β-decay in Neutron Star Crusts

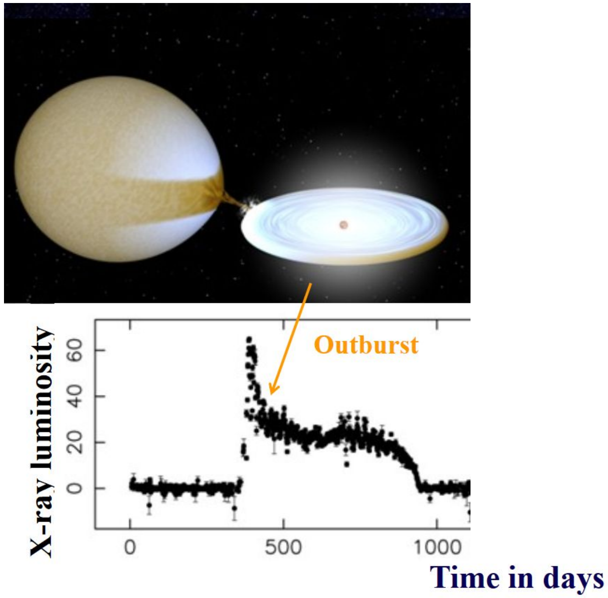
NSCL

FRIB

-Rahul Jain

NPA X Conference, CERN, September 7, 2022

Transient Systems

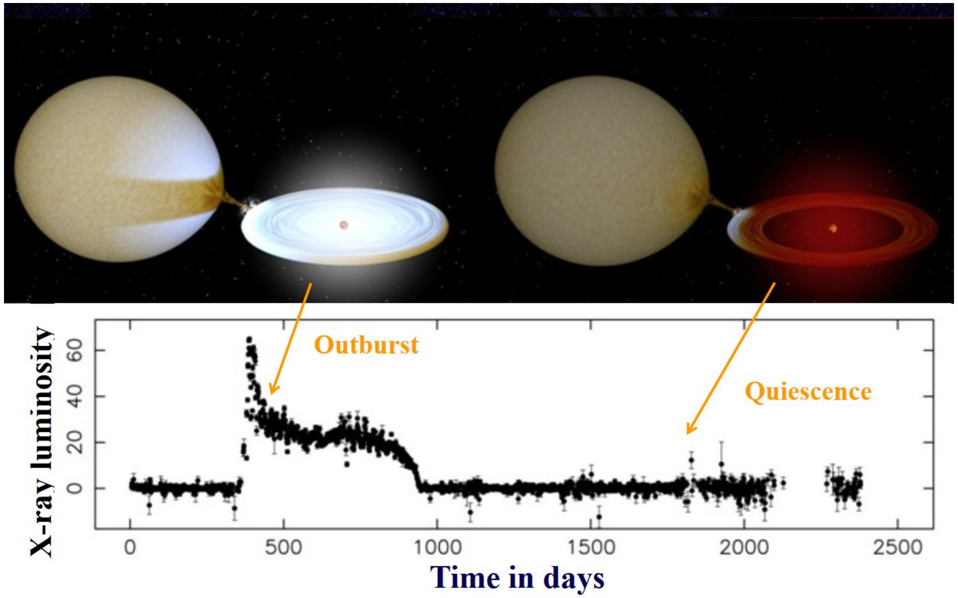


<u>Accretion Outburst:</u>

Rapid Accretion

Bright X-ray Emission

Transient Systems



<u>Accretion Outburst:</u>

Rapid Accretion

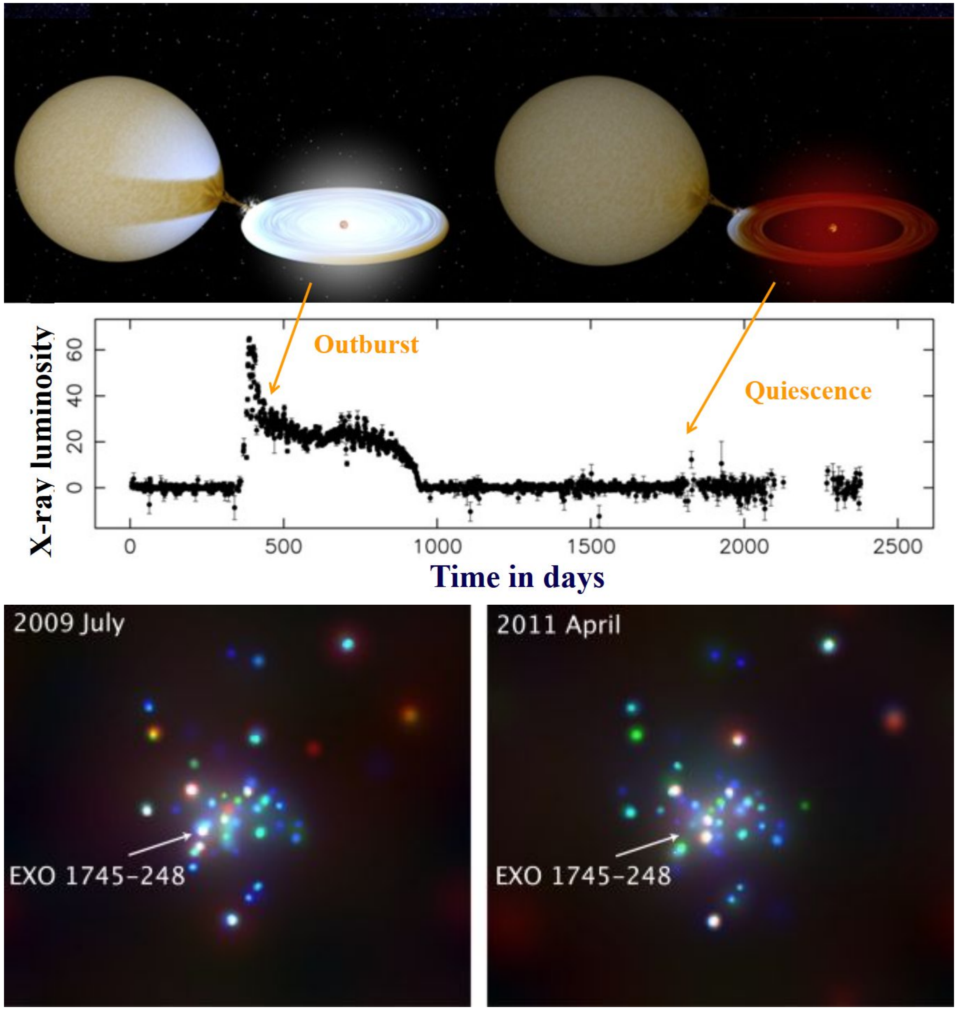
Bright X-ray Emission

<u>Quiescence</u>:

Little/No Accretion

Faint X-ray Emission

Transient Systems



<u>Accretion Outburst:</u>

Rapid Accretion

Bright X-ray Emission

<u>Quiescence</u>:

Little/No Accretion

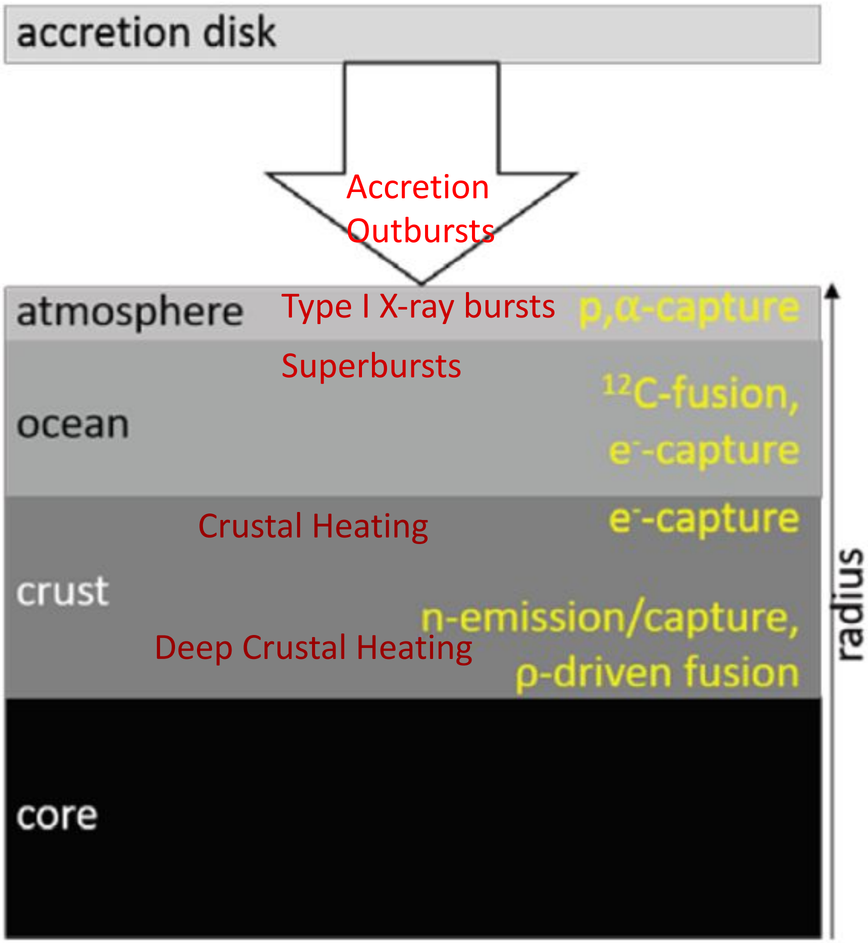
Faint X-ray Emission

Globular Cluster Terzan 5

with

Chandra X-ray Satellite

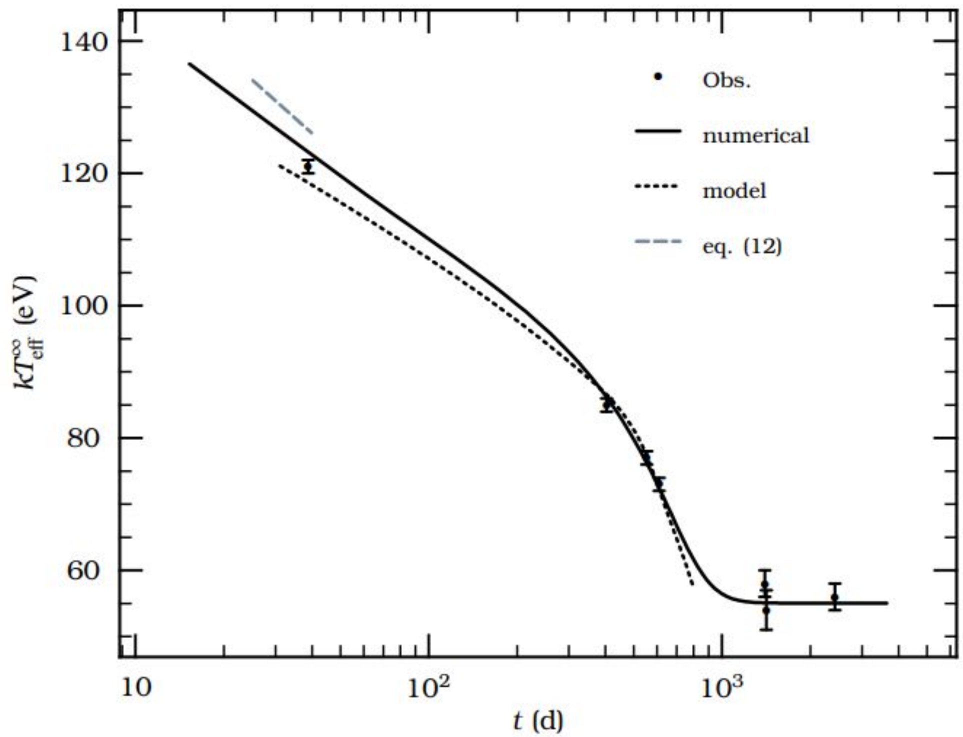
Outburst Phase



Nuclear reactions deposit energy in the crust during outburst.

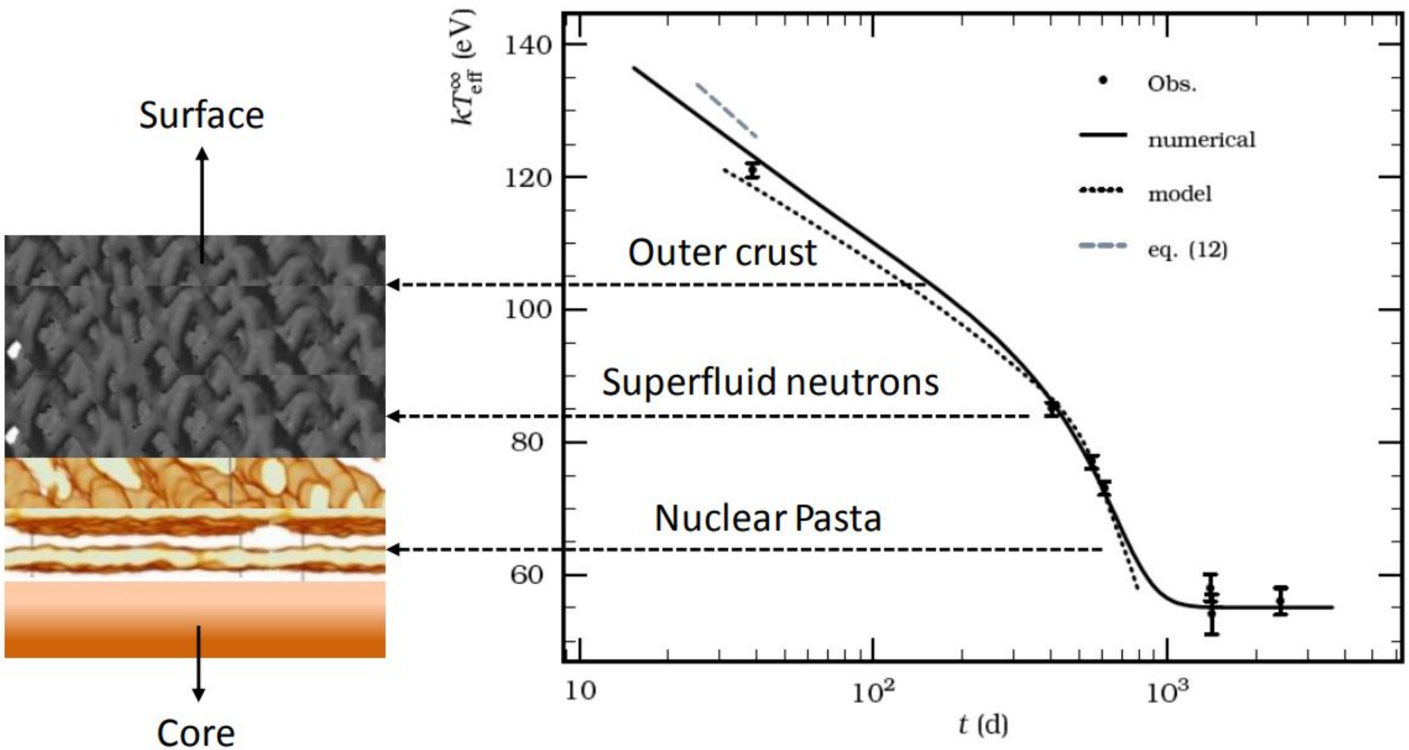
Quiescence Phase

The crust is thermally relaxed during quiescence.



Brown and Cumming 2009 *ApJ* 698 1020

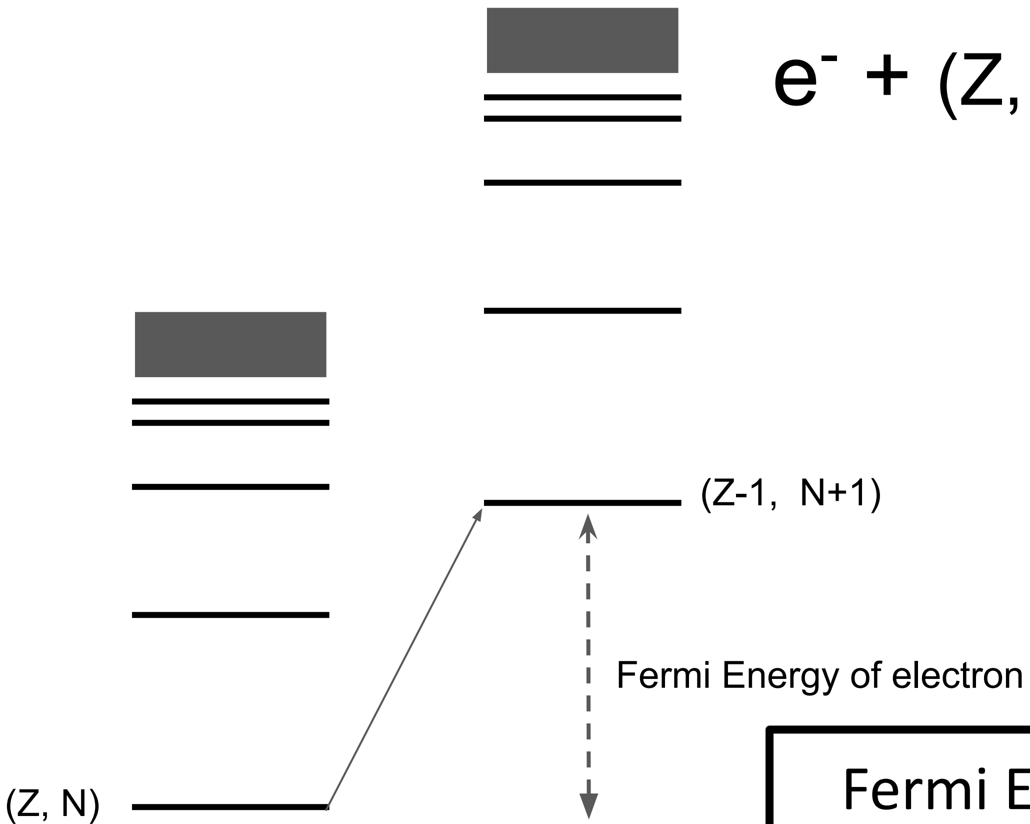
Quiescence Phase

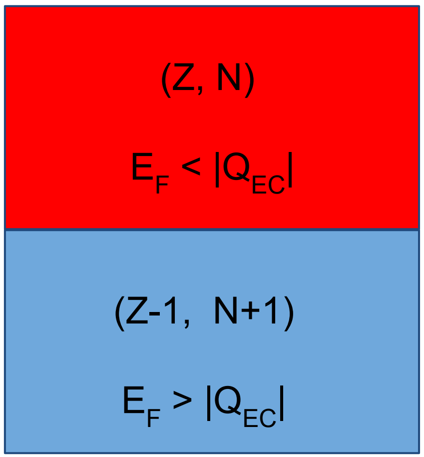


Brown and Cumming 2009 *ApJ* 698 1020

e^- Captures in Neutron Star Crusts

$$e^- + (Z, N) \longrightarrow (Z\text{-}1, N\text{+}1) + \nu_e$$

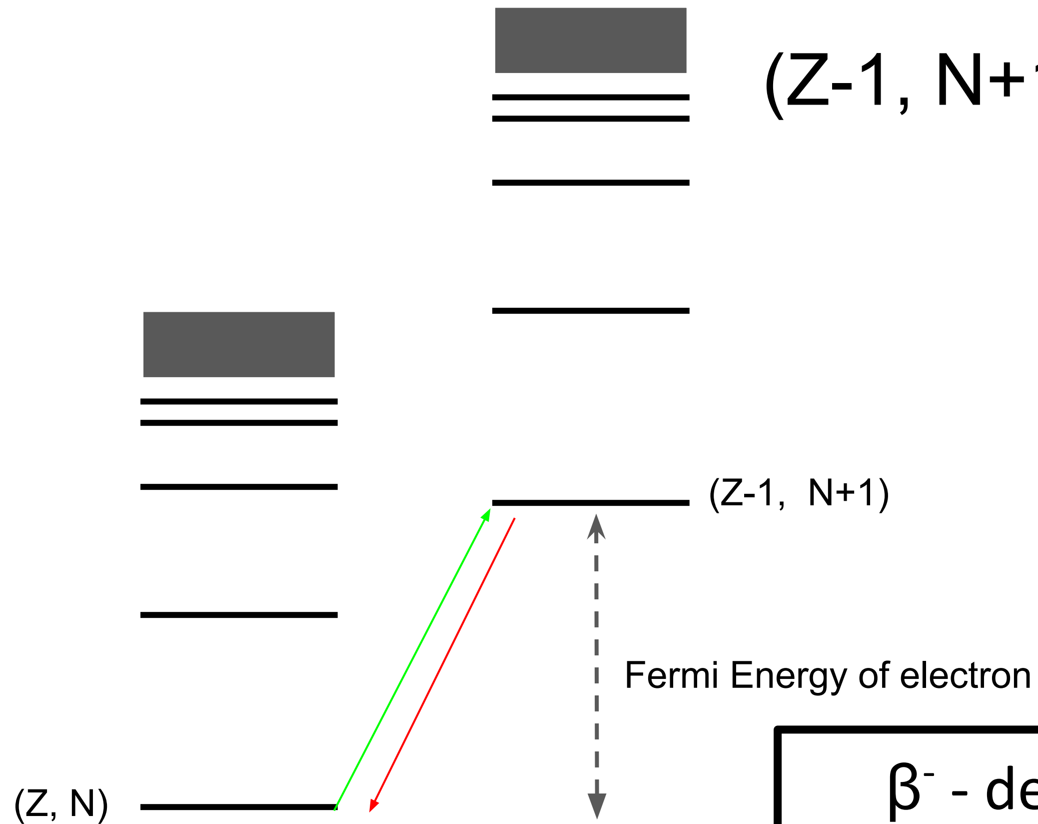




Fermi Energy of the electron helps overcome Electron Capture Threshold

e^- Captures in Neutron Star Crusts

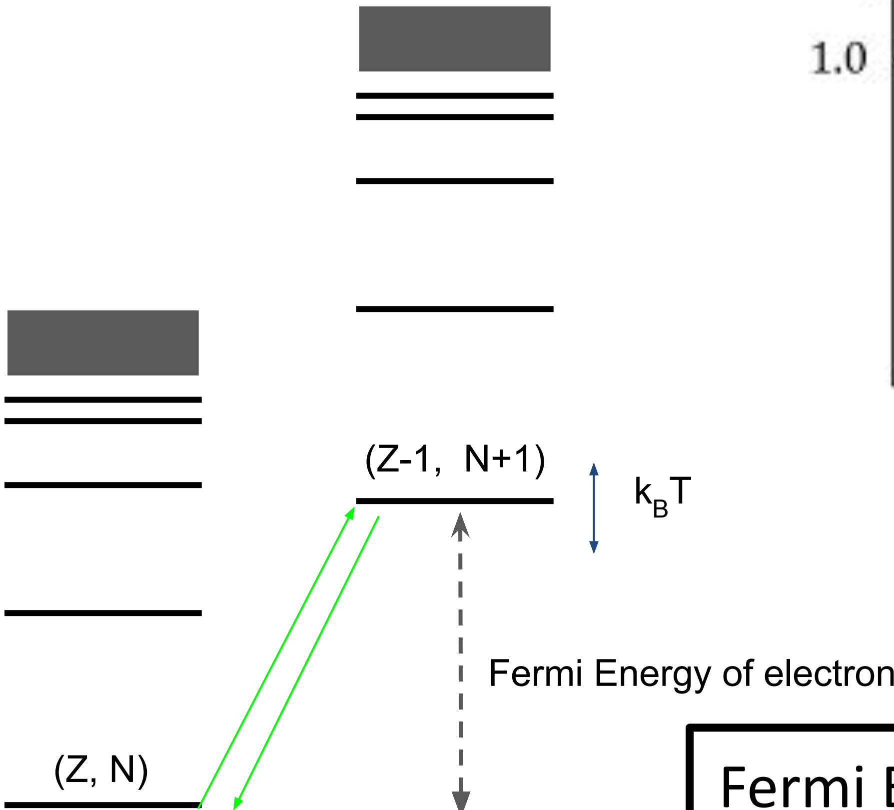
$$(Z\text{-}1, N\text{+}1) \not\longrightarrow (Z, N) + e^- + \bar{\nu}_e$$

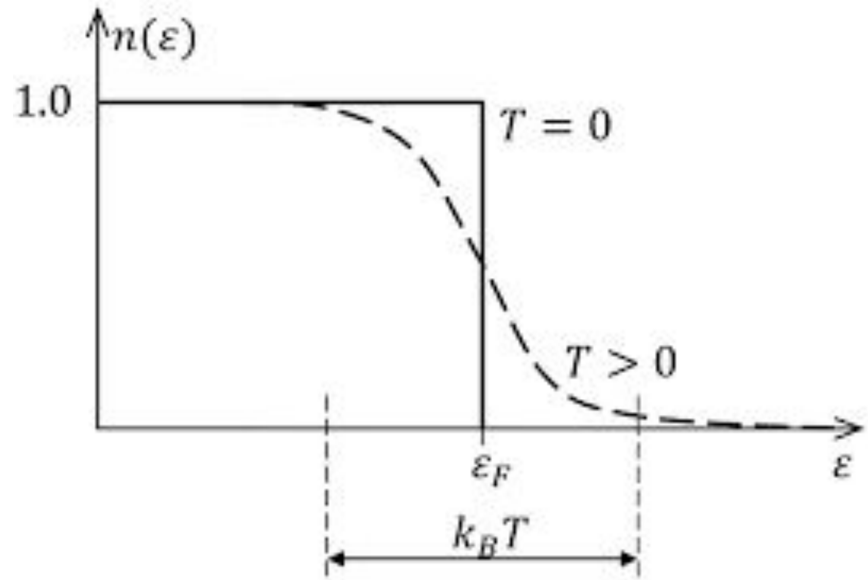


(Z, N) $E_F < \lvert Q_{EC} \rvert$
(Z-1, N+1) $E_F > \lvert Q_{EC} \rvert$

β^- - decay not allowed since the emitted electron has no phase space

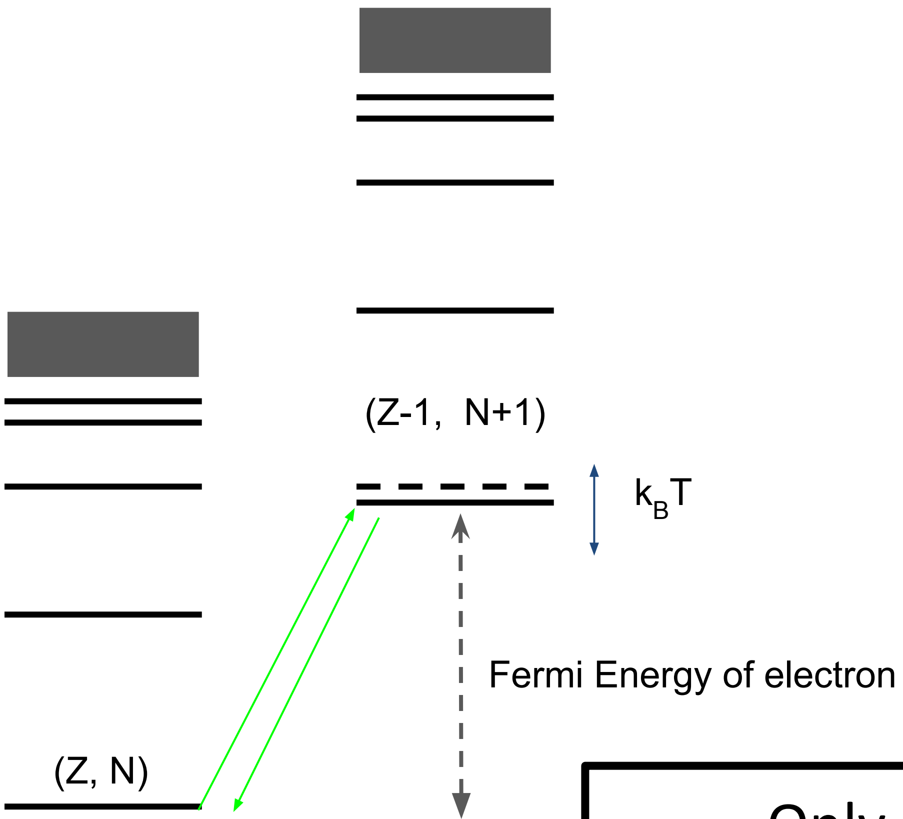
Urca Cooling

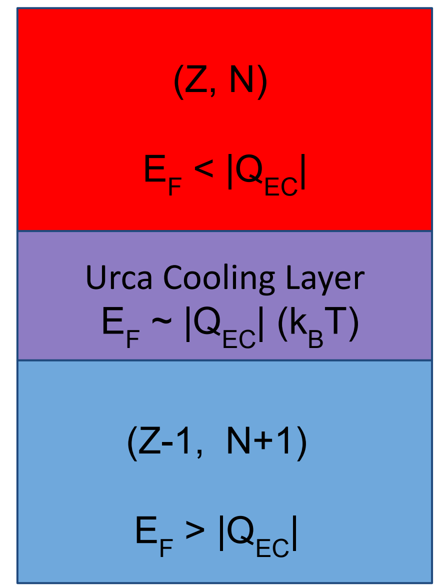




Fermi Energy of electron has a spread at finite temperature

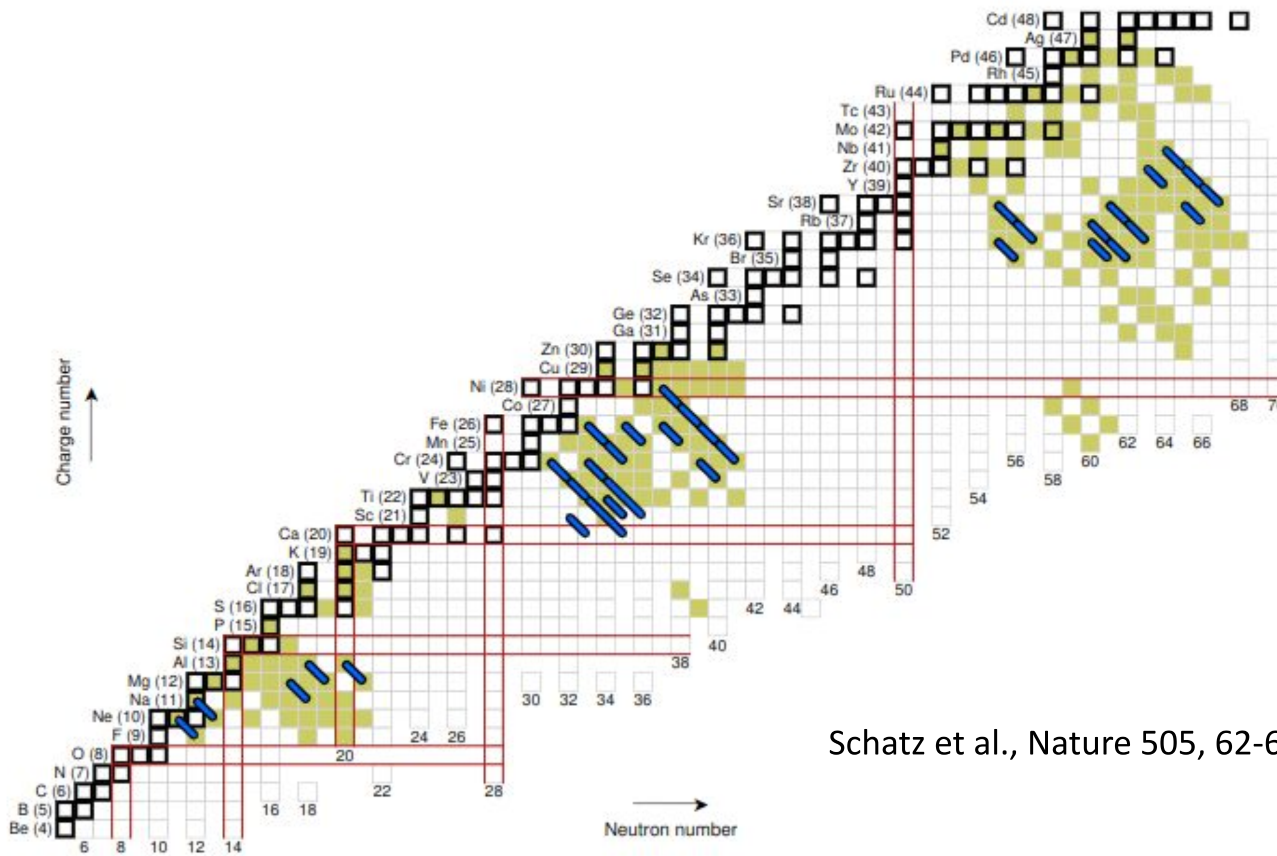
Urca Cooling





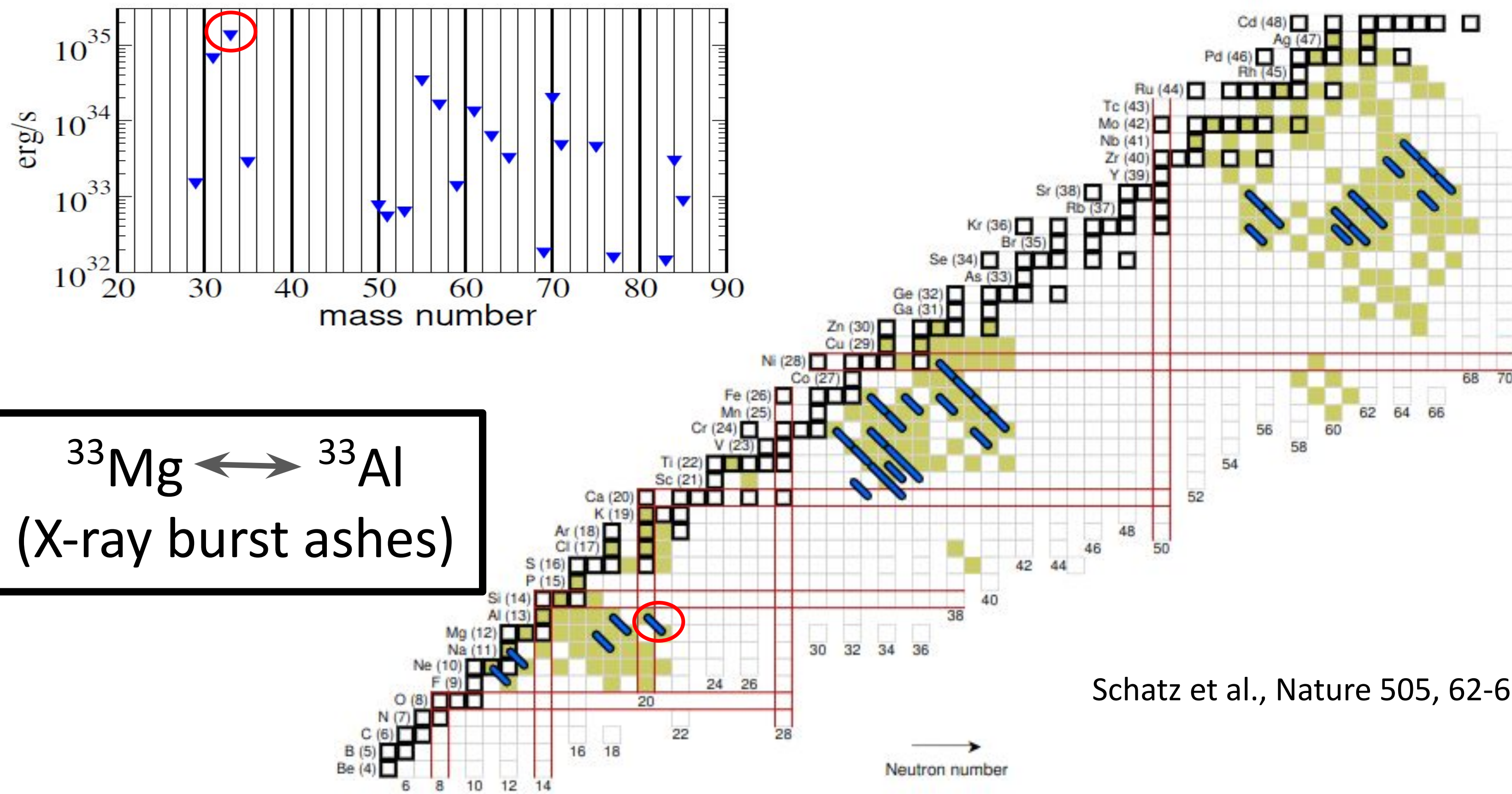
Only gs-gs transitions important.
Low-lying excited within k_BT also contribute.

Dominant Cooling Agents



Schatz et al., Nature 505, 62-65 (2014).

Dominant Cooling Agents



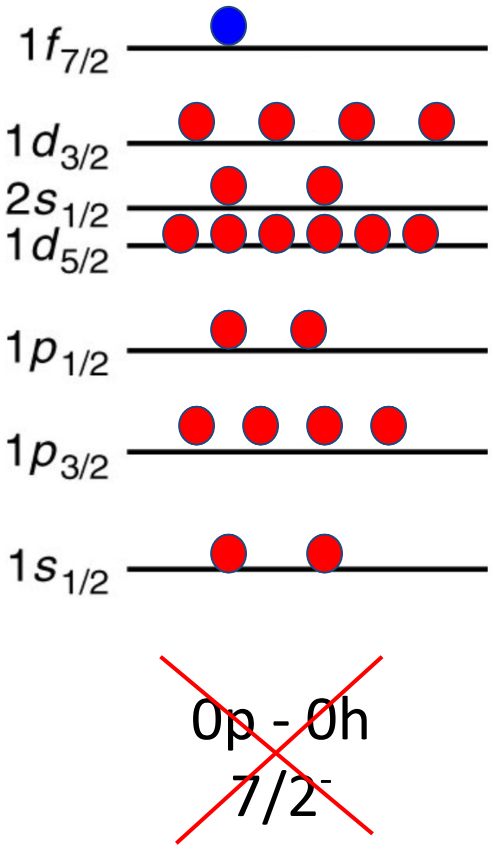
$^{33}Mg \longleftrightarrow {}^{33}Al$

(X-ray burst ashes)

Schatz et al., Nature 505, 62-65 (2014).

^{33}Mg ground-state Anomaly

^{33}Mg: 12 protons, 21 neutrons



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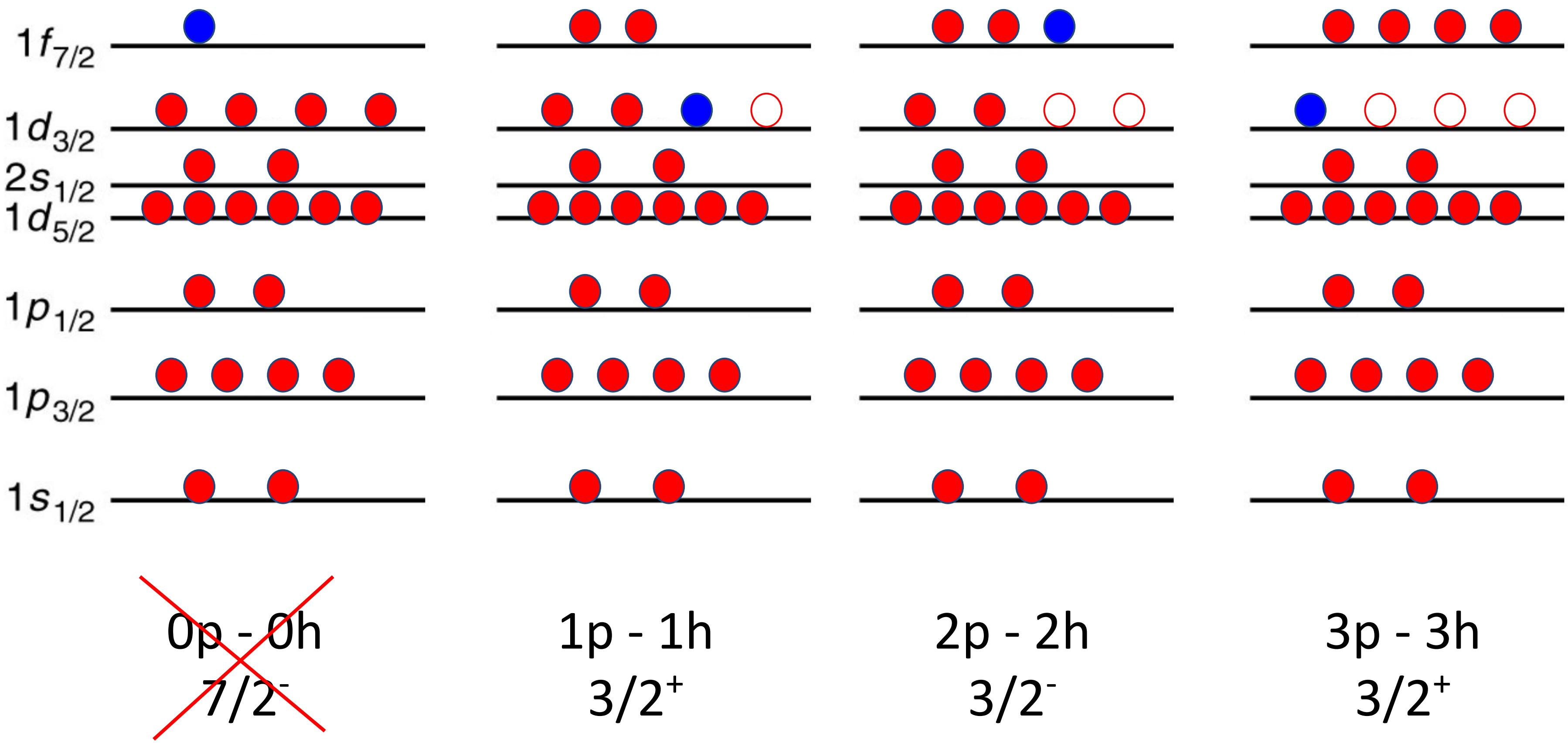
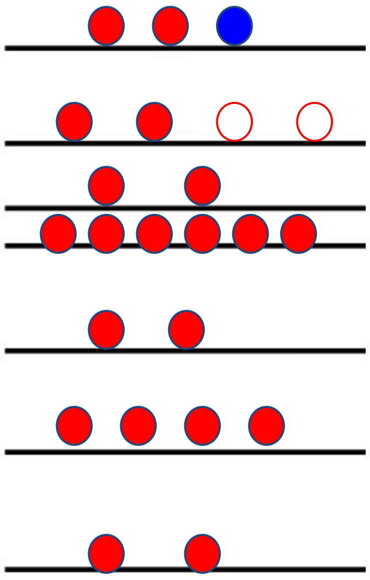


^{33}Mg ground-state Anomaly

^{33}Mg: 12 protons, 21 neutrons

Yordanov et al., Phys. Rev. Lett. **99**, 212501 (2007)



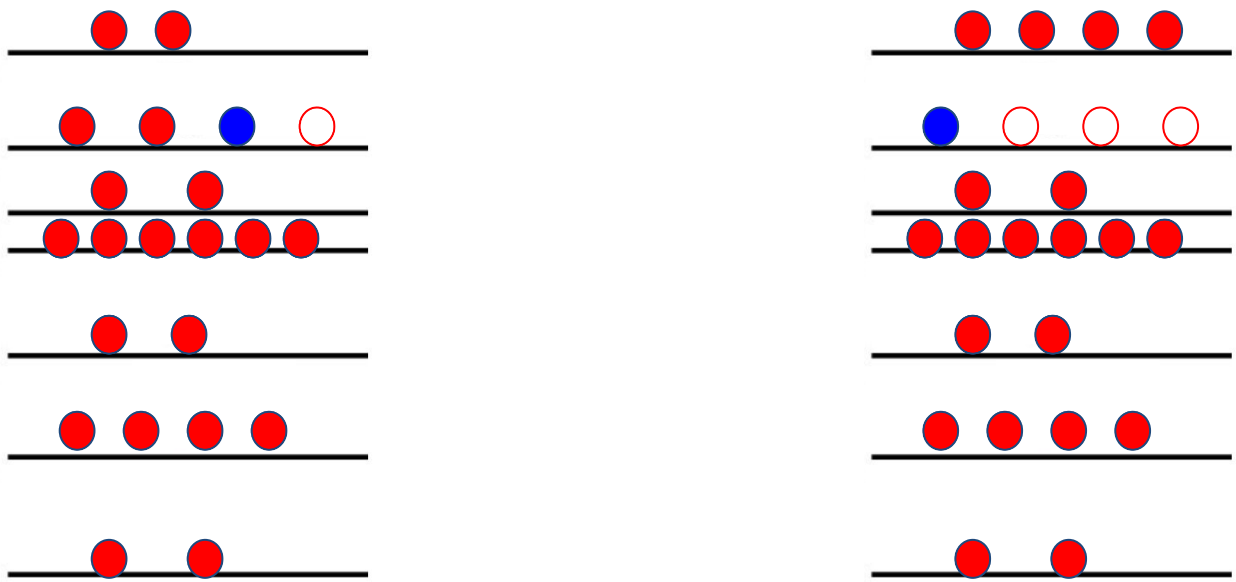
2p - 2h

$3/2^-$

^{33}Mg ground-state Anomaly

^{33}Mg: 12 protons, 21 neutrons

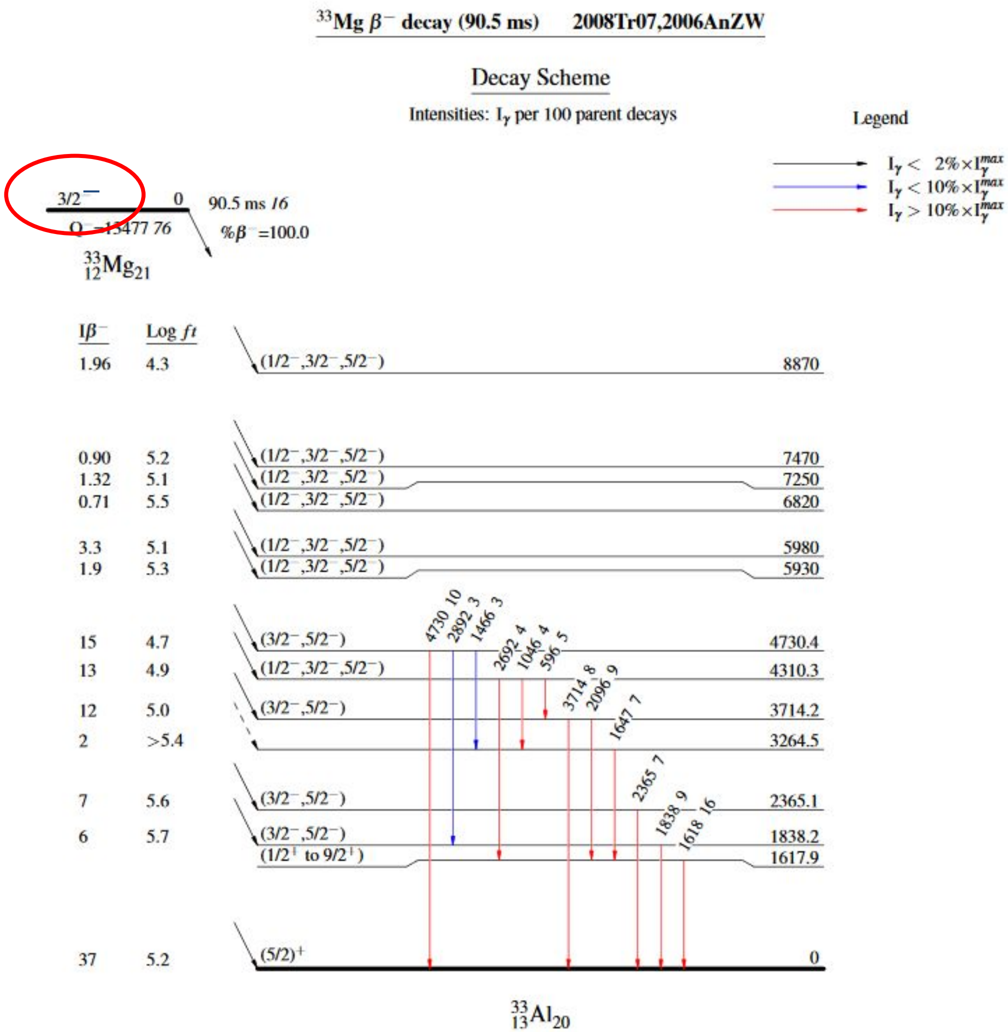
Tripathi et al., Phys. Rev. Lett. **101**, 142504 (2008)



1p - 1h
$3/2^+$

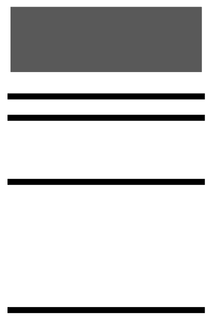
3p - 3h
$3/2^+$

^{33}Mg ground-state Anomaly



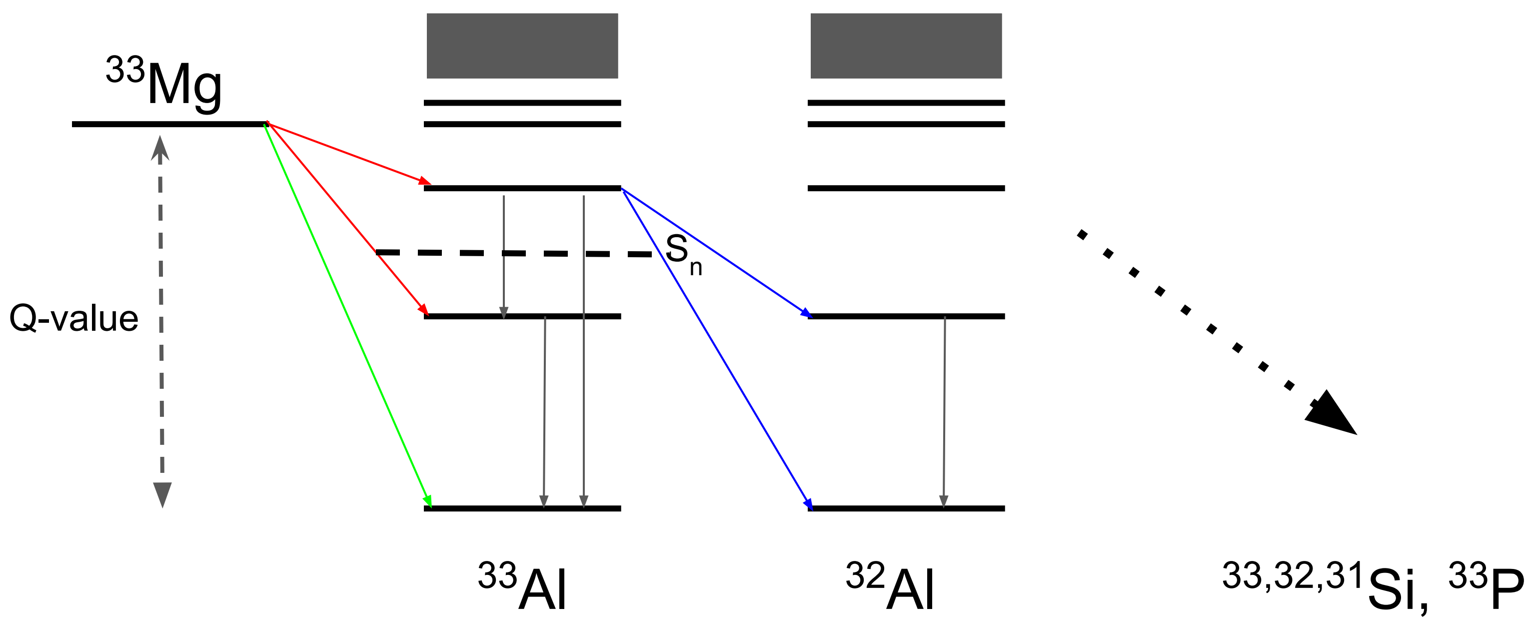
First forbidden transition unlikely to have such a large branching ratio.

^{33}Mg β^--decay at NSCL



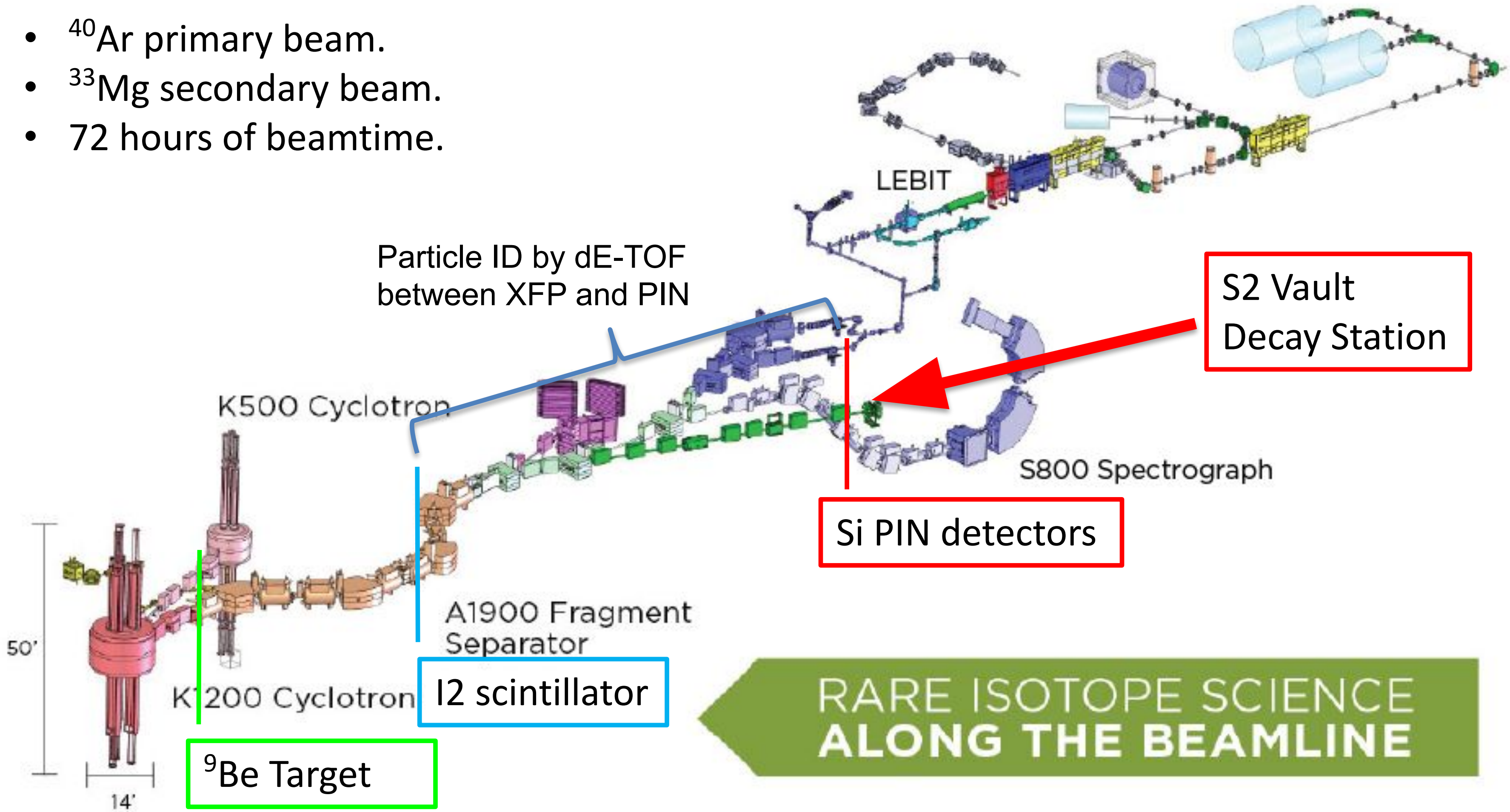
$$(Z, N) \longrightarrow (Z+1, N-1)^* + e^- + \bar{\nu}_e$$

$$I_{gs} = I_{Total} - I_{Excited} - I_{Neutron}$$



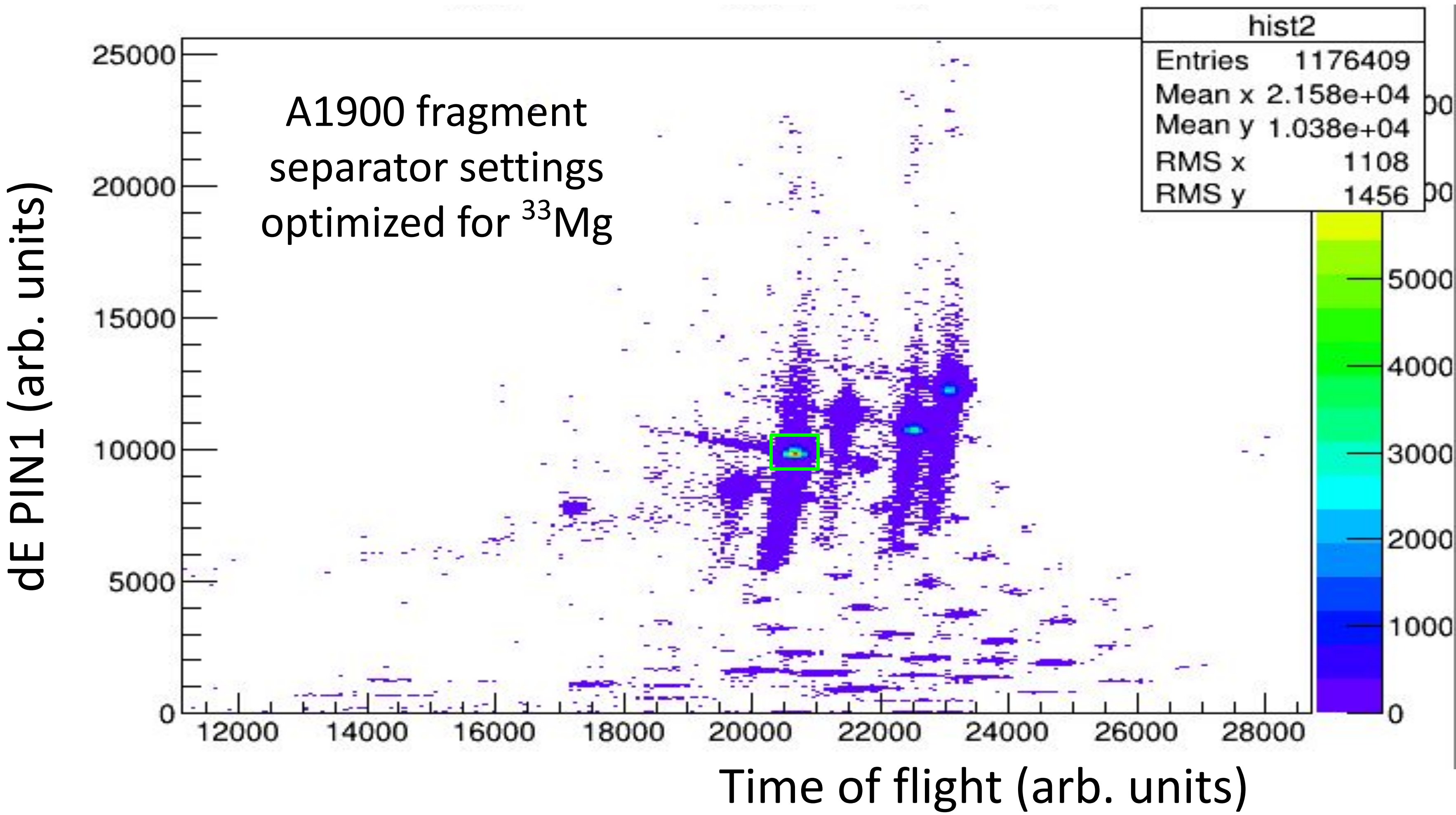
^{33}Mg Production

- ^{40}Ar primary beam.
- ^{33}Mg secondary beam.
- 72 hours of beamtime.



Adapted from NSCL

^{33}Mg Production



Experimental Set-up

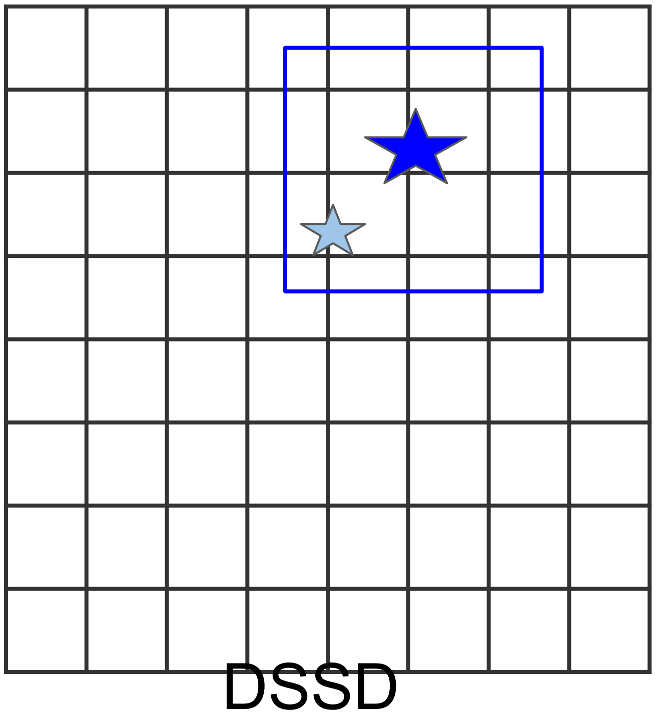
$$I_{gs} = I_{Total} - I_{Excited} - I_{Neutron}$$

SuN Detector measures γ-rays to estimate $I_{Excited}$

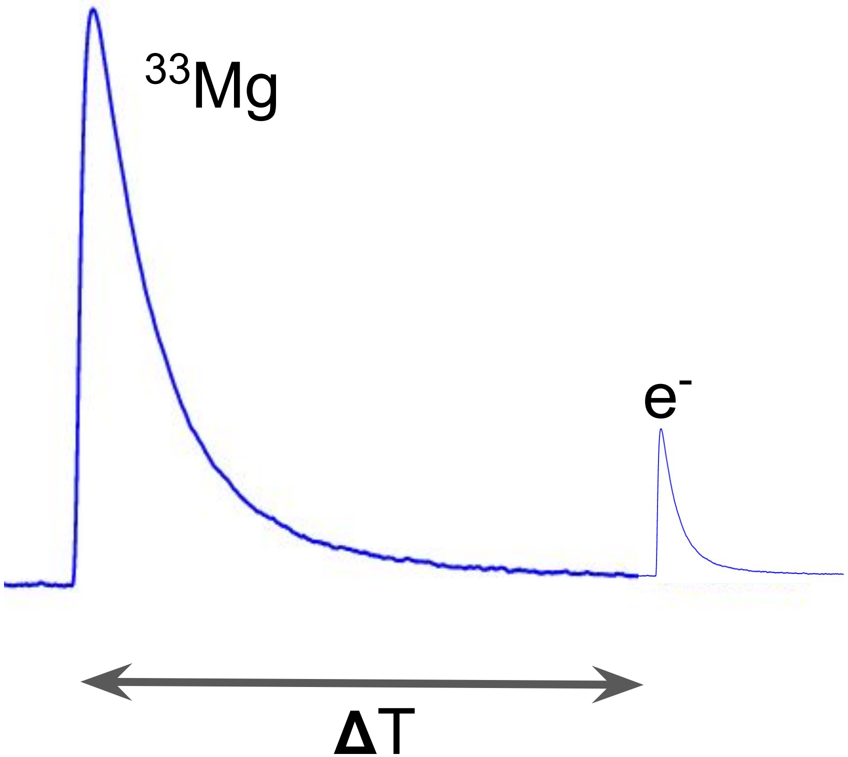
NERO Detector measures neutrons to estimate $I_{Neutron}$

β^--decay Correlations

Spatial Correlation

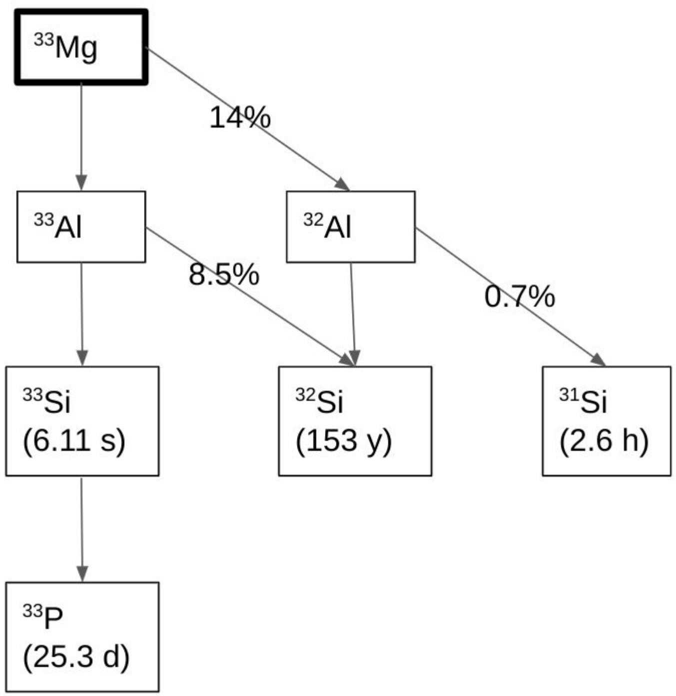


Temporal Correlation

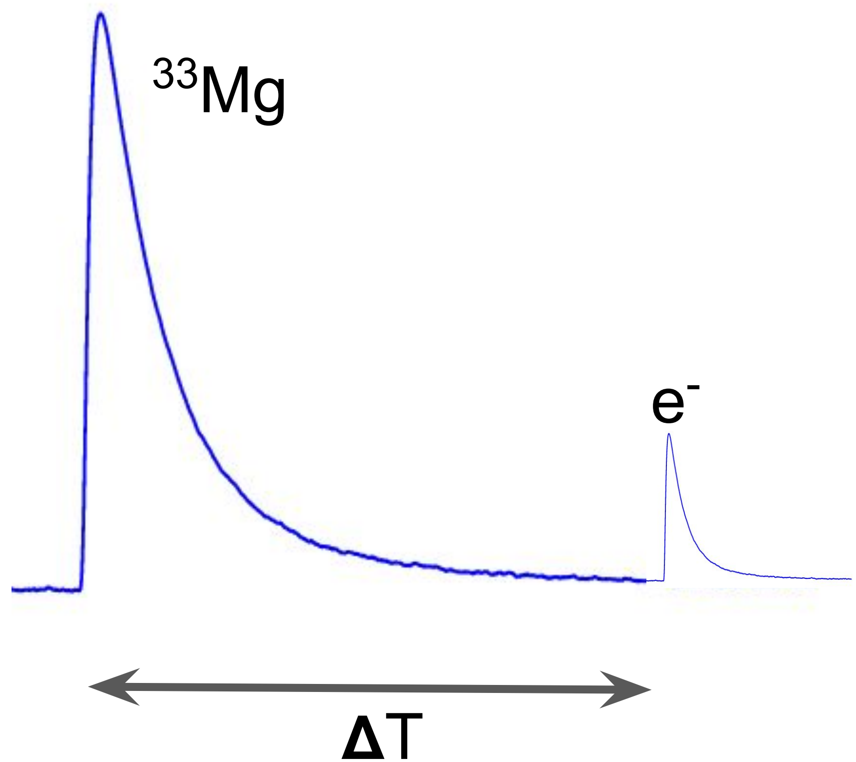


β^--decay Correlations

$$N_n(t) = N_1(0) \times \left(\prod_{i=1}^{n-1} \lambda_i\right) \times \sum_{i=1}^{n} \frac{e^{-\lambda_i t}}{\prod_{j=1, j\neq i}^{n} (\lambda_j - \lambda_i)}$$



Temporal Correlation



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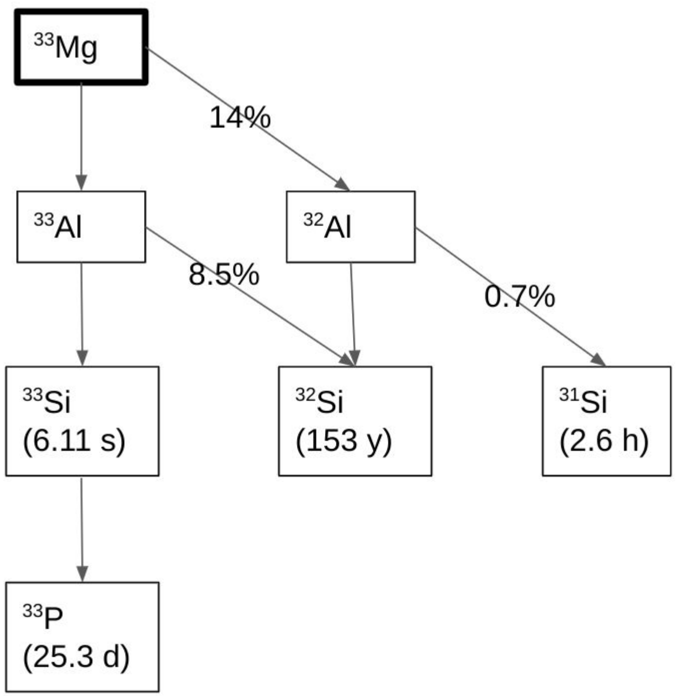
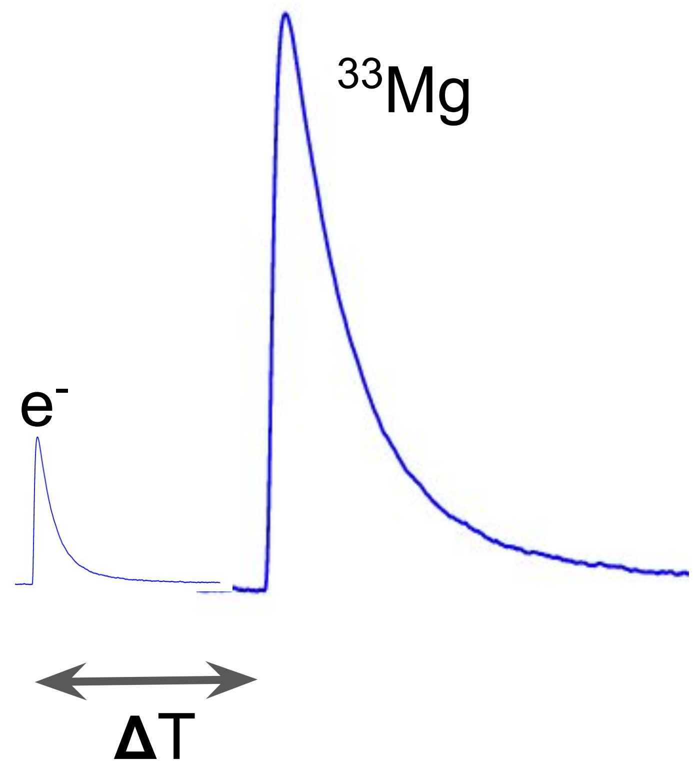
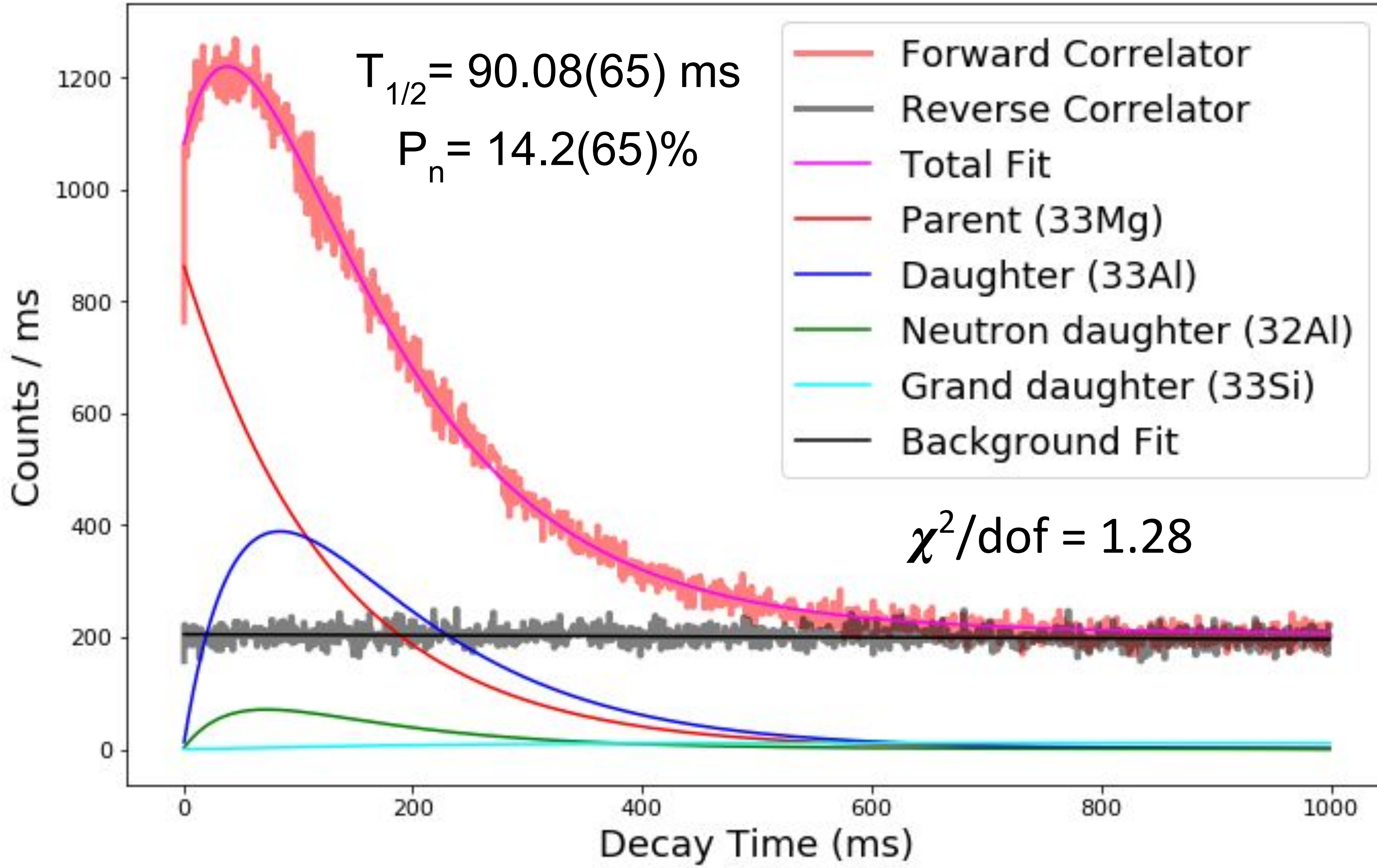


Random Correlations
(Background)



Results



$T_{1/2}$= 90.08(65) ms
P_n= 14.2(65)%
Forward Correlator
Reverse Correlator
Total Fit
Parent (33Mg)
Daughter (33Al)
Neutron daughter (32Al)
Grand daughter (33Si)
Background Fit
χ^2/dof = 1.28
Counts / ms
Decay Time (ms)
0
200
400
600
800
1000
1200

Summary

- Urca cooling takes place in the crusts of accreting neutron stars and the cooling strength depends on ground-state to ground-state ***β***-decay transition strengths of neutron-rich nuclei.

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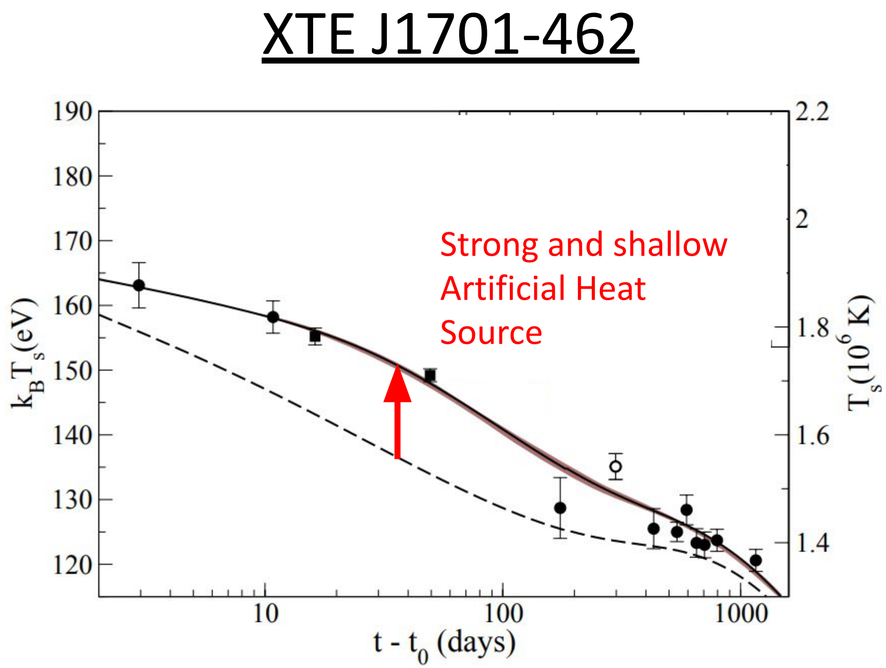
Summary

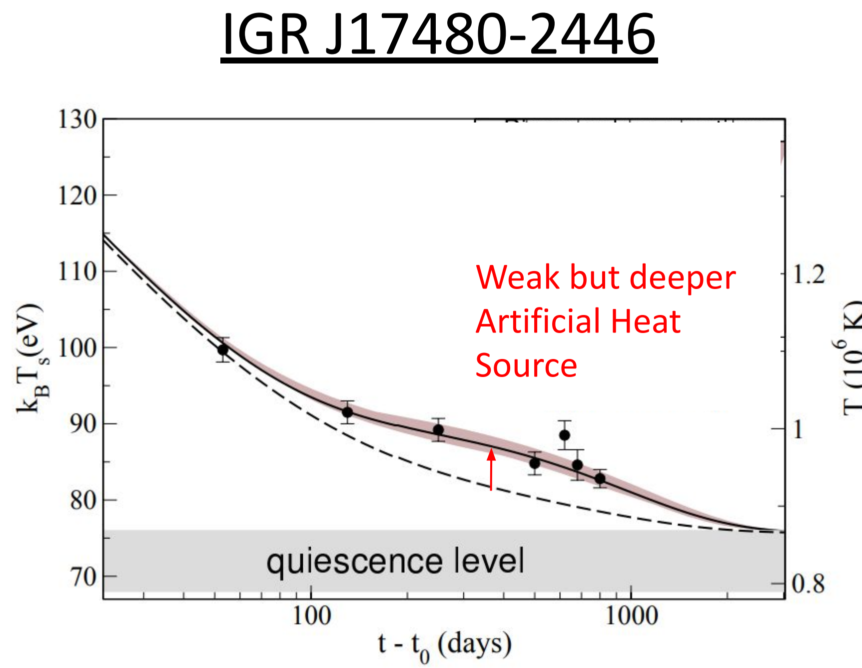
- Urca cooling takes place in the crusts of accreting neutron stars and the cooling strength depends on ground-state to ground-state ***β***-decay transition strengths of neutron-rich nuclei.
- ^{33}Mg is currently the strongest Urca cooler in our models currently but the discrepancy in its ground state parity needs to be resolved to have better model observation comparisons.
- This is another example of how nuclear structure effects manifest in astrophysical systems.

Thank you!

Backup

Shallow Heat Source





A Turlione et al., A&A 577, A5 (2015)

Artificial heat source has to be accounted for to match models to observations for almost all systems.

Nuclear Inputs for Urca Cooling Luminosity

Mass Fraction

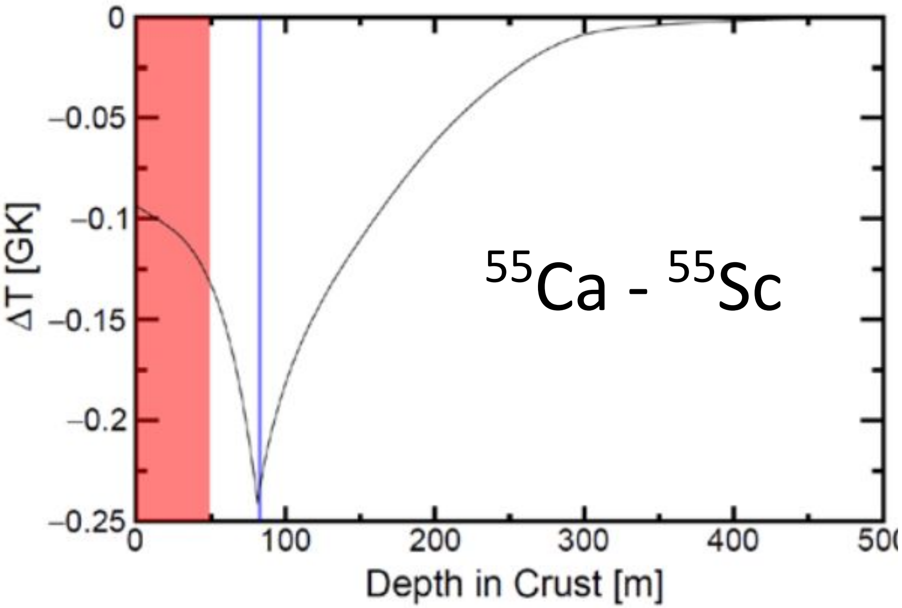
$$L_\nu \approx L_{34} \times 10^{34} \text{erg s}^{-1} X(A) T_9^5 \left(\frac{g_{14}}{2}\right)^{-1} R_{10}^2$$

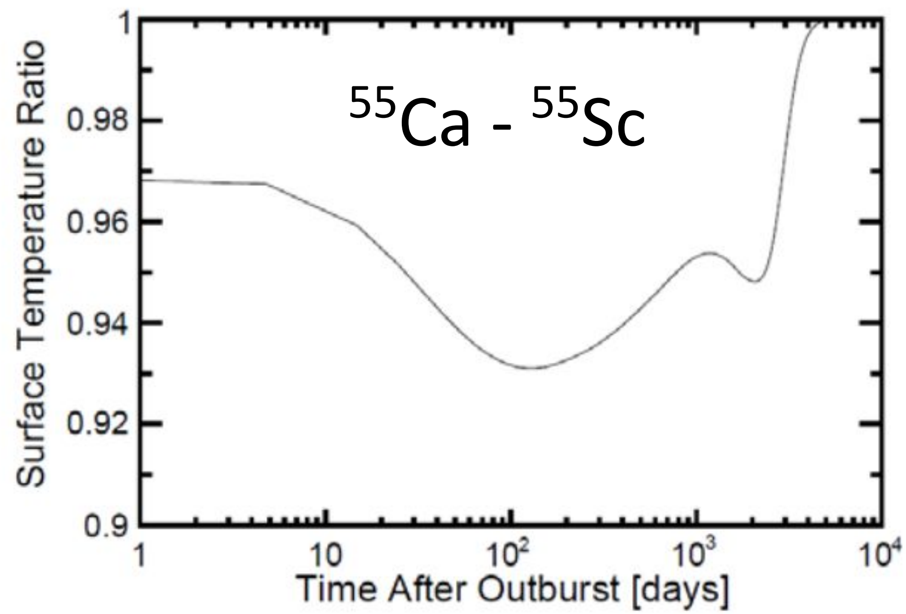
$$L_{34} = 0.87 \left(\frac{10^6 \text{ s}}{ft}\right) \left(\frac{56}{A}\right) \left(\frac{Q_{\text{EC}}}{4 \text{ MeV}}\right)^5 \left(\frac{\langle F \rangle^*}{0.5}\right)$$

gs-gs β^- - decay transition strengths

Nuclear Masses

Impact of Urca Cooling

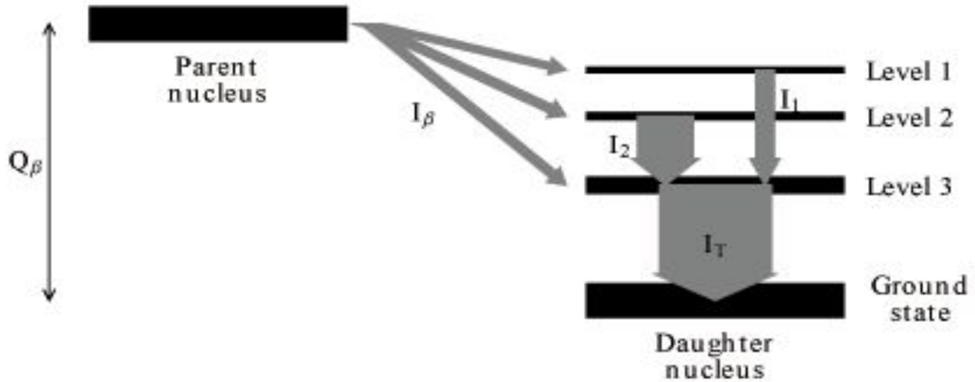


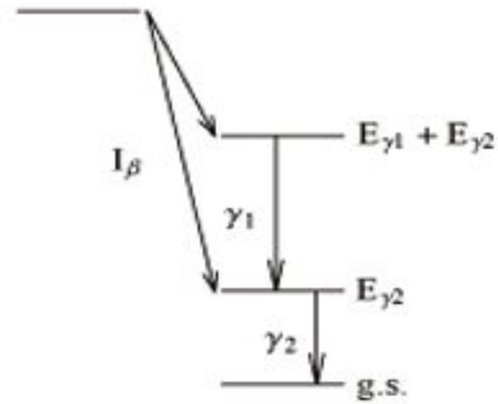


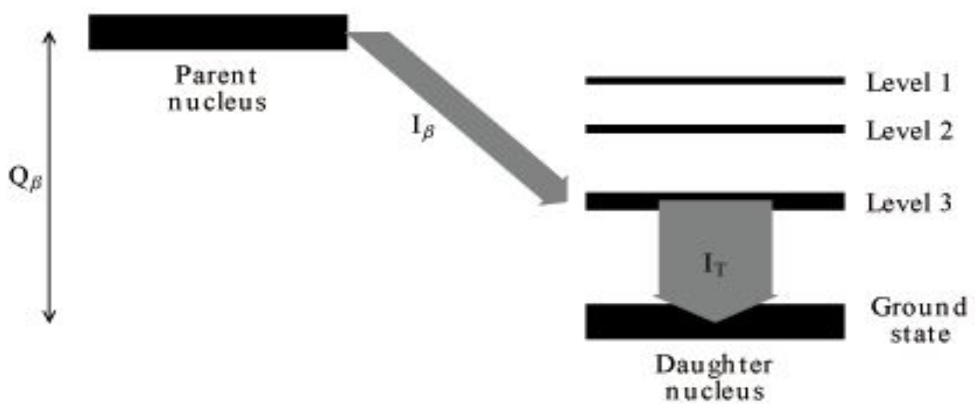
Meisel, Zach, *Physics & Astronomy Open Access Publications*. 146.

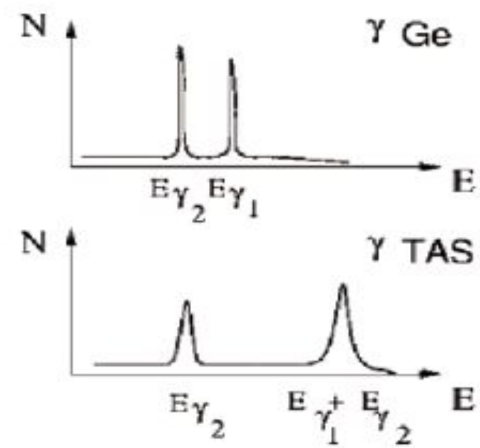
Introducing Urca Cooling changes both the temperature profile in the crust as well as the resulting cooling curves

Pandemonium Effect and TAS

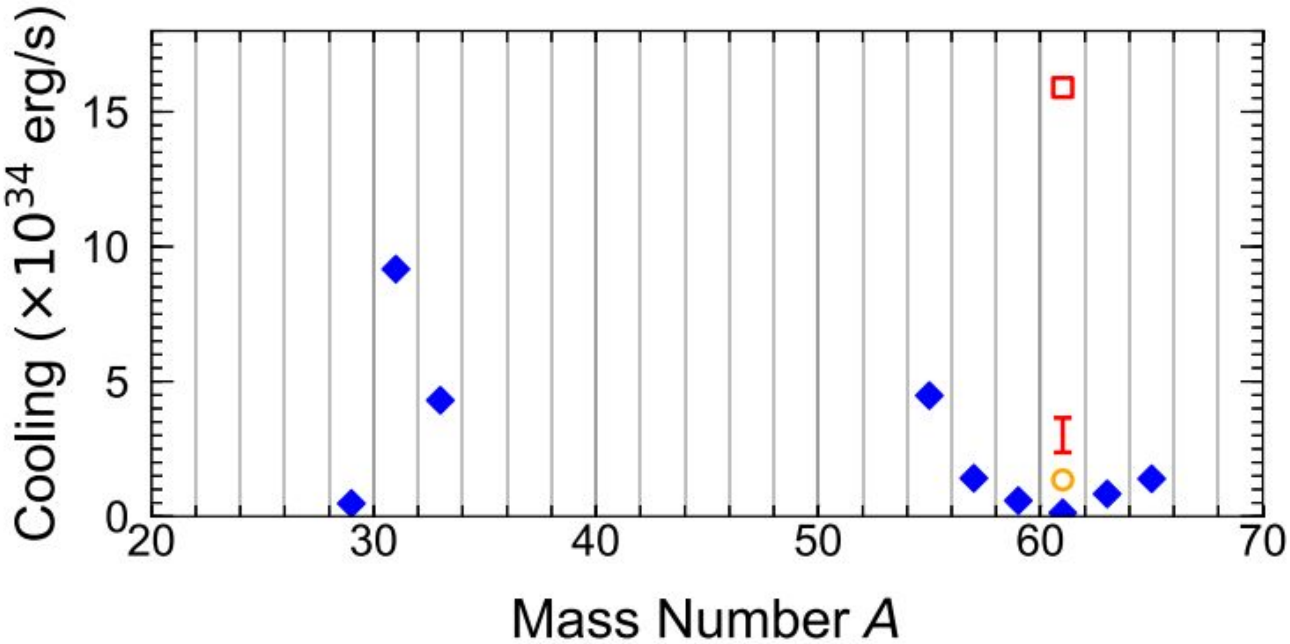








Previous Results at NSCL



W J Ong et al Phys. Rev. Lett. **125**, 262701

Mass A = 61 chain is not as strong a cooler as previously expected based on ^{61}V - ^{61}Cr transition.