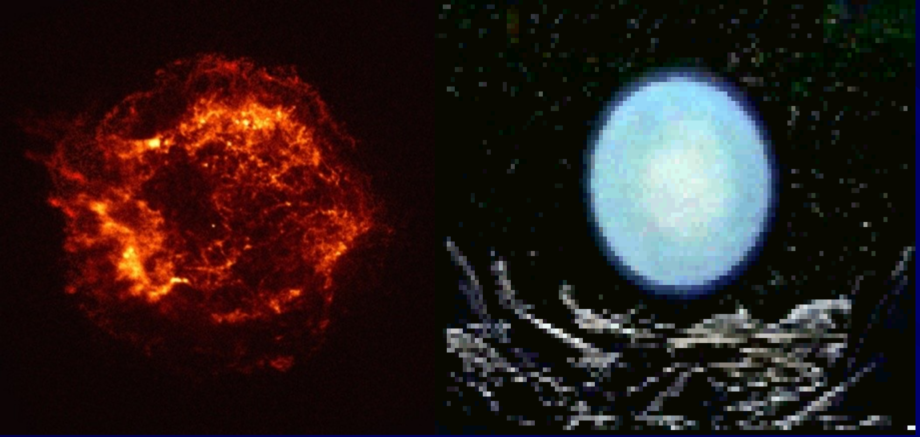


2011년 9월 17일
@KIAS

Nuclear Physics and Astrophysics at KoRIA

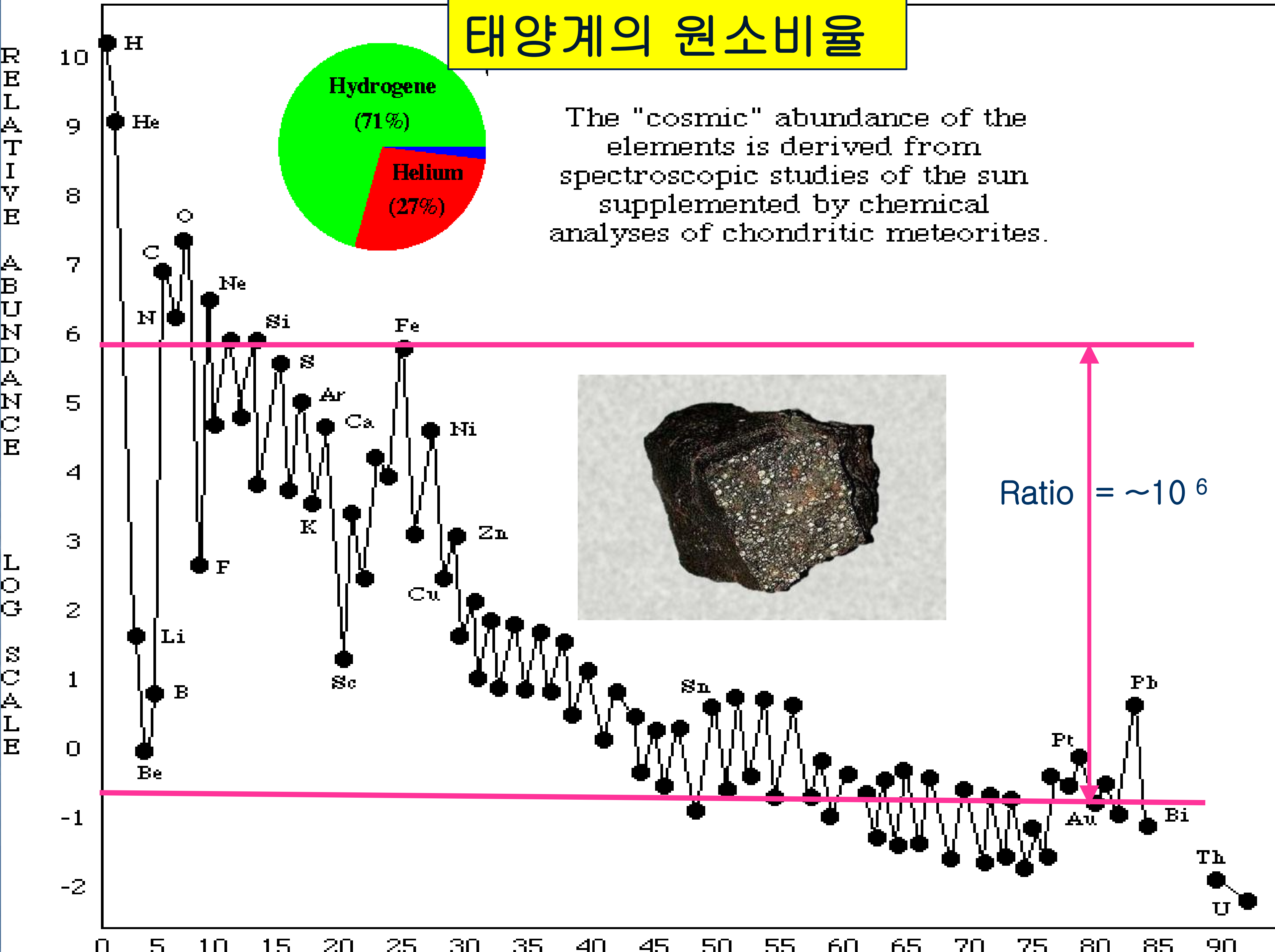
한인식

이화여자대학교

Outline

- Introduction (past)
  - Nuclear Physics and Astrophysics
  - Nuclear reactions in the Sun
- Selective experiments (present)
  - Stellar Thermonuclear reactions
  - Experiments with RIB
- Prospect (future)
  - Benchmarking for BSI
  - Nuclear Astrophysics @ KoRIA
  - Summary

태양계의 원소비율



The "cosmic" abundance of the elements is derived from spectroscopic studies of the sun supplemented by chemical analyses of chondritic meteorites.

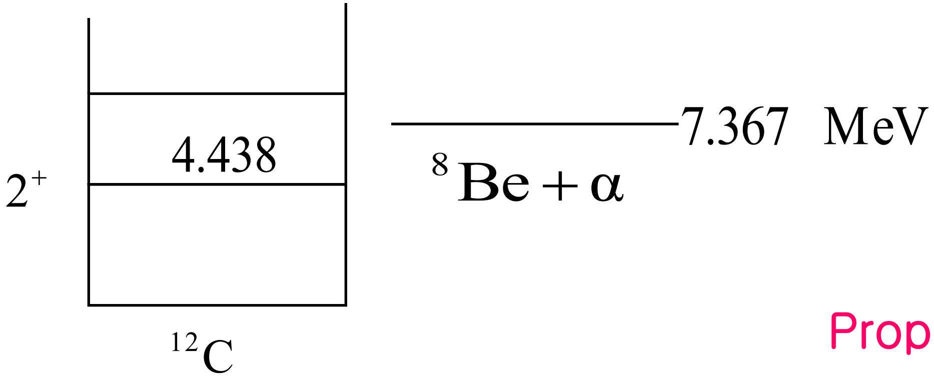
$\mathrm{H},\ {}^{4}\mathrm{He},\ {}^{3}\mathrm{He},\ \mathrm{Li}$ - Big Bang

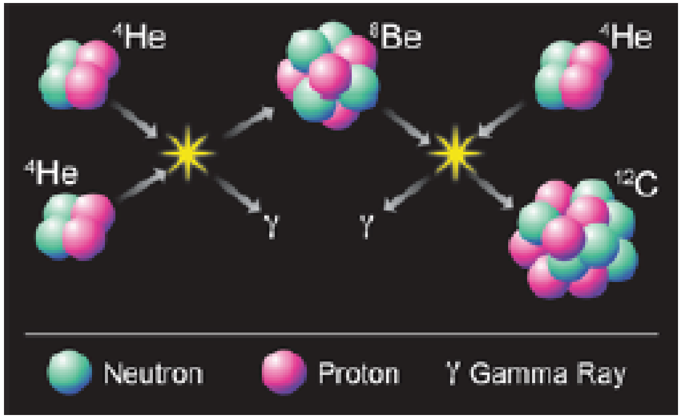
$${}^{4}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{8}\mathrm{Be} \rightarrow \alpha\text{ - decay}$$

< Hoyle in 1953 >

$3\,\alpha \rightarrow {}^{12}\mathrm{C}$ Is insufficient to explain the observed abundance

$${}^{8}\mathrm{Be} + \alpha \rightarrow {}^{12}\mathrm{C} + \gamma$$





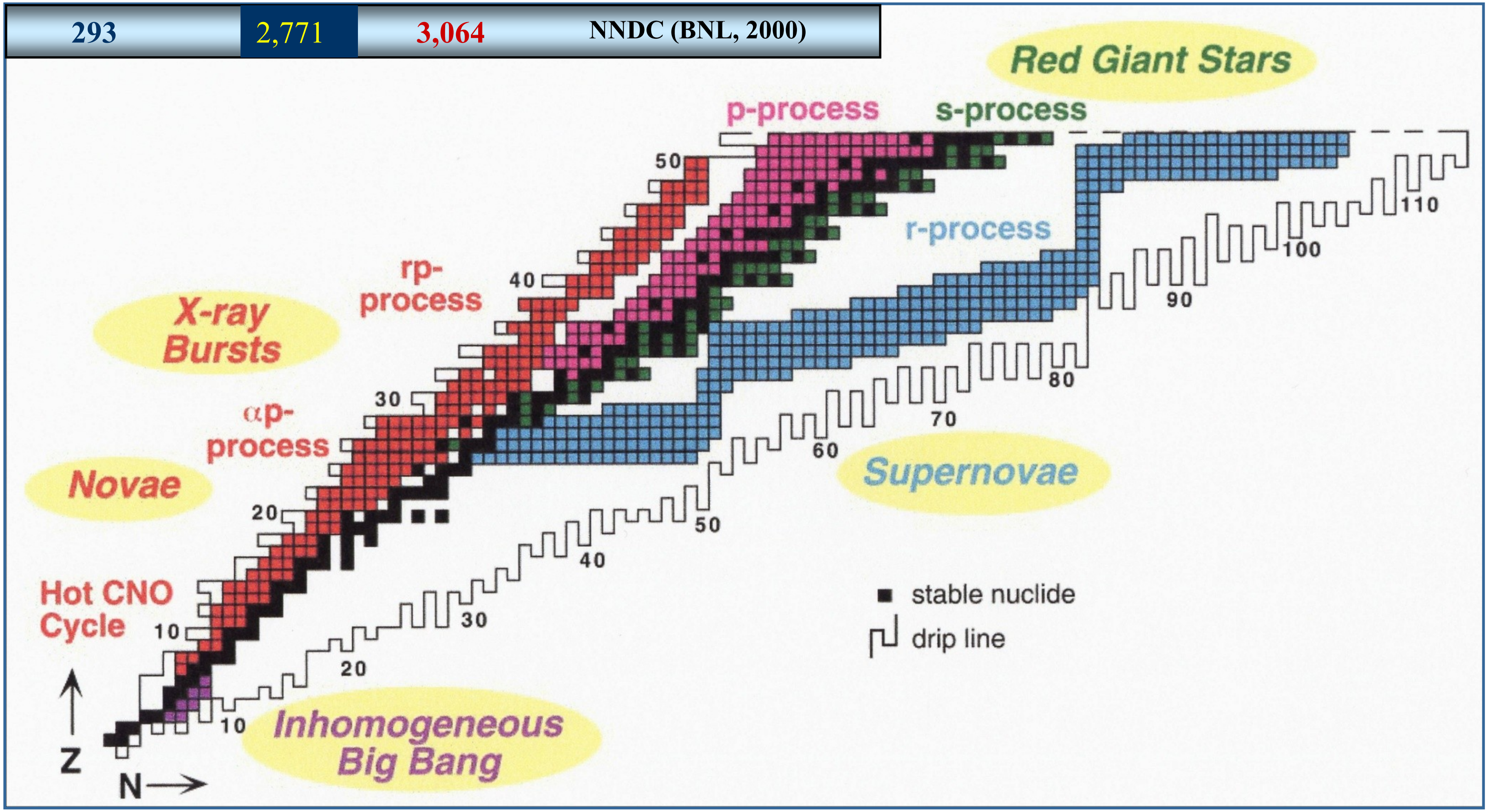
Proposed 0^{+} at 7.68 MeV in 1953

Measured at 7.65 MeV in 1957

→ **removed the major roadblock for the theory that elements are made in stars**

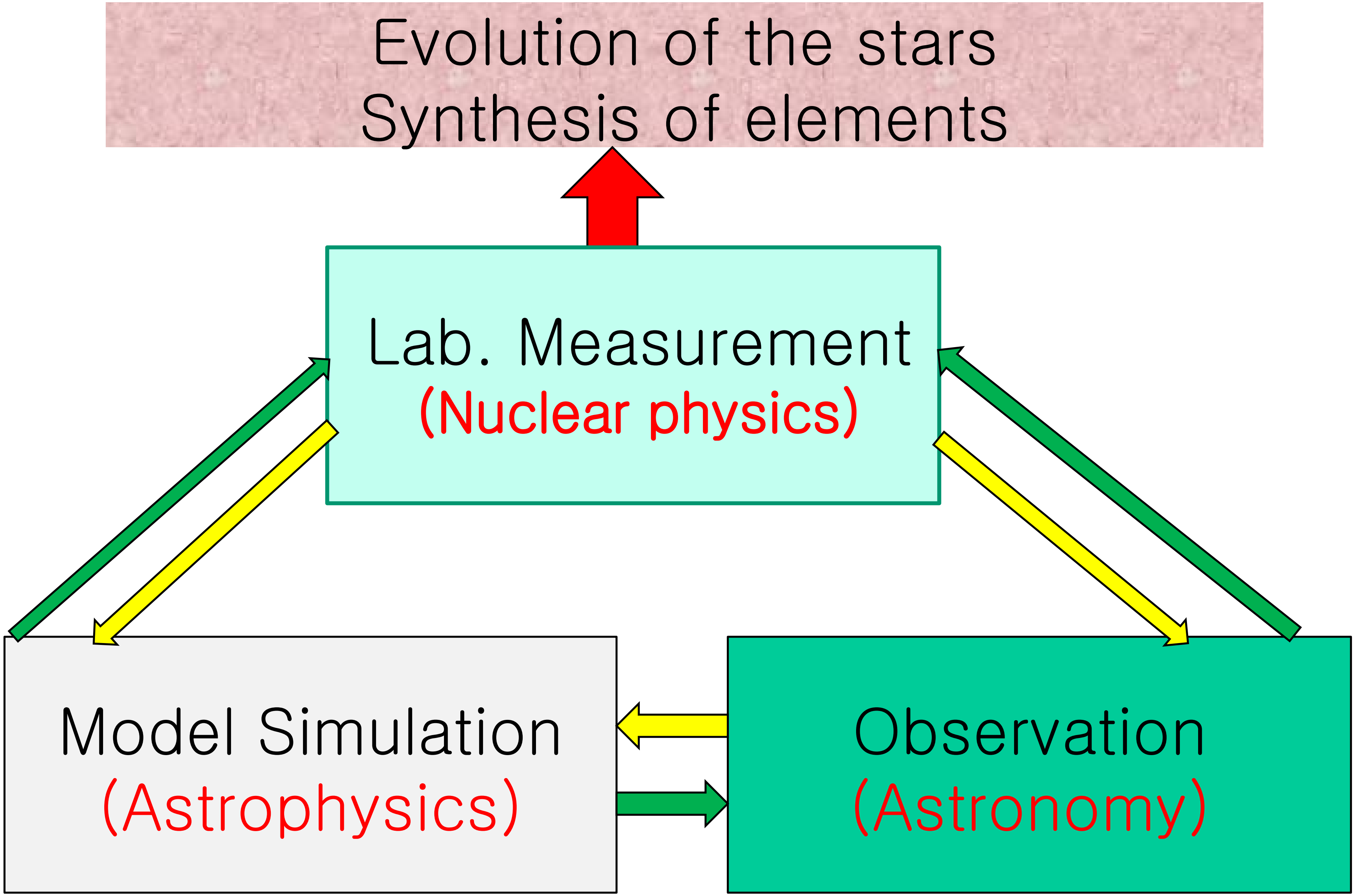
→ **Nobel Prize in Physics 1983 for Willy Fowler**

M.S. Smith and K.E. Rehm,
Ann. Rev. Nucl. Part. Sci, 51 (2001)



In many cosmic phenomena, radioactive nuclei play an influential role, hence the need for Radioactive Ion Beams / Rare Isotope Beams

- We try to observe nuclear reaction processes from
  - Heat from stars
    - probes only surface
  - Abundances of elements
  - Neutrino’s from stars
    - probes interior of star
  - Lab studies of reaction cross-sections
    - Experimental nuclear astrophysics



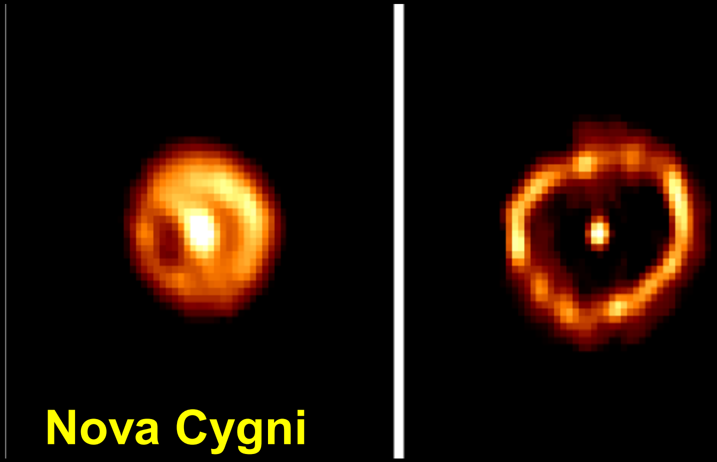
Evolution of the stars
Synthesis of elements

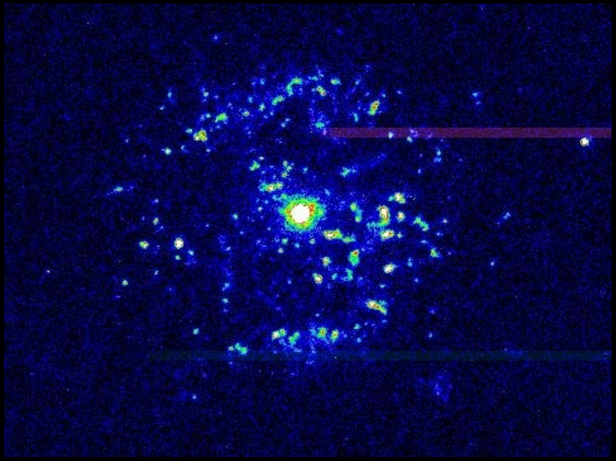
Lab. Measurement
(Nuclear physics)

Model Simulation
(Astrophysics)

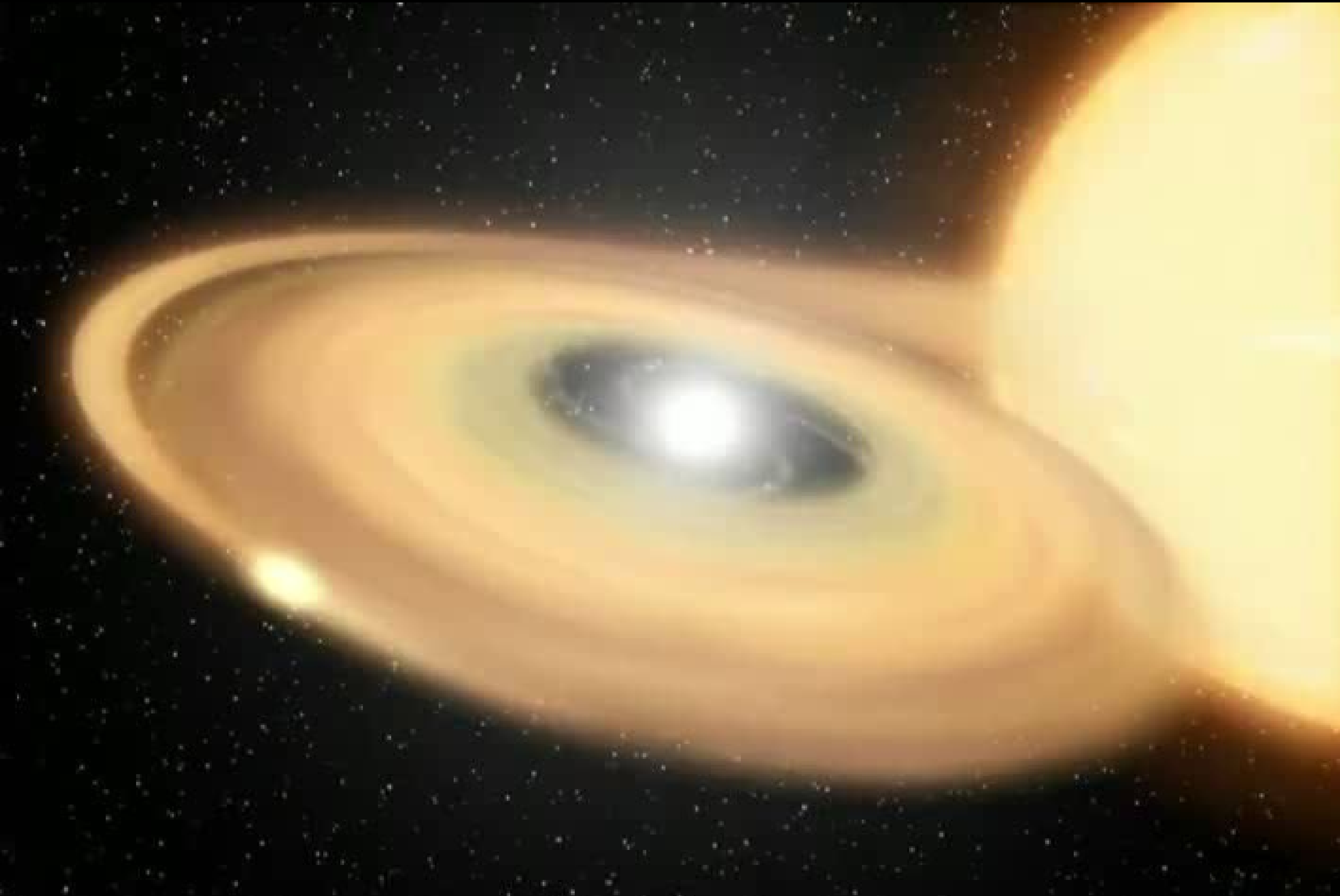
Observation
(Astronomy)

Nova observations


Nova Cygni


Nova Persei

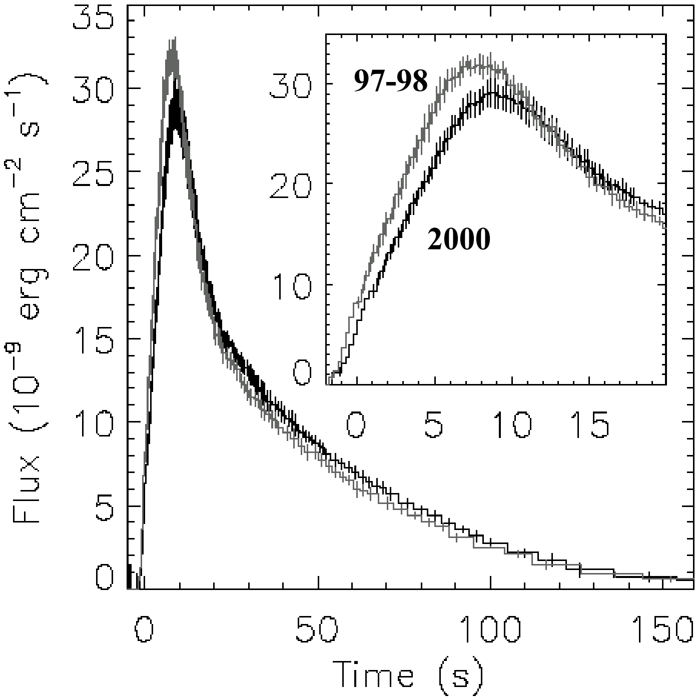
Nova models



example: observation – model – nuclear astrophysics

Precision X-ray observations

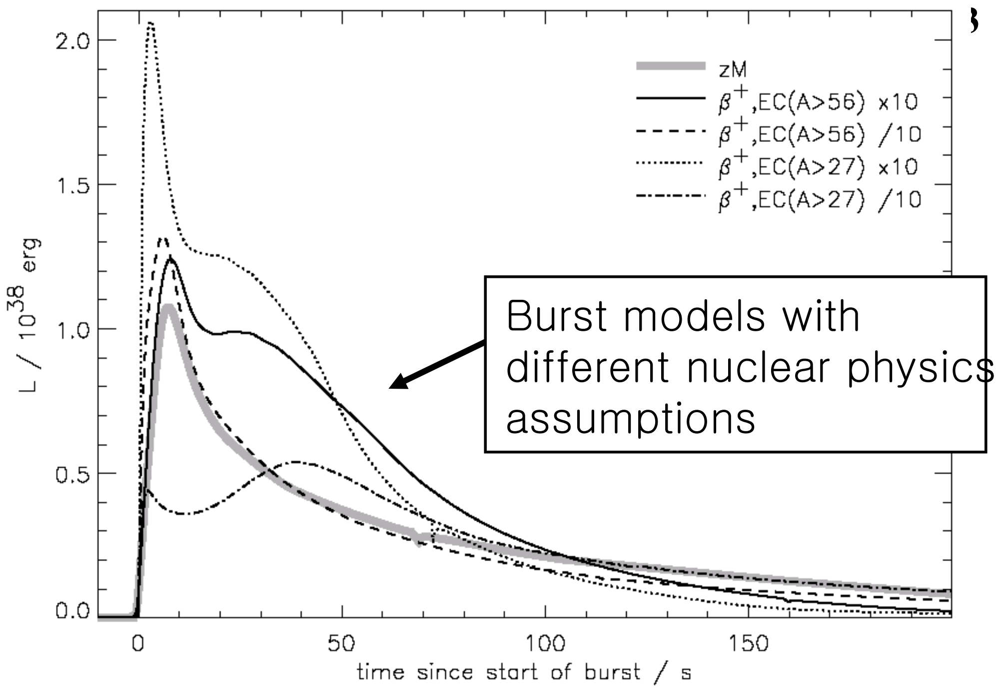
(NASA's RXTE)



→ GS 1826-24 burst shape changes !

(Galloway 2003 astro/ph 0308122)

Uncertain models due to nuclear physics



Burst models with different nuclear physics assumptions

Woosley et al. 2003 astro/ph 0307425

- Need much more precise nuclear data to make full use of high quality observational data

From Schatz

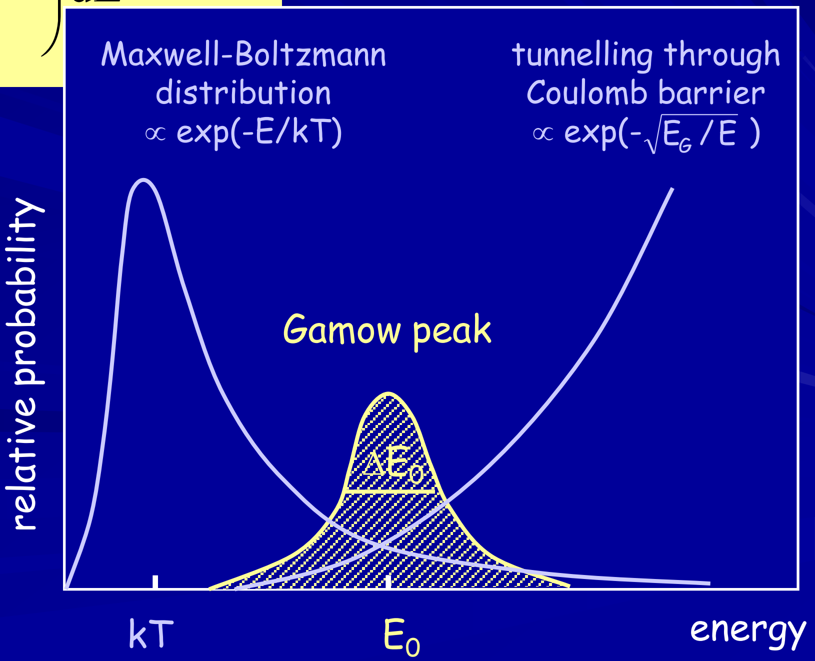
Thermonuclear reactions in stars

$$S(E) \equiv \sigma(E)E\exp\left(\frac{2\pi Z_1Z_2e^2}{\hbar\nu}\right)$$

$$\lambda = \langle\sigma\nu\rangle = \int_0^\infty \sigma(E)\nu(E)\Psi(E)dE$$

$$= \int_0^\infty \frac{S(E)}{E}\exp(-bE^{-1/2})\sqrt{\frac{2E}{\mu}}\,\frac{2}{\sqrt{\pi}}\frac{E}{kT}\exp\left(-\frac{E}{kT}\right)\frac{dE}{(kTE)^{1/2}}$$

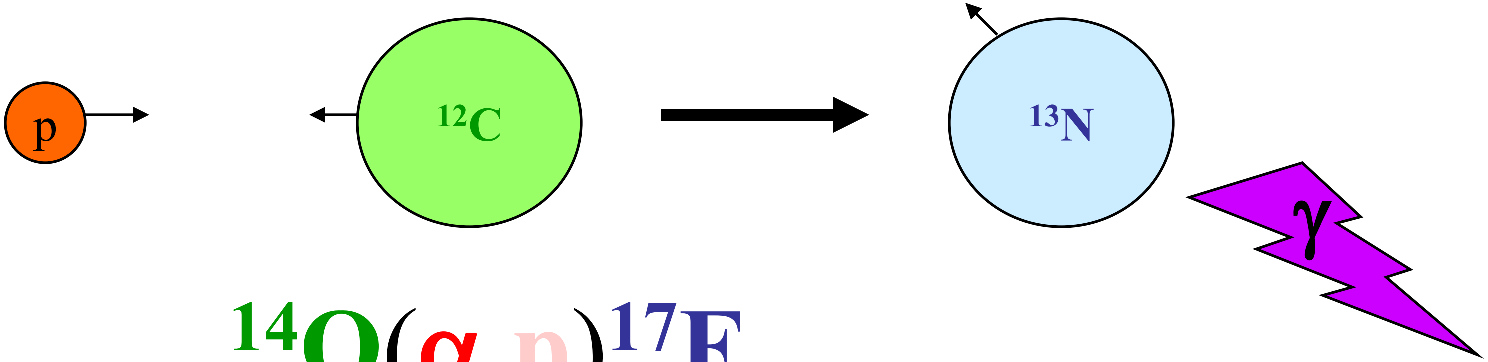
$$= \left(\frac{8}{\mu\pi}\right)^{1/2}\frac{1}{(kT)^{3/2}}\int_0^\infty \frac{S(E)}{E}\exp\left(-\frac{E}{kT}-bE^{-1/2}\right)dE$$



Nuclear Reactions

$^{12}C + p$ -> $^{13}N + \gamma$

Notation



$^{14}O(\alpha,p)^{17}F$

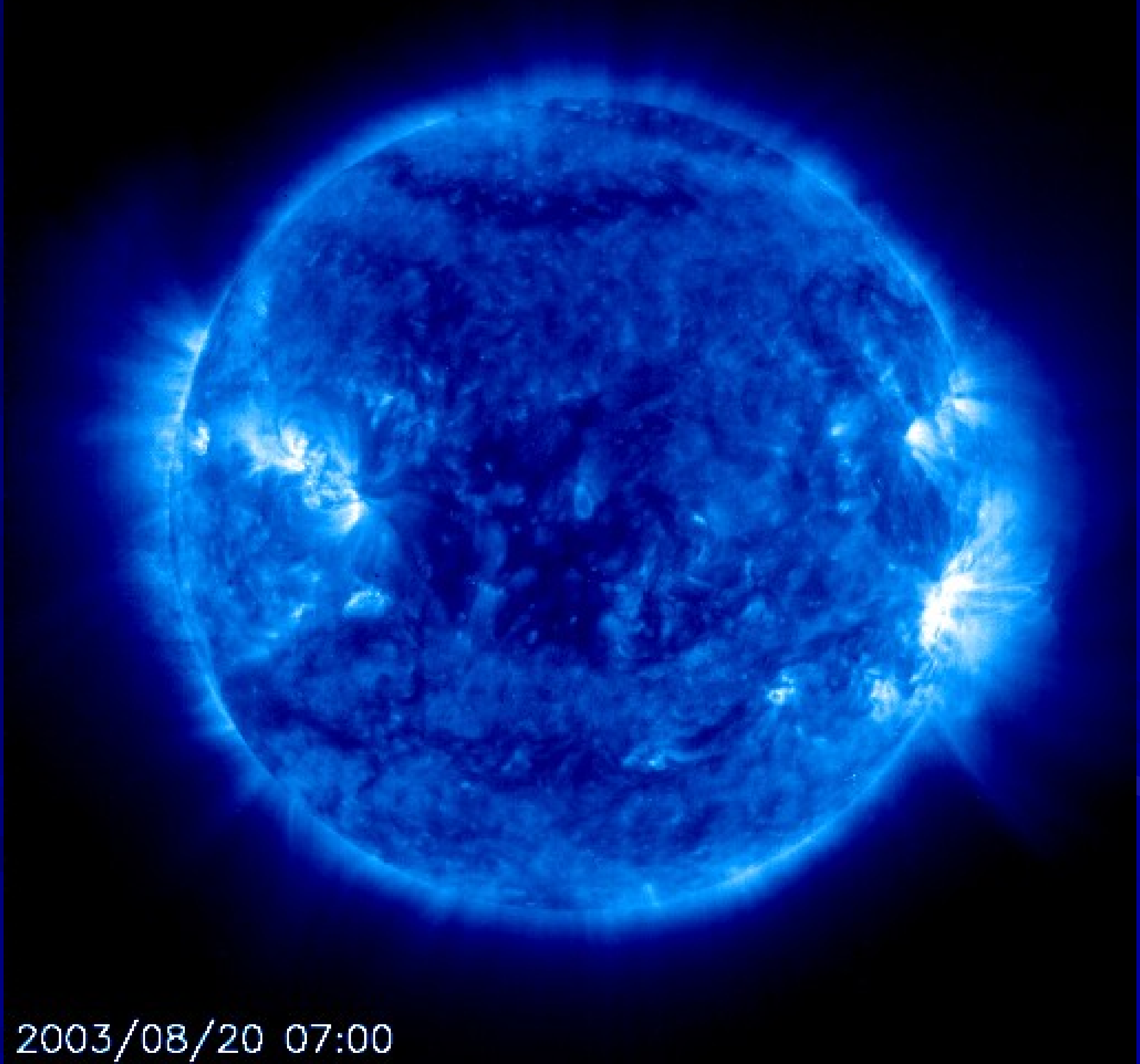
The heavier "target" nucleus (Lab: target)

the lighter "incoming projectile" (Lab: beam)

the lighter "outgoing particle" (Lab: residual of beam)

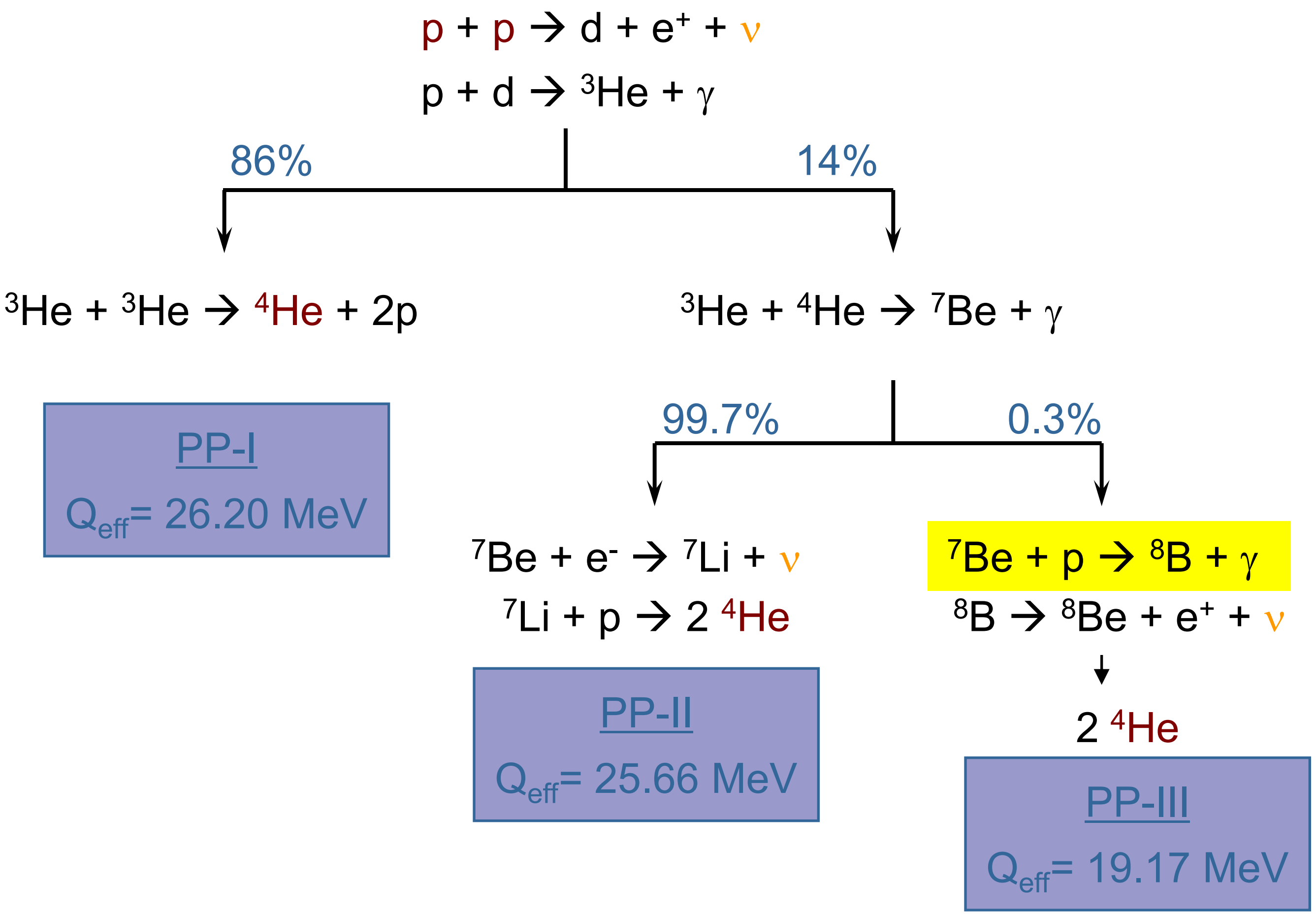
the heavier "residual" nucleus (Lab: residual of target)

Nuclear Reactions in the Sun



Nuclear Reactions in the Sun

proton-proton chain



$p + p \rightarrow d + e^+ + \nu$

$p + d \rightarrow {}^3He + \gamma$

86%

14%

${}^3He + {}^3He \rightarrow {}^4He + 2p$

PP-I

$Q_{eff} = 26.20$ MeV

${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

99.7%

0.3%

${}^7Be + e^- \rightarrow {}^7Li + \nu$

${}^7Li + p \rightarrow 2\ {}^4He$

PP-II

$Q_{eff} = 25.66$ MeV

${}^7Be + p \rightarrow {}^8B + \gamma$

${}^8B \rightarrow {}^8Be + e^+ + \nu$

$\downarrow$

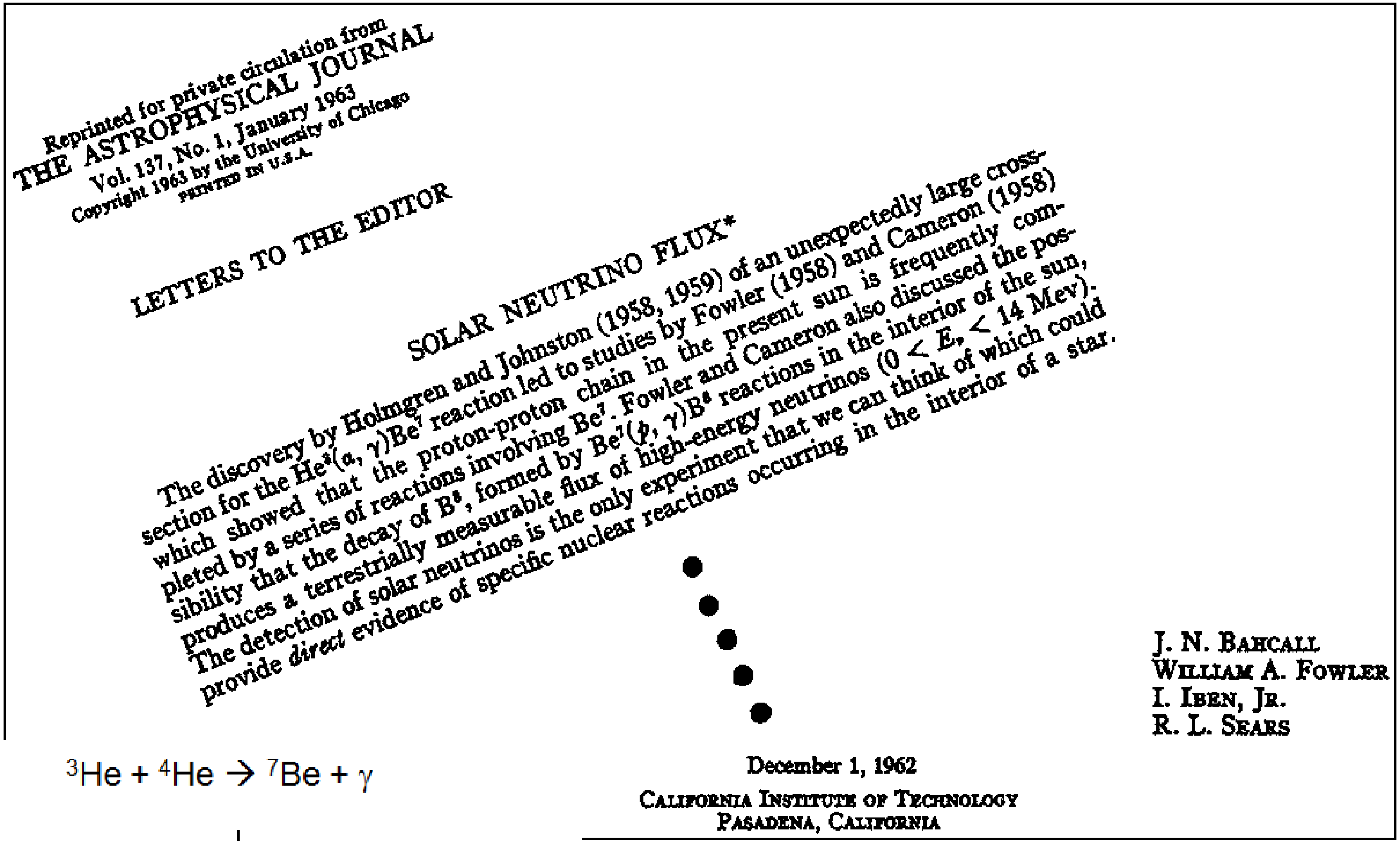
$2\ {}^4He$

PP-III

$Q_{eff} = 19.17$ MeV

net result: $4p \rightarrow {}^4He + 2e^+ + 2\nu + Q_{eff}$

From M. Aliotta



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THE ASTROPHYSICAL JOURNAL
Vol. 137, No. 1, January 1963

LETTERS TO THE EDITOR

SOLAR NEUTRINO FLUX*

The discovery by Holmgren and Johnston (1958, 1959) of an unexpectedly large cross-section for the $He^3(\alpha, \gamma)Be^7$ reaction led to studies by Fowler (1958) and Cameron (1958) which showed that the proton-proton chain in the present sun is frequently completed by a series of reactions involving Be^7. Fowler and Cameron also discussed the possibility that the decay of B^8, formed by $Be^7(p, \gamma)B^8$ reactions in the interior of the sun, produces a terrestrially measurable flux of high-energy neutrinos ($0 < E_\nu < 14$ Mev). The detection of solar neutrinos is the only experiment that we can think of which could provide *direct* evidence of specific nuclear reactions occurring in the interior of a star.

……

J. N. Bahcall
William A. Fowler
I. Iben, Jr.
R. L. Sears

December 1, 1962

California Institute of Technology
Pasadena, California

$^3He + {}^4He \rightarrow {}^7Be + \gamma$

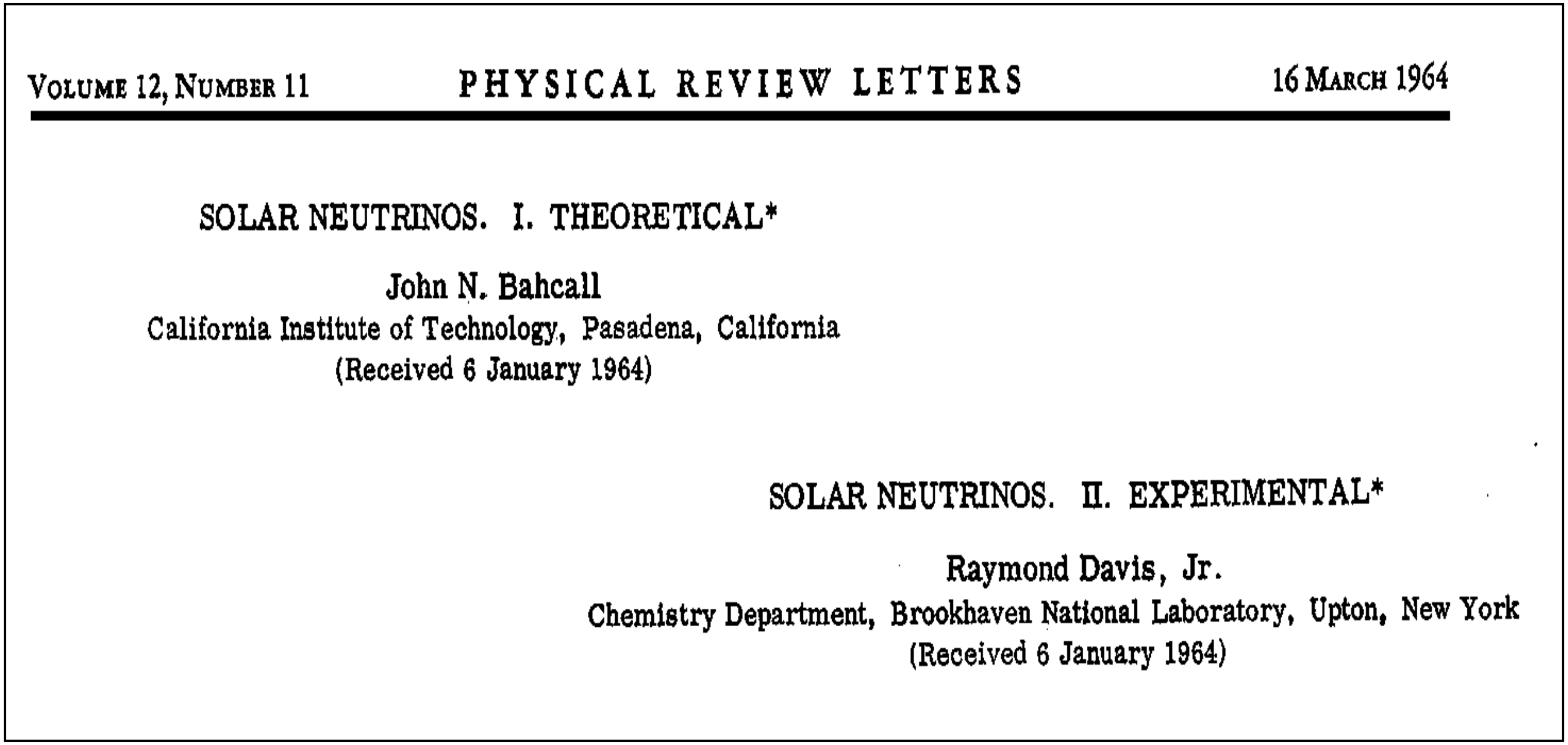
99.7% 0.3%

$^7Be + e^- \rightarrow {}^7Li + \nu$

$^7Li + p \rightarrow 2\,{}^4He$

$^7Be + p \rightarrow {}^8B + \gamma$

$^8B \rightarrow {}^8Be + e^+ + \nu$



VOLUME 12, NUMBER 11 PHYSICAL REVIEW LETTERS 16 MARCH 1964

SOLAR NEUTRINOS. I. THEORETICAL*

John N. Bahcall
California Institute of Technology, Pasadena, California

(Received 6 January 1964)

SOLAR NEUTRINOS. II. EXPERIMENTAL*

Raymond Davis, Jr.
Chemistry Department, Brookhaven National Laboratory, Upton, New York

(Received 6 January 1964)

First experimental detection of solar neutrinos:

- **1964** John Bahcall and Ray Davis have the idea to detect solar neutrinos using the reaction:

$$^{37}Cl + \nu_e \longrightarrow {}^{37}Ar + e^-$$

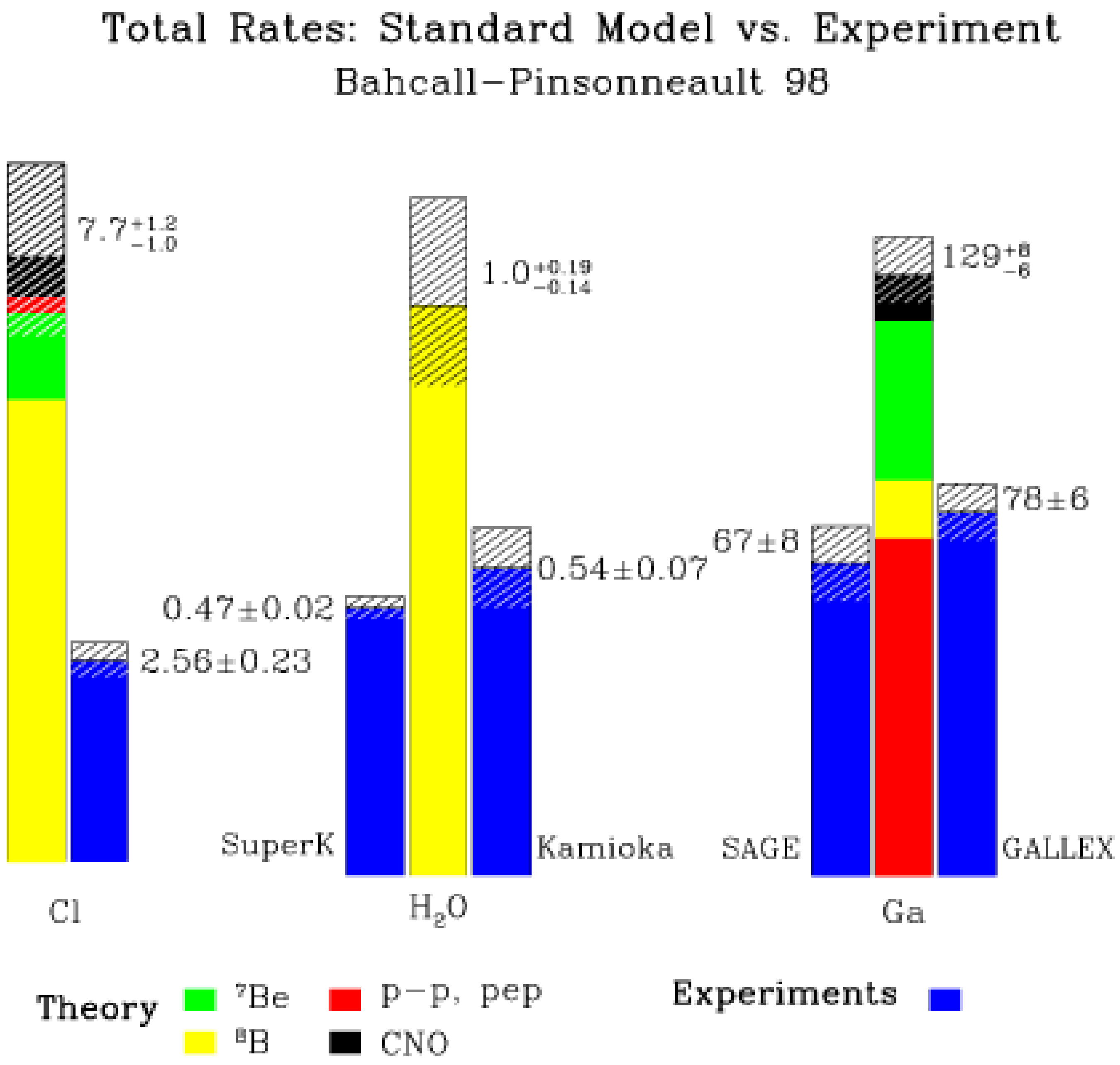
- **1967** **Homestake experiment starts taking data**
  - 100,000 Gallons of cleaning fluid in a tank 4850 feet underground
  - ^{37}Ar extracted chemically every few months (single atoms !) and decay counted in counting station (35 days half-life)
  - event rate: ~1 neutrino capture per day !
- **1968** **First results: only 34% of predicted neutrino flux !**

solar neutrino problem is born - for next 20 years no other detector !

Neutrino production in solar core ~ T^{25}

$\longrightarrow$ **nuclear energy source of sun directly and unambiguously confirmed**

$\longrightarrow$ **solar models precise enough so that deficit points to serious problem**


Total Rates: Standard Model vs. Experiment
Bahcall–Pinsonneault 98
$7.7^{+1.2}_{-1.0}$
2.56 ± 0.23
Cl
$1.0^{+0.19}_{-0.14}$
0.47 ± 0.02
0.54 ± 0.07
SuperK
Kamioka
H_2O
129^{+8}_{-6}
67 ± 8
78 ± 6
SAGE
GALLEX
Ga
Theory
🟩 ^{7}Be
🟨 ^{8}B
🟥 p–p, pep
⬛ CNO
Experiments 🟦

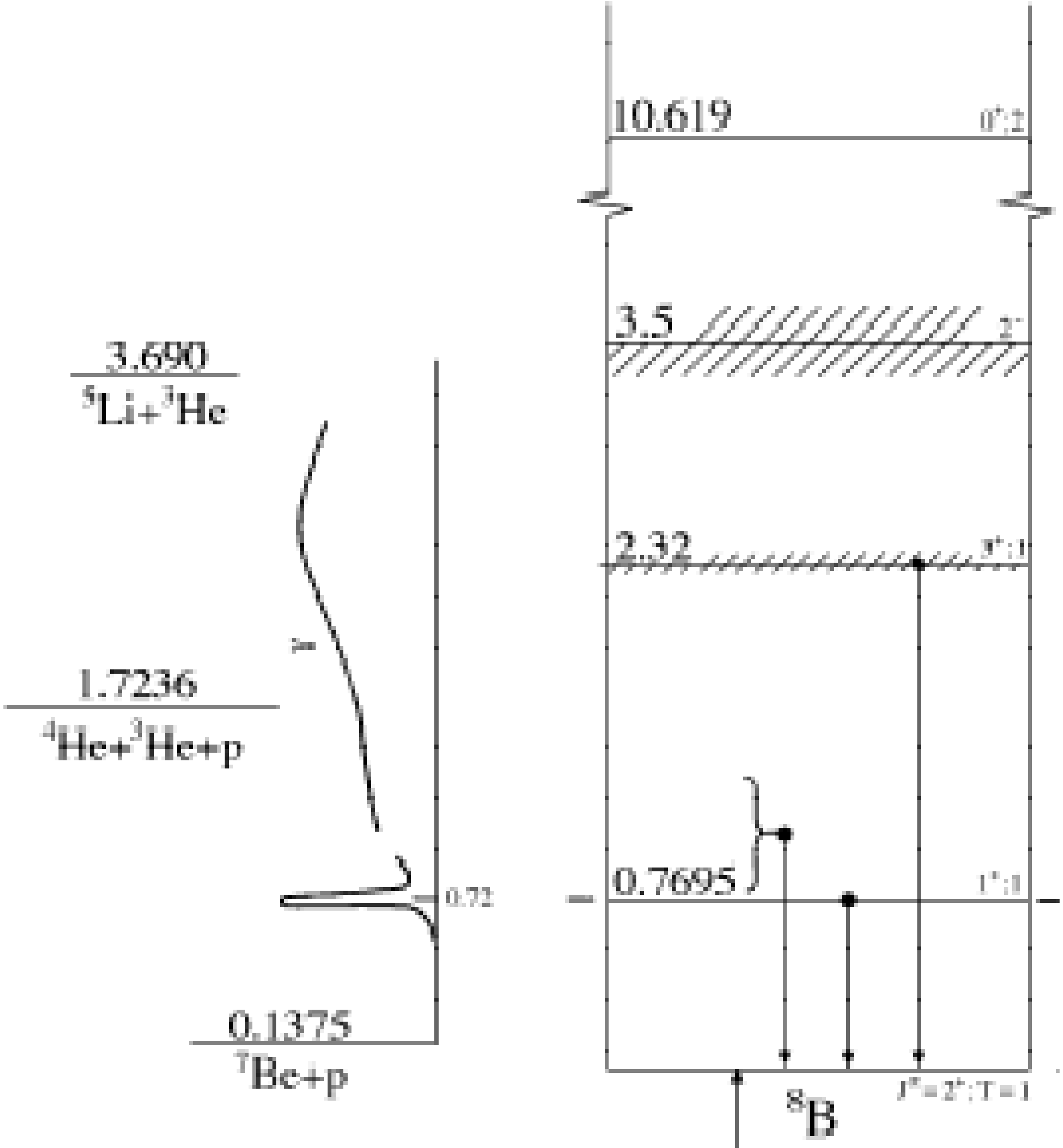
Levels and γ-ray branchings:

0, 2^+, 770 *3* ms, *[ABCDEFGH]*, T=1,
%EC+%β^+=100, %EC2α=100,
μ=1.0355 *3*

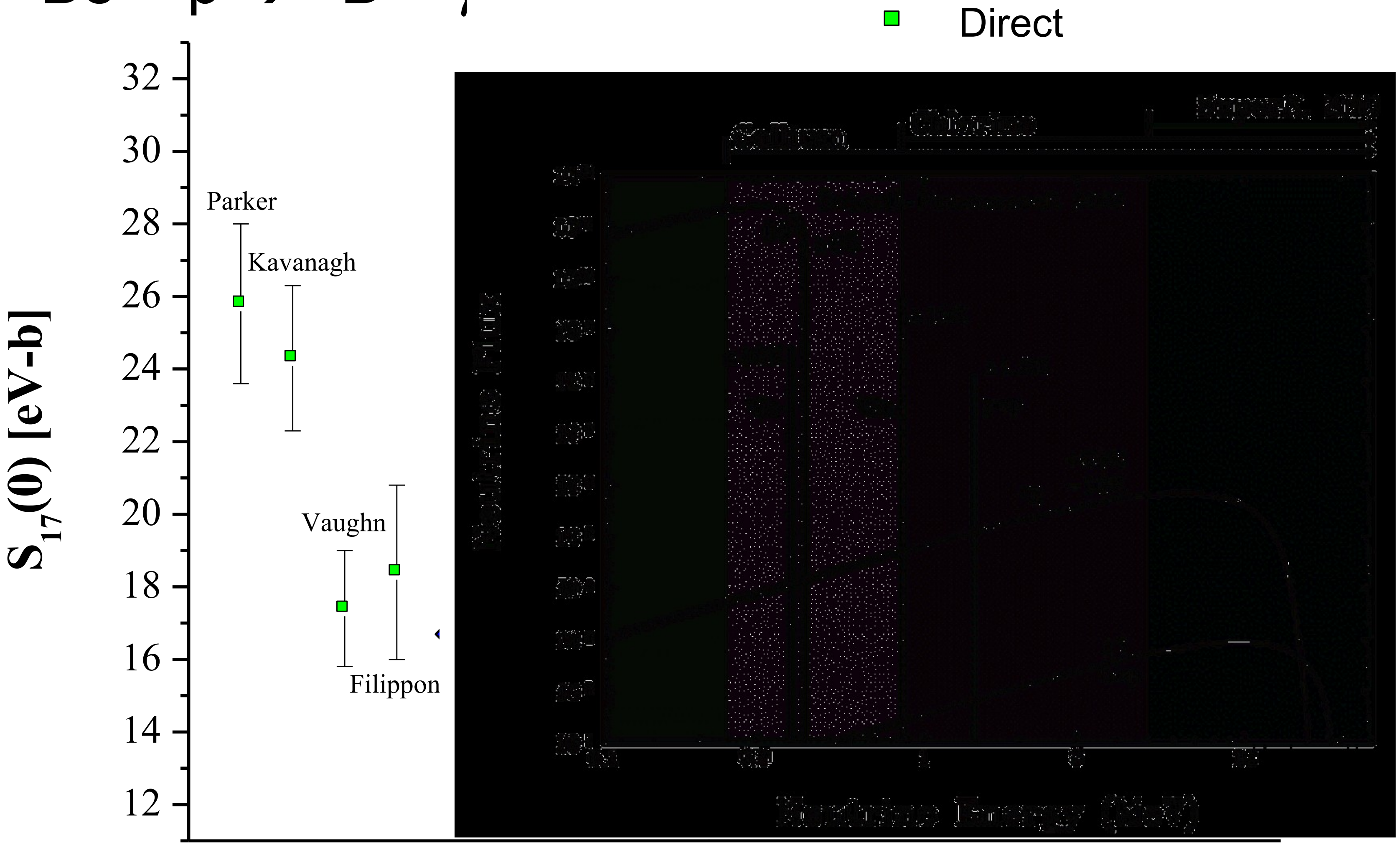
774 *6*, Γ=37 *5* keV, *[ABCEGH]*
γ_0 *774* M1

2320 *30*, 3^+, Γ=350 *40* keV, *[CGH]*, T=1

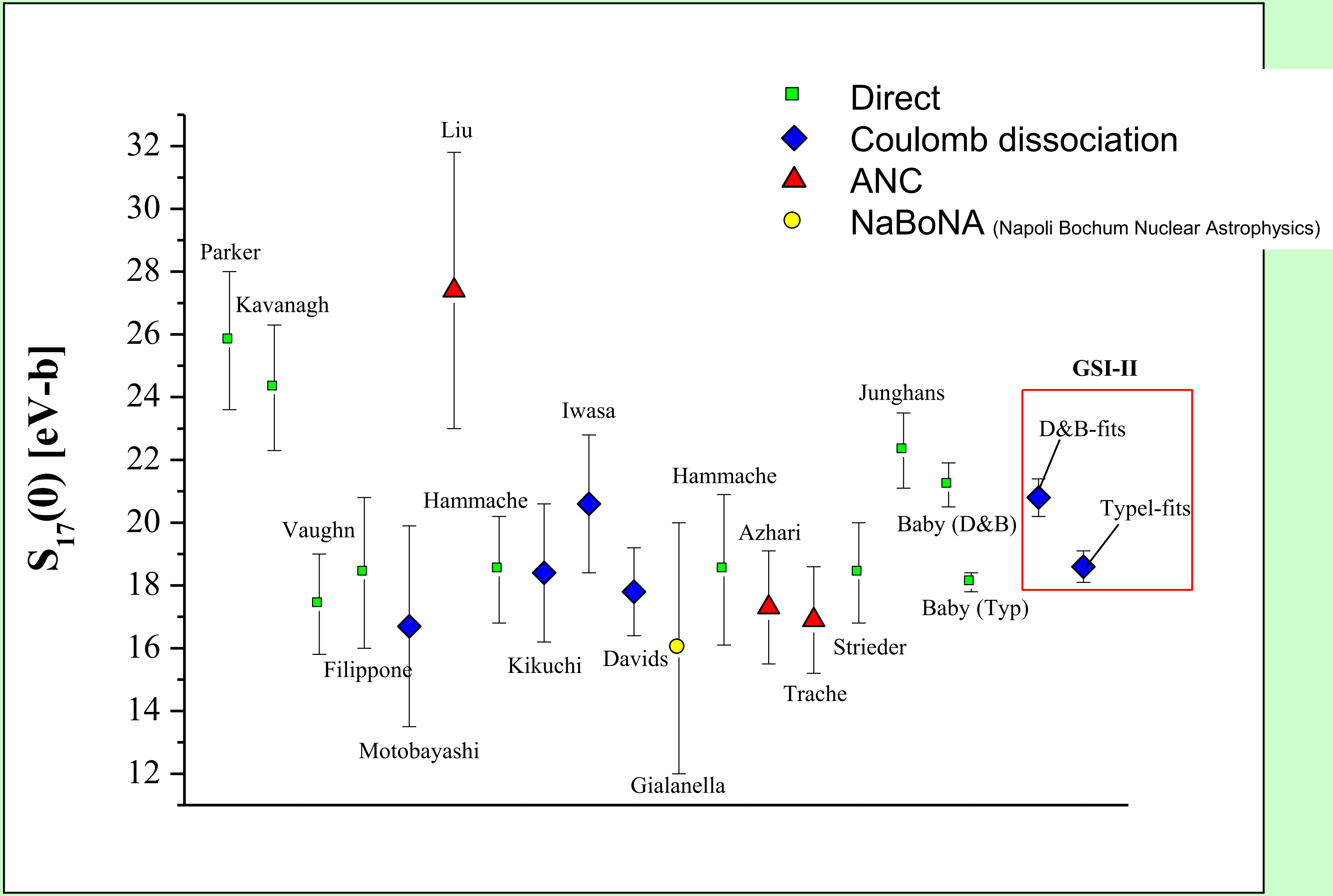
10619 *9*, 0^+, Γ<60 keV, *[H]*, T=2



$^{7}Be + p \rightarrow {}^{8}B + \gamma$



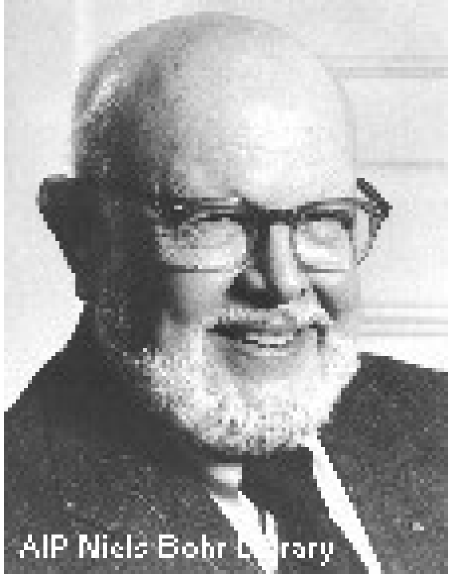
From L. Gialanella @ INFN



From L. Gialanella @ INFN

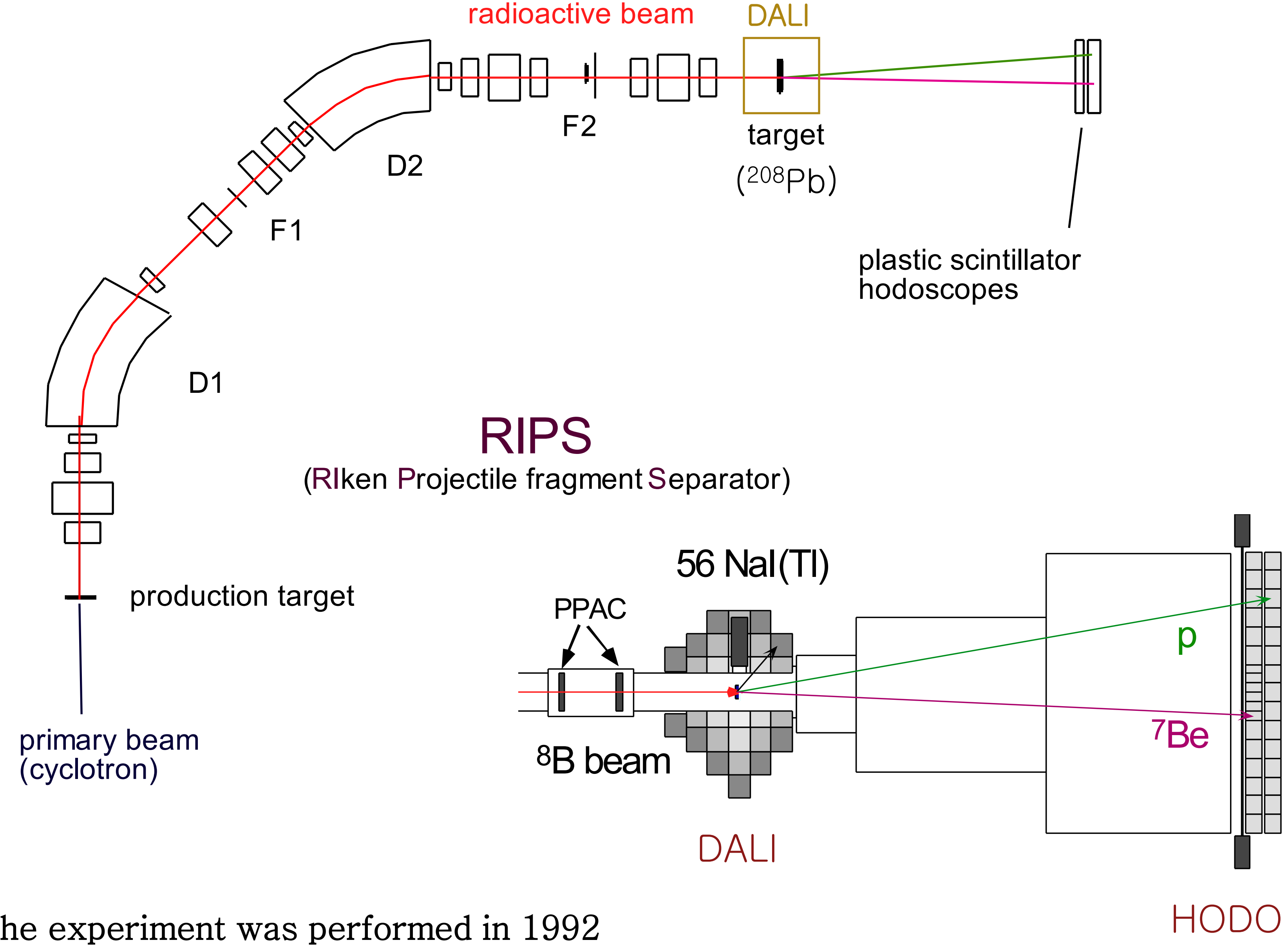
1985 by Fowler (Nobel prize 1983)

- "We stand on the verge of one of those exciting periods which occur in science from time to time. **...**there is an urgent need for data on the properties and interactions of radioactive nuclei **...** for use in nuclear astrophysics."


AIP Niels Bohr Library

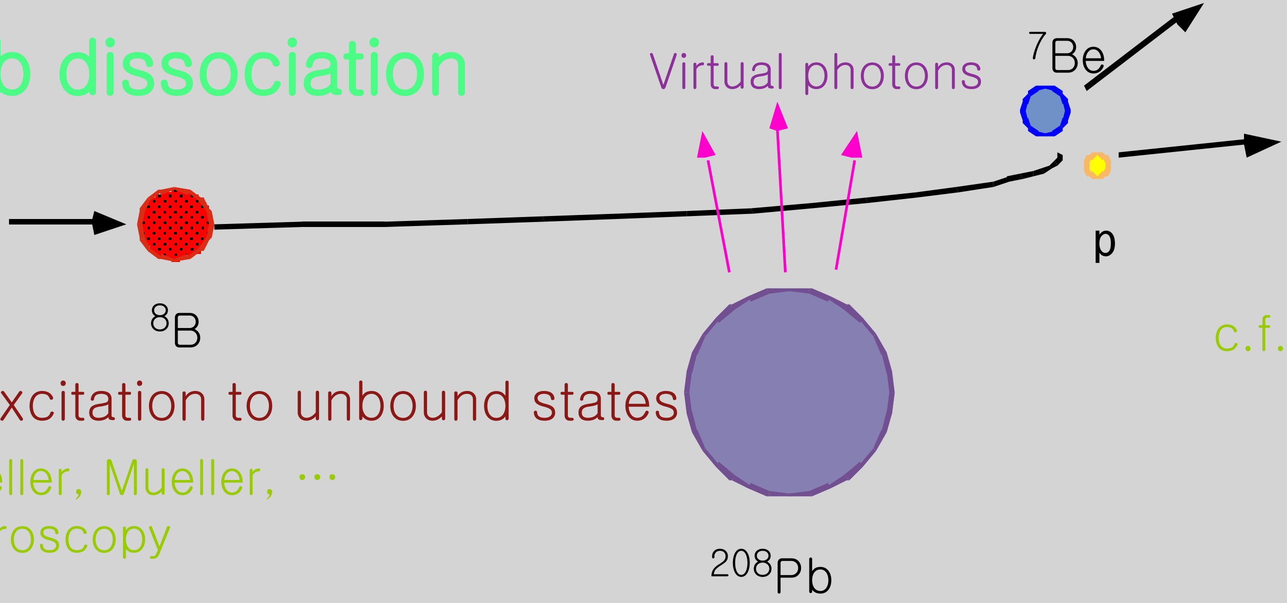
^{8}B Coulomb dissociation

50 – 90 MeV/nucleon



The experiment was performed in 1992

Coulomb dissociation



= Coulomb excitation to unbound states

c.f. Mueller, Mueller, …
spectroscopy

c.f. Nakamura
halo nuclei

$^{8}\mathrm{B}+{}^{208}\mathrm{Pb} \to {}^{7}\mathrm{Be}+\mathrm{p}+{}^{208}\mathrm{Pb}$ (C.D.)

↓ virtual photon theory or DWBA

$^{8}\mathrm{B}(\gamma,\mathrm{p}){}^{7}\mathrm{Be}$ (abs.)

↓ detailed balance

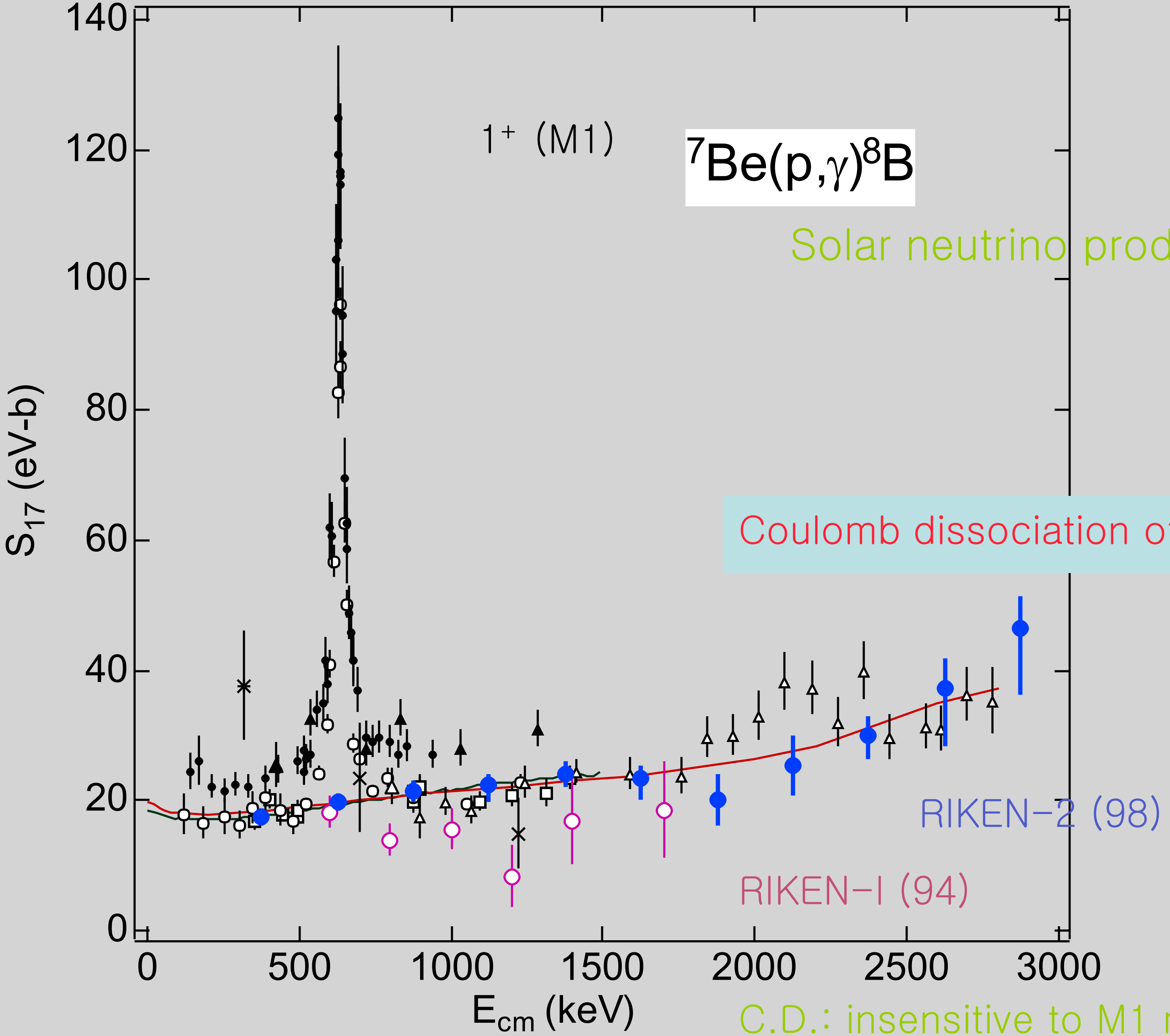
$^{7}\mathrm{Be}(\mathrm{p},\gamma){}^{8}\mathrm{B}$ (capt.)

large σ
thick target (intermediate energy)

experiments with R.I. beams

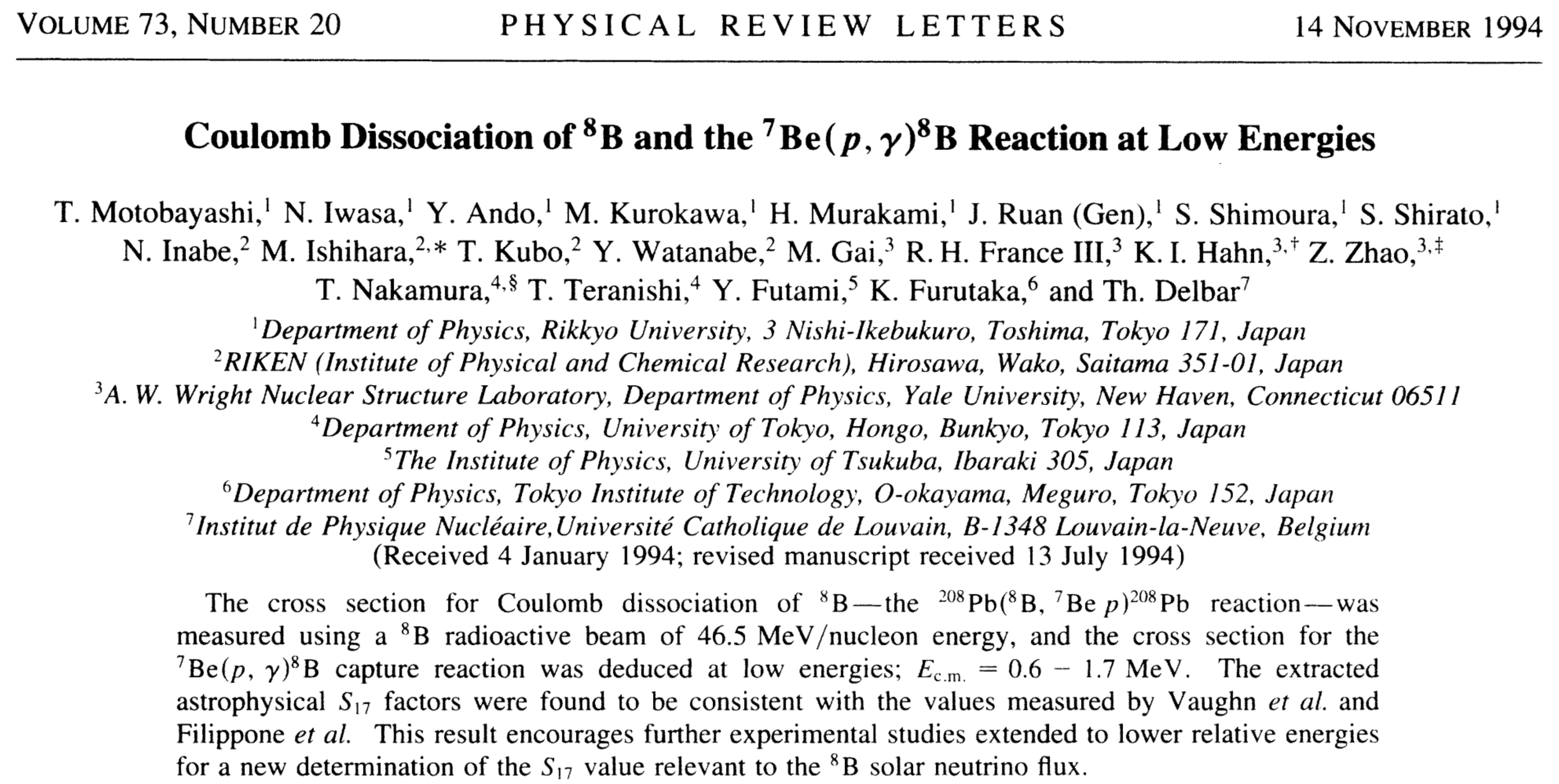
^{7}Be(p,γ)^{8}B

Solar neutrino production



Coulomb dissociation of ^{8}B

C.D.: insensitive to M1 resonance

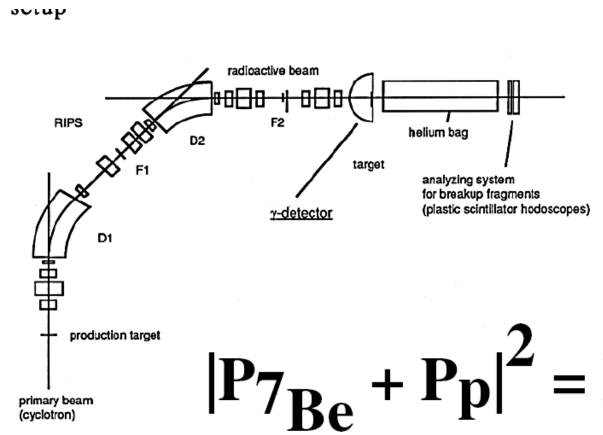


VOLUME 73, NUMBER 20 PHYSICAL REVIEW LETTERS 14 NOVEMBER 1994

Coulomb Dissociation of ^{8}B and the ^{7}Be$(p,\gamma)^8$B Reaction at Low Energies

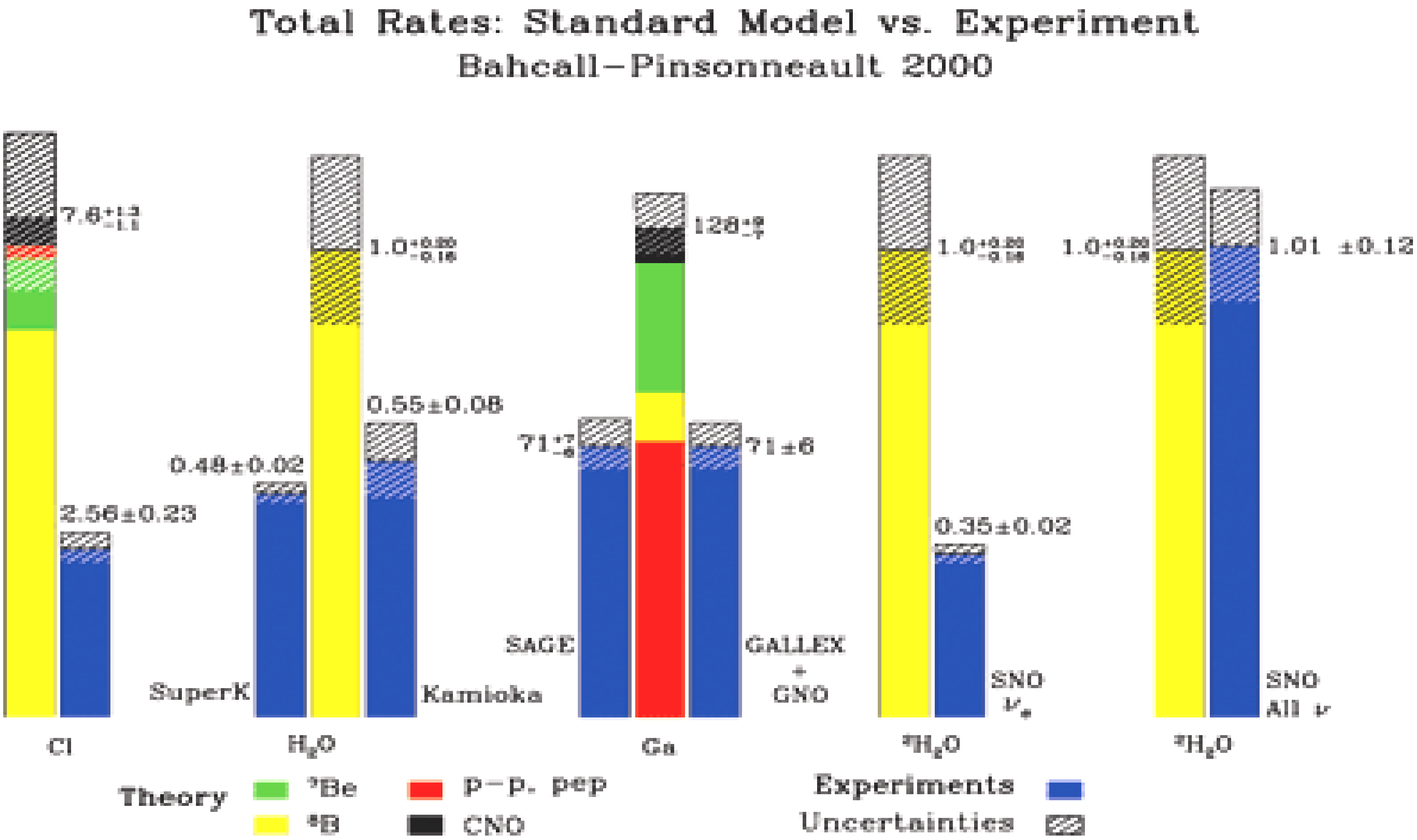
T. Motobayashi,[1] N. Iwasa,[1] Y. Ando,[1] M. Kurokawa,[1] H. Murakami,[1] J. Ruan (Gen),[1] S. Shimoura,[1] S. Shirato,[1]
N. Inabe,[2] M. Ishihara,[2,*] T. Kubo,[2] Y. Watanabe,[2] M. Gai,[3] R. H. France III,[3] K. I. Hahn,[3,†] Z. Zhao,[3,‡]
T. Nakamura,[4,§] T. Teranishi,[4] Y. Futami,[5] K. Furutaka,[6] and Th. Delbar[7]
[1]*Department of Physics, Rikkyo University, 3 Nishi-Ikebukuro, Toshima, Tokyo 171, Japan*
[2]*RIKEN (Institute of Physical and Chemical Research), Hirosawa, Wako, Saitama 351-01, Japan*
[3]*A. W. Wright Nuclear Structure Laboratory, Department of Physics, Yale University, New Haven, Connecticut 06511*
[4]*Department of Physics, University of Tokyo, Hongo, Bunkyo, Tokyo 113, Japan*
[5]*The Institute of Physics, University of Tsukuba, Ibaraki 305, Japan*
[6]*Department of Physics, Tokyo Institute of Technology, O-okayama, Meguro, Tokyo 152, Japan*
[7]*Institut de Physique Nucléaire, Université Catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium*
(Received 4 January 1994; revised manuscript received 13 July 1994)

The cross section for Coulomb dissociation of ^{8}B—the ^{208}Pb(^{8}B, ^{7}Be p)^{208}Pb reaction—was measured using a ^{8}B radioactive beam of 46.5 MeV/nucleon energy, and the cross section for the ^{7}Be$(p,\gamma)^8$B capture reaction was deduced at low energies; $E_{\mathrm{c.m.}} = 0.6 - 1.7$ MeV. The extracted astrophysical S_{17} factors were found to be consistent with the values measured by Vaughn *et al.* and Filippone *et al.* This result encourages further experimental studies extended to lower relative energies for a new determination of the S_{17} value relevant to the ^{8}B solar neutrino flux.



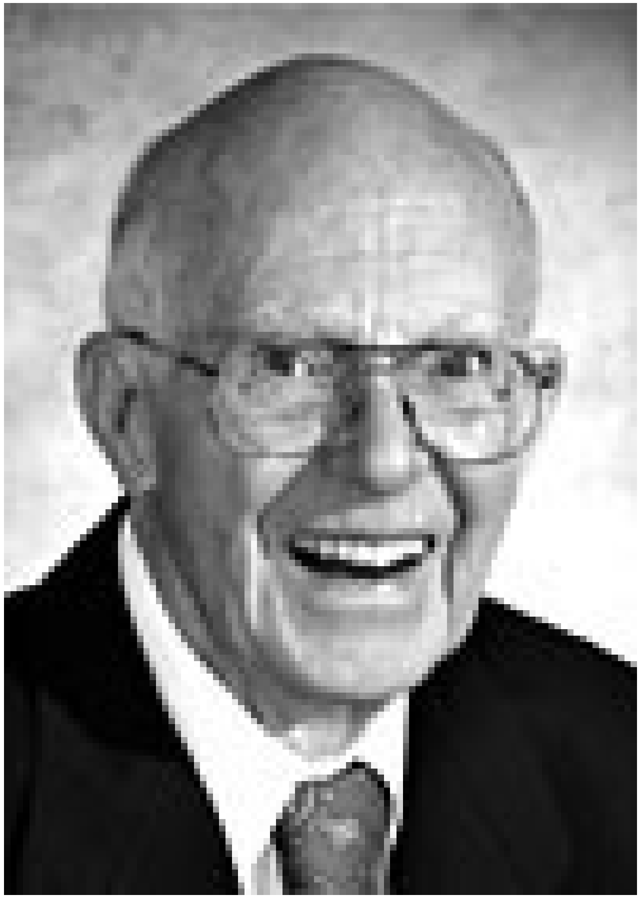
$$|P_{^7\mathrm{Be}} + P_p|^2 = M^2$$

Comparison of results



The Nobel Prize in Physics 2002

"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"



Selected Experiments with RIB

Astrophysically Important Nuclear Reactions

$^{7}\mathrm{Be}(p,\gamma)^{8}\mathrm{B}$

$^{8}\mathrm{Li}(\alpha,n)^{11}\mathrm{B}$

$^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$

$^{14}\mathrm{O}(\alpha,p)^{17}\mathrm{F}$

$^{15}\mathrm{O}(\alpha,\gamma)^{19}\mathrm{Ne}$

$^{17,18}\mathrm{F}(p,\alpha)^{14,15}\mathrm{O}$

$^{25}\mathrm{Al}(p,\gamma)^{26}\mathrm{Si}$

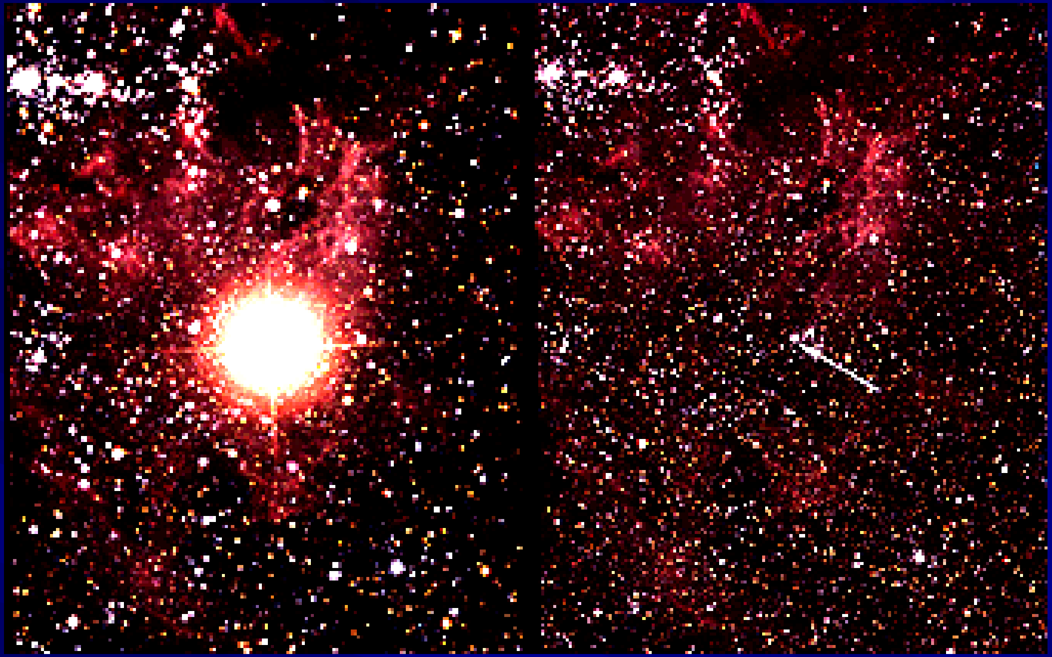
$^{56}\mathrm{Ni}(p,\gamma)^{57}\mathrm{Cu}$

$^{85}\mathrm{Kr}(n,\gamma)^{86}\mathrm{Kr}$

$^{134}\mathrm{Cs}(n,\gamma)^{135}\mathrm{Cs}$

…

Nuclear Astrophysics



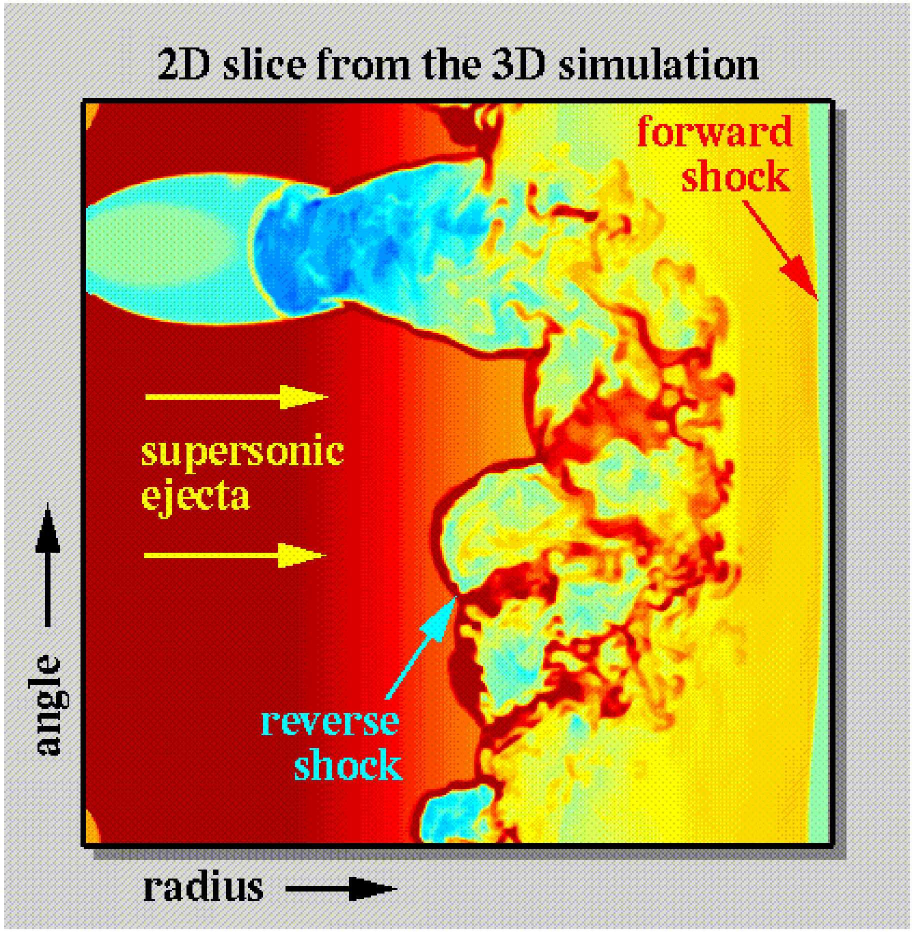
Nuclear reactions in stars

⟹ produce energy

⟹ generate the elements

A Better Set of Models for Explosive Events

- Hydrodynamic Properties
  - Temperature
  - Density
  - Flow
  - Etc.



Requires a Better Understanding of Nuclear Processes

Unstable Isotopes

- Reaction rates
- Excited states
- Decay rates

Bounds of Stability

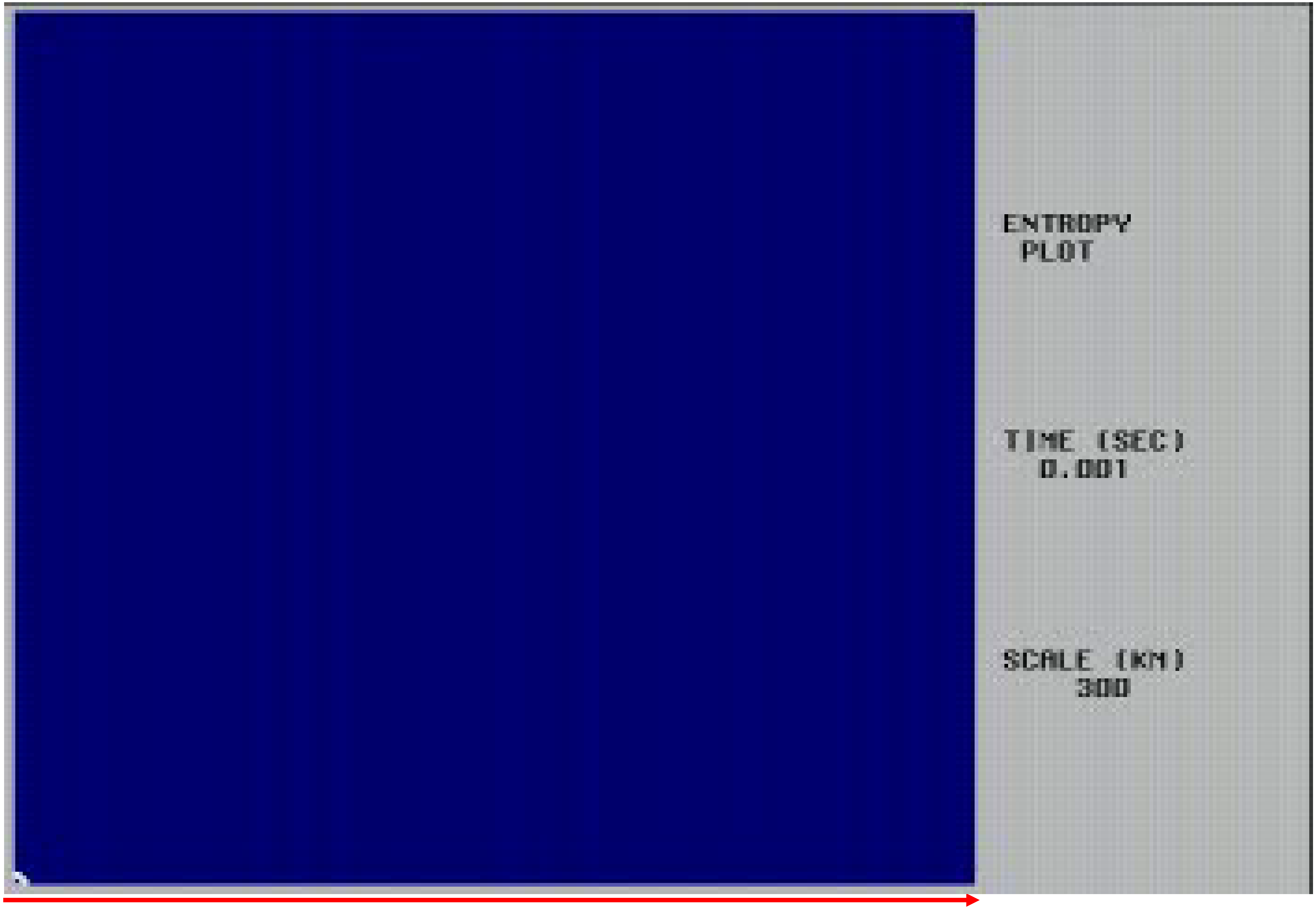
- Proton drip-line
- Neutron drip-line

Understanding Nucleosynthesis & Energy Generation in Explosive Events

To study unstable isotopes we need radioactive beams!

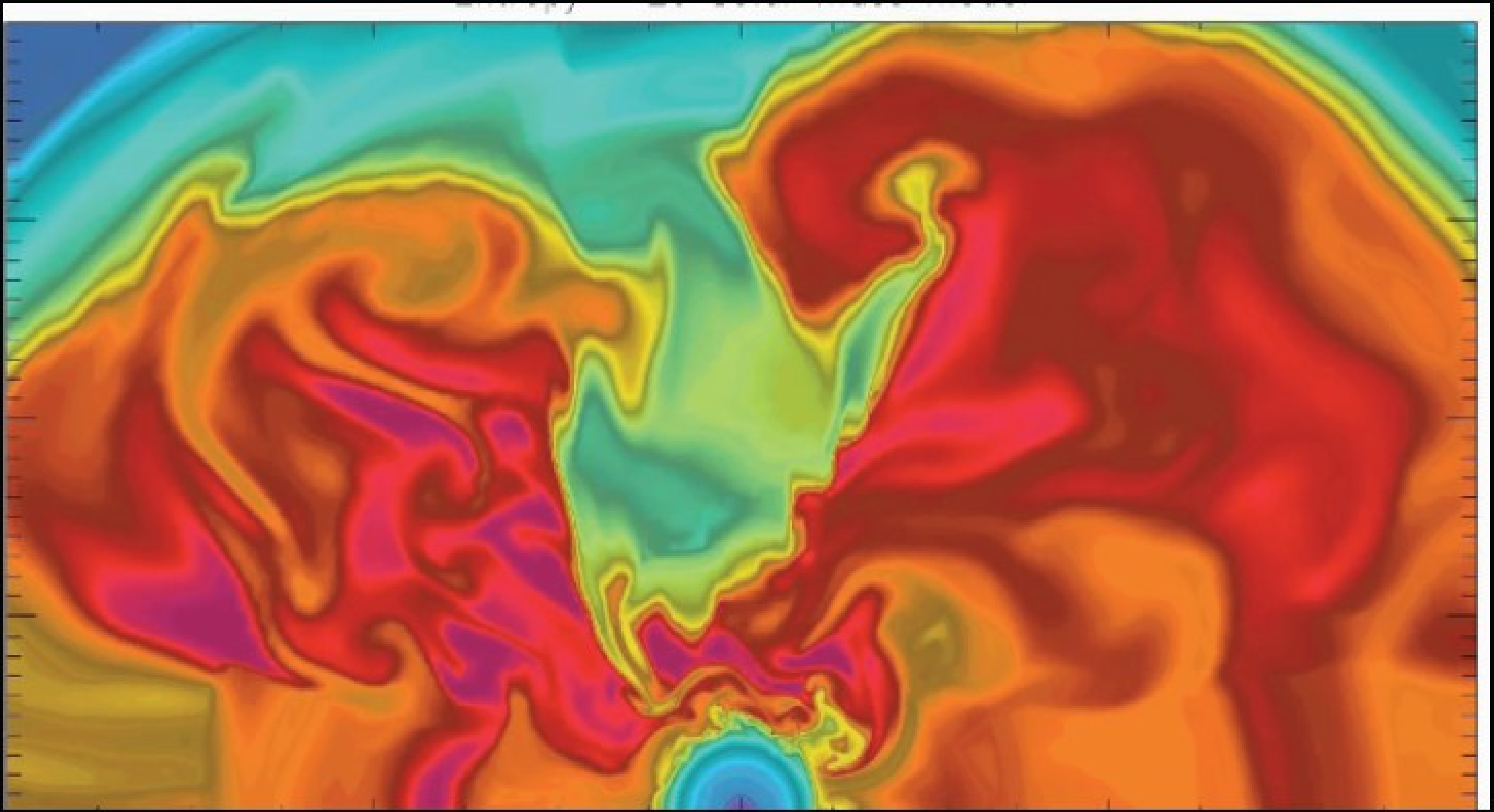
Supernova Simulations

First 300 ms: A. Burrows



→ 10 km

300 km



supernova simulation at ORNL

- supercomputer simulations

Jaguar at ORNL: fastest supercomputer in world
37376 6-core processors for 1.759 petaflops/sec

- supercomputer simulations

SUPERNOVA R-PROCESS

Otsuki, Tagoshi, Kajino & Wanajo
2000, ApJ 533, 424
Wanajo, Kajino, Mathews & Otsuki
2001, ApJ 554, 578

t = 0

Neutrino-driven wind forms right after SN core collapse.

$n + p \longrightarrow n + \alpha$

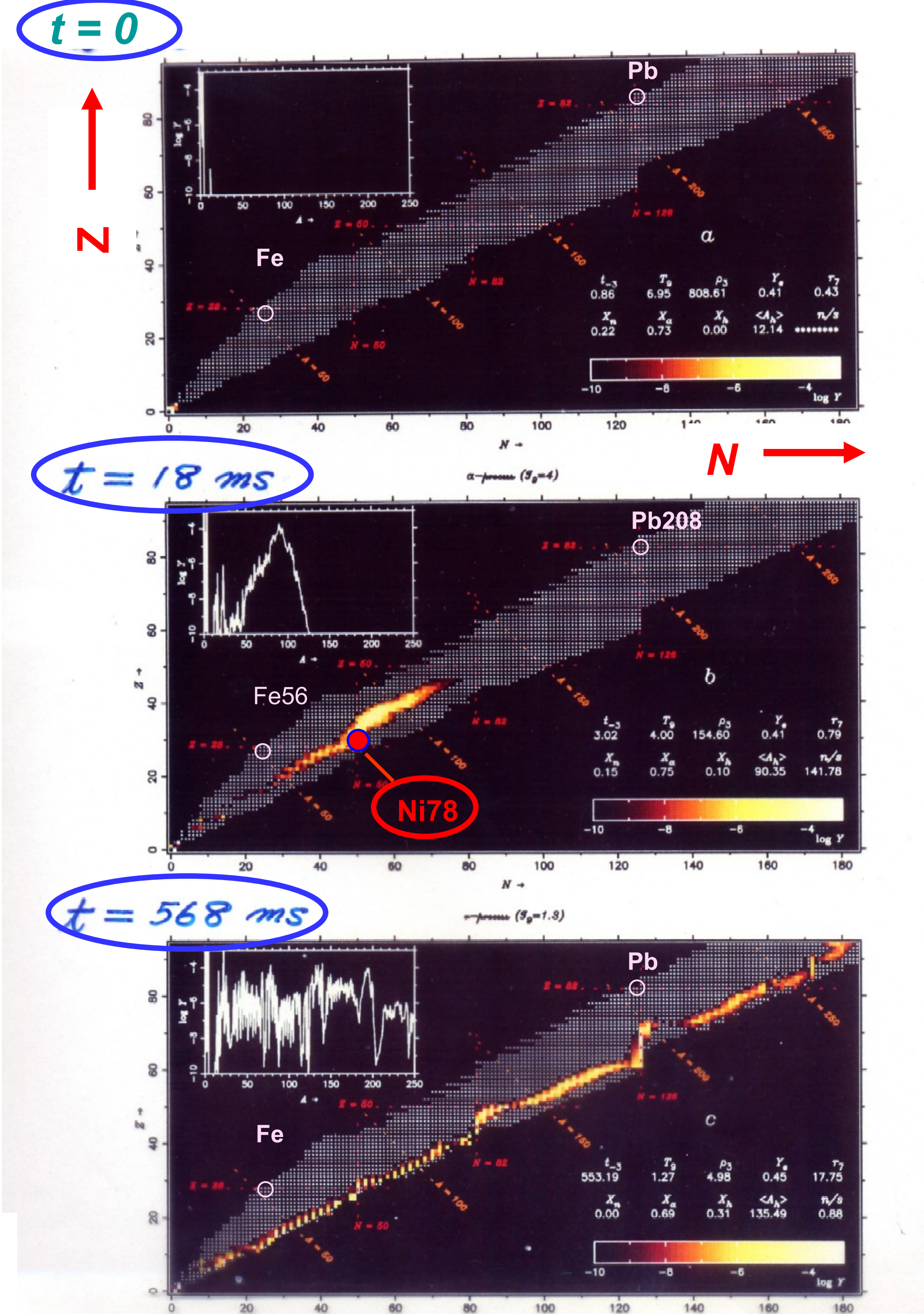
t = 18 ms

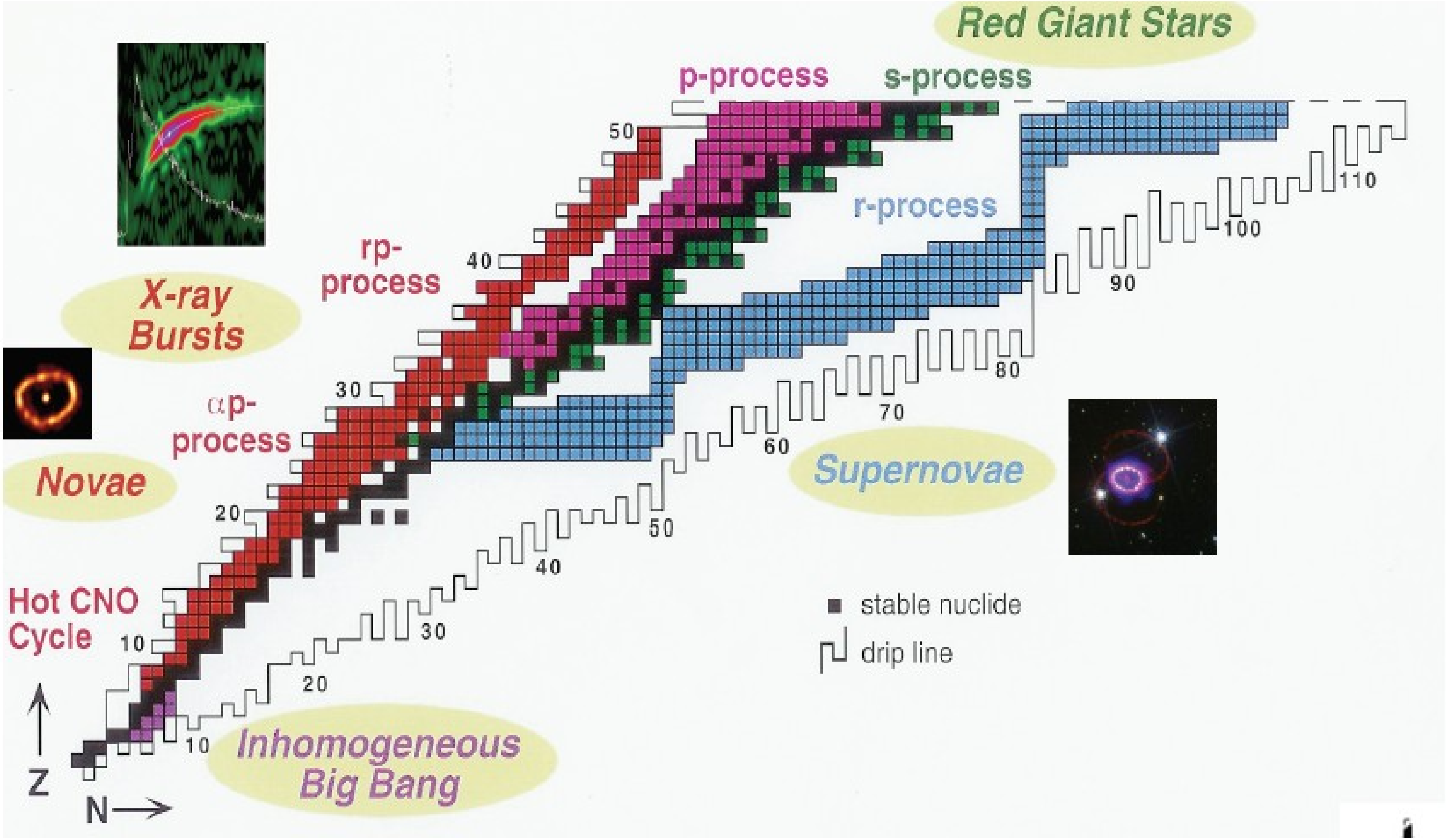
Seeds form.

Exotic neutron-rich ^{78}Ni

t = 568 ms – 1 s

Heavy r-elements synthesize.



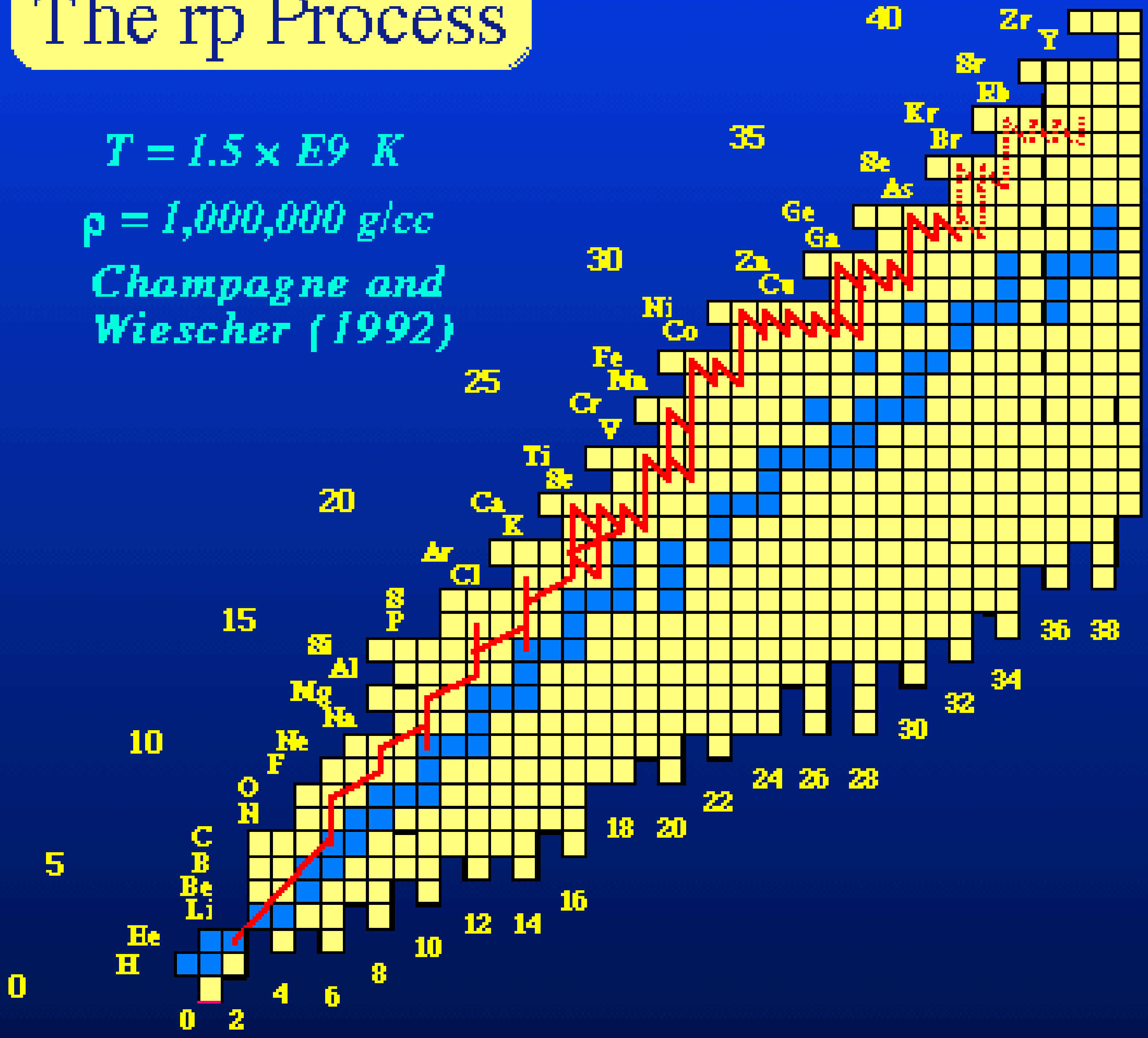

Red Giant Stars
p-process
s-process
r-process
rp-process
X-ray Bursts
αp-process
Novae
Hot CNO Cycle
Supernovae
Inhomogeneous Big Bang
■ stable nuclide
drip line
Z
N
10
20
30
40
50
10
20
30
40
50
60
70
80
90
100
110

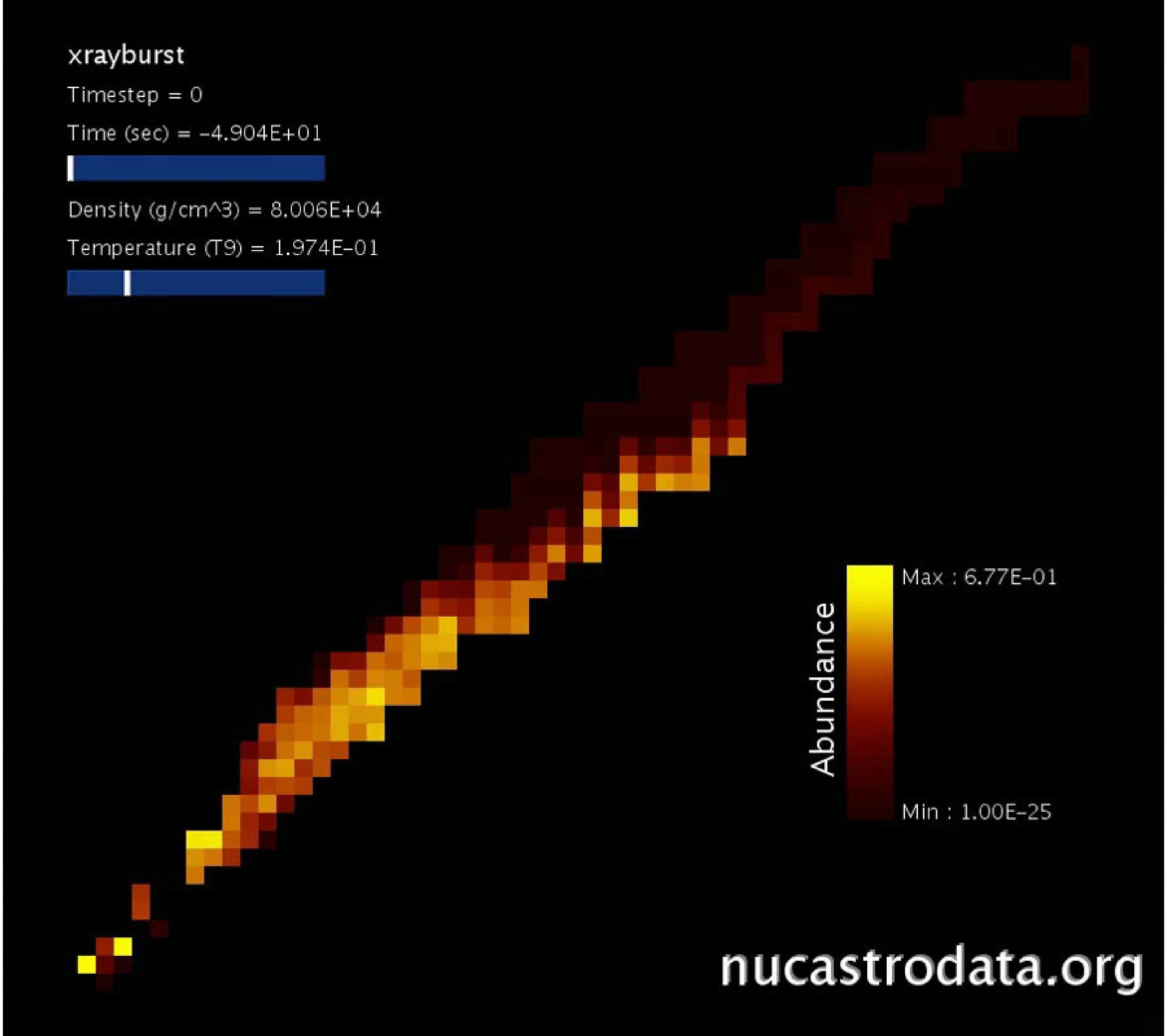
The rp Process

$T = 1.5 \times E9\ K$

$\rho = 1{,}000{,}000$ g/cc

Champagne and Wiescher (1992)





xrayburst

Timestep = 0

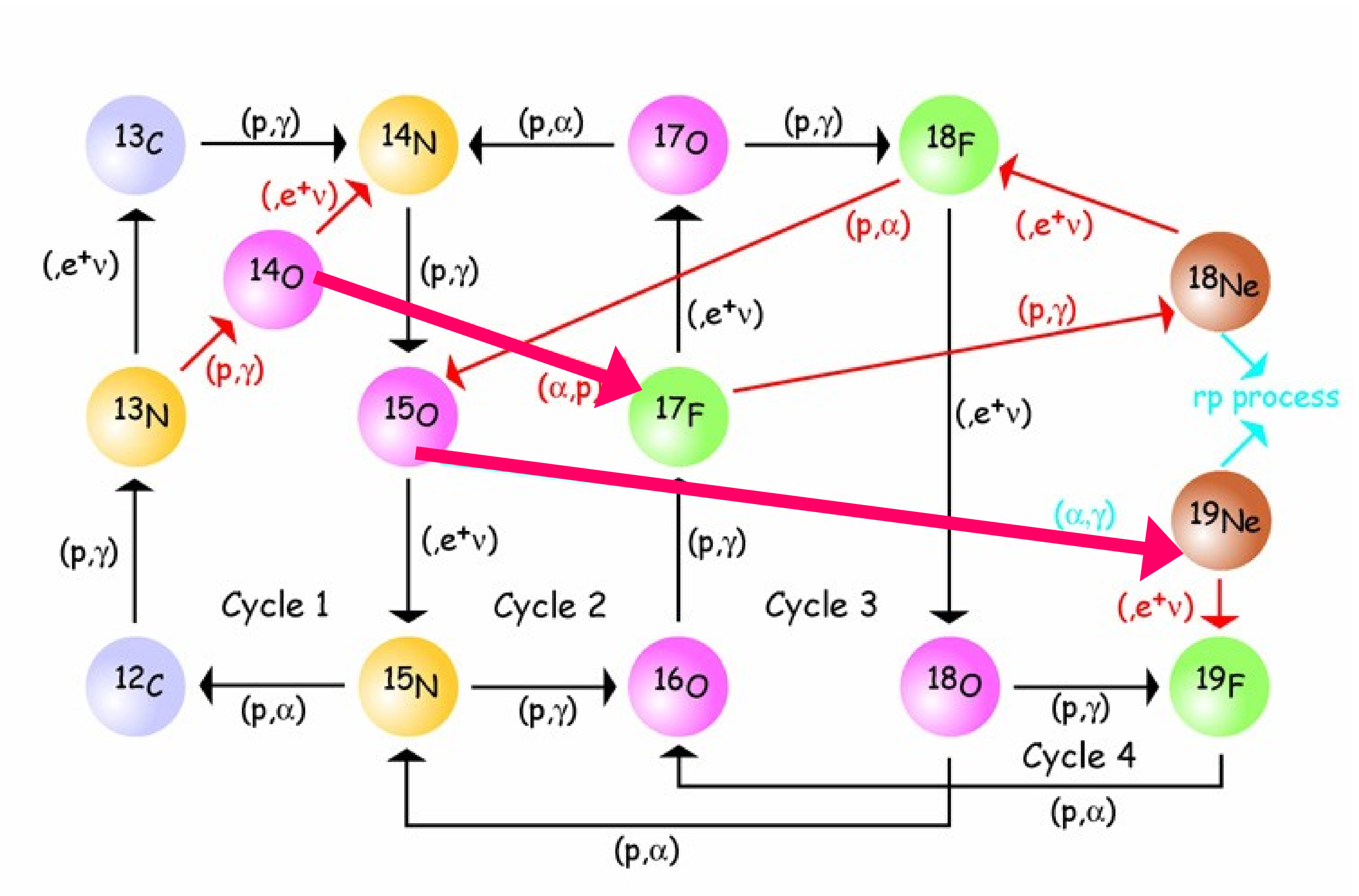
Time (sec) = -4.904E+01

Density (g/cm^3) = 8.006E+04

Temperature (T9) = 1.974E-01

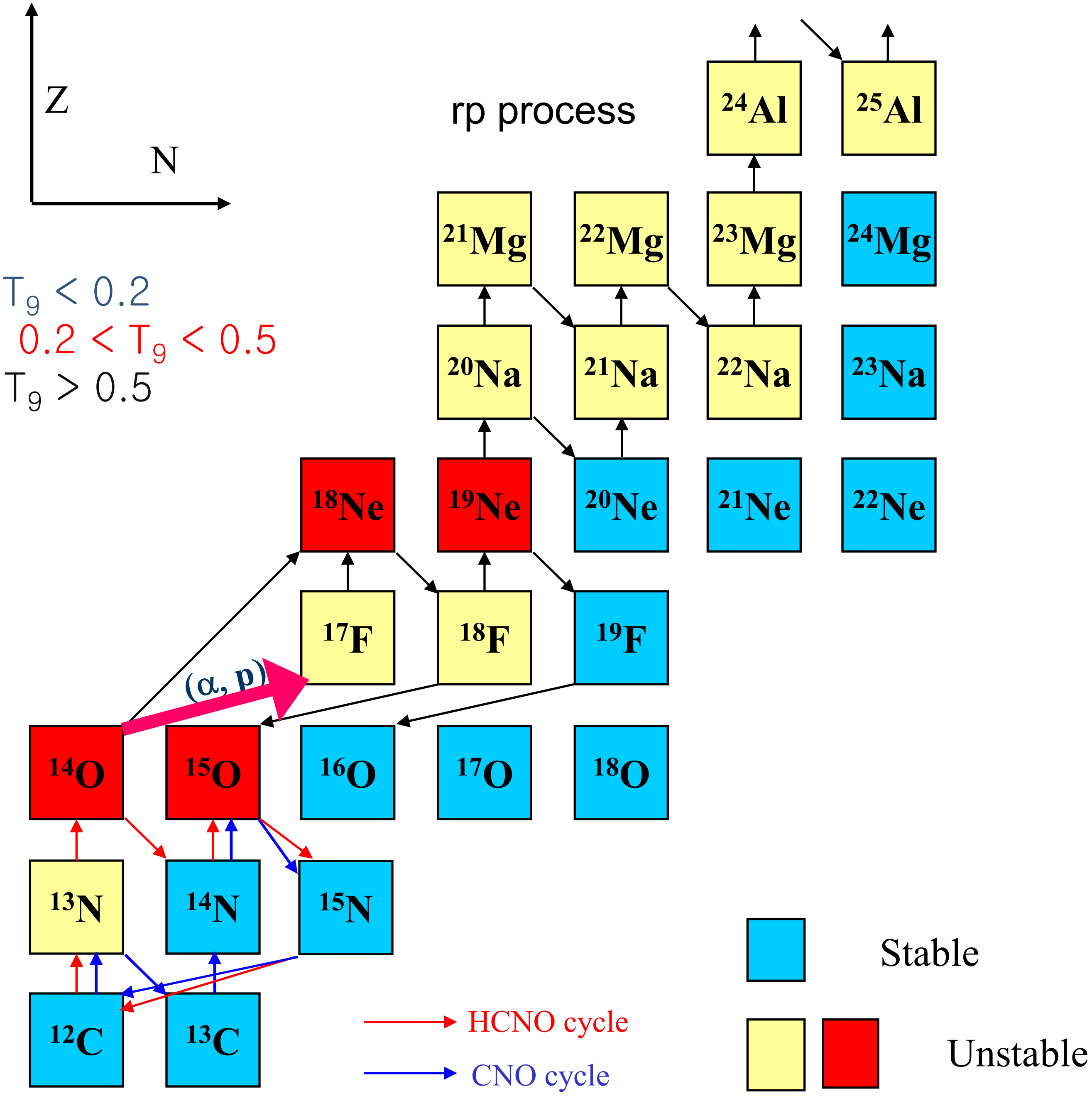
nucastrodata.org

X-ray burst and novae

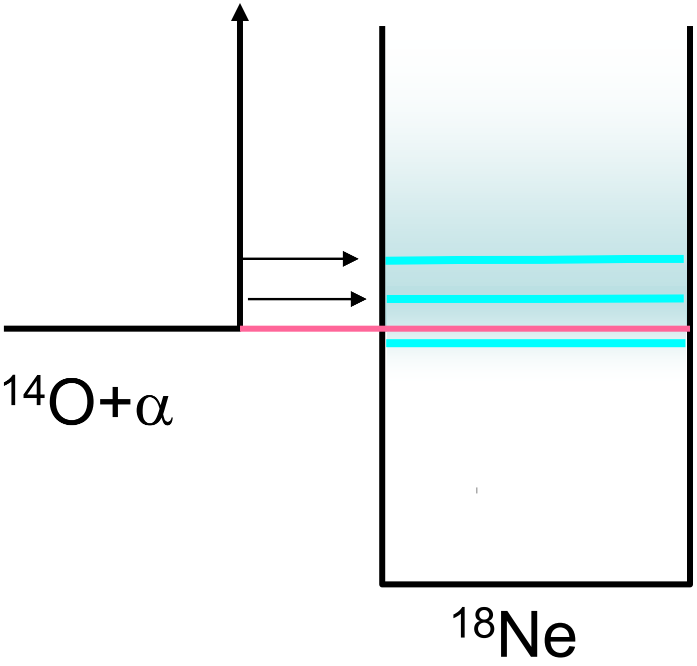


CNO: T9 < 0.2 Hot CNO: 0.2 < T9 < 0.5 rp process: T9 > 0.5

CNO cycle : $T_9 < 0.2$
HCNO cycle: $0.2 < T_9 < 0.5$
rp process : $T_9 > 0.5$

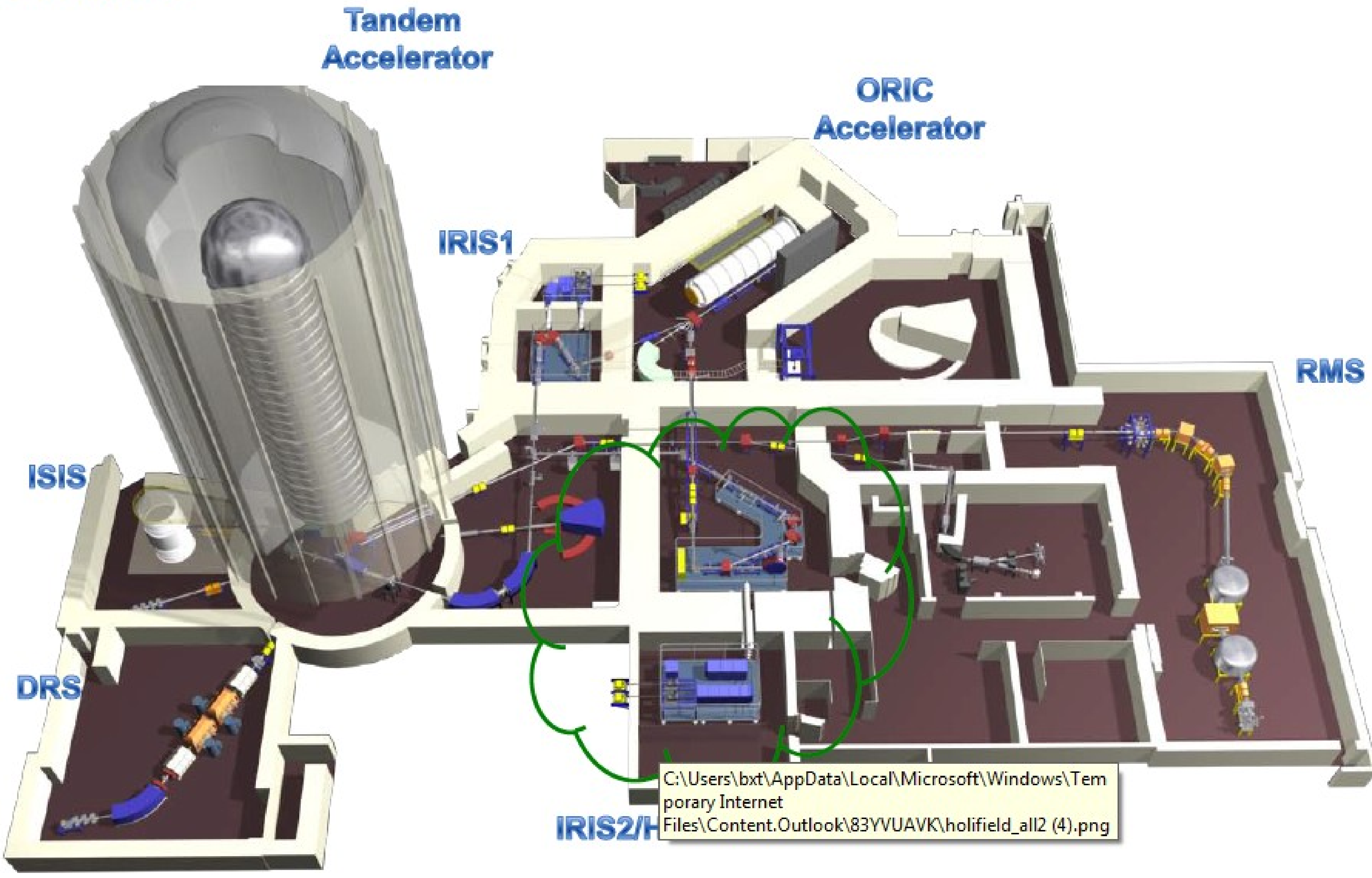


Break-out: $^{14}O(\alpha,p)$



$^{14}O(\alpha,p)^{17}F$ $^{17}F(p,\alpha)^{14}O$ $^{17}F(p,p)^{17}F$

HRIBF



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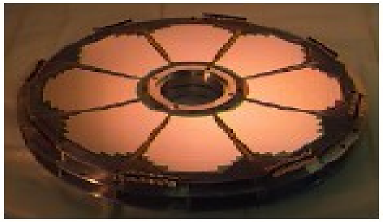
HRIBF Silicon Detector Array (SIDAR)

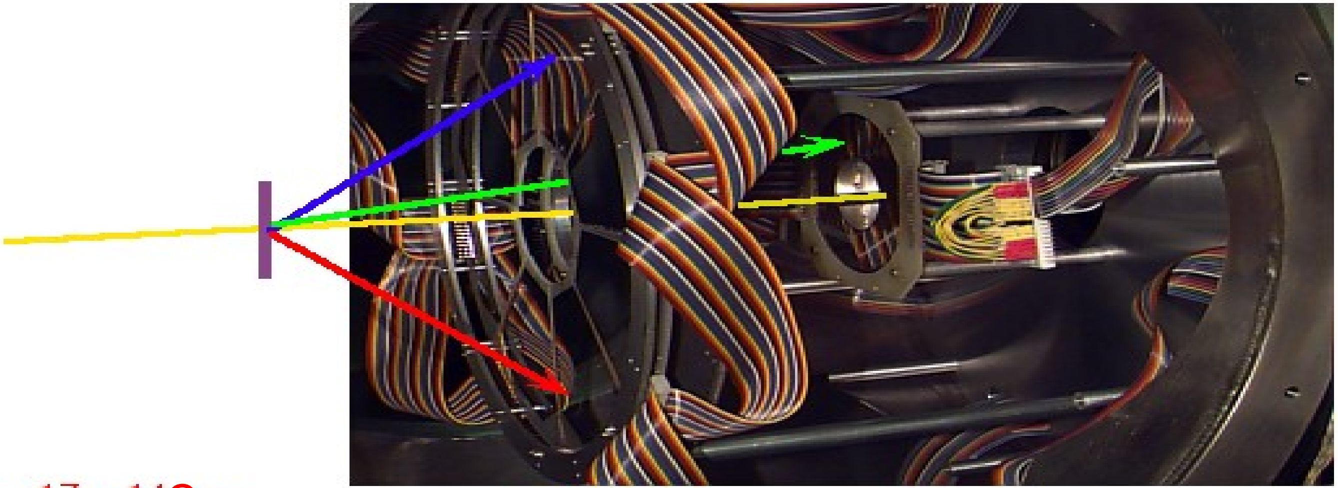
Utilization

- *measure crucial resonance parameters $^{17}F(p,p)$ ...*
- *directly measure astrophysical reactions $^{18}F(p,\alpha)$ ...*



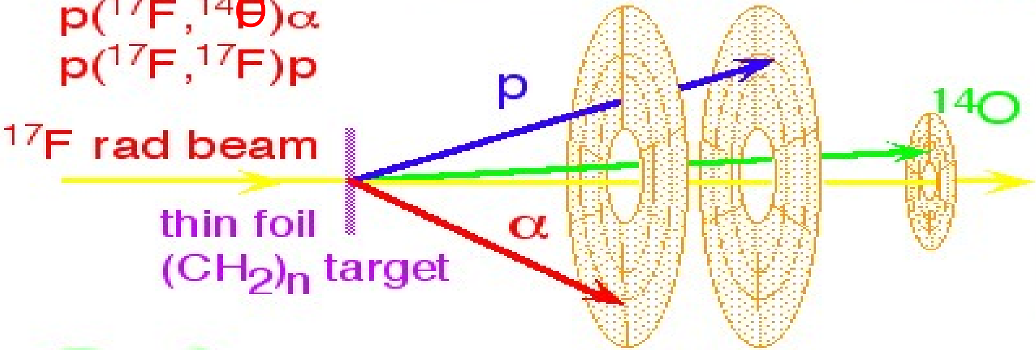
Specifications

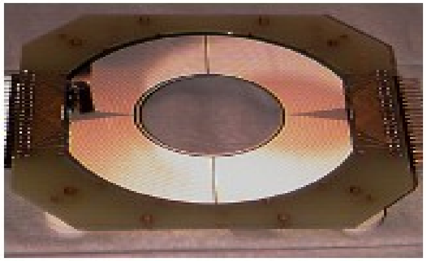
- *3 arrays of 128, 128, and 64 Si strip detectors*
- *stacked detectors ⇒ particle ID*



$p(^{17}F,^{14}O)\alpha$

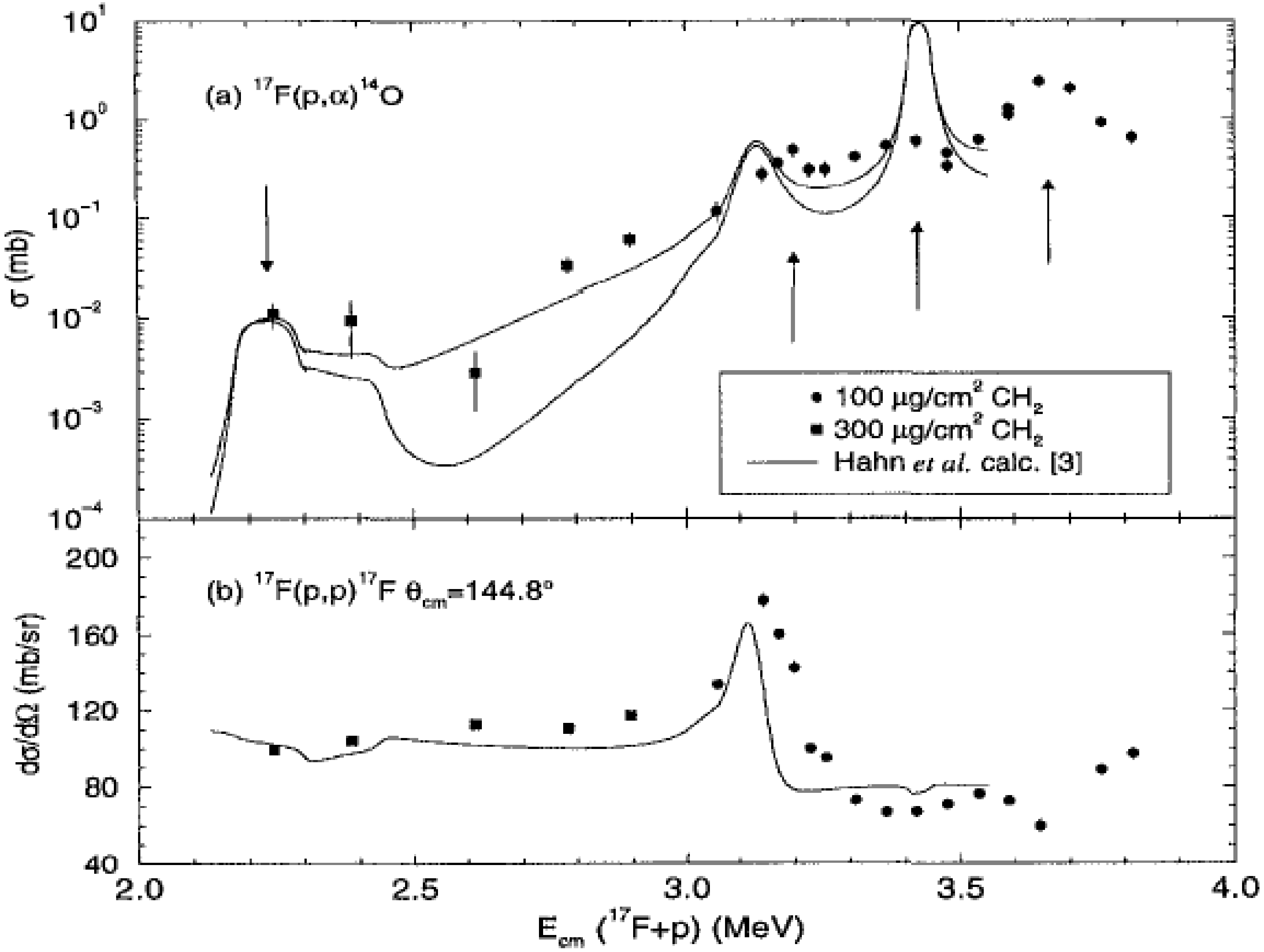
$p(^{17}F,^{17}F)p$





Performance

- ***Completed RIB experiments: $^{17,18}F(p,p)$, $^{17,18}F(p,\alpha)$, $^{17}F(p,p')$***
- ***High Energy Resolution, Low Backgrounds***

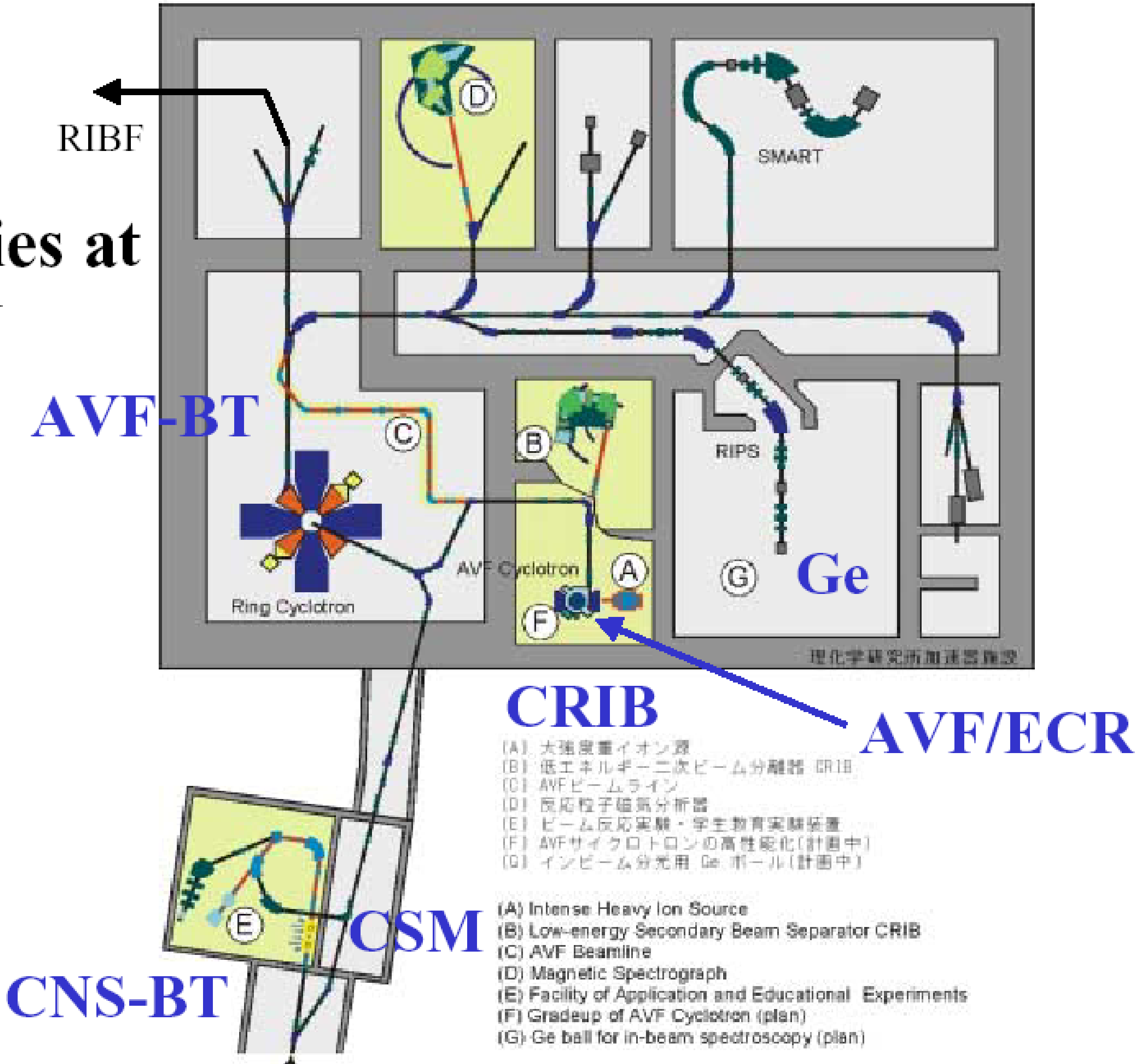


Blackmon et al. @Oak Ridge

일본 이화학연구소 가속기 시설

CNS Facilities at RIKEN

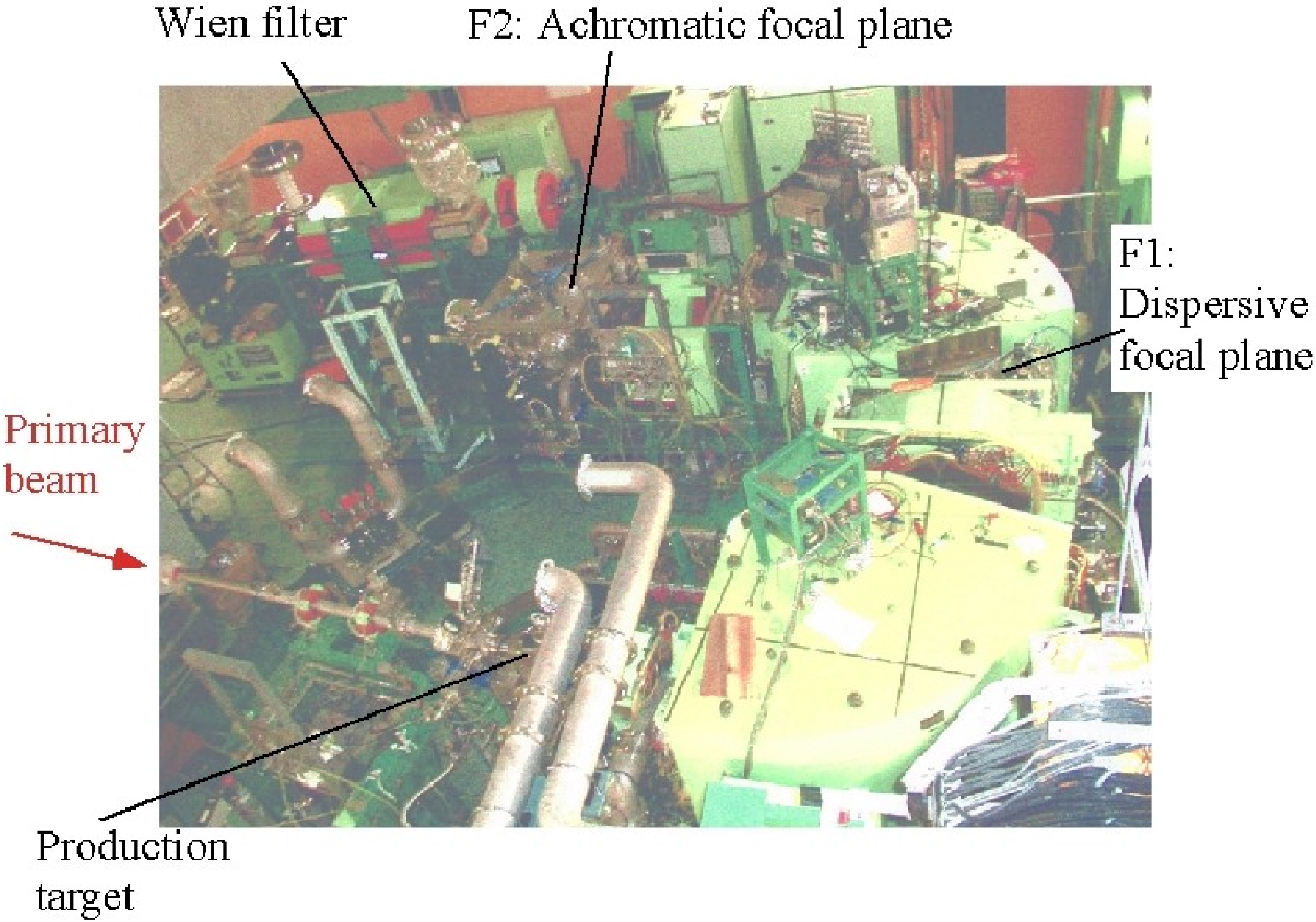
(Under CNS-RIKEN joint venture)



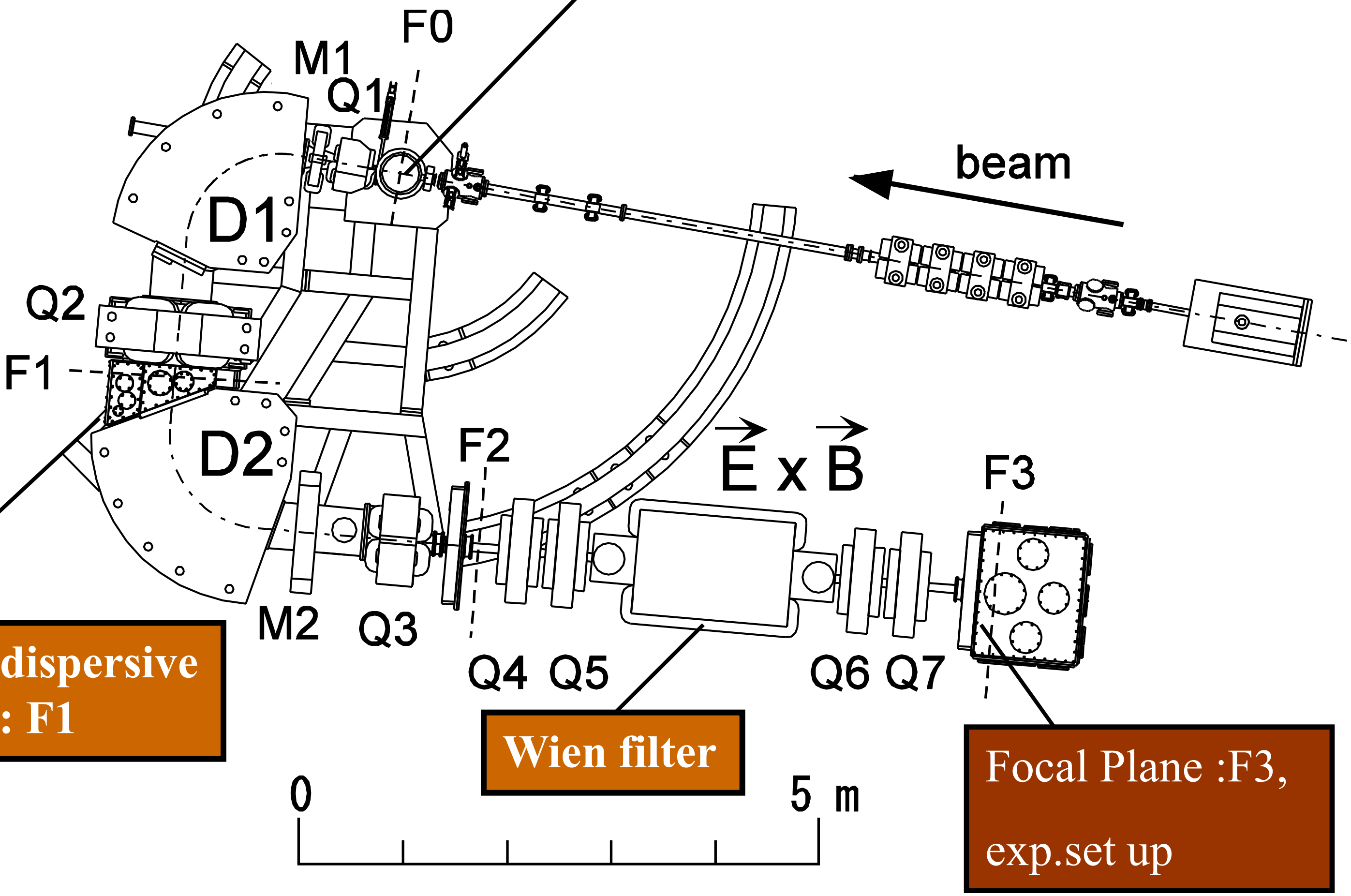
(A) 大強度重イオン源
(B) 低エネルギー二次ビーム分離器 CRIB
(C) AVFビームライン
(D) 反応粒子磁気分析器
(E) ビーム反応実験・学生教育実験装置
(F) AVFサイクロトロンの高性能化（計画中）
(G) インビーム分光用 Ge ボール（計画中）

(A) Intense Heavy Ion Source
(B) Low-energy Secondary Beam Separator CRIB
(C) AVF Beamline
(D) Magnetic Spectrograph
(E) Facility of Application and Educational Experiments
(F) Gradeup of AVF Cyclotron (plan)
(G) Ge ball for in-beam spectroscopy (plan)

CNS RIB Separator (CRIB)



Experiment: June 25~July 1, 2008



Production Target : F0

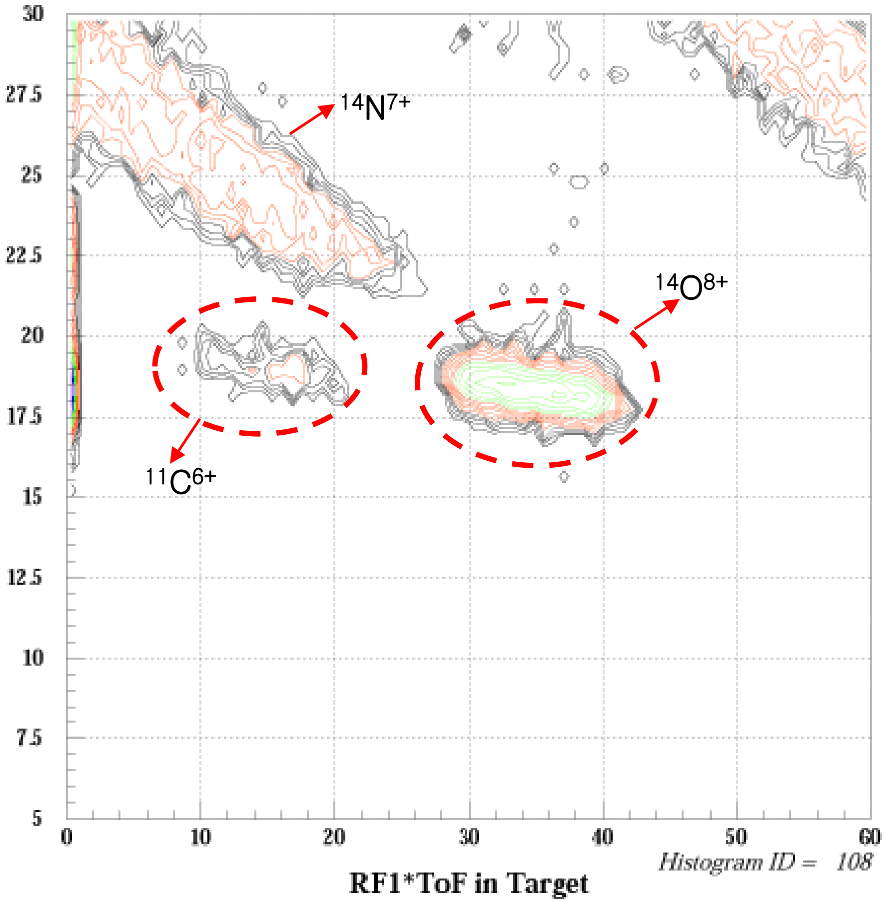
Momentum dispersive
Focal Plane : F1

Wien filter

Focal Plane :F3,

exp.set up

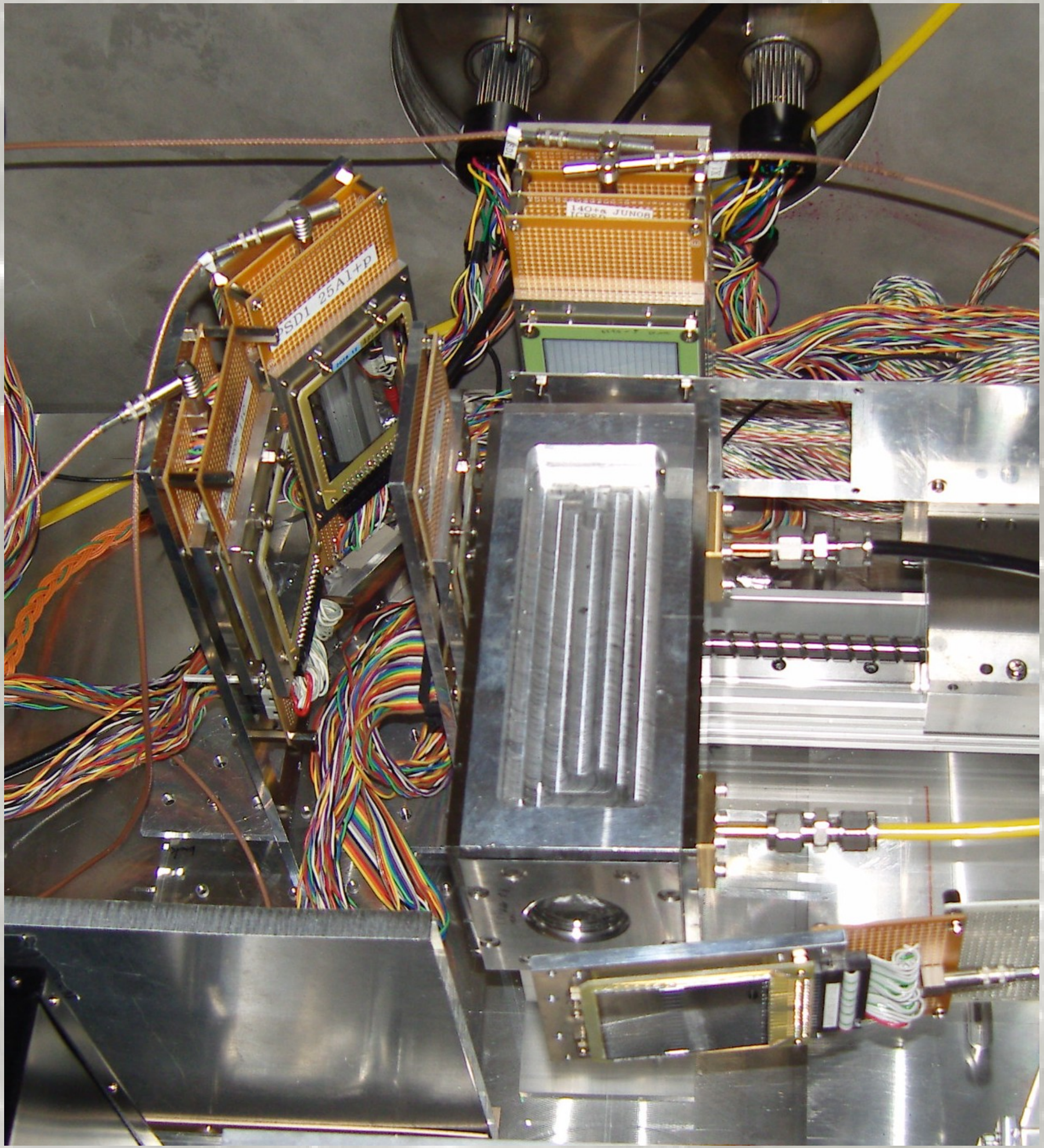
Separation of secondary beam



Two dimensional plot of
RF1 vs TOF at F3

^{14}O beam was distinguished very cleanly.

He target & Detectors



Aram Kim @ Ewha, Ph.D. Thesis (2010)

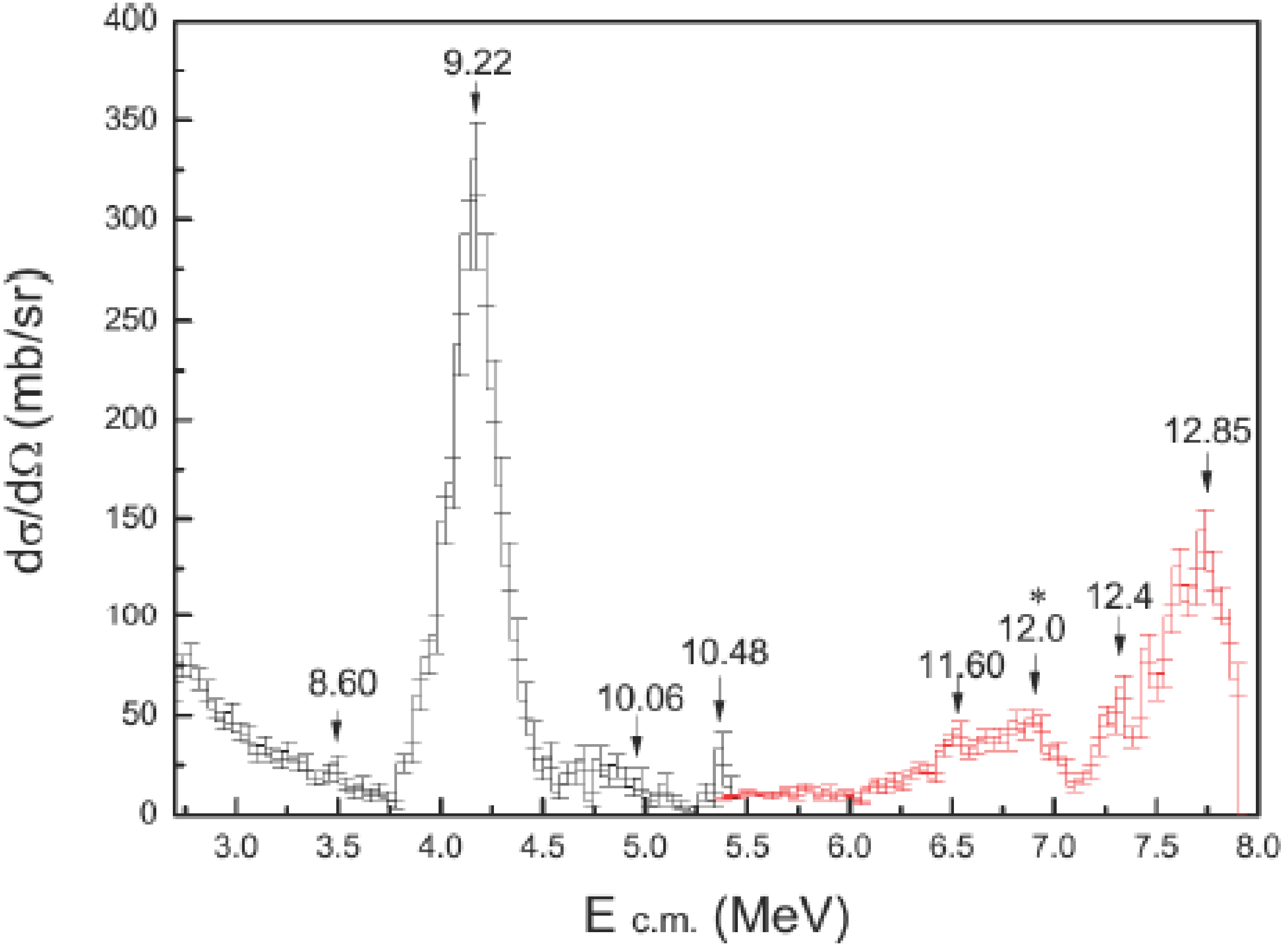
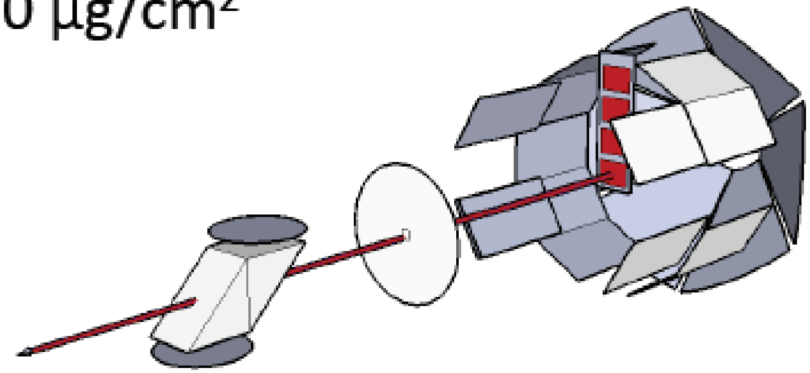


Fig. 5. (Color online) Excitation function of the $^{14}O(\alpha,\alpha)^{14}O$ reaction at the 0 degrees telescope. The level marked by $*$ has not been seen before.

First results for a recent ^{10}Be(d,p) experiment in inverse kinematics

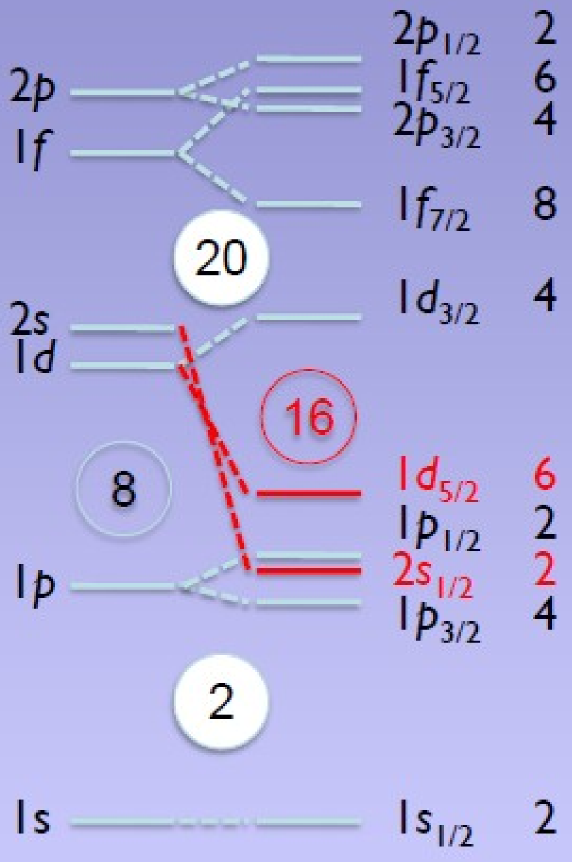
Experimental Tools: ^{10}Be Batch Mode Beam and CD_2 Targets

- Long-lived, mass-separated ^{10}Be purchased in solution from Y-12
- Accelerated from a sputter source as beryllium oxide, oxygen dissociated at upper terminal
- Post stripping to remove ^{10}B contaminants
- 107 MeV (V_T = 24.4 MV) and 60 MeV (V_T = 17.7 MV) beams
- Self-supporting CD_2, 100 – 300 μg/cm^2



^{11}Be - Background

- Both bound states are single neutron halo states
  - Very weakly bound: S_n = 504 keV, 184 keV
  - Small angular momentum: ℓ = 0,1
- Level inversion: $2s_{1/2}$ intruder ground state
- Breakdown of the N=8 magic number



Revised rates for the stellar triple-α process from measurement of ^{12}C nuclear resonances

Hans O. U. Fynbo[1], Christian Aa. Diget[1], Uffe C. Bergmann[2], Maria J. G. Borge[3], Joakim Cederkäll[2], Peter Dendooven[4], Luis M. Fraile[2], Serge Franchoo[2], Valentin N. Fedosseev[2], Brian R. Fulton[5], Wenxue Huang[6], Jussi Huikari[6], Henrik B. Jeppesen[1], Ari S. Jokinen[6,7], Peter Jones[6], Björn Jonson[8], Ulli Köster[2], Karlheinz Langanke[1], Mikael Meister[8], Thomas Nilsson[2], Göran Nyman[8], Yolanda Prezado[3], Karsten Riisager[1], Sami Rinta-Antila[6], Olof Tengblad[3], Manuela Turrion[3], Youbao Wang[6], Leonid Weissman[2], Katarina Wilhelmsen[8], Juha Äystö[6,7] & The ISOLDE Collaboration[2]

[1] *Department of Physics and Astronomy, University of Aarhus, 8000 Århus C, Denmark*
[2] *CERN, CH-1211 Geneva 23, Switzerland*
[3] *Instituto Estructura de la Materia, CSIC, Serrano 113bis, E-28006, Madrid, Spain*
[4] *KVI, Zernikelaan, 9747 AA Groningen, The Netherlands*
[5] *Department of Physics, University of York, Heslington, YO10 5DD, UK*
[6] *Department of Physics, University of Jyväskylä, FIN-40351 Jyväskylä, Finland*
[7] *Helsinki Institute of Physics, FIN-00014 University of Helsinki, Finland*
[8] *Experimental Physics, Chalmers University of Technology and Göteborg University, S-41296 Göteborg, Sweden*

In the centres of stars where the temperature is high enough, three α-particles (helium nuclei) are able to combine to form ^{12}C because of a resonant reaction leading to a nuclear excited state[1]. (Stars with masses greater than ~0.5 times that of the Sun will at some point in their lives have a central temperature high enough for this reaction to proceed.) Although the reaction rate is of critical significance for determining elemental abundances in the

Publishing Group

Impact of recent publications

Short-lived tin is doubly magic

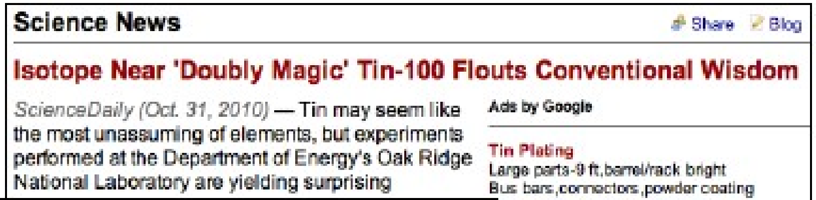
May 27, 2010 7 comments

Researchers in the US and UK have confirmed that a short-lived isotope of tin is the latest member in an exclusive club of "doubly magic" nuclei, a nuclear equivalent to the noble gases. This is only the seventh of these rigidly

qualities meas ured. And the

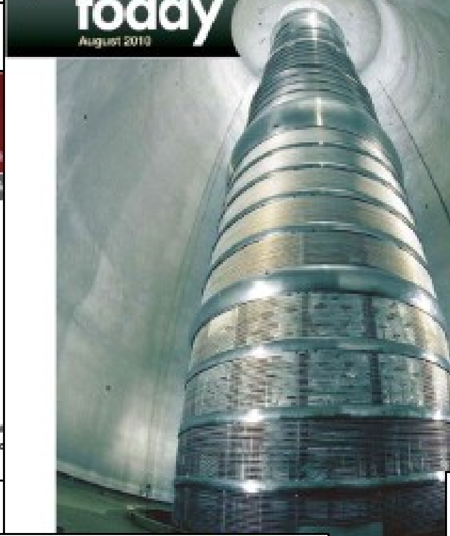
heavy elements are created

stars.



Isotope Near 'Doubly Magic' Tin-100 Flouts Conventional Wisdom

ScienceDaily (Oct. 31, 2010) — Tin may seem like the most unassuming of elements, but experiments performed at the Department of Energy's Oak Ridge National Laboratory are yielding surprising



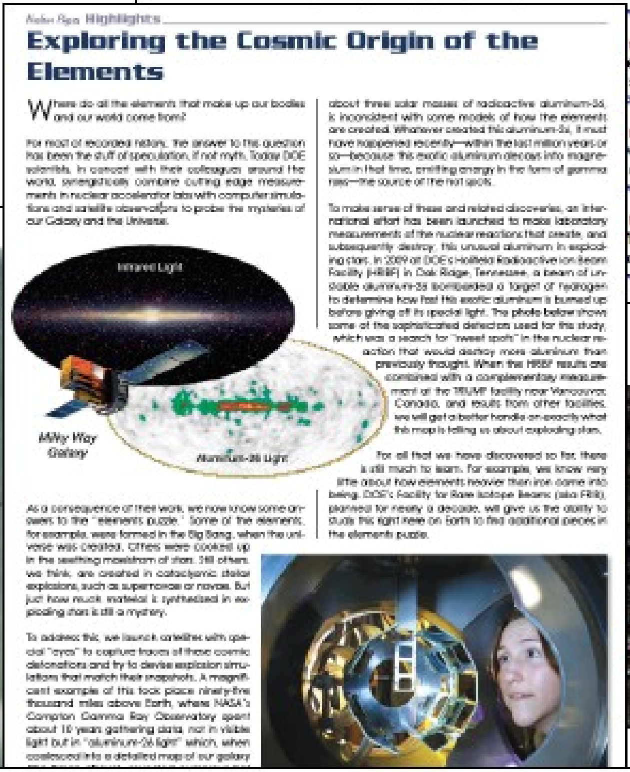
NATURE | NEWS AND VIEWS

Nuclear physics: Doubly magic tin

Paul Cottle

Nature **465**, 430–431 (27 May 2010) | doi:10.1038/465430a
Published online 26 May 2010
Correction (June, 2010)

By swapping the roles of the target and beam in an experiment tha
implement, researchers have confirmed the doubly magic nature o
isotope ^{132}Sn.



Exploring the Cosmic Origin of the Elements

Where do all the elements that make up our bodies and our world come from?

For most of recorded history, the answer to this question has been the stuff of speculation, if not myth. Today DOE scientists, in concert with their colleagues around the world, synergistically combine cutting edge measurements in nuclear accelerator labs with computer simulations and satellite observations to probe the mysteries of our Galaxy and the Universe.

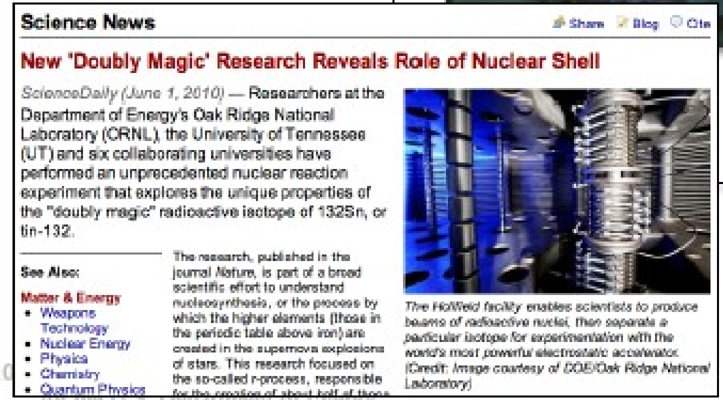
As a consequence of their work, we now know some answers to the "elements puzzle." Some of the elements, for example, were formed in the Big Bang, when the universe was created. Others were cooked up in the seething maelstrom of stars. Still others, we think, are created in cataclysmic stellar explosions, such as supernovae or novae. But just how much material is synthesized in exploding stars is still a mystery.

To address this, we launch satellites with special "eyes" to capture traces of these cosmic detonations and try to devise explosion simulations that match their snapshots. A magnificent example of this took place ninety-five thousand miles above Earth, where NASA's Compton Gamma Ray Observatory spent about 10 years gathering data, not in visible light but in "aluminum-26 light" which, when coalesced into a detailed map of our galaxy

about three solar masses of radioactive aluminum-26, is inconsistent with some models of how the elements are created. Whatever created this aluminum-26, it must have happened recently—within the last million years or so—because this exotic aluminum decays into magnesium in that time, emitting energy in the form of gamma rays—the source of the hot spots.

To make sense of these and related discoveries, an international effort has been launched to make laboratory measurements of the nuclear reactions that create, and subsequently destroy, this unusual aluminum in exploding stars. In 2009 at DOE's Holifield Radioactive Ion Beam Facility (HRIBF) in Oak Ridge, Tennessee, a beam of unstable aluminum-26 bombarded a target of hydrogen to determine how fast this exotic aluminum is burned up before giving off its special light. The photo below shows some of the sophisticated detectors used for this study, which was a search for "sweet spots" in the nuclear reaction that would destroy more aluminum than previously thought. When the HRIBF results are combined with a complementary measurement at the TRIUMF facility near Vancouver, Canada, and results from other facilities, we will get a better handle on exactly what this map is telling us about exploding stars.

For all that we have discovered so far, there is still much to learn. For example, we know very little about how elements heavier than iron come into being. DOE's Facility for Rare Isotope Beams (aka FRIB), planned for nearly a decade, will give us the ability to study this right here on Earth to find additional pieces in the elements puzzle.

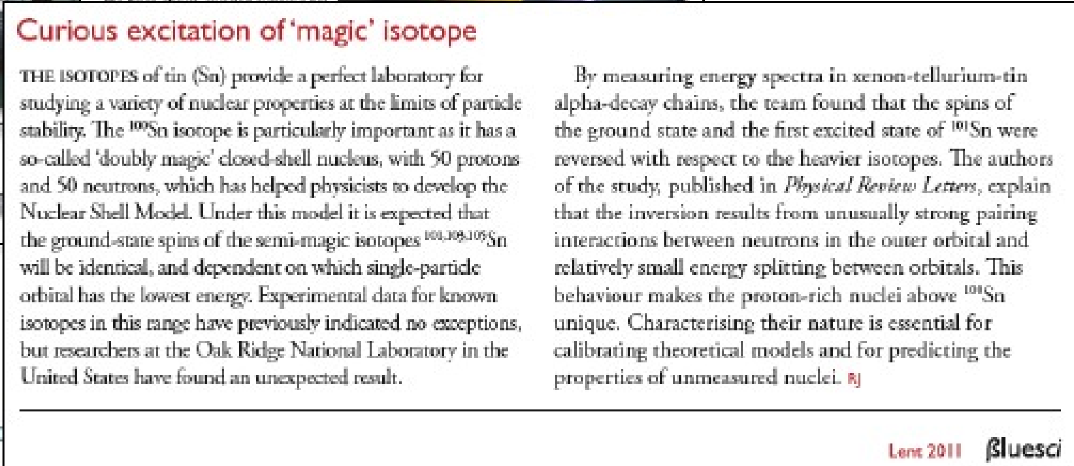


New 'Doubly Magic' Research Reveals Role of Nuclear Shell

ScienceDaily (June 1, 2010) — Researchers at the Department of Energy's Oak Ridge National Laboratory (ORNL), the University of Tennessee (UT) and six collaborating universities have performed an unprecedented nuclear reaction experiment that explores the unique properties of the "doubly magic" radioactive isotope of 132Sn, or tin-132.

The research, published in the journal *Nature*, is part of a broad scientific effort to understand nucleosynthesis, or the process by which the higher elements (those in the periodic table above iron) are created in the supernova explosions of stars. This research focused on the so-called r-process, responsible for the creation of about half of those

The Holifield facility enables scientists to produce beams of radioactive nuclei, then separate a particular isotope for experimentation with the world's most powerful electrostatic accelerator. (Credit: Image courtesy of DOE/Oak Ridge National Laboratory)



Curious excitation of 'magic' isotope

THE ISOTOPES of tin (Sn) provide a perfect laboratory for studying a variety of nuclear properties at the limits of particle stability. The ^{100}Sn isotope is particularly important as it has a so-called 'doubly magic' closed-shell nucleus, with 50 protons and 50 neutrons, which has helped physicists to develop the Nuclear Shell Model. Under this model it is expected that the ground-state spins of the semi-magic isotopes ^{101,103,105}Sn will be identical, and dependent on which single-particle orbital has the lowest energy. Experimental data for known isotopes in this range have previously indicated no exceptions, but researchers at the Oak Ridge National Laboratory in the United States have found an unexpected result.

By measuring energy spectra in xenon-tellurium-tin alpha-decay chains, the team found that the spins of the ground state and the first excited state of ^{101}Sn were reversed with respect to the heavier isotopes. The authors of the study, published in *Physical Review Letters*, explain that the inversion results from unusually strong pairing interactions between neutrons in the outer orbital and relatively small energy splitting between orbitals. This behaviour makes the proton-rich nuclei above ^{100}Sn unique. Characterising their nature is essential for calibrating theoretical models and for predicting the properties of unmeasured nuclei. RJ

PROSPECT

The Joint Institute for Nuclear Astrophysics

Core Institutions

University of Notre Dame
Michigan State University
University of Chicago

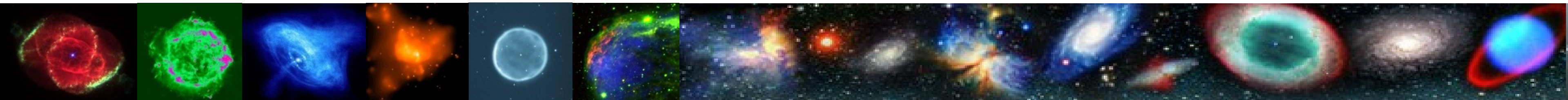
Associate Institutions

University of Arizona
Arizona State University
University of California (SB, SC)
Argonne National Laboratory
Los Alamos National Laboratory
ViSTAR-GSI

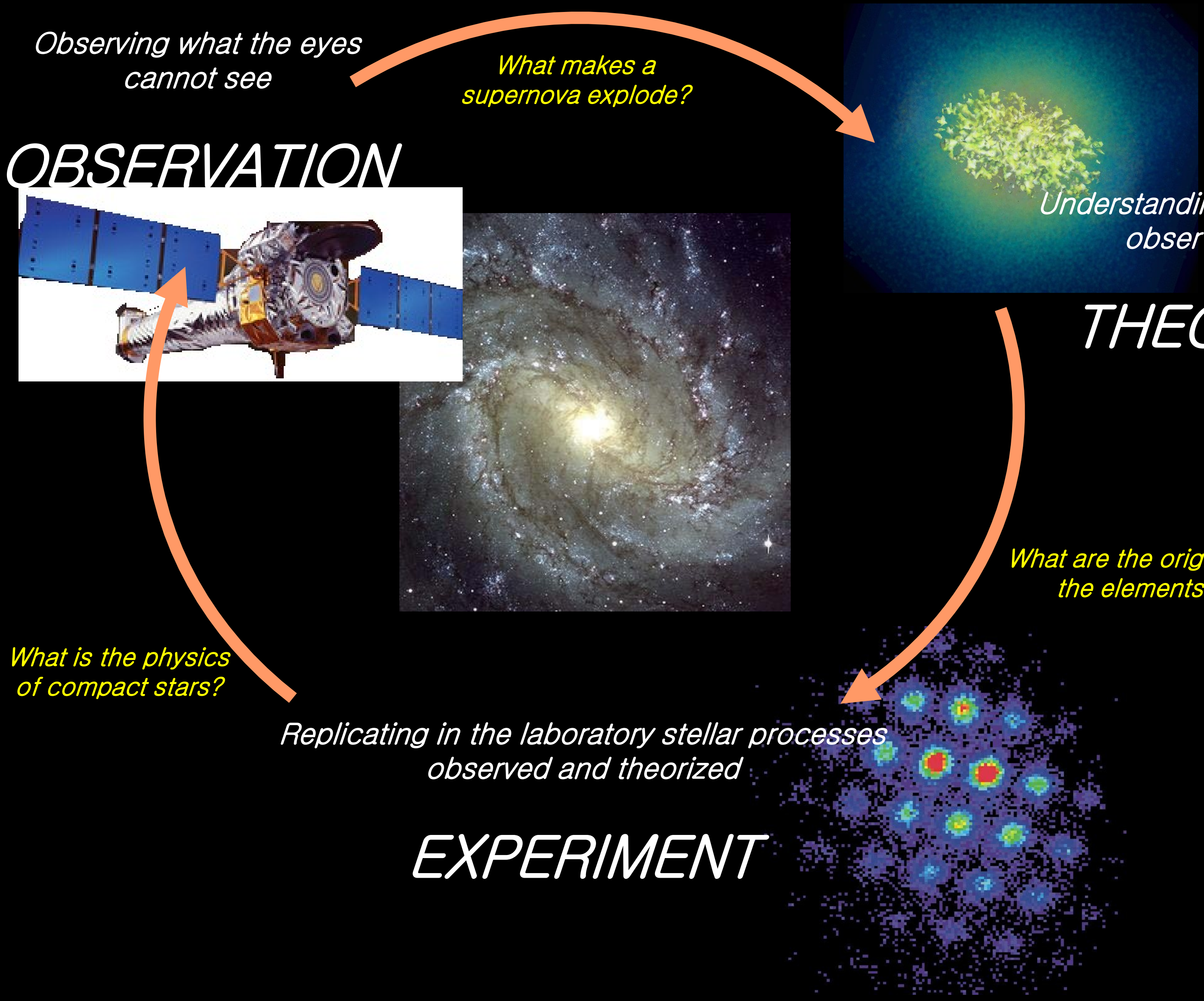
Collaborations

SciDAC SN Center
SDSS-II-SEGUE
DUSEL
RIA-ARIA

12 research groups –
20 faculty members –
21 postdocs – 25 graduate students



JINA research



Observing what the eyes cannot see

OBSERVATION

What makes a supernova explode?

Understanding what is observed

THEORY

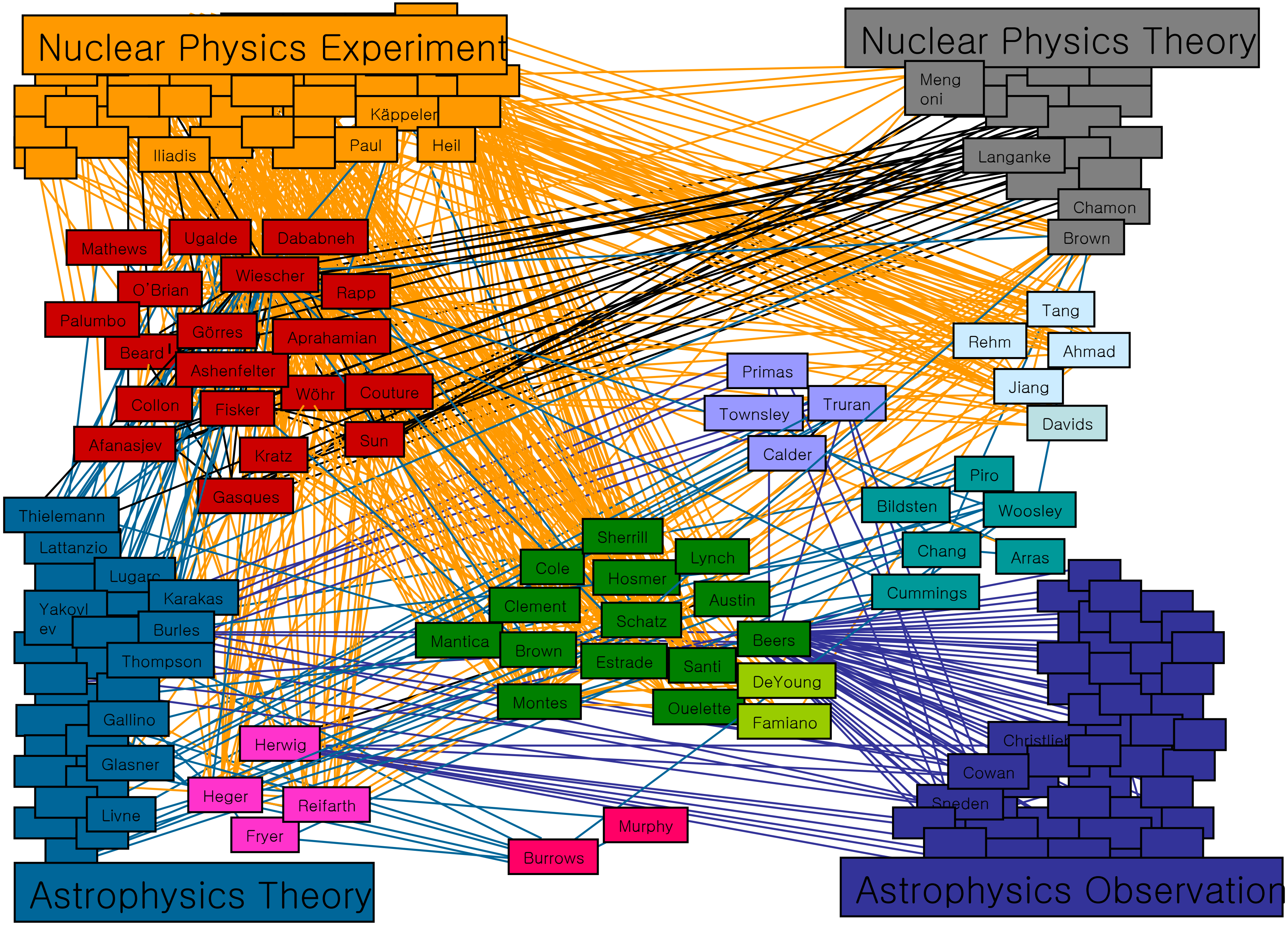
What are the origins of the elements?

Replicating in the laboratory stellar processes observed and theorized

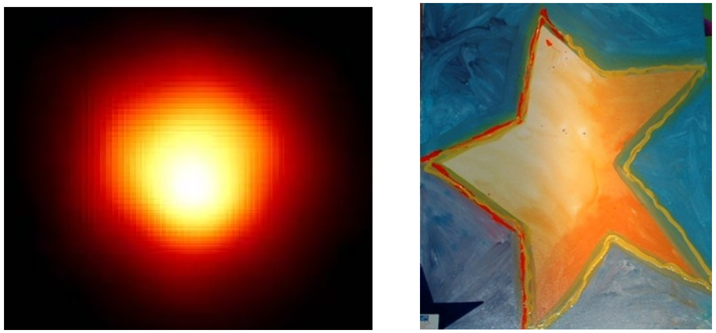
EXPERIMENT

What is the physics of compact stars?

The JINA collaboration Network



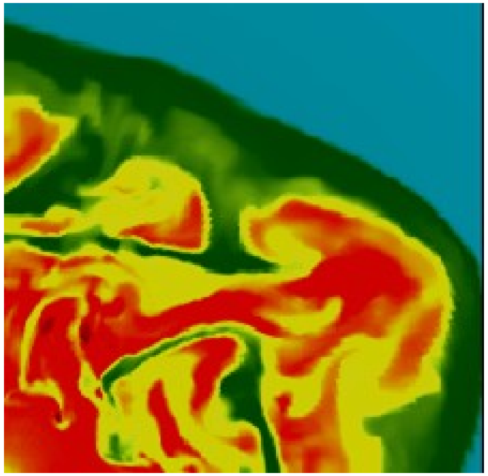
Major Research Focus & Components



MRC1 – Nucleosynthesis
and Stellar Evolution

MRC2 – Nucleosynthesis in
Supernova Shock Front

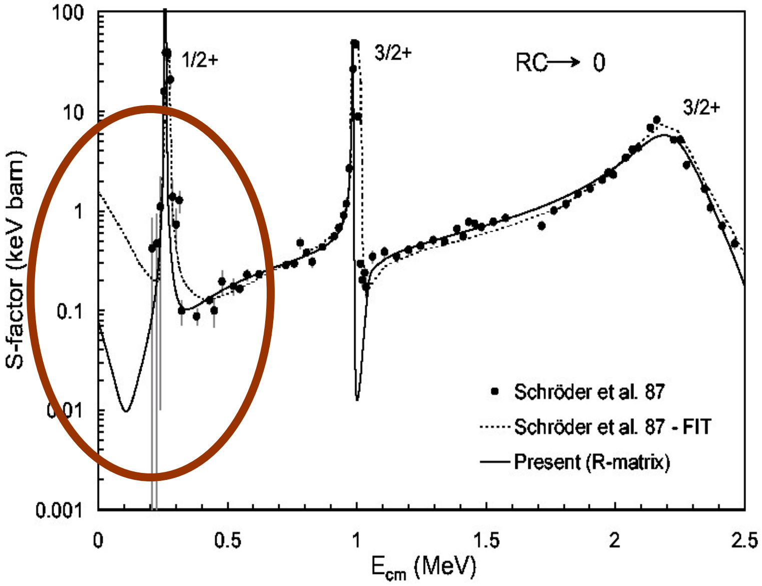
MRC3 – Nucleosynthesis in
Cataclysmic Binaries



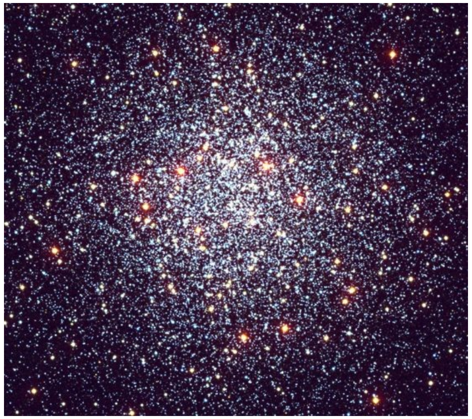
MRC1

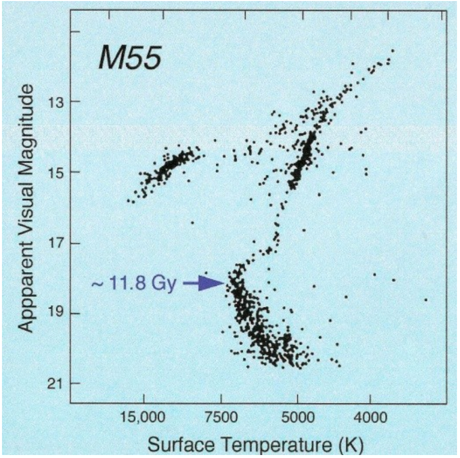
$^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}$ and the limits of measurement

Top line is previous accepted value; bottom line is present measurement.



New experiments at LUNA, LENA, TAMU confirm lower S-factor extrapolation !





- reduction of total reaction rate
- increases globular cluster age by ~1 billion years

Korean Researchers in this area

Neutrino Reaction in Nuclear-Astro Physics

1. Motivation for ν-processes in Nucleosynthesis

2. Indirect (Multi-step or Compound nuclei)
   and
   Direct (One-step or Knock-out) Processes
   for ν-^{12}C

From M. K. Cheoun @ Soongsil Univ.

Nuclear Symmetry Energy and Compact Stars

- Astrophysical Compact Object

n, p, e,
muon, pion,
kaon, …

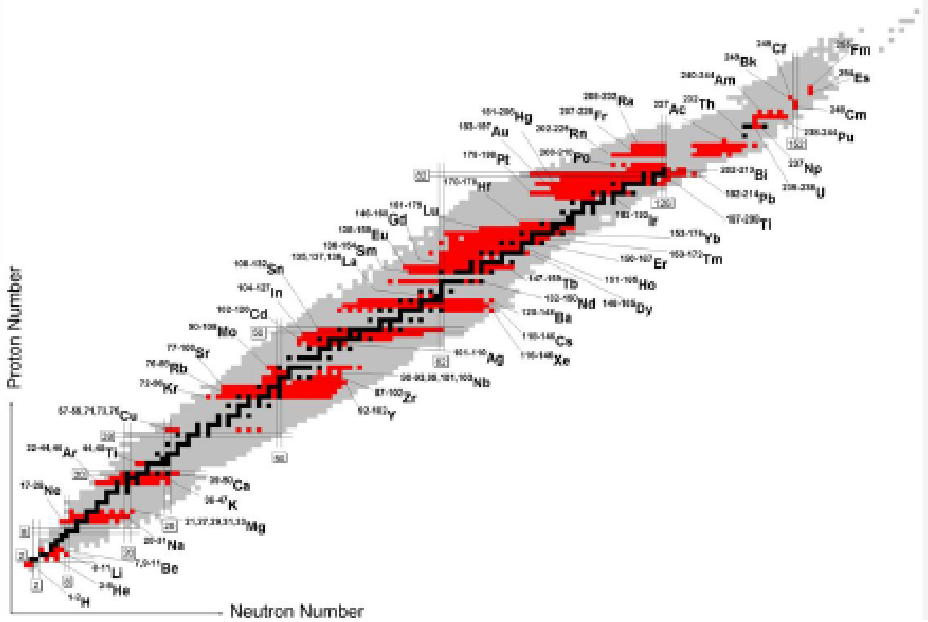
R ~ 10-15 km
M ~ 1-3 M_{sun}

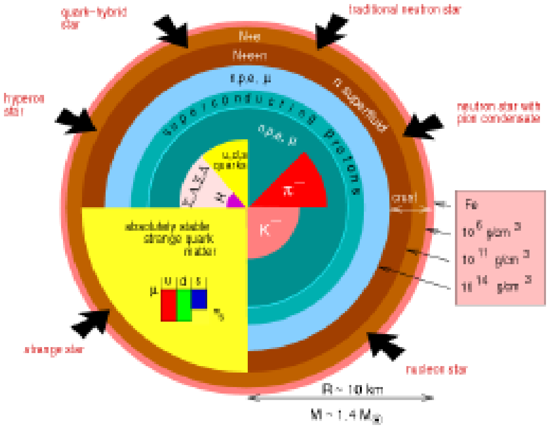
- **Chemical equilibrium** ($\mu_n - \mu_p = \mu_e = \mu_\mu$) and
- **Electrical charge neutrality** ($n_p = n_e + n_\mu$) between particles.
- Pressure ⟷ Gravity: **TOV equation**
- **Equation of State**(EOS) ⟵
  - Free-fermion gas
  - Nuclear Physics (Symmetry Energy)
  - Hadron Physics

Prospects for KoRIA

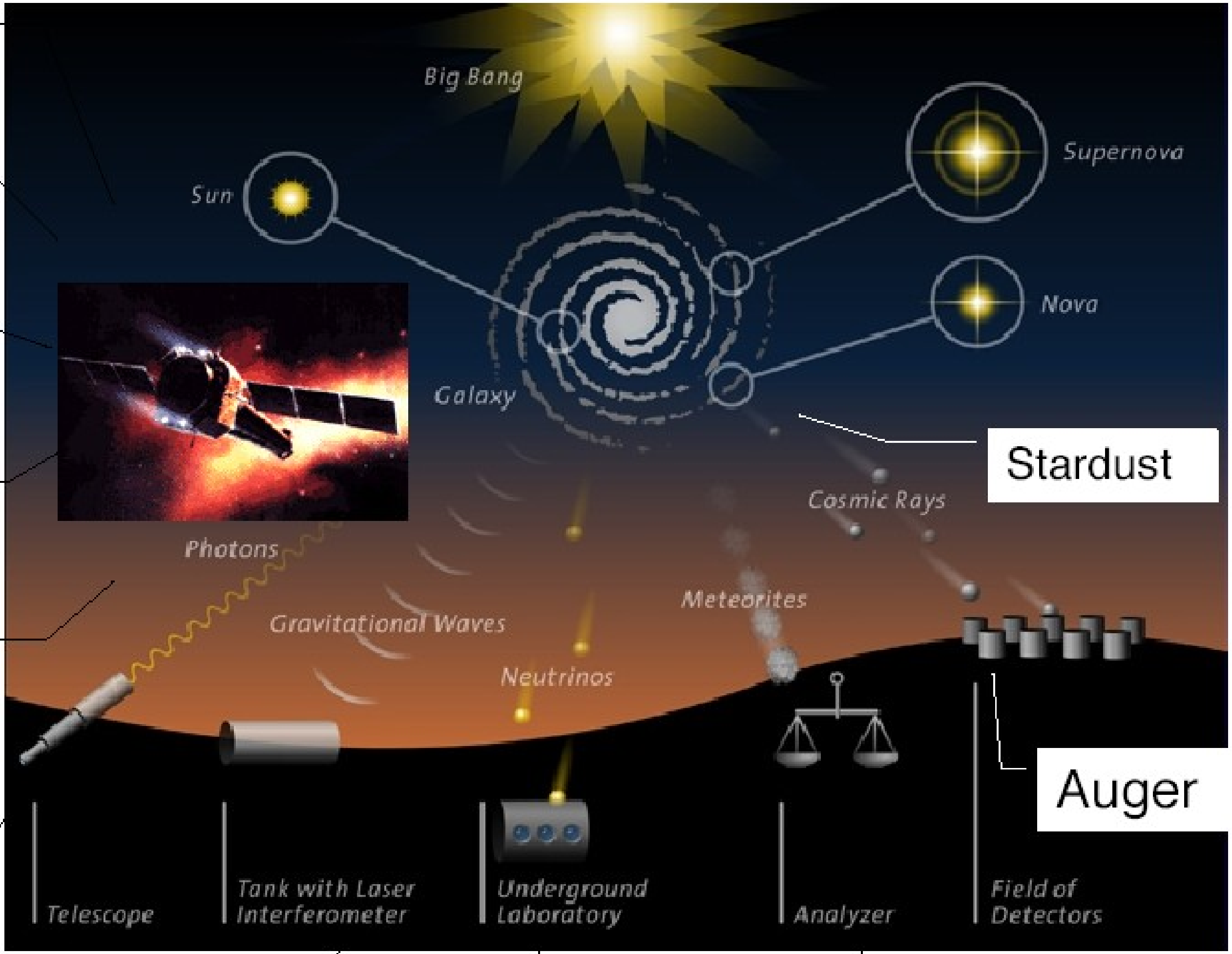
From C. H. Lee @ Pusan Univ.

- Nuclear Synthesis from various types of Supernovae
- Symmetry Energy in Neutron Stars
- Leading role in Astrophysics
  - gamma-ray bursts & gravitational wave radiation from colliding NS binaries





Observations



INTEGRAL (γ-rays)

Hubble (visible)

Chandra (X-rays)

SIRTF (infrared)

WMAP (microwave)

Keck, Subaru, ESO

LIGO

SuperK

SIMS

Stardust

Auger

*Smith, M. 2003

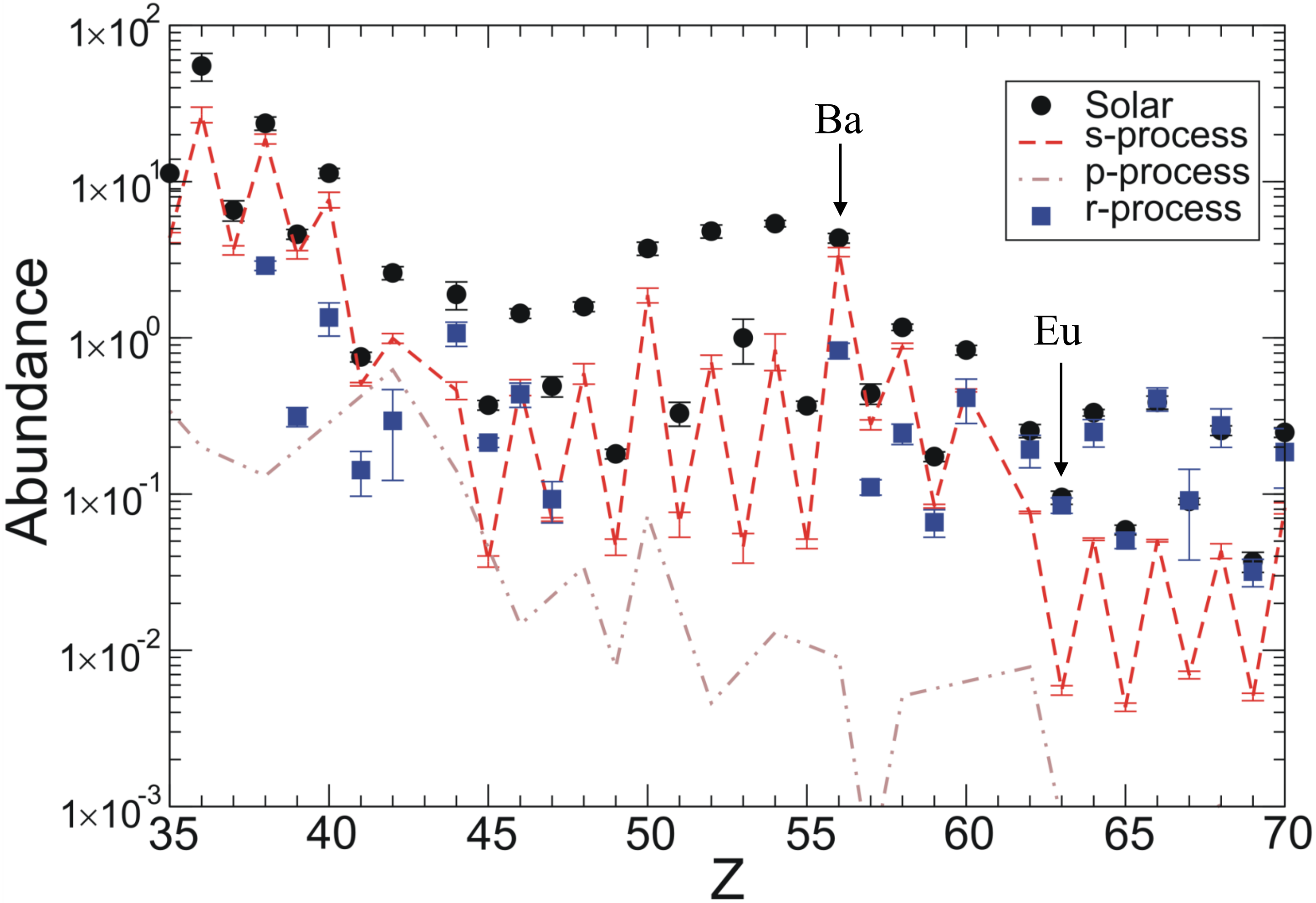
Physics Objectives of KoRIA

- Nuclear Physics
  - New Radioactive Isotopes
  - New, comprehensive understanding of nuclei
- Nuclear Astrophysics
  - Properties of radioactive isotopes
  - Cross section measurements with RIB
  - Origin of elements in the Universe

Contribution of different processes

Contribution of the diff. processes to the solar abundances

Ba: s−process
Eu: r−process



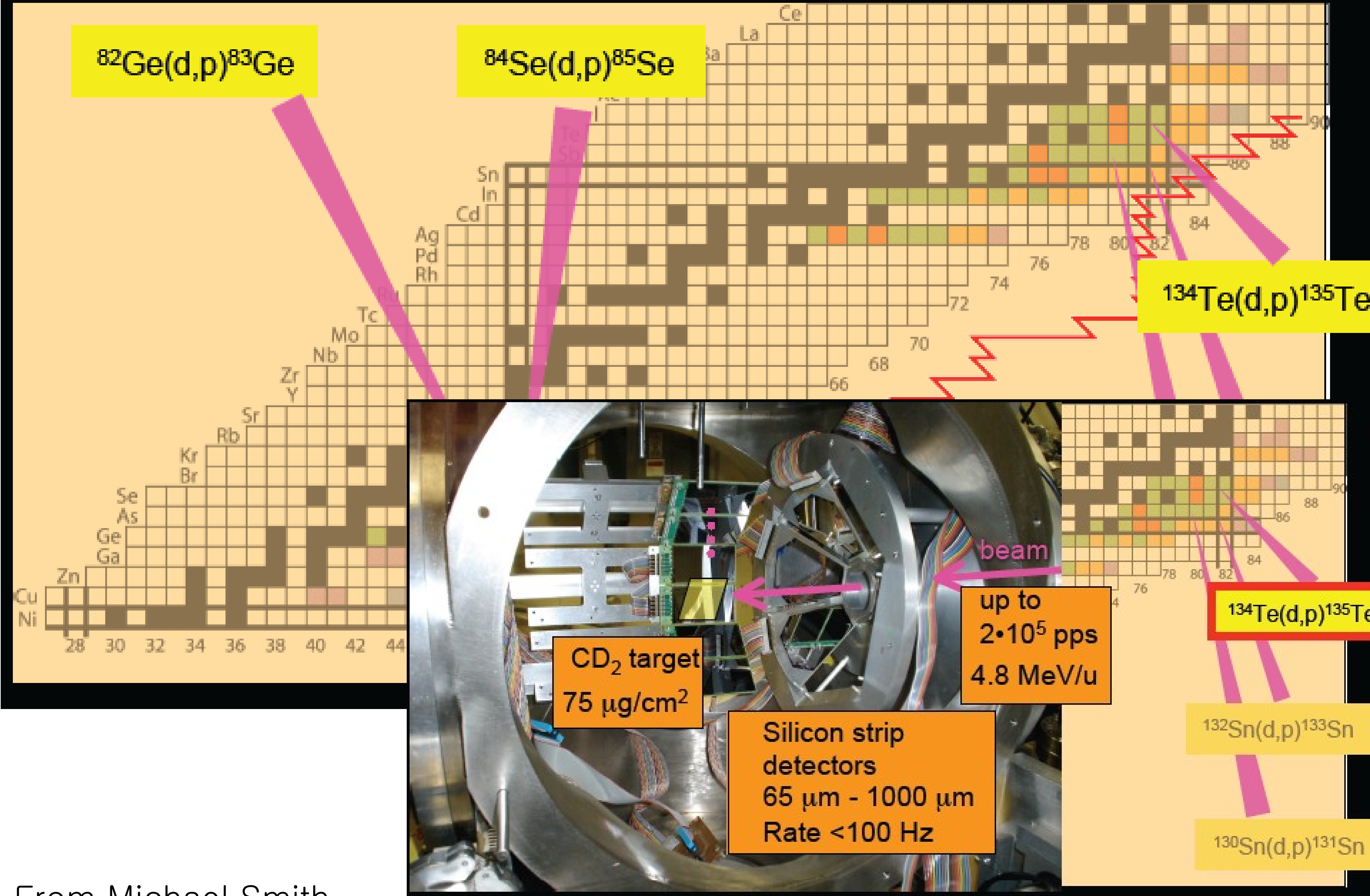
s−process:
Astrophysical model

p−process:
Astrophysical model

r−process:
Abundance of enriched−r−process star

from F. Montes

pioneering results with neutron-rich unstable beams



^{82}Ge(d,p)^{83}Ge

^{84}Se(d,p)^{85}Se

^{134}Te(d,p)^{135}Te

^{134}Te(d,p)^{135}Te

^{132}Sn(d,p)^{133}Sn

^{130}Sn(d,p)^{131}Sn

CD$_2$ target
75 μg/cm^2

up to
2•10^5 pps
4.8 MeV/u

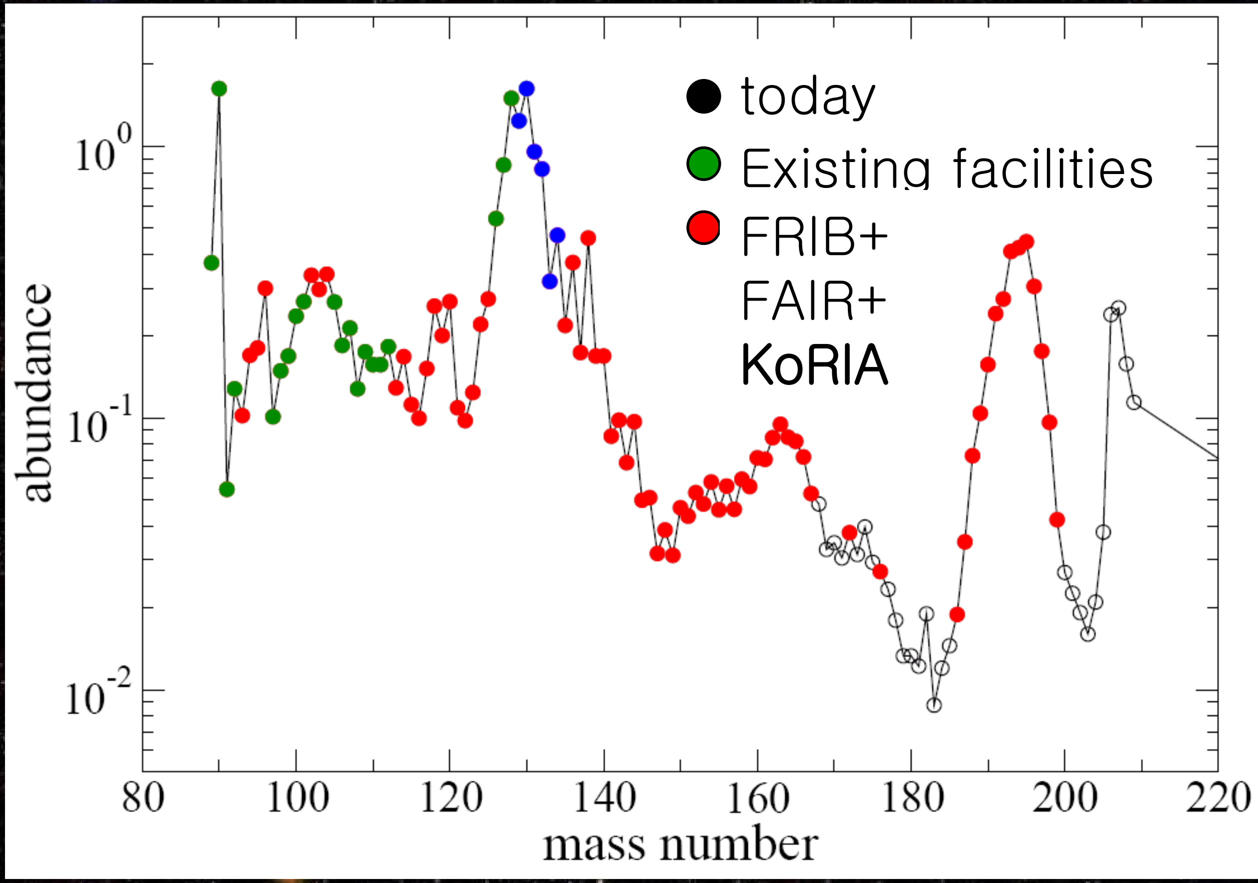
Silicon strip
detectors
65 μm - 1000 μm
Rate <100 Hz

From Michael Smith

New Era due to RIB Facilities

At present, except for a few cases (blue), output of models cannot be matched to measured abundances.

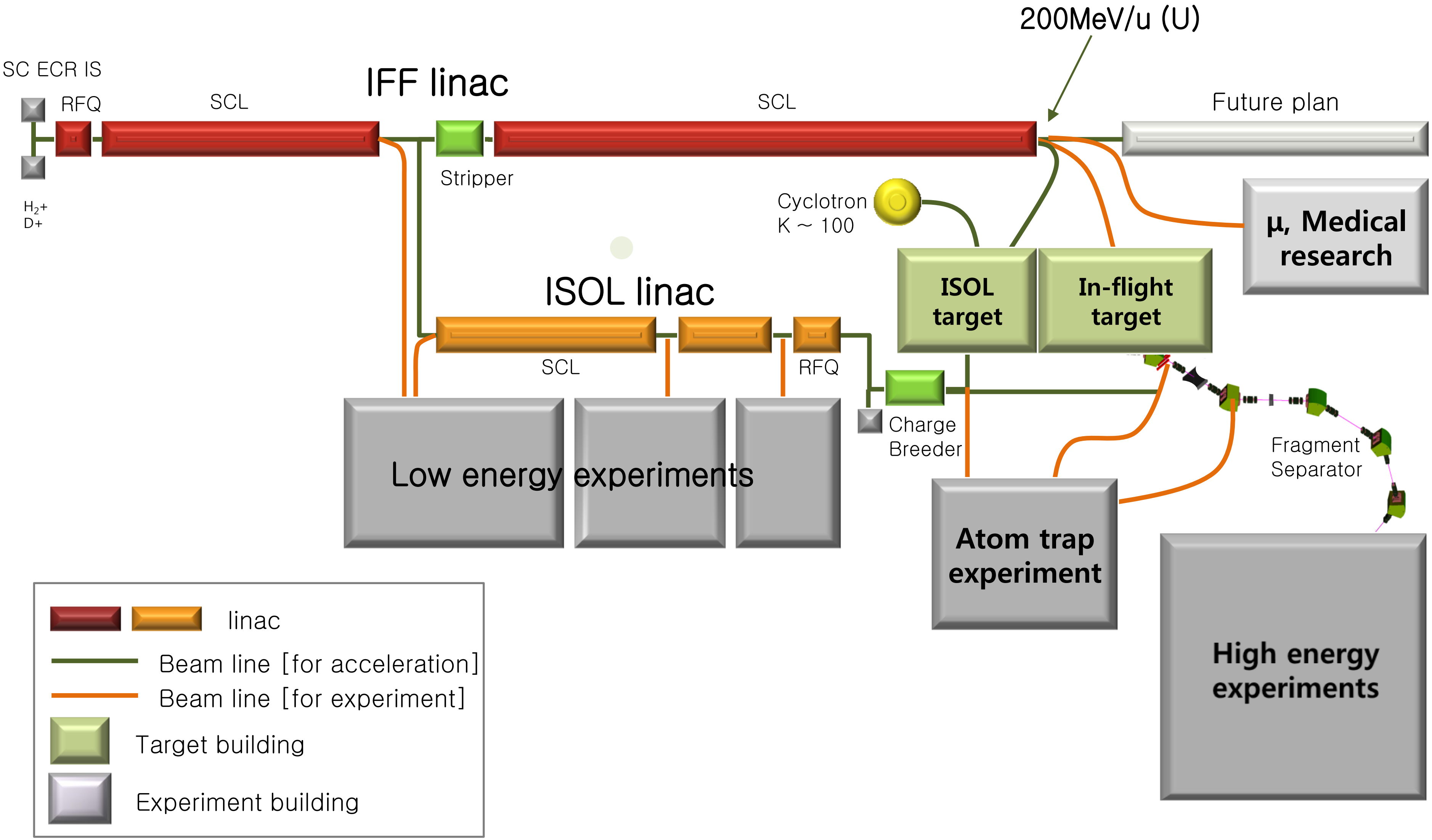
Future RIB facilities will allow one to constrain r-process models using abundance data



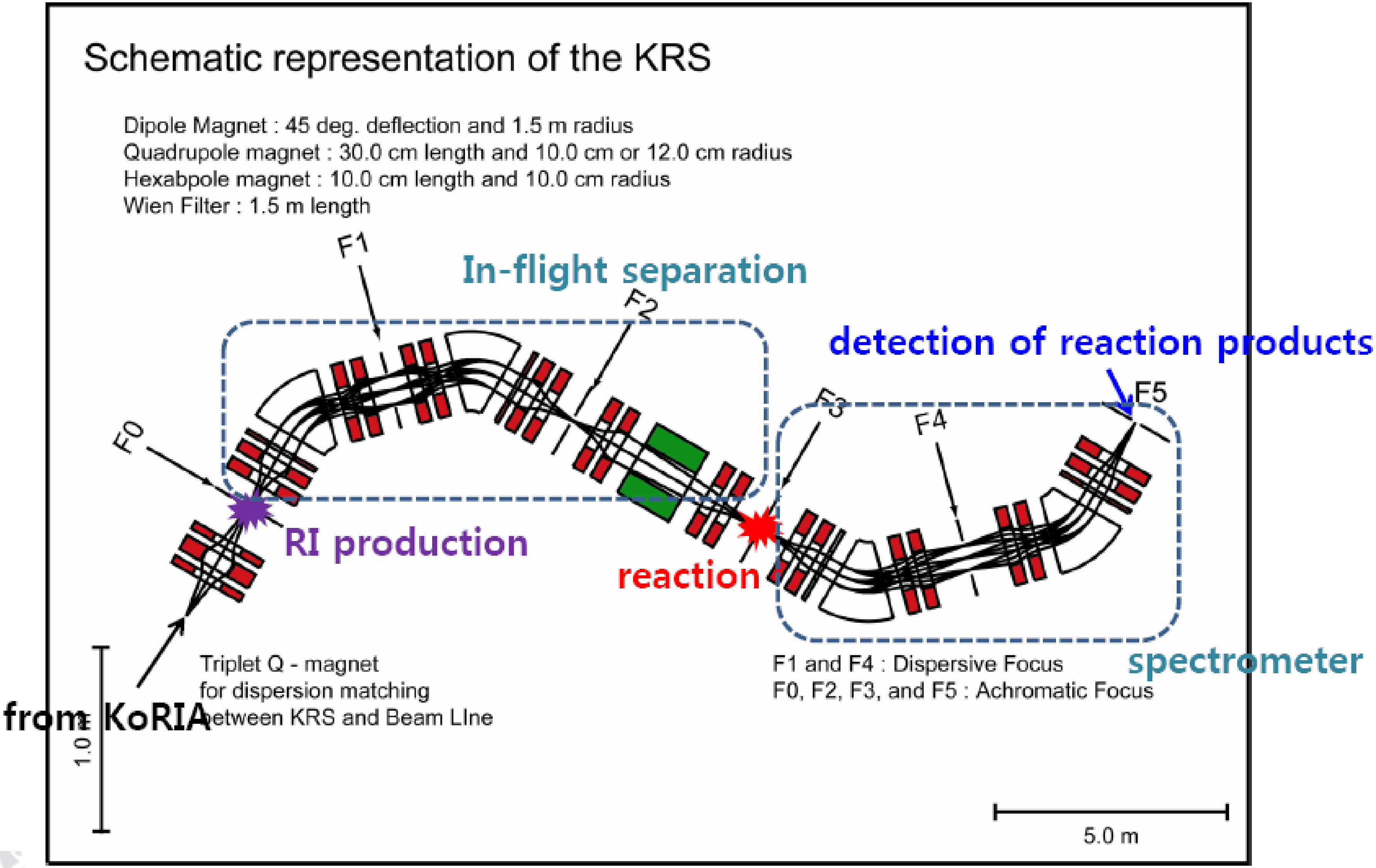
Constrain r–process environment by comparison of simulations with observation!

From Langanke

KoRIA layout (2010. 10.05)



- IRIS mode



Schematic representation of the KRS

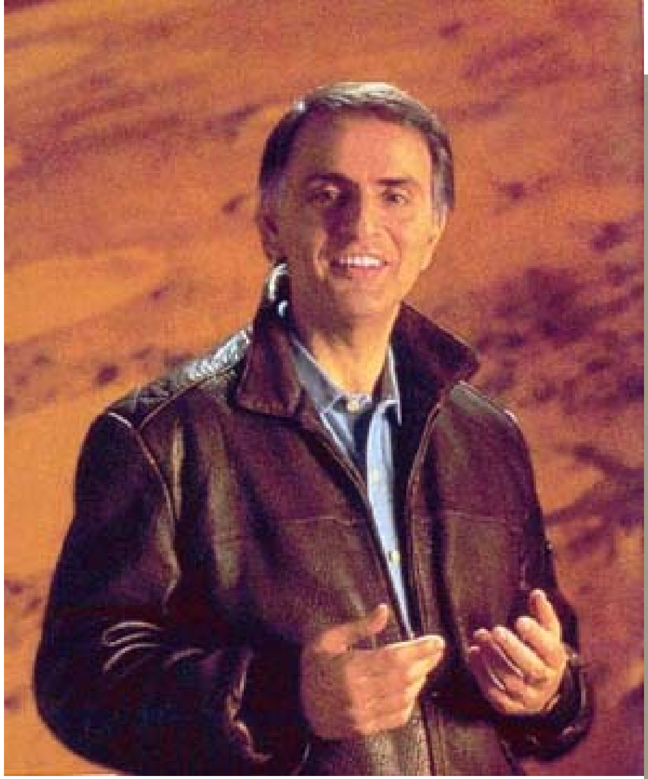
Dipole Magnet : 45 deg. deflection and 1.5 m radius
Quadrupole magnet : 30.0 cm length and 10.0 cm or 12.0 cm radius
Hexabpole magnet : 10.0 cm length and 10.0 cm radius
Wien Filter : 1.5 m length

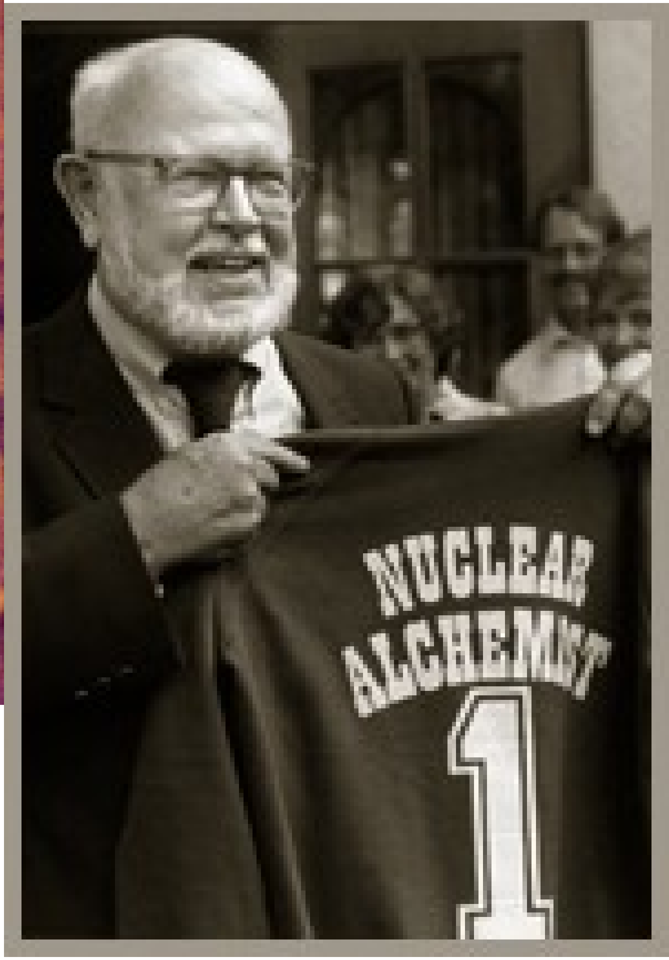
Triplet Q - magnet
for dispersion matching
between KRS and Beam Line

F1 and F4 : Dispersive Focus
F0, F2, F3, and F5 : Achromatic Focus

Summary

- Measurements using RI beams at KoRIA will give us a deeper understanding of explosive stellar sites by providing nuclear properties for stellar explosion models
  - X-ray burst, novae, supernovae, etc
  - the origin of elements (r-process)
- Combined Efforts from Astrophysics, Astronomy, Nuclear and Particle Physics communities are crucial.
  - BSI





We are all made of stardust that were created by nuclear reactions