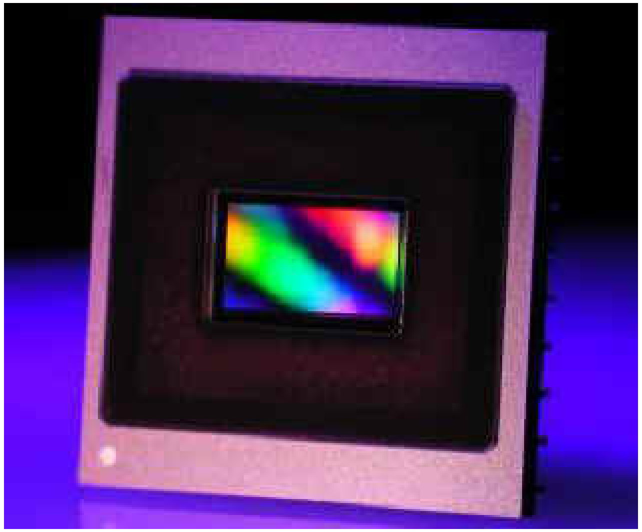
Introduction to Silicon Detectors

Marc Weber, Rutherford Appleton Laboratory

- Where are silicon detectors used?
- How do they work?
- Why silicon?
- Electronics for silicon detectors
- Silicon detectors for the ATLAS experiment
- Radiation-hardness
- Future

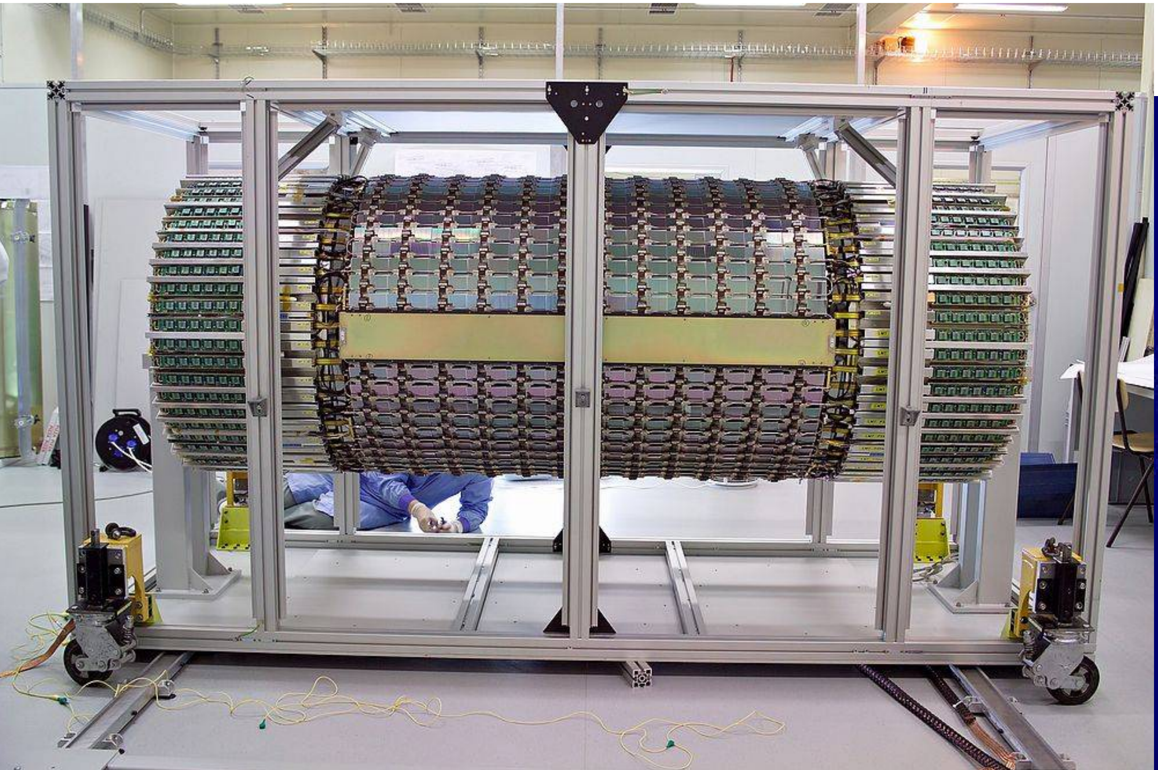
Where are silicon detectors used?

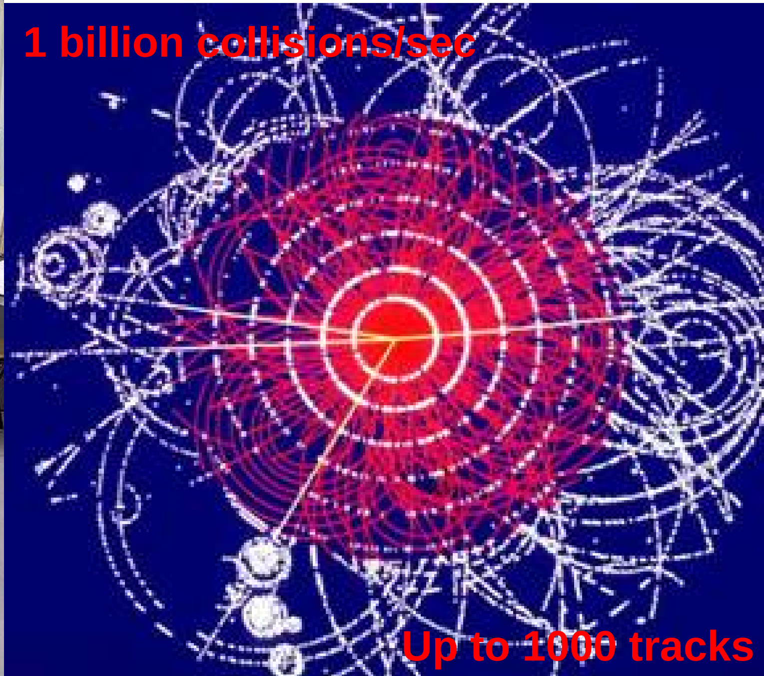
in your digital Cameras to detect visible light



in particle physics experiments to detect charged particles

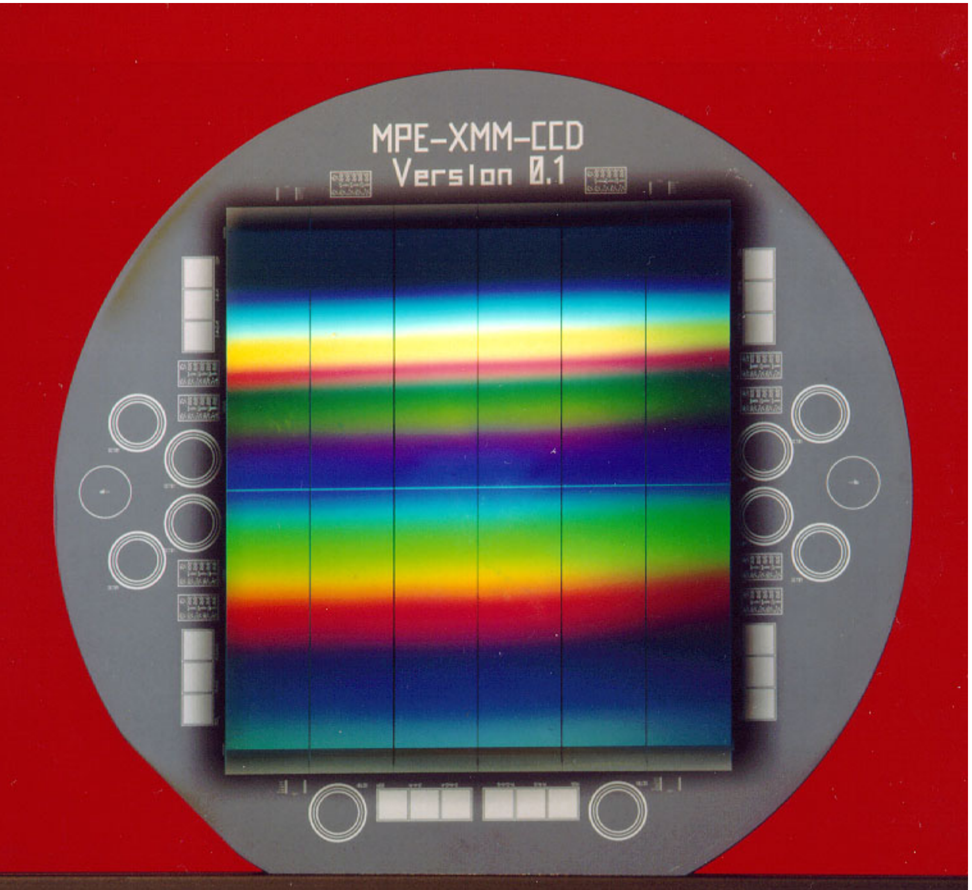
Example: ATLAS Semiconductor Tracker (SCT); 4000 modules; 6 M channels



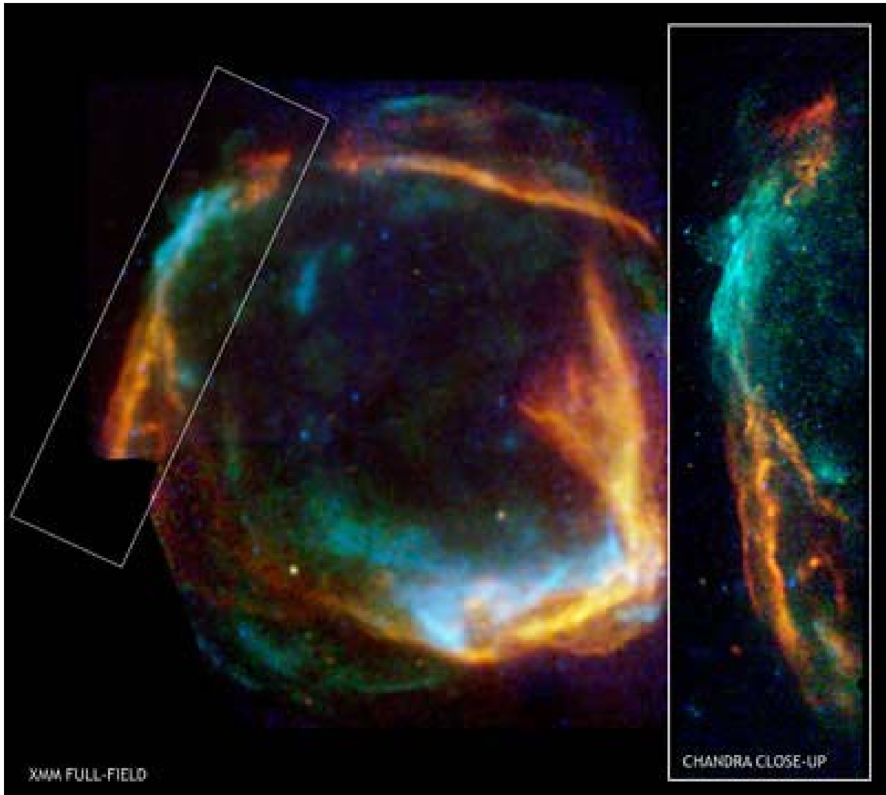


in astrophysics satellites to detect X-rays

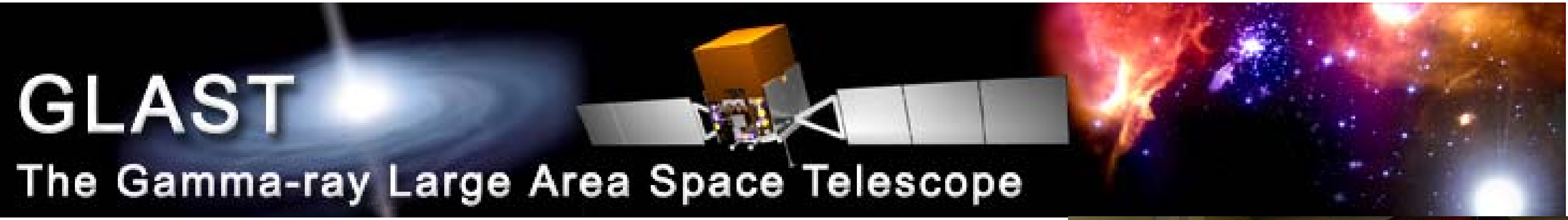
Example: EPIC p-n CCD of XMM Newton

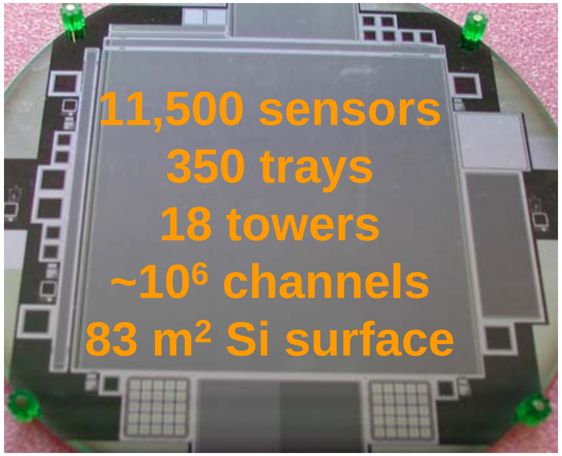


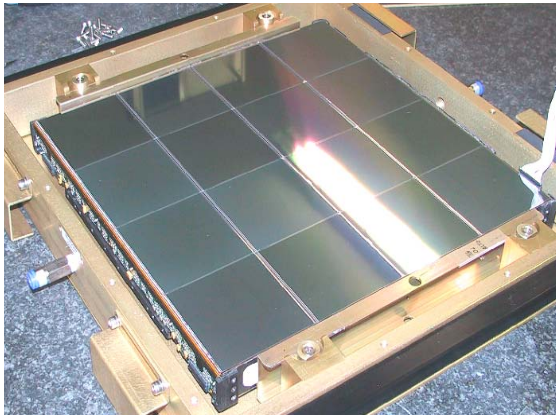
New picture of a supernova observed in 185 AD by Chinese astronomers



in astrophysics satellites to detect gamma rays







Silicon detectors are used at many other places

- in astrophysics satellites and telescopes to detect visible and infrared light
- in synchrotrons to detect X-ray and synchrotron radiation
- in nuclear physics to measure the energy of gamma rays
- in medical imaging

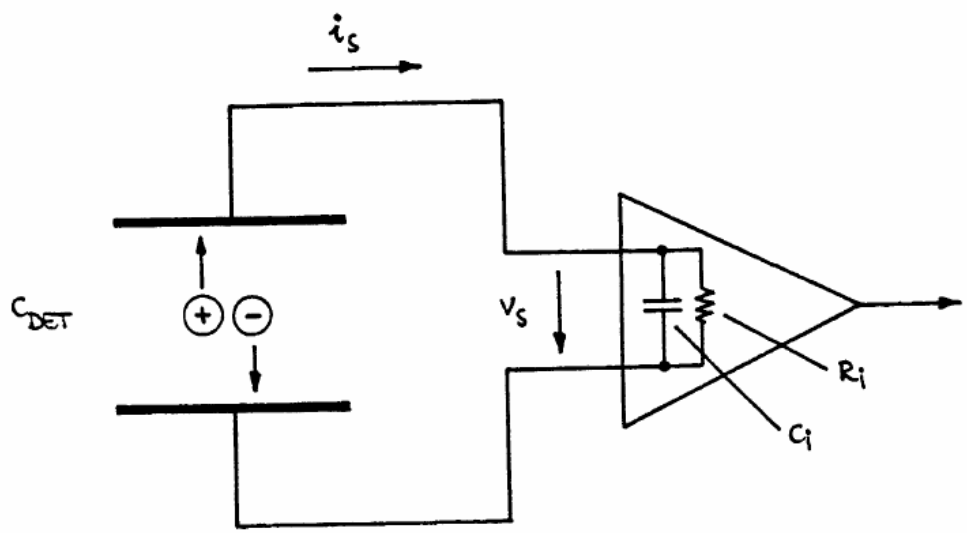
What makes silicon detectors so popular and powerful?

Operation principle ionization chamber

1. Incident particle deposits energy in detector medium ⇔ positive and negative charge pairs

2. Charges move in electrical field ⇔ electrical current in external circuit

Most semiconductor detectors are ionization chambers



How to chose the detection medium ?

Desirable properties of ionization chambers

Always desirable: signal should be big; signal collection should be fast

for particle energy measurements: particle should be fully absorbed ⇔
high density; high atomic number Z; thick detector
Example: Liquid Argon

for particle position measurements: particle should not be scattered ⇔
low density; low atomic number; thin detector
Example: Gas-filled detector; semiconductor detector

Typical ionization energies for gases ⇔ 30 eV
for semiconductor ⇔ 1-5 eV

Get (much) more charge per deposited energy in semiconductors

Semiconductor properties depend on band gap

Small band gap ⇔ ≈ conductor

Very large charge per energy, but

electric field causes large DC current >> signal current

Charged particle signal is “Drop of water in the ocean”

Large band gap ⇔ ≈ insulator (e.g. Diamond)

little charge per energy
small DC current; high electric fields

Medium band gap ⇔ ≈ semiconductor (e.g. Si, Ge, GaAs)

large charge per energy

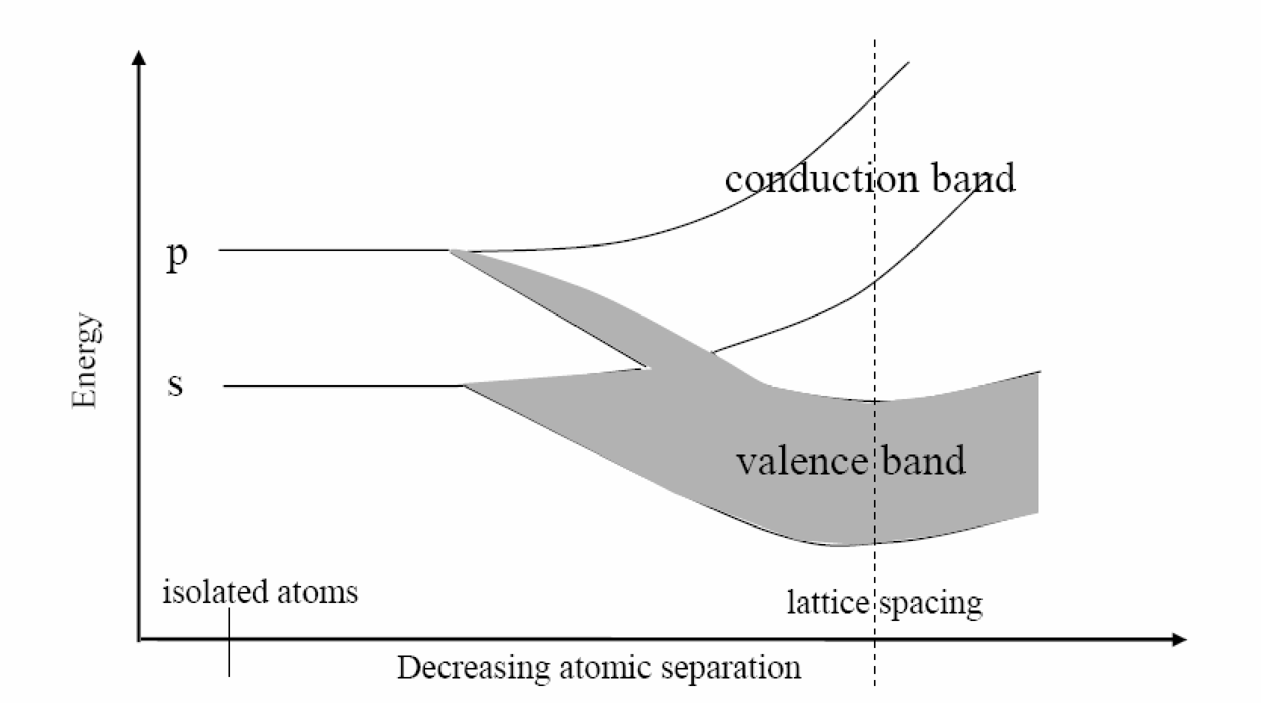
What about DC current ?

Semiconductor basics

When isolated atoms are brought together to form a crystal lattice, their wave functions overlap

The discrete atomic energy states shift and form energy bands

Properties of semiconductors depend on band gap



Semiconductor basics

Intrinsic semiconductors are semiconductors with no (few) impurities

At 0K, all electrons are in the valence band; no current can flow if an electric field is applied

At room temperature, electrons are excited to the conduction band

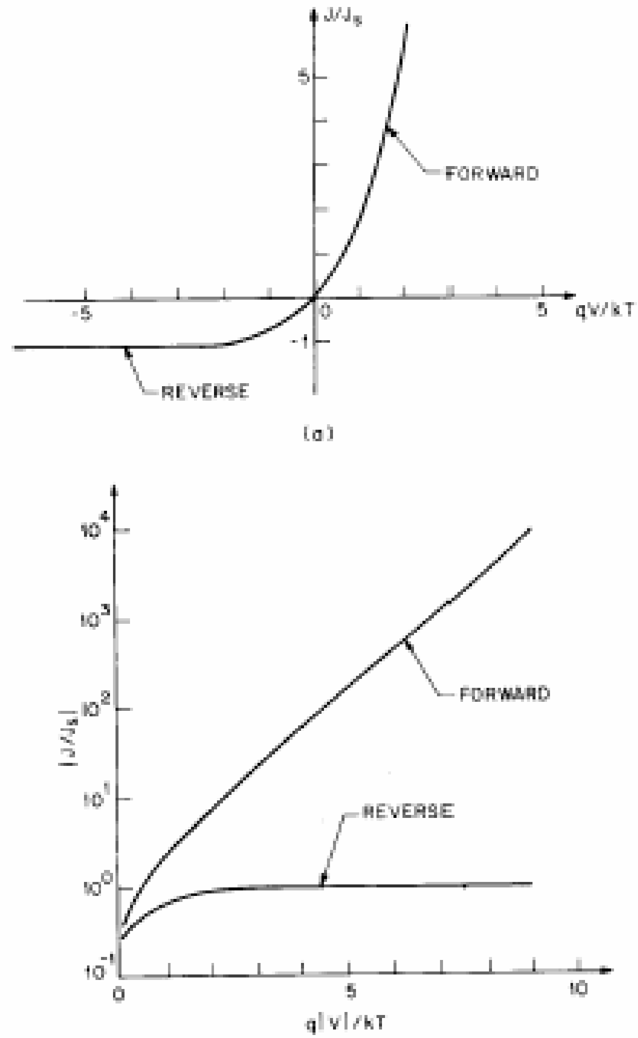
	Si	Ge	GaAs	Diamond
E_g[eV]	1.12	0.67	1.35	5.5
n_i (300K) [cm^{-3}]	1.45×10^{10}	2.4×10^{13}	1.8×10^{6}	$< 10^{3}$

There are too many free electrons build detectors from intrinsic semiconductors other than diamond

How to detect a drop of water in the ocean ?
⇔ remove ocean by blocking the DC current

Most semiconductor detectors are diode structures

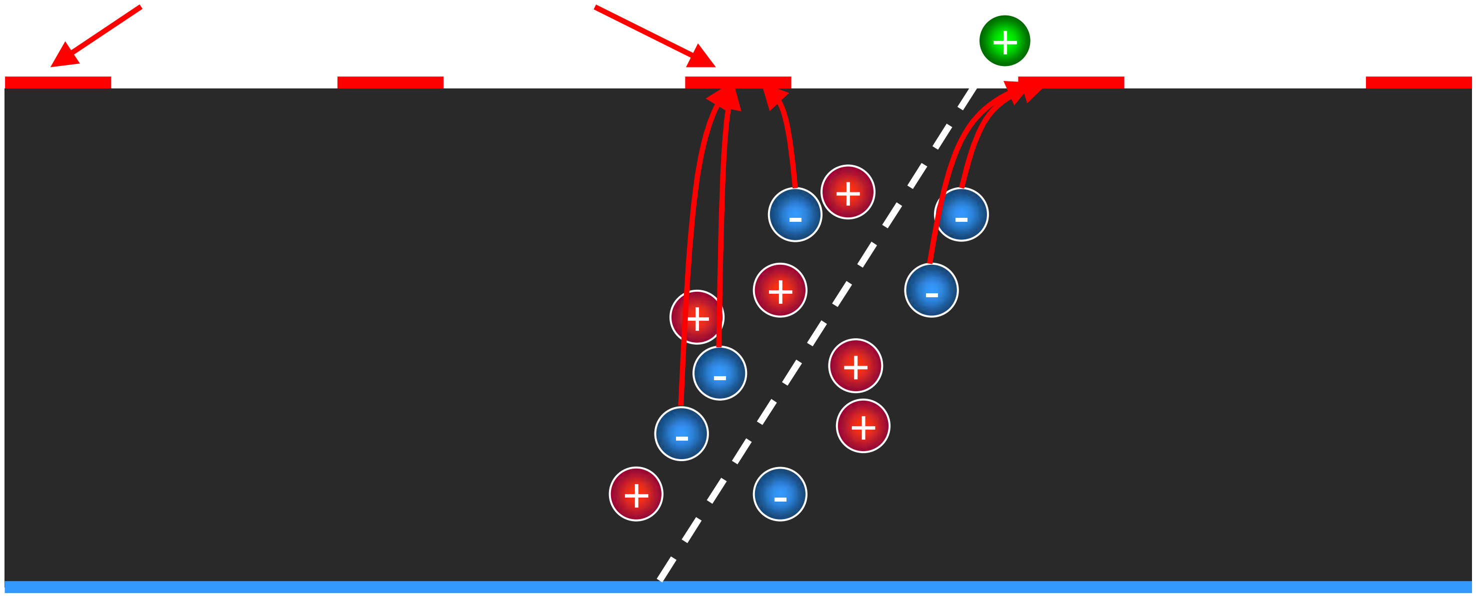
The diodes are reversely biased only a very small leakage current will flow across it



Operation sequence

Charged particle crosses detector and creates electron hole pairs

these drift to nearest electrodes ⇔ position determination



Components of a silicon detector

Silicon sensor with the reversely biased pn junctions

Readout chips

Multi-chip-carrier (MCM) or hybrid

Support frame (frequently carbon fibre)

Cables

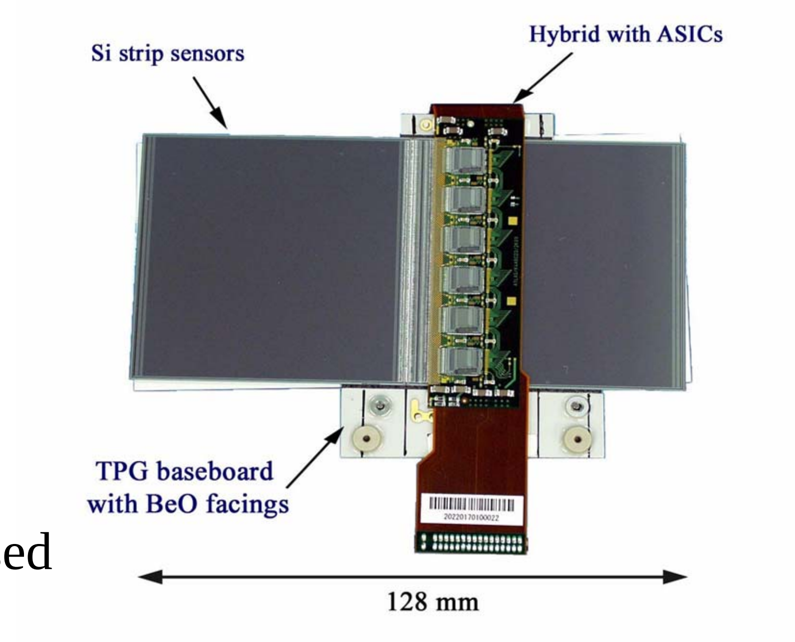
Cooling system

+ power supplies and data acquisition system (PC)

Let's look at a few examples now before moving on with the talk

Detector readout electronics

Typically the readout electronics sits very close to the sensor or on the sensor



Basic functions of the electronics:

- Amplify charge signal ⇔ typical gains are 15 mV/fC
- Digitize the signal ⇔ in some detectors analog signals are used
- Store the signal ⇔ sometimes the analog signal is stored
- Send the signal to the data acquisition system

The chips are highly specialized custom integrated circuits (ASICs)

Critical parameters for electronics

- Noise performance

  output noise is expressed as equivalent noise charge [ENC]

  ENC ranges from 1 e- to 1000 e-;

  for strip detectors need S/N ratios > 10

- Power consumption

  typical power of strip detectors is 2-4 mW/channel; for pixels at LHC 40-100 μW/pixel; elsewhere can achieve << 1 μW/pixel

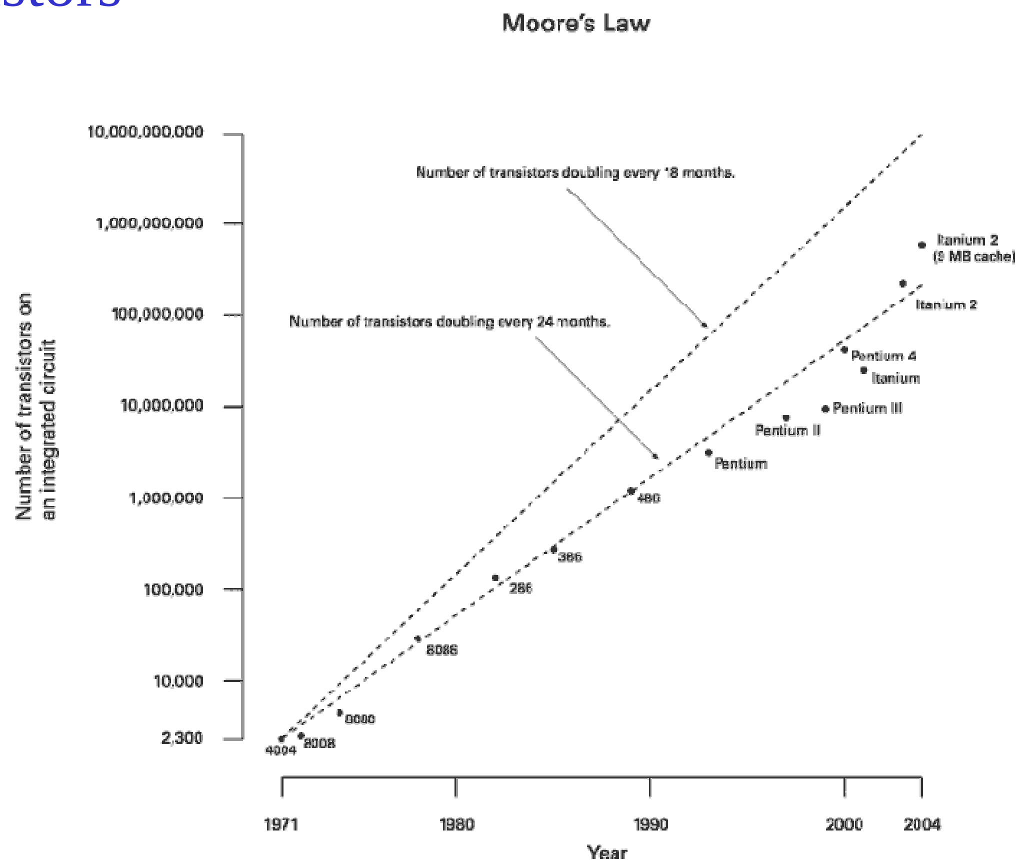
- Speed ⇔ requirements range from 10 ns to ms

- Chip size ⇔ smaller and thinner is usually best
- Radiation hardness ⇔ needed in space, particle physics and elsewhere

These requirements are partially conflicting; compromise will depend on specific application

Moore’s Law

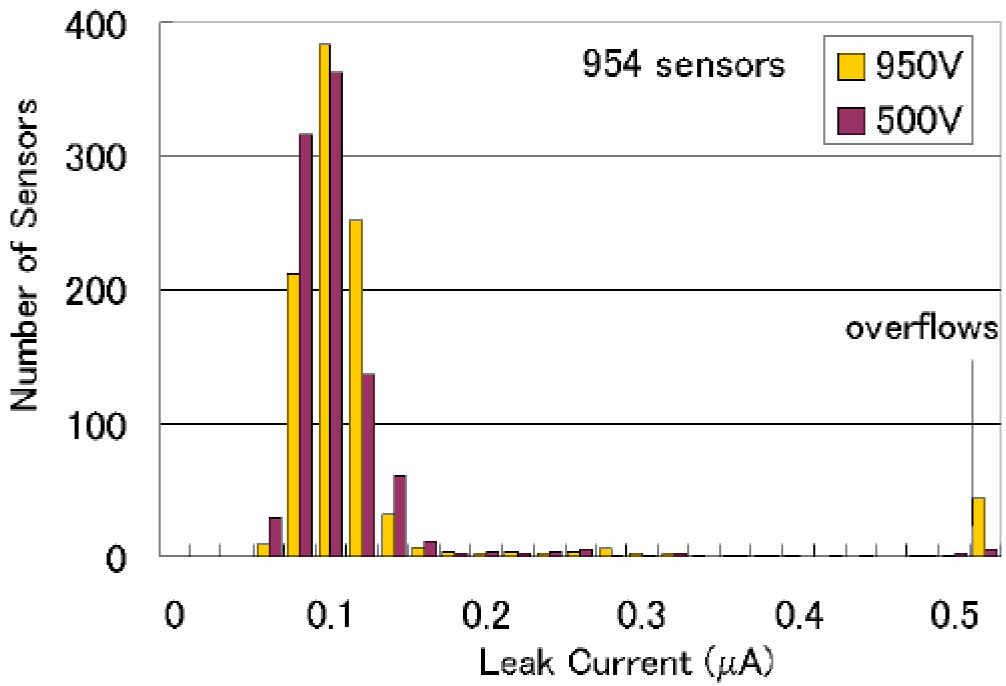
Number of transistors per chip increases exponentially due to shrinking size of transistors



Unfortunately the fixed costs (NRE) increase for modern technology; bad for small-scale users like detector community

Silicon strip sensors

- ATLAS SLHC silicon area: >150 m^2; CMS LHC: 200 m^2 today; GLAST: 80 m^2; variants of CALICE (MAPS): 2000 m^2
- Industry is achieving incredible performance for sensors



p-in-n; 6 inch wafers;

300 μm thick; AC- coupling;

RO strip pitch 80 μm;

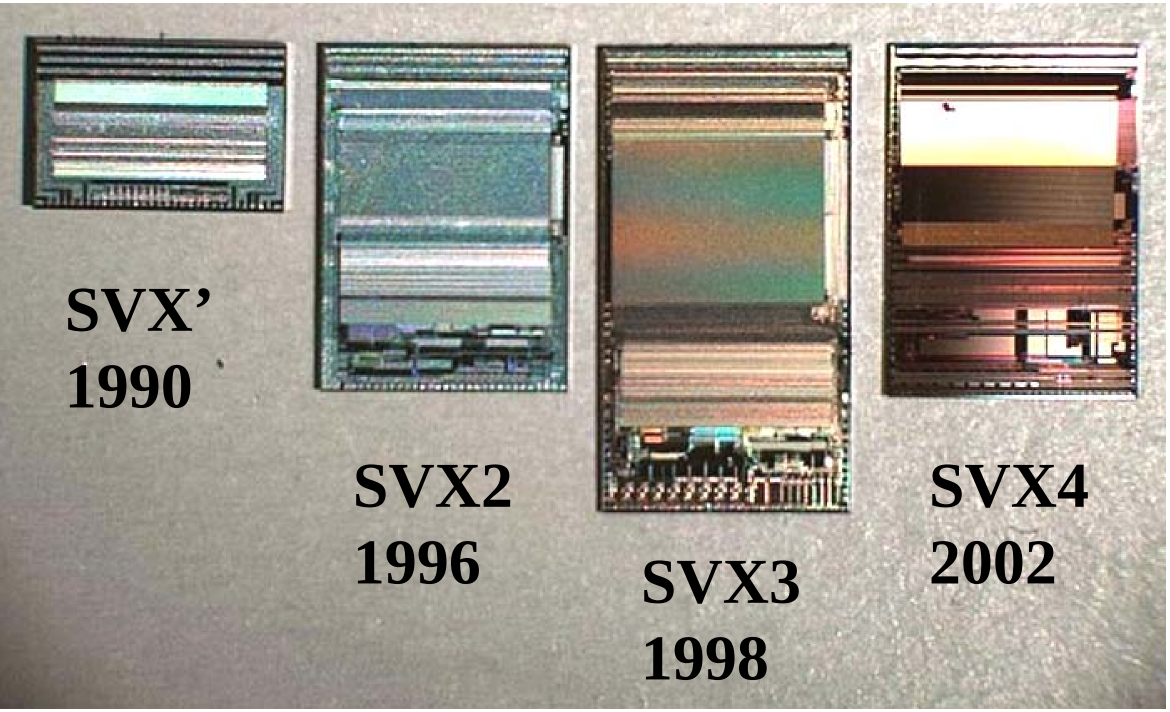
Area: 4x9.6 cm^2;

Depl. voltage: 100-250 V

K. Hara; IEEE NSS Portland 2004

However there are not many vendors and SLHC is tougher

The SVX readout chip family



- Increasing feature size makes chips smaller
- Adding new features (e.g. analog-to digital conversion; deadtime-less readout) makes them bigger

The SVX2 was a crucial ingredient to the top quark discovery at the Tevatron collider at FNAL near Chicago

Multi-chip-carrier/hybrid

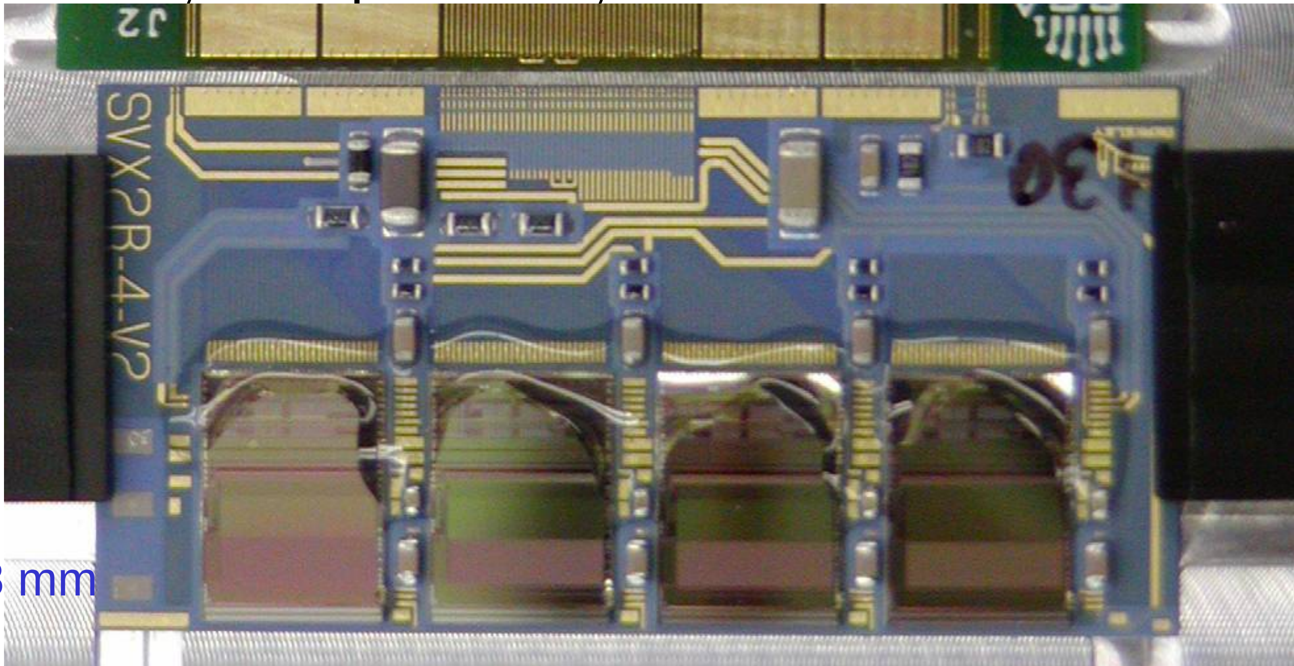
• carries readout chips and passive components (resistors and capacitors

• distributes power and control signals to chips; routes data signals out

• filters sensor bias voltage

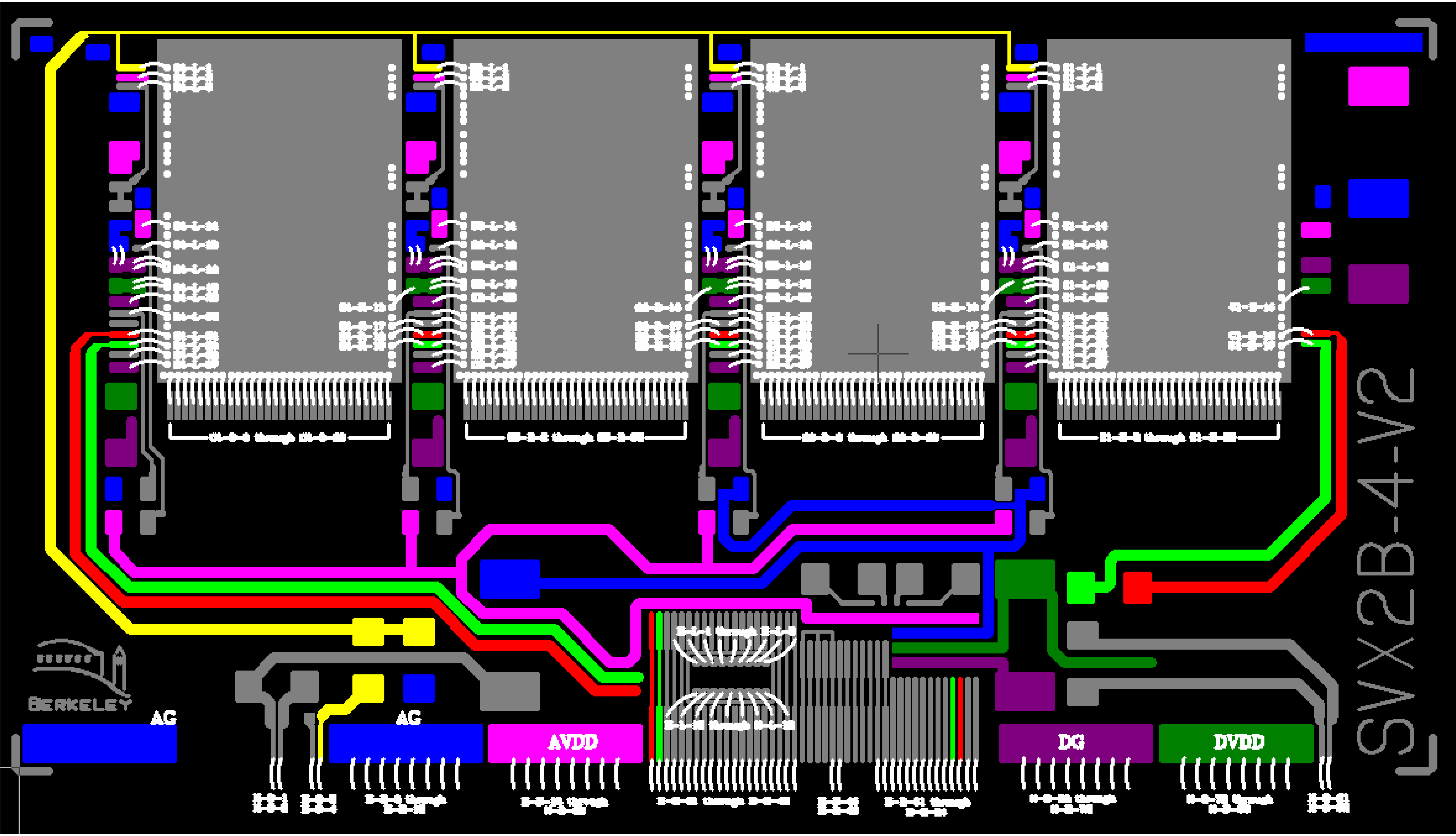
Typical have 4 conductor layers separated by dielectric/insulation layers

Example: ceramic BeO hybrid for the CDF detector



Size: 38 mm x 20 mm x 0.38 mm

4-chip hybrid: top layer



Package efficiency: 31%; 30 passive components; material: 0.18% rad. length; no technical problems; yield on 117 hybrids: 90% (after burn-in)

Critical parameters for hybrids

- want low-Z material and small feature size and thickness
(minimize multiple scattering)

- good heat conduction to cooling tubes

- reliability/ high yield

- good electrical performance

Packaging

“Packaging is what makes your cell phone small”

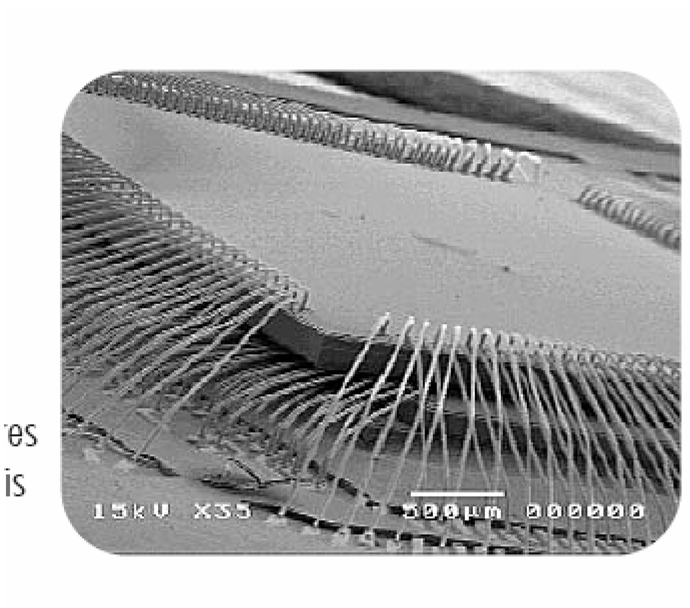
Cell phone,

Digital camera,

PDA, Web access,

Outlook

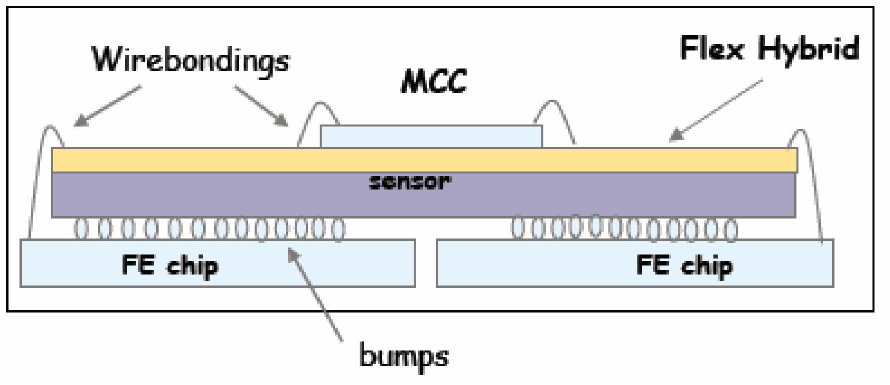
3D packaging

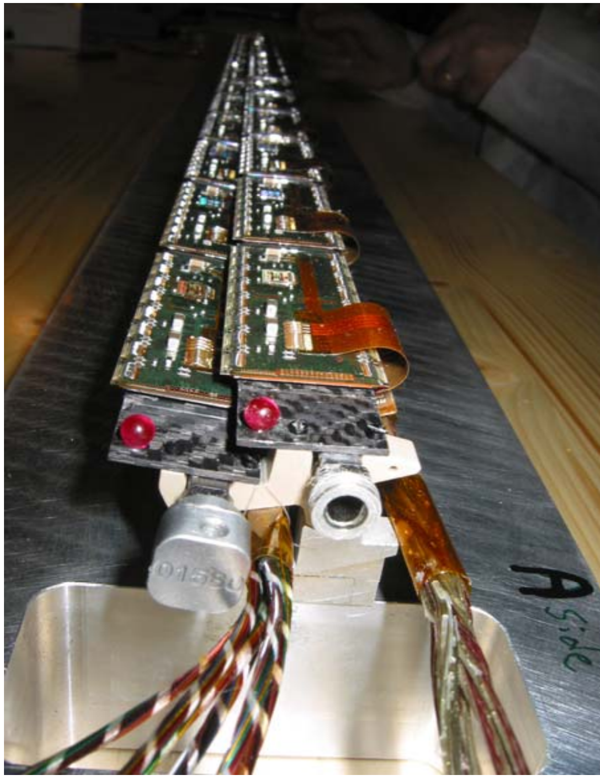


How to stack sensors; MCMs; chips; CF support; cables and cooling while connecting them electrically, thermally and mechanically ?

Technological challenges: Pixel detector

- **innovative packaging of sensor/chips/support structure/cooling**
  - sophisticated, crowded flex-hybrid
  - carbon-carbon support structures
  - bump-bonding of chips to sensors
  - direct cooling of chips



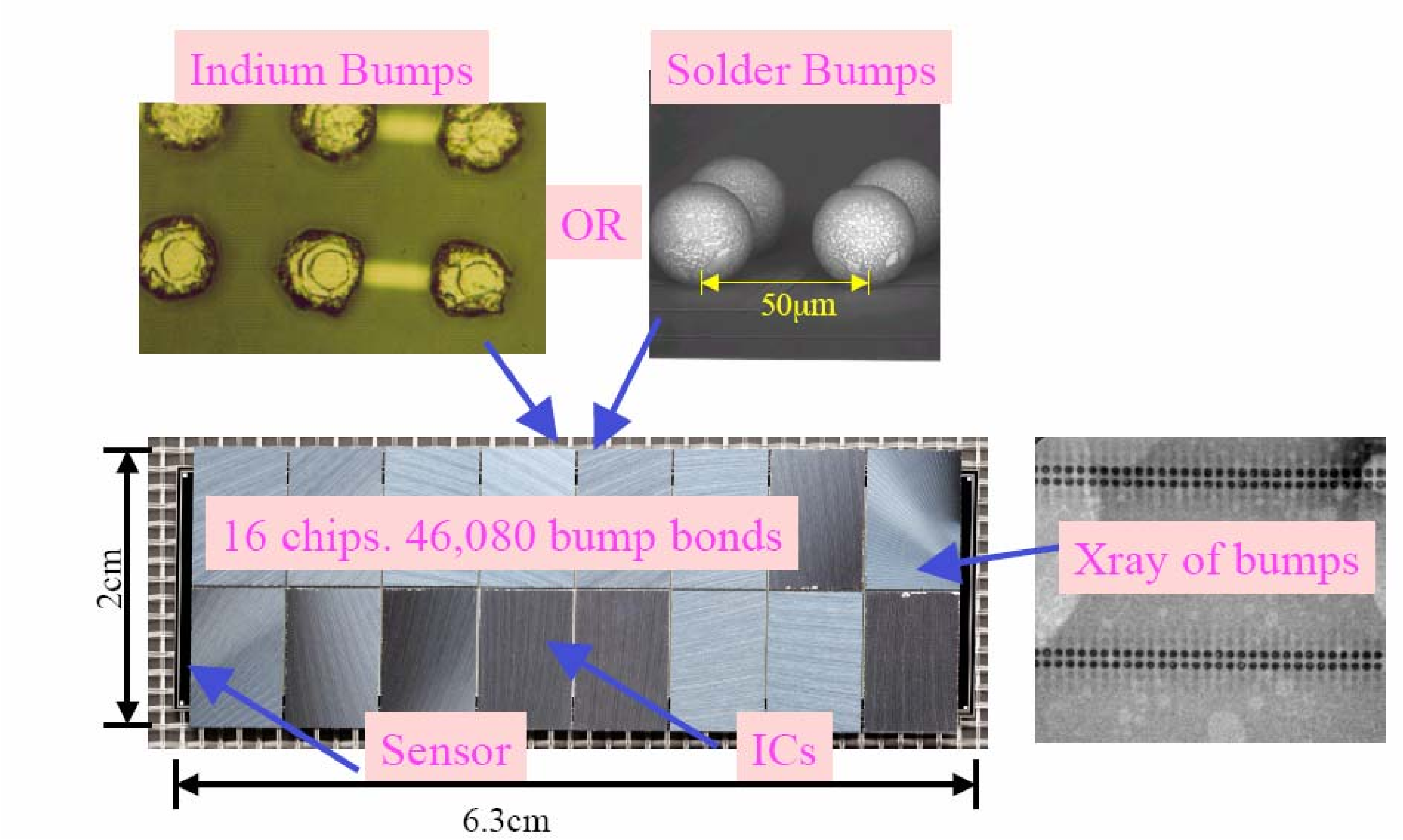


- **Global and local support structures:** stiff; lightweight; precise; "zero" thermal expansion

Technological challenges: Pixel detector

- **Bump-bonding of chips to sensors:**

pitch of only 50 µm (commercial pitches ≈200 µm)



Packaging solution for SCT

Still very compact

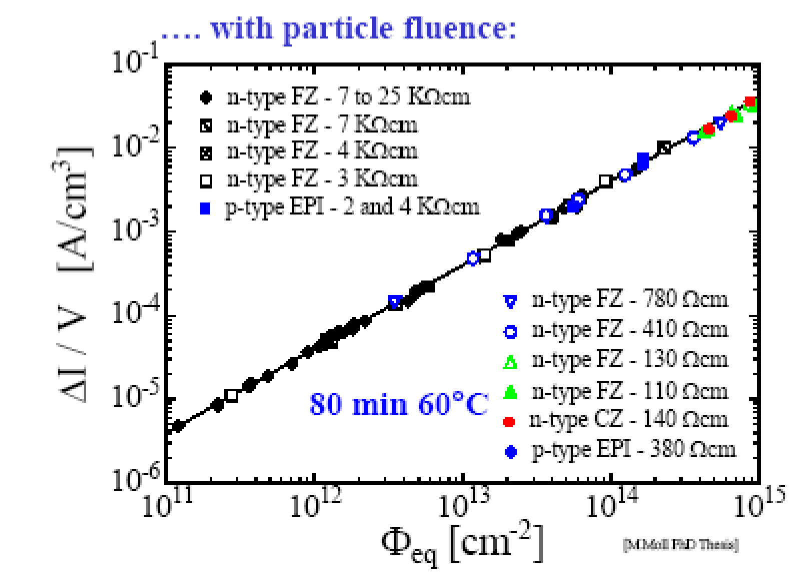
- flex-hybrid with connectors
- separate optical readout for each module
- separate power for each module
- cooling pipes not integrated to structure

Radiation-hard sensors

1. Radiation induced leakage current

independent of impurities; every 7°C of temperature reduction halves current

⇔ cool sensors to ≈ -25°C (SCT = -7°C)



2. "type inversion" from n to p-bulk

⇔ increased depletion voltage

oxygenated silicon helps (for protons);

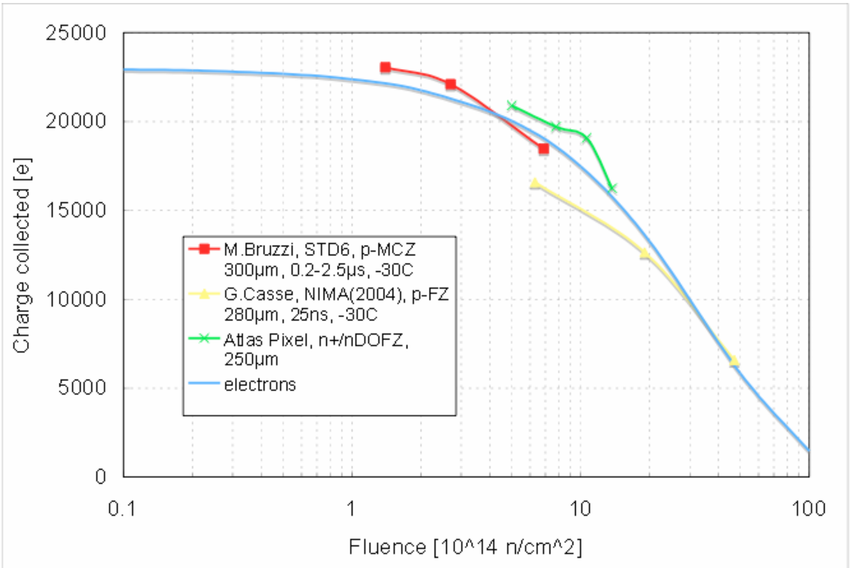
n+-in-n-bulk or n+-in-p-bulk helps

3. Charge trapping

the most dangerous effect at high fluences

⇔ collect electrons rather than holes

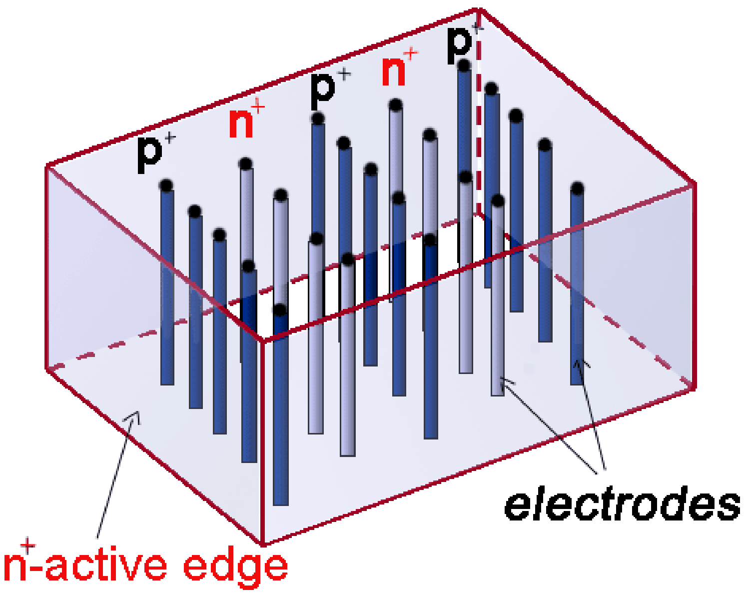
⇔ reduce drift distances

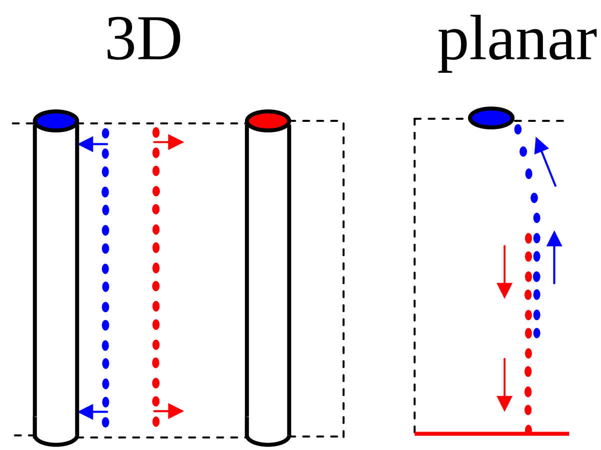


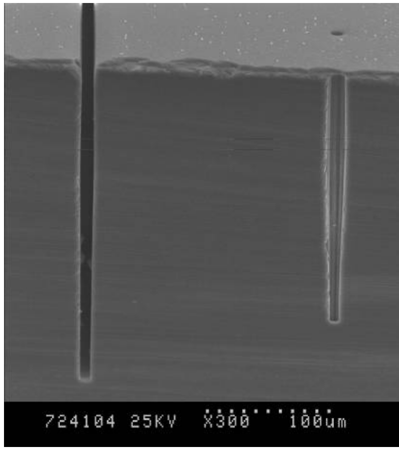
Strong candidate for inner layer: 3D pixels

- 3D pixel proposed by Sherwood Parker in 1985
- vertical electrodes; lateral drift; shorter drift times; much smaller depletion voltage
- Difficulty was non-standard via process; meanwhile much progress in hole etching; many groups; simplified designs

see talk of Sabina R. (ITC-irst)

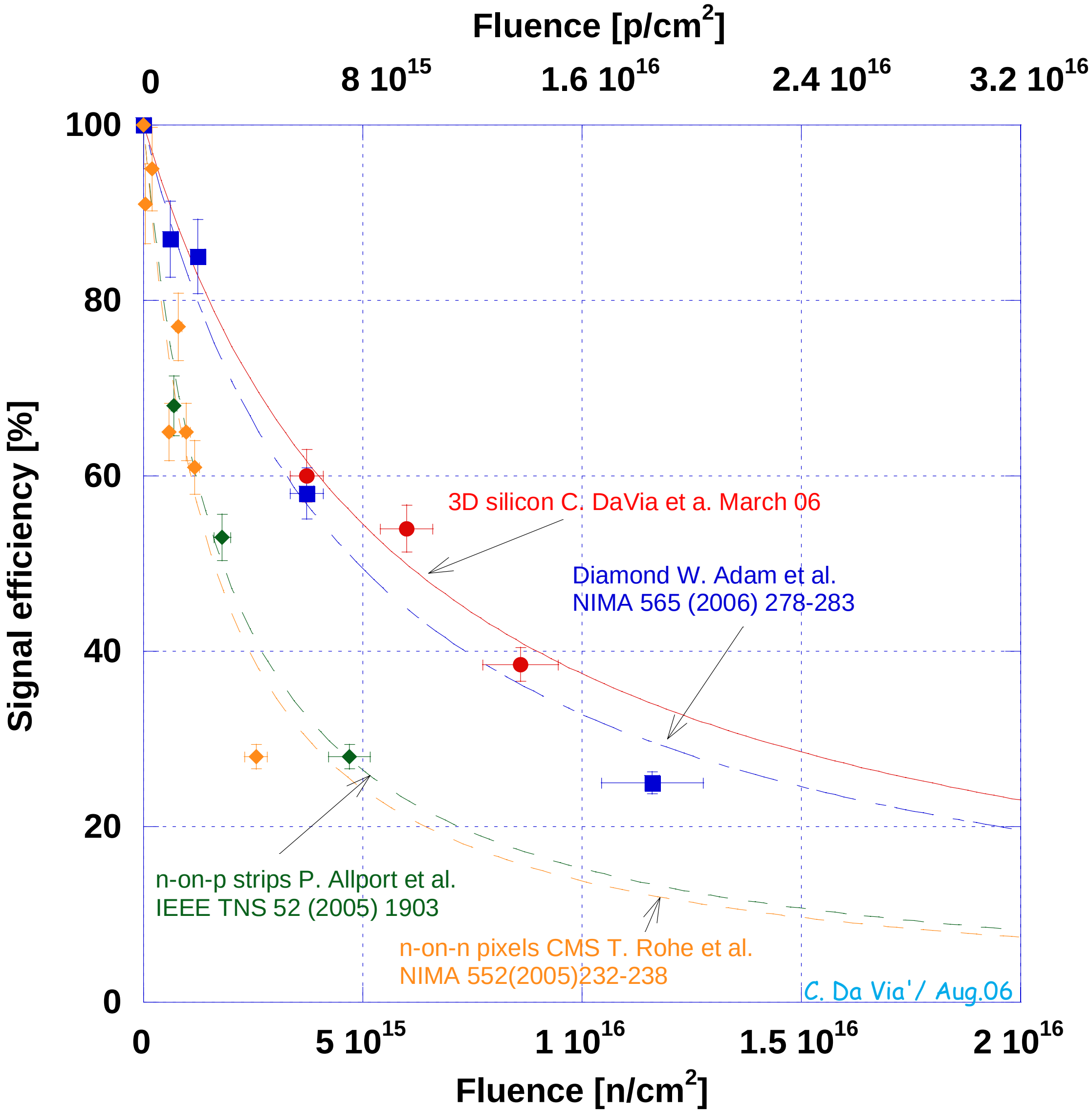






Signal loss vs. fluence

see C. da Via's talk at STD6 "Hiroshima" conference

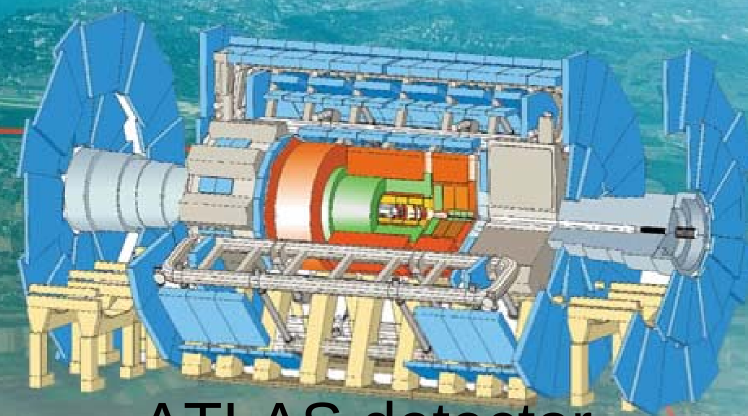


3D pixels perform by far the best

Large Hadron Collider: the world's most powerful accelerator

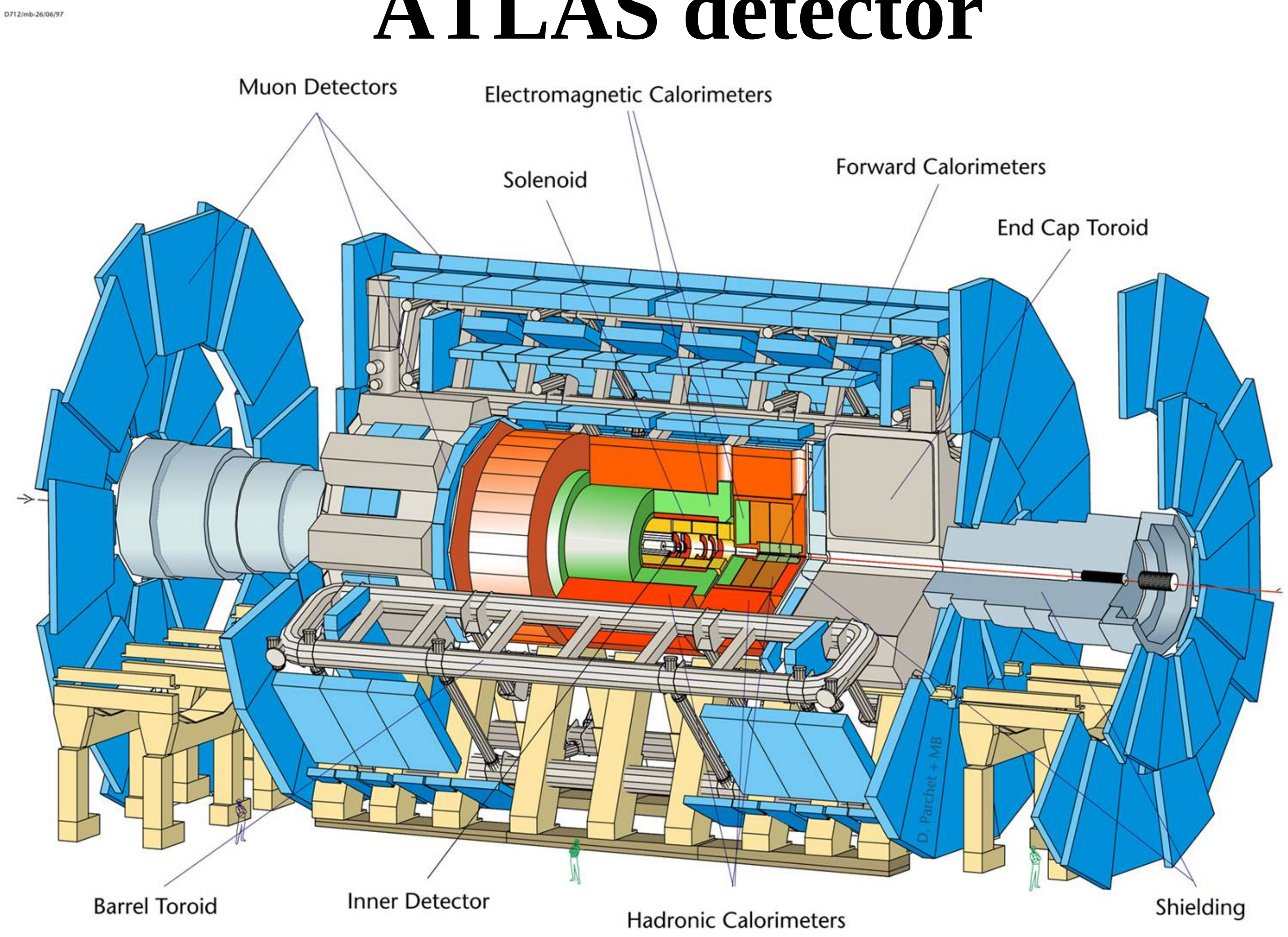
7 TeV protons vs. 7 TeV protons; 27 km circumference

7 x the energy and 100 x the luminosity of the Tevatron



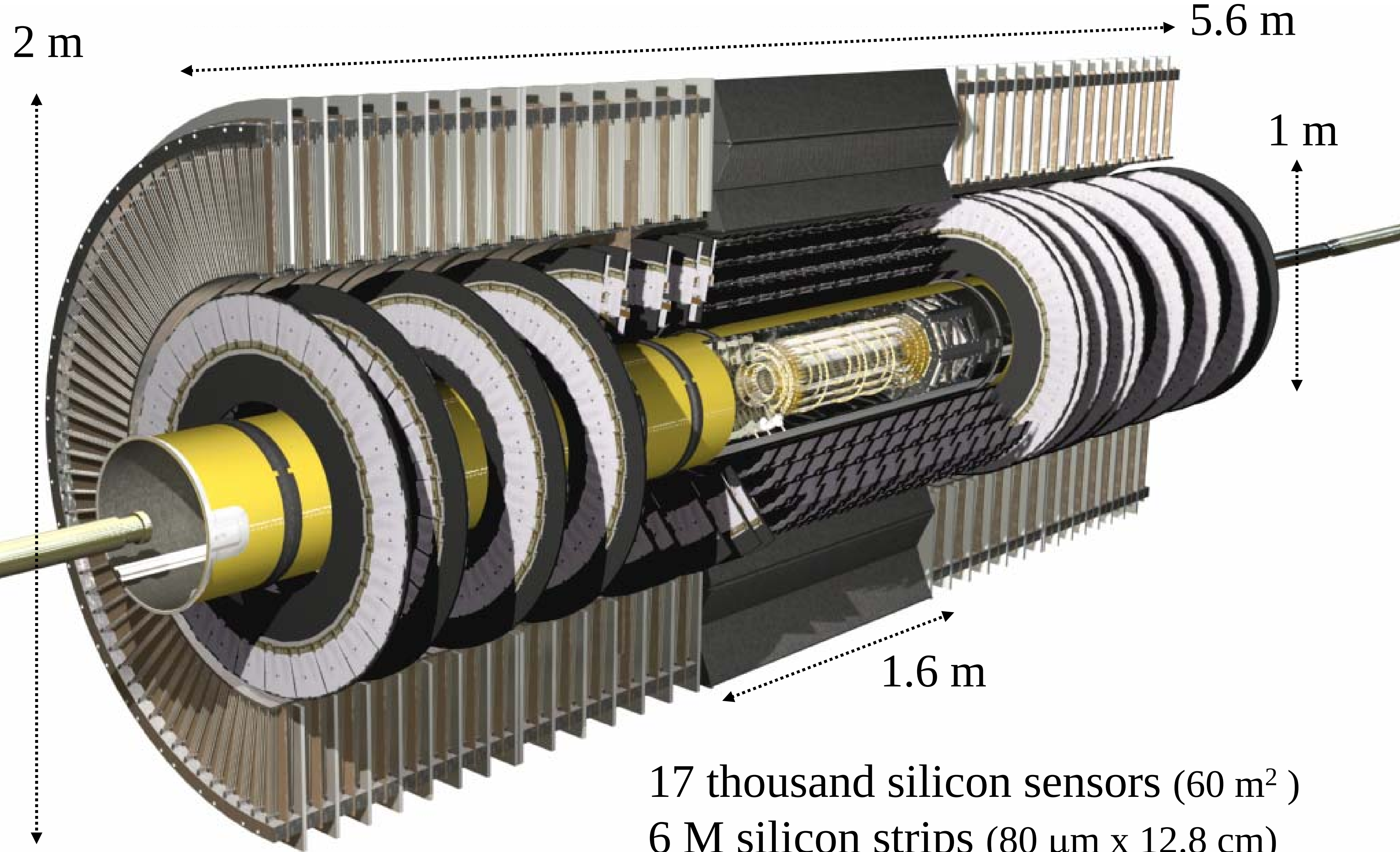
ATLAS detector

ATLAS detector



- Huge multi-purpose detector; 46 m long; diameter 22 m; weight 7000 t
- Tracking system much smaller; 7 m long; diameter 2.3 m; 2 T field

ATLAS Silicon Tracker



17 thousand silicon sensors (60 m^2)
6 M silicon strips (80 μm x 12.8 cm)
80 M pixels (50 μm x 400 μm)

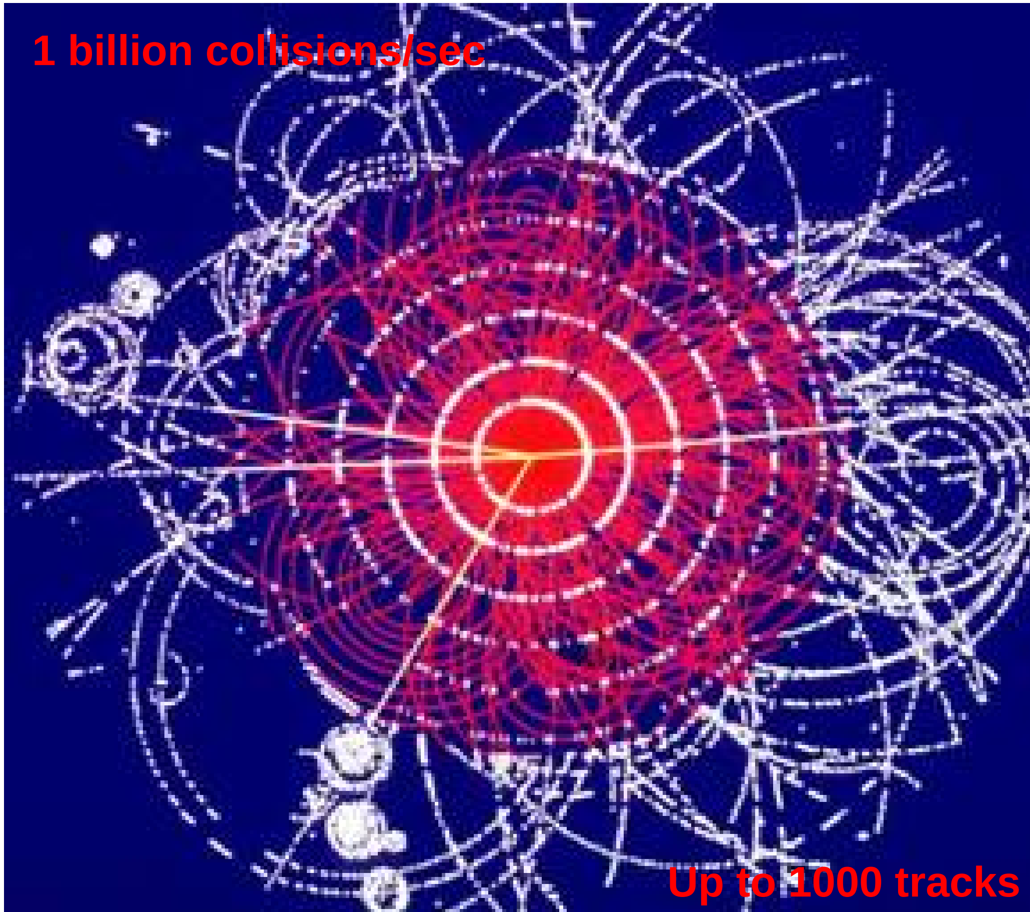
40 MHz event rate; > 50 kW power

What's charged particle tracking ?

1. Measure (many) space points/hits of charged particles
2. Sort out the mess and reconstruct particle tracks

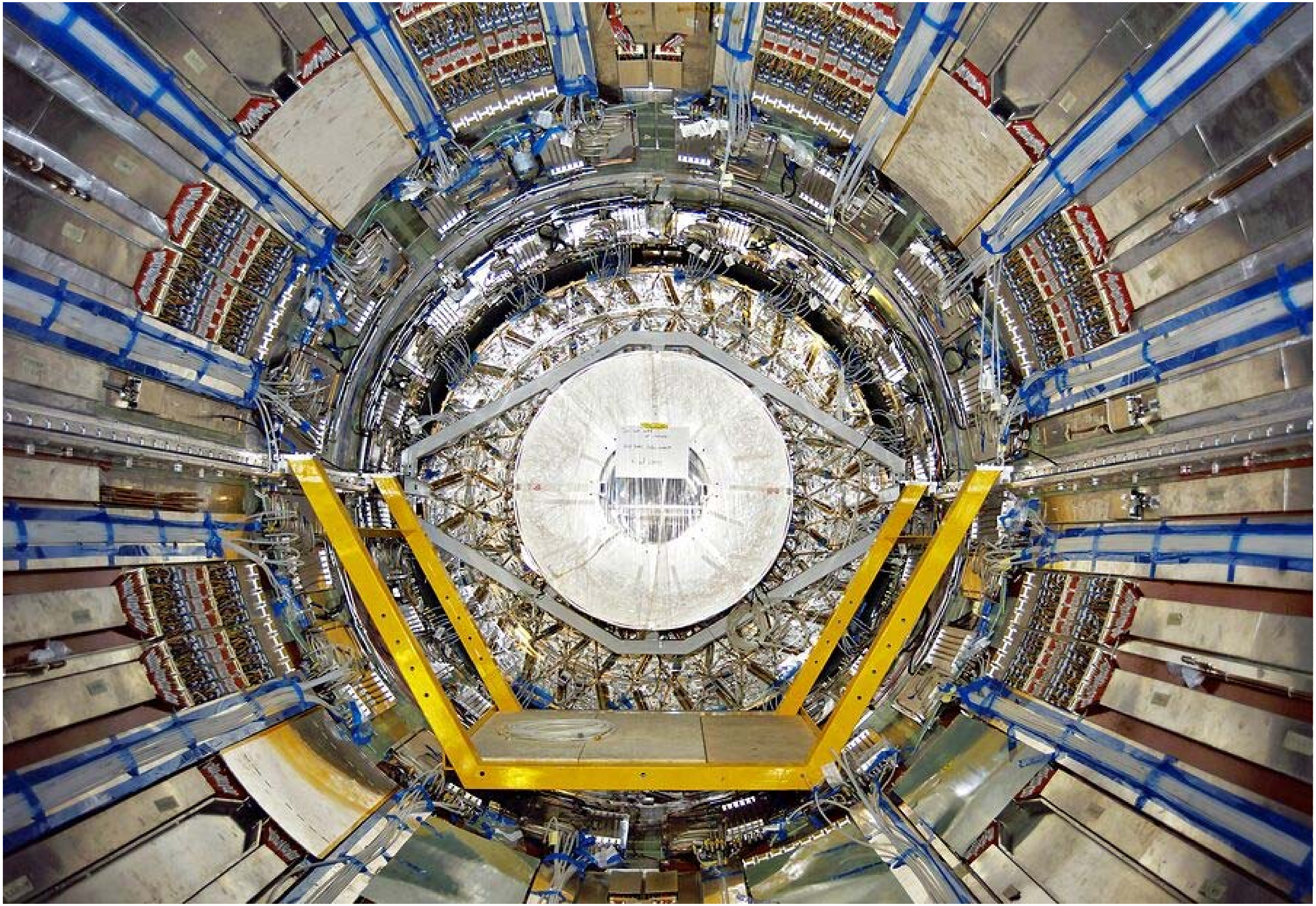
Difficulty is:

- not to get confused
- achieve track position resolution of 5-10 μm



…it's not easy !

Status as of October 2006



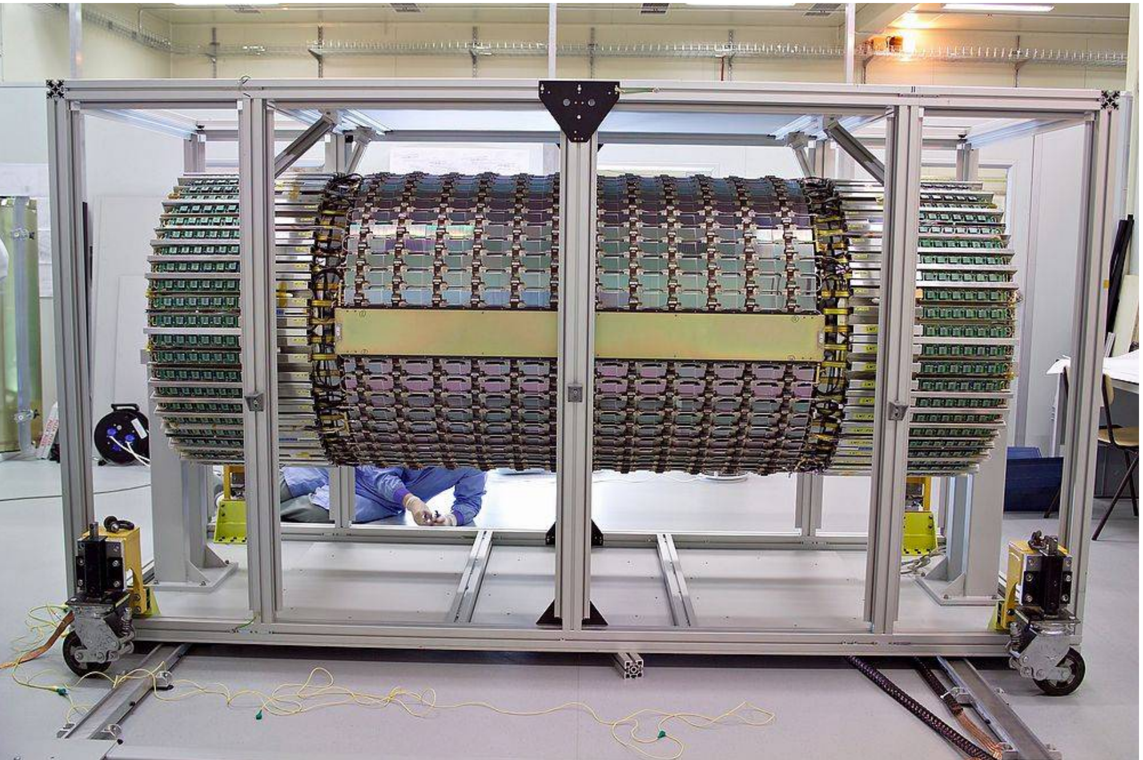
How does it look in real life ? SCT Detector

• 4 barrel layers at 30, 37, 45, 52 cm radius and 9 discs (each end)

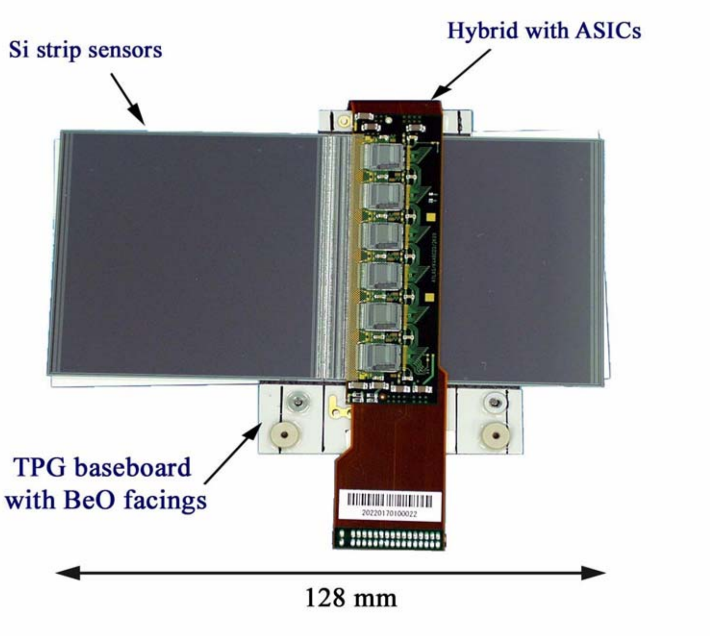
• 60 m^2 of silicon; 6 M strips; typical power consumption ≈50 kW

• Precision carbon fiber support cylinder carries modules, cables, optical fiber, and cooling tubes

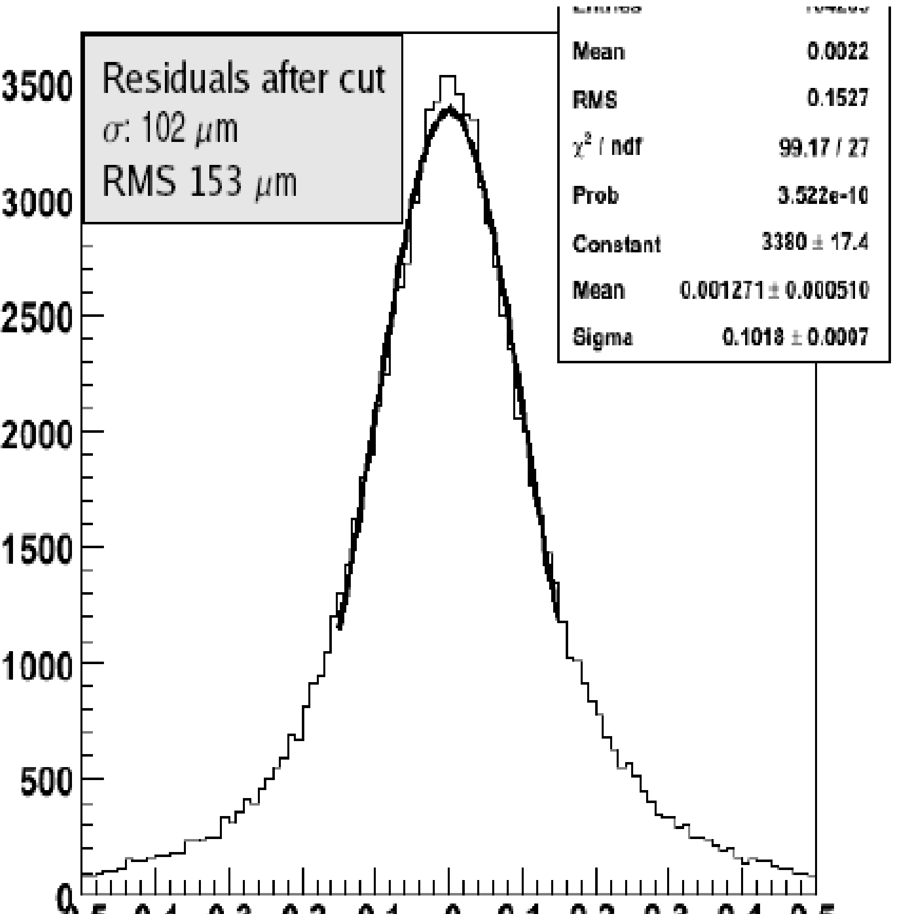
• Evaporative cooling system based on C_3F_8 (same for pixel detector)

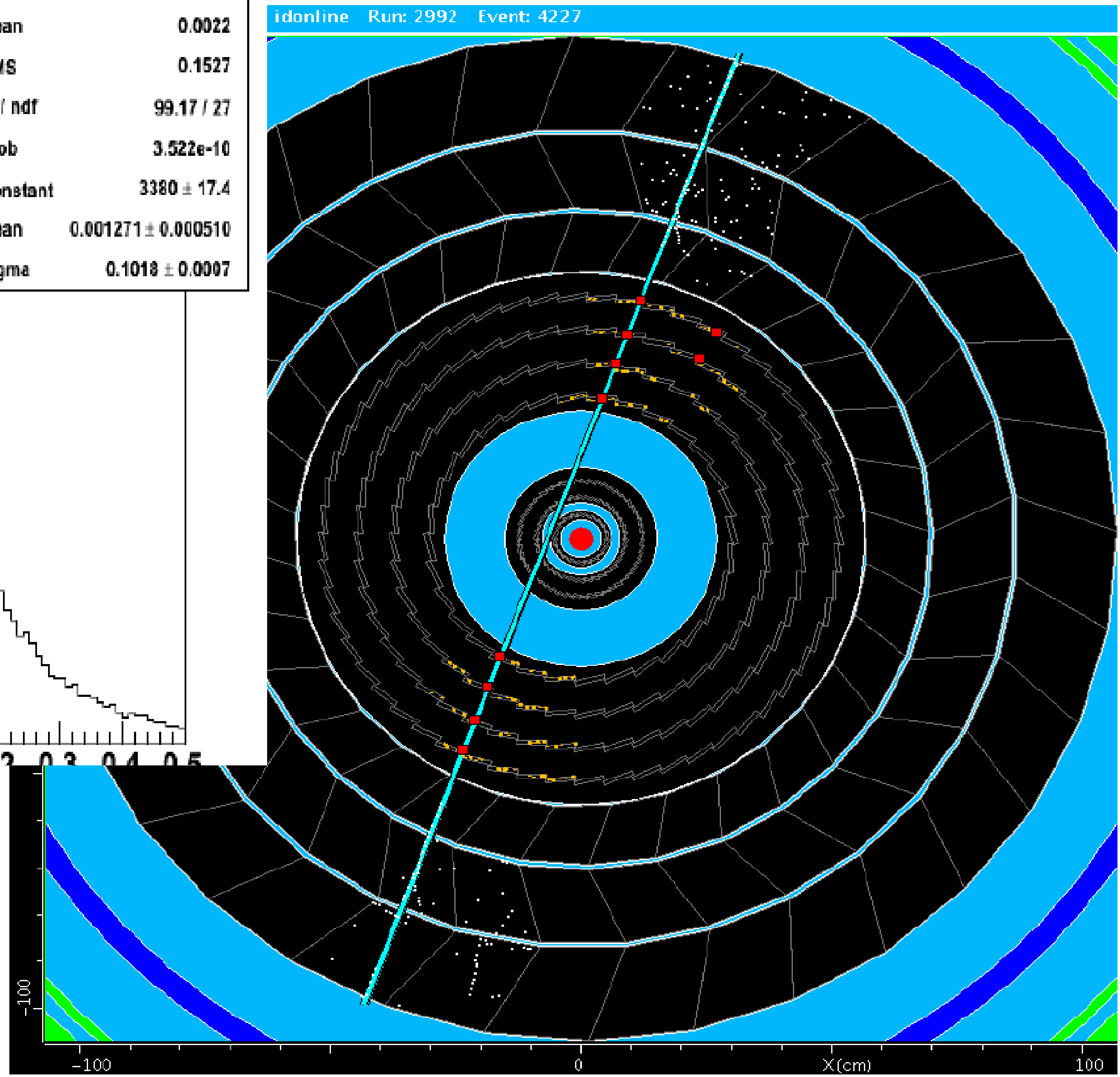


Barrel 6 at CERN



First Cosmic Particle Tracks *(Summer 2006)*





Excellent build precision! Resolution will improve after alignment and for higher momentum tracks

Why tracking at LHC is tough ?

- Too many particles in too short a time
  - 1000 particles / bunch collision
  - too short: collisions every 25 ns

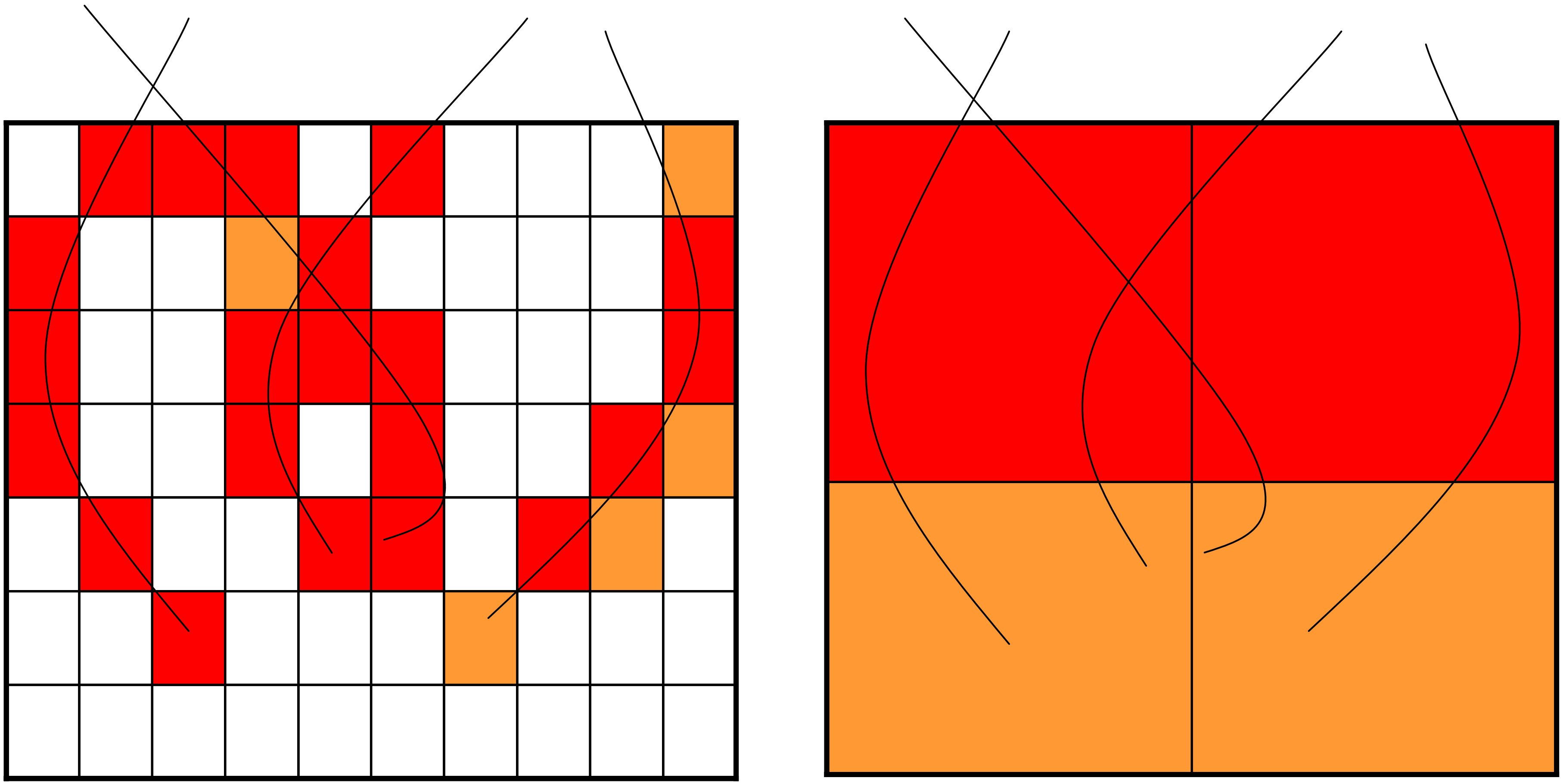
- Too short ⇔ need fast detectors and electronics; power!

- Too many particles ⇔
  - need high resolution detectors with millions of channels
  - detectors suffer from radiation damage

  to date this requires silicon detectors

Example

Need many channels to resolve multi-track patterns



Expect 30-60 M strips and >100 M pixels

Extreme radiation levels !

- Radiation levels vary from 1 to 50 MRad in tracker volume

  - less radiation at larger radii; more close to beam pipe

  - more radiation in forward regions

- Fluences vary from to 10^{13} to 10^{15} particles/cm^2

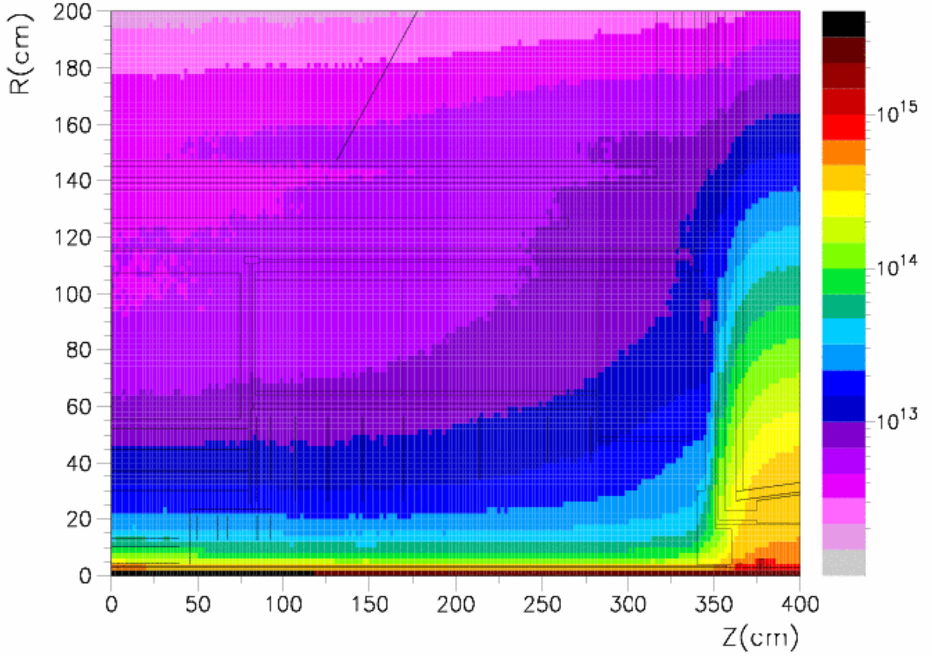
- **Vicious circle:** need silicon sensors for resolution and radiation hardness ⇔ cooling (sensors and electronics) ⇔ more material ⇔ even more secondary particles etc.

Don’t win a beauty contest in this environment, but detectors are still very good !

Extreme radiation levels !

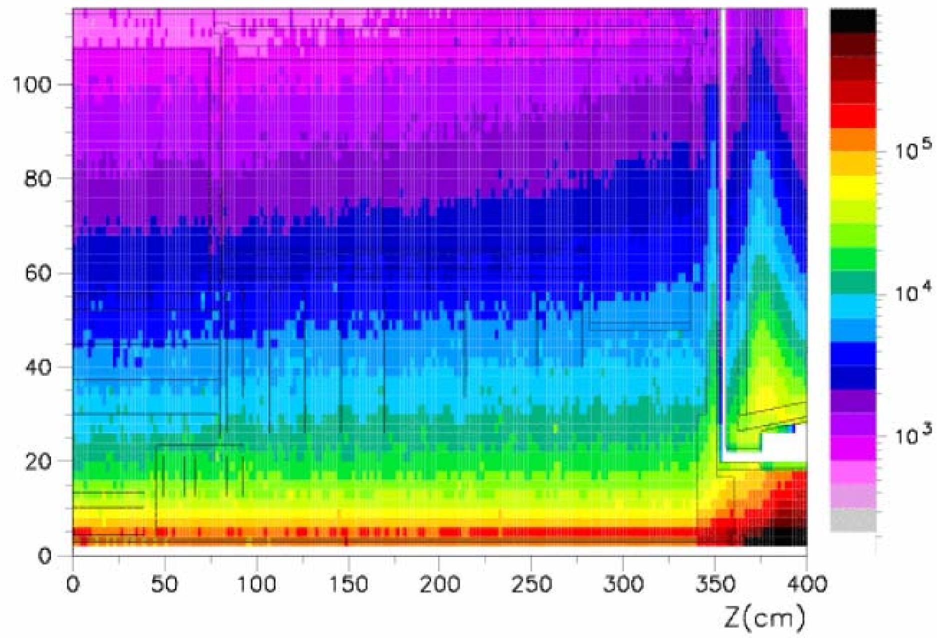
Plots show radiation dose and fluence per high luminosity LHC year for ATLAS (assuming 10^7 s of collisions; source: ATL-Gen-2005-001)

Fluence [1 MeV eq. neutrons/cm^2]



"Uniform thermal neutron gas"

Radiation dose [Gray/year]



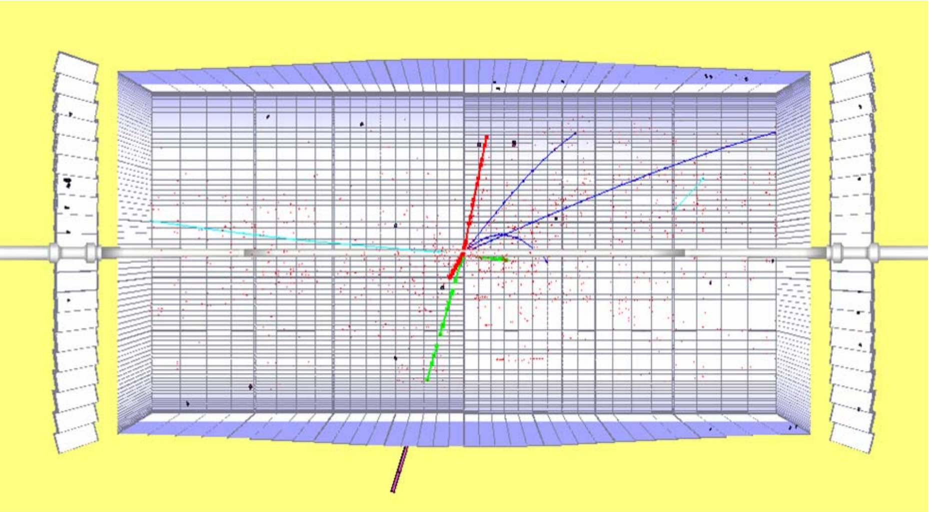
Put your cell phone into ATLAS !
It stops working after 1 s to 1 min.

- Neutrons are everywhere and cannot easily be suppressed

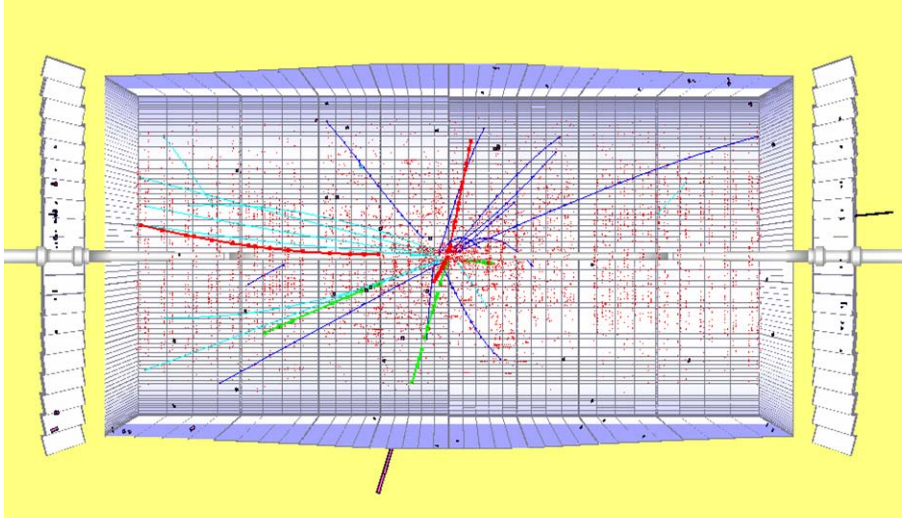
The Boring masks the Interesting

H→ZZ → μμee + minimum bias events (M_H= 300 GeV)

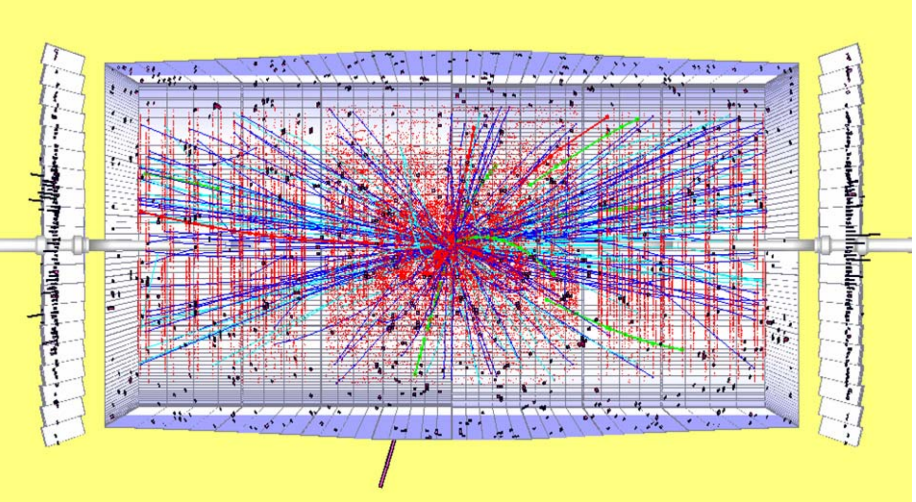
LHC in 2008 ?? : 10^{32} $cm^{-2}s^{-1}$



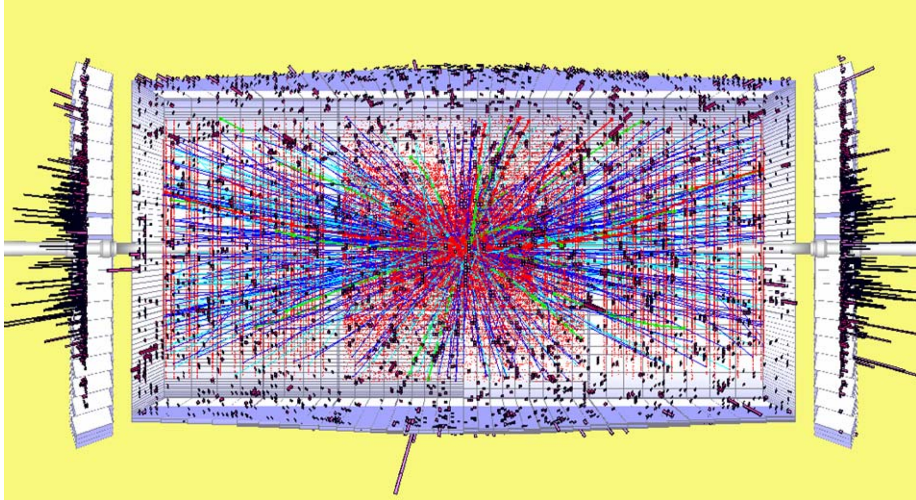
LHC first years: 10^{33} $cm^{-2}s^{-1}$



LHC: 10^{34} $cm^{-2}s^{-1}$



SLHC: 10^{35} $cm^{-2}s^{-1}$



Why are silicon detectors so popular ?

- **Start from a large signal** ⇔
  good resolution; big enough for electronics
- **Signal formation is fast**

- **Radiation-hardness**
- **SiO_2 is a good dielectric**

- **Ride on technological progress of Microelectronics industry**

⇔ extreme control over impurities; very small feature size; packaging technology

- **Scientist and engineers developed many new concepts over the last two decades**

Technologies come and go

Technologies come and go

Silicon detectors are not yet going!

Future detectors are being designed and will be

- **Larger:** 200-2000 m^2
- **More channels:** Giga pixels
- **Thinner:** 20 μm
- **Less noise**
- **Better resolution**

Your next digital camera will be better and cheaper as well