Explosive Hydrogen Burning

The αp- and rp-processes

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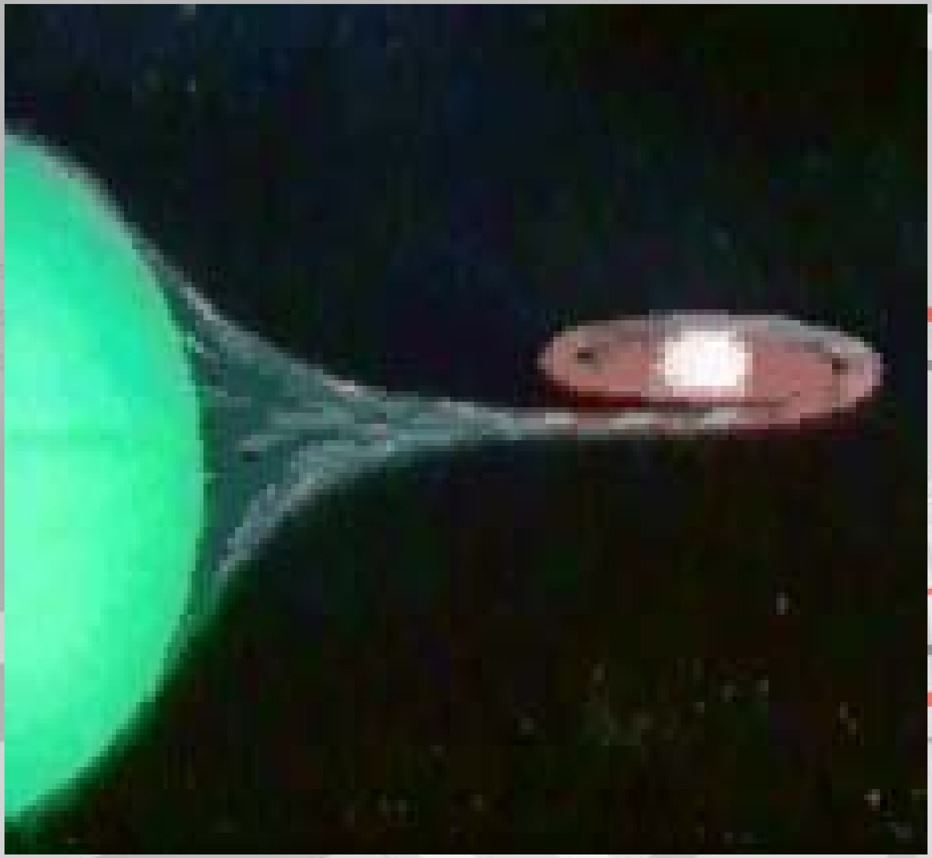
The αp-process

- Series of (α,p), (p,γ) and β^+ reactions
- Dominant branch begins with ^{14}O → even Z, T_z= -1 nuclei undergo (α,p)
- Reaction path stays near the proton drip line
- Ends in A ≈ 42-46 region (Coulomb barrier to high)

The rp-process

- Series of (p,γ) and β^+ reactions
- Begins with the breakout of CNO cycle or (if hot enough) the end products of the αp-process
- Reaction pathway remains near proton drip line
- Endpoint depends on number of seed nuclei, temperature and burst length (up to A≈100)



Processes are thought to occur in accretion layers of neutron stars and white dwarfs in binary systems

Evidence is seen in x-ray bursters

Physical parameters

- $T \sim 0.5 – 1.5$ GK
- Accr. rate ~ $1.8 \times 10^{18} gs^{-1}$
- $\rho \sim 10^4 g/cm^3$
- Time scale ~ 1-1000 s

Basics: degenerate material with H and He needs to heat up

Where the processes occur

What do we see when the processes occur

Light curves from x-ray bursters

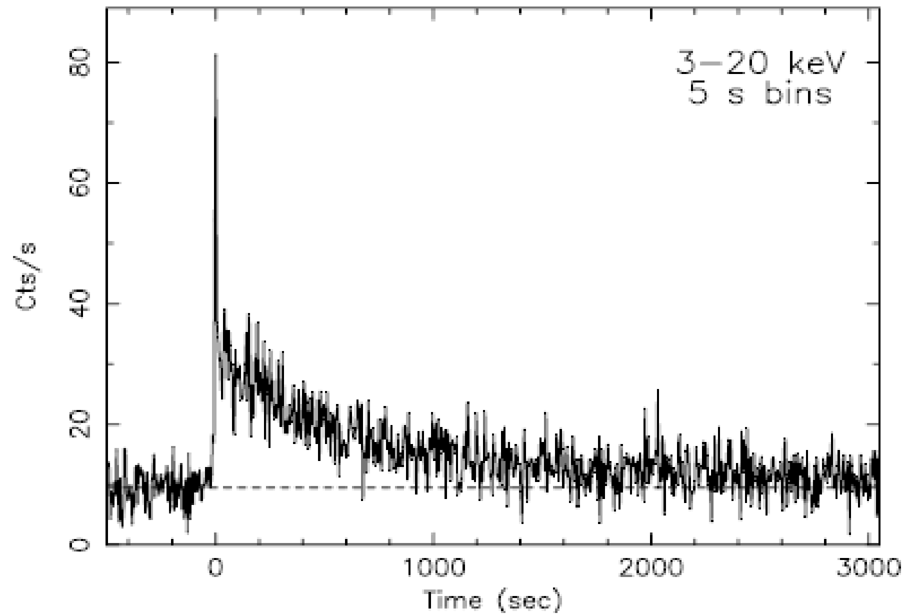
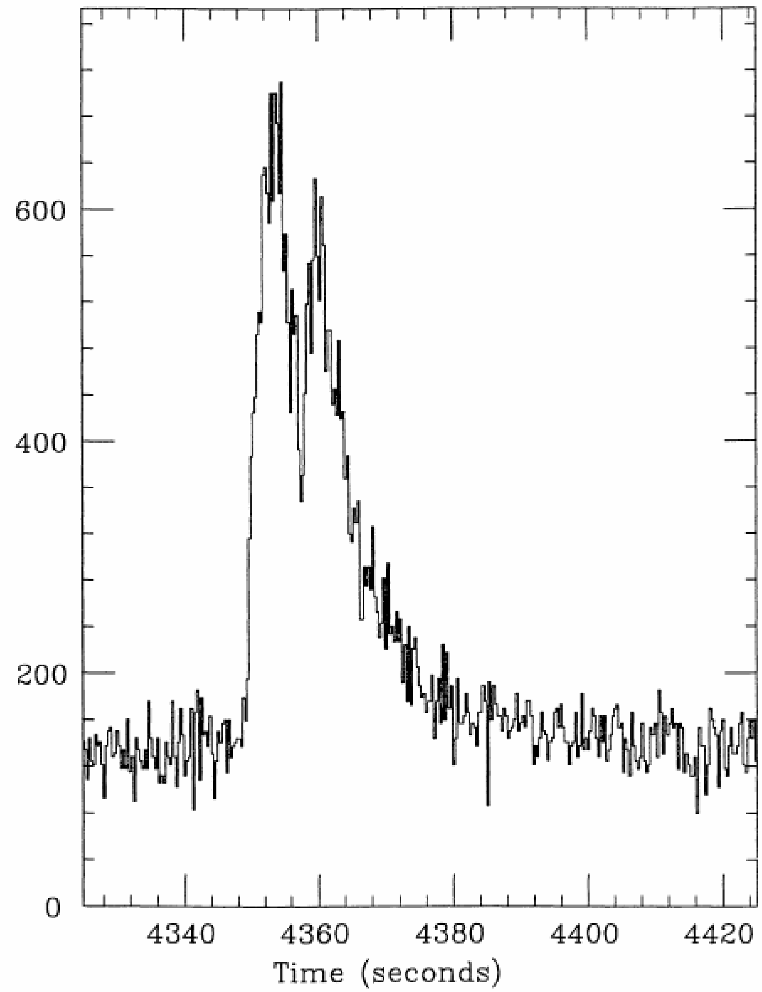


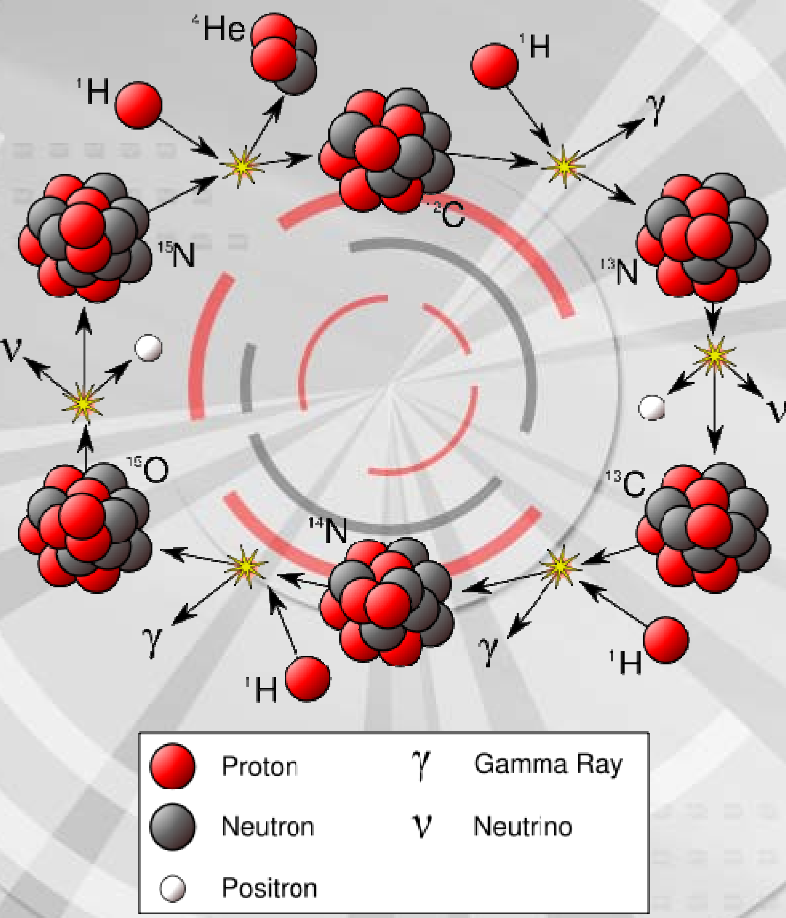
Fig. 1. Long X-ray burst from GX 3+1 on August 31, 2004. The time zero corresponds to UTC 18:55:11.

A&A 449, L5–L8 (2006)



1993SSRv...62..223L

The Beginning -
during accretion, the CNO cycle dominates H burning



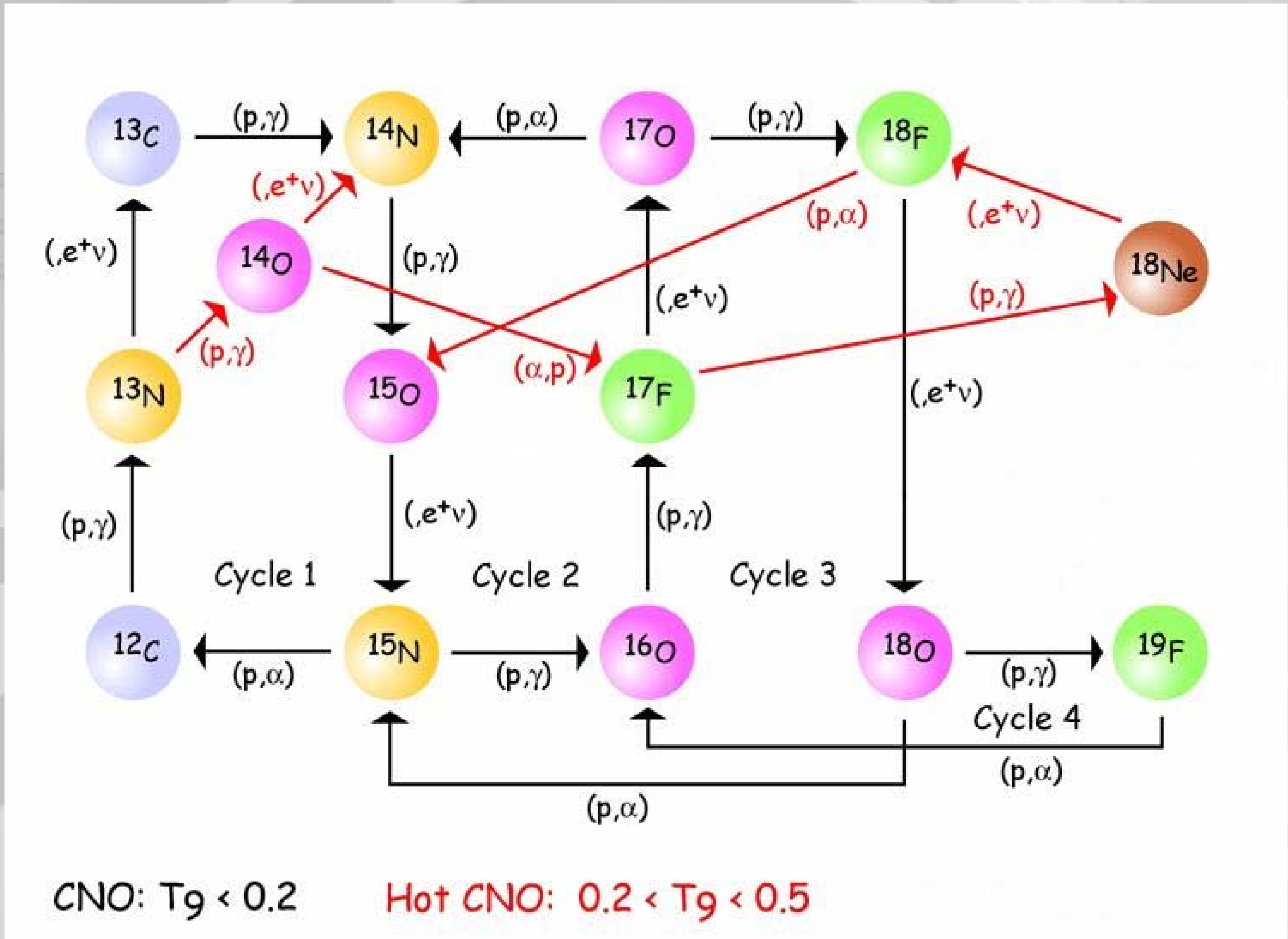
Total energy release is
about 27 MeV per cycle

http://www.cococubed.com/images/net_hotcno/cno_cycles_rp_web.jpg

Explosive timeline

Things heat up -

As the temperature increases, the hot CNO cycle becomes active



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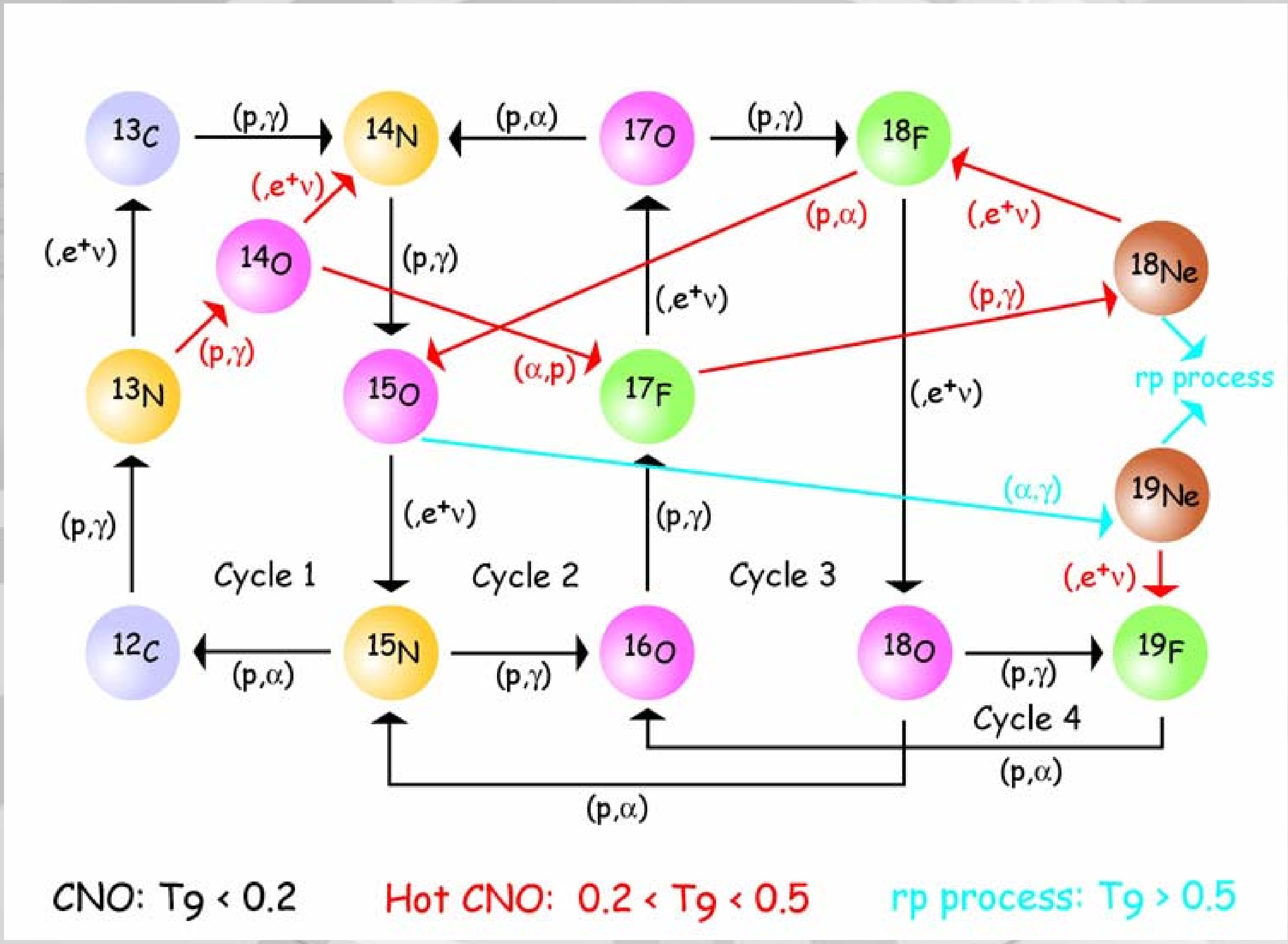
The Breakout -

αp-process begins with the breakout of the hot CNO cycle



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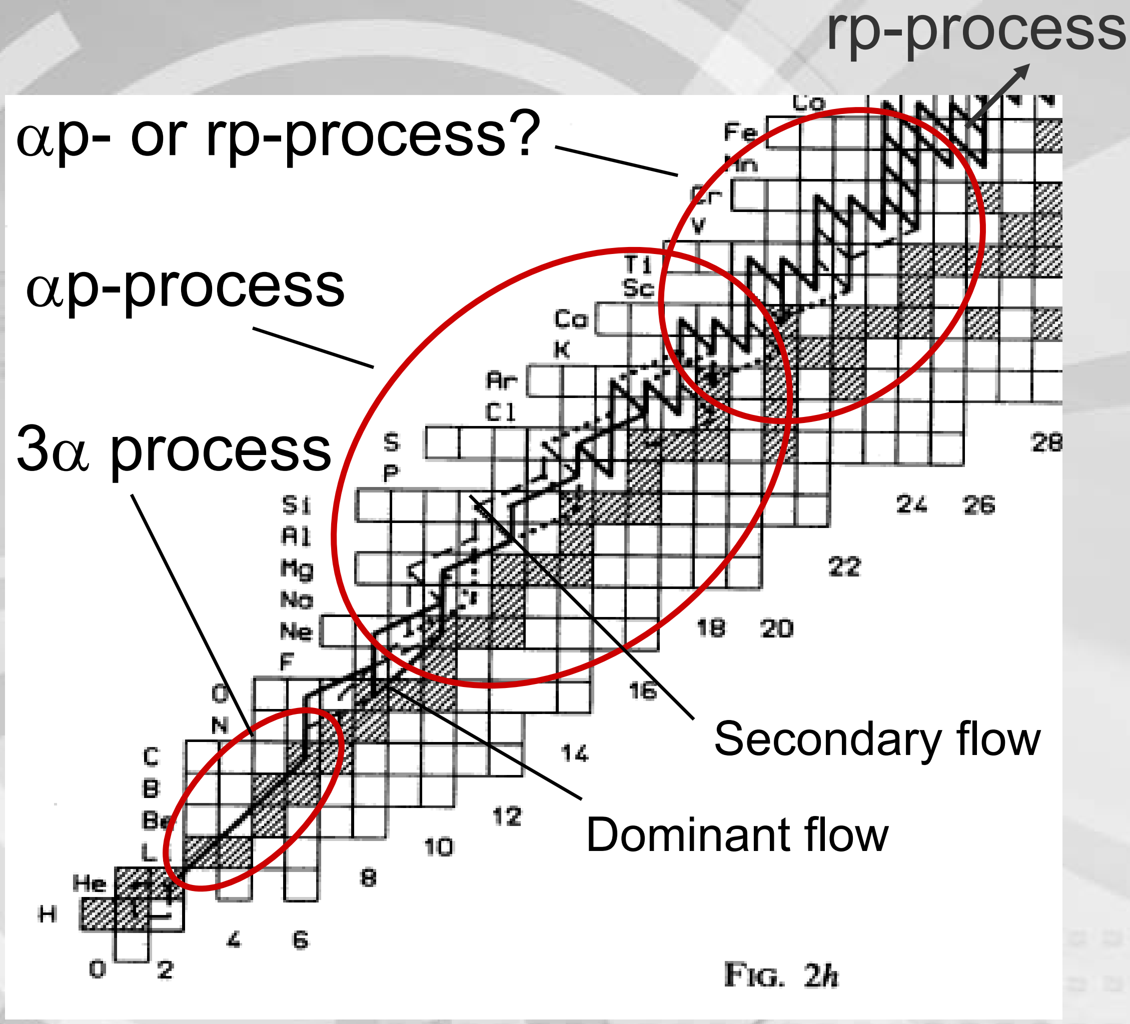
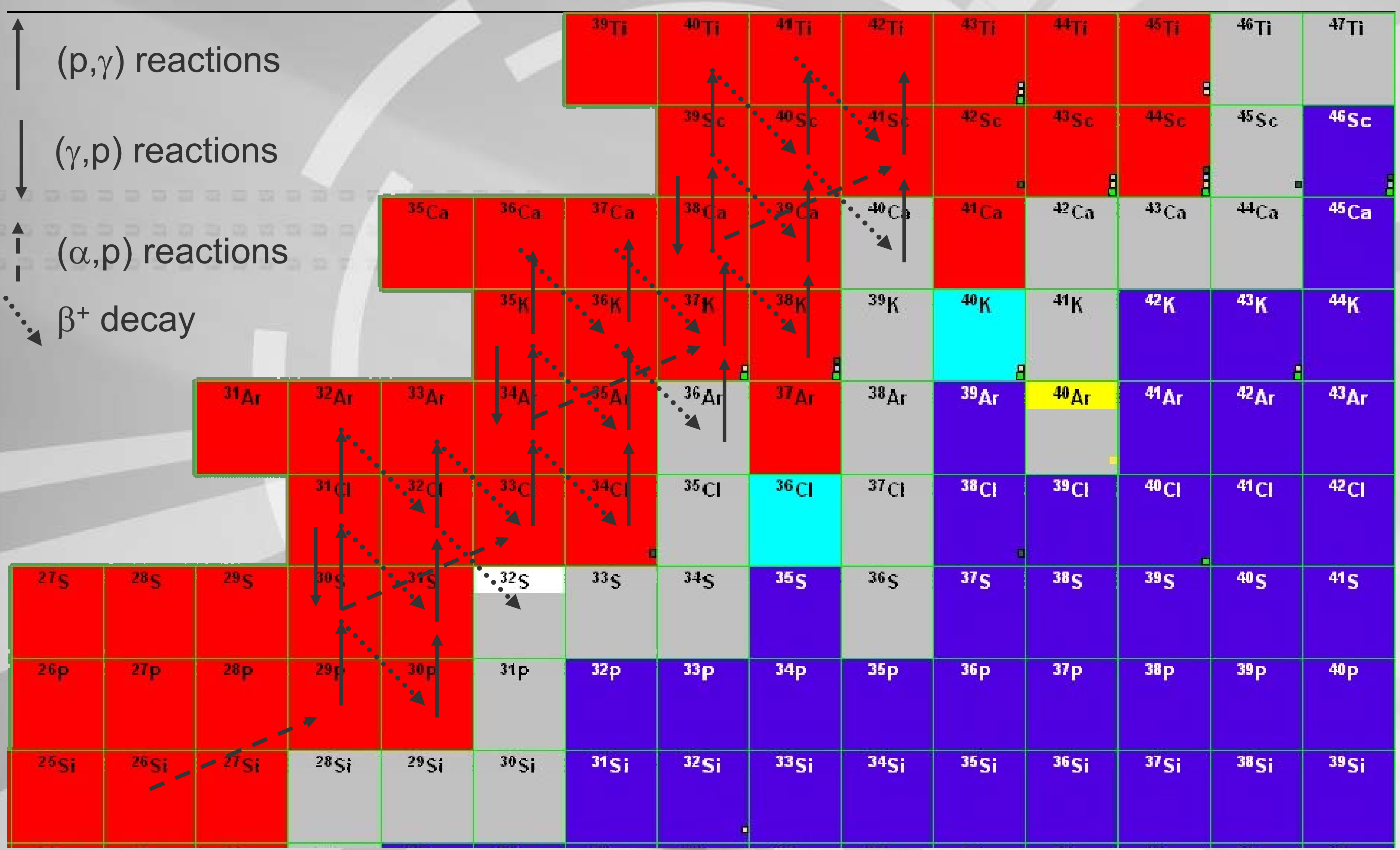
Basic reaction flow



Integrated flow with parameters:
$t=10^3$ s
$T=1.5 \times 10^9$ K
$\rho=10^4$ g/cm^3

Van Wormer et al, 1994

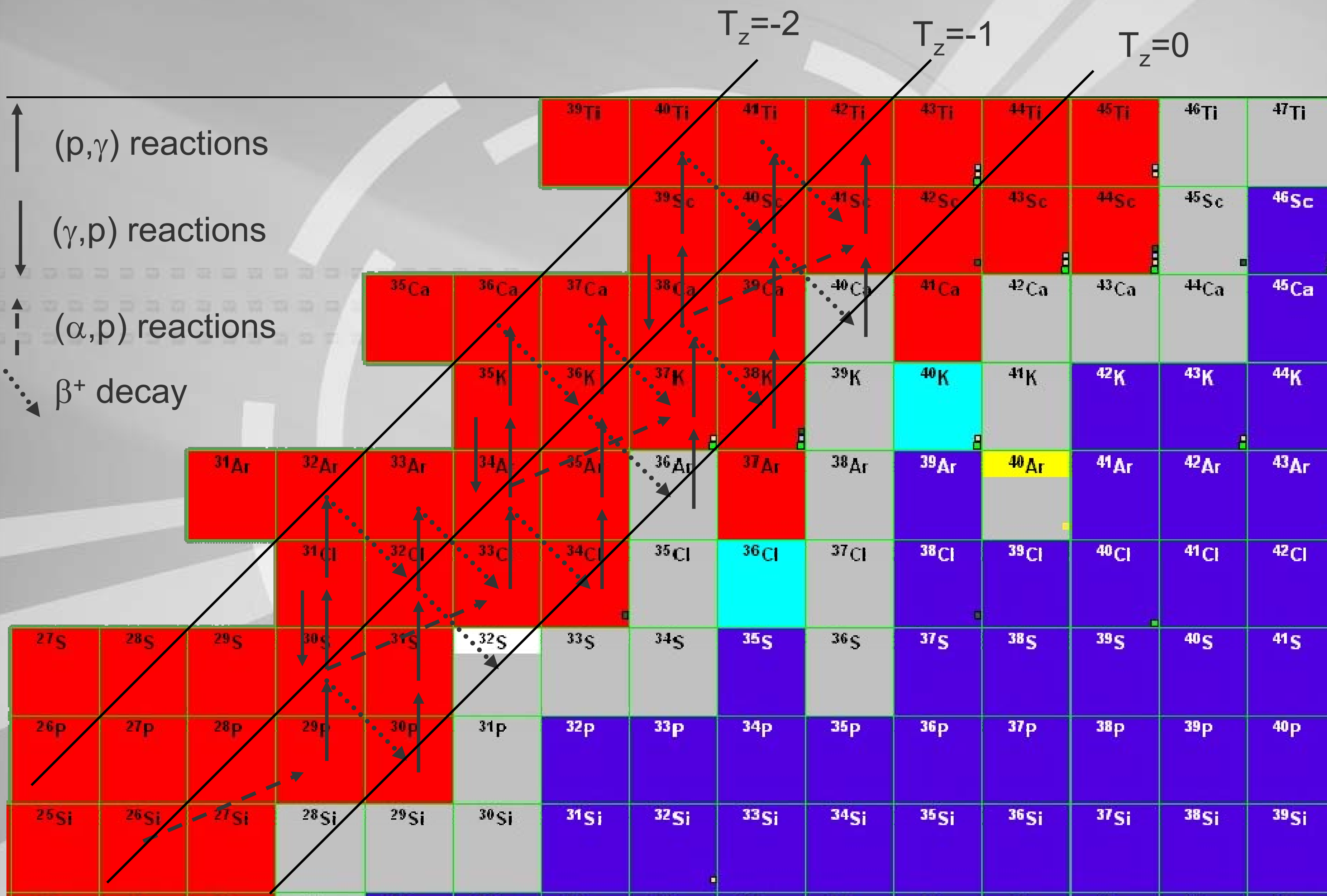
Possible reaction paths



The nuclear physics involved

- p and α capture competing with β^+ decay
  - Time scale for each reaction determines reaction path
- after α capture, p emission competes with γ decay
  - Strong force typically 3-4 orders of magnitude stronger than the EM force
- Some β^+ half-lives are long enough to give 2p capture reactions competitive chance
  - First capture is to an unbound state in intermediate nuclei, therefore treated as a three body reaction
  - Q-values for the first p capture determine equilibrium abundance fractions (Saha Equation)
    - Masses are therefore important

The nuclear physics involved



Determining the reaction pathway

Simulate the events occurring in the stars

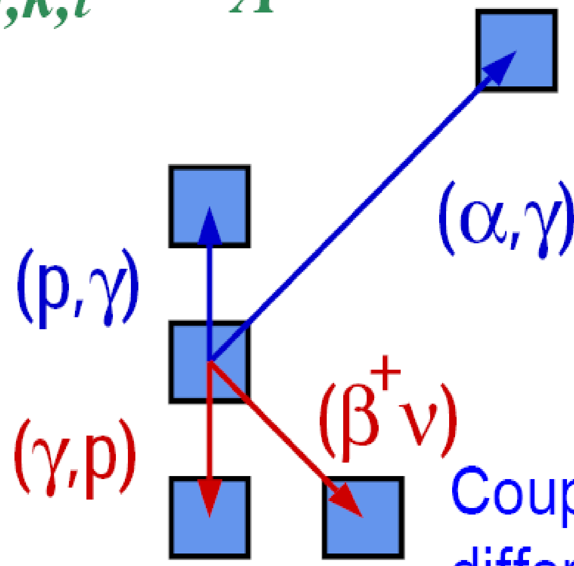
- Involves tracking the physical characteristics of the space (T, ρ, etc.)
- Keeping track of abundances of each isotope
- Dissipating the energy created from the nuclear reactions
- Using a reaction network to simulate the nuclear reactions occurring in the stars

→ Implement a reaction network to simulate the nuclear reactions occurring in the stars

Reaction network basics

Change of istopic abundances:

$$\frac{dY_i}{dt} = \sum_j N_j^i \lambda_j Y_j + \sum_{j,k} N_{j,k}^i \rho N_A < j,k > Y_j Y_k + \sum_{j,k,l} N_{j,k,l}^i \rho^2 N_A^2 < j,k,l > Y_j Y_k Y_l$$



Coupled system of nonlinear differential equations

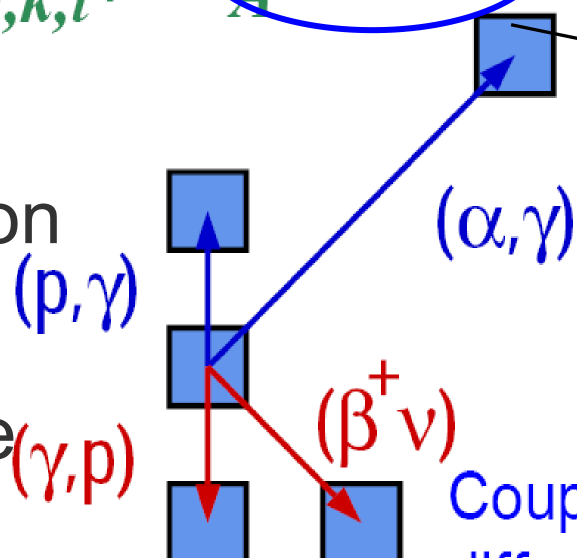
Reaction network basics

Change of istopic abundances:

$$\frac{dY_i}{dt} = \sum_j N^i_j \lambda_j Y_j + \sum_{j,k} N^i_{j,k} \rho N_A < j,k > Y_j Y_k + \sum_{j,k,l} N^i_{j,k,l} \rho^2 N_A^2 < j,k,l > Y_j Y_k Y_l$$

Reaction rates

Most reaction rates are temperature dependent



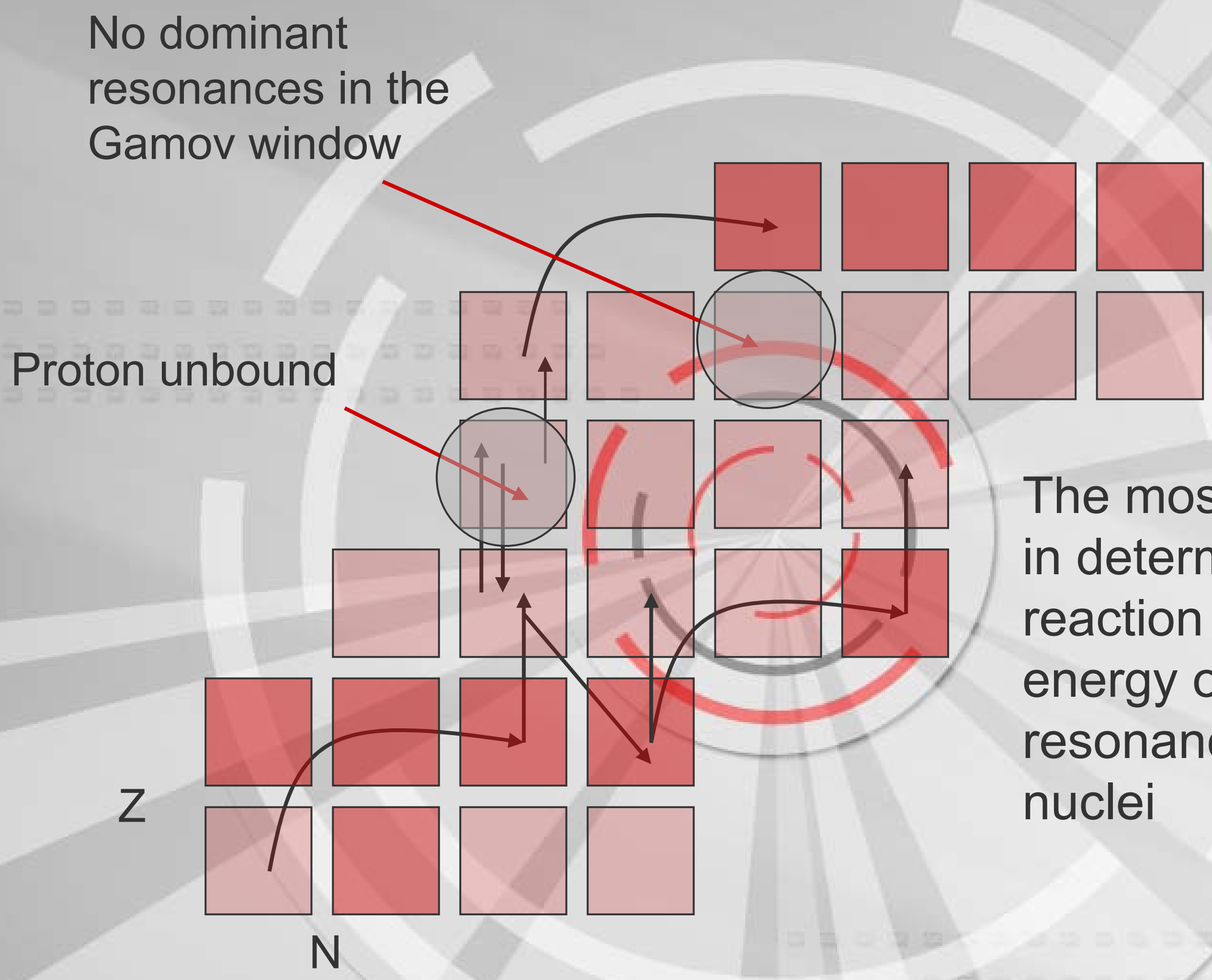
Coupled system of nonlinear differential equations

Reaction Rate Calculations

$$N_A < \sigma v > = 1.540 \times 10^{11} (\mu T_9)^{-\frac{3}{2}} \omega\gamma \times e^{-\frac{E_{res}}{kT}}$$

- The resonance energy is the most important factor in calculating the reaction rate
- Shell models calculations give errors of the order 100 keV on resonance energies
  - This may result in reactions rates with errors of 3 orders of magnitude

Complex reaction pathways



The most critical factor in determining the reaction path is the energy of the resonances in these nuclei

Understanding the breakout reactions

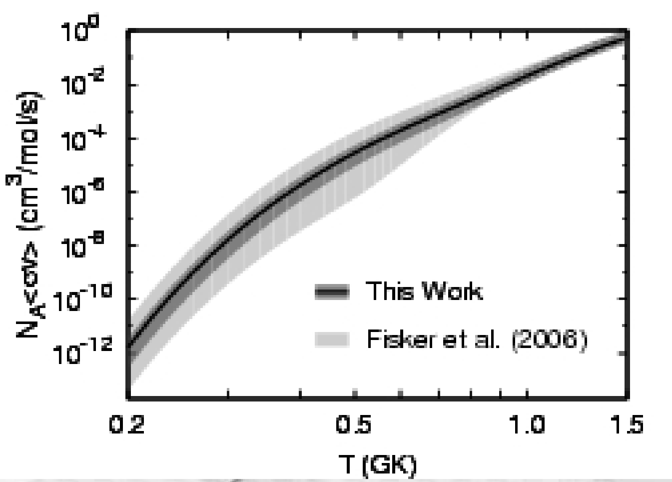
2 important experiments by W. Tan related to $^{15}O(\alpha,\gamma)^{19}Ne$

4.03 MeV state in ^{19}Ne dominates reaction – important nuclear parameters are E_r, Γ_γ, B_α

E_r and Γ_γ measured with Doppler Shift Attenuated Method on $^{17}O(^3He,n\gamma)^{19}Ne$

B_α measured via $^{19}F(^3He,t)^{19}Ne$

Places stronger restrictions on simulations – which do not match observations right now



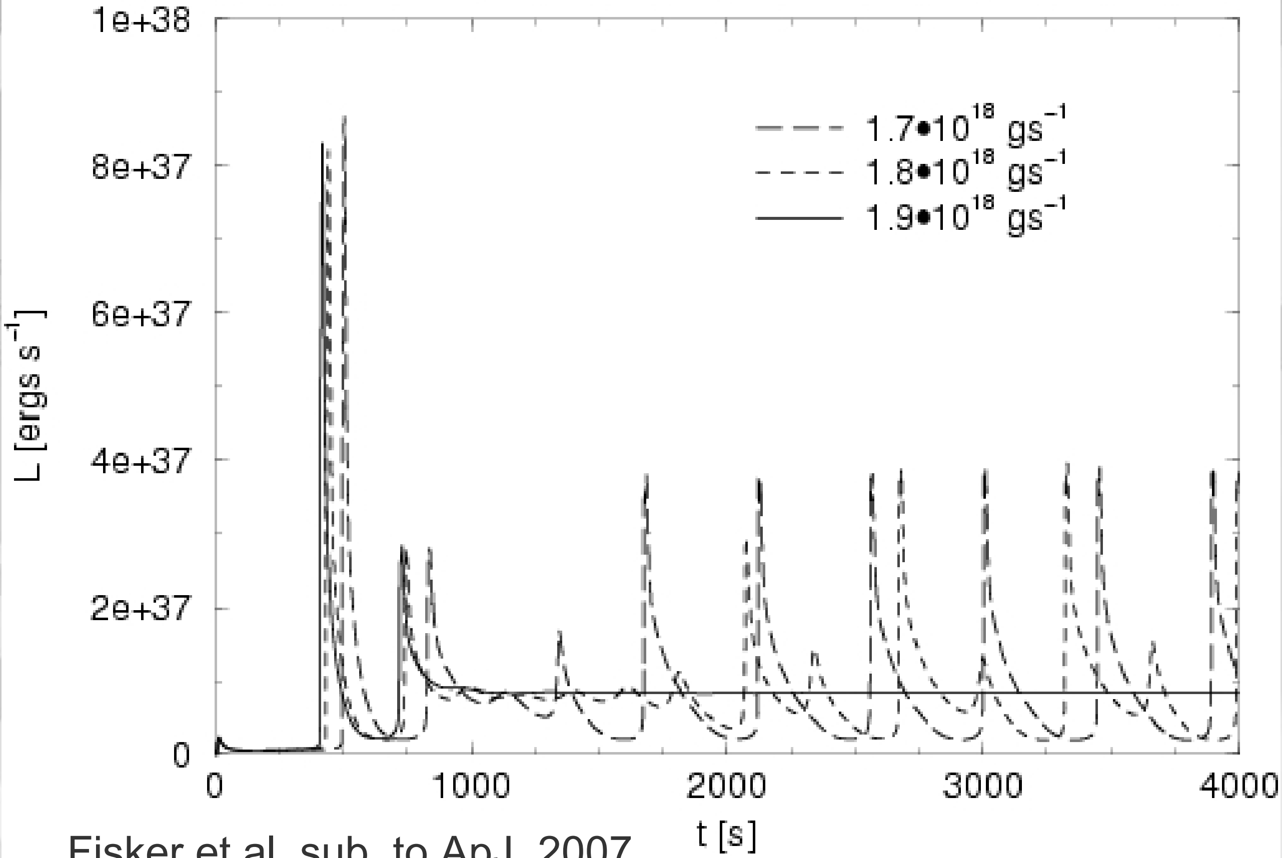
Fisker et al, sub. to ApJ, 2007

$^{14}O(\alpha,p)^{17}F$ reactions done with RIB

First direct observations of the states important in this breakout reaction

Simulating the processes with greater precision

- Each new experimentally measured reaction rate can be applied to the reaction networks
- Timescales are important in determining how high in mass the process reaches



Fisker et al, sub. to ApJ, 2007

More detailed networks can pinpoint the most important reactions – waiting points or those with the largest meaningful uncertainties

Experimentally probing the processes

Using transfer reactions to probe the proton rich nuclei

- Experiments performed
  - $^{24}Mg(p,t)^{22}Mg$, $^{28}Si(p,t)^{26}Si$
  - $^{24}Mg(\alpha,^{6}He)^{22}Mg$, $^{28}Si(\alpha,^{6}He)^{26}Si$
- Experiments planned
  - $^{32}S(p,t)^{30}S$, $^{36}Ar(p,t)^{34}Ar$, $^{40}Ca(p,t)^{38}Ca$
  - $^{50}Cr(\alpha,^{8}He)^{46}Cr$, $^{46}Ti(\alpha,^{8}He)^{42}Ti$

Stable targets used to probe the proton rich nuclei near the proton drip line

Requirements

- Beams fully dispersion matched to a powerful spectrometer
- Ability to detect light reaction product at 0°

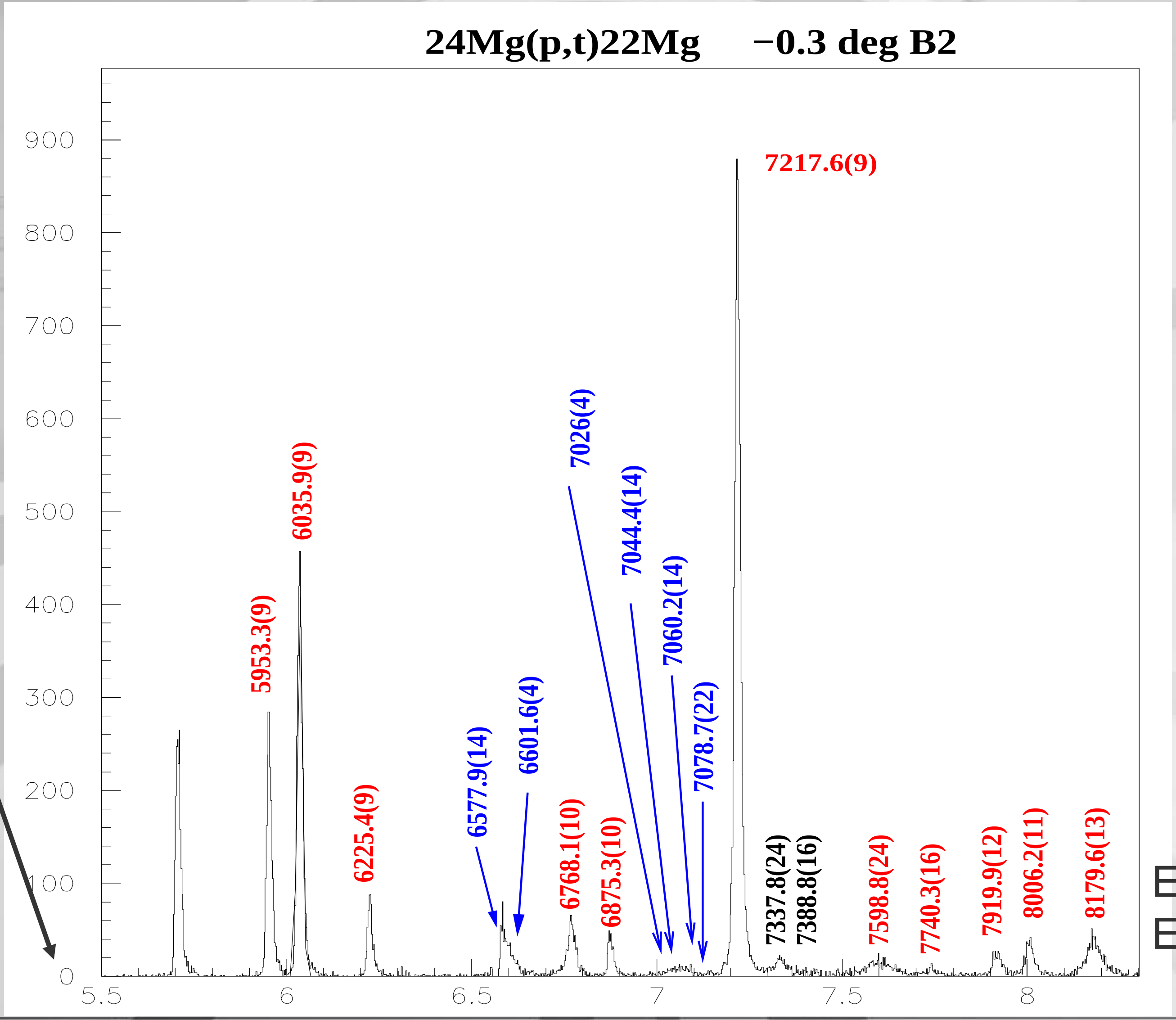
Experimentally probing the processes

Quality of the data

Errors on the order of 1-2 keV

p threshold

A. Matic - Thesis



Reminder:

Errors must be small to constrain reaction rate and reaction path

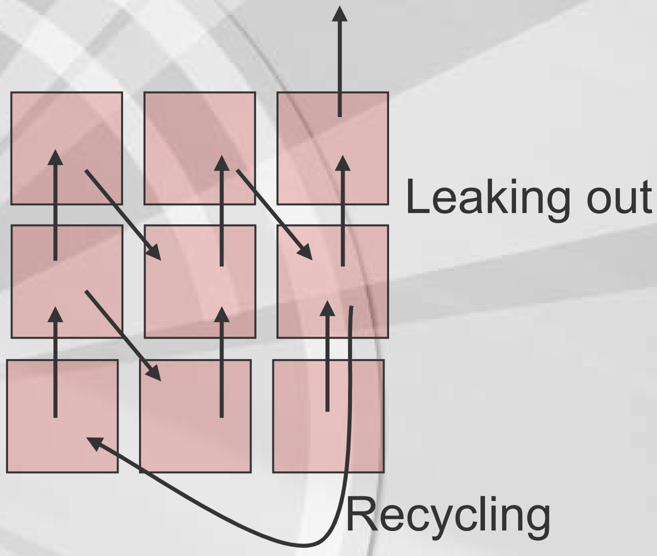
Excitation Energy (MeV)

Conclusions

- Basics of αp- and rp-processes understood
  - Currently working on the details
- Improved reaction rates help define the path and understand the light curves
- RIB will prove helpful
  - Direct measurements of the reactions involved
  - Precise determination of resonance energies will be a good starting place

Understanding cycles in the processes

Cycles can occur when a (p,α) reaction is favored over a (p,γ) reaction



$^{23}Na(p,\gamma)^{24}Mg$ measured at TUNL

Conclusion is that over the temperature range of 0.2-0.4 GK, there is no closed NeNa cycle.