# Perspectives for nuclear astrophysics using ultra-dense ion beams and highly brilliant γ beams

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Outline:

- generation of intense highly brilliant γ beams
  → perspective for astrophysical photonuclear reactions
- generation of ultra-dense laser-accelerated ion beams
  → novel reaction mechanism: fission-fusion
- ELI: Extreme Light Infrastructure

# $\gamma$ Sources for Photonuclear Transitions

- photon-induced nuclear transitions can be probed by keV – MeV photons from:
  - tagged photons from electron scattering:
    e.g.: NEPTUN tagger at S-DALINAC (TU Darmstadt)
  - undulator at large storage ring
    e.g.: HI$\gamma$S facility (Duke Univ., USA)
  - Compton backscattering sources:

    $$\hbar\omega' = 4\gamma^2\hbar\omega$$

    - of laser from fast electron beam:
      e.g.: T-REX @ Livermore, LCLS @ Stanford
      ELI-Nuclear Physics @Bucharest
    - future: laser-driven production of brilliant photon beams:
      use laser-accelerated dense electron sheet as relativistic mirror to (coherently) reflect second laser
      e.g.: present R&D at Garching

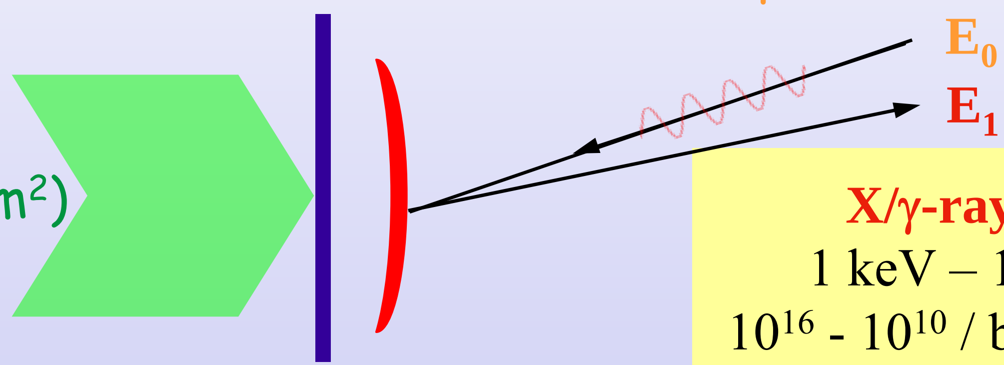
# Perspective:
# Laser-driven X/γ-ray source

relativistic dense electron mirror +
(coherently) backscattered production laser:

diamond-like carbon
(DLC) foil, 3 – 30 nm

production laser

driver laser
($10^{21}$-$10^{24}$ W/cm$^2$)




$$E_1 = 4\gamma^2 E_0$$

$$\tau_1 = \frac{\tau_0}{4\gamma^2}$$

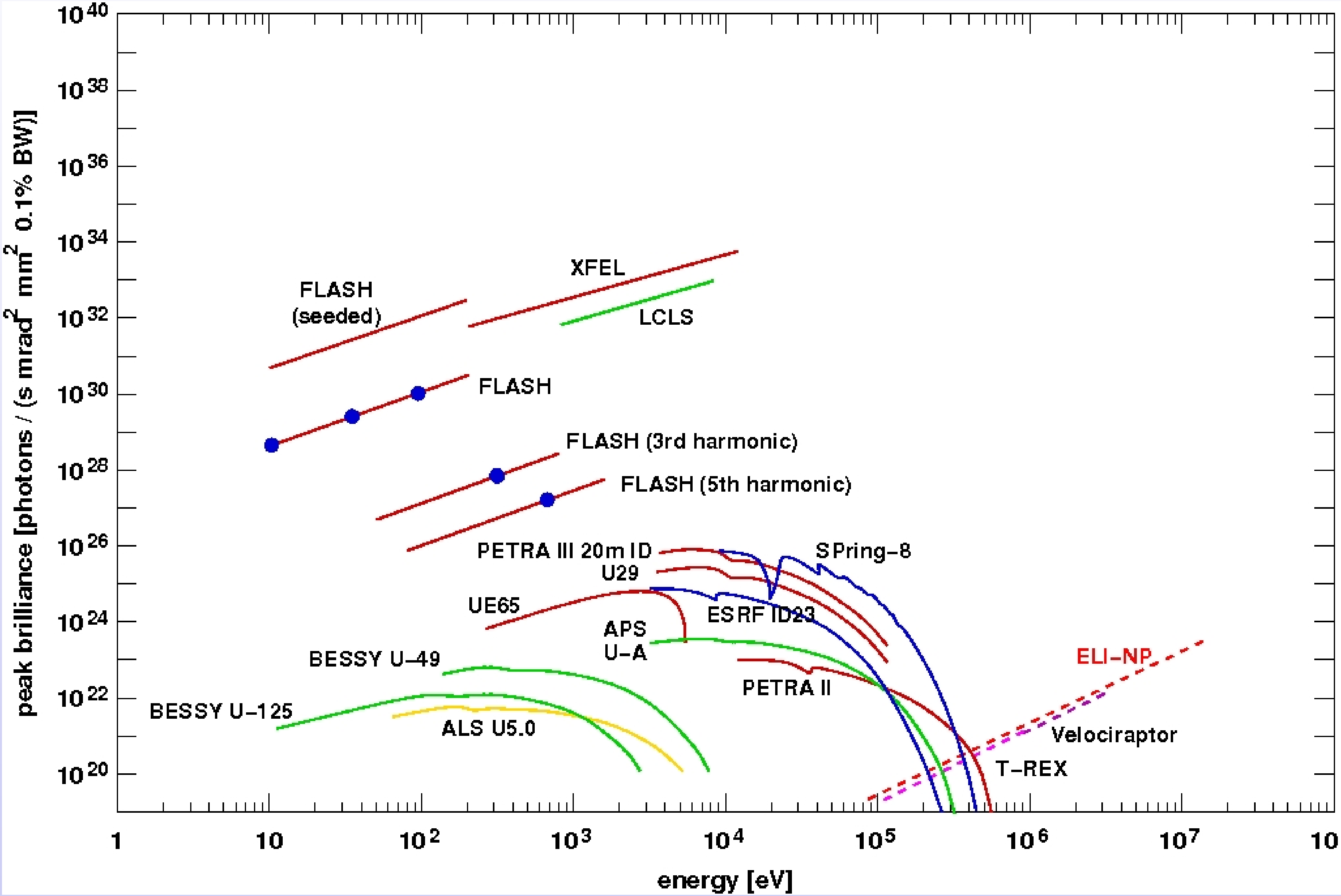
**X/γ-ray laser:**
1 keV – 100 MeV
$10^{16}$ - $10^{10}$ / bunch, 10 Hz
30 as – sub-zs

dense electron sheet:
relativistic mirror
5 MeV – 2.5 GeV
($\gamma$ = 10 - 5000), $N_e$ = $10^{10}$ - $10^{14}$

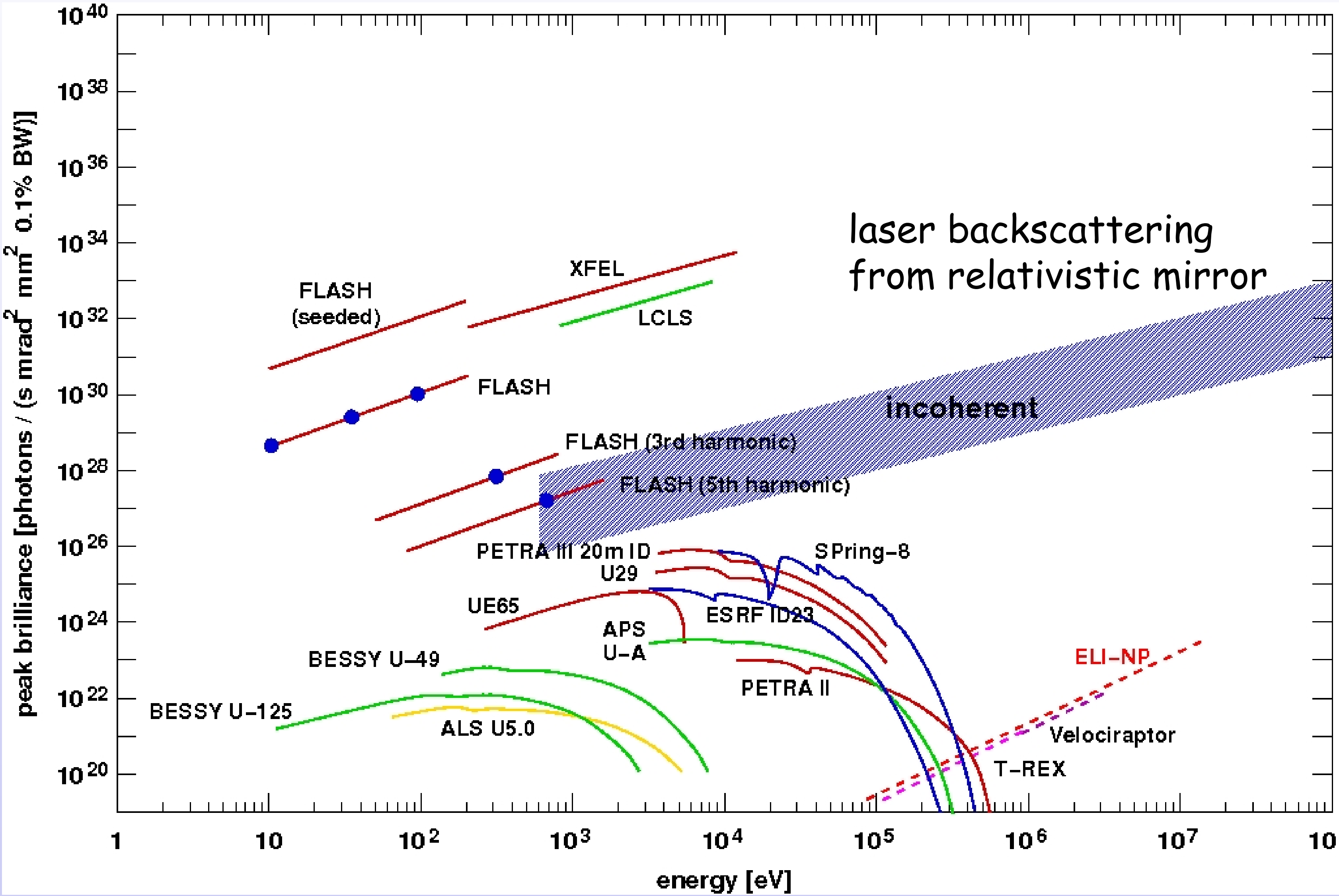
# Comparison of γ sources

| | NEPTUN | HIγS | ELI-NP | rel. γ mirror |
|---|---|---|---|---|
| $E_{electron}$ | 30 MeV | 0.3 - 1.2 GeV | 600 MeV | 0.01 – 2 GeV |
| $E_{\gamma}$ | 6 -20 MeV | 2-50 MeV | 0.1–19 MeV | 1 keV–50 MeV |
| prod. laser | -- | XUV FEL | optical | optical |
| (av.) γ rate | $10^5$/s | $10^7$/s | > $10^{13}$/s | >$10^{14}$/s |
| $\Delta E_{\gamma}/E_{\gamma}$ | 3x $10^{-3}$ | $10^{-2}$ | < $10^{-3}$ | $10^{-2}$ |
| γ beam | incoherent | incoherent | incoherent | coherent (?) |
| γ pulse | $10^{-9}$s | $10^{-12}$ s | $10^{-12}$ s | $10^{-21}$ – $10^{-15}$s |
| γ beamsize | ~1 mm | ~1 mm | ~1 μm | ~1 μm |
| polarization | switchable | switchable | switchable | -- |
| γ background | untagged γ's | -- | -- | -- |

# Peak Brilliances



# Peak Brilliances



# Photonuclear Reactions

- Benefits of using monoenergetic polarized $\gamma$ source from Compton backscattering:

  - small band width:
    allows for energy dependent determination of photon absorption cross sections even in cases of high level density

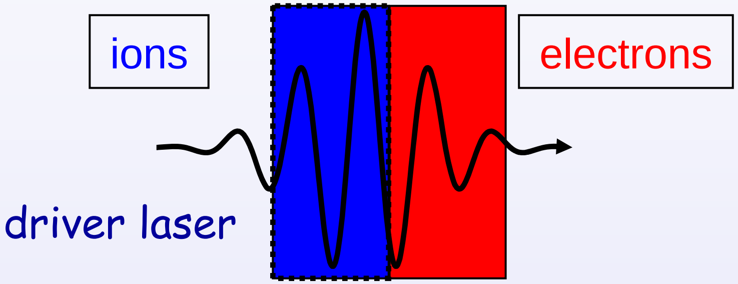
  - polarized $\gamma$ beam:
    allows for unambiguous disentanglement of E1,M1,E2 contributions to photoabsorption cross section

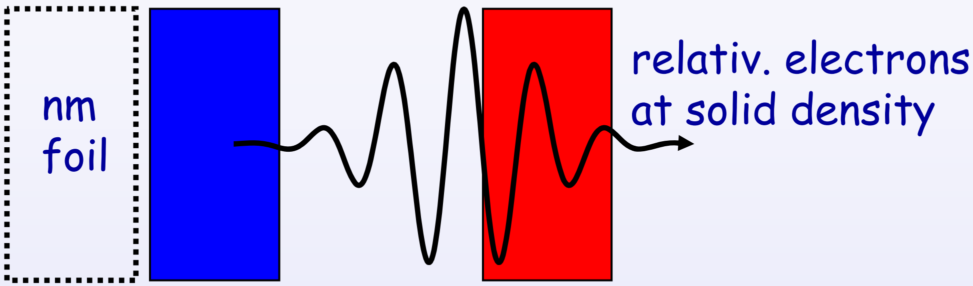
- Possible experiments:

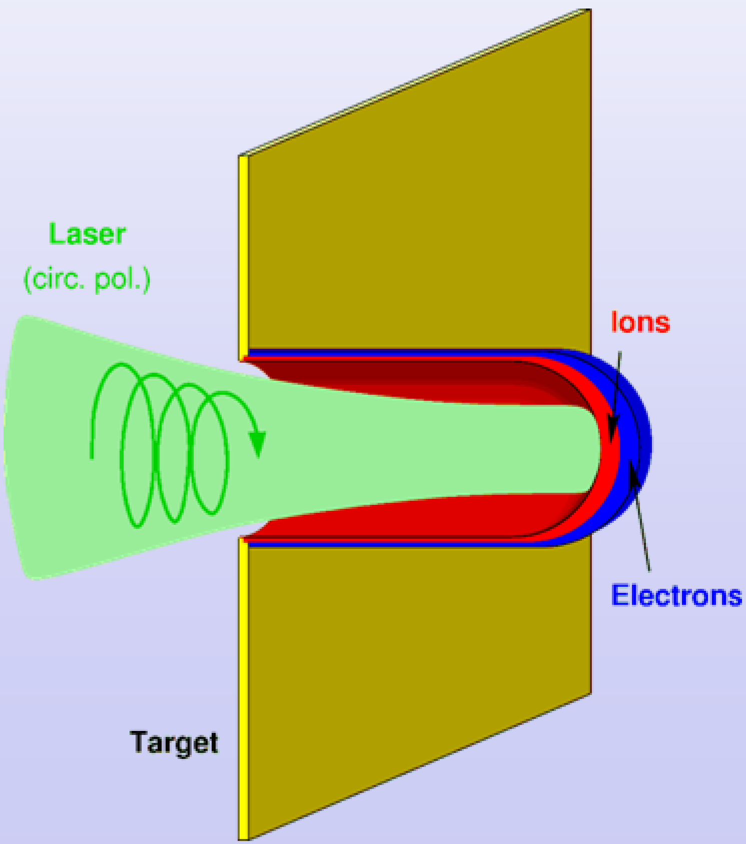
  - (inverse) neutron capture cross sections of s-process branching nuclei
  - ($\gamma$,p) and ($\gamma$,$\alpha$) reaction cross sections for p process nucleosynthesis
  - Pygmy dipole resonance (PDR): influence of deformation
  - fine structure of photo-response above particle threshold

(N. Pietralla, D. Savran, K. Sonnabend et al., TU Darmstadt)

# Radiation Pressure Acceleration



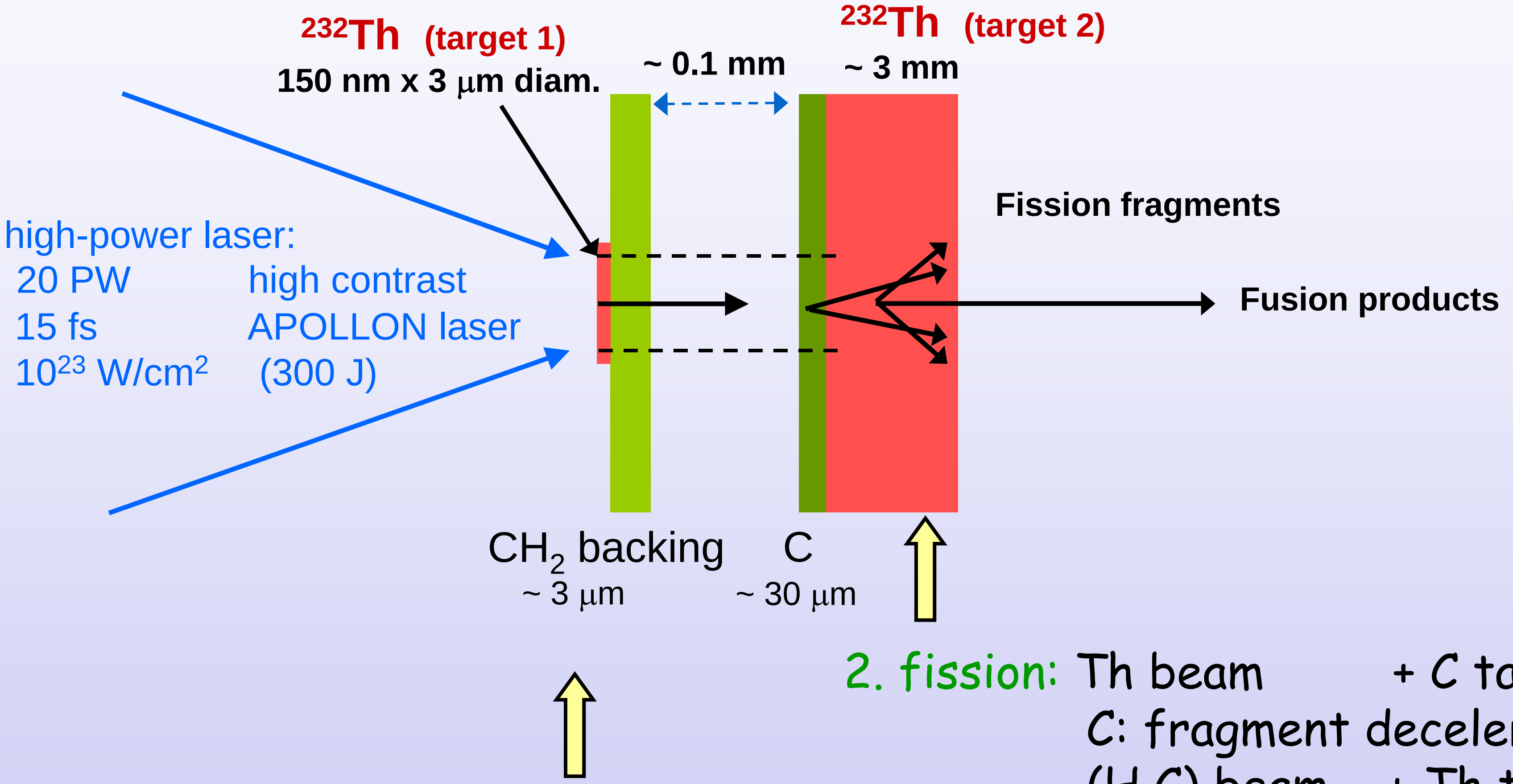




- cold compression of electron sheet, followed by electron breakout
- dipole field between electrons and ions
- ions + electrons accelerated as neutral bunch (→ no Coulomb explosion !)
- solid-state density: $10^{24}$ e cm$^{-3}$
- classical bunches: $10^{8}$ e cm$^{-3}$
- very efficient:

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

A. Henig et al., PRL 103 (2009) 245003.

# Exp. Scheme for “Fission-Fusion”




2. fission: Th beam + C target
C: fragment deceleration
(H,C) beam + Th target

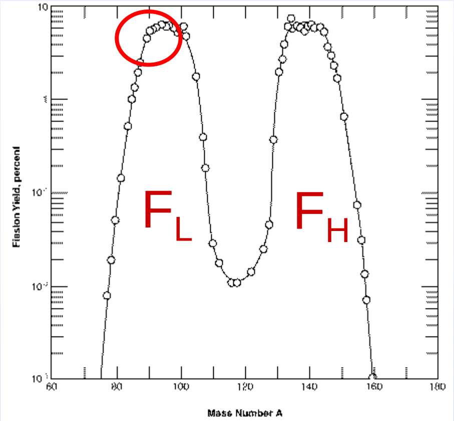
1. RPA laser acceleration: dense $^{232}$Th (and light ion) beam
ca. 7 MeV/u
ca. $10^{24}$ /cm$^3$

# Reaction Scheme: Fission-Fusion

**1. Fission:**

beam (~ 7 MeV/u): H, C, $^{232}Th$
target: C, $^{232}Th$

H, C + $^{232}Th$ → $F_L + F_H$ : fission fragments in target
$^{232}Th$ + C → $F_L + F_H$ : fission fragments of beam




$^{232}Th$:
$\langle A_L \rangle \sim 91$, $\Delta A_L \sim 14$ amu (FWHM)
$\Delta AL \sim 22$ amu (10%)
$\langle Z_L \rangle \sim 37.5$
(Rb,Sr)

**2. Fusion:**

light fission fragments of beam + light fission fragments of target

- $F_L + F_L$ → $\langle ^AZ \rangle \approx {}^{182}75$ : nuclei close to N=126 waiting point
- $F_L + F_H$ → $^{232}Th$ : original nuclei
- $F_H + F_H$ → unstable

# Fusion Yield Estimate

- $10^{12}$ Th ions accelerated / laser shot: fully fissioned in thick target

- $5 \times 10^{13}$ protons accelerated / laser shot :
  → $p_{fis}$ (thick target) ca. $10^{-3}$ (range with $E_p > V_C$ ~ 50 μm)

- fusion probability $F_L$(beam) + $F_L$ (target) ~ $10^{-3}$
  (for beam with solid density)

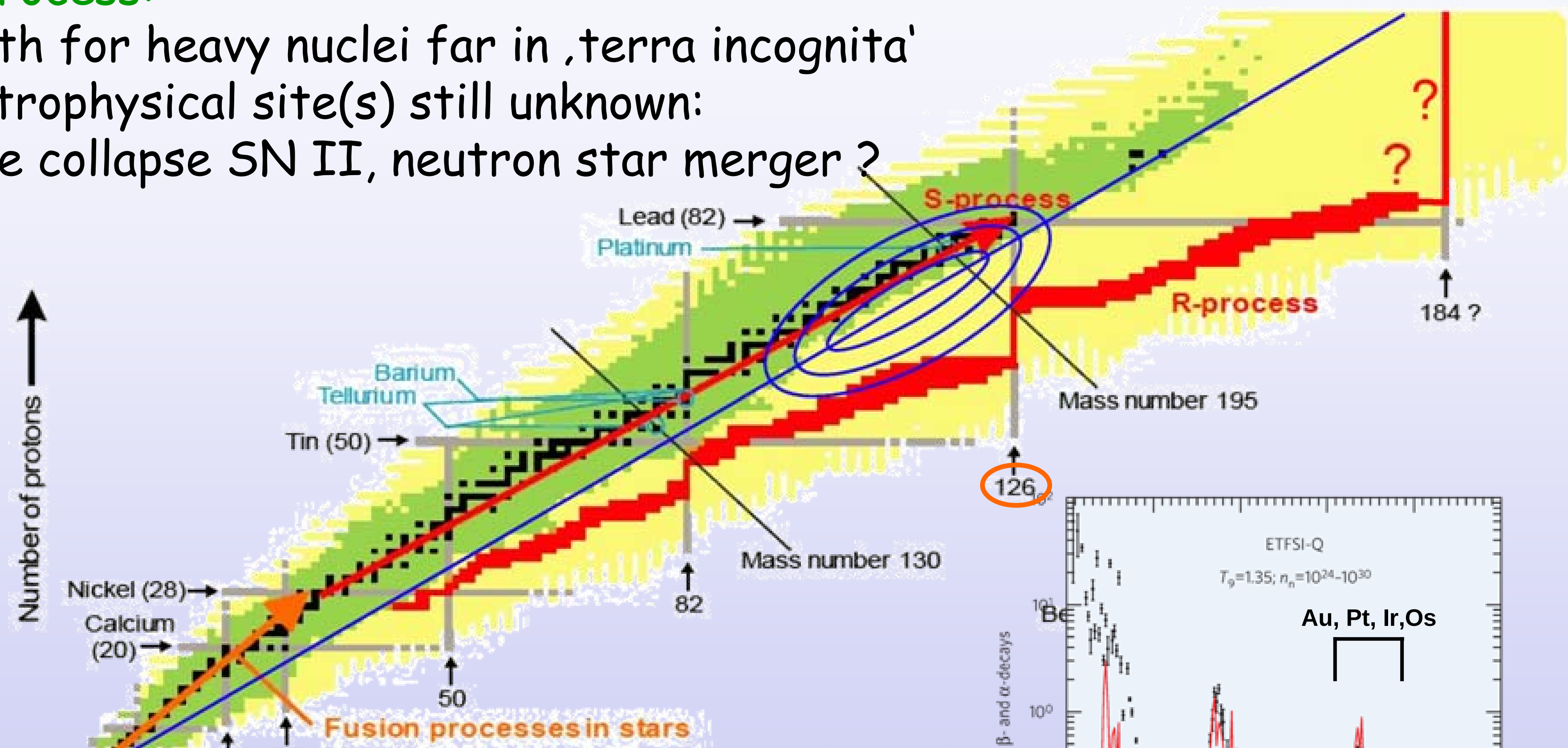
→ ~$10^6$ neutron-rich fusion products / laser shot (in $A \approx$ 180-190)

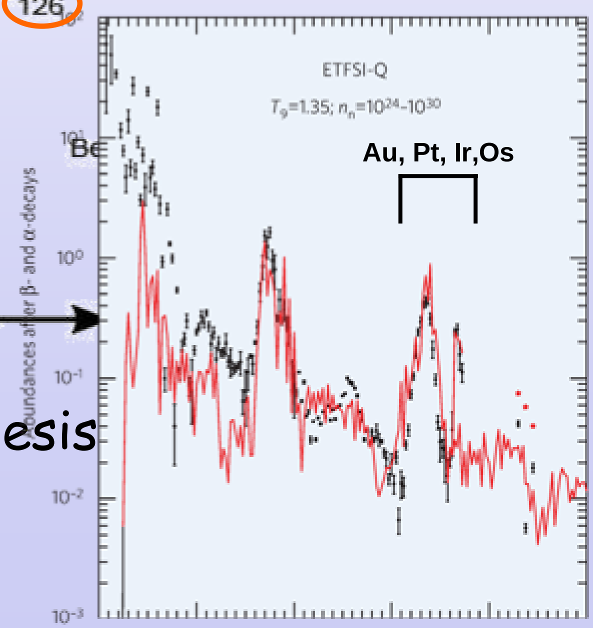
- dense ion beams:
  - reduction of stopping power expected due to collective effects
  - ‚snowplough effect': first layers of dense ion bunch remove electrons
  - $n_e$ reduced for dominant part of ion bunch
  → range enhancement

→ ~$10^6$ fusion products / sec. (in $A \approx$ 180-190)

# r process: waiting point N=126

- r process:
  - path for heavy nuclei far in ‚terra incognita'
  - astrophysical site(s) still unknown:
    core collapse SN II, neutron star merger ?

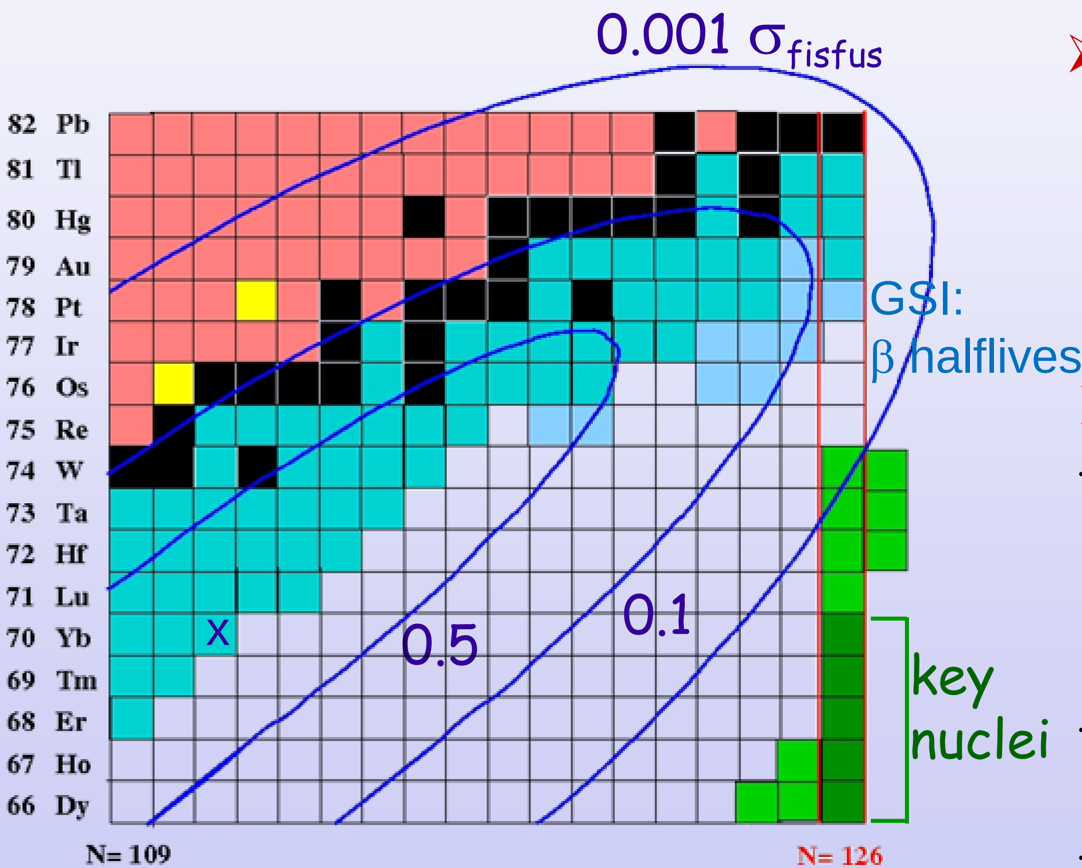



- waiting point N=126: bottleneck for nucleosynthesis of actinides
- last region of r process 'close' to stability

# Towards N=126 Waiting Point

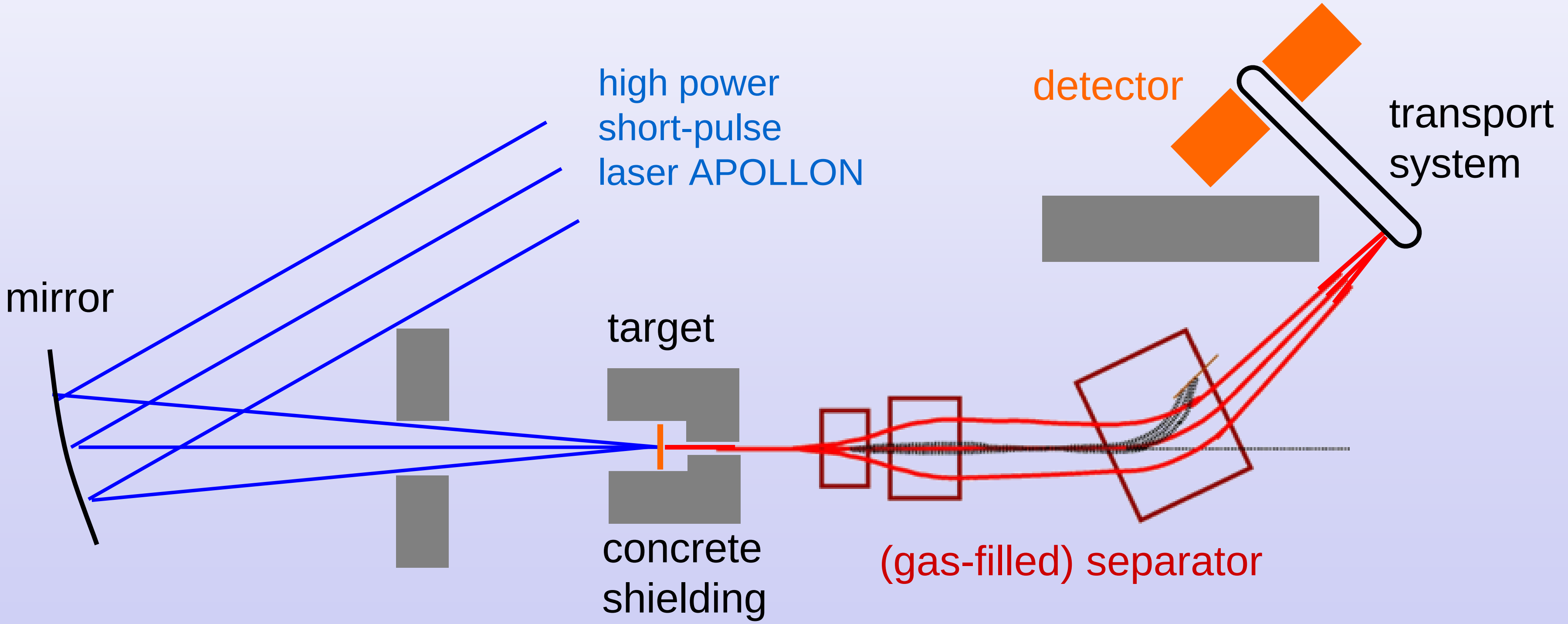
- r process path:
  - known isotopes ~15 neutrons away from r process path (Z≈ 70)




- measure:
  - masses, lifetimes, structure
  - β-delayed n emission prob. $P_{\nu,n}$
  - lifetime measurements: already with ~ 10 pps
- visions:
  - test predictions: r process branch to long-lived (~ $10^9$ a) superheavies (Z≥110) → search in nature ?
  - improve on formation predictions for U, Th
  - recycling of fission fragments in (many) r process loops ?

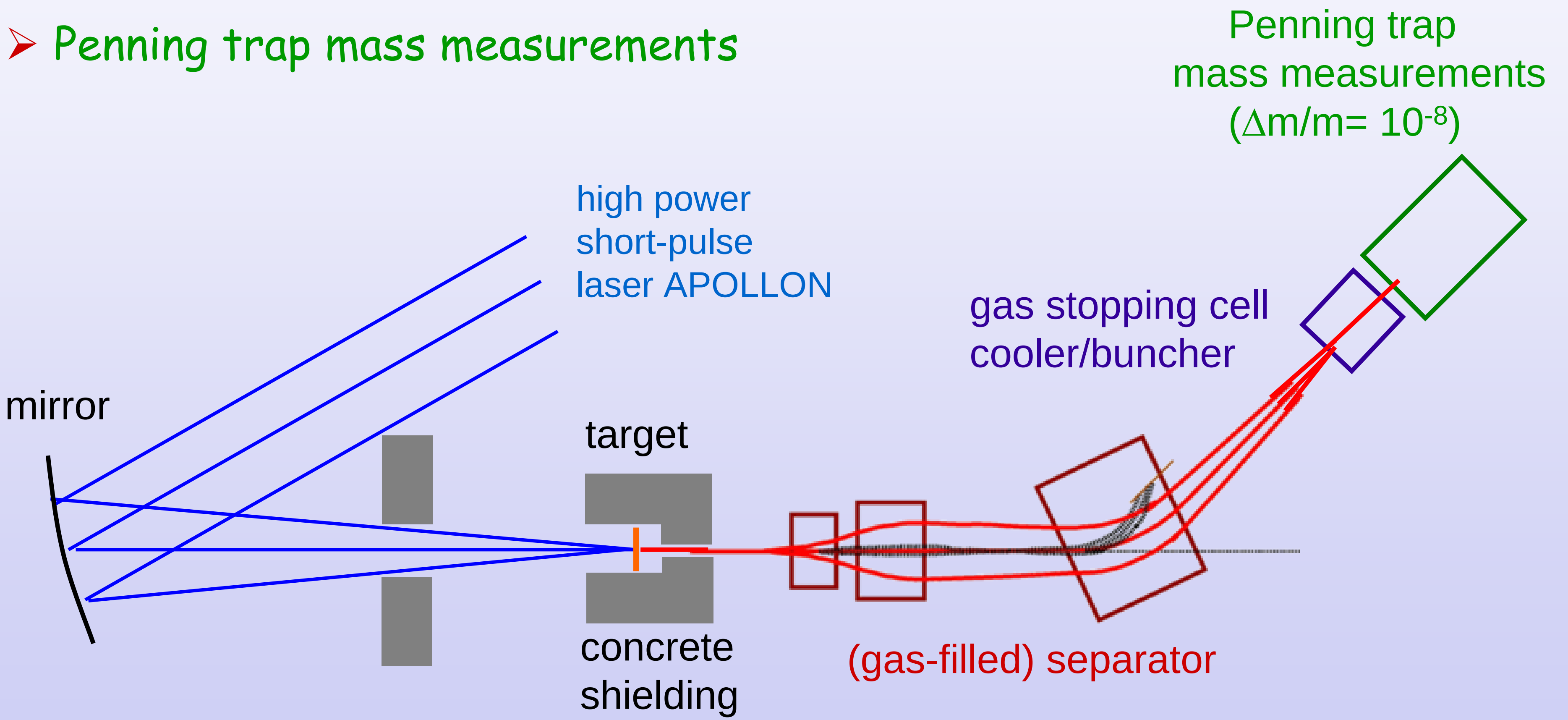
# Experimental layout

- characterization of reaction products
  - decay spectroscopy



# Experimental layout

- characterization of reaction products
  - decay spectroscopy
- Penning trap mass measurements



# ELI: Extreme Light Infrastructure

- ELI:
  - new EU-funded scientific infrastructure
  - devoted to scientific research with high-intensity lasers
  - laser-matter interaction:
    → 5 orders of magnitude higher than today's laser intensity

- Pillars of ELI
  1. physics with ultrashort laser pulses: Szeged
  2. laser acceleration: electrons, ions; applications: Prague
  3. nuclear physics (ELI-NP): Bucharest

- Project dimensions:
  - ELI in total: ca. 740 MEUR from EU structural funds
  - ELI-NP: ca. 280 MEUR
    - ca. 3500m² laser clean rooms
    - ca. 15000m² experimental areas
    - ca. 2000 m² ‚other' areas (infrastructure, prep. labs, offices ..)
    - availability of funding requires facility to be operational in 2015 !

# Conclusions

- generation of highly-brilliant $\gamma$ beam via laser Compton-backscattering:
  - high flux
  - small $\gamma$ band width ($\Delta$E)
  
  → ideal for astrophysical reactions: ($\gamma$,p),($\gamma$,$\alpha$), Pygmy resonance etc.

- novel laser ion acceleration (RPA):
  - generation of ultra-dense ion bunches
  - enables fission-fusion reactions
  
  → fusion between 2 neutron-rich fission fragments
  - reduction of electronic stopping ?
  - rapid laser development will increase repetition rate and energy
  - may lead much closer towards N=126 r-process waiting point

- realization of these schemes:

  → ELI laser research infrastructure

# Thanks ……

D. Habs, M. Gross, T. Tajima (LMU Munich)

G. Korn, J. Schreiber (MPQ Garching)

Thank you for your attention !