X-Ray Bursts: An Experimentalist's Perspective

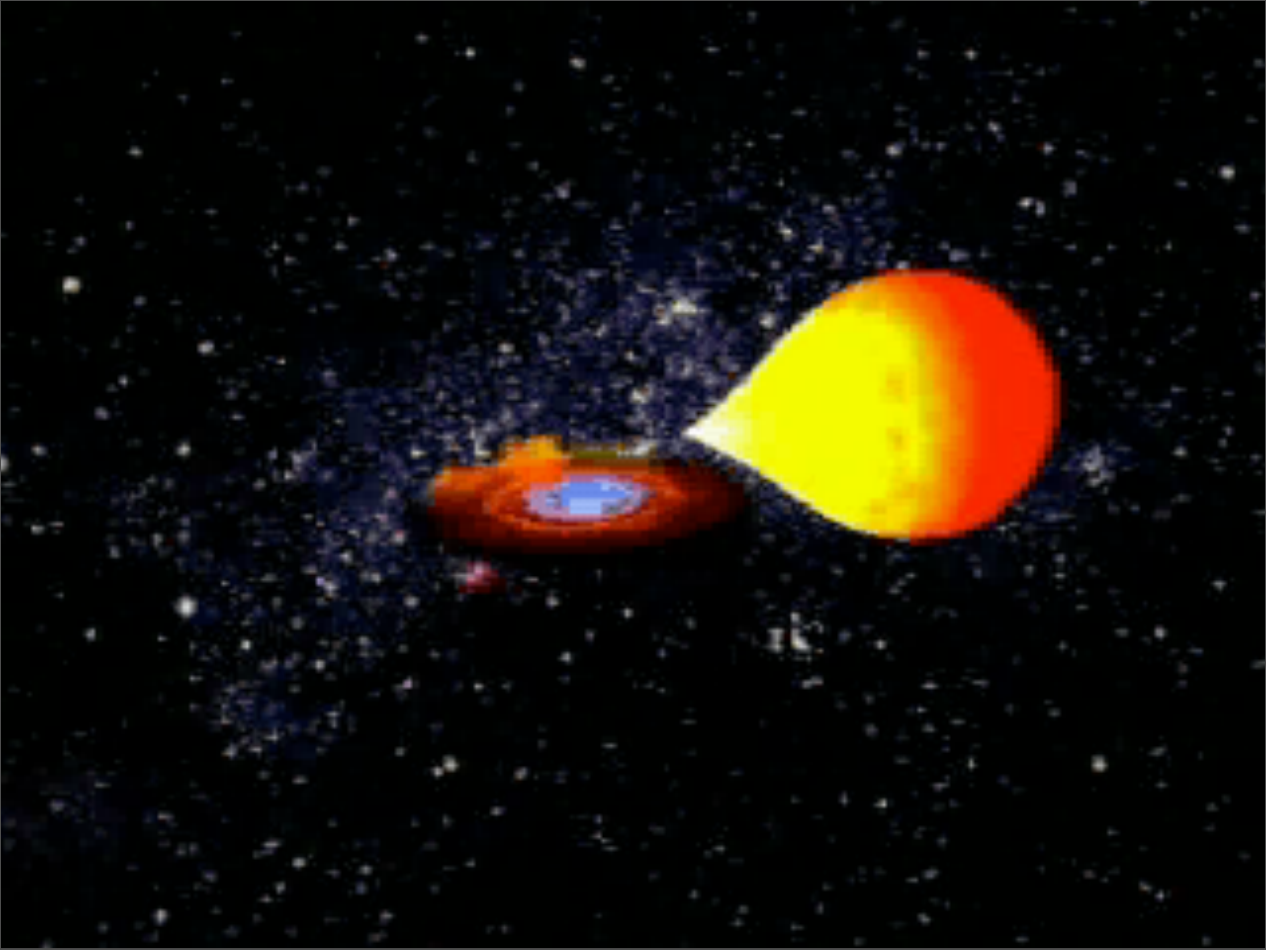
Catherine M. Deibel

Joint Institute for Nuclear Astrophysics
Michigan State University

Physics Division
Argonne National Laboratory

X-Ray Bursts!

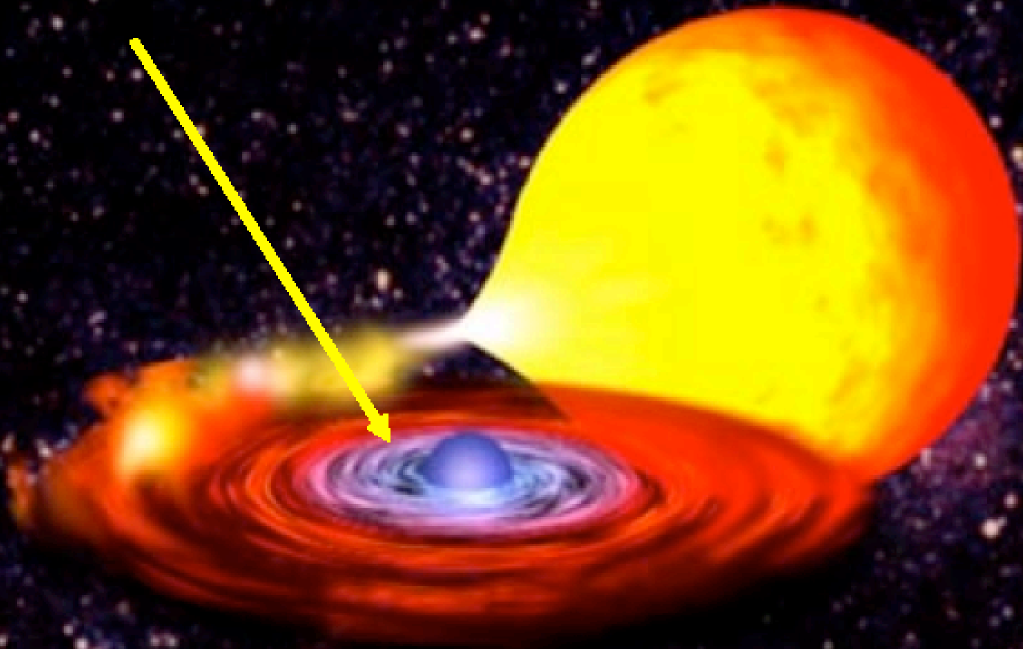
- What are X-Ray Bursts (XRBs)?
  - Types of x-ray bursts
  - Luminosity profiles and other observables
- Nucleosynthesis in XRBs
  - Nucleosynthetic processes
  - Waiting points
  - Final elemental abundances
- How do we study XRBs?
  - Models and simulations
  - Experimental Studies
    - Mass measurements
    - β-decay lifetimes
    - Reaction rate measurements



Type I X-Ray Bursts (XRBs)

Neutron stars:
1.4 M_o, 10 km radius

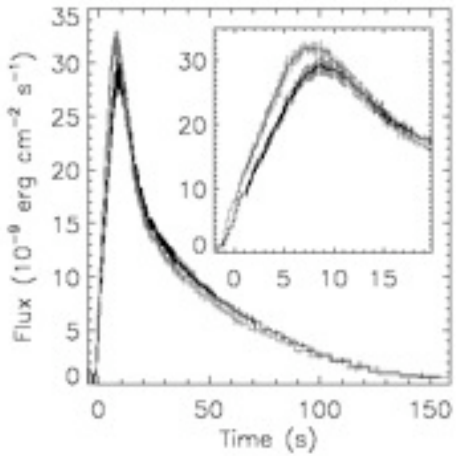
Normal star



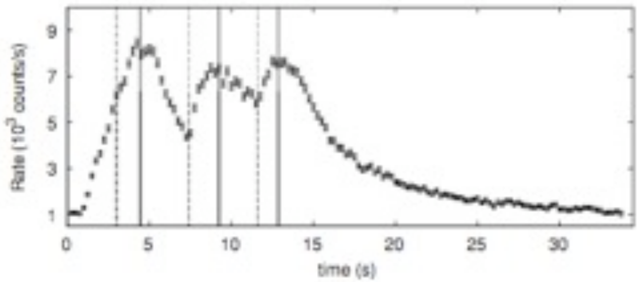
Accretion rate ~ $10^{-8}/10^{-10}$ M_o/year
Peak x-ray burst temperature ~ 1.5 GK
Recurrence rate ~ hours to days
Burst duration of 10 – 100 s
Observed x-ray outburst ~10^{39} – 10^{40} ergs

Observables

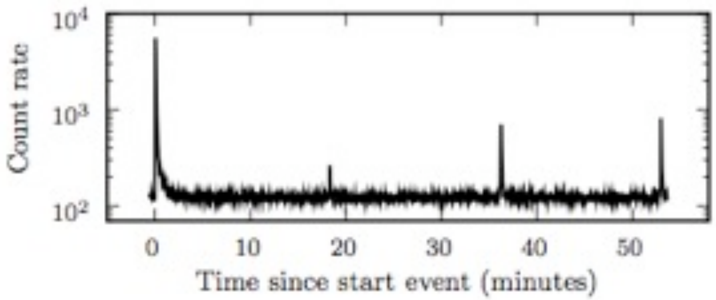
- Luminosity profiles
  - During thermonuclear runaway observed x-ray outbursts of 10^{39}–10^{40} ergs
  - Typical bursts:
    - last for 10 - 100s
    - single peaked
    - reoccur every few hours or weeks
  - Atypical bursts:
    - higher luminosities: 10^{42} ergs (superbursts- Laurens Keek)
    - multiple peaks
    - short recurrence times (Andrew Steiner)
- Energy generation
- Conductivity
- Gravitational waves



D.K. Galloway *et al.*, ApJ **601** 466 (2004).



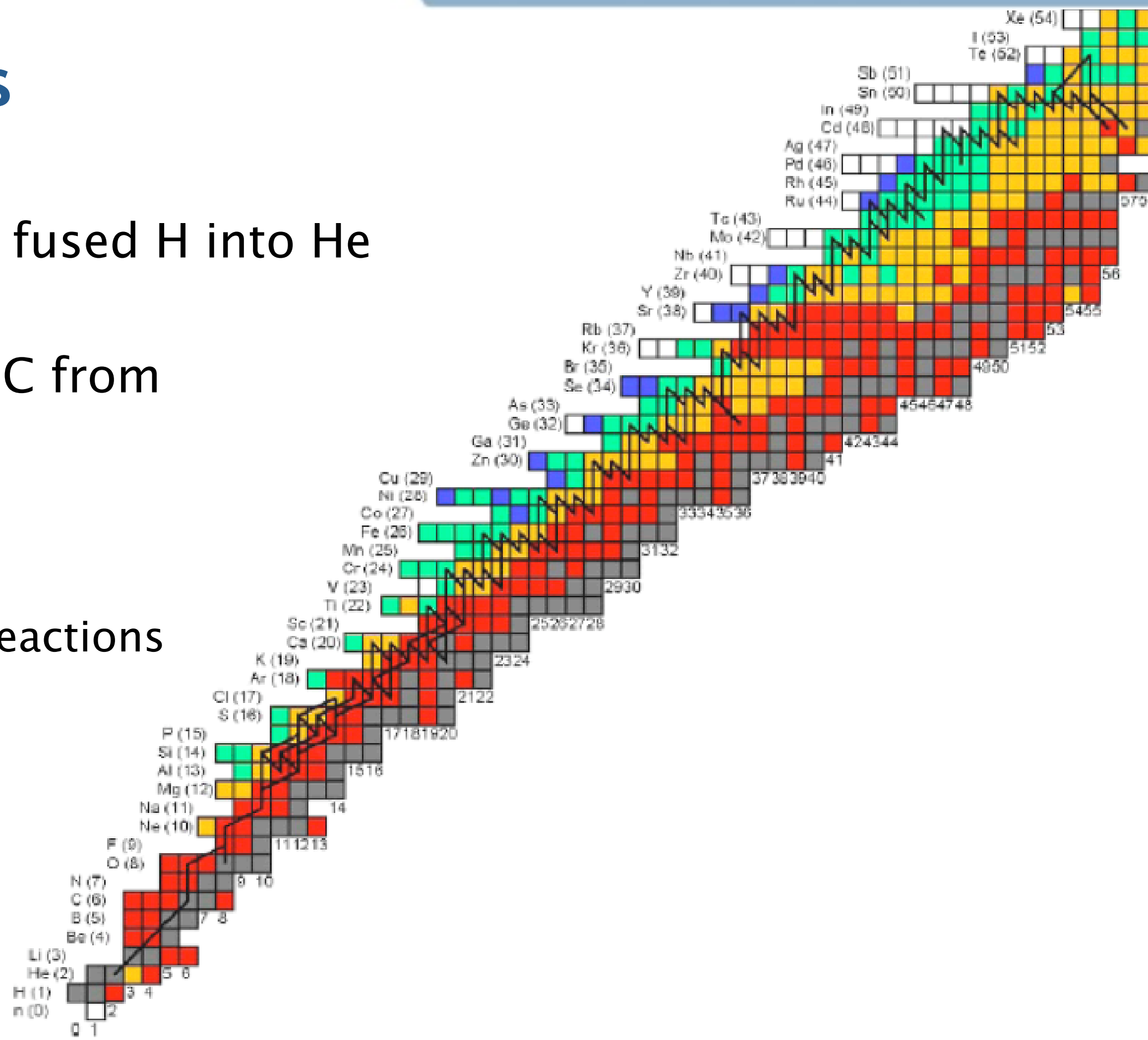
G. Zhang et al., Mon. Not. R. Astron. Soc., **398**, 368 (2009).



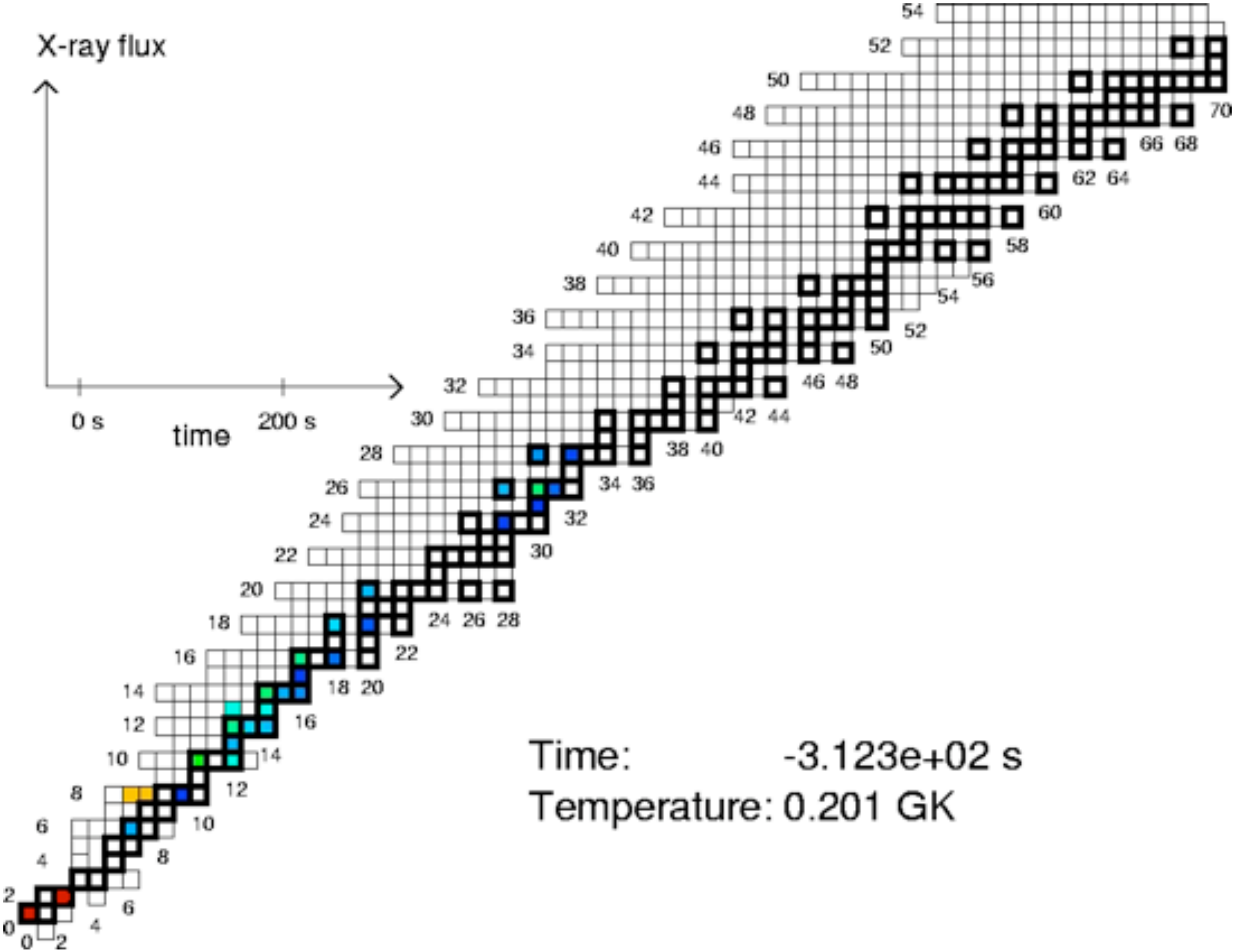
L. Keek et al., ApJ 718, 292 (2010).

XRB Nucleosynthesis

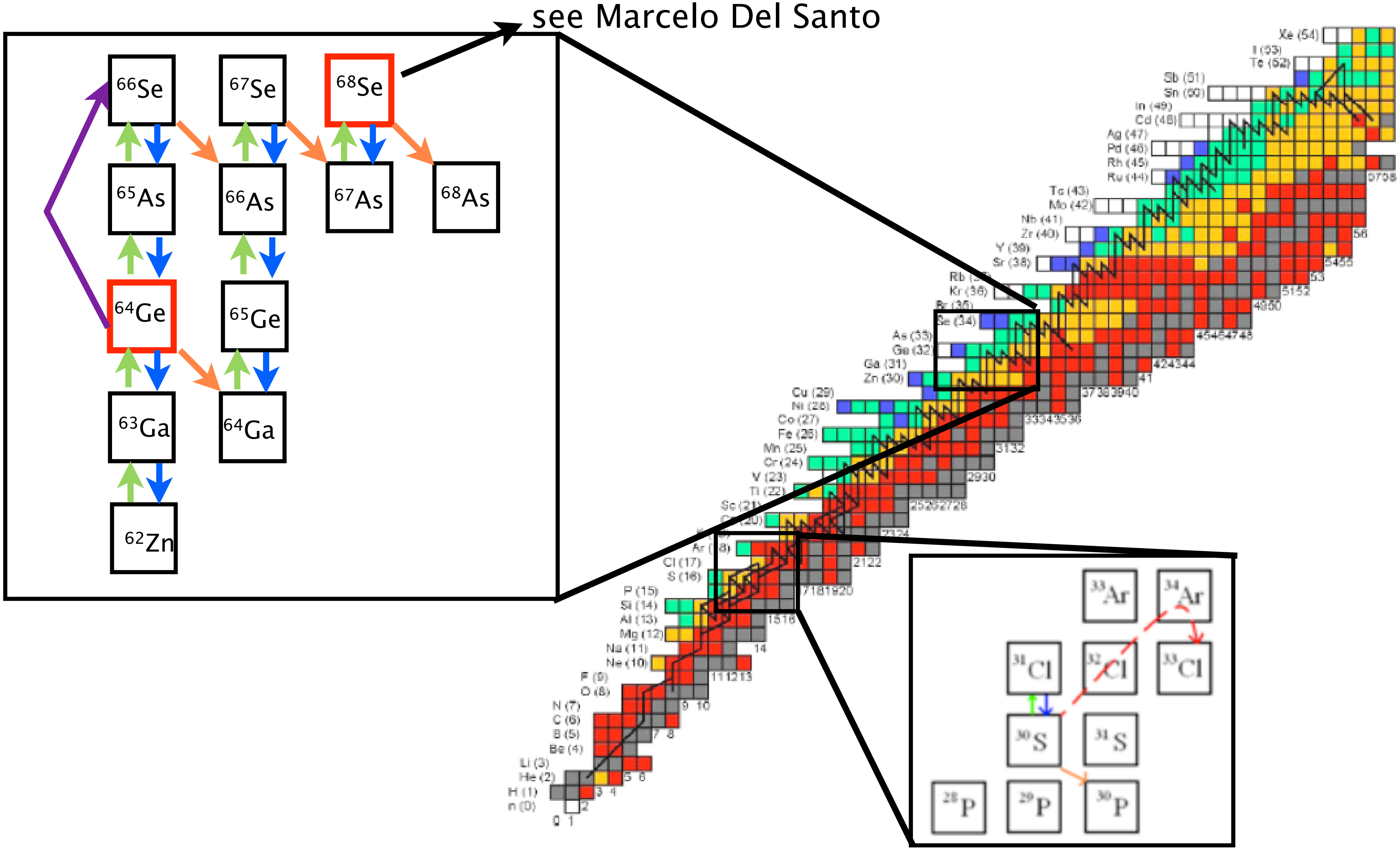
- Before burst hot CNO cycle fused H into He
- Triple–α reaction creates ^{12}C from three α particles
- αp–process
  - a series of (α,p) and (p,γ) reactions
- rp–process
  - a series of (p,γ) reactions followed by β^+ decays
  - possible endpoints for the rp–process
    - SnSbTe–mass region
    - leakage from the SnSbTe mass region? (J. Jose et al, ApJS **189**, 204 (2010))
    - weaker branch into the SnSbTe cycle (V.–V. Elomaa et al., PRL **102**, 252501 (2010))



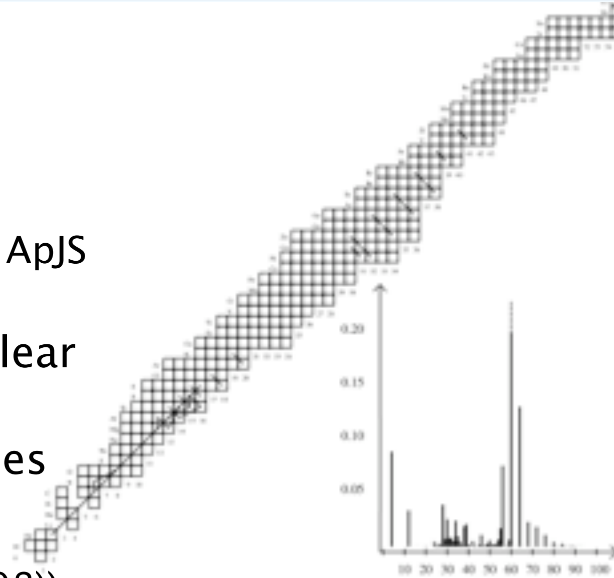
XRB Nucleosynthesis



Waiting Points



Modeling XRB Nucleosynthesis



- Thermodynamical codes (e.g. AGILE– J. L. Fisker et al., ApJS **174**, 261 (2008))
  - Fully 1D, multi-zone model coupled to complete nuclear reaction network
  - Include hundreds of nuclei and thousands of processes

- Sensitivity studies (e.g. A. Parikh et al., ApJS **178**, 110 (2008))
  - Post-processing calculations
  - Used to determine “important” reaction rates
  - vary rates by factors of 10 up and down
  - thousands of reactions:
    - under 30 reactions that significantly impact final elemental abundances of 3 or more nuclei
    - under 20 reactions that affect the energy output by > 5%

- Model inputs
  - nuclear masses
  - decay half-lives
  - accurate reaction rates

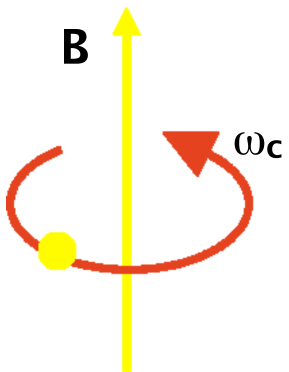
Studying XRBs in the Laboratory

- Mass Measurements
  - Penning Traps (e.g. Jonathon Van Schelt, Dan Lascar, Sebastian George)
    - Canadian Penning Trap (CPT) at ANL, ISOLDETRAP at CERN, JYFLTRAP at Jyvaskyla, SHIPTRAP at GSI, LEBIT at MSU, etc.
  - TOF measurements
  - Q-value measurements

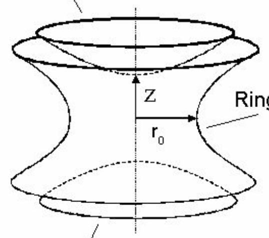
- β-decay lifetime measurements

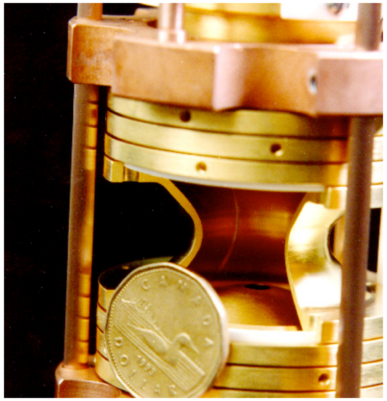
- Reaction rate measurements
  - Direct measurements
    - Radioactive Ion Beams production
    - Experiments
  - Indirect measurements

Penning Trap Measurements

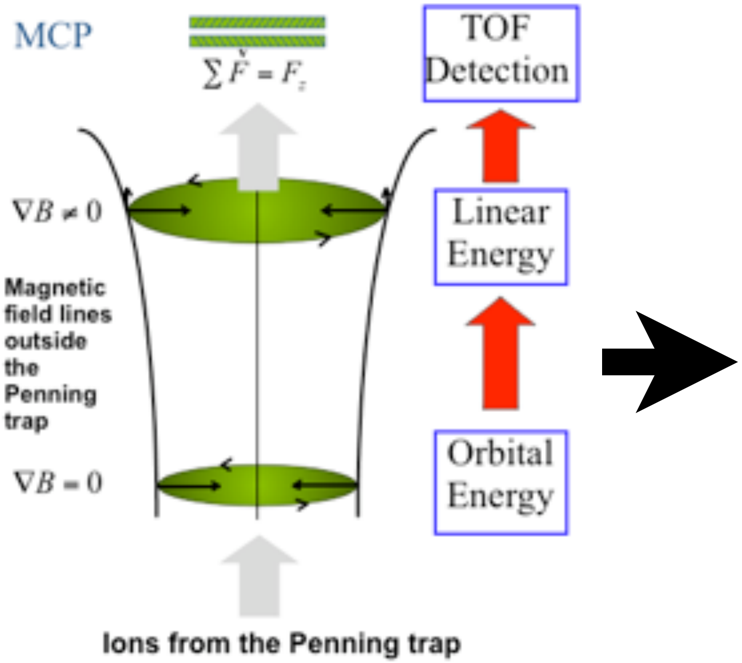


- Constant axial magnetic field **B**
- Ions orbit **B** with cyclotron frequency $\omega_c = qm/B$
- Harmonic field along **B** confines particles in trap

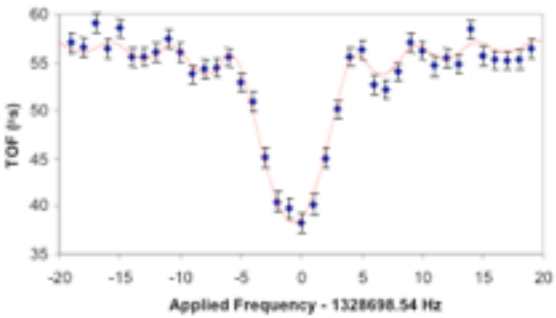




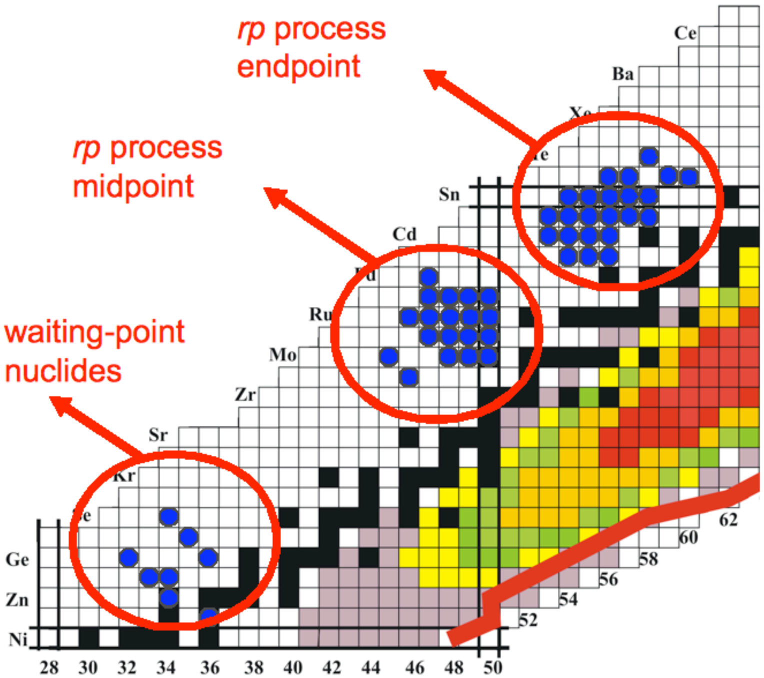
- Applying ω_c to the ring electrode gives the greatest orbital energy to the ions
- When the ions are ejected from the trap the orbital energy gets translated to linear energy
- The TOF from the trap to a detector is measured
- The minimum times occurs when the ions have the highest energy – ω_c



Time of flight spectrum: minimum at frequency of ω_c

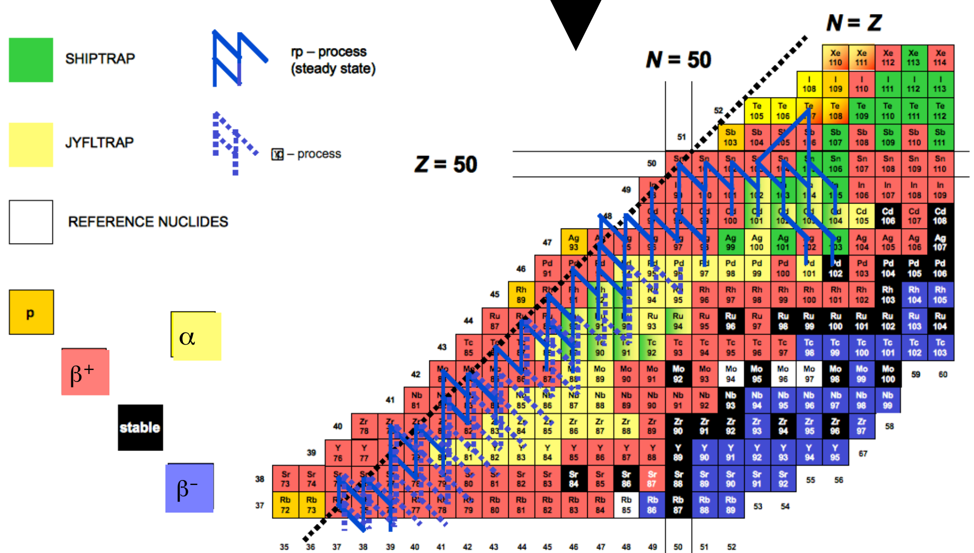


Measured Masses along the rp-process



CPT mass measurements

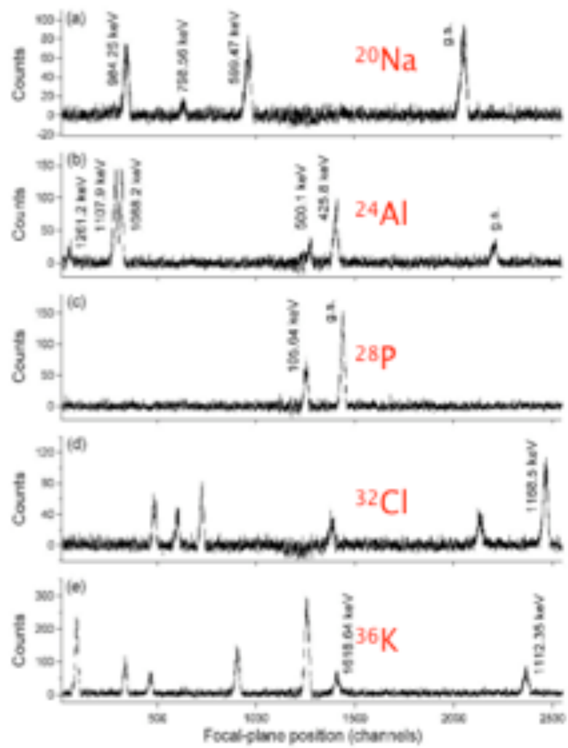
SHIPTRAP and JYFLTRAP measurements

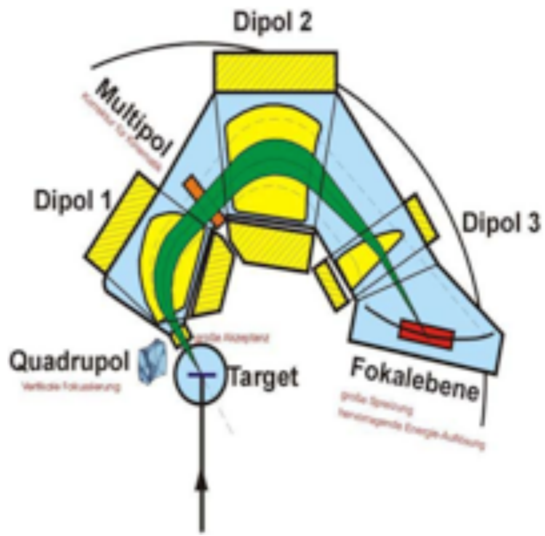


A. Kankainen *et al.*, Eur. Phys. J. A **29**, 271 (2006).
A. Martín *et al.*, Eur. Phys. J. A **34**, 341 (2007).
C. Weber *et al.*, Phys. Rev. C 78, 054310 (2008).

Q-value measurements:

- Using (^{3}He,t) reactions on thin, ion-implanted foils of ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, and ^{36}Ar
- Momentum analyzing the reaction products gives the momentum of the tritons at the focal plane
- Masses of ^{20}Na, ^{24}Al, ^{28}P, and ^{32}Cl are determined from momenta





Reaction	Q value [22]	Q value (present)
^{19}Ne$(p,\gamma)^{20}$Na	2193(7)	2190.1(11)
^{23}Mg$(p,\gamma)^{24}$Al	1872(3)	1863.0(14)
^{27}Si$(p,\gamma)^{28}$P	2063(3)	2051.7(12)
^{31}S$(p,\gamma)^{32}$Cl	1574(7)	1578.2(19)[b]
^{35}Ar$(p,\gamma)^{36}$K	1668(8)	1658.4(8)[c]

C. Wrede, J. Clark, C. M. Deibel et al., PRC **82**, 035805 (2010).

Studying XRBs in the Laboratory

- Mass Measurements
  - Penning Traps (e.g. Jonathon Van Schelt, Dan Lascar, Sebastian George)
    - Canadian Penning Trap (CPT) at ANL, ISOLDETRAP at CERN, JYFLTRAP at Jyvaskyla, SHIPTRAP at GSI, LEBIT at MSU
  - TOF measurements
  - Q-value measurements

- β-decay lifetime measurements

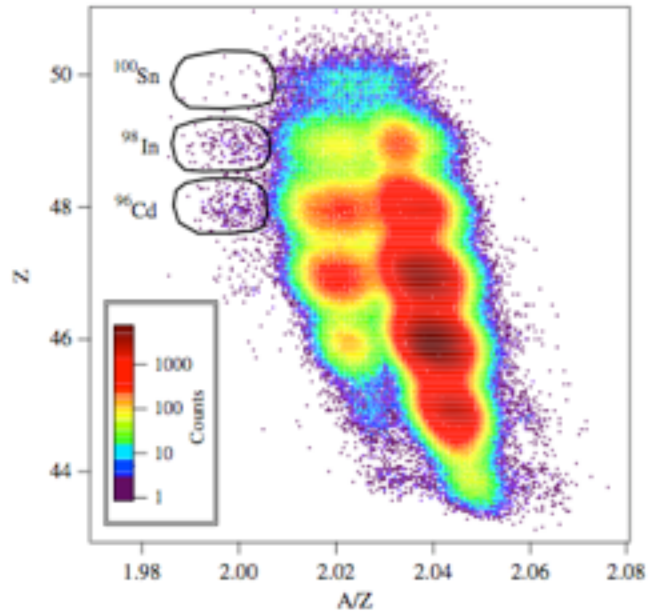
- Reaction rate measurements
  - Direct measurements
    - Radioactive Ion Beams production
    - Experiments
  - Indirect measurements

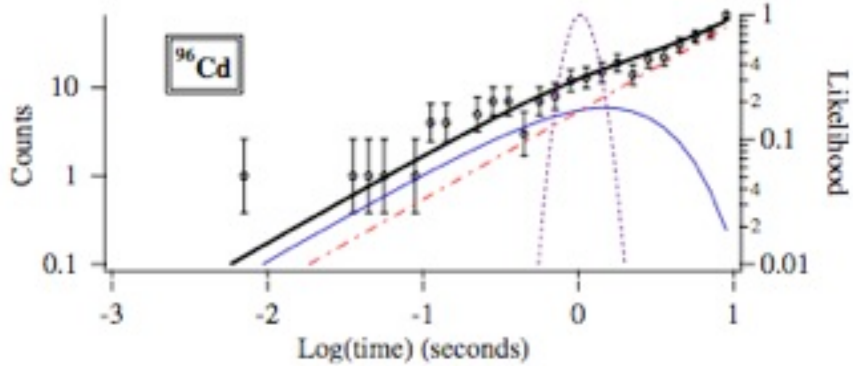
β-decay lifetimes

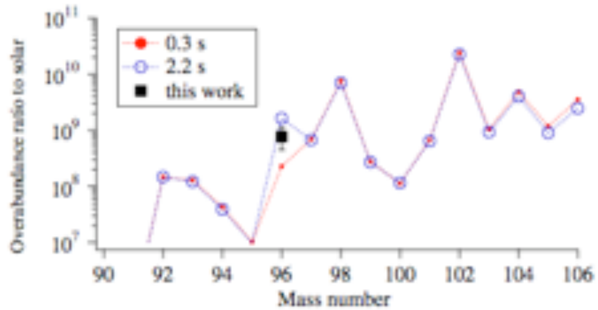
- β–decay lifetimes set the time scale for XRBs since the they partially define how long the heavier elements can build up at waiting point nuclei

- ^{96}Cd half-life measured at NSCL
  - Projectile fragmentation technique was used to produced ^{96}Cd
  - Ions implanted in a double-sided Si strip detector and decays counted

- Most of the important β–decay halflives are now thought to be measured







D. Bazin et al., PRL **101**, 252501 (2008)

Studying XRBs in the Laboratory

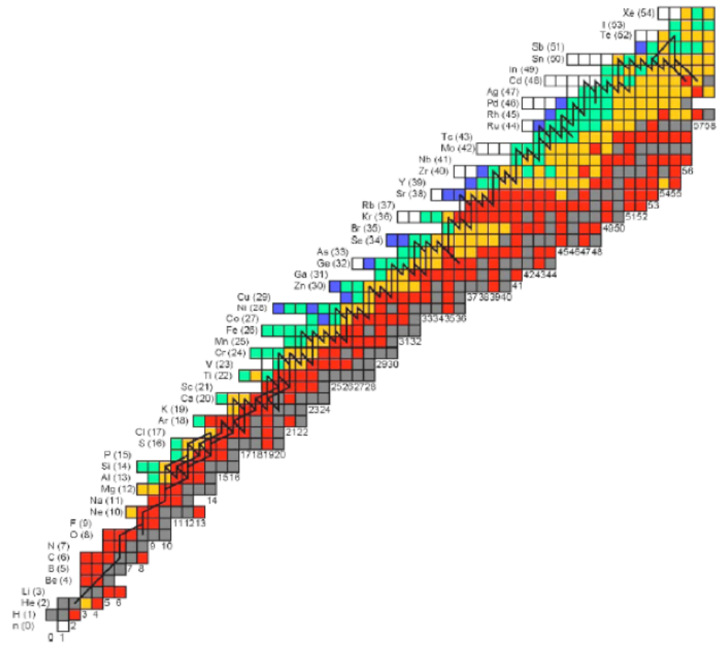
- Mass Measurements
  - Penning Traps (e.g. Jonathon Van Schelt, Dan Lascar, Sebastian George)
    - Canadian Penning Trap (CPT) at ANL, ISOLDETRAP at CERN, JYFLTRAP at Jyvaskyla, SHIPTRAP at GSI, LEBIT at MSU
  - TOF measurements
  - Q-value measurements
- β-decay lifetime measurements
- Reaction rate measurements
  - Direct measurements
    - Radioactive Ion Beams production
    - Experiments
  - Indirect measurements

Reaction Rates

- Reaction rates important for XRBs
  - (p,γ), (α,p), and (α,γ) (see Richard Cyburt)

- Direct measurements of reaction rates
  - Radioactive Ion Beams (RIBs)
  - Recoil separators (DRAGON @ TRIUMF, St. George @ ND, SHARQ @ RIKEN, SECAR @ FRIB)
  - Coincidence measurements (ANL)
  - Active target measurements (ORNL, ReA3)

- Indirect measurements:
  - Determine resonance energies, spins, and partial widths
  - Use transfer reactions to populate states in compound nuclei

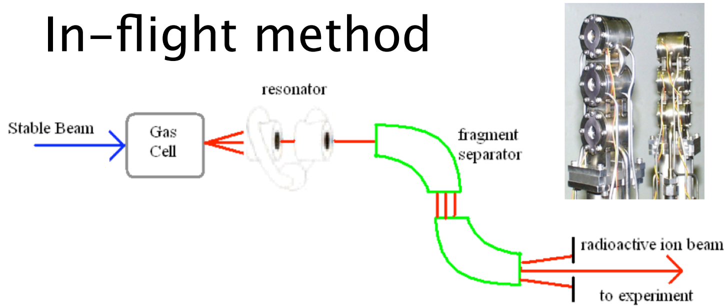


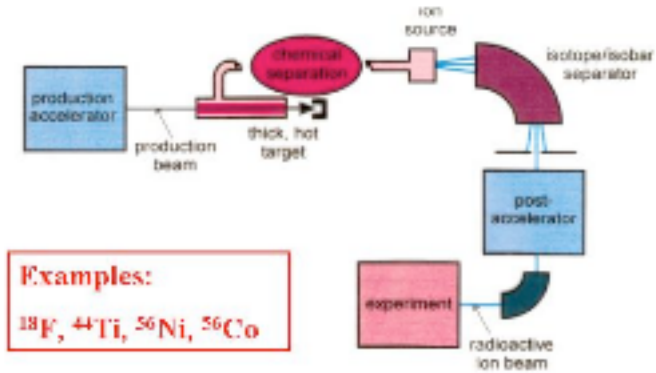
$$N_A \langle \sigma v \rangle = \frac{1.5399 \times 10^{11}}{(\mu T_9)^{3/2}} \sum_i (\omega\gamma)_i \, e^{-11.605 E_i / T_9}$$

$$\omega\gamma_i = \frac{(2J_i + 1)}{(2J_{Al} + 1)(2J_p + 1)} \left(\frac{\Gamma_p \Gamma_\gamma}{\Gamma_{total}} \right)_i$$

Radioactive Ion Beams

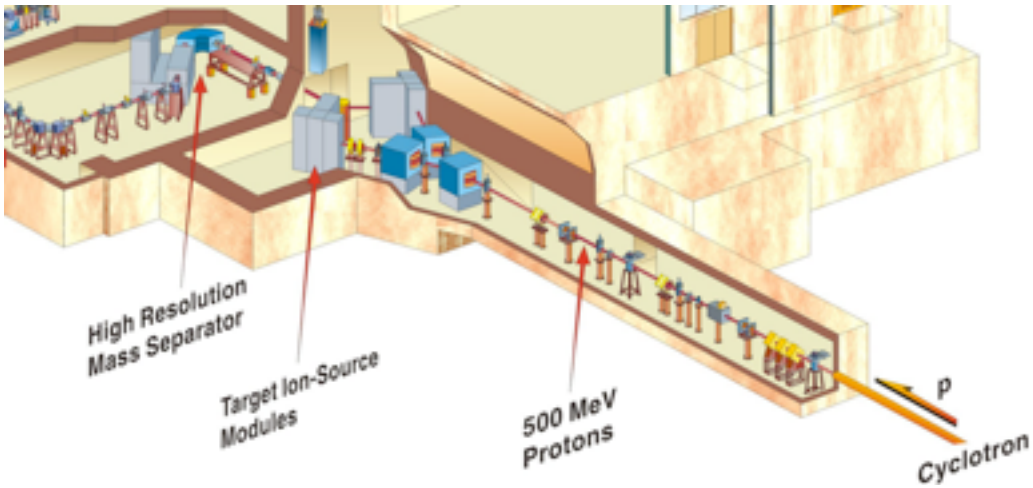
In-flight method





Two accelerator method

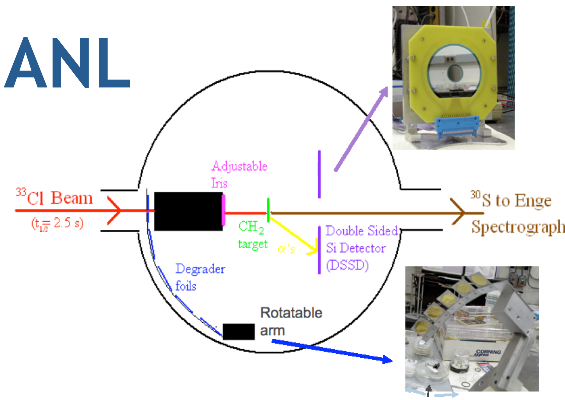
ISOL (Isotope Separation On-Line) method



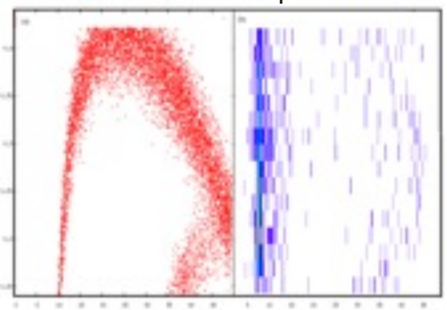
Reacceleration of fragmentation and fission products (ReA3 and CARIBU)

Direct Measurements:
(α,p)- process measurements at ANL

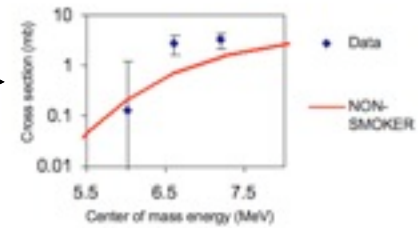
- Uses the in-flight method to produce RIBs
- Studies the time-inverse (p,α) reactions in inverse kinematics
- Detects the α-particles in coincidence with the heavy residual nuclei
- Normalizing to beam current and target thickness cross sections are determined
- Future direct (α,p) reaction measurements planned with new HELIOS device



Monte Carlo simulations and coincidence Spectrum

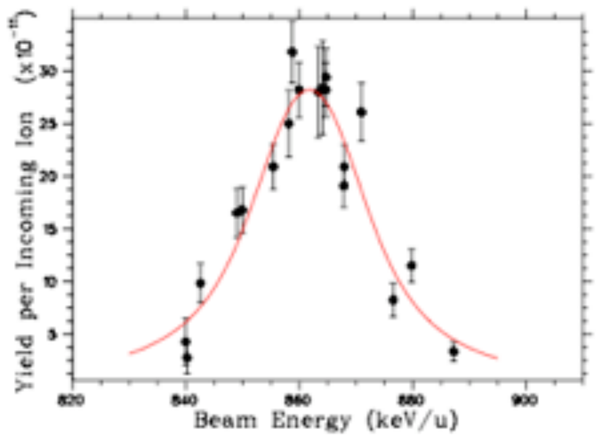


Preliminary p(^{33}Cl,^{30}S)α cross sections



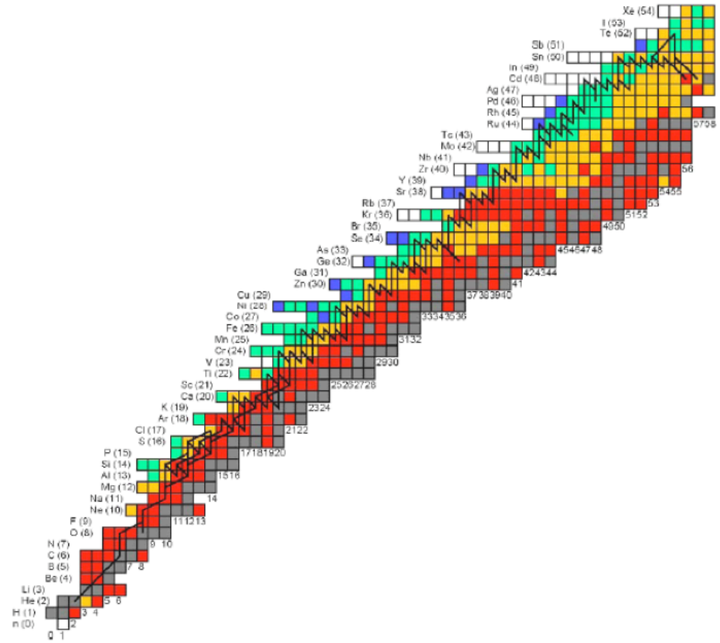
Direct Measurements: $^{21}Na(p,\gamma)^{22}Mg$ at TRIUMF

- Radioactive ^{21}Na beam was delivered by the ISAC facility at TRIUMF
- RIB incident on a hydrogen-gas target
- γ's were detected by a BGO array in coincidence with the ^{22}Mg particles
- ^{22}Mg particles separated from beam and other reaction products using the DRAGON recoil separator (a series of magnetic dipoles and quads and electrostatic dipoles) and detected with an MCP
- The position of the resonance in the gas target gives the resonance energy and the yield gives the resonance strength



A. A. Chen et al., Nucl. Phys. **A752**, 510 (2005)

Reaction Rates

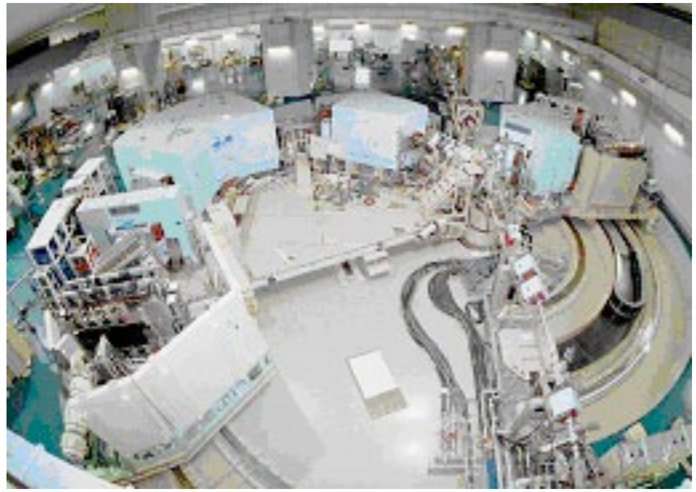


- Reaction rates important for XRBs
  - (p,γ), (α,p), and (α,γ) (see Richard Cyburt)
- Direct measurements of reaction rates
  - Radioactive Ion Beams (RIBs)
  - Recoil separators (DRAGON @ TRIUMF, St. George @ ND, SHARQ @ RIKEN, SECAR @ FRIB)
  - Coincidence measurements (ANL)
  - Active target measurements (ORNL, ReA3)
- Indirect measurements:
  - Determine resonance energies, spins, and partial widths
  - Use transfer reactions to populate states in compound nuclei

$$N_A\langle\sigma v\rangle = \frac{1.5399\times10^{11}}{(\mu T_9)^{3/2}}\sum_i (\omega\gamma)_i\, e^{-11.605 E_i/T_9}$$

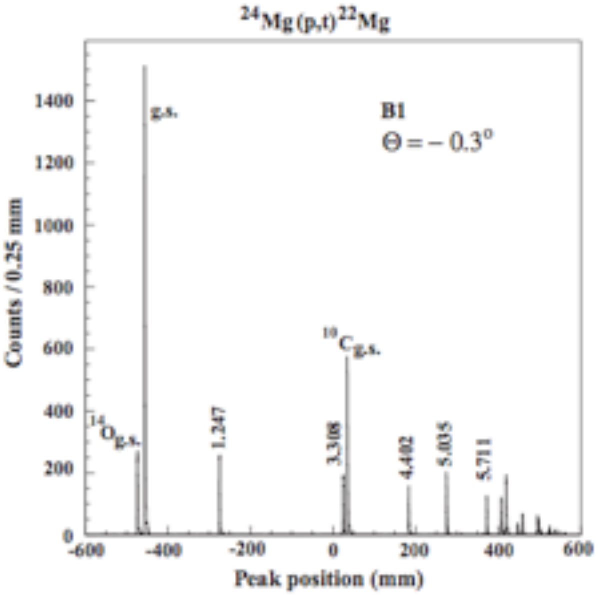
$$\omega\gamma_i = \frac{(2J_i+1)}{(2J_{Al}+1)(2J_p+1)}\left(\frac{\Gamma_p\Gamma_\gamma}{\Gamma_{total}}\right)_i$$

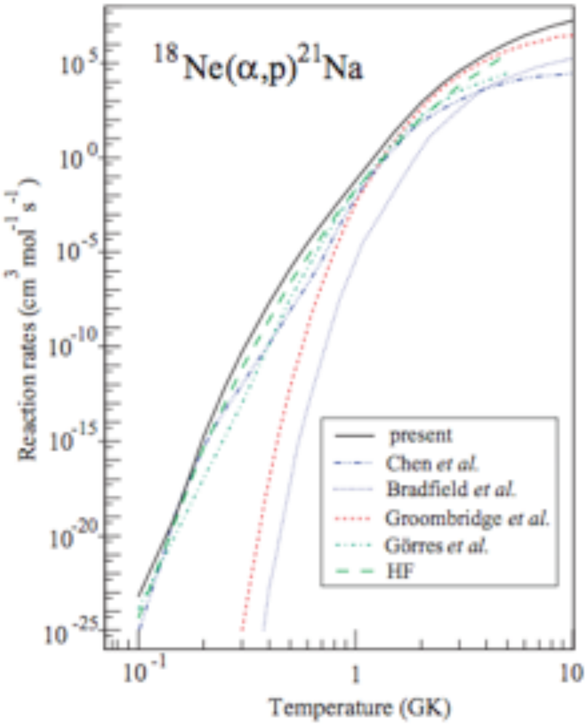
Indirect Measurements: Studying states in ^{22}Mg for the ^{18}Ne(α,p)^{21}Na reaction

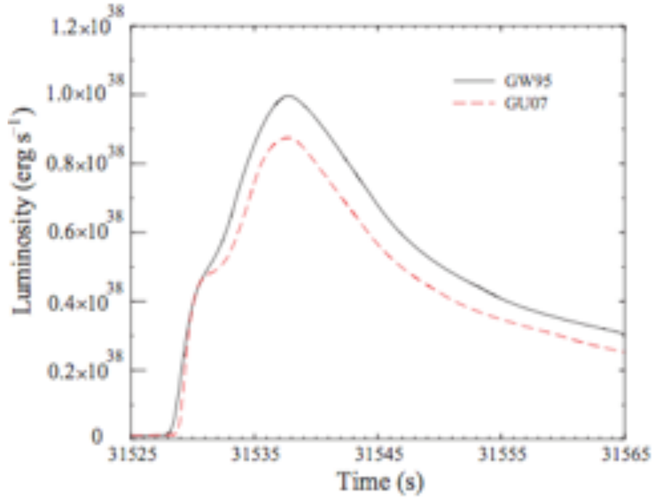


Grand Raiden Spectrometer at RCNP, Osaka, Japan

- Using transfer reactions (e.g. (p,t) at Osaka by ND group) states of the compound nucleus can be populated and their properties measured
  - Resonance energies E_r
  - Spins J^π
- These values can be use to calculate
  - Reaction rates
  - Model XRBs



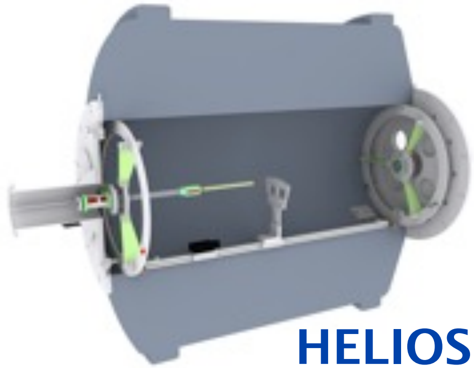


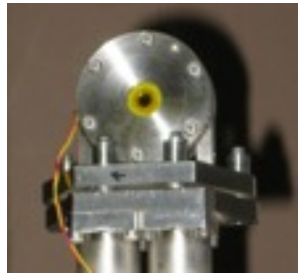


A. Matic et al., PRC **80**, 055804 (2009).

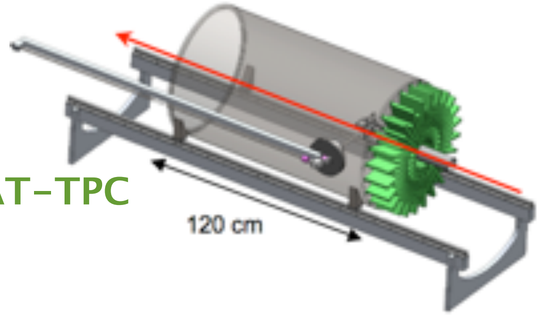
Reaction rate measurements in the future

- HELIOS
  - Direct (α,p) measurements
  - Indirect studies (e.g. (^{3}He,d))
- Gas-jet target
  - Direct (p,γ) measurements
  - Indirect transfer measurements
- ReA3 and FRIB at MSU
  - AT-TPC for indirect measurements (e.g. (^{3}He,d))
  - ANASEN for direct (α,p)
  - SECAR for direct reaction rate measurements

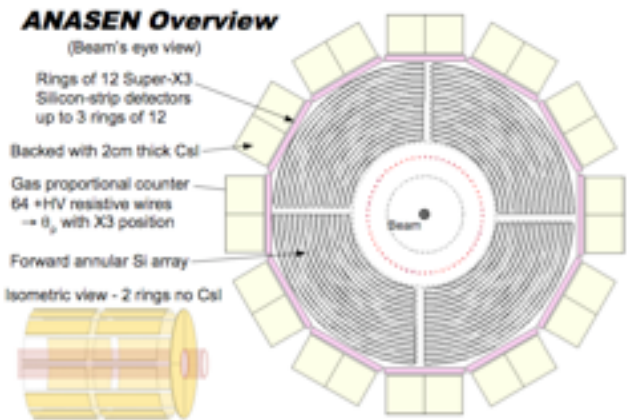


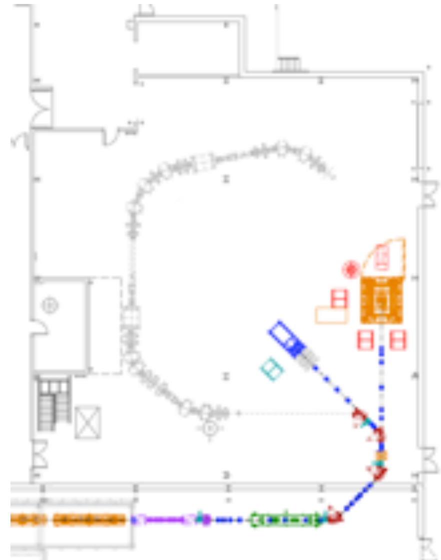


HELIOS with gas target



AT-TPC





SECAR

Conclusions

- XRBs represent the necessary interplay between observers, modelers, and experimentalists
- Many observed phenomena still unexplained
- Models have just recently been able to incorporate multiple zones **and** large reaction rate networks, but are still based mostly on theoretical reaction rates
- Most -decay lifetimes have now been measured
- Still need actual experimental reaction rates
  - Future efforts using indirect methods with new equipment
  - Future RIB facilities and upgrades will help!
- THANKS!