Simulation of low energy nuclear recoils using Geant4

[heavy ions, T < 1 keV/amu]

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12th Geant4 Collaboration Workshop

LIP - Coimbra

Hebden Bridge
14 Set 2007

Outline

1. a review of Geant4's models of stopping power

2. nuclear recoils full cascade

3. nuclear quenching estimates

4. summary and present work

Versions used: geant4.8.2 and geant4.8.2.p01

Stopping power

ion = projecticle particle Z_1

atom = target particle Z_2

Stopping power

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G4hLowEnergyIonisation

G4hBetheBlochModel
G4hParametrisedLossModel
G4hIonEffChargeSquare

$$-\frac{dE}{dx} = S_e + S_n$$

G4hNuclearStoppingModel

(assuming no correlations)

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- Low energy extension
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- Very small step sizes (~1% of the particle range)
- Continuous slowing down approximation:

- Cut energy very high: no delta-rays
- Actually no secondaries what so ever! Just follow our primary till it stops (default MinKineticEnergy = 10eV)
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Geometry:

- just a square box, filled with pure material

- Cut energy very high: no delta-rays
- Actually no secondaries what so ever! Just follow our primary till it stops (default MinKineticEnergy = 10eV)
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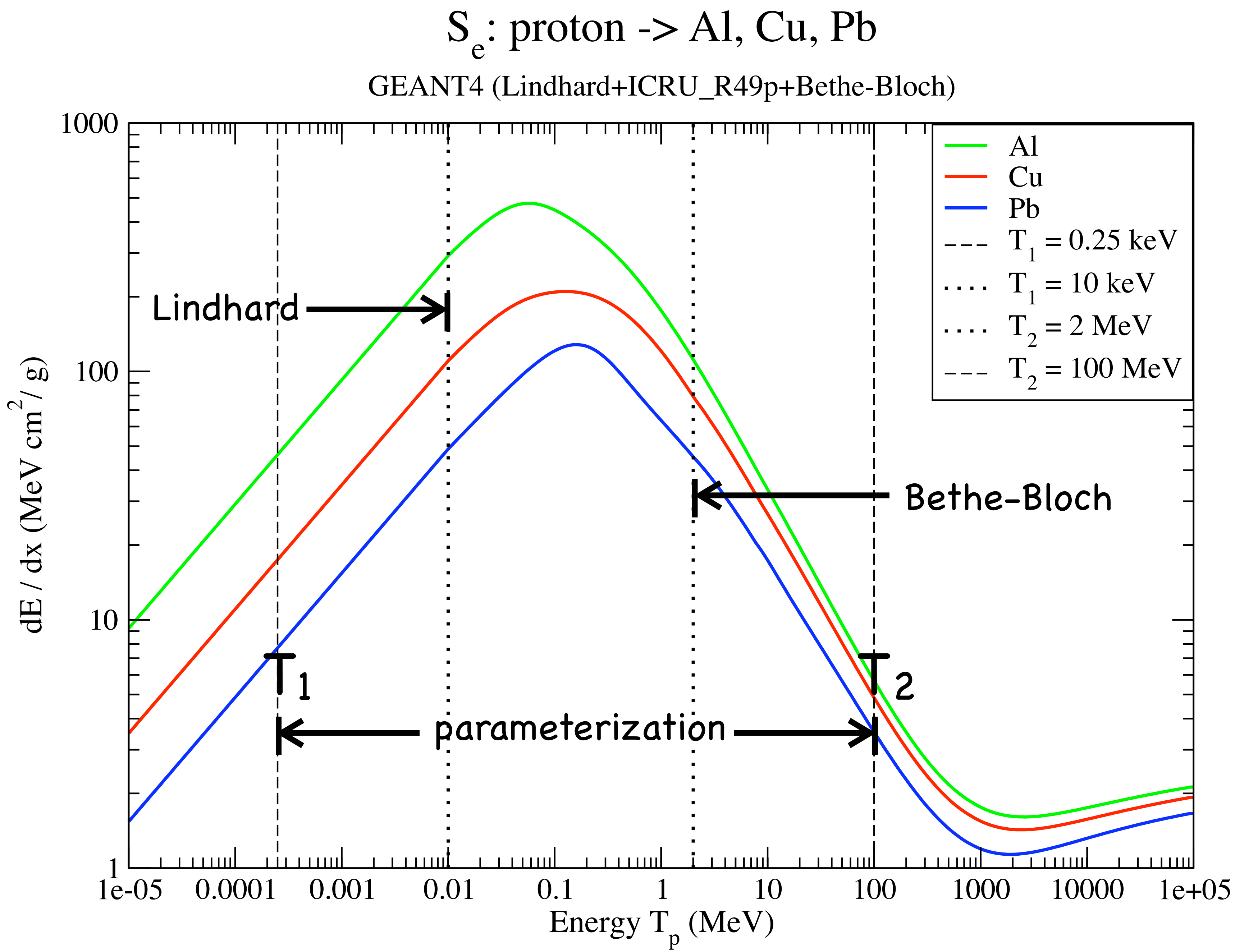
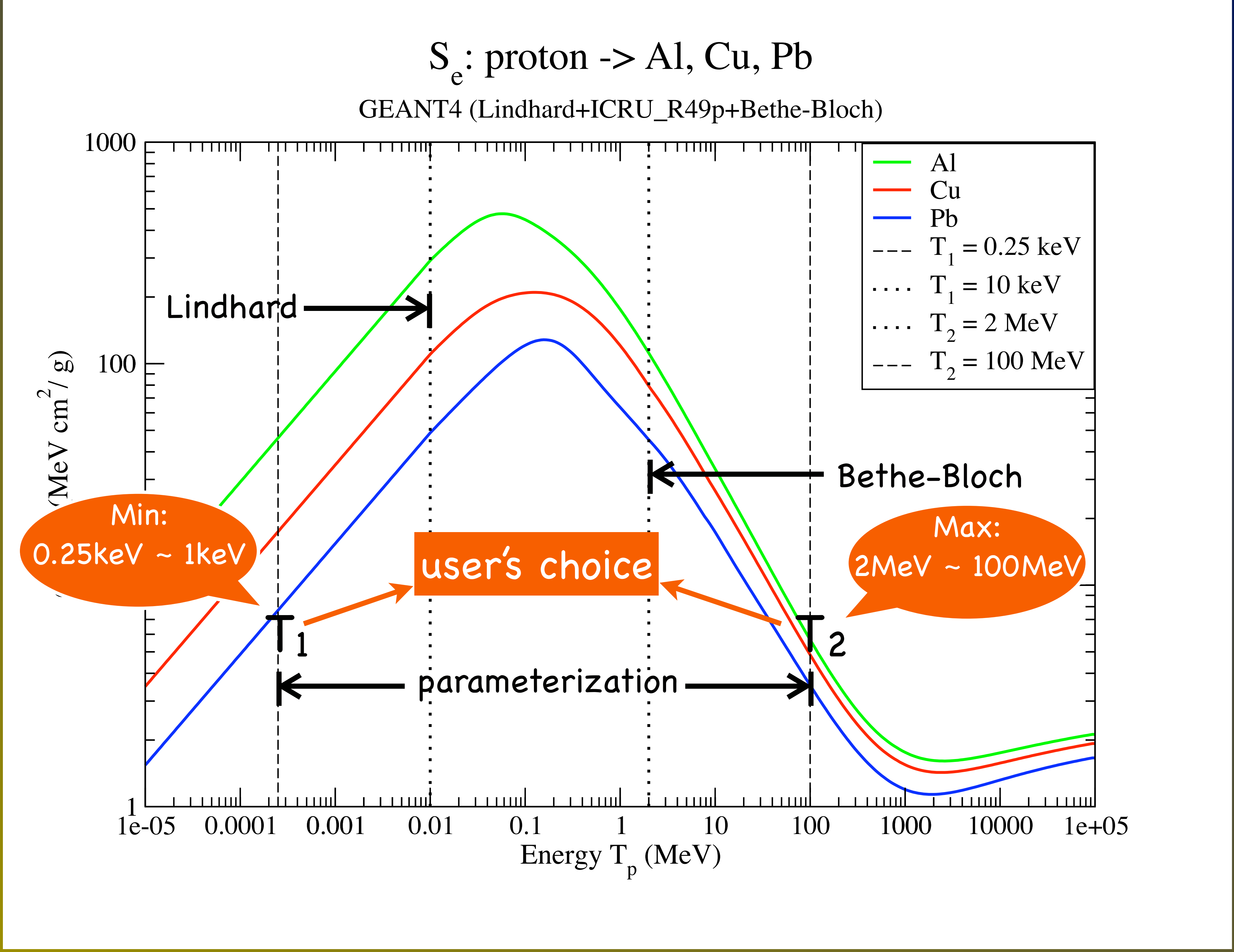
- shoot primary from the center of the box, random direction



S_e: proton -> Al, Cu, Pb
GEANT4 (Lindhard+ICRU_R49p+Bethe-Bloch)
1000
100
10
1
dE / dx (MeV cm^2 / g)
1e-05
0.0001
0.001
0.01
0.1
1
10
100
1000
10000
1e+05
Energy T_p (MeV)
Al
Cu
Pb
T_1 = 0.25 keV
T_1 = 10 keV
T_2 = 2 MeV
T_2 = 100 MeV
Lindhard
Bethe-Bloch
T_1
T_2
parameterization



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Lindhard
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user's choice
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T1
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parameterization

Geant4

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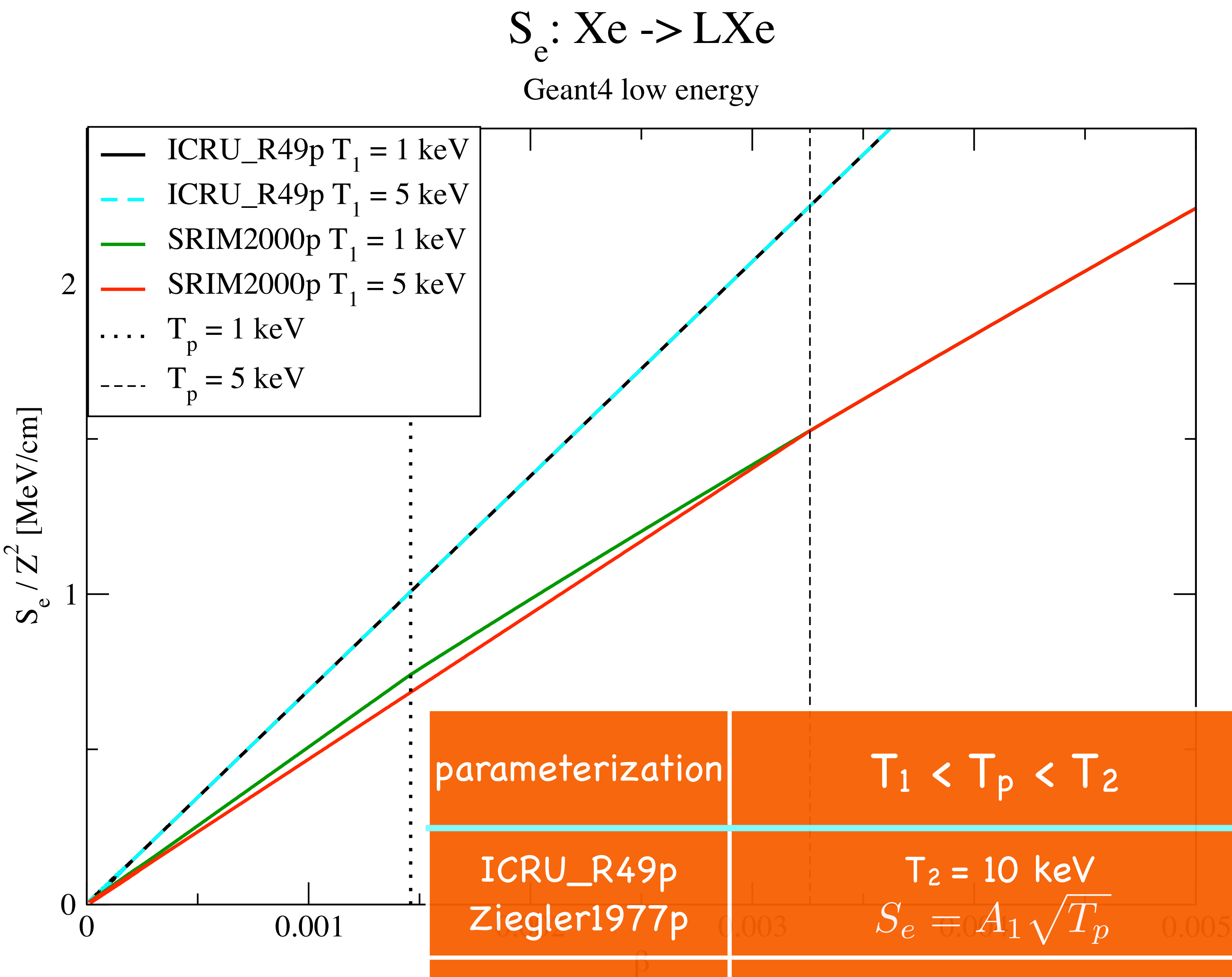
effective charge parameterization $Z_{eff}(v, v_F)$

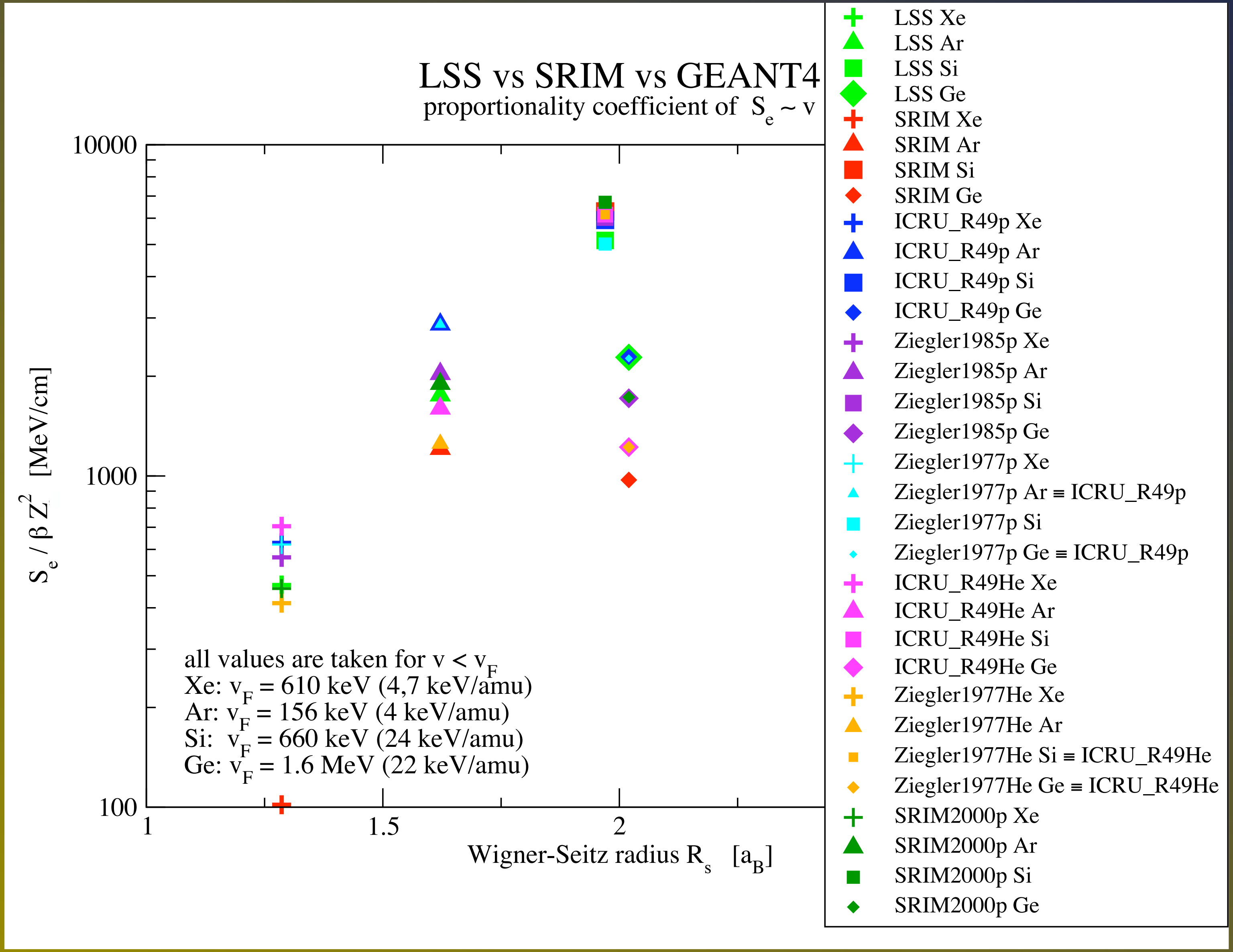
- Ziegler, 1985, Brandt and Kitagawa, 1982



parameterization	$T_1 < T_p < T_2$	$T_p < T_1$ (default = 1 keV)
ICRU_R49p Ziegler1977p	T_2 = 10 keV $S_e = A_1\sqrt{T_p}$	$S_e = A_1\sqrt{T_p}$
SRIM2000p Ziegler1985p	$S_e = A_1 T_p^{0.25}$, $Z_2 < 6$ $S_e = A_1 T_p^{0.375}$, $Z_2 = 6, 14, 32$ $S_e = A_1 T_p^{0.45}$, other	$S_e = A\sqrt{T_p}$

Geant4

Electronic stopping



Nuclear Stopping S_n

ion-atom interaction potencial

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$$V(r) = \frac{Z_1 Z_2 e^2}{r}\,\Phi \qquad \begin{cases} \lim\limits_{r\to 0} & \Phi = 1 \\ \lim\limits_{r\to\infty} & \Phi = 0 \end{cases}$$

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Classical (or statistical) treatment: the Thomas-Fermi atom

Approximations:

- elastic
- static (velocity independent)
- universal $\boxed{\Phi = \Phi(r/a)}$ screening length
- no shell structure (as opposed to modern Hartree-Fock solid state models)

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$$V(r) \xrightarrow[\text{pertubation treatment}]{\text{classical scattering}} d\sigma \longrightarrow S_n = \int T' d\sigma$$

T′ = energy transfered to an atom at rest (target)

Universal screening functions proposed in the literature:

- Bohr
- Thomas-Fermi → Lindhard (LSS)
- Lenz-Jensen
- Moliere
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Nuclear stopping

Universal stopping in reduced units scales back to ion-atom dependent stopping in physical units. Available choices:

- (default) ICRU_R49 - parameterization of Moliere's screening function
- Ziegler1977
- Ziegler1985

the ZBL universal potencial

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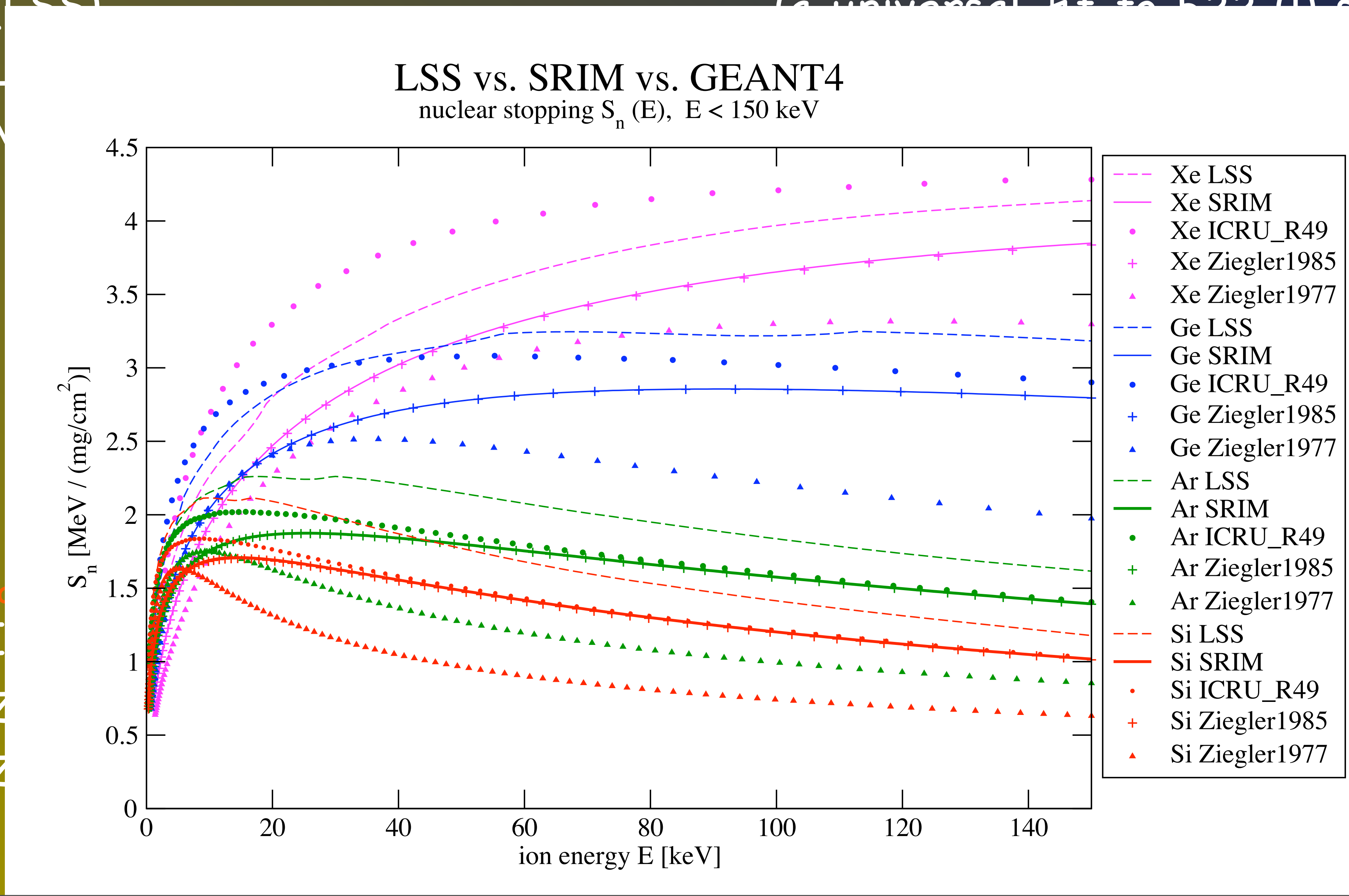
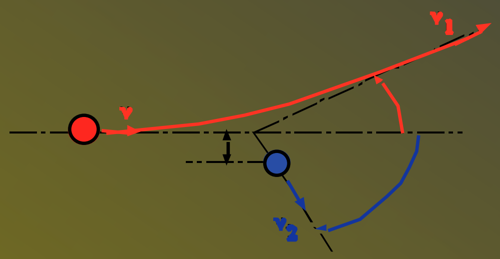
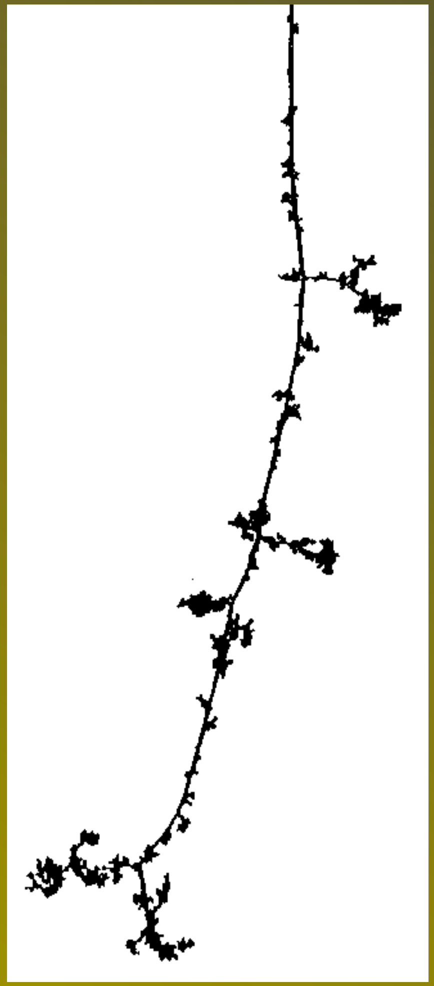


Nuclear recoil full cascade



Note: the primary particle is already a recoil, doesn't matter if it originated from WIMPs or neutron scattering



recoil CUT energy (default MinKineticEnergy = 10eV)

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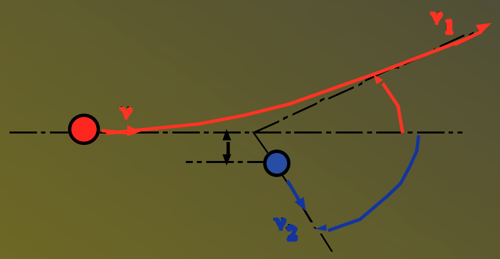

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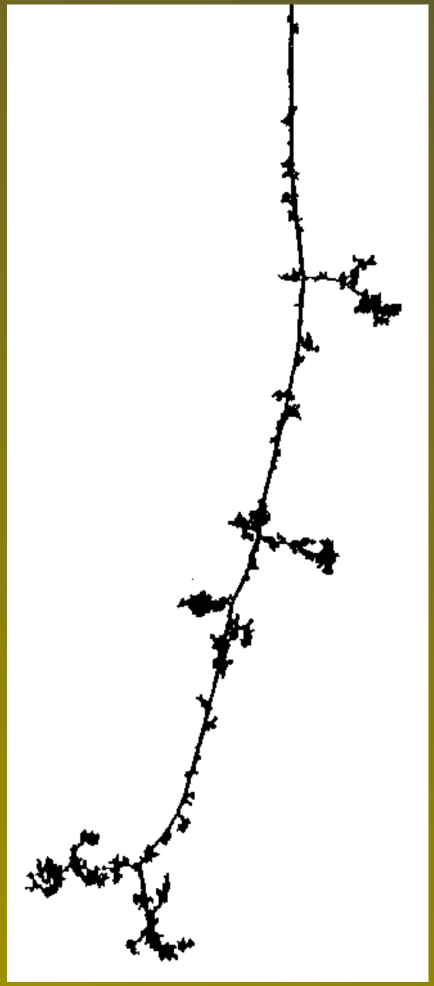

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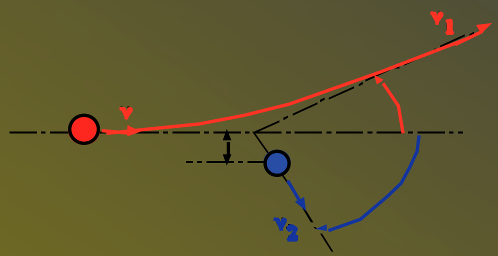

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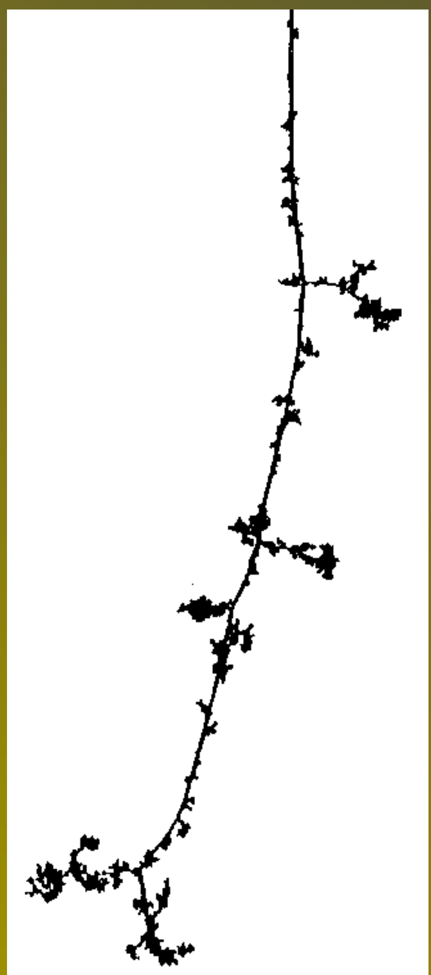

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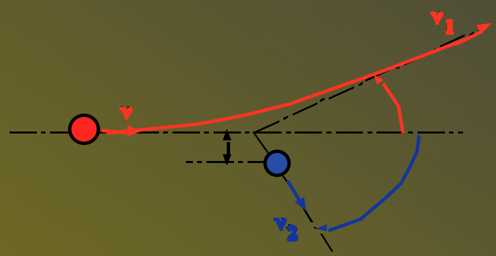

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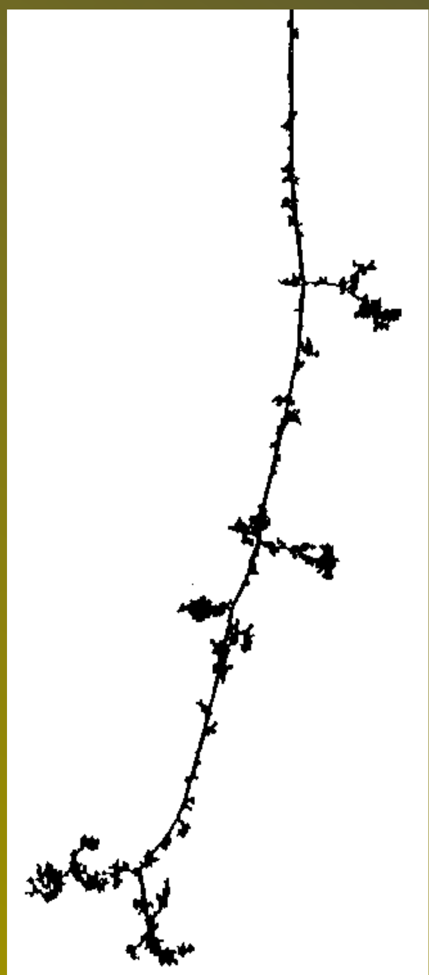

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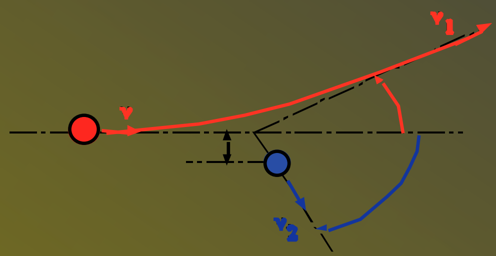

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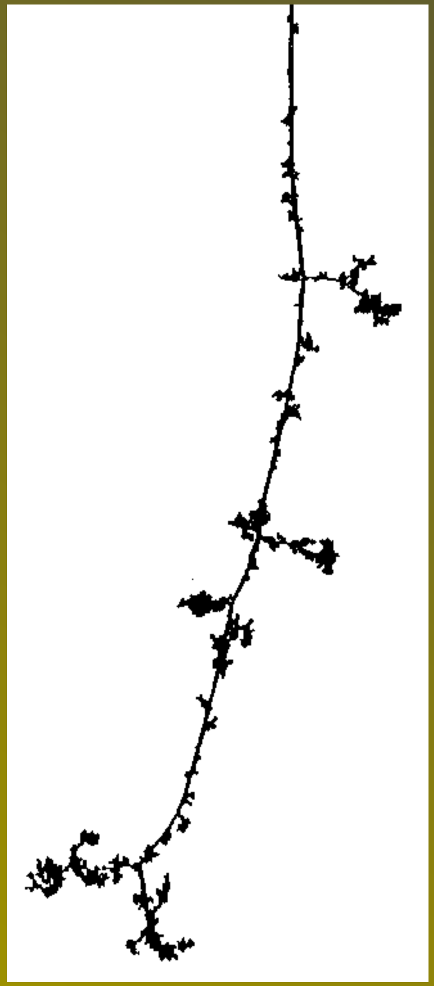

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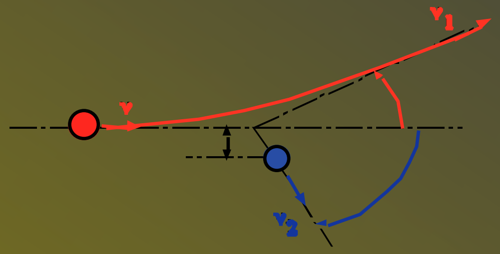

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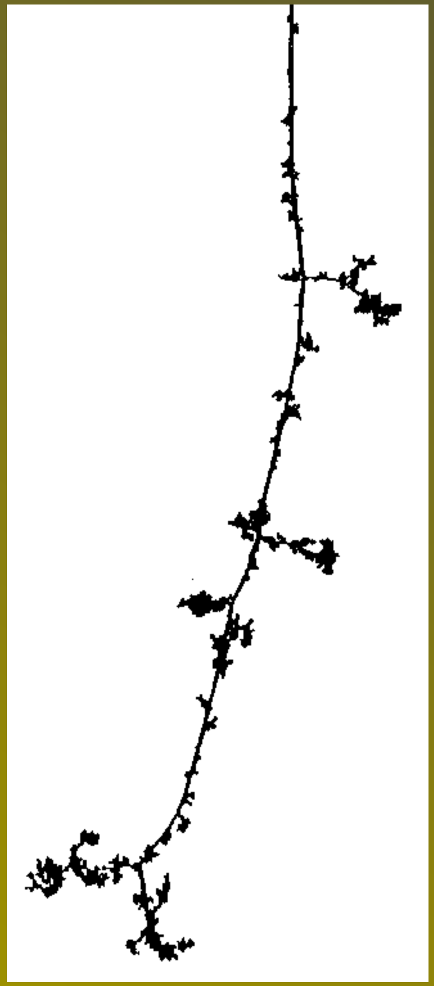

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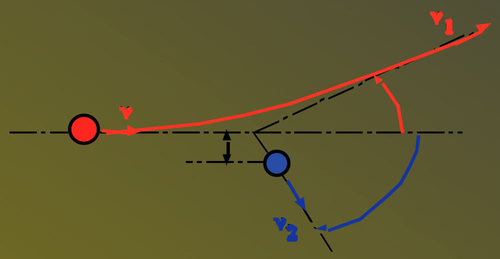

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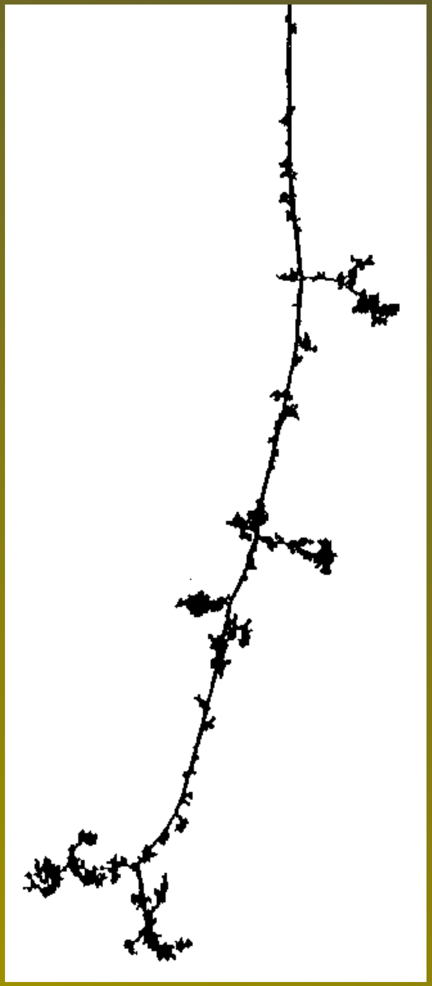

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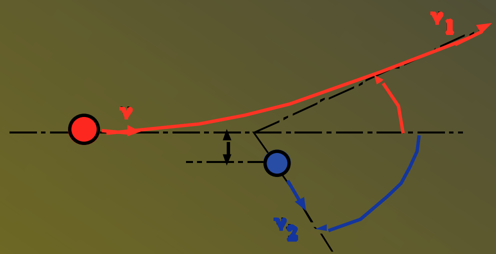

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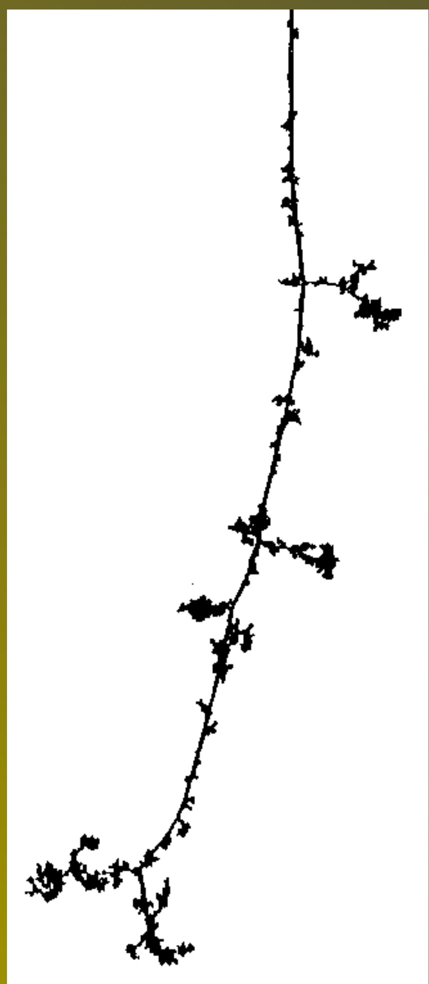

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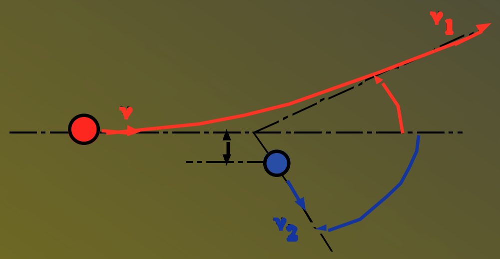

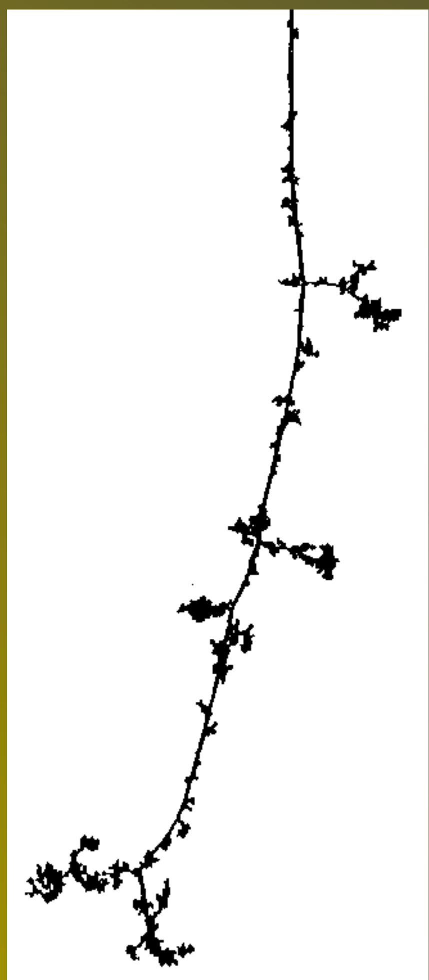

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V... ng

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nuclear quenching

➡ competition between total energy ultimately given to electrons and energy permanently lost to recoils

Geant4

Recoil cascade

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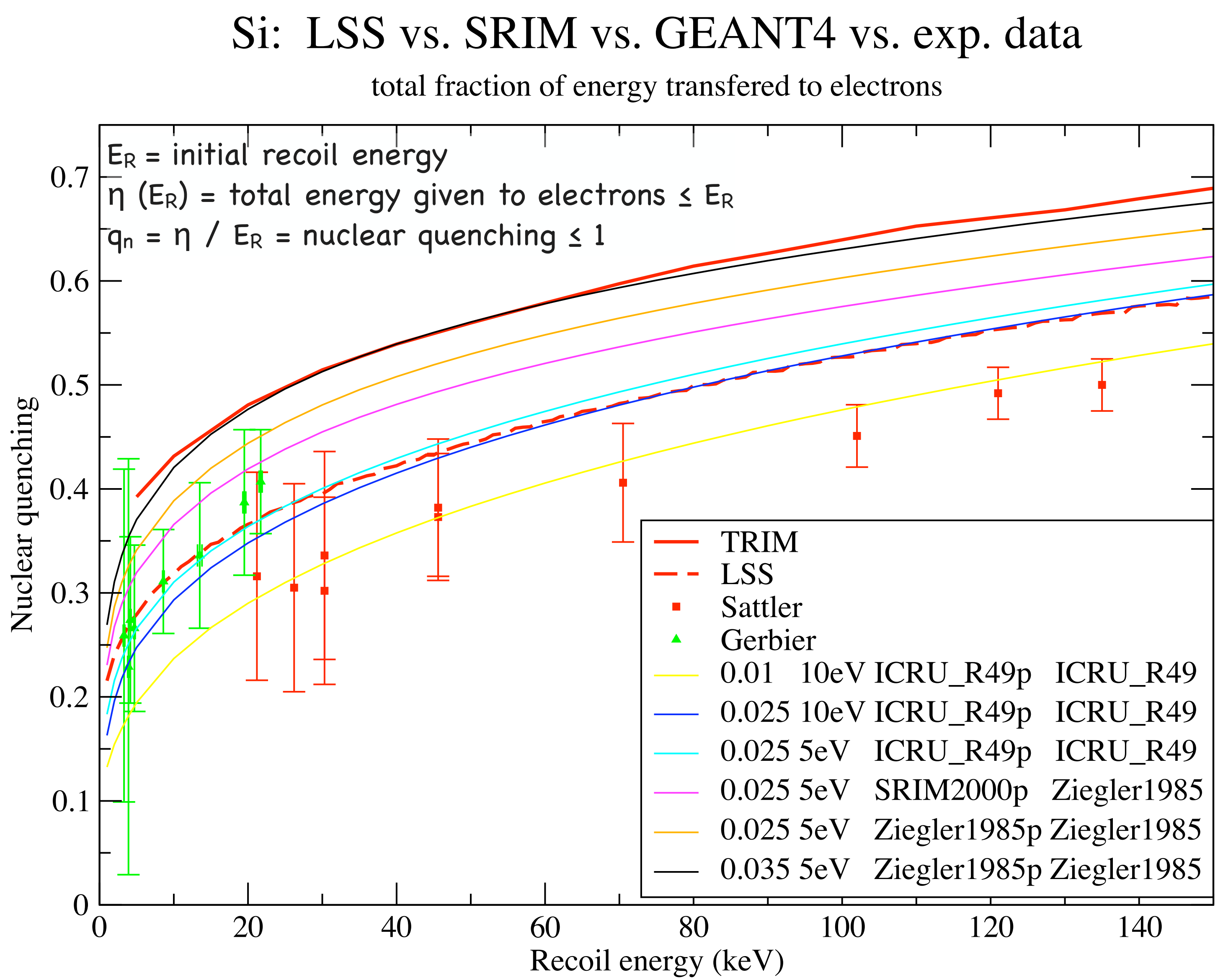
actually, we shouldn't even try to approximate nuclear collisions as a continuous process (as opposed to electronic stopping) as you're not supposed to get a recoil every step, just every now and then

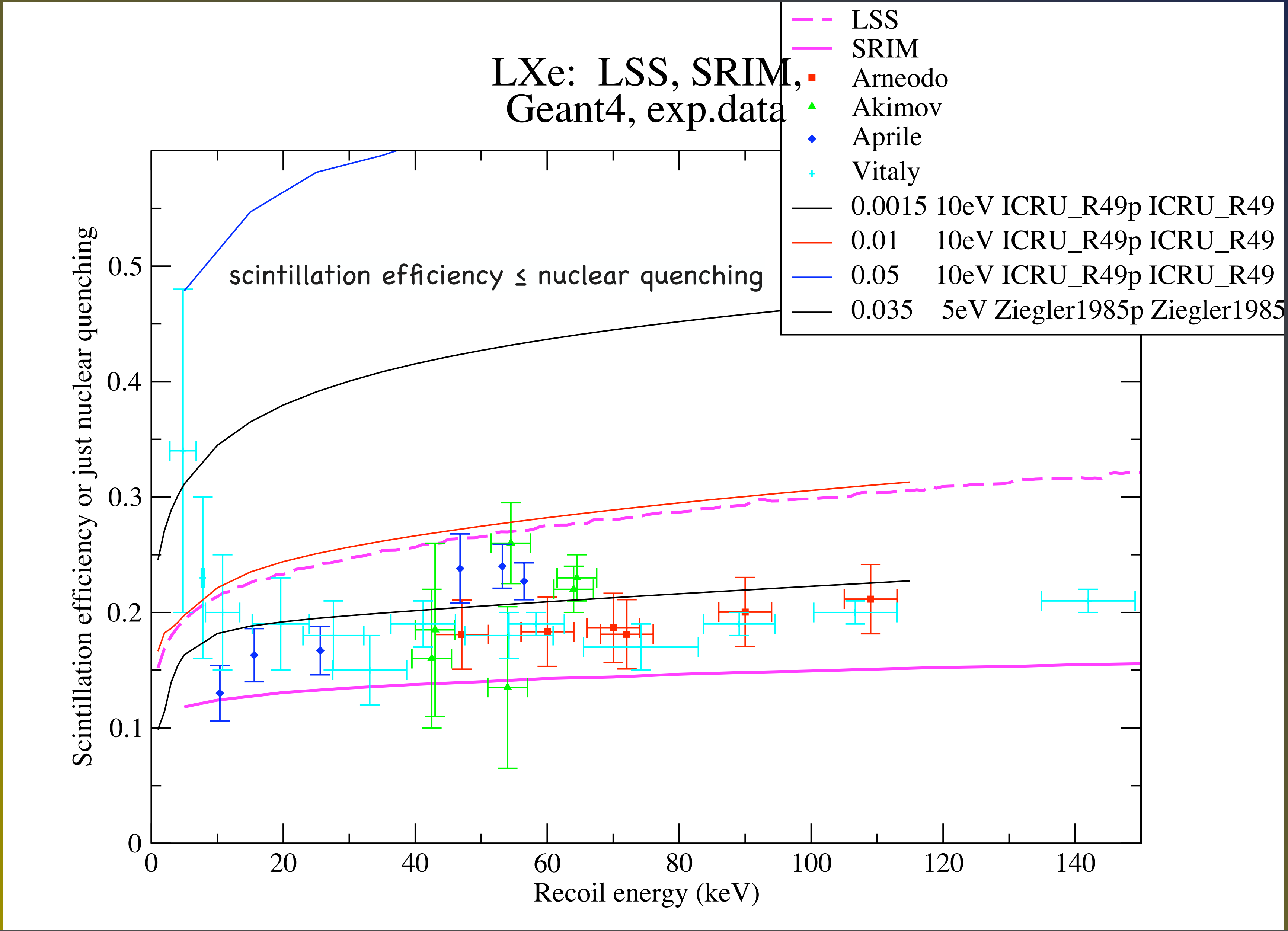
Geant4

Nuclear quenching: Si



Geant4

Nuclear quenching: LXe



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work in progress

Present work

$$d\sigma = \Pi a^2 \frac{f(t^{1/2})}{2t^{3/2}}$$

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write the DiscreteProcess functions

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To do:

implement the sampling

put it in tables and load them in Geant4, with interpolation

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- M.H. Mendenhalla and R.A. Weller, An algorithm for computing screened Coulomb scattering in GEANT4, Nuclear Instruments and Methods in Physics Research B227, 3 (2005) 420

Extras

Electronic Stopping S_e

Fermi-Teller: $\boxed{S_e \propto v}$ (ion velocity) if $v < v_F \sim v_0$

Lindhard: uniform free electron gas, Thomas-Fermi atom, particle-plasma interaction as a perturbation

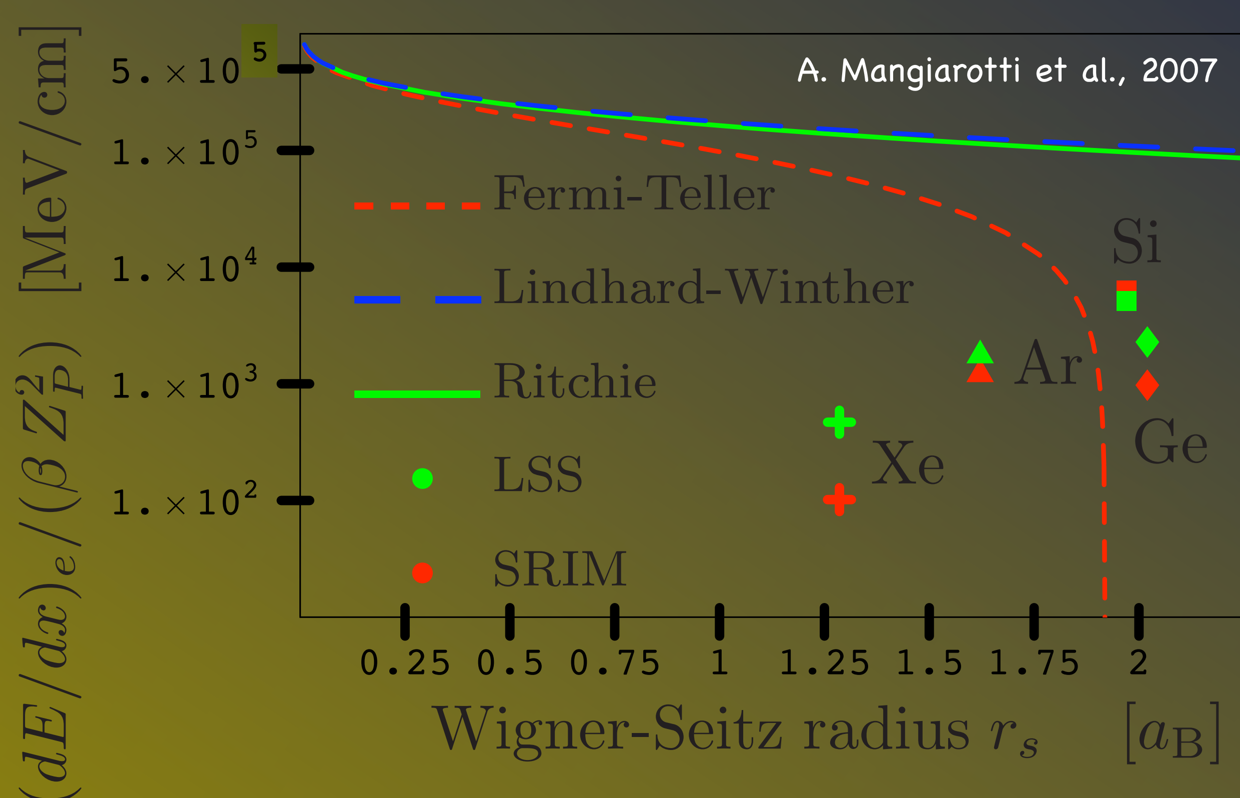
$S_e = k\epsilon^{1/2}$ if $v <$ Bragg peak ($\sim v_0 Z_1^{2/3} \approx 500 MeV$ for Xe)

$0.10 < k < 0.20$

(reduced units)

$k_{Xe} \approx 0.166$

SRIM: local density approximation using Hartree-Fock solid state atoms; semi-empirical fit of charge state of the ion



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(relative) Scintillation efficiency

$$\boxed{q_n \times \frac{W_S(E_\gamma)}{W_S(E_R)}}$$

Is everybody clear about this definition ?!

derivation from the traditional/experimental formula

comparison with Hitachi definition

traditional definition of $W_S = \frac{E}{N_{ph}}$ for γ, Recoils, whatever!

back

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traditional/experimental definition of relative scintillation efficiency

$$= \frac{W_S(E_\gamma)}{W_S(E_R)}$$

< 1 because it takes more energy to produce a photon in RC than in γ

2 "quenching" effects all mixed up!

back

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remember $\eta_\gamma \approx E_\gamma$

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Hitachi

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scintillation only

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