Macroscopic effects of radiation on silicon detectors

School on Radiation Effects on Detectors and Electronics for High Energy Physics, Astrophysics, Space Applications and Medical Physics

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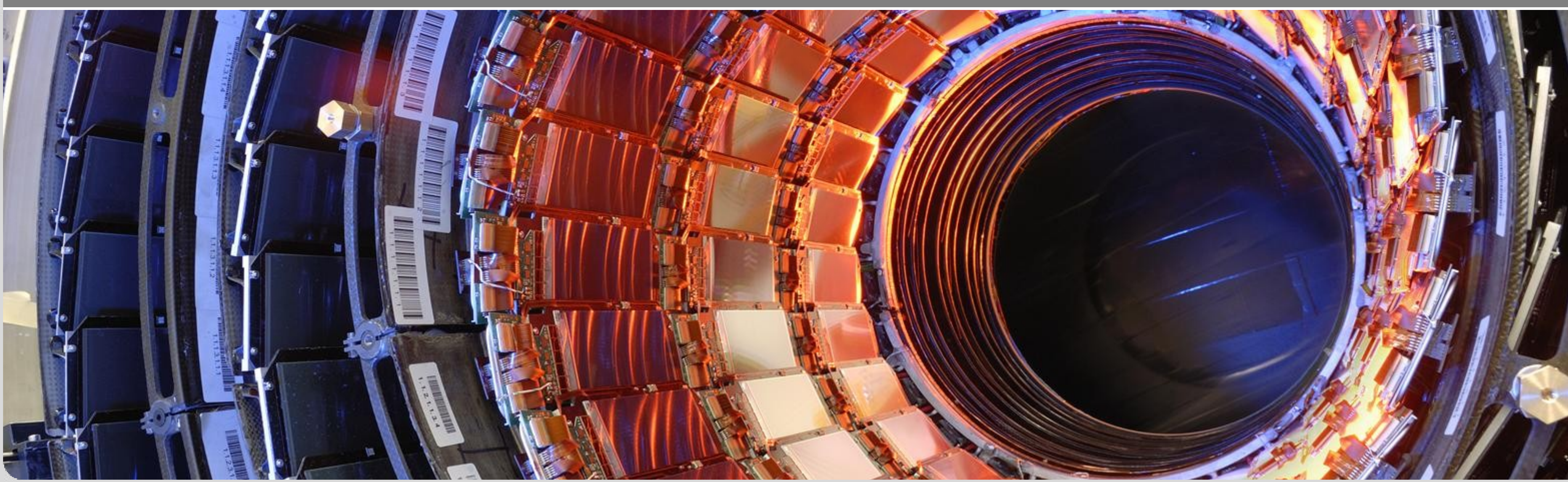
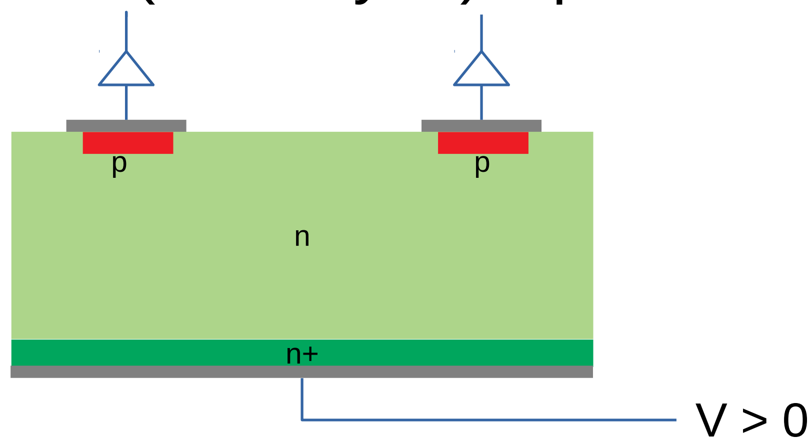


Brief recap – Silicon-based detectors

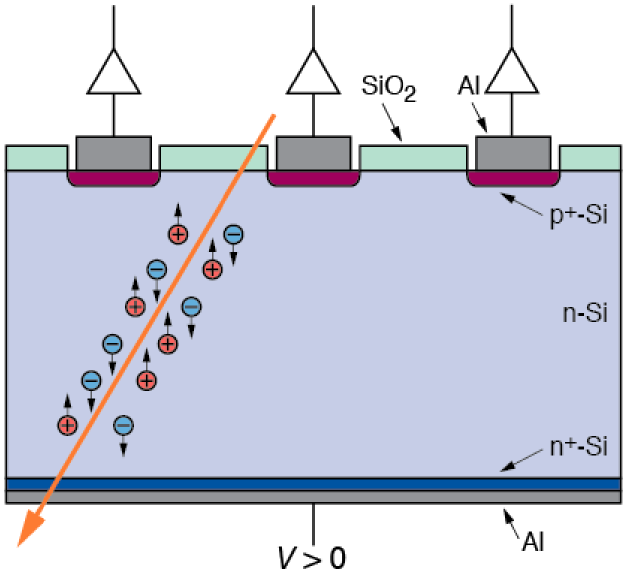
- The basic principle is always similar:
  - Take a piece of (let's say n-)doped silicon



  - We add some p-doped implants → we now have a (or actually several) semi-conductor diodes!
  - Let's add some metal pads on top
  - Now we can bias our sensor and connect it to the readout

Silicon Detectors – the actual particle detection

- Charged particle crosses detector and creates electron-hole pairs along its path



- Electrons and holes start to drift towards respective electrodes → induce measurable signal on readout electronics
- Finely segmented diode → precise position resolution

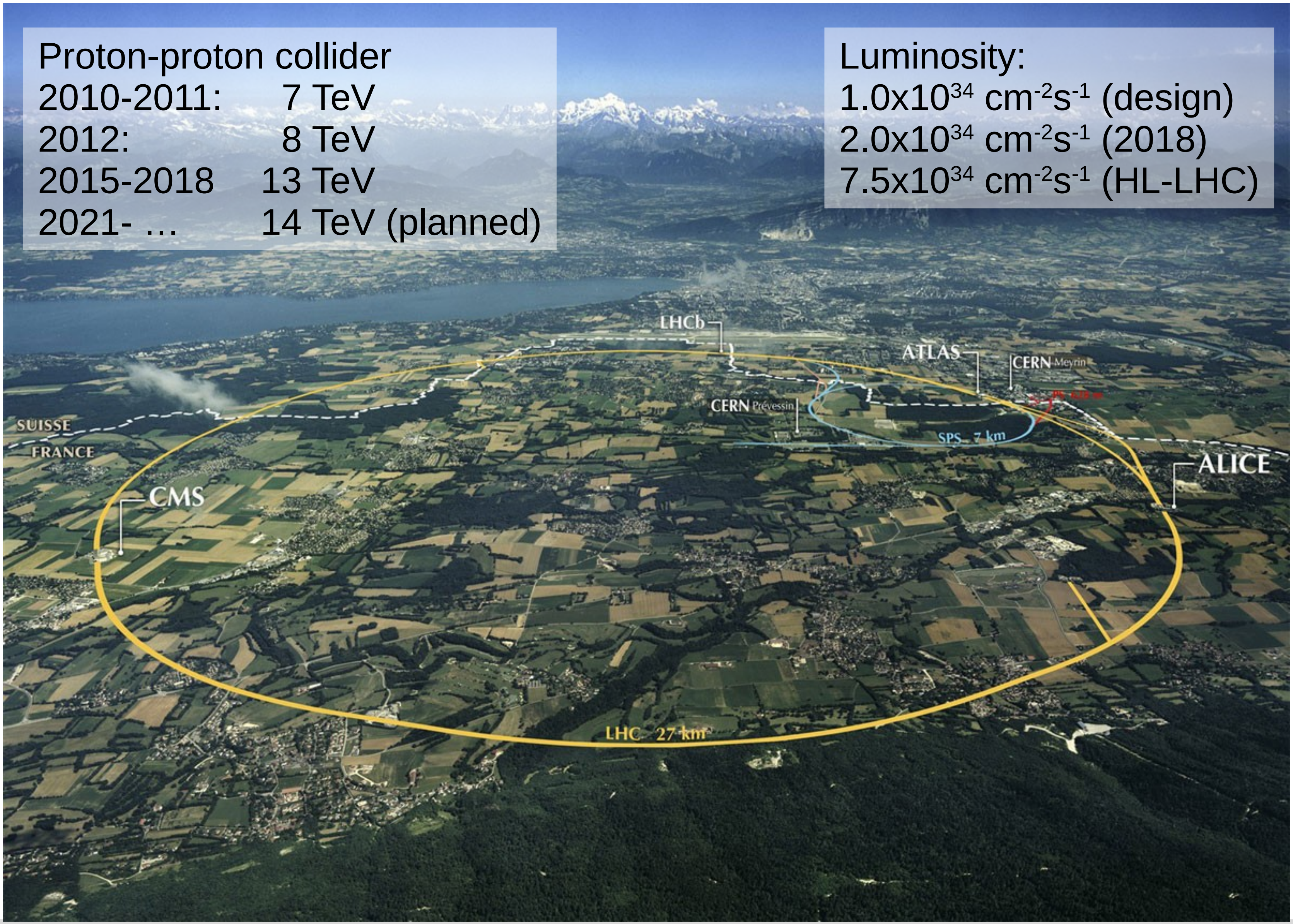
Radiation damage in silicon detectors

Setting the stage – CERN LHC

- The most prominent example of a place where we have large silicon-based detector getting irradiated

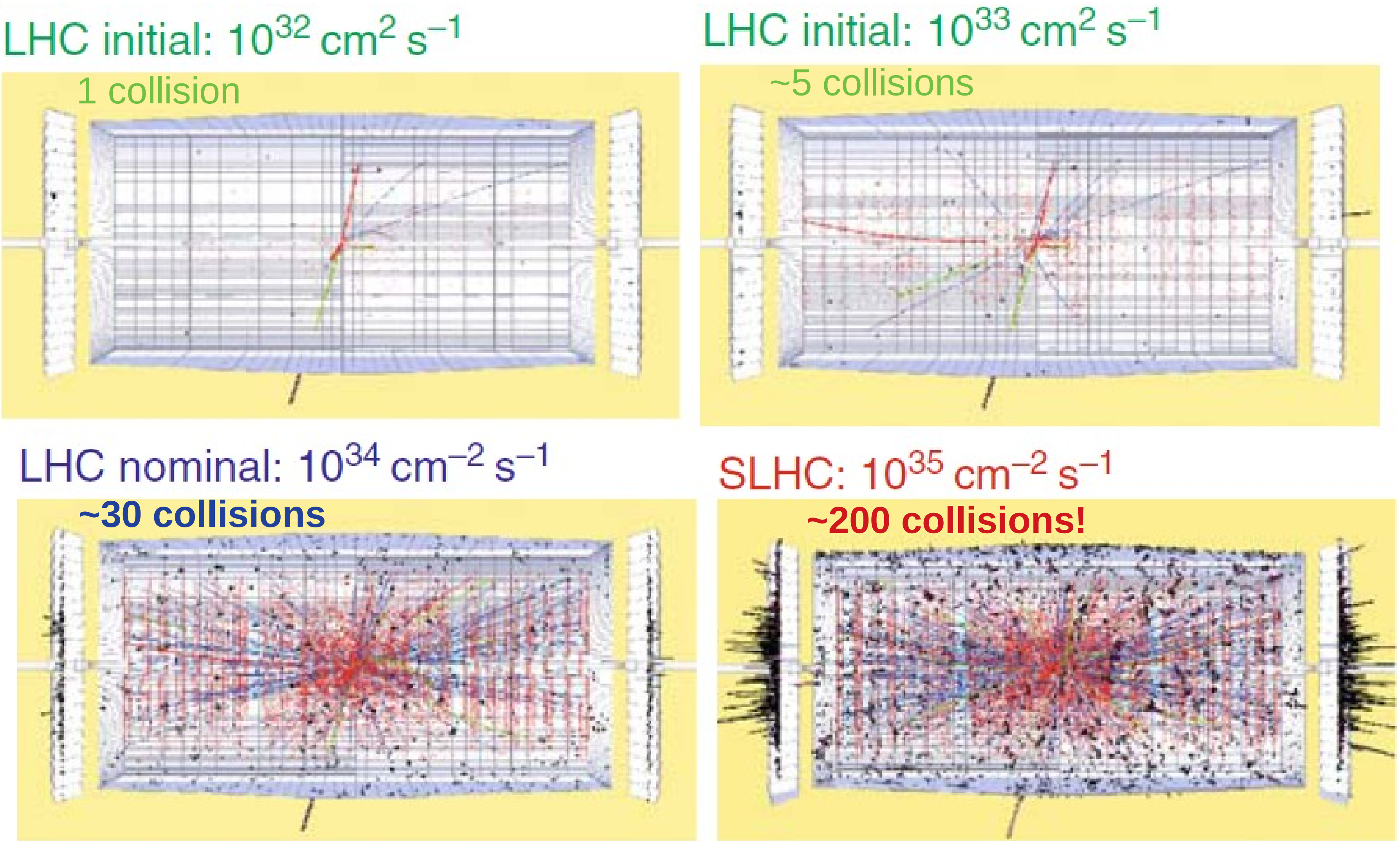
Proton-proton collider
2010-2011: 7 TeV
2012: 8 TeV
2015-2018 13 TeV
2021- … 14 TeV (planned)

Luminosity:
1.0×10^{34} cm^{-2}s^{-1} (design)
2.0×10^{34} cm^{-2}s^{-1} (2018)
7.5×10^{34} cm^{-2}s^{-1} (HL-LHC)



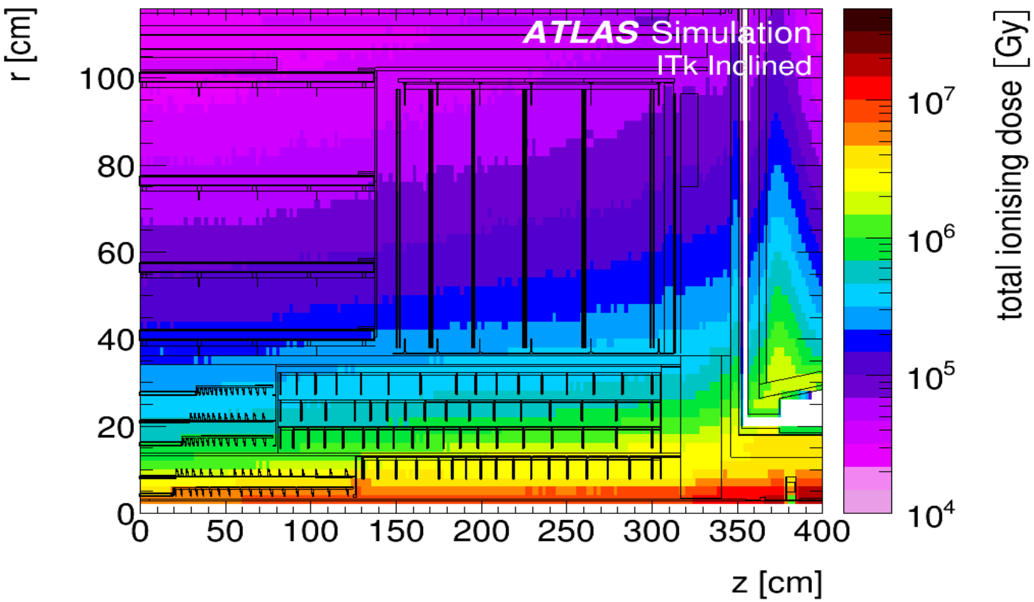
Particle Collisions at the LHC

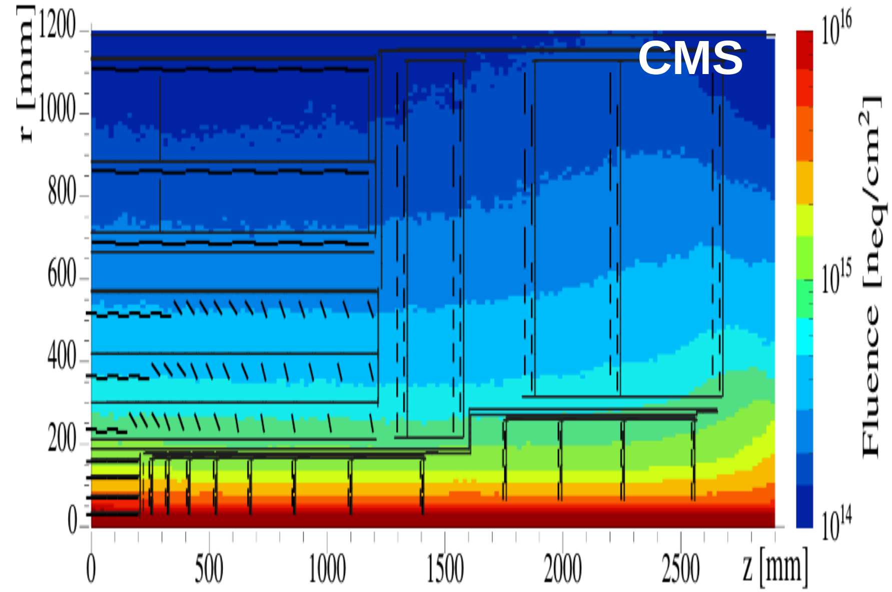
- Not just one pp collision happening at a time, but MANY



Radiation environment

- The way we present the radiation field at the LHC typically looks like this:



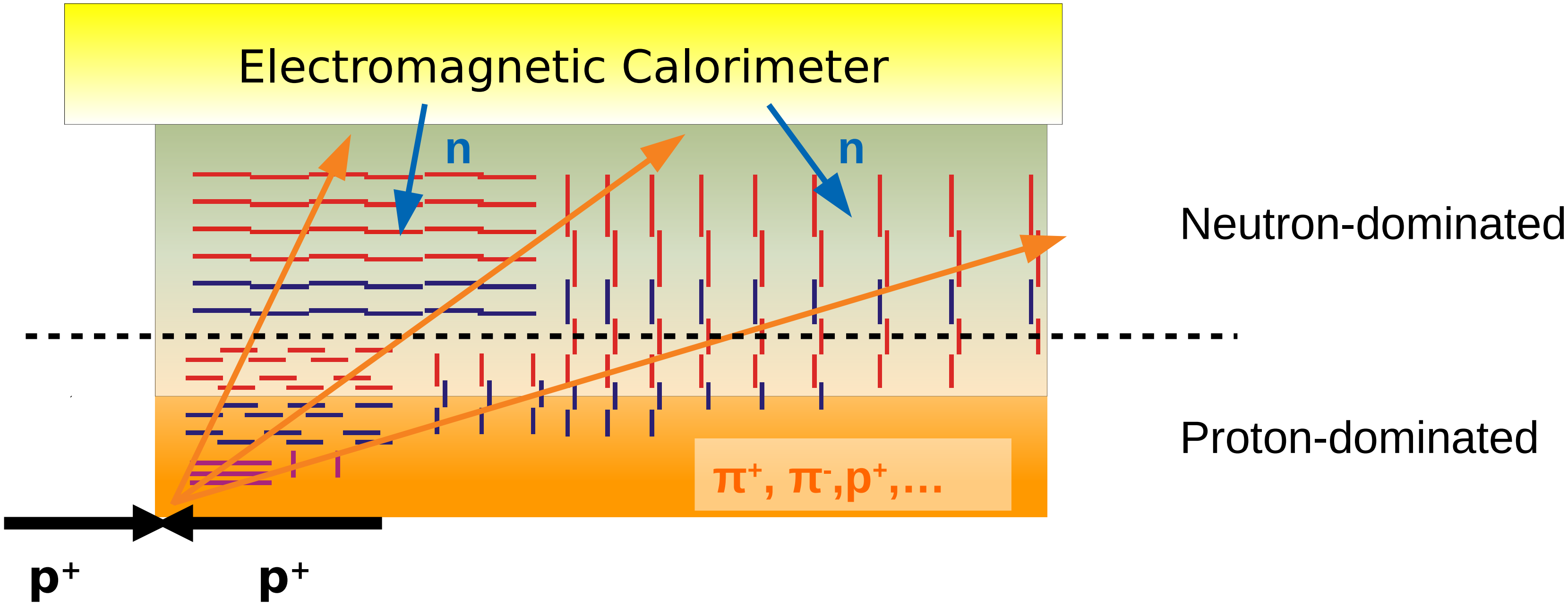


- After 3000 fb-1 of HL-LHC running (factor 10 less for LHC)
  - Doses of 10^7 Gray
    (recall: you are surely dead from about 6 Gy)
  - 10^{16} particles passing through the innermost layers

    (about the same as neutrinos from the sun pass through your hand every day)

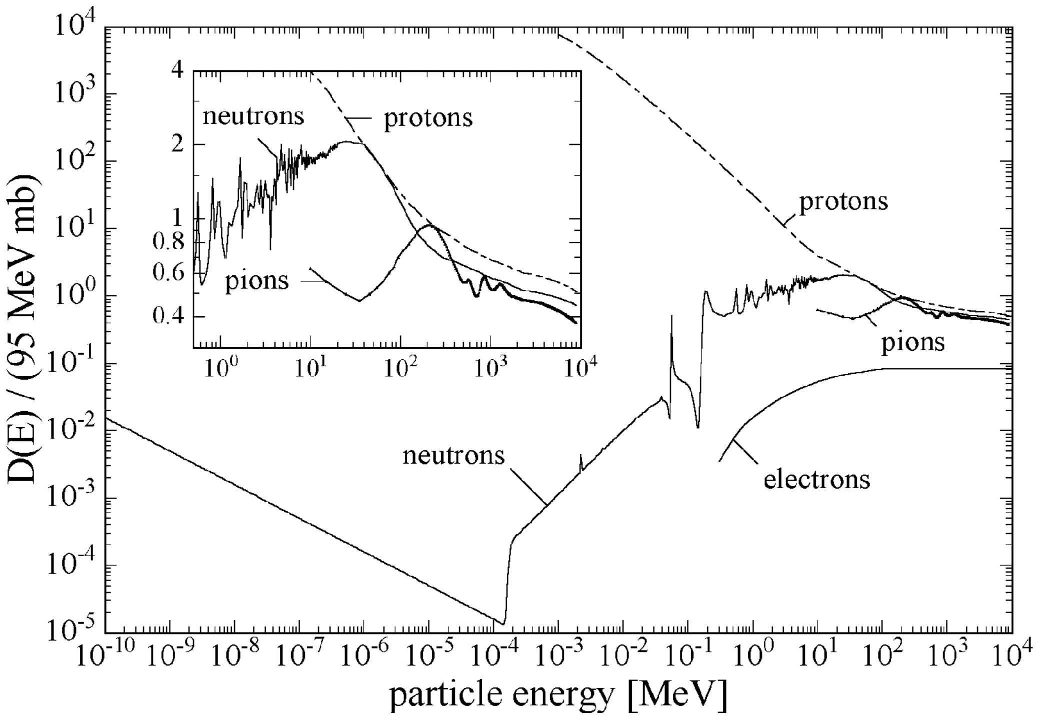
Source: xkcd.com

A bit more in detail



- Inner part of the detector is dominated by proton(pion) irradiation
- Outer part is dominated by neutron irradiation

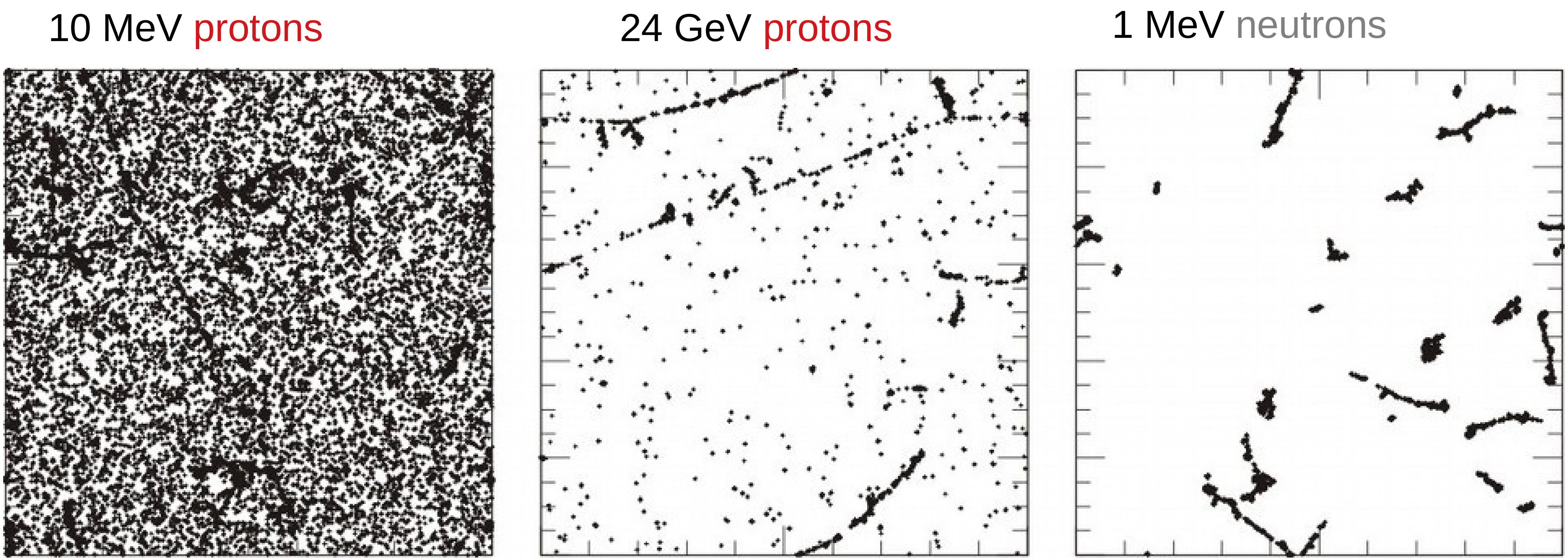
NIEL Hypothesis



- Non-ionizing energy loss
- Covered already in yesterday’s lecture
- Bottom line: it doesn’t matter if you do proton or neutron irradiation, everything can be scaled to the same reference (damage measured in “1 MeV neutron equivalent”)
- Damage from proton and neutrons can simply be added

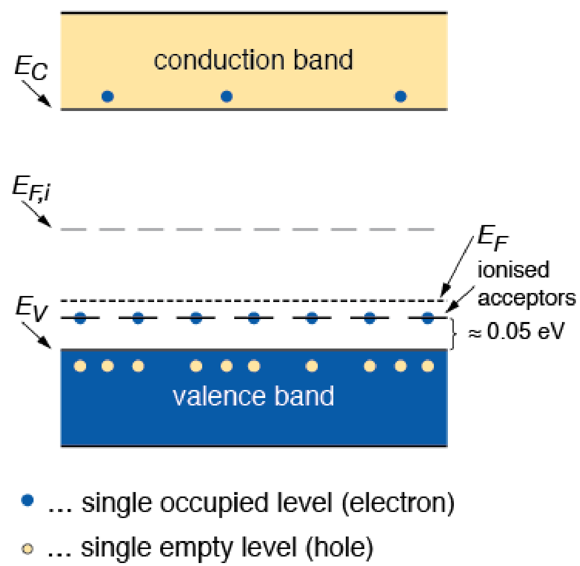
What are the microscopic effects of radiation?

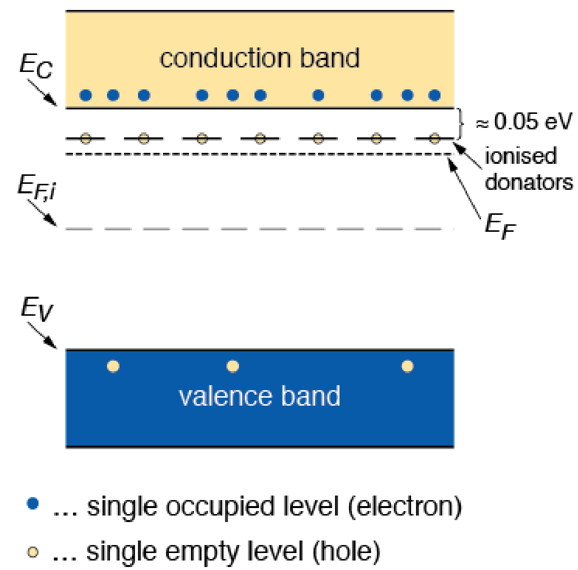
- Point-like defects
- Cluster defects
- A mixture of the two



Brief recap on doped silicon

- Acceptors and donors enable “creation” of electrons(holes) in the conduction(valence) band



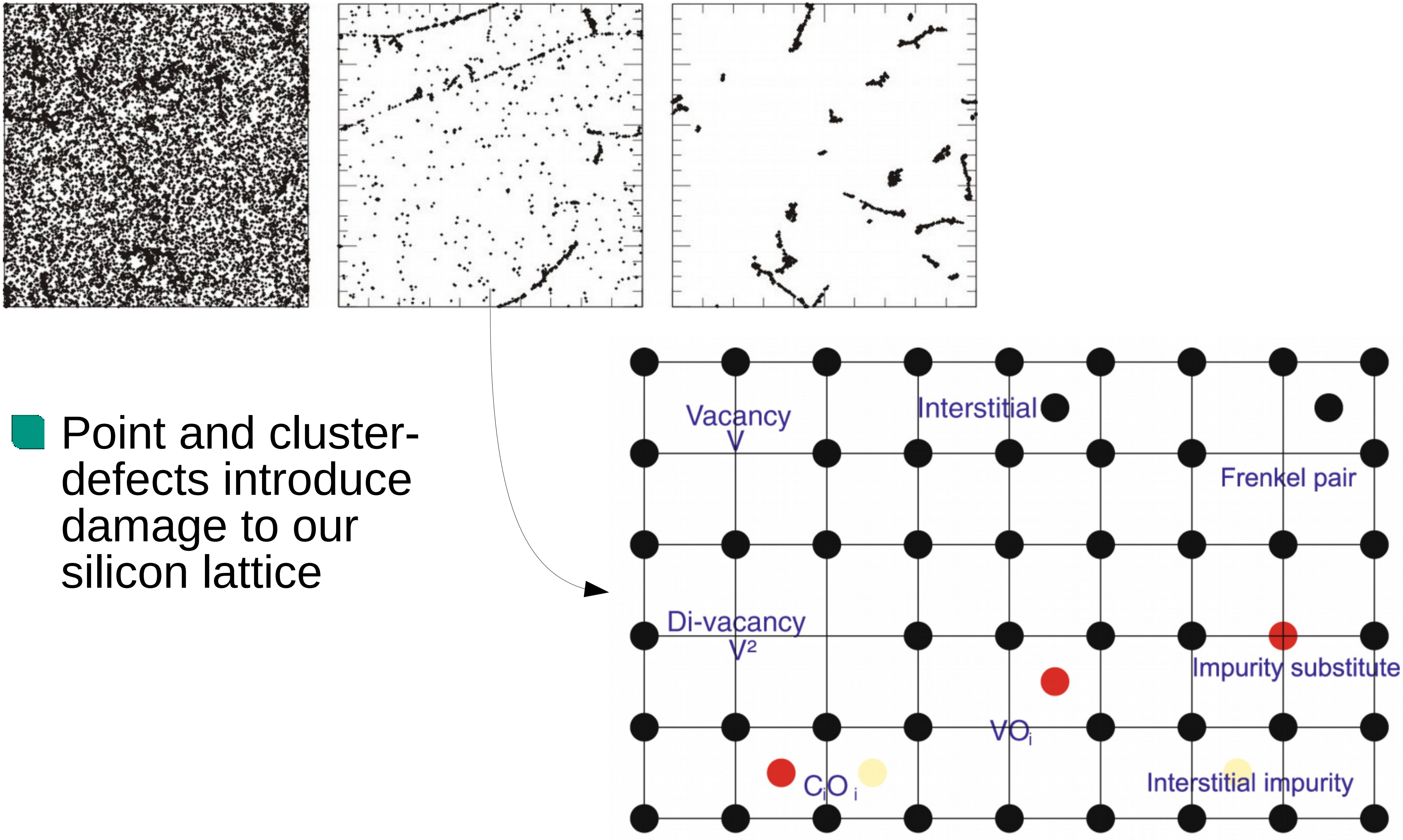


Acceptor level close to valence band
→ at room temperature electrons from valence band will be lifted into acceptor level leaving free holes in the valence band

Donor level close to conduction band
→ at room temperature electrons from donor atoms will be lifted into conduction band
→ free electrons in conduction band

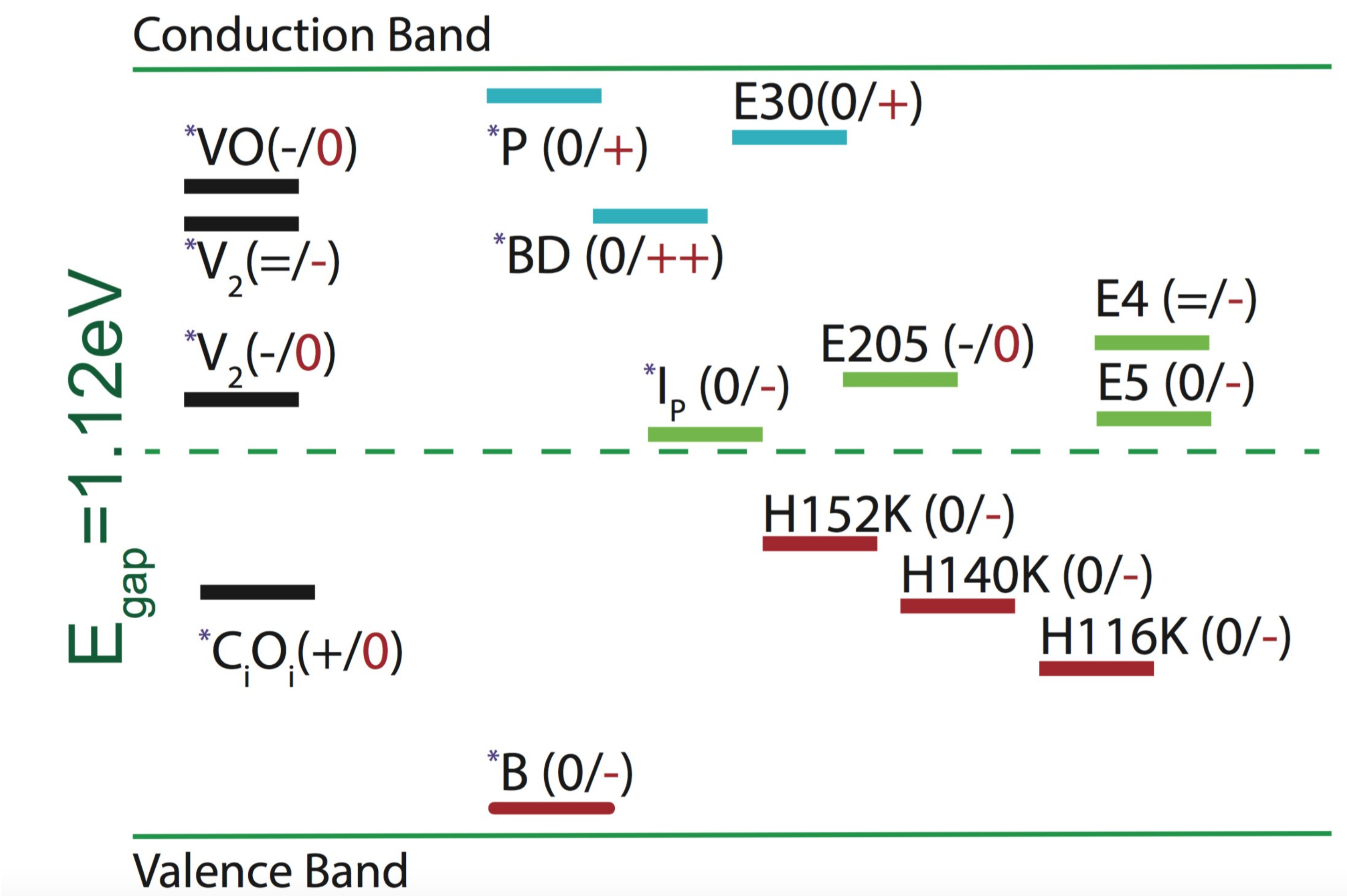
How do defects manifest in our crystal?

- Point and cluster-defects introduce damage to our silicon lattice



Note: not just silicon creates defects, also various doping atoms

…and what do they do to our bandgap?

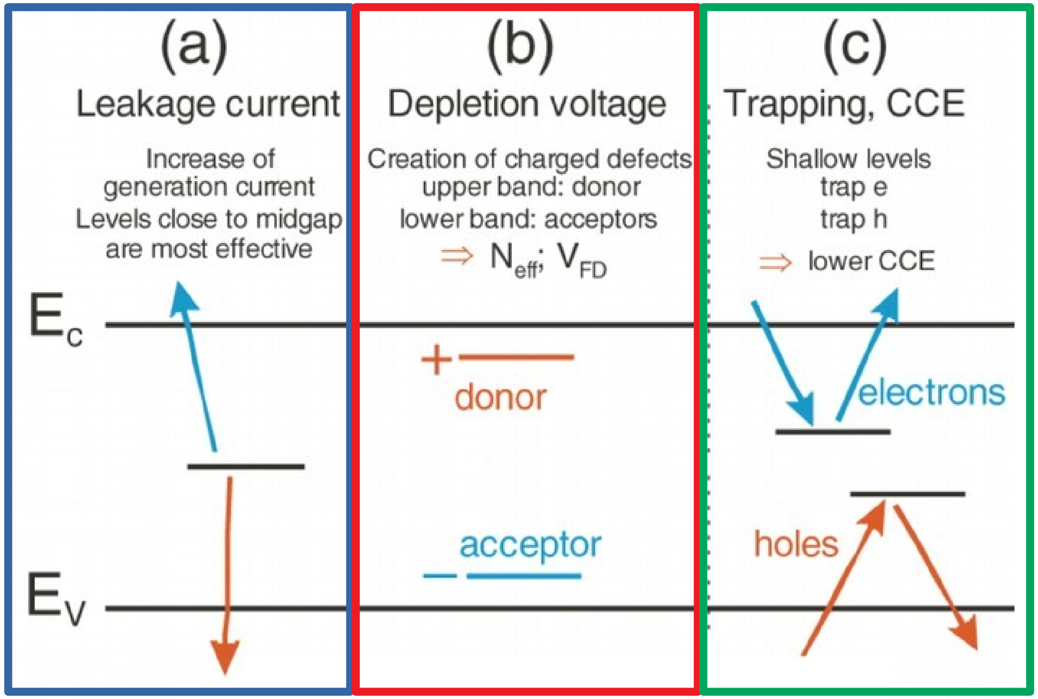


→ Defects can create new energy levels at basically any point in the bandgap

→ What do these do to our silicon detector?

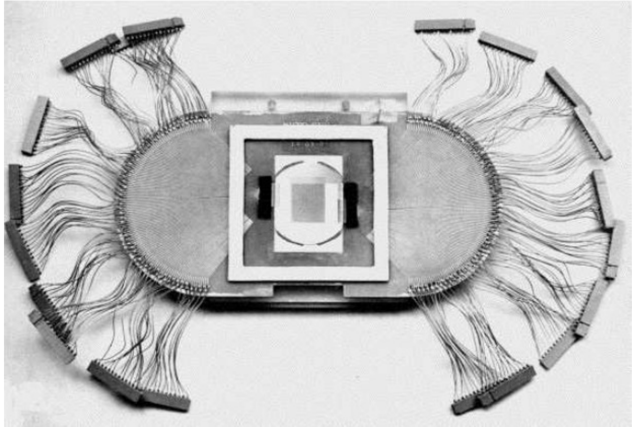
What do do they do to our detector?

- Three main effects:
  - Increased dark or leakage current
  - Change in depletion voltage
  - Reduced charge collection



Finally going to the macroscopic world...

Silicon detectors in real life



...back then…
(1983)

Surface 24 cm^2 (2” wafer)
1200 strip, 20 µm pitch

x8

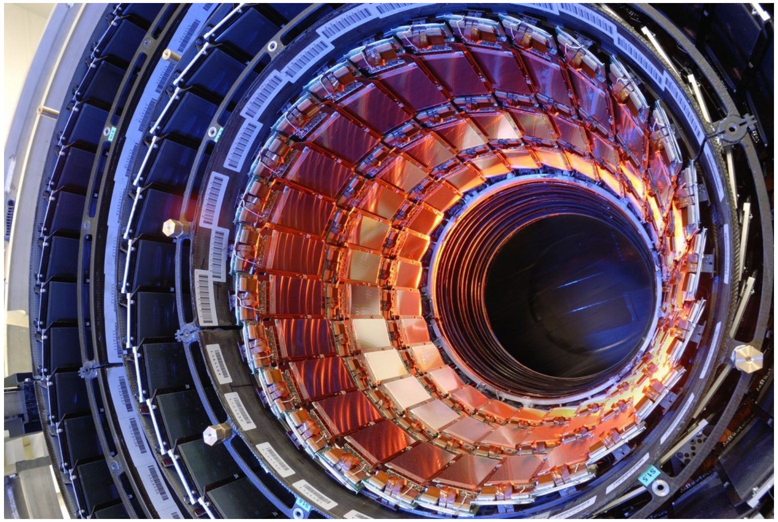
Silicon detectors in real life*)

...back then…
(1983)

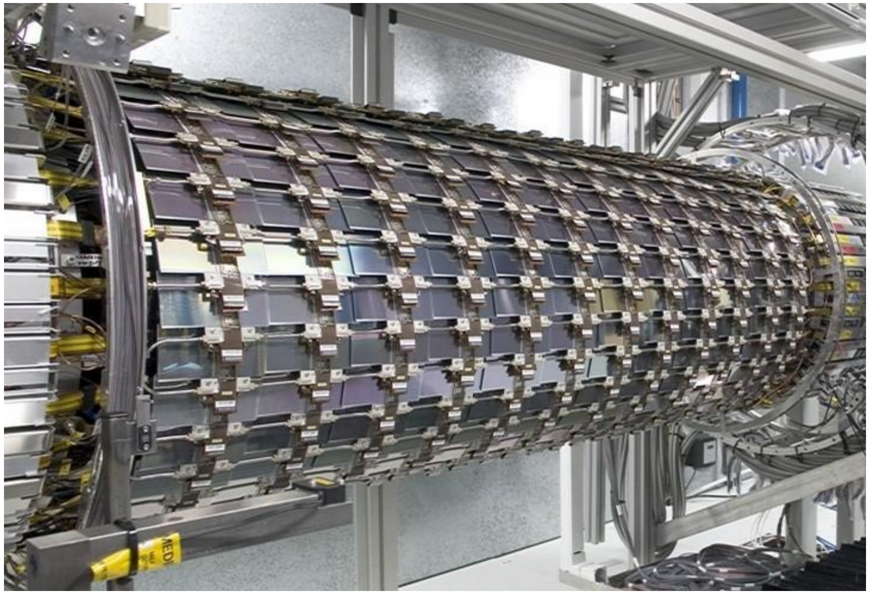
Surface 24 cm² (2” wafer)
1200 strip, 20 µm pitch

x8

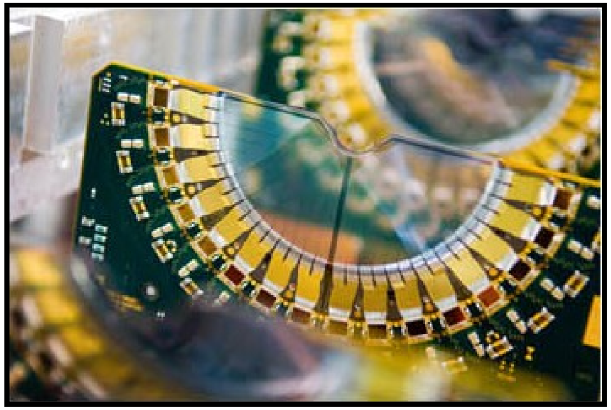
...and today...



CMS Strip Tracker



ATLAS SCT

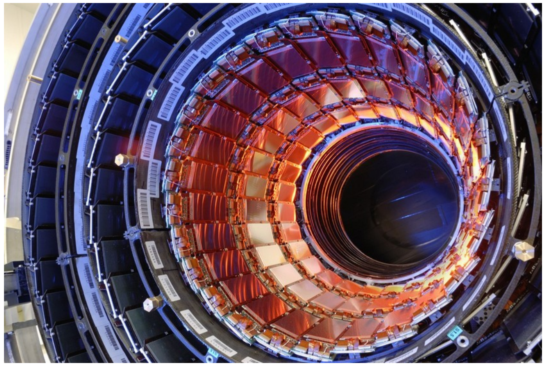


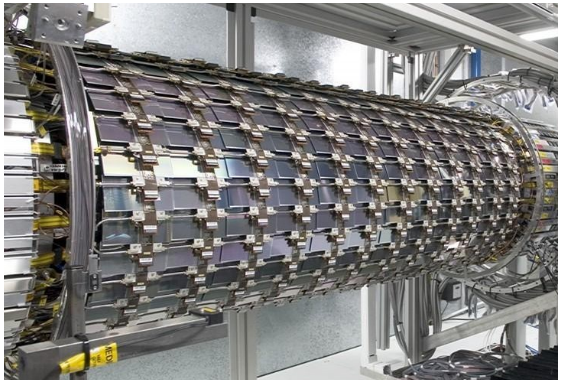
LHCb Velo

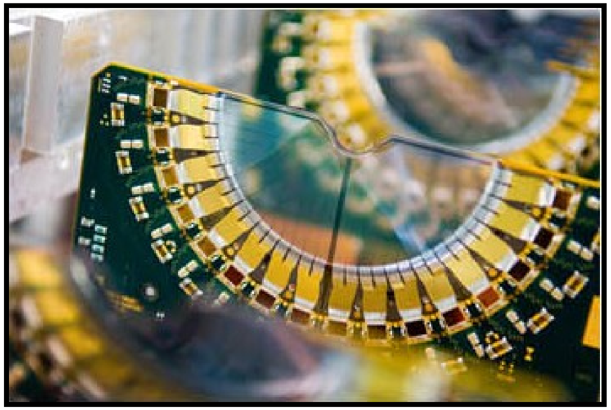
*) you will notice that while I am trying to show several examples, I will be somewhat biased towards CMS as it is my ``home’’

Silicon Detectors at the LHC

- CMS Strips:
  - 200 m^2 of p-in-n planar silicon sensors(320/500 μm)
- CMS Pixels
  - 1.75 m^2 of n-in-in planar sensors (285 μm)
- ATLAS Strips:
  - 60 m^2 p-in-n planar silicon sensors(320/500 μm)
- ATLAS Pixels
  - 1.9 m^2 n-in-in planar sensors (mostly 285 μm)
    IBL: 200 μm planar and 3D sensors
- LHCb IT and TT
  - 12.4 m^2 p-in-n planar silicon (320 μm)
- LHCb Velo
  - 0.1 m^2 n-in-in planar silicon (300 μm)







Silicon Detectors at the LHC

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- CMS Pixels
  - 1.75 m^2 of n-in-in planar sensors (285 μm)
- ATLAS
  - 60 m^2
- ATLAS
  - 1.9 m
    IBL: 2
- LHCb IT
  - 12.4 m^2 p-in-n planar silicon (320 μm)
- LHCb Velo
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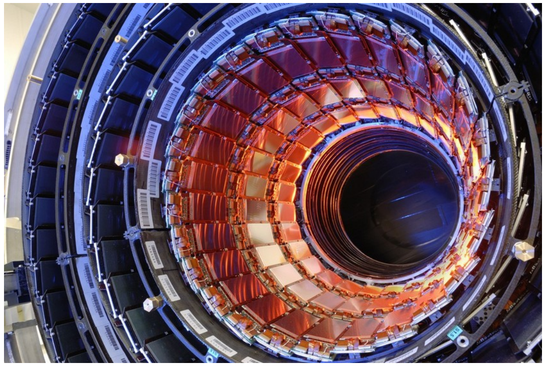
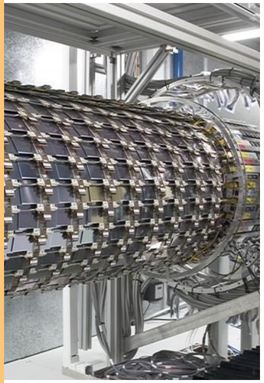
To summarize:
Large volume sensors at LHC are p-in-n planar sensors

Innermost layers are made from n-in-n
First usage also of 3D sensors





Very few words about

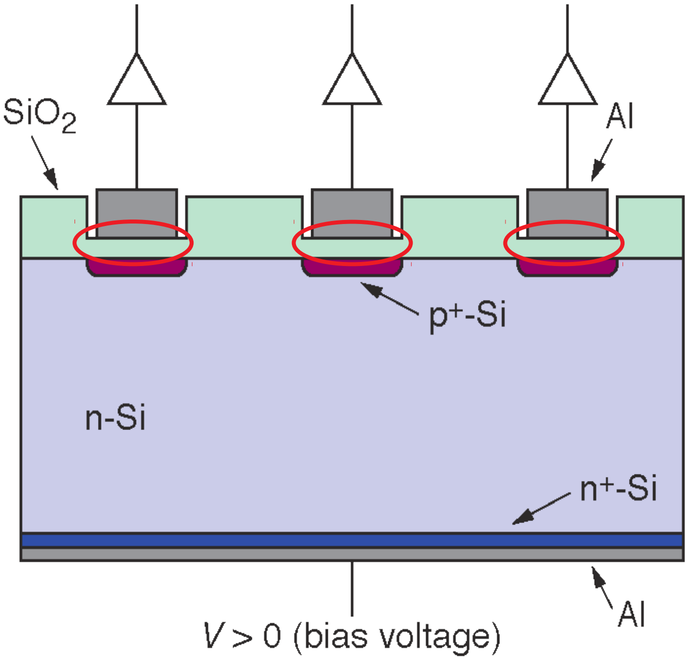
Surface Damage

Surface damage

- Unfortunately the surface of our detectors needs to be segmented
- Surface damage occurs in the SiO_2 layer and SiO2-Si interface
- Build up of charge due to ionization because of charged hadrons, γ, or electrons
- Problems caused by this:
  - increase of inter-strip capacitance → increasing noise
  - decrease of inter-strip resistance → increasing cross-talk
  - decrease in breakdown voltage

→ all effects that deteriorate our detector

AC coupled strip detector:

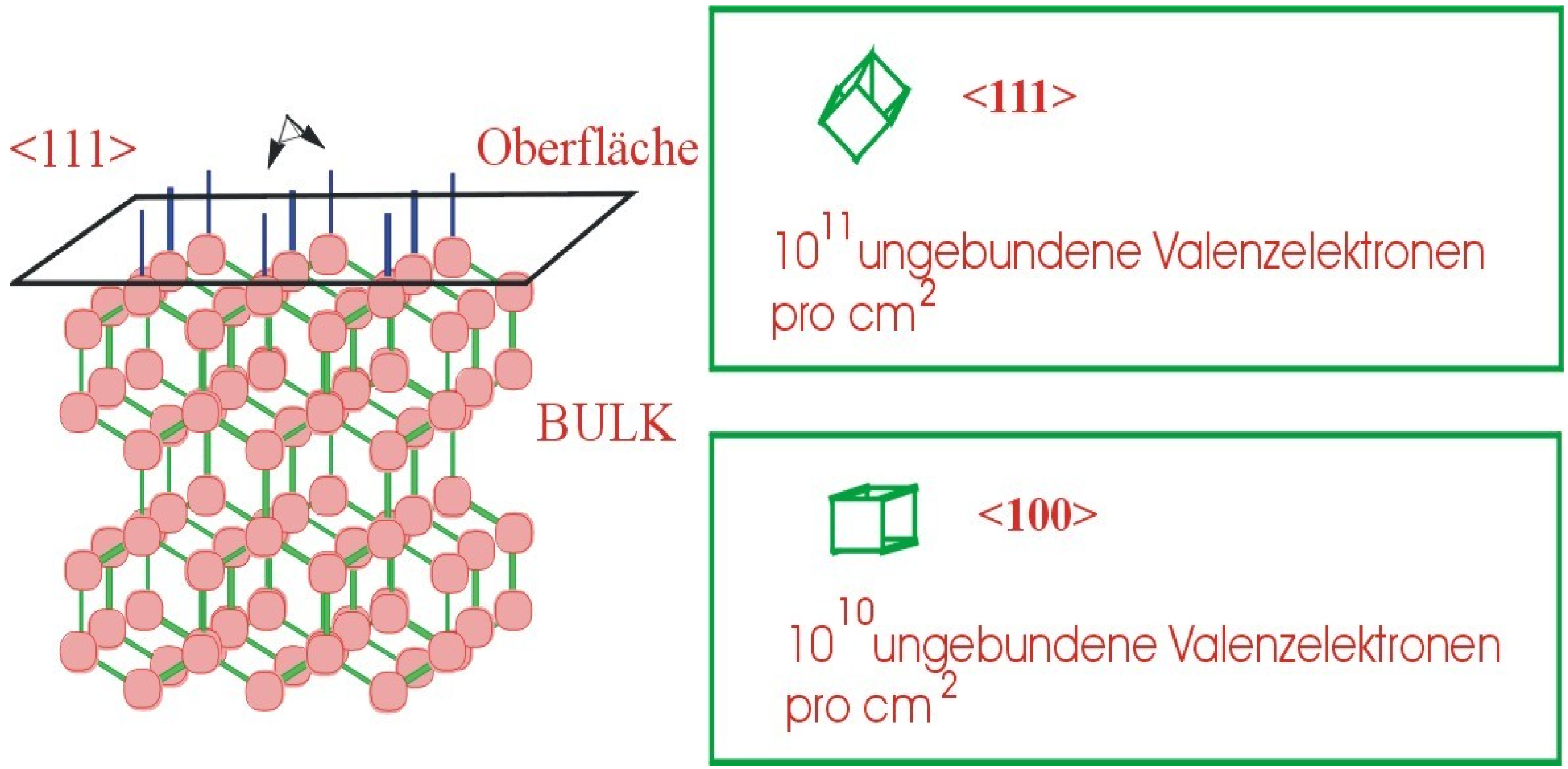


Surface damage

- At the Si-SiO_2 interface we have lattice mismatch
  → dangling bonds
- One technique to avoid/reduce surface damage choose <100> crystal orientation instead of <111>

  → Fewer dangling bonds at the interface

  - About 1 order of magnitude between <111> and <100>



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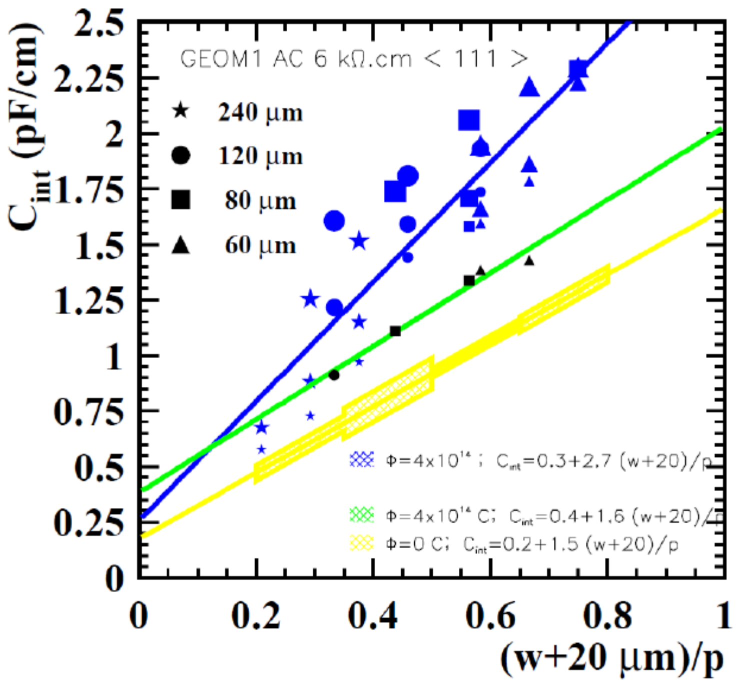
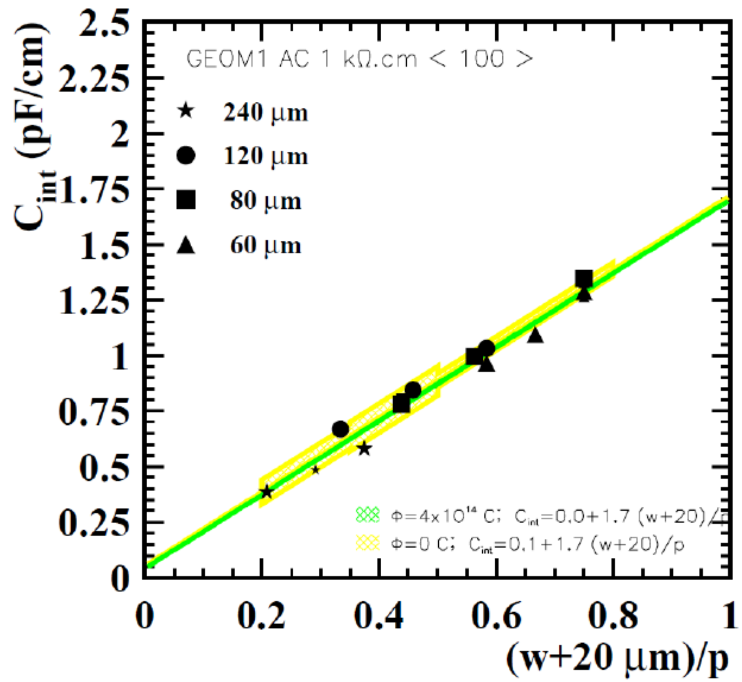
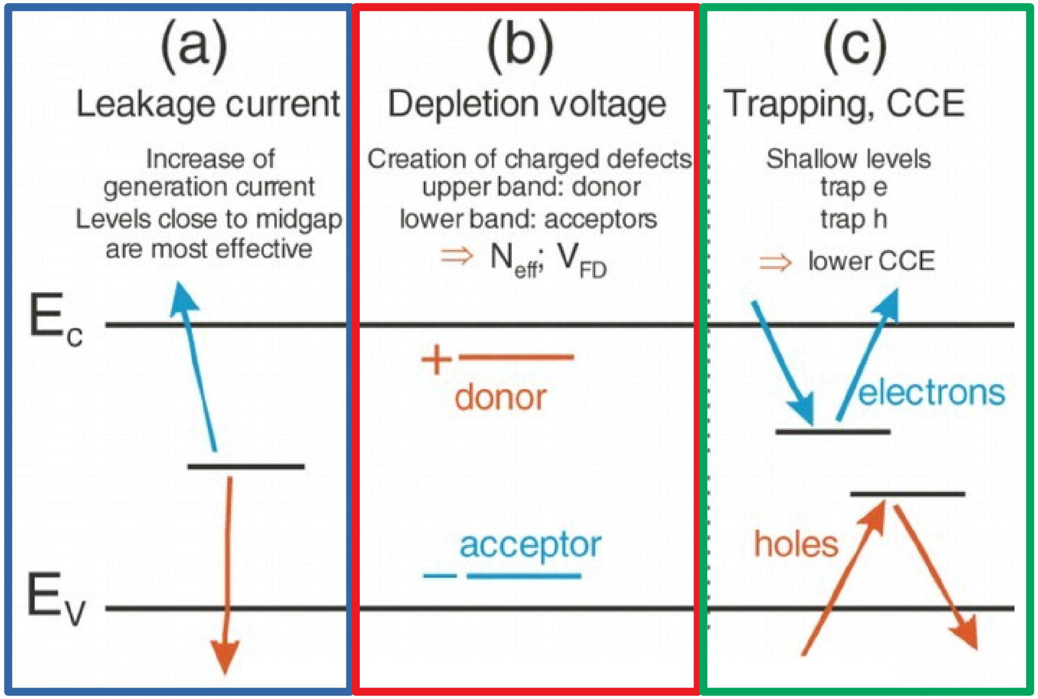
Interstrip capacitance stays constant up to 4x10^{14} particle fluence with <100>





Back to our three main effects on our detectors

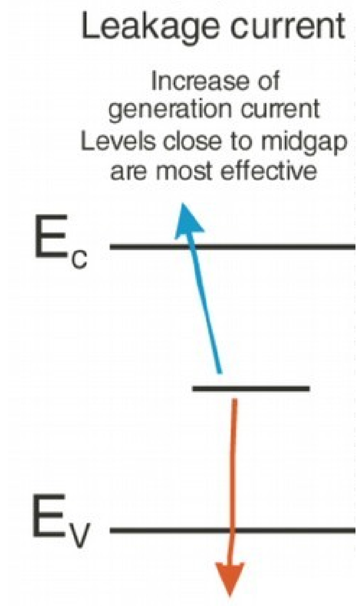
- Three main effects:
  - Increased dark or leakage current
  - Change in depletion voltage
  - Reduced charge collection

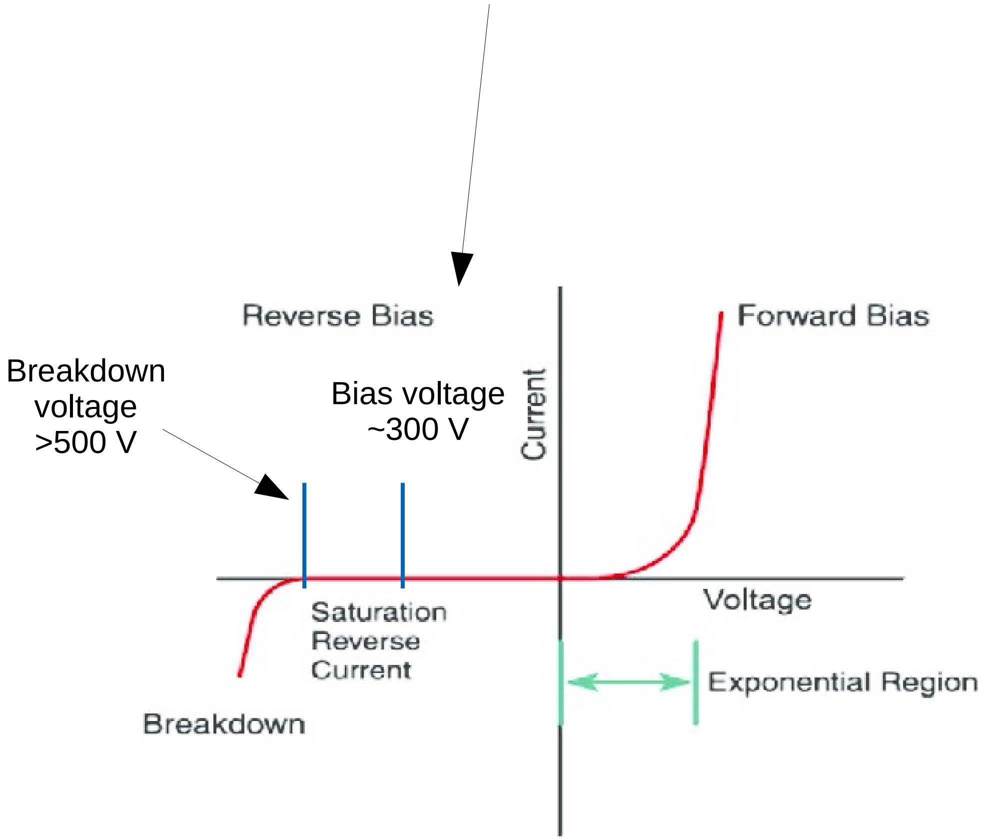


Leakage Current

Radiation effects in silicon detectors in real life

- How does our leakage current “look” like?
- Initially our detector has a dark current of only a few μA





Radiation effects in silicon detectors in real life

- How does our leakage current “look” like?
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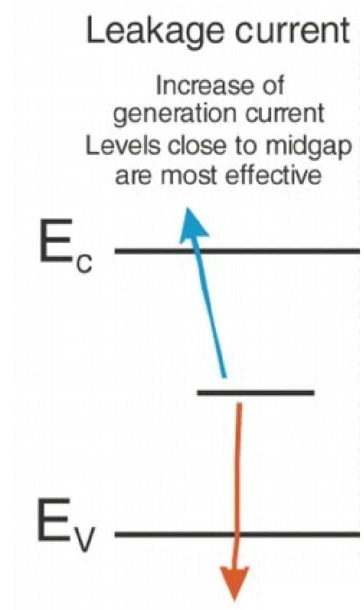
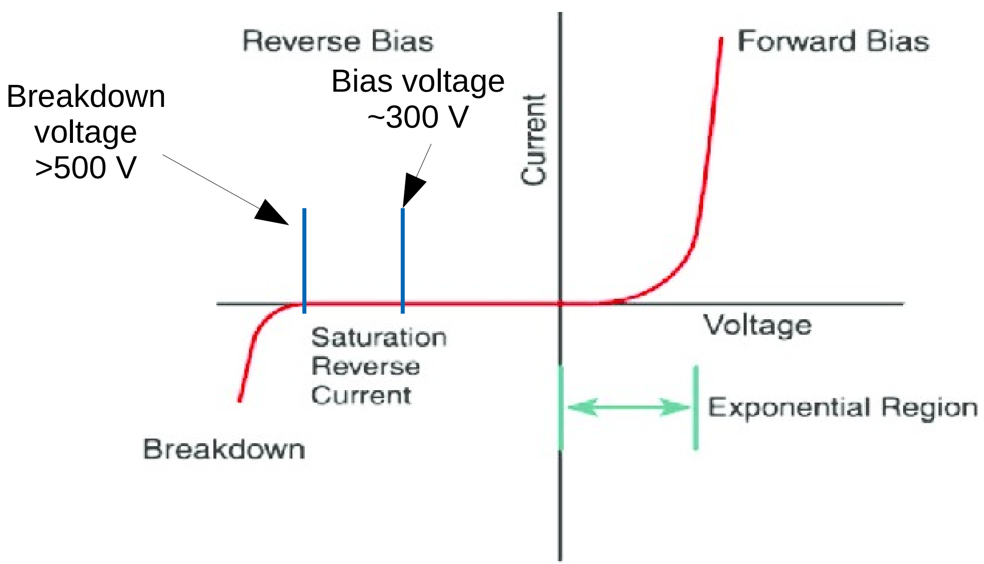
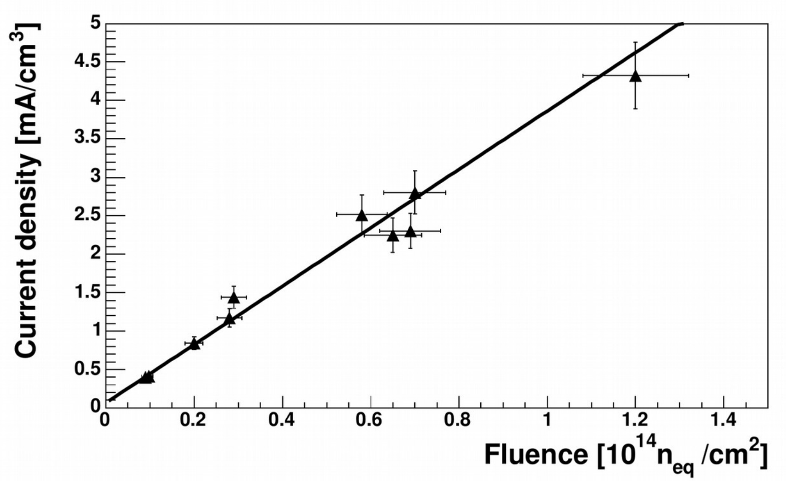
- Leakage current (without annealing) increases linearly with the fluence







JINST 2008 S08004

CMS Strip Tracker Modules and fluences

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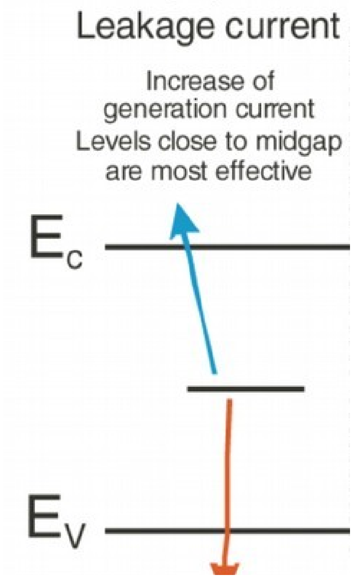
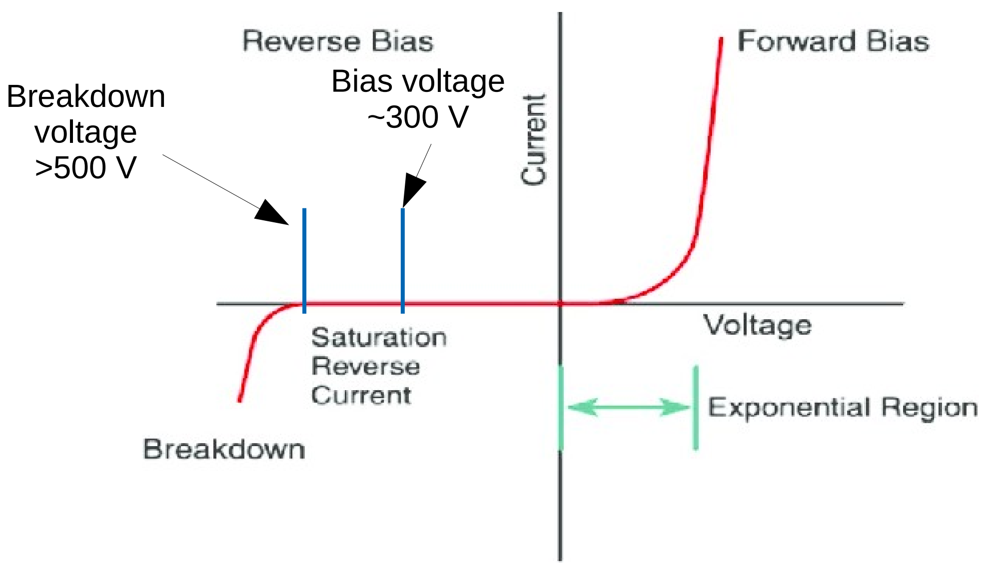
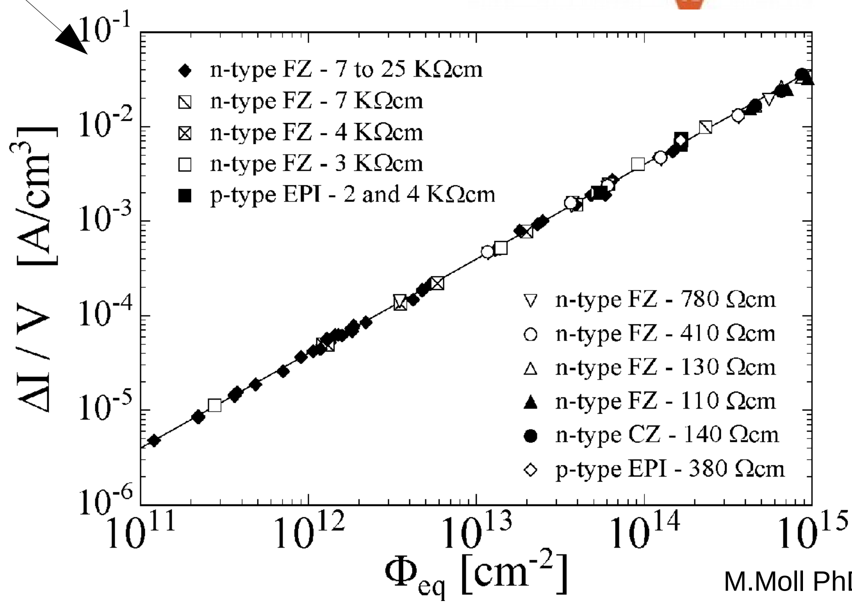






M.Moll PhD thesis

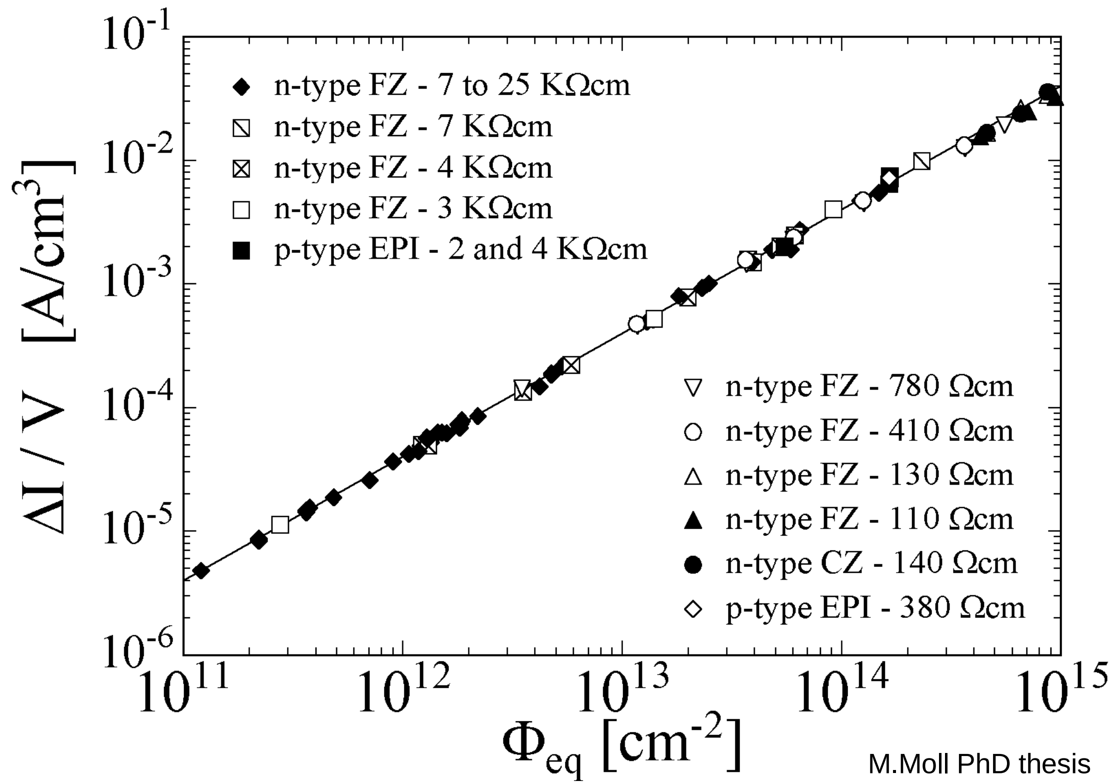
...holds for **many** materials, fluences,.....

Leakage Current

- **current related damage rate** α relates current increase ΔI and fluence

$$\frac{\Delta I}{V} = \alpha \Phi_{eq} \quad \rightarrow \left\{ \begin{array}{lcl} \Phi_{eq} & = & \text{equiv. Fluence} \\ V & = & \text{Sensor volume} \end{array} \right.$$

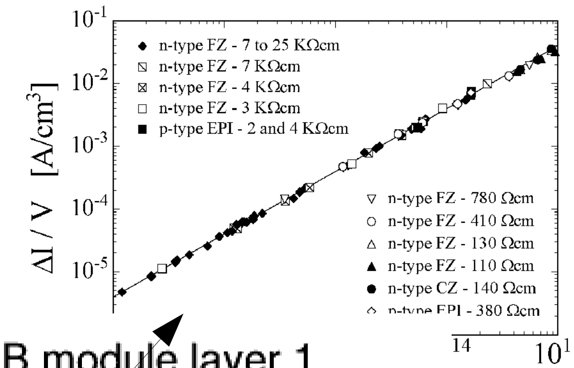
Damage parameter is independent of
- resistivity
- bulk type
- fabrication technology
- ...

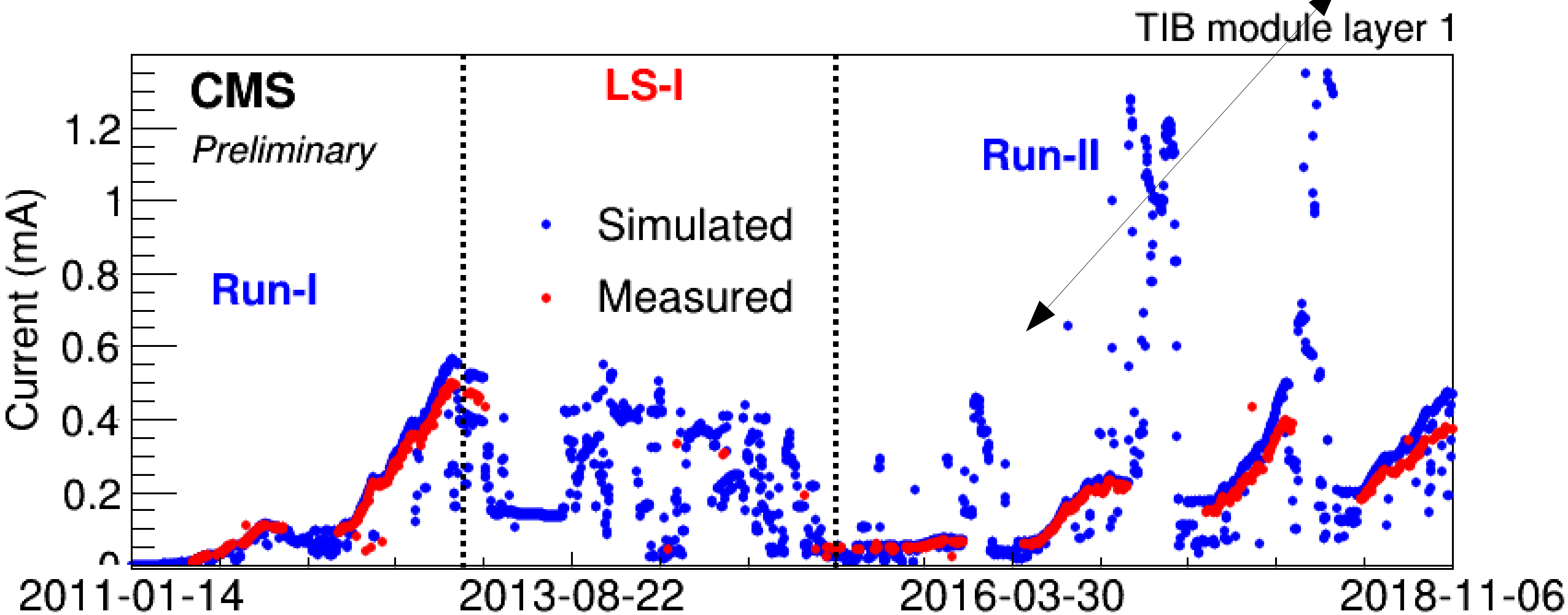


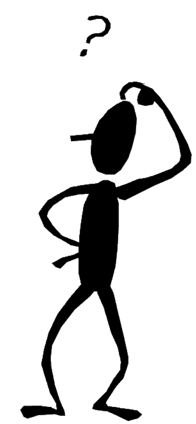
M.Moll PhD thesis

In real life

- One module from the CMS strip tracker at 20 cm from the beam
- 7 years, 200 fb-1

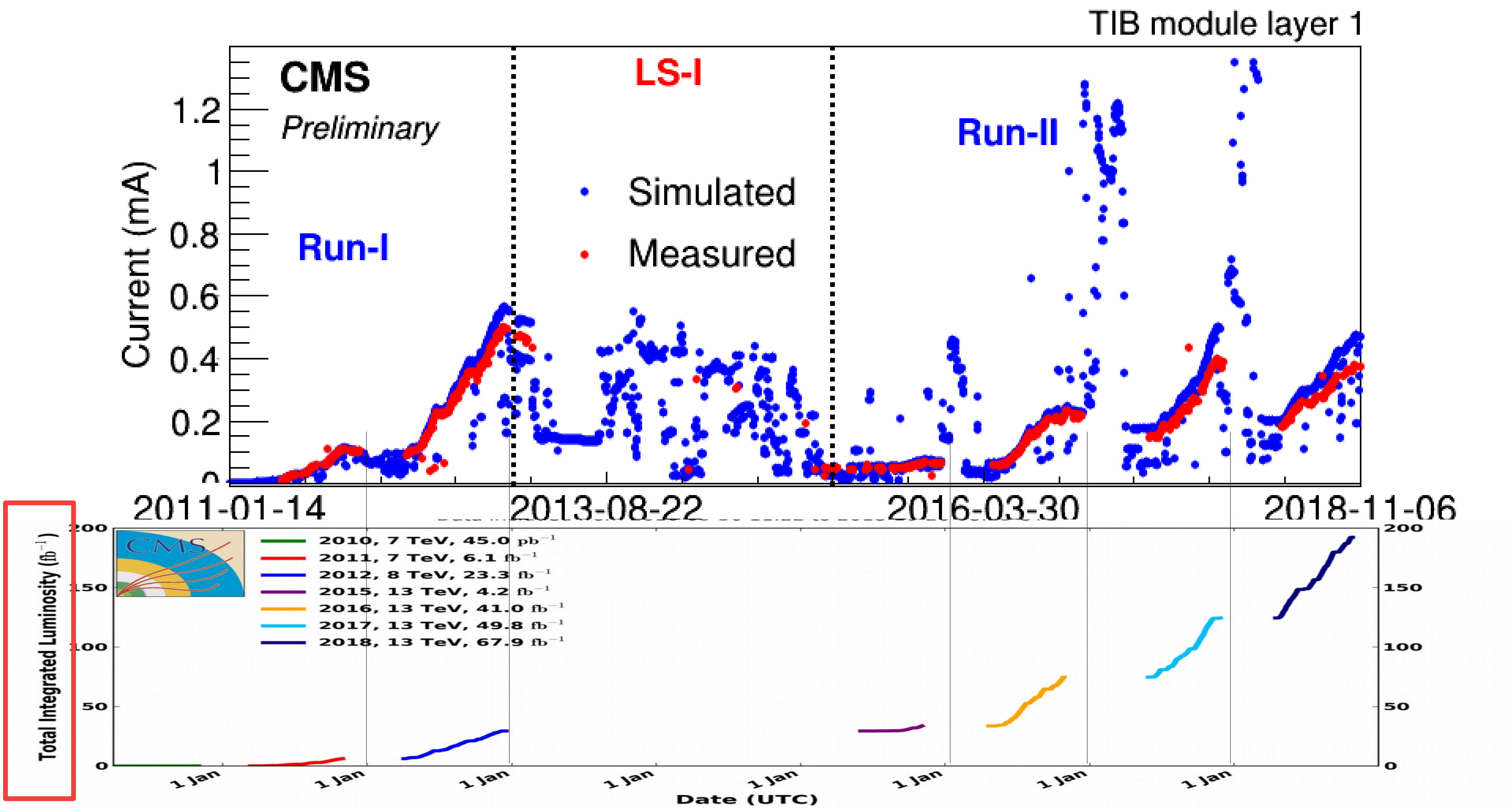






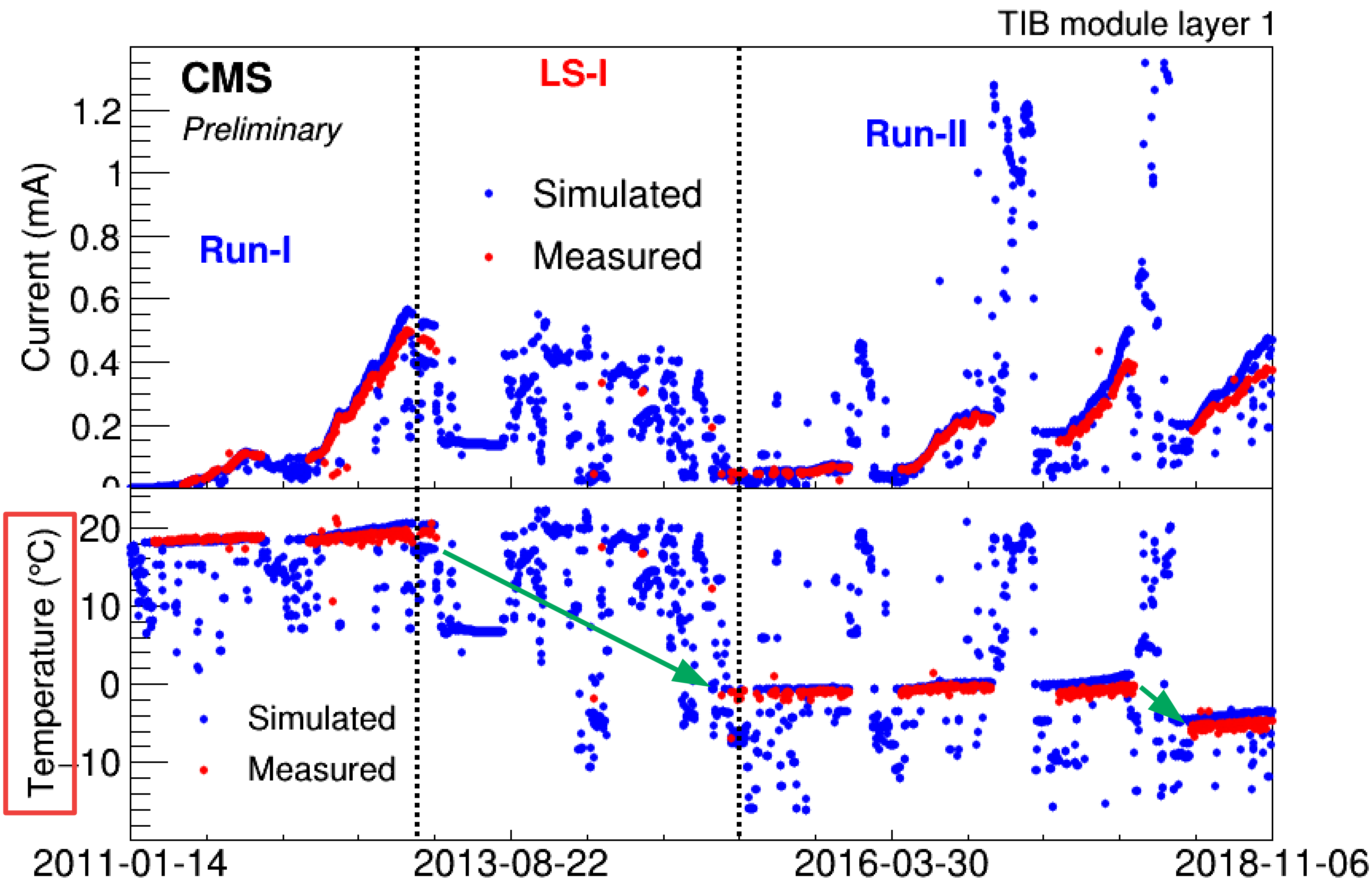
In real life

- Fluence in real life gets accumulated over time
  with interruptions, increasing performance (fluence per time),….



In real life

- Sensor temperature has a strong influence (on several things as we will see)



Leakage current scaling with temperature

- Leakage current scale with temperature

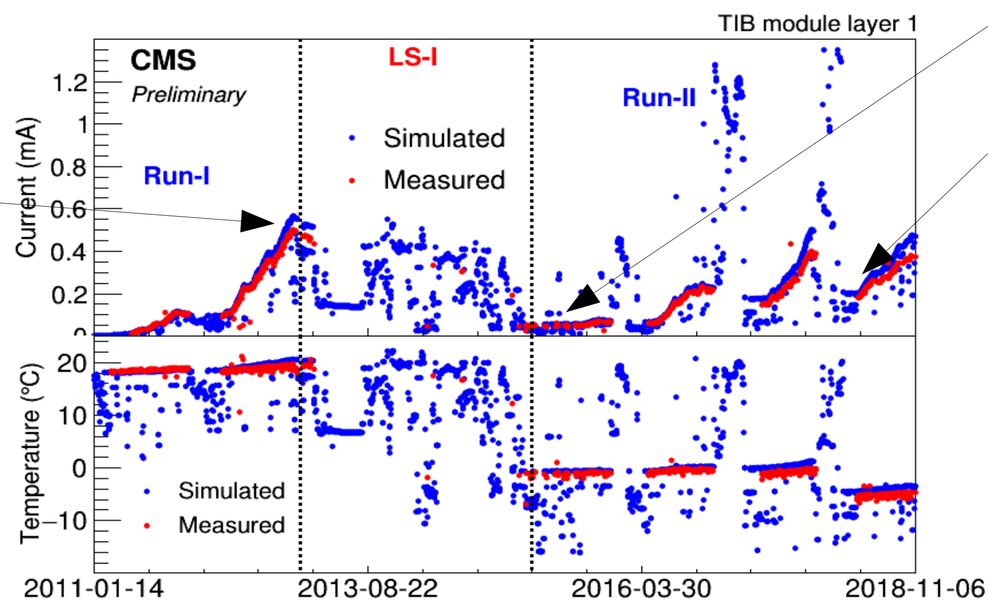
$$I \propto T^2 \exp\left[\frac{-E_{g,\mathrm{eff}}}{2k_B T}\right]$$

- Factor of 2 reduction for every ~7°C of temperature
  → running our detectors cold is good
  → less power on sensor (V_{bias} x I_{leak})
  → less cooling power required to get rid of it!

Sensor at ~15°C

Sensor at ~0°C

Sensor at ~-5°C

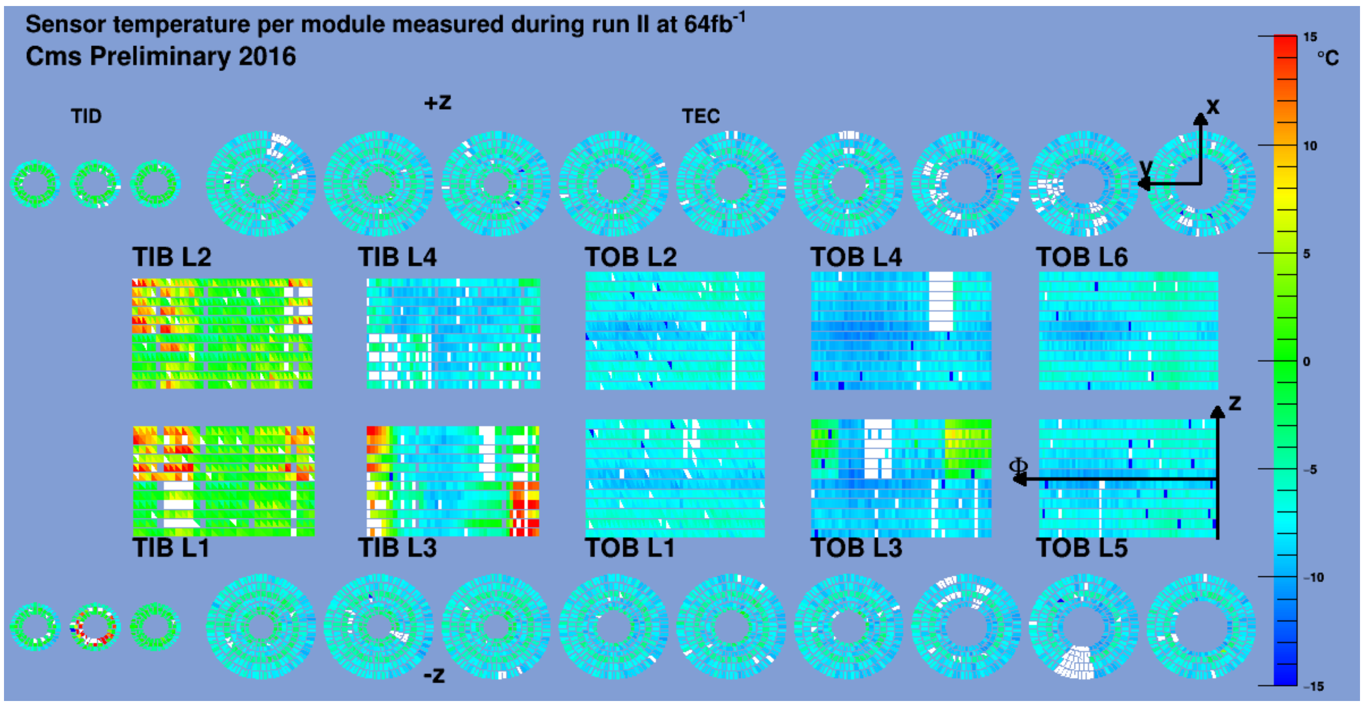


15°C → 0°C
→ reduction by factor ~4

0°C → -5°C
→ reduction by another factor of ~2

Other uses of temperature scaling

- In case temperature is not uniform in your detector you can scale everything to a common reference temperature
  - Better to compare different parts of your detector
  - Easier to compare to other detectors (e.g. around LHC)



+15°C

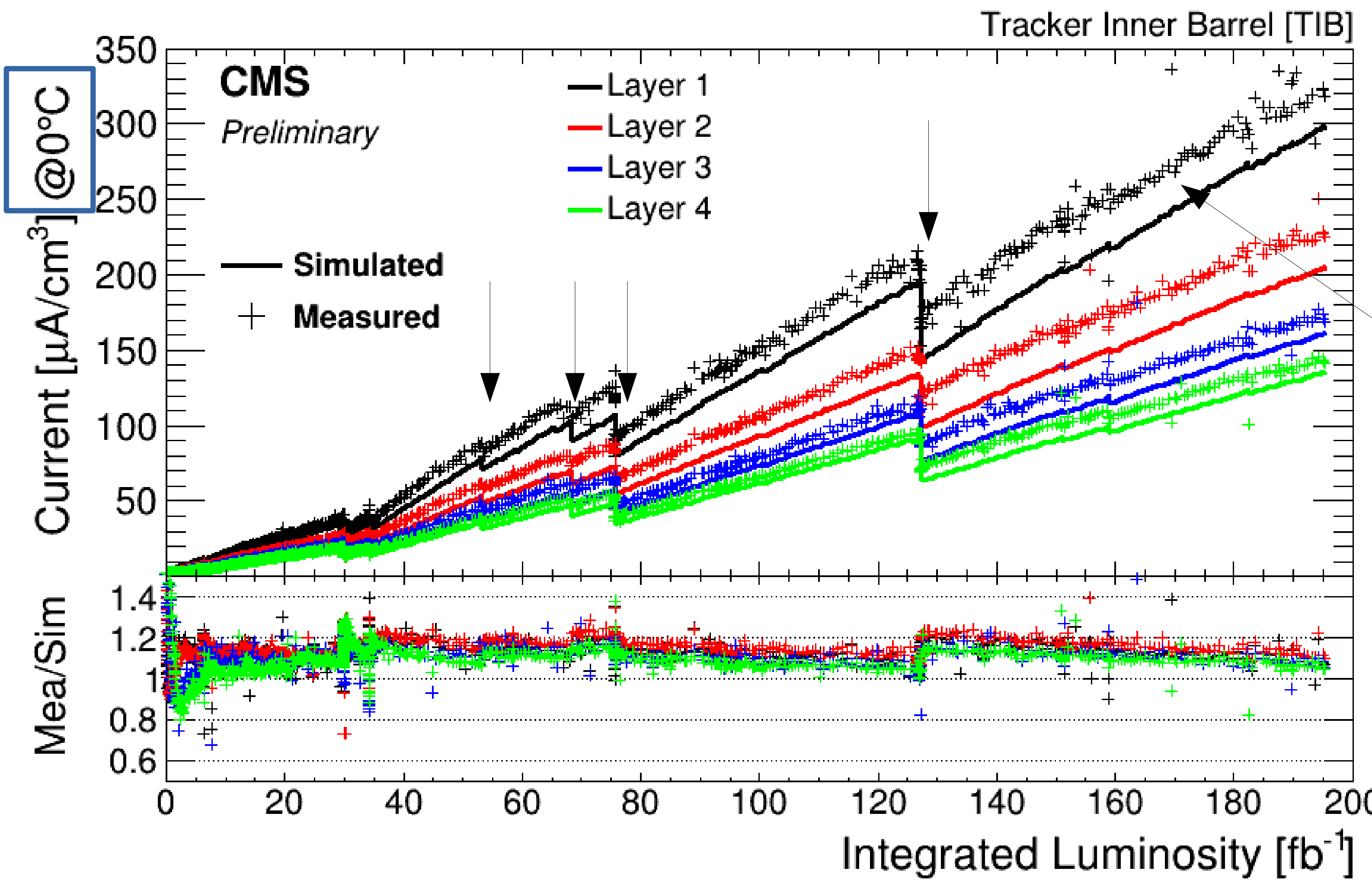
ΔT = 25°C!!

-10°C

CMS Silicon Strip Tracker: some regions have degraded cooling → high temperatures

Scaling everything to a common reference

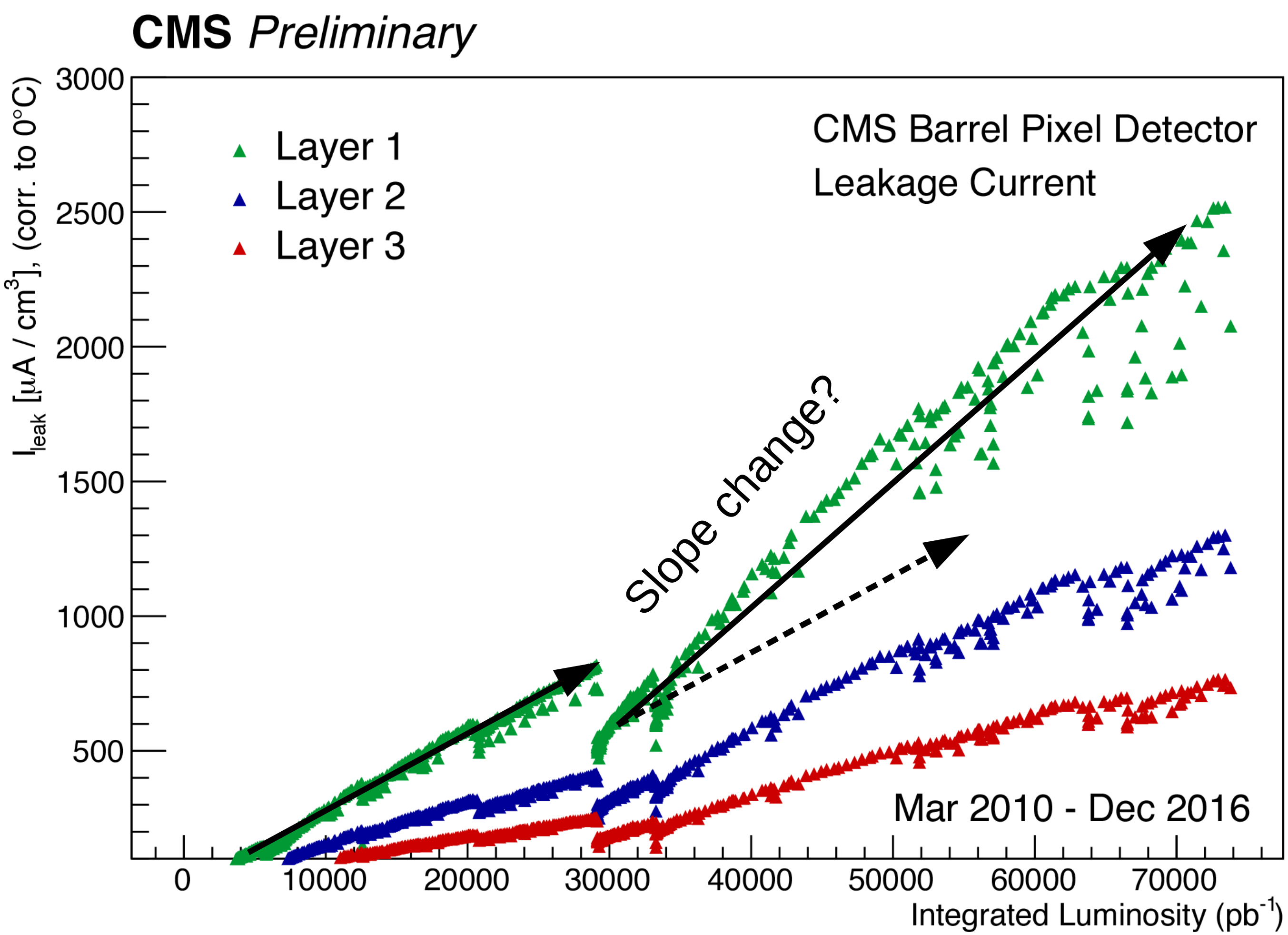
- Still bumps in the distribution (will see about those in a second)
- But scaling with luminosity and temperature works



Slope is our α parameter

Example: CMS Pixel detector

- Leakage current in the CMS Pixel detector
- Scaling works, but our slope (and hence α) changes??



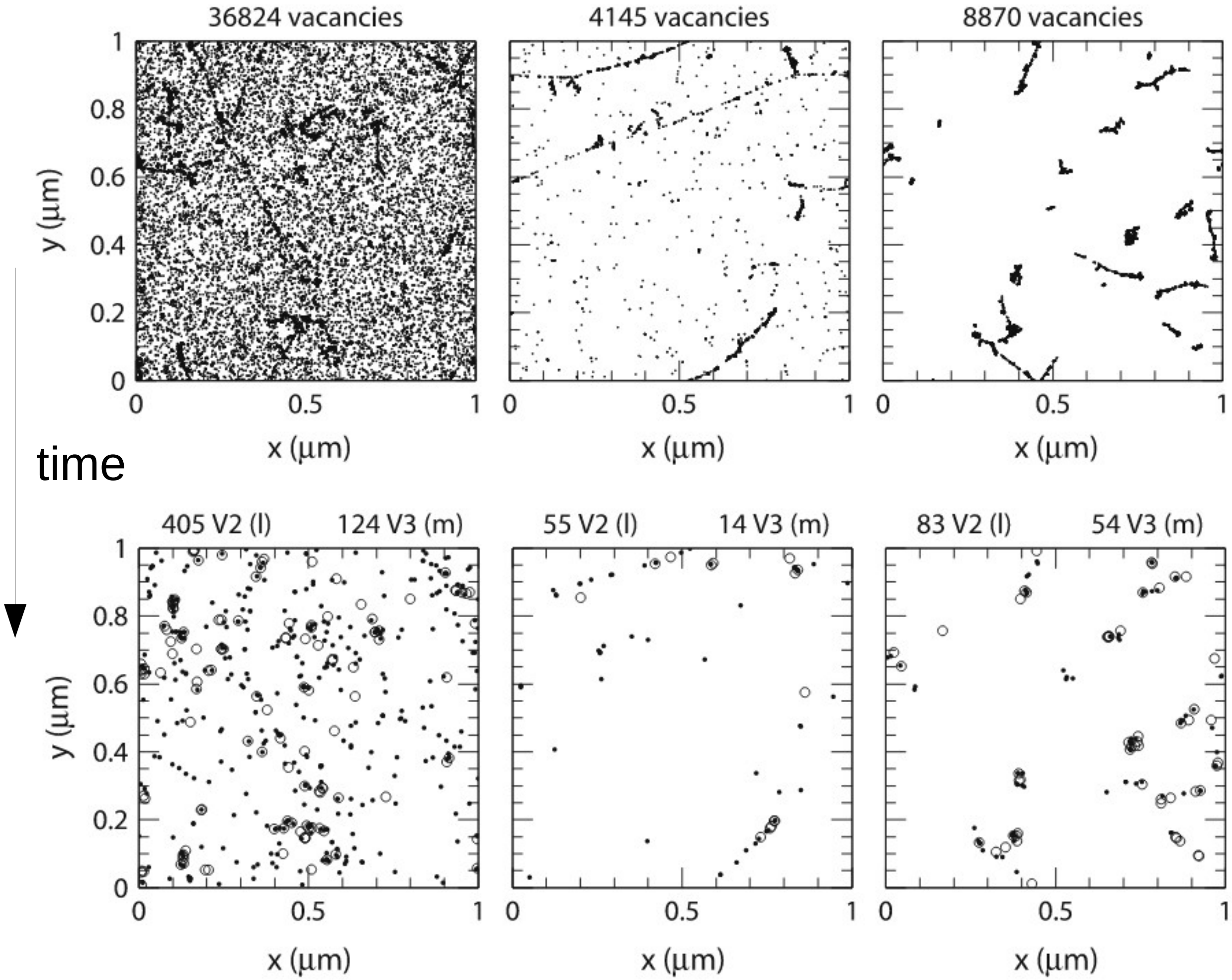
Diffusion of Defects

- Defects can migrate, break-up, reconfigure given time and (sufficiently high) temperature

- Mostly summarized as “annealing”

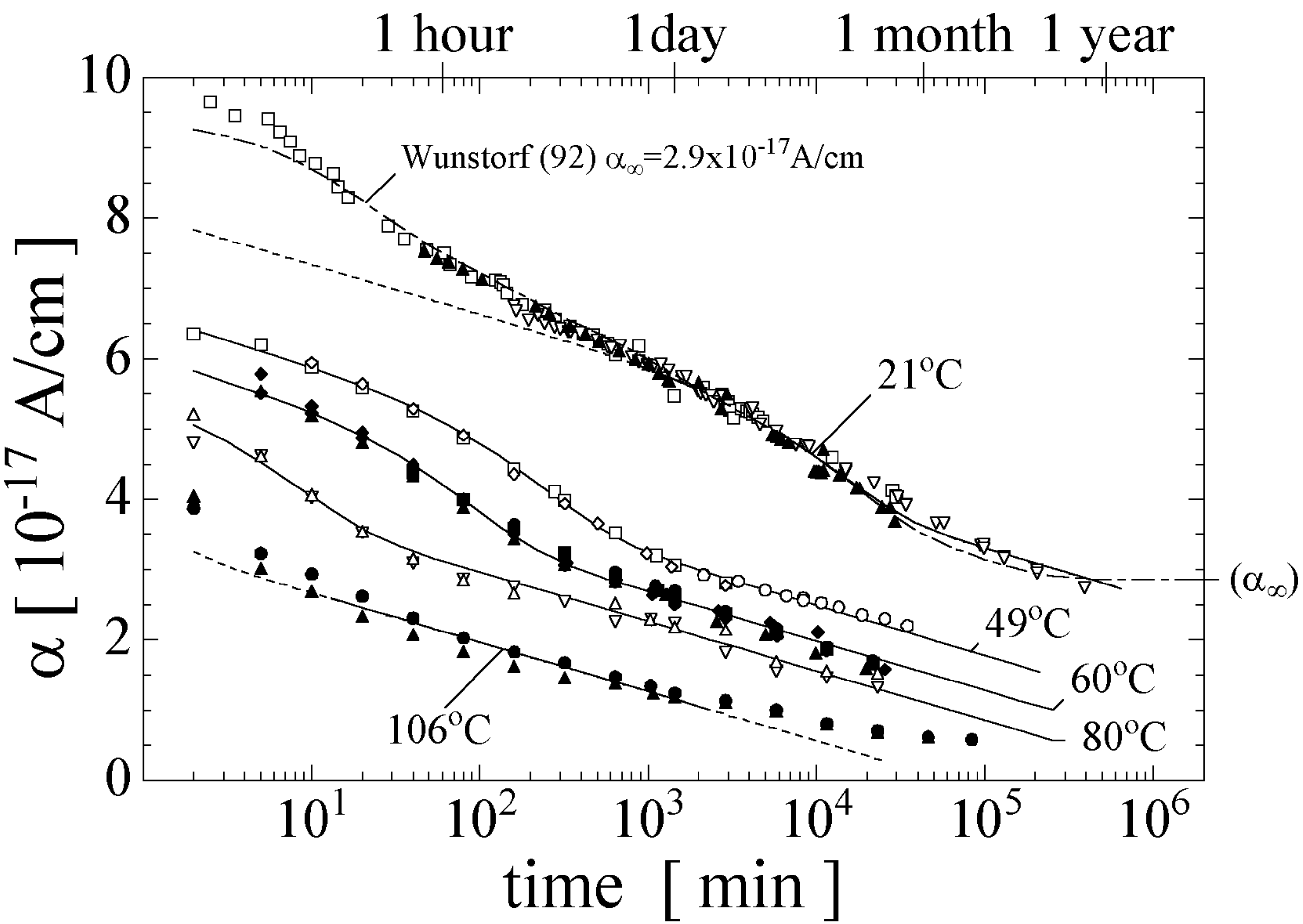
- Annealing can “heal” part of our radiation damage

We will see later that there is more than one type of annealing and we don’t like all of them...



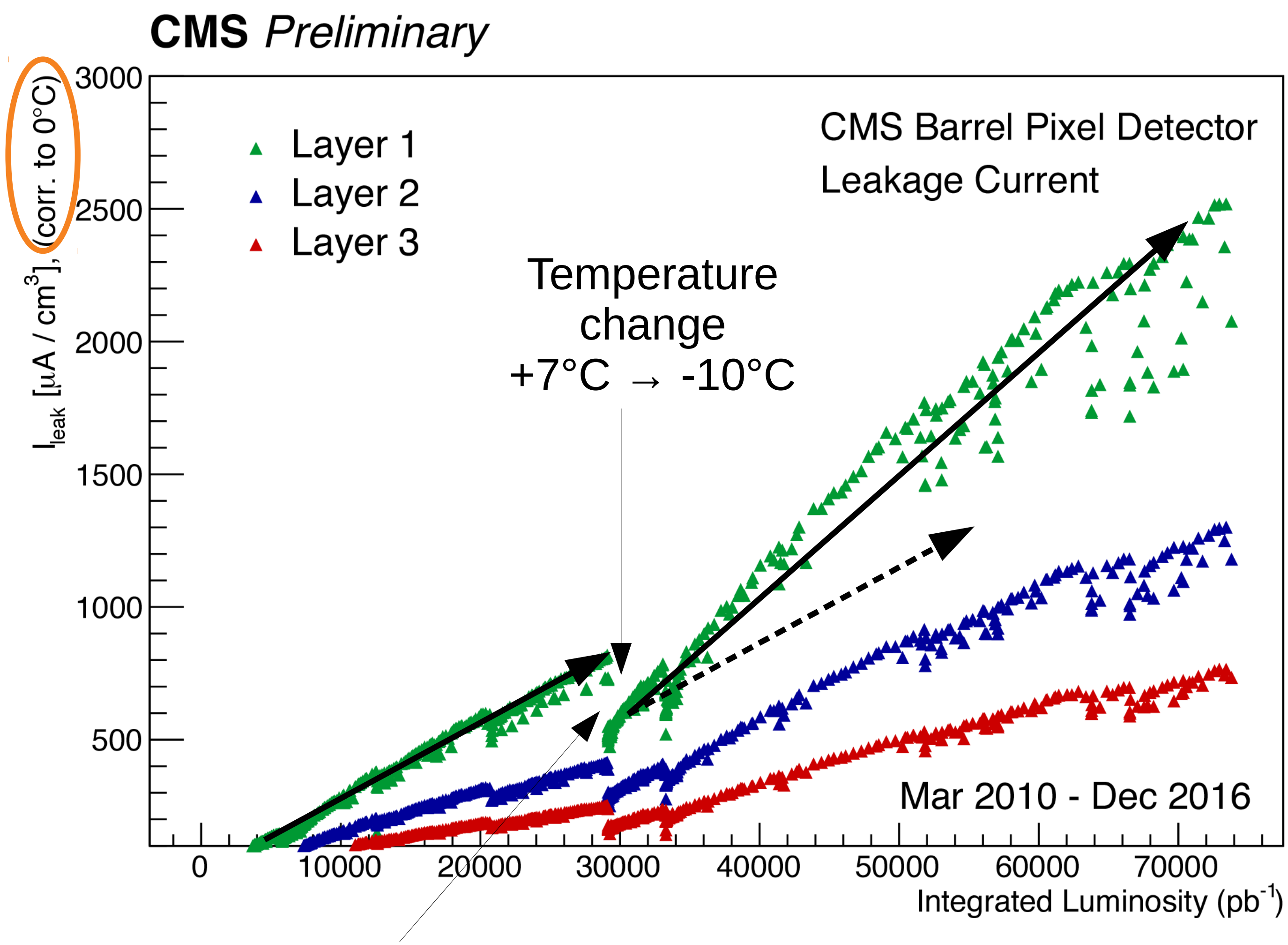
Annealing of leakage current

- Leakage current only anneals beneficially
  → leakage current goes down the longer we anneal
- Anneal **also** happens while we operate/irradiate if the temperature is high enough



Example: CMS Pixel detector

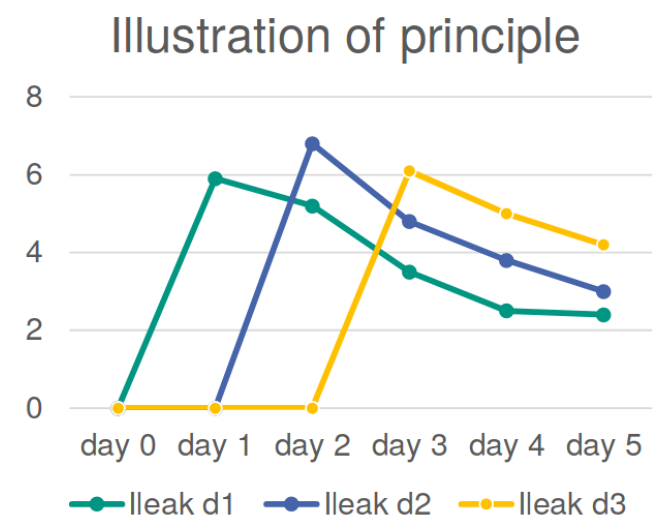
- At lower temperature we have *less* annealing while running
  → increase of leakage current per fluence is *higher*



Note: the step downwards is annealing, not the temperature change, this plot is already scaled for temperature

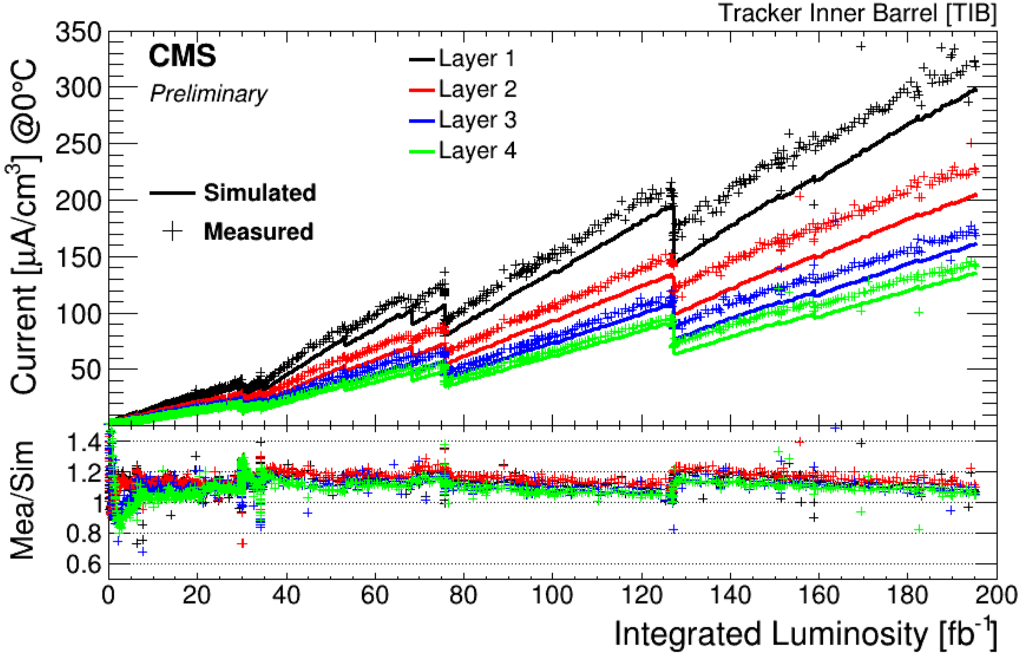
How to model the leakage current evolution?

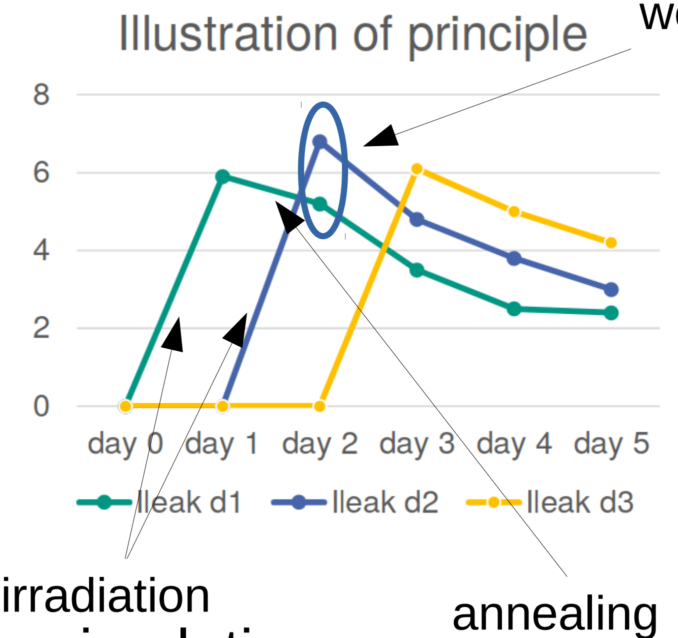
- Ingredients needed
  - What is the temperature of our sensor?
  - How much fluence does it get?
  - How well is it cooled?
- Then for each day (or several days) we take the irradiation and calculate the increase in leakage current
- For the next day we do the same taking into account how much the damage from the last day annealed
- This is needed for a running experiment where you acquire doses over long periods of time
  - In irradiation campaigns you get the full dose in very(!) short time (hours or days)
    → otherwise these campaigns would never finish



How to model the leakage current evolution?

- What we measure in our detector is the combination of irradiation and annealing (an effective α)

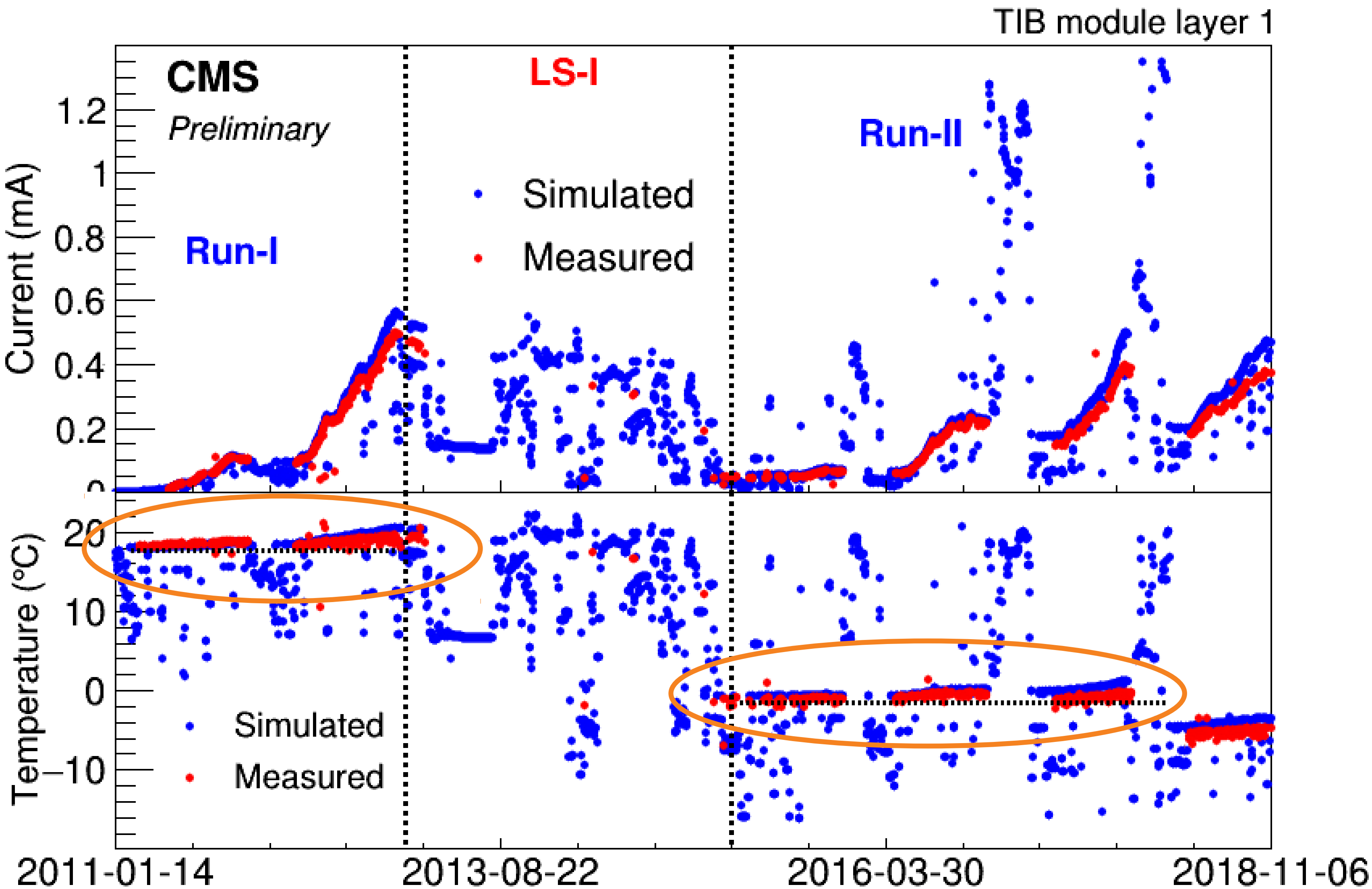




- Need to take both into account when simulating
- In addition: need to account for self-heating
- Main uncertainties:
  - Sensor temperature, Particle fluence

Self heating in real life

- Self heating visible as slight increase in temperature as irradiation increases



Self-heating and Thermal Runaway

- If our cooling is insufficient, the increased leakage current heats our sensor which increases the current…
- Worst case: thermal runaway

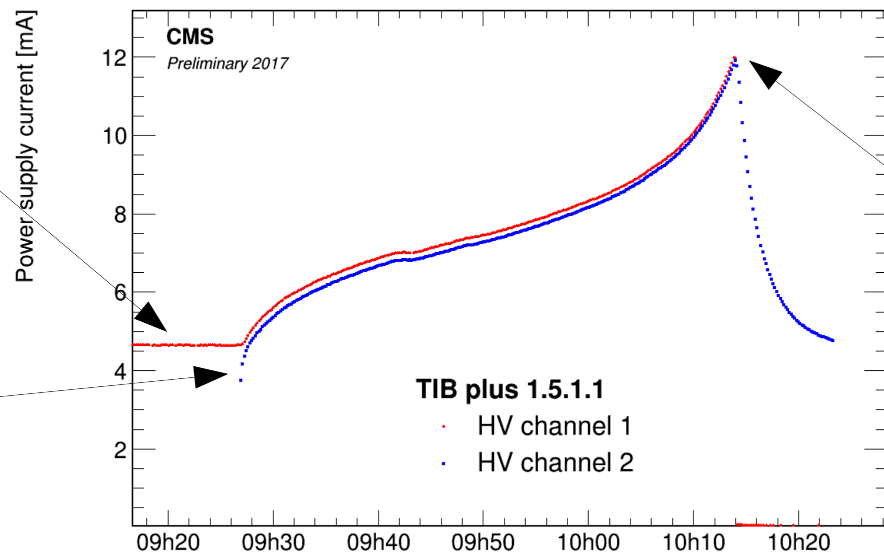
$$I \propto T^2 \exp\left[\frac{-E_{g,\mathrm{eff}}}{2k_B T}\right]$$

Modules connected to HV channel 1 | Modules connected to HV channel 1 | Modules connected to HV channel 1

Modules connected to HV channel 2 | Modules connected to HV channel 2 | Modules connected to HV channel 2

''upper'' modules off

both sets of modules on



Closely spaced modules heat each other

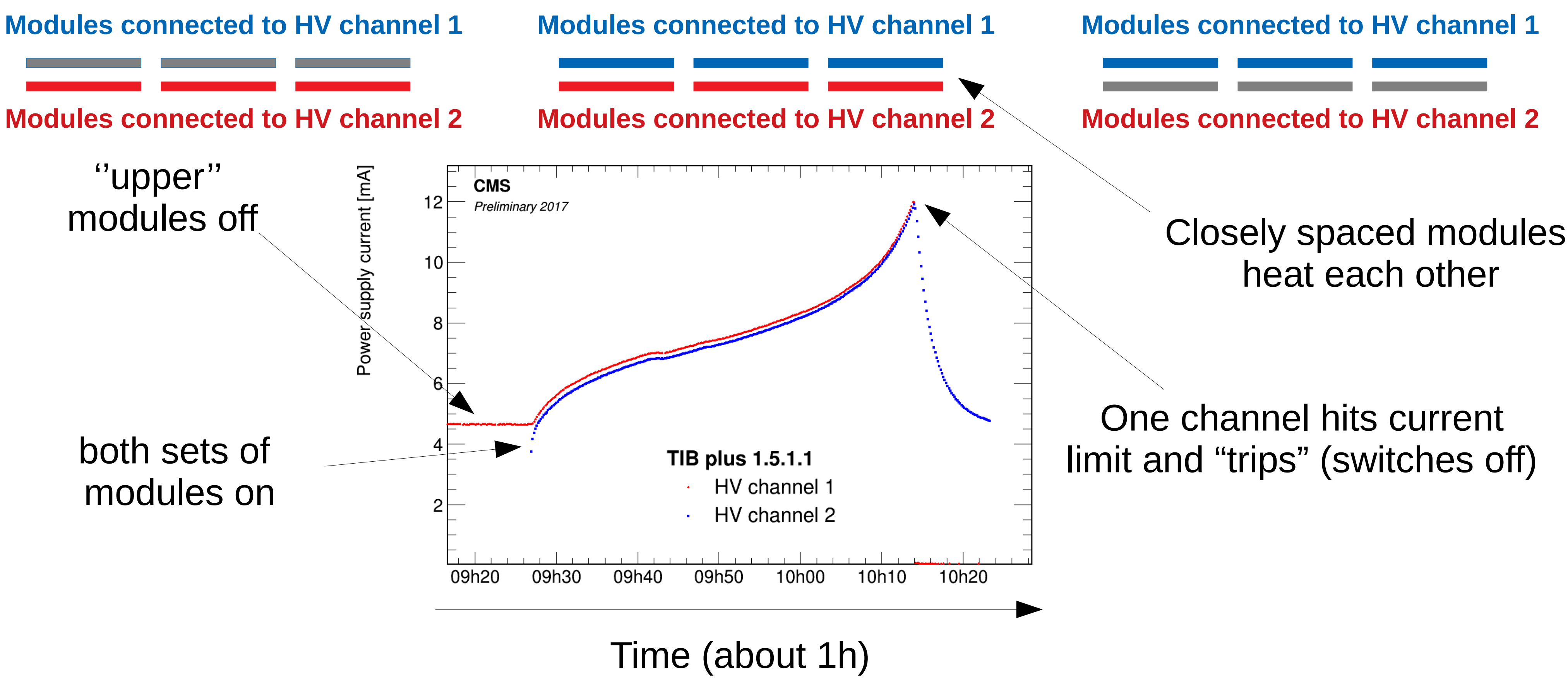
One channel hits current limit and "trips" (switches off)

Time (about 1h)

Self-heating and Thermal Runaway

- What to do against thermal runaway
  - Lower coolant temperature (if we can)
  - Lower bias voltage (if we can)
  - Switch off part of our detector (which we want to avoid)

$$I \propto T^2 \exp\left[\frac{-E_{g,\mathrm{eff}}}{2k_B T}\right]$$



Summarizing considerations on leakage current

- Leakage current scales with temperature

  → running at low temperature is good
- Leakage current anneals at high temperature

  → staying warm is good

- Other considerations:
  - Our power system is limited (we cannot provide arbitrary power to sensors)
  - Out cooling system is limited
    - Self-heating is an amplifying effect which gets worse at high current (recall: doubling every ~7°C)
    - Worst case: thermal runaway
  - Leakage current contributes to noise

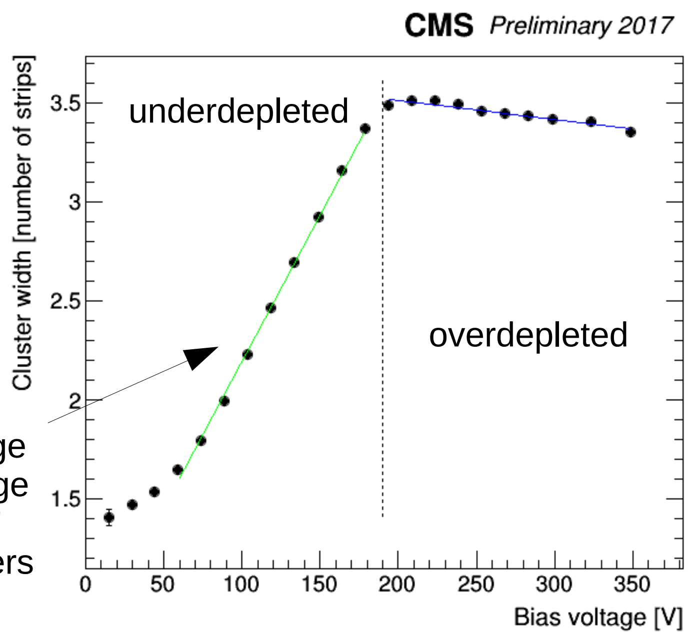
    → higher leakage current means lower S/N

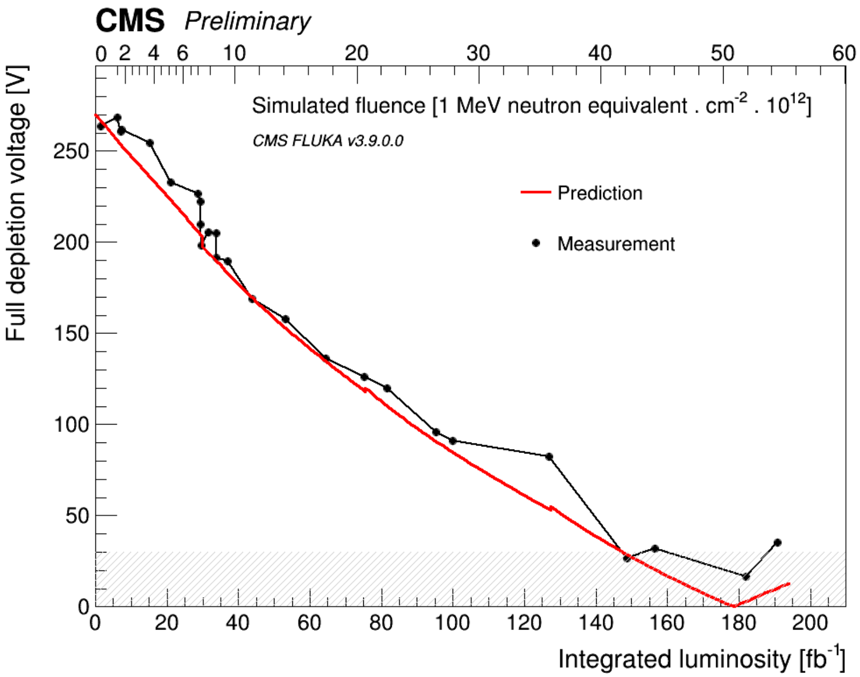
Depletion Voltage

How to measure full depletion voltage?

- In the lab:
  - Measure IV or CV curve of the sensor
  - Not possible after it has been installed
- For a detector in operation: Bias scan
  - vary bias voltage during a physics fill from very low to (very) high voltages
  - check evolution of quantities

Fraction of charge is lost, low charge strips get “cut” → smaller clusters

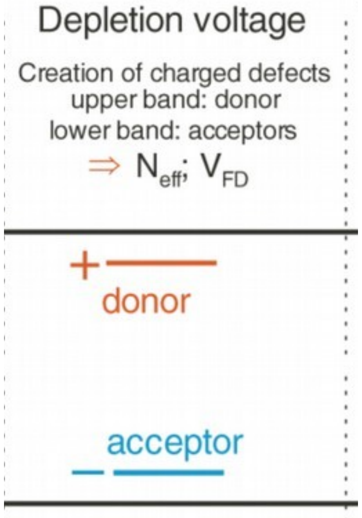




Evolution of depletion voltage

- Effective doping concentration of our n-type bulk material changes with irradiation
- Donors get removed, acceptor levels get created

→ N_{eff} changes and eventually we have space charge sign inversion (SCSI) for n-type bulk

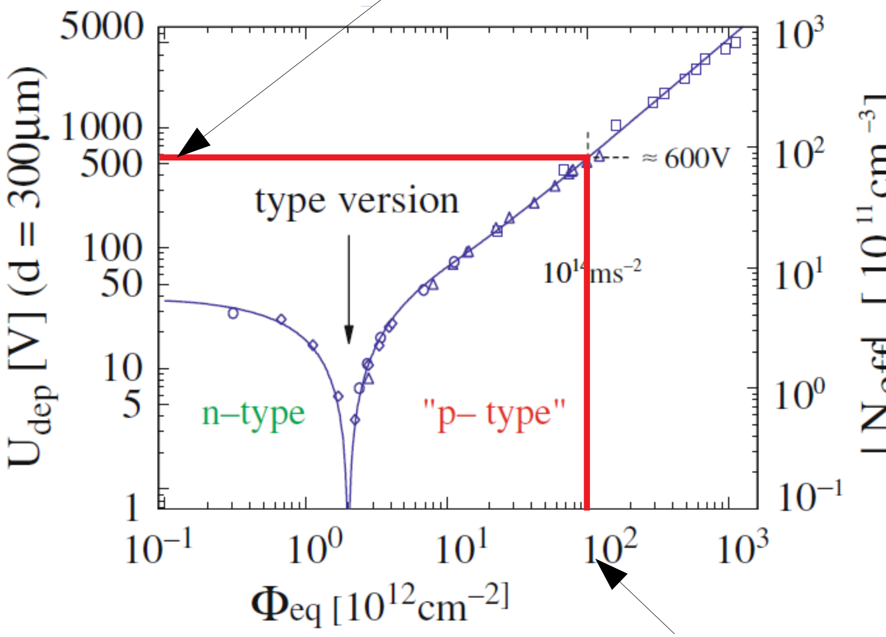


$$N_{\text{eff}} = |N_D - N_A|$$

$$U_{\text{FD}} = \frac{e}{2\epsilon_r} |N_D - N_A| D^2$$

At LHC ~everything has n-type bulk, so follows ~this behavior

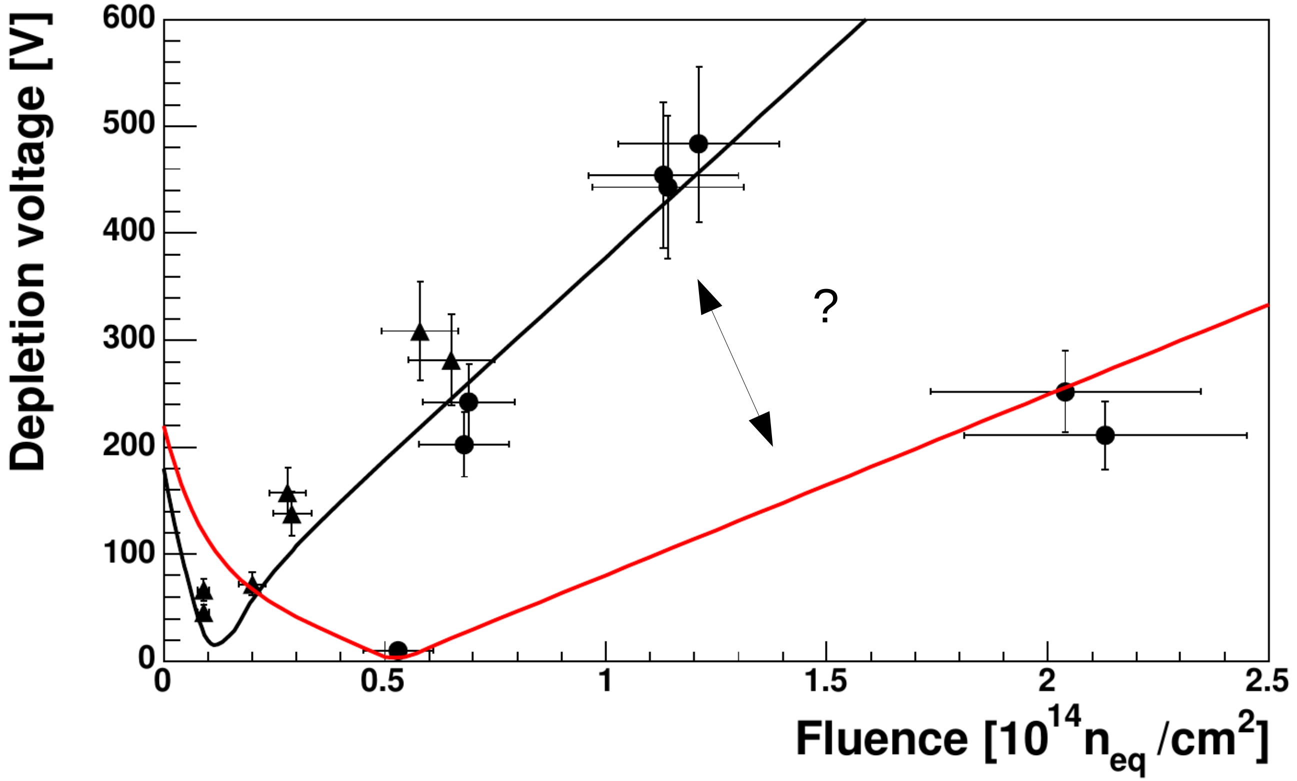
Max bias voltage ~600 V



Fluence of 10^{14}

Evolution in real life (but with results from before installation)

- Two groups of sensors that start at ~same V_{dep} but evolve differently
  - Why?



Evolution in real life
(but with results from before installation)

- Two groups of sensors that start at ~same V_{dep} but evolve differently
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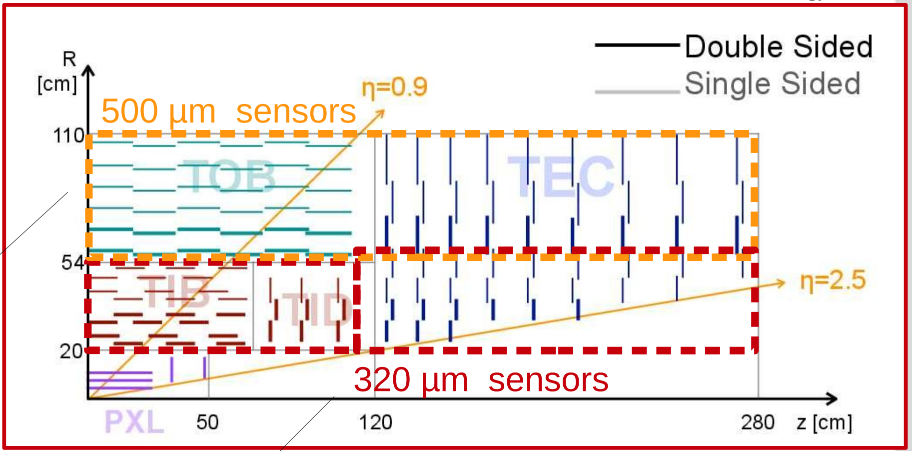
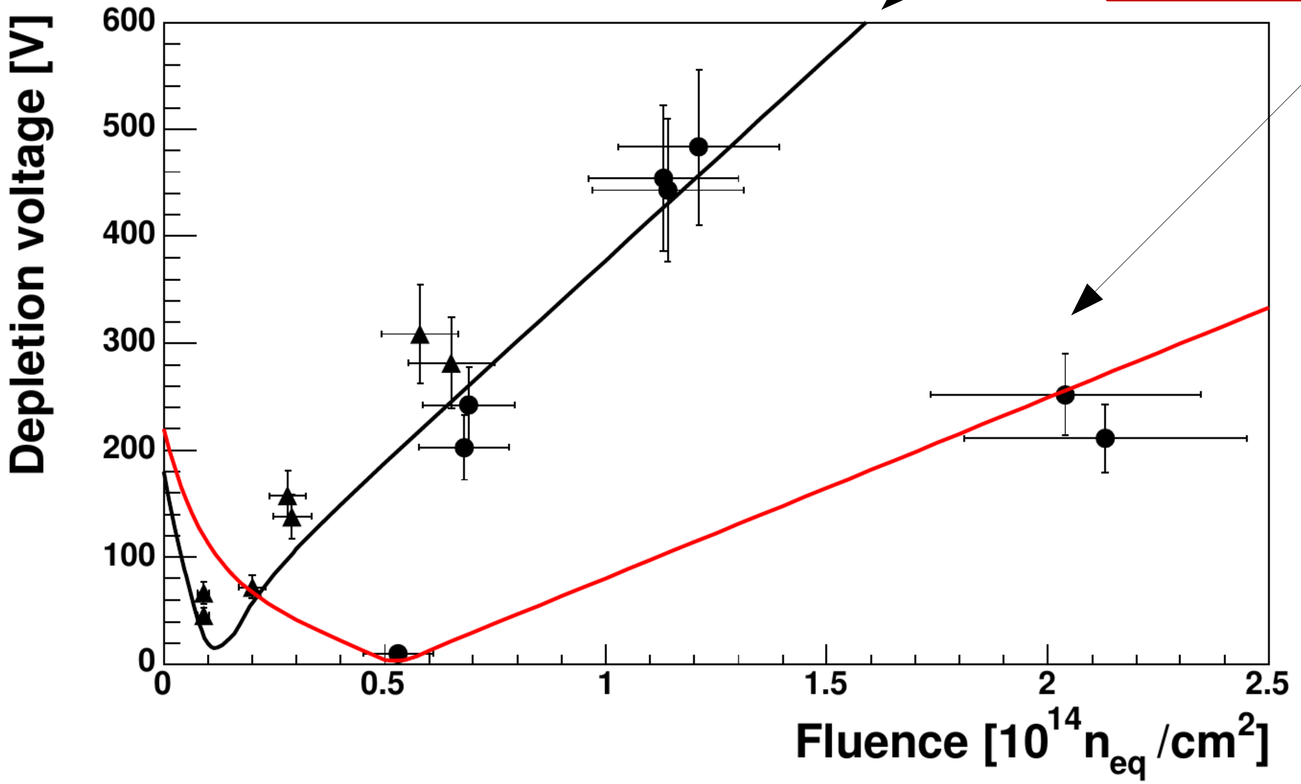




$$V_{\mathrm{FD}} \propto \frac{D^2}{\rho}$$

Initial ρ:

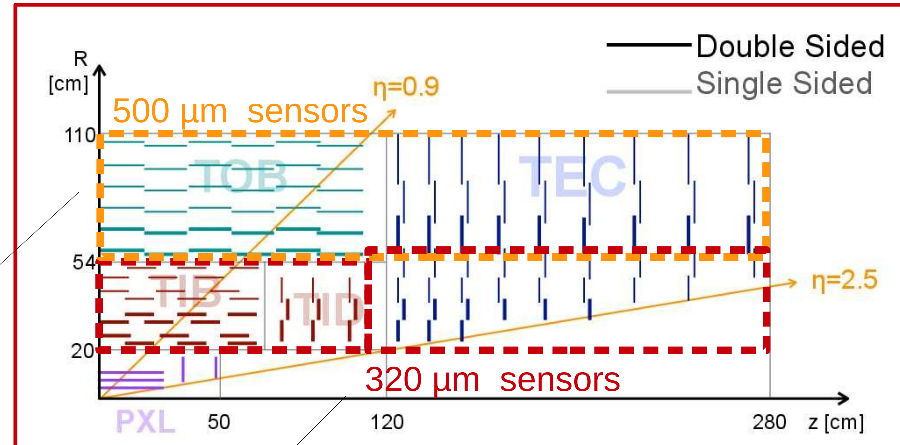
1.5 – 3.2 kΩcm (320 µm)

4 – 8 kΩcm (500 µm)

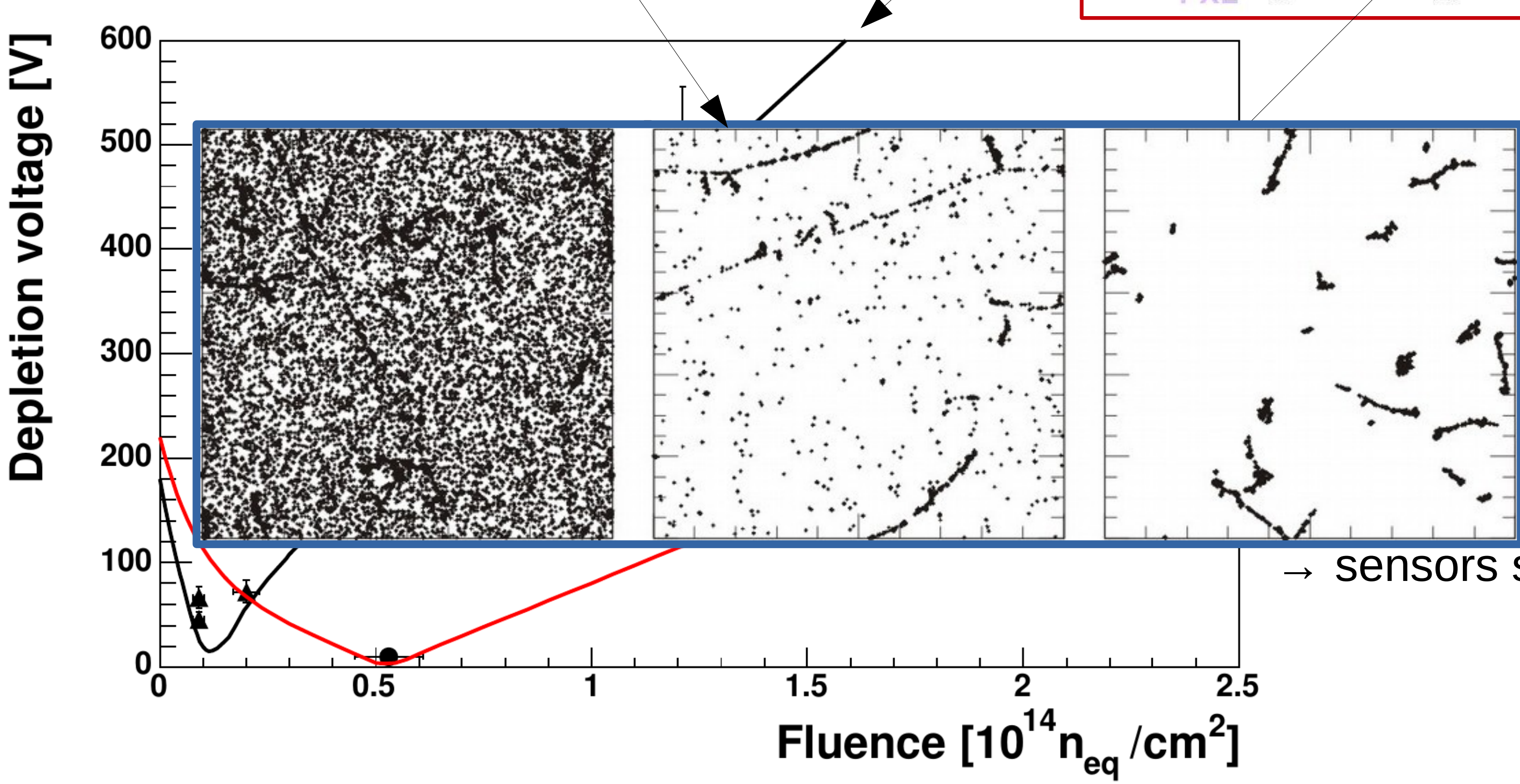
→ sensors start with similar V_{FD}

Evolution in real life
(but with results from before installation)

- Two groups of sensors that start at ~same V_{dep} but evolve differently
  - Why?



Each mm³ of your material changes like this
→ thick sensors change their *total* N_{eff} quicker



$\frac{D^2}{\rho}$

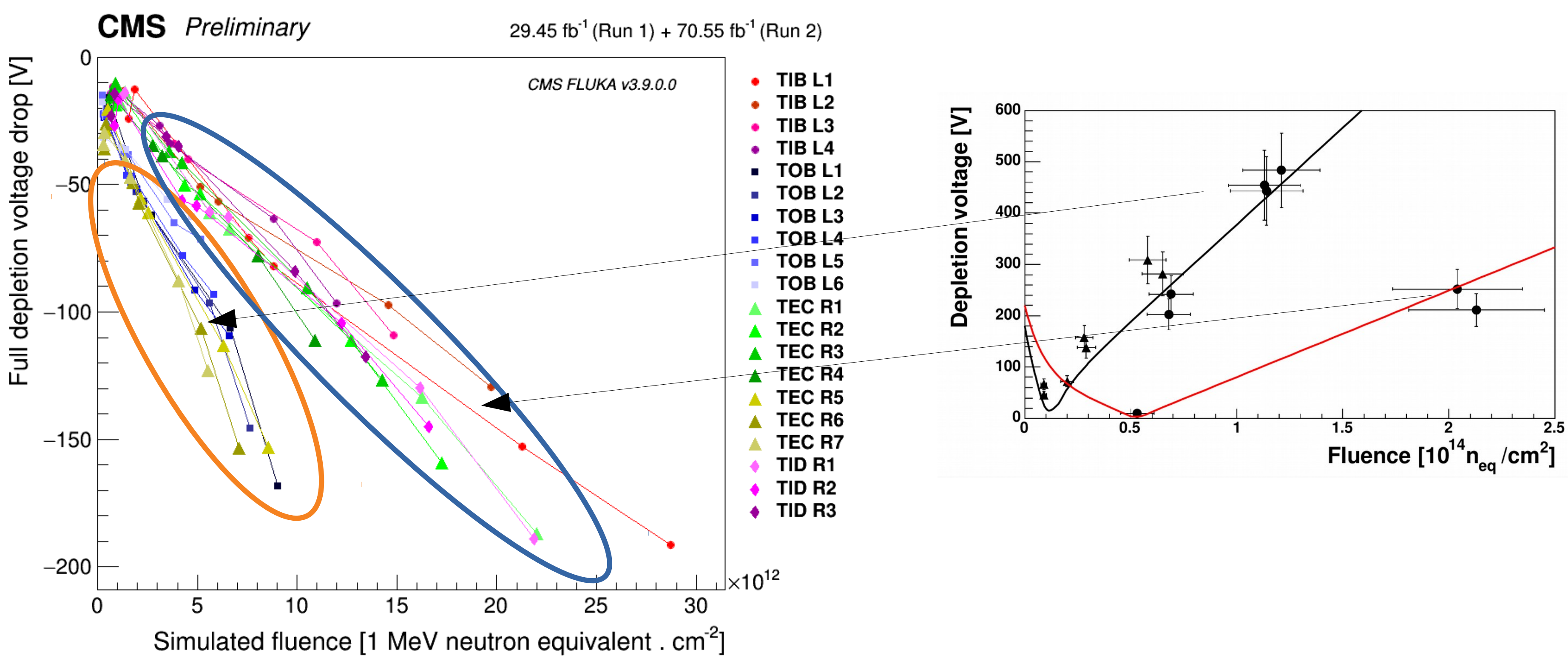
2 kΩcm (320 μm)
Ωcm (500 μm)

→ sensors start with similar V_{FD}

Different sensors and different locations

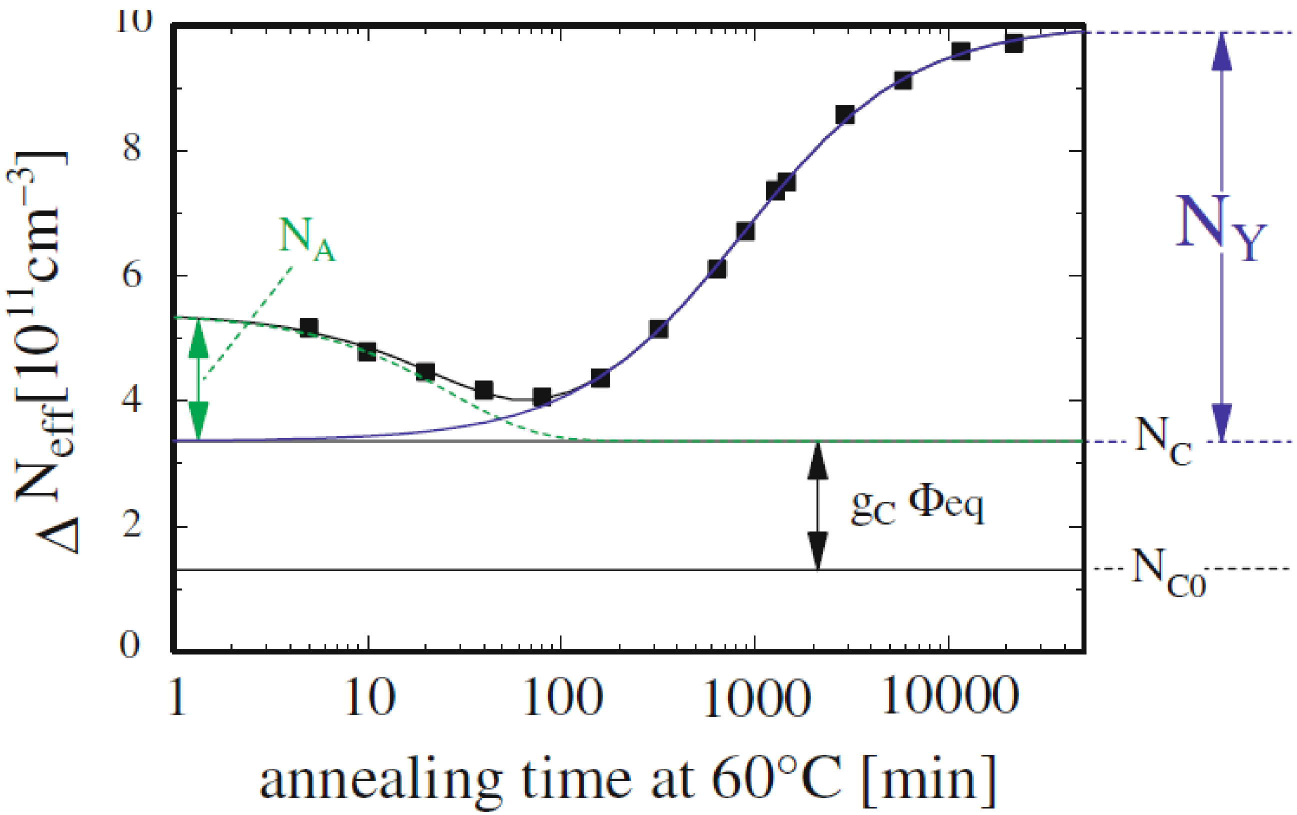
Karlsruhe Institute of Technology

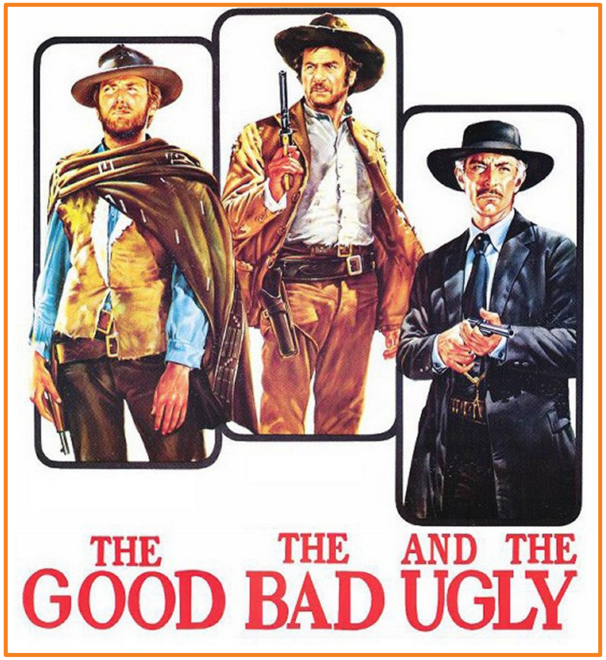
- Different slope for V_{FD} evolution for thin and thick sensors also after installing our detector



Depletion Voltage also has annealing

- Beneficial Annealing + Stable Damage + Reverse Annealing

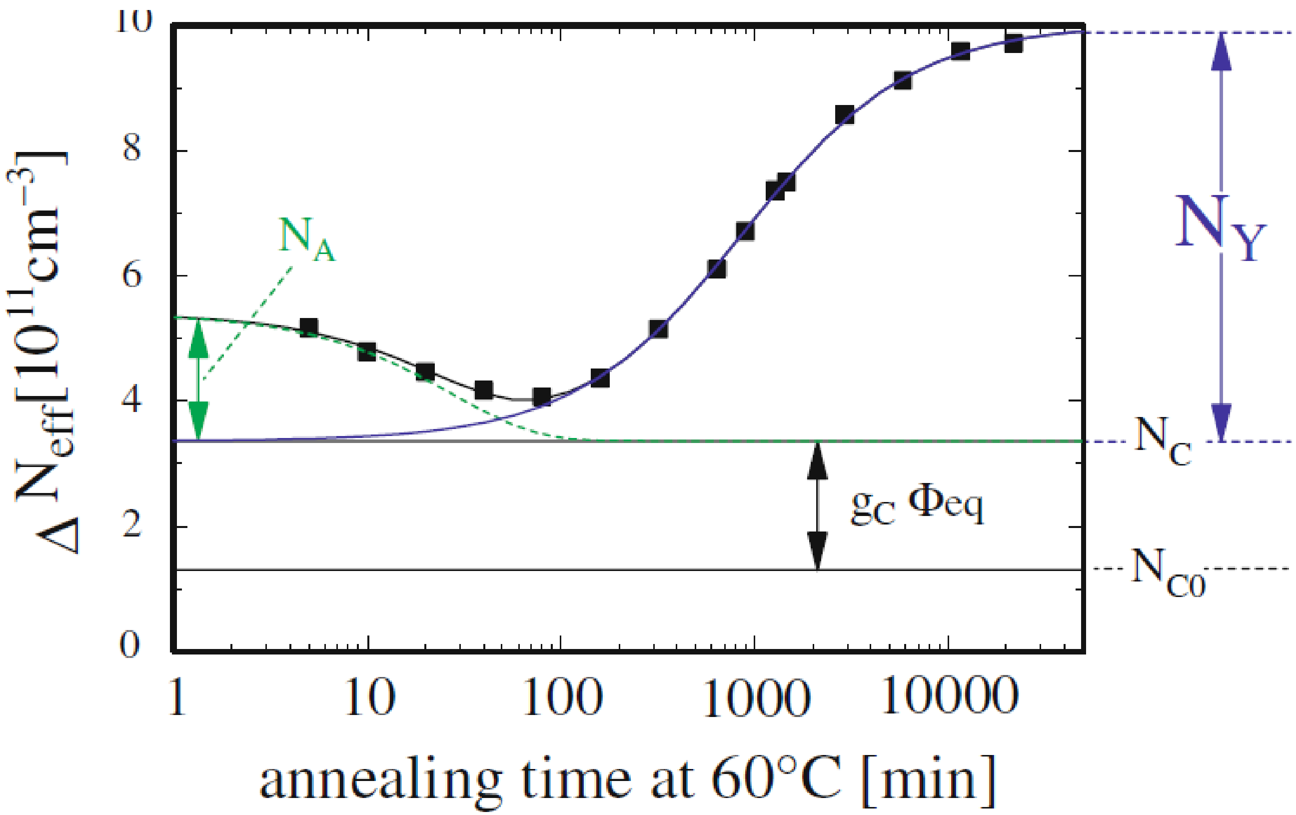


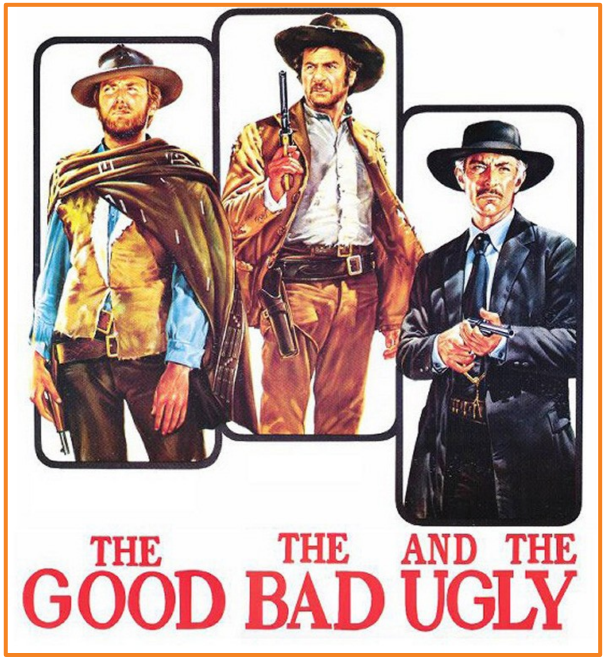


Depletion Voltage also has annealing

- Beneficial Annealing + Stable Damage + Reverse Annealing

$$\Delta N_{\text{eff}}(\Phi_{\text{eq}}) = N_A(\Phi_{\text{eq}}, t, T) + N_C(\Phi_{\text{eq}}) + N_Y(\Phi_{\text{eq}}, t, T)$$

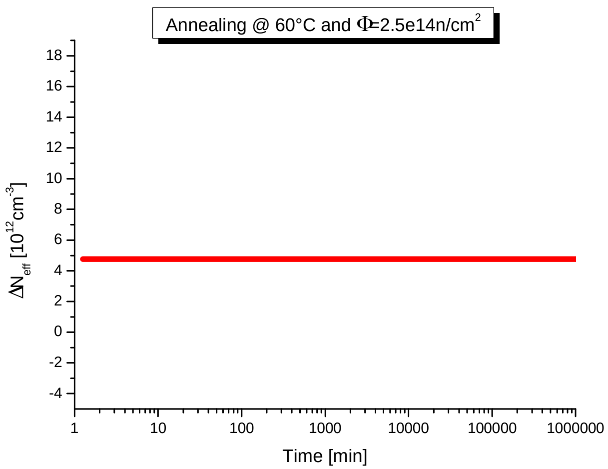




Once more things are dependent on temperature

Stable Damage

- Most important factor at LHC
- Incomplete donor removal
- Introduction of stable acceptors



$$N_C = N_{C_0}\left(1 - \exp\left(-c\Phi_{\mathrm{eq}}\right)\right) + g_c\Phi_{\mathrm{eq}}$$

...but there is nothing we can do about it

Beneficial Annealing

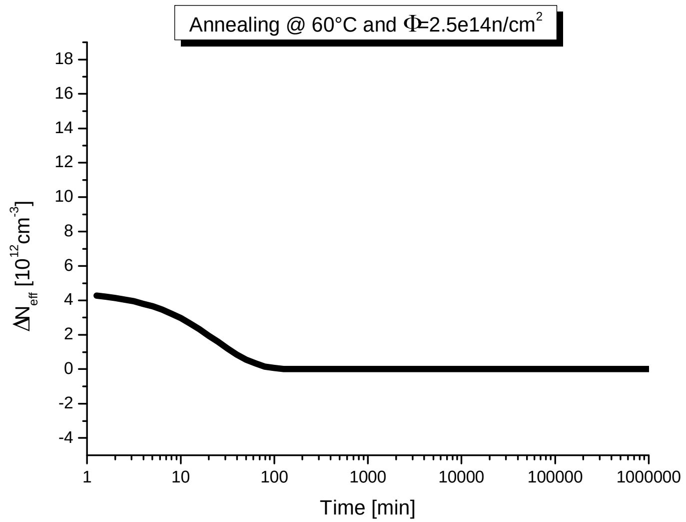
- At ``sufficiently'' high temperature we can break up (anneal) defects – acceptors

This we can do during maintenance periods

T [°C]	-10	-7	0	10	20	40	...
τ_a	306 d	180 d	53 d	10 d	55 h	4 h	...

This is where we operate

→ we don't get much annealing while we run the detector (if detector is in good shape!!)



...helps us, so we try to get as much as we can

$$N_A(\Phi_{eq}) = \Phi_{\mathrm{eq}} g_A \exp\left[-\frac{t}{\tau_a}\right]$$

Actually a sum over many contributions, but consider only the one (with longest decay time)
Things which anneal in minutes or hours are not relevant anyway, we won't see them

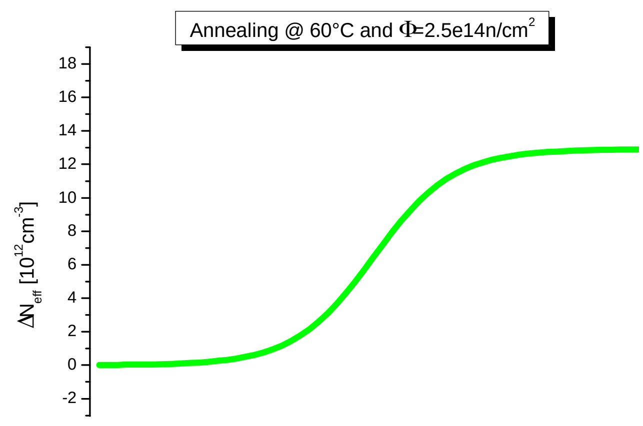
Reverse Annealing

- Long-term process which activates electrically inactive defects

T [°C]	-10	0	10	20	40	60	...
τ_a	516 y	61 y	8 y	475 d	17 d	21 h	...

Nothing (or very little) happens during operation

...but we must not stay at high temperature too long (e.g. during long shutdowns like NOW)

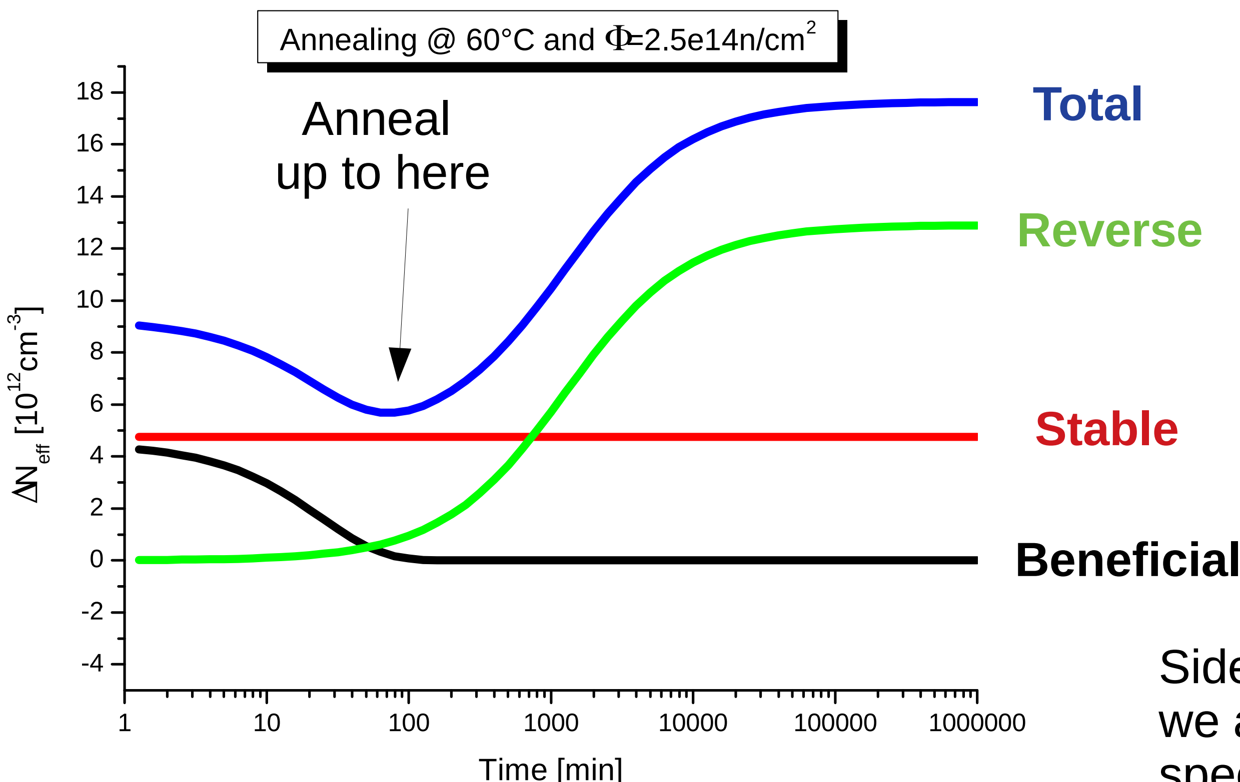


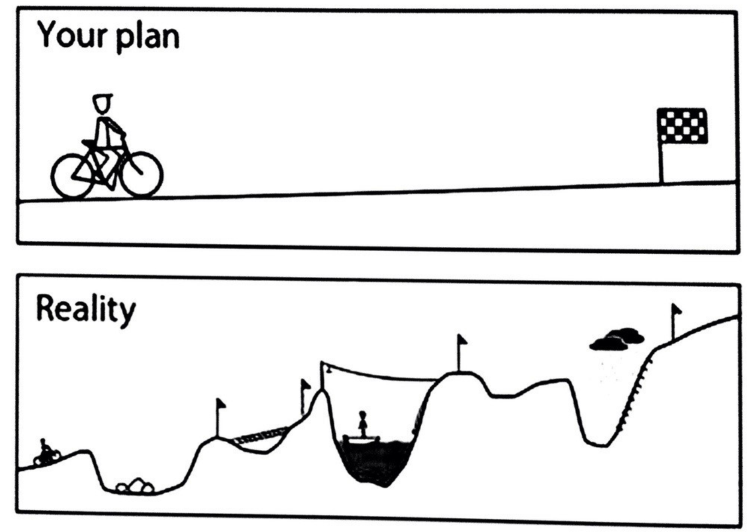
$$N_Y(\Phi_{eq}, t) = g_Y \Phi_{eq} \left(1 - \frac{1}{1 + \frac{t}{\tau_Y}}\right)$$

...this is bad in addition to the stuff we cannot avoid

How do we use all of these things in operating?

- We cannot do anything about stable damage
- Get all of the beneficial annealing
- Get no reverse annealing



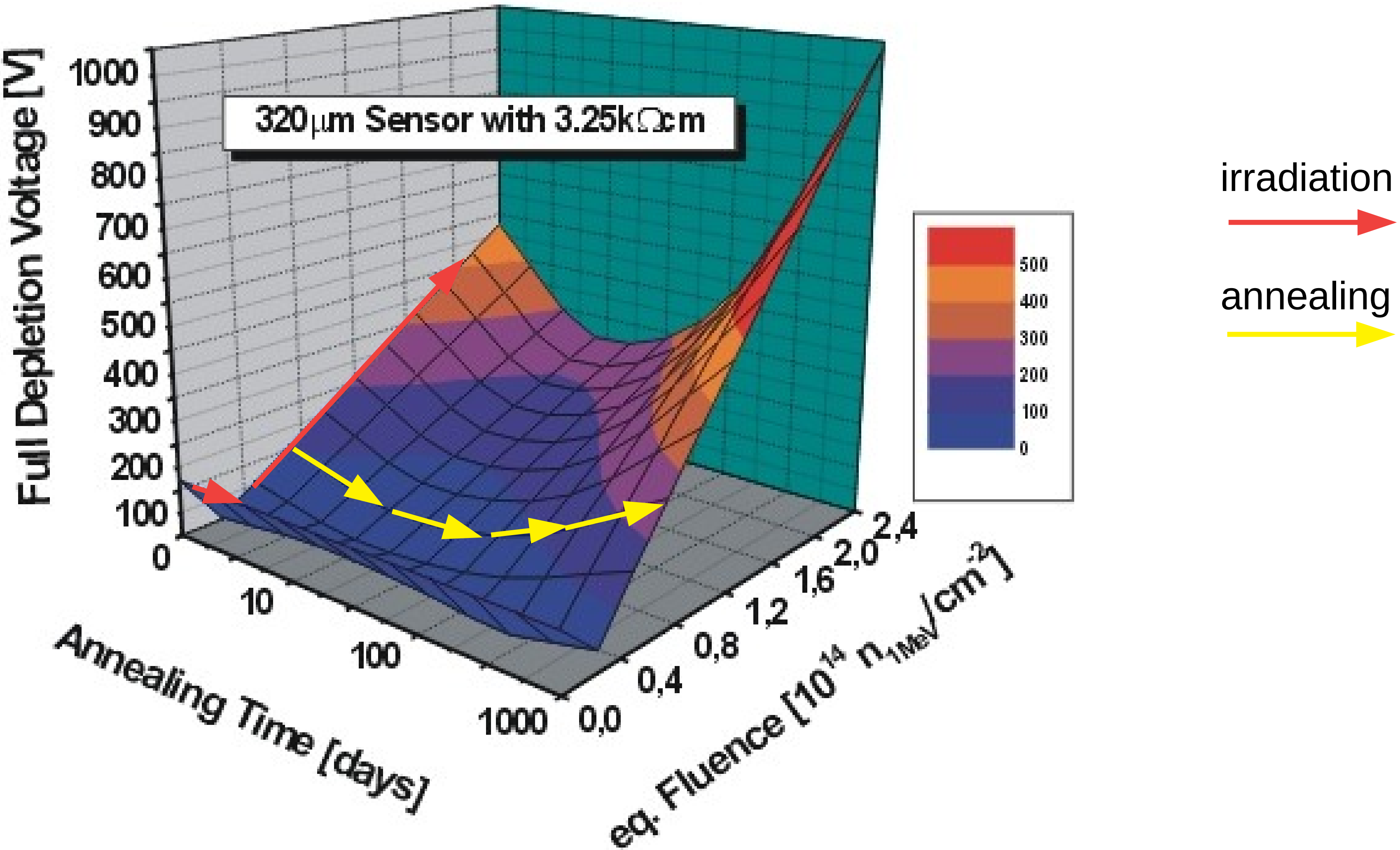


What to do in practice:

- Stay cold as much as possible
- Warm up for ~two weeks per year

Side note:
we always have 60°C on these plots
speed-up needed to be able to qualify
sensors and on reasonable timescale!!

The 2-dimensional view of the change of V_{dep}



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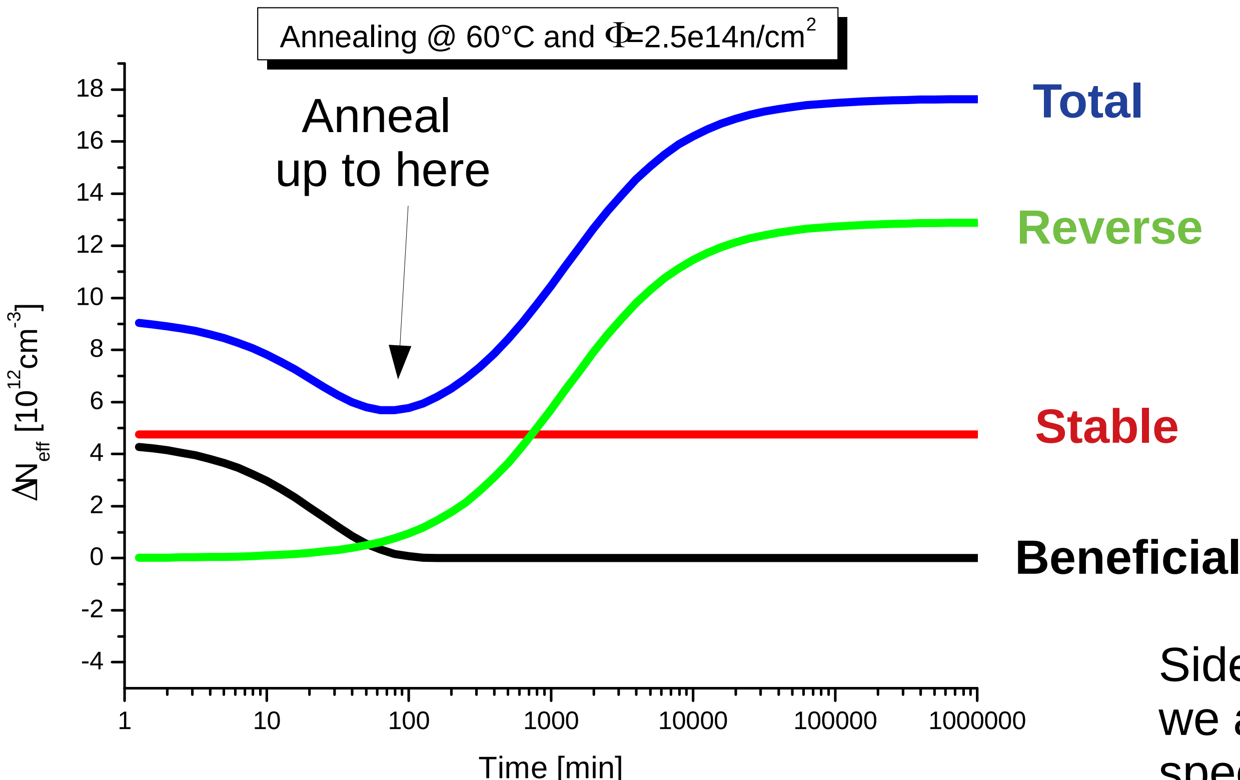
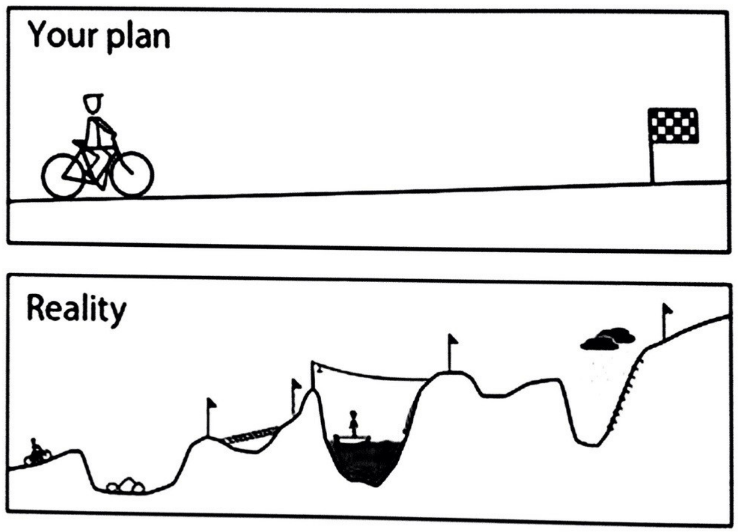




What to do in practice:

- Stay cold as much as possible
- Warm up for ~two weeks per year

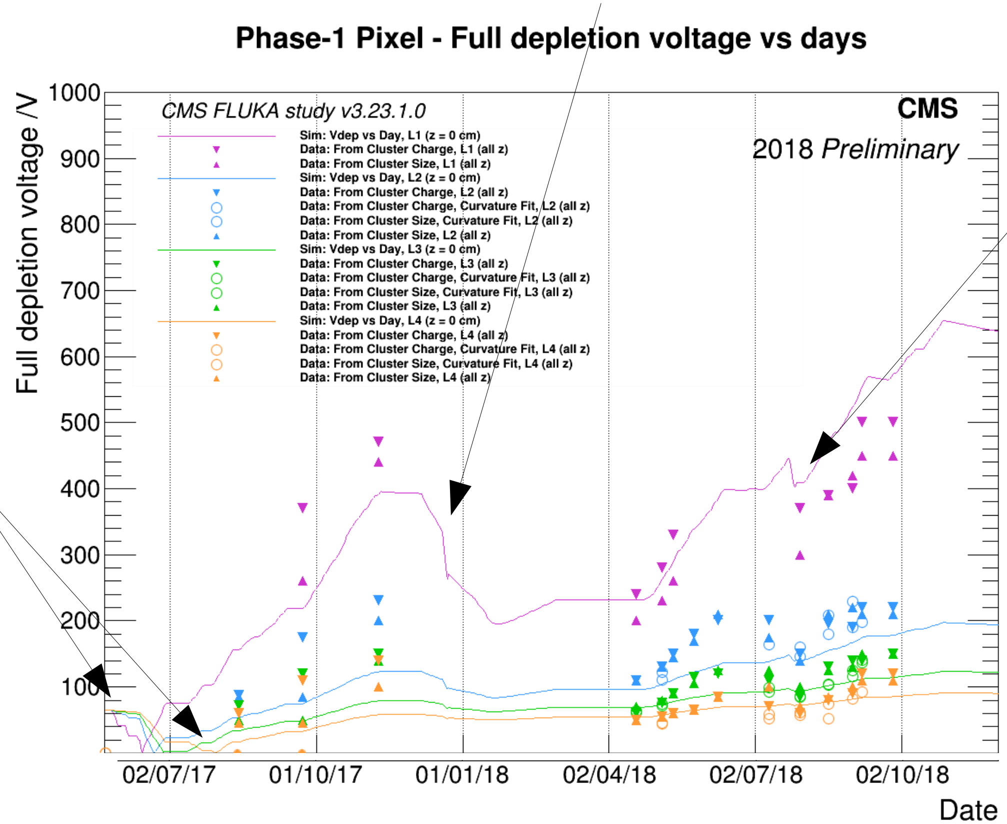
Side note:
we always have 60°C on these plots
speed-up needed to be able to qualify sensors and on reasonable timescale!!

A practical example

- The full irradidation history of the CMS Phase-1 pixel

Beneficial annealing
(end of year stop)

More beneficial annealing
(deliberate warm-up
during LHC
``machine development'')



Type inversion!

Warm detector to +10-12°C
for few days

T [°C]	10	20
τ_a	10 d	55 h

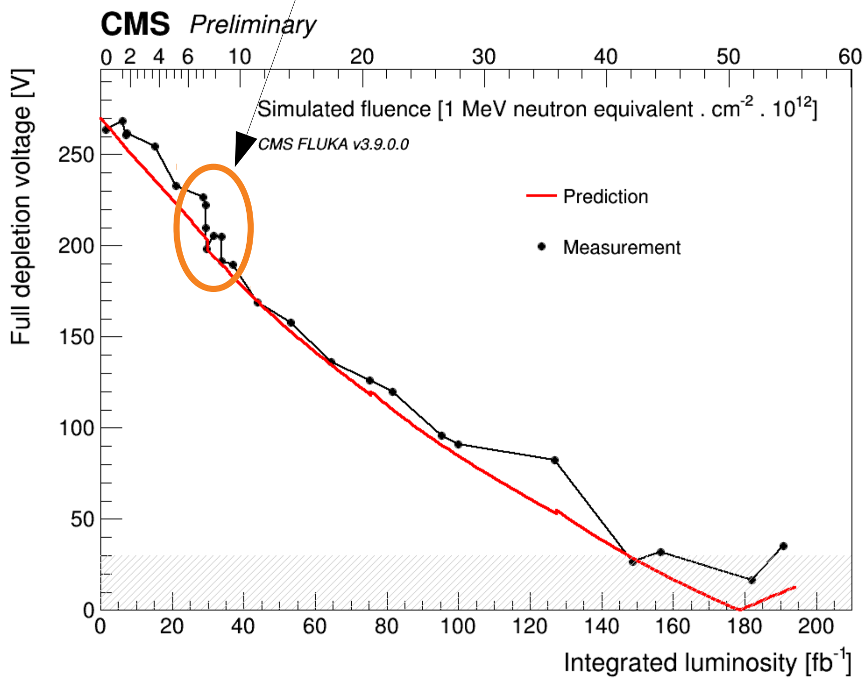
Side Note: CO_2 cooling is great to cool things down but less good to warm things up….

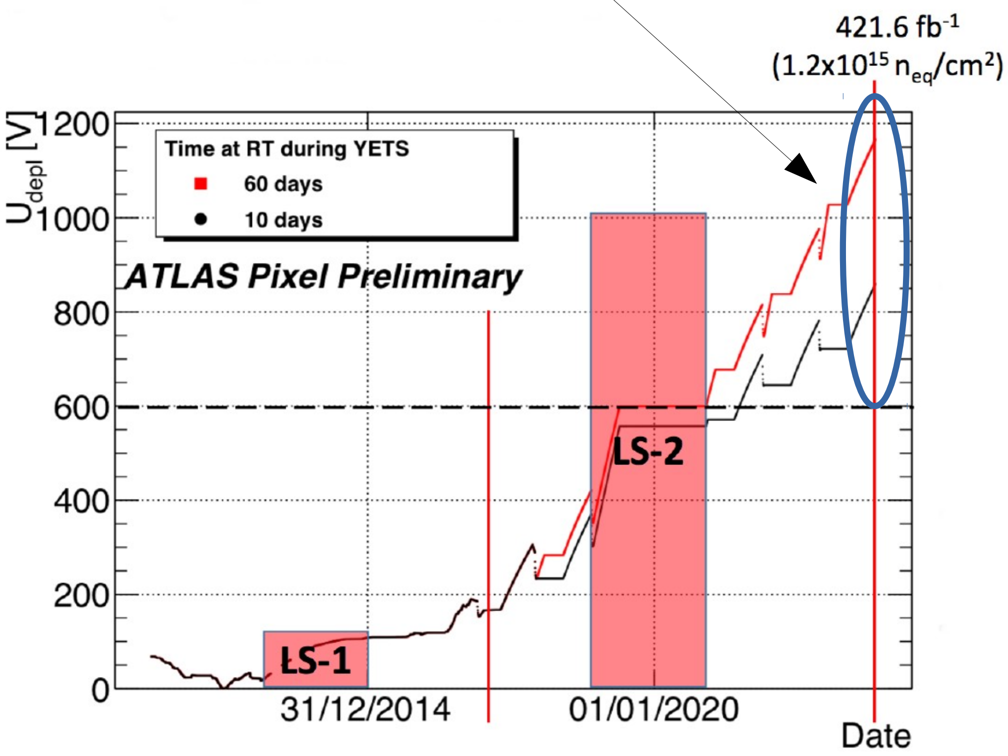
Reverse annealing in real life

- Two examples

Reverse annealing during long-shutdown 1

Big effect on V_{dep} at end of life if we allow too much reverse annealing





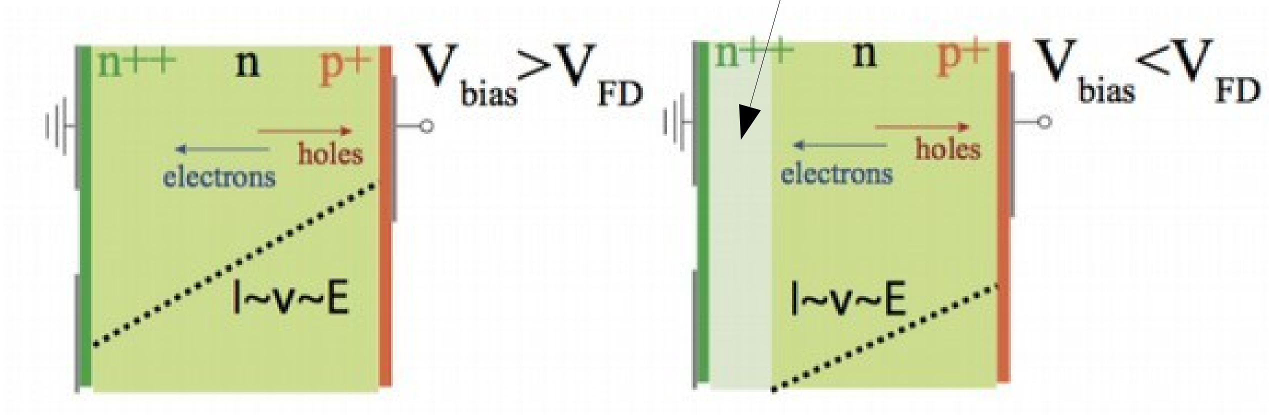
Crucial to stay cold as much as possible even during the couple of weeks at the end of the year!

Also: plan the maintenance of your cooling system properly!

Electric field and depletion zone

- p-in-n sensors before type inversion

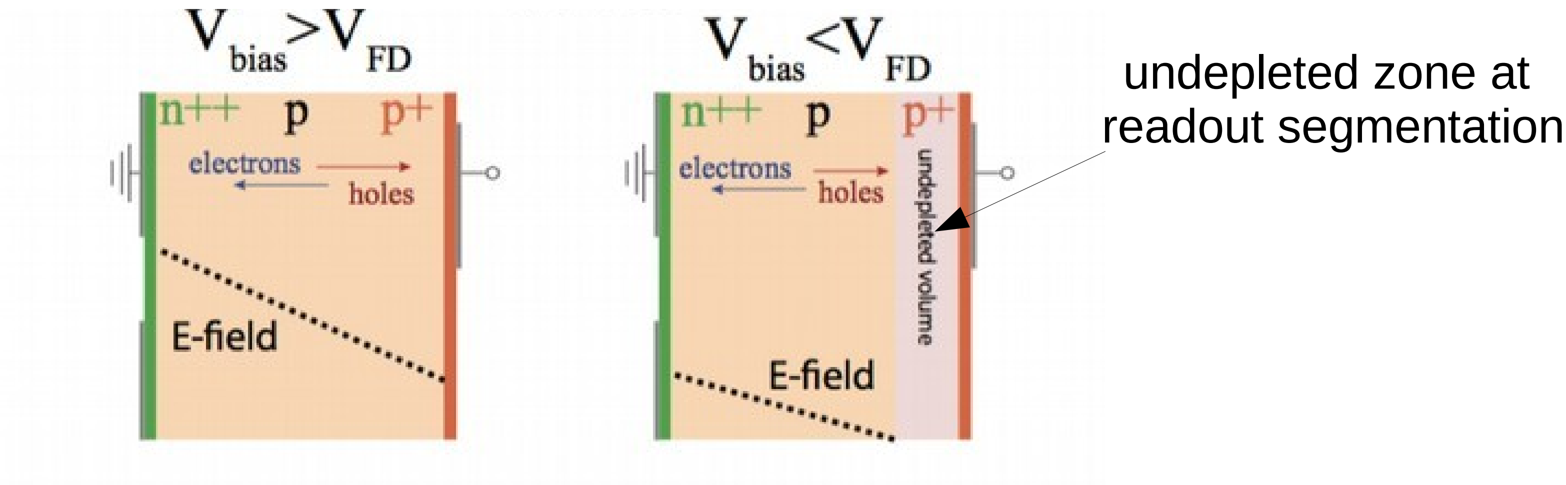
undepleted zone



- Hole collection
- At under-depletion: depletion region grows from strip side

Electric field and depletion zone

- The situation after type inversion
  - pn junction is now at the **back** of the sensor
  - Depletion zone grows from the back towards the strips

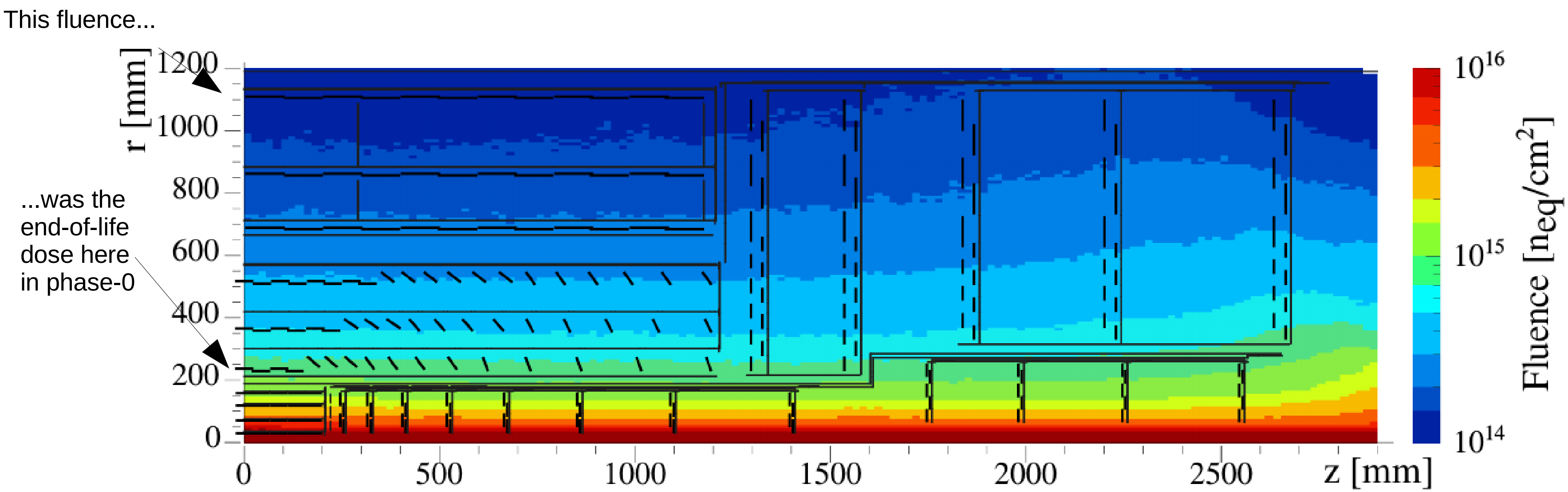


- If we do not manage to fully deplete the sensor we “go blind”
- No problem for **n-in-n or n-in-p** detectors where the depletion zone grows from the segmented side
  → underdepleted operation possible

A Look into the future
HL-LHC

Radiation environment at the HL-LHC

- Radiation environment at HL-LHC will be a factor of 10 more hostile than for the current detectors
- Put differently: what is a problem for the innermost layers will be a problem also for the outer layers



- The innermost layers will be exposed to unprecedented fluences
- New problems that are not (or not too) relevant at LHC

Charge Trapping

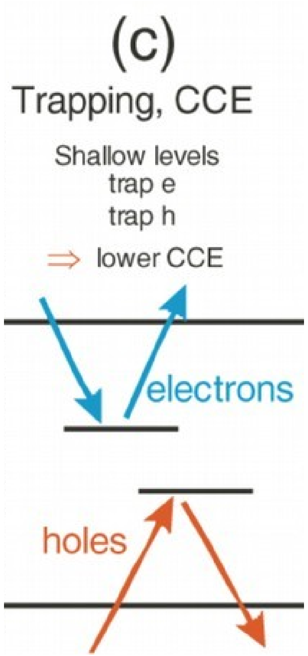
Charge Trapping

- Radiation regimes/main problem:
  - At 10^{14} 1 MeV neq: leakage current
  - At 10^{15} 1 MeV neq: increase in depletion voltage
  - At 10^{16} 1 MeV neq: degrading charge collection efficiency
- The main problem of charge trapping is that generated charge ”disappears” (is trapped) before it can reach/get close to the electrodes and contribute to the readout

Charge Trapping

- Charge trapping is characterized by inverse trapping time which increases with the fluence

$$\frac{1}{\tau_{\mathrm{eff}}} = \gamma \Phi_{\mathrm{eq}}$$



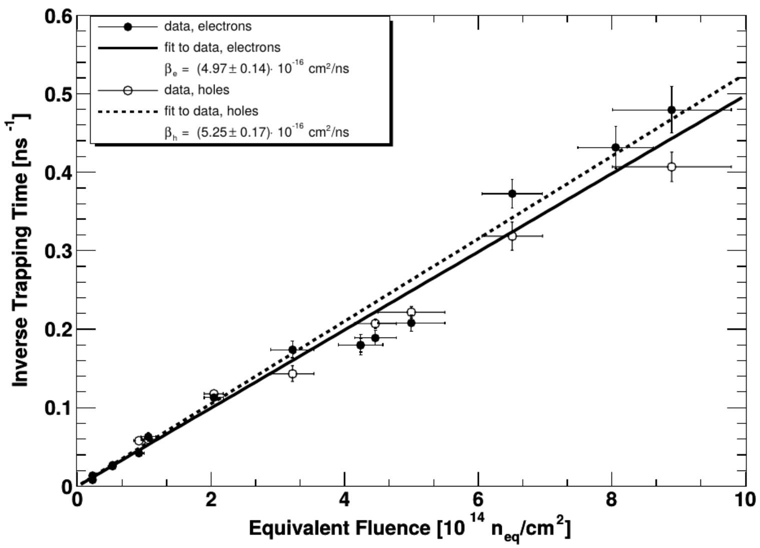
- Signal charge gets reduced as:

$$I = I_0 \exp\left[-t/\tau_{\mathrm{eff}}\right]$$

- Characteristic trapping times:
  - 2 ns @ 10^{15}
    → charges travel ~200 μm
  - 0.2 ns @ 10^{16}
    → charges travel ~20 μm!

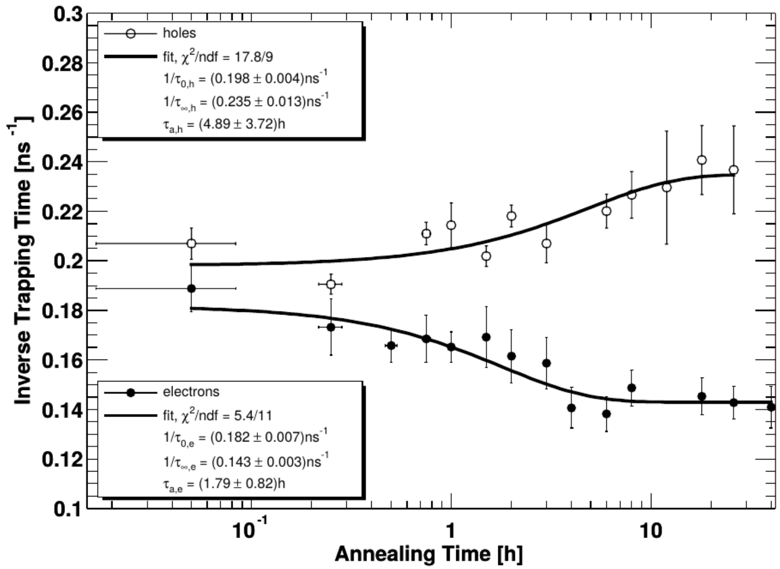
→ onset of trapping visble at LHC (CMS Pixel: 285 μm sensors)

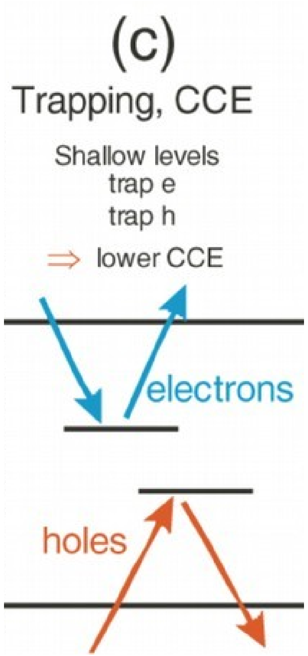
→ trapping very important at HL-LHC



Also trapping anneals

- Trapping anneals differently for electrons and holes





- Annealing for holes increases inverse trapping time

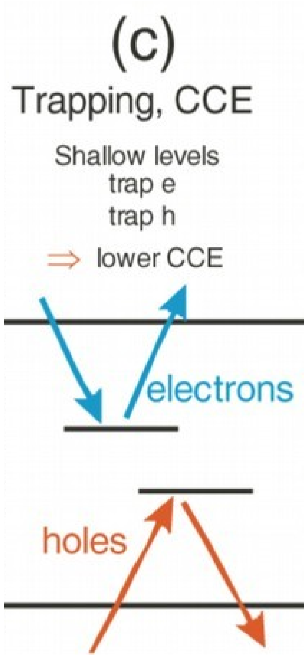
  → shorter trapping times
  → more signal lost!

- Annealing for electron decreases inverse trapping time

  → larger trapping times
  → charge collection efficiency increases

How to “beat” trapping

- 10^{16} 1 MeV n_{eq} are doses expected for innermost pixel layers at HL-LHC
  → trapping is our dominant problem
- With trapping times of 0.2 ns bulk volumes beyond few 10s of μm do not really contribute to our signal
  → not worth investing in thick sensors as they won’t give us more charge anyway
- Indeed: plans are for 100-150 μm thick sensors or 3D sensors for CMS and ATLAS pixel detectors
- Minimize the time needed to collect the charge
  → read out electrons (higher mobility)
    → n-in-p or n-in-n sensor configurations
  - Additional advantages:
    - They both can run under-depleted
    - Annealing of electron trapping is beneficial



What are other reasons to want thin sensors?

- Full depletion voltage goes with square of sensor thickness

$$U_{\mathrm{FD}} = \frac{e}{2\epsilon_r} \left| N_D - N_A \right| D^2$$

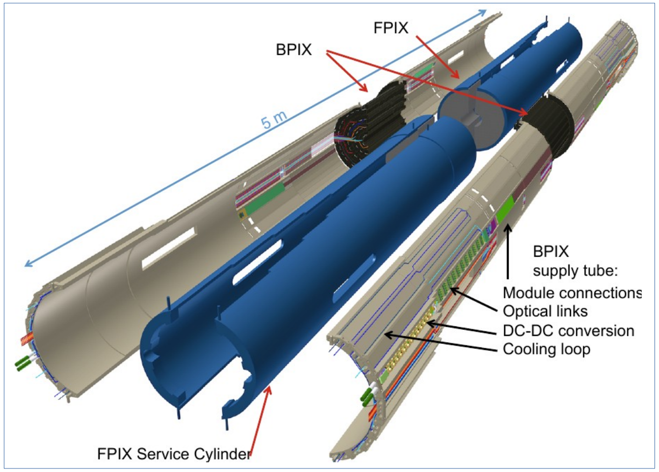
→ Can use smaller bias voltage or for same bias voltage we have higher fields

→ Faster, i.e. more signal from induction, more charge collected before trapping

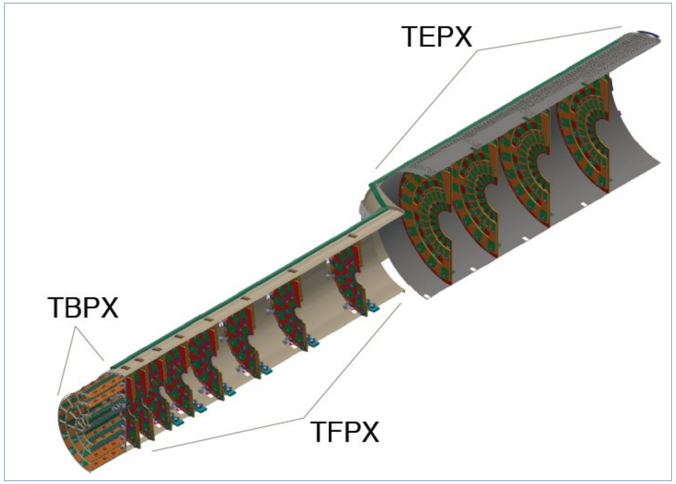
- Also leakage current scales with the sensor volume
→ reduces power dissipation
→ important because of increased power density

Same volume (6m x 25 cm)

CMS Phase-1 pixel: 6 kW

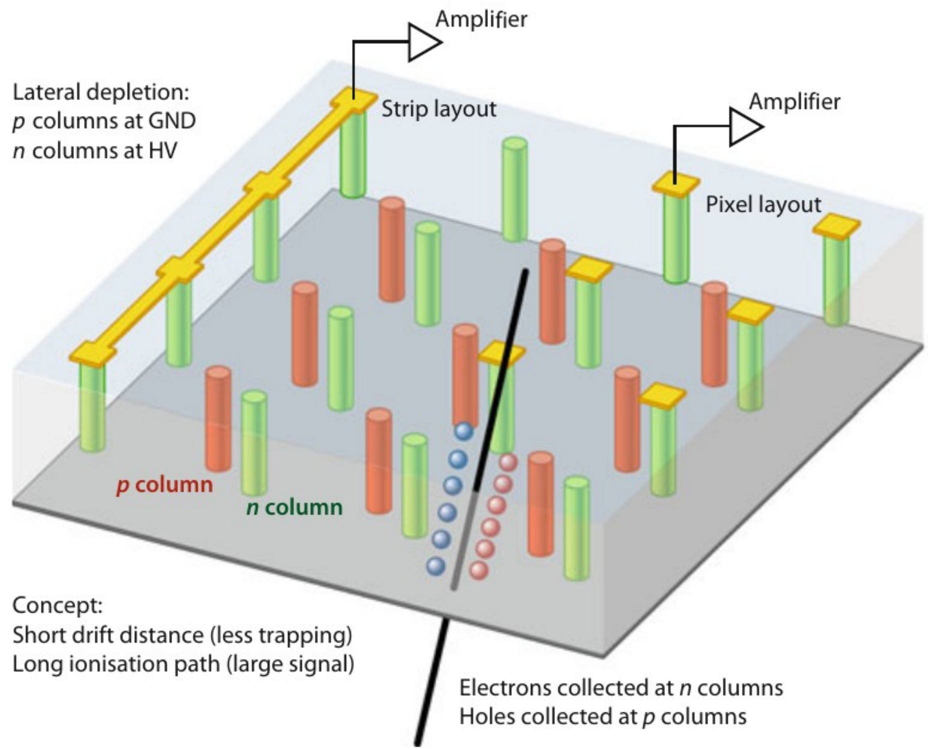


CMS Phase-2 pixel: 50 kW



3D sensors

- p- and n-type columns are etched into the bulk material

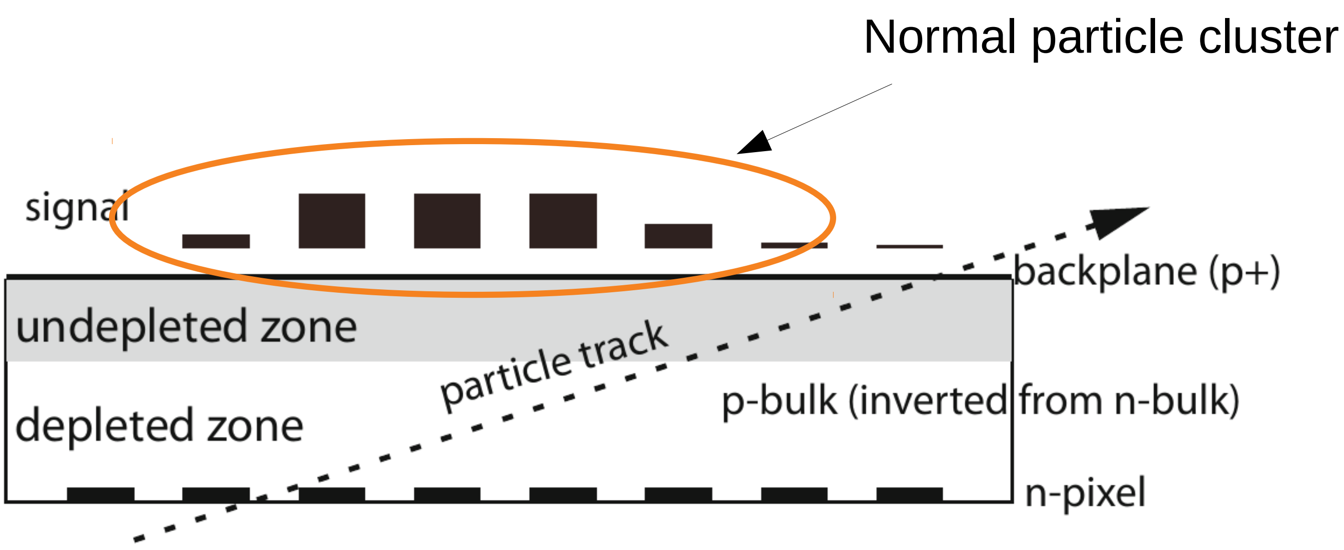


- Drift path length same as for planar sensors
- Short drift path: less time for trapping → more signal (or better: less reduction)
- Distance between electrodes is small → Low depletion voltage required

From high-ish irradiation: Double Junction

- “Normal” case for underdepletion in n-in-n sensors after type inversion:
  - pn junction is between n+ pixelated structures and (type inverted) p-type bulk

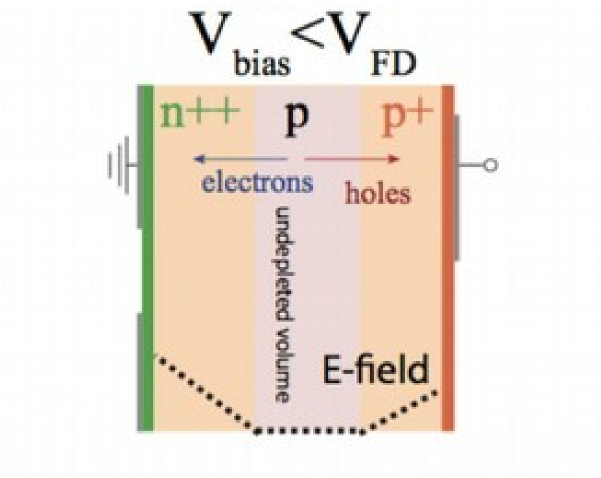
    → depletion zone grows from there



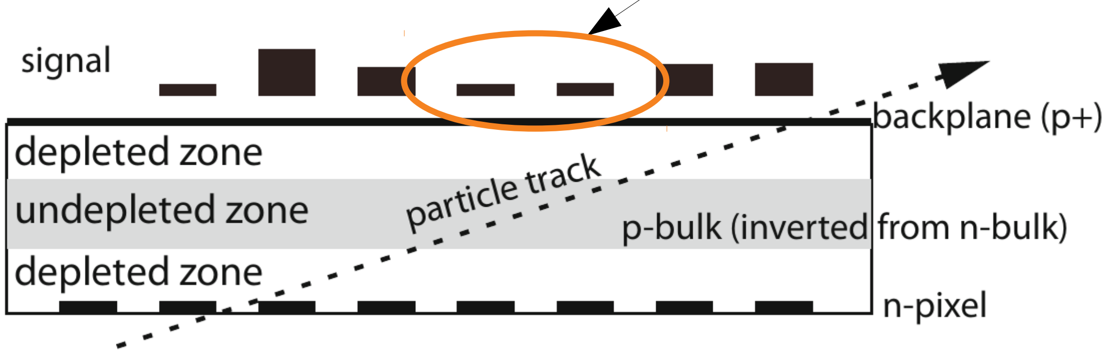
From high-ish irradiation: Double Junction

- “Normal” case for underdepletion in n-in-n sensors after type inversion:
  - pn junction is between n+ pixelated structures and (type inverted) p-type bulk

    → depletion zone grows from there
  - Actually: undepleted zone in the center of bulk
    → onset of charge trapping



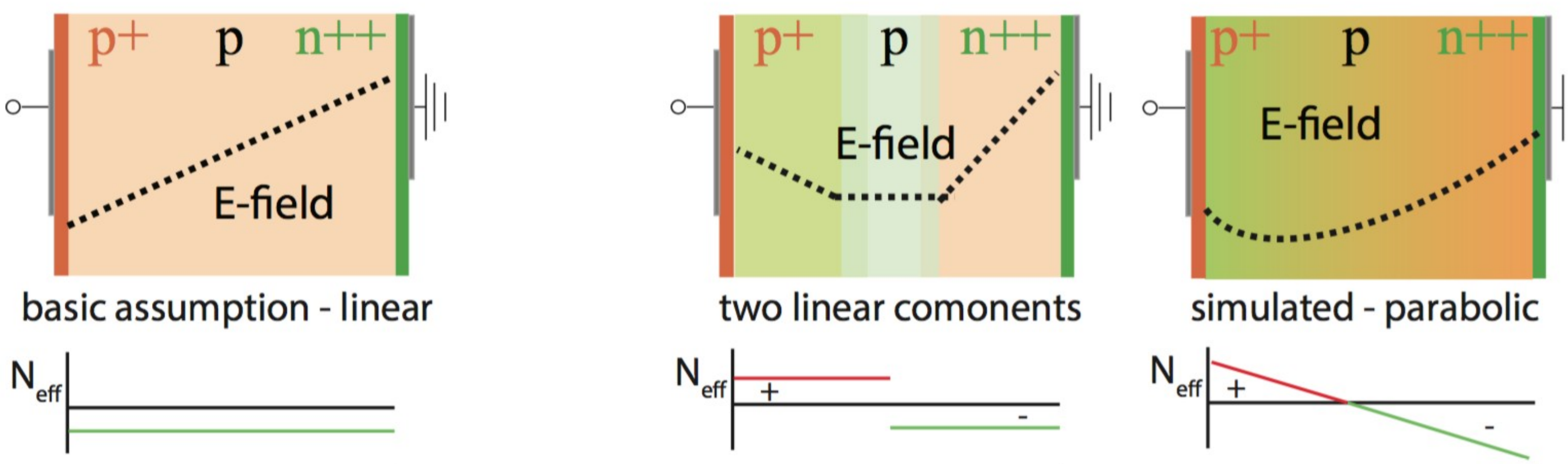
Can cause “broken” cluster



One way to measure a double junction:
gracing angle tracks

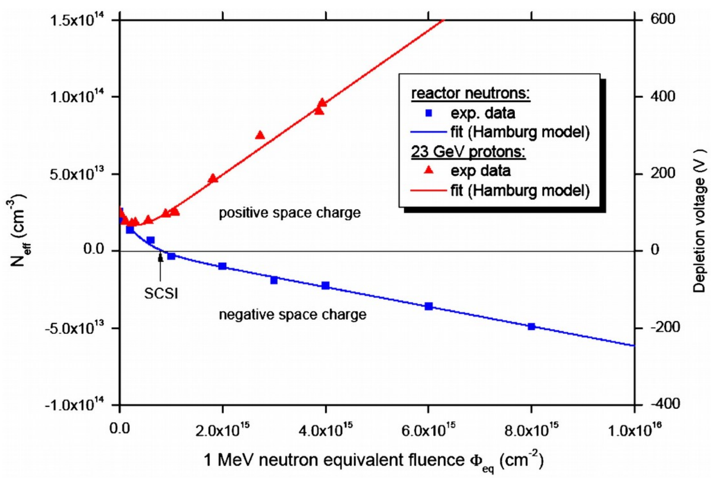
A more realistic picture

- At very high fluences concept of V_{dep} becomes less relevant
- Because of trapping: holes and electrons drift towards the electrodes and get trapped → Asymmetric change of N_{eff}
- Electric field inside the sensor becomes parabolic and is non-zero everywhere with different signs at the two electrodes
- Below depletion voltage the undepleted zone is in the middle of the sensor
- Field strength and collected charge matter more than V_{dep}

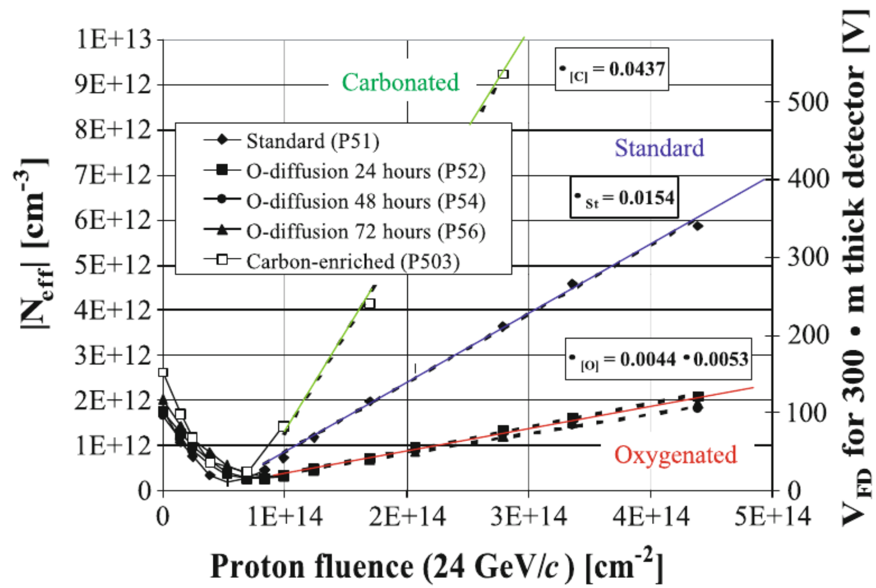


A few more words on NIEL

- NIEL is a very useful concept for radiation in silicon detectors
- But: NIEL is violated in various ways (just few examples)



Different space charge sign defects introduced by p and n

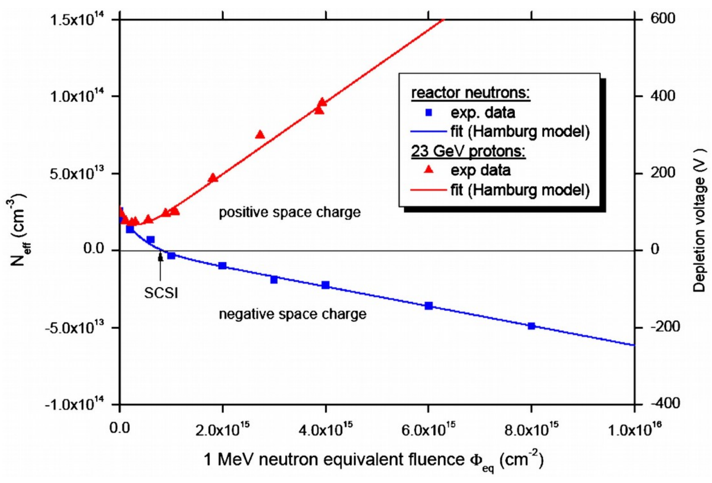


Different material composition (doping) can change susceptibility to irradiation (Oxygen seems good, best to avoid carbon..)

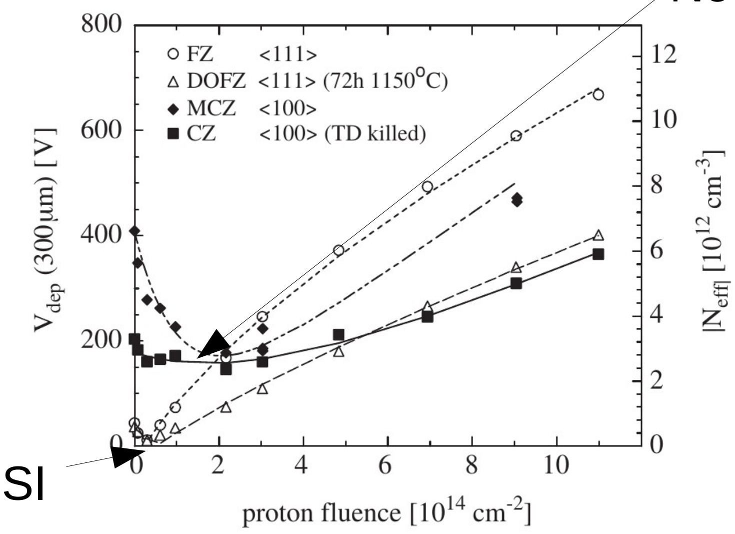
- Still useful for
  - Leakage current after hadron irradiation
  - Trapping of electrons and holes (within 20%)

A few more words on NIEL

- NIEL is a very useful concept for radiation in silicon detectors
- But: NIEL is violated in various ways (just few examples)



Different space charge sign defects introduced by p and n



Not all materials exhibit SCSI

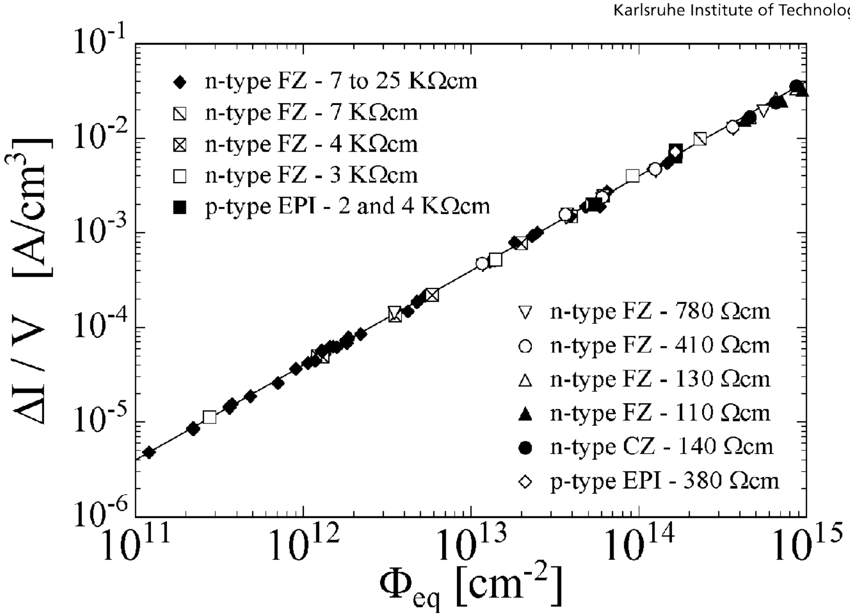
- Still useful for
  - Leakage current after hadron irradiation
  - Trapping of electrons and holes (within 20%)

A word on leakage current at the HL-LHC

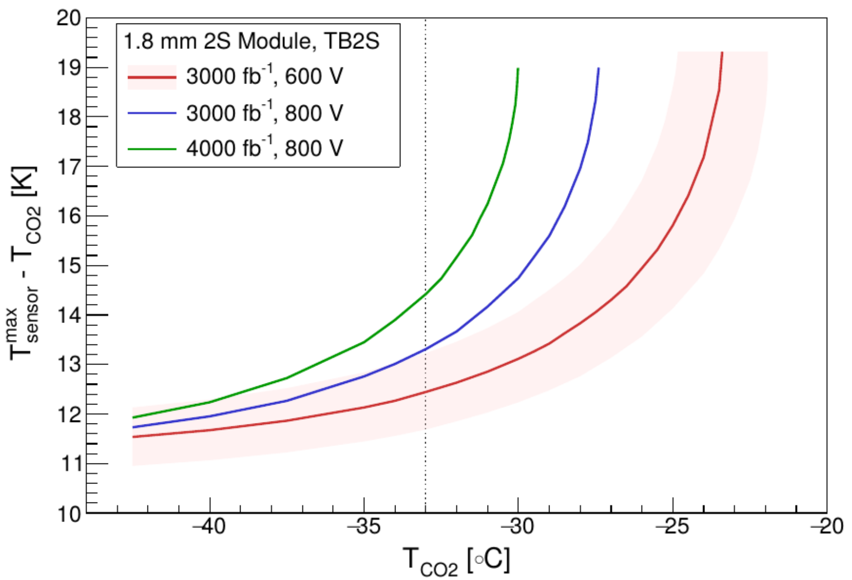
- Scaling with fluence still holds

  → Factor 10 more leakage current
- Need to counteract with lower temperatures
- For LHC detectors:
  - Coolant at -10°C
- For HL-LHC detectors
  - Coolant at -35°C
- In both cases: ΔT ~ 10°C

  → Leakage current “dialed down” by factor of 8-10



Yes, thermal runaway can also happen



Some kind of summary?

- Radiation damage in silicon detectors is a complex and still evolving subject
- Different effects dominant depend on the total irradiation level you are exposed to
  - Leakage current
  - Depletion voltage change
  - Charge trapping
- Radiation types do not all behave the same for all material
  → NIEL violation
  - When you choose the material for your next detector, be sure to subject it to realistic radiation mix
- Pay attention to the plumbing
  - Cooling seems like an afterthought to your beautiful detector, but you need it limit leakage current prevent reverse annealing,...