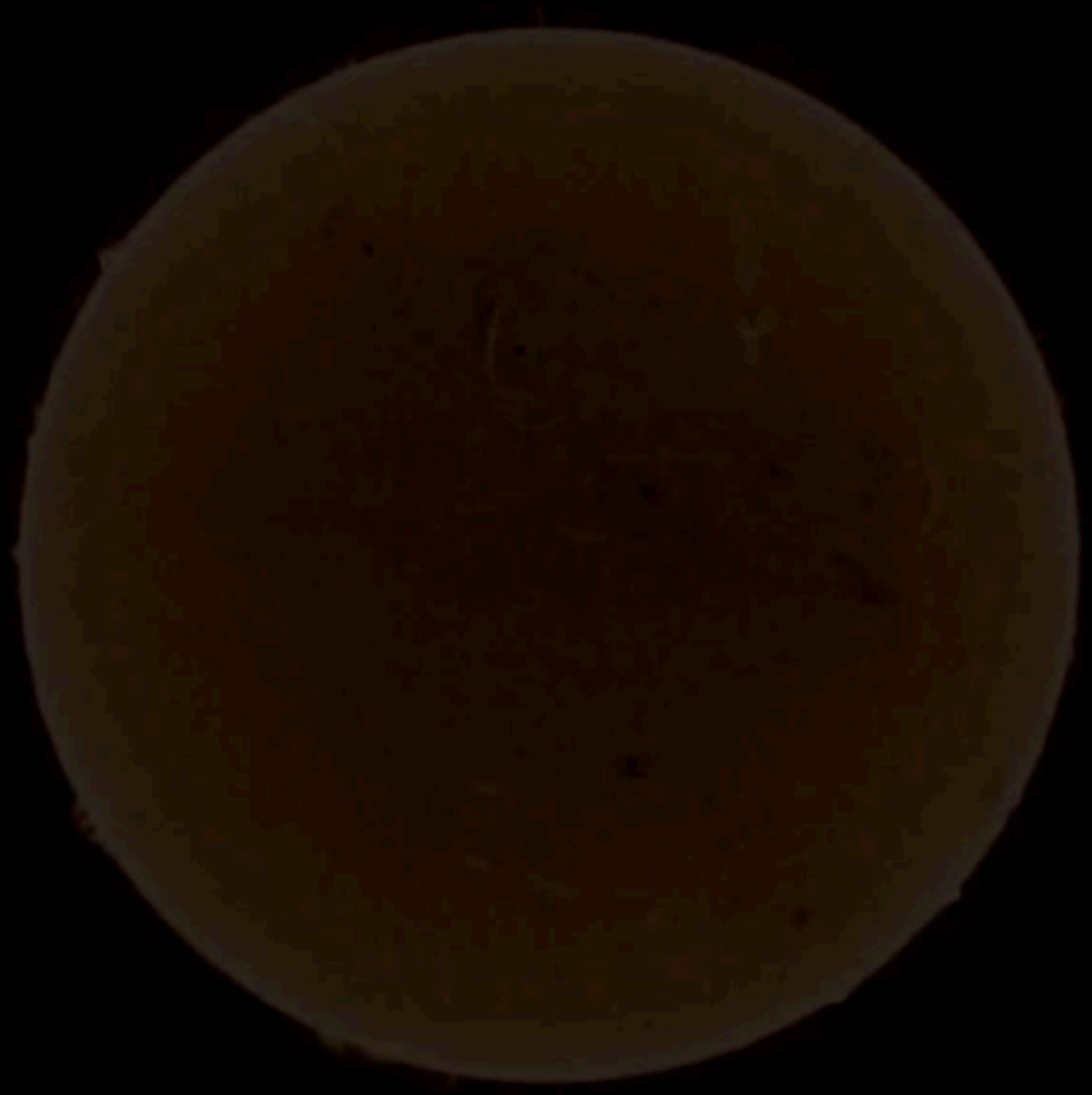
Superconductivity in space: the SRS2 project and beyond

R. Battiston
INFN-TIFPA and University of Trento
Italian Space Agency

CEA Saclay

“Anything a man could imagine,
other men could make it possible”

Jules Verne



The Consortium

SR2S

Space Radiation Superconducting Shield

SPA 2012 2.2.02 Key technologies for in-space activities

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Commissariat a l’Energie Atomique
Thales Alenia Space Italia
Compagnia Generale dello Spazio
Columbus Superconductors
Carr Communication

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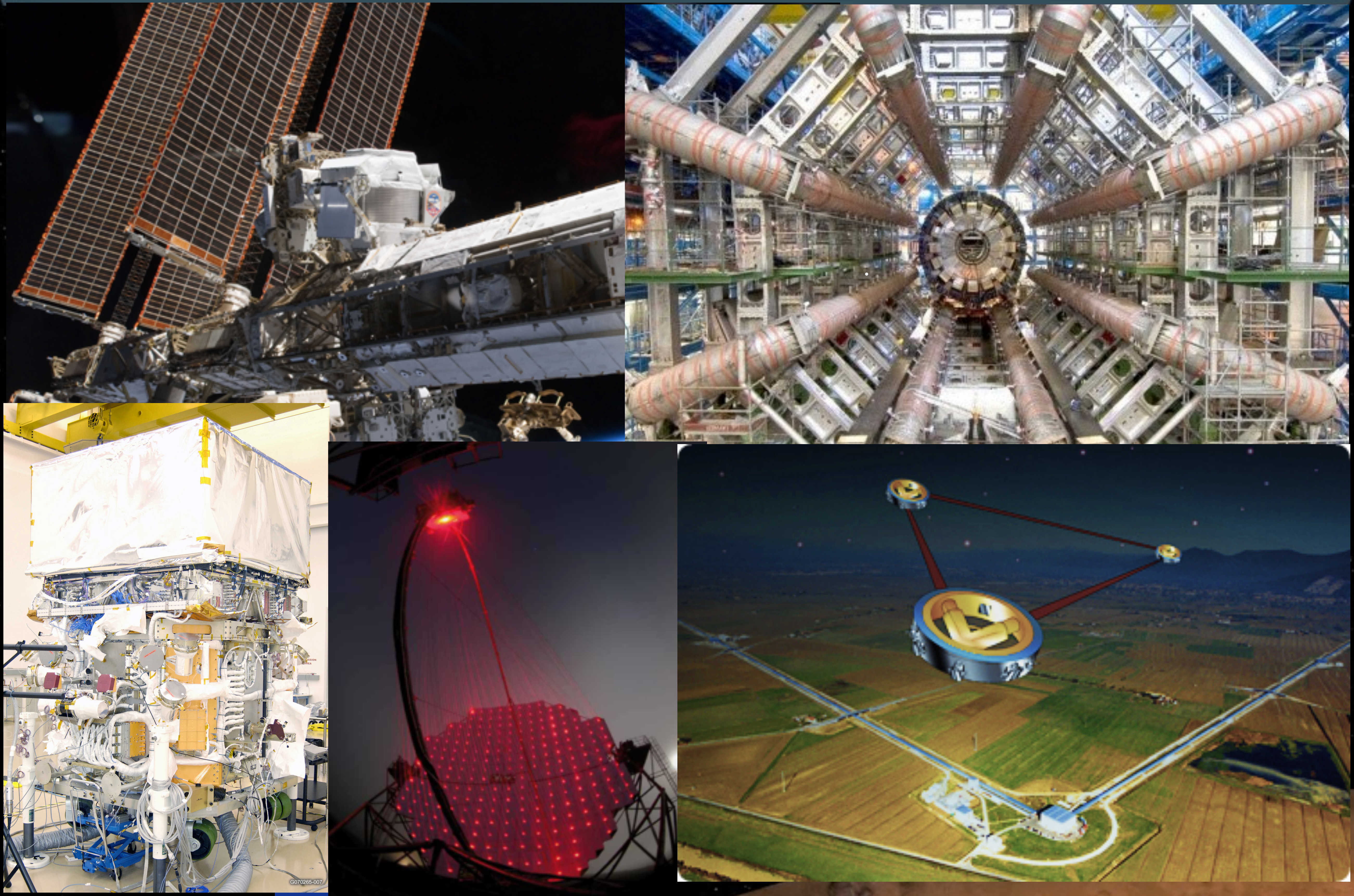

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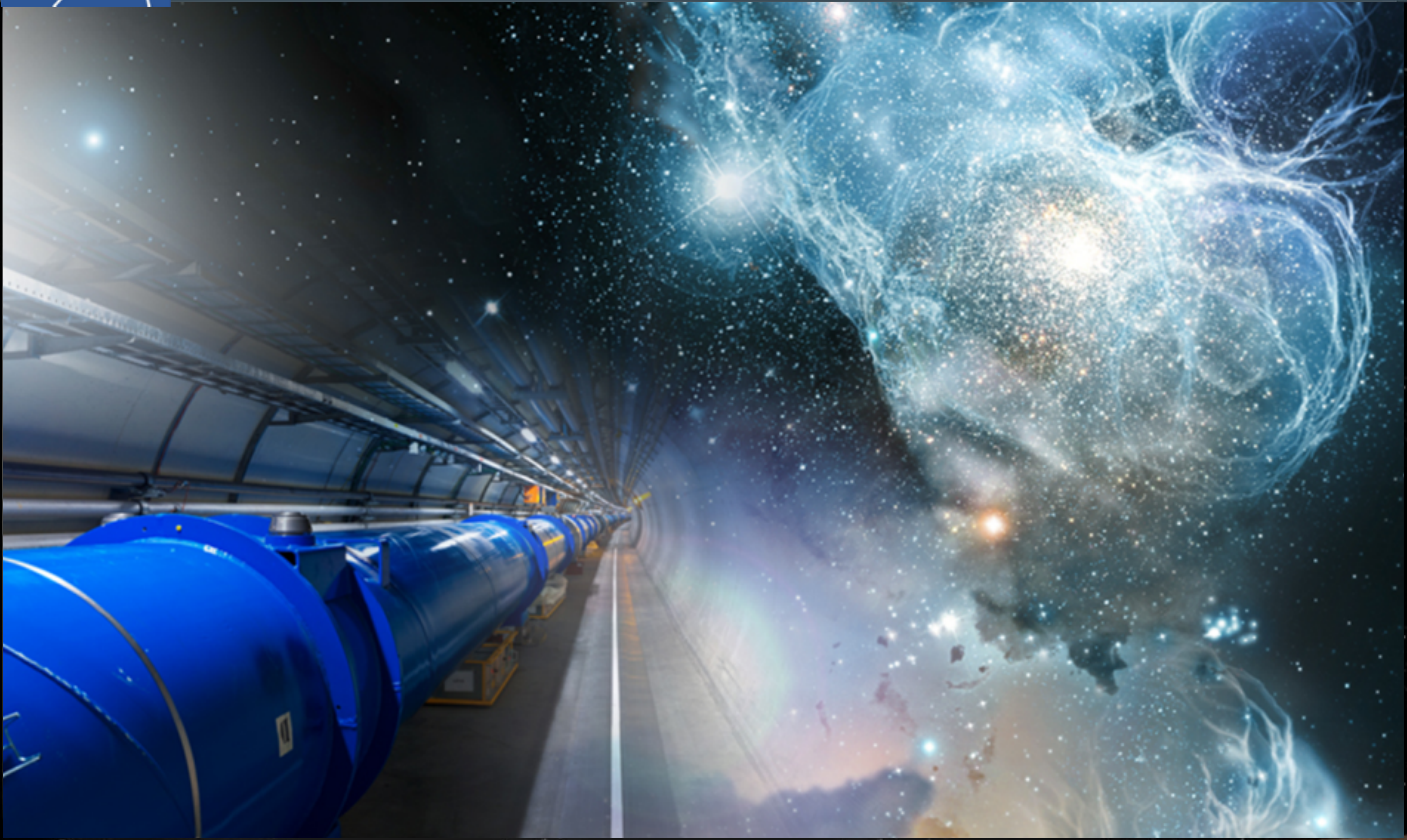
European Laboratory for Nuclear Research



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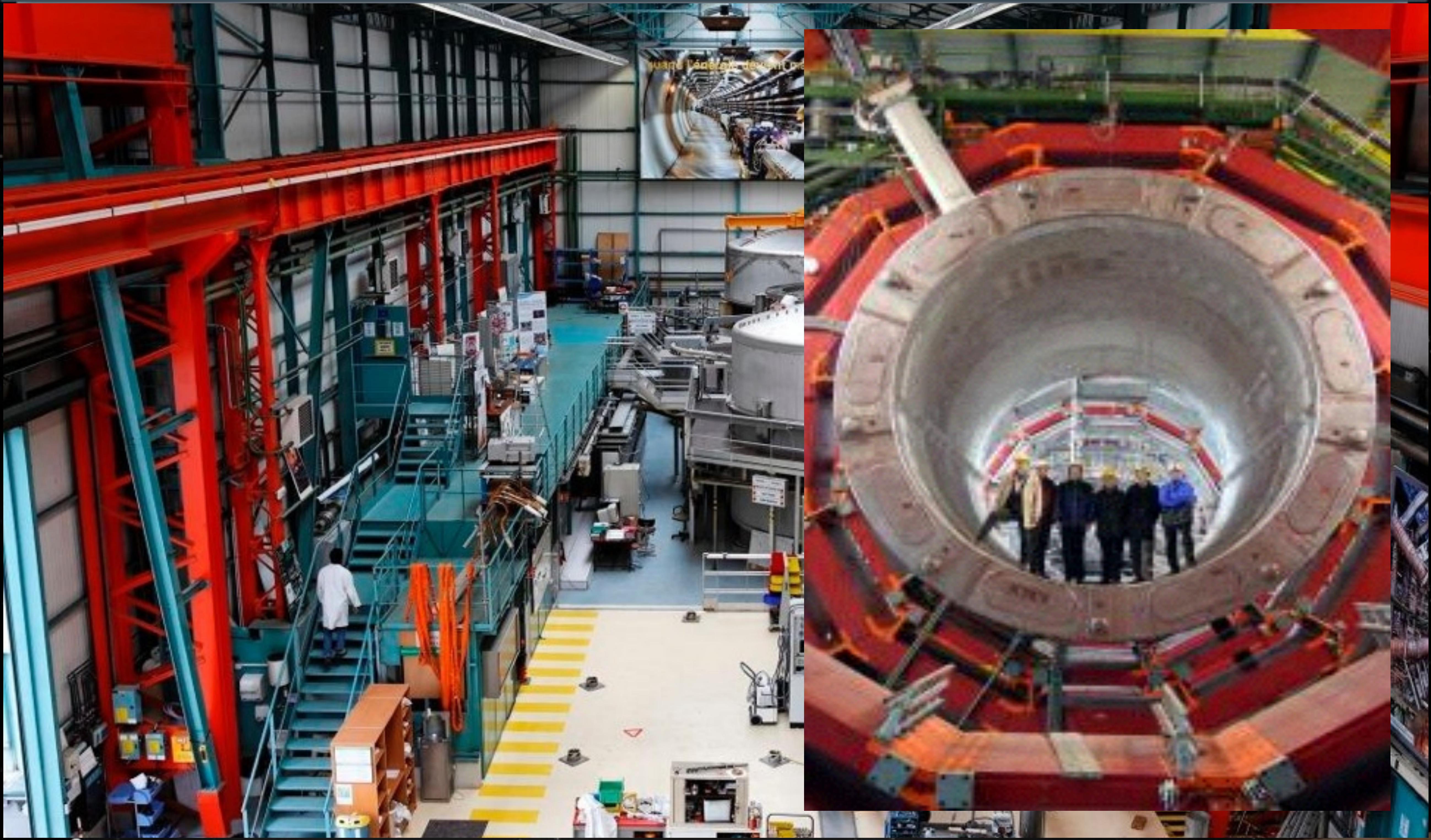

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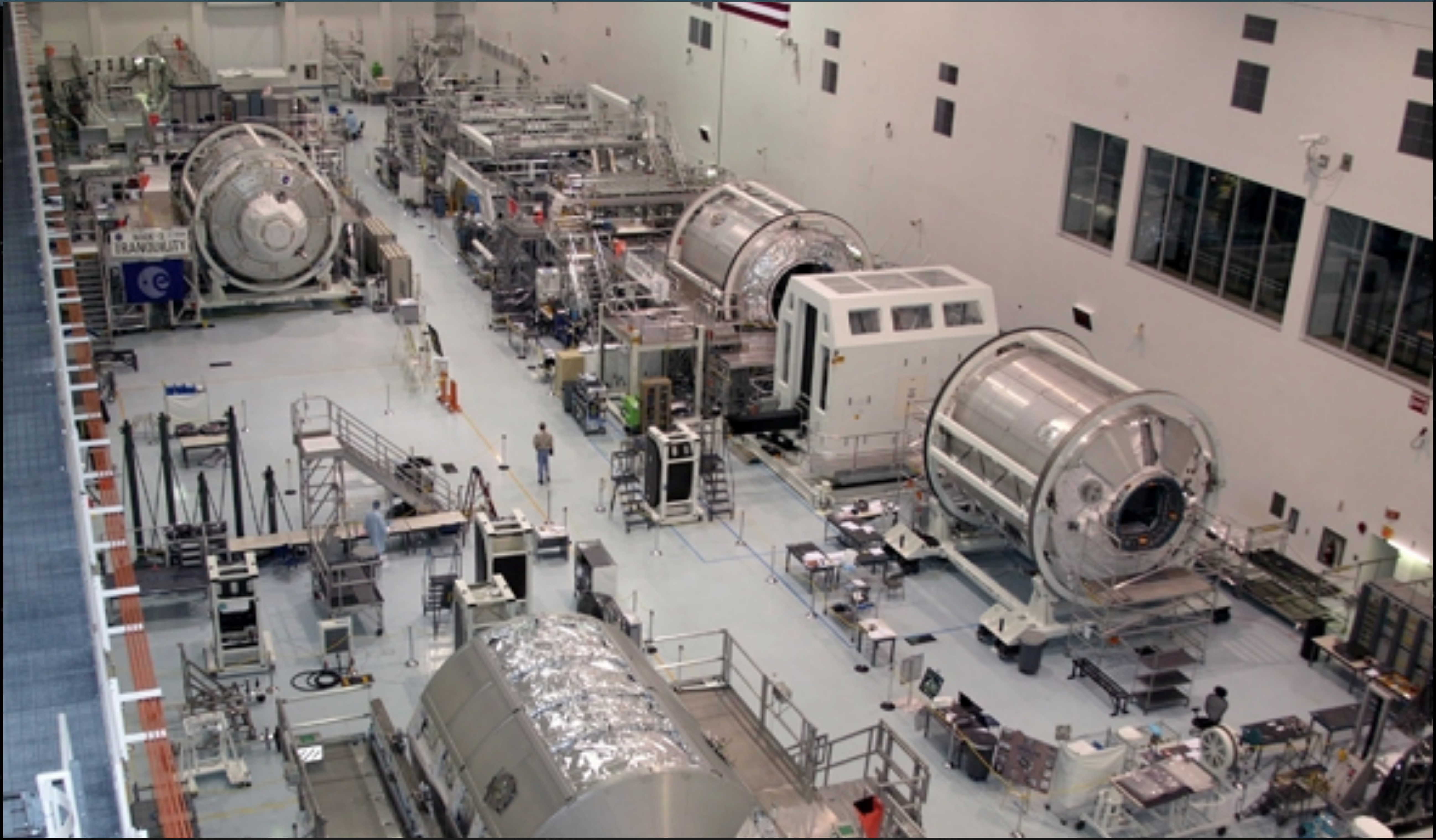
Torino



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Companía Generale dello Spazio - Milano

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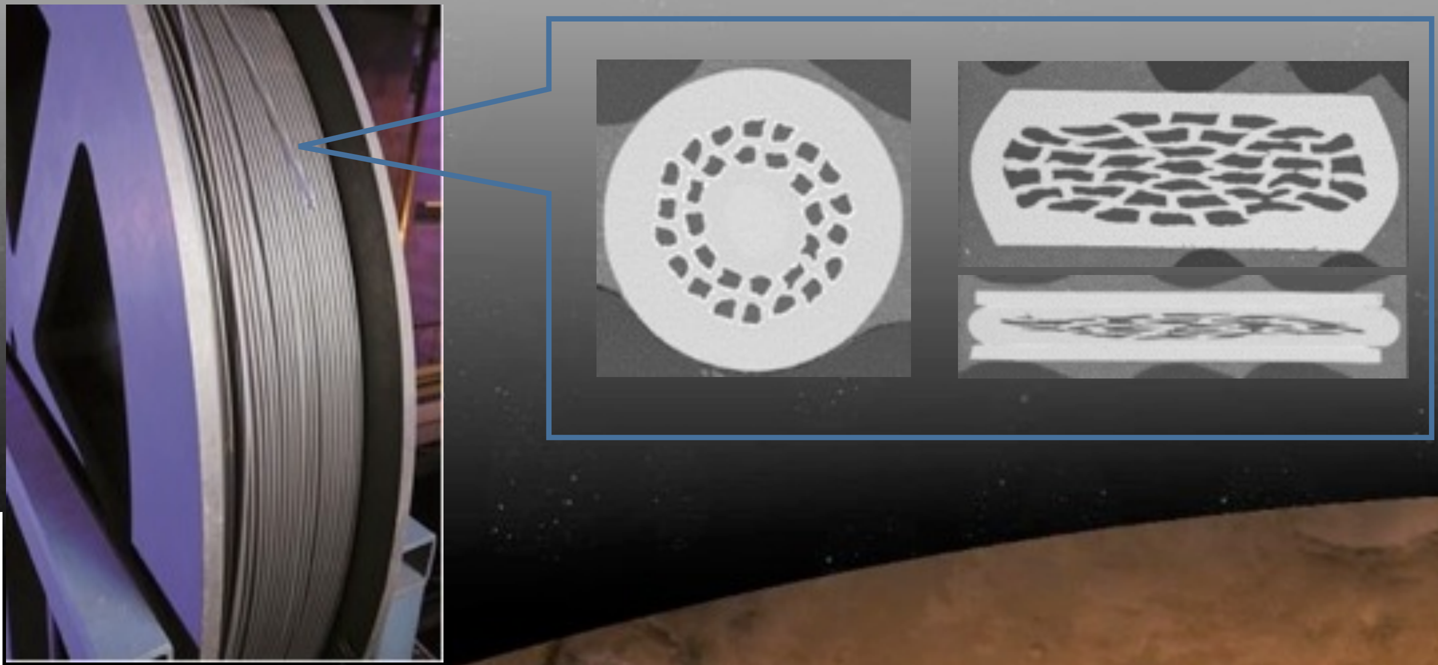
The Company

- **Columbus** is a world leader in the production of the new superconductor **MgB_2**, that is distinguished for its workability in **long lengths** and **high performances**
- The actual plant is fully operational for **MgB_2 wire production** and has recently completed its scaling up (plant area now is **4’400 m^2**)
- **MgB_2 chemical synthesis** is now also fully implemented
- Wire unit length today possible up to **20 Km** in combination with a nominal plant full capacity exceeding **5’000 Km/ year**
- Columbus **MgB_2 production is** already **implemented in commercial products** and has a **long record** of fully tested and qualified wires



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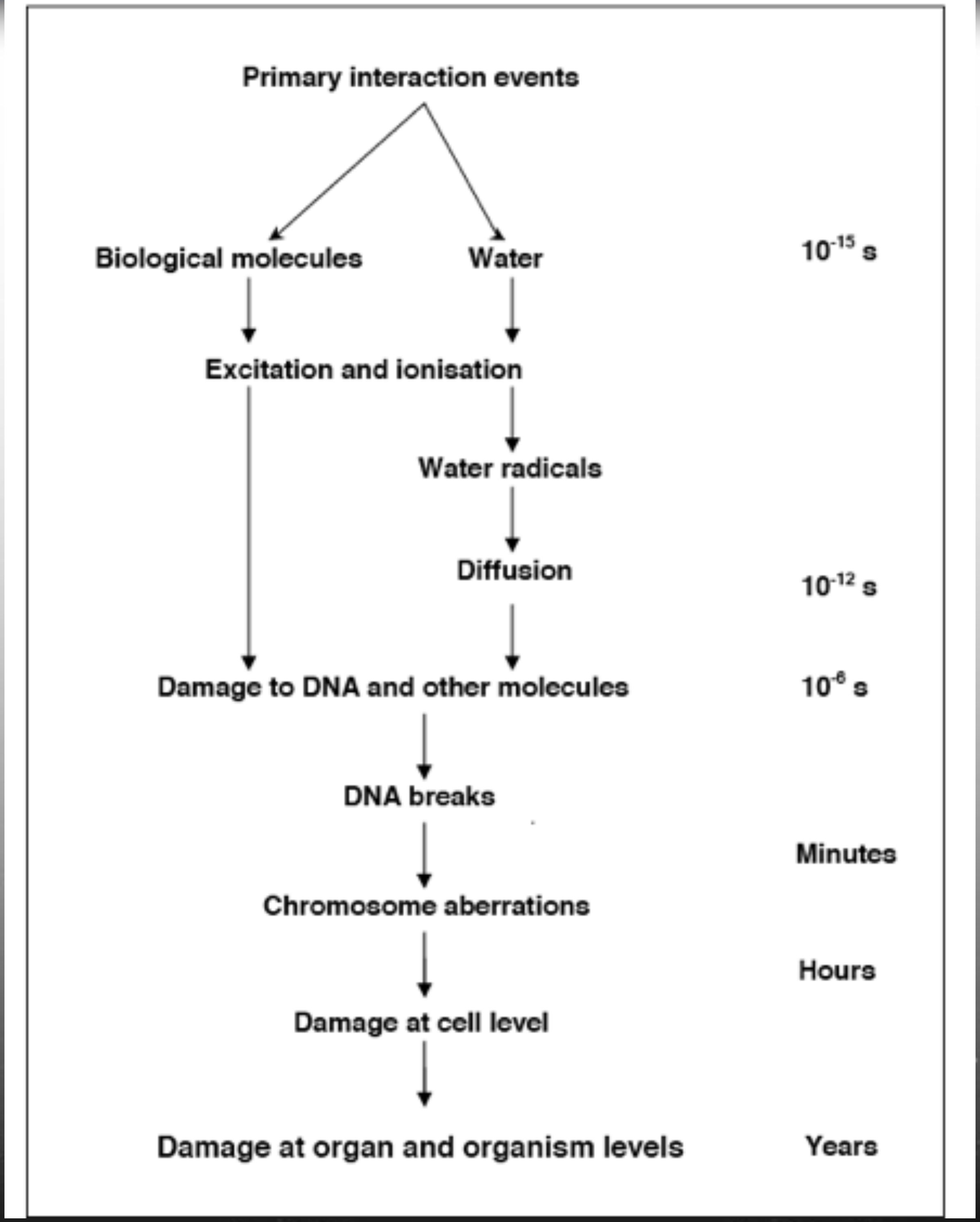
FP7 SR2S program (2013-15)

R. Battiston, Università di Trento, INFN, Italy
W.J. Burger, Università di Perugia, INFN, Italy
F. Ambroglini, INFN-Perugia, Italy
R. Musenich, INFN-Genova, Italy
V. Calvelli, INFN-Genova, Italy
S. Farinon, INFN-Genova, Italy
P. Spillantini, INFN-Firenze, Italy
G. Volpini, INFN-Milan, Italy
M. Sorbi, INFN-Milan, Italy
G. Laurenti, INFN-Bologna, Italy
M. Guerzoni, INFN-Bologna, Italy
P. Rapagnani, INFN-Roma1. Italy
B. Spataro, INFN-Frascati, Italy
P. Fazilleau, CEA, France
B. Baudoy, CEA, France
L. Quettier, CEA, France
A. Ballarino, CERN. Switzerland
C. Gargiulo, CERN, Switzerland
B.Romain, CEA, France
L. Rossi, CERN, Switzerland
V.I. Datskov, CERN, Switzerland
D. Schinzel, CERN, Switzerland
G. Grasso, Columbus Superconductors, Italy
S. Brisigotti, Columbus Superconductors, Italy
D. Nardelli, Columbus Superconductors, Italy
V. Cubeda, Columbus Superconductors, Italy
M. Tropeano, Columbus Superconductors, Italy
R. Piccardo, Columbus Superconductors, Italy
F. Maillard, CGS, Italy
E. Monchieri, CGS, Italy
F. Zurla, CGS, Italy
G. Ober, CGS, Italy
E. Tracino, Thales Alenia Space, Italy
M. Giraudo, Thales Alenia Space, Italy
R. Destefanis, Thales Alenia Space, Italy
C. Lobascio, Thales Alenia Space, Italy
E. Gaia, Thales Alenia Space, Italy
B. Bordini CERN, Switzerland

Radiation effects on biological tissues



Primary interaction events

Biological molecules — Water — 10^{-15} s

Excitation and ionisation

Water radicals

Diffusion — 10^{-12} s

Damage to DNA and other molecules — 10^{-6} s

DNA breaks

Minutes

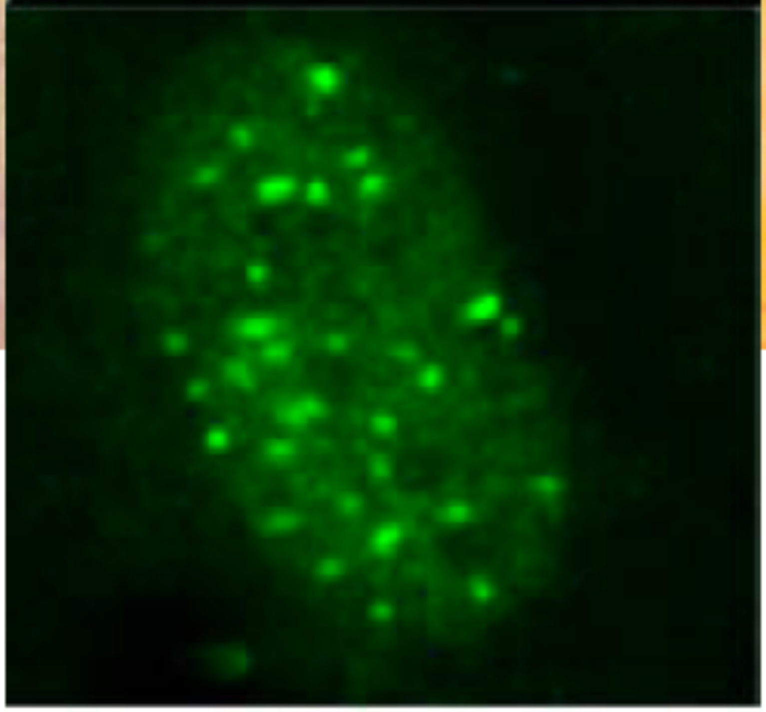
Chromosome aberrations

Hours

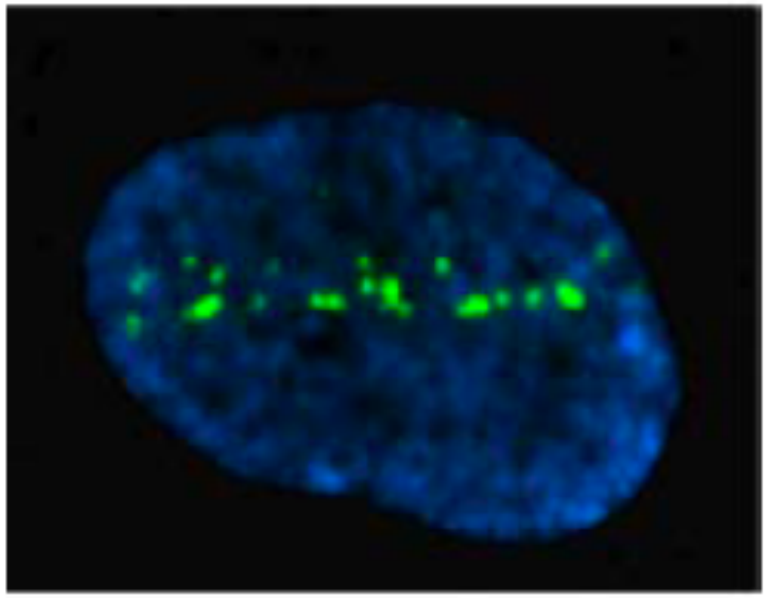
Damage at cell level

Damage at organ and organism levels — Years

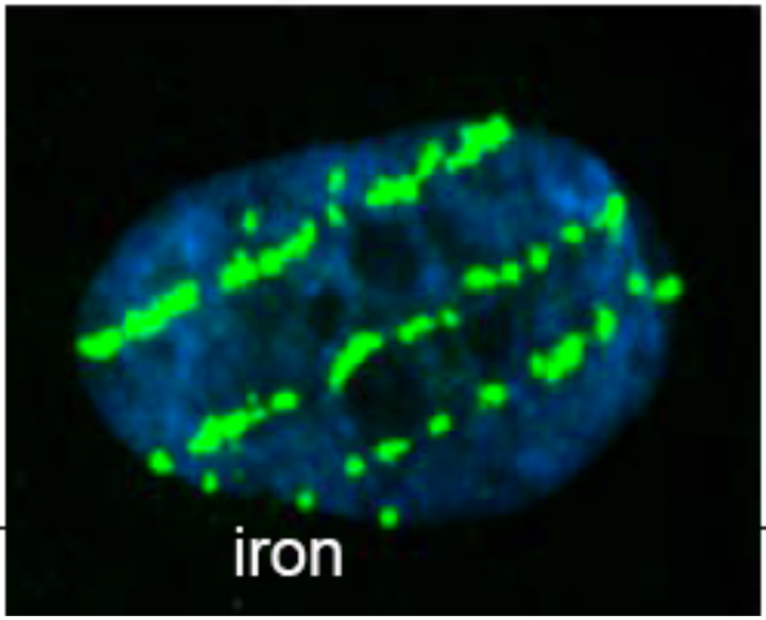
Tracks in cells



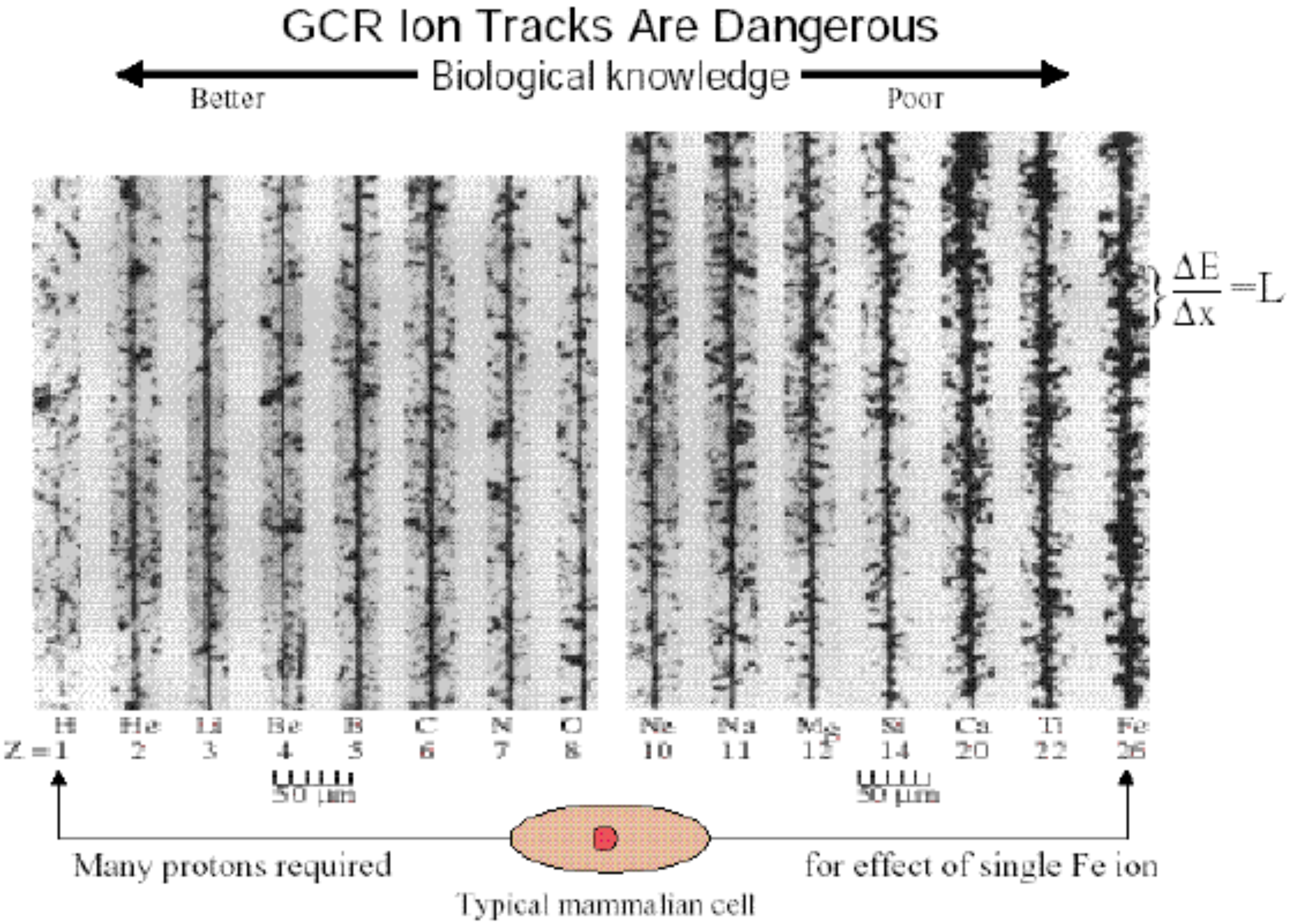
γ-rays



silicon

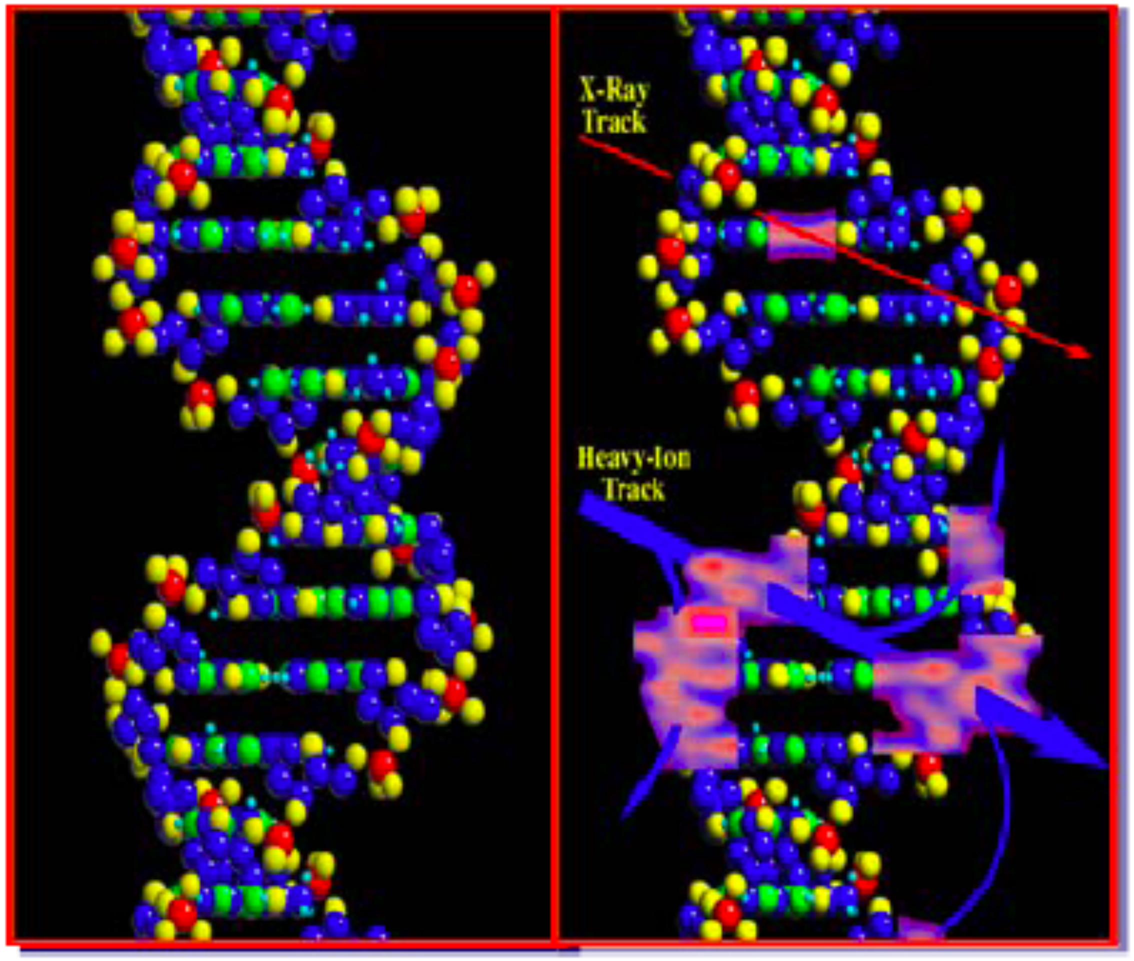


iron

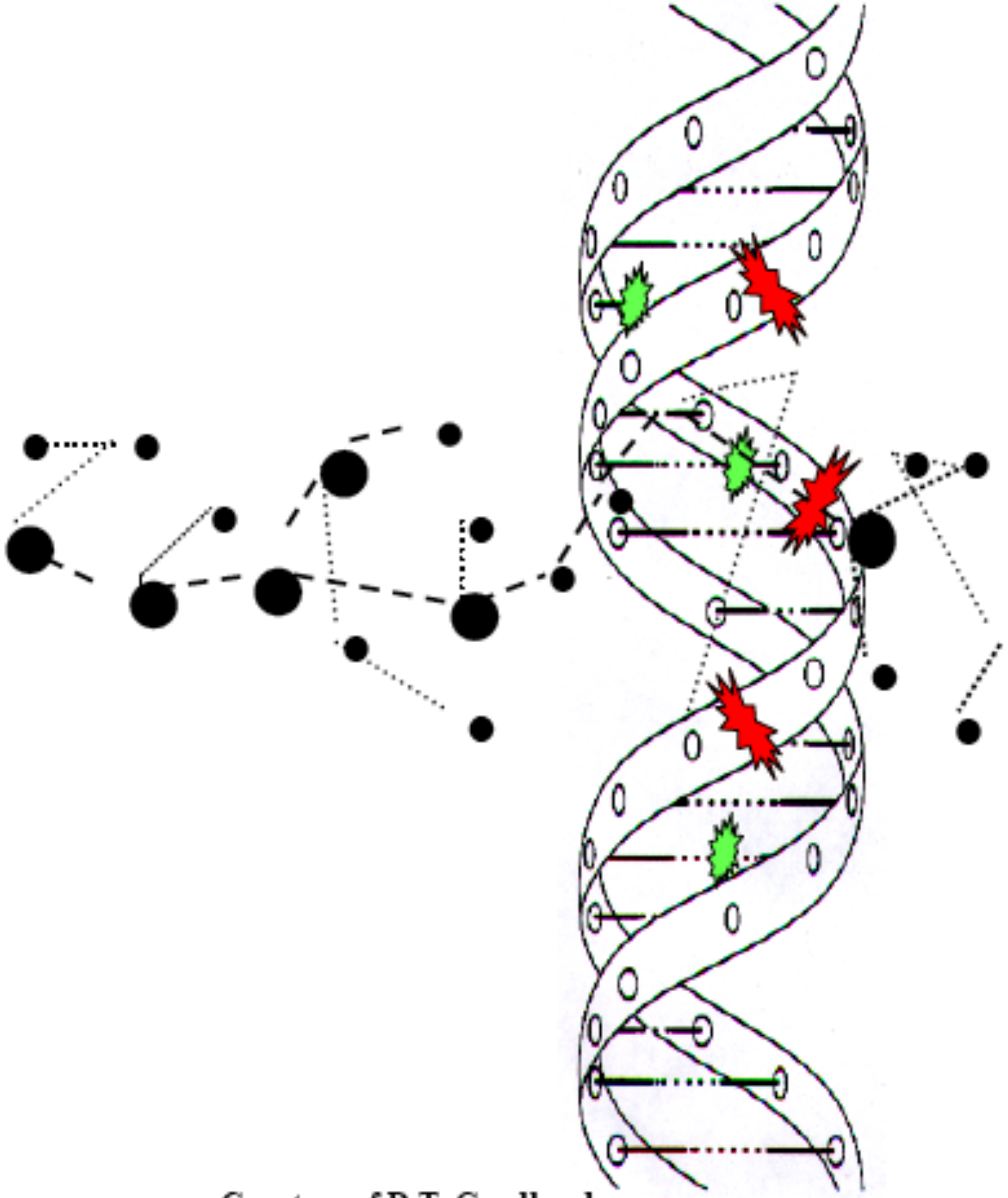


Cucinotta and Durante, *Lancet Oncol.* 2006

Radiation effects on biological tissues



Courtesy of NASA



Courtesy of D.T. Goodhead

The interplanetary travel case

The evidence for cancer risks from humans who are exposed to *low-LET* radiation is extensive for doses above *100 mSv (10 rem).*

The doses that are to be expected on space missions, as well as the nuclear type and energies, are quite well understood.

The main contribution to the ionizing radiation encountered in space are

- Solar Particle Events *(SPE)*
- Galactic Cosmic Rays *(GCR)*

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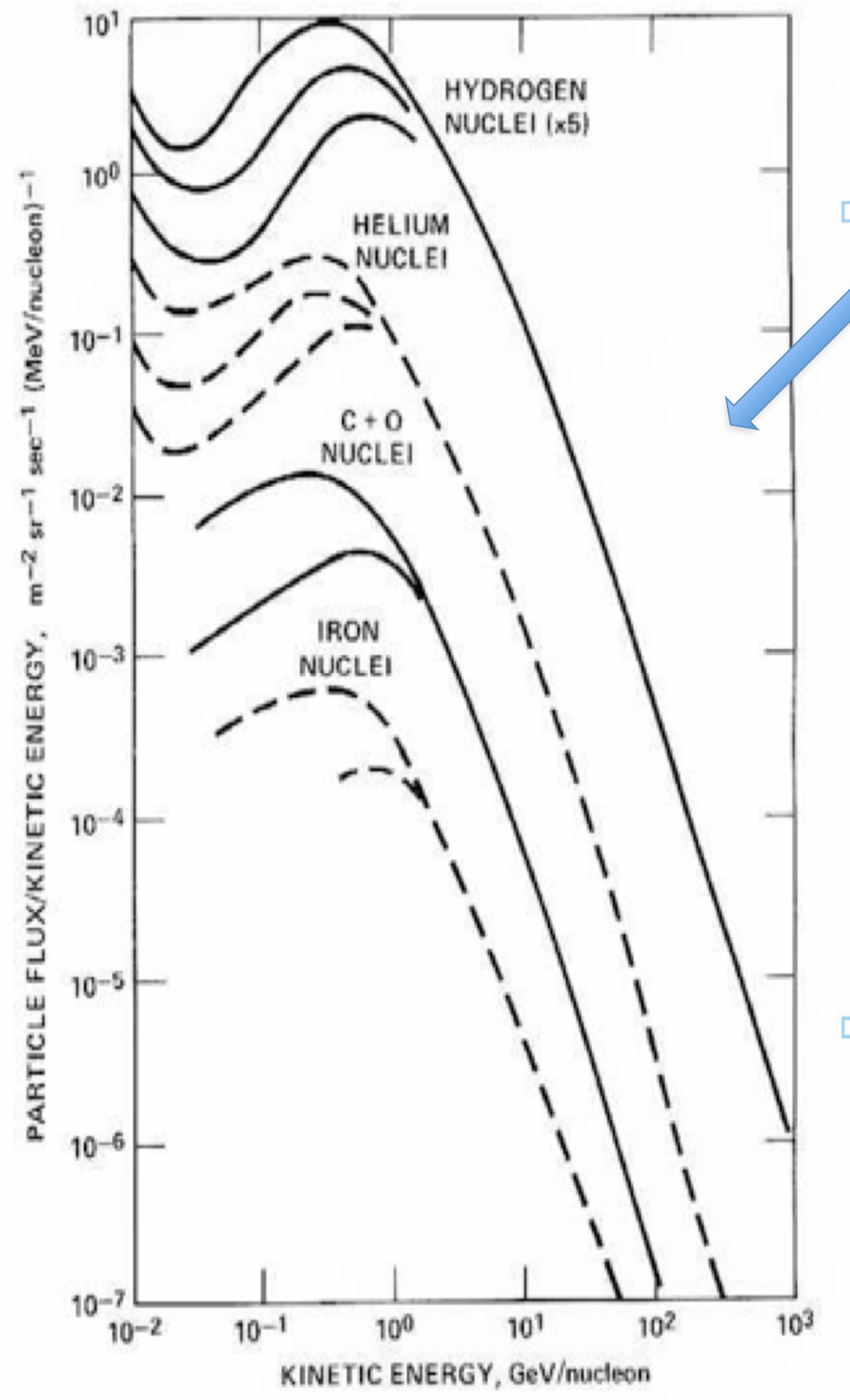
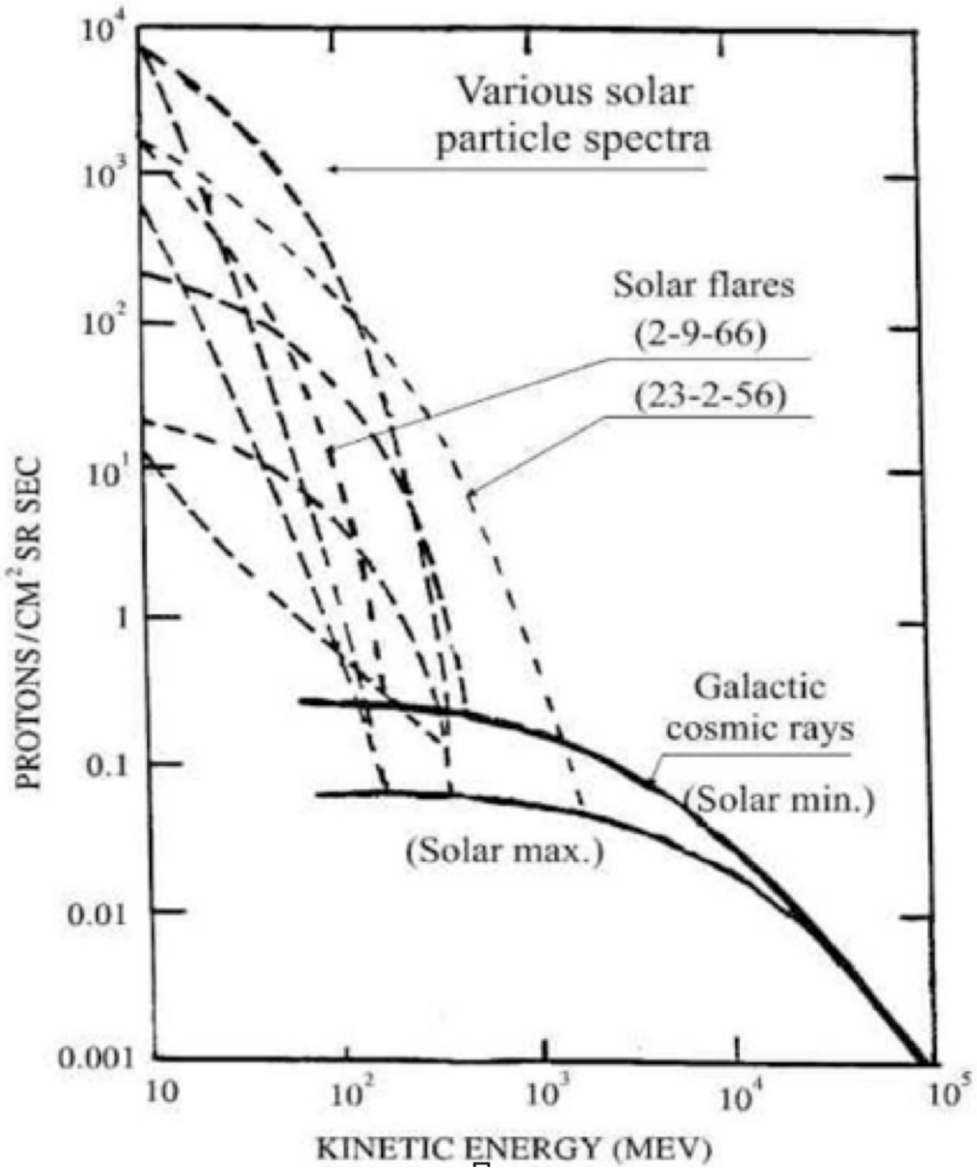
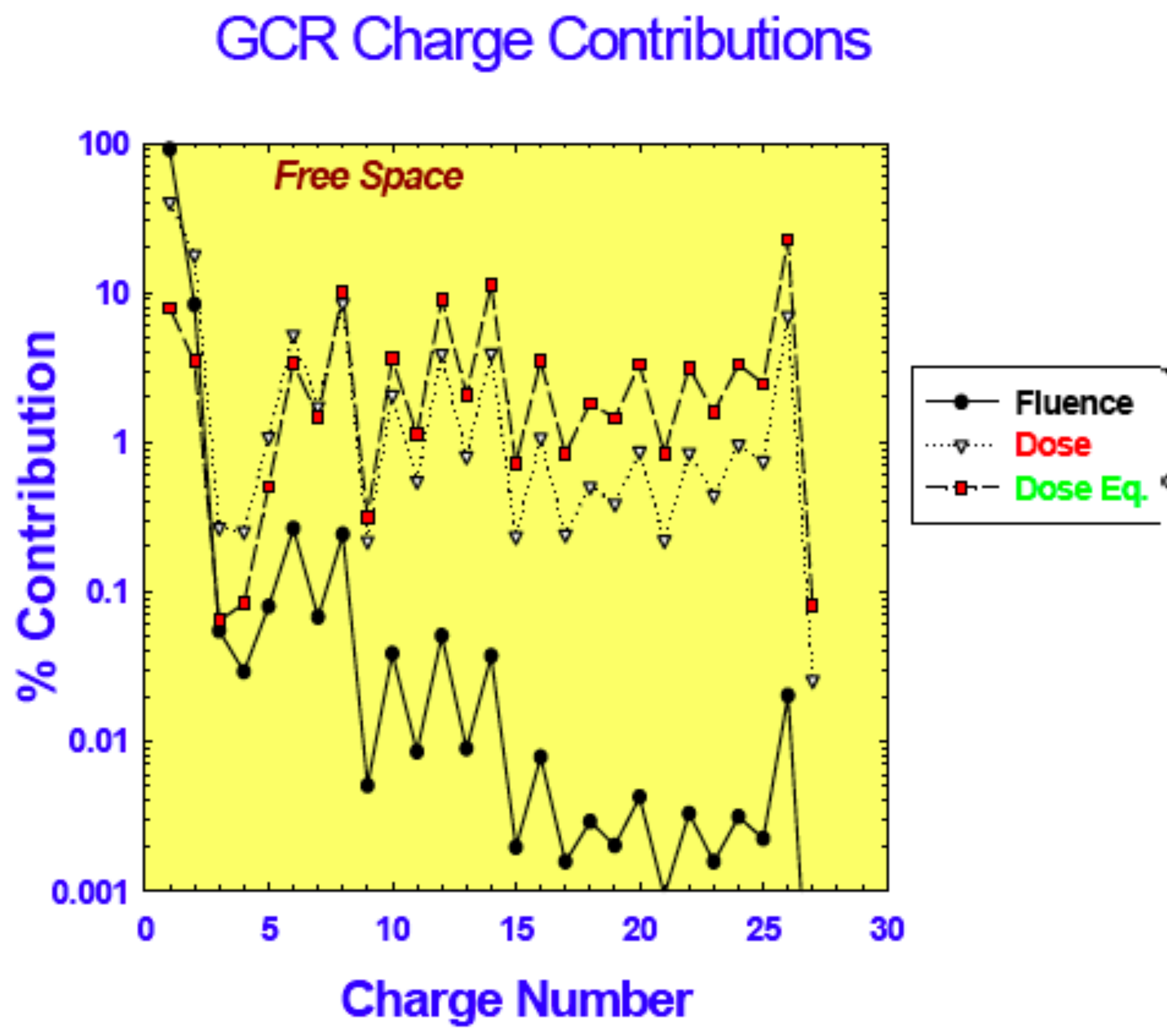
Distribution of energies of GCR. This is a graph of the more abundant nuclear species in CR as measured near Earth. Below a few GeV/nucleon these spectra are strongly influenced by the Sun. The different curves for the same species represent measurement extremes resulting from varying solar activity (Physics Today, Oct. 1974, p. 25)

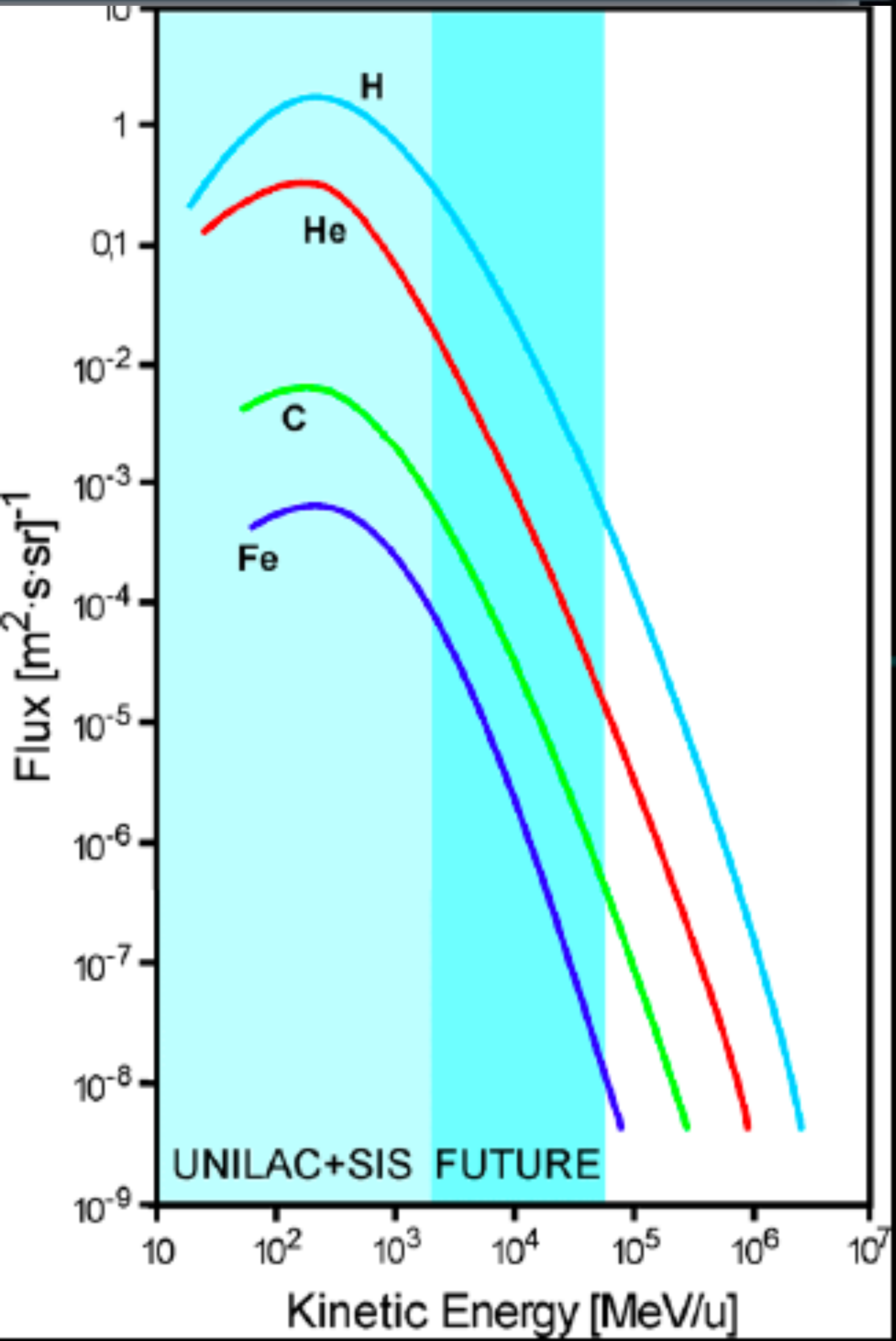


Particle spectra observed in SPE compared with the GCR spectrum

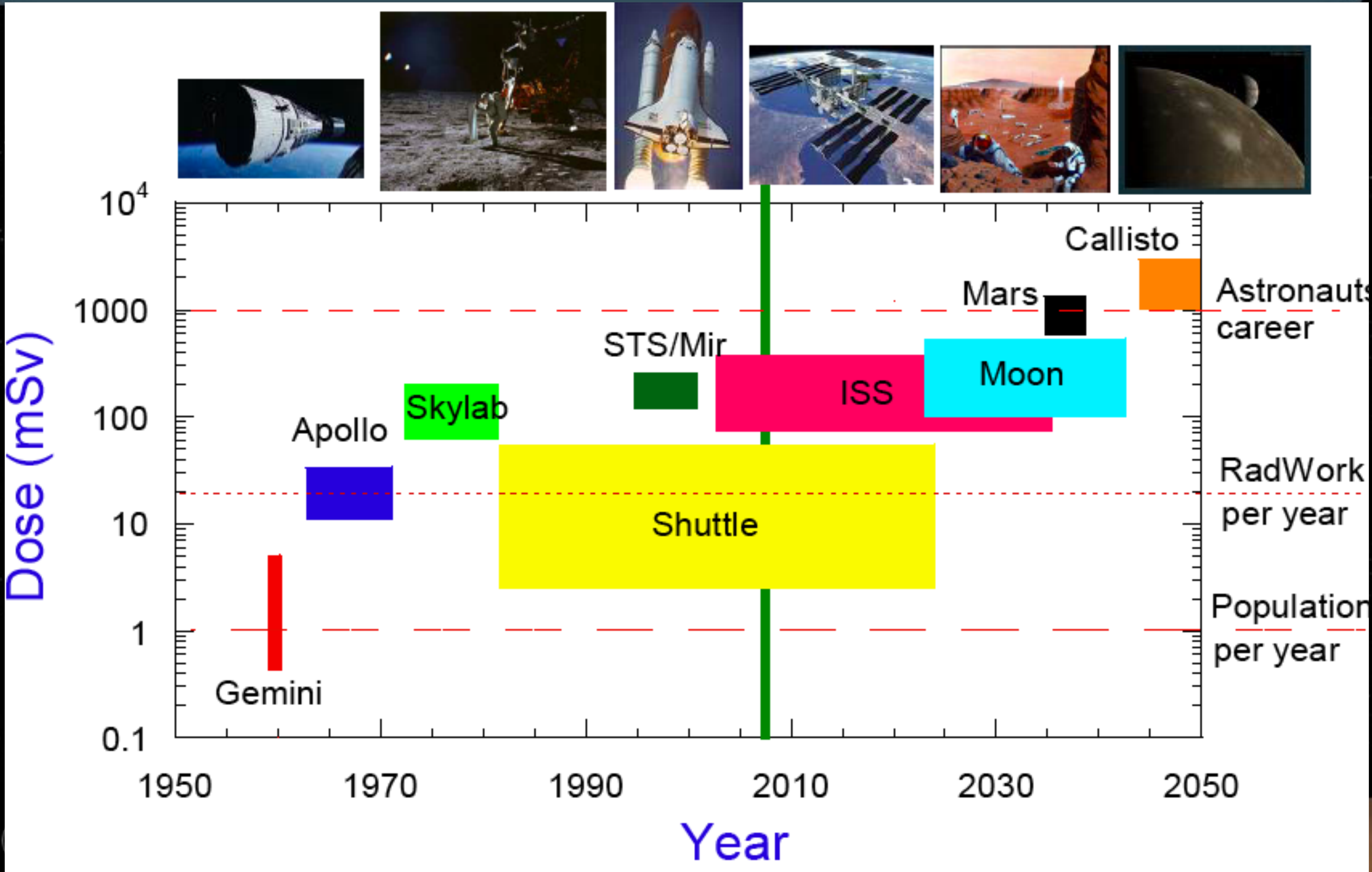


Galactic cosmic radiation



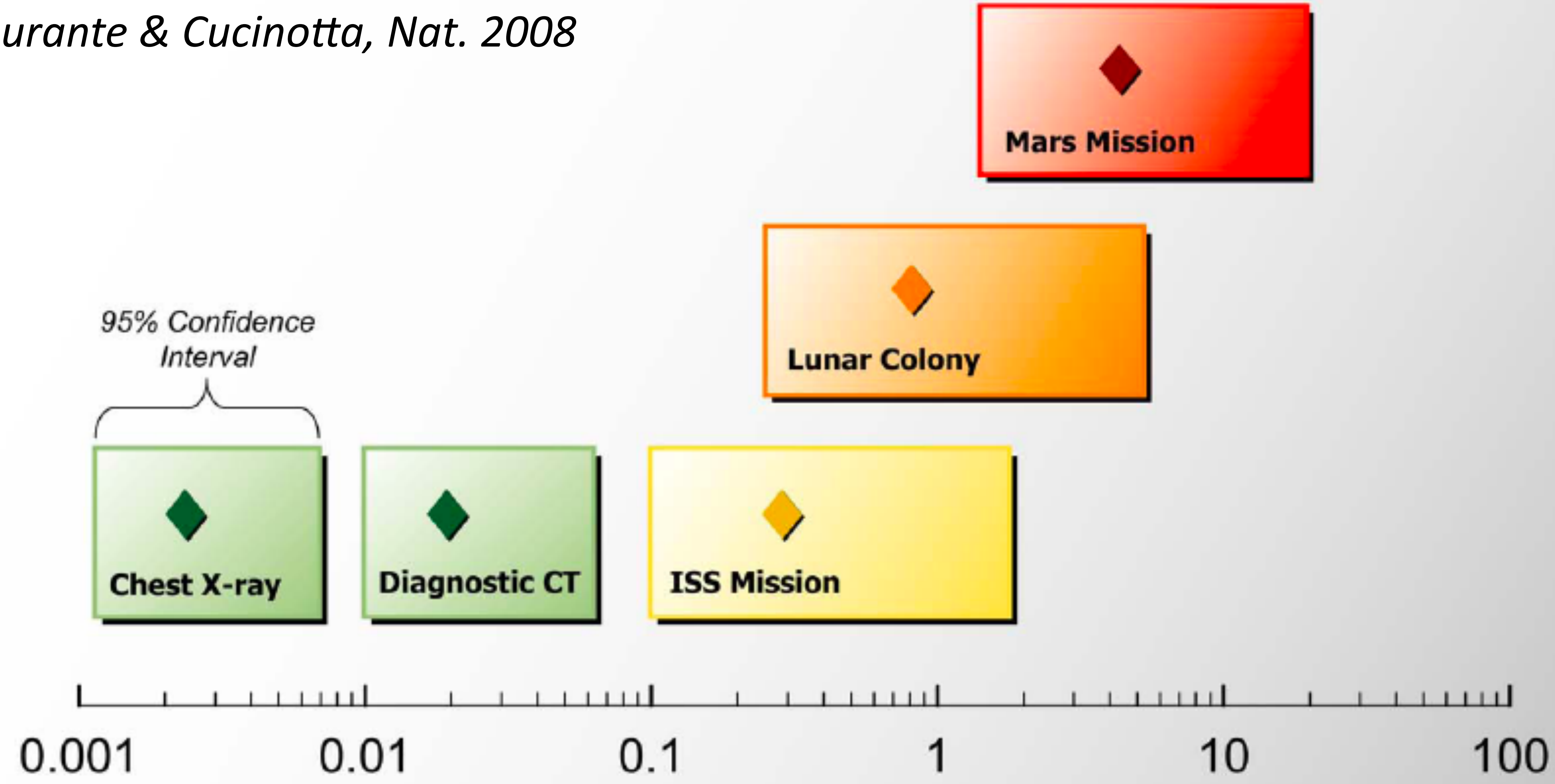


Radiation doses in different missions



% of death due to cancer - 95% CL

Durante & Cucinotta, Nat. 2008



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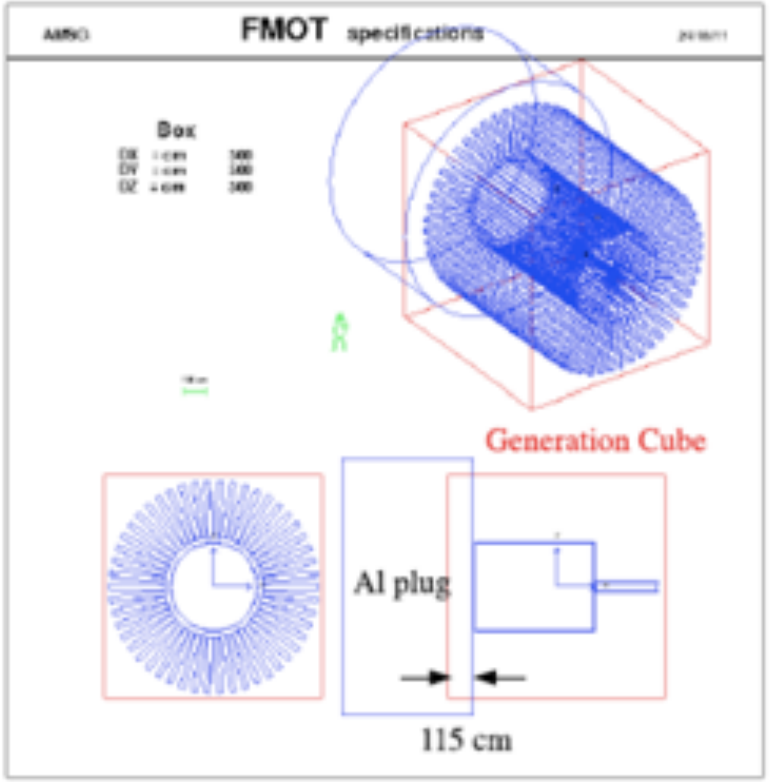
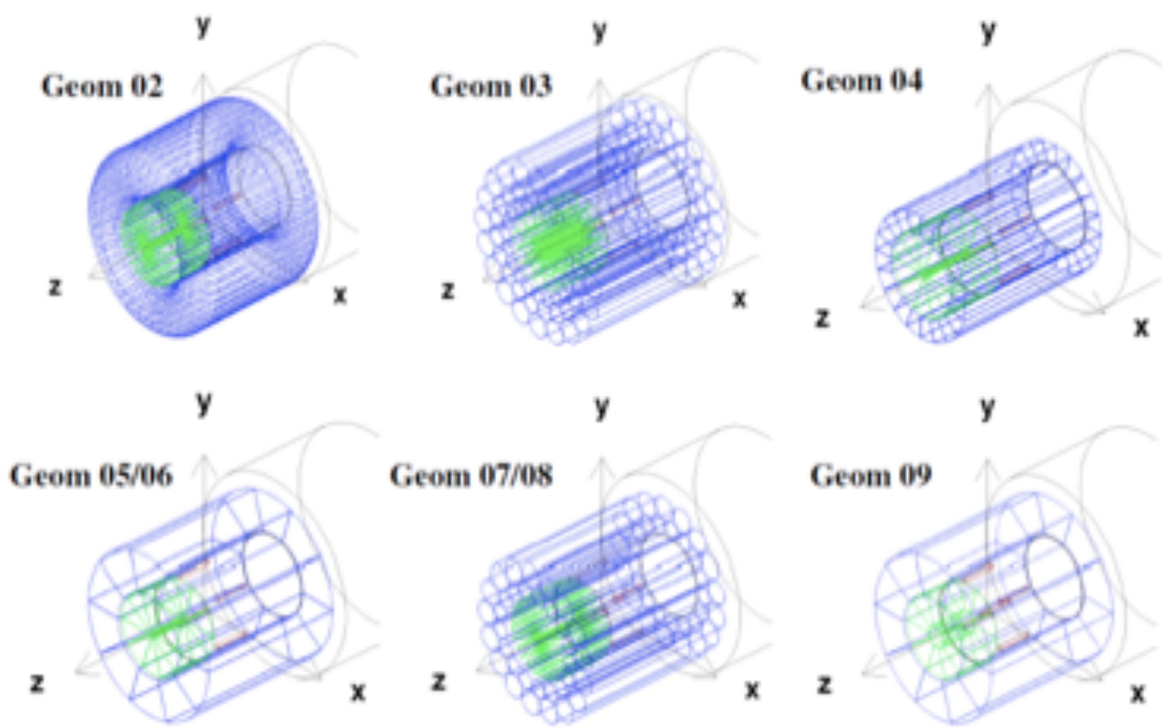
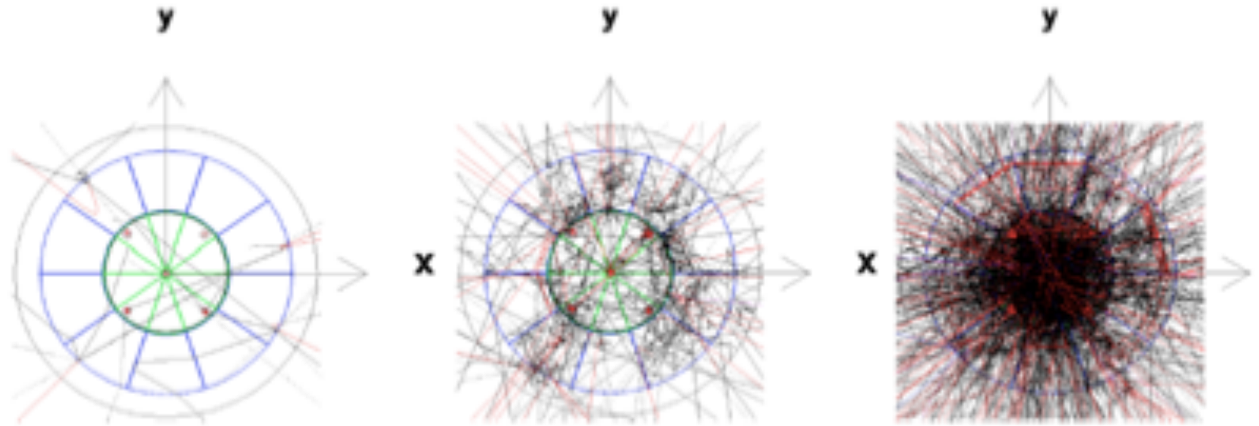
Physics simulation





particles: p $e^{\pm}$ $\pi^{\pm}$ n γ π^0 ...



1 GV
0.43 GeV

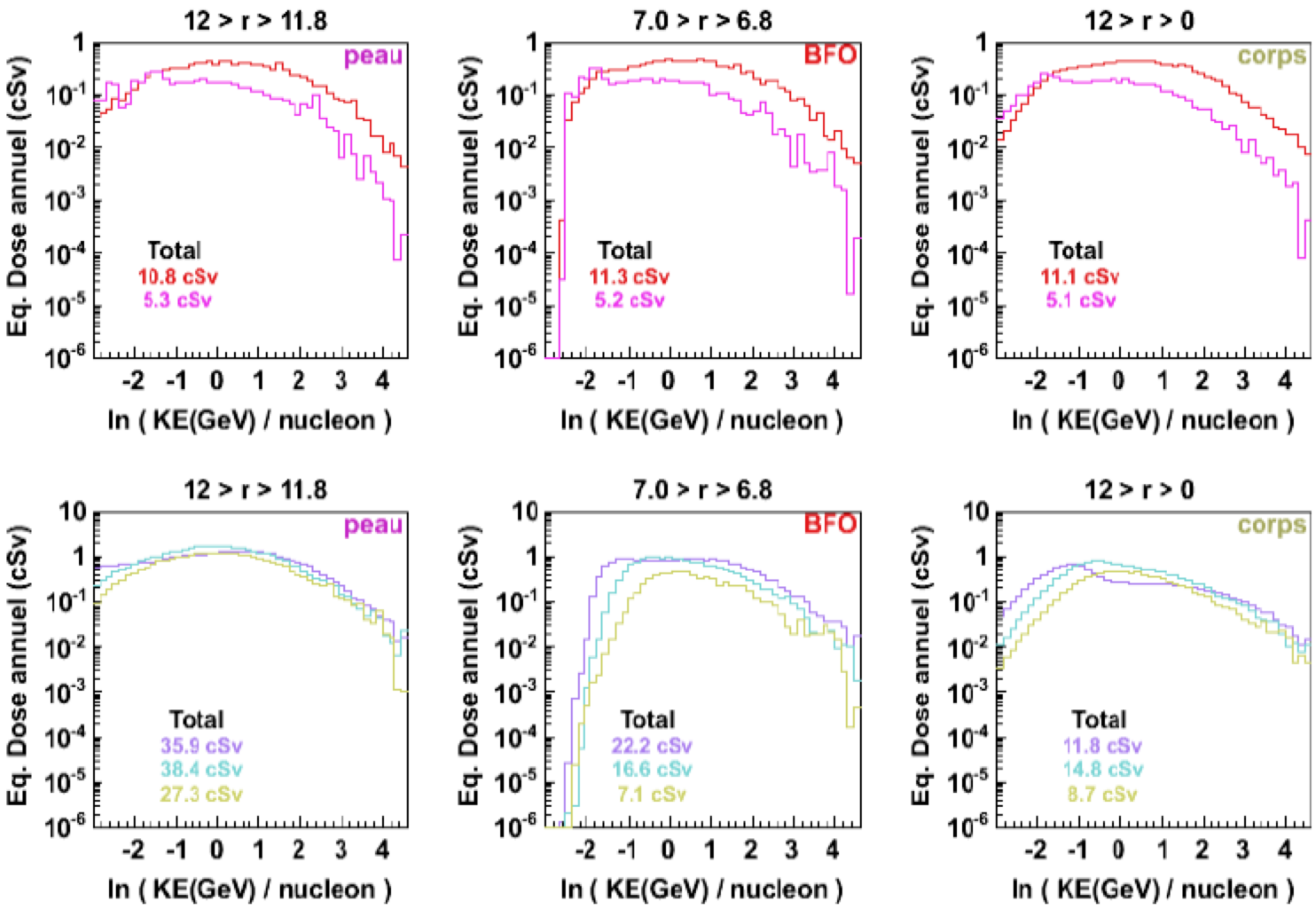
1.7 GV
1.0 GeV

2.5 GV
1.73 GeV

see W. Burger talk

1977 Solar Minimum

GCR protons, He and charged nuclei Z= 3-10 , 11-20 , 21-28



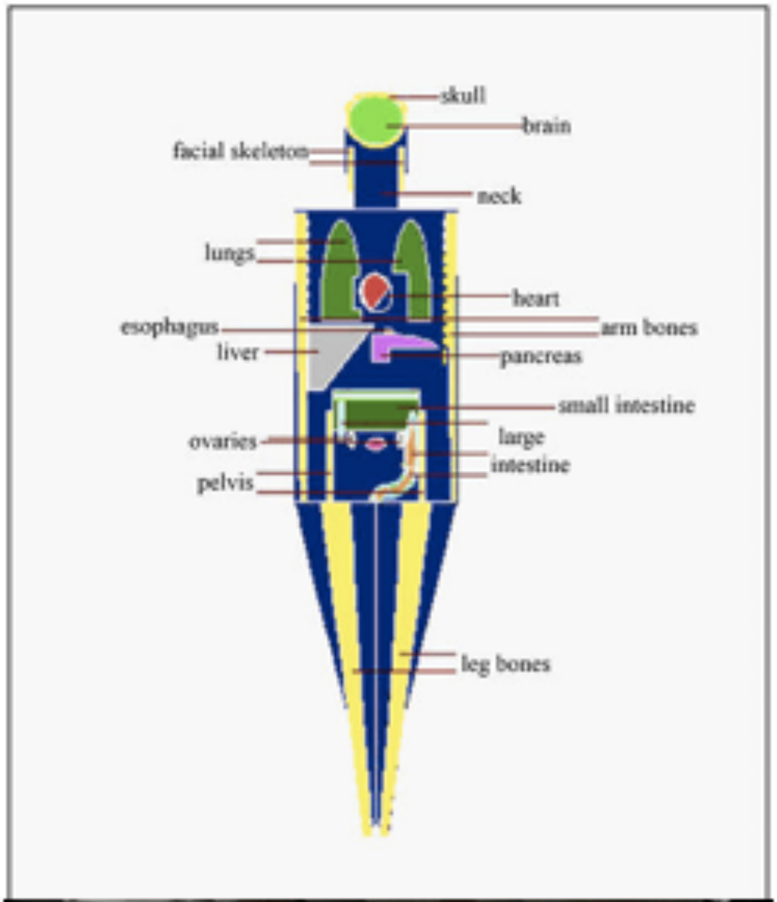
Doses vary significantly with the solar cycles. There is a *60%* difference between *solar maximum* and *solar minimum* total doses (factor 1,6).

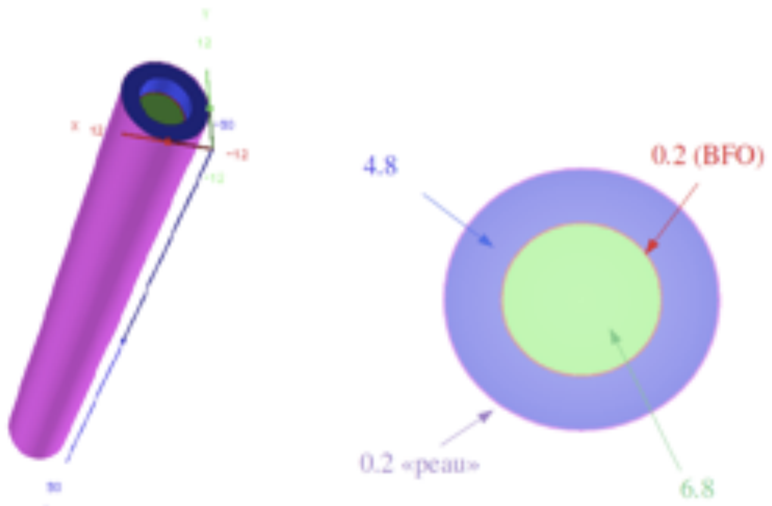
Doses vary greatly on different parts of the body. *Skin* is exposed to the highest dose, *90%* higher (factor *1,9*) than *BFO* and *130%* higher (factor *2,3*) than *whole body*.

Doses vary greatly with the *CR* species. Although protons are by far most abundant (*85%* of the total flux), their dose is only a factor *2* higher than He (*14%* of the total flux), but it is *10* time lower (*skin*) than the contributions of ions having *Z>2* (1% of the total flux).

Z	Solar Minimum			Solar Maximum		
	skin	BFO	body	skin	BFO	body
1	10.8	11.3	11.1	5.5	5.6	5.6
2	5.3	5.2	5.1	2.9	2.8	2.7
3-10	35.9	22.2	11.8	22.1	14.8	6.8
11-20	38.4	16.6	14.8	23.1	11.2	9.2
21-28	27.3	7.1	8.7	17.4	5.1	5.8
total	117.7	62.4	51.5	71.0	39.5	30.1

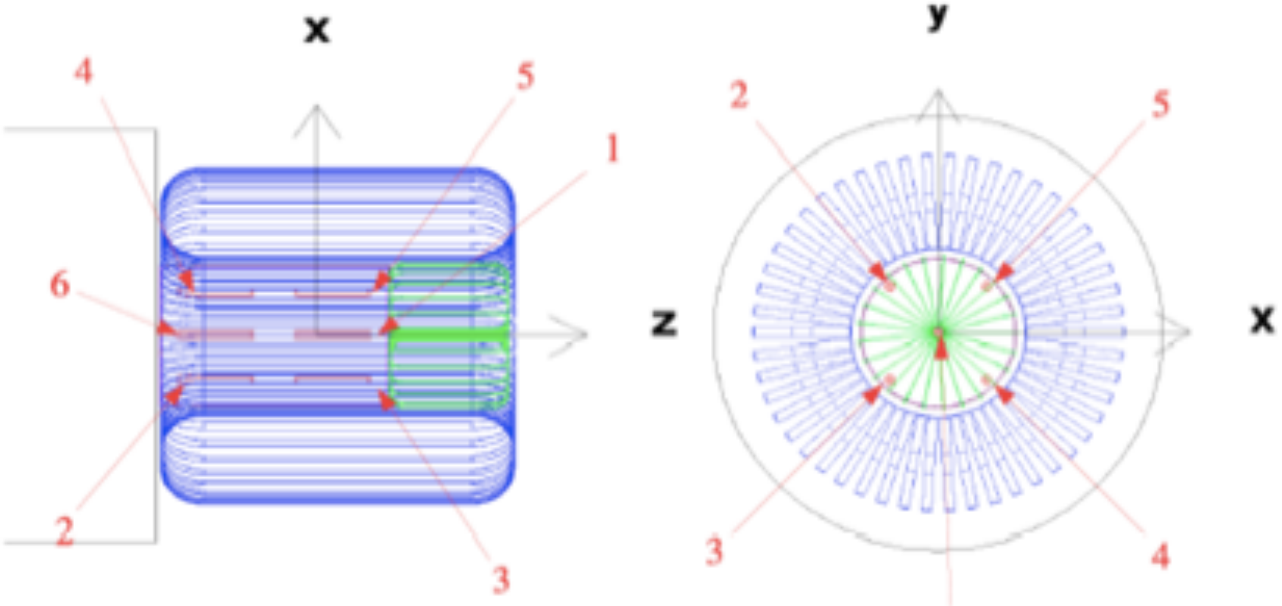
The astronauts.....





H_2O cylinder: ⌀ 24 cm, length 180 cm

The cylindrical water volumes used to compute the dose of the skin and blood forming organs (BFO). The total dose refers to the full volume of the 24 cm diameter. 180 cm long cylinder



Doses for exploration missions.....

- FREE SPACE: equivalent doses in excess of ***1.2 Sv /yr (~120 rem/yr)***
- SPACECRAFT (thin) SHIELDING: about **700-800 mSv/yr (70-80 rem/yr)**
- *ON THE MARS SURFACE:* between **100 and 200 mSv/yr (10 and 20 rem/yr)**, depending on the location
- ON THE MOON SURFACE : **223 mSv/yr** (**22,3 rem/yr)** with oscillations of **± 10 rem/yr** as a function of solar activity
  - *for comparison: ISS about **18 rem/yr --> 6 month expeditions***

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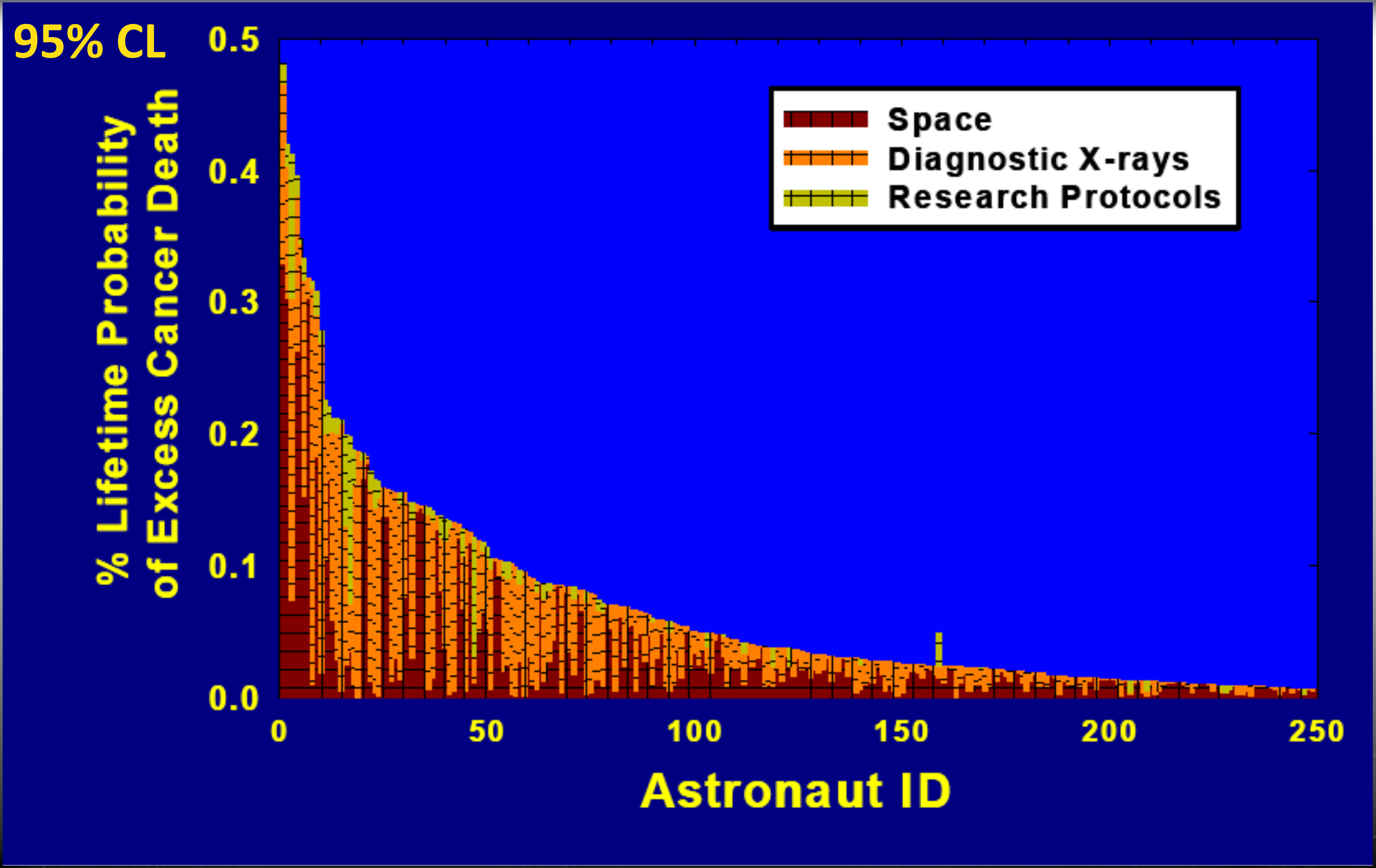
Projection of risk of radiation



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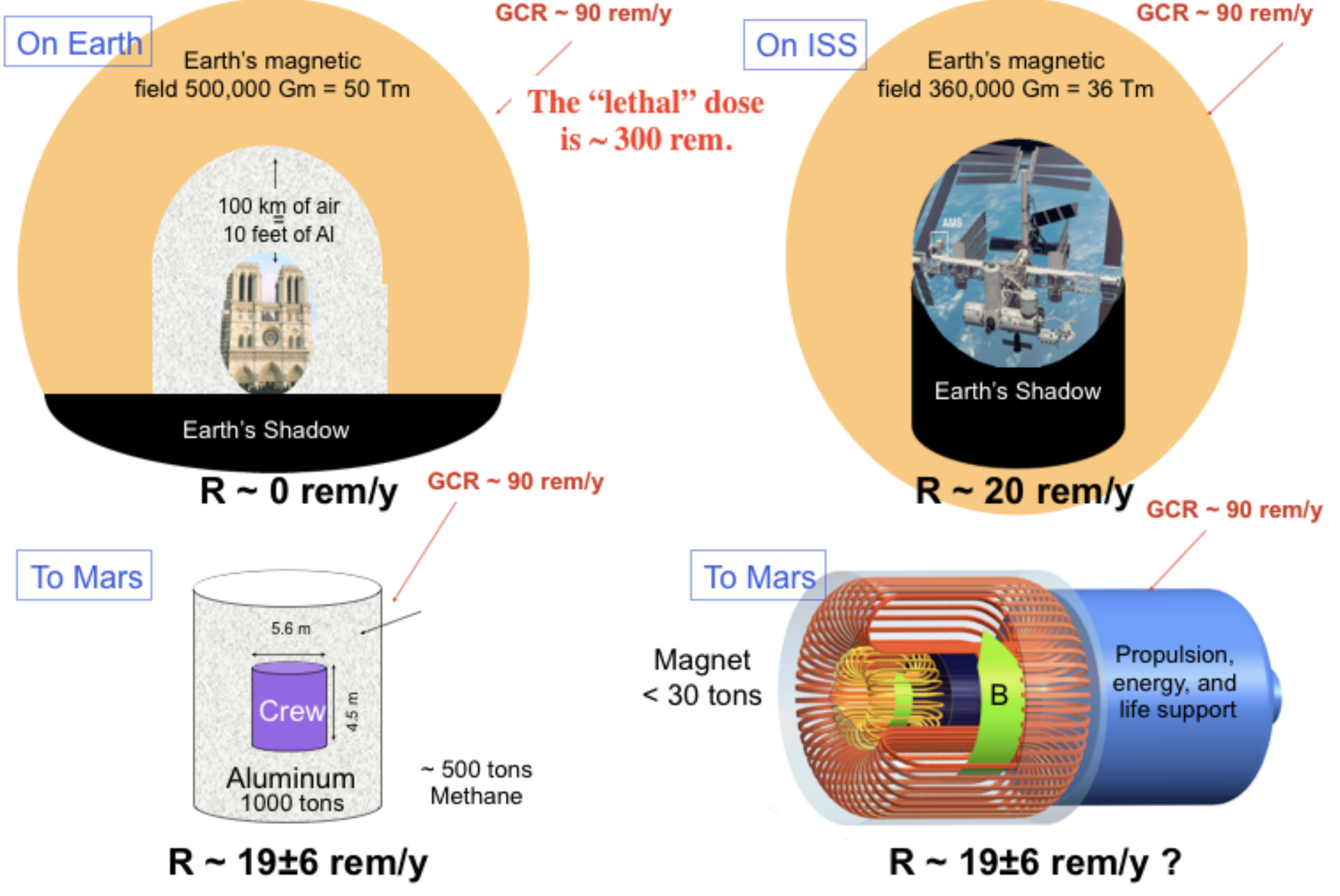
Various form of shielding



The "lethal" dose is ~ 300 rem.

R ~ 0 rem/y

R ~ 20 rem/y

R ~ 19±6 rem/y

R ~ 19±6 rem/y ?

Of the 26892 man-days spent in space only 303 have been in Apollo Mission outside the magnetosphere (1.1%)

3% REID limit =>increase of P(cancer death)

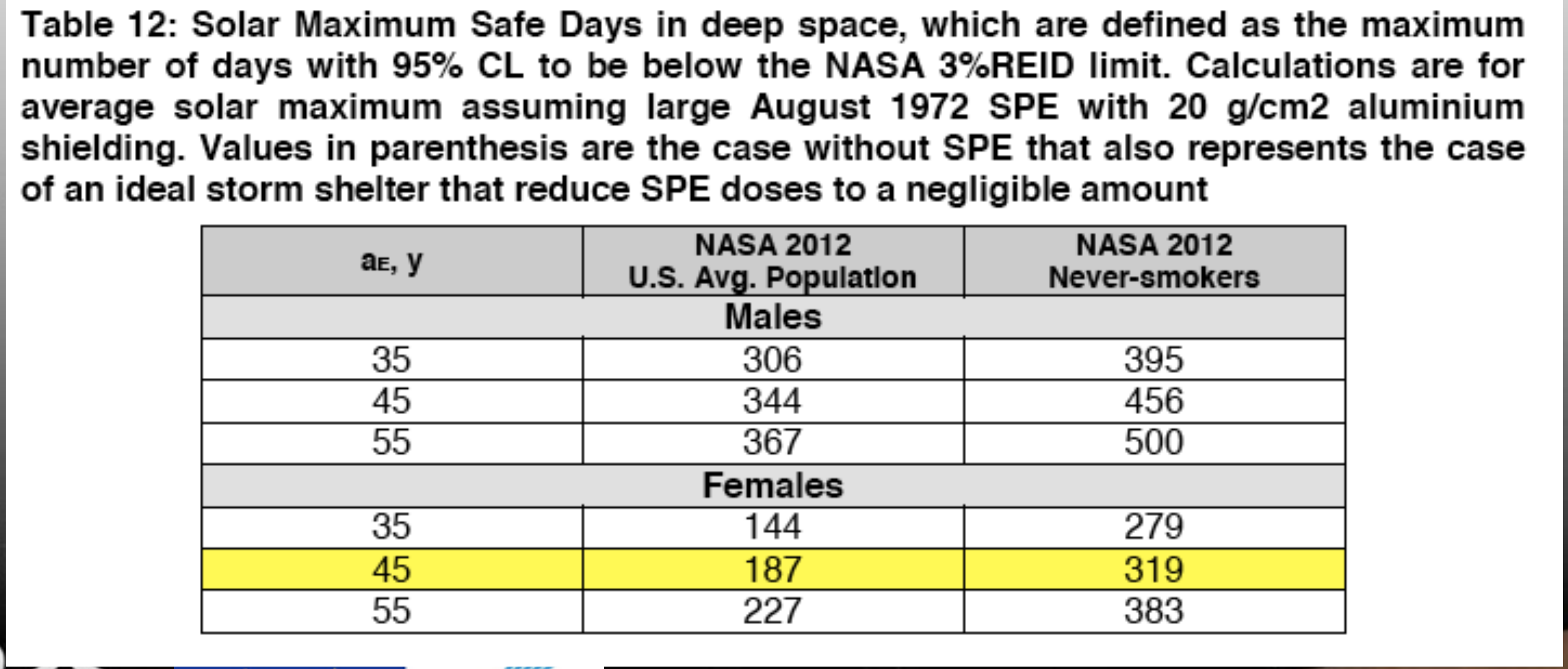


Table 12: Solar Maximum Safe Days in deep space, which are defined as the maximum number of days with 95% CL to be below the NASA 3%REID limit. Calculations are for average solar maximum assuming large August 1972 SPE with 20 g/cm2 aluminium shielding. Values in parenthesis are the case without SPE that also represents the case of an ideal storm shelter that reduce SPE doses to a negligible amount

a_E, y	NASA 2012 U.S. Avg. Population	NASA 2012 Never-smokers
	Males	
35	306	395
45	344	456
55	367	500
	Females	
35	144	279
45	187	319
55	227	383

Mars Mission 1000 days in space

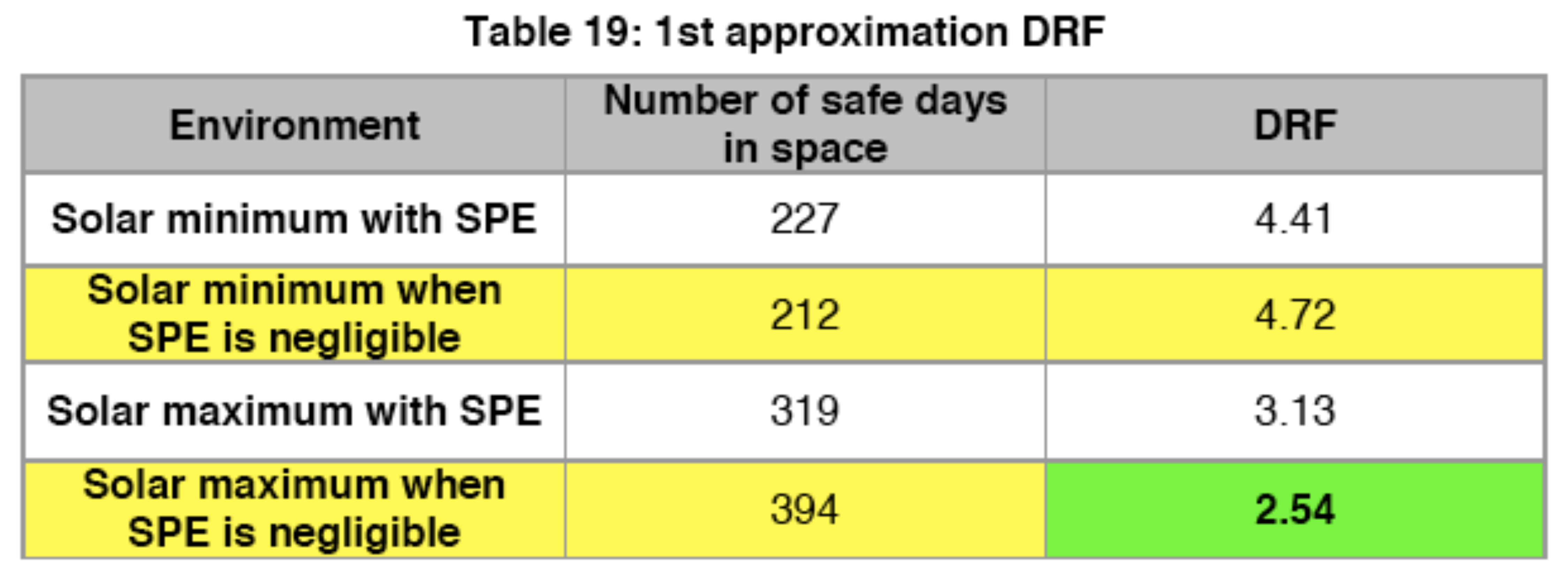


Table 19: 1st approximation DRF

Environment	Number of safe days in space	DRF
Solar minimum with SPE	227	4.41
Solar minimum when SPE is negligible	212	4.72
Solar maximum with SPE	319	3.13
Solar maximum when SPE is negligible	394	**2.54**

SR2S mission scenarios

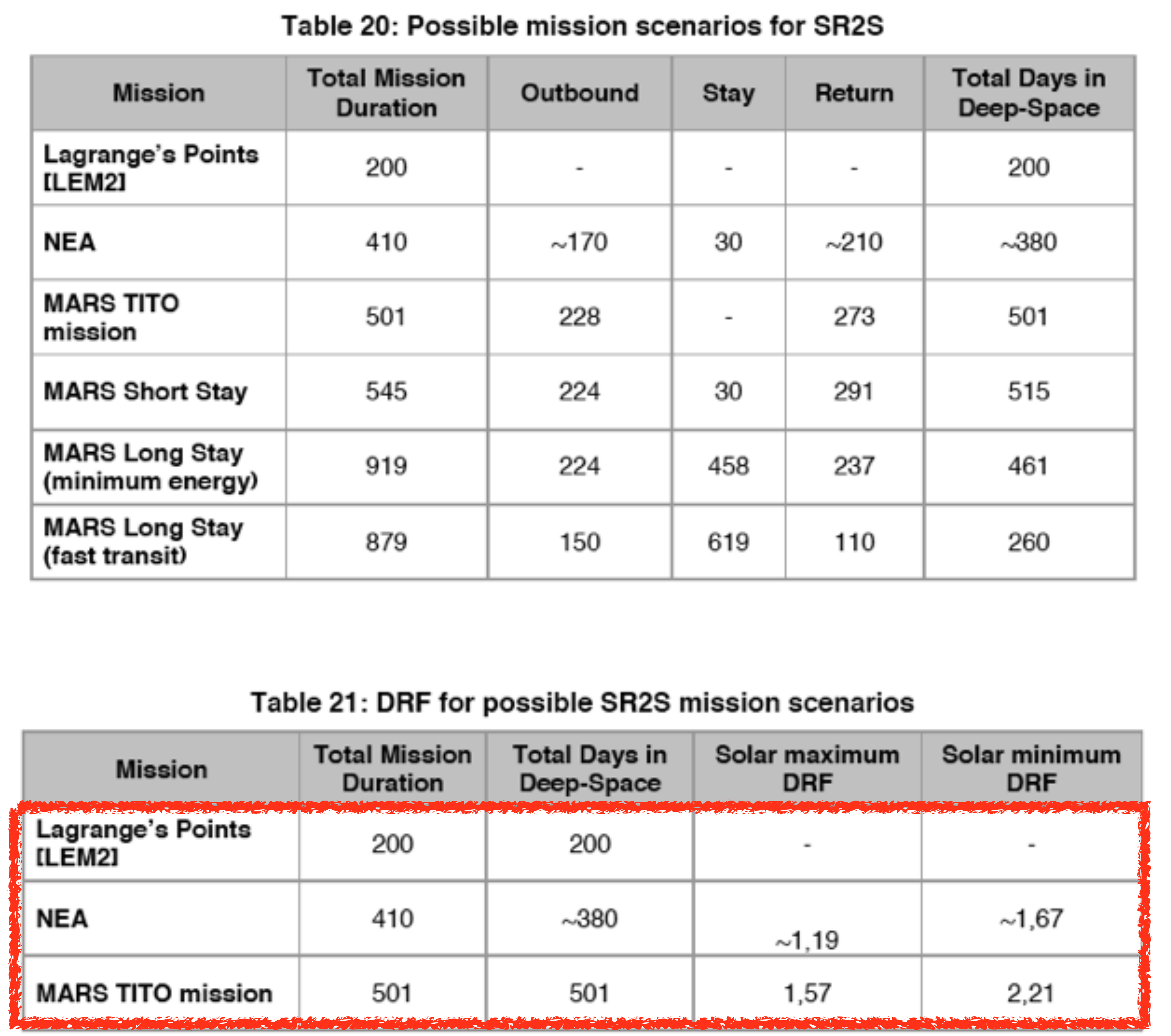


Table 20: Possible mission scenarios for SR2S

Mission	Total Mission Duration	Outbound	Stay	Return	Total Days in Deep-Space
Lagrange's Points [LEM2]	200	-	-	-	200
NEA	410	~170	30	~210	~380
MARS TITO mission	501	228	-	273	501
MARS Short Stay	545	224	30	291	515
MARS Long Stay (minimum energy)	919	224	458	237	461
MARS Long Stay (fast transit)	879	150	619	110	260

Table 21: DRF for possible SR2S mission scenarios

Mission	Total Mission Duration	Total Days in Deep-Space	Solar maximum DRF	Solar minimum DRF
Lagrange's Points [LEM2]	200	200	-	-
NEA	410	~380	~1,19	~1,67
MARS TITO mission	501	501	1,57	2,21

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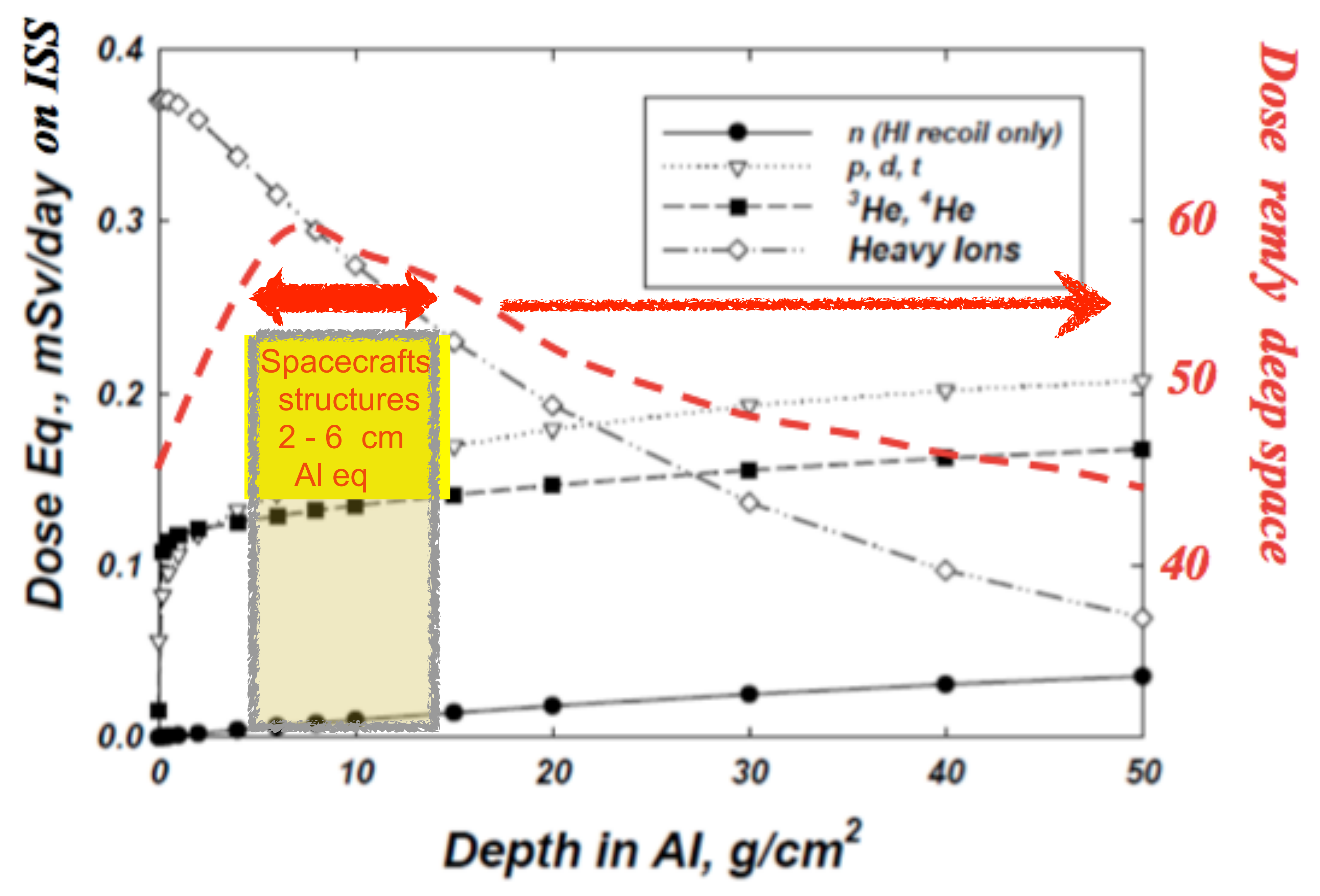
Shield in space if it is "thin" … ……..then it "adds" dose



Spacecrafts structures 2 - 6 cm Al eq

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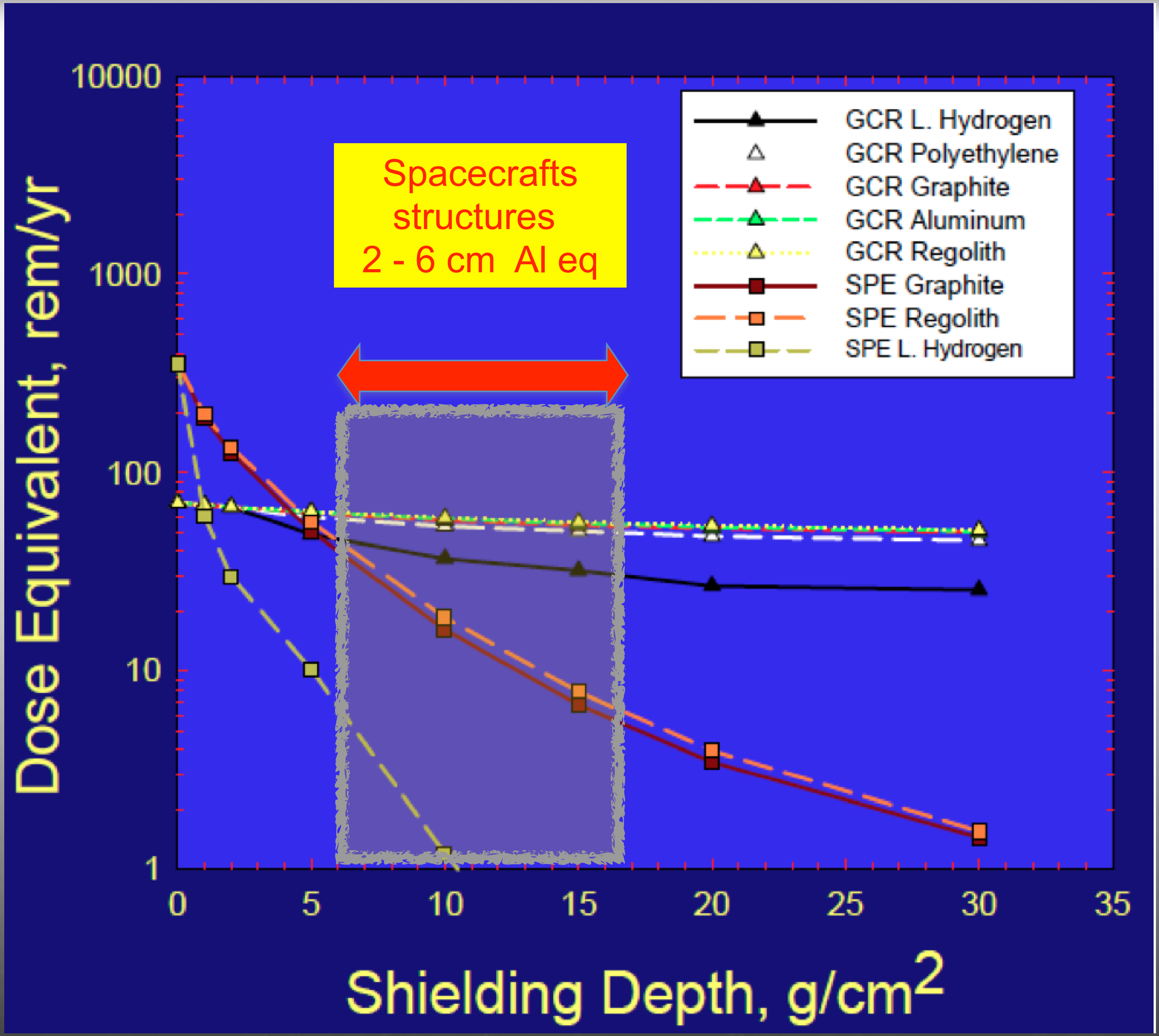
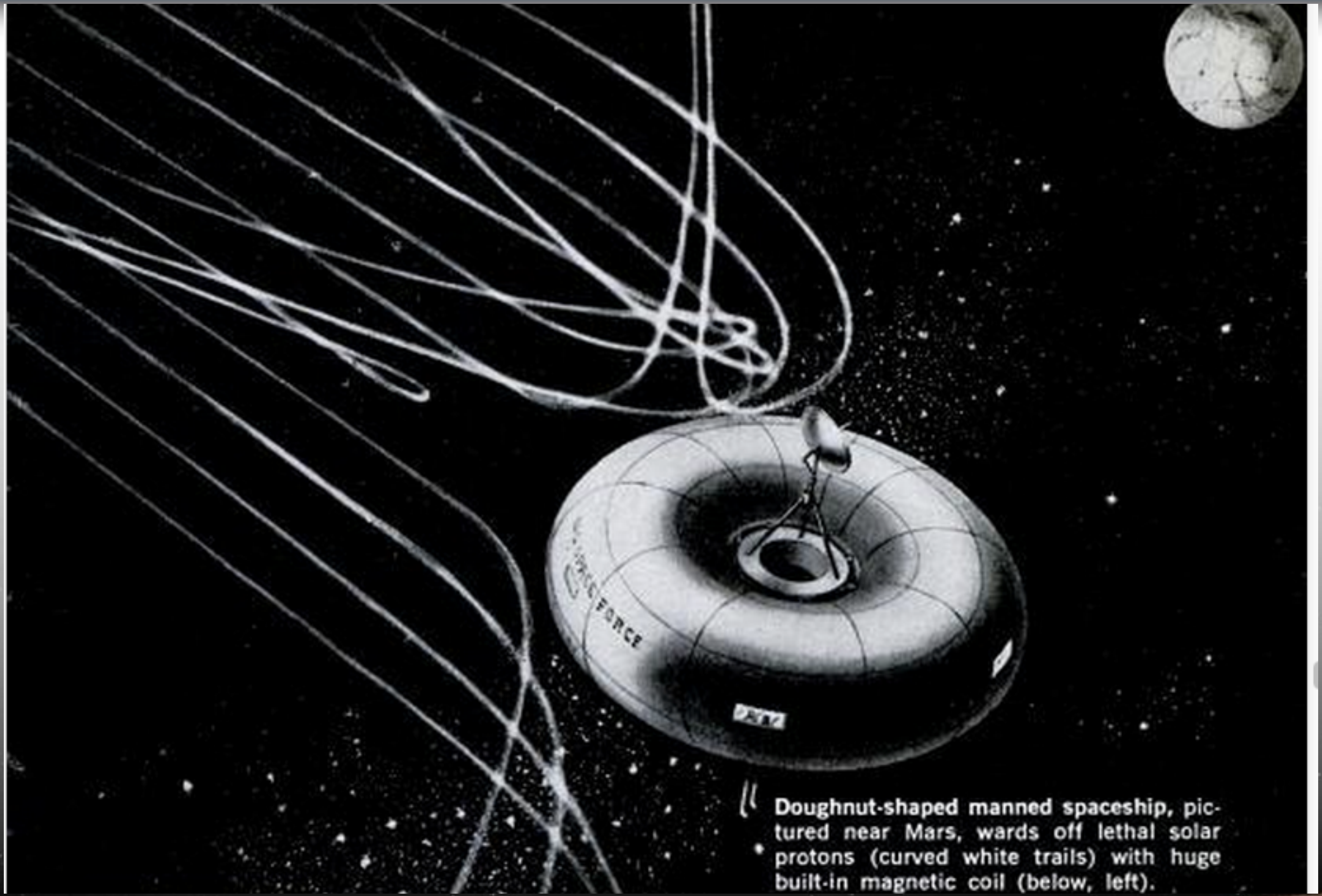
Advanced materials can help SPE not GCR



Spacecrafts structures
2 - 6 cm Al eq

So we turn to active radiation shields

Active magnetic shielding



Doughnut-shaped manned spaceship, pictured near Mars, wards off lethal solar protons (curved white trails) with huge built-in magnetic coil (below, left).

Magnetic shield configurations

- The angular deflection in the magnetic field may be compared to the kinetic energy lost by ionization, where BL replace the electromagnetic and nuclear radiation length to characterizing the shielding performance of the material
- Unconfined Field (e.g. Earth's field), very large volume (L), lower field strength (B)
- **Confined field: small volume (L), higher field (B) and larger mass**

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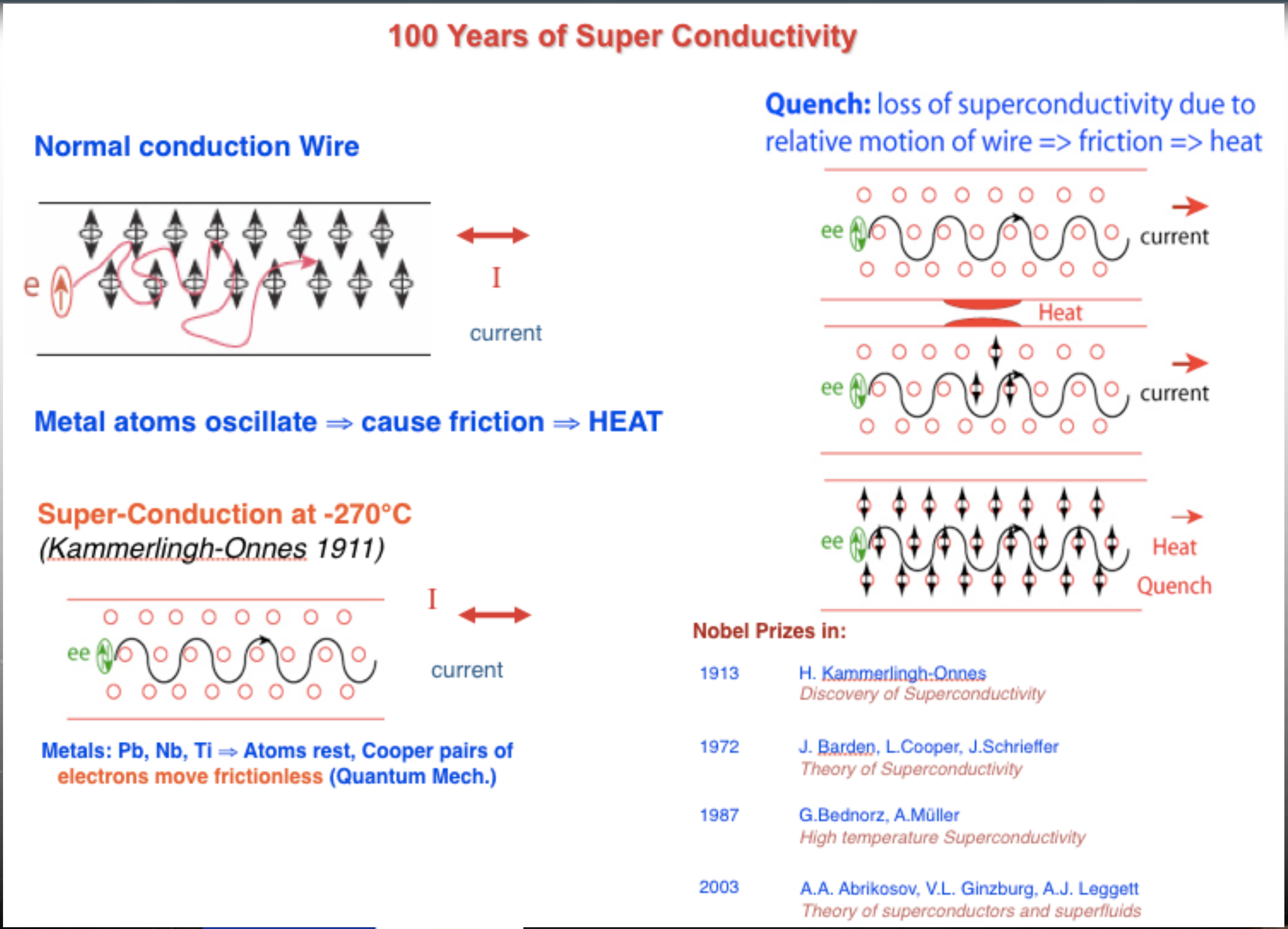
Superconductivity



100 Years of Super Conductivity

Normal conduction Wire

Metal atoms oscillate ⇒ cause friction ⇒ HEAT

Super-Conduction at -270°C
(Kammerlingh-Onnes 1911)

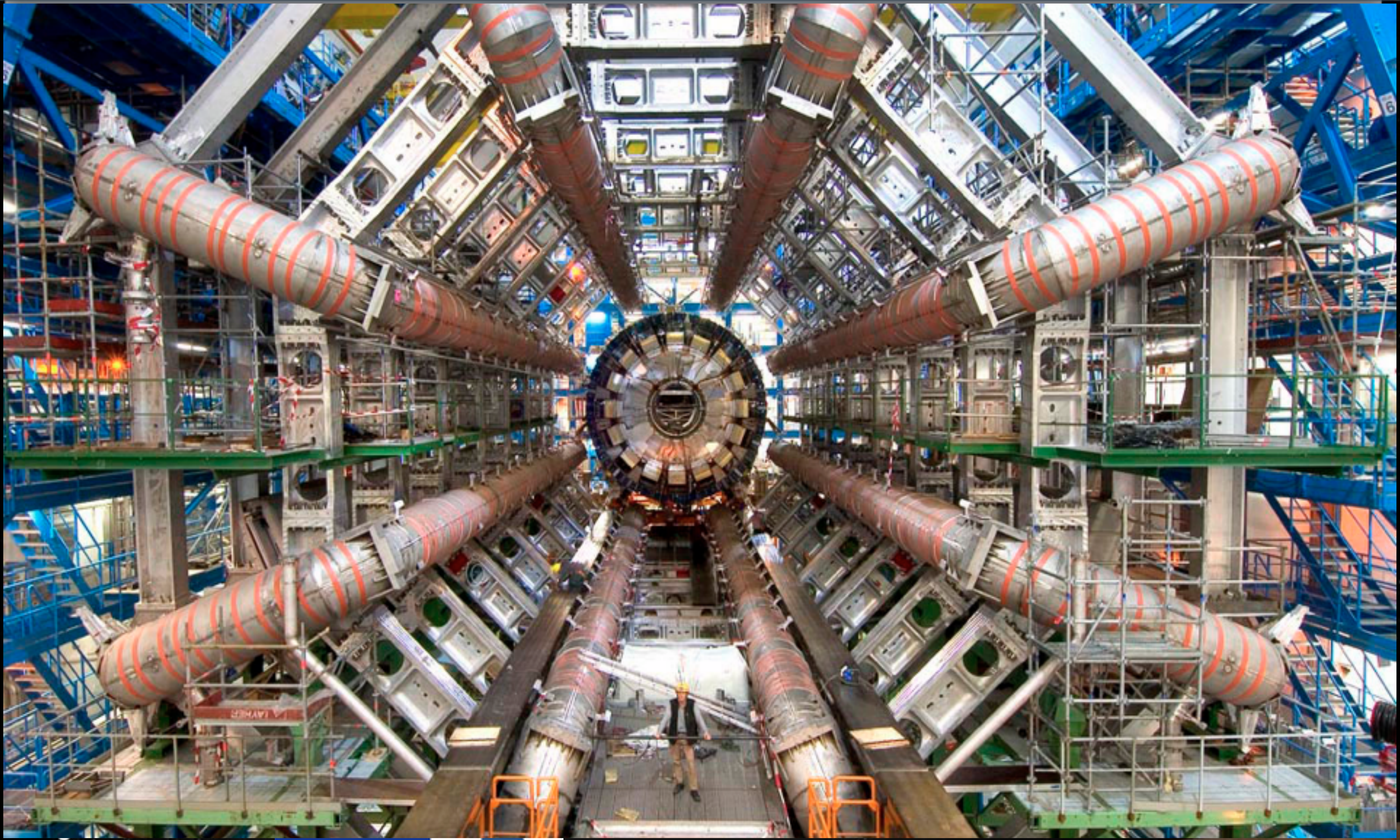
Metals: Pb, Nb, Ti ⇒ Atoms rest, Cooper pairs of electrons move frictionless (Quantum Mech.)

Quench: loss of superconductivity due to relative motion of wire => friction => heat

Nobel Prizes in:

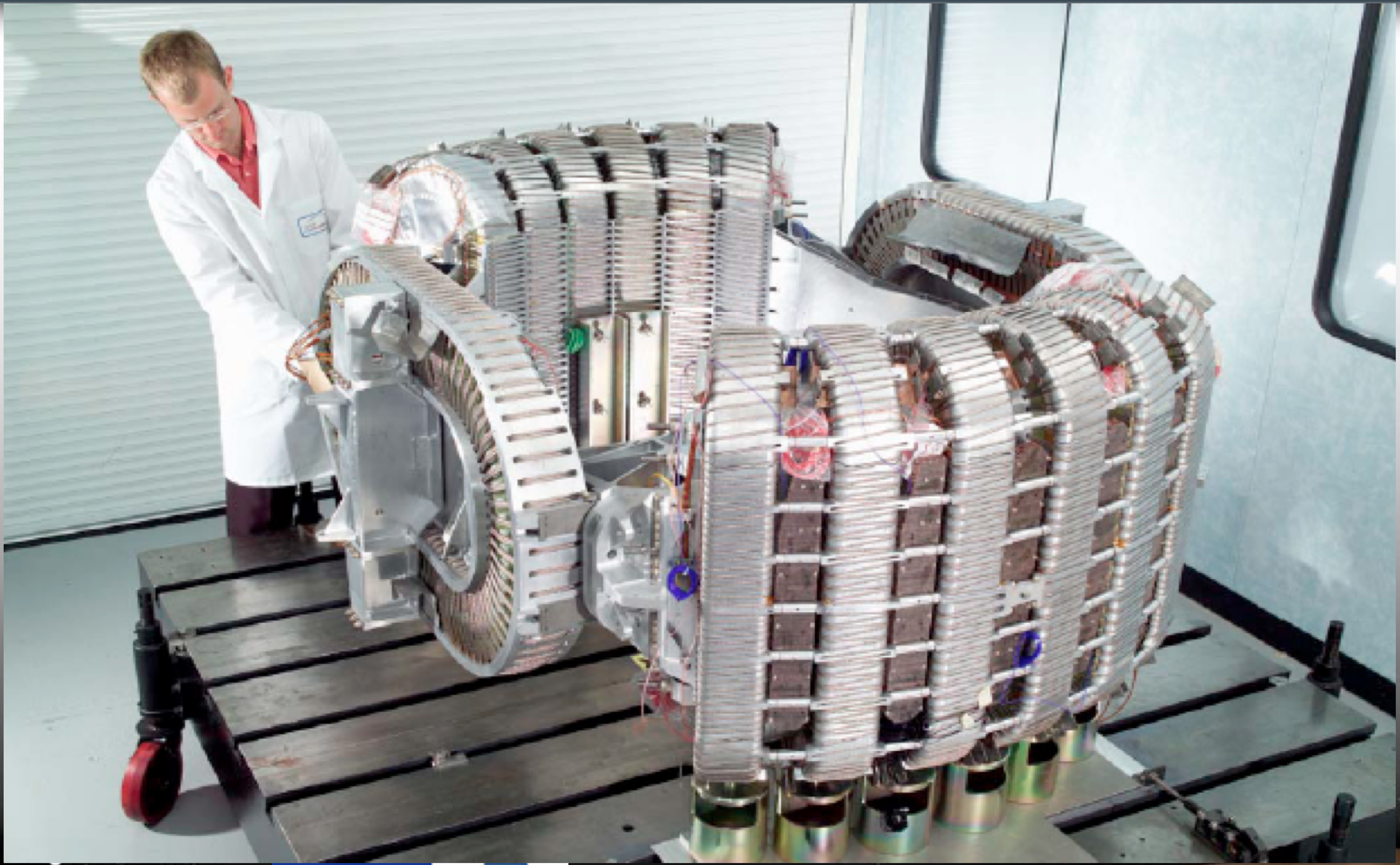
1913	H. Kammerlingh-Onnes *Discovery of Superconductivity*
1972	J. Barden, L.Cooper, J.Schrieffer *Theory of Superconductivity*
1987	G.Bednorz, A.Müller *High temperature Superconductivity*
2003	A.A. Abrikosov, V.L. Ginzburg, A.J. Leggett *Theory of superconductors and superfluids*

The ATLAS superconducting toroid



Superconductivity in space : why?

AMS SC magnet qualified for space



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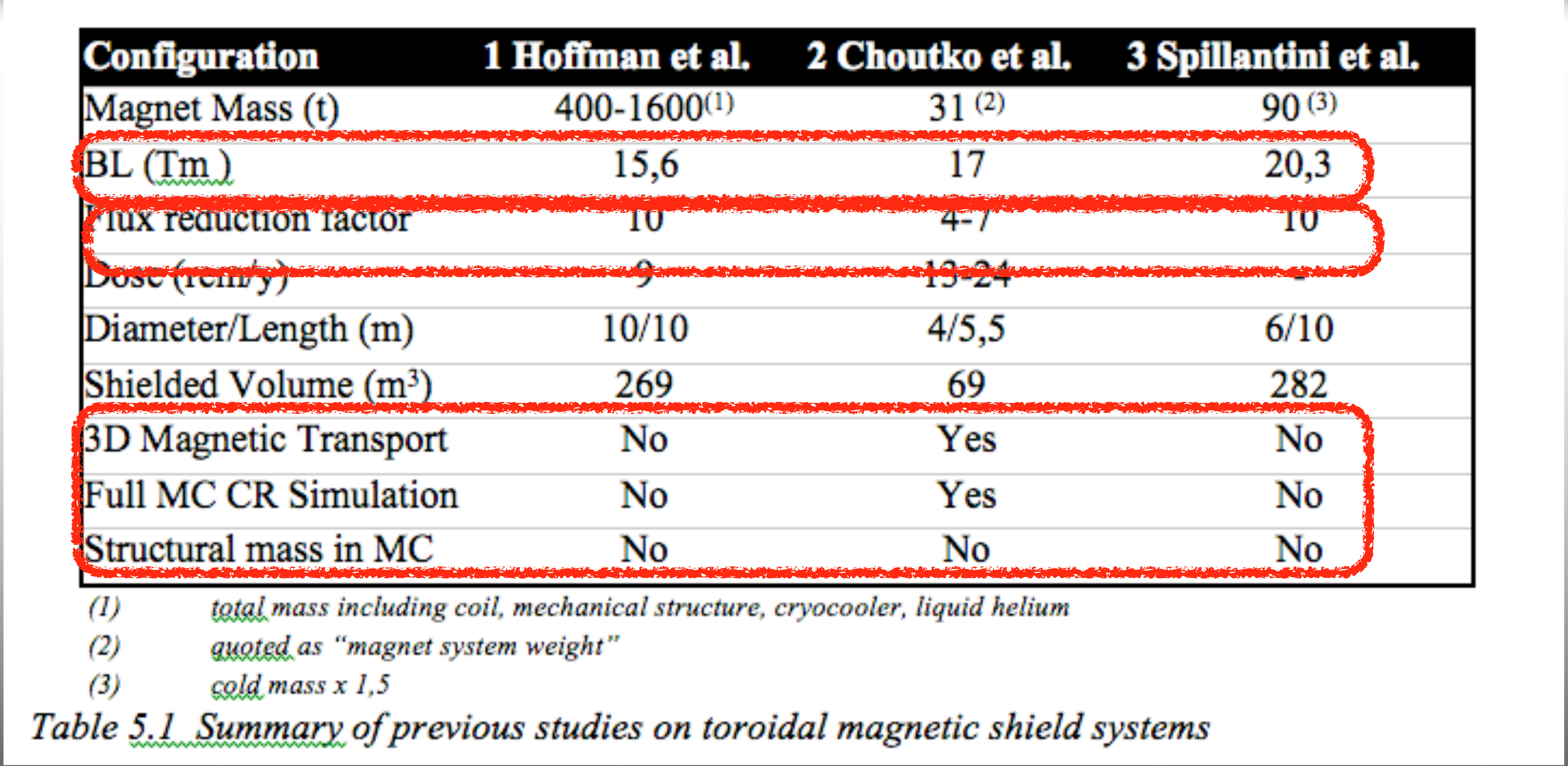
Previous Monte Carlo Studies



Configuration	1 Hoffman et al.	2 Choutko et al.	3 Spillantini et al.
Magnet Mass (t)	400-1600(1)	31 (2)	90 (3)
BL (Tm)	15,6	17	20,3
Flux reduction factor	10	4-7	10
Dose (rem/y)	9	13-24	-
Diameter/Length (m)	10/10	4/5,5	6/10
Shielded Volume (m^3)	269	69	282
3D Magnetic Transport	No	Yes	No
Full MC CR Simulation	No	Yes	No
Structural mass in MC	No	No	No

(1) total mass including coil, mechanical structure, cryocooler, liquid helium

(2) quoted as "magnet system weight"

(3) cold mass x 1,5

Table 5.1 Summary of previous studies on toroidal magnetic shield systems

Active magnetic shielding

Principle of operation

B field tangent to the shielded volume bends particle away

1) toroidal B field, orthogonal to Hab axis

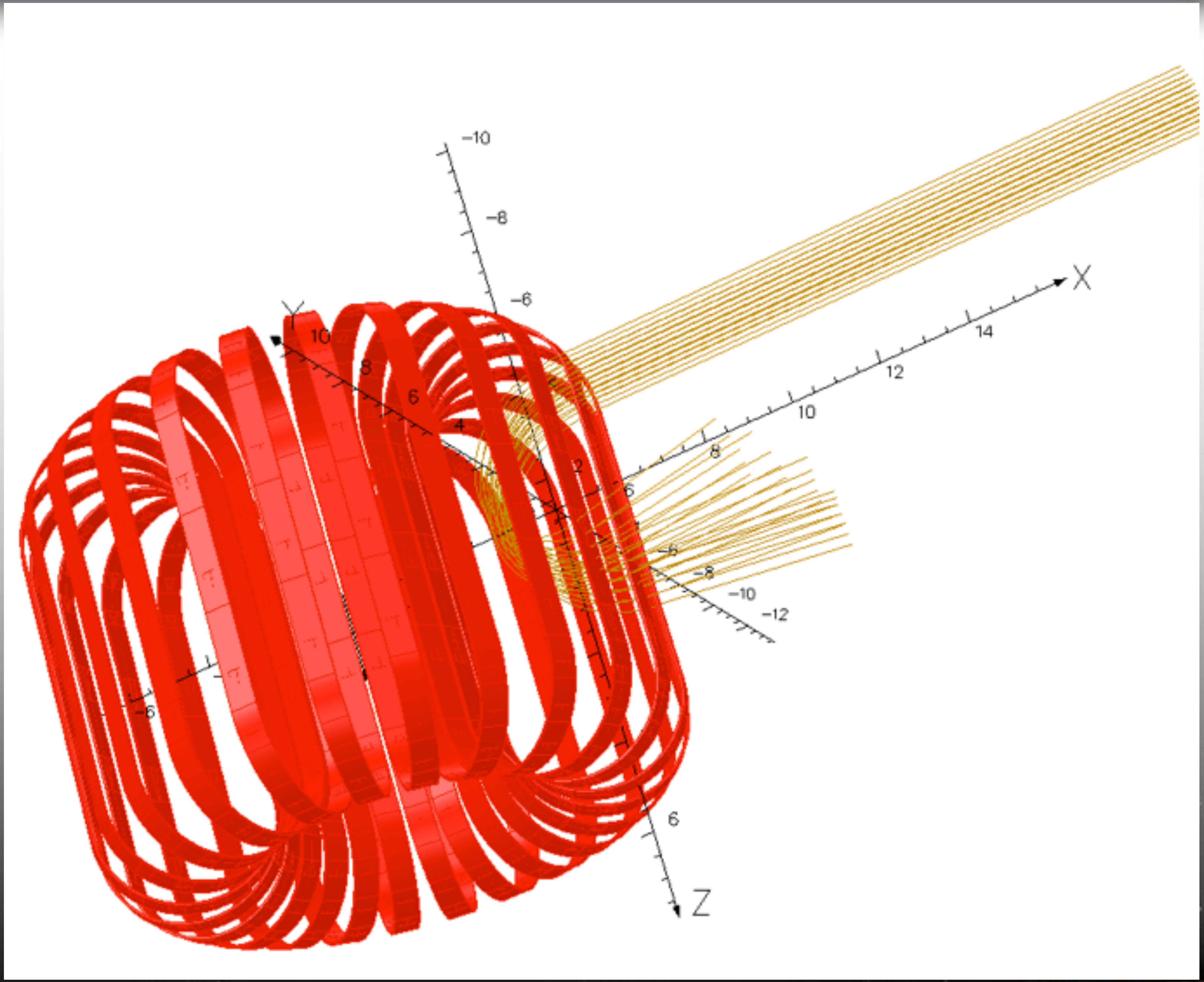
2) solenoidal B field, parallel to Hab axis

SR2S
Space Radiation
Superconducting Shield

SEVENTH FRAMEWORK PROGRAMME

1) TOROIDAL-ORTHOGONAL FIELD

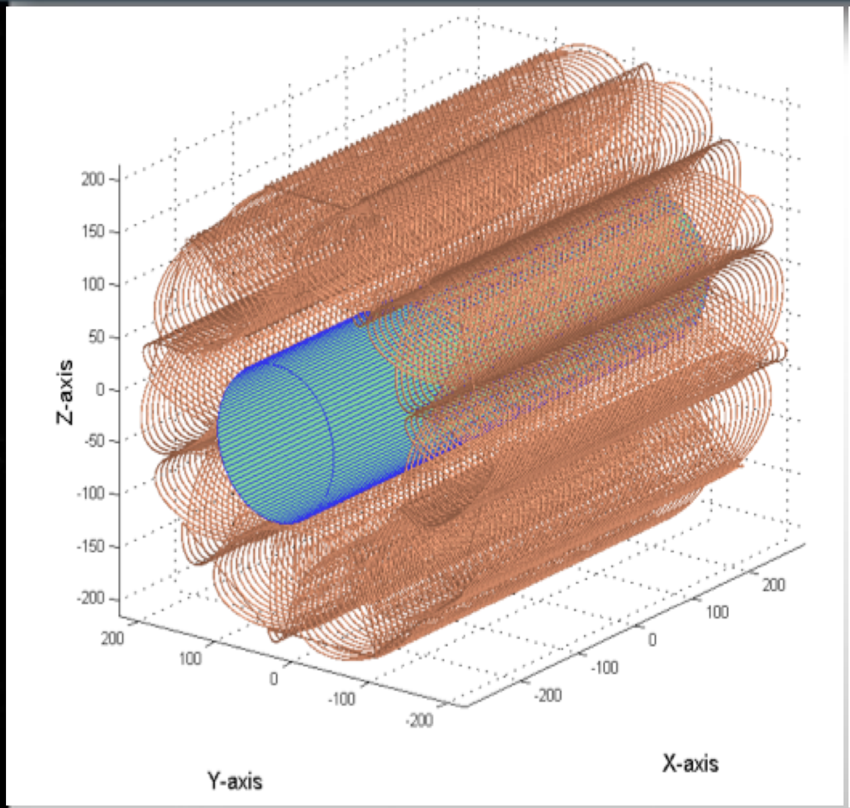
eg. racetracks toroid



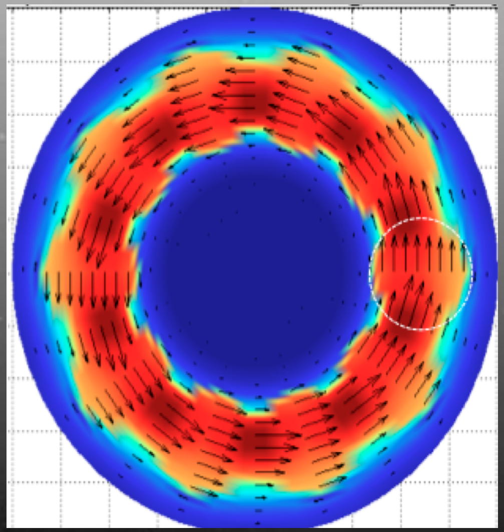
SR2S Space Radiation Superconducting Shield

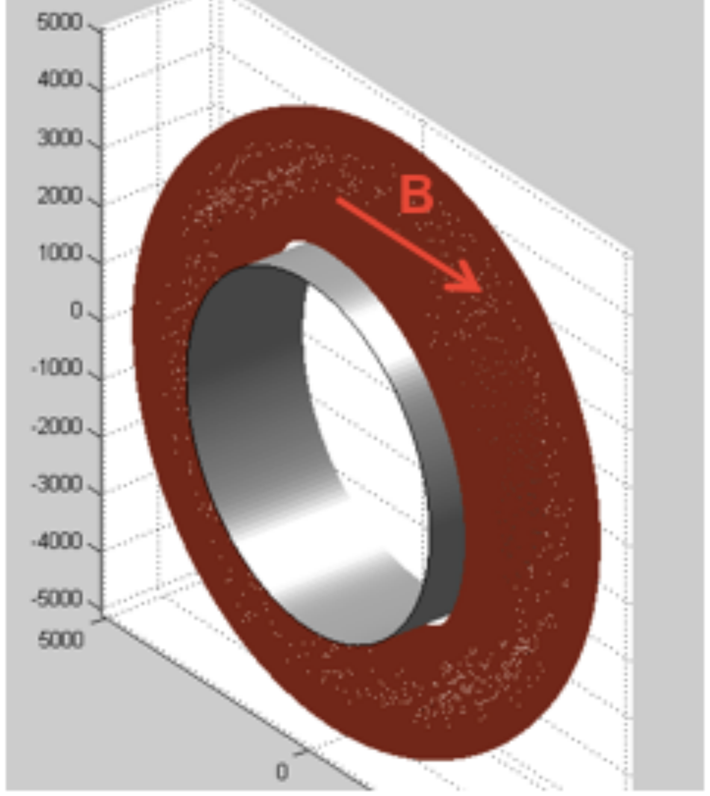
SEVENTH FRAMEWORK PROGRAMME

...but also



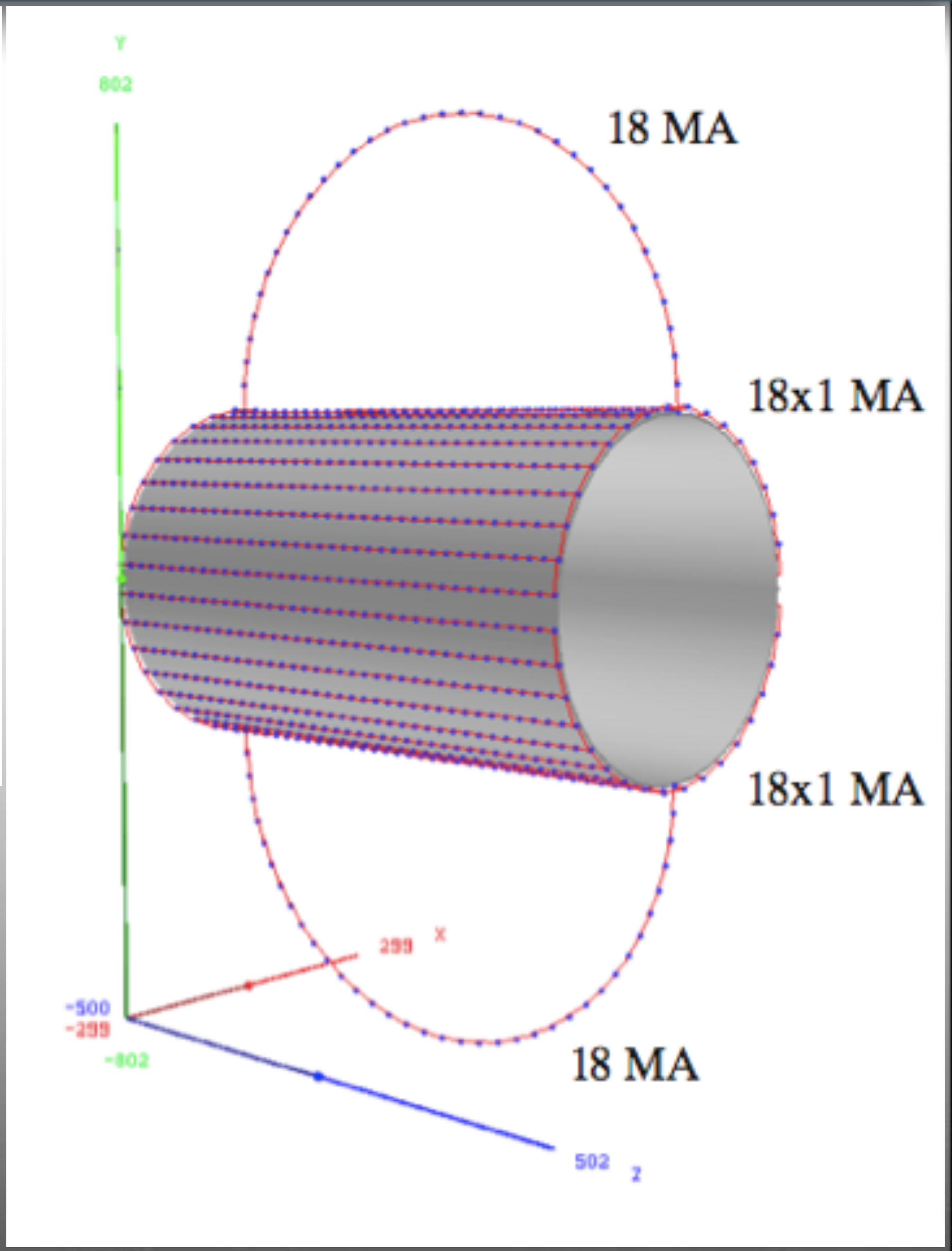
double helix





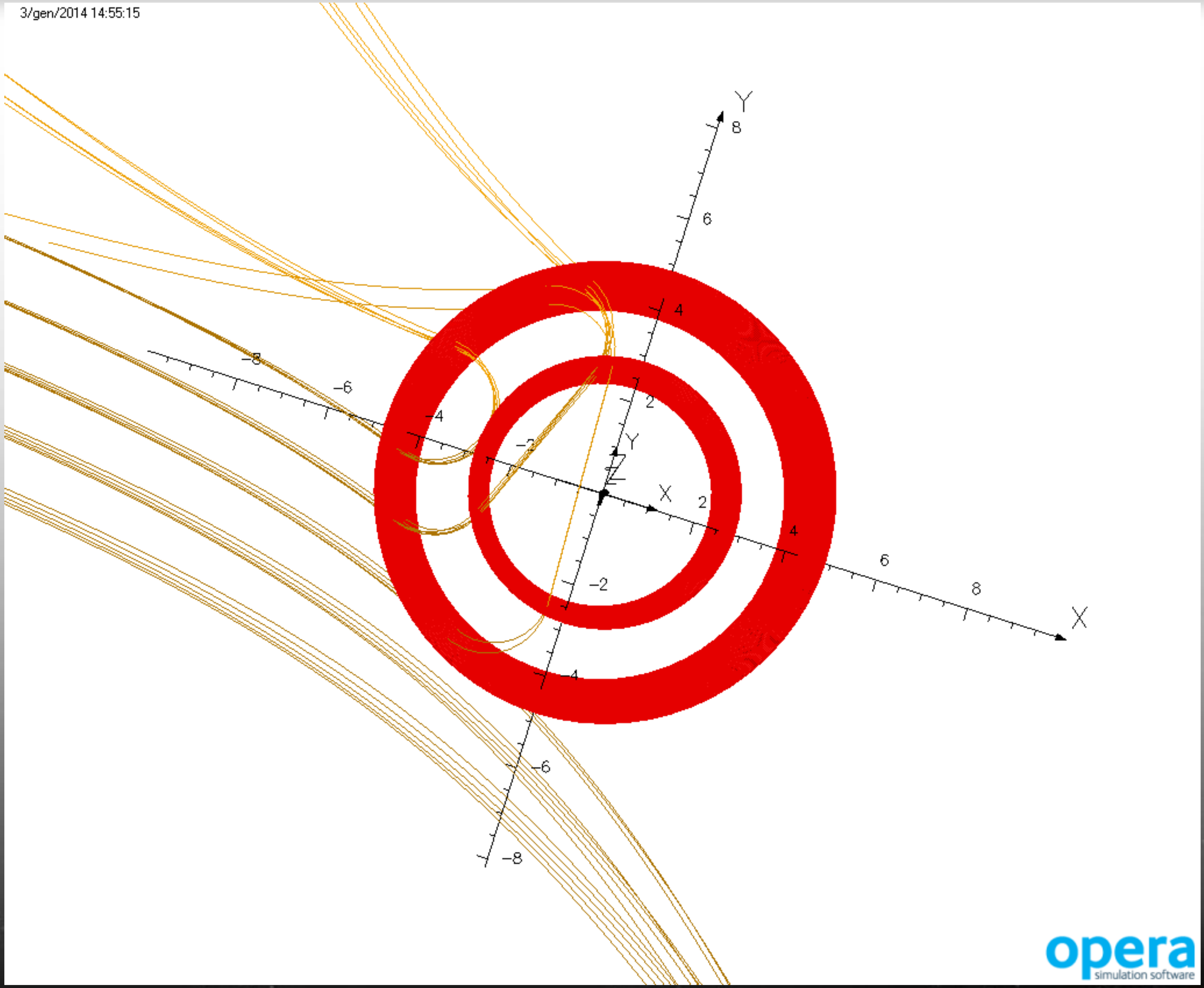
donut

double handle



2) SOLENOIDAL-PARALLEL FIELD

eg. coaxial solenoids



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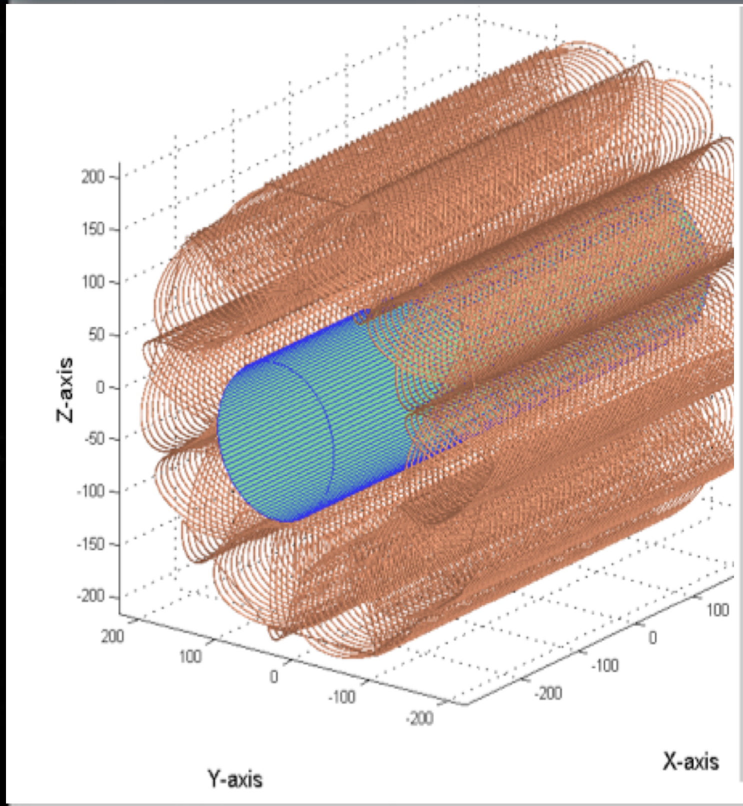
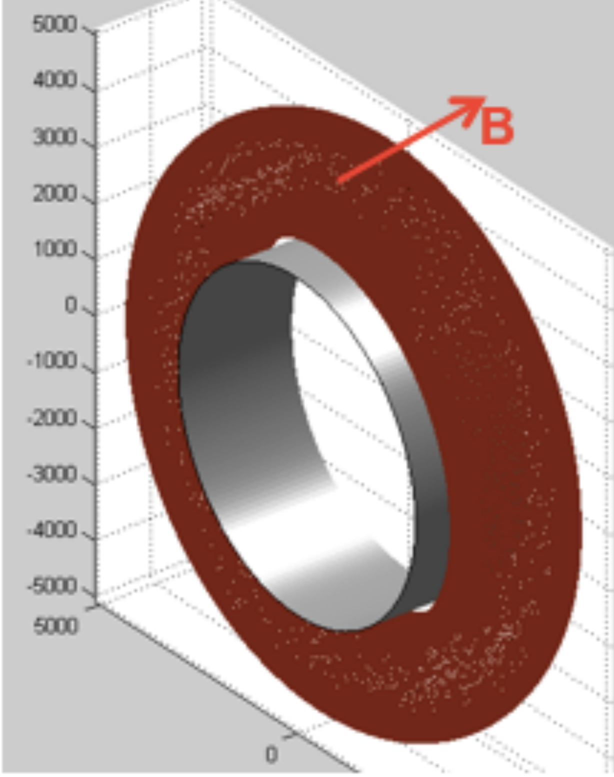
Superconducting Shield

SEVENTH FRAMEWORK PROGRAMME

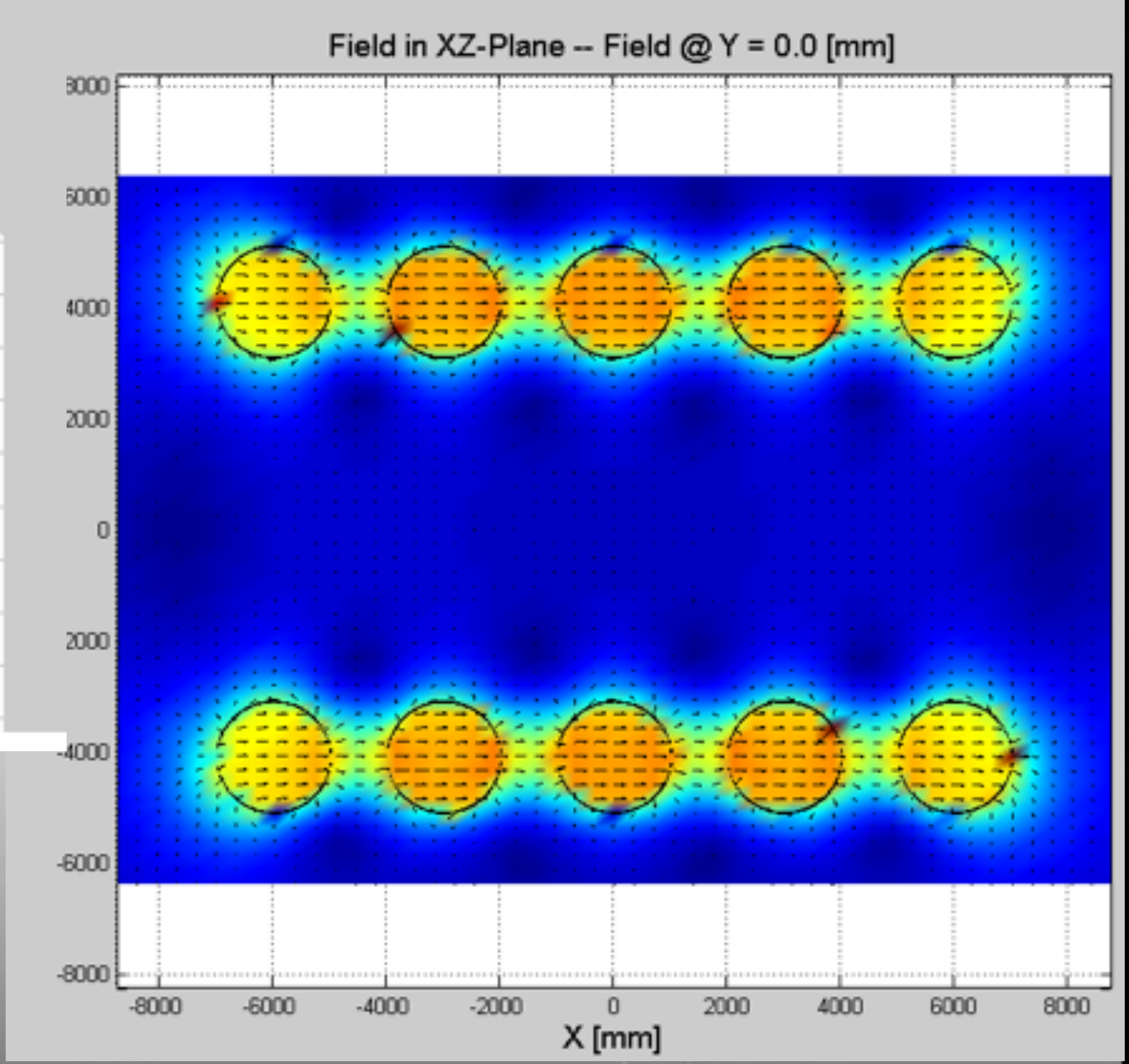
...but also



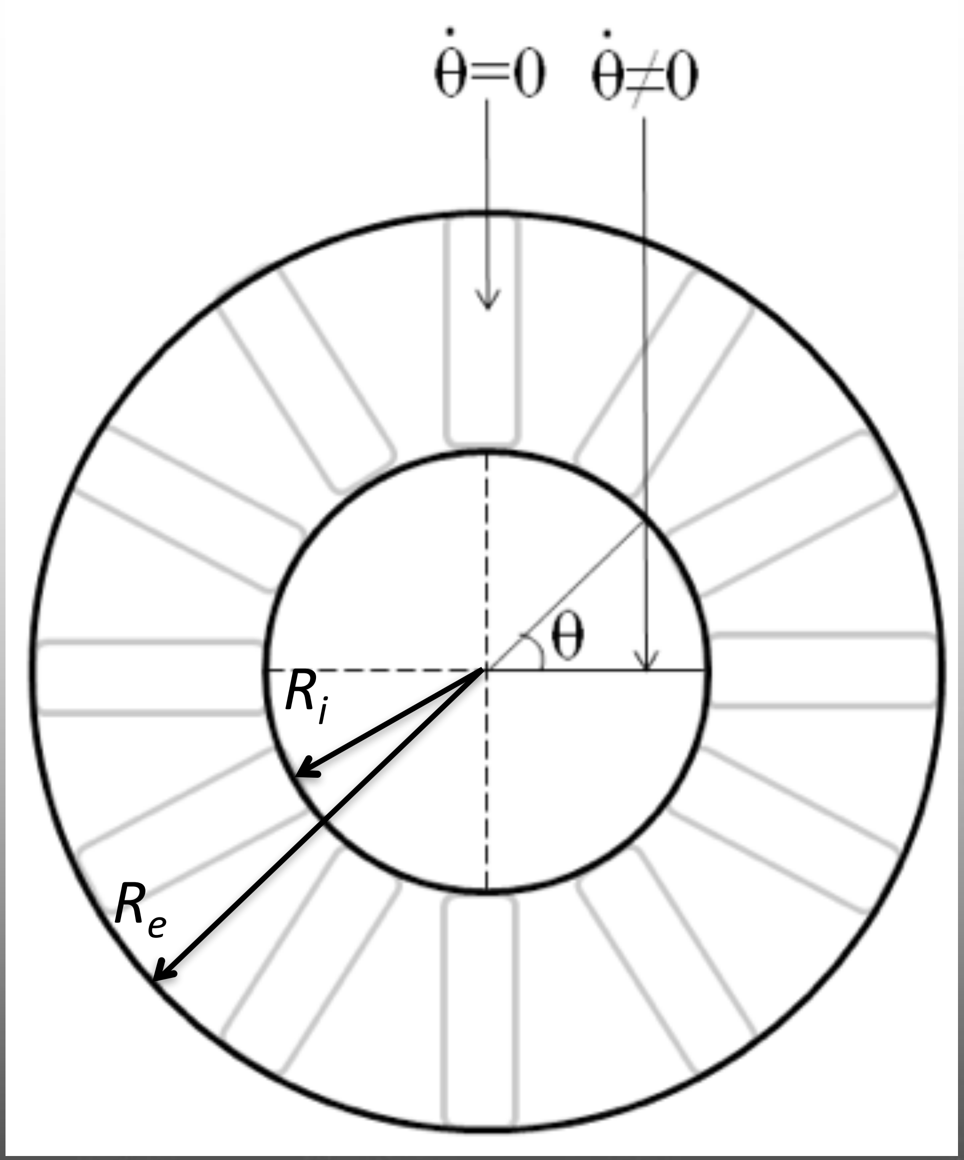
multisolenoid



axial
multidonut



Shielding power : ∫BdL



For an ideal toroid, the shielding power is defined as

$$\Xi = \int_{R_i}^{R_e} BdR = \frac{\mu_0 NI}{2\pi} \ln\frac{R_e}{R_i}$$

--> large radius
--> large B
 we would reach effective shielding with **∫BdL≈15 Tm**

Magnet mechanical structure

$$P(Pa) = B^2/\,2\mu_o\,(T^2)$$

Toroidal field →B non uniform→
1-large inward pressure →structural mass
2-low leakage field

Solenoidal field → B is uniform →
1-large outward forces
2-large leakage field→ compensation coil

Avoid stresses on superconducting cable →coil support

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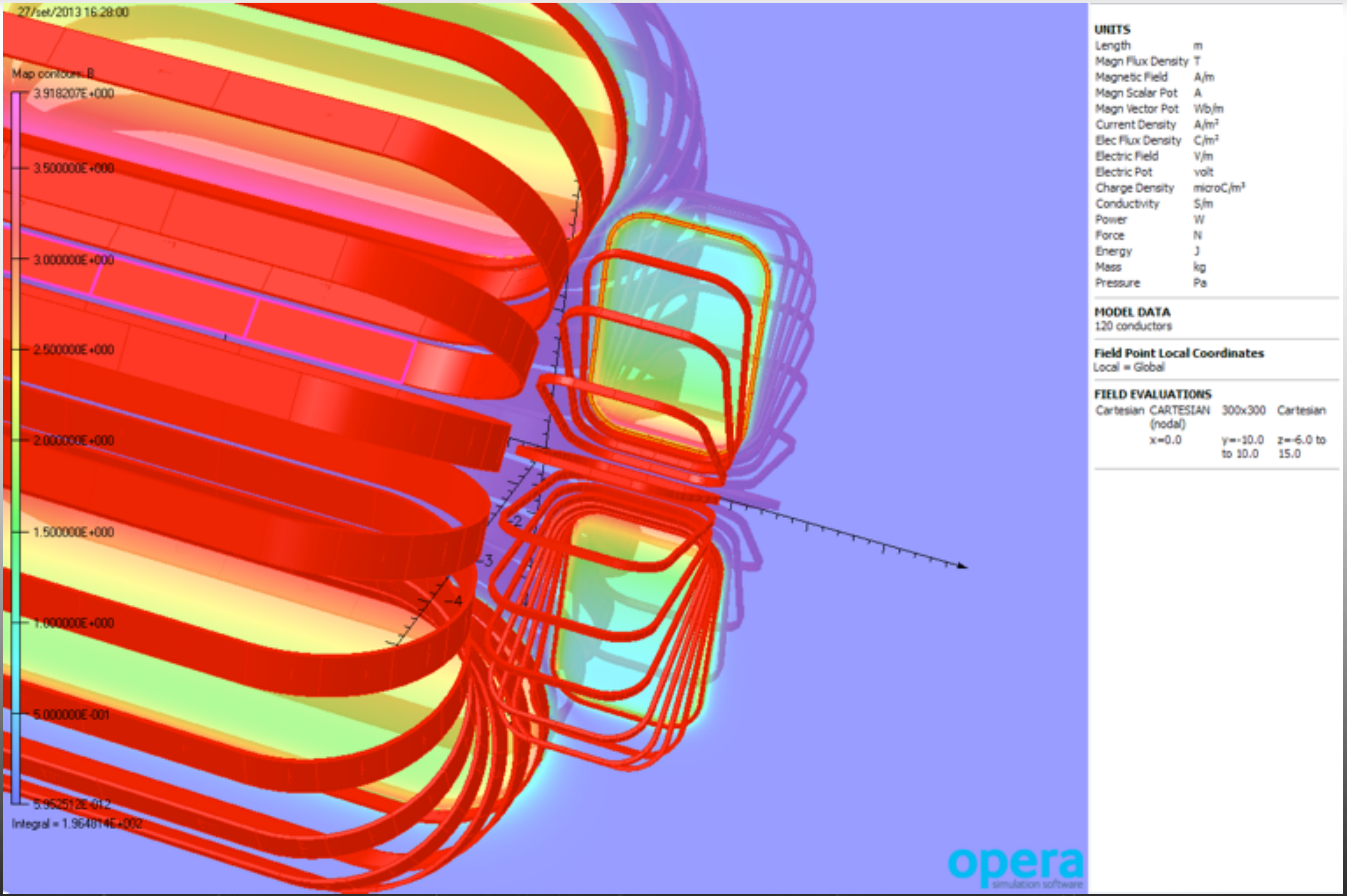
Space Radiation
Superconducting Shield

SEVENTH FRAMEWORK PROGRAMME

SRS2 tradeoff -> racetrack toroid system



UNITS

Length	m
Magn Flux Density	T
Magnetic Field	A/m
Magn Scalar Pot	A
Magn Vector Pot	Wb/m
Current Density	A/m²
Elec Flux Density	C/m²
Electric Field	V/m
Electric Pot	volt
Charge Density	microC/m³
Conductivity	S/m
Power	W
Force	N
Energy	J
Mass	kg
Pressure	Pa

MODEL DATA
120 conductors

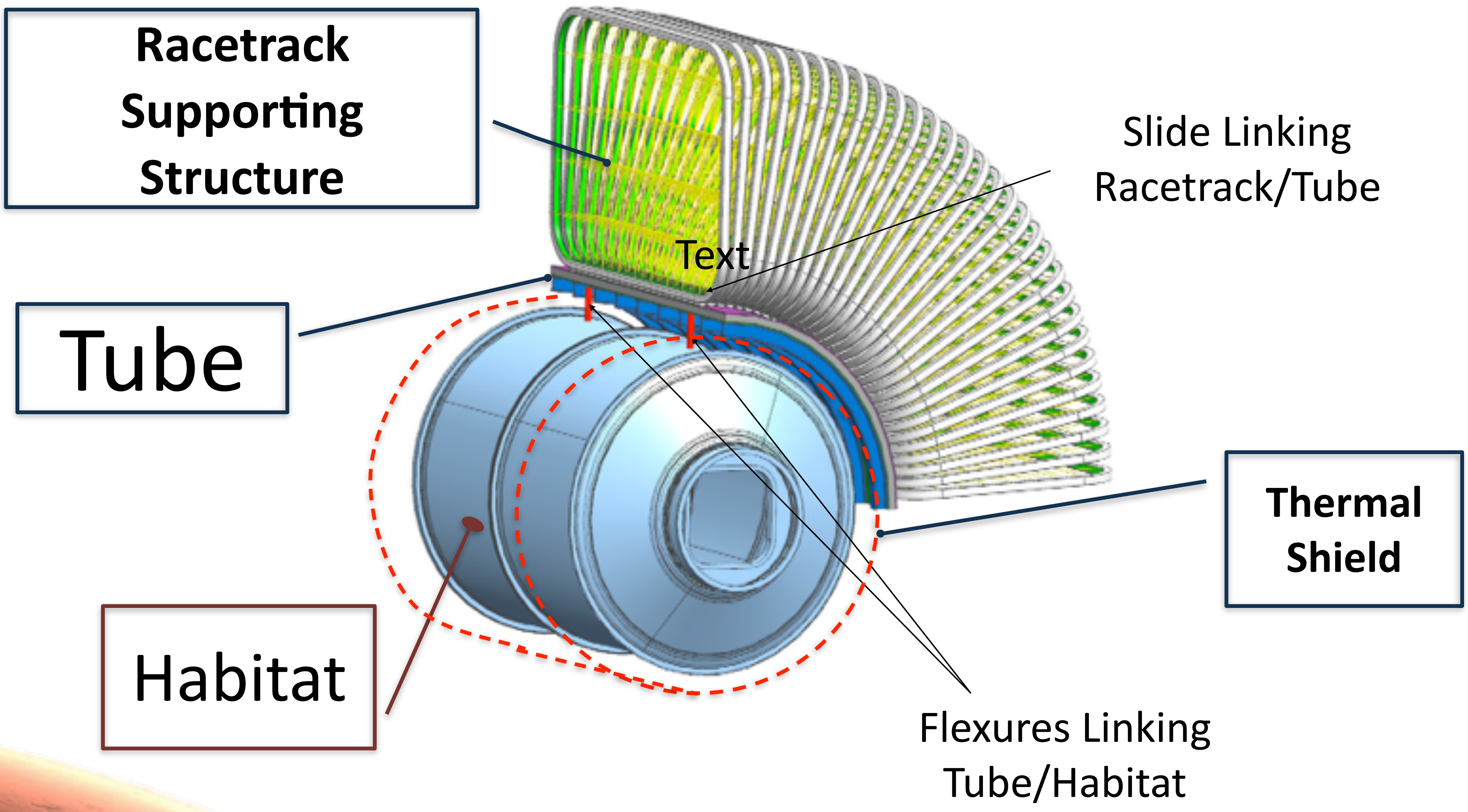
Field Point Local Coordinates
Local = Global

FIELD EVALUATIONS

Cartesian	CARTESIAN (nodal)	300x300	Cartesian
	x=0.0	y=-10.0 to 10.0	z=-6.0 to 15.0

SR2S
Space Radiation
Superconducting Shield

Structure configuration



Racetrack Supporting Structure

Slide Linking Racetrack/Tube

Tube

Thermal Shield

Habitat

Flexures Linking Tube/Habitat

see F. Tunesi talk

Magnet mechanical structure

Magnet design iterations in SR2S

- **Structure design optimization:**
    - **minimize the material traversed by *GCR* to avoid secondary production**
    - **maximize the BdL to deflect away Z<3 particles**
    - **exploit the passive material to absorb Z>2 particles (stopping power)**

- **Perform Monte Carlo calculations of the dose reduction factor for GCR and SPE**

- **Improve the use advanced materials and mechanical solutions to reduce mass.**

- **Current design configuration: BdL ≈ 8 Tm**

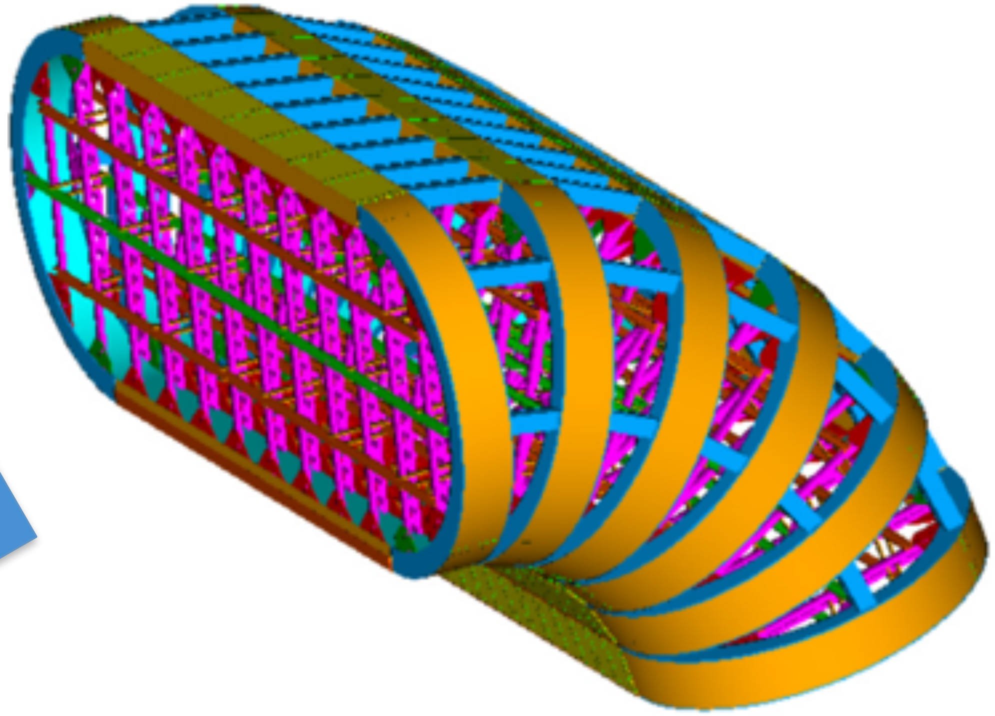
SR2S
Space Radiation Superconducting Shield

SEVENTH FRAMEWORK PROGRAMME

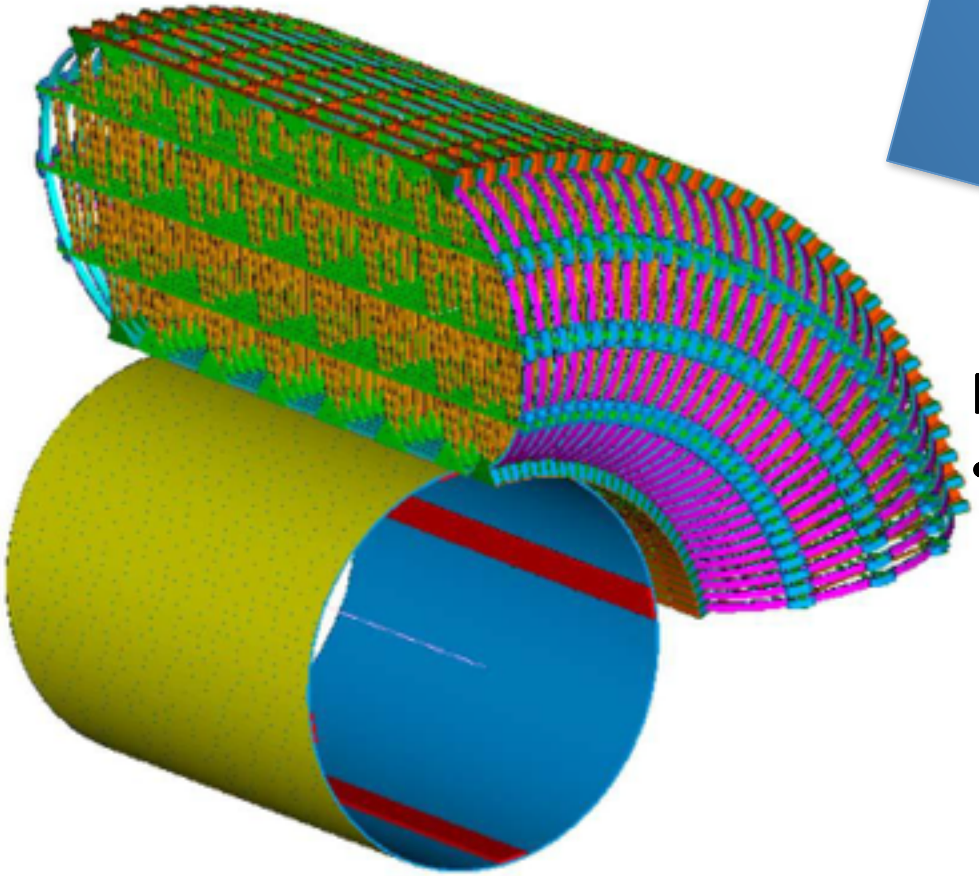
Example of mass optimization

First Design:

- 24 Coils → High loads on the racetrack
  - → Concentrated Loads on the Tube
  - → High Local Deformation
  - → More sensitive at mechanical tolerance



Smart Solution



New Design:

- 120 coils → Lower loads on the racetrack
  - → Loads uniformly distributed on the tube
  - → Lower Deformation
  - → Less Sensitive at mechanical tolerance

SR2S
Space Radiation Superconducting Shield

Analytical and Monte Carlo analyses

$$K_\eta = -\frac{E}{\eta}\left(1-\sqrt{\left(\frac{q}{m_0}\frac{\chi}{c(1-sin\varphi)}\right)^2+1}\right)$$

K_η:Cut off energy per nucleon

E: *rest mass*

η: *number of nucleons*

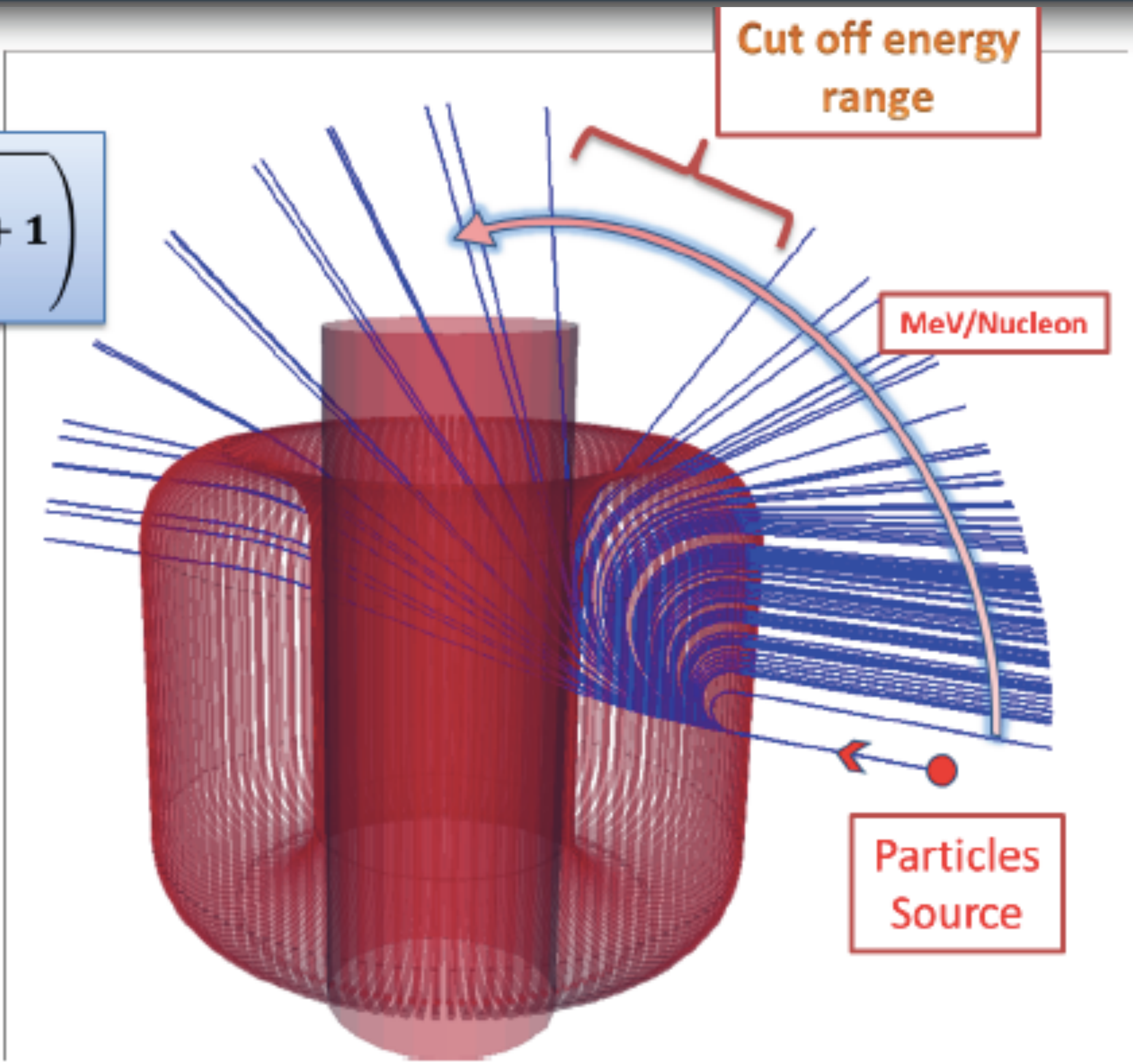
q: *charge*

m_0:*mass*

c: *light speed*

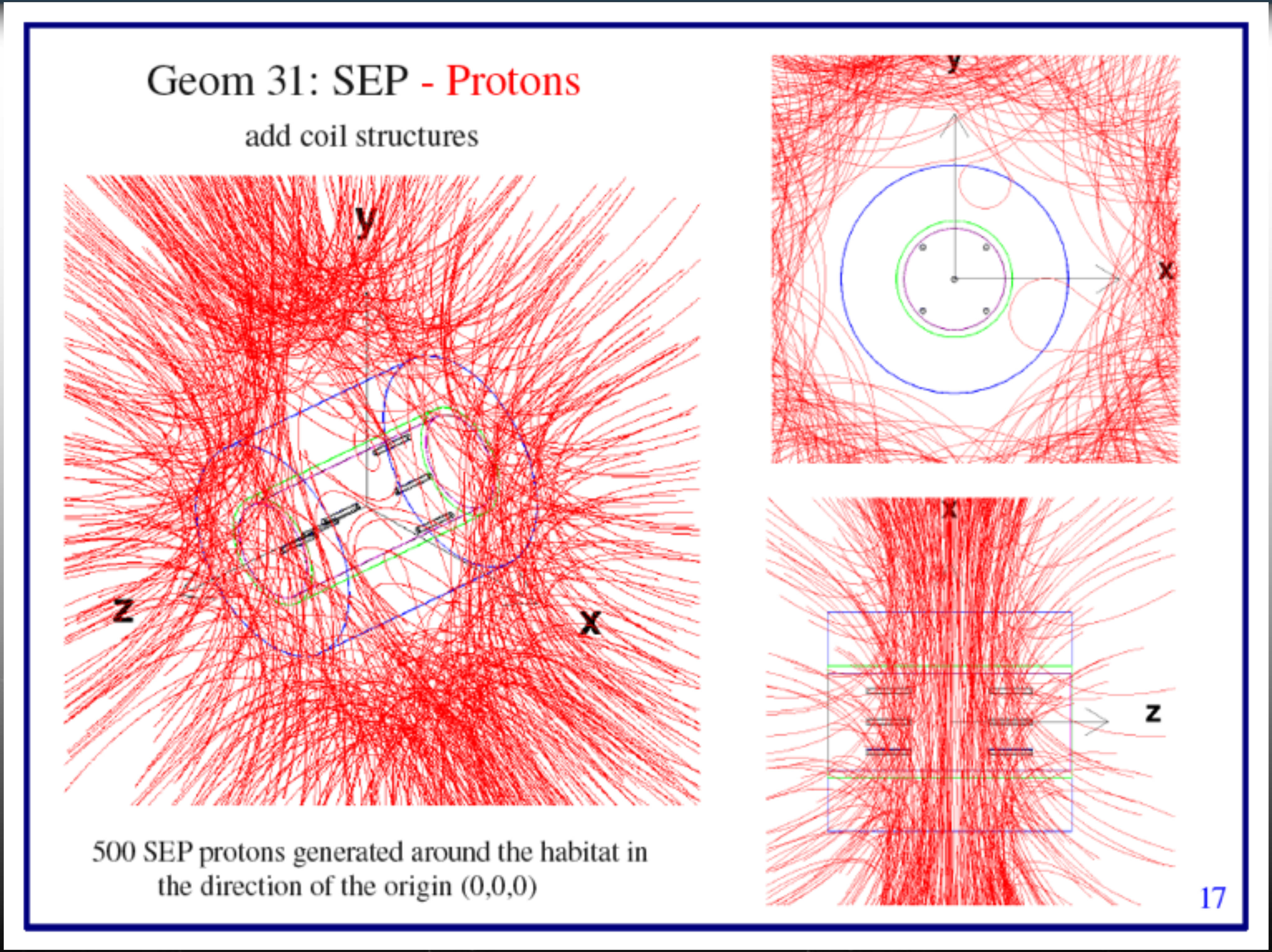
χ: *Shielding power*

φ:*incidence angle*



See M. Giraudo talks

Magnetic shielding of a SPE event



Geom 31: SEP - Protons

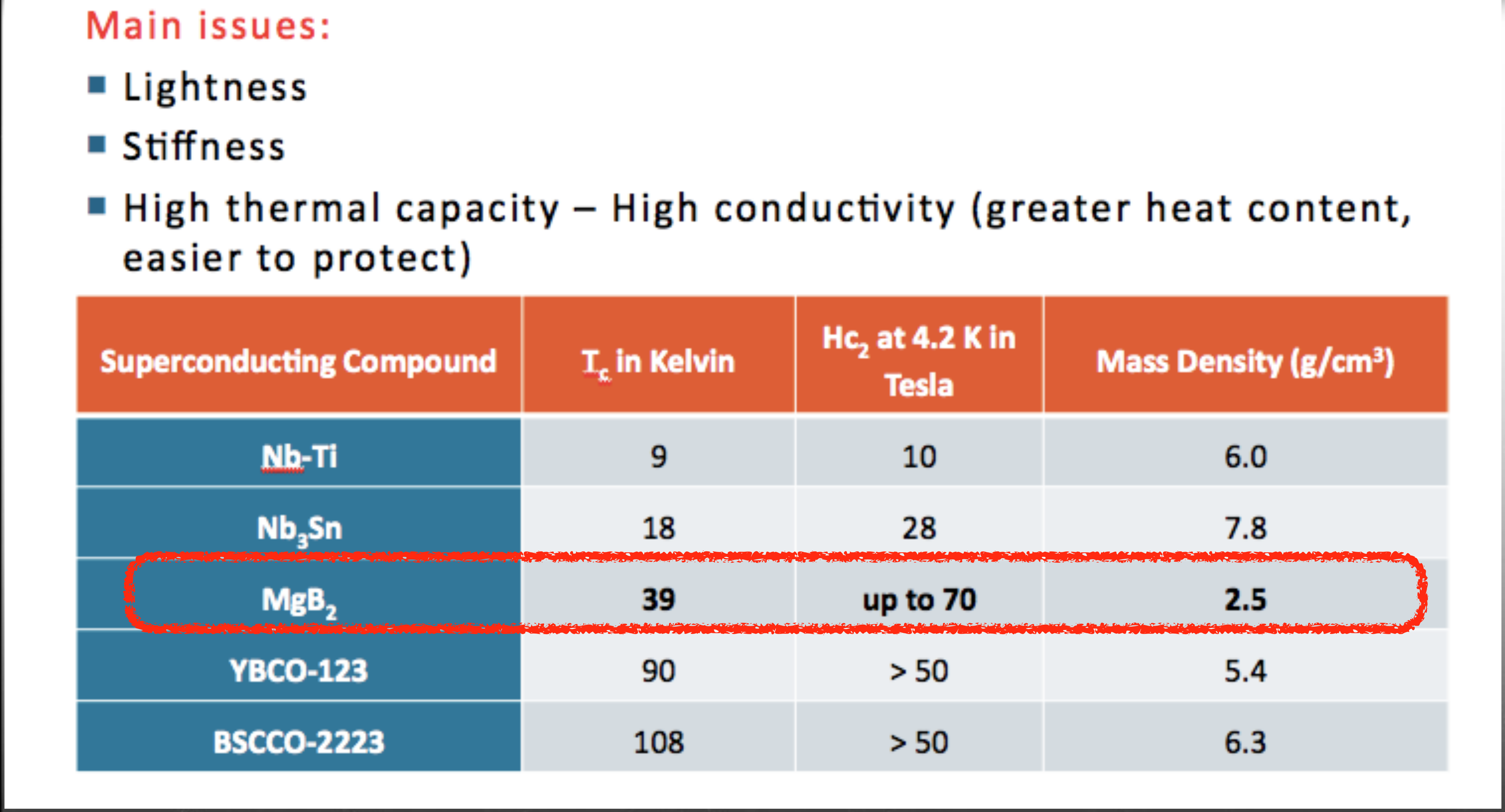
add coil structures

500 SEP protons generated around the habitat in the direction of the origin (0,0,0)

17

Superconducting cable for space applications

Superconductors for space



Main issues:

- Lightness
- Stiffness
- High thermal capacity – High conductivity (greater heat content, easier to protect)

Superconducting Compound	T_c in Kelvin	Hc_2 at 4.2 K in Tesla	Mass Density (g/cm^3)
Nb-Ti	9	10	6.0
Nb_3Sn	18	28	7.8
MgB_2	**39**	**up to 70**	**2.5**
YBCO-123	90	> 50	5.4
BSCCO-2223	108	> 50	6.3

SR2S Space Radiation Superconducting Shield

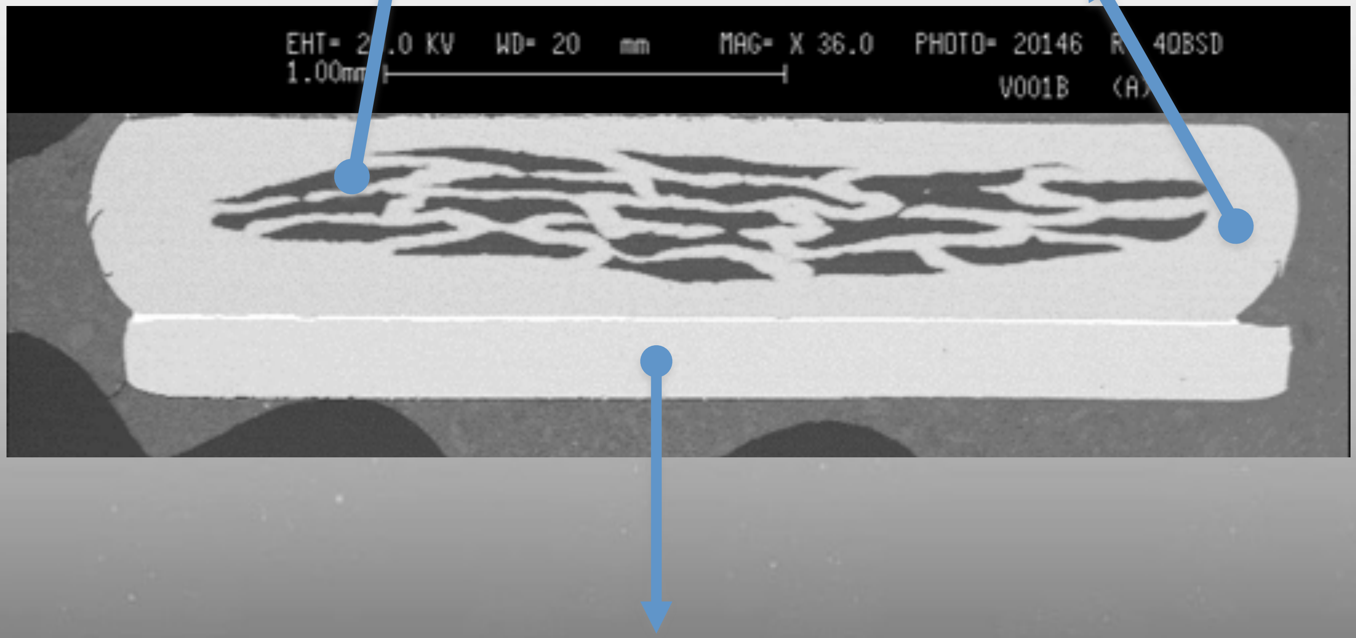
SEVENTH FRAMEWORK PROGRAMME

Columbus cable for magnet applications

Overall weight per 1m of MgB2 standard cable: 17 grams

19 MgB_2 filaments

Nickel cladding



OFHC copper tape laminated (by tin soldering)

MgB_2 superconducting cable for magnet applications:

- Flat tape (3x0,5mm) multifilamentary tape, nickel clad
- Overall dimensions: 3x0,7mm

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Space Radiation
Superconducting Shield

Columbus cable for SPACE applications

Which way is it possible to reduce the averall weight for reducing the launching load?

1- REDUCE THE WEIGHT:

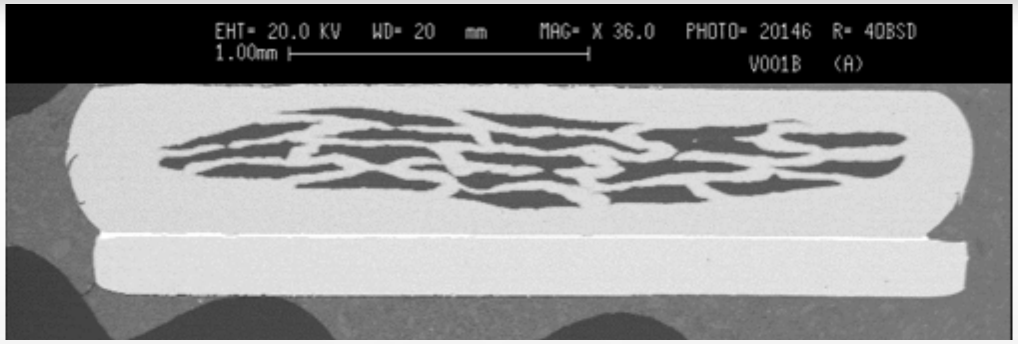
-substitute nickel cladding with a lighter metal (titanium)

-substitute copper stabilizer with aluminum stabilizer

2- IMPROVE CRITICAL CURRENT DENSITY:

-If we are able to improve the current density, we can reduce the overall amount of conductor to be wound in the magnet

Columbus cable for SPACE applications



Materials densities:

titanium: ρ= 4.5 g/cm^3

alluminium: ρ= 2.7 g/cm^3

MgB_2: ρ= 2.55 g/cm^3

Materials percentages:

titanium: 40%

alluminium: 50%

MgB_2: 10%

Materials weights per component (per meter):

titanium: 5.4g

alluminium: 4.0g

MgB_2: 0.77g

Global weight per 1m of MgB2 SPACE app. cable: 10.2 grams

SR2S
Space Radiation Superconducting Shield

Columbus cable for SPACE applications

FROM:

3x0,5 nickel clad wire

3x0,2 copper stabilization

TO:

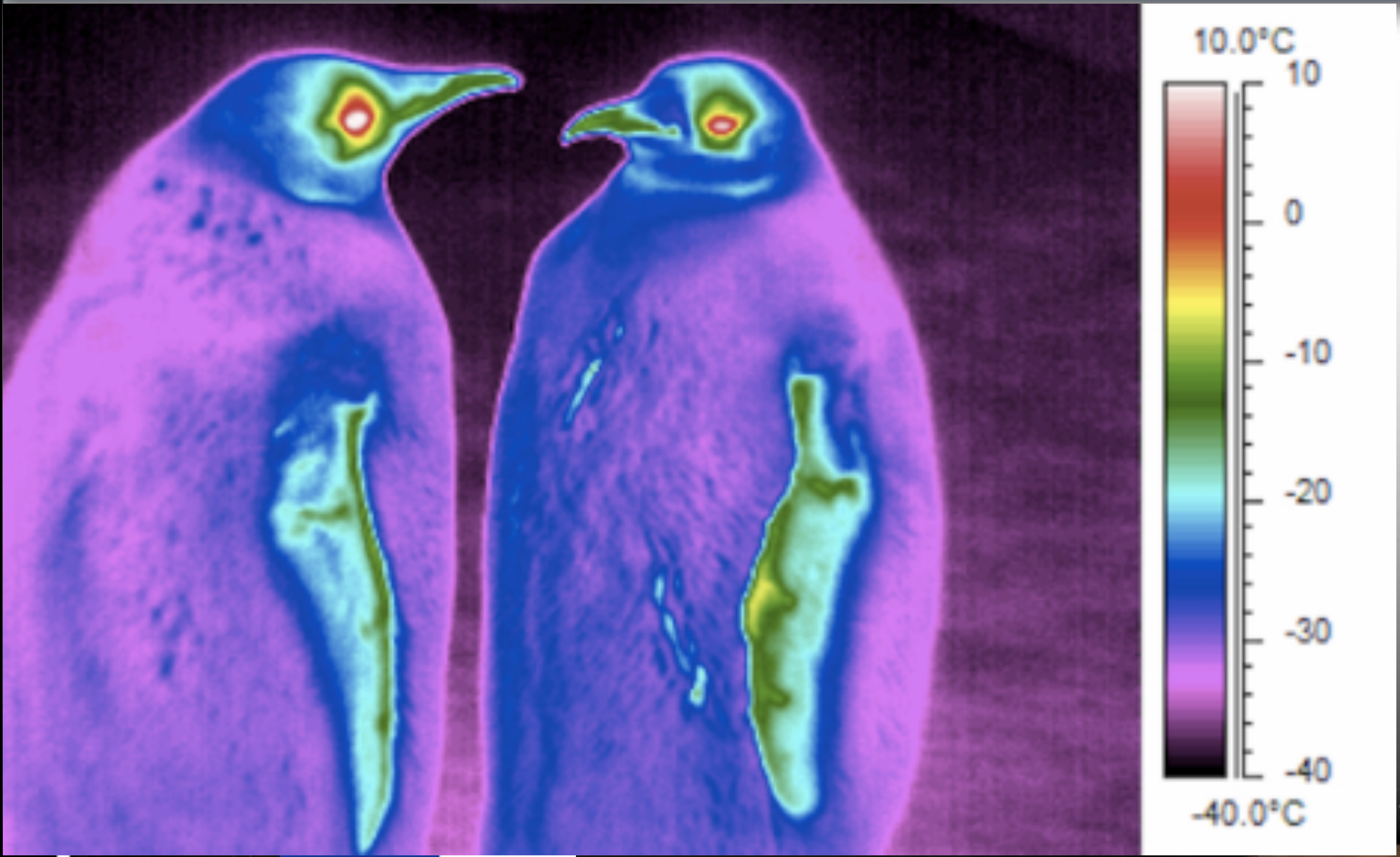
3x0,5 titanium clad wire

3x0,5 alluminium stabilization

FROM 17 TO 10.2 grams,

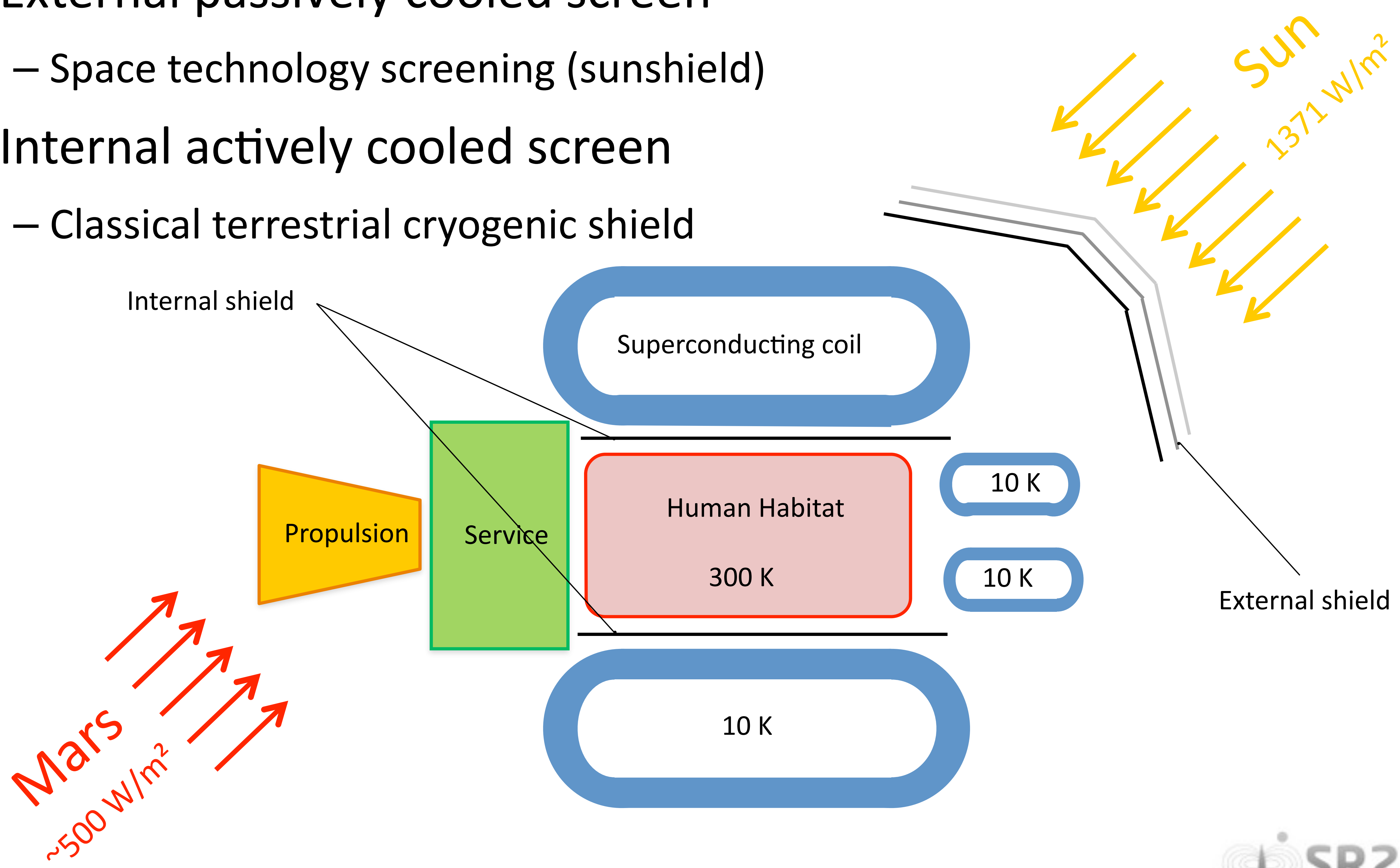
40% weight reduction

Cryogenics and thermal control system



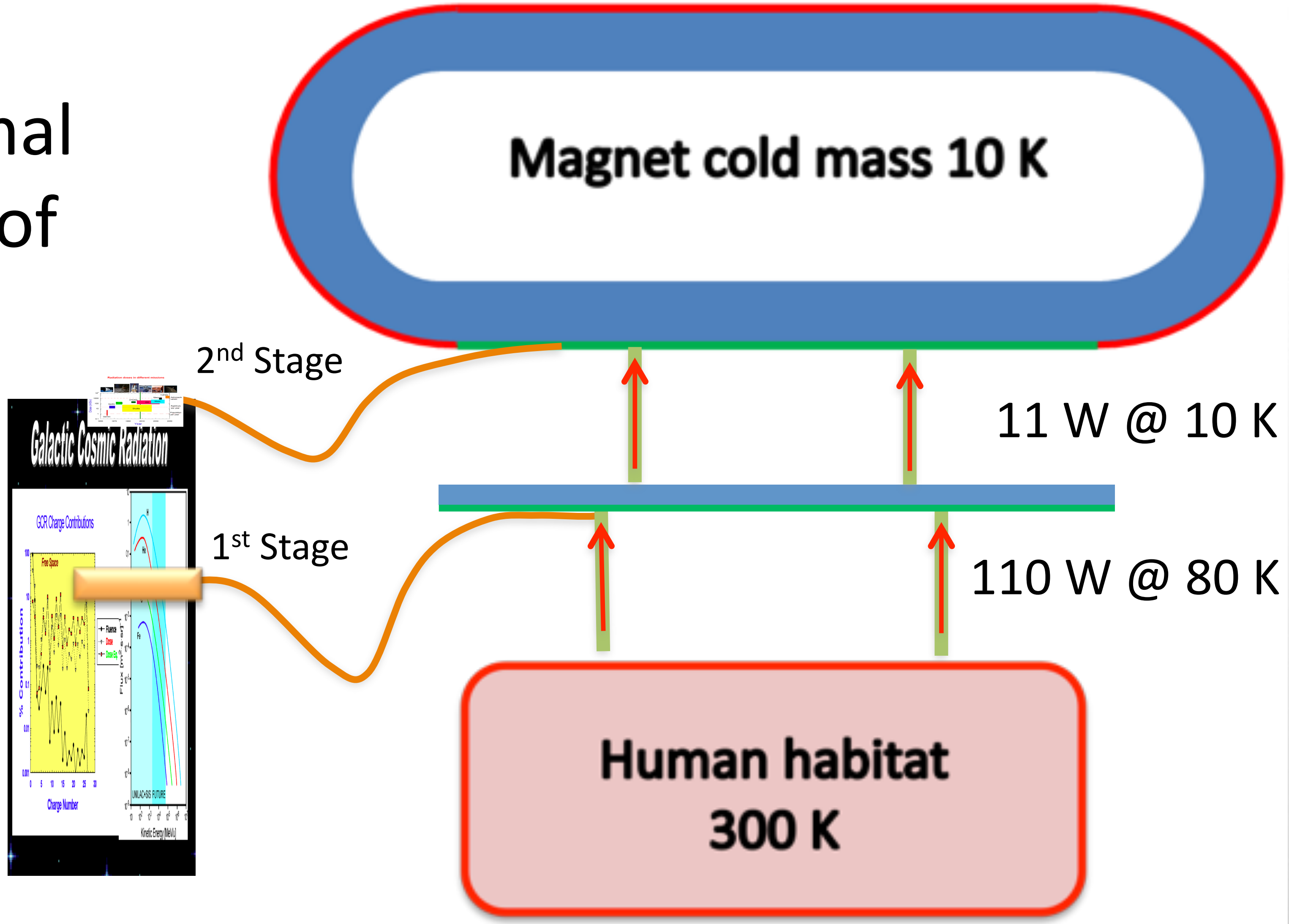
Cryogenics concept

- External passively cooled screen
  - – Space technology screening (sunshield)
- Internal actively cooled screen
  - – Classical terrestrial cryogenic shield



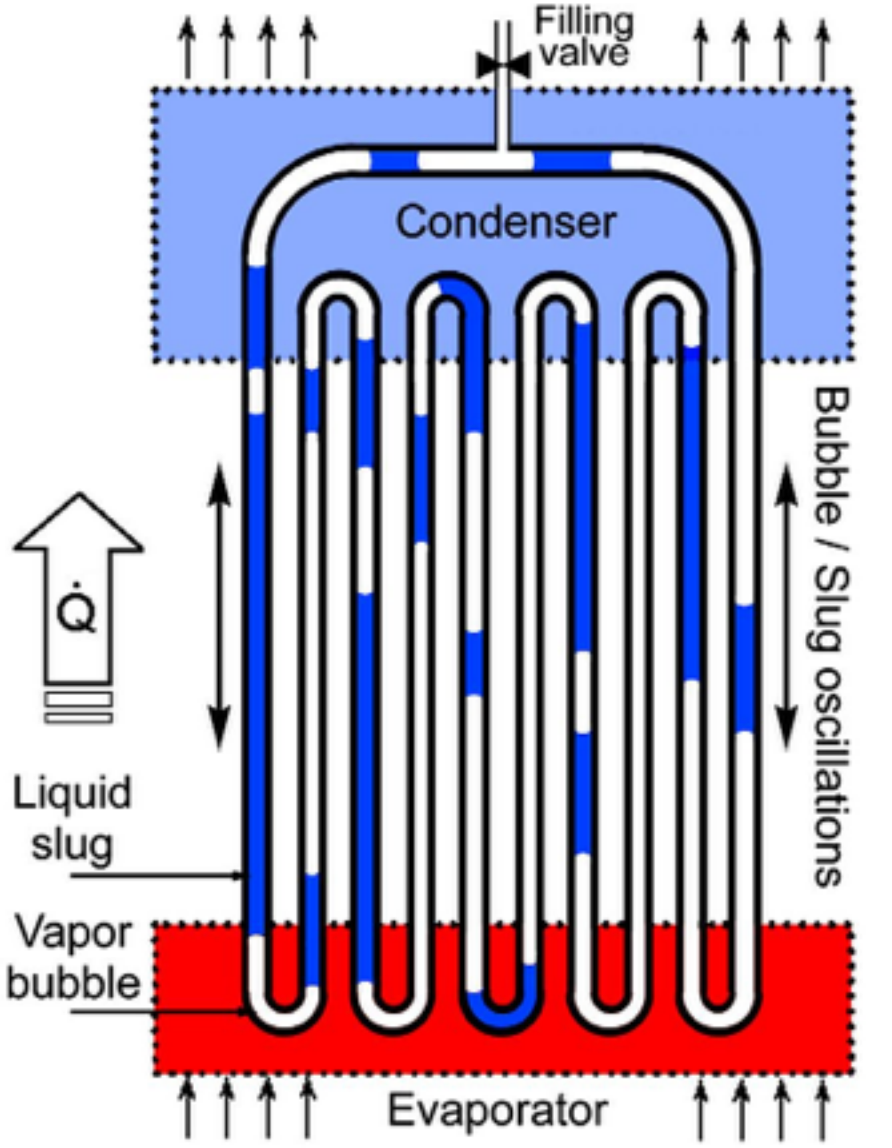
Thermal links

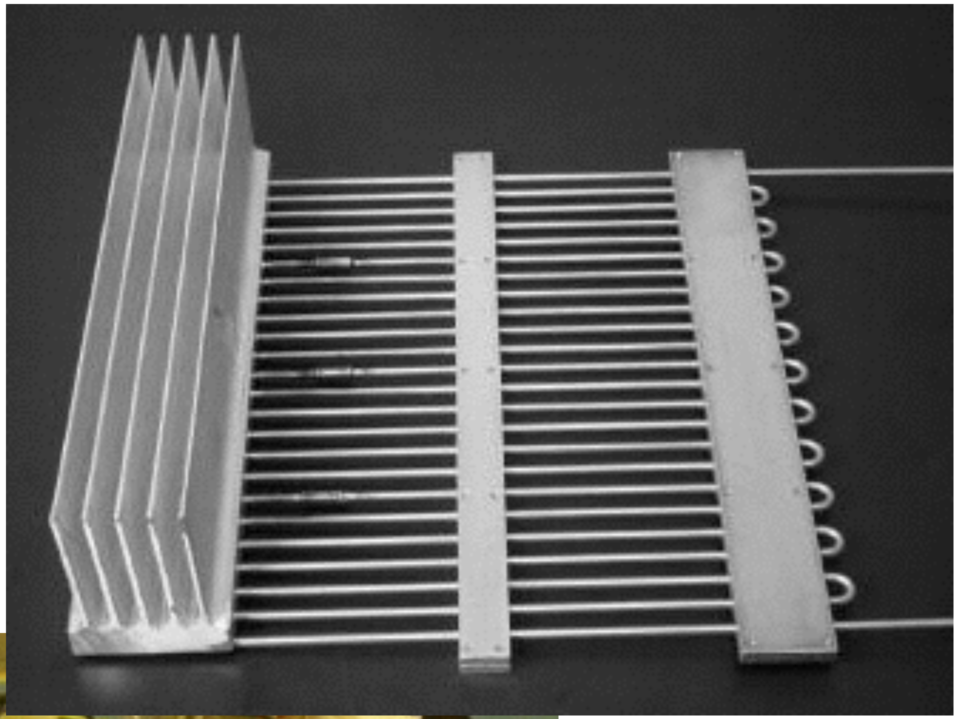
- Conductive thermal link between the cold mass of the magnet and the 2nd stage of the cryocoolers
- Efficient thermal links between the 80 K thermal shield and the 1st stage of cryocoolers
- No gravity, high heat transfer, passive (no pump) and long thermal link
- **Pulsating Heat Pipe**

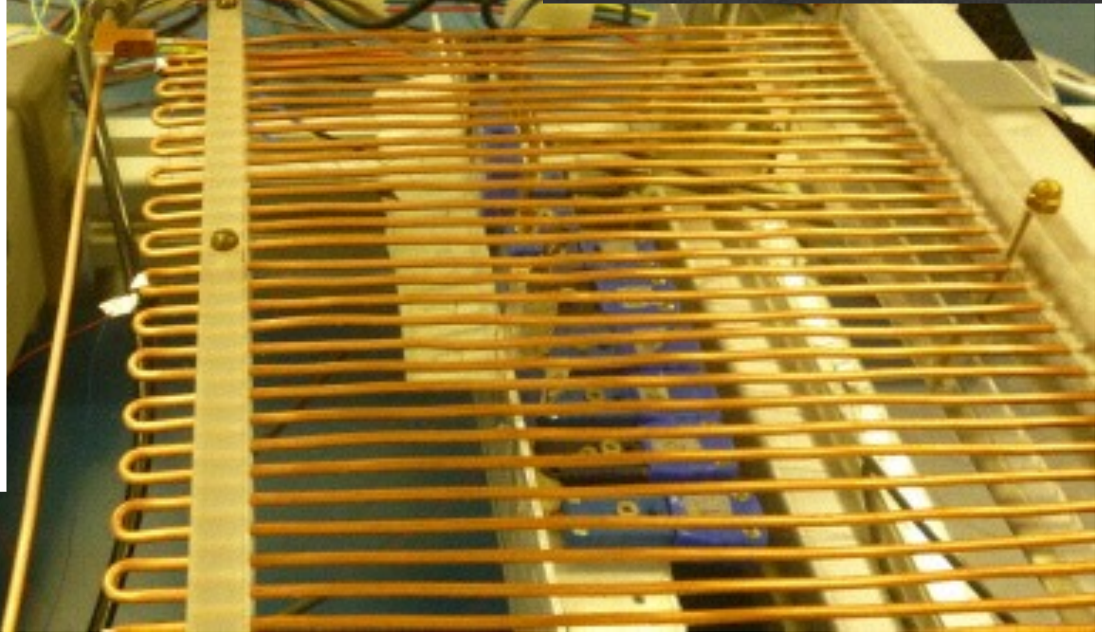


R&D on large Cryo-Pulsating Heat Pipes

- A pulsating heat pipe is a small tube without wick structure partially filled with a working fluid and arranged in many turns

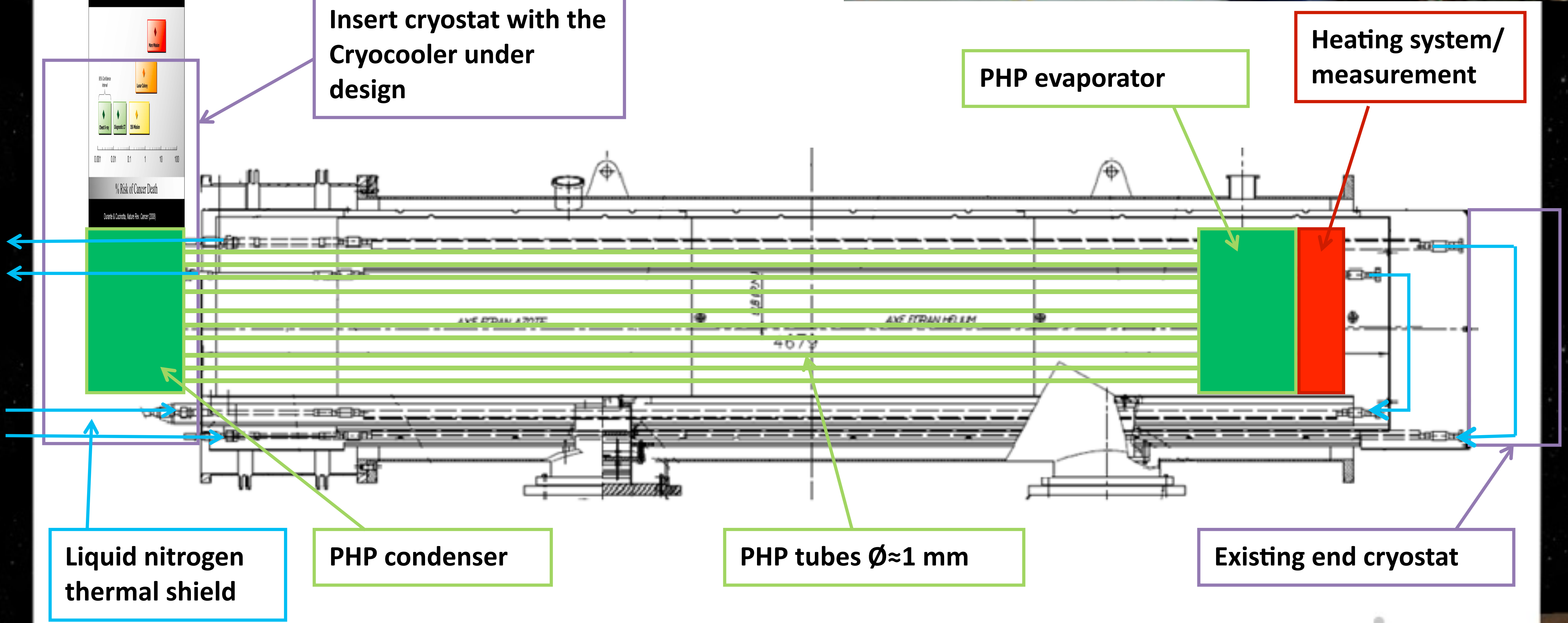






R&D on Cryo-PHP

- Use of 4-m horizontal cryostat
- Use of 8-m vertical cryostat



Insert cryostat with the Cryocooler under design

PHP evaporator

Heating system/ measurement

Liquid nitrogen thermal shield

PHP condenser

PHP tubes Ø≈1 mm

Existing end cryostat

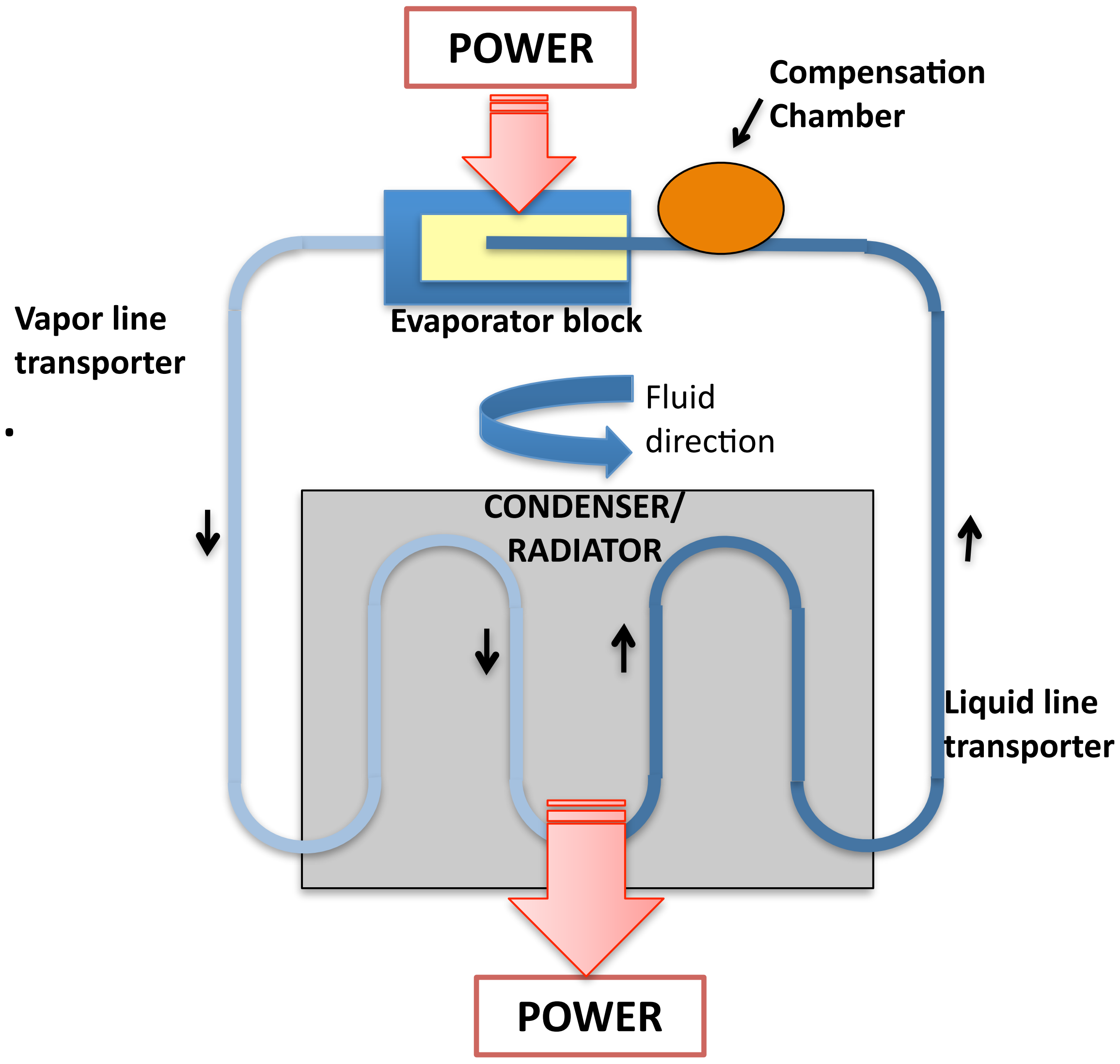
SR2S
Space Radiation Superconducting Shield

R&D on Cryo-Loop Heat Pipe

Selected TCS devices

LHP is based on the fluid evaporation inside a porous wick

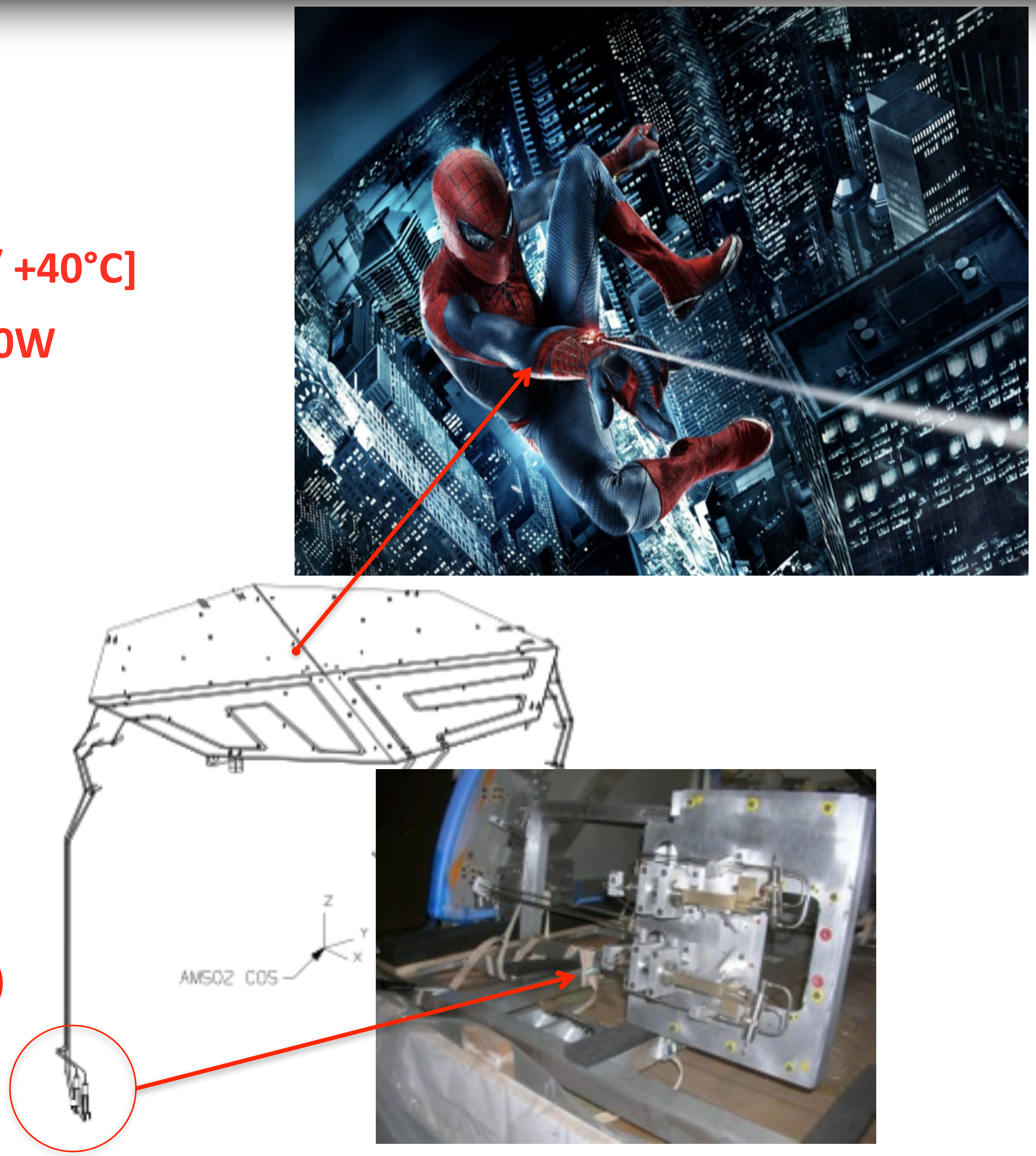
- Completely Passive System
- Self regulating heat transport (e.g. valves)
- Possible long transportation line
- Highest thermal conductance



R&D on AMS-02 Loop Heat Pipe

Similar TCS concept for SR2S

- Cryocooler Temperature Limit → [-30°C / +40°C]
- Cryocooler Power to be dissipated → ~630W



TCS solution adopted

- 4 Cryocooler (Stirling Cycle)
- 8 LHP lines : 4 (main)+ 4(red) lines
- Radiator with embedded LHP (Area ~6m^2)

Identify critical technologies and TRL

We have identified *10 Critical Technologies* which would need significant *R&D* to meet the requirements of an active shield for Space Exploration.

Critical Technology #1 *ITSC* and *HTSC* wires of better suitable quality (MgB_2, *YBCCO*)

Critical Technology #2 Lightweight coils, congifuration, design and assembly

Critical Technology #3 Cryogenically stable, light mechanics

Critical Technology #4 Gas/liquid based recirculating large cooling systems

Critical Technology #5 Cryo-coolers operating a low temperature

Critical Technology #6 Magnetic field flux charging devices

Critical Technology #7 Quench protection for ITS/*HTS* coils

Critical Technology #8 Space deployment and assembly of magnetic elements

Critical Technology #9 Super cryo-insulation, radiation shielding, heat removal

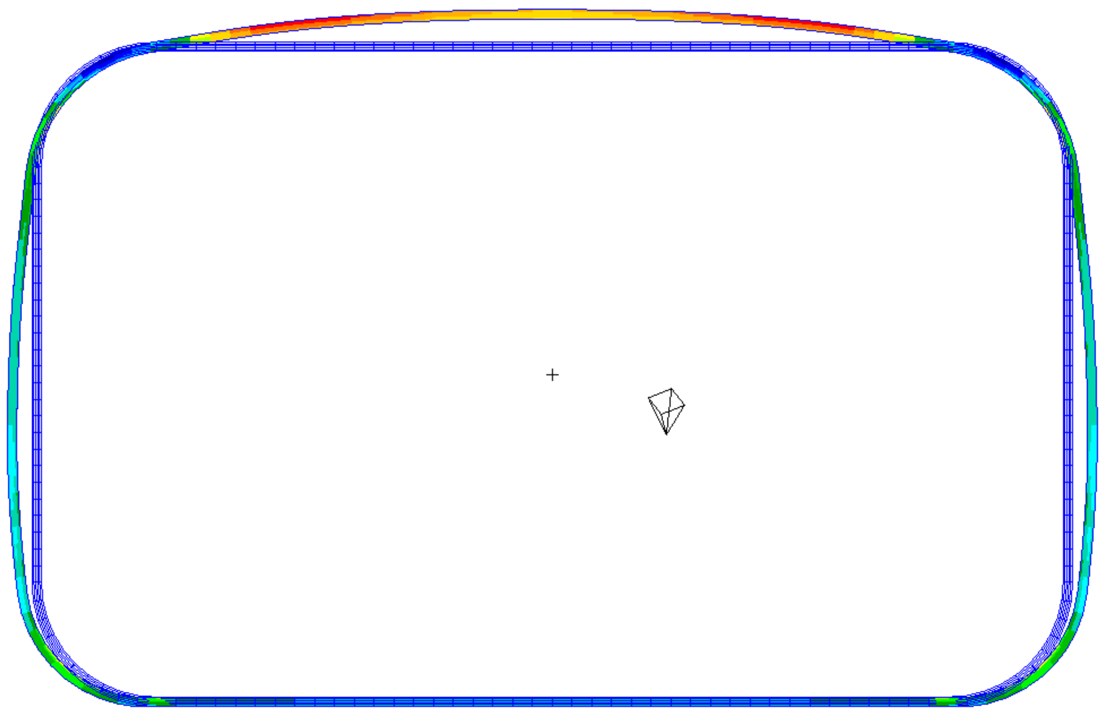
Critical Technology #10 Superconducting Cable splicing in space

Critical technologies and TRL

- **Improvement of SC cable : MgB_2, YBCO**

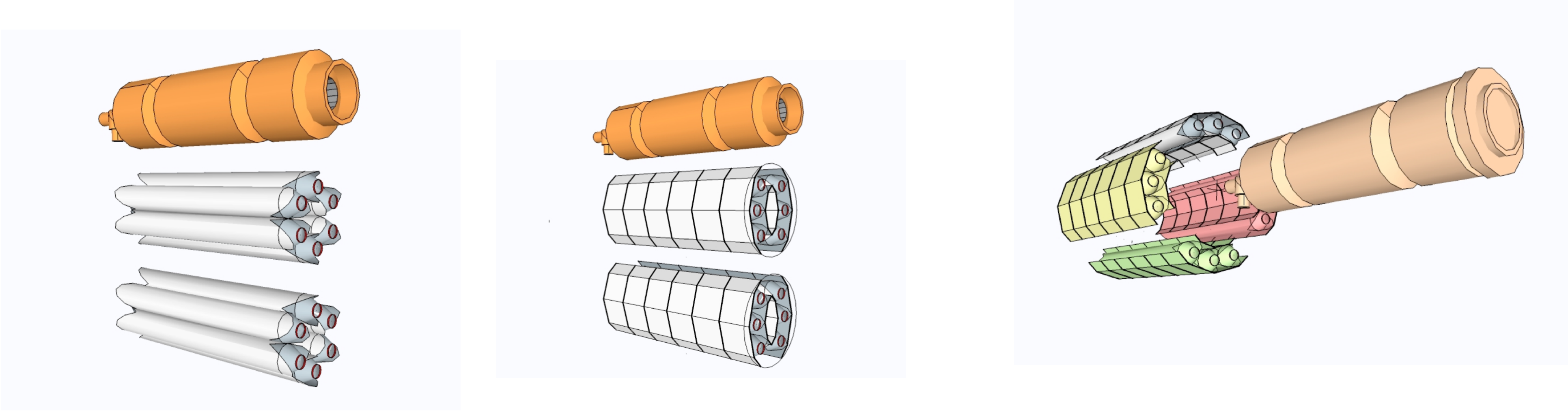
Process	J_e (A/mm^2) at 10K, 2 T	J_e (A/mm^2) at 10K, 4 T
Carbon doping	200	130
Ball milling	250	200
Improved Boron	450	350
High pressure process	700	500

- **Development of large, light coils**

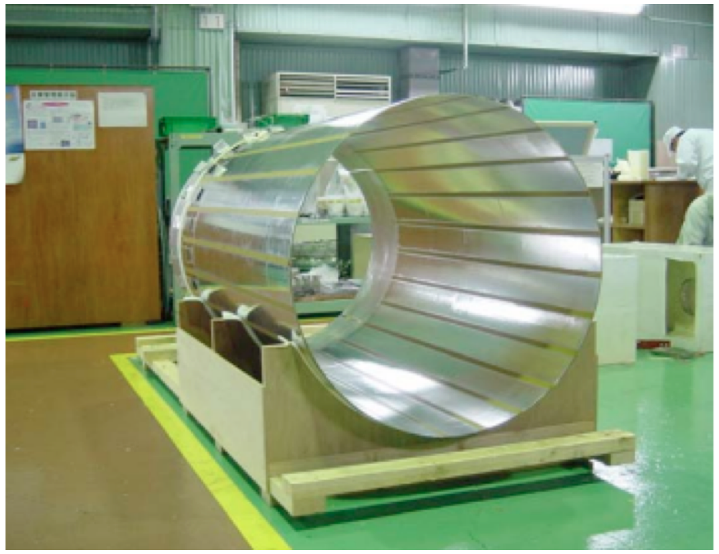


Critical technologies and TRL

- **Deployable technologies**

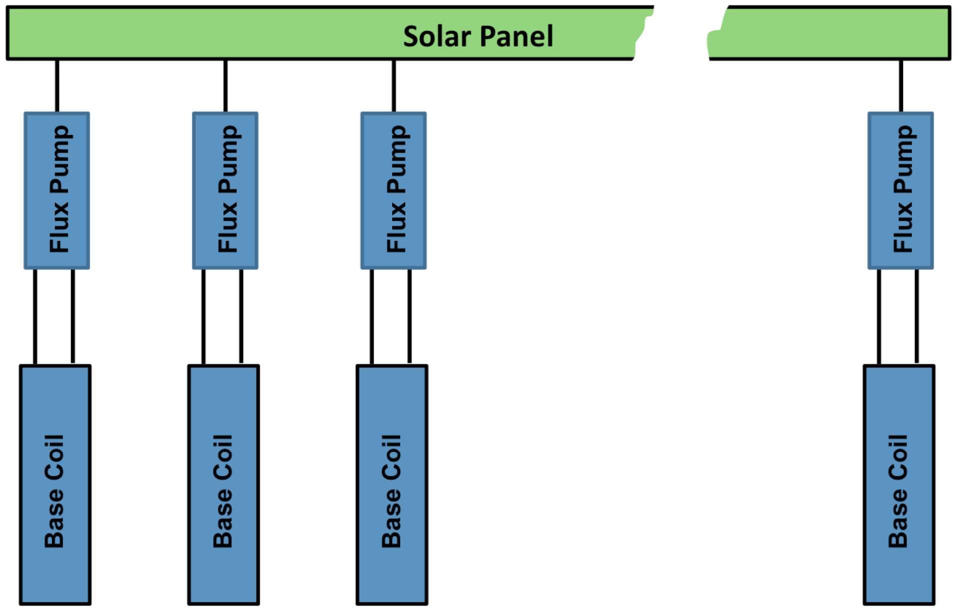


- **Low heat leakage cryostats and cryogen-free technologies**

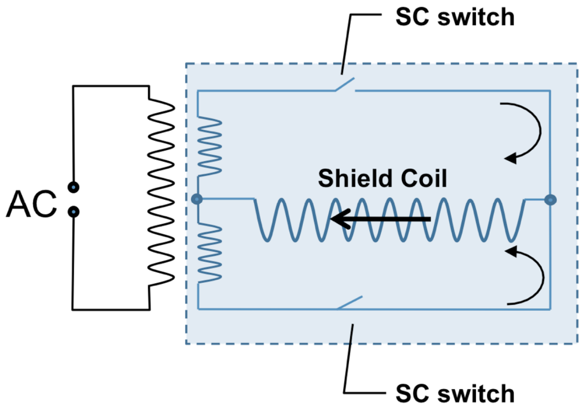


Critical technologies and TRL

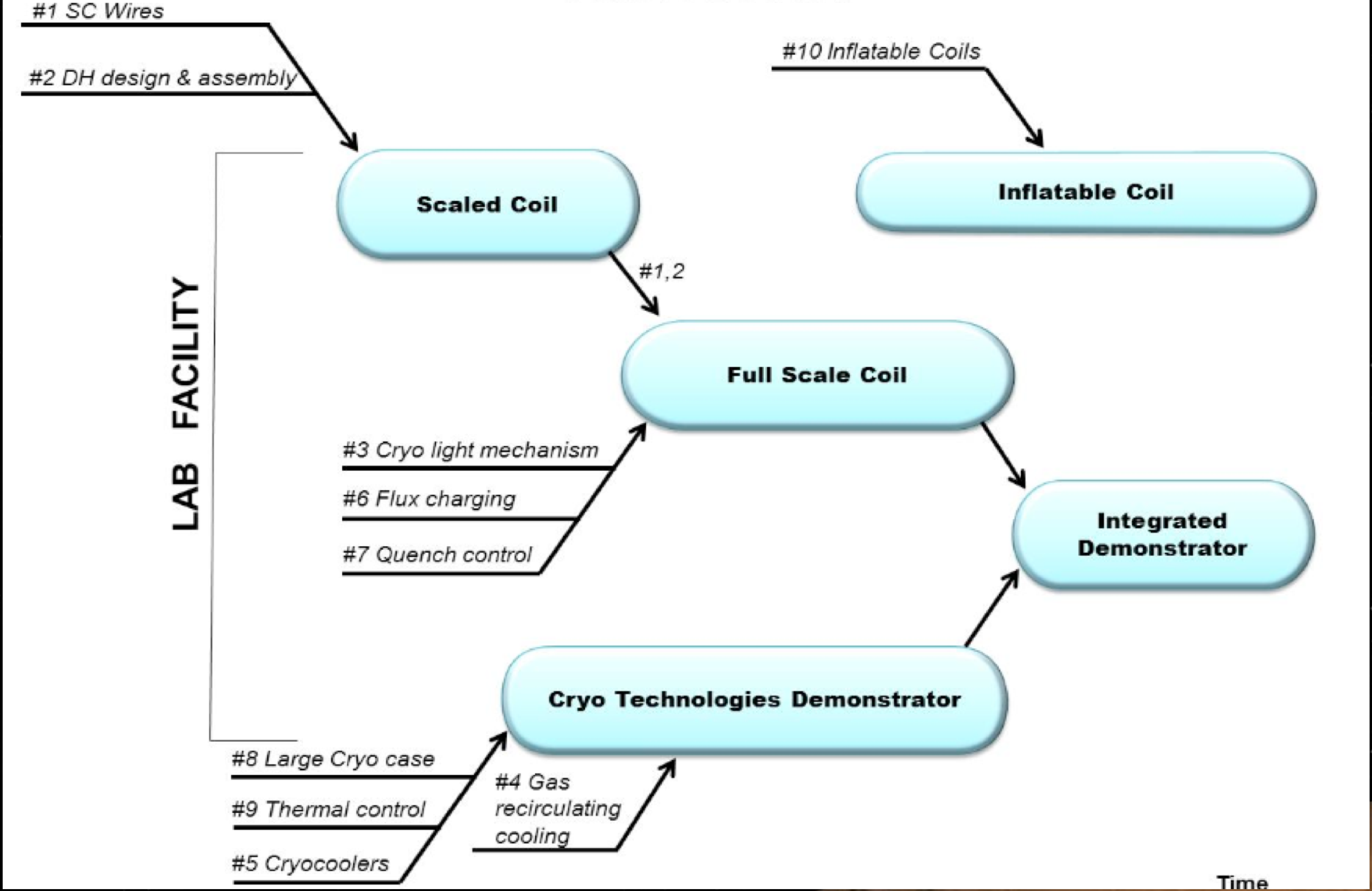
- **Flux pump power supplies**



- **Quench protection systems for HT SC**



Ground demonstrator philosophy



#1 SC Wires

#2 DH design & assembly

#10 Inflatable Coils

Scaled Coil

Inflatable Coil

LAB FACILITY

#1,2

Full Scale Coil

#3 Cryo light mechanism

#6 Flux charging

#7 Quench control

Integrated Demonstrator

Cryo Technologies Demonstrator

#8 Large Cryo case

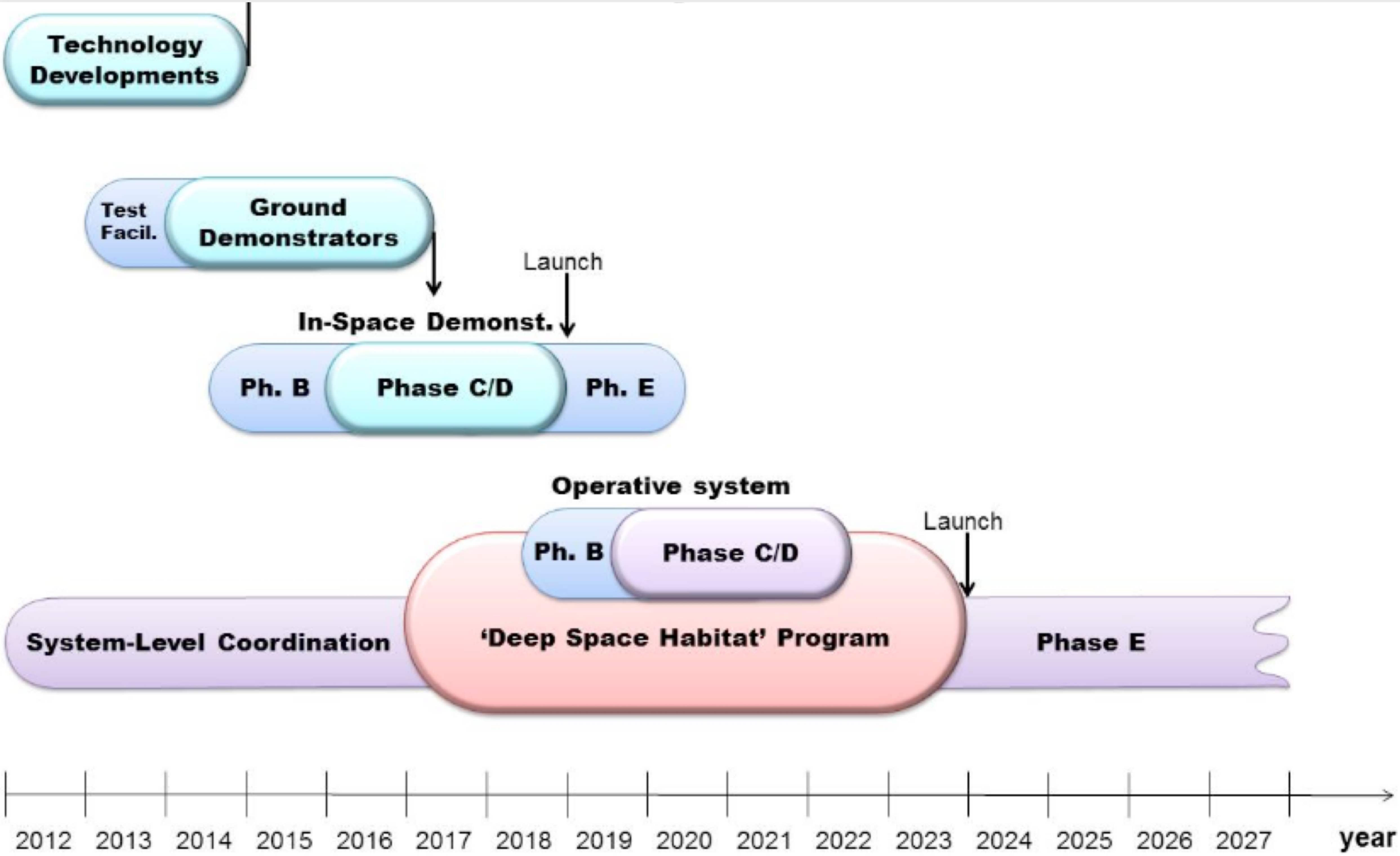
#9 Thermal control

#5 Cryocoolers

#4 Gas recirculating cooling

Time

Radiation shield development plan



Technology Developments

Test Facil.

Ground Demonstrators

Launch

In-Space Demonst.

Ph. B

Phase C/D

Ph. E

Operative system

Ph. B

Phase C/D

Launch

System-Level Coordination

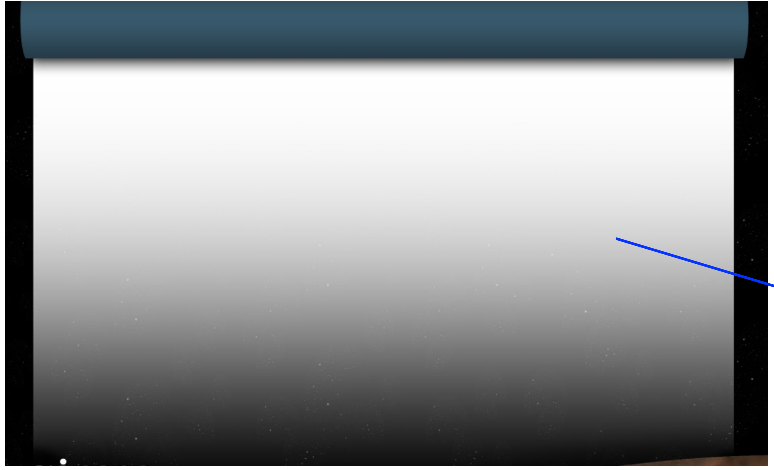
'Deep Space Habitat' Program

Phase E

2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 year

AMS: A TeV precision, multipurpose spectrometer

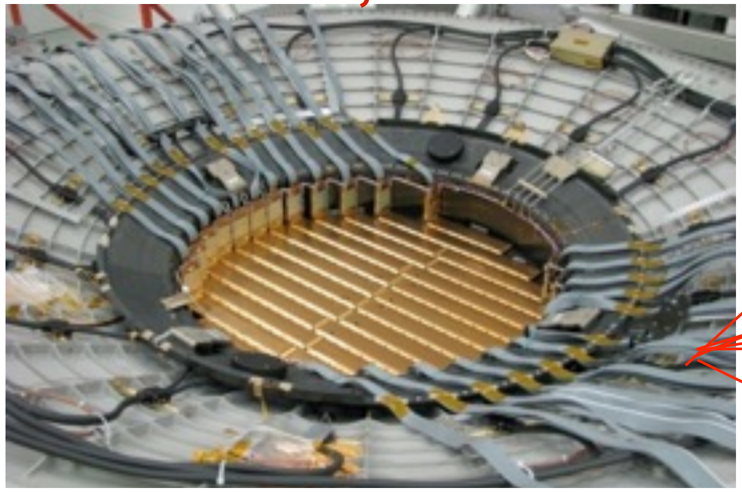
TRD
Identify e^+, e^-

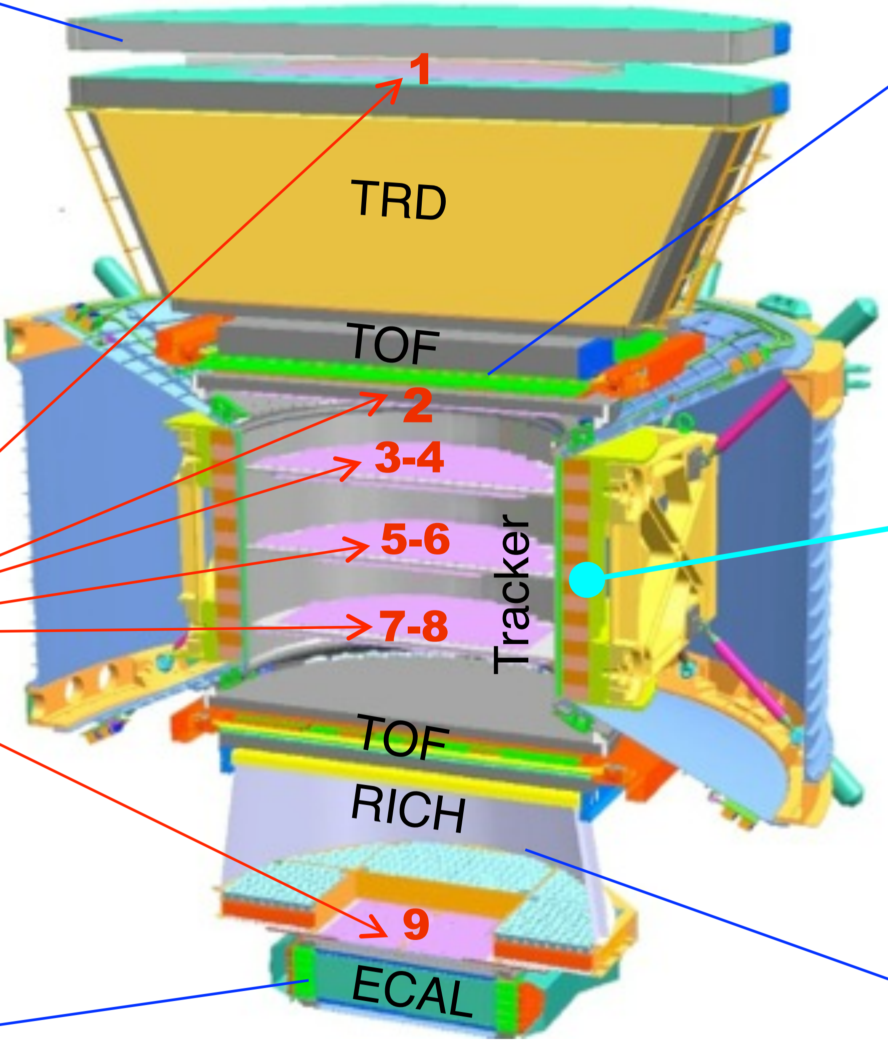


Particles and nuclei are defined by their charge (**Z**) and energy (**E ~ P**)

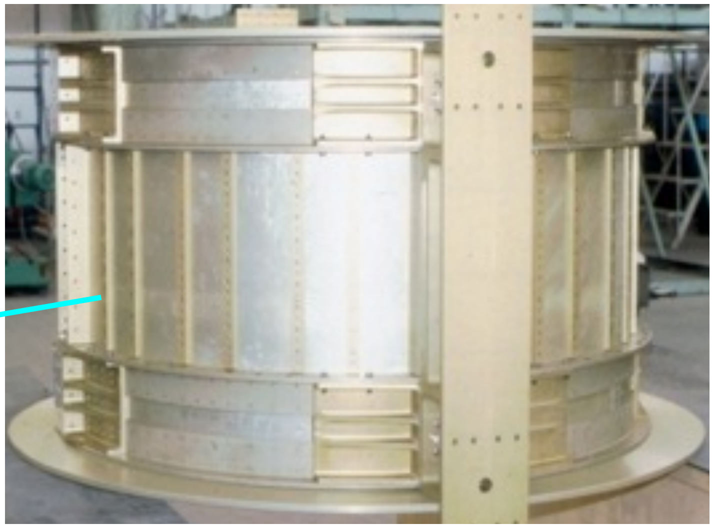
TOF
Z, E

Silicon Tracker
Z, P

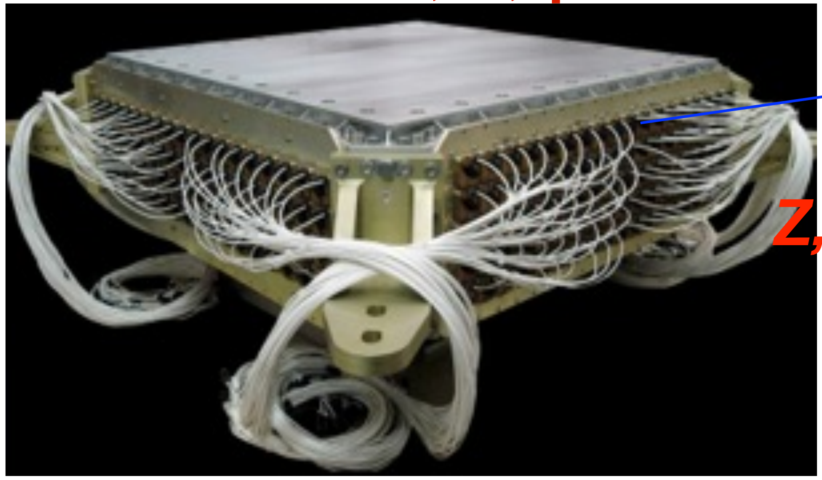




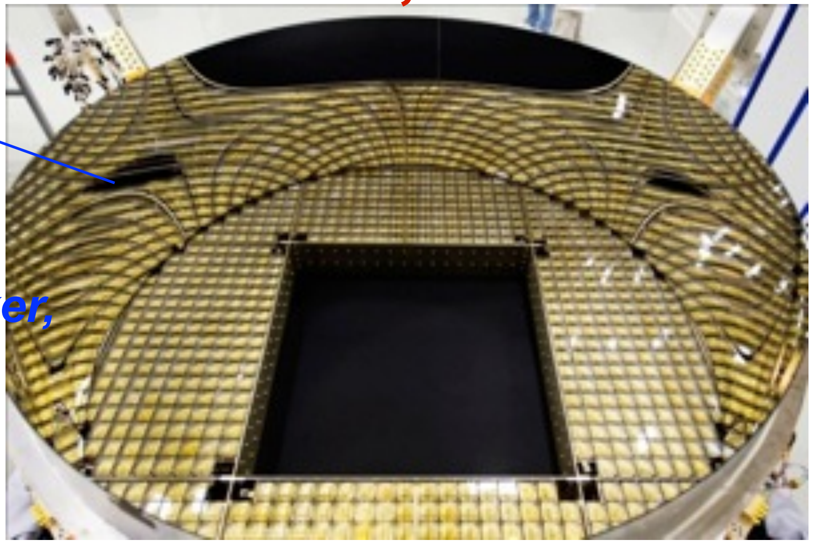
Magnet
±Z



ECAL
E of e^+, e^-, γ



RICH
Z, E

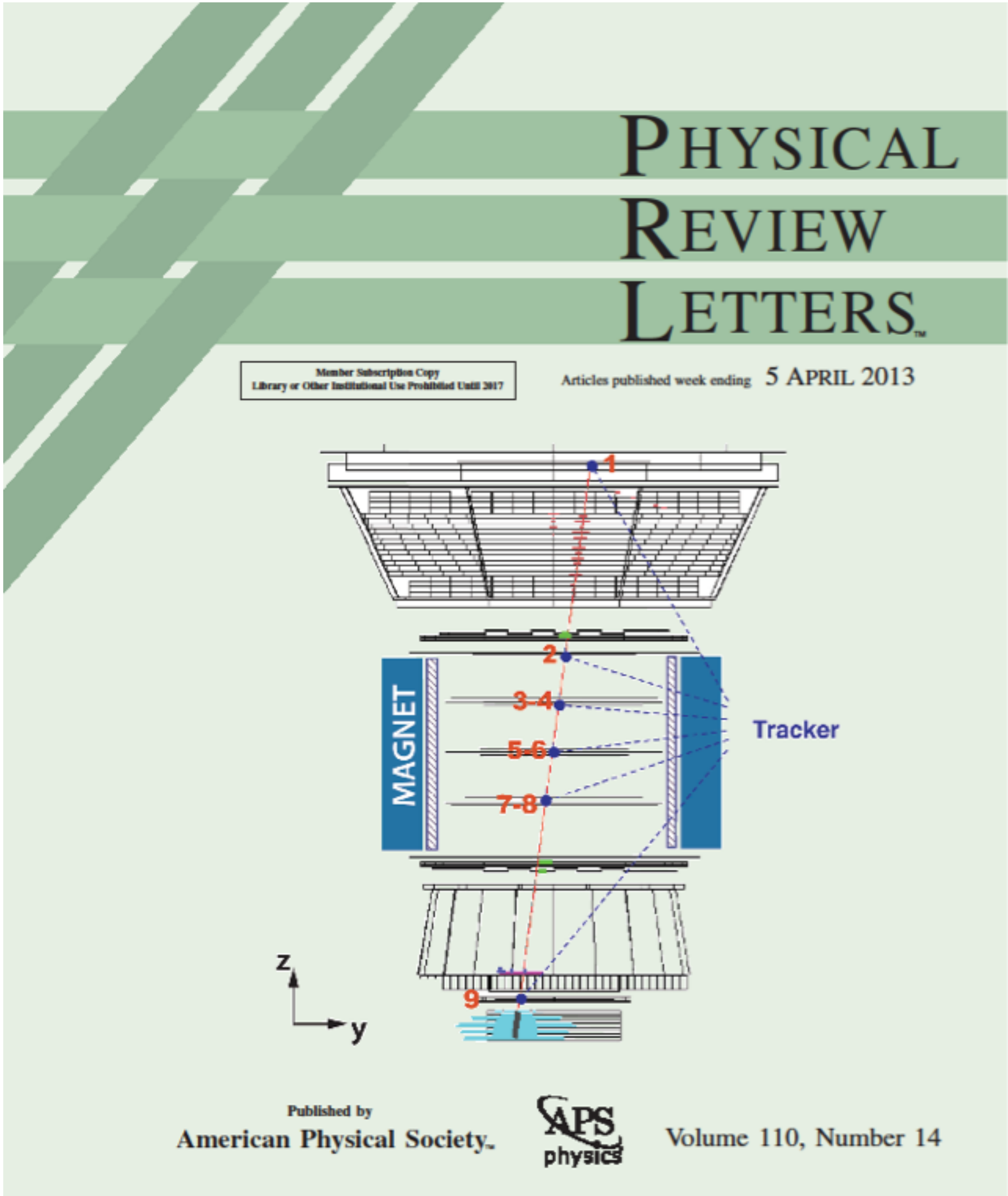


Z, P are measured independently by the Tracker, RICH, TOF and ECAL

AMS today

“First Result from the AMS on the ISS: Precision Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5-350 GeV”

Selected for a Viewpoint in Physics and an Editors’ Suggestion [Aguilar,M. et al (AMS Collaboration) Phys. Rev. Lett. 110, 1411xx (2013)]



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APS physics

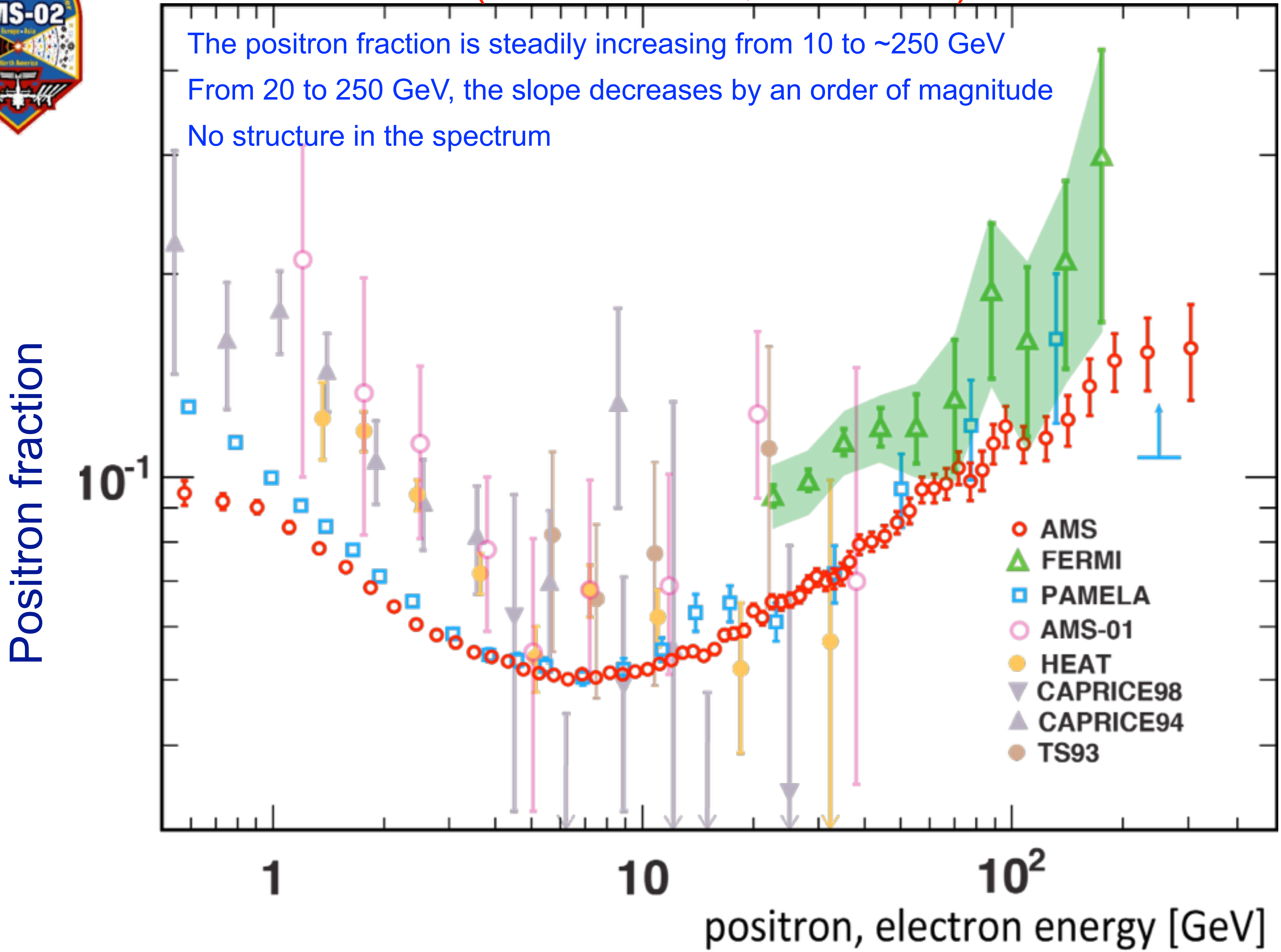
Volume 110, Number 14

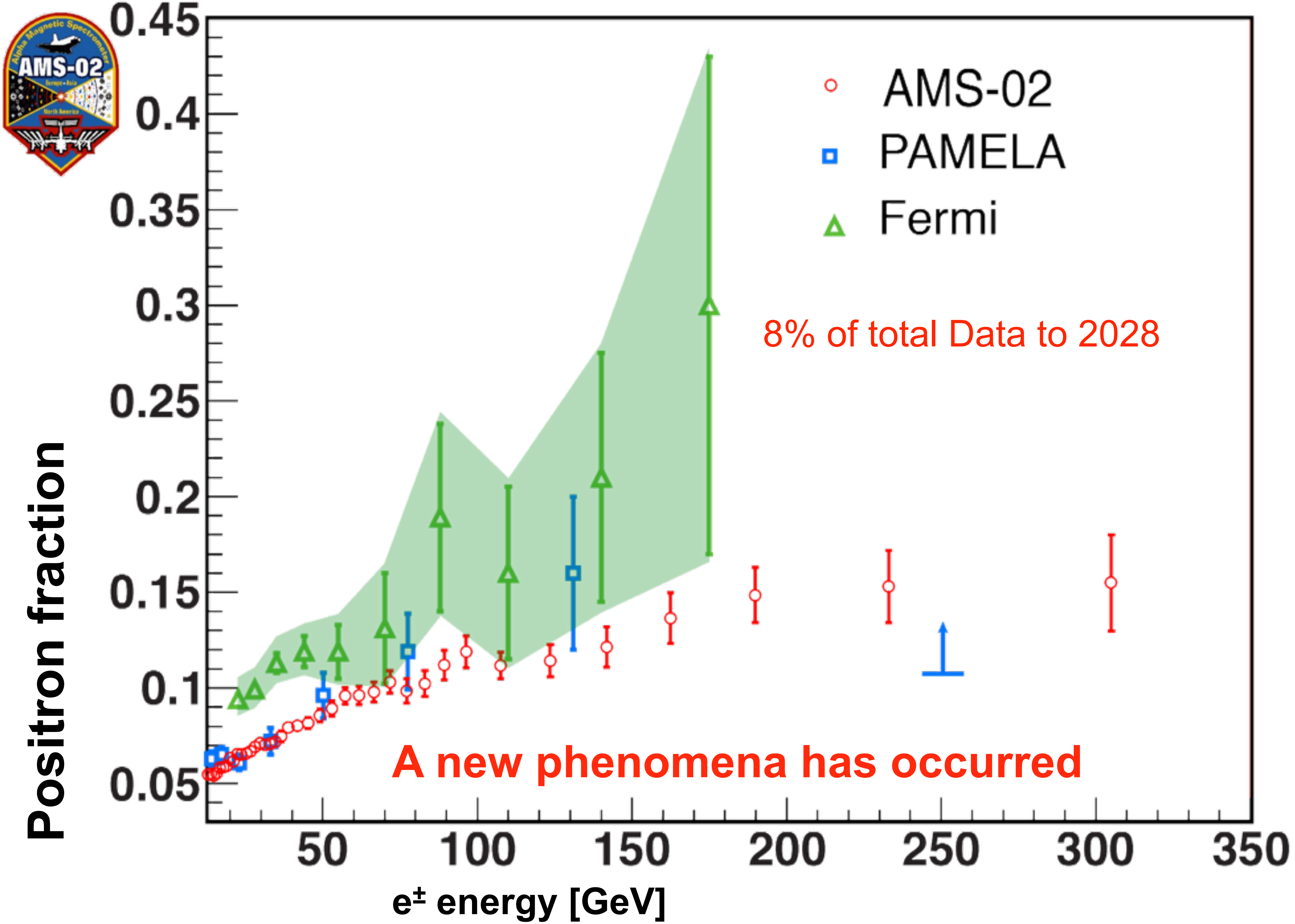
AMS-02 (6.8 million e^+, e^- events)

The positron fraction is steadily increasing from 10 to ~250 GeV

From 20 to 250 GeV, the slope decreases by an order of magnitude

No structure in the spectrum





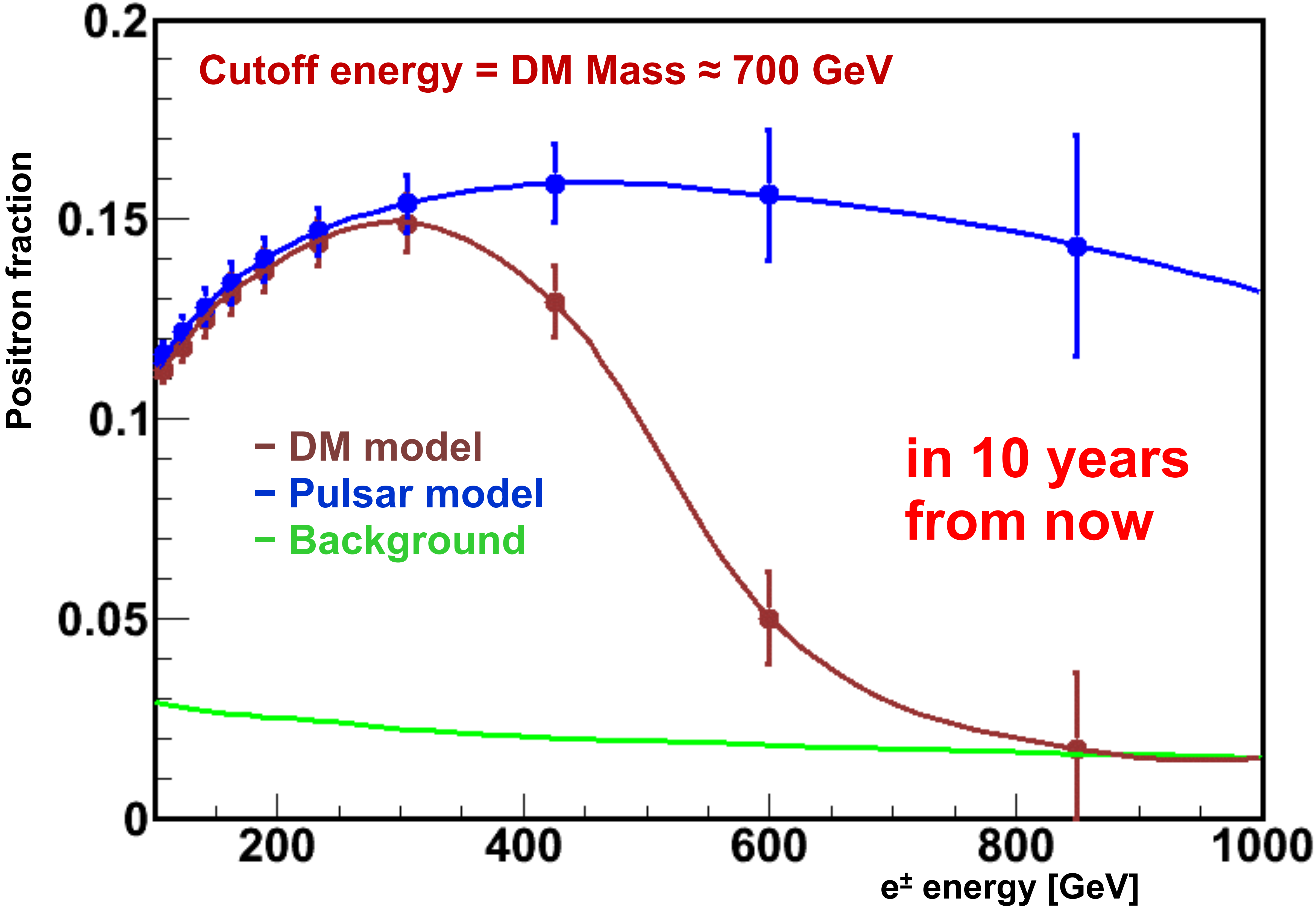
8% of total Data to 2028

A new phenomena has occurred

Open issues after AMS-02

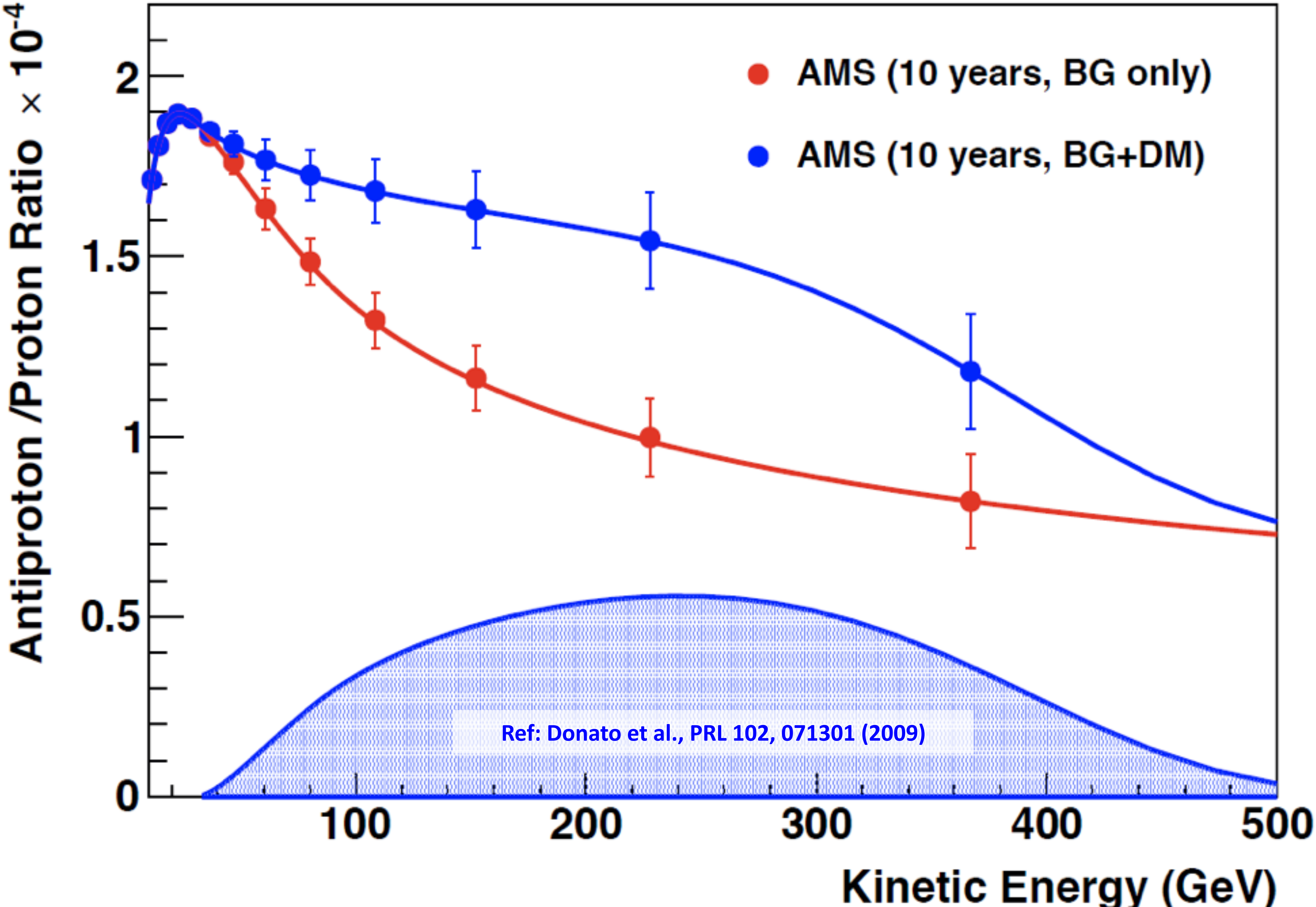
- Dark matter (LHC will not be able to explore $m_\chi >$ O(100)GeV)
  - Positrons at the 1-10 TeV scale
  - Antiprotons at the 1 TeV scale
  - Gamma rays at the TeV scale
  - Antideuterons at the GeV scale
- Spectral features at the knee scale
  - Protons at the PeV scale
  - Helia at the PV scale
  - Ions at the 100 TV scale

Expected AMS-02 reach in 10 more years



What will the Positron Fraction look like at high energy?

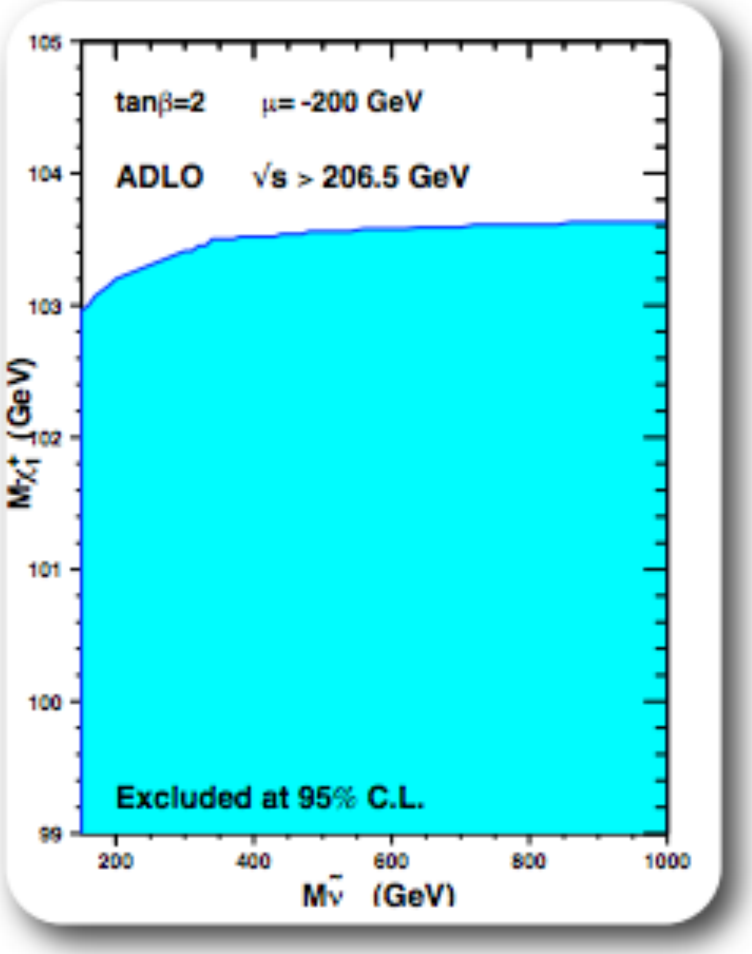
Expected AMS-02 reach in 10 more years



Ref: Donato et al., PRL 102, 071301 (2009)

Current limits: neutralino/chargino

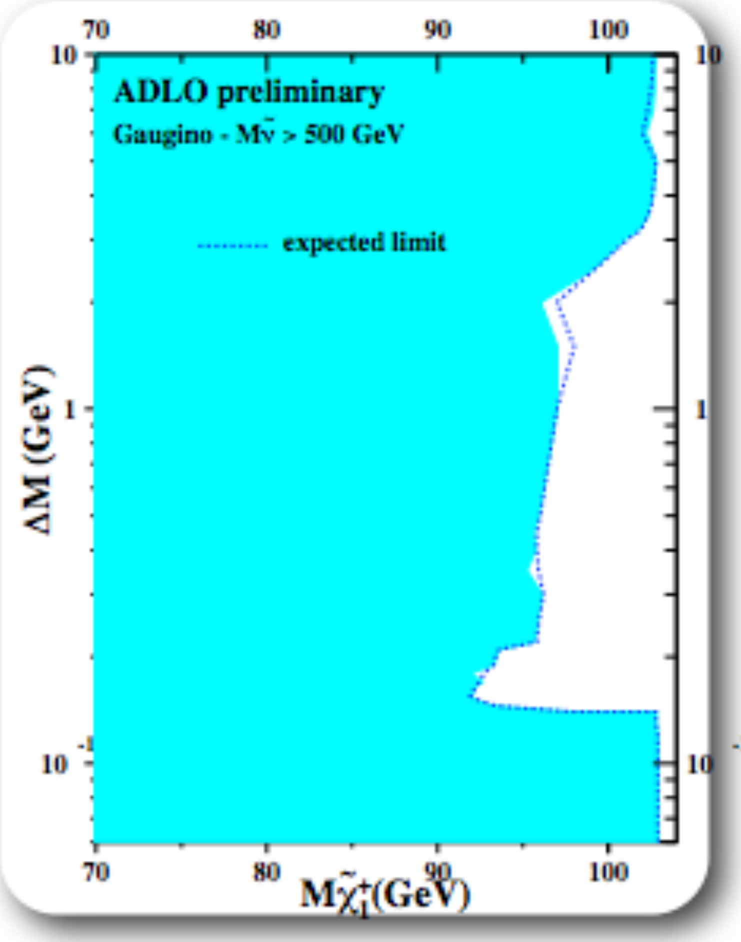
canonical case



$m\chi_1^{\pm} > 103.5$ GeV
for $m_{snue} > 300$ GeV

LEPSUSYWG/01-03.1

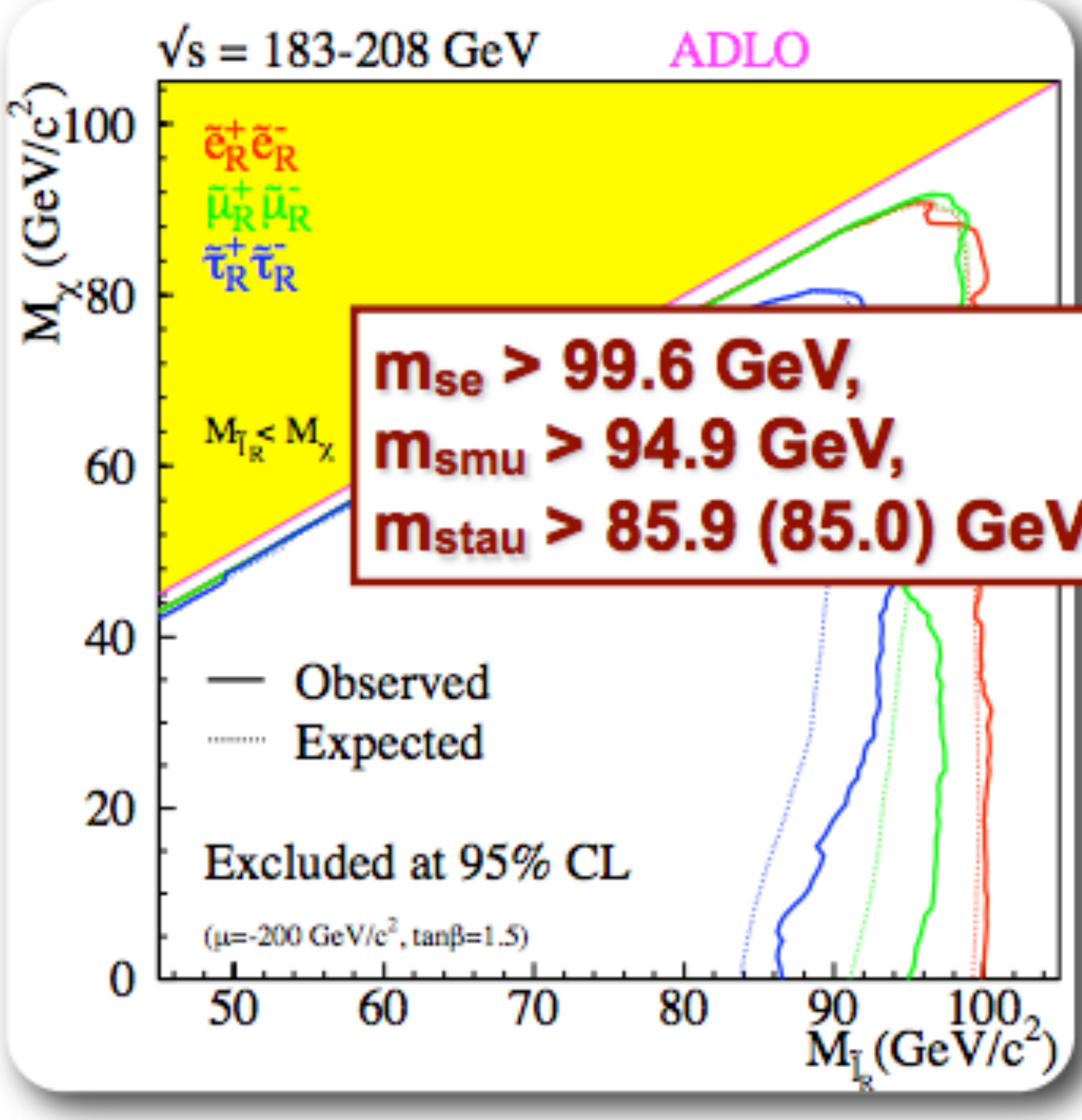
degenerate case



$m\chi_1^{\pm} > 91.9$ /92.4 GeV

LEPSUSYWG/02-04.1

$m\chi_1^0 > 47/50$ GeV
(CMSSM, mSUGRA)
No mass limit in general



$m_{se} > 99.6$ GeV,
$m_{smu} > 94.9$ GeV,
$m_{stau} > 85.9$ (85.0) GeV

LEPSUSYWG/04-01.1

How to reach the O(10 TeV) scale ?

- **Exposure : increase by a factor O(100) for e+**

  From 0.05 to 5 m2sr

- **Detector : capable to deal with 10 TeV particles**
  - **Tracker + Magnet → MDR > 20 TV**
  - **ECAL → ECAL+HCAL**

AMS-03 : expected rates
detection tools/limitations

ELECTRON AND POSITRON PHYSICS @ AMS-03

5	m2 sr	3,14E+07	s/y			ACCESSIBLE	EXCLUDED	EXCLUDED
eV	**10^8**	**10^9**	**10^10**	**10^11**	**10^12**	**10^13**	**10^14**	**10^15**
scale	**100MeV**	**GV**			**TV**			**PV**
Integral . 1/y	**.@ 0,1-1**	**.@ 1-10**	**.@ 10-100**	**.@ 100-1000**	**.@ 1.000 ->**	**.@ 10.000 ->**	**.@ 100.000 ->**	**.@ 1.000.000 ->**
e-	4,99E+10	3,11E+09	1,56E+08	9,33E+05	7,78E+03	7,78E+01	7,78E-01	7,78E-03
e+	2,50E+09	1,56E+08	1,56E+07	1,40E+05	1,17E+03	1,17E+01	1,17E-01	1,17E-03
Detectors	tracker, TOF, TRD, ECAL	tracker, TOF, TRD, ECAL	Tracker, TRD, ECAL	Tracker, TRD, ECAL	Tracker,SRD,ECAL	Tracker,SRD,ECAL		
Variables	R, beta, gamma, energy	R, beta, gamma, energy	R, gamma, energy	R, gamma, energy	R,Energy, Syncrotron Radiation	R, Energy, Synchroton Radiation		
Physics	Van Allen, solar, subcutoff	solar, geomagnetic, galactic	DM, galactic, asymmetries	DM, galactic, asymmetries	DM, galactic	DM, galactic, moon shadow, sun shadow	DM, galactic	DM, extragalactic, knee

AMS-03 : expected rates and detection tools/limitations

PROTON and HELIUM PHYSICS @ AMS-03

5	m2 sr	3,14E+07	s/y			ACCESSIBLE	ACCESSIBLE	ACCESSIBLE
	10^8	10^9	10^10	10^11	10^12	10^13	10^13	10^13
	100MeV	GV			TV			PV
Integral . 1/y	**.@ 0,1-1**	**.@ 1-10**	**.@ 10-100**	**.@ 100-1000**	**.@ 1.000 ->**	**.@ 10.000 ->**	**.@ 100.000 ->**	**.@ 1.000.000 ->**
p	4,99E+10	9,96E+10	1,99E+10	3,97E+08	7,19E+06	1,44E+05	2,86E+03	5,71E+01
He	1,80E+09	1,79E+10	3,58E+09	7,14E+07	1,29E+06	2,58E+04	5,15E+02	1,03E+01
Detectors	tracker, TOF, RICH	Tracker, (RICH)	Tracker	Tracker	Tracker	Tracker+ HCAL	Tracker+ HCAL	Tracker+ HCAL
Variables	R, beta	R	R	R	R	R, Energy	Energy	Energy
Physics	Van Allen, solar, subcutoff	solar, geomagnetic, galactic	galactic	galactic	galactic, moon shadow, sun shadow	galactic, moon shadow, sun shadow	galactic	extragalactic, knee

PRELIMINARY DESIGN (25-10-2013) _(B) with SC magnet

ToF + Tracker + Ecal/HCAL + SRD-Like

SRD-like: 2D X-ray detector to be installed on the top of the magnet on the space station

Magnet: (B) MgB2 double helix (perfect dipole) : Inner radius 130 cm, Height 100 cm,
B-field 1 Tesla
Weight: 1 Ton , MDR 56 TV,
Acceptance 6 times AMS-02-Magnet

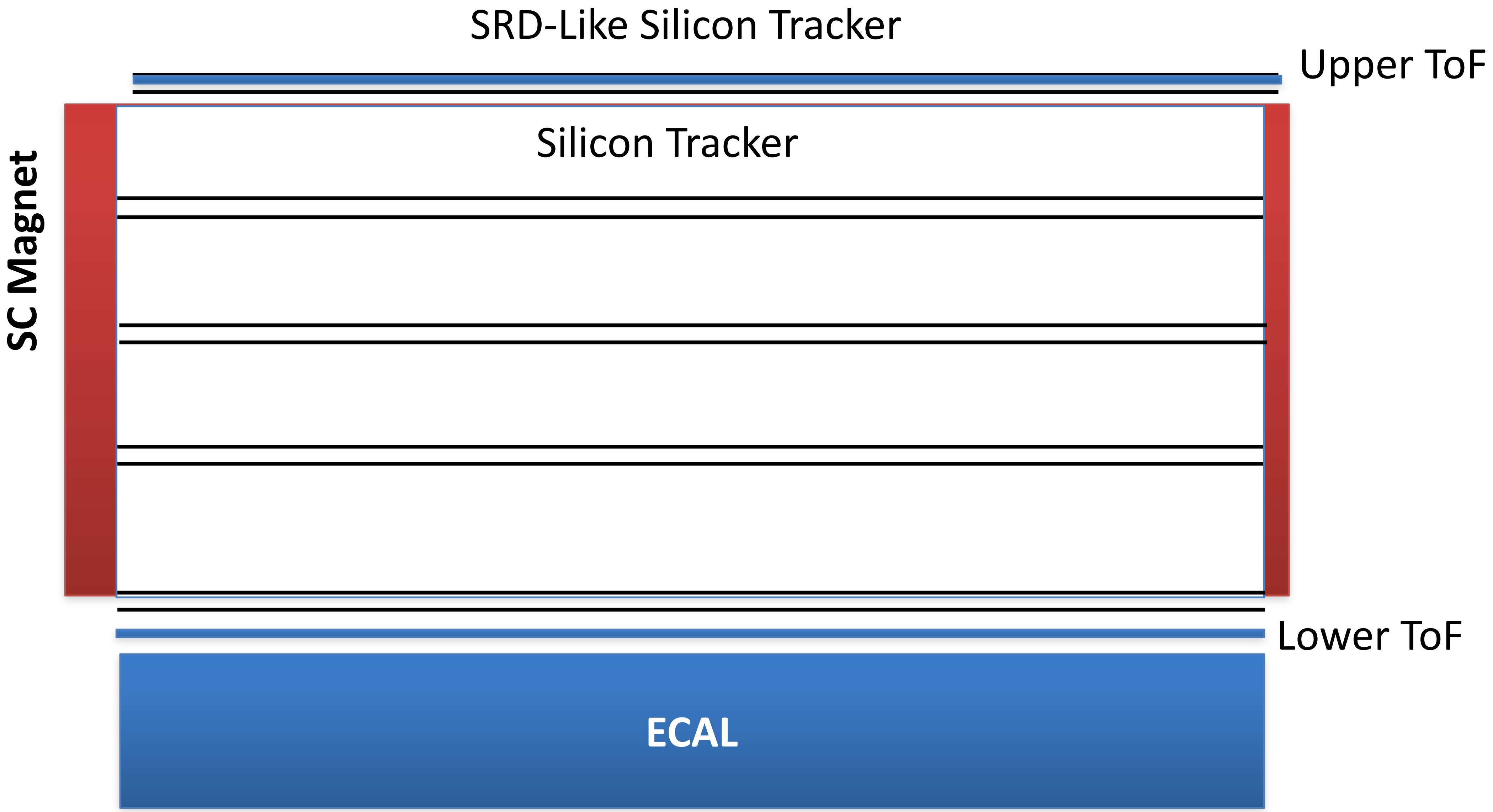
ECAL: Radius 130cm, tungsten absorber, scintillating fibers with SiPM readout,
Thickness 32 cm, 37 Radiation Length,
Weight < 15 Tons Acceptance 75 times AMS-02 ECAL

Hadronic energy resolution of the ECAL : to be calculated , expected 30-40% @ TV scale

Tracker: 5 carbon fiber disks in a carbon fiber support structure with a top and bottom silicon layer on each disk.
Single Point resolution < 0.002 mm. Technology : CMOS camera arrays being developed for LHC during the last 10 years (record resolution 600 nanometers)

Expected Acceptance: 9 m^2 sr
MDR: 56 TV

AMS-03-SC


SRD-Like Silicon Tracker
Upper ToF
SC Magnet
Silicon Tracker
Lower ToF
ECAL

How to get to micron tracking accuracy

- 1) AMS experience show us that through suitable cooling micron level stability can be achieved over O(1)m^3 using stiff CR as alignement tool
- 2) Space seems to be the right place to implement O(1) um resolution tracking which is considered for LHC upgrades and has been developed for at least 10 years.

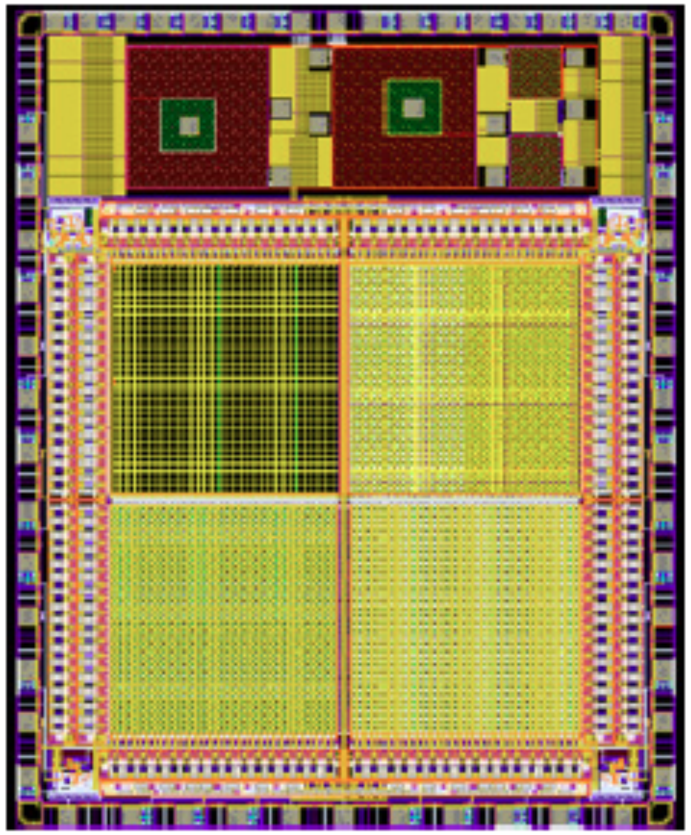


Fig. 3. Layout of a Successor2 prototype, showing four arrays of 32x32 pixels. The arrays described in this work are located in the bottom part: the 3 transistor standard structures are on the left while the self-biased diodes are on the right. Two upper arrays contain a novel PhotoFET charge sensing element, not discussed in this work. On top of the device, large test structures for the study of irradiation effects through C-V and I-V measurements are included

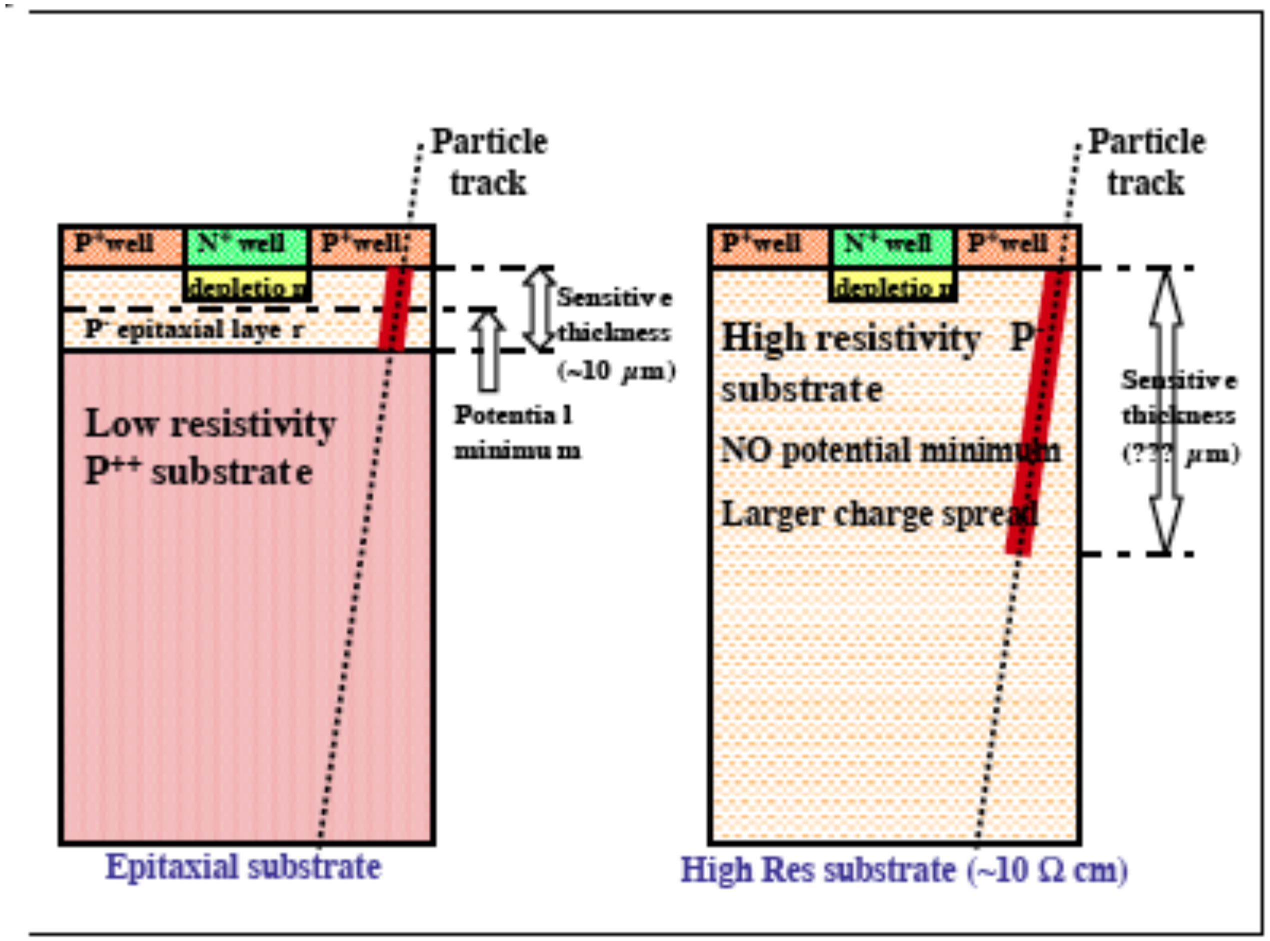


Fig. 1. Cross section of silicon wafers used for the fabrication of CMOS monolithic pixel sensors. On the left, the structure of epitaxial type wafer is shown. On the right the non-epitaxial, high resistivity wafer is presented.

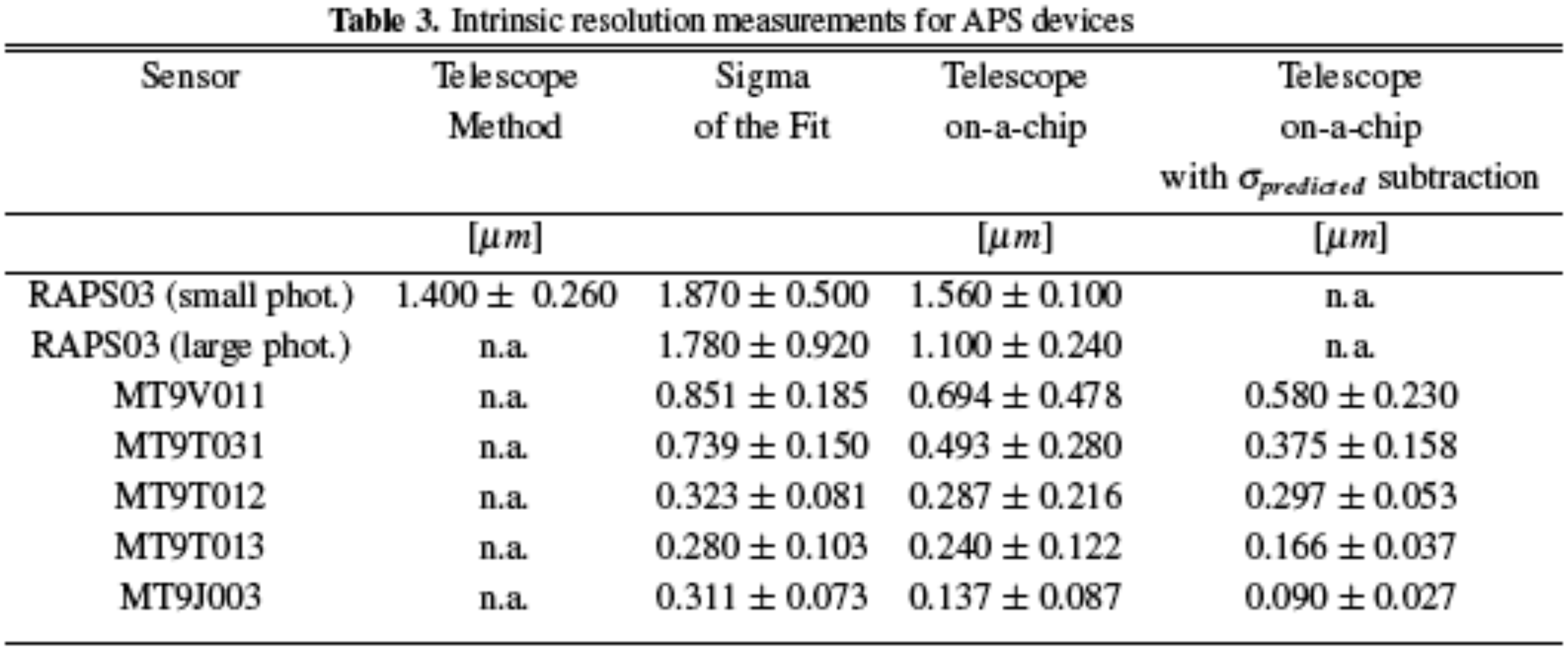
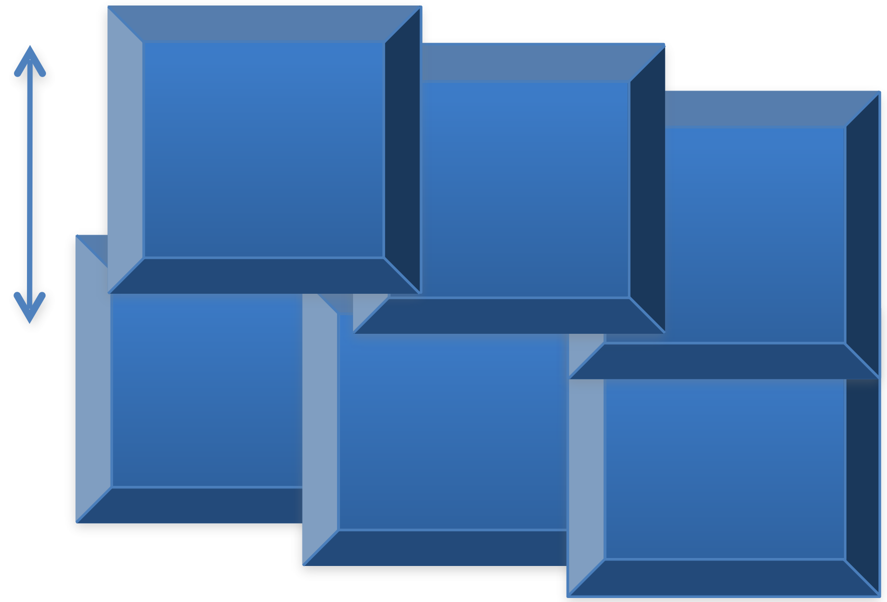
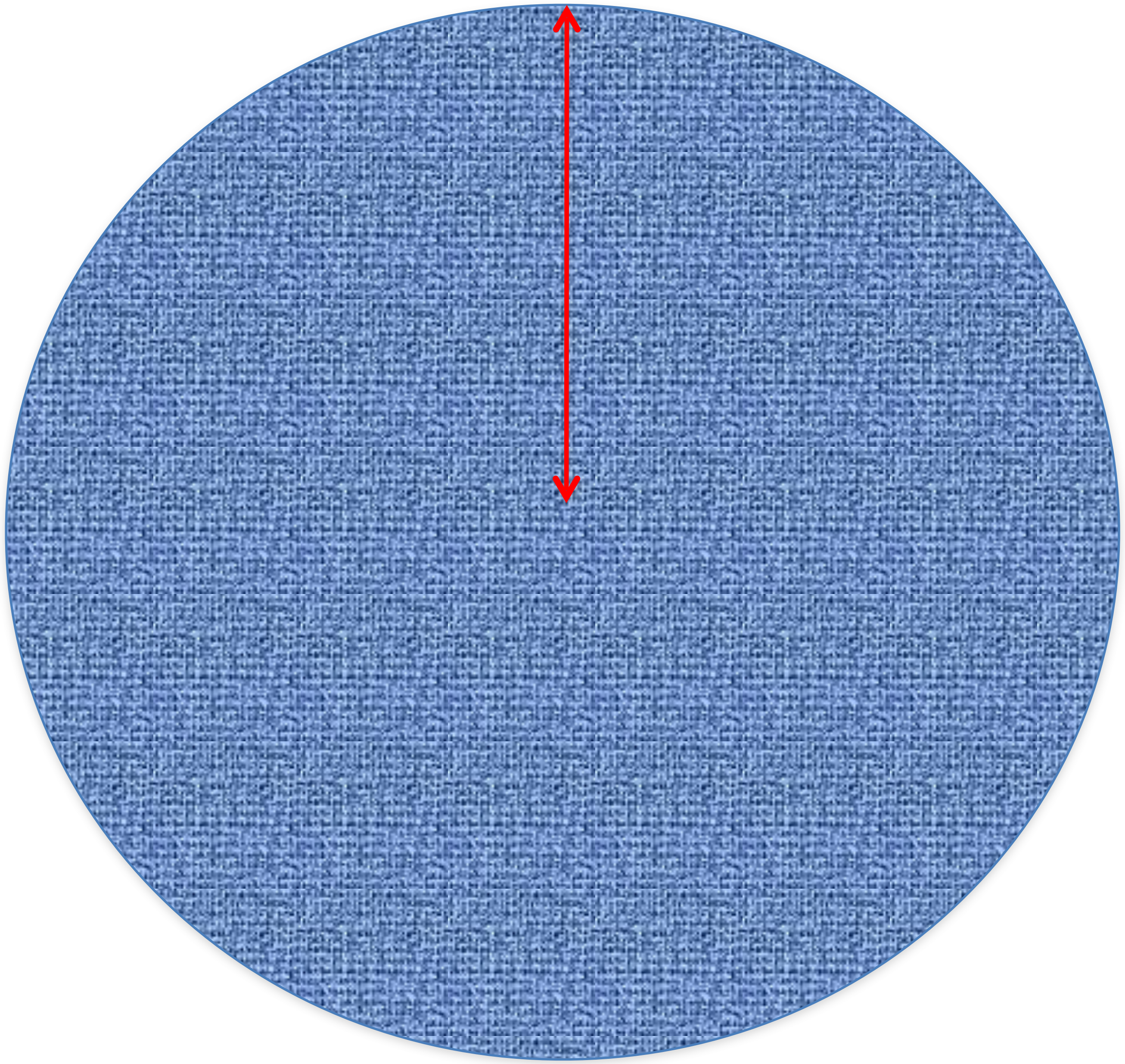


Table 3. Intrinsic resolution measurements for APS devices

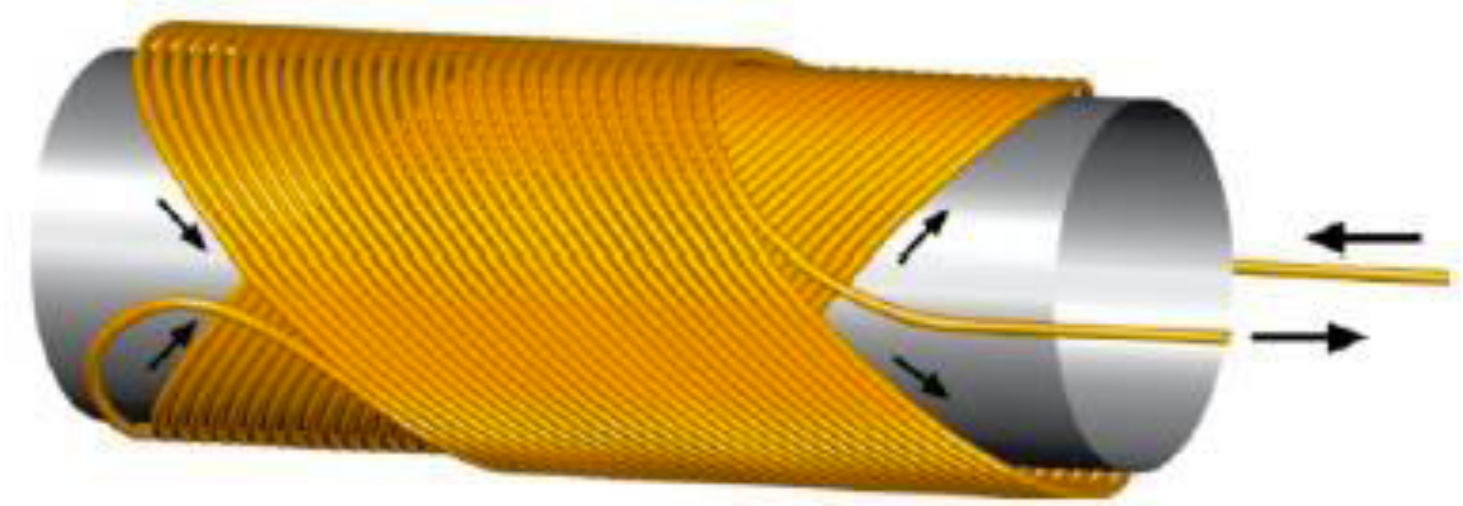
Sensor	Telescope Method [μm]	Sigma of the Fit	Telescope on-a-chip [μm]	Telescope on-a-chip with $\sigma_{predicted}$ subtraction [μm]
RAPS03 (small phot.)	1.400 ± 0.260	1.870 ± 0.500	1.560 ± 0.100	n.a.
RAPS03 (large phot.)	n.a.	1.780 ± 0.920	1.100 ± 0.240	n.a.
MT9V011	n.a.	0.851 ± 0.185	0.694 ± 0.478	0.580 ± 0.230
MT9T031	n.a.	0.739 ± 0.150	0.493 ± 0.280	0.375 ± 0.158
MT9T012	n.a.	0.323 ± 0.081	0.287 ± 0.216	0.297 ± 0.053
MT9T013	n.a.	0.280 ± 0.103	0.240 ± 0.122	0.166 ± 0.037
MT9J003	n.a.	0.311 ± 0.073	0.137 ± 0.087	0.090 ± 0.027

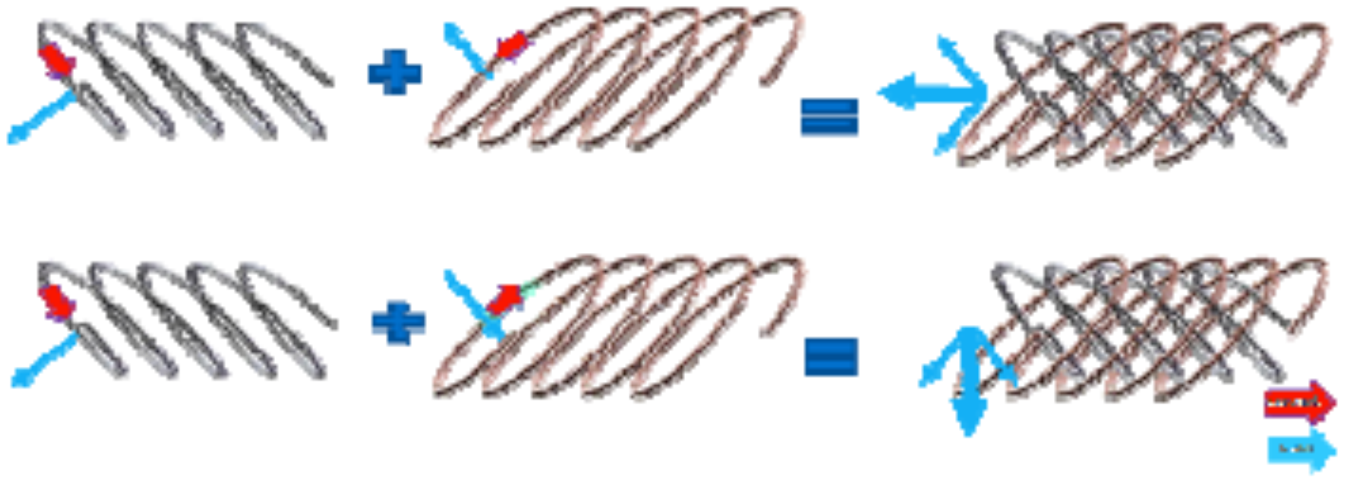
Micron accuracy, tiles tracker





High accuracy dipolar MgB_2 magnet





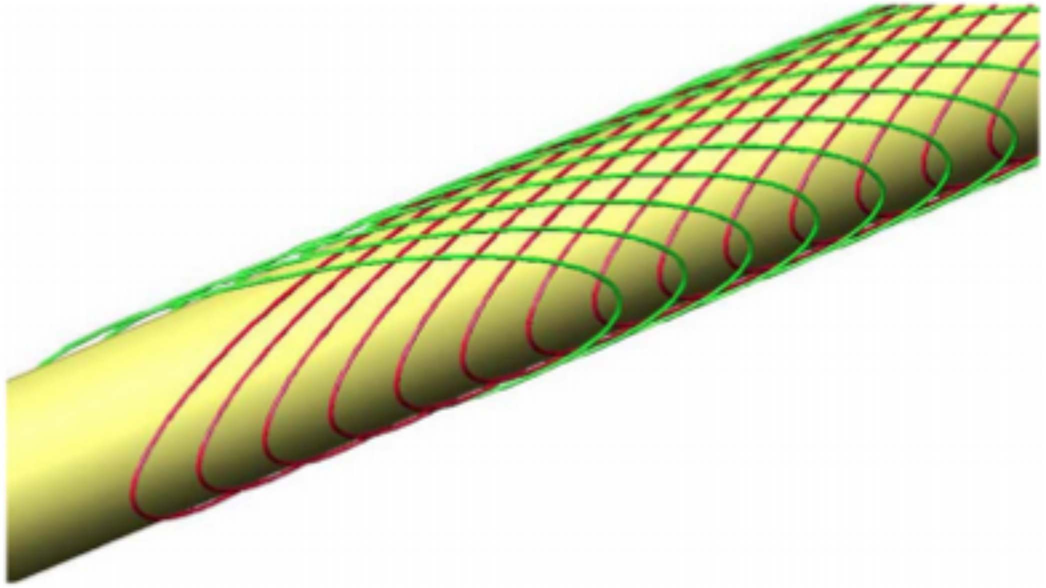


Fig. 2. Conceptual view of pure dipole windings.

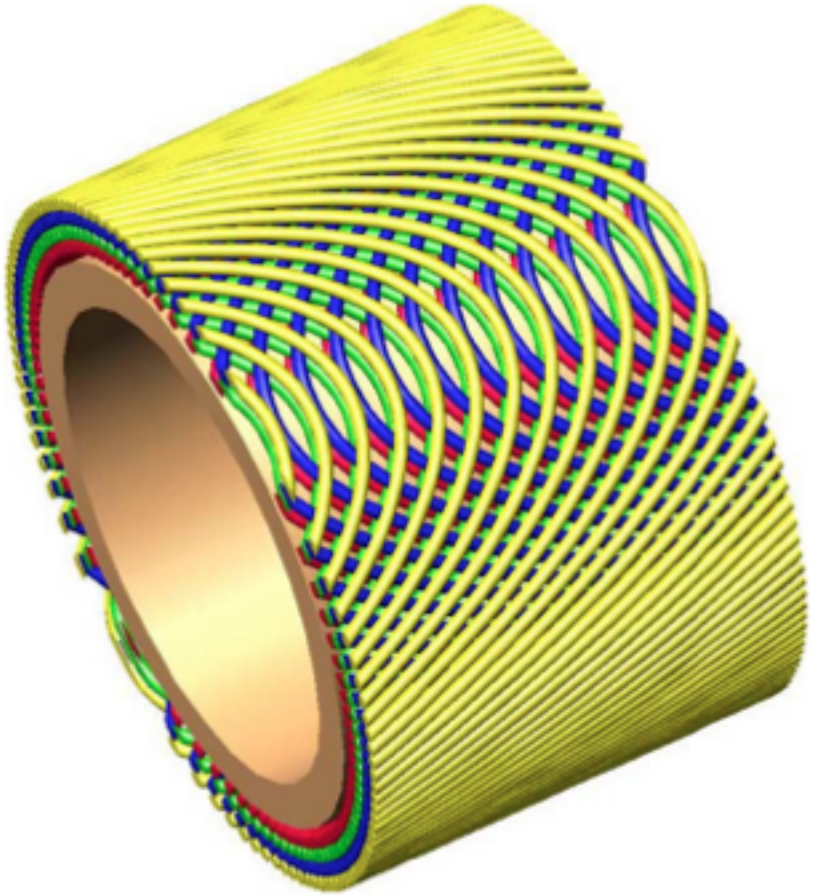


Fig. 3. Center cut of the 4 layer "cos-theta" dipole.

The current density at any given location in z is a function of ϑ only, whereas $J = J_0(\vartheta)$ and its components are proportional to:

Fig. 8. Actual cross section of the dipole tested.

Conclusions (1)

- The SR2S project brings one of the most challenging magnet systems to be built
- Various of the technologies for such a space superconducting system do not exist yet
- SR2S is an extraordinary technology development field and technology driver

Conclusions (2)

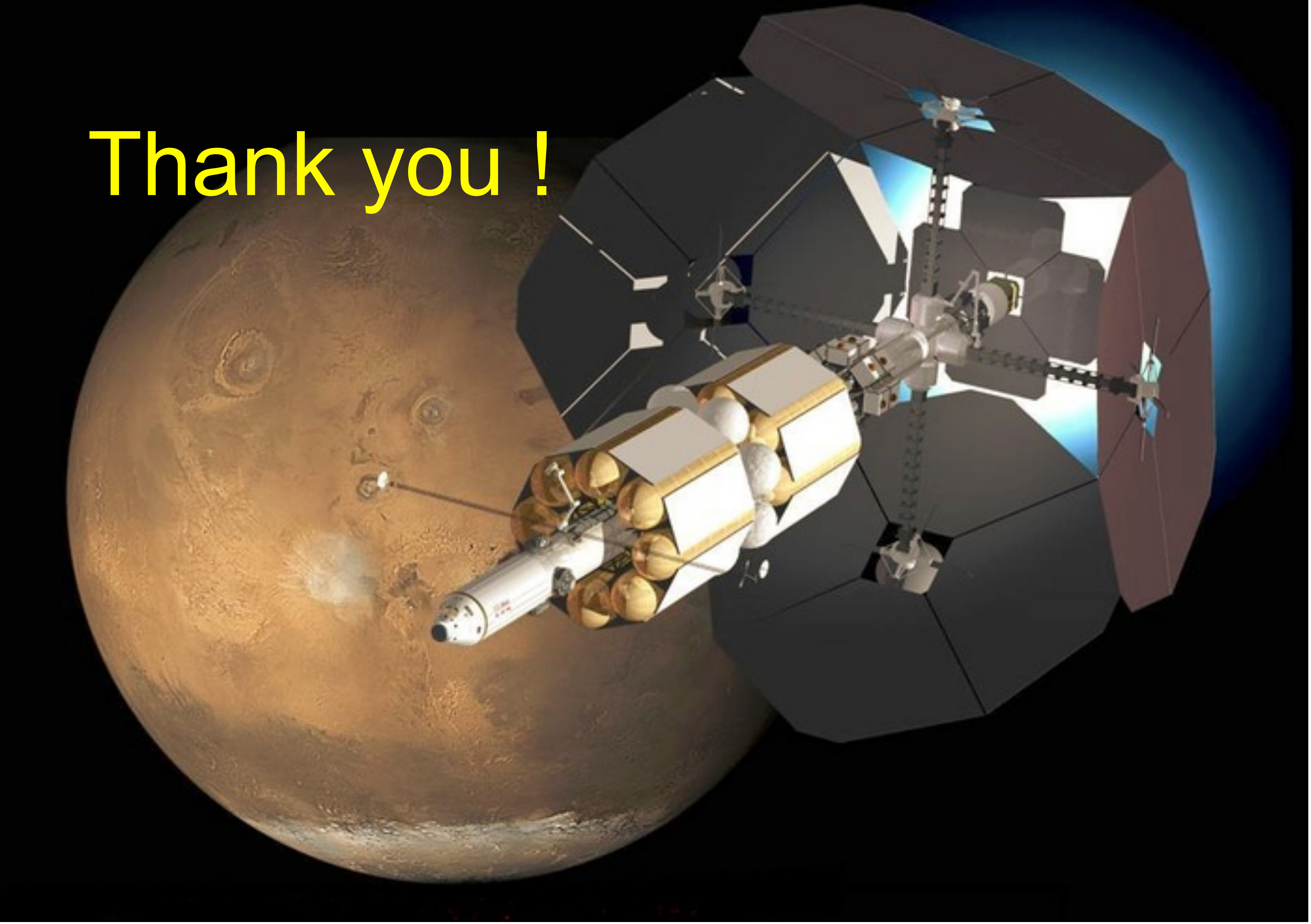
- Active Radiation Shielding for exploration is a necessity
- Passive shielding for GCR is not adequate and for SPE can only protect limited volumes
- Active magnetic shielding becomes effective at high $\int BdL$ values and only if the material thickness traversed by the GCR is "small"
- Interplay between active and passive shielding is complex and detailed simulations are needed to understand it

Conclusions (3)

- Optimization of magnetic and structural forces is mandatory
- During the first year SR2S has developed the basic tools for active shield analysis, started a sistematic investigation and achieved important technological developments
- We are analyzing a toroidal configuration: other magnetic configurations would also deserve careful study
- Collaboration and synergy with NASA, ESA and EU

- A R&D path towards future developments for *light, high field, modular* toroidal shield design has been identified
- Multi-TeV Cosmic Ray physics would be accessible with a SC spectrometer based on SR2S technology and based on recirculating cryogenics

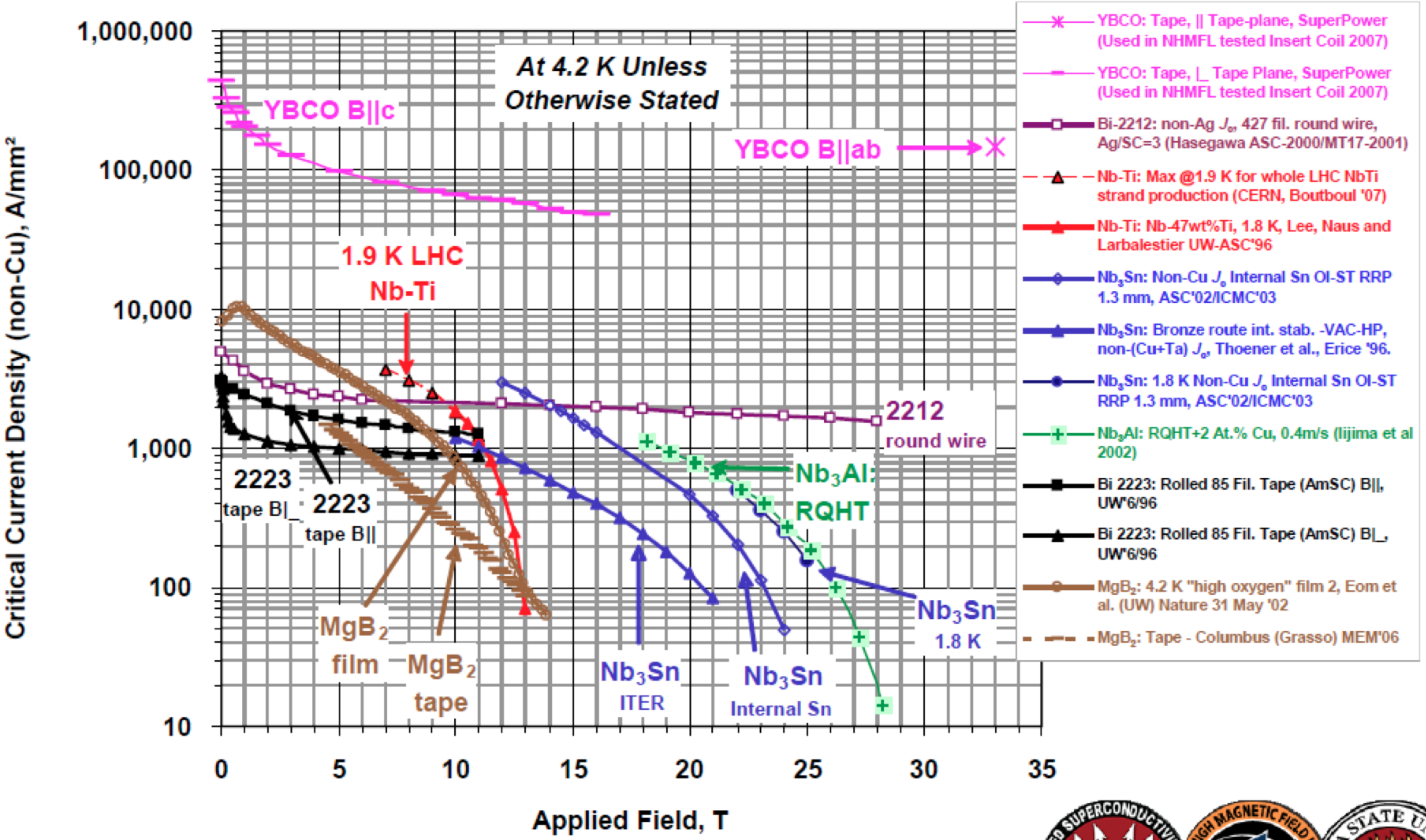
Thank you !

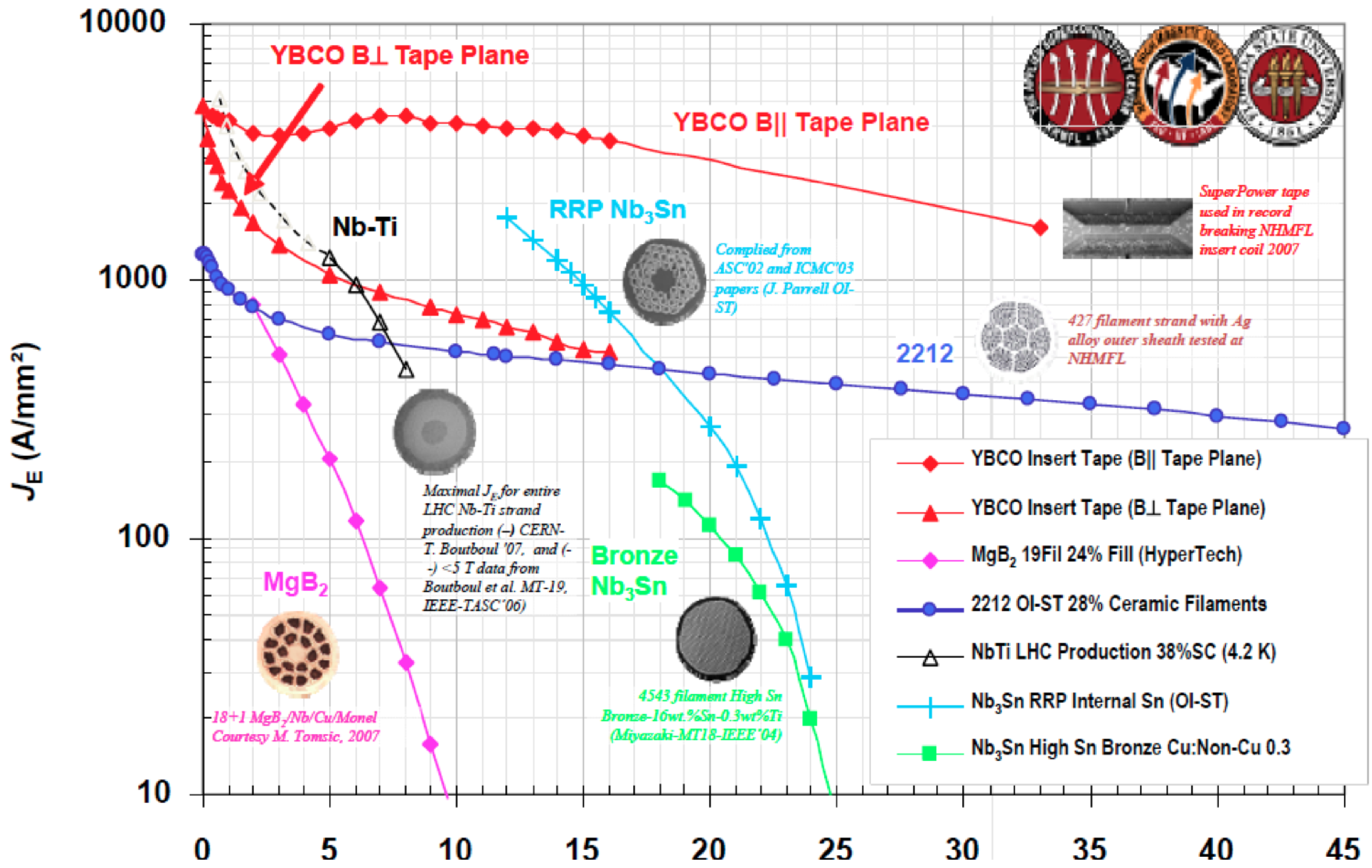


backup

SC cables


12500 AMPERES
CABLES NORMAUX
12500 AMPERES
CABLE
SUPRA-CONDUCTEUR


At 4.2 K Unless Otherwise Stated
Critical Current Density (non-Cu), A/mm²
Applied Field, T
1,000,000
100,000
10,000
1,000
100
10
0
5
10
15
20
25
30
35
YBCO B||c
YBCO B||ab
1.9 K LHC Nb-Ti
2212 round wire
Nb₃Al: RQHT
2223 tape B|_
2223 tape B||
MgB₂ film
MgB₂ tape
Nb₃Sn ITER
Nb₃Sn Internal Sn
Nb₃Sn 1.8 K
YBCO: Tape, || Tape-plane, SuperPower (Used in NHMFL tested Insert Coil 2007)
YBCO: Tape, |_ Tape Plane, SuperPower (Used in NHMFL tested Insert Coil 2007)
Bi-2212: non-Ag Jc, 427 fil. round wire, Ag/SC=3 (Hasegawa ASC-2000/MT17-2001)
Nb-Ti: Max @1.9 K for whole LHC NbTi strand production (CERN, Boutboul '07)
Nb-Ti: Nb-47wt%Ti, 1.8 K, Lee, Naus and Larbalestier UW-ASC'96
Nb₃Sn: Non-Cu Jc Internal Sn OI-ST RRP 1.3 mm, ASC'02/ICMC'03
Nb₃Sn: Bronze route int. stab. -VAC-HP, non-(Cu+Ta) Jc, Thoener et al., Erice '96.
Nb₃Sn: 1.8 K Non-Cu Jc Internal Sn OI-ST RRP 1.3 mm, ASC'02/ICMC'03
Nb₃Al: RQHT+2 At.% Cu, 0.4m/s (Iijima et al 2002)
Bi 2223: Rolled 85 Fil. Tape (AmSC) B||, UW'6/96
Bi 2223: Rolled 85 Fil. Tape (AmSC) B|_, UW'6/96
MgB₂: 4.2 K "high oxygen" film 2, Eom et al. (UW) Nature 31 May '02
MgB₂: Tape - Columbus (Grasso) MEM'06



Superconducting Compound	T_c in Kelvin	Hc_2 at 4.2 K in Tesla	ξ (nm)	Mass Density (g/cm^3)
Nb-Ti	9	10	5	6.0
Nb_3Sn	18	28	5	7.8
MgB_2	39	up to 70	5	2.5
YBCO-123	90	> 50	<< 1	5.4
BSCCO-2223	108	> 50	<< 1	6.3