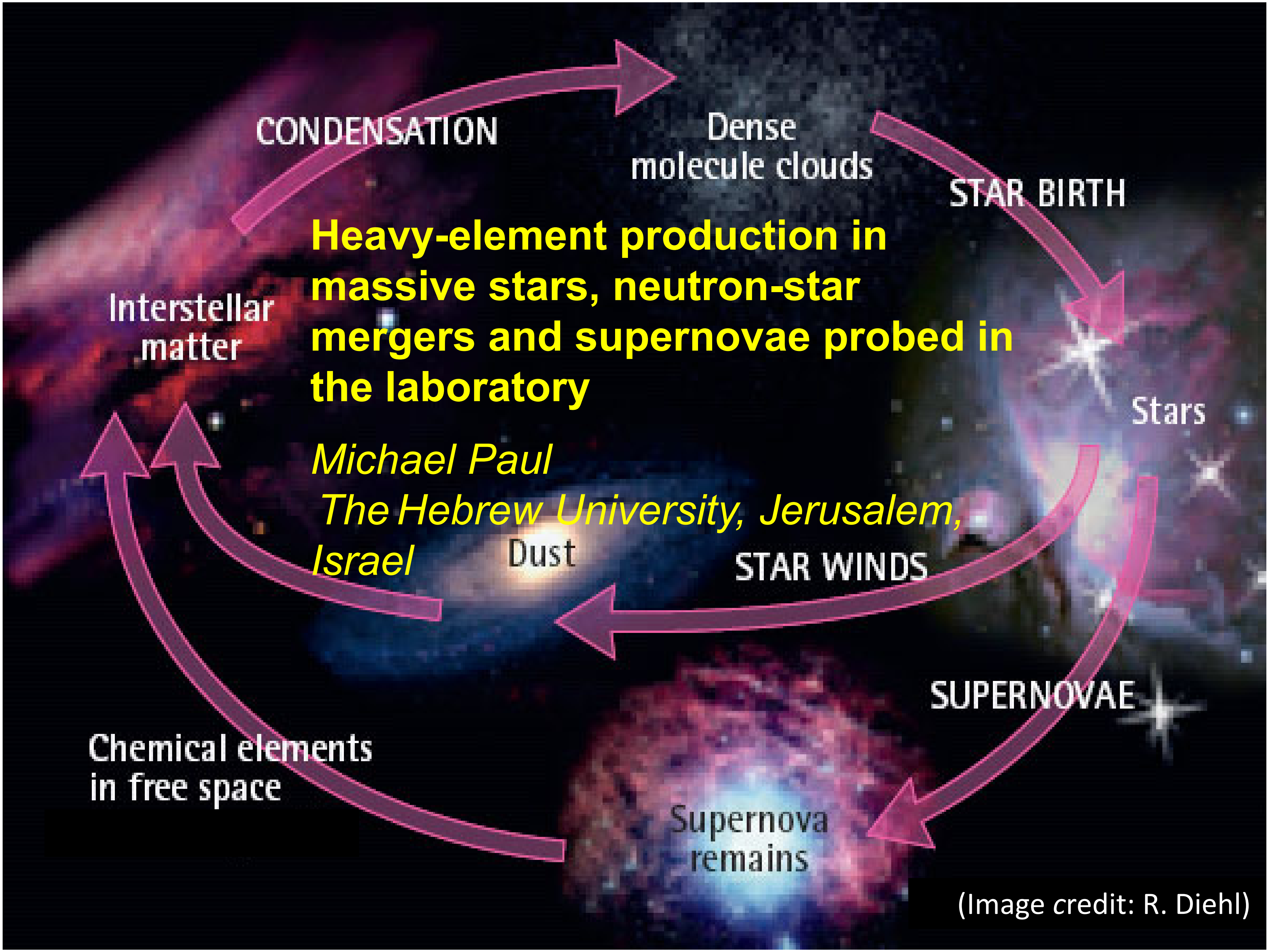
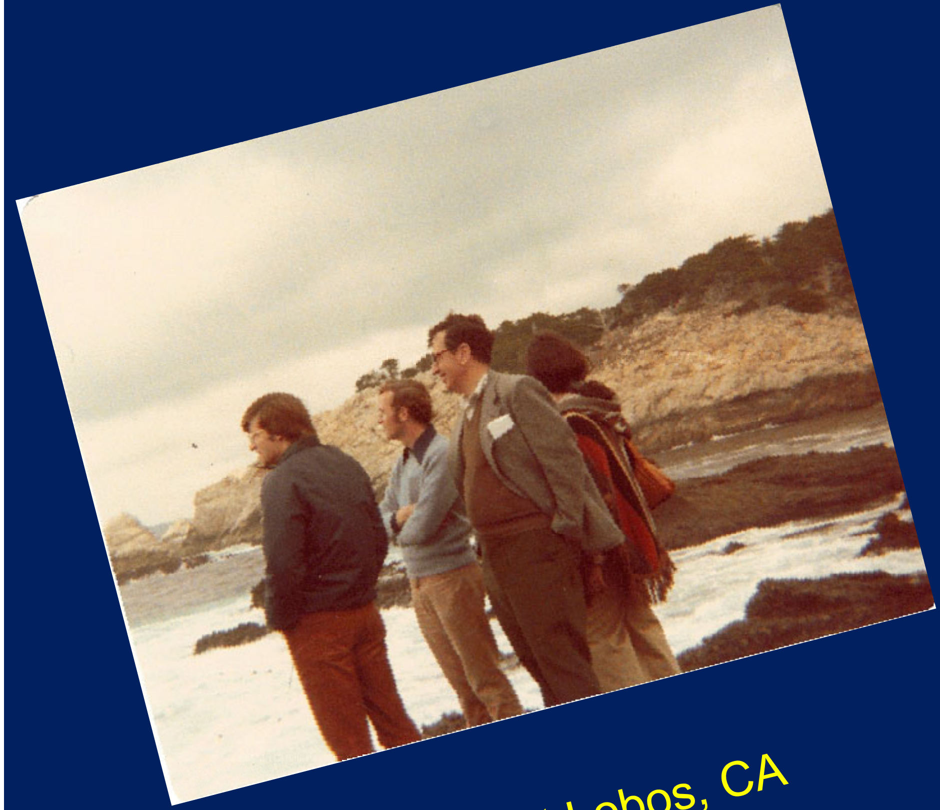
Heavy-element production in massive stars, neutron-star mergers and supernovae probed in the laboratory

Michael Paul

The Hebrew University, Jerusalem, Israel

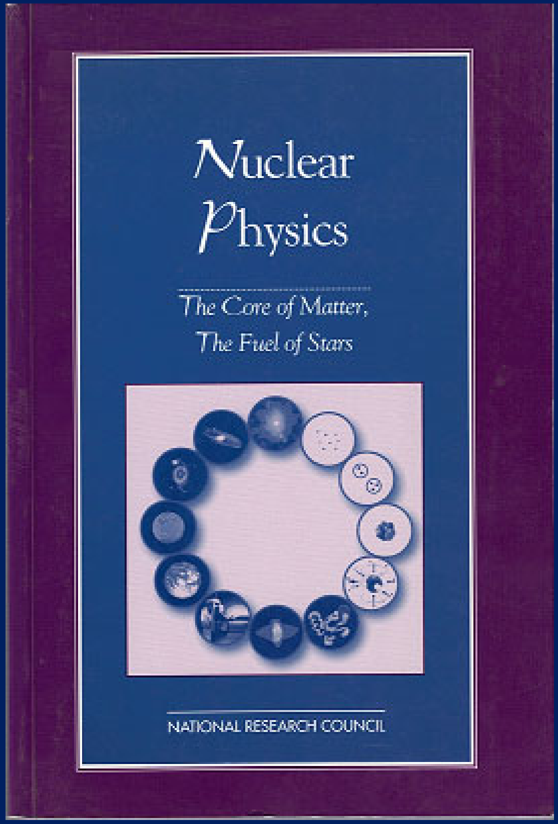


(Image credit: R. Diehl)



Point Lobos, CA
Nov 1978

An important-birthday celebration

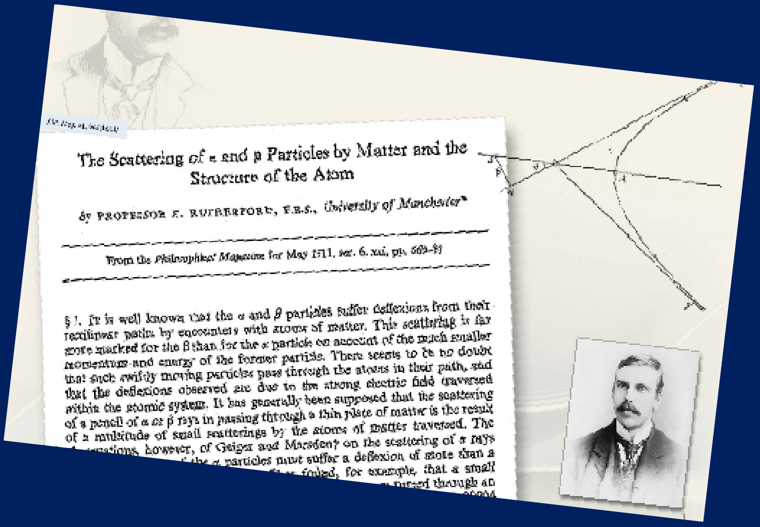


National Academy Press, 1999
Nuclear Physics – The Core of Matter
The Fuel of Stars

“Facilities and instrumentation are essential for progress, but science ultimately depends on people who carry it out –on their individual creativity, drive, and enterprise.”

Perspectives on nuclear physics
over the past 100 years,

John P. Schiffer , J. Phys.: Conf. Ser. (2012)



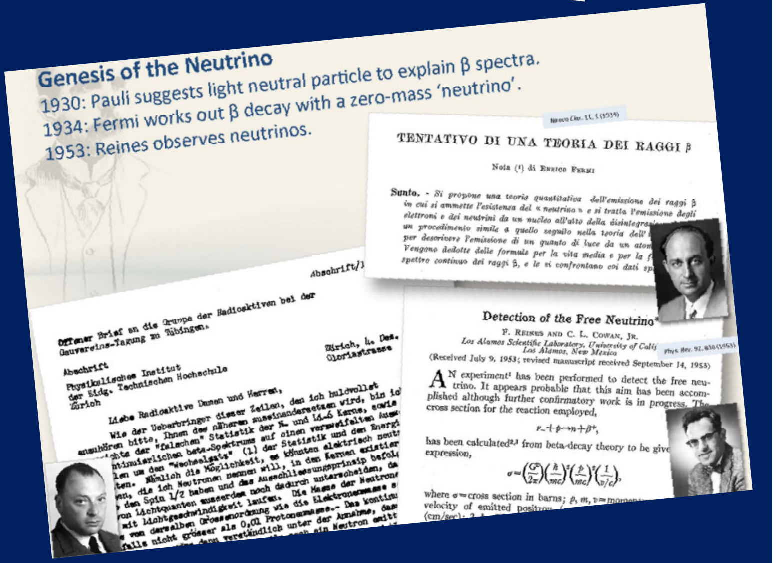
The Scattering of α and β Particles by Matter and the Structure of the Atom

by PROFESSOR E. RUTHERFORD, F.R.S., *University of Manchester**

From the *Philosophical Magazine* for May 1911, ser. 6, xxi, pp. 669–88

§ 1. It is well known that the α and β particles suffer deflexions from their rectilinear paths by encounters with atoms of matter. This scattering is far more marked for the β than for the α particle on account of the much smaller momentum and energy of the former particle. There seems to be no doubt that such swiftly moving particles pass through the atoms in their path, and that the deflexions observed are due to the strong electric field traversed within the atomic system. It has generally been supposed that the scattering of a pencil of α or β rays in passing through a thin plate of matter is the result of a multitude of small scatterings by the atoms of matter traversed. The observations, however, of Geiger and Marsden† on the scattering of α rays

particles must suffer a deflexion of more than a
found, for example, that a small
passed through an



Genesis of the Neutrino
1930: Pauli suggests light neutral particle to explain β spectra.
1934: Fermi works out β decay with a zero-mass ‘neutrino’.
1953: Reines observes neutrinos.

Nuovo Cim. 11, 1 (1934)

TENTATIVO DI UNA TEORIA DEI RAGGI β

Nota (¹) di Enrico Fermi

Sunto. - *Si propone una teoria quantitativa dell'emissione dei raggi β in cui si ammette l'esistenza del « neutrino » e si tratta l'emissione degli elettroni e dei neutrini da un nucleo all'atto della disintegra un procedimento simile a quello seguito nella teoria dell' per descrivere l'emissione di un quanto di luce da un atom Vengono dedotte delle formule per la vita media e per la f spettro continuo dei raggi β, e le si confrontano coi dati sp*

Abschrift/1

Offener Brief an die Gruppe der Radioaktiven bei der
Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez.
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst
anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich
chte der "falschen" Statistik der N- und Li-6 Kerne, sowie
ntinuierlichen beta-Spektrums auf einen verzweifelten Ausw
len um den "Wechselsatz" (1) der Statistik und den Energi
ten. Nämlich die Möglichkeit, es könnten elektrisch neutr
en, die ich Neutronen nennen will, in den Kernen existier
den Spin 1/2 haben und das Ausschliessungsprinzip befolg
von Lichtquanten ausserdem noch dadurch unterscheiden, da
mit Lichtgeschwindigkeit laufen. Die Masse der Neutrone
von derselben Grössenordnung wie die Elektronenmasse s
falls nicht grösser als 0,01 Protonenmasse.- Das kontinu
dann verständlich unter der Annahme, dass
ein Neutron emitt

Detection of the Free Neutrino*

F. Reines and C. L. Cowan, Jr.
Los Alamos Scientific Laboratory, University of Cali
Los Alamos, New Mexico
(Received July 9, 1953; revised manuscript received September 14, 1953)

Phys. Rev. 92, 830 (1953)

AN experiment¹ has been performed to detect the free neutrino. It appears probable that this aim has been accomplished although further confirmatory work is in progress. The cross section for the reaction employed,

$$\nu_- + p \rightarrow n + \beta^+,$$

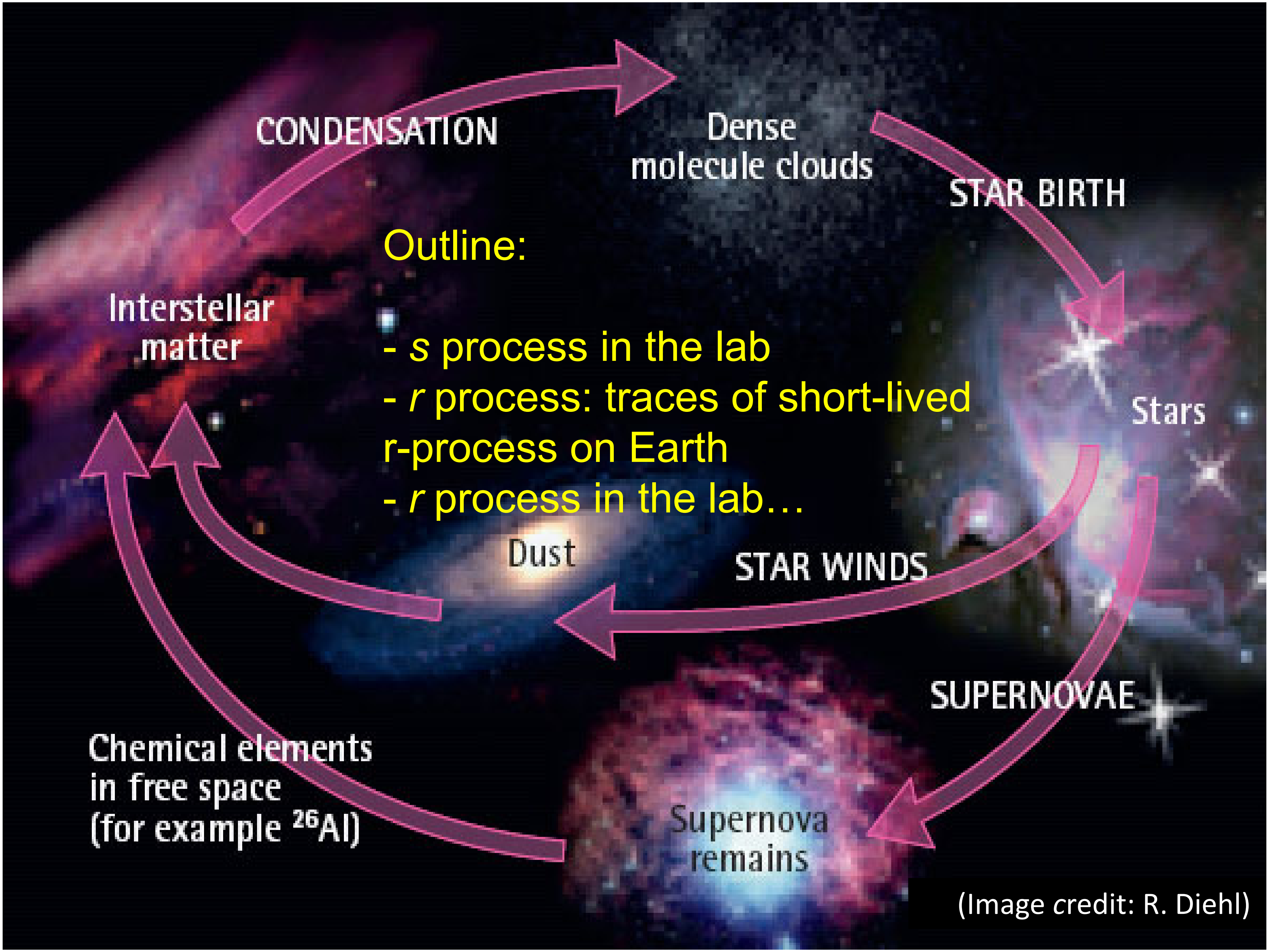
has been calculated²,³ from beta-decay theory to be give expression,

$$\sigma = \left(\frac{G^2}{2\pi}\right)\left(\frac{h}{mc}\right)^2\left(\frac{p}{mc}\right)^2\left(\frac{1}{v/c}\right),$$

where σ = cross section in barns; p, m, v = momen velocity of emitted positron (cm/sec);

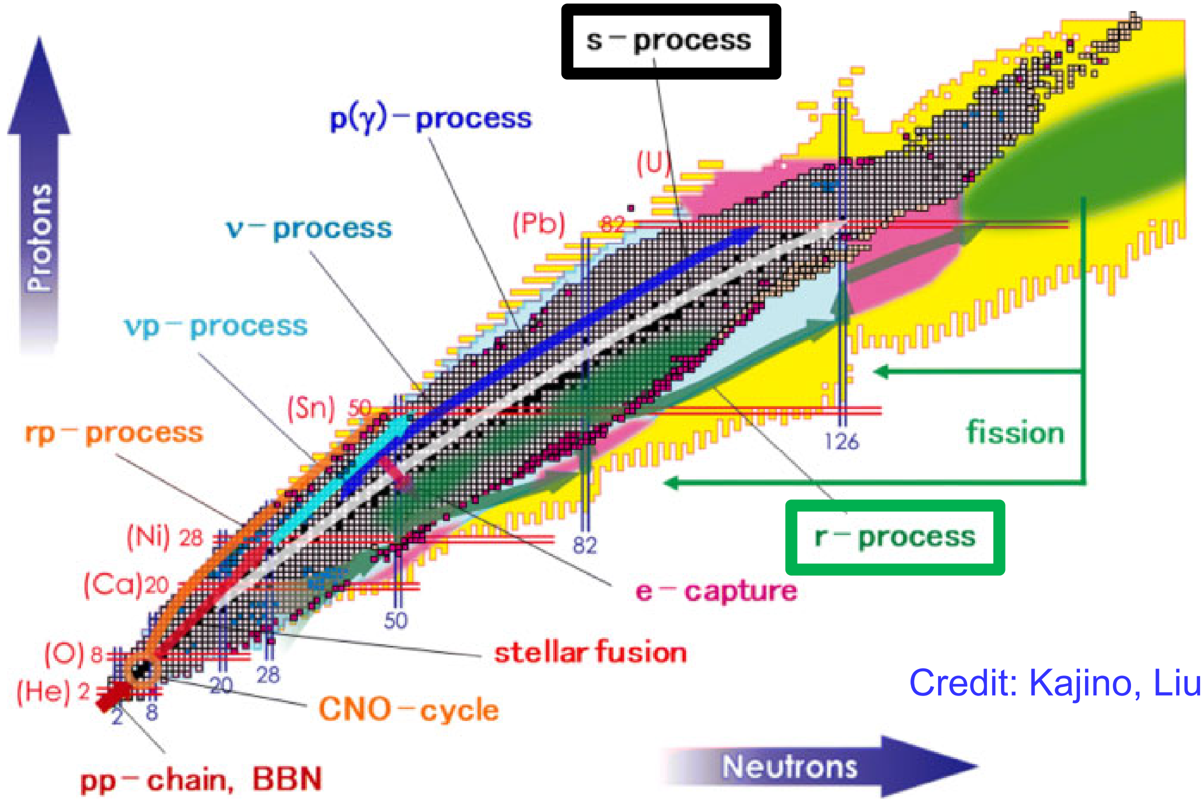
Outline:

- *s* process in the lab
- *r* process: traces of short-lived r-process on Earth
- *r* process in the lab…



(Image credit: R. Diehl)

Nucleosynthesis

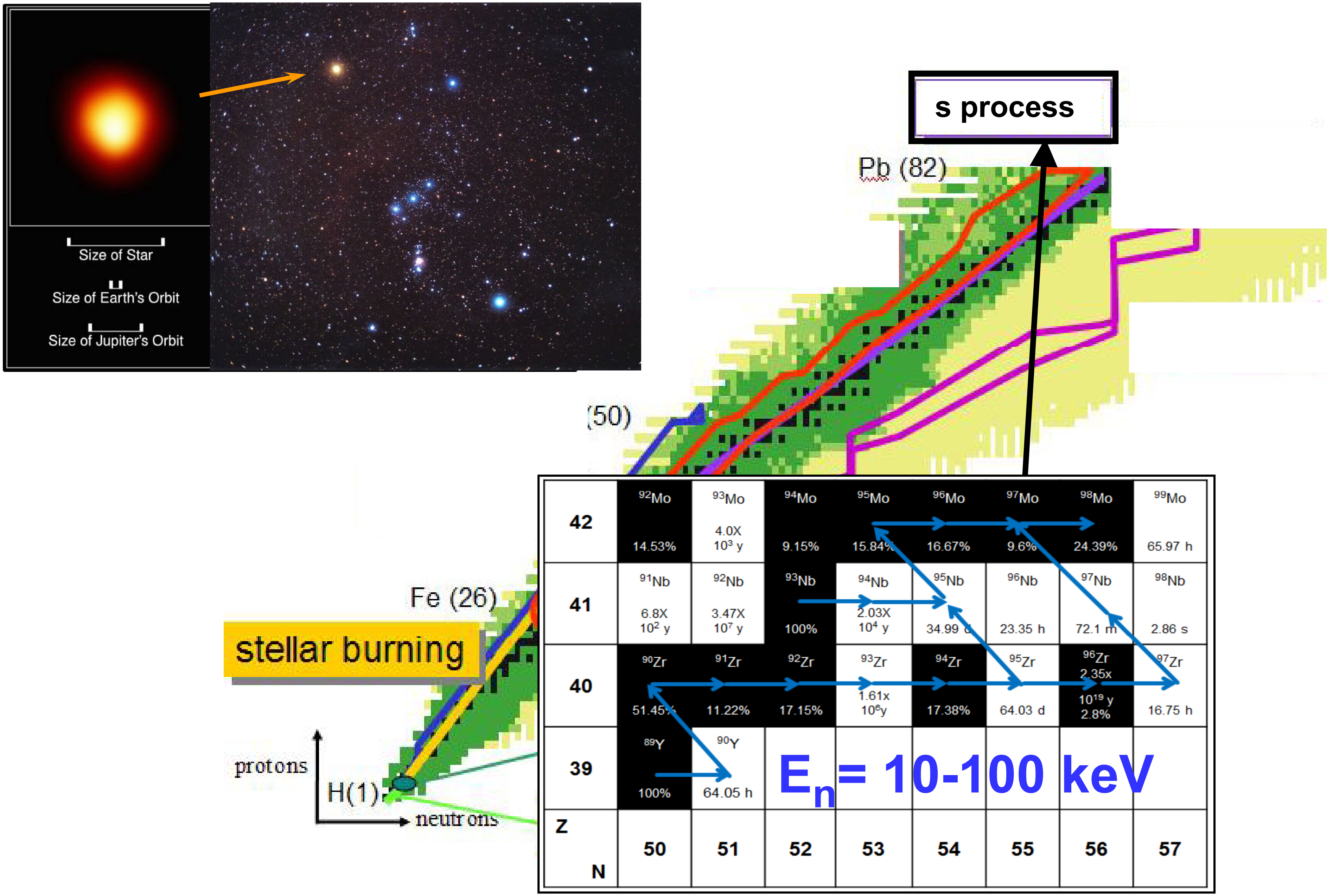


Credit: Kajino, Liu, Tang

Most of nature heavy elements are produced by **neutron captures** via the ***slow (s)*** process and the ***rapid (r)*** process:

A.G.W. Cameron (1957)
E. M. Burbidge, G. R. Burbidge,
W. A. Fowler, and F. Hoyle (1957)

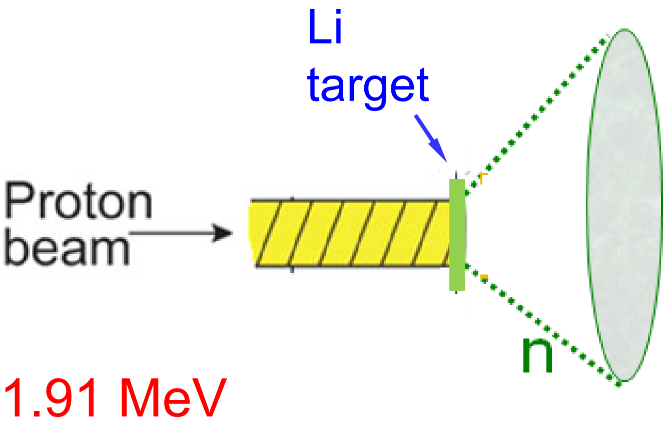
Red Giant Betelgeuse in constellation „Orion“

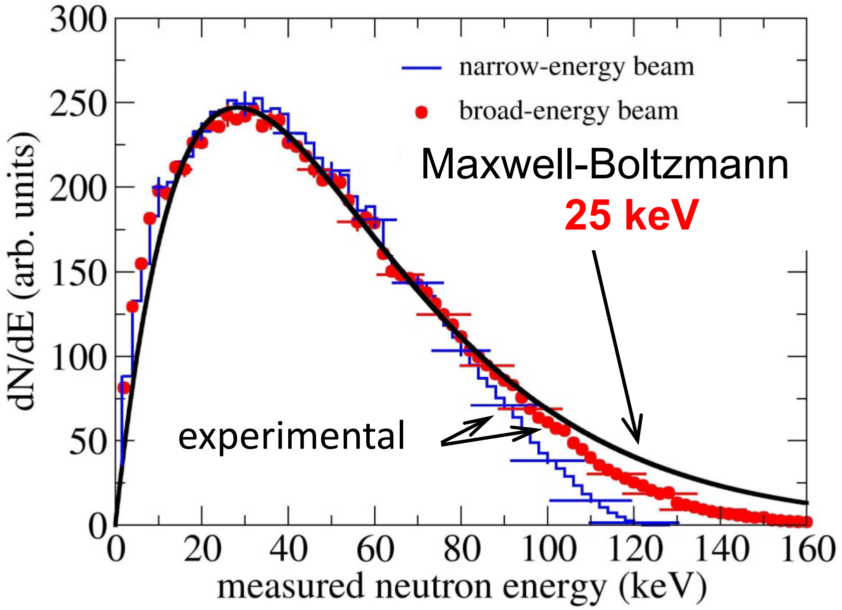


42	^{92}Mo 14.53%	^{93}Mo 4.0X 10^3 y	^{94}Mo 9.15%	^{95}Mo 15.84%	^{96}Mo 16.67%	^{97}Mo 9.6%	^{98}Mo 24.39%	^{99}Mo 65.97 h
41	^{91}Nb 6.8X 10^2 y	^{92}Nb 3.47X 10^7 y	^{93}Nb 100%	^{94}Nb 2.03X 10^4 y	^{95}Nb 34.99 d	^{96}Nb 23.35 h	^{97}Nb 72.1 m	^{98}Nb 2.86 s
40	^{90}Zr 51.45%	^{91}Zr 11.22%	^{92}Zr 17.15%	^{93}Zr 1.61x 10^6y	^{94}Zr 17.38%	^{95}Zr 64.03 d	^{96}Zr 2.35x 10^{19} y 2.8%	^{97}Zr 16.75 h
39	^{89}Y 100%	^{90}Y 64.05 h						
Z N	50	51	52	53	54	55	56	57

E_n= 10-100 keV

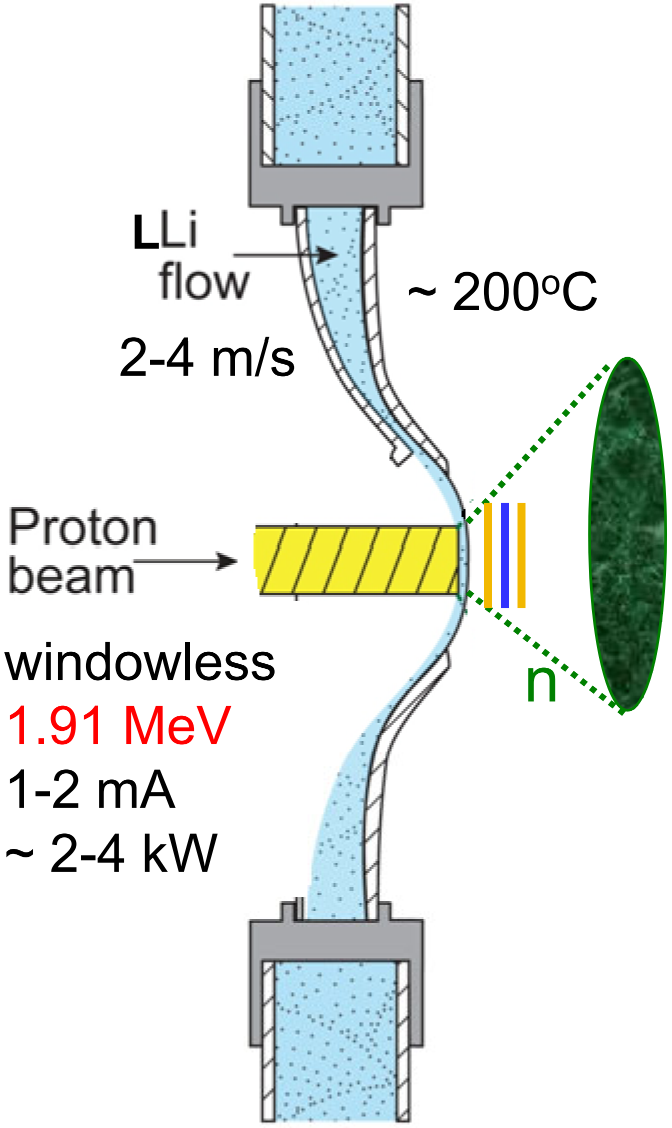
^{7}Li(p,n)^{7}Be reaction just above threshold
E_n= 1.91 MeV



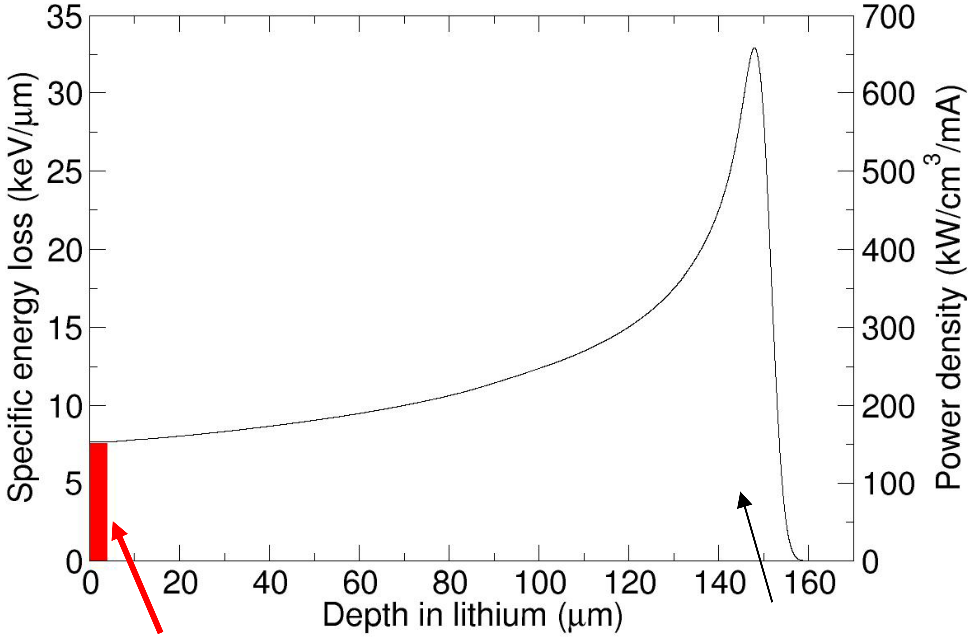


Ratynski & Kaeppeler,1988
Feinberg et al, 2012
Lederer et al, 2012

LiLiT (*Li*quid-*Li*thium *T*arget) : neutrons from ^{7}Li(*p*,*n*) with a mA-proton (kW) beam



windowless
1.91 MeV
1-2 mA
~ 2-4 kW



neutron production
E_p^{thresh} = 1.880 MeV

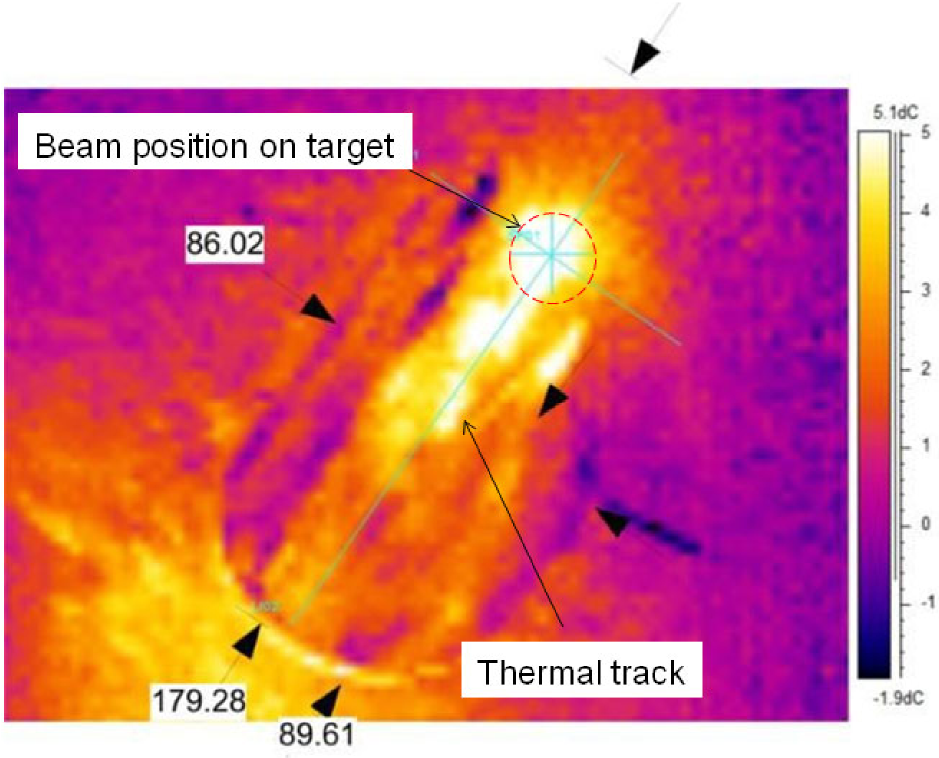
power dissipation
by fast flow

S. Halfon et al., RSI (2014)
M.P. et al (2019)

Li flow: both neutron producing target and power dump

Optical camera

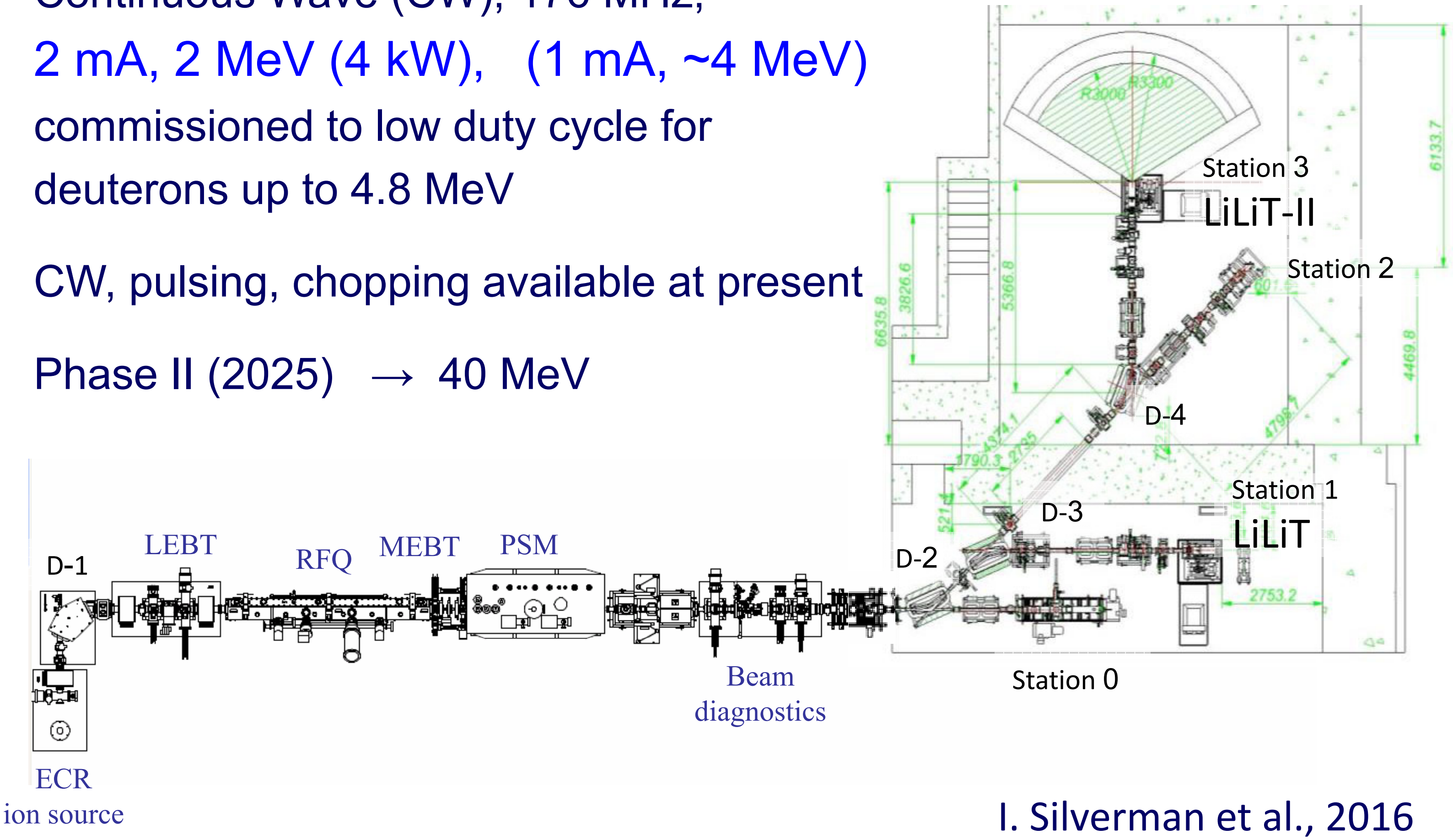
Power dissipation
1.91 MeV/1.5 mA
3 kW beam CW
35 kW/cm^2
0.7 MW/cm^3
vacuum 10^{-5} Torr



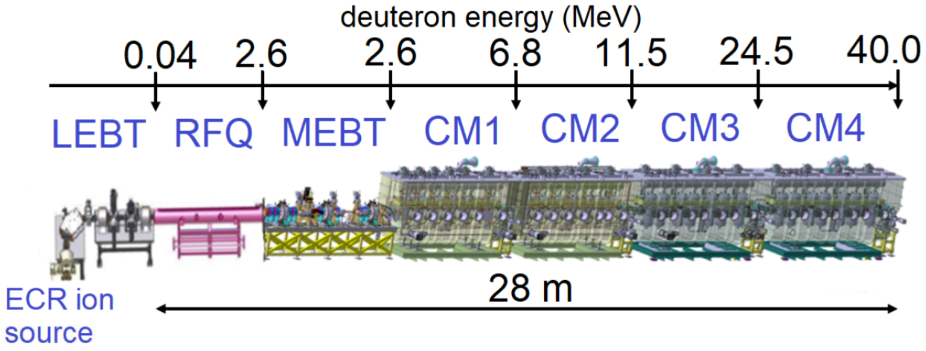
Infrared camera

SARAF (Soreq Applied Research Accelerator Facility)

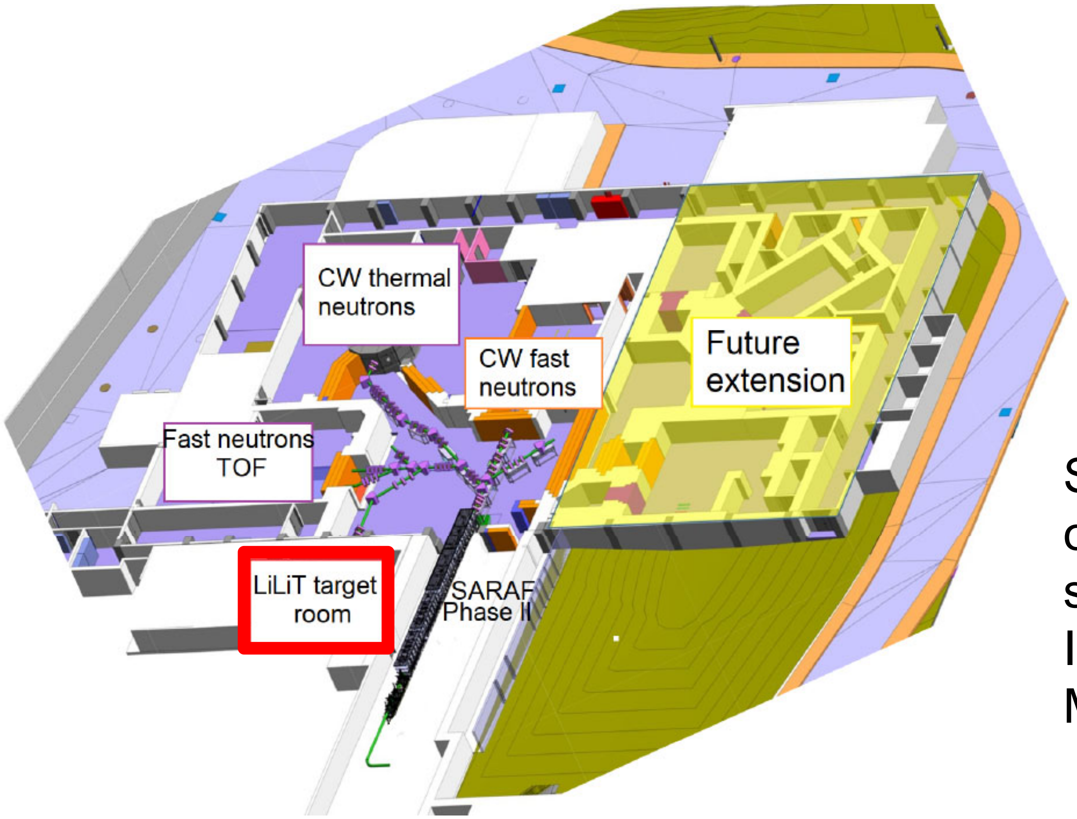
- Superconducting linear accelerator, Phase I (2012-2019)
  Continuous Wave (CW), 176 MHz,
  2 mA, 2 MeV (4 kW), (1 mA, ~4 MeV)
  commissioned to low duty cycle for
  deuterons up to 4.8 MeV
- CW, pulsing, chopping available at present
- Phase II (2025) → 40 MeV



I. Silverman et al., 2016
M.P. et al., 2019



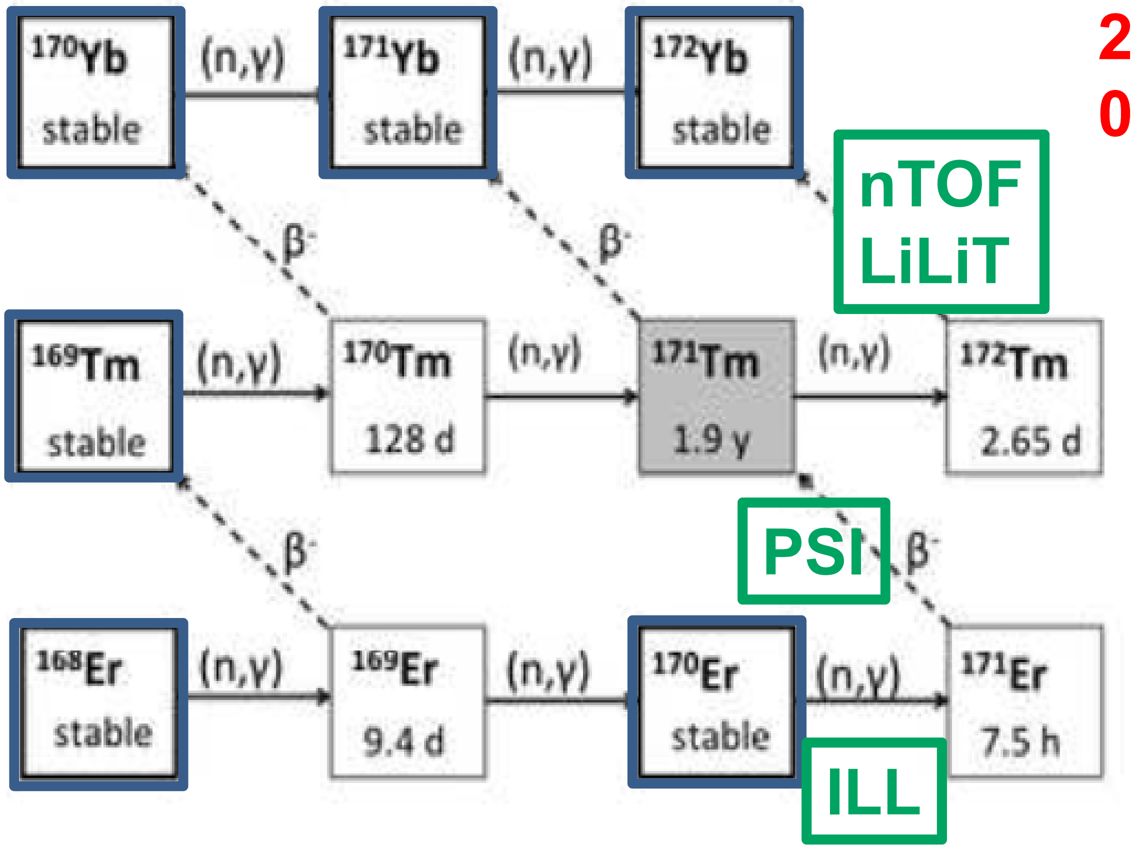
Phase II (2025) :
p/d: 30/40 MeV/5 mA



SARAF Phase II
operational ~2025
see:
I. Mardor et al., EPJA 2019
M.P. et al, EPJA 2022

^{171}Tm (1.9 y)
s- process branching points

^{171}Tm
24 GBq
0.60 mg



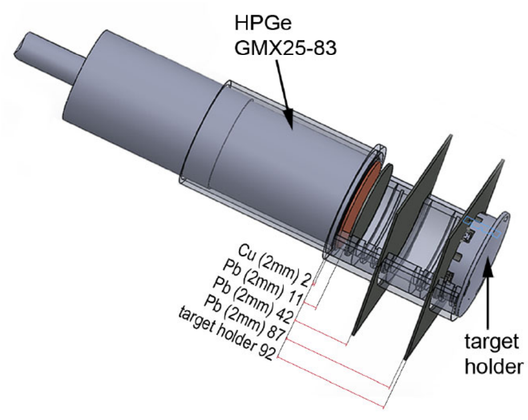
nTOF
LiLiT

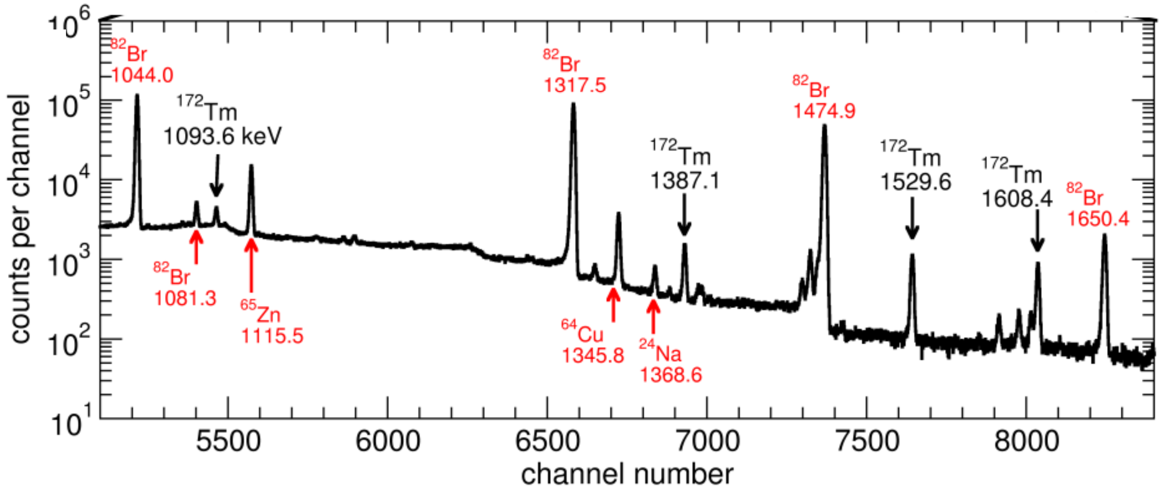
U of Seville

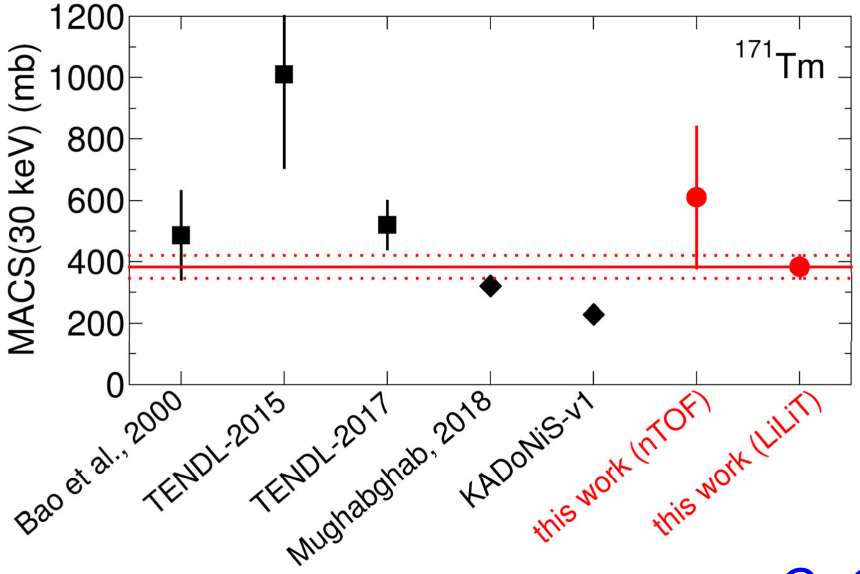
PSI

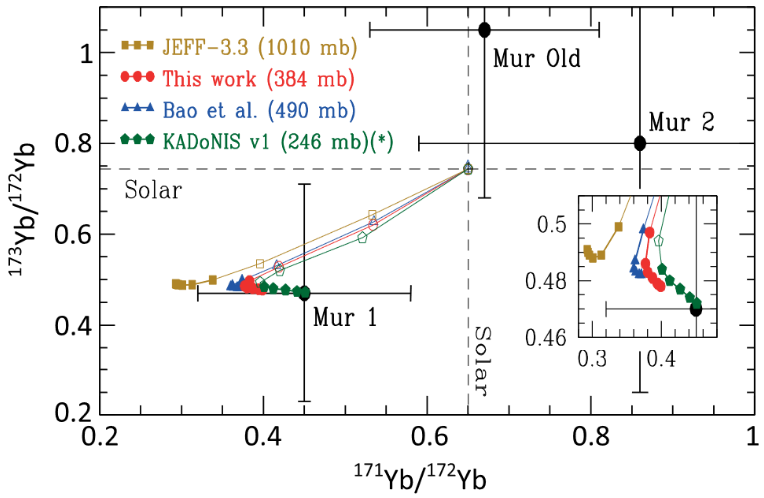
ILL

Activation of small mass radioactive targets

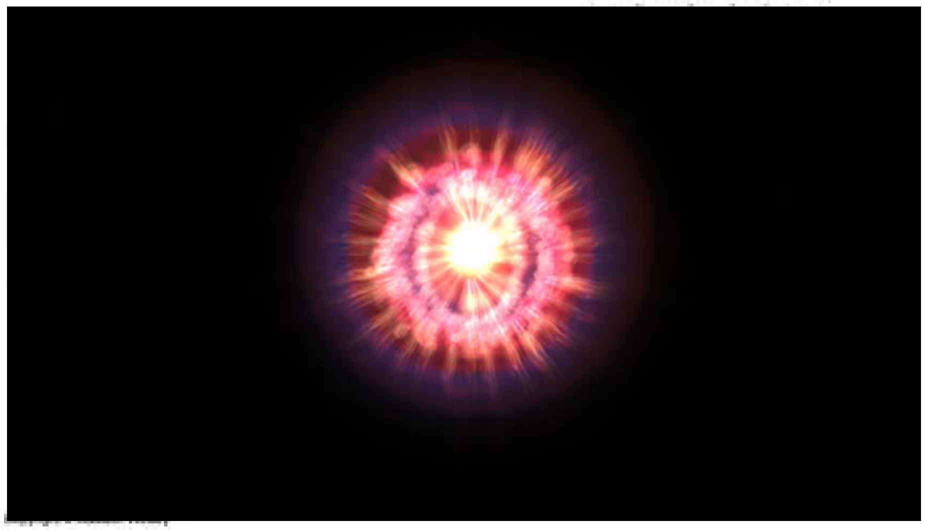






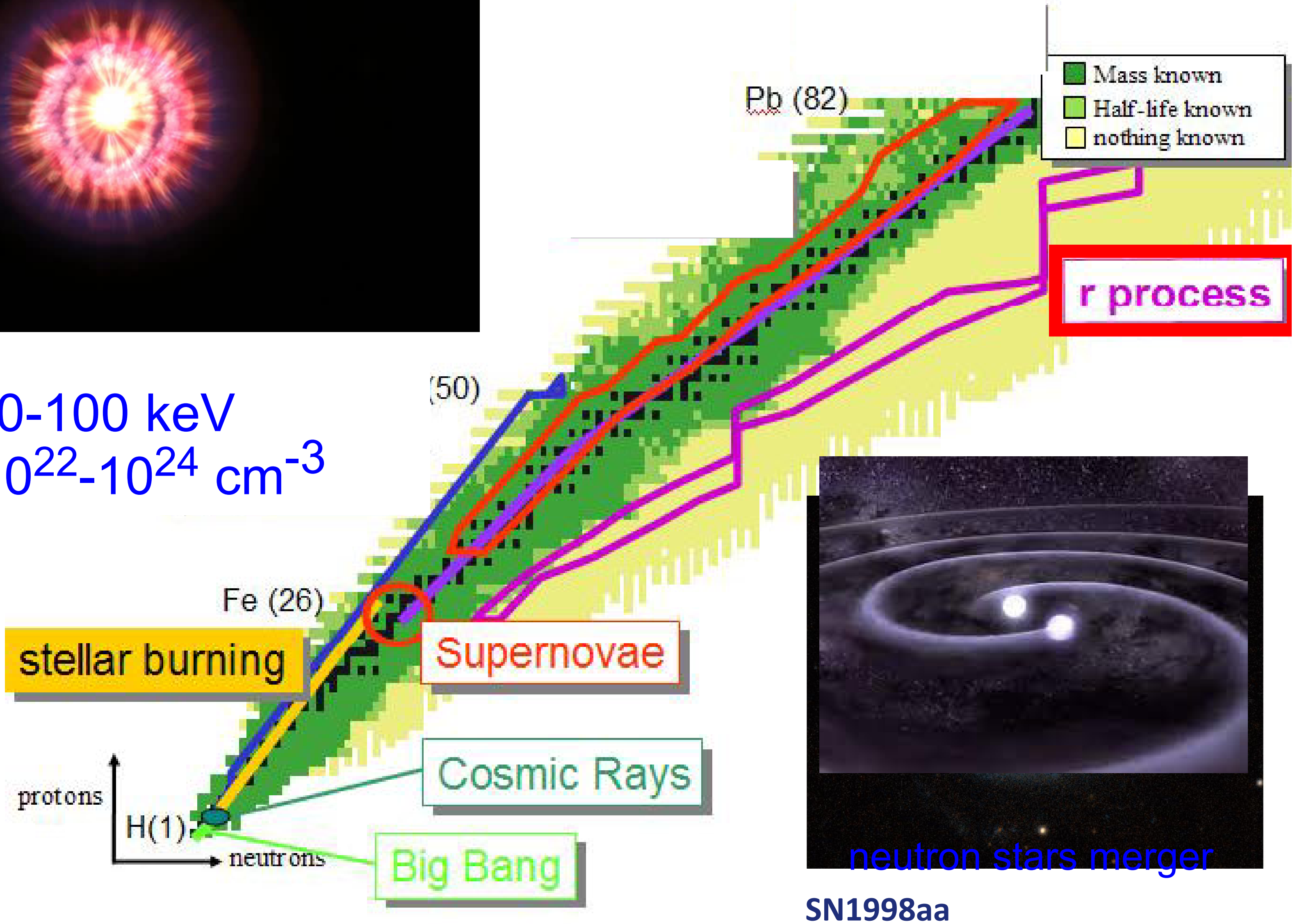


C. Guerrero et al.
PRL (2020)

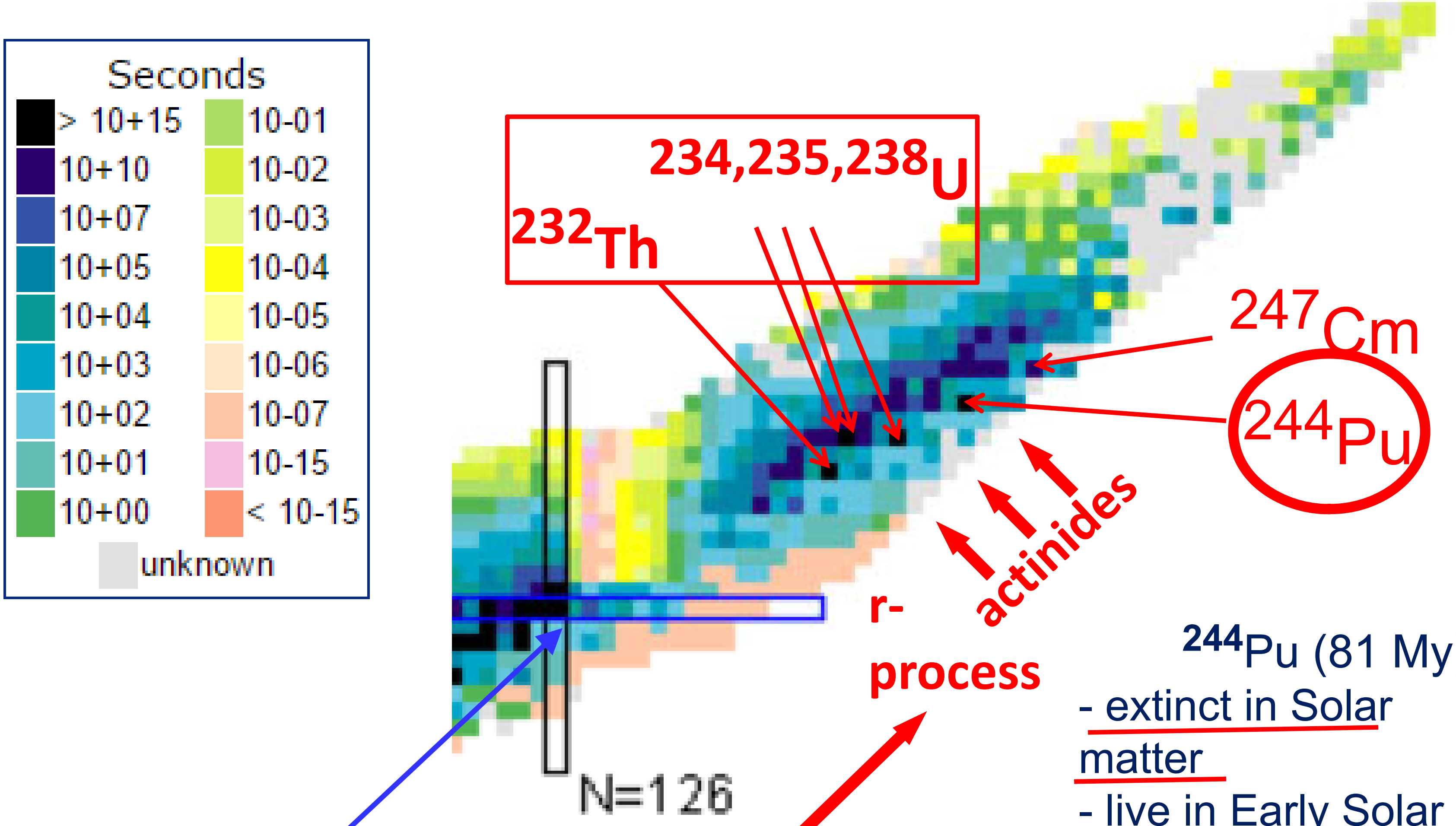


$E_n \sim 80\text{-}100\ \mathrm{keV}$

$\rho_n = 10^{22}\text{-}10^{24}\ \mathrm{cm}^{-3}$



SN1998aa



end of
slow n captures
(s-process)

Supernovae
Neutron star mergers

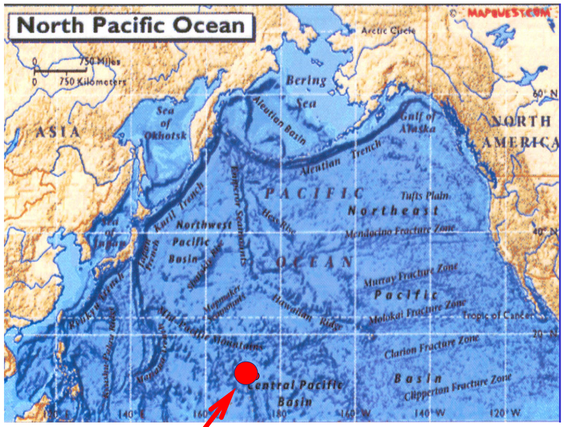
^{244}Pu (81 My)

- extinct in Solar matter
- live in Early Solar System (ESS)

(^{244}Pu/^{238}U ~ 0.6%)

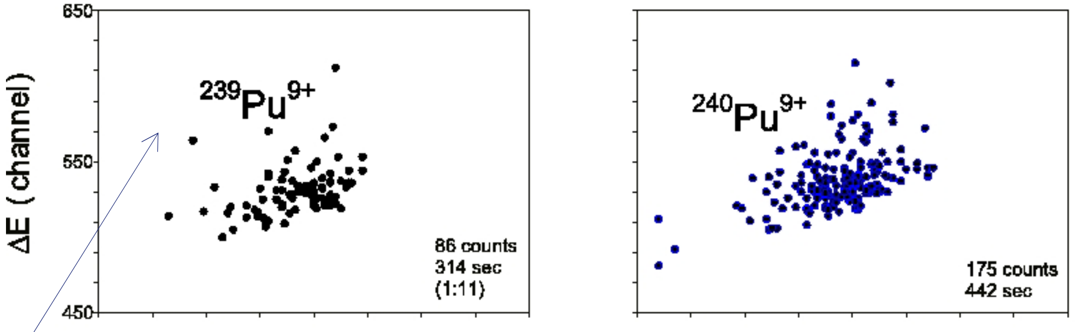
- live in Interstellar Medium?

A search for ^{244}Pu deposited from InterStellar Matter deposited on Earth

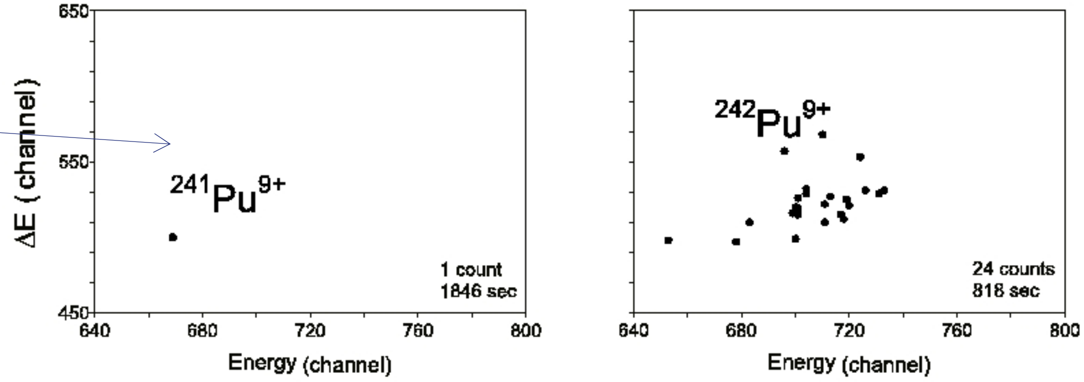


1-kg deep-sea floor sediment

nuclear tests global fallout



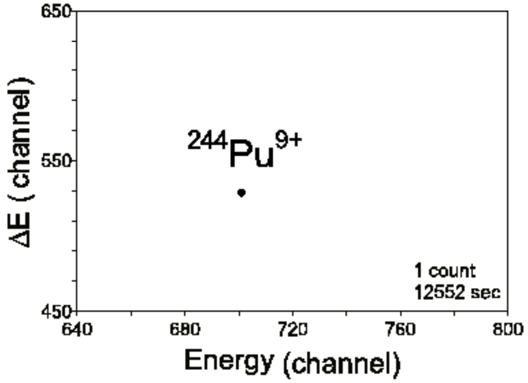
Accelerator Mass Spectrometry (AMS) of Pu isotopes



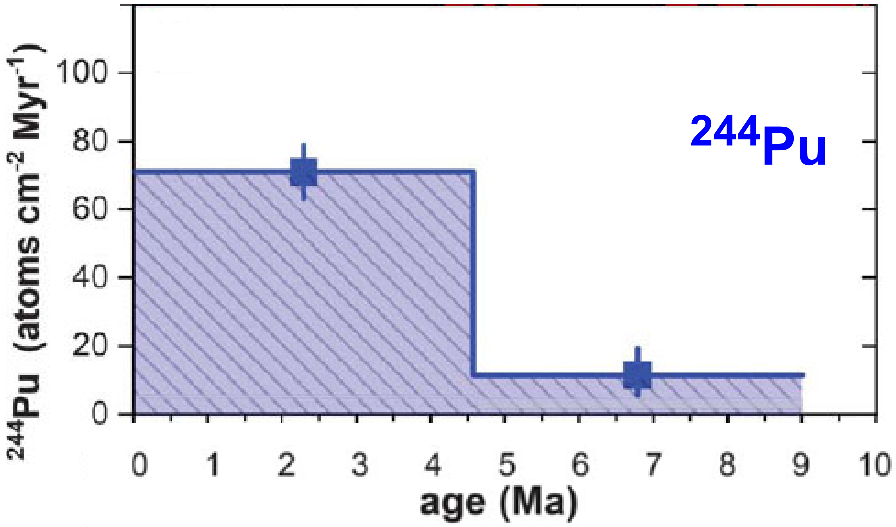
under reasonable assumptions:

^{244}Pu(ISM) < 0.1-0.3 ^{244}Pu(ESS)

MP et al., ApJL (2001)



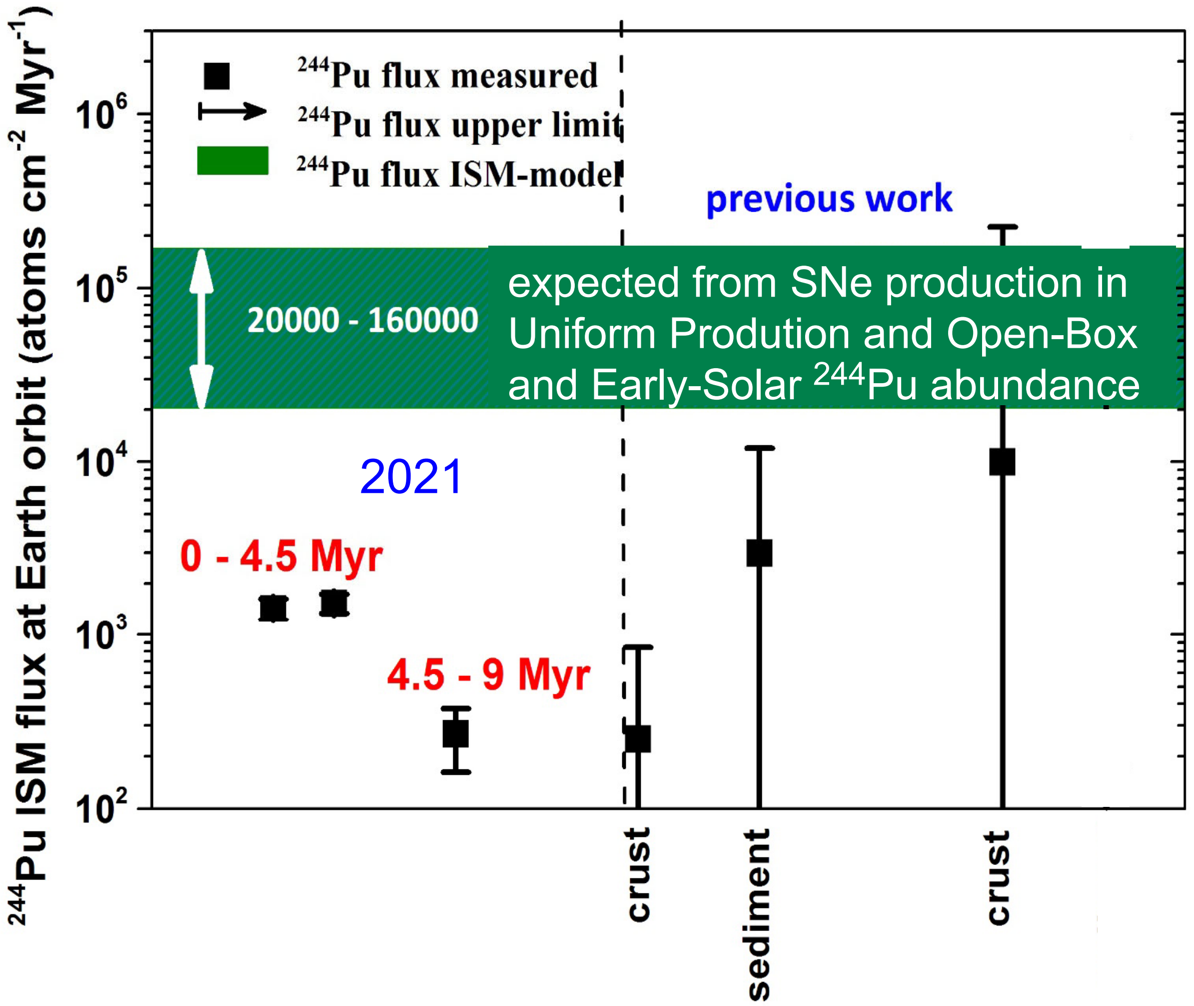
^{244}Pu/total ~ 1.5×10^{-20}



Detection of
r-process ^{244}Pu
in a deep-sea crust
sample

A. Wallner et al.,
Nature Commun. (2015)

A. Wallner et al.,
Science (2021)

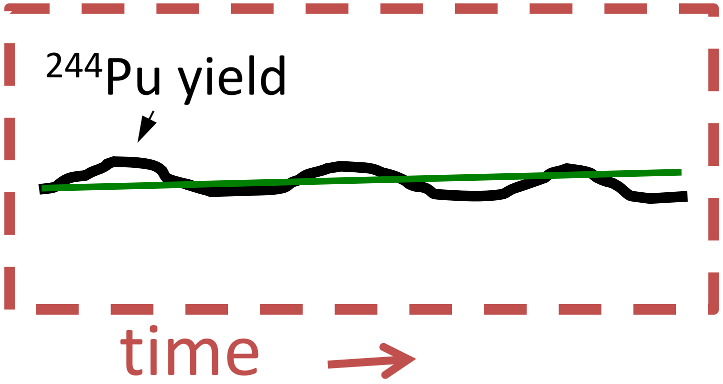


- ^{244}Pu deposited from the ISM is “**rare**” compared to the ESS value and to Uniform Production by Supernovae

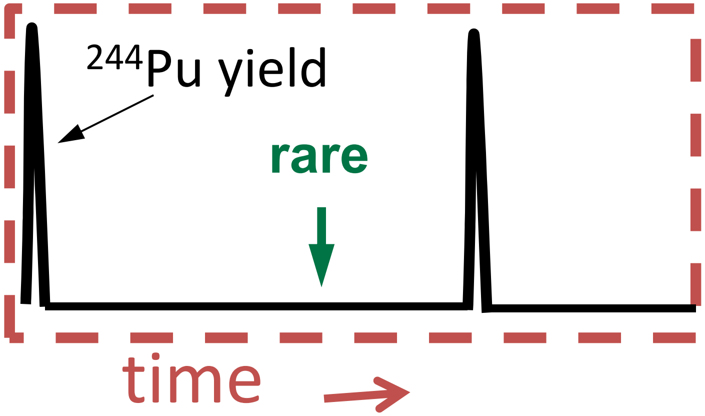
r-process sites: supernovae (Sne), neutron star mergers (NSM)

SNe: low-yield high-rate

SNe Uniform Prodution



NSM: high-yield low-rate

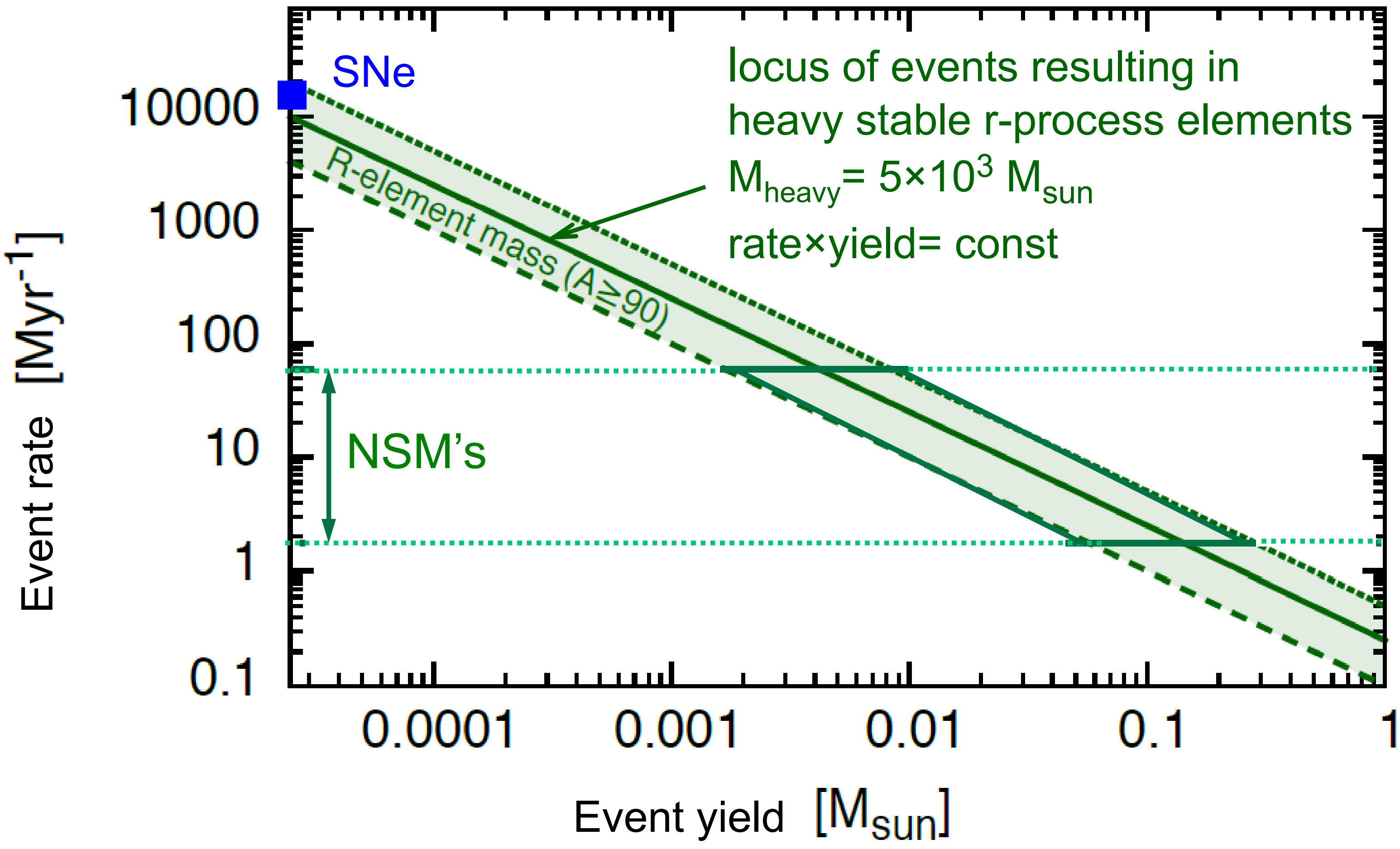


“Short-lived” ^{244}Pu can help resolve the ambiguity:

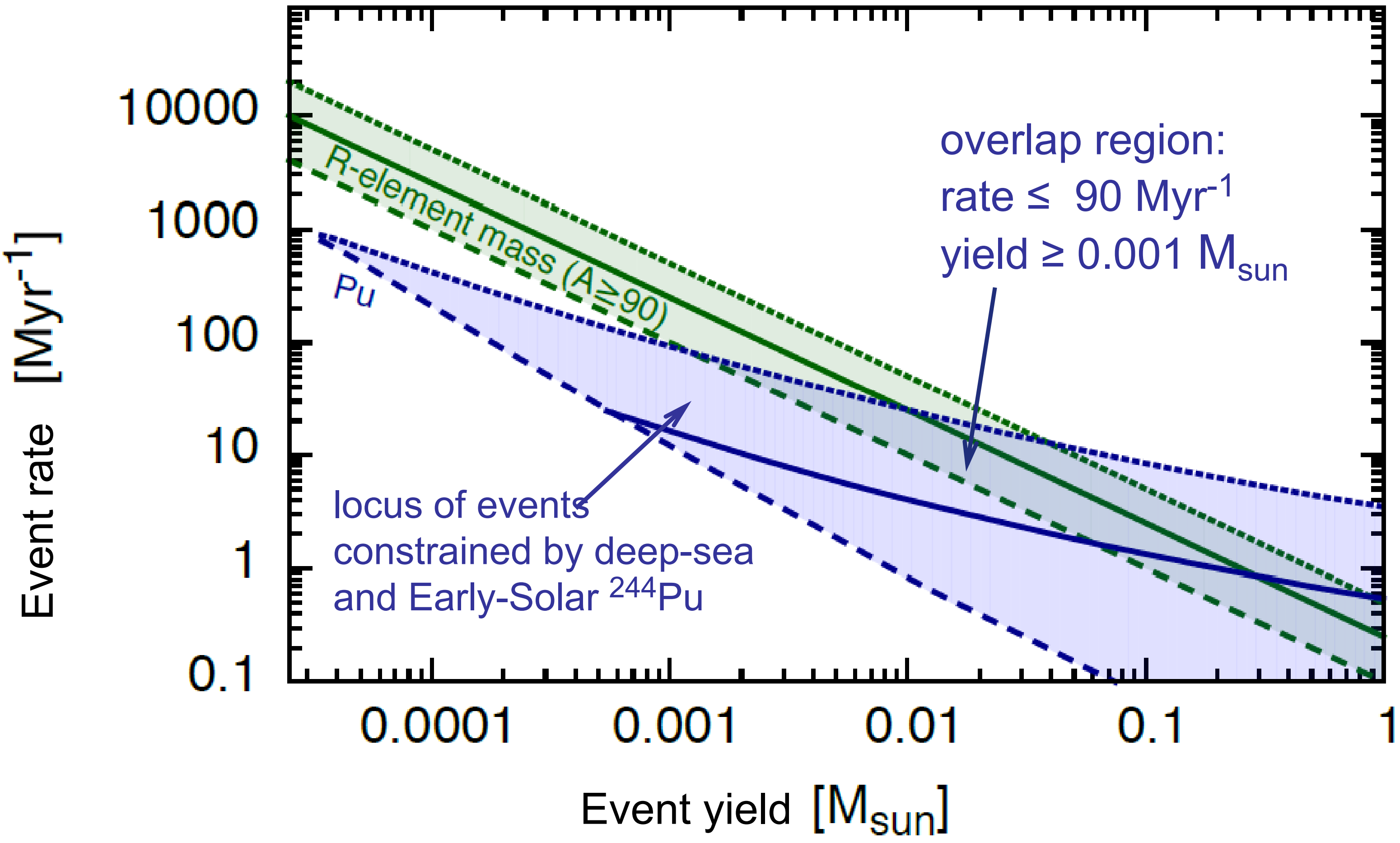
Supernovae (SNe) have “high” rate and “low” r-process yield

Neutron star mergers (NSM) Have “low” rate and “high” yield

rate(SN)/rate(NSM) ~ 1000
yield(SN)/rate(NSM ~ 1/1000



"Short-lived" *r*-nuclides (e.g. ^{244}Pu) can resolve the ambiguity: SNe vs NSM's

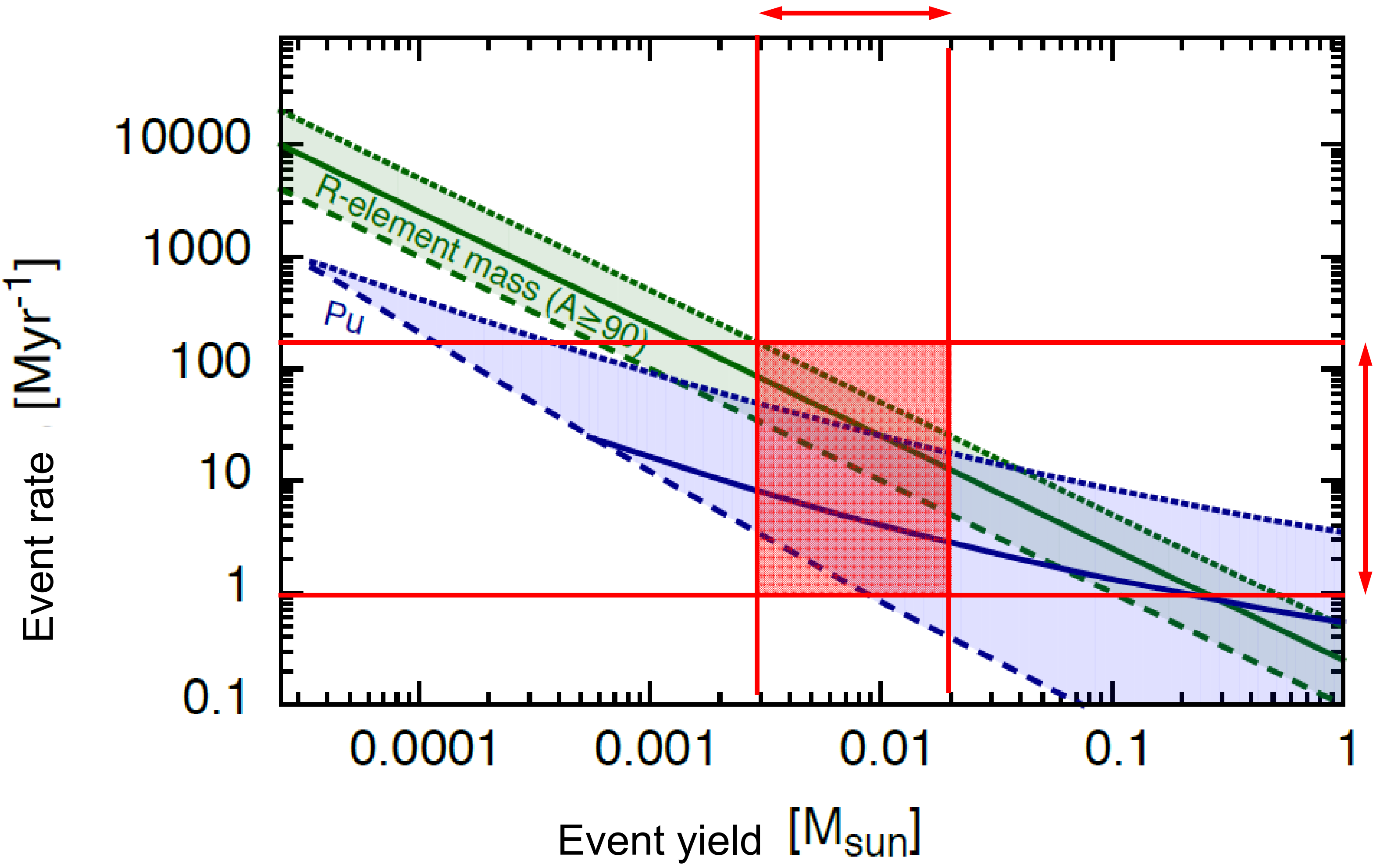


overlap region:
rate ≤ 90 Myr^{-1}
yield ≥ 0.001 M_{sun}

locus of events constrained by deep-sea and Early-Solar ^{244}Pu

K. Hotokezaka, T. Piran, M.P., Nat. Phys. 2015

r-process yield of NSM
Bauswein et al., ApJ 2013, Thielemann et al., ARNPS 2017



GW (NSM)
observations:
LIGO-
VIRGO-
KAGRA,
PR X (2023)

Rarity of ^{244}Pu observed in deep-sea sediments is consistent with yield and rate of “macronovae” from NSM’s

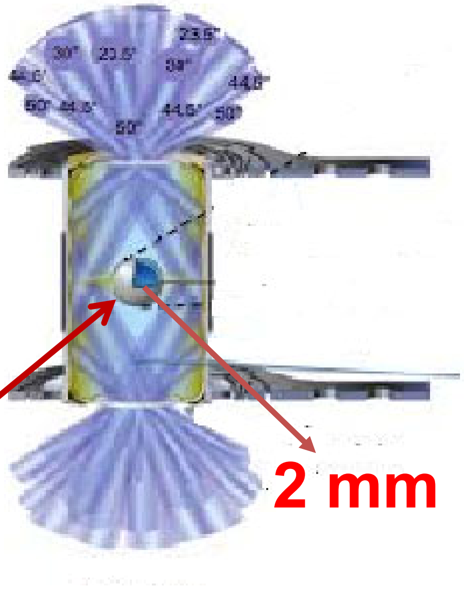
Can one reproduce r-process conditions in the lab?

National Ignition Facility (NIF) at LLNL

dia 10 m

192 laser beams directed towards the center of the chamber

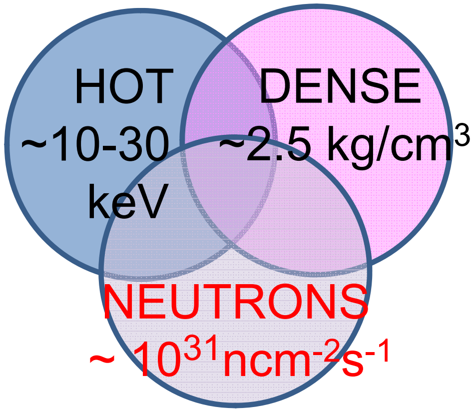
Laser energy/power:
1.8 MJ/400 TW



2 mm

D + T → ^{4}He+n

ρ_n~10^{22} cm^{-3}
Φ_n~ 10^{31} cm^{-2} s^{-1}



HOT
~10-30 keV

DENSE
~2.5 kg/cm^3

NEUTRONS
~ 10^{31}ncm^{-2}s^{-1}

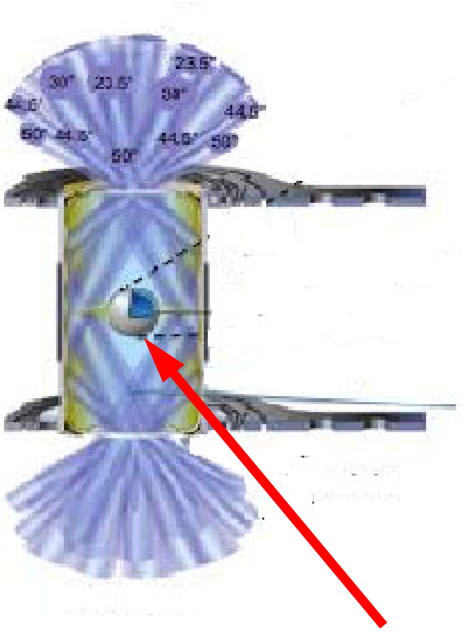
Zylstra et al., Nature (2022)
Abu-Shawareb et al., PRL (2022)

The closest analog to explosive stellar conditions in the laboratory

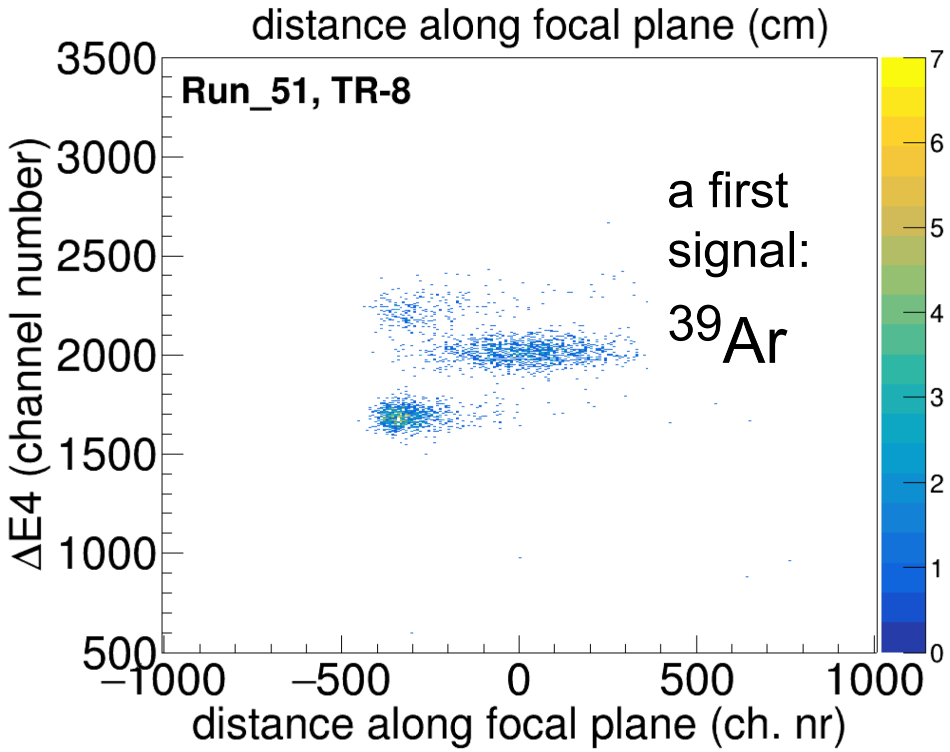
r- process site:
10^{22}-10^{24} n cm^{-3}

NIF experiment: DT+Ar shot at NIF

$^{40}\mathbf{Ar(n,2n)}^{39}\mathbf{Ar}$ collected and shipped to ATLAS-ANL



noble gas argon
added to DT gas



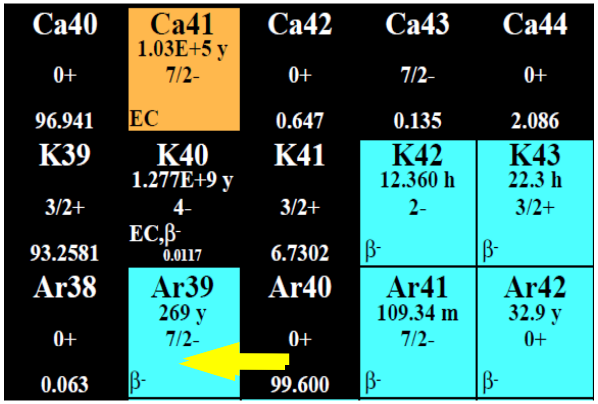
a first signal: ^{39}Ar

DT (1:1)+ ^{40}Ar (0.05 at%)

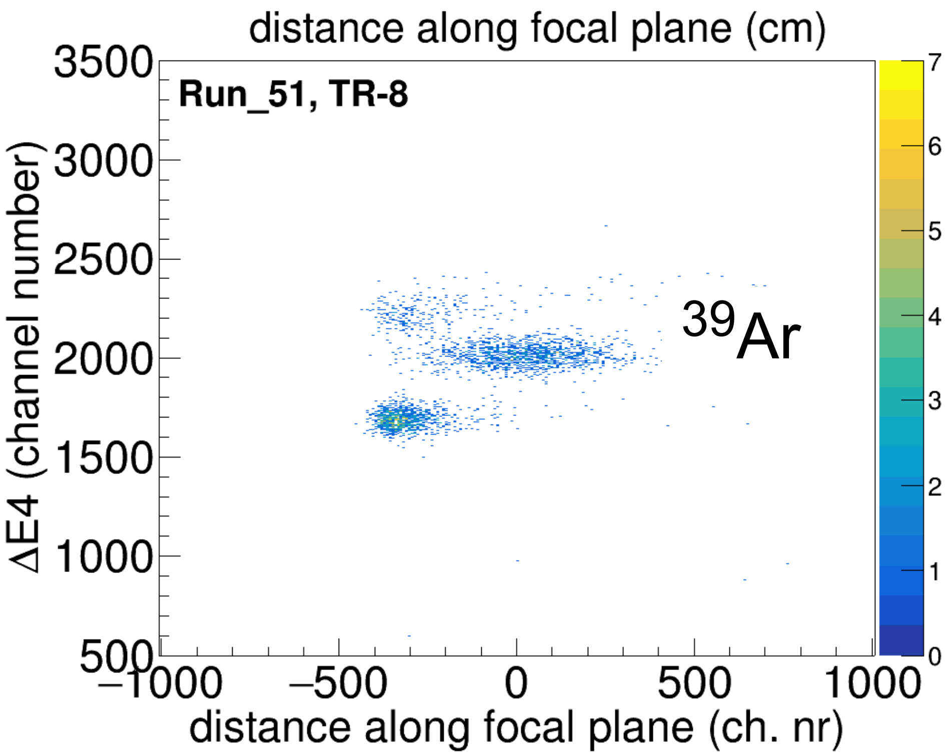
8×10^{9} ^{39}Ar atoms

NIF experiment: DT+Ar shot at NIF

$^{40}\mathrm{Ar}(n,2n)^{39}\mathrm{Ar}$ collected and shipped to ATLAS-ANL



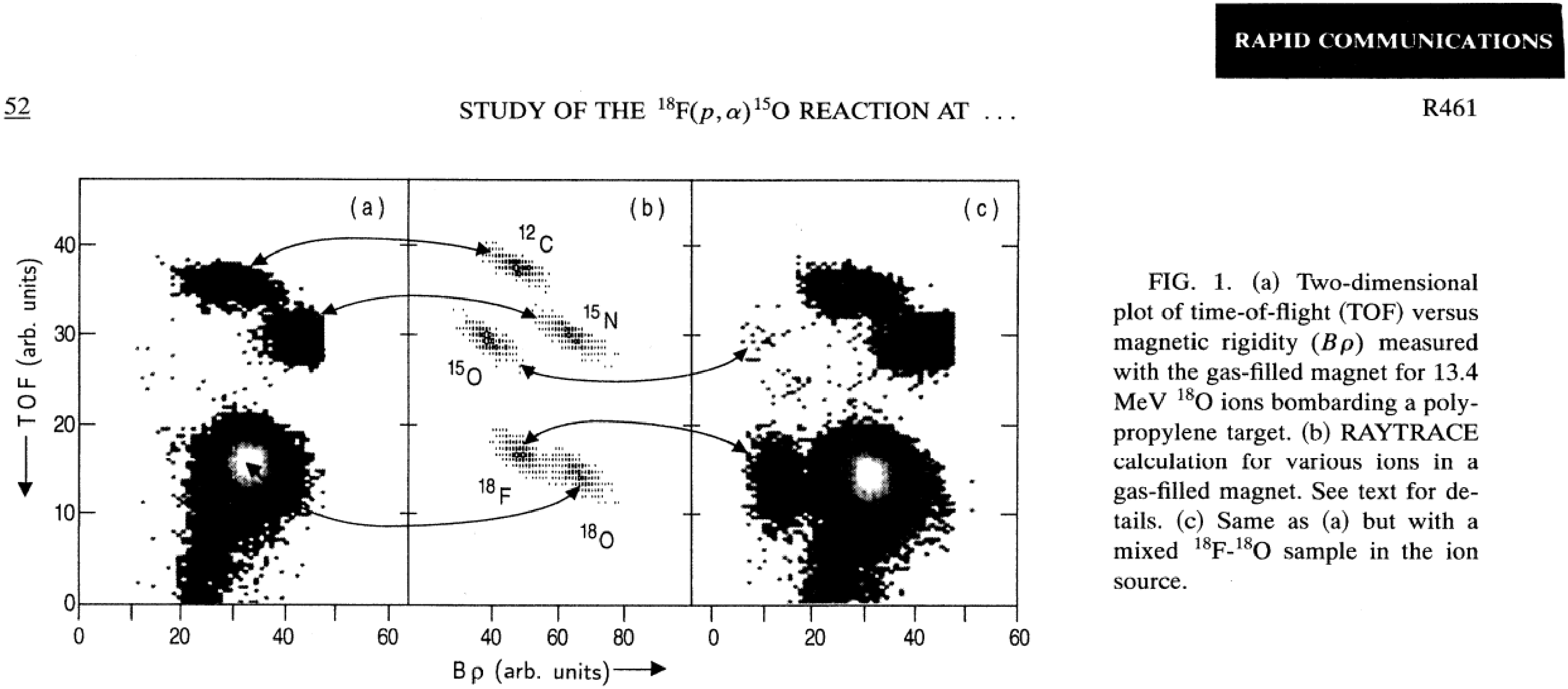
Ca40 0+ 96.941	Ca41 1.03E+5 y 7/2- EC	Ca42 0+ 0.647	Ca43 7/2- 0.135	Ca44 0+ 2.086
K39 3/2+ 93.2581	K40 1.277E+9 y 4- EC,β- 0.0117	K41 3/2+ 6.7302	K42 12.360 h 2- β-	K43 22.3 h 3/2+ β-
Ar38 0+ 0.063	Ar39 269 y 7/2- β-	Ar40 0+ 99.600	Ar41 109.34 m 7/2- β-	Ar42 32.9 y 0+ β-



8×10^{9} ^{39}Ar atoms

AMS detection in the Enge gas-filled magnetic spectrograph

First radioactive beam experiments at Argonne: p(^{18}F,α)^{15}O…
K.E. Rehm et al., PRC (1995) with John P. Schiffer



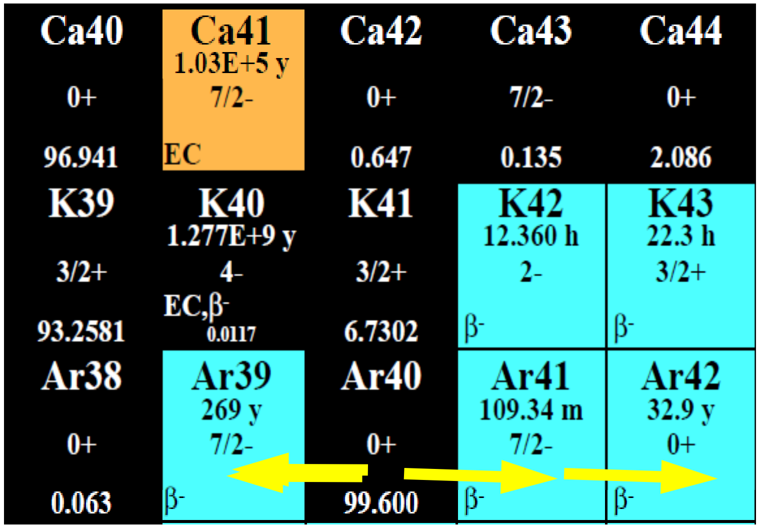
RAPID COMMUNICATIONS

52 STUDY OF THE ^{18}F(p,α)^{15}O REACTION AT . . . R461

FIG. 1. (a) Two-dimensional plot of time-of-flight (TOF) versus magnetic rigidity ($B\rho$) measured with the gas-filled magnet for 13.4 MeV ^{18}O ions bombarding a polypropylene target. (b) RAYTRACE calculation for various ions in a gas-filled magnet. See text for details. (c) Same as (a) but with a mixed ^{18}F-^{18}O sample in the ion source.

AMS detection in the Enge gas-filled magnetic spectrograph

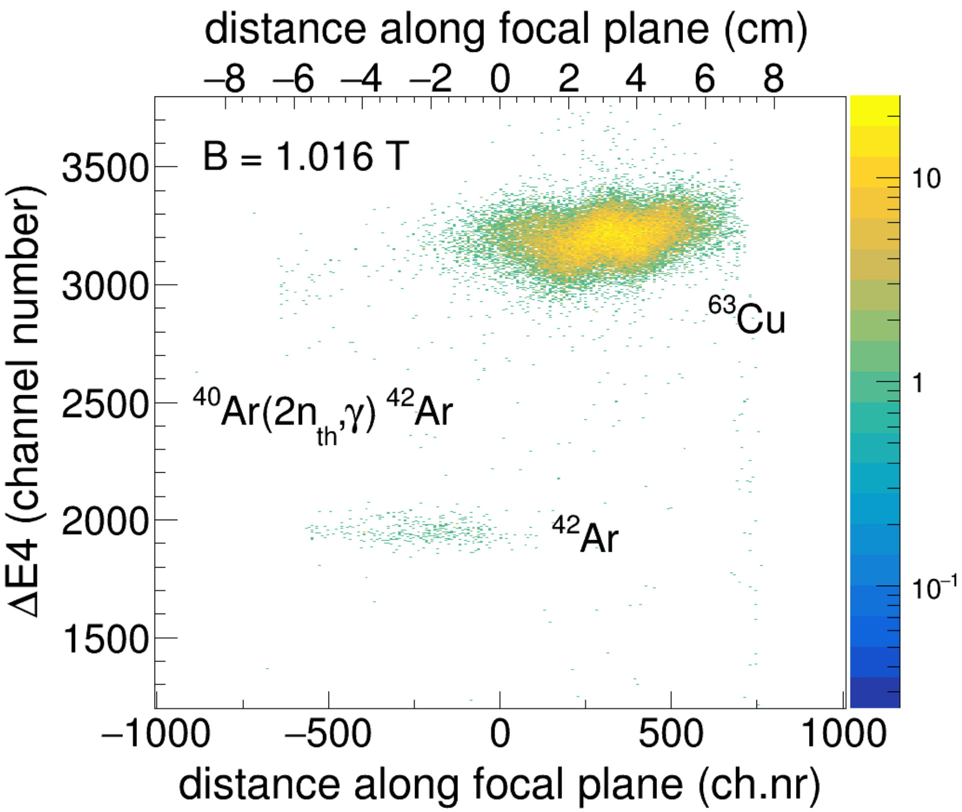
A preliminary measurement: ^{42}Ar produced by “slow” two-neutron capture on ^{40}Ar at the ILL high-flux reactor detected by AMS



Ca40 0+ 96.941	**Ca41** 1.03E+5 y 7/2- EC	**Ca42** 0+ 0.647	**Ca43** 7/2- 0.135	**Ca44** 0+ 2.086
K39 3/2+ 93.2581	**K40** 1.277E+9 y 4- EC,β- 0.0117	**K41** 3/2+ 6.7302	**K42** 12.360 h 2- β-	**K43** 22.3 h 3/2+ β-
Ar38 0+ 0.063	**Ar39** 269 y 7/2- β-	**Ar40** 0+ 99.600	**Ar41** 109.34 m 7/2- β-	**Ar42** 32.9 y 0+ β-

AMS **γ spec** **AMS ?**

Can a “mini-rapid” process be produced and detected in NIF inertial confinement fusion environment?



This talk was heartfully dedicated to the memory of John P. Schiffer.

New accelerators and techniques…
or the importance of being experimentalist

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