Simulation of hadronic interactions

Neutrons

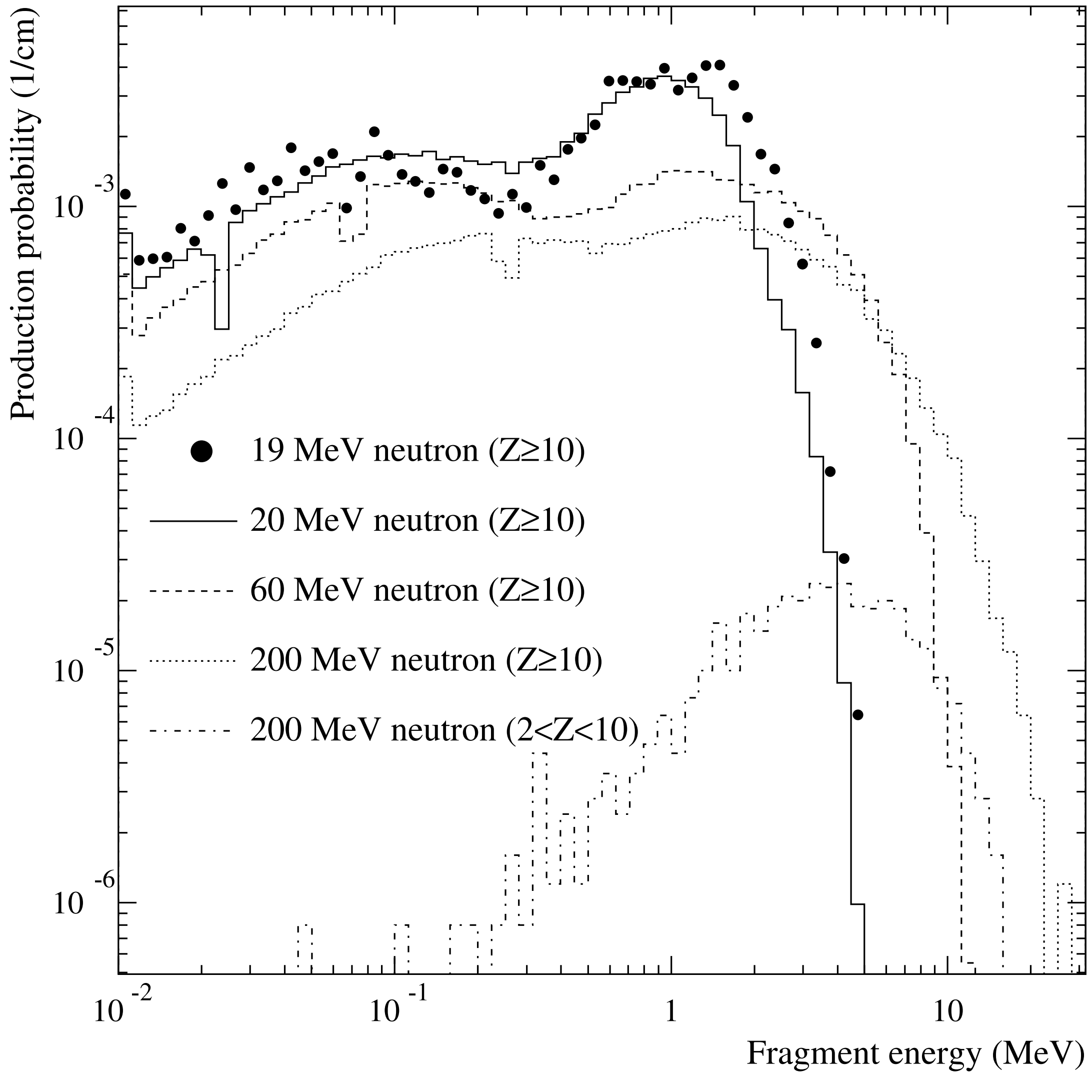
Below 20 MeV direct sampling from ENDFB-VI data.

Above 20 MeV FLUKA event generators

Protons and Pions

Elastic scattering: optical Glauber formalism

Inelastic scattering: FLUKA event generators



Transport of recoils

Use modified version of TRIM85 code

Features:

- **Generate all atomic recoils explicitly down to the threshold of 20 eV**
- **Transport all atomic recoils until their energy is below 20 eV**

Results:

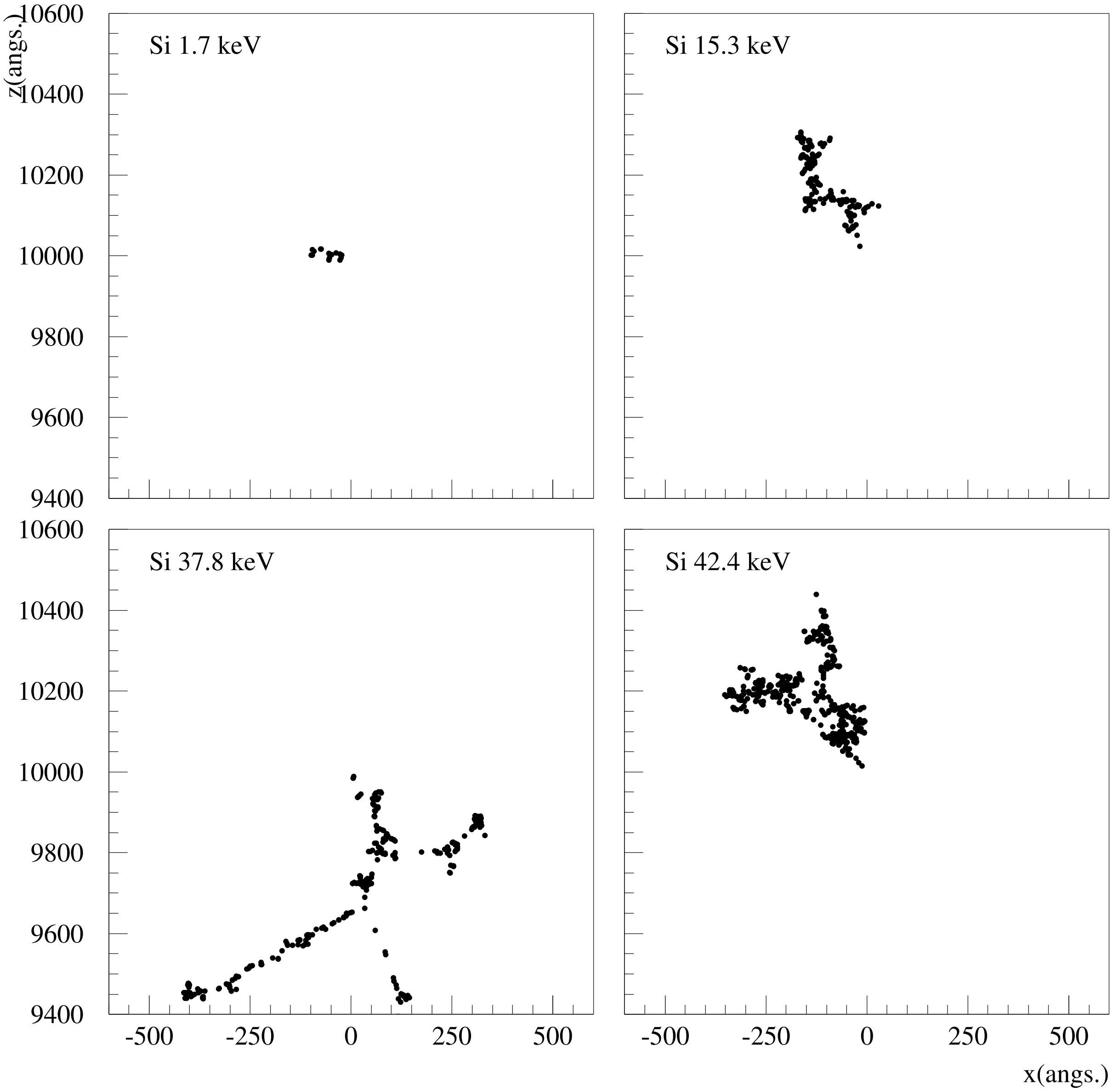
Full final state of each collision with explicit knowledge of all interstitial (I) and vacancy (V) positions.

1 MeV neutron interactions

Calculated NIEL Xsec (at 981 keV) : 102 MeV mb

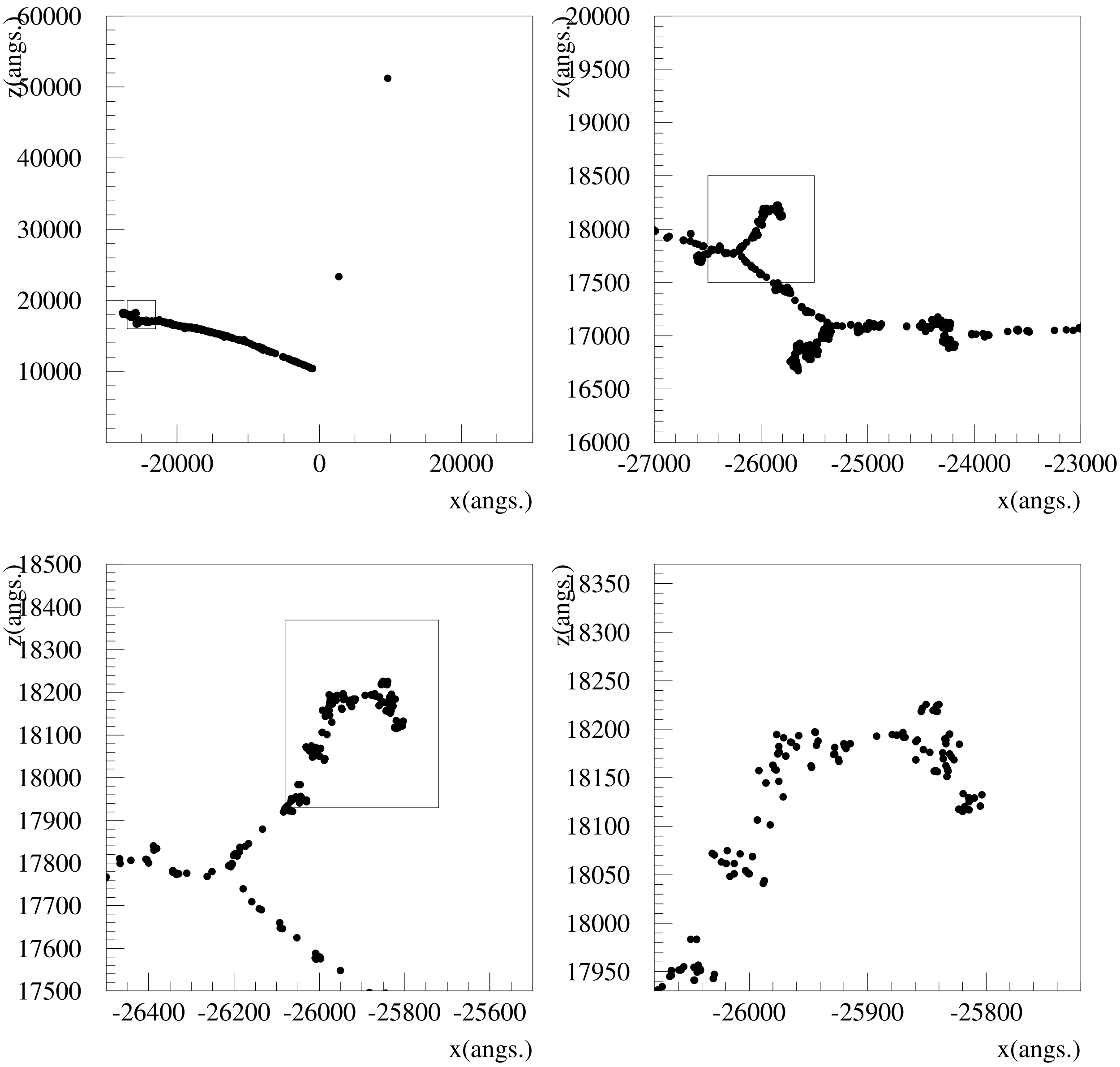
(NIEL varies rapidly with energy for 1 MeV neutrons)

XZ-projection of initial Interstitial positions for 4 neutron events



19 GeV protons – A closer look

Zoomed XZ-projection of a 19 GeV proton event (Interstitials)



Simulation of defect migration

Each defect undergoes a random walk (jump to neighbouring lattice site)

•

Interstitials diffuse 10000 times faster than vacancies

•

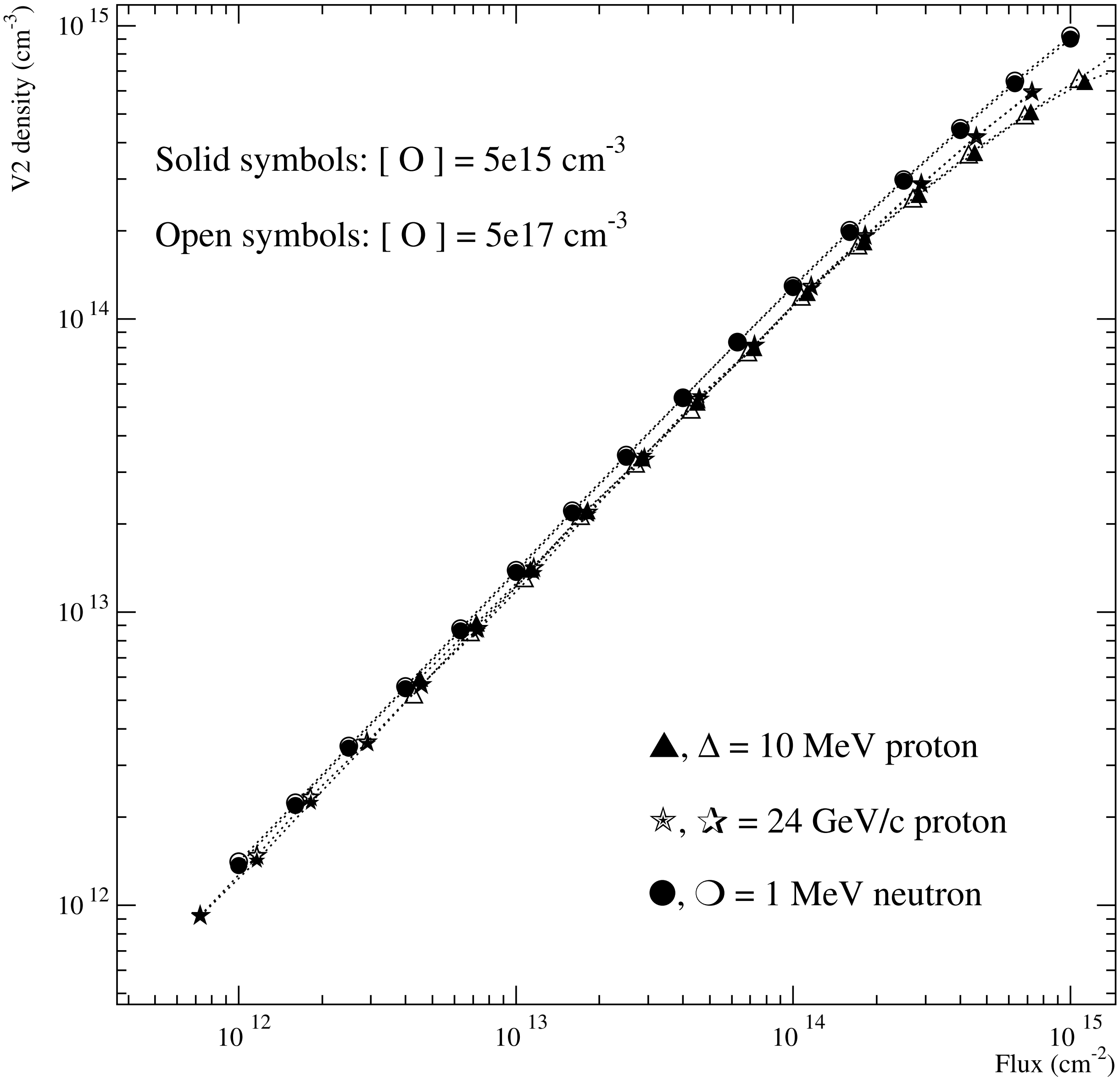
If 2 defects come closer than 16.2 Åthey might recombine. The probability for this is $(R/16.2)^3$, where R is the capture radius.

•

If defects get far (1000 Å) from their initial position and the nearest neighbour is far (200 Å) they are considered free. For these the standard Davies model is applied.

Note: Contrary to Davies model VV is NOT a primary defect, but introduced by V+V combination.
Only I and V are primary.

Evolution of VV

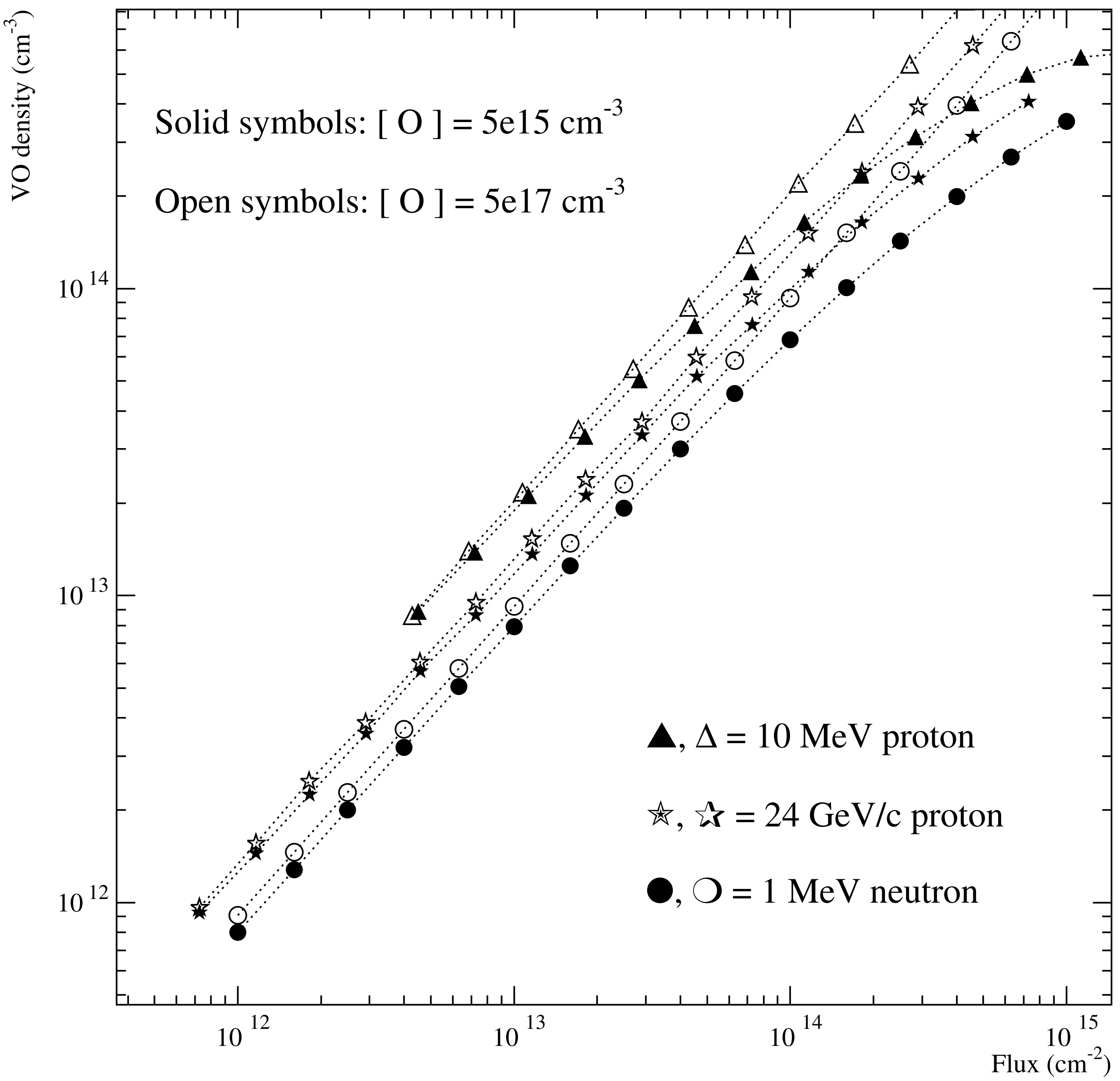


VV scales rather well with NIEL

●

Oxygen has only very minor effect on VV

Evolution of VO

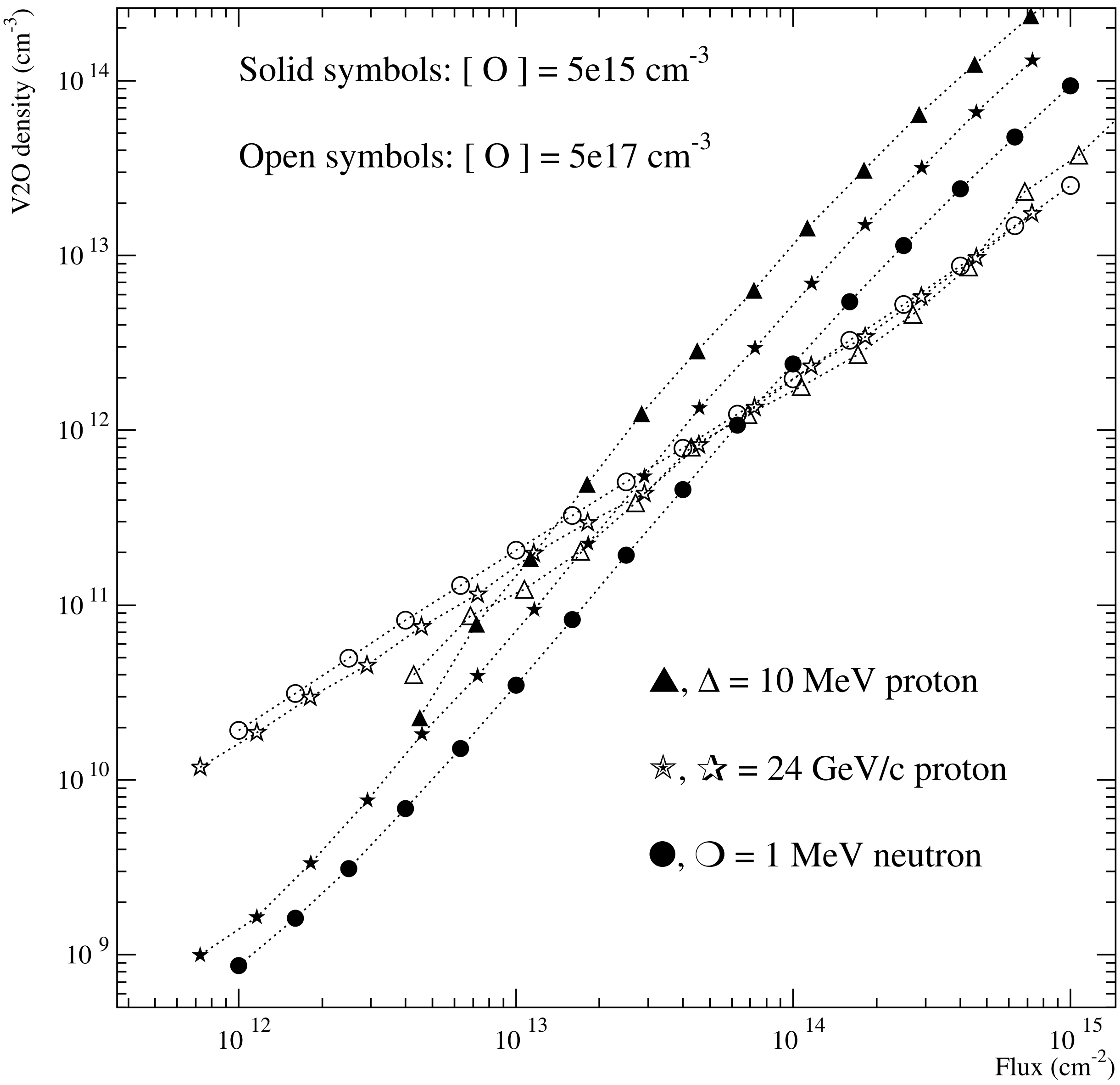


VO does not scale with NIEL

●

Point defects produce more VO than clusters

Evolution of V2O



V2O does not scale with NIEL if low oxygen

●

V2O does scale with NIEL if high oxygen !!!

●

Behaviour is consistent with expectation and VO development
BUT V2O cannot explain N_{eff} changes...

N_{eff} changes...

Need a defect which scales with NIEL to get NIEL scaling for standard Si.

$$\Downarrow$$

VV is the best (only) candidate

$$\Downarrow$$

$$\boxed{|N_{\mathrm{eff}}| = [P] - C1 \times [V_2] - C2 \times [V_2O]}$$

$$\Downarrow$$

Does not work as such

$$\Downarrow$$

$$\boxed{|N_{\mathrm{eff}}| = [P] - C_{ave} \times [V_2] - C2 \times [V_2O]}$$

where C_{ave} is an average e-occupancy of VV states.

Value of C_{ave} depends on clustering, i.e. irradiation type

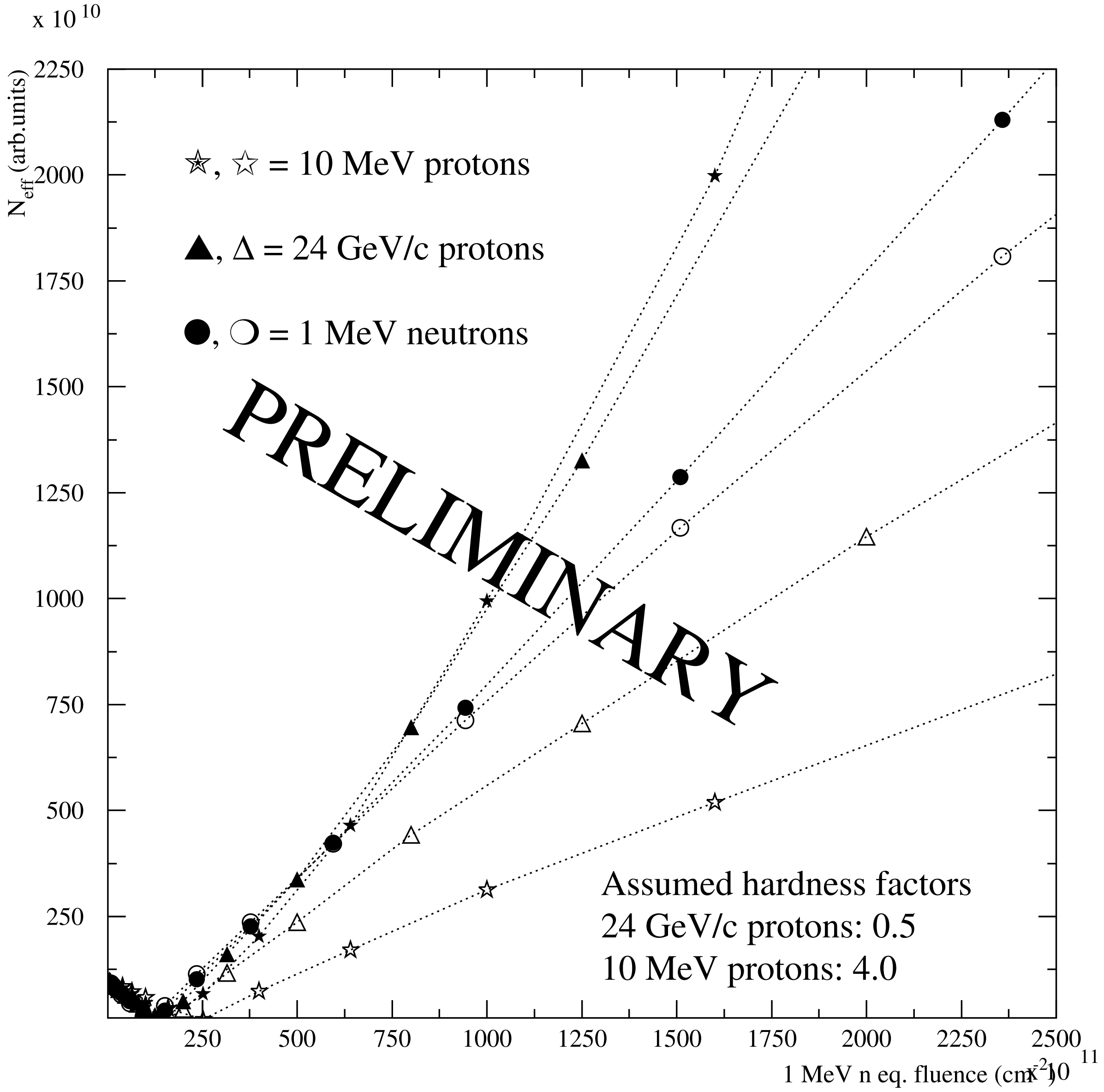
- **C_{ave} needs to be fixed to get type inversion at ~1E13 1 MeV neutrons.**
- **C2 must be adjusted to give an effect by the oxygen**

(there is quite a lot of freedom and uncertainty)

...and this seems to work for N_{eff}

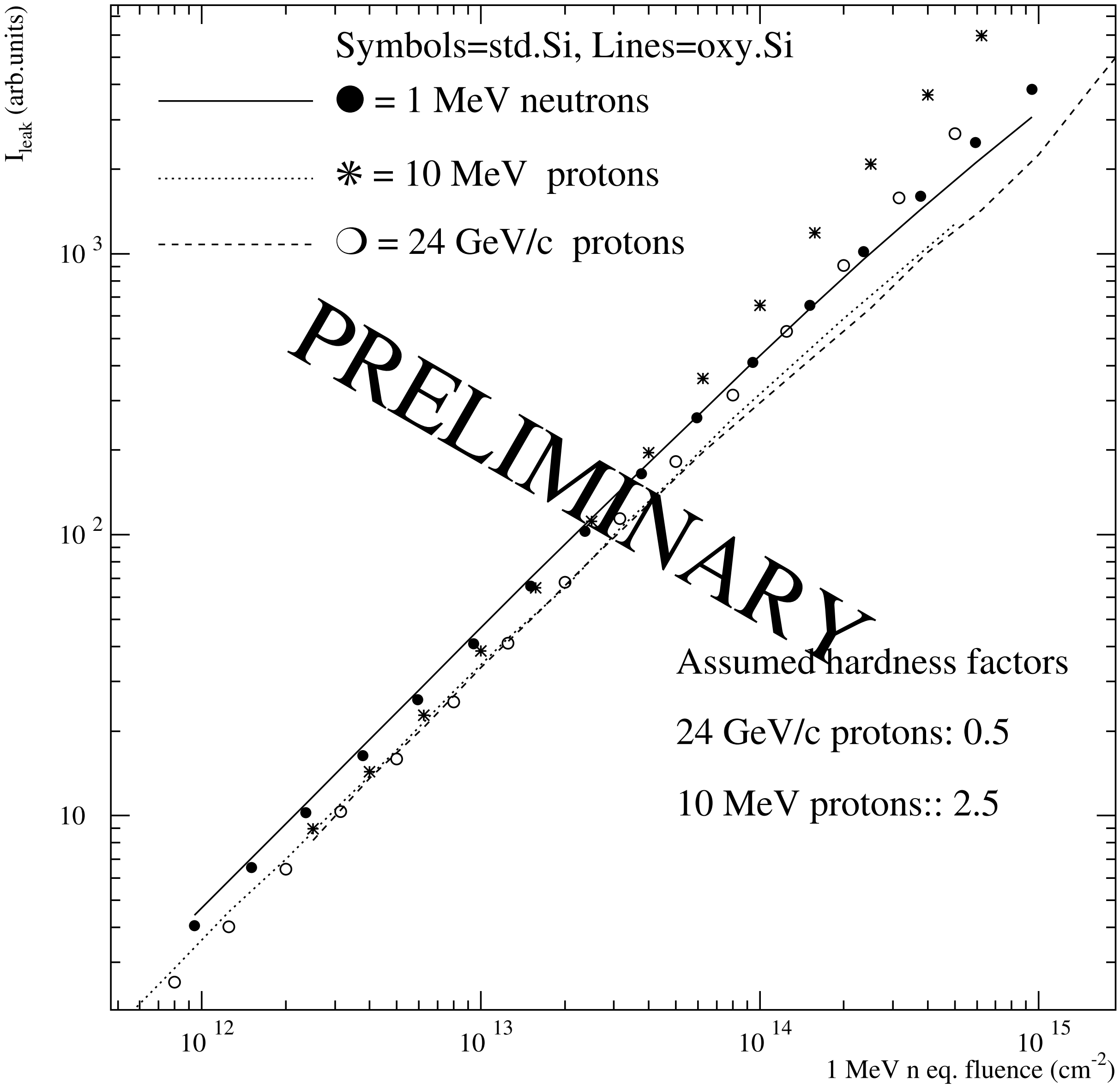
	Minimum Cluster size (N_{min})				
	2	**3**	**4**	**5**	**6**
10 MeV proton	**0.174**	**0.093**	**0.051**	**0.027**	**0.014**
24 GeV/c proton	**0.204**	**0.112**	**0.062**	**0.033**	**0.018**
1 MeV neutron	**0.265**	**0.164**	**0.098**	**0.055**	**0.030**

Values of $C1_{ave}$ for various irradiation types and different requirements for the minimum cluster size (preliminary).



...but leakage current gets affected also...

Consider contribution from V2O and VV



NIEL scaling violated by few tens of percent

Preliminary conclusions

Still some unresolved discrepancy in central assumptions

but IF these are OK, then

- **Oxygen effect can be at least qualitatively explained**
- **NIEL scaling for alpha must be slightly violated**
- **There is no single microscopic reason for NIEL scaling at all**

Consequences (predictions)

- **Deviations from NIEL scaling for all hadrons should become very clear at fluences above 1E15**
- **The oxygen effect should become visible for neutrons at fluences well above 1E14**
- **The oxygen effect should be very pronounced for 10 MeV protons**
- **The alpha for 10 MeV protons should have significant deviation from NIEL scaling.**