On the waiting point at A=30 in X-Ray Bursts: $^{30}S(\alpha,p)^{33}Cl$ with CRIB

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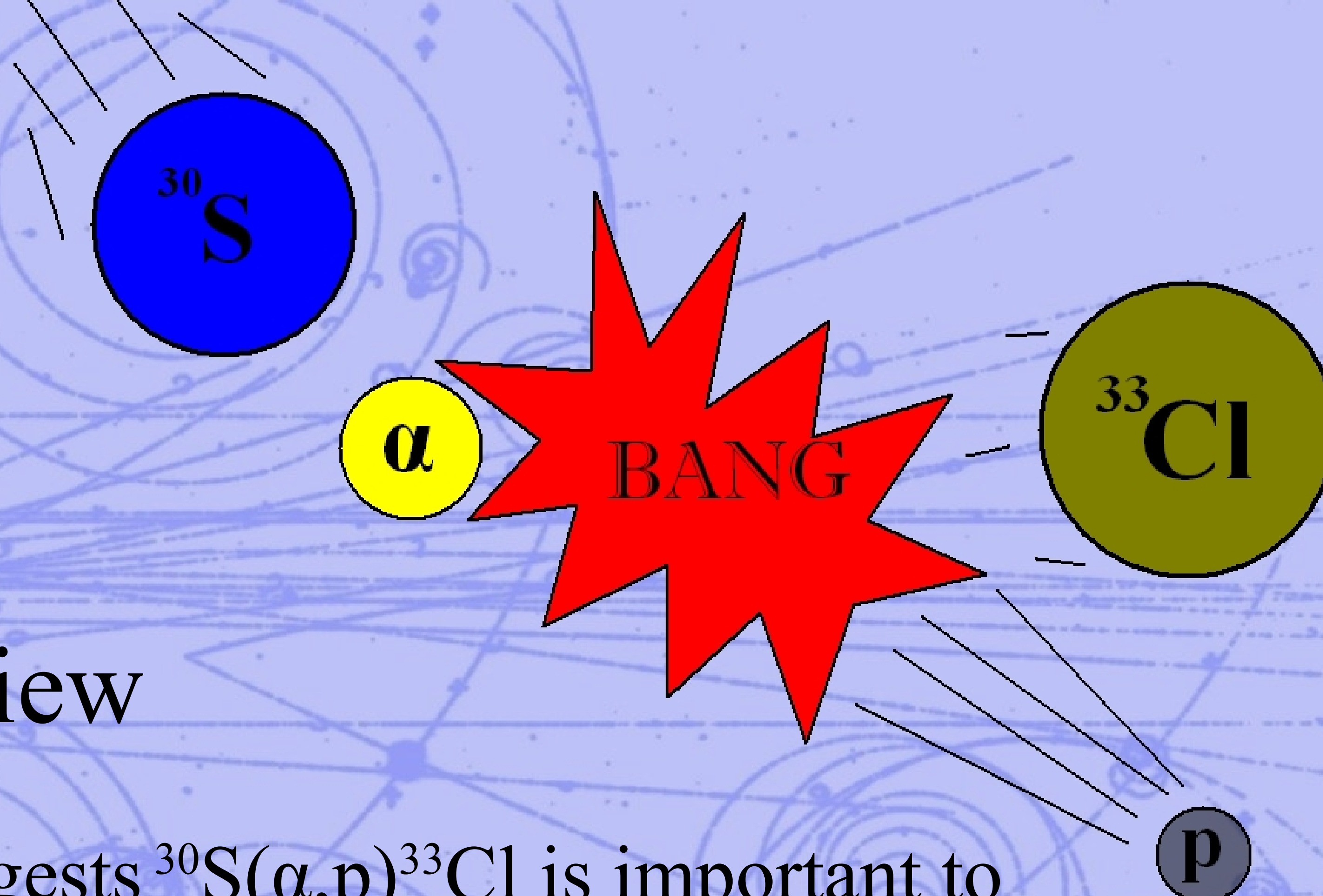
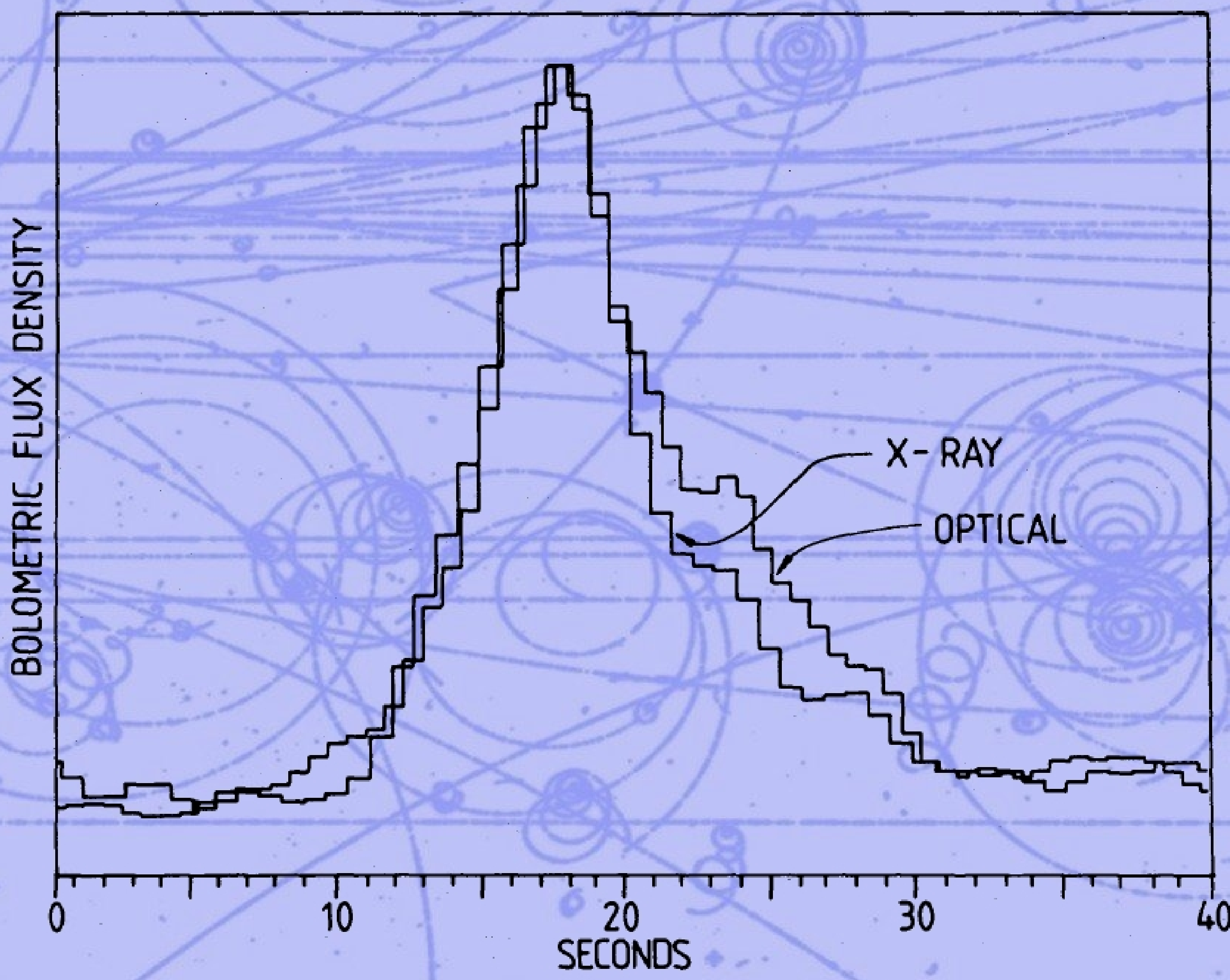


Overview

- Modelling suggests $^{30}S(\alpha,p)^{33}Cl$ is important to energy generation in X-Ray Bursts (XRBs)
- Reaction cross sections are the main uncertain factor in stellar reaction rates
- We want to measure the cross section of the inverse reaction – $\alpha(^{30}S,p)^{33}Cl$, so we need a ^{30}S beam

Typical XRB (~100 Known Systems)

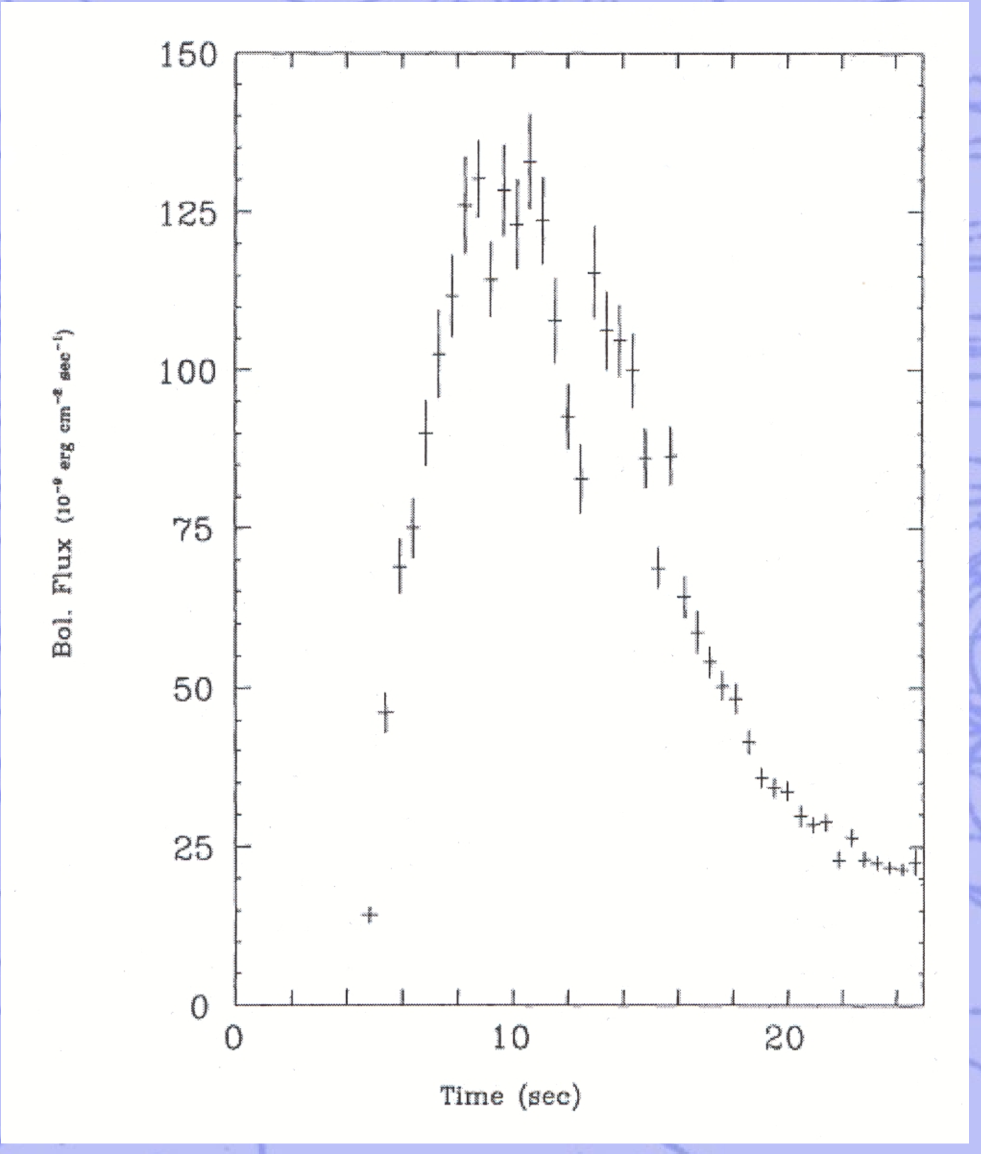
4U 1636-53



A. Lawrence *et al.* 1983, ApJ, 271, 793.

One of Four Multi-peaked XRBs

4U 1608-52



Penninx, W., Damen, E., van Paradijs, J, & Lewin, W. H. G. 1989, A&A, 208, 146.

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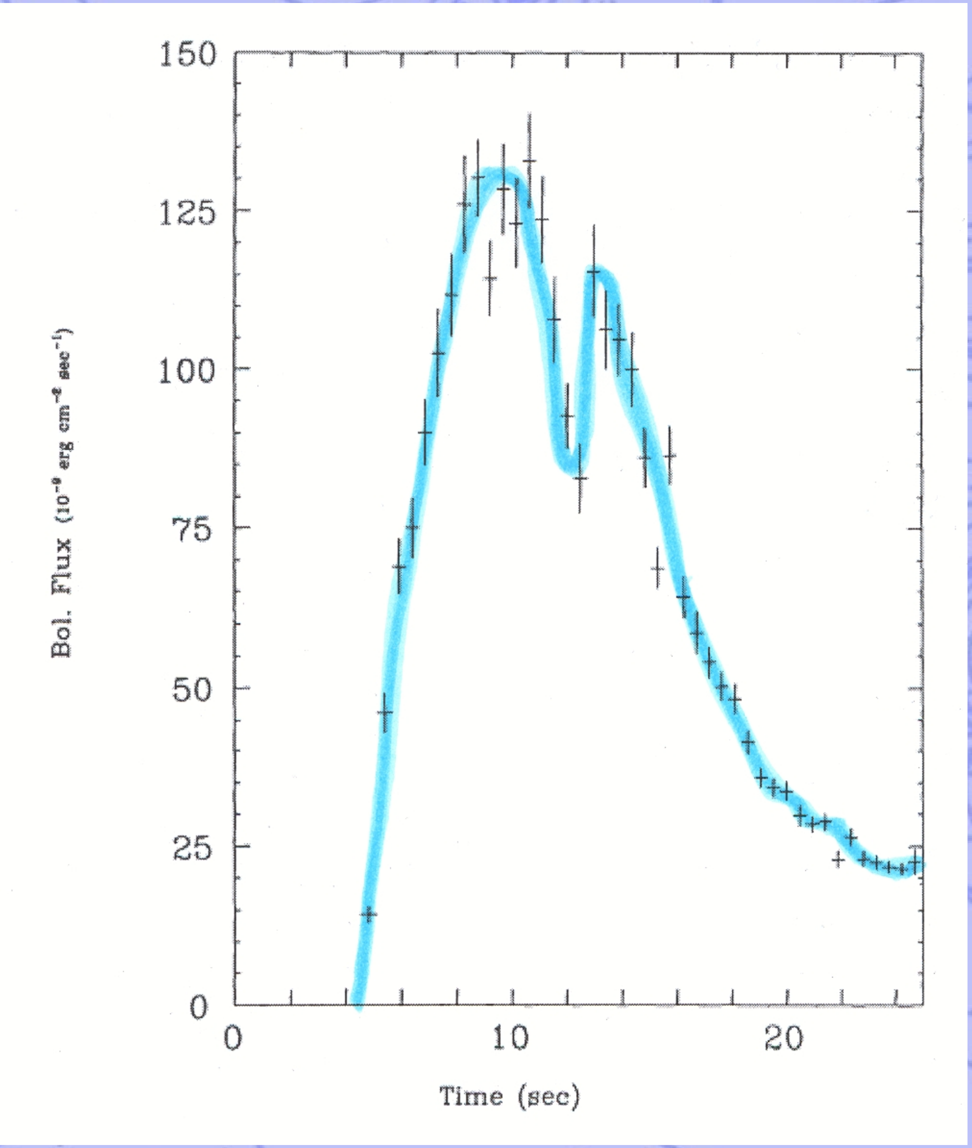


Penninx, W., Damen, E., van Paradijs, J, & Lewin, W. H. G. 1989, A&A, 208, 146.

Assumed Initial Conditions

- Fisker, Thielemann & Wiescher model (2004)
  - J. Fisker, F.-K. Thielemann, and M. Wiescher, Ap. J. **608** (2004) 61
- Low mass binary systems
- Accretion material of solar composition
  - Anders & Grevesse 1989
- Atmosphere initial T = 0.1 – 0.2 GK
  - Burst temperature will be 1 – 2 GK
- Constant accretion rate of 7.65×10^{-6} solar masses/year
  - 4.5% of the Eddington accretion rate

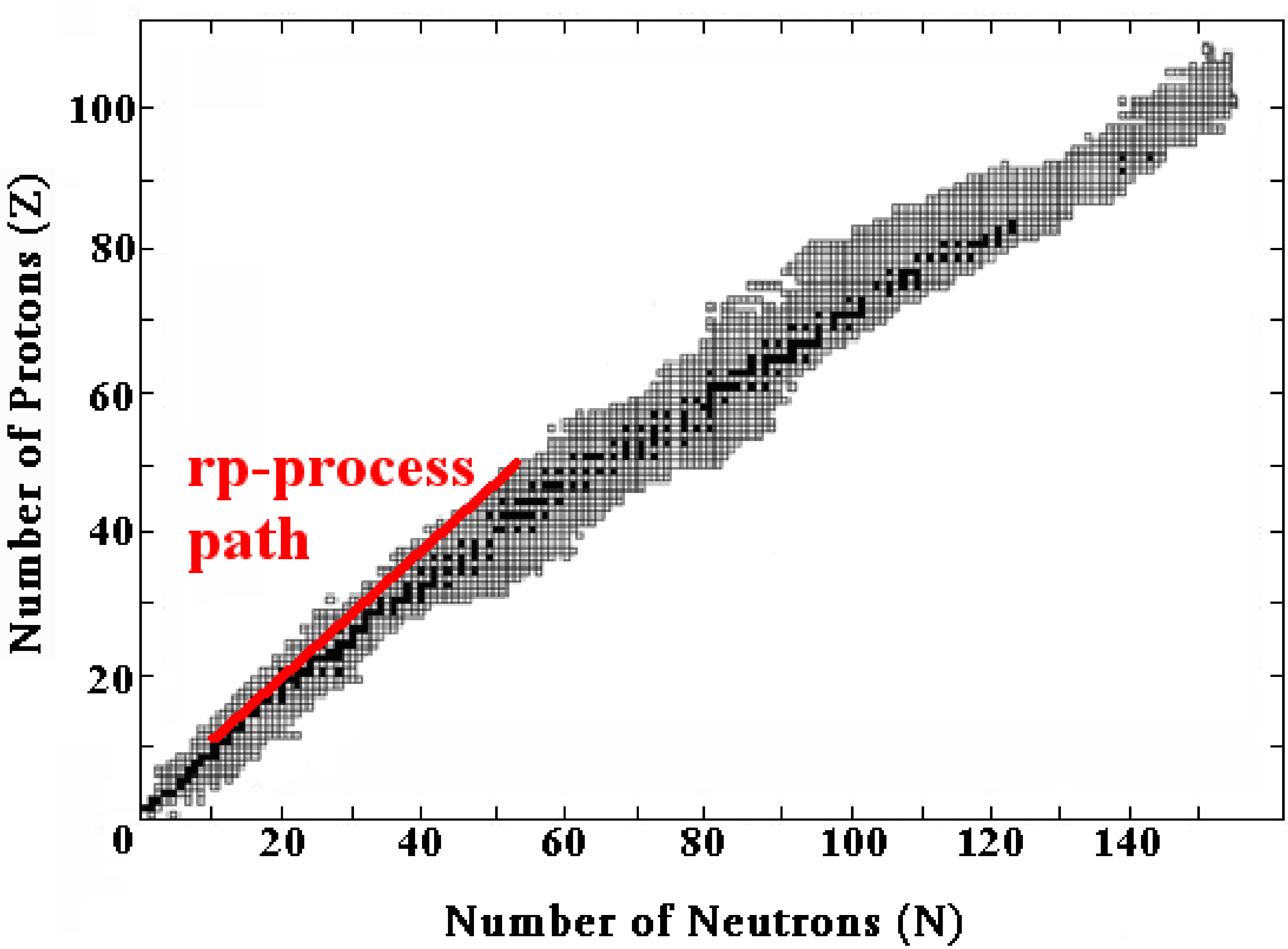
Uncertain Factors of XRB Model

- Models of Convection
  - Not easily testable / falsifiable
- Accretion rate & material
  - Rate may vary by 6 orders of magnitude!
- Restrictions of Spherically Symmetric Models
  - Close binary pairs are not spherical
- Nuclear cross sections with no experimental data
  - $^{30}S(\alpha,p)$ and $^{34}Ar(\alpha,p)$ reactions rates

Some XRBs are Double Peaked. Why?

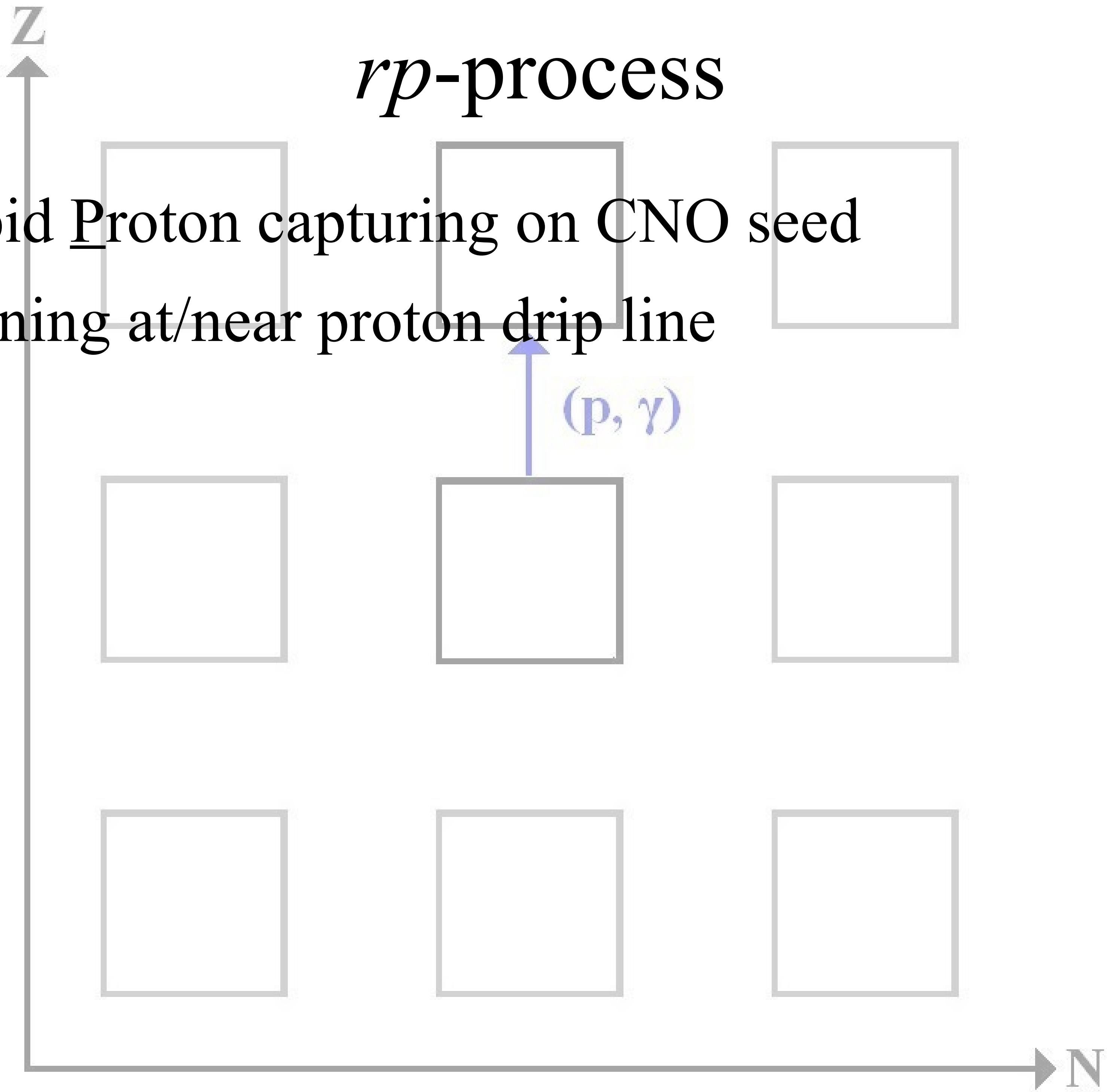
- Satellite counter energy range
  - Some double-peaks may be from radius expansion
  - Drop is in bolometric luminosity for 3 systems
- Modeling of Heat Transport
  - Artificial impedance with < 20 zones
- Spatially Localized Burning Region
  - Frequency
- Accretion Disk Scattering
  - Recurrence time, fluence, peak flux
- **Multiple Release of Nuclear Energy**

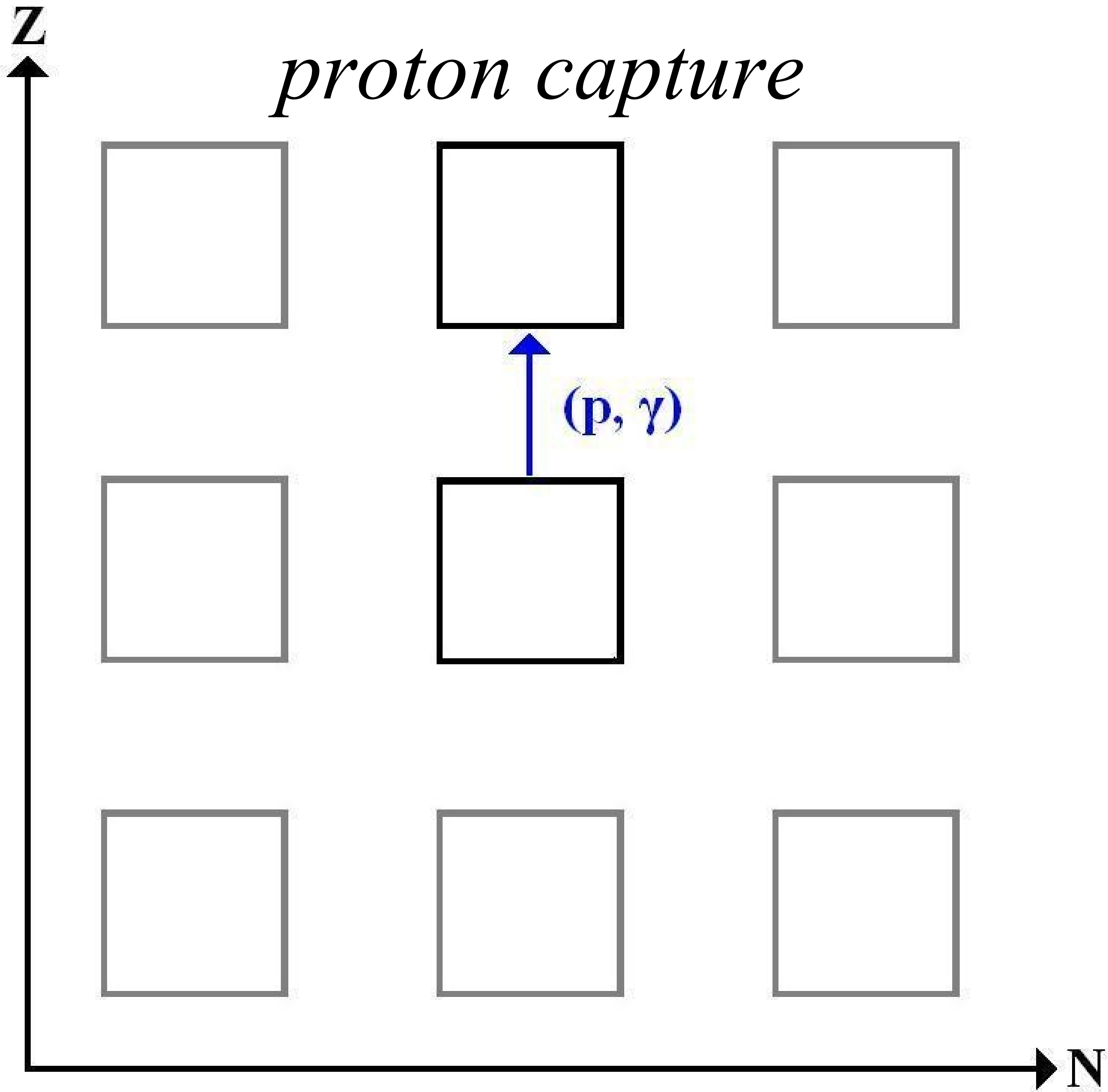
rp-process Burning Path

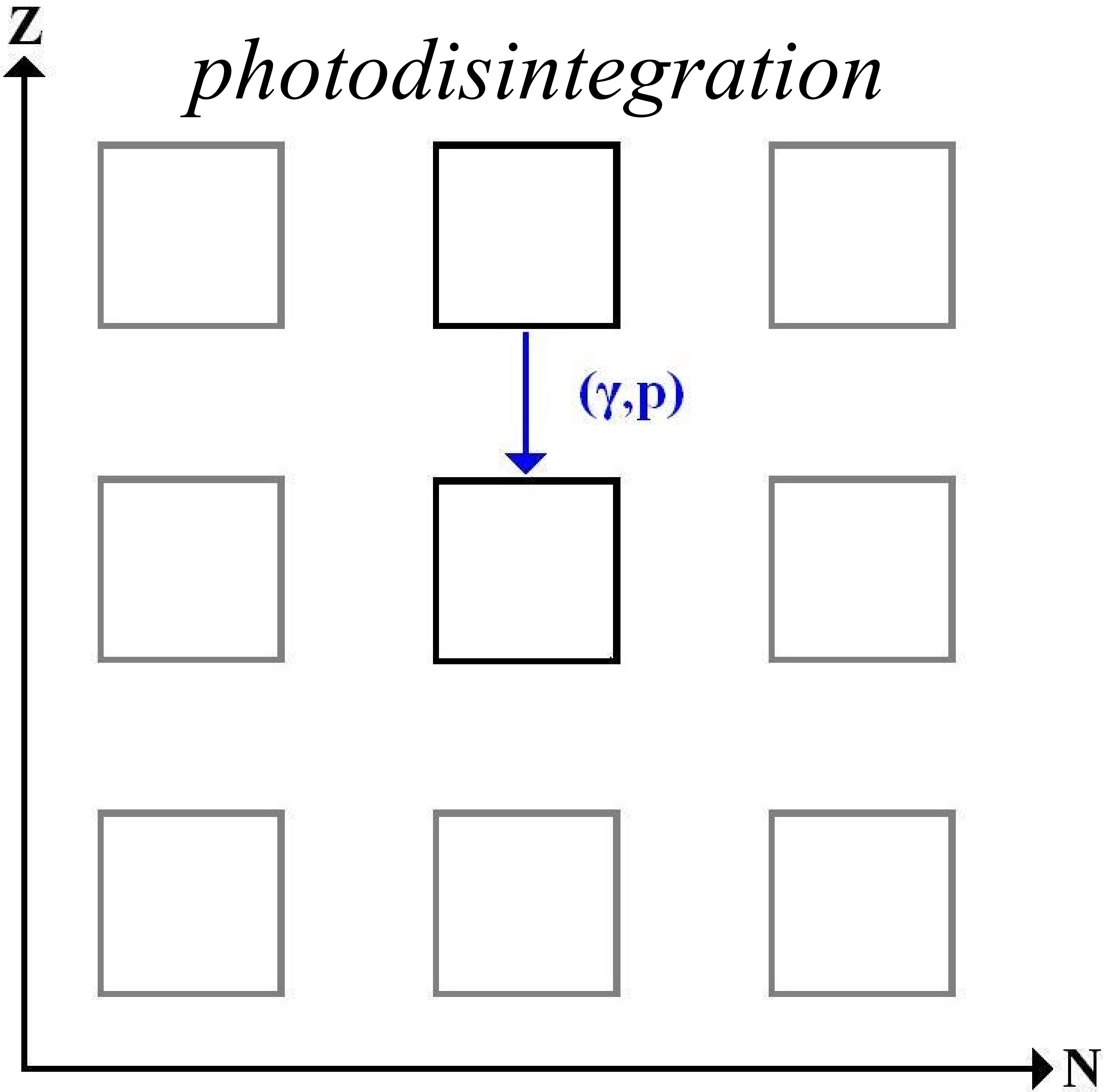


rp-process

- Rapid Proton capturing on CNO seed
- Burning at/near proton drip line

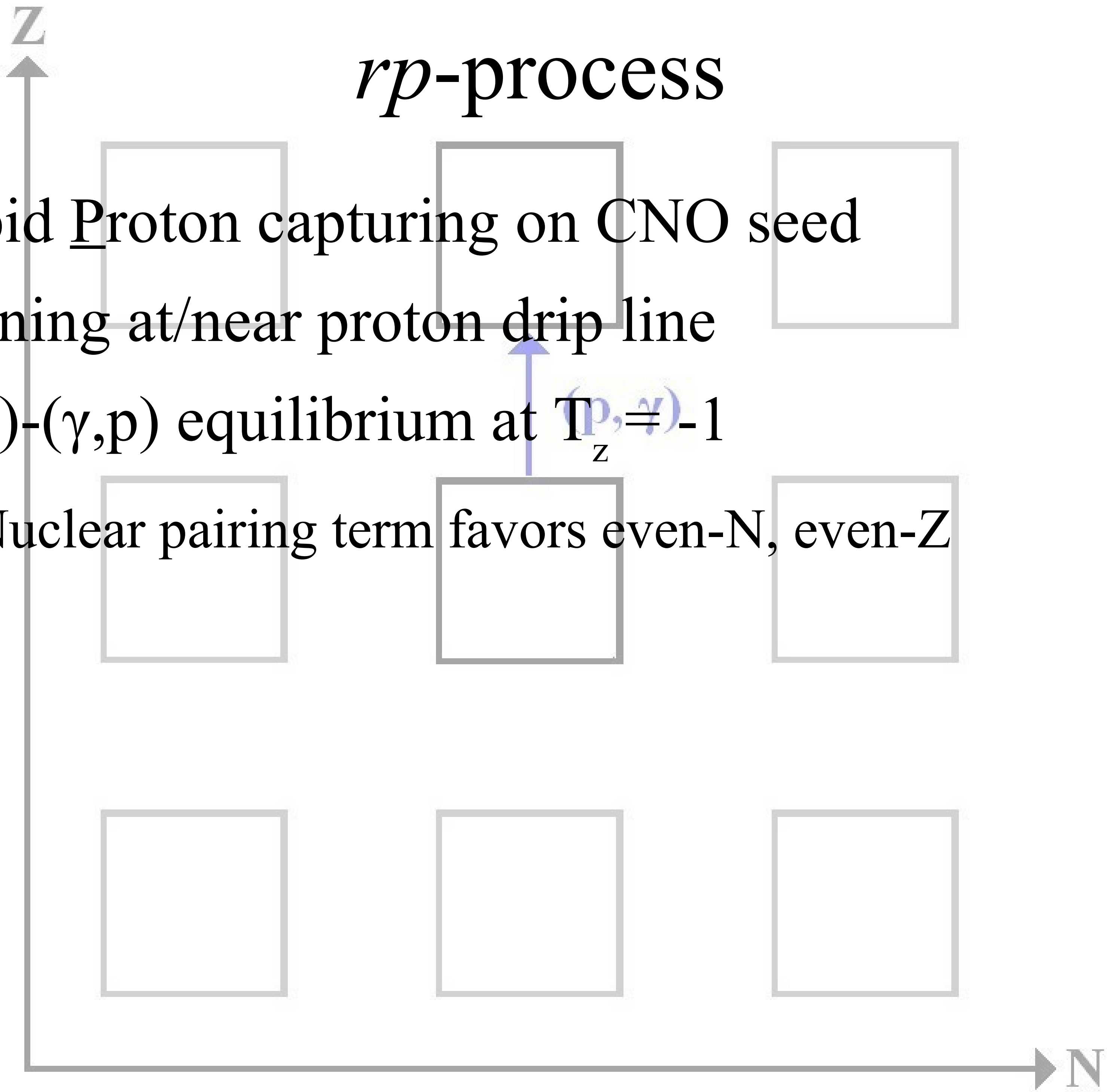



Z
proton capture
(p, γ)
N


Z
photodisintegration
(γ,p)
N

rp-process

- Rapid Proton capturing on CNO seed
- Burning at/near proton drip line
- (p,γ)-(γ,p) equilibrium at $T_z = -1$
  - Nuclear pairing term favors even-N, even-Z



rp-process

- <u>R</u>apid <u>P</u>roton capturing on CNO seed
- Burning at/near proton drip line
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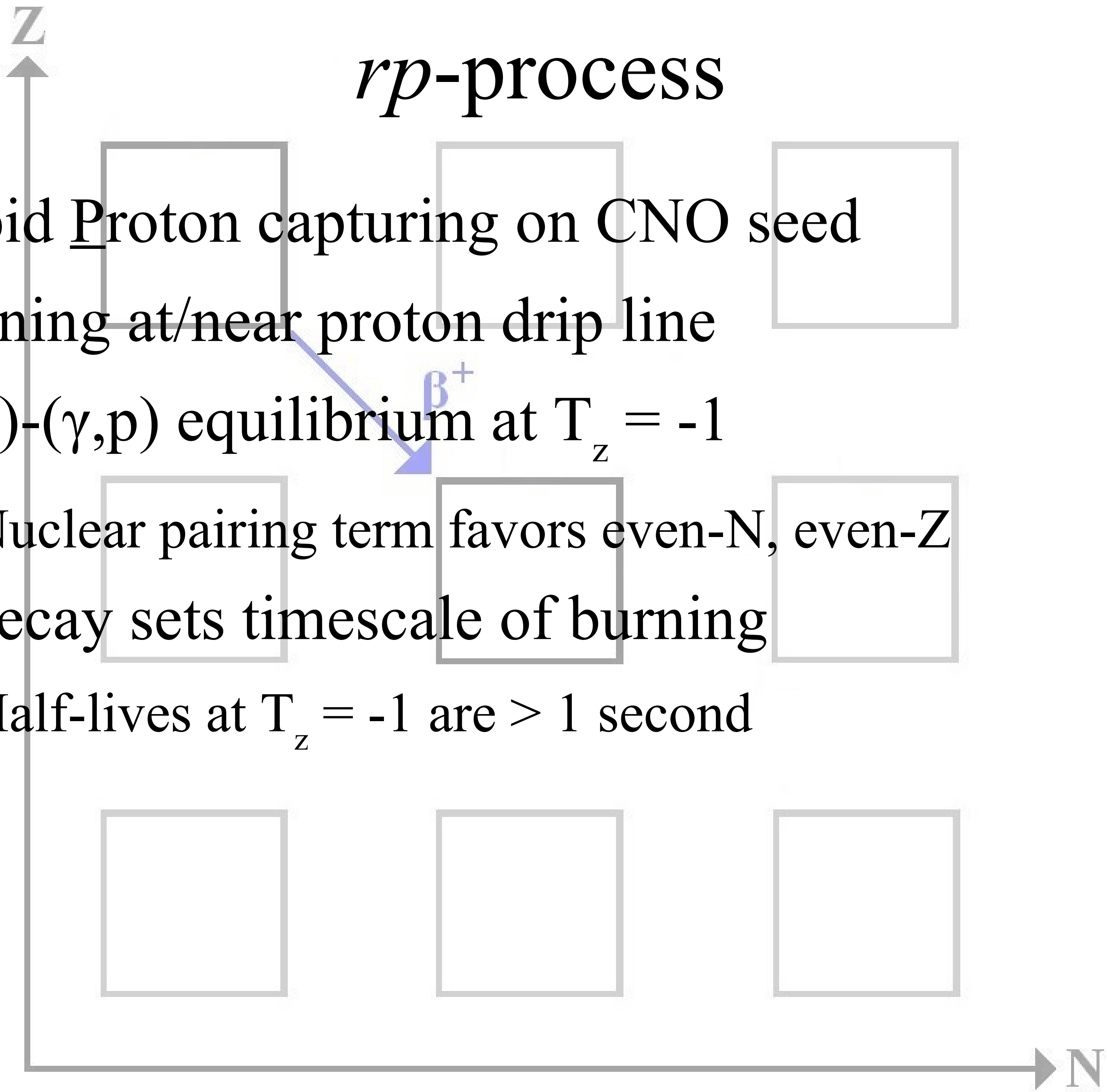
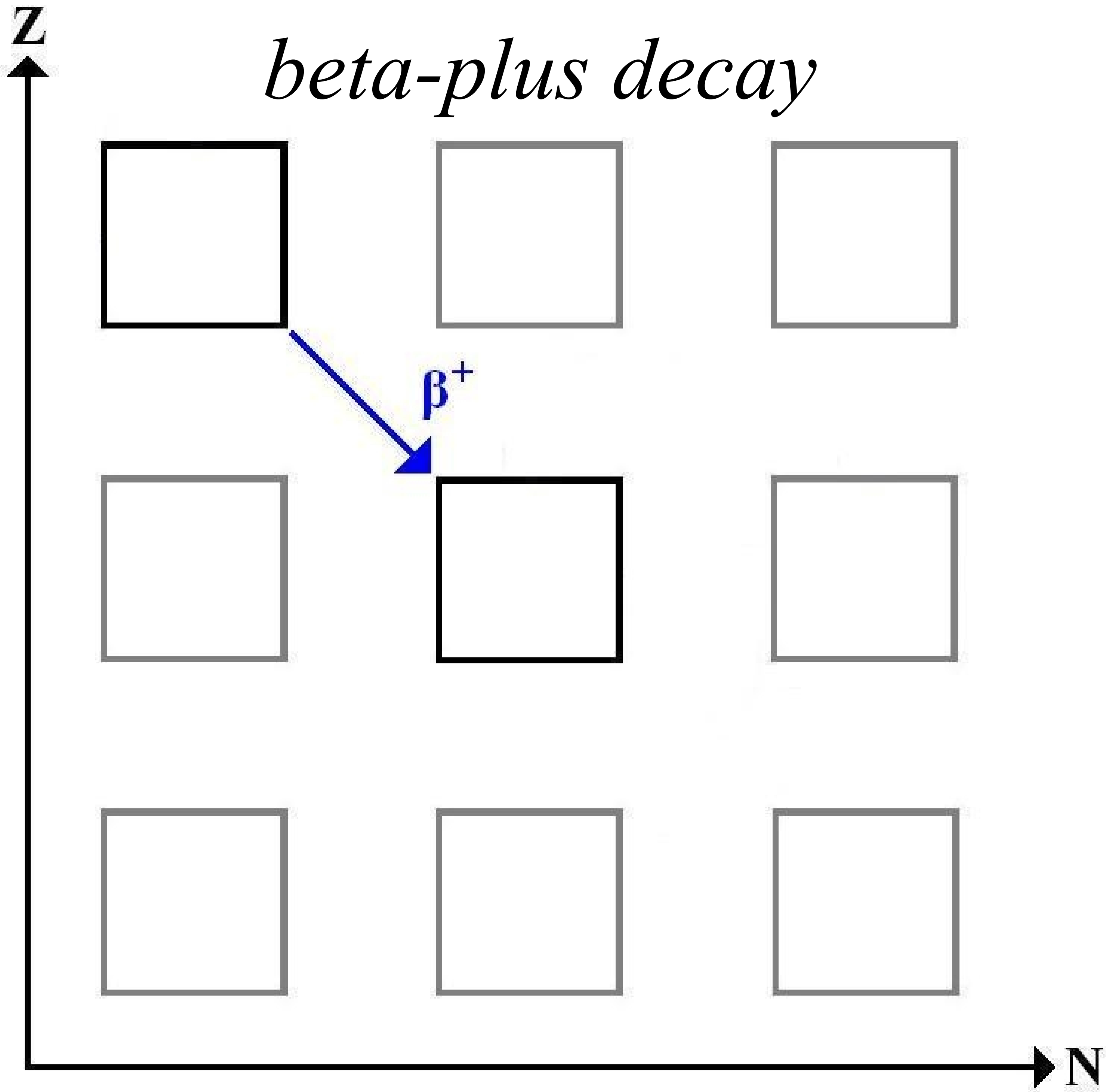
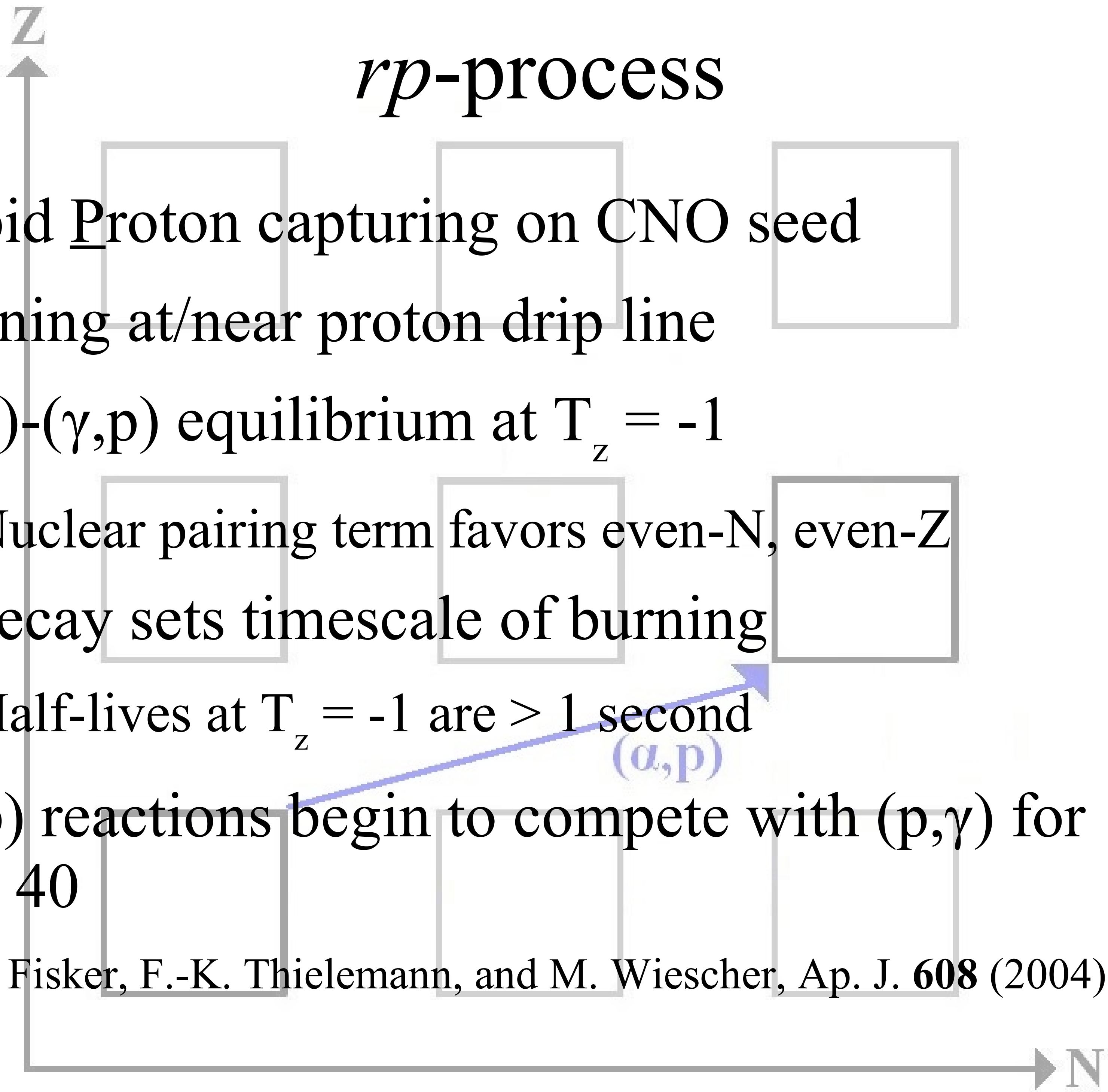
- β^+ decay sets timescale of burning
  - Half-lives at $T_z = -1$ are > 1 second



beta-plus decay



rp-process



- Rapid Proton capturing on CNO seed
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- (p,γ)-(γ,p) equilibrium at $T_z = -1$
  - Nuclear pairing term favors even-N, even-Z
- β^+ decay sets timescale of burning
  - Half-lives at $T_z = -1$ are > 1 second
- (α,p) reactions begin to compete with (p,γ) for A < 40
  - J. Fisker, F.-K. Thielemann, and M. Wiescher, Ap. J. **608** (2004) 61

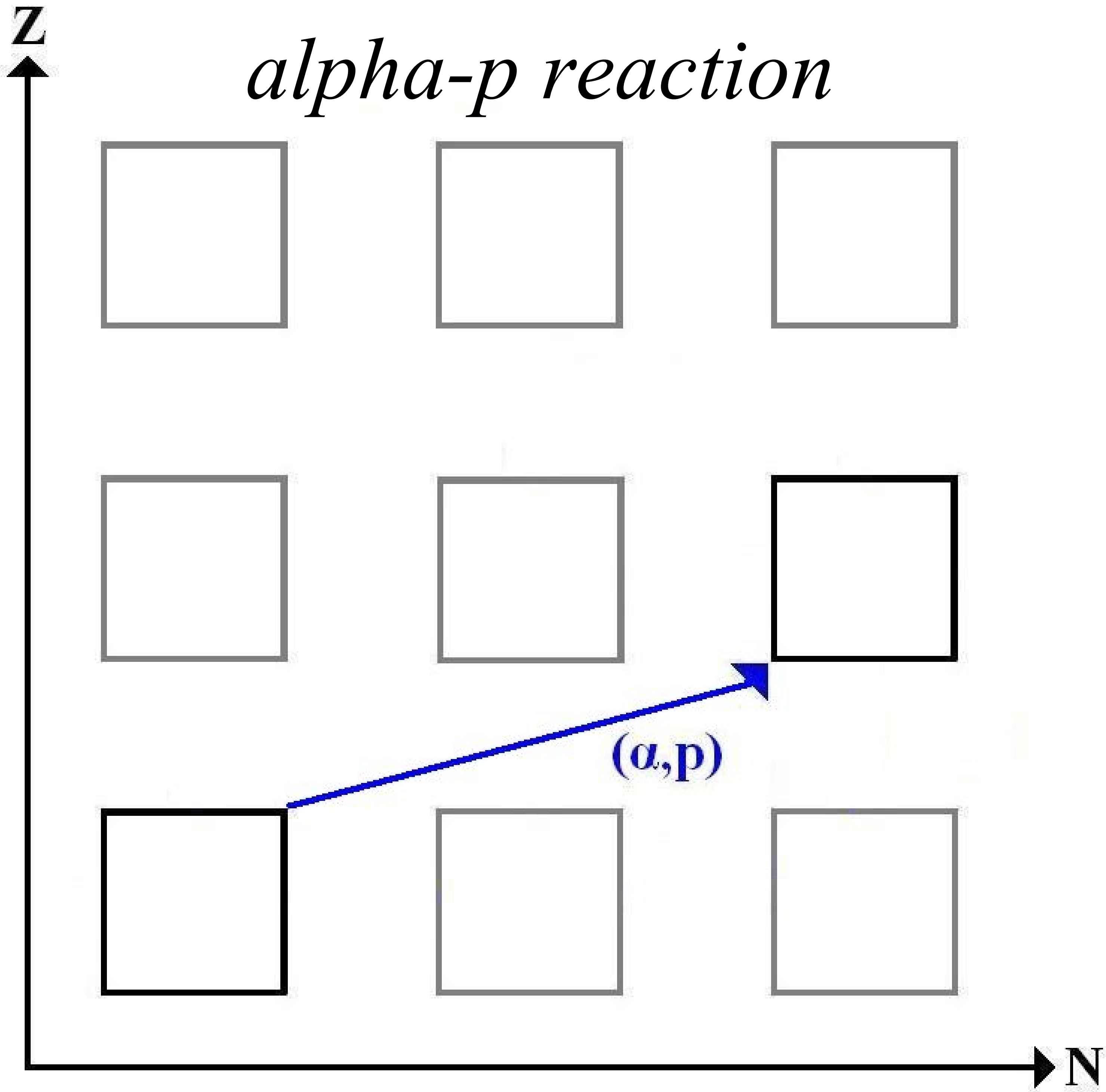
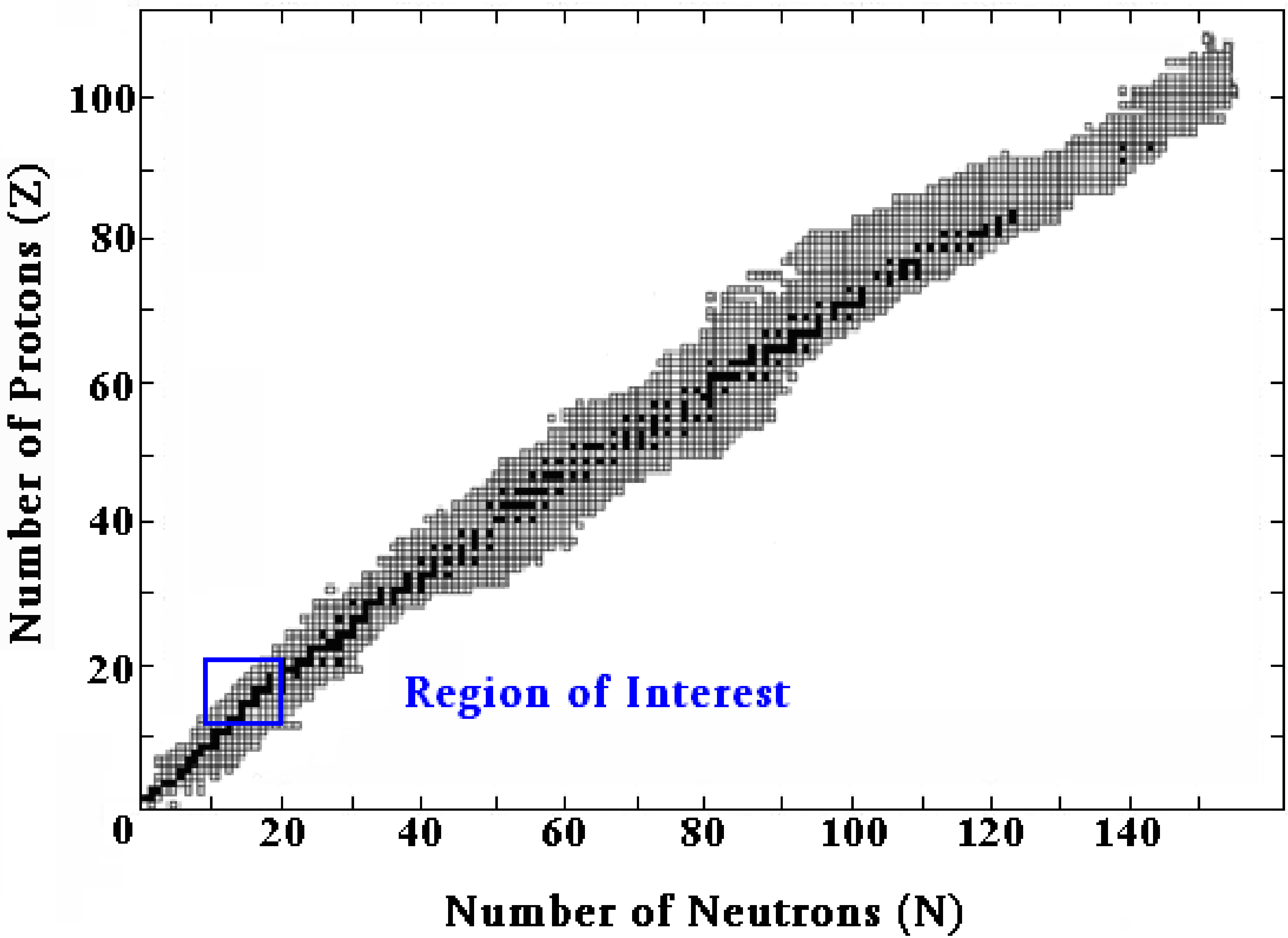
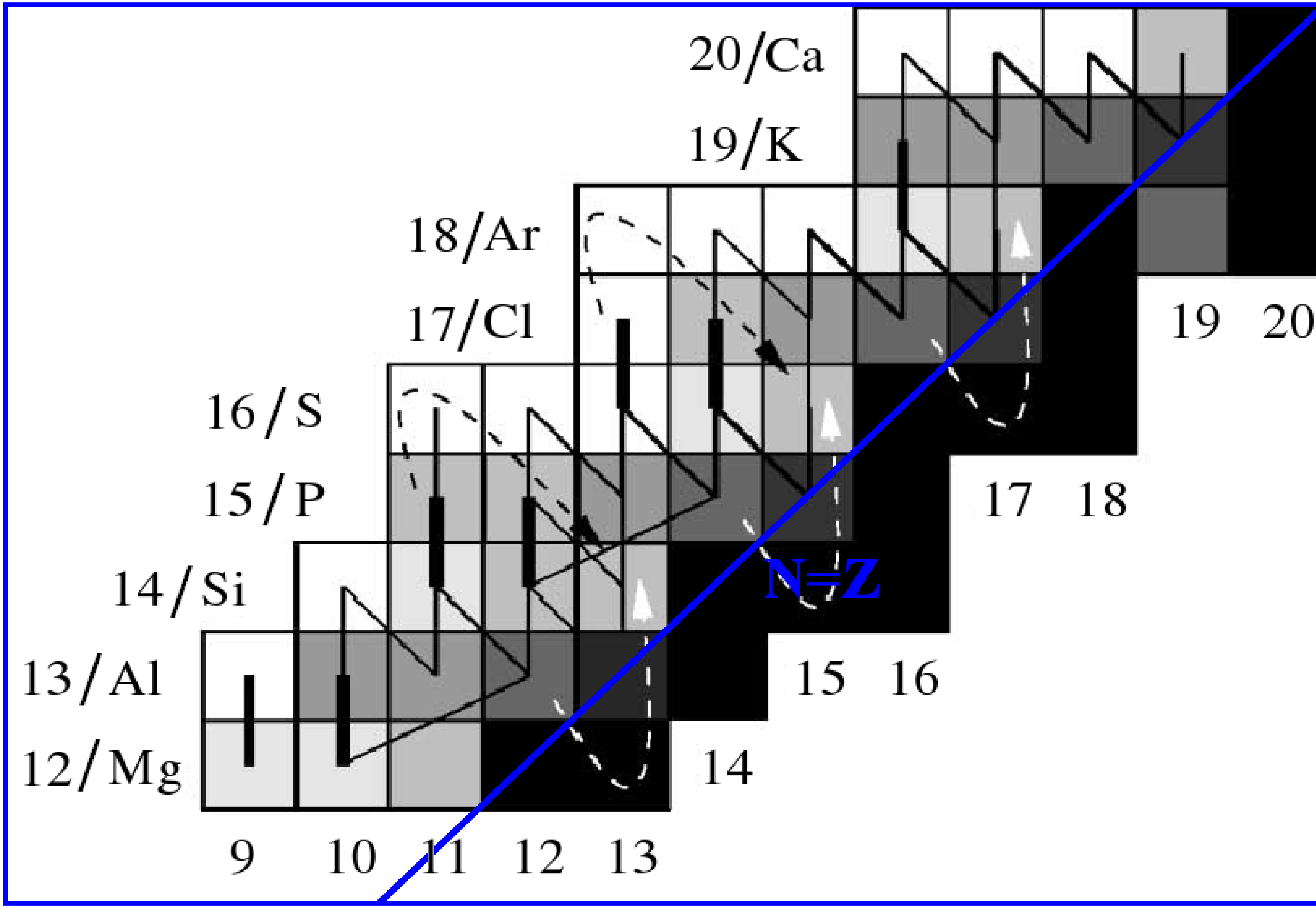

Z
alpha-p reaction
(α,p)
N

Chart of the Nuclides



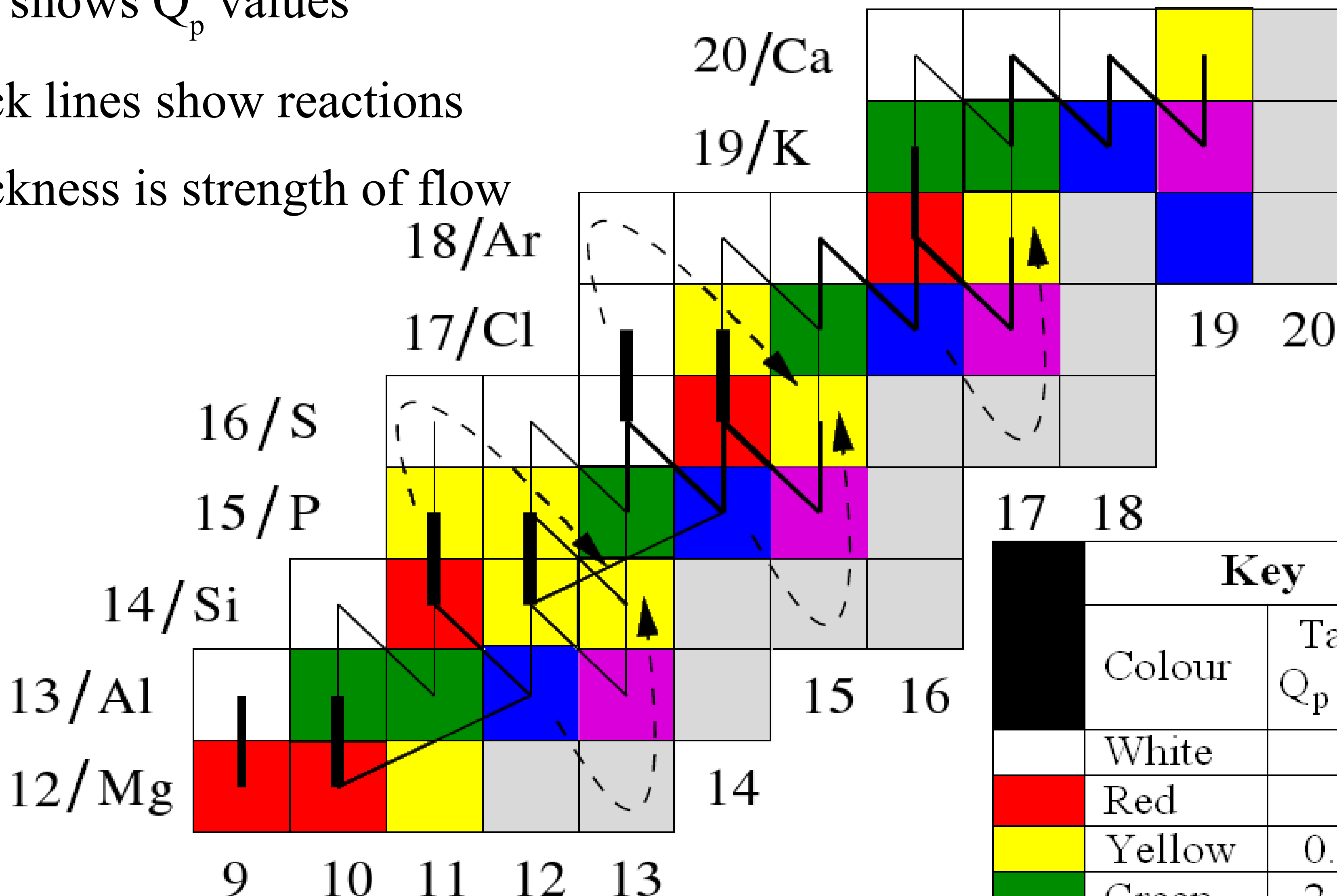
Region of Interest



Modified image from: J. Fisker, F.-K. Thielemann, and M. Wiescher, Ap. J. **608** (2004) 61.

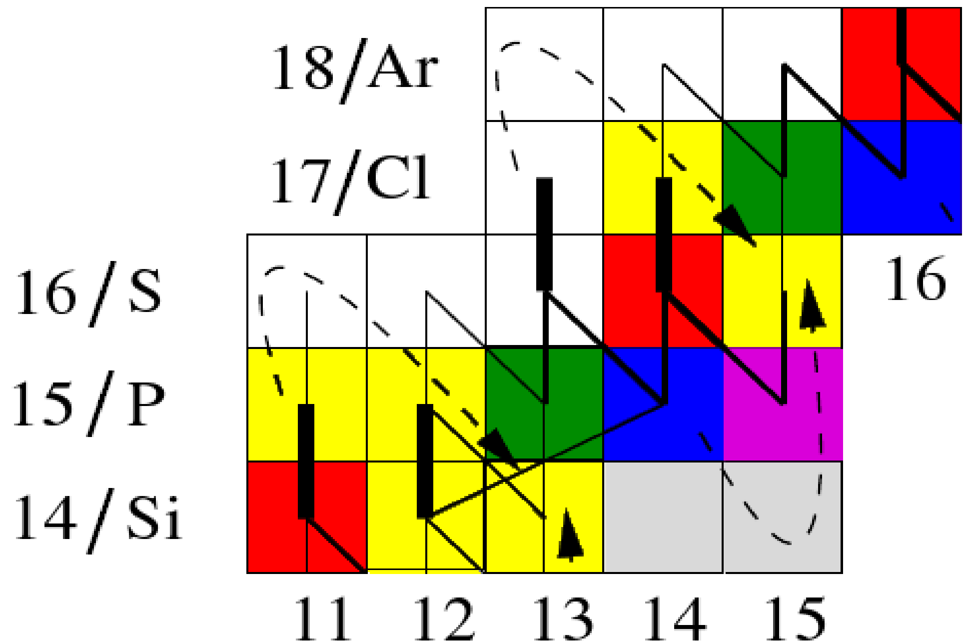
Burning Pathway

- Key shows Q_p values
- Black lines show reactions
- Thickness is strength of flow



Key	
Colour	Target Q_p (MeV)
White	< 0
Red	0 - 0.5
Yellow	0.5 - 2.5
Green	2.5 - 3.5
Blue	3.5 - 5.0
Purple	5.5 - 8.0
Grey	stable

Bottleneck at ^{30}S



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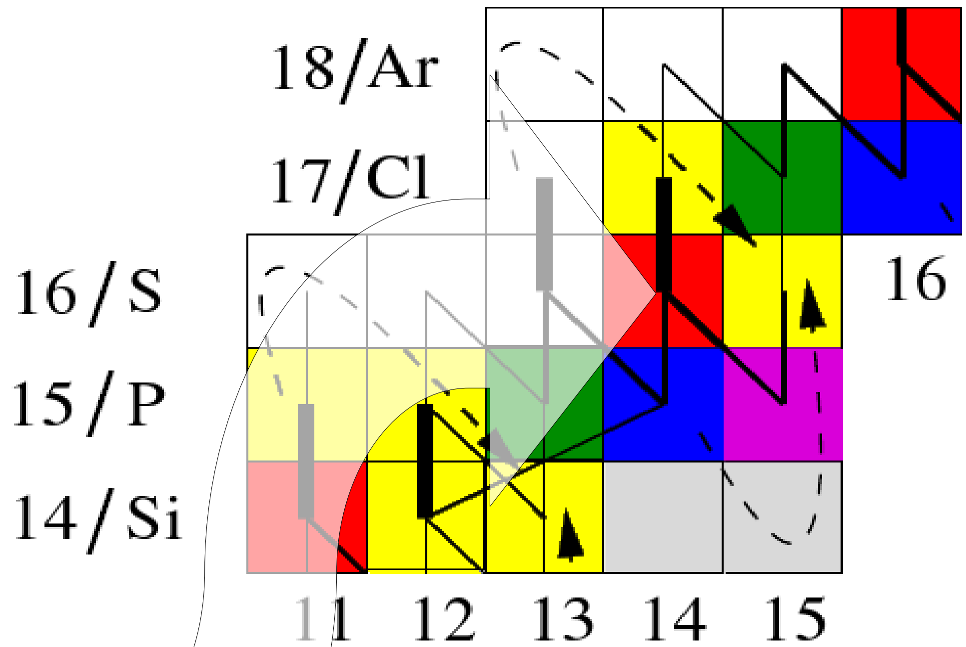

^{30}S is this red block

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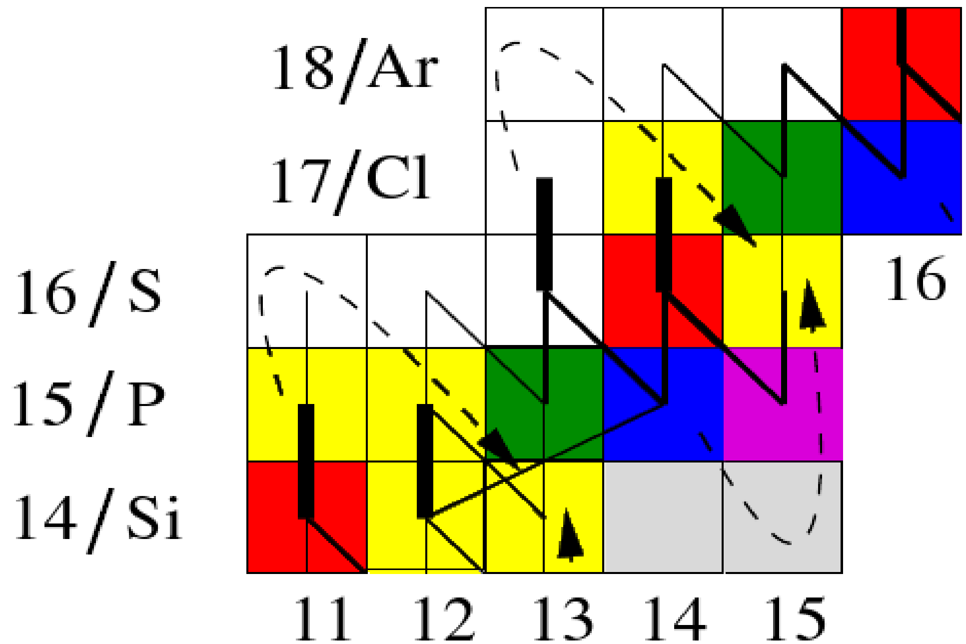
	Blue	3.5 - 5.0
	Purple	5.5 - 8.0
	Grey	stable

Bottleneck at ^{30}S

- All roads lead to ^{30}S
- The roads that lead away from ^{30}S are traffic jammed or low speed limit



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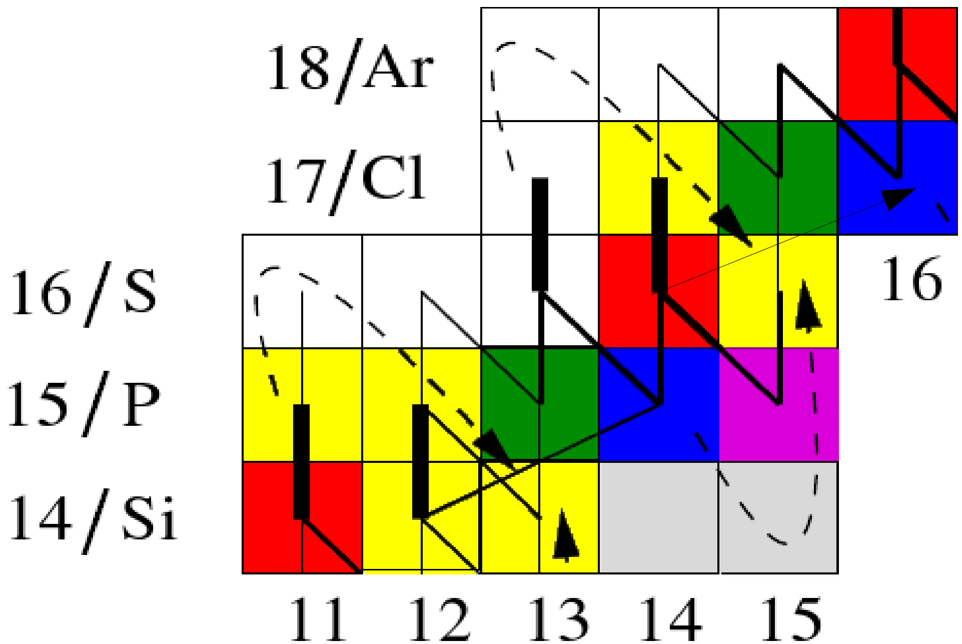
Bottleneck at ^{30}S

- Clearly $^{30}S(\alpha,p)^{33}Cl$ is important here
- It's omitted in the previous diagrams because the rate is not known



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$\lambda_{\beta+} = N_A\, \rho\, Y_\alpha\, \Delta(T)\, \langle\sigma v\rangle_{(\alpha,p)}$

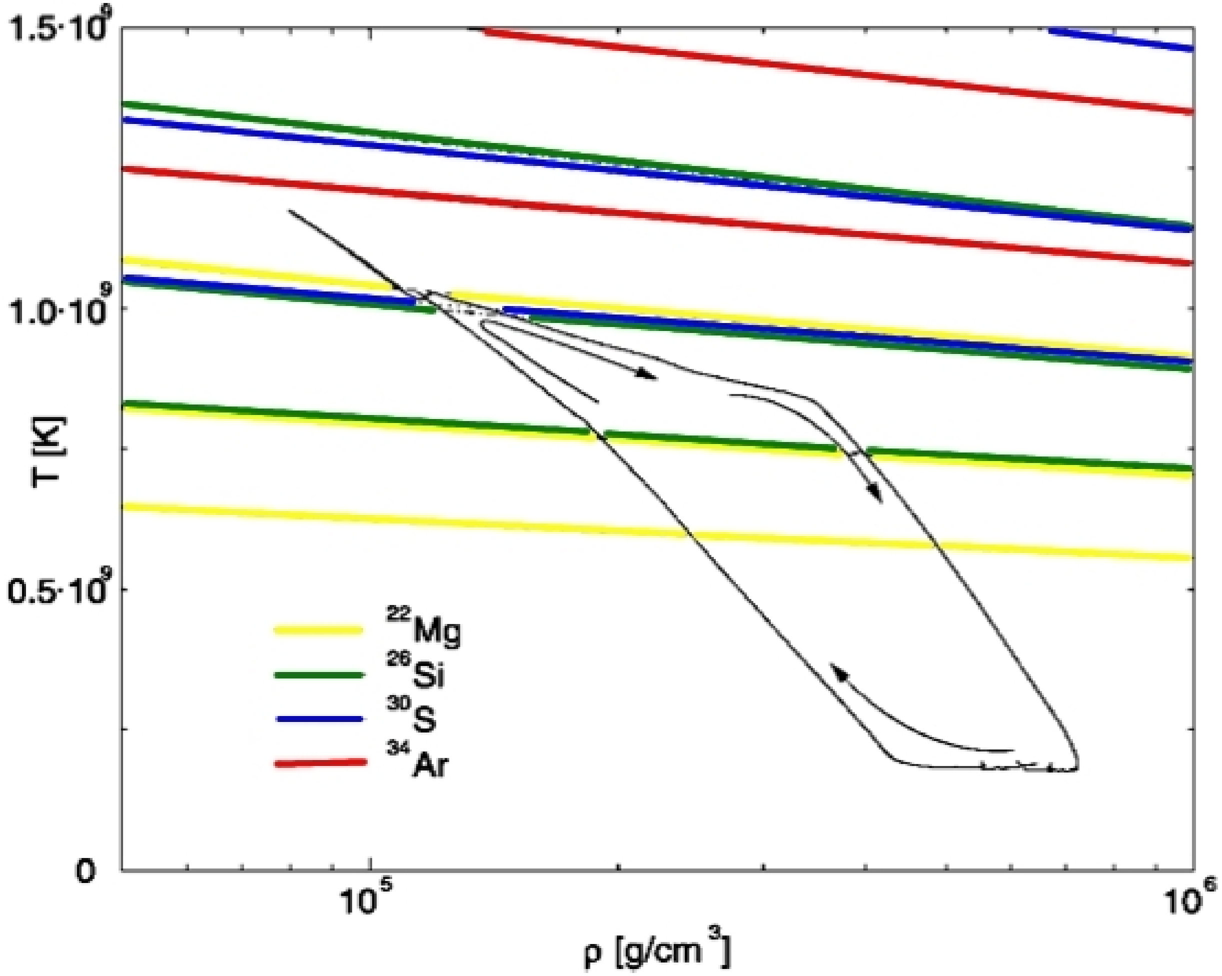
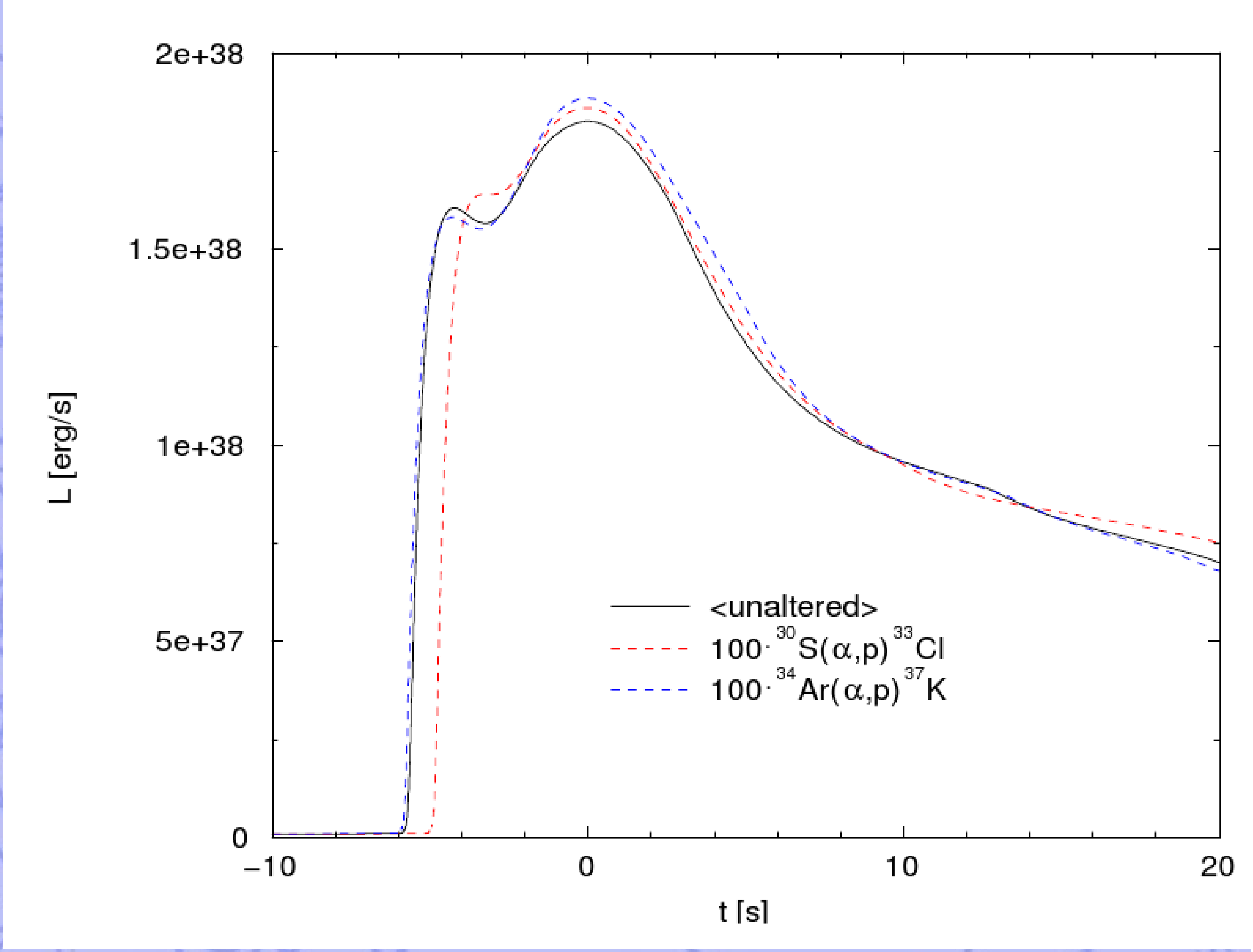


FIG. 2.—Demarcation lines of eq. (1) are plotted thrice with $\Delta(T) = \{10^{-2}, 1, 10^2\}$ and $Y_\alpha = 0.125$ for the ^{22}Mg, ^{26}Si, ^{30}S, and ^{34}Ar isotopes. The demarcation line for underestimating $^{34}\mathrm{Ar}(\alpha, p)^{37}\mathrm{K}$ by a factor of 10^2 falls outside the graph. In addition, the solid line shows the thermodynamic trace of the shell conditions during a full burst cycle that is computed in § 4. The arrows indicate the time direction of the cycle.

Modified image from: J. Fisker, F.-K. Thielemann, and M. Wiescher, Ap. J. **608** (2004) 61.

$^{30}S(\alpha,p)^{33}Cl$ **is** a waiting point!

- ^{30}S $t_{1/2}$ = 1.178 seconds
- Model reproduces double peak using best available nuclear data
- Double peak is greatly reduced if reaction rate of $^{30}S(\alpha,p)$ is increased by factor of 100
- Model is consistent with a waiting point at ^{30}S
- We can experimentally test this model



Computed luminosity vs. time for three parameters; light curves have been synchronized to make second burst coincide.

Modified image from: J. Fisker, F.-K. Thielemann, and M. Wiescher, Ap. J. **608** (2004) 61.

$^{30}S(\alpha,p)^{33}Cl$: stars to the lab

- Gamow window / peak
- Burst T = 1 – 2 GK
- Inverse kinematics in lab
- 1 GK, E_{cm}=1.4 – 2.3 MeV
  - Using ^{30}S beam, for 1 GK E_{lab}=12.0 – 19.9 MeV
- 2 GK, E_{cm}=2.1 – 3.8 MeV
  - Using ^{30}S beam, for 2 GK E_{lab}=18.2 – 32.3 MeV

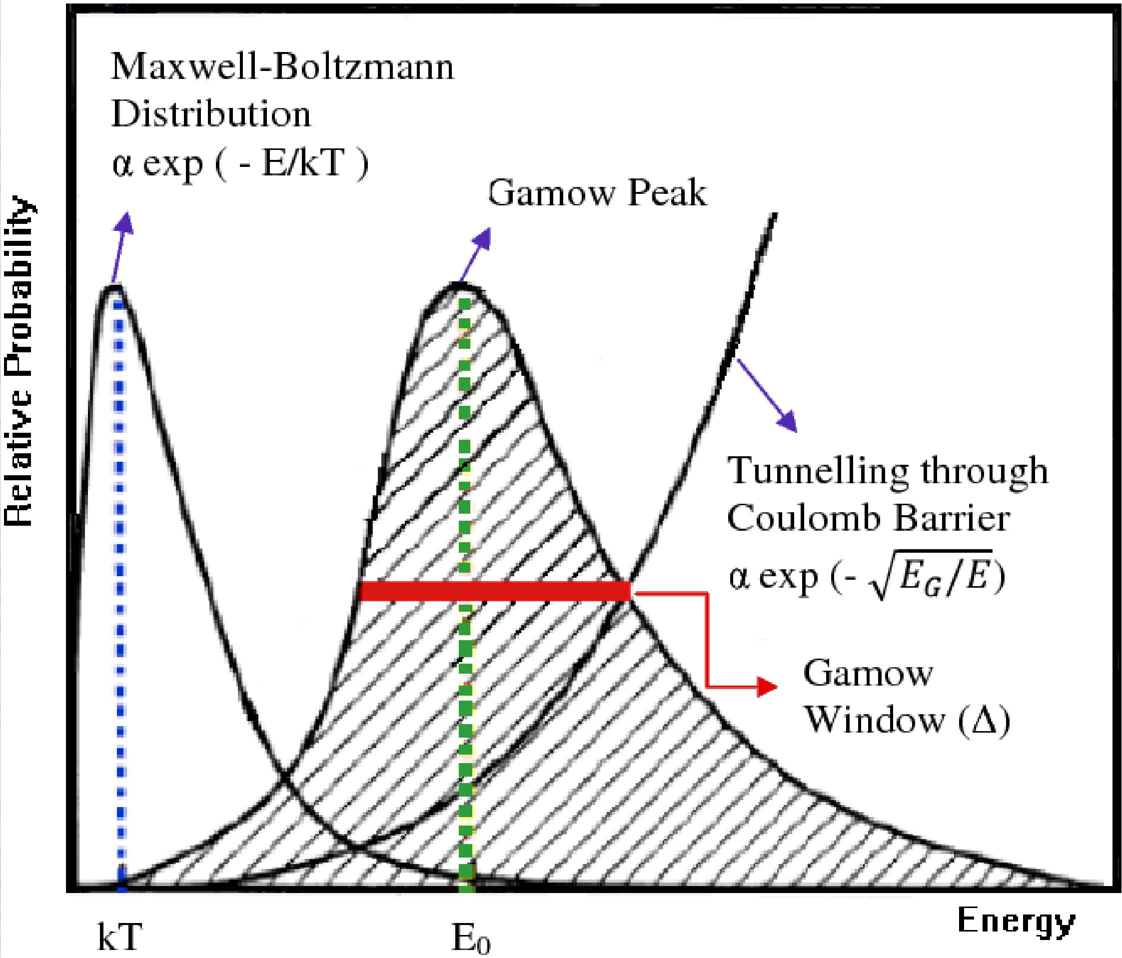
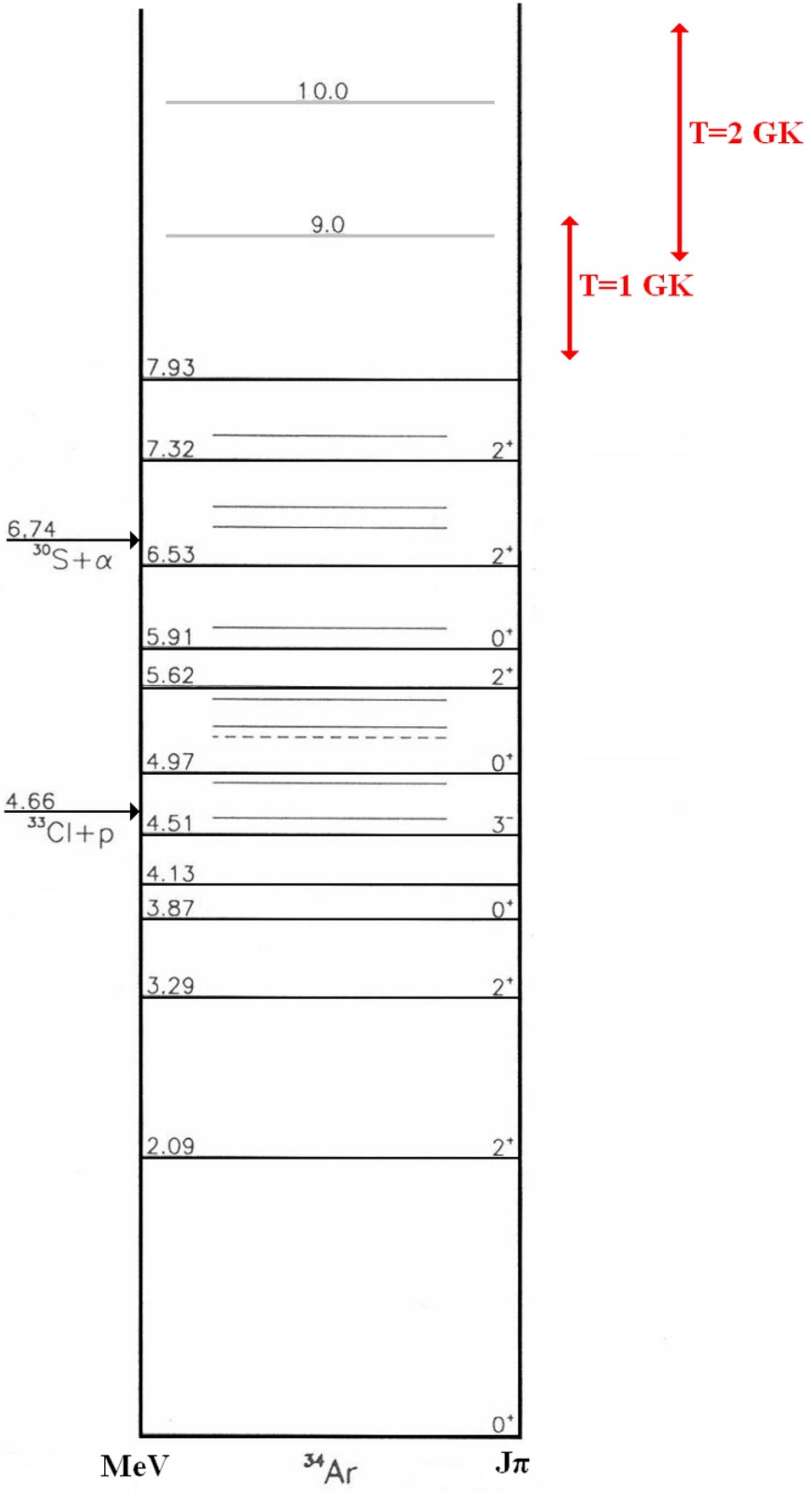


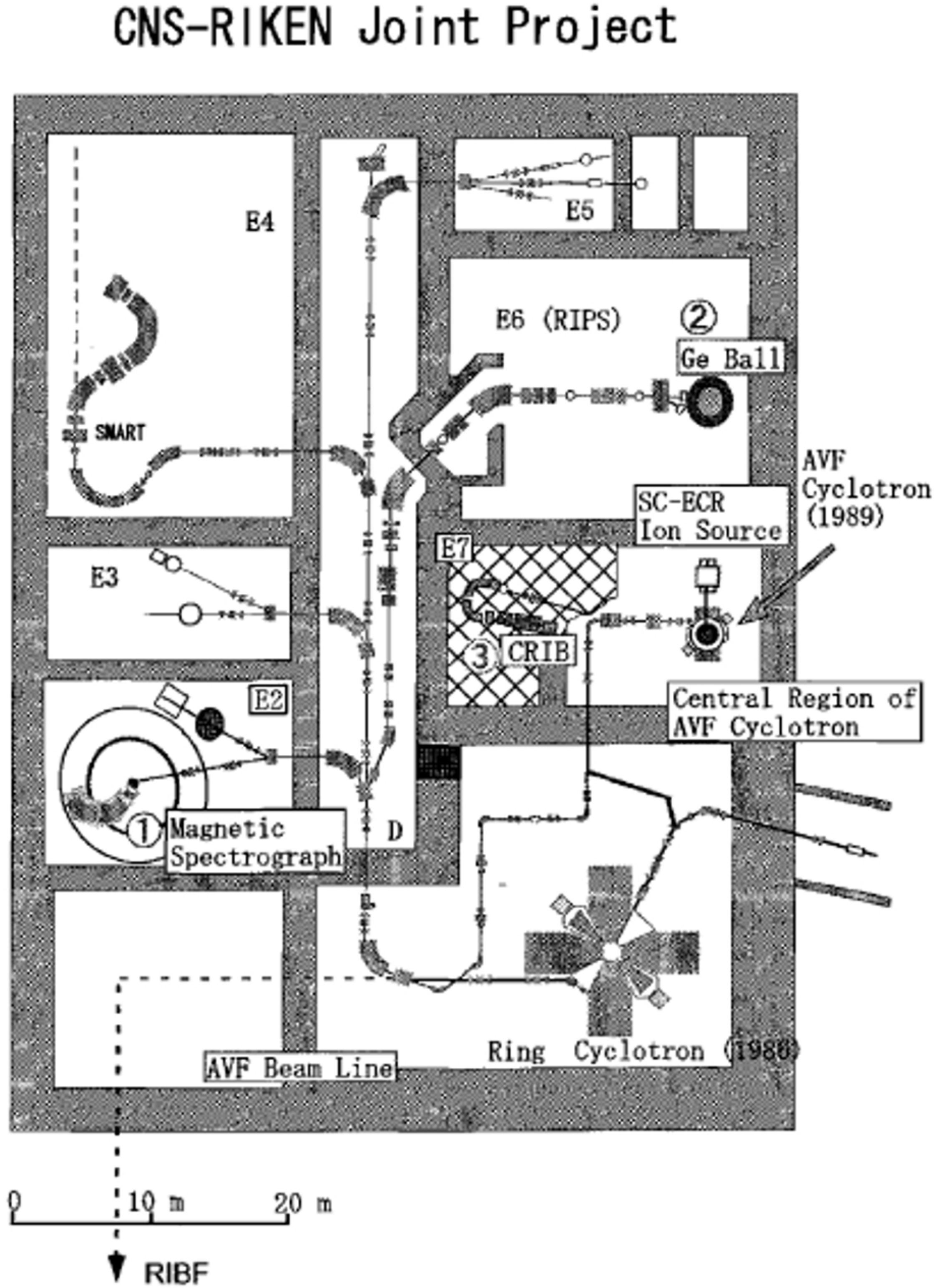
Image modifed from:
Rolfs, Claus E., Rodney, William S., *Cauldrons in the Cosmos,* University of Chicago Press, Chicago, 1988.

^{34}Ar Reaction Channel

- Are there resonances?
- Very little data
- $Q_{\alpha,p} = 2.08$ MeV
- Experiment!
- Proposed experiment could not identifiy levels

Image adapted from P. Endt, Nucl. Phys. A **521** (1990) 1.





RIKEN RIBF

- Ion Source (ECR)
- Cyclotron (AVF)
- Deliver beam to CRIB
  - CNS Radioactive Ion Beam Facility

S. Kubono *et al.* Eur. Phys. J. A **13** (2002) 217.

Beam Production via $^{3}He(^{28}Si,n)^{30}S$

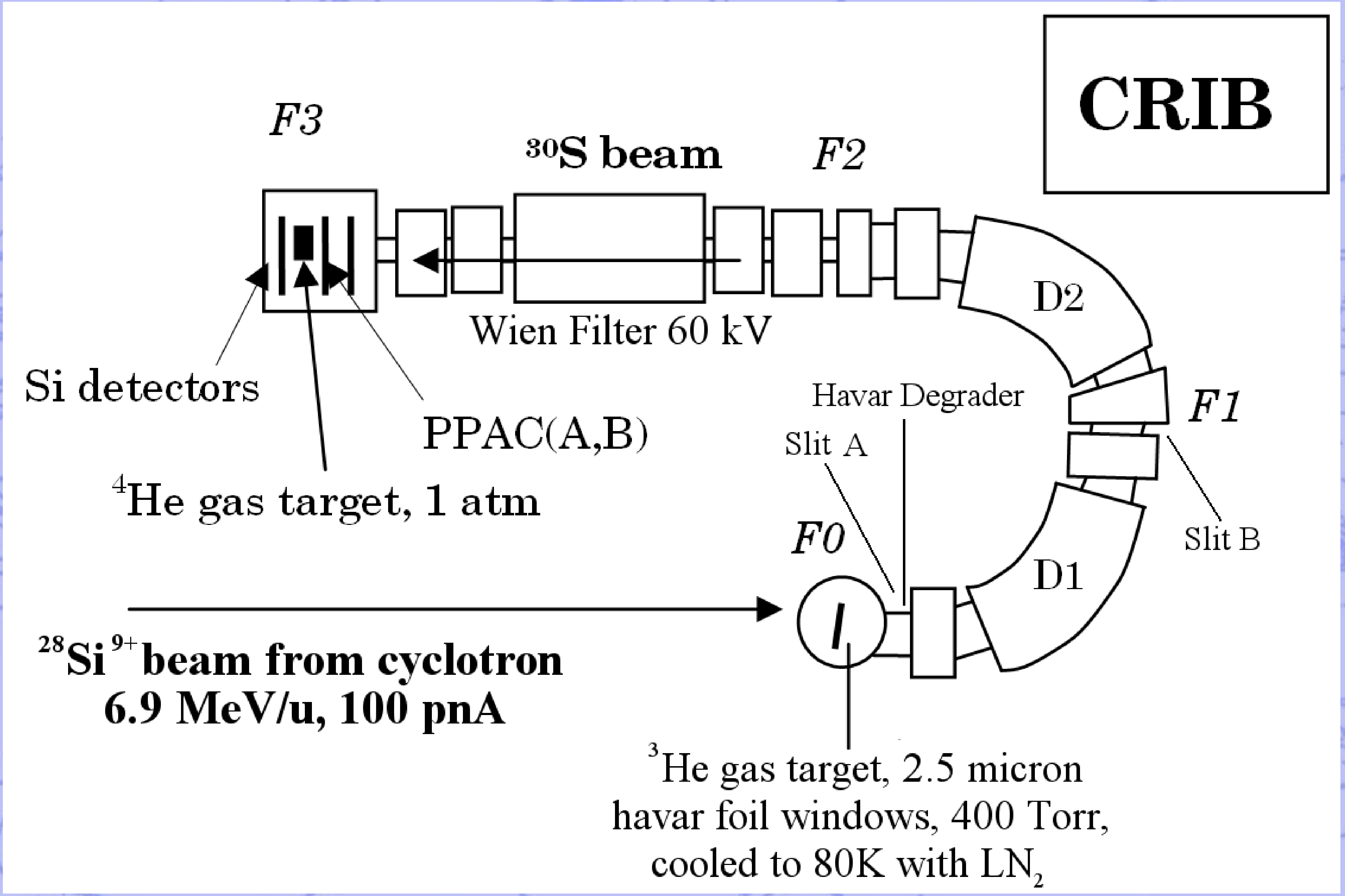


Image modified from S. Kubono, private communication via A. A. Chen.

Scattering Chamber (F3) Detector Schematic

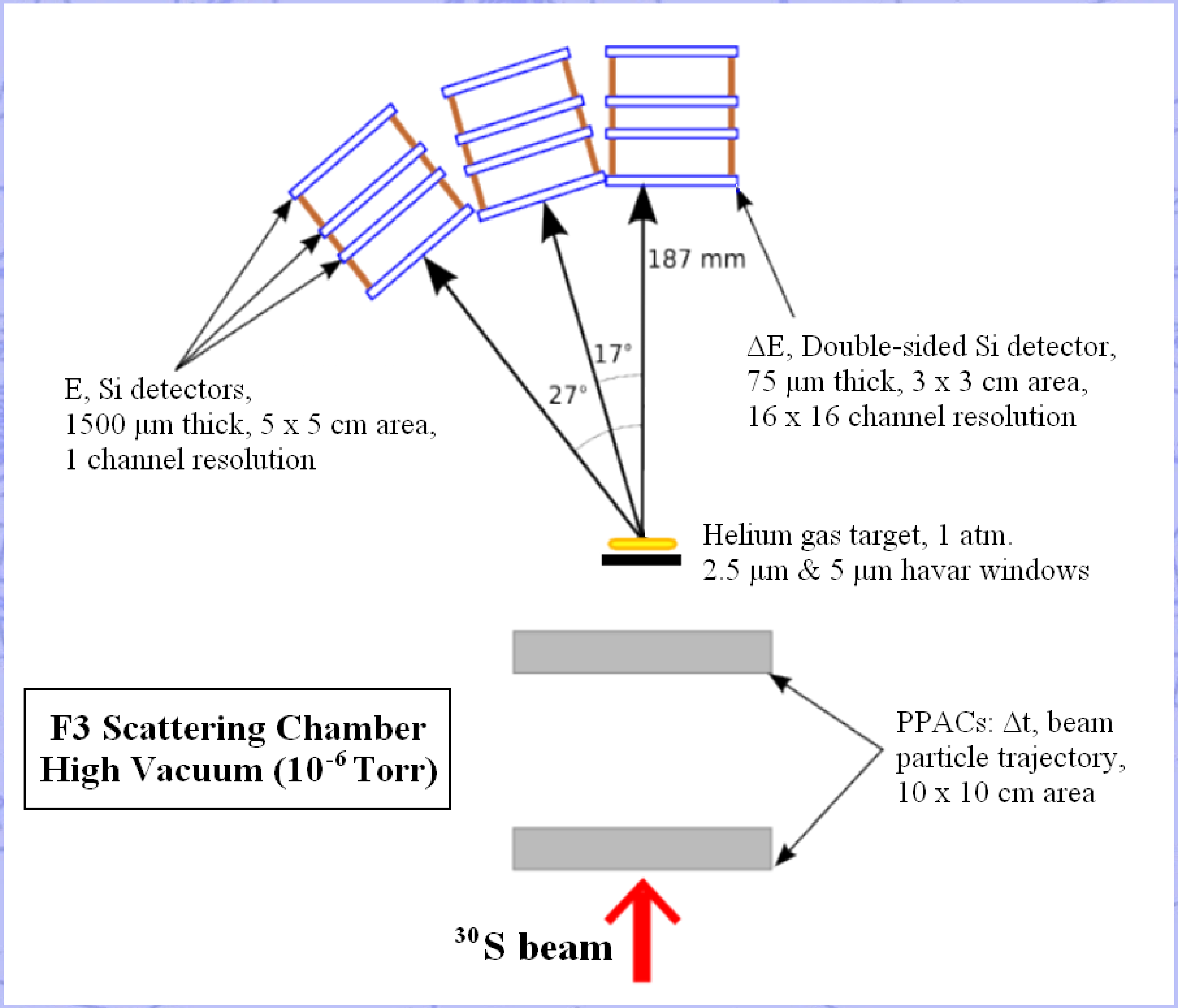
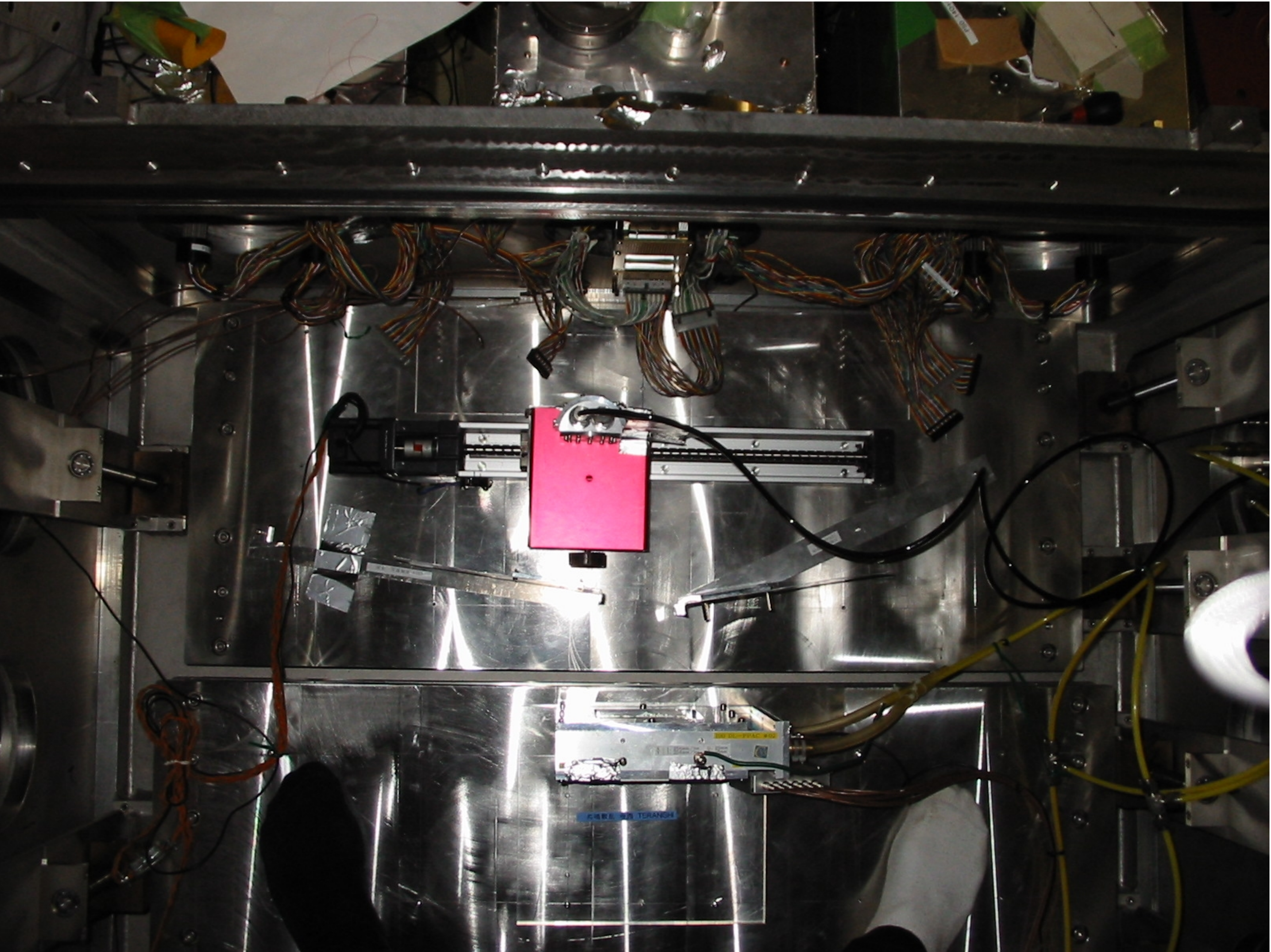
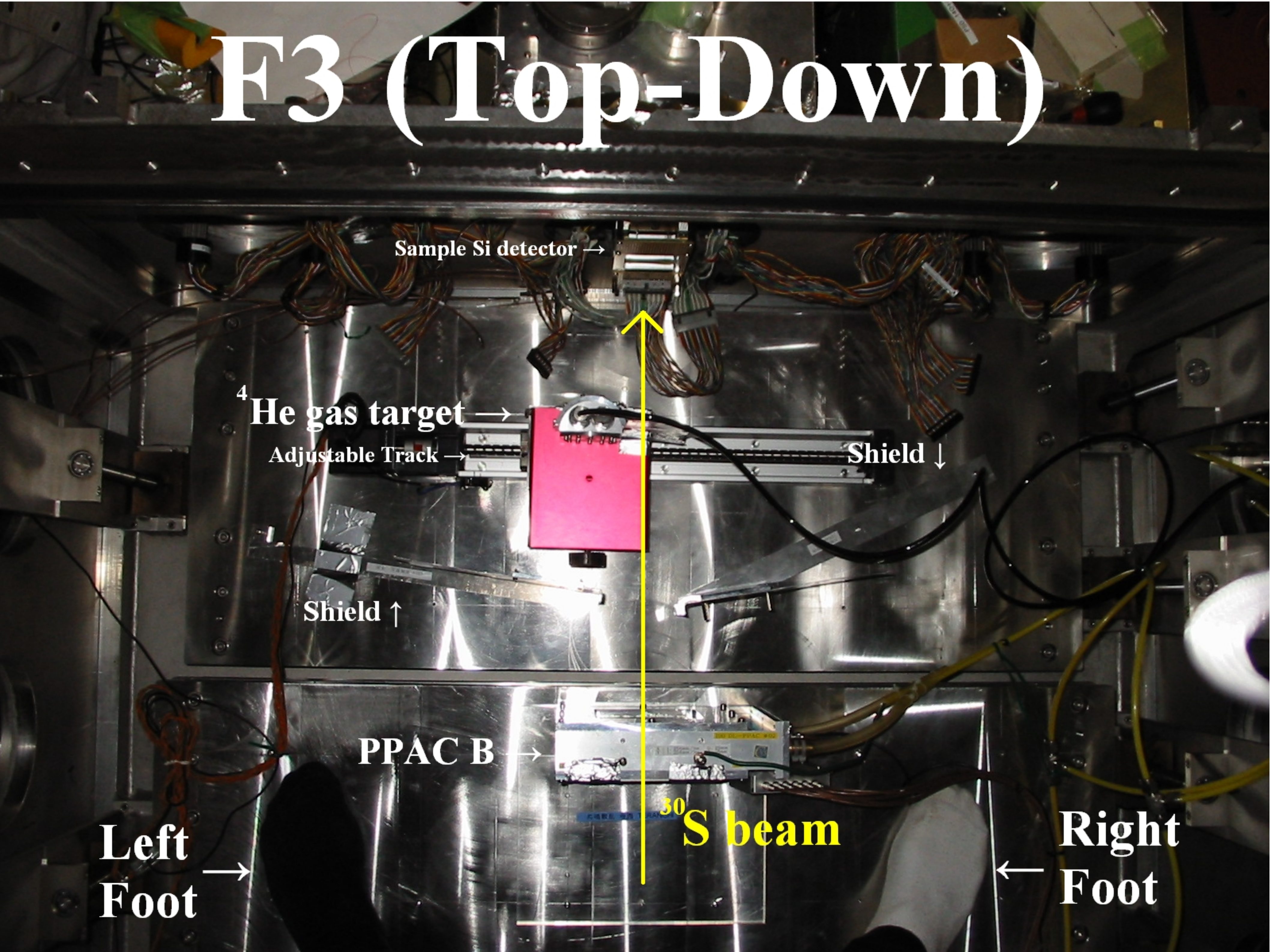


Image modified from original: A. A. Chen, private communication.

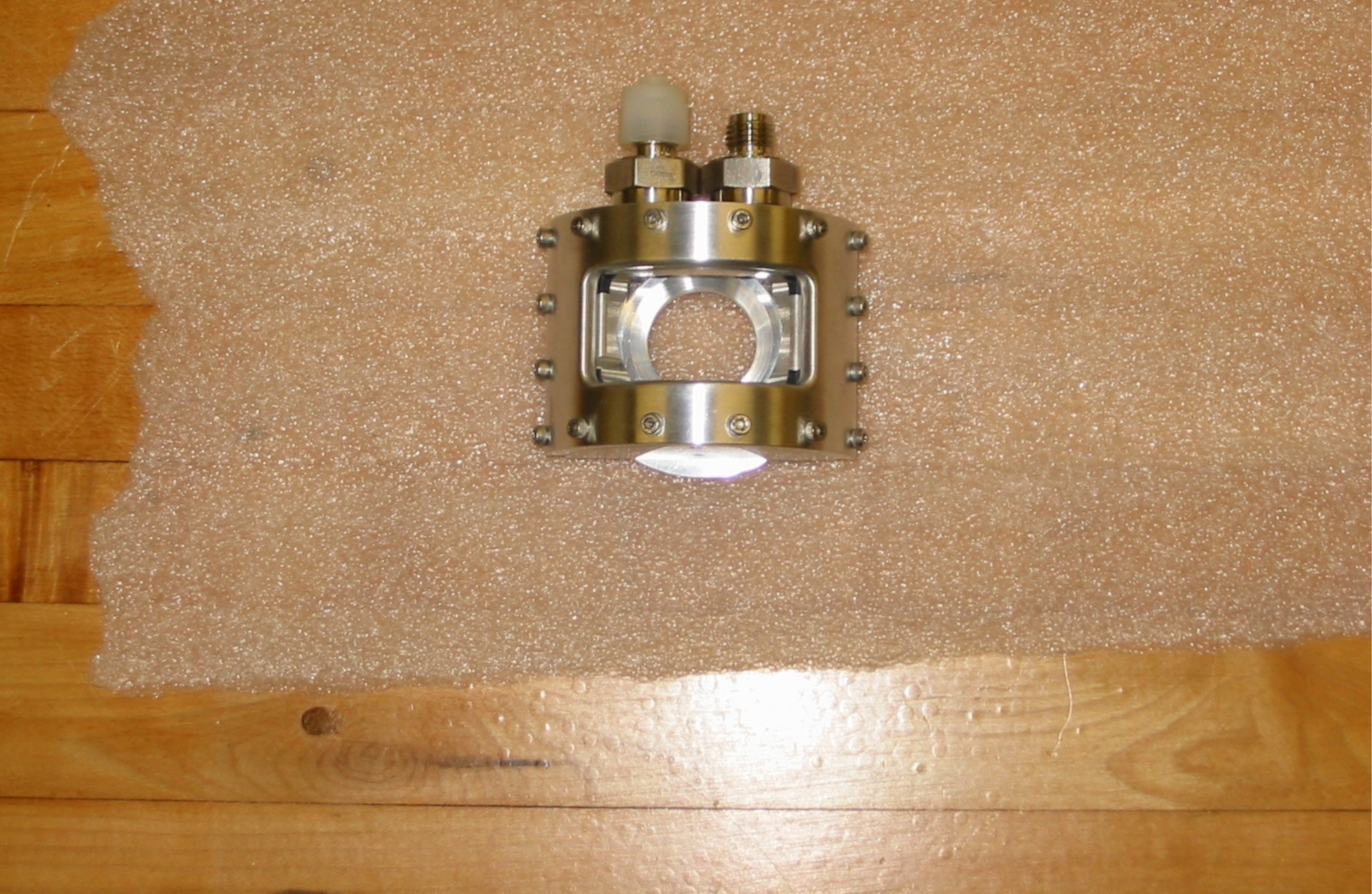


F3 (Top-Down)


Sample Si detector →
^{4}He gas target →
Adjustable Track →
Shield ↓
Shield ↑
PPAC B →
^{30}S beam
Left
Foot →
← Right
Foot

^{4}He gas cell

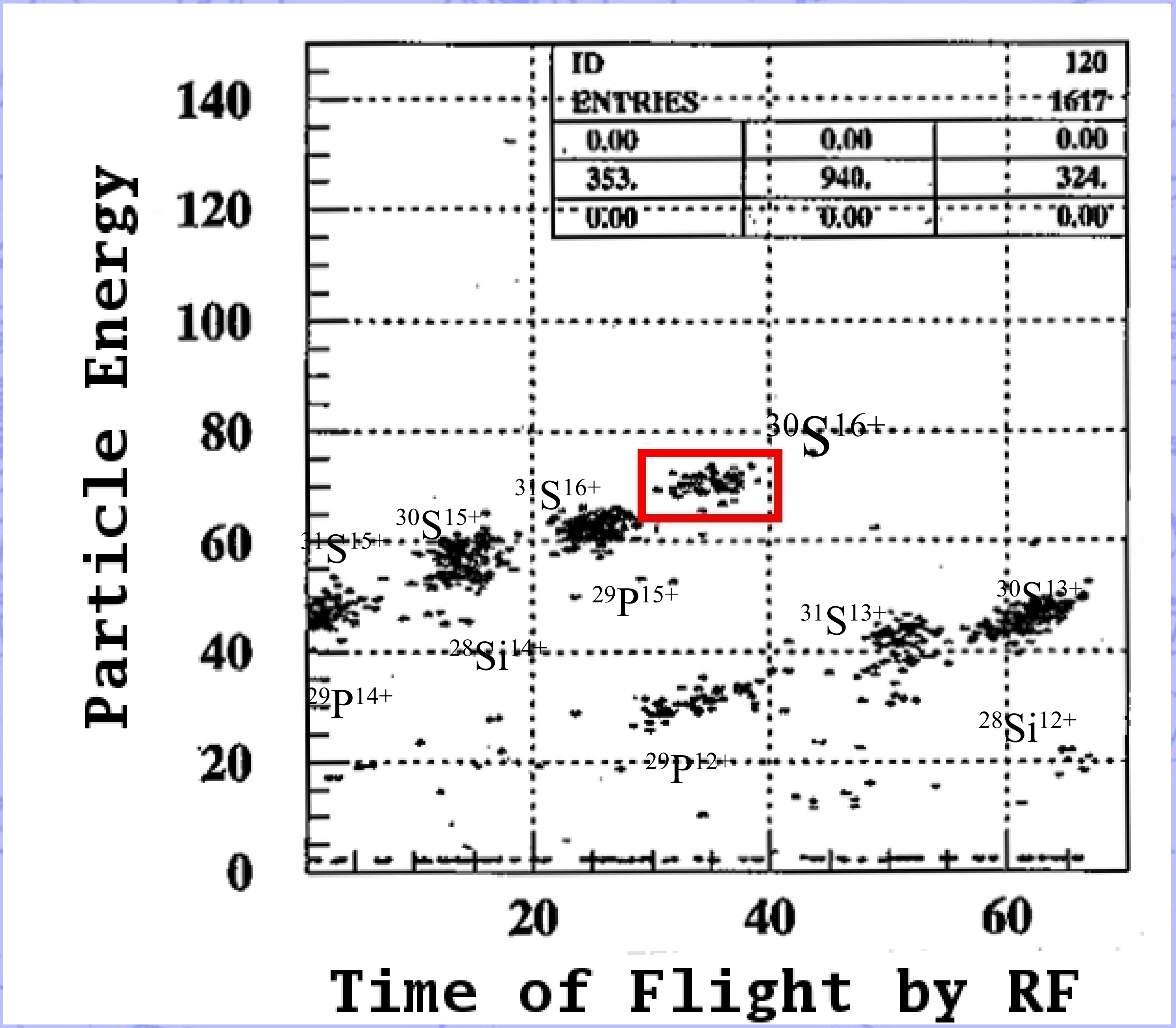
^{4}He gas cell (Havar windows absent)



Results of ^{30}S Beam Development

- Spent 2 days developing the beam
- We looked at $^{30}S^{+16}$, $^{30}S^{+15}$, and $^{30}S^{+14}$
- Need 10^5 particles per second ^{30}S
  - Otherwise we don't get good reaction statistics
- Only got 10^3 pps!
- Beam energy was low
  - 11.3 MeV attained, desired 20 MeV +
- Purity was a bit low when not fully stripped
  - $^{30}S^{+16}$ was 50% of final beam
  - For $^{30}S^{+15}$ and $^{30}S^{+14}$, purity of only 2 – 13 %

Online Particle Identification



Future Plans

- Another ^{30}S beam development run in early 2008
- Higher voltage on Wien Filter will increase purity
  - 90 kV compared to 60 kV
- Thinner foils on PPACs will decrease energy loss
  - 2.5 μm mylar compared to 5 μm mylar
- Optimize beam energy for $^{28}Si(^{3}He,n)^{30}S$ cross-section
  - Energy dependent cross section not well known
- Do experiment in spring 2008
  - Set lower limit on $^{30}S(\alpha,p)^{33}Cl$ reaction rate if we can't measure it
  - Confirm detector efficiency with known (α,p) reaction

Collaborators

- *McMaster University (Canada):* **A. A. Chen**, J. Chen, K. Setoodehnia
- *University of Tokyo (Japan):* **S. Kubono**, H. Yamaguchi, Y. Wakabayashi, S. Hayakawa, S. Michimasa
- *Ewha Womans University (Korea):* A. Kim

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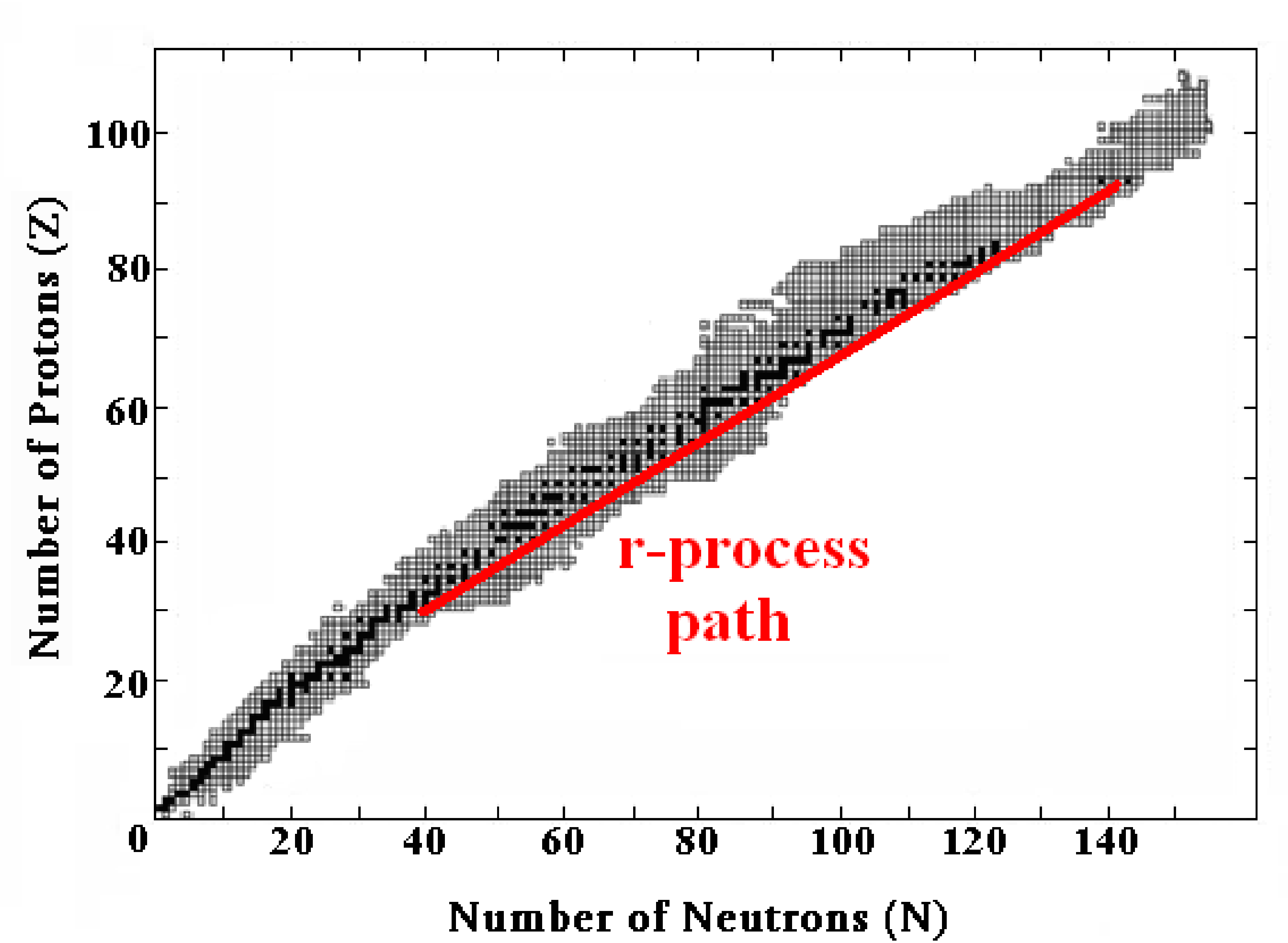
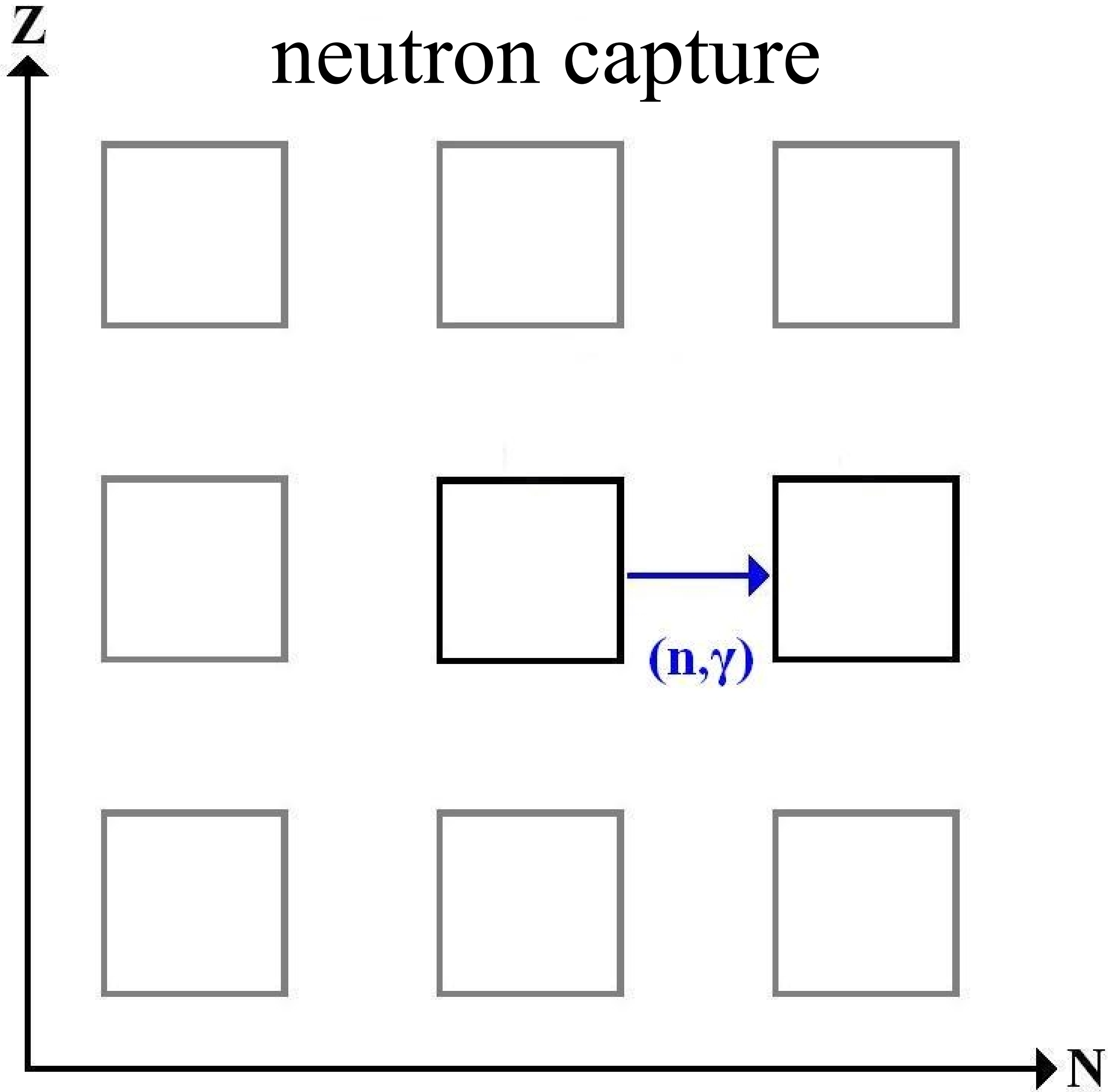
- S. Kubono, private communication (2007).
- A. A. Chen, private communication (2006, 2007).
- D. Kahl *et al*, CNS Annual Report (2007).
- Sources used for graphics are cited in their respective slides. They are also cited here if those sources were used for scientific information.

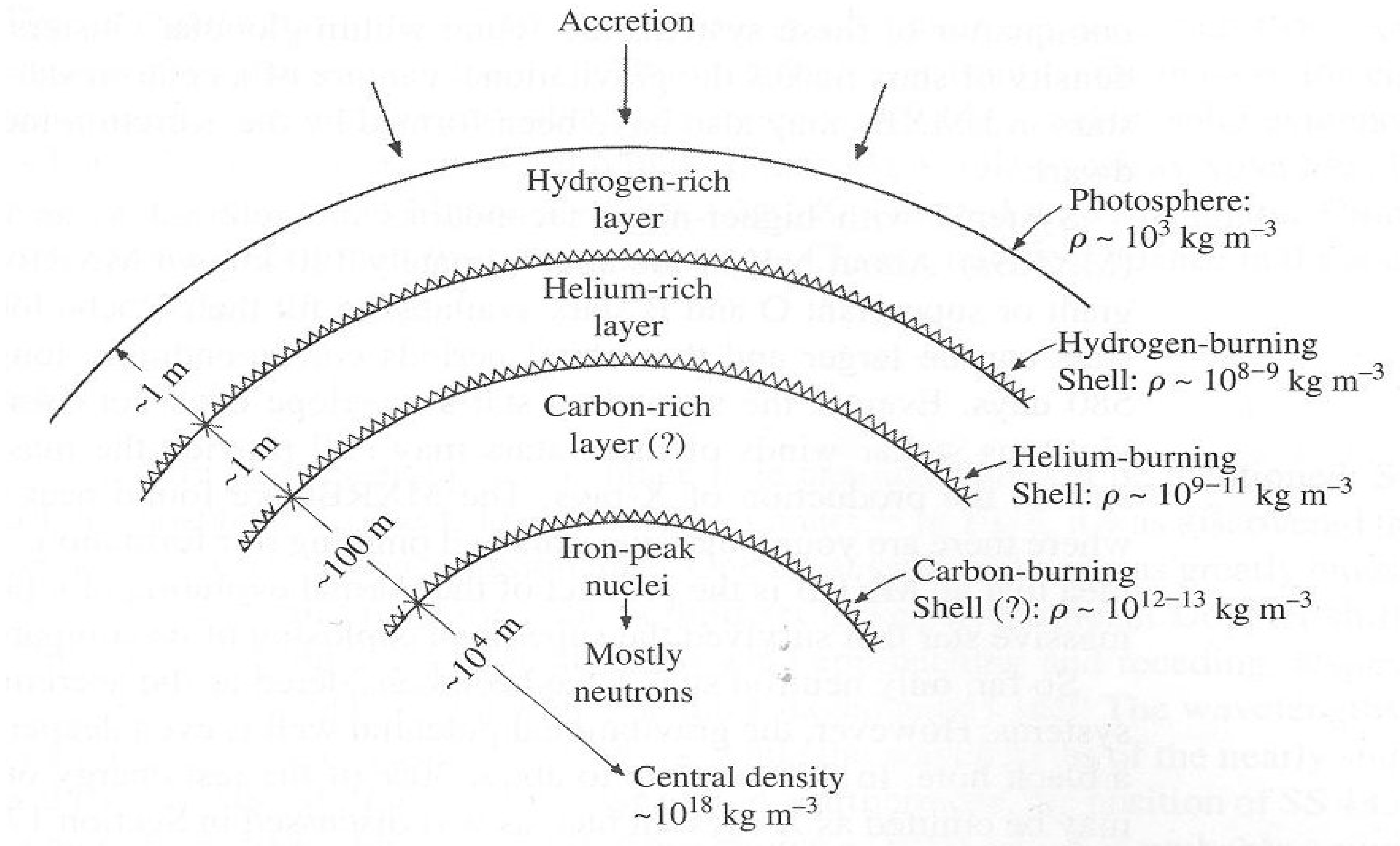
r-process path



neutron capture



Neutron Star Cross Section



Caroll, Bradley W., and Ostlie, Dale A., *An Introduction to Modern Astrophysics*, Second Edition, Pearson Education, New York, 2007.

Nuclear Burning in Normal XRBs

- See Schatz *et al.* 1998 Phys Rep, Schatz *et al.* Ap J 1999
- Explosive nuclear burning of matter accreted on surface of a neutron star
  - Recurring Bursts
- Accreted material is primarily hydrogen and helium
- Rapid sequence of proton captures and beta-plus decays up to mass A ~ 140
  - CNO seed nuclei (β-limited Hot CNO cycle)
- Single peaked
    - ~ 400 known X-ray bursting systems
    - Burst times are 10 – 100 seconds
    - Temperatures are 1 – 2 GK

Havar Foil

- Used in windowed gas targets to confine gas but allow high-energy particles to penetrate
  - Front window thin enough to allow beam through
  - Rear window thick enough to stop beam
- Iron group alloy
  - High Coulomb barrier
  - 42.50% Co, 20% Cr, 19.06 % Fe, 13% Ni, 2.8% W, 2.0% Mo, 1.6% Mg, 0.04% Be.
- Low thermal conductivity
- High tensile strength
- Expensive


2.5 μm
havar


5 μm
havar