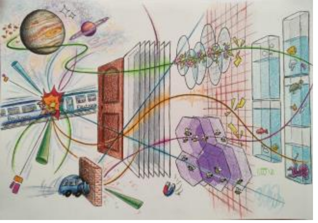



DRD3

# WG3: Radiation Damage & Extreme Fluences

## Extreme Fluences

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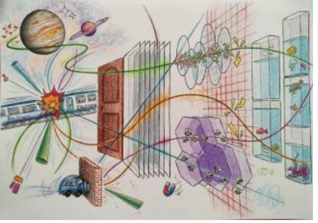
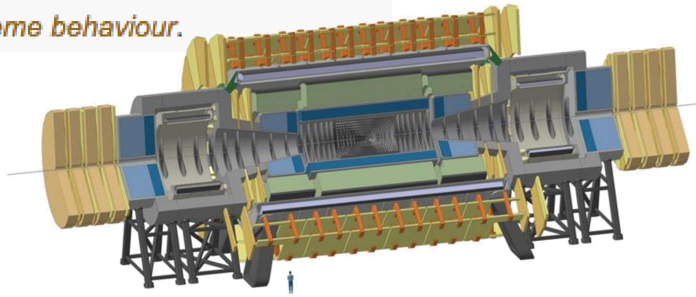
on behalf of the DRD3 proposal writing team

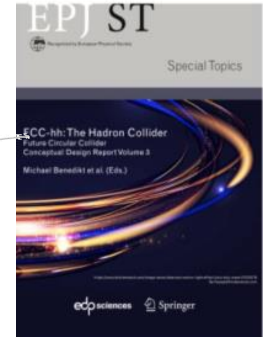


# Extreme fluences ?

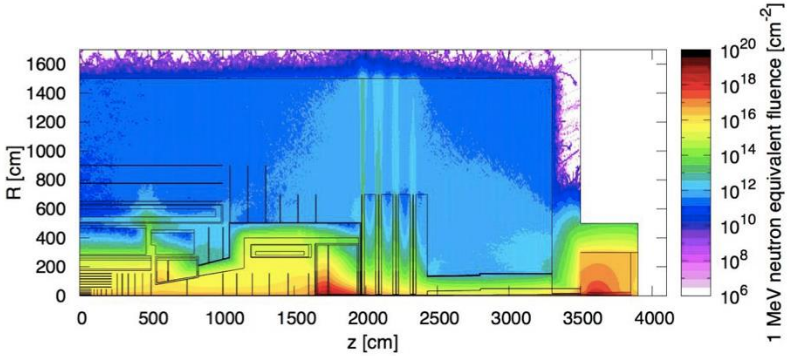
- What is extreme ?

**extreme** (ɪkˈstriːm)
*adj*
1. being of a high or of the highest degree or intensity: *extreme cold*; *extreme difficulty*.
2. exceeding what is usual or reasonable; immoderate: *extreme behaviour*.

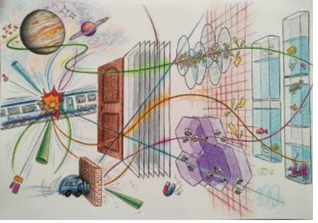





- A rather subjective measure
  - for *LHC* $10^{15}$ $n_{eq}/cm^2$ was considered extreme
    - design was 730/fb @14TeV...
  - *HL-LHC* takes it to nx$10^{16}$ (vertex) or even $10^{17}$ (FW calo)
    - 4000/fb @14TeV
  - *FCC-hh* is *specifying* towards $10^{18}$ for the tracker ( *FCC-hh CDR*)
    - 30/ab @100TeV
    - 300 MGy TID in addition
  - Ratio 1:20:600 !
    - well, you *need* ~$7^2$≈50 in HL/FCC lumi…
- What is the limit of tracking sensors ?
  - *TRIGA*, *NPP* and *ITER* are $10^{21}$ ↔$10^{24}$

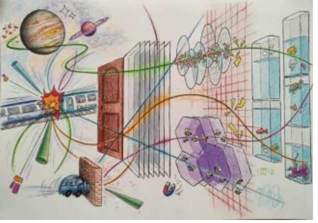



First tracking layer:
- 10 GHz/$cm^2$ charged particles
- $10^{18}$ hadrons/$cm^2$ for 30/ab



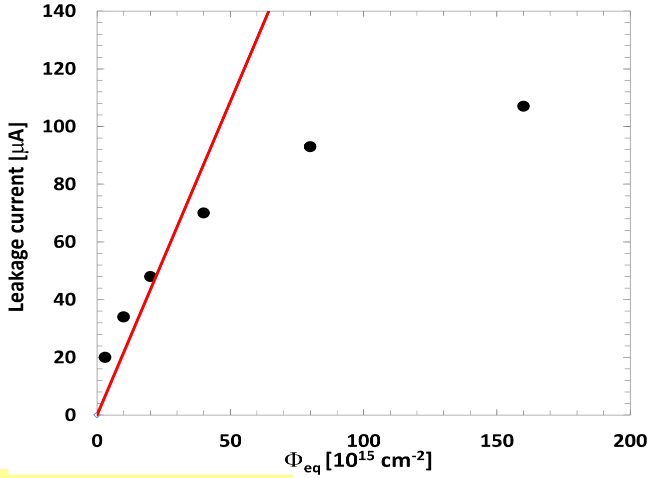
# Expectations for $10^{17}$ $n_{eq}/cm^2$

- For a ~yearly replacement of *FCC-hh* inner tracker !
  - Or a 2-stage operation 5->30/ab
- Linear extrapolation from low fluence data
  - Current: $I_{leak}$ = 4 A/cm$^3$ @20°C
    - 2 mA/cm$^2$ (2W @ 1 kV) for 300 µm thick detector @ -20°C
  - Depletion: $N_{eff} \approx 1.5\text{x}10^{15}$ cm$^{-3}$
    - *FDV* ≈ 100 kV
  - Trapping $\tau_{eff} \approx$ 1/40 ns = 25 ps
    - $Q \approx Q_0/d\ v_{sat}\tau_{eff} \approx$ 80 e/µm 200 µm/ns 1/40 ns = 400 e in very high electric field (>>1 V/µm)
- But what about data ?
  - Unfortunately, very little experimental data exist beyond $10^{17}$ $n_{eq}/cm^2$…



# *CCE* measurements up to $1.6 \times 10^{17}\ n_{eq}/cm^2$

- *n⁺p* ”spaghetti” strips, 300 µm
- Observed signal not at all compatible with expectations
  - Above $3 \times 10^{15}$ linear $CCE(V_{bias})$
  - Power law scaling with fluence, $b \approx -⅔$
  - Leakage current “saturating”

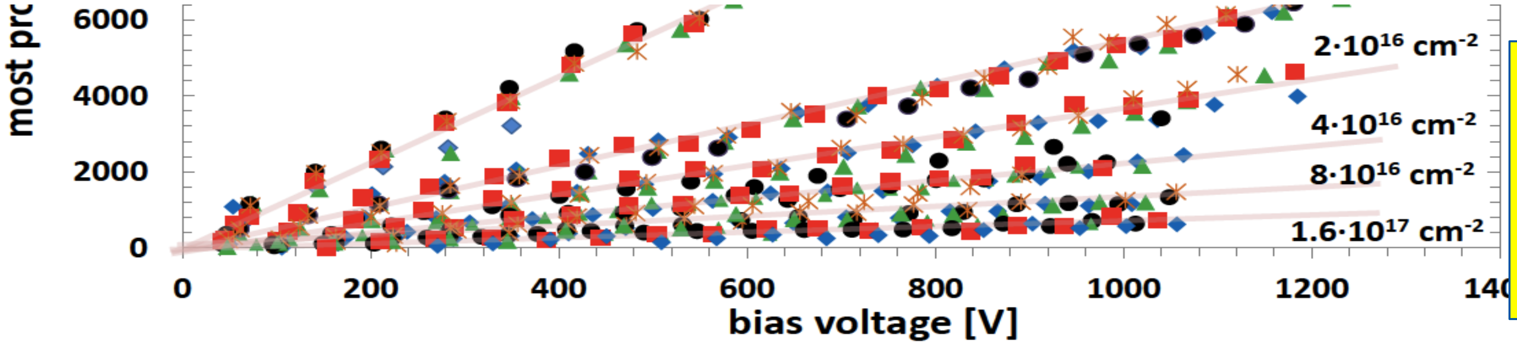



$$Q_{MPV}(V,\mathrm{F}) = k \times (\mathrm{F}/10^{15}\ \mathrm{n_{eq}}/\mathrm{cm}^2)^b \times V$$

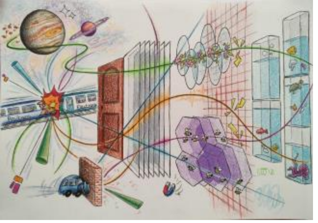
$$k = 26.4\ \mathrm{e_0/V}$$

$$b = -0.683$$

**“Magic formula”**

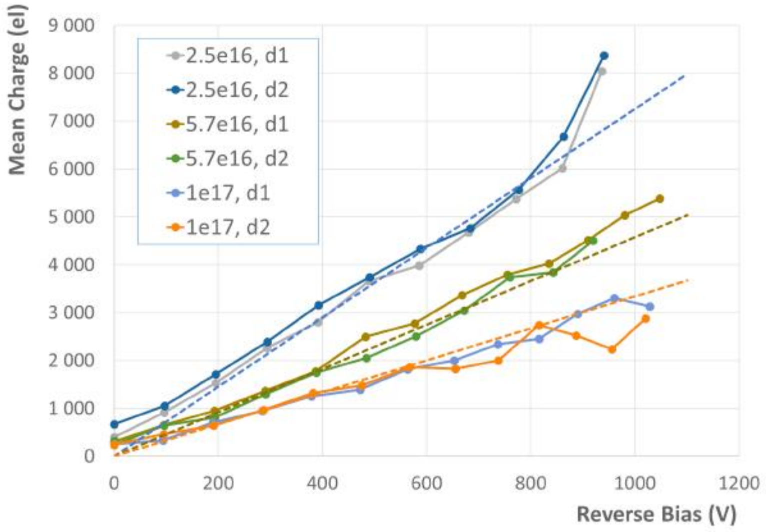


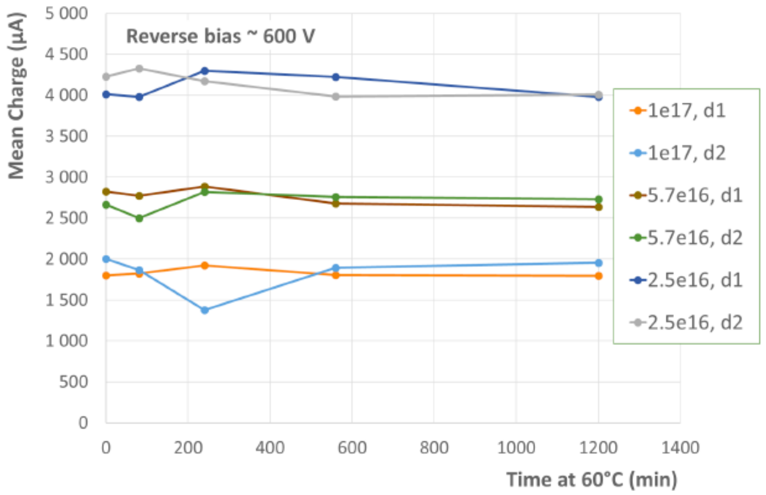

From:
**G. Kramberger et al.,**
***JINST 8 P08004 (2013).***



# More measurements on thin detectors

- 75 µm epi detectors from CNM on low-resistivity substrate
- Irradiated to 0.25, 0.57 and 1.0x10$^{17}$ $n_{eq}/cm^2$
- *CCE* in reverse and FW
- Annealing 1200 min @ 60°C

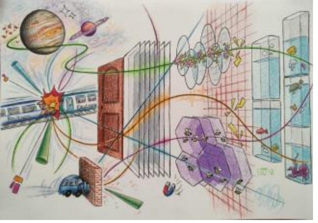



From:
**I.Mandić et al.,**
***JINST 15 P11018 (2020)*.**

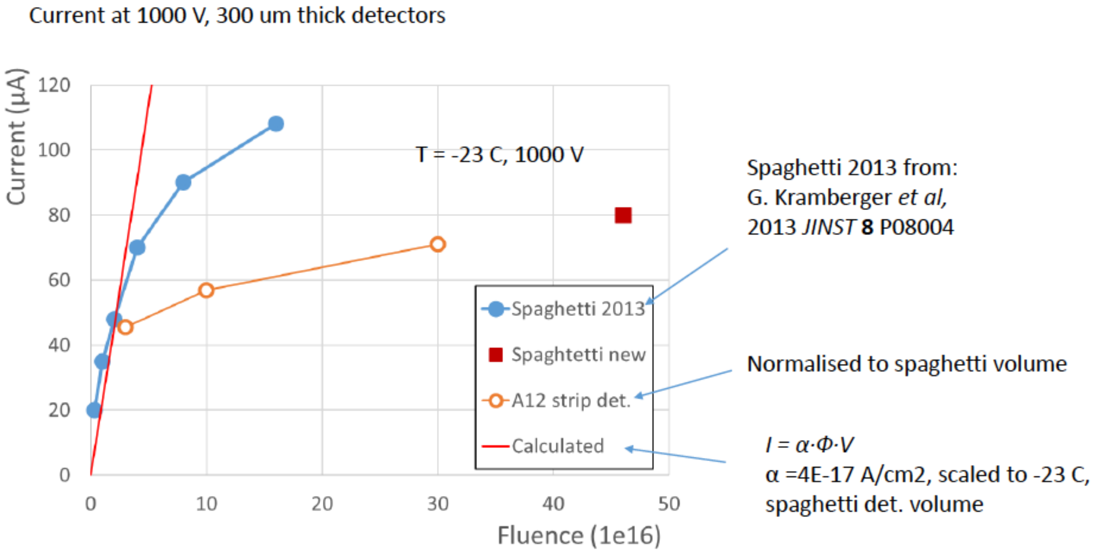
$$Q_{mean} = k \cdot \phi^b \cdot V$$
$$k_{75} = 44\ \mathrm{e_0/V}$$
$$b_{75} = -0.56$$

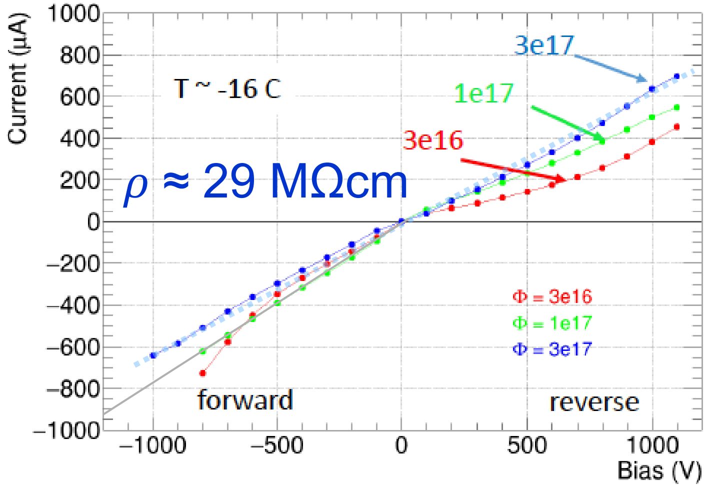
Thinner is better!

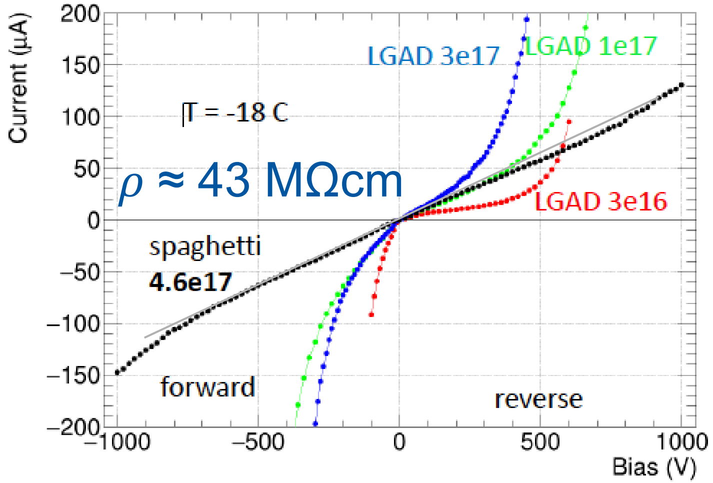


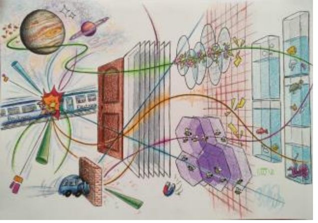
# Basic Measurements above $10^{17}\ n_{eq}/cm^2$

- *I-V* for 3&4.6e17 looks very linear with little difference between reverse/FW bias
  - No breakdown, as observed in LGAD's
- *I* @1000 V does not scale linearly with fluence !
  - Not governed by generation current ?
- Tried to measure 4.6e17 spaghetti *CCE* with $^{90}$Sr
  - No signal above background observed up to 320 V
  - Magic formula predicts 120e for 4.6e17 @320 V





# Mobility Analysis

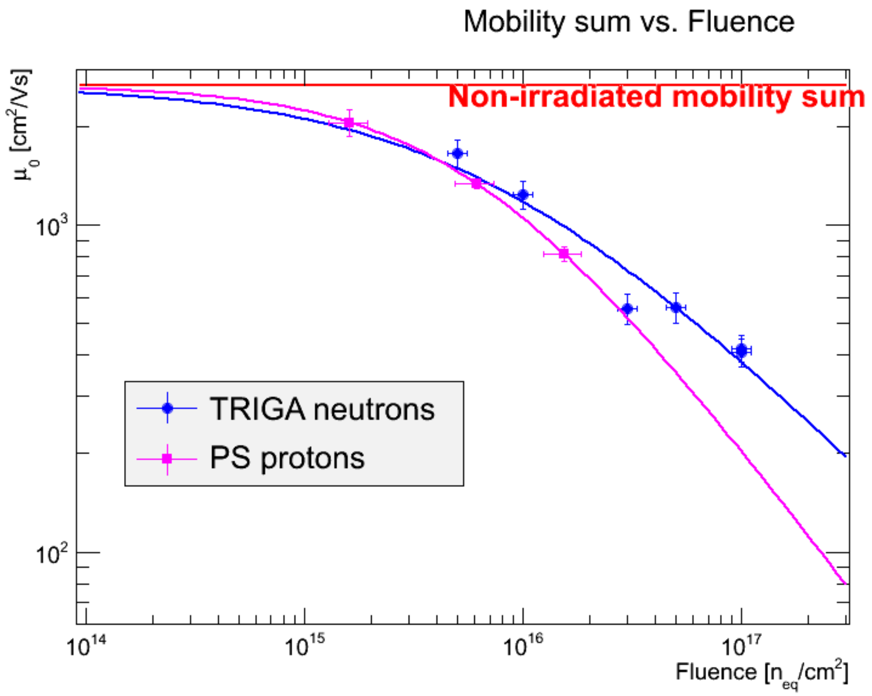
- Mobility governed by hard scattering on acoustic phonons and traps

$$\frac{1}{t} = \frac{1}{t_{ph}} + \frac{1}{t_{trap}}$$

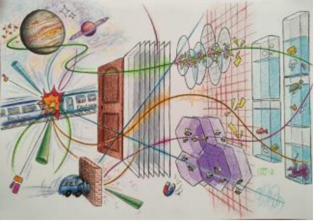
- Fit mobility dependence on fluence with a power law

$$m_{0,sum}(F) = \frac{m_{0,sum,phonon}}{1 + \left(\frac{F}{F_{1/2}}\right)^{a}}$$

- Fits perfectly, value of *a* close to linear
  - 10% error assumed for all neutron data
- At same NIEL, mobility decrease worse for protons
  - NIEL violation ? Large errors ?



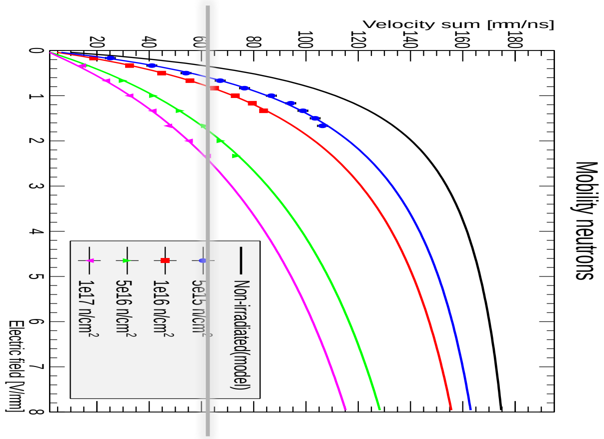

| Irradiation particle | $a$ | $\sigma_a$ | $\Phi_{½}$ /10$^{15}$ | $\sigma_{\Phi½}$ /10$^{15}$ |
|---|---|---|---|---|
| Reactor neutrons | -0.68 | 0.08 | 6.9 | 1.7 |
| PS protons | -0.90 | 0.19 | 6.1 | 1.0 |



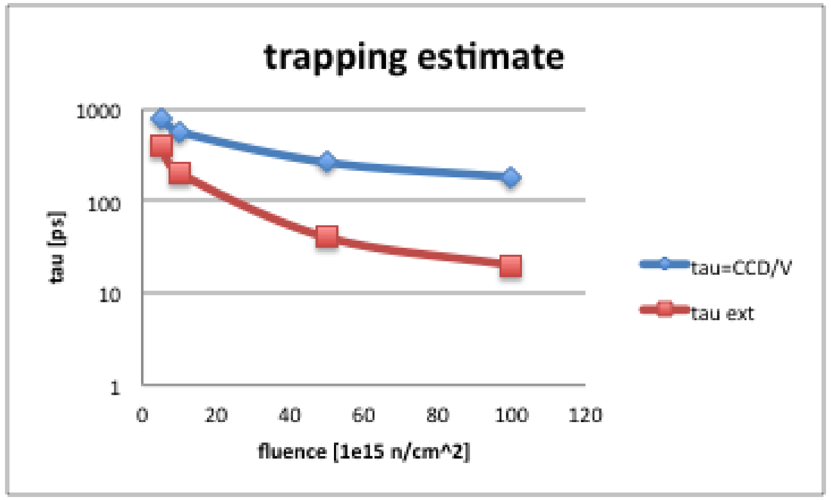
# Trapping analysis

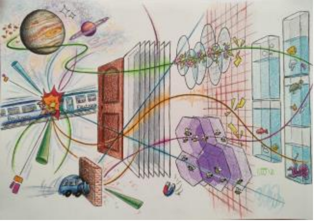
- Take $v_{sum}$ at average $E$ = 3.3 V/µm
- Calculate *CCD* from "magic formula"

| Φ [1e15] | 5 | 10 | 50 | 100 |
|---|---|---|---|---|
| $v_{sum}$(3.3 V/µm) | 137 | 126 | 90 | 77 |
| $CCD_{1000\ V}$ [µm] | 110 | 70 | 23 | 14 |
| $\tau \approx CCD/v$ [ps] | 800 | 560 | 260 | 180 |
| $\tau_{ext}$ [ps] | 400 | 200 | 40 | 20 |




- Implies factor of 6-9 less trapping at highest fluences
  - lowest fluence still x2 from extrapolation
  - weak dependence on fluence as anticipated
  - CM would effectively shorten trapping times
  - not good when large *E* variations  (*v(E)* saturates)
  - not good when *CCD* ≈ thickness (less signal at same *τ* )





# Trapping revisited

- From *I.Mandić et al., JINST 15 P11018 (2020)*
  - FW bias *CCE* estimated by

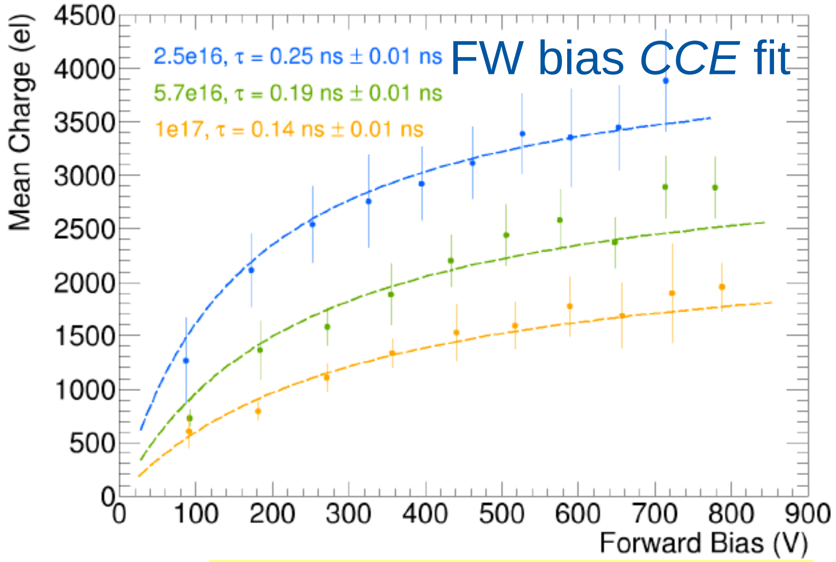
$$Q = \frac{\Delta Q}{\Delta x} \cdot v \cdot \tau$$

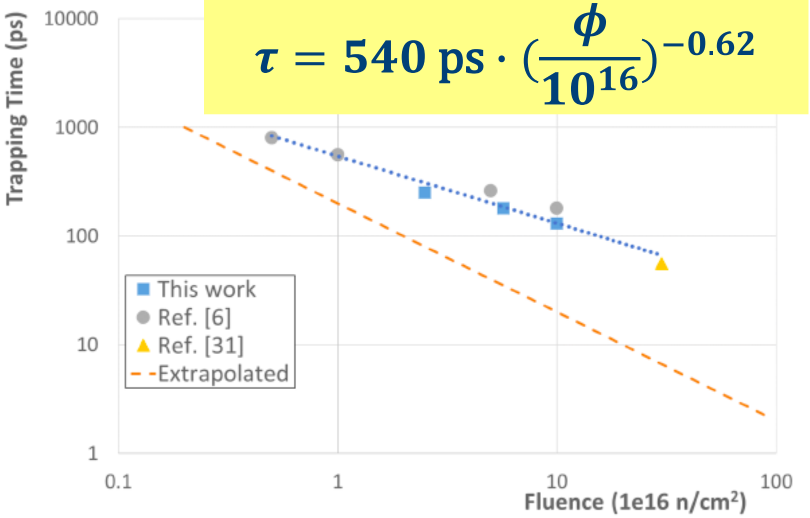
    - *v(E)* with fluence dependent *μ*
    - constant *E=V/D* (FW)

😀 Order of magnitude smaller than extrapolated !

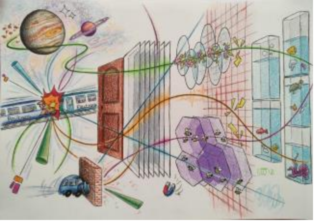
😀 Agrees with estimates from reverse bias *CCE*

- Trapping independent of bias, seen in wave-forms




$$\tau = 540\ \mathrm{ps} \cdot \left(\frac{\phi}{10^{16}}\right)^{-0.62}$$

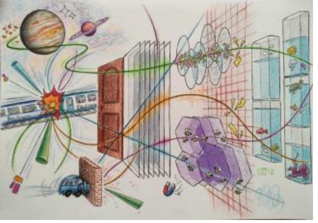


# State of the Art at Extreme Fluences

DRD3

- Measurements performed on Si detectors irradiated to extreme fluences
  - Neutrons from $10^{15}$ to $4.6\times10^{17}$ $n_{eq}/cm^2$ , PS protons from $5\times10^{14}$ to $3\times10^{16}$ $p/cm^2$
  - Velocity vs. electric field radiation impact observed and interpreted as reduction of zero field mobility
    - Zero field mobility follows power law with $|a| \leq 1$, $\Phi_{½} \approx 10^{16}$ $n/cm^2$
    - Protons degrade mobility more than neutrons
    - Induces resistivity increase in-line with measured *I-V*
    - Exhibits adverse effect on charge multiplication !
  - Simple field profile for very high neutron fluences
    - Diminishing SCR and highly resistive ENB
    - Effective acceptor introduction rates reduced by factor ~100 wrt low fluences
    - Current much lower than anticipated. Generated in SCR only ? Ohmic at highest fluences…
  - Trapping estimates for very high neutron fluences
    - from charge collection in FW and reverse bias
    - from waveforms
    - All estimates point to severe non-linearity of trapping with fluence, 10x lower at $10^{17}$
    - Trapping appears independent of electric field
- Conclusion: ***Low fluence extrapolations do not work at all !***

… go out and ***measure*** to get anything working at ***extreme*** fluences !!!



# Implications for WG3 of DRD3

- Basic bulk silicon properties in the fluence range to master are the prerequisite to any inner tracking detector design for *FCC-hh*
- They need to be ***measured***
  - Only pioneering consistency checks done so far
- Need resources **far beyond** current ones
  - Facilities (EURO-LABS, LDG/ECFA WG…)
    - There are 4 slots with up to $10^{18}$ secured within EURO-LABS at JSI !
  - Measurement techniques
  - **People**

  at least for the first ~5 of the 20++ years
- WG3 within DRD3 Collaboration essential for achieving the goal
  - Nice to observe big interest for working on the subject !
  - EU funding should help to rise funds at national level