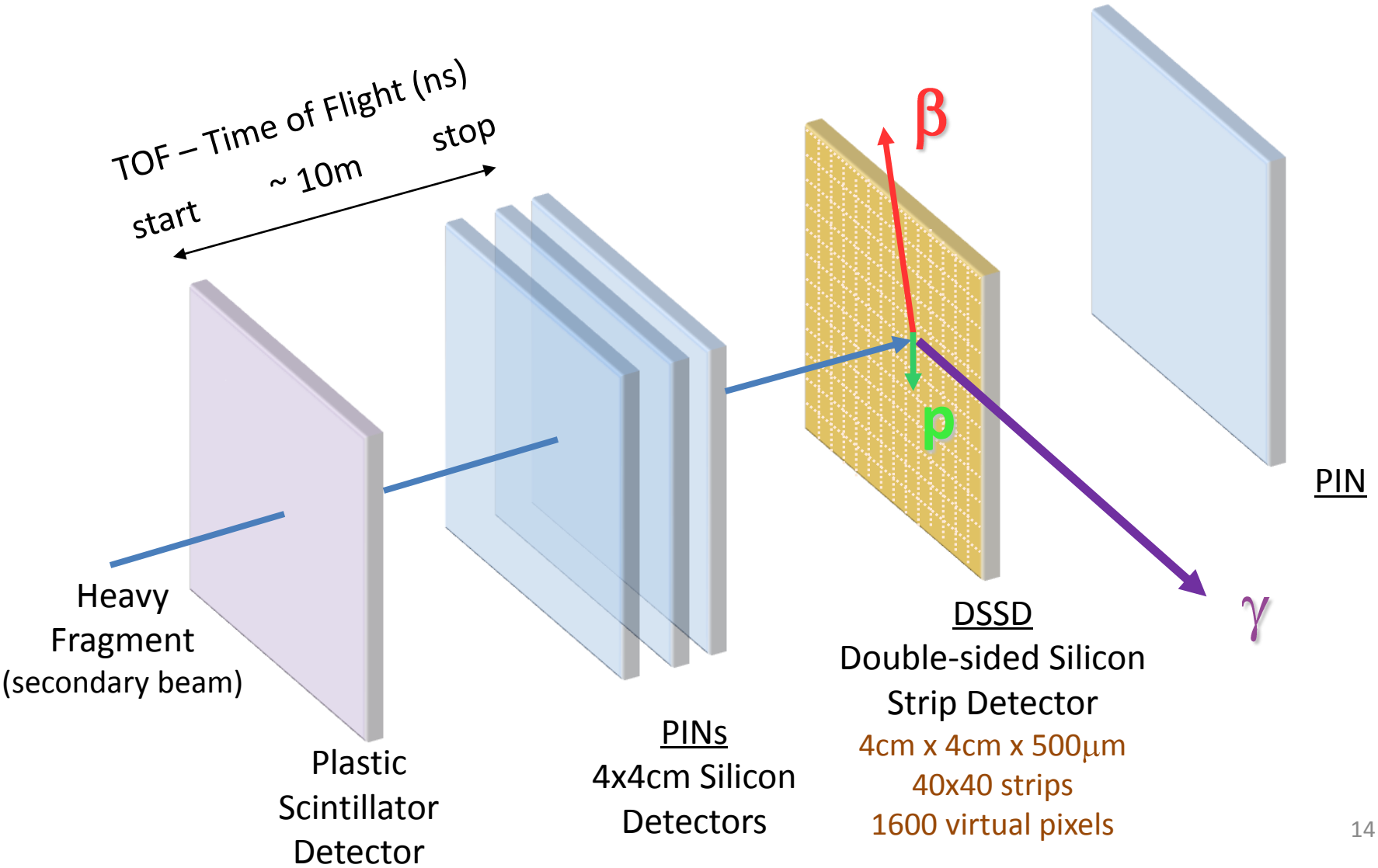
Electrodes parallel deflecting plates:
1.5m long, 5cm gap

	69Kr (pps)	Contaminants (pps)	Purity (%)
Without RFFS	0.02	4500	0.00044
With RFFS	0.02	70	0.028

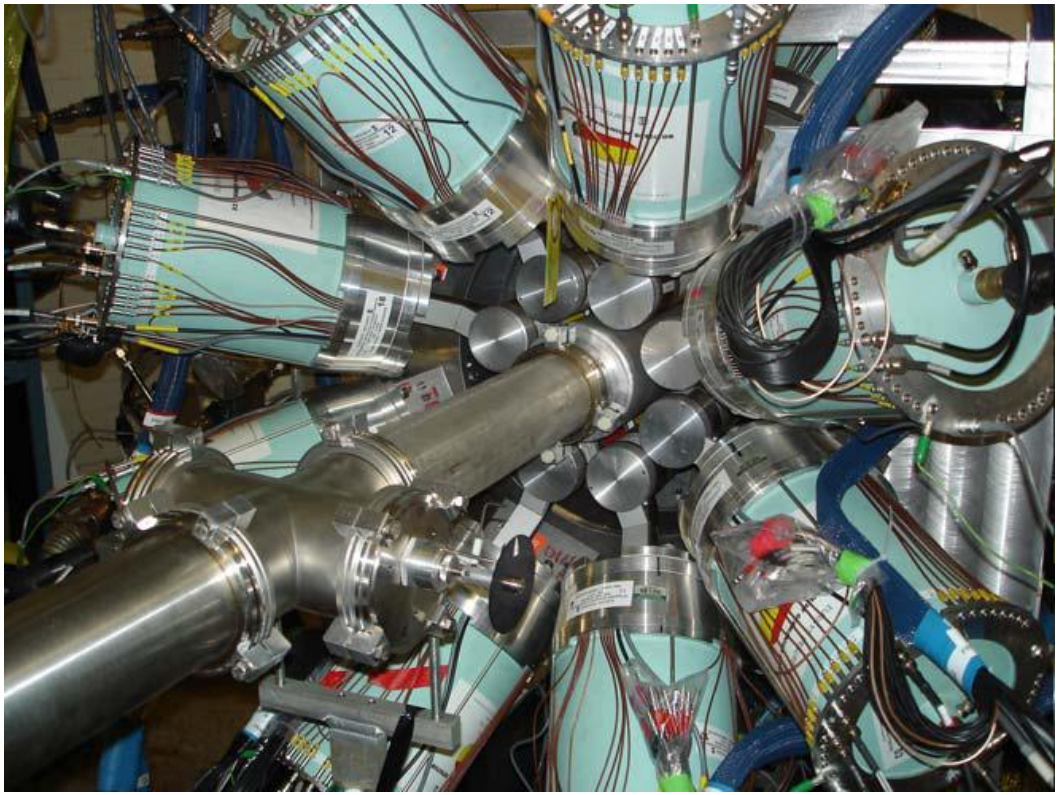
~ factor 60

Beta Counting System - BCS

Identify each fragment and correlate with their subsequent β or βp decay



BCS and SeGA

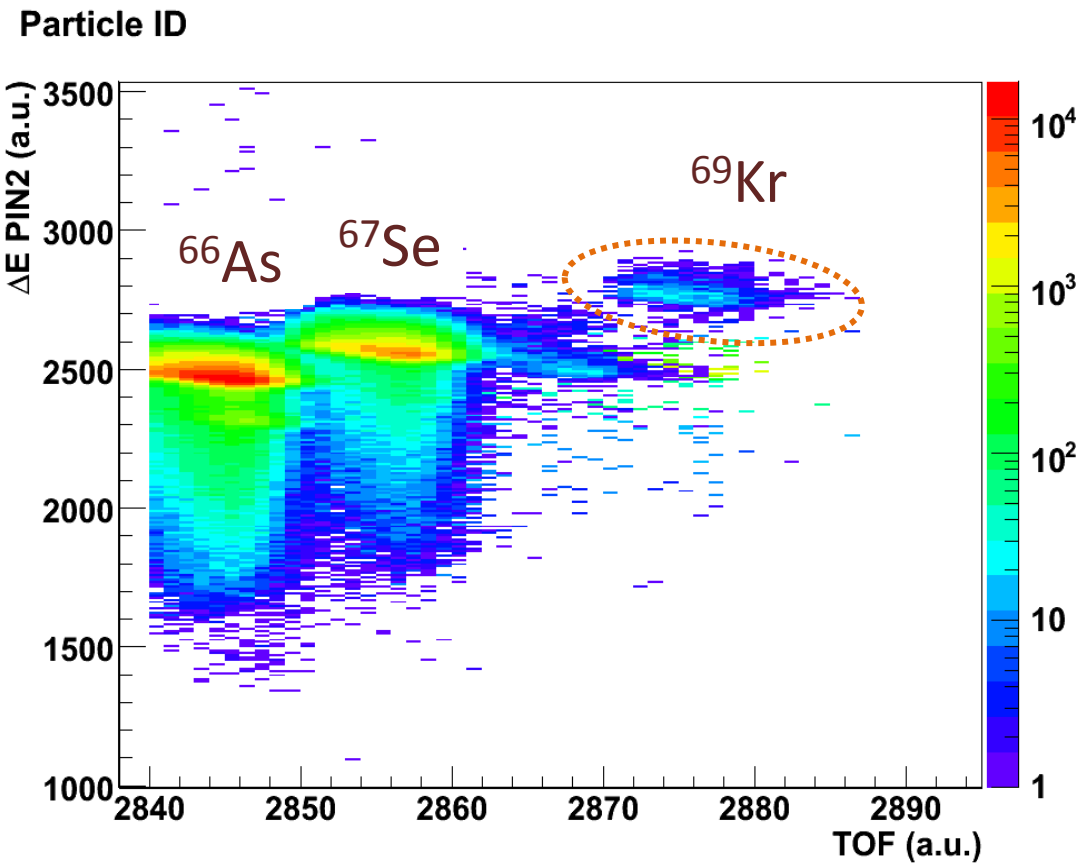


SeGA: 16 high purity segmented Ge detectors surrounding BCS for for gamma detection

Total efficiency 7% at 1MeV

BCS: PIN detectors + 3 DSSDs
Resolution of 100 keV at 8 MeV

Particle Identification (PID)



- Implants on DSSD

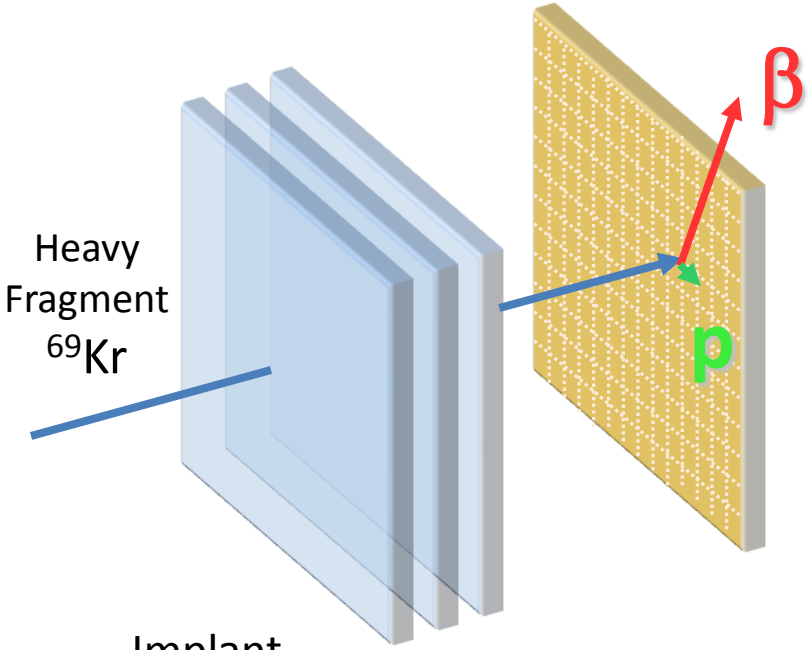
^{66}As and ^{67}Se: β

^{69}Kr: 100% βp

<u>Next step:</u>

Look for correlated decays in the same pixel of the implant in the DSSD

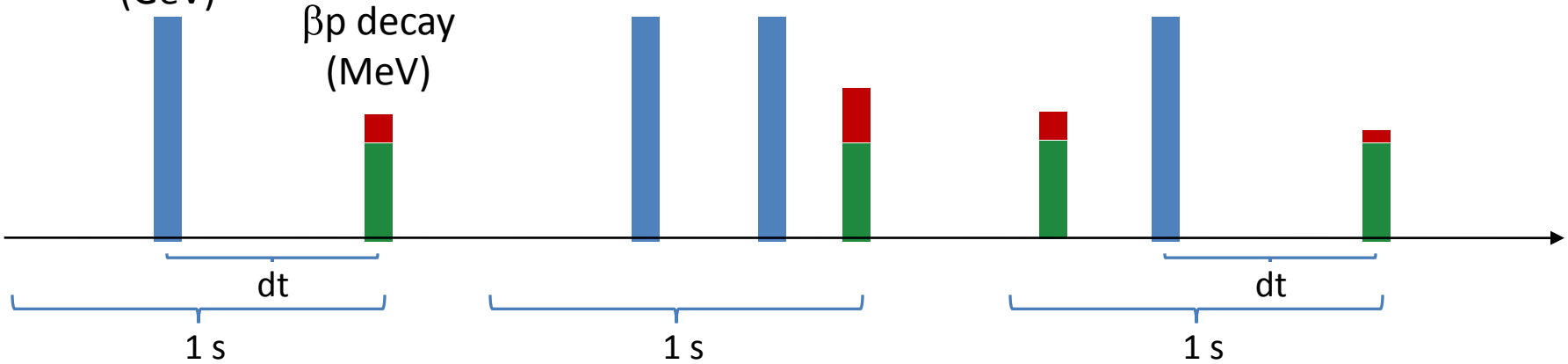
Correlations



How correlation works:

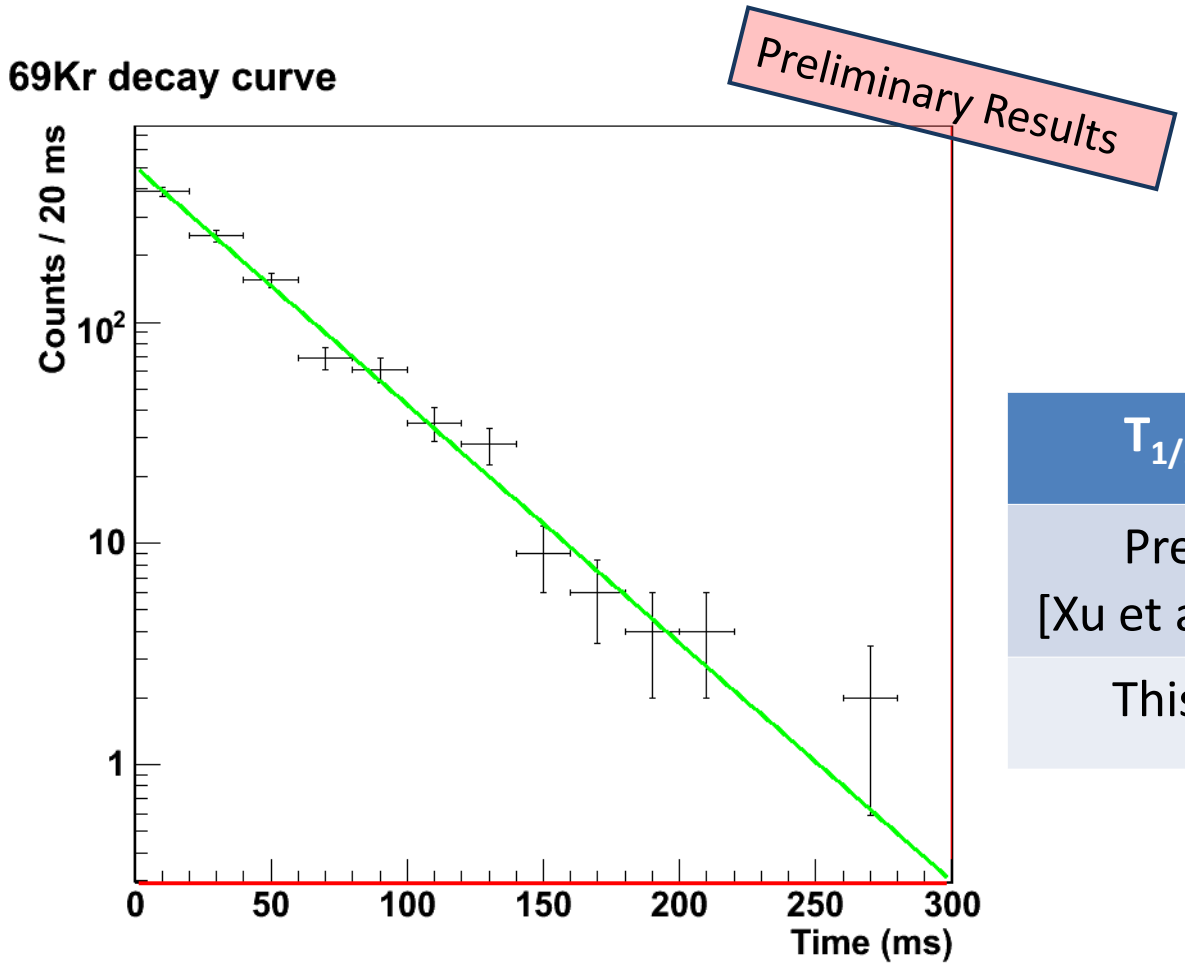
Implant or decay event

- Find a decay:
  - only a signal in DSSD
- look back for implants:
  - a signal in PIN1,2,3 and in DSSD
  - in the same pixel (or in a small box)
  - within 1 second
  - particle ID: gate on ^{69}Kr
  - decay time (dt)



Event Time Line (ms)

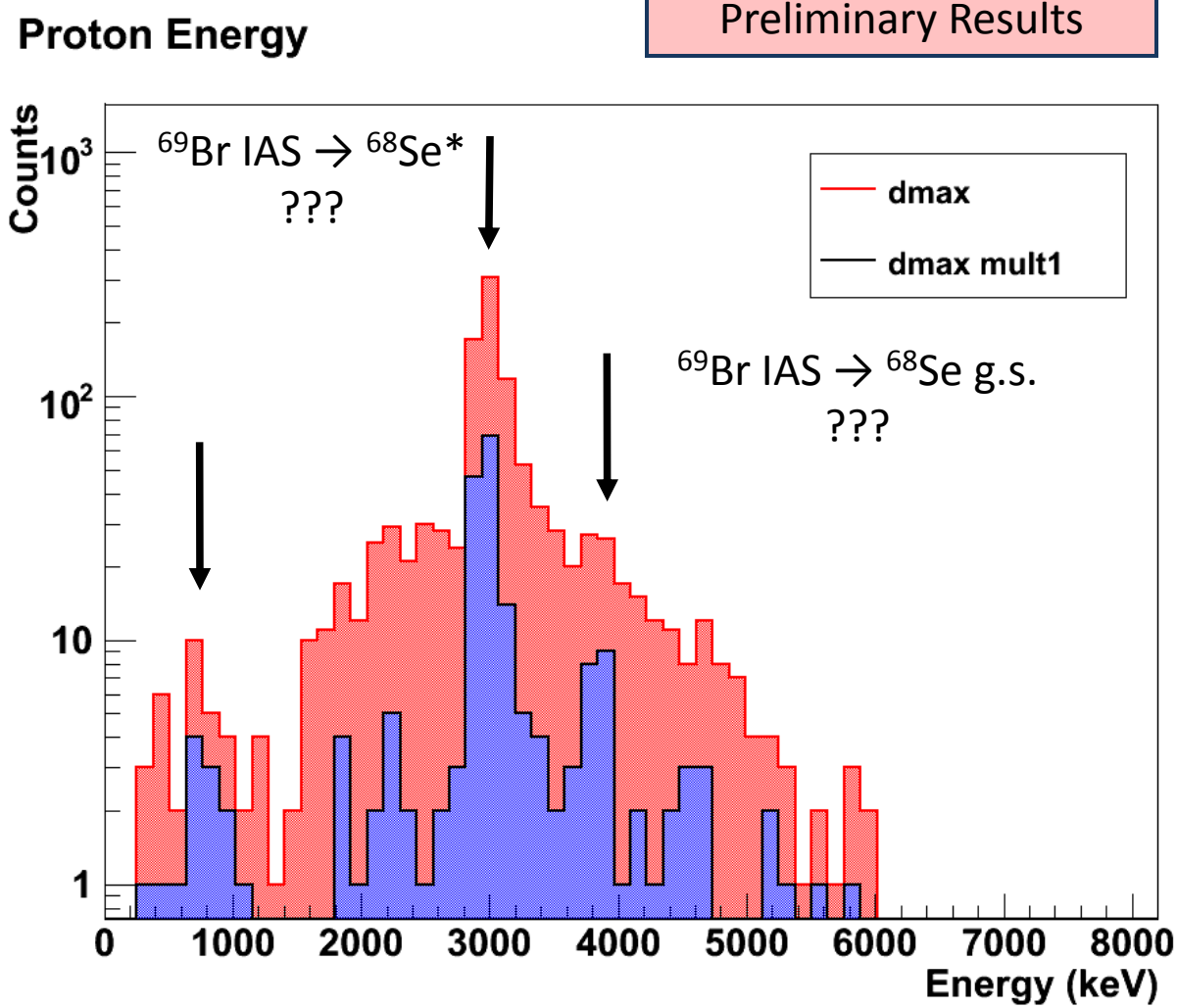
^{69}Kr decay curve and half life

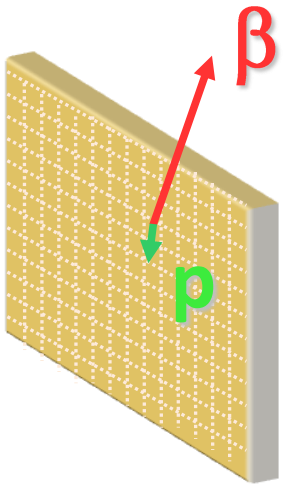


$T_{1/2}$ (ms)	^{69}Kr
Previous [Xu et al. (1997)]	32 ± 10
This work	28 ± 1

β delayed proton energy spectra

Preliminary Results





Summing Effect

$$E_T = E_p + E_\beta$$

[see Zach Meisel´s talk]
Corrections ~100 keV
GEANT 4 simulation

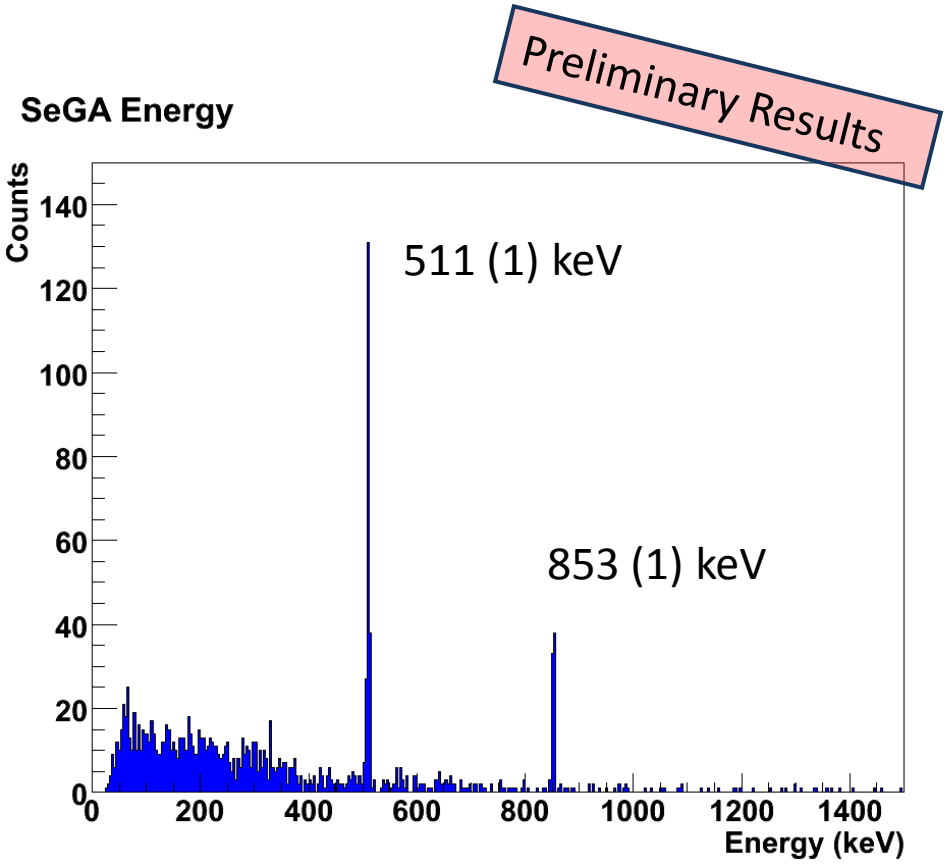
minimize summing effect
select mult. 1 events

Summary

- Waiting point nuclei slow down the energy generation and can explain some observed bursts with long duration
- Effective life time of the ^{68}Se depends on the S_p
- Determines the shape and duration of X-ray Bursts light curves
- Experiment to constrain the S_p of ^{69}Br
- β-decay branches to low energy levels

Collaboration: Hendrik Schatz, Paul Mantica, Marcelo Del Santo, Heather Crawford, Geoff Grinyer, Jorge Pereira, Fernando Montes, Giuseppe Lorusso, Ana Becerril, Zach Meisel, Alfredo Estrade, Karl Smith, Richard Cyburt

γ-ray spectra



- 511 keV line
  Electron-positron annihilation energy
  Good test for calibration

- 853 (1) keV
  γ decay from $^{68}Se^{*} \rightarrow {}^{68}Se$ g.s.

Beta Decay Campaign @ NSCL MAR-APR 2010

- B-delayed proton decay of the proton rich 39Ti:

  - improve constraints on the energy window for 2p emission
  - prediction of direct 2p candidates below 45Fe

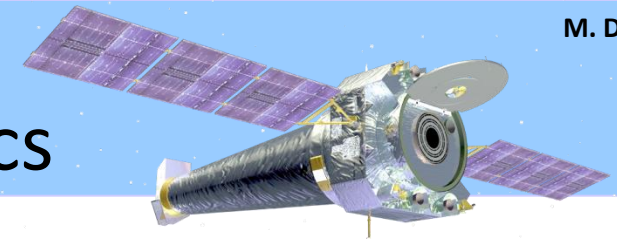
- Charged particle decay of proton rich 22,23 Si isotopes:

  - ground state two proton (2p) emitter candidate
  - characterize the β-decay and subsequent charged particle emission (β2p, β3p, βα, βαp)

- Beta delayed proton emission of 69Kr and the rp-process in X-ray bursts:

  - identify branches of beta delay proton-emission
  - better constrain the proton separation energy of 69Br

Bursts characteristics

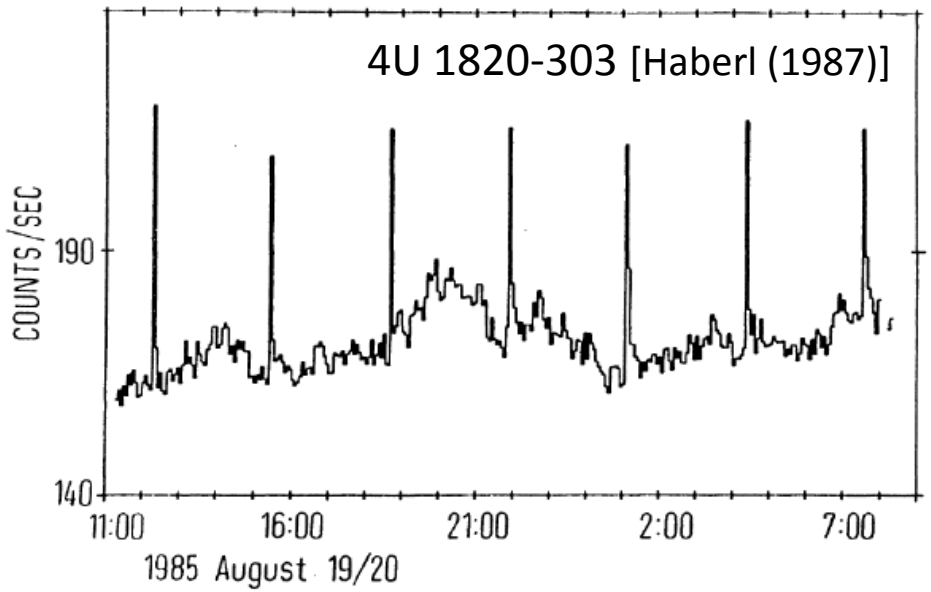


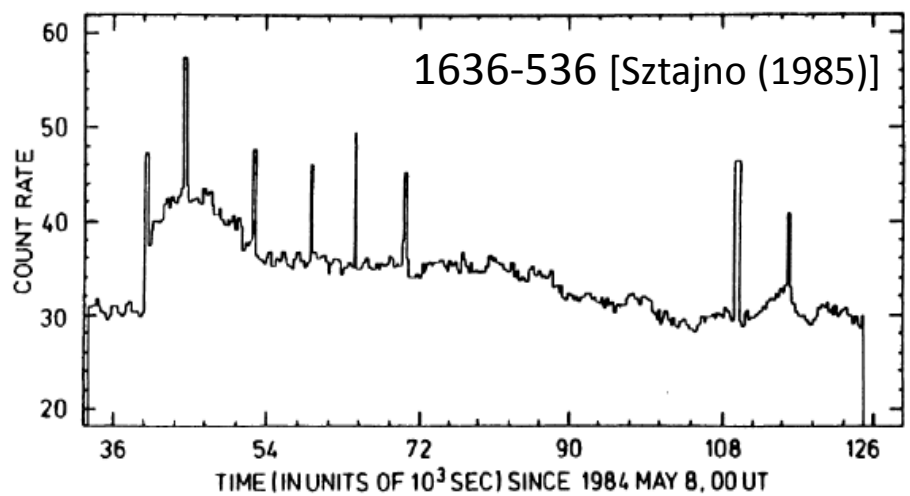
Typical X-ray bursts:

- duration: 10s – 100s
- recurrence: hours-days
- regular or irregular
- energy: 10^{36}-10^{38} erg/s

(stars 10^{33}-10^{35} erg/s)

Very bright and frequent phenomenon !





Today:
~230 X-ray binaries known
~160 LMXB's (low mass x-ray binary)
~70 burst sources

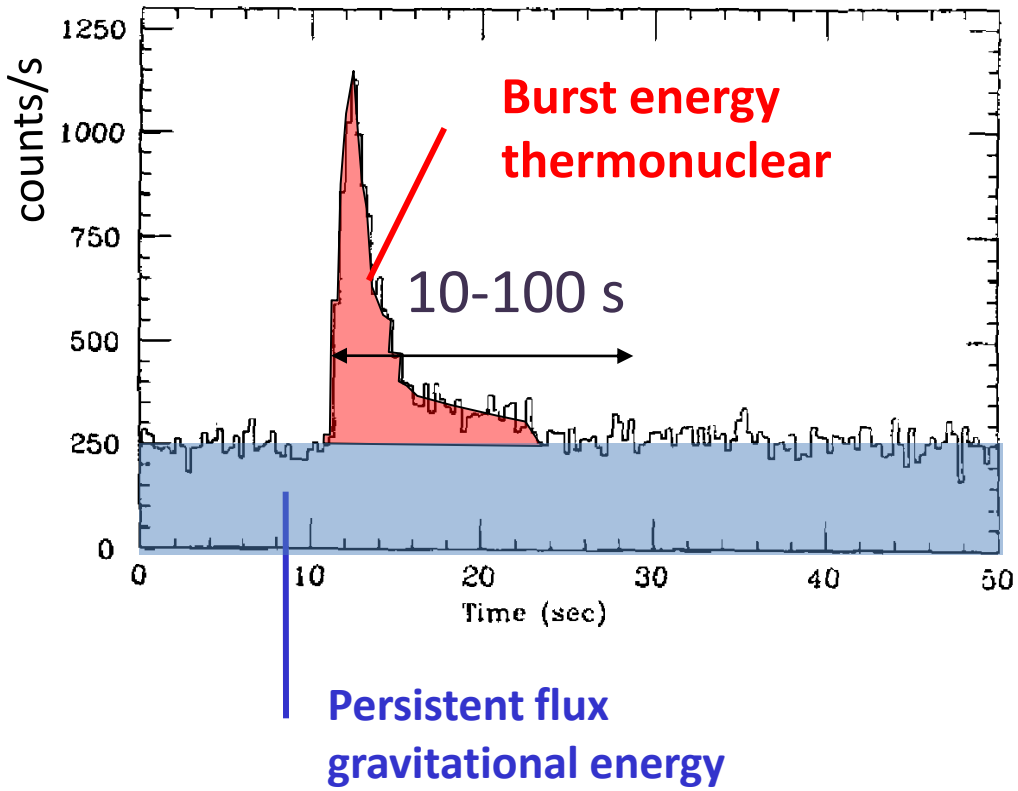
X-Ray Burst profile and classification

Type I:

- Nuclear energy (rp-process)
- Energy proportional to preceding inactivity period
- Fast rise: 1-2s
- Exponential decay profile

Type II:

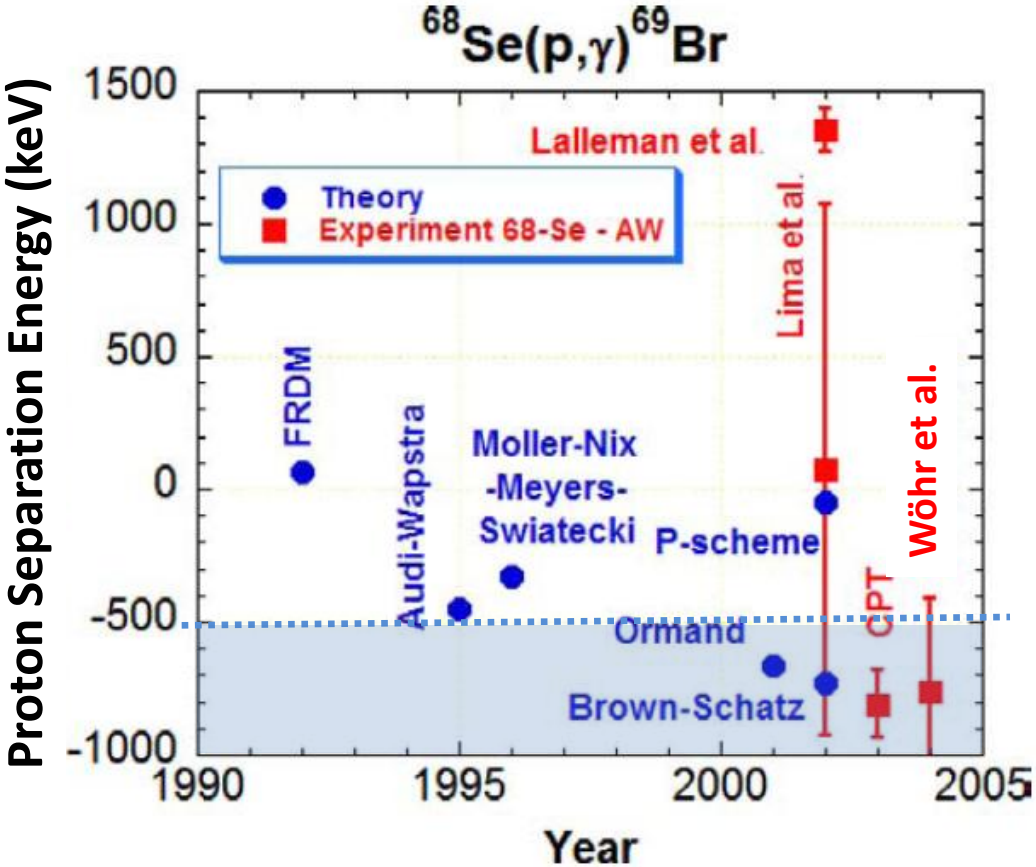
- Gravitational energy
- Energy proportional to following inactivity period



To interpret type I X-ray bursts:

- masses (proton separation energies)
- β-decay rates
- reaction rates (p-capture, α,p)

$^{68}Se(p,\gamma)^{69}Br$ Q-value



non-observation of ^{69}Br in projectile fragmentation experiments [Pfaff1996]

^{69}Br lifetime $T_{1/2} < 24$ ns

Sp < -500 keV

	Sp (keV)	Error (keV)	
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