Title: R-process nucleosynthesis in quark-novae and the origin of heavy elements

Date: Dec 07, 2005 02:00 PM

URL: http://pirsa.org/05120006

Abstract: The origin of the chemical elements that make up our world is one of the oldest most fundamental scientific questions. The universe after the Big Bang consisted only of hydrogen and helium with traces of lithium. All the other elements, including the carbon in our bodies, the iron, silicon, and oxygen that makes up most of our earth, have been created later by nuclear reactions in stars. However, the origin of many elements beyond iron, including gold and uranium, is still a mystery. These elements are attributed to a process called the r-process (rapid neutron capture process) which is of fundamental importance in explaining the origin of stable nuclei and isotopes beyond the iron group (A>90-100). The site of the r process is not known but supernova explosions and/or colliding neutron stars are prime suspects. The problem is that none of the models (related to these sites) can produce r-process elements in the correct proportions as we find them, for example, in the solar system or in certain very old stars. I will discuss an exciting alternative related to quark stars, a new class of compact stars that contain matter at the highest densities. Proposed observational features of quark stars, the probability of their detection, as well as some interesting connections to r-process nucleosynthesis will be presented. I will focus on an alternative based on a dynamical picture of decompressing neutron matter from the surface of quark stars in the scenario termed the Quark-Nova, which is particularly effective for producing the r-process pattern of heavy elements.

The Origin of Heavy Elements

r-process Nucleosynthesis

in

Quark Novae

Rachid Ouyed (Calgary/CITA)

Collaborators

Prashanth Jaikumar (Argonne National Lab.)

Bradley Meyer (Clemson University)

Kaori Otsuki (University of Chicago)

The 11 Greatest Unanswered Questions of physics

Resolution of these profound questions could unlock the secrets of existence and deliver a new age of science within several decades

. What is dark matter?

. What is dark energy?

. How were the heavy elements from iron to uranium made?

. Do neutrinos have mass? ---------- YES!

. Where do ultrahigh-energy particles come from?

. Is a new theory of light and matter needed to explain what happens at very high nergies and temperature?

. Are there new states of matter at ultrahigh temperatures and densities?

. Are protons unstable?

. What is gravity?

0. Are there additional dimensions?

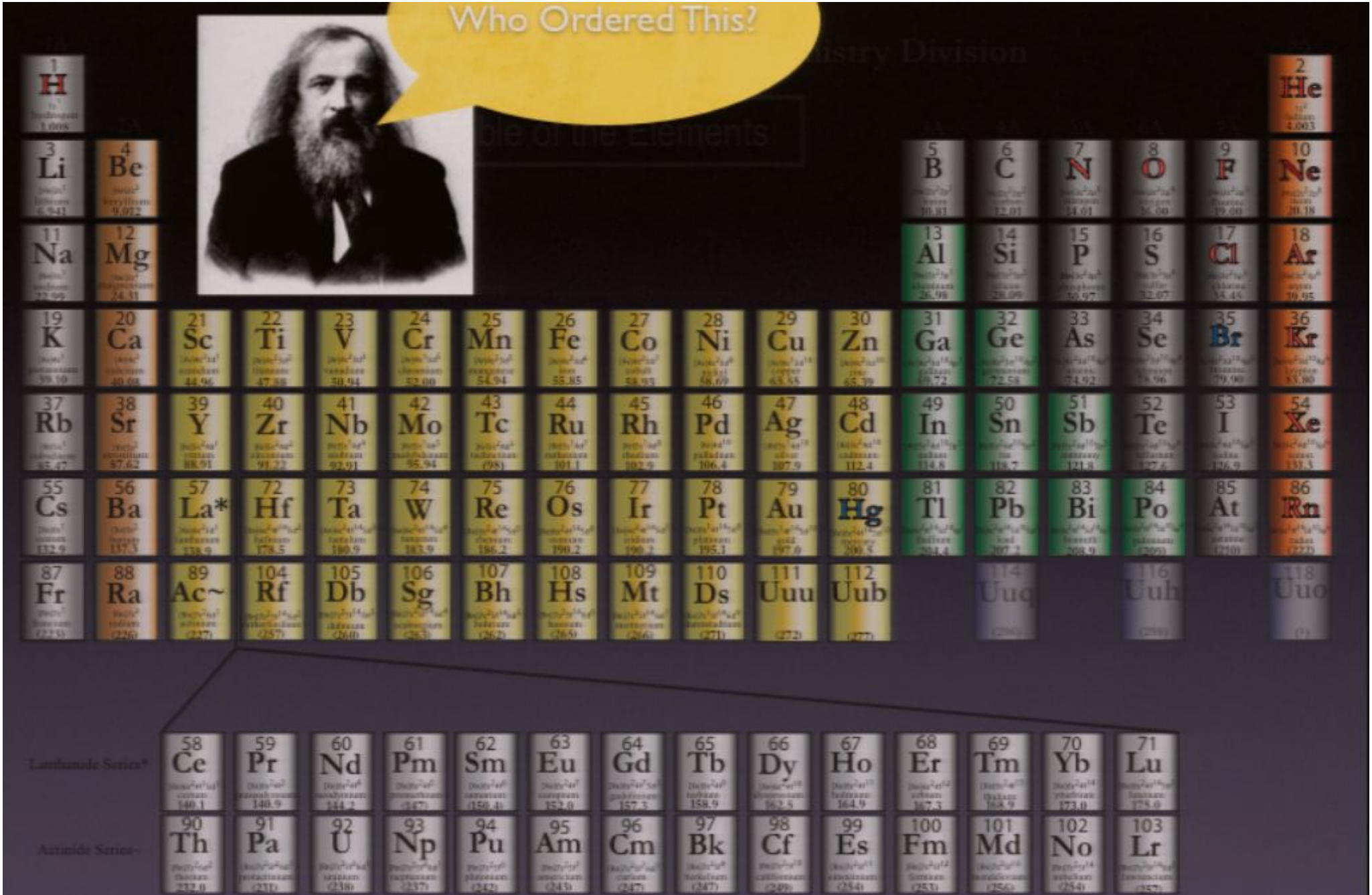
1. How did the universe begin?

Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century

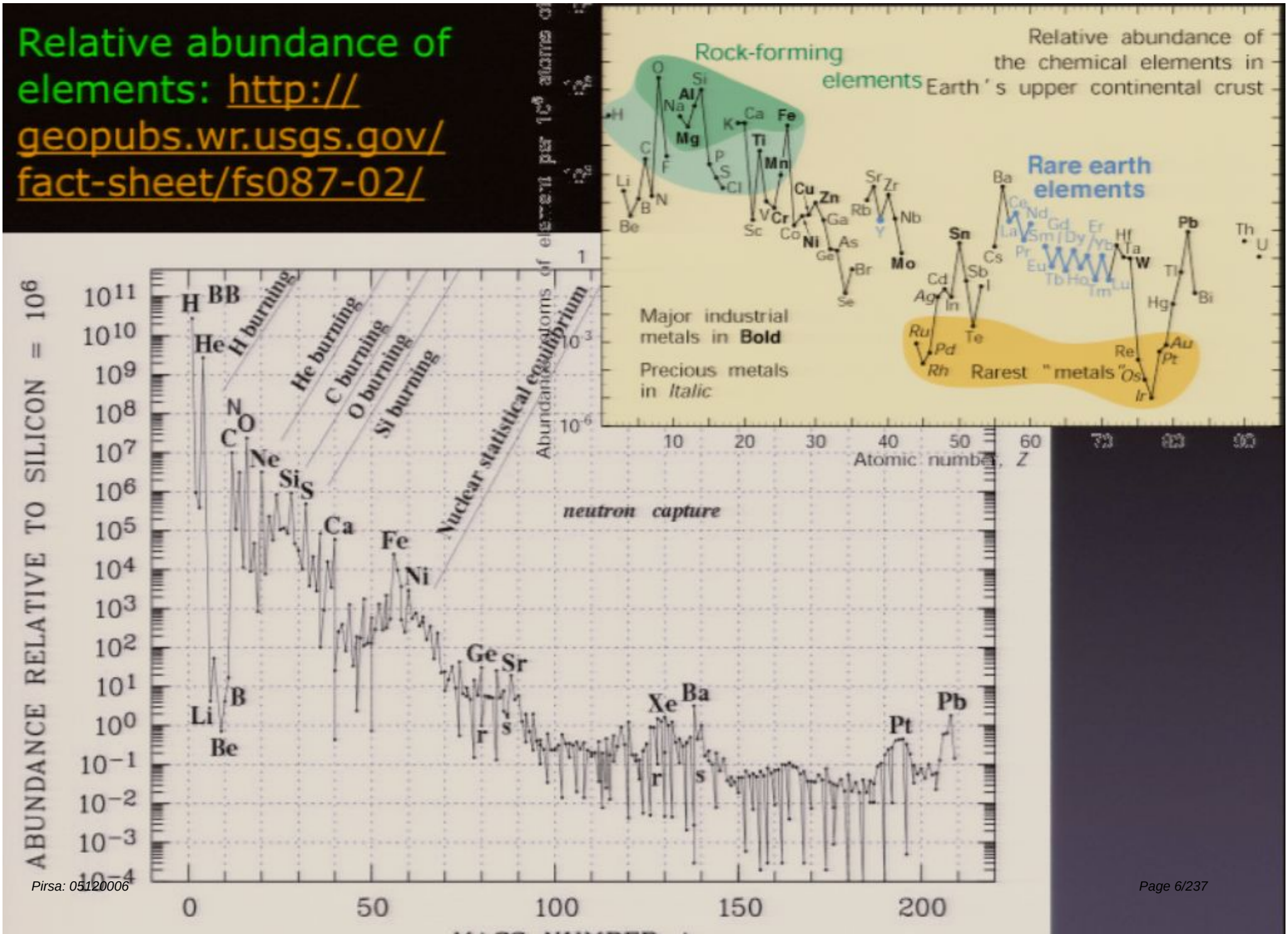
Committee on the Physics of the Universe
Board on Physics and Astronomy
Division on Engineering and Physical Sciences
National Research Council

National Academy Press

The turner report as presented in the Discover Magazine 2002



Relative abundance of elements: http://geopubs.wr.usgs.gov/fact-sheet/fs087-02/



Where

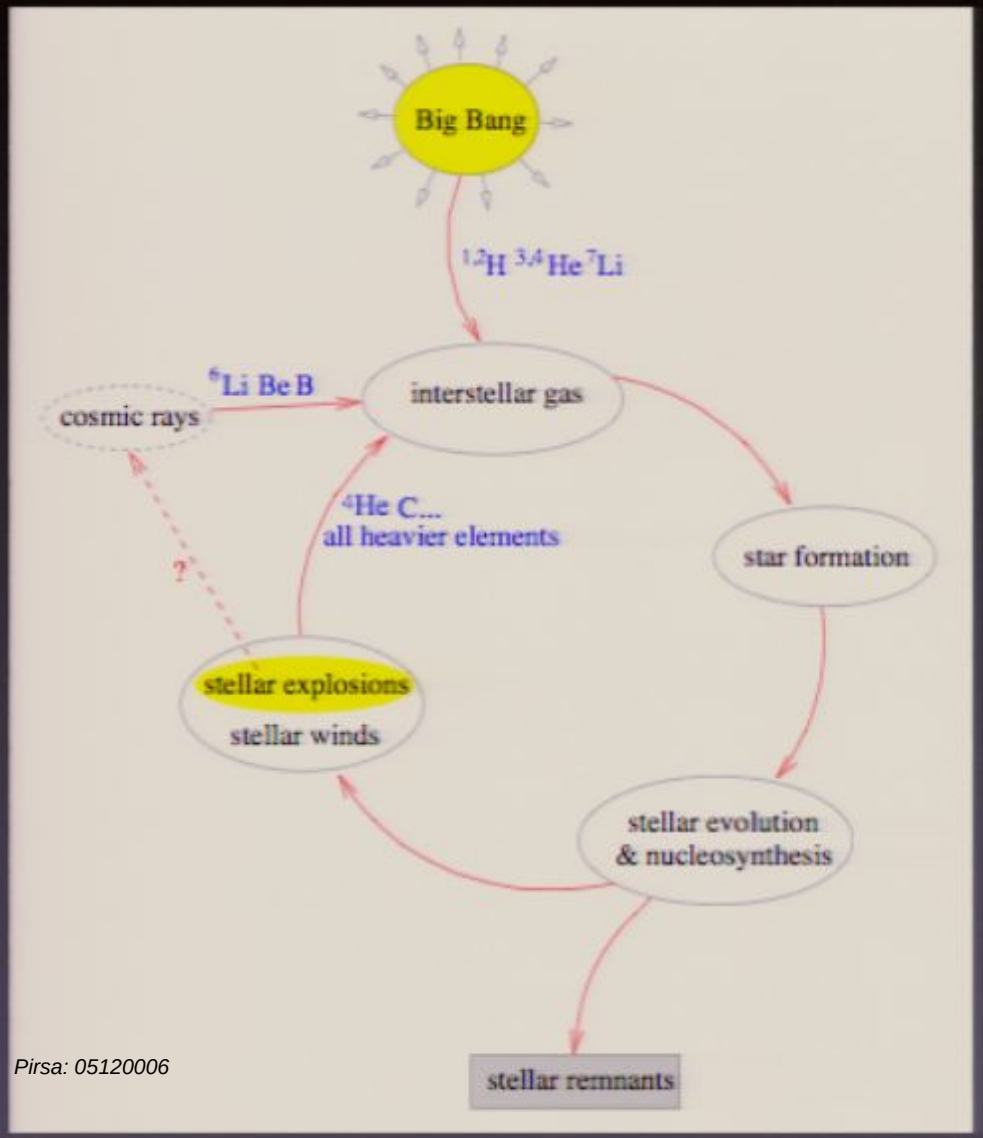
do they

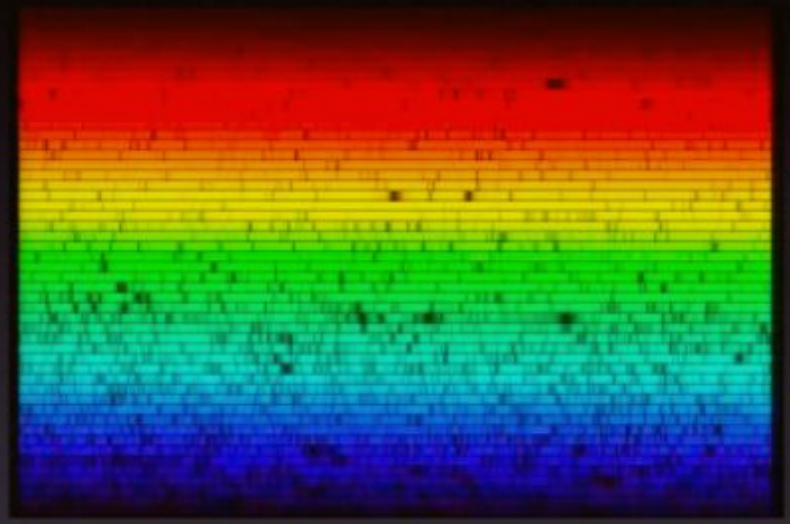
come from?


ORIGINS
ORIGINS
HR HELENA RUBINSTEIN
BIOTHERM
MEN'S CARE
CLINIQUE
Best Sellers
Best Sellers

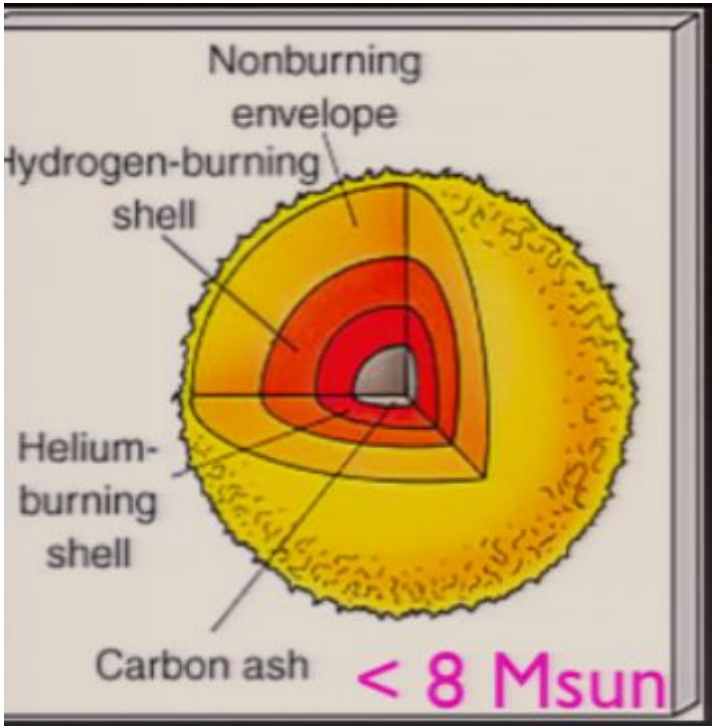
Nucleosynthesis occurs outside of the big bang

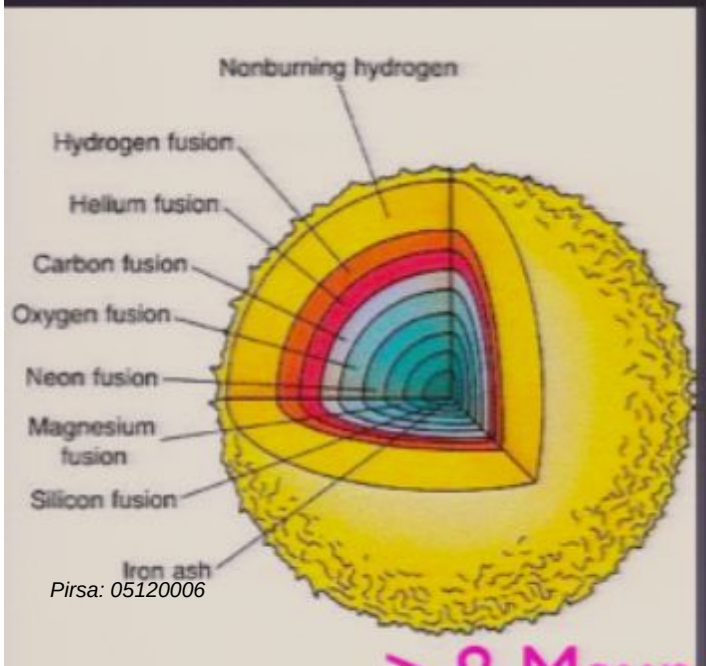
Spectra of stars
H, He, and heavier elements.

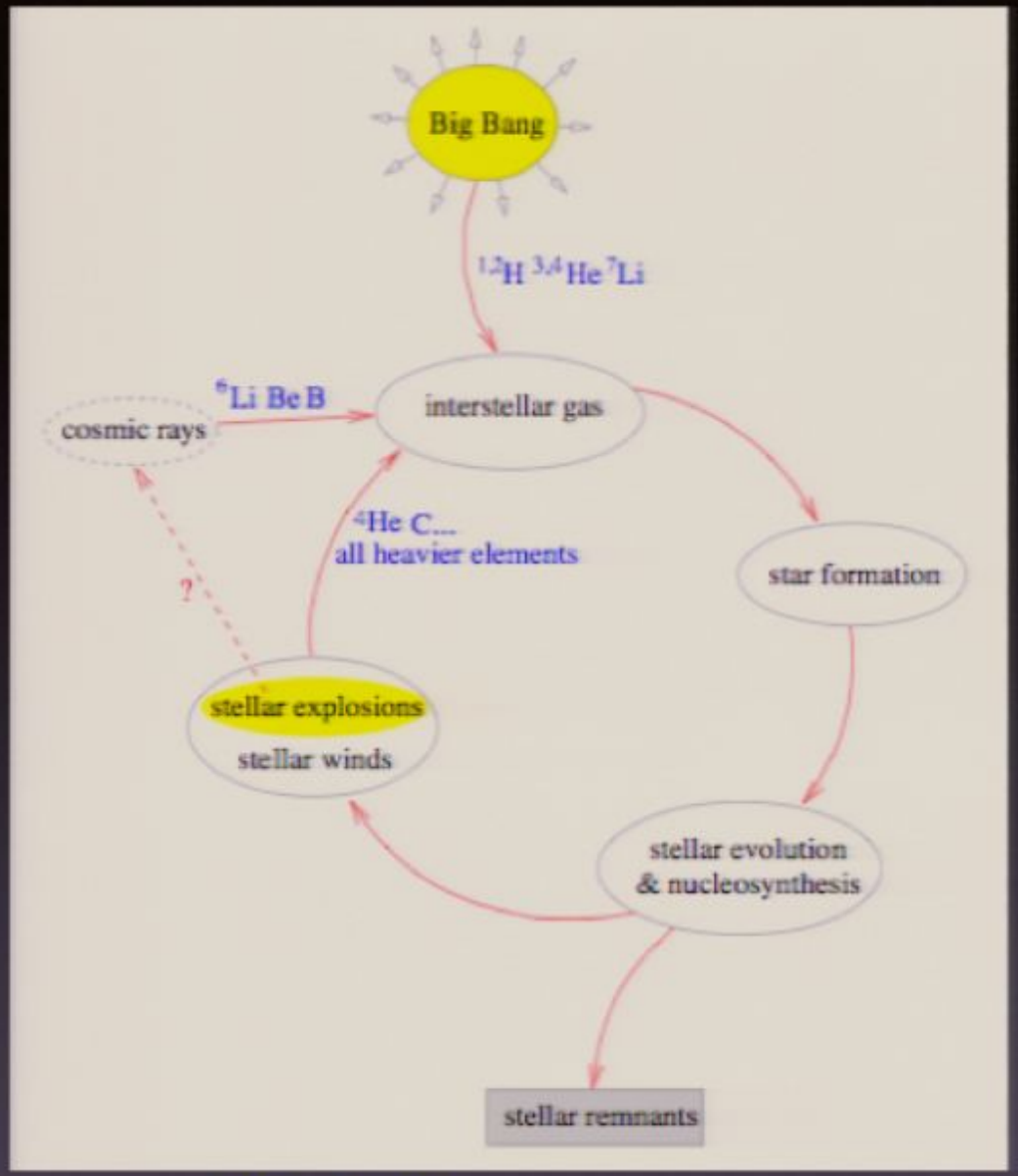




"It is the stars, The stars above us, govern our conditions"
(King Lear, Act IV, Scene 3)







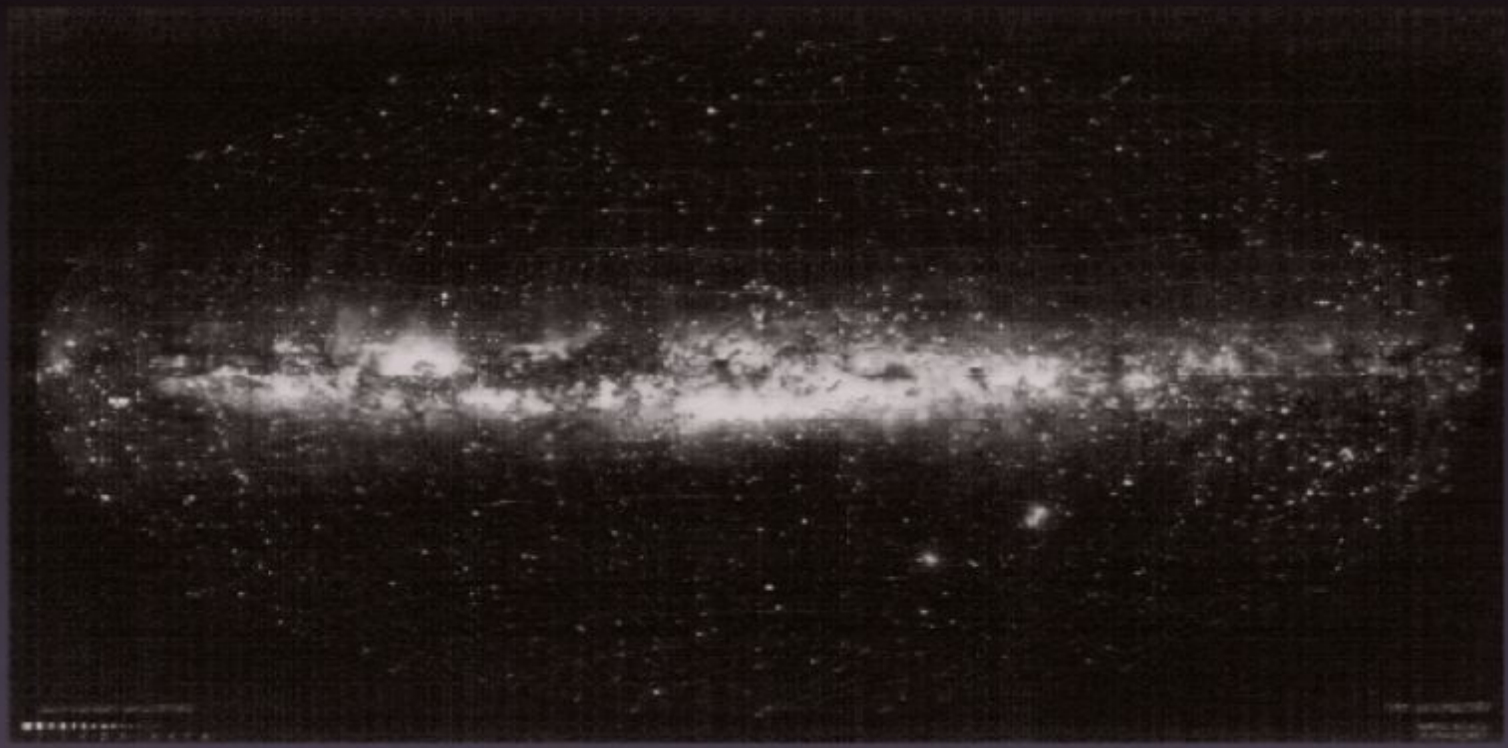
[Fe/H] correlates directly with the age of the universe

Observations

... going back in time ...

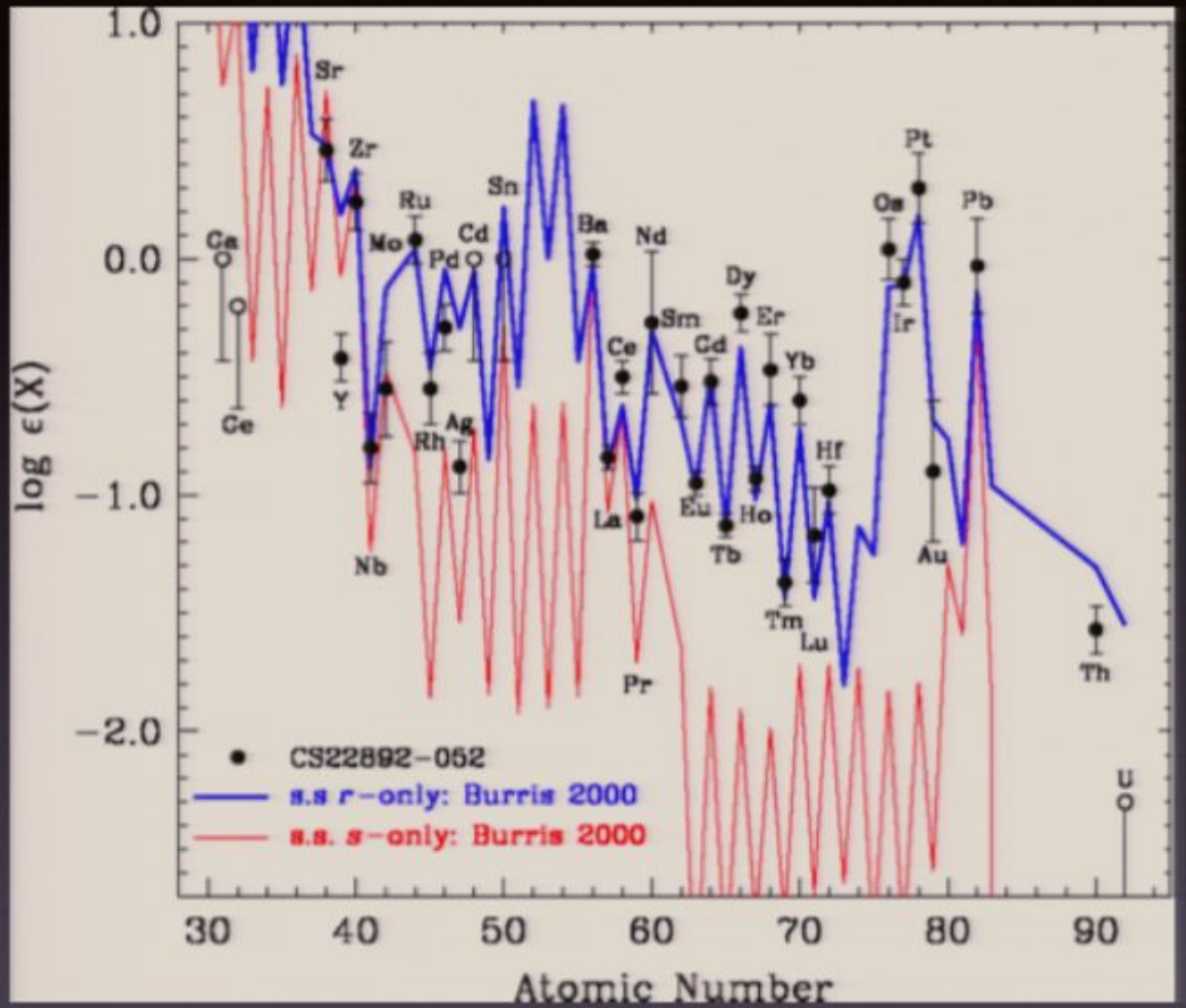
THE CHEMICAL COMPOSITIONS OF HALO FIELD STARS

Ultra-metal-poor stars serve a critical role for understanding the initial epoch of our galaxy.



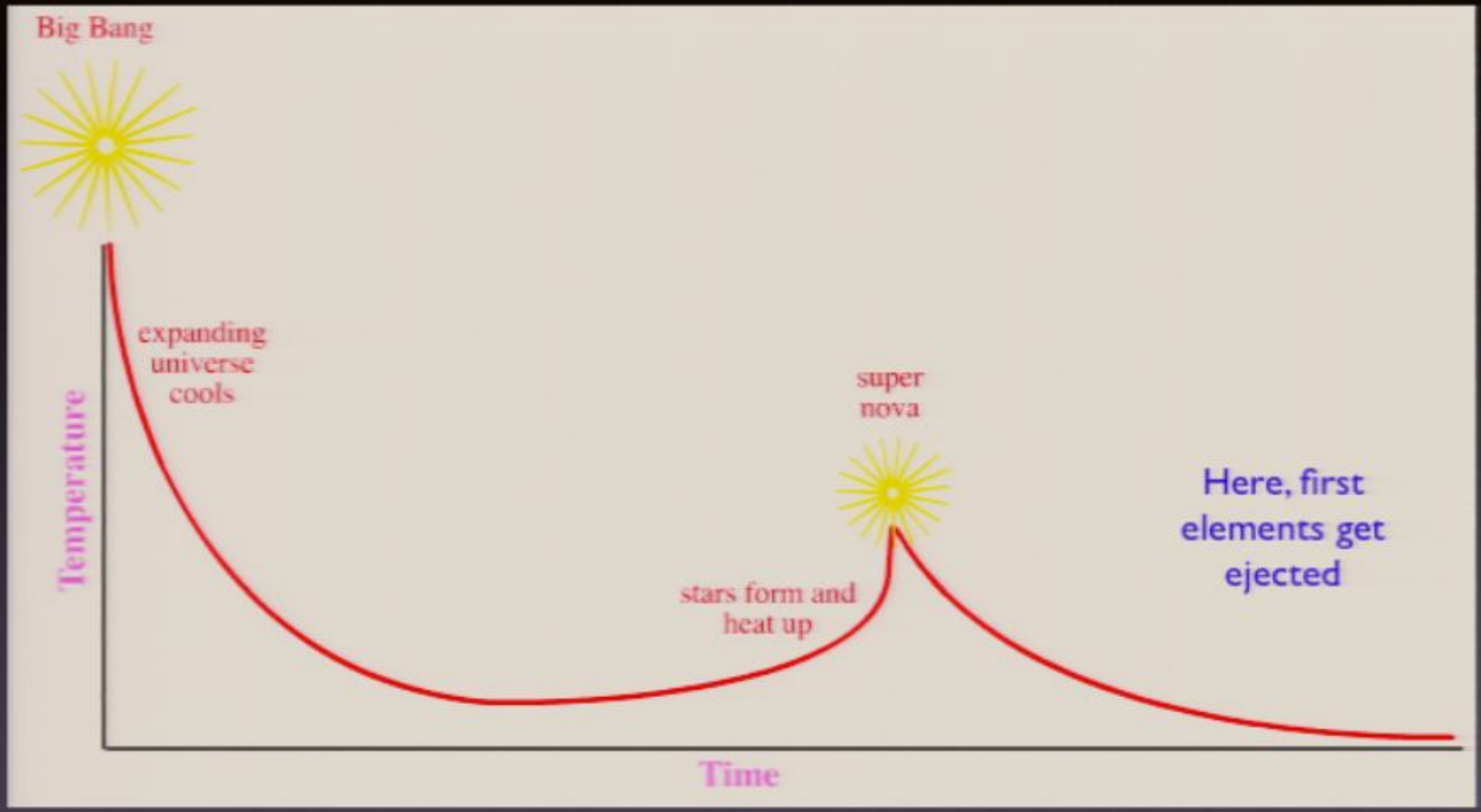
The observed abundances in these very old stars provide clues to nucleosynthesis processes in the earliest Galactic stellar generations.

Sneden et al. 2000 (ApJ, 533, L139)



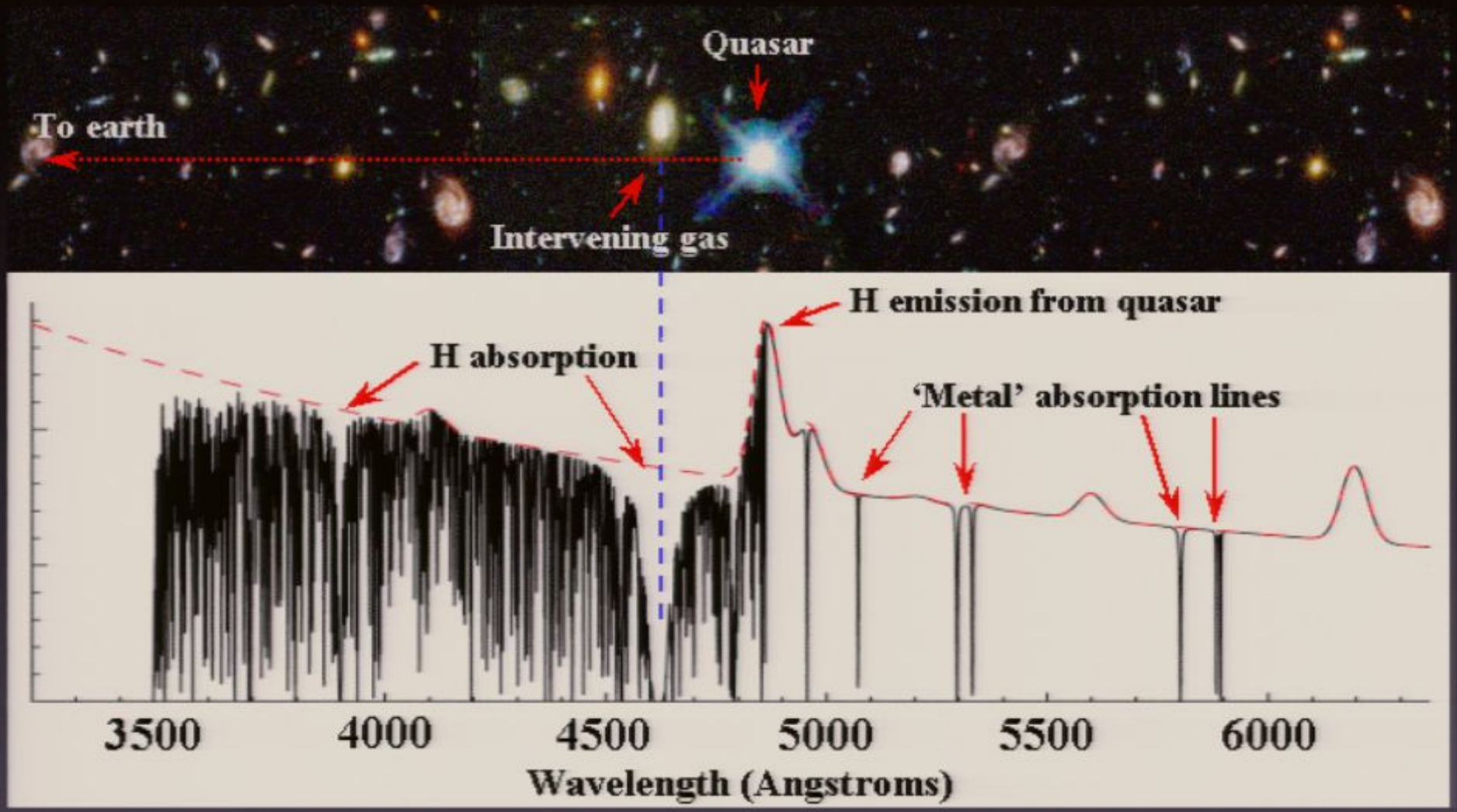
- Other r-element rich halo stars show heavy element abundance pattern similar to CS 22892-052

Elements in earliest galaxies



Shells of debris – consisting of a zoo of atomic nuclei – are ejected into the interstellar medium. Over millions of years this material cools to mildly radioactive clinker. The star dust is collected by gravity where participates in next generation of star formation.

*) Recently, element abundances in gas inside high-redshift galaxies has been probed through the absorption lines imprinted on the spectra of background quasars.

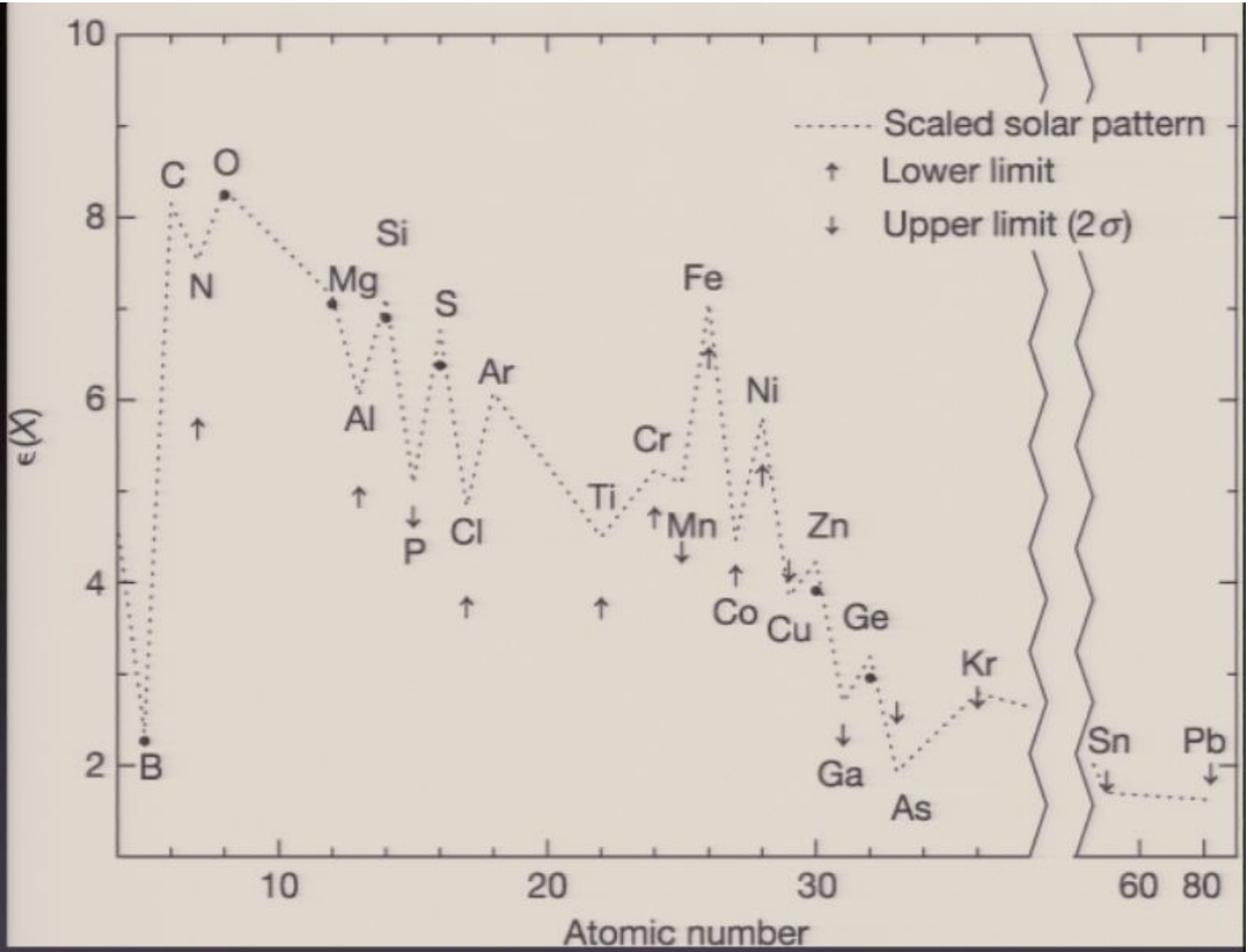


*) Over 25 elements in a galaxy at red-shift $z = 2.626$ were reported (Prochaska et al. 2003). With these data, one can examine nucleosynthetic processes independent of the uncertainty arising from depletion.

*) These studies show that these very old galaxies was enriched mainly by massive stars ($M > 15$ solar masses).

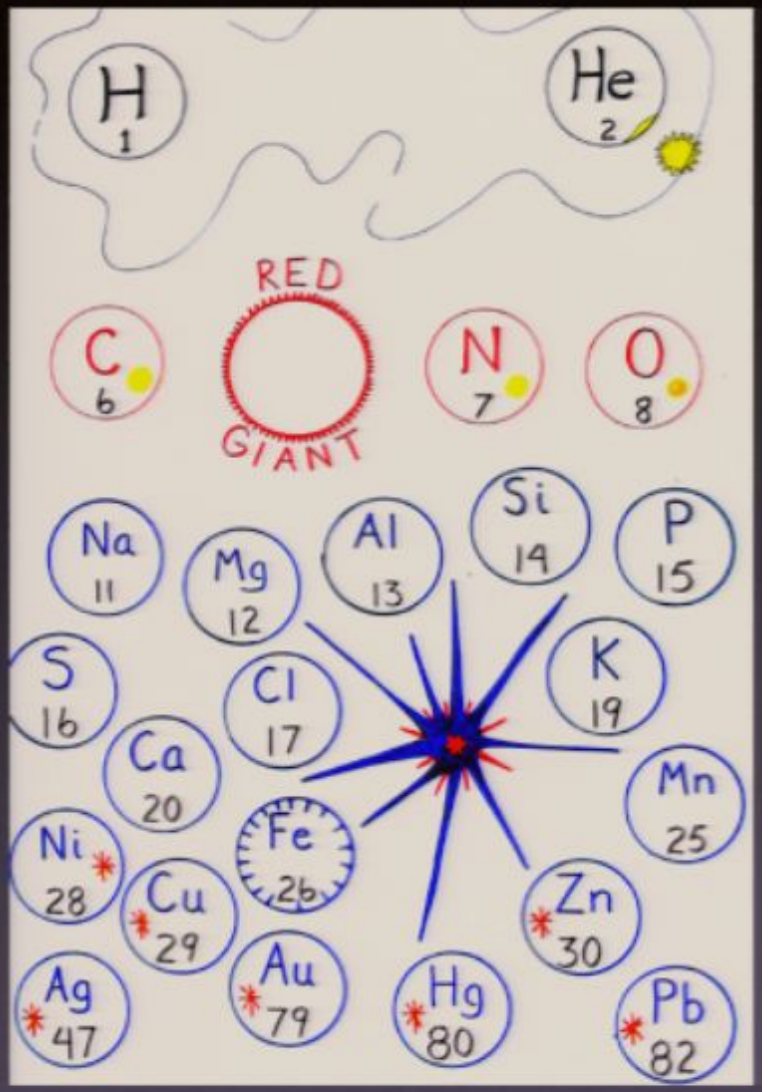
Protogalaxy FJ081240.6 +320808 (z=2.626).

Prochaska et al. 2003, Nature,423, 57 (also earlier studies by Burris et al. 2000, ApJ, 544, 302).



- The r-process is robust and has operated unchanged since the first generation of stars

But, ...how do we go from Iron to Uranium?

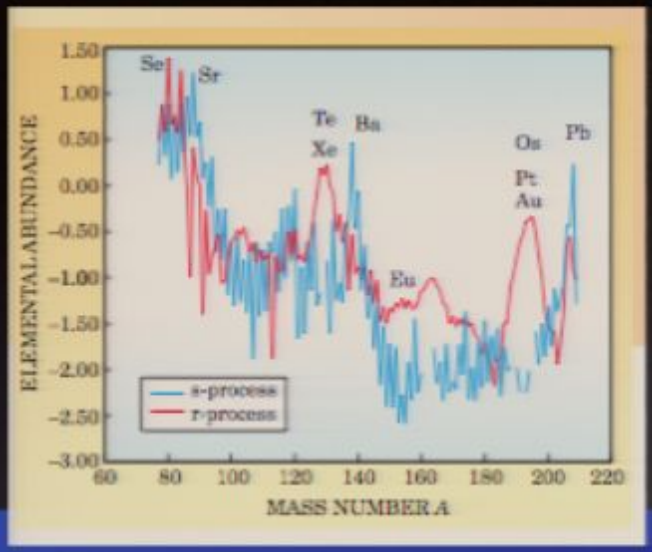


Nuclear Physics

Burbidge, Burbidge, Fowler, & Hoyle

(Review of Modern Physics, October, 1957)

r-process



s-process

- (r)-apid neutron capture
  $\tau_n << \tau_\beta$
- $\tau_n \sim 0.01 - 0.1$ sec
- astrophysical site unknown

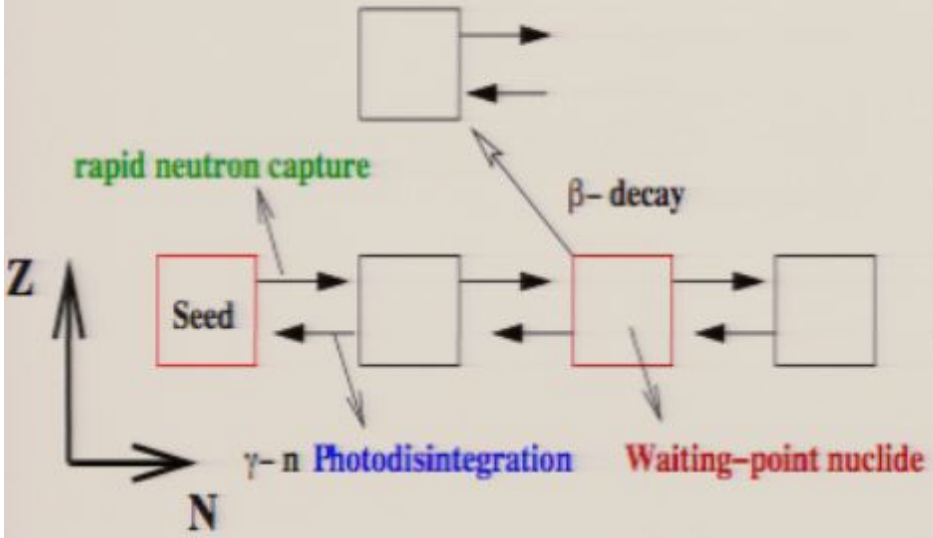
- (s)-low neutron capture
  $\tau_n >> \tau_\beta$
- $\tau_n \sim 100 - 1000$ yrs
- AGB stars

Nuclei are bombarded with neutrons, which they rapidly capture.

The process continues with more neutron captures and decays creating heavier and heavier elements.

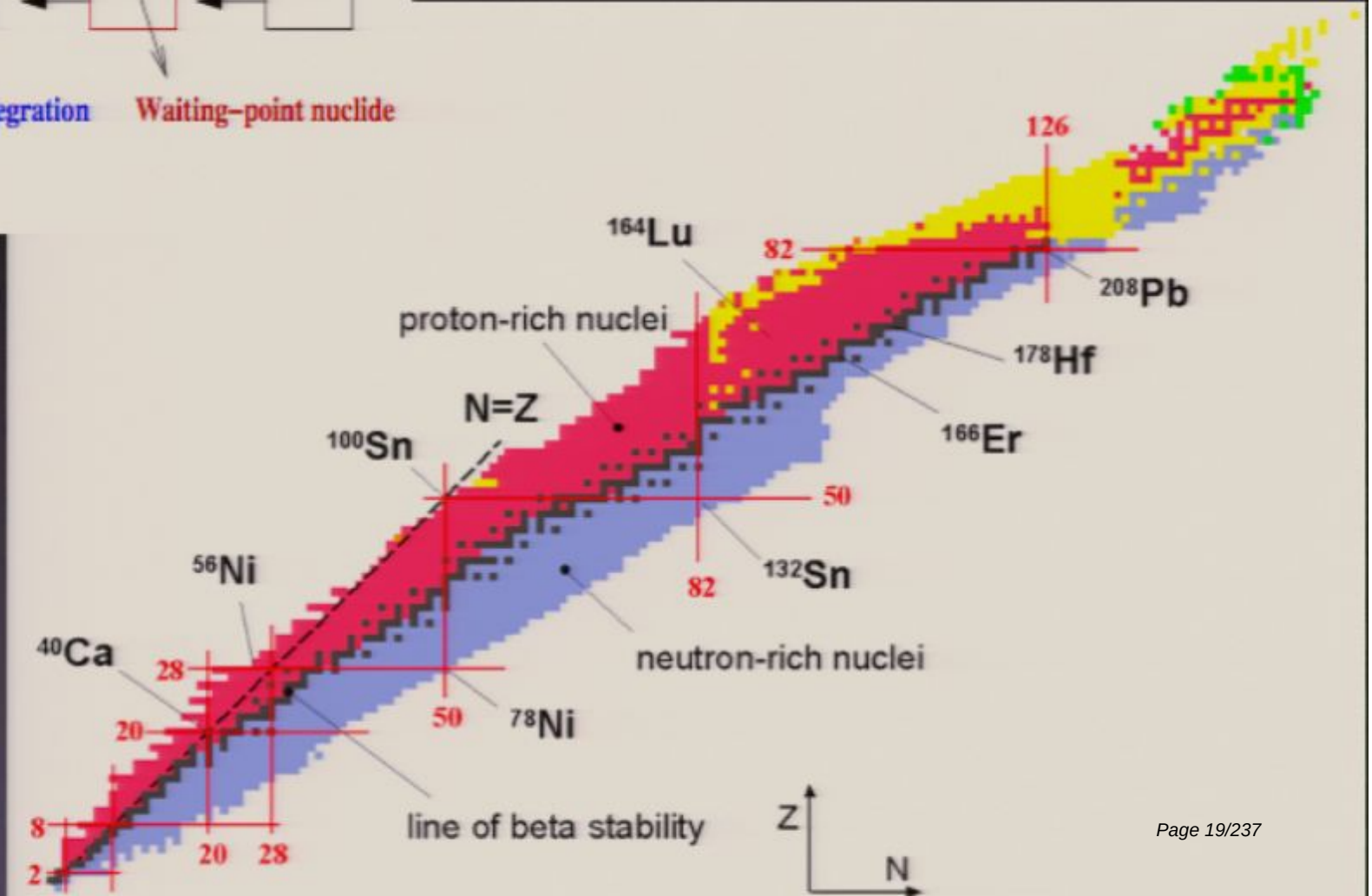
- The s-process cannot produce actinides, which definitely are present in significant abundance in the Solar System.
- The most abundant isotope of osmium is ^{192}Os, which cannot be synthesized in abundance by the s-process, because ^{191}Os is beta-unstable with a

The "Valley of Stability"



1] The ratio of neutrons to protons in stable nuclides gradually increases as the number of protons in the nucleus increases.

2] The greater number of neutrons is needed to stop the nucleus flying apart, in effect diluting the repulsive force of the positively charged protons.



Nucleosynthesis in the r-process

JINA

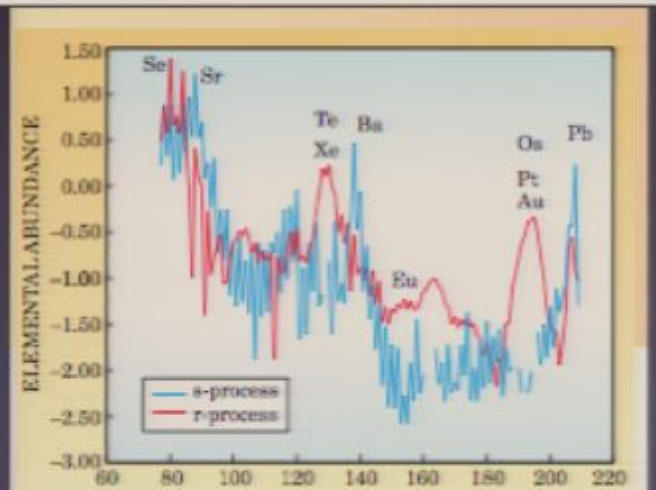
Joint Institute for Nuclear Astrophysics 2002

Movie : H. Schatz, T. Elliot
NSCL, Michigan State University

Calculation : K. Vaughan, J.L. Gallache,
and A. Aprahamian, University of Notre Dame

Mode : B. Meyer, Clemson University
and R. Surman, North Carolina State

Temperature: 1.50 GK
Time: 2.7e-14 s



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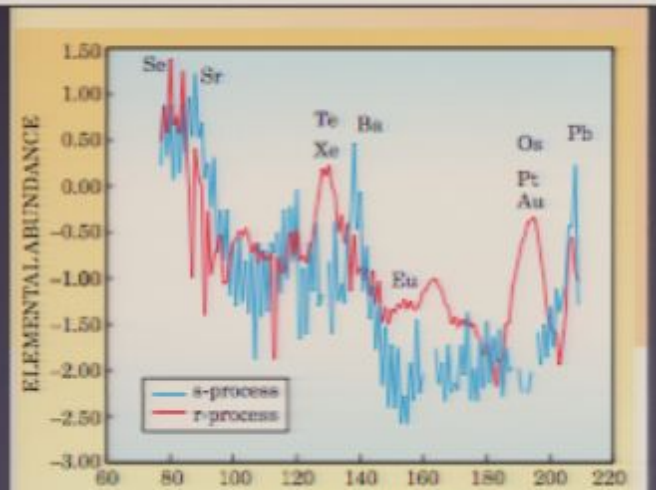
Temperature: 0.92 GK
Time: 1.3e+00 s



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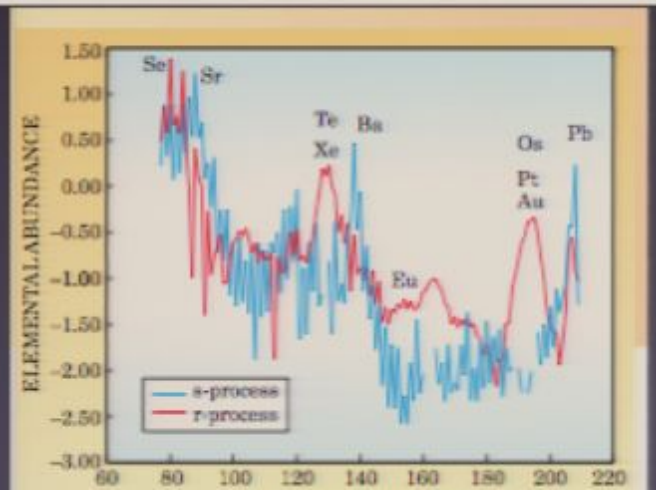
Temperature: 0.80 GK
Time: 1.6e+00 s



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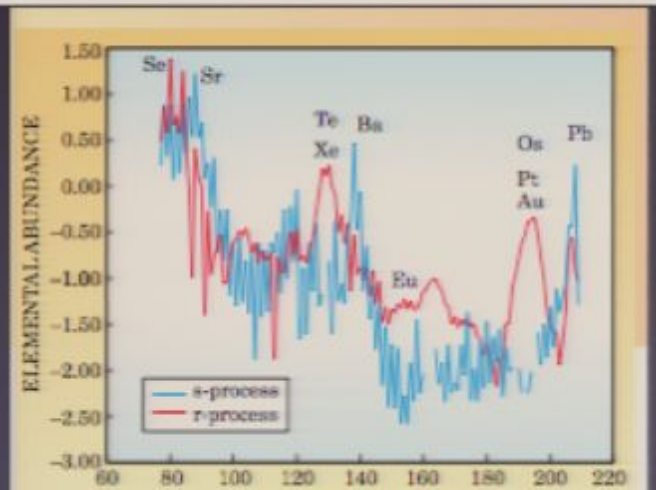
Temperature: 0.78 GK
Time: 1.7e+00 s



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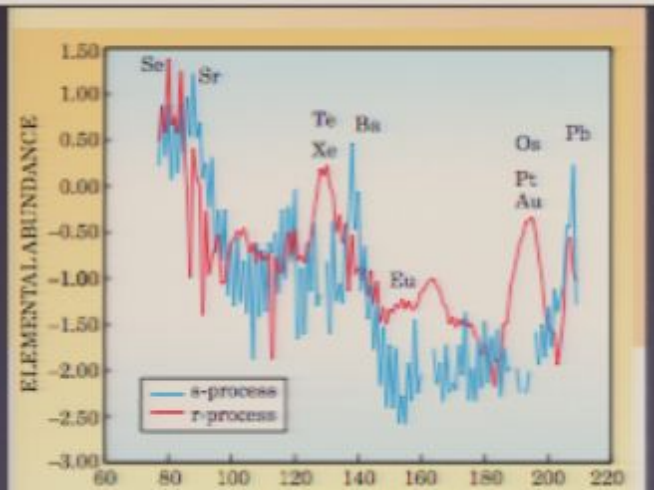
Temperature: 0.75 GK
Time: 1.8e+00 s



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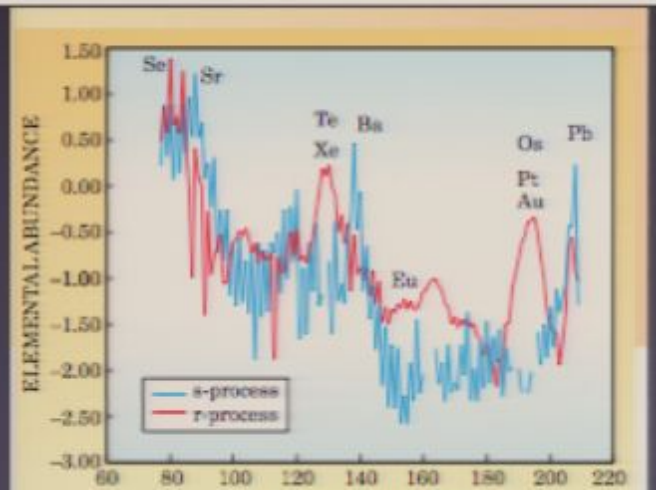
Temperature: 0.73 GK
Time: 1.8e+00 s



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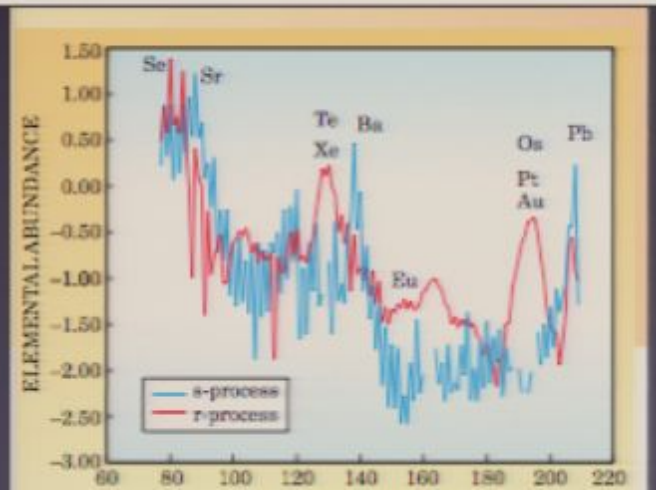
Temperature: 0.72 GK
Time: 1.9e+00 s



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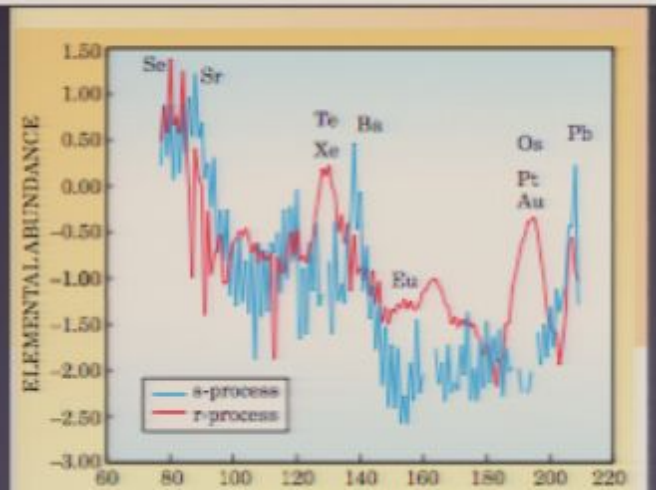
Time: 1.9e+00 s



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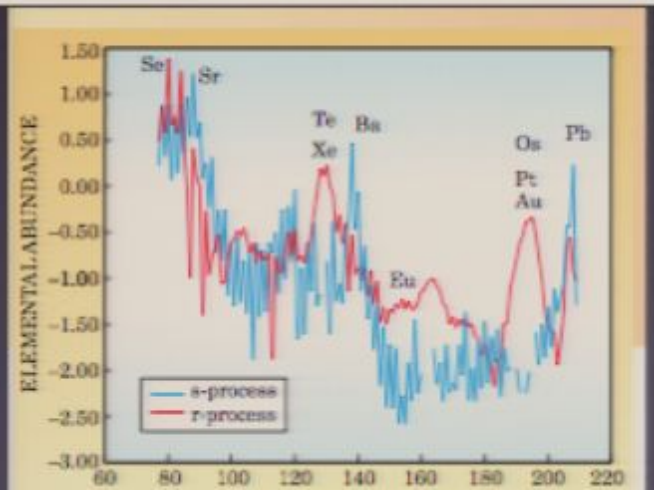
Temperature: 0.69 GK
Time: 2.0e+00 s



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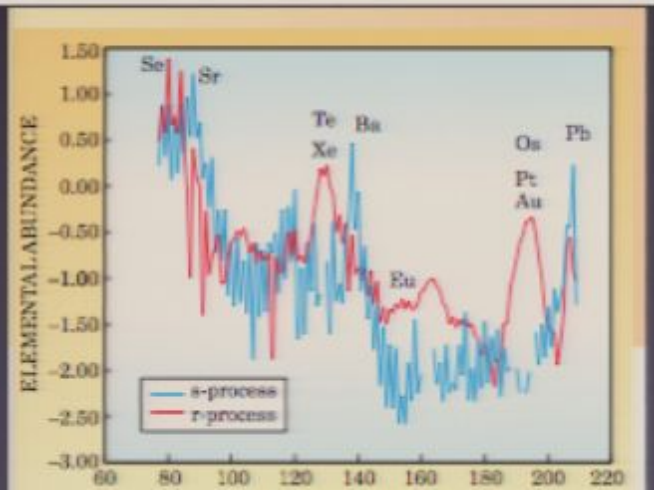
Temperature: 0.68 GK
Time: 2.0e+00 s



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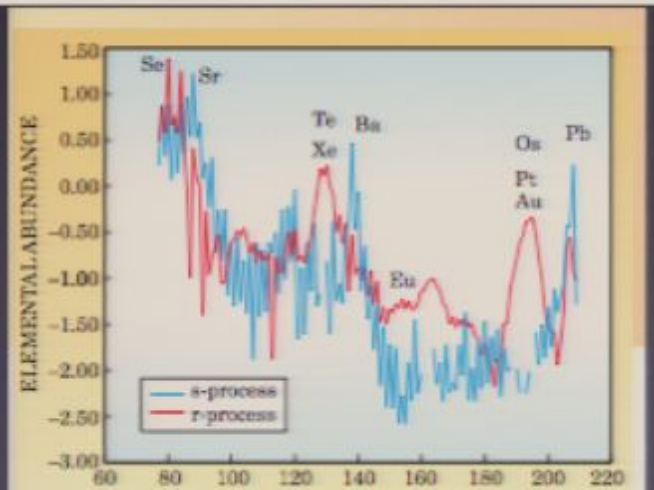
Temperature: 0.67 GK
Time: 2.1e+00 s



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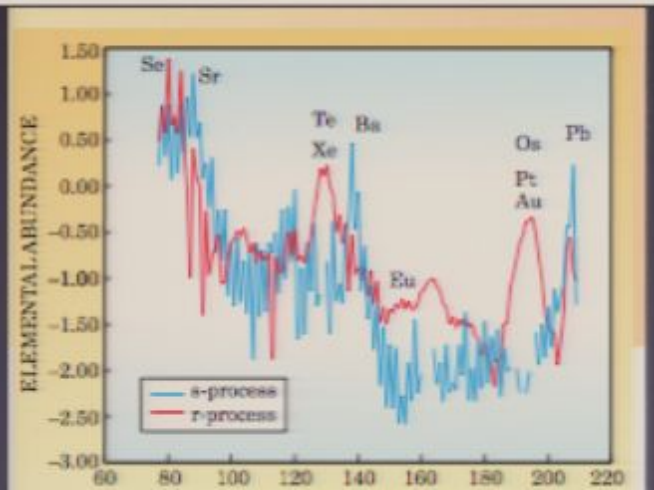
Temperature: 0.65 GK
Time: 2.1e+00 s



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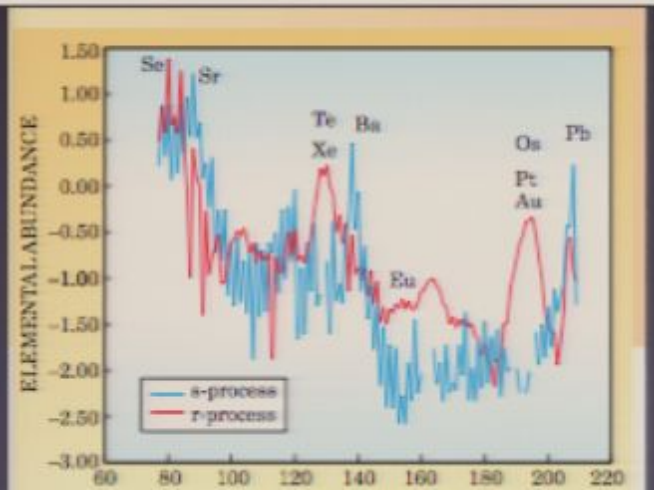
Temperature: 0.63 GK
Time: 2.3e+00 s



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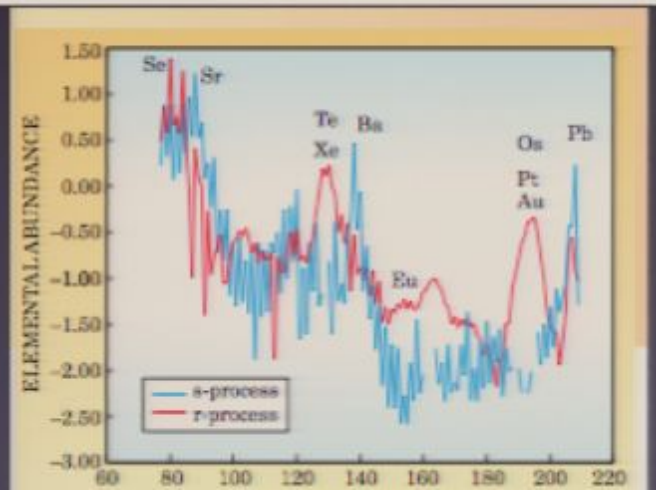
Temperature: 0.62 GK
Time: 2.3e+00 s



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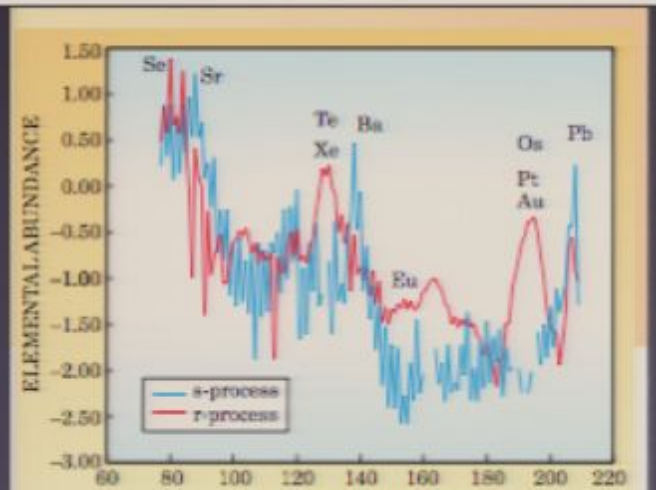
Temperature: 0.62 GK
Time: 2.3e+00 s



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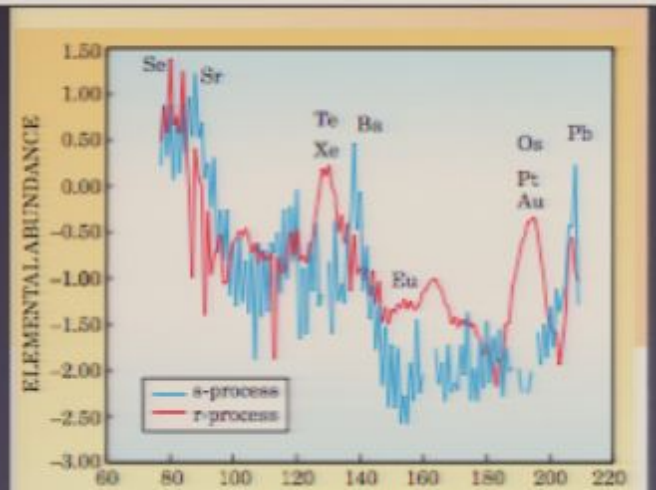
Temperature: 0.60 GK
Time: 2.4e+00 s



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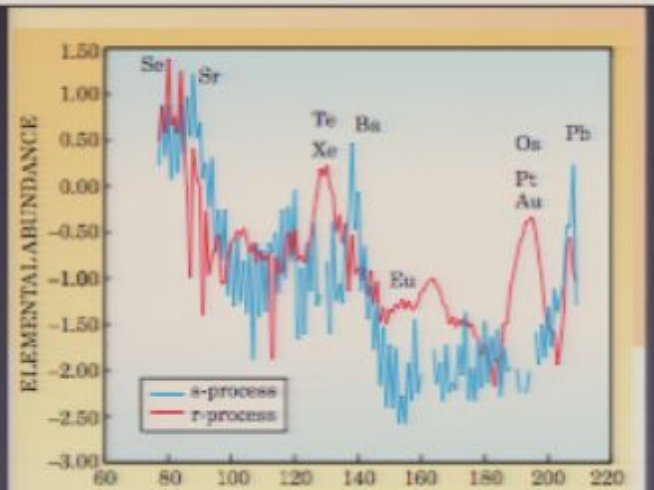
Time: 2.5e+00 s



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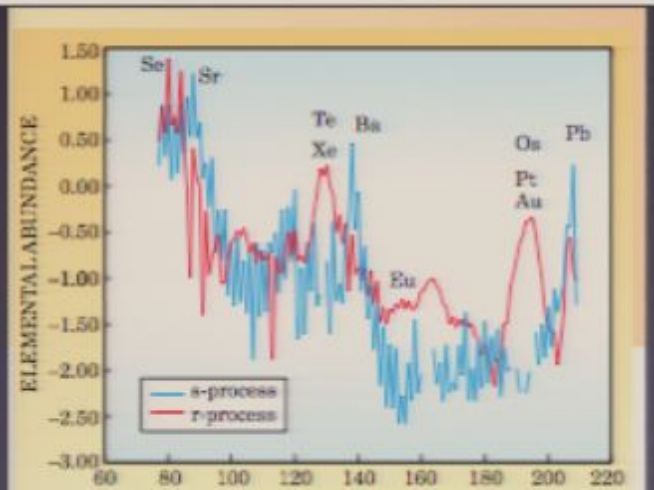
Temperature: 0.56 GK
Time: 2.5e+00 s



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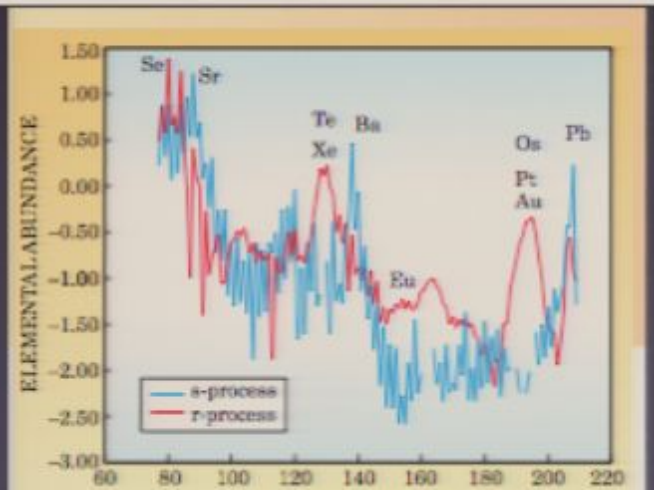
Mode : B. Meyer, Clemson University
and R. Surman, North Carolina State

Time: 2.5e+00 s



Nucleosynthesis in the r-process

JINA

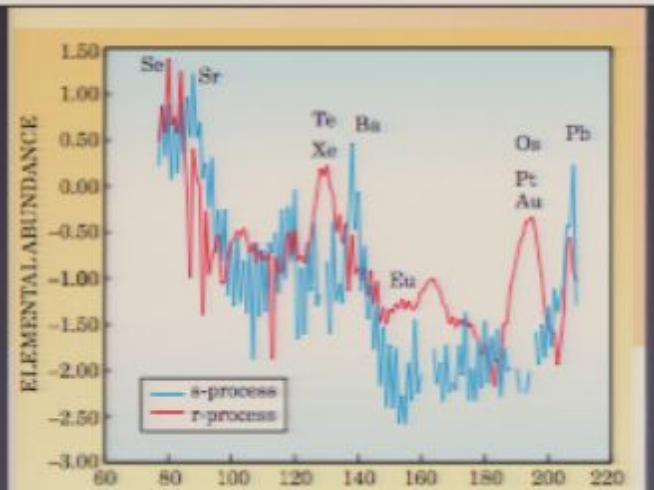
Joint Institute for Nuclear Astrophysics 2002

Movie : F. Schatz, T. Elliot
NSCL, Michigan State University

Calculation : K. Vaughan, J.L. Gallache,
and A. Aprahamian, University of Notre Dame

Mode : B. Meyer, Clemson University
and R. Surman, North Carolina State

Time: 2.6e+00 s



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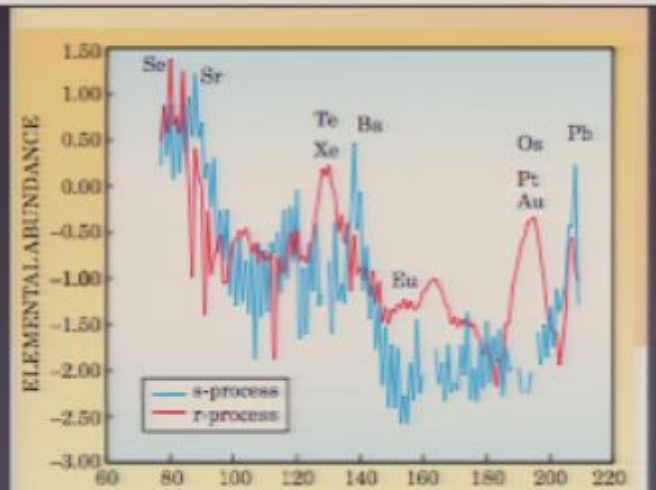
Time: 3.0e+00 s



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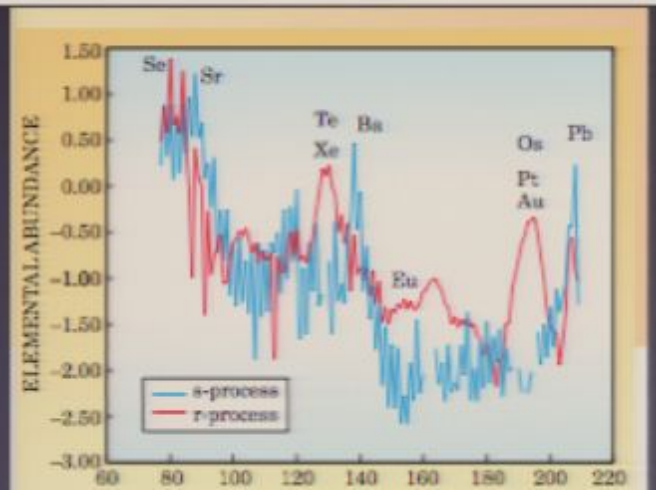
Time: 4.8e+00 s



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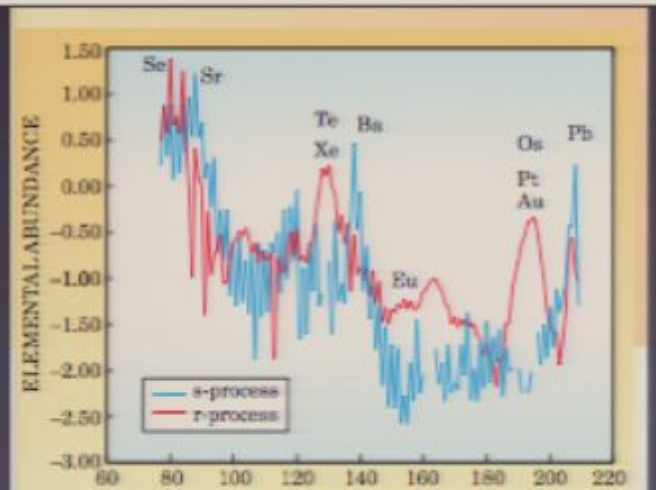

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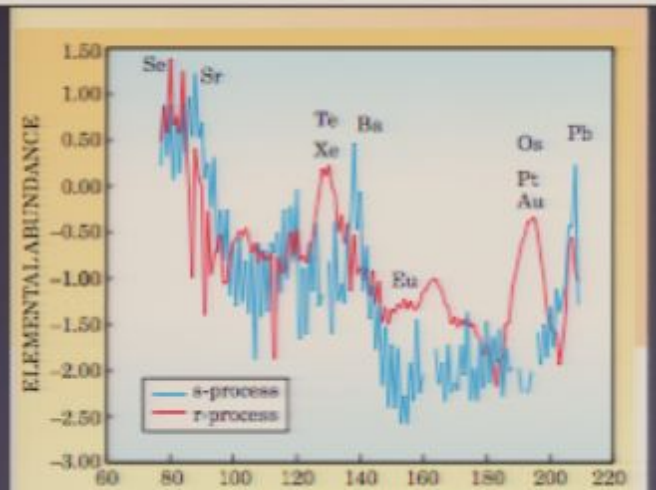
Time: 7.1e+00 s



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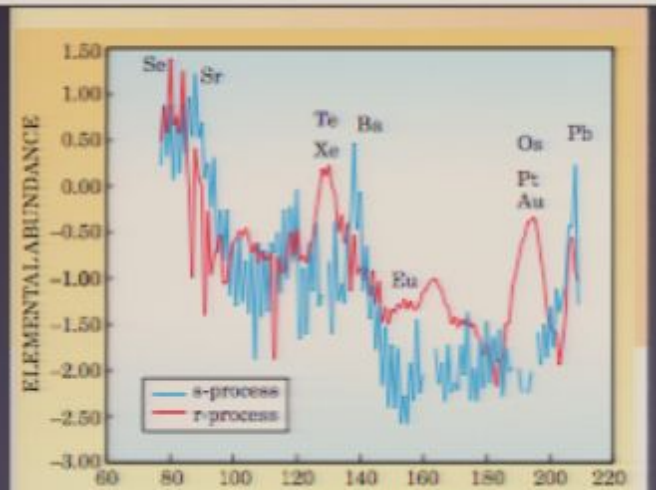
Time: 1.1e+01 s



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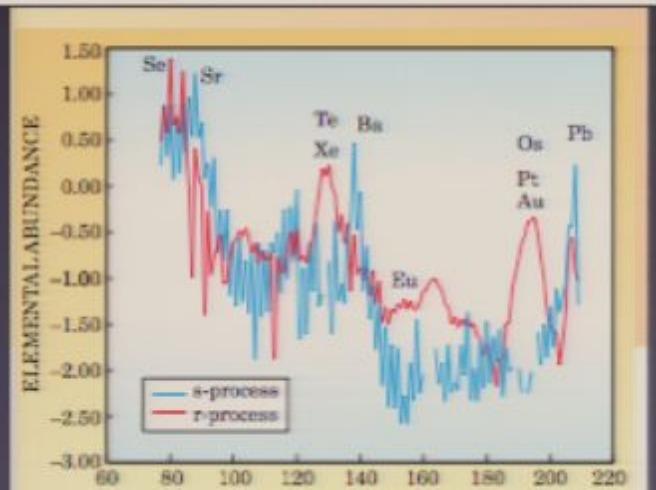
Time: 1.4e+01 s



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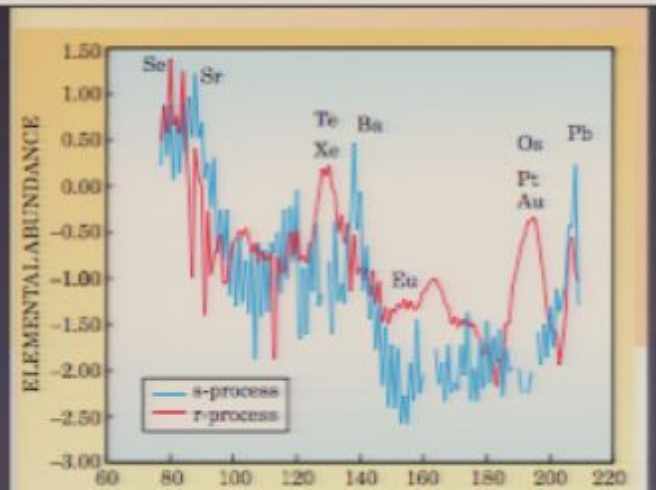

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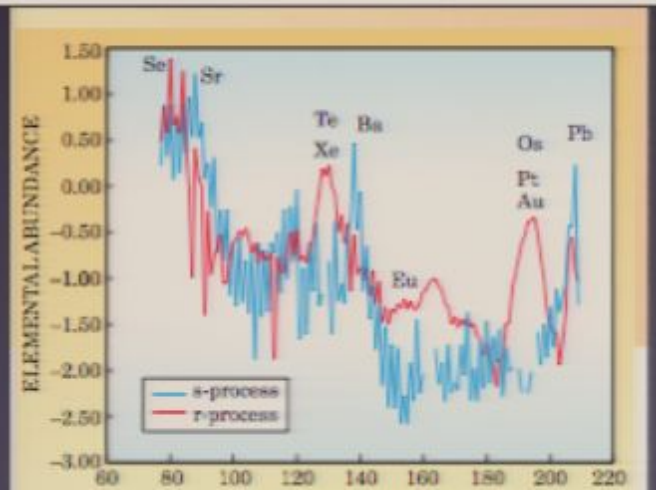

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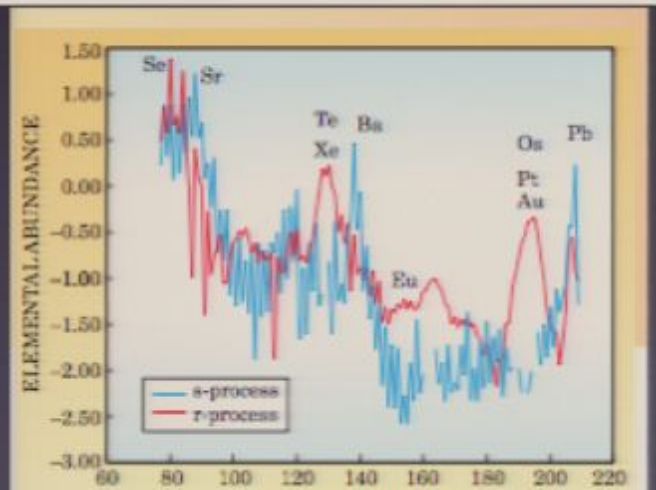
Time: 2.6e+01 s



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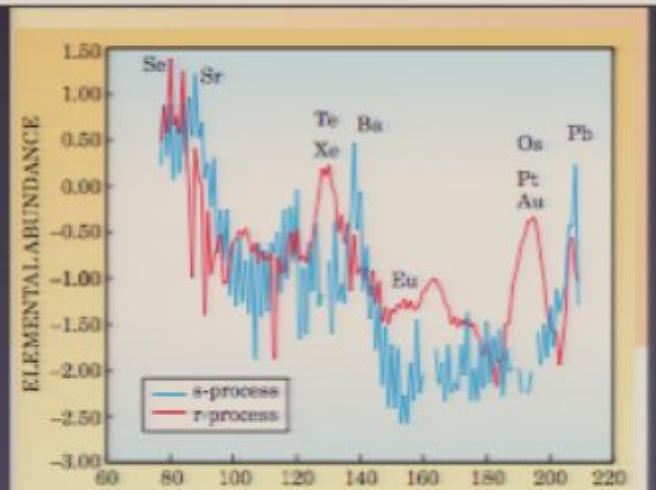
Time: 4.3e+01 s



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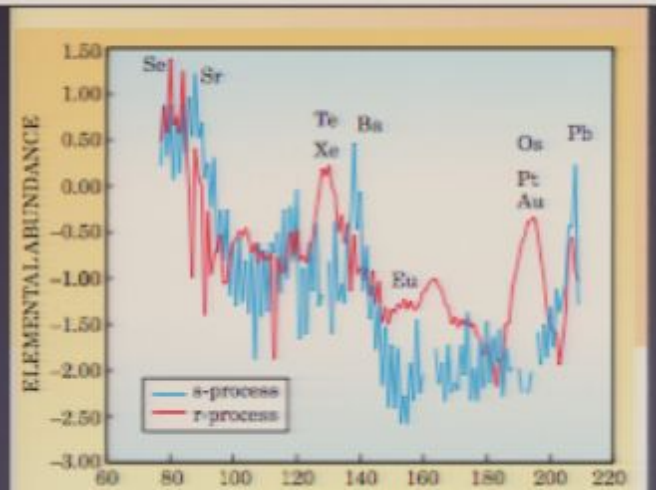
Time: 4.3e+01 s



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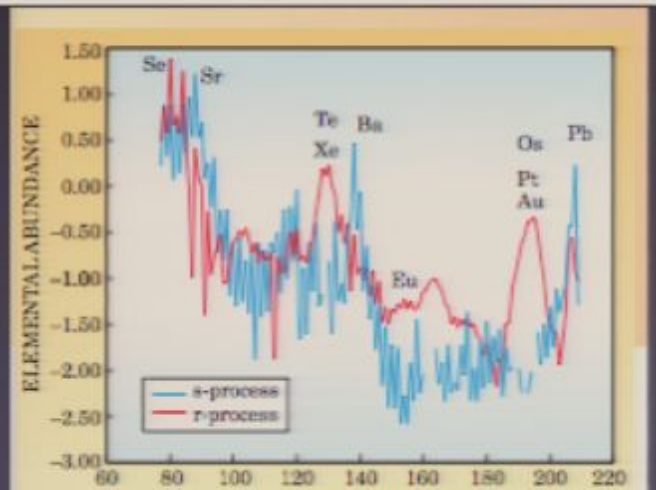
Time: 7.9e+01 s



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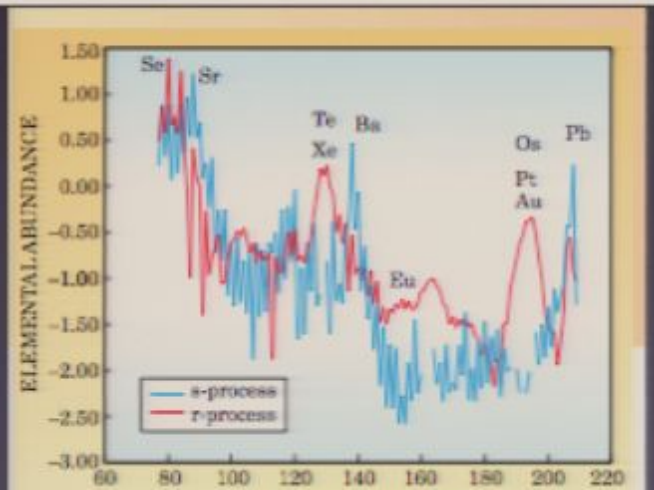
Time: 1.4e+02 s



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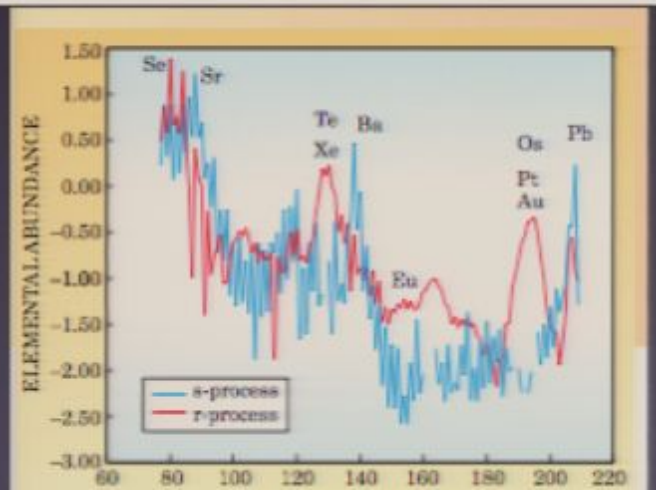
Time: 2.8e+02 s



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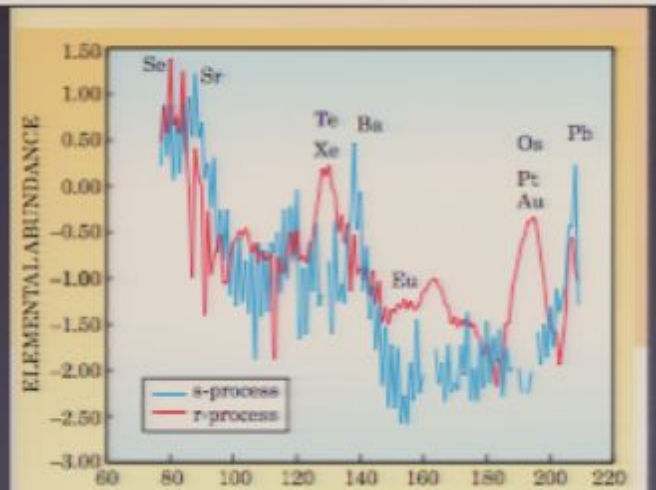
Time: 5.0e+02 s



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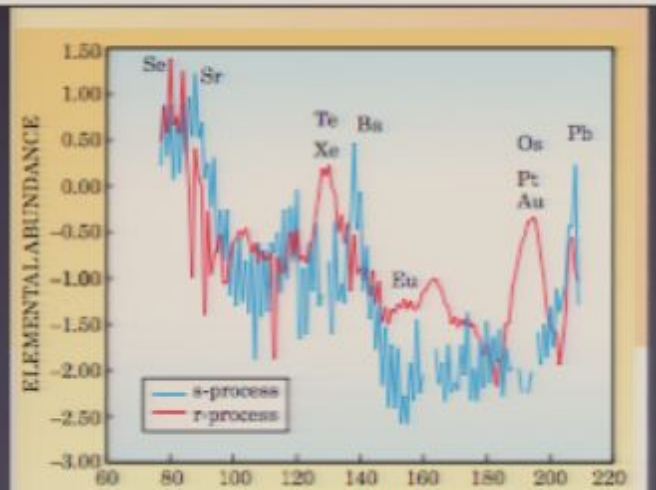
Time: 9.7e+02 s



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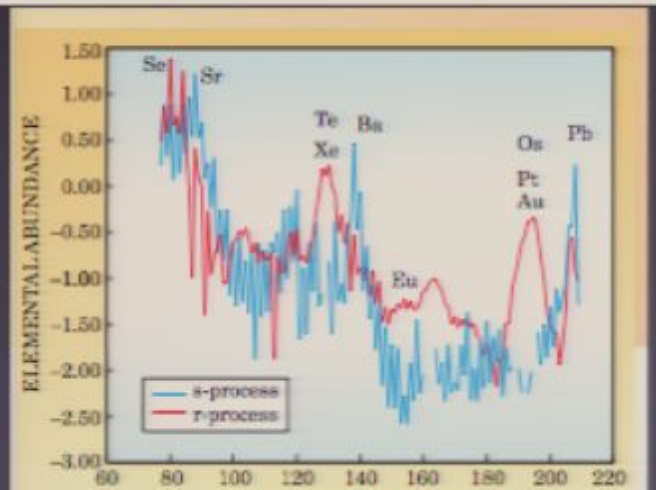
Time: 9.7e+02 s



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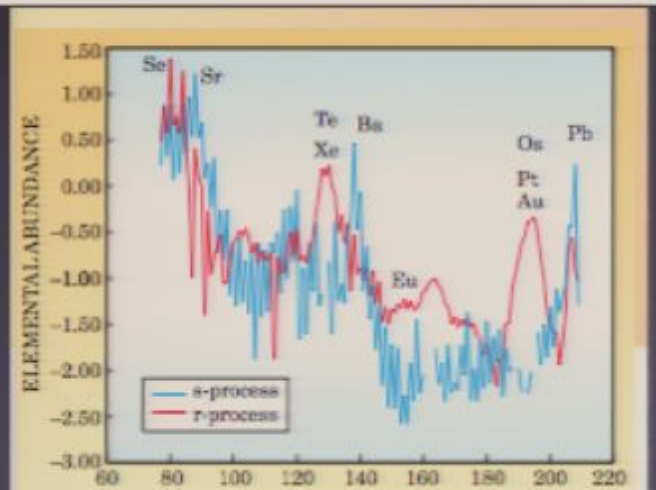
and R. Surman, North Carolina State

Time: 1.8e+03 s



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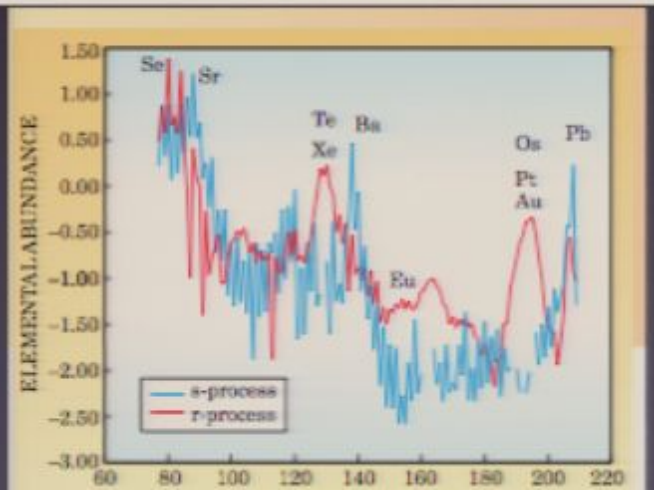
Time: 3.4e+03 s



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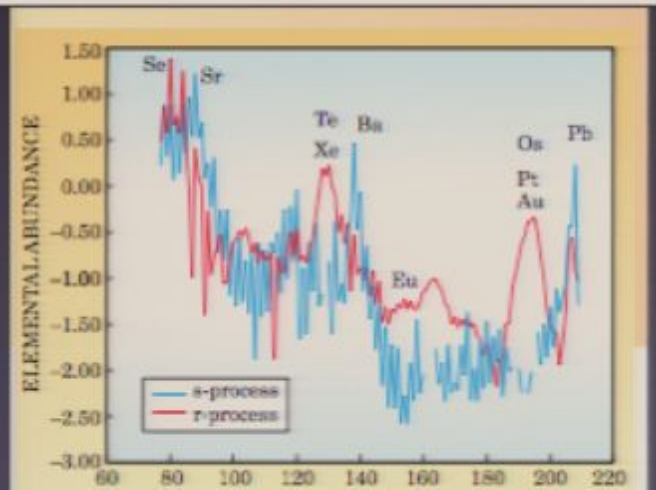
Time: 6.3e+03 s



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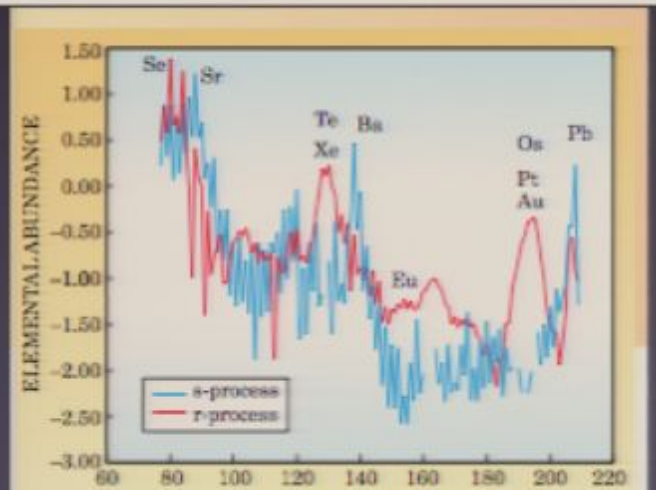

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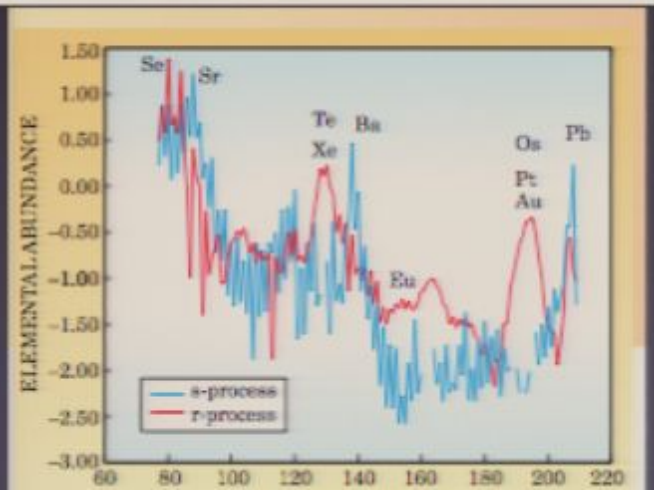
Time: 1.2e+04 s



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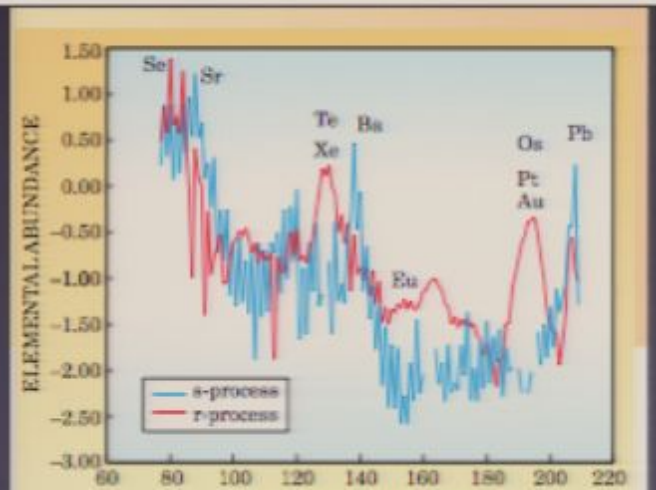
Time: 2.3e+04 s



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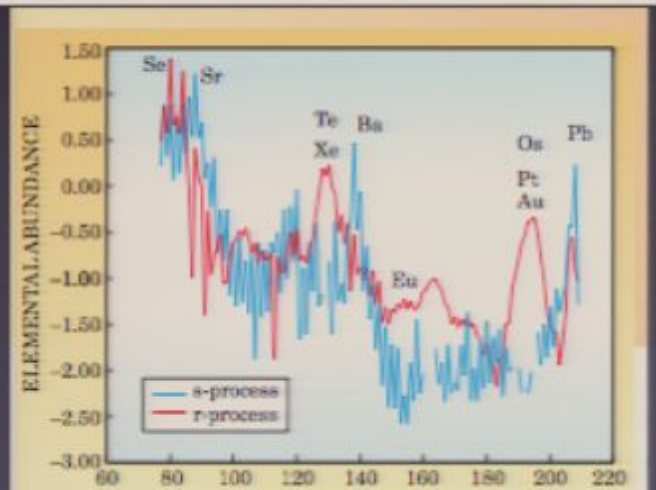
Time: 4.4e+04 s



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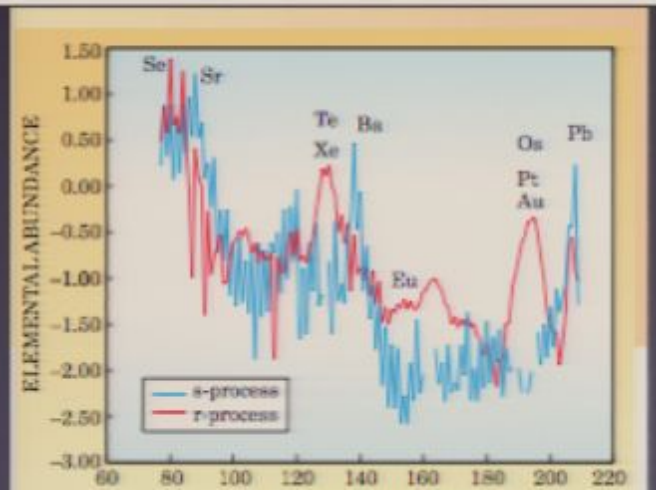
Time: 8.1e+04 s



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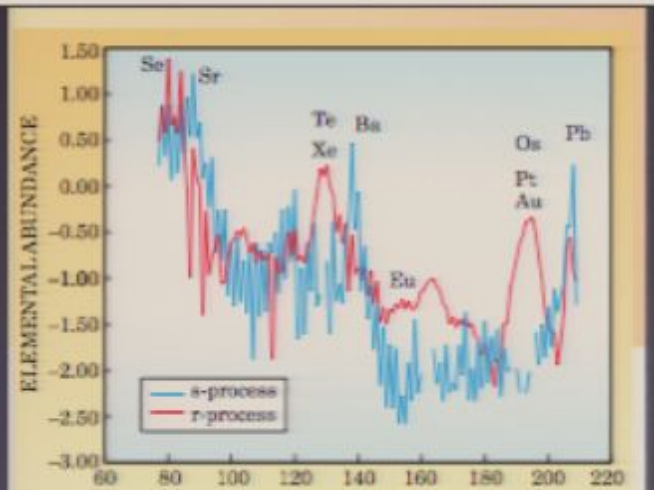

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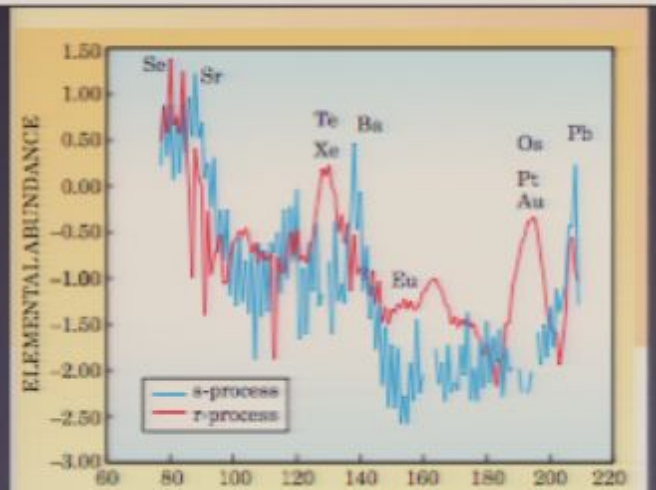

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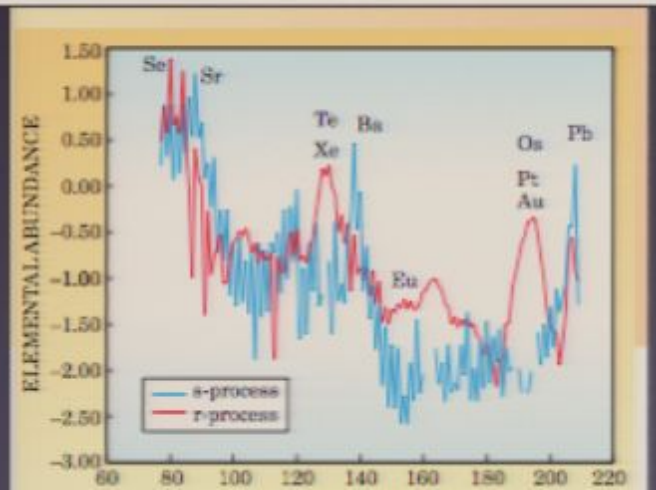

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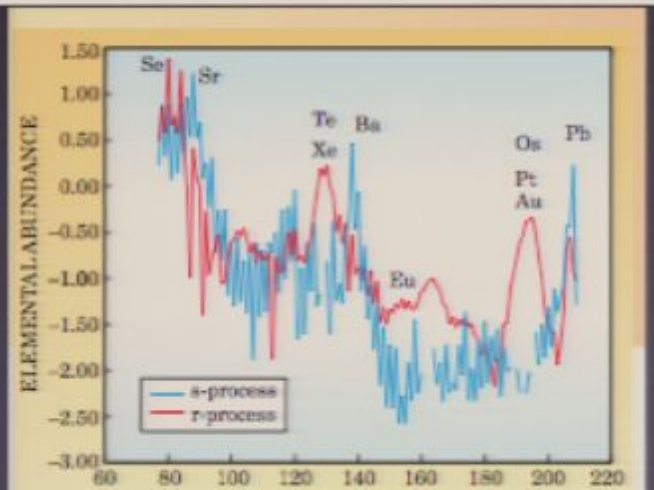

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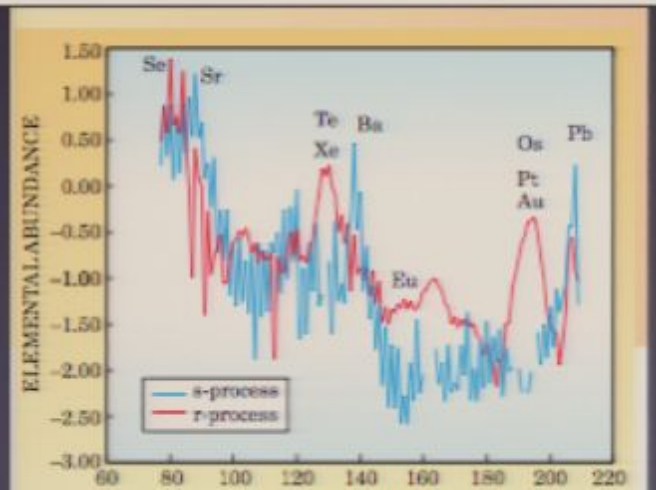
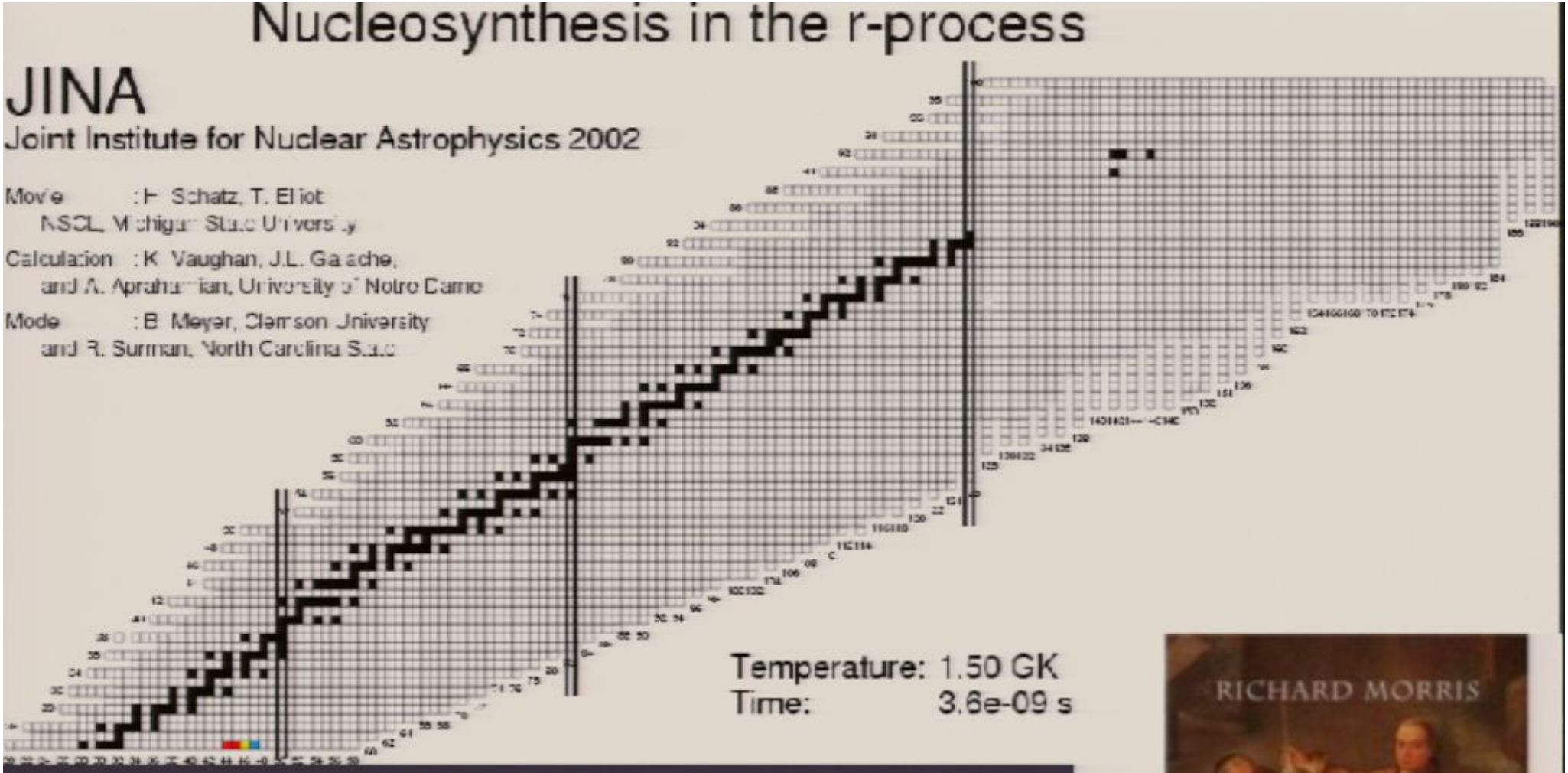
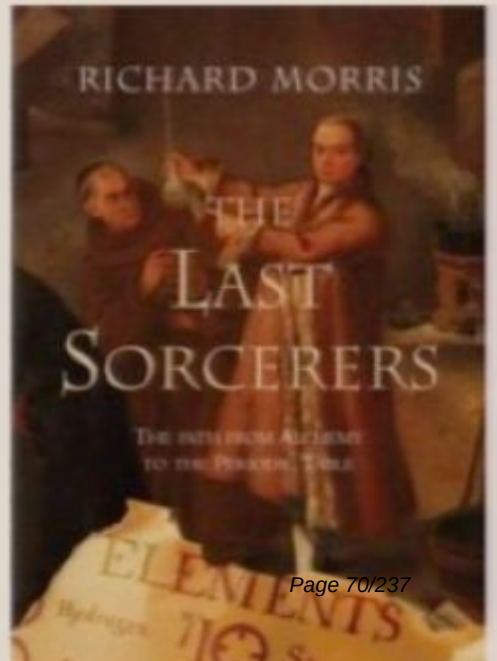


Nucleosynthesis in the r-process

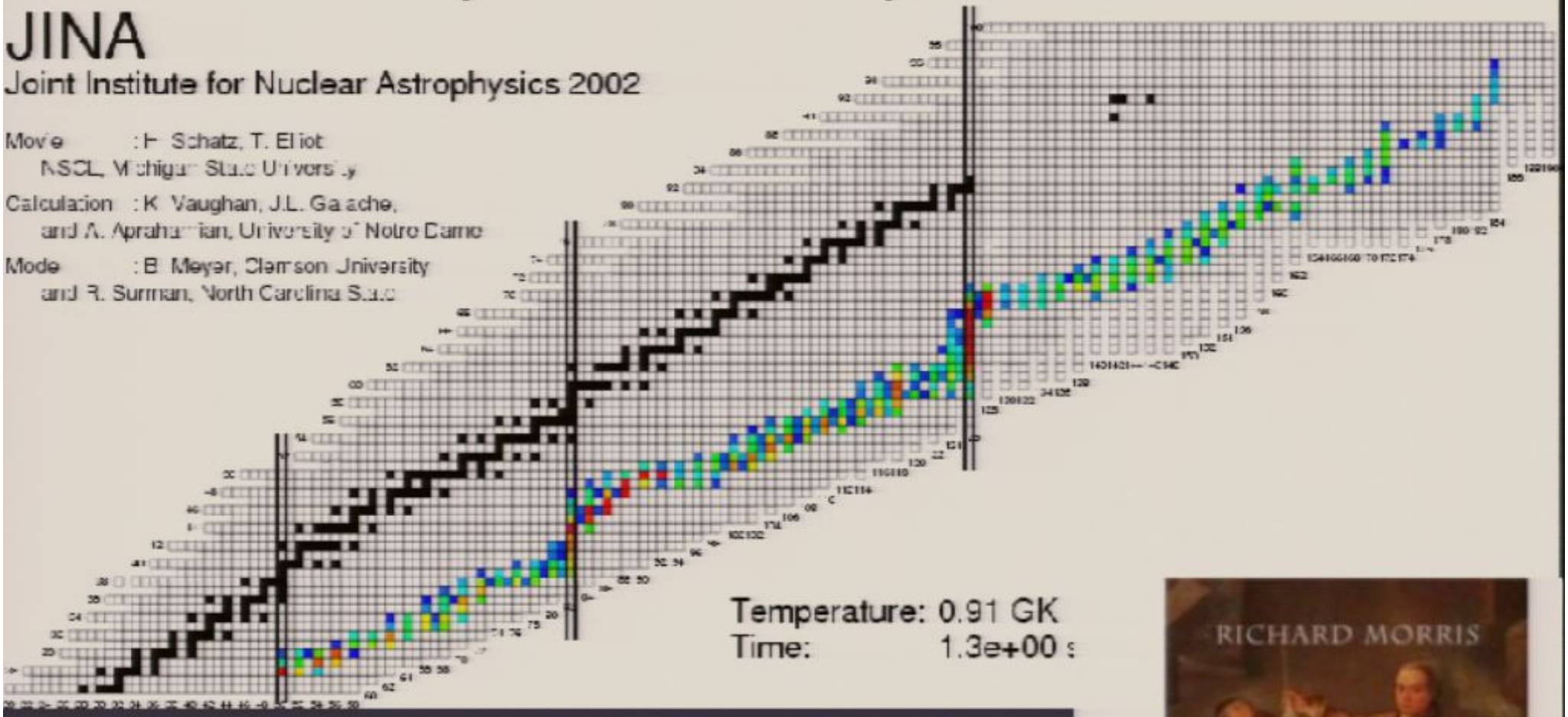


Unfortunately, no closed-shell nucleus decays to:

gold !



Nucleosynthesis in the r-process



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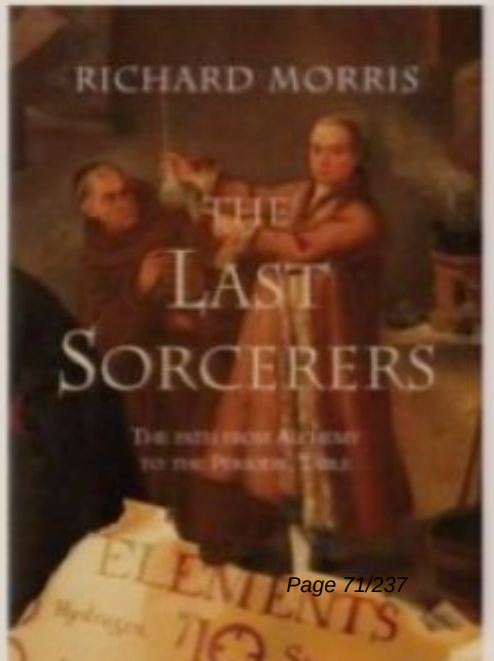
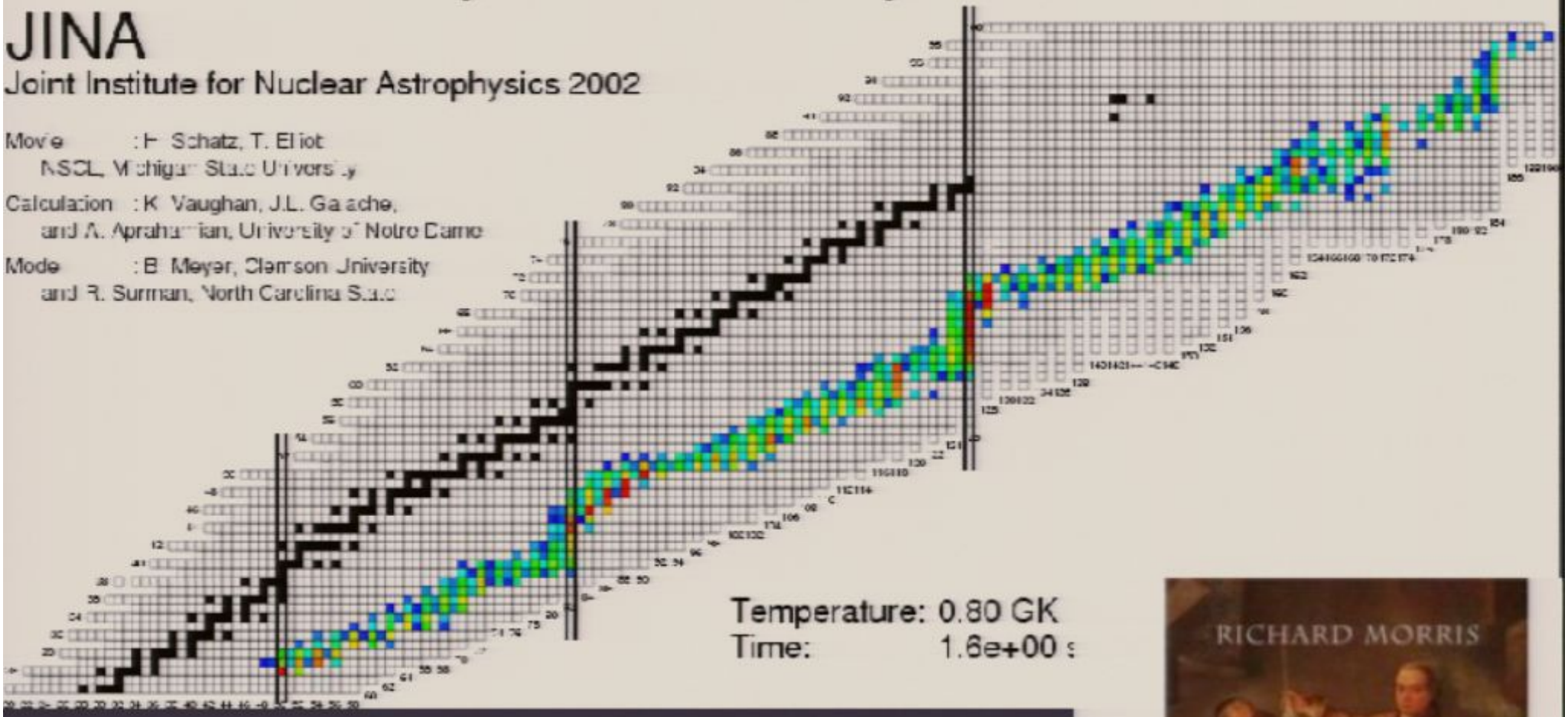
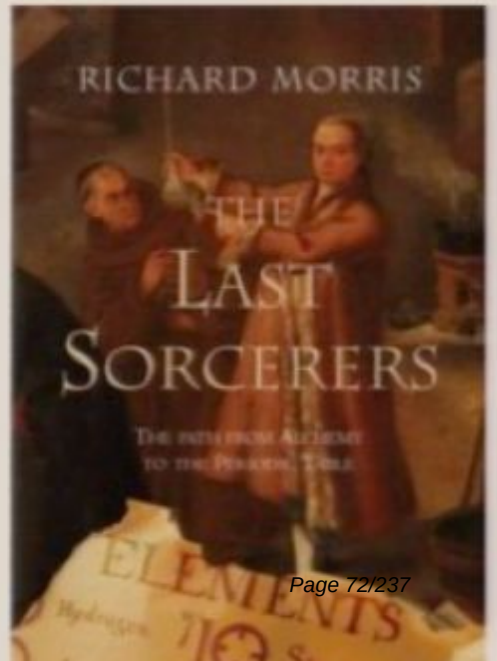


Nucleosynthesis in the r-process



Unfortunately, no closed-shell nucleus decays to:

gold !



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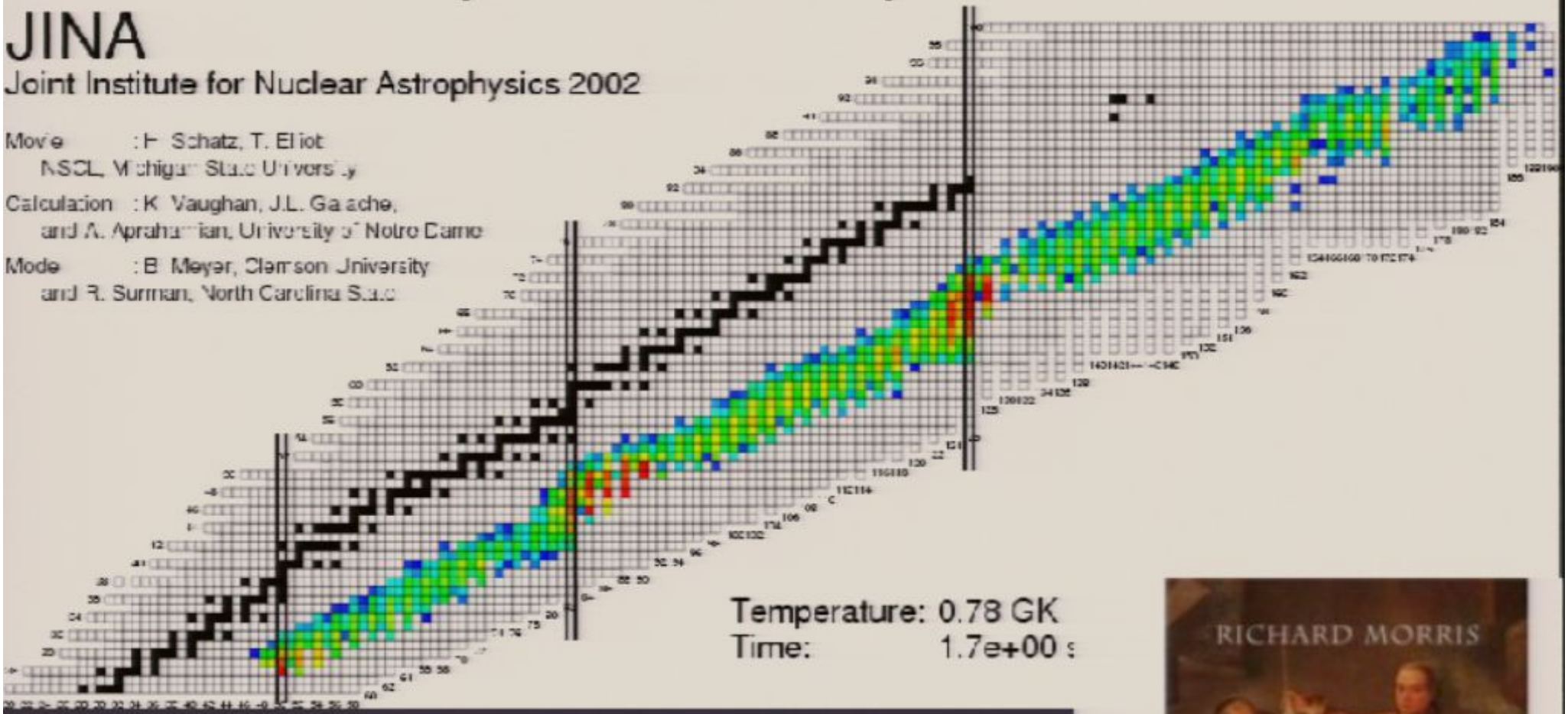

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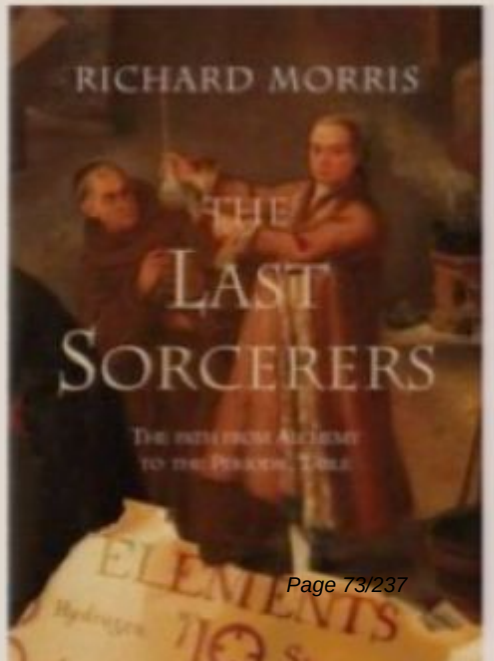

Nucleosynthesis in the r-process

JINA
Joint Institute for Nuclear Astrophysics 2002

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NSCL, Michigan State University
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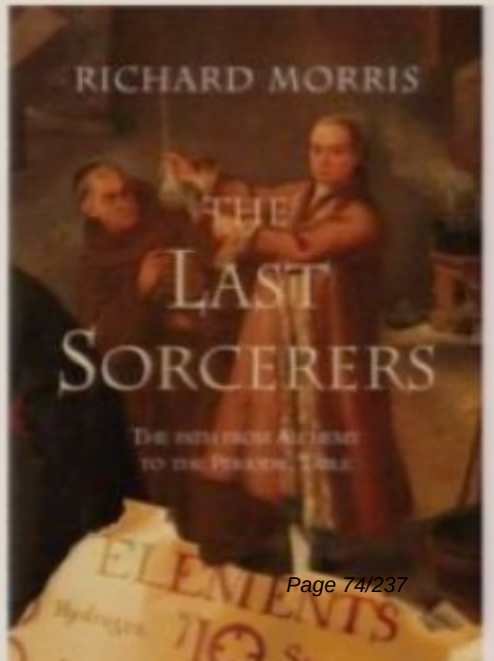
Mode : B. Meyer, Clemson University
and R. Surman, North Carolina State

Temperature: 0.72 GK
Time: 1.9e+00 s

Unfortunately, no closed-shell nucleus decays to:

gold !



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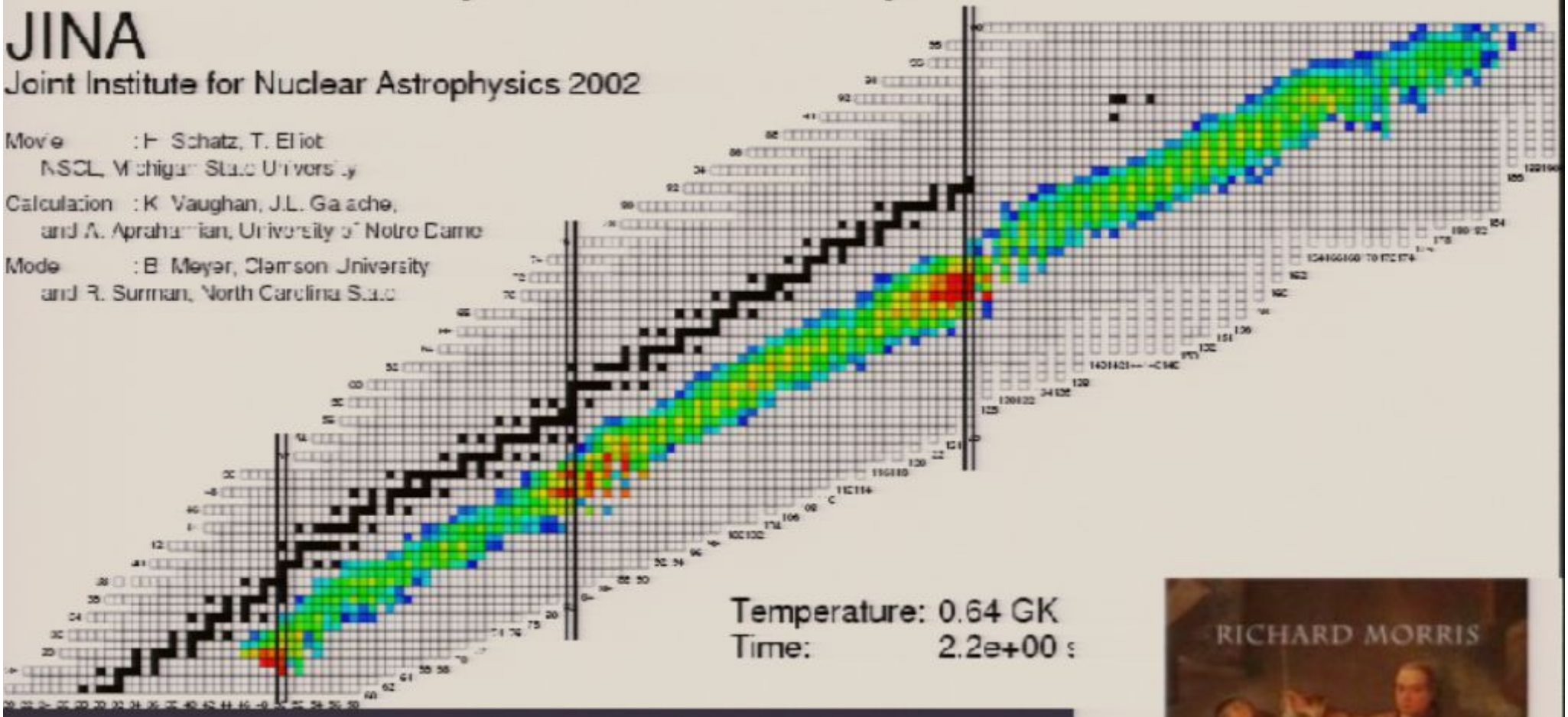

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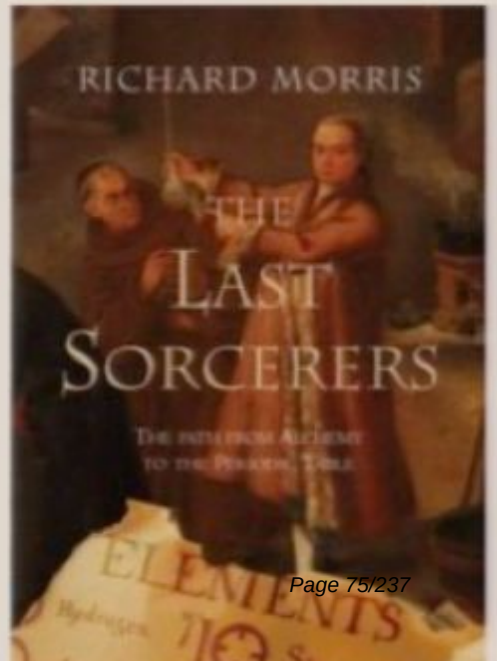

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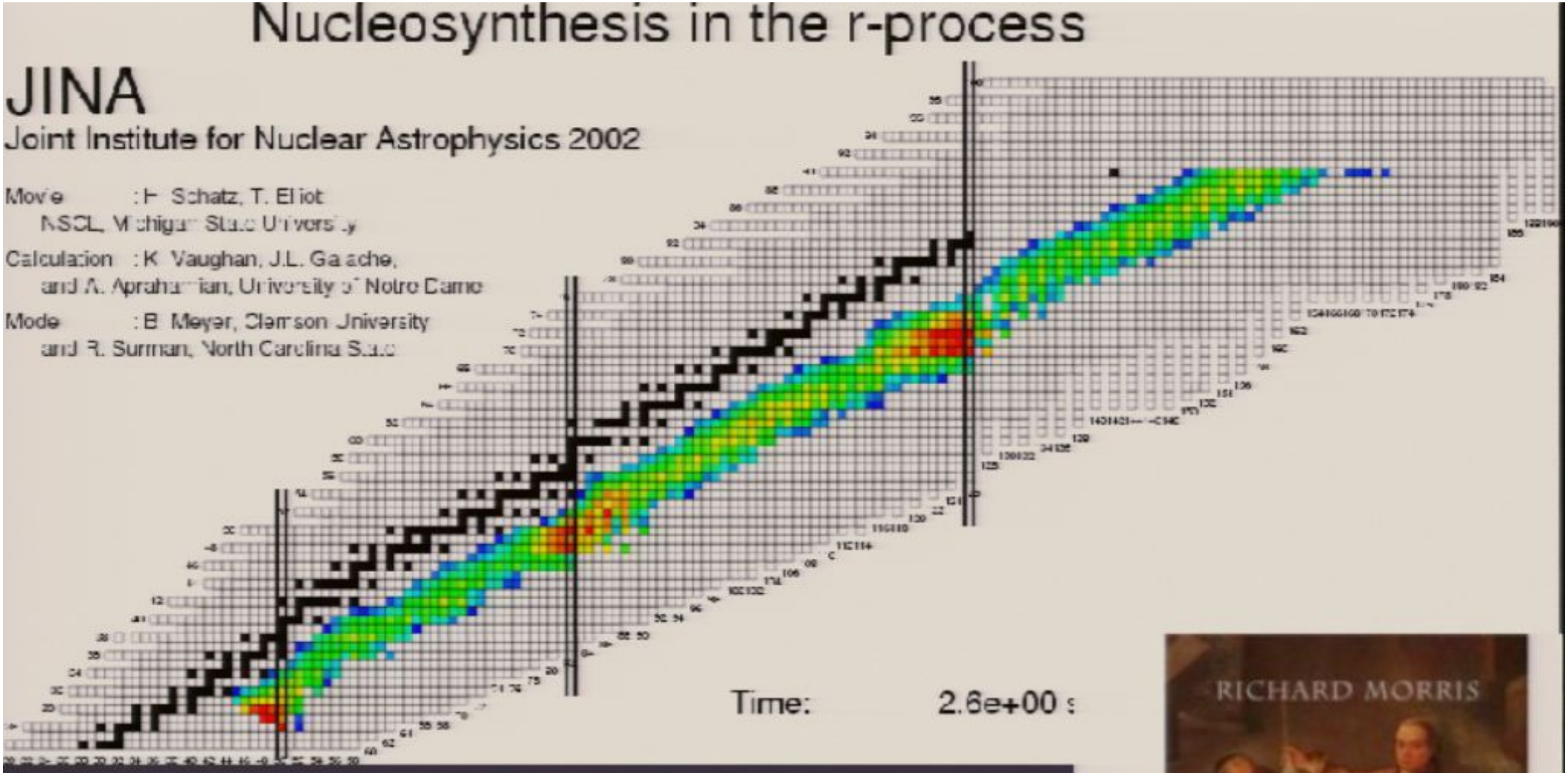

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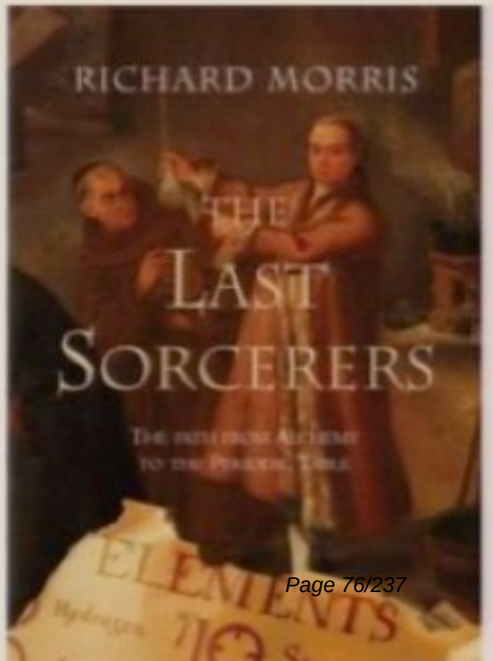

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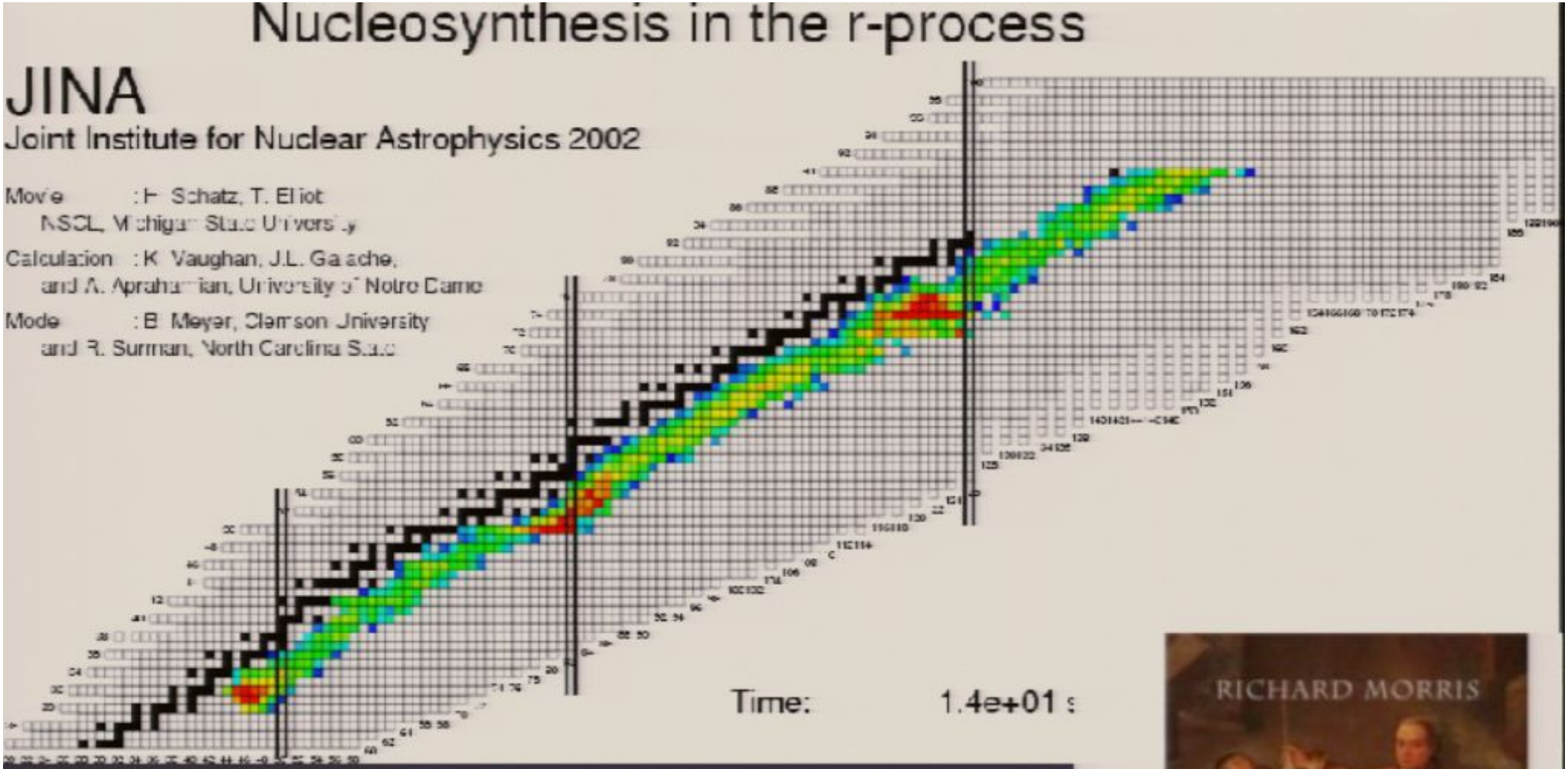

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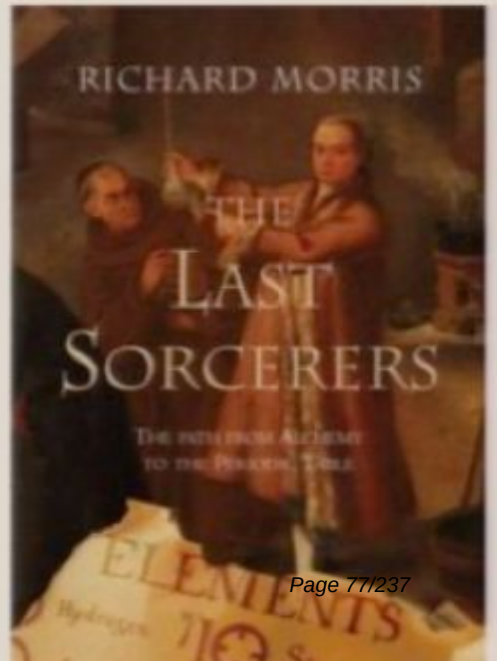

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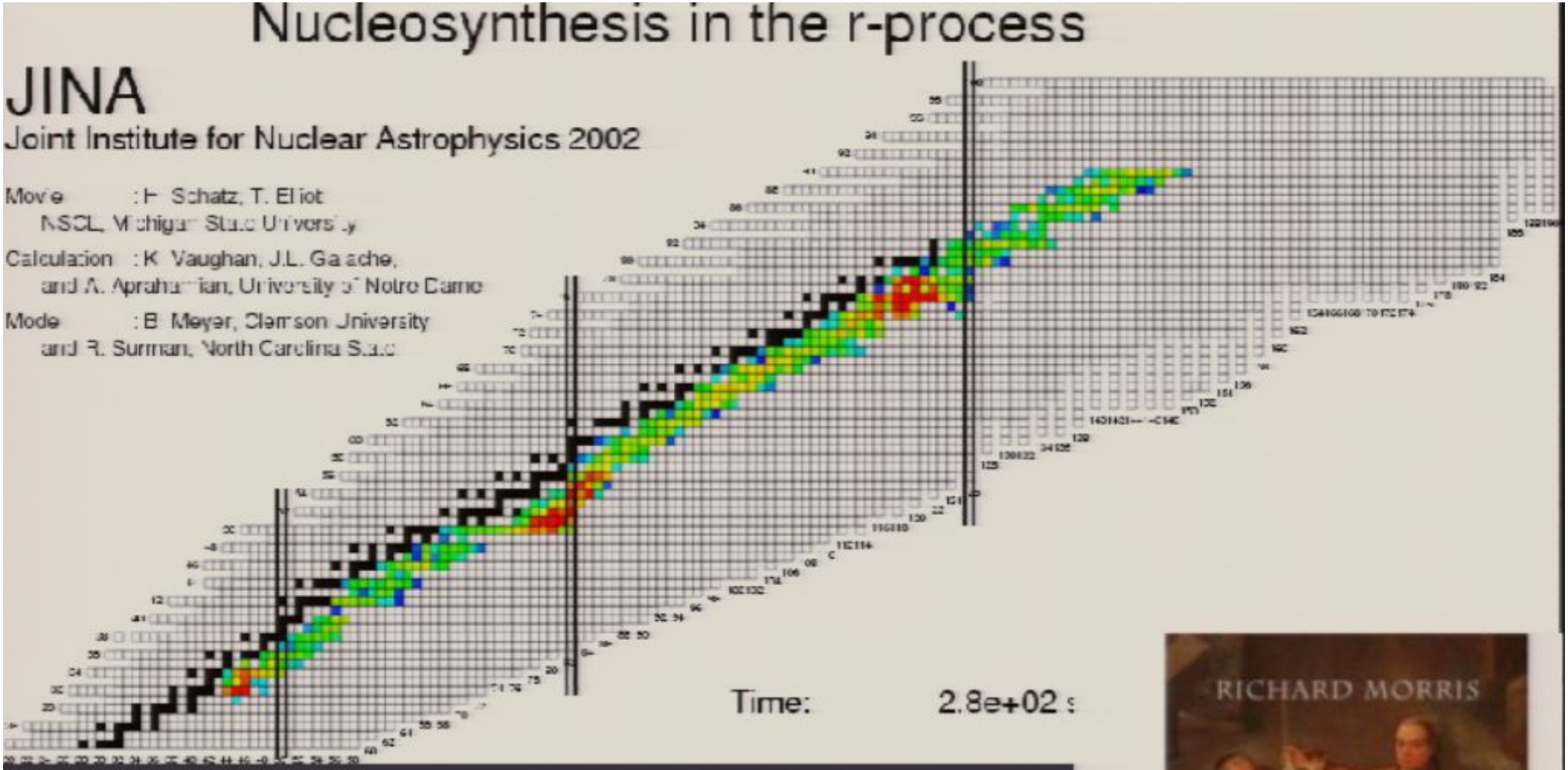

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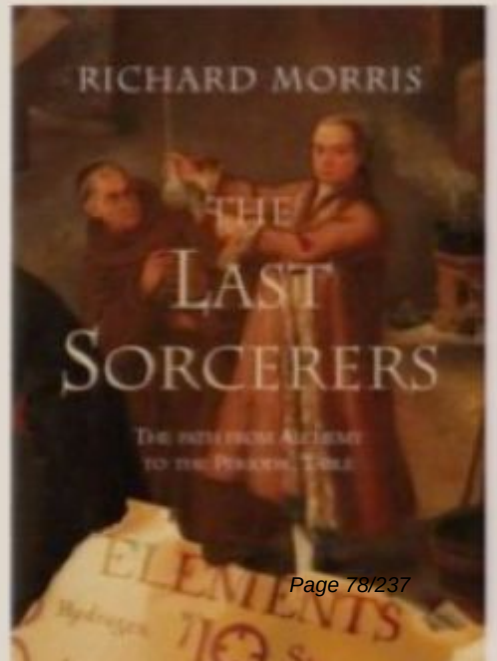

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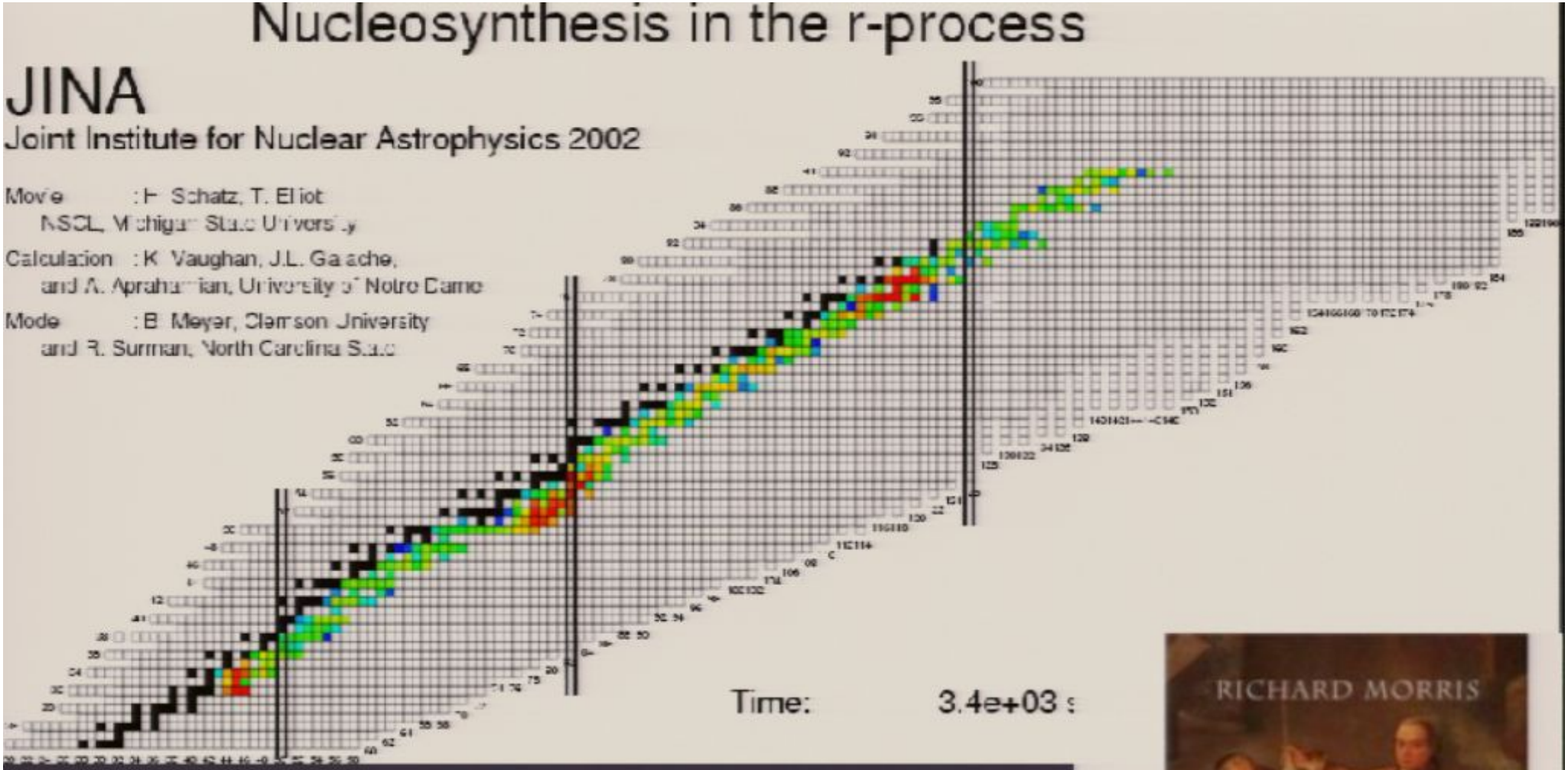

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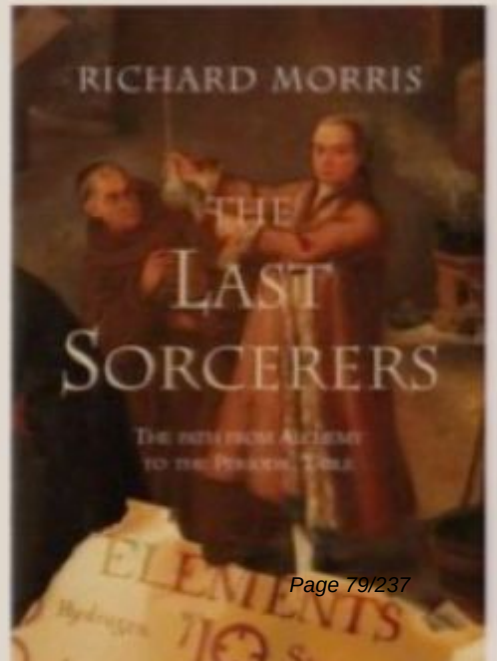

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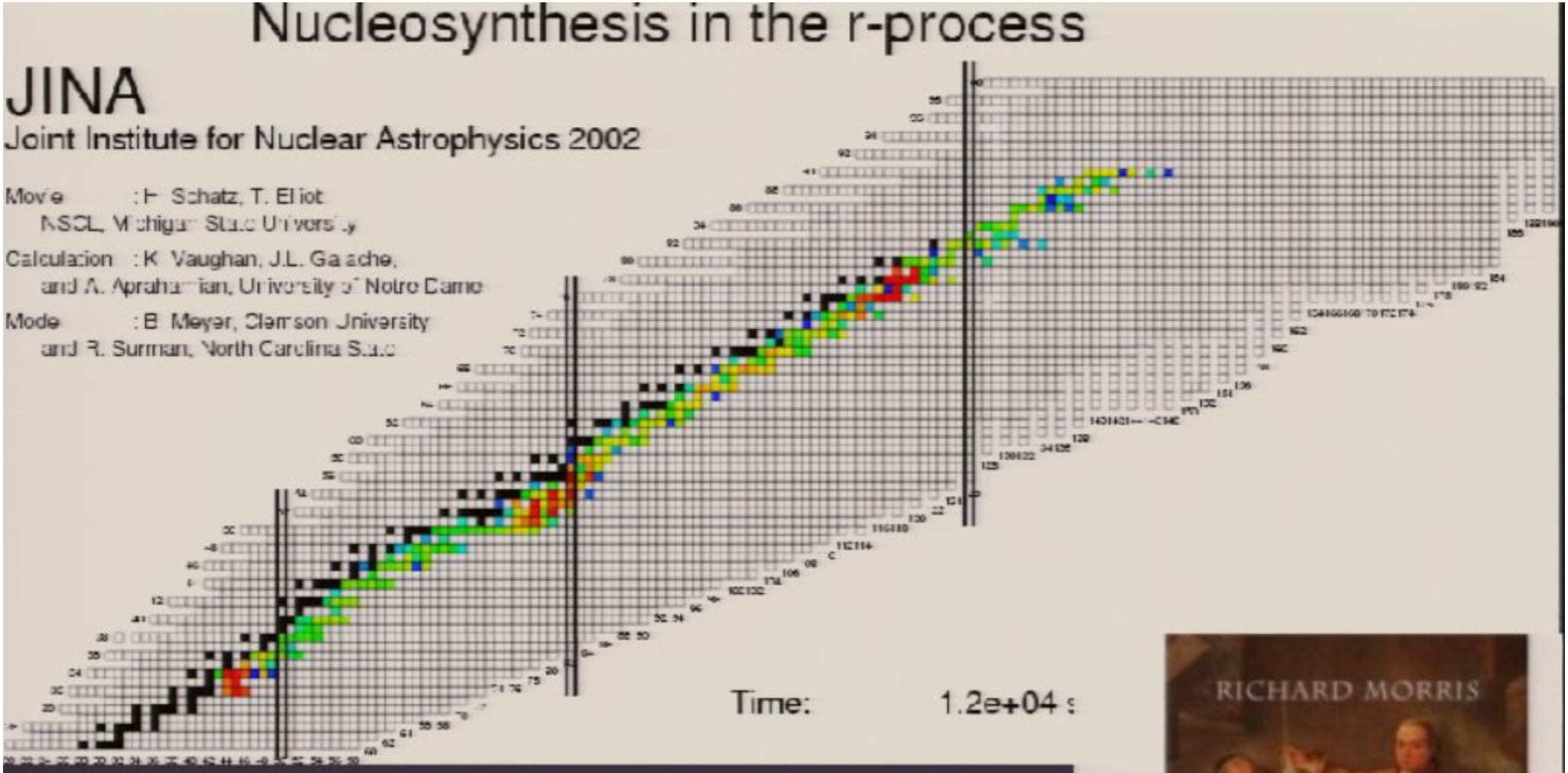

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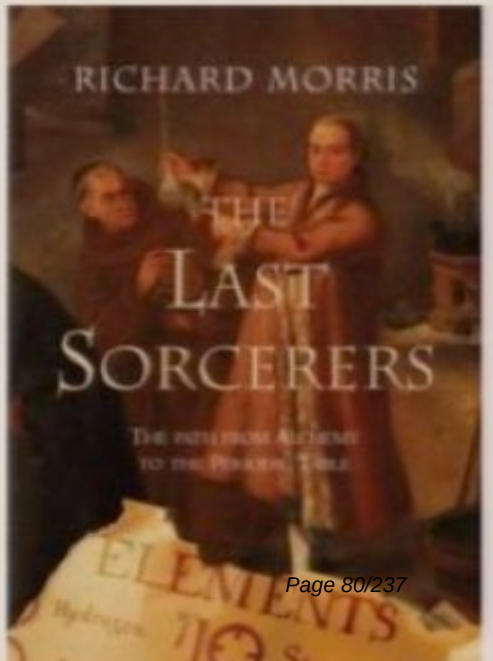

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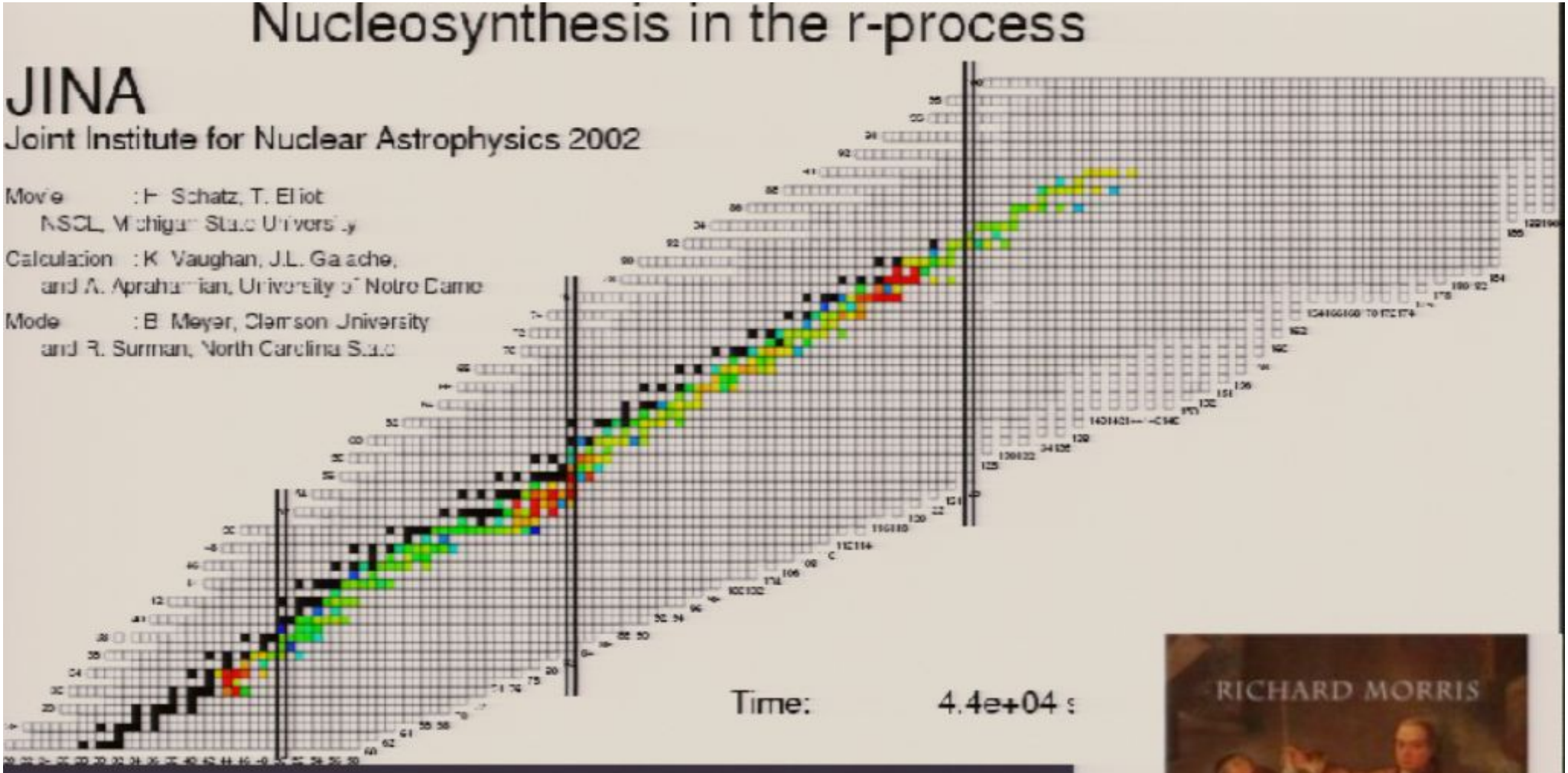

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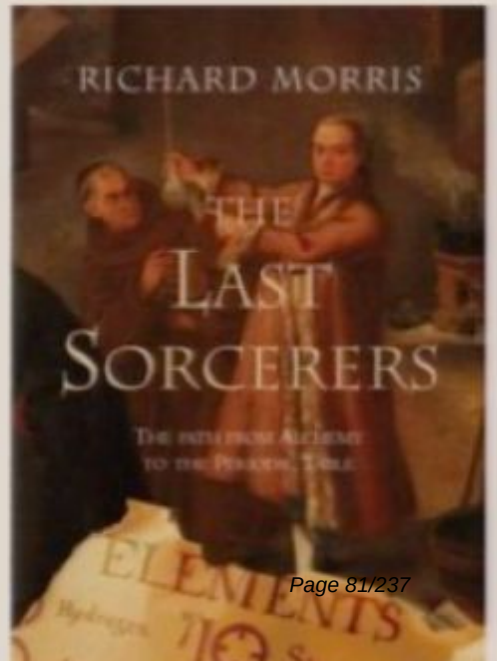

Which astrophysical environments provide conditions supporting r-process nucleosynthesis?

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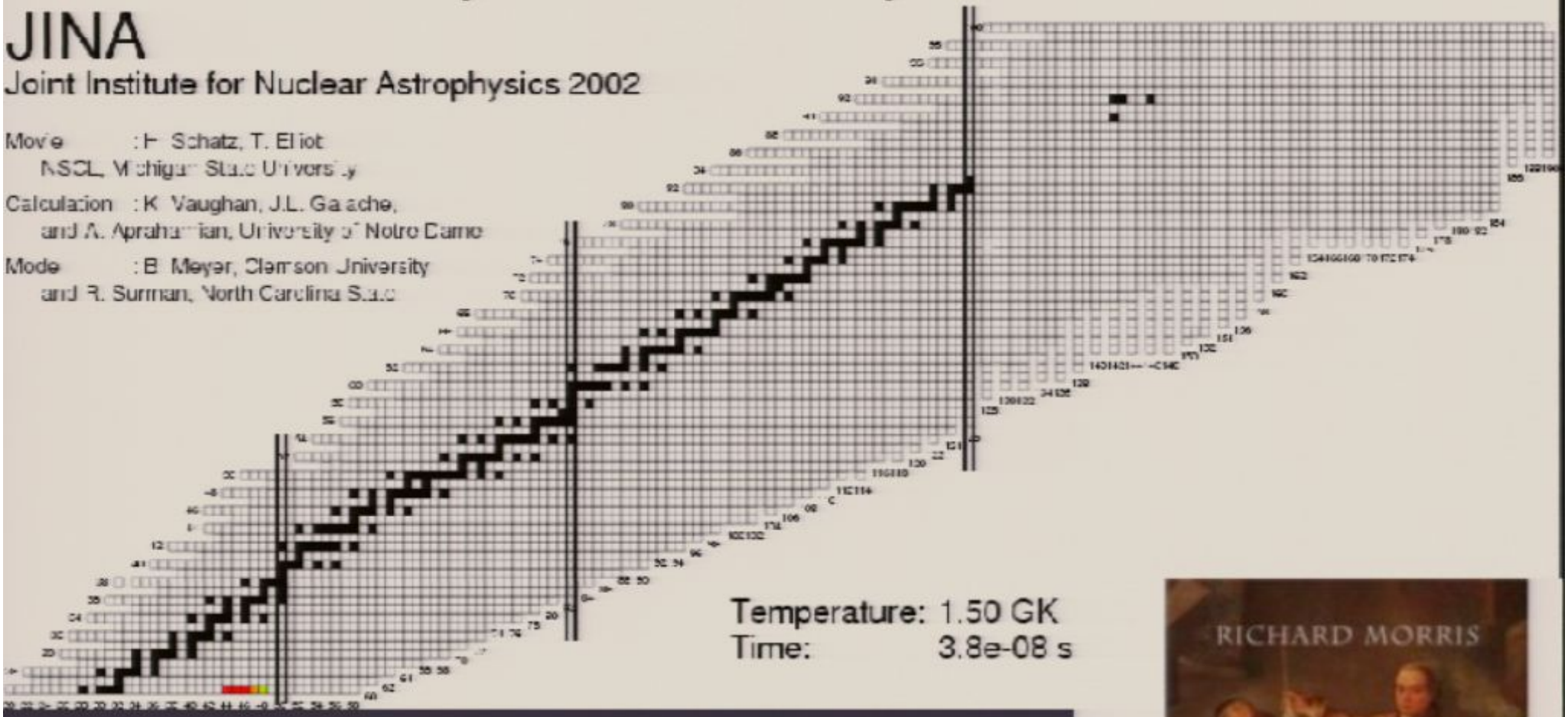
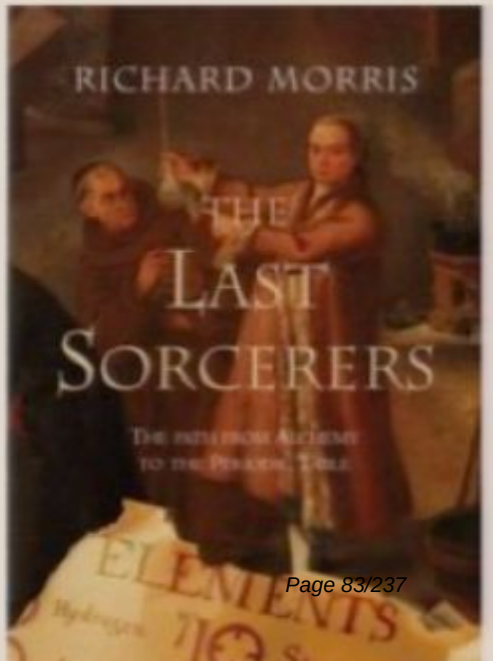


Temperature: 1.50 GK
Time: 3.8e-08 s

Unfortunately, no closed-shell nucleus decays to:

gold !



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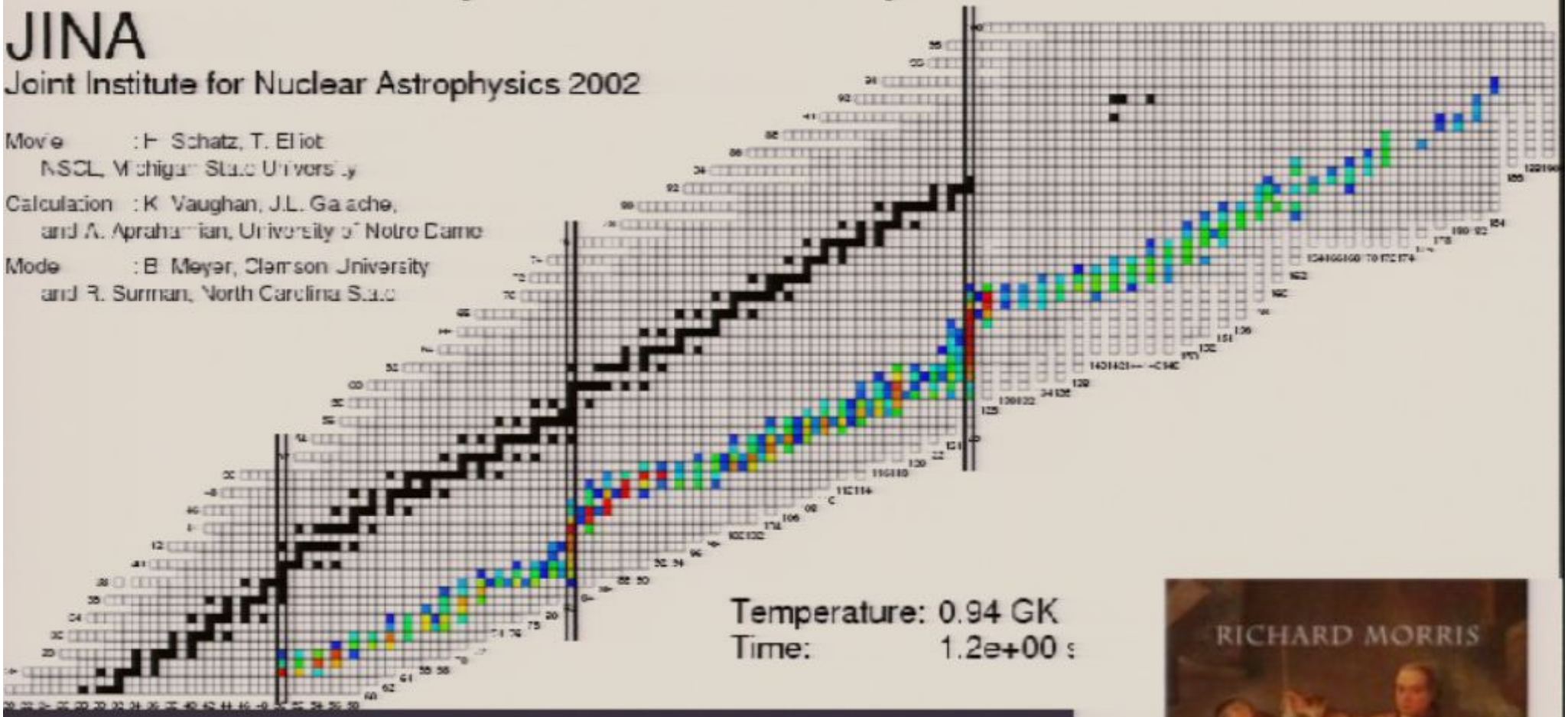
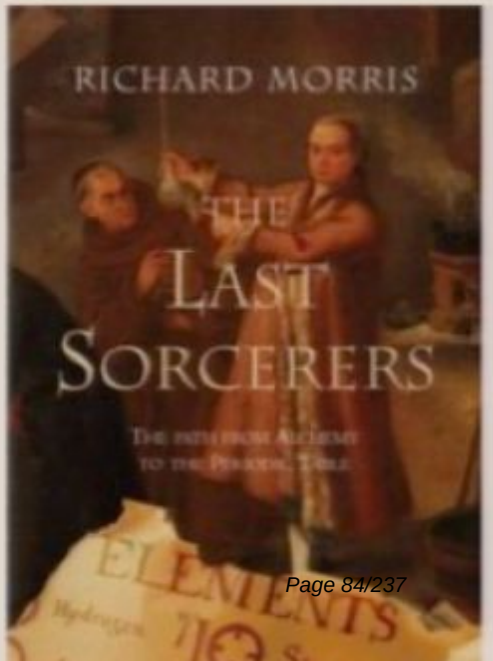


Temperature: 0.94 GK
Time: 1.2e+00 s

Unfortunately, no closed-shell nucleus decays to:

gold !



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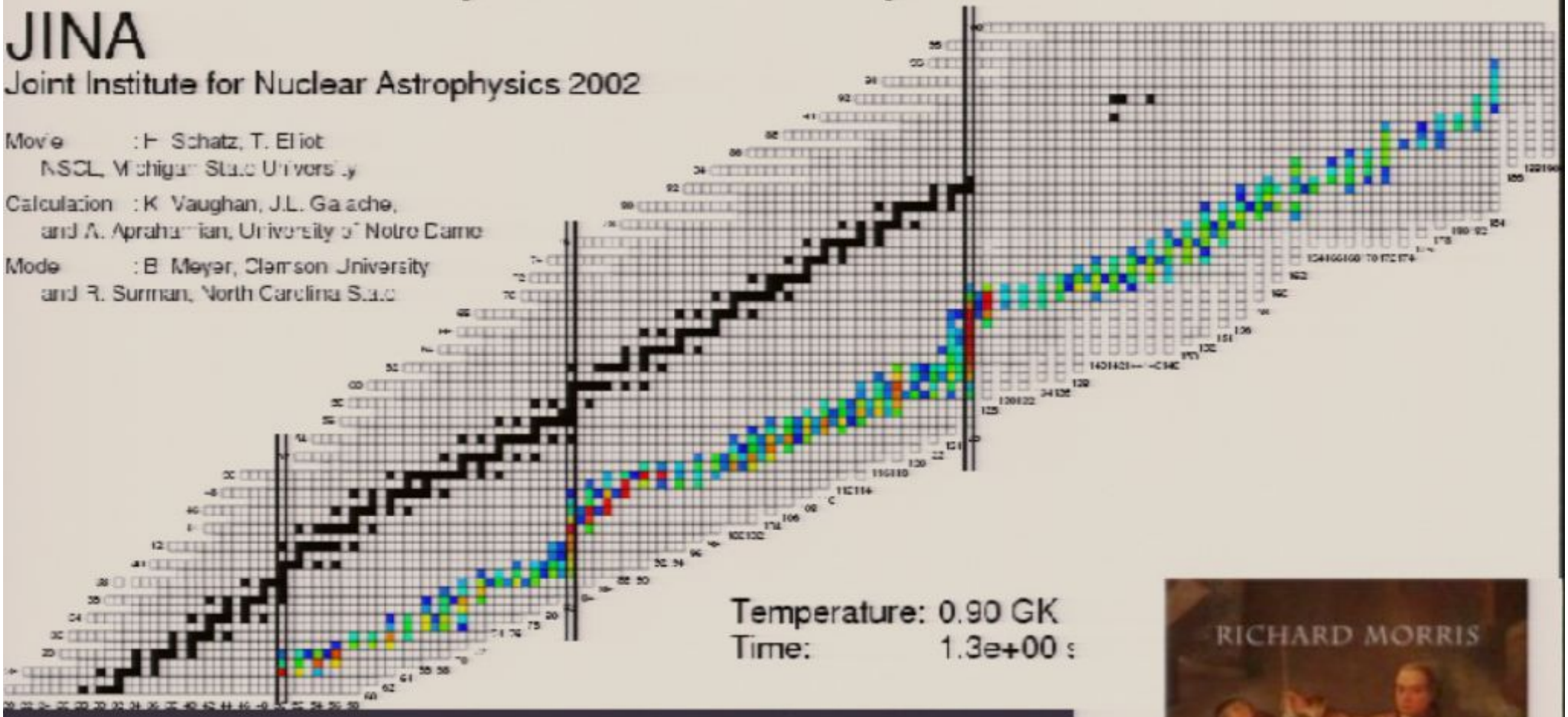
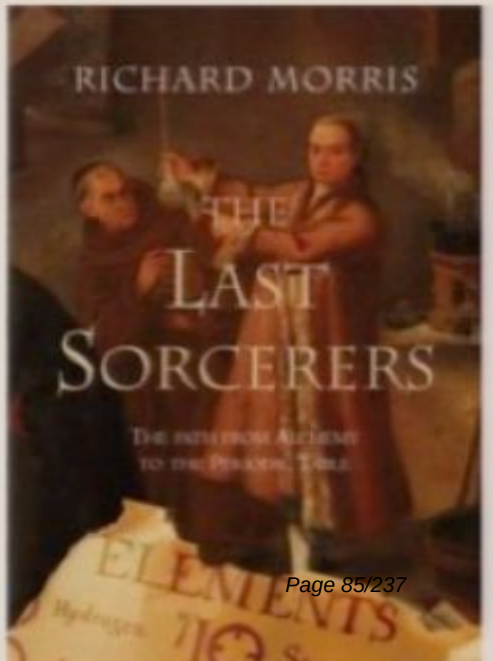


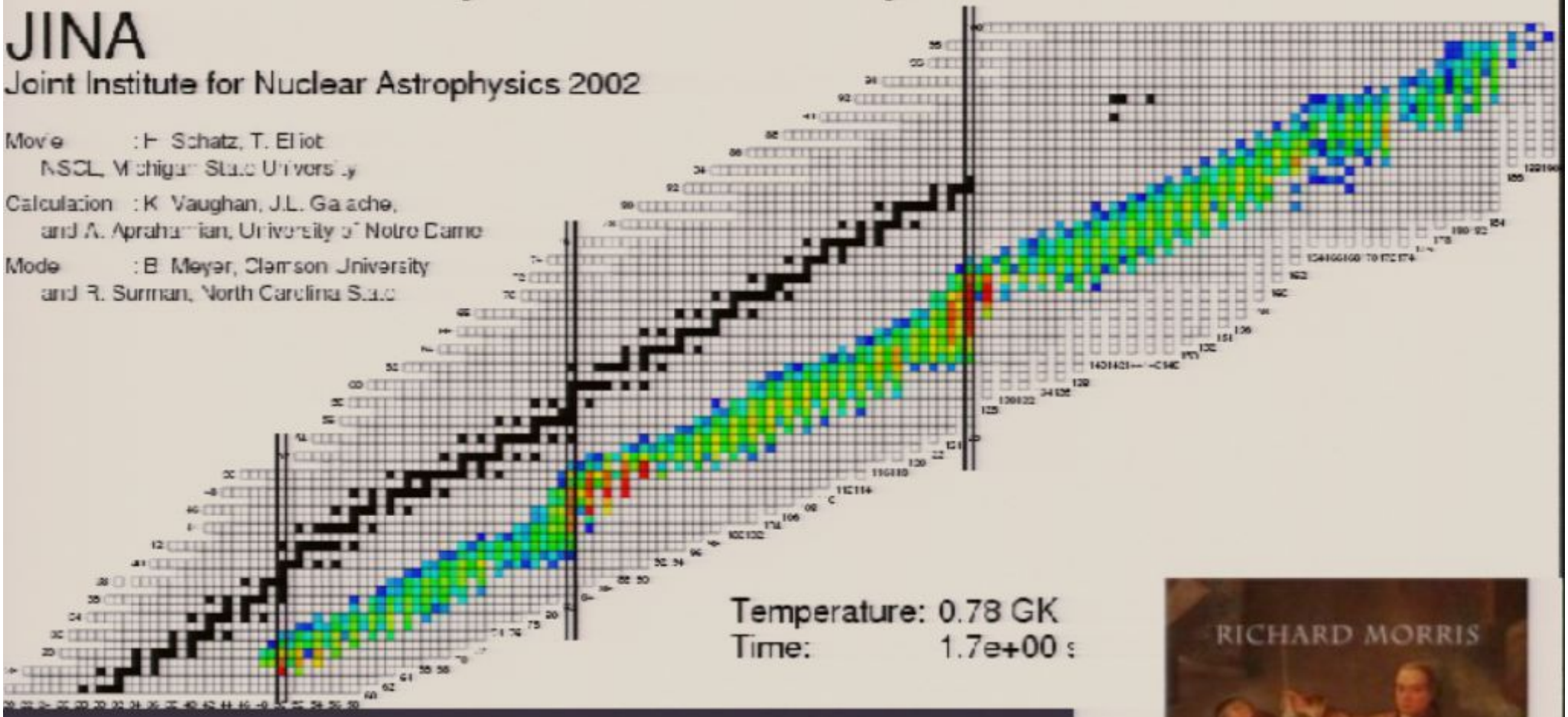
Temperature: 0.90 GK
Time: 1.3e+00 s

Unfortunately, no closed-shell nucleus decays to:

gold !



Nucleosynthesis in the r-process



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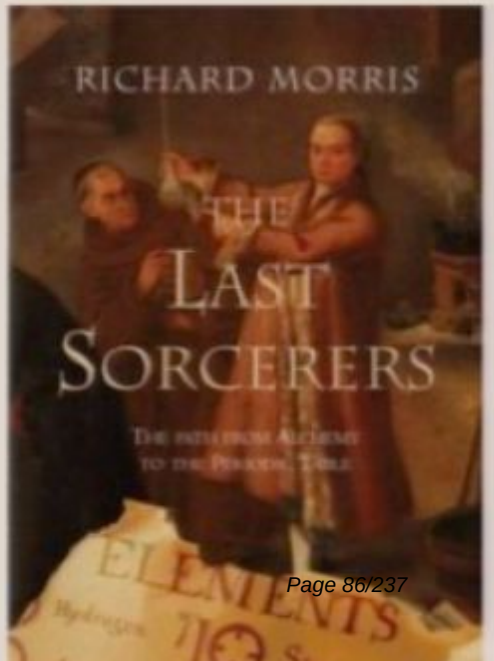

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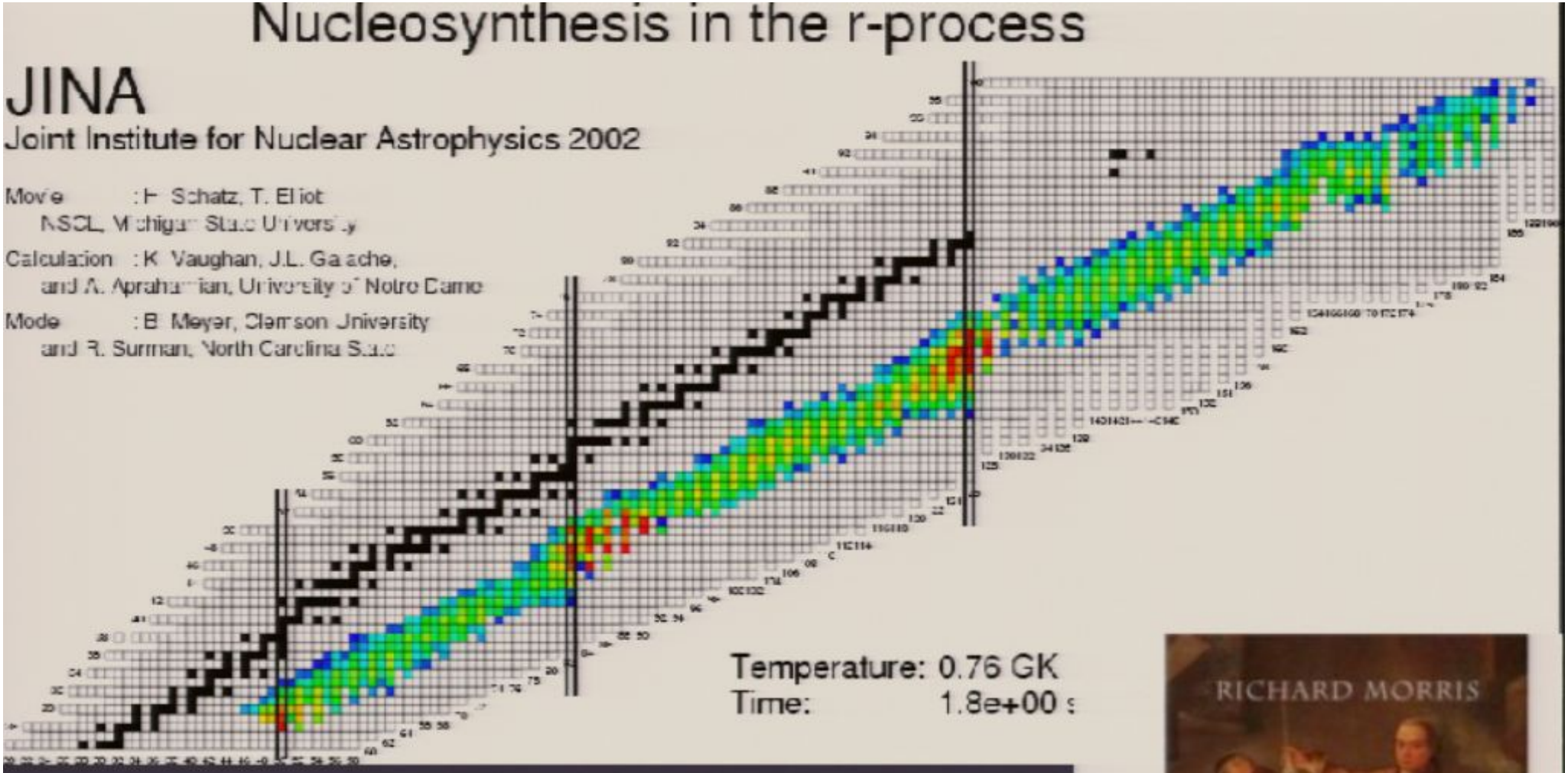

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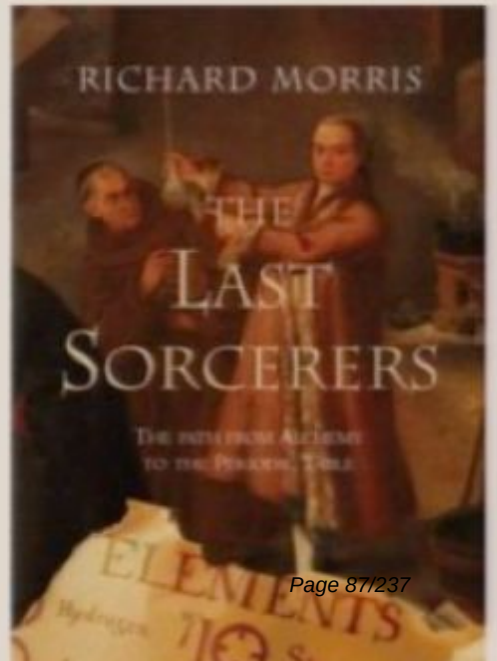

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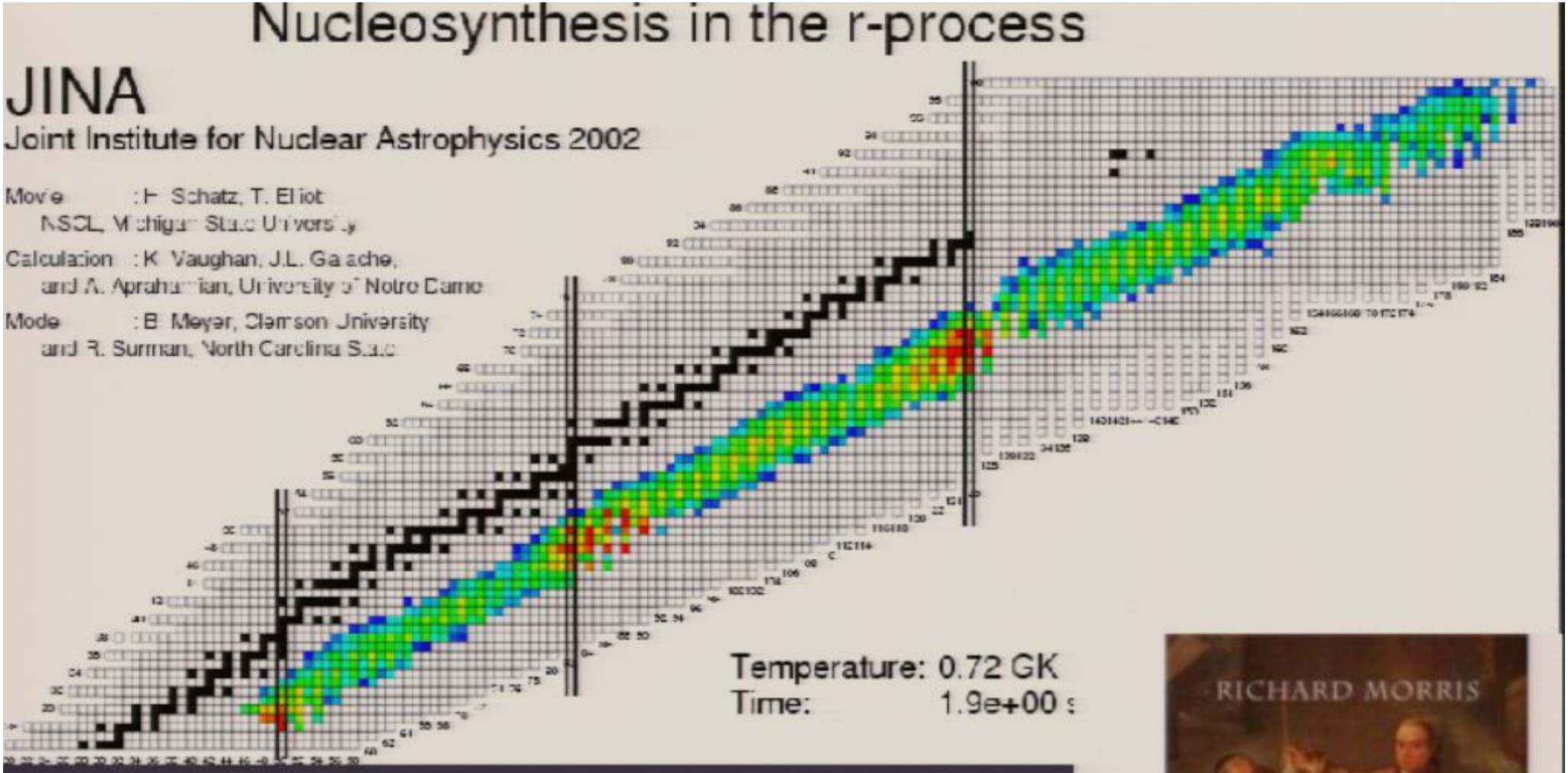

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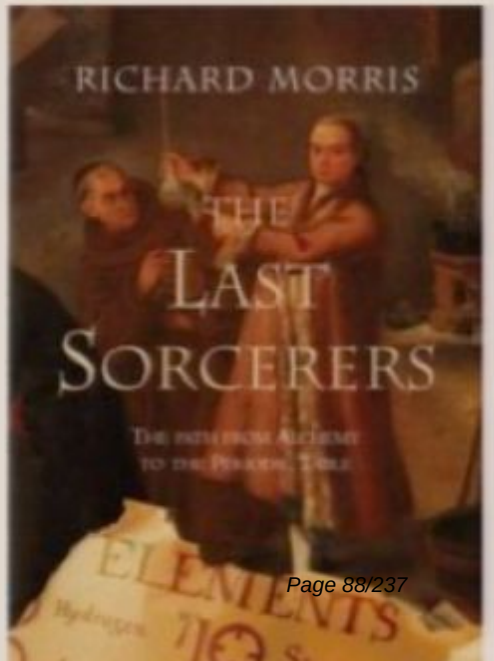

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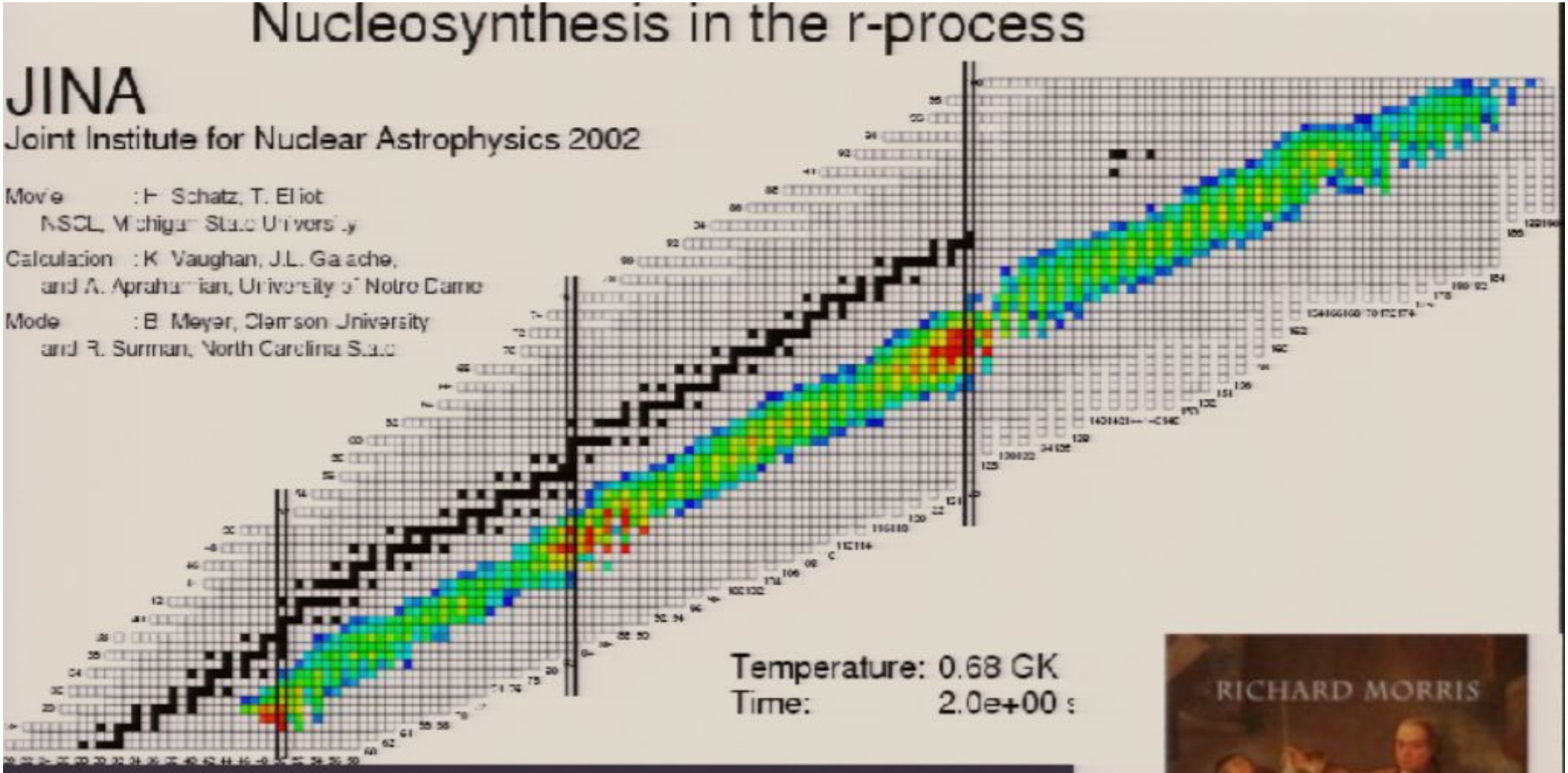

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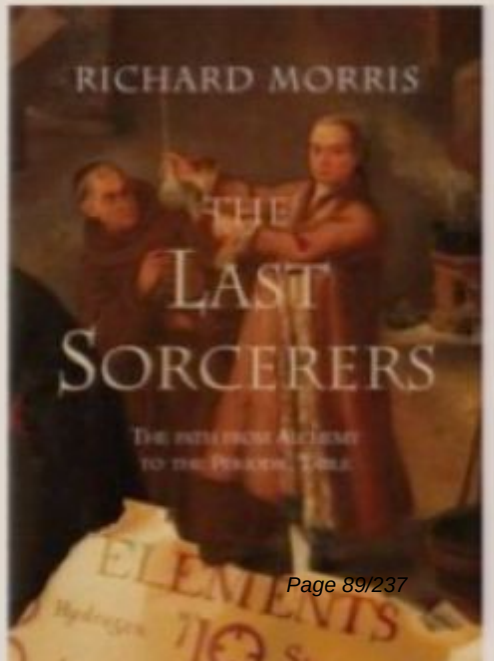

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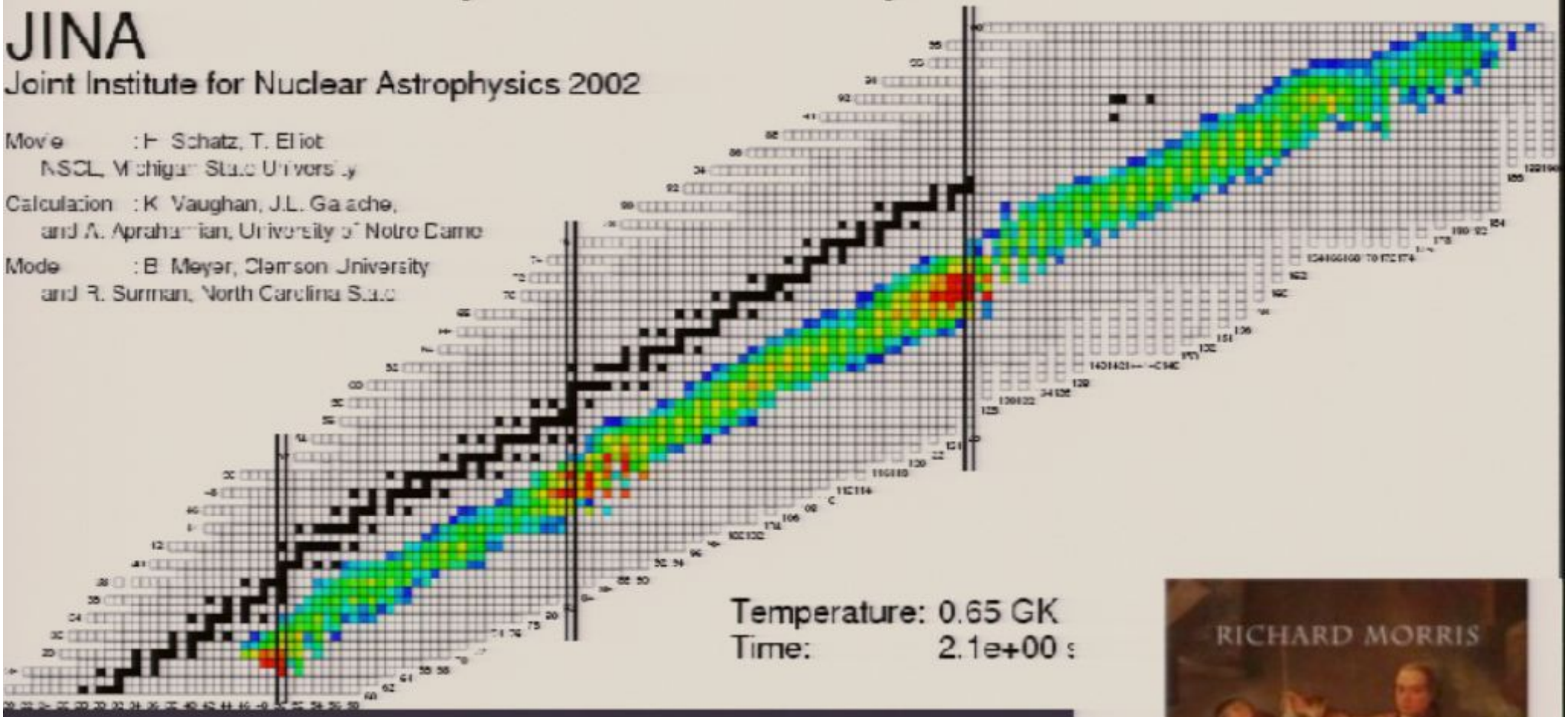
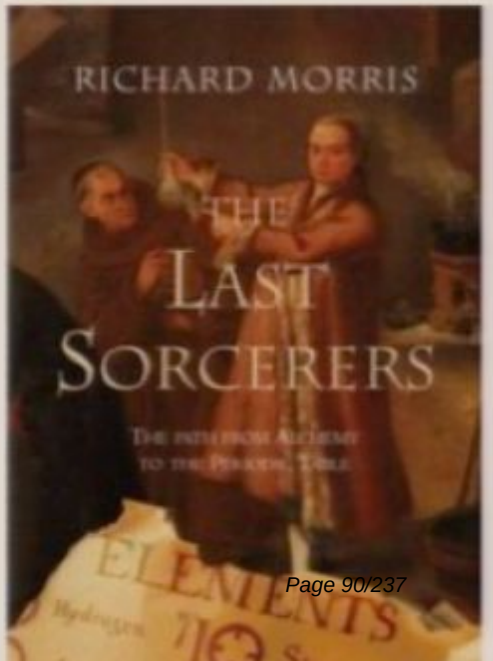


Temperature: 0.65 GK
Time: 2.1e+00 s

Unfortunately, no closed-shell nucleus decays to:

gold !



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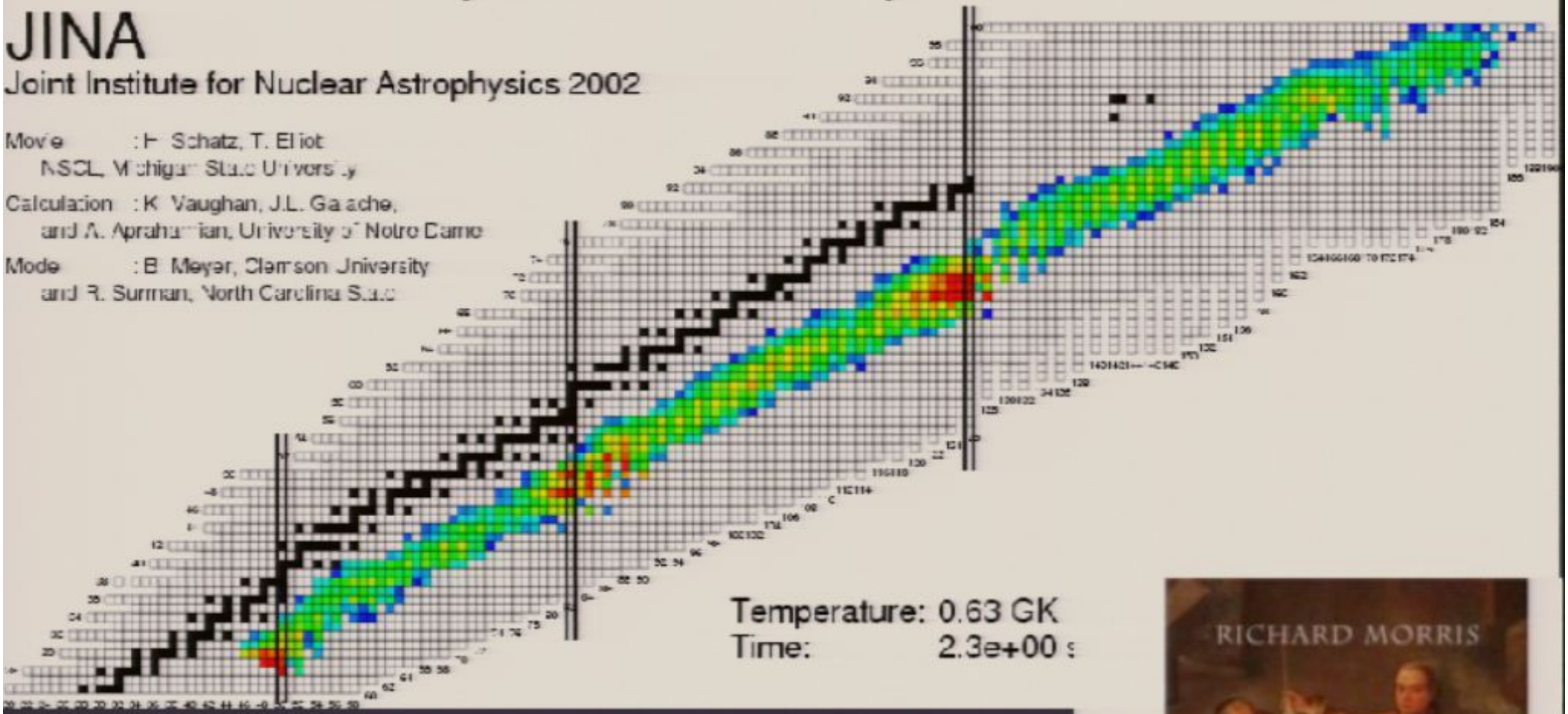

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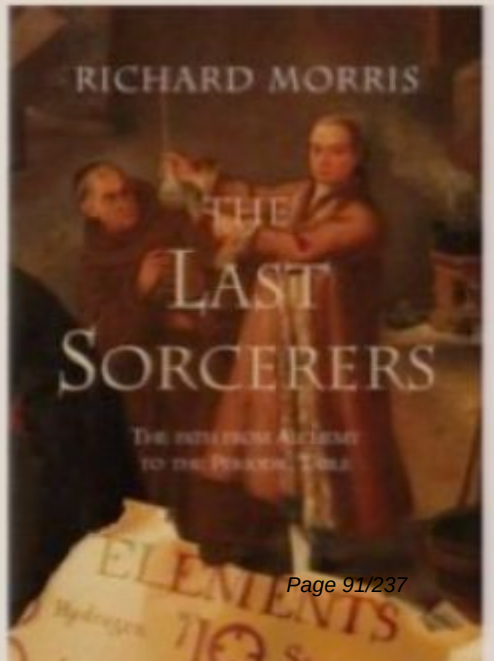

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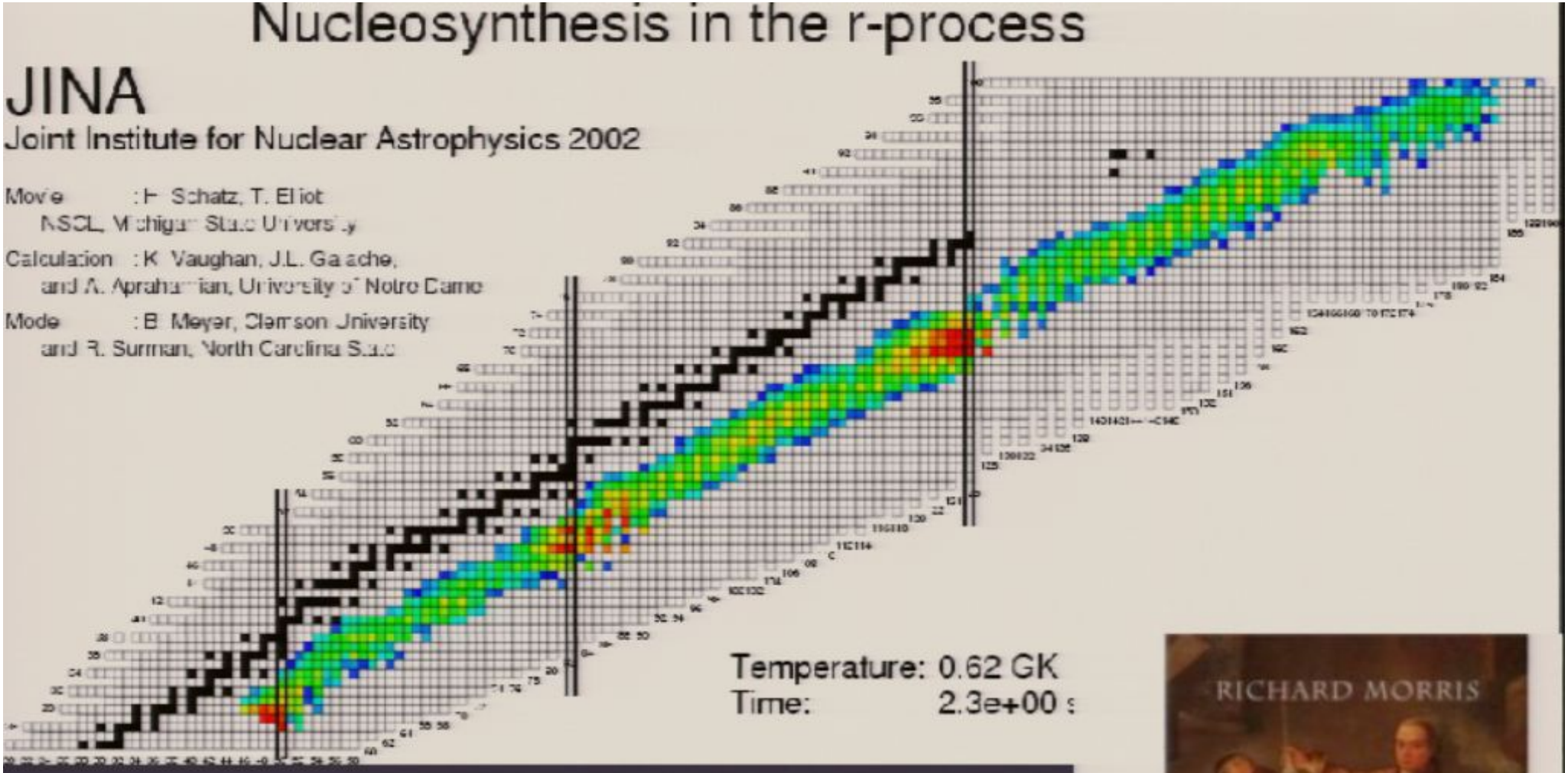

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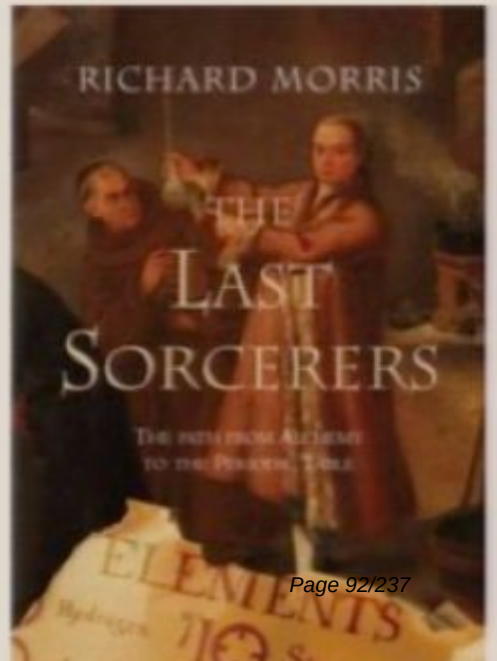

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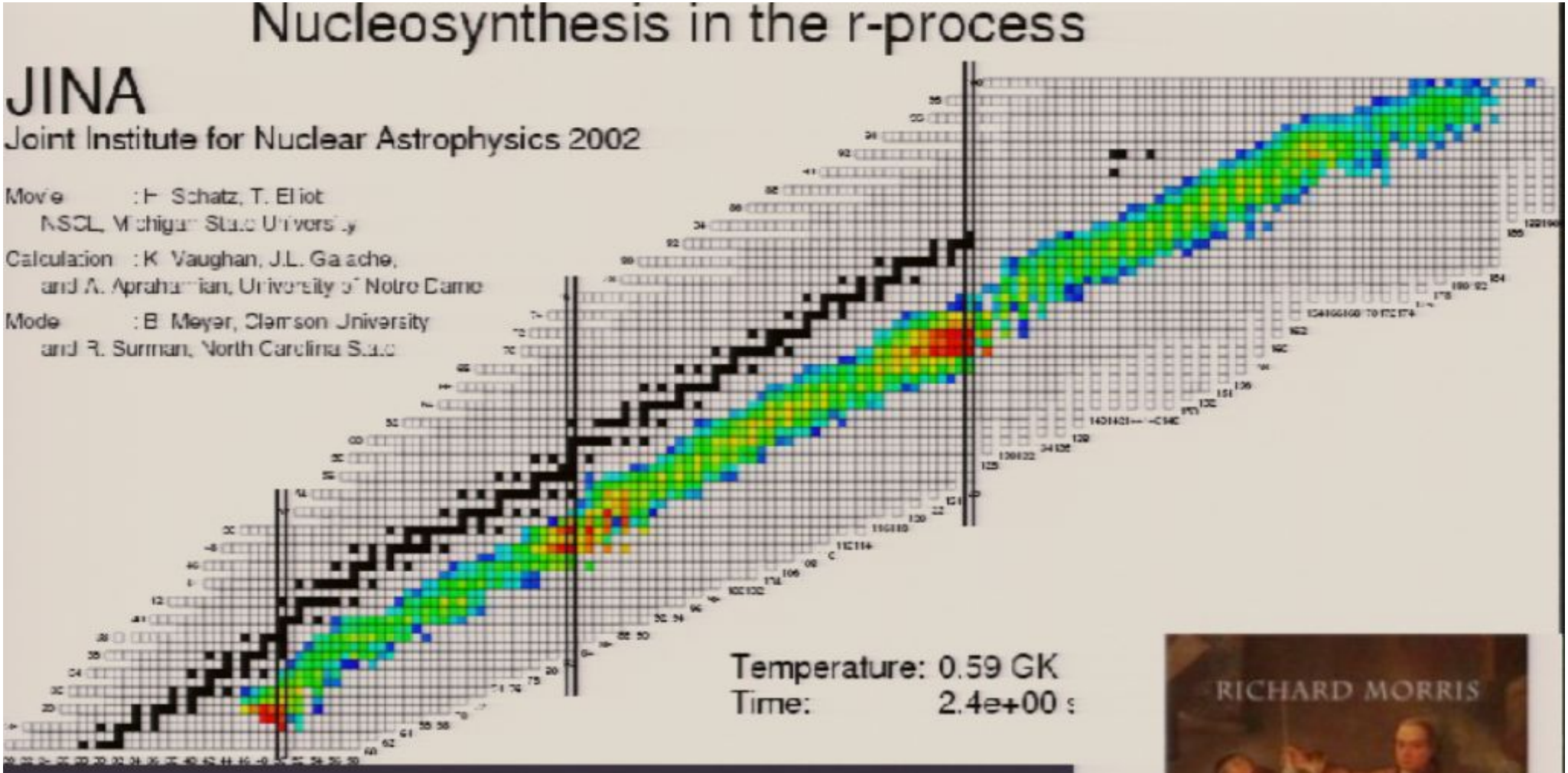

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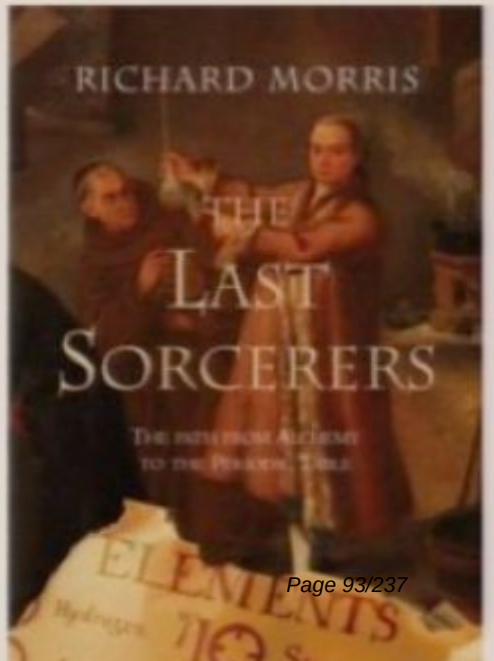

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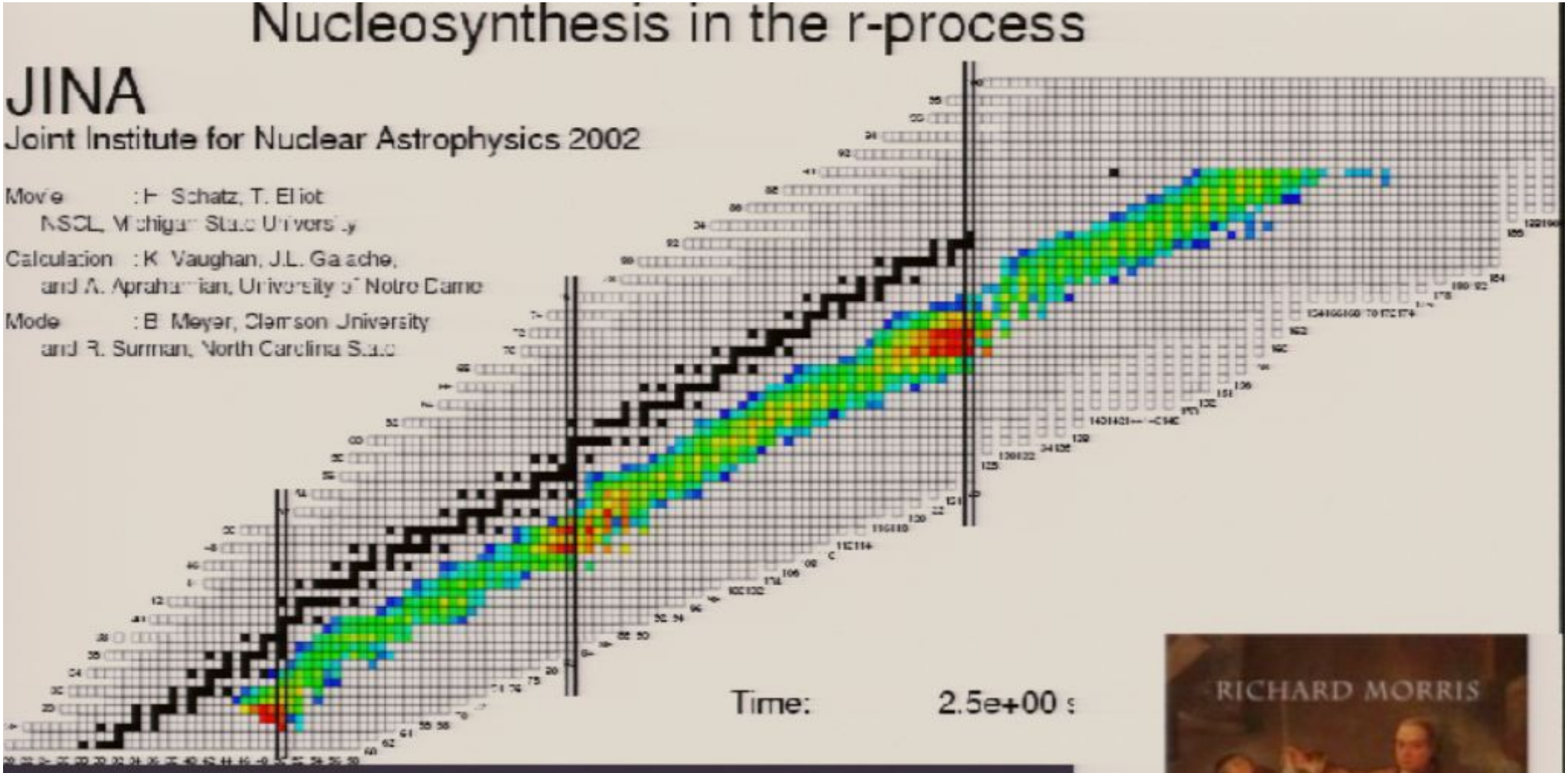

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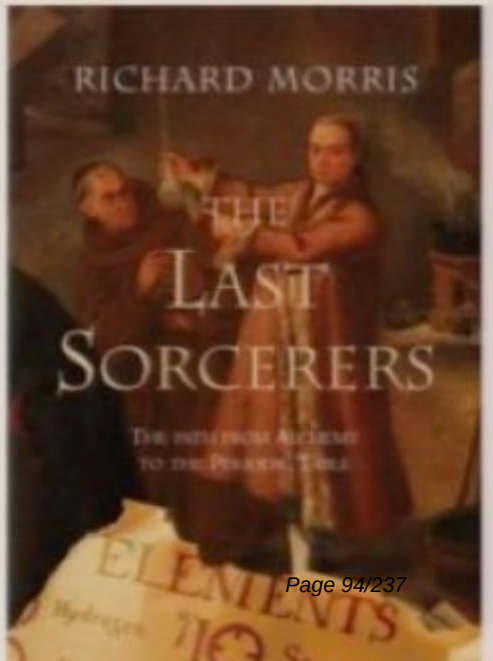

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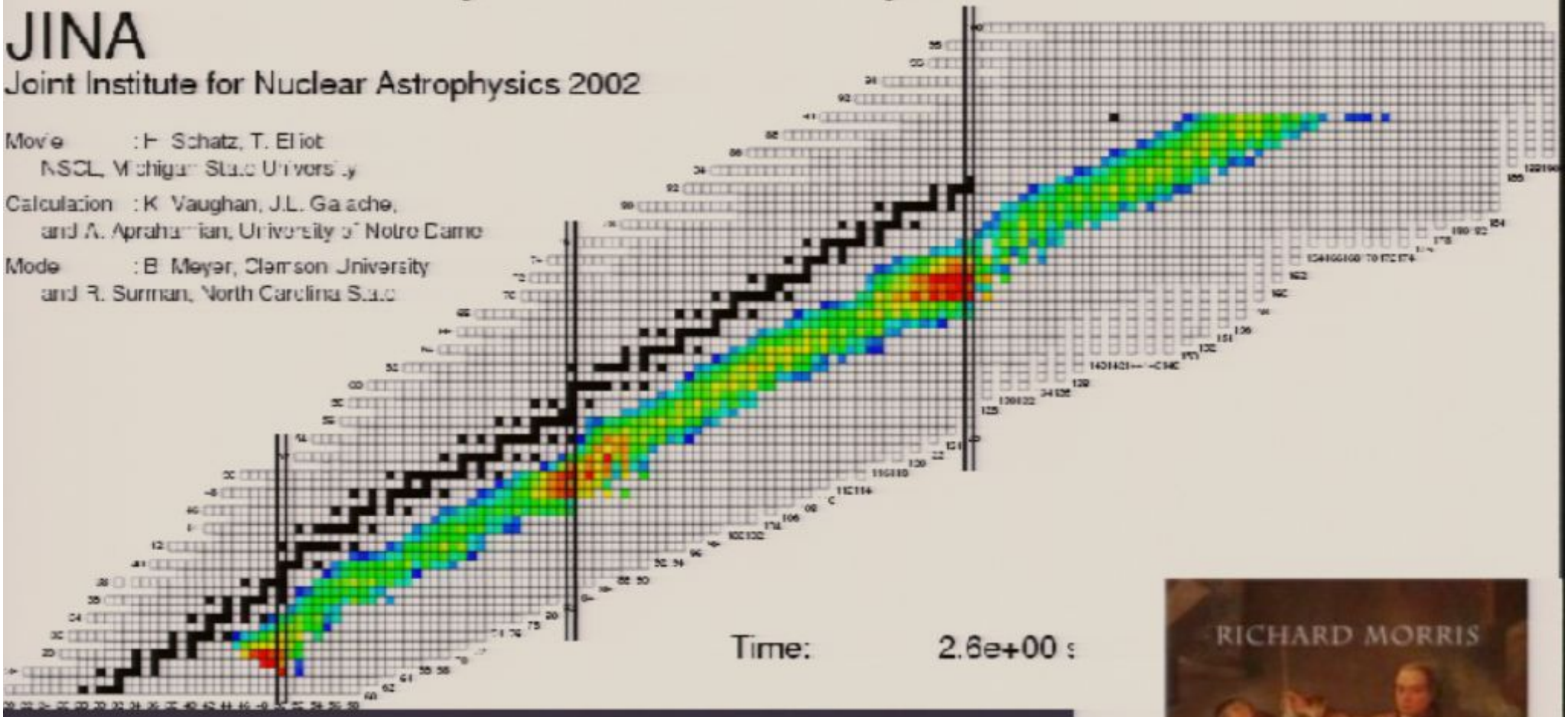

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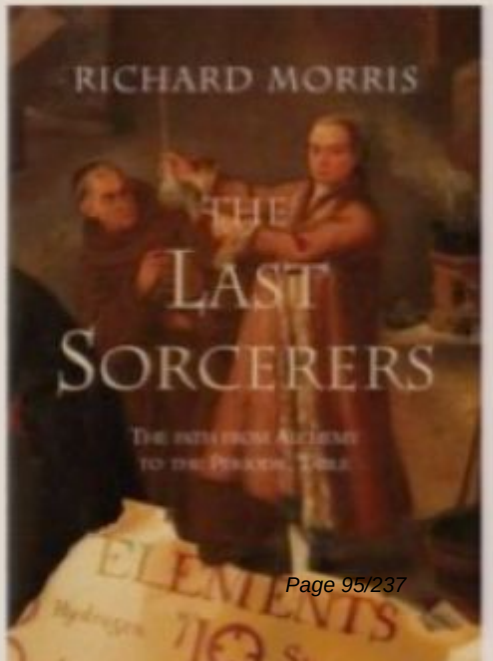

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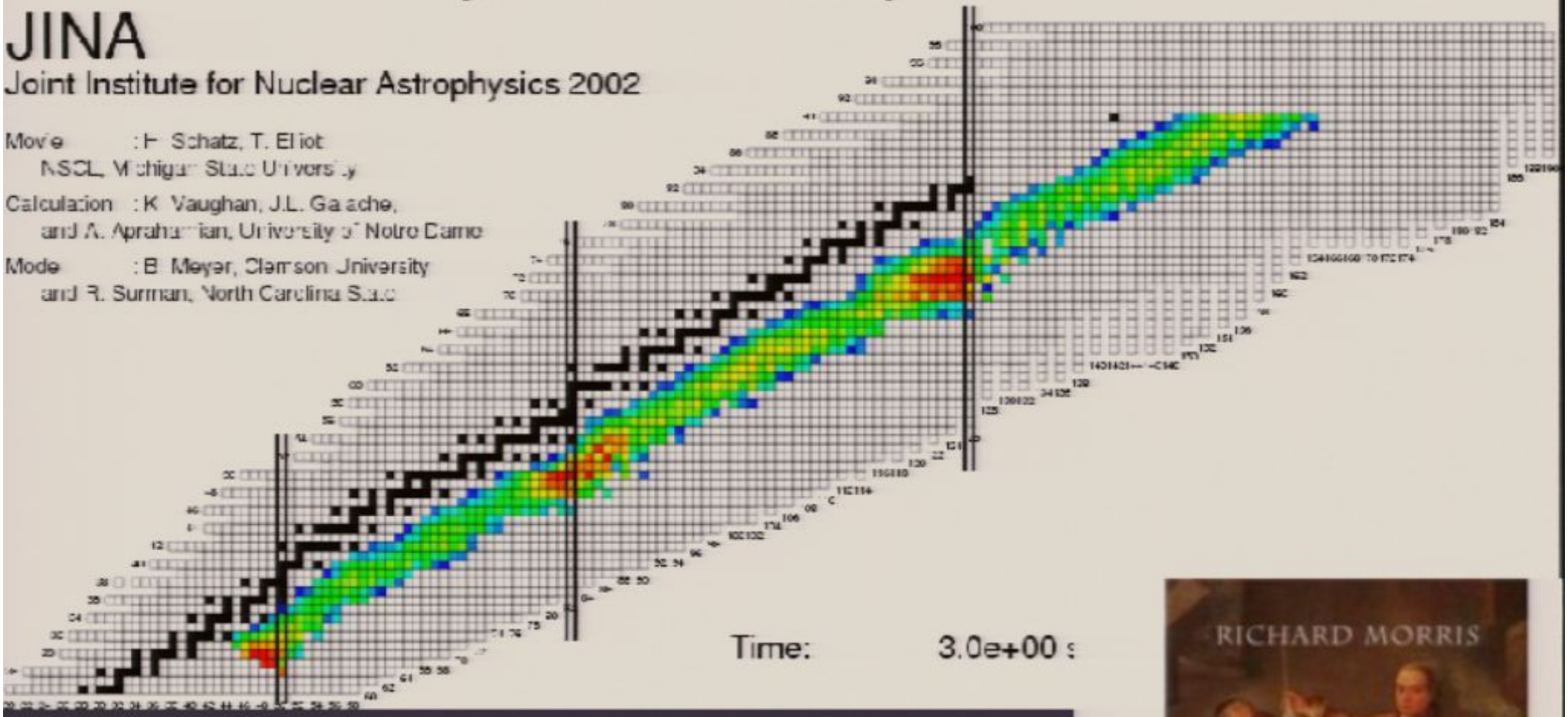

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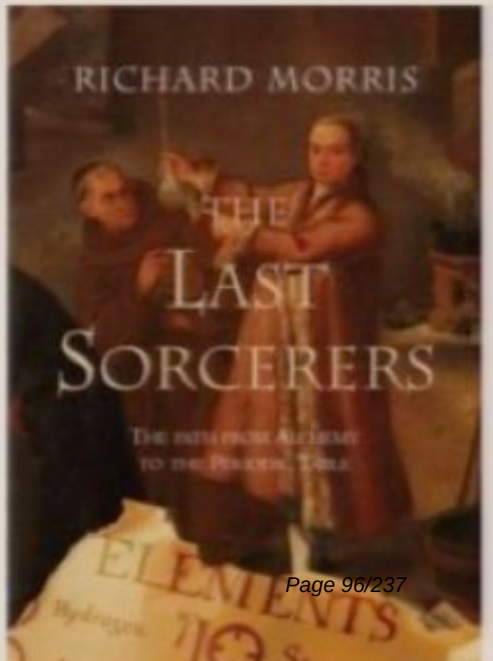

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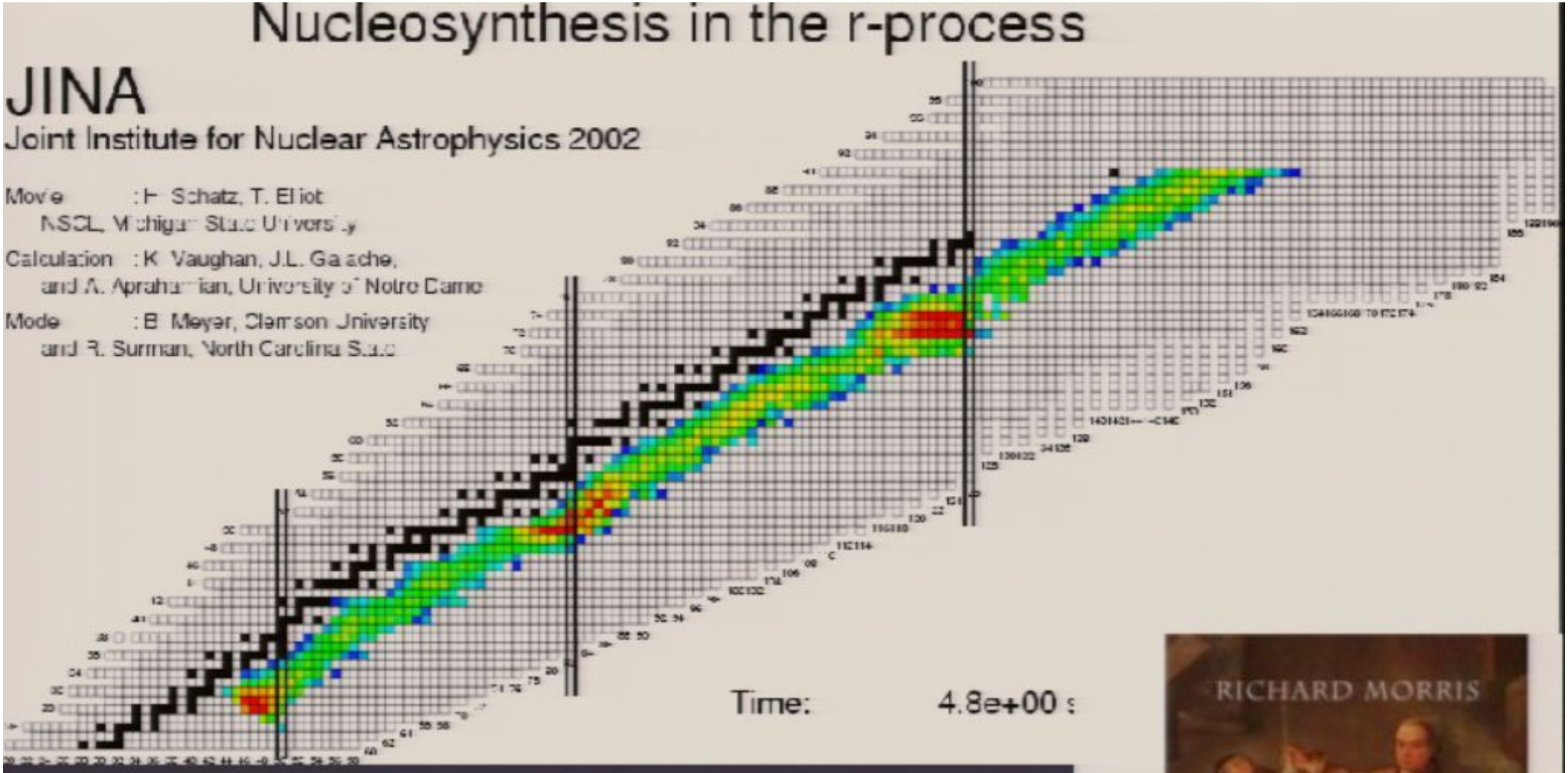

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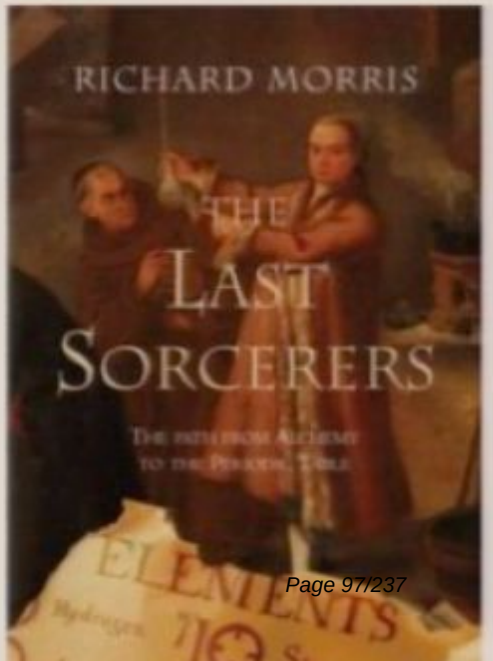

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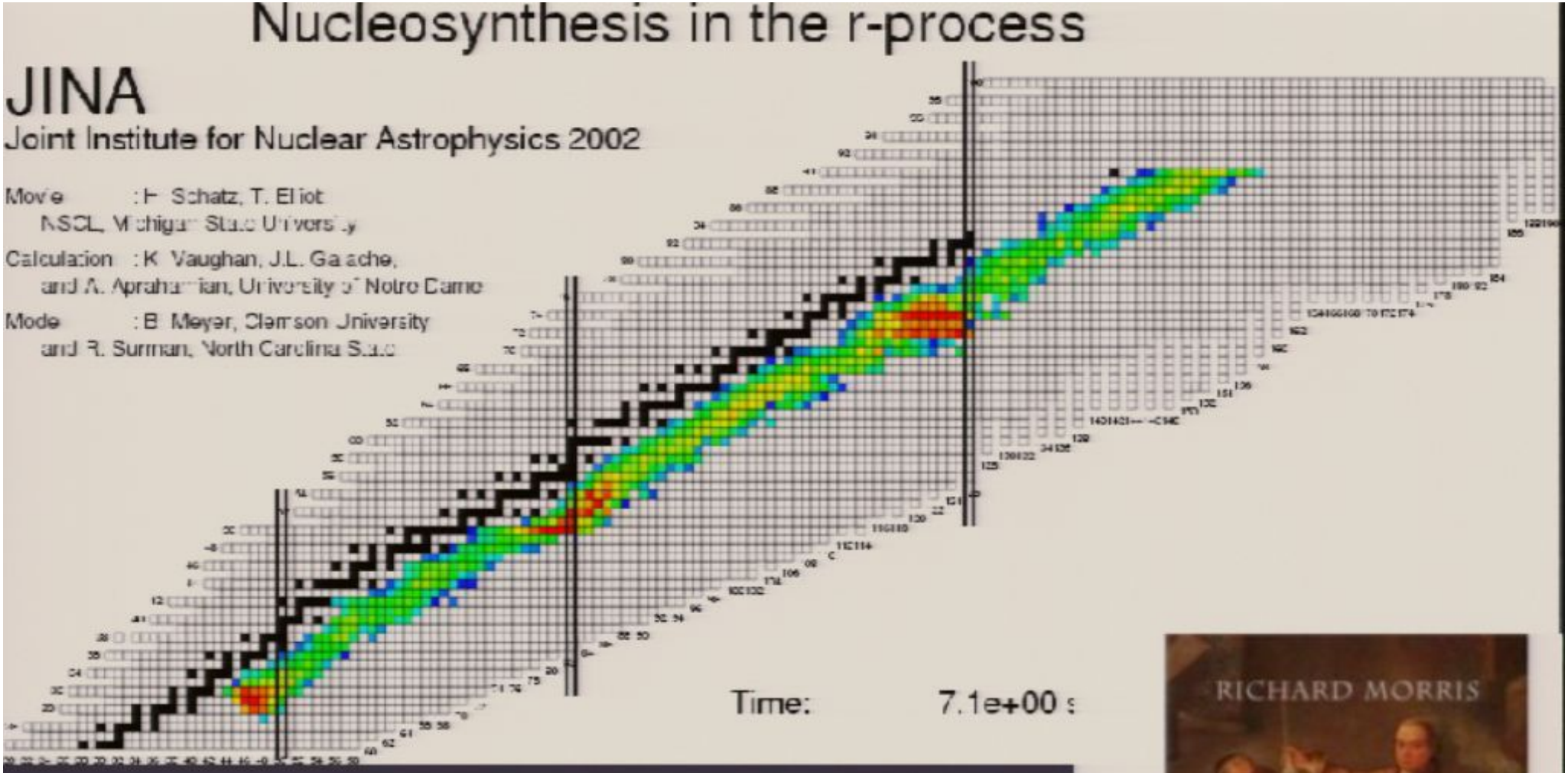

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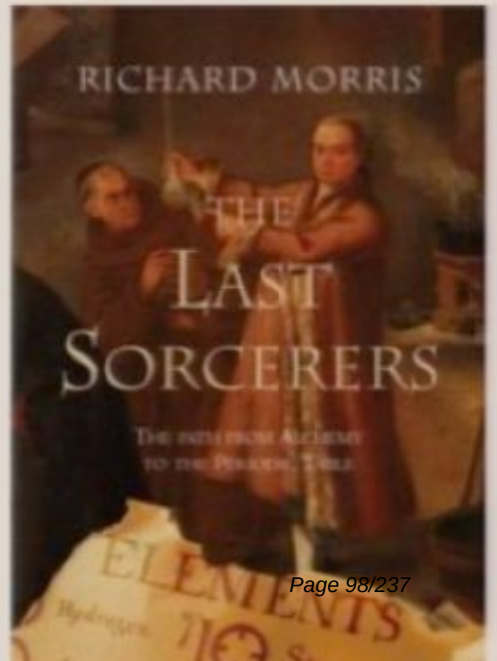

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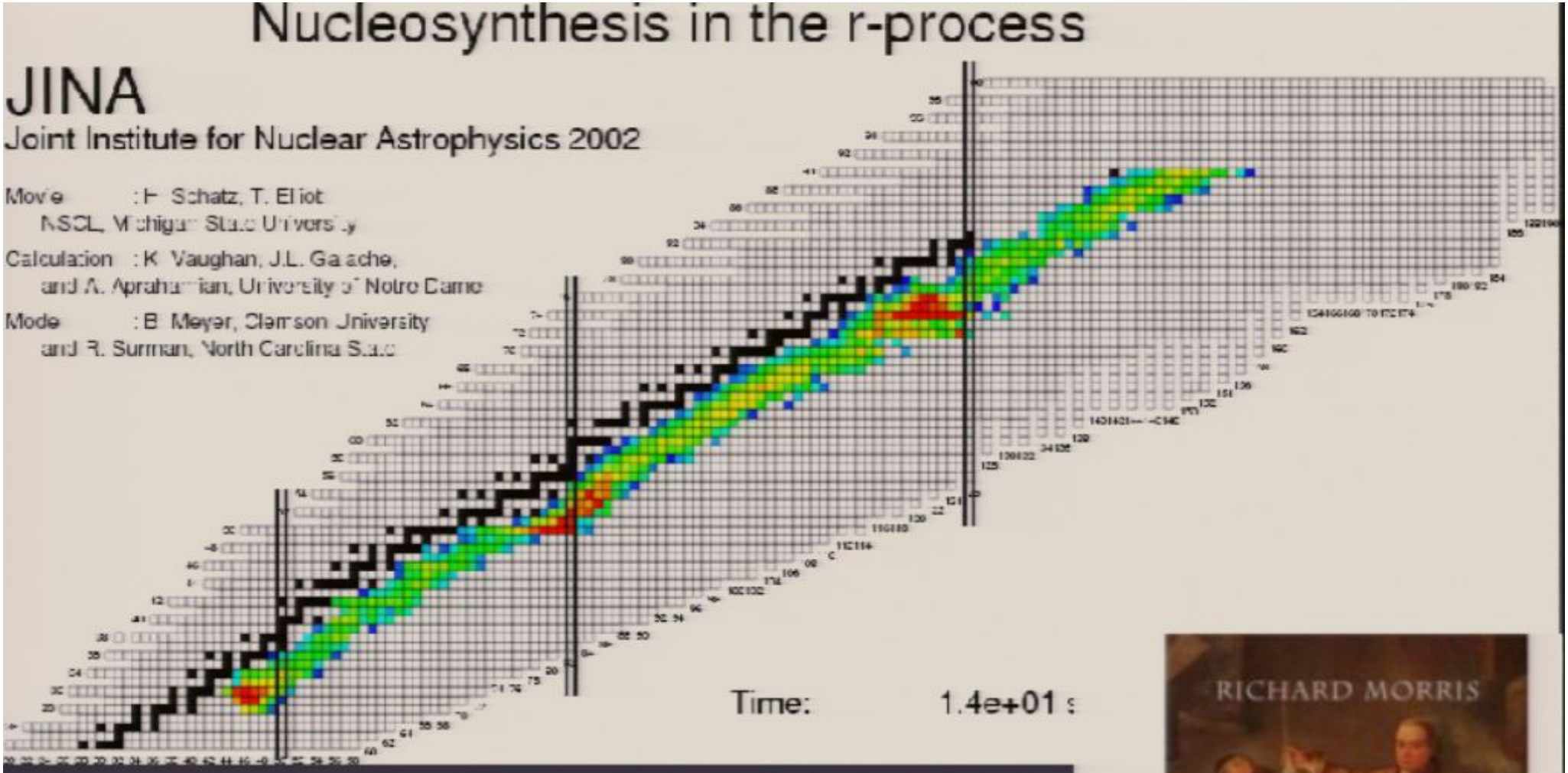
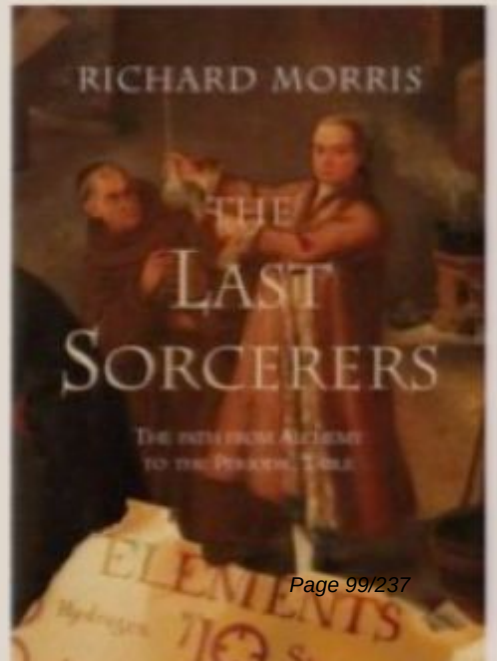
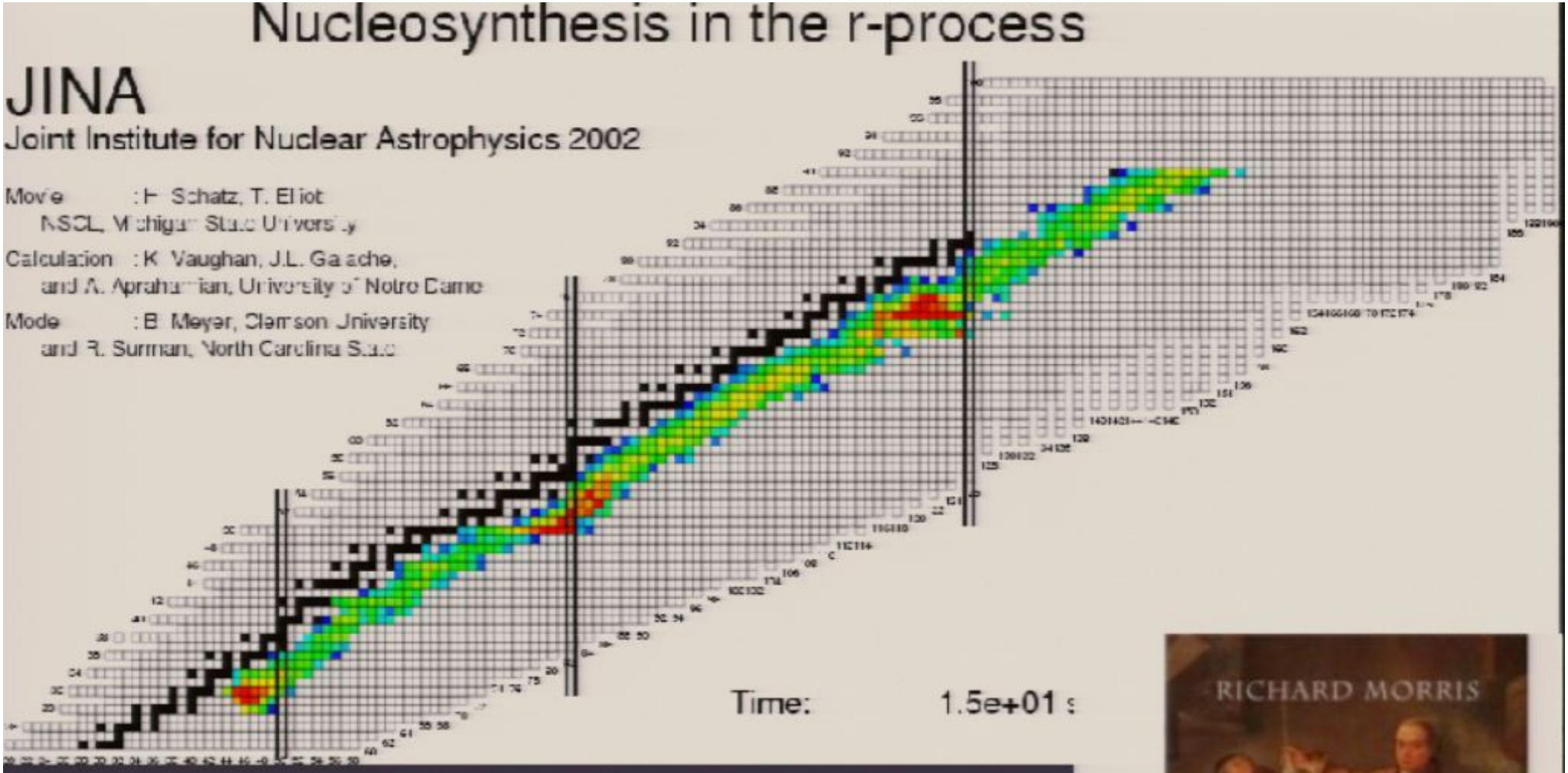


Unfortunately, no closed-shell nucleus decays to:

gold !



Nucleosynthesis in the r-process



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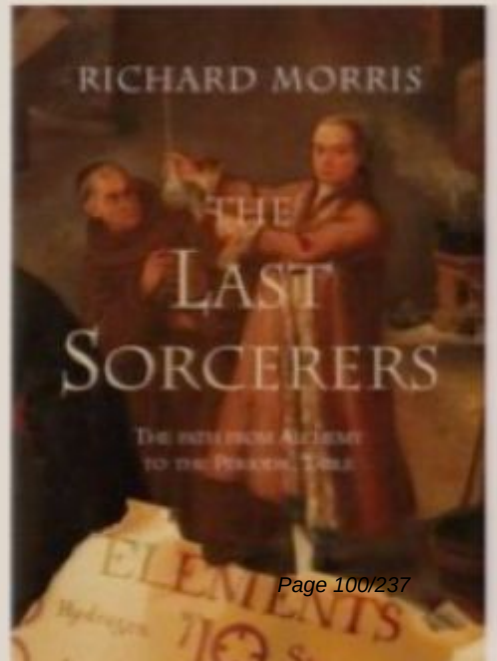

Nucleosynthesis in the r-process

JINA

Joint Institute for Nuclear Astrophysics 2002

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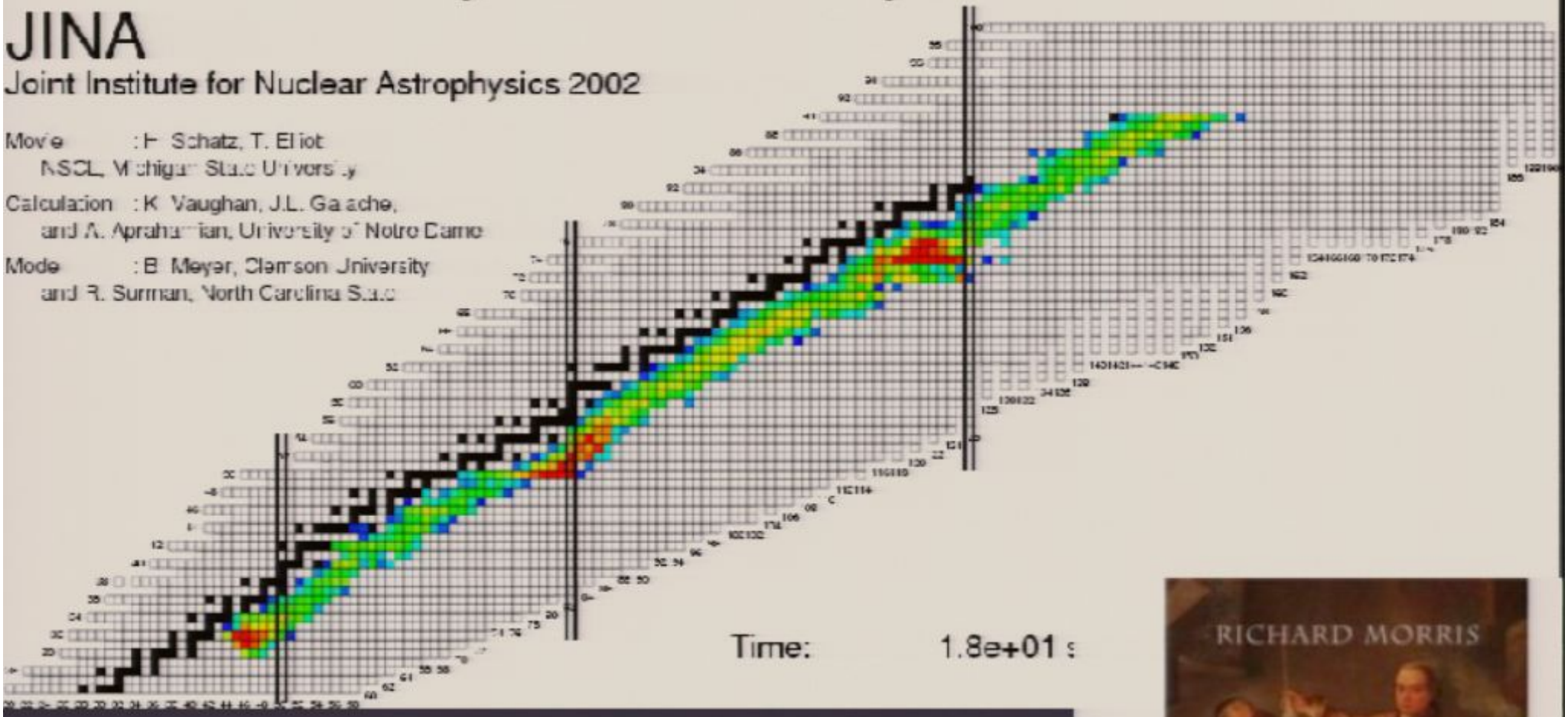

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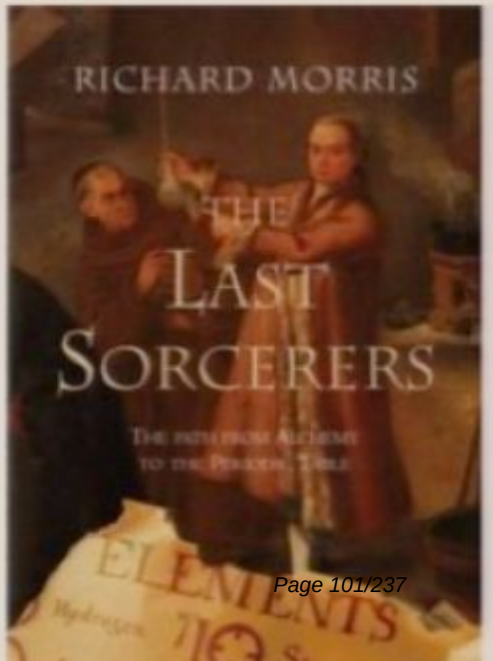
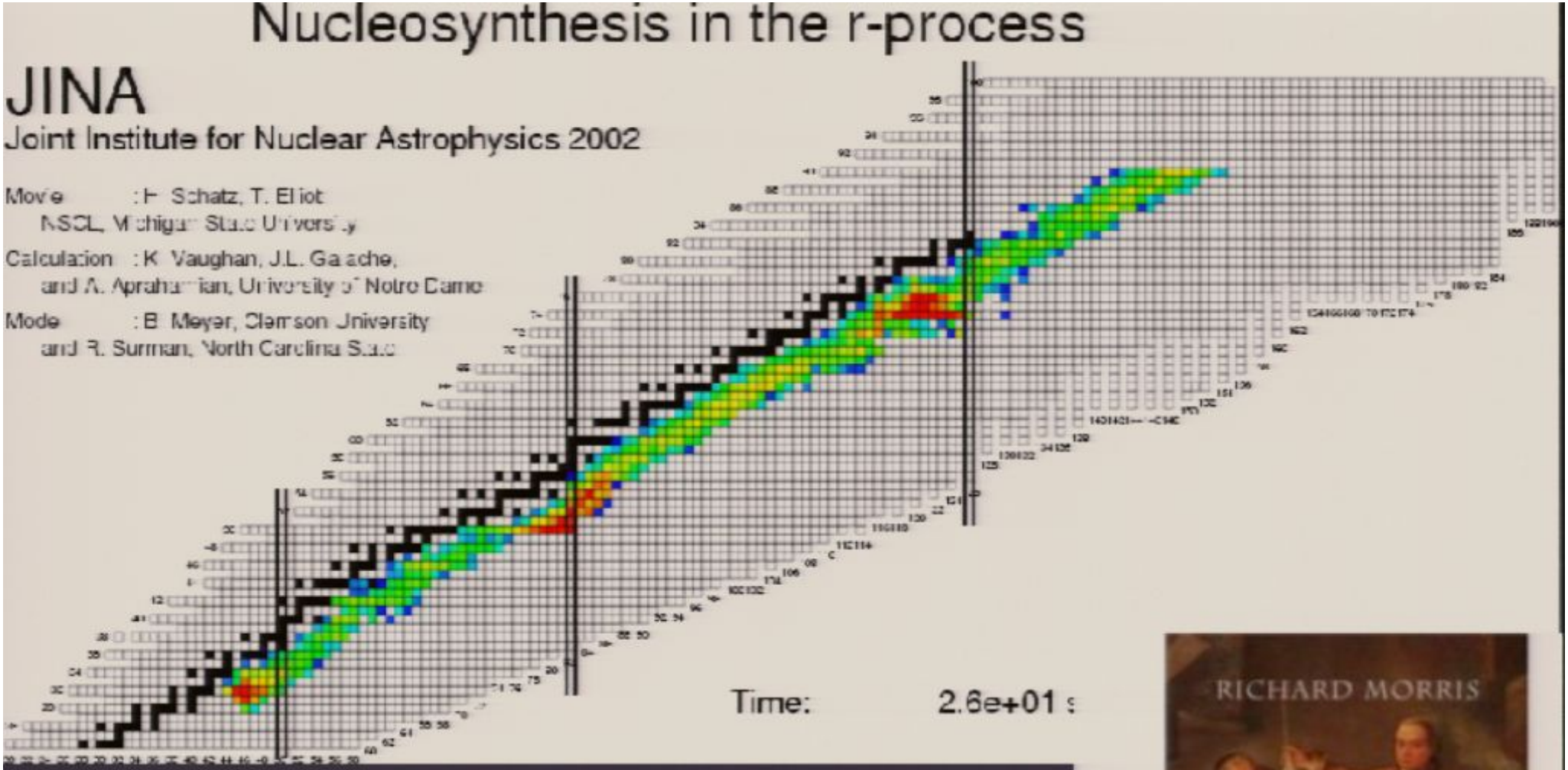


Nucleosynthesis in the r-process



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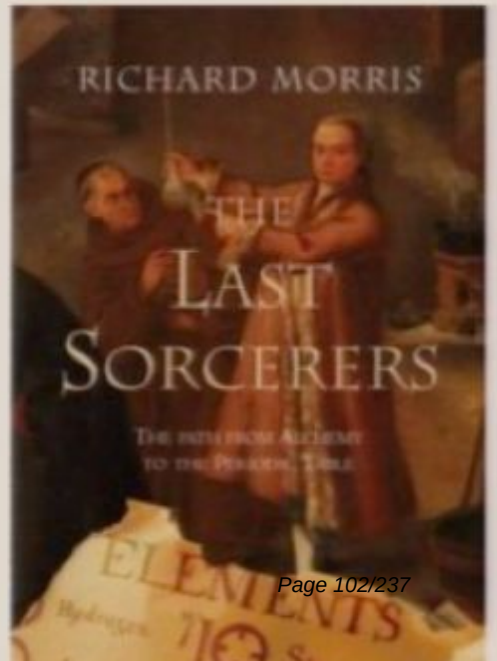
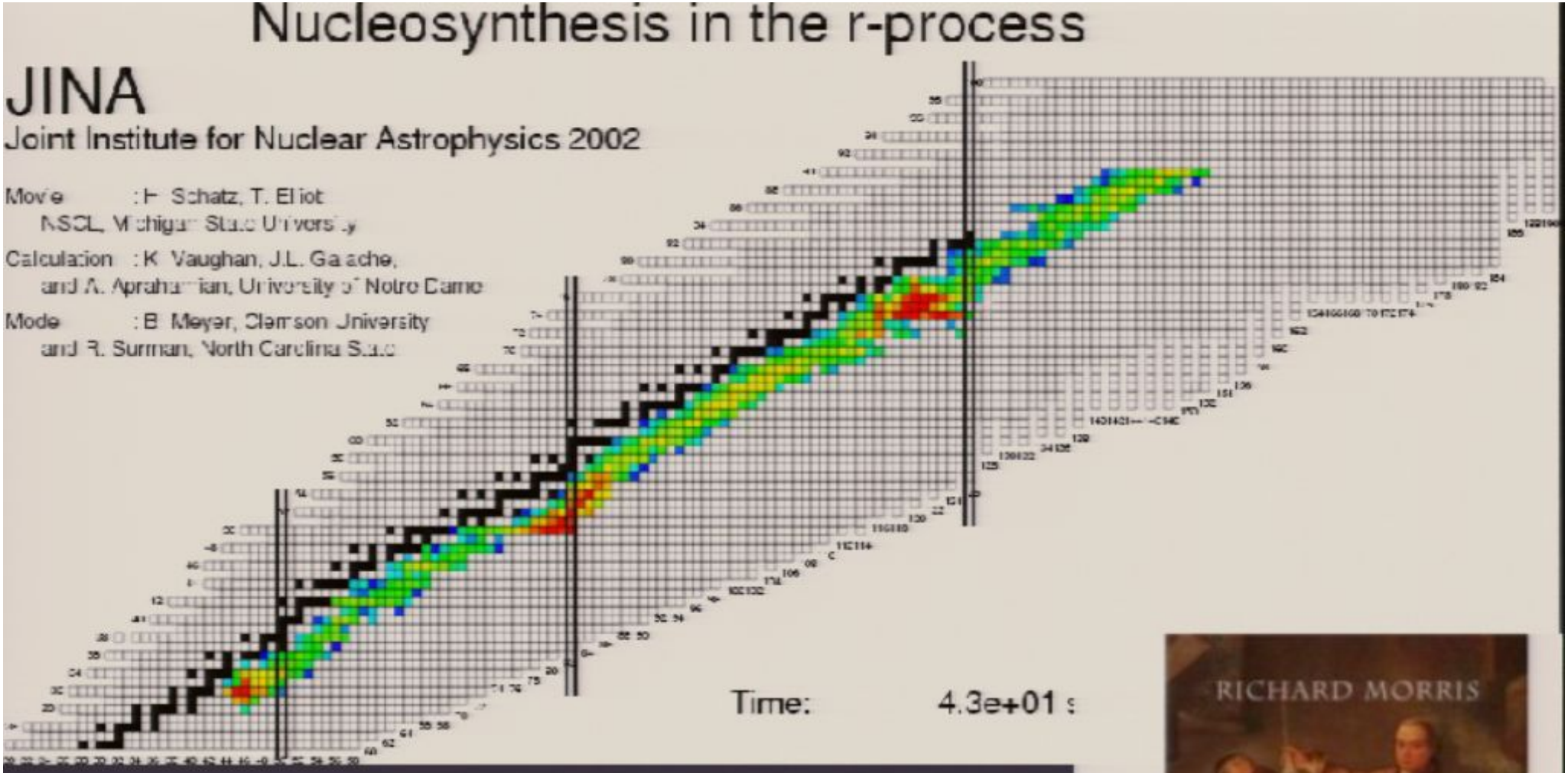


Nucleosynthesis in the r-process



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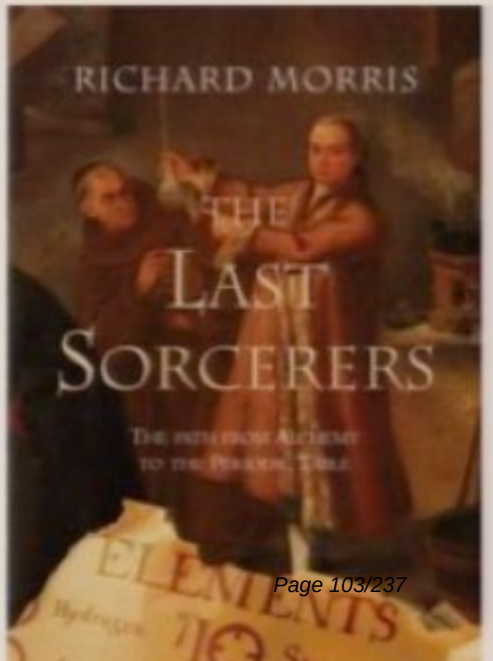

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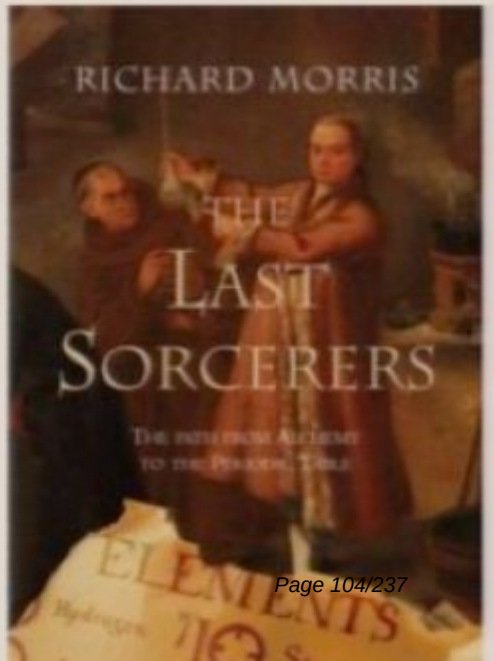
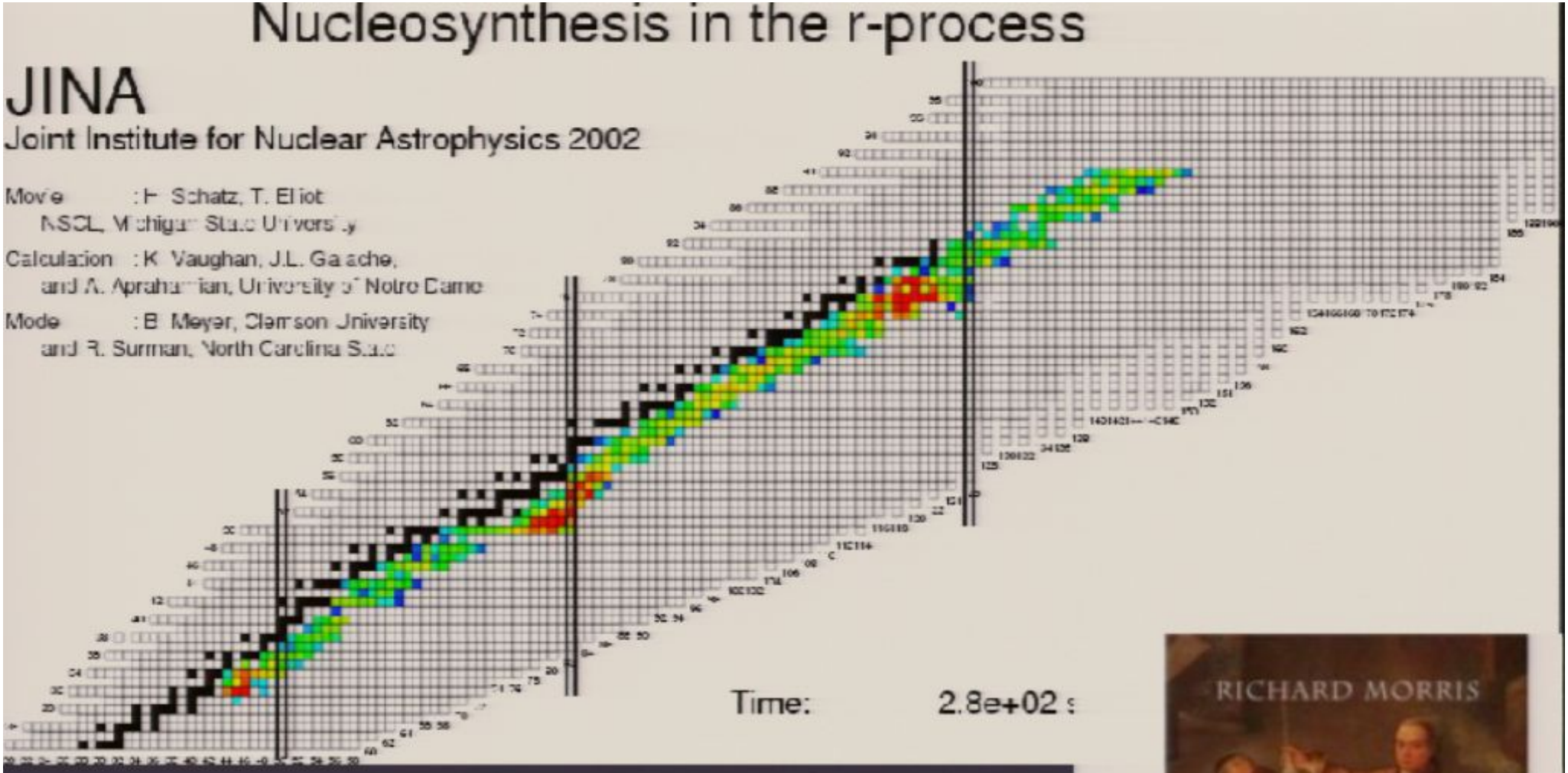
Time: 1.4e+02 s

Unfortunately, no closed-shell nucleus decays to:

gold !



Nucleosynthesis in the r-process



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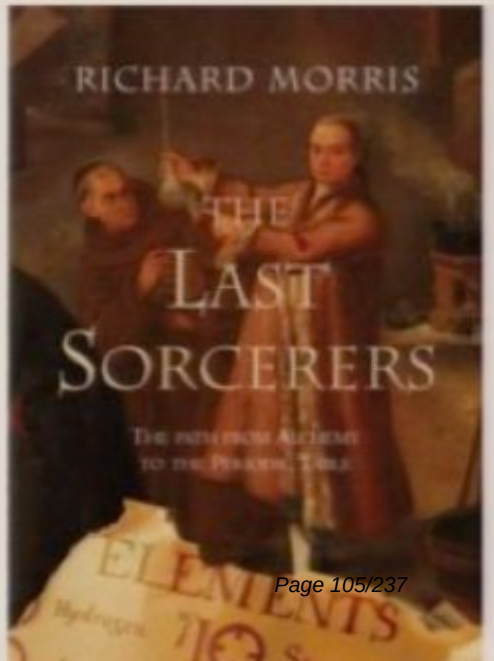
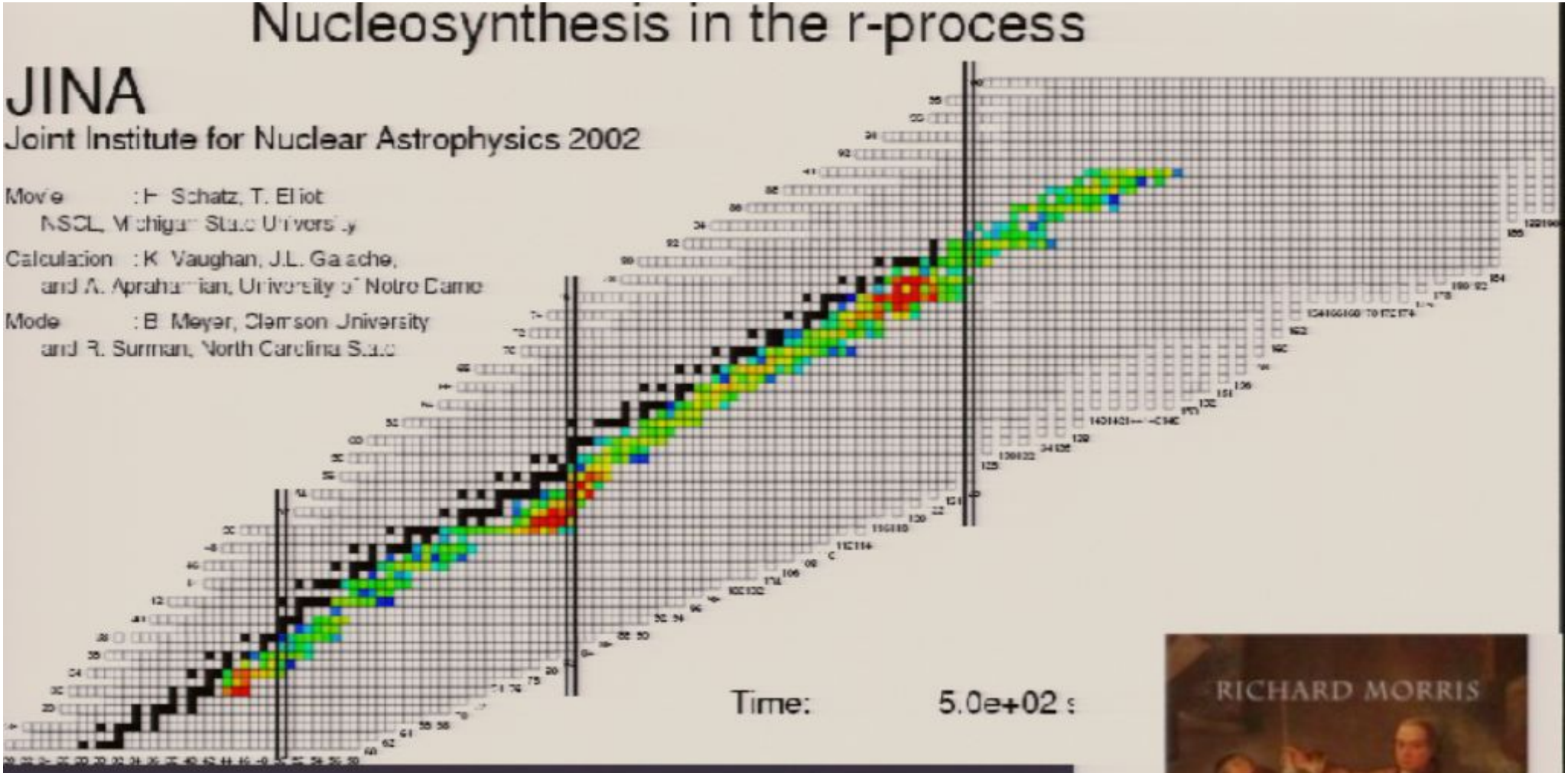


Nucleosynthesis in the r-process



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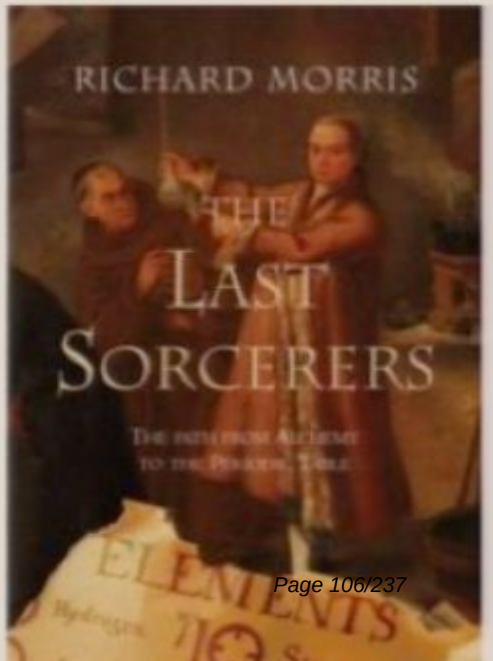
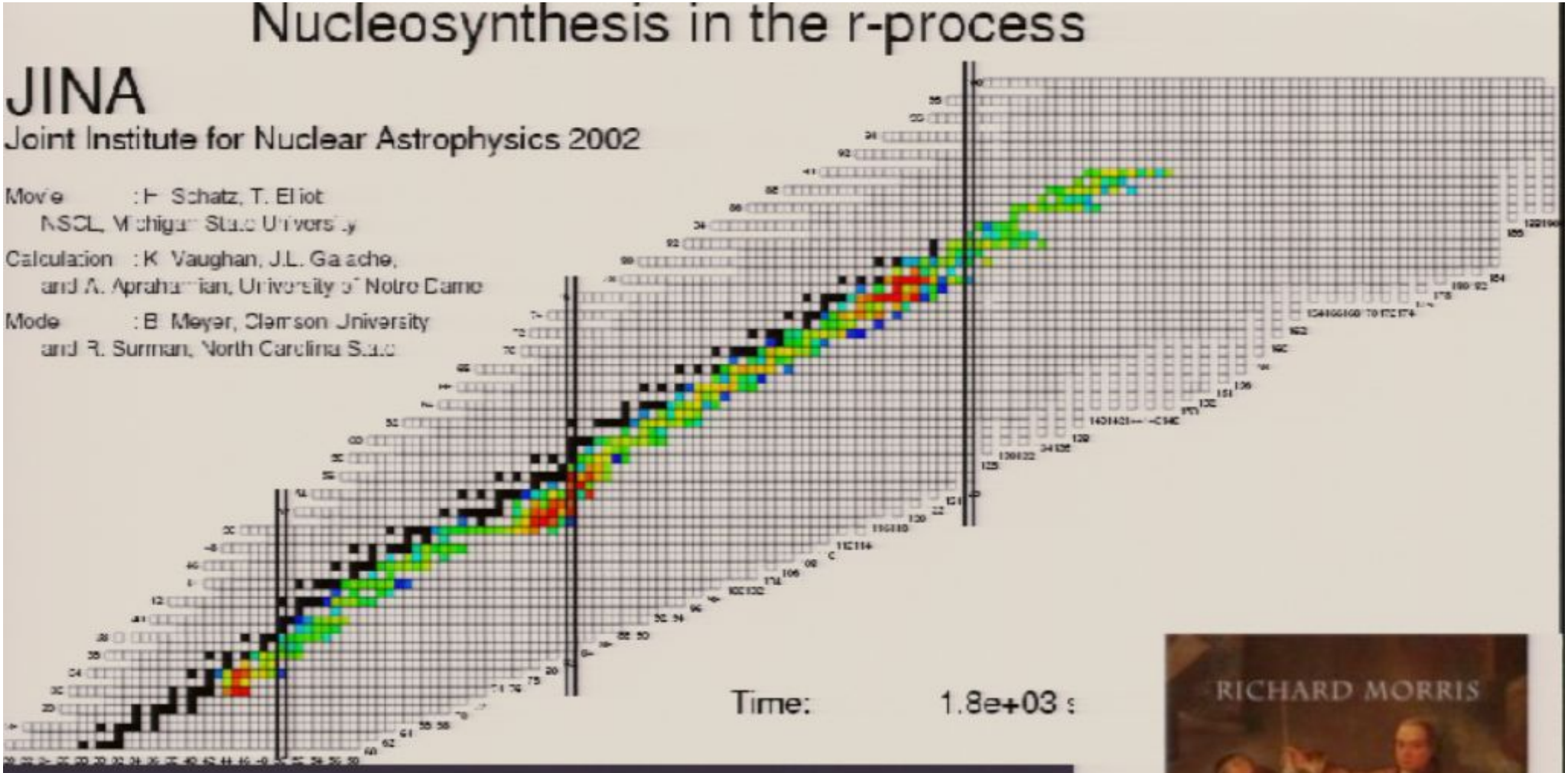


Nucleosynthesis in the r-process



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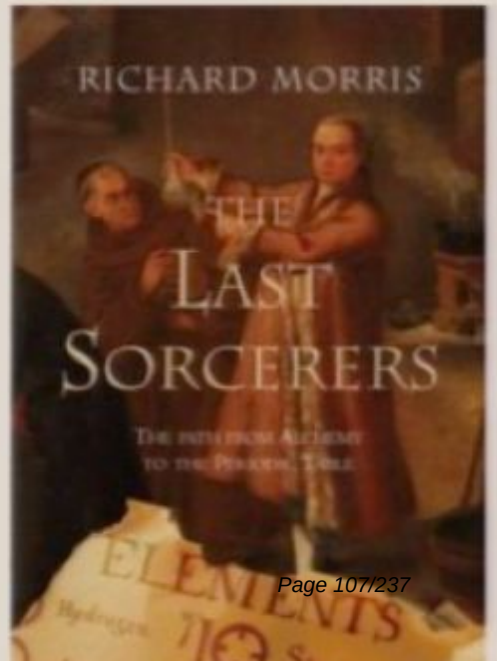
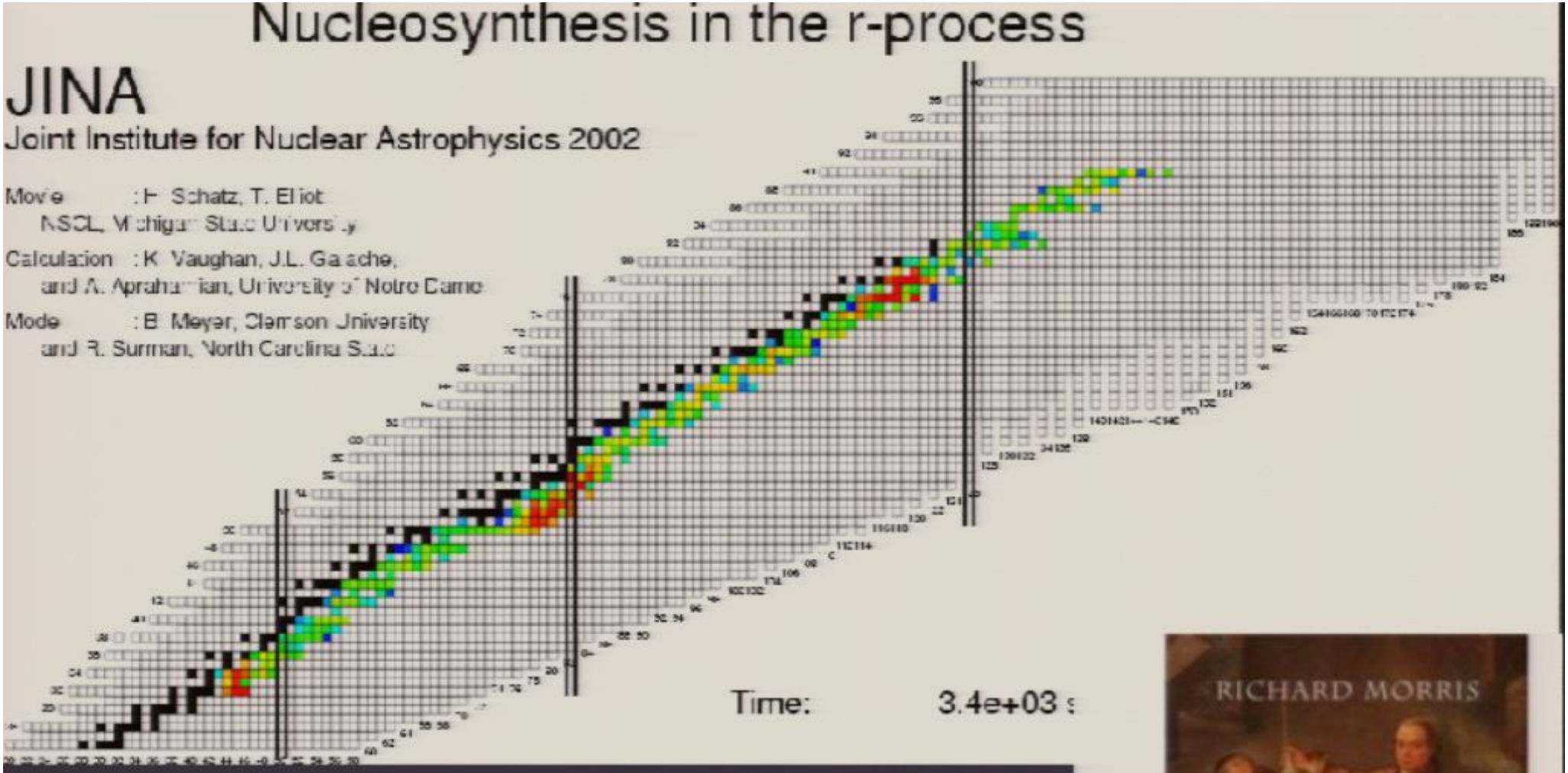


Nucleosynthesis in the r-process



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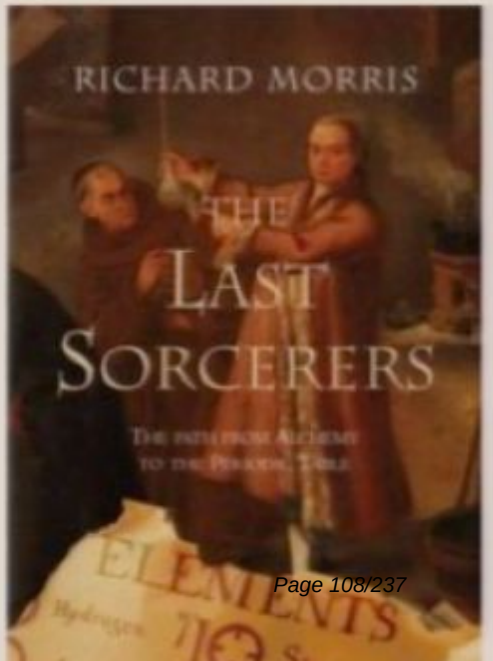

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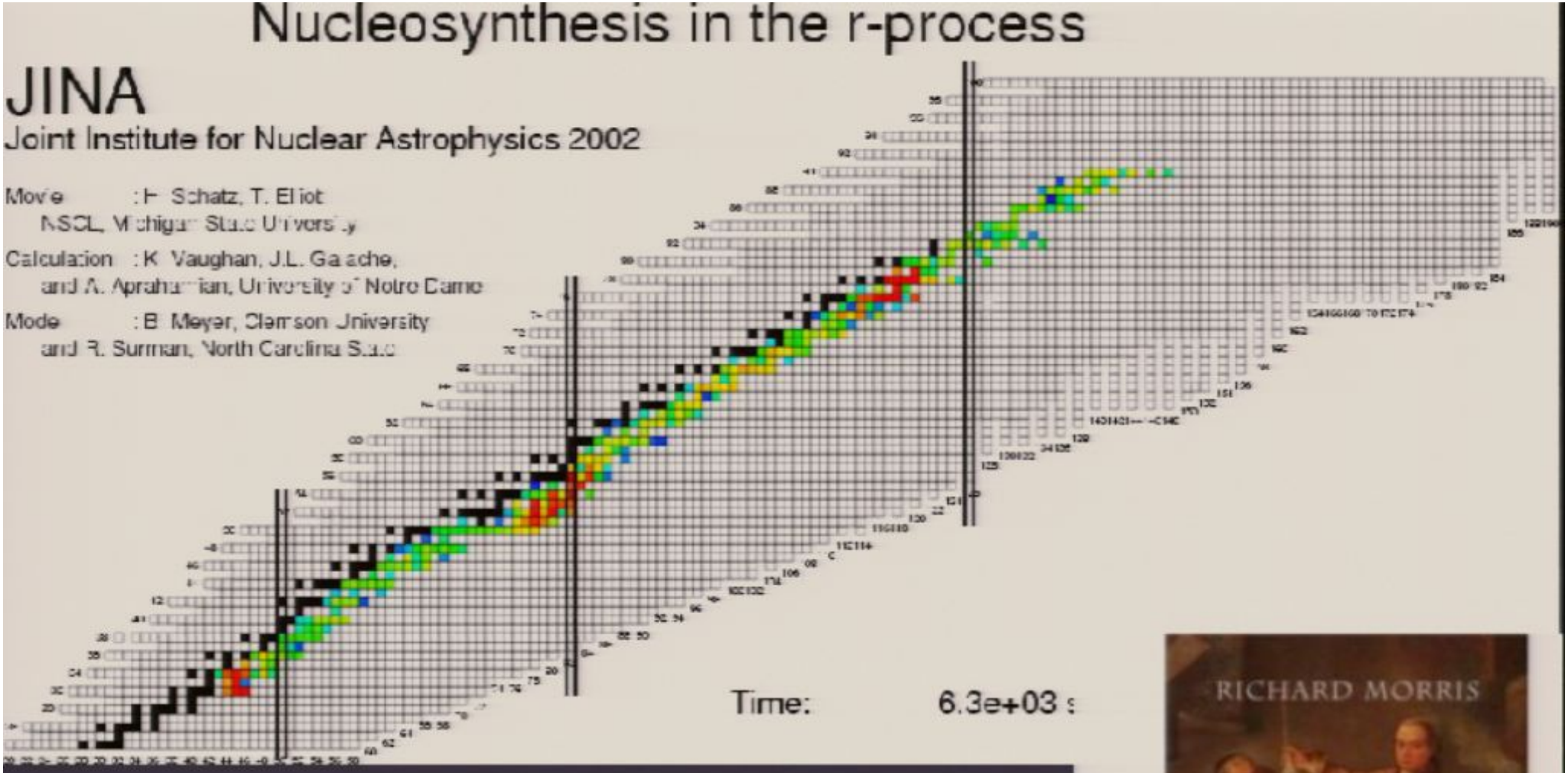

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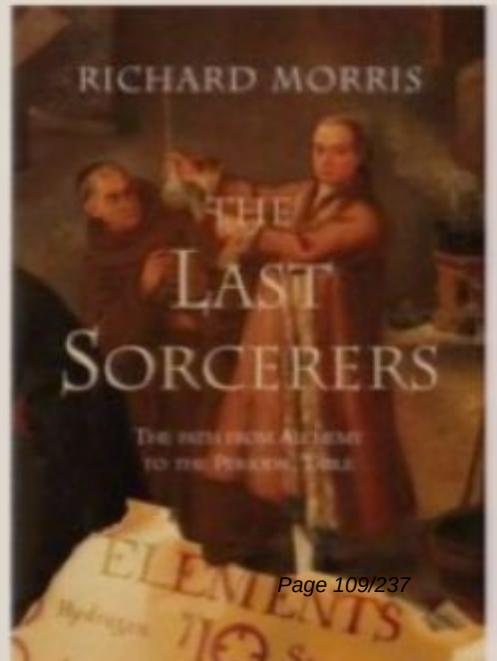

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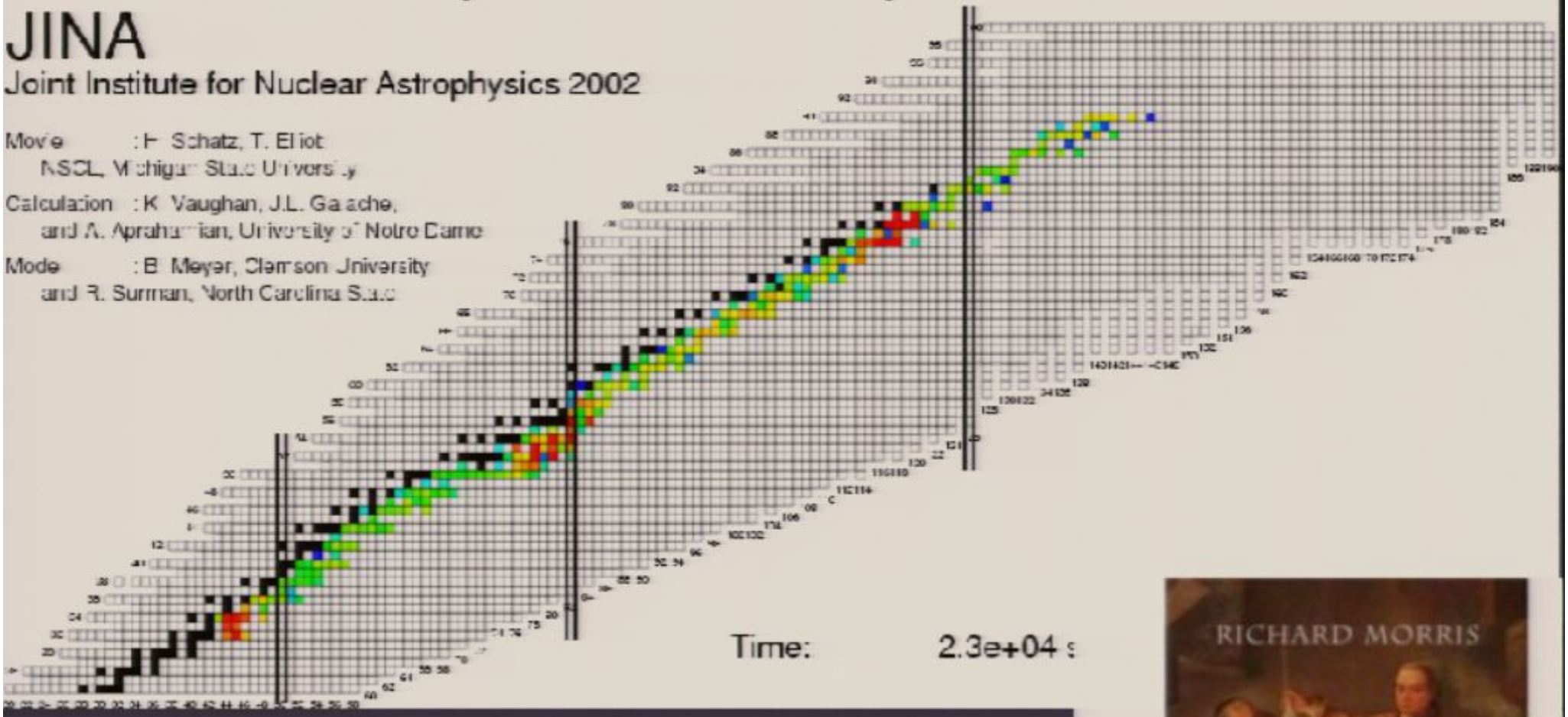

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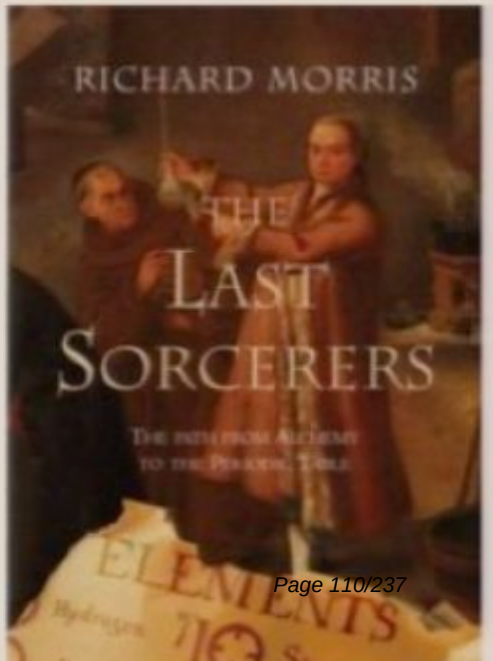
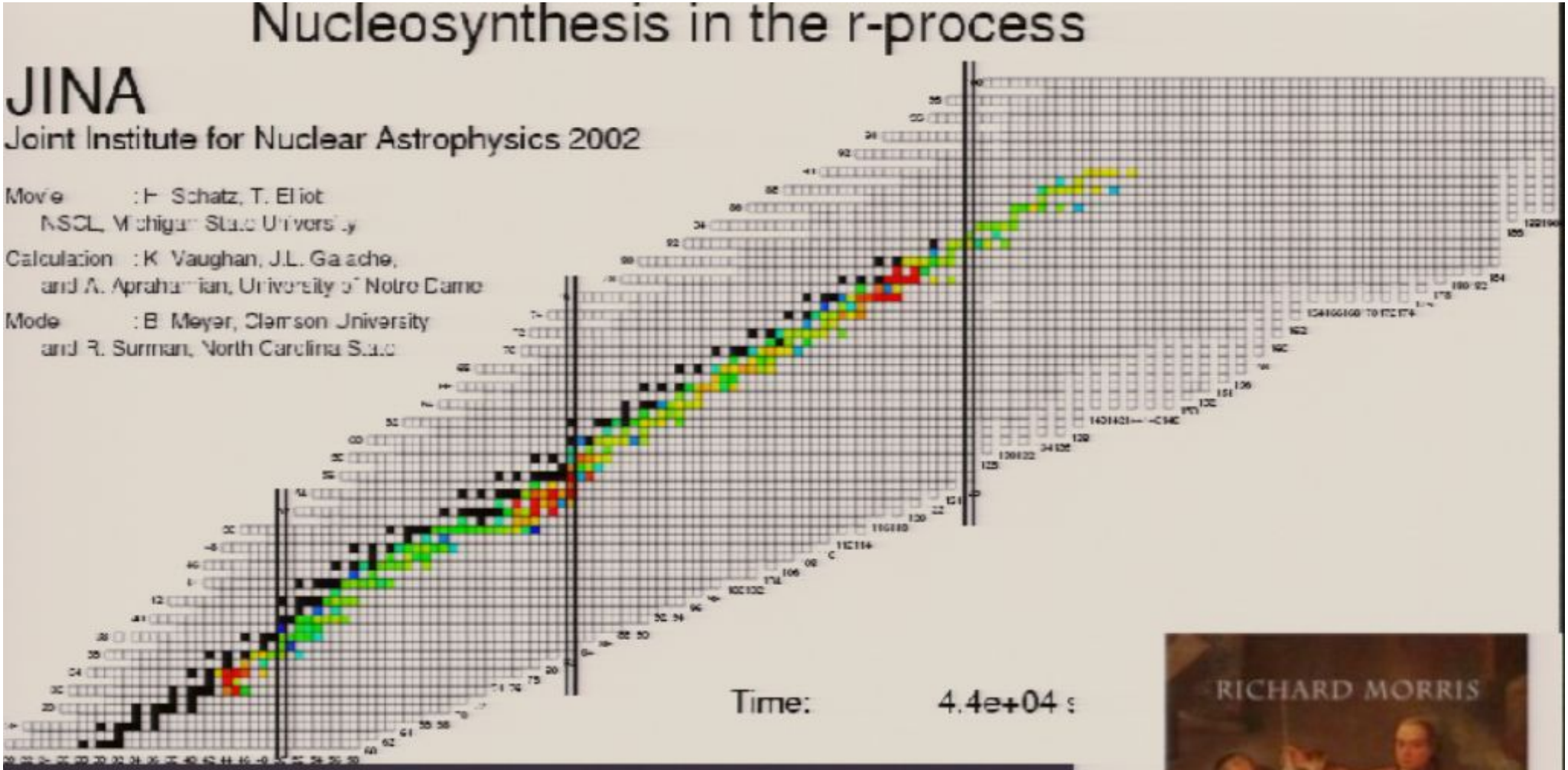


Nucleosynthesis in the r-process



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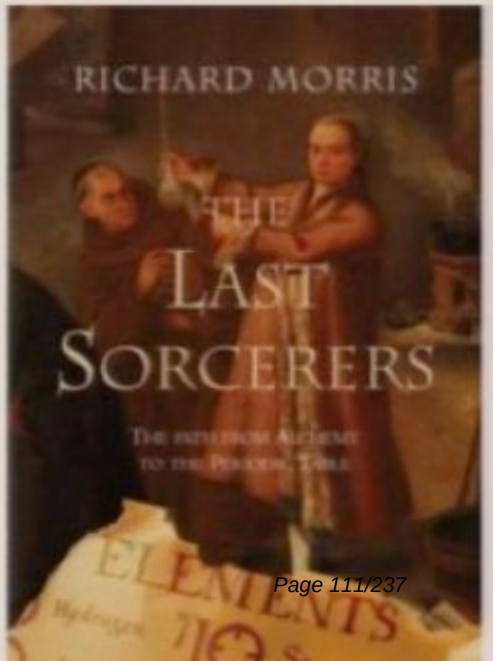

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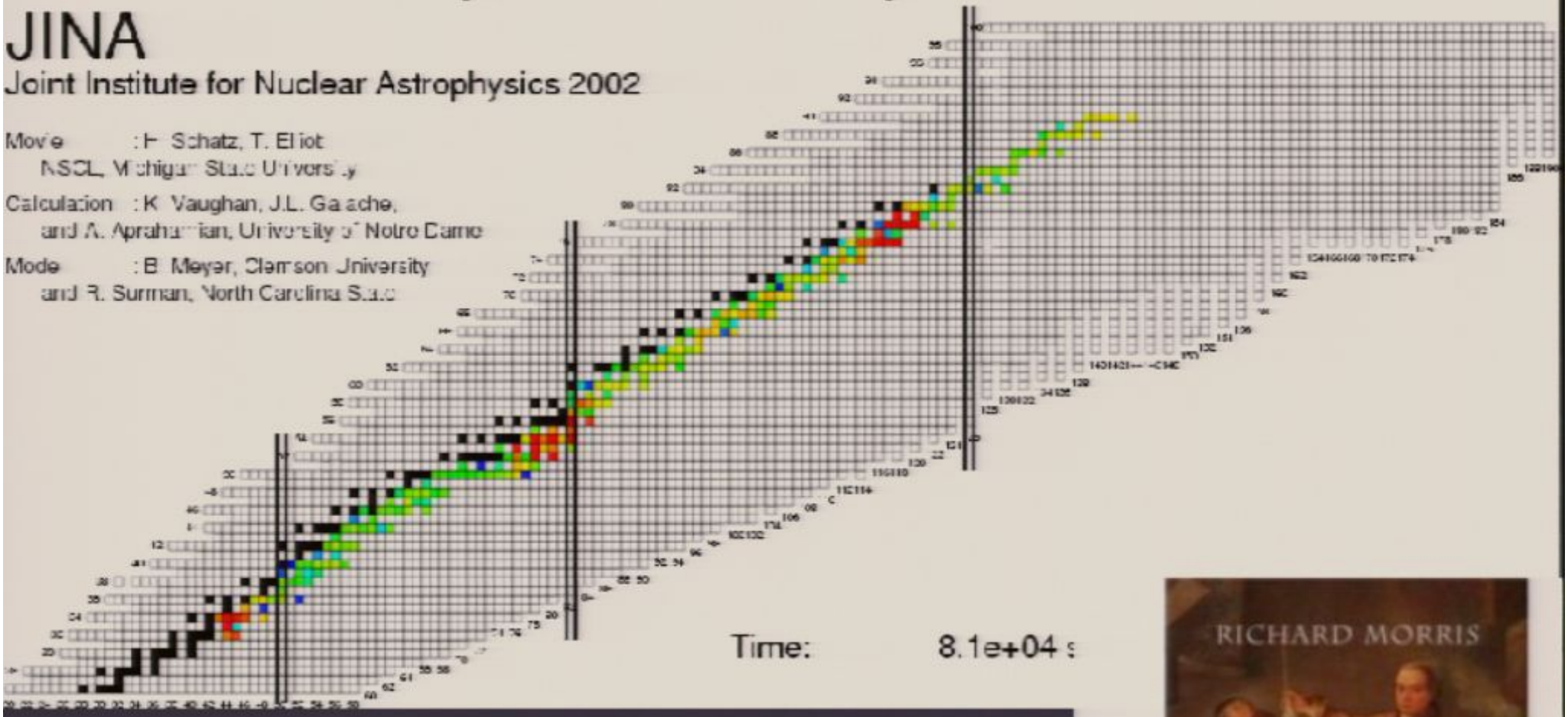

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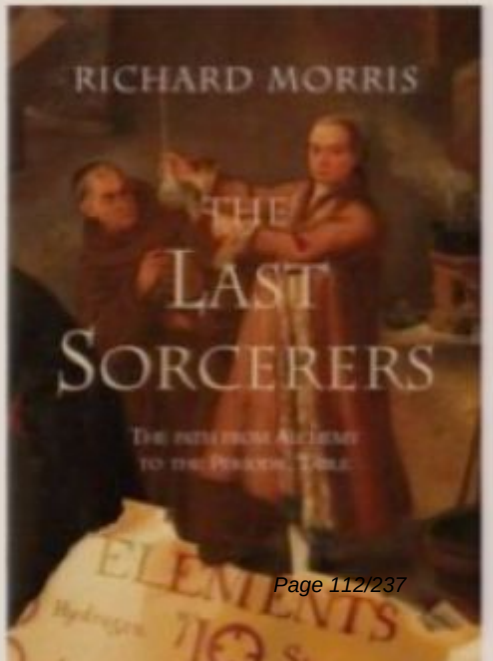
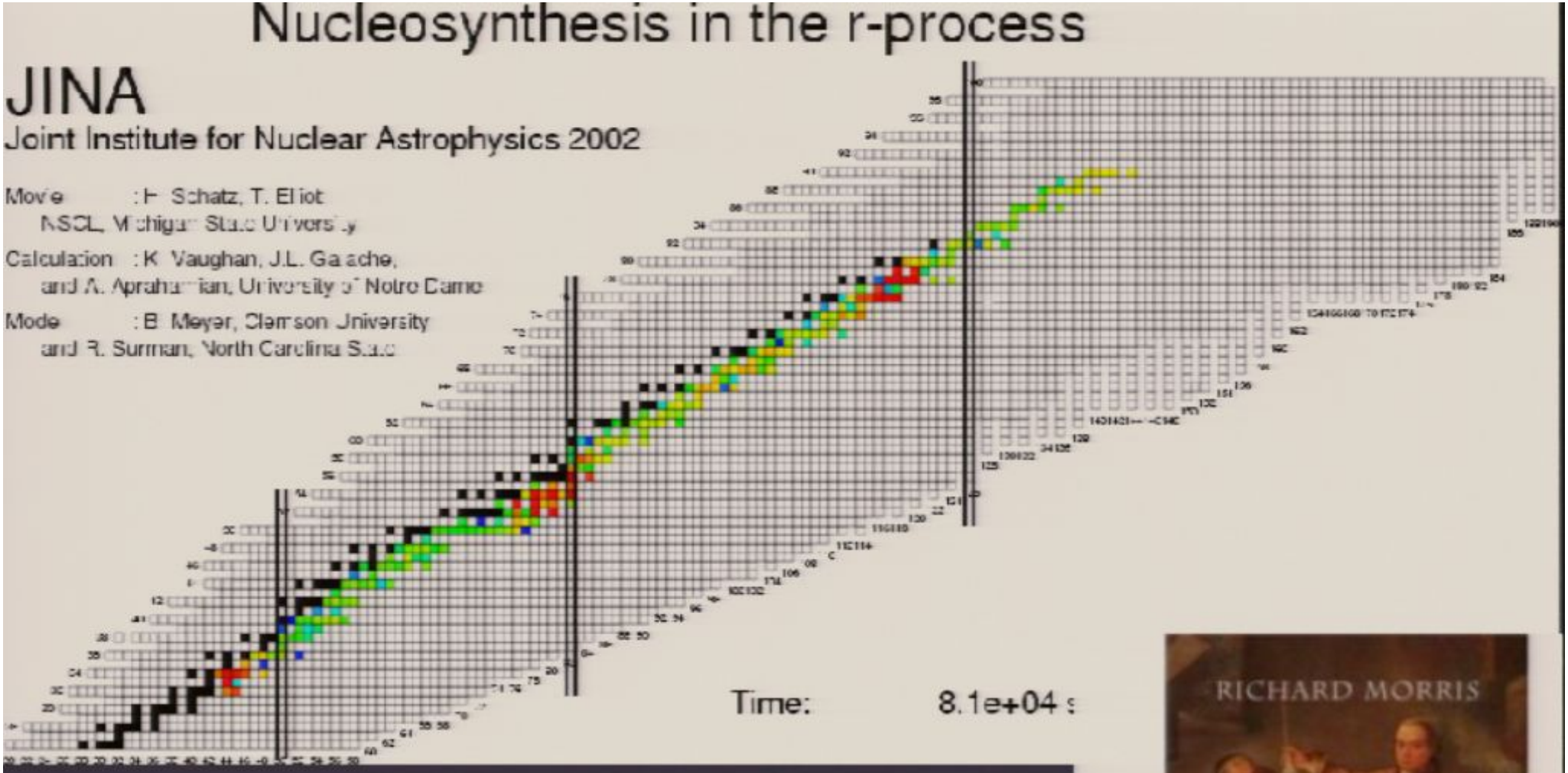


Nucleosynthesis in the r-process



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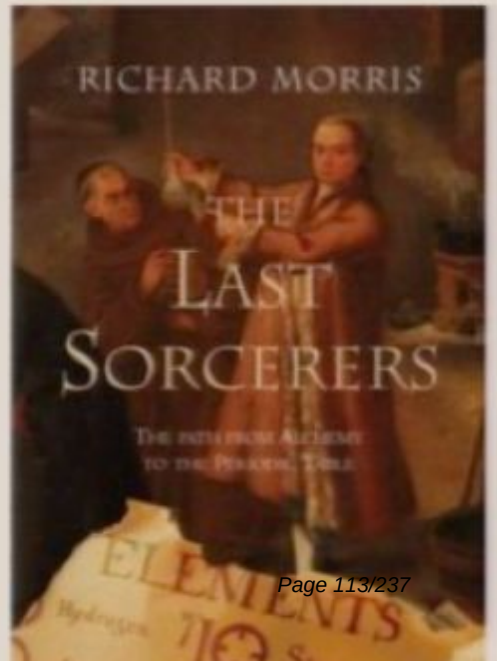

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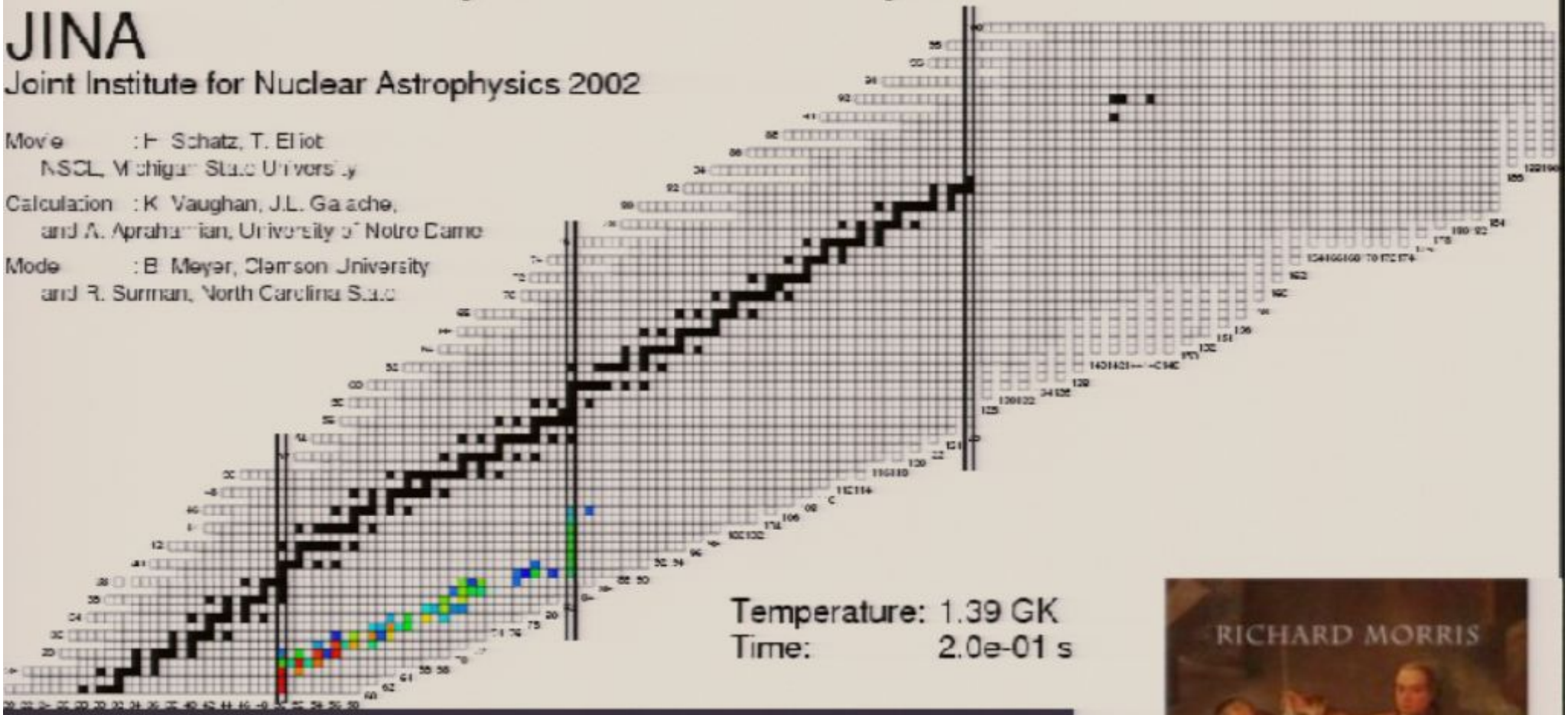
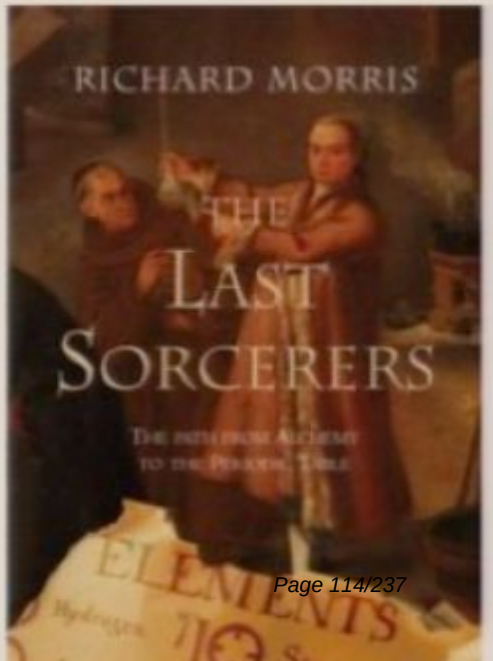


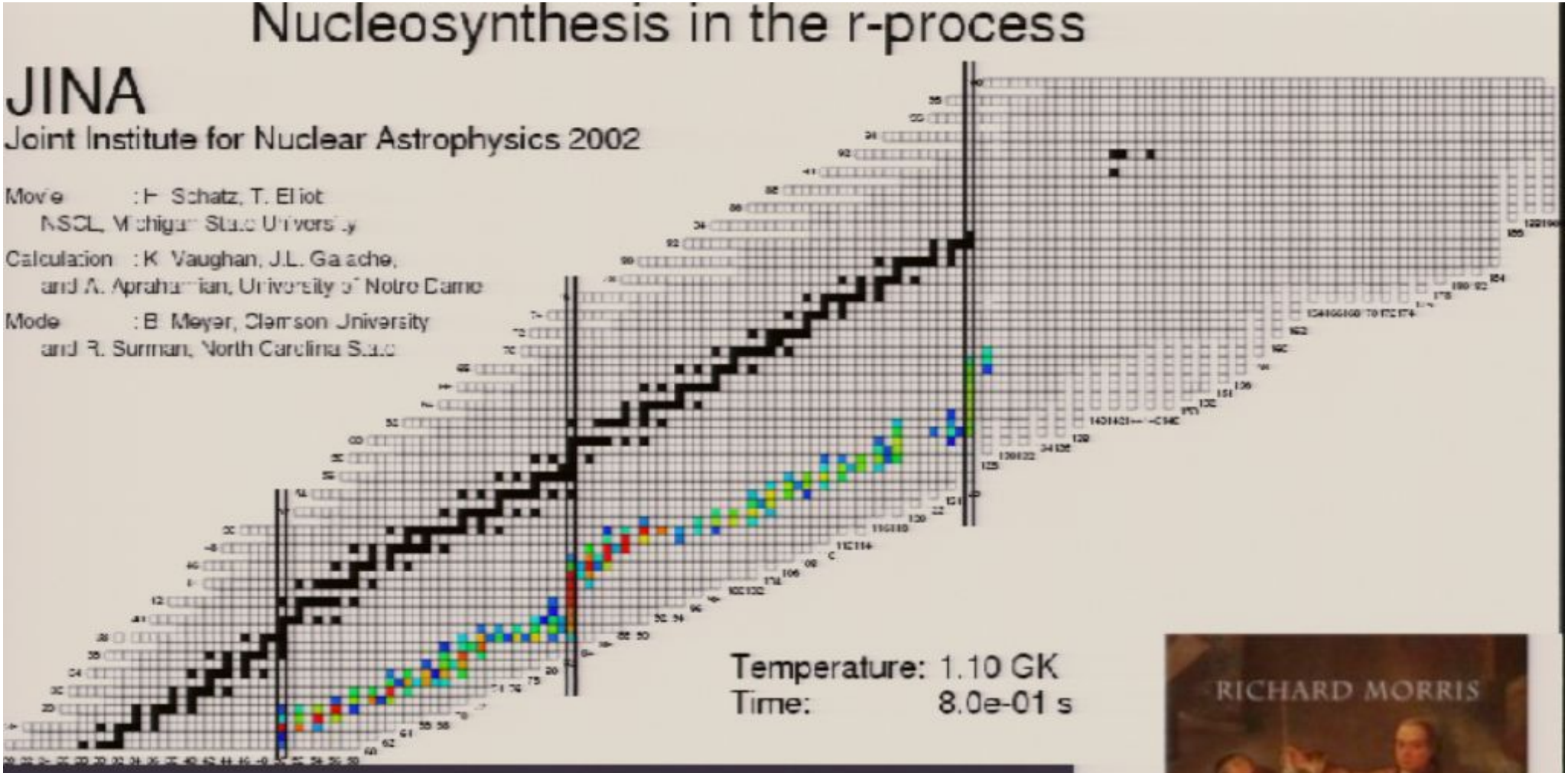
Temperature: 1.39 GK
Time: 2.0e-01 s

Unfortunately, no closed-shell nucleus decays to:

gold !



Nucleosynthesis in the r-process



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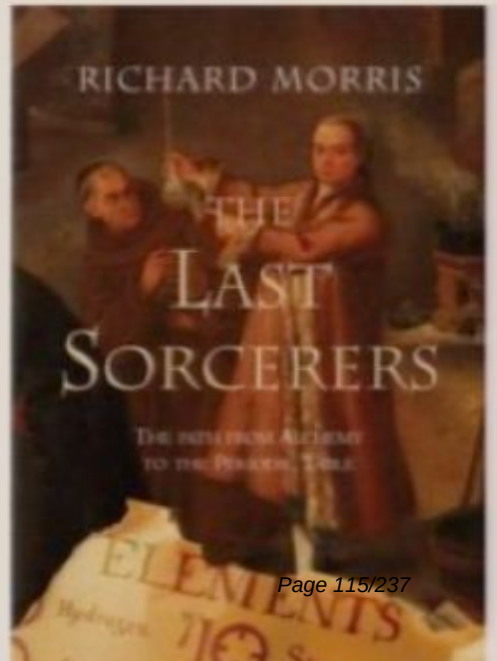
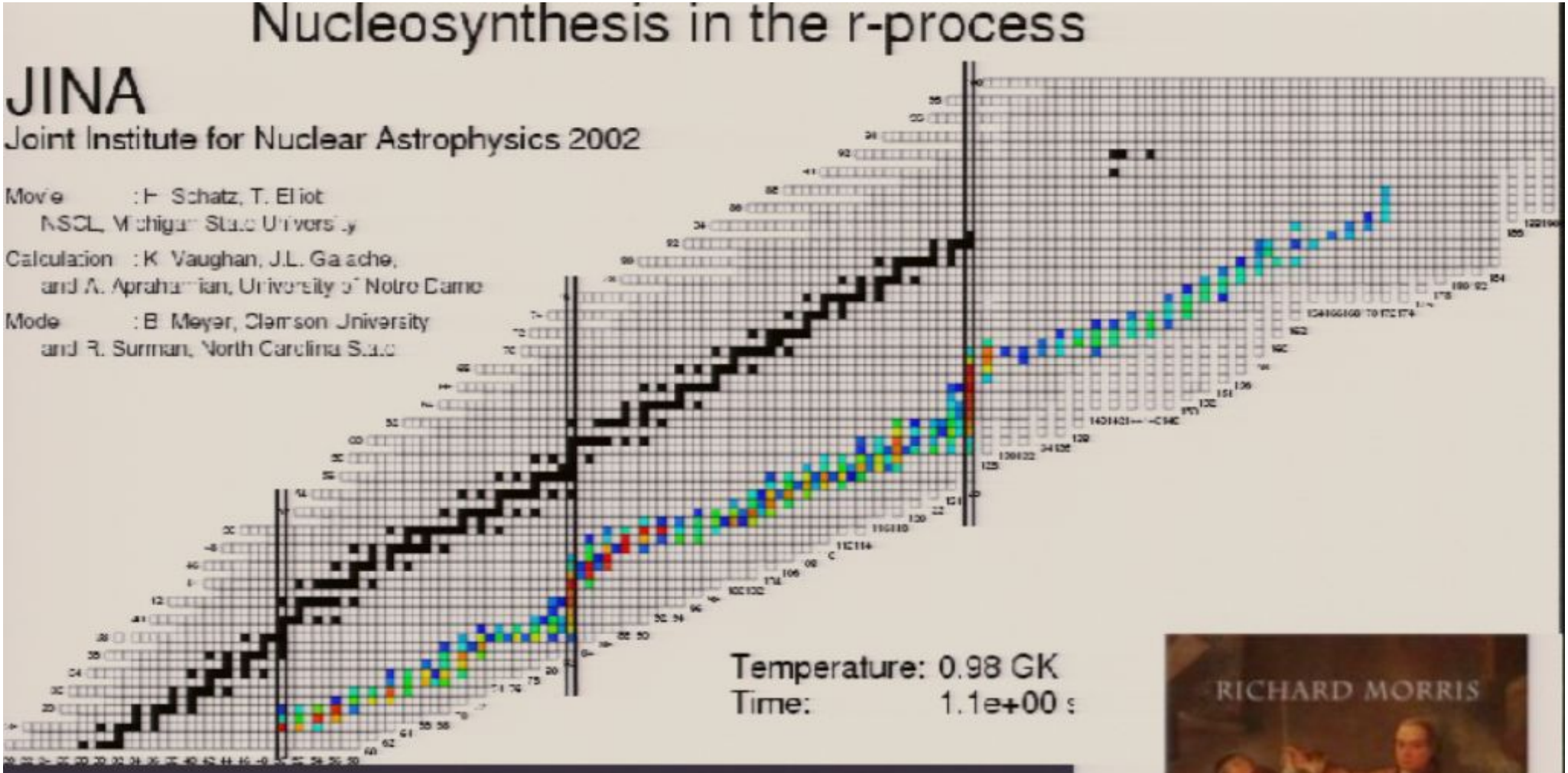


Nucleosynthesis in the r-process



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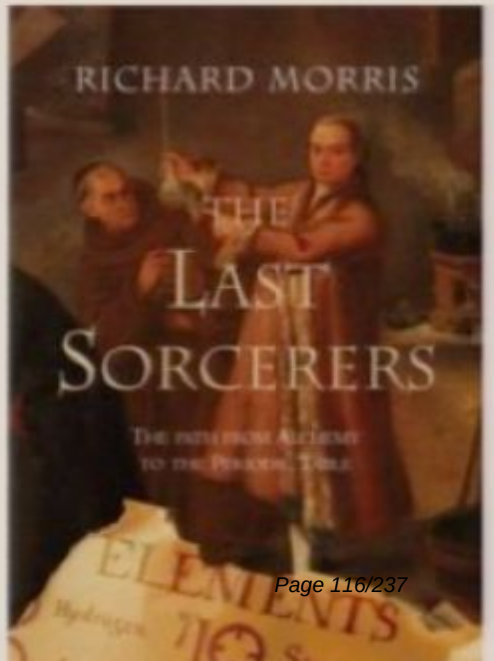

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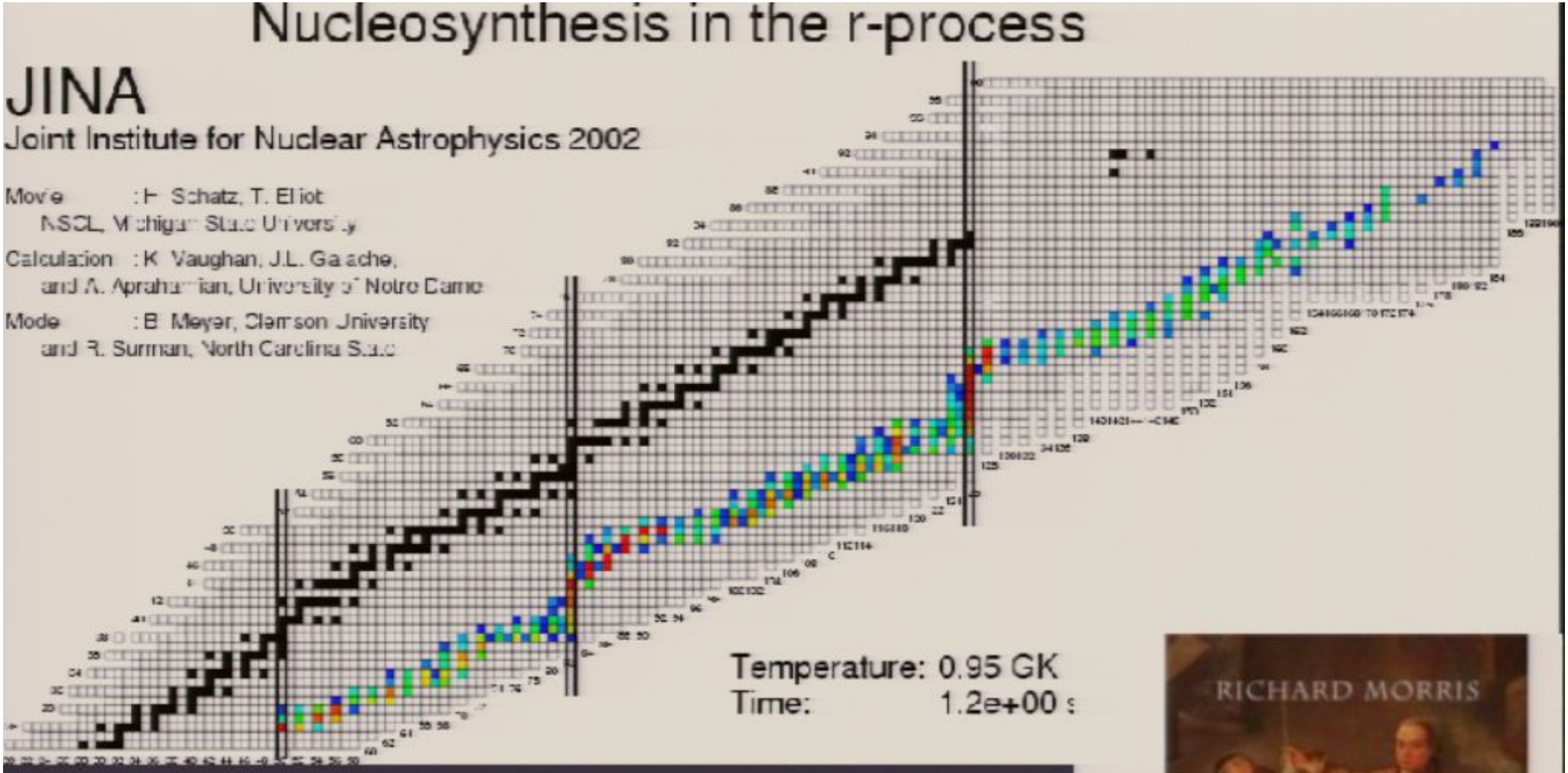

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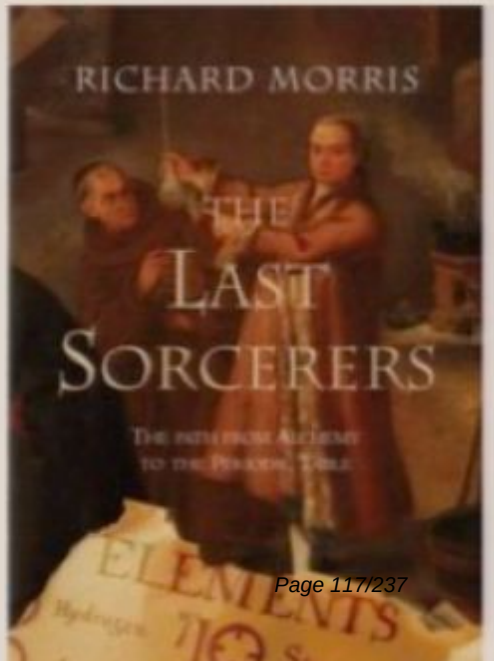

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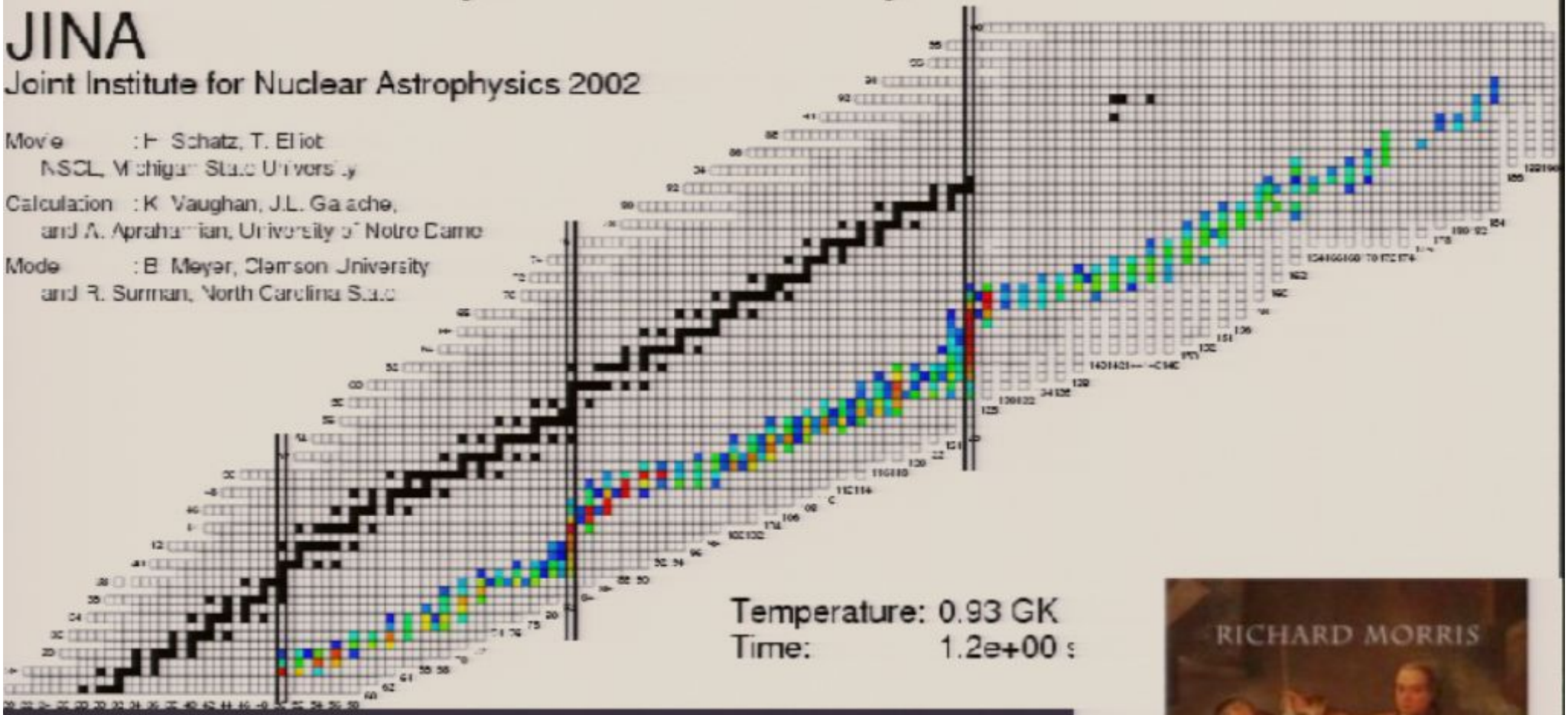

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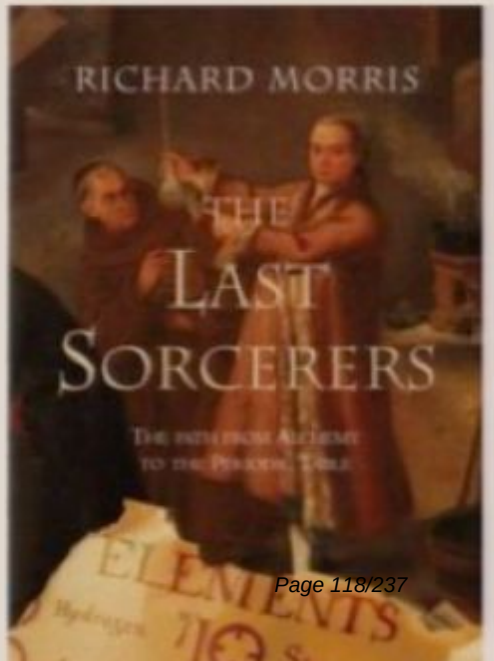

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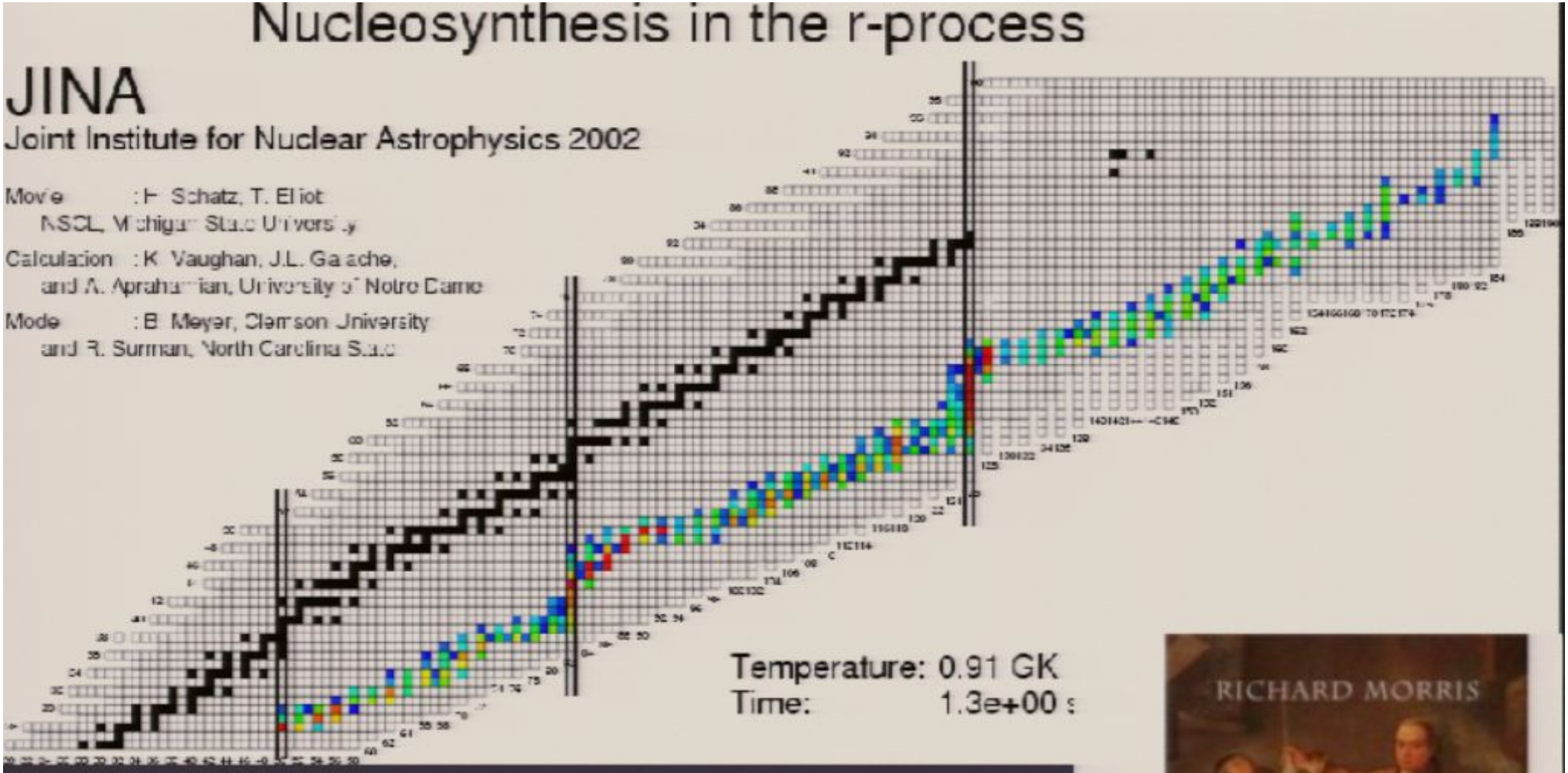

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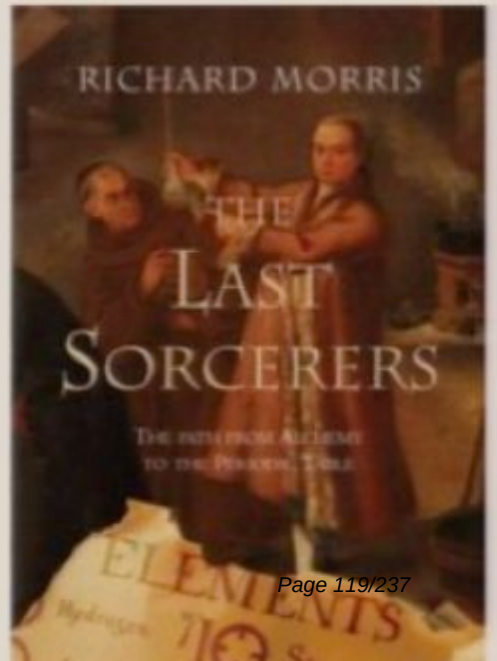

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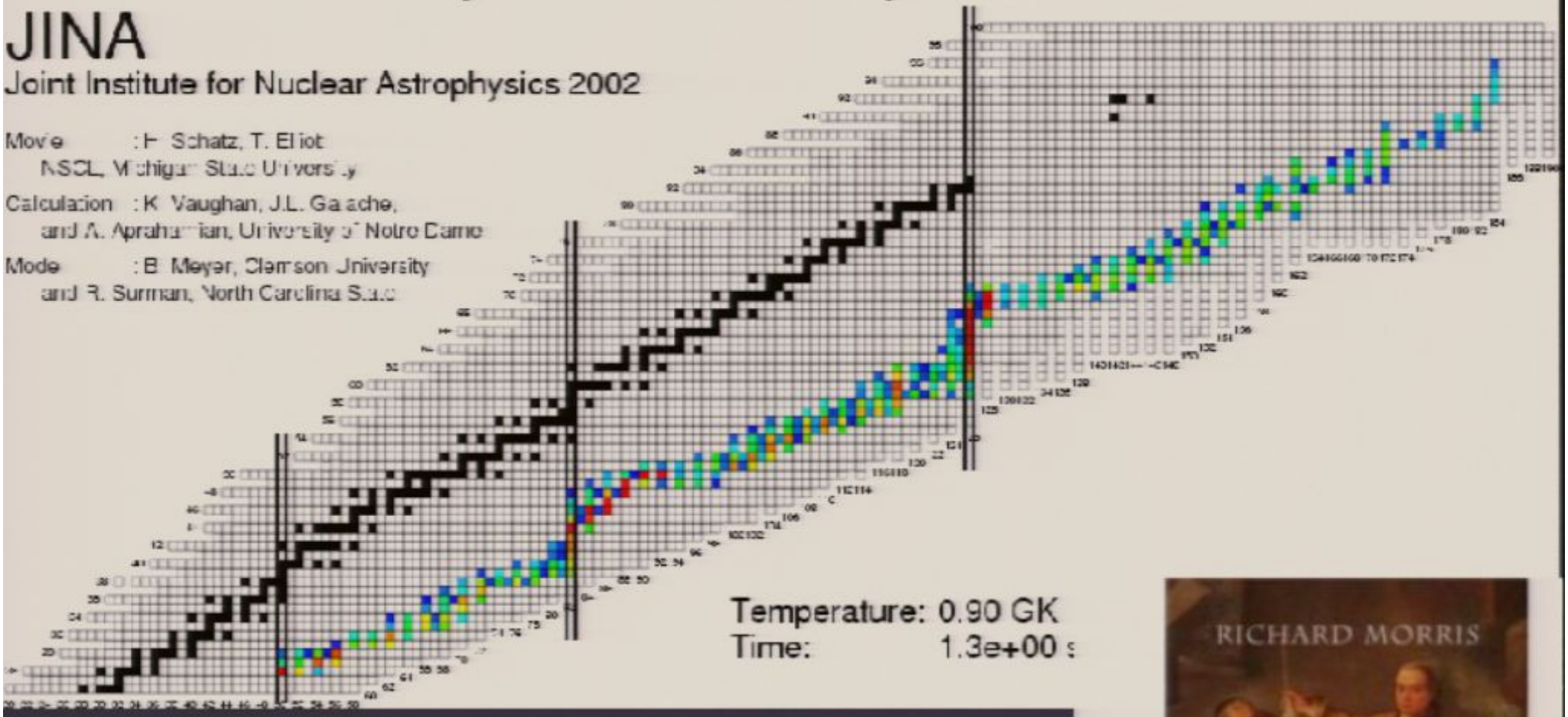

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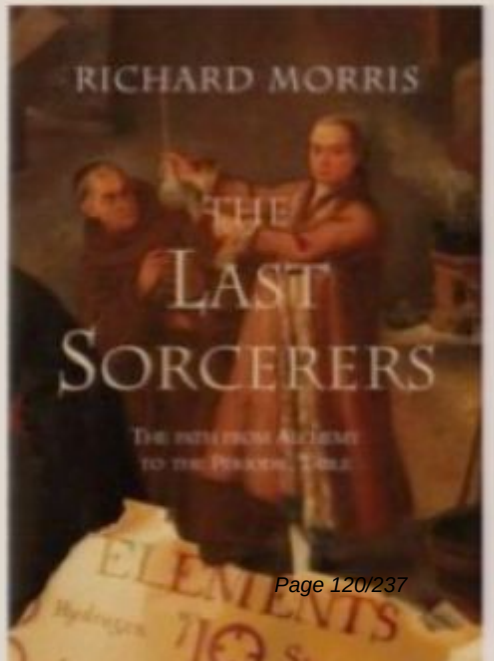

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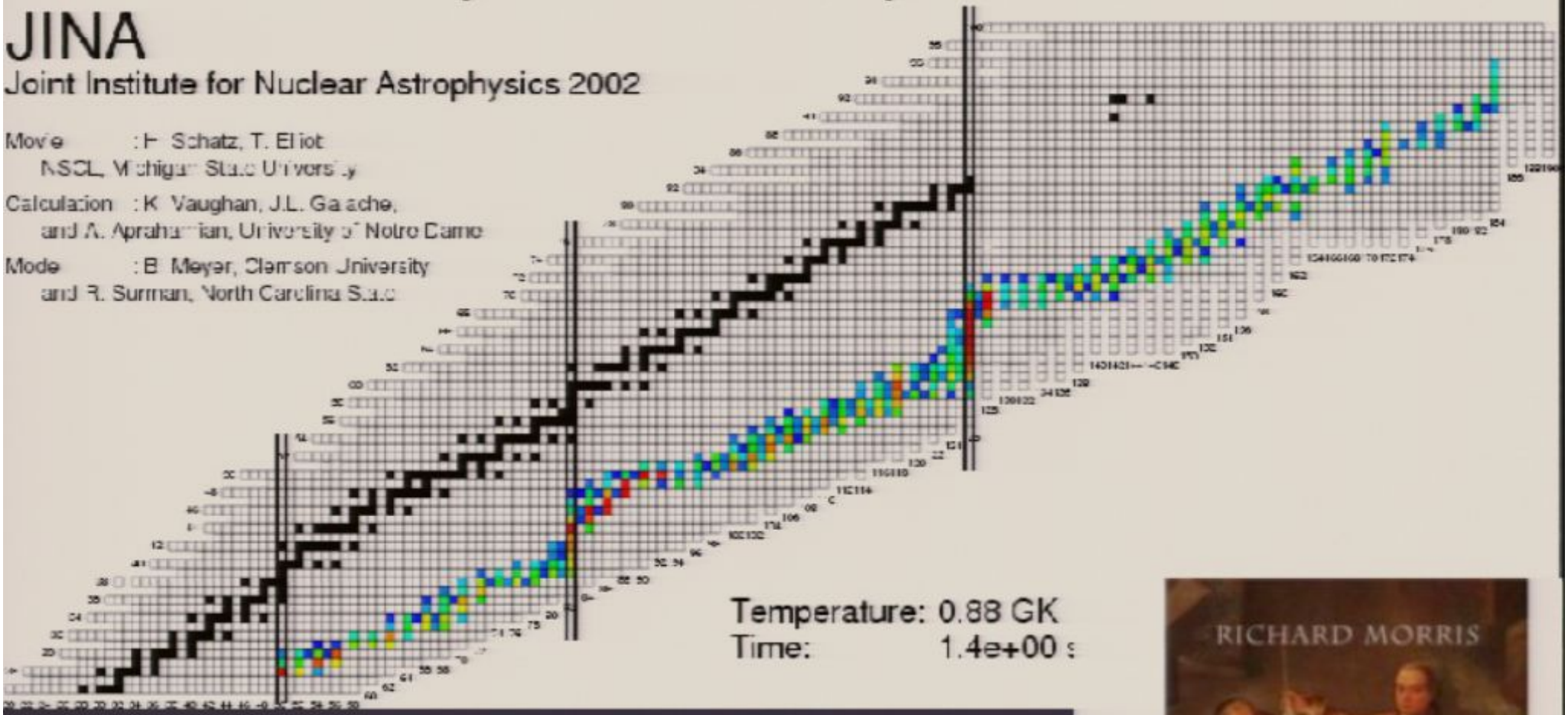

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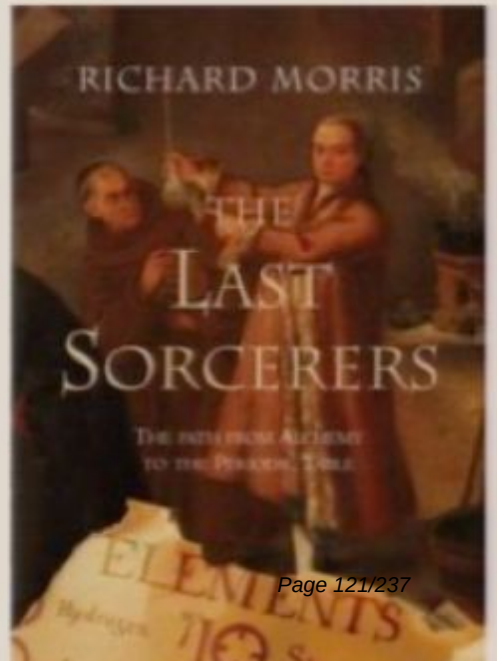

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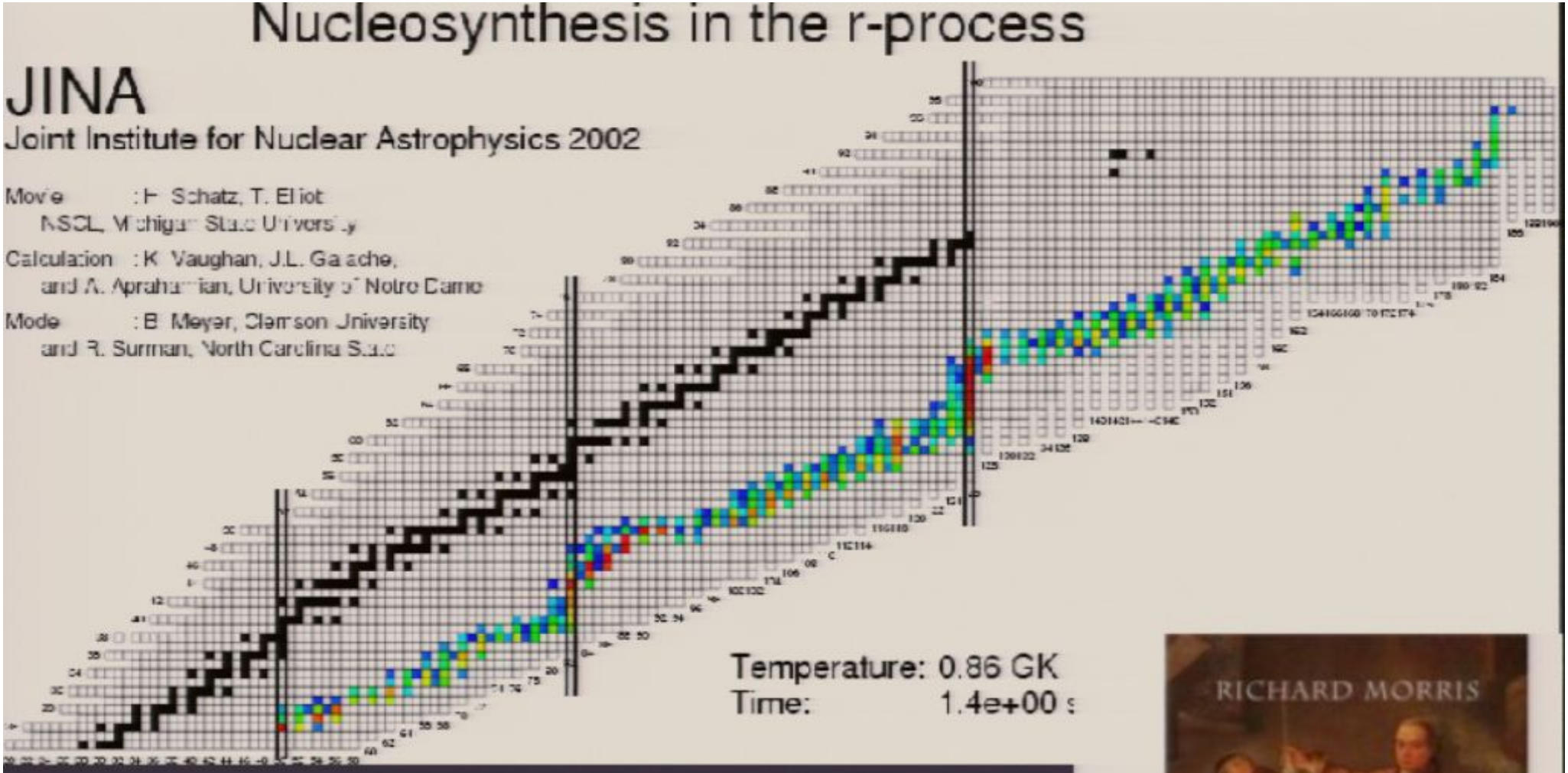

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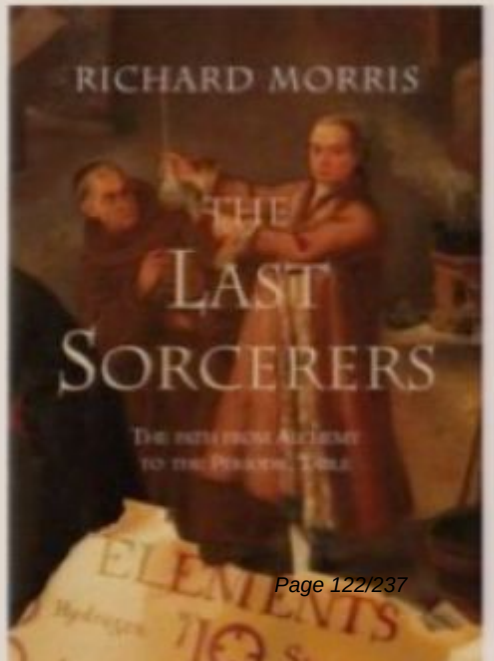
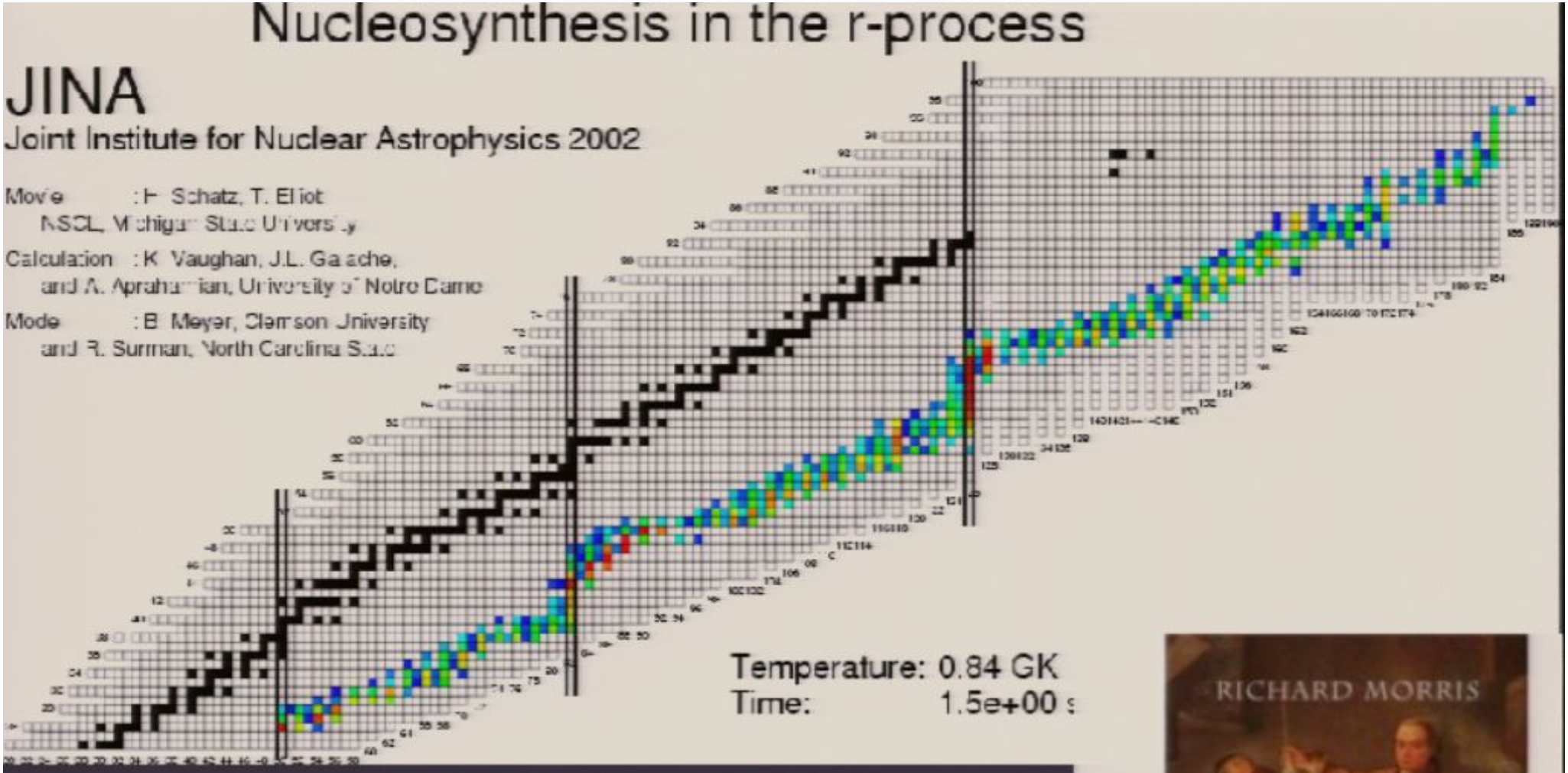


Nucleosynthesis in the r-process



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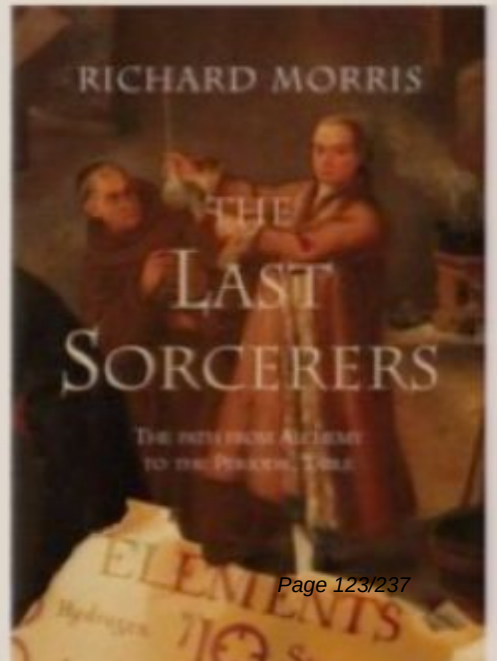

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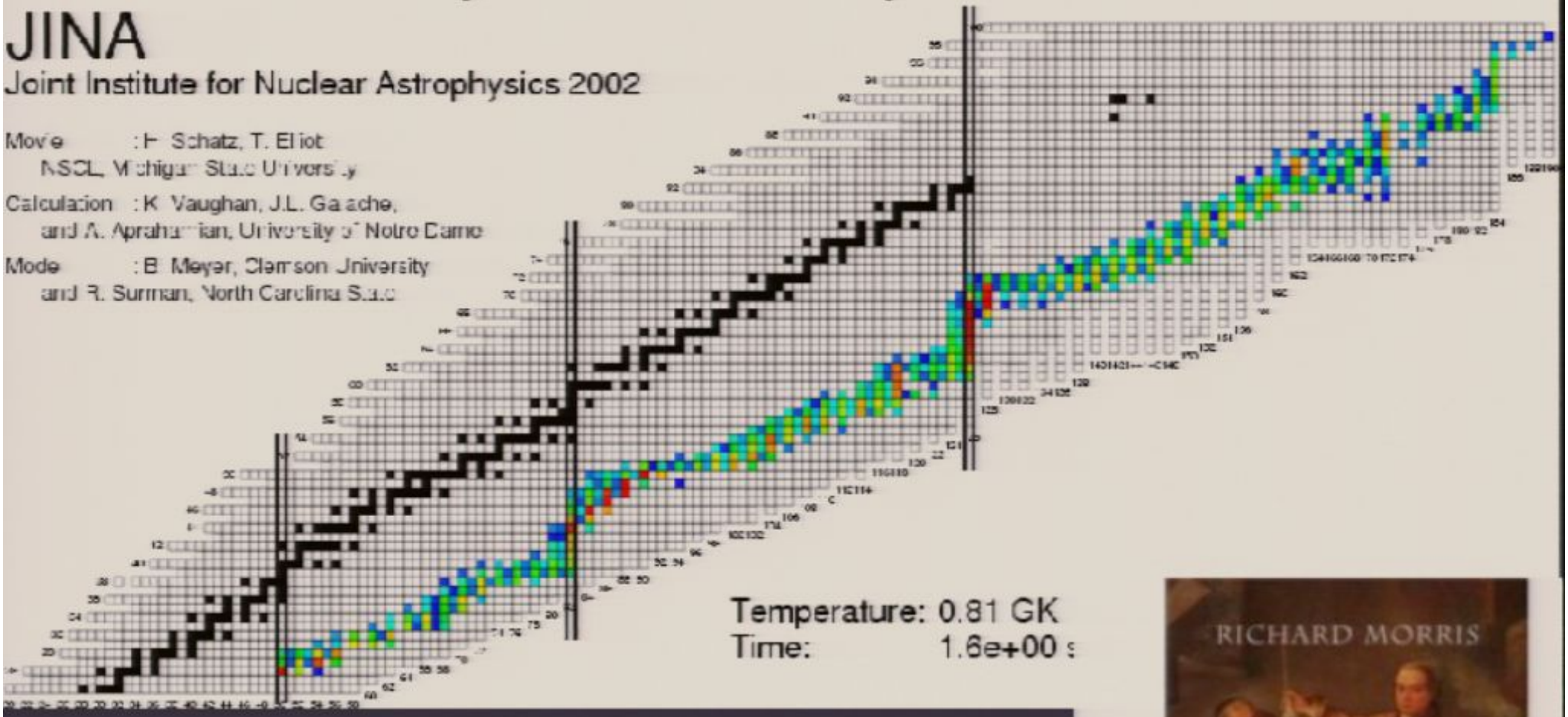

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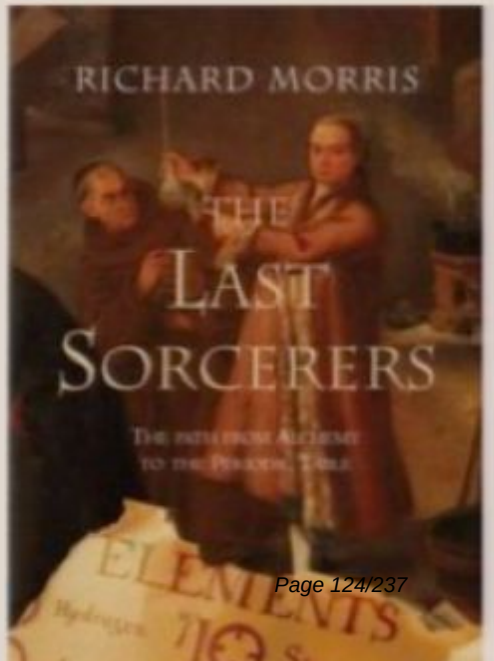

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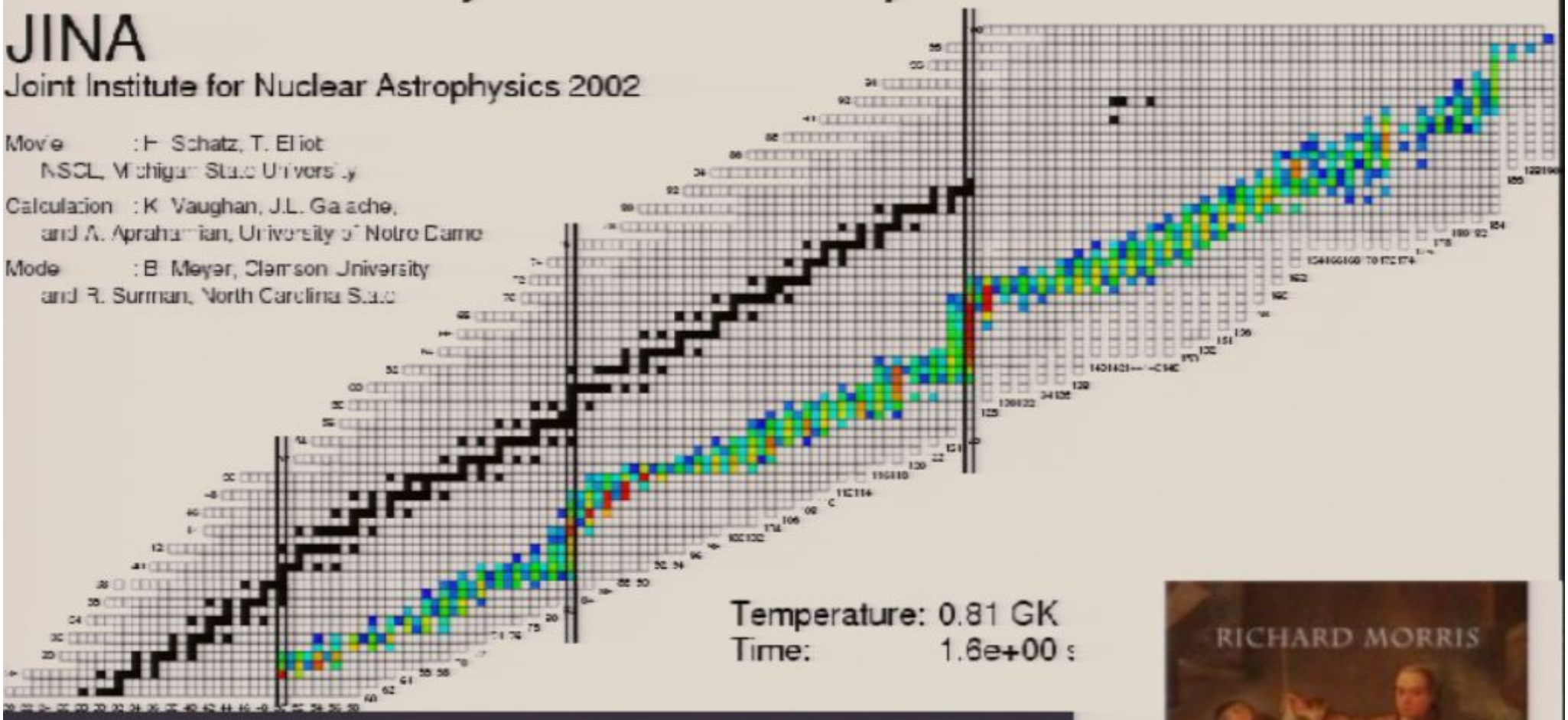

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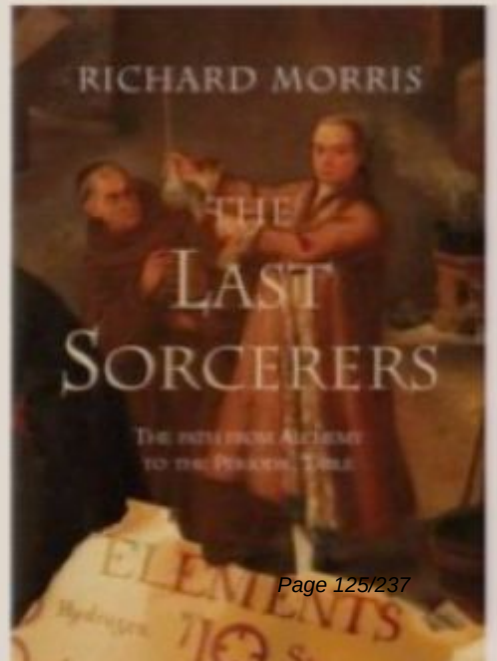

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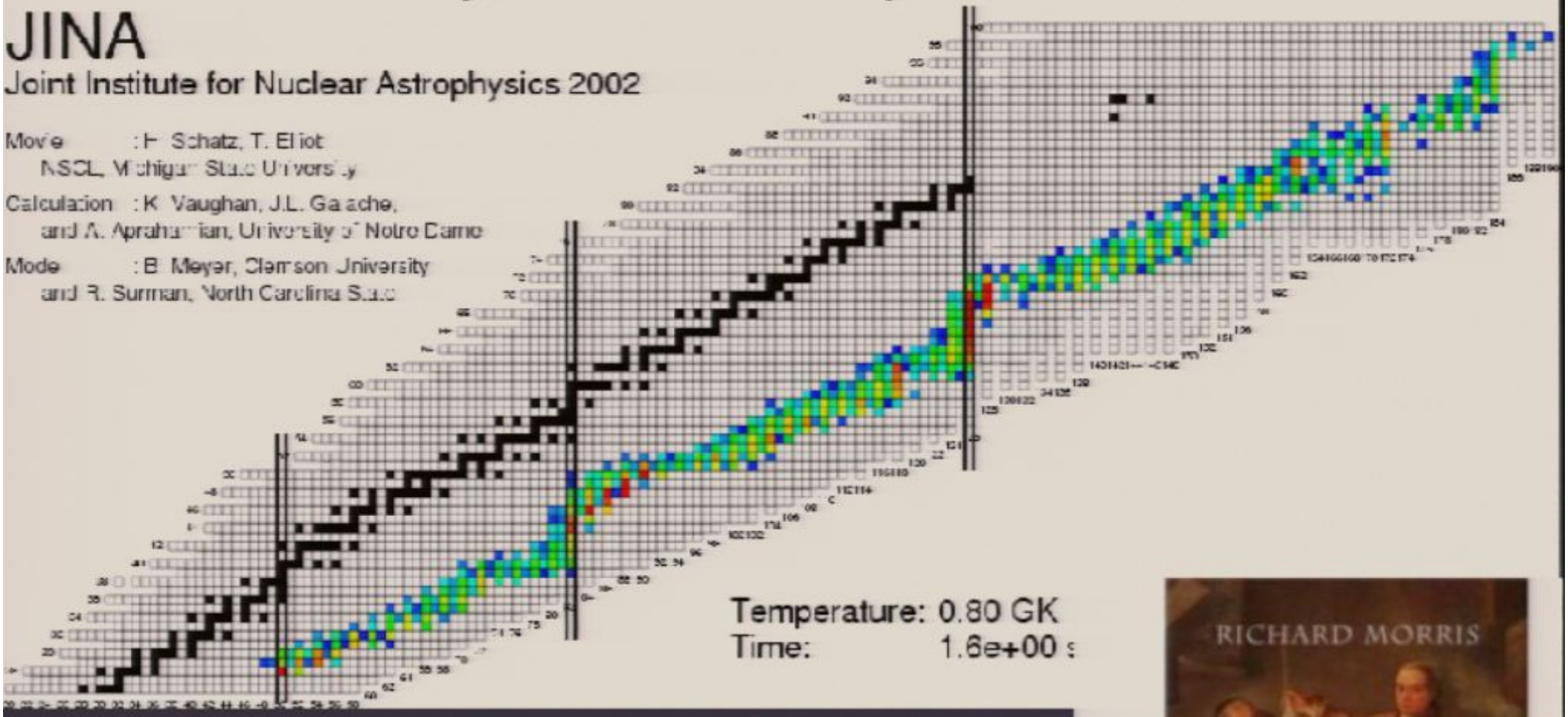

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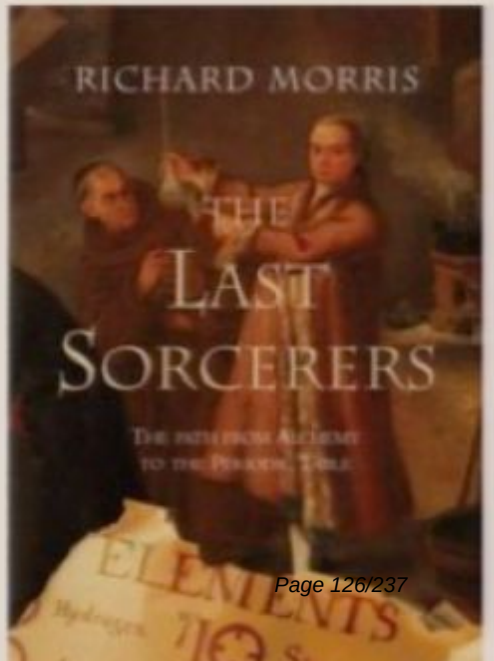
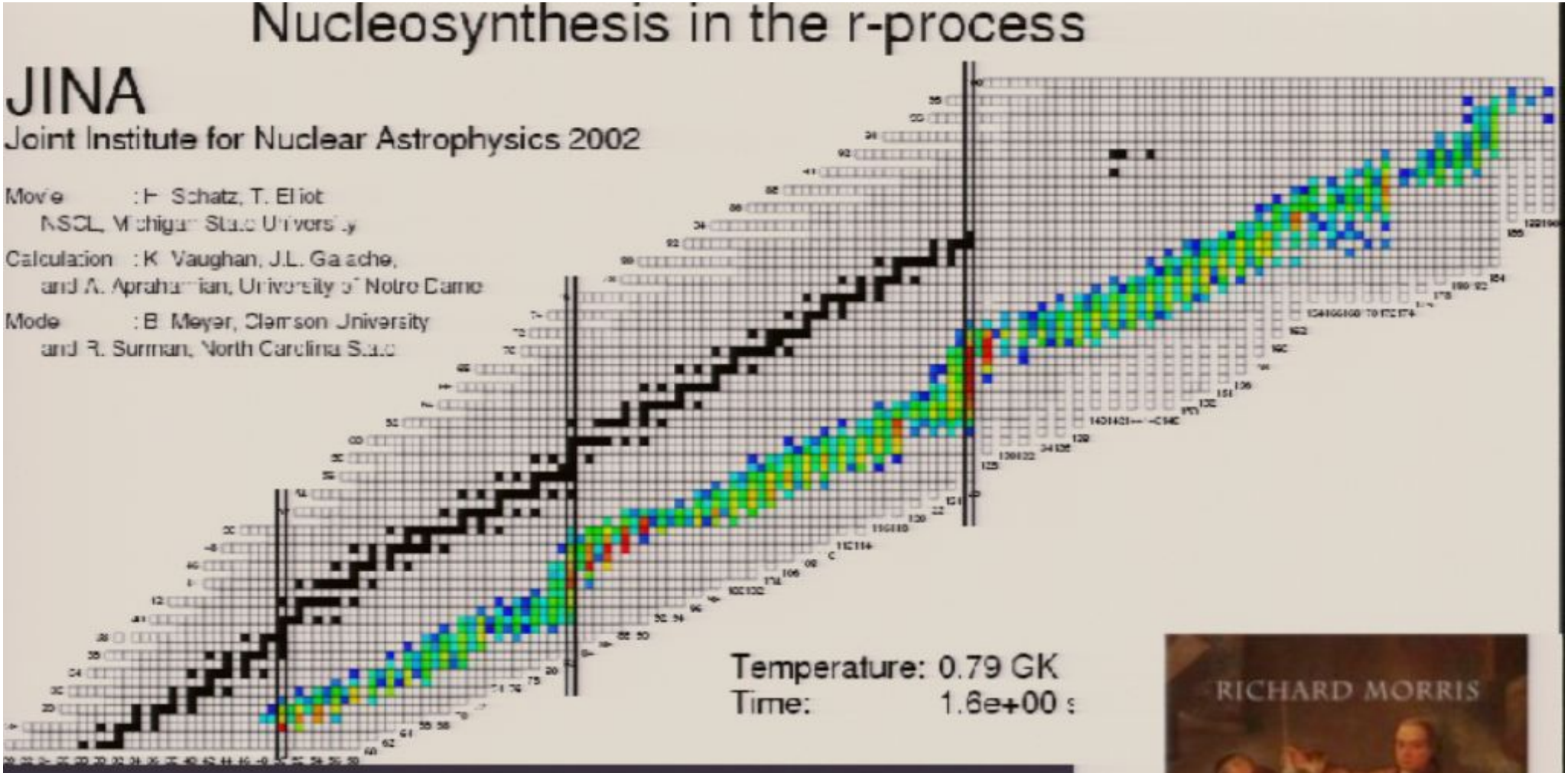


Nucleosynthesis in the r-process



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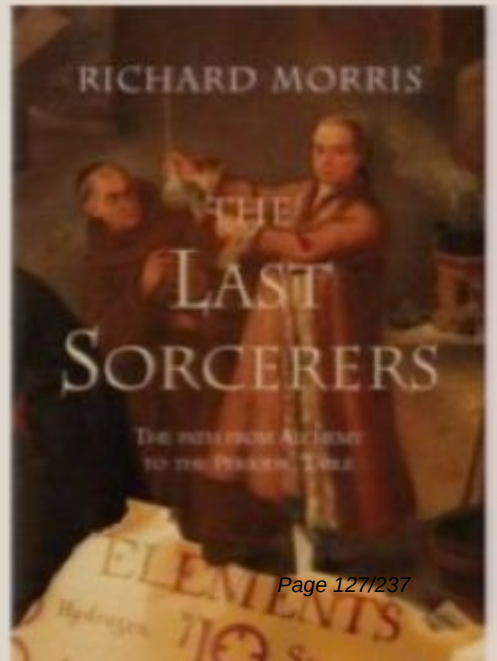

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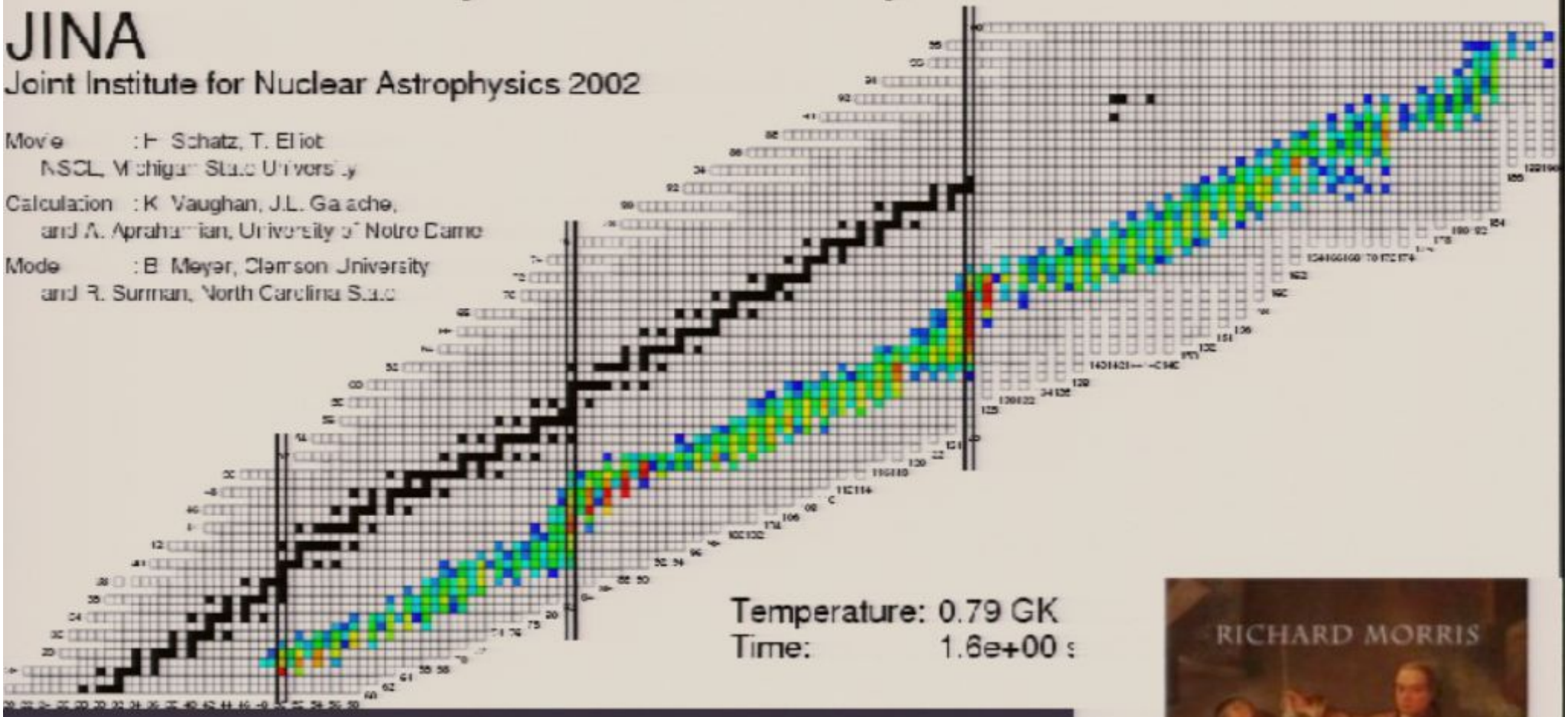

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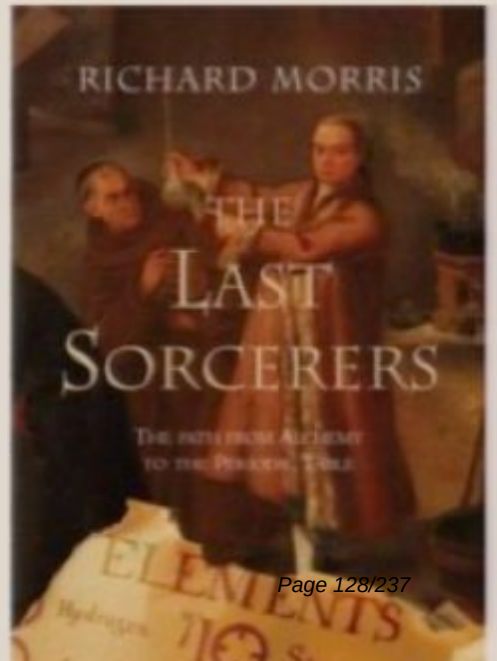

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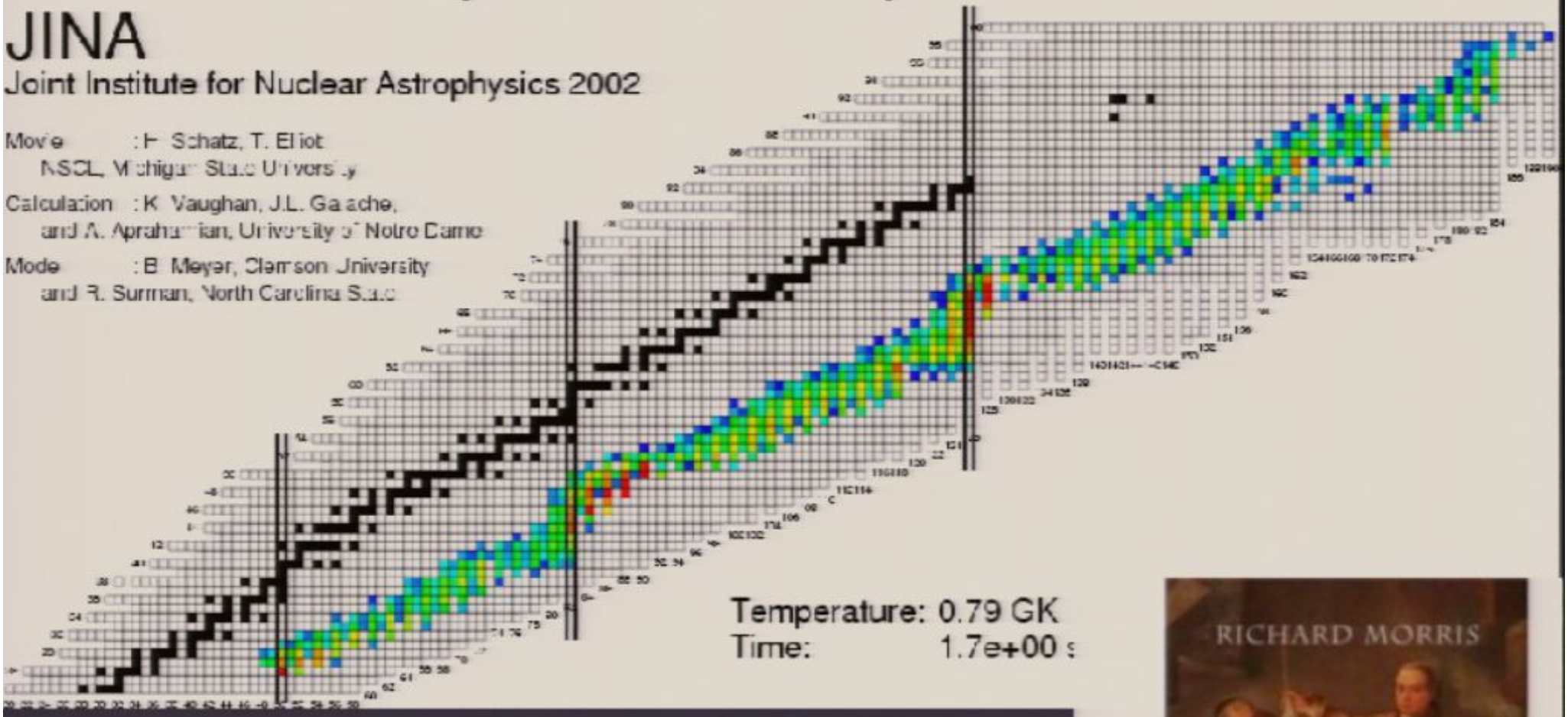

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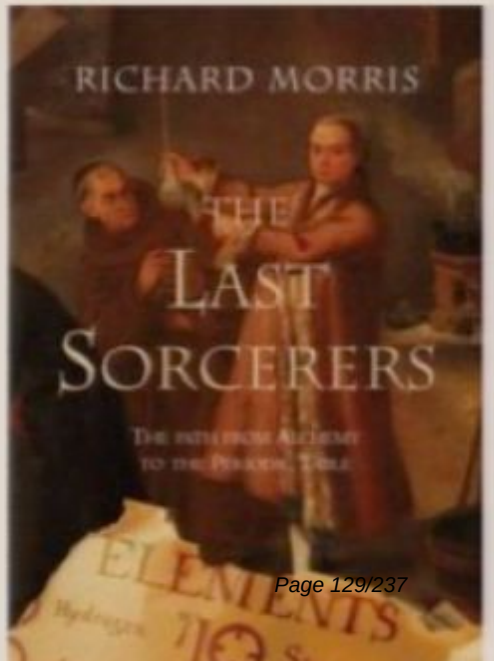
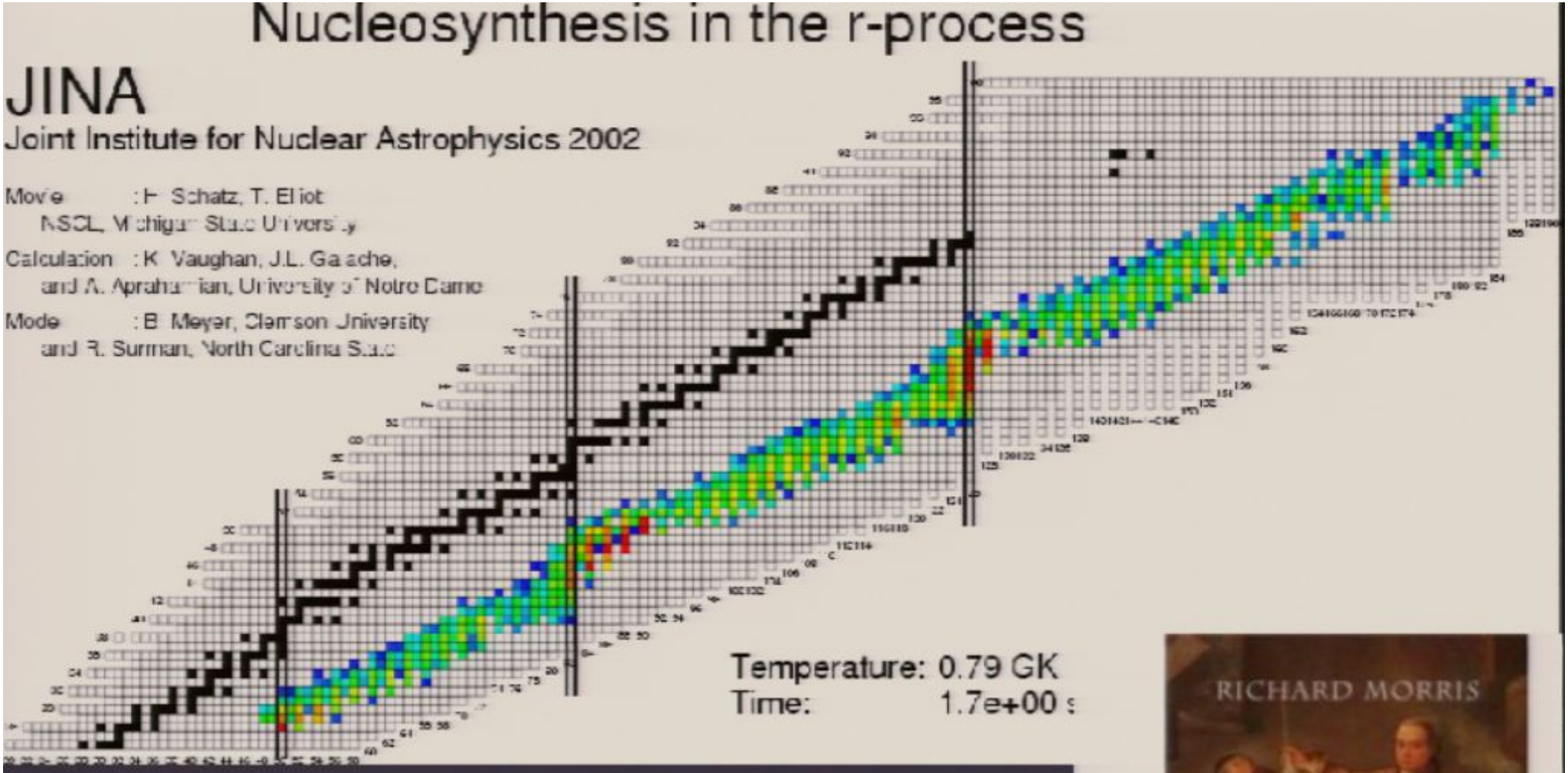


Nucleosynthesis in the r-process



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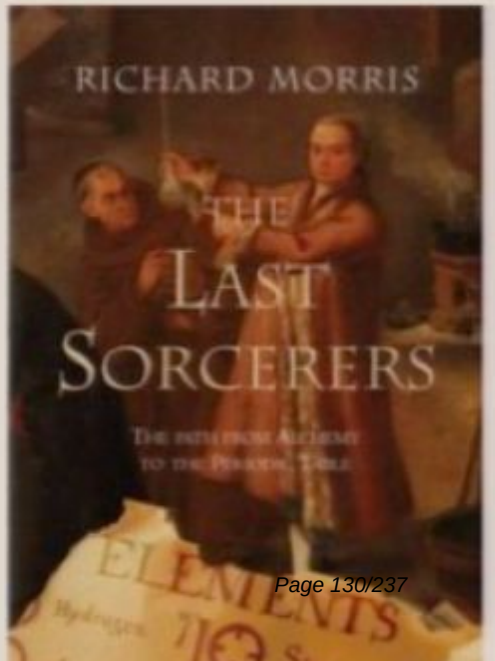

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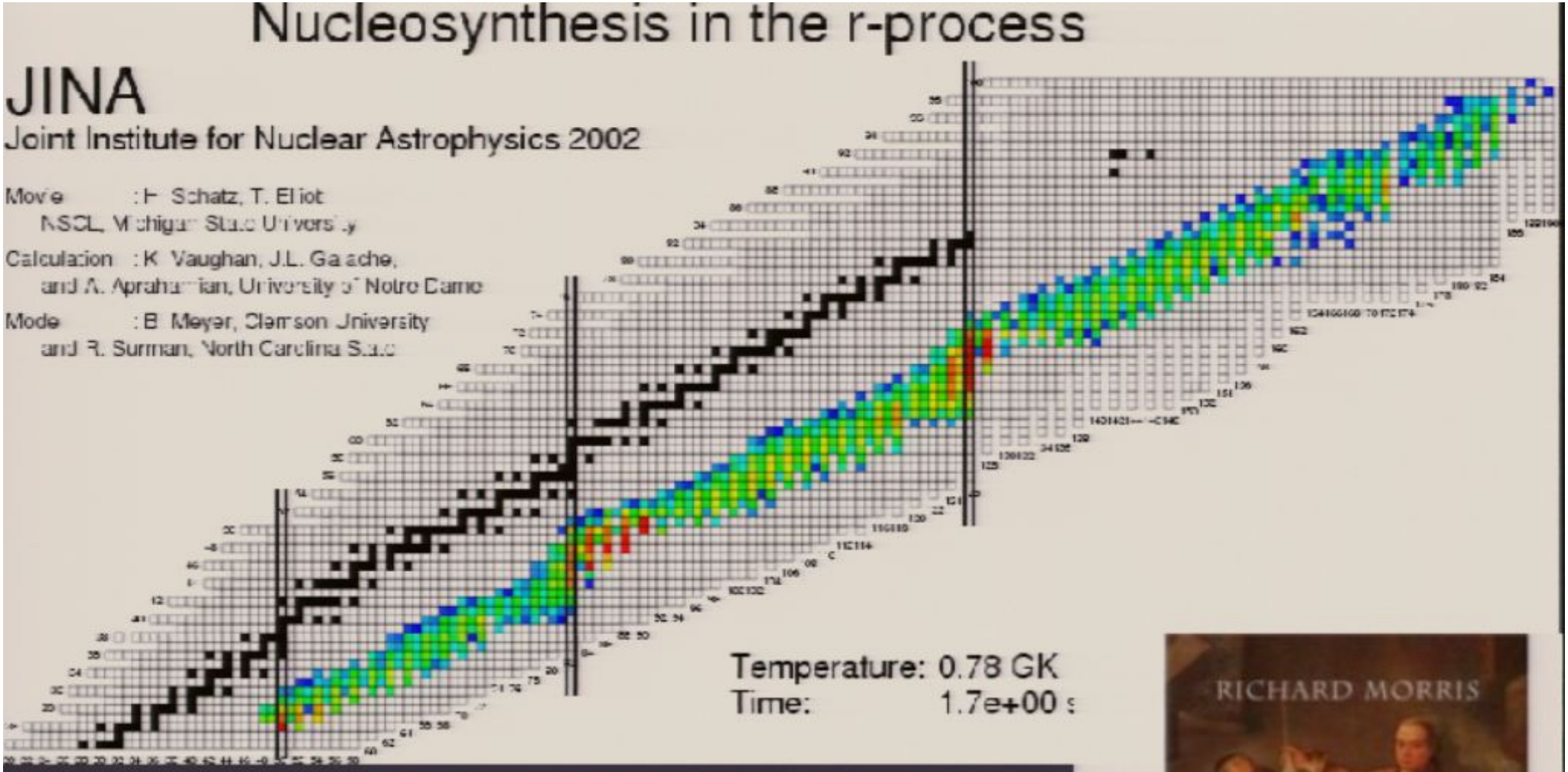

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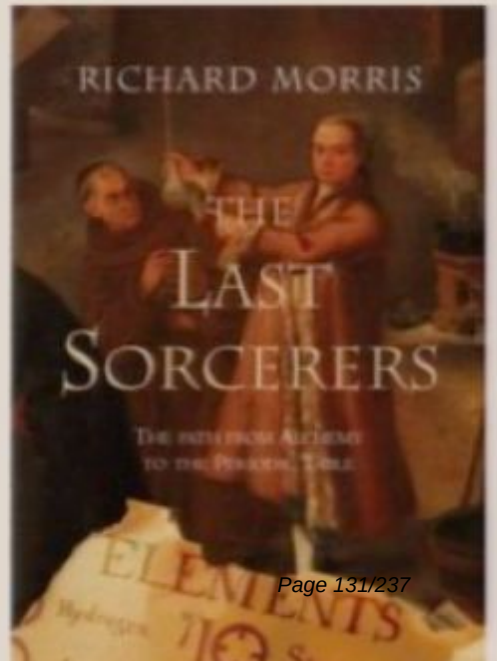
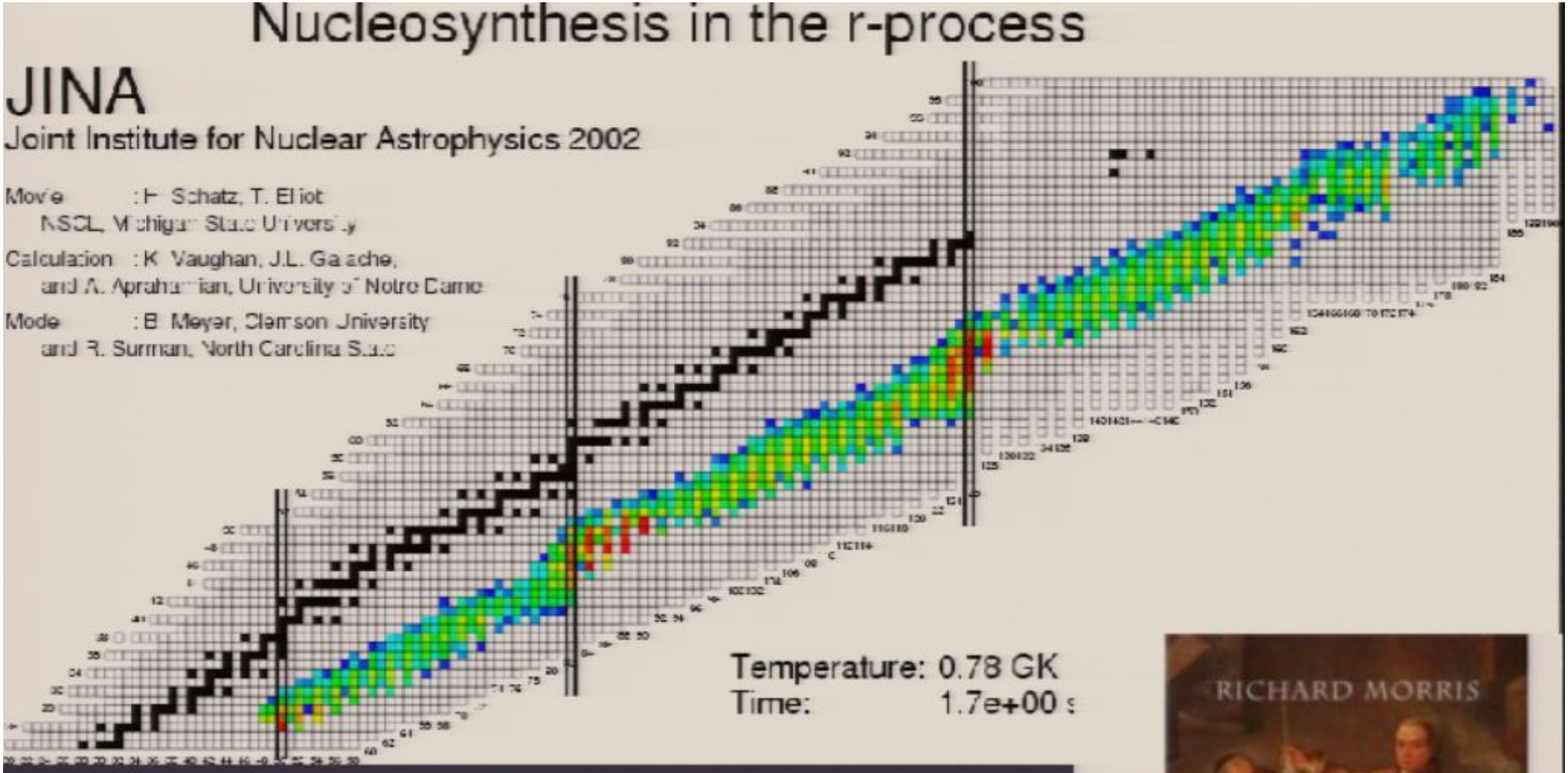


Nucleosynthesis in the r-process



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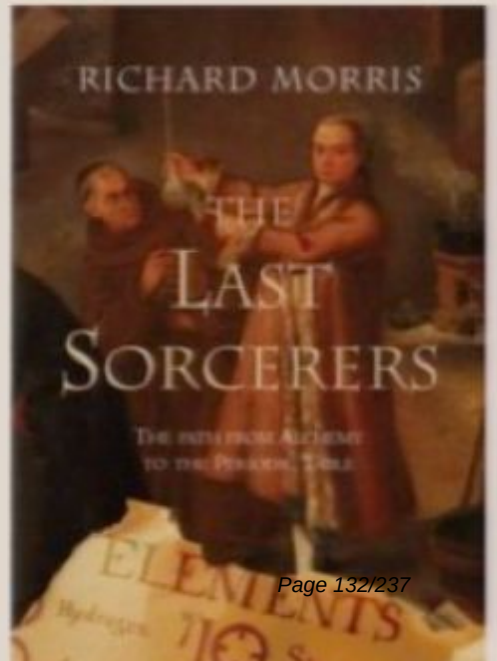
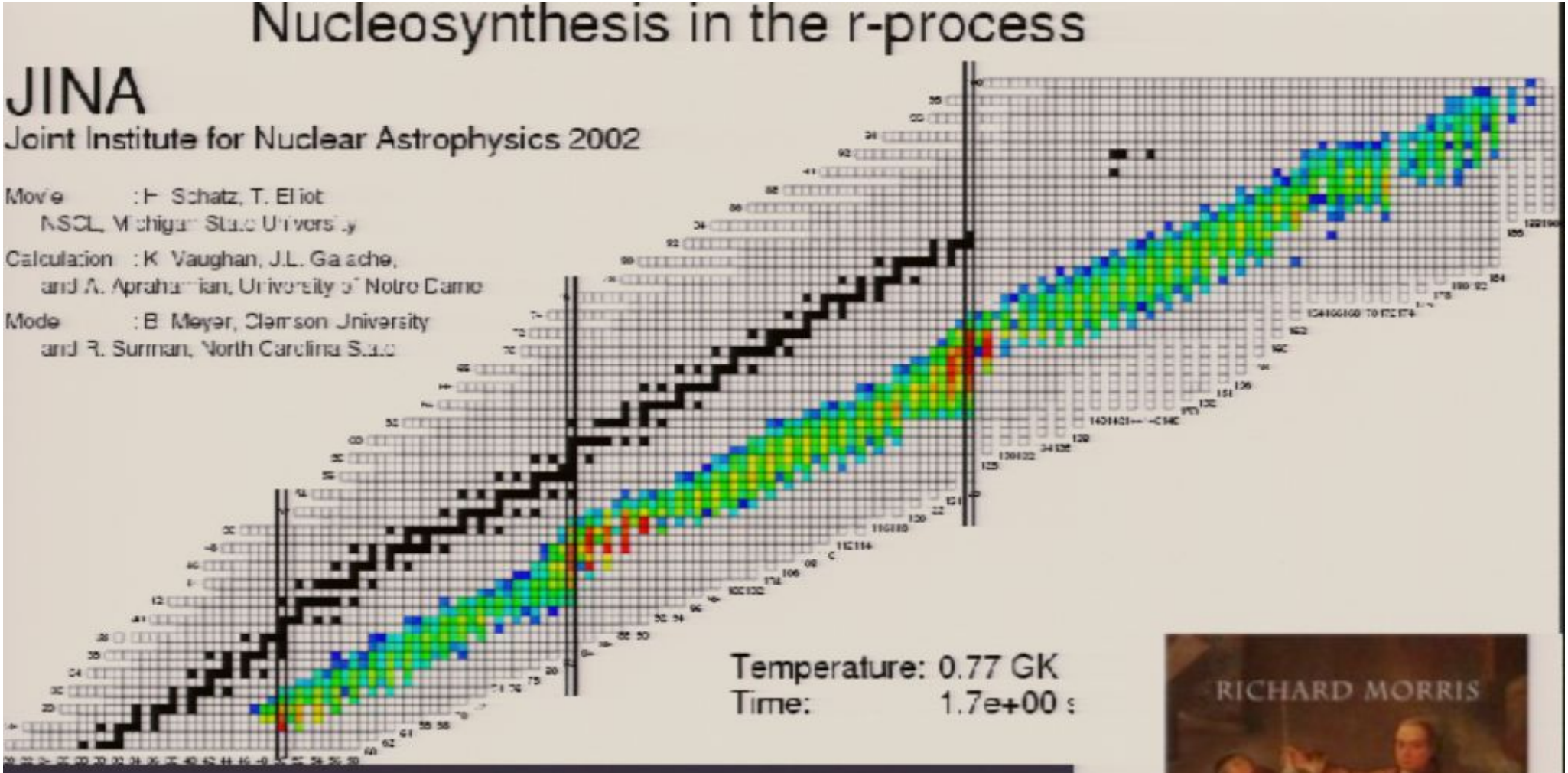


Nucleosynthesis in the r-process



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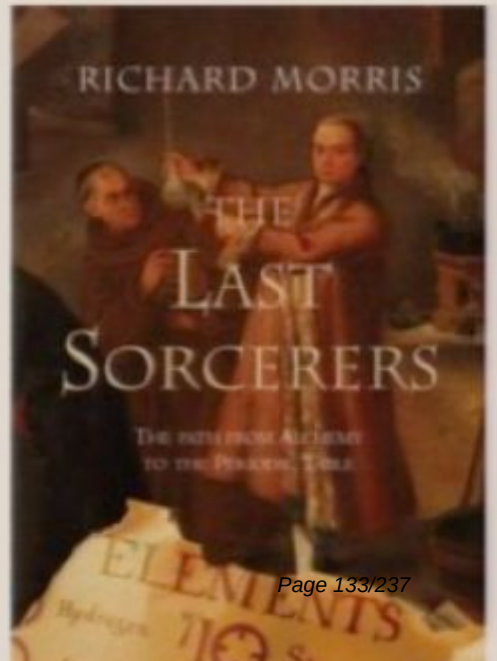
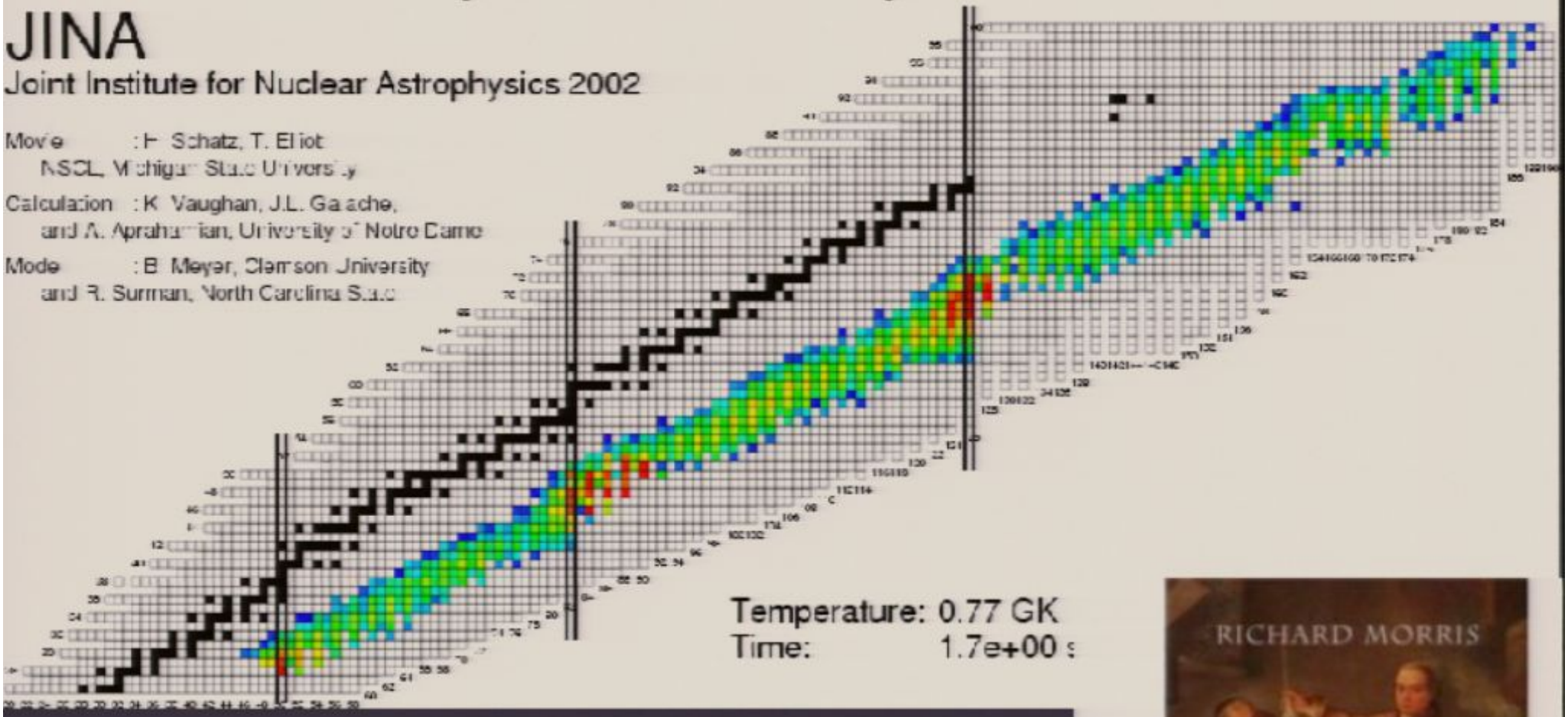


Nucleosynthesis in the r-process



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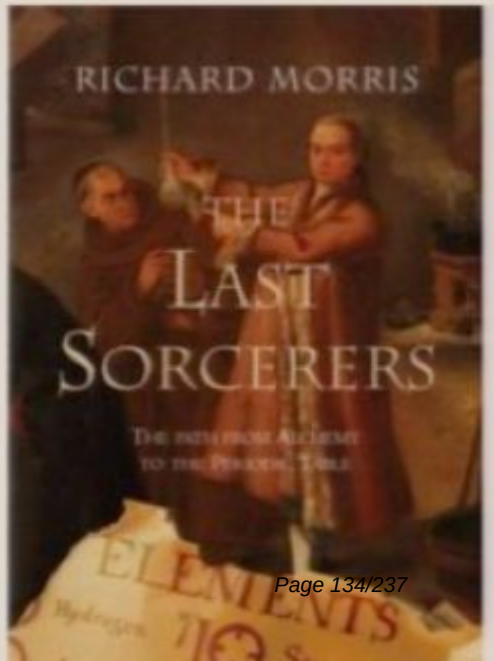
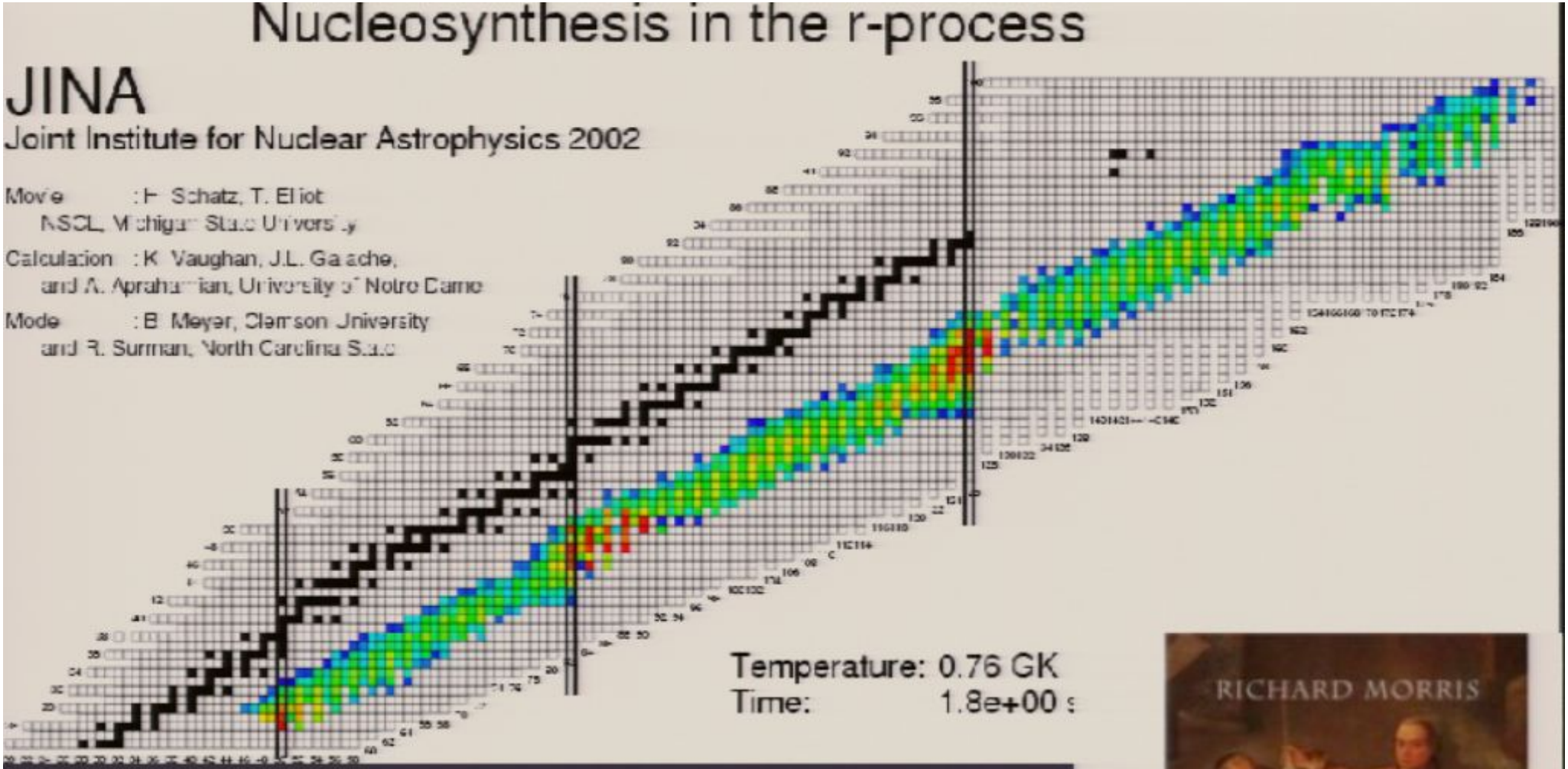


Nucleosynthesis in the r-process



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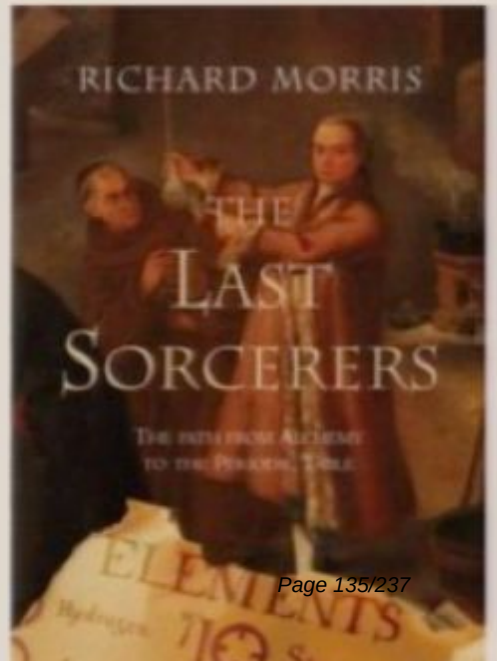

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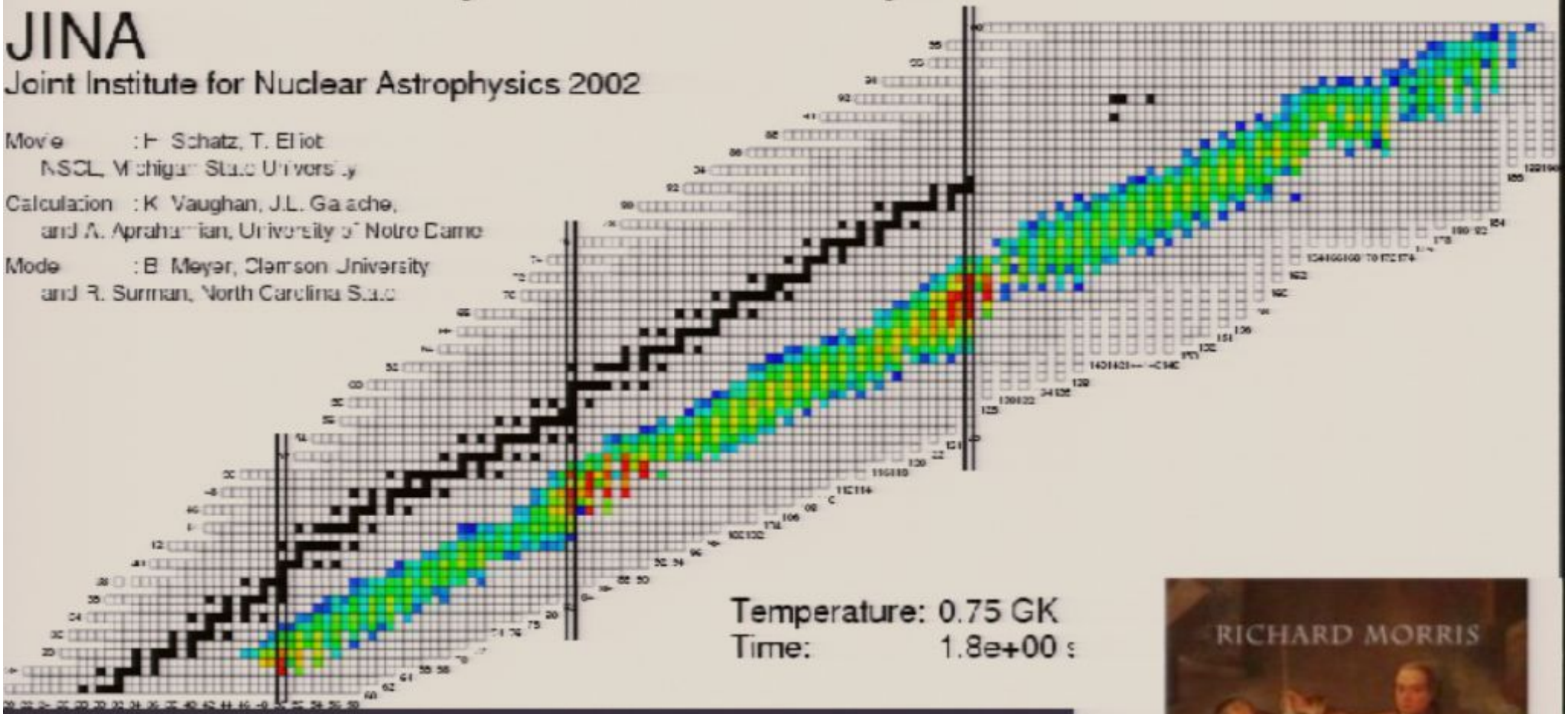

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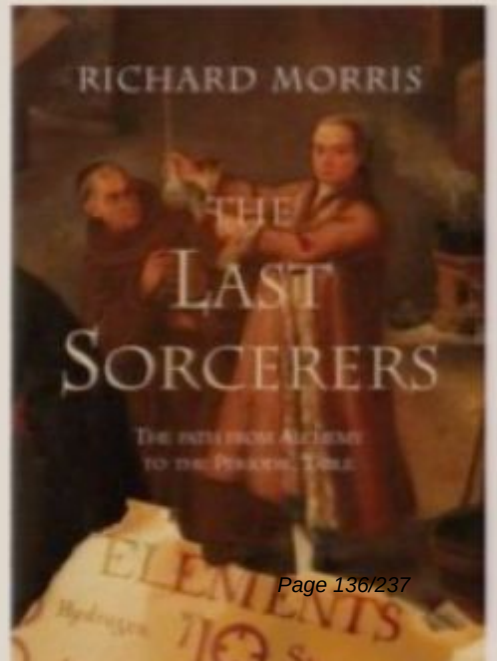

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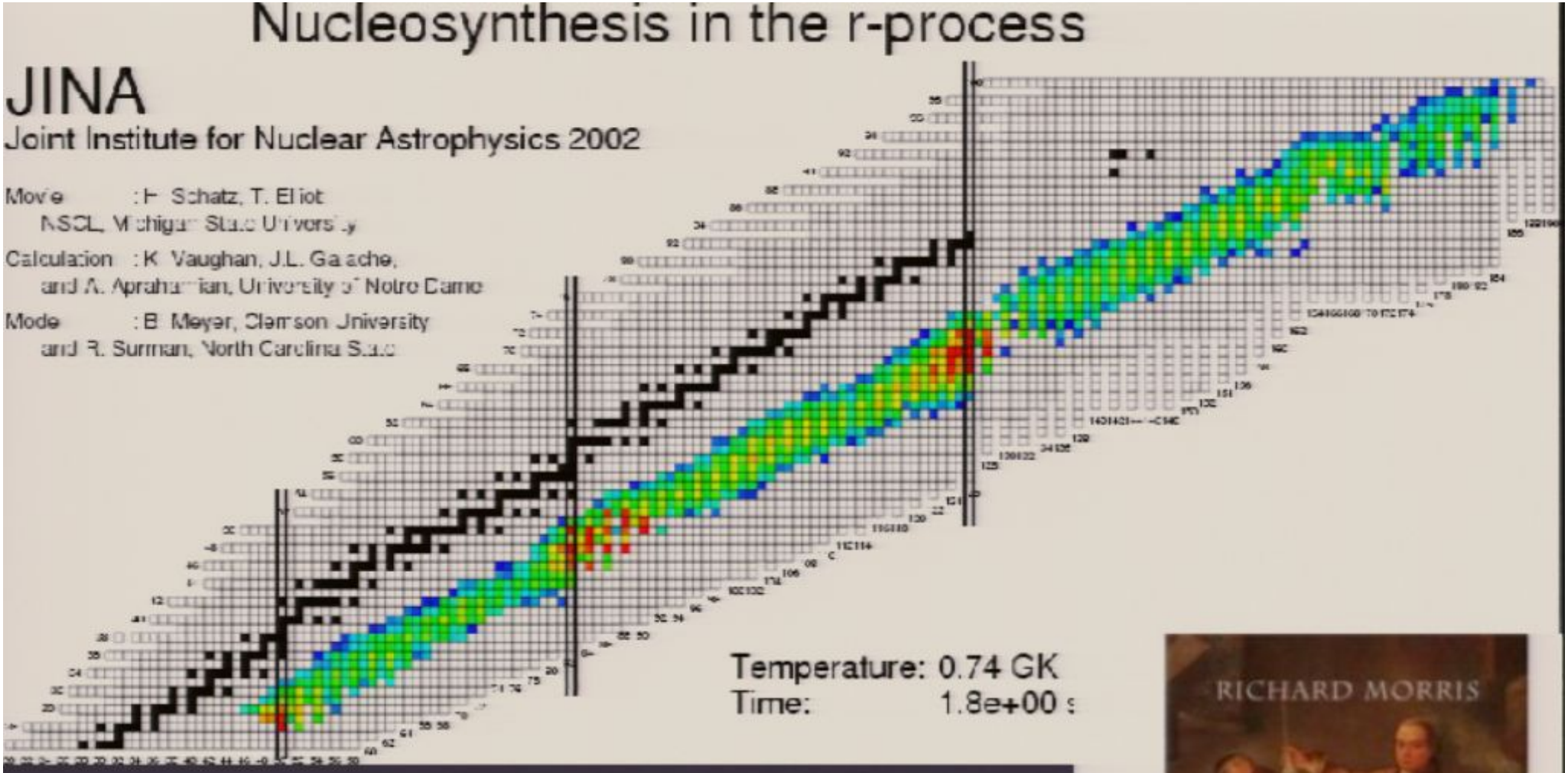

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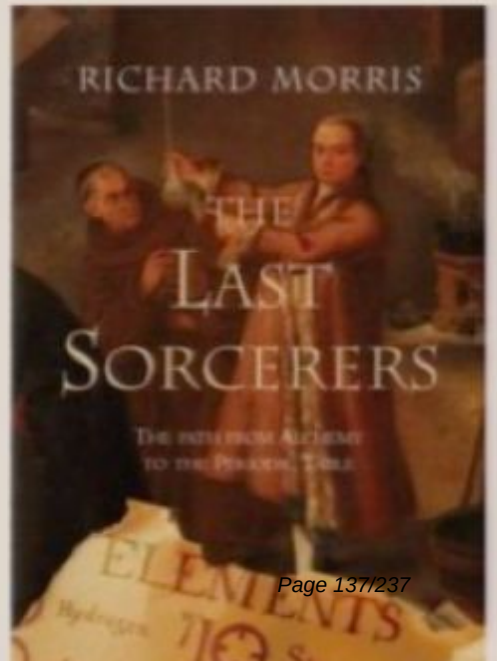
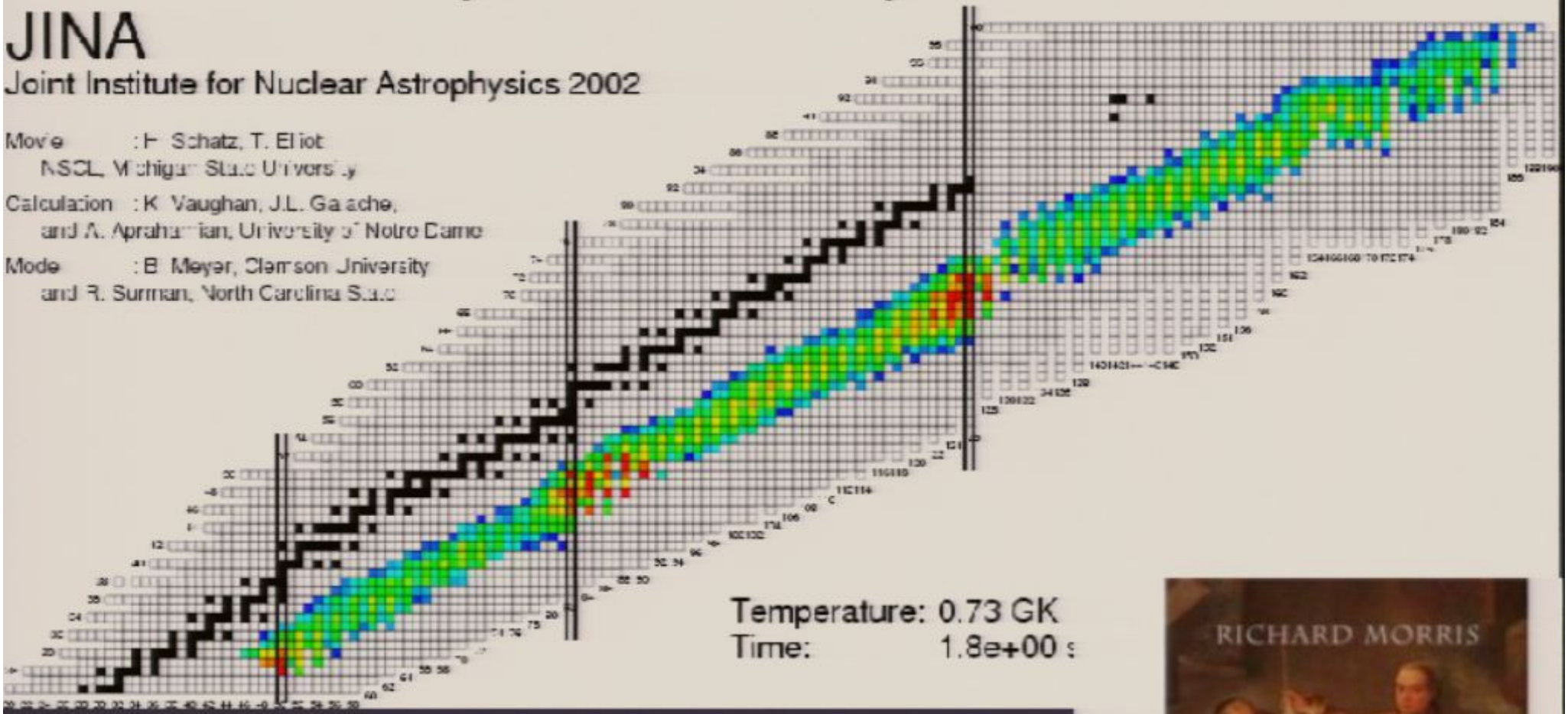


Nucleosynthesis in the r-process



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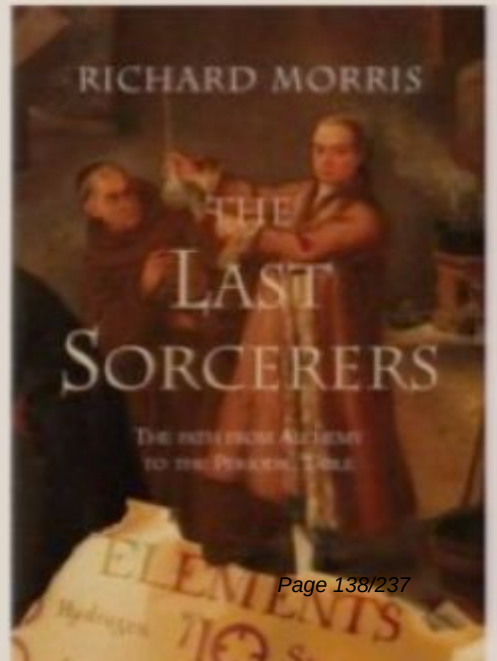

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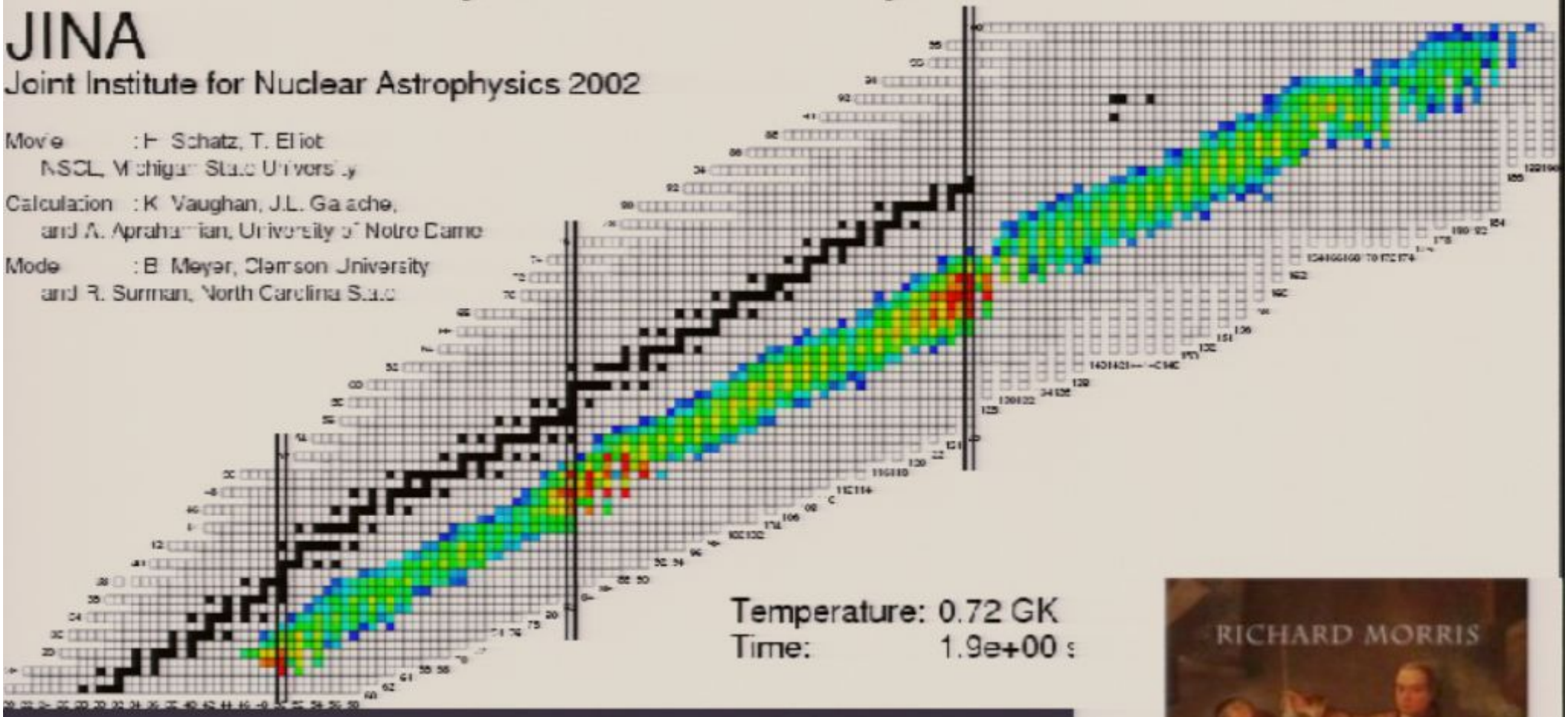

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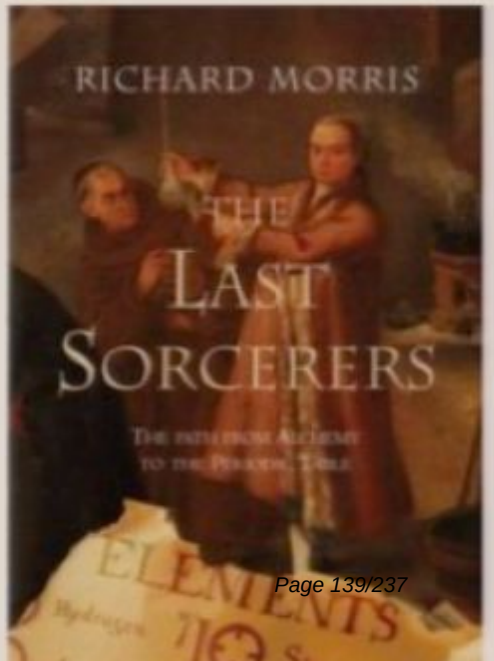

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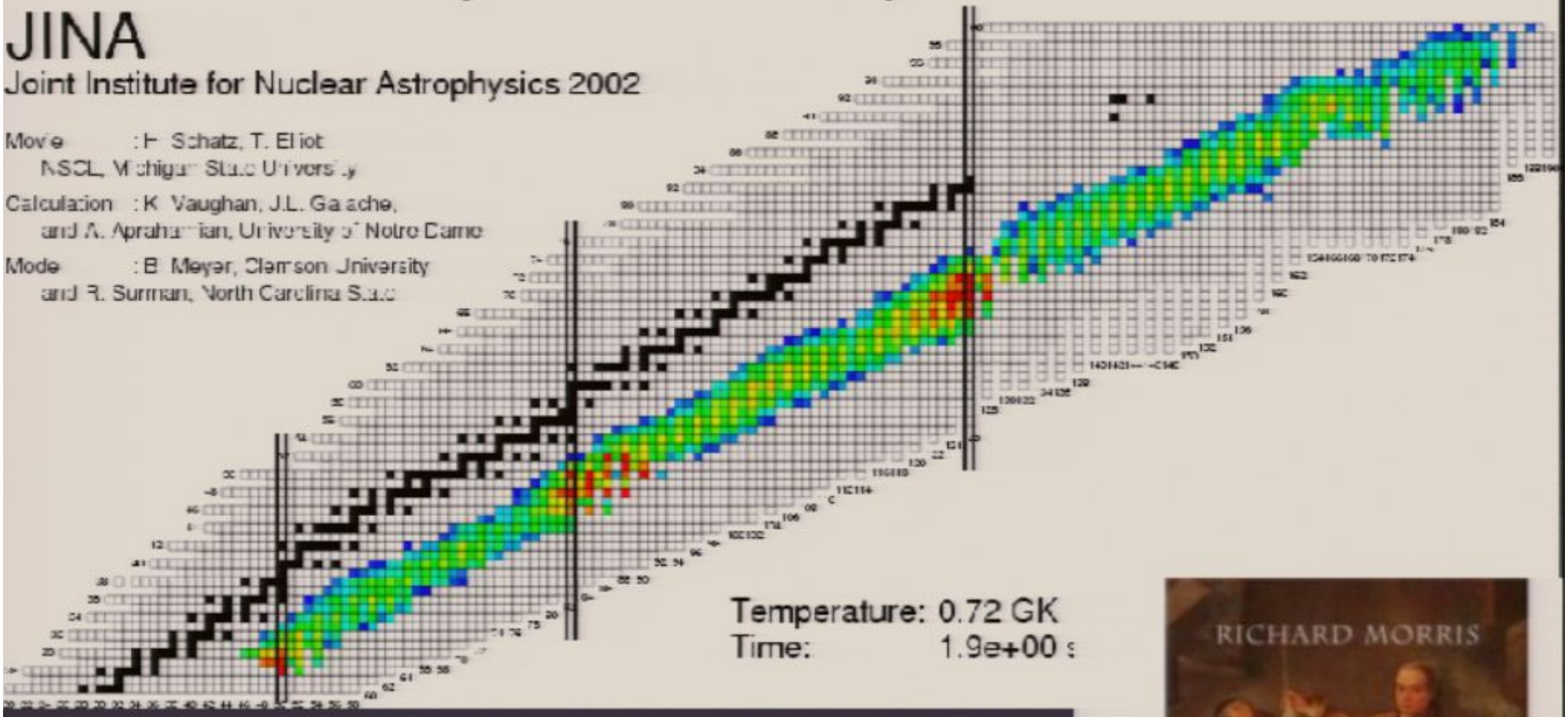

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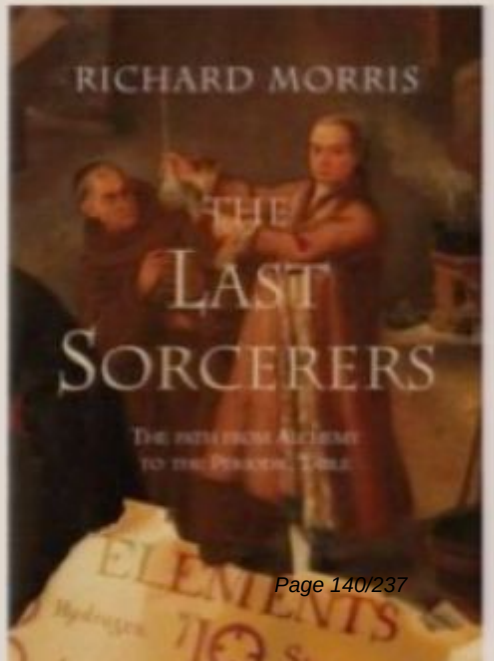
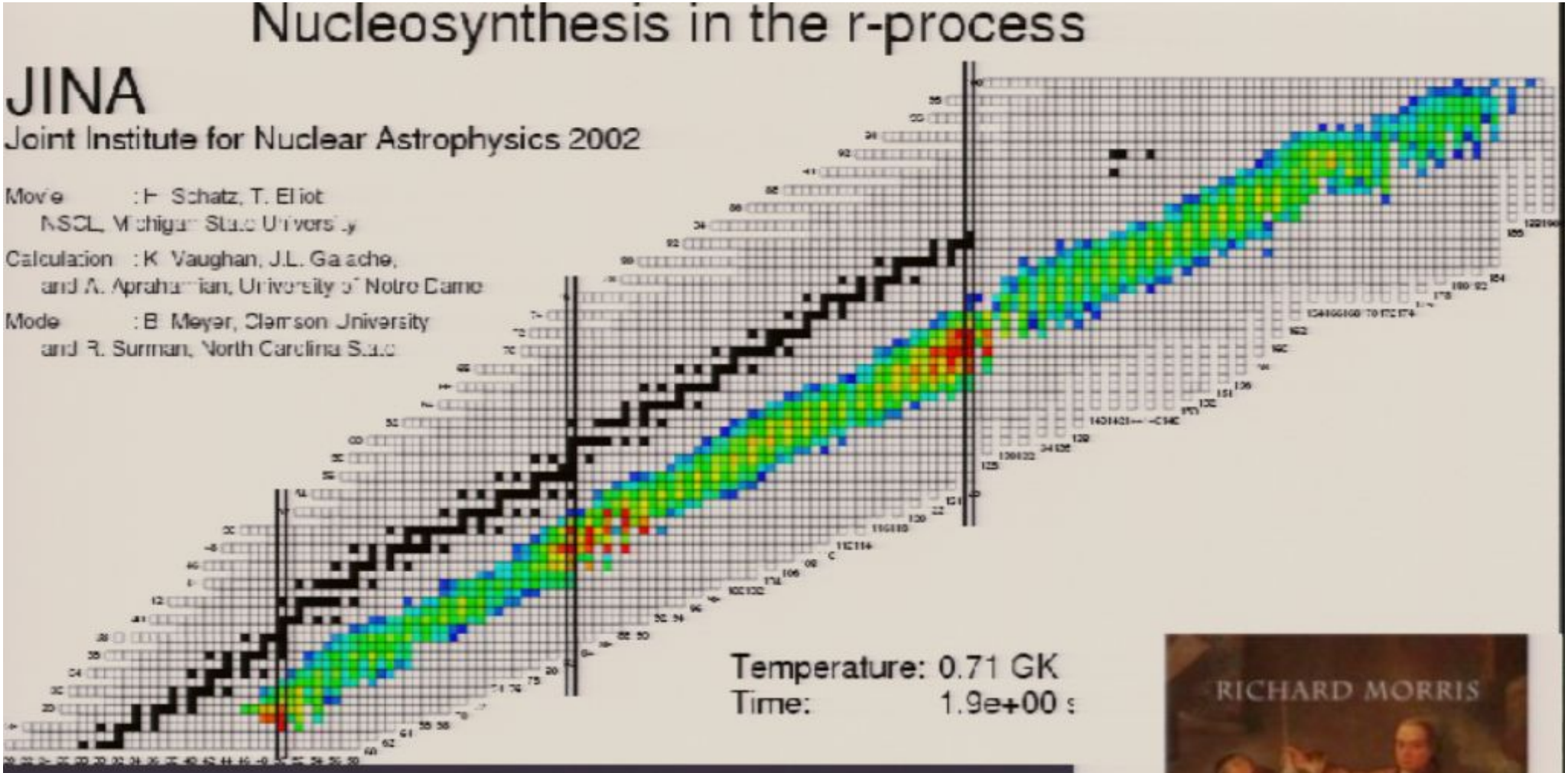


Nucleosynthesis in the r-process



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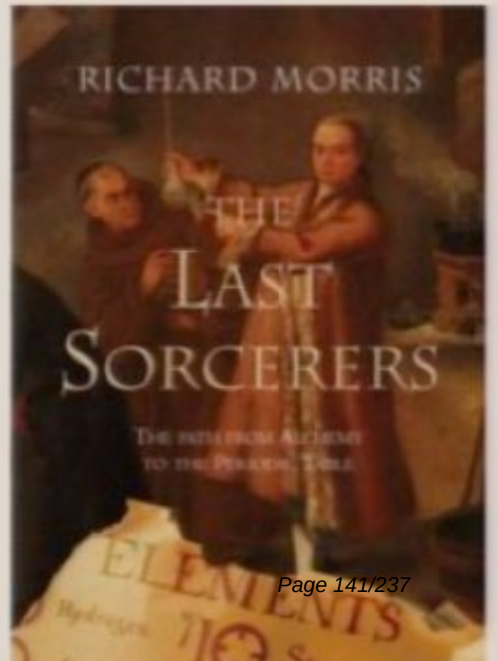
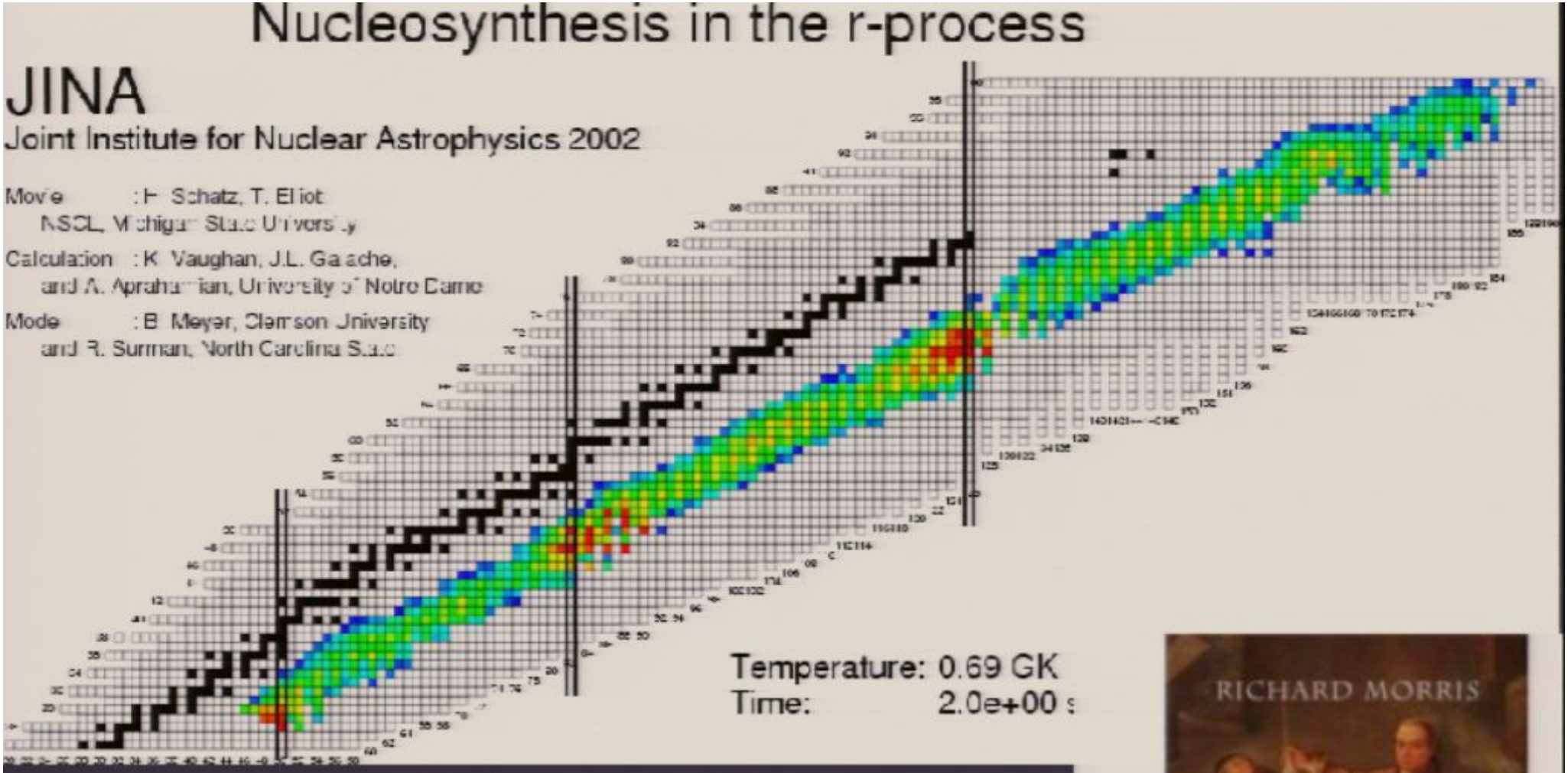


Nucleosynthesis in the r-process



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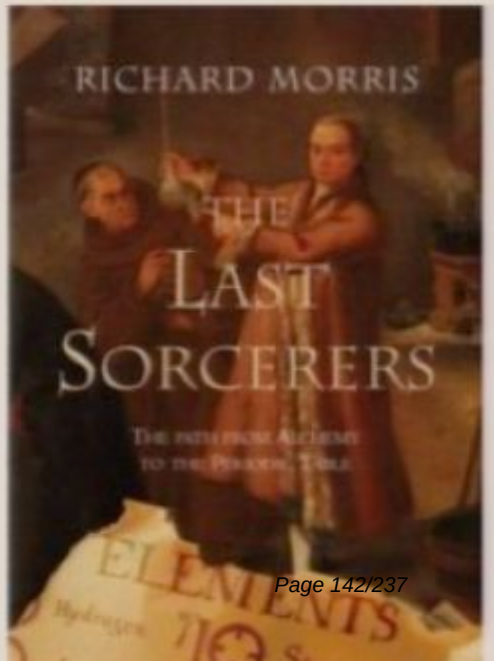

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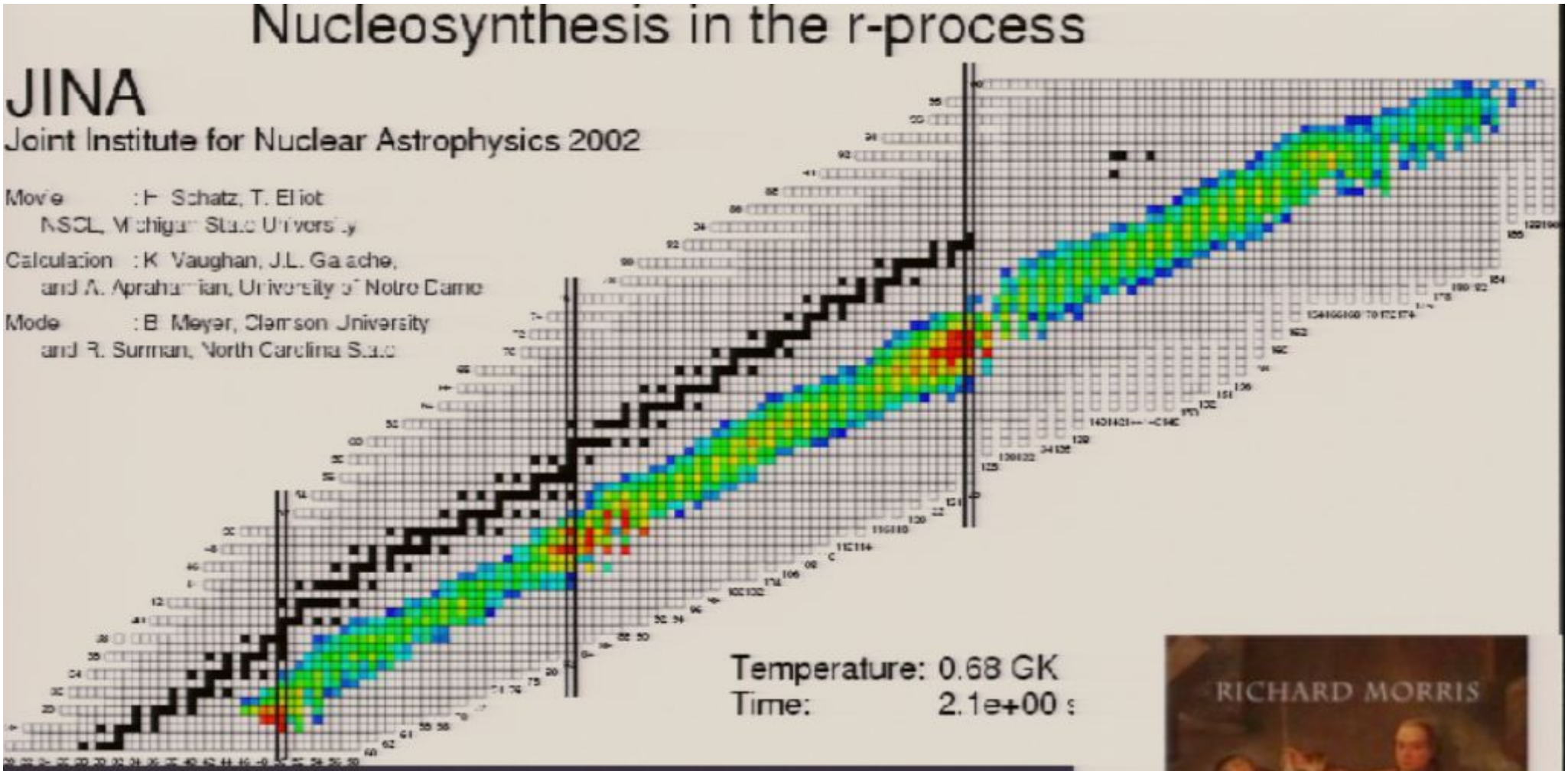

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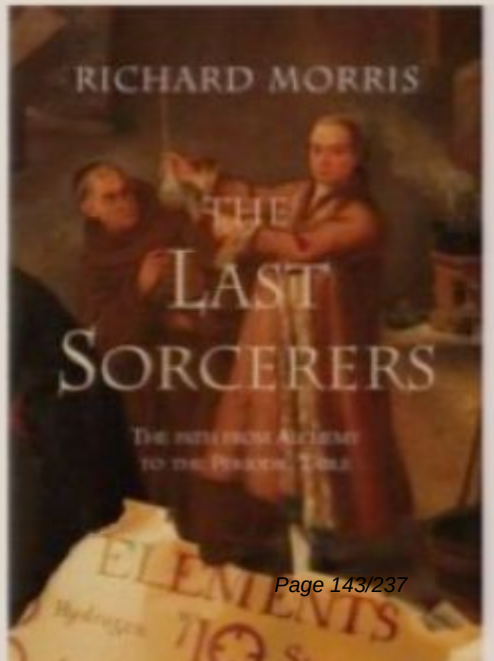

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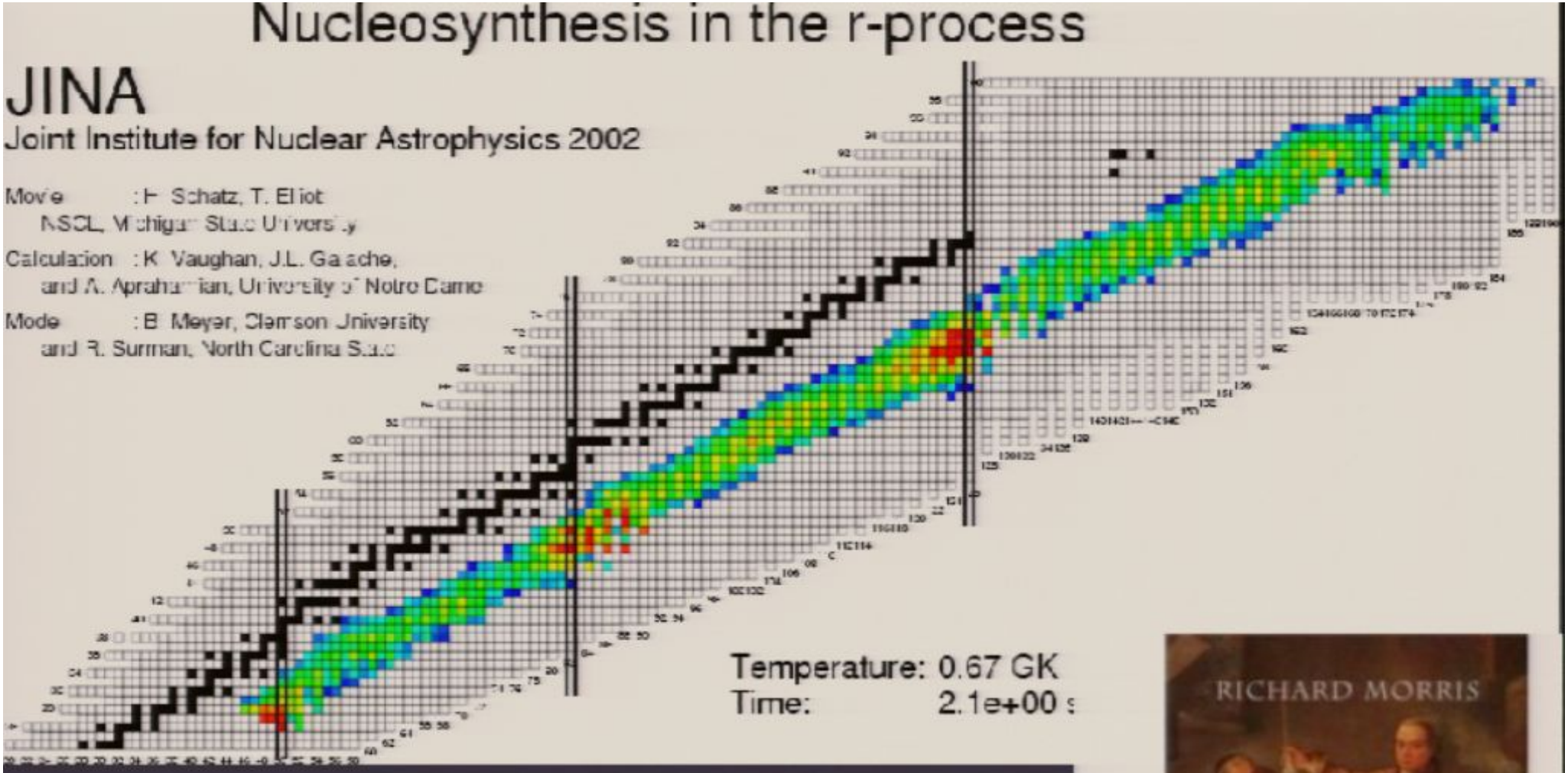

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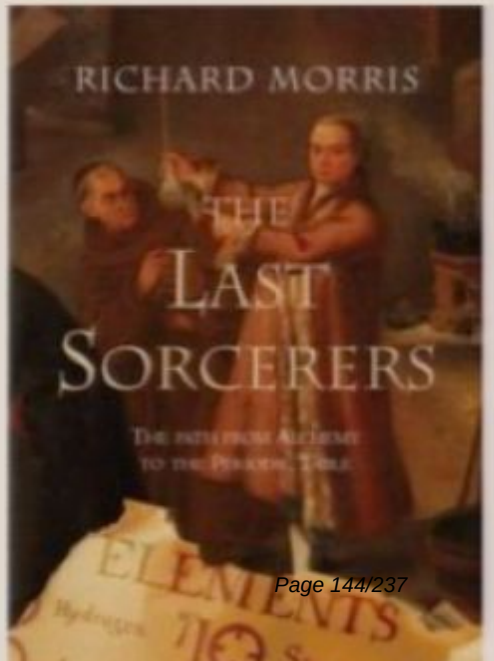

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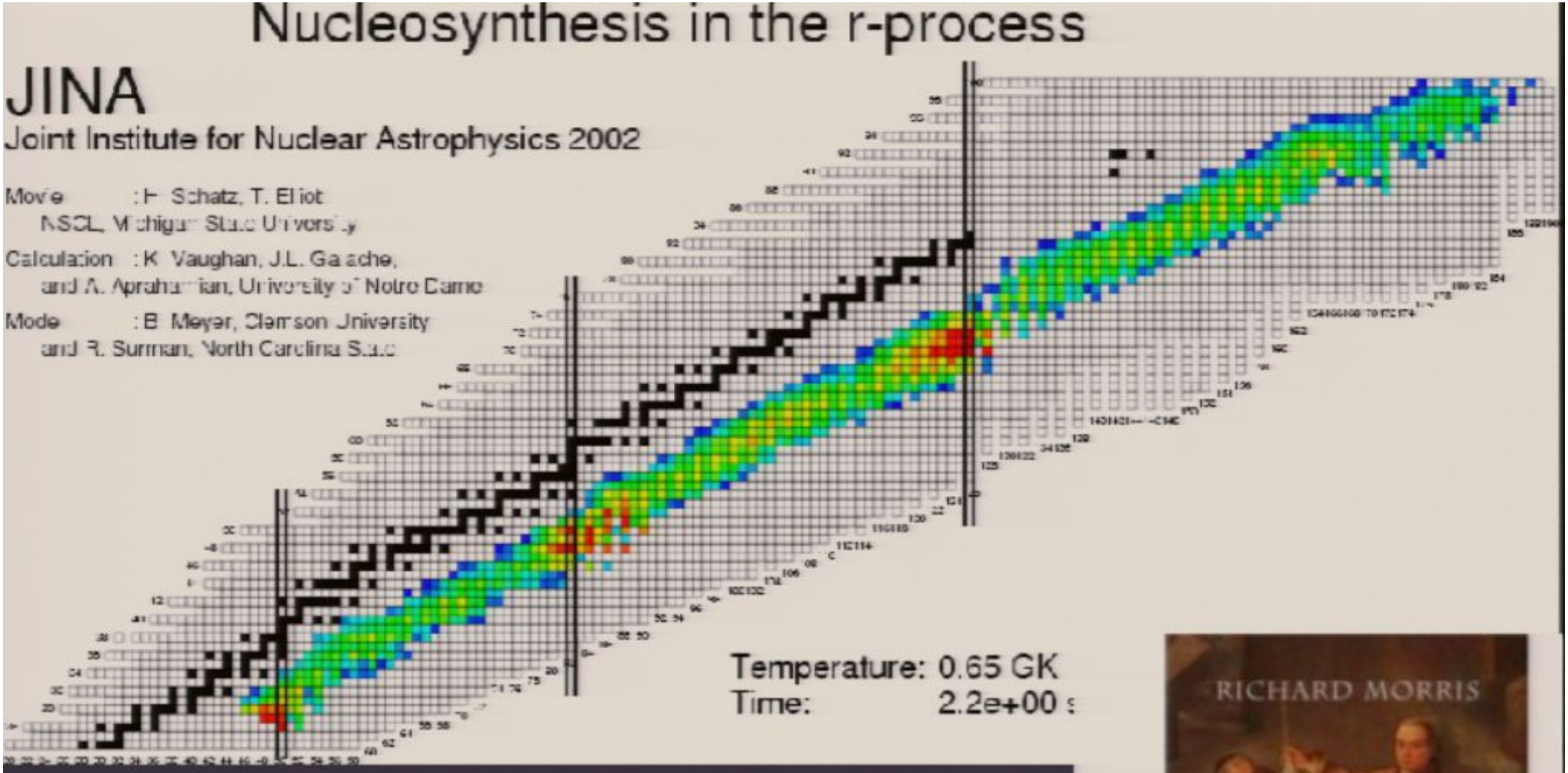

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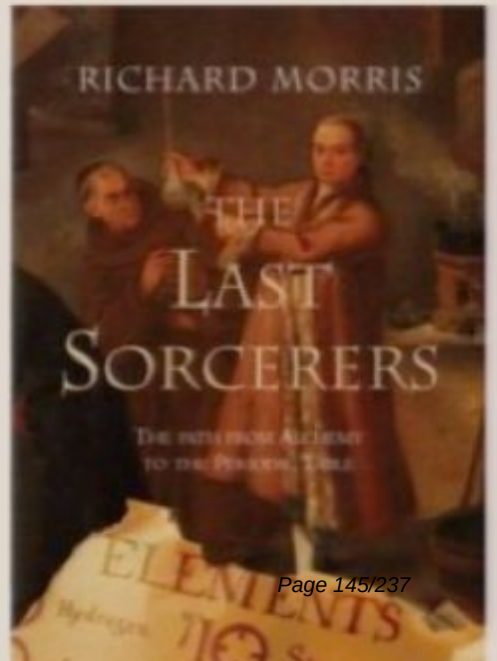

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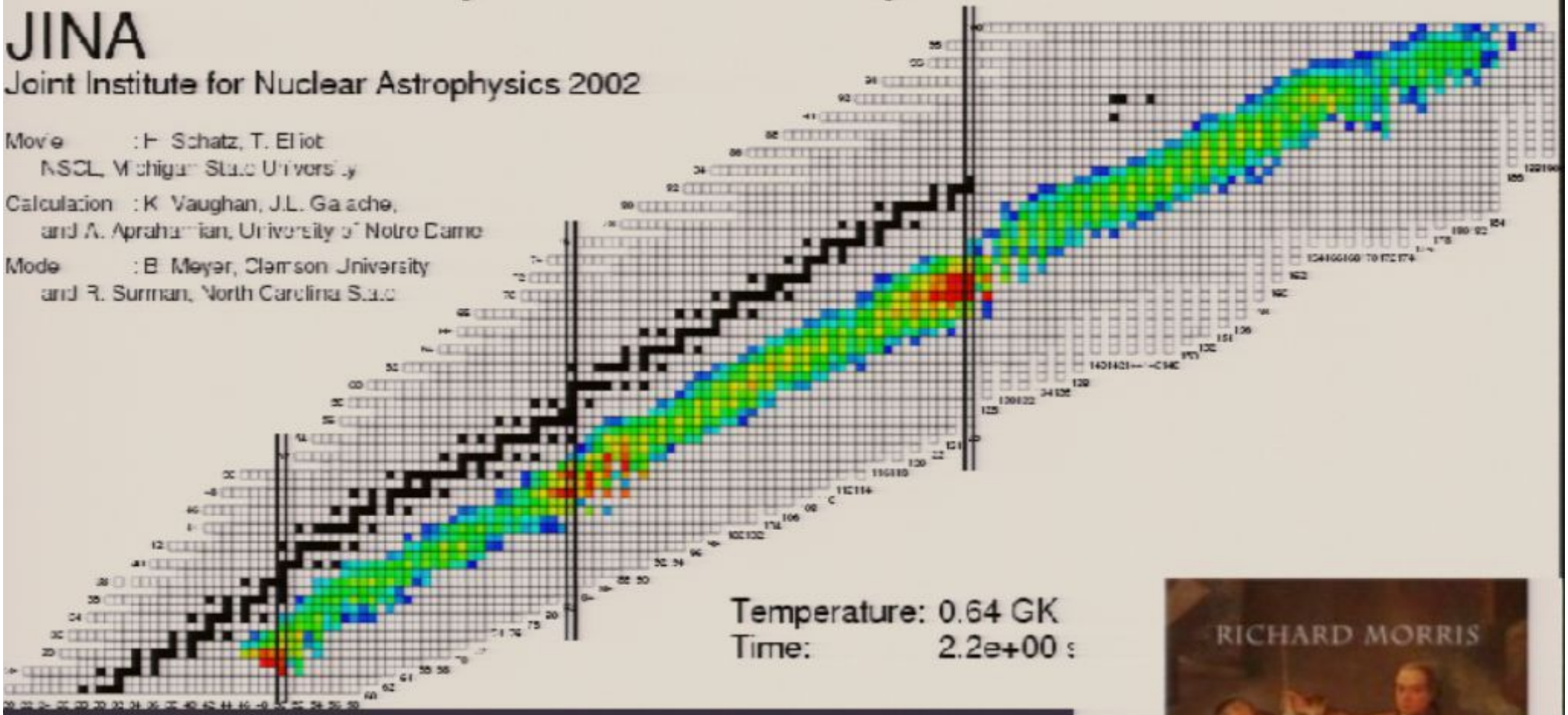

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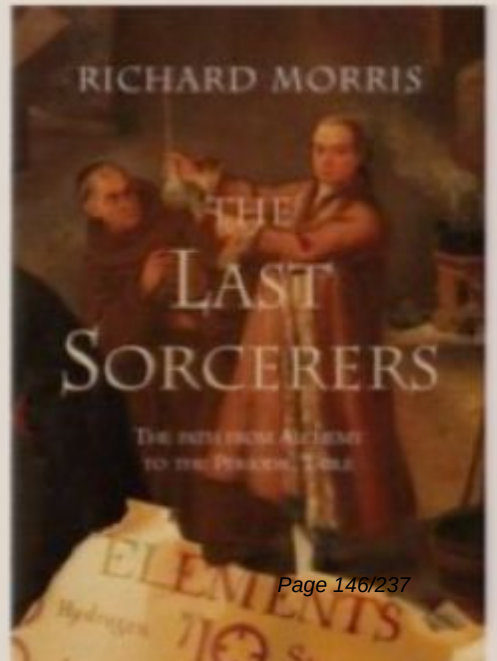
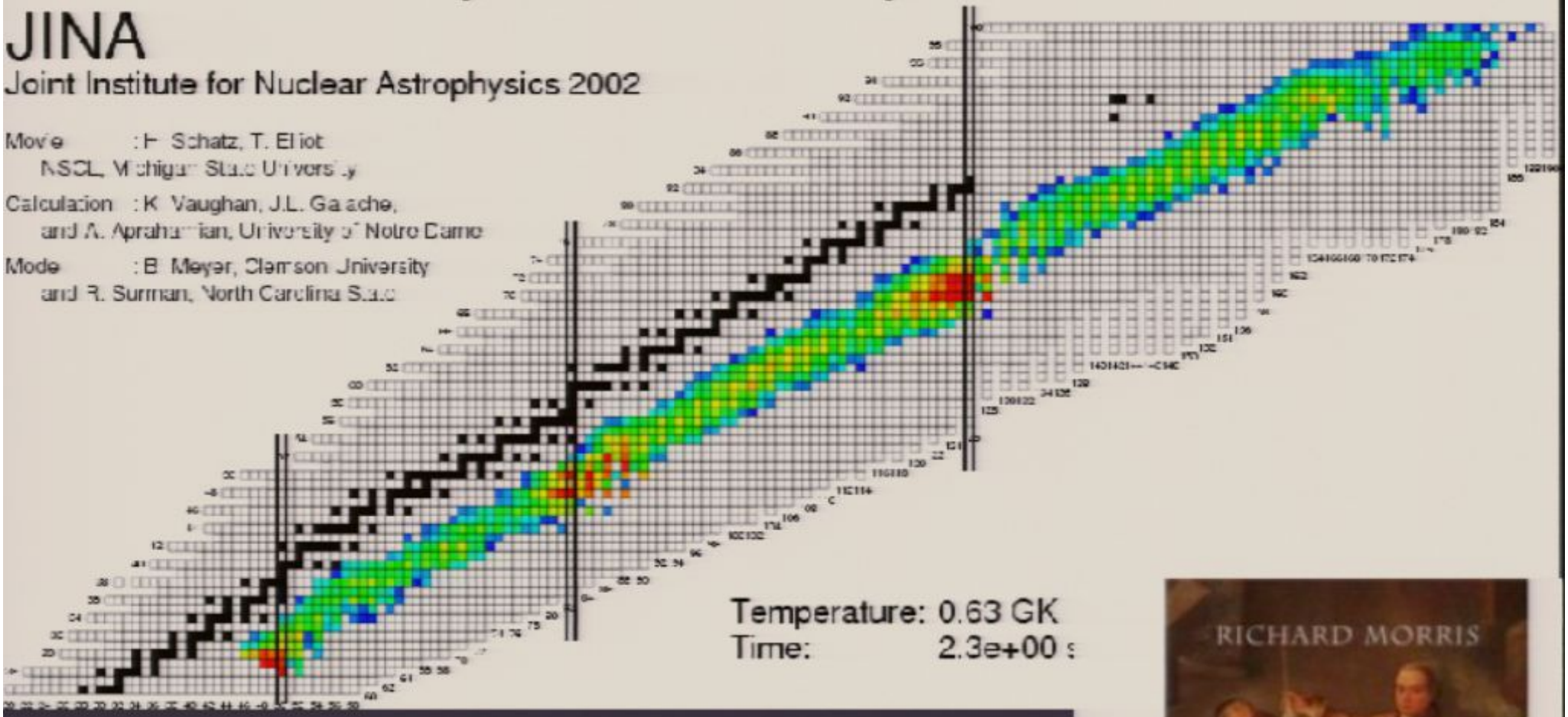


Nucleosynthesis in the r-process



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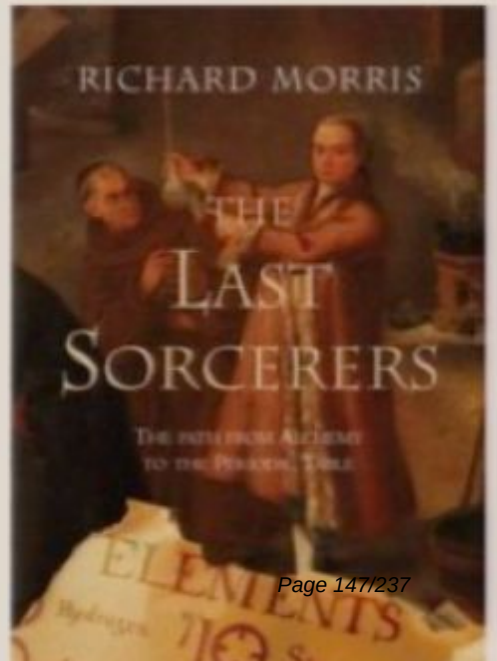

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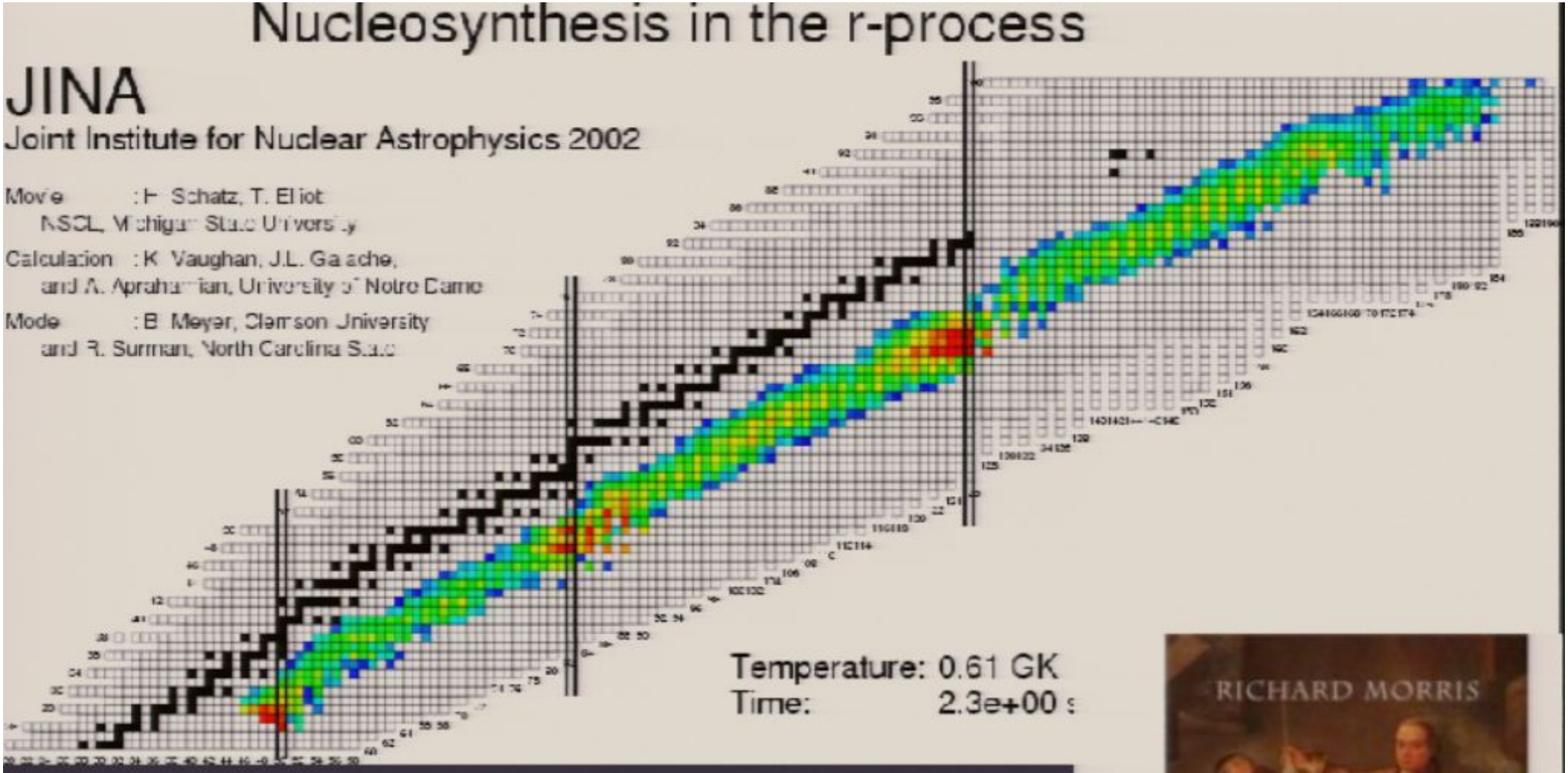

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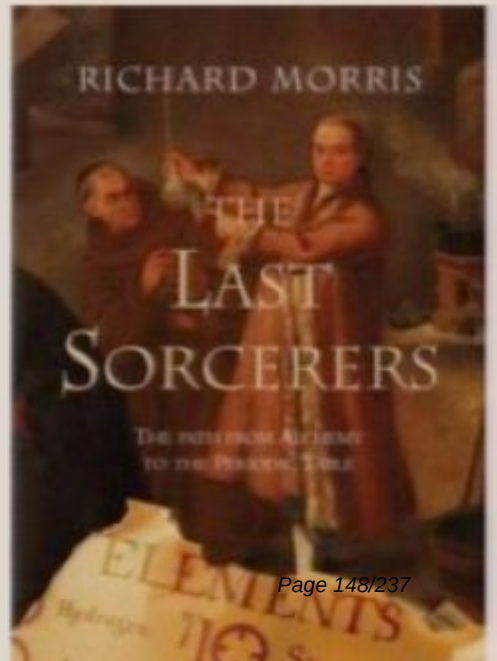

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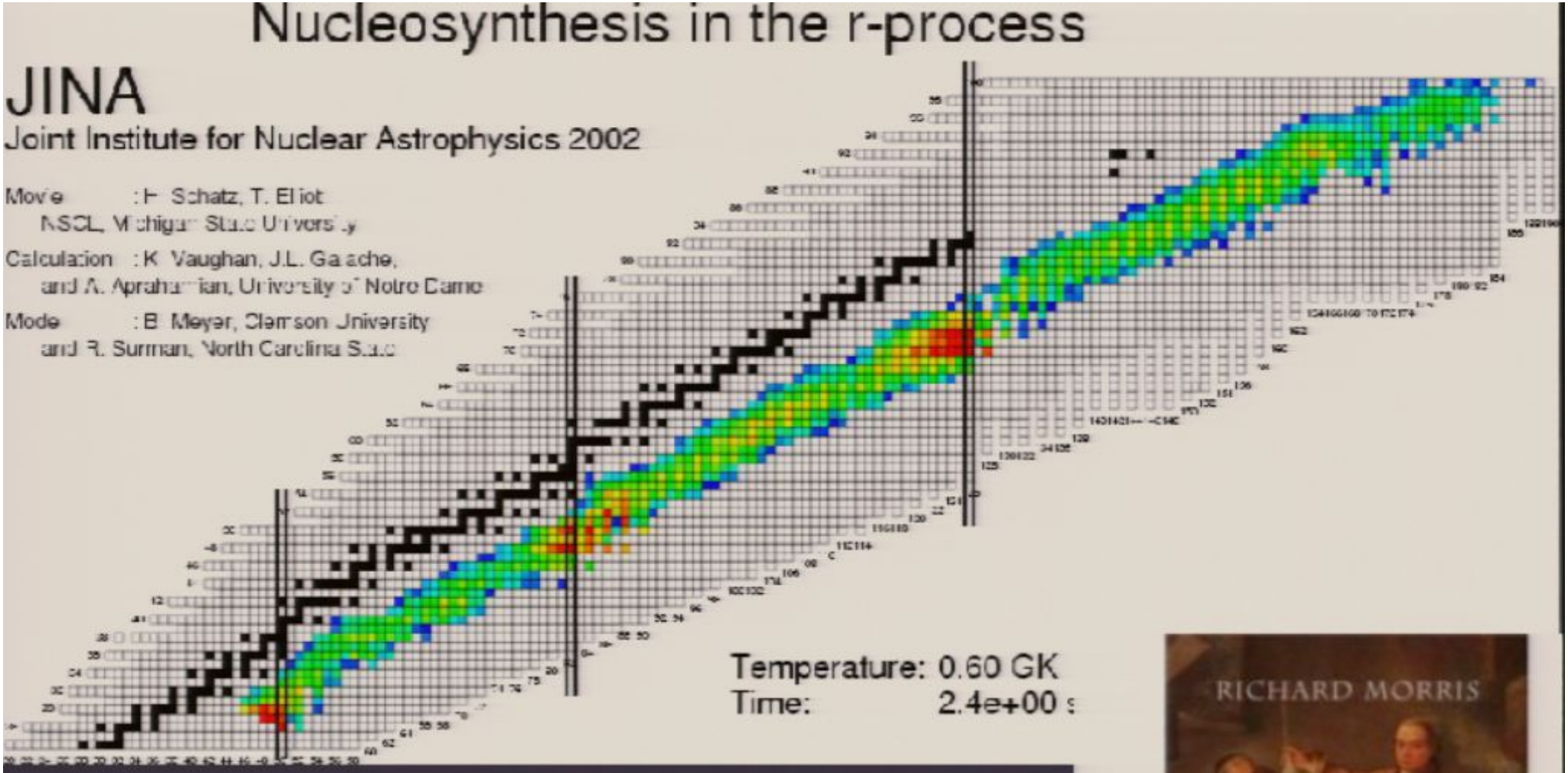

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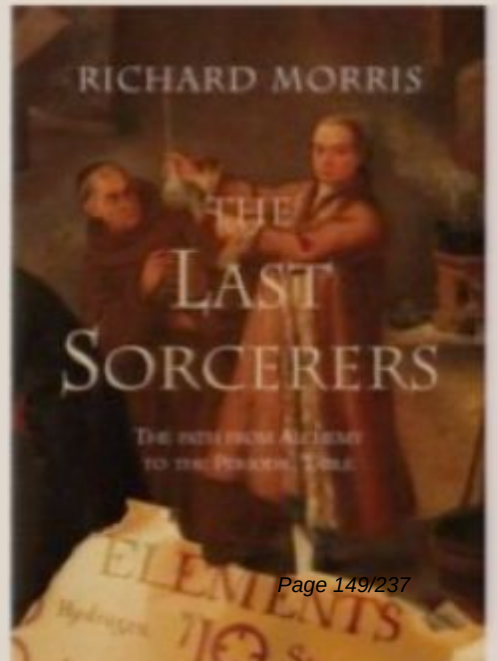

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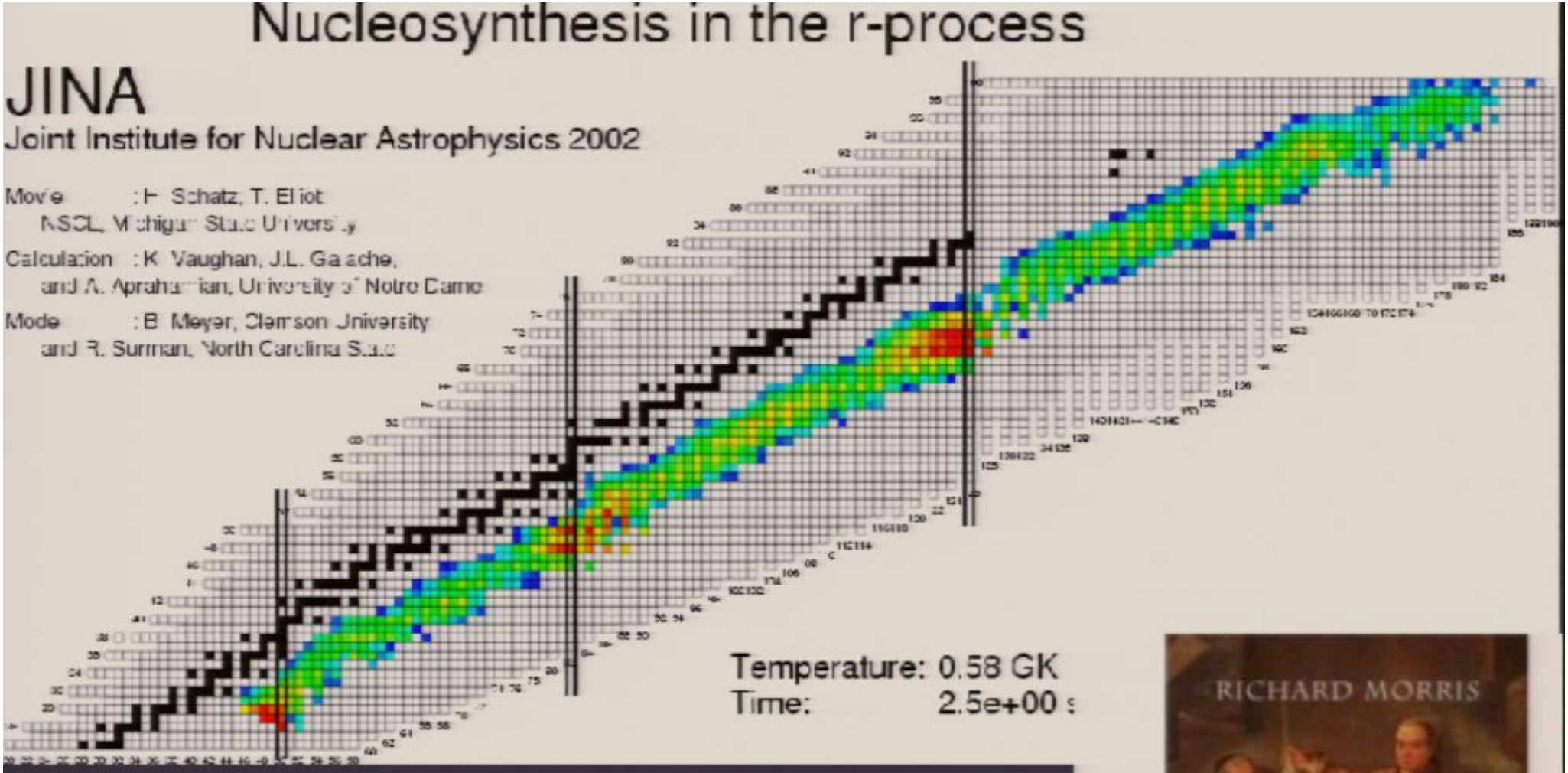

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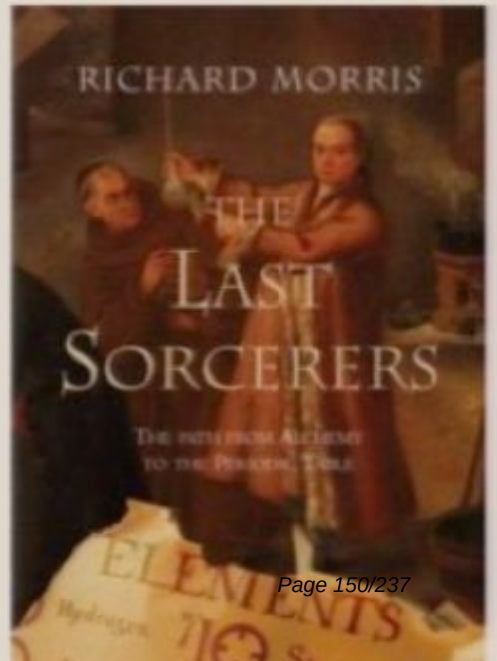

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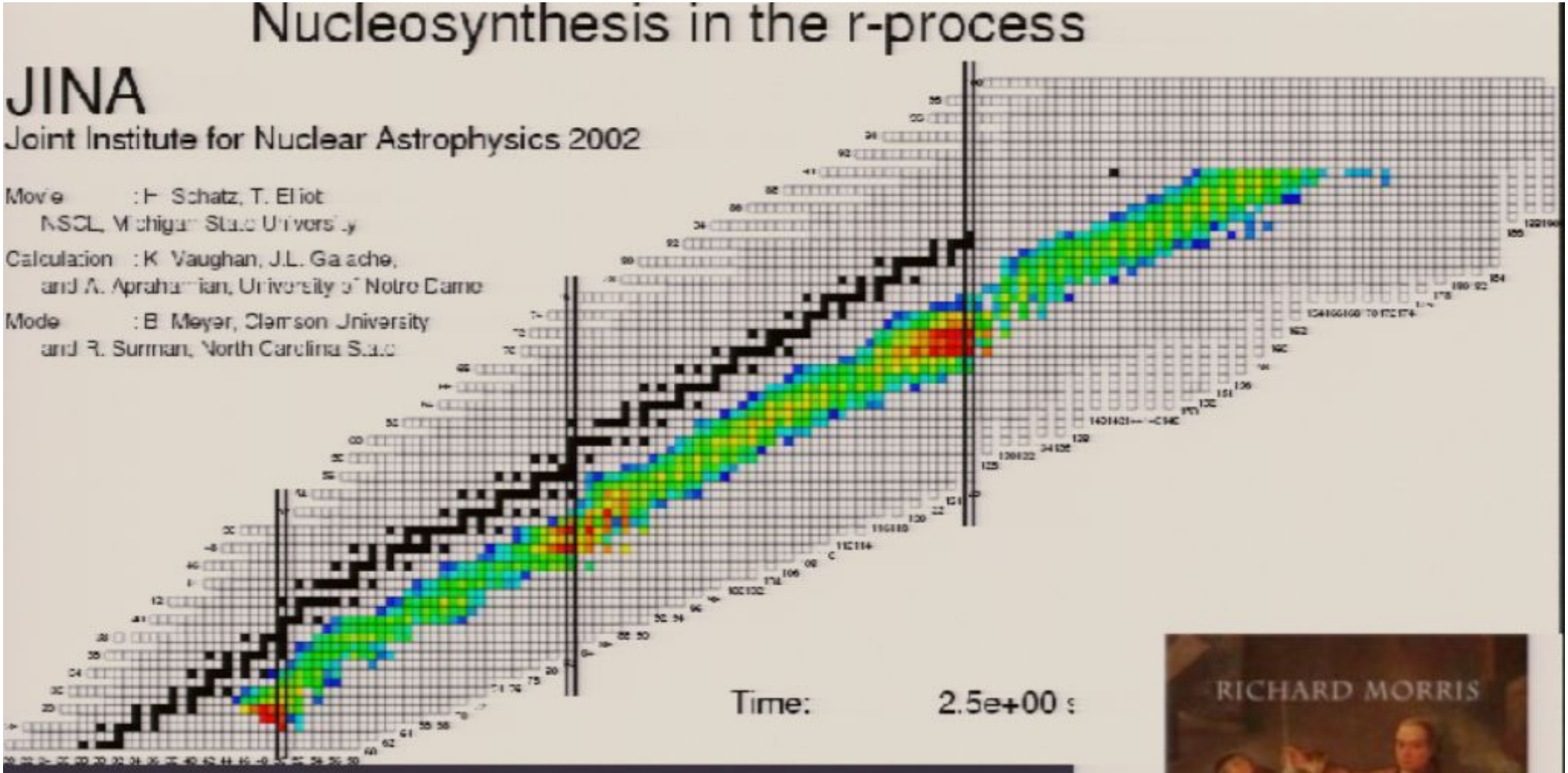

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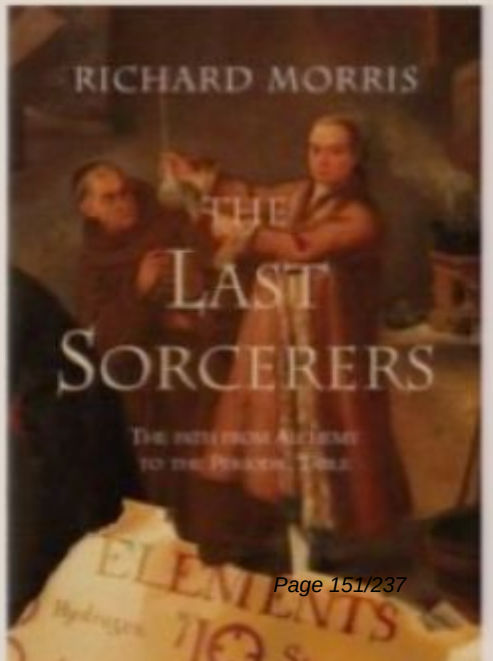

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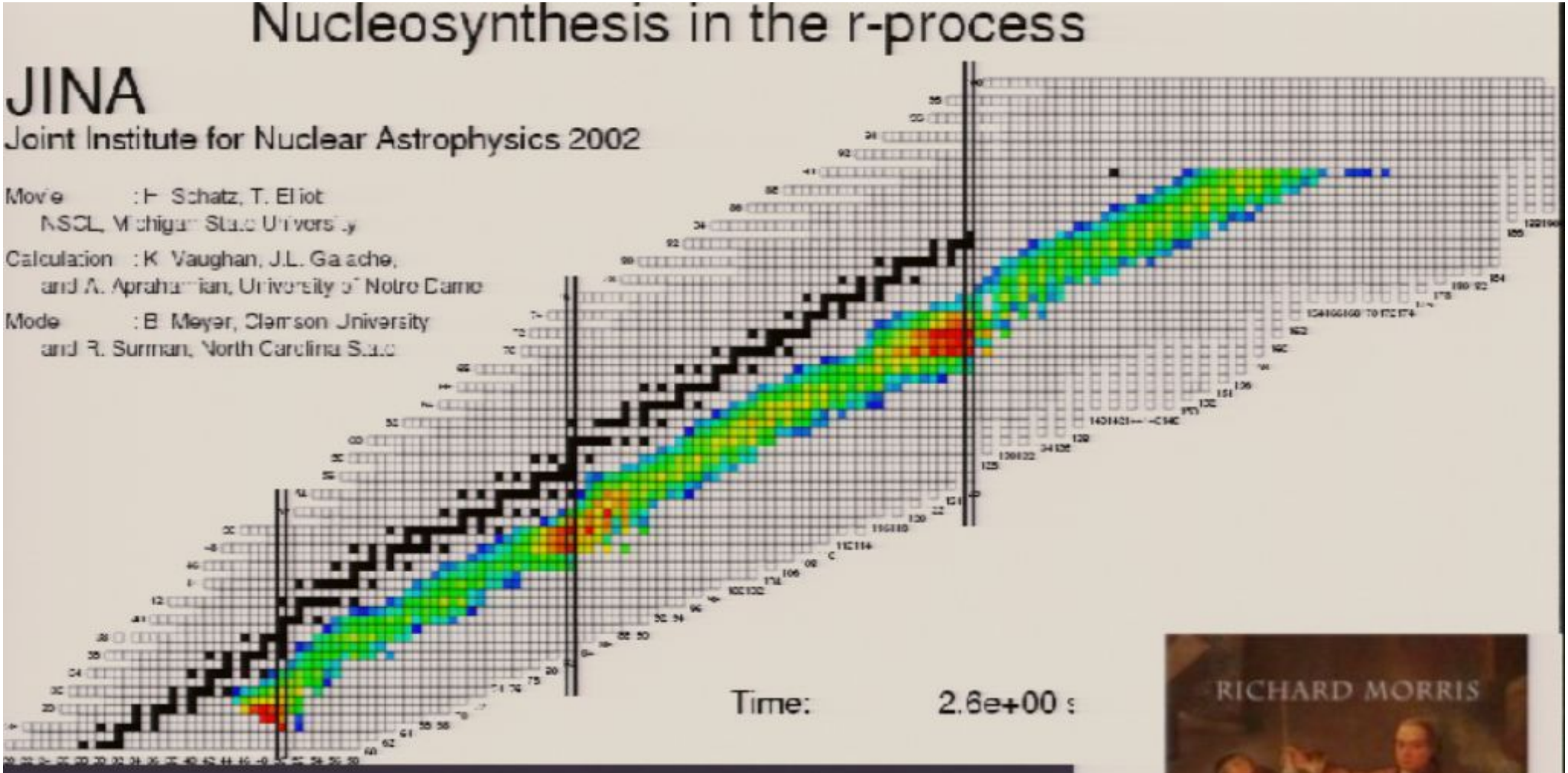

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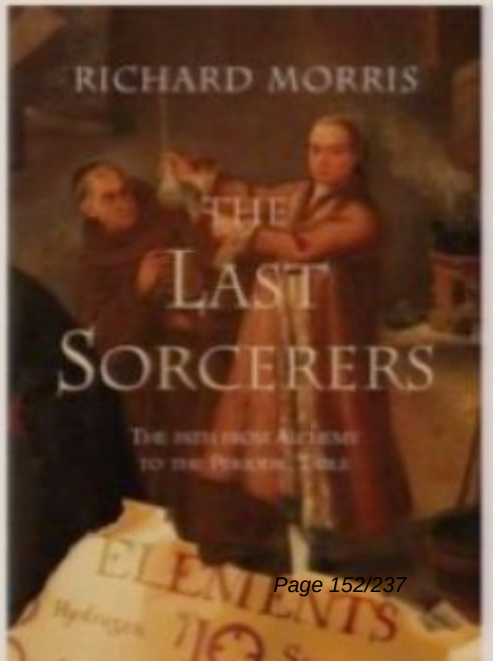

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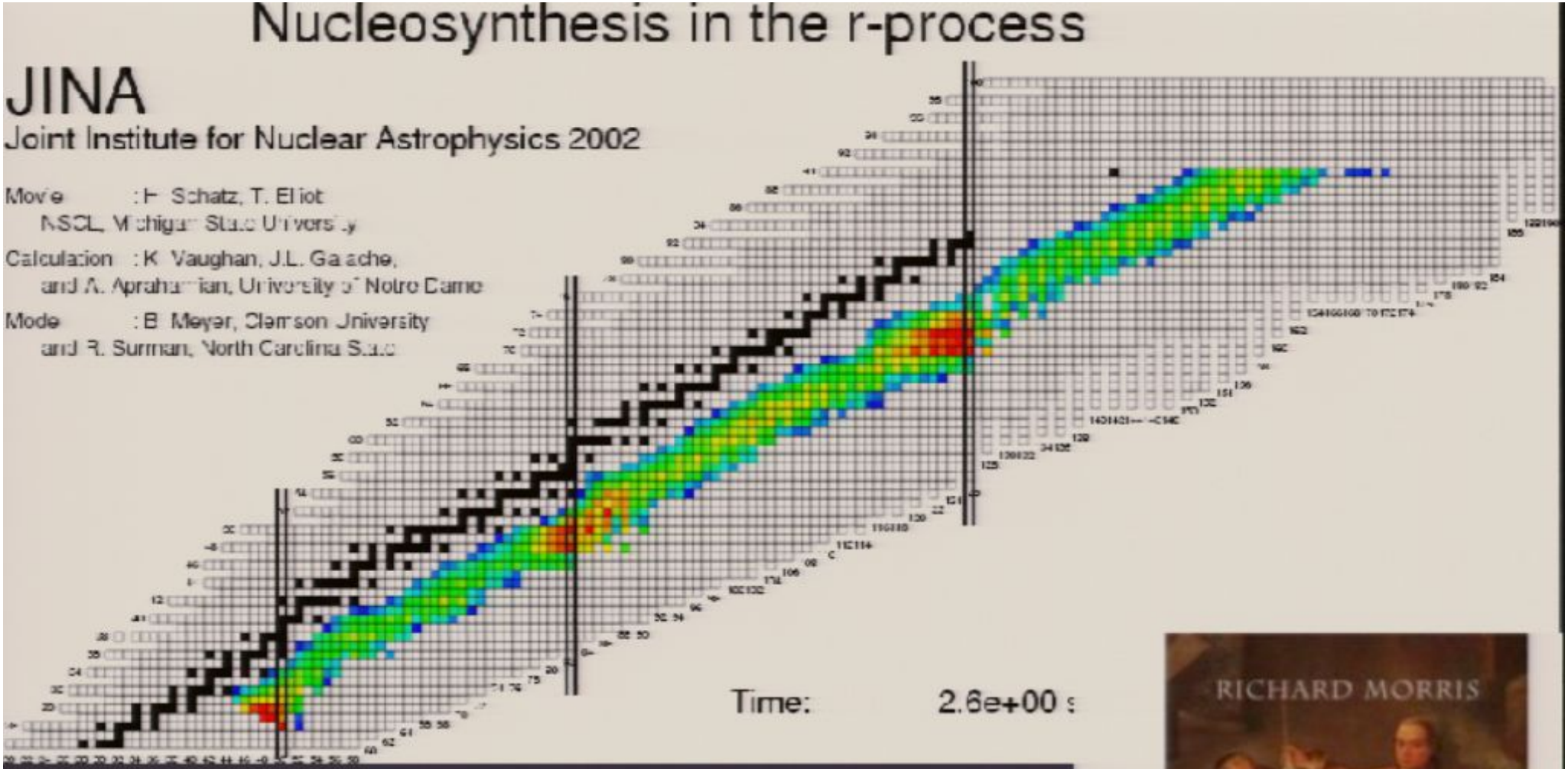

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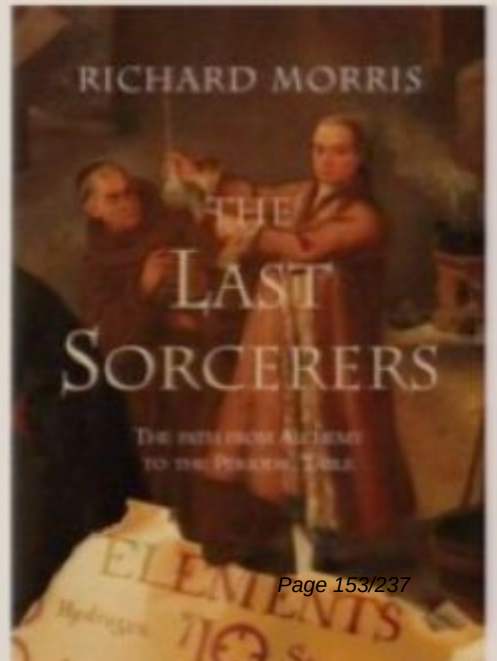

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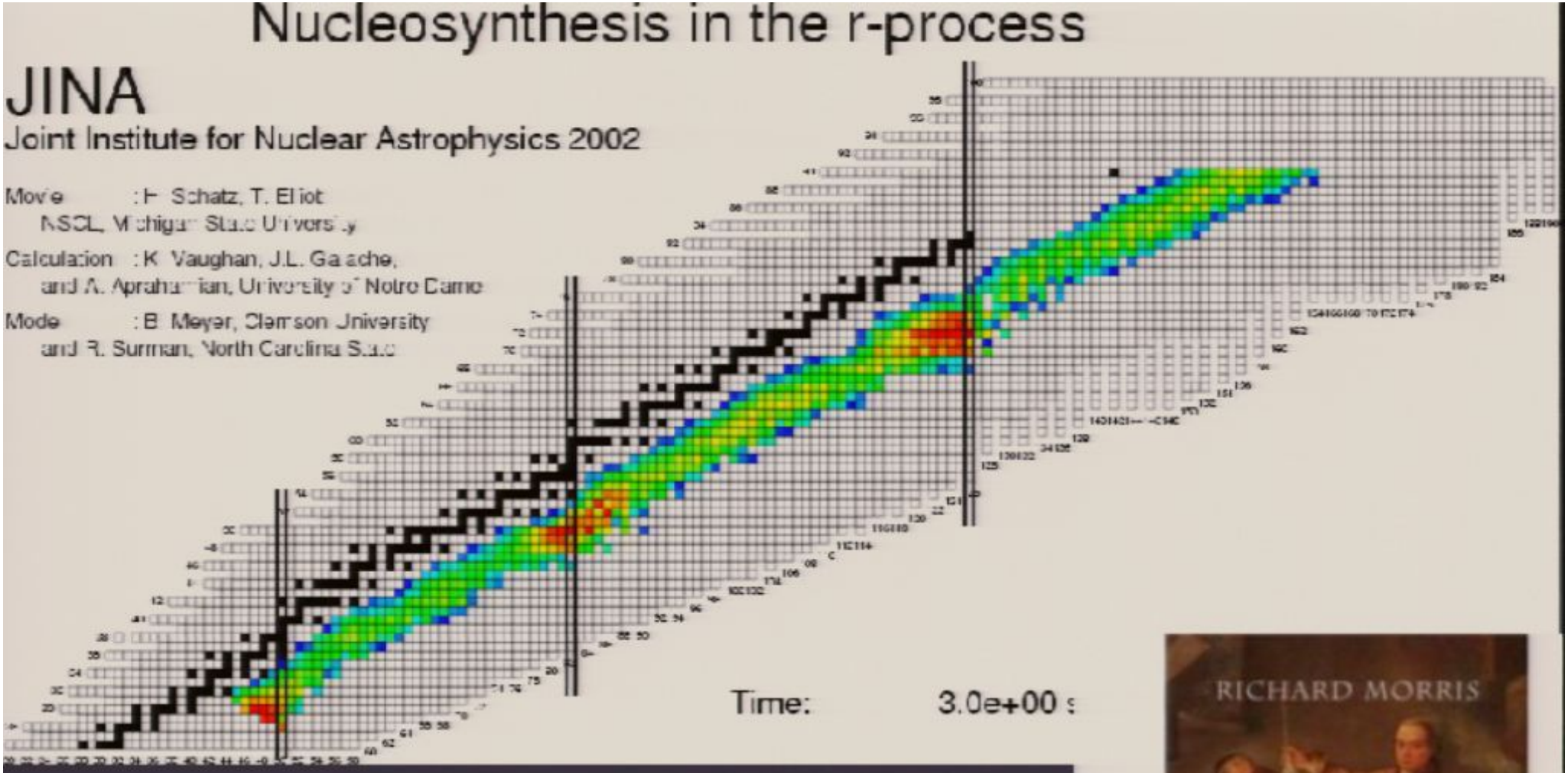

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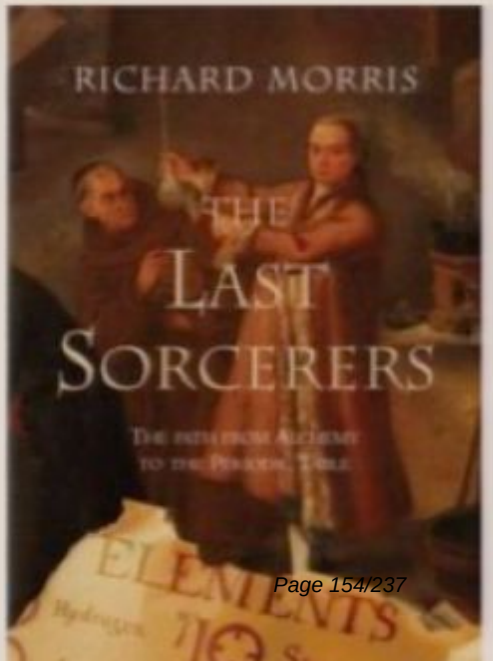
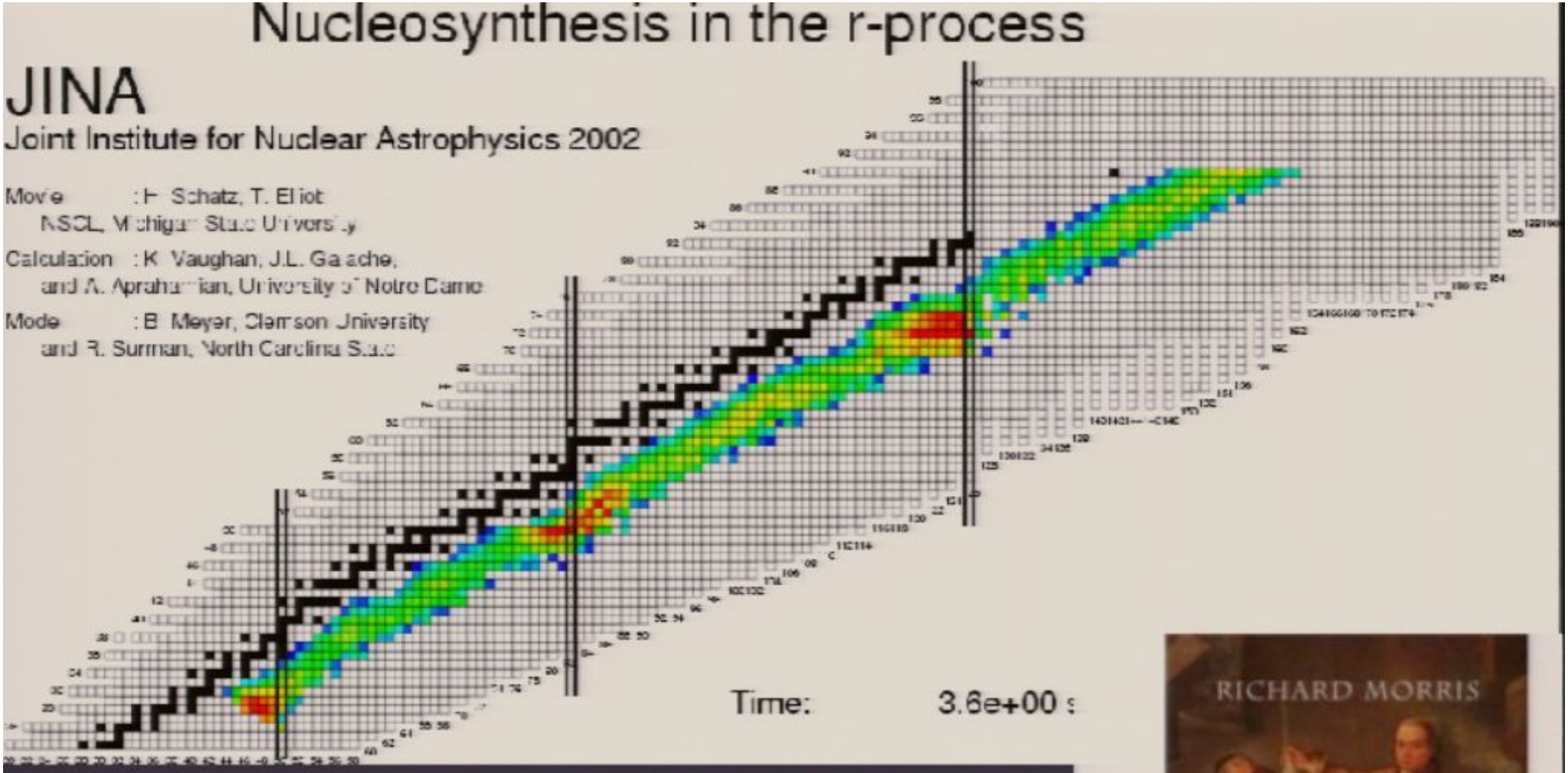


Nucleosynthesis in the r-process



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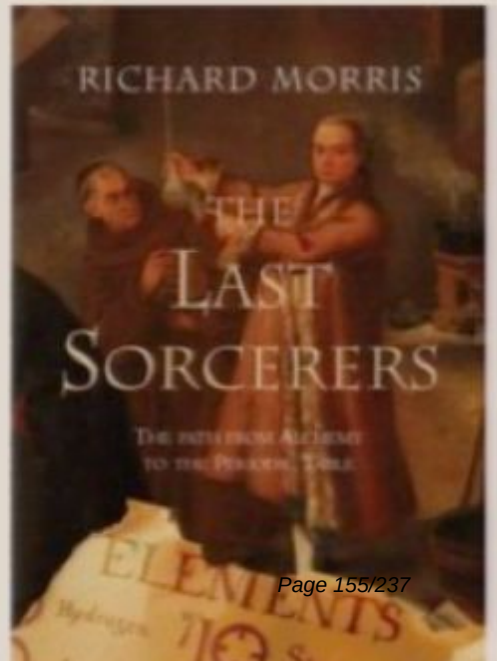

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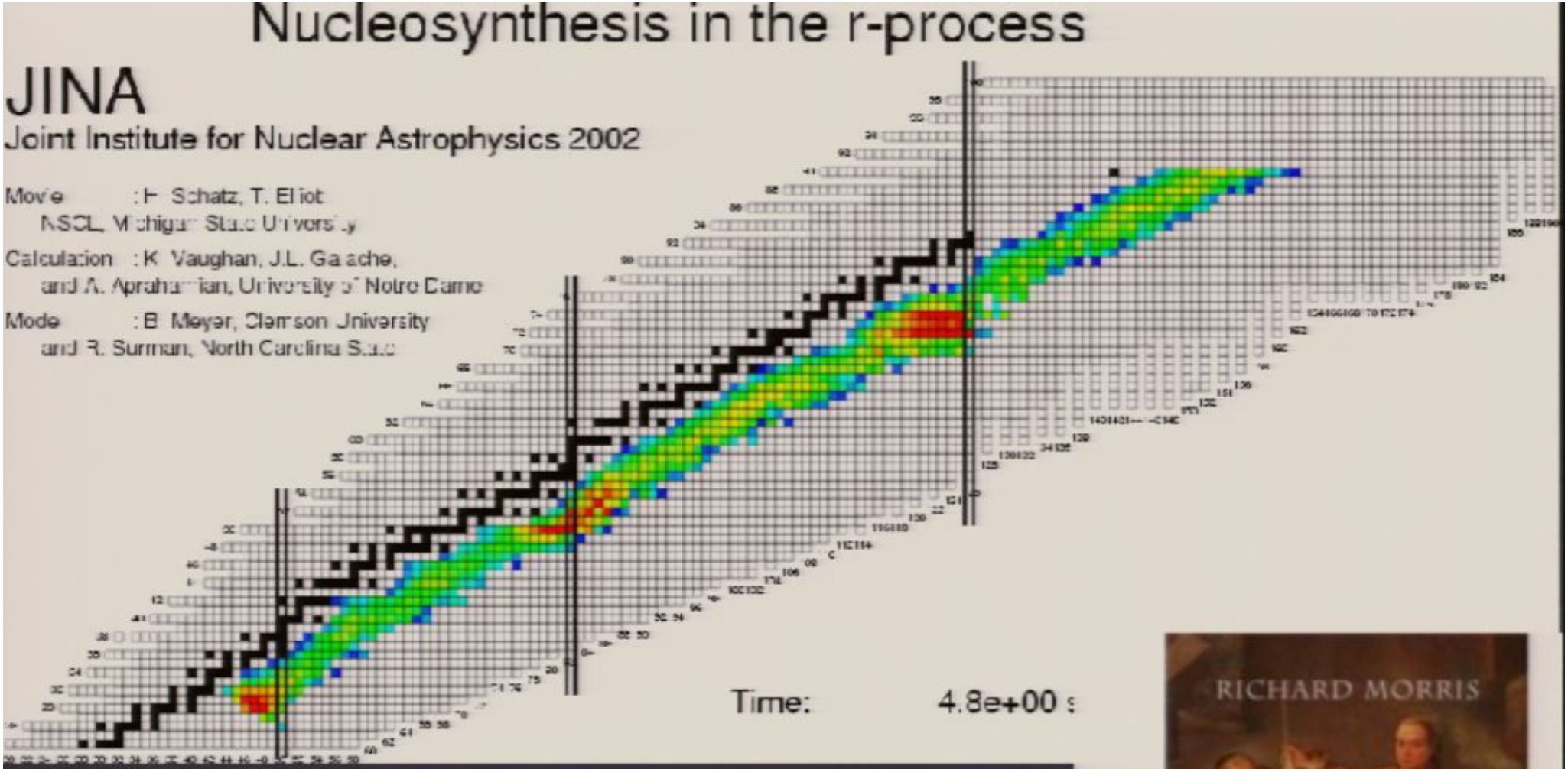

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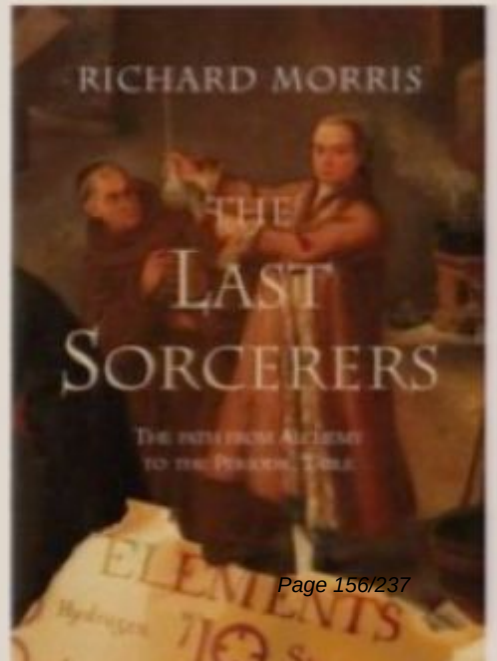

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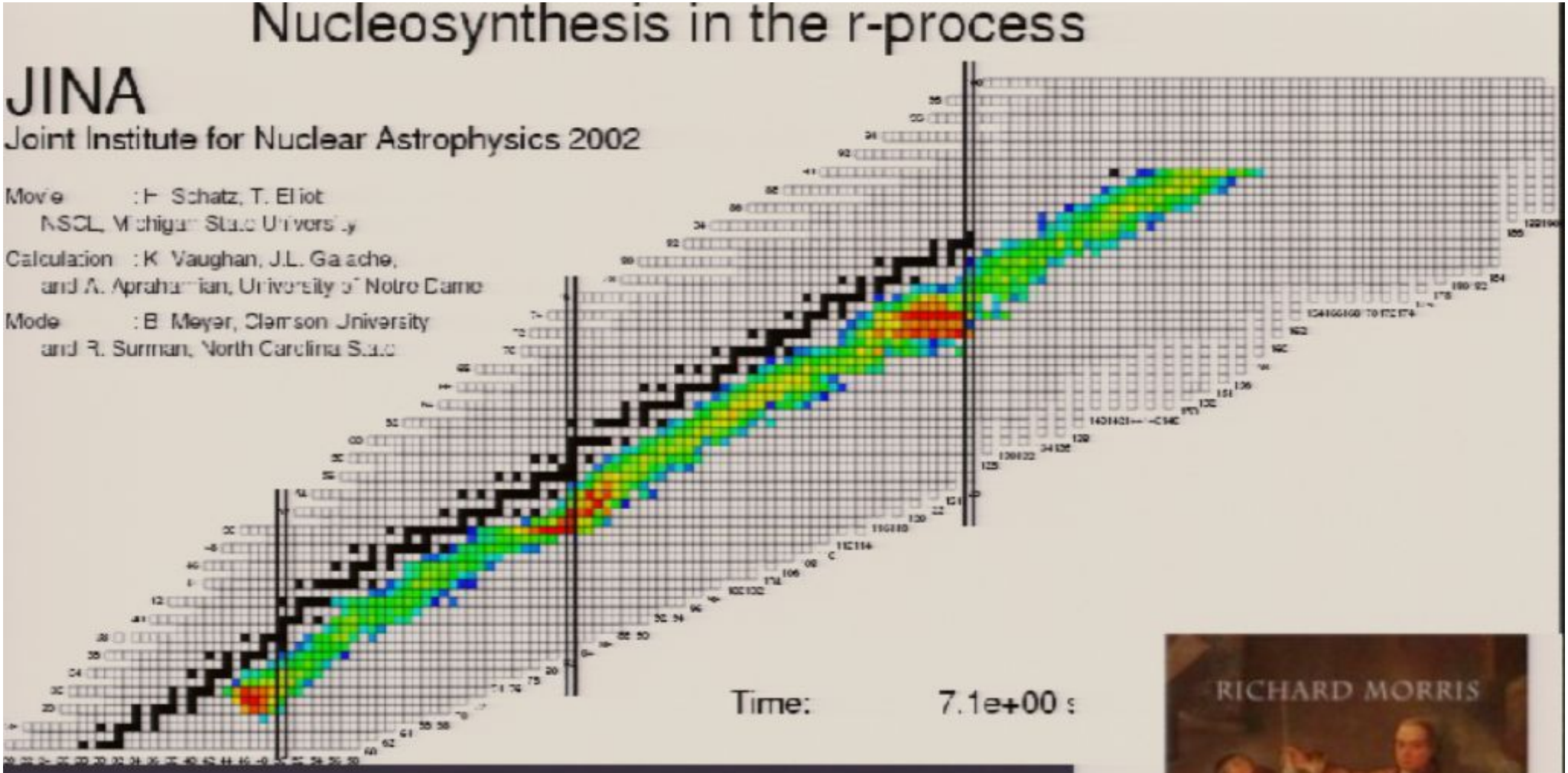

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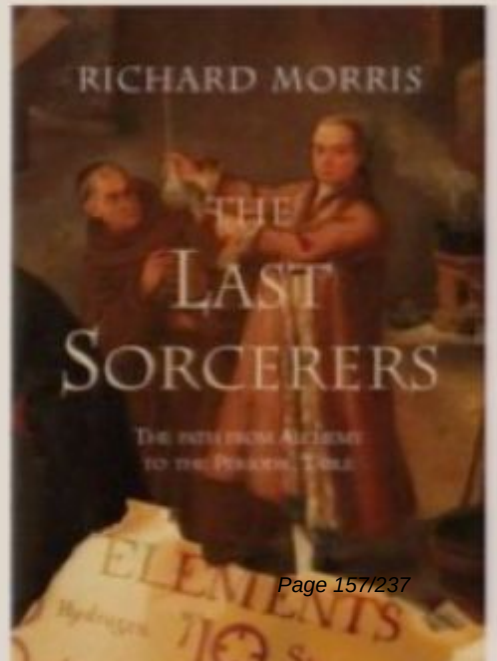

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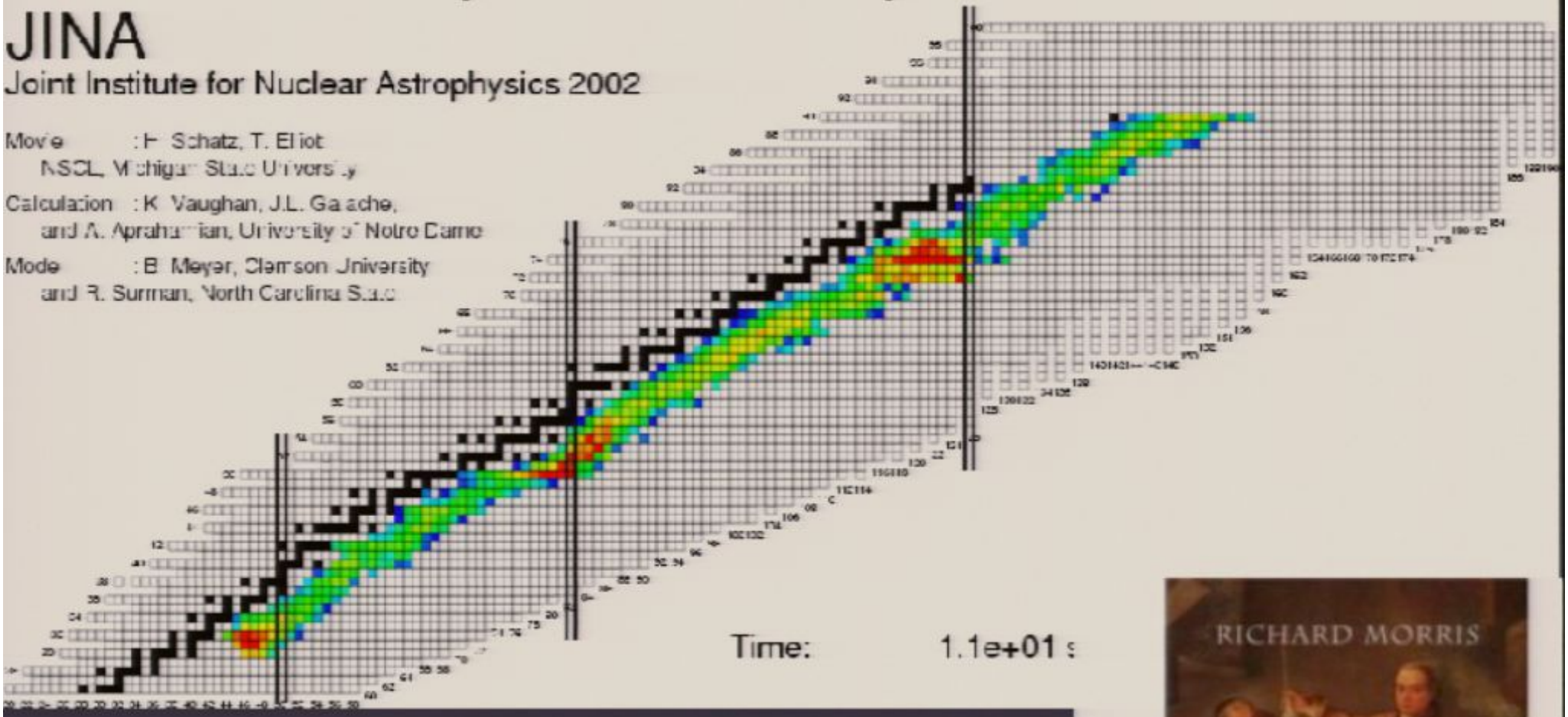

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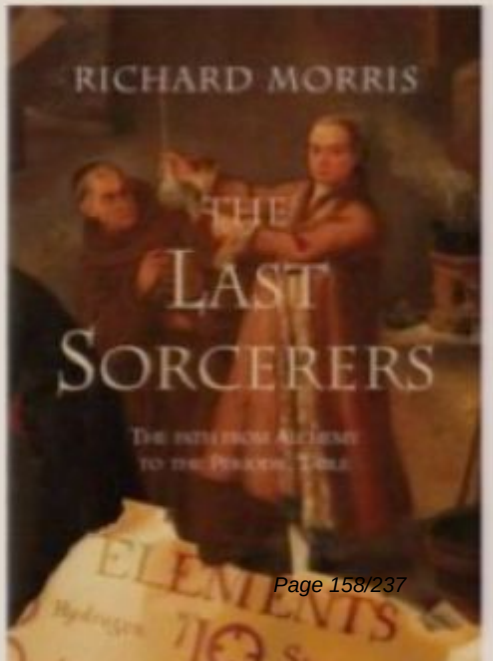

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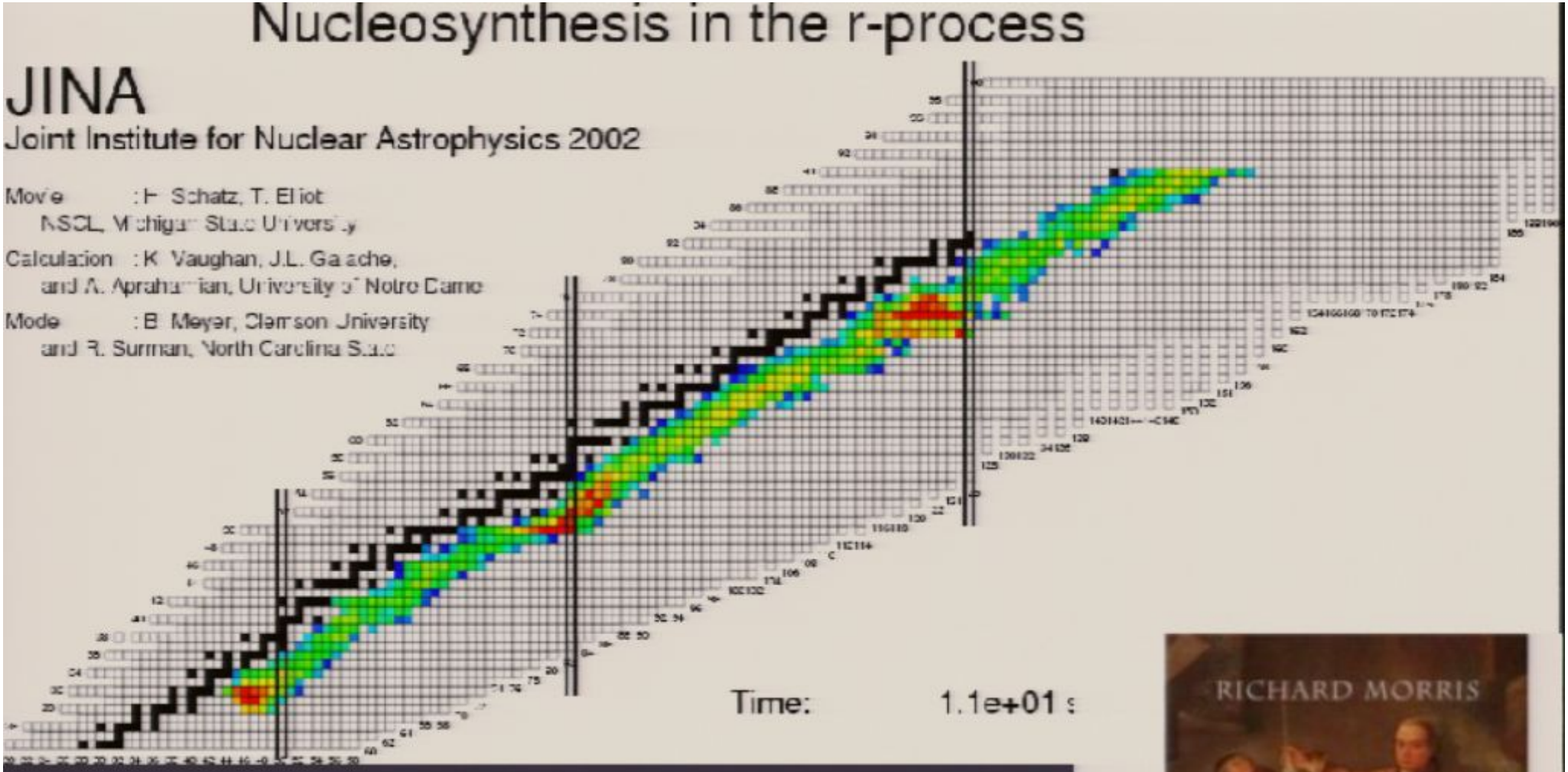

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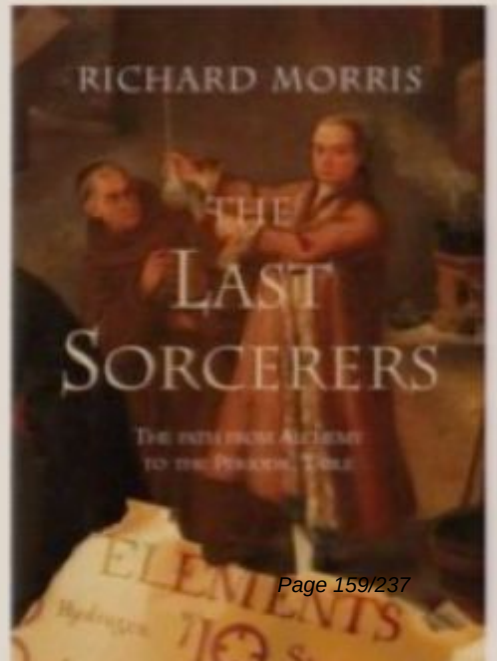

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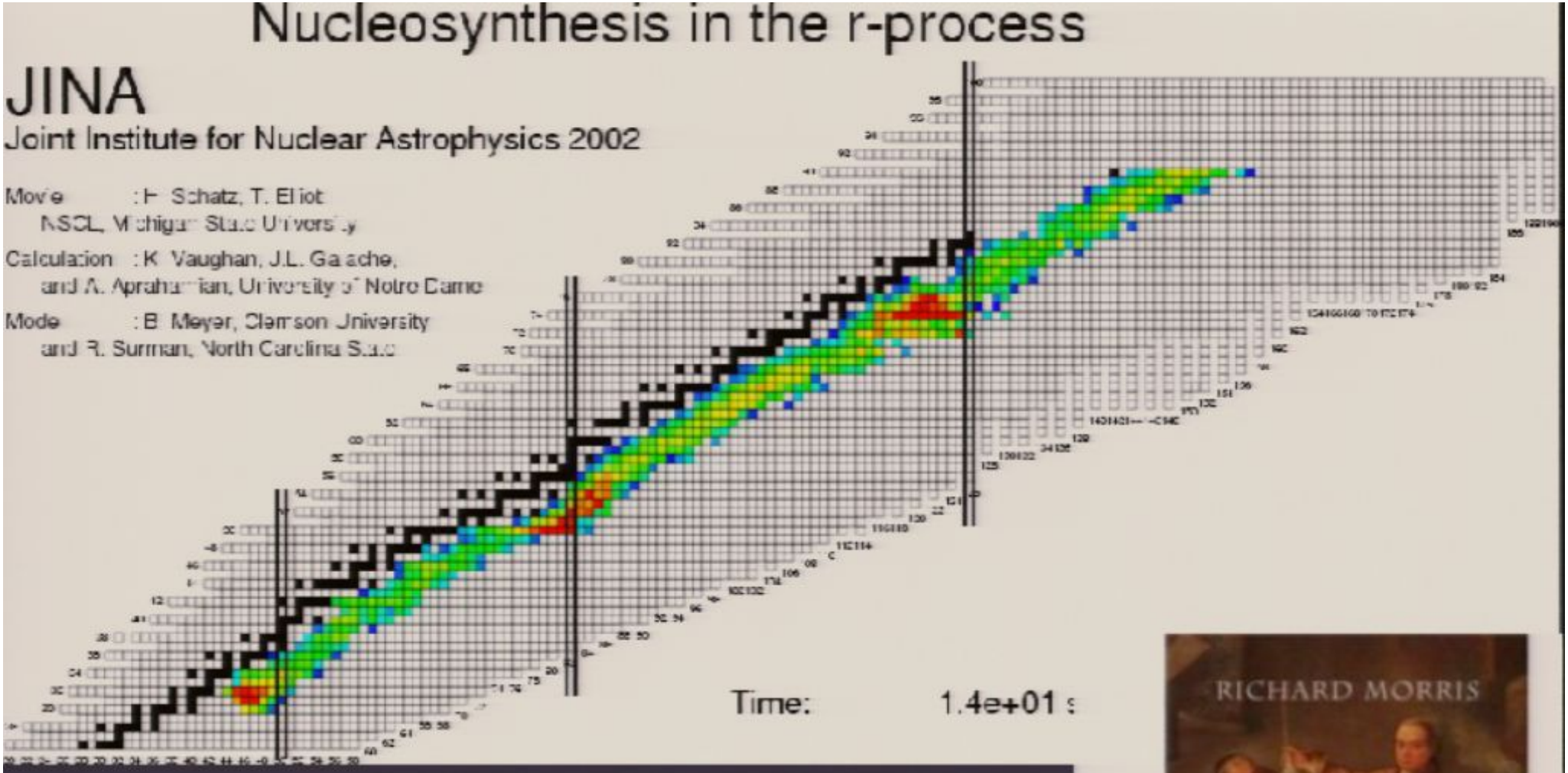

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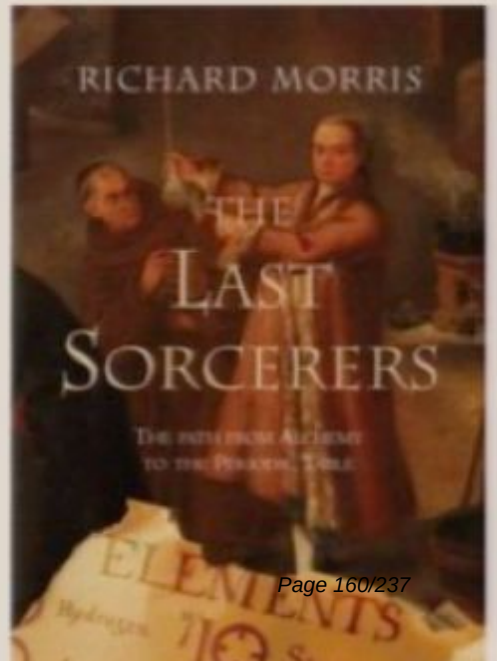

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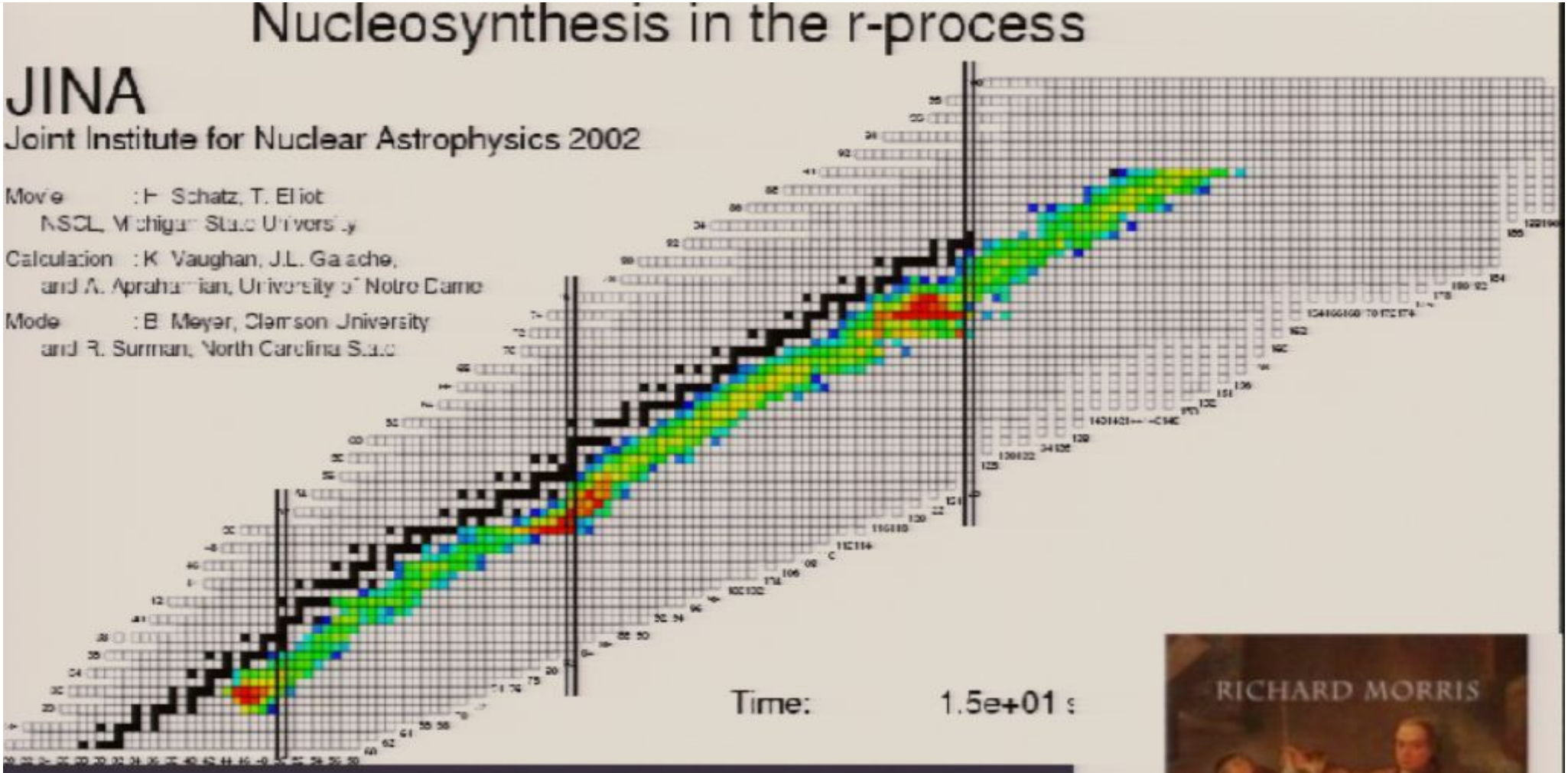

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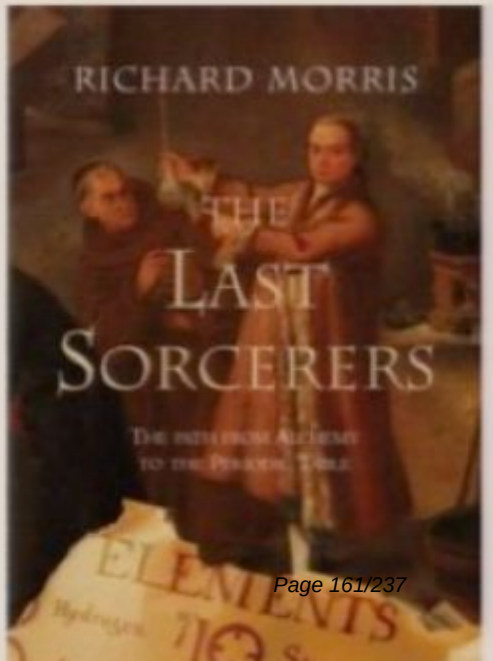

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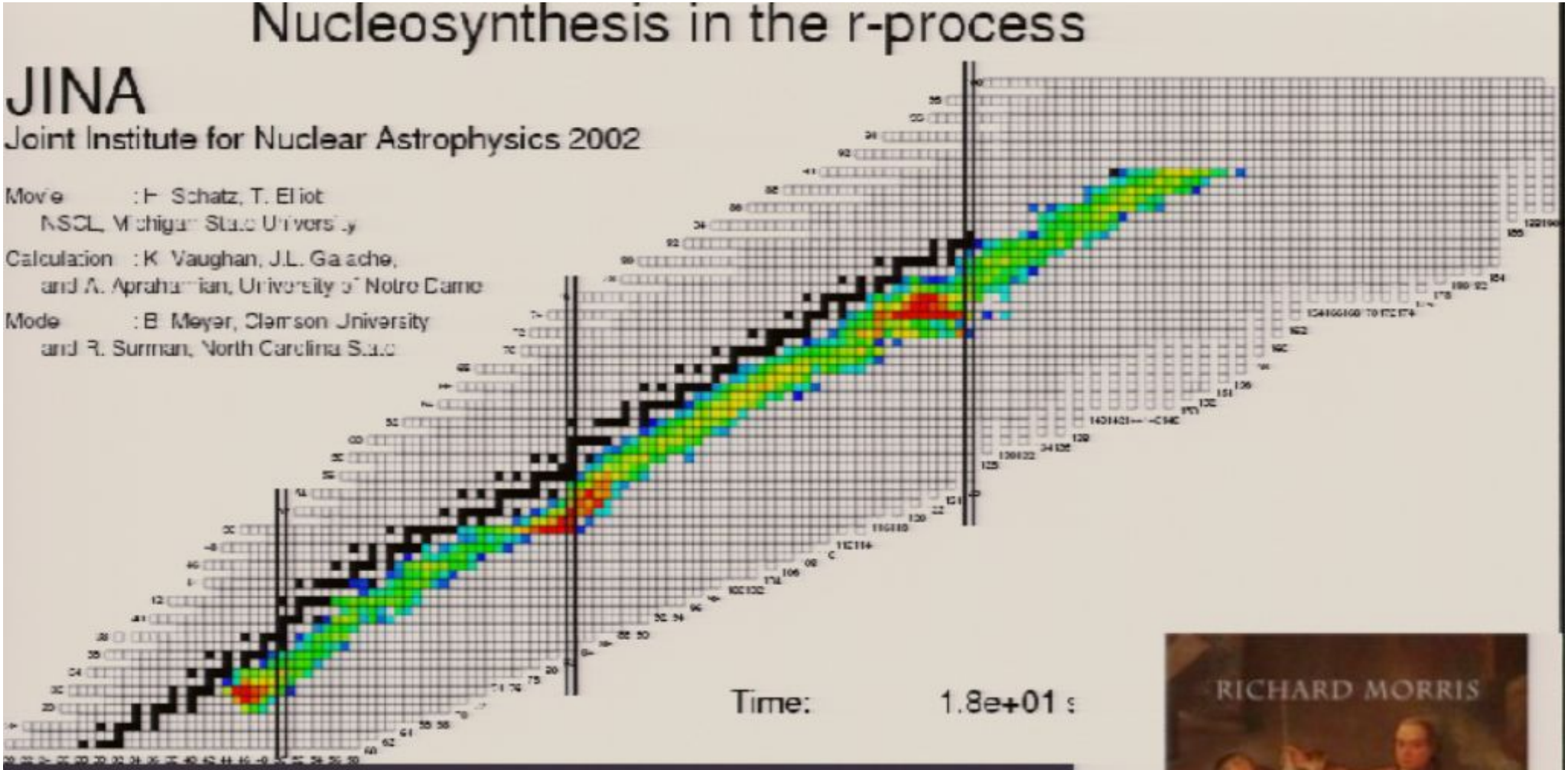

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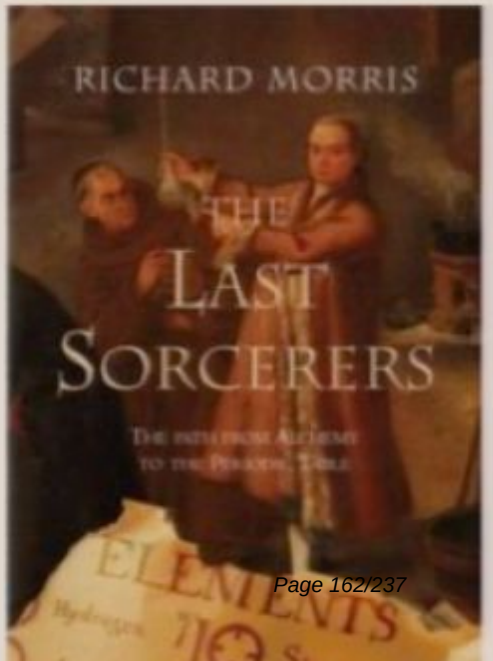

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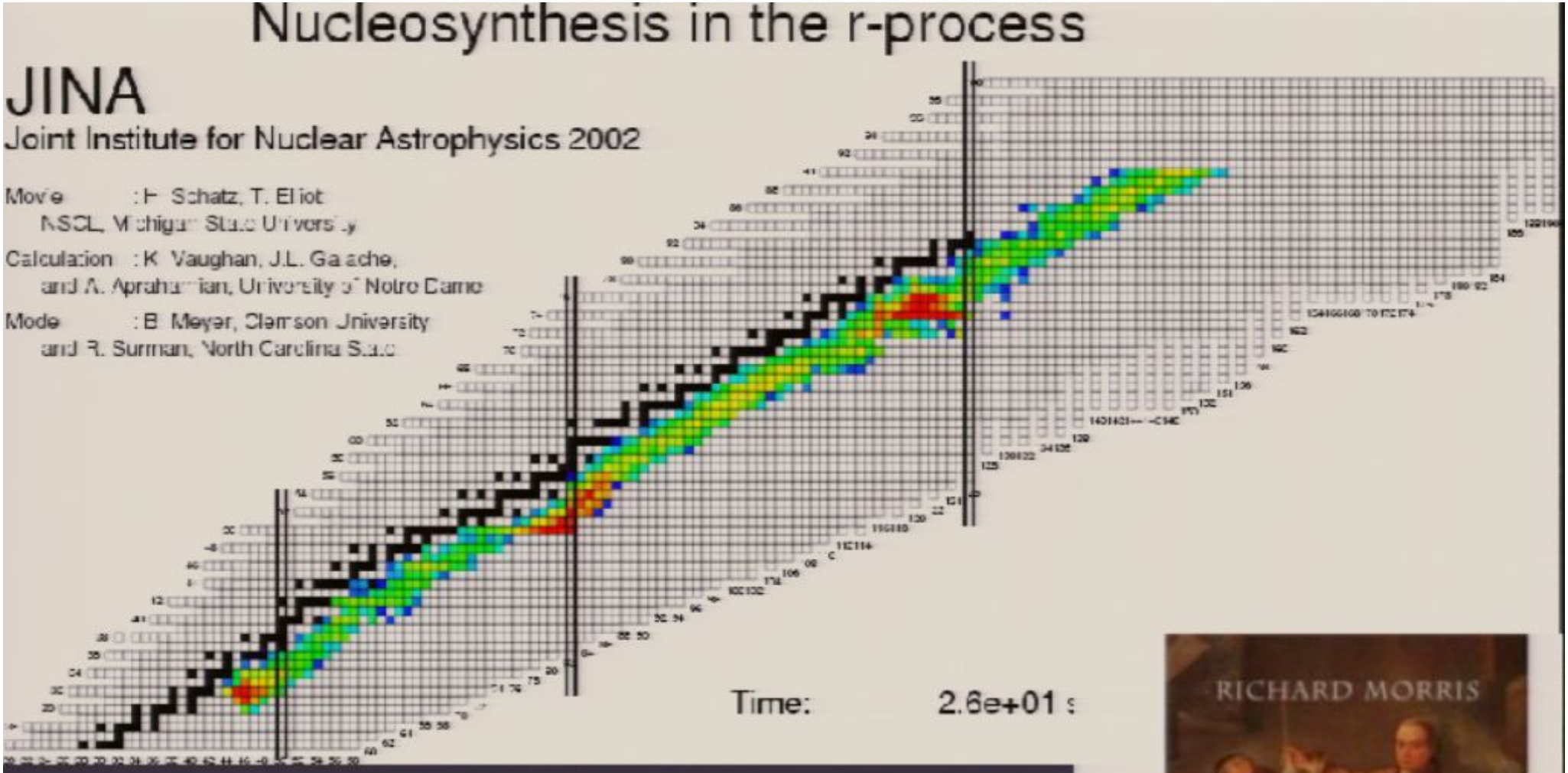

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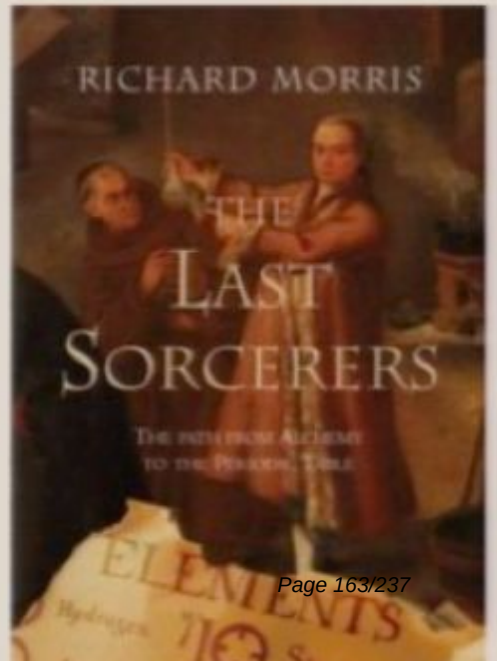

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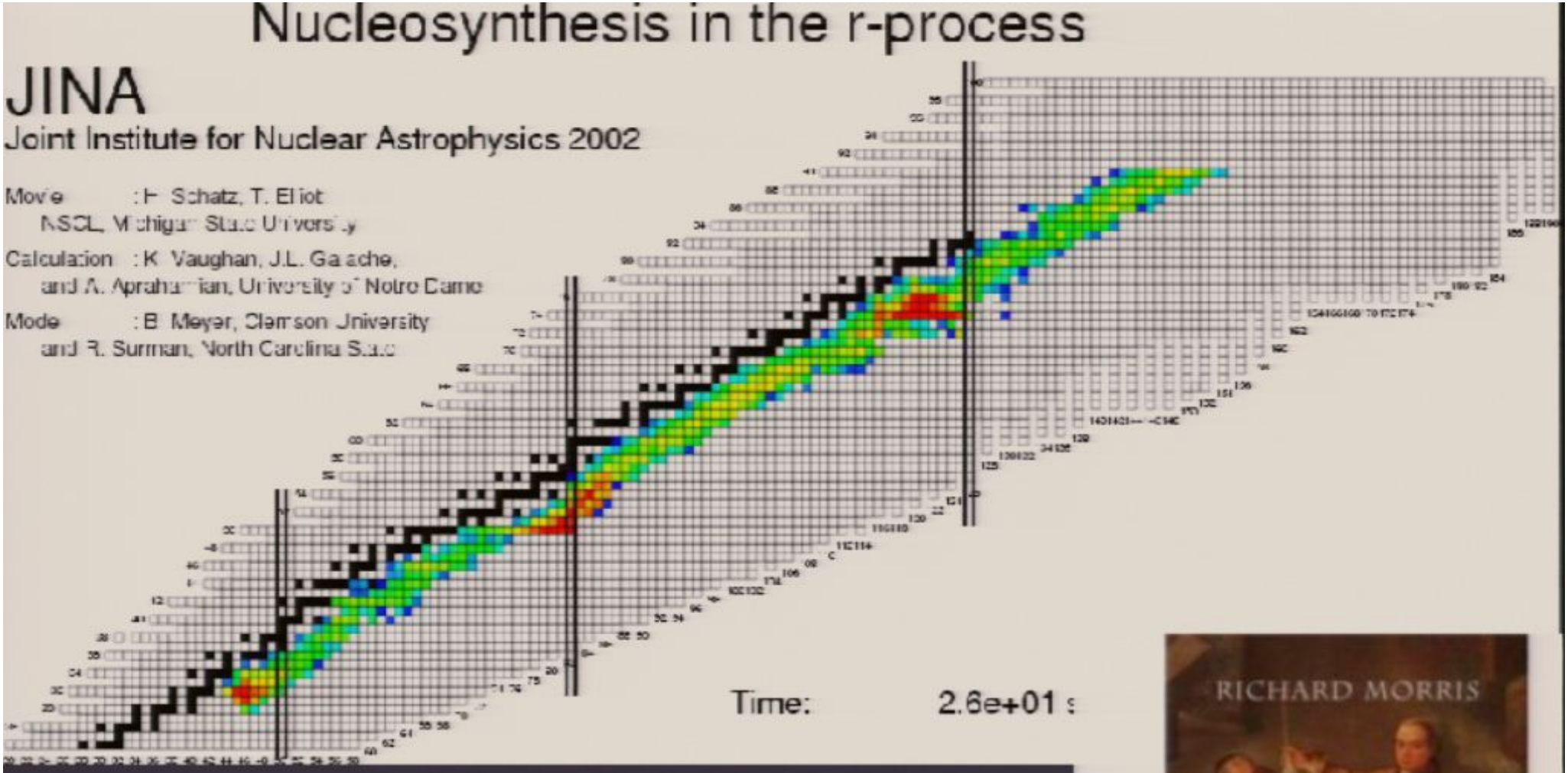

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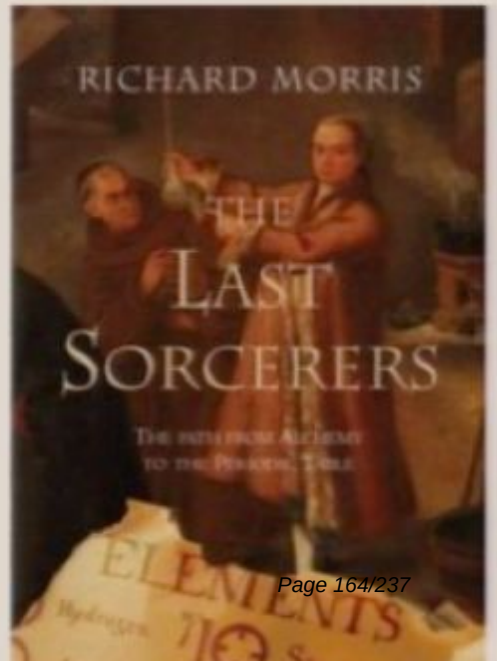

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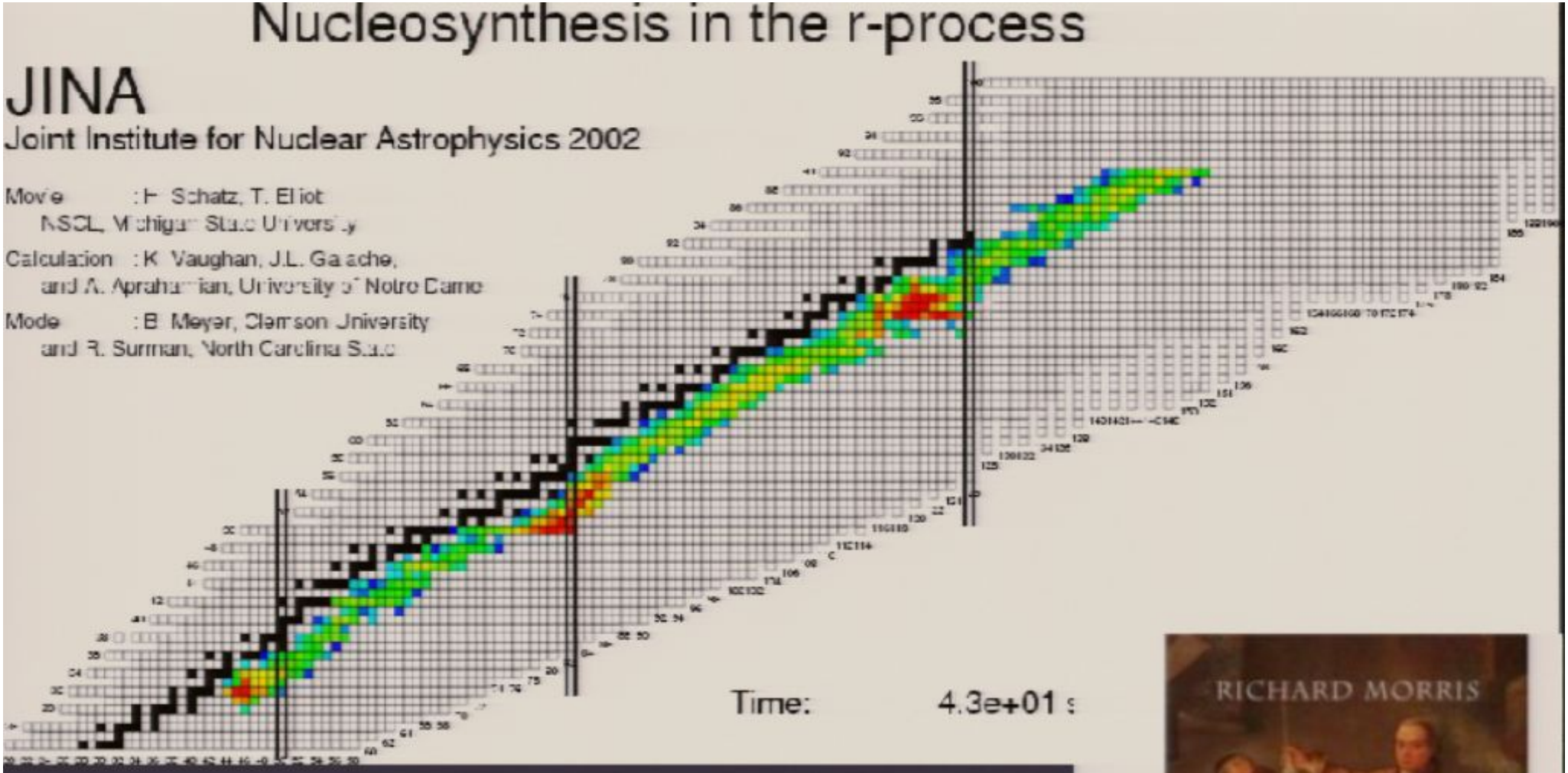

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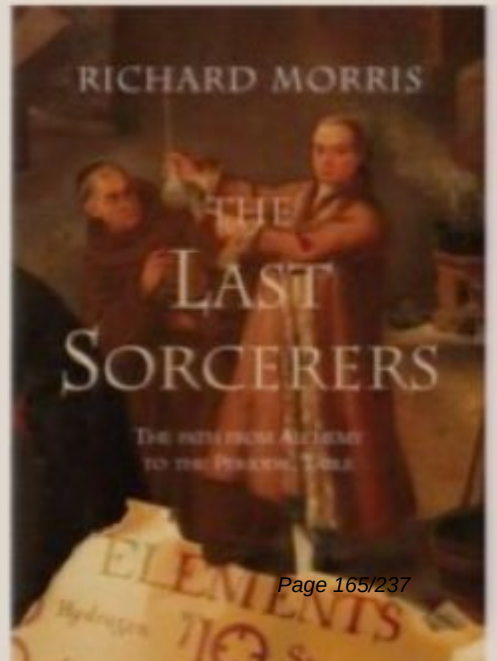

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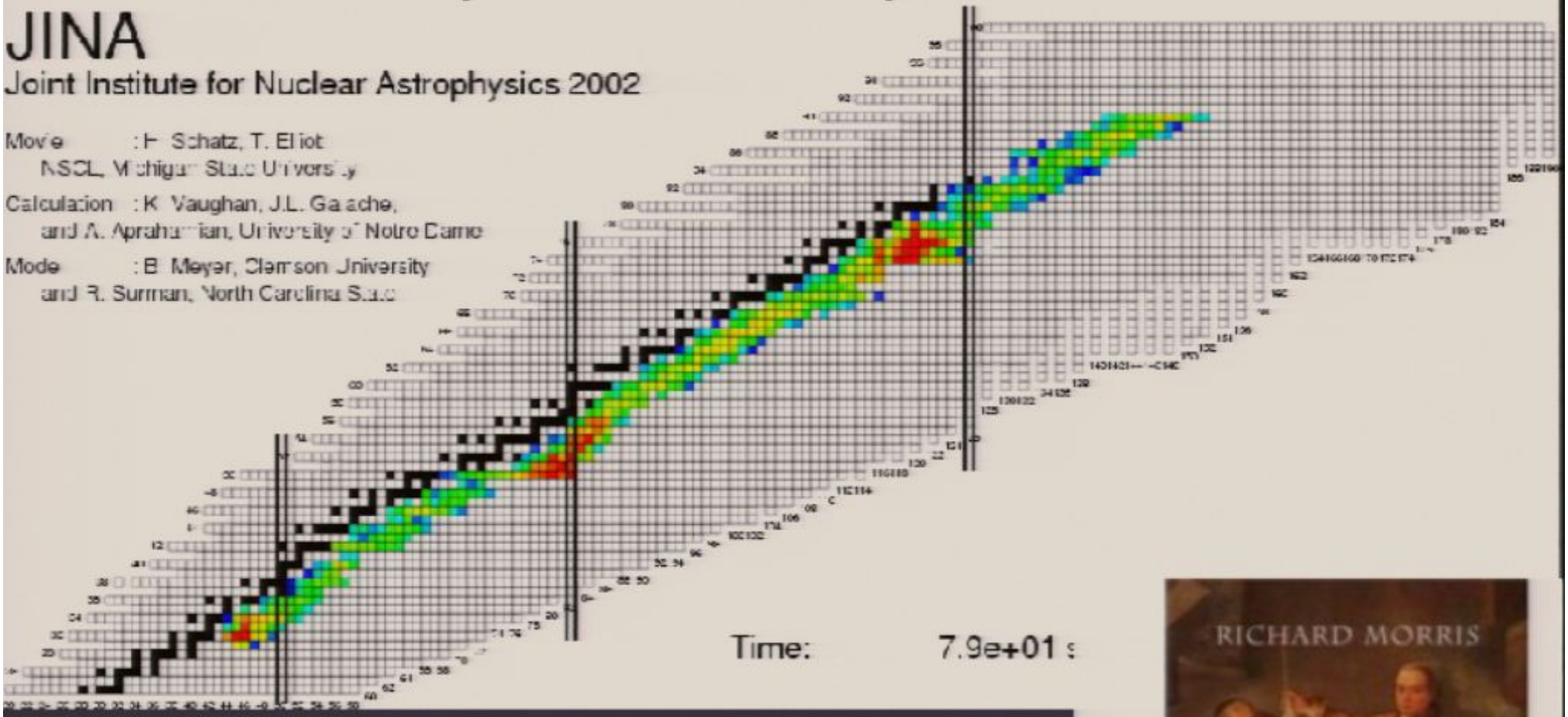

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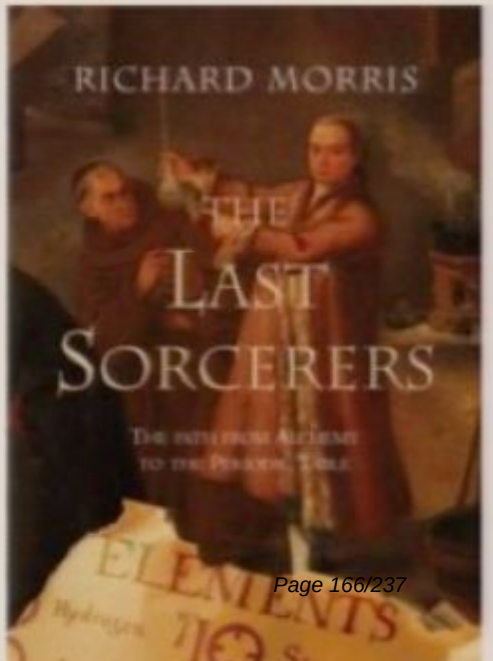

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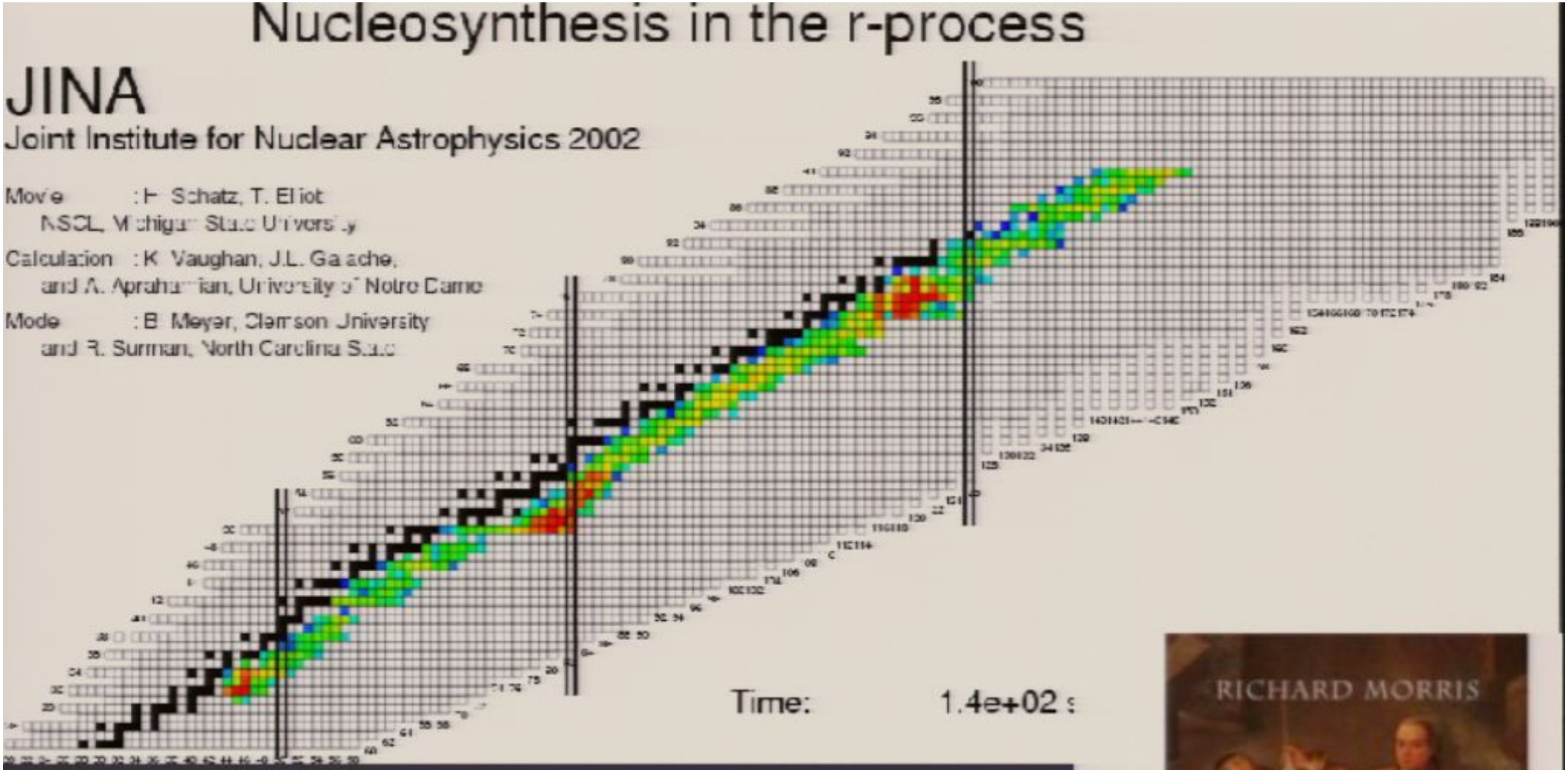

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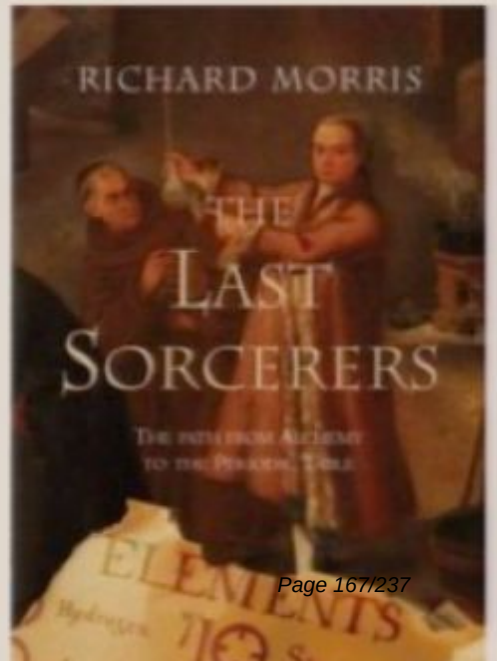

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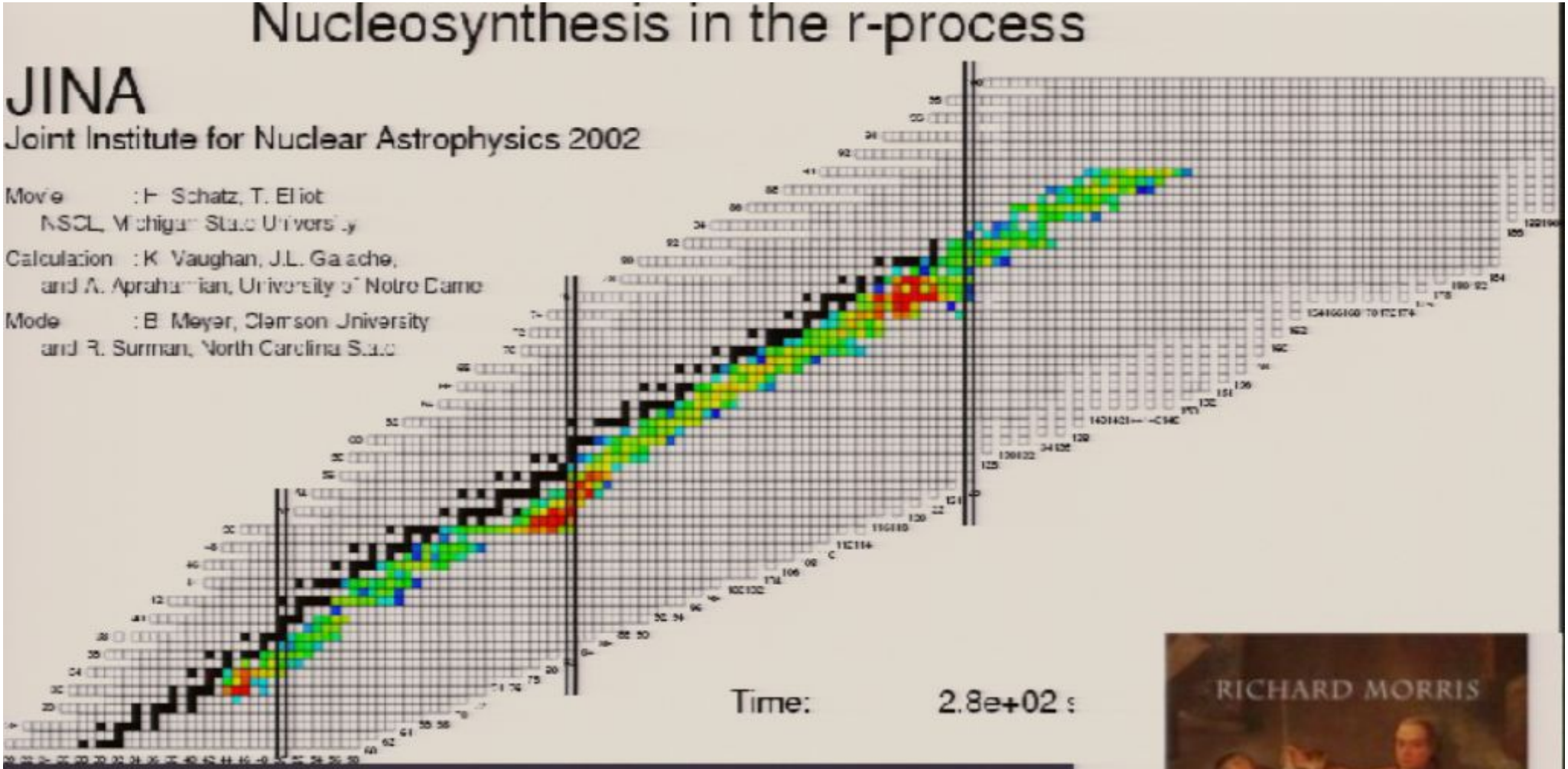

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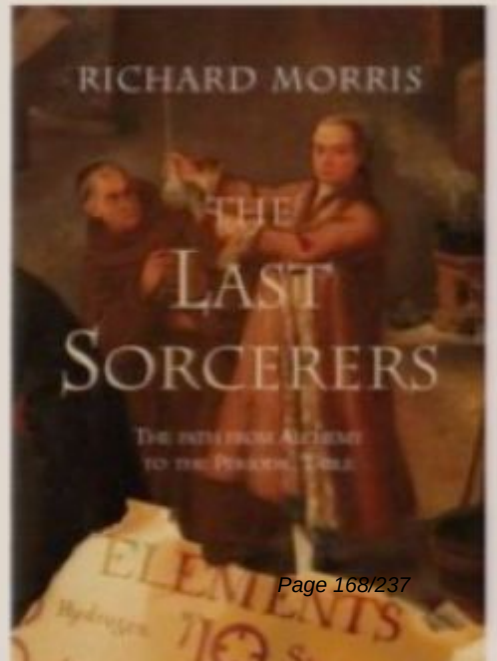

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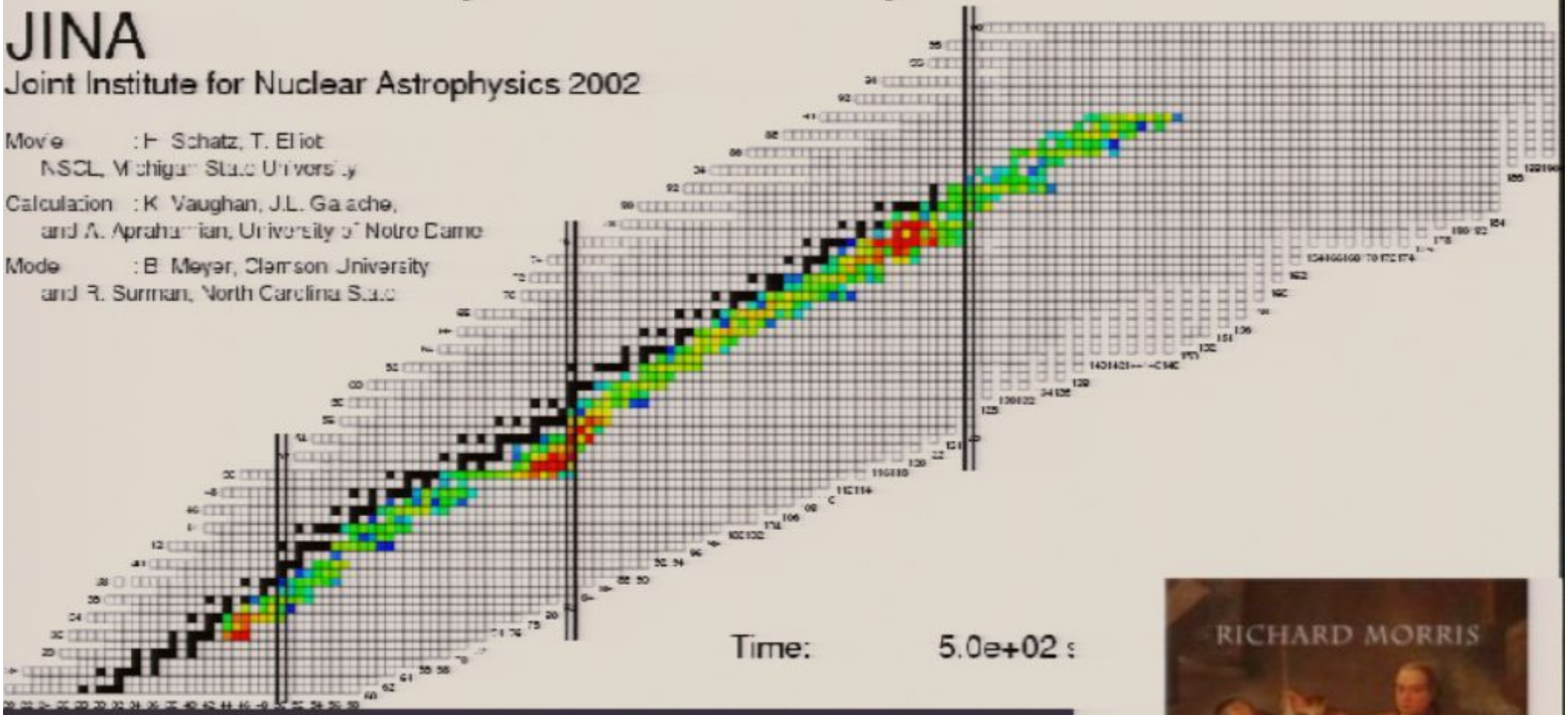

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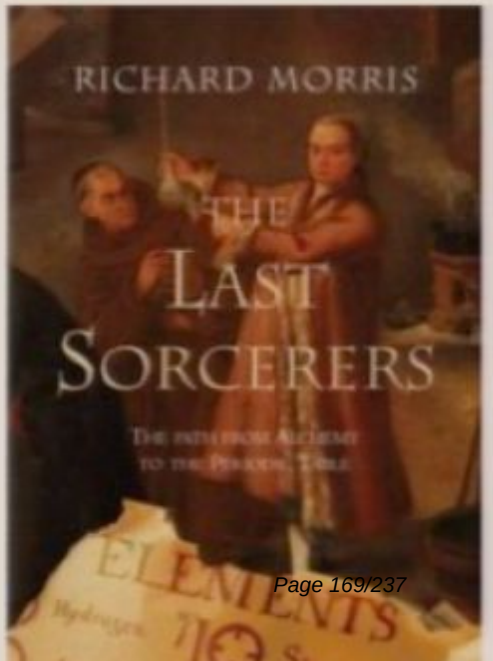

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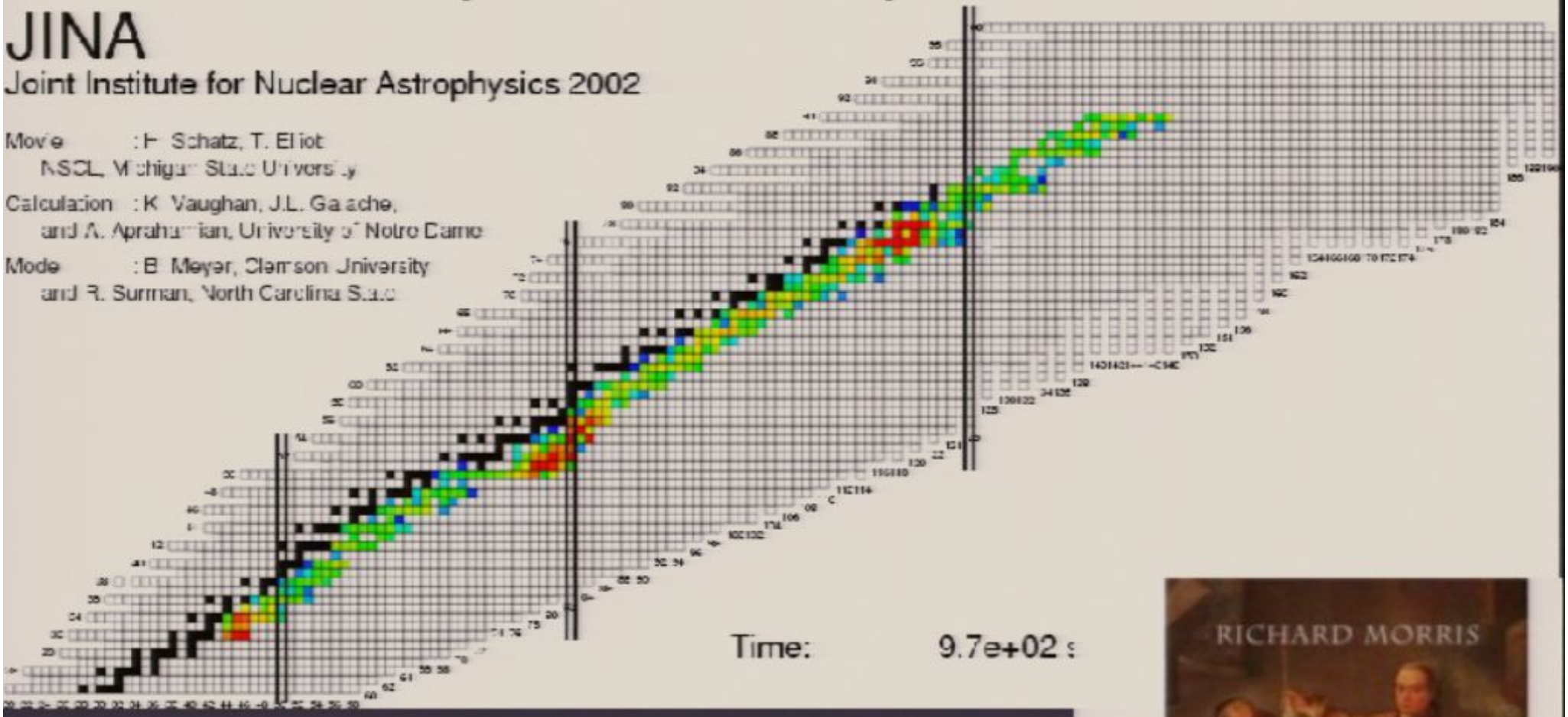

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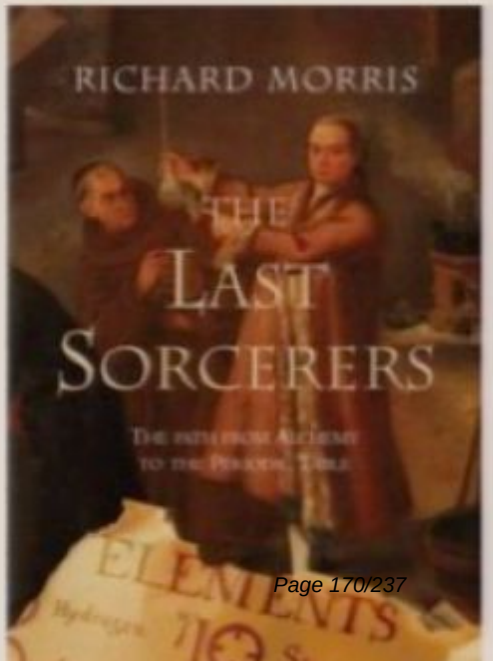

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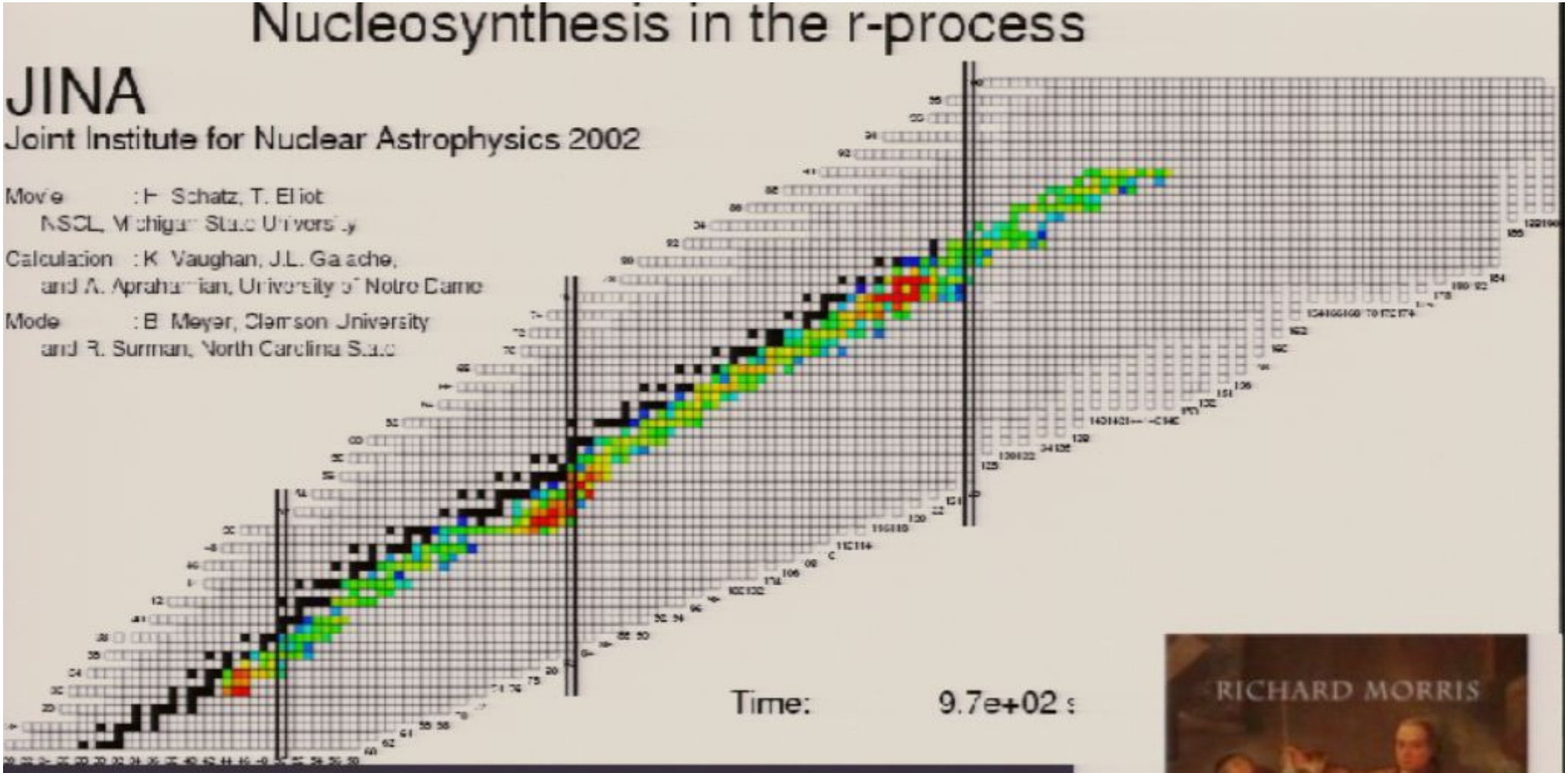

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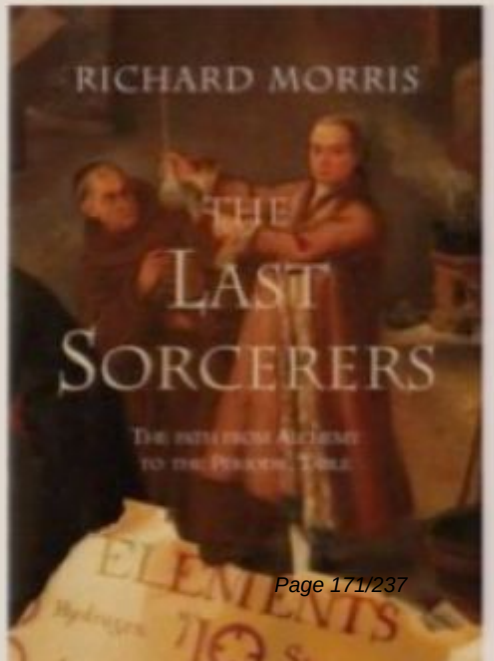

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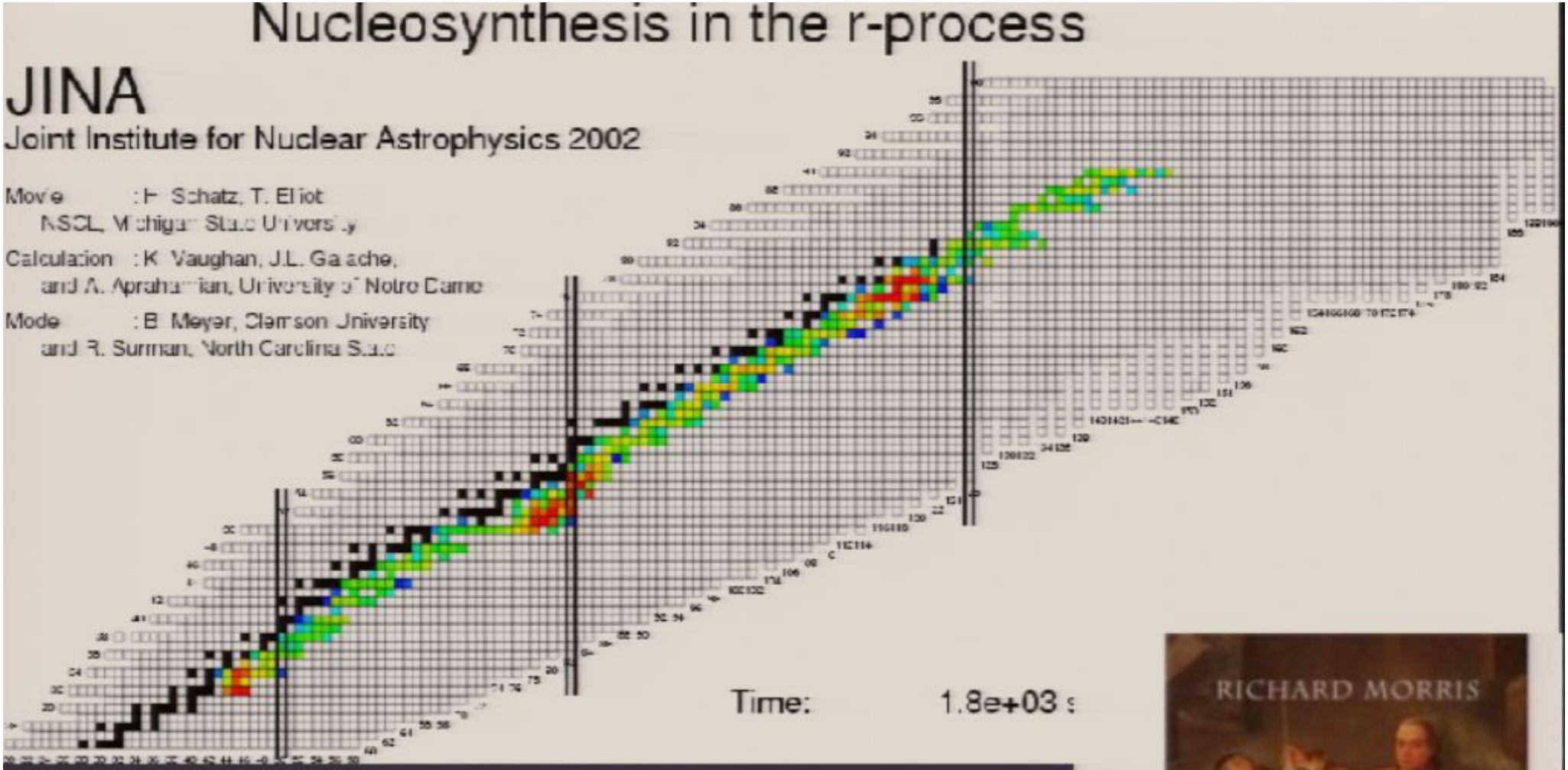

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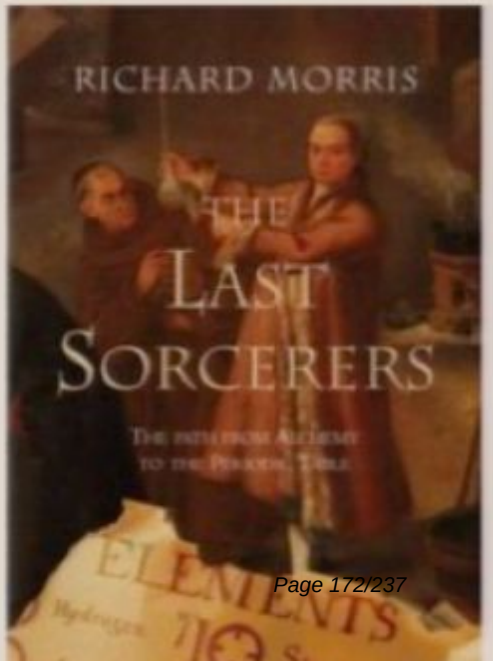

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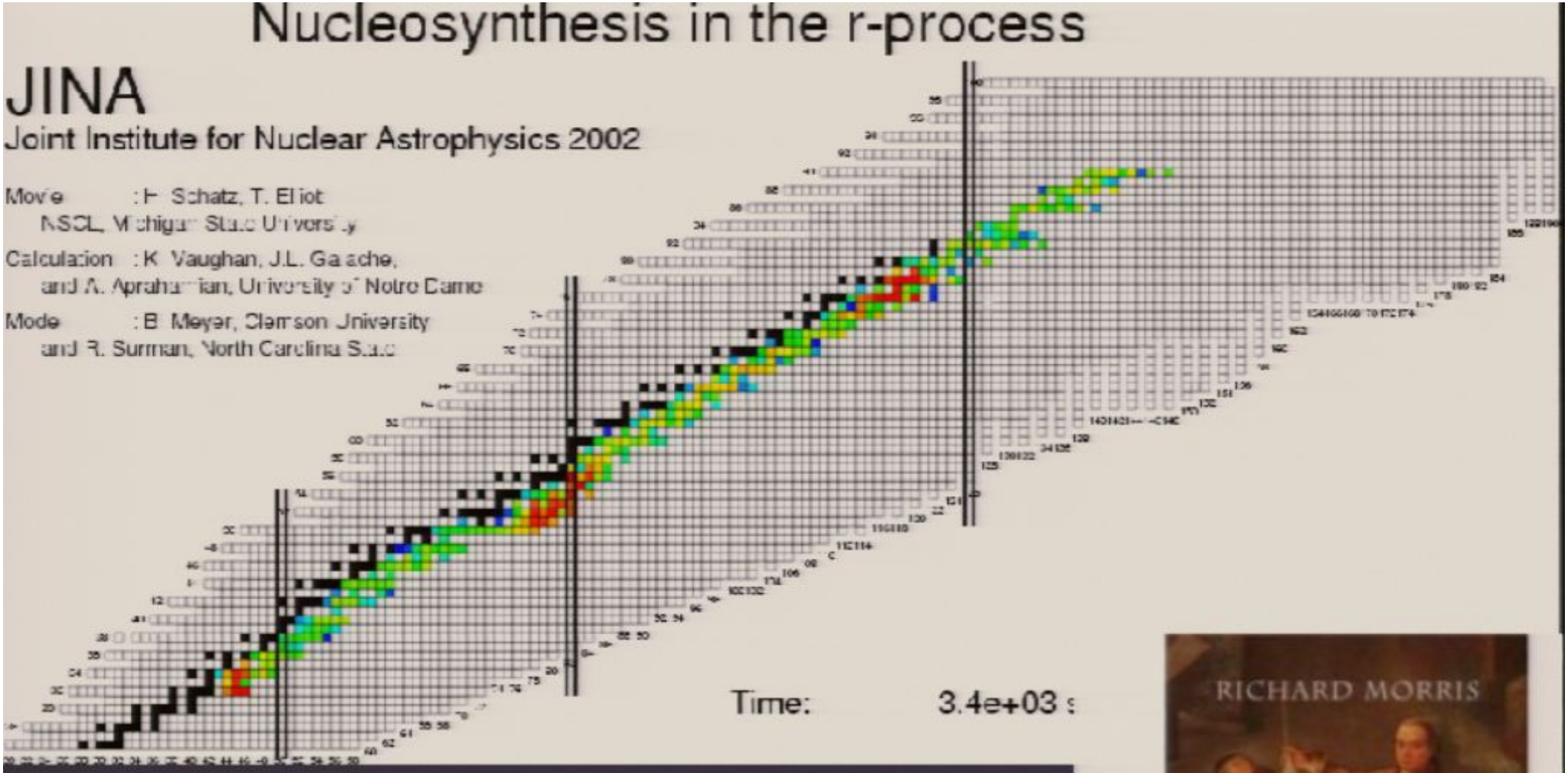

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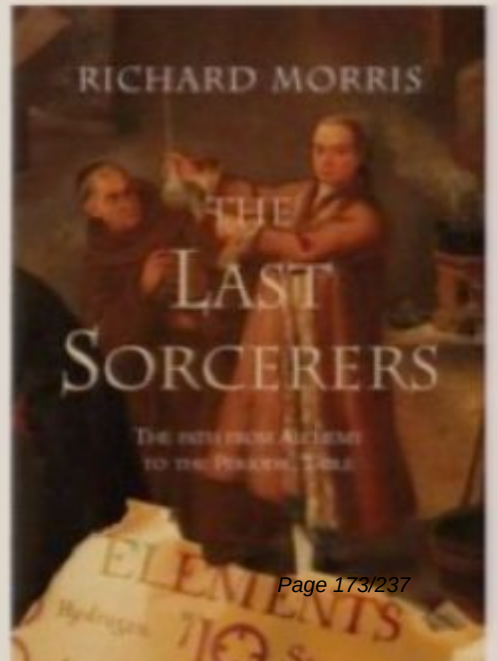

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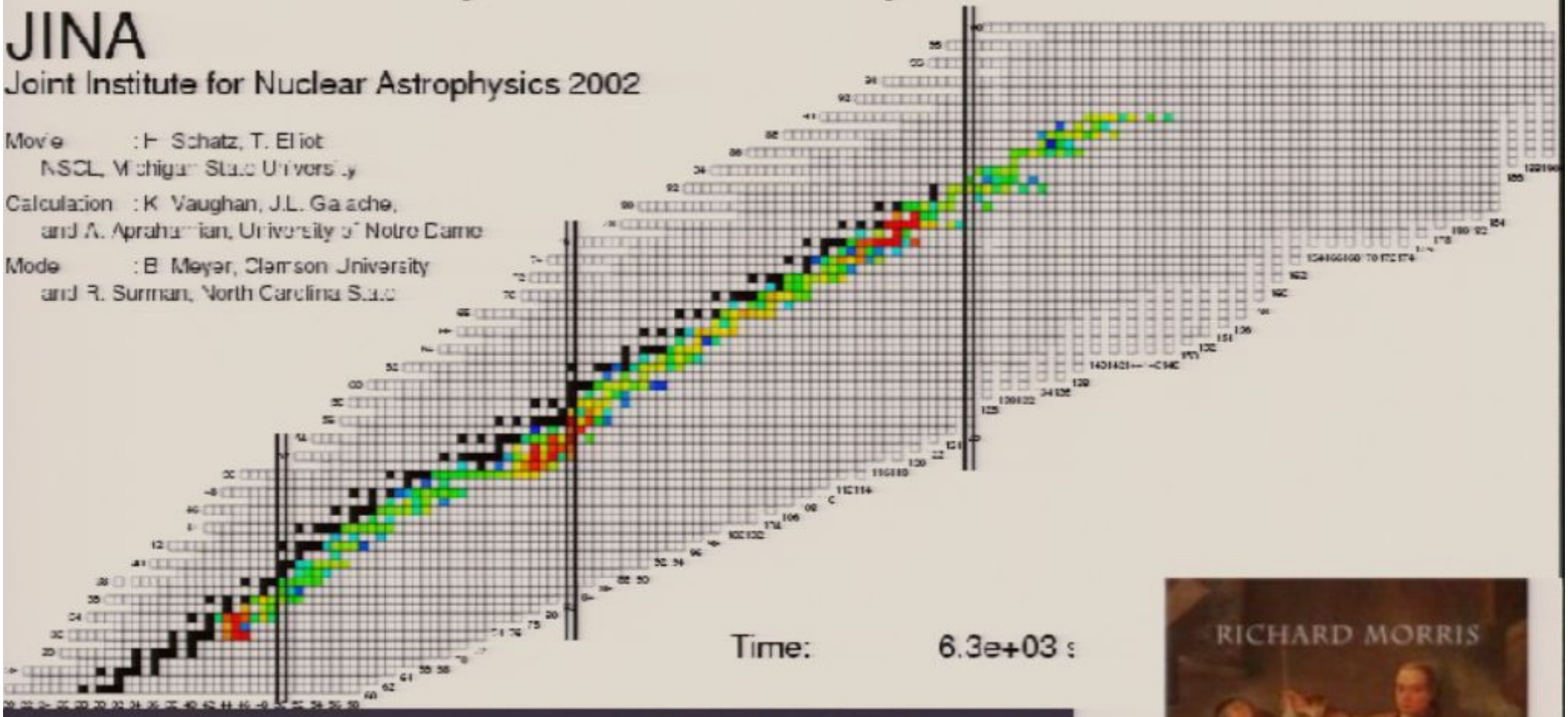

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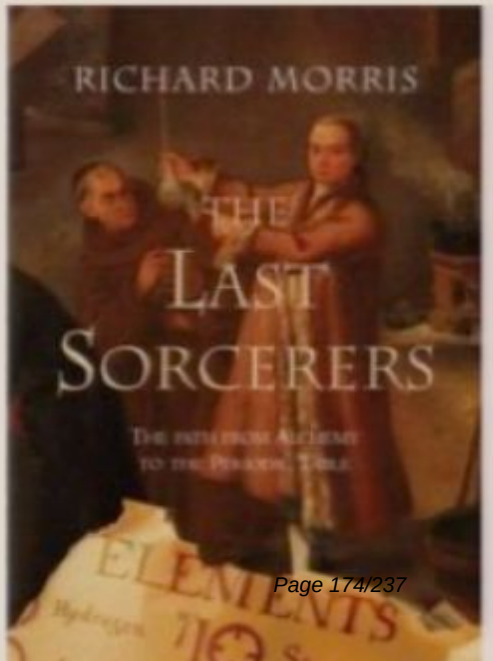

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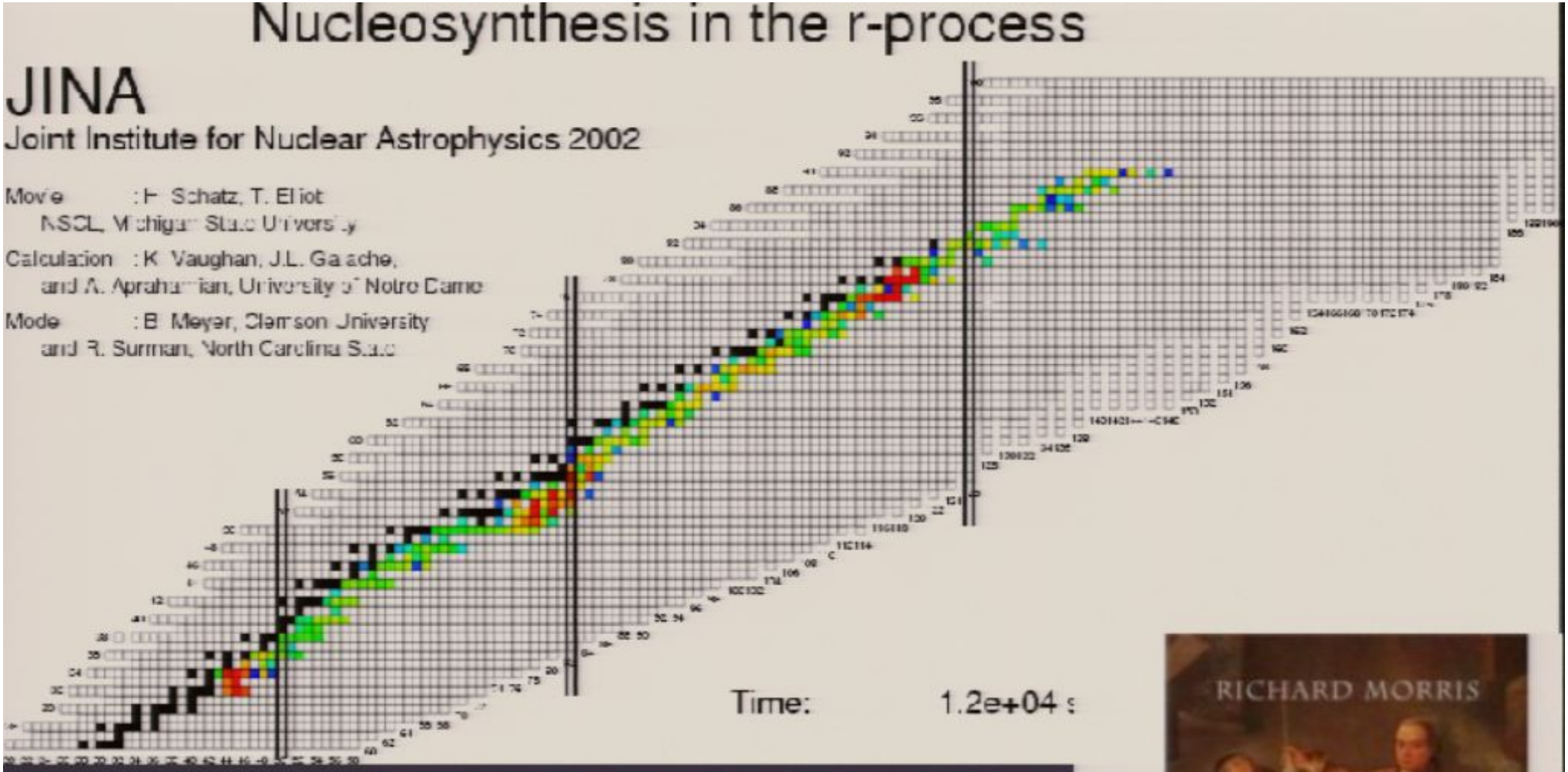

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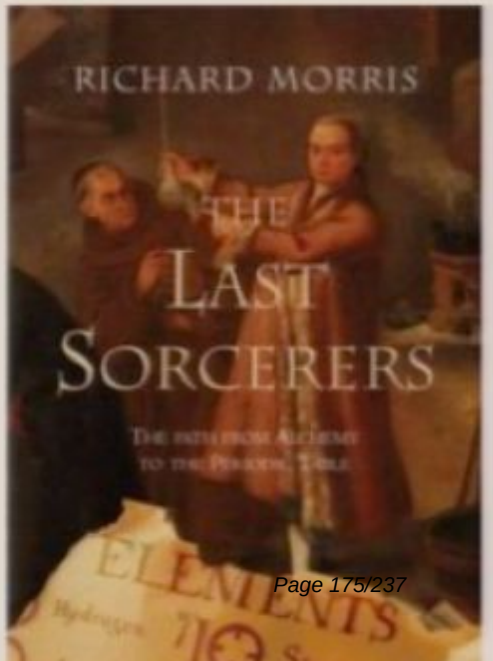
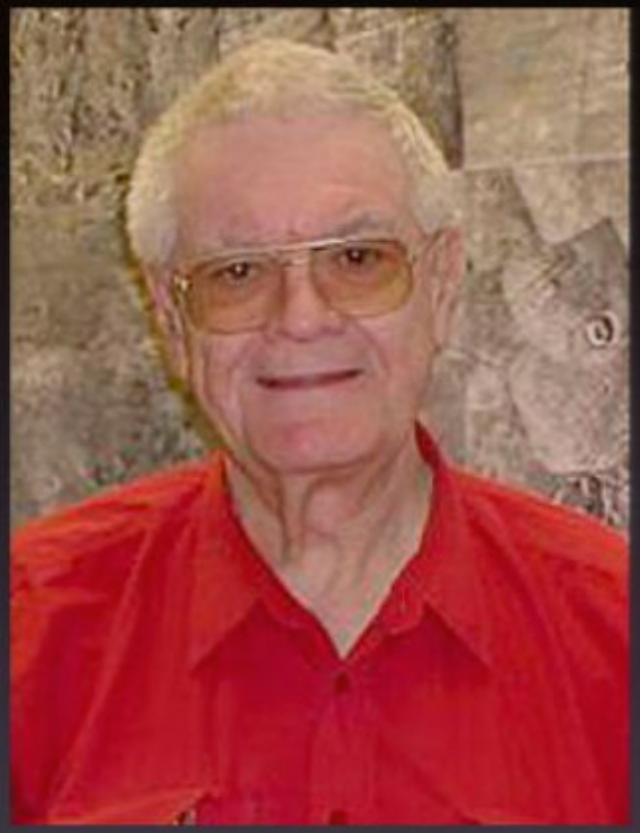


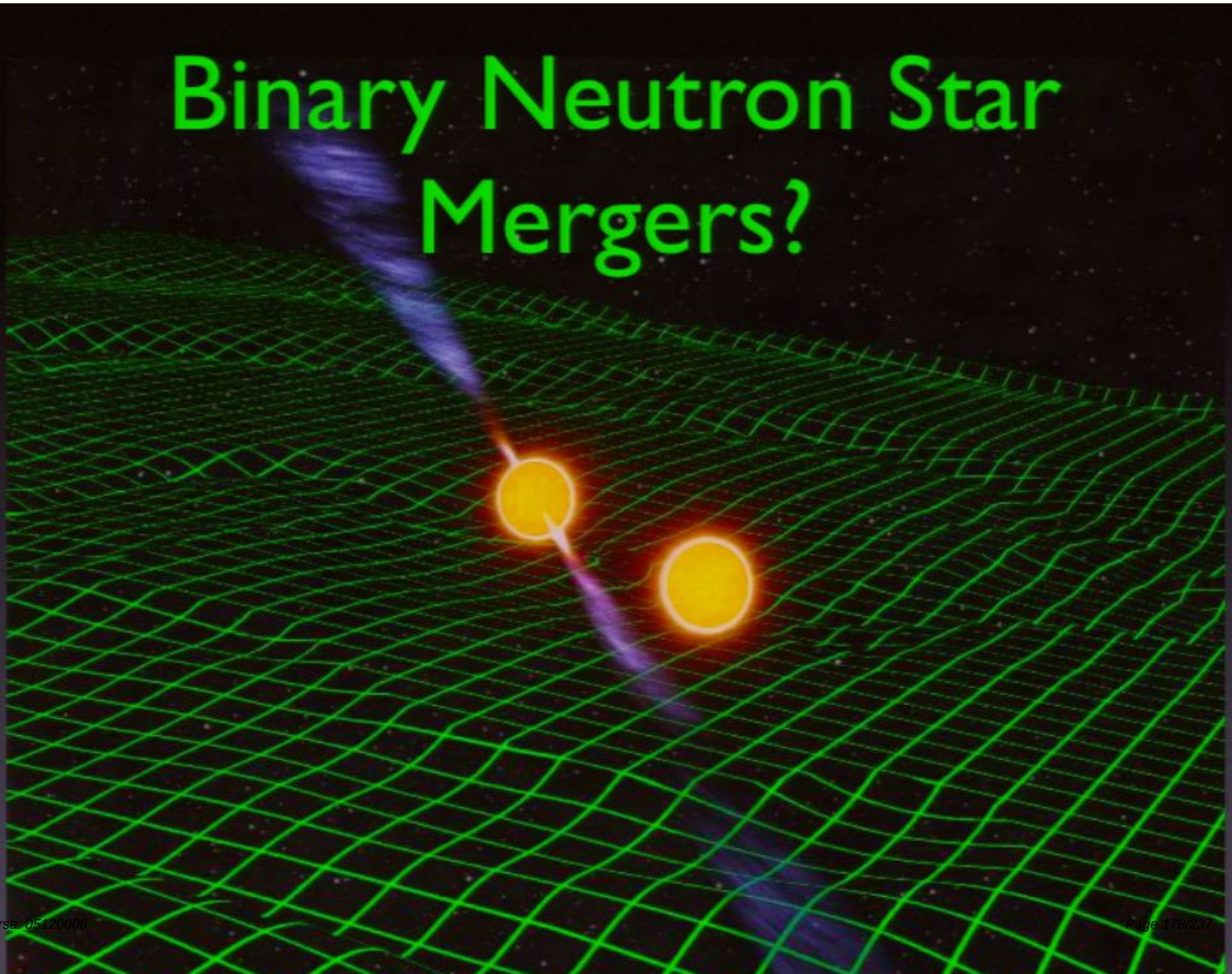
Which astrophysical environments provide conditions supporting r-process nucleosynthesis?

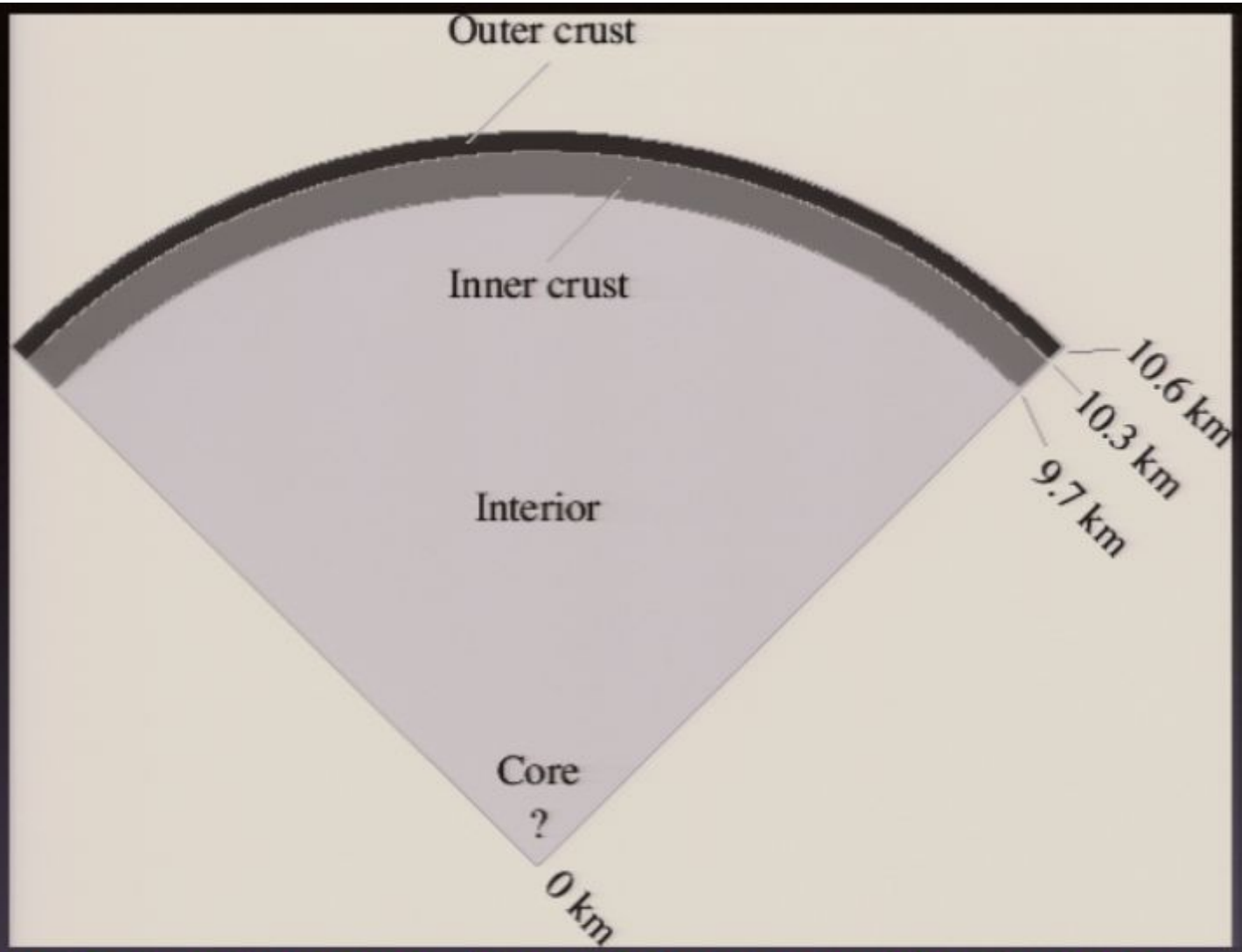


Alistair G. W. Cameron
(1925-2005)

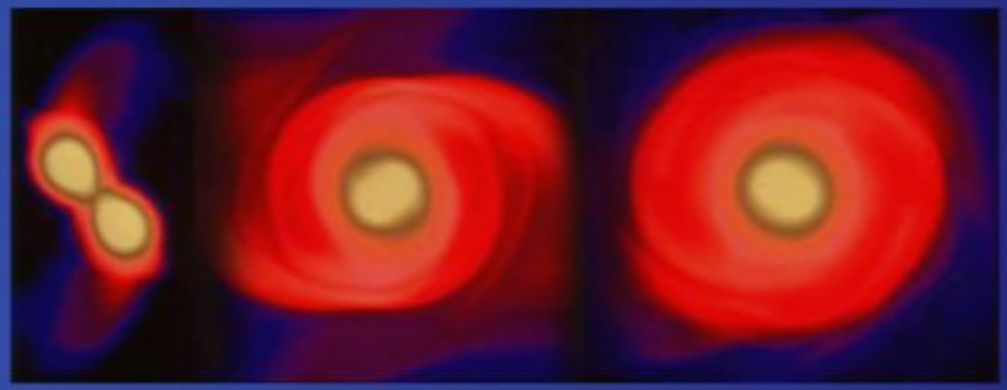
"If you want lots of neutrons, go where you know there are lots of neutrons"

Binary Neutron Star Mergers?





- **Outer crust:** Iron and neutron rich nuclei, mixed with relativistic degenerate electrons
- **Inner crust:** Neutron rich nuclei, free **super-fluid** neutrons (from **neutron drip**), and relativistic degenerate electrons
- **Interior:** full of super-fluid neutrons
- **Core:** who knows? Pions?



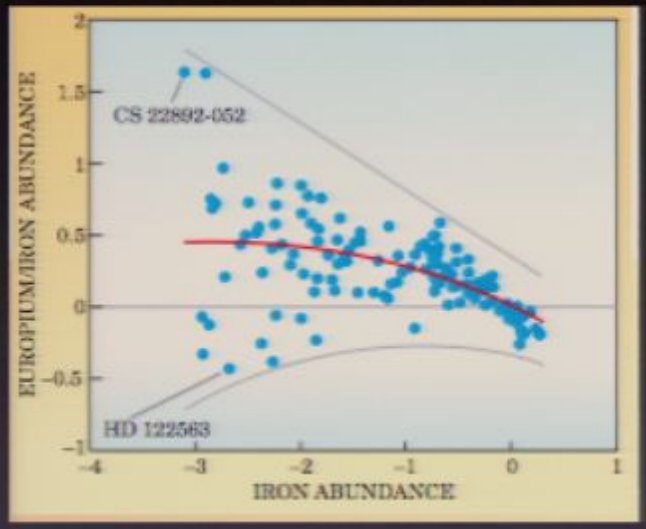
- mergers provide large neutron-to-seed density
- less frequent than type II SNe but eject more mass

..cannot explain scatter plot for metal-poor stars

- mergers are infrequent; cannot explain early r-enrichment of halo stars.
- lead to large scatter (more chemical inhomog.) at late times; not consistent with observed scatter at [Fe/H]> -1.

Cowan

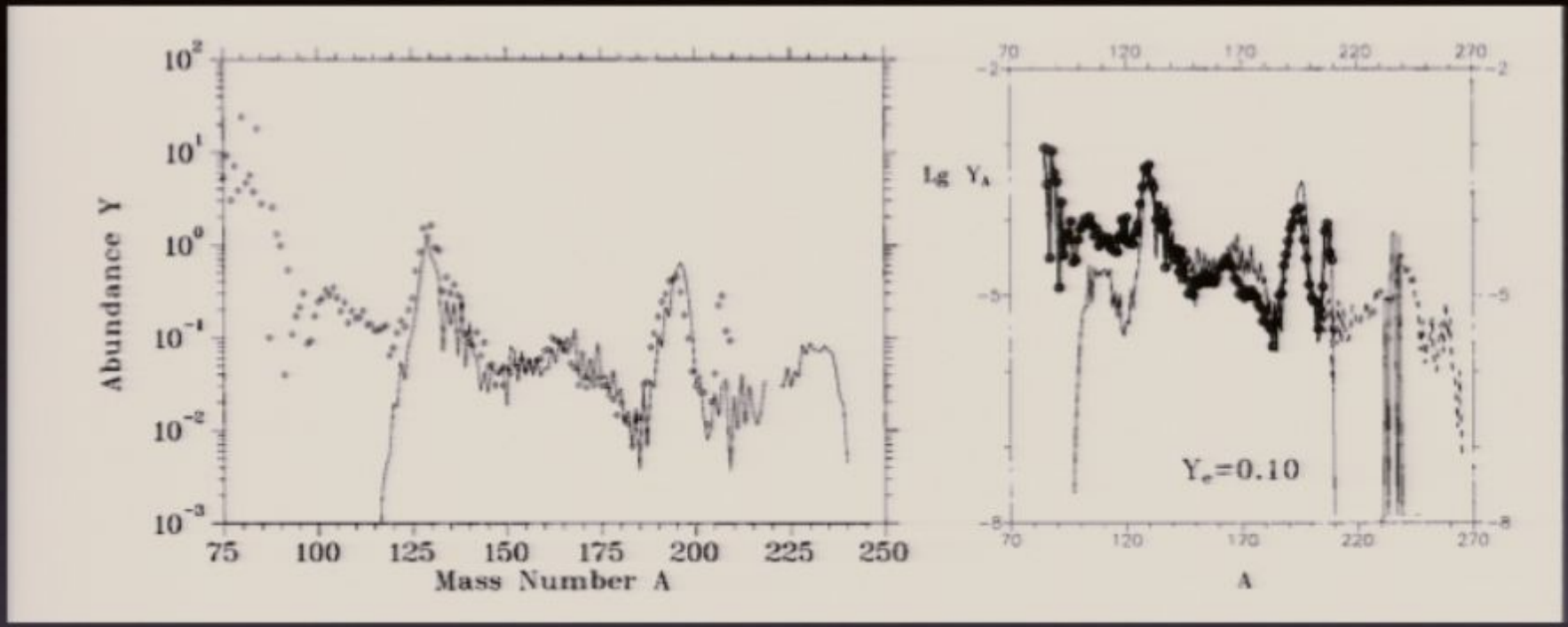
Physics Today, Volume 57
Number 10, 47 (October, 2004)



The halo star HD 122563 is almost as Fe-poor (old) as CS 22892-052, but it has much less Eu

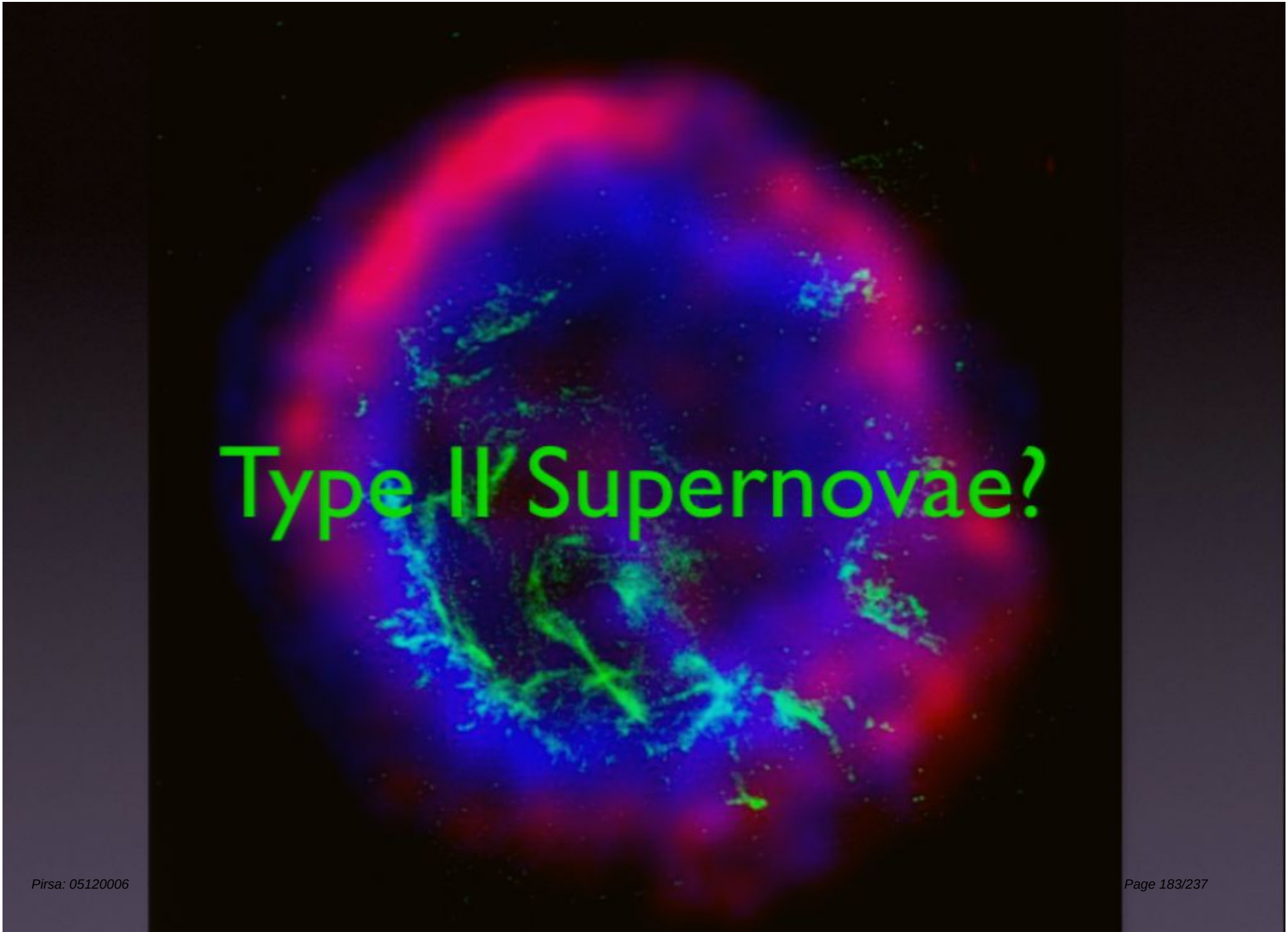
Early scatter from star-to-star

Other issues with mergers

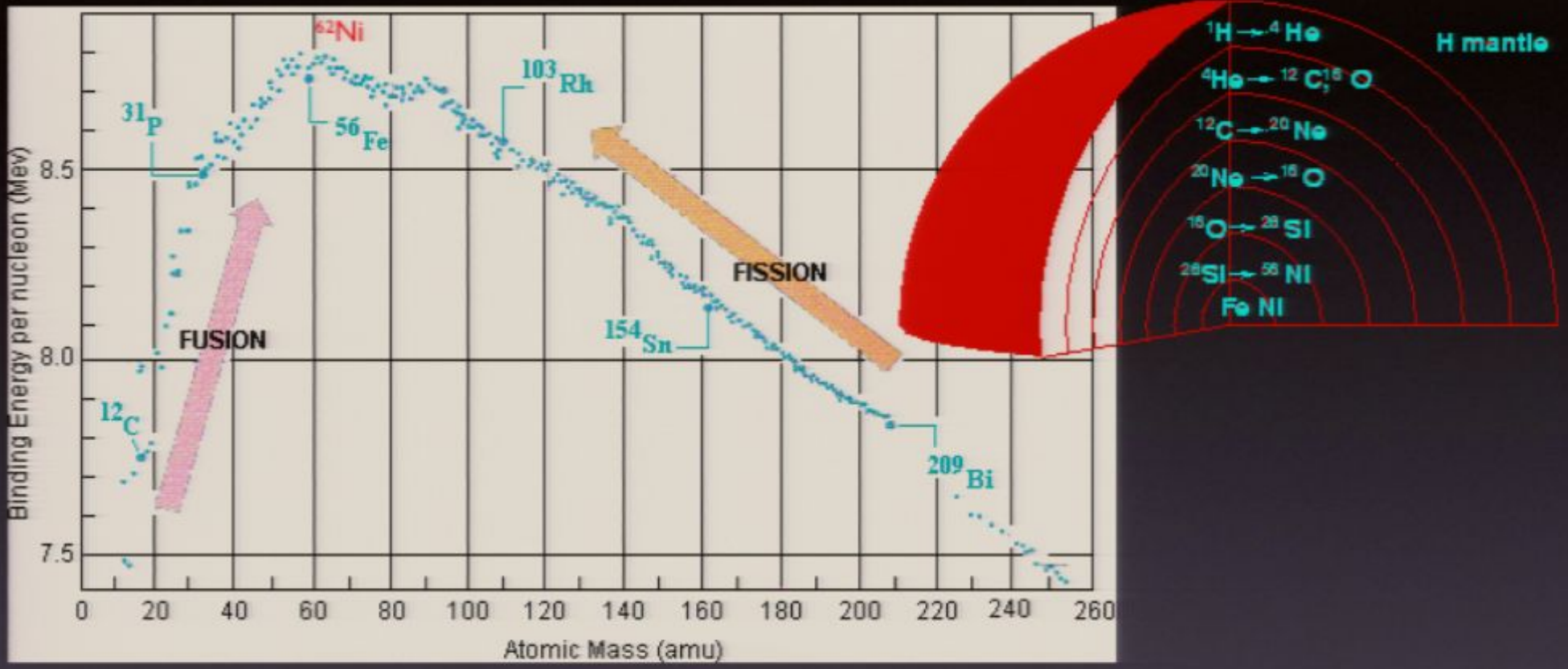


The mass region below A=125 becomes empty (Freiburghaus et al. 1999; Panov et al. 2005)!

^{73}Ge not produced!


Type II Supernovae?

Binding Energy

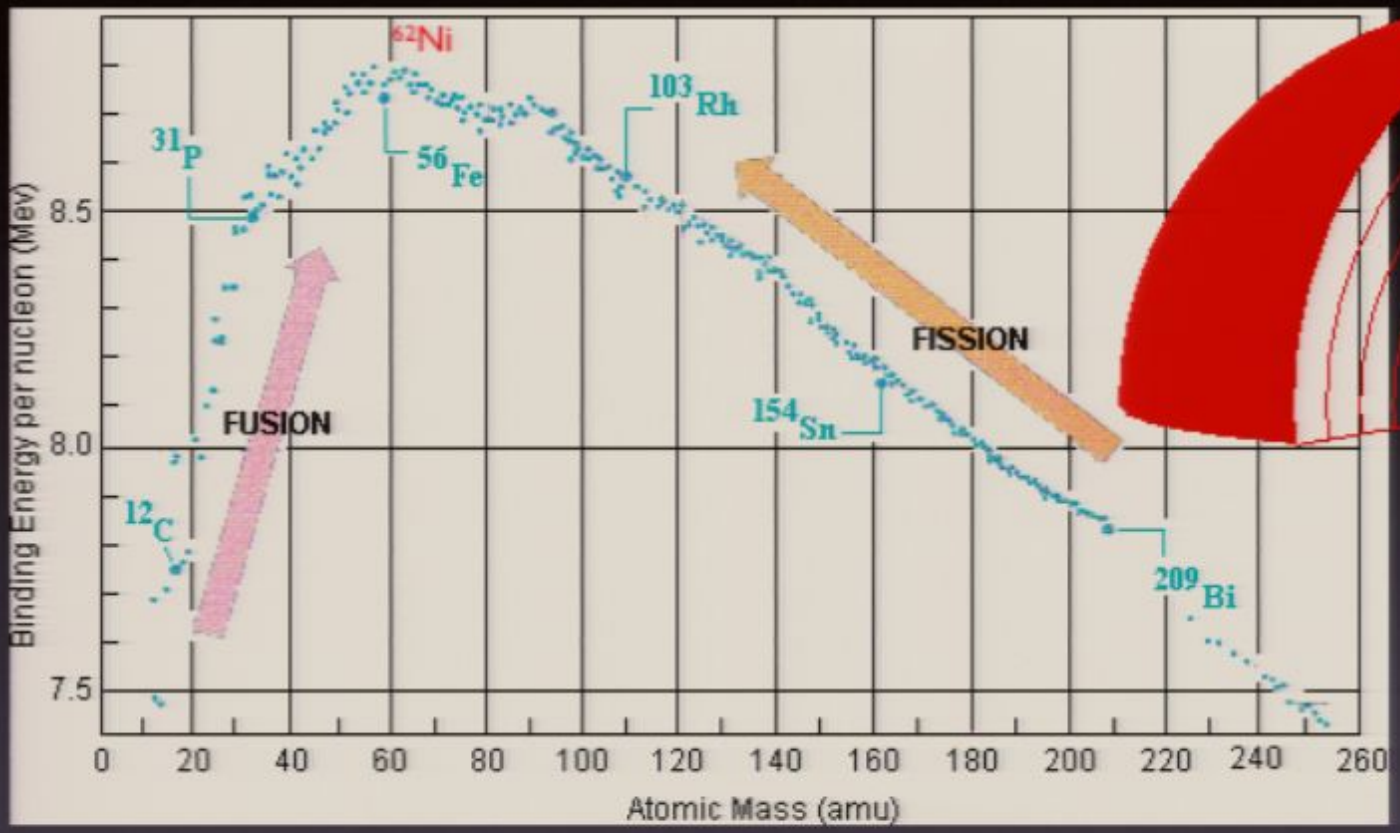


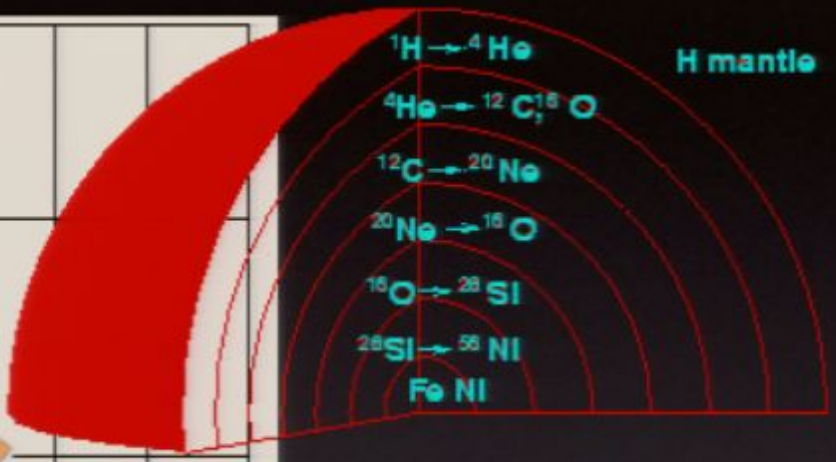
The build-up of complex atomic nuclei from the simpler comes to a dead halt with IRON !!

^{56}Fe → ^{62}Ni

^{56}Fe → ^{56}Co (gamma disintegration)

Binding Energy





The build-up of complex atomic nuclei from the simpler comes to a dead halt with IRON !!

$^{56}Fe \rightarrow {}^{62}Ni$

$^{56}Fe \rightarrow {}^{56}Co$ (gamma disintegration)

Stars 8 times heavier than our sun:

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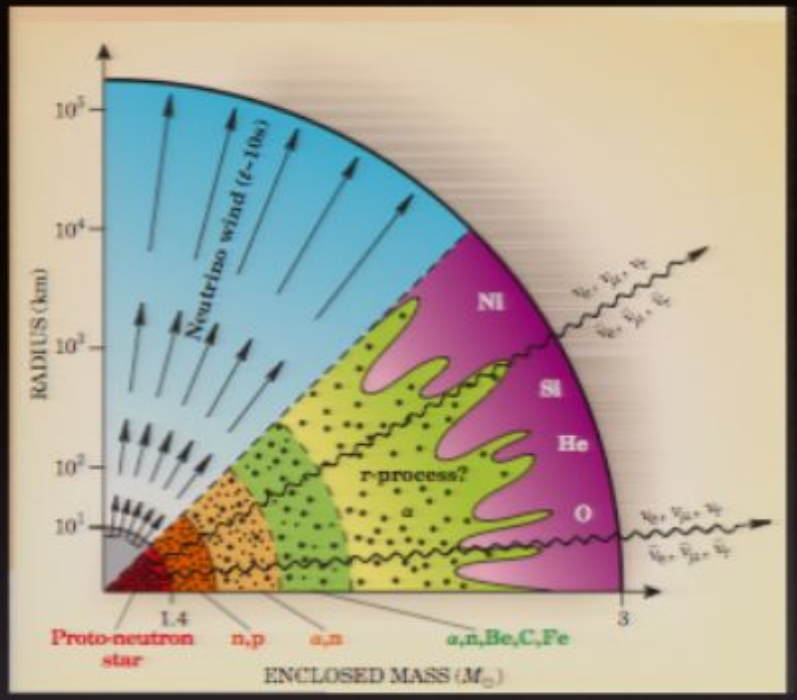

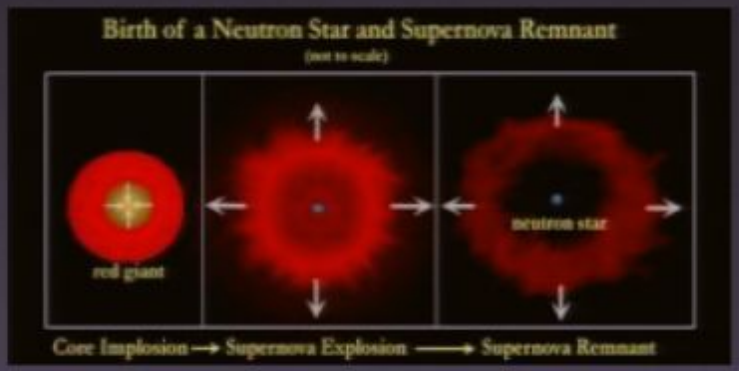

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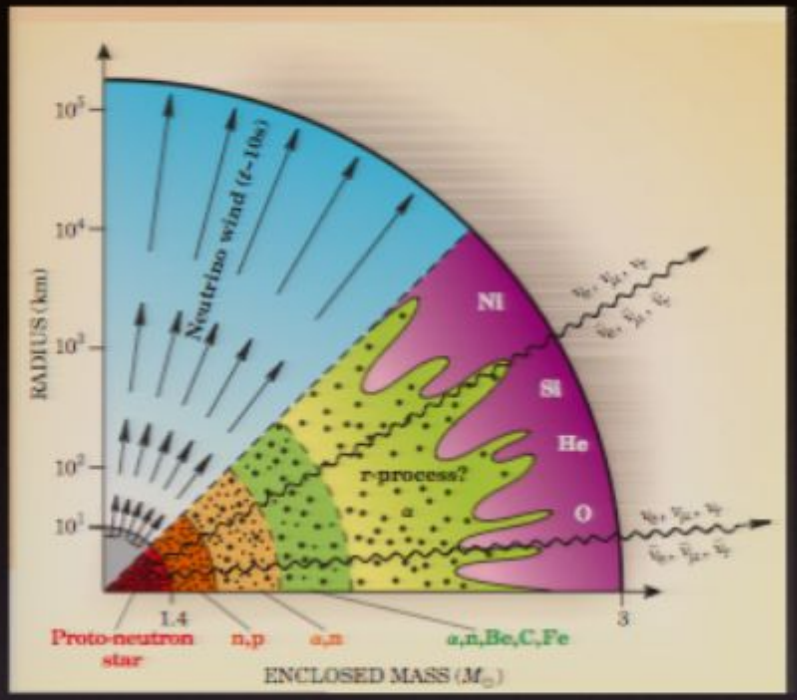

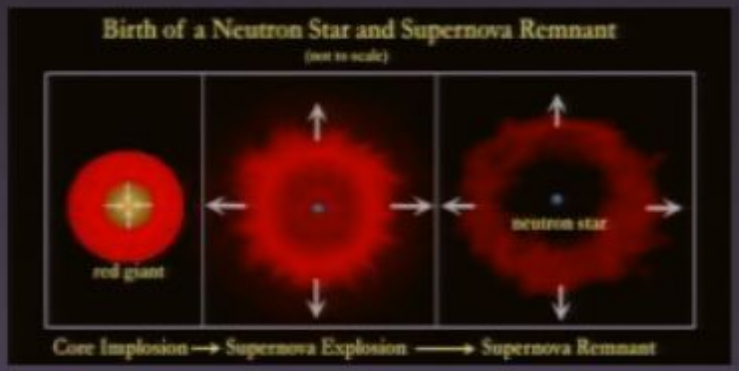

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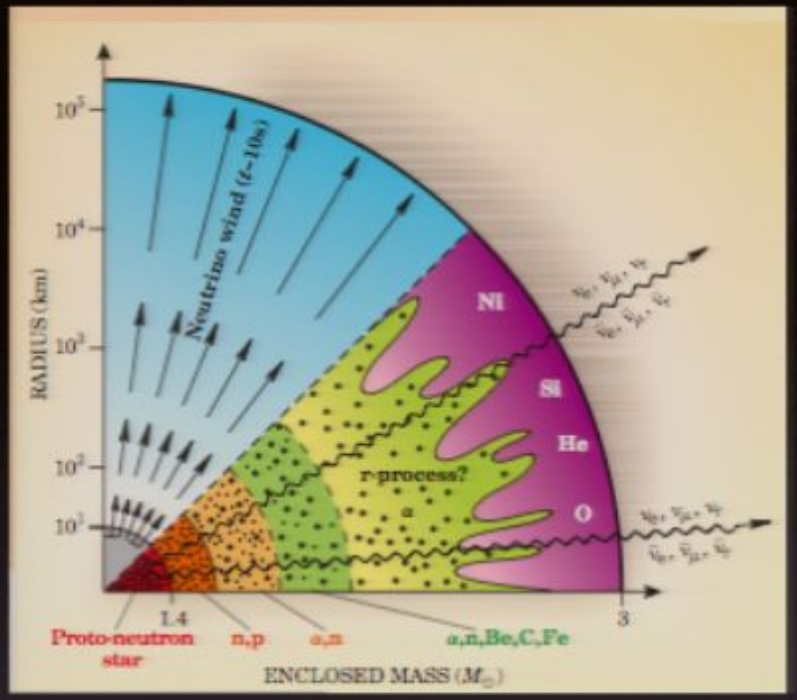

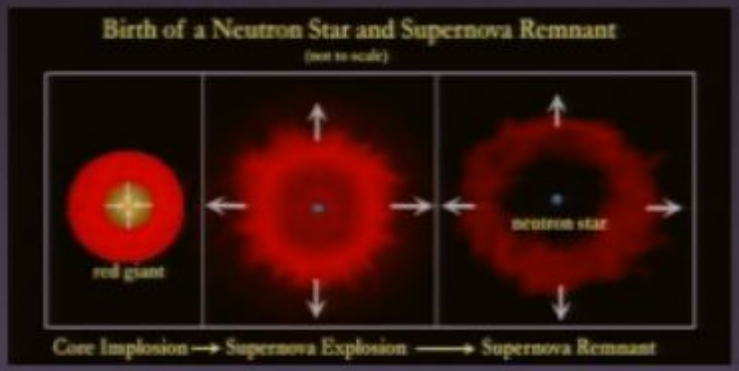

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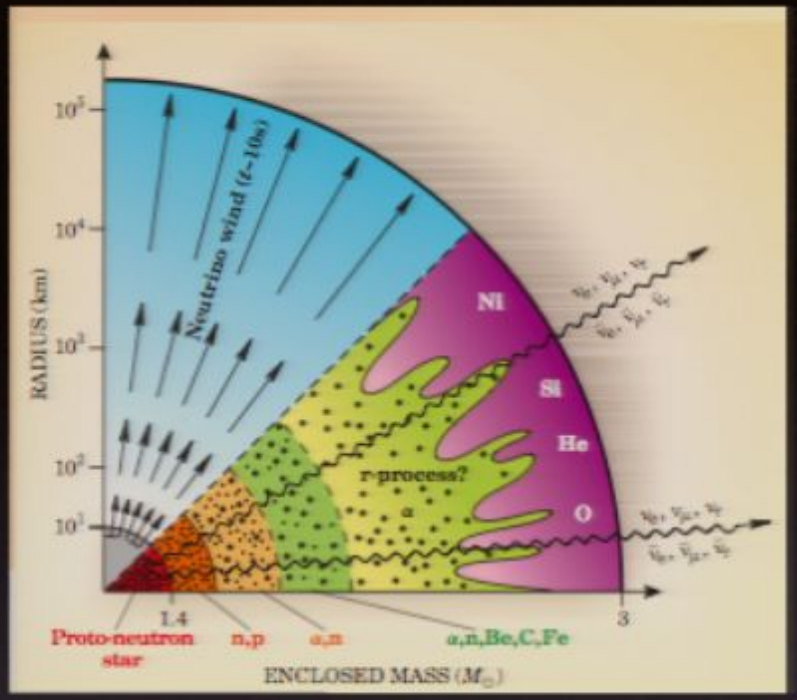

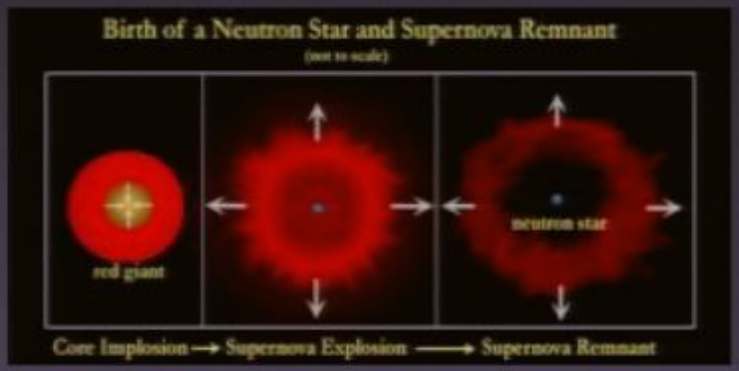

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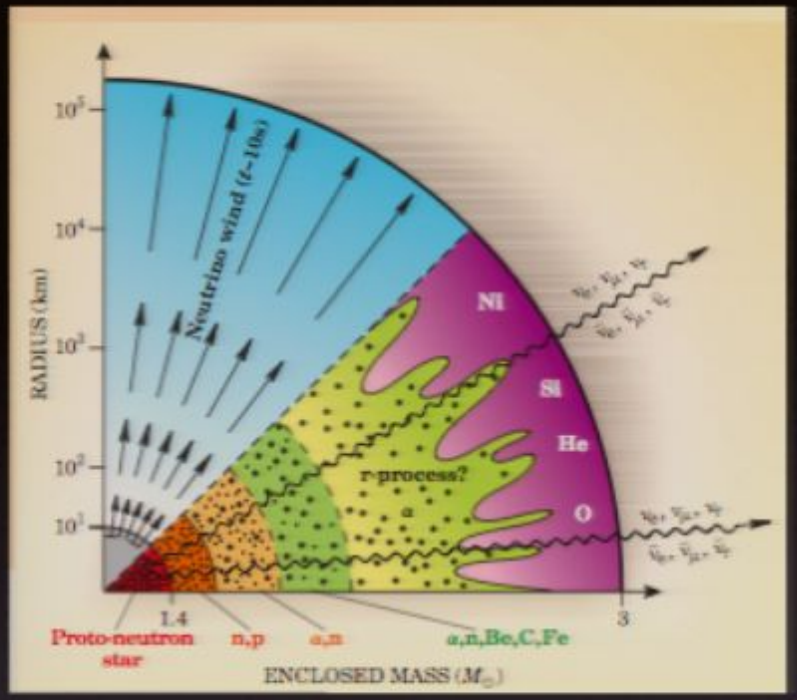

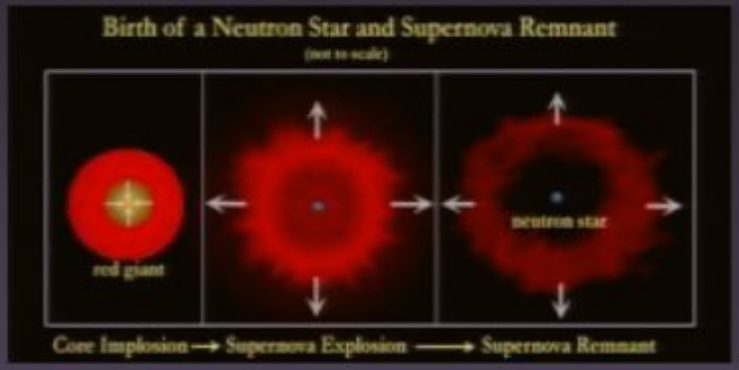

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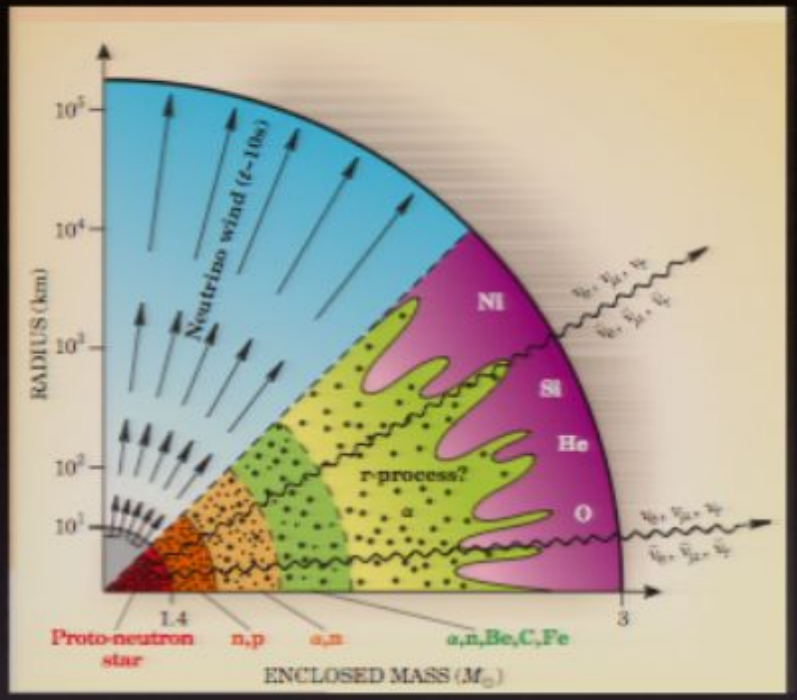

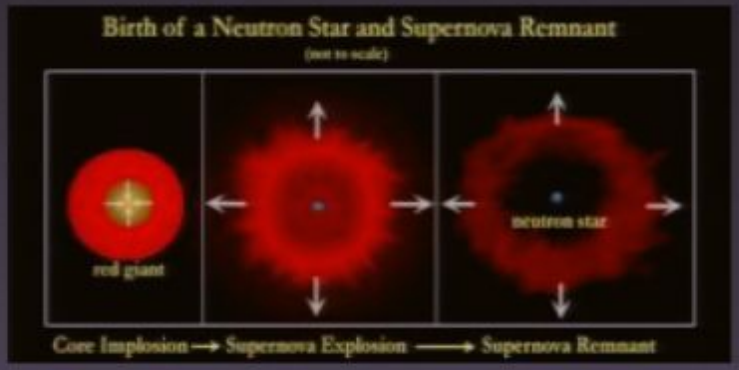

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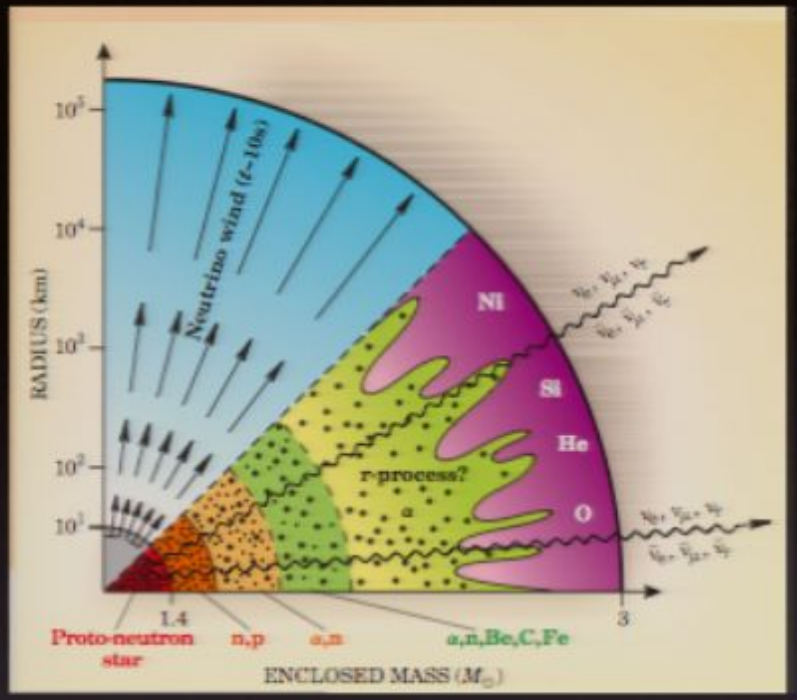

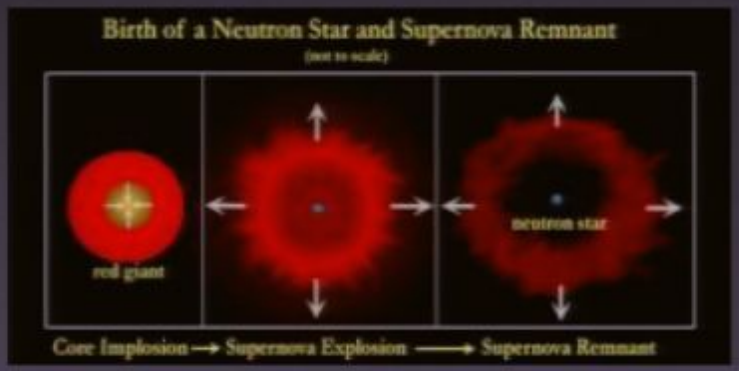

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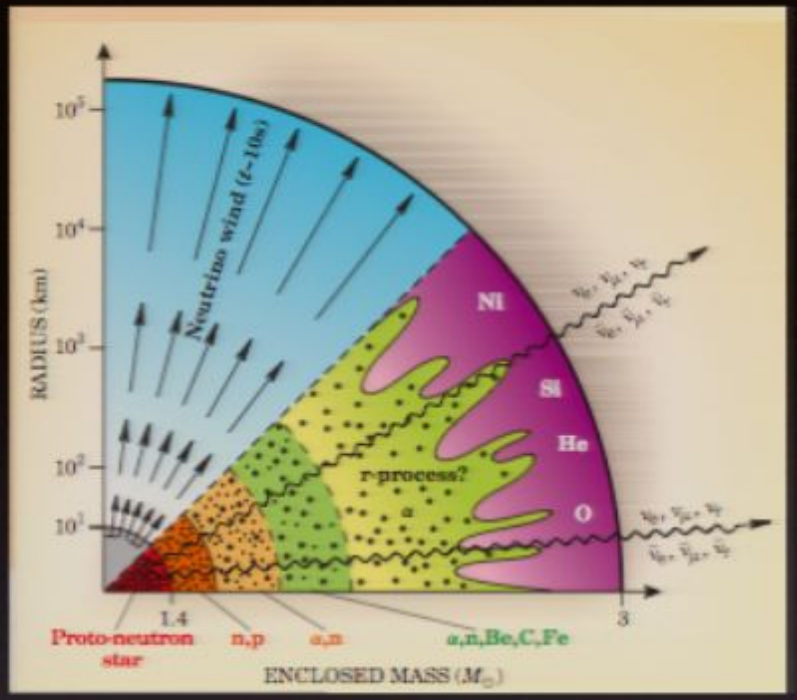

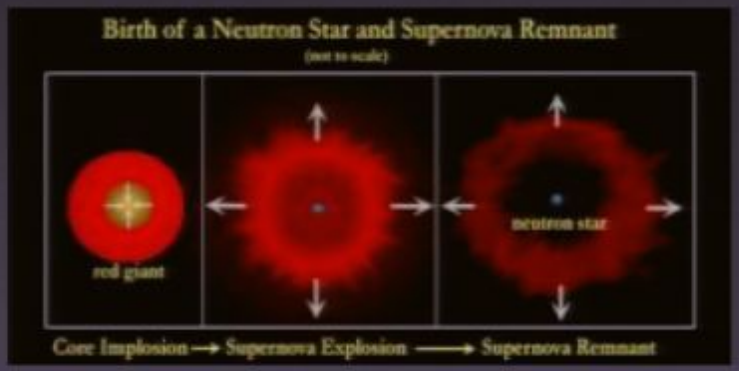

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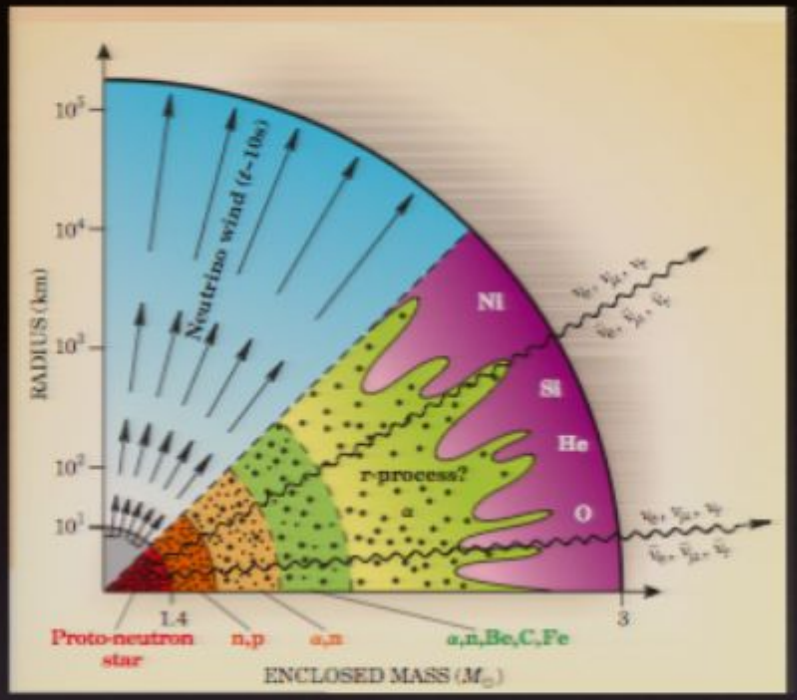

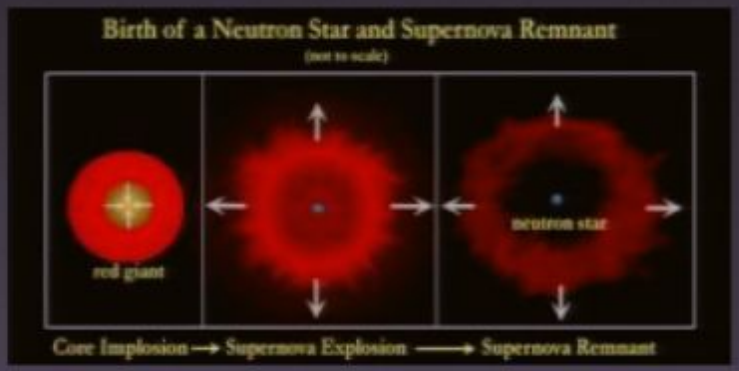

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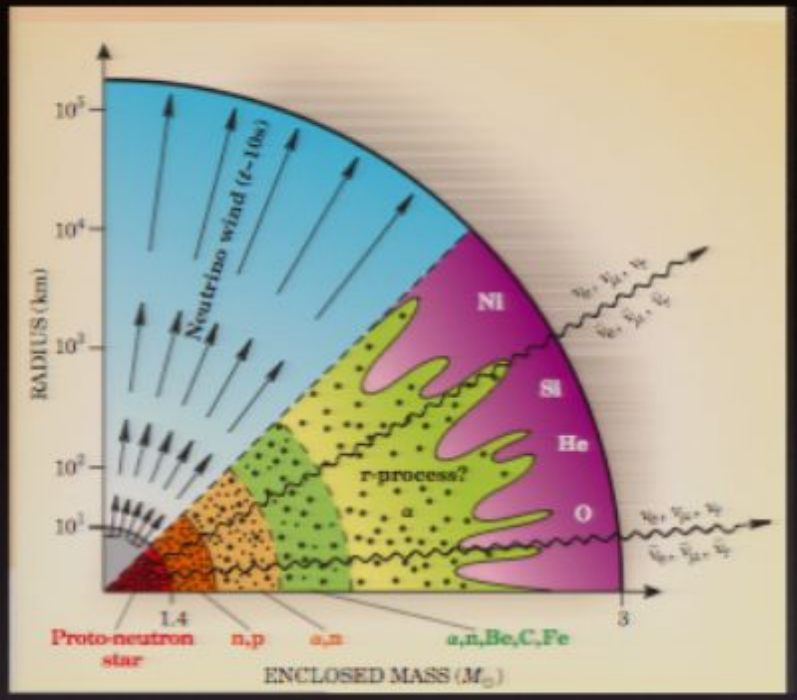

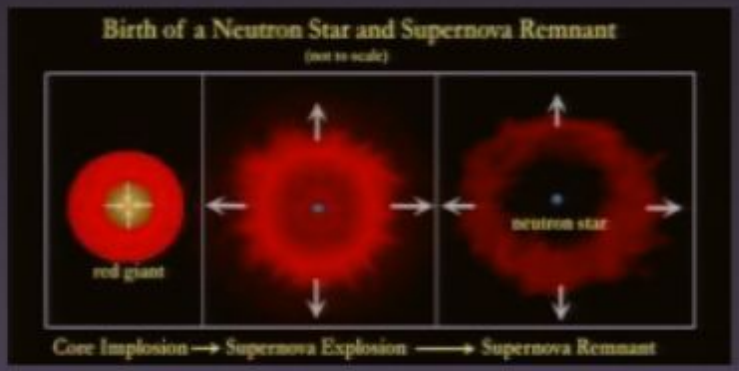

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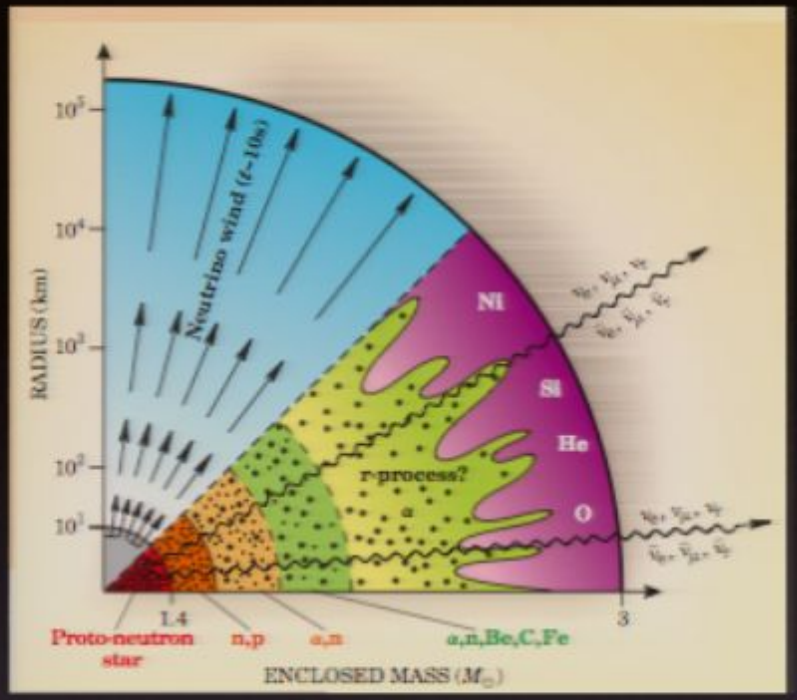

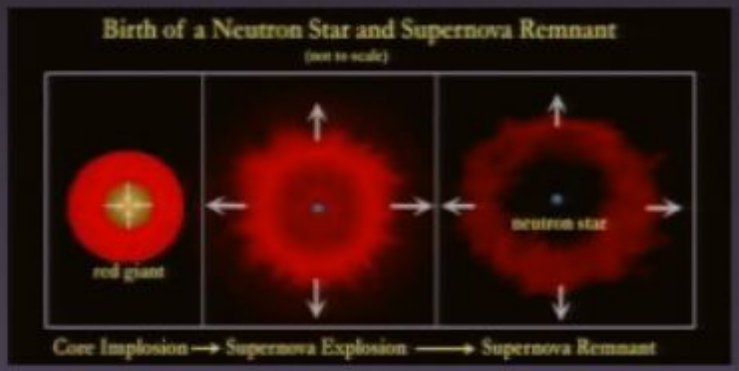

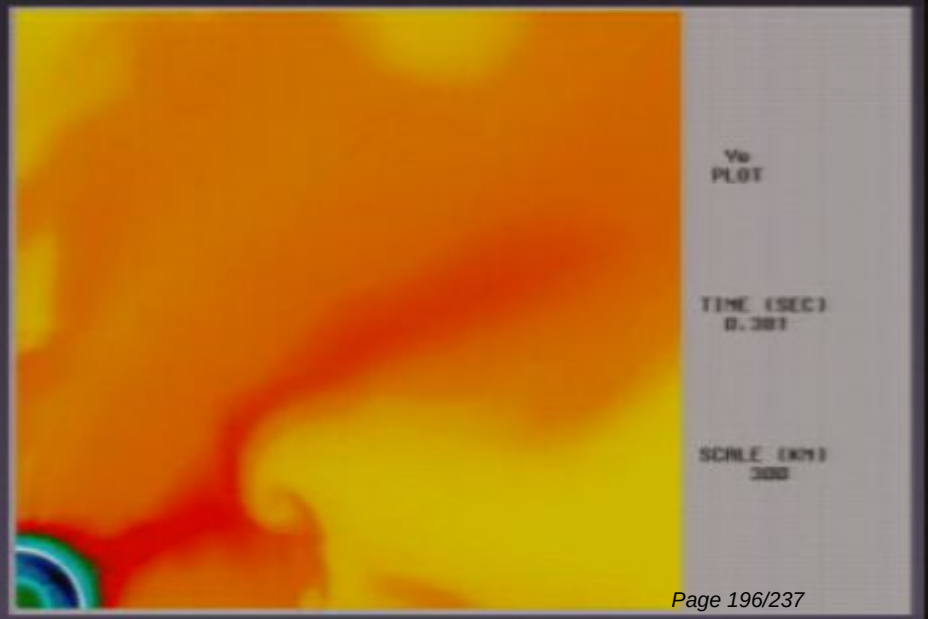

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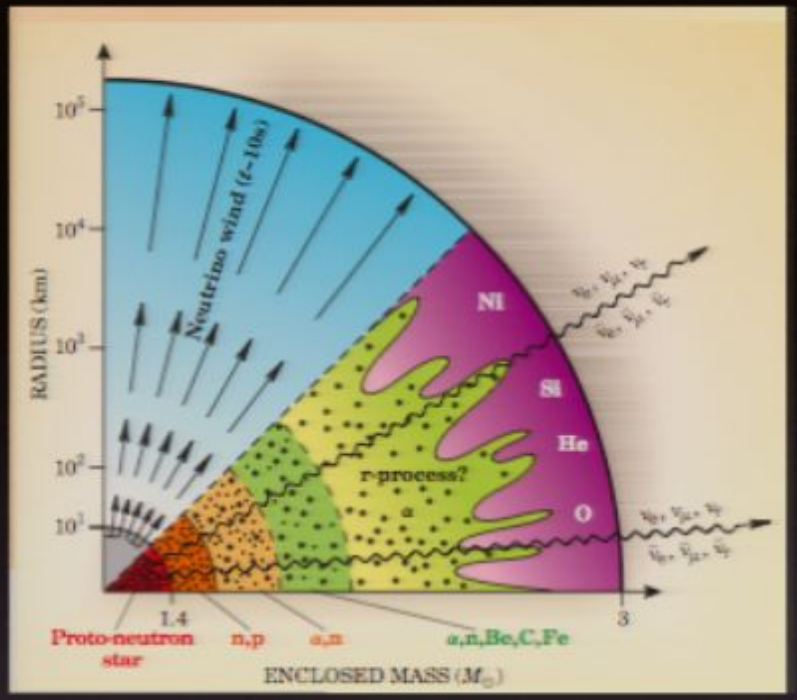

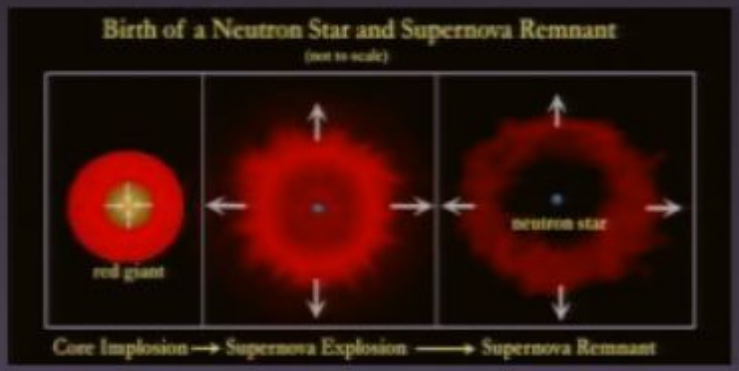

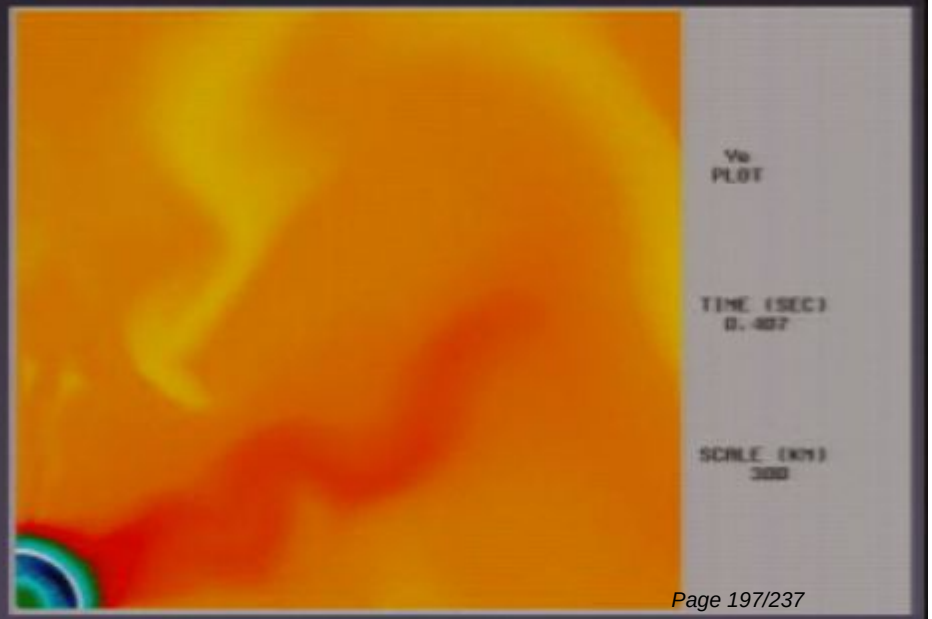

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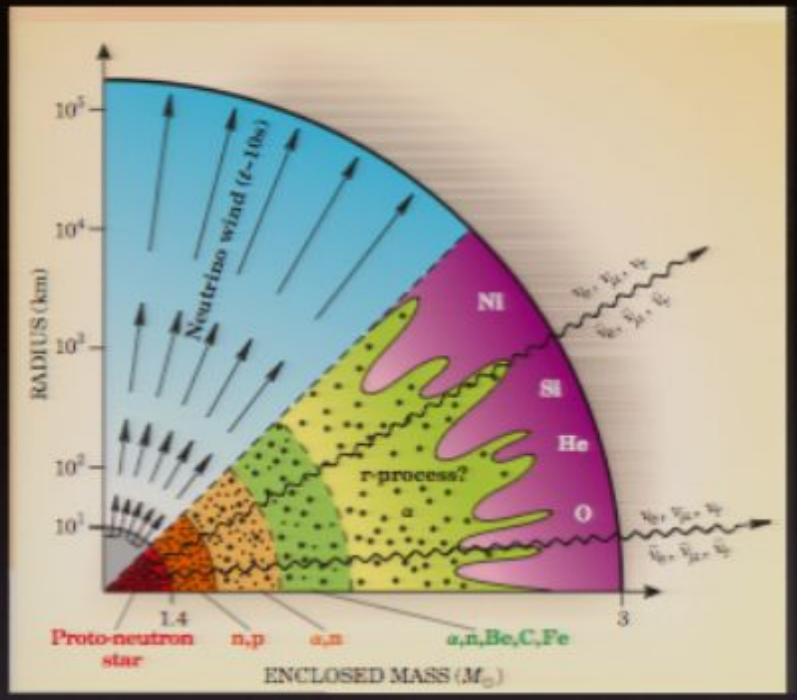

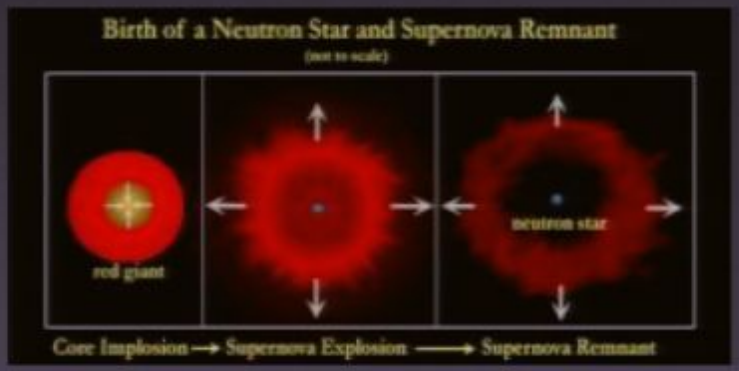

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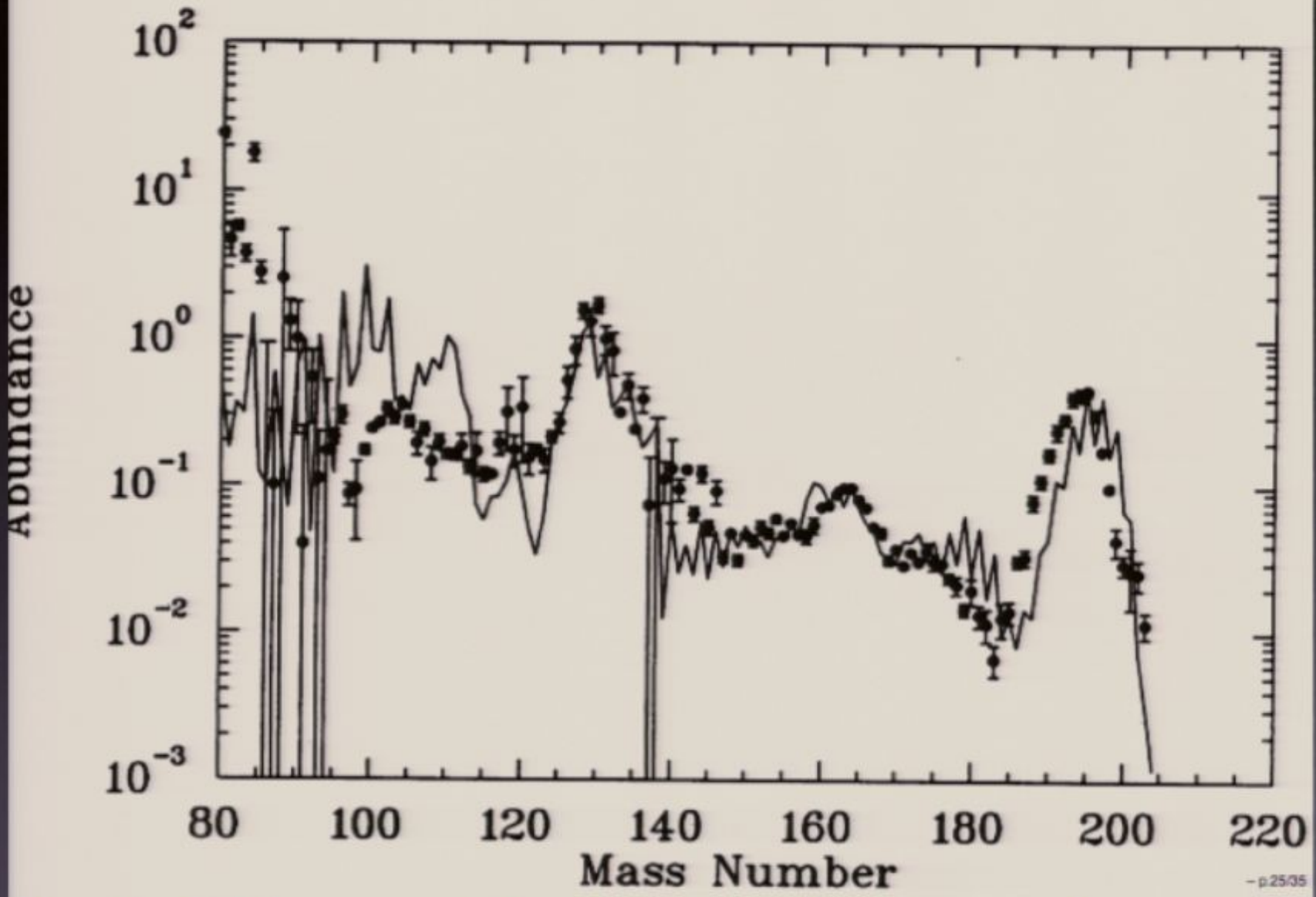
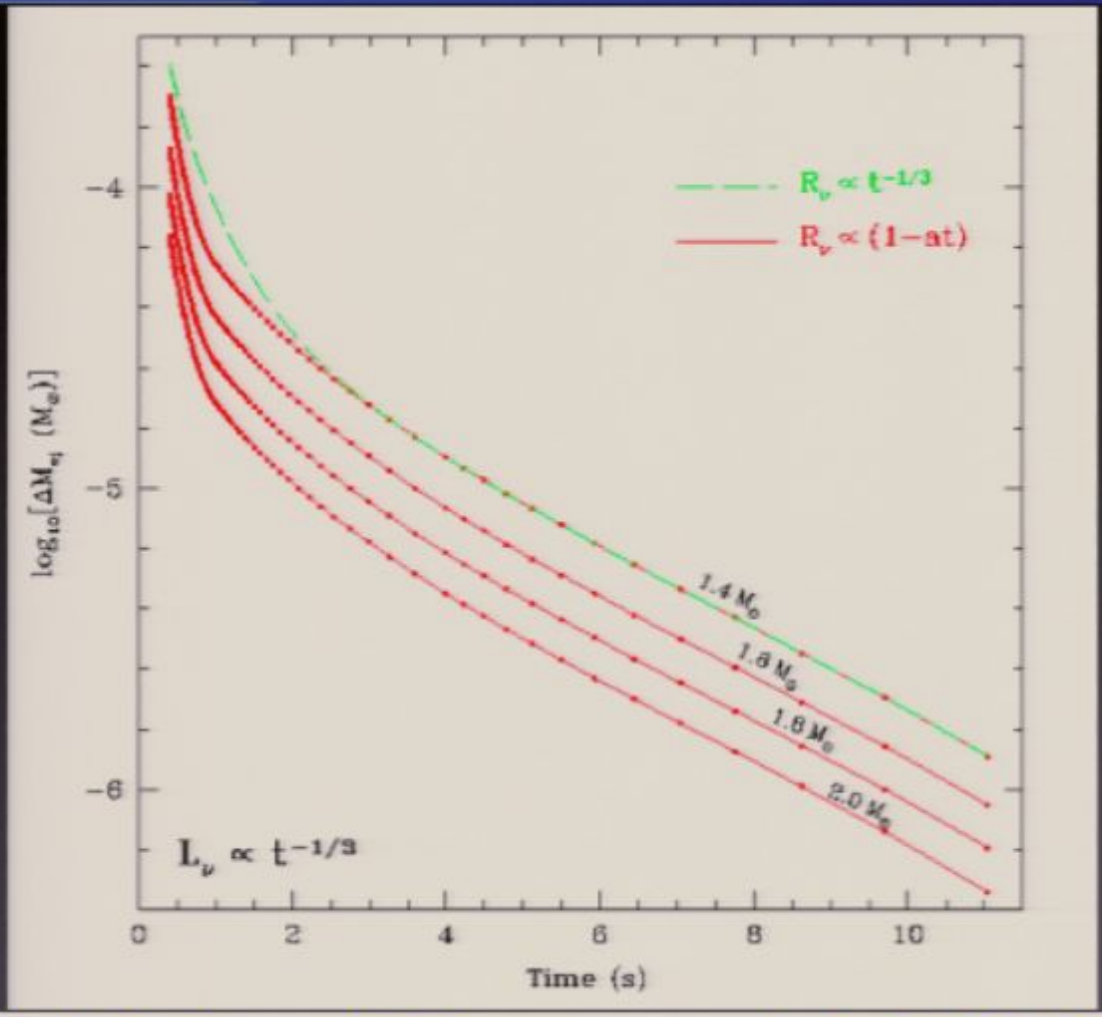


Woosley/Wilson model never reproduced, even by same group

Takahashi, Janka et al. needed to multiply entropy by 5.5!!

2. Prompt explosions require high-density core and assume fallback to avoid overproducing $r-$ nuclei.

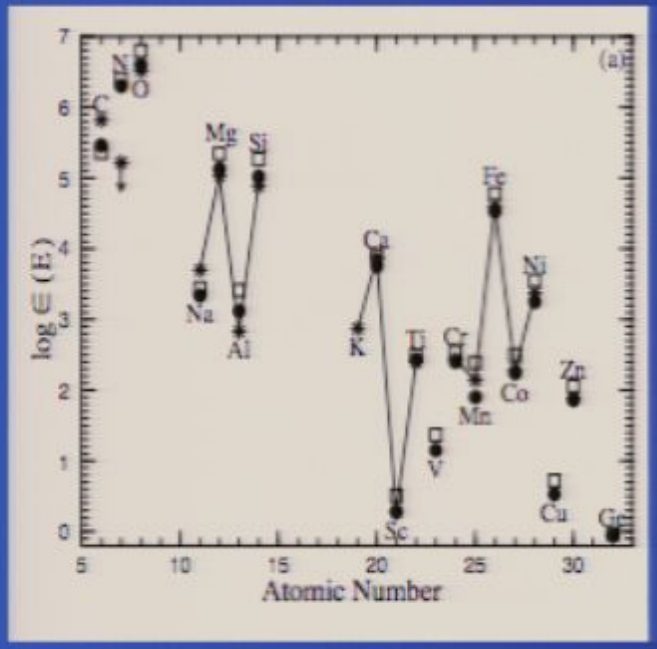


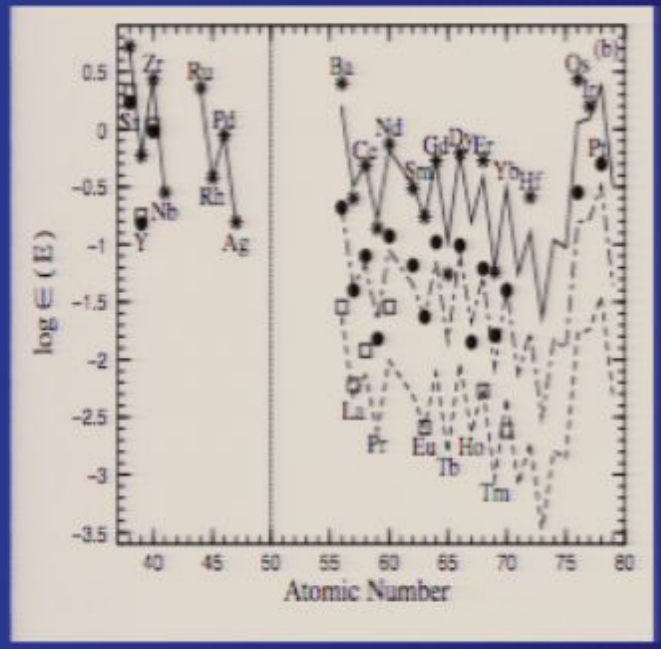
Need Important Fall-back Rates ...

In further detailed work Thompson et al. 2001, Wanajo et al. 2001 found that the neutrino-driven wind can only produce heavy r-process nuclei for massive neutron stars close to 2 $M_\odot$

1. Neutrino-driven wind mechanism has not realized quantitative agreement (SNe fail to explode)

... one size does not fit all ...





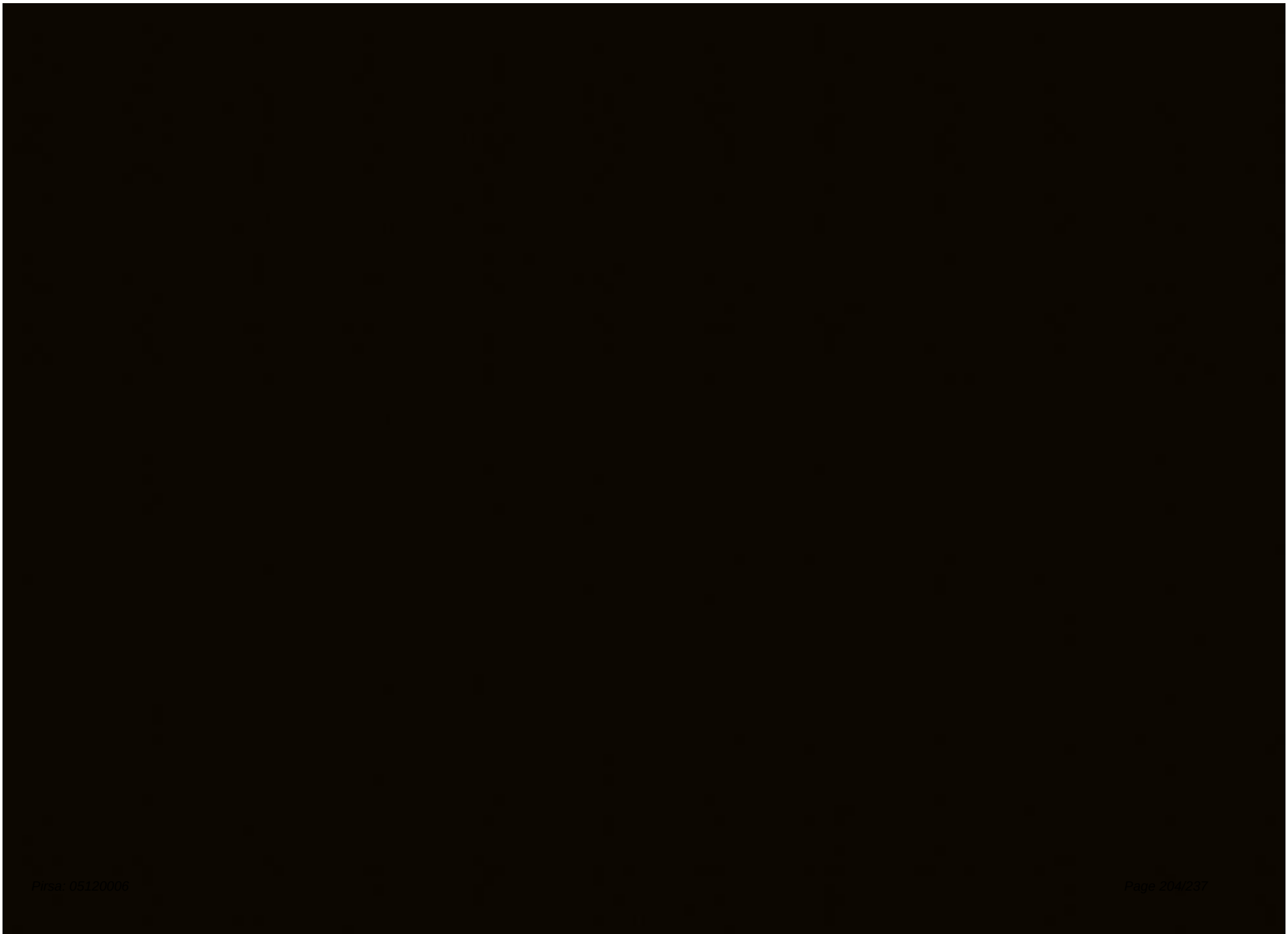
(Y.-Z. Qian, *astro-ph*/0501237)

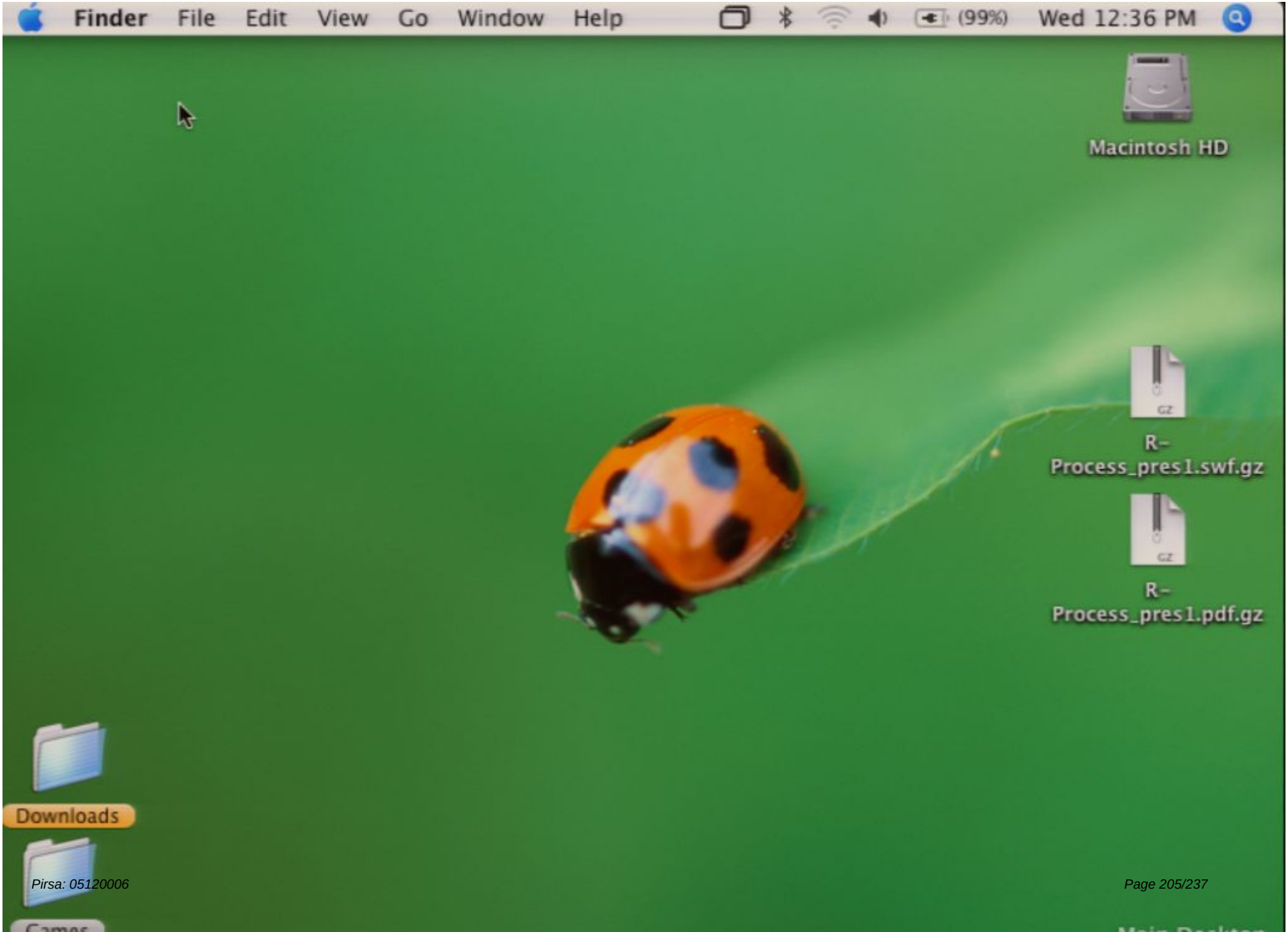
- data from 3 different halo stars shows that abundances below $A = 130$ are in agreement (O to Ge pattern is identical)...but abundances above $A = 130$ differ by over a factor of 100!
- different progenitor masses produce different elements!

Quark-Nova

http://www.myspace.com/quarknova

The Quark Nova Scenario is a solo 8-bit pop freak-out helmed by Quark Nova, a clone sent back from 2369. The Quark Nova Scenario will appear live at the Silver-lake Lounge at midnight on May 4th, following the band Modern Memory...

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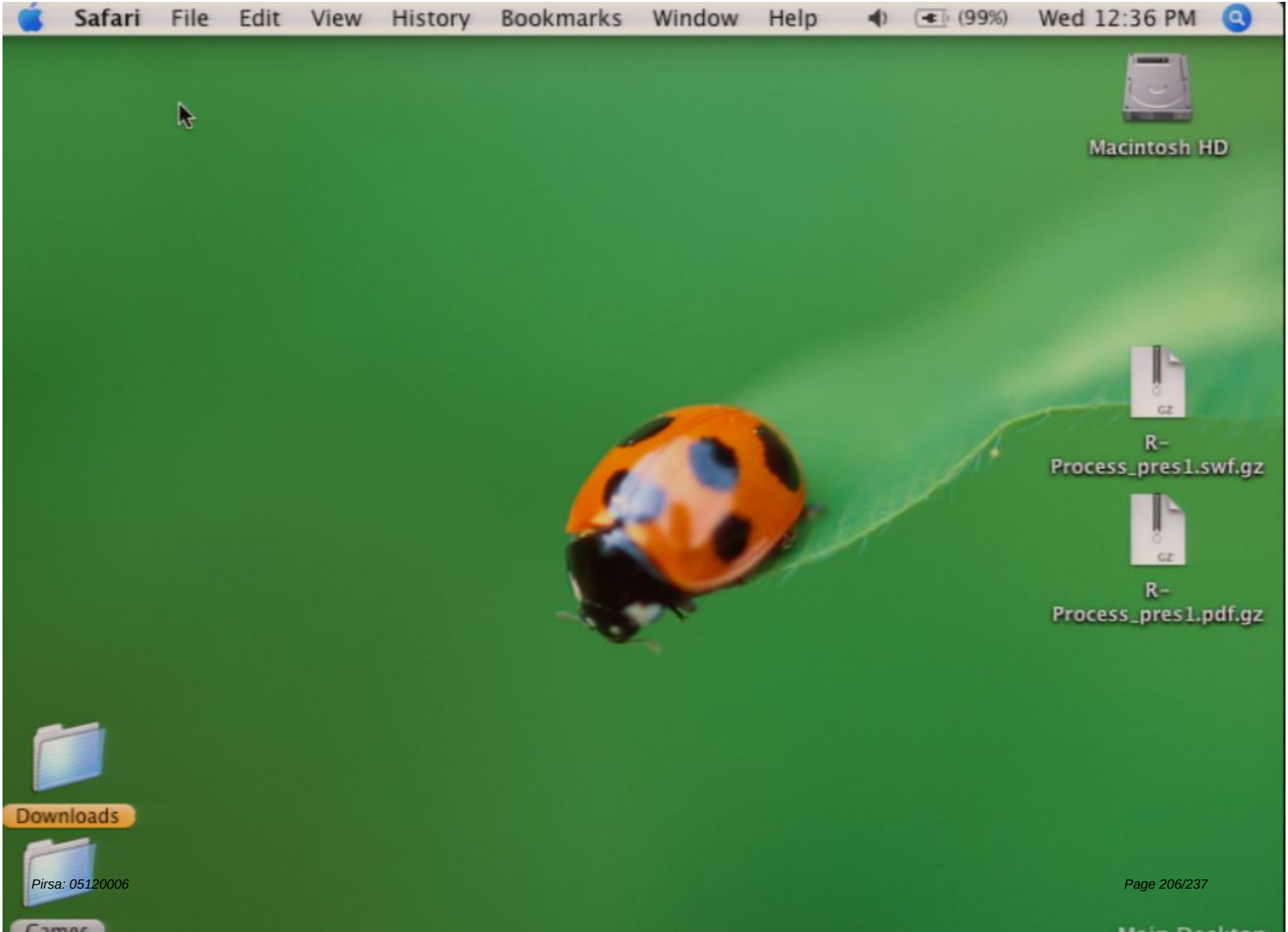
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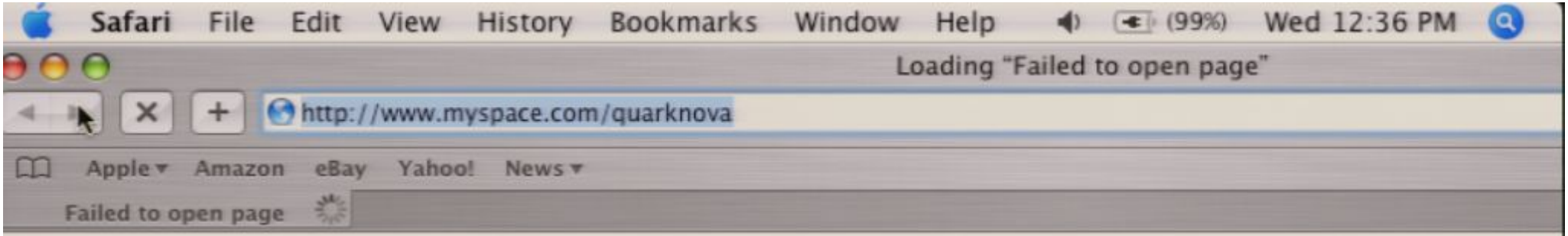
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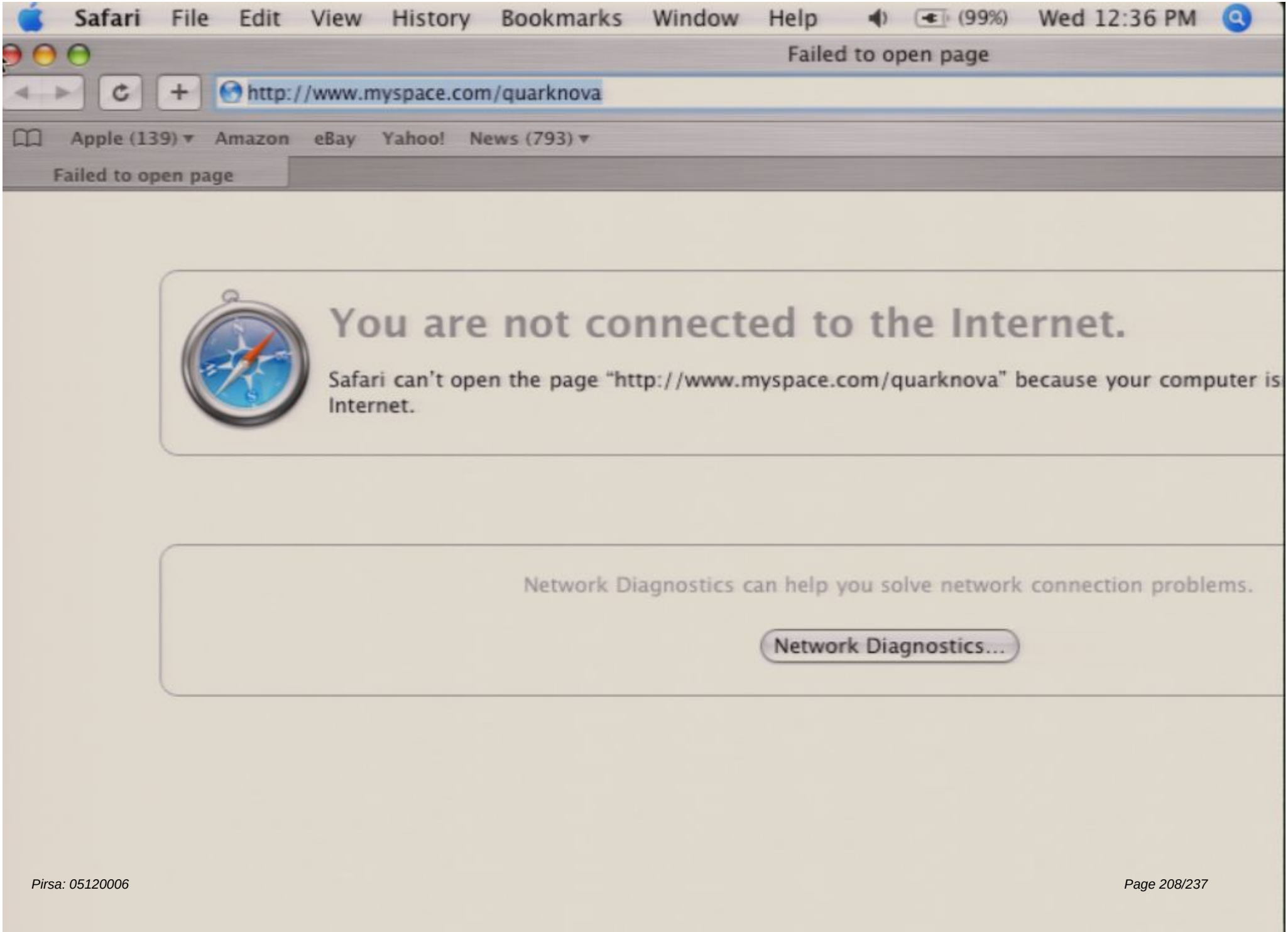
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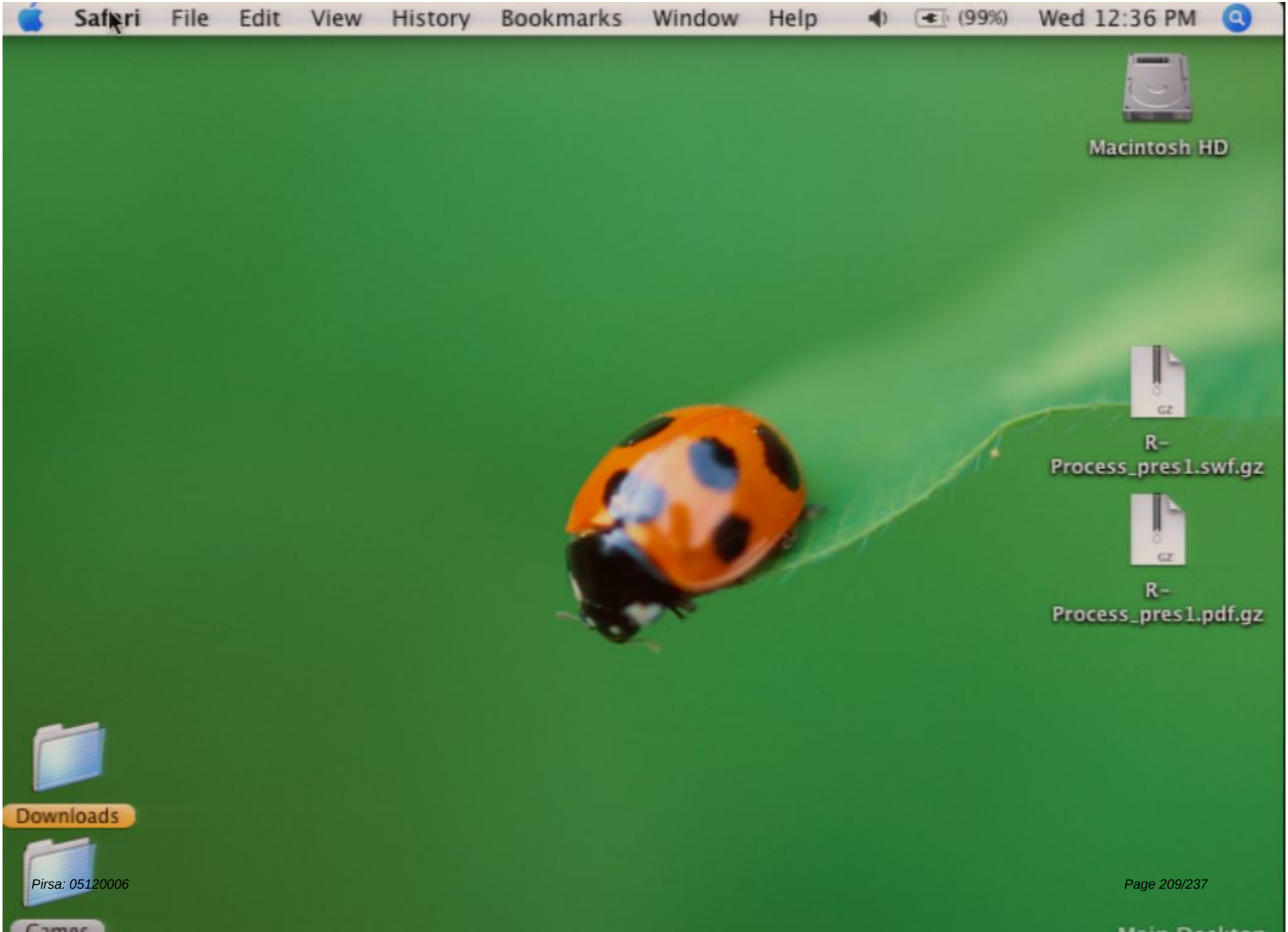
Network Diagnostics can help you solve network connection problems.
Network Diagnostics...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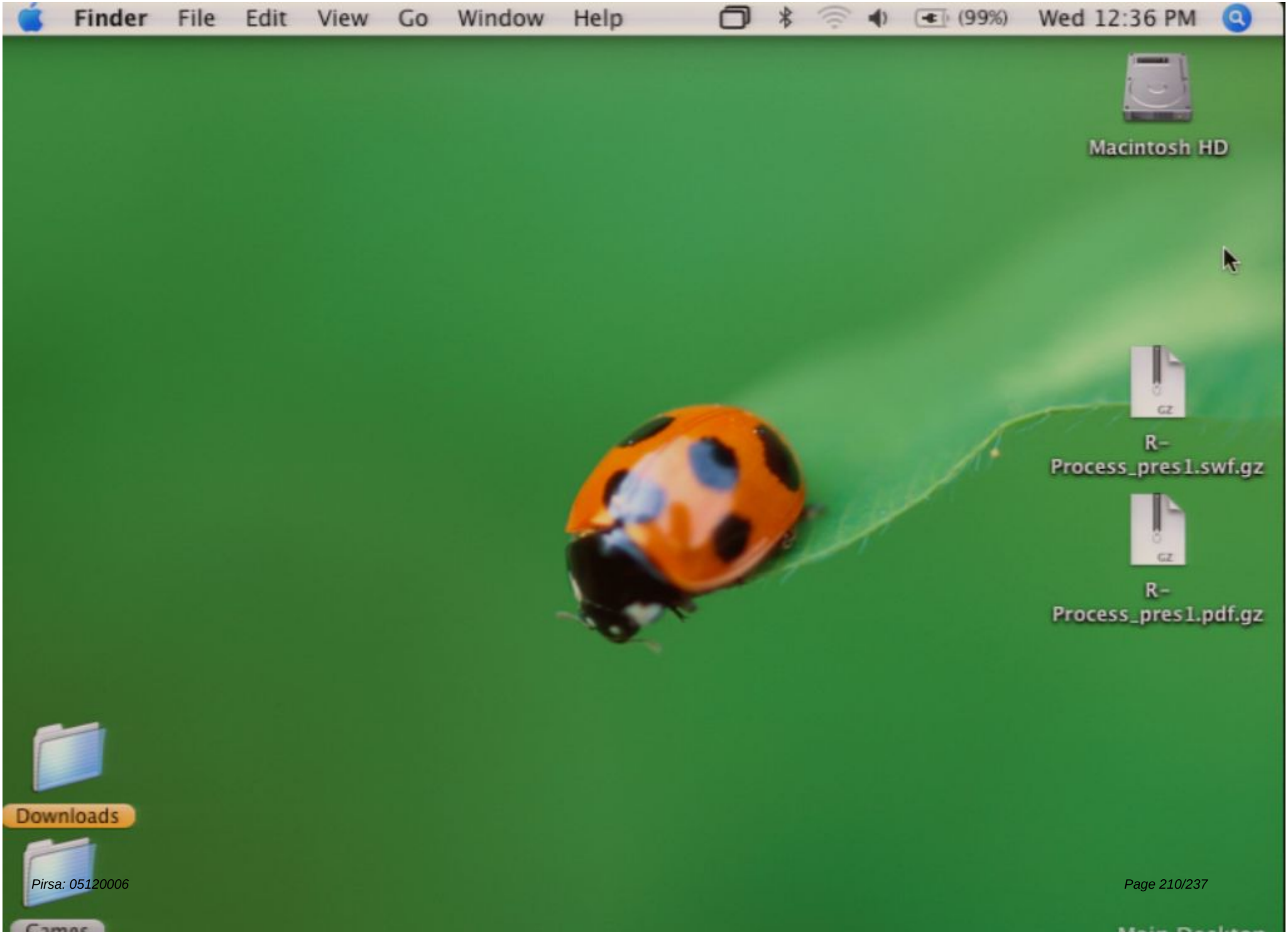
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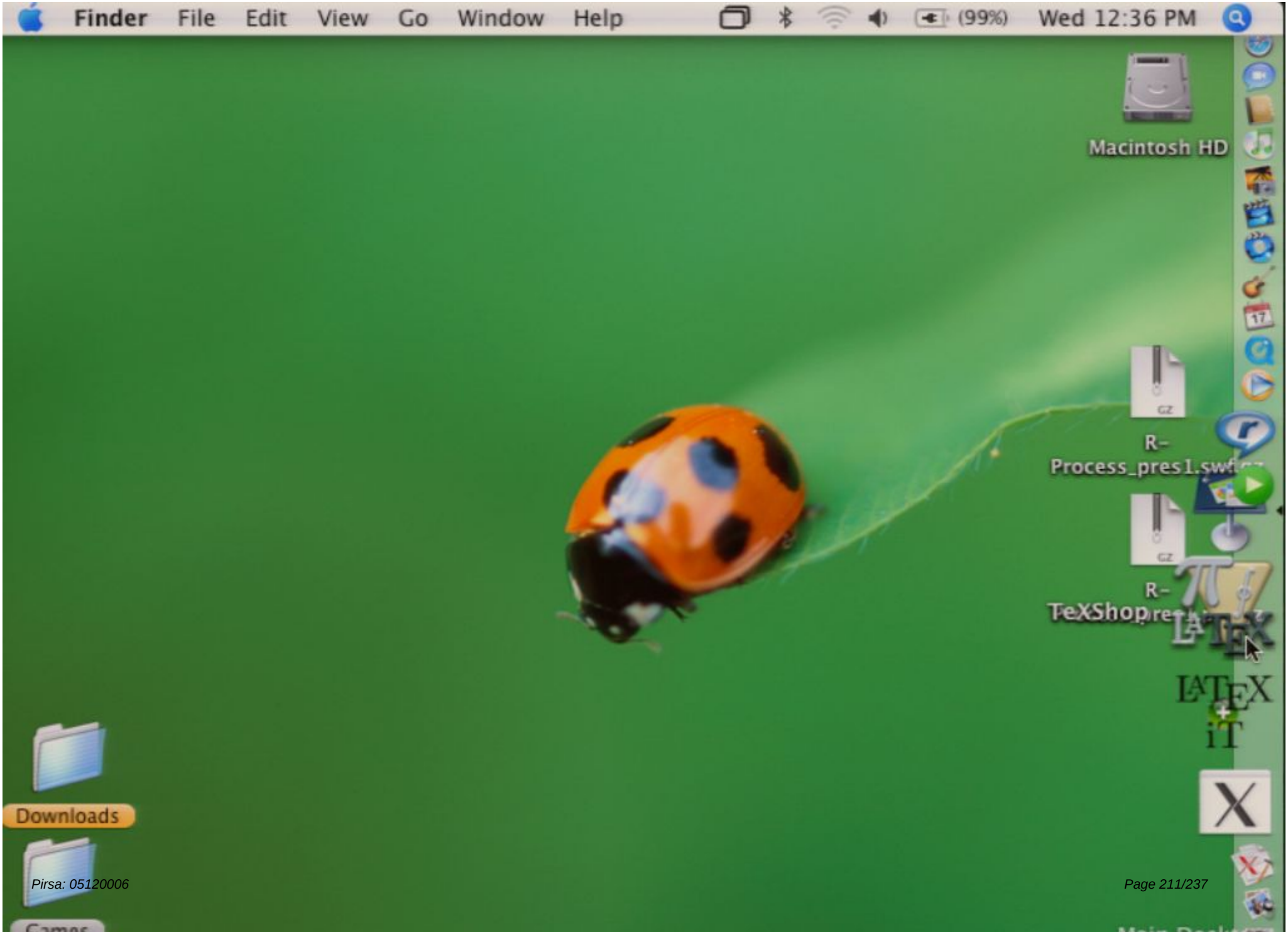
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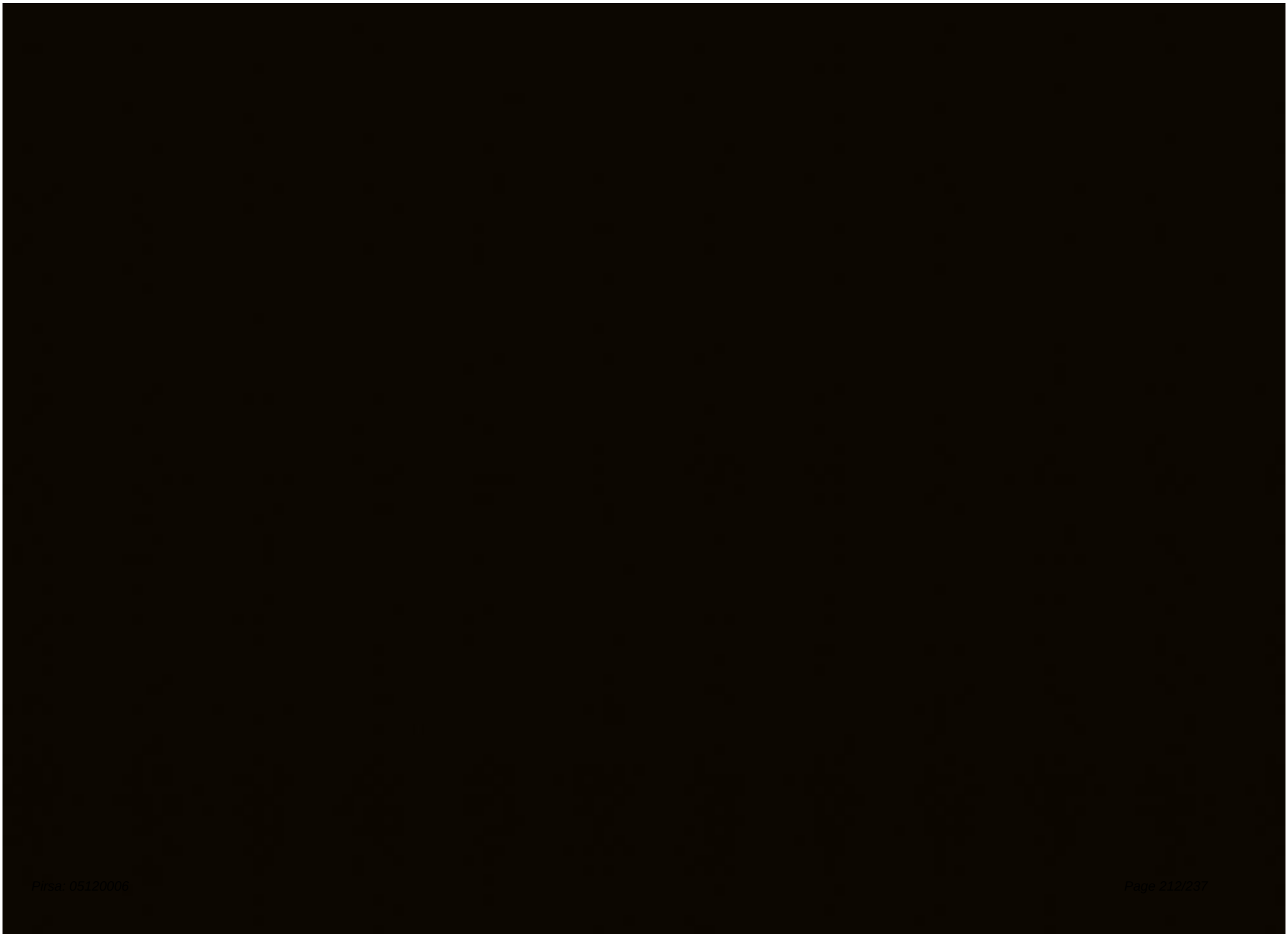

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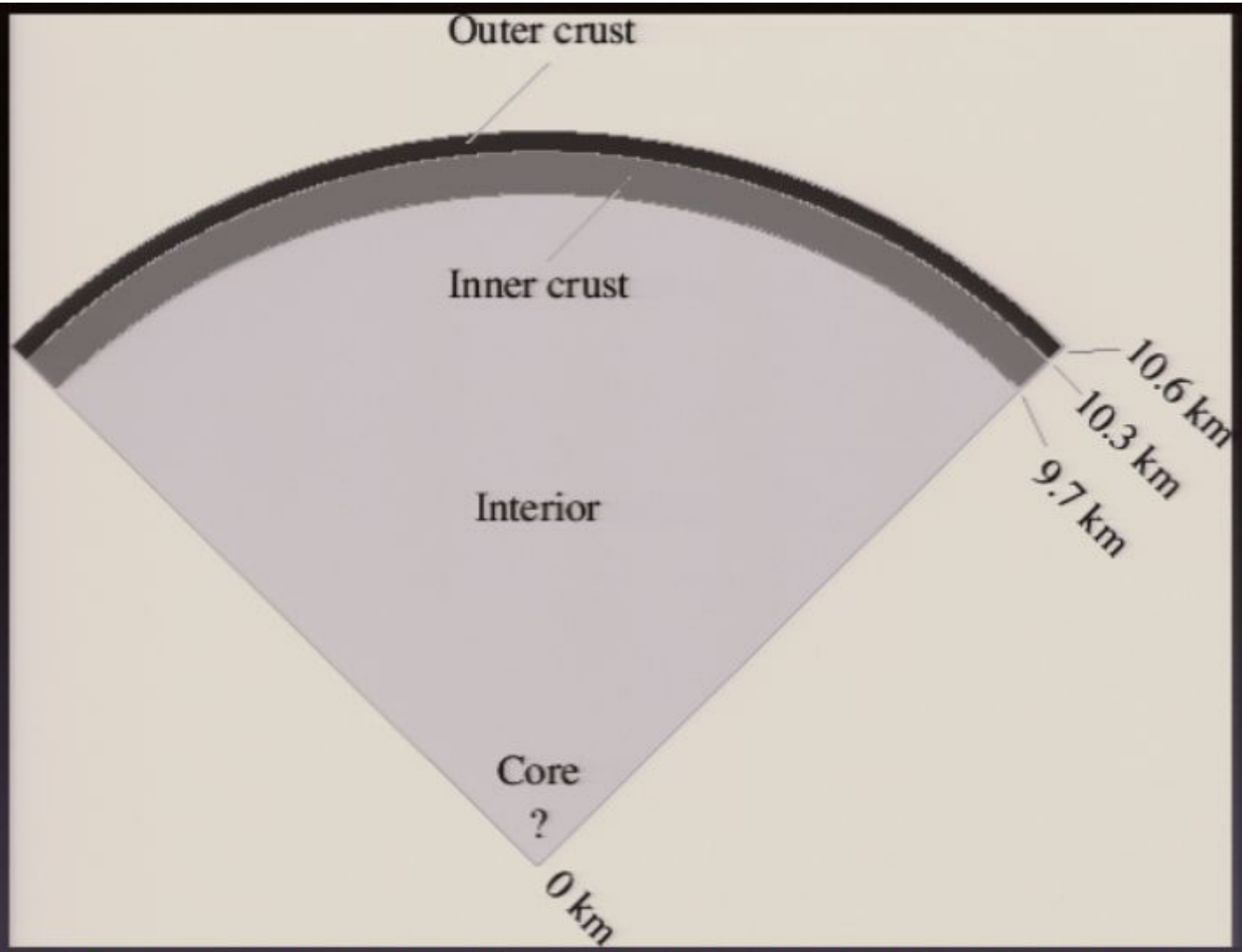
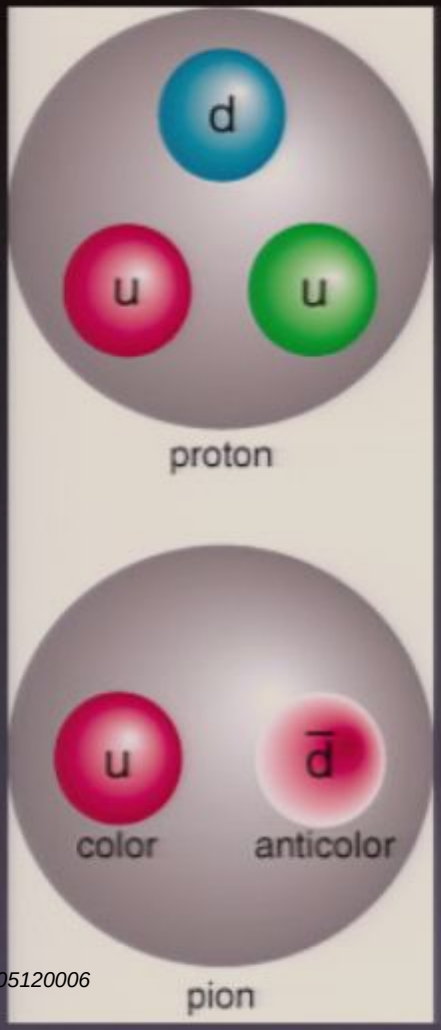
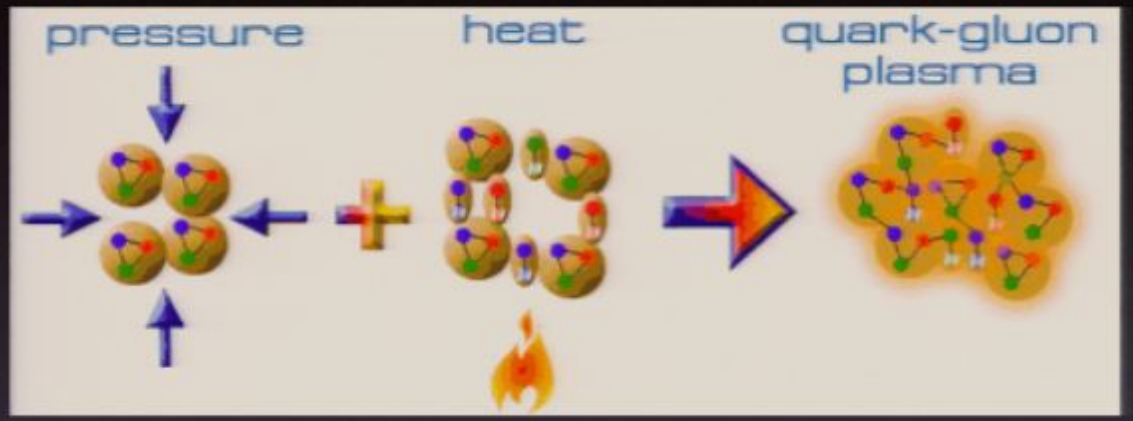
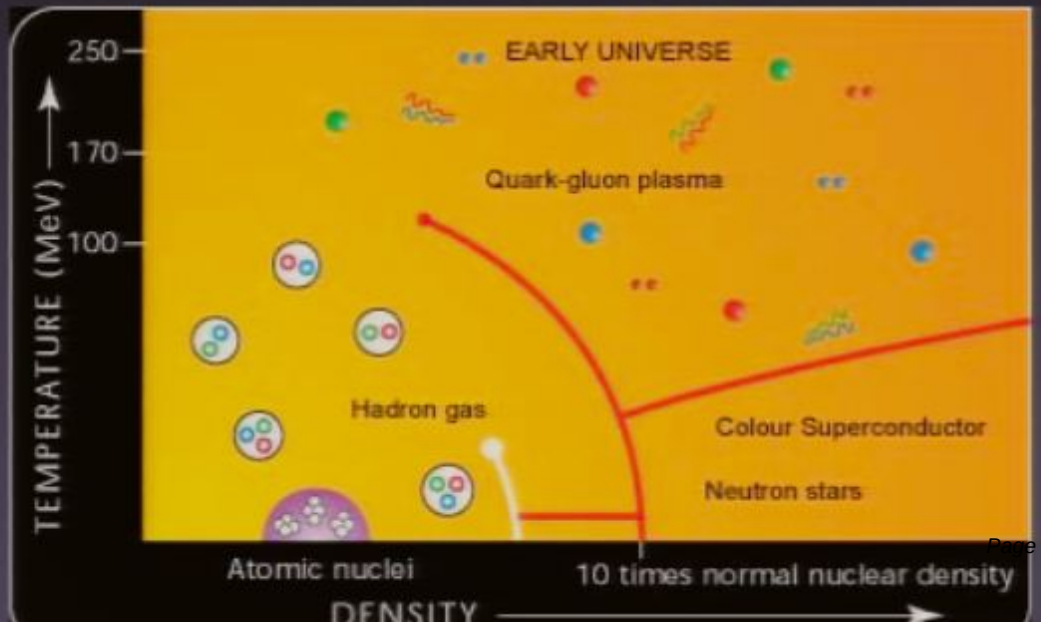


- **Outer crust:** Iron and neutron rich nuclei, mixed with relativistic degenerate electrons
- **Inner crust:** Neutron rich nuclei, free **super-fluid** neutrons (from **neutron drip**), and relativistic degenerate electrons
- **Interior:** full of super-fluid neutrons
- **Core:** who knows? Pions? Quark Matter?

QCD Phase Diagram

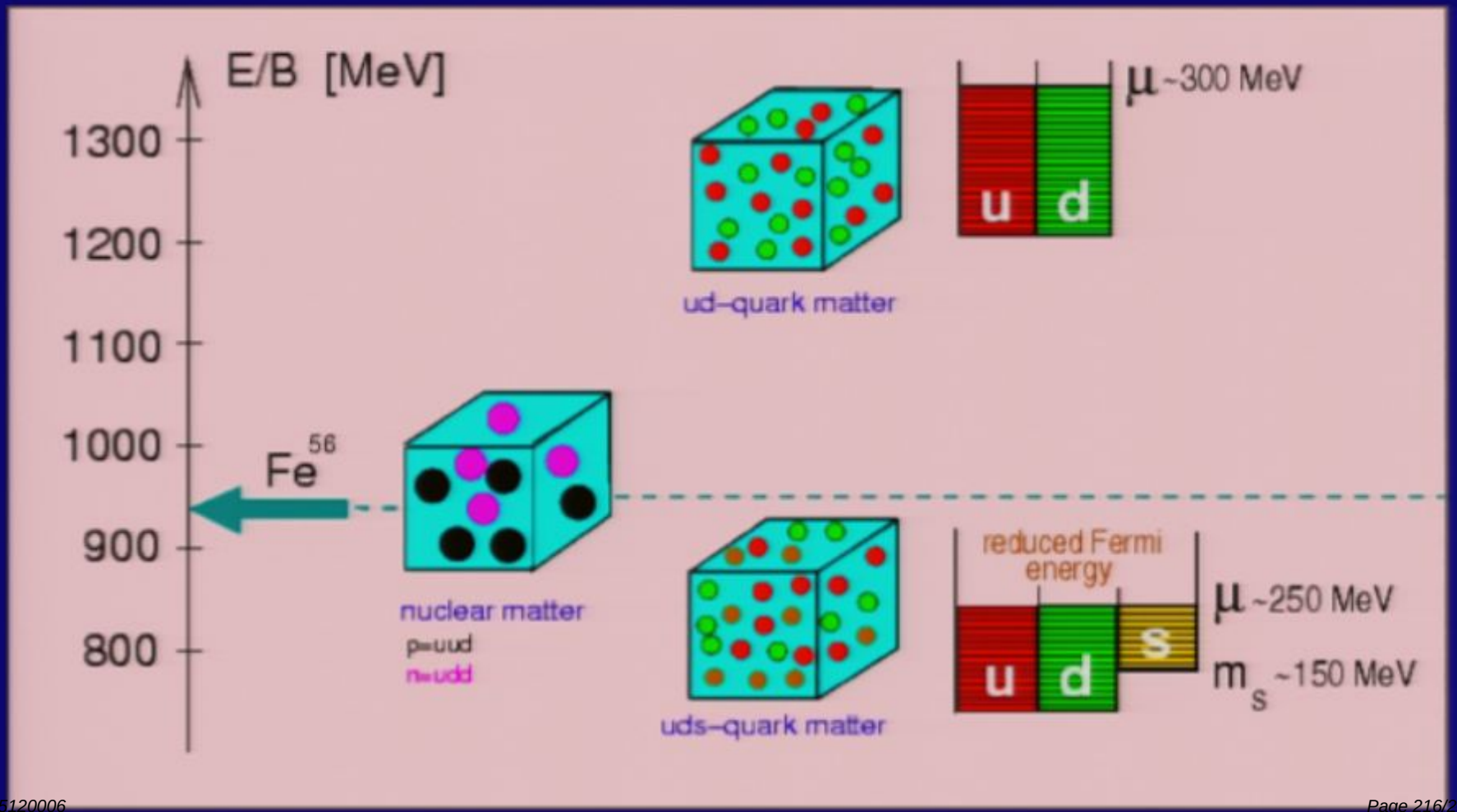






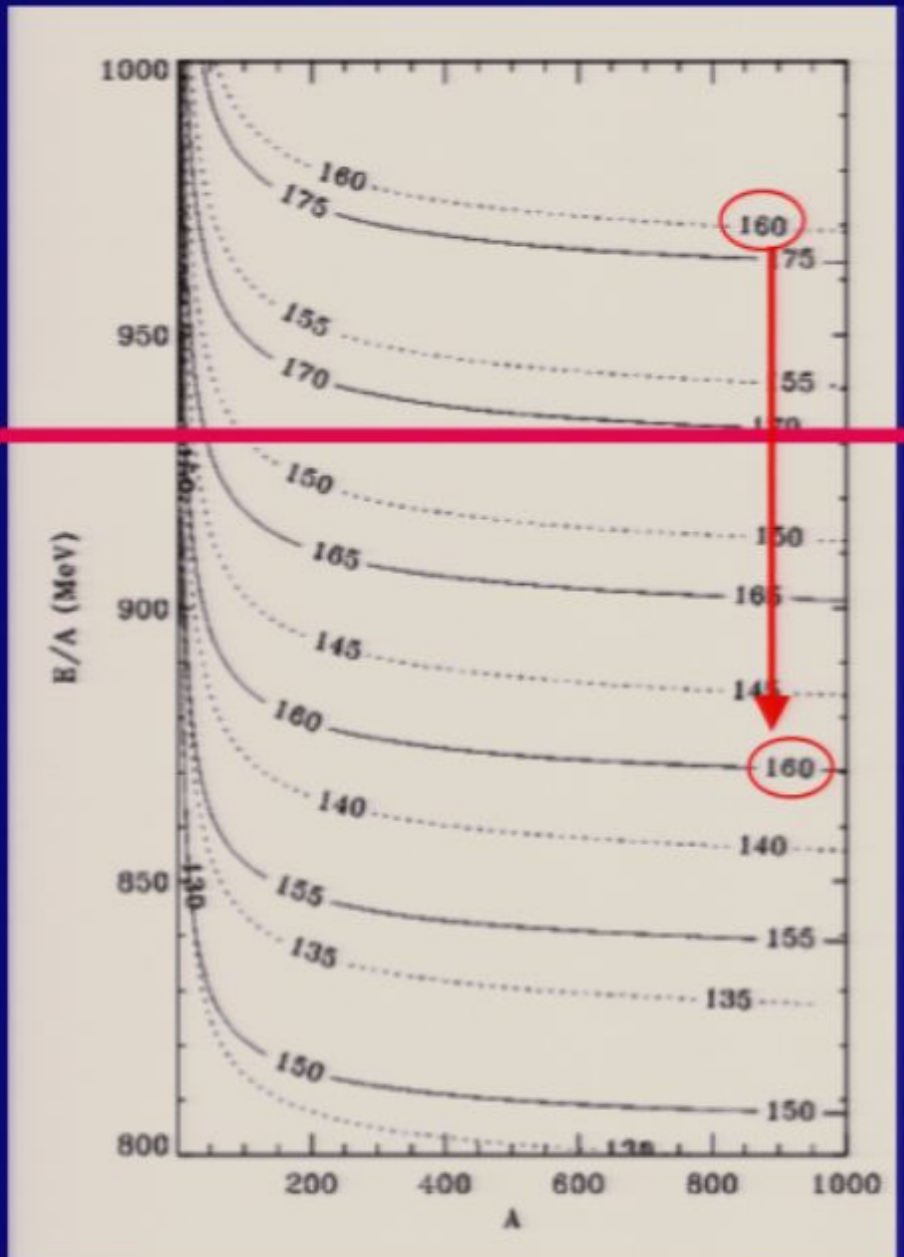
True Ground-State Mystery

(Bodmer, Terazawa, Witten)



Energy per Baryon of Strange Quark Matter

J. Madsen, PRL 87 (2001) 172003



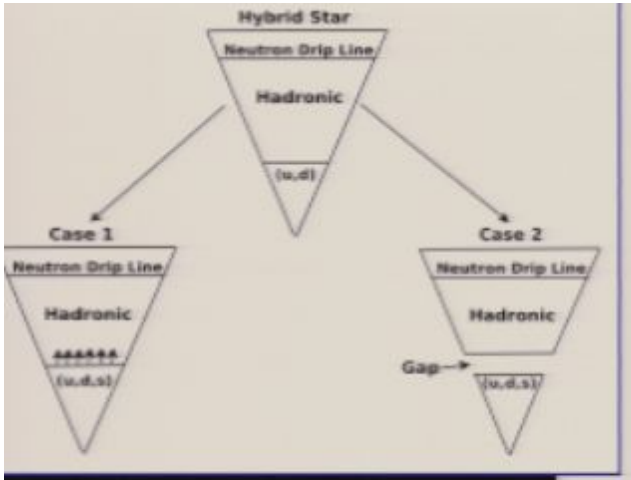
Nuclear matter (^{56}Fe)

ordinary SQM

CFL SQM

Δ=100 MeV

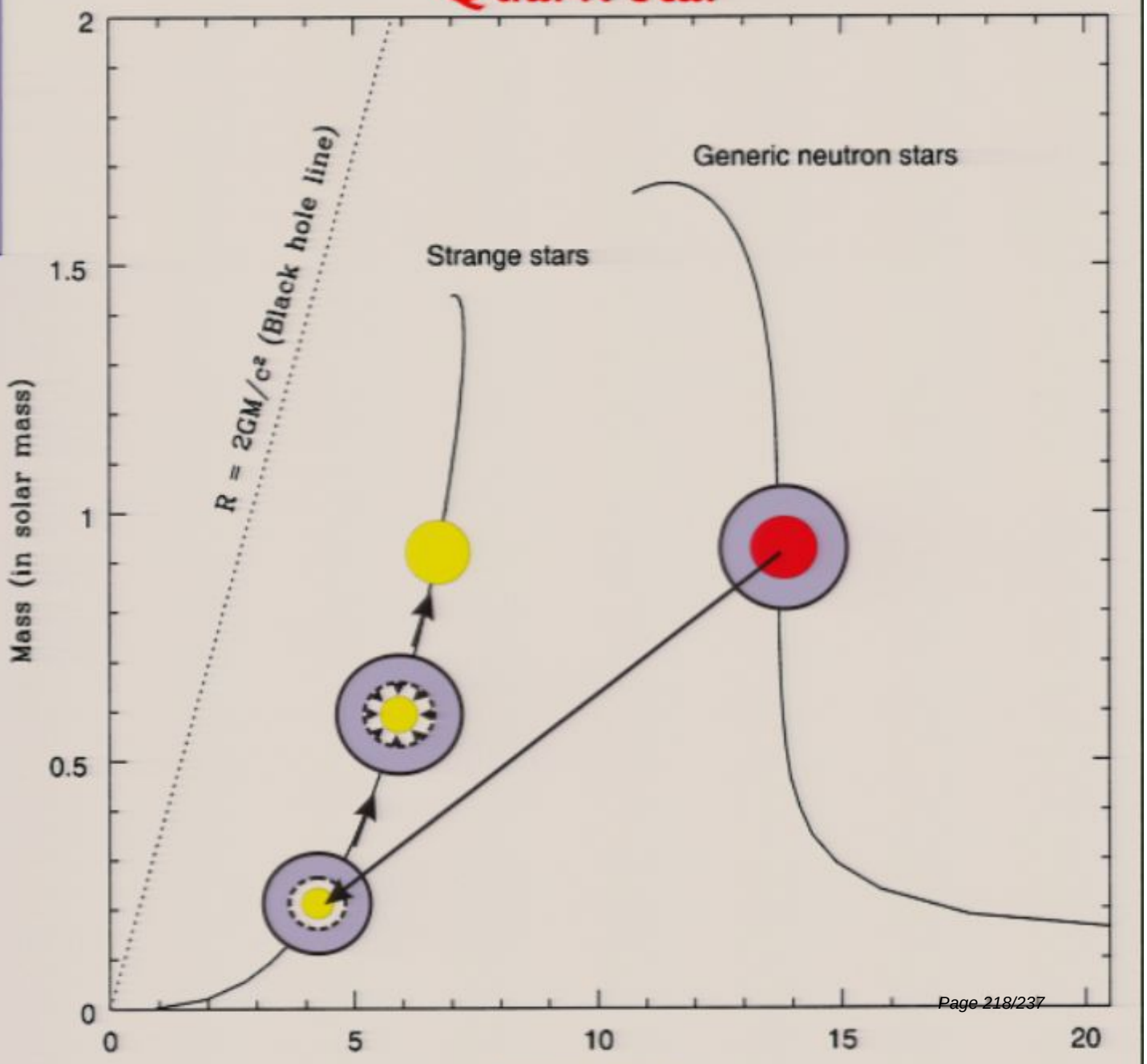
m_s=150 MeV



Transition from Neutron Star to Quark star

The quark matter core becomes unstable and shrinks faster than the envelope response time!

QUARK-NOVA SCENARIO!



What is so unique to the Quark-Nova?

More energy released during the phase transition

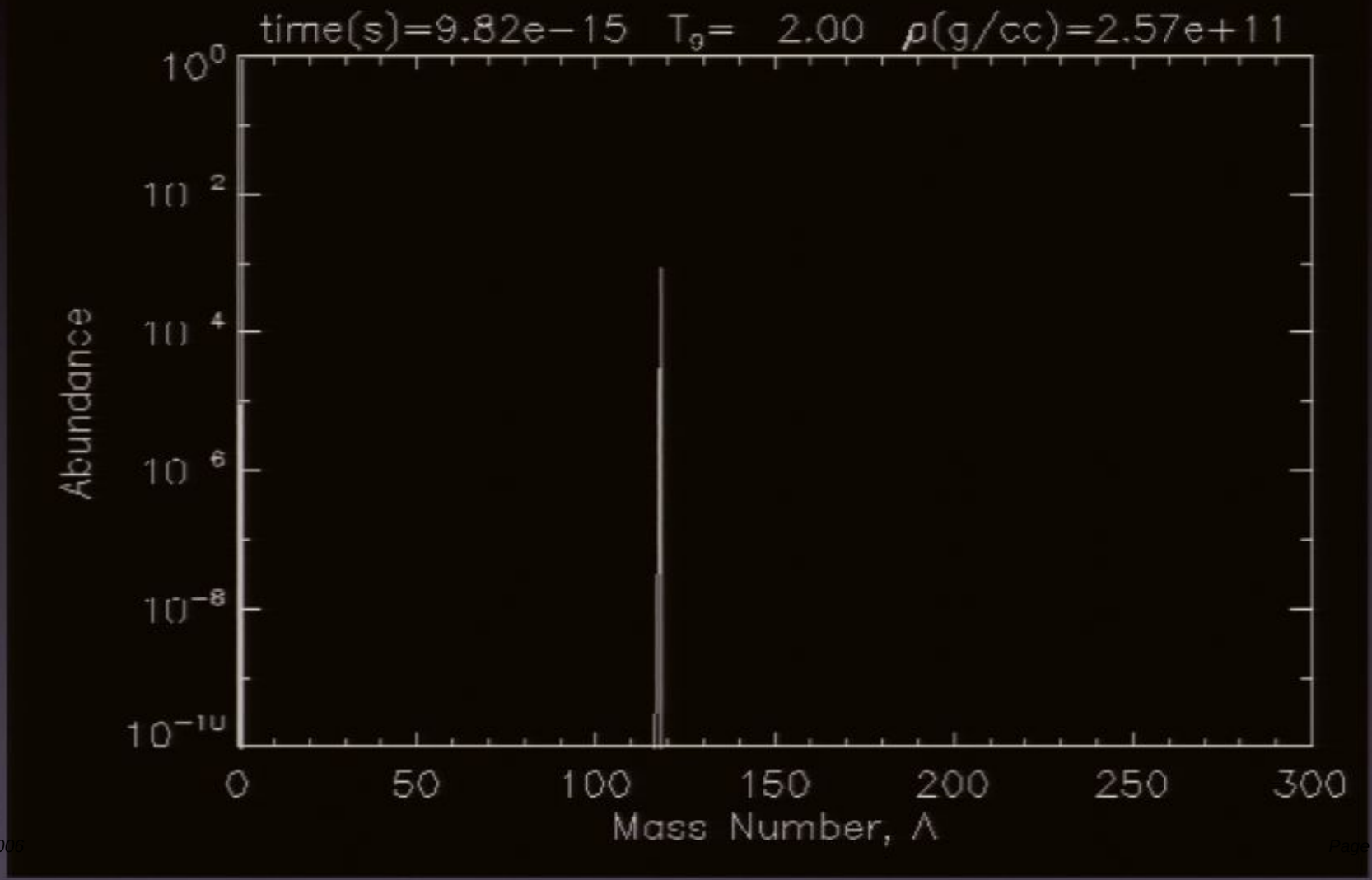
Explosive expansion of neutron-rich matter

Seed nuclei up to Z=70

Large neutron capture rates

Range of timescales (1yr to 10^9 yrs)

Seed Nuclei (40 < Z < 70)



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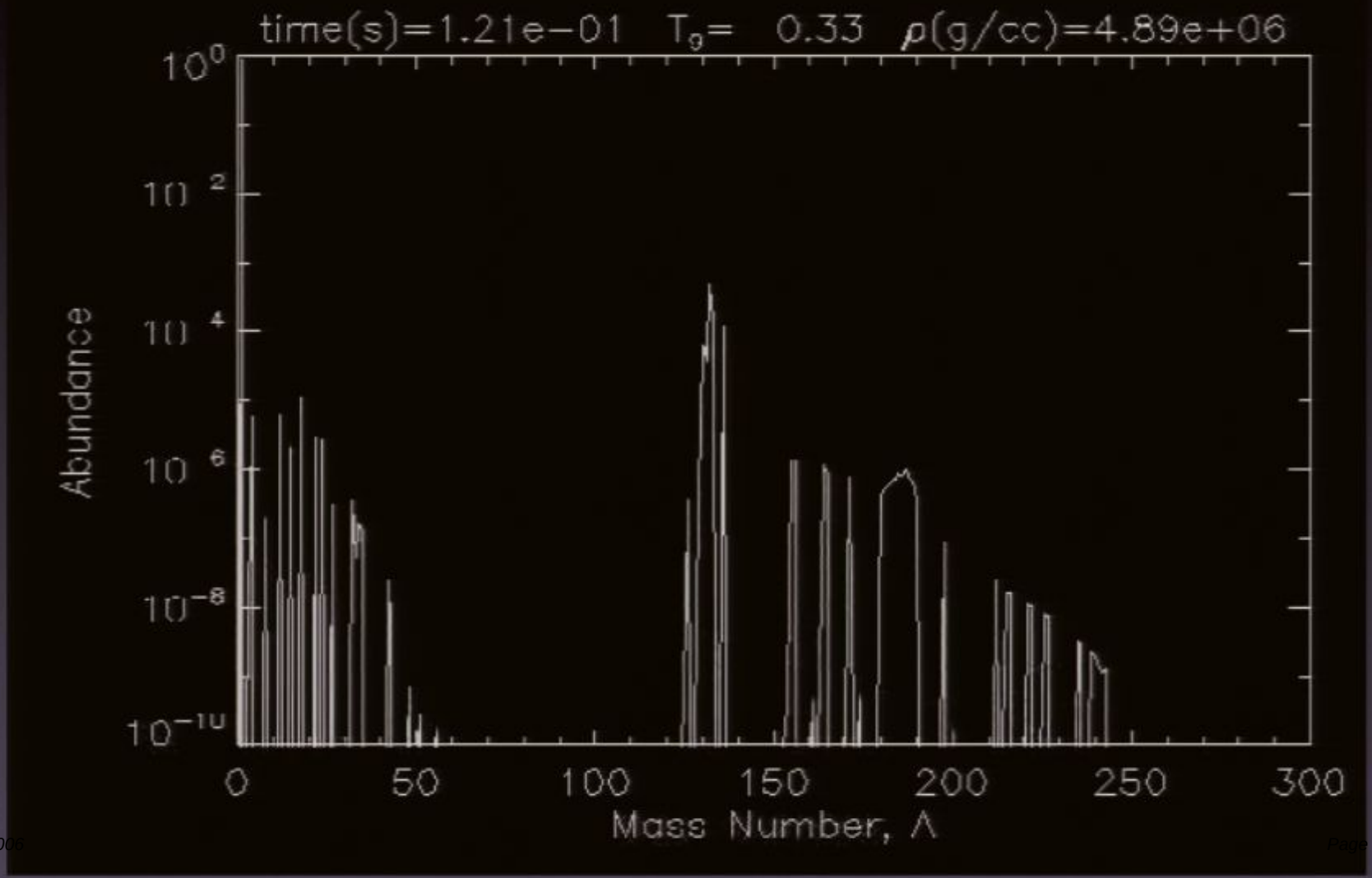

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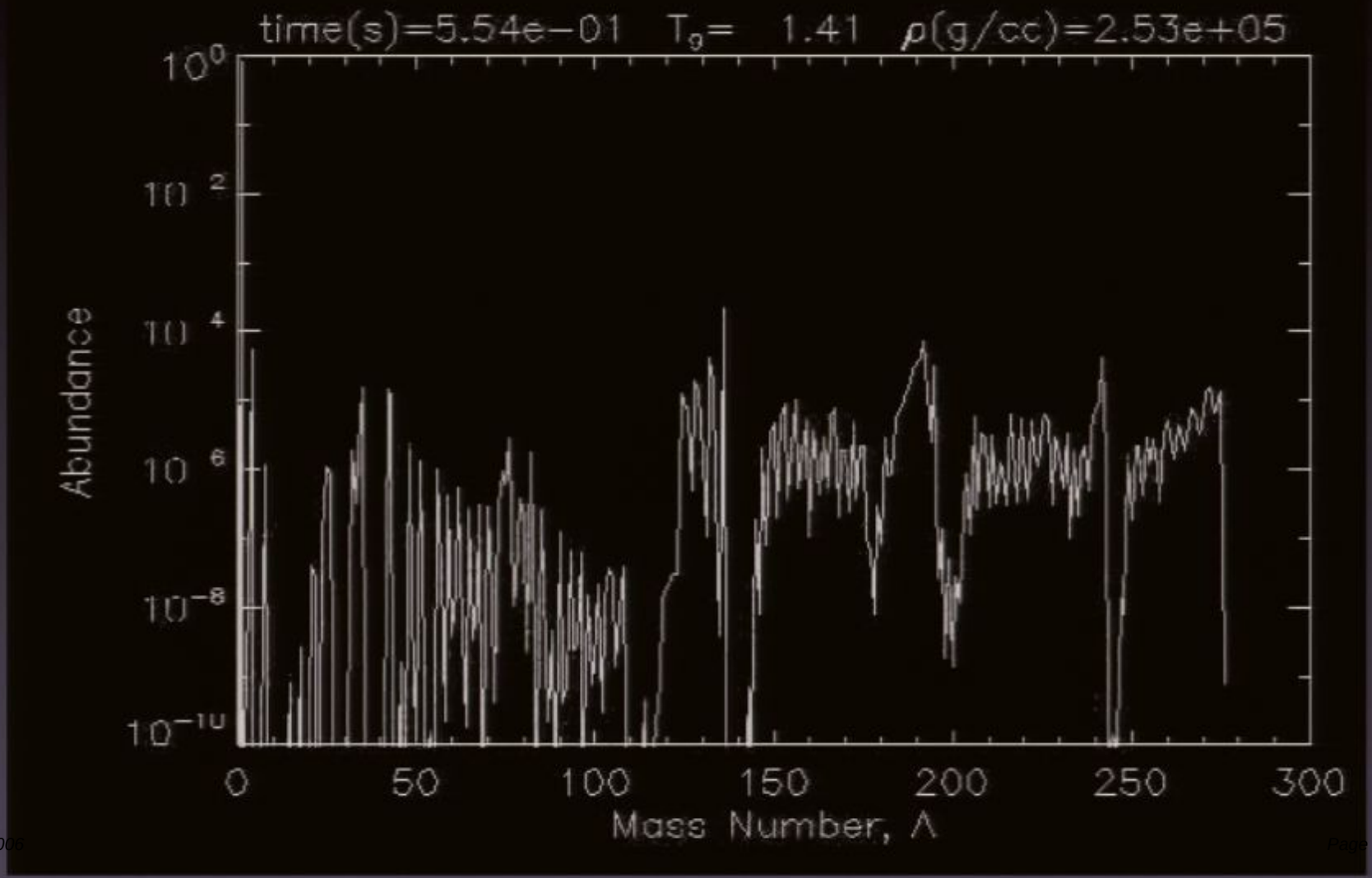

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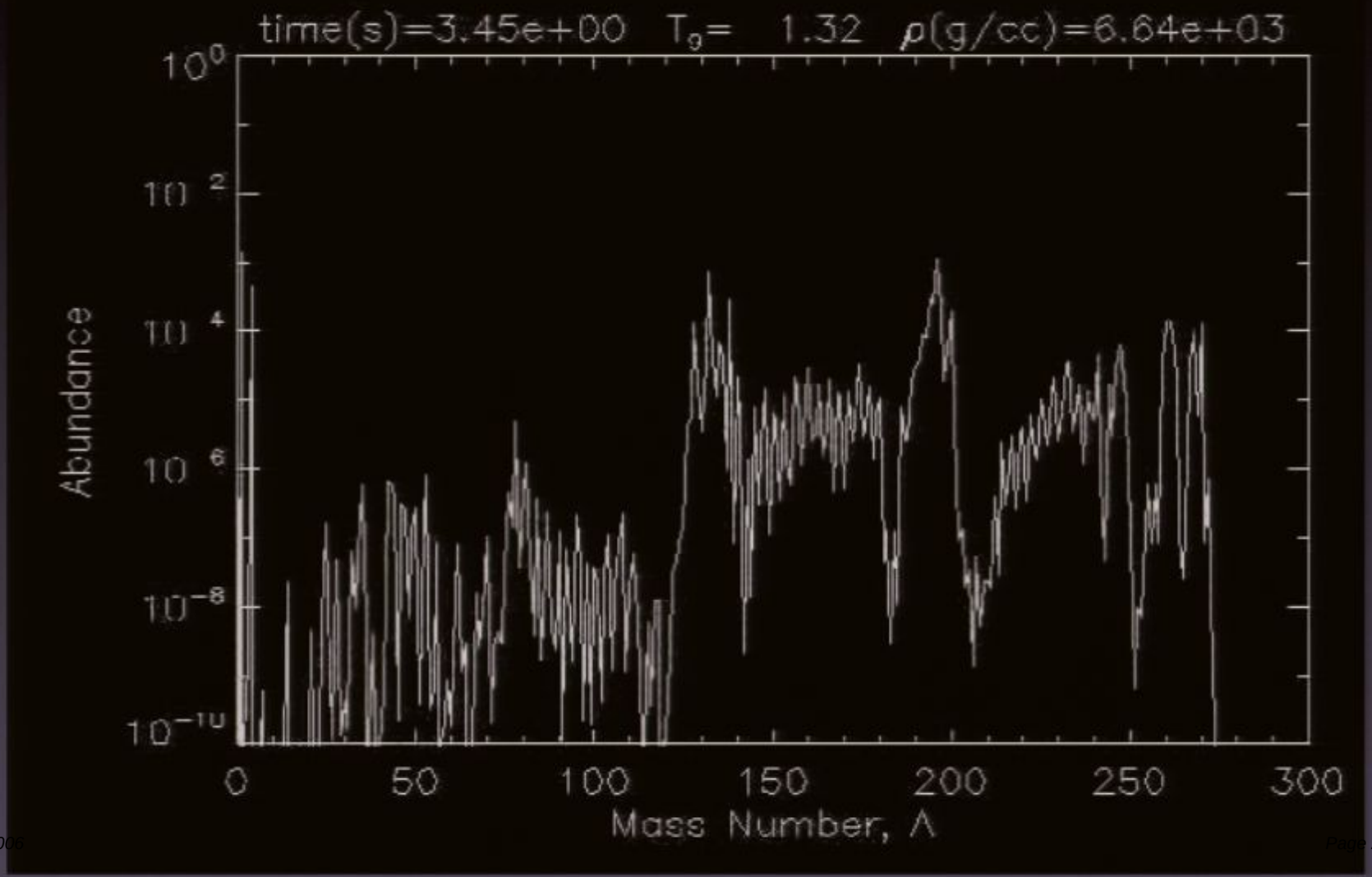

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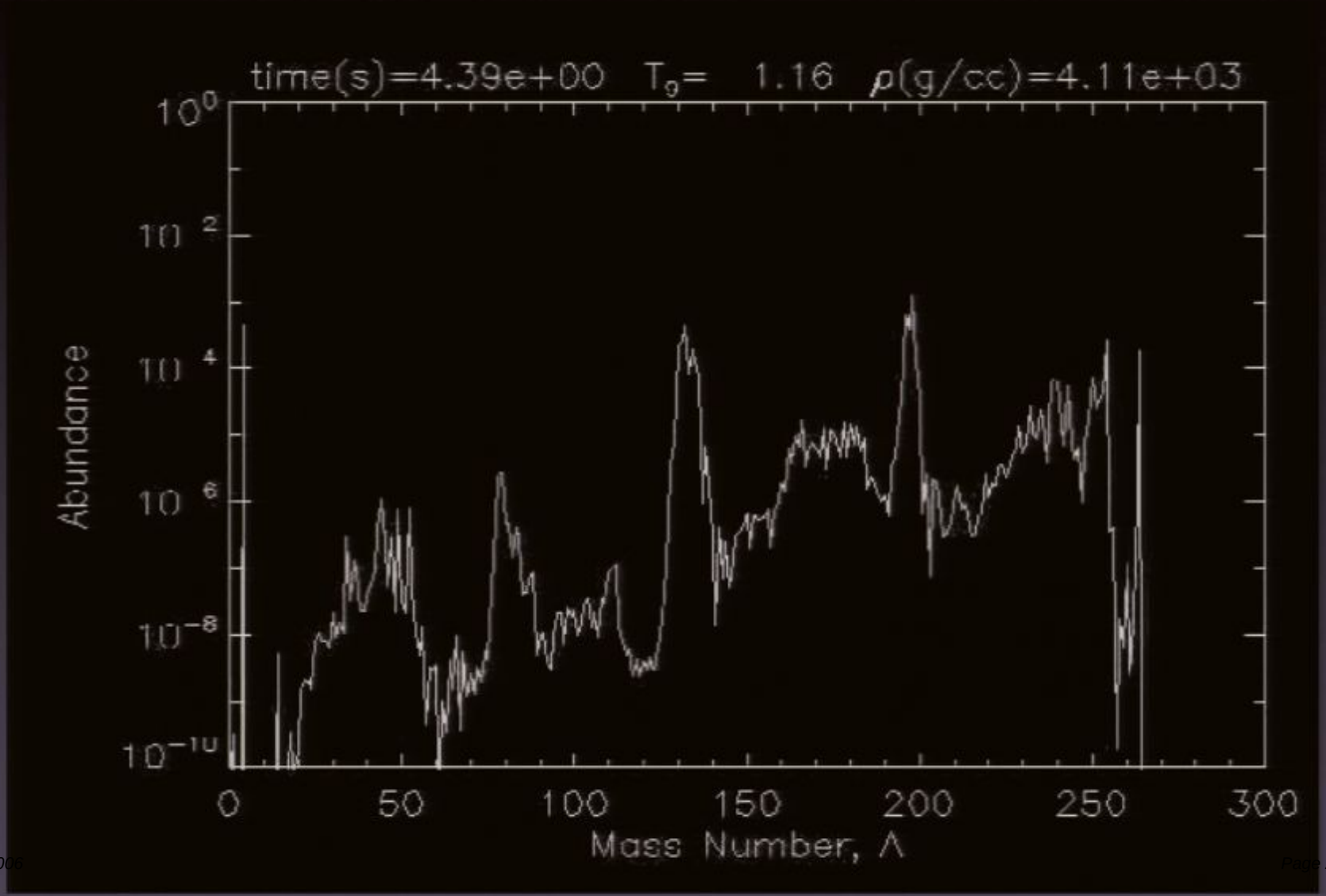

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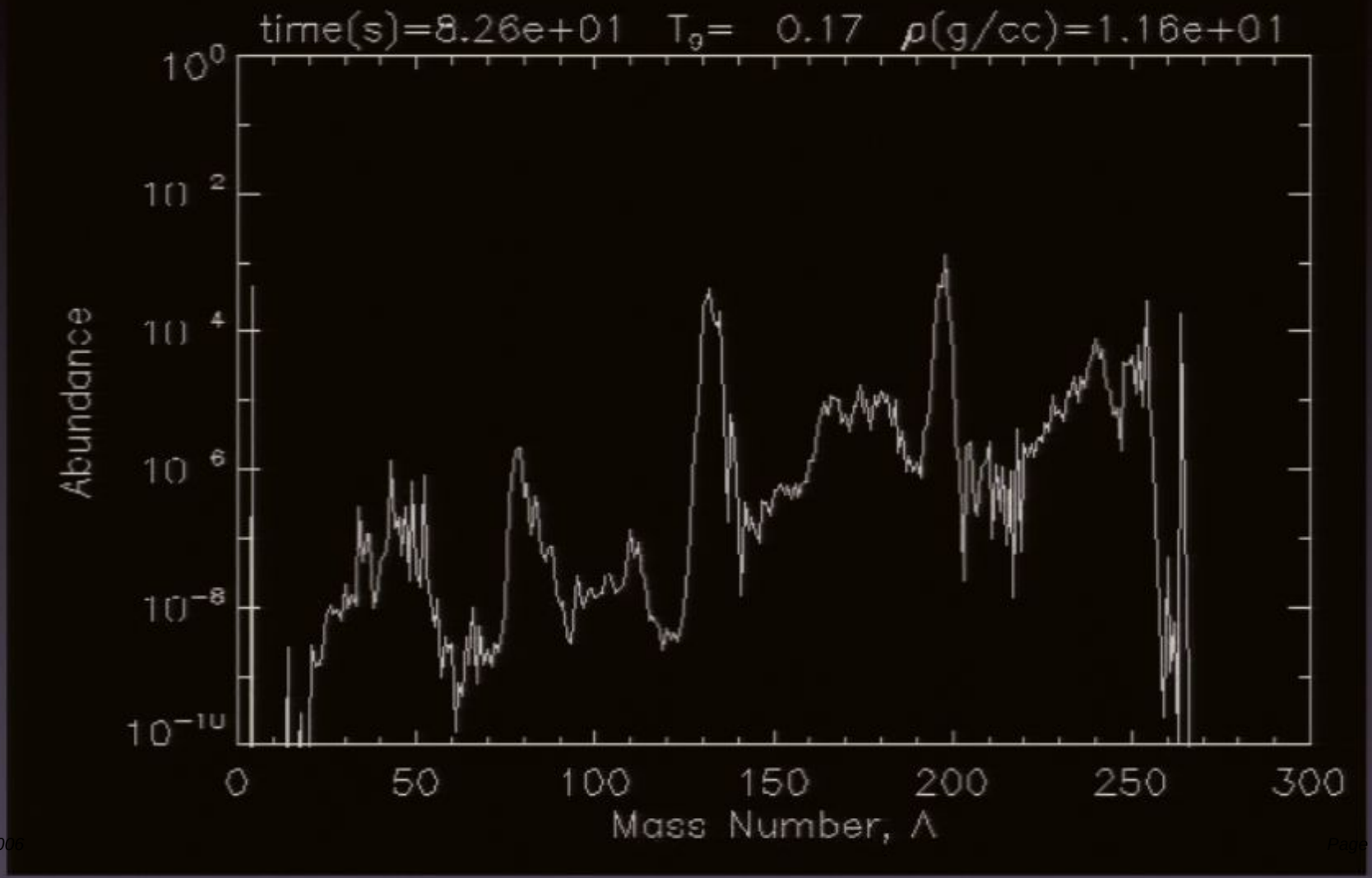

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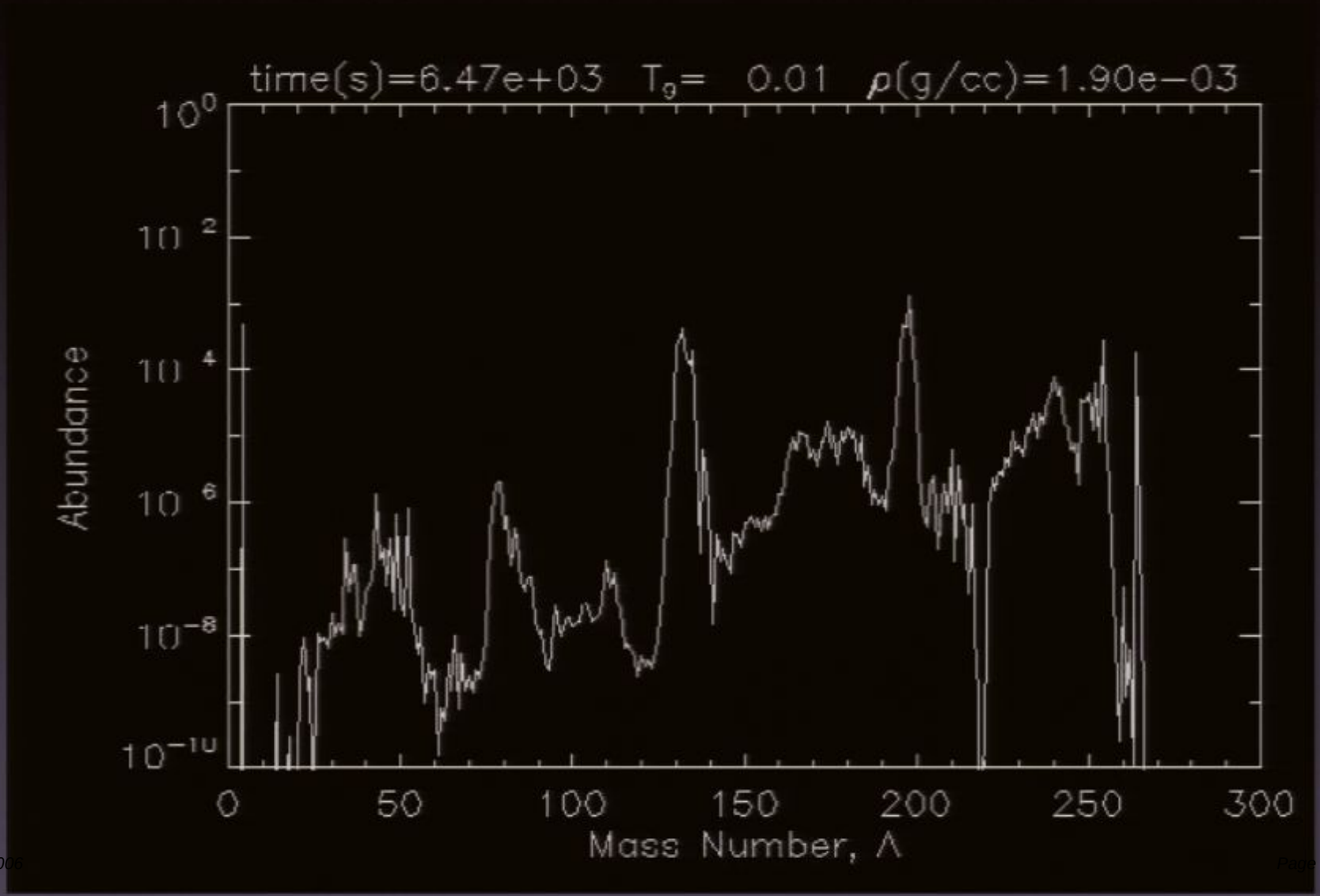
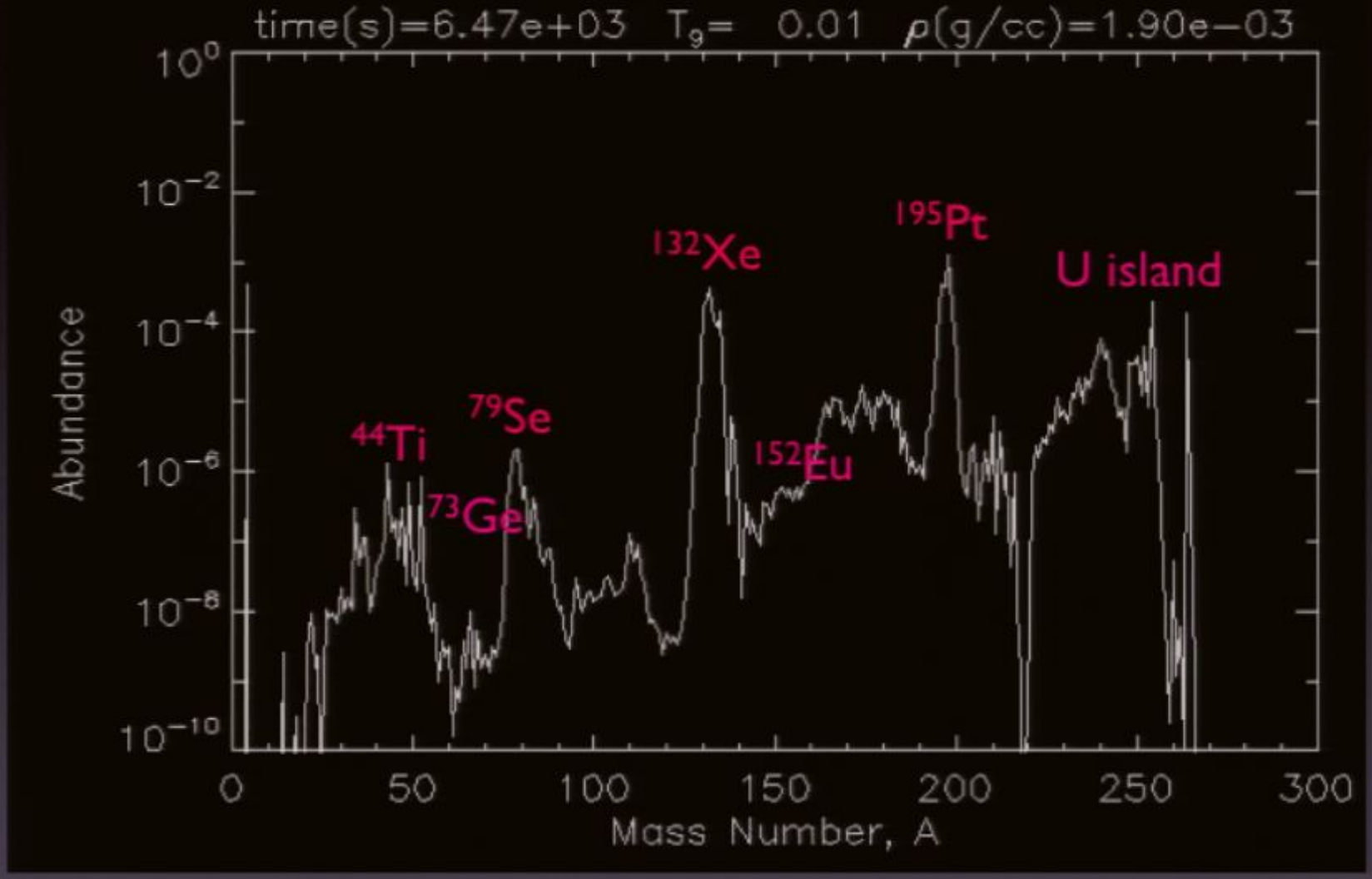
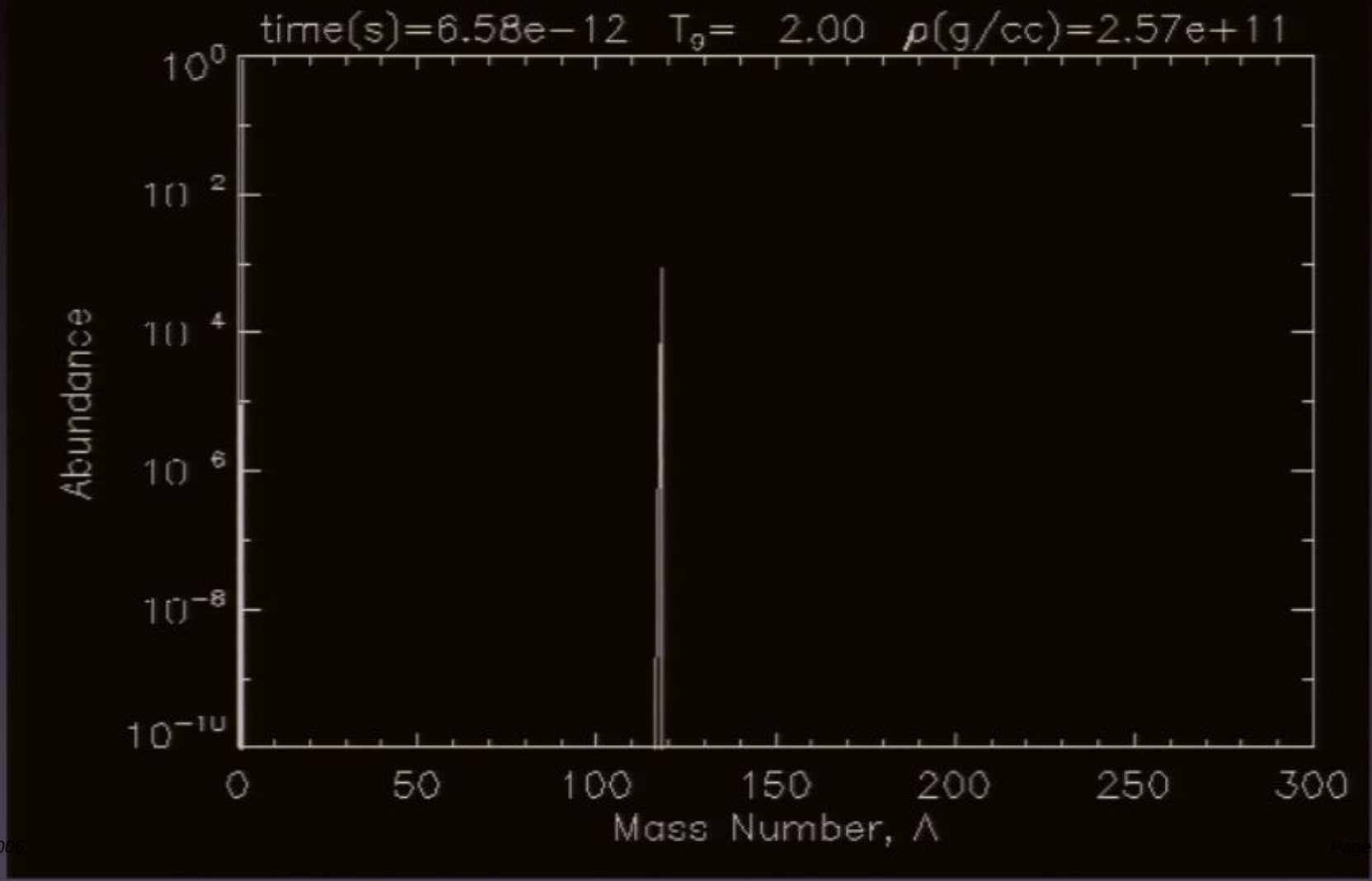


Light element (Ge, Ti) production by alpha-burning



Observations of Gamma-rays from ^{44}Ti (half-life=90 years) can confirm the Quark-Nova Scenario

Seed Nuclei (40 < Z < 70)



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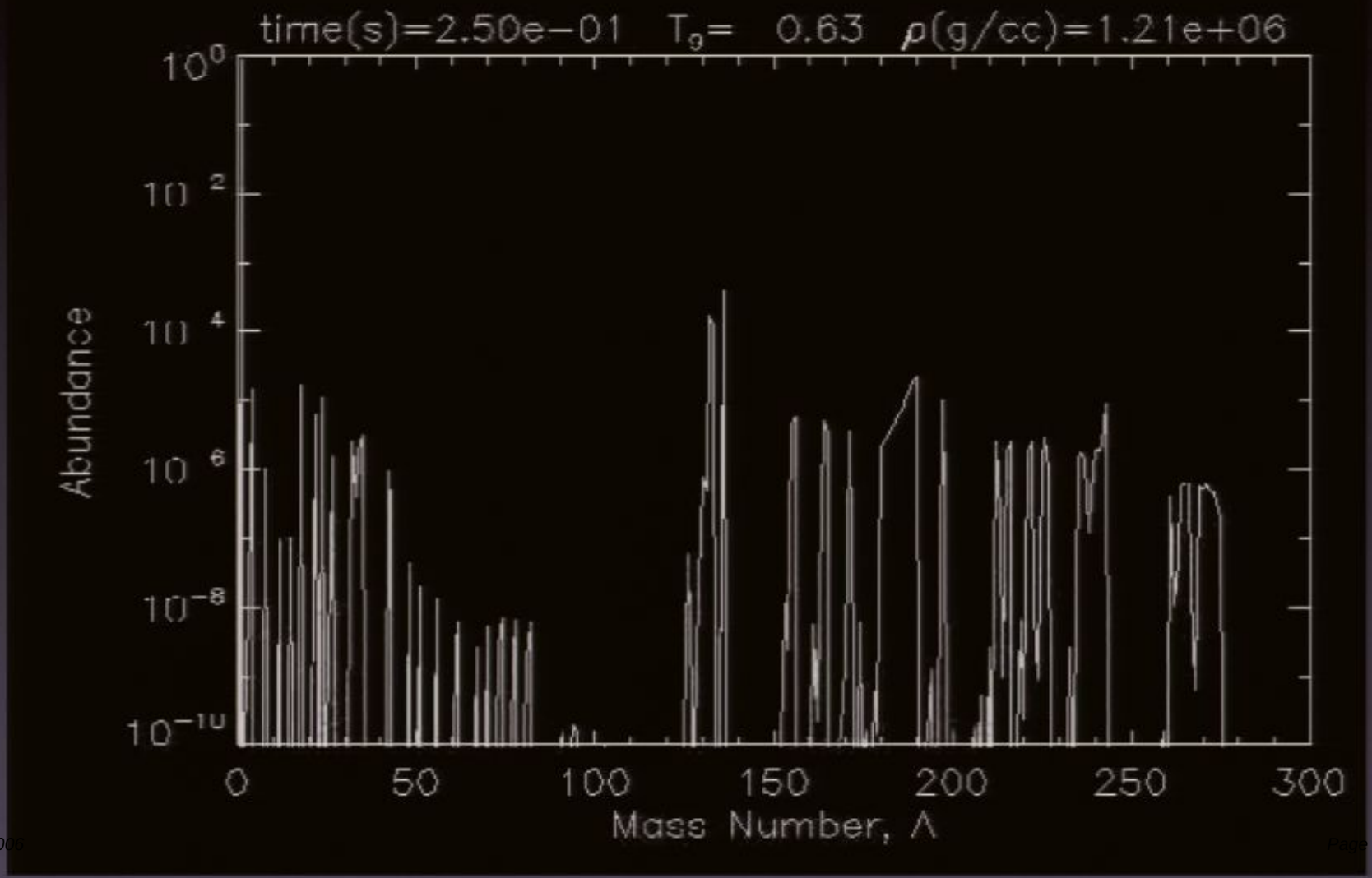

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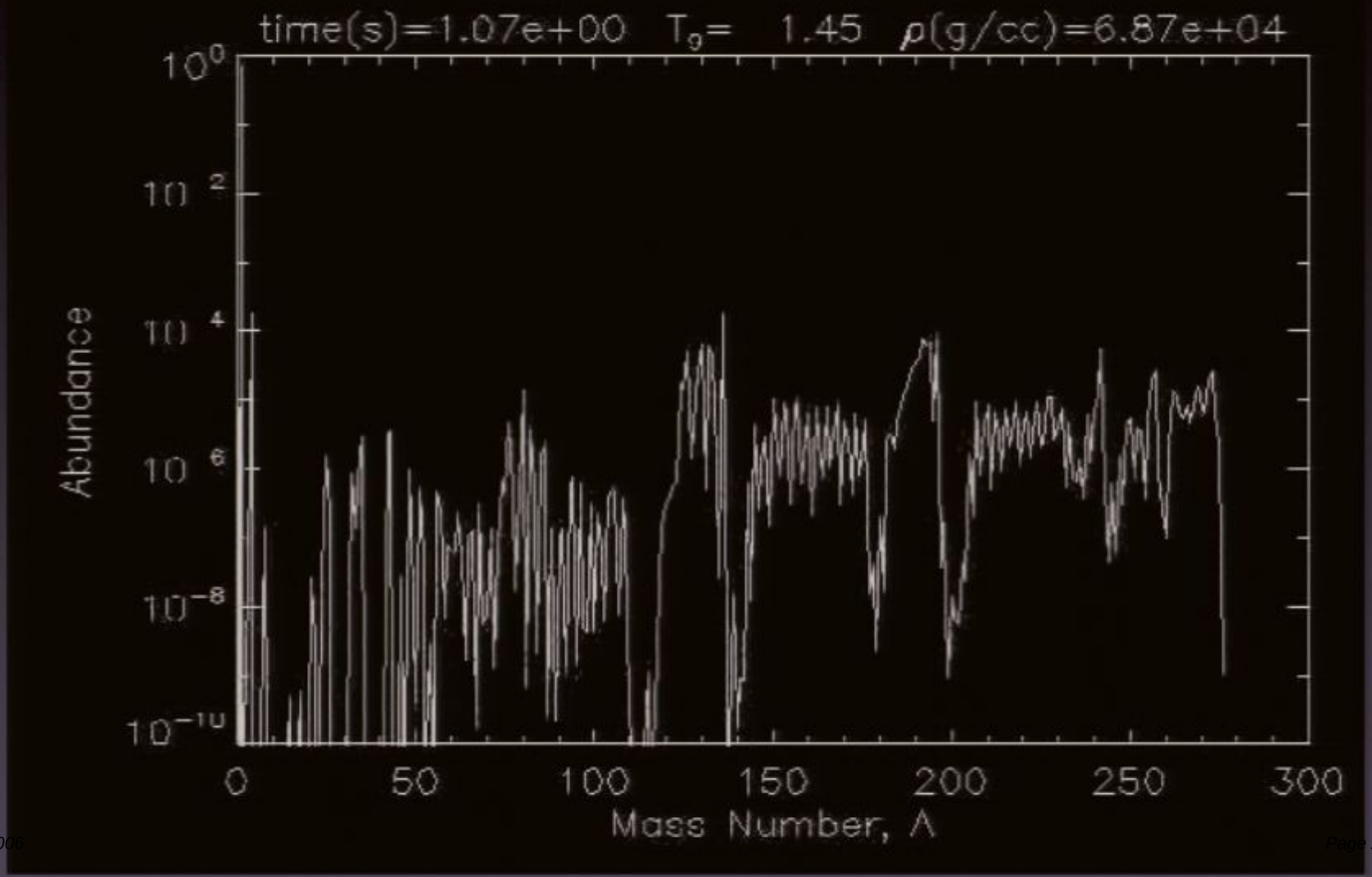

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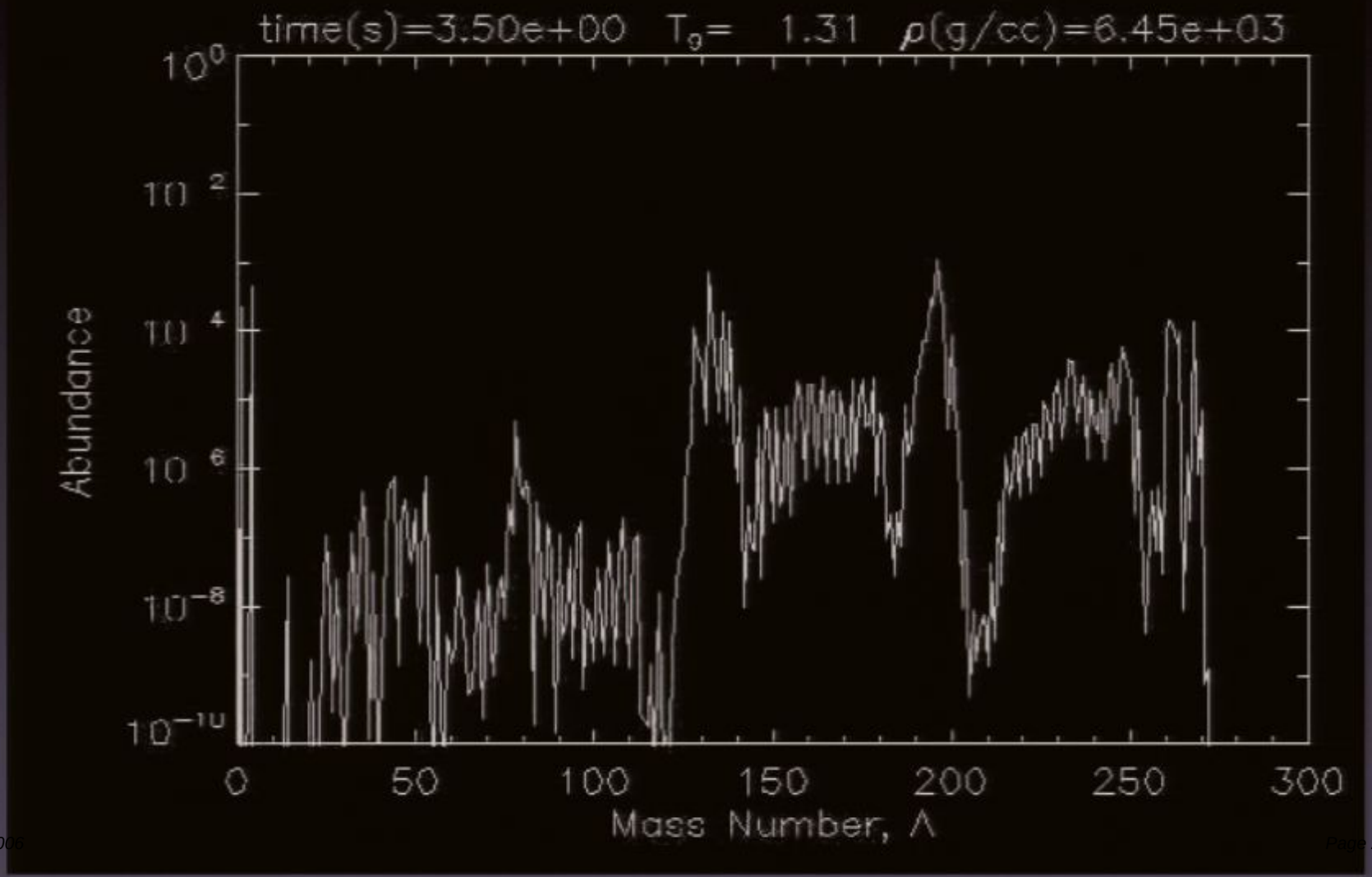

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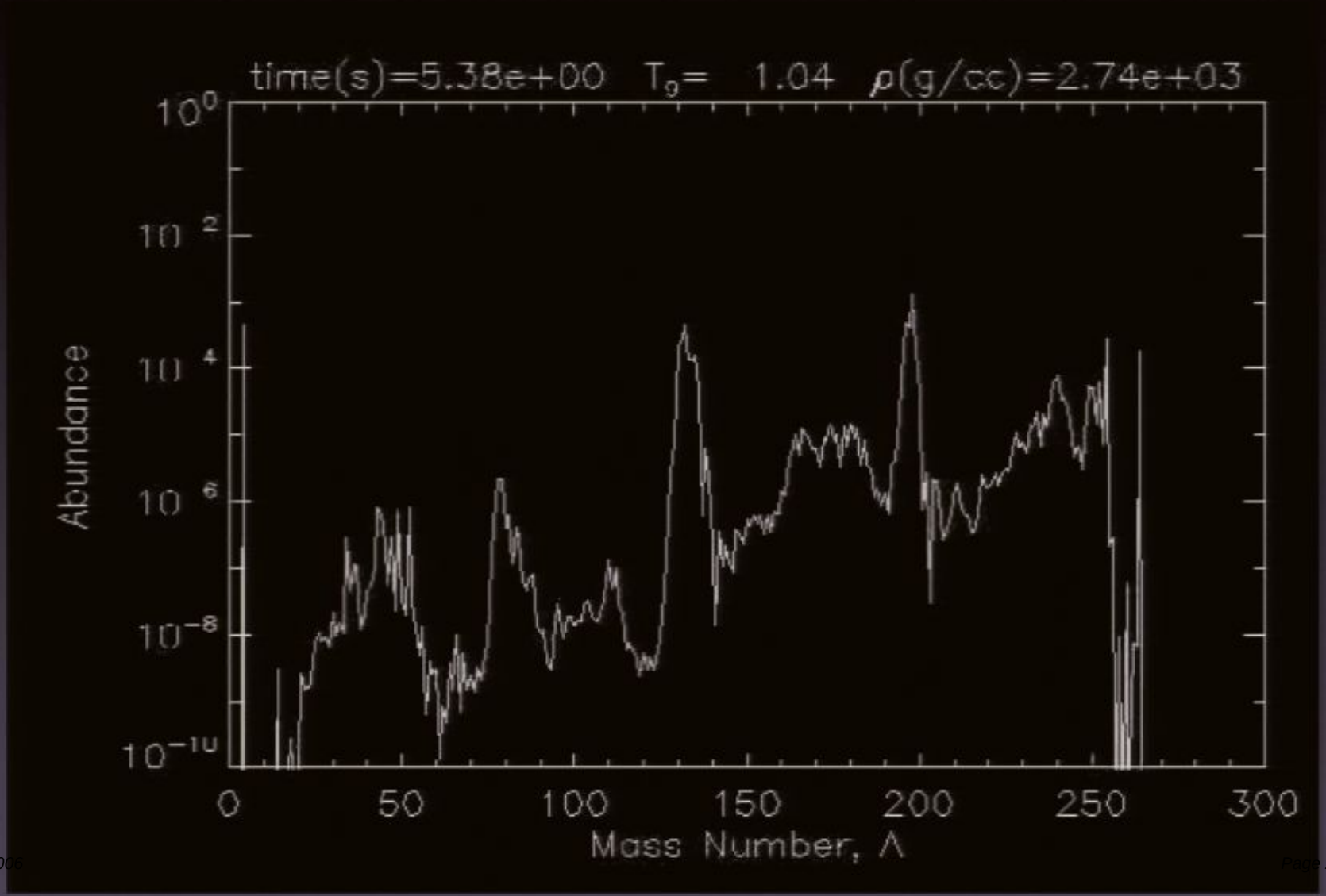

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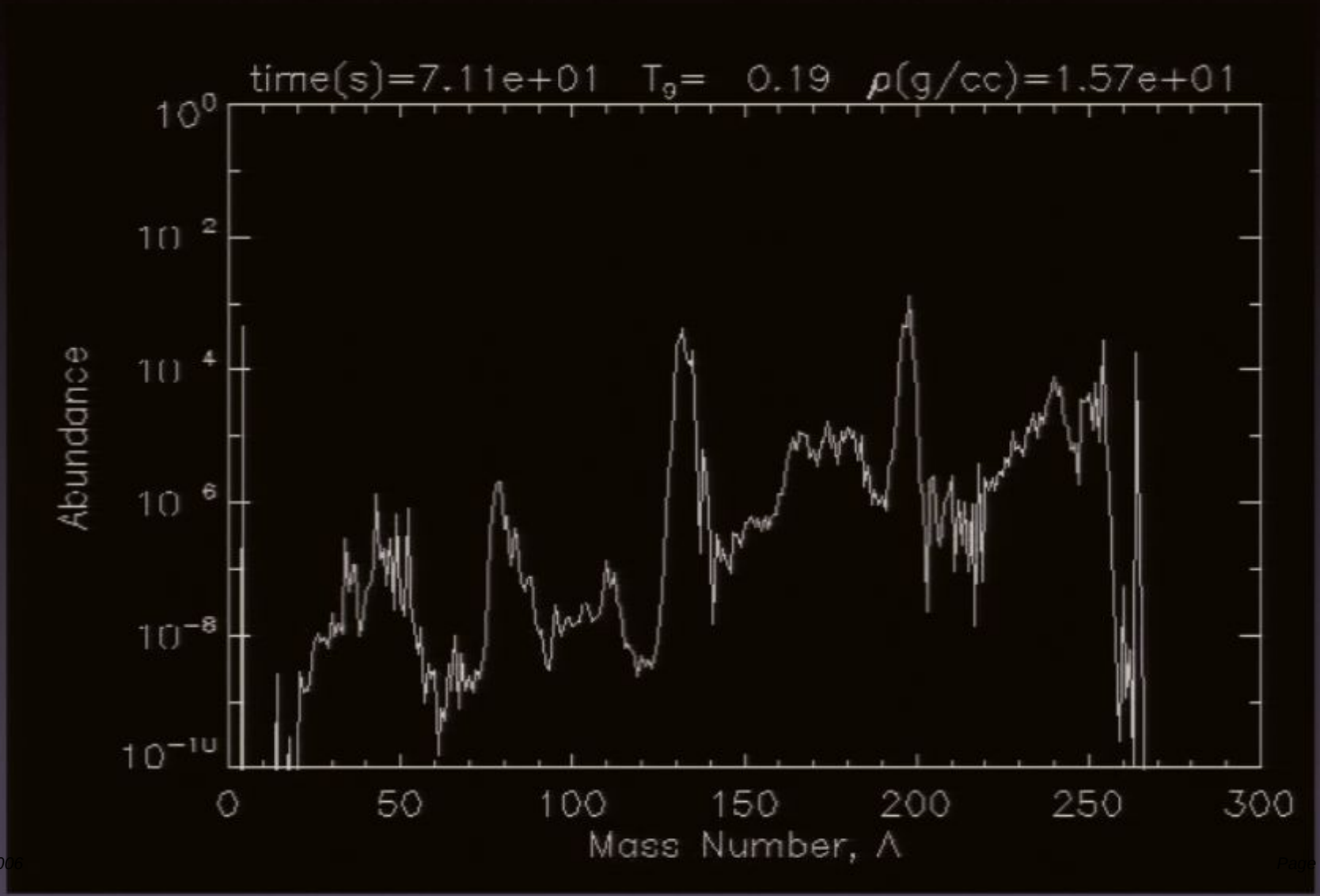

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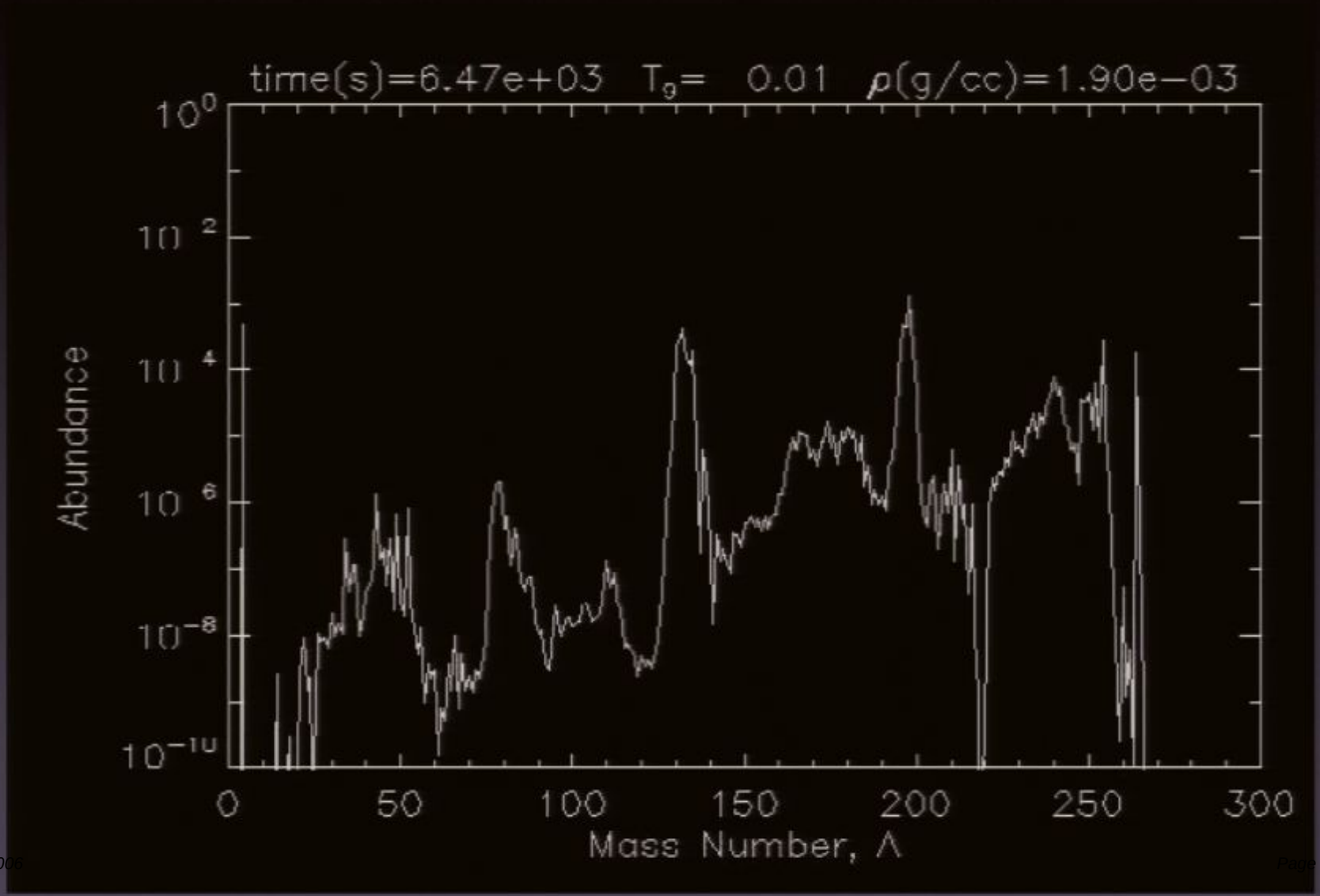

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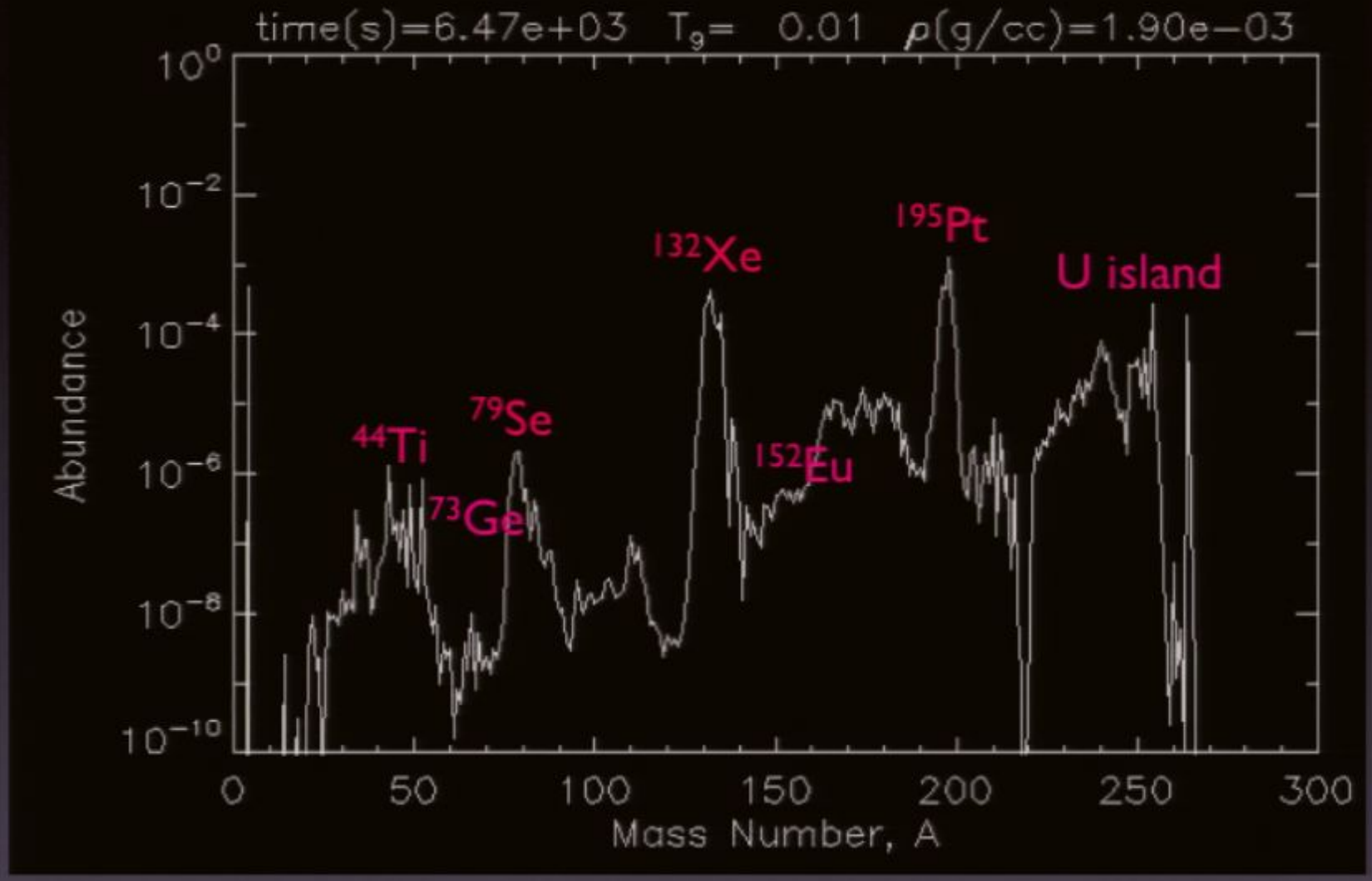

Observations of Gamma-rays from ^{44}Ti (half-life=90 years) can confirm the Quark-Nova Scenario

Finally, ... a bit of philosophy

We are all ...
13 Billion years old !

Quark-Nova

Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century

THE END