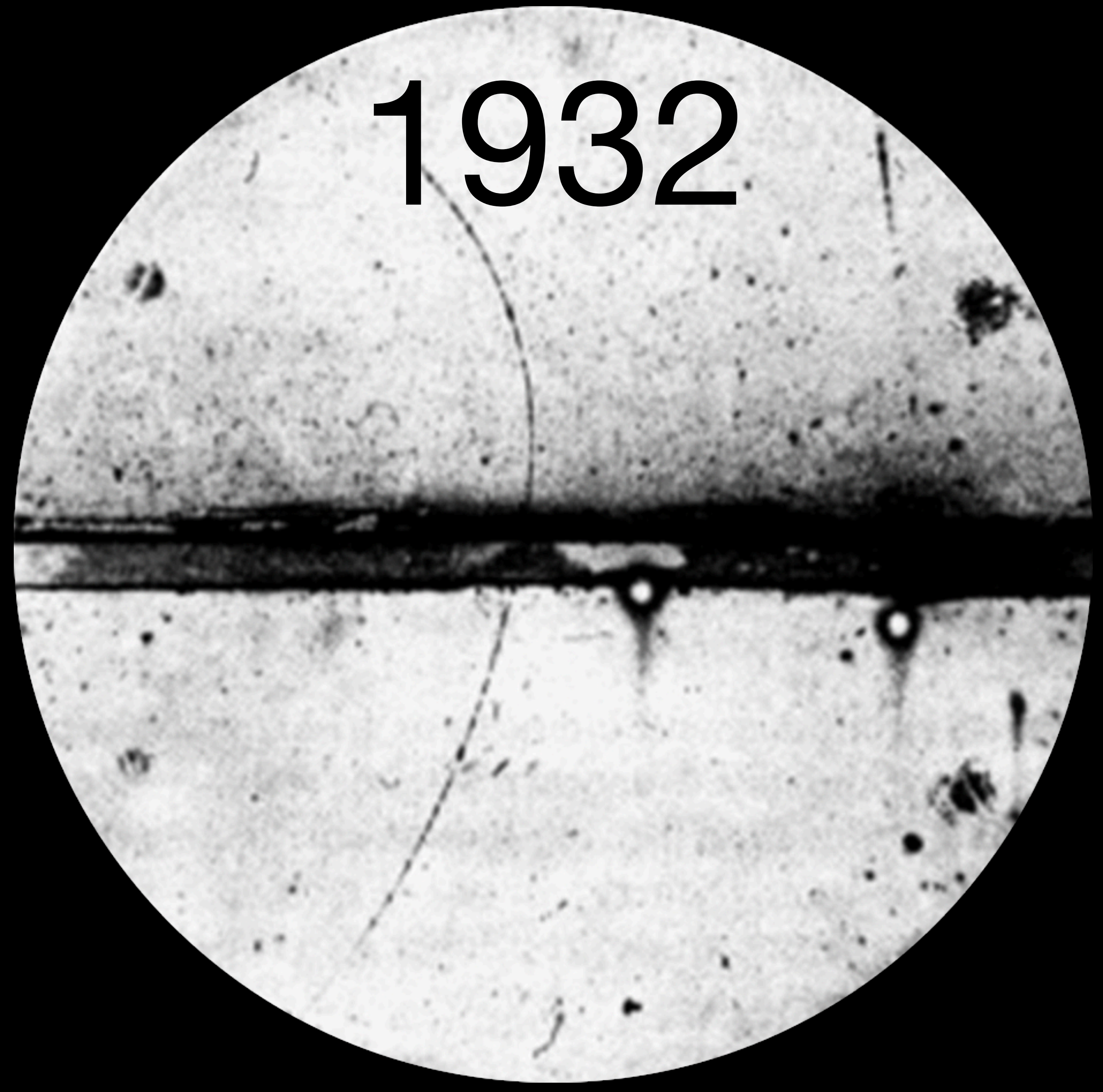
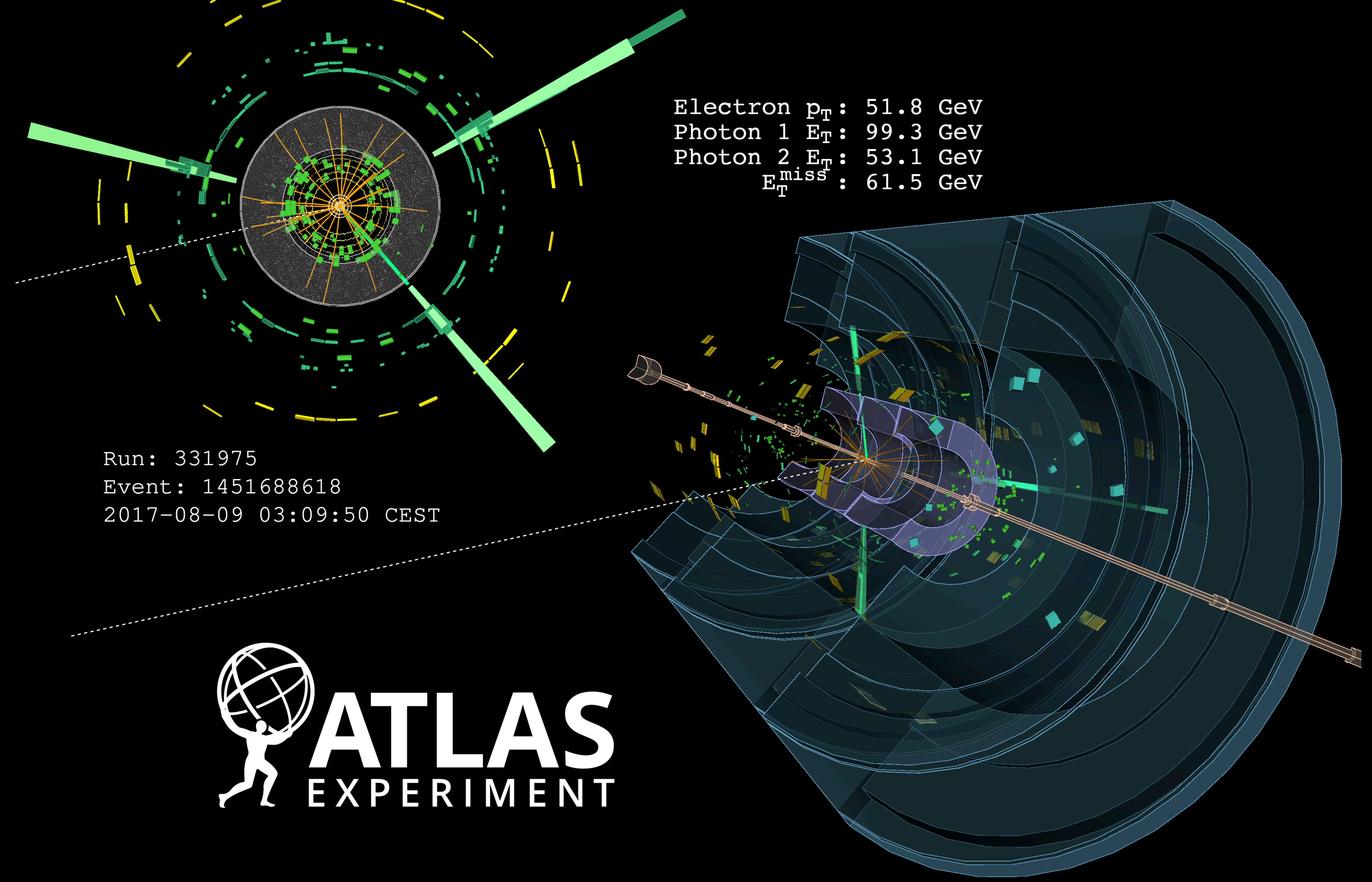
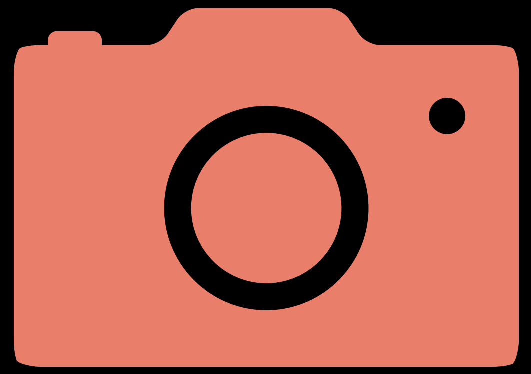
PHYS 7363 - Experimental Particle Detection and Detectors I



2017

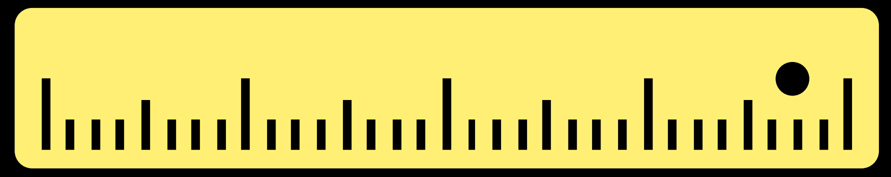


Particle detectors are the workhorses of experimental physics. In this course, we'll dive deep into their physics, exploring the incredible evolution of our experimental techniques over the past nine decades. You'll gain a solid understanding of *particle detection* and *identification*, examine the intricate designs of modern detectors, and learn how machine learning is being harnessed to push the boundaries of detector design. If you're intrigued by how we "see" subatomic particles, this course is for you!



Detect

Identify



Measure

To discuss prerequisites (and any questions on the content of the course), please contact me: saptaparnab@smu.edu

Schedule

Month	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
August	18	19	20	21	22	23	24
	25 ✅	26	27	28	29 ✅	30	31
September	1	2	3 ✅	4	★ 5 ✅	6	7
	8 1.5 hours	9	Zoom 10	11	12 1.5 hours	13	14
	15	16	17	18	19	20	21
	22	23	24	25	26	27	28
October	29	30	1	2	3	4	5

Key dates

- Weeks 1-4: Particle interaction with matter
  - Interaction of charged and neutral particles
  - Particle showers
- Weeks 5-9: Detector technologies:
  - Tracking detectors (gaseous detectors, semiconductor detectors)
  - Particle detection with photons (scintillators, Cherenkov detectors)
  - Calorimetry (electromagnetic and hadronic calorimeters)
- Weeks 10-12: Large and small scale experiments:
  - Triggering and data acquisition
  - Tracking
  - Full reconstruction (particle flow)
- Week 13-15: Preparation for final project:
  - FCC-ee: https://indico.fnal.gov/event/67484/contributions/314057/attachments/187076/257915/US%20FCC%20Tutorial_FullSim.pdf
  - Muon collider: https://mcd-wiki.web.cern.ch/software/tutorials/fermilab2024/

Resources

- PDG review: Passage of particles through matter
  - https://pdg.lbl.gov/2020/reviews/rpp2020-rev-passage-particles-matter.pdf
- N. Wermes / H. Kolanoski, “Particle Detectors”, Oxford University Press, 2020
- Georg Viehhauser/Tony Weinberg, “Detectors in Particle Physics: A Modern Introduction”, CRC Press, Taylor and Francis Group
- C. Grupen / B. Schwartz, “Particle Detectors”, Cambridge University Press, 2011
- F. Hartmann, “Evolution of Silicon Sensor Technology in Particle Physics”
- A. Strandlie, R. Frühwirth, Pattern Recognition, Tracking and Vertex Reconstruction in Particle Detectors
- LHC experiment design: https://www.nature.com/articles/nature06078

Career Development

https://www.jumptrading.com/fellowship-program

Jump TRADING

Careers | AI/ML | Trading | Research & Programs | Join Us →

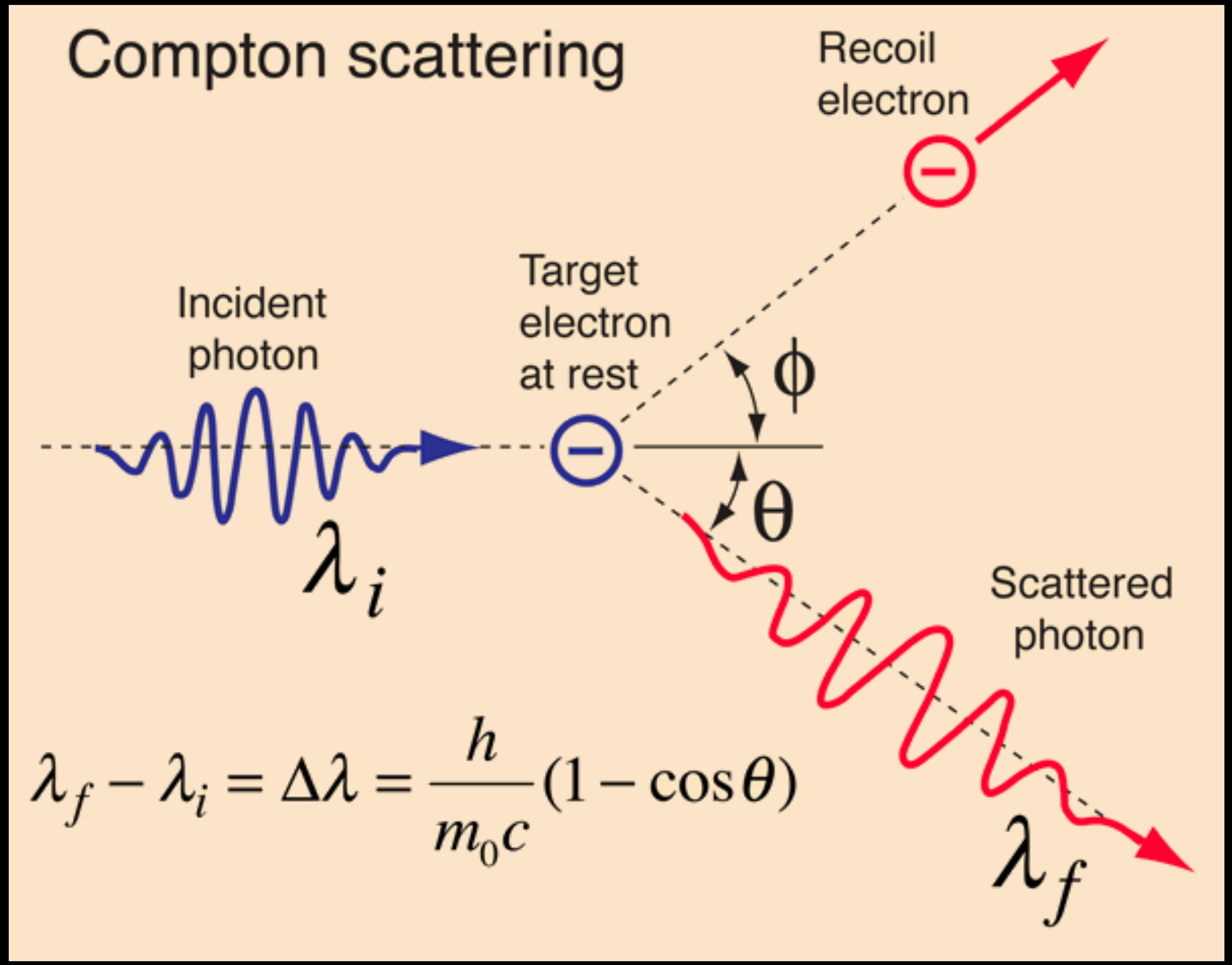
We fund bold research, no strings attached

Nominations for the 2026-2027 Fellowship Cycle are now open

Particle interaction with matter

Particle detection through interaction

- Particles can be detected by their interaction with matter. Detectors typically use the following processes:
  - Ionization and excitation of atoms in media by charged particles (electron-ion pairs)
  - bremsstrahlung: photon radiation emitted by charged particles in the fields of atomic nuclei
  - photon scattering (Compton scattering) and photon absorption (registers the presence of light by absorbing photons and converting that absorbed energy into an electrical signal, such as a current or voltage, proportional to the number of photons)
  - Cherenkov (charged particle traveling faster than speed of light in a medium) and transition radiation
  - nuclear reactions: hadrons (p, n, π, α) with nuclear matter
  - weak interactions constituting the only possibility to detect neutrinos

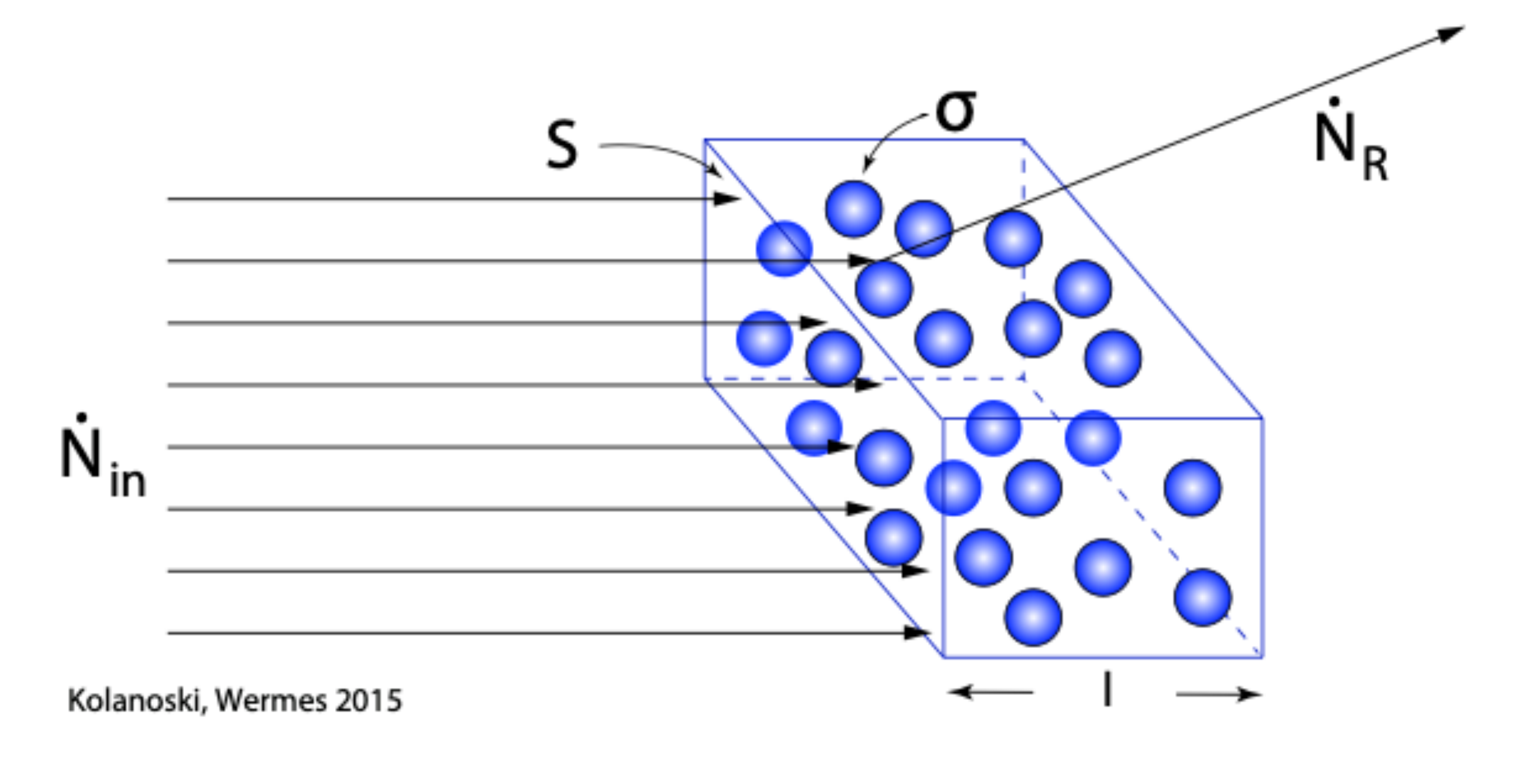


Particle detection through interaction

- Generally, a particle will undergo more than just one interaction process on its path through matter if it is not absorbed in its first interaction. For example, charged particles usually lose energy in a large number of subsequent ionization and excitation interactions with atoms of the medium they pass through.
- The probability that a particle interacts with the atoms of a medium is defined by the cross section of a reaction. The definition of the cross section and related terms will be given in the following section.

Particle detection through interaction: cross sections

- The cross section is a measure of the probability of a particle reaction
- Depends on the kind and strength of the interactions between particles
- Represented by an effective area
- The cross section σ represents the effective area of the target particle as seen by an incoming beam
- Assume beam has no spatial extent

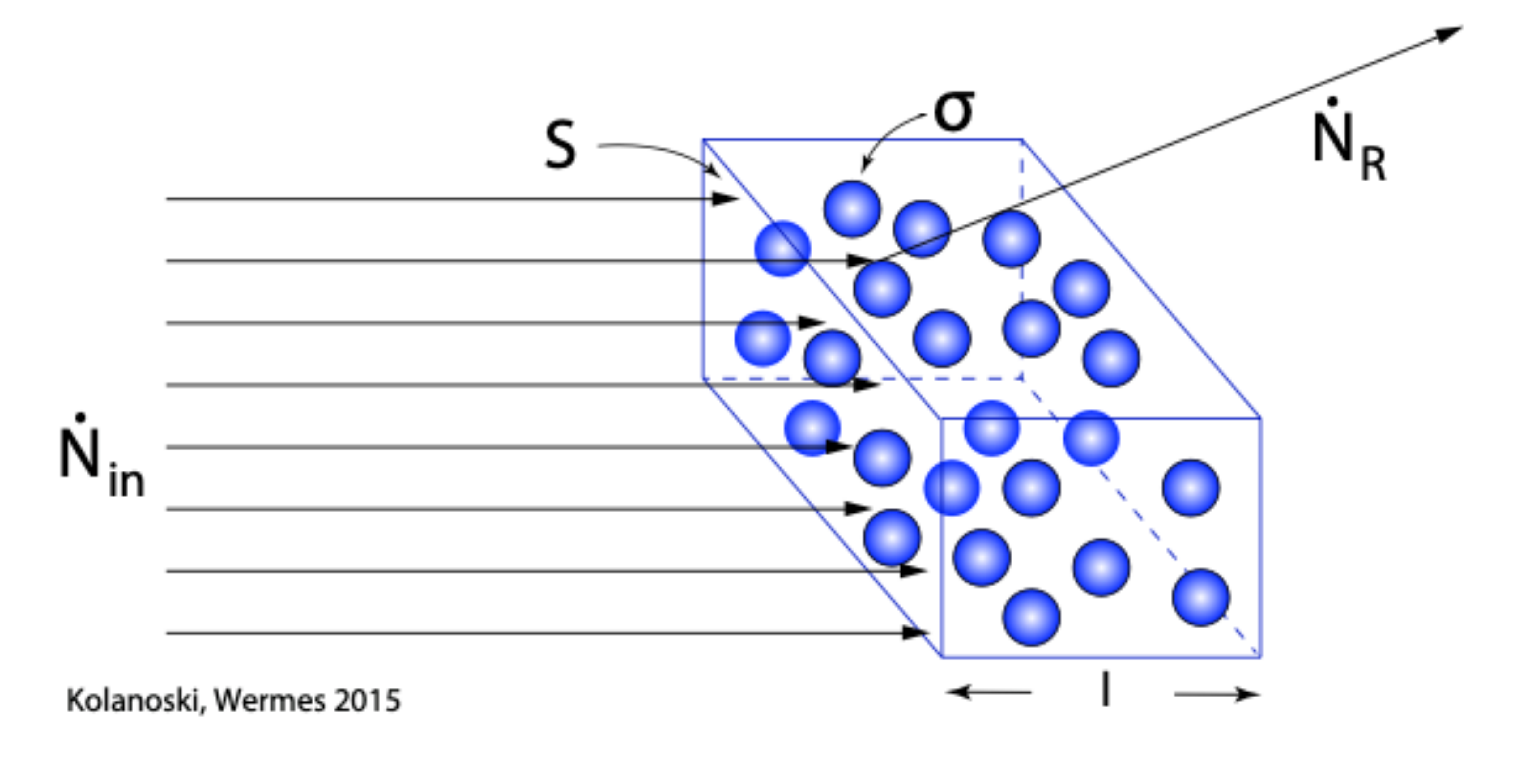


$\dot{N}_{\text{in}}$: incoming particle rate

$\dot{N}_R$: incoming reaction rate

Particle detection through interaction: cross sections

- Beam enters target area with rate $\dot{N}_{\text{in}}$
- There are the following number of particles in the target volume:
  - $N_T = \frac{\rho V}{A} N_A$
  - Target volume, $V = Sl$
  - Target mass density, ρ
  - Atomic mass per mole of the target particles, A
  - $N_A = 6.02214076 \times 10^{23}$/mol

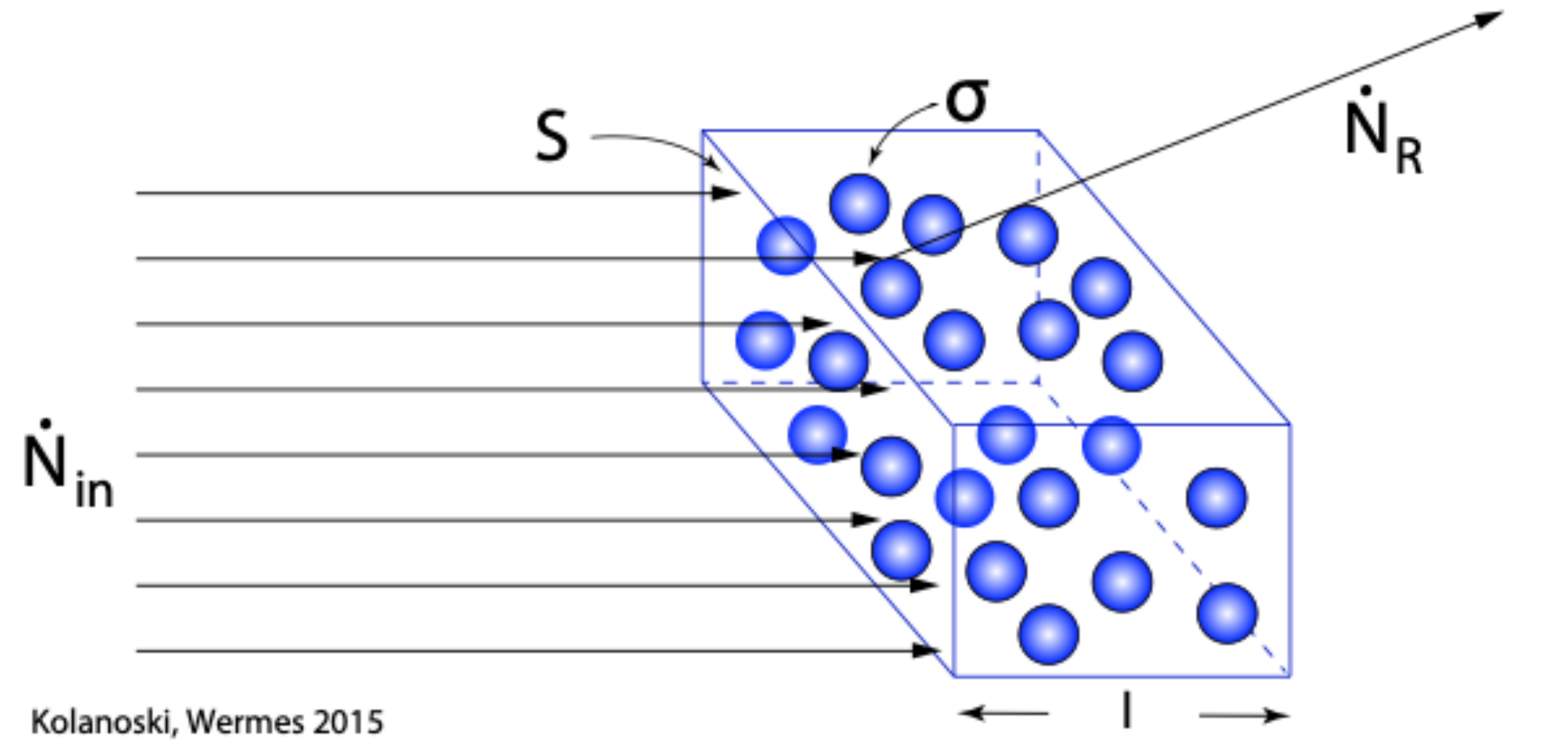


$\dot{N}_{\text{in}}$: incoming particle rate

$\dot{N}_R$: incoming reaction rate

Particle detection through interaction: cross sections

- $N_A = 6.02214076 \times 10^{23}$/mol is Avogadro's number
- Used to define mole since 2019
- Target can be any type of particle (atom, molecule, electron)
- Number density given by
  - $n = \frac{N_T}{V} = \frac{\rho}{A} N_A$
- The incoming beam "sees" a total area:
  - $N_T \sigma$ of target particles
- Probability to hit a particle target
  - $P = N_T \sigma / S$
  - This probability can be expressed by the scattering or reaction rate ($\dot{N}_R$) relative to the rate of incoming beam particles ($\dot{N}_{\text{in}}$)



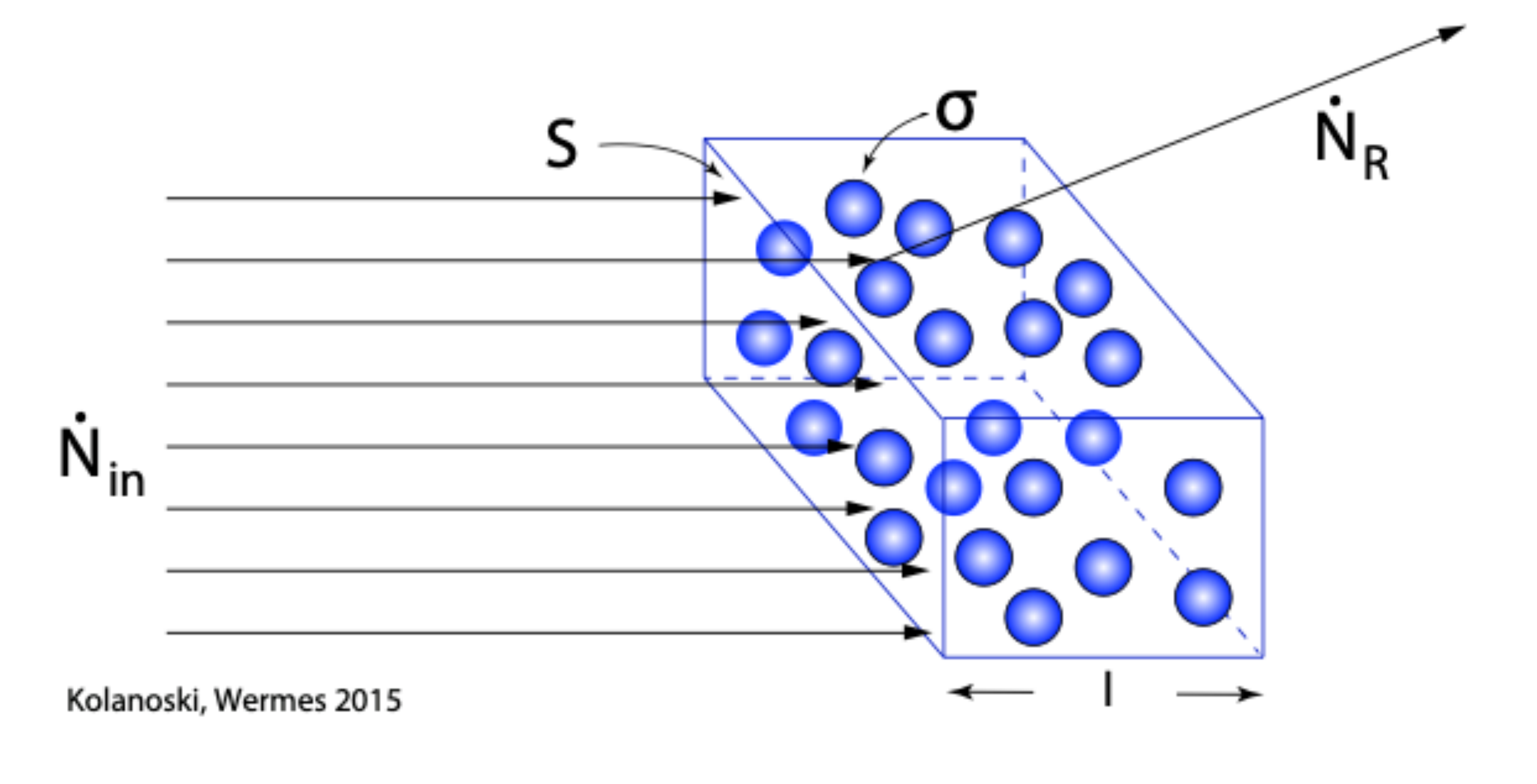
Kolanoski, Wermes 2015

$\dot{N}_{\text{in}}$: incoming particle rate

$\dot{N}_R$: incoming reaction rate

Particle detection through interaction: cross sections

- This probability can be expressed by the scattering or reaction rate ($\dot{N}_R$) relative to the rate of incoming beam particles ($\dot{N}_{\text{in}}$)
  - $P = \frac{\dot{N}_R}{\dot{N}_{\text{in}}} = \frac{N_T \sigma}{S} = n\sigma l$
  - The cross section (σ) can be expressed as:
    - $\sigma = \frac{\dot{N}_R}{\dot{N}_{\text{in}}} \frac{1}{nl}$
    - Reaction rate is proportional to the cross section, proportionality constant is L
    - $\dot{N}_R = \sigma L, L = \dot{N}_{\text{in}}\, nl$

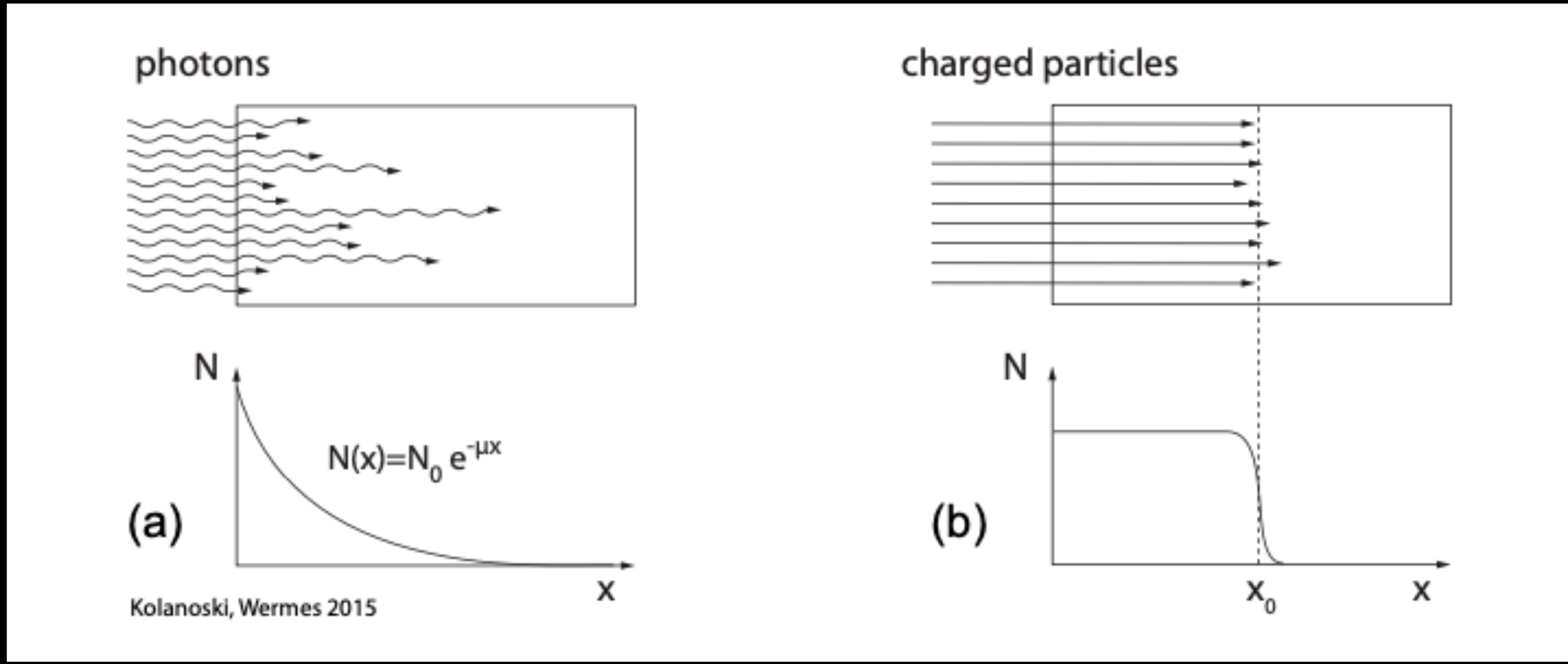


$\dot{N}_{\text{in}}$: incoming particle rate

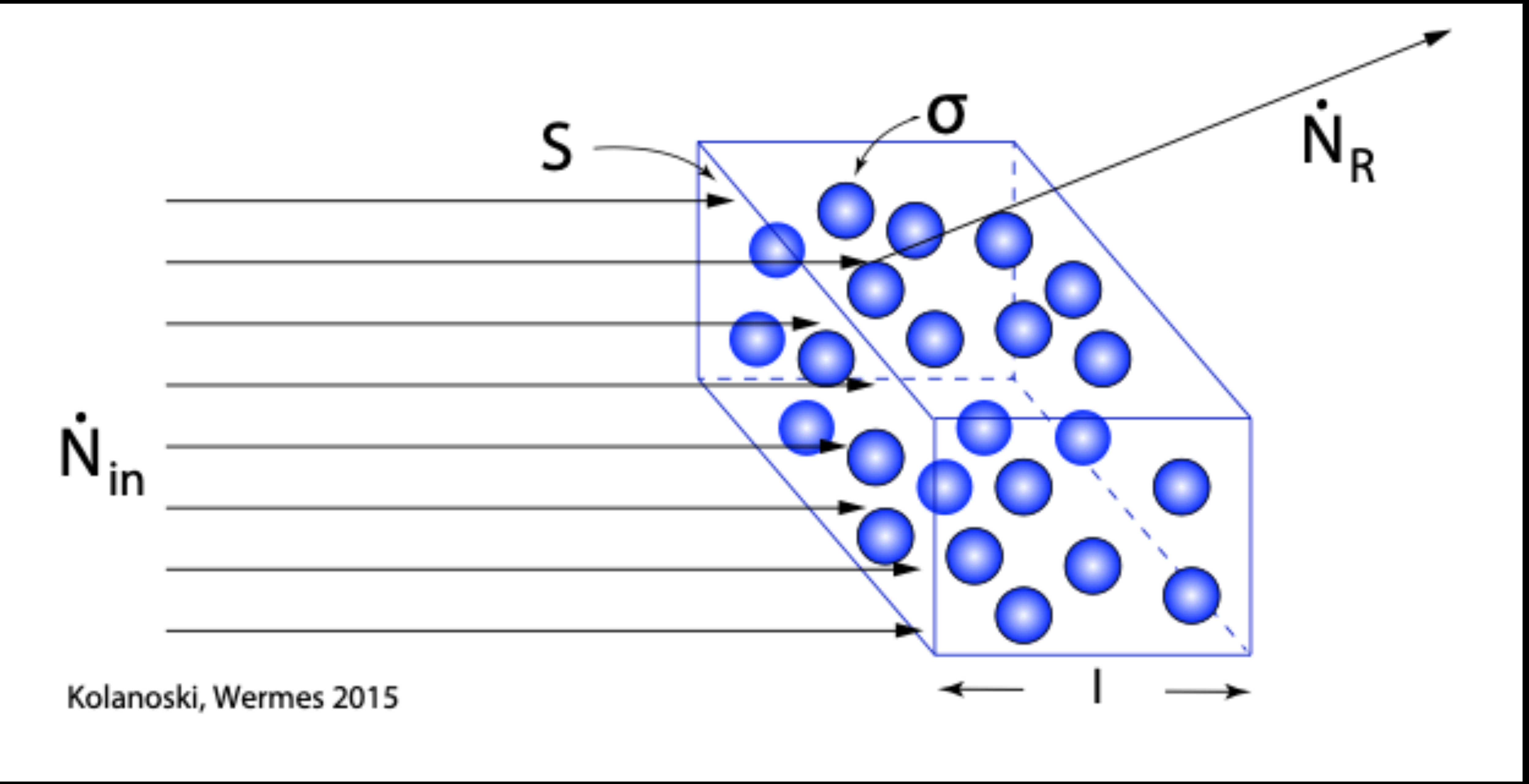
$\dot{N}_R$: incoming reaction rate

Particle detection through interaction: cross sections

- The term luminosity defined here for fixed target experiments is used for collider experiments
- If the target is not sufficiently thin:



Radiation length: The average distance an electron travels in a material to lose 1/e (about 37%) of its energy through bremsstrahlung

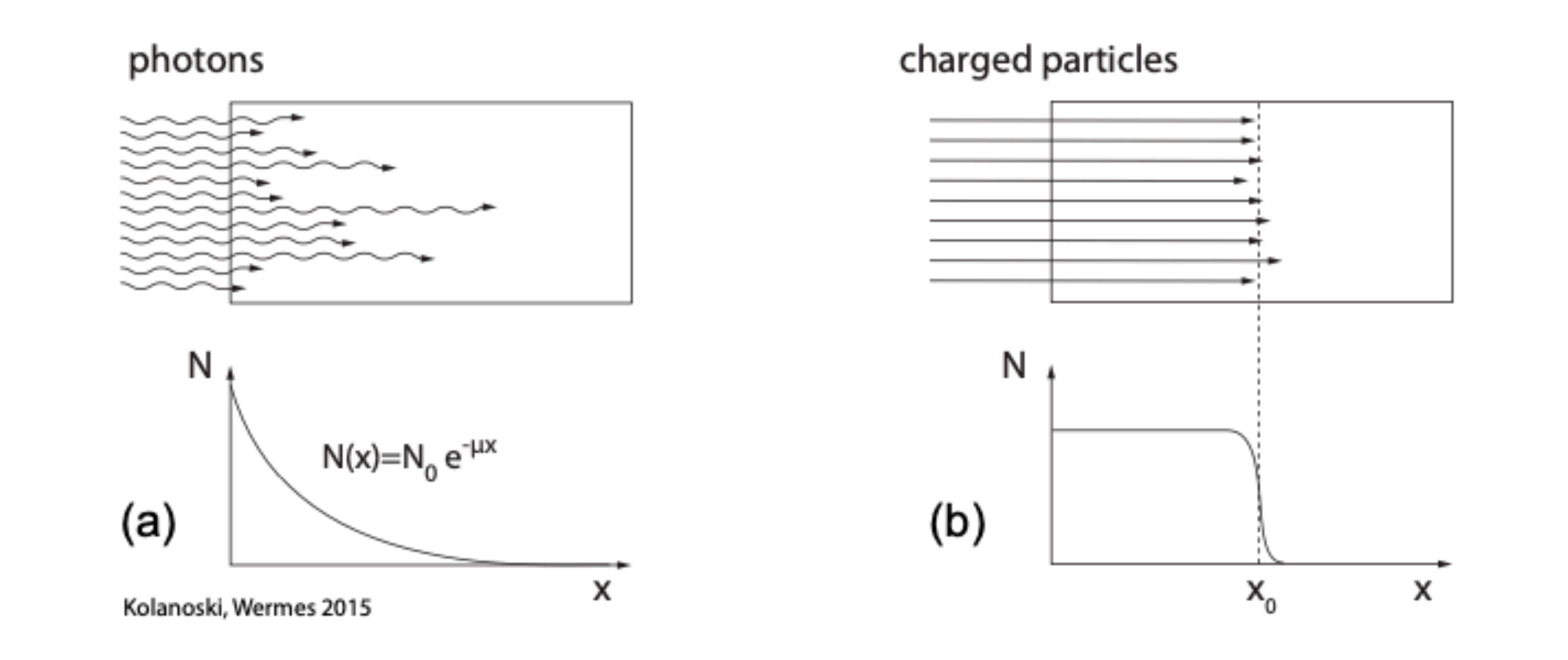


$\dot{N}_{\text{in}}$: incoming particle rate

$\dot{N}_R$: incoming reaction rate

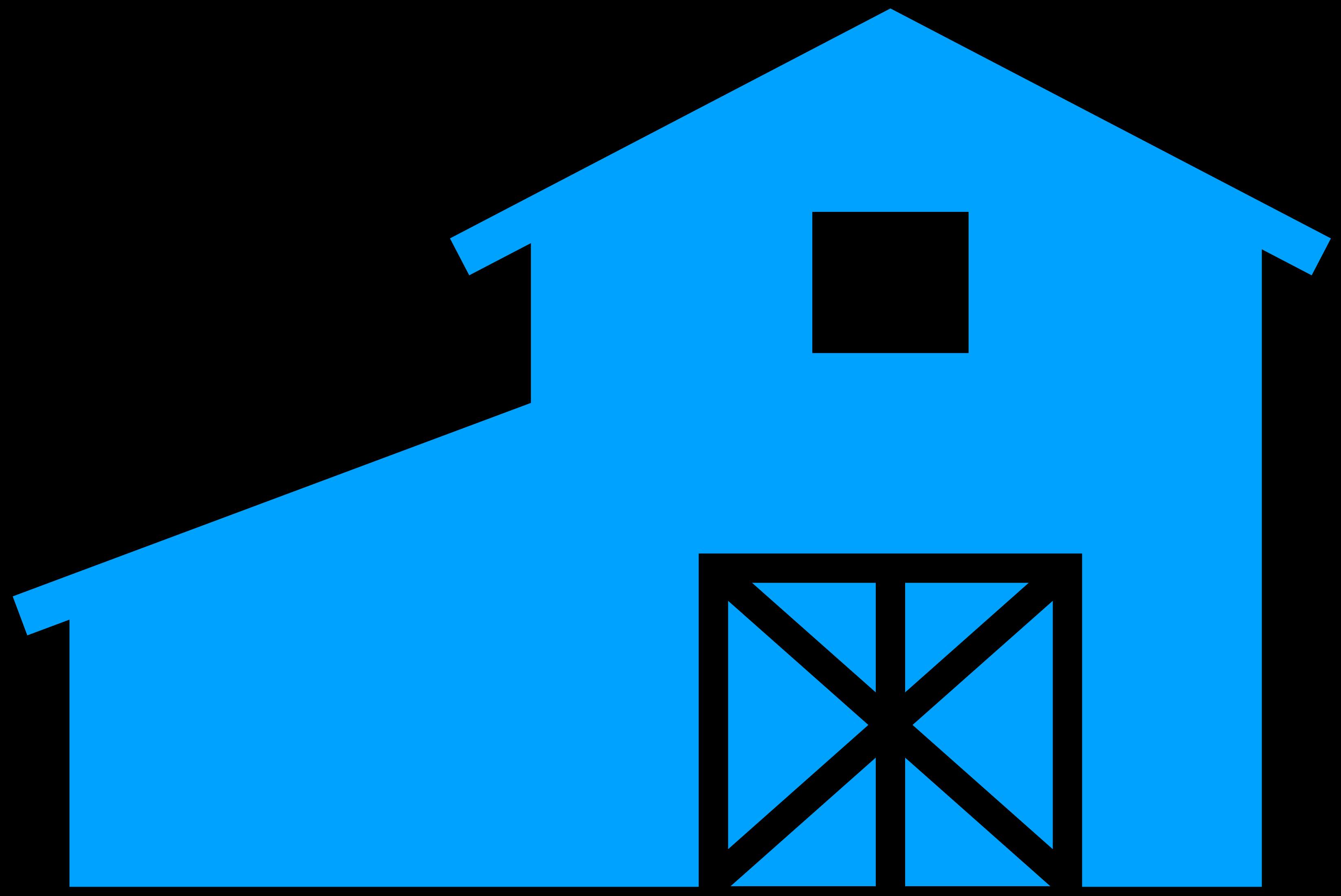
Particle detection through interaction: interaction depth

- If the assumption of a thin target is no longer valid
  - Take into account the number of particles $N(x)$ that have thus far not interacted with the target decreases exponentially with the depth x
    - $\dfrac{dN}{N} = -n\sigma\, dx$
    - $N(x) = N_0 e^{-\mu x}$, $\mu = n\sigma$, N_0 = original number of particles
    - Mean free path (interaction length): $\lambda = \dfrac{1}{\mu} = \dfrac{1}{n\sigma}$



Particle detection through interaction: units

- The cross section has dimensions of area, units: barn
  - 1 barn = 1 b = 10^{-24} cm^2
- The name originated during the Manhattan Project, where colliding large nuclei was considered as easy as “hitting the side of a barn”

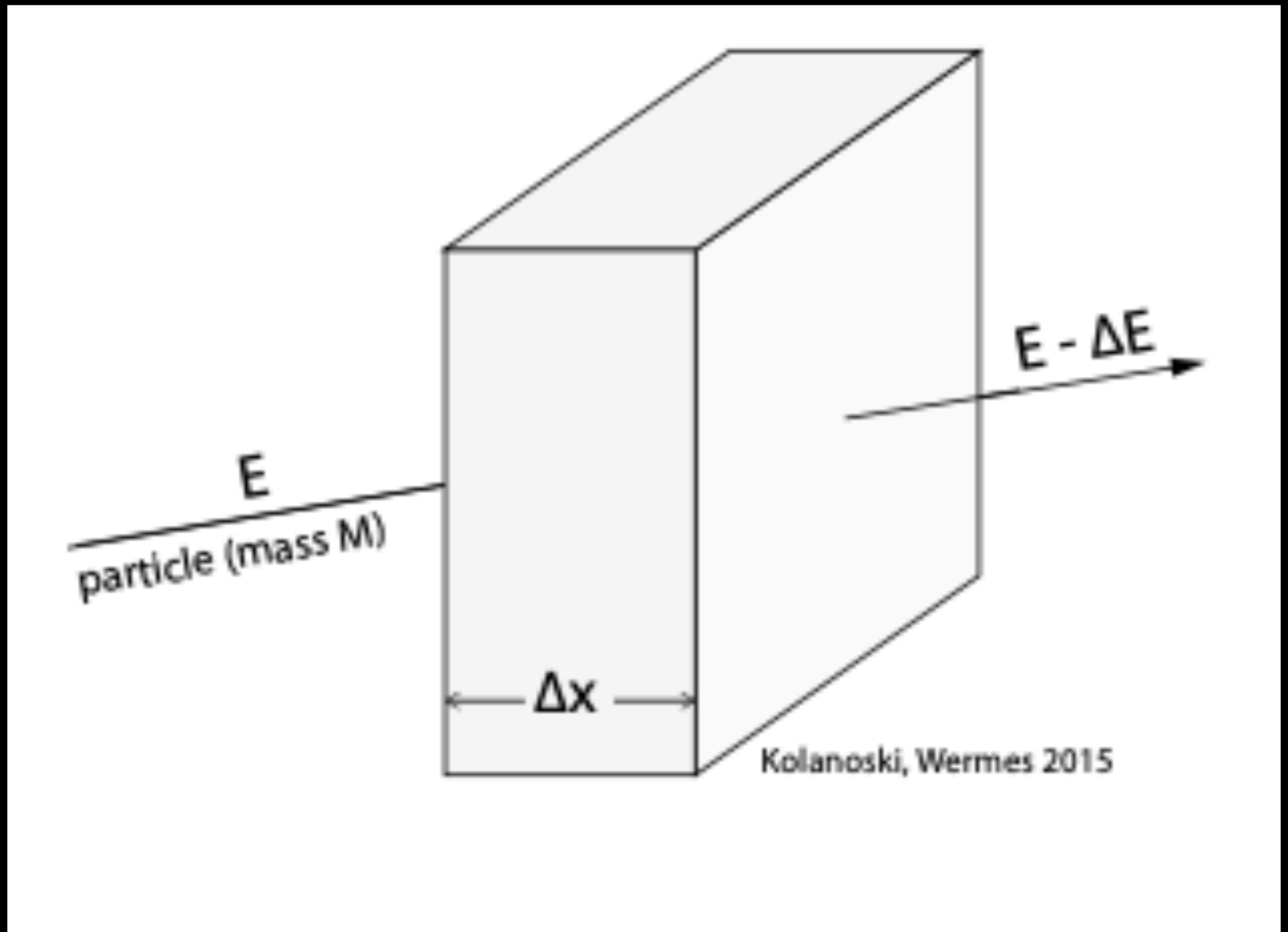


Energy loss of charged particles by ionization

- When penetrating a medium, charged particles lose energy by ionization and excitation of the medium's atoms
- The energy loss per path length is described by the Bethe-Bloch formula
- Energy loss of a particle passing through matter arises from a sequence of individual stochastic processes
- The average energy loss per path length depends on the properties of the medium a, mass of the particle M and the velocity of the particle, β
  - $$-\left\langle \frac{dE}{dx} \right\rangle = n \int_{T_{min}}^{T_{max}} T \frac{d\sigma_a}{dT}(M, \beta, T)\ dT$$
  - Here n is the target number density and $d\sigma_a/dT$ (differential cross section for a loss of kinematic energy T in the collision)
  - The integral from T_{min} to T_{max} comprises the region of all possible energy transfers

Energy loss of charged particles by ionization

- Restricting ourselves to heavy charged particles
  - Representative of all charged particles except electrons and positrons
- Subdivide energy losses ($T \geq T_1$) with large losses T of the particle's kinetic energy
  - Low energy region ($T < T_1$), where binding energies of the electrons cannot be neglected (quantum mechanical treatment)
  - $$-\left\langle \frac{dE}{dx} \right\rangle = n_e \int_{T_1}^{T_{max}} T \frac{d\sigma}{dT} dT - \left\langle \frac{dE}{dx} \right\rangle_{T<T_1}$$



T_1 dividing these regions is typically between 0.01 MeV to 0.1 MeV