Physics/Accelerator Experiments Needed for Improving Particle/Heavy Ion Transport Codes

- What has been done and what should be done

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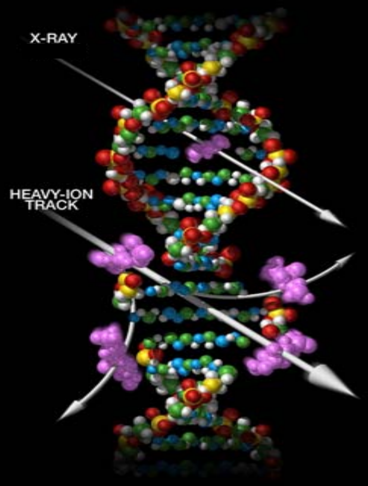
Outline

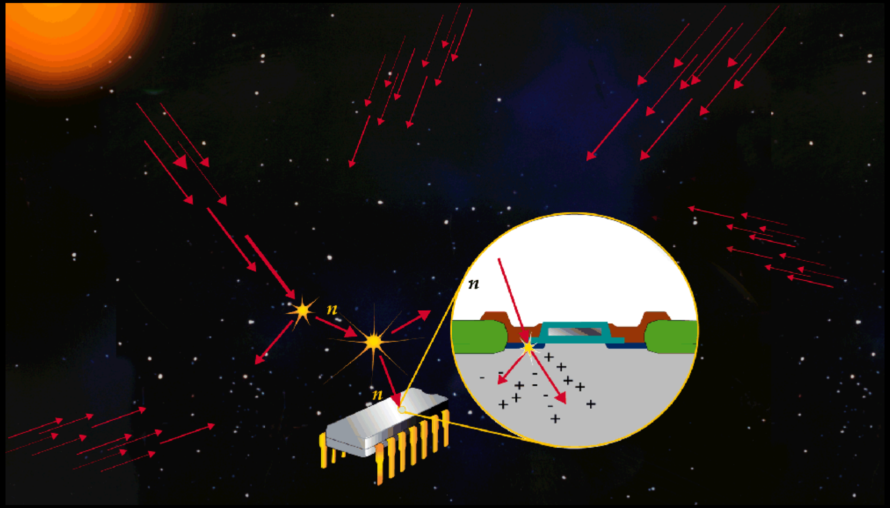
- What do we need to know ?
- What accelerator exp. have been performed ?
  - Examples without claming to be complete in any way….
- What is still missing ?
  - Suggestions of what additional accelerator exp. should be performed ?
- Accelerator / Experimental requirements
- Summary and conclusions

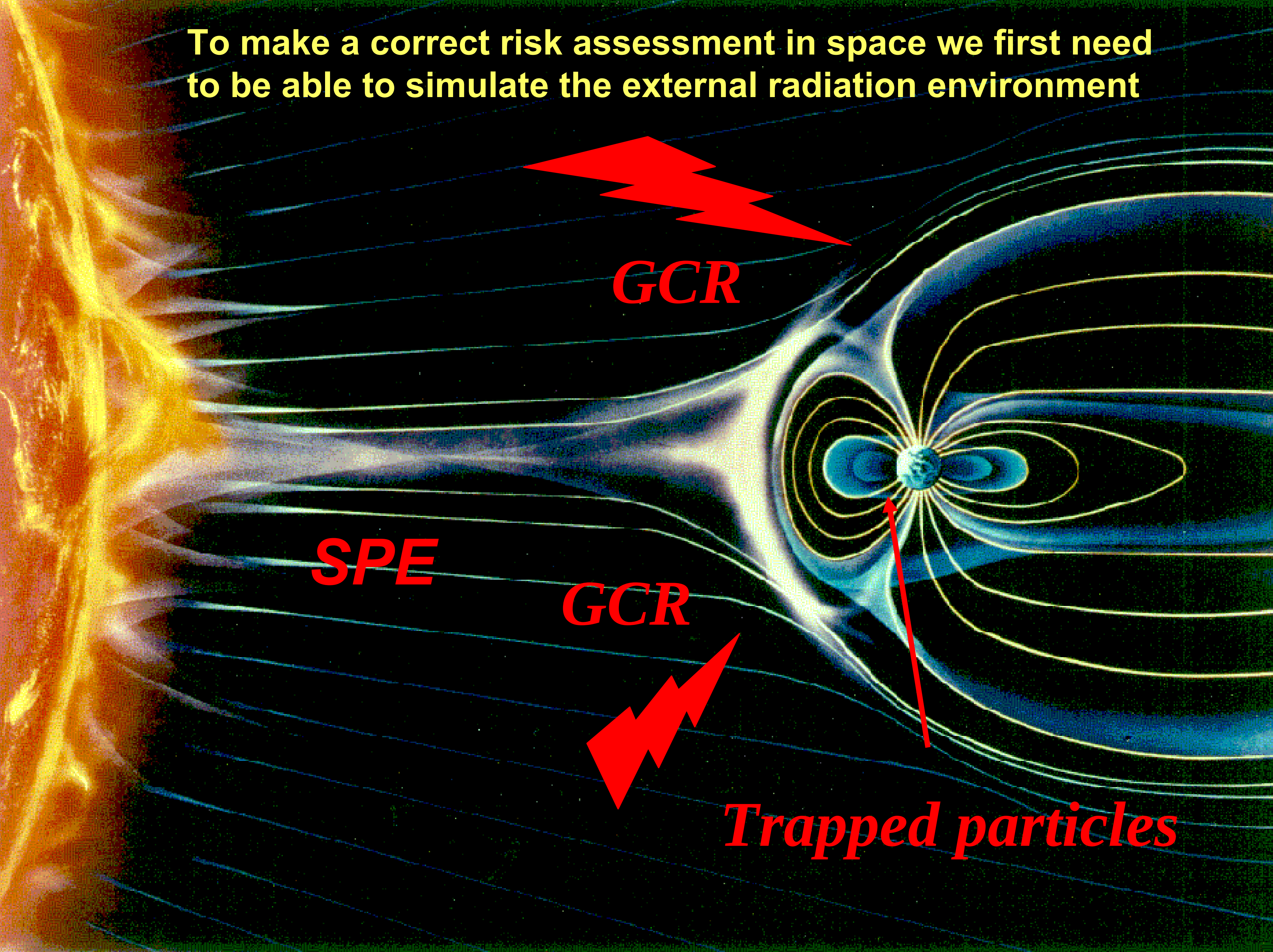
What do we need to know?

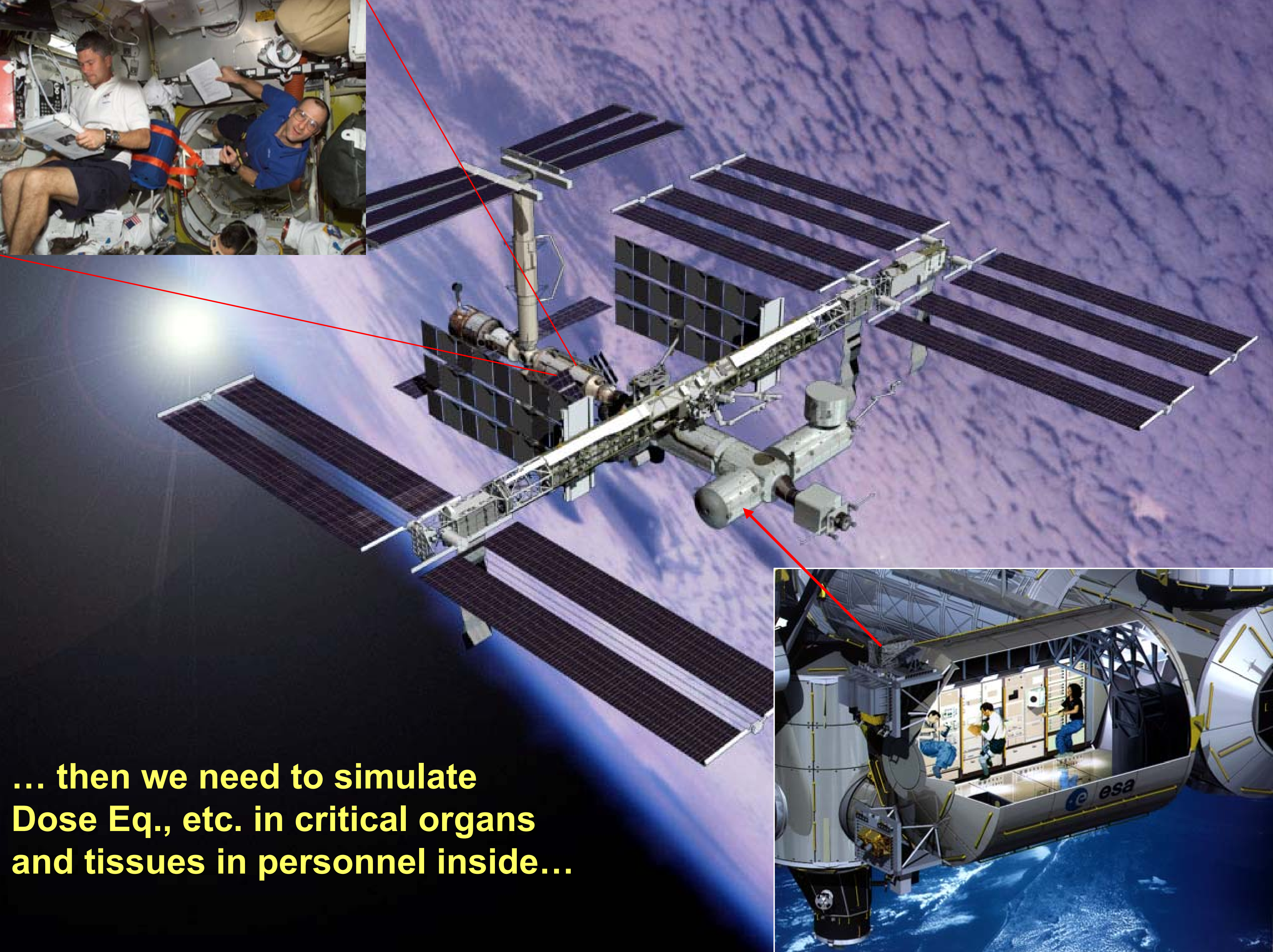
- Radiation risk estimation for humans in space
  - *Acute effects*
    - CNS damage, fatigue, skin ertihema, hair loss
    - digestive problems, reduced level of white blood cells, emotional upsets, etc
  - *Late effects*
    - ✓ CNS damage, cataracts, cancer, cardiac, circulatory and digestive diseases

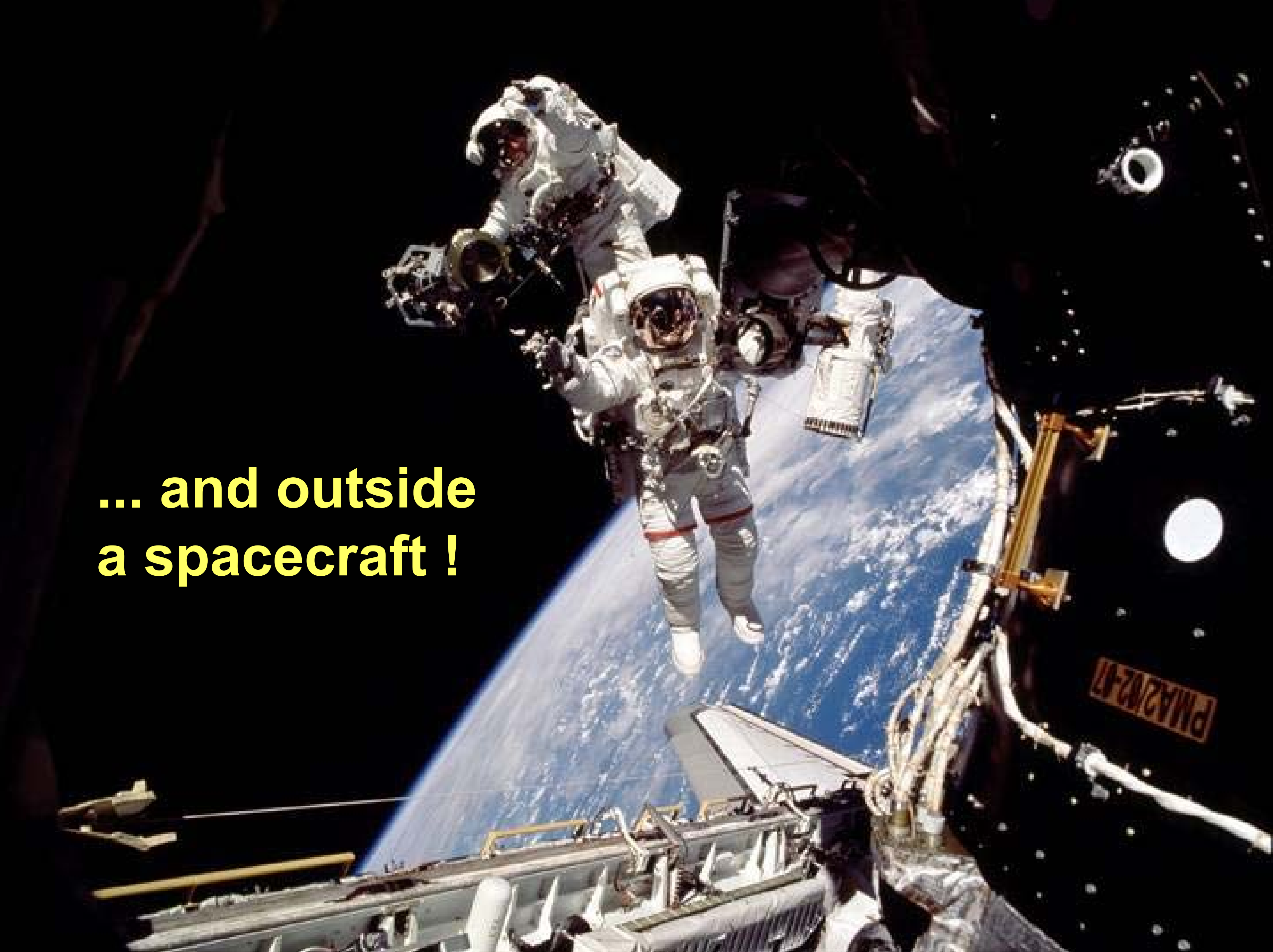


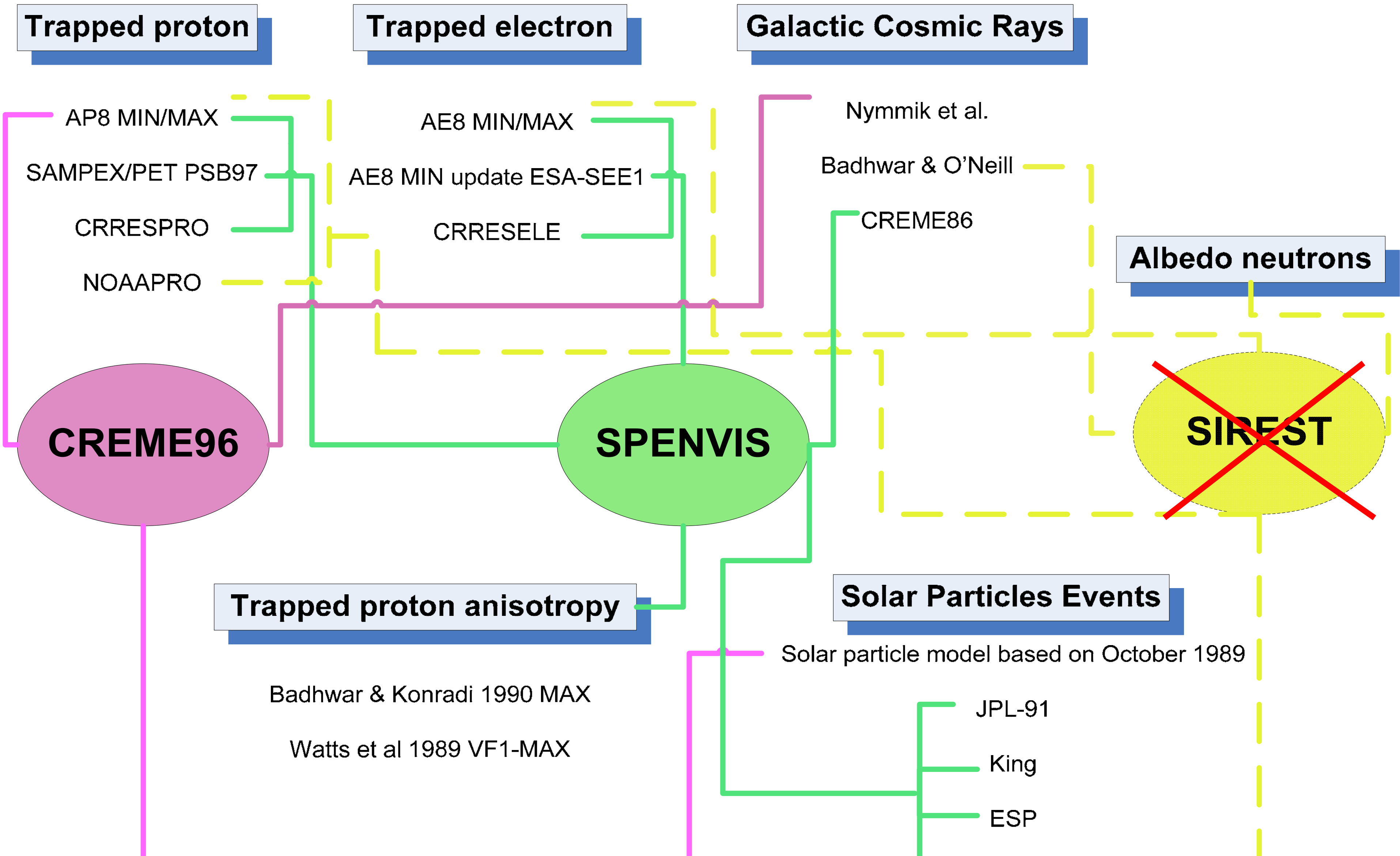
- Radiation effects on non-biological material
  - Shielding
  - SEU in electronic devices
  - …




To make a correct risk assessment in space we first need to be able to simulate the external radiation environment
GCR
SPE
GCR
Trapped particles

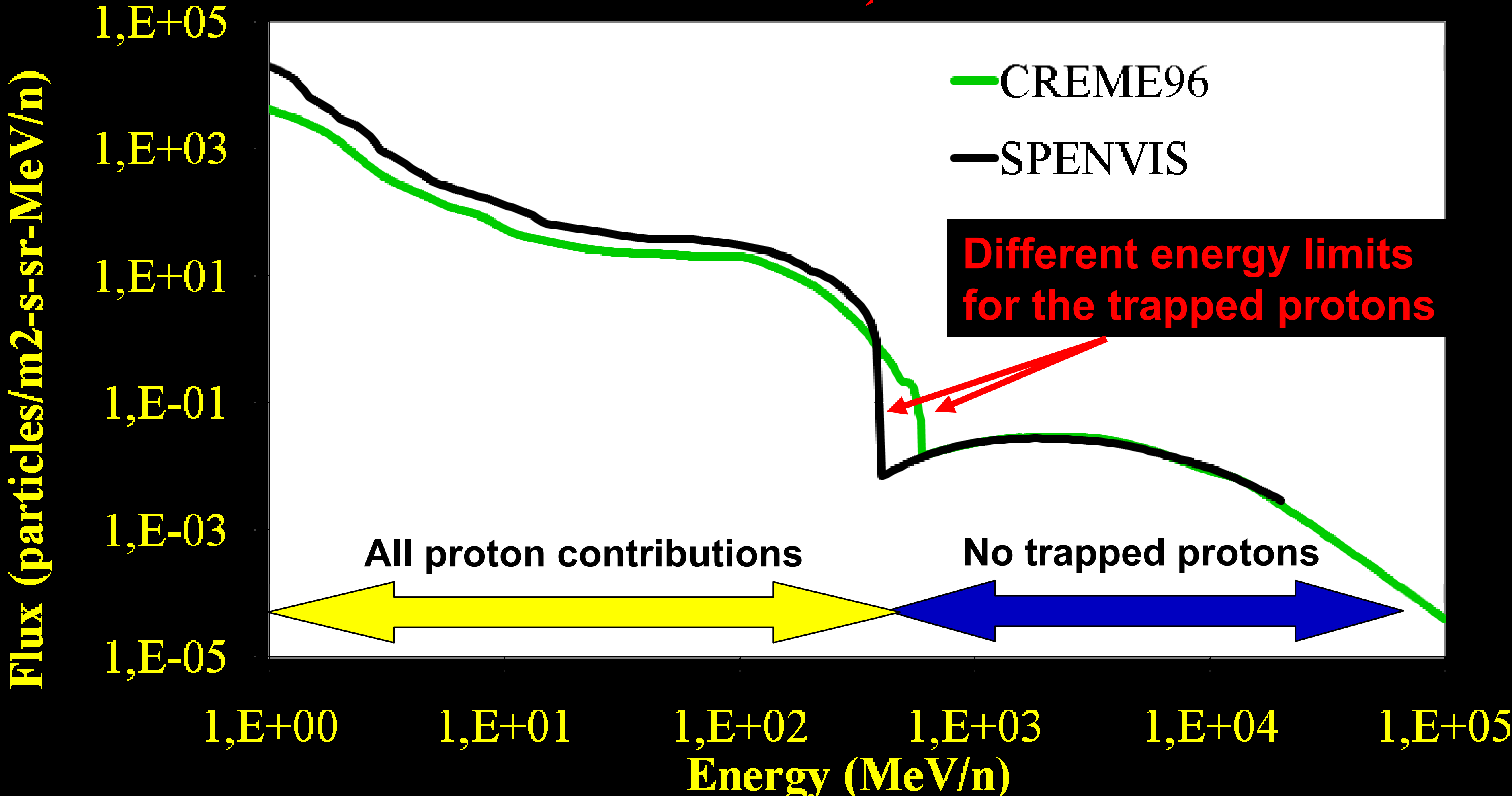

… then we need to simulate
Dose Eq., etc. in critical organs
and tissues in personnel inside…
esa


... and outside
a spacecraft !

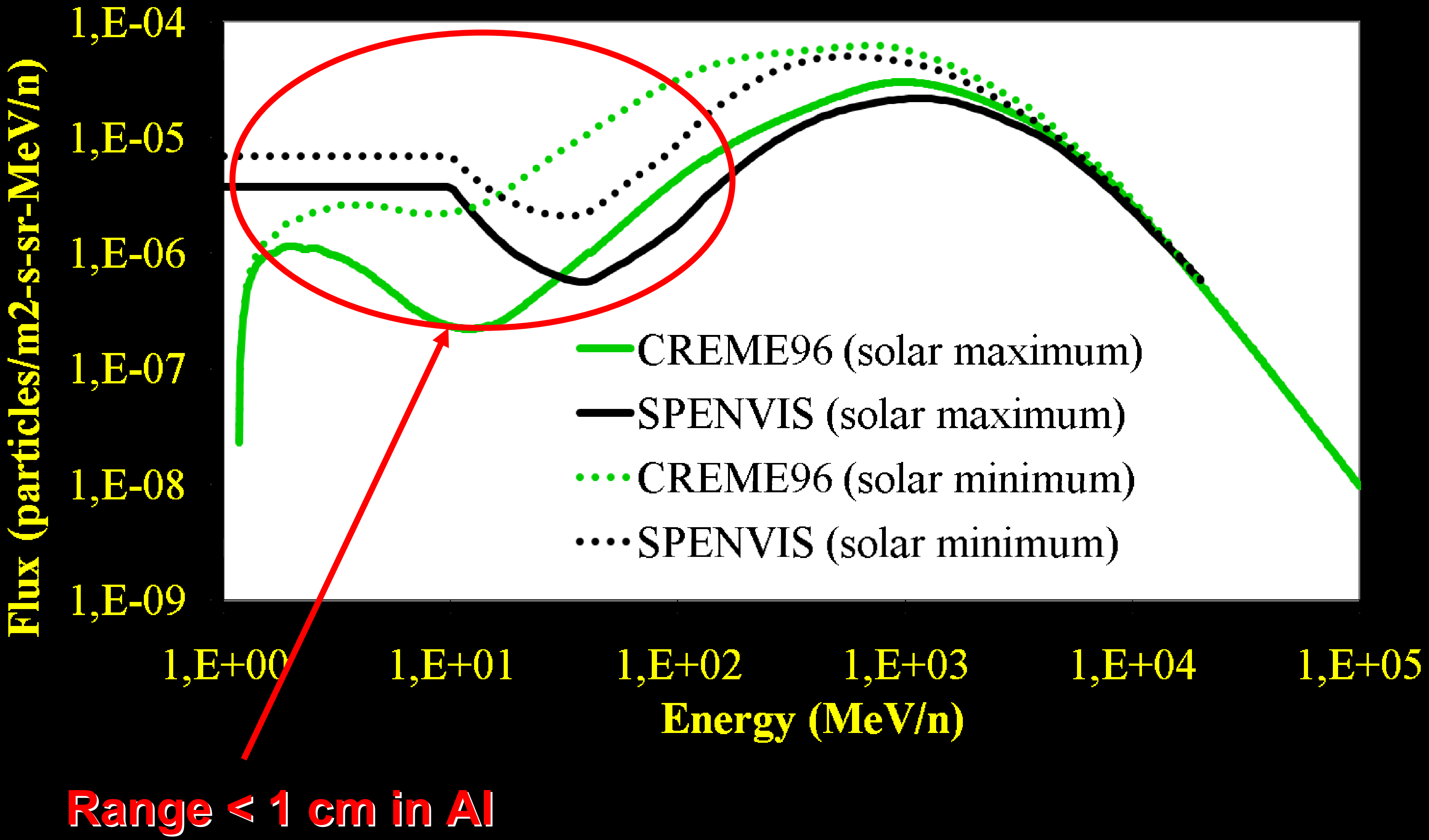


Space radiation environment codes / interfaces available on the www

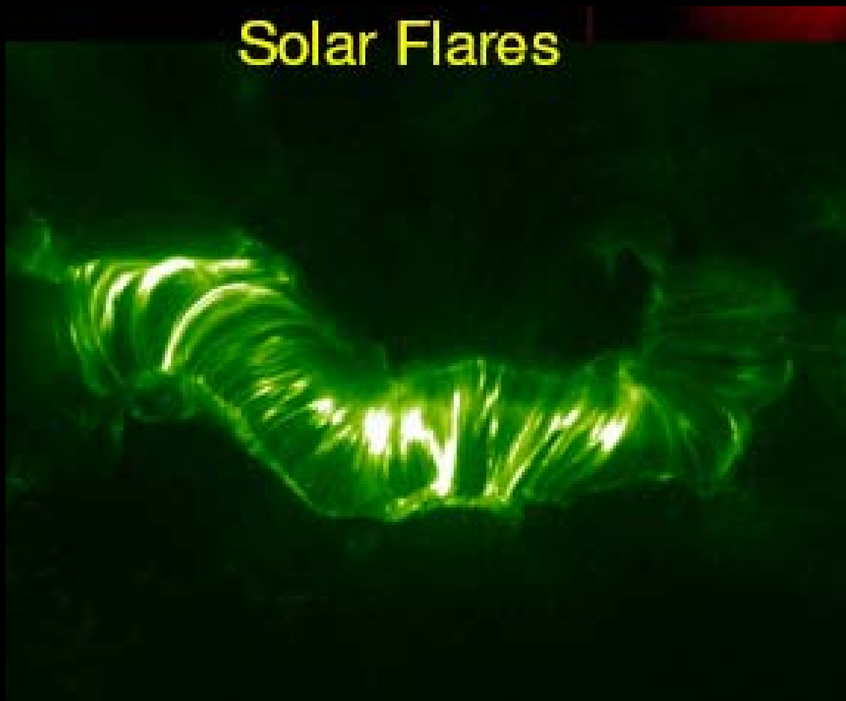
CREME96 and SPENVIS (Protons)
altitude 400 km, solar maximum



CREME96 and SPENVIS (Iron)
altitude 450 km

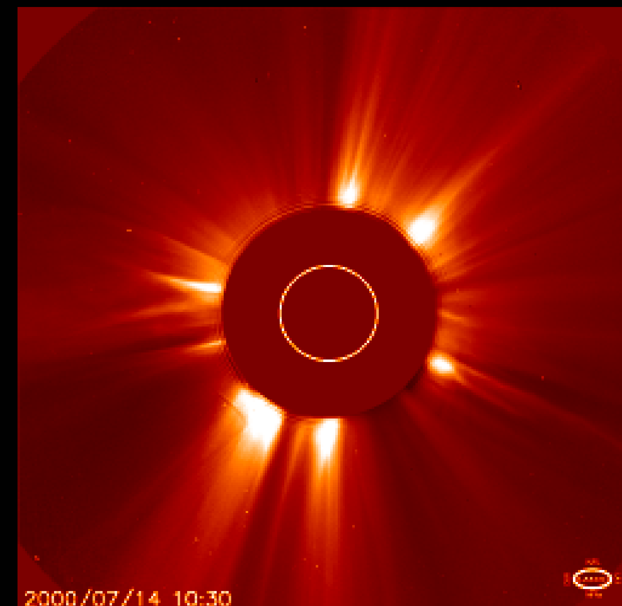


Largest risk / uncertainty SPE



- Short lived, in the order of hours
- Rel. large fluxes of e^-

Coronal mass ejection(CME)

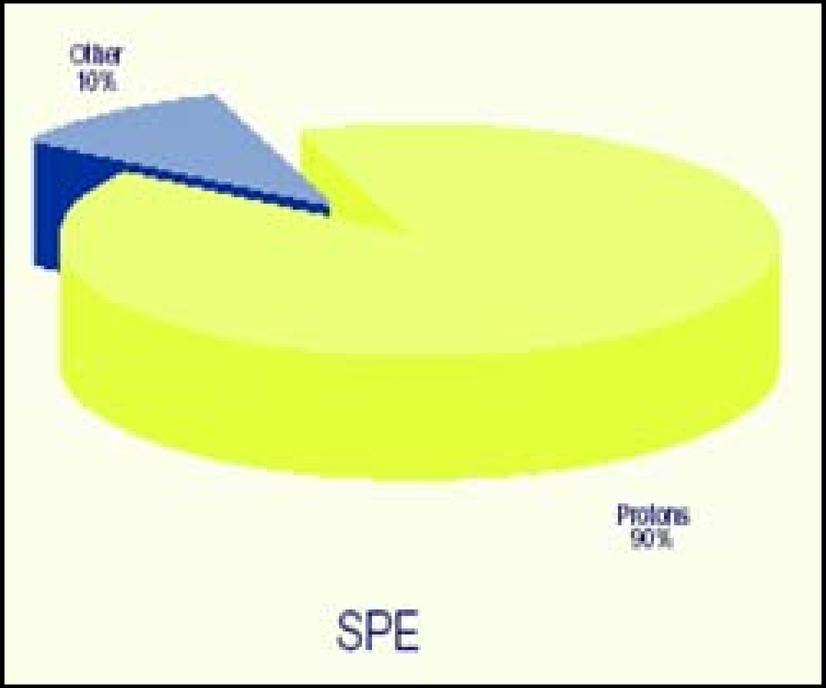


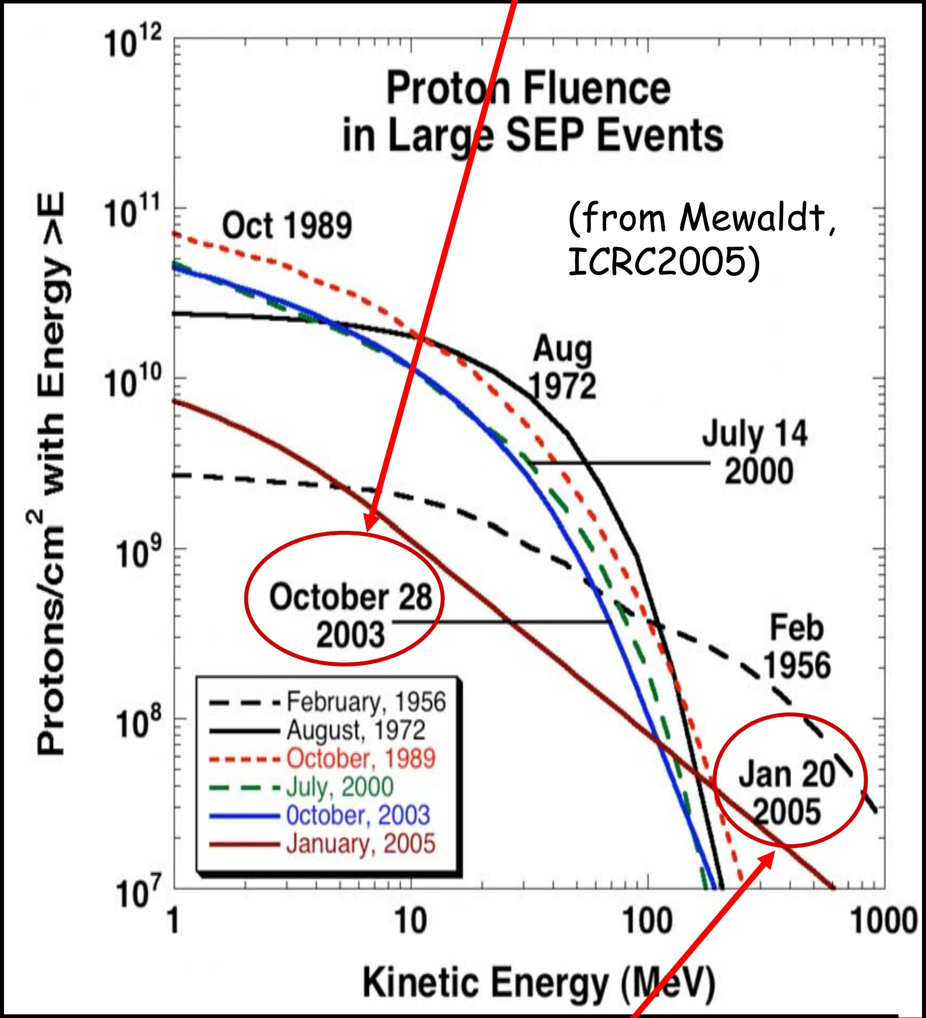
- Longer lived, in the order of days
- Rel. large fluxes of p

- **High particle fluxes → large doses**
- **Acute illness, death possible w/o shielding**

Solar Particle Events (SPE)

28-Oct-2003:
Whole body Dose Eq.: 4.9 ± 0.1 Sv !!



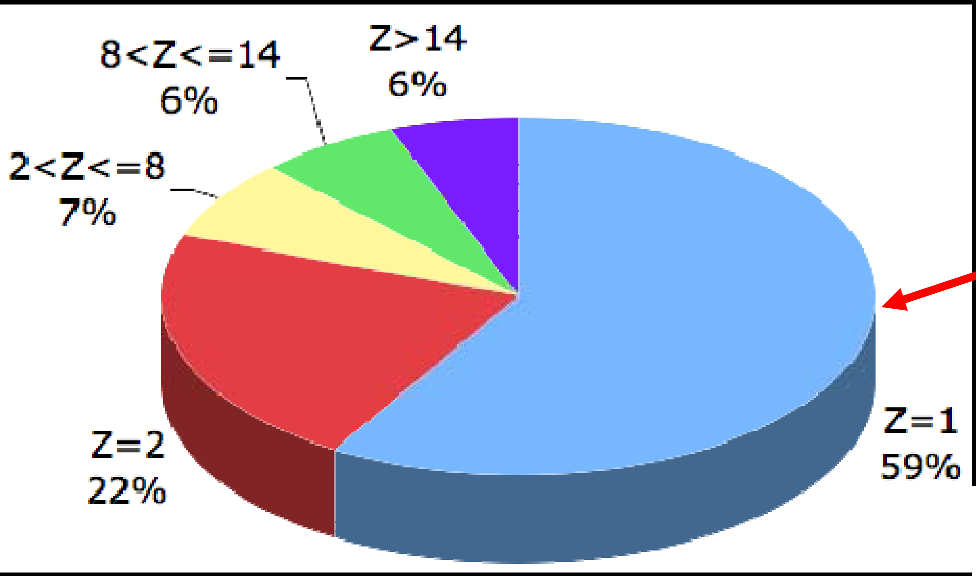


Nightmare scenarios for (manned) missions beyond Earth low orbits !

FLUKA calc: with courtesy to Dr. A. Ferrari

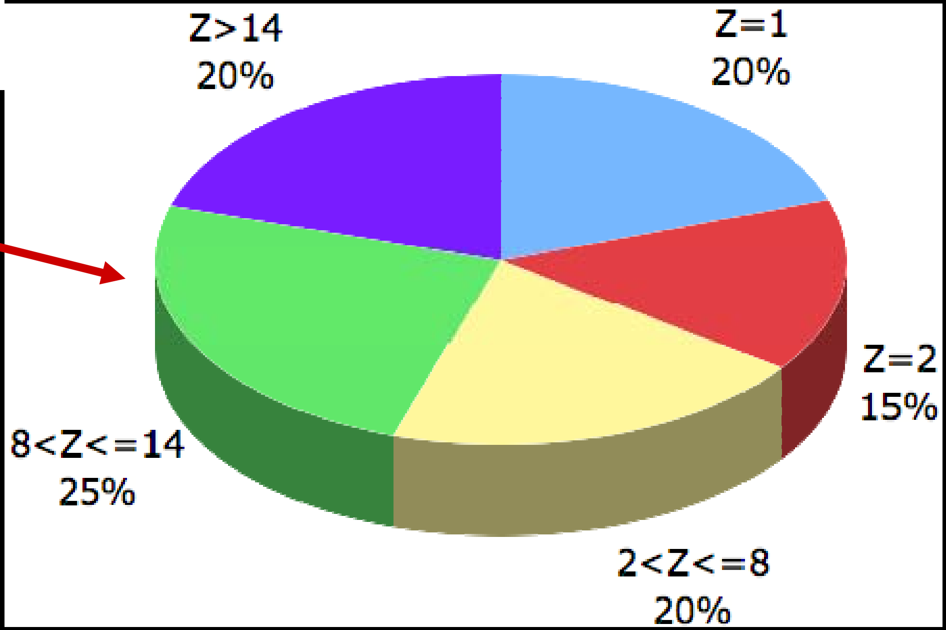
20-Sep-2005:
Whole body Dose Eq.: 1.83 ± 0.05 Sv !!

SPE 20 Sep 2005: open space skin doses after 1 g/cm² Al



Organ Dose: 1.363 ± 0.004 Gy
(Uncollided contr.: 1.250 ± 0.004 Gy)

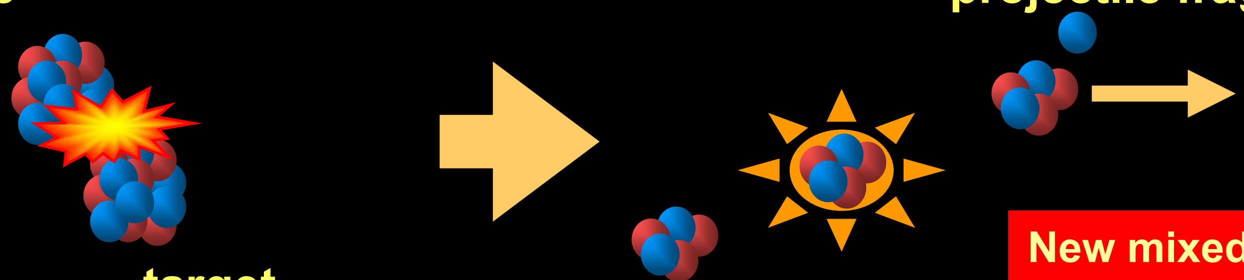
Organ Dose Equivalent: 6.16 ± 0.03 Sv
(Uncollided contr.: 5.61 ± 0.02 Sv)



Whole body Dose Eq.: 1.83 ± 0.05 Sv

FLUKA calc: with courtesy to Dr. A. Ferrari

Outer radiation fields



New mixed inner radiation field !

Interaction of the radiation with the spacecraft hulls, the body...

Target Fragments

... lower charge than target
... high LET
... short ranges

Projectile fragments

... lower charge than primaries
... mixed LET
... long ranges

... so we need to simulate the nuclear fragmentation process !!

….to do that we need a reliable nuclear reaction model !!

Semi-inclusive models

- Do not reconstruct the collision

+ Fast

- No correlations

- Not so informative

- Example: NUCFRG2

Exclusive models ("event generators")

- Reconstruct collisions

- Slow

+ Preserve all correlations

+ Very informative

- Example: QMD

NUCFRG2 → Deterministic codes; NUCFRG2 → Stochastic MC codes

QMD → Stochastic MC codes

Deterministic codes

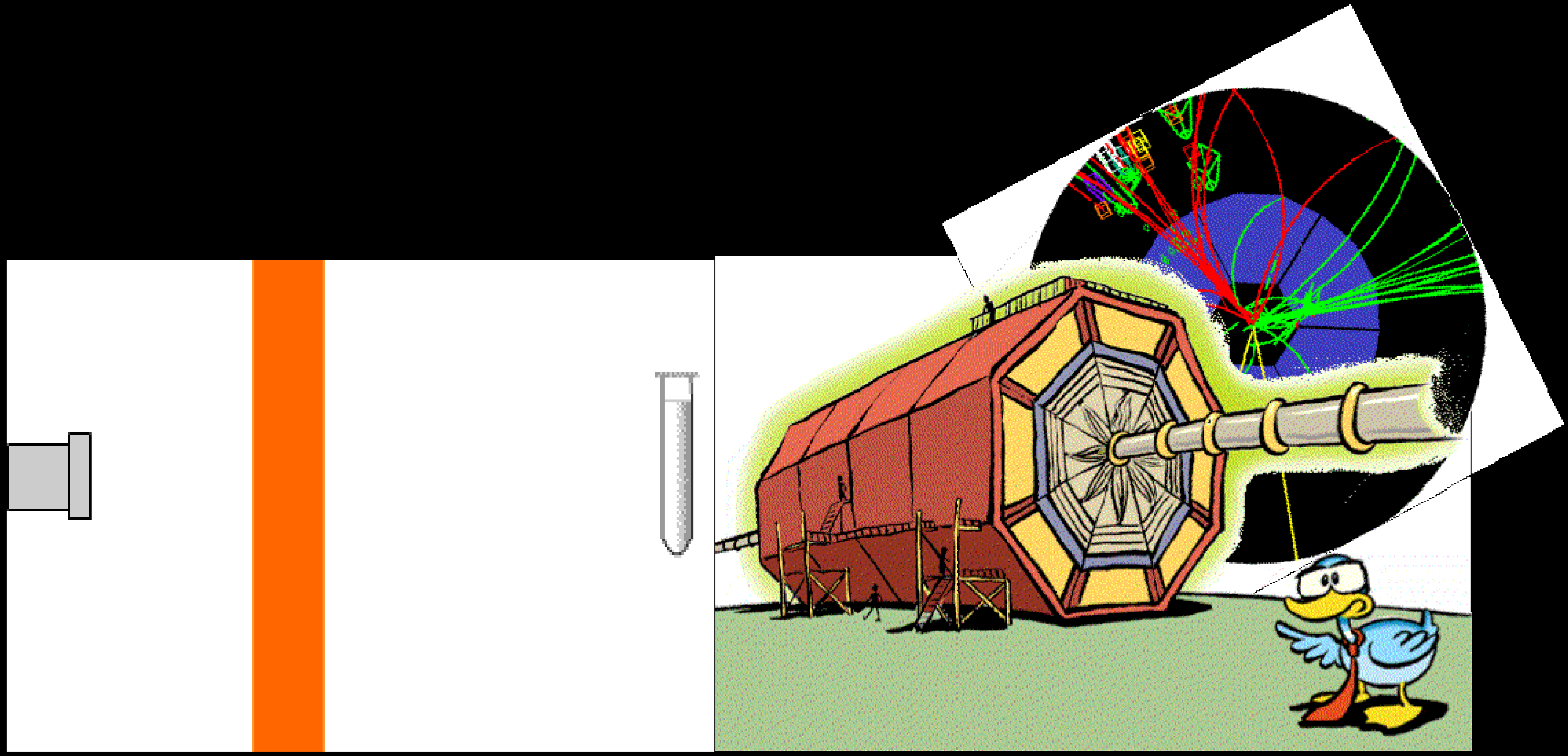
Stochastic MC codes

To be able to estimate the dose equivalents to critical organs we also need to be able to transport the primary and the secondary particles…

- **Stochastic 3-D MC Codes**
  - Geant4
    - ✓ The Geant Collaboration
  - HETC-HEDS
    - ✓ NASA Transport Consortium
  - FLUKA
    - ✓ The Fluka Collaboration
  - Shield-HIT
    - ✓ Sobolevsky et al.
  - PHITS
    - ✓ RIST, JAEA, Chalmers and GSI
  - MCNPX
    - ✓ Los Alamos National Lab.
  - MARS
    - ✓ Fermi National Accelerator Laboratory

- **Deterministic codes 1-D codes**
  - HZTREN
    - ✓ NASA Langley Research Center
  - HIBRAC
    - ✓ Chalmers

... and we need accelerator experiments to compare the calculations with!!



Measurements of H.I. fragmentation cross sections (thin targets) and yields behind shielding (thick targets) has mainly been performed at:

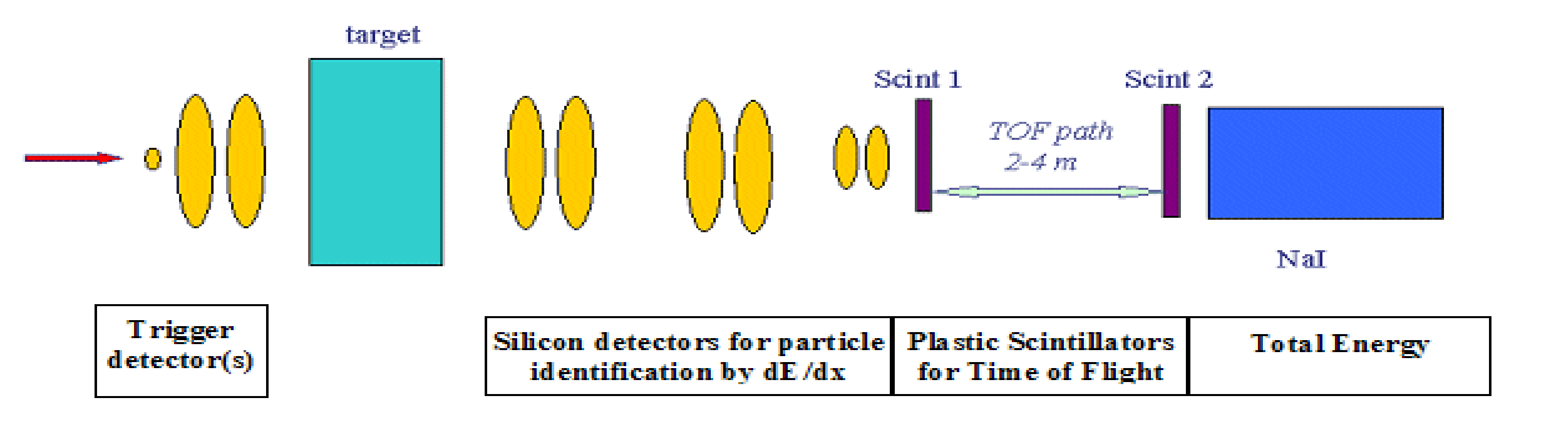
	Z_{proj} (max)	E_{proj} (MeV/u)	E_{proj} (^{56}Fe) (MeV/u)
NSRL (BNL)	79	40-3000	100-1100
AGS (BNL)	79	600-30000	600-5000
HIMAC (NIRS-Chiba)	36	100-800	500
LLUPTC (Loma Linda)	1	40-250	—

Neutron exposures have been performed at e.g.:

- Los Alamos National Laboratory Neutron Science Center (LANSCE), US
- Gustaf Werner Cyclotron at TSL, Sweden
- Secondary neutrons from protons on heavy targets at several facilities

Projectile fragmentation measurements performed by C. Zeitlin et al. at LBNL

1) Total charge changing cross sections
2) Partial charge changing cross sections



- Inclusive cross sections
  - When no distinction is made as how the fragment is produced
- Fully depleted, unsegmented, Si detectors
- Detectors aligned on the beam axis, at $\approx 0^{\circ}$

Secondary Particles - LNBL fragmentation / charge changing cross section data base

- Extensive work
- Good Statistics, but “only”
  - projectile fragments in forward direction
  - charge changing detection
    - no *n* stripping
  - “leading particles” detected (large θ_{acc})
    - high charge ($Z > Z_{beam} / 2$)
    - all charges resolved at small θ_{acc}

Primary Particles - LNBL fragmentation / charge changing cross section data base *

Targets: H, C, Al, Cu, Sn and Pb

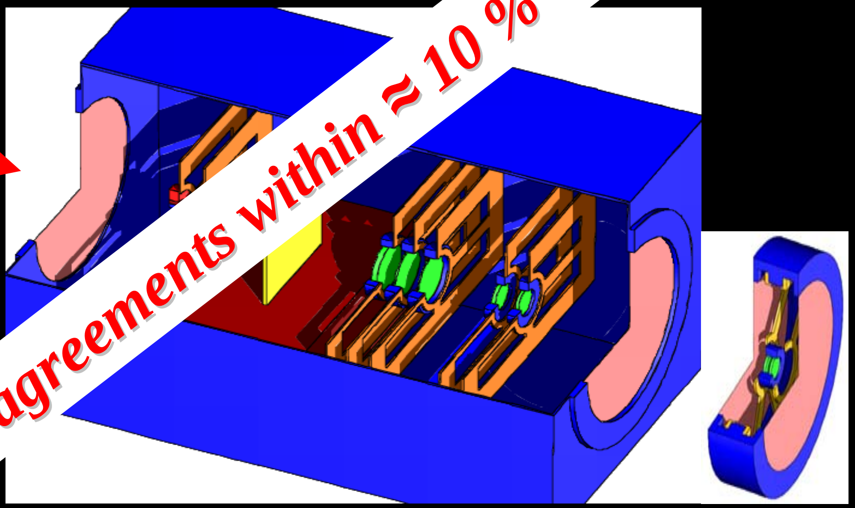
Ion	Energy (MeV/nucleon)							
^{56}Fe	400	500	600	800	1,000	3,000	5,000	10,000
^{48}Ti					1,000			
^{40}Ar	290	400	650					
^{35}Cl			650		1,000			
^{28}Si	290	400	600	800	1,200	3,000	5,000	10,000
^{24}Mg		400						
^{20}Ne	290	400	600					
^{16}O	290	400	600		1000			
^{14}N	290	400						
^{12}C	290	400				3000	5000	10000
^{11}B		400						
^{10}B		400						
^{4}He	230							

* With courtesy to C. Zeitlin, L. Heilbronn, S. Guetersloh, and J. Miller

First we calculated charge-changing cross sections with different methods usin ITS

Exp. Performed by C. Zeitlin et al., LBNL (USA)

Beam

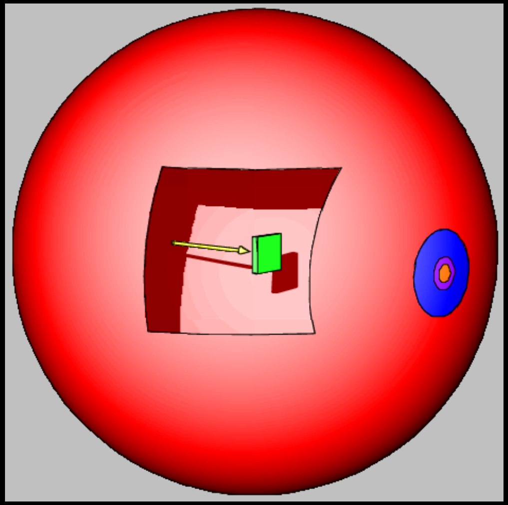


1. Simulate the whole experimental setup

The different methods gave agreements within ≈ 10 %

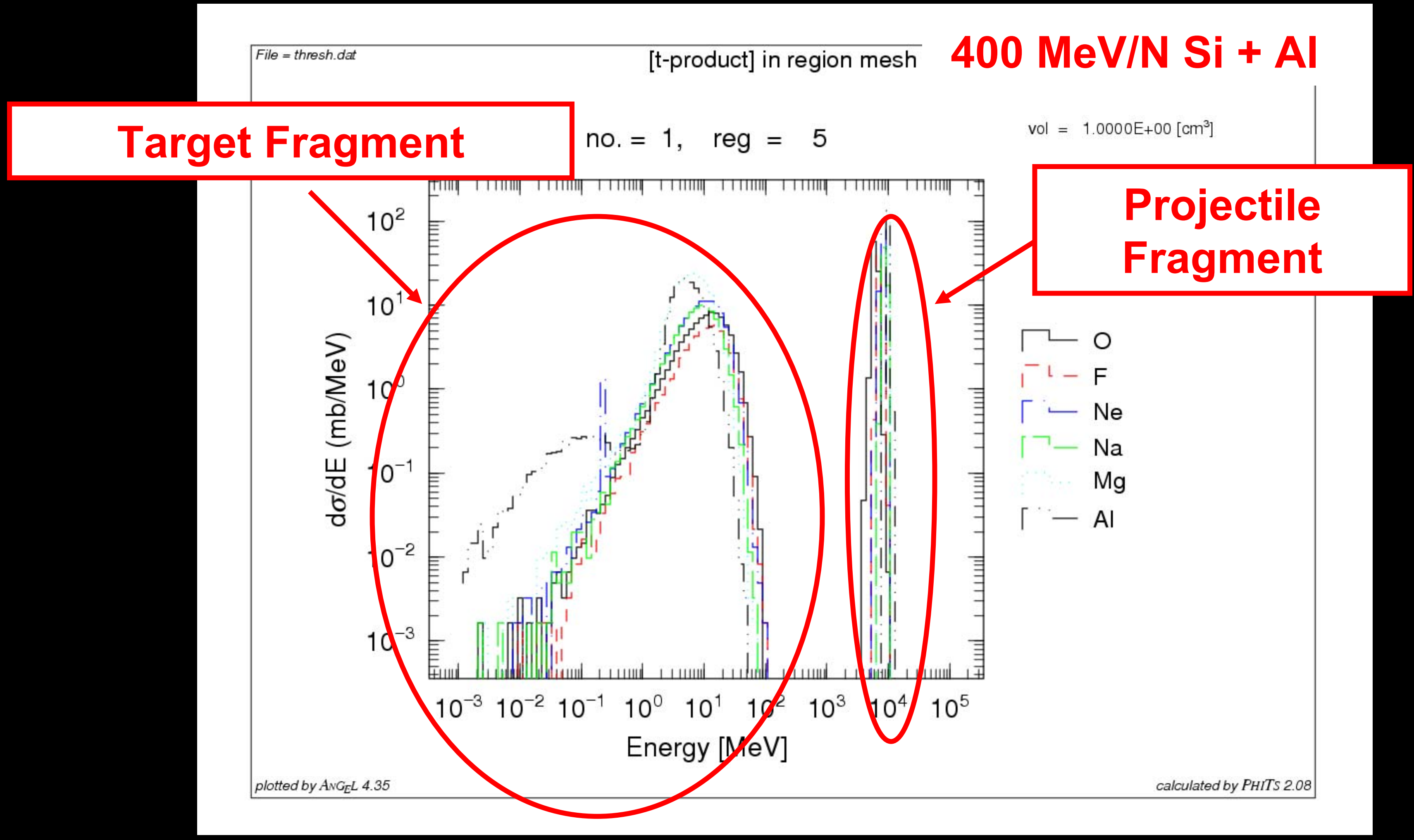
A thin target pl d in a sphere filled with v

2. T-cross
3. T-product



T-product used

- Projectile fragmens separated from target fragments by their kin energy



Bencharking against measurements and other codes

Benchmarked

- ➢ total & partial cross sections

- Transport Codes
  - ➢ PHITS, FLUKA, MNCPX_HI, HETC-HEDS, NUCFRG2
- Targets: H, C, Al, Cu, Sn and Pb
- Projectiles:

Ion	Energy (MeV/nucleon)							
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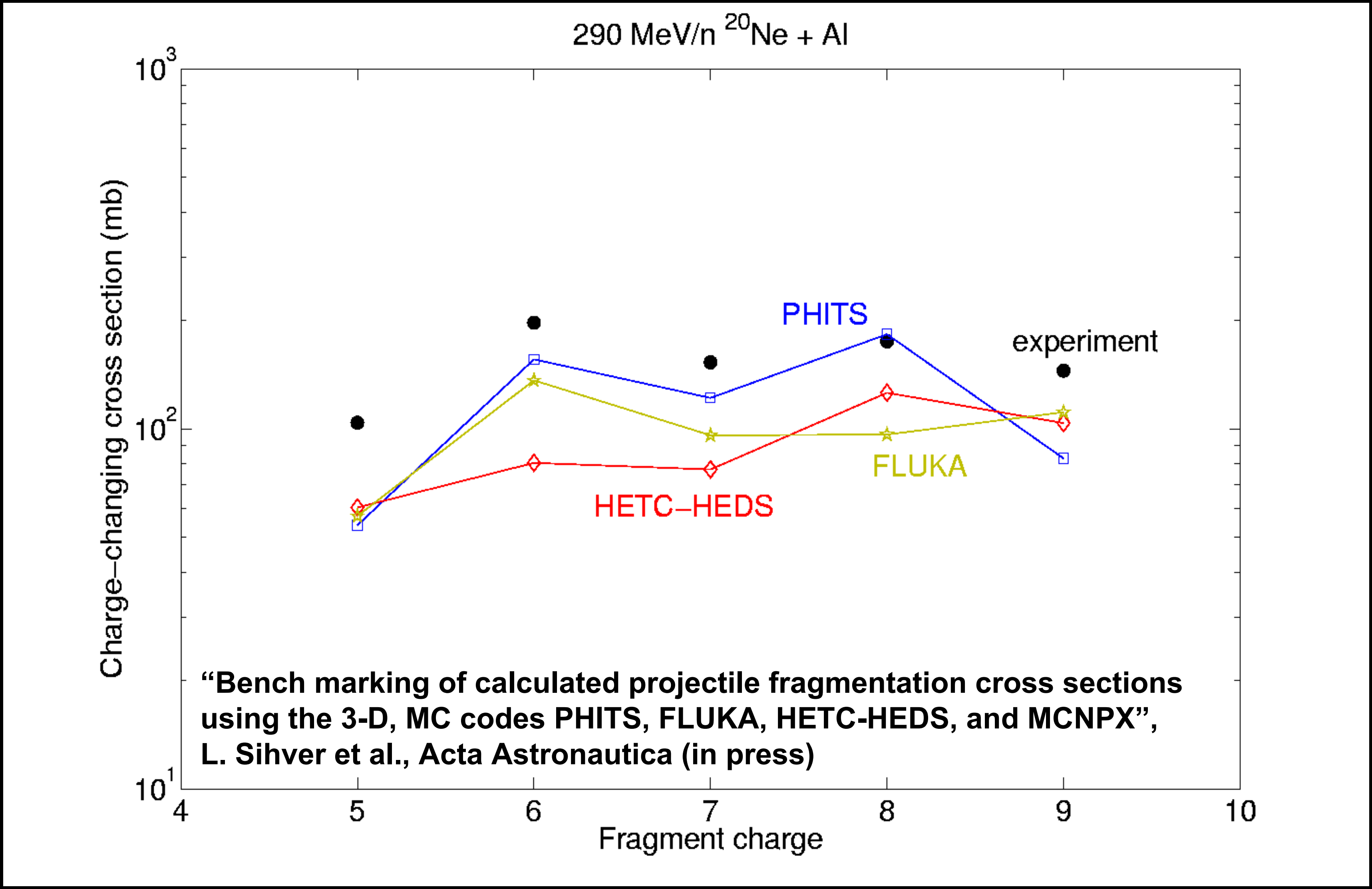
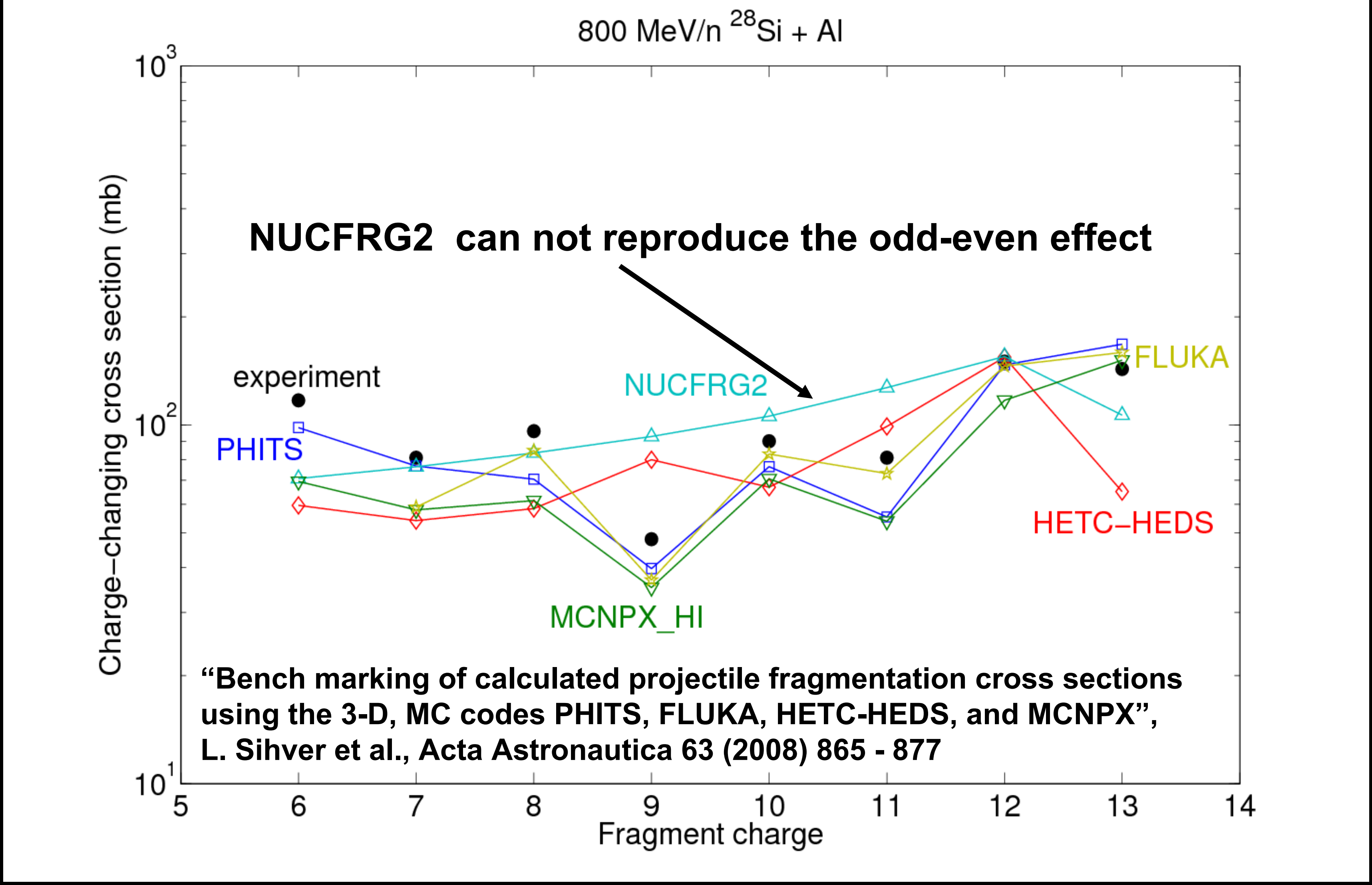
^{14}N	290	400						
^{12}C	290	400				3000	5000	10000
^{11}B		400						
^{10}B		400						
^{4}He	230							

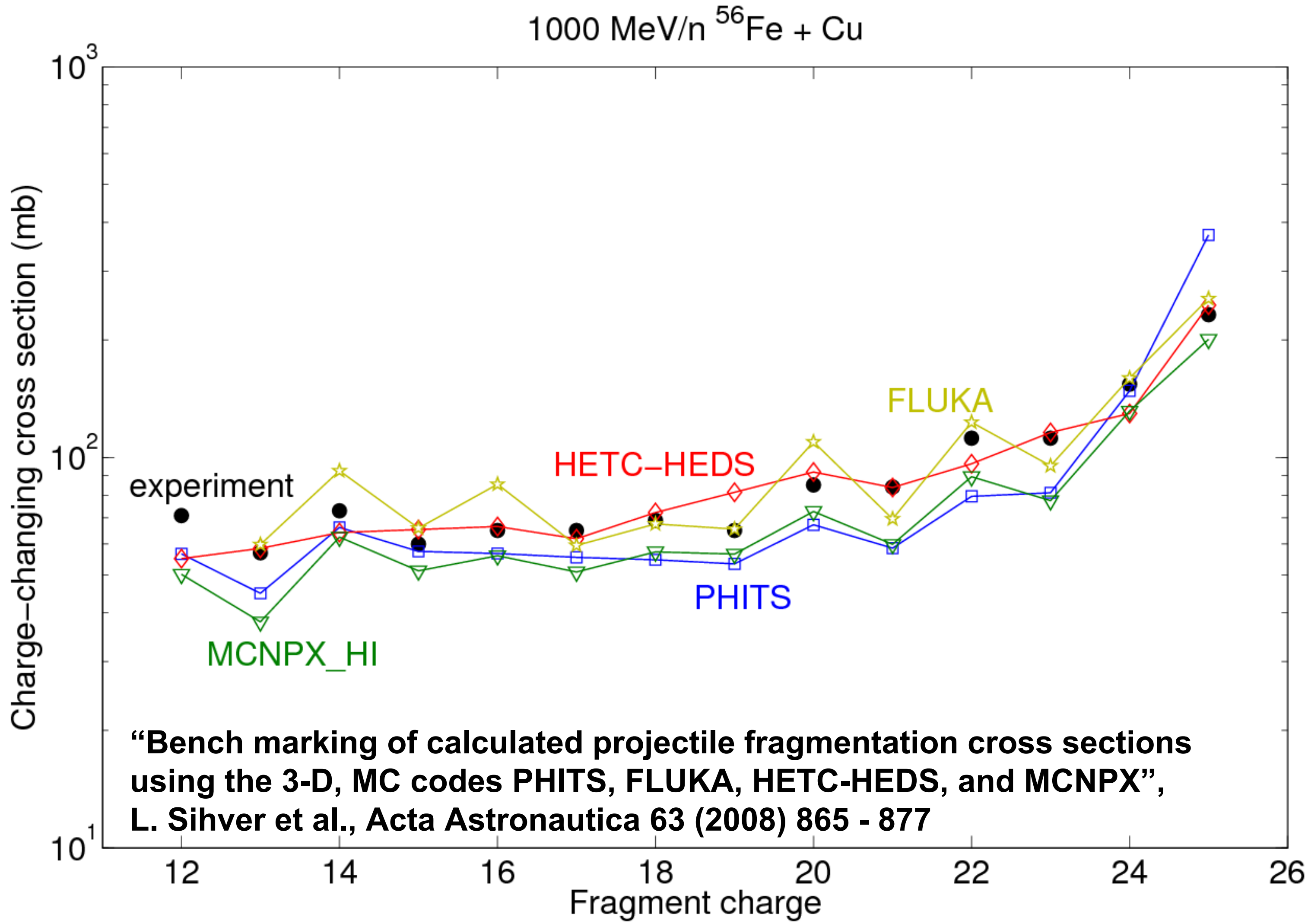
RESULTS


290 MeV/n ^{20}Ne + Al
Charge–changing cross section (mb)
Fragment charge
PHITS
experiment
FLUKA
HETC–HEDS
10^3
10^2
10^1
4
5
6
7
8
9
10
"Bench marking of calculated projectile fragmentation cross sections using the 3-D, MC codes PHITS, FLUKA, HETC-HEDS, and MCNPX", L. Sihver et al., Acta Astronautica (in press)

RESULTS


800 MeV/n ^{28}Si + Al
NUCFRG2 can not reproduce the odd-even effect
Charge−changing cross section (mb)
10^3
10^2
10^1
experiment
NUCFRG2
PHITS
FLUKA
HETC−HEDS
MCNPX_HI
“Bench marking of calculated projectile fragmentation cross sections using the 3-D, MC codes PHITS, FLUKA, HETC-HEDS, and MCNPX”, L. Sihver et al., Acta Astronautica 63 (2008) 865 - 877
5
6
7
8
9
10
11
12
13
14
Fragment charge

RESULTS



"Bench marking of calculated projectile fragmentation cross sections using the 3-D, MC codes PHITS, FLUKA, HETC-HEDS, and MCNPX", L. Sihver et al., Acta Astronautica 63 (2008) 865 - 877

Benchark Condtions

No projectile lighter than Si was included in this benchmarking !

- Benchmarked
  - ➢ total & partial cross sections
- Transport Codes
  - ➢ PHITS, FLUKA, MNCPH_HI, HETC-HEDS, NUCFRG2
- Targets: H, C, Al, Cu, Sn and Pb
- Projectiles:

Ion	Energy (MeV/nucleon)							
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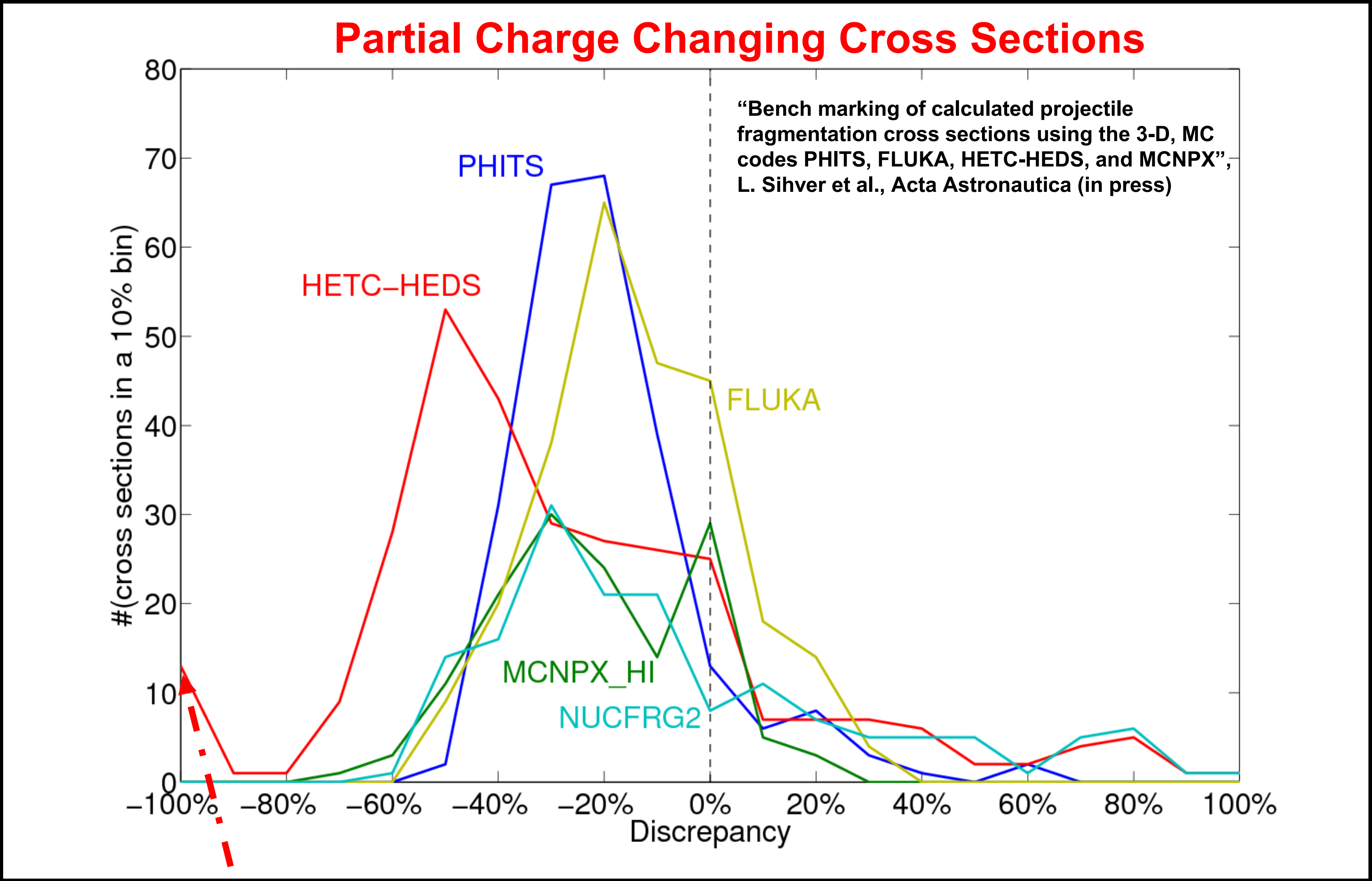
^{28}Si	290	400	600	800	1,200	3,000	5,000	10,000
^{24}Mg		400						
^{20}Ne	290	400	600					
^{16}O	290	400	600		1000			
^{14}N	290	400						
^{12}C	290	400				3000	5000	10000
^{11}B		400						
^{10}B		400						
^{4}He	230							

RESULTS

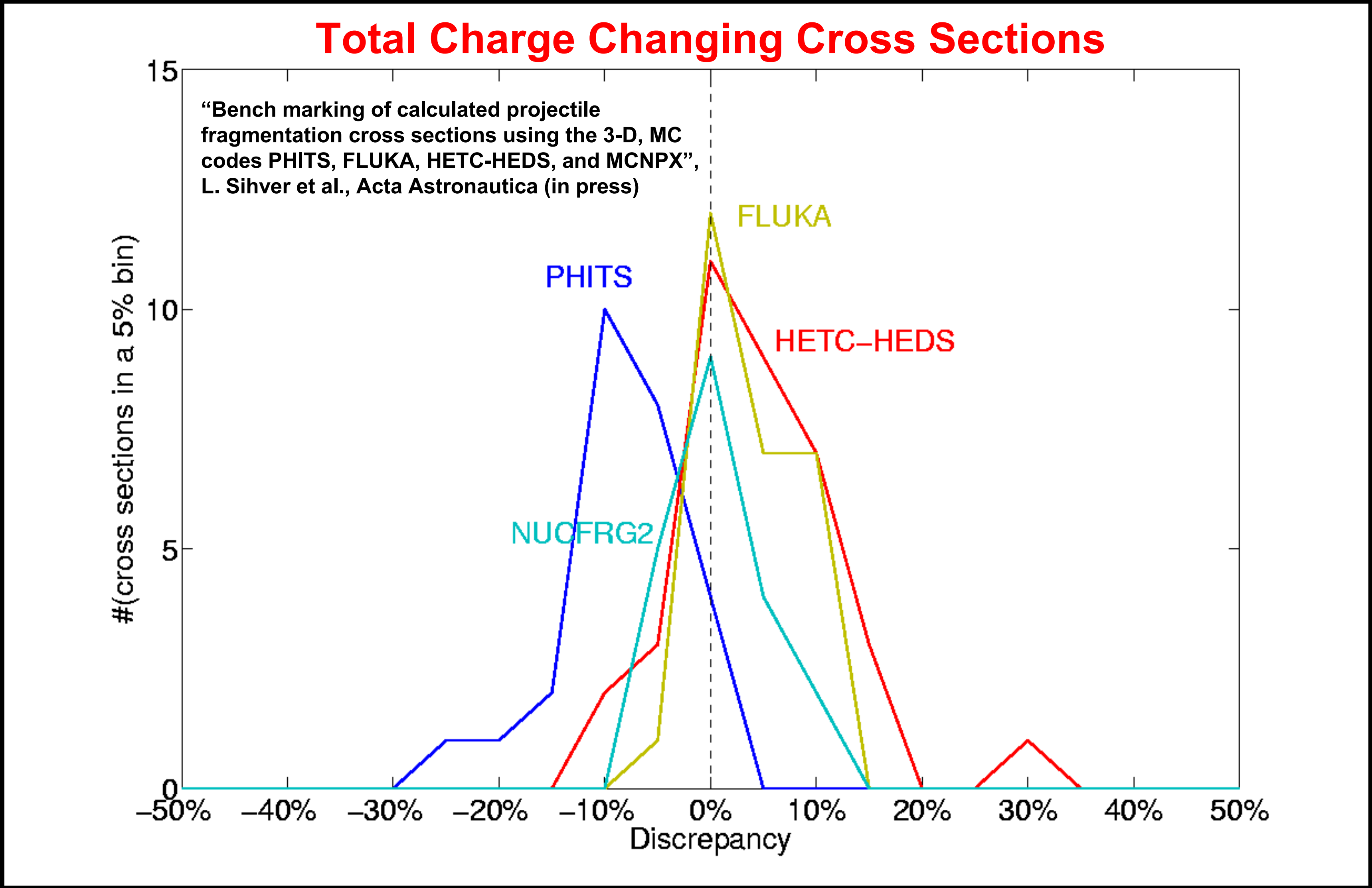
No projectile lighter than Si was included !



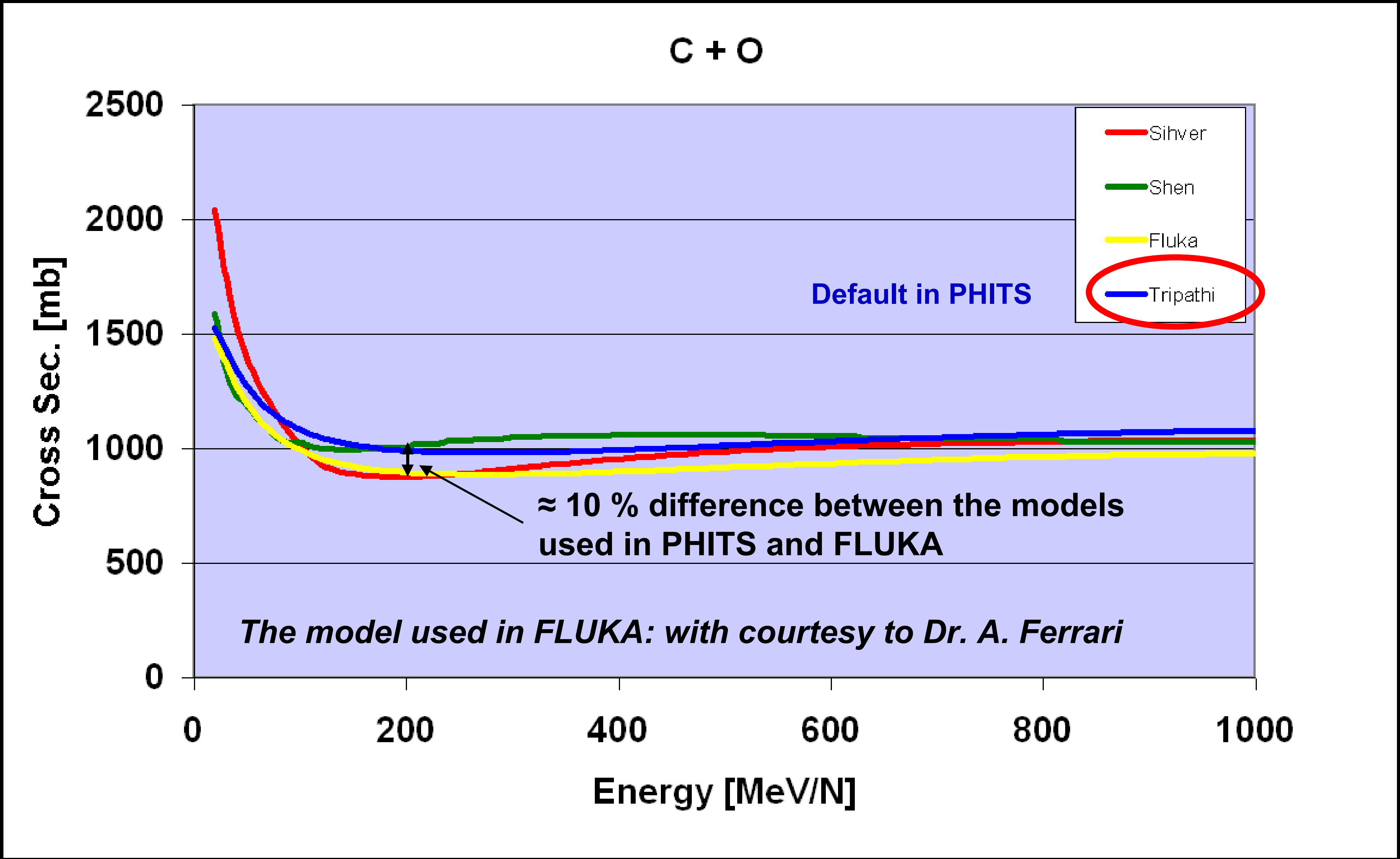
Several calc. cross sections for light fragments = 0

RESULTS

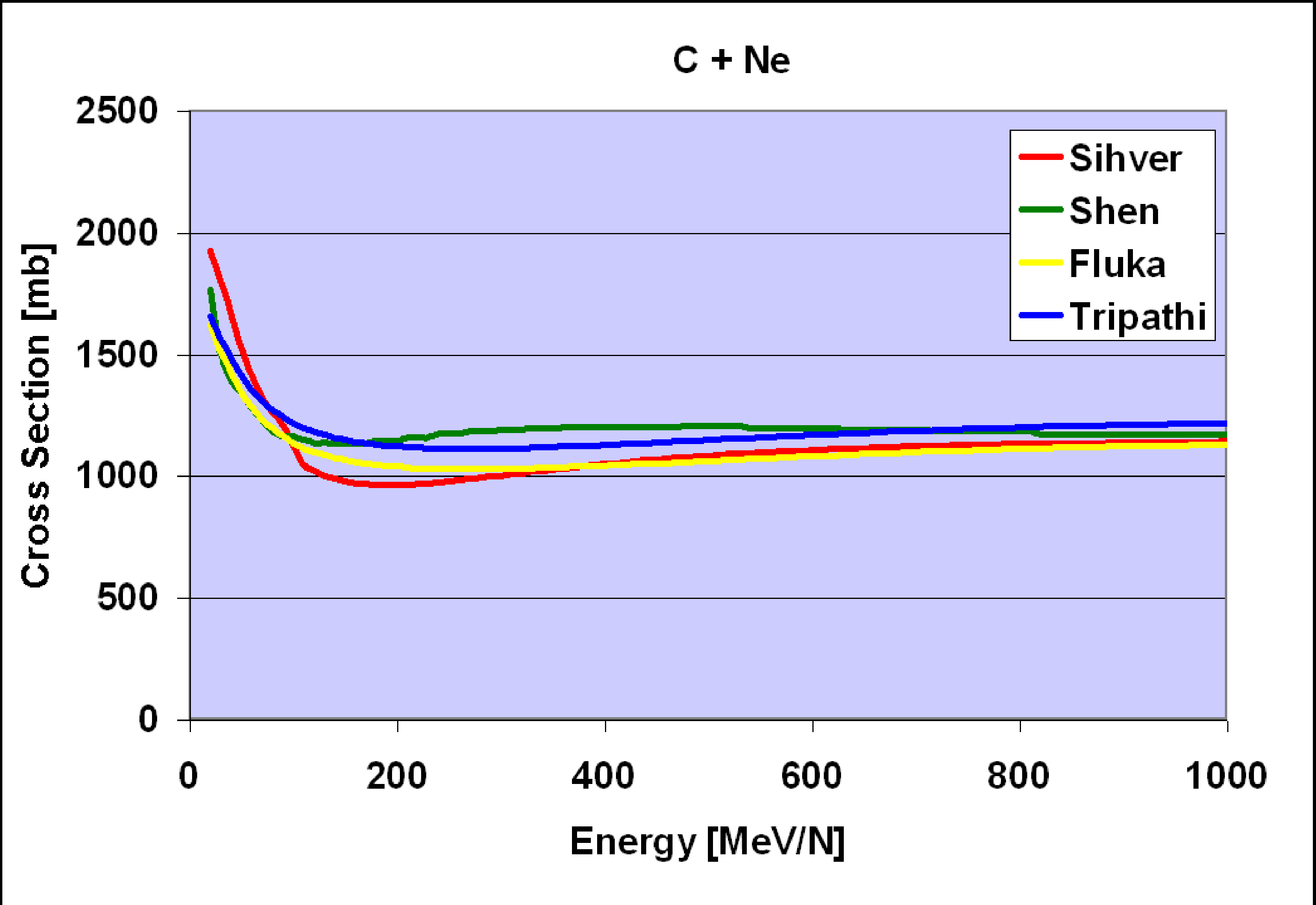
No projectile lighter than Si was included !



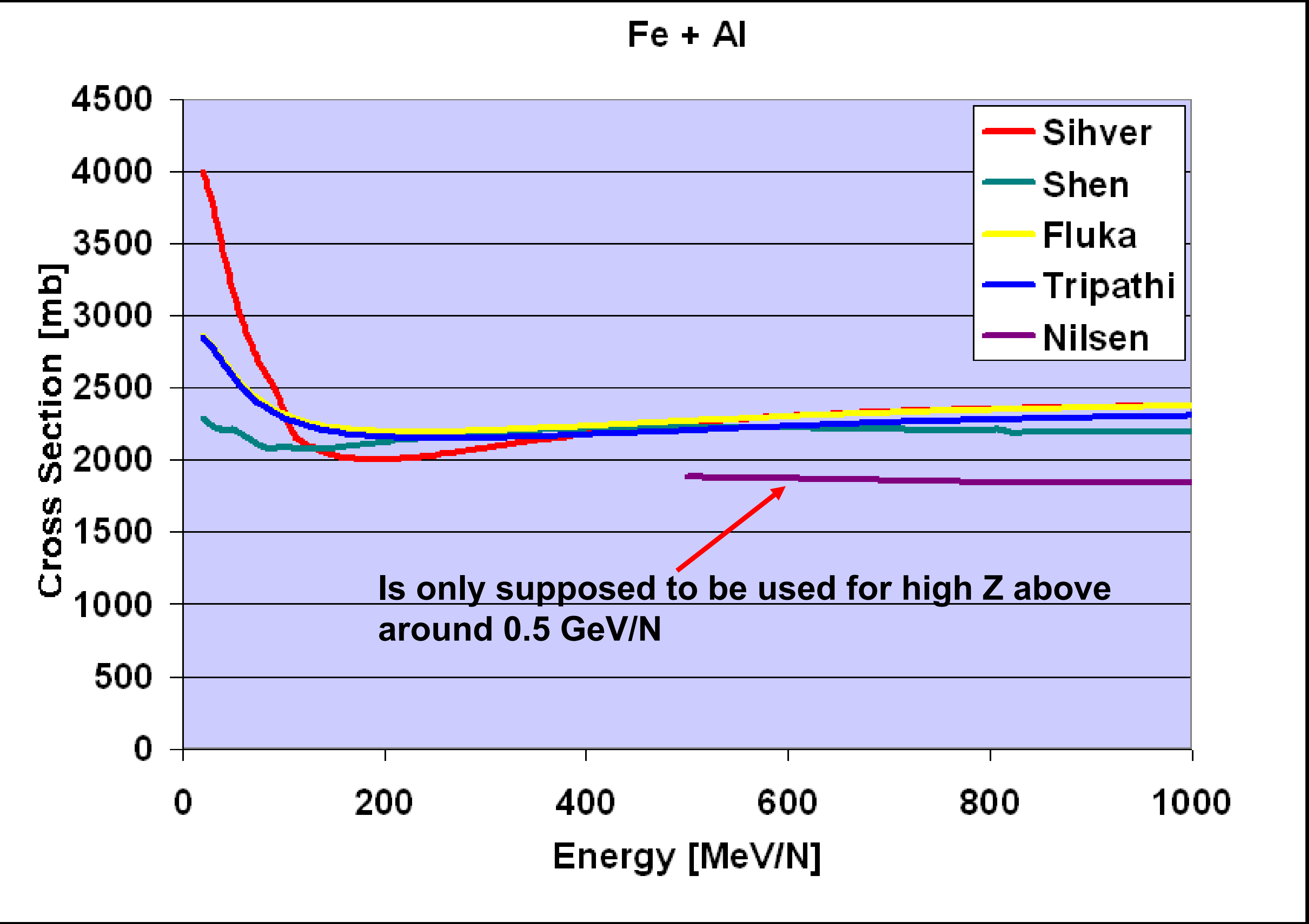
Total Reaction Cross Section



Total Reaction Cross Section

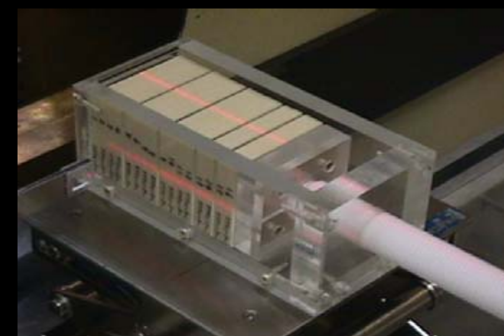


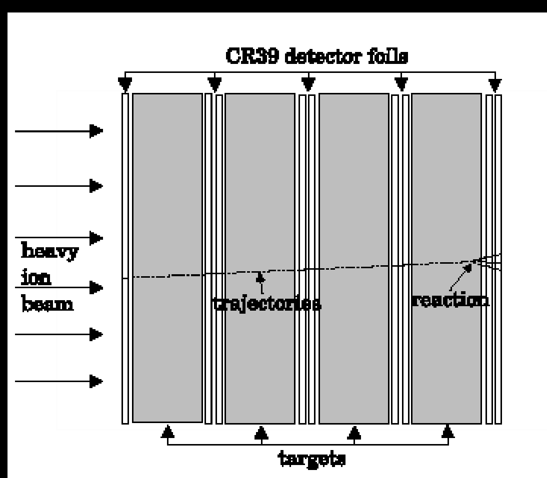
Total Reaction Cross Section



Projectile fragmentation and yields behind shielding measured with CR-39 PNTD Detectors

Exp. at HIMAC (NIRS, Japan), NSRL (BNL, USA) performed by E. Benton et al., N. Yasuda et al, M. Durante et al., etc





- **Total charge changing cross sections**
- **Partial charge changing cross sections**
- **LET distributions, etc.**

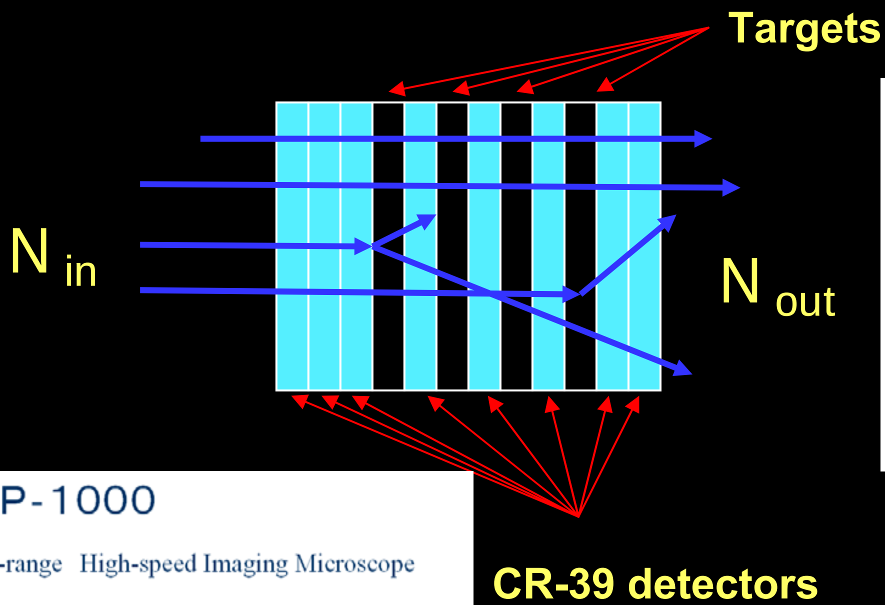
Advantages:

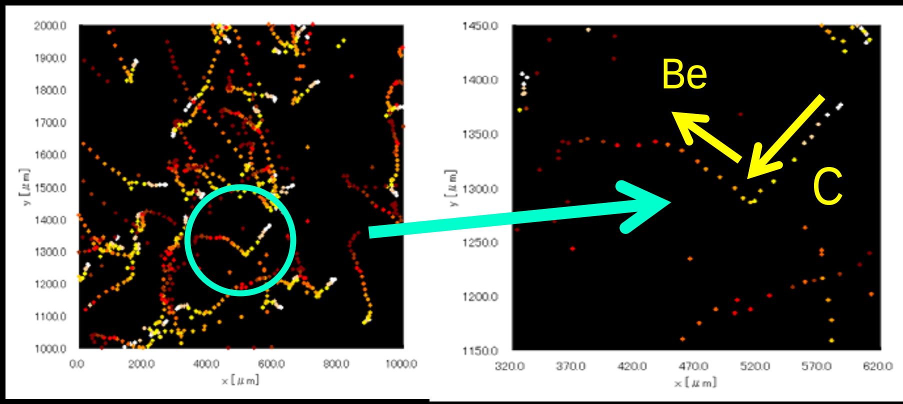
- **Spatial information close to 4π**
  - **Fragments with Z=4 $\Rightarrow$ Z_{proj} can be measured**
  - **Target fragmentation can be measured**

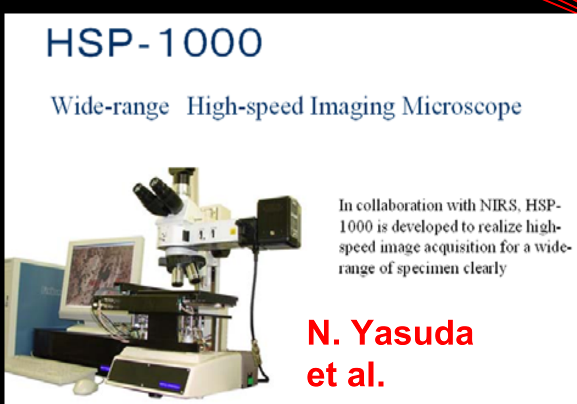
Disadvantages:

- **“Bad” statistics**
  - **… but with a**

    ”High-speed Imaging Microscope”, imaging acquisition can be performed rather fast

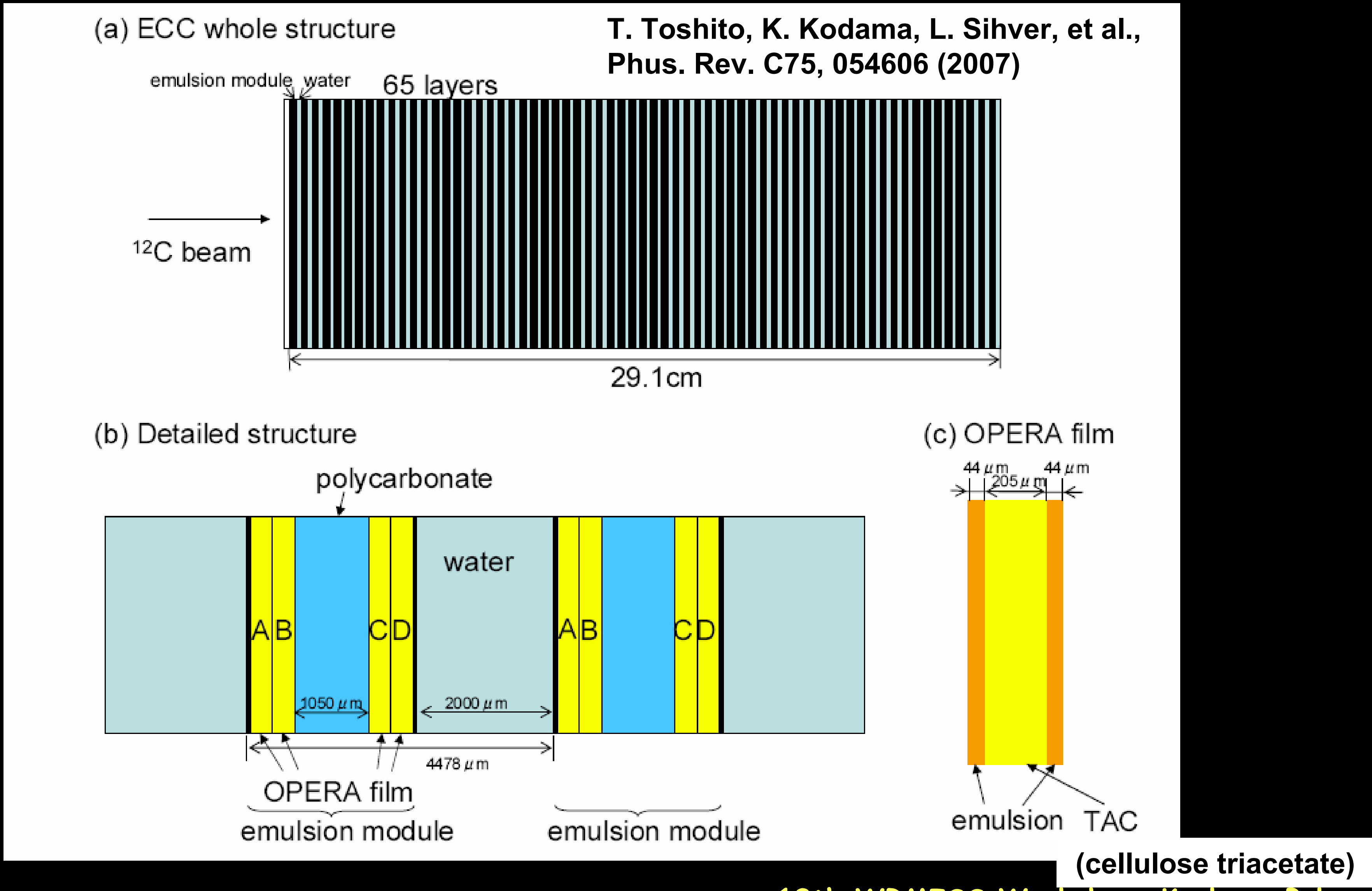






Emulsion Cloud Chamber (ESS)

Can detect framgments up to around Z = 6



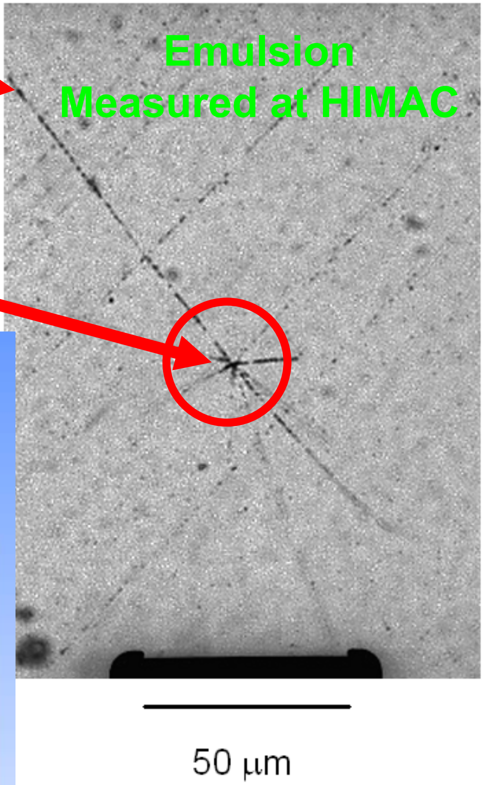
Target fragmentation

- Target fragments are recoil products with short ranges
  - ≈ 1 – 20 μm
  - Same order of magnitude as biological cells
  - High LET → Large local "biological damage"
- At high energies
  - n interacts similar to p, so results from p induced target fragmentation is also relevant for high energetic n

Target fragmentation measured by CR-39 and emulsion !

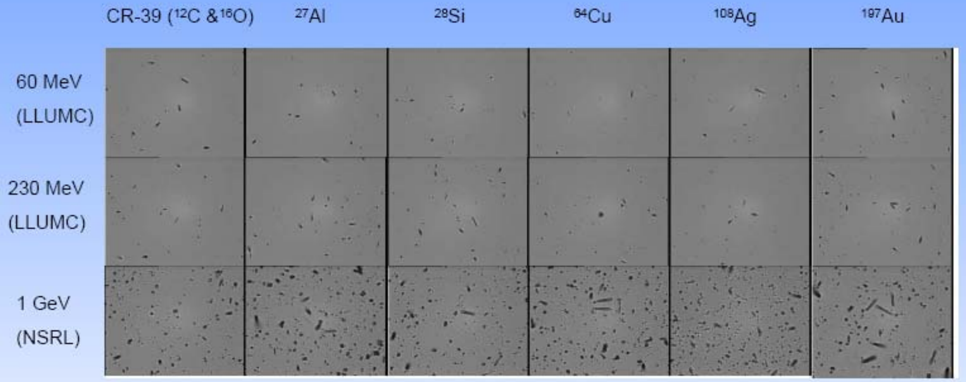
Incident 290 MeV/nucleon C

> 7 - 8 tracks, i.e. target has also broken up



With courtesy to N. Yasuda

Proton-induced Target Fragmentation as functions of Target Z and Energy



All targets/detectors received 50 Gy.

4 hr etch, 1 µm removed, 100 × 80 µm^2

With courtesy to E. Benton

Eril Research, Inc.
25 January 2006

Measurements of neutron energy spectra, at different angles, from thin / full-stop thick targets

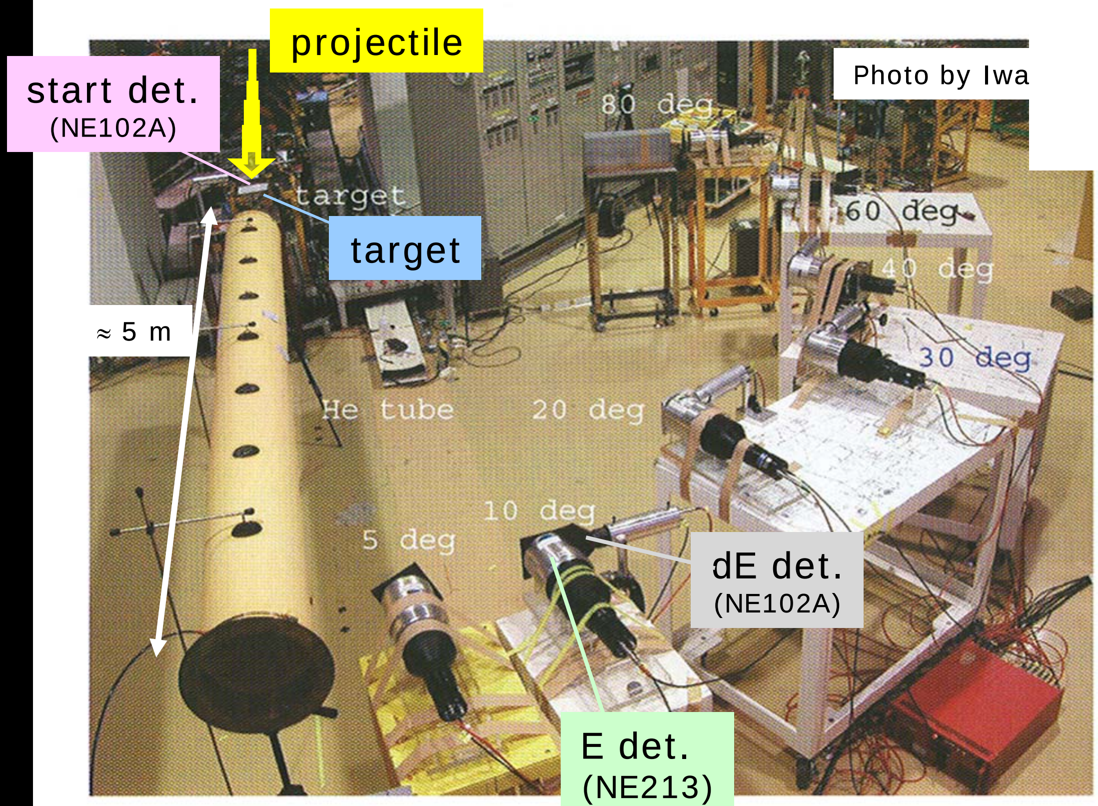
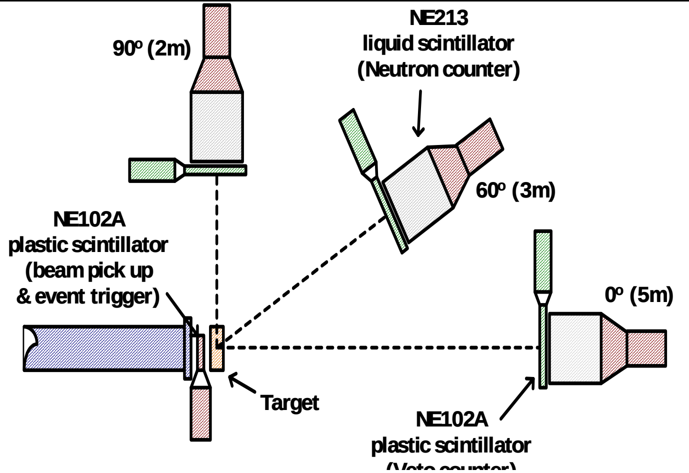
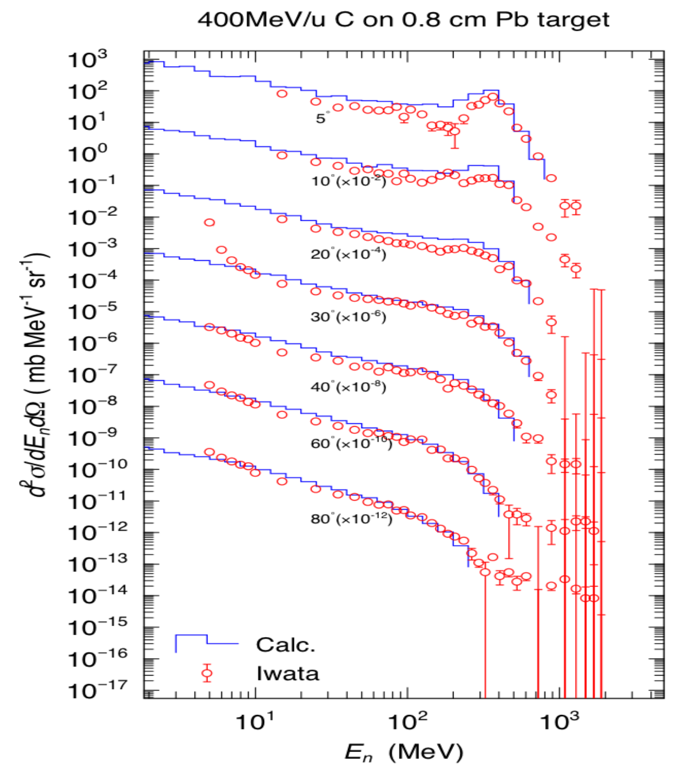


Figure 3.2: General layout of the experimental setup on the SB2 beam line. The yellow tube is a He-filled tube that was used to reduce the background created by beam interactions in air. The picture was taken from the top of the beam dump.





Thick target

Projectile	Energy [MeV/N]	Target	
^{4}He	100, 180	C, Al, Cu, Pb	HIMAC by Kurosawa et al.
^{12}C	100, 180,400	C, Al, Cu, Pb	
^{20}Ne	100, 180,400	C, Al, Cu, Pb	
^{28}Si	800	C, Al, Cu, Pb	
^{40}Ar	400	C, Al, Cu, Pb	
^{56}Fe	400	C, Al, Cu, Pb	
^{126}Xe	400	C, Al, Cu, Pb	
^{20}Ne	337	C, A, Cu and U	BEVALAC by Schimmerling et al.
^{93}Nb	272	Al, Nb	BEVALAC by Heilbronn et al.
^{93}Nb	435	Nb	
^{4}He	155	Al	NSRL by Heilbronn et al.
^{12}C	155	Nb	
^{4}He	160	Pb	SREL by Cecil
^{4}He	180	C, H_2O, steel, Pb	
^{12}C	200	H_2O	GSI by Günzert-Marx et al.
^{12}C	400	H_2O	GSI by Haettner et al.

Thin target

Projectile	Energy [MeV/N]	Target	
^{4}He	135	C, Poly, Al, Cu, Pb	RIKEN by Sato et al.
^{12}C	135	C, Poly, Al, Cu, Pb	
^{20}Ne	135	C, Poly, Al, Cu, Pb	
^{40}Ar	95	C, Poly, Al, Cu, Pb	
^{12}C	290, 400	C, Cu, Pb	HIMAC Iwata et al.
^{20}Ne	400, 600	C, Cu, Pb	
^{40}Ar	400, 560	C, Cu, Pb	
^{4}He	230	Li, C, CH_2, Al, Cu, Pb	HIMAC Heilbronn et al.
^{14}N	400	Li, C, CH_2, Al, Cu, Pb	
^{28}Si	600	Li, C, CH_2, Al, Cu, Pb	
^{56}Fe	500	Li, C, CH_2, Al, Cu, Pb	
^{86}Kr	400	Li, C, CH_2, Al, Cu, Pb	
^{126}Xe	400	Li, C, CH_2, Al, Cu, Pb	

Examples of tested shielding materials

LET and y-distributions, dose and dose equivalents after shielding

Detectors

CR-39, TLD, TEPC, Liulin-4 Mobile Dosimetry Unit (MDU), and Si det.

Materials

Polyethylen
SpectraShield Composite
Fiberglass Composite
pure Fiberglass
pure Epoxy
Al
Graphite
CompositesCarbon Foam
Kapton (polyimide)
Polyethersulfone
Torlon (polyamide-imide)
Polyvinyl chloride
....

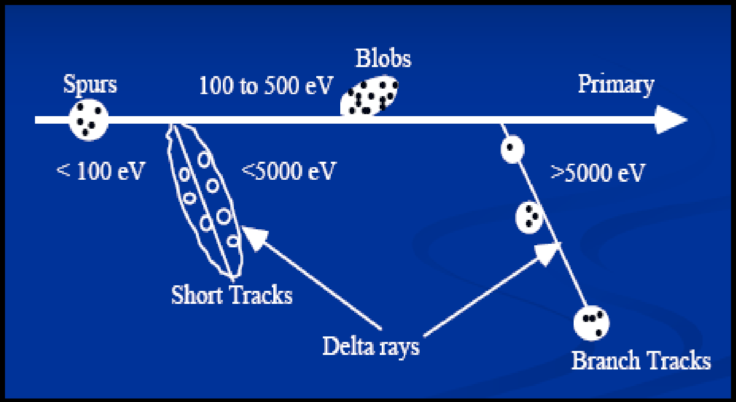
Carbon Composite
Kevlar (aramid) Composit
Nextel Composite
pure Kevlar
Polyethylene
H2O
Carbon & Fiberglass
Ultem (polyetherimide)
Polysulfone
Radel R (polyphenylsulfone)
Teflon (polytetrafluoroethylene)
Nylon (polyamide)

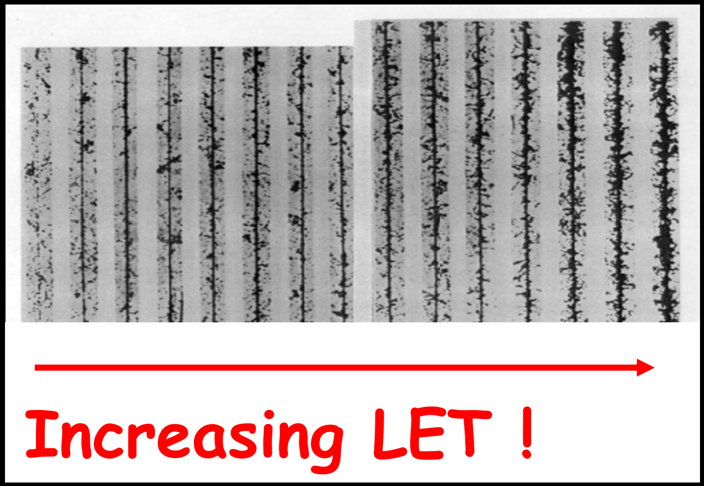
What is still missing ??

Still to be done for model & code verification:

1. Production and transport of delta rays

- Lineal energy distributions before and after shielding
- Clustering (multiply locally damage sites)
  - ✓ Large effects on subsequent chemistry, biochemistry, and the production of biologic lesions
- More information about the *low energy delta rays, close to the track core* is needed !





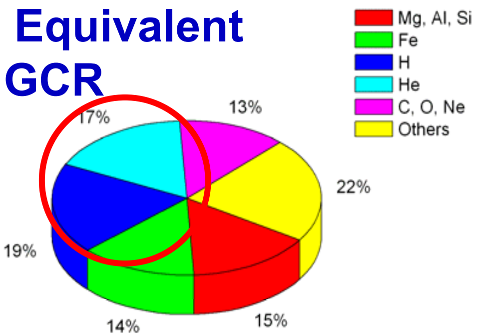
Still to be done for model & code…:

2. Inclusive measurements

- **Missing σ_{frag} e.g. of 0.2 – 2 GeV/N He**
  - BNL/NSRL can not yet accelerate He, but soon..?
  - HIMAC goes only up to 230 MeV/N for He
- **Precise measurements of σ_{reac} (tot)**
  - Including all final states

Ion	Energy (MeV/nucleon)							
^{56}Fe	400	500	600	800	1,000	3,000	5,000	10,000
^{48}Ti					1,000			
^{40}Ar	290	400	650					
^{35}Cl			650		1,000			
^{28}Si	290	400	600	800	1,200	3,000	5,000	10,000
^{24}Mg		400						
^{20}Ne	290	400	600					
^{16}O	290	400	600		1000			
^{14}N	290	400						
^{12}C	290	400				3000	5000	10000
^{11}B		400						
^{10}B		400						
^{4}He	230							

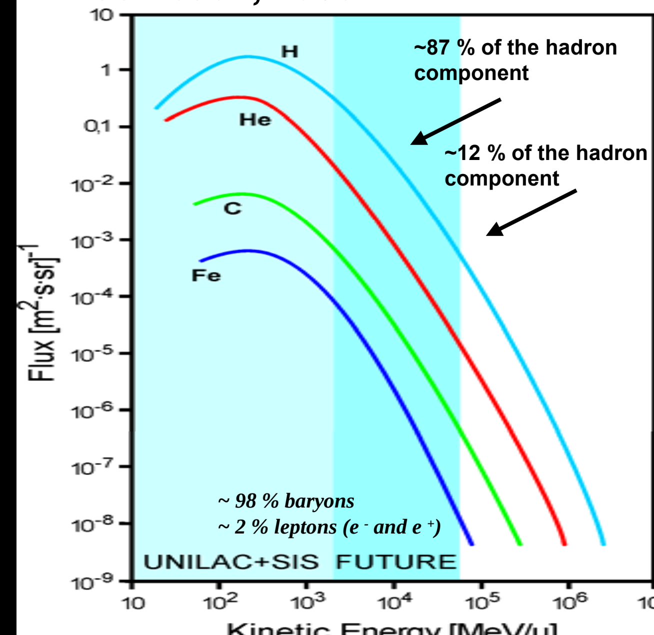
Dose Equivalent from GCR



HZE particles important because D ∝ Z^2, but of course also p and α !

At solar minimum behind 2 cm Al shielding

Wilson et al., 1985



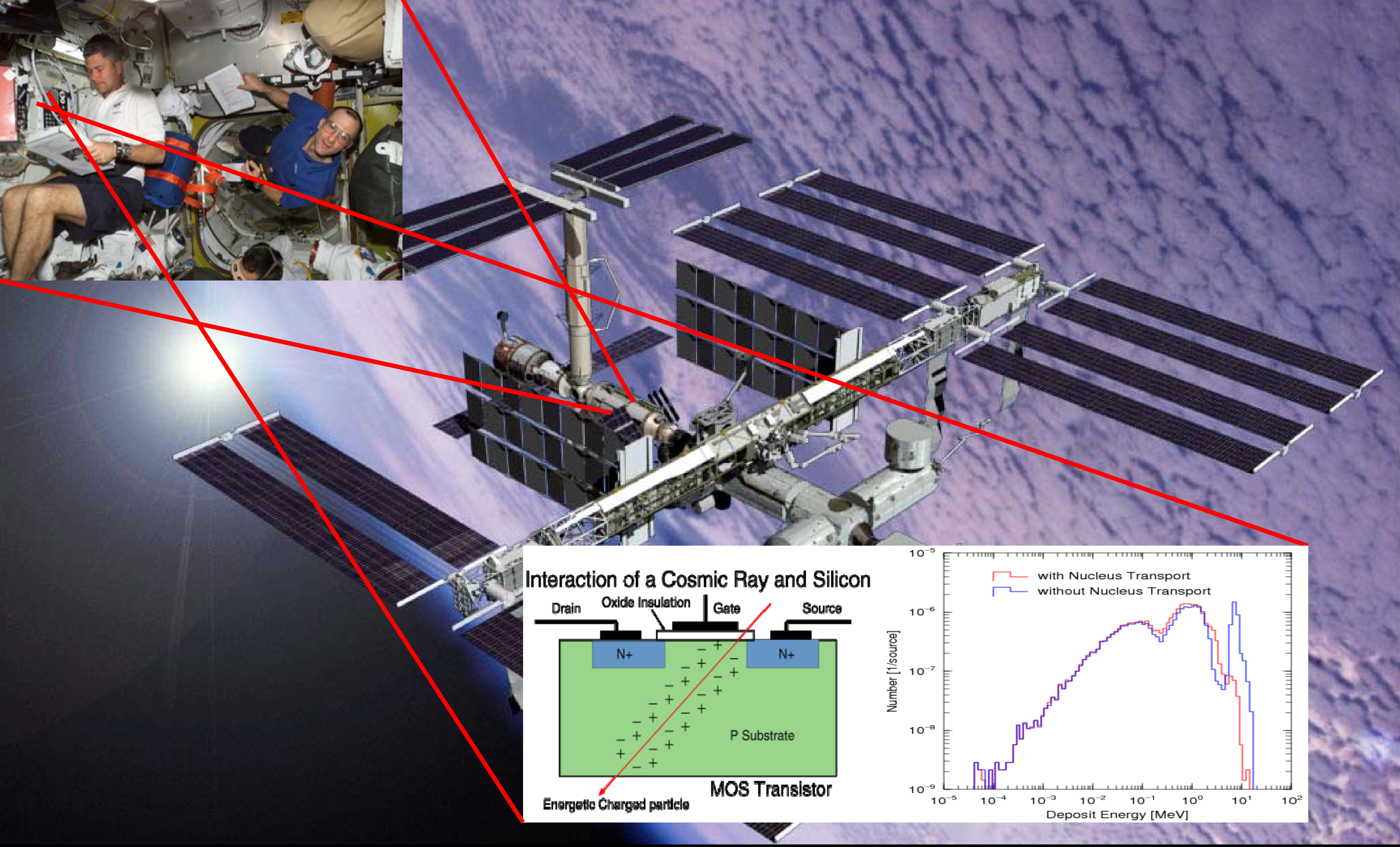
Still to be done for model & code verification (cont.):

3. Semi-inclusive measurements

- Cross Sections
  - Differential and double differential (E and Θ)
    - ✓ Projectile fragmentation
    - ✓ Production of evaporation residues and light fragments
    - ✓ Target fragmentation
- Multiplicity distributions of secondary particles
- Coincidence measurements
  - E.g. pions + projectile fragments

Still to be done for model & code verification (cont.):

4. *Differential cross sections for ionization by heavy ions*
   - *Energies below which electron capture become important*
     - ✓ *Representative of the slowing down of GCR in different material*
5. *LET, fluence, dose and dose eq. distributions after new shielding materials*



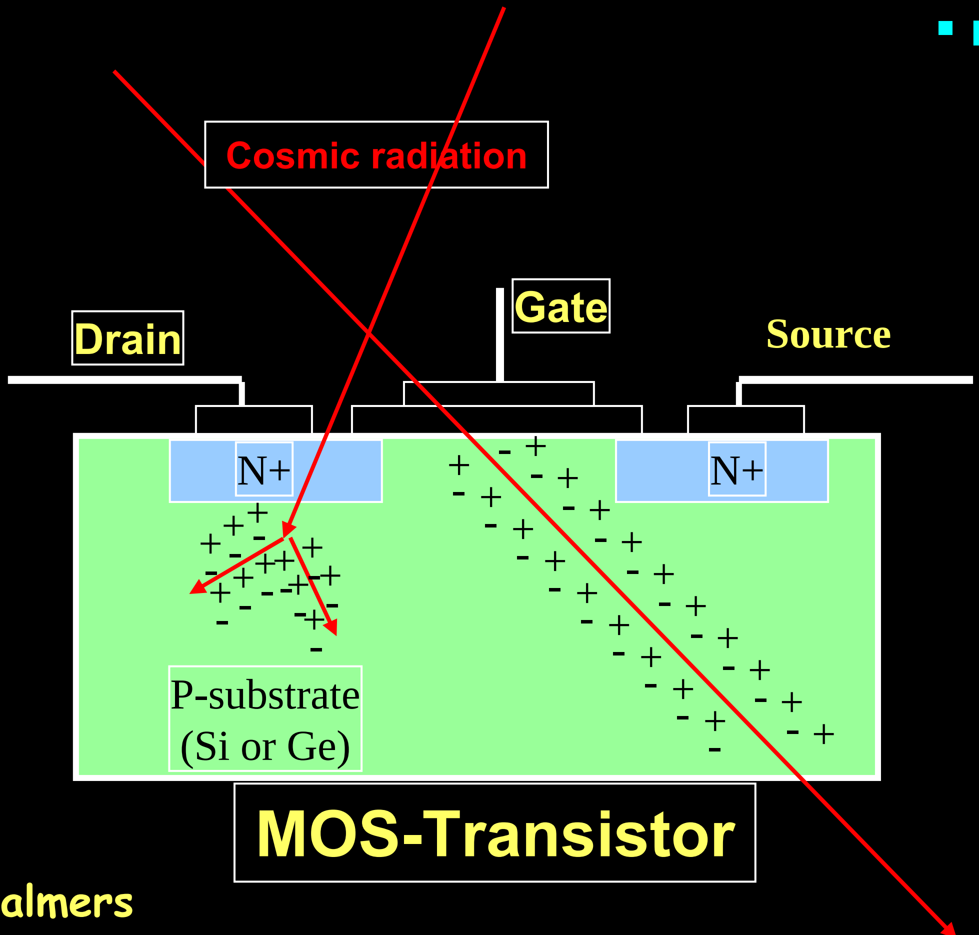
Single Event Effects (SEE) in electronic devices

- E_{mean} needed to create an e^- - hole pair in Si: 3.6 eV
- Depth of the $V_{sensitive}$ ≈1 µm → ionization of ≈ 1 MeV/ µm is required

To simulate the SEE the following exp. data are important

- **Double diff. cross sections (E and Θ) of**
  - light projectile fragments
  - heavy recoil target fragments

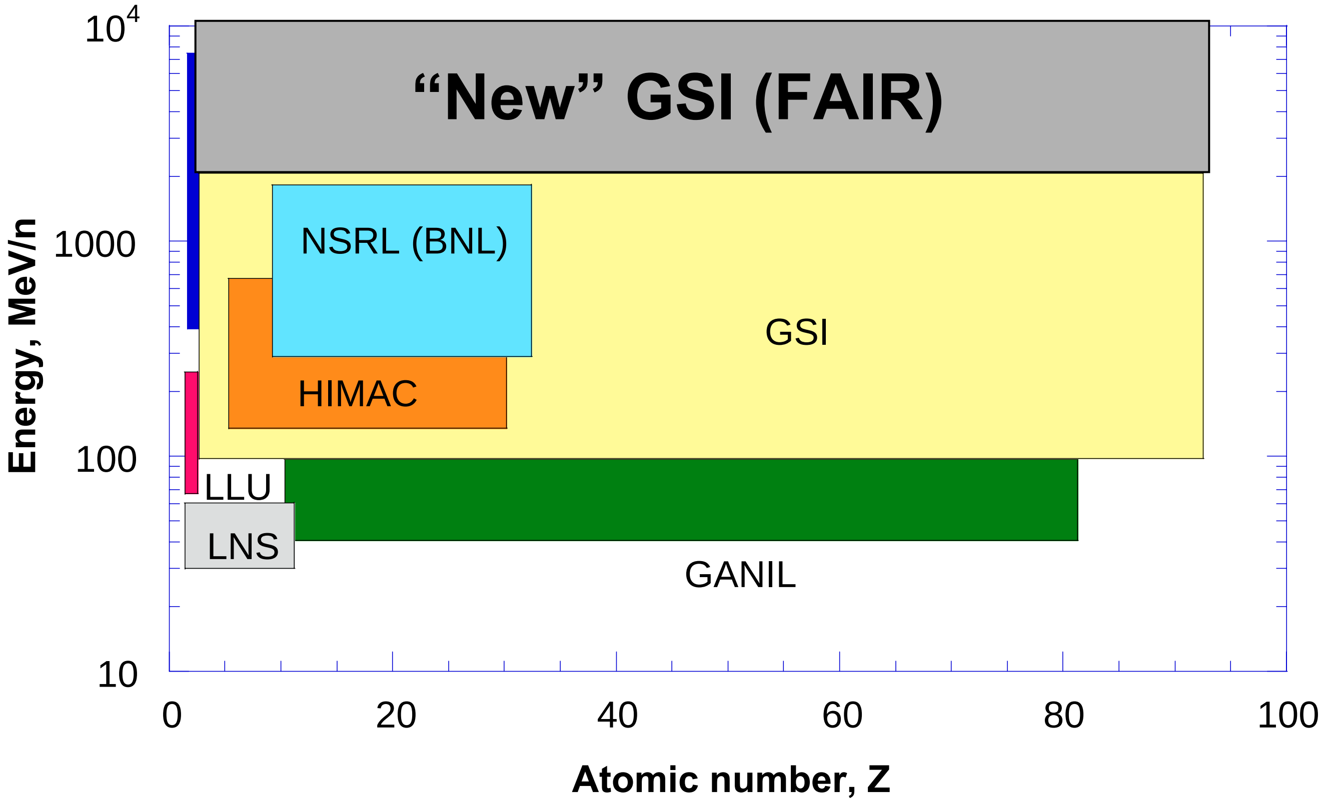
from reactions of ≈ 20 - 150 MeV/N n, p and heavy ions in Si, Ge, etc.



- **n+ H.I. elastic scattering data**
  - to determine the optical potentials involved, i.e. the effective interaction between a neutron and a nucleus, which are used in σ_n calculations

Accelerator requirements / Available Accelerators

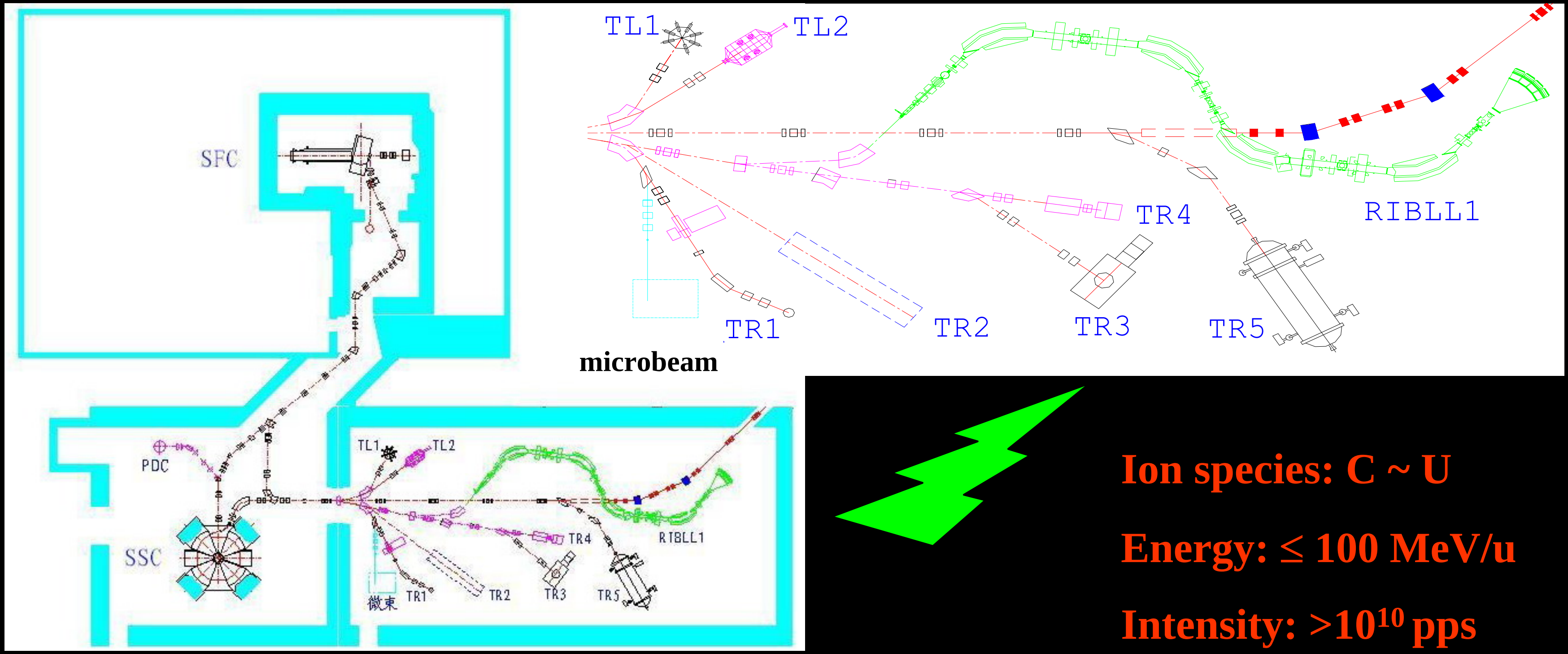
- Accelerate ions at least from He to Fe with E ≈ 100 – 2000 MeV/N
- Have "available" beam time
- ...



Institute of Modern Physics (IMP), Chinese Academy of Sciences (CAS)

Heavy Ion Research Facility in Lanzhou (HIRFL), China

Overall layout of the HIRFL



Ion species: C ~ U

Energy: ≤ 100 MeV/u

Intensity: >10^{10} pps

Heavy Ion Accelerators @ IMP (cont.)

HIRFL-Cooling Storage Ring (CSR):
Main synchrotron ring (CSRm)
Experimental ring (CSRe)

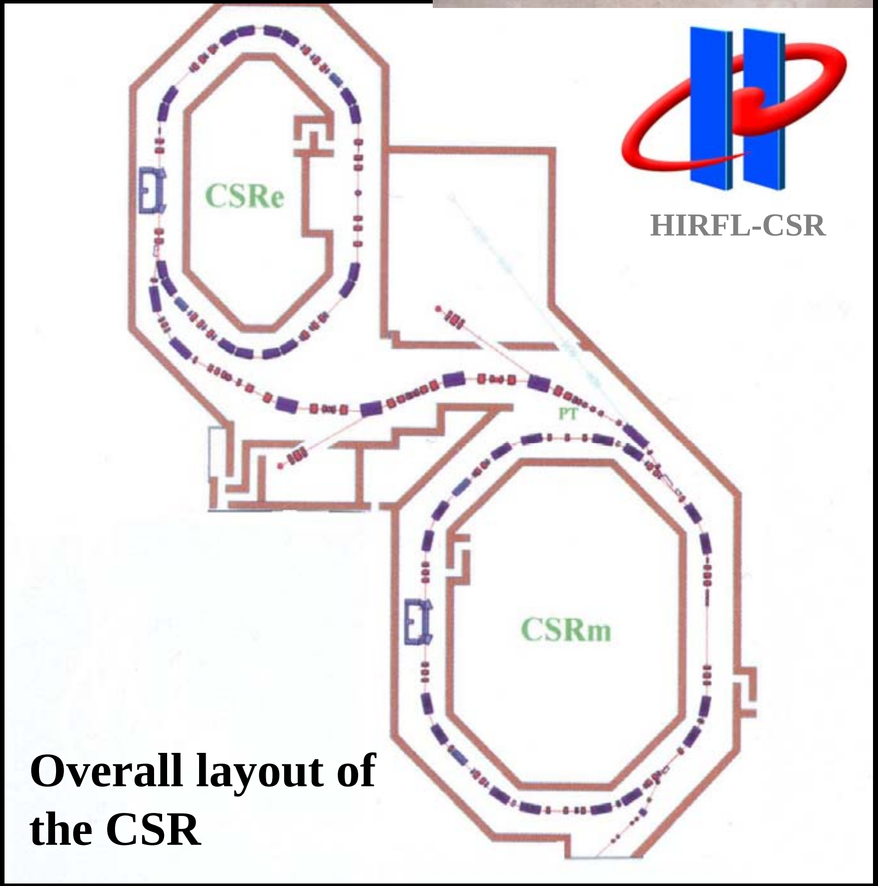
Now under operation:

Ion species: C ~ U

$E_p \leq 1$ GeV/u for C

Intensity ≤ 1 mA

Intensity: $10^5 \sim 10^8$ ppp



Overall layout of the CSR

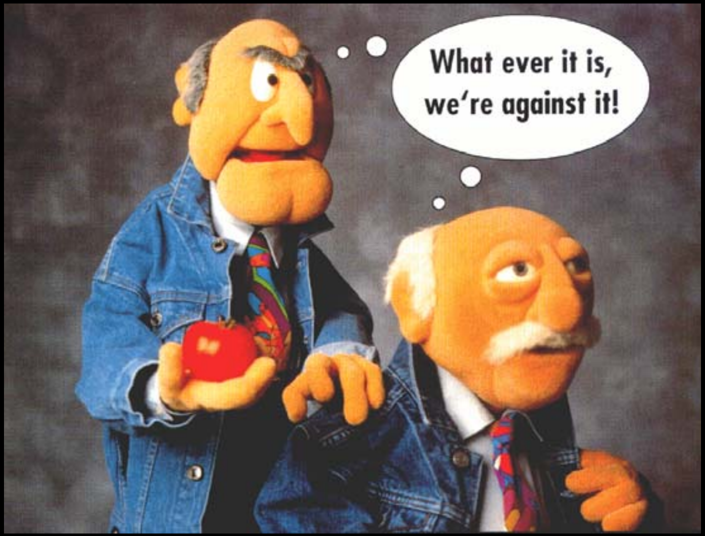
Summary and Conclusions

- Much has been done

….but more needs to be done,

even if not everybody agree to that !

- To improve Risk Assessments for
  - Humans
  - Electronics



Physics models and transport codes need to be benchmarked & validated !!!

More and different experiments must therefore be performed !

Acknowledgements

PHITS collaboration

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Cary Zeitlin

Jack Miller

Lawrence Heilbronn

Günther Reitz

Larry Townsend

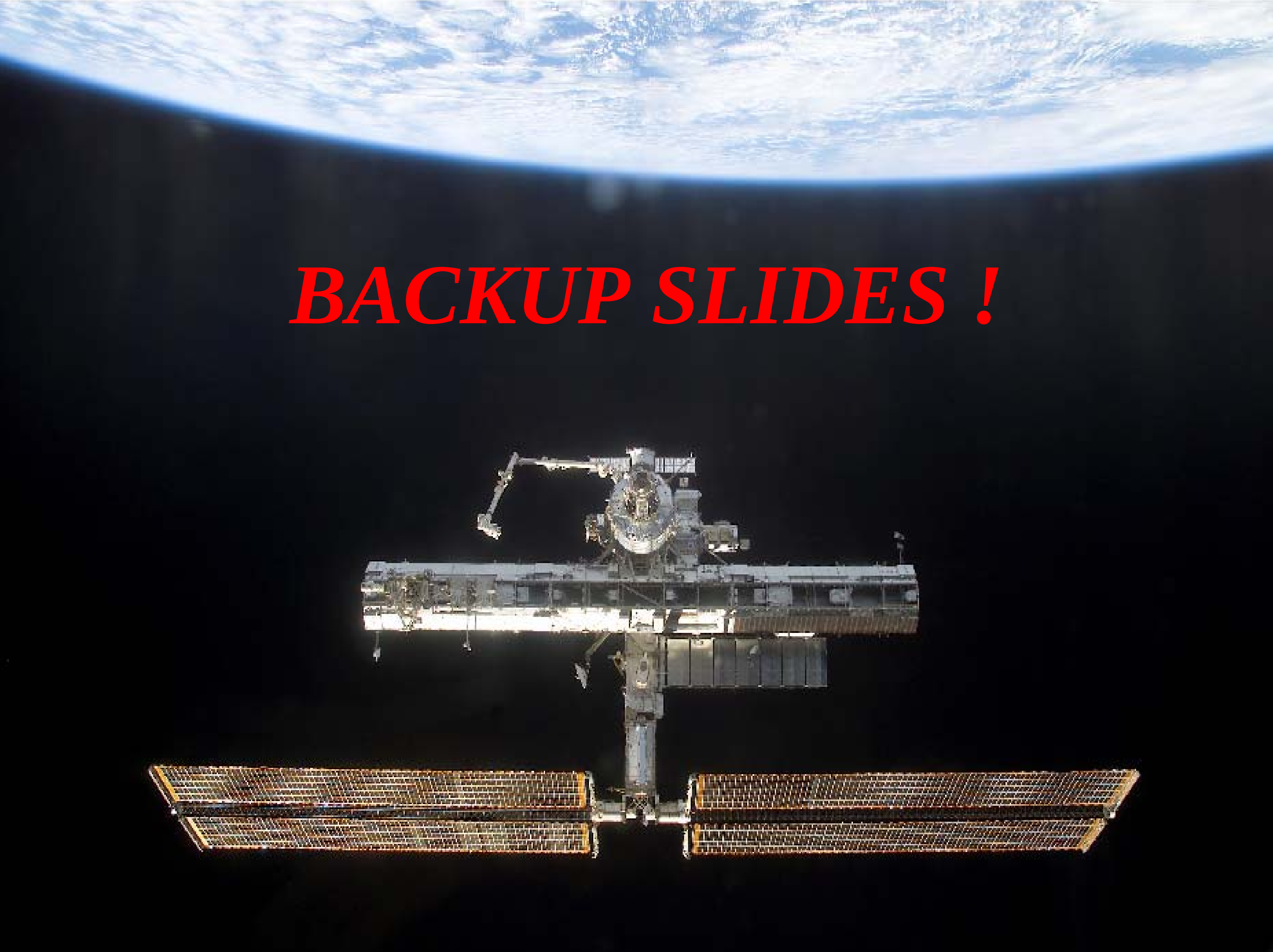
Toshiyuki Toshito

Qiang Li

...

Thank you !!!!!!


Thank you very much for your attention!!!


BACKUP SLIDES !

Cross Sections Measurements

- Inclusive
  - E.g. charge changing cross sections
    - Break up of He between 200 and 2000 MeVN !
- Exclusive
  - When there are distinctions made as how the fragment "F" is produced, e.g. as to what comprises "X"
- Semi-inclusive
  - When some but not all components ("final states") of "X" are measured

Off-axis measurements (differential cross sections)

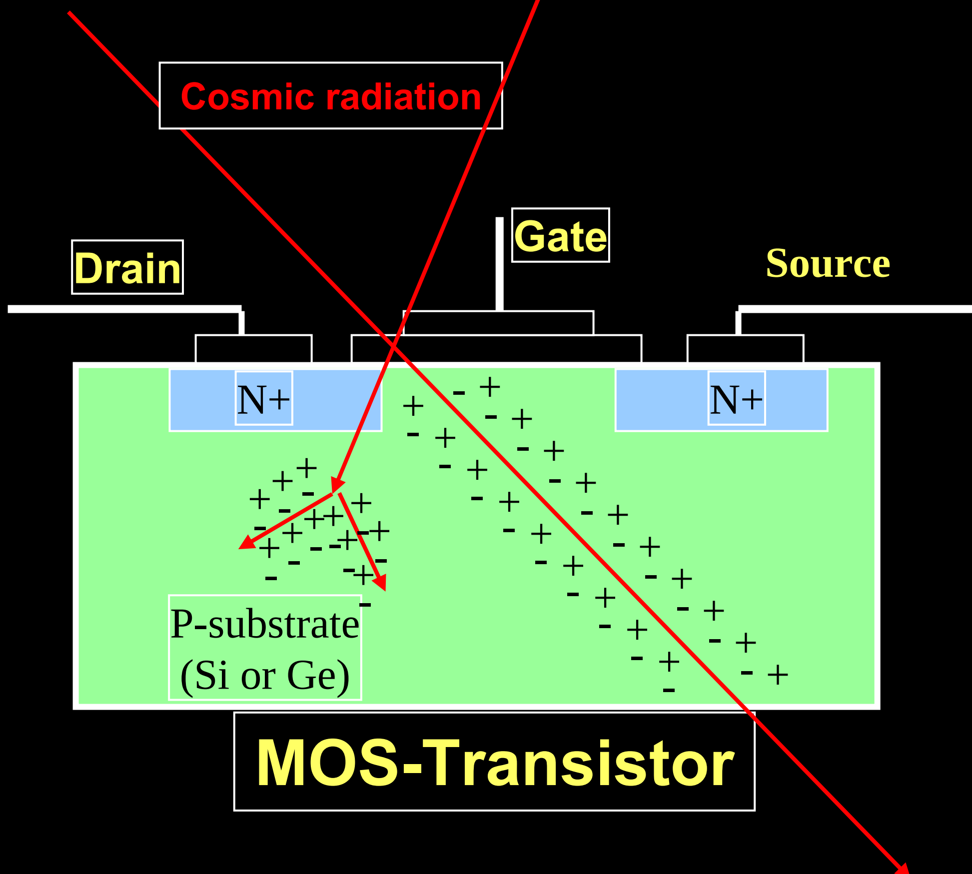
4. Production of evaporation residues and light fragments

Double differential cross sections

Energy and angle

The average energy needed to create an electron-hole pair in Si is 3.6 eV

⇒ Critical charge (Q_C) to casue a SEU: < 10 fC in modern SRAMS
⇒ Min. deposition in to cause a SEU: ≈ 10 fC * 3.6 / 1.6 * $10^{-19} = 0.2$ MeV
⇒ Assume depth of the sensitive volume ≈1 µm → ionization of ≈ 1 MeV/ µm is required
⇒ … but the distances are decreasing all the time



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6. Double diff. cross sections (energy and angle) of the produced
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   from reactions of ≈ 20 - 150 MeV/N n, p and heavy ions in Si, Ge, etc.

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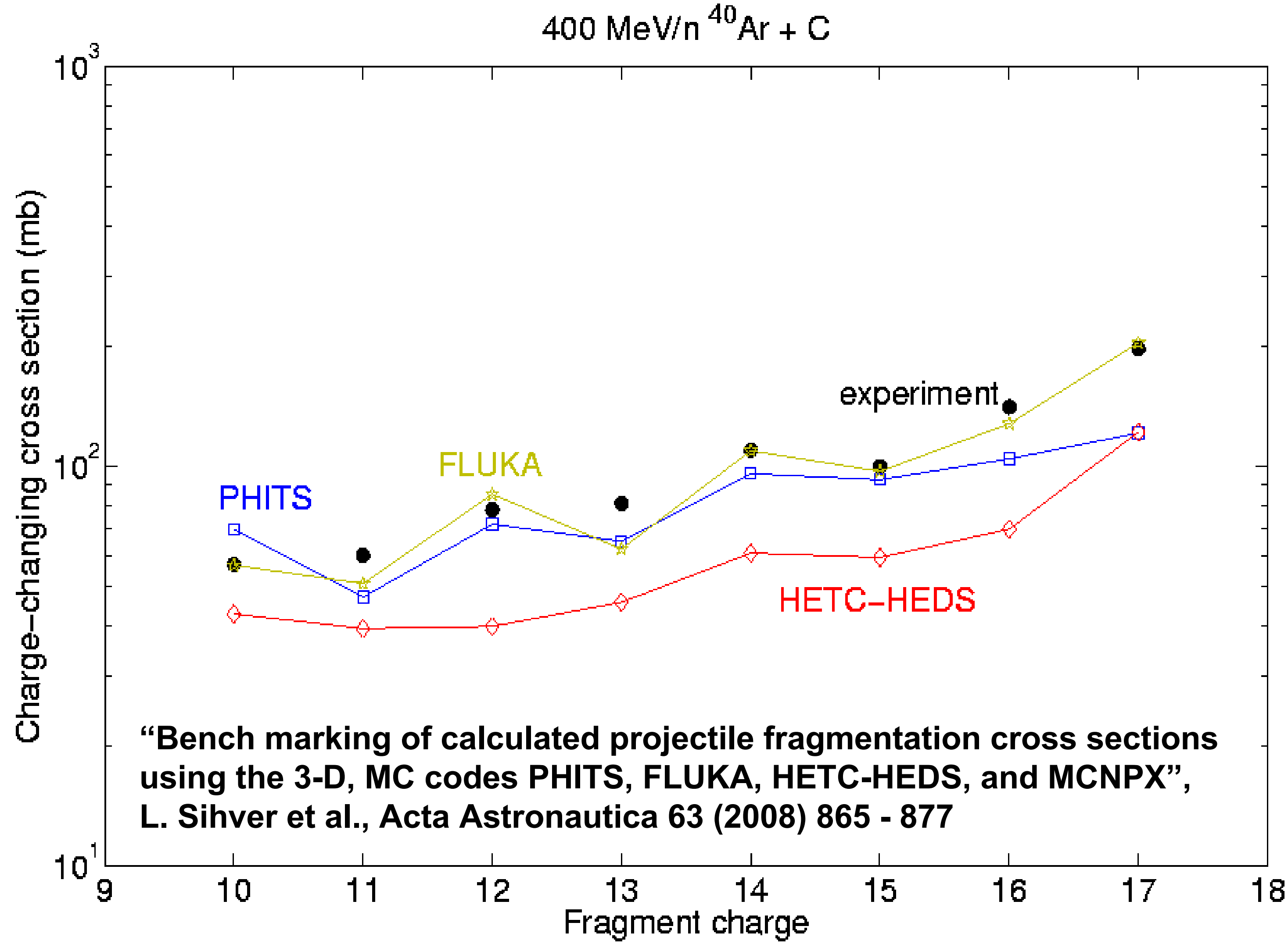
   - ➢ to determine the optical potentials involved, i.e. the effective interaction between a neutron and a nucleus, which are used in n cross section calculations

RESULTS



"Bench marking of calculated projectile fragmentation cross sections using the 3-D, MC codes PHITS, FLUKA, HETC-HEDS, and MCNPX", L. Sihver et al., Acta Astronautica 63 (2008) 865 - 877