Presentation at the
2016 Fraunhofer IMS
CMOS imaging workshop

Image sensors in space applications

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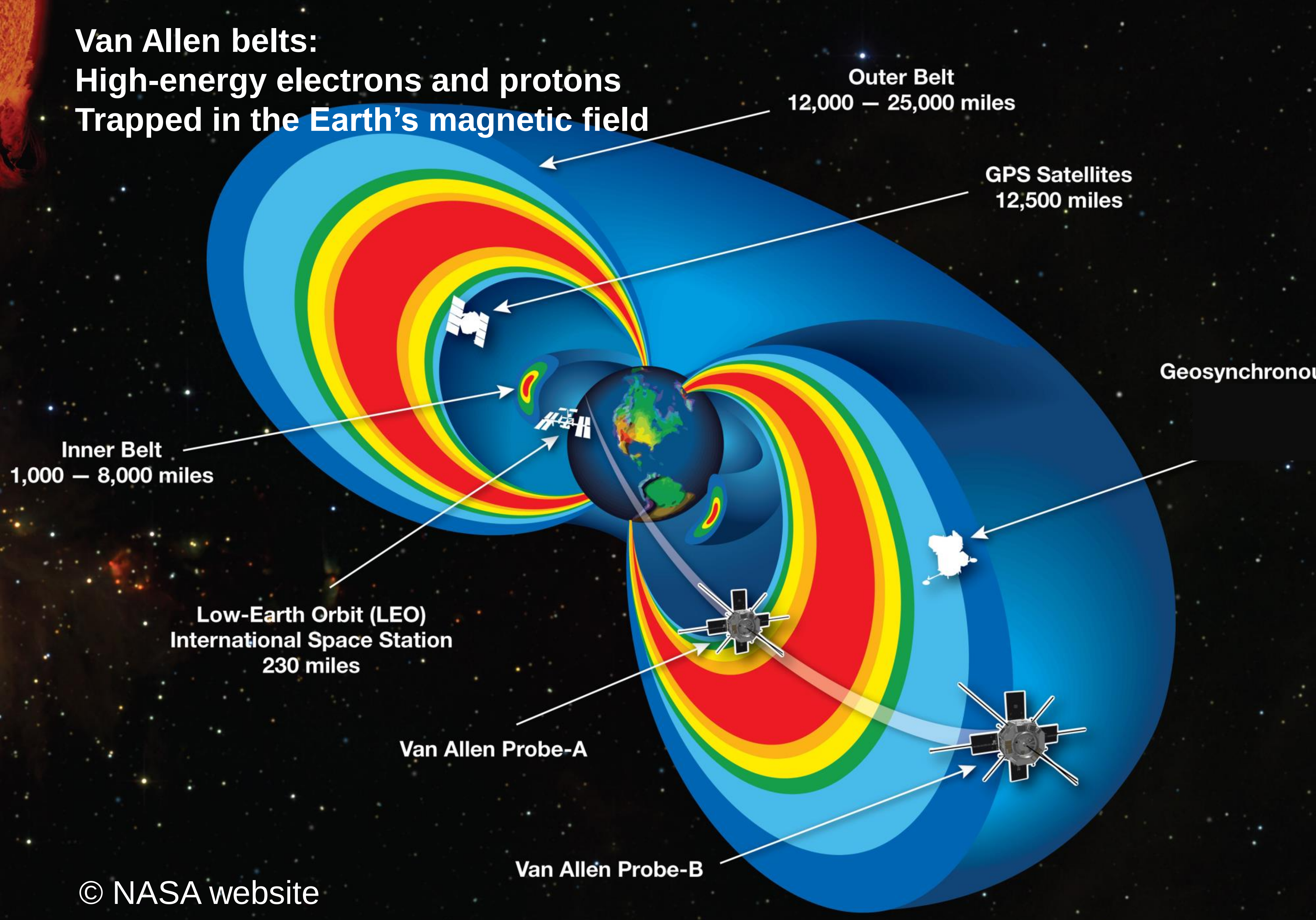
26 March 2016:
Japanese space observatory dies

(press release) Hitomi’s troubles began in the weeks after launch, with its 'star tracker' system, which is one of several systems on board that are designed to keep the satellite oriented in space. The star tracker experienced glitches whenever it passed over the eastern coast of South America, through a region known as the South Atlantic Anomaly. Here, the belts of radiation that envelop Earth dip relatively low in the atmosphere, exposing satellites to extra doses of energetic particles.

Van Allen belts:
High-energy electrons and protons
Trapped in the Earth's magnetic field



© NASA website

Outline

1. Introduction: space missions
2. Requirements in space missions
3. Total dose radiation effects & counter measures
4. Single event radiation effects & counter measures
    a) SEU
    b) SEL
5. Take home message

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1. INTRODUCTION

Image sensors in space missions

Why do we go to space

and take image sensors along?

1. **Earth observation**
   ⇒ Including atmospheric analysis
2. **Astronomy**
   ⇒ Of celestial objects and deep space
3. **Other science**
   ⇒ Including interplanetary missions
4. **Satellite housekeeping**
   ⇒ Including star- and sun trackers
   ⇒ Including experiment telemetry

Earth observation

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LEO low earth orbit:

- “pushbroom” scanning, with pan-, multi-, hyperspectral multi-linear arrays,
- for visible light often TDI

GEO geo-synchronous orbits

- often for weather, climatology etc.
- Staring arrays, Visible + multi spectral

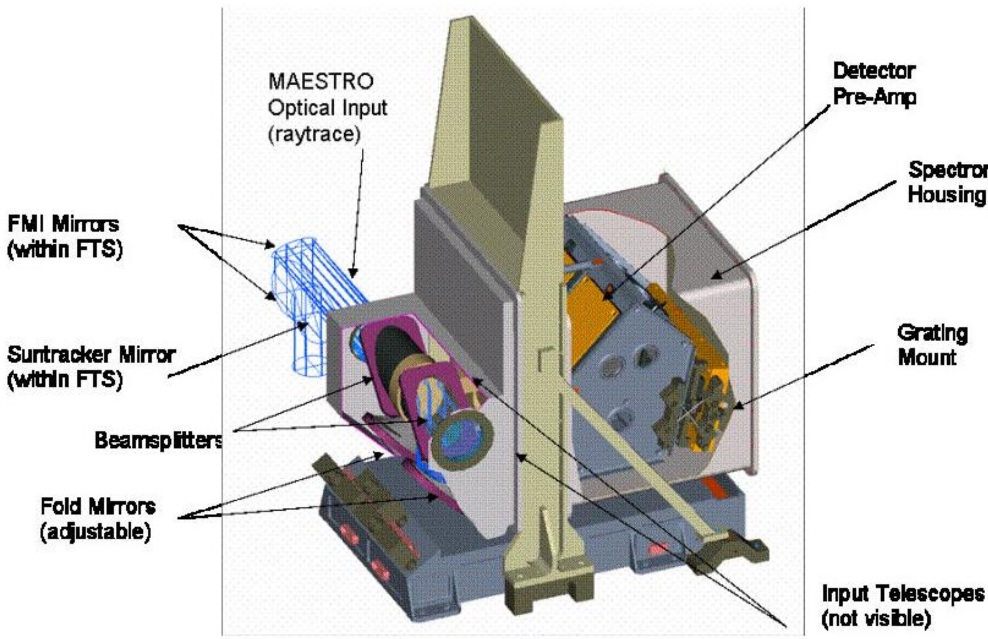
ACE atmospheric chemistry experiment

Canadian Space, in collaboration with ABB-BOMEM

2009: ACE is still operating very well on-orbit, and has celebrated its 6th anniversary in space in August 2009. Performance is still exceeding original requirements. Over 10 molecules have been measured for the first time from space using the on-board FTS instrument. Over 125 scientific papers published so far. It is certainly a project all stakeholders and contributors can be very proud of"

Design 2001

Mission 2003-2009



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Astronomy

Wide variation of wavelength ranges

- X-ray
- Visible
- “classic” infrared (SWIR, MIR, TIR)
- Far infrared up to mm waves

Arrays types

- Large, often stitched or mosaic, arrays
- Hybrid: Si ROIC + non-Si detectors
- Cryogenically cooled

ISO/Isophot

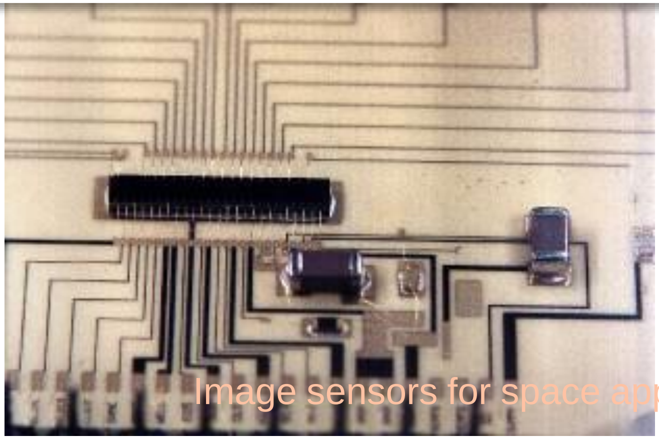
focal plane instrument sensor

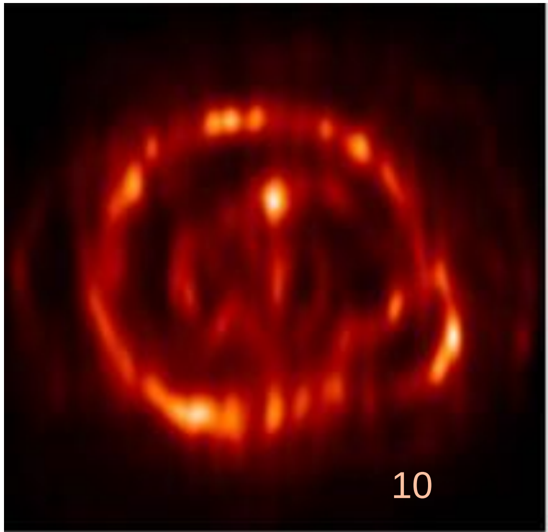
Infrared Space Observatory (ISO) was the most sensitive infrared telescope ever launched. ISO made particularly important studies of the dusty regions of the Universe, where visible light telescopes can see nothing. The wealth of data collected by ISO still produce important science results.

Multiple version (sizes) of the pioneering cryogenic readout electronics (“CRE”) for extrinsic Si::X and Ge::X Frad infrared photoreceptor arrays.

- 3µm CMOS
- Operating temperature between 1 and 7 Kelvin
- Very low power between 1µW and 100µW per ROIC
- Below 10nW standby power
- SEU hard

Design 1986
Mission 1990-1998





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Inter-planetary

Wide variation of instruments

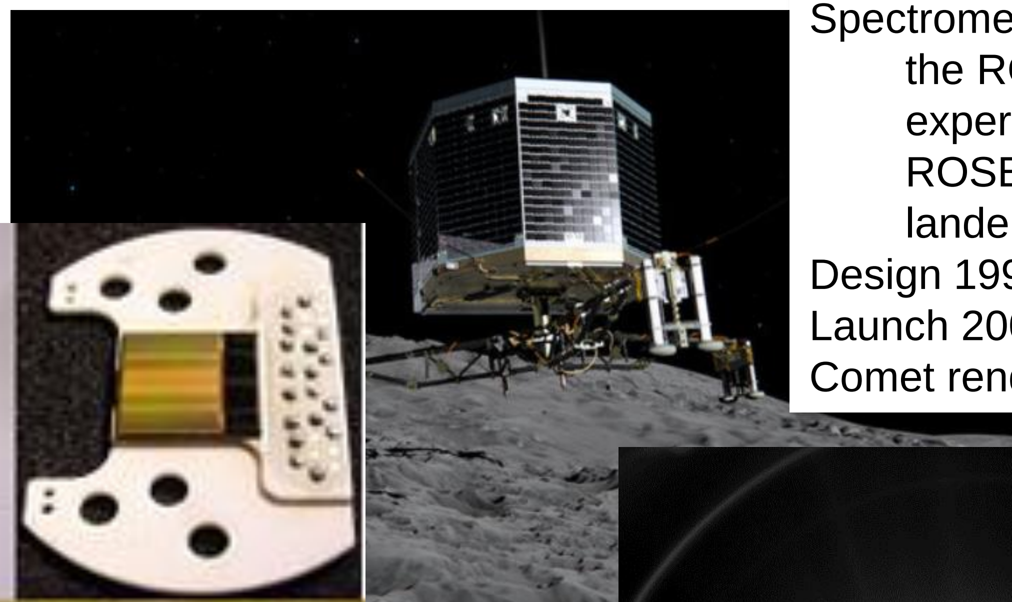
- Visible & other imaging
- Autonomous approach sensors
- Non-imaging instruments, spectrometers …

Special requirements

- Wide range of operation temperatures
- Wide range of radiation doses
- Low standby power, low weight

LEDA512

Mass spectrometer focal plane

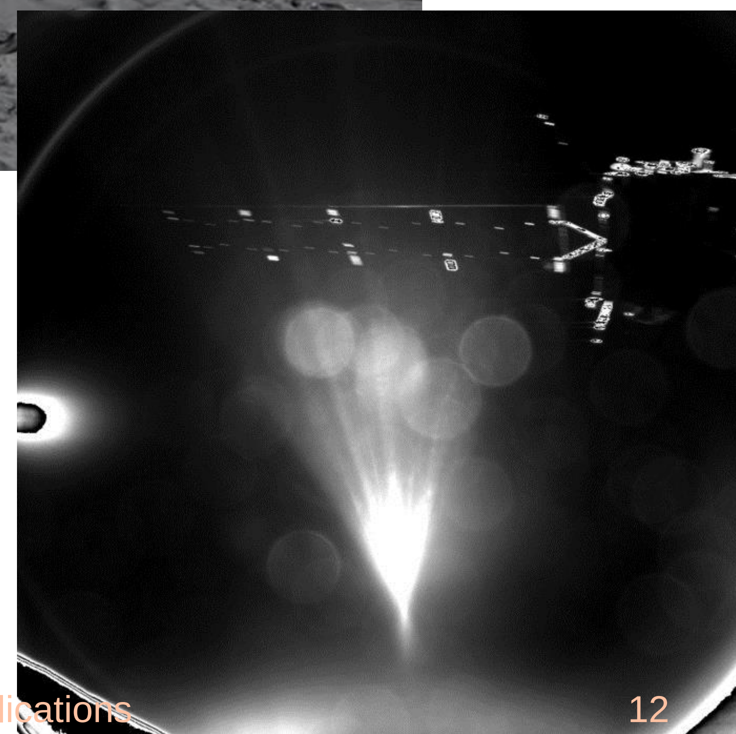


Spectrometer front-end for the ROSINA/DFMS experiment on the ROSETTA comet lander

Design 1998

Launch 2004

Comet rendez-vous 2014



Satellite housekeeping

Wide variation of applications

- Experiment telemetry
- Satellite attitude: sun & star trackers
- Satellite monitoring, docking, witness

Sensor types

- Often the “lower end” (as compared to “astronomical”)
- Often visible and monolithic
- No protection whatsoever for radiation and temperature

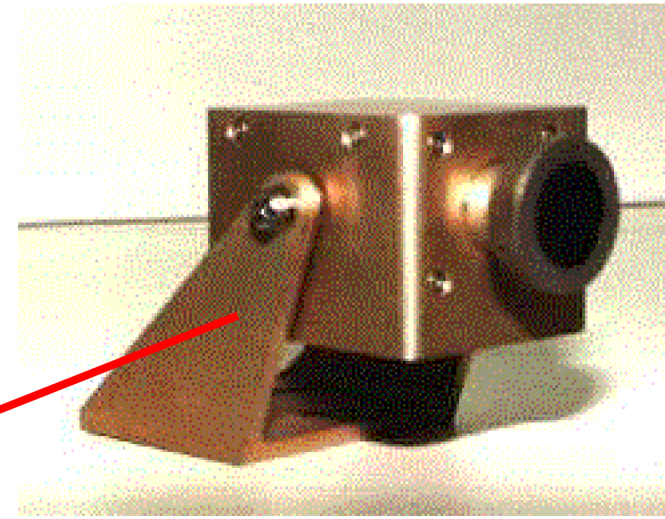
VTS visual telemetry system

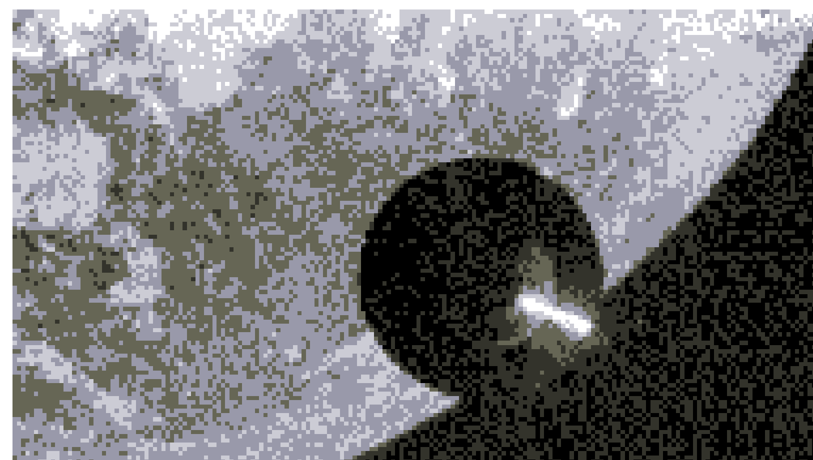
By IMEC, MMS, OIP/DEP
For ESA-ESTEC

Observation of space craft during launch and afterwards.

Miniature camera 5x6x6 cm^3 based on 512 x 512 pixel logarithmic response imager.

This was the first CMOS camera in space. Launched with Ariane 502, 30 October 1997.





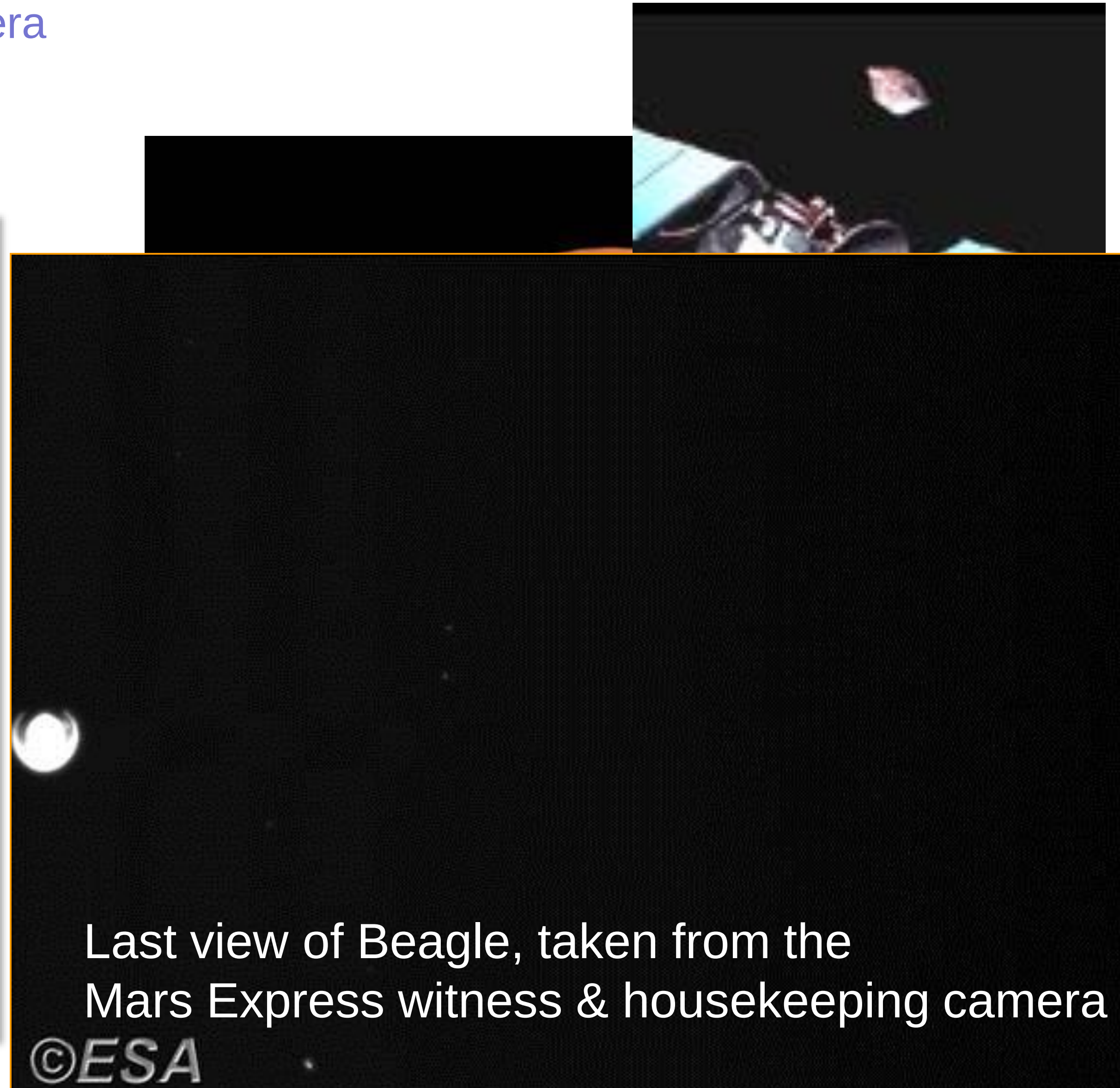
"separation of SPELTRA from MAQSAT-H" pictures received from VTS, 30oct97. ©ESA

Mars Express

witness & housekeeping camera

2 June 2003 lauch on a Soyuz/Fregat launcher at Baikonur, Kazakhstan. Mars Express took six months to reach the Red Planet, arriving 25 December 2003.

Six days after separation from Mars Express, the lander entered the Martian atmosphere. Its rocky ride through the atmosphere to land on the surface should have taken no longer than ten minutes. No signals were received by orbiting spacecraft or Earth-based radio telescopes



Last view of Beagle, taken from the Mars Express witness & housekeeping camera

2. REQUIREMENTS

For image sensors in space missions

Unlike you might think
space technology is very conservative

(1) space qualifications requires a lot of effort and time

(2) due to the launch costs and risks, proven technologies are systematically preferred

(3) experiments take years of preparation

(4) after launch it may take years before the space craft reaches its final target

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It's a different place

Earth

Temperature: -10°…50°C, air

radiation: don't worry

Power? kW

Weight? Size? Doesn't matter

Reliability? If fails: replace

Qualification: for a lot of things

Space

Temperature: -273°…400°, vacuum

Ionizing radiation: γ, X

NIEL non-ionizing energy loss: e^-, H^+, N°, ions..

SE single events: SEU, SEL, …

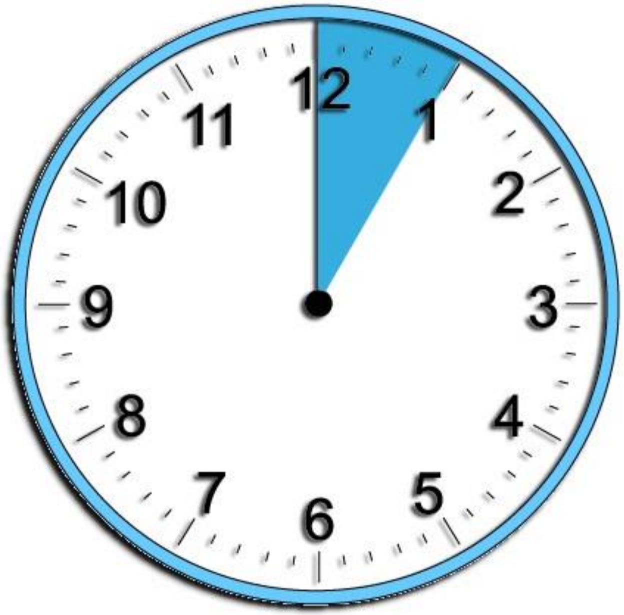
Power! W

Weight! Size! matters

Reliability: if fails: backup modes

Qualification: to guarantee mission

Taken an earth-grade image sensor to space



After 1 hour

- ✓ The Silicon and the package likely survive the launch
- ✓ The device will work fine, apart from spurious pixel events
- ✓ The die bond, the bondwires and the glass cover may suffer
- ✓ The optical train may be shattered

Taken an earth-grade image sensor to space

After 1 week

- Depending on the orbit the image sensor will degrade under radiation.
- If crossing the Van Allen belts (or South Atlantic Anomaly - SAA)
  - From day one, the number of hot pixels will steadily increase
  - after a few weeks an increase of dark current and other performance decrease
  - complete failure after few months
- *Occasionally* the frame data will be corrupted due to SEU/SEE
- *Exceptionally* the camera will self-destruct by SEL (single event latchup)

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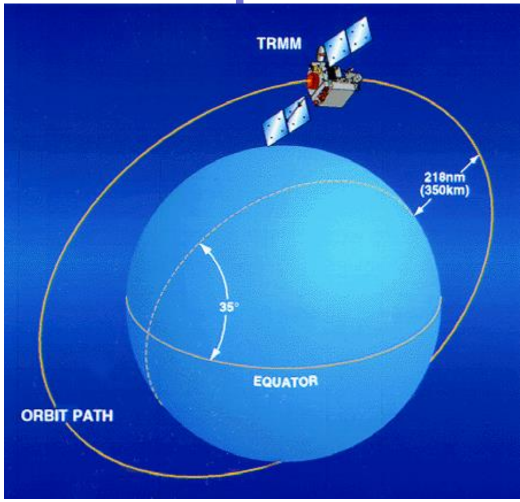
Taken an earth-grade image sensor to space

During lifetime



Things may go terribly wrong

- ✓ *Many* missions have passive thermal housekeeping
  - ✓ On the average earth-like temperature (~25°C), +/-150°C
  - ✓ Earth shadow -100°C and at "dawn" brutal heat up.

    Can the camera survive such thermal cycles?
- ✓ *Some* scientific missions need cooling
  - ✓ for background and dark current reasons.
  - ✓ Your imager and camera will be cryogenically cooled to the 77Kelvin range or even below. Many devices halt operation there.
  - ✓ Mechnical parts, connectors, polymers become brittle or self-destruct under thermo-mechanical stress.
- ✓ *Accidental* pointing to the sun
  - ✓ Will the Silicon locally evaporate or just melt?
- ✓ *Radiation damage*
  - ✓ From instrument degradation to complete malfunction and latch-up

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3. TOTAL DOSE

Effects and counter measures

Radiation effects
in a nutshell (1)

Radiation *itself* is divided in two types:

- photons (gamma & X rays) →*deep penetration*
- particles (protons, neutrons, electrons, ions and other) →*impact damage*

A key element in bringing hardware to space is radiation hardness.

- Space environment represents about 10-10000 Gy/Y.
- Radiation tolerance up to about 1kGy (100kRad) total dose required for most missions
- Most commercial electronics die after 100 Gy (10 kRad)

Radiation effects
in a nutshell (2)

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Total Dose radiation damage is roughly divided in

- charge built-up (ionization)
- secondary effects thereof (shift of device parameters as MOSFET Vth, mobility degradation, and increased leakage)
- displacement damage: HE particles create localized (point) defects

The Single Events of interest are

- SEU single event upset: flipping a bit in a register of memory
- SEL single event latch-up: high supply current initiated by particle

TID total ionizing dose

Radiation:

⇒Primarily X and γ radiation; also all charged particles

Dominant effect :

⇒Creation of positive space charge in the SiO2 (SiN) dielectric layers

⇒Increase of interface states at Si-SiO2 interface

Effect on CMOS circuits:

⇒ Moderate shift of Vth, μ degradation and 1/f noise increase

⇒ Parasitic S-D leakage via STI/field in nMOSFETs resulting in large leakage currents and malfunction

TID total ionizing dose (2)

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Effect on CMOS pixels:

- ⇒ Moderate offset shift and 1/f noise increase
- ⇒ Lateral shunting between pixels
- ⇒ Lower gain and increased PRNU

- ⇒ Increased average I_{dark} and DNSU

Most publications only describe this last effect

TID Gamma
Radhard pixels

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LAP2010 device

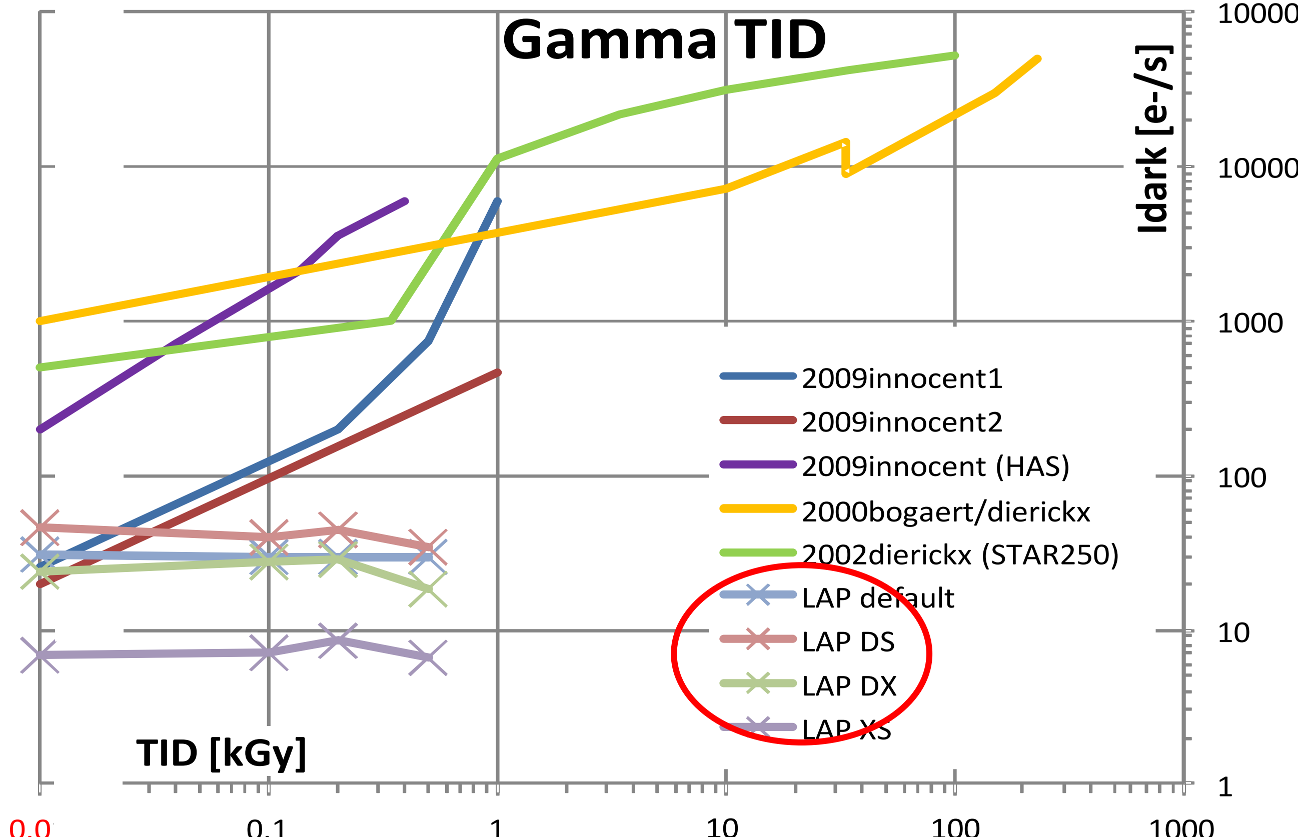
Tower TSL018

TID of

gamma ^{60}Co

Compared to

published SotA



TID Gamma ≠ Electrons

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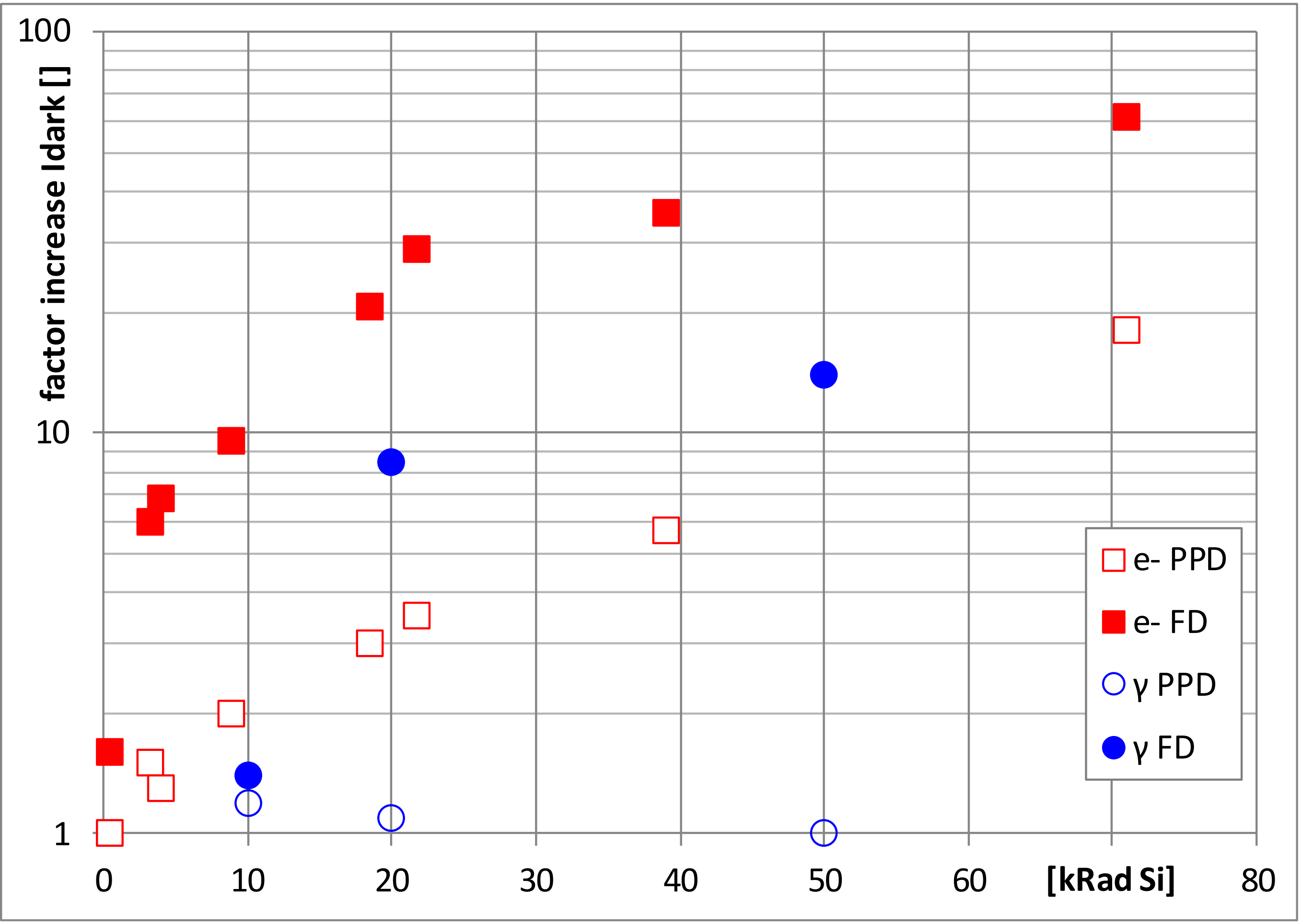

Device

- LAP2010 Designed for medical X-ray
- Tower TSL018
- 10 devices; many pixels per device

TID of

- 300keV electrons
- 1.2/1.3 MeV gamma ^{60}Co

Effect on

- Buried PPD
- Surface FD

TID design countermeasures

- **Buried (pinned) diodes as the general way to reduce dark current**
- **Avoiding the parasitic source-drain leakage in nMOSFETs**
- **Other case-by-case measures**

TID-hard nMOSFET

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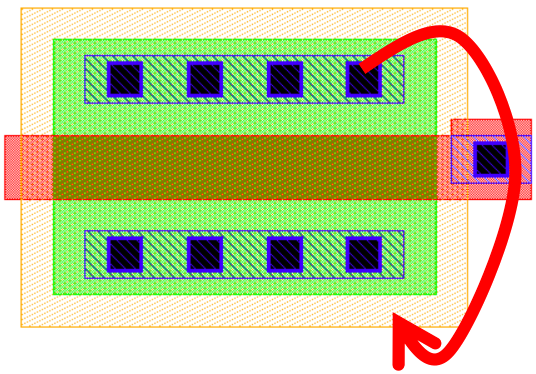
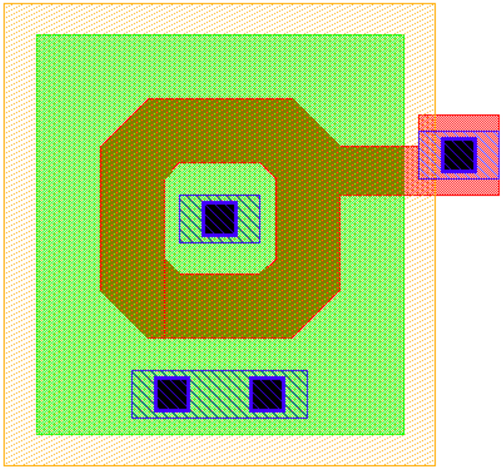
avoid de parasitic source-drain leakage

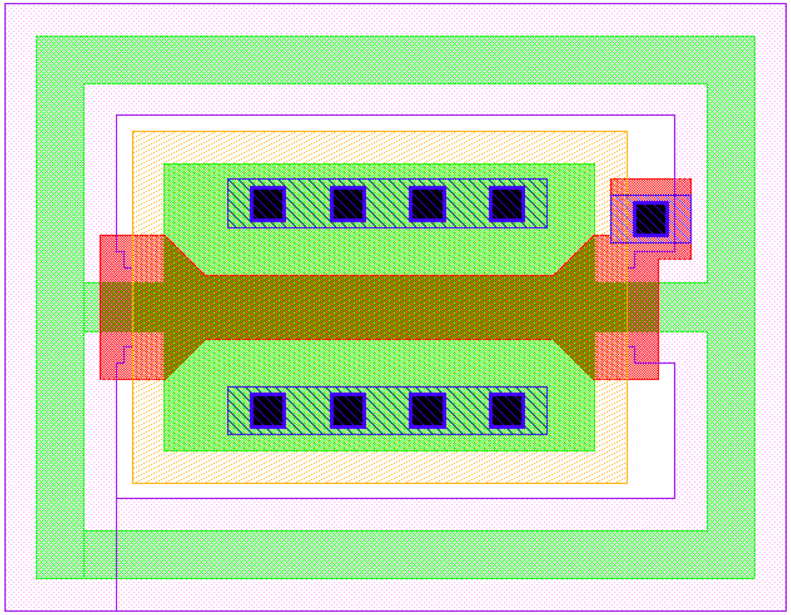


Regular transistor

Leaks when STI/field inverts due to positive charge built-up due to ionizing radiation



Annular transistor:
No path over STI/field



H-gate transistor:
Leakage path over STI/field is blocked by P-implant

Caeleste RH library

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Available in 4 technologies

Analog & mixed mode

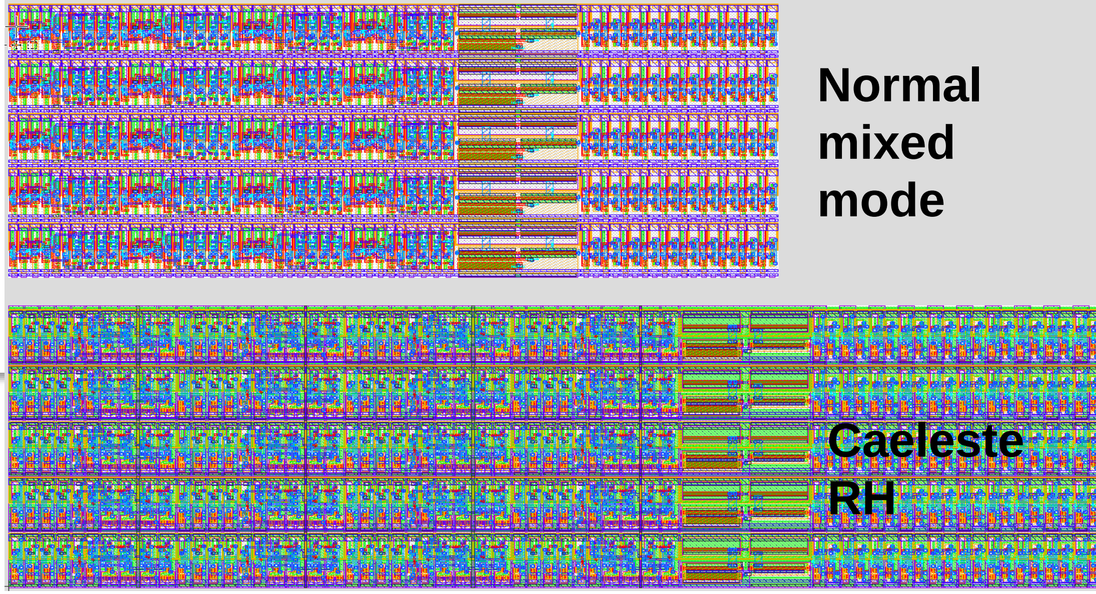
Very high TID & TnID hardness

Very high SEL hardness

Very high SEU hardness *wo TR*

<20% increased Cin and power

<50% area increase



The “Campanion” ASIC

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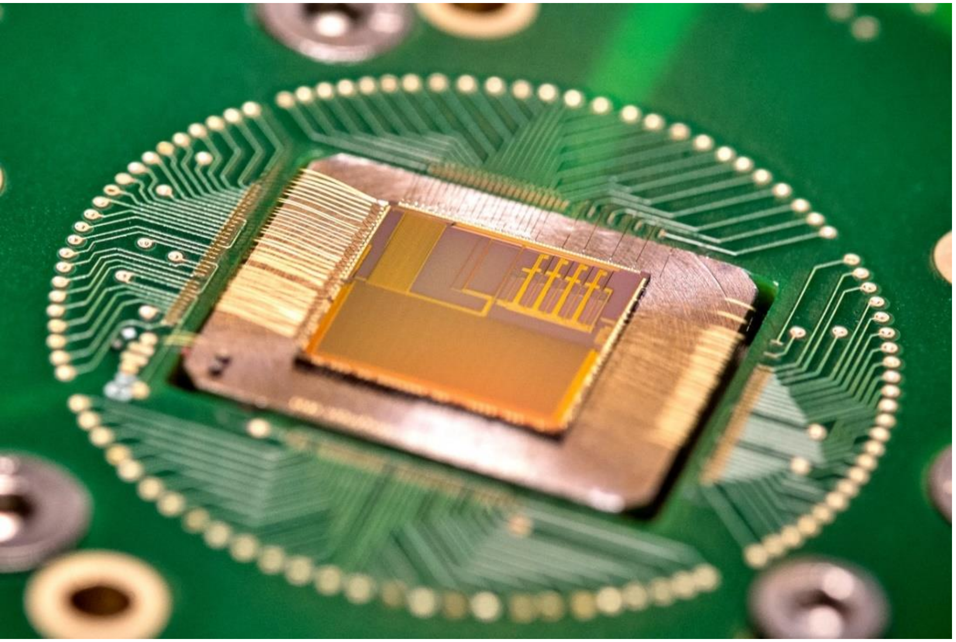


By Caeleste+Easics+Selex

For ESA

2014

Fully radhard & $cryo_{77K}$

UMC018

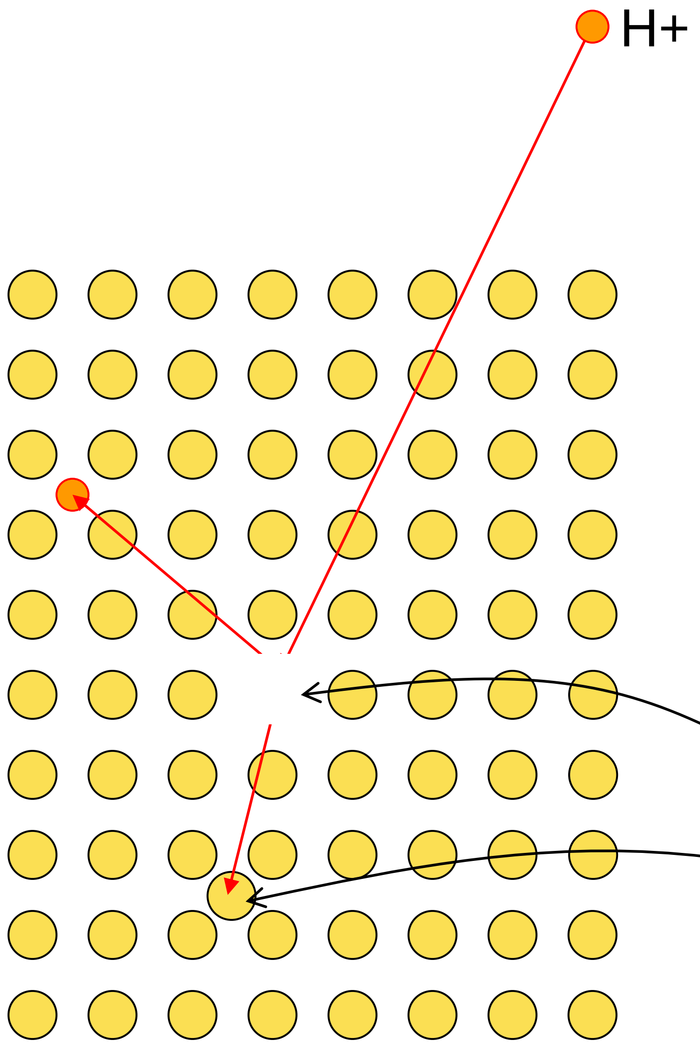
Digital: DARE library

Analog: CaelesteRH

Target >>1Mrad TID

Displacement damage

- "ionizing" dose: by kicking out electrons
- non-ionizing "displacement damage": by kicking out atoms.



Silicon lattice

A simplification:

Often
Displacement damage
=
Vacancy + nearby interstitial
(+diffusion, decoration)

Displacement Damage

a.k.a. Non-Ionizing Energy Loss

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Radiation:

⇒ High Energy *particles*: protons and heavier ions
(*photons* have too little impulse)

Dominant effect :

⇒ *Non-elastic* displacement of Si atoms
⇒ Often creating an initial vacancy+interstitial

Effect on CMOS pixels:

⇒ Point-wise heavily leaking diodes, hot pixels
⇒ Often blinking “RTS” dark current pixels

Pixel redundancy?

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Proton / Neutron / other particle - damage

⇒ Displacement damage creates “hot” or “RTS” pixel

⇒ Or the SE creates a flash (see further)

Is there a way to remove or cancel this?

Suppose

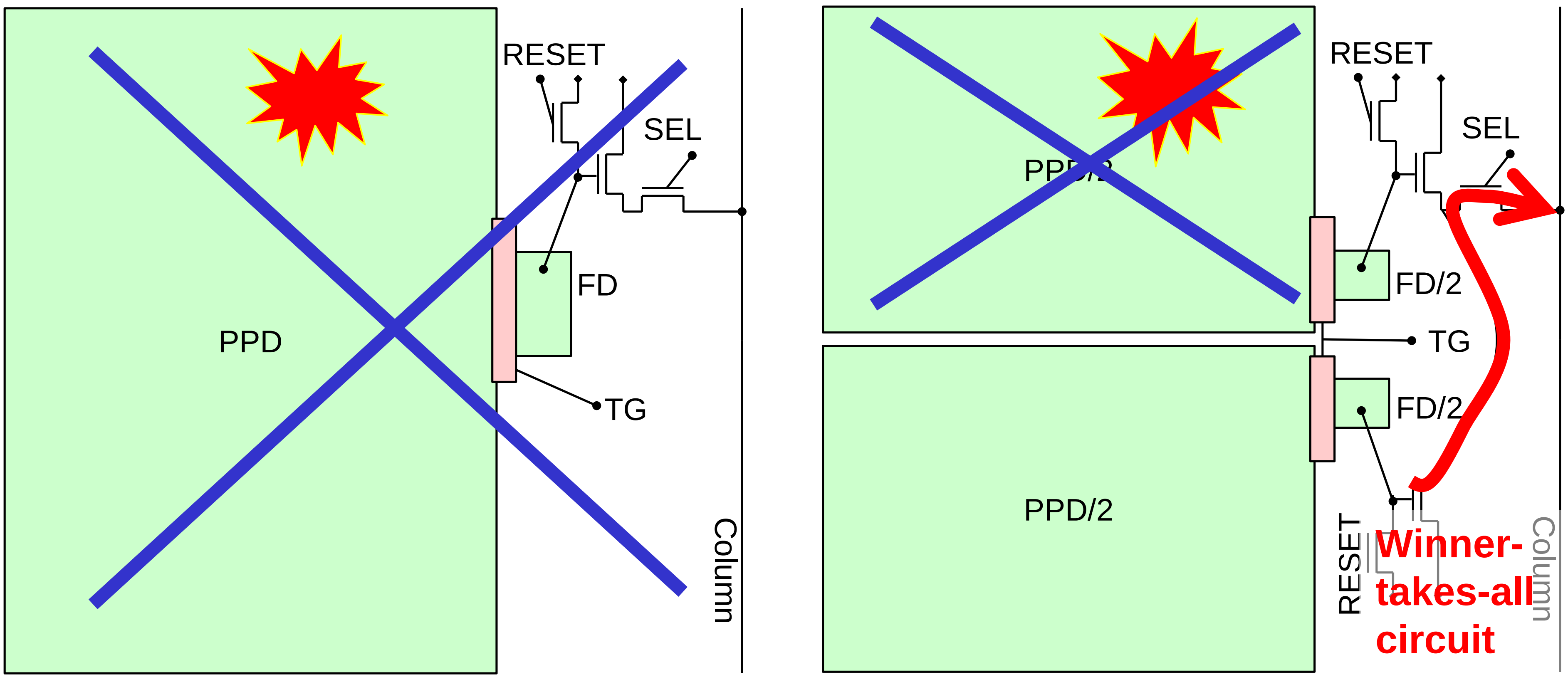
⇒ split the pixel in 2...100 parts.

⇒ The defect will reside in only one

⇒ Readout all, remove the defect part’s signal and average.

⇒ Take a weighted maximum voltage by winner-take-all circuit or sourcefollower

Photodiode redundancy



US patent US8426828

1. Introduction: IS in space missions
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4. Single event effects & counter measures
5. Take home

SINGLE EVENT EFFECTS

1. Single event upset

Kinds of single events

SEE “single event effect”

⇒SEFI, SET, SEGR, SEB ... ()

The two most prominent in this context:

⇒**SEU** single event upset

⇒**SEL** single event latch-up

SEU single event upset

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Radiation

⇒Sometimes X, γ, e-, but heavier particles are far more efficient

Dominant effect :

⇒ Creation of instantanous + or – charge packet sufficient to toggle a latch/SRAM/FF

Effect on CMOS imagers and pixels:

⇒ register or memory losing information

⇒ flash seen by the photodiode

SEU

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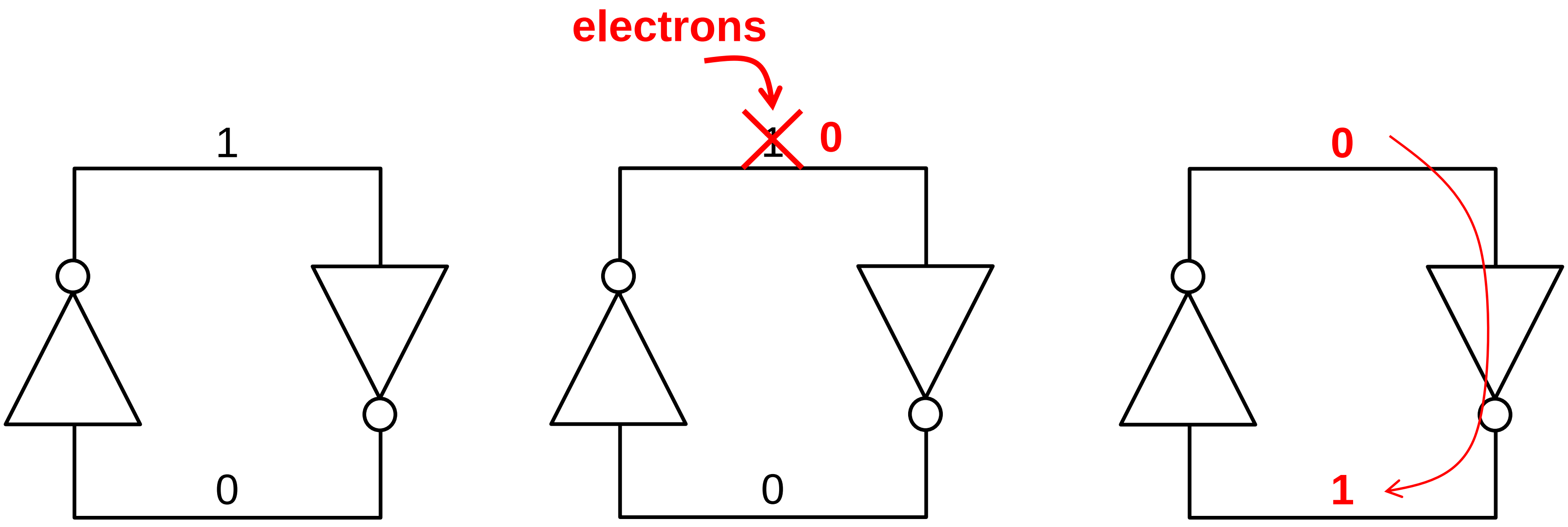
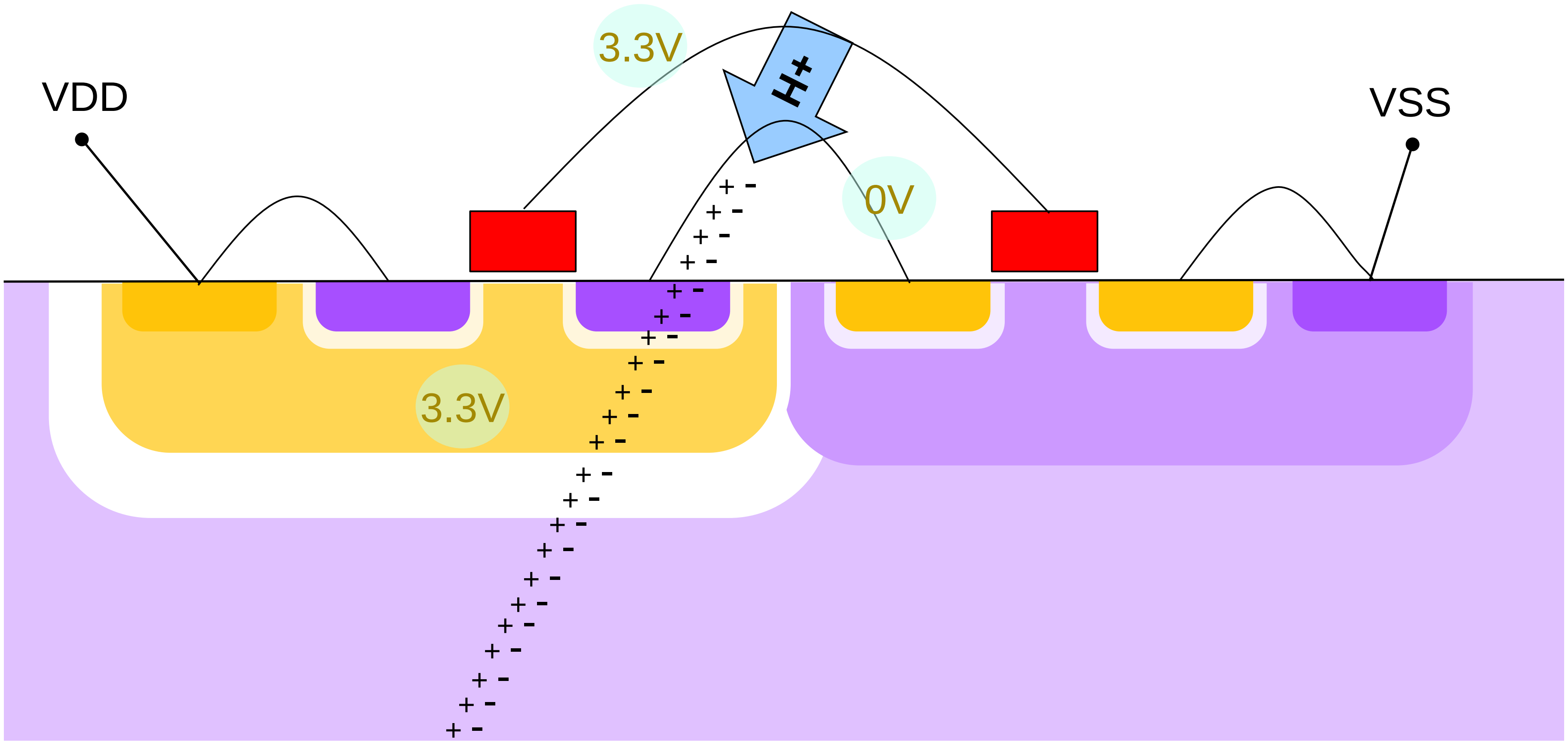
= Corruption of bit in SRAM or Flip-flop

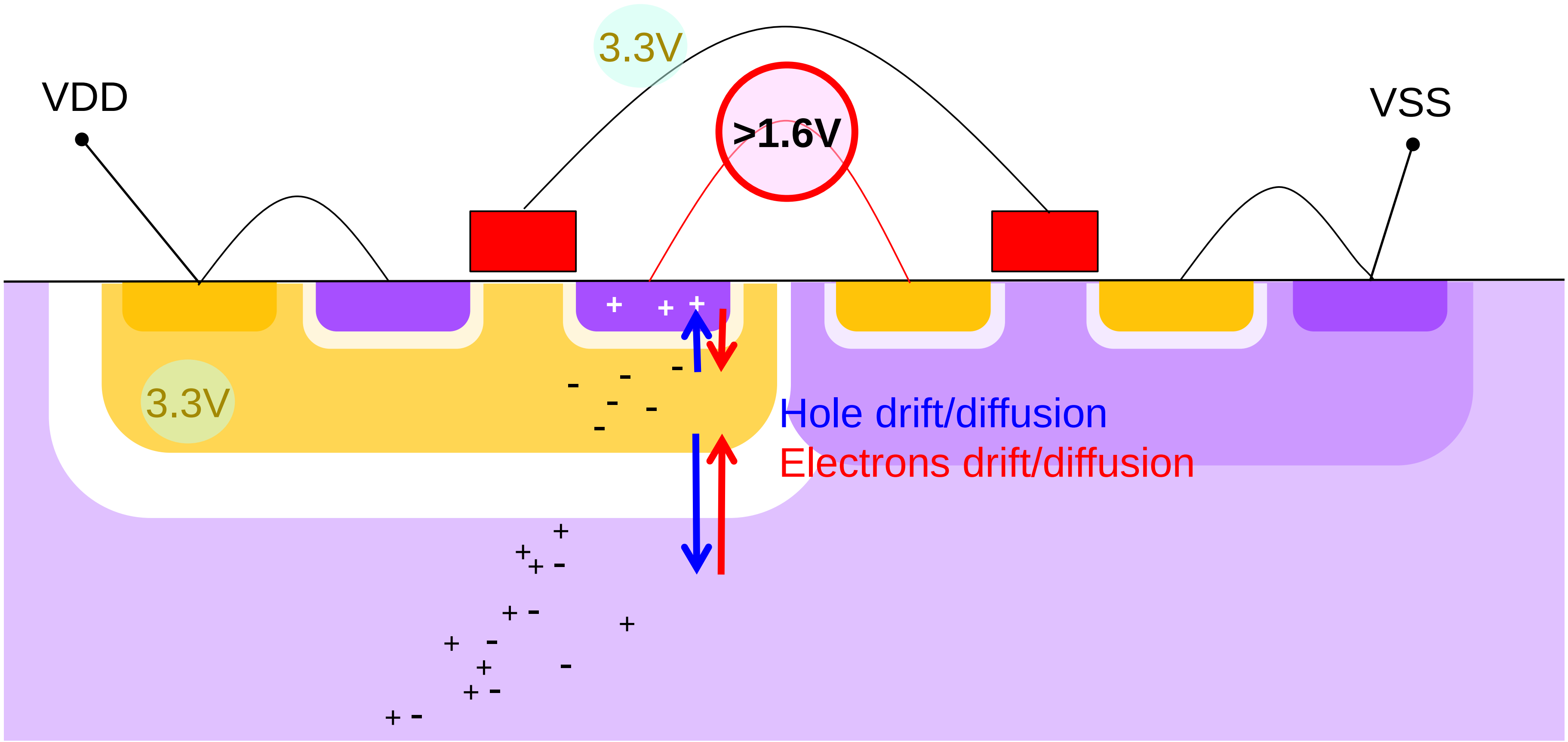
charge packet deposited by particle charges one node of a latch to the opposite logic value



Flipping the invertor @t_0



Flipping the invertor @t_0+0.5ns



SEU countermeasures

	Adequate	Helps	Minor effect	disadvantages
• Shield against particles	☆	★	★	instrument weight
• Make vulnerable volume small	☆	★	★	technology limit
• Make vulnerable node capacitance large	★	★	★	area, speed, power
• Triple (and other froms of) redundancy	★	★	★	area, speed, power
• Detectability, read-back, re-upload	☆	☆	★	not real-time

SINGE EVENT EFFECTS

2. single event latch-up

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SEL single event latch-up

Radiation

⇒Protons but rather heavier particles as *huge* local and instantanous charge packets are required

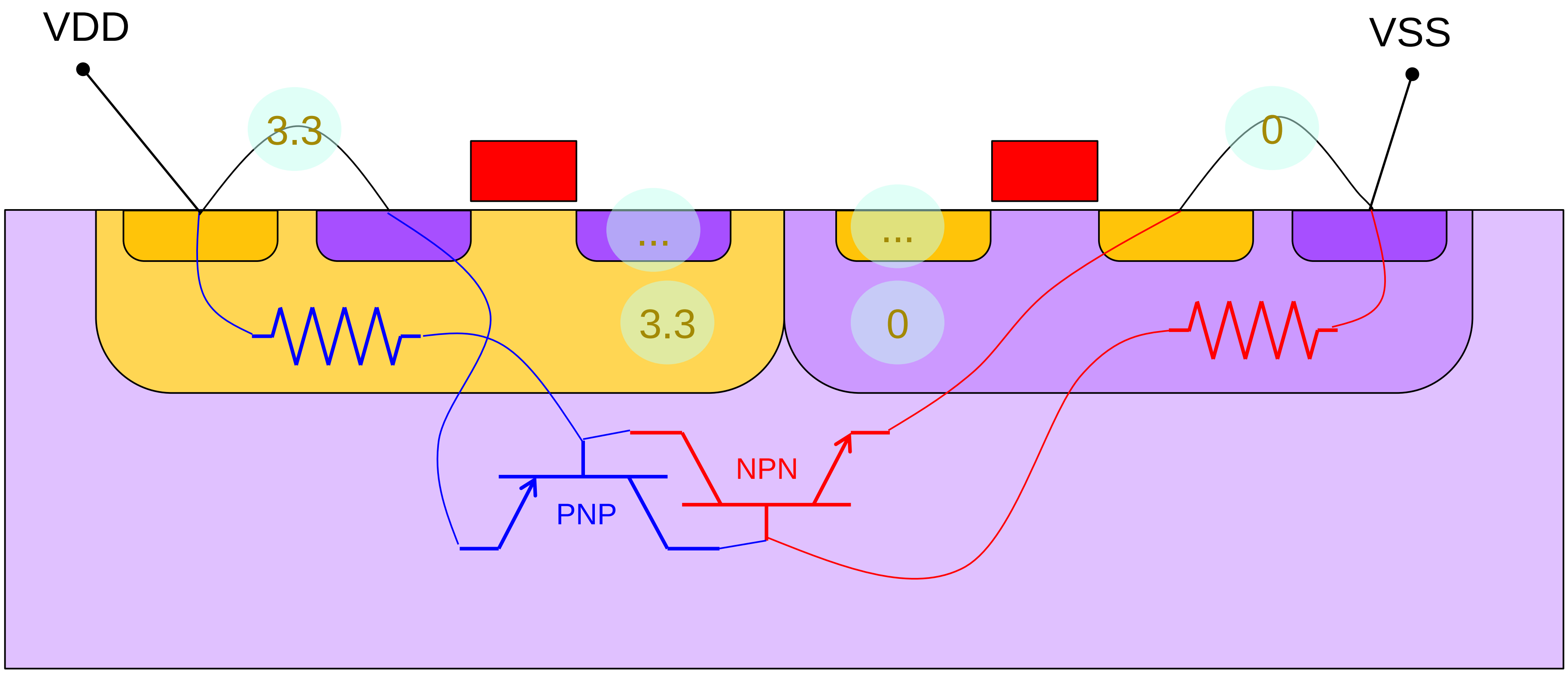
Dominant effect :

⇒Creation of instantanous + or – charge packet sufficient to initiate a *PNPN latch-up* between VDD and VSS

Effect on CMOS circuits:

⇒ Circuit collapsing and potential destruction due to excessive supply current VDD-VSS

Bulk CMOS has an annoying thyristor



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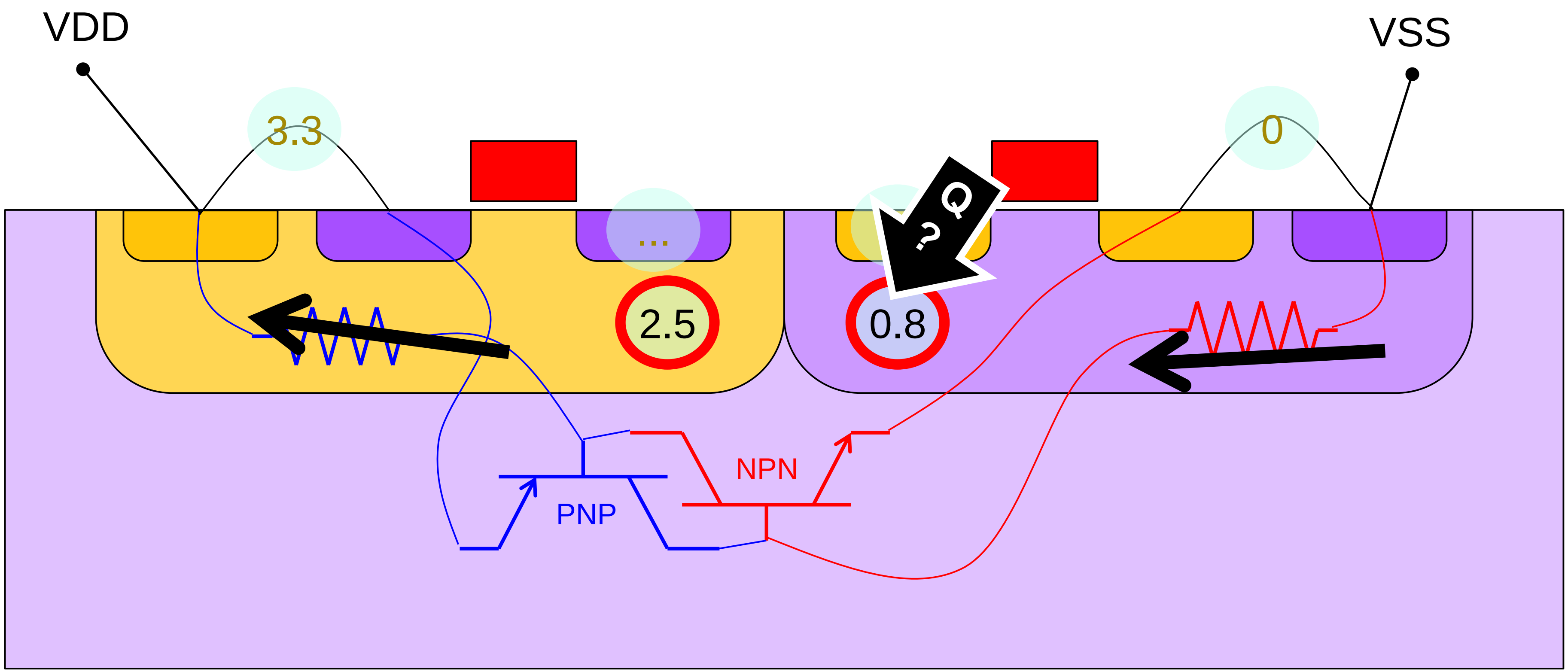
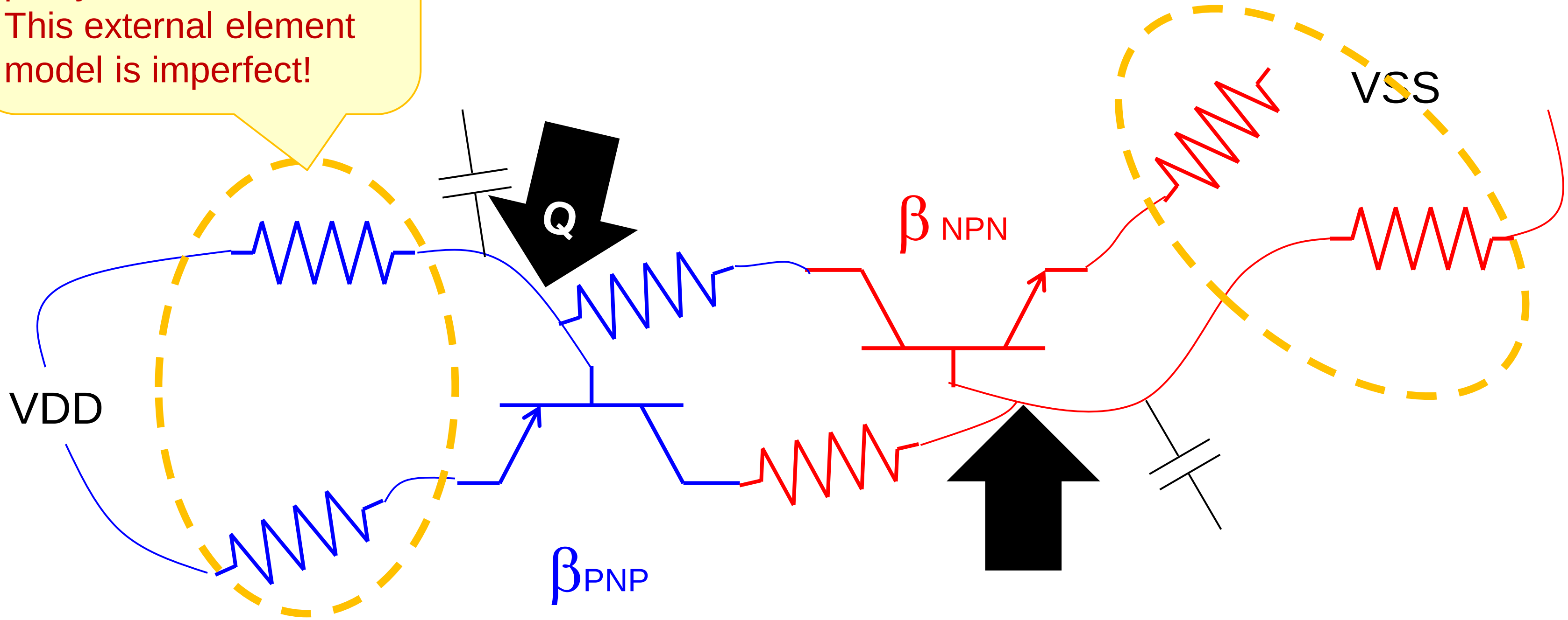
Bulk CMOS has an annoying thyristor



Thyristor = 2 * BJT

Attention: these two resistors are physically partly the same
This external element model is imperfect!



- Threshold for ignition: Q, C
- Conditions for sustaining: β, R

Modeling SEL?

Quantitative compact (=SPICE) model?

- **What lacks: value for series resistances**
  - ⇒ Series resistances in E, B, C. Can estimate it from techology data.
  - ⇒ Pay attention that “resistance” applies to majority carriers. Base resistance is thus over/underestimated and
  - ⇒ Emitter and Base resistances partly overlap: Emitter current increases IR drop of Base.
- **What lacks: models of the parasitic BJTs**
  - ⇒ β: could eventually “measure” that.
- **Qualitiative modeling is possible, without predictive value**

Only realistic route: TCAD modeling

SEL countermeasures

Avoid ignition

		disadvantages
⇒ Reduce pick-up: minimize sensitive volume	☆★★	technology limitation
⇒ maximize C/Q: increase node capacitances	☆☆★	speed / power / area
⇒ No thyristor: SOI, nMOS only, FINFET	★★★	yes/no imager compatible

Avoid sustaining

The “earthly” methods to reduce CMOS latch-up:

⇒ Reduce the series resistance in the thyristor	☆★★	technology limit
⇒ guard rings metallically tied to VDD/VSS	☆★★	layout limitation

Avoid proliferation

⇒ Fragment nWELLs	☆☆★	confines not cures
⇒ Detect & reboot	☆☆★	only after it happens

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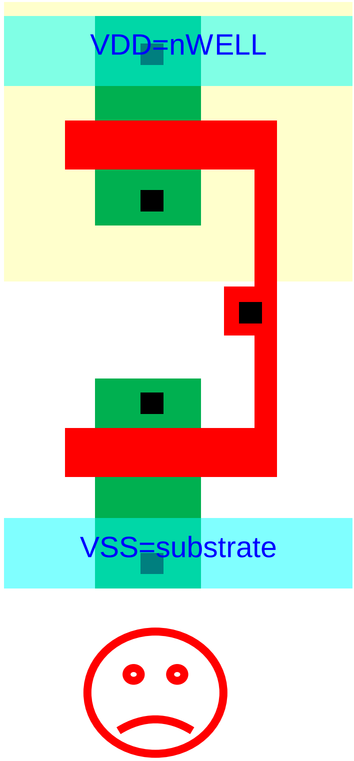
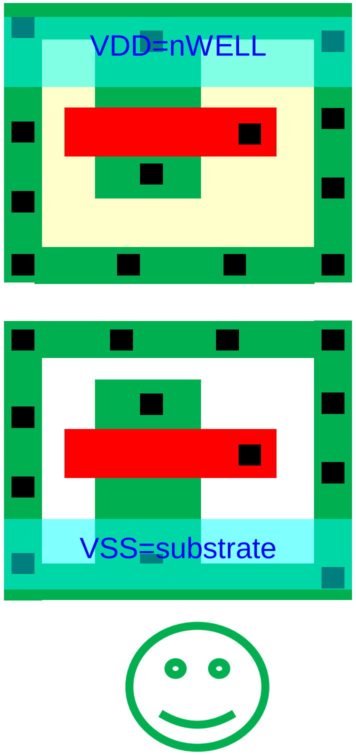
SEL

design countermeasures using guard rings

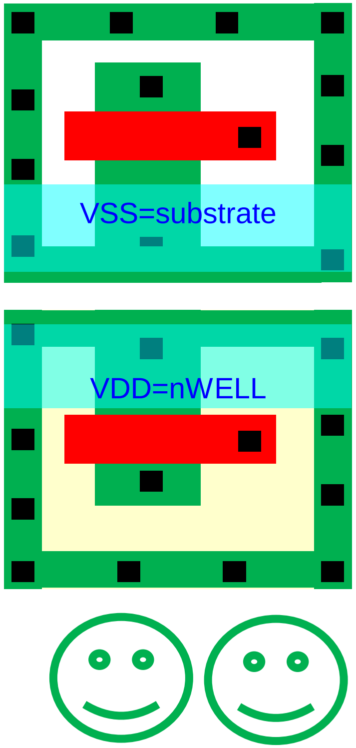
Classic CMOS design style



Metal guardring around wells



Rails in the middle



Good to know about SEL

- nMOS-only or pMOS-only circuit parts cannot latch-up.
- An nMOSFET-only pixel does not latch-up
- A standalone BJT does not latchup

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5. TAKE HOME

Conclusions

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conclusions

Temperature

⇒ Si can handle that. Package and instrument issue

Total Dose (ionizing and Displacement damage)

⇒ High radiation hardness can be designed for

⇒ Weak points remains I_{dark} due to displacements damage

Single Events (mainly SEU and SEL)

⇒ Nearly perfect protection against SEU and SEL can be designed for.

⇒ Remains weak for: very heavy ions

⇒ Inherent weak point: the pixel itself is *made* to detect radiation.

Thank you

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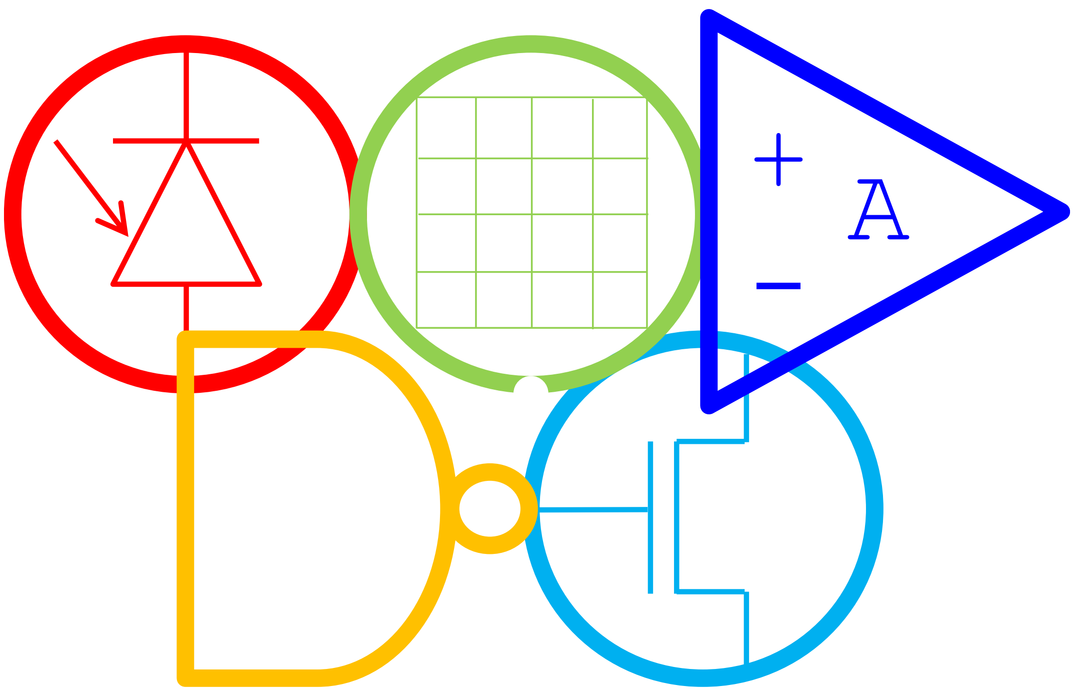
invitation & announcement

WWW.ELECTRONIADE.ORG



10-th anniversary of Caeleste

QUIZ of 4-person teams

14 Oct 2016

Technopolis Museum
Mechelen, Belgium