SILICON DETECTORS

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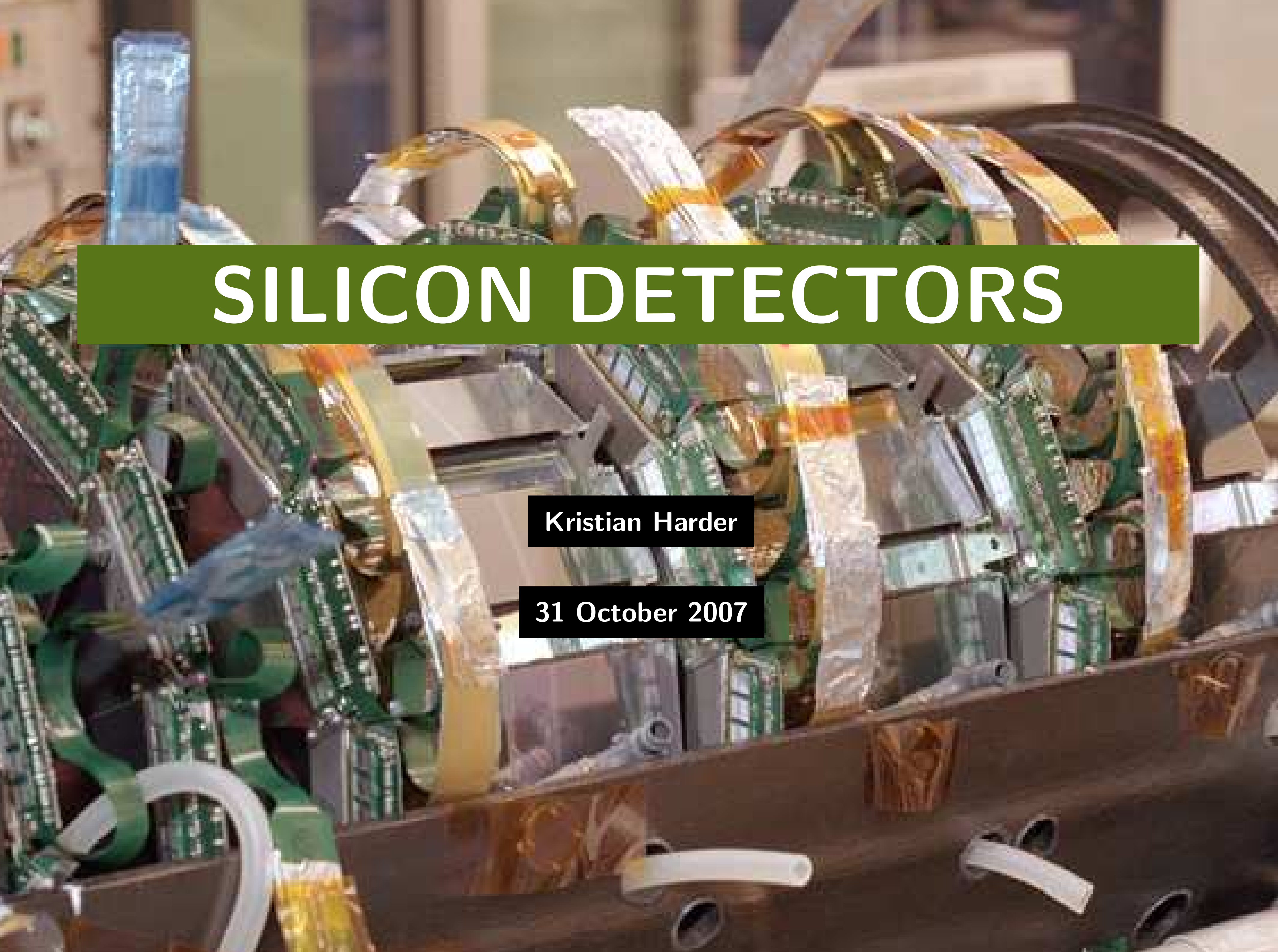
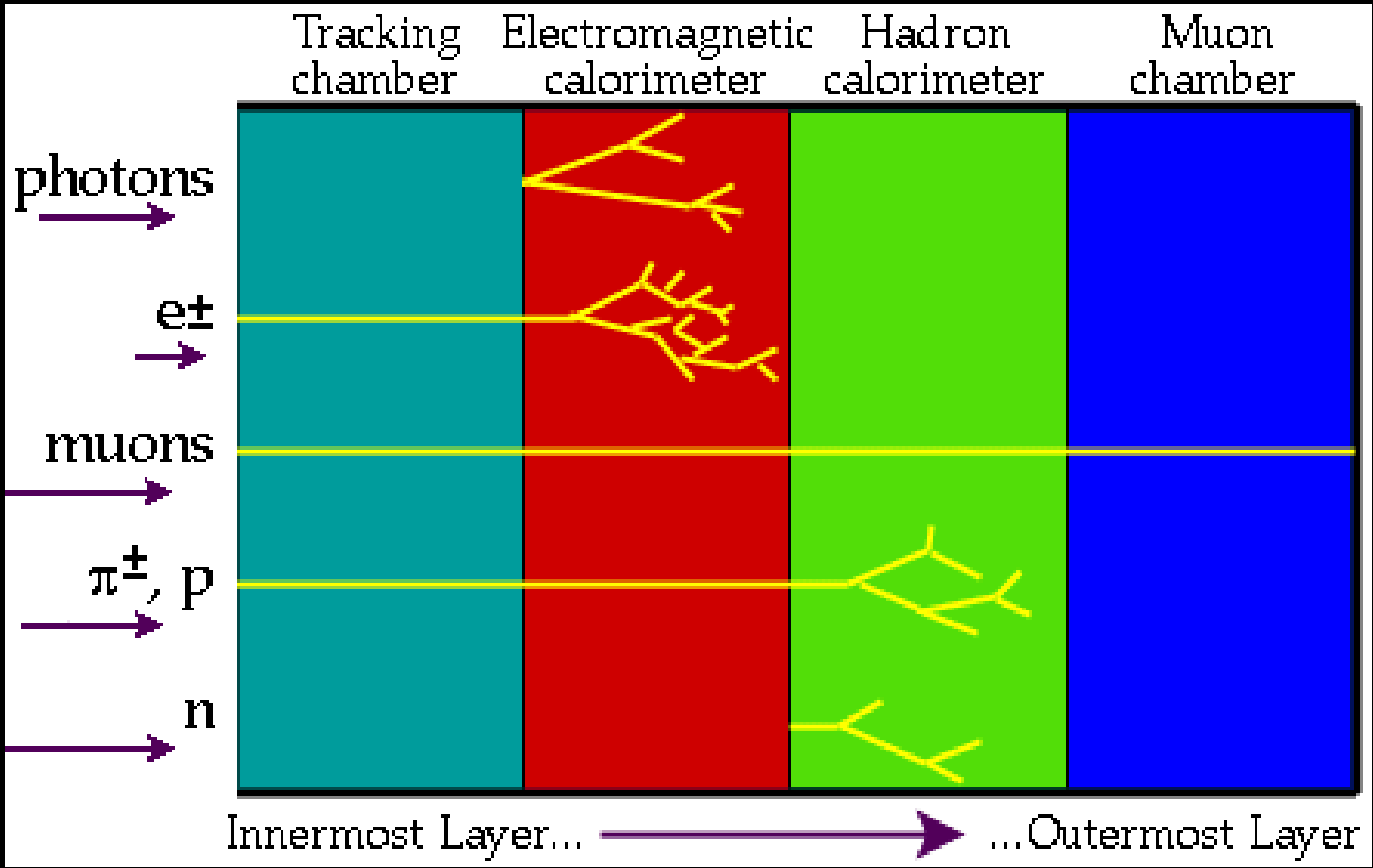
31 October 2007



outline

- general particle physics detector introduction
- more specific particle physics detector introduction: silicon
- why we love silicon
- why we hate silicon
- how (not) to build a detector from it

basic detector concepts



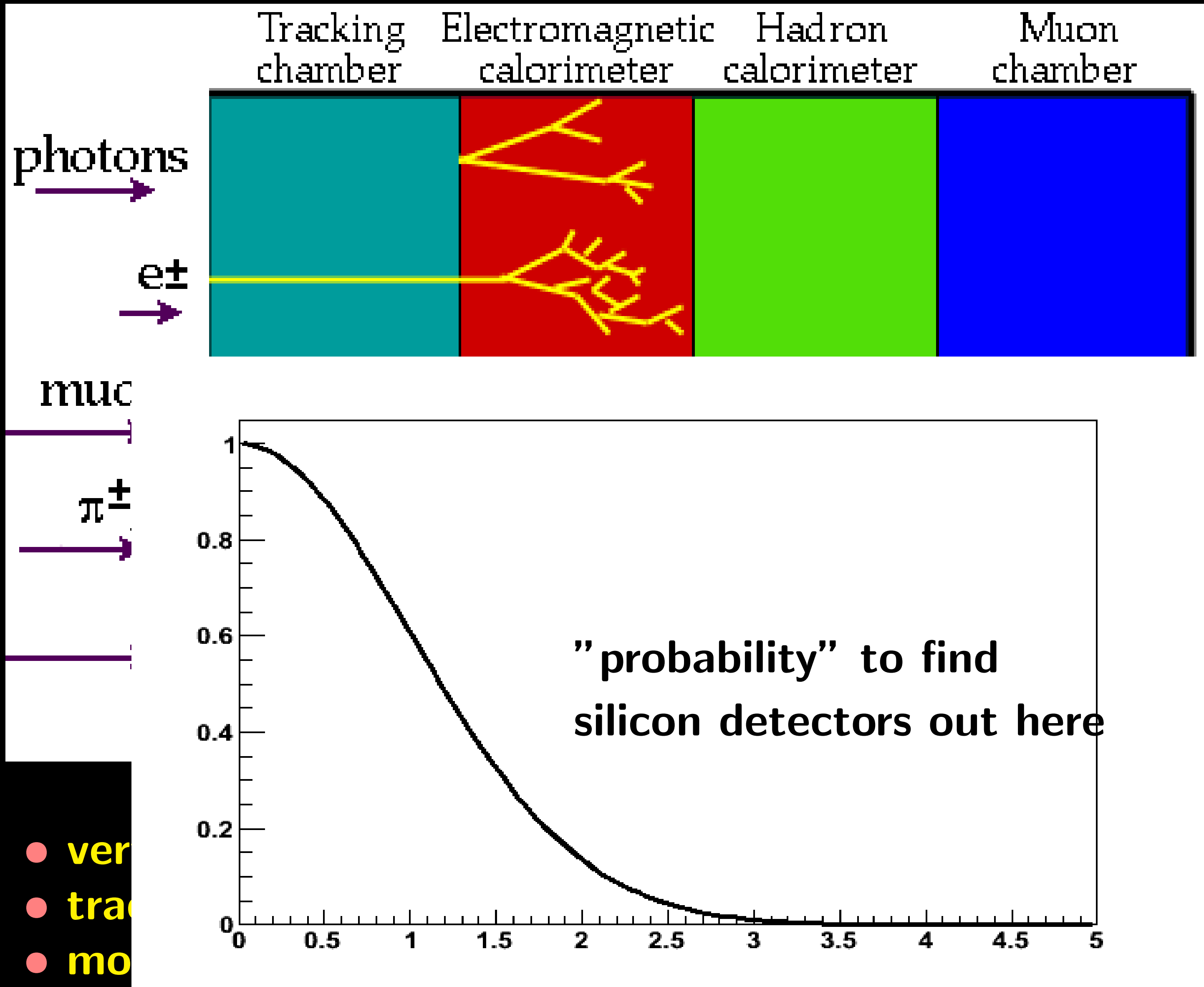
left part:
- vertices
- tracks
- momenta (magnetic field!)

try to leave particles undisturbed

right part:
- energy measurement
- particle identification

use massive material

basic detector concepts

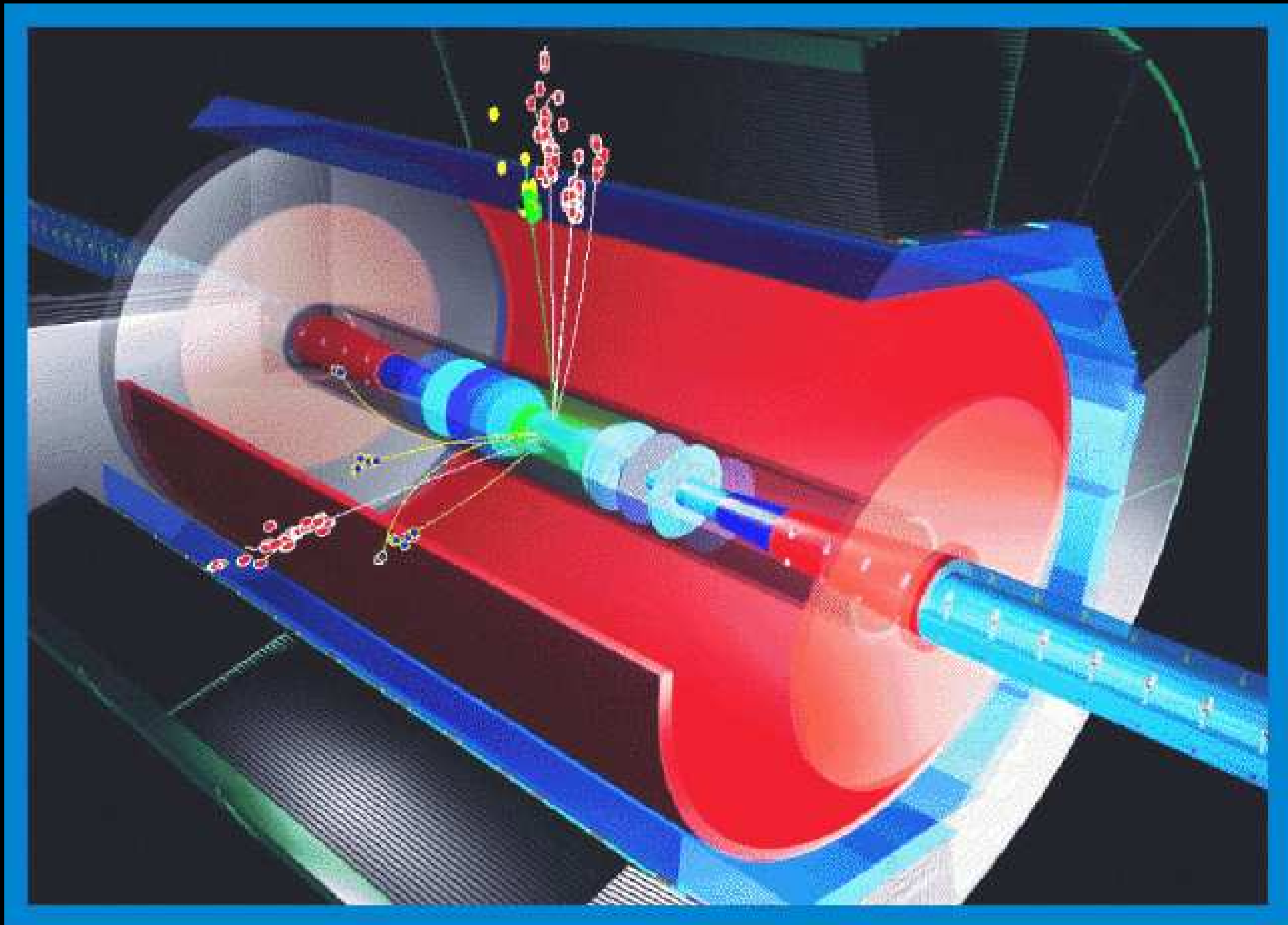


left part:
- ver … easurement
- tra… dentification
- mo… e material

try to leave particles undisturbed

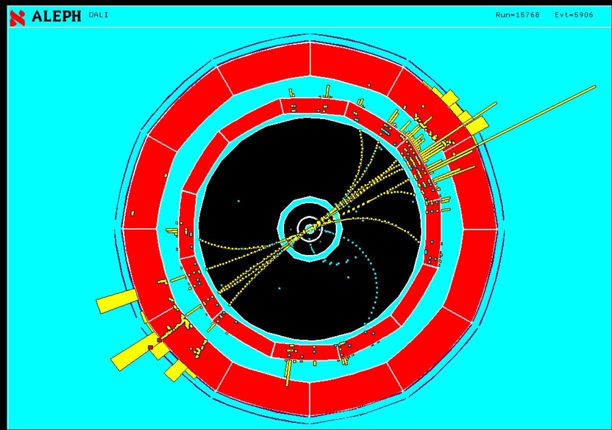
an almost actual detector

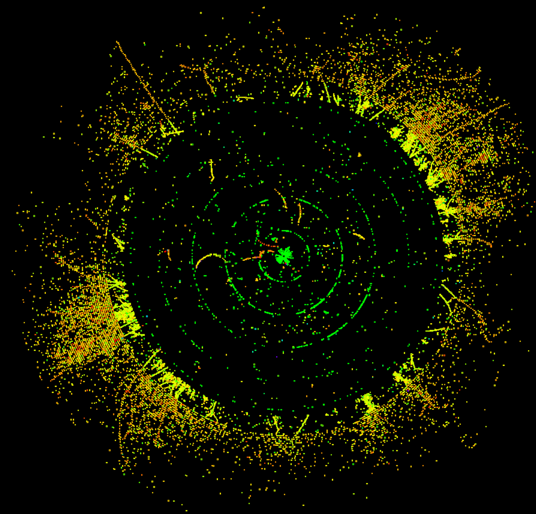
simulation of a rather generic collider detector:



Large Detector Concept for the International Linear Collider

silicon detectors are transforming the way we look at particles



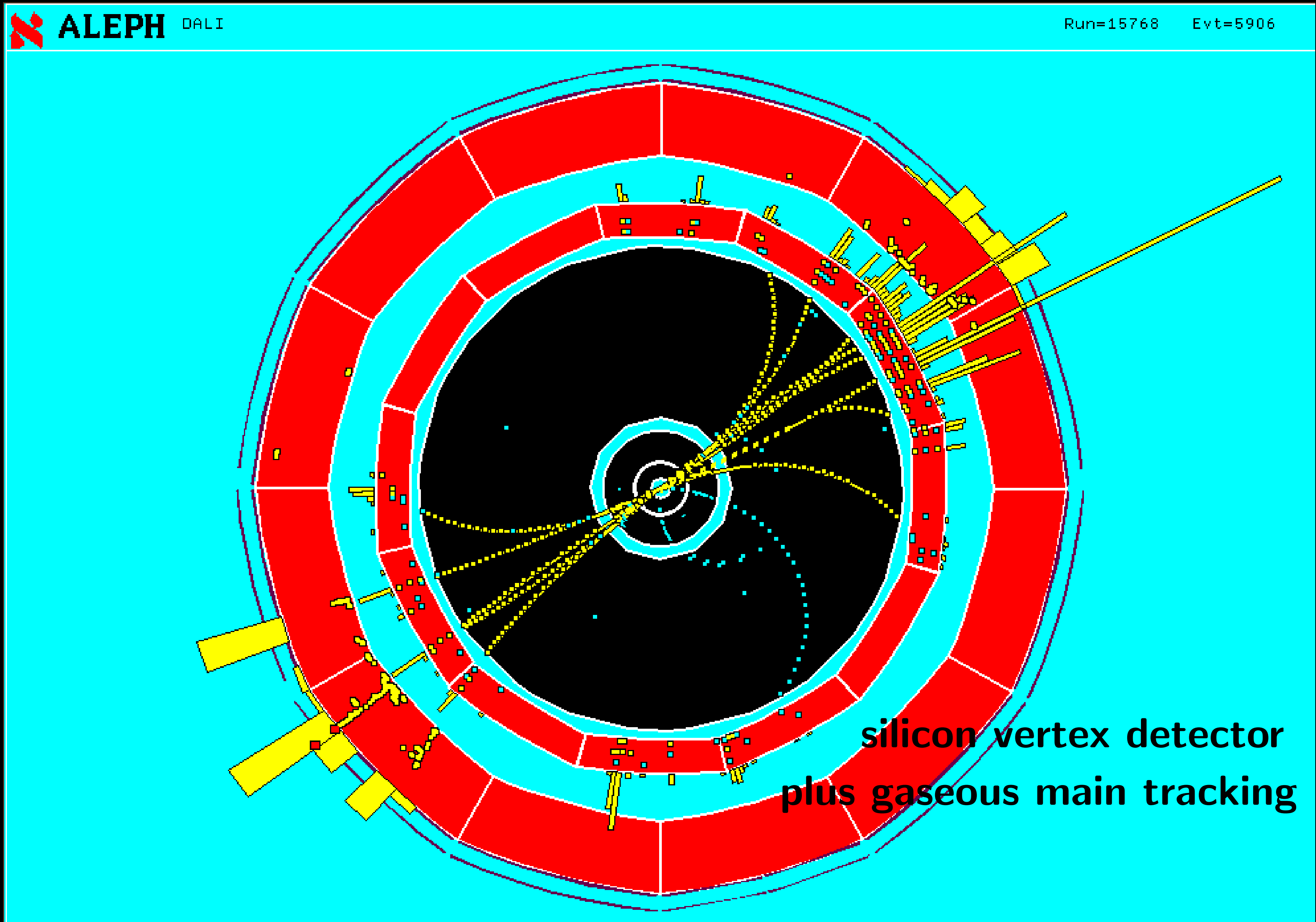


reconstructing particles: 1970s

pre-silicon era

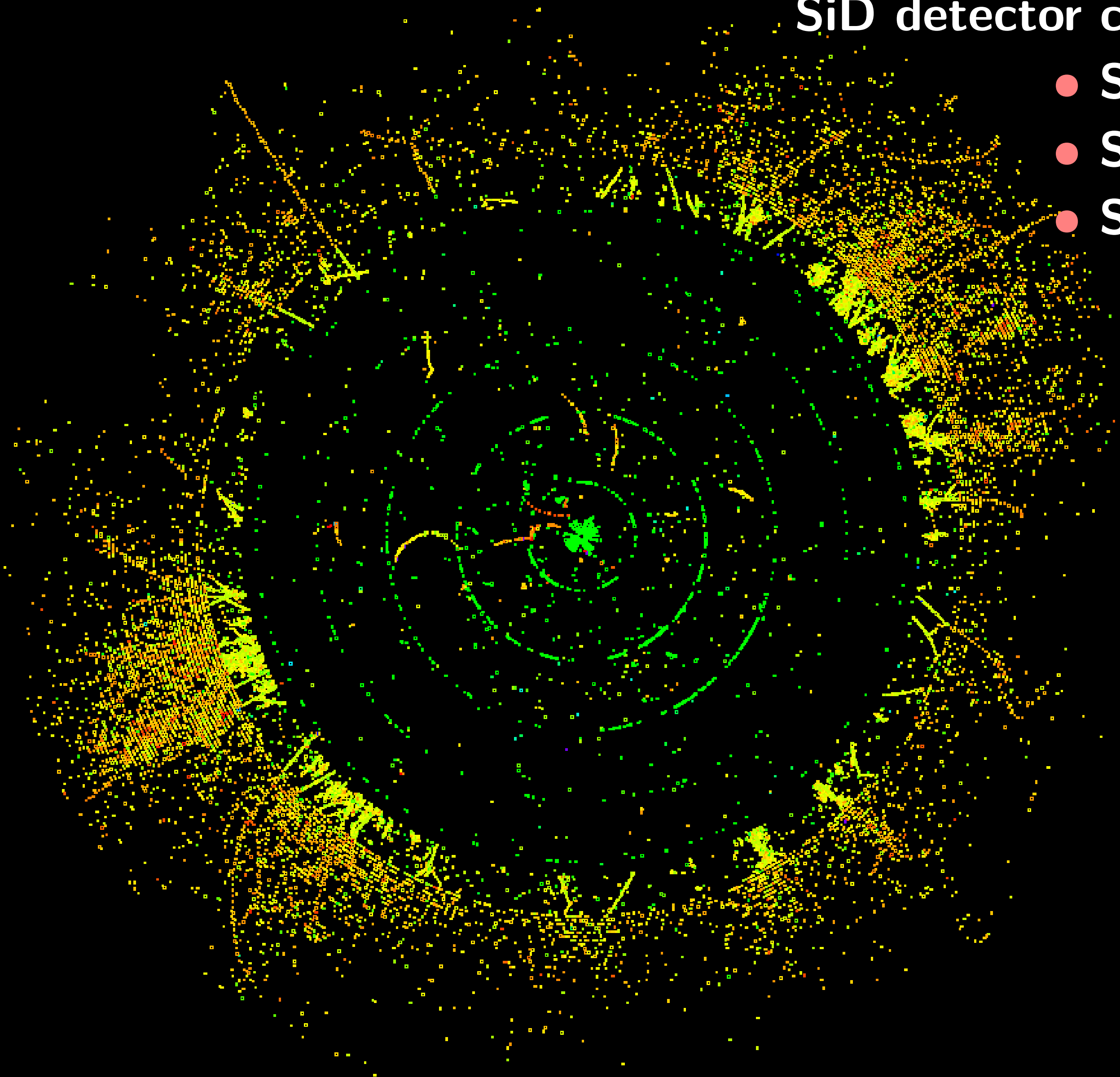
photograph of ionization trails

reconstructing particles: 1990s



silicon vertex detector
plus gaseous main tracking

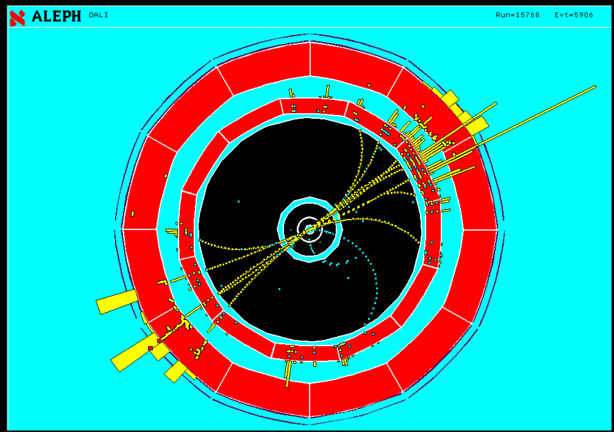
reconstructing particles: 2010s

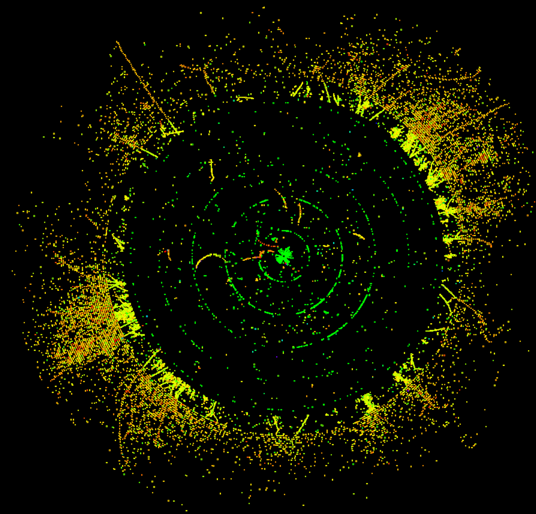


SiD detector concept for ILC

- Si vertexing
- Si tracking
- Si calorimetry

silicon detectors are transforming the way we look at particles





It might look like we are actually seeing less now,
but we can see a lot more than in pre-silicon times!

why detectors change

We are looking at increasingly rare processes
and increasingly small potential deviations from expectations
at increasingly large particle energies

➡ need high precision
- high granularity
- small amount of material

➡ need to look at enormous number of particle collisions
- high speed electronic readout
- high level of background tolerance
- radiation hardness

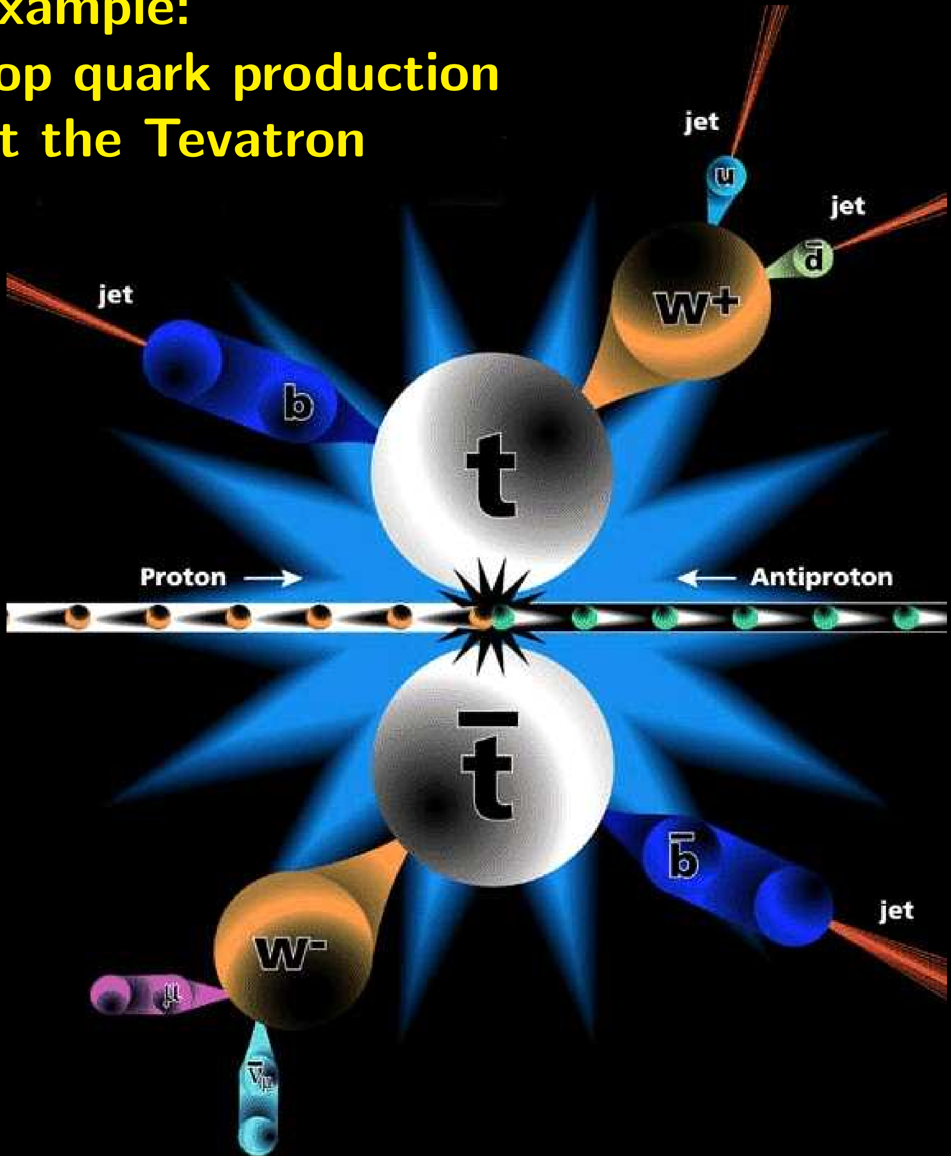
continually developing new detection technologies!

★ many dropped out meanwhile

★ silicon is on the rise!

performance requirements

example:
top quark production
at the Tevatron



readout speed:

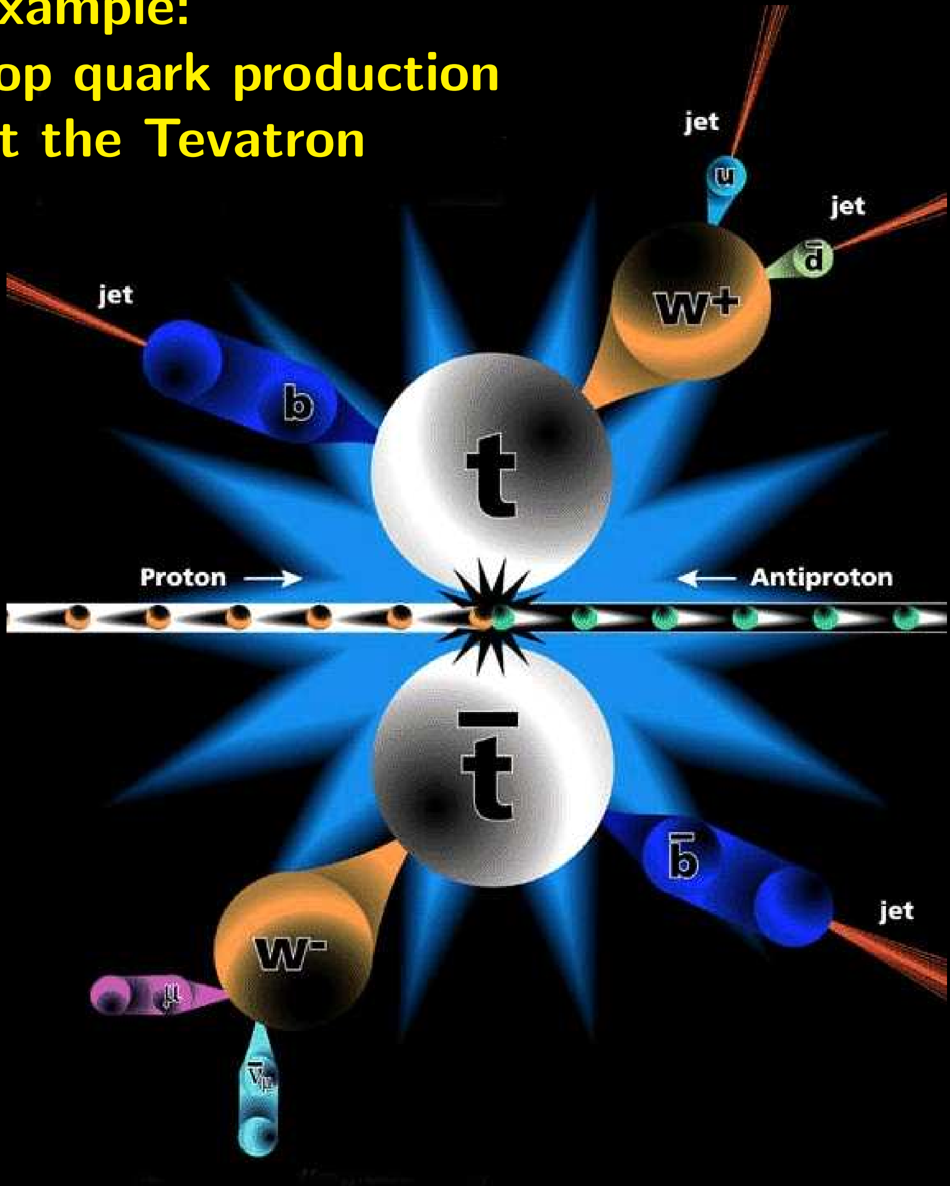
fraction of $t\bar{t}$ events
in Tevatron collisions:
$\sigma(t\bar{t})/\sigma(total\ inelastic) \approx 1/10^{10}$

Assume we want 10k $t\bar{t}$ pairs
in 10 years of 24/7 running:
10^{14} collisions/10 years
$\approx$ 300k collisions/second!

(neglecting the role of triggers,
efficiencies and similar "details".
actually have 1.7M collisions/second)

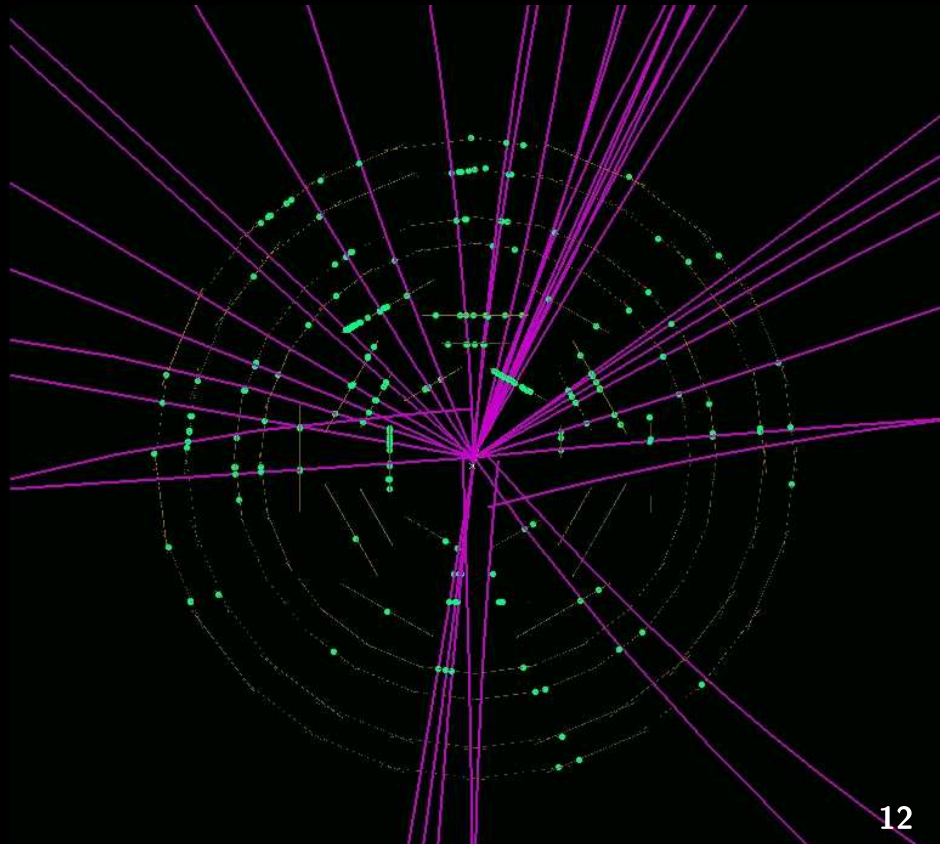
performance requirements

example:
top quark production
at the Tevatron



precision:

b **jet identification is crucial,**
making use of $\approx$**1.5 ps** b **lifetime:**
flight distance $\approx$ **few 100** μ**m**
$\rightarrow$ **want hit precision** $< 10\,\mu$**m**



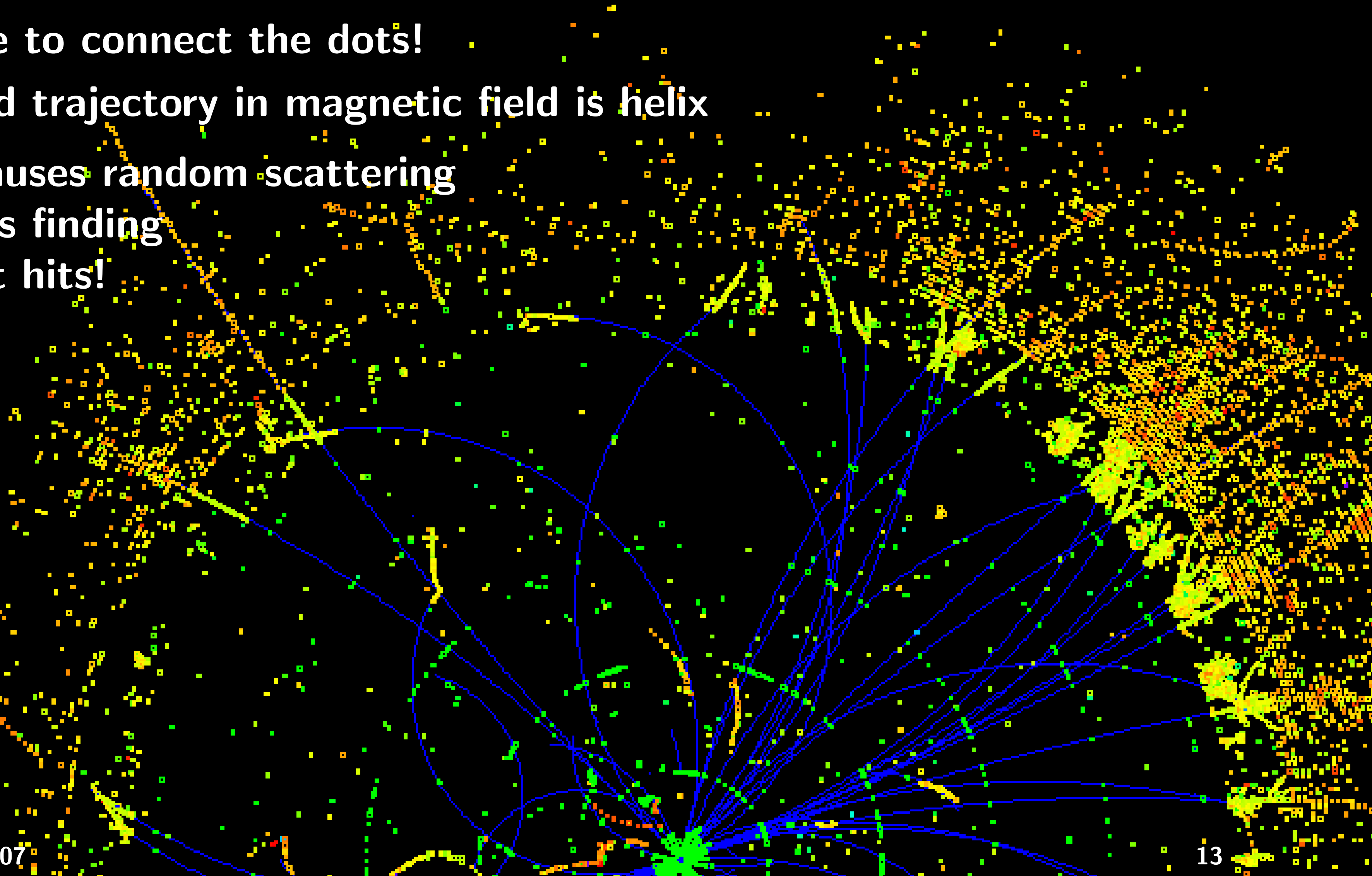
performance requirements

material budget:

need to be able to connect the dots!

- undisturbed trajectory in magnetic field is helix
- material causes random scattering
  → problems finding
  the right hits!

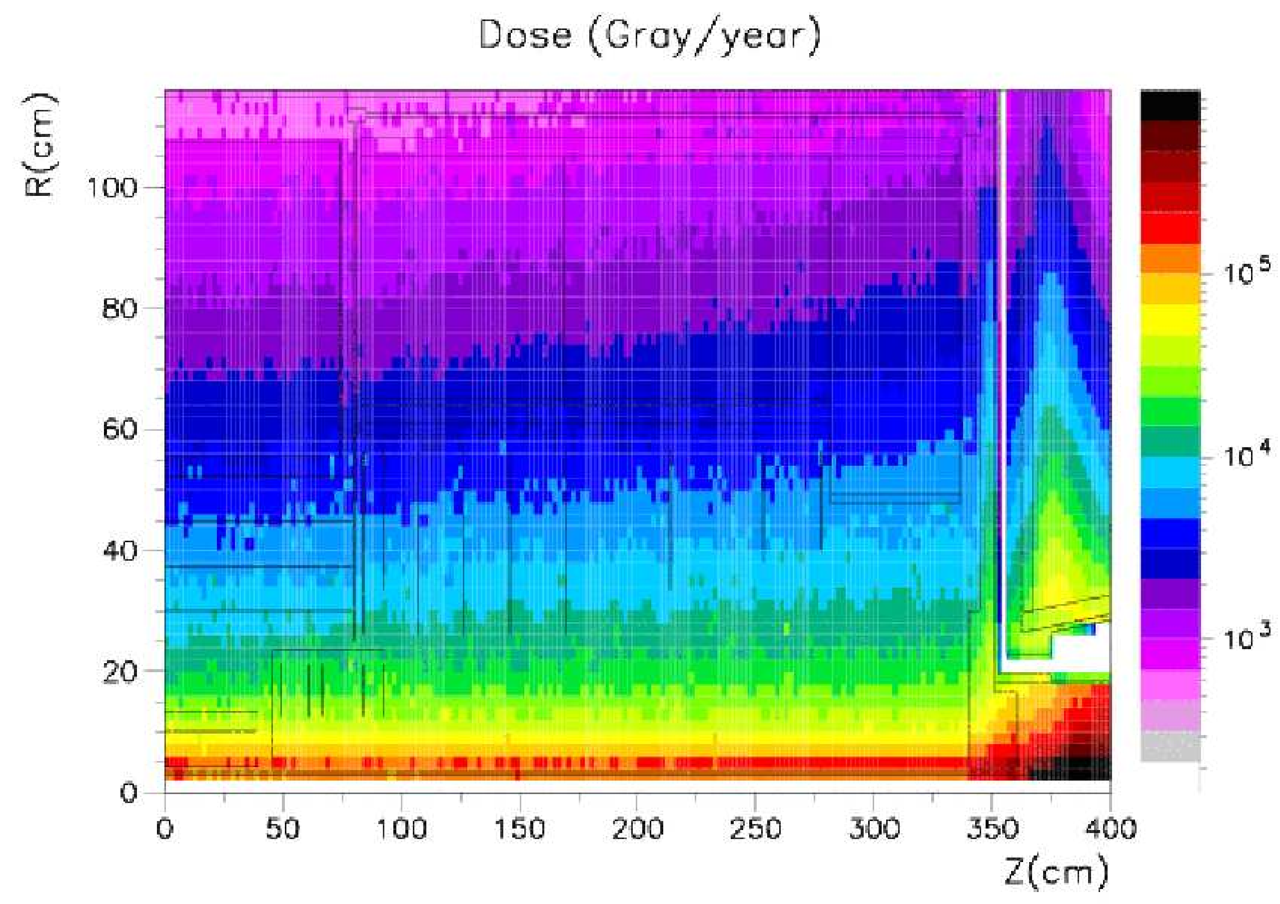
more problems:
momentum resolution, energy loss, secondary particles, ...

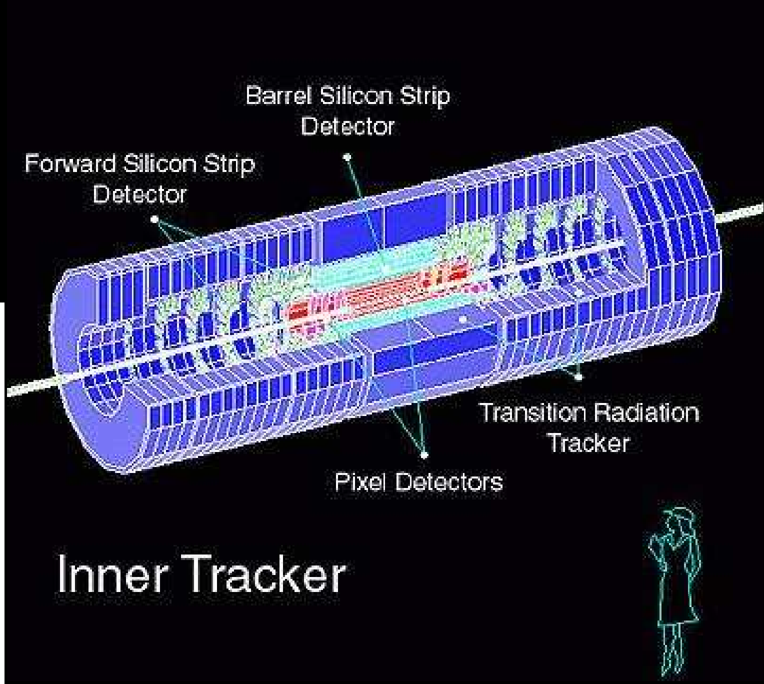


performance requirements

radiation hardness:

ATLAS detector at LHC: annual neutron dose





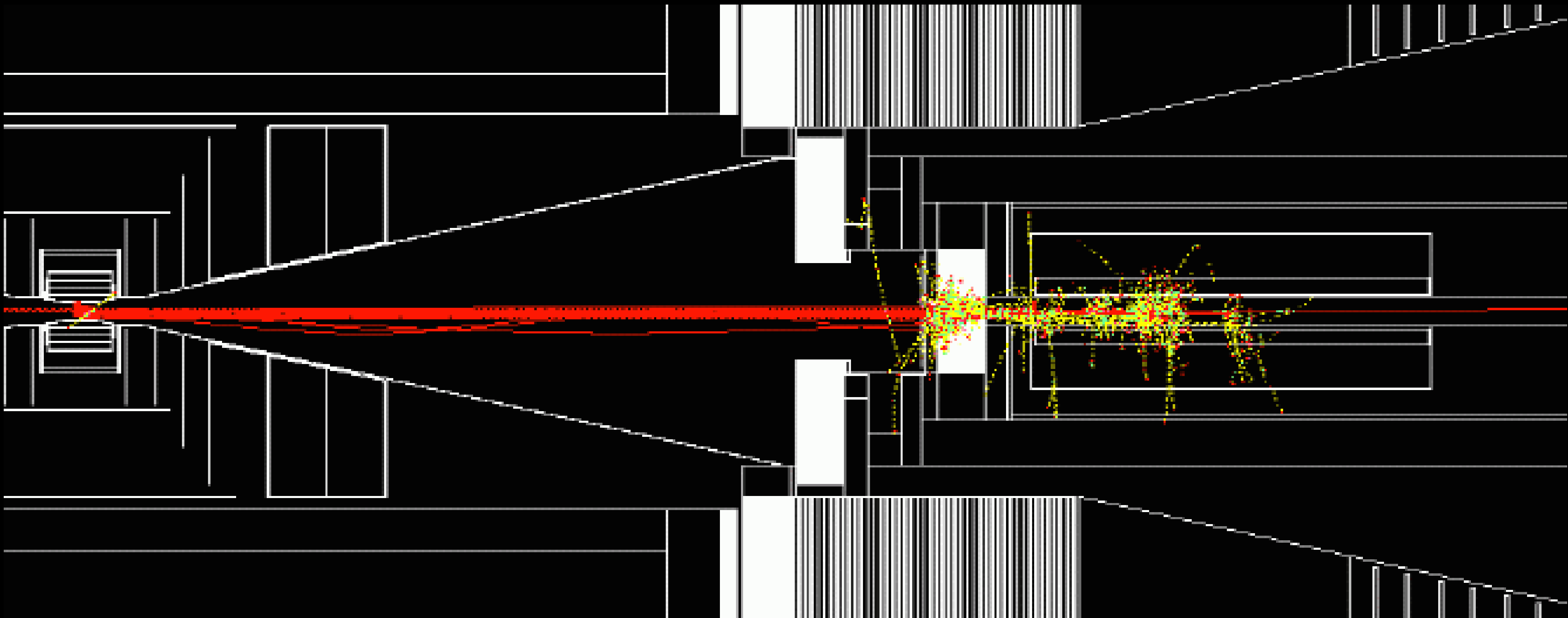
1 Gy = 100 rad
lethal dose ≈ few Gy

typical annual limit for physicists:
$\mathcal{O}(10)$ mGy

pretty harsh in there!

performance requirements

background levels:



- most types of radiation cause extra hits in detectors
- need to make sure granularity is fine enough to reduce occupancy to manageable level

silicon: beauty and the beast

Why are silicon detectors such a success?

- position resolution down to few microns
- readout speed: depending on technology, but they are rather fast
- radiation hardness: best option we have

But:

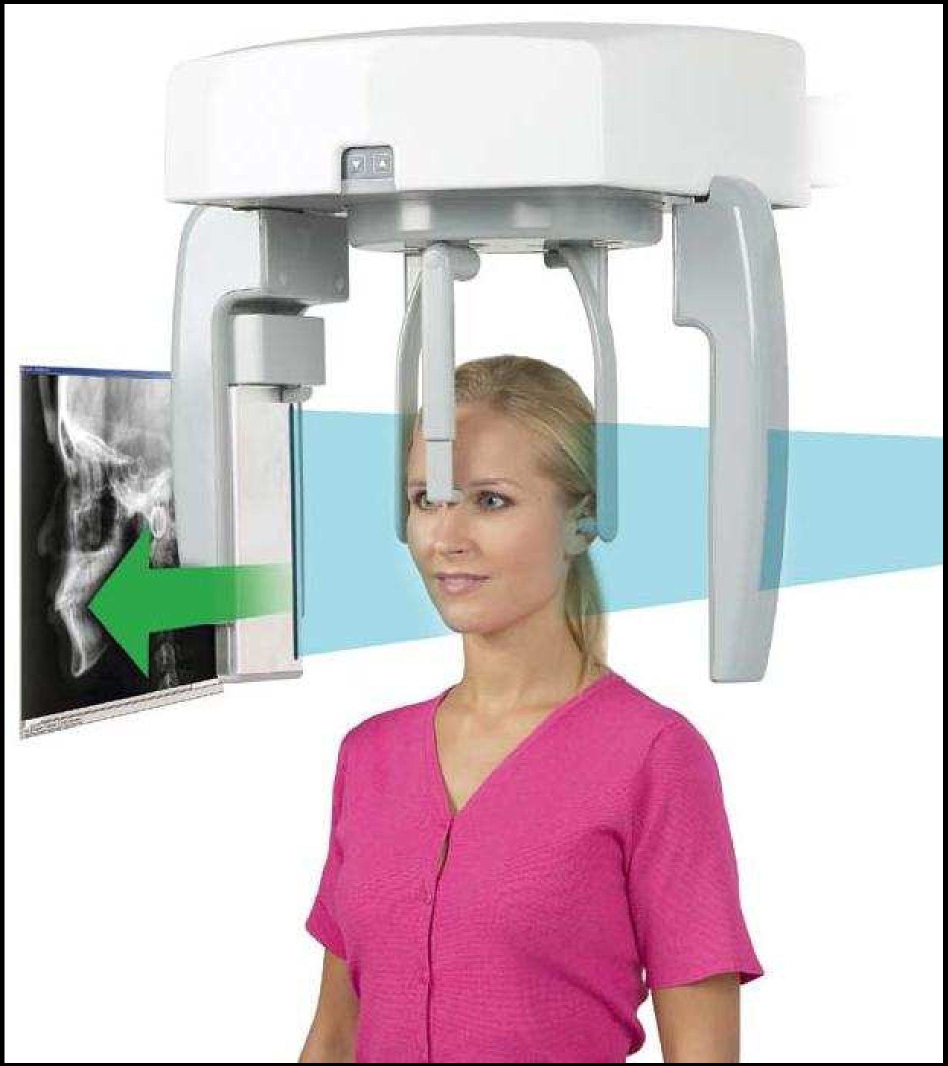
- material budget: so-so...
  sensors and infrastructure rather massive compared to gaseous trackers
  - ➡ use fewer layers (compensated by better resolution than gas readout)
    - ➡ pattern recognition is more difficult
- any attempt to reduce material budget makes detectors more fragile.
  notoriously difficult (if not impossible) to access for repair

another big benefit: lots of commercial silicon technology to exploit!

commercial silicon detectors

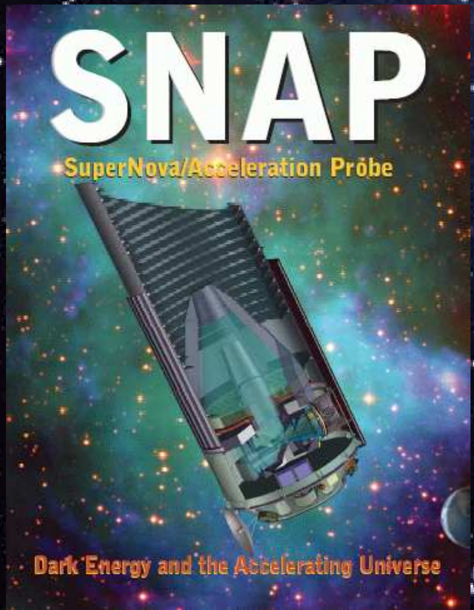
lots of mass market silicon pixel photon detectors available on ebay:

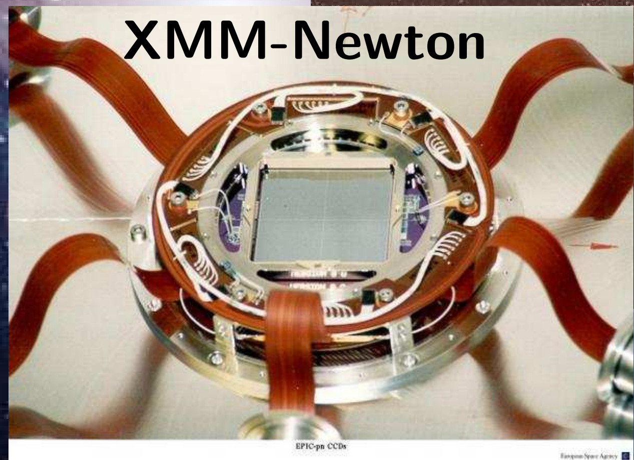
commercial silicon detectors



even many dentists use
silicon pixel detectors nowadays!

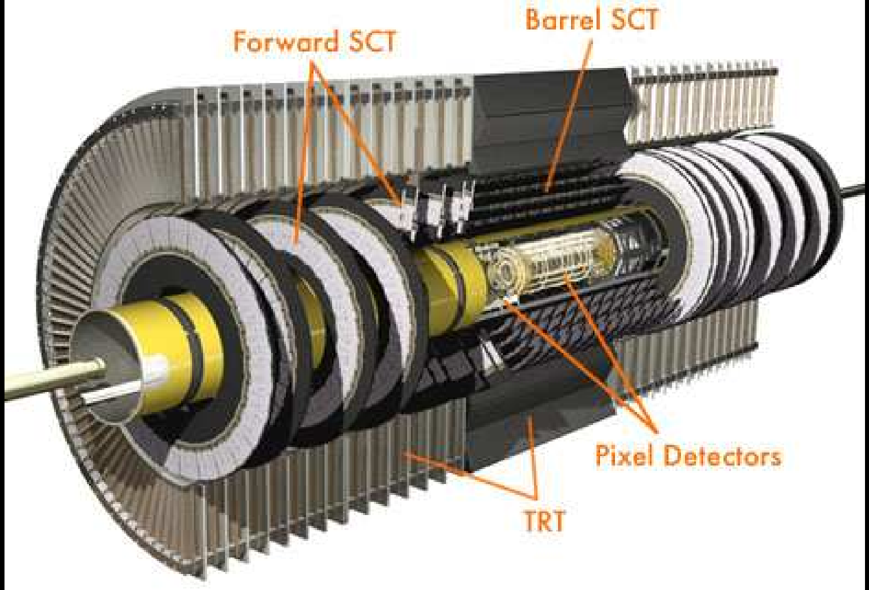
astronomers like silicon detectors:

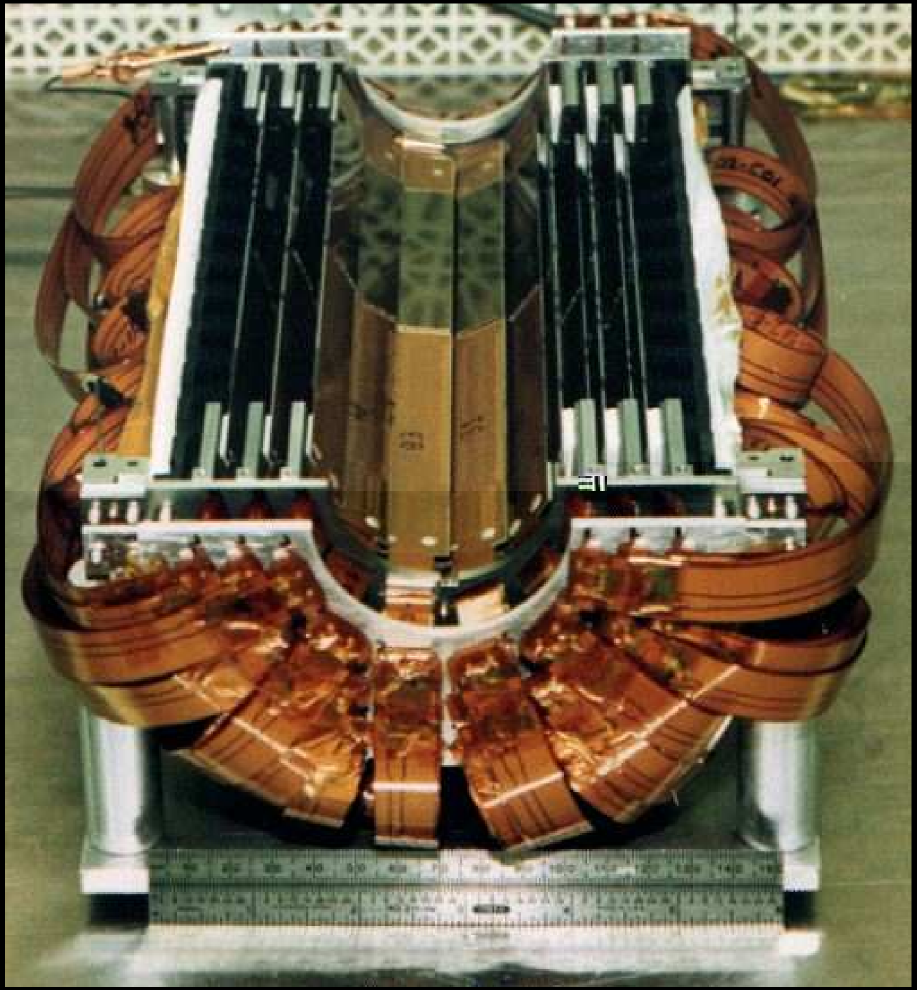




...and then there are materials analysis, nuclear science, and of course particle physics!

silicon in particle physics





silicon operating principle

silicon detector is essentially diode with reverse bias

- depleted of free charge carriers
- high resistance, only small leakage current
- charge deposition by ionising particle causes current

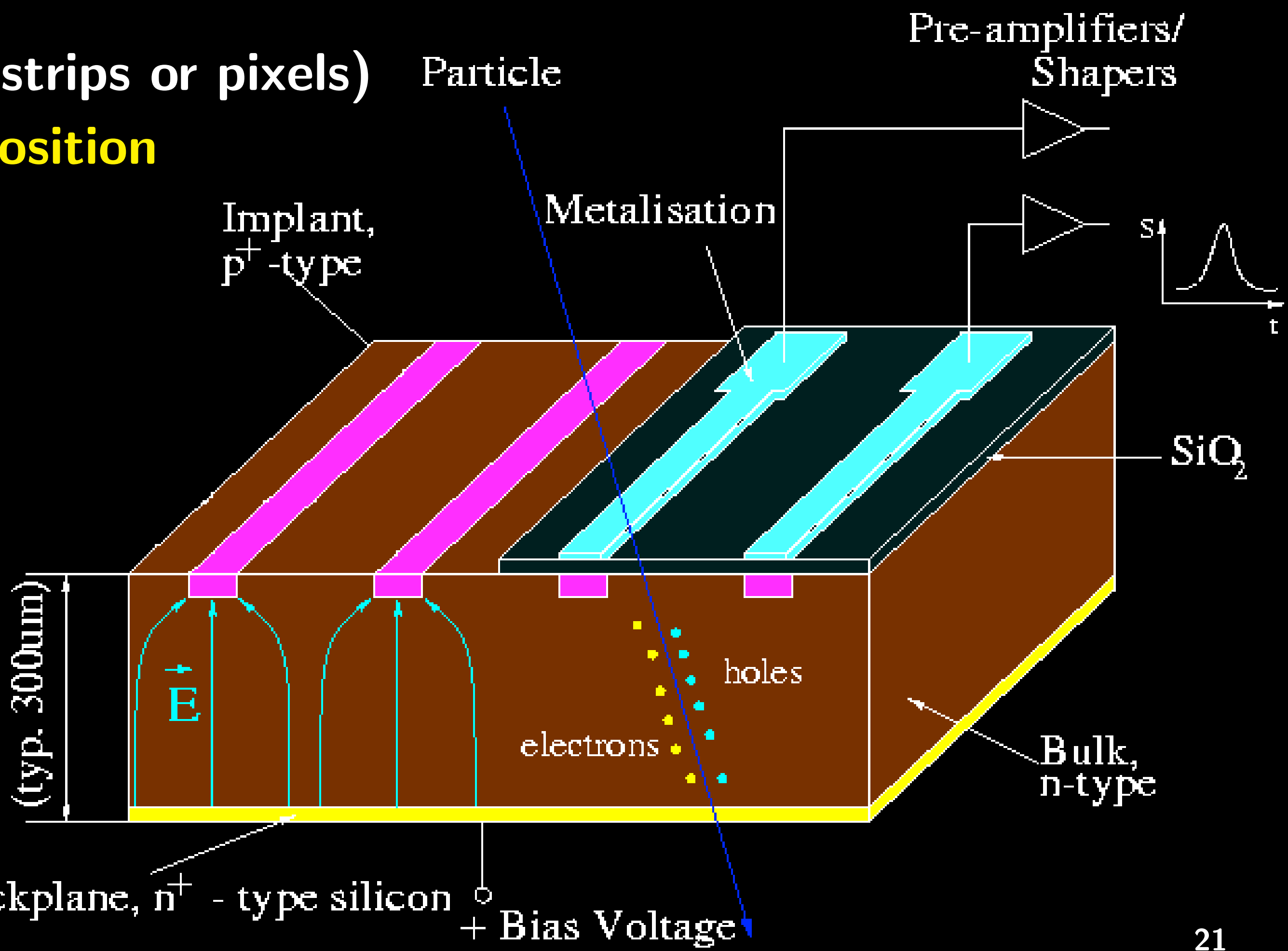
use segmented electrodes (strips or pixels)

- can localise charge deposition

much better resolution
than strip pitch
if taking charge sharing
into account

only few eV per ionisation
(gases: factor ≈10 more)

- good size signal

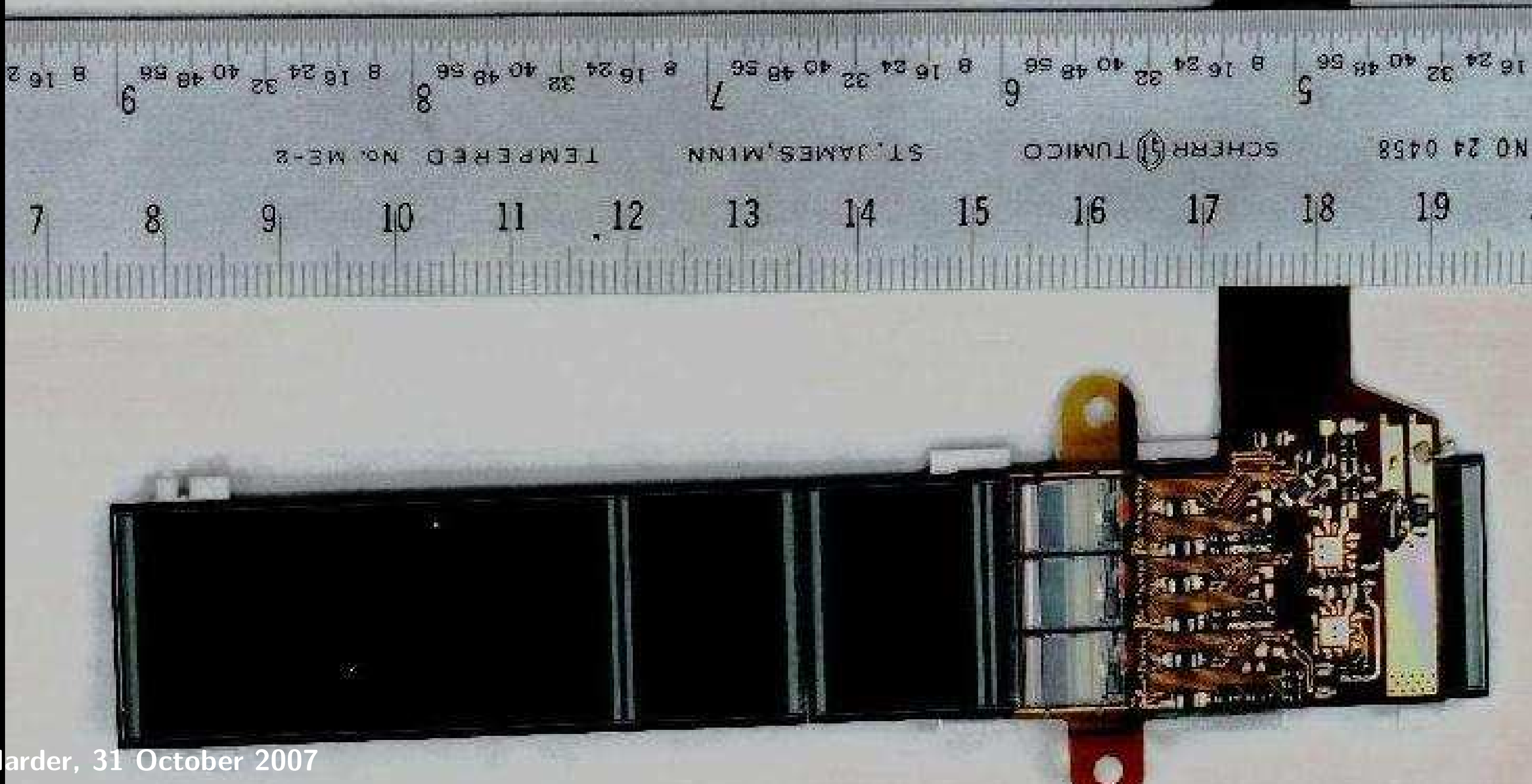


readout

Readout of strip sensor, power distribution and control: hybrids

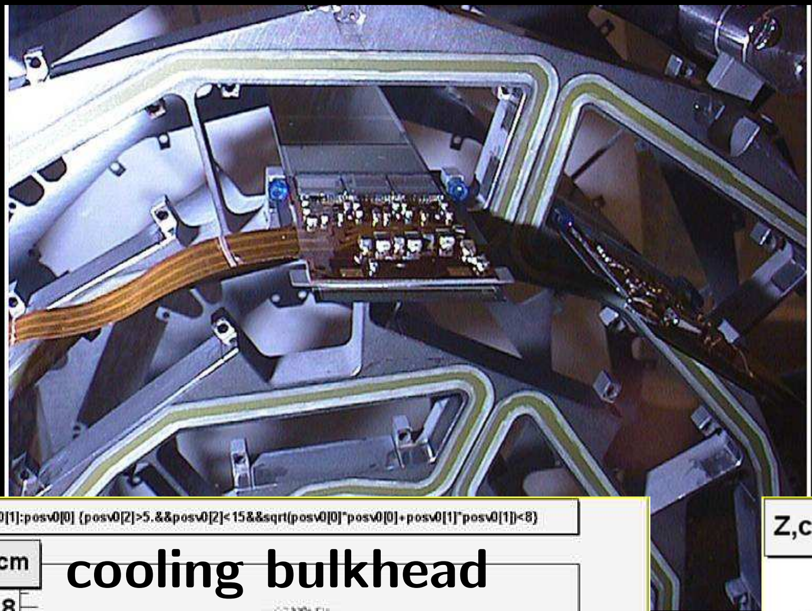
- custom readout chips wirebonded to electrodes on sensor
- chips have amplifiers, ADCs, zero suppression, cluster finder, storage, digital communication with outside world

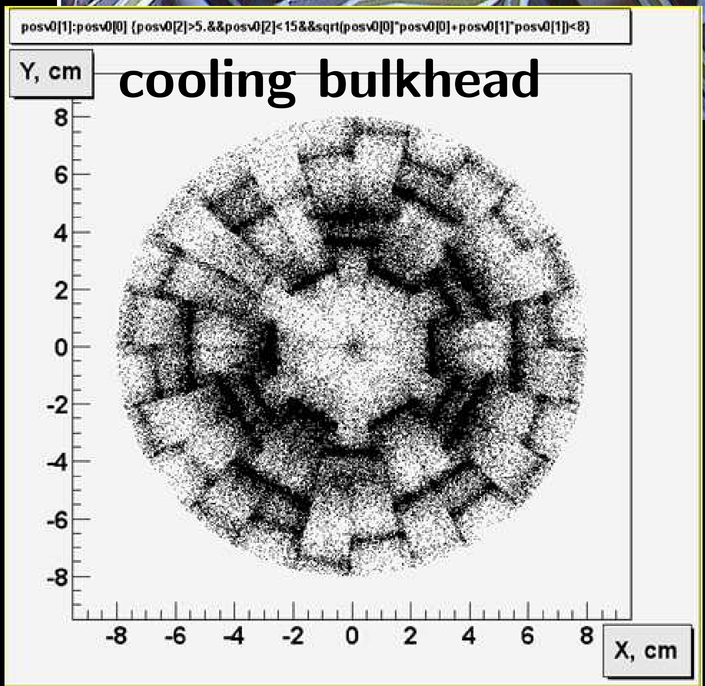
keep material budget low! (also by minimising power consumption → lighter cooling system)

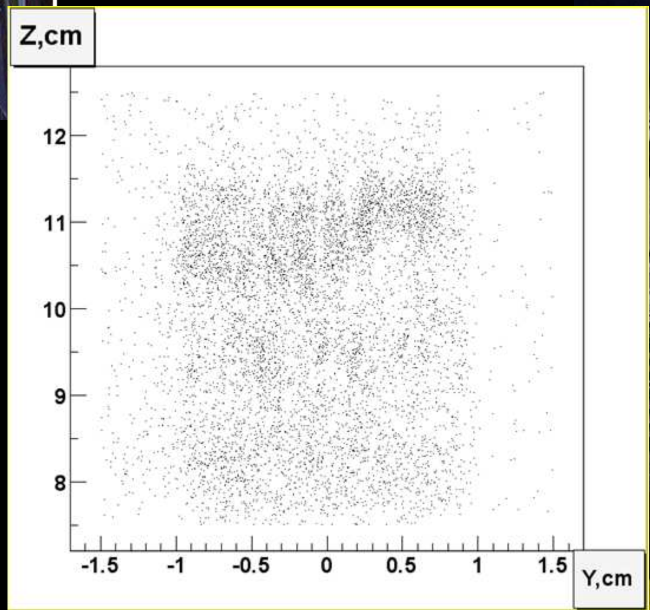


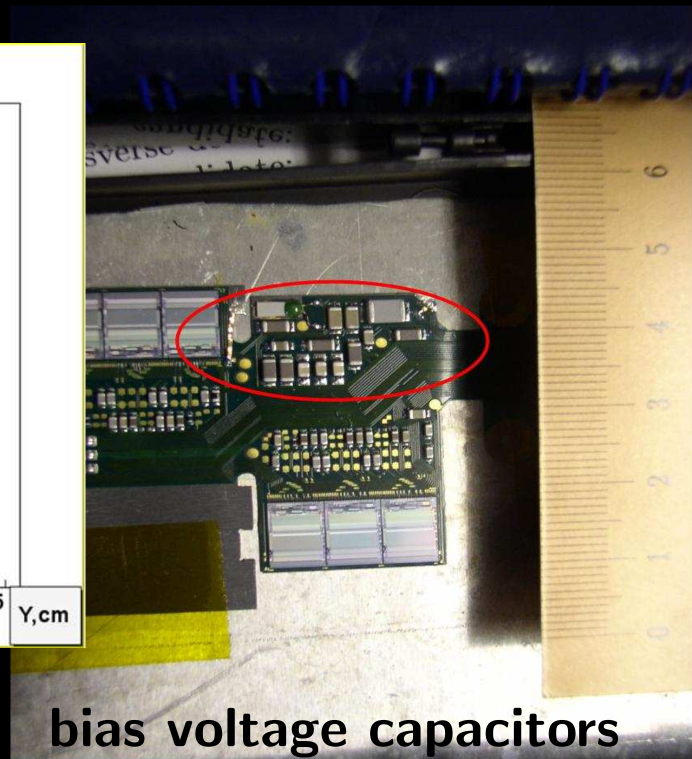
reminder: material budget

plot location of reconstructed
$\gamma \rightarrow e^+e^-$ (material interaction)
$\rightarrow$ "x-ray" image of detector!



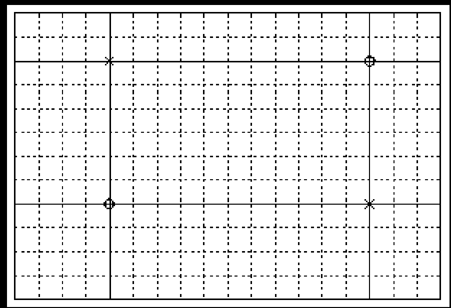






reminder: occupancy

strip detectors would exceed useful occupancy in many modern systems!
also, strip information can make hit reconstruction ambiguous:



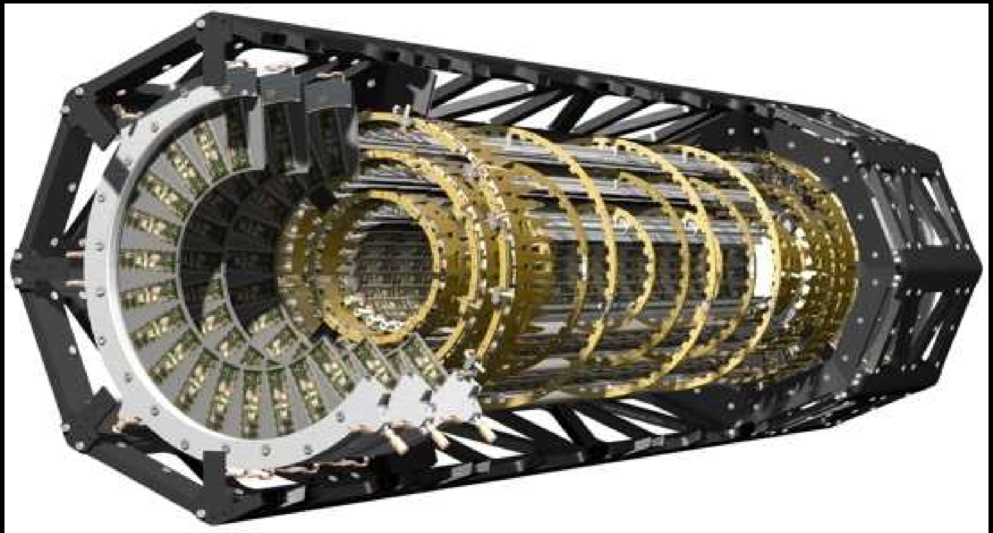
➡ silicon pixel detectors do better here!
problem: how to read them out?
reading out strips is comparatively easy — just attach chips to the end

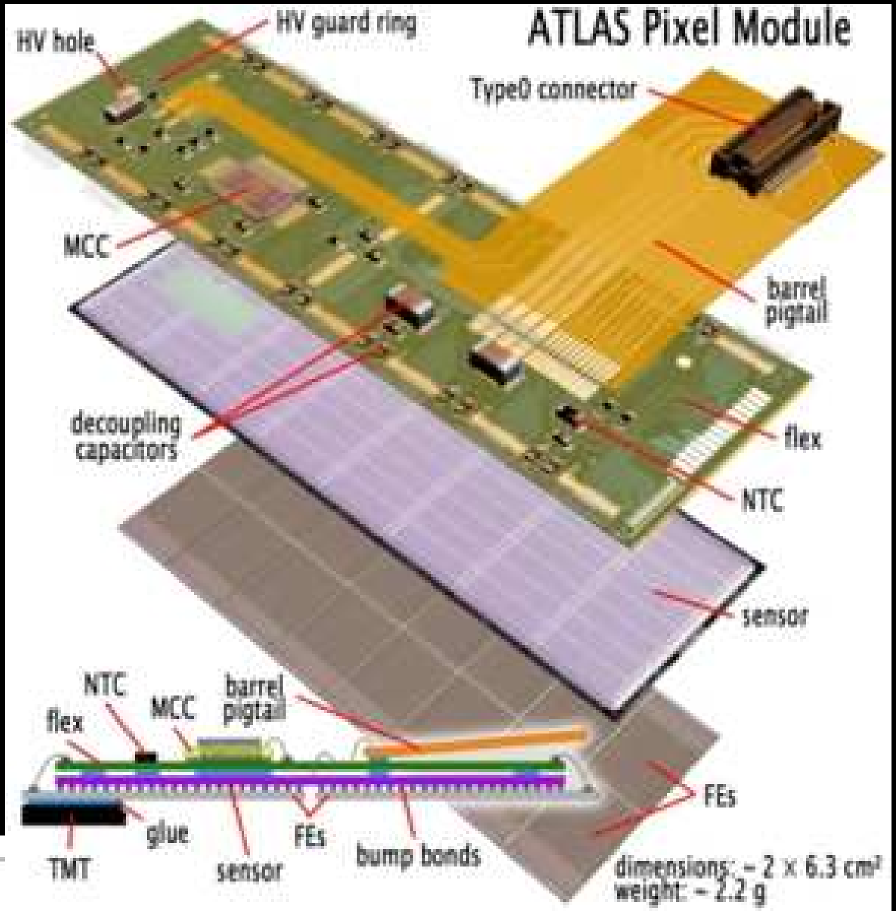
main options for pixels:

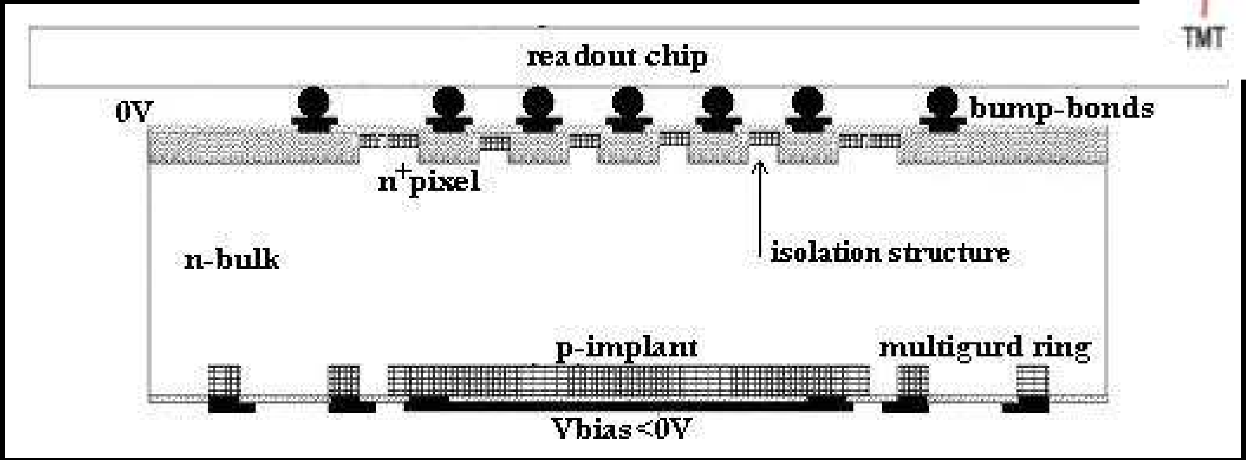
- place readout chips all over the sensors (more material)
- integrate readout electronics into sensor (larger pixels)
- clock signals through to end of sensor (slower)

hybrid pixels

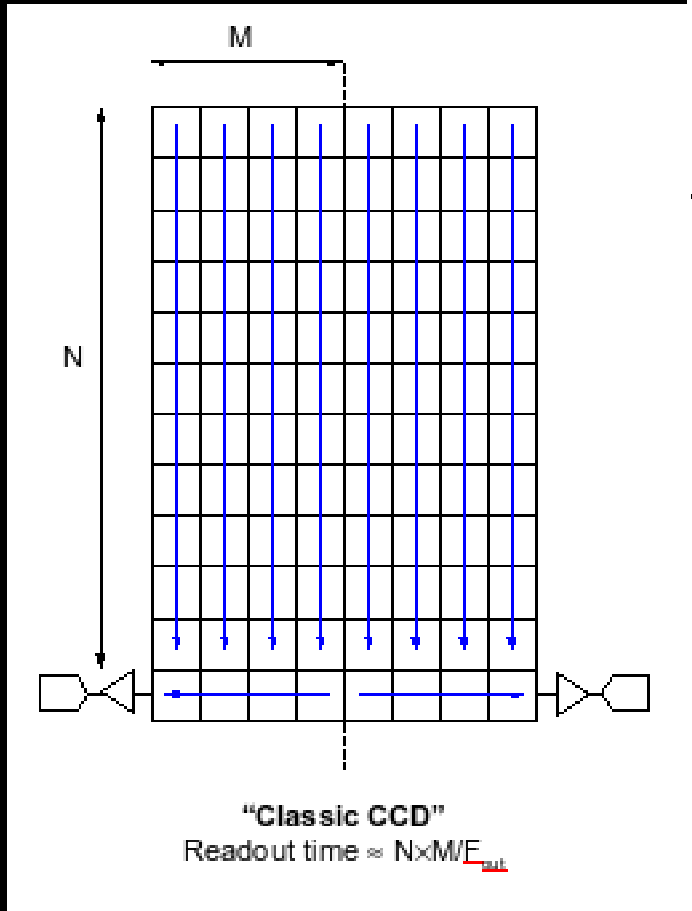
ATLAS pixel detector

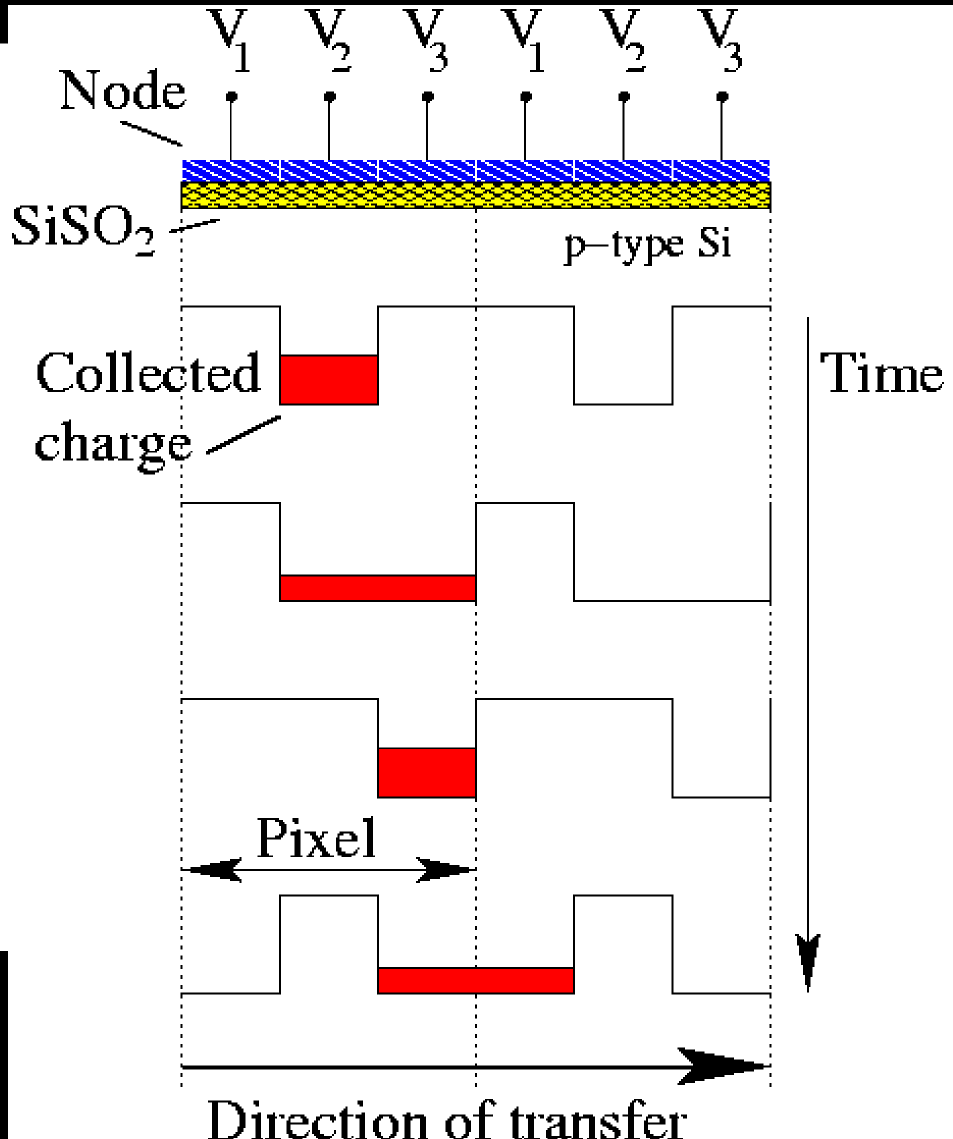






CCDs





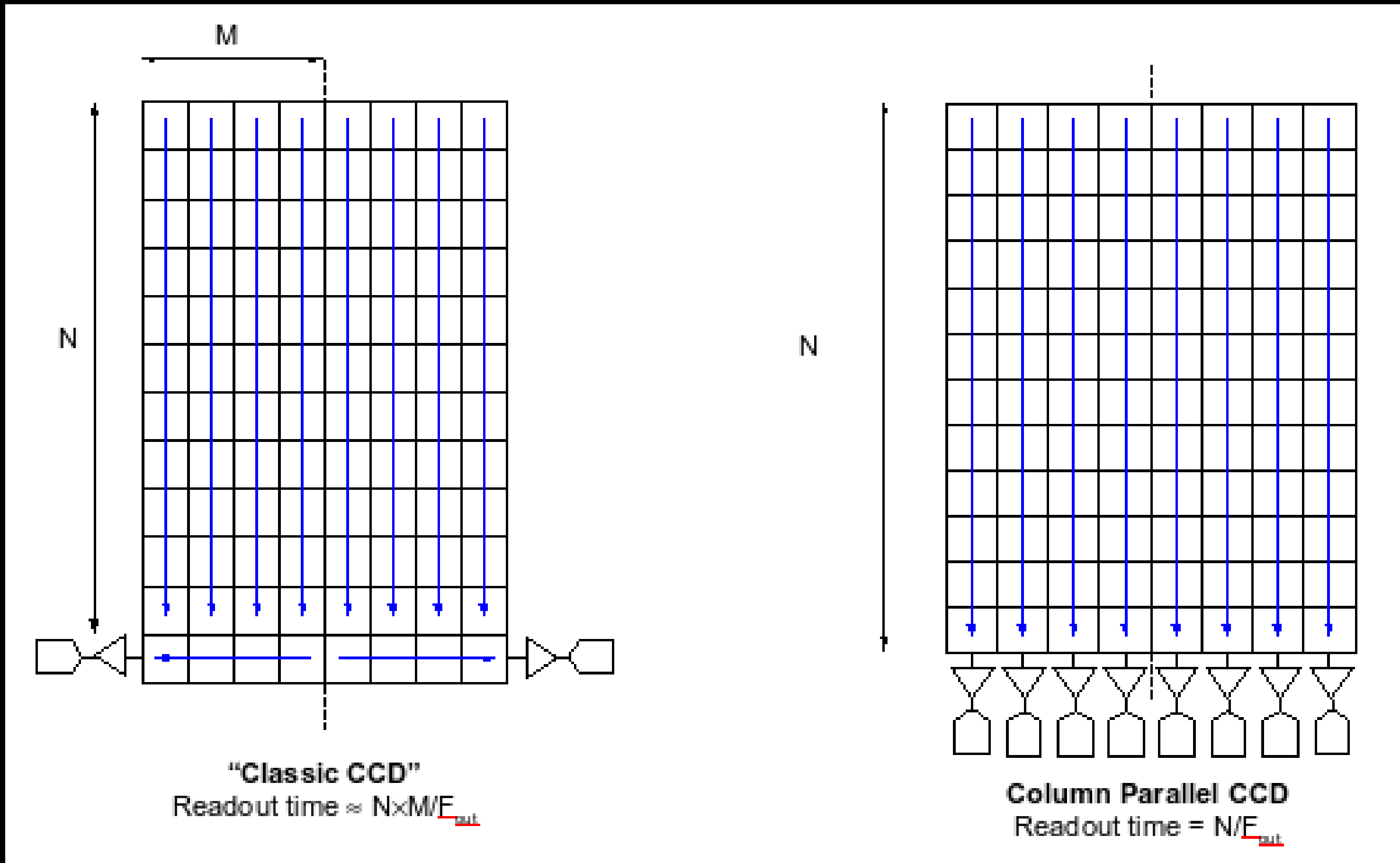
CCD = most common Si sensor outside particle physics!

clock charge deposits across sensor towards output node.

side-effect: time vs length ambiguity

problem: takes a long time to read out

column parallel CCDs



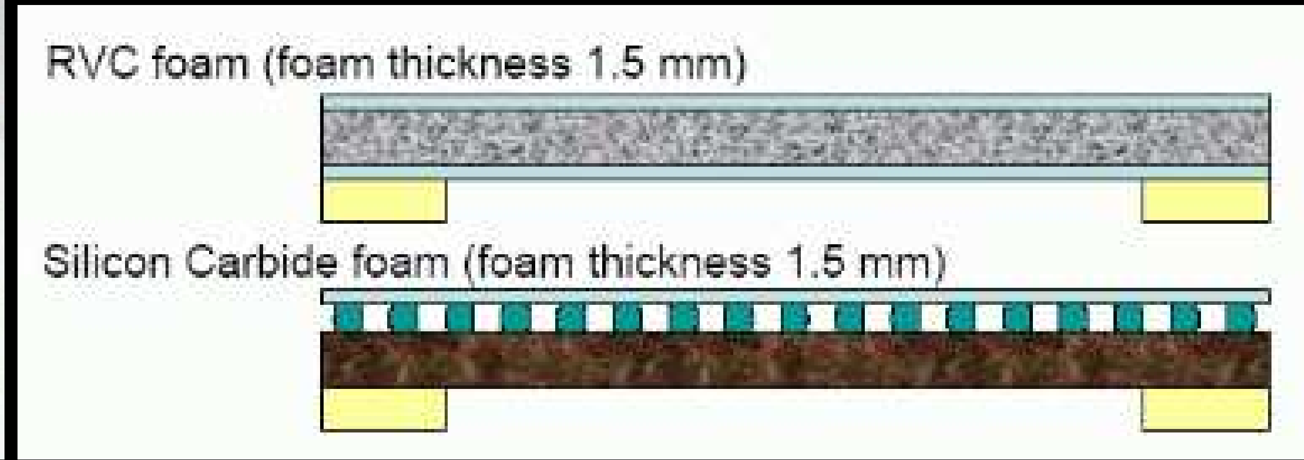
- regular CCDs (like in digital cameras) clock charge out to corners of sensor
- LCFI collaboration develops faster version with column parallel readout
- high speed parallel readout ⟶ rather large power consumption

sensor support

typical sensor thickness so far: 300 μm. we need to do better!

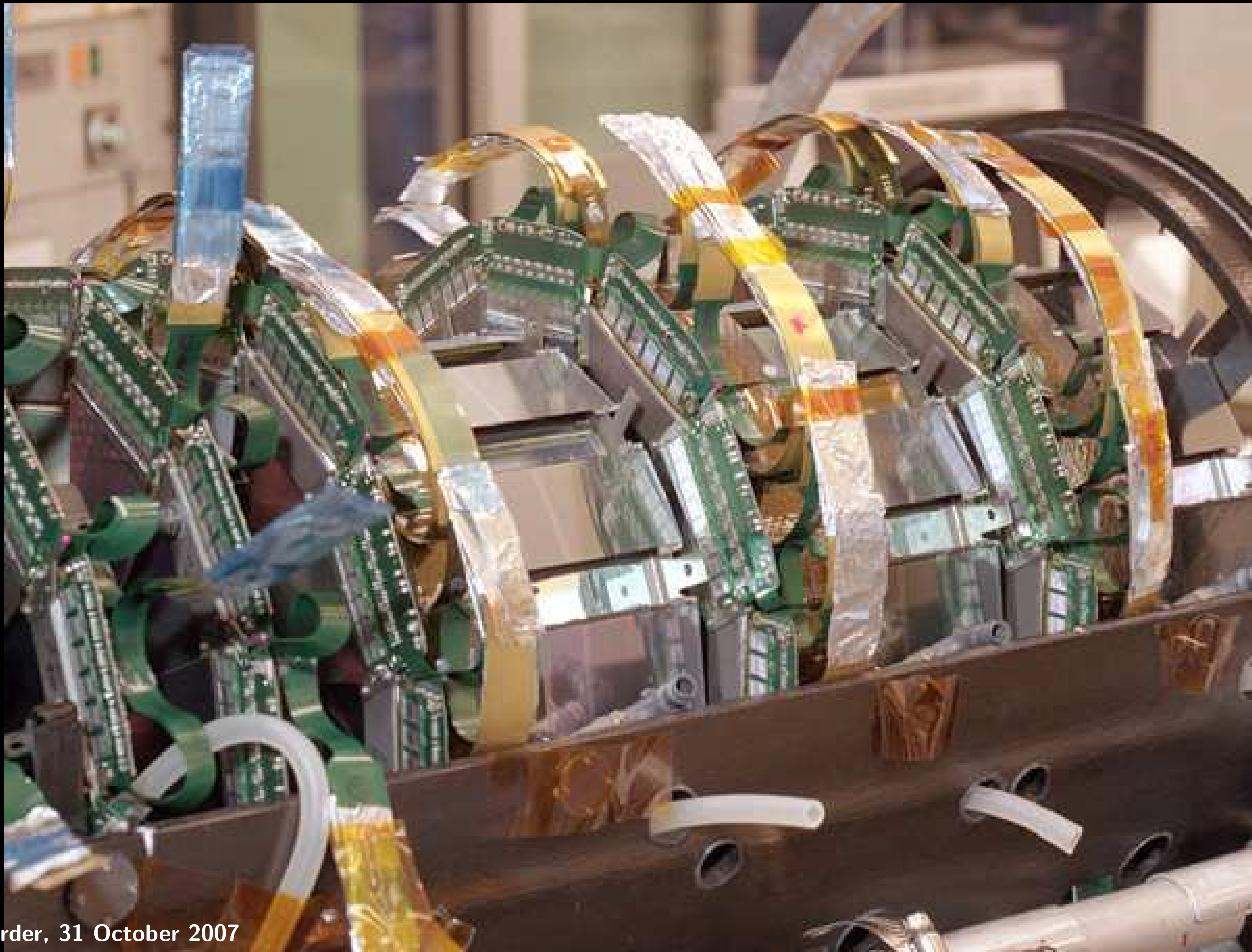
- CCDs should work just as well if ground down to 20 μm thickness!
- 20 μm thin silicon is veeeery floppy
- micron size pixel resolution won't help if the sensor is wobbling around!
  - strong currents in strong magnetic fields,
  - temperature cycles during readout, ...

➡ active R&D trying to identify suitable support structures

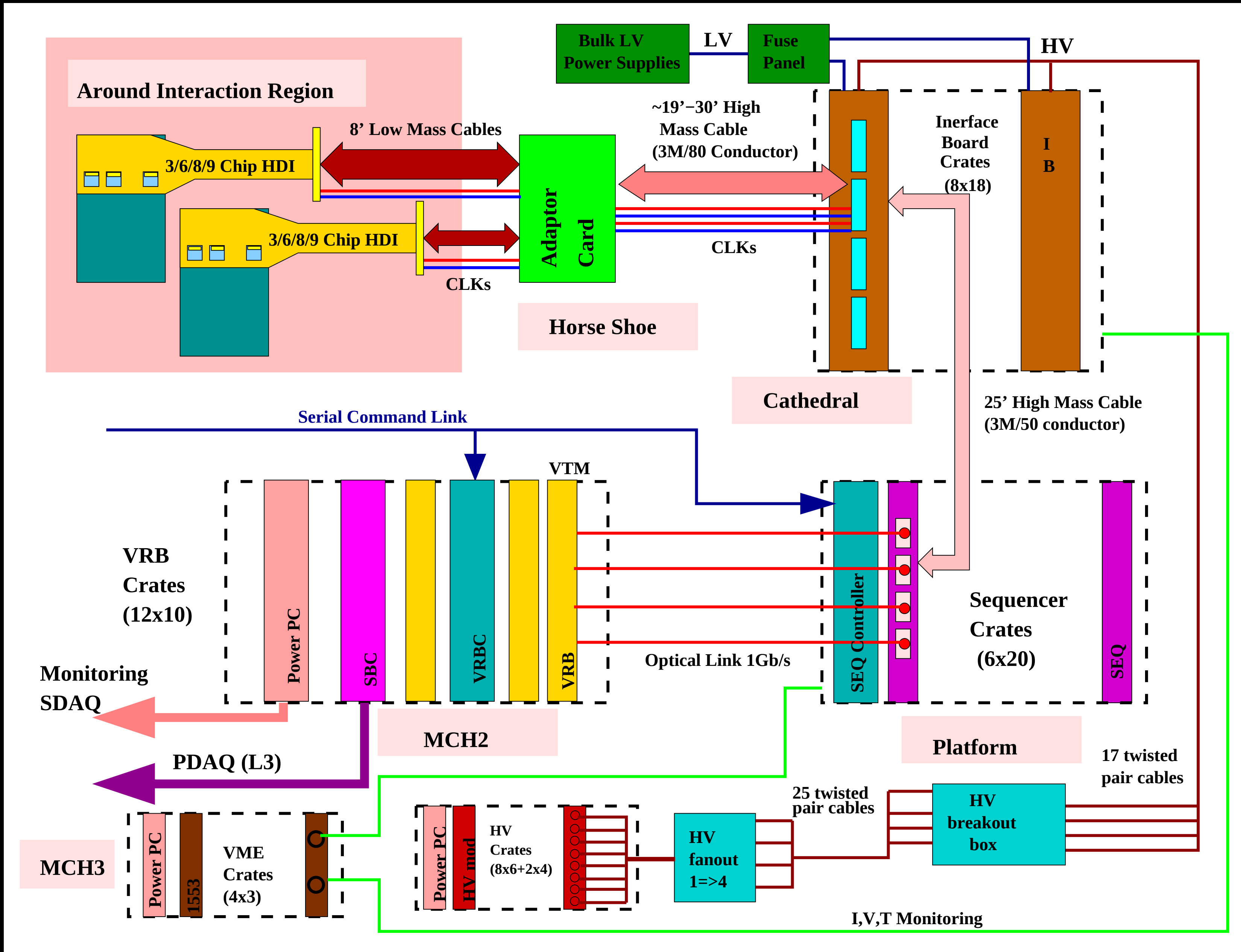


Particle Physics
Rutherford Appleton Laboratory

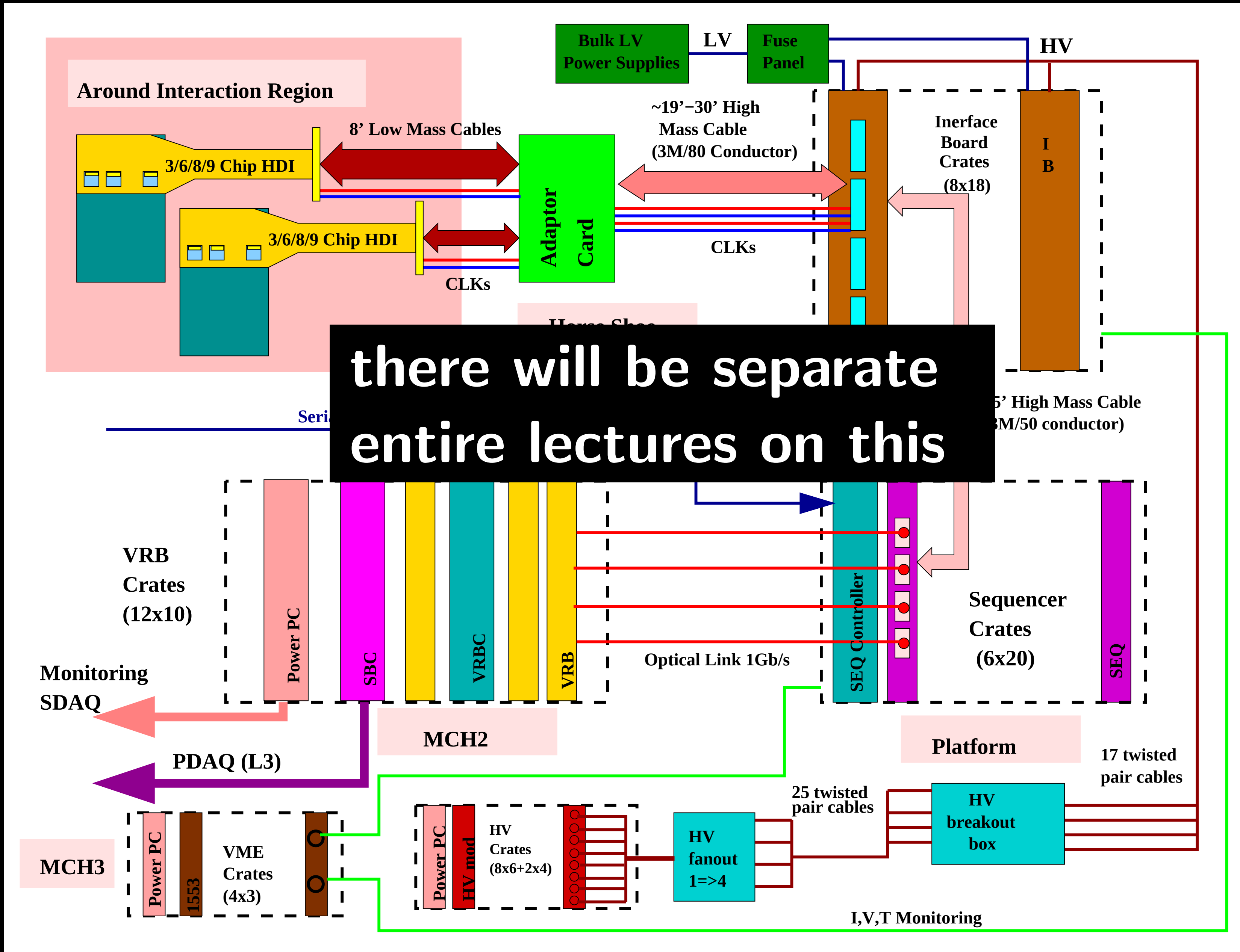
putting it all together



a full system



a full system



there will be separate entire lectures on this

the dark side

I talked a lot about how silicon detectors work.
Now, let us discuss how silicon detectors stop working!

Common problems:

- radiation damage
- design mistakes

radiation damage

radiation damage is expected!

- steady irradiation from beam halo, scattered particles
- acute doses from loss of control over beam

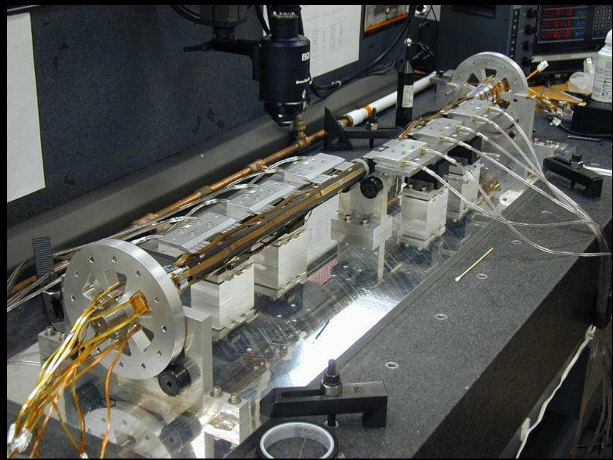
effects on silicon:

- surface damage: charge build-up $\longrightarrow$ noise
- bulk damage: displacements in crystal lattice
  - $\longrightarrow$ reduced charge collection efficiency (charge lost in traps)
  - $\longrightarrow$ change dopant levels and distribution (affects bias voltage)
  - $\longrightarrow$ increased leakage current ($\longrightarrow$ noise)

what can we do?

- radiation hard detector (and electronics) design
  (careful choice of material, dopants; pre-irradiation, ...)
- monitor beam conditions (ask CDF)
  $\longrightarrow$ shut down bias voltage before beam hits your detector
- keep detectors cooled at all times
  $\longrightarrow$ reduces mobility of lattice defects

some lessons learned



CDF added new inner layer to its silicon detector for Tevatron Run II

- pedestal was found to be unstable across chip and event by event
- identified as noise pickup from cables.
- additional shielding would fix it, but the cables are inaccessible.

fortunately, CDF was able to work around it:

- disable zero suppression
- fit pedestals offline event by event

as a consequence, DØ revised the grounding scheme of their new inner layer

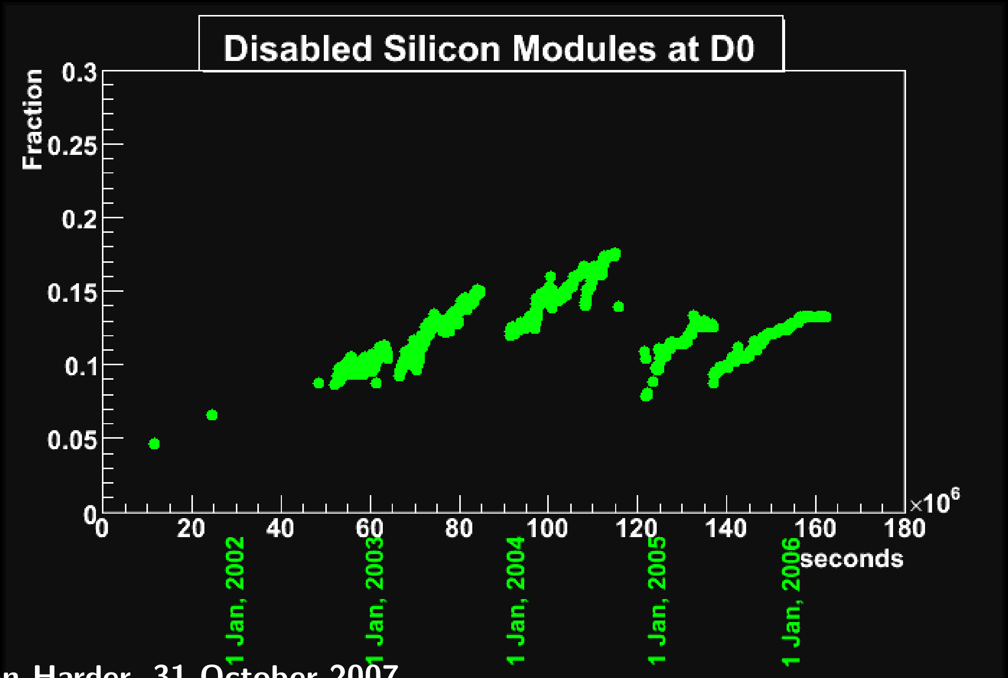
some lessons learned

DØ silicon detector based on SVXIIe readout chip.
this chip turned out to have two big problems:

- runaway currents during power on (no proper initialization)
- runaway currents during inactivity

revised chip version SVX3 was made available;

- CDF took it,
- DØ didn't think they had enough time for electronics redesign

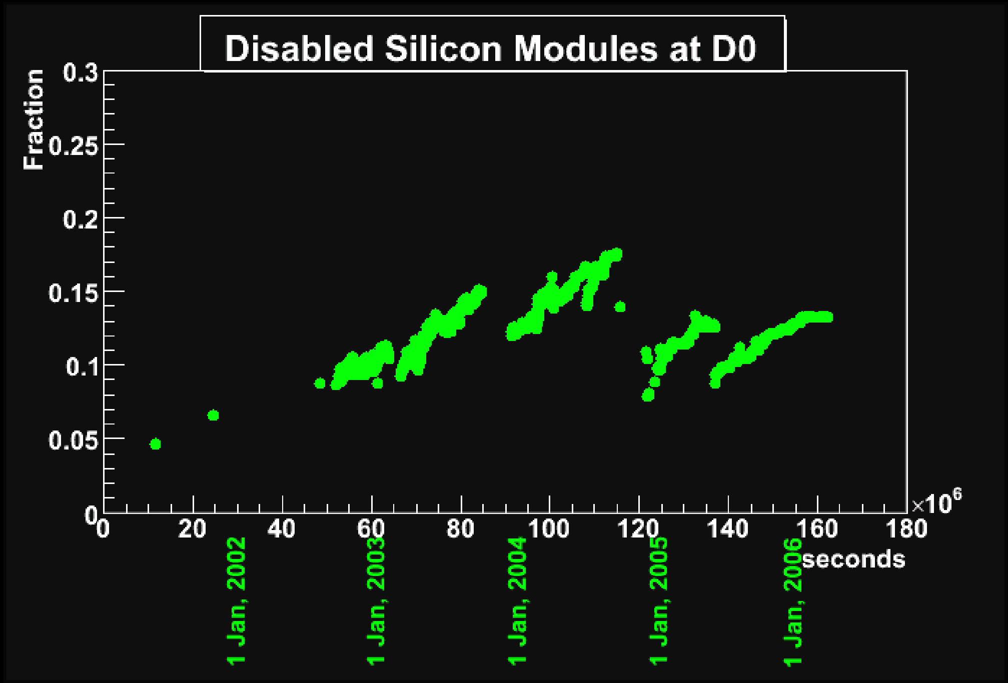


interventions:

- repair external electronics
- modify external electronics to cope with damaged chips
- design heartbeat trigger to eliminate inactivity periods

more lessons learned

look more closely:



- 5% of the modules dead after detector insertion! cabling?
- few percent not really dead, but too noisy for use
  - forward disks were produced by two manufacturers
  - disks from one manufacturer work normally
  - the other disks had many modules develop serious noise problems
  - even after years of pondering, this is not understood

conclusion

- silicon detectors are probably our most powerful and most versatile detection instruments
- many new silicon detectors in preparation (LHC, ILC)
- treat them with care

Beyond silicon?

Maybe, in the far future, this lecture will be about diamond detectors

- more radiation hard
- larger band gap $\longrightarrow$ smaller signal (factor $\approx$3)
- no 6 inch single-crystal diamond wafers in mass production yet...