A Laser-Accelerated Th Beam is Used to Produce Neutron-Rich Nuclei Around the N = 126 Waiting Point of the r-Process Via the Fission-Fusion Reaction Mechanism

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Outline

A laser-accelerated Th beam is used to produce neutron-rich nuclei around the waiting point $N = 126$ of the r-process via the fission-fusion mechanism

- Radiation Pressure Acceleration (RPA)
- Atomic stopping of dense ion bunches
- The astrophysical r-process and the $N = 126$ waiting point
- Experimental setup

D. Habs et al., "Introducing the Fission-Fusion Reaction Process: Using a Laser-Accelerated Th Beam to produce Neutron-Rich Nuclei towards the N=126 Waiting Point of the r Process", arXix:1007.1251v1 [nucl-ex], submitted to Appl. Phys. B

Major components of ELI-NP

APOLLON laser stand alone

- 3·10 PW
- 15 fs
- ~ 1/min
- 10^{24} W/cm^2
- ~10^{15} V/m

γ beam stand-alone

- E_{max} = 13 MeV (19 MeV)
- 12 kHz
- ring-down cavity for photons
- warm electron linac, 600 MeV
- high brilliance ($\Delta E_\gamma / E_\gamma \geq 10^{-3}$)
- high flux ($I = 10^{13}$ s^{-1})

APOLLON + γ beam

- $E_{max} \approx 100$ MeV
- ~ 1/min
- flux: $I = 10^8$ s^{-1}
- higher harmonics + e bunches
- timing with fibre optics (fs)

Laser acceleration schemes
Former schemes

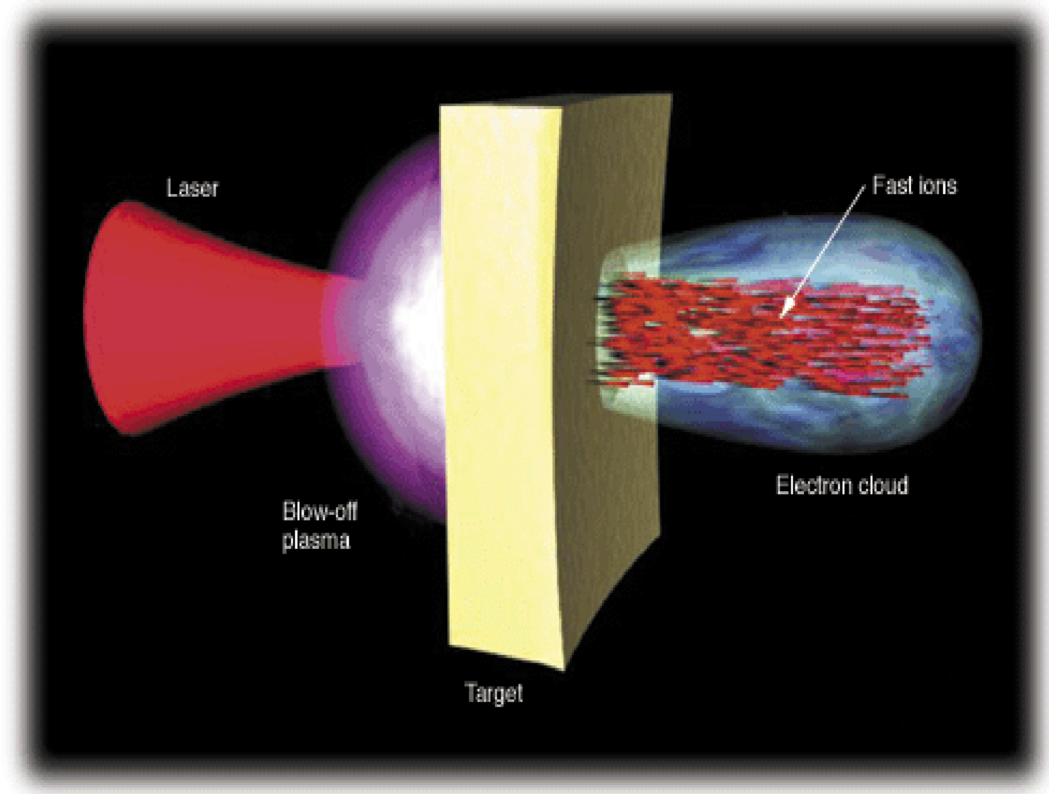
Ion acceleration

TNSA

(target-normal sheath acceleration)

- **Low conversion efficiency**
- **Huge lasers are required**

$$E_{\text{ion}} \propto \sqrt{I_{\text{Laser}}}$$



In laboratory experiments, the Petawatt laser's tremendous power produced intense beams of protons, proving the laser to be a powerful ion accelerator.

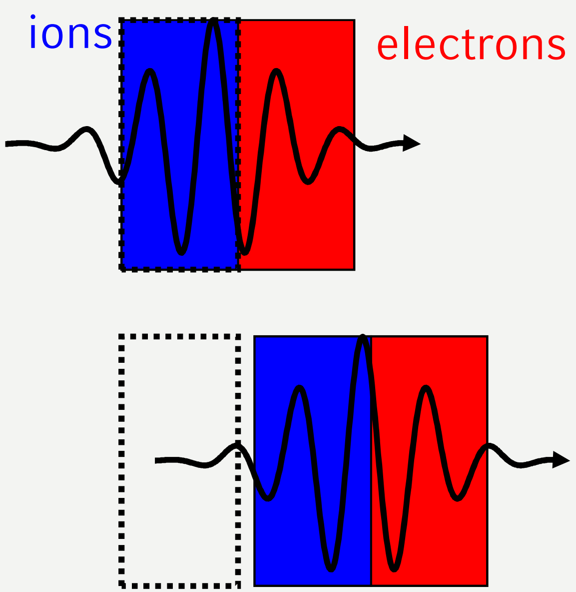
S.C. Wilks et al., Phys. Plasmas **8**, 542 (2001).

New Acceleration Mechanism

Radiation Pressure Acceleration (RPA)

Optimum ion acceleration

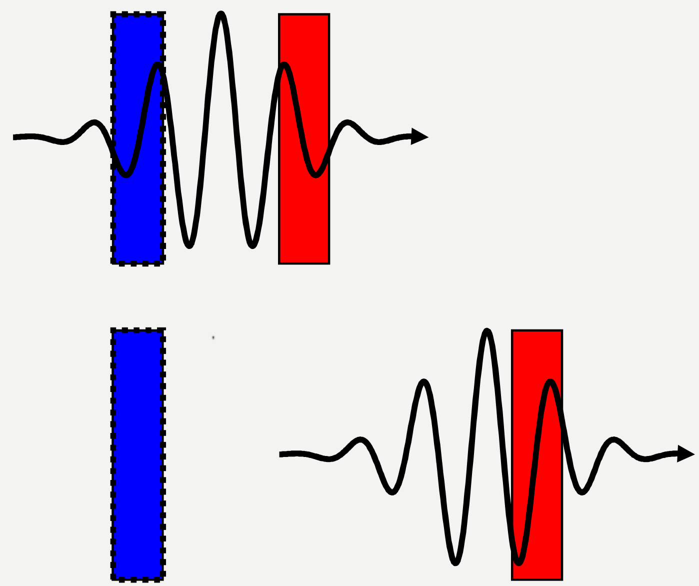
$$a_L \approx \sigma$$



$D \approx 4nm$ for $a_L = 5$

Optimum electron acceleration

$$a_L \approx \sigma \cdot 2\pi$$



$D \approx 0.65nm$ for $a_L = 5$

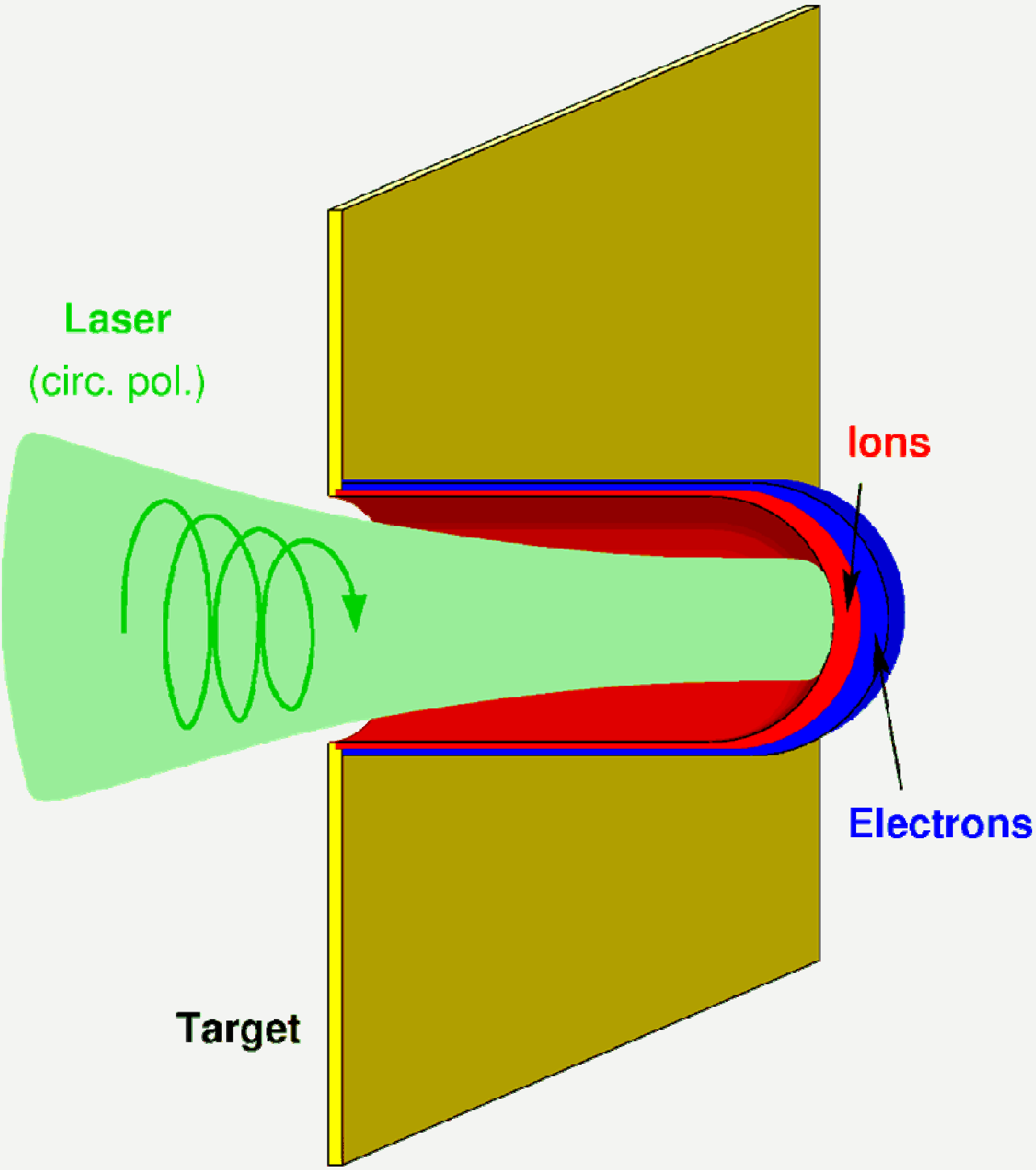
Normalized areal electron density: $\sigma = (n_e \cdot D)/(n_c \cdot \lambda) = \left(\frac{n_e}{n_c}\right)\left(\frac{D}{\lambda}\right) =$ dimensionless

Normalized vector potential: $a_L^2 = I\lambda^2 / 1.38 \times 10^{18} Wcm^{-2} \mu m^2 =$ dimensionless

S.G. Rykovanov et al.,
New J. Phys. **10**, 113005 (2008).

O. Klimo et al.,
Phys. Rev. ST AB **11**, 031301 (2008).

Radiation pressure acceleration
(RPA)



Cold compression of electron sheet.

Rectified dipole field between electrons and ions.

Neutral bunch of ions + electrons accelerated.

Solid-state density: 10^{24} e cm^{-3}

Classical bunches: 10^{8} e cm^{-3}

$$E_{\text{ion}} \propto I_{\text{Laser}}$$

Very efficient!

Radiation pressure acceleration
(RPA)

radiation pressure = intensity / c

high power (10^{15} W)
high intensities (>10^{21} W/cm²)
short acceleration times (10's, 100's fs)
Target 5 nm, 2 μm focus: many J rest energy

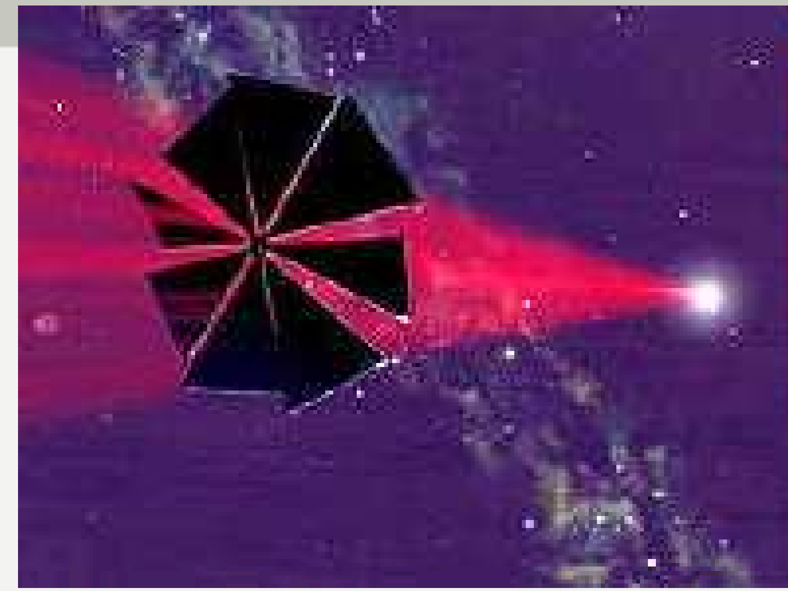


Photo courtesy The Planetary Society

small intensities (0.14 W/cm²)
"infinite" acceleration times (years)

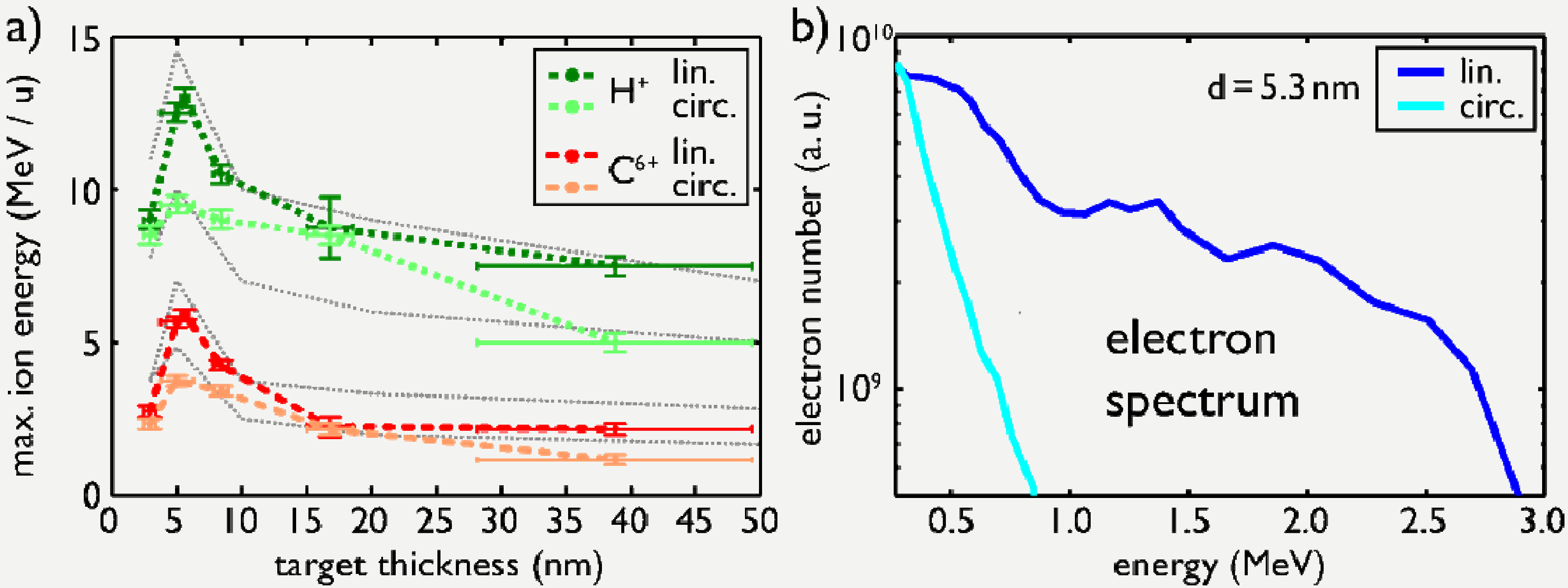
JFL Simmons et al, Am J Phys 1993 (Marx Nat 1966)

fuel is avoided but at a cost. A laser of 10 GW powered over 10 years or so would provide an energy equivalent to about the rest mass of a vehicle of 30 kg, and so would be sufficient to accelerate it to relativistic speeds. In fact, the

RPA ion accel. + DLC foils (I)

Max-Born Institute (MBI), Berlin

Laser Power: 15 TW (700 mJ in 45 fs)
Focused Intensity: $a_L = 5$, **Contrast:** $> 10^{11}$



Peak at very low target thickness of 5.6 nm

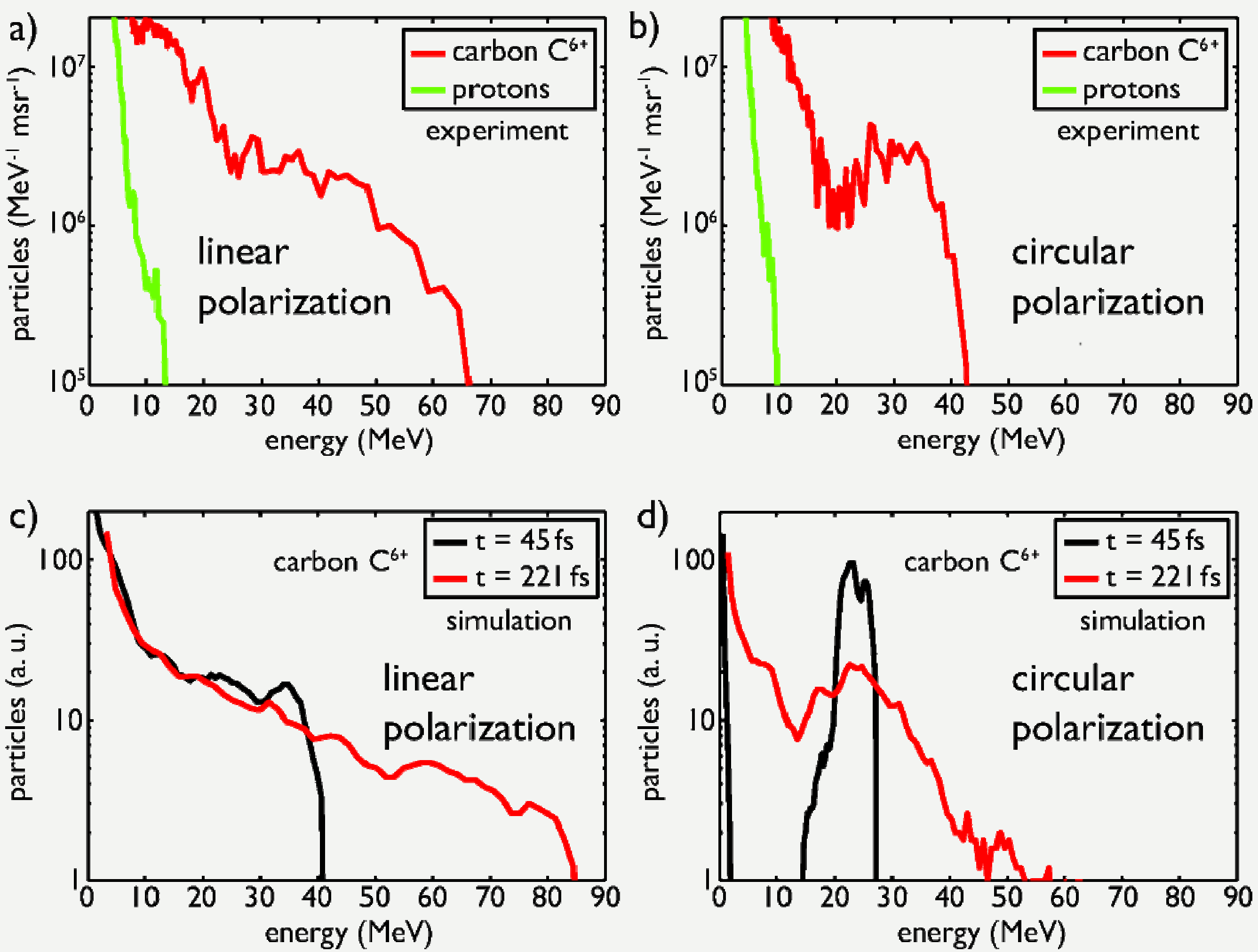
Cold target for circular polarization

$$a_L \approx \sigma\,, \qquad \sigma = \left(\frac{n_e}{n_c}\right)\cdot\left(\frac{D}{\lambda}\right), \qquad a_L = \sqrt{I_L \cdot \lambda^2}$$

A. Henig et al., *"Radiation pressure acceleration of ion beams driven by circularly polarized laser pulses"*, Phys. Rev. Lett. **103**, 245009 (2009).

RPA ion accel. + DLC foils (II)

Hot electrons cold electrons



Experiment

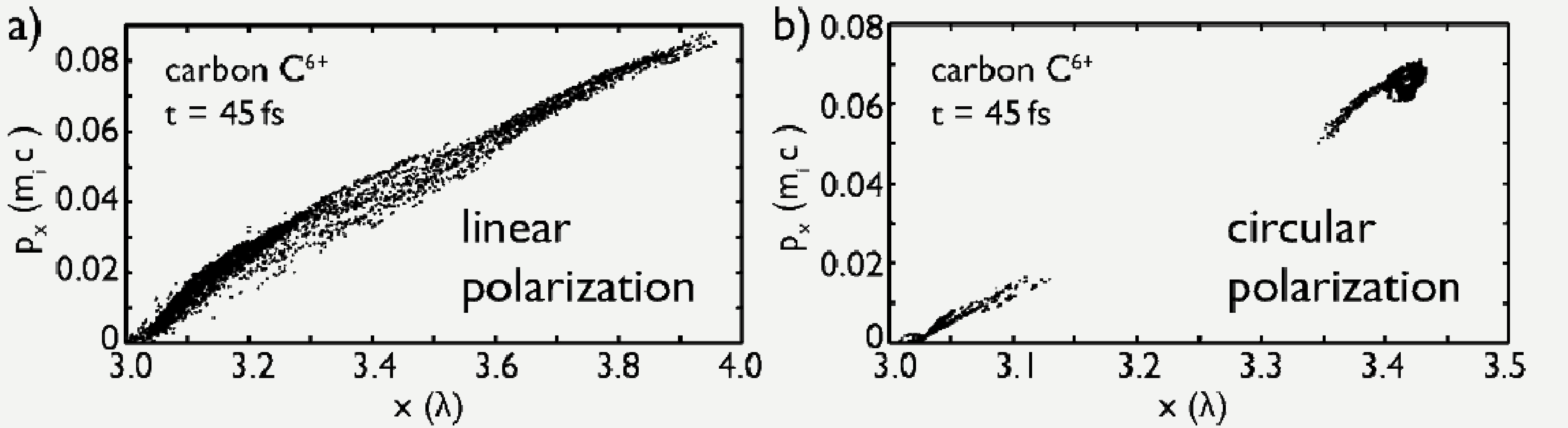
Theory

2D PIC simulations

RPA ion accel. + DLC foils (III)

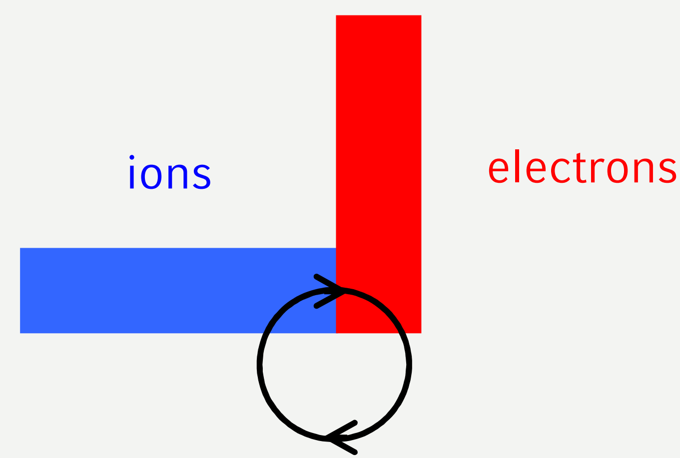
Theory

2D PIC simulations



Phase space rotation

Peak in ion spectrum



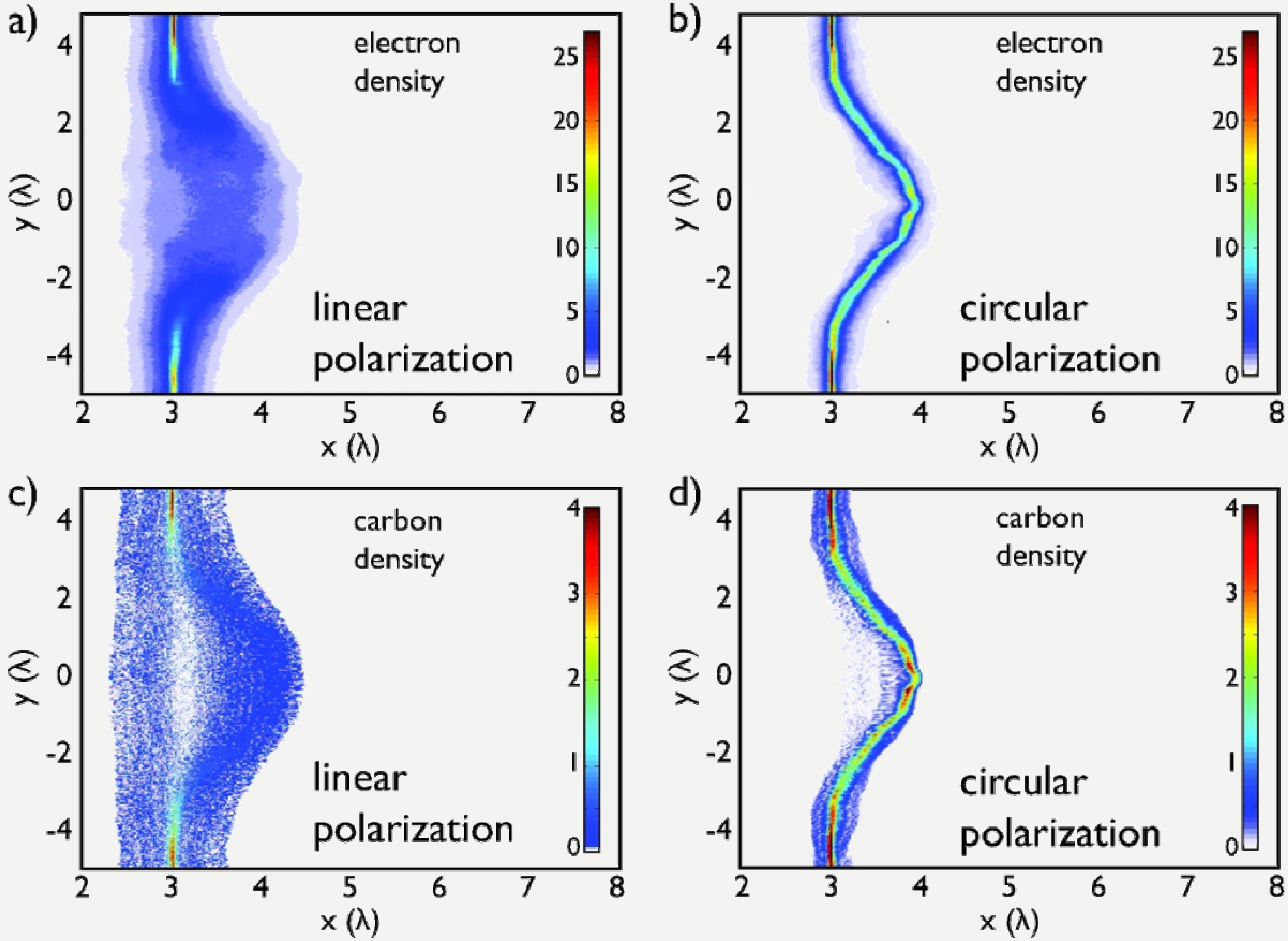
RPA ion accel. + DLC foils (IV)

Theory

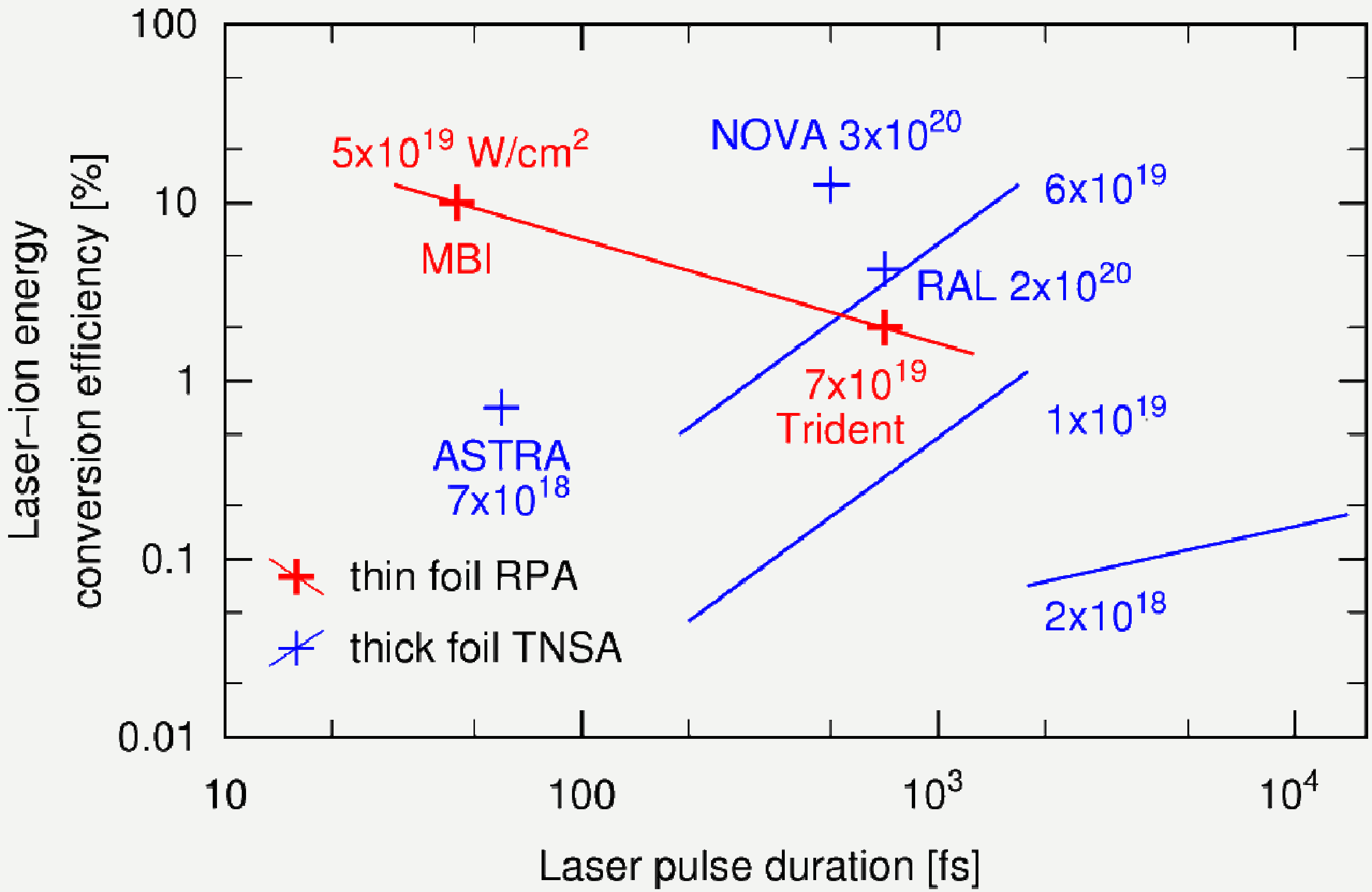
Hot electrons exploding foil

Cold electrons

$\tau = 61$ fs



RPA ↔ TNSA
Ion acceleration



Ultra-thin foils:

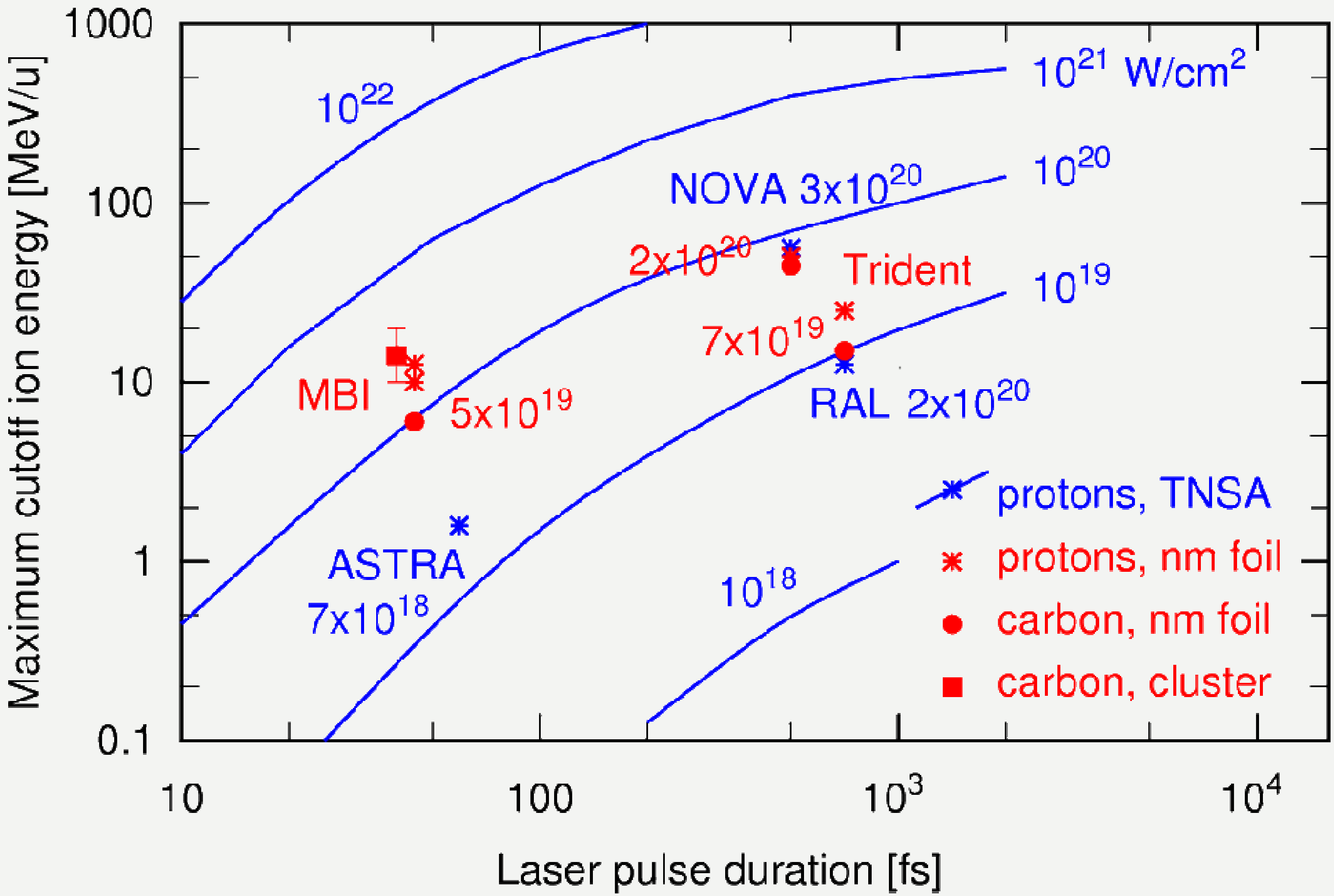
MBI-laser (Berlin)
45 fs

Trident-laser (LANL)
500 fs

RPA: much higher conversion efficiency at short pulse durations.

RPA ↔ TNSA

Ion acceleration



Stopping power
of ion bunches with solid state density

Bethe-Bloch formula for individual ion:

$$-\frac{dE}{dx} = 4\pi n_e \frac{Z_{\text{eff}}^2 e^4}{m_e v^2}\left(\ln\left(\frac{m_e v^2}{e^2 k_D}\right) + \ln\left(\frac{k_D v}{\omega_p}\right)\right)$$

binary collisions
k_D = Debye wave number

long-range
collective interaction
ω_p = plasma frequency

a) enhanced stopping (10^5 ×) in low-density targets
dense bunch interacts with collective wake
→ reduced fraction of nuclear reaction

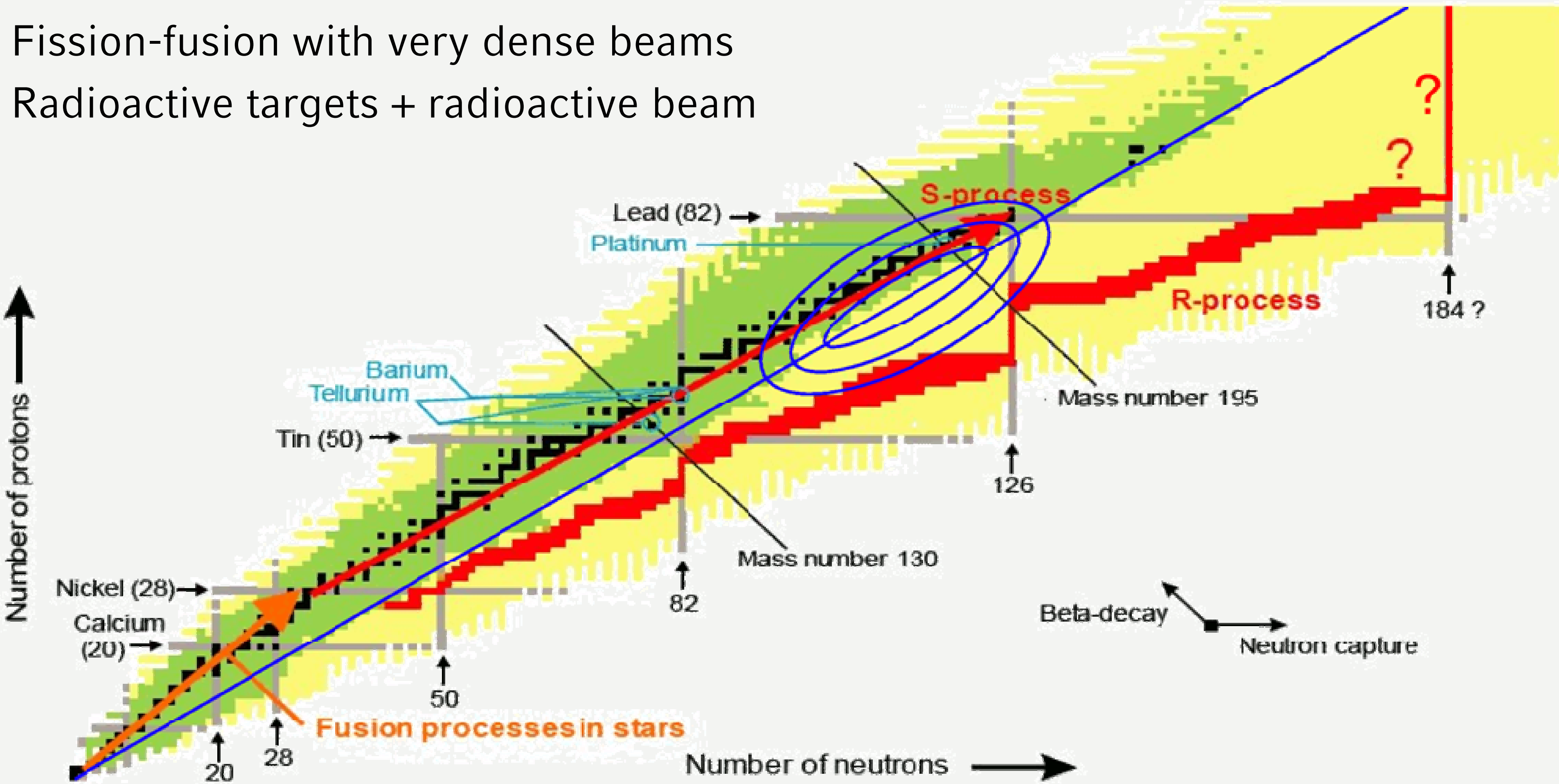
b) reduced stopping in solid target
first electrons of bunch kick out electrons of foil like a snow plow.
→ enhanced fraction of nuclear reactions.

Chart of the Nuclides

r-process and waiting points

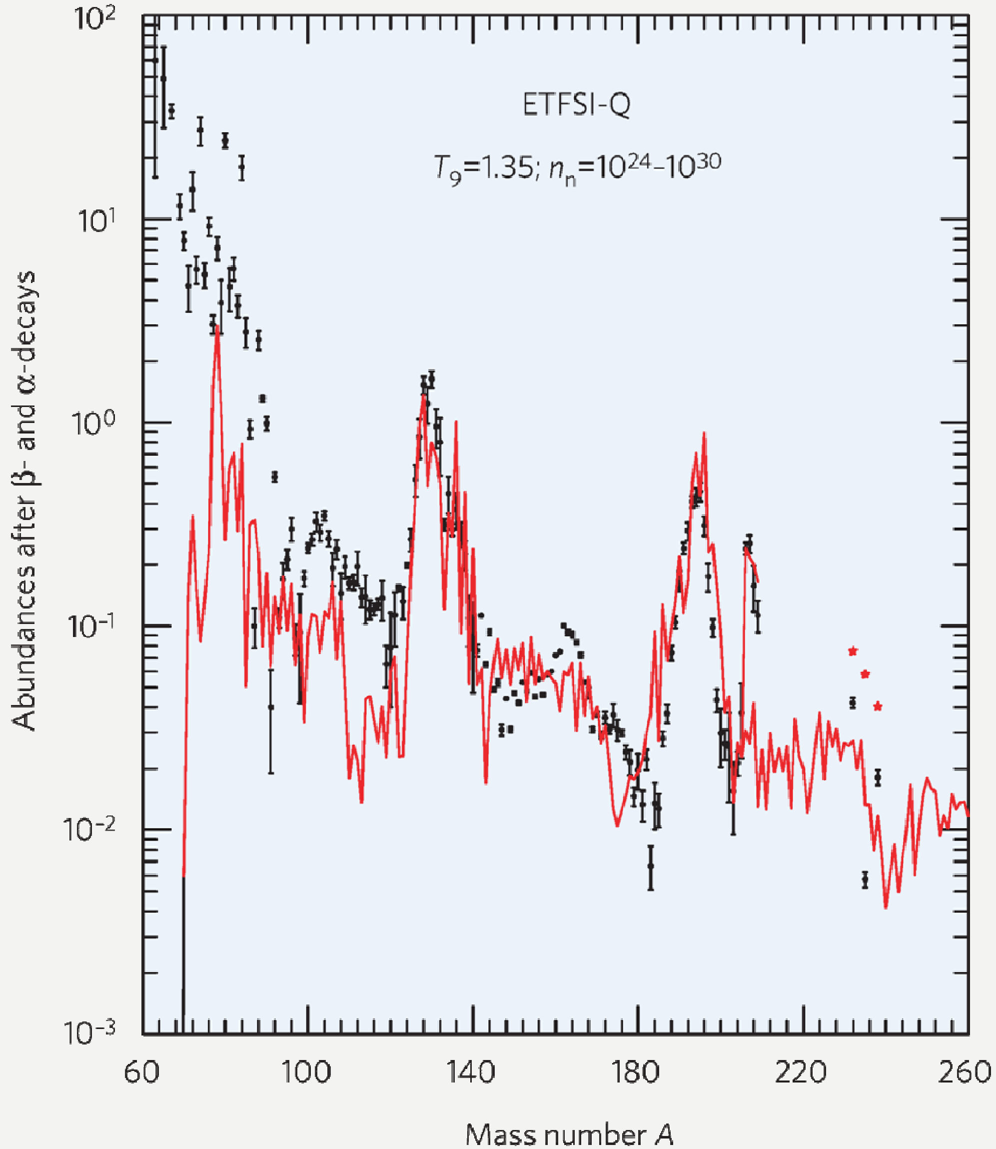
Fission-fusion with very dense beams

Radioactive targets + radioactive beam



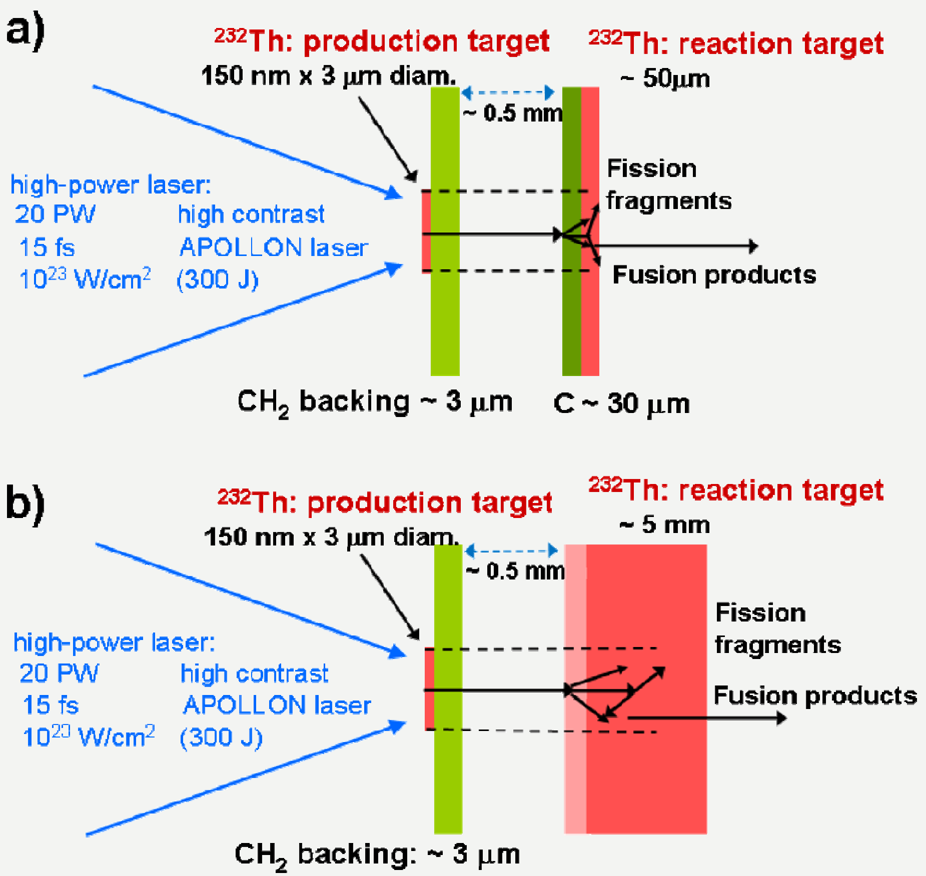
- Superheavies: $Z = 110, \quad T_{1/2} = 10^9$ a ?
- recycling of fission fragments ?

r-process
Solar abundances



Fission-fusion reaction

very neutron-rich nuclei



a) Normal Bethe-Bloch stopping
$N_{fissfus} = 5 \cdot 10^2$

b) Reduced Bethe-Bloch stopping
$N_{fissfus} = 10^6$

7 MeV/u H, C, O, ^{232}Th, beam + ^{232}Th target

1)Fission

H, C, O + Th $\rightarrow$ $F_L + F_H$

fission fragments in target

^{232}Th + ^{232}Th $\rightarrow$ fission of beam in $F_L + F_H$

Reaction of radioactive short-lived light fission fragments of beam +
Radioactive short-lived light fission fragments of the target

2)Fusion:

$F_L + F_L \rightarrow {}^{A}Z \approx {}^{185}80$

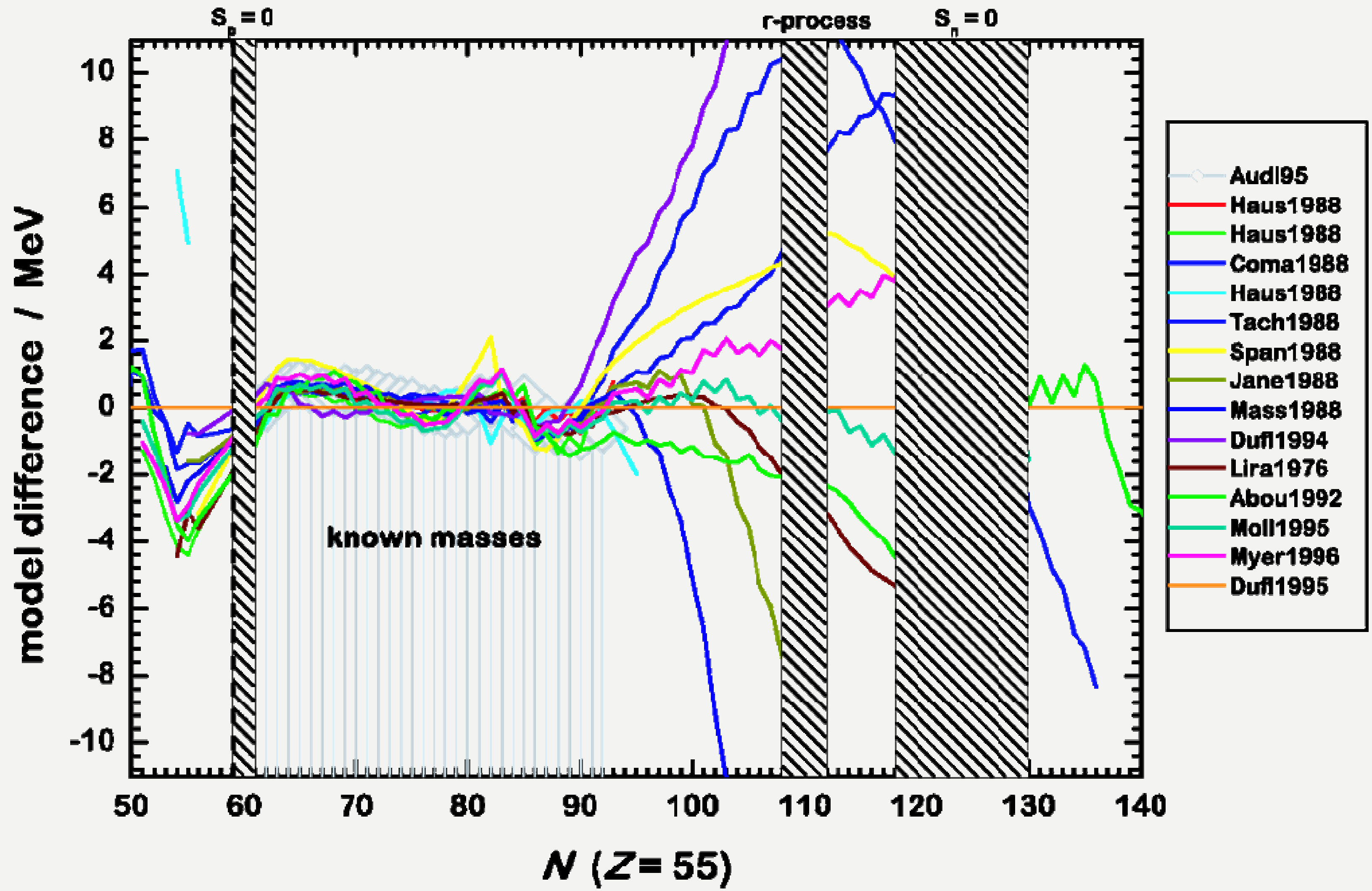
nuclei close to N=126 waiting point

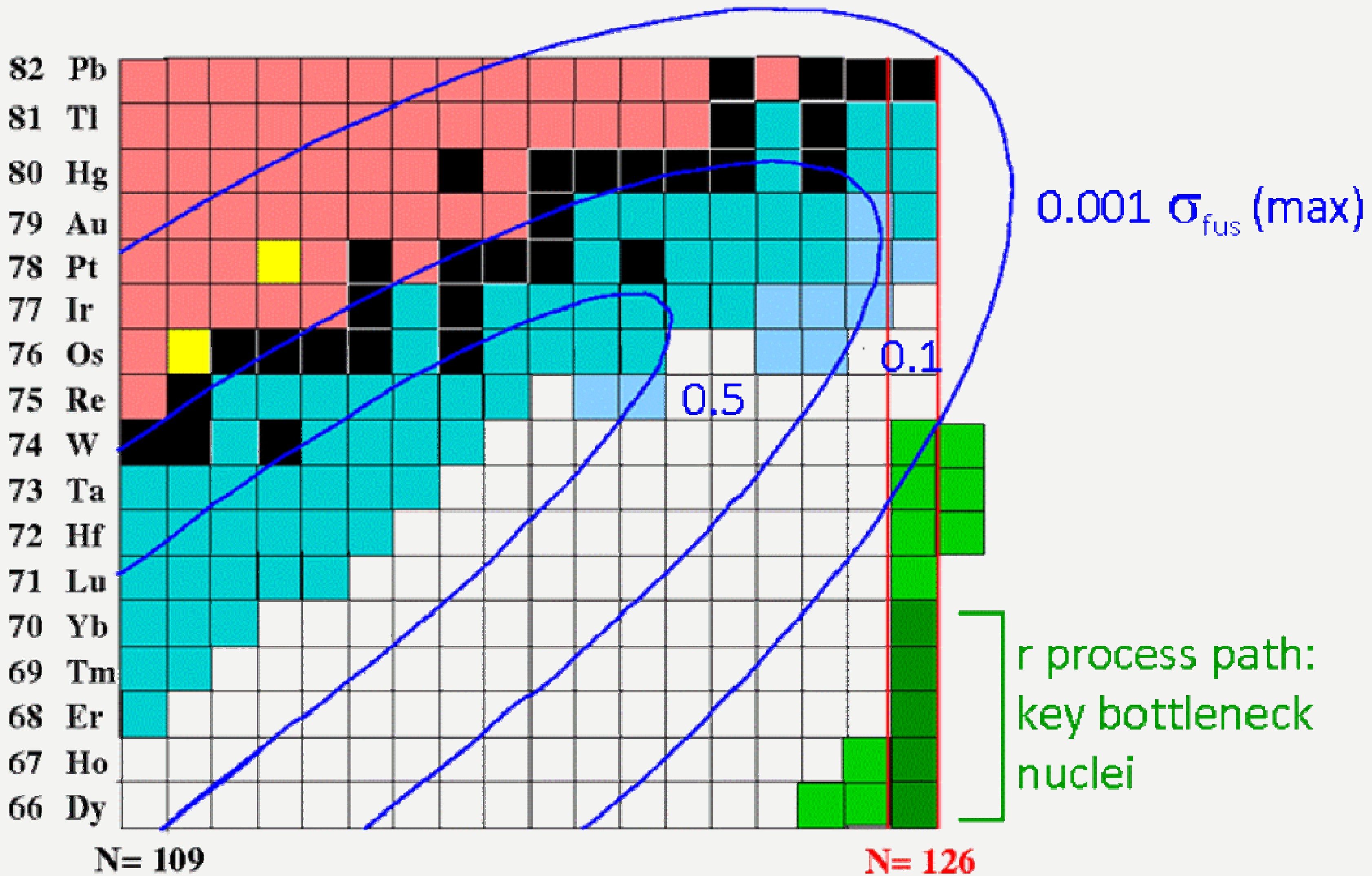
$F_L + F_H \rightarrow$ ^{232}Th old nuclei

$F_H + F_H \rightarrow$ unstable

Nuclear masses

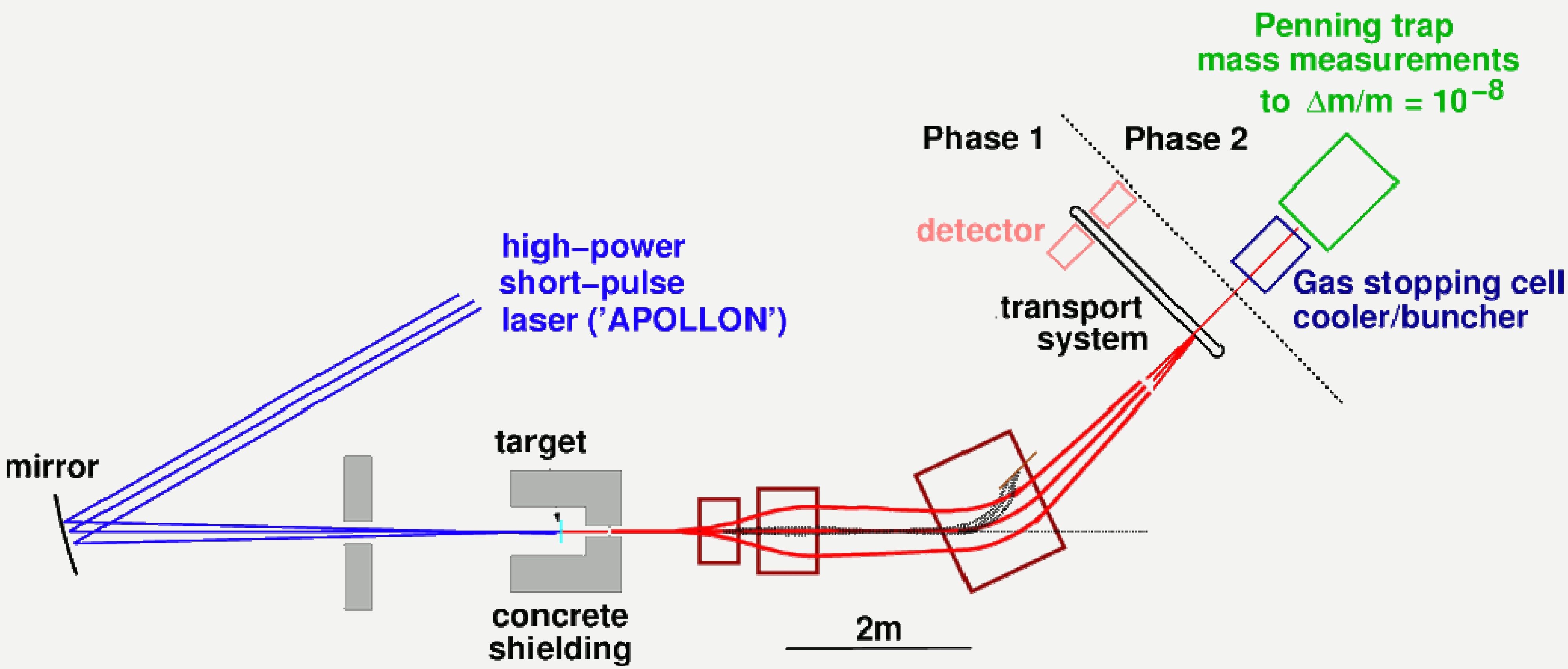
Theories and experiment




82 Pb
81 Tl
80 Hg
79 Au
78 Pt
77 Ir
76 Os
75 Re
74 W
73 Ta
72 Hf
71 Lu
70 Yb
69 Tm
68 Er
67 Ho
66 Dy
N= 109
N= 126
0.001 σ_{fus} (max)
0.1
0.5
r process path:
key bottleneck
nuclei

Experimental setup

neutron-rich nuclei in fission-fusion



Conclusion

New scheme: Radioactive beam + radioactive target produced at the same time

Perspective: With diode pumping of fiber lasers much higher repetition rates are possible:

from 1/min → 1 kHz

from PW peak power → kW to MW average power

factories for HiPER, etc. will make pumping devices much cheaper