

# Transfer-induced fission in inverse kinematics with solenoidal spectrometers

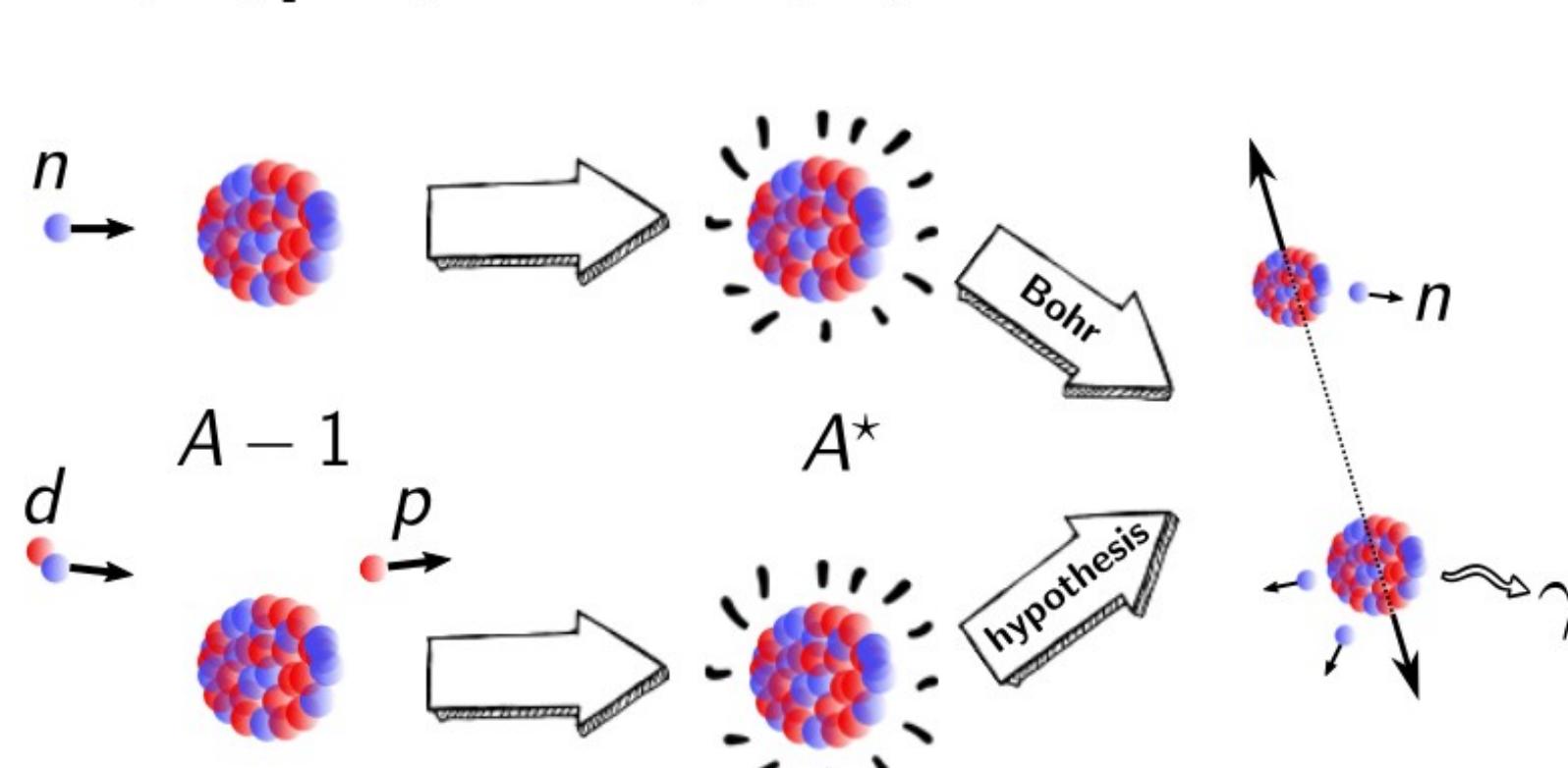
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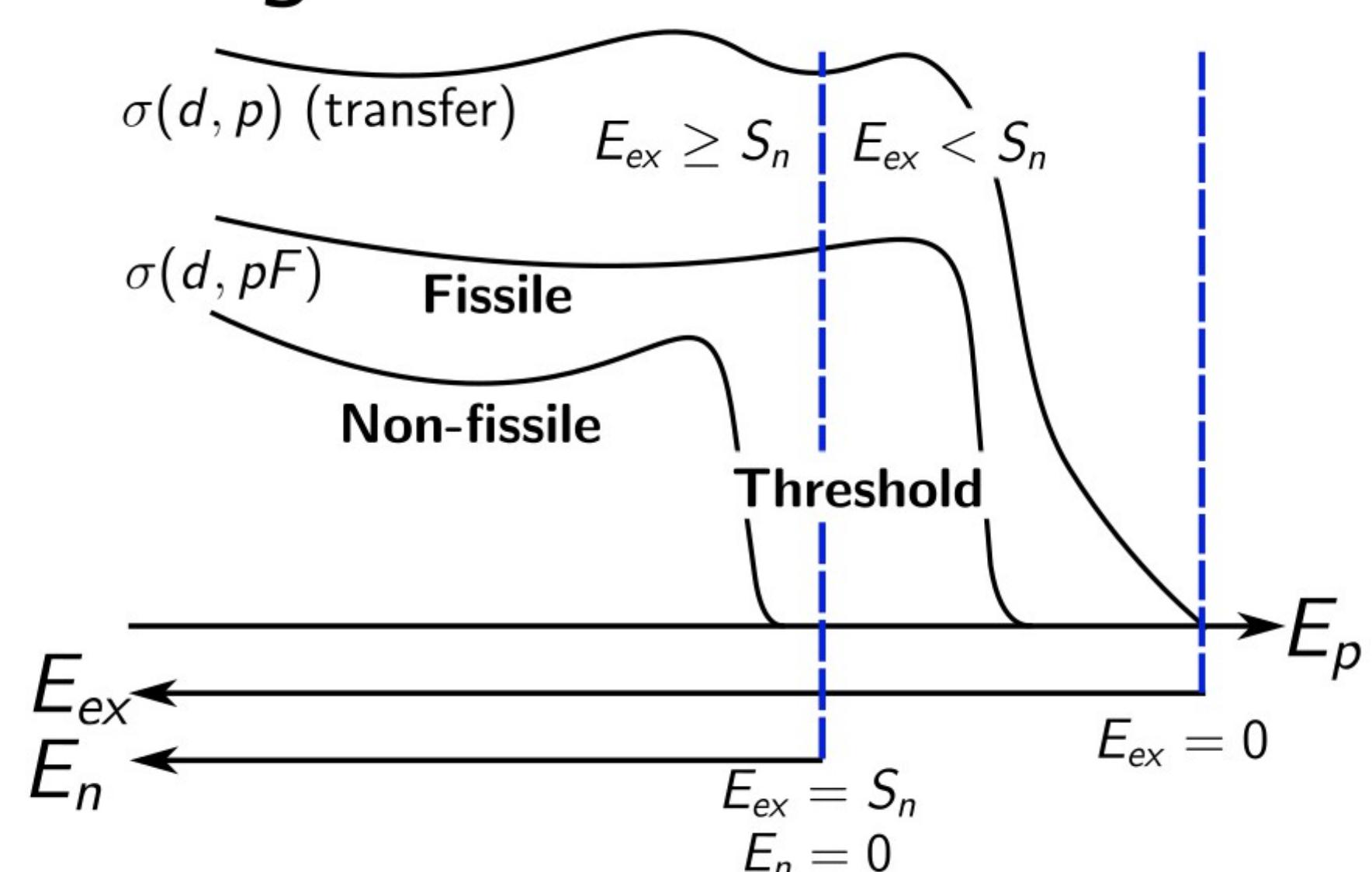
## (d,pF) in inverse kinematics

- The single-neutron adding ( $d, p$ ) reaction used as a precursor to fission — a surrogate for the ( $n, F$ ) reaction [1]
- Excitation energy  $E_{ex} \geq 0$  — fission barrier is accessible
- Actinide beam — study fission properties of short-lived nuclei
- Kinematic boost allows Bragg curve spectroscopy of fission fragments — charge yields
- Measure fission probabilities,  $P_F$  — deduce ( $n, F$ ) cross section

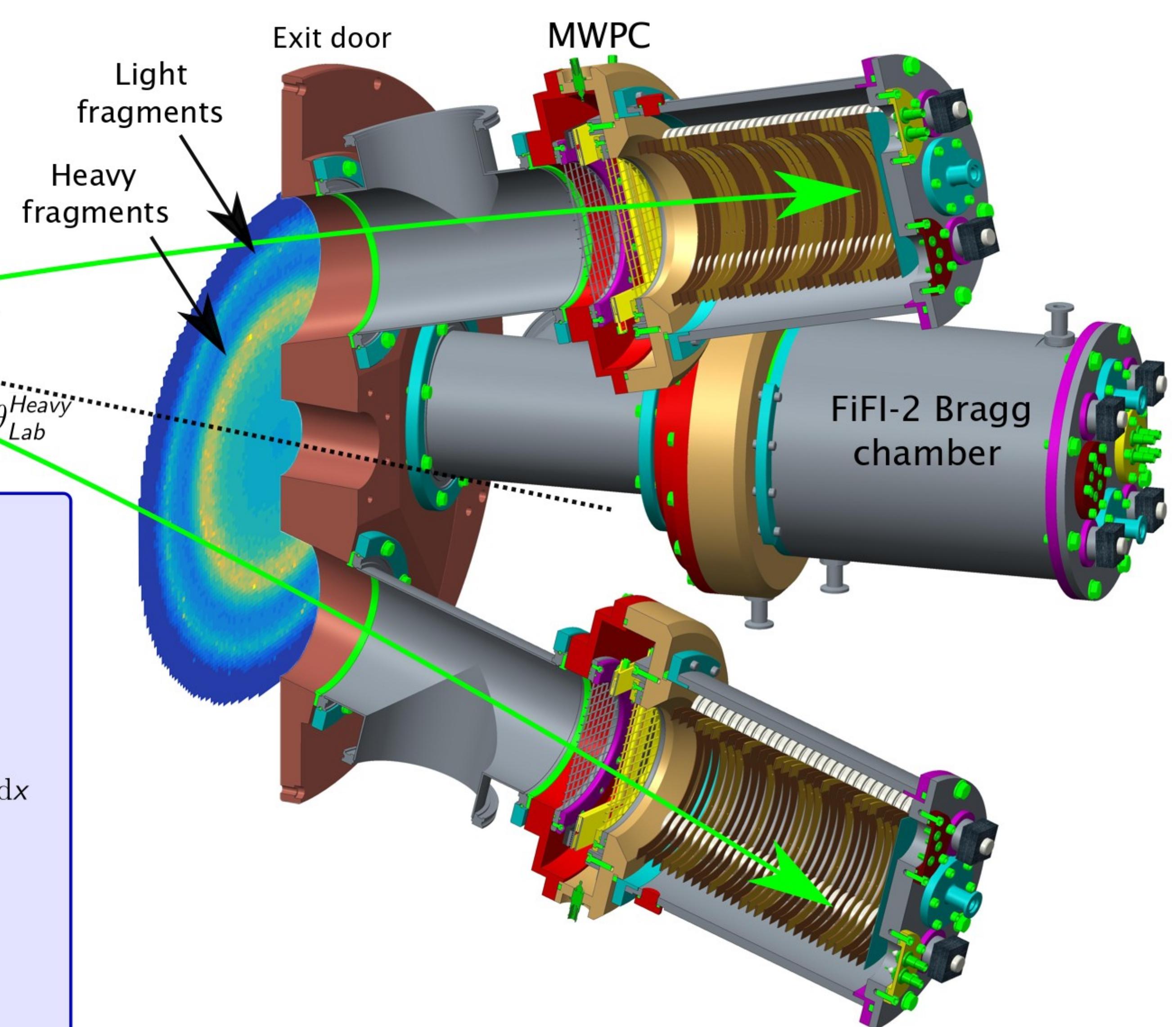
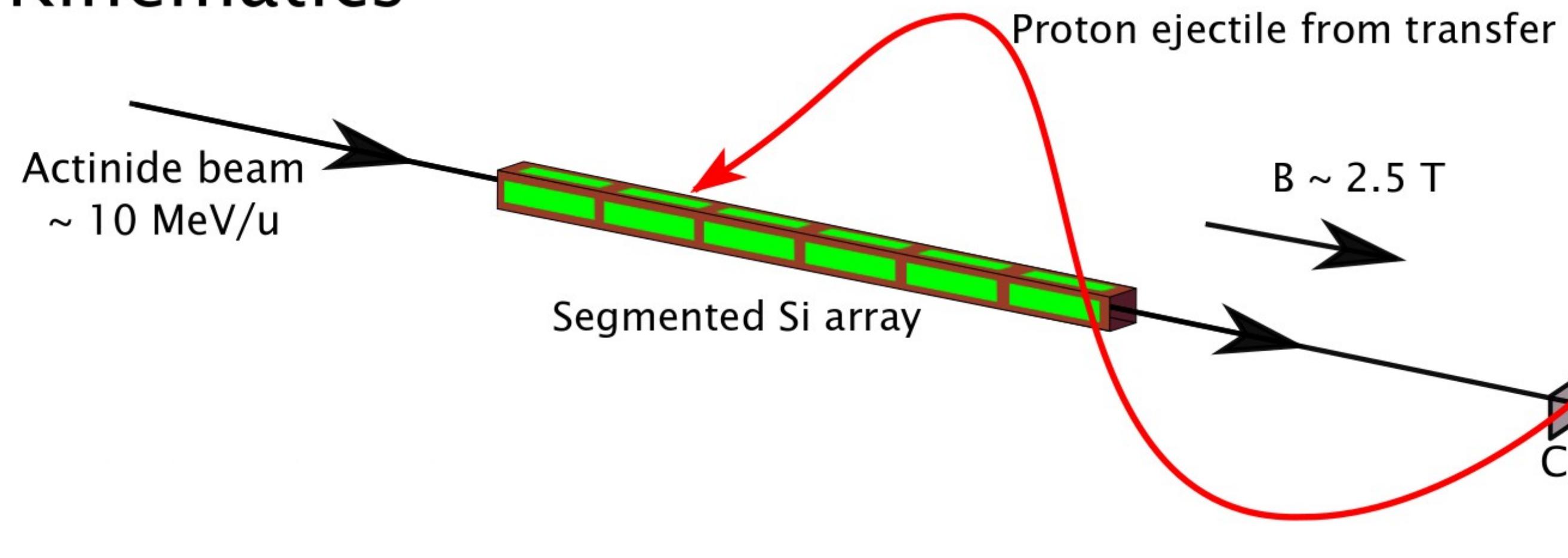
## (d,pF) vs (n,F)



## Energetics



## Kinematics

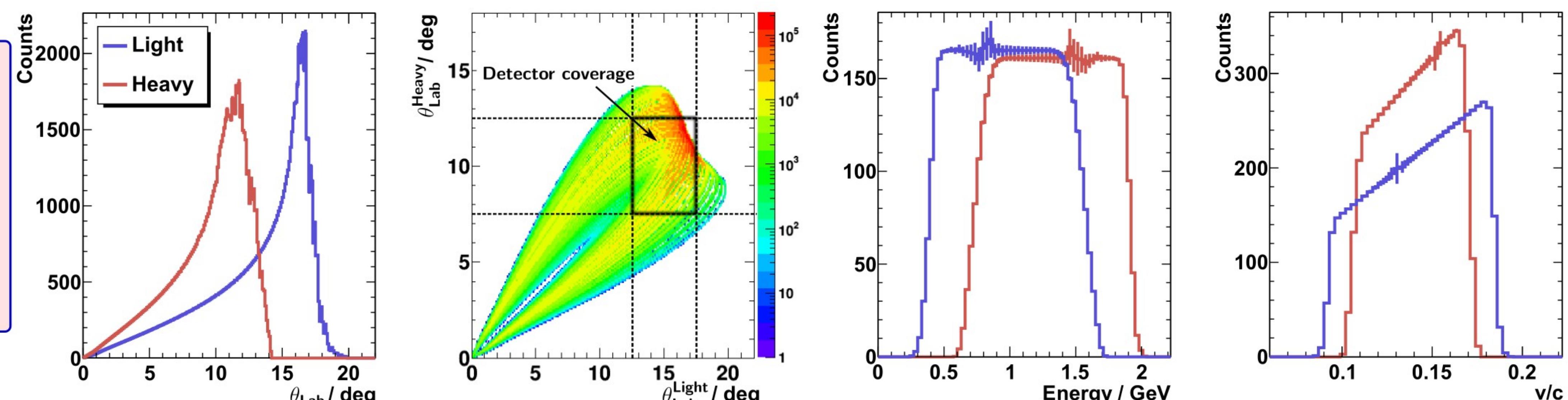


### Protons:

- Measure lab energy  $E_p$  and array position  $z$
- Light transfer ejectile
- CM energy and angle calculable and give  $E_{ex}$  [2]
- Inherent problems in inverse kinematics are solved by using a solenoidal spectrometer (kinematic shift and kinematic compression) — greater excitation energy resolution [2]
- Centre-of-mass angular distribution — DWBA comparison gives  $L$  transfer information

### Fission fragments:

- Measure lab energies  $E_{Lab}^{Light}$ ,  $E_{Lab}^{Heavy}$  and angles  $\theta_{Lab}^{Light}$ ,  $\theta_{Lab}^{Heavy}$  and specific energy losses  $dE/dx$
- Large CM velocity boost
- Light and heavy fragments pass into narrow cones (~ 15° and 10° for beam energy = 9 MeV)
- Catch fission fragments in FiFl-2 (fission fragment identification) detectors — 4 × axially segmented back-to-back Frisch-grid ionisation chambers (UHV constraints)
- Position sensitive MPWC detectors for  $\theta_{Lab}$  and fast timing (proton Si array + fission MWPC coincidence)



### Fragment collection efficiency: (FiFl-2 array)

- At the door: ~ 10 %
- At the FiFl detectors: ~ 3 % (Solid angle reduction and curved trajectories)
- Heavy + light fragment coincidence: ~ 1.5 %
- Function of fragment mass and charge, target position,  $B$  field strength, beam energy

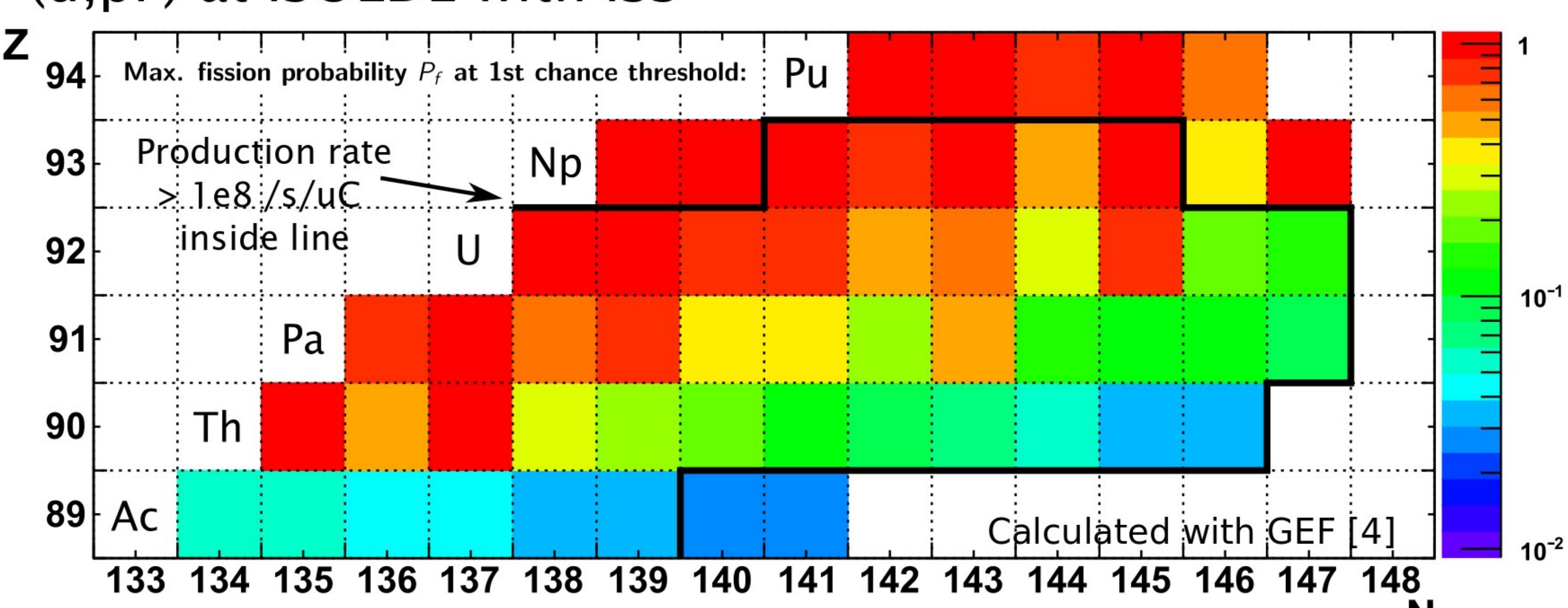
### Background:

- Fusion-fission and fusion evaporation ( $D, {}^{238}U$ ) and ( ${}^{12}C, {}^{238}U$ ) ~ all reaction products forwards in lab (some protons backwards, ~ 1 %)
- Proton ejectile from transfer backwards in lab — **clean background rejection**
- Deuteron breakup

### Measureable fission parameters:

- **Barrier heights** (fissile + non-fissile nuclei)
  - Measure (relative) ( $d, pF$ ) and ( $d, p$ ) cross sections
  - Hauser-Feshbach in Weiskopf-Ewing limit:  $\sigma_{d,pF}(E_{ex}) \approx \sigma_{d,p}^{CN*}(E_{ex}) \cdot P_F(E_{ex})$
- **Mass yields**
  - $f(E_{Lab}^{Light}, E_{Lab}^{Heavy}, \cos \theta_{Lab}^{Light}, \cos \theta_{Lab}^{Heavy}, m_{Light}, m_{Heavy}) = 0$
  - Sensitivity study: expect resolution of ~ 2 - 3 %.
- **Charge yields**
  - Bragg curve spectroscopy
  - Resolution ~ 1.5 % [3]
  - (Spin distribution of fissioning states)
    - Angular anisotropy of protons in CM indicative of  $J_{rms}$  of fissioning states
    - (Deduce  $\sigma(n, F)$  using  $P_F$  measurement)

## (d,pF) at ISOLDE with ISS



- **FiFl-2 array + Solenoidal spectrometer**
  - Test measurement with HELIOS, ANL in 2020:  ${}^{238}U(d, pF)$
  - **Rates**
    - For  ${}^{238}U(d, pF)$ ,  $\sigma \approx 17$  mb [1].
    - On left plot: large overlap of isotopes with large fission probabilities and large production rates in ISOLDE targets
    - Many candidates
  - **Applications**
    - Measurements of exotic fissioning systems → fission models
    - Nuclear astrophysics: r-process, fission recycling
    - Nuclear energy: GEN-IV reactors, actinide recycling and transmutation

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## References

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