GENESIS:

« GEnerating extreme NEutrons for achieving controlled r- process nucleosyntheSIS »

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Since its inception, laser-driven astrophysics allowed remarkable advances

REVIEW: EXPERIMENTAL ASTROPHYSICS

Modeling Astrophysical Phenomena in the Laboratory with Intense Lasers

Bruce A. Remington,[1] David Arnett,[2] R. Paul Drake,[3] Hideaki Takabe[4]

Science, 1999

Breakthroughs:

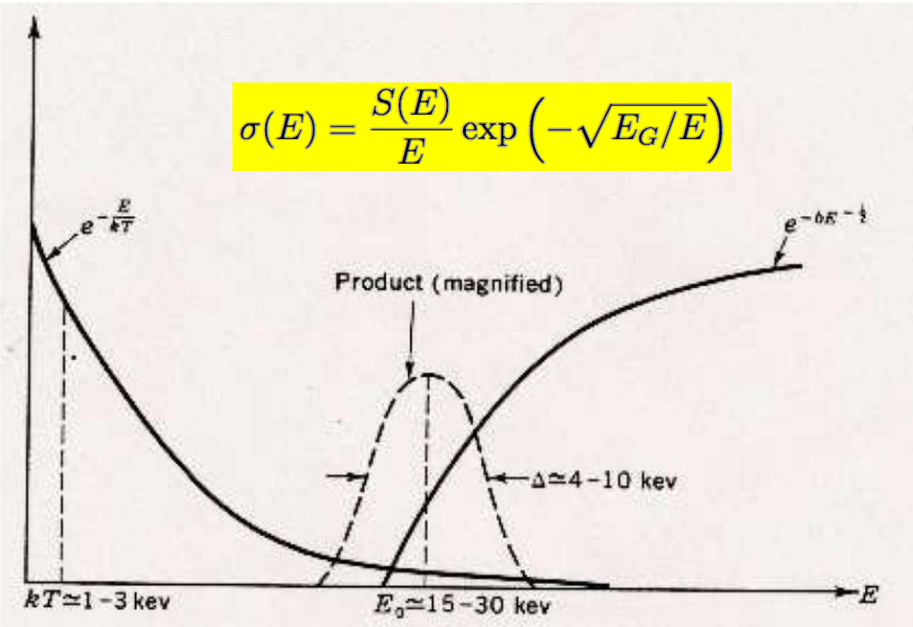
- Hydrodynamic (fluid) instabilities
- Measuring dense, high-pressure plasma states (equation of state)

New paths;

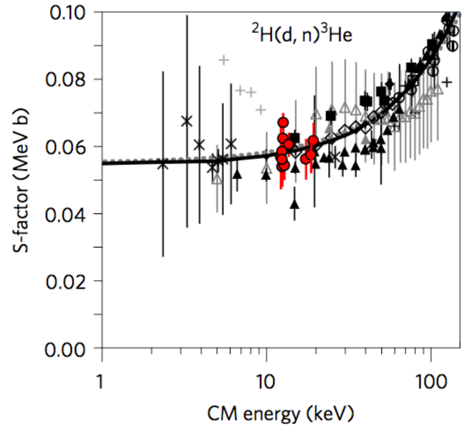
- Magnetized fluid dynamics
- Shocks
- Particle acceleration
- Magnetic reconnection
- etc

Laser-driven nuclear astrophysics as a new page

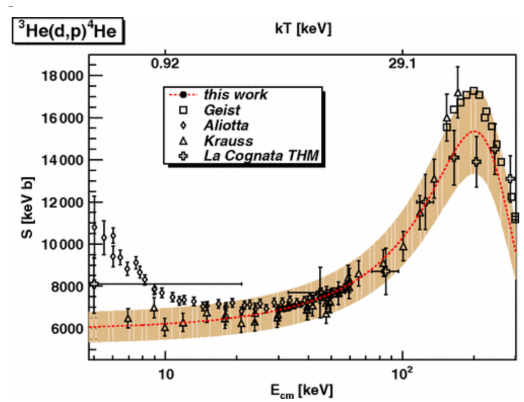
Recent measurements of the S-factor of the fusion cross-section



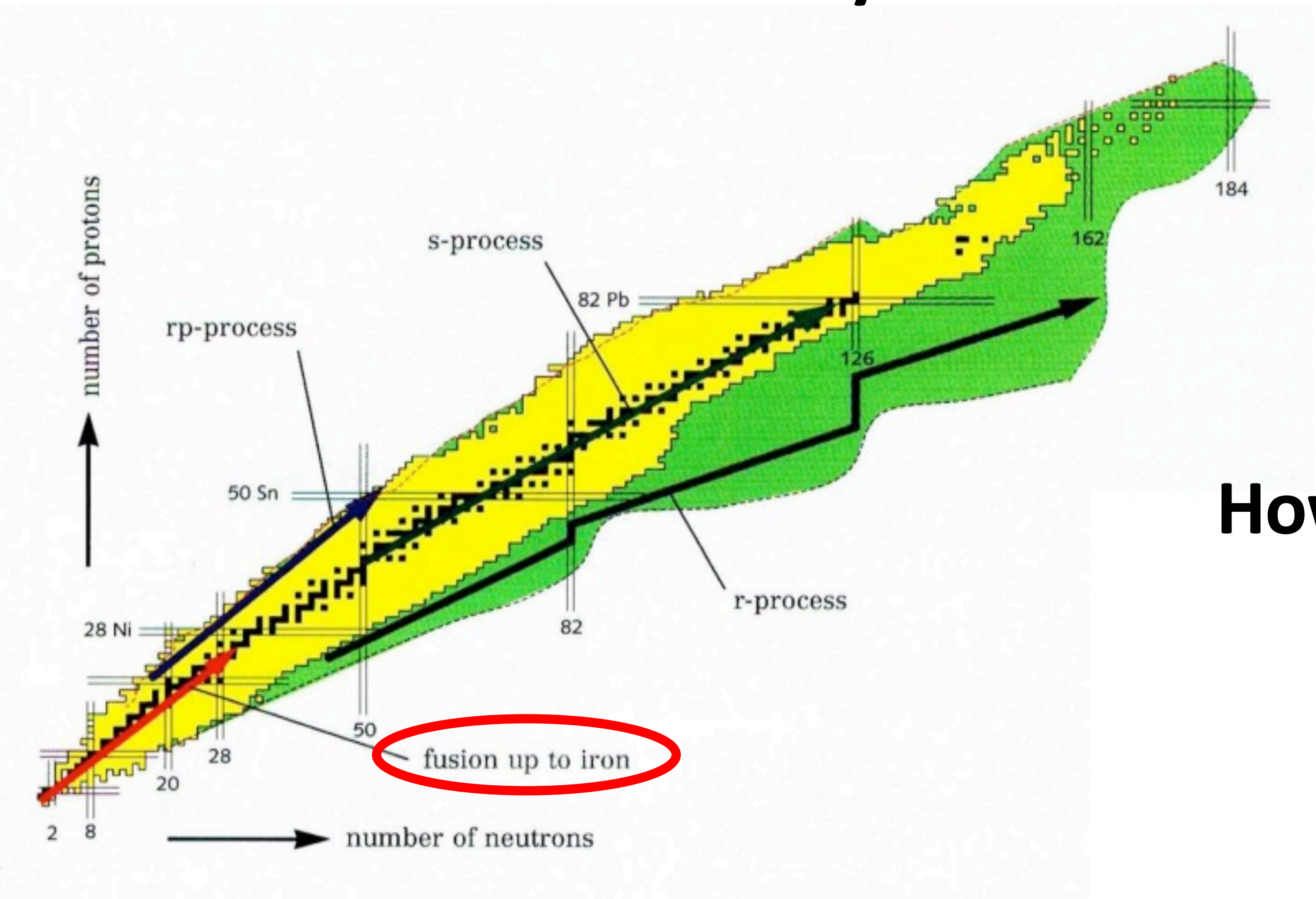
Casey et al.,
Nat Phys (2017)



Barbui et al.,
PRL (2013)

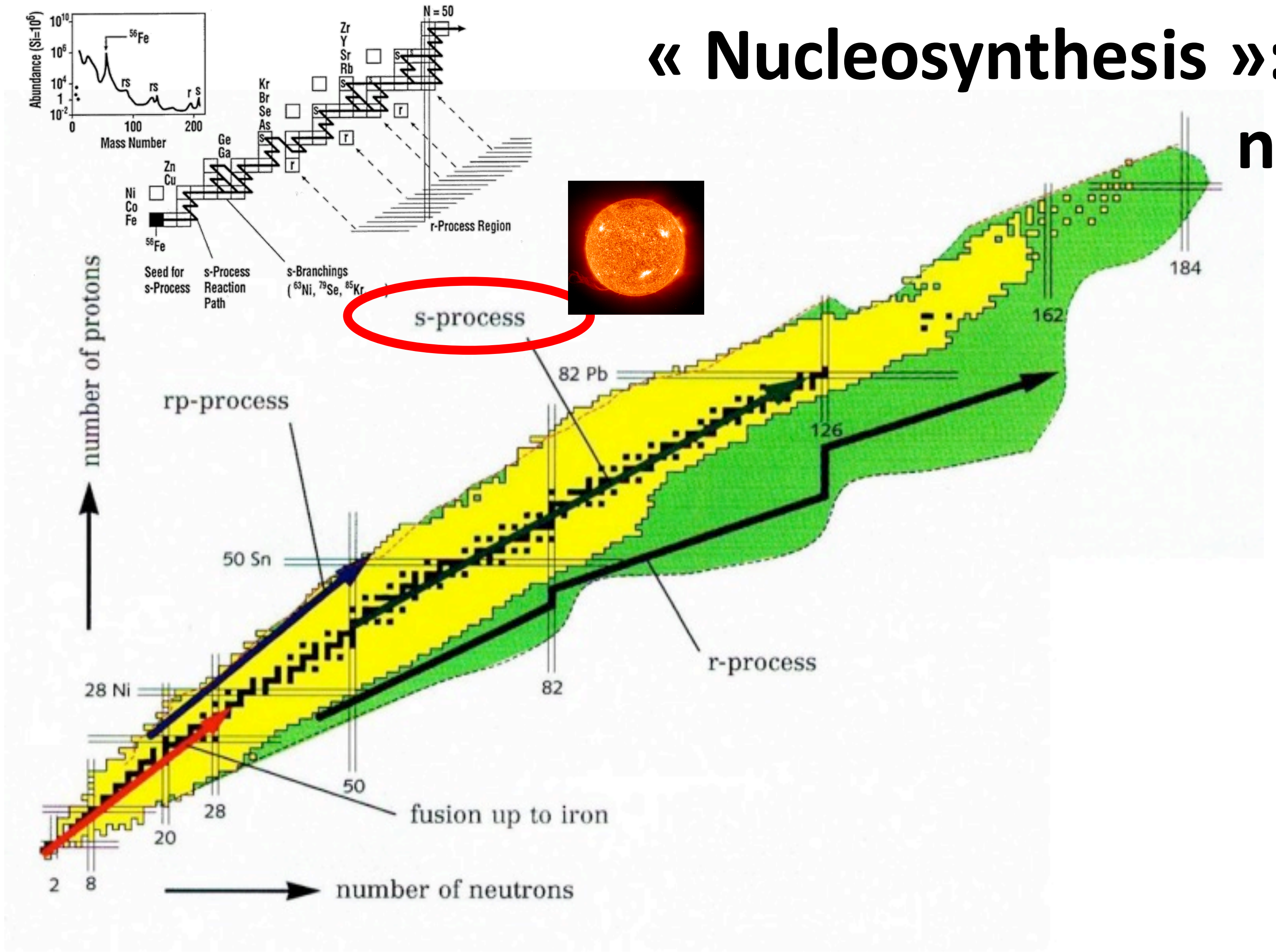


A new direction: « Nucleosynthesis »

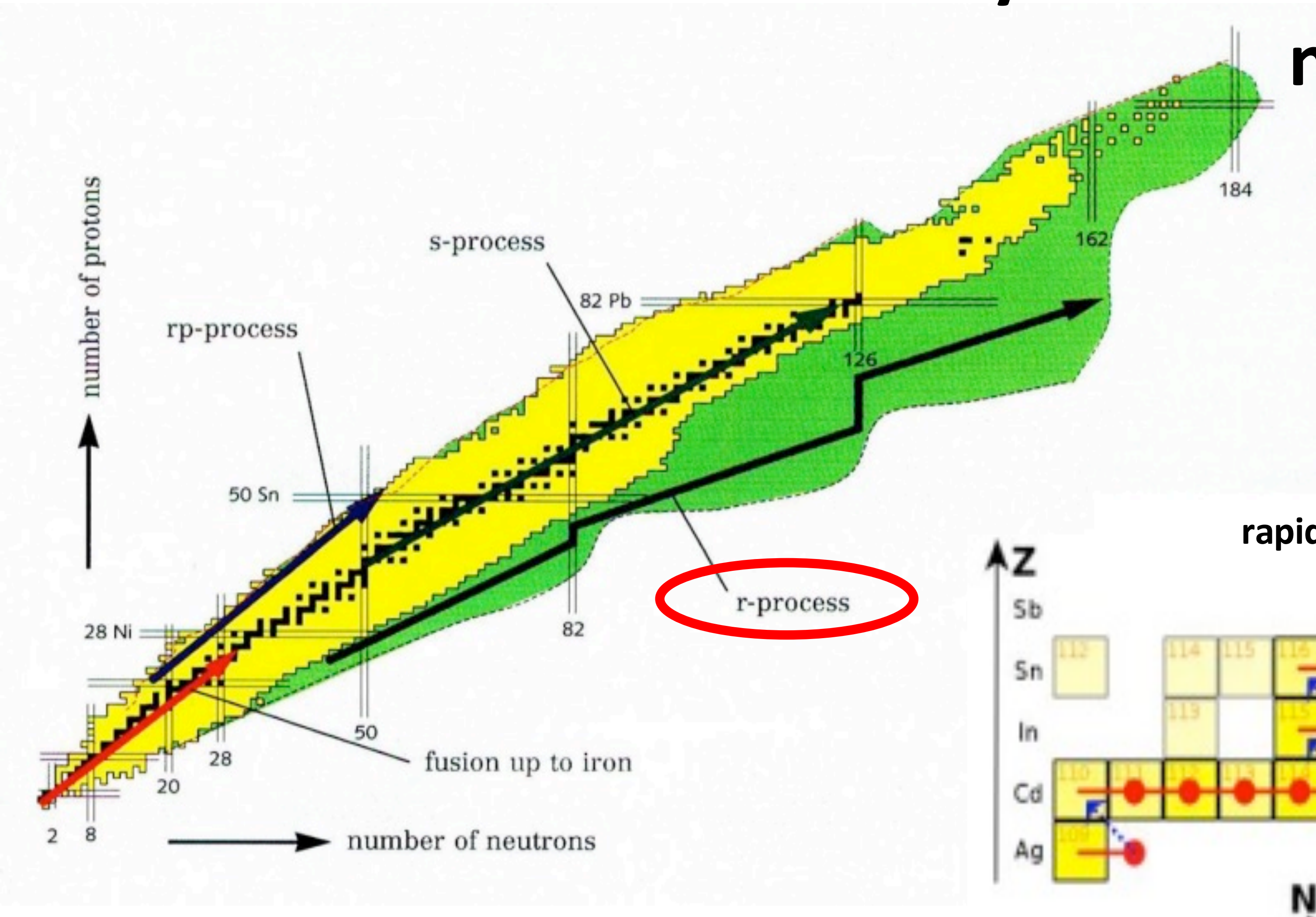


How are the nuclides built?

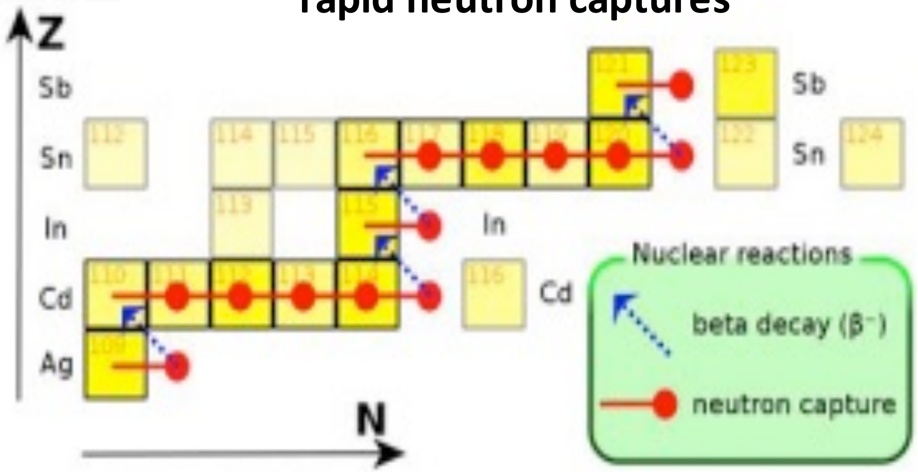
« Nucleosynthesis »: How are the nuclides built?



« Nucleosynthesis »: How are the nuclides built?



r- process
rapid neutron captures



The r-process "in the laboratory" up to now

PHYSICAL REVIEW VOLUME 102, NUMBER 1 APRIL 1, 1956

Transplutonium Elements in Thermonuclear Test Debris*

P. R. Fields, M. H. Studier, H. Diamond, J. F. Mech, M. G. Inghram, G. L. Pyle, C. M. Stevens, S. Fried, and W. M. Manning,
Argonne National Laboratory, Lemont, Illinois

and

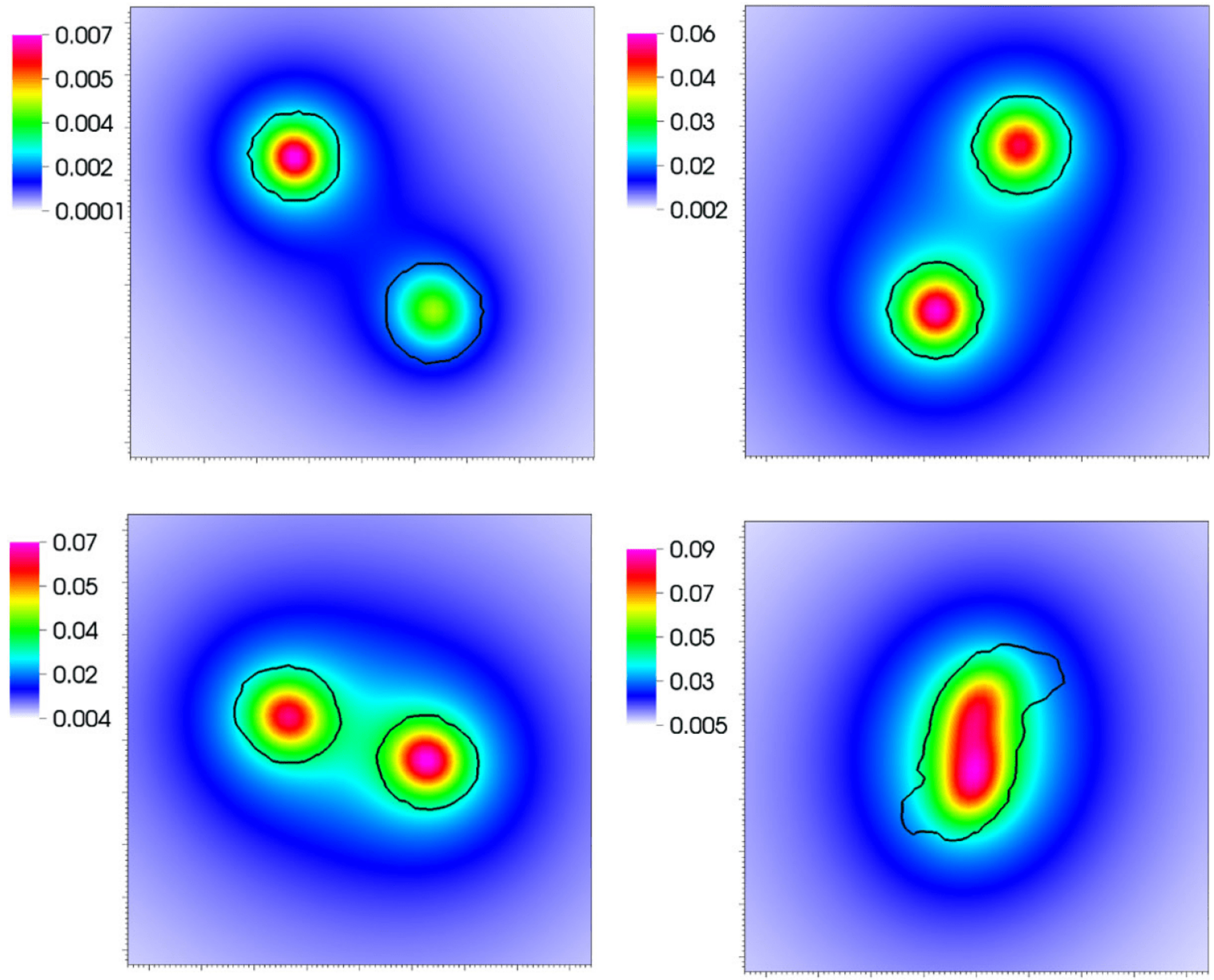
A. Ghiorso, S. G. Thompson, G. H. Higgins, and G. T. Seaborg, *University of California, Berkeley, California*

(Received December 5, 1955)

In nature: Supernova and/or neutron star merger and/or ?

- Signatures of heavy elements production
- Modeling of the electromagnetic emission following the merger → point to pending **uncertainties in nuclear models** of the r-process elements created in the plasma environment

BARAUSSE *et al.*



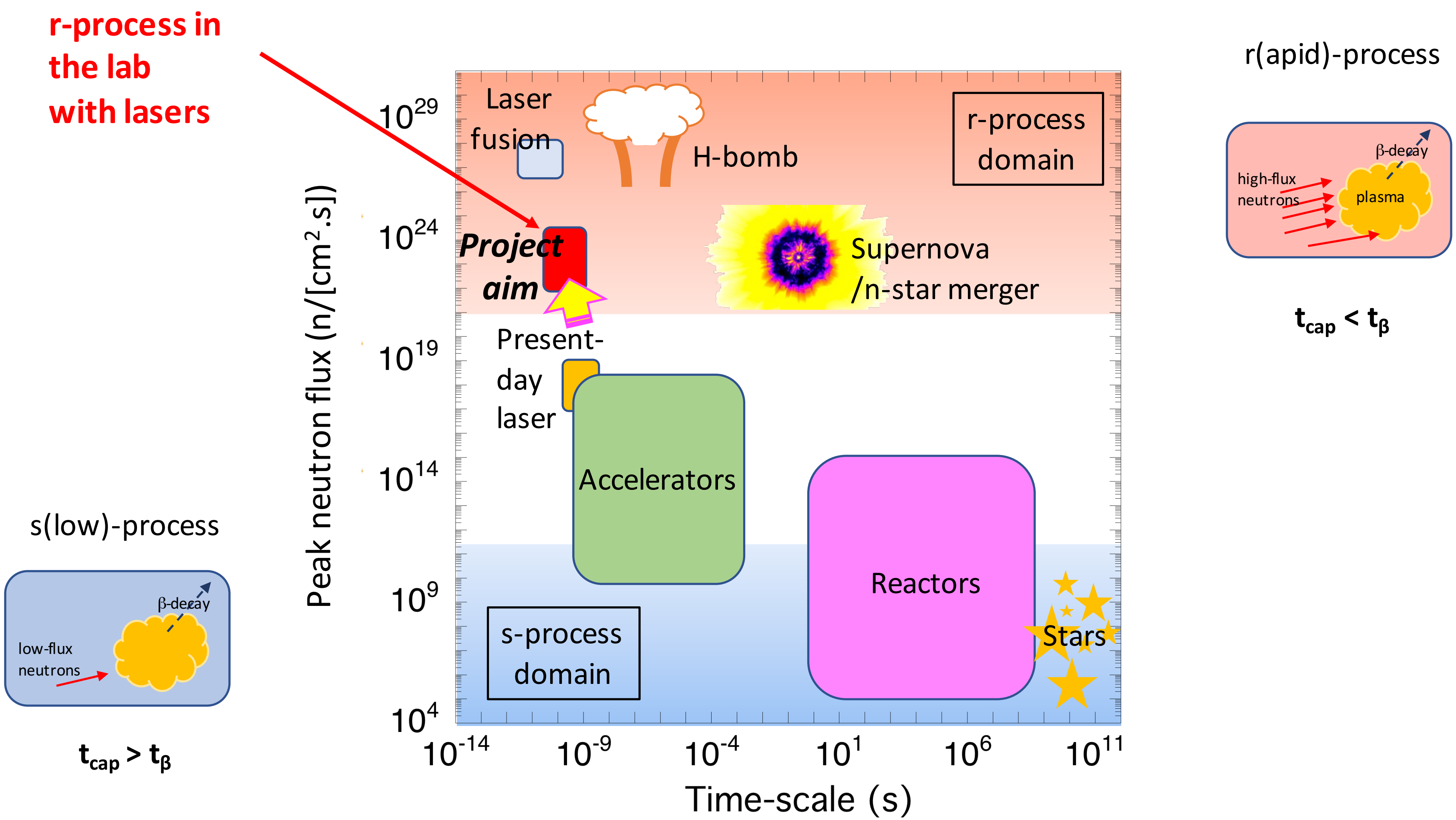
What is at stake?

- No clear picture of the abundance of elements in the universe
- We characterize heavy elements
- But NOT the neutron capture process of unstable elements
- No nuclear parameter is measured in a hot and dense plasma.

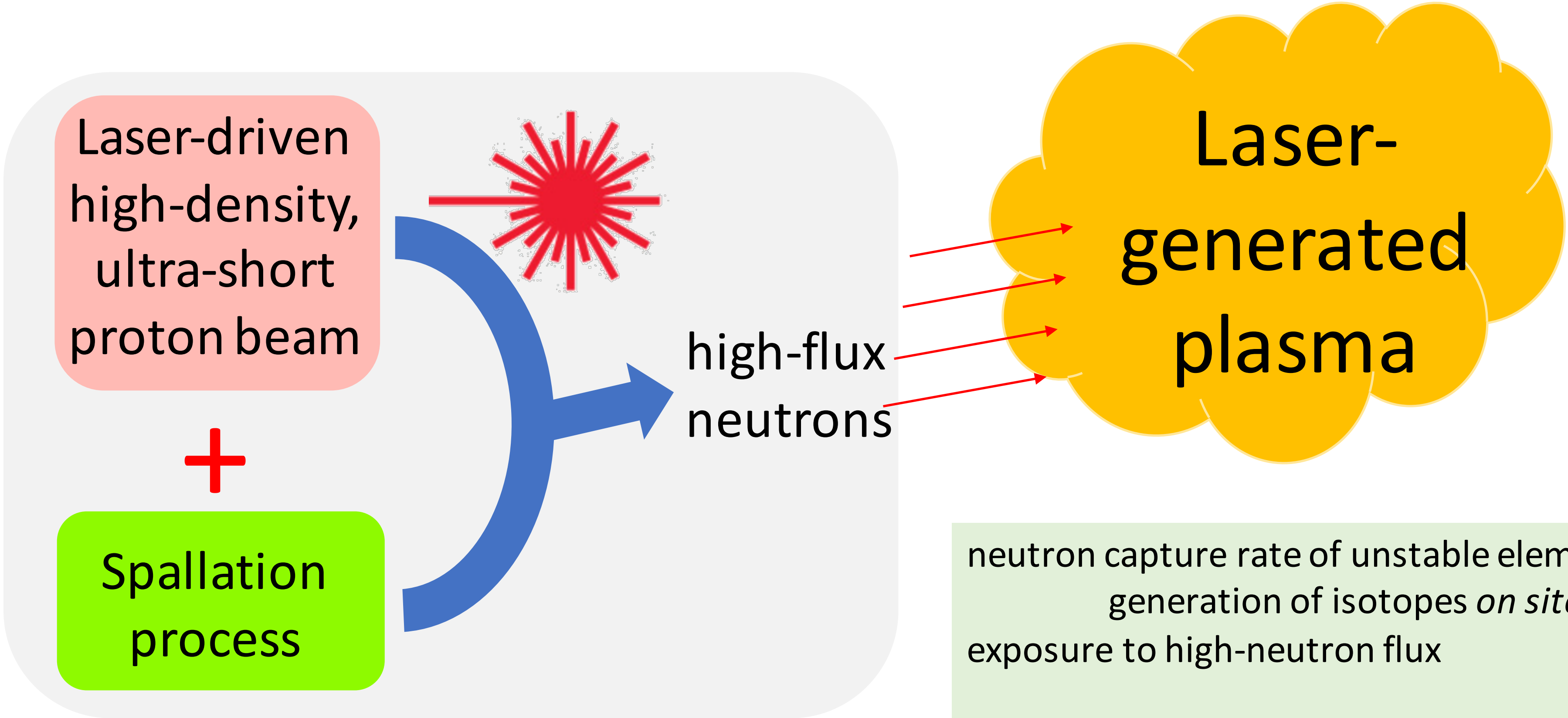
→ Key in pinning down models of elements abundance

- Present research is done with dissociated facilities :
  (i) accelerator based radioactive heavy ion facilities,
  (ii) accelerator or reactor based neutrons sources.

How can we solve this?



A novel pathway for r-process investigation

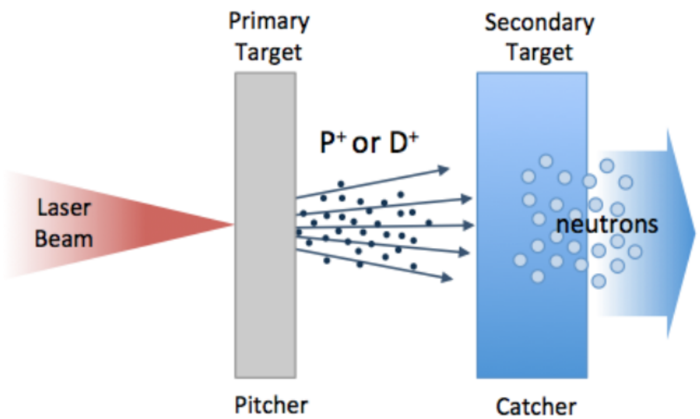


neutron capture rate of unstable elements : generation of isotopes *on site* + exposure to high-neutron flux

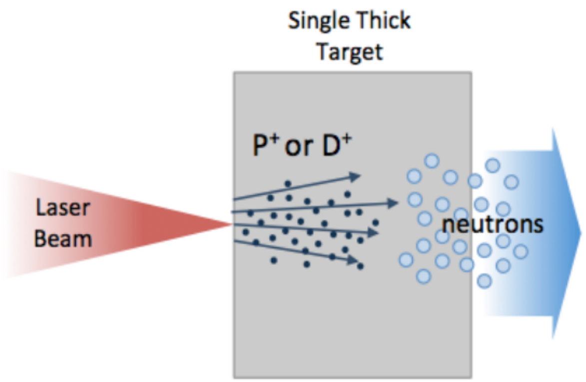
- control of the initial seed abundance

Generating neutrons using intense lasers is not a new idea (RAL, Trident, GSI, LLNL, LULI, Osaka…)

“Catcher-pitcher”



Direct



Due to (i) the high number of ions/bunch, and (ii) their short duration at the source, neutrons can be produced with **record brillance and short duration (<ns)**

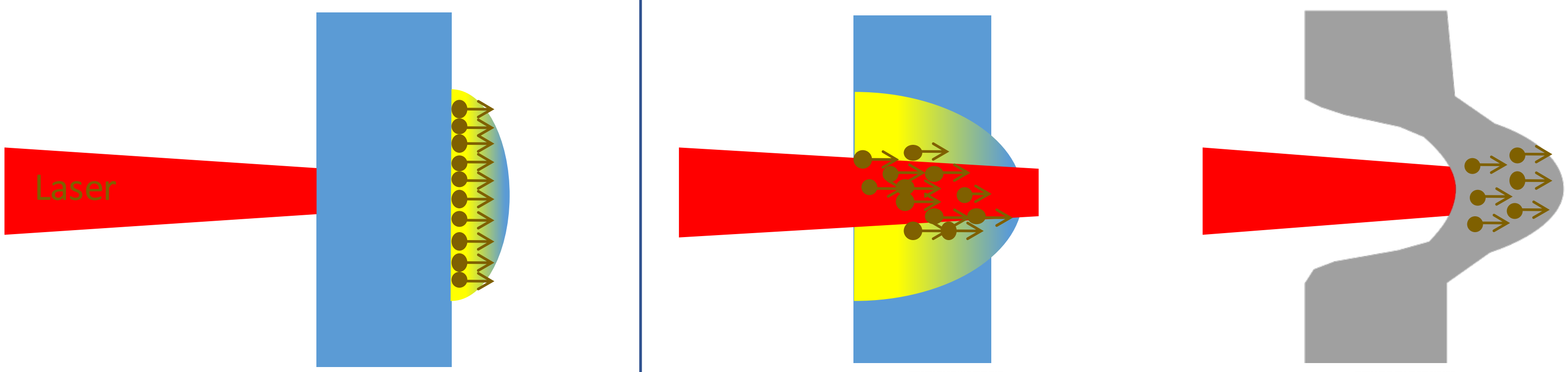
Transition from standard TNSA (surface) acceleration to volumetric acceleration, with prospect of higher ion energies

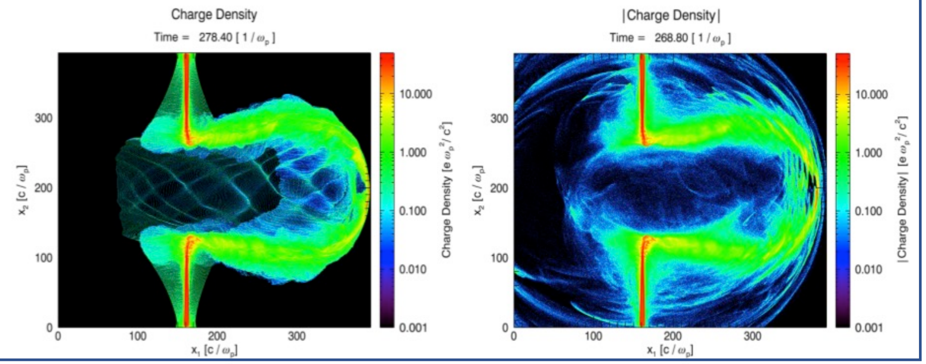
→ requires enhanced capability of ultra-intense lasers

TNSA
Target Normal Sheath Acceleration
(surface)

BOA
Break-Out Afterburner
+Shock Acceleration
(bulk/volume)

RPA
Radiation Pressure Acceleration
(bulk/volume)





T. Esirkepov (2004)
L. Silva (2004)
L. Yin (2011)

- Narrow spectrum + GeV @ 10^{22} W.cm^{-2}
- High efficiency

Key points of laser vs. conventional ion accelerators in allowing higher *peak* flux

	Lasers	**Conv. accelerators**
Versatility of ion source	X (solid or gas as sources)	
Repetition rate	(10 Hz at best)	X (MHz)
Energies	(10-100 MeV)	X (GeV-TeV)
Current	X (MA)	(A)
beam densities/bunch	X (10^{13})	(10^{10})
bunch length	X (ps)	(ns)

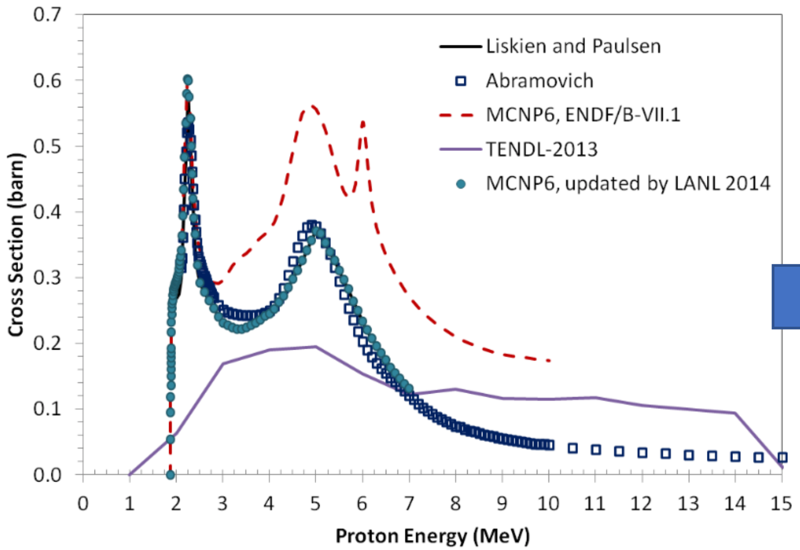
Critical points for further development

- Increase repetition rate → next gen. lasers

- Enhance
  - maximum ion energy
  - beam monochromatization
  - laser-to-ions conversion efficiency (number of ions)

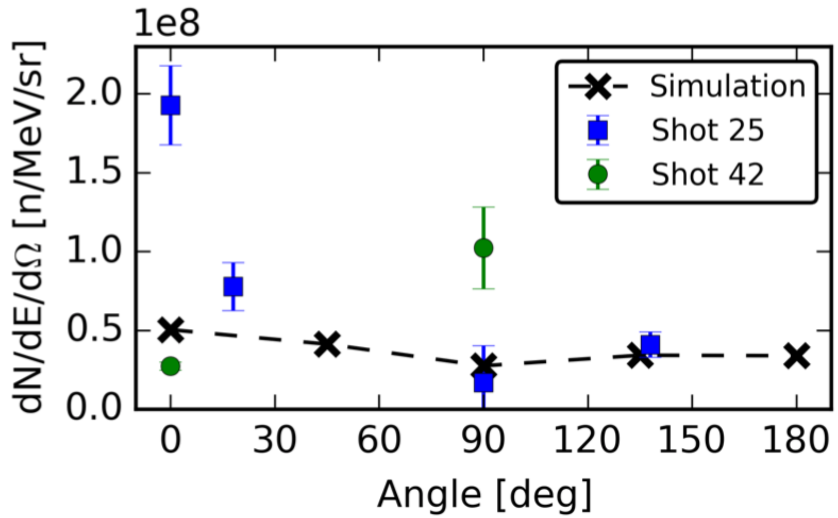
Present limitation in efficiency of neutron production

$^{7}Li(p,n)^{7}Be$



Using 10^{12} TNSA protons (30 MeV cut-off)

Experiment at Titan (200 J / 1 ps)



Efficiency ~ 10^{-4}

Going > 100 MeV protons should open the way to spallation

Neutron production by spallation

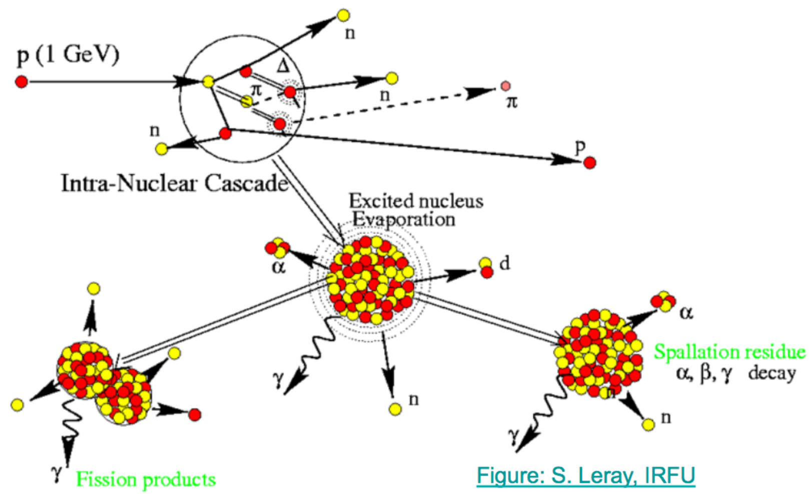


Figure: S. Leray, IRFU

Nucleon-Nucleus collisions at relativistic energies
(de Broglie wavelength < mean free path)
in two phases:

$T_{coll} < 10^{-22}$s :	Collisions of the projectile nucleon with nucleons in the target (Intranuclear Cascade, emission of **fast** particles π,**n**,p,…)
$T_{equil} > 10^{-21}$s – 10^{-16}s	Reorganisation of the residual nuclei, thermalization, **particle evaporation** (**n**,p,d,α,…), gamma ray emission

Spallation neutron yield

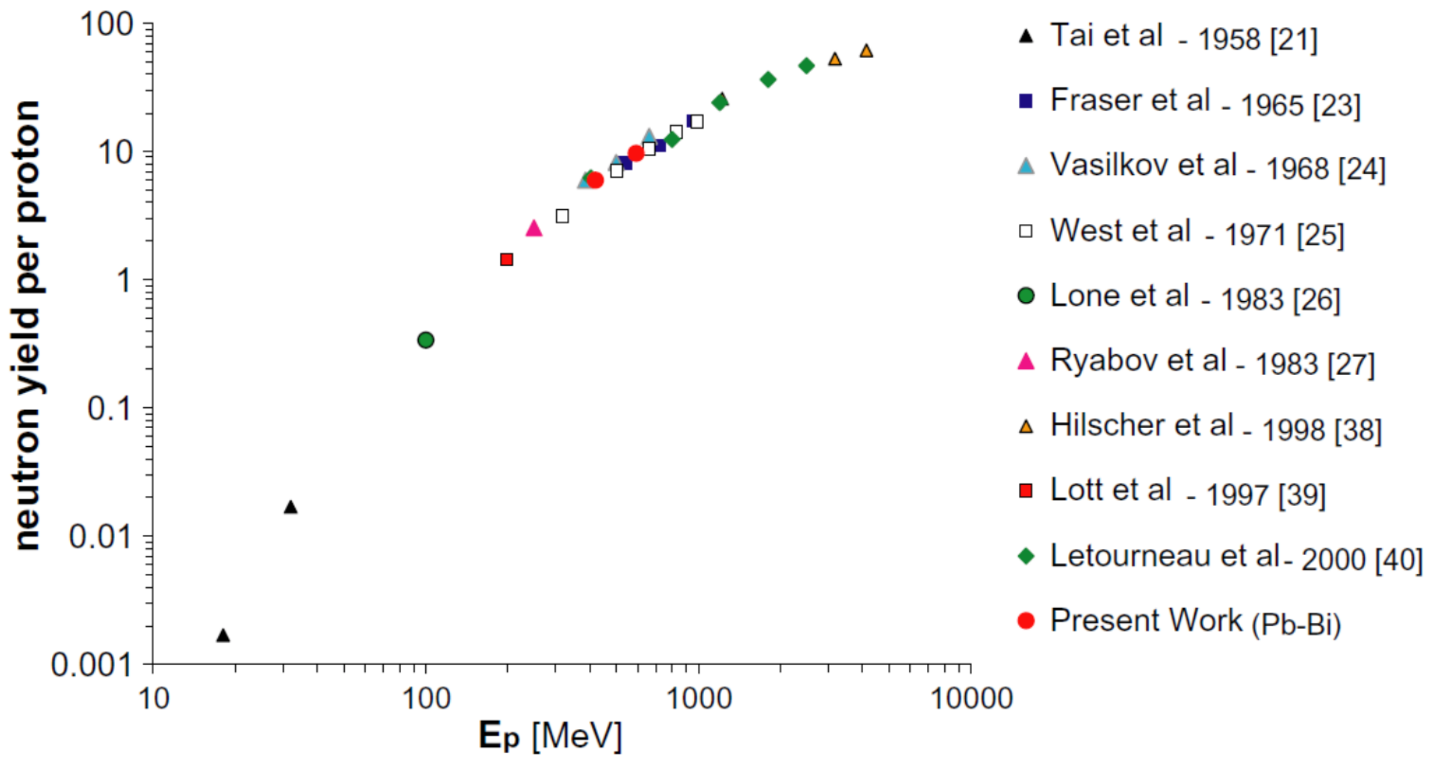
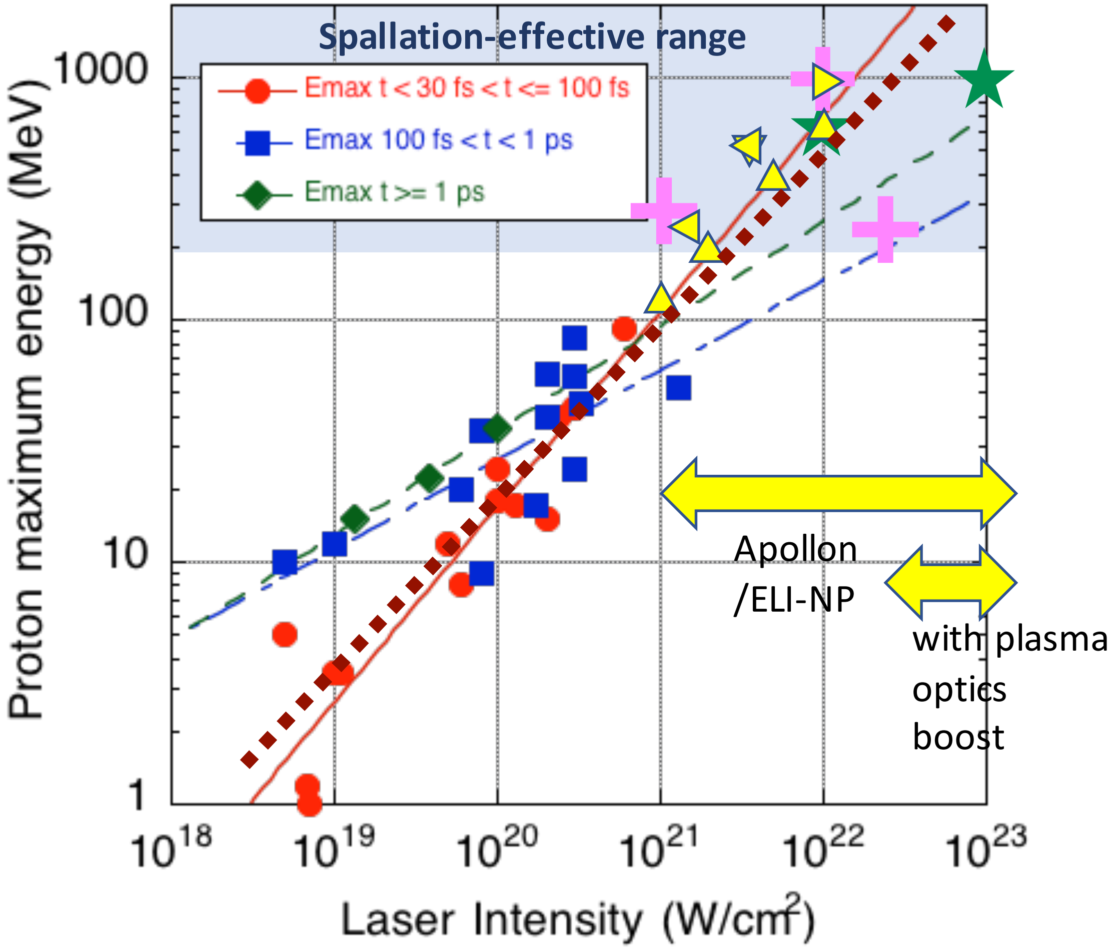


Fig. 10. Compilation of thick-target n/p values for p + Pb and Pb/Bi measured to date at all incident energies.

CERN nTOF ca. 300 n/p 20 GeV protons on Pb

Multi-PW lasers should open the way for spallation



Experiments

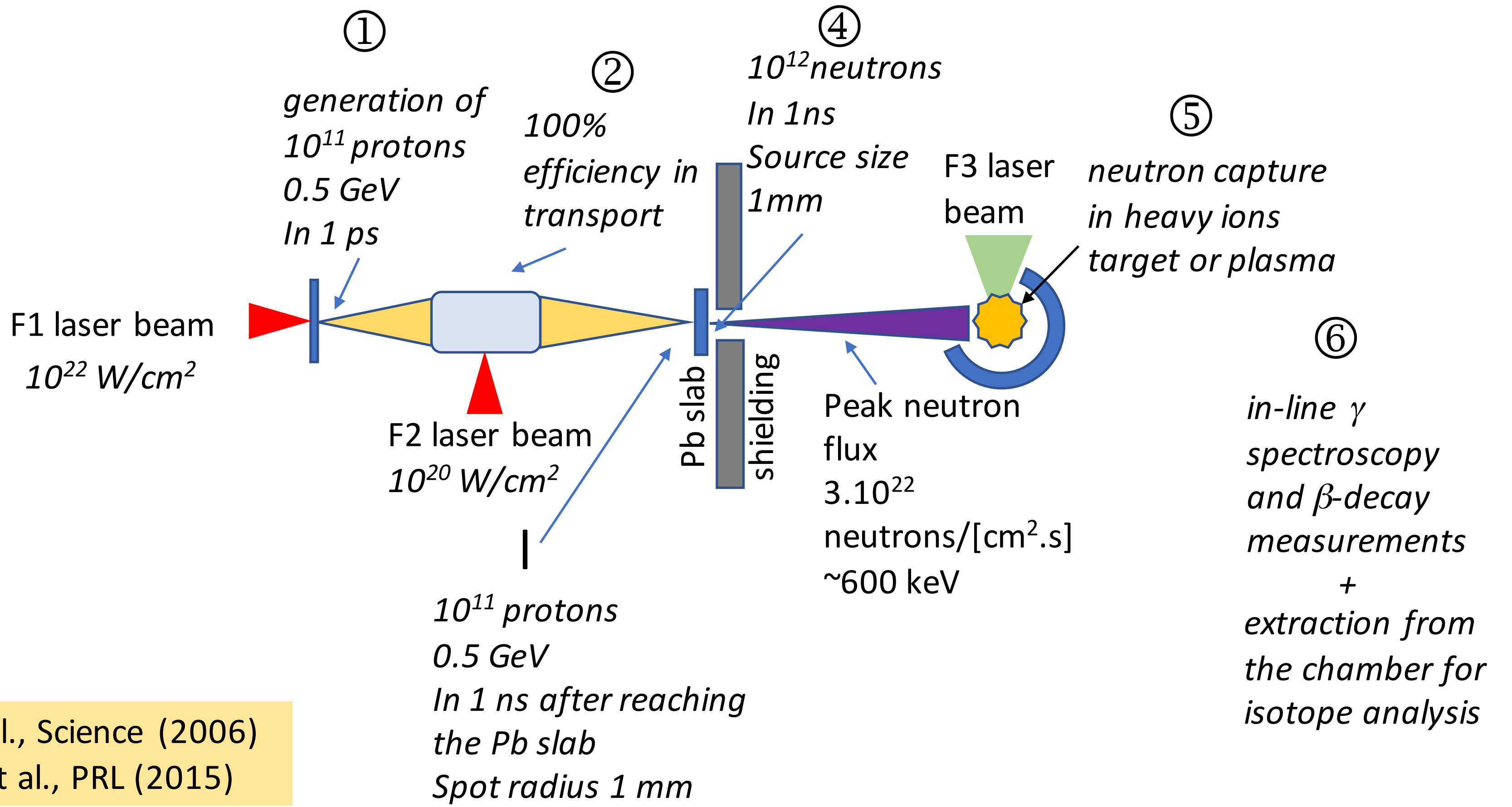
Electrostatic acceleration of protons (TNSA)

Numerical simulations
Radiation pressure acceleration
(RPA)

Numerical simulations
Collisionless Shock Acceleration
(CSA)

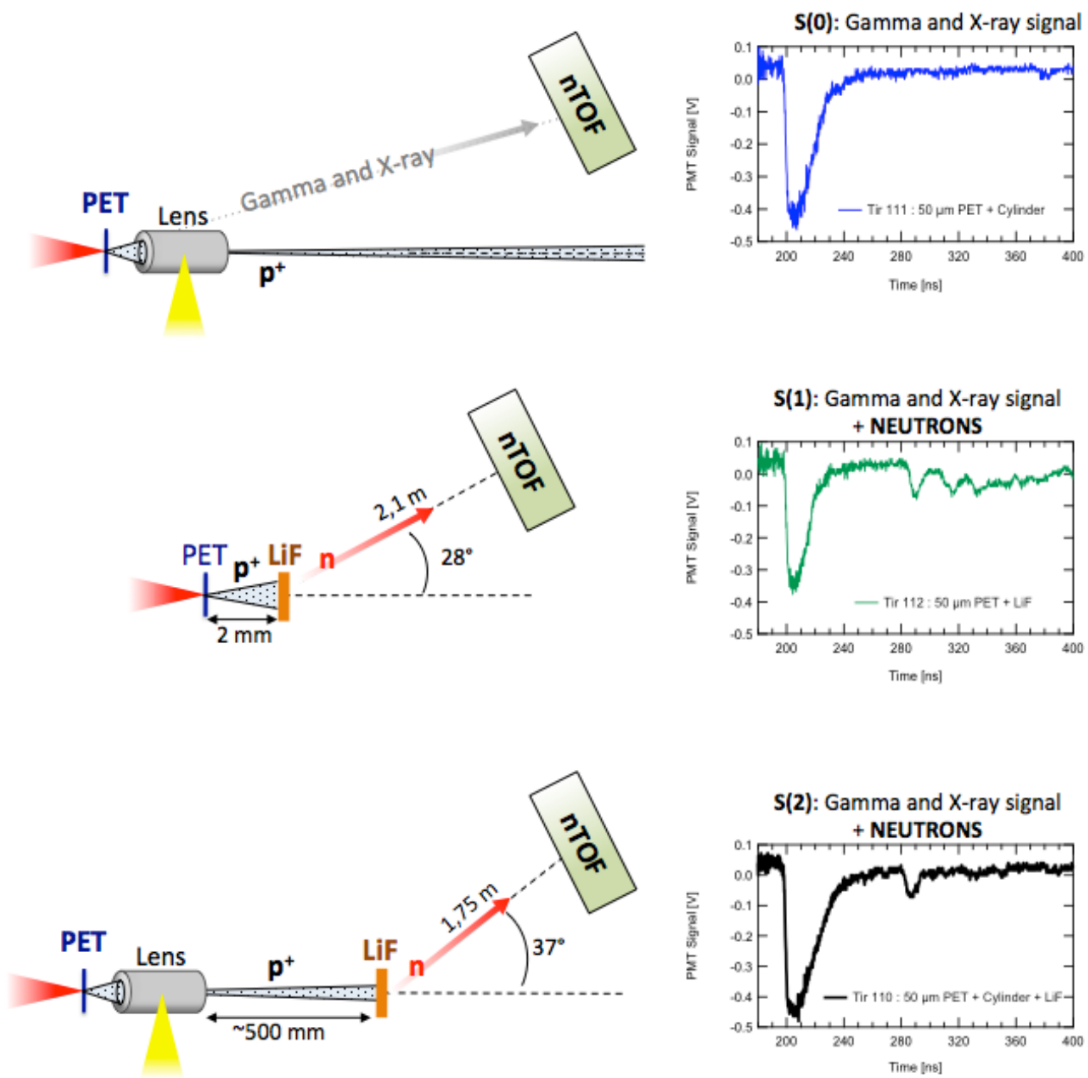
Numerical simulations
(TNSA)

Concept of this approach



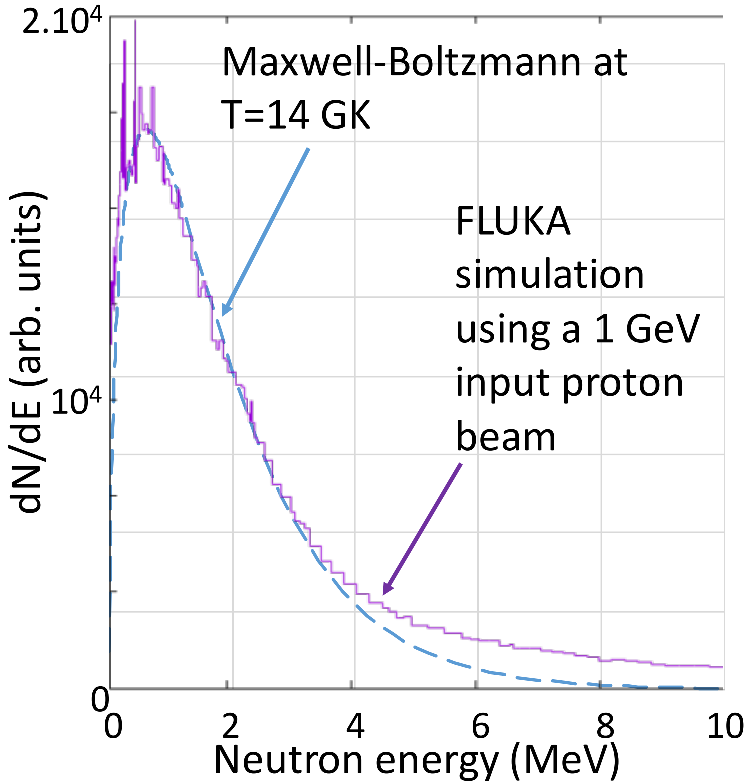
Toncian et al., Science (2006)
Higginson et al., PRL (2015)

The proton transport scheme *(Science, 2006)* allows to narrow down the proton spectrum, and thus the neutron bunch duration down to the ns-level



Higginson et al., PRL (2015)

The simulated neutron spectrum moreover fits the range of expected high-T environment of r-process events

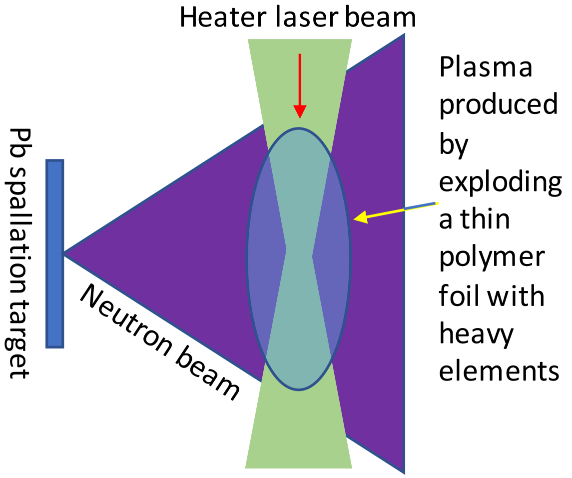


The neutron spectrum peaks around 600 KeV (an energy region where no existing facility produce significant neutrons)

Overview of expected neutron beam performances vs. existing neutron facilities

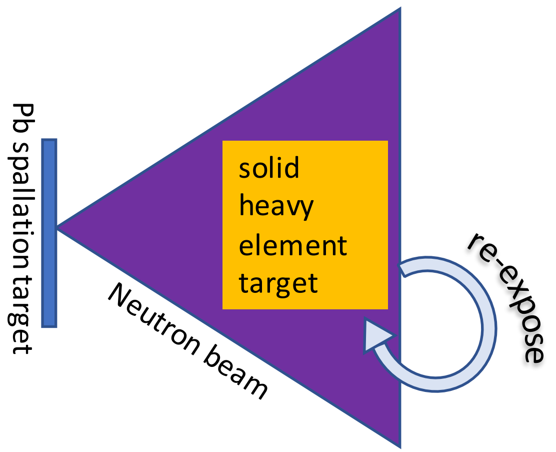
Facility	Peak neutron flux (neutrons/[cm^2.s])	Average neutron flux (neutrons/[cm^2.s])	Neutron bunch duration (ns)	Repetition rate (Hz)
ILL (reactor-based)	~10^{15}	~10^{15}	(continuous)	(continuous)
SNS (accelerator-based)	~10^{16}	~10^{12}	~1 μs	60
Present-day lasers	**10^{18}-10^{19}**	**5×10^{5}-5×10^{6}**	**~1 ns**	**5×10^{-4}** (1 shot/30’)
Prospect with PetaWatt lasers	**10^{22}-5×10^{24}**	**10^{11}-5×10^{13}**	**~1 ns**	**1.6×10^{-2} (1 shot/min)**
NIF (laser fusion-based)	> 10^{26}	> 10^{10}	~10 ps	10^{-5} (1 shot/day)

Proposed experiments to study r-process in relevant astro conditions



Neutron capture and β decay rate in a plasma environment

This is crucial since neutron capture and β decay rates are essentially well known only for stable elements at room temperature



Neutron capture and β decay rate of heavy exotic elements

<u>First step</u> : generate exotic nuclei by exposure to neutrons
<u>Second step</u> : re-expose on the next shot and generate another neutron capture in the exotic nuclei produced in the first step

Wrap-up

- Lasers have already for some years opened new perspectives in "laboratory astrophysics"
- New capabilities (e.g. magnetic field) widens the perspectives
- Ultra-intense lasers add many new directions: positron beams, collisionless plasmas, **neutrons**, etc
- Ultra-high fluxes of neutrons seem achievable using Apollon & ELI-NP
  → pathway to r-process investigations