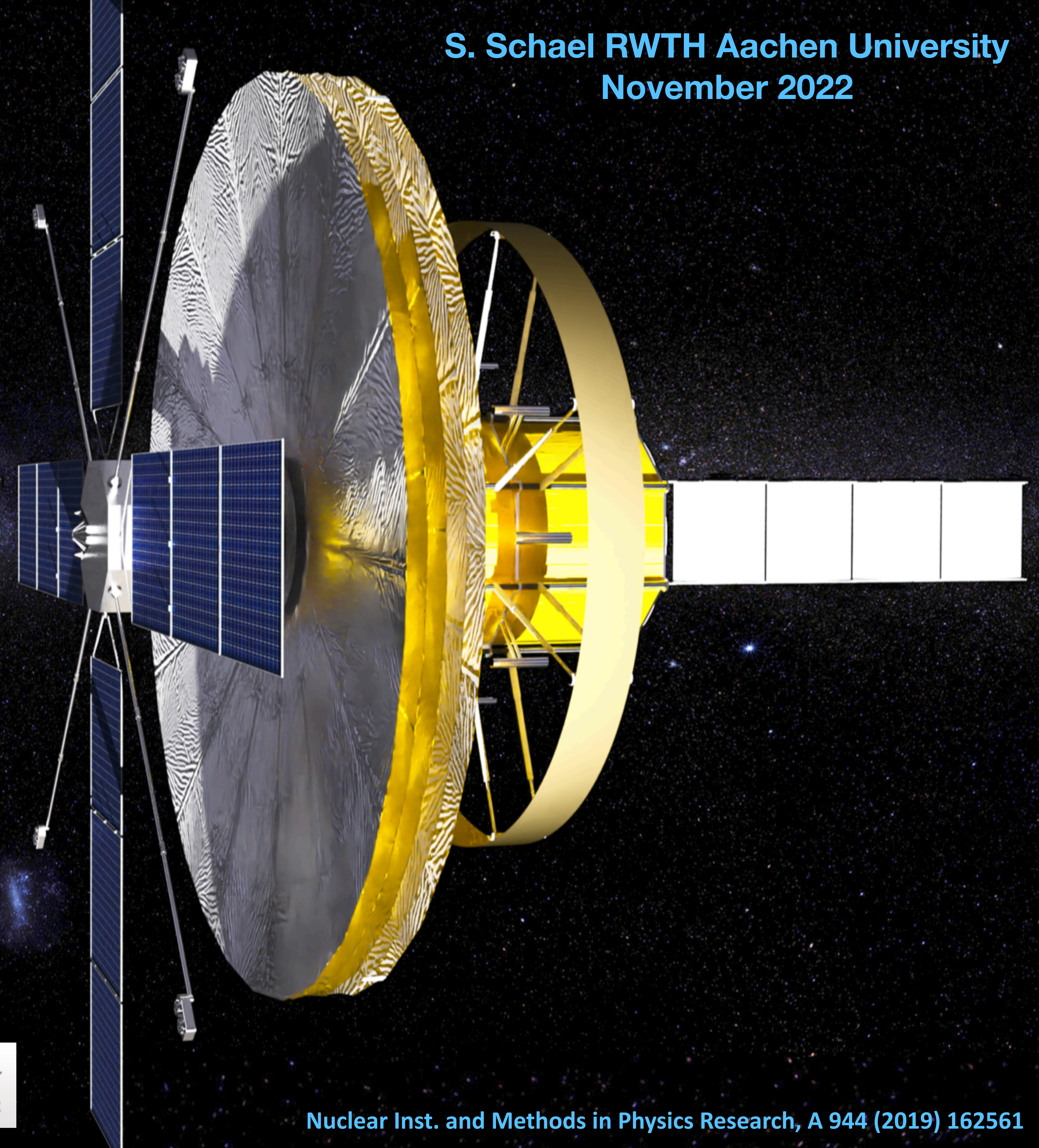
AMS-100

S. Schael RWTH Aachen University
November 2022

A Magnetic Spectrometer with an acceptance of 100 m² sr in Space

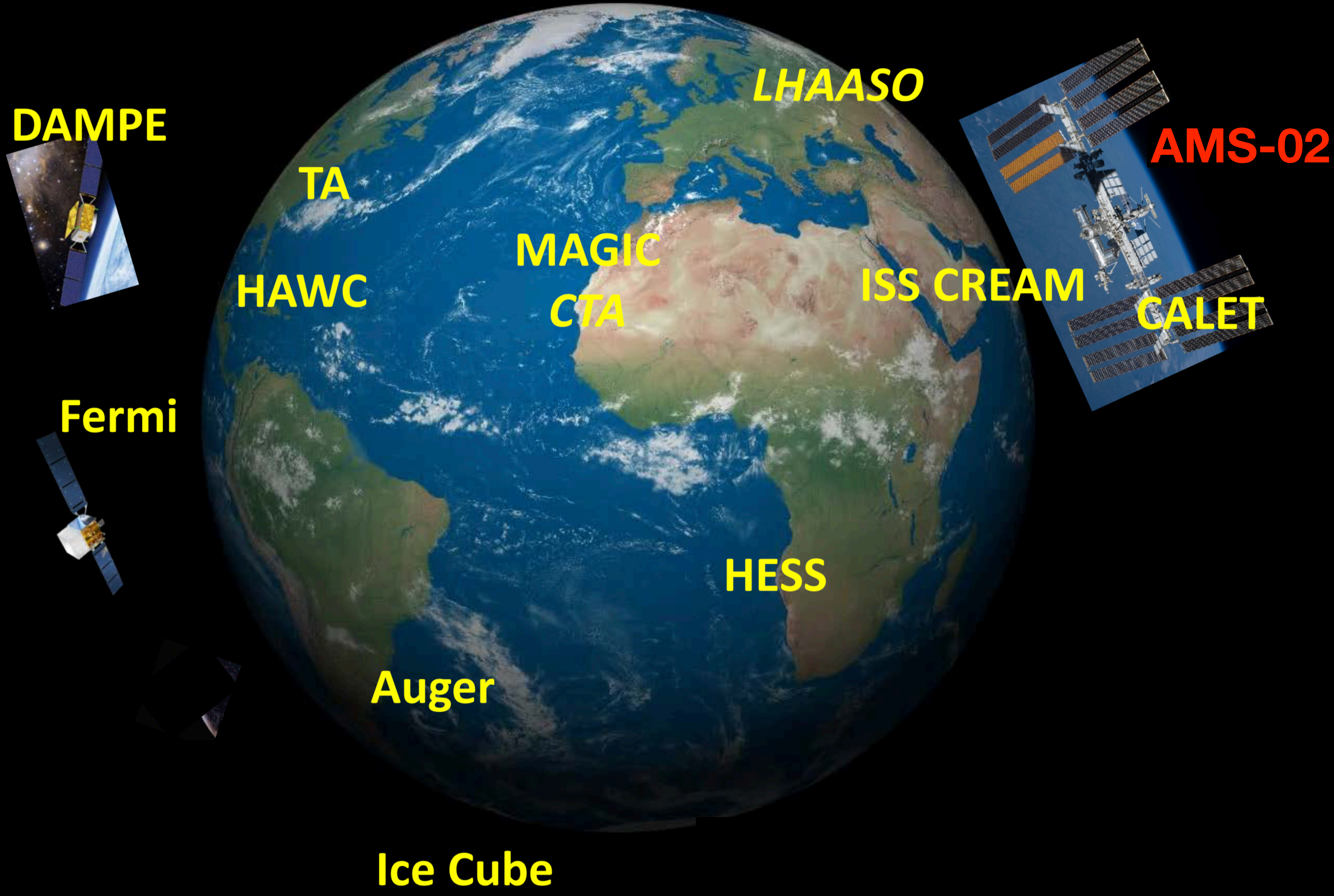


Structural- & Thermal Design, Service Module, Sunshield & Magnet
T. Bagni, Ch. von Byern, M. Czupalla, B. Dachwald, A. Dudarev, D. Fehr, H. Gast, D. Louis, T. Mulder, W. Karpinski, Th. Kirn, D. Kohlberger, M. Mentink, D. Pridöhl, S. Schael, T. Schalm, K.-U. Schröder, A. Schultz von Dratzig, P. Seefeldt, C. Senatore, Th. Siedenburg, H. Silva, D. Uglietti, A. Vaskuri, M. Wlochal, J. Zimmermann

RWTHAACHEN UNIVERSITY | FH AACHEN UNIVERSITY OF APPLIED SCIENCES | EPFL | CERN | UNIVERSITÉ DE GENÈVE | DLR

Nuclear Inst. and Methods in Physics Research, A 944 (2019) 162561

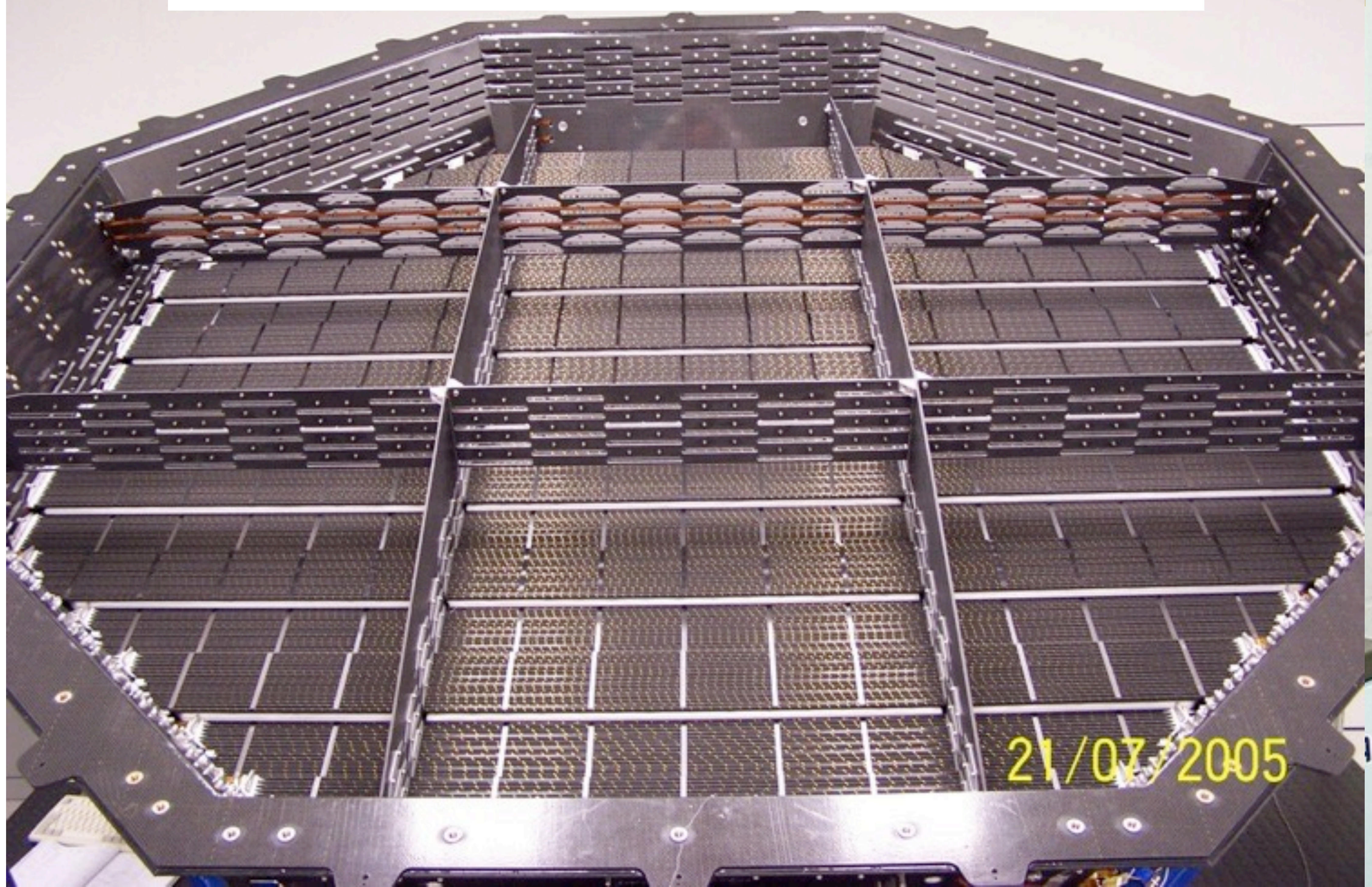
Major Cosmic Ray Experiments 2022



We have only one magnetic spectrometer in space: AMS-02

In Space since May 2011

TRD Construction at RWTH

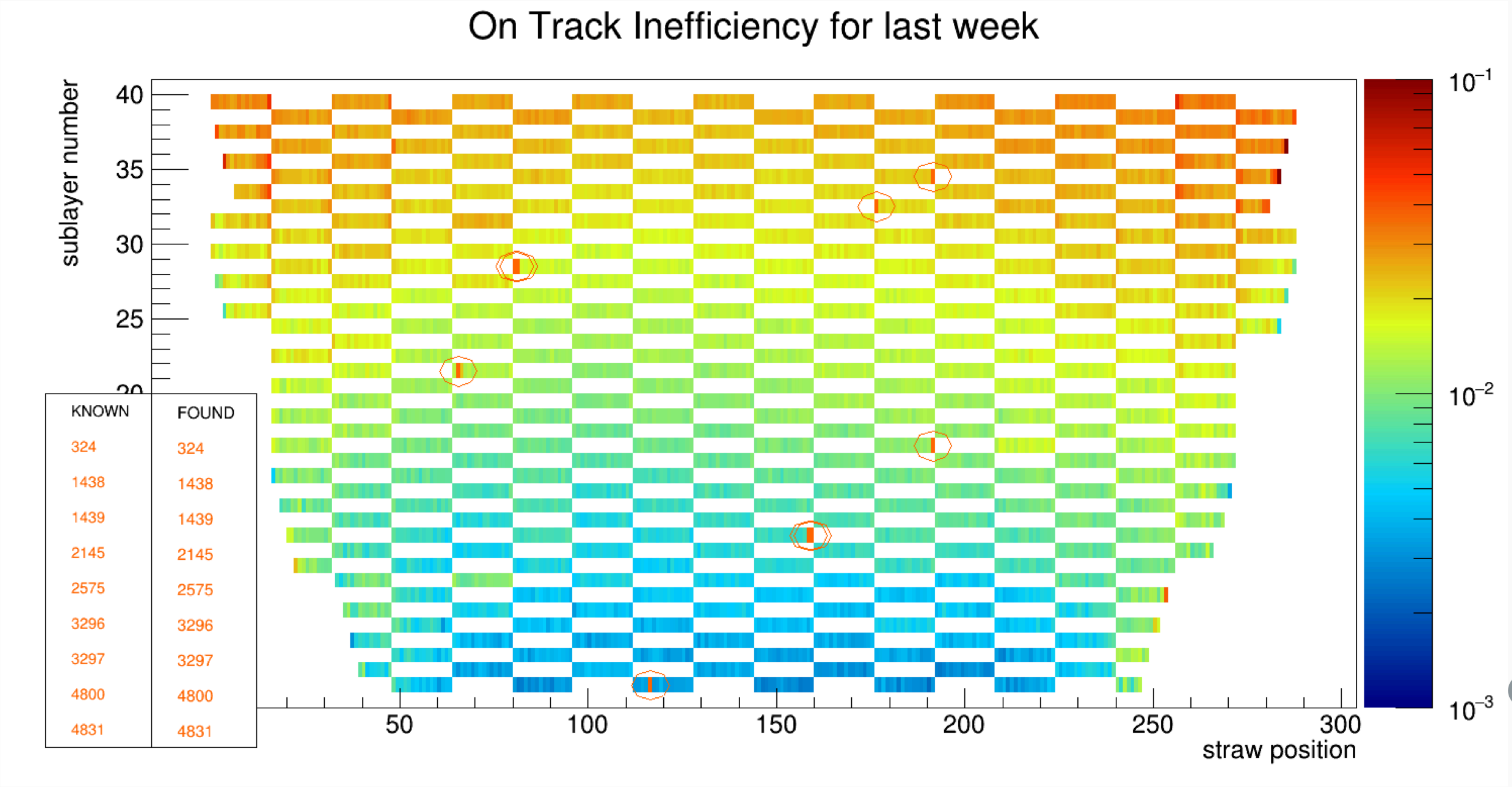


TRD Gas System
Thermo Vacuum Test
at RWTH

AMS-02 TRD

5248 Readout Channels,
482 Temperature Sensors,
8 Pressure Sensors,
24 Heaters.

TRD Straw Inefficiency 2D

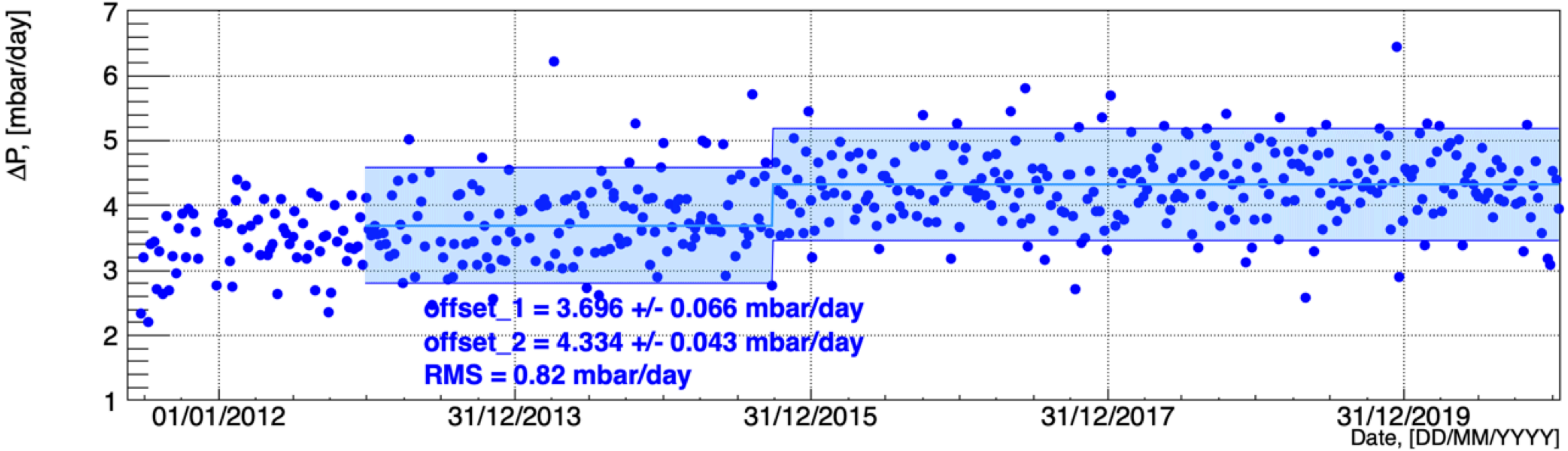


KNOWN	FOUND
324	324
1438	1438
1439	1439
2145	2145
2575	2575
3296	3296
3297	3297
4800	4800
4831	4831

Back

In total, 7.2 m out of 7500 m of total wire length are ineffective, i.e. 99.9% of the TRD are working as expected.

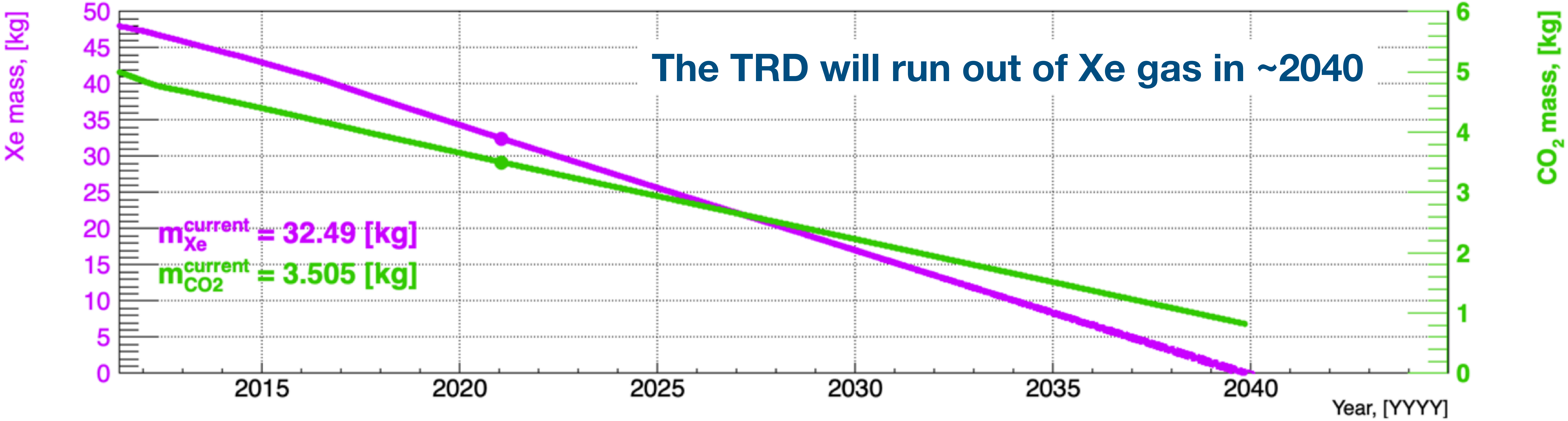
TRD Gas Losses



offset_1 = 3.696 +/- 0.066 mbar/day

offset_2 = 4.334 +/- 0.043 mbar/day

RMS = 0.82 mbar/day

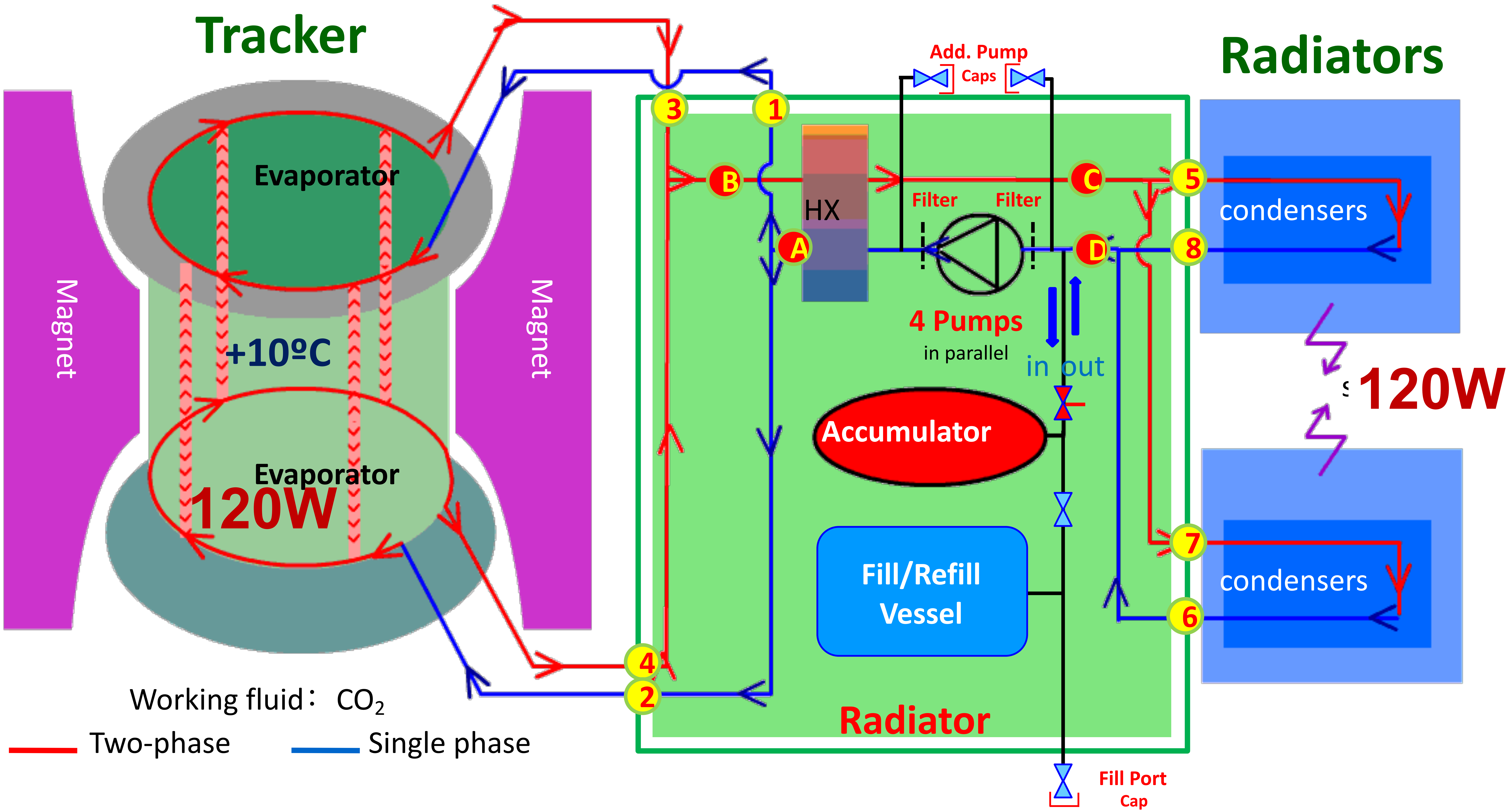


The TRD will run out of Xe gas in ~2040

$m_{Xe}^{current} = 32.49$ [kg]

$m_{CO2}^{current} = 3.505$ [kg]

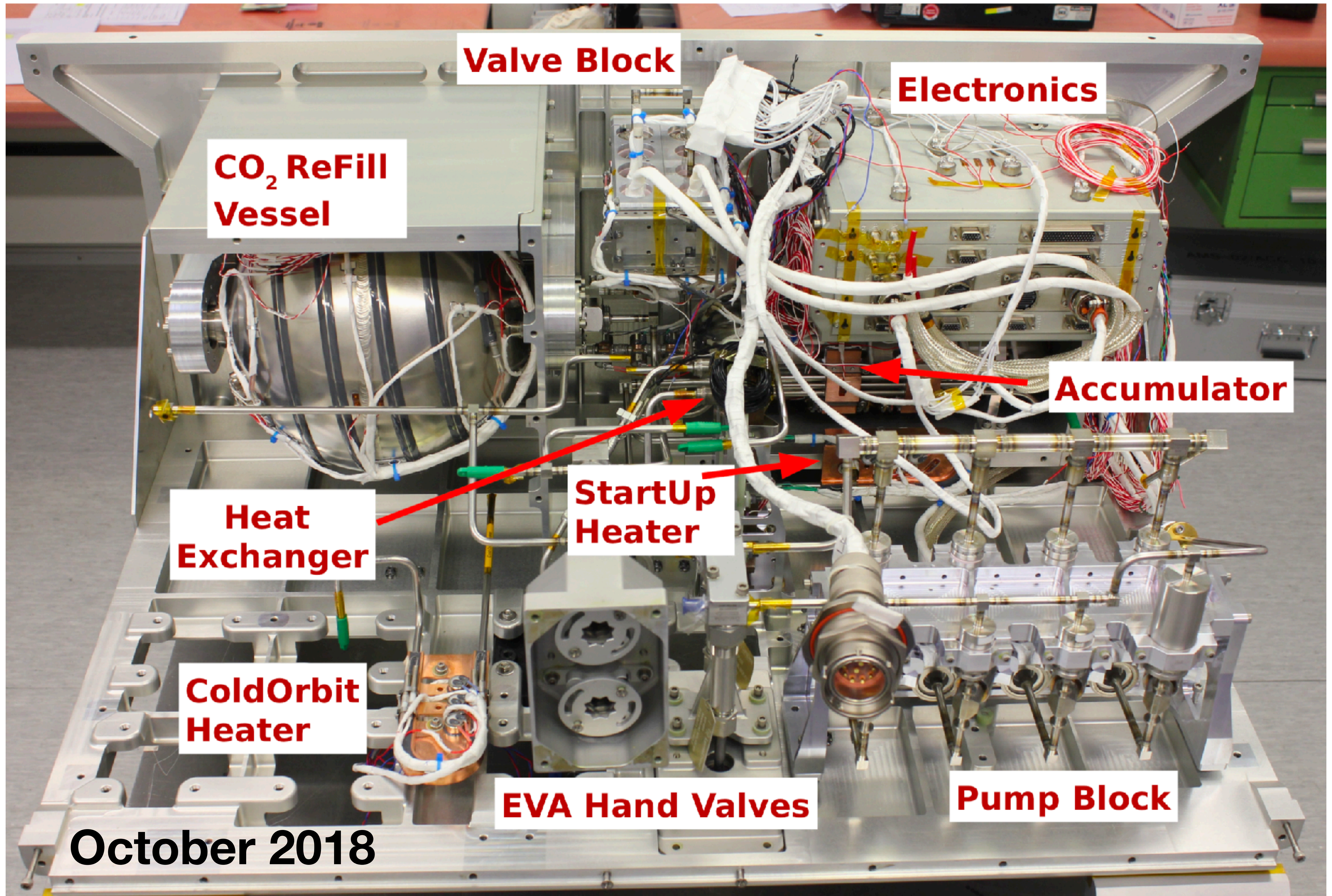
Tracker Thermal Control System with UTTPS



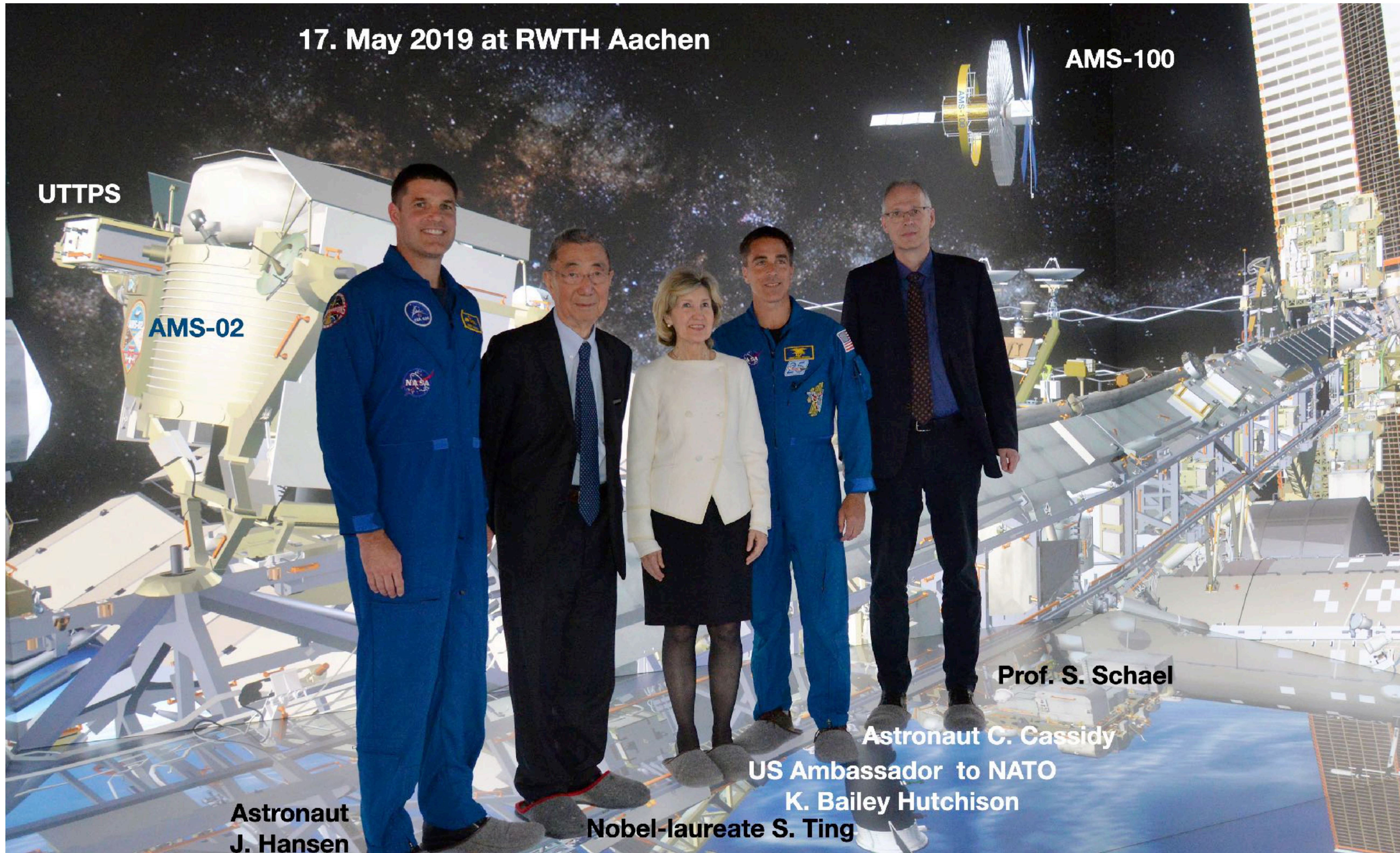
The UTTPS was constructed at RWTH Aachen with strong support from NASA and MIT

4 years - 70 Scientists and Engineers


Luca Parmitano and Andrew Morgan at RWTH Aachen University, May 2019



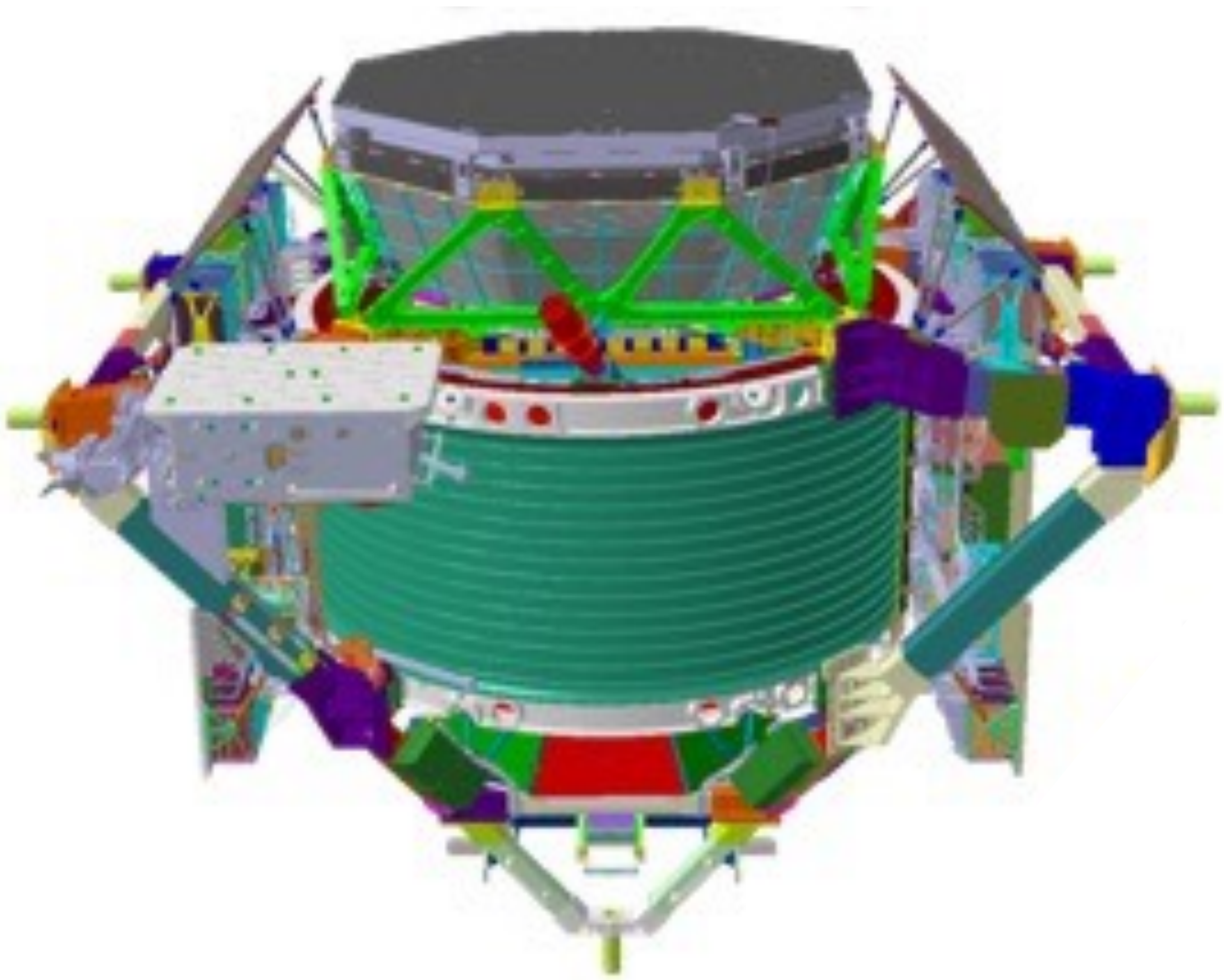
October 2018

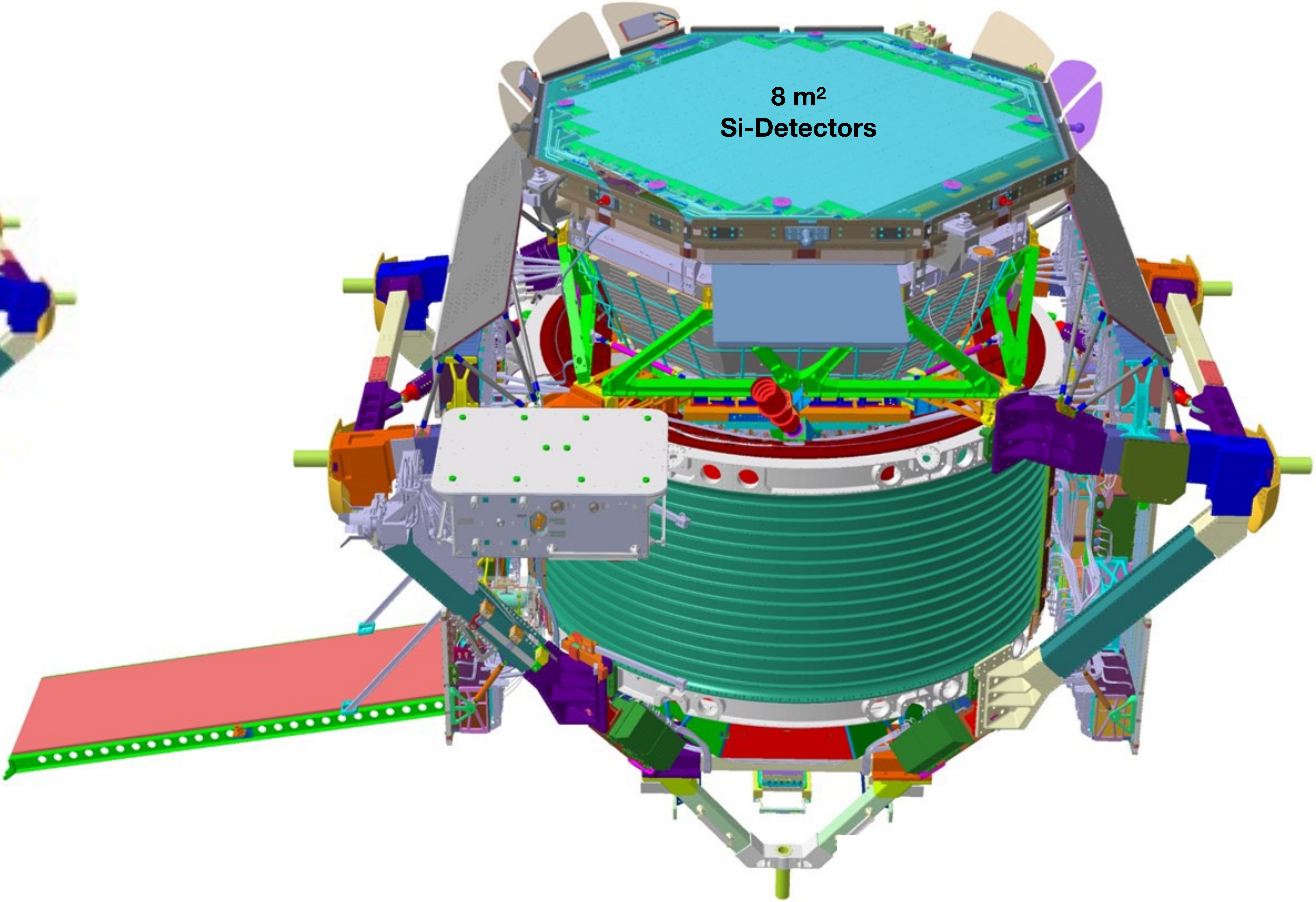

17. May 2019 at RWTH Aachen

EVA 3,
L. Parmitano
02. December 2019

AMS-02 & AMS-02.1
2011 - 2025

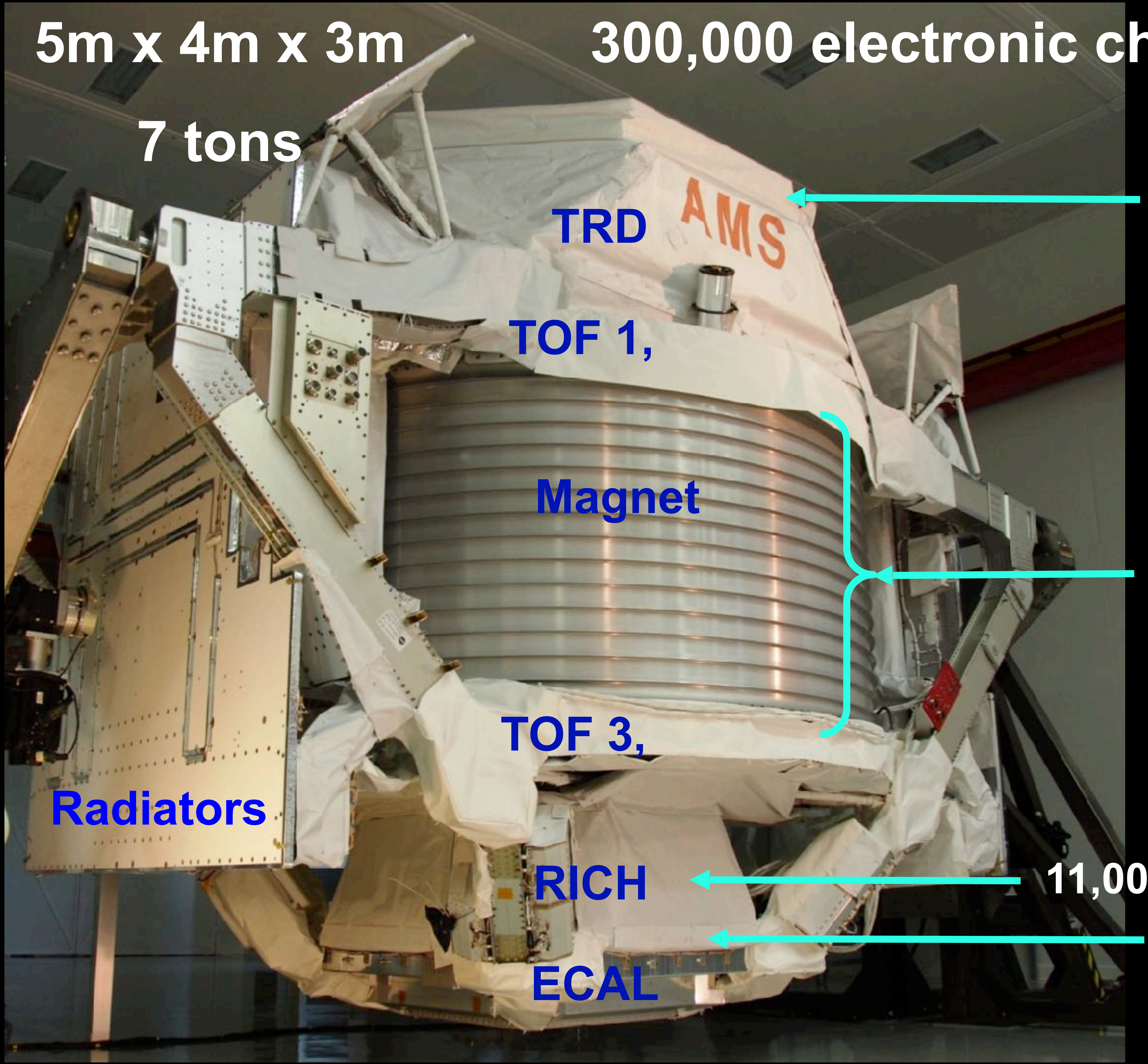
AMS-02.2
2025 - 2030





With the new tracker plane on top of AMS-02 its acceptance will be increased by 300%.

It took 600 Physicists and Engineers from 16 Countries and 60 Institutes 17 years to construct the Alpha Magnetic Spectrometer.



5m x 4m x 3m

300,000 electronic channels

7 tons

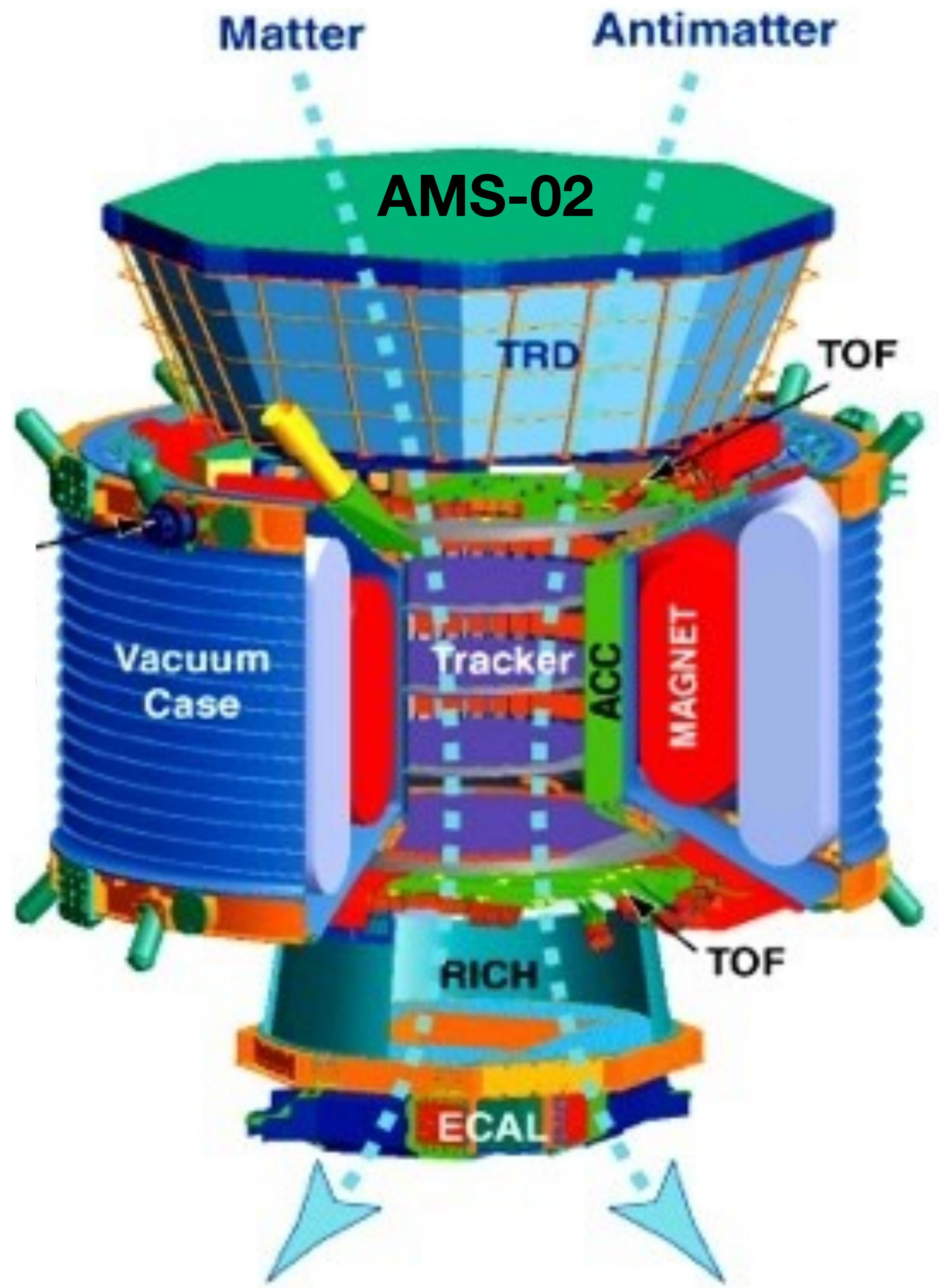
Silicon layer

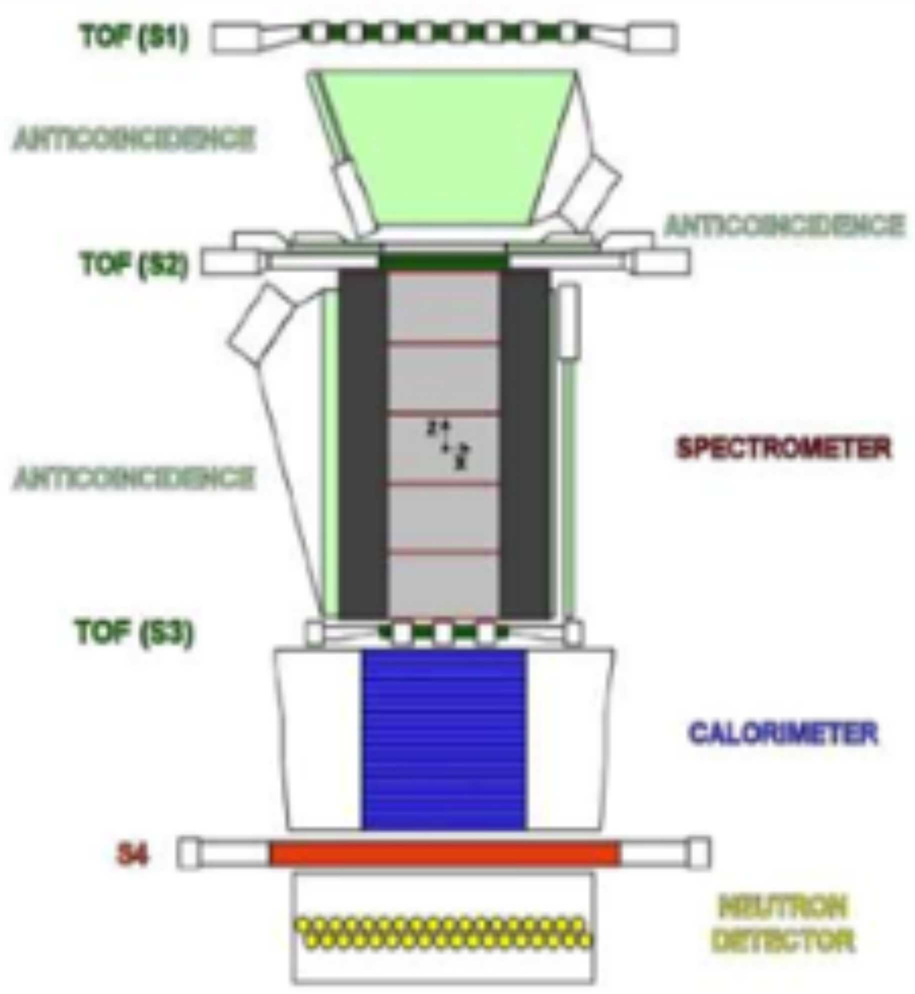
7 Silicon layers

11,000 Photo Sensors

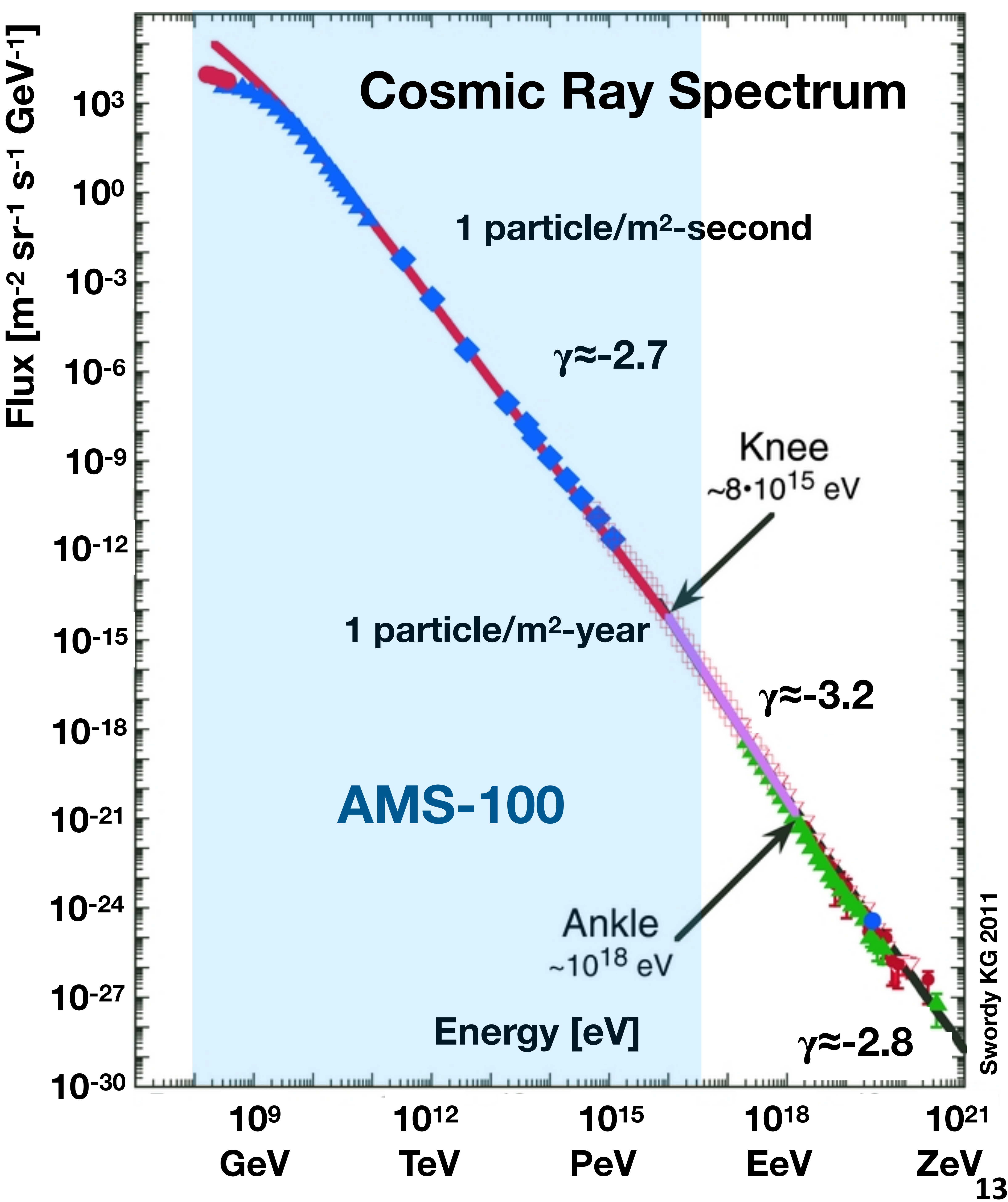
Silicon layer

We have to start now to work on the next generation magnetic spectrometer in space !

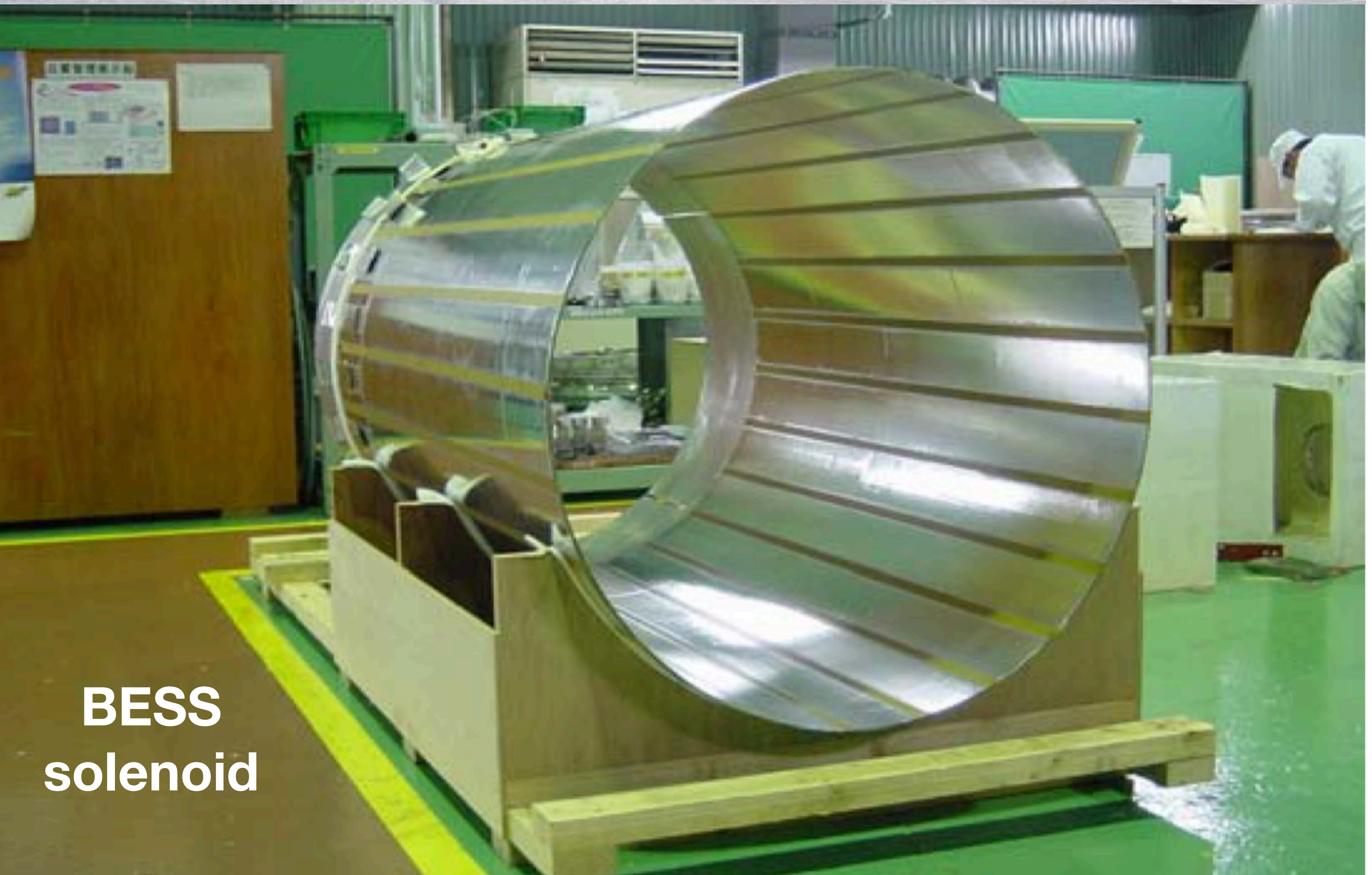




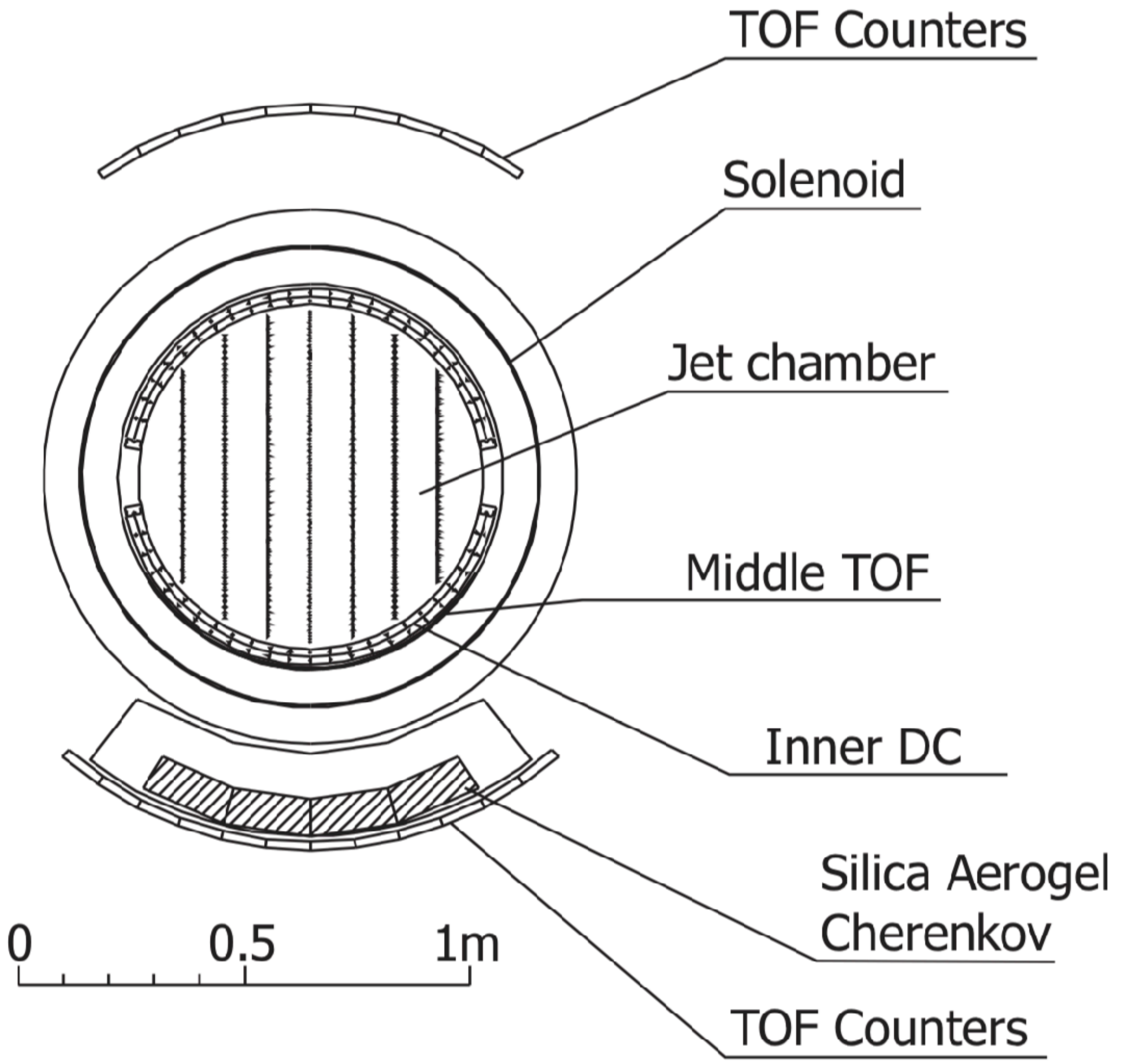
PAMELA



- The cosmic ray flux follows a power law $\Phi \approx C\,E^{-3}$
- An increase in energy by a factor 10 requires an increase in acceptance by 1000. AMS-02 weights 7 tons.
- Both PAMELA and AMS-02 have a telescope like geometry.
- Just scaling such a geometry does not allow to increase the energy reach by a factor 10 and simultaneously the acceptance by a factor 1000.

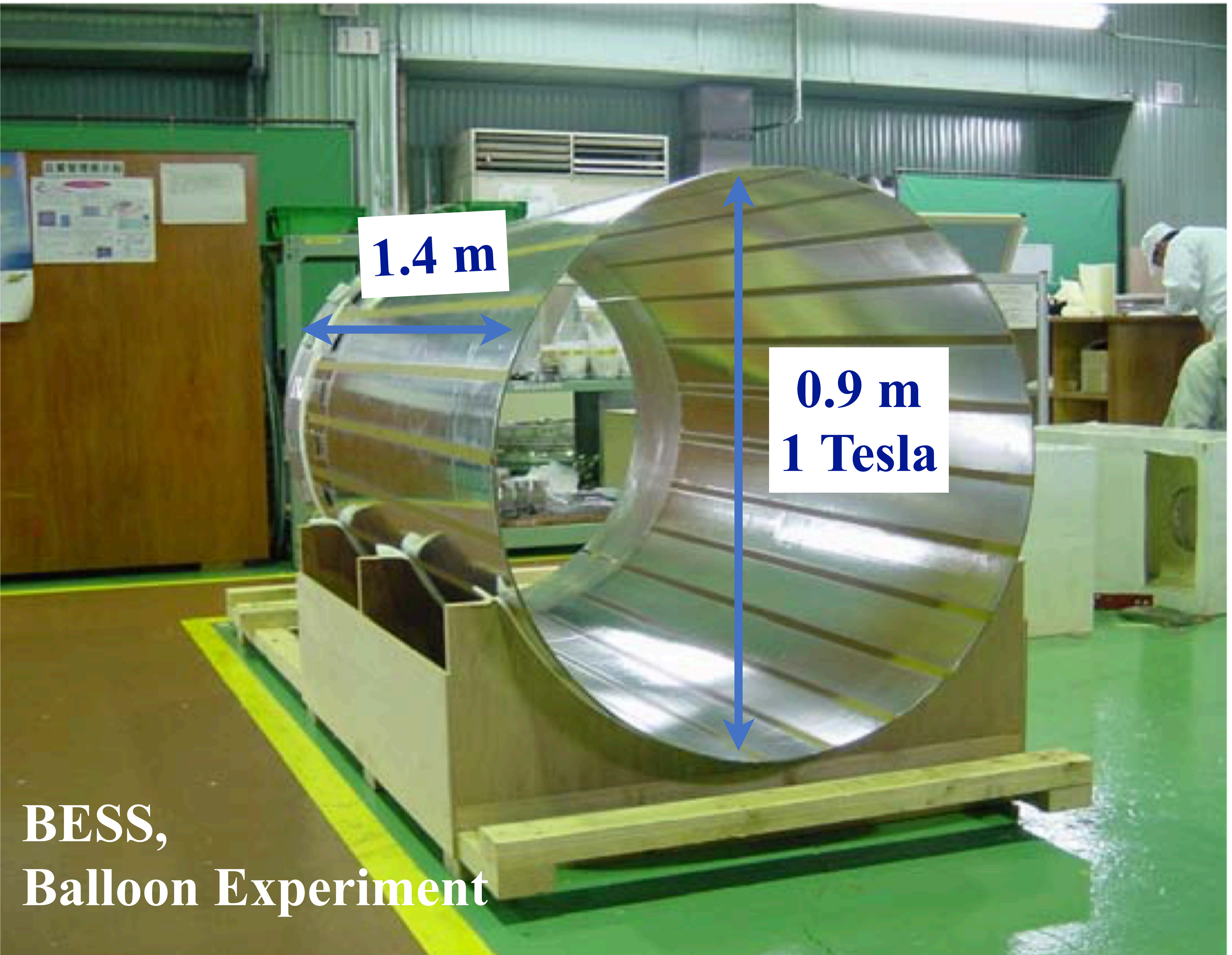


- **The design of AMS-100 was inspired by the BESS Ballon Experiment.**
- **A thin solenoid instrumented on the inside with a tracker like a classical collider experiment has an angular acceptance for cosmic rays of 4π, if operated in space far away from earth, superior to any telescope like geometry.**
- **The B-Field of a long solenoid depends only on the number of turns, the current and the length, but not on the radius.**
- **Increasing the radius will therefore quadratically increase both the energy reach and the acceptance of the spectrometer at the same time.**

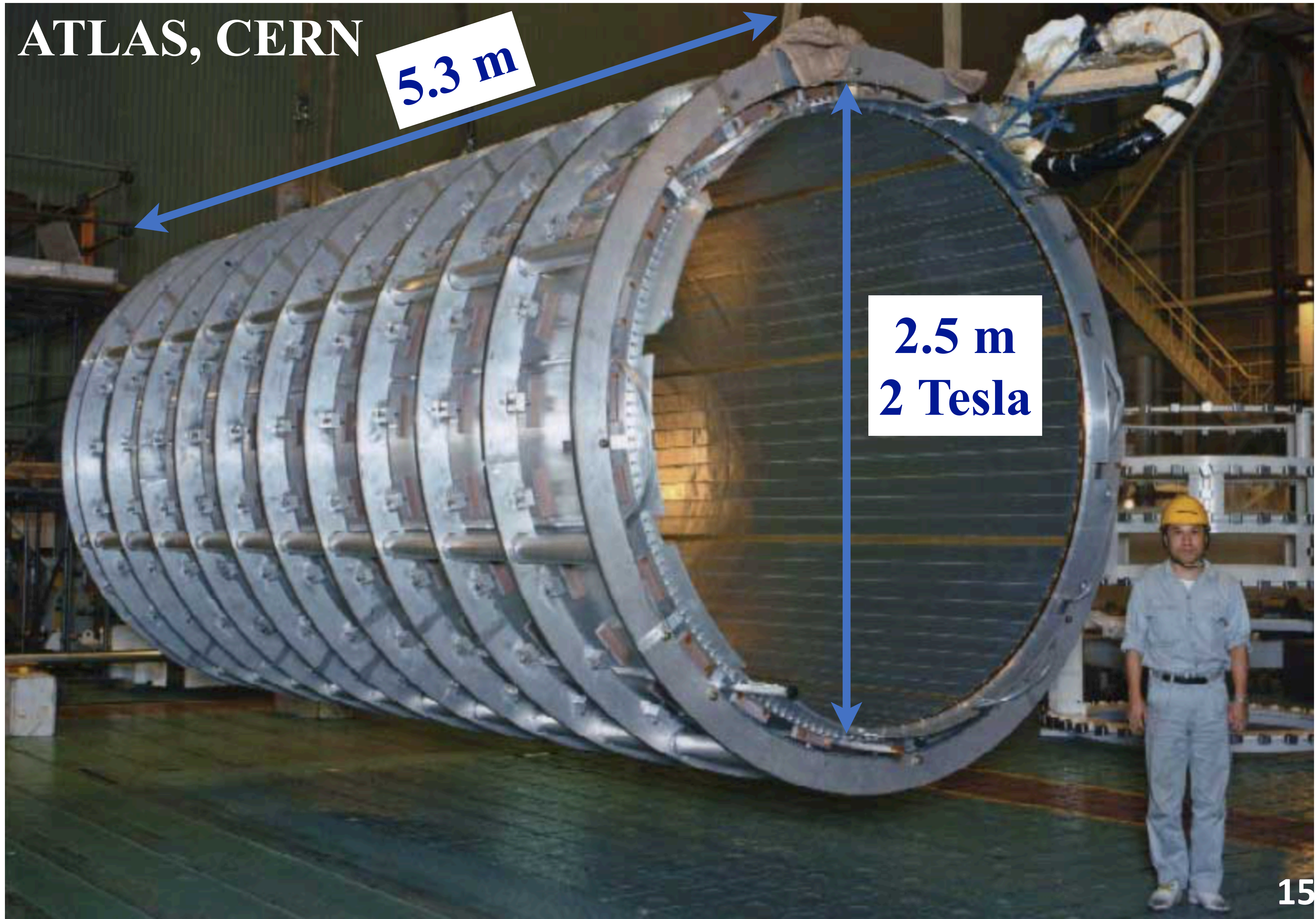


Example of Thin Solenoids
using Low Temperature Superconductors (Nb-Ti) at T = 4 Kelvin

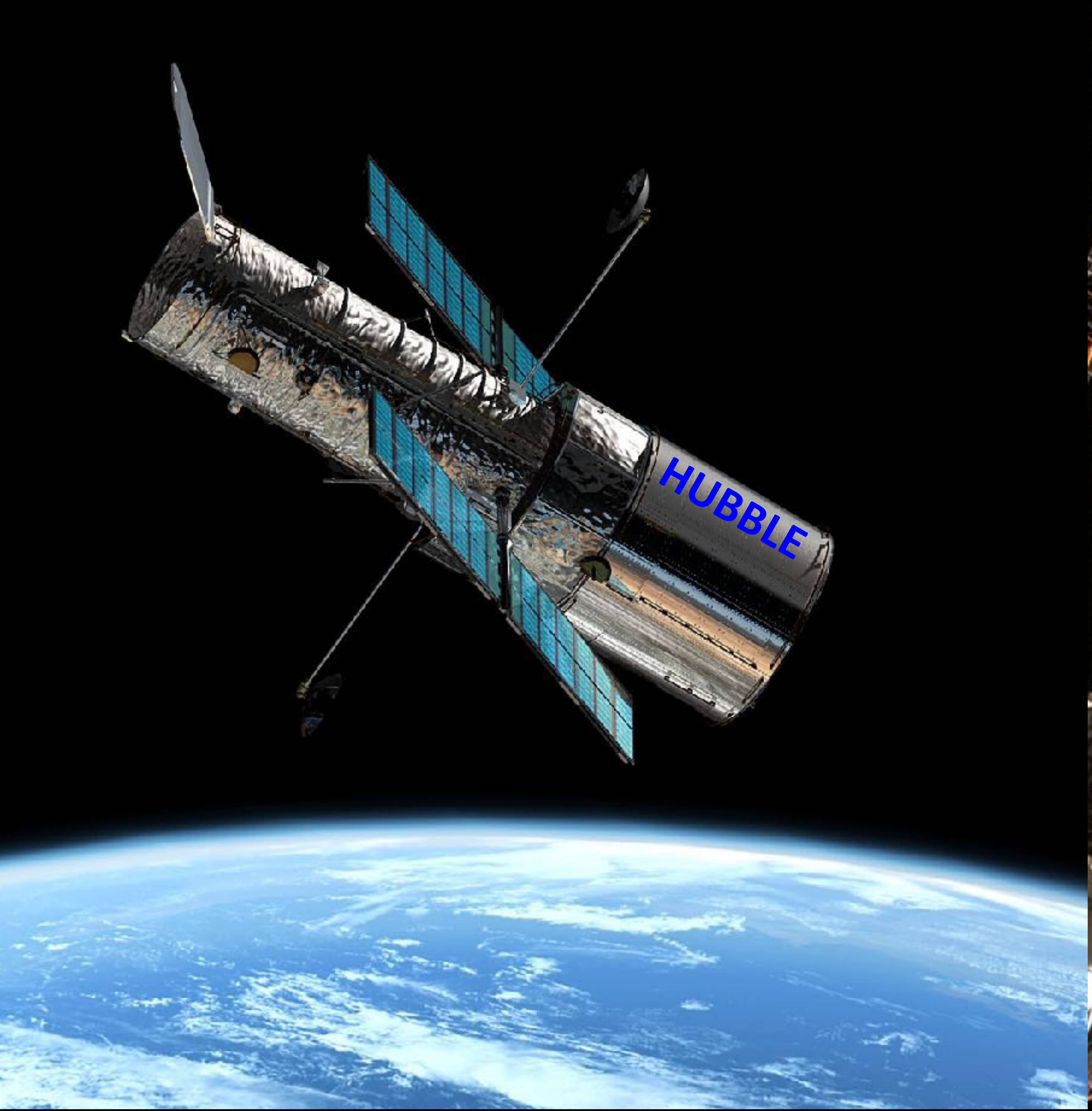
The coil weights 43 kg and has a radial thickness of 3.4 mm and was build at KEK, Japan.

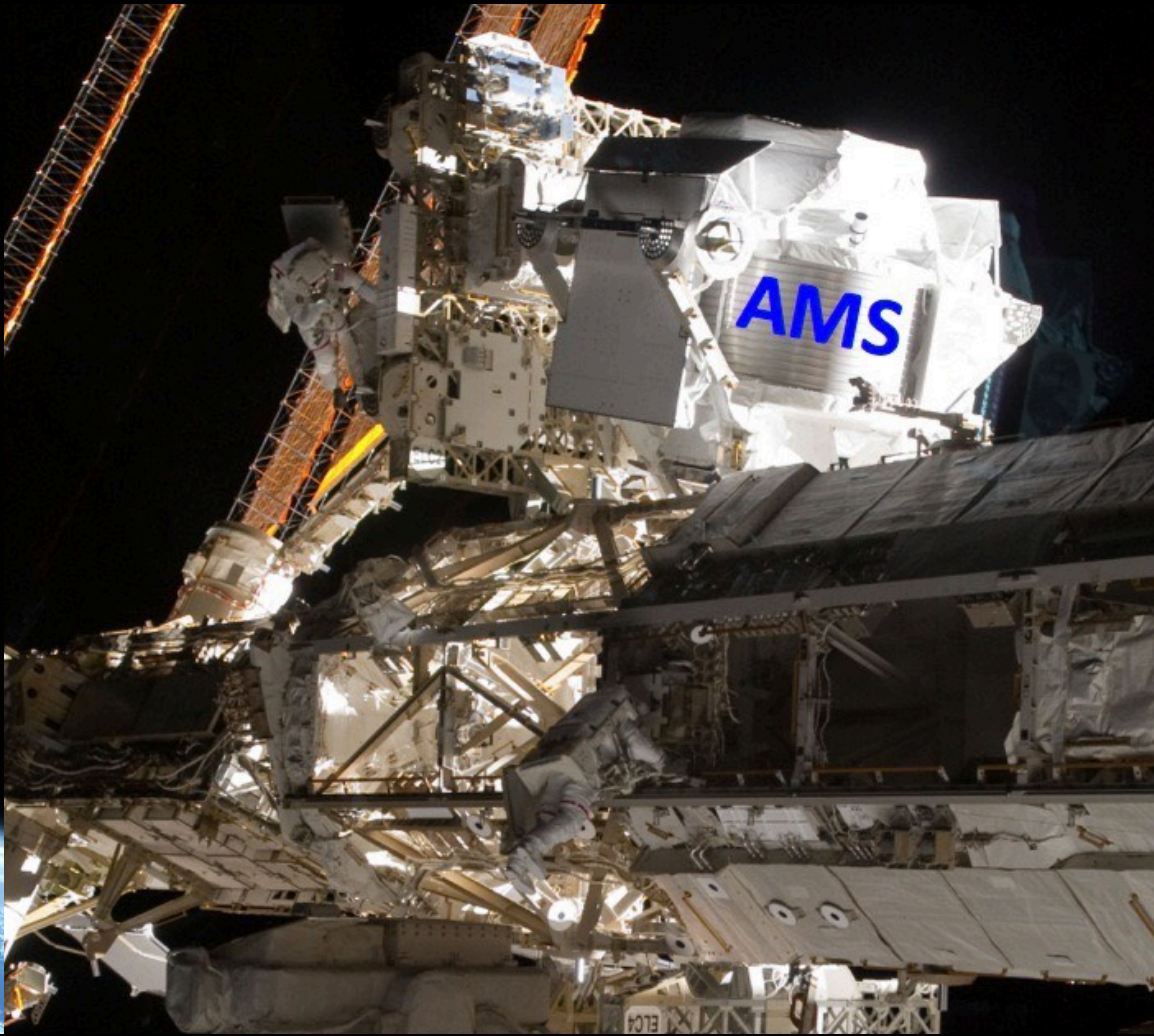


The coil weights 5.5 tons and has a radial thickness of 4.5 cm and was build at Toshiba, Japan.



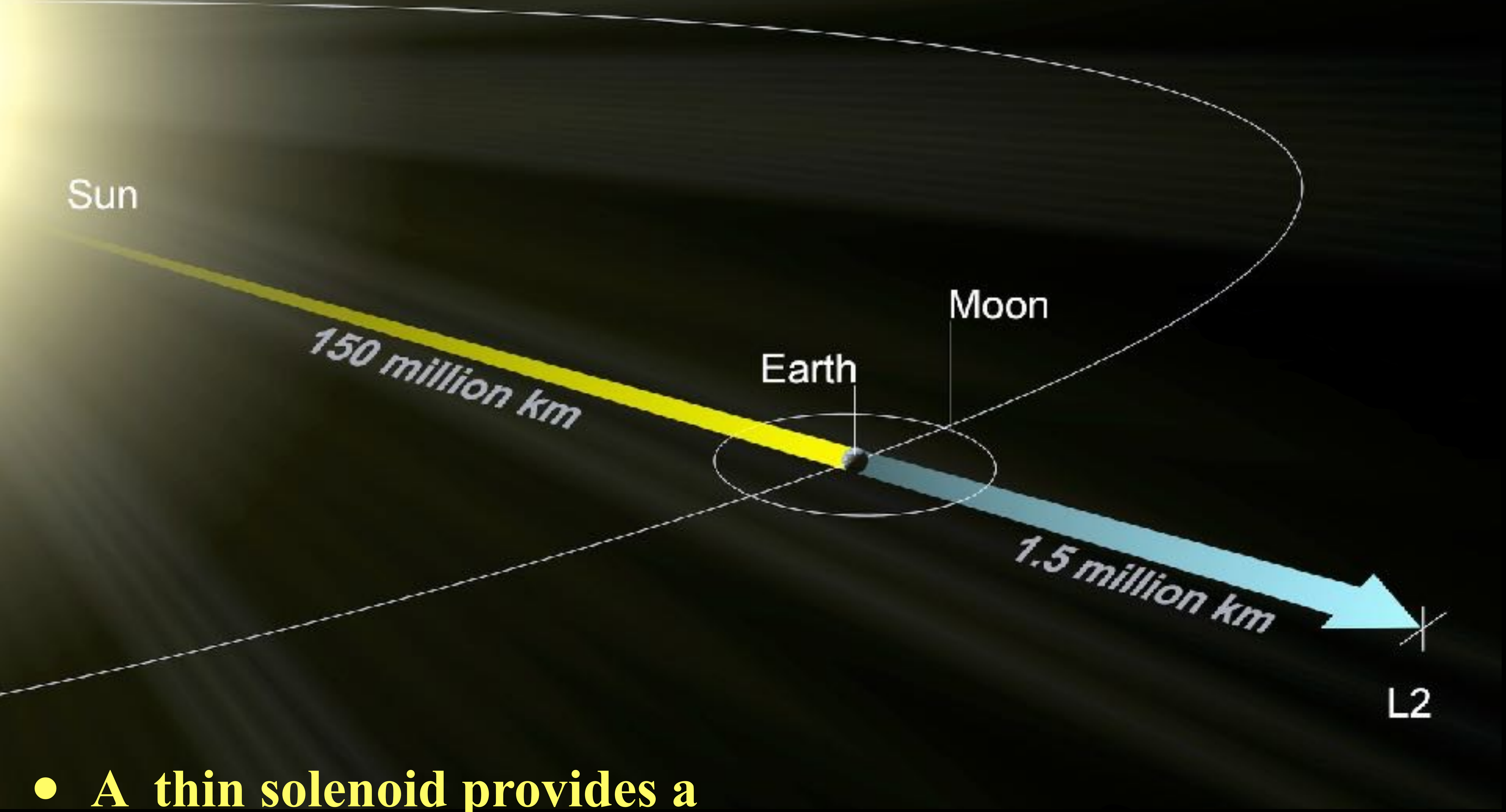
James Webb, the next generation space telescope will be operated at Lagrange Point 2,



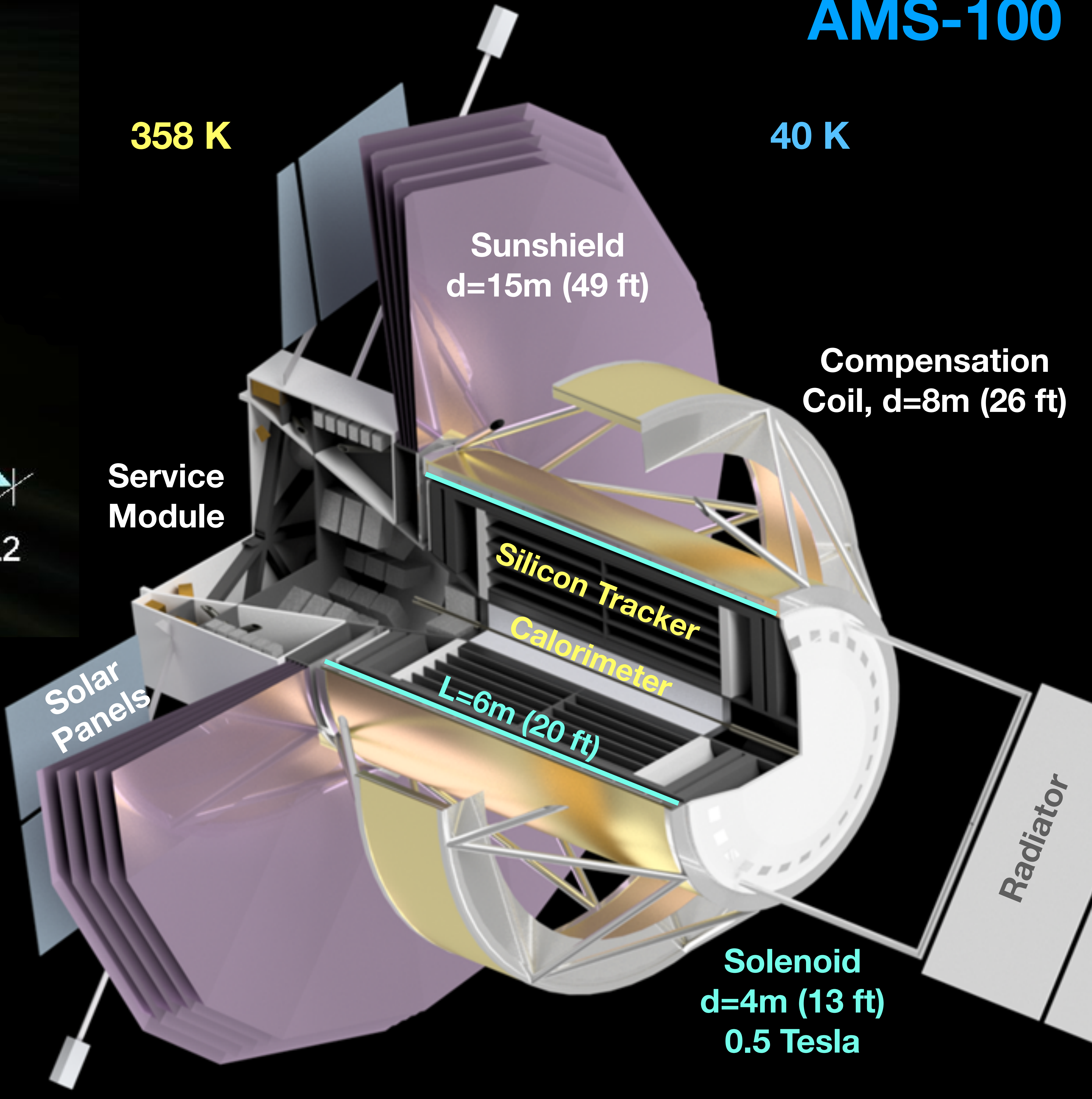


and this is also the only option to significantly extend the AMS-02 physics program.

AMS-100



- A thin solenoid provides a magnetic field of 0.5 Tesla.
- The solenoid is operated at 60 K behind the sunshield in thermal equilibrium with the environment.
- A compensation coil balances the magnetic dipole moment of the solenoid.
- The solenoid is instrumented on the inside with a silicon tracker and a calorimeter system.

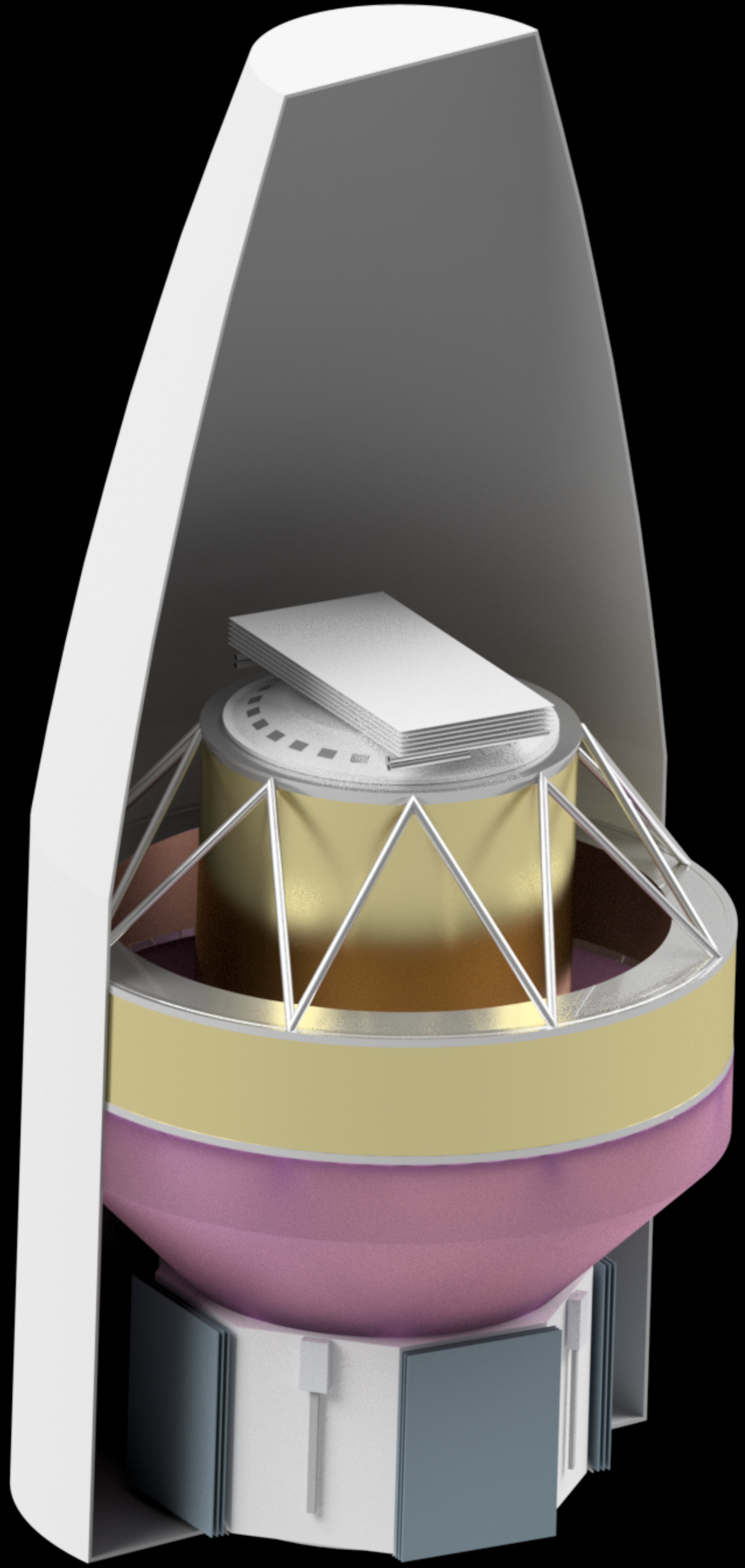


Weight
40 t

The Expedition to Lagrange Point 2

Vehicle and Launch:

- Target launch year: ~2035.
- Operational for 10+ years.
- Total estimated mass of AMS-100: 40 Tons
  - ~4 Tons for the magnet system,
  - ~16 Tons of detector equipment,
  - ~20 Tons of auxiliary equipment and cabling.
- Launched with SpaceX's Starship rocket.



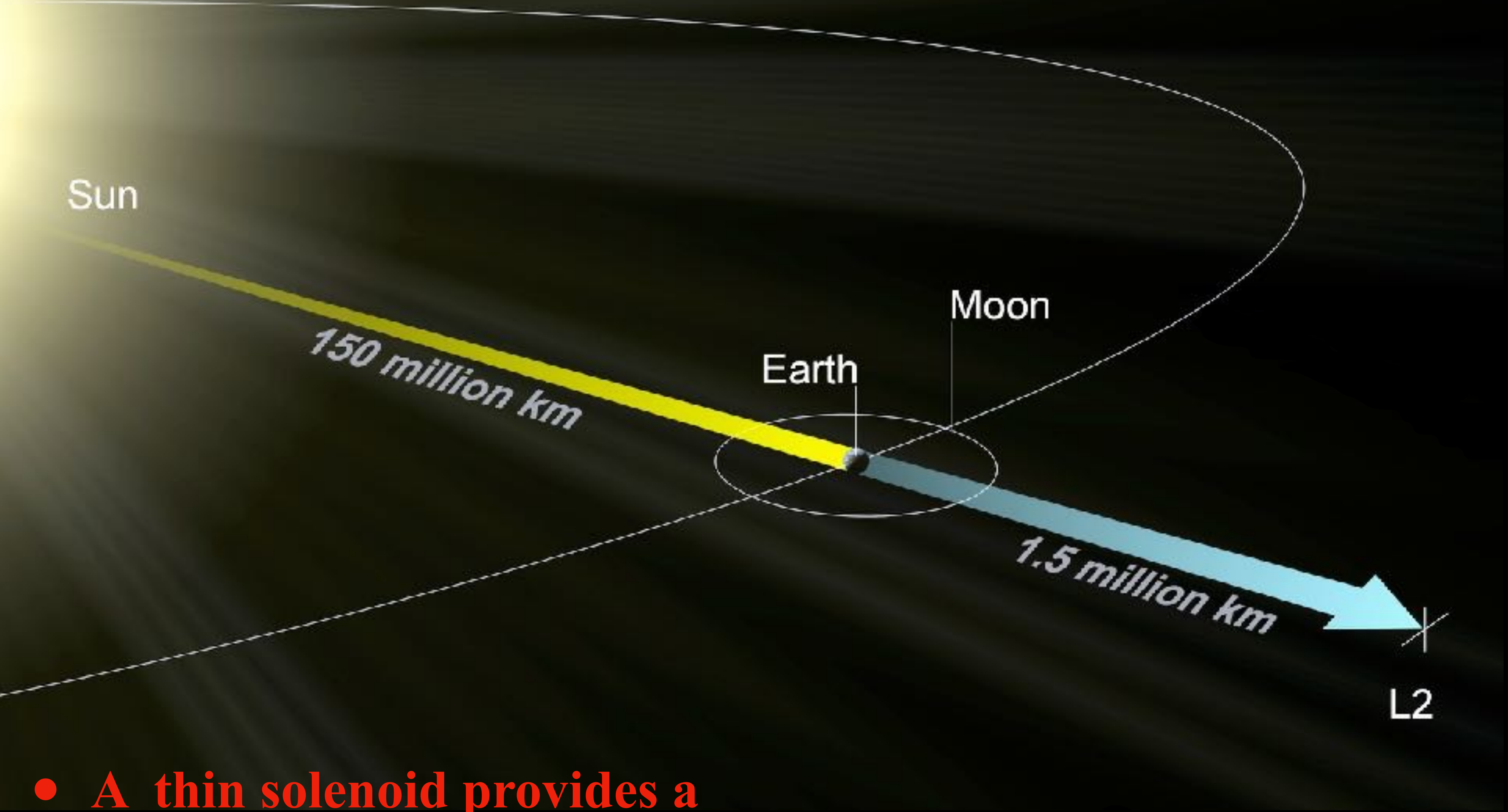
Starship's 8 m (26 ft) diameter
payload dynamic
envelope

SpaceX

- In 2019, the cost per launch for Starship was estimated by SpaceX to be as low as US$2 million.
- Elon Musk has said in 2020 that, with a high flight rate, they could potentially go even lower, with a fully-burdened marginal cost on the order of US$10 per kilogram of payload launched to low Earth orbit.

NASA LUVOIR space telescope

AMS-100



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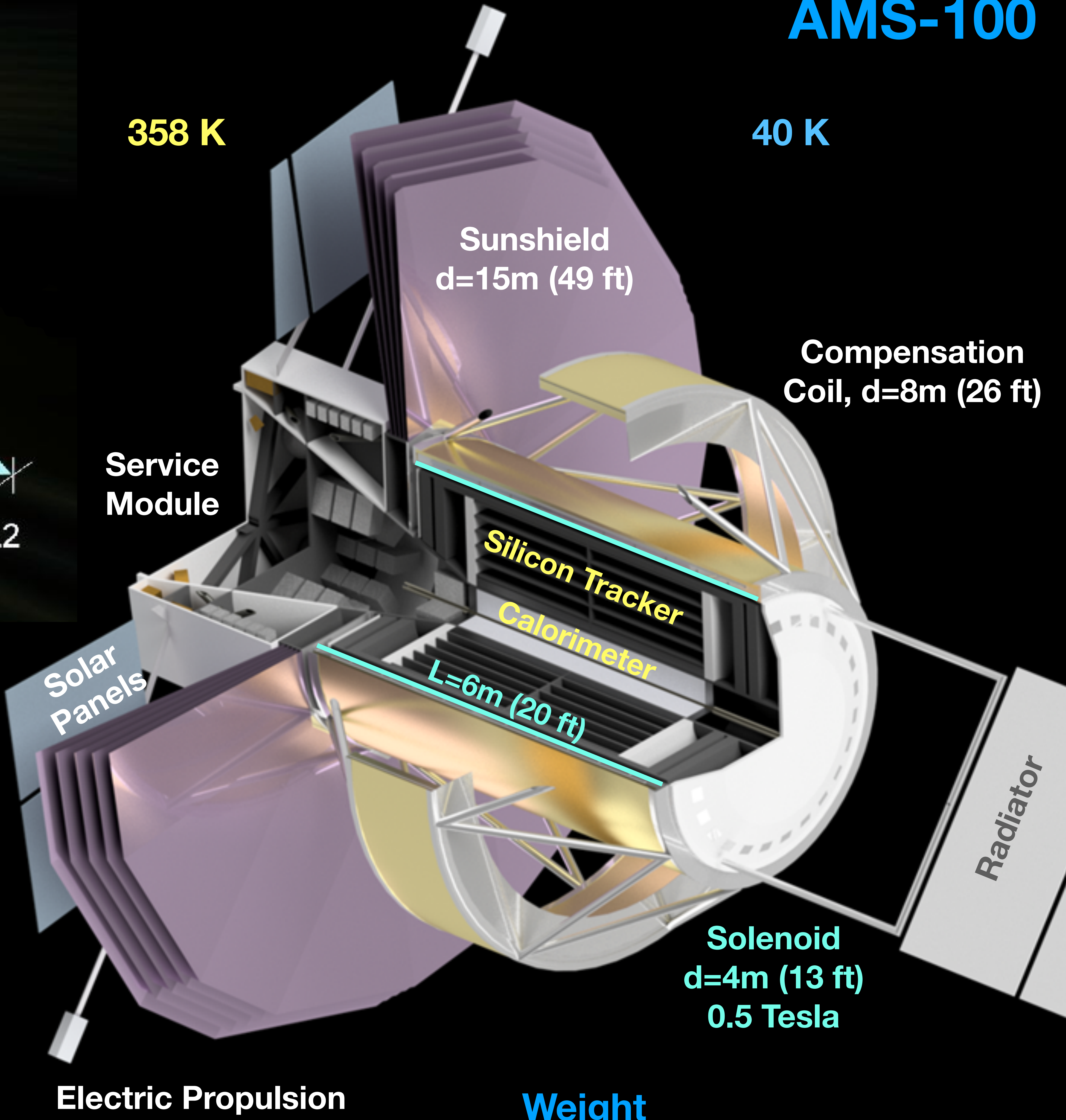
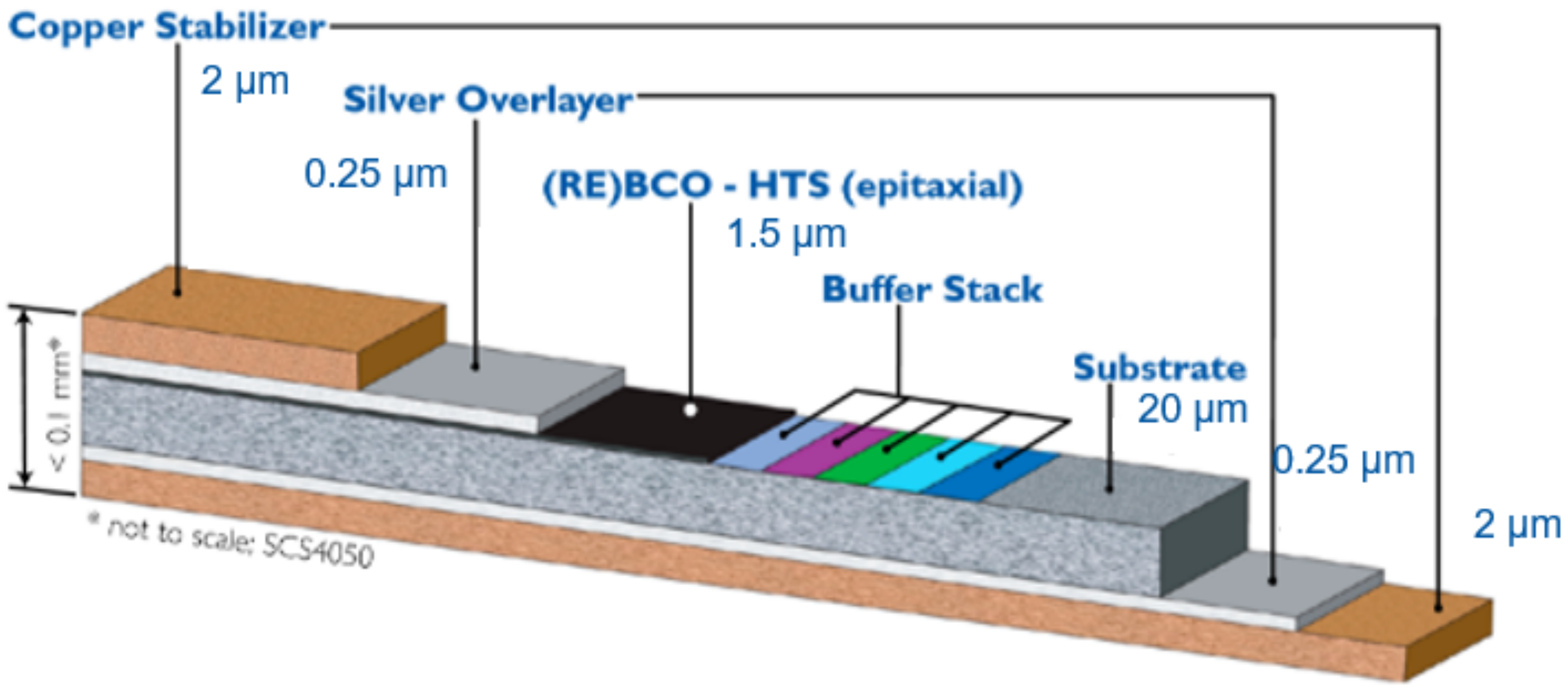


Weight
40 t

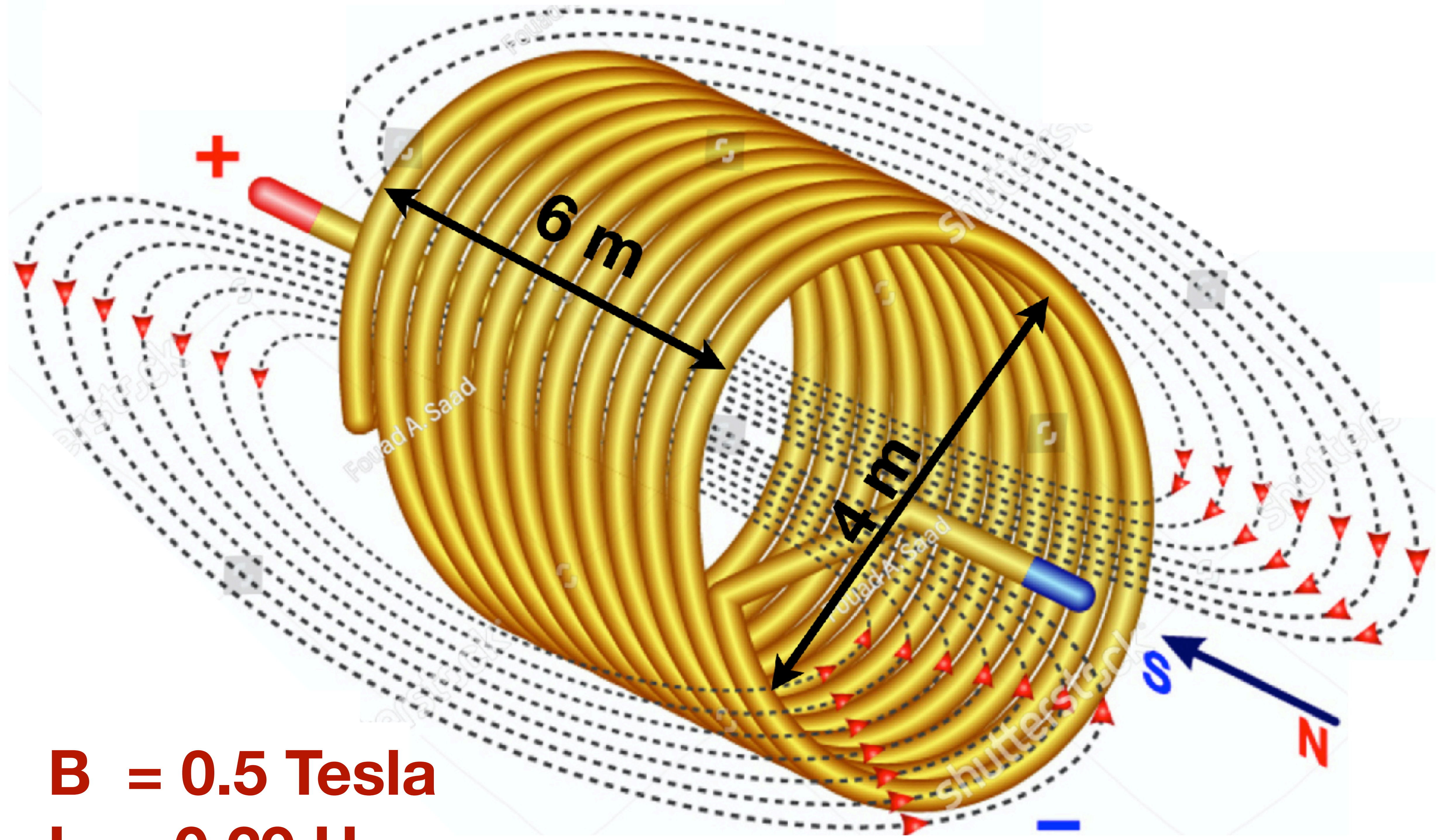
AMS-100 Solenoid - a non-insulated coil

90 km
of High Temperature Superconducting Tape

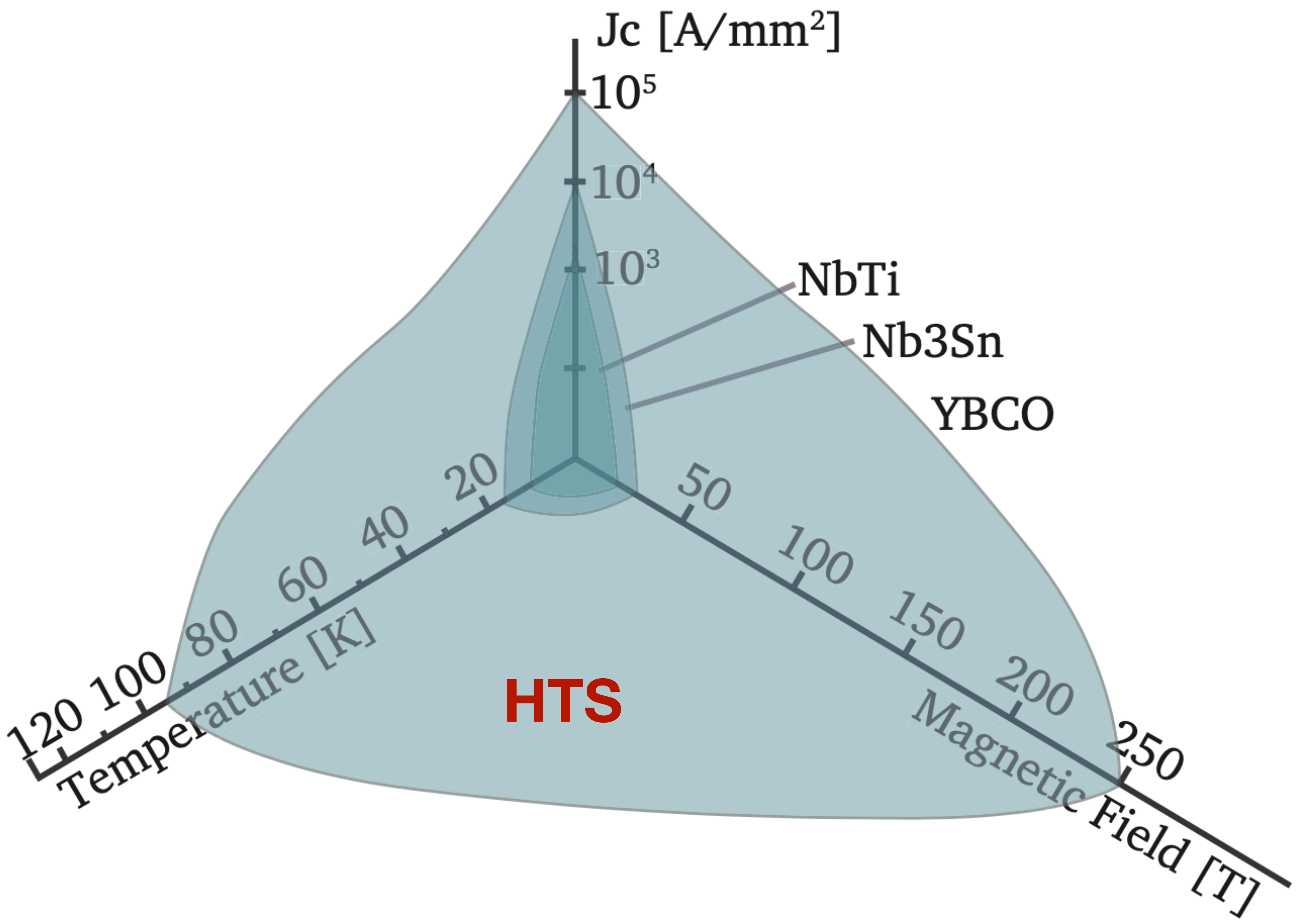
Thickness: 18 x 0.04 mm = 0.72 mm !

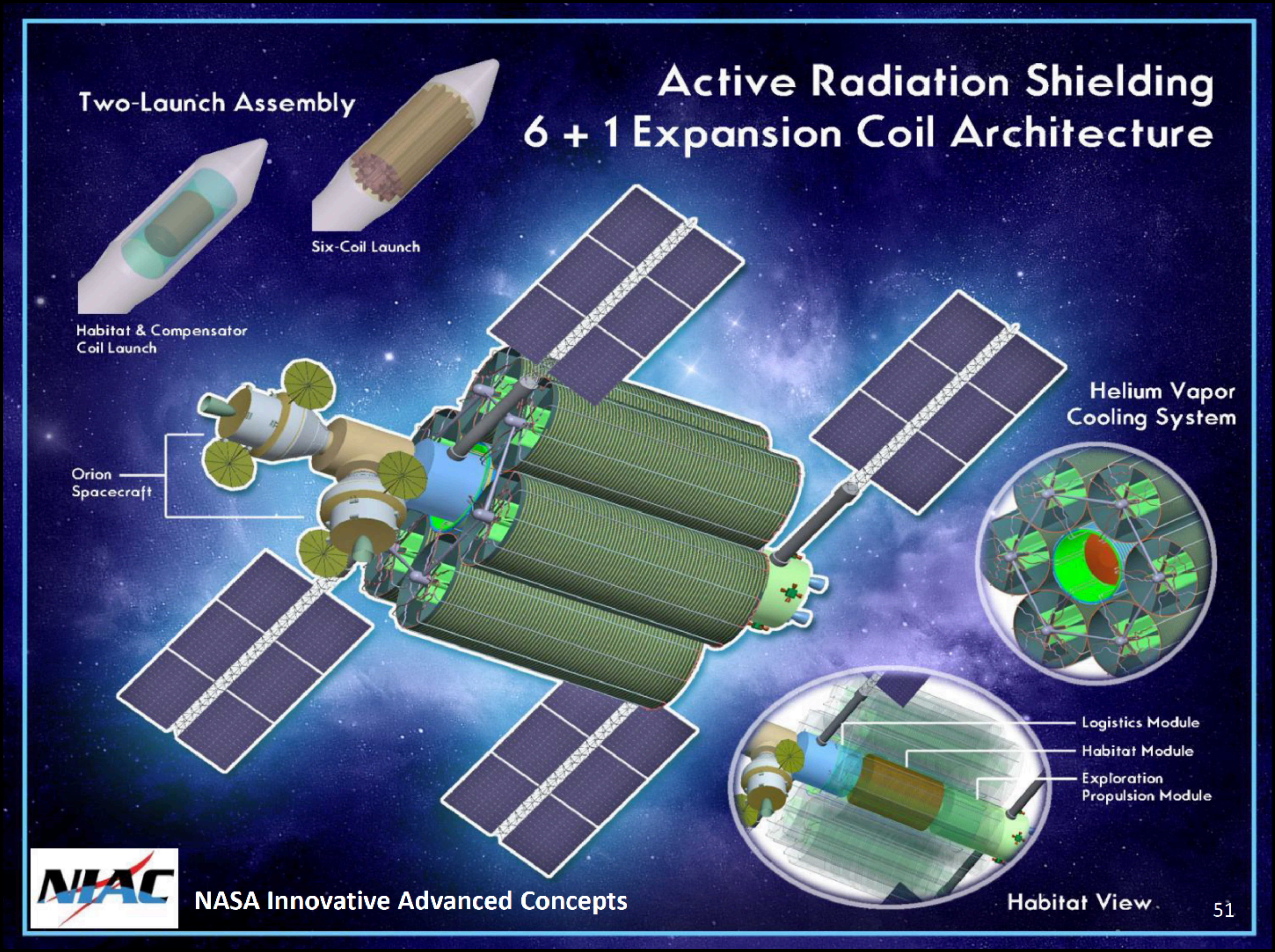


Stack of 18 Tapes
12 mm wide; Fujikura, 700 A @ 77K, SF



B = 0.5 Tesla
L = 0.29 H
E = 14 MJ

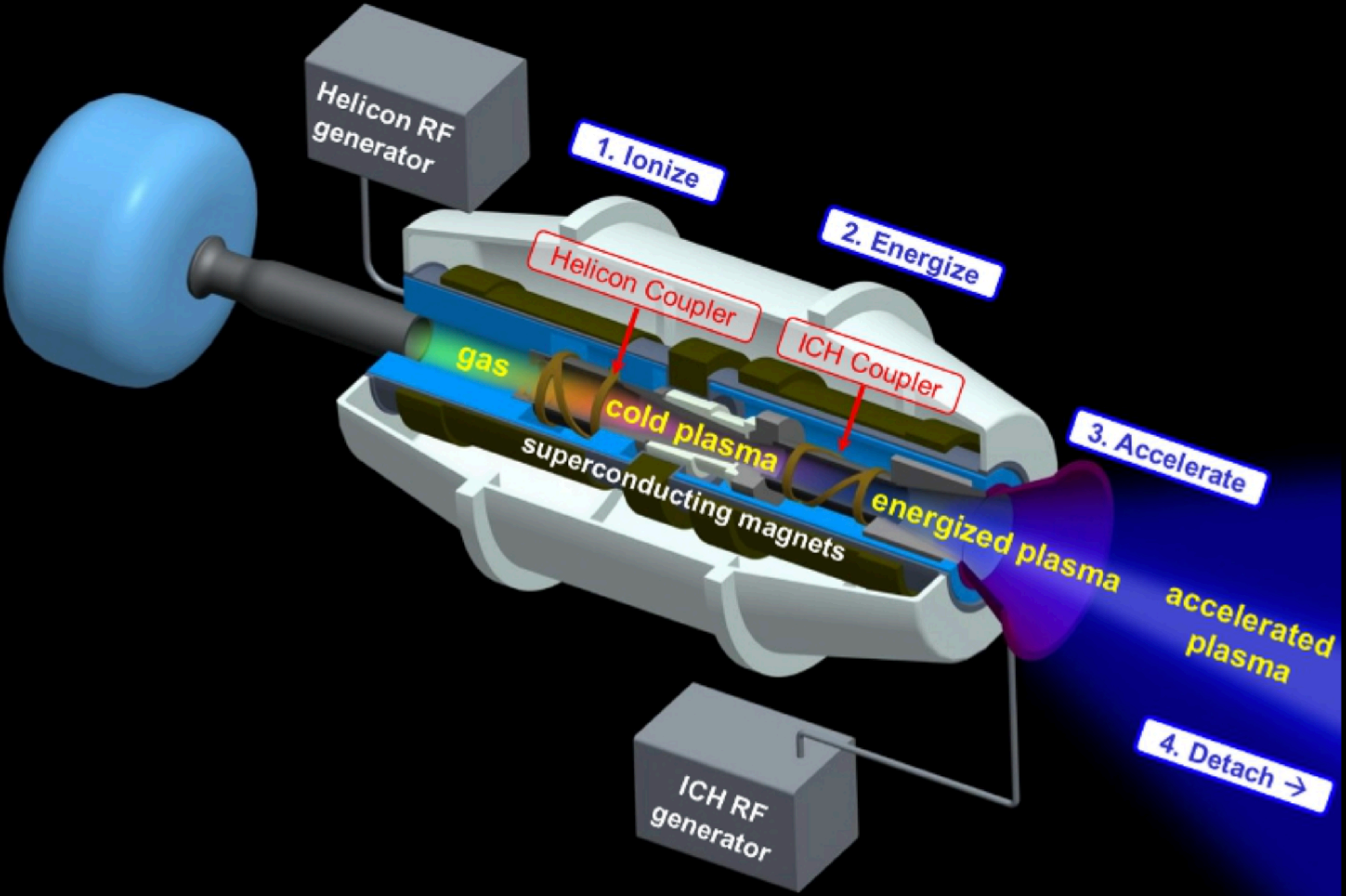


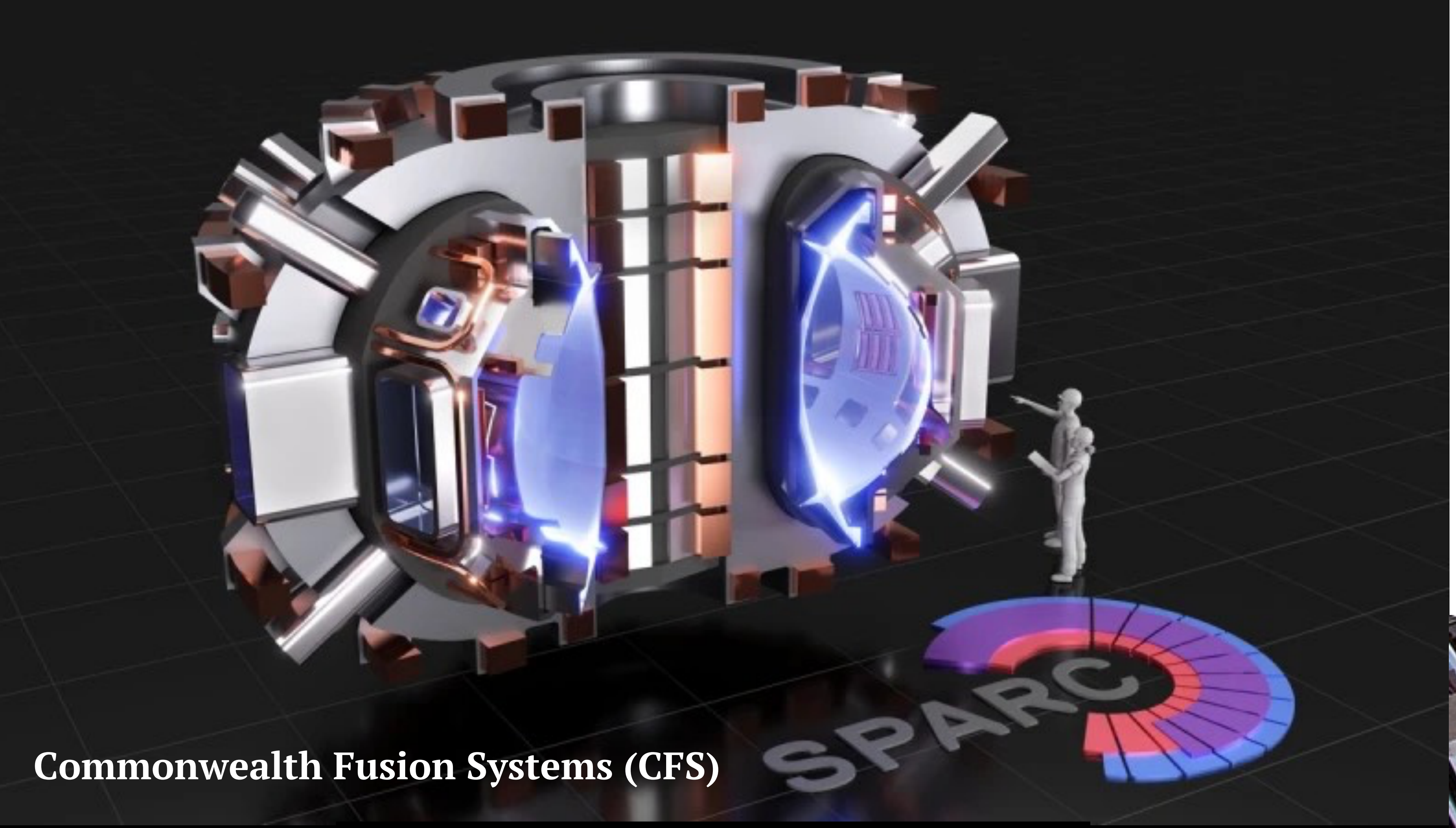


Active Radiation Shielding
6 + 1 Expansion Coil Architecture

NASA Innovative Advanced Concepts

Variable Specific Impulse Magnetoplasma Rocket (VASIMR®)

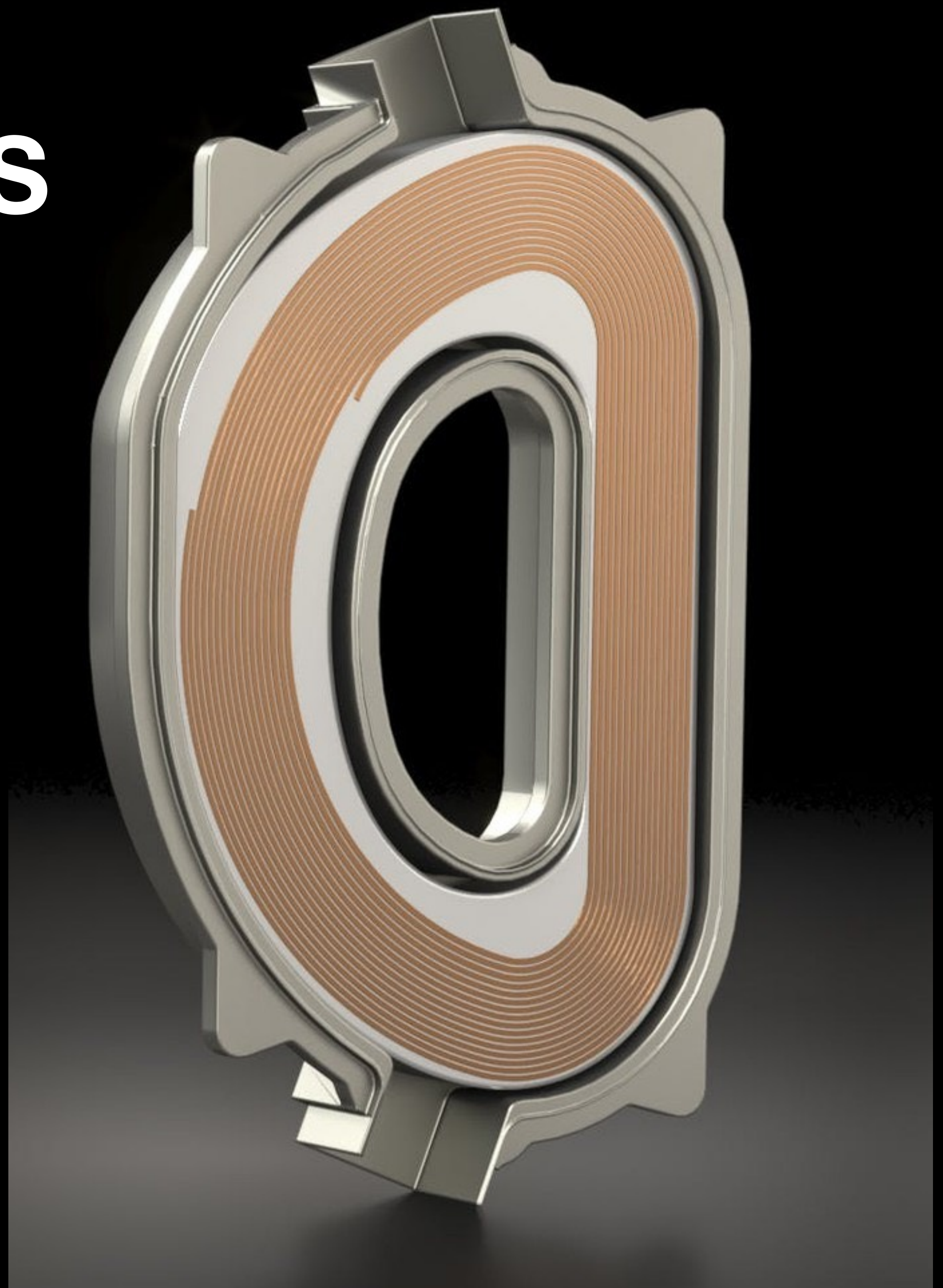




Commonwealth Fusion Systems (CFS)

	SPARC	AMS-100
B-Field	20 Tesla	0.5 Tesla
Temperature	20 K	55 K
I_{op}	40 kA	10 kA
Stored Energy	110 MJ	14 MJ
HTS Length	270 km	85 km

16 HTS coils



Science, Sep. 2021

https://cfs.energy

AMS-100: A Magnetic Spectrometer

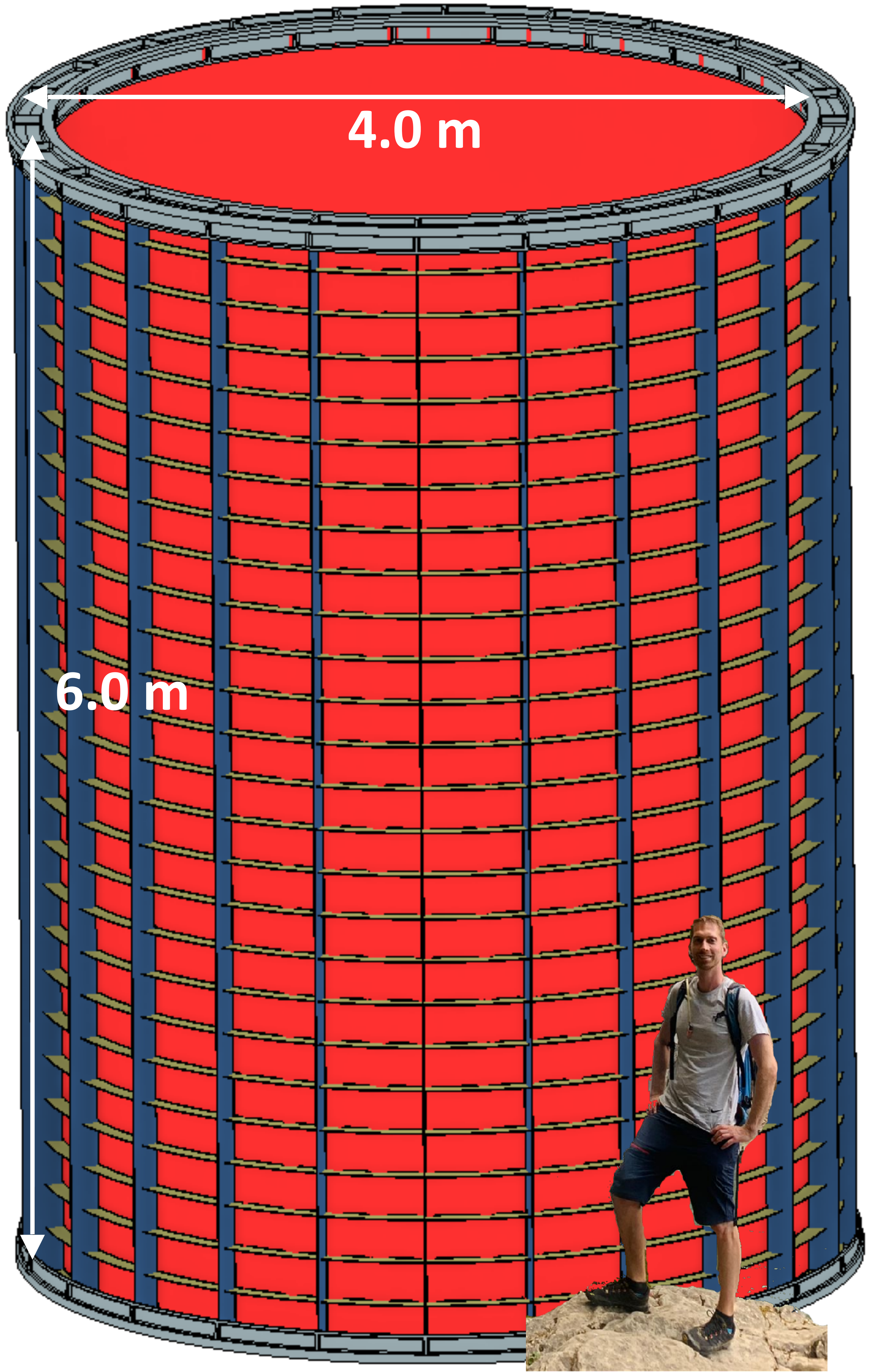


Table of properties for the AMS-100 main solenoid and compensation coil.

	Main	Compensation	Combined	Unit
Coil radius	2.0	4.0		m
Coil length	6.0	1.5		m
Tape width	12	12		mm
Stabilizer	Al-6063	Al-6063		
Cable thickness	2.85	2.85		mm
Cable width	16	16		mm
Layers	1	1		-
Turns	376	94		-
Inductance	286	114	287	mH
Number of tapes	18	18		-
Total tape length	85	43	128	km
Operating current	10.0	-10.0		kA
Cable mass	1090	545	1635	kg
Stored Energy	14.3	5.7	14.4	MJ
Energy Density*	14	11	9	kJ/kg

*Considering only the mass of the cable.

Magnetic Field and Stability

Design **B-field of 0.65 T** in the center, ~1 T on the conductor at the edge of the solenoid.

B-field of 0.5 T when the compensation coil is on.

Operating temperature range of 50 to 60 K:

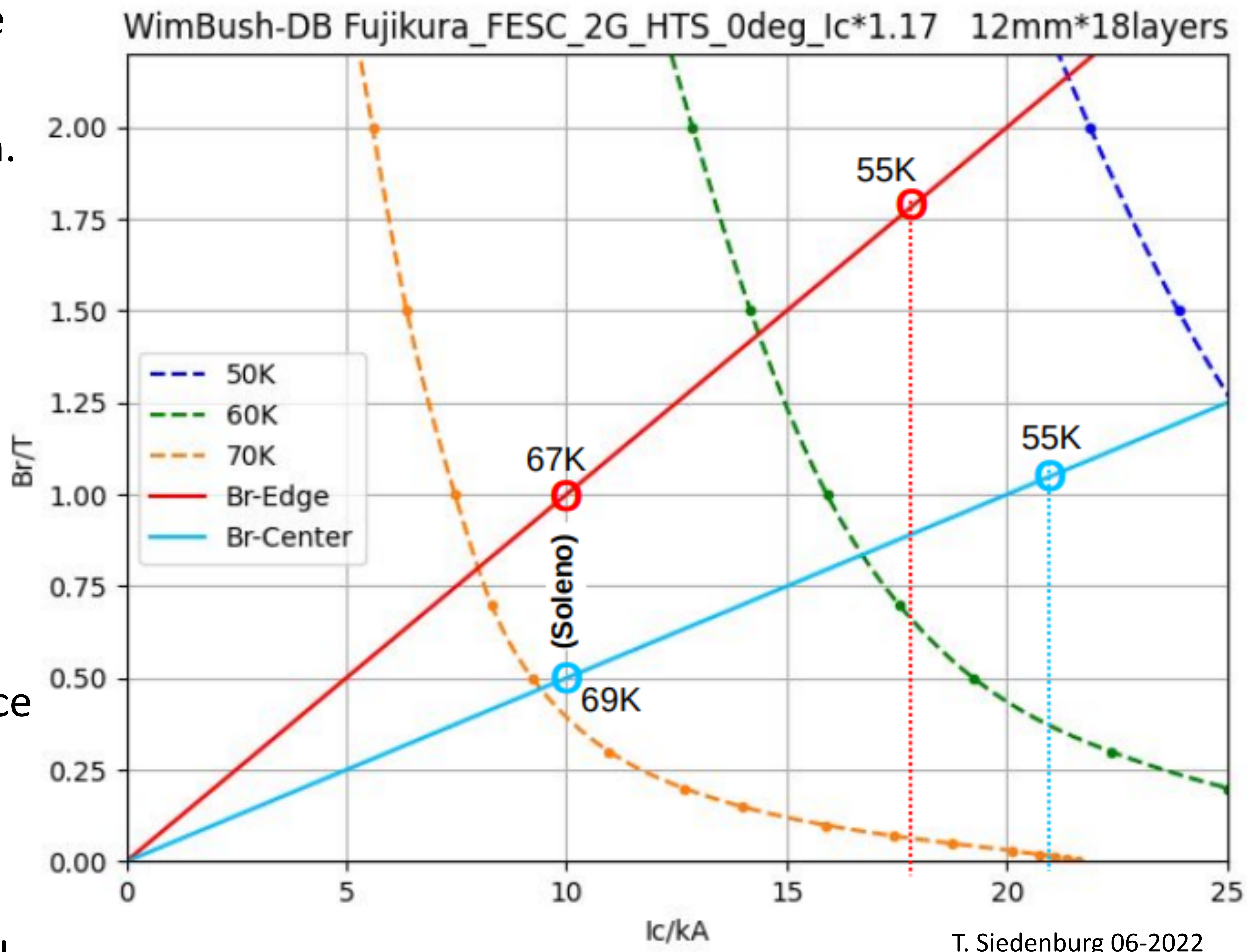
- ΔT of 12 K @ 55 K

Large temperature margin is important:

- cooling power is very limited,
- high energy density,
- no intervention possible.

Smart spacing of the conductor / additional HTS tape is envisioned at the coil extremities to reduce the peak field. And allow possible operation at higher current/magnetic field.

The field homogeneity is not an operation critical parameter.



T. Siedenburg 06-2022

AMS-100

100 cm

Radiator & Debris shield: 0.5 mm Al 6110, 50 mm Al-Honeycomb, 0.5 mm Al 6110

outer-stringers, AL 6063
5 mm x 130 mm

h=8.6 cm

MLI

X_0=1.8%

SciFi-Tracker: 0.5 mm CFRP - 10 mm Nomex

GFRP

Magnet

inner-stringers,
AL 6063
10 mm x 25 mm

h=7.5 cm

MLI

Magnet Interfaces

10 cm

MLI

Main Support Cylinder
1.0 mm CFRP - 30 mm Al-Honeycomb - 1.0 mm CFRP

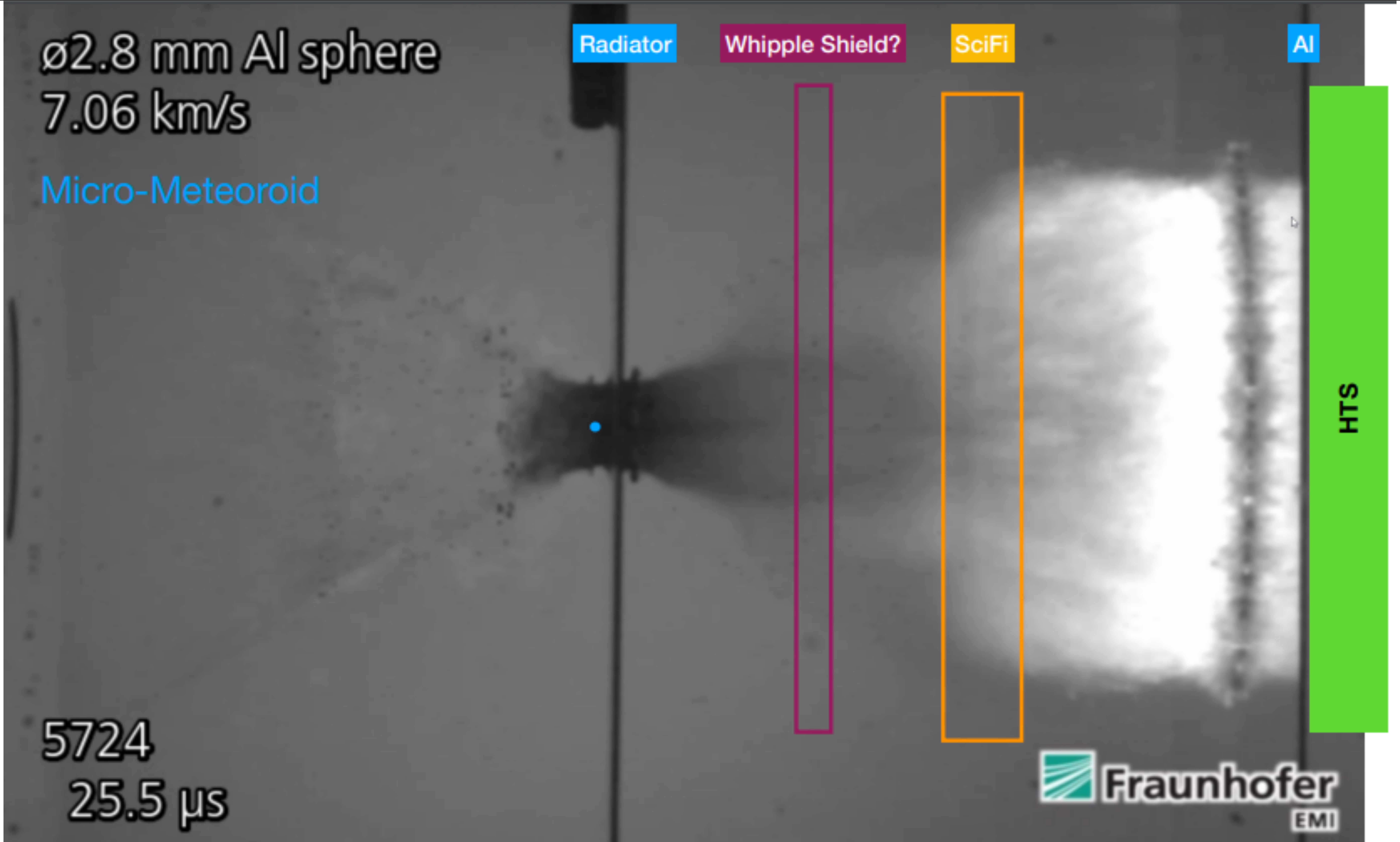
X_0=14.7%, NIL=2.8%
(without MLI)

Y

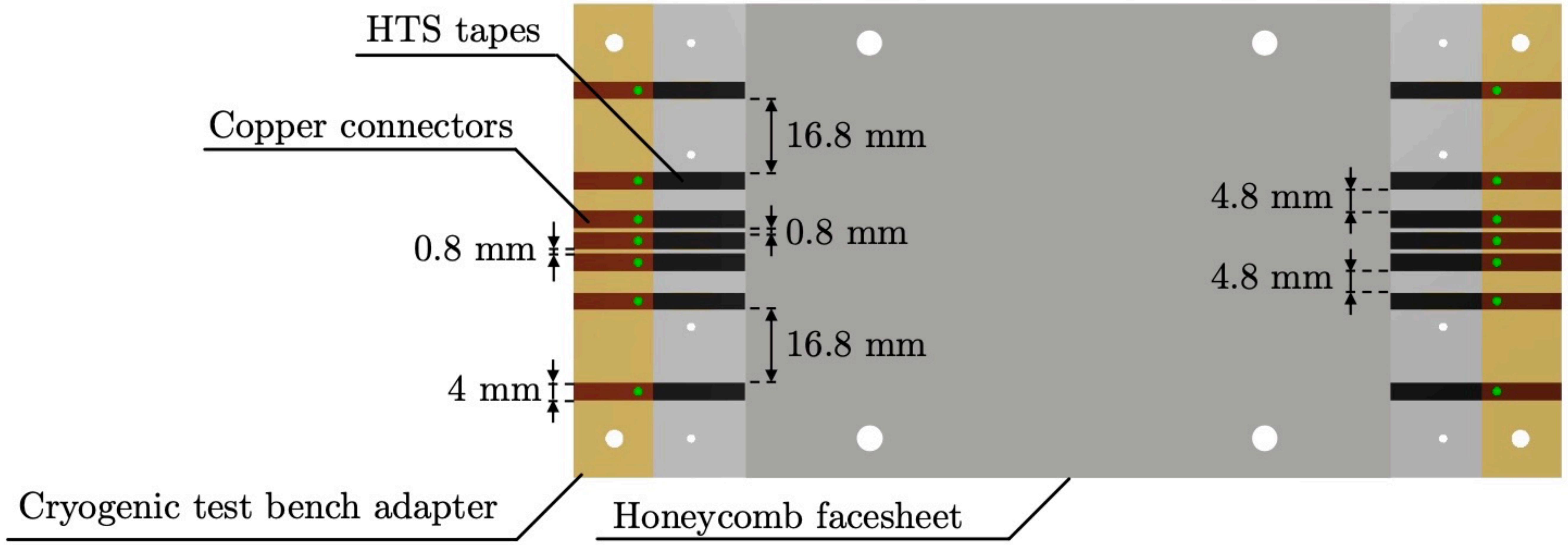
X

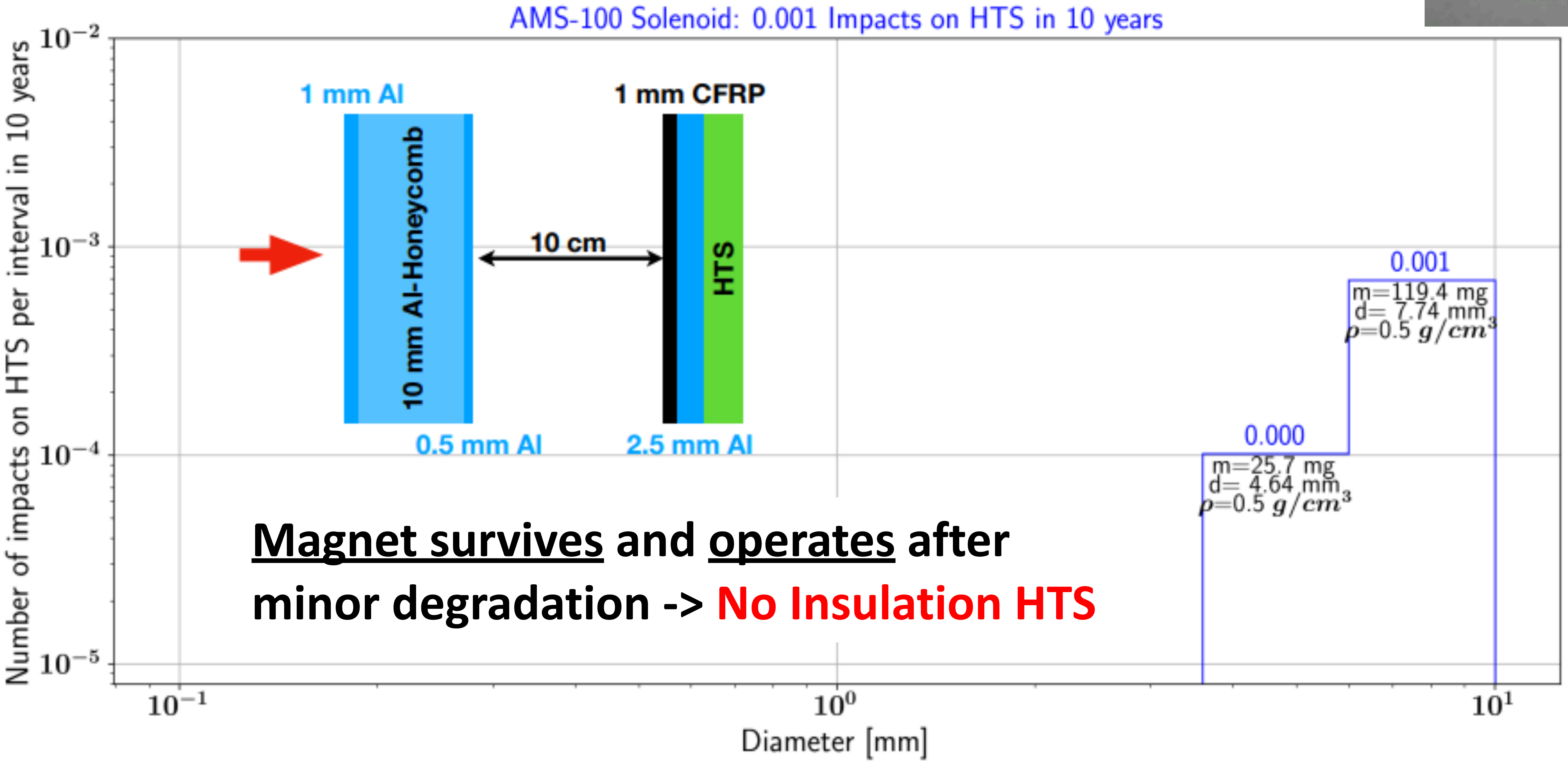
1mm =2 pt

Dangers of Space: Micrometeorite Impact

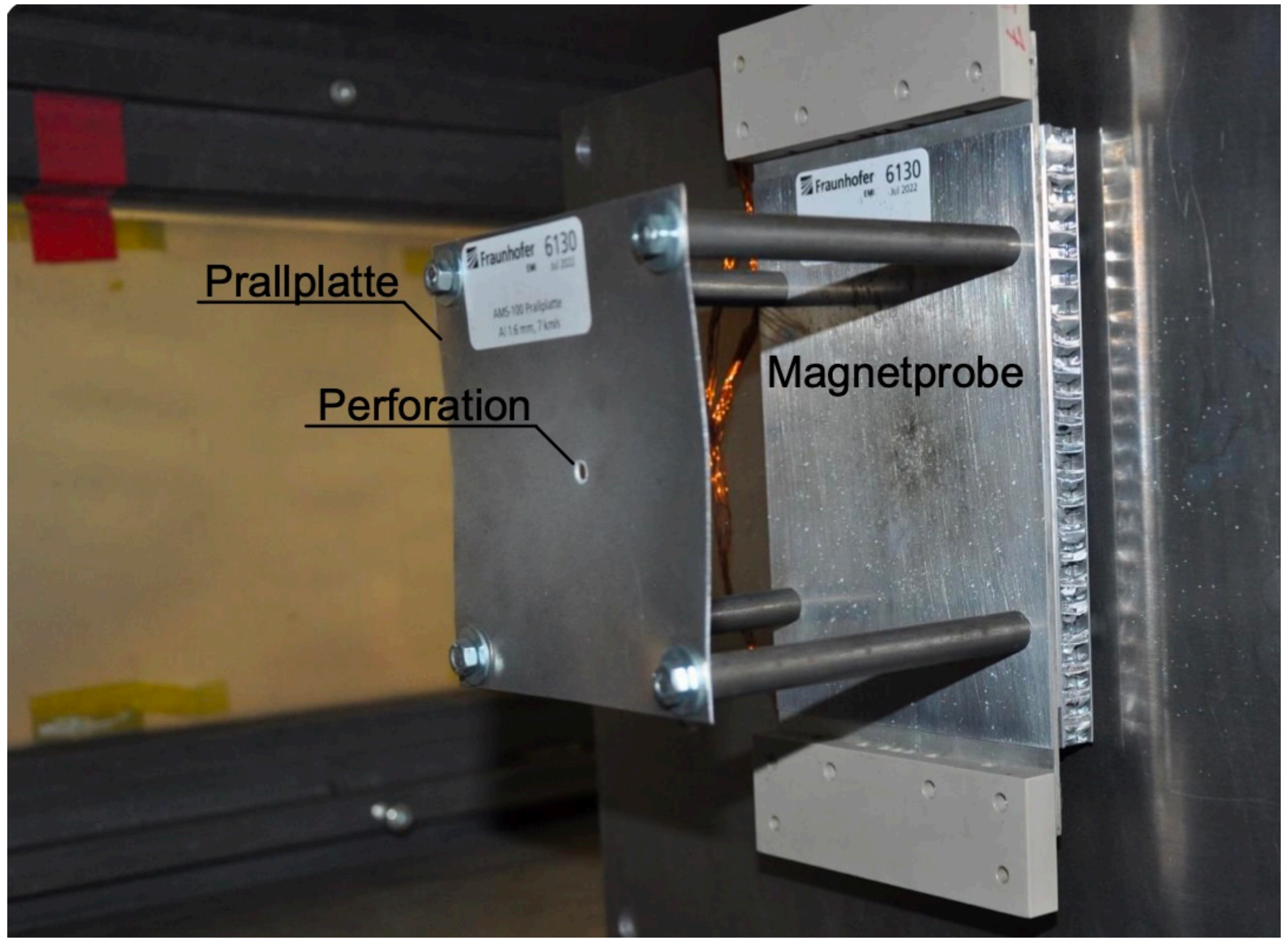


T. Schalm, Master Thesis 2022, RWTH Aachen & Fraunhofer EMI





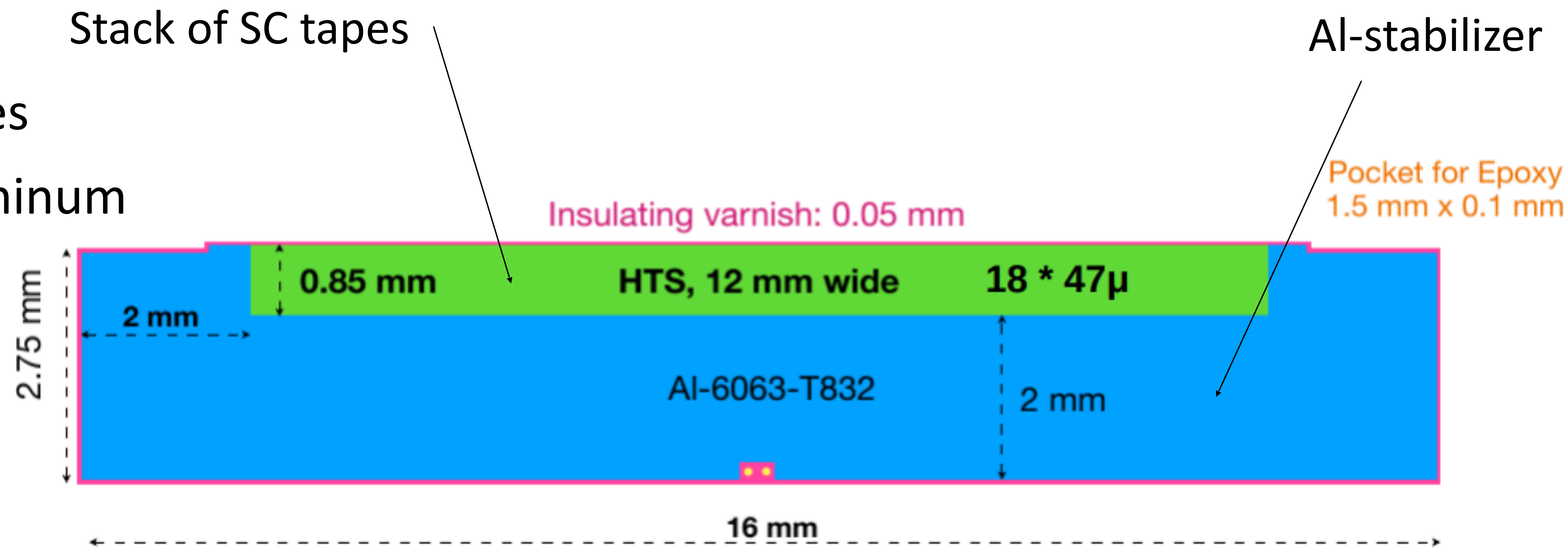
<u>Magnet survives</u> and <u>operates</u> after minor degradation -> No Insulation HTS

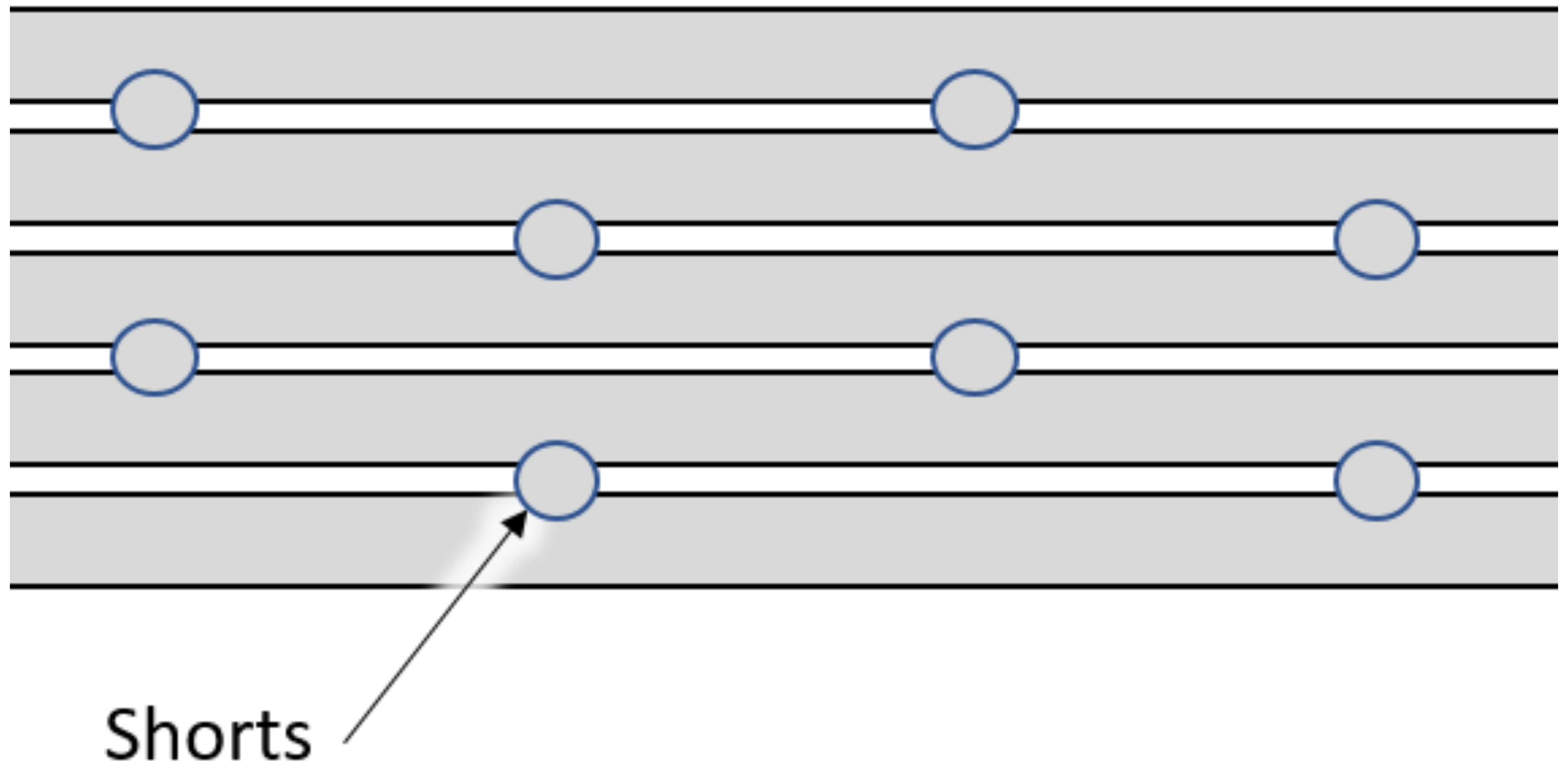


Conductor and Coil Layout

Current conductor layout:

- Stack of eighteen 12 mm wide HTS tapes
- HTS stack is soldered to tin-coated aluminum (6000 series) conductor stabilizer.
- Conductor thickness of 2.75 mm.
- Outer surface anodized / varnished to provide turn-to-turn insulation.

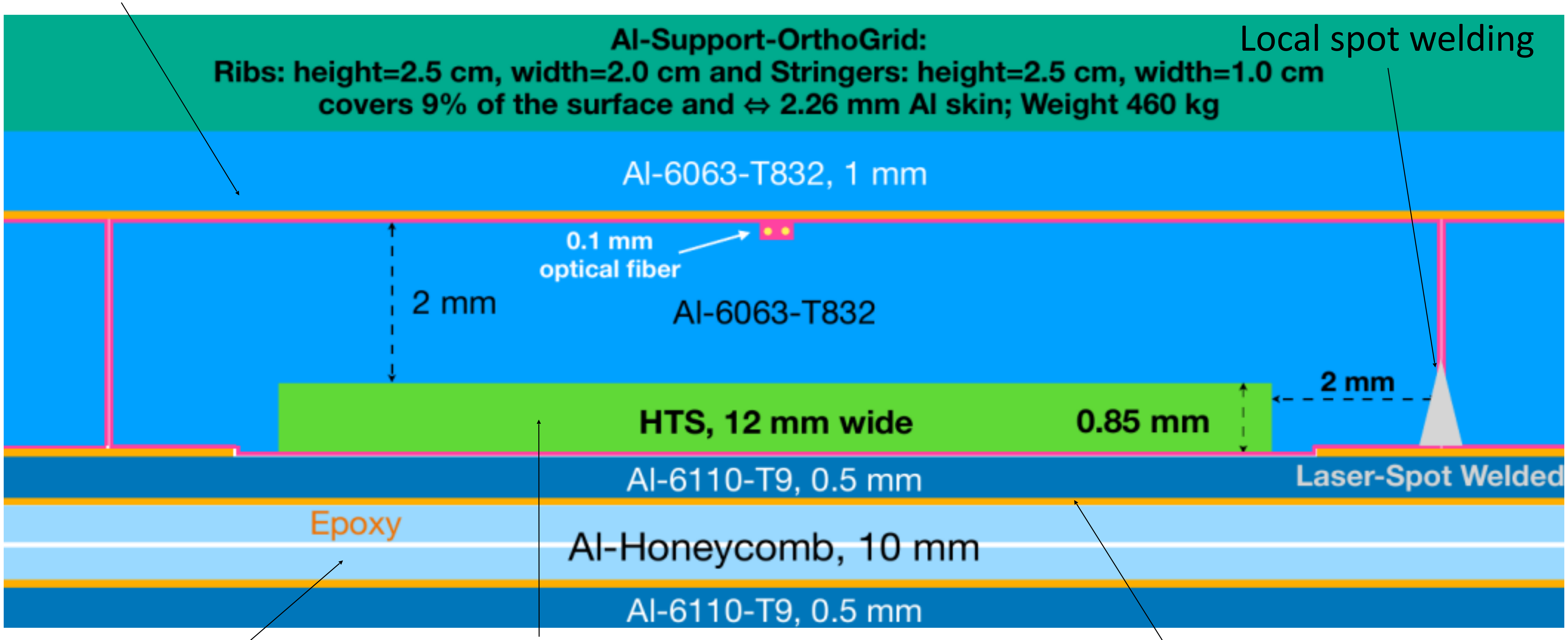




Shorting turns by (EB / laser) point welding.

- 1 mm^2 weld provides a turn-to-turn resistance of about 3e-5 Ω.
- AMS-100 -> 1250 mm^2 per turn (10 % of the circumference) covered with point welds of 1 mm^2 -> $\tau = 10$ hours.
- Provides mechanical strength and provides thermal/electrical path.
- Shorts are within the envelope of the conductor pack.
- To be tested and to be demonstrated.

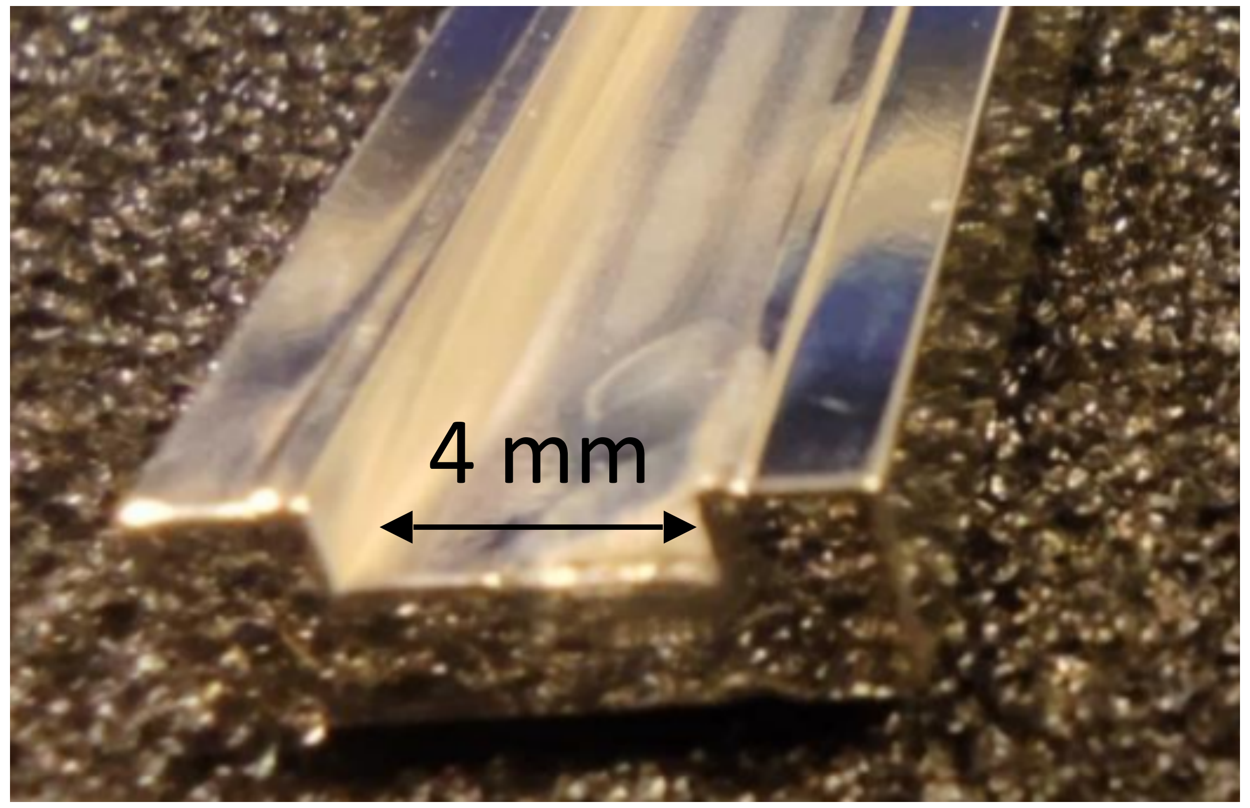
Structure of the Main Solenoid

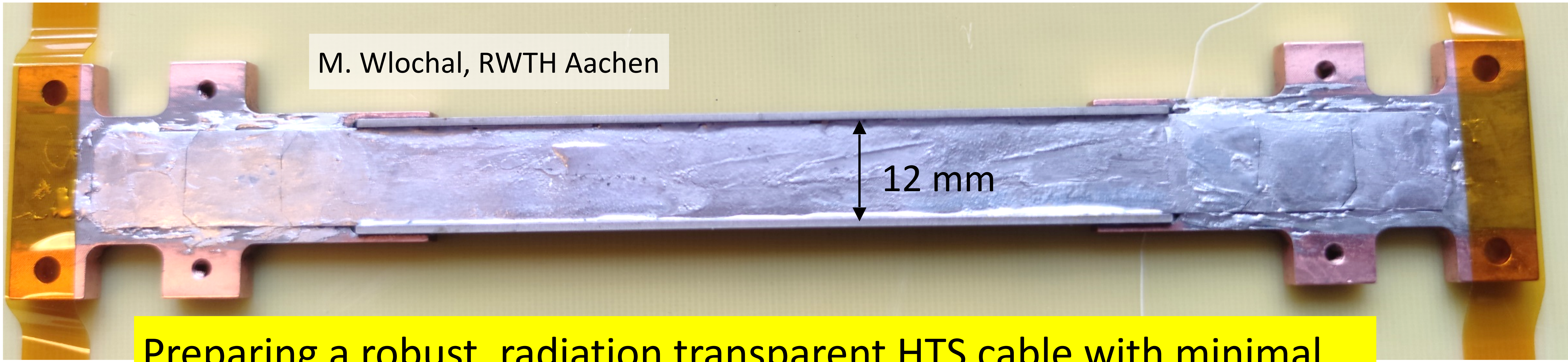


X_0 = 10.2% = Thickness of structure / Radiation length

Conductor Testing: Single- and Multi-Tape Samples

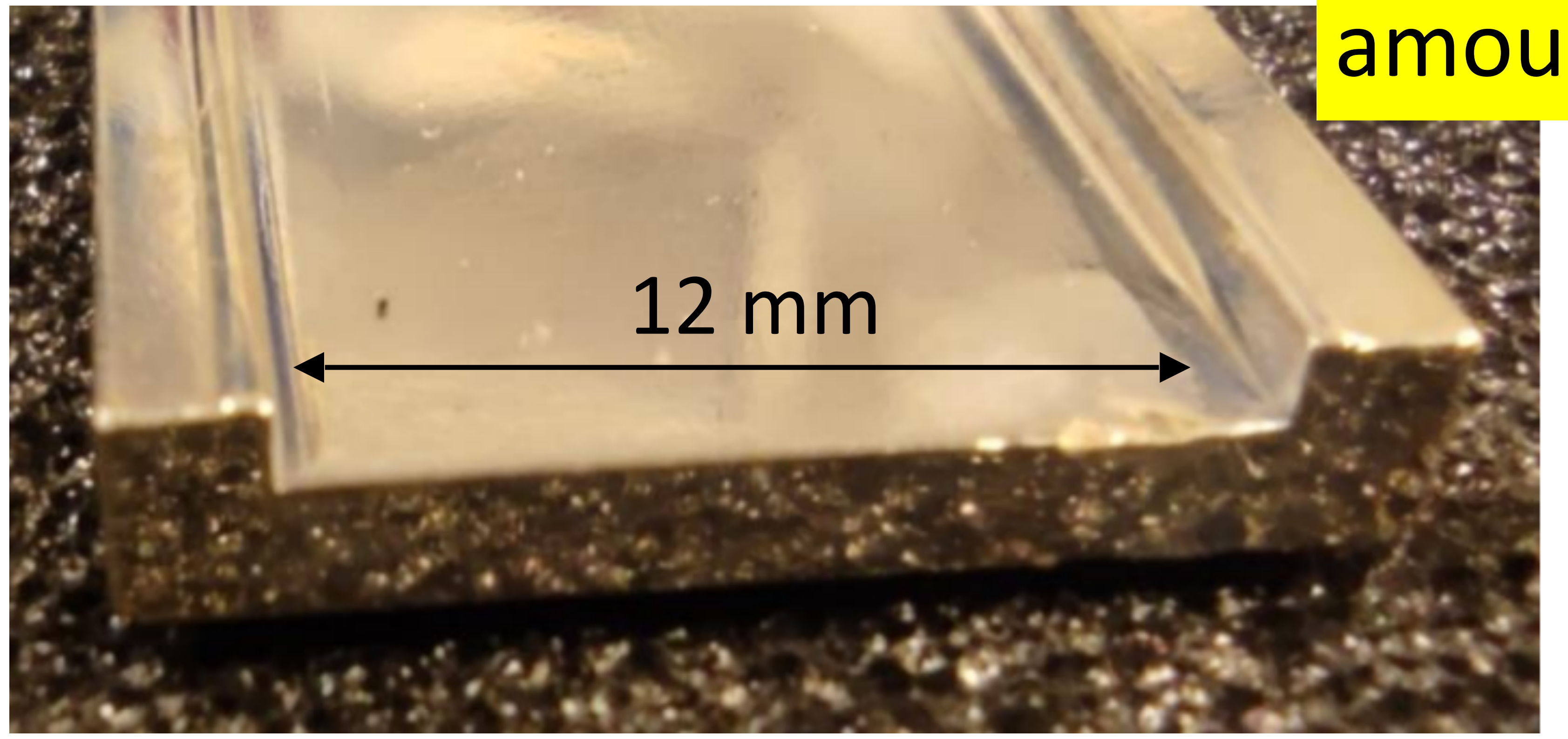
- Single tapes have been extensively characterized .
- Many short samples of Al-alloy stabilized multi-tape HTS conductors are in preparation.
- Few-tape samples in good agreement with expectations.
- Next: more tapes, bending, micro-meteorite impact testing, etc.

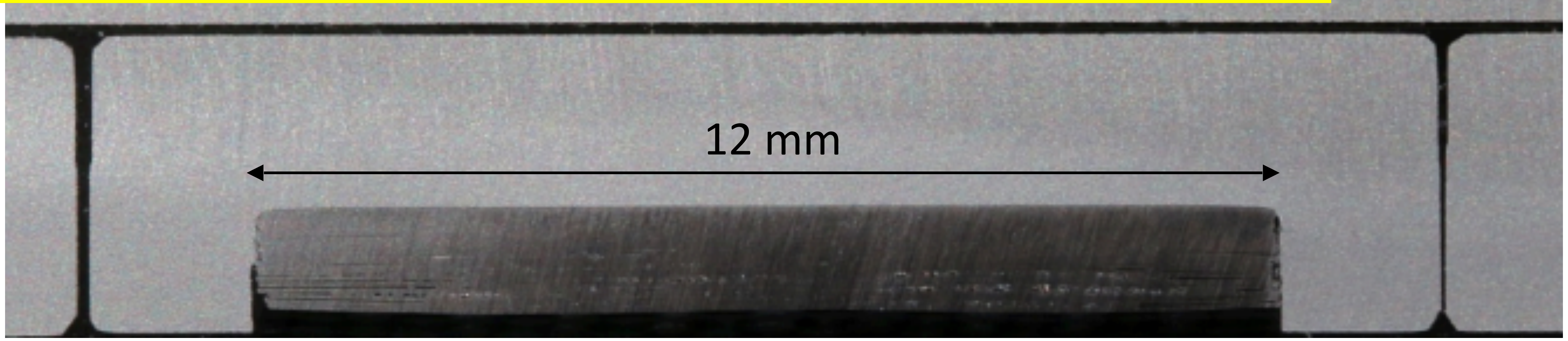




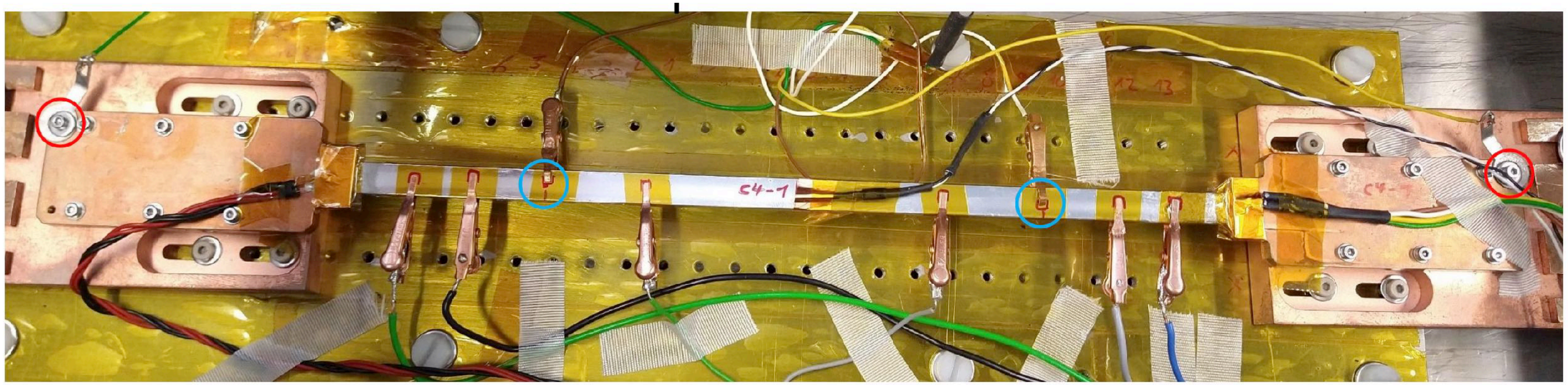
M. Wlochal, RWTH Aachen

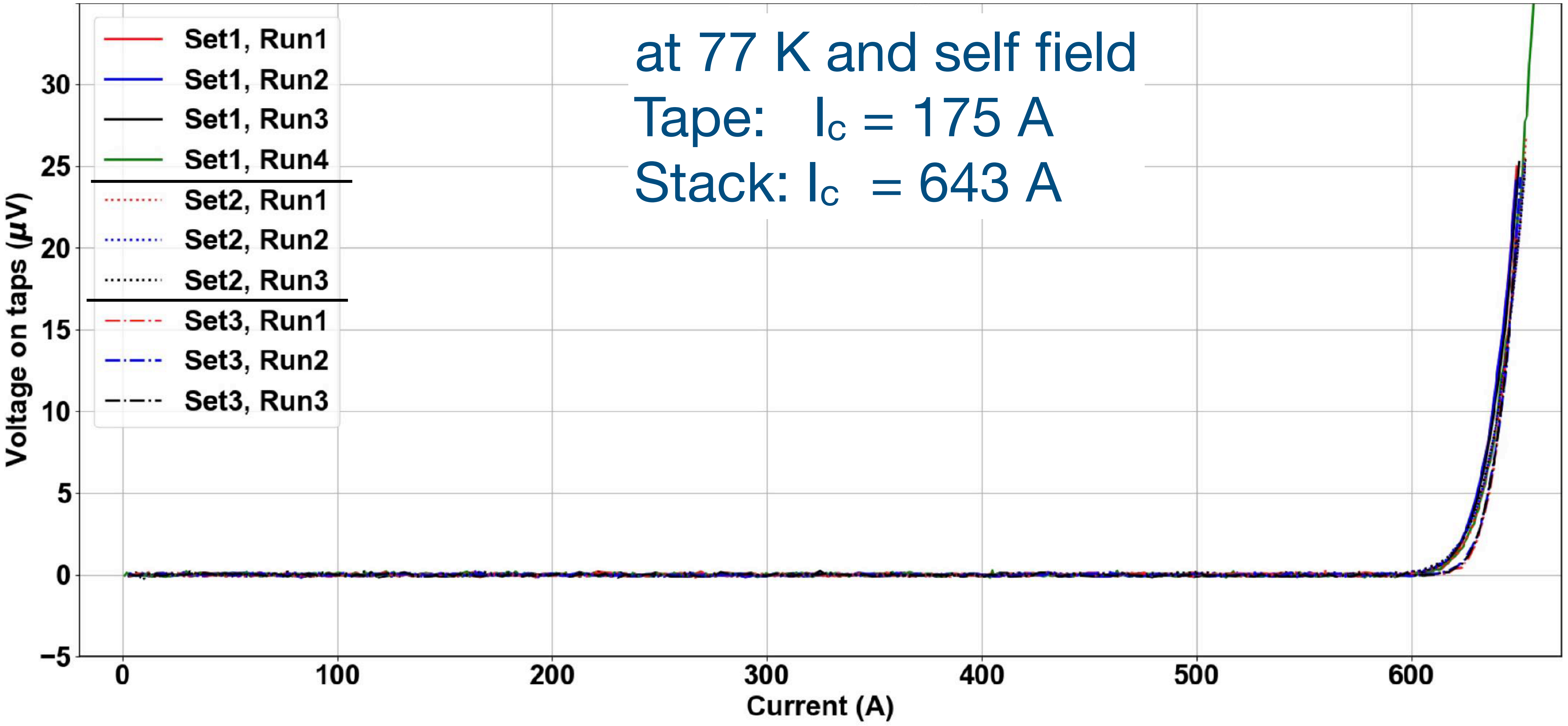
Preparing a robust, radiation transparent HTS cable with minimal amount of solder and proper bonding is still a **<u>major challenge</u>**!





Stack of 5 HTS Tapes (4 mm wide)

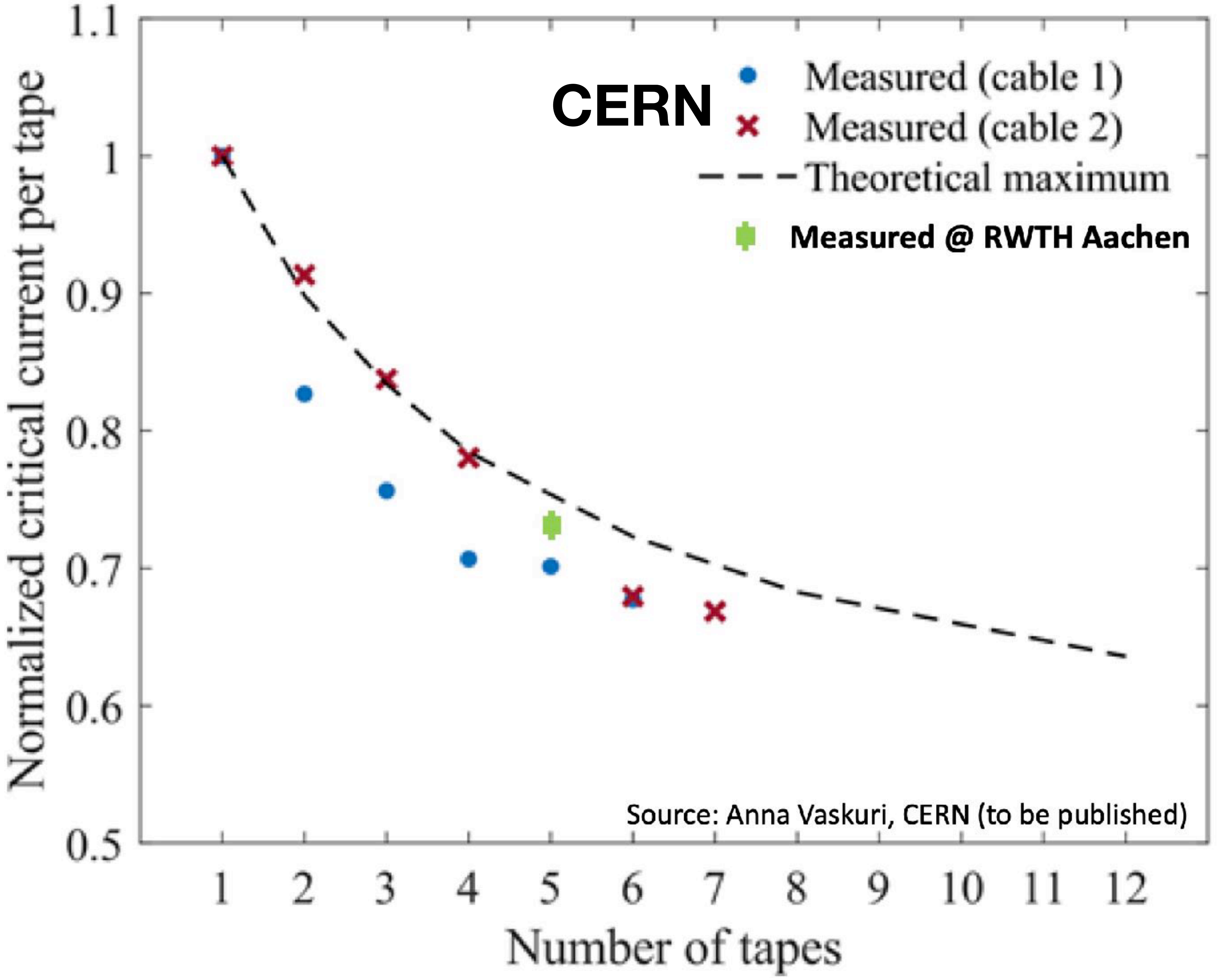




at 77 K and self field

Tape: I_c = 175 A

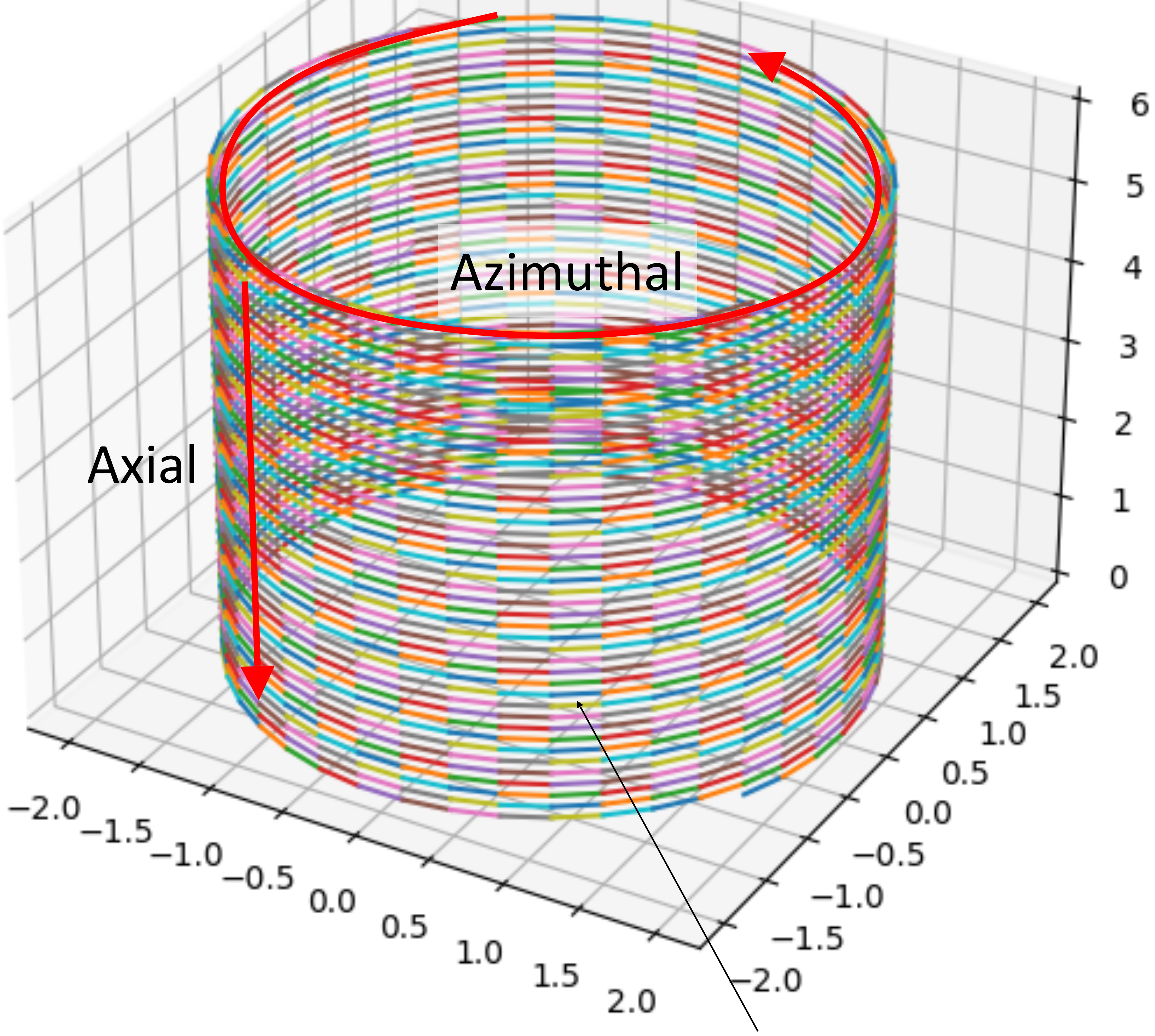
Stack: I_c = 643 A



Source: Anna Vaskuri, CERN (to be published)

Thermal-ElectroMagnetic Quench Model

Thermally and electrically connected:
Axial and azimuthal direction



Turns divided in
to line elements

Quench behavior of the non-insulated AMS-100 main solenoid

- Quench behavior of the AMS-100 main solenoid is studied for several quench scenarios.
- Quasi 3D thermal, electrical and magnetic nodal-network model is built using python.
- Results from this model are analyzed in ANSYS/Abacus to evaluate the resulting mechanical response.
- Model studies the effect of slow thermal runaway and consequently a fast quench as function of a small defect.
- Not enough resolution at the moment for sudden and very local defects (due for e.g. micrometeorite impact).
- Other structural elements, such as end-flanges and ribs, are not yet included in the model.
- Simulations performed using a previous design iteration: 428 turns, an operating current of 13.5 kA and a field of 1 T.

Simulated Quench Behavior and Survival

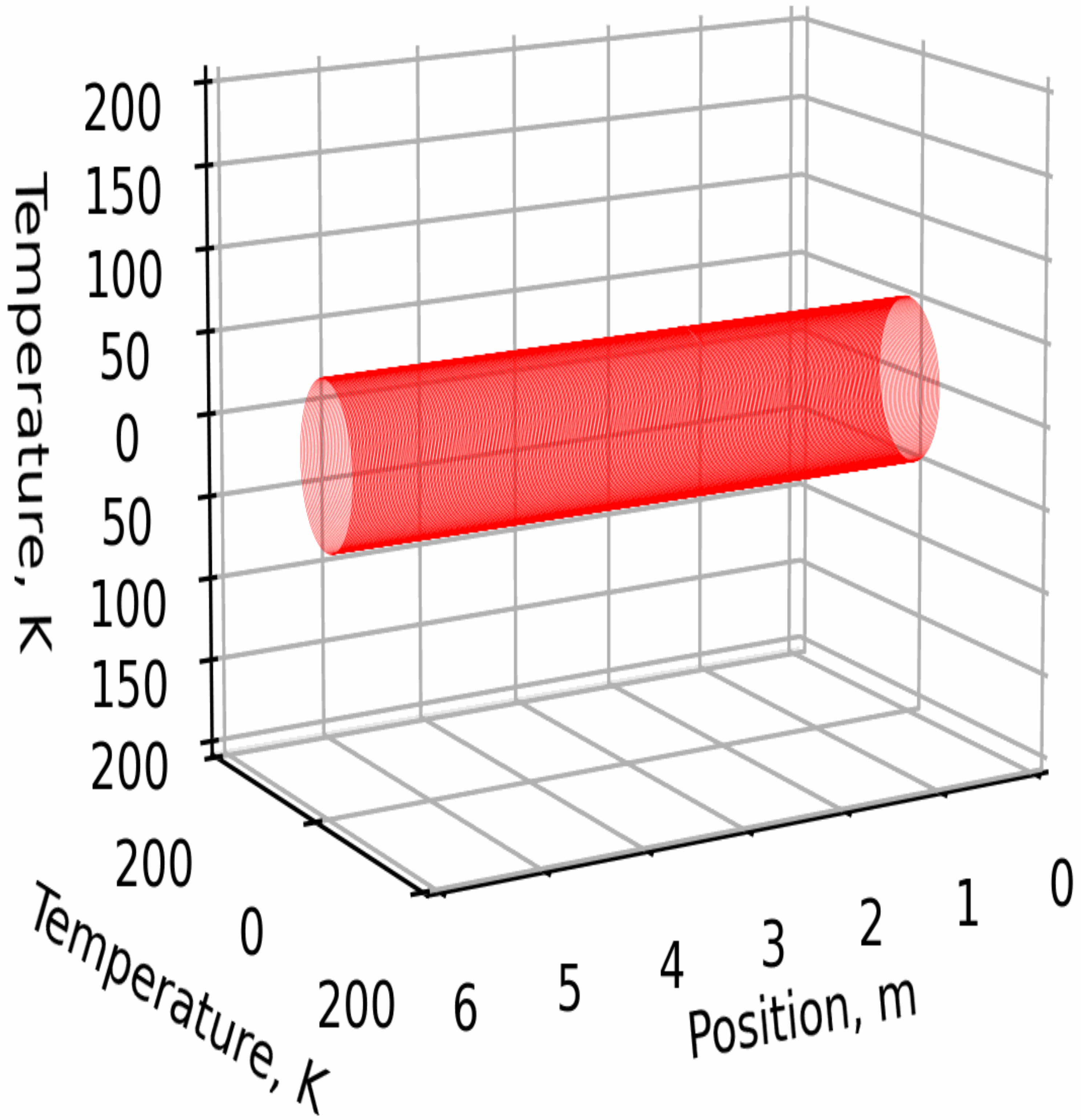
428 turn main solenoid, I_{op} = 13.5 kA, B = 1 T.

t = 0.2428 s

t = 0.2428 s

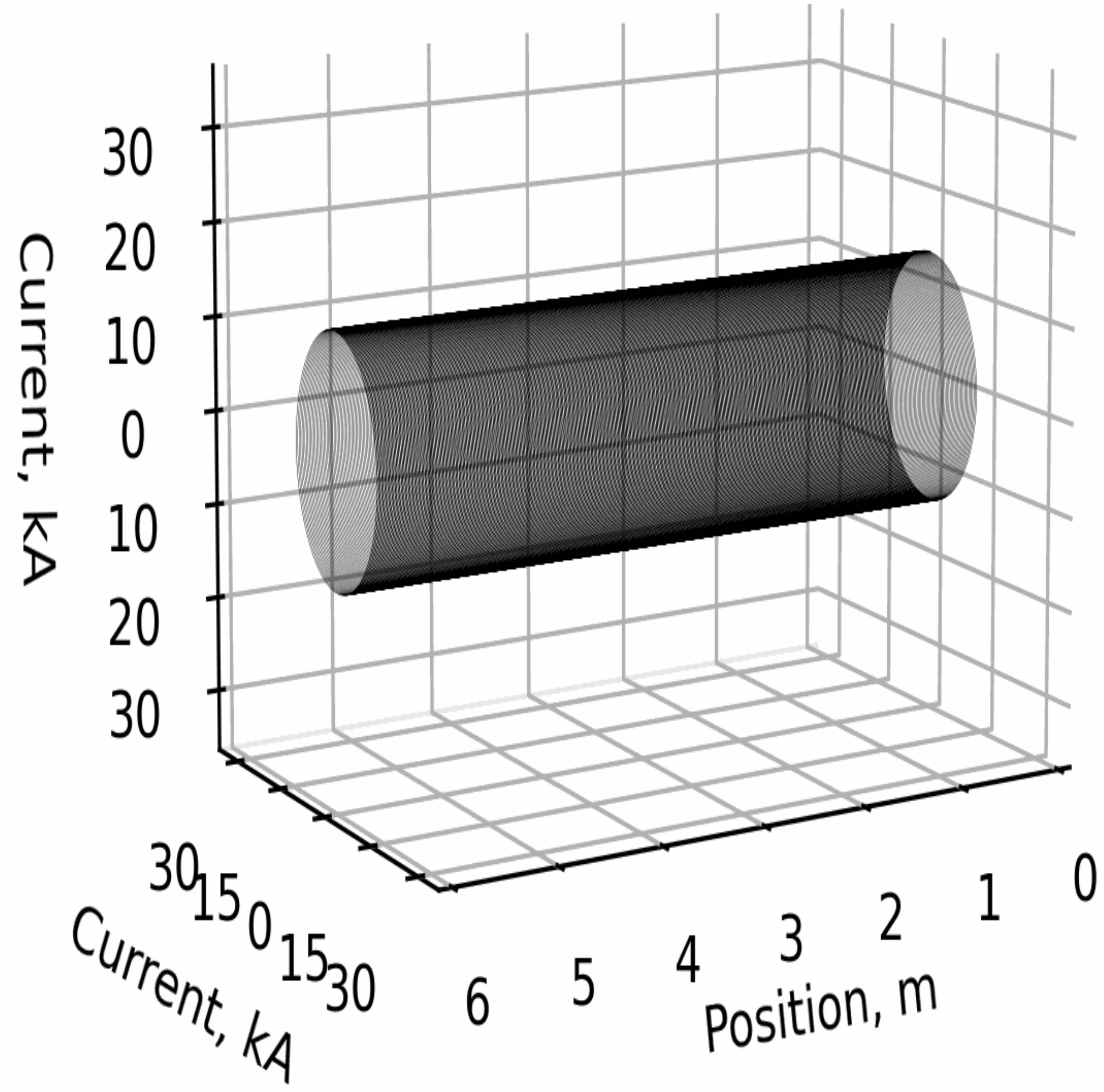
Simulations indicate that the main solenoid is thermally self-protected.

Peak hot-spot near extremities



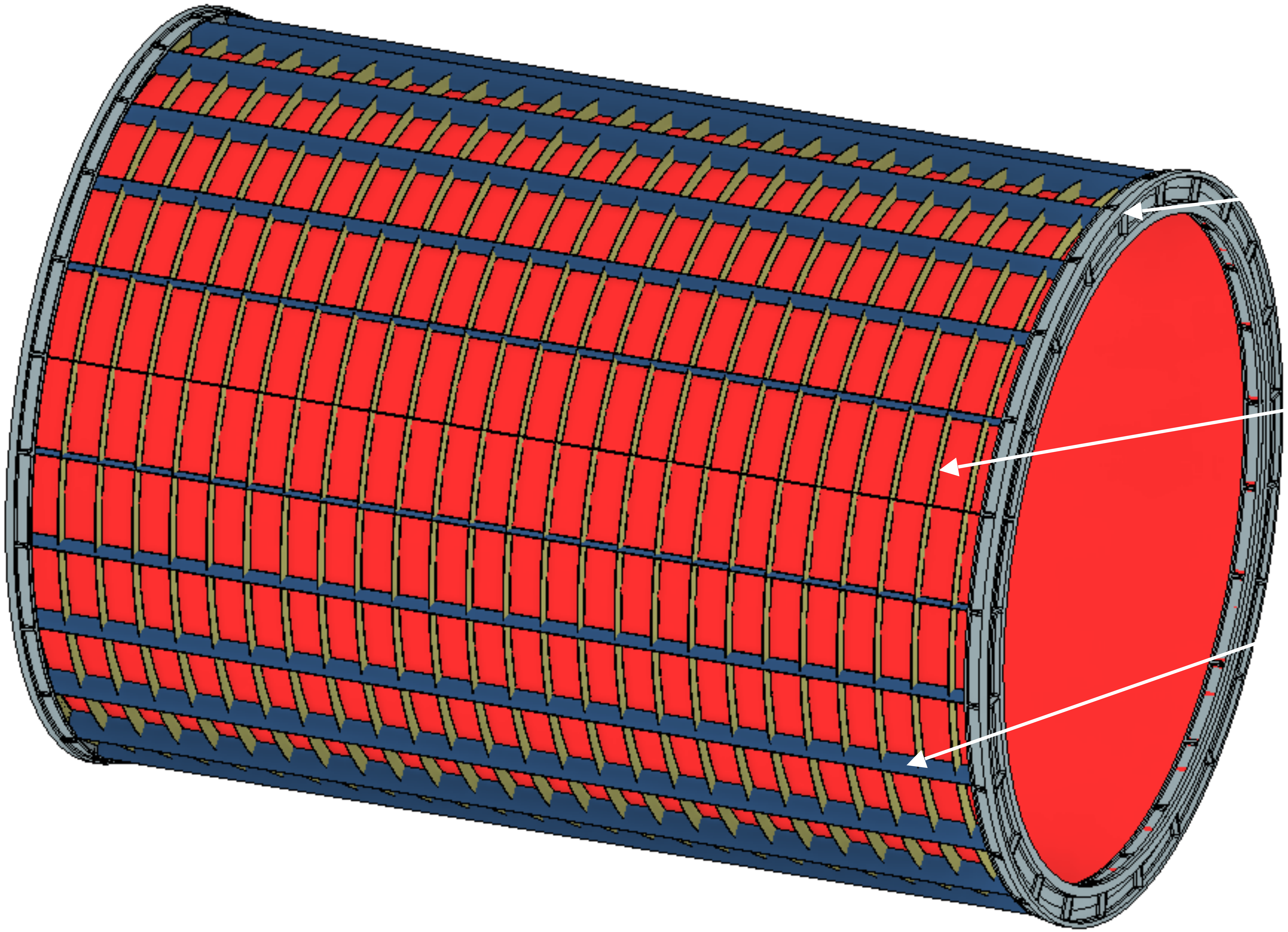
Temperature

NZPV of ~ 4-8 m/s



Current

End-flanges, Ribs and Stringers



End-Flanges (grey): Mechanical support of the magnet during manufacturing, launch and operation.
Circular, allows quench-back.

Ribs (yellow): Mechanical support of the magnet during operation and quench events.
Circular, allows quench-back.

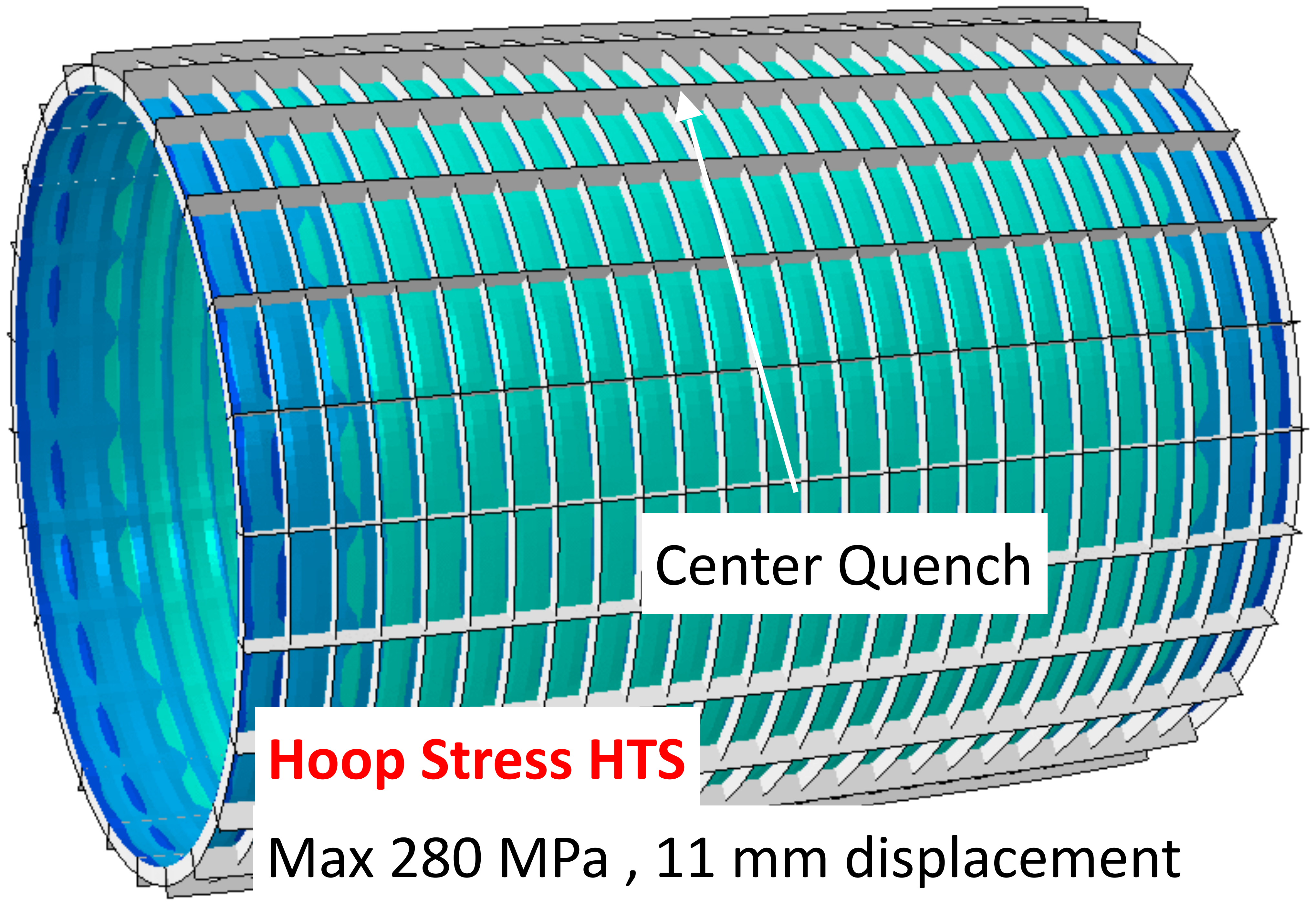
Stringers (blue): Mechanical support during launch.

Mechanical load on the conductor is exported from the thermal-electrical model to Abaqus.

Mechanical Quench Analyses

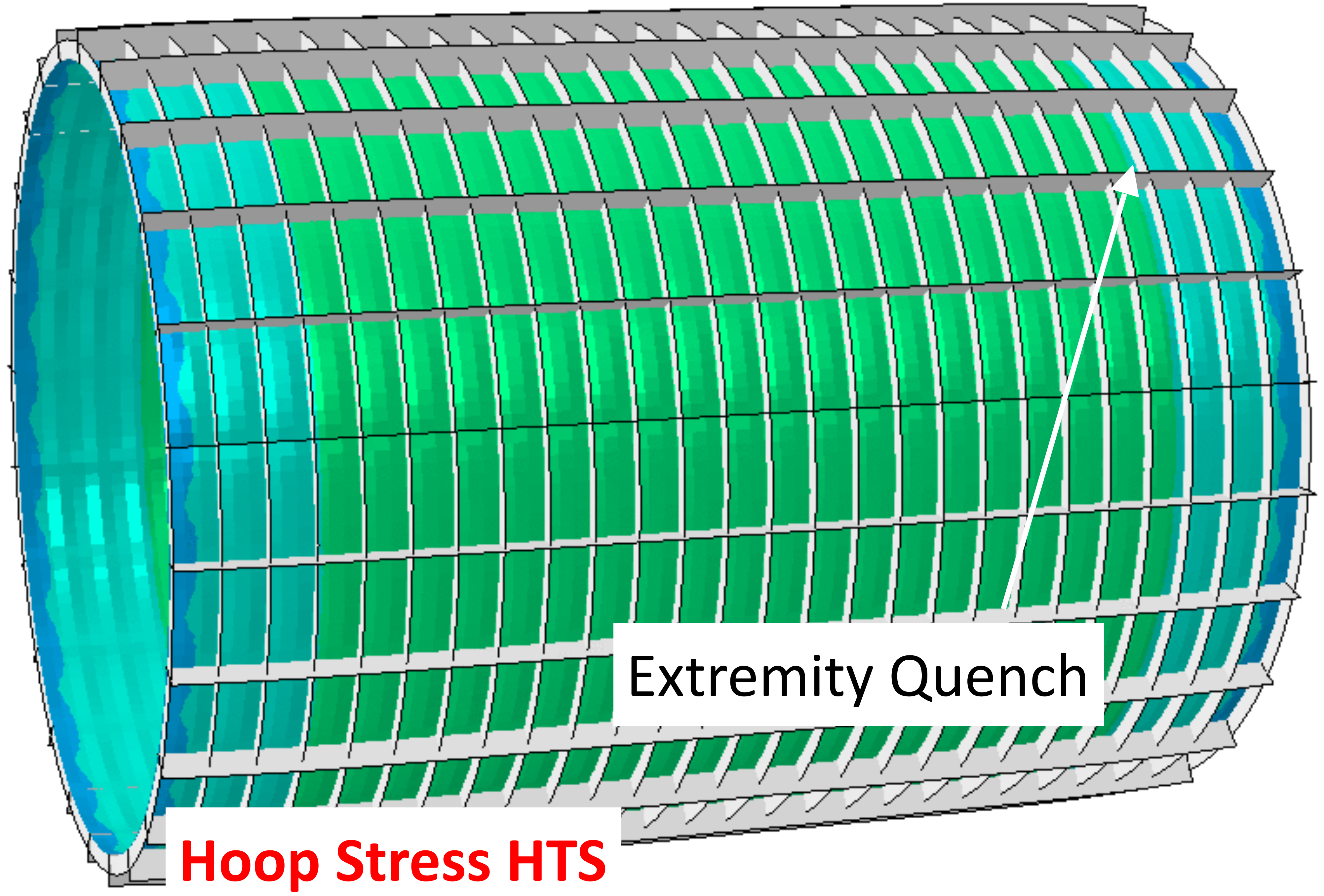
- Shell model set-up in Abaqus to calculate stress in the HTS, Al-alloy conductor and structural components.
- Model includes the conductor, ribs and stringers.
- Stress in the conductor is almost tripled during a quench due to enormous induced current.

- Ribs locally reduce the stress in the conductor.
- Stress in the conductor due to thermal gradients not critical, strength of the epoxy to be validated experimentally.
- Peak stress (~300 MPa) caused by radial Lorentz force.
- Support structure requires optimization.



Hoop Stress HTS

Max 280 MPa , 11 mm displacement



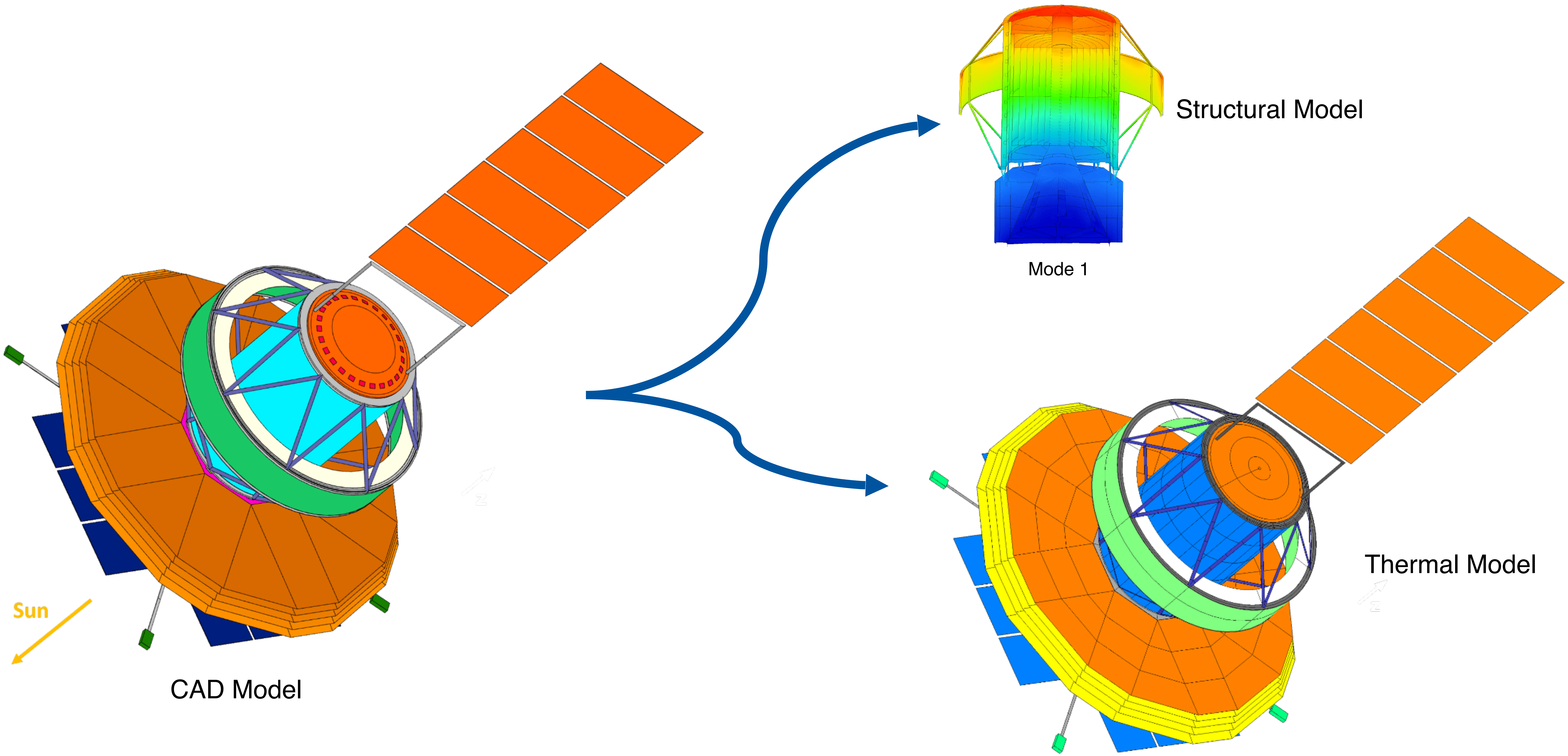
Hoop Stress HTS

Max 240 MPa, 10 mm displacement

J. Zimmermann & D. Pridöhl, RWTH Aachen

Boundary condition: outer rings fixed to circular shape, free thermal shrinkage

ARCHITECTURE | MODELS

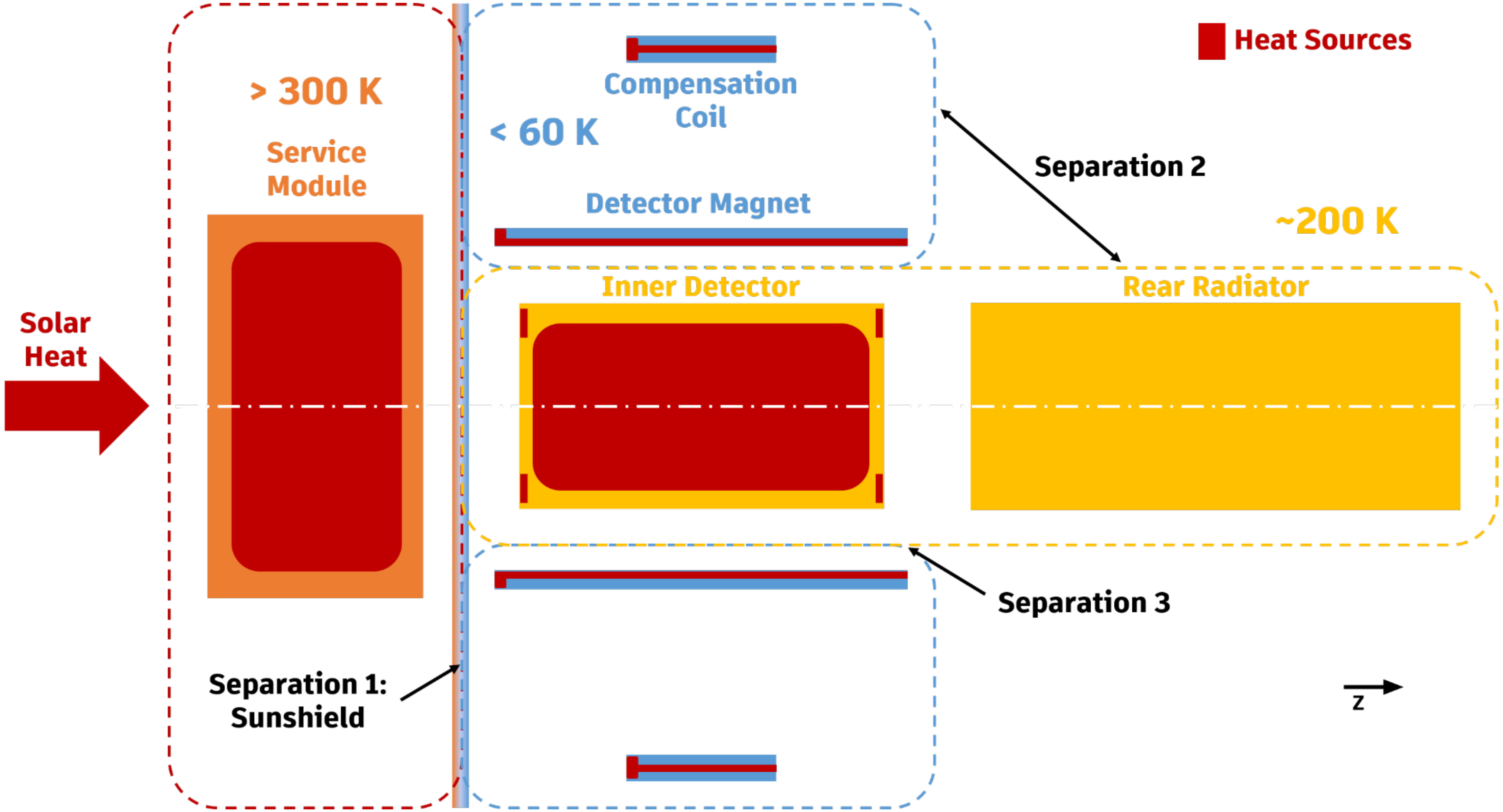


CAD Model

Structural Model

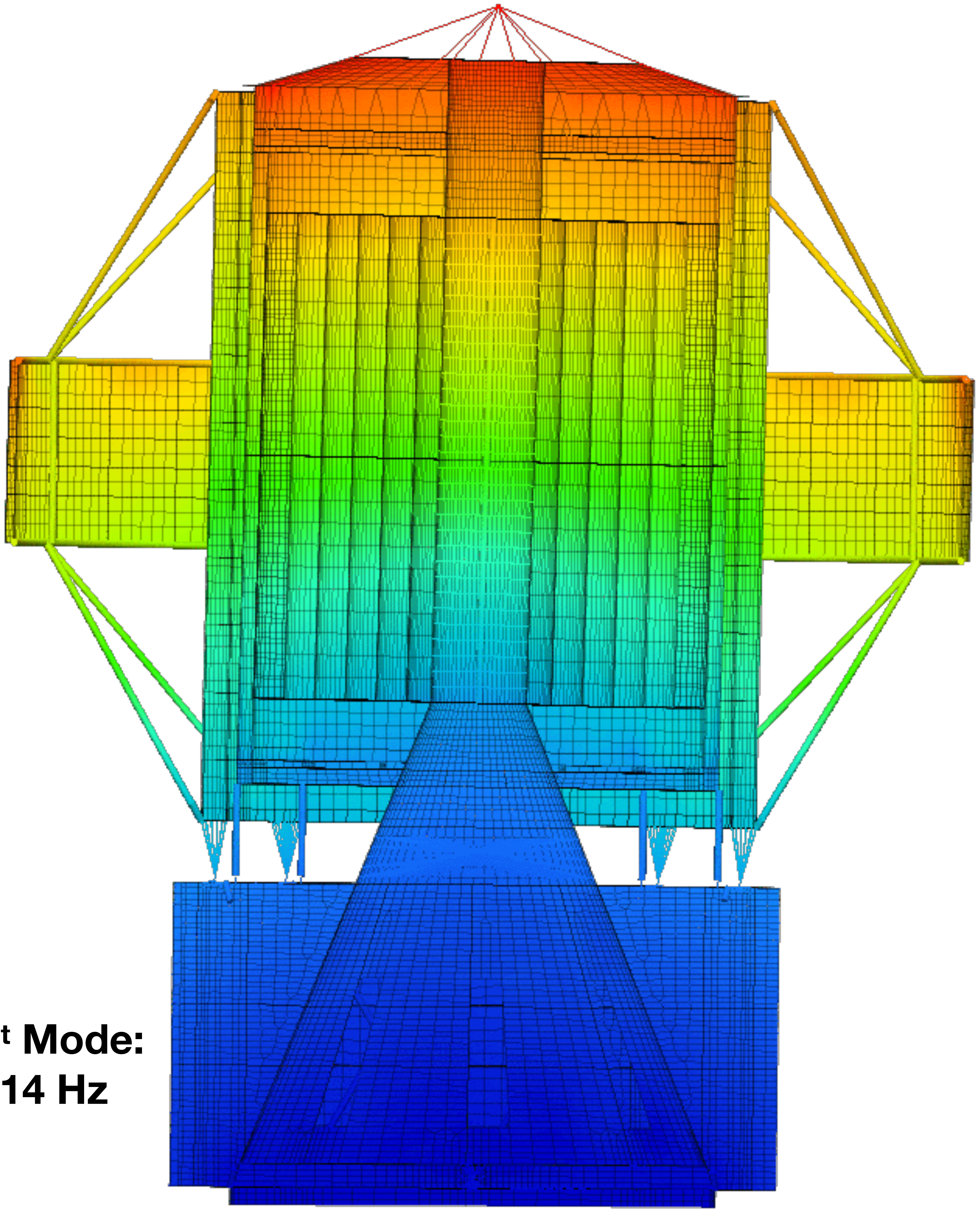
Thermal Model

THERMAL DESIGN | HEAT SOURCES



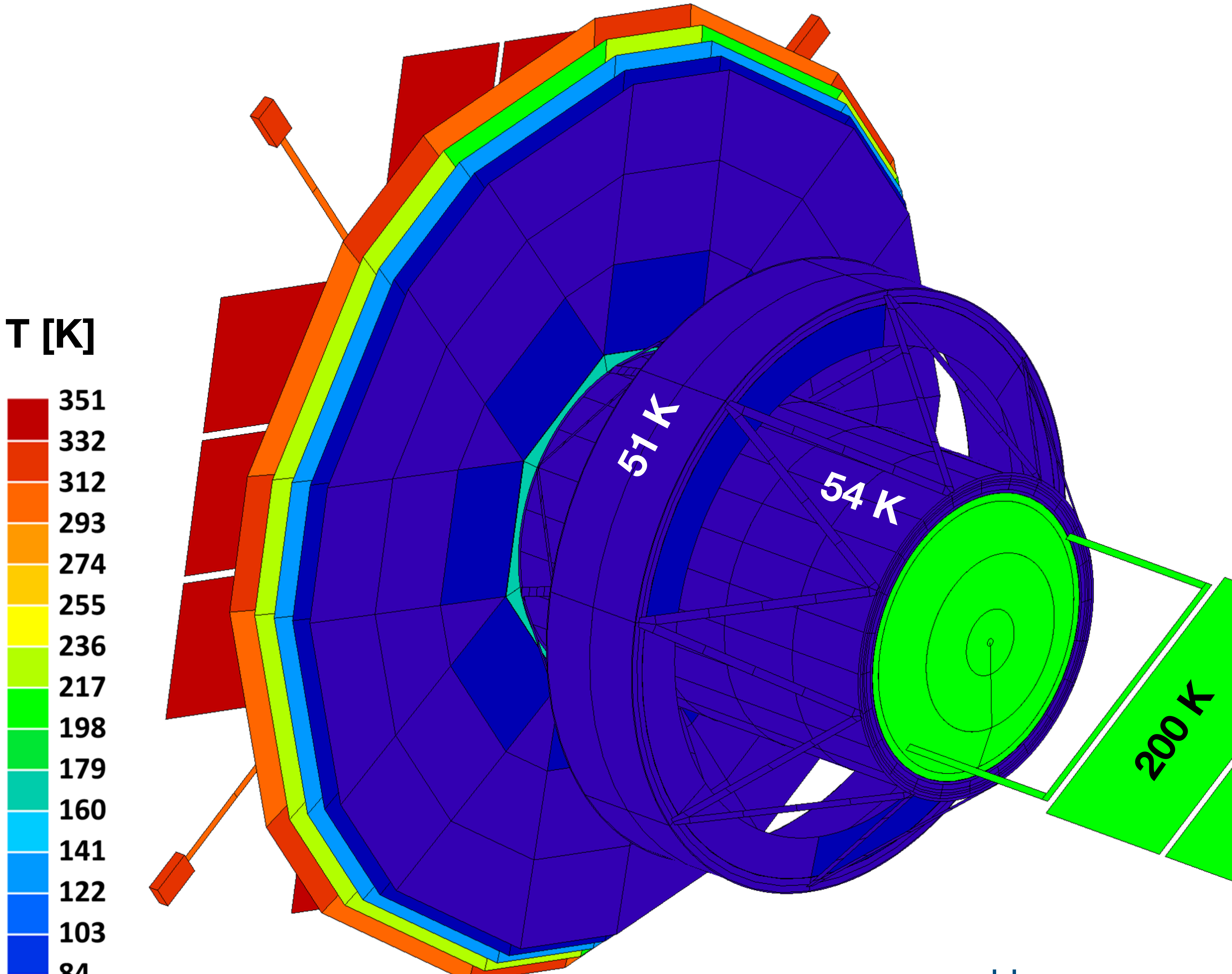
- Service module & payload data handling
  - ~8000 W
- Inner detector
  - ~8000 W
- Solenoids
  - ~15 W

AMS-100: Structural Model



1st Mode: 14 Hz

AMS-100: Thermal Model



sponsored by

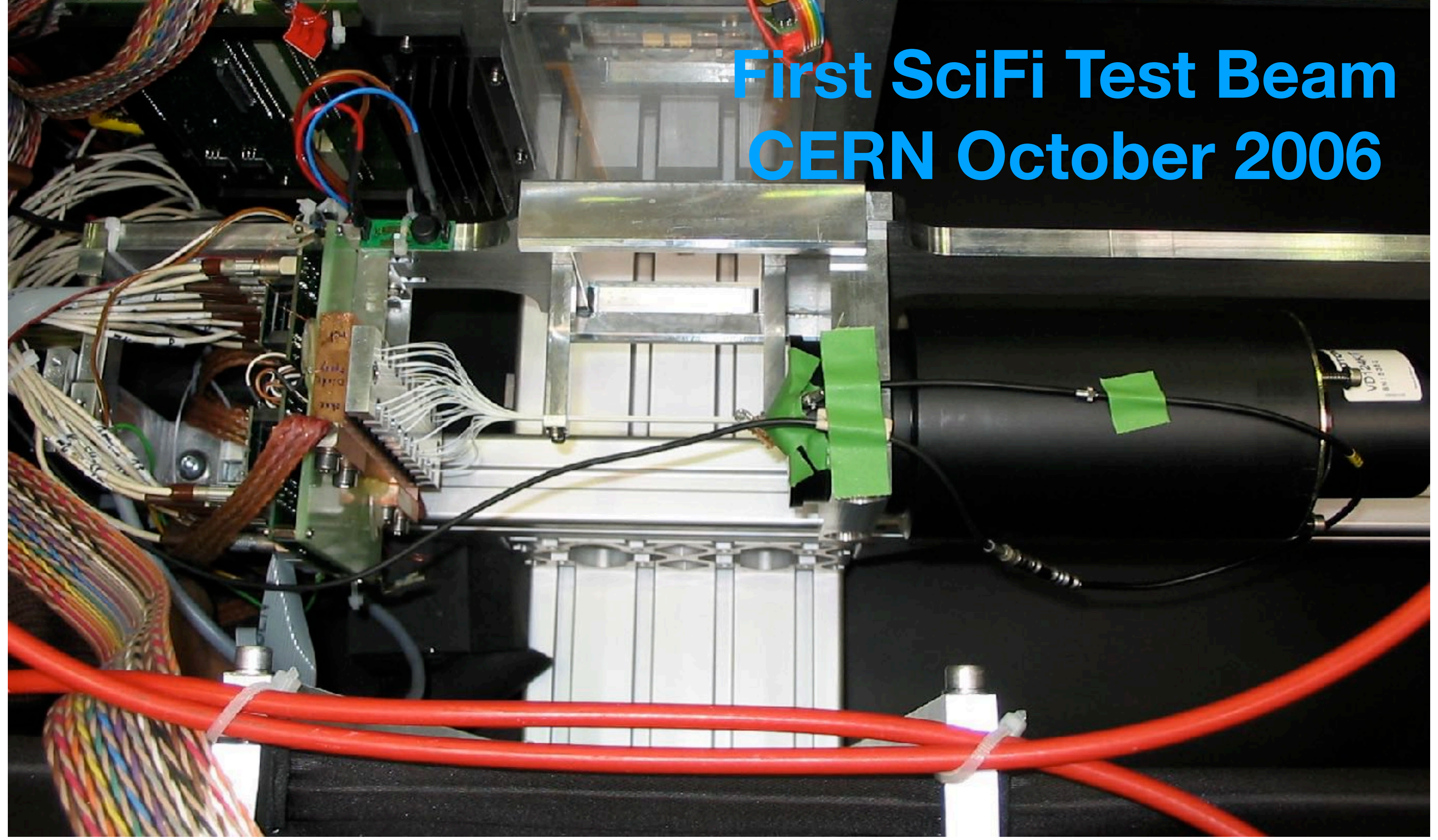
ESATAN-TMS

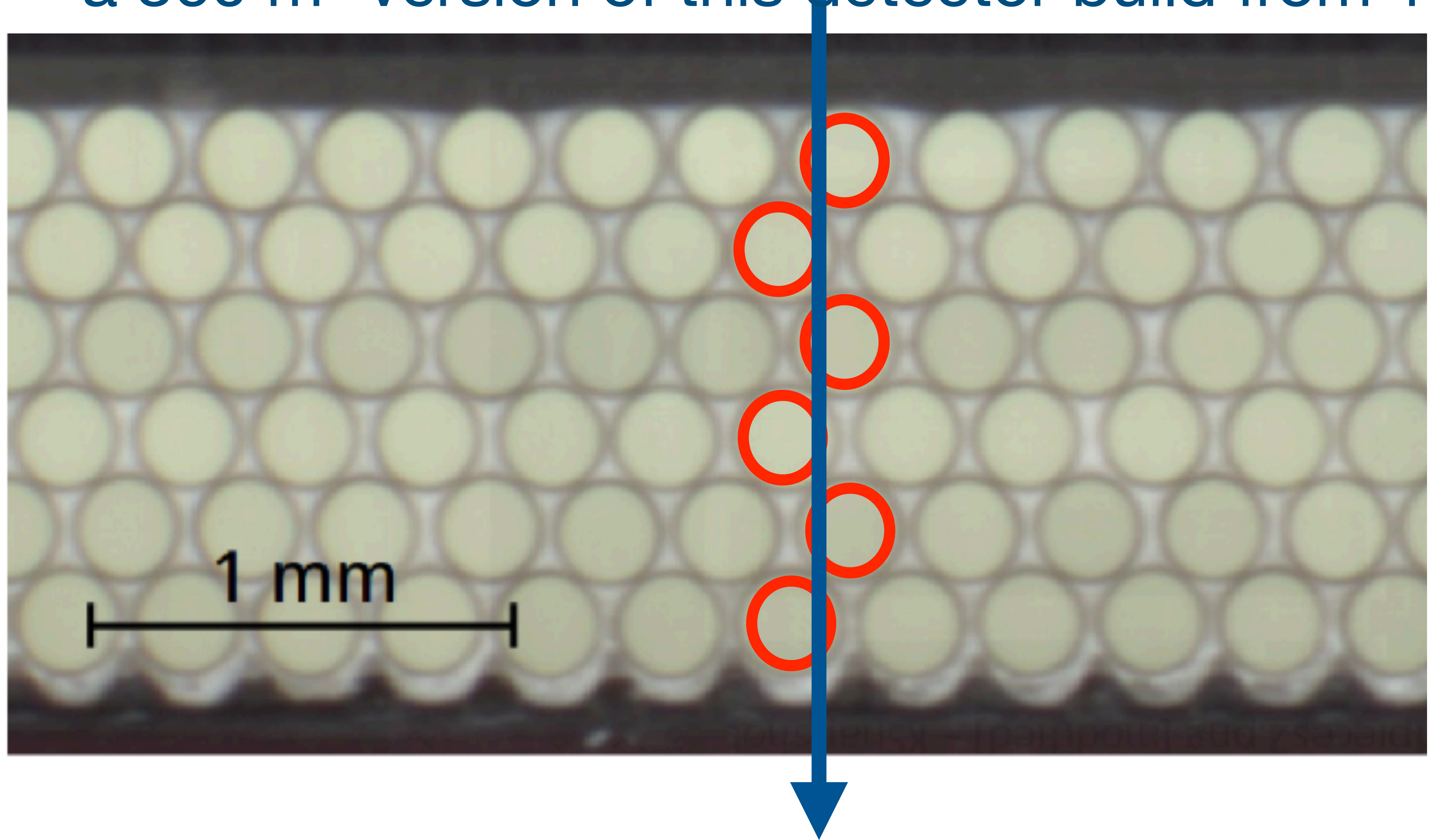
thermal modelling suite

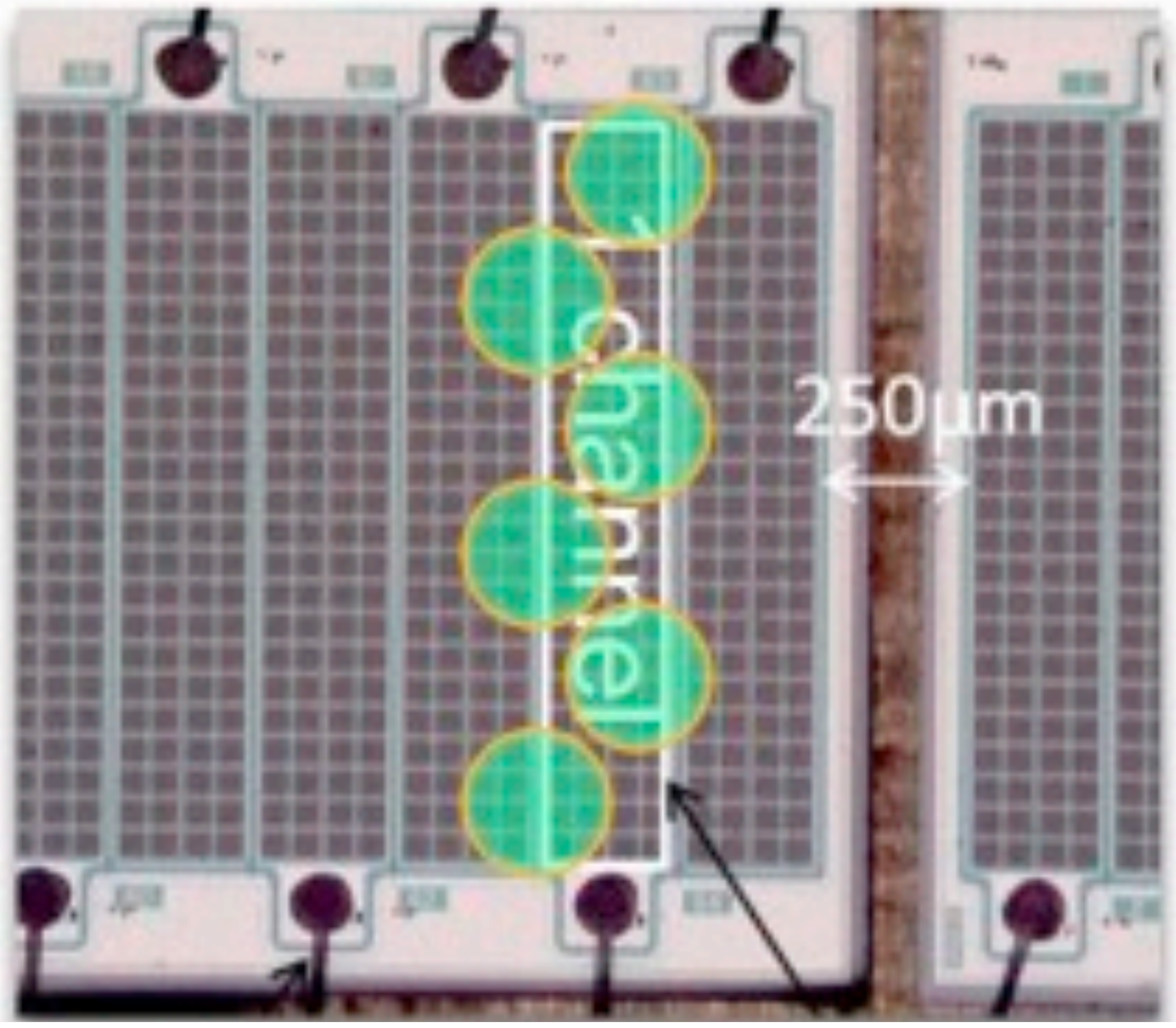
AMS-100

Weight: 40 t
Readout-Channels: 8 10^6
Power: 15 kW
Measurement Time: 10 years
MDR: 70 TV
Acceptance: 100 m^2 sr
B-Field: 1 Tesla
Calorimeter: 70 X_0, 4λ

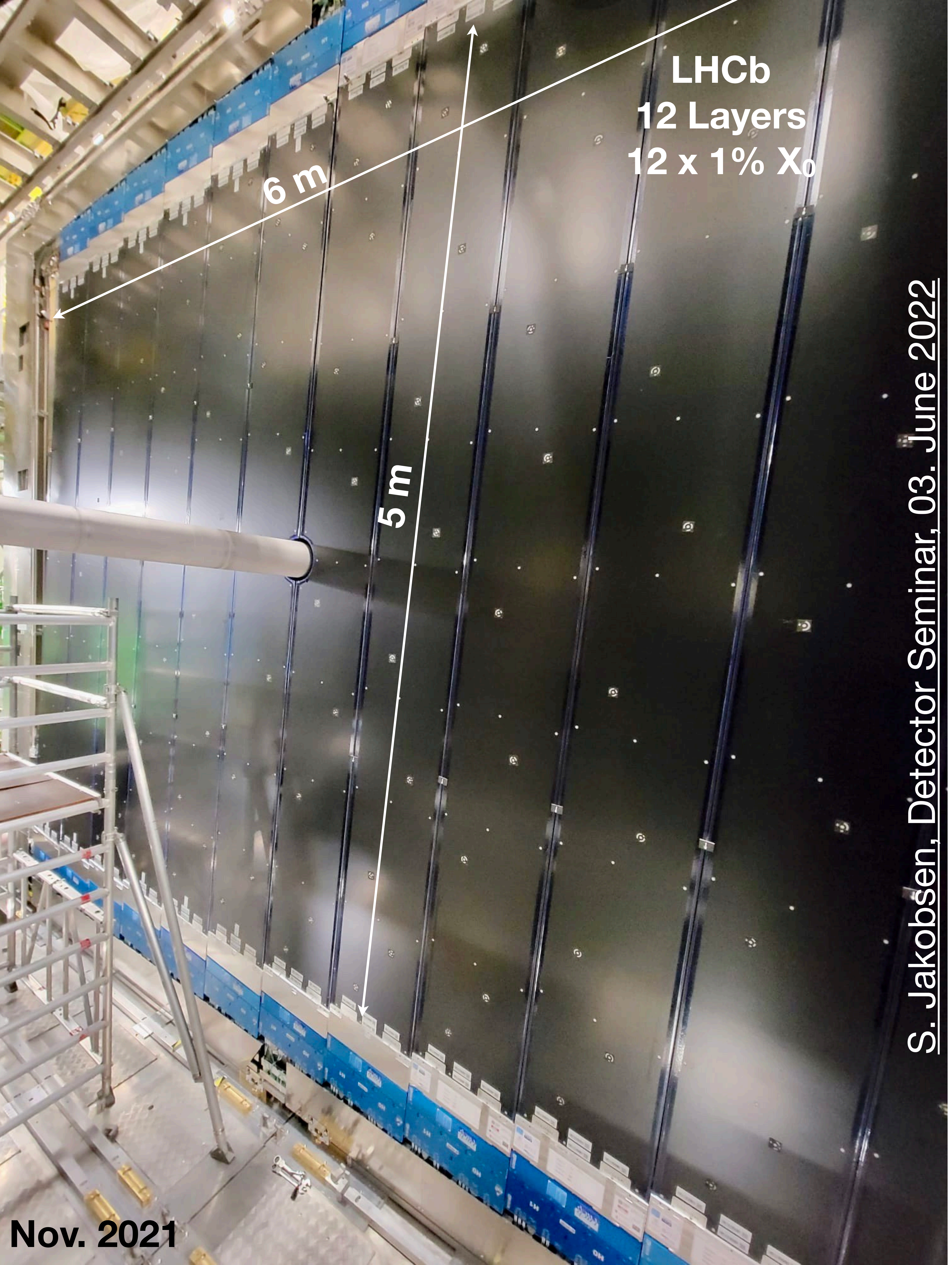
- In 2005 NASA canceled the AMS-02 Space Shuttle Flight.
- At RWTH Aachen a concept for a balloon experiment (PEBS) was developed to measure cosmic ray positrons.
- A new scintillating fiber tracker with SiPM readout was the key element for the tracking system.
- In 2008 the group of T. Nakada, EPFL joined the team.
- In 2010 a prototype (PERDAIX) was launched from Kiruna, Sweden. 300 000 protons and Helium nuclei were recorded at an altitude of 34 km.
- The paper describing this new SciFi detector was published in Nucl. Instrum. Meth.A 622 (2010) 542-554 (10.1016/j.nima.2010.07.059).
- In 2014 the LHCb Upgrade I TDR was published, describing a 360 m² version of this detector build from 11,000 km of fiber.


First SciFi Test Beam
CERN October 2006



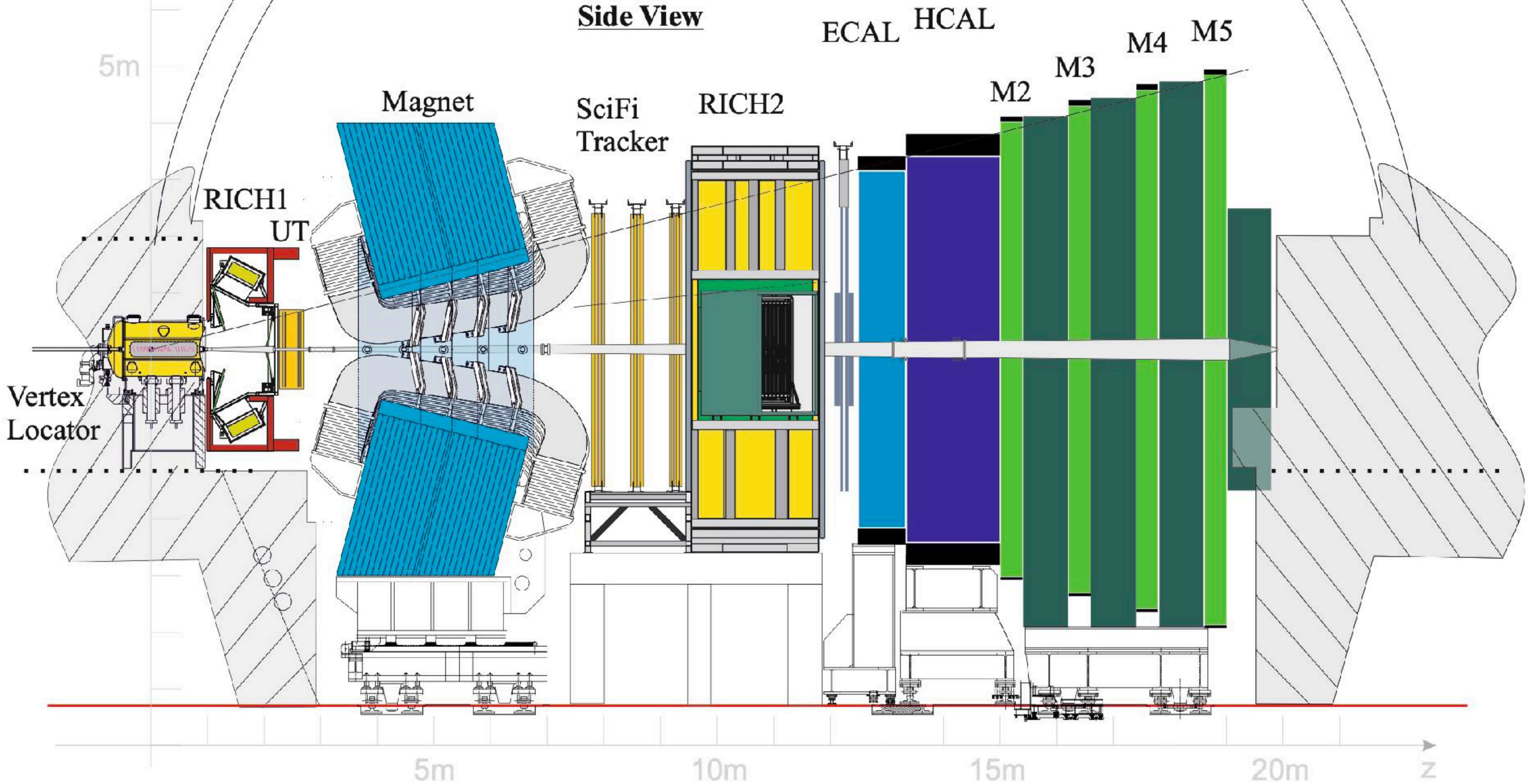


PERDAIX



S. Jakobsen, Detector Seminar, 03. June 2022

Nov. 2021



A large international team from several institutes, including EPFL and RWTH Aachen, constructed the LHCb SciFi Tracker in the past years.

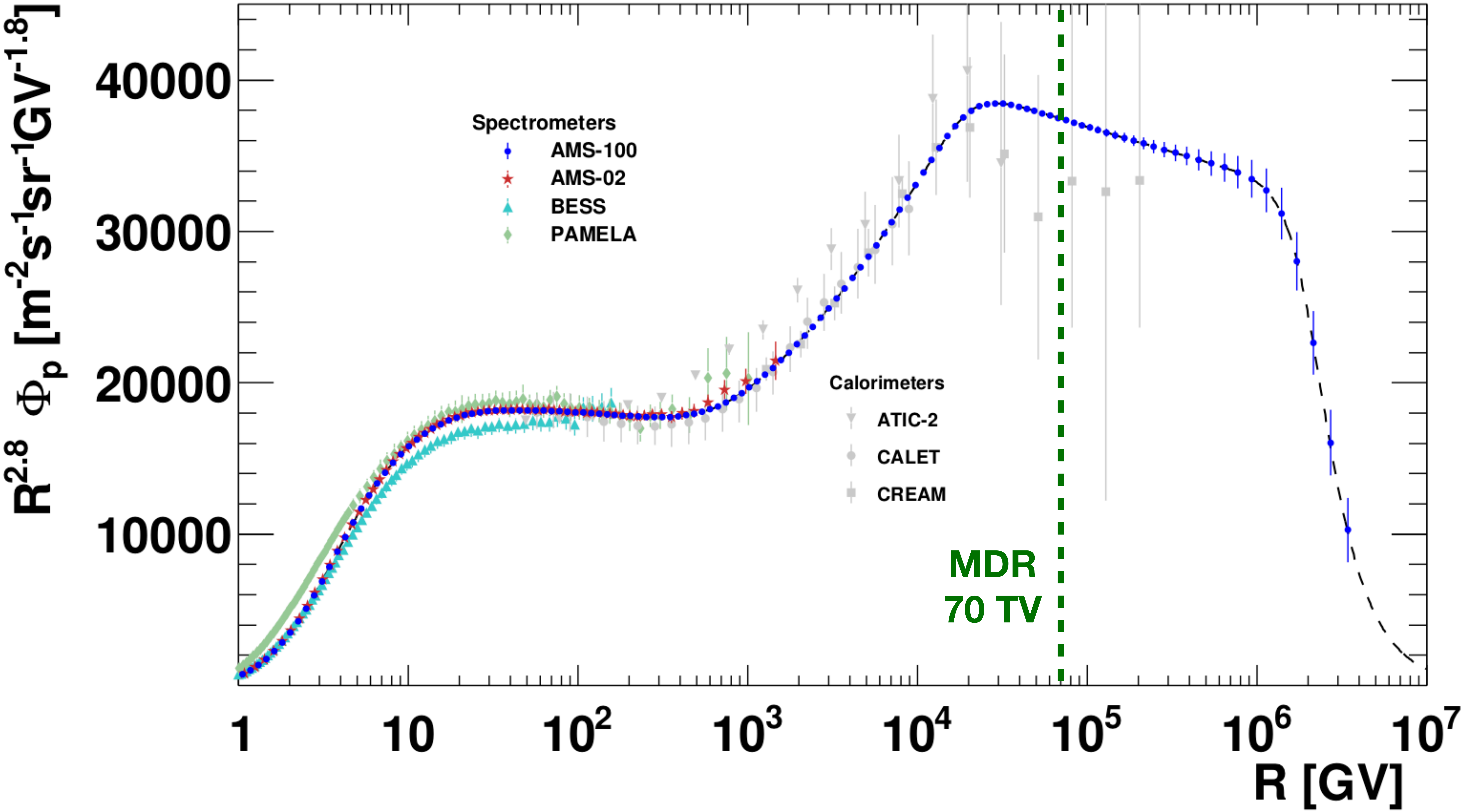
AMS-100

Weight: 40 t **Readout-Channels: 8 10^6** **Power: 15 kW** **Measurement Time: 10 years**

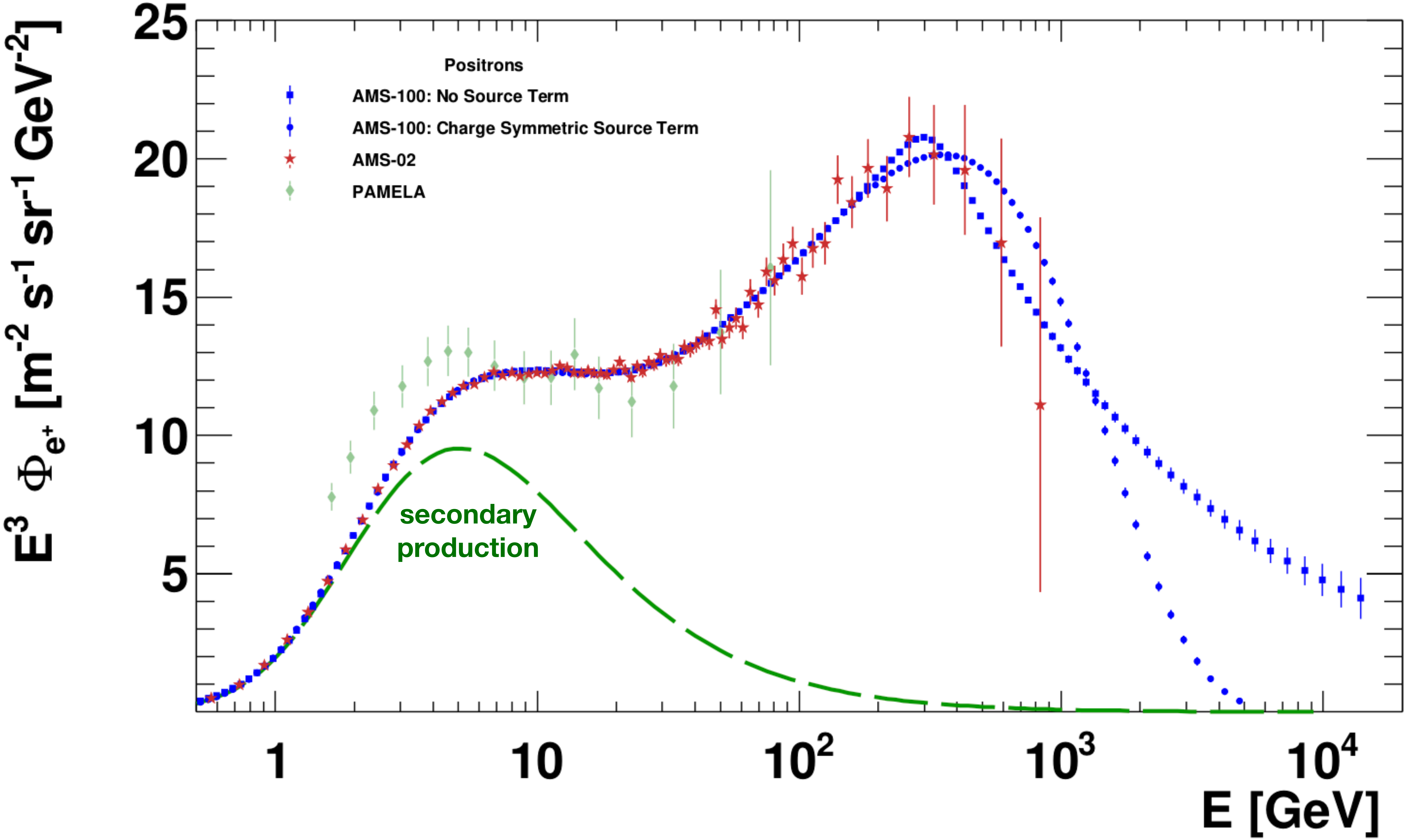
MDR: 70 TV **Acceptance: 100 m² sr** **B-Field: 1 Tesla** **Calorimeter: 70 X_0, 4λ**

Th. Kirn, "The AMS-100 experiment: The next generation magnetic spectrometer in space", Nucl.Instrum.Meth.A 1040 (2022) 167215 • Proceedings of: VCI2022

AMS-100 will measure light Nuclei in Cosmic Rays up to the maximum energy that can be reached by cosmic ray accelerators in our galaxy.

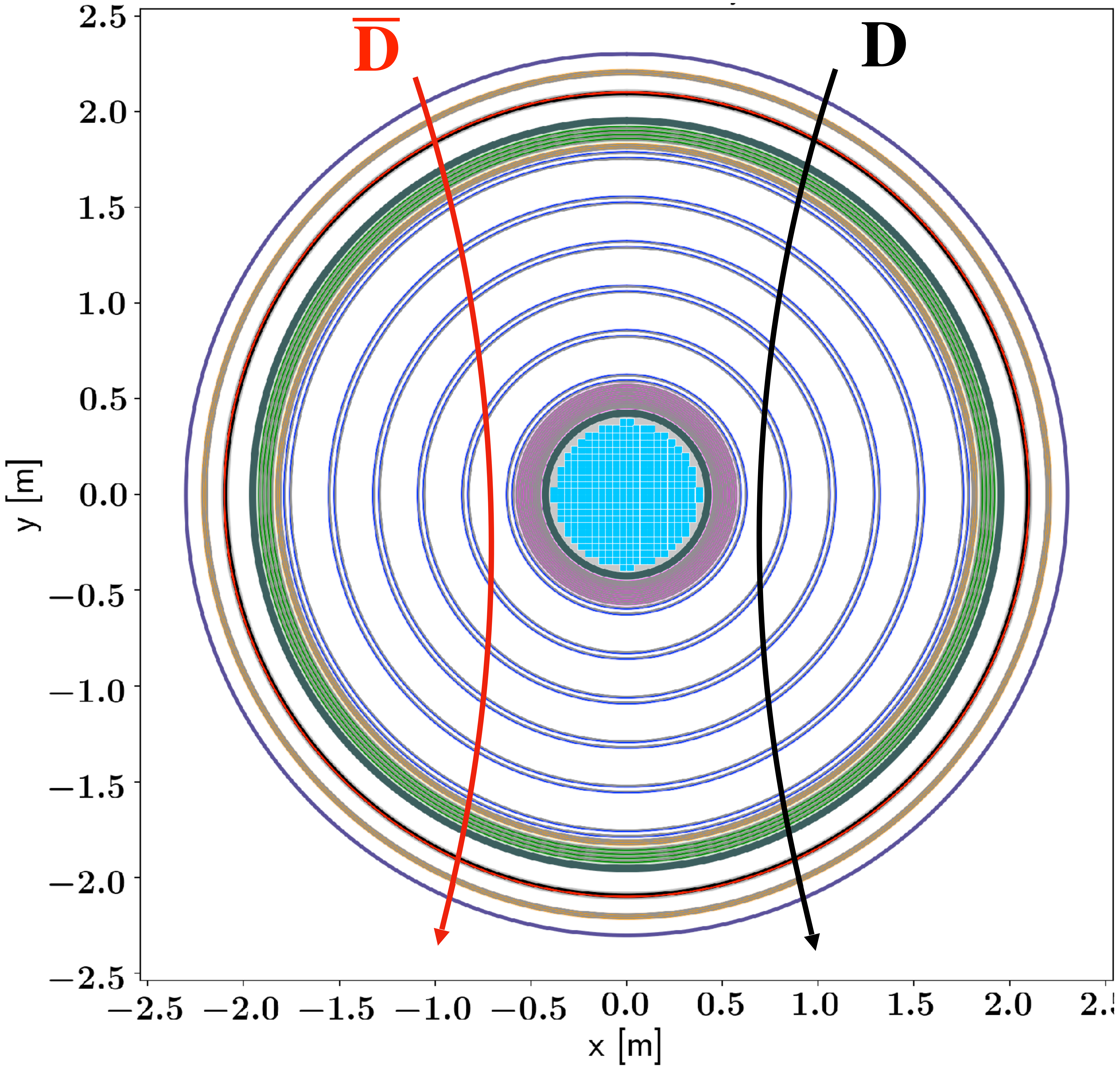


Positrons in Cosmic Rays

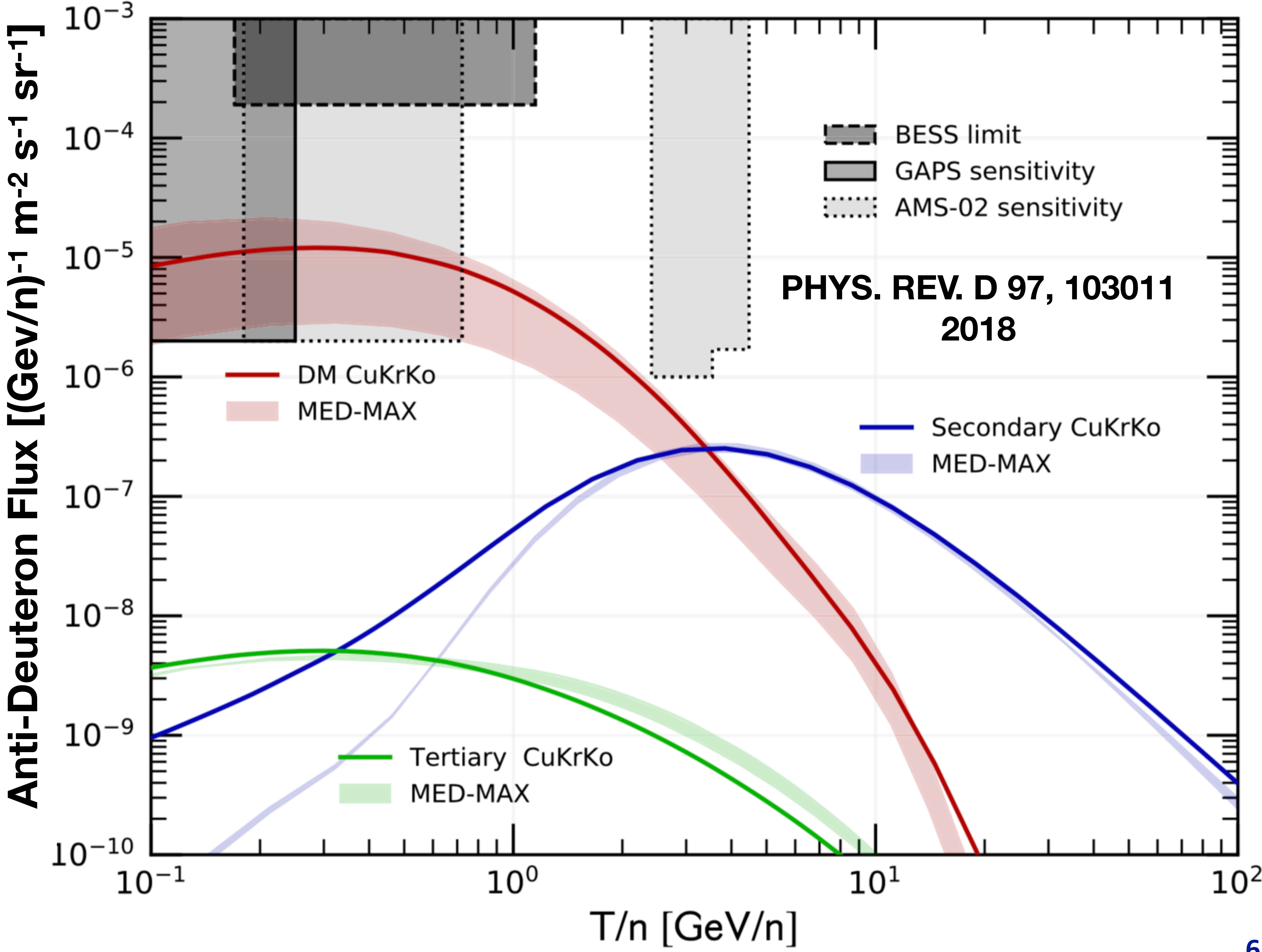


Anti-Deuterons are a very sensitive probe for New Physics in Cosmic Rays

As a Magnetic Spectrometer AMS-100
can separate Anti-Matter from Matter.

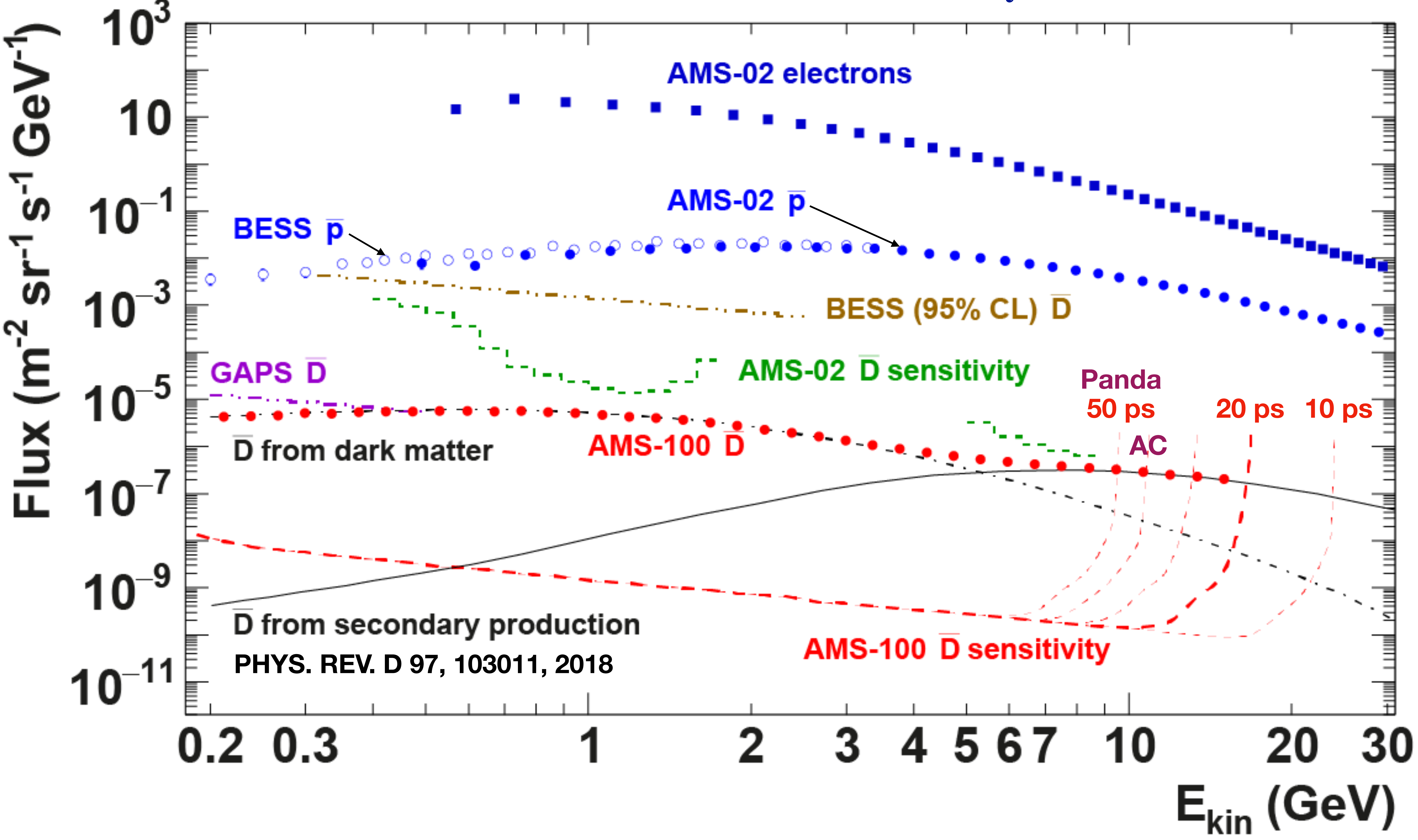


M. Korsmeier, F. Donato, N.Fornengo



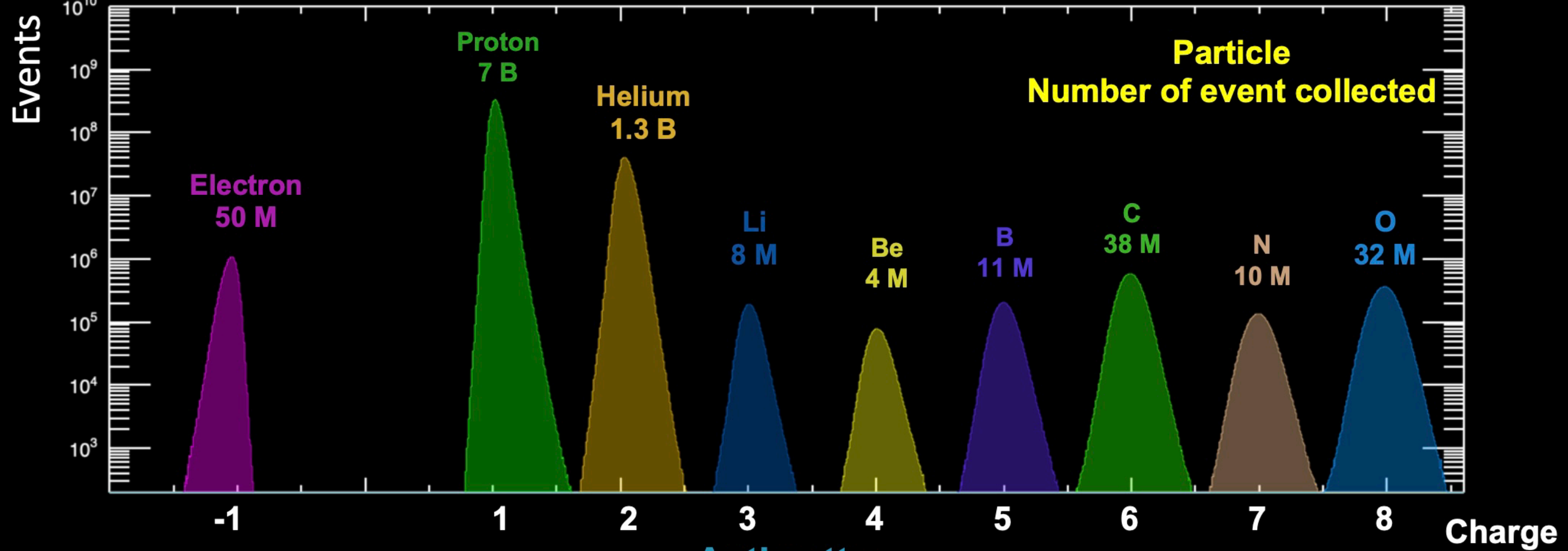
PHYS. REV. D 97, 103011 2018

Z = − 1 Particles in Cosmic Rays

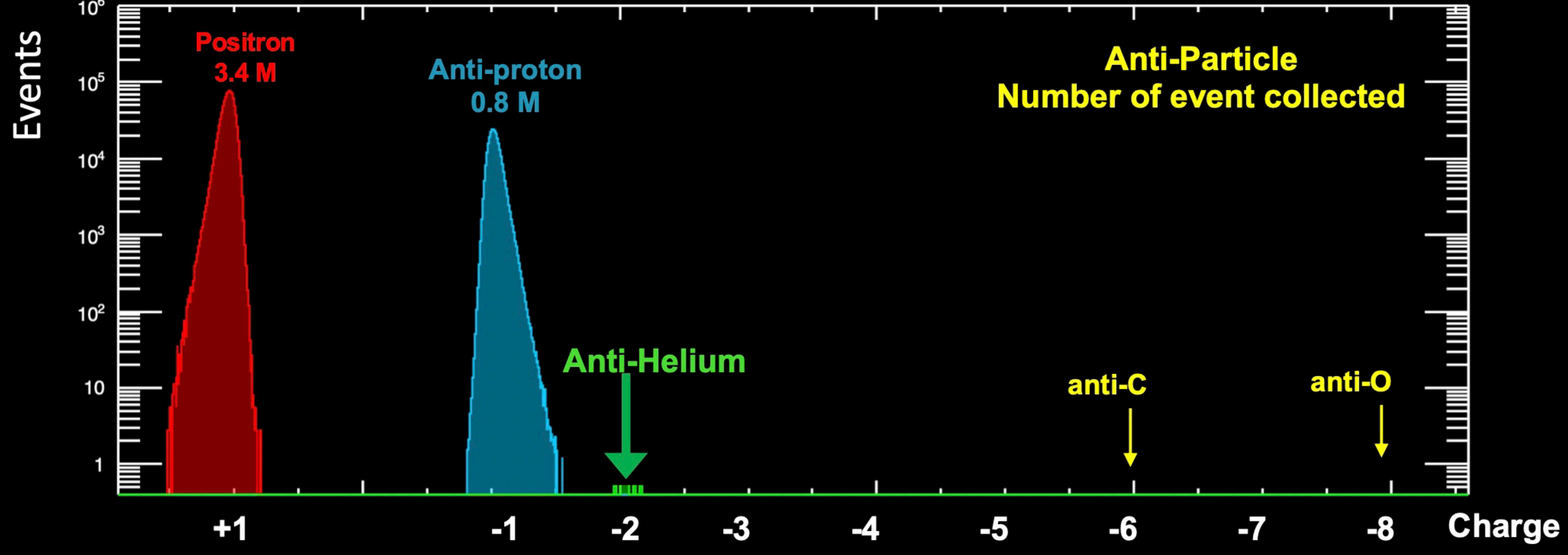


PHYS. REV. D 97, 103011, 2018

AMS-02 Measurements of Matter and Antimatter



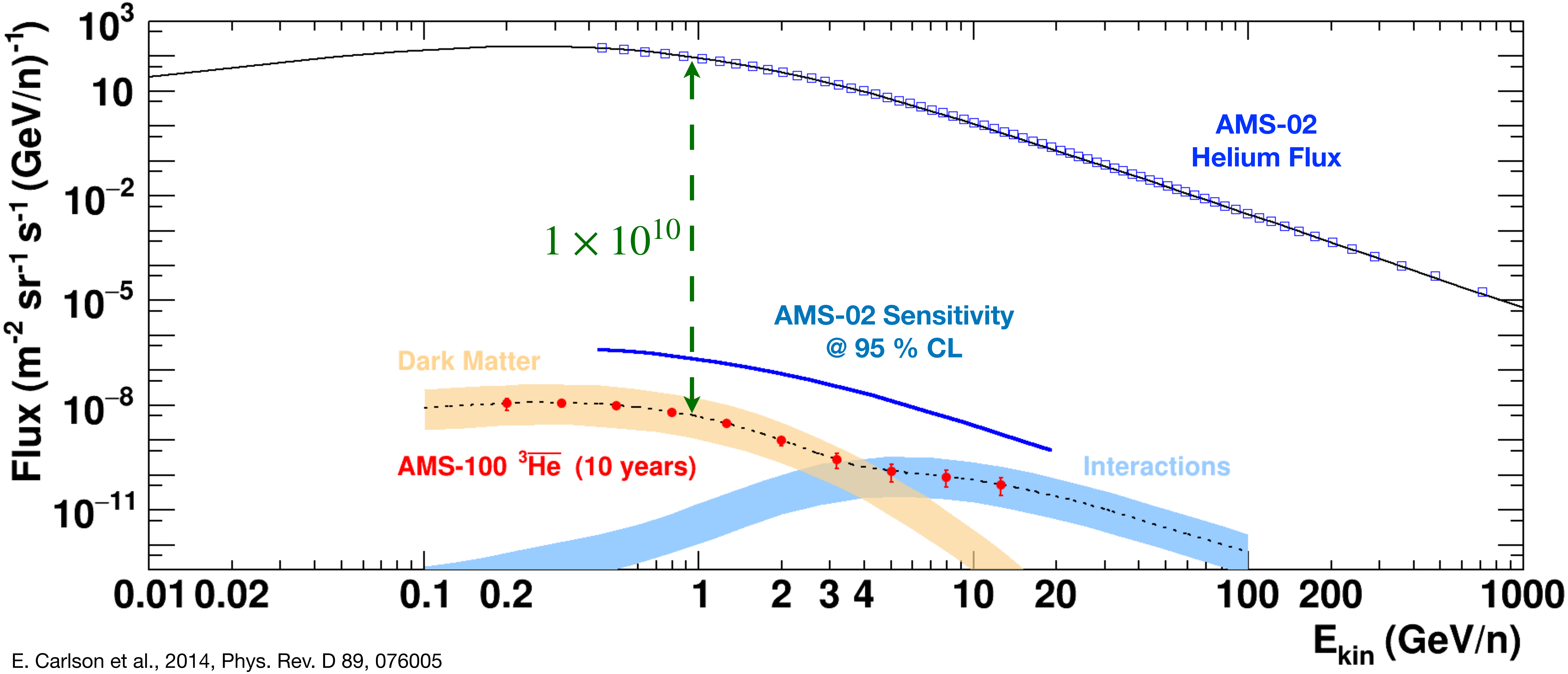
Matter



Antimatter

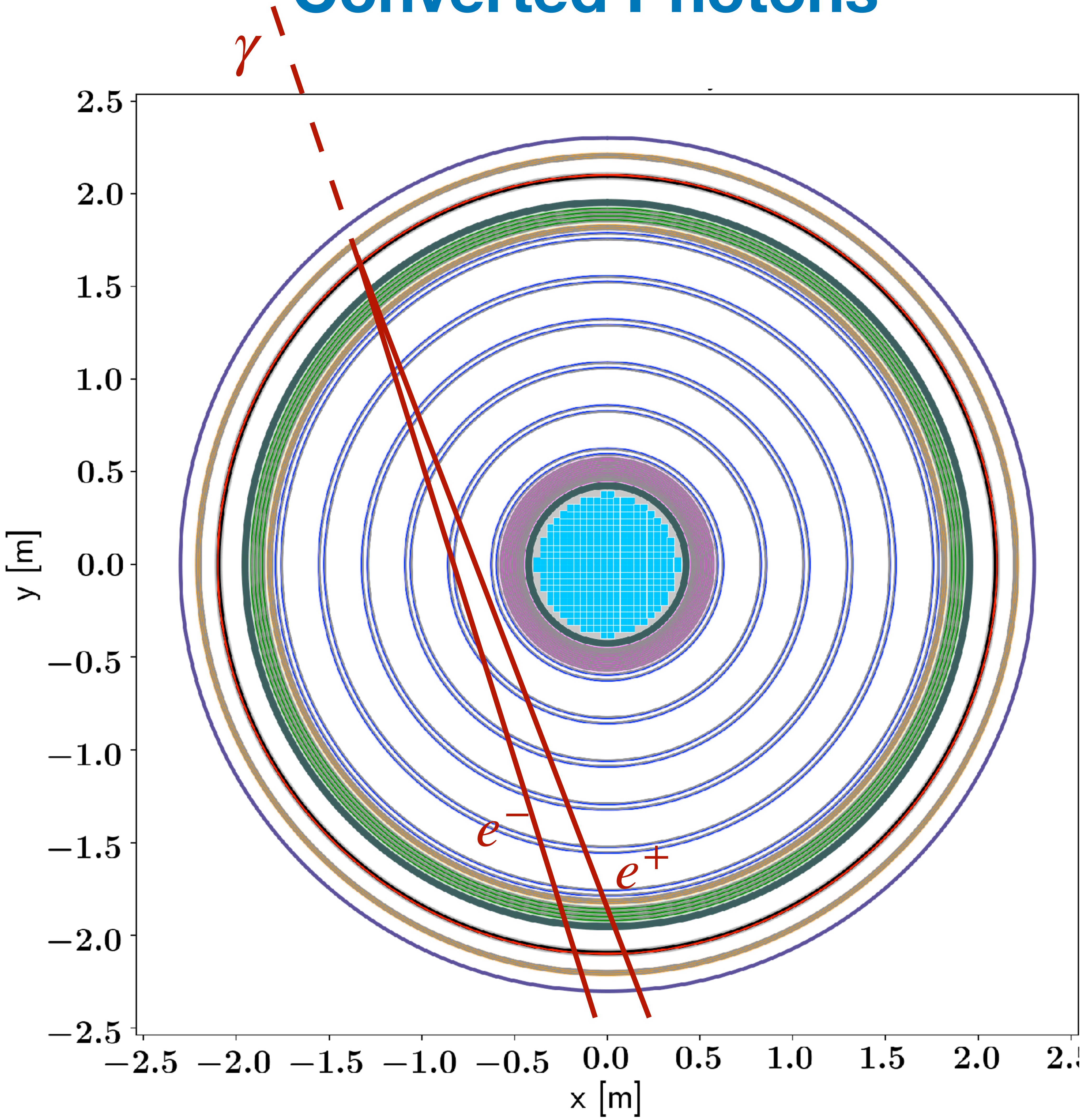
V. Choutko
COSPAR 2022
Athens

Anti-Helium in Cosmic Rays

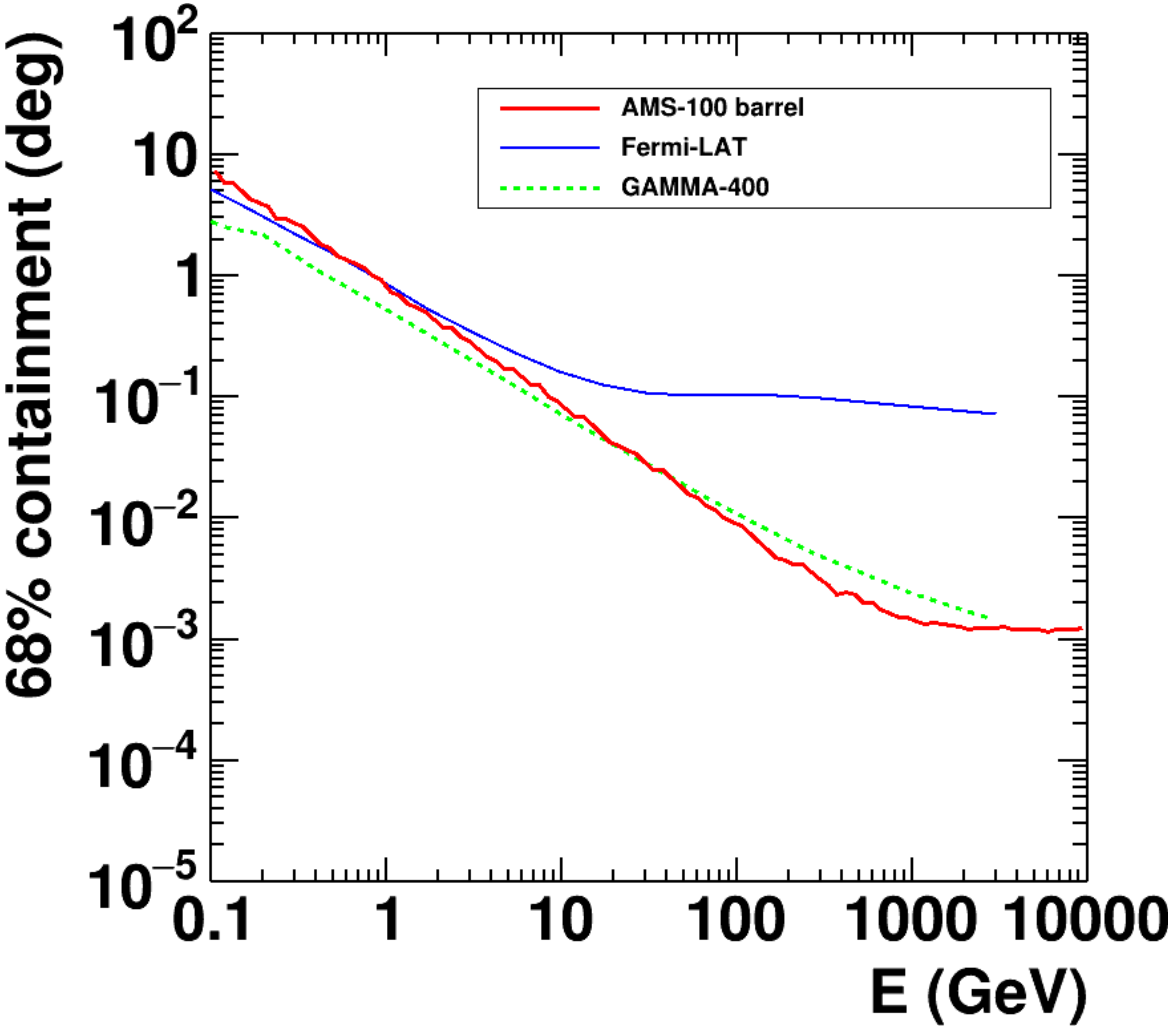


E. Carlson et al., 2014, Phys. Rev. D 89, 076005
M. Cirelli et al., 2014, JHEP 1408, 009
A. Coogan and S. Profumo, 2017, Phys. Rev. D 96, 083020

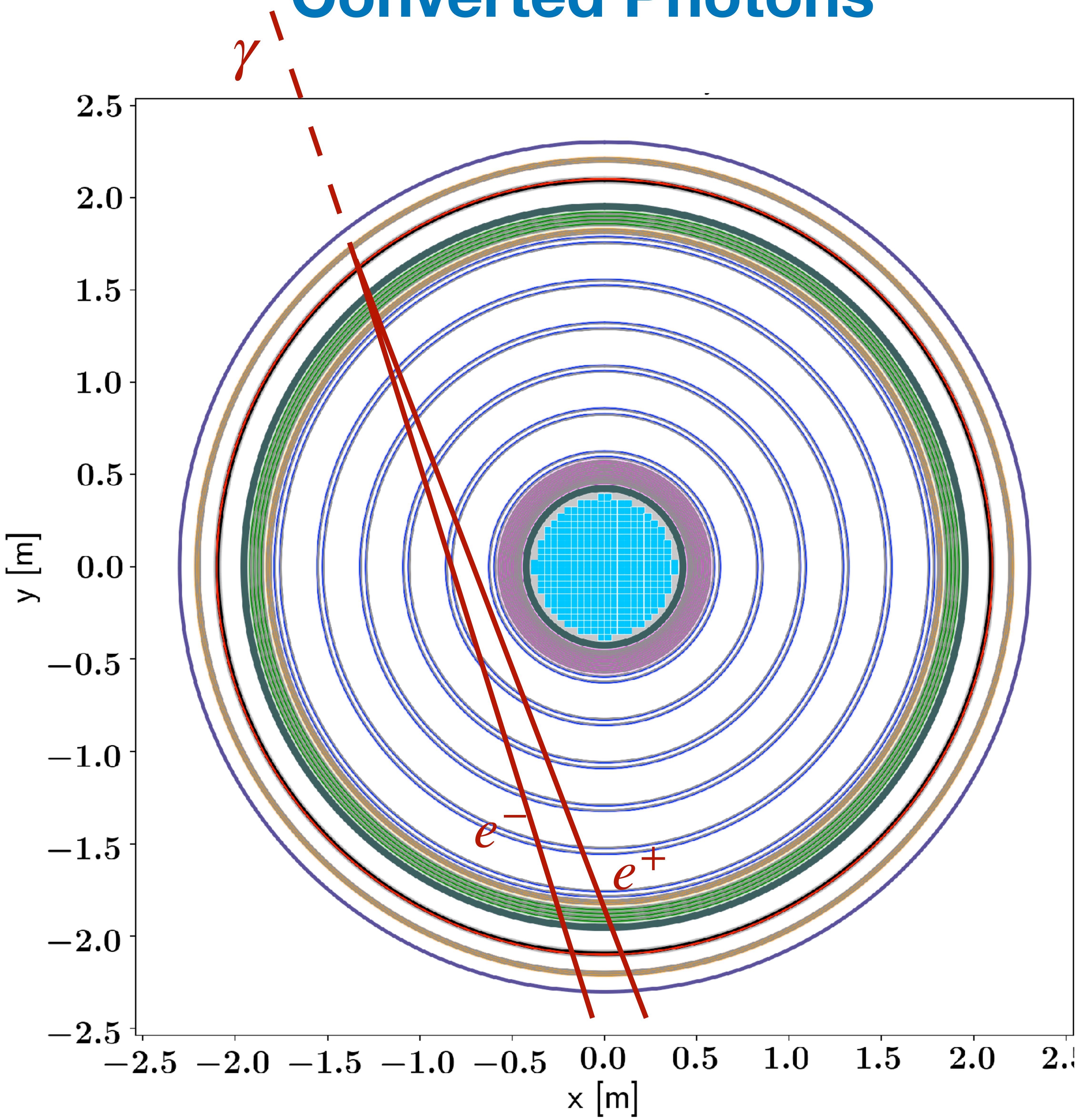
AMS-100 Converted Photons



Angular Resolution for Converted Photons



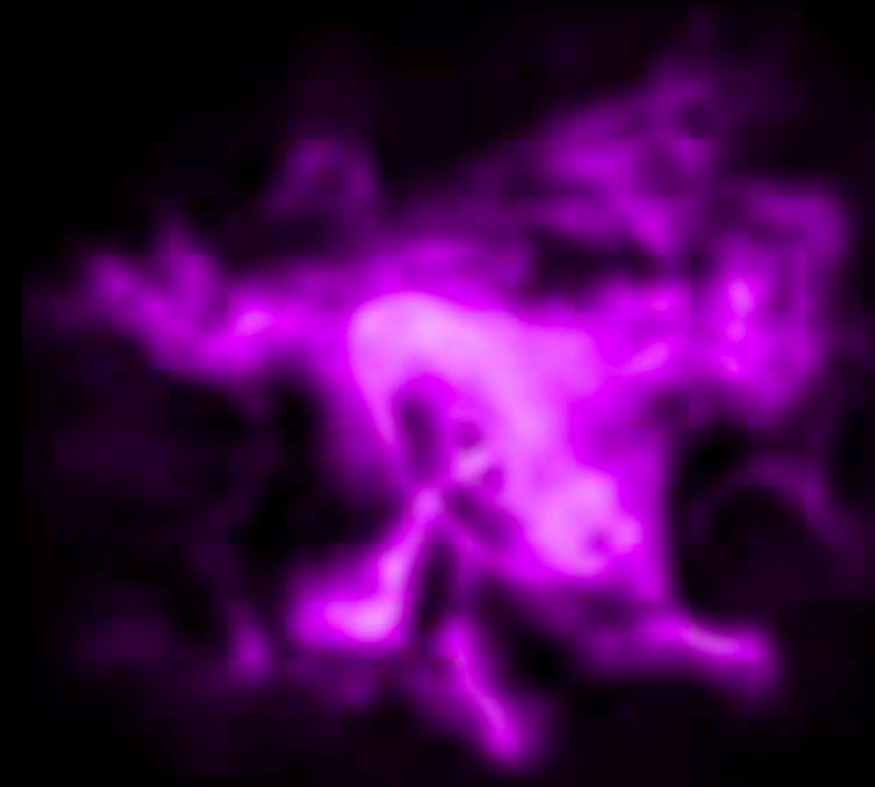
AMS-100
Converted Photons



Crab Nebula with Chandra (blue and white), Hubble (purple), and Spitzer (pink) data.

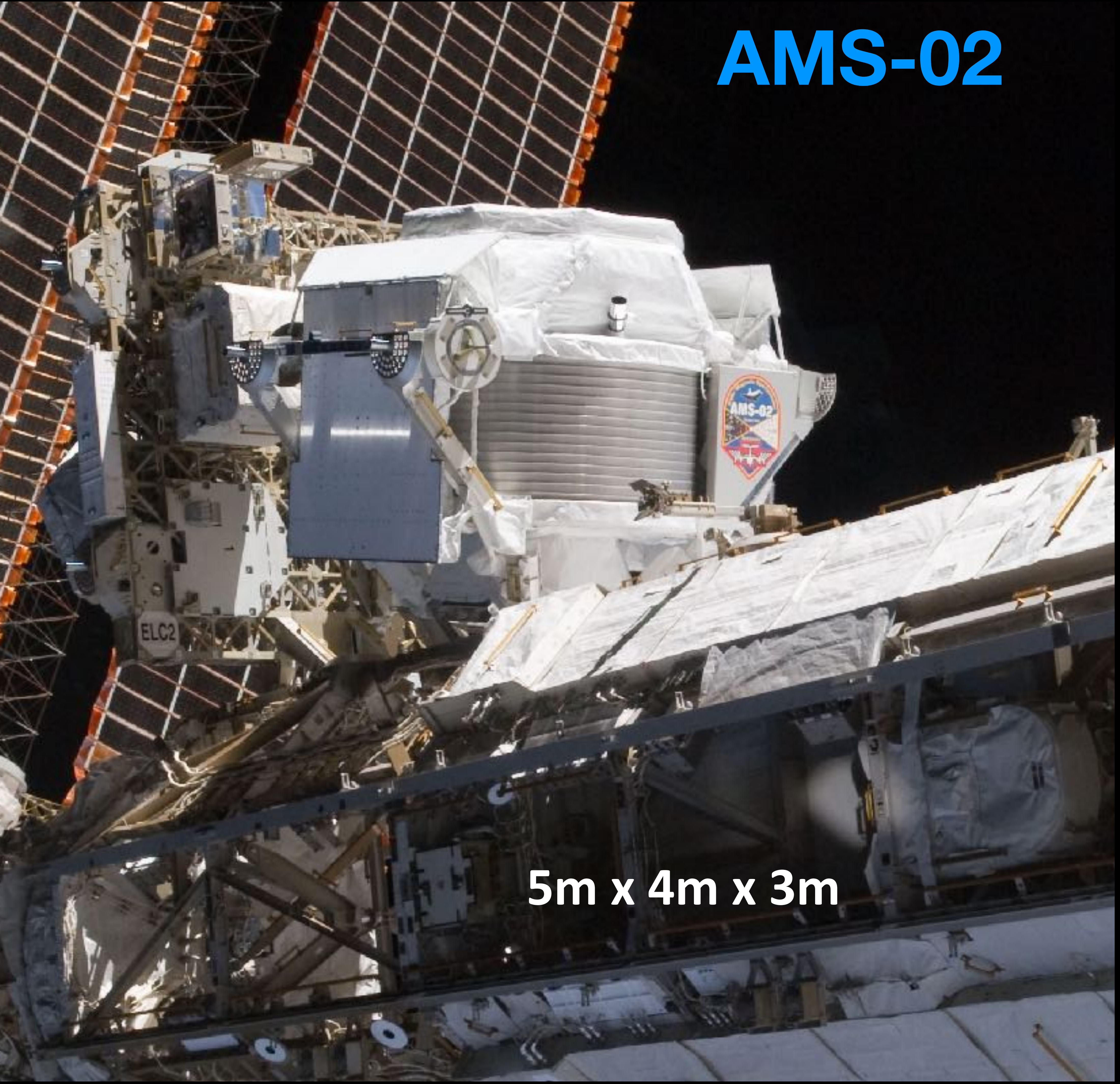
FERMI, CTA

AMS-100

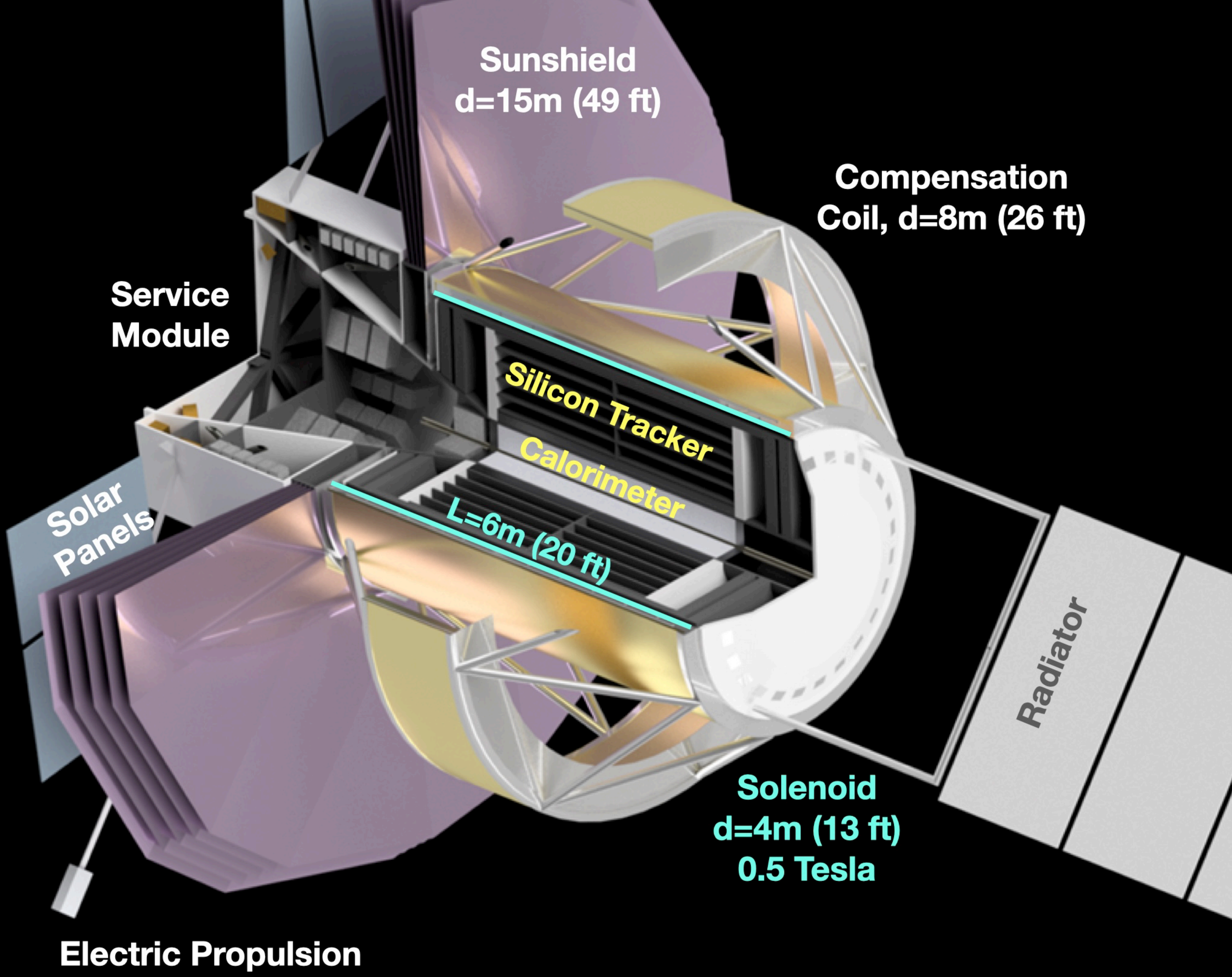


CRAB Nebula TeV - Photons

AMS-02



5m x 4m x 3m



- AMS-02 has collected more than 200 Billion cosmic rays since 2011 and will continue to take data for the lifetime of the ISS. It is a unique scientific instrument in Space.
- AMS-100 will improve the sensitivity of AMS-02 by a factor 1000 and will explore a completely new territory in precision cosmic ray physics.