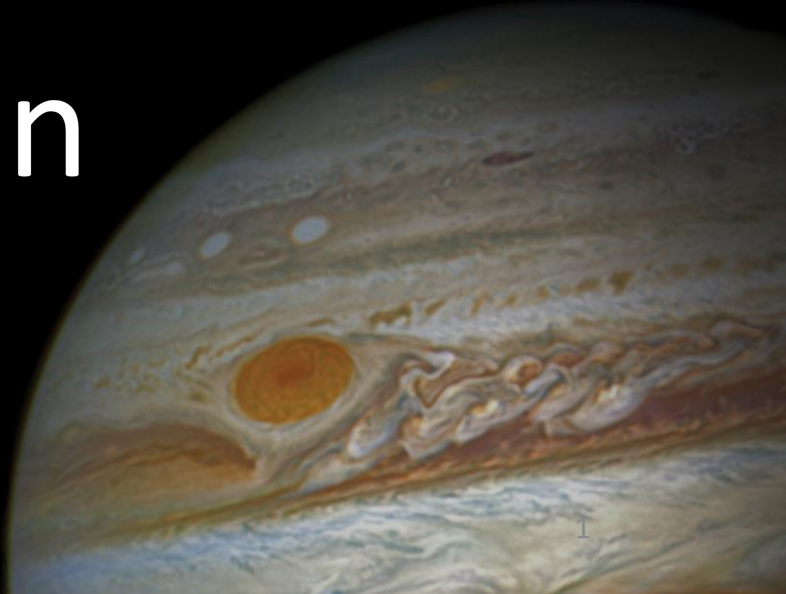
Radiation challenges and perspectives for the ESA JUICE mission



Marco Pinto

Outline

- JUICE
- Jupiter and its moons
- Jovian Radiation Environment
- RADEM
- Radiation Hardness Assurance for RADEM and JUICE

Jupiter Icy Moons Explorer

Cosmic Vision
L-class Mission

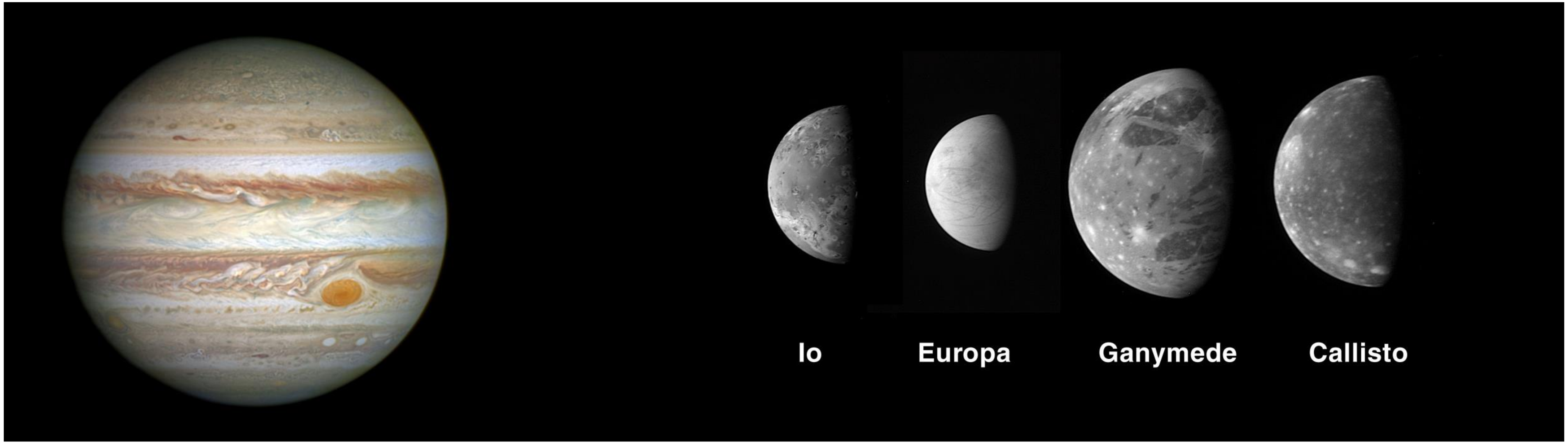
Launch in 2022

What are the conditions for planet formation and emergence of life?

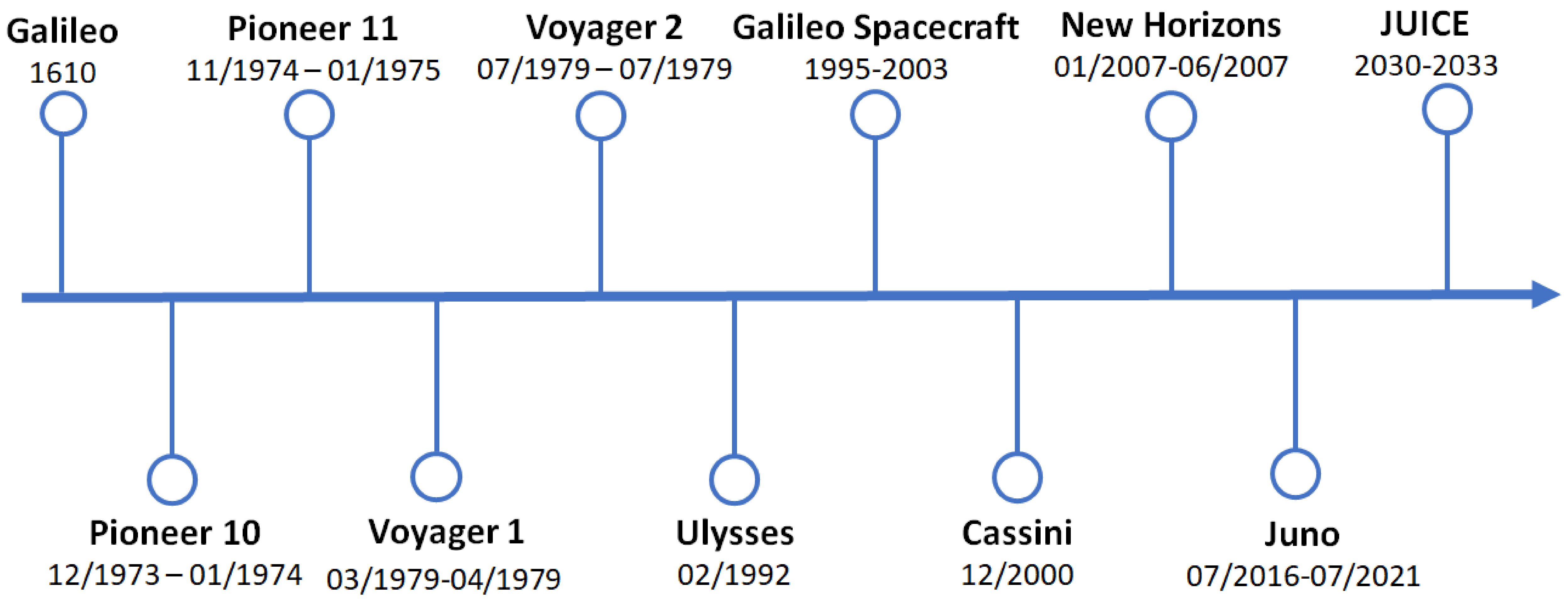
- Emergence of habitable worlds around gas giants

How does the Solar System work?

- Jupiter system as an archetype for gas giants



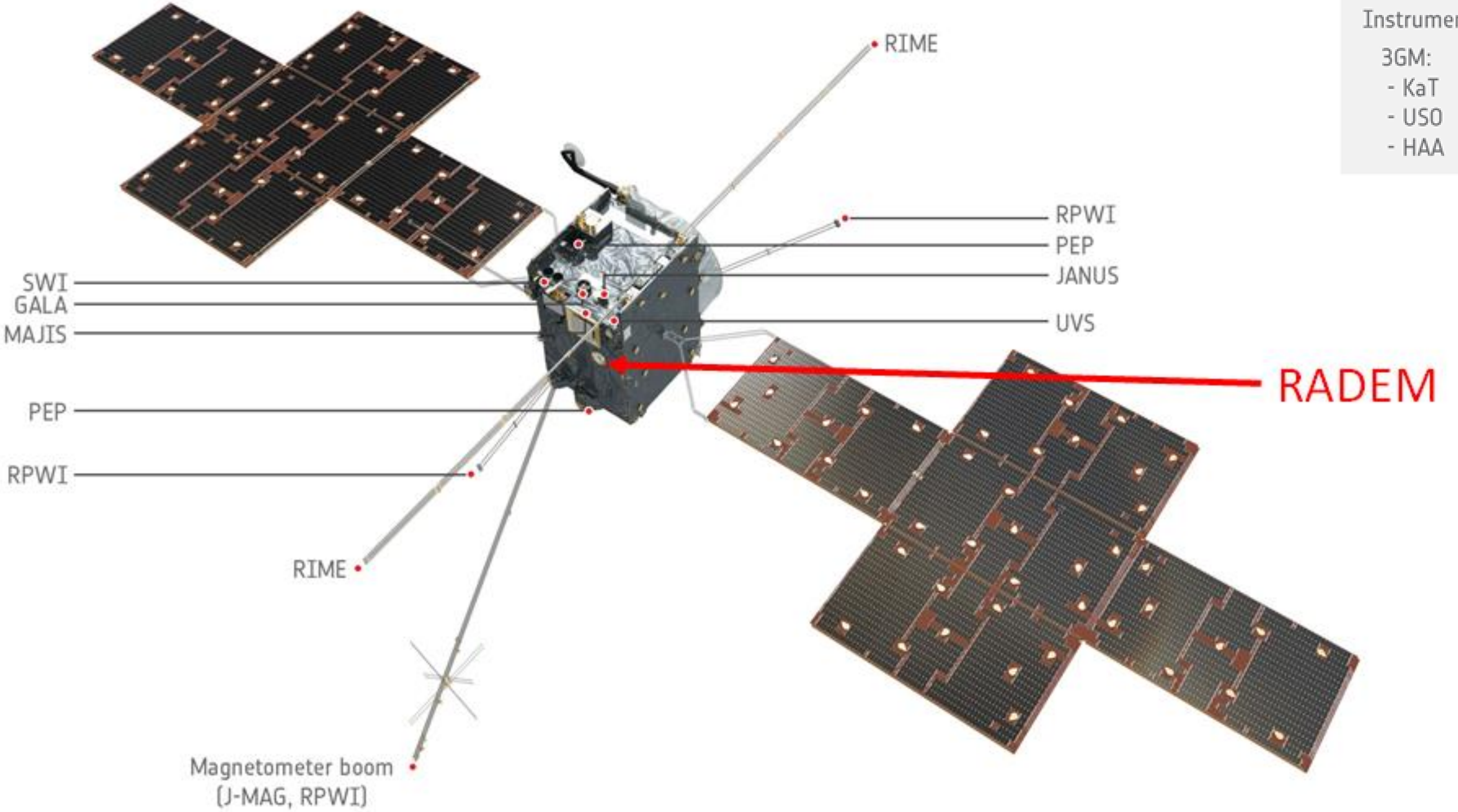
Exploration



JUICE S/C

- **Dry mass ~1900 kg, propellant mass ~2900 kg**
- **High Δ*v* required: 2600 m/s**
- **Payload ~105 kg, ~ 150 W**
- **3-axis stabilized s/c**
- **Power: solar array ~ 80 m^2, ~ 800 W**
- **HGA: >3 m, fixed to body, X & Ka-band**
- **Data return >1.4 Gb per day**

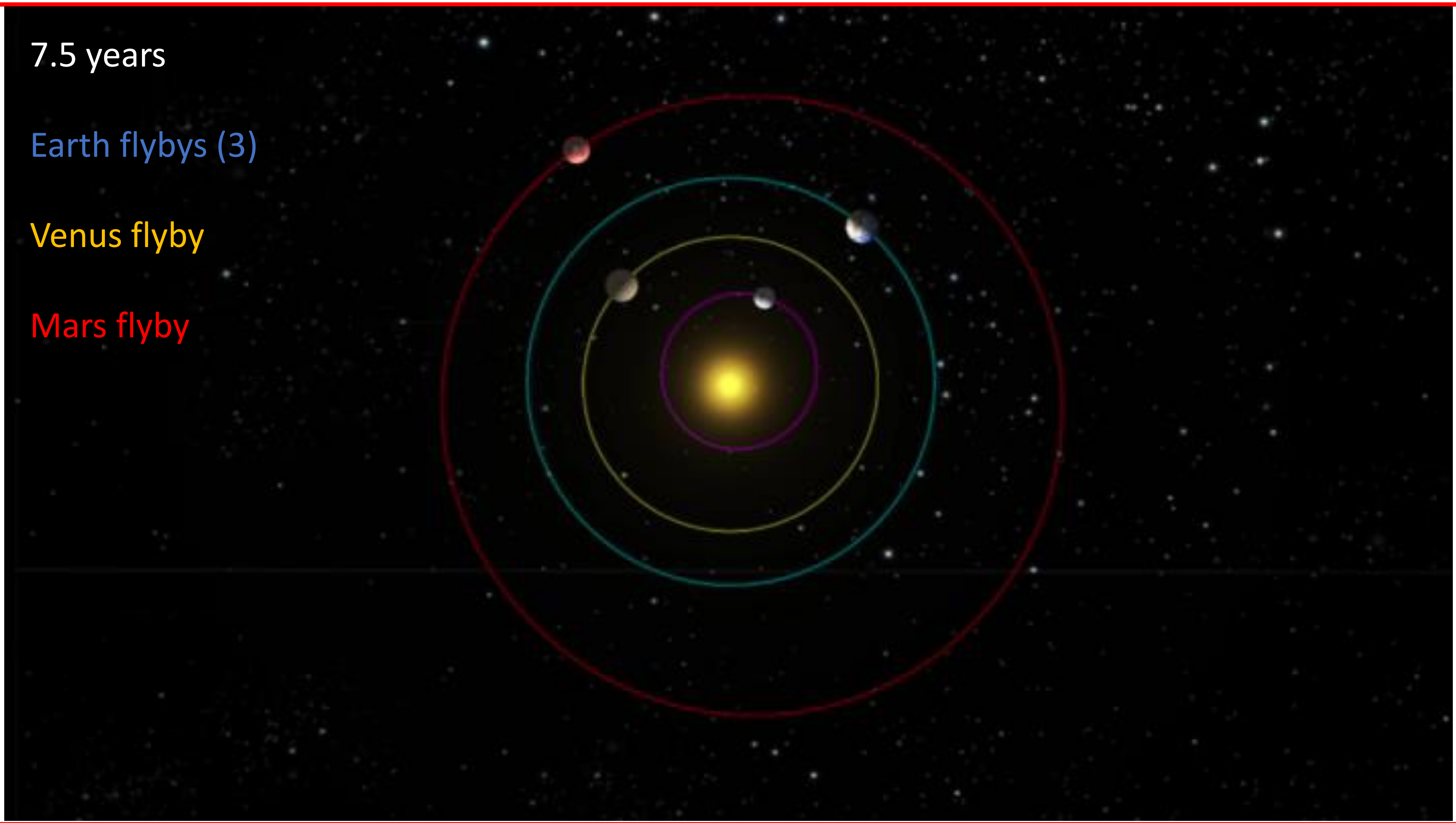
JUICE Scientific Instruments



Instruments inside the spacecraft:

3GM:
- KaT
- USO
- HAA

JUICE Interplanetary Cruise



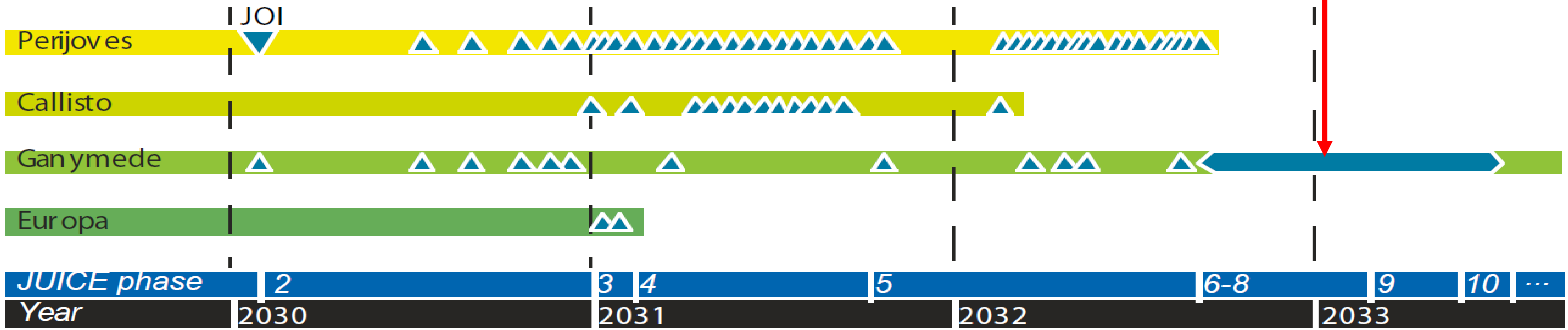
JUICE @Jupiter

Jovian tour

1. Jupiter Orbit Insertion	01.2030
2. Jupiter equatorial phase #1	~11 mon
3. Two Europa flybys	36 days
4. Jupiter high-latitude phase including Callisto flybys	260 days
5. Jupiter equatorial phase #2	~11 mon

Ganymede Orbit

6. Elliptic #1	30 days
7. High altitude (5000 km)	90 days
8. Elliptic #2	30 days
9. Circular (500 km)	102 days
10. Circular (200 km)	30 days



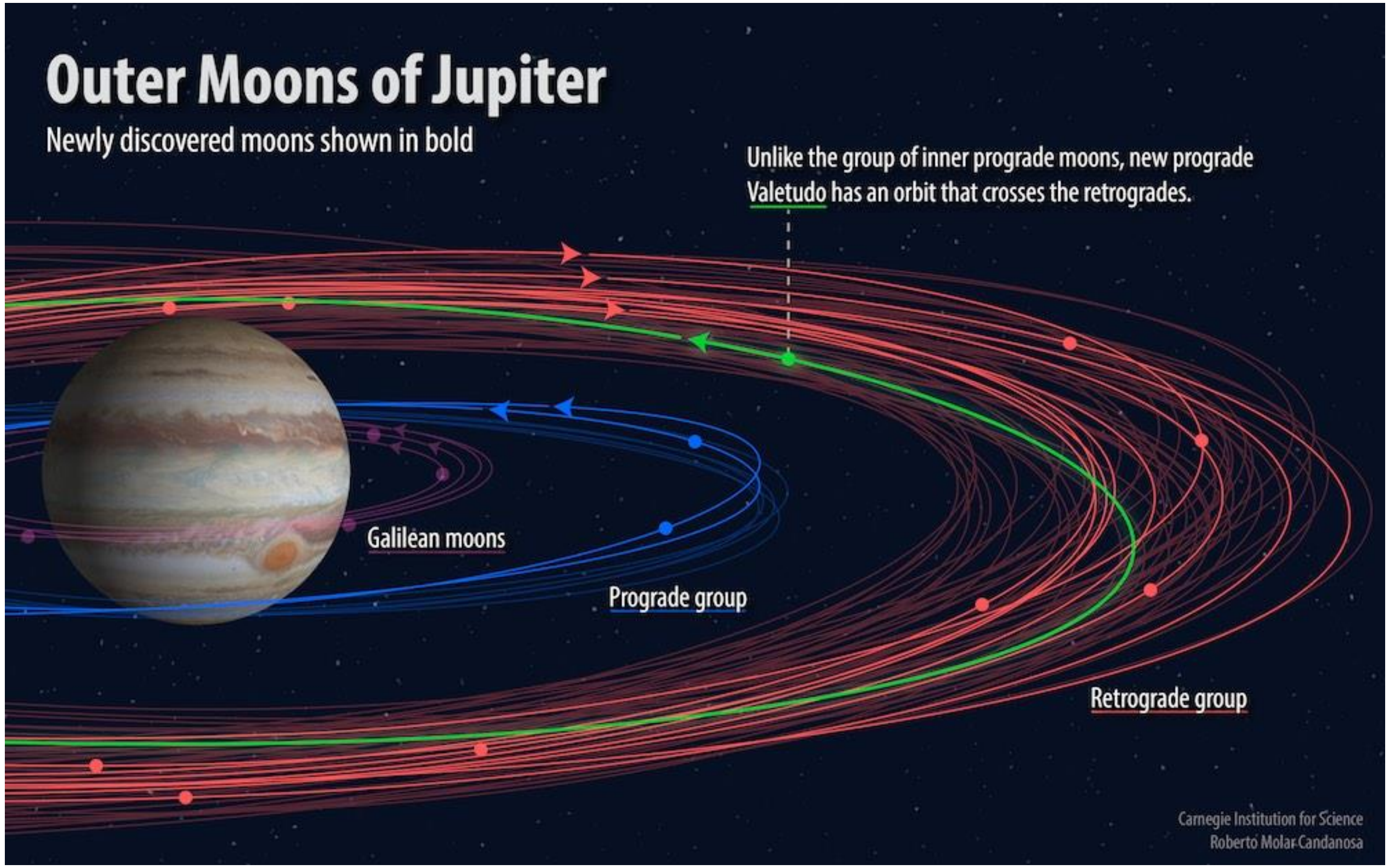
Jupiter

Largest planet on the Solar System
Mass: 10^{27} kg

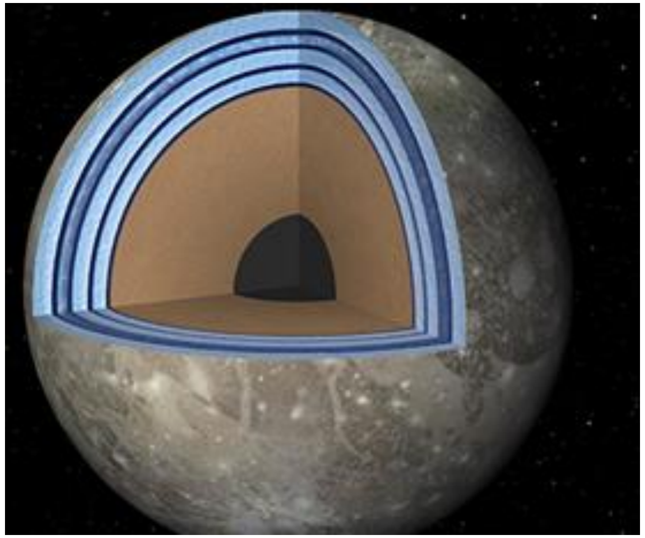
Large influence over the dynamics and evolution of the Solar System

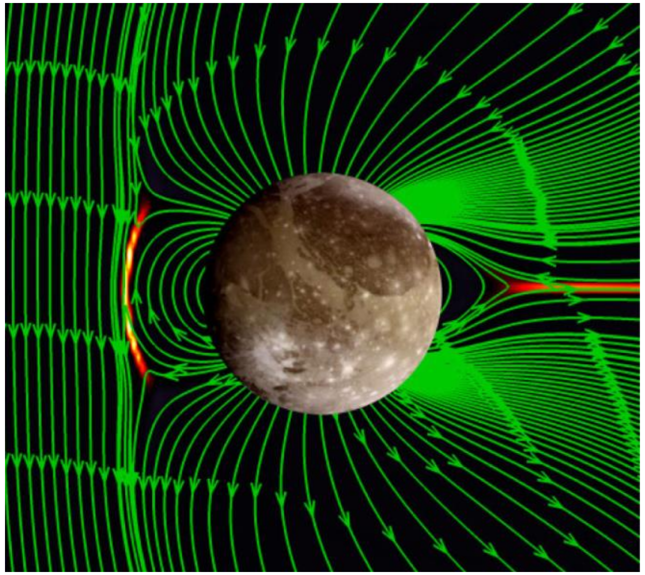
79 known moons (12 found in 2018)
1 larger than Mercury
1 with a magnetosphere
3 with liquid water oceans (possibly)
And more…

Strong magnetic field
extends past the orbit of Saturn
giant accelerator (10h rotation)



Icy moons - Ganymede





Larger than Mercury:

Mass: 1.48*10^{23} kg
Radius: 2634.1 km
Orbital distance: 1 070 400 km
Orbital Period: 7.15 days

Ice shell + ocean

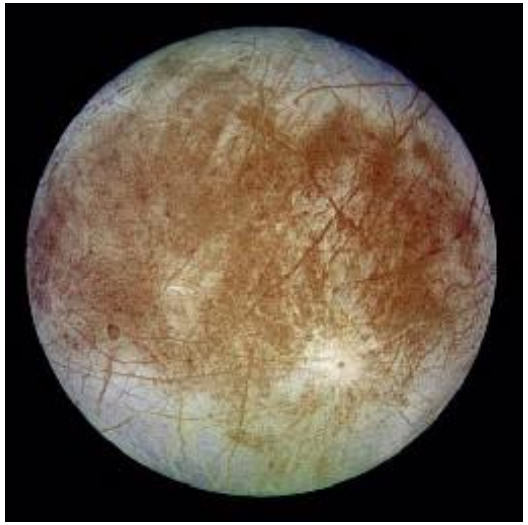
Unknown thickness
Difficult to separate intrinsic and induced magnetic field

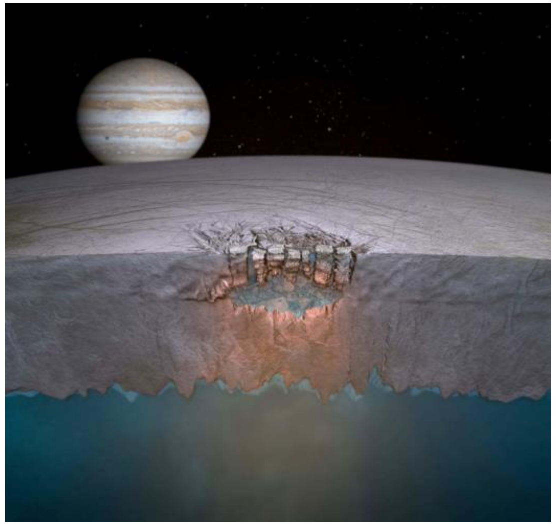
Atmosphere + ionosphere

H, O, Si, Na, H_20

Dipole-like magnetic field - magnetosphere

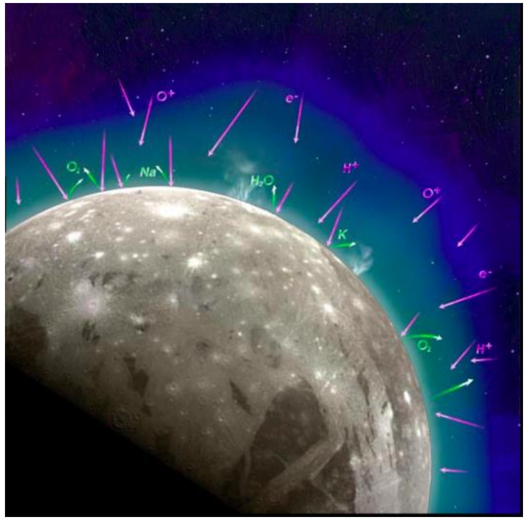
Icy moons - Europa

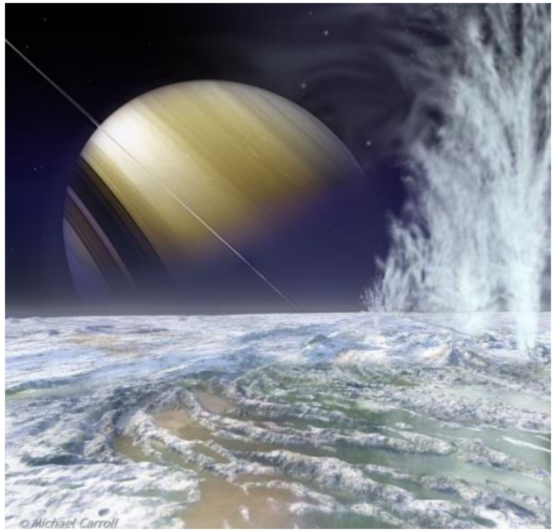




Properties

Mass: $0.48*10^{23}$ kg
Radius: 1560.8 km
Orbital distance: 670.800 km
Orbital period: 3.51 days





Ice shell + ocean

Induced field

Atmosphere + ionosphere + exosphere

H, O, Si, Na, H_20

Sink and possible source of radiation

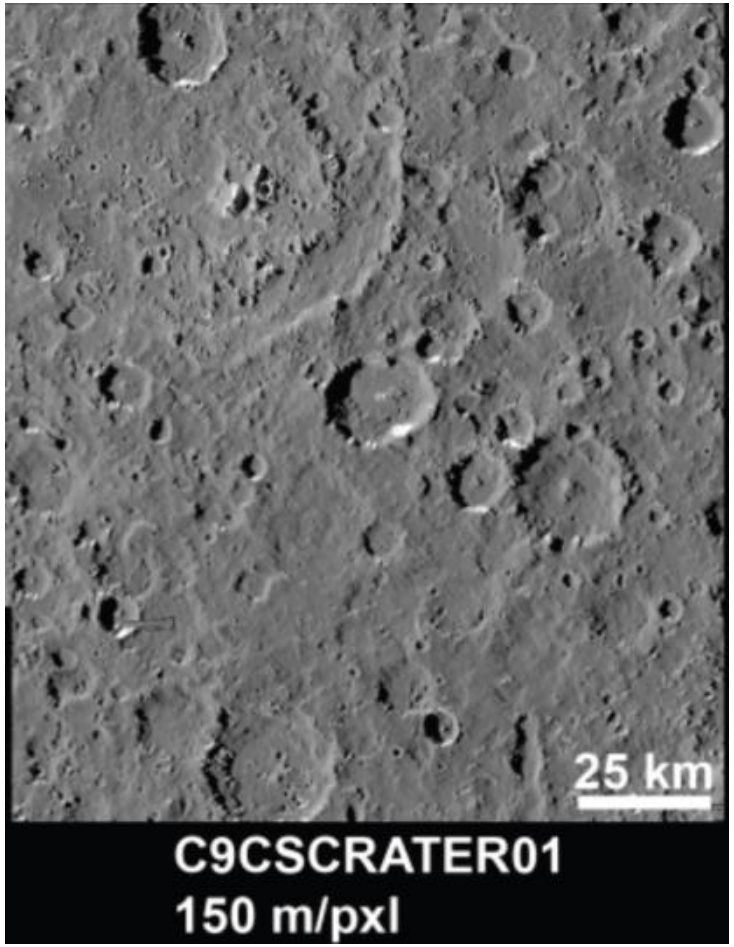
Icy moons - Callisto

Properties
Mass: $1.076*10^{23}$ kg
Radius: 2 410.3 km
Orbital distance: 1 882 700 km
Orbital period: 16.69 days

Ice shell+Ocean
Not in orbital resonance
Induced field

Surface composition
No spatial resolution so far

Heavily cratered
Old impacts
Window to the primordial Solar System



Challenges

Power

Communication

Temperature

Distance from the Sun/Earth

Radiation

Total Ionizing Dose (TID)

Displacement Damage Dose (DDD)

Single Event Effects (SEE)

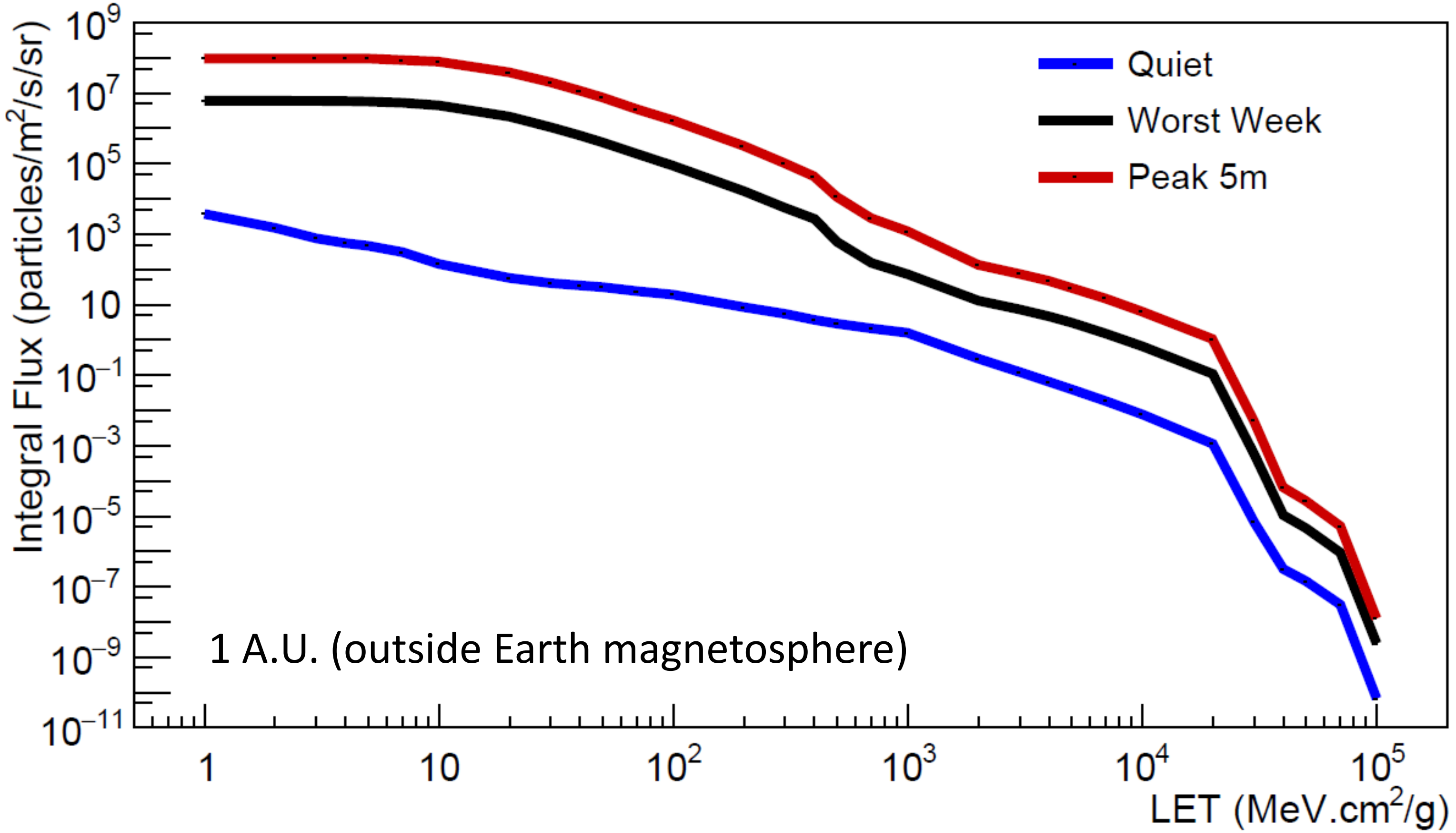
Noise

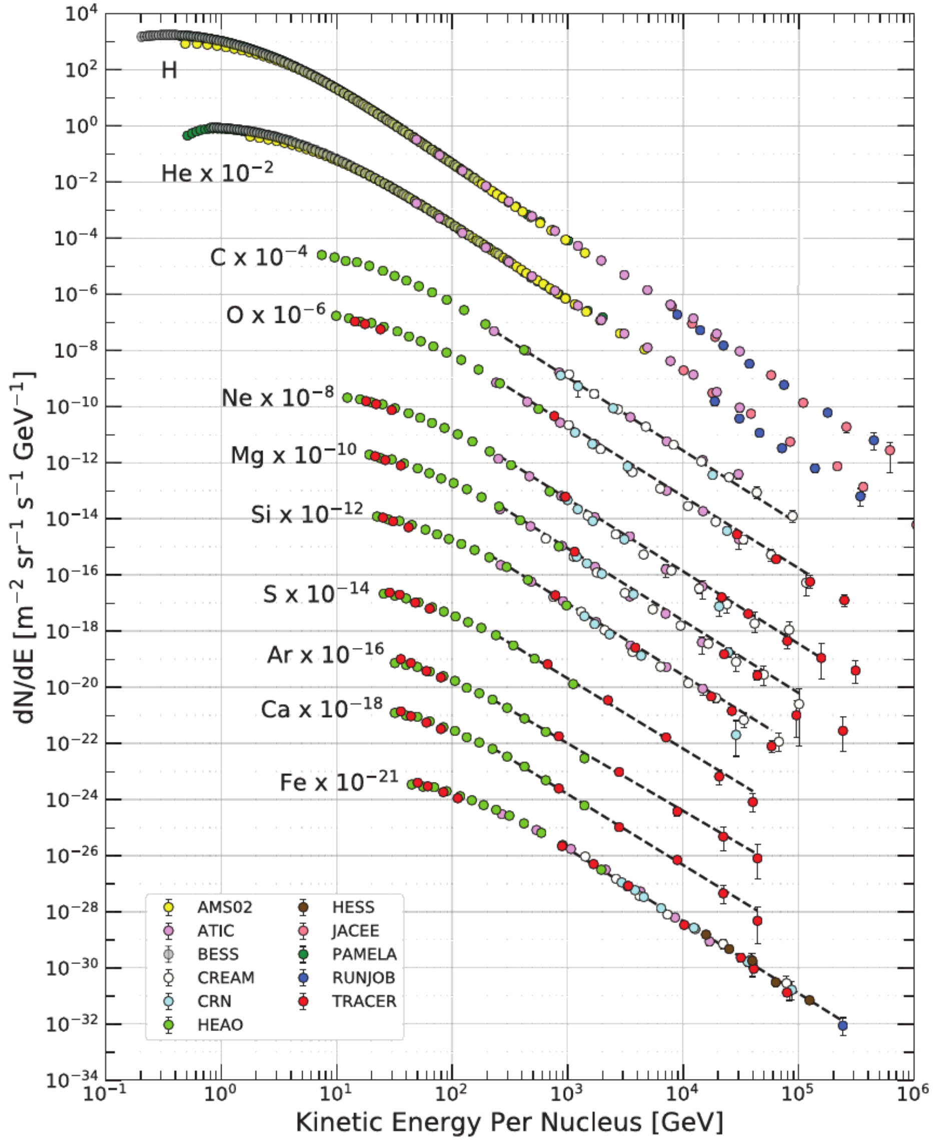
Radiation Environment

- Galactic Cosmic Rays (GCR) → Constant low flux high energy ions
- Solar Energetic Particles (SEP) → Sporadic high flux p, e- and ions
- Trapped Particles → Complex variable flux e-, p and ions

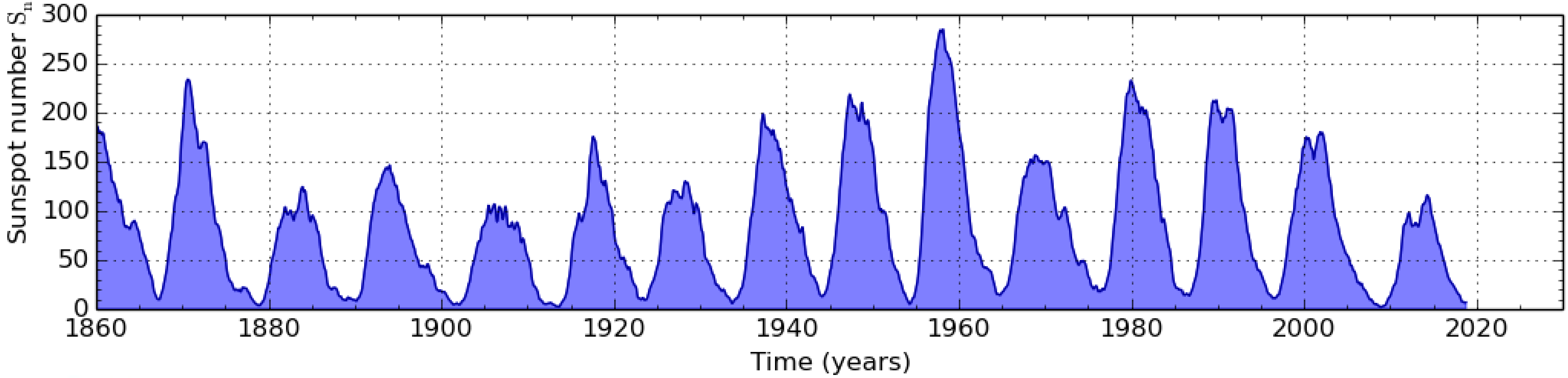
Cosmic Rays

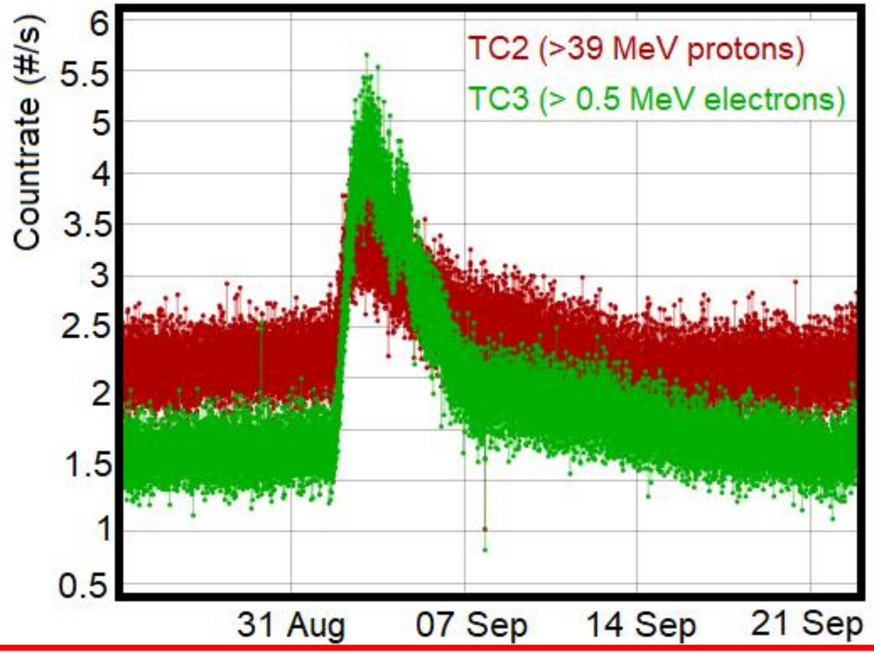
- Constant high energy omni-directional flux
  - Low energy modulated by Solar activity
- Can cause Single Event Effects on electronics
  - Linear Energy Transfer is the Figure Of Merit

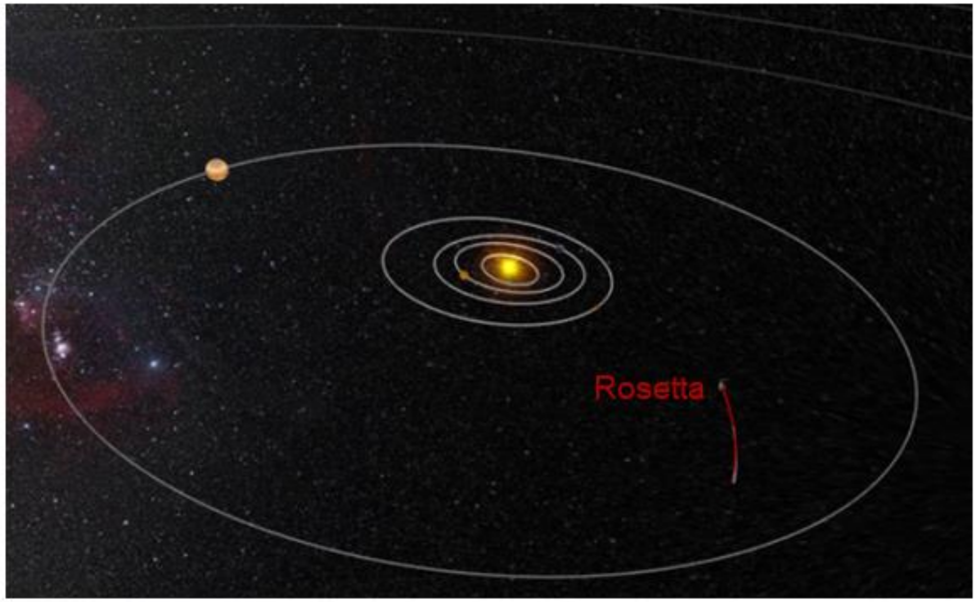




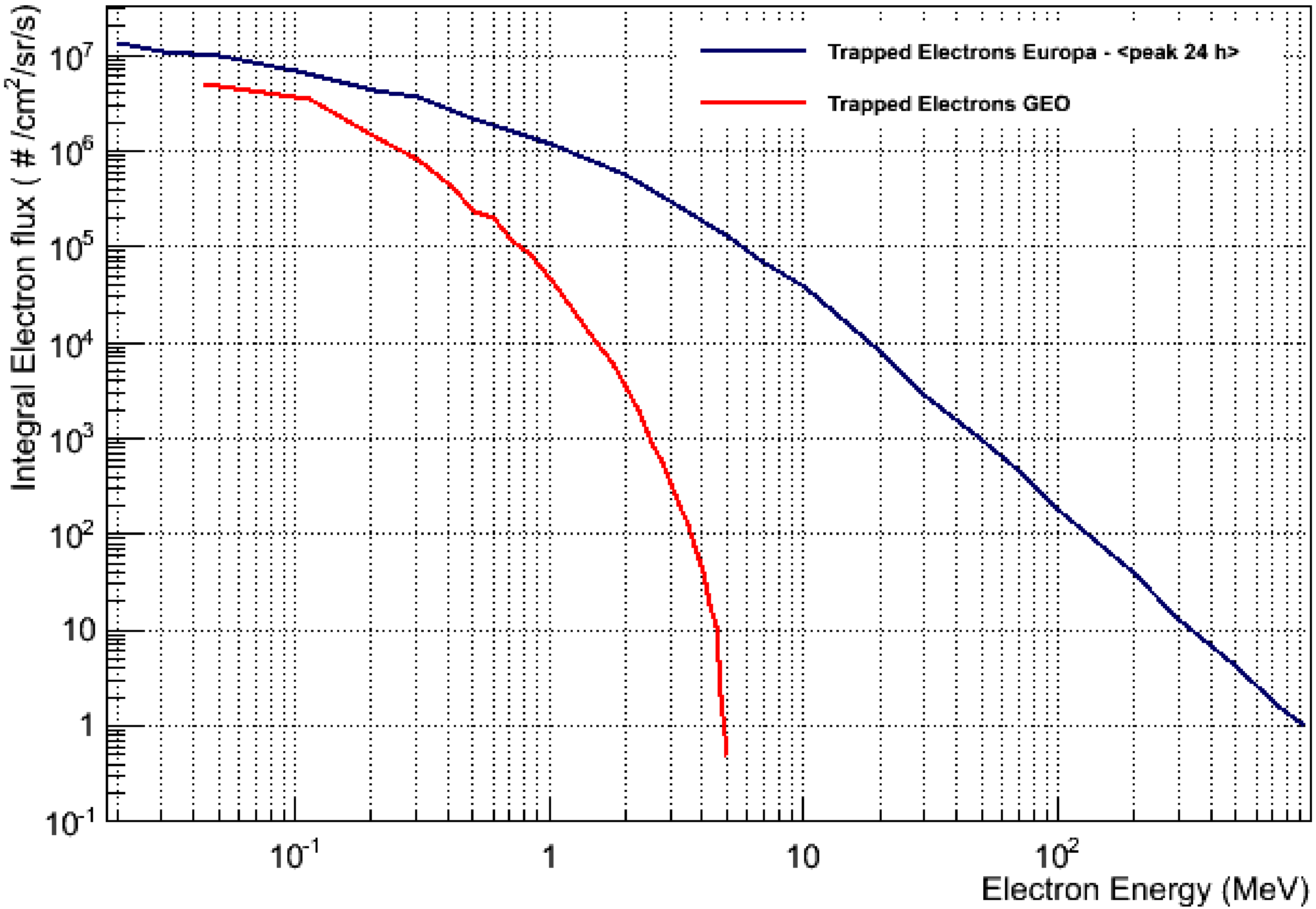
Solar Energetic Particles



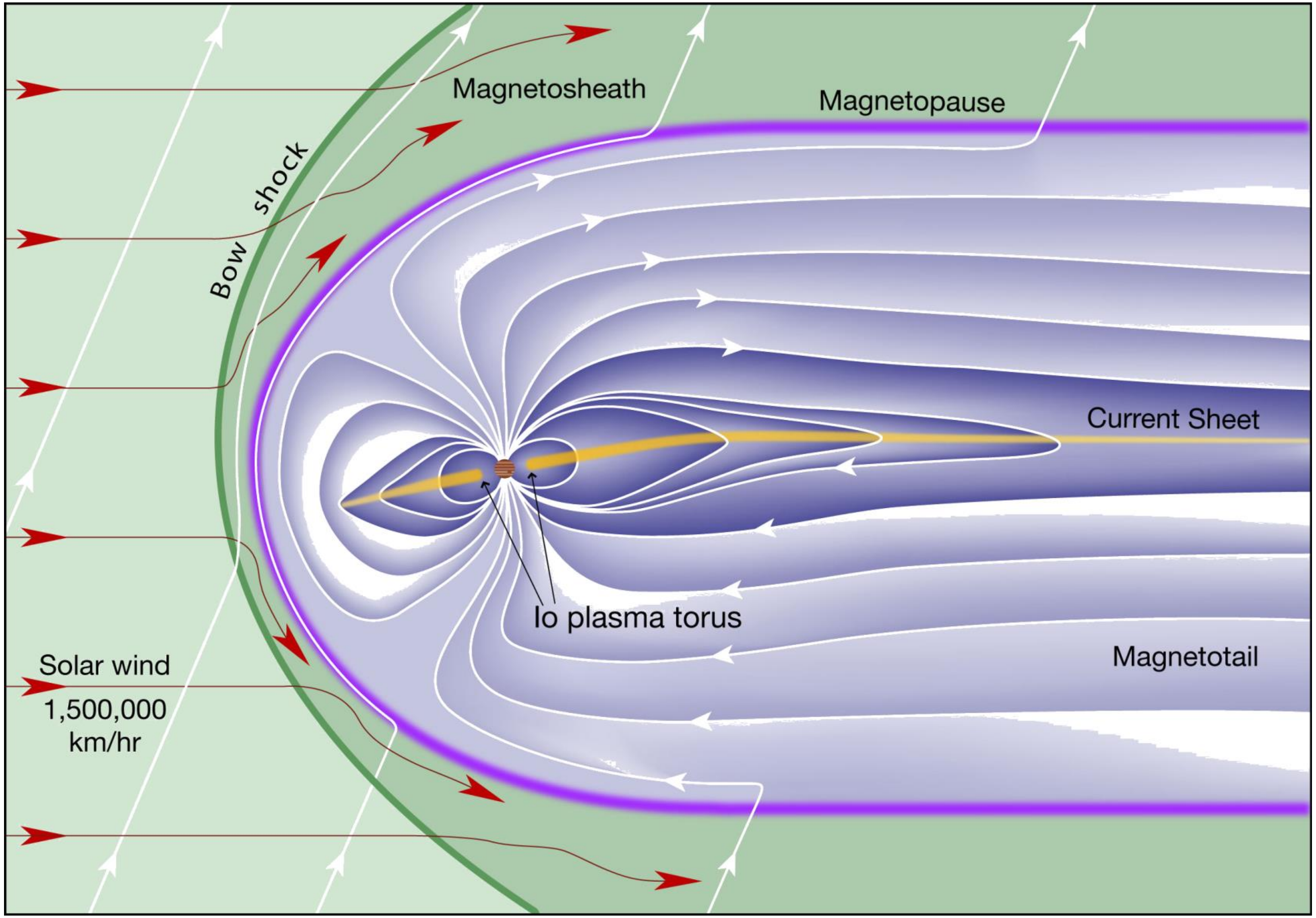




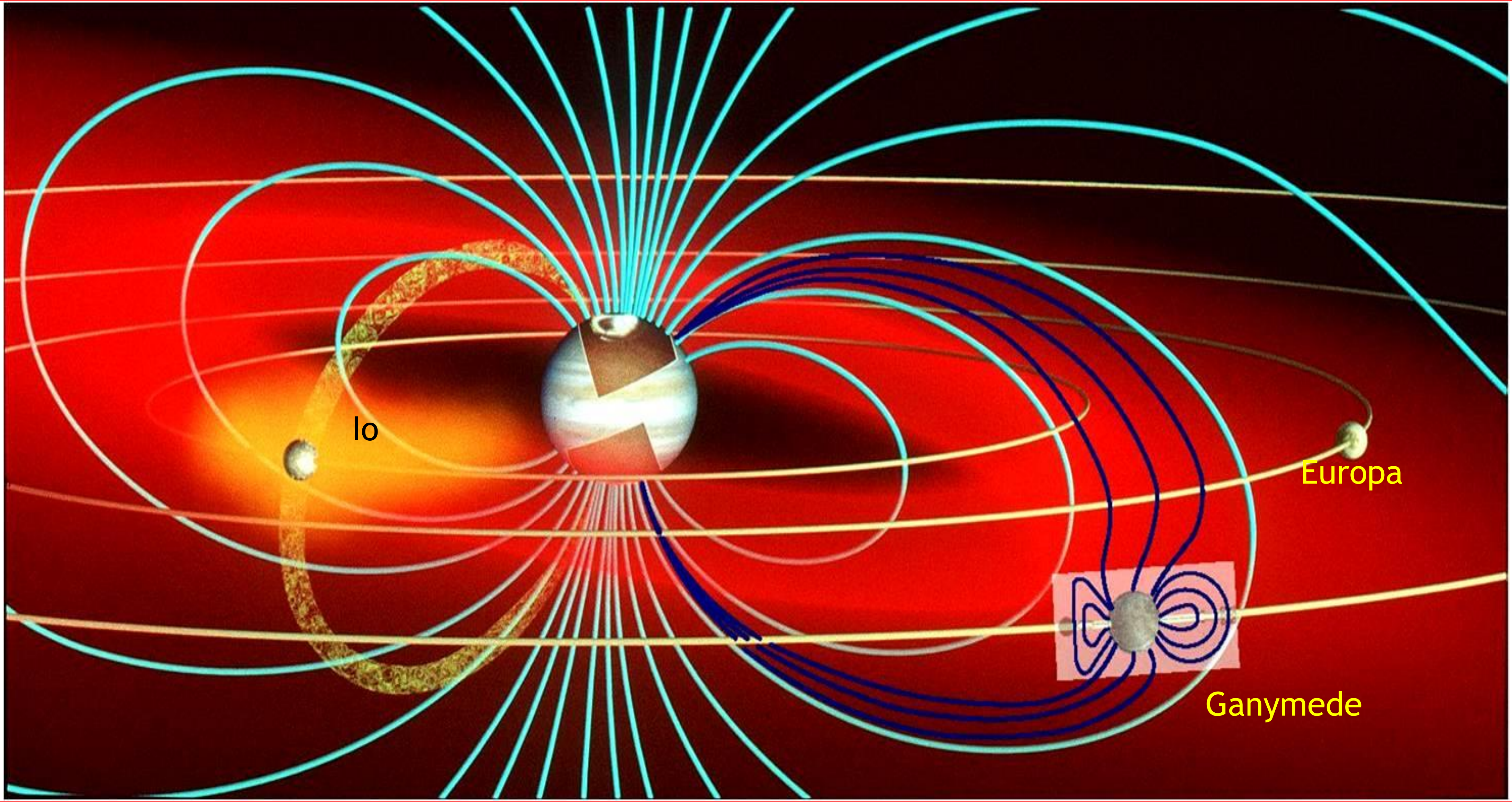
Trapped Particles



Jovian Magnetosphere



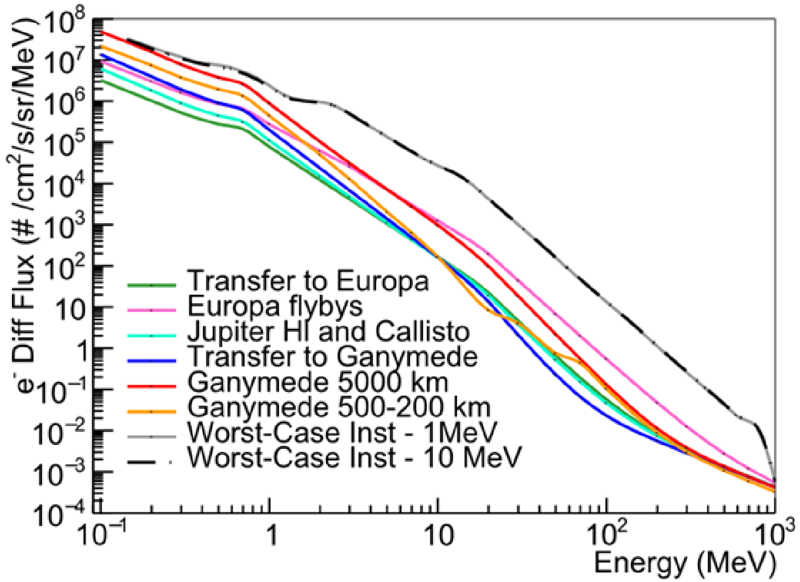
Magnetosphere



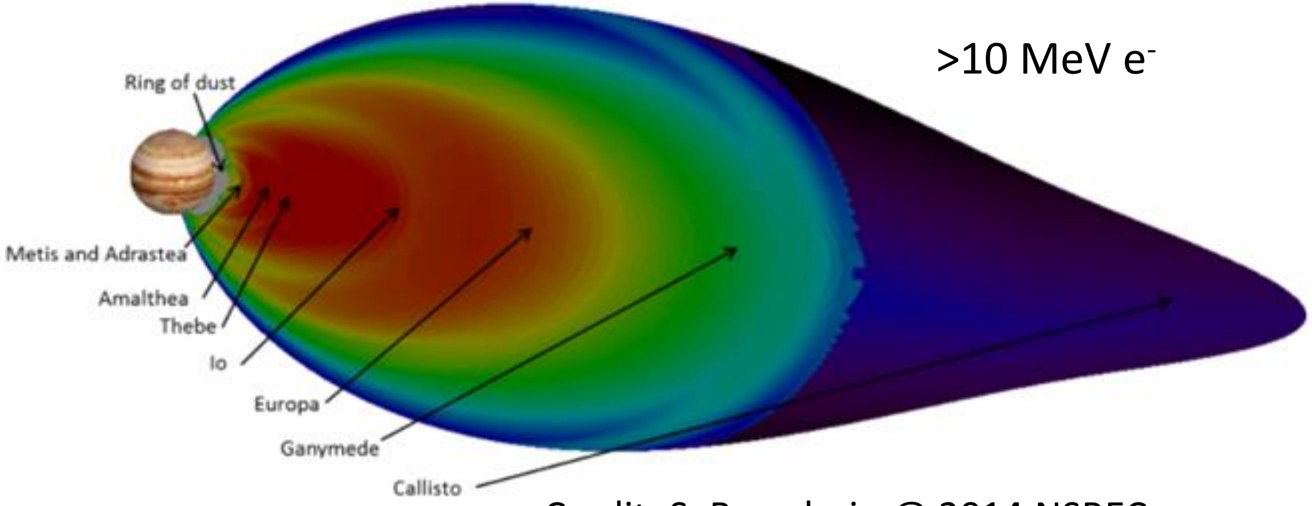
Trapped Particles - Models

- Models have evolved based on new data:
  - Only long-term measurements made by Galileo
  - Short-term Pioneer, Voyagers, Ulysses

- JOSE Model
  - Semi-empirical
  - Average fluxes
  - Used for the JUICE mission



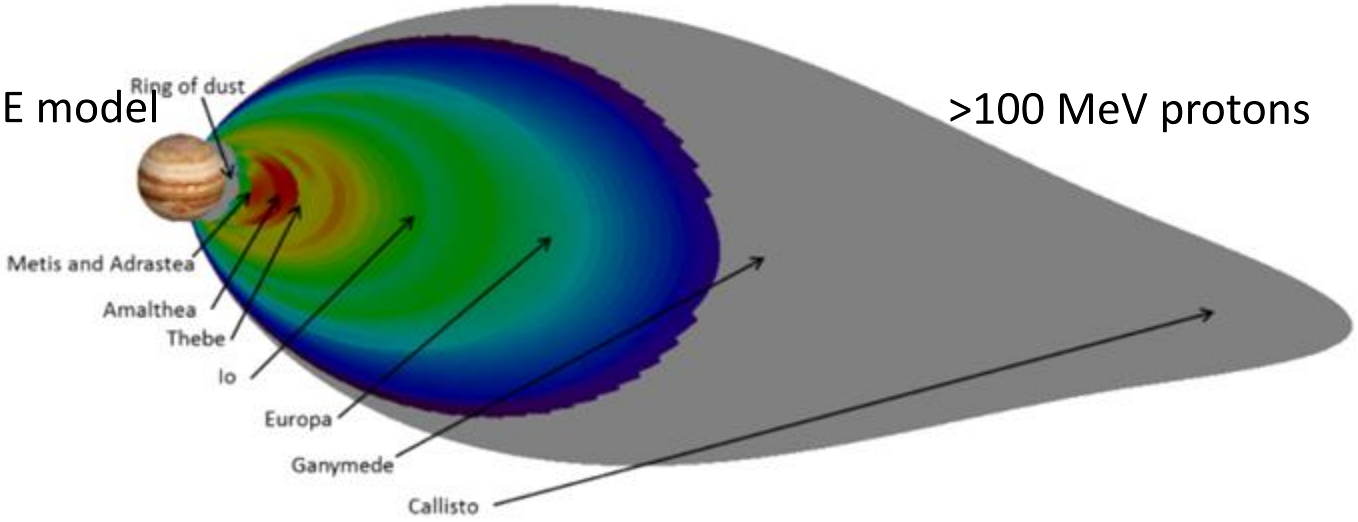
>10 MeV e$^-$



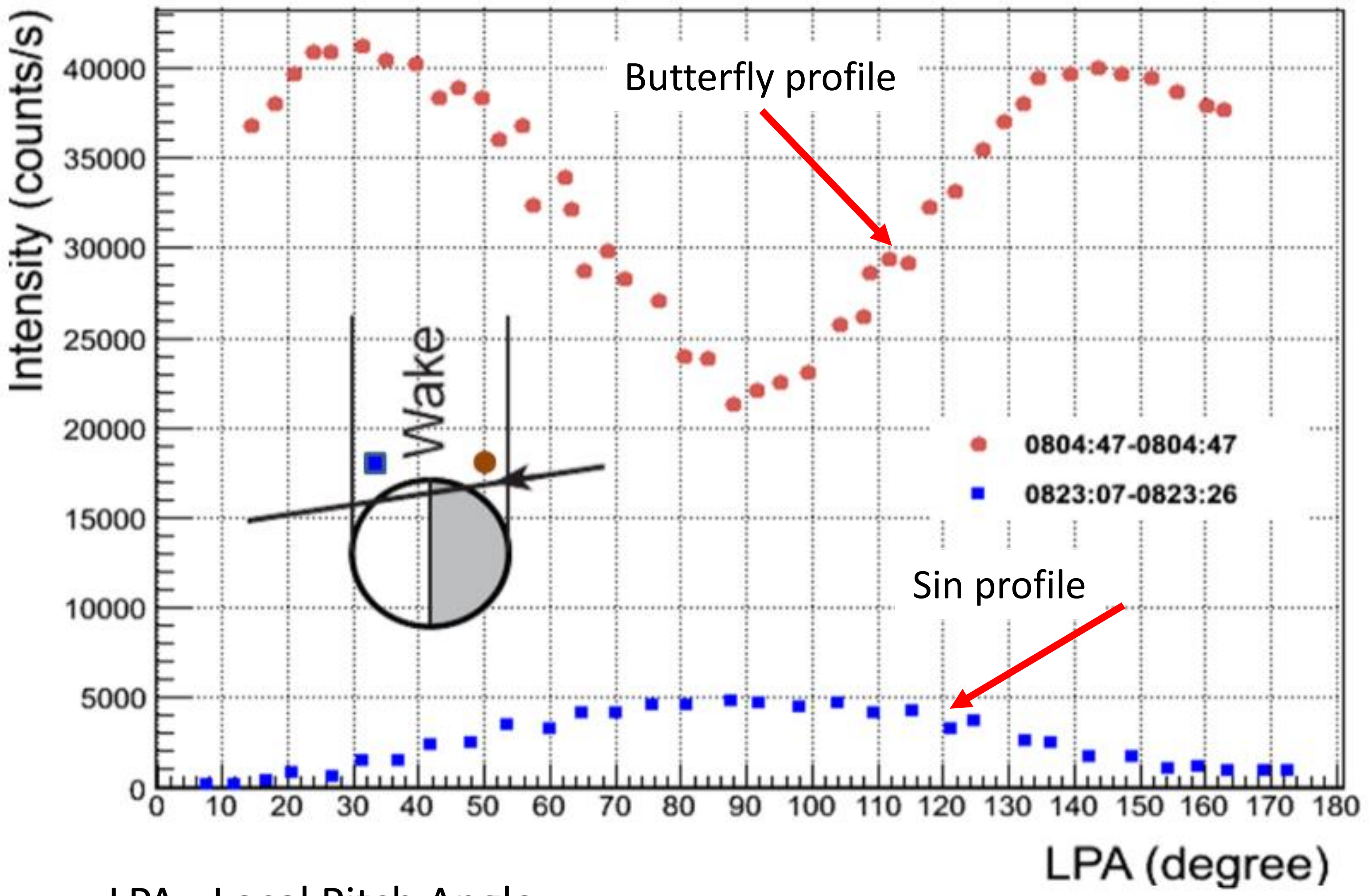
Credit: S. Bourdarie @ 2014 NSREC course

JOSE model

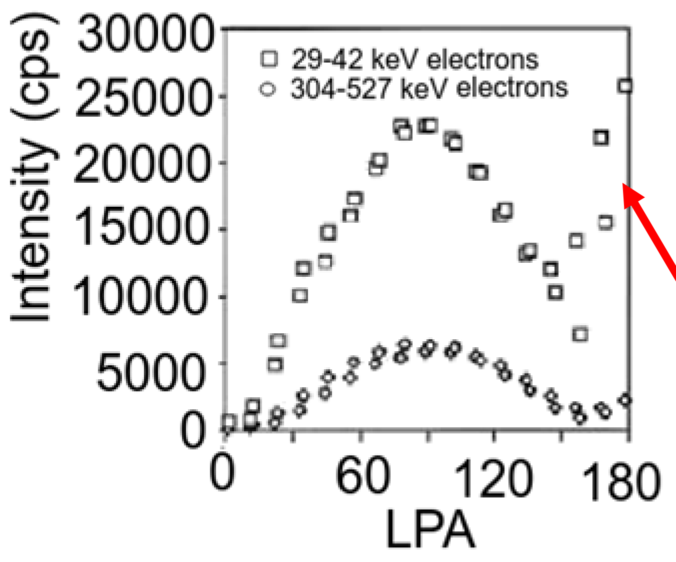
>100 MeV protons



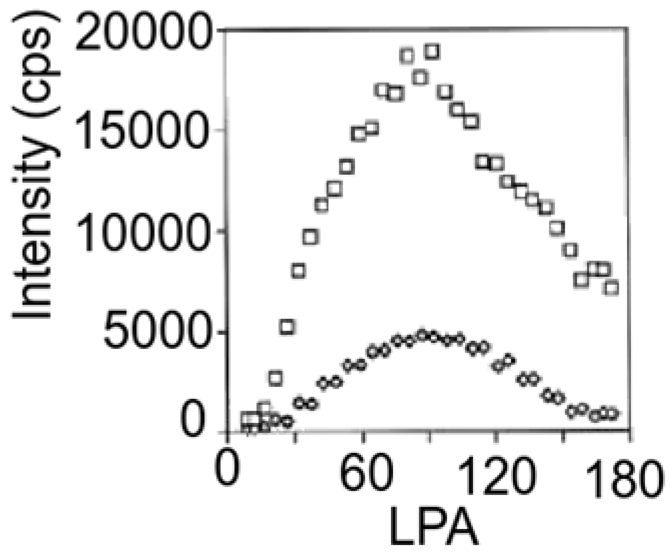
Angular Variability



LPA - Local Pitch Angle

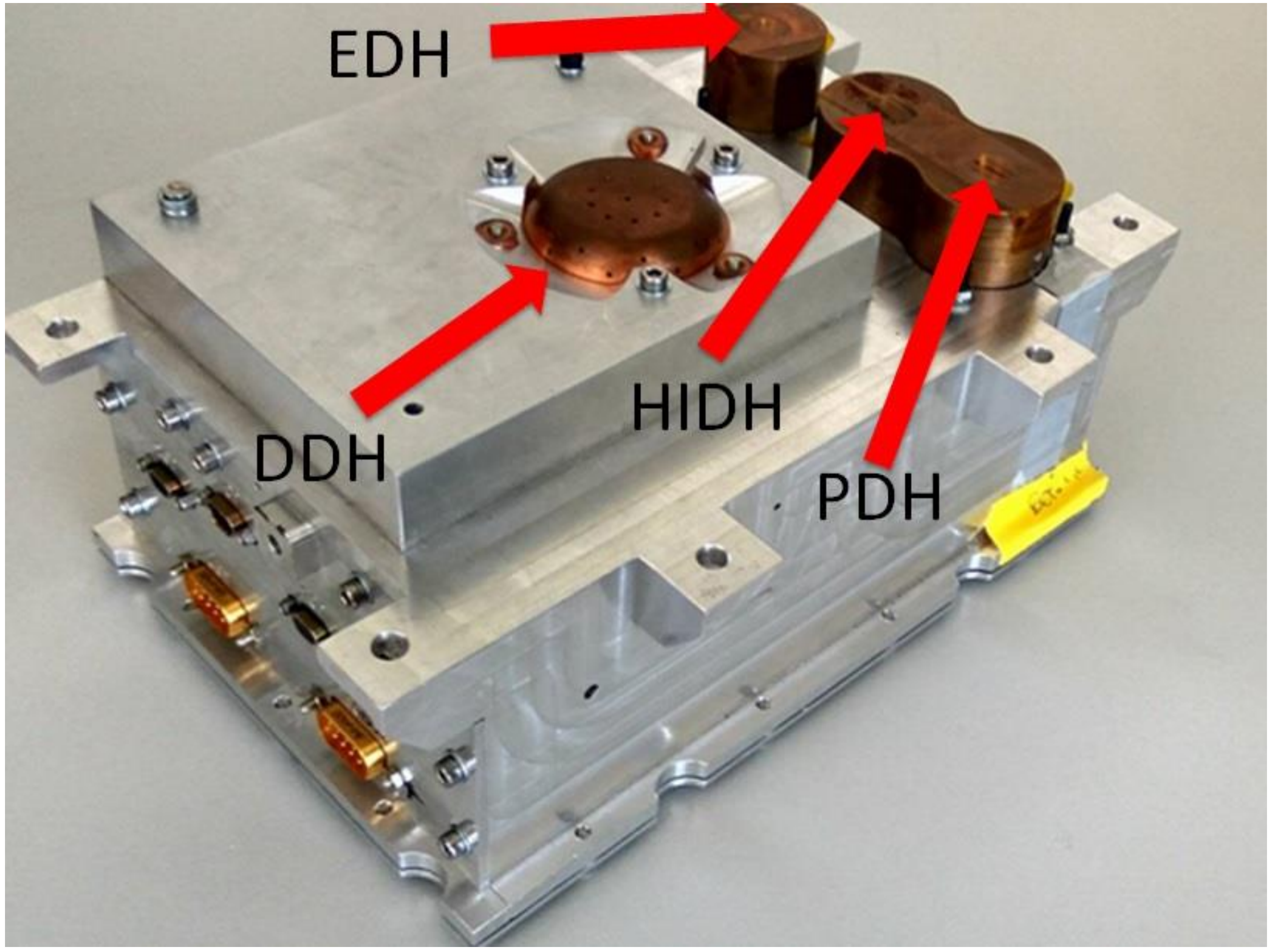


Beam profile



RADEM

ESA/ESTEC Contract 1-7560/13/NL/HB



Requirements:

- Electron detector
  - Spectral range 300 keV – 40 MeV
  - Peak Flux 10^9 e/cm^2/s
- Proton Detector
  - Spectral range 5 MeV– 250 MeV
  - Peak Flux 10^8 p/cm^2/s
- Particle Separation
  - From Helium to Oxygen
- Dose determination
- Low mass (~3 kg currently)
- Low power

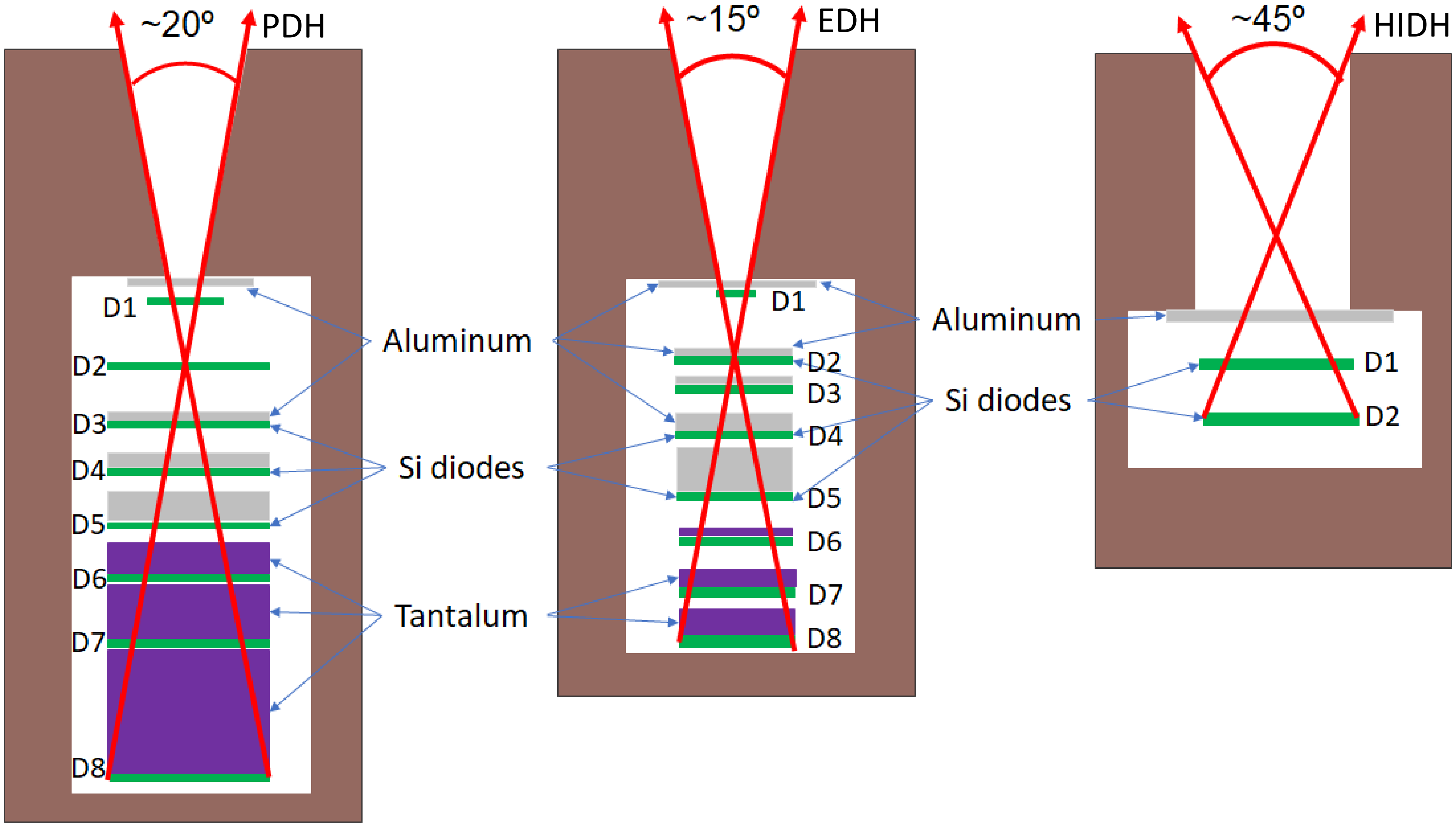
Stack Detector Heads

Traditional Stack Detectors
SREM, MFS, BERM..

Copper Collimator
⬇
Al/Ta Absorbers
⬇
Silicon PIN-diodes

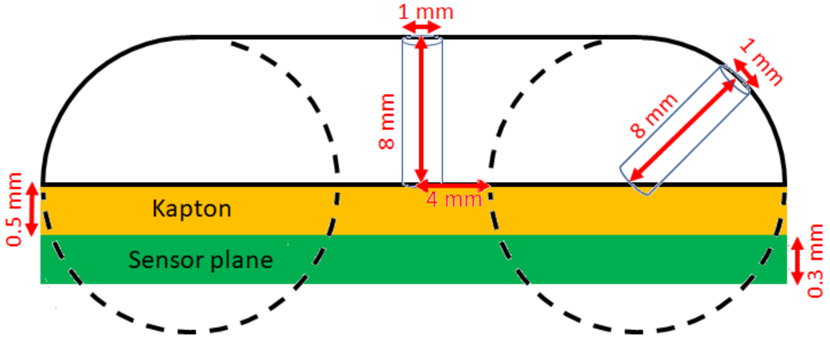
Energy bins (MeV)

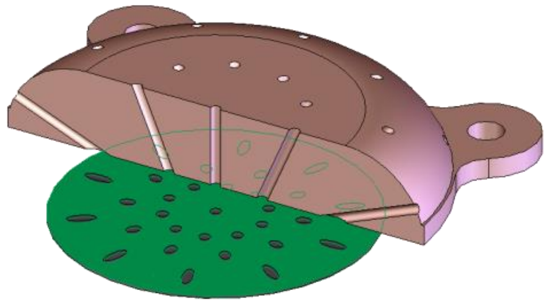
PDH	EDH
4-7	0.35-0.5
7-12.5	0.5-1.25
12.5-20	1.25-2
20-35	2-4
35-50	4-7
50-80	7-17.5
80-125	17.5-35
>125	>35



Directionality Detector

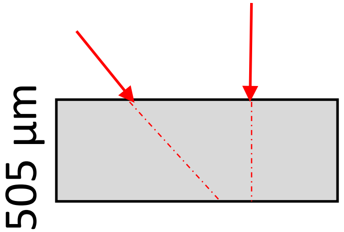
LIP concept





Copper Collimator

- ❑ 28 holes (directions)
  - Diameter: 1mm
  - Length: 8mm



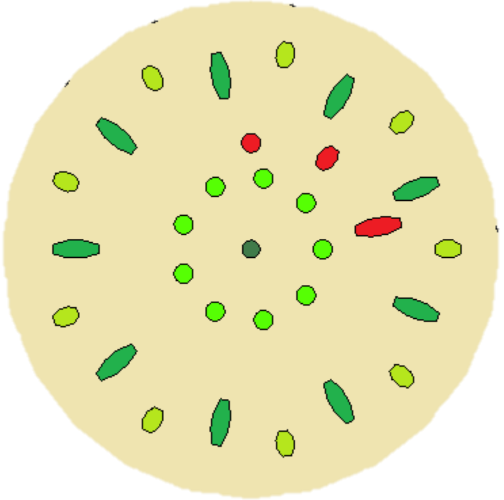
Single 505 µm Kapton absorber

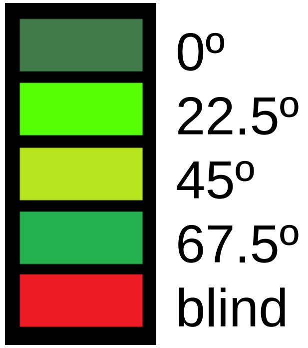
- ❑ Different energy thresholds

Zenith Angle	0 deg	22.5 deg	45 deg	67.5 deg
Electrons	0.3 MeV	0.3 MeV	0.35 MeV	0.5 MeV
Protons	7 MeV	7 MeV	8.5 MeV	12.5 MeV

Detection Plane (instrumented PIN diode):

- ❑ 31 sensors
  - Si Diodes
  - 4 zenithal directions
  - 9 azimuthal directions
  - 3 blind sensors



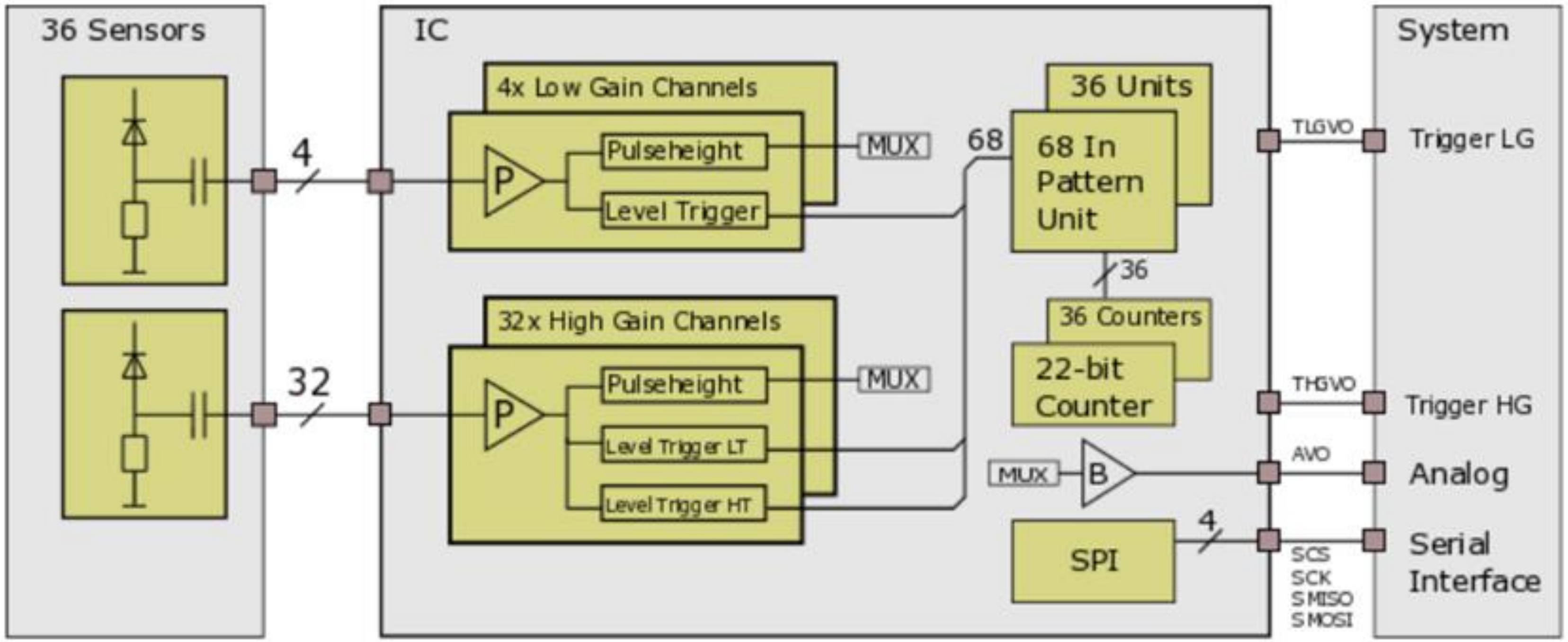


Readout

3x ASIC VATA 466 – developed specifically for RADEM → PDH+HIDH, EDH, DDH

- 36 channels:
  - 4 Low-Gain
  - 32 High Gain
- 1 MHz count rate / channel
- Programable Low and High Thresholds
- Programable Gain
- Programable Integration Time
- Coincidence Logic
- Radiation Hard
  - Based on same technology results

ideas
Integrated Detector Electronics AS



DDH – Proof of Concept

Geant4 simulations

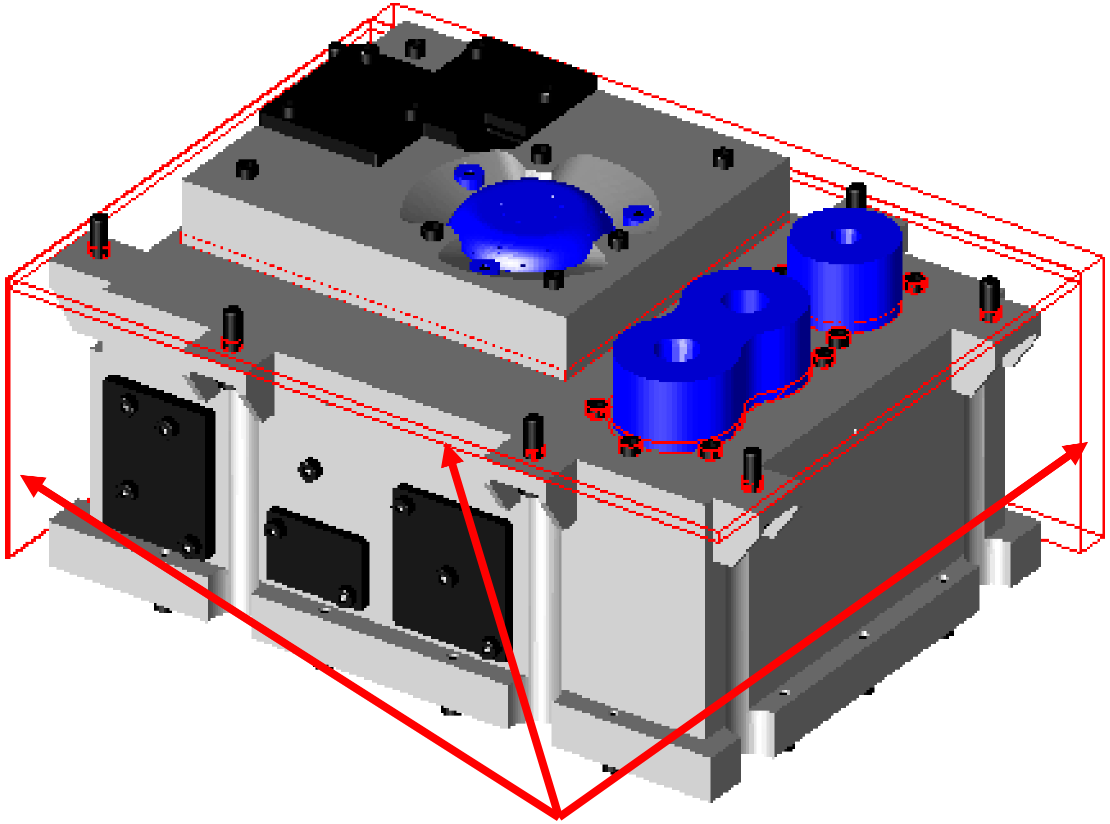
- ❑ Design optimization
- ❑ Directional response
- ❑ Maximum count rate assessment
- ❑ Background removal
- ❑ Electron/proton discrimination
- ❑ Radiation Analysis (of the full instrument)

Beam Tests

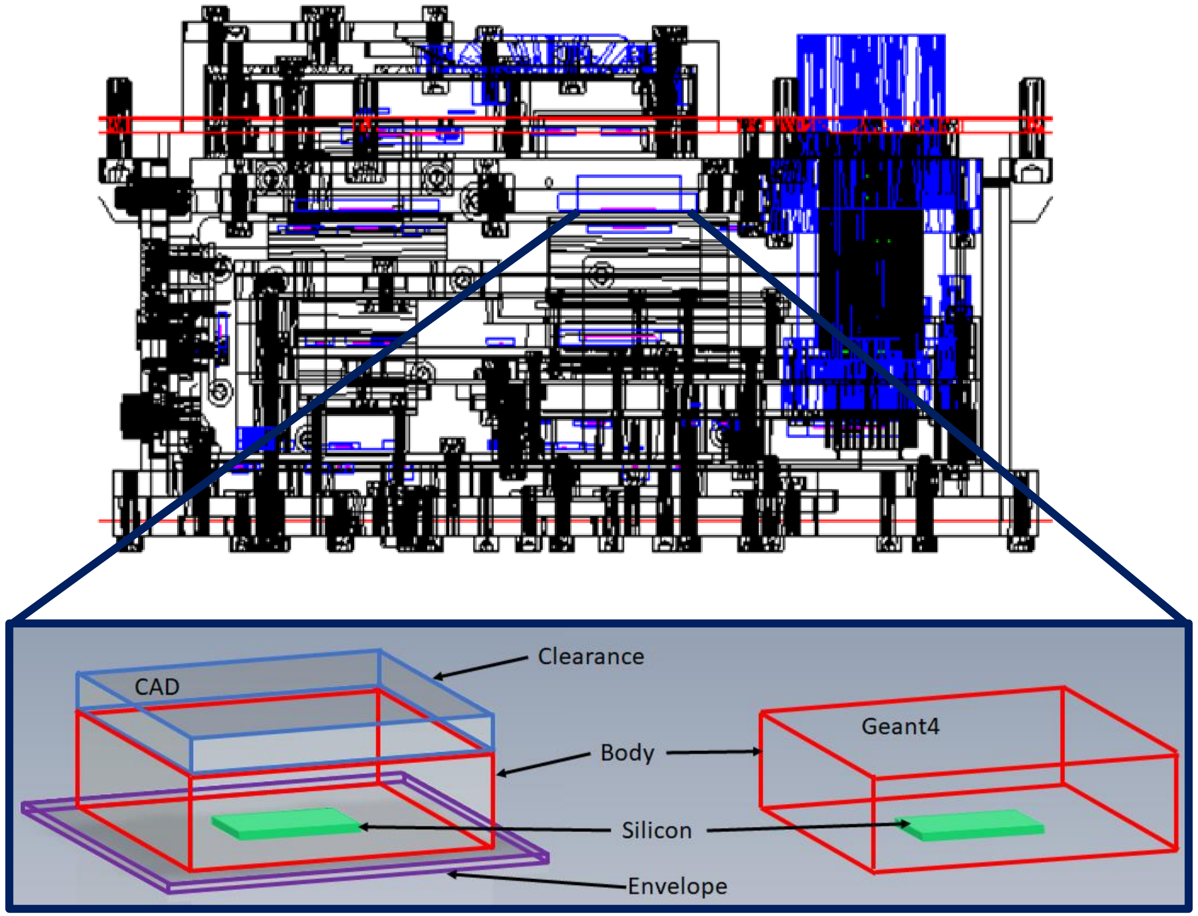
- ❑ Validation of new parts functionality and coupling ASIC VATA466 + Silicon plane sensor
- ❑ Detection of electrons and protons
- ❑ Count rate
- ❑ Charge collection

Geant4 Simulations

Full geometry imported as tessellated solids via GDML with GUIMesh
(M. Pinto et al, DOI: https://doi.org/10.1016/j.cpc.2019.01.024)



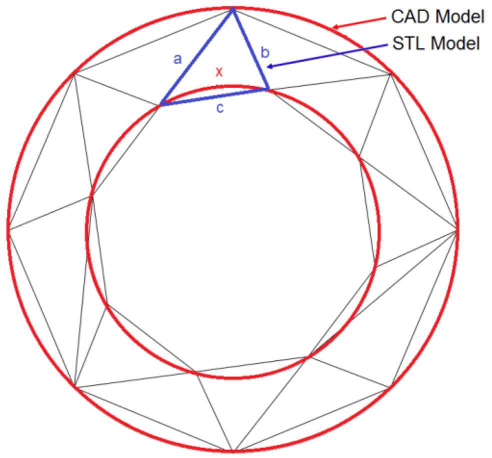
Spacecraft described as Aluminum shielding equivalent
(M. Pinto et al, DOI: https://doi.org/10.1016/j.cpc.2019.01.024)



GUIMesh

- ❑ Mechanical geometries can be rather complex:
  - Complicated geometries
  - Large number of solids
  - CAD format (STEP)
- ❑ Difficult to implement via Geant4 C++ geometry classes:
  - Great number of volumes
  - Volumes with different complexities
  - No open-source free tool to convert STEP to Geant4
- ❑ FreeCAD
  - General purpose 3D CAD modeler
  - Open-source
  - Imports CAD formats (STEP)
  - Exports Mesh formats (STL, PLY)
  - **Supports Python**

STL (STereoLithography) – Mesh format



Describes solids as series of triangles adjacent to each other enclosing the full volume.
Equivalent to Geant4 tessellated solids.

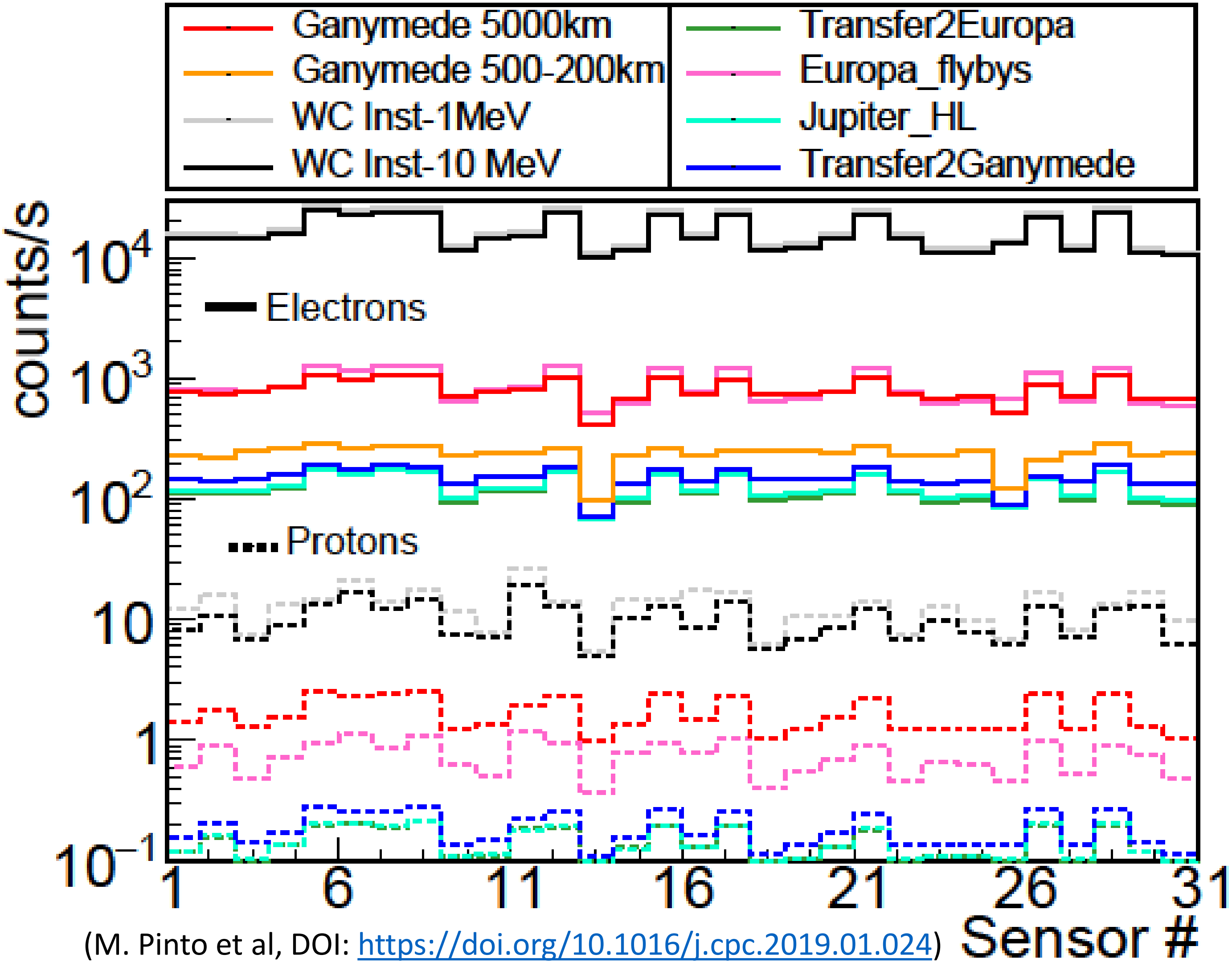
❑ GUIMesh

1. Open STEP file
2. Assign material (database + custom materials)
3. Mesh geometry (User defined precision)
4. Writes GDML

Fully developed at LIP!
Application extends to other relevant fields
Open source
(M. Pinto et al, DOI: https://doi.org/10.1016/j.cpc.2019.01.024)

DDH – Count rate

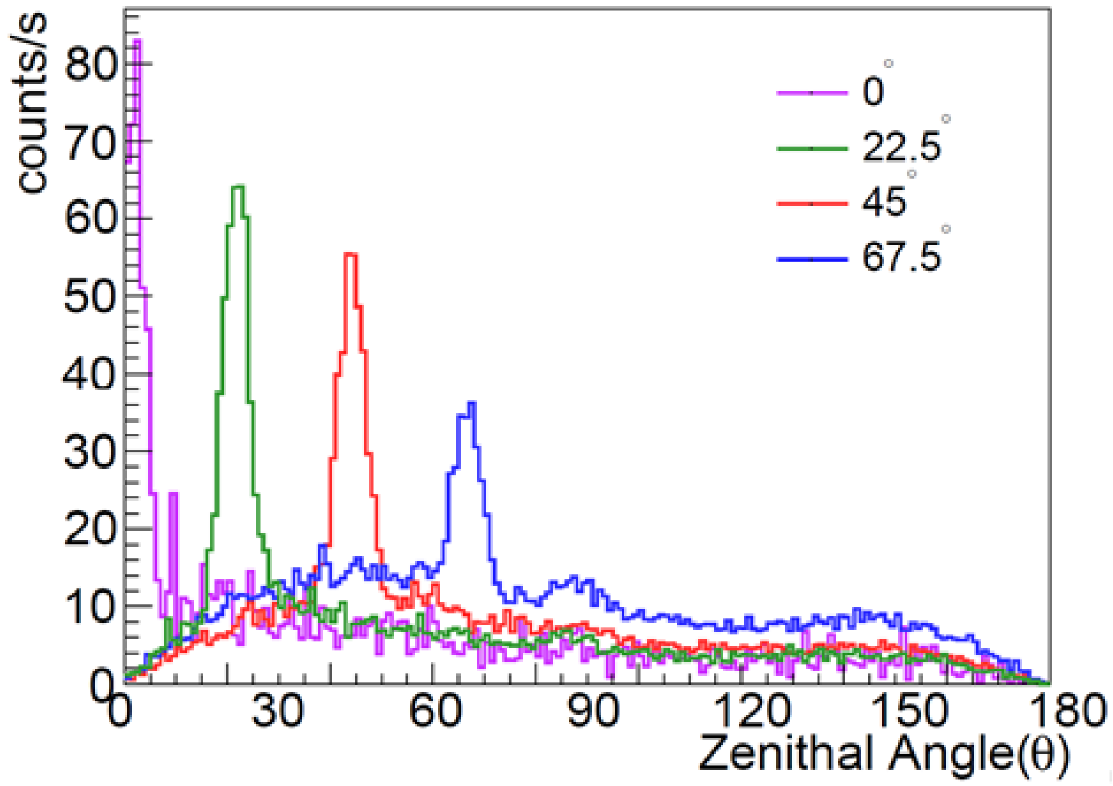
- ❑ Count rate < 1 MHz / channel
  - True even for worst-case
- ❑ Phase dependent
  - Spatial resolution
  - Direction resolution
  - Background removal
- ❑ # Proton << # electrons
  - Contamination very low



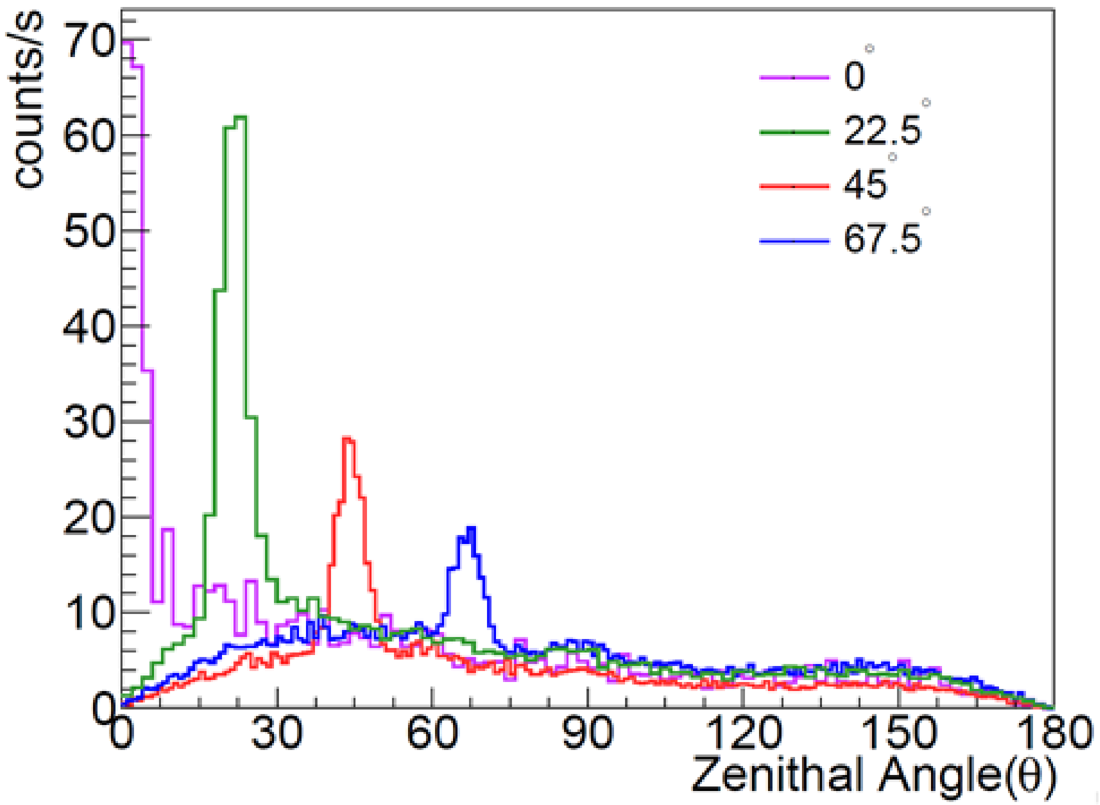
(M. Pinto et al, DOI: https://doi.org/10.1016/j.cpc.2019.01.024)

DDH – Baseline Directional Response

Ganymede



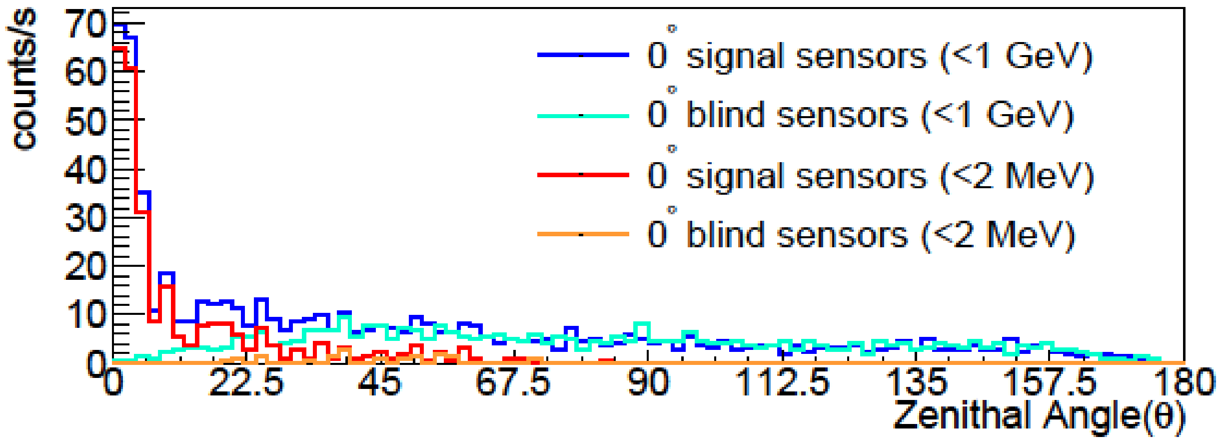
Europa

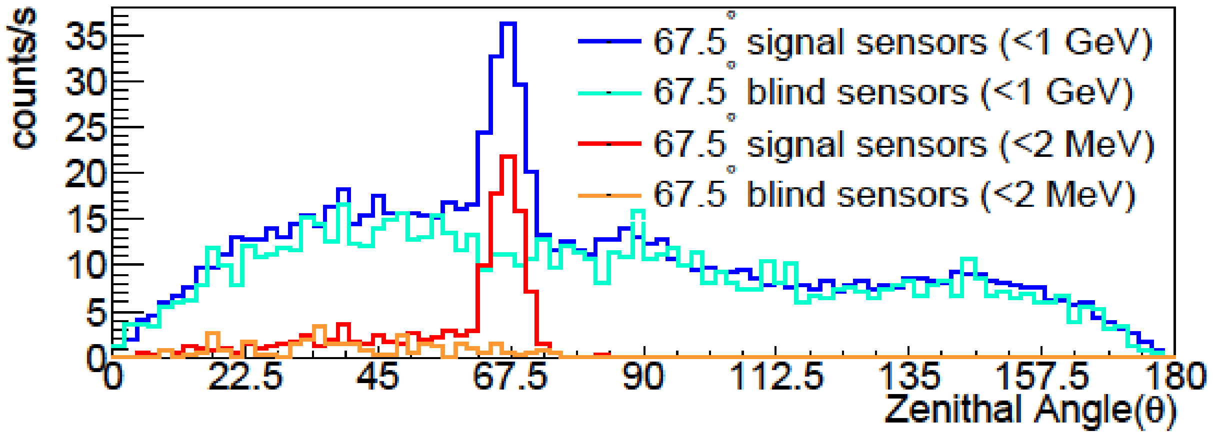


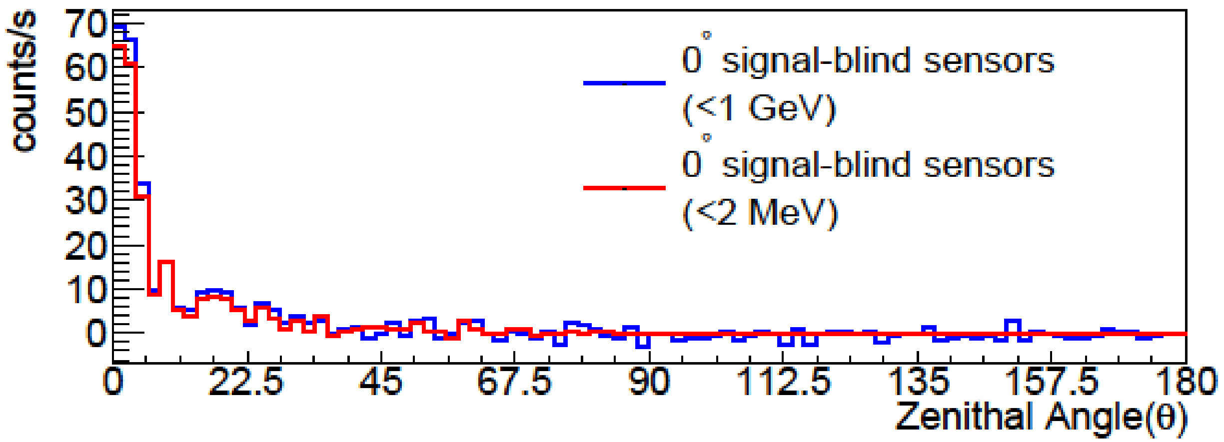
Directional Response depends on electron spectrum → EDH

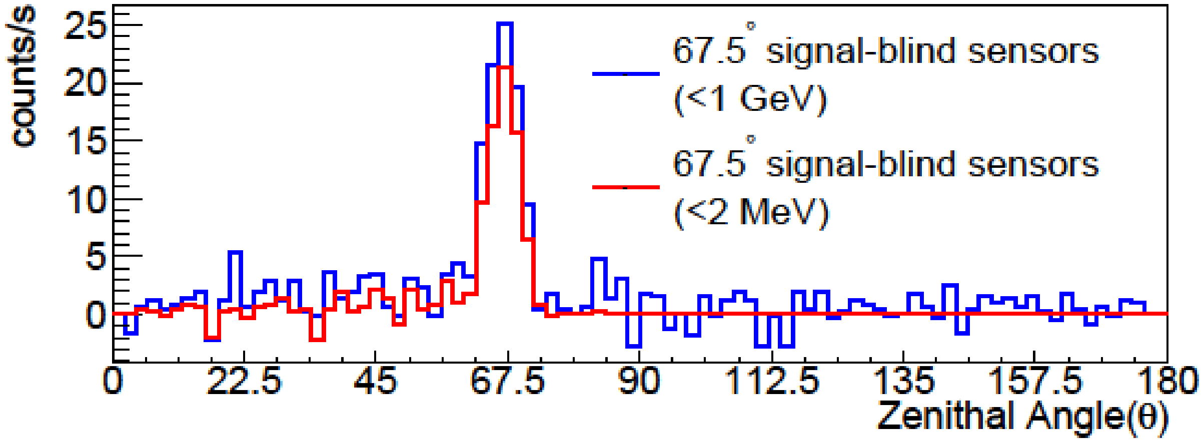
(M. Pinto et al, DOI: https://doi.org/10.1016/j.cpc.2019.01.024)

DDH – Background







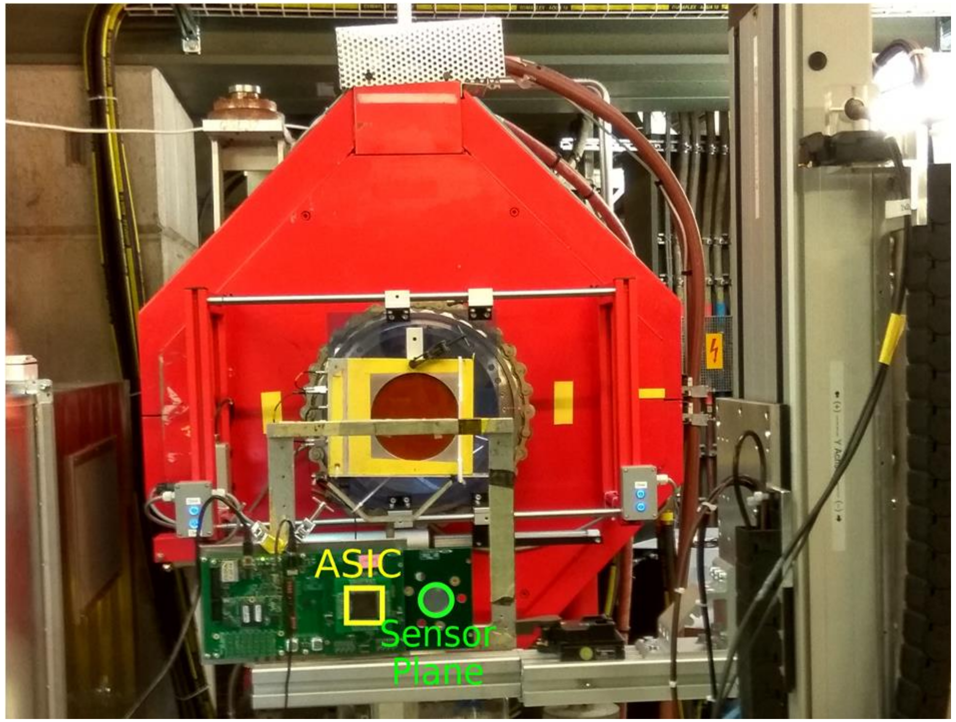


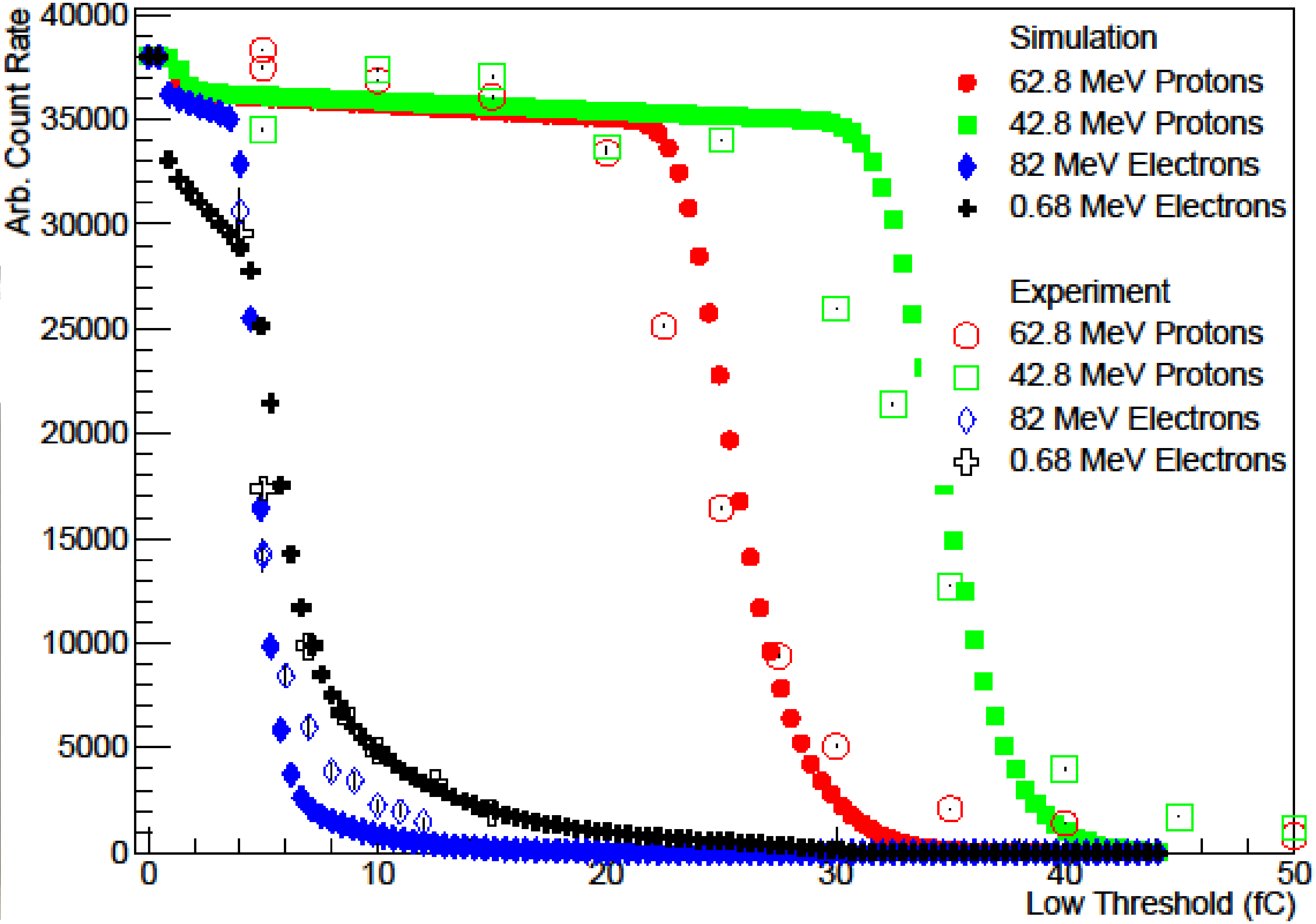
(M. Pinto et al, DOI: https://doi.org/10.1016/j.cpc.2019.01.024)

DDH – Beam tests

ASIC + Sensor Plane

Tests with protons and electrons @PSI
2 proton energies (PiM1)
2 electron energies (PiM1, EMC)





(M. Pinto et al, DOI: https://doi.org/10.1016/j.cpc.2019.01.024)

RADEM Development

Breadboard → Engineering Model → Engineering Qualification Model → Flight Model

08/2019-09/2019

2020

HW

SW

Detectors

- ❑ Working principle
- ▪ Energy bins
- ▪ Directionality

- ❑ ASIC
- ▪ Noise
- ▪ Thresholds
- ▪ Coincidences
- ▪ Linearity

Same ASIC
for all detectors

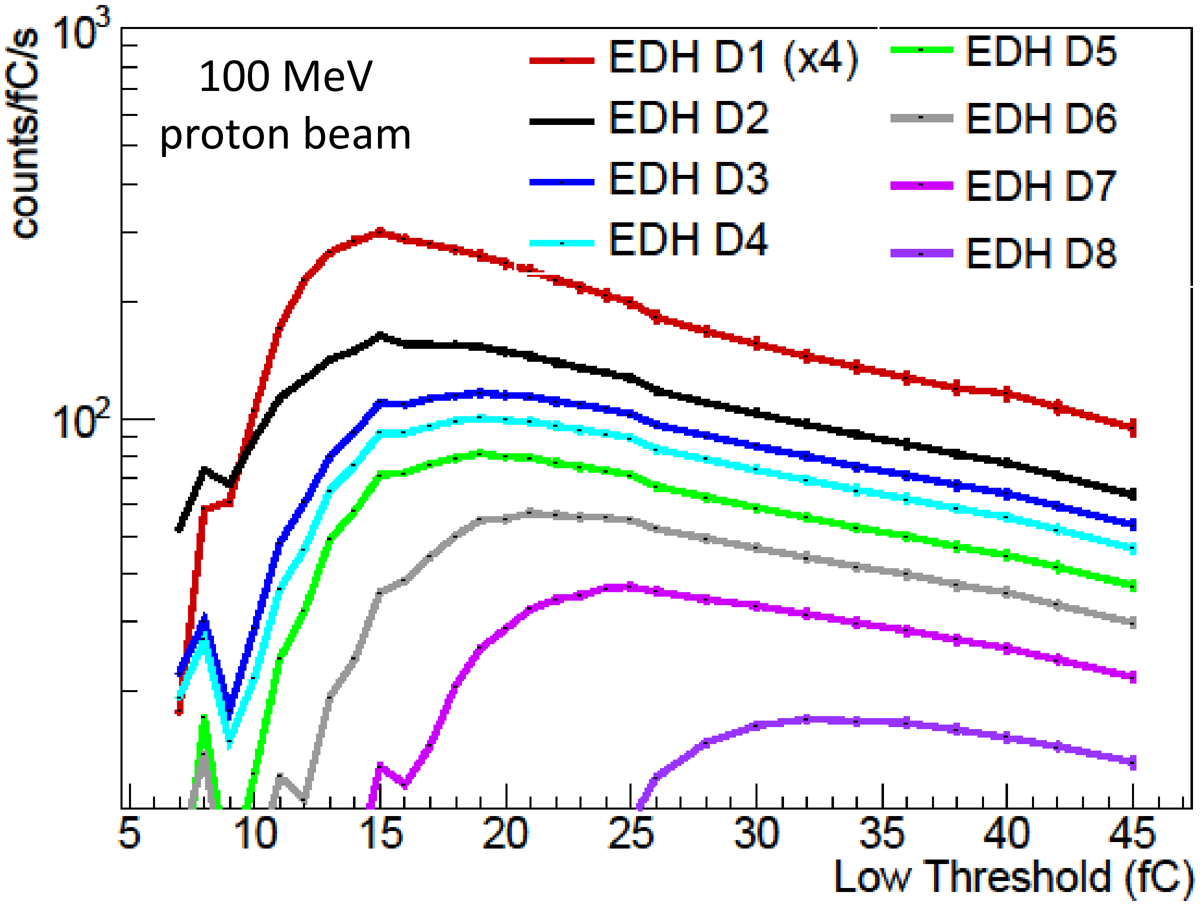
HG channels -> EDH and DDH

LG channels -> IDH

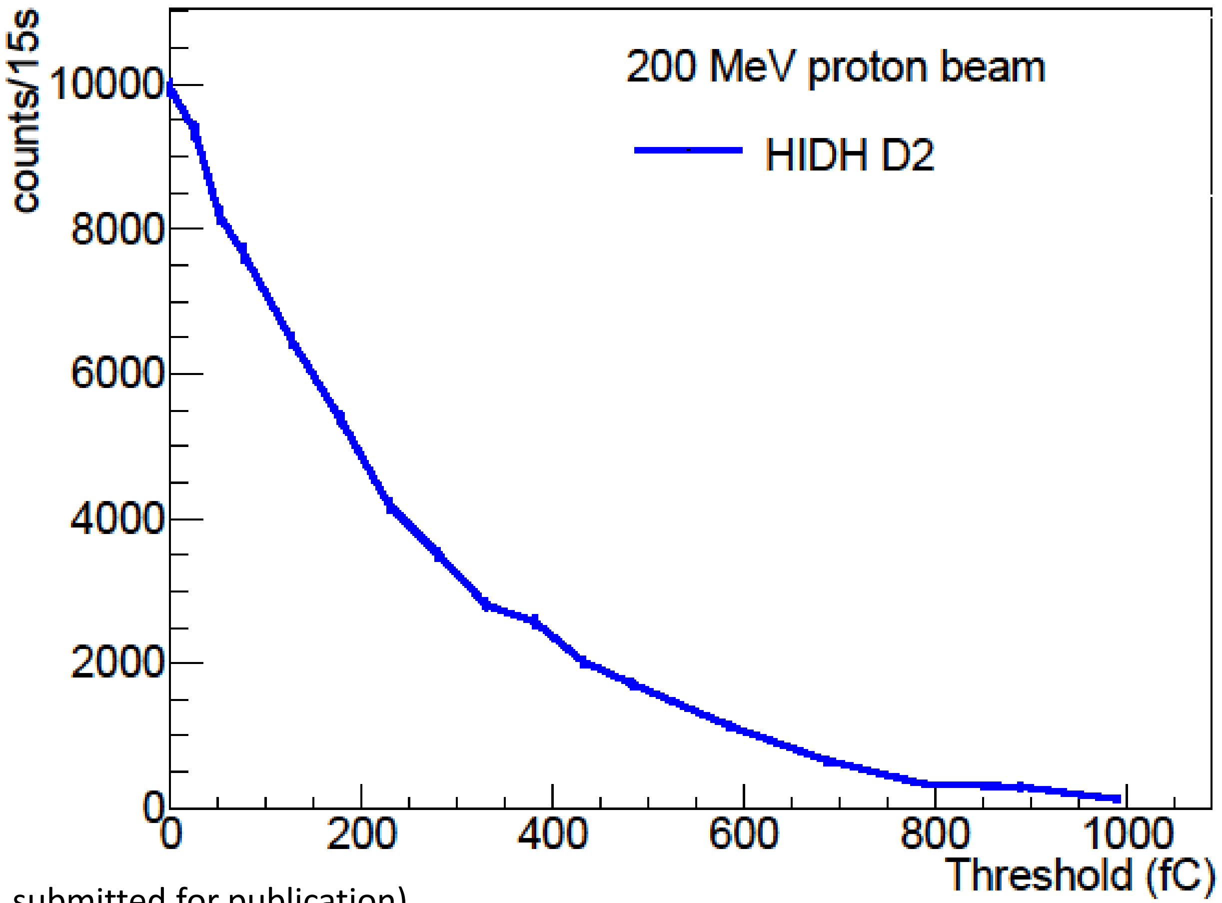
RADEM EM – Thresholds

Tests done at PIF (protons)

High Gain channels



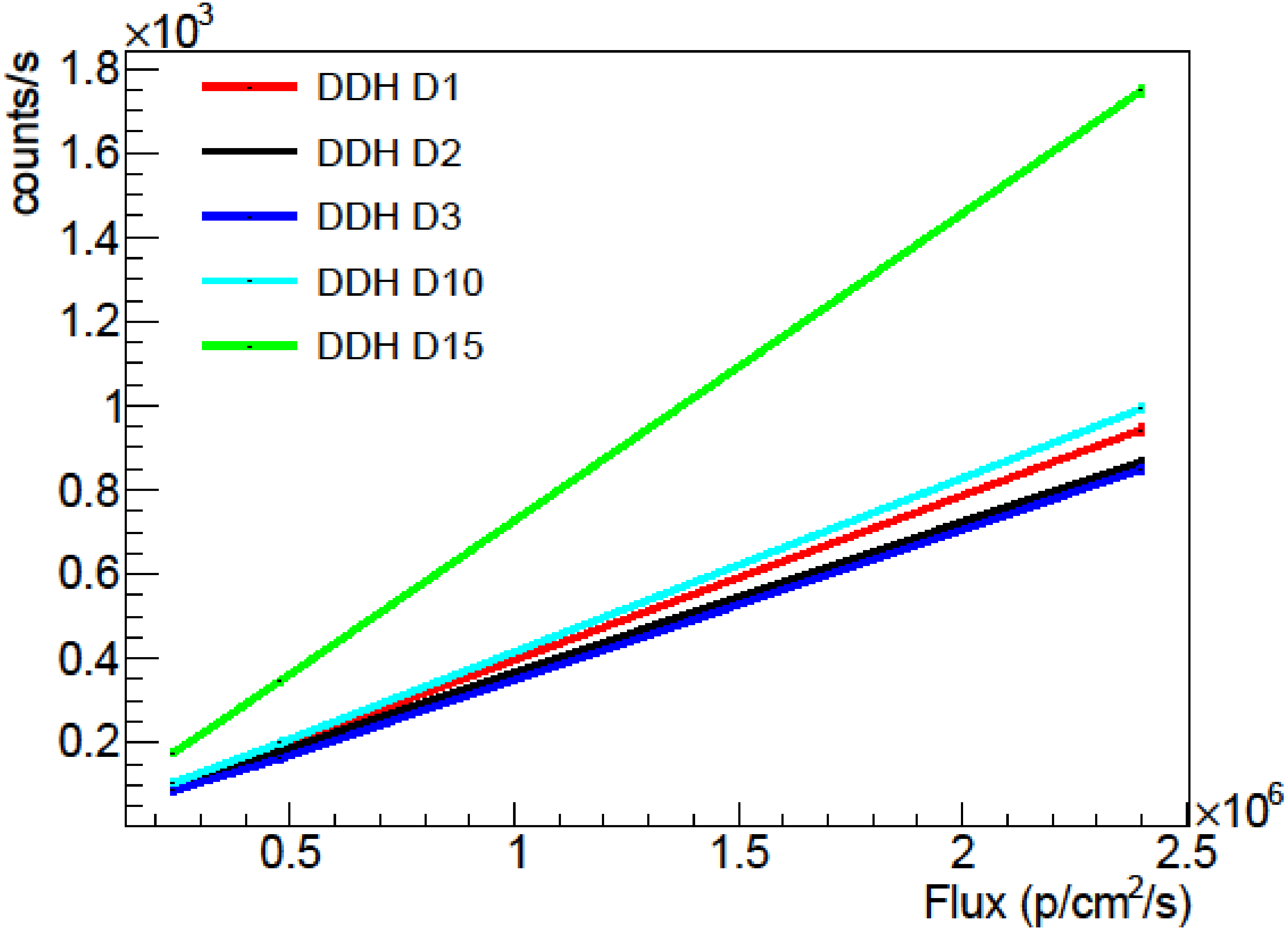
Low Gain channels



(M. Pinto et al, submitted for publication)

RADEM EM - Linearity

- Tests performed with 200 MeV protons
- All pixels were analysed
- Linear response on all pixels
- Tests need to be extended to higher fluxes

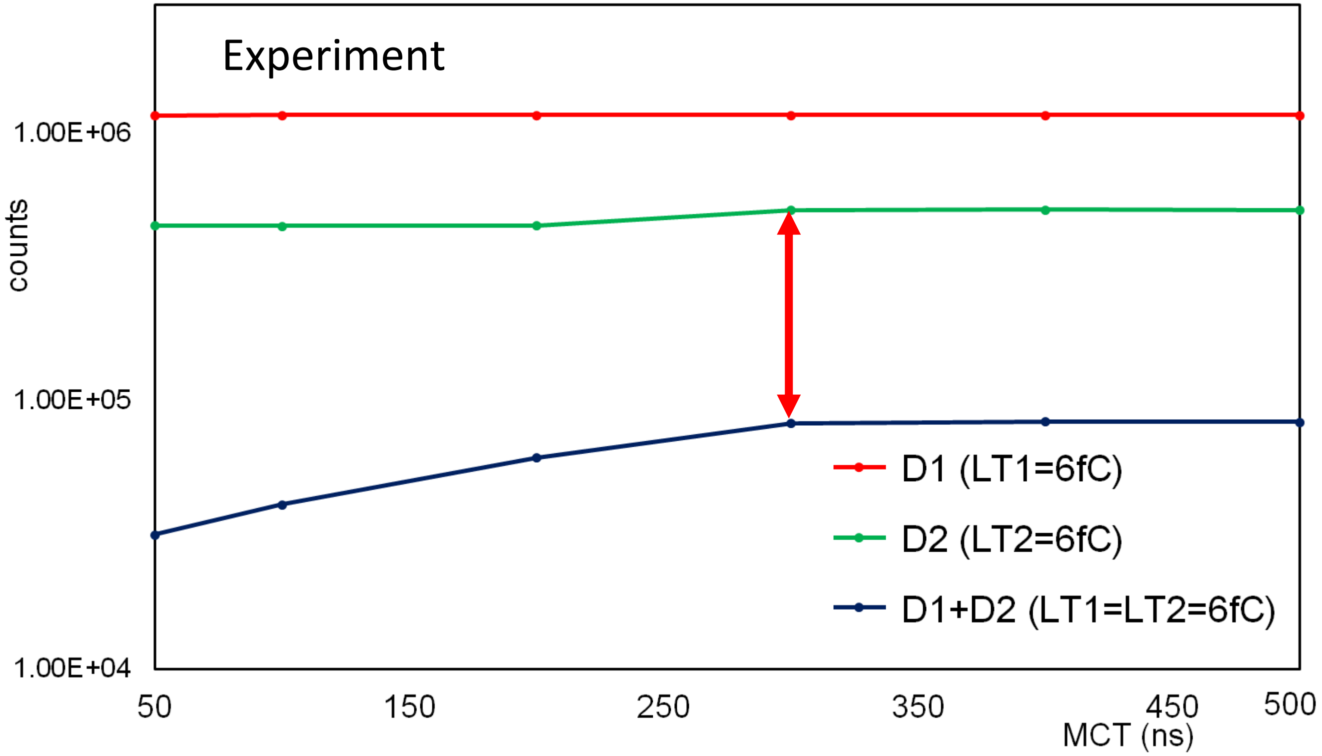


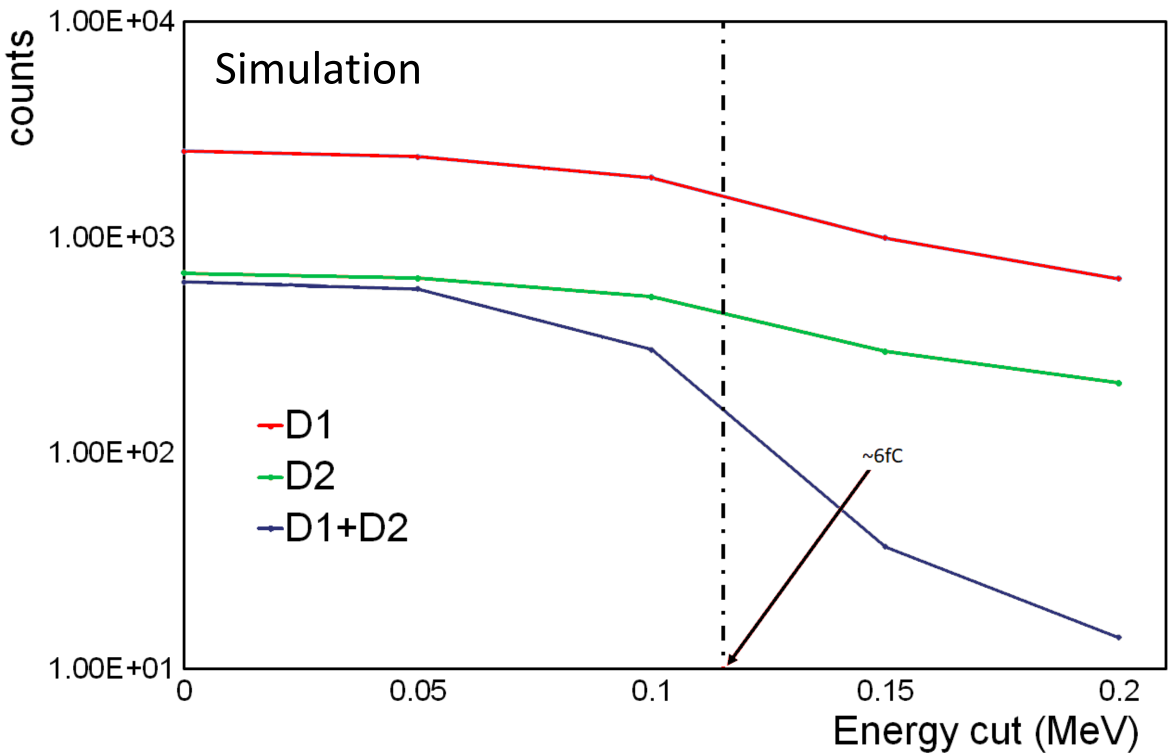
(M. Pinto et al, submitted for publication)

RADEM EM - Coincidences

Tests done with 200 MeV protons with th EDH

(M. Pinto et al, submitted for publication)



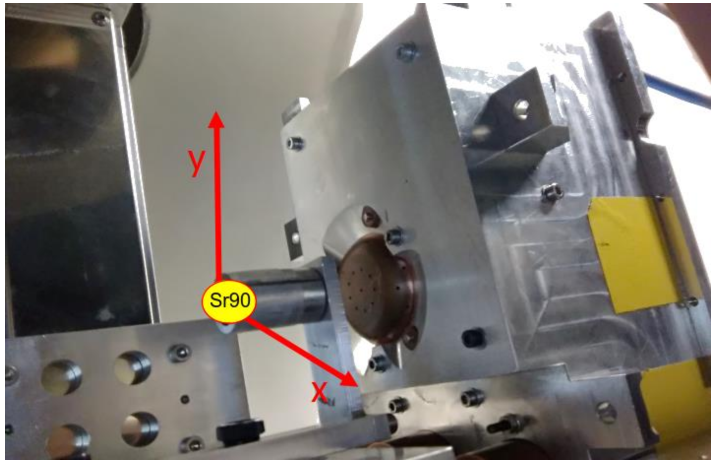


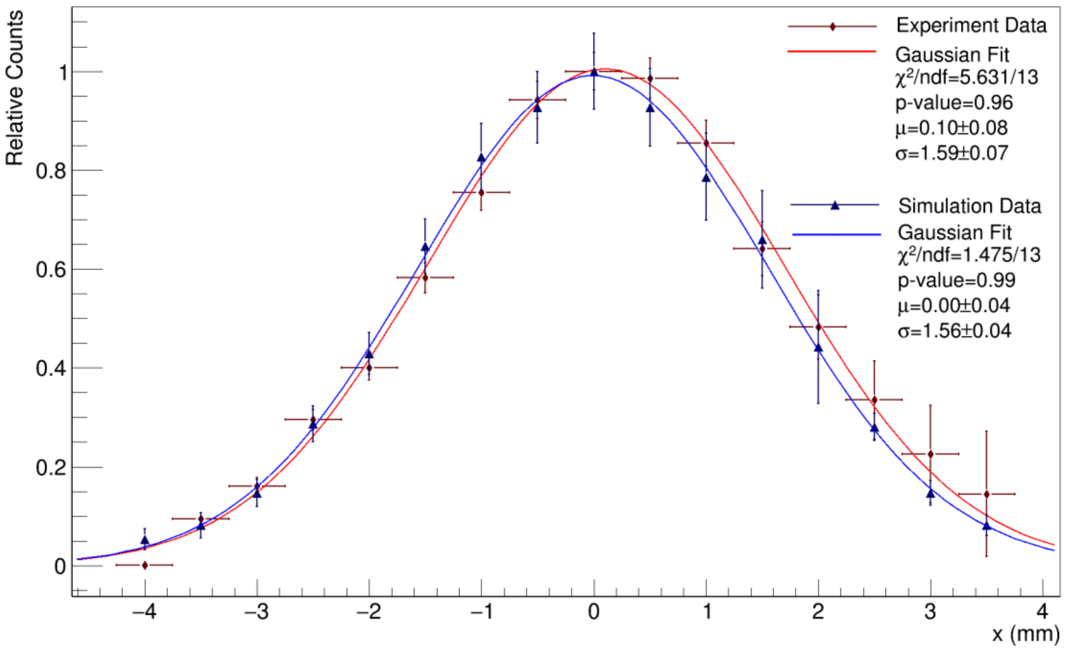
Coincidence logic shown to work

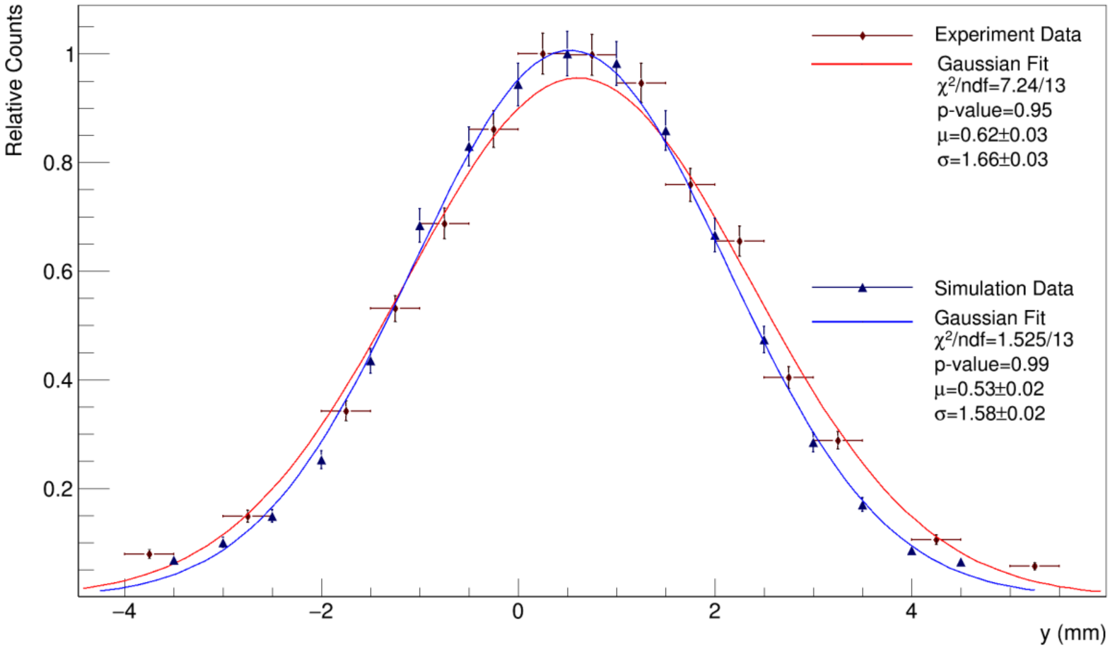
Discrepancy due to energy cut

RADEM EM – DDH alignment

- Preliminary setup
  - Sr90 source
  - In air
  - X-Y table
- Only 2 diodes measured
  - Mechanical constraints







RADEM EM - Conclusions

- ❑ Concept is validated

- ❑ Full instrument functional
  - ✓ H/W
  - ✓ S/W

- ❑ Detector Heads
  - ✓ Energy response
  - ✓ Alignment (preliminary)

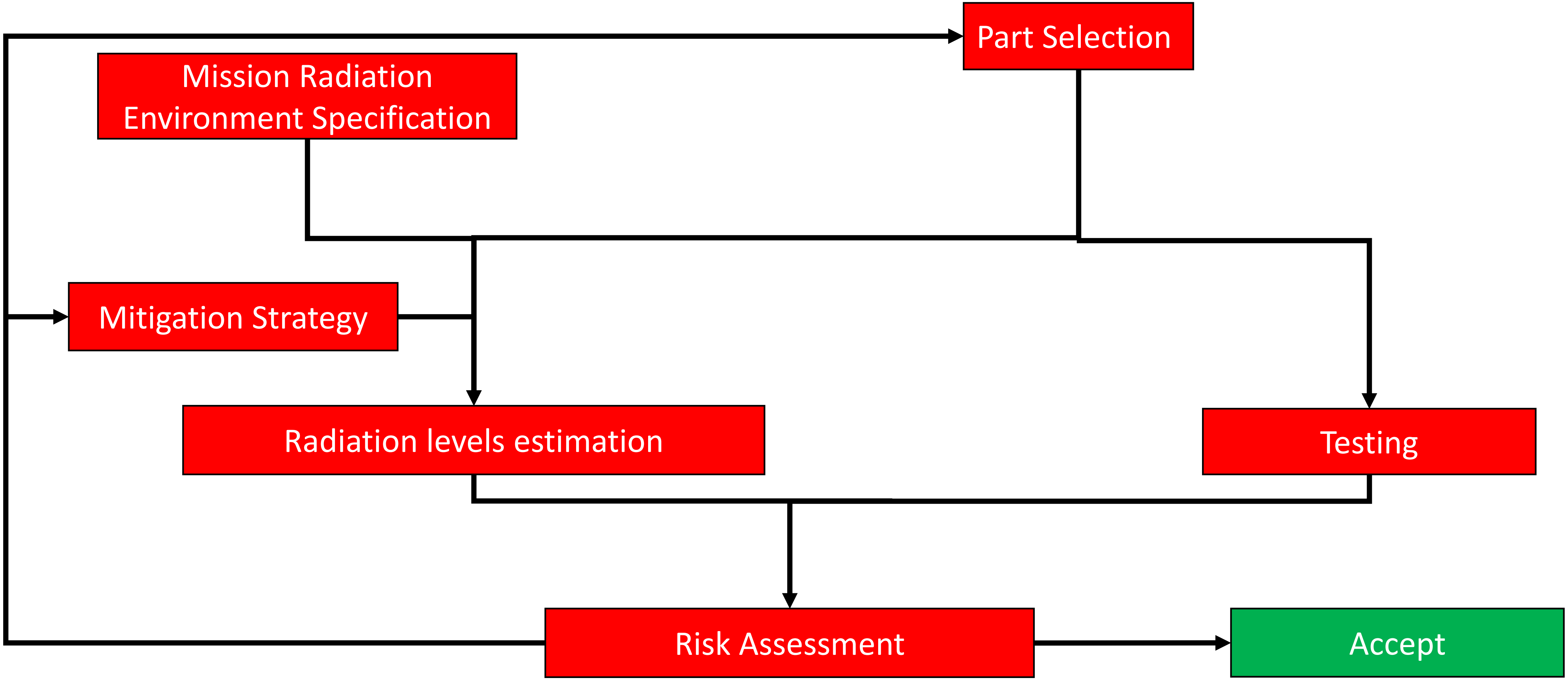
→ **Noise issues**

From a variety of sources

Must be solved in the next models!

- ❑ ASIC
  - ✓ Coupling to diodes
  - ✓ Trigger
  - ✓ Logic
  - ✓ Linearity

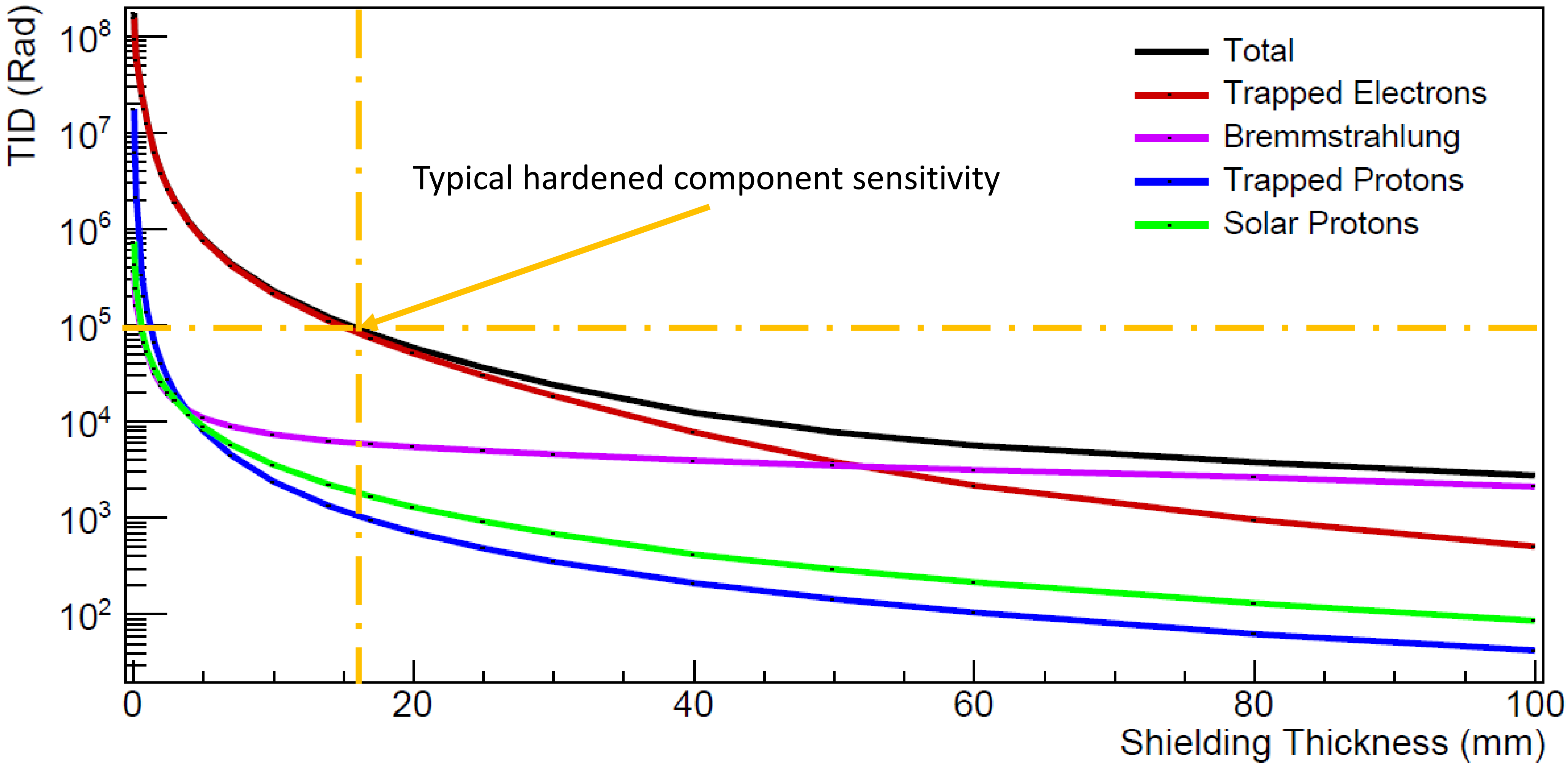
Radiation Hardness Assurance



TID

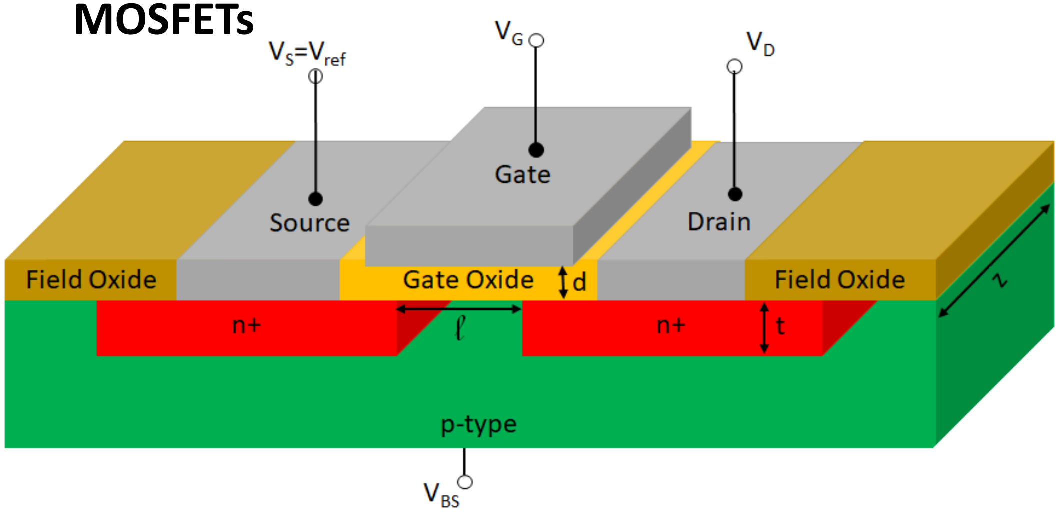
Particularly problematic in Jupiter

1 Gy = 100 rad

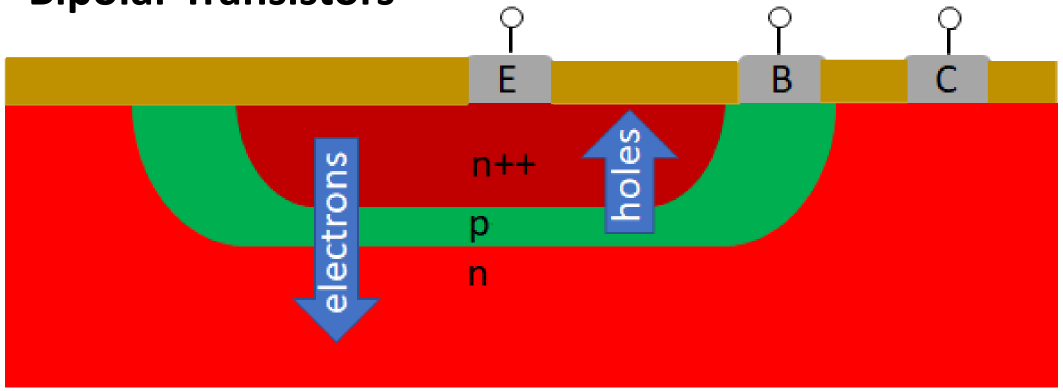


TID Effects

MOSFETs



Bipolar Transistors



ΔVG_{th}

Parasitic Path

Cross talk

Decrease in the Gain

Parasitic Path

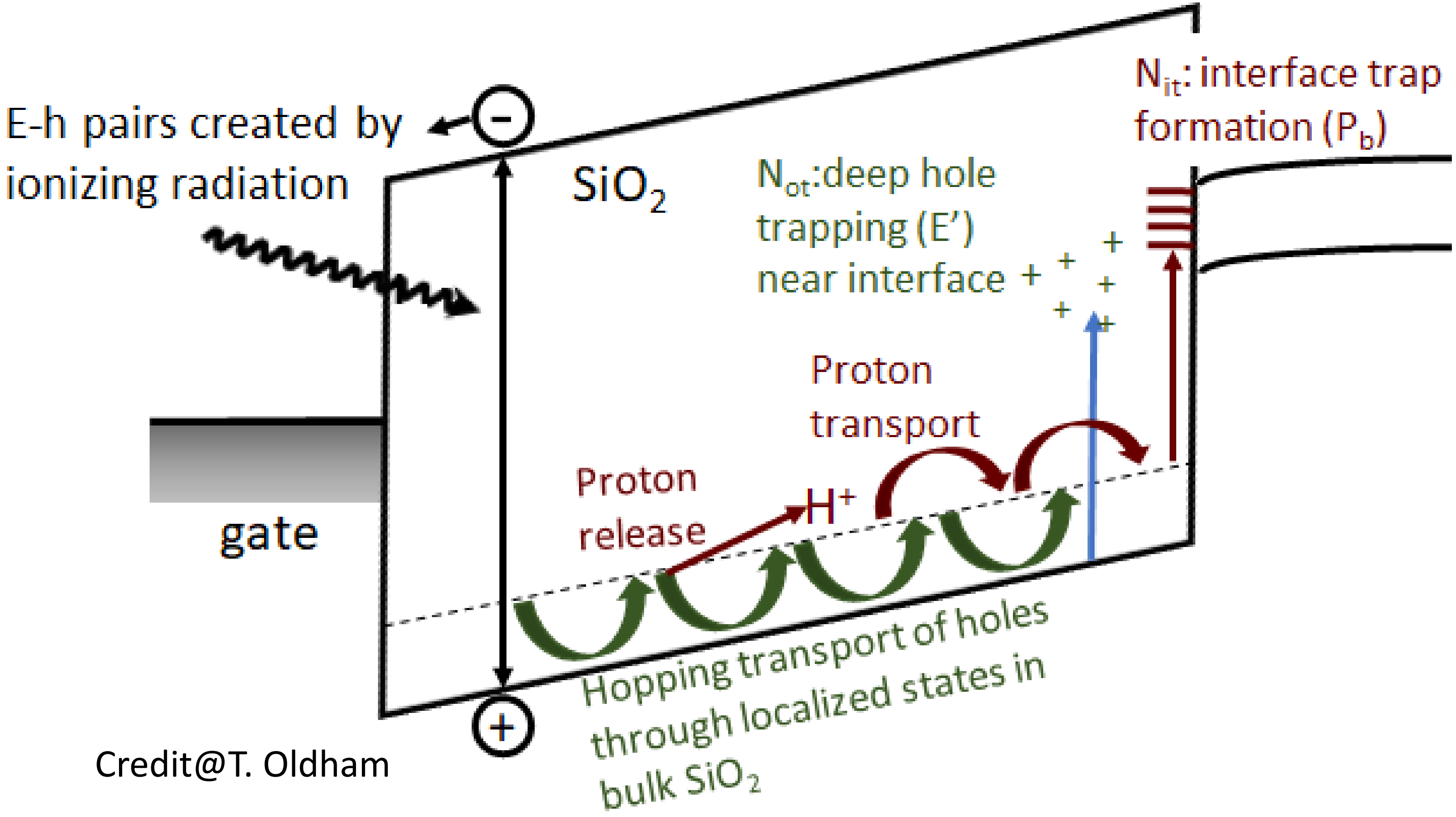
Cross talk

Parametric

and

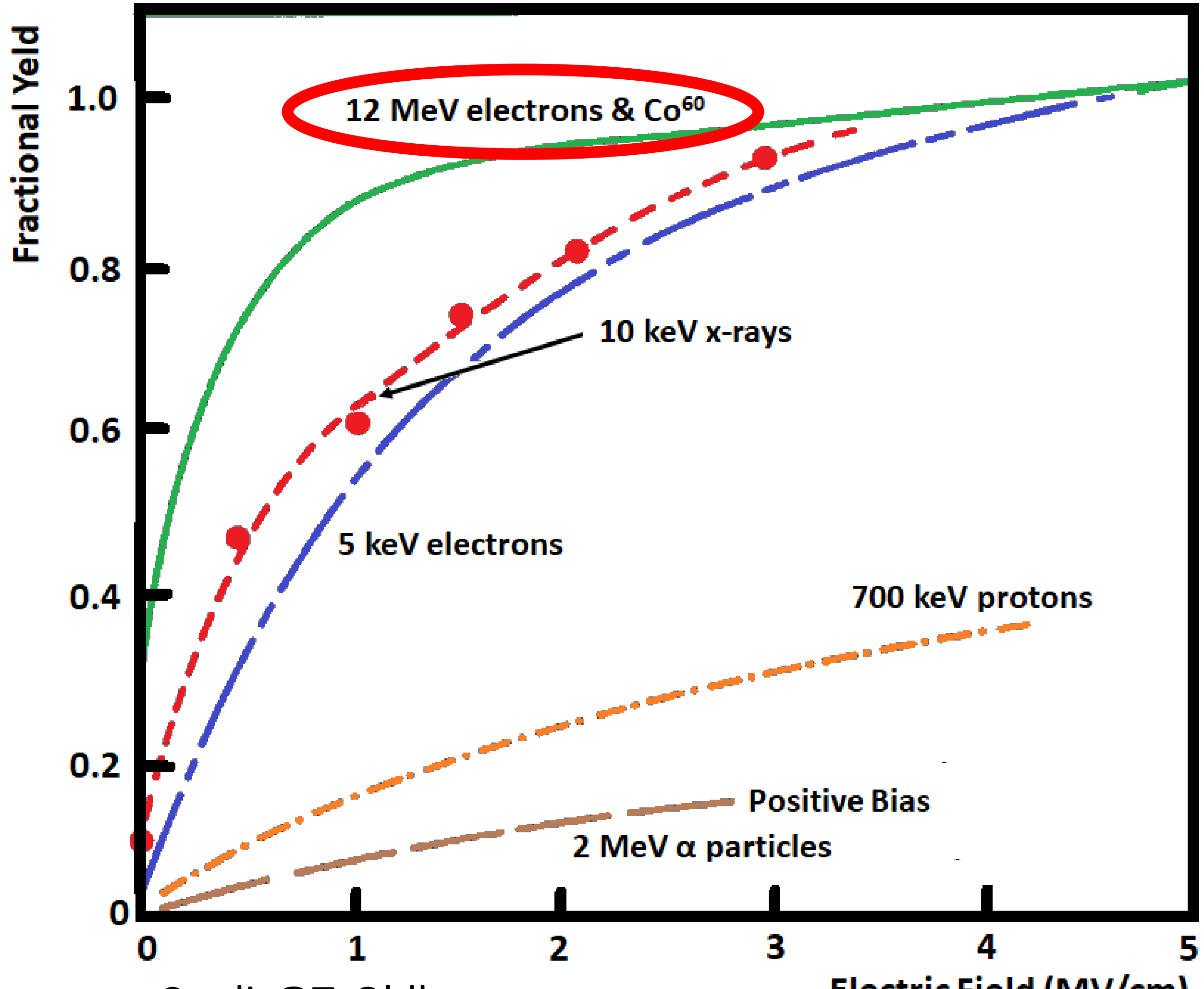
Functional Failures

TID mechanism - MOSFETs



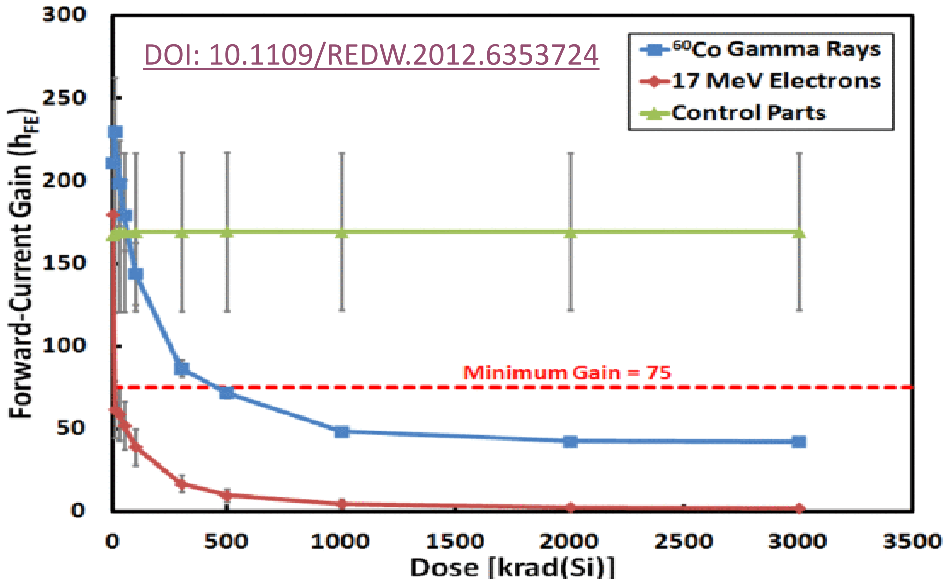
Credit@T. Oldham

TID mechanism - Recombination



Credit@T. Oldham

- Calculated with several assumptions
- Empirically shown only for a small subset of cases
- Depends on bias/temperature/technology/dose rate…
- Recent indications that it might not always be true



- Extremely important for the Jovian environment

Eco60 - Components

Extensive test campaign to compare effects on different technologies

LIP - ESA Contract No: RFQ/3-13975/13/NL/PA

Component Type		Component		
		Reference	Manufacturer	# of Parameters
A	Transistor (discrete MOS/CMOS)	STRH100N10	STMicroelectronics	6
B	FLASH-NAND Memory (MOS/CMOS IC)	MT29F32G08ABAAAWP-ITZ	Micron	8+2
C	Transistor (Bipolar)	2N2222	STMicroelectronics	4+4
D	Analog ICs non ELDRS	LM124	Texas Instruments	11
E	Analog ICs displaying ELDRS	LM4050WG5.0-MPR	Texas Instruments	5

(M. Pinto et al, DOI: 10.1109/NSREC.2017.8115475)

Eco60 – Test Campaign

4 Facilities

- ❑ Campus Tecnológico e Nuclear (CTN) ⟷ Co2
- ❑ Hospital Santa Maria (HSM) ⟷ Eb1
- ❑ ESA-ESTEC ⟷ Co1
- ❑ RADEF ⟷ Eb2 / Eb3

5 irradiation campaigns

Co2	Co60 at HDR(24krad/hour)
Eb1	12 MeV e^- at HDR (24krad/hour)
Co1	Co60 at LDR(~280rad/hour)
Eb2	12 MeV e^- at HDR (24krad/hour)
Eb3	20 MeV e^- at HDR (24krad/hour)

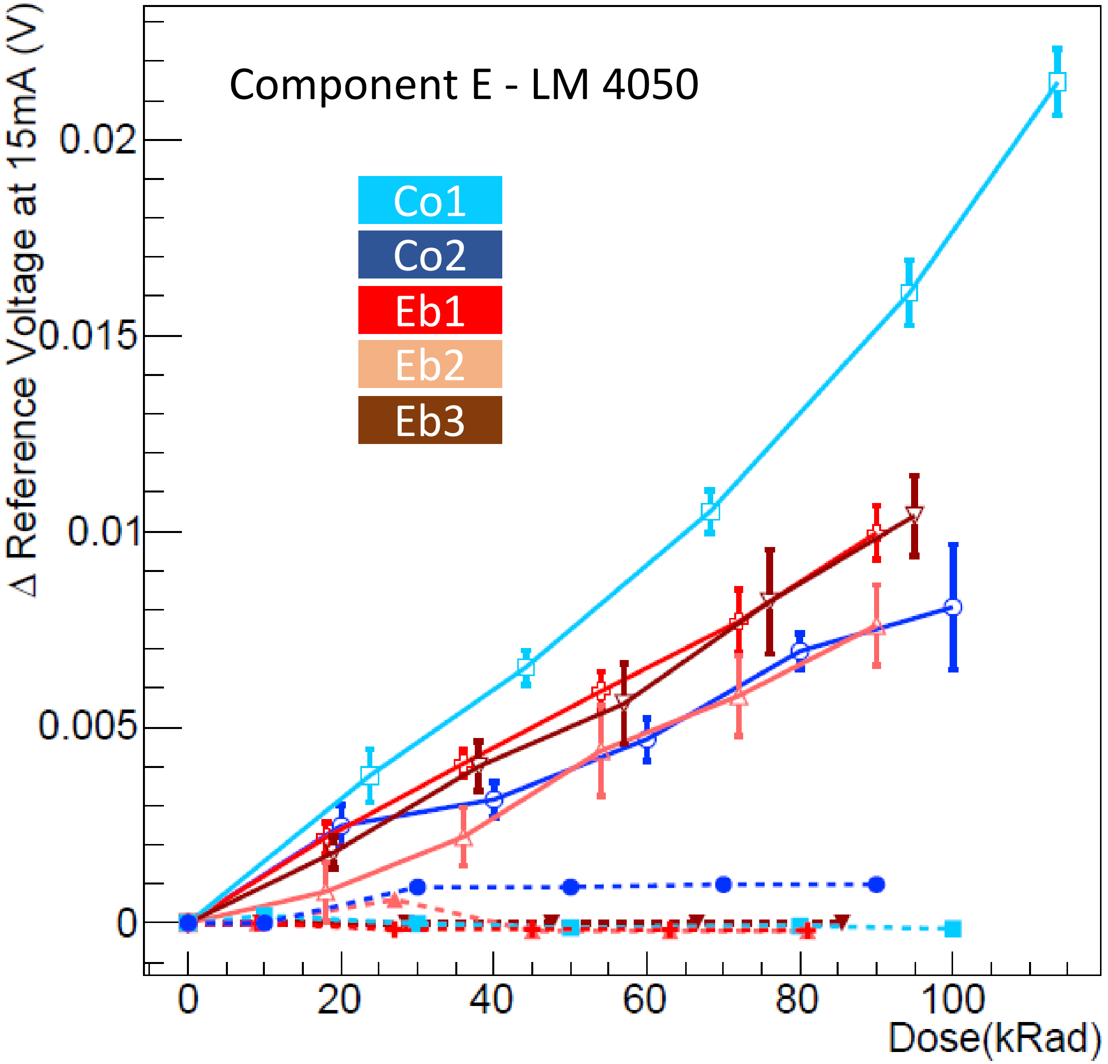
Irradiation

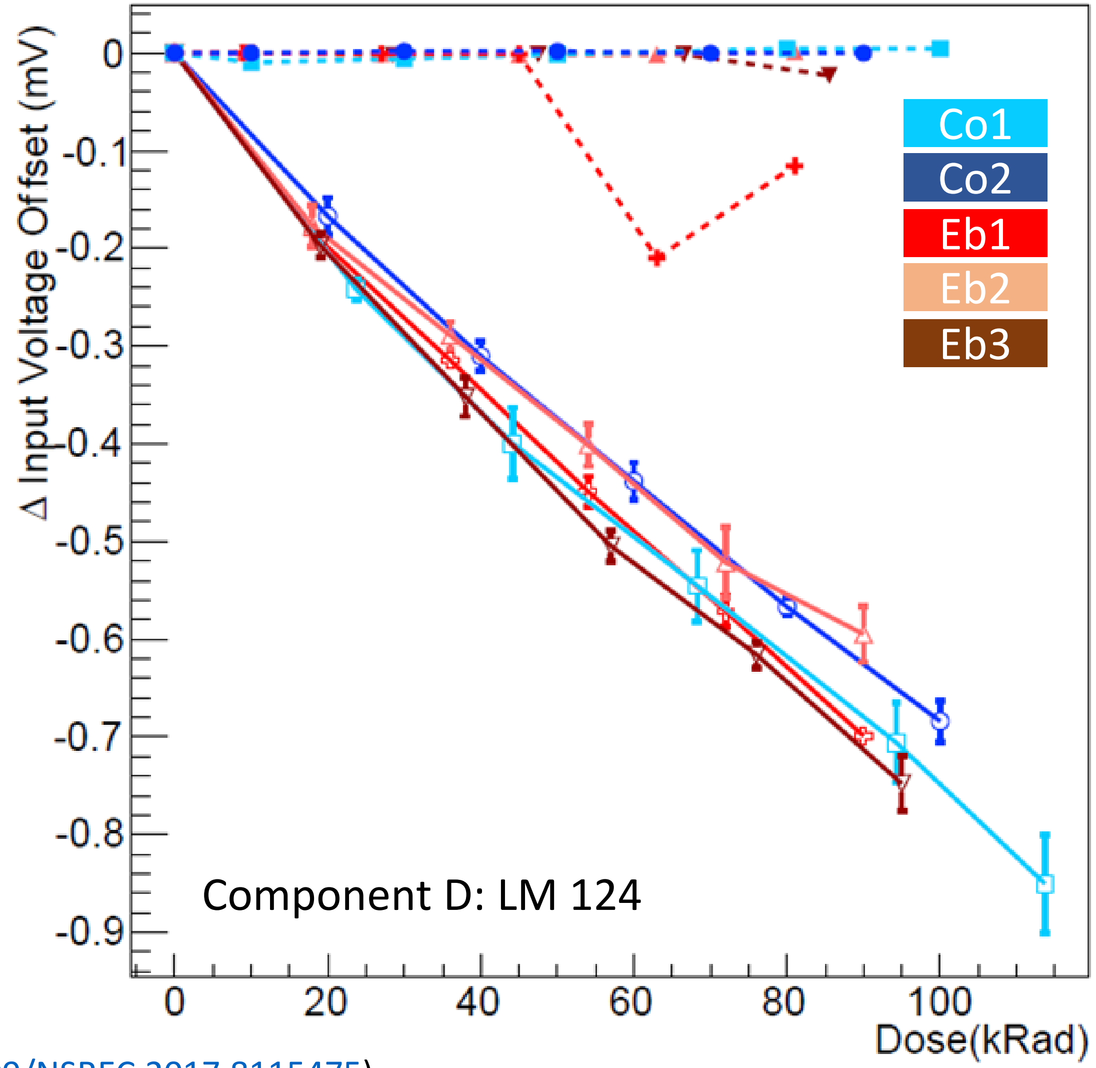
20* krad steps irradiations up to 100 krad
Components measured before and between irradiation steps
Reference measured at several points for comparison

Component	Co1	Co2	Eb1	Eb2	Eb3
A	5	5	5	0	5
B	5	5	5	0	0
C	5	5	5	2	0
D	5	5	5	5	5
E	5	5	5	5	5

*A factor had to be applied for electron dosimetry purposes

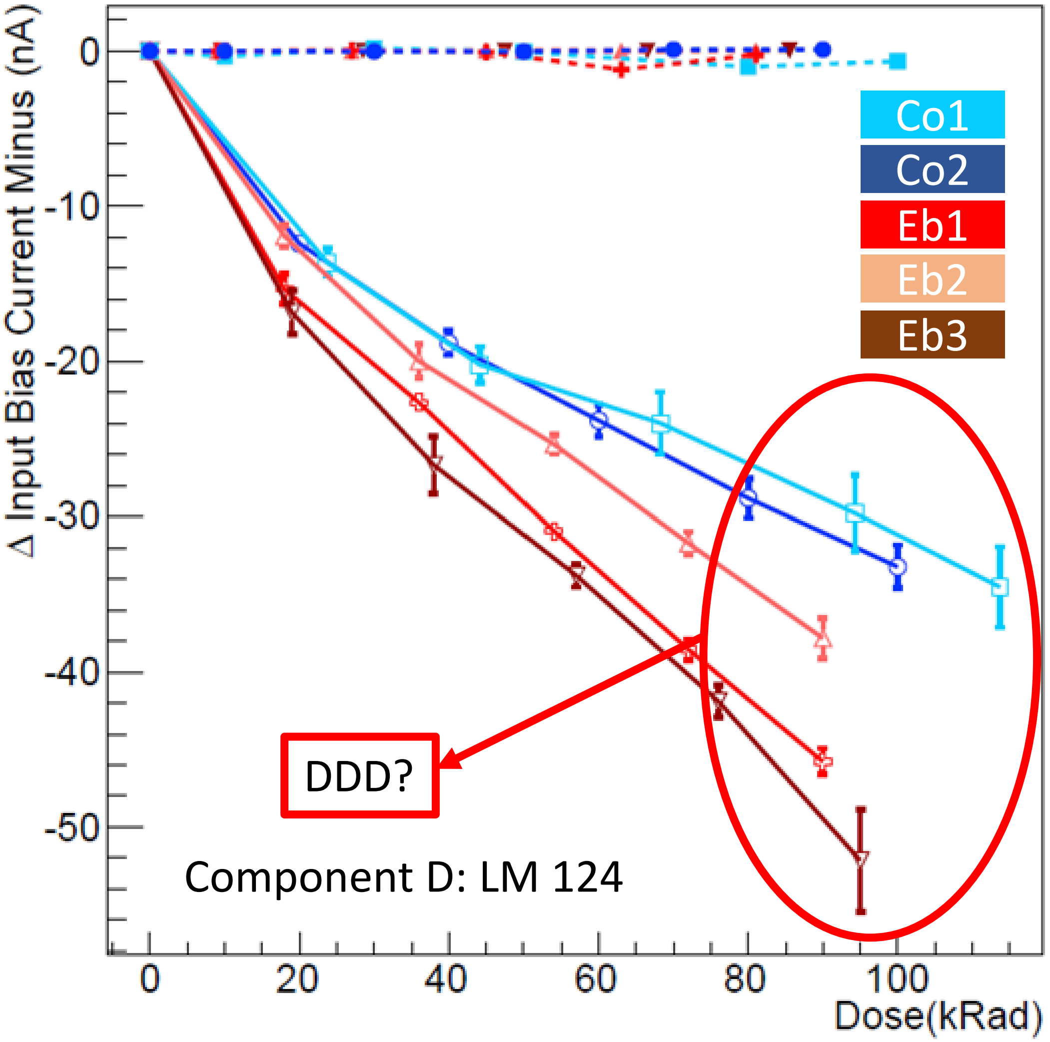
Eco60 – Results



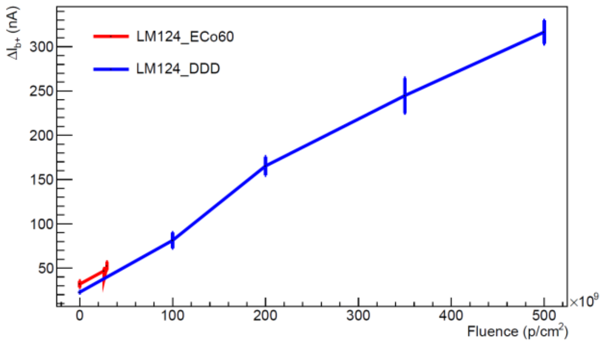


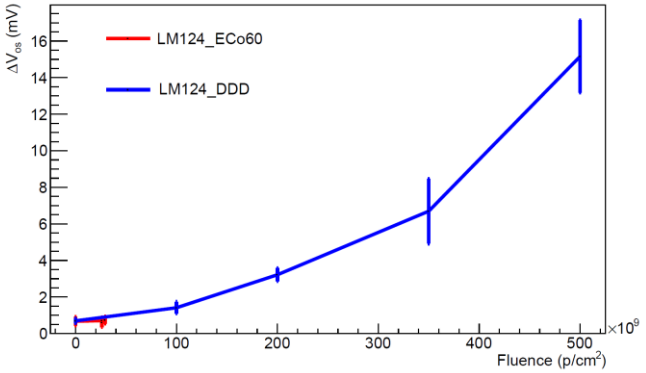
(M. Pinto et al, DOI: [10.1109/NSREC.2017.8115475](https://doi.org/10.1109/NSREC.2017.8115475))

Eco60 – Results



- ❑ Clear enhanced effect in electron irradiation
- ❑ Strong evidence for DDD contribution
- ❑ Results compared to TID + DDD tests on the same component
  - DDD in ECo60 much lower
  - Different test lot
  - Same trends!





- ❑ Known presence of neutrons in LINACs

(M. Pinto et al, DOI: [10.1109/NSREC.2017.8115475](https://doi.org/10.1109/NSREC.2017.8115475)

Eco60 – Conclusions

- 5 component types were selected for irradiation:
  - Power MOSFET (MOS)
  - Flash-NAND Memory (MOS IC)
  - Bipolar Transistor (Bipolar)
  - OPAMP (Analogue IC)
  - Reference Voltage (Analogue IC ELDRS)

- Components showed similar sensitivity to Co60 than to 12 MeV and 20 MeV electron beams

- LM 124 showed increased sensitivity to electrons
  - Electron NIEL
  - Neutrons

- Co60 is representative of worst-case scenario damage to components flown in the missions to the Jovian system

Radiation levels

TID and DDD

Ray-tracing
- Fast
- Conservative

Monte Carlo
- Includes Physics
- Accurate
- Slow

Level < Sensitive*RDM

Several shielding options

SEE

LET based calculations

GCR
LET spectrum

Proton belts/solar (same as TID)
+
LET spectrum

Impact is application dependent

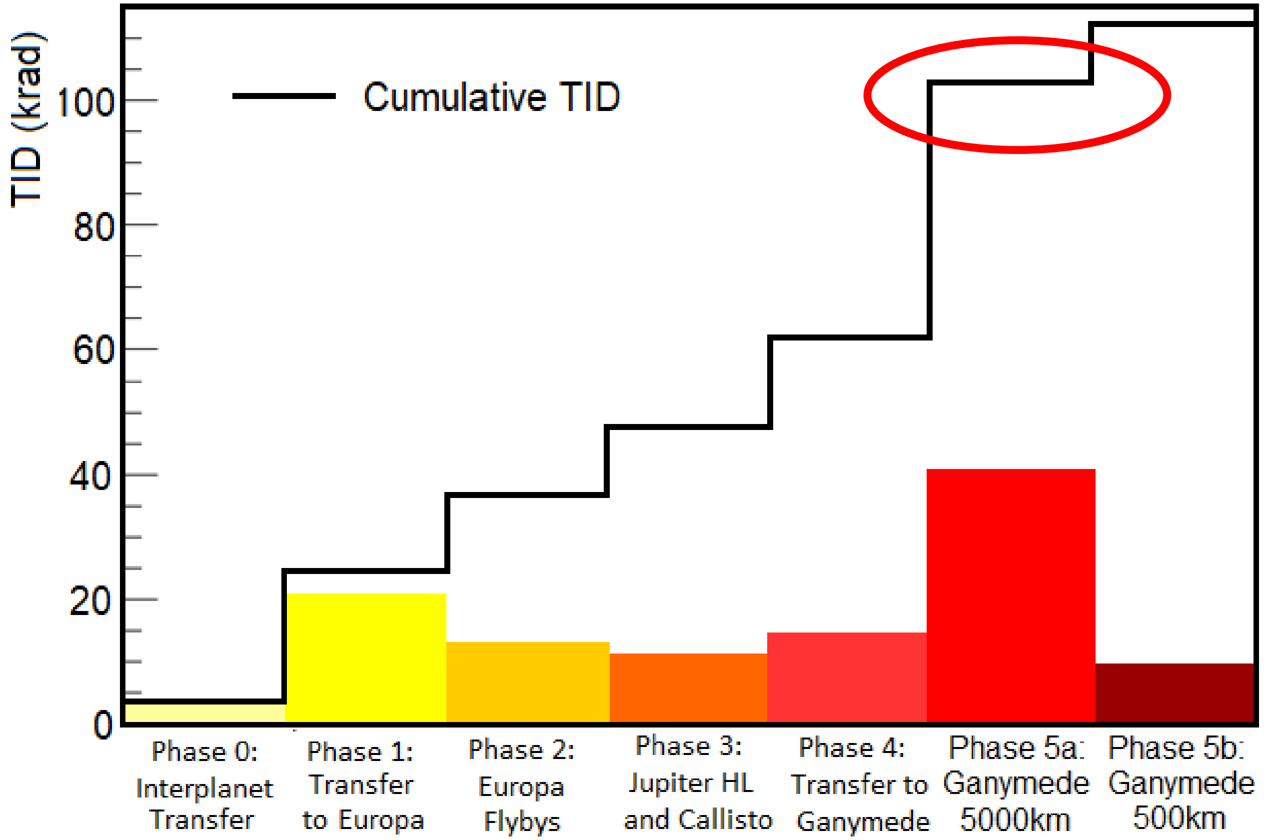
No shielding

RADEM – TID

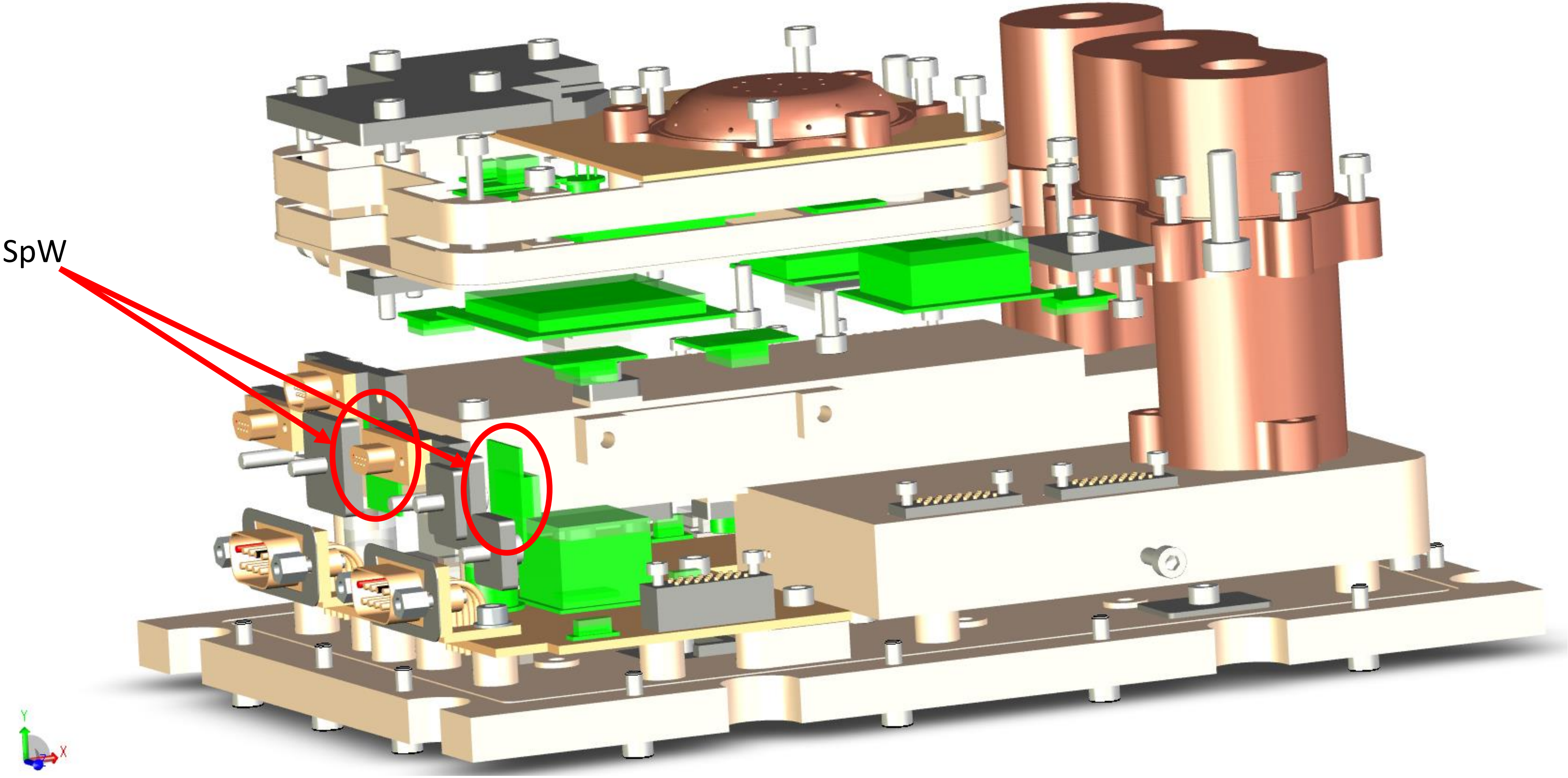
- 129 sensitive components

- Total shielding mass ~2kg

- SpaceWire Transceiver
  - Responsible for communication
  - 100 krad sensitivity
  - TID level = 112.39 ± 1.03 krad
  - RDM=2
  - Only at the end of the mission
  - Redundant!

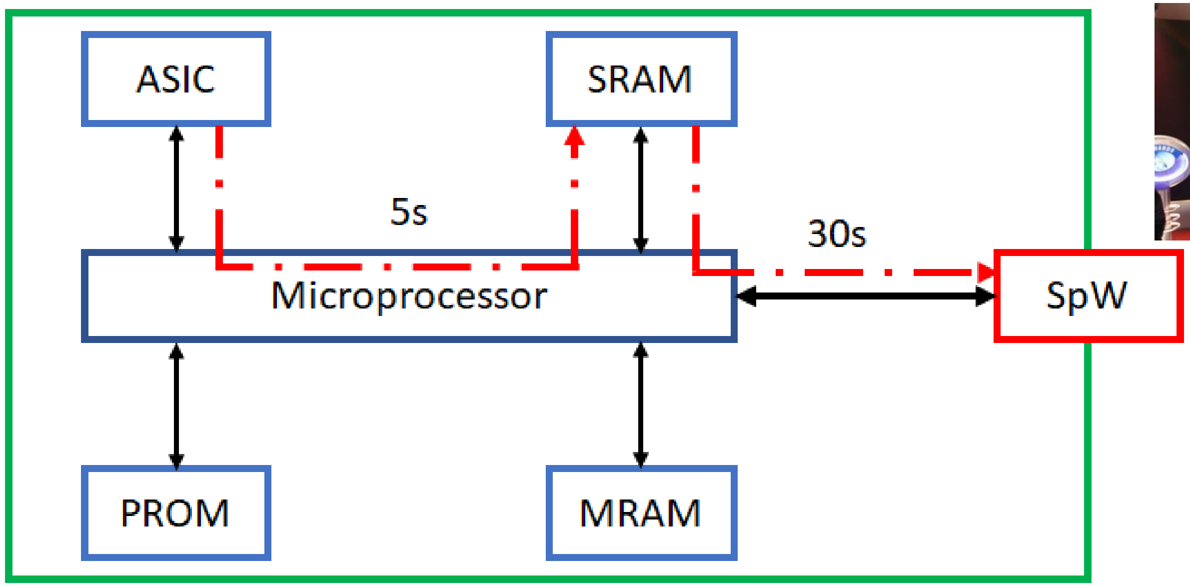


RADEM – TID



RADEM – SEE

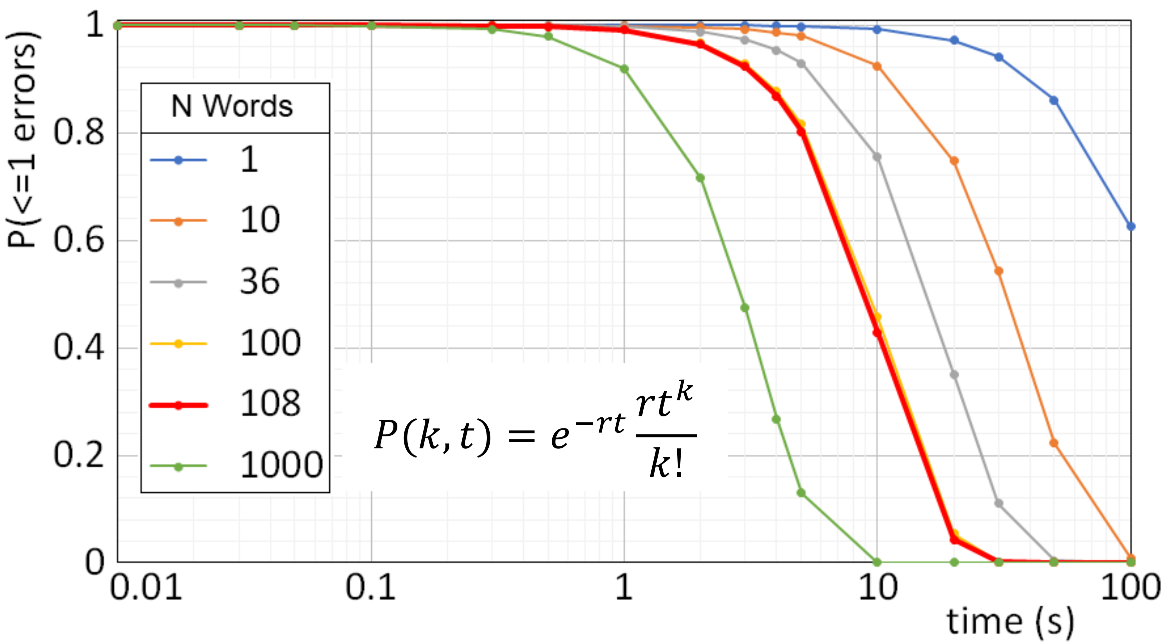
Data flow from ASIC to S/C



- ASIC data size full at max rate in 5s
- Data is stored in SRAM
- S/C receives data every 30s
- Bits must be read or written for EDAC to correct errors

SRAM is the weakest link → Average error rate: 29.3 $(\text{bit.day})^{-1}$!
(worst-case trapped protons)

EDAC and scrubbing



Conclusion

- RADEM is being developed and is now moving on to the EQM
- It fullfills all requirements
- Altough there are some delays it is still within mission schedule
- Main concern are the ASIC radiation sensitivity
- And the noise…

Perspectives

- ❑ Interplanetary radiation environment
  - Jupiter is the main source of electrons in quiet times!
  - SEPs at different A.U. with multiple instruments
  - Forbush decrease during ICME

- ❑ Extend Jovian system radiation models to higher energies with actual data
  - Better engineering models (dynamical)
  - Better understanding of the acceleration processes

- ❑ Study Ganymede radiation belts
  - First long-term modelling
  - Coupling to the Jovian radiation belts

- ❑ Interaction of radiation with the moons
  - Sputtering
  - Exchange of materials between surface and the environment

- ❑ Synergy between plasmas and high energy particles with RADEM and PEP… and also JMAG

Future Work

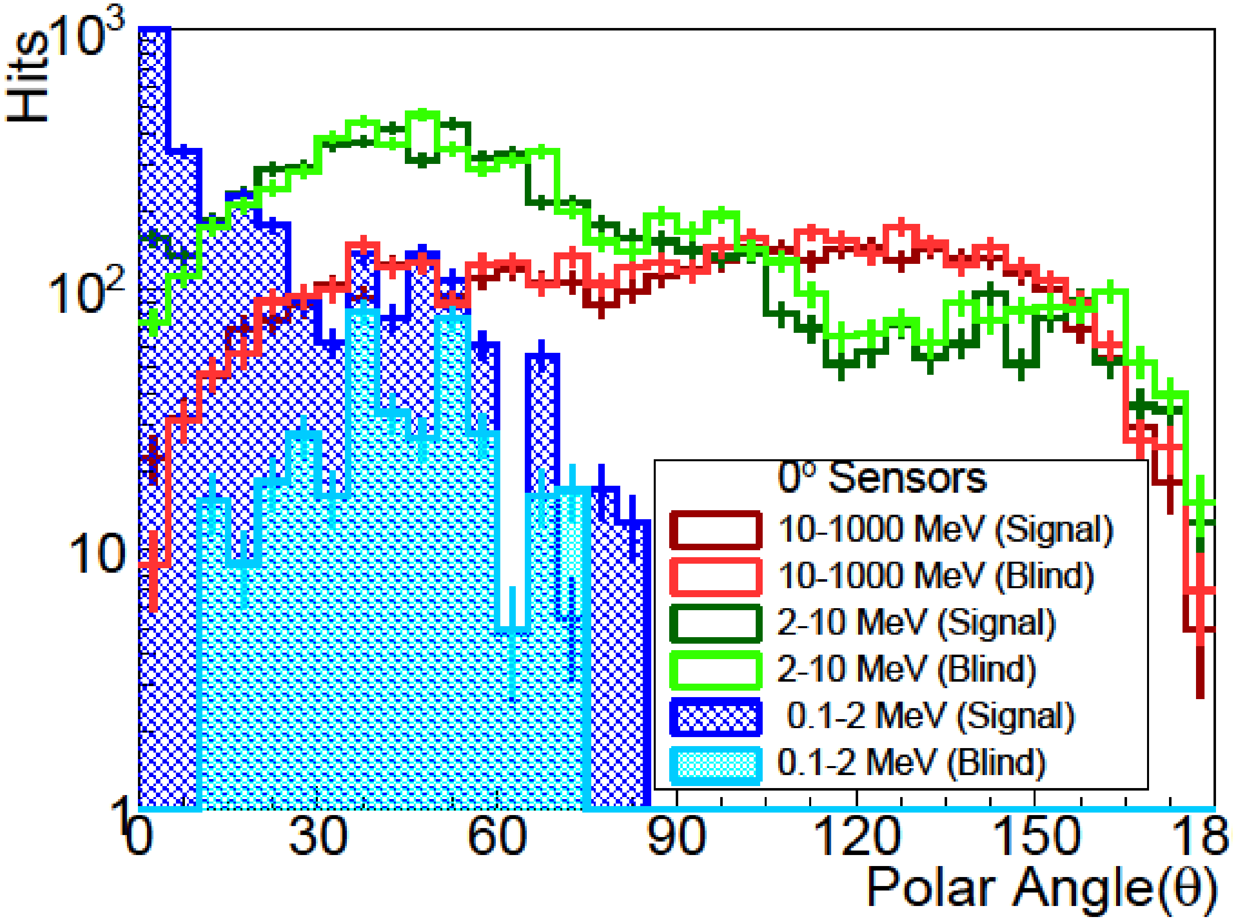
- EQM and FM calibration
- ASIC testing
- Development of flux reconstruction algorithms
- In-flight data analysis
- Cross-calibration in Earth flybys
- SEP analysis during cruise phase
- Jovian Radiation environment data analysis and model construction
- And more for over a decade of time
- ECo60 and GUIMesh can also benefit from more exploration

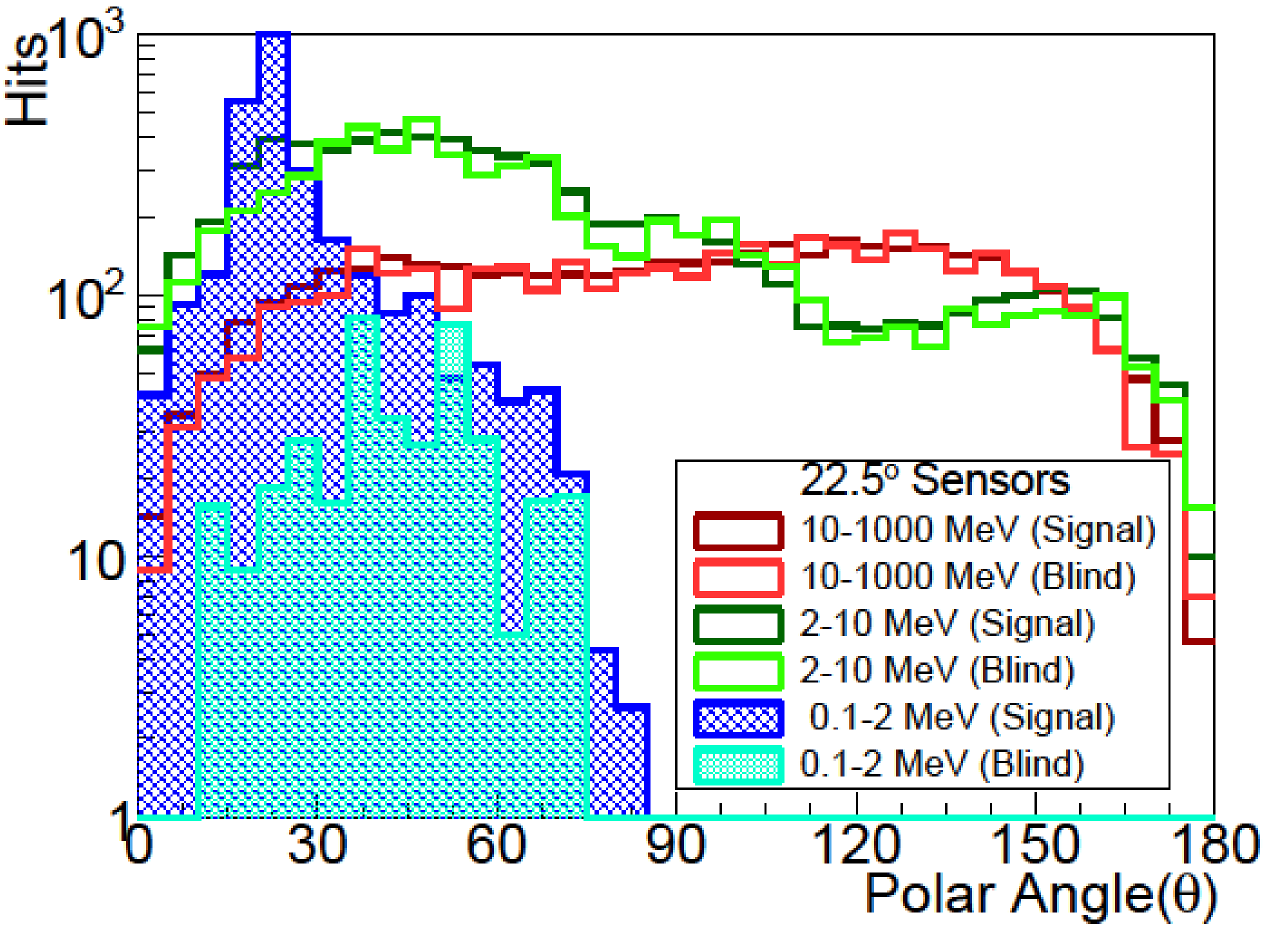
Thank you

Questions?

DDH – Baseline Directional Response

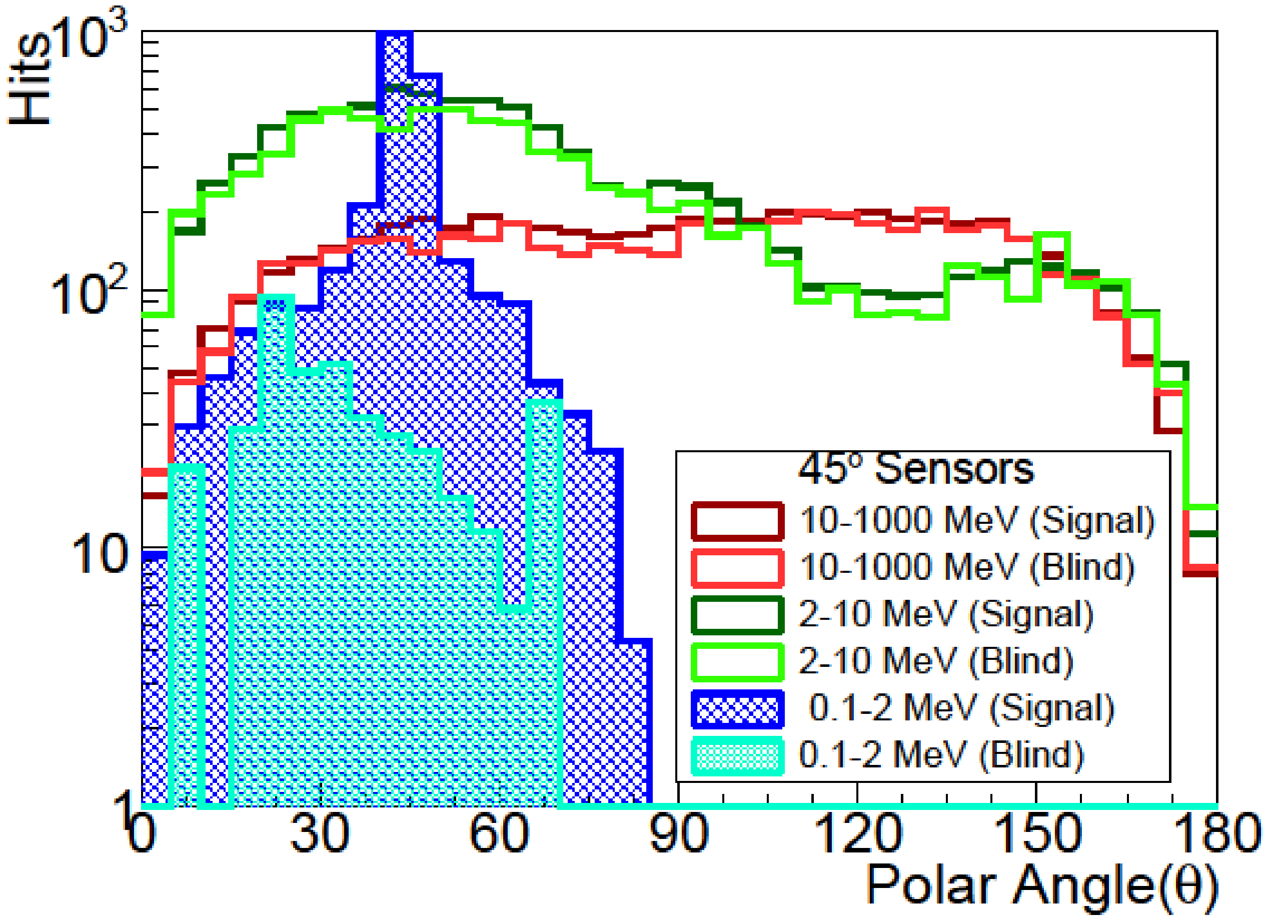
dN/dE=k

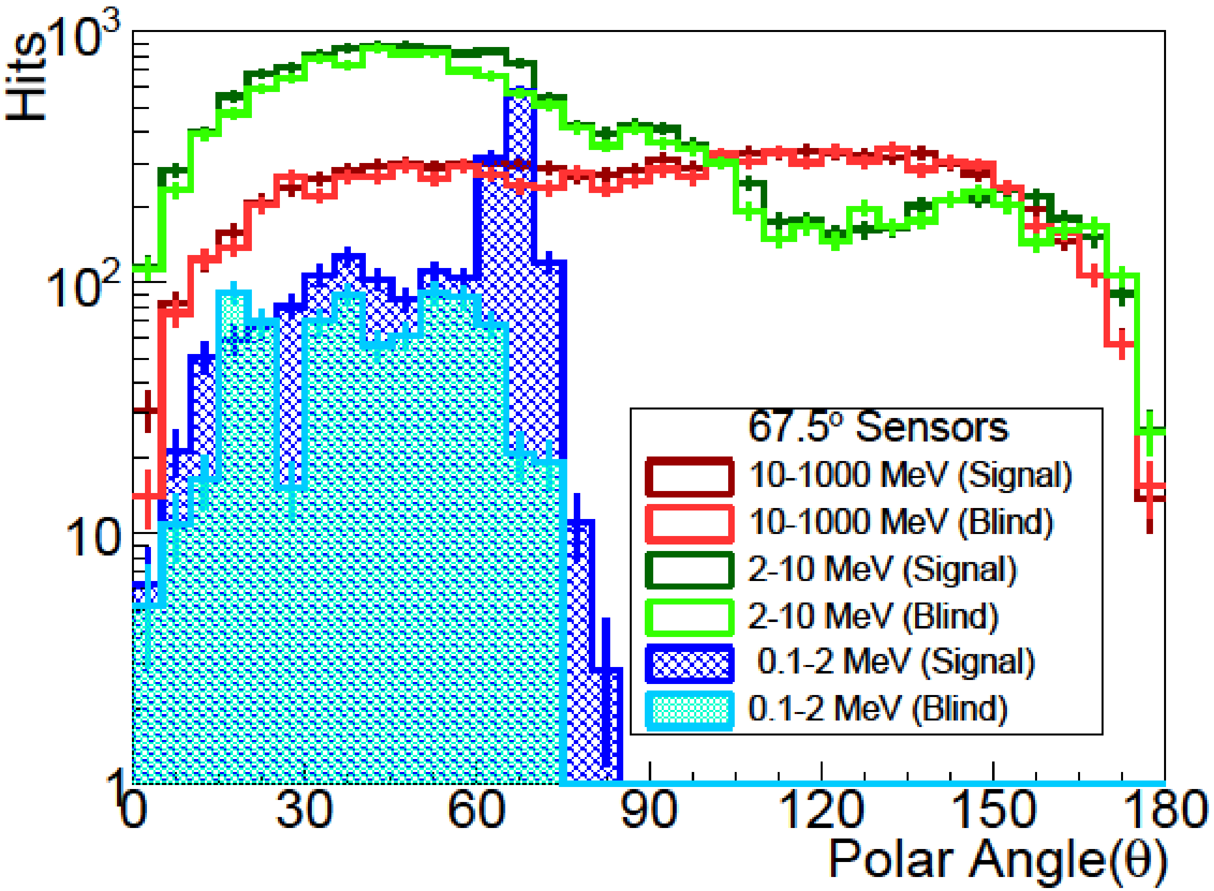




(M. Pinto et al, DOI: https://doi.org/10.1016/j.cpc.2019.01.024)

dN/dE=k





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