# Highlights From The SEPTIMESS Project

Fan Lei
on behalf of the SEPTIMESS collaboration

11-05-2004

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# SETPTIMESS

## Space Energetic Particle Transport and Interaction Modelling for ESA Science Studies

An ESA funded project (Contract No. 16339/02/NL/FM)

- Consortium:
  - QinetiQ: prime contractor
  - Imperial College
  - University of Southampton
  - INFN (Genova)/CERN
  - University of Geneva
  - University of Burn
- Started in 09/02, and last for 30 months.

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# Key Personnel

- ESTEC/ESA:
  - Petteri Nieminen
- QinetiQ:
  - Fan Lei, Pete Truscott, Clive Dyer, Ramón Nartallo
- Imperial College:
  - Henrique Araújo, Peter Wass, Alex Howard, Tim Sumner
- University of Southampton:
  - Dave Wallis, Tony Bird, Tony Dean
- INFN (GE)/CERN:
  - Maria Grazia Pia, Sussana Guatelli, Andreas Pfeiffer
- University of Geneva:
  - Vladimir Grichine, Simone Gilardoni, Alain Blondel
- University of Bern:
  - Laurent Desorgher, Erwin Flüeckiger

# Main Study Objectives:

- Review the potential energetic particle radiation effects on payloads of future ESA missions, science missions in particular.
- Identify radiation transport analysis requirements to quantify those effects and thereby reduce risks for these missions.
- Develop Geant4 based applications for quantifying the specific radiation effects.

# Main Activities (I):

Review of radiation effects to future ESA science missions:

- Radiation environments
- Radiation as background noise and potential damage to the scientific instruments
- Possible method for quantifying such effects

Status: completed

# Major Activities (II):

Geant4 Developments:

- Low energy proton scattering at grazing incident angles: G4FirsovScattering (completed).
- Improvements to Atomic relaxation and Radioactive decay physics (on-going).
- Utilities and tools:
  - Hadron data format and data set (completed).
  - Statistic testing toolkit (completed).
  - Design iteration of G4GeneralParticleSource (completed).

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# Major Activities (III):

- Mission specific Geant4 simulations
  - XMM-Newton (completed)
  - INTEGRAL (on-going)
  - LISA (completed)
  - SMART-2 (completed)
  - Bepi-Colombo (completed/on-going)
- Other Geant4 applications
  - Atmocosmics (completed)
  - Magnetocosmics (completed)
  - Advanced Example on Radioactive Decay (on-going)

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# List of Missions Reviewed

- Mercury Orbiter/Bepi-Colombo
- Solar Orbiter
- GAIA
- LISA
- Eddington
- Darwin
- XEUS
- FIRST-Herschel
- Planck
- Rosetta
- JWST
- SMART-1
- Mars Express
- Galileo (GSTB)

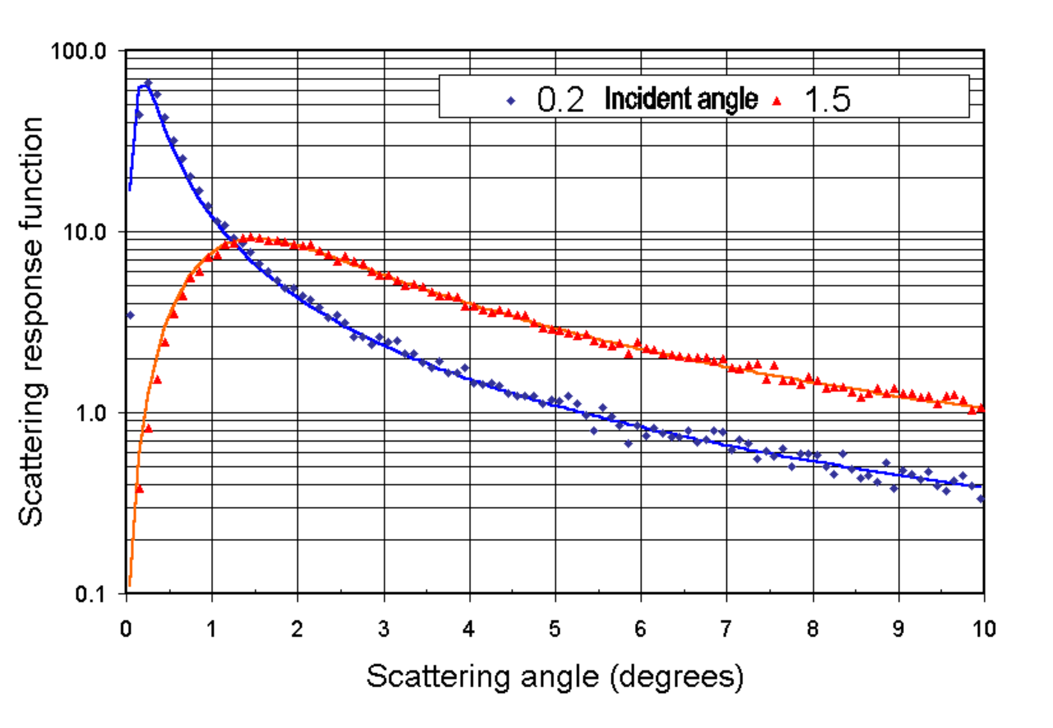
Technical Report: http://reat.space.qinetiq.com/septimess/septimess_docs.html

# G4FirsovScattering: proton scattering at incidence angles

Firsov formulated the scattering angle distribution for grazing incidence ions in the 60's (Soviet Physics – Doklady, Vol. 11, No. 8, 1967)

$$p(\varphi,\theta) = \frac{3}{2\pi}\frac{(\varphi\theta)^{3/2}}{\varphi(\varphi^3+\theta^3)}$$

where φ is the proton incident angle and θ the scattering angle

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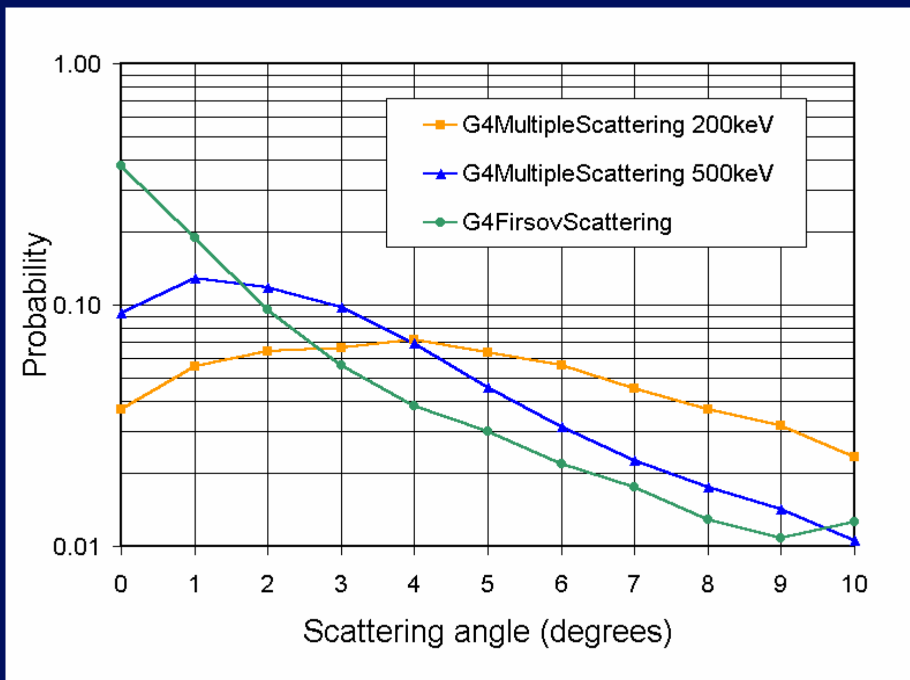
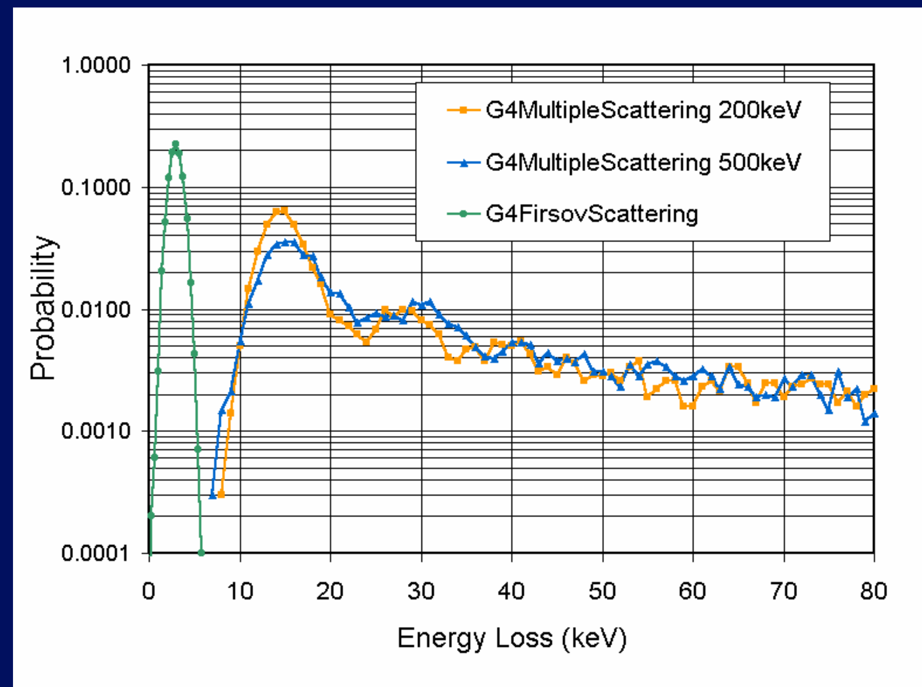
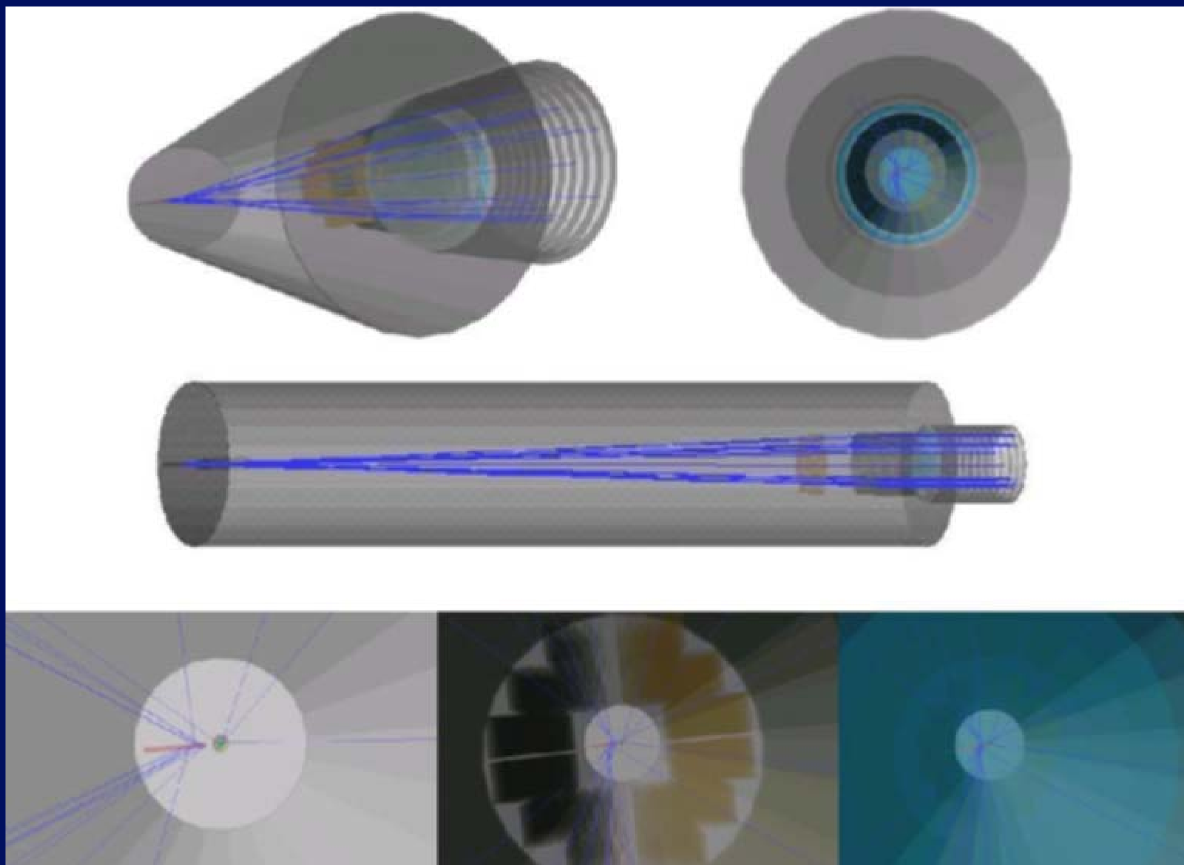
# G4FirsovScattering vs G4MutilpleScattering




Incident angle randomly distributed between 0 - 1 degree

# XMM-Newton revisited: geometry



Introducing
G4SurfaceProperty to
The mirror surface

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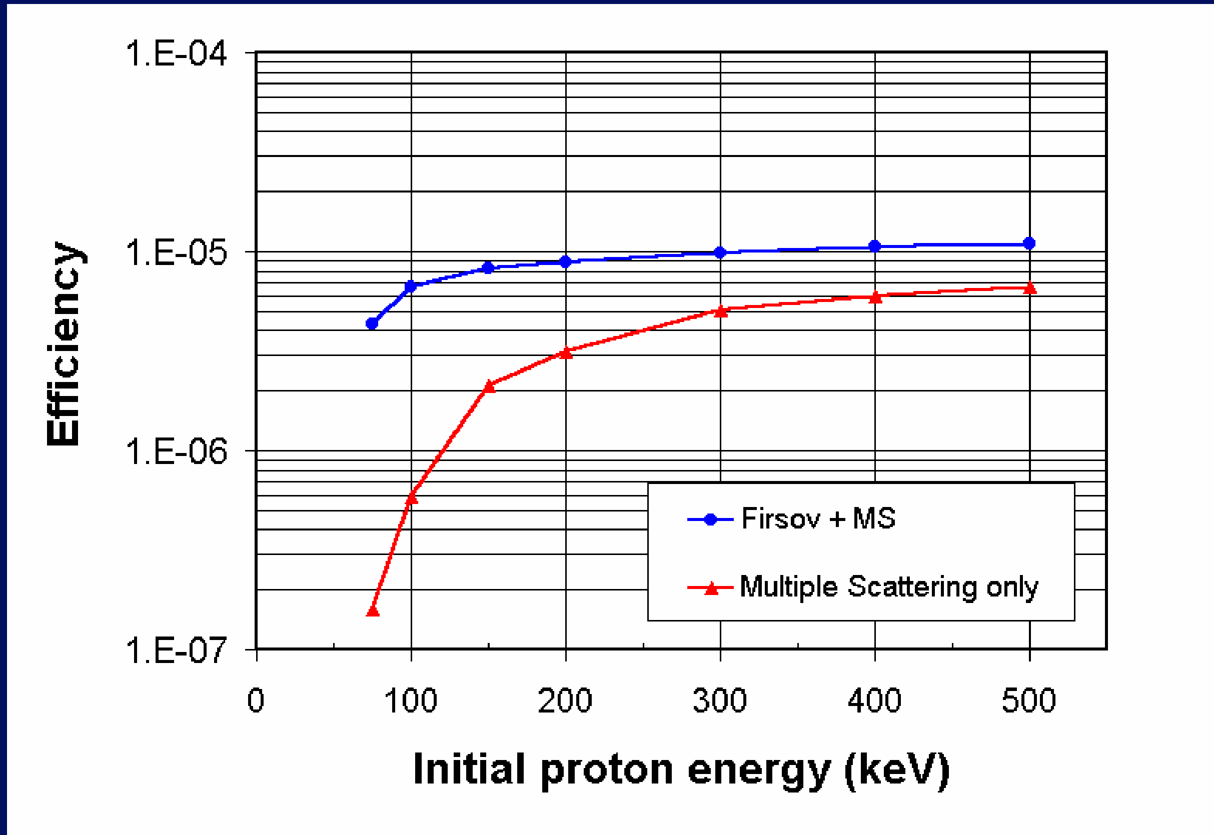
# XMM-Newton: proton propagation efficiency




$$\eta = \frac{\Omega}{4\pi}\left(\frac{A_{source}}{A_{detector}}\right)\left(\frac{N_{detected}}{N_{incident}}\right)$$

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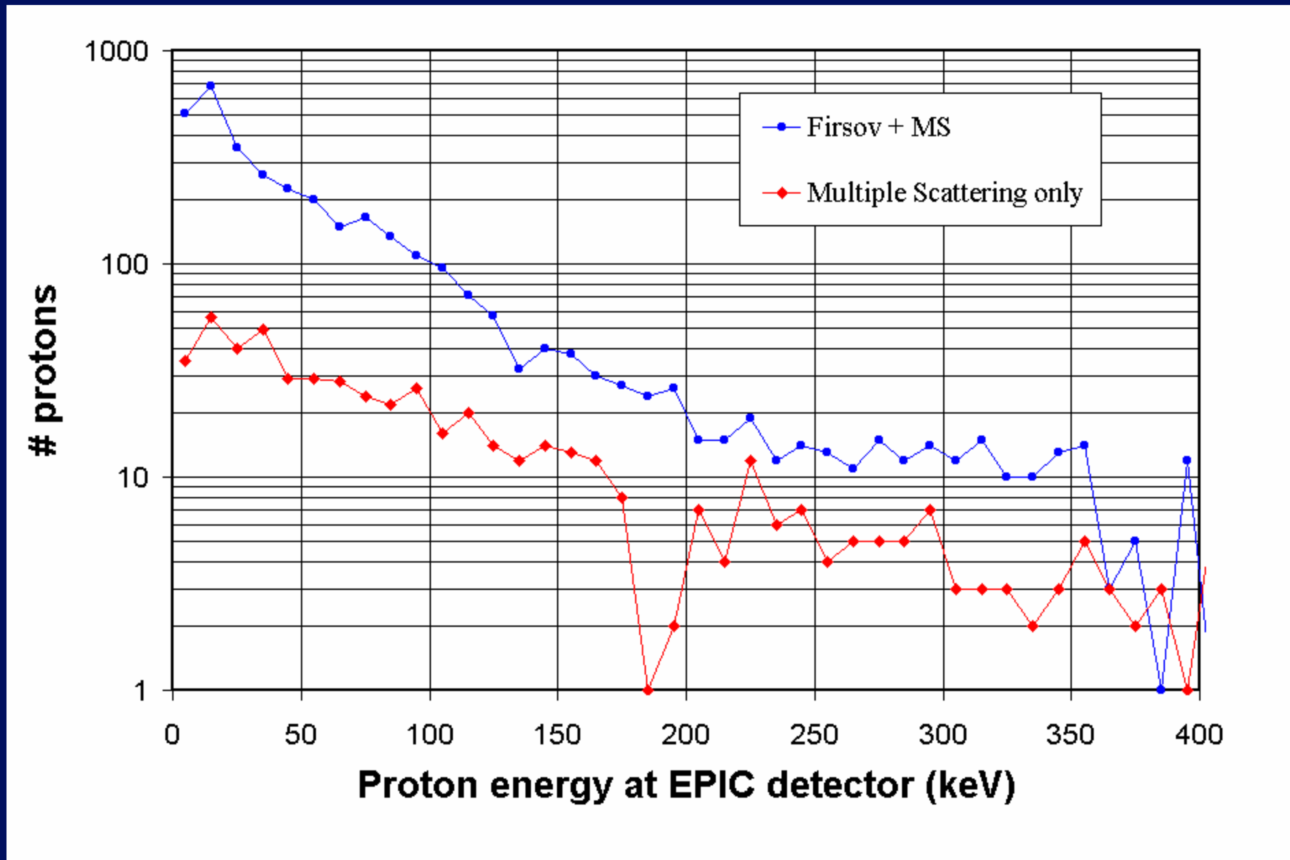
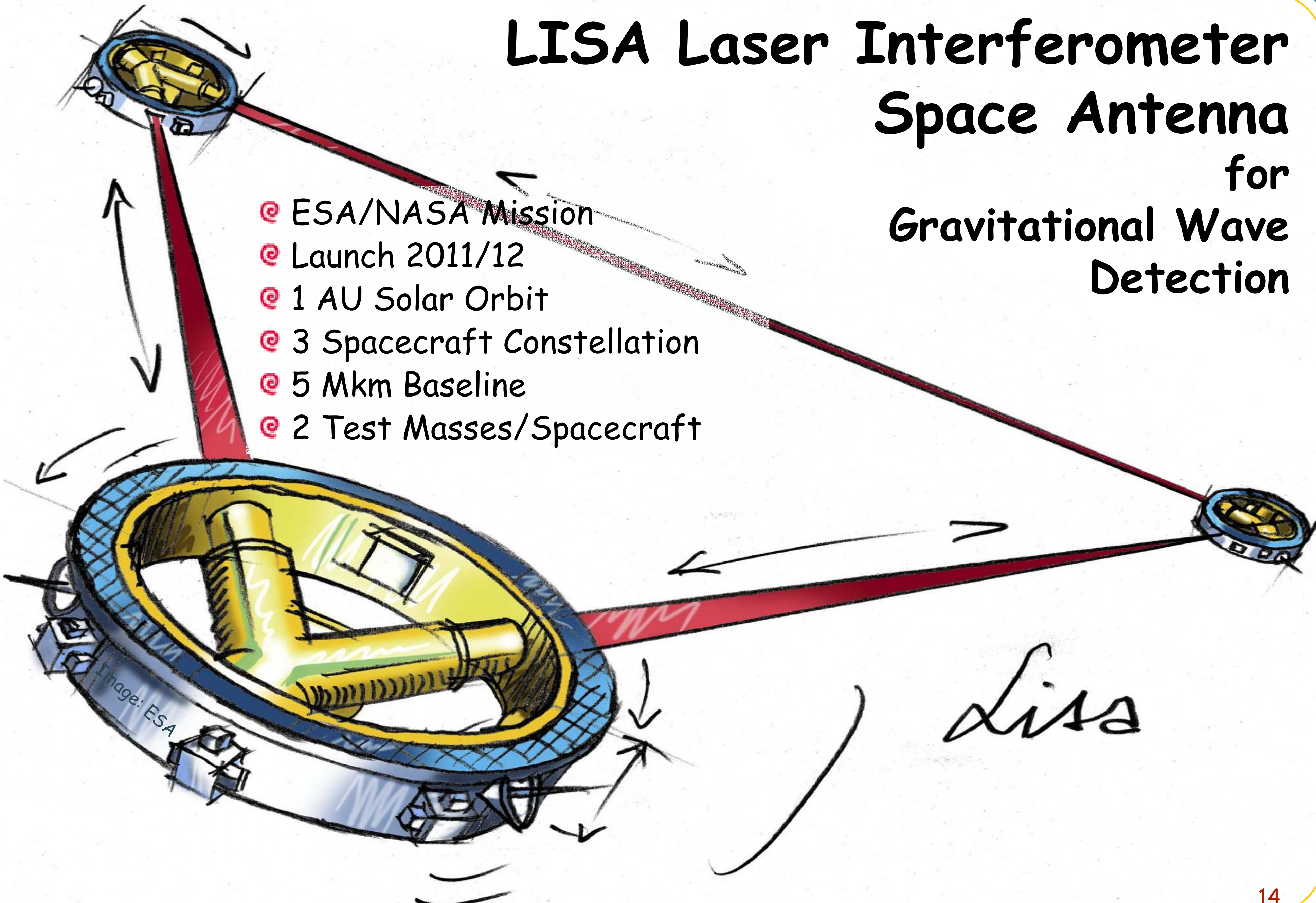
# XMM-Newton: EPIC proton spectrum




New result is ~ 5x higher @ 100 keV

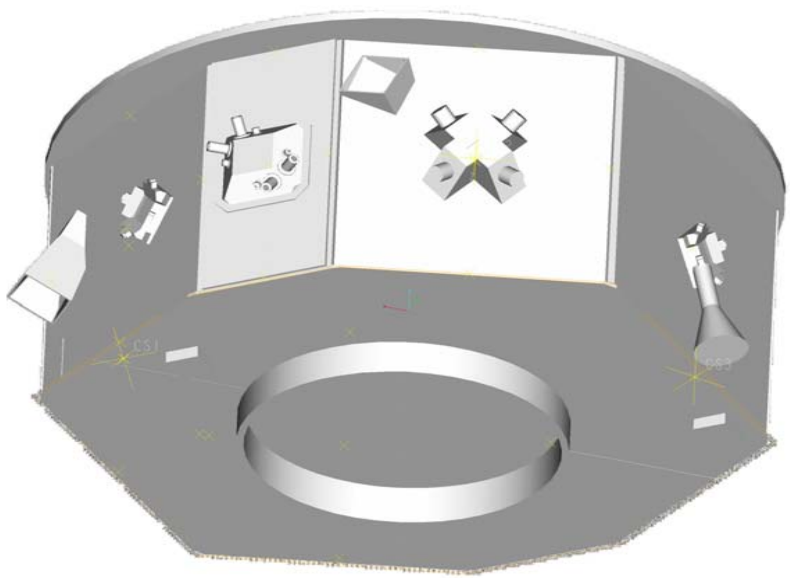
# LISA Laser Interferometer Space Antenna for Gravitational Wave Detection

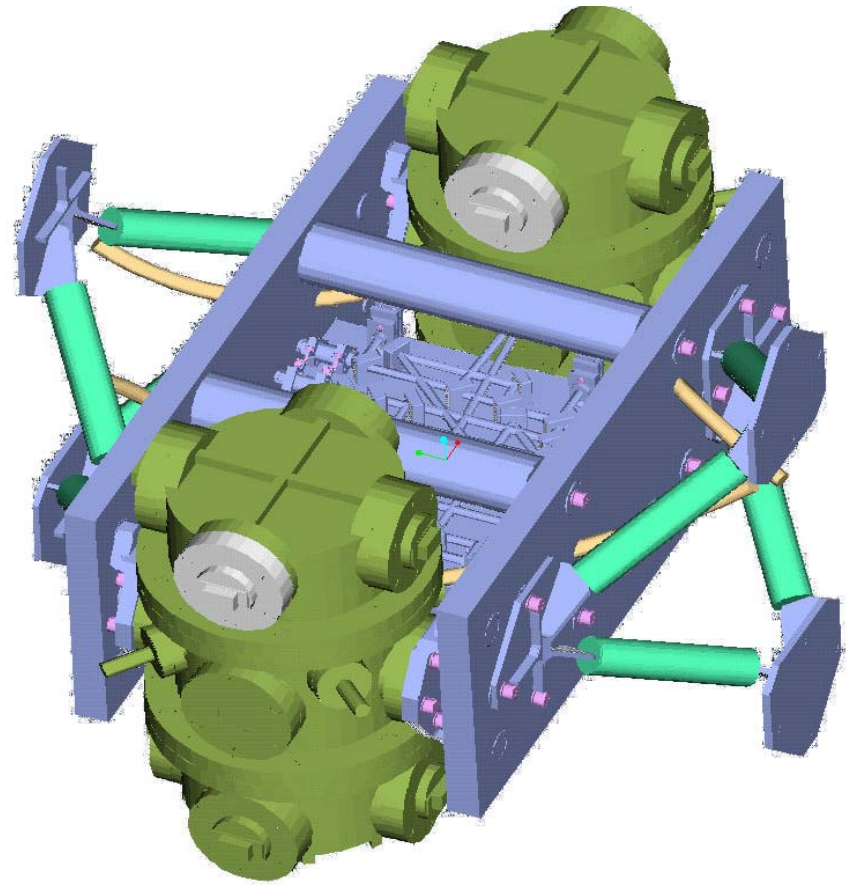
- ESA/NASA Mission
- Launch 2011/12
- 1 AU Solar Orbit
- 3 Spacecraft Constellation
- 5 Mkm Baseline
- 2 Test Masses/Spacecraft



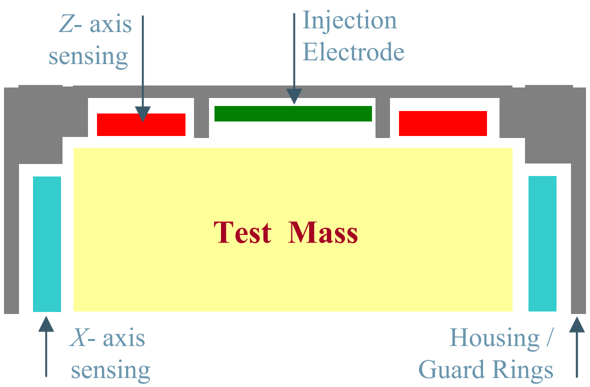
# LISA Pathfinder (SMART-2)

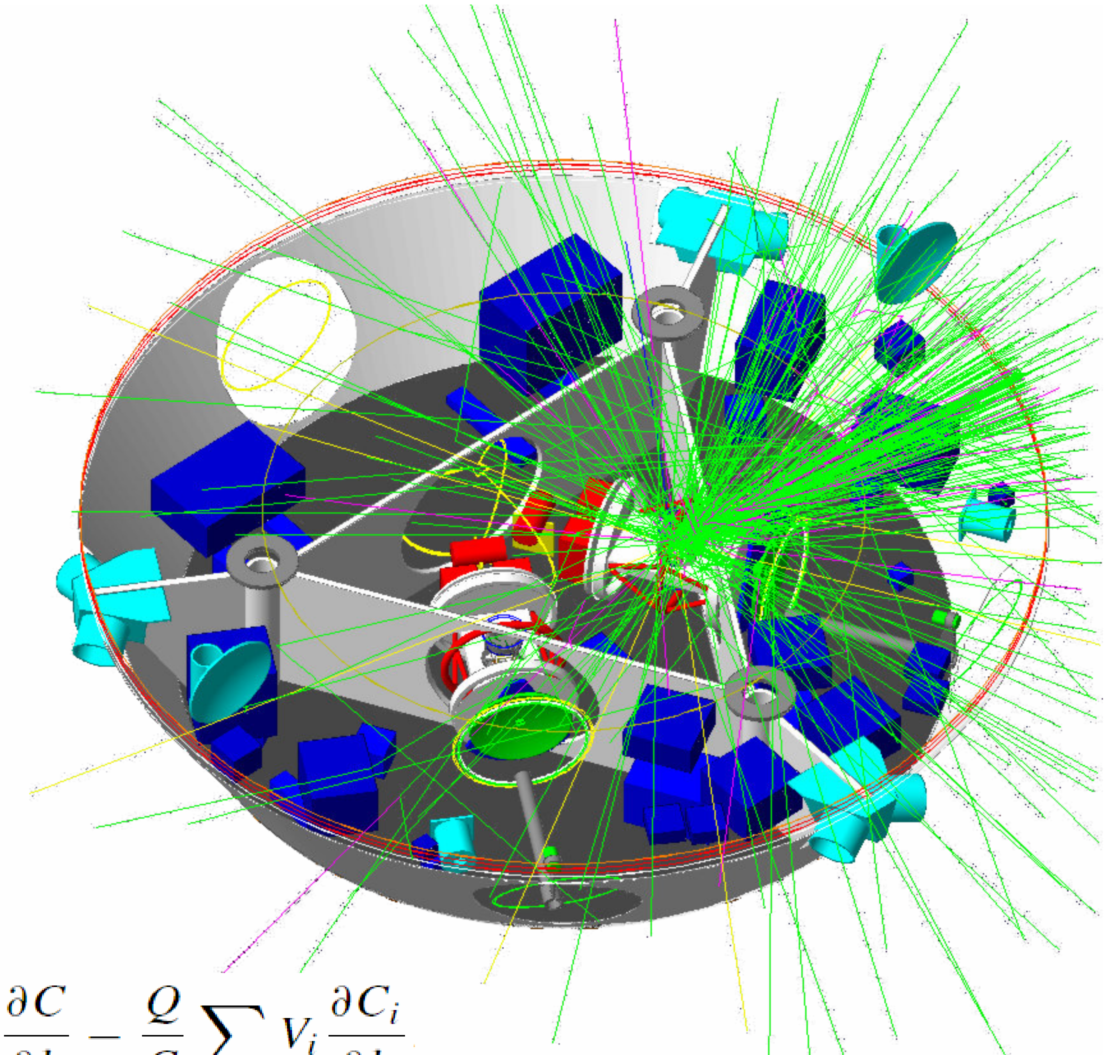
- Drag-Free Technology Demonstrator
- L1 Libration Point
- 2 Test Masses, 30 cm apart
- LTP (ESA) + DRS (NASA) Sensors
- Launch 2007
- UV photoelectric discharging





# Test-Mass Charging



- **Requirements** (0.1 mHz—0.1 Hz)
  - Accel. noise $< 4\times10^{-16}$ m/s$^2$/Hz$^{1/2}$
  - Pos. accuracy $< 1\times10^{-9}$ m/Hz$^{1/2}$
  - TM attitude $< 4\times10^{-7}$ rad/Hz$^{1/2}$

- **Lorentz forces**

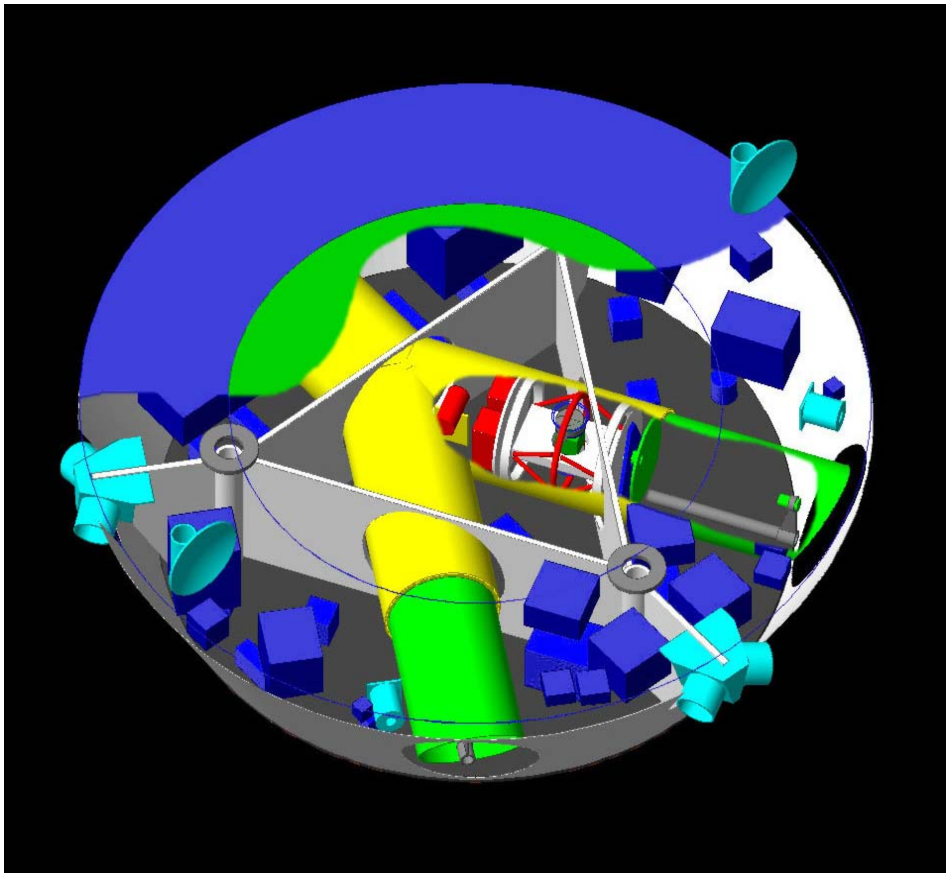
$$\mathbf{a} = \frac{\dot{\bar{Q}}t}{m}\mathbf{v}\times\bar{\mathbf{B}} + \frac{\delta Q}{m}\mathbf{v}\times\bar{\mathbf{B}} + \frac{\dot{\bar{Q}}t}{m}\mathbf{v}\times\delta\mathbf{B}$$

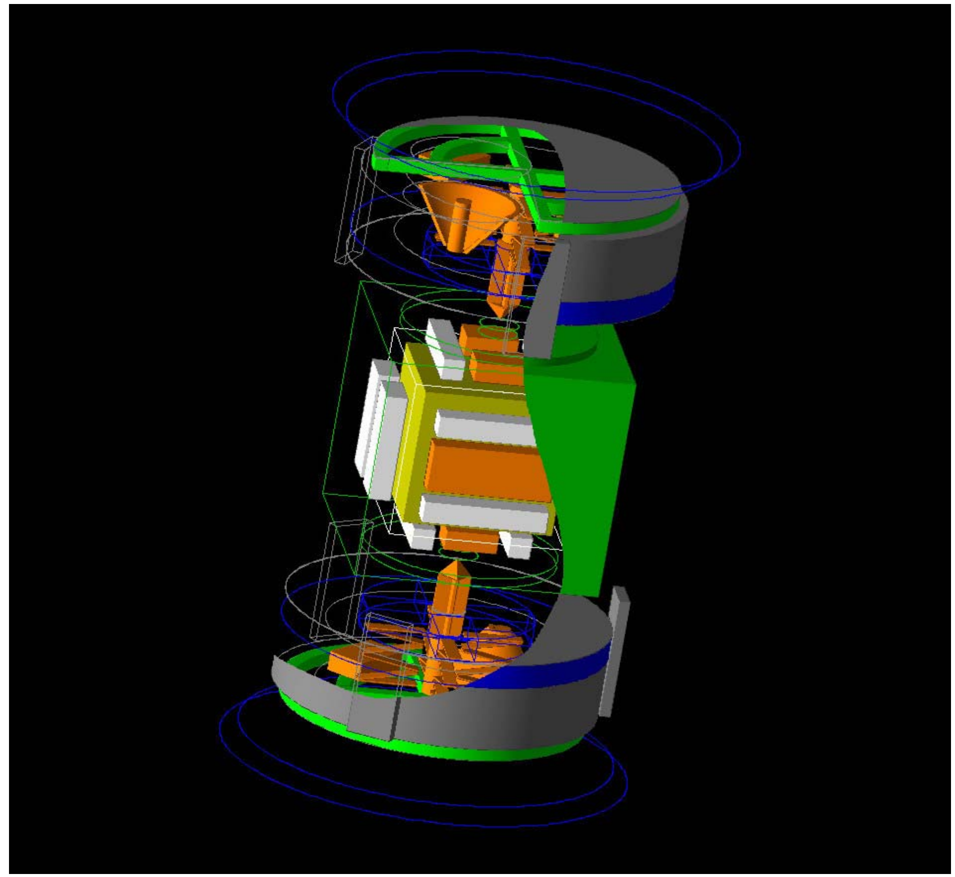
- **Coulomb forces**

$$F_k = -\sum_i \frac{\partial U_i}{\partial k} = \frac{1}{2}\sum_i \frac{\partial C_i}{\partial k}V_i^2 + \frac{Q^2}{2C^2}\frac{\partial C}{\partial k} - \frac{Q}{C}\sum_i V_i\frac{\partial C_i}{\partial k}$$

# LISA Geant4 Geometry Model

- S/C: LISA Solid Model (GSFC/NASA)
- ~200 placed volumes (85% total mass)
- LTP IS: CAD (Carlo Gavazzi Space)
- 46 mm cube test mass, YZ injection

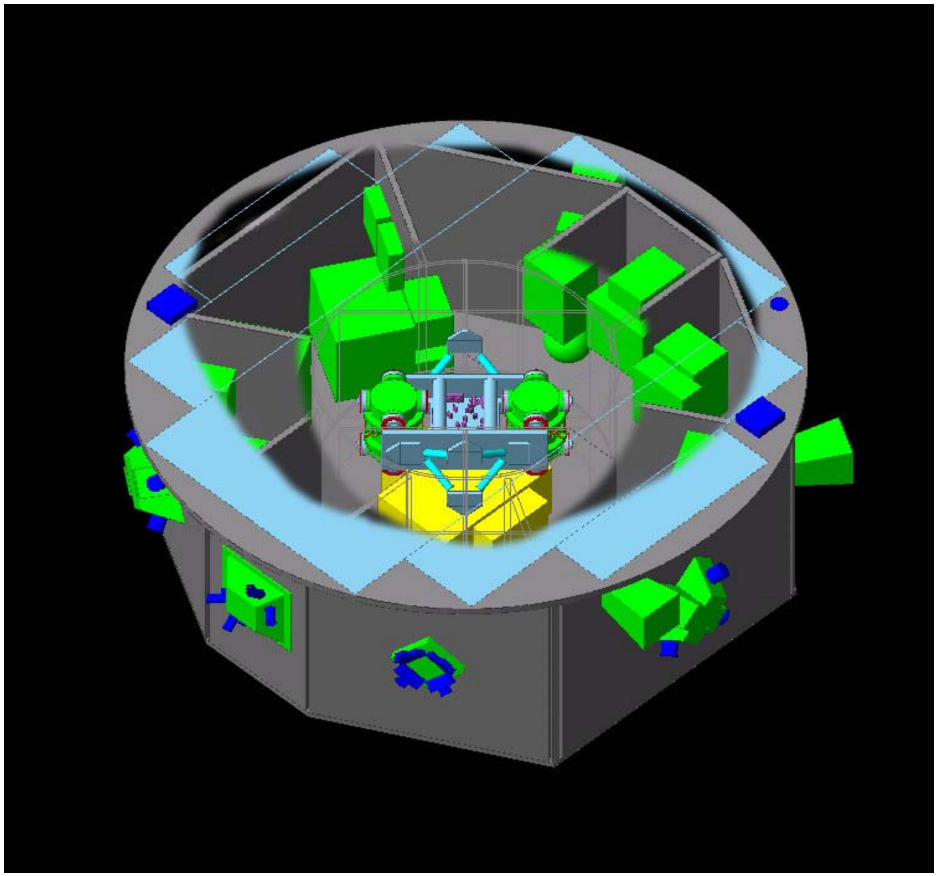


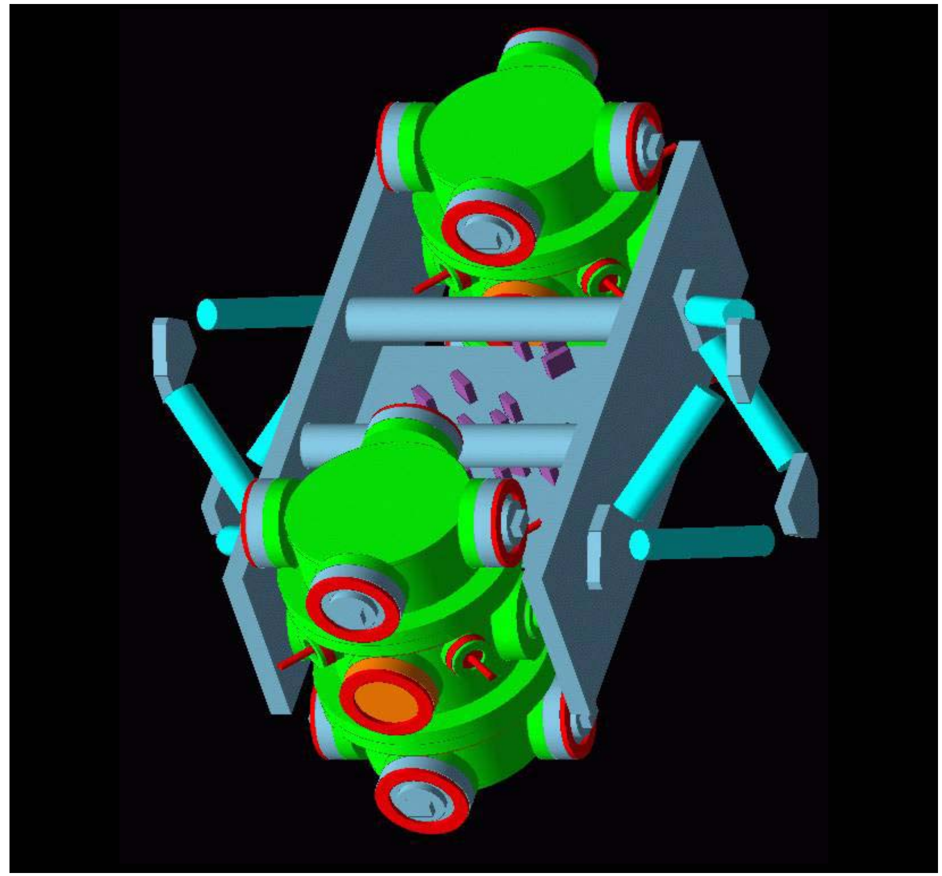


# LTP/SMART-2 G4 Geometry Model

- S/C: CAD (Astrium Germany/UK)
- ~400 placed volumes (80% total mass)

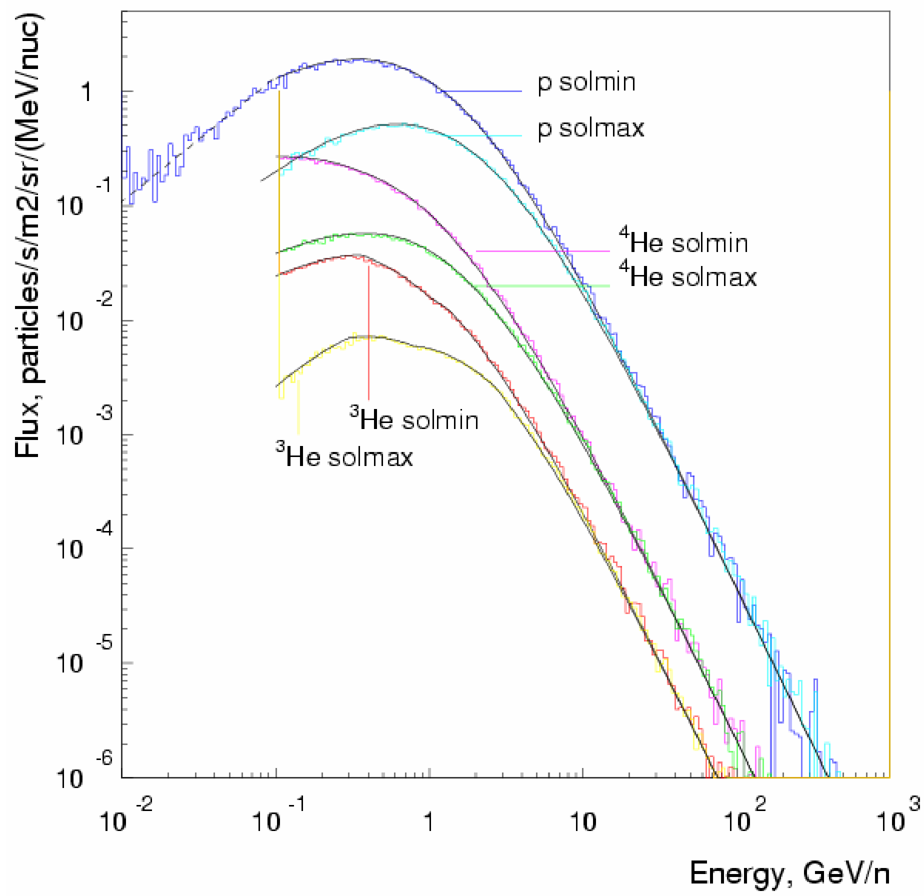
- LTP IS: CAD (Carlo Gavazzi Space)
- 46 mm cube test mass, YZ injection

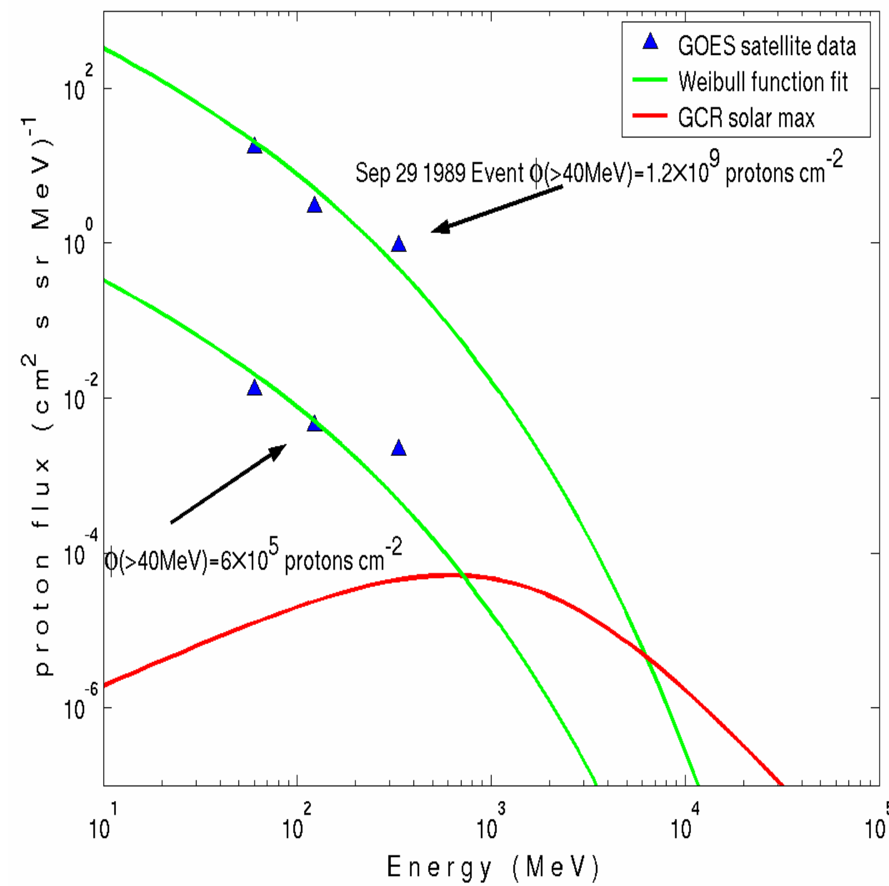




# Radiation Environment

## G4GeneralParticleSource (GPS)



# Geant4 Physics Processes

Most G4 physics, including latest developments

**Electromagnetics**

$E_{th}$ = 250 eV

hIonization: $\delta$-ray production

and mean excitation energy

**Photo/Electronuclear**

**Hadronics**

Intra-nuclear cascades

for protons and light ions

**Decays**

## Hadronic Models

| Particle | Model | Emin | Emax |
|---|---|---|---|
| **p, n** | G4PreCompound | 0 | 70 MeV |
| | G4BinaryCascade | 65 MeV | 6.1 GeV |
| | G4QGSP | 6 GeV | 100 TeV |
| **$\pi$+, $\pi$-** | G4BinaryCascade | 0 | 1.5 GeV |
| | LEP | 1.4 GeV | 6.1 GeV |
| | G4QGSP | 6 GeV | 100 TeV |
| **d, t, $\alpha$** | LEP | 0 | 100 MeV |
| | G4BinaryLightIonReaction | 80 MeV | 10 GeV/n |
| **$^{3}$He, GenericIon** | G4BinaryLightIonReaction | 0 | 10 GeV/n |
| **$K^+$, $K^-$, $K_{0L}$, $K_{0S}$** | LEP | 0 | 6.1 GeV |
| | G4QGSM | 6 GeV | 100 TeV |
| **$\underline{p}$, $\underline{n}$, $\Lambda$, $\underline{\Lambda}$, $\Omega^-$, $\underline{\Omega^-}$, $\Sigma^-$, $\underline{\Sigma^-}$, $\Sigma^+$, $\underline{\Sigma^+}$, $\Xi^0$, $\underline{\Xi^0}$, $\Xi^-$, $\underline{\Xi^-}$** | LEP | 0 | 25 GeV |
| | HEP | 25 GeV | 10 TeV |
| **$\pi^-$, $K^-$** | G4AbsorptionAtRest | — | — |
| **$\underline{p}$, $\underline{n}$** | G4AnnihilationAtRest | — | — |
| **n** | G4LCapture | — | — |
| **n** | G4LFission | — | — |
| **All hadrons** | G4LElastic | 0 | 25 GeV |

# LISA Results

| primary particle | solar activity | GCR flux $\Phi$, /s/cm$^2$ | $\Phi$, % | timeline $N_0$ (x$10^6$) | CPU, days | T, s | $N_0/N_Q$ |
|---|---|---|---|---|---|---|---|
| protons | min | 4.29 | 92.0 | 121.1 | 150 | 200 | 2189 |
| He-4 | min | 0.315 | 6.8 | 14.4 | 12 | 321 | 1002 |
| He-3 | min | 0.0591 | 1.3 | 14.1 | 12 | 1683 | 1073 |
| **Total** | | **4.66** | **100** | **149.6** | **174** | – | **419** |
| protons | max | 1.89 | 91.9 | 53.3 | 70 | 200 | 1889 |
| He-4 | max | 0.142 | 6.9 | 9.3 | 11 | 462 | 849 |
| He-3 | max | 0.0236 | 1.1 | 8.0 | 10 | 2402 | 928 |
| **Total** | | **2.06** | **100** | **70.6** | **91** | – | **359** |

- CERN LSF Cluster
- $2.2 \times 10^8$ Events
- ~1 CPU Year
- 200 s exposure time

- Solar minimum
  - R~100 +e/s
  - $S_R$=34.6 +e/s/Hz$^{1/2}$
- Previous G4 work
  - R=58 +e/s
  - $S_R$=23 +e/s/Hz$^{1/2}$

| primary particle | solar activity | TM 0 R, e/s | TM 0 $\sigma_M$, e/s | TM 0 $S_R$, e/s/√Hz | TM 1 R, e/s | TM 1 $\sigma_M$, e/s | TM 1 $S_R$, e/s/√Hz |
|---|---|---|---|---|---|---|---|
| protons | min | 79.5 | 1.6 | 30.0 | 82.3 | 1.6 | 30.4 |
| He-4 | min | 14.5 | 0.6 | 14.9 | 15.3 | 0.6 | 15.5 |
| He-3 | min | 2.15 | 0.1 | 5.6 | 2.07 | 0.1 | 5.7 |
| **Total** | | **96.2** | **1.7** | **34.0** | **99.7** | **1.7** | **34.6** |
| protons | max | 35.6 | 1.2 | 23.8 | 39.4 | 1.3 | 25.4 |
| He-4 | max | 7.1 | 0.4 | 12.4 | 7.0 | 0.4 | 12.8 |
| He-3 | max | 0.90 | 0.06 | 3.9 | 0.89 | 0.06 | 4.0 |
| **Total** | | **43.6** | **1.3** | **27.1** | **47.3** | **1.4** | **28.7** |

# SMART-2 Results

| primary particle | solar activity | GCR flux Φ, /s/cm² | Φ, % | timeline $N_0$ (x$10^6$) | CPU, days | T, s | $N_0/N_Q$ |
|---|---|---|---|---|---|---|---|
| protons | | 4.29 | 92.0 | 142.6 | 143 | 235 | 2096 |
| He-4 | min | 0.315 | 6.8 | 22.0 | 22 | 491 | 958 |
| He-3 | | 0.0591 | 1.3 | 33.1 | 33 | 3958 | 1010 |
| **Total** | | **4.66** | **100** | **197.6** | **198** | – | **398** |
| protons | | 1.89 | 91.9 | 59.4 | 59 | 222 | 1758 |
| He-4 | max | 0.142 | 6.9 | 8.8 | 9 | 440 | 798 |
| He-3 | | 0.0236 | 1.1 | 31.8 | 32 | 9524 | 874 |
| **Total** | | **2.06** | **100** | **99.9** | **100** | – | **337** |

- CERN LSF Cluster
- $3\times10^8$ Events
- ~1 CPU Year
- >200 s exposure time

- Solar minimum
  - R~88 +e/s
  - $S_R$=35.4 +e/s/$Hz^{1/2}$
- Solar maximum
  - R~43 +e/s
  - $S_R$=28.2 +e/s/$Hz^{1/2}$

| primary particle | solar activity | TM 0 R, e/s | $\sigma_M$, e/s | $S_R$,e/s/√Hz | TM 1 R, e/s | $\sigma_M$, e/s | $S_R$,e/s/√Hz |
|---|---|---|---|---|---|---|---|
| protons | | 71.7 | 1.4 | 31.3 | 68.9 | 1.4 | 30.3 |
| He-4 | min | 14.2 | 0.5 | 15.5 | 13.7 | 0.5 | 15.2 |
| He-3 | | 2.22 | 0.06 | 5.6 | 2.06 | 0.06 | 5.5 |
| **Total** | | **88.1** | **1.5** | **35.4** | **84.7** | **1.5** | **34.3** |
| protons | | 33.5 | 1.1 | 24.1 | 34.8 | 1.2 | 25.1 |
| He-4 | max | 7.1 | 0.4 | 12.7 | 7.2 | 0.4 | 12.1 |
| He-3 | | 0.85 | 0.03 | 4.2 | 0.85 | 0.03 | 4.1 |
| **Total** | | **41.4** | **1.2** | **27.6** | **42.9** | **1.3** | **28.2** |

# Conclusions

## LISA

| solar activity | charging rate | | | charging fluctuations | | | | |
|---|---|---|---|---|---|---|---|---|
| | R, e/s | $\sigma_T$, e/s | $\delta$/s | $S_R$,e/s/√Hz | $S_\delta$,e/s/√Hz | $S_D$,e/s/√Hz | $S_T$,e/s/√Hz | $R_{eff}$, +e/s |
| **solar minimum** | **99.7** | **1.7** | **60** | **34.3** | **15.5** | **14.1** | **40.2** | **807** |
| **solar maximum** | **47.3** | **1.4** | **36** | **27.9** | **12.0** | **9.7** | **31.9** | **509** |

- The MC results are similar for LISA and LTP/SMART-2 (same IS!)
- The existing Charge Management System is adequate for the solar quiet charging rates as well as for most SEP events
- MC charging rates ~2x higher than in previous G4 work (Araújo *et al.* 2003, CQG 20, S311), and ~10x higher than in original Geant3 work with a smaller test mass (Jafry & Sumner 1997, CQG 14, 1567).
- Kinetic electron emission can affect charging rates and fluctuations.
- Coulomb acceleration noise 2x higher than in previous G4 work, but still acceptable ($4 \times 10^{-16}$ m/s$^2$).
- Solar flare events are a concern. Small but frequent SEP events will appear in the LISA science data; a radiation monitor should be considered to help data analysis!

# INTEGRAL Simulations

- Geant4 INTEGRAL Mass Model
  - Current mass model based on G3
    - ~ 300,000 volumes
  - G3toG4 dose not work well here
  - Re-implemented in G4/C++, ~ 20,000 lines of code
    - SPI: 19 HPGe array, shield by ~ 900 kg BGO
- Simulations (on going)
  - In-flight background higher than predicted (G3 + others)
  - Continuum spectra: veto on/off
  - Gamma ray lines: Isotope production and radioactive decay

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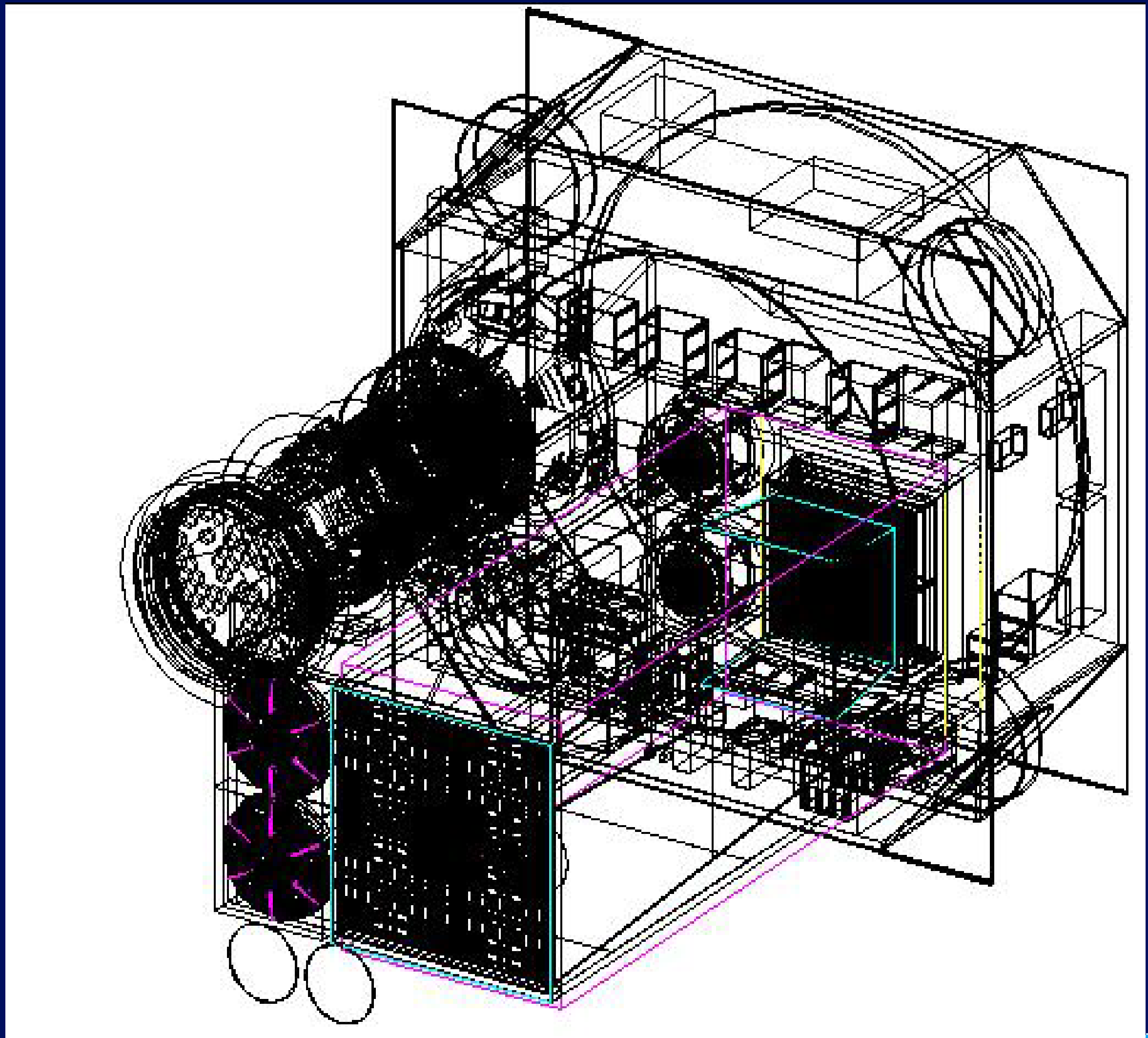
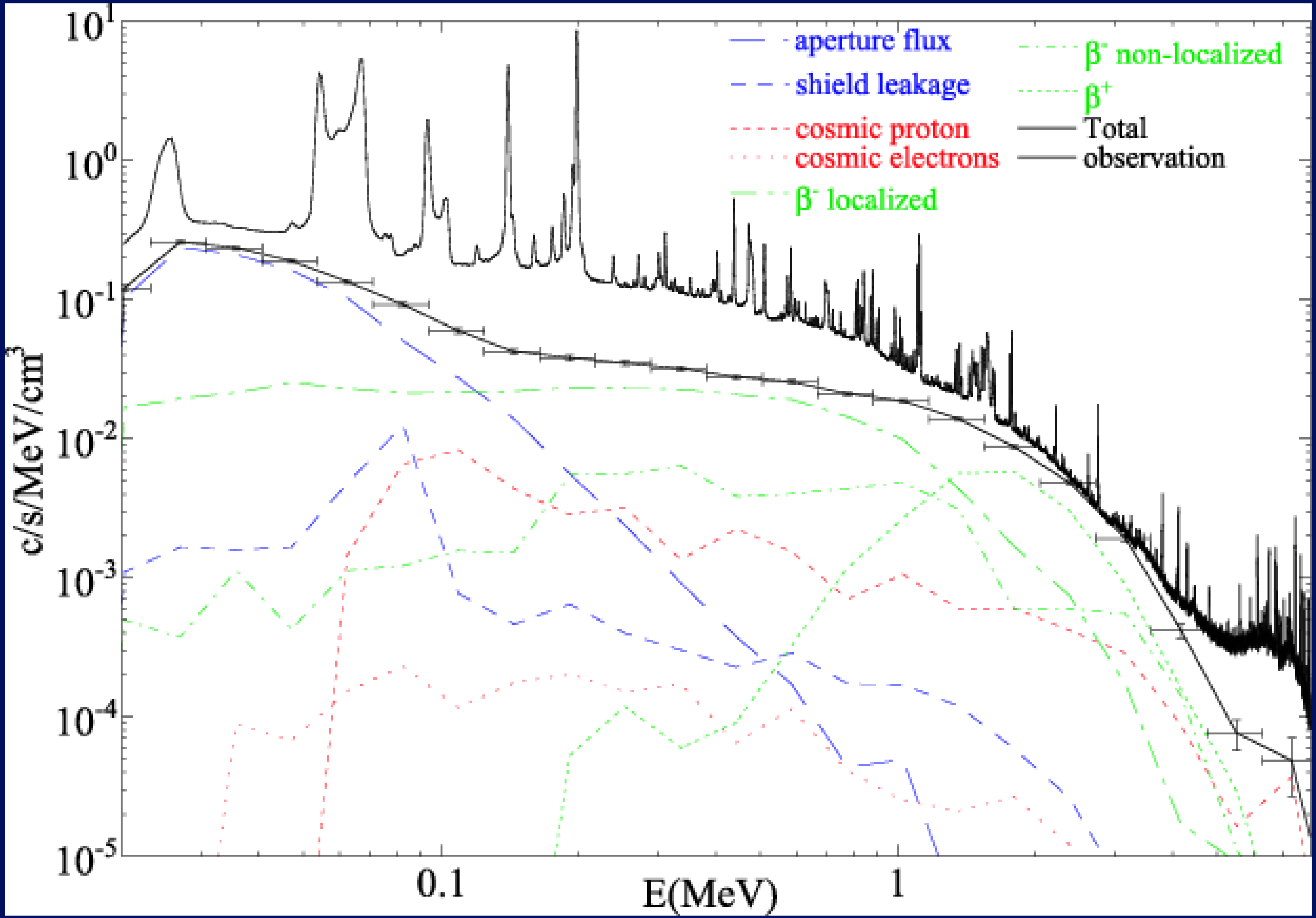
# INTEGRAL G4 Mass Model



# SPI Continuum background




Old Simulations:
Geant3+
GCALOR+
ORIHET+
DECAY

Geant4 Sims.
On-going

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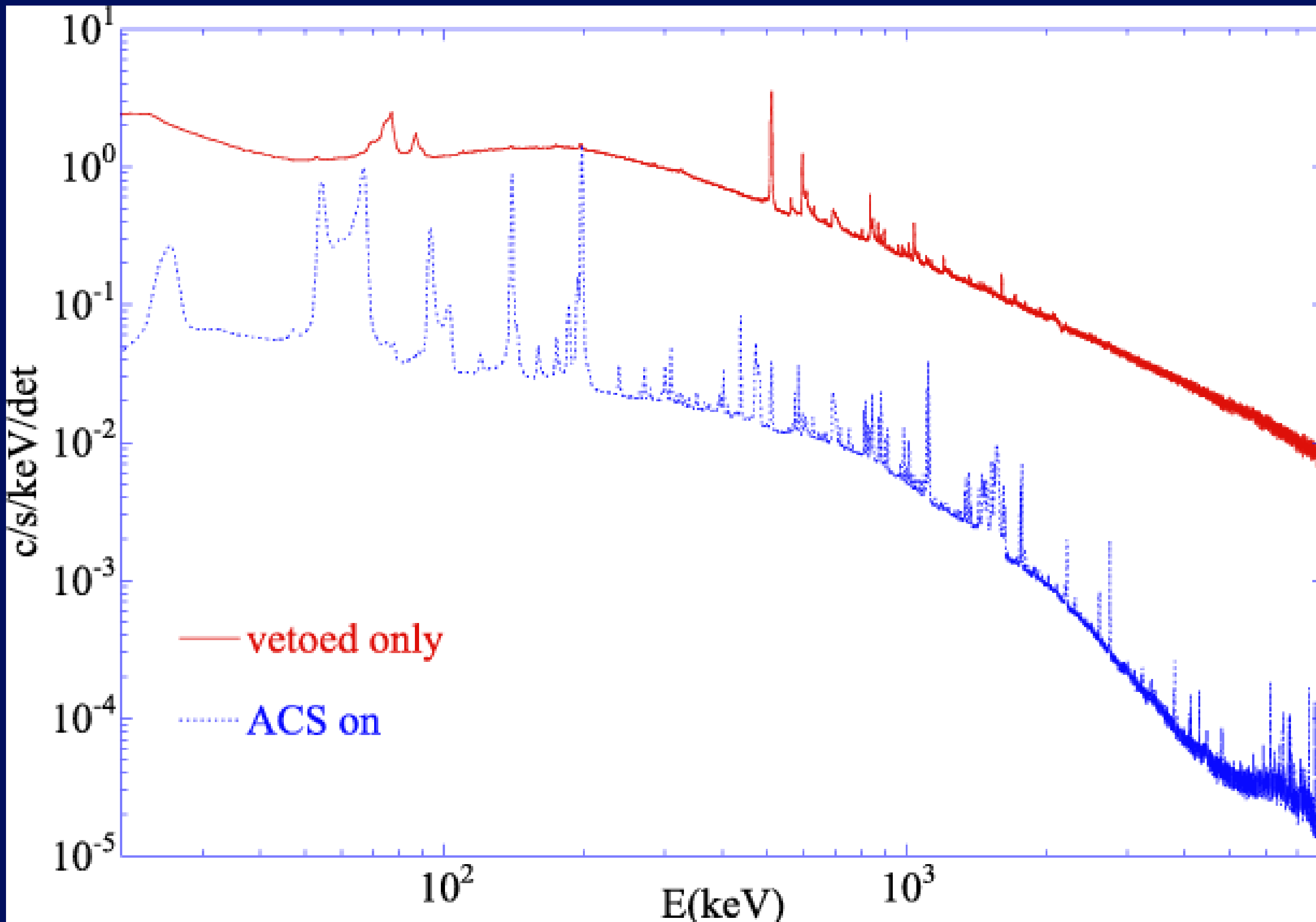
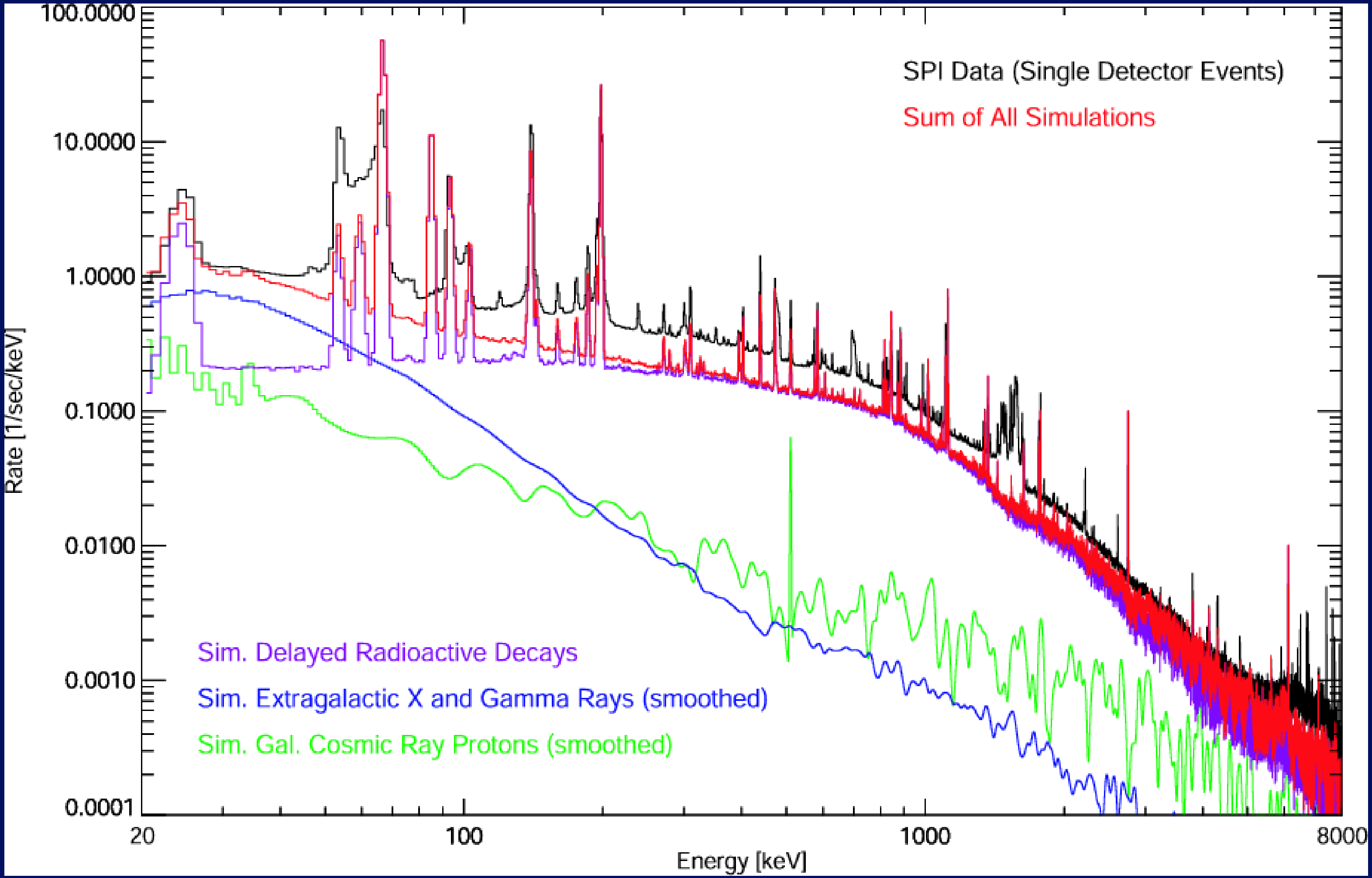
# SPI background: veto on/off



# SPI: Gamma ray background  lines




Old Simulations:
Geant3+
GCALOR+
ORIHET+
DECAY

Geant4 Sims.
On-going

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# MAGNETCOSMICS

Geant4 based application to

- Calculate the trajectory of cosmic ray particle in the Earth magnetosphere
  - Visualisation of the trajectory and field lines
- Rigidity cut-off calculation
  - Dynamical out field model
- Additional option of Bulirsh-Stoer integration method

Code and Documents:

http://reat.space.qinetiq.com/septimess/magcos

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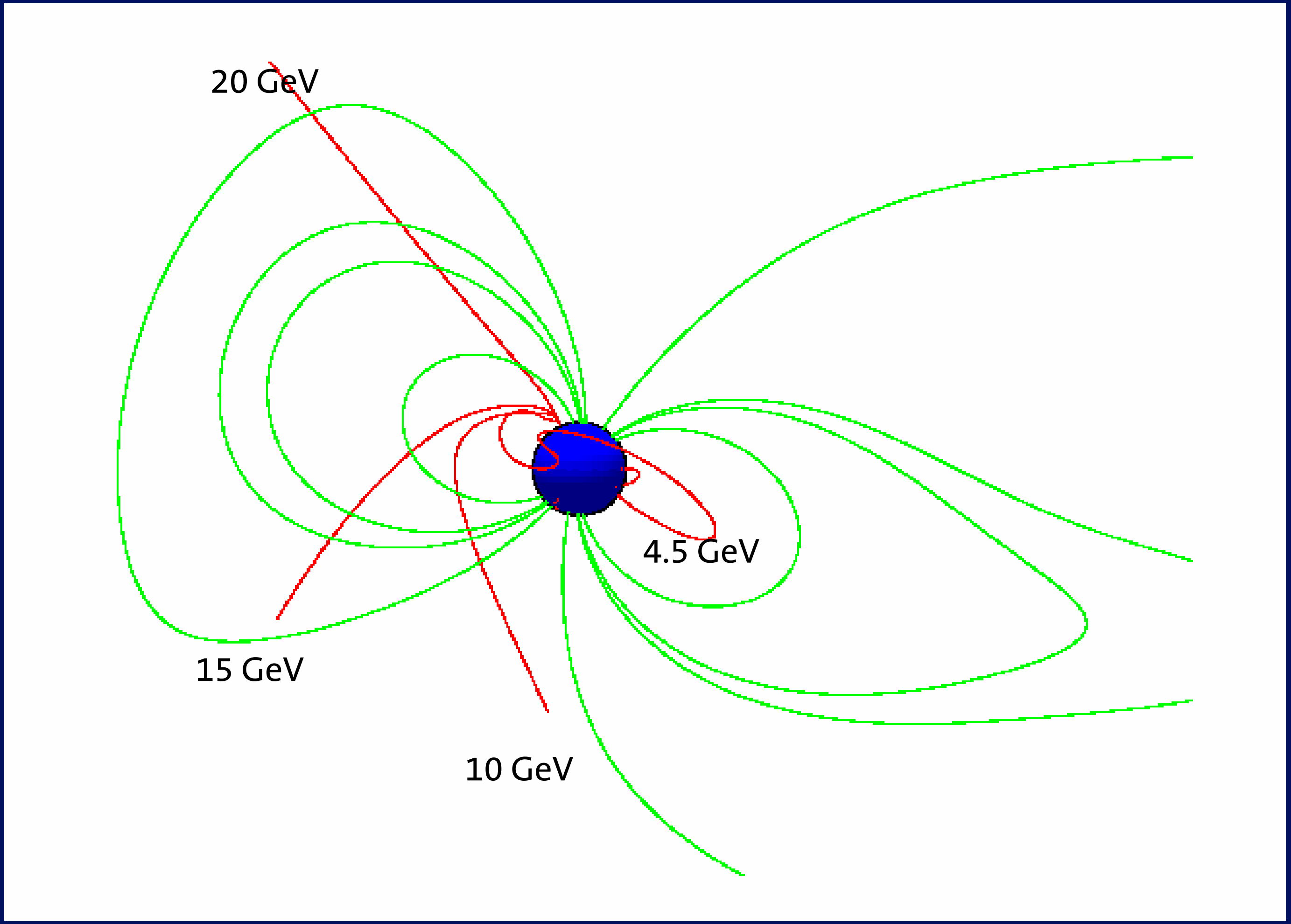
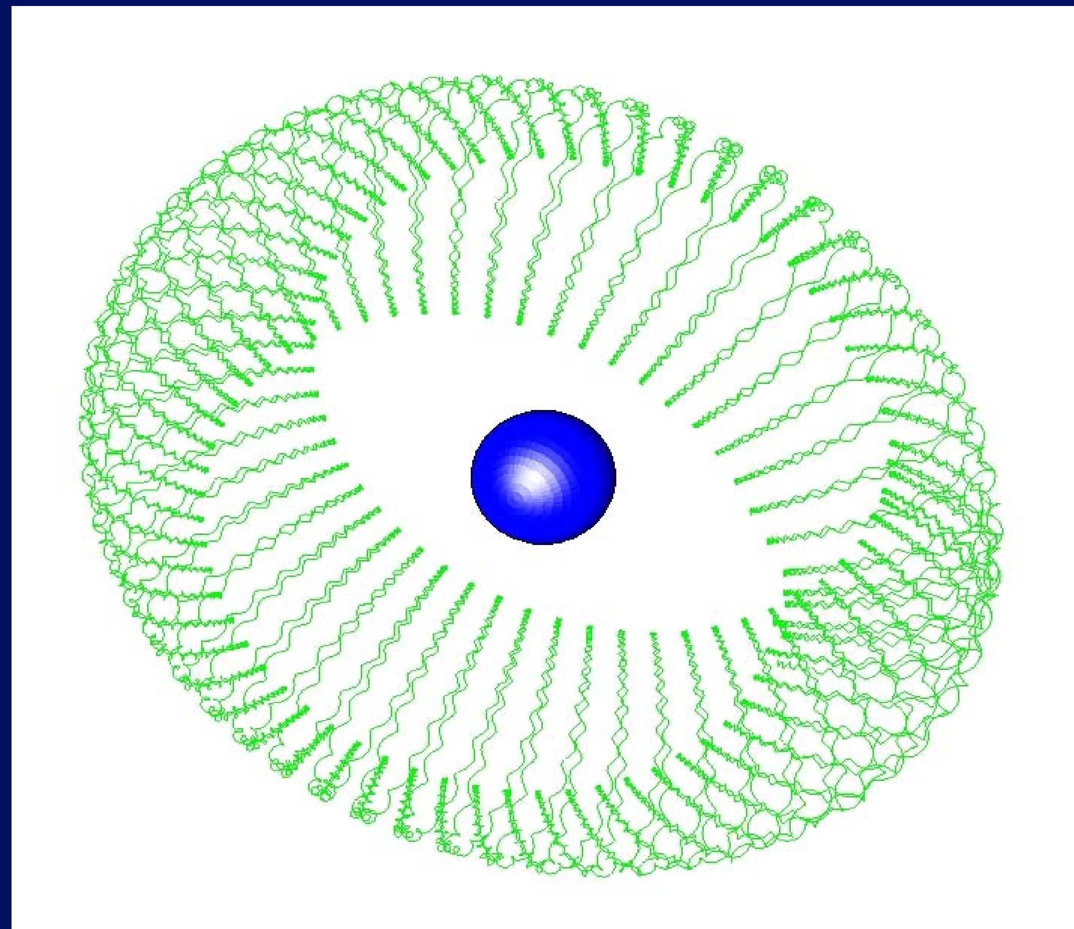
# Tracking of cosmic ray in the magnetosphere




Field Model:
IGRF + Tsyganenko-2001

# Gyration, bounce and drift

**500 keV proton @ 5.5 Re**



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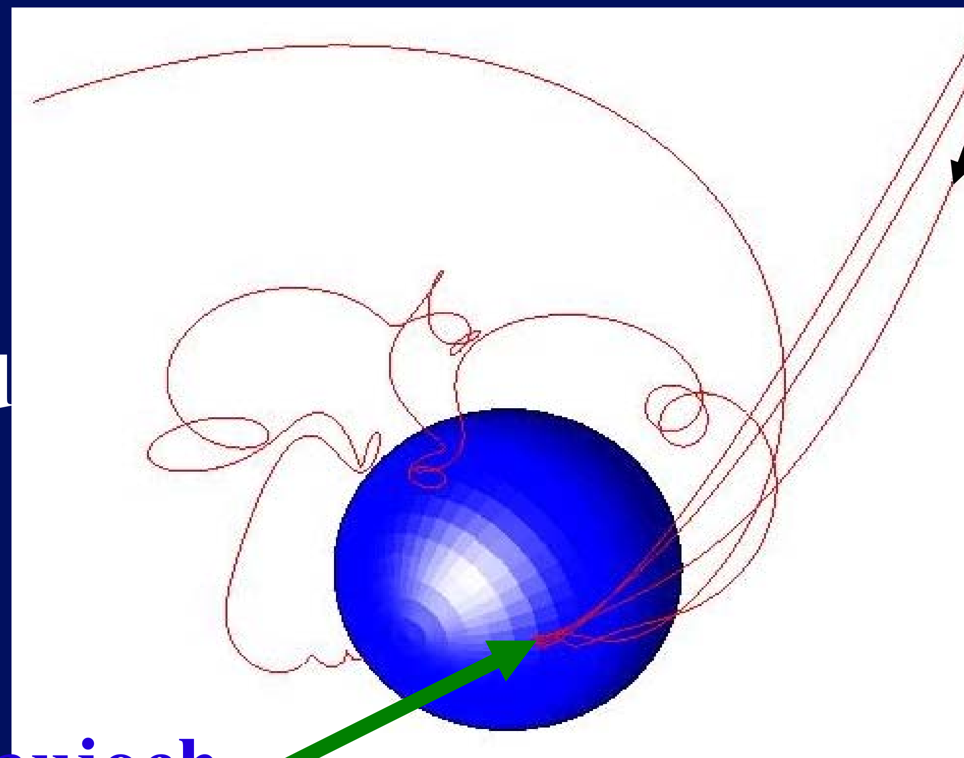
# Cutoff rigidities and asymptotic directions

Reverse time trajectory tracing

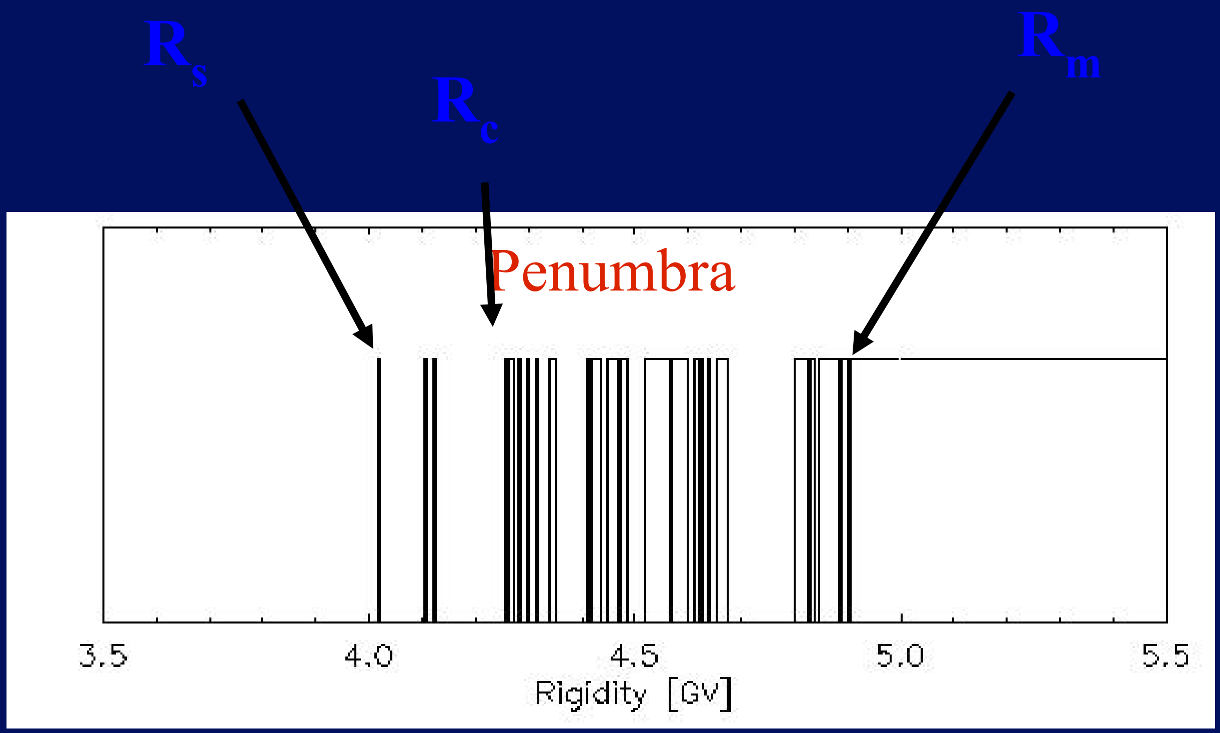
Computation of rigid cutoff

Asymptotic direction



Jungfraujoch

# *Cutoff rigidities*

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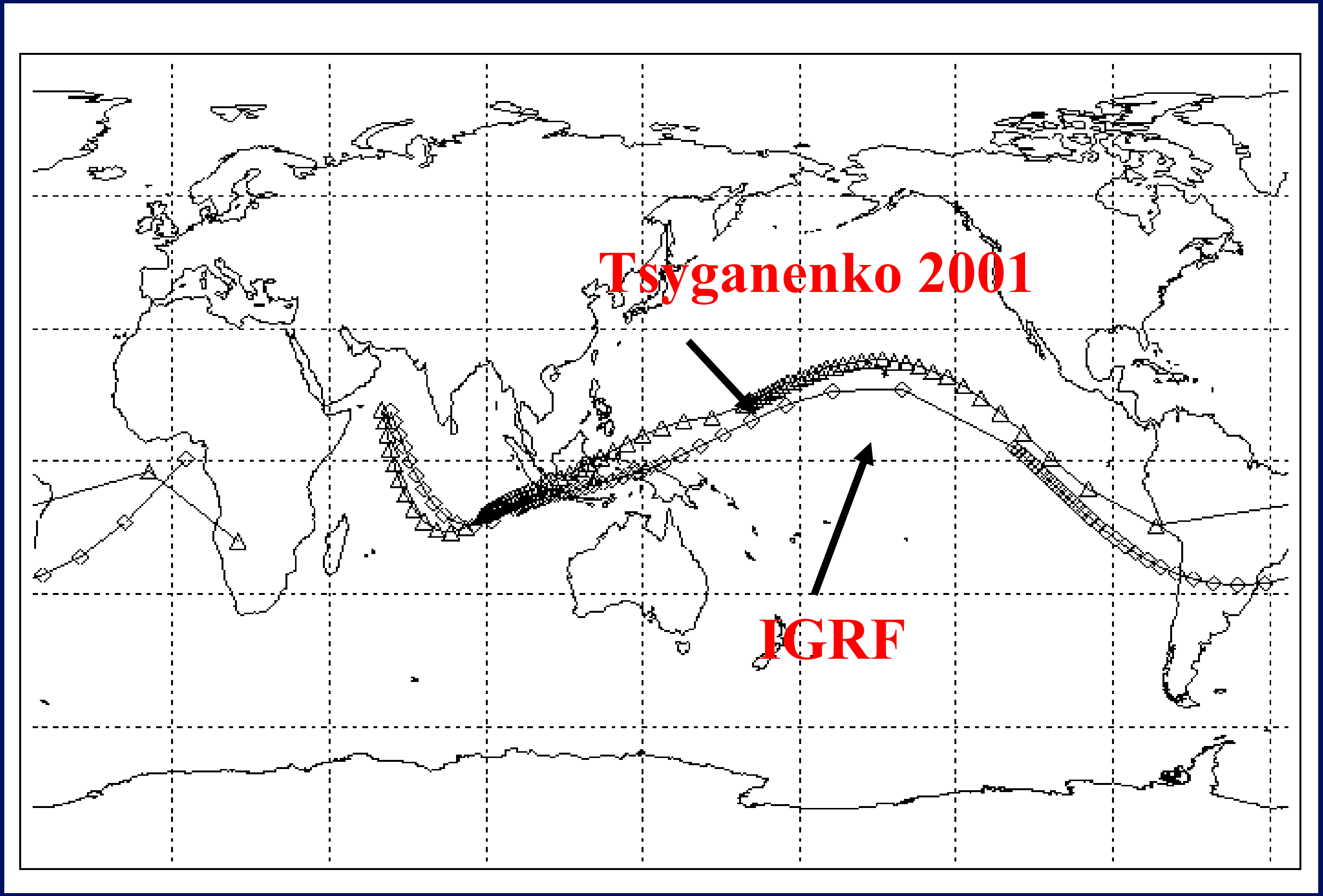
# Asymptotic directions

**Alt.: 20. km**
**Lat: 46.55 N**
**Long:7.98 E**
**March 26, 1995, 18 h**

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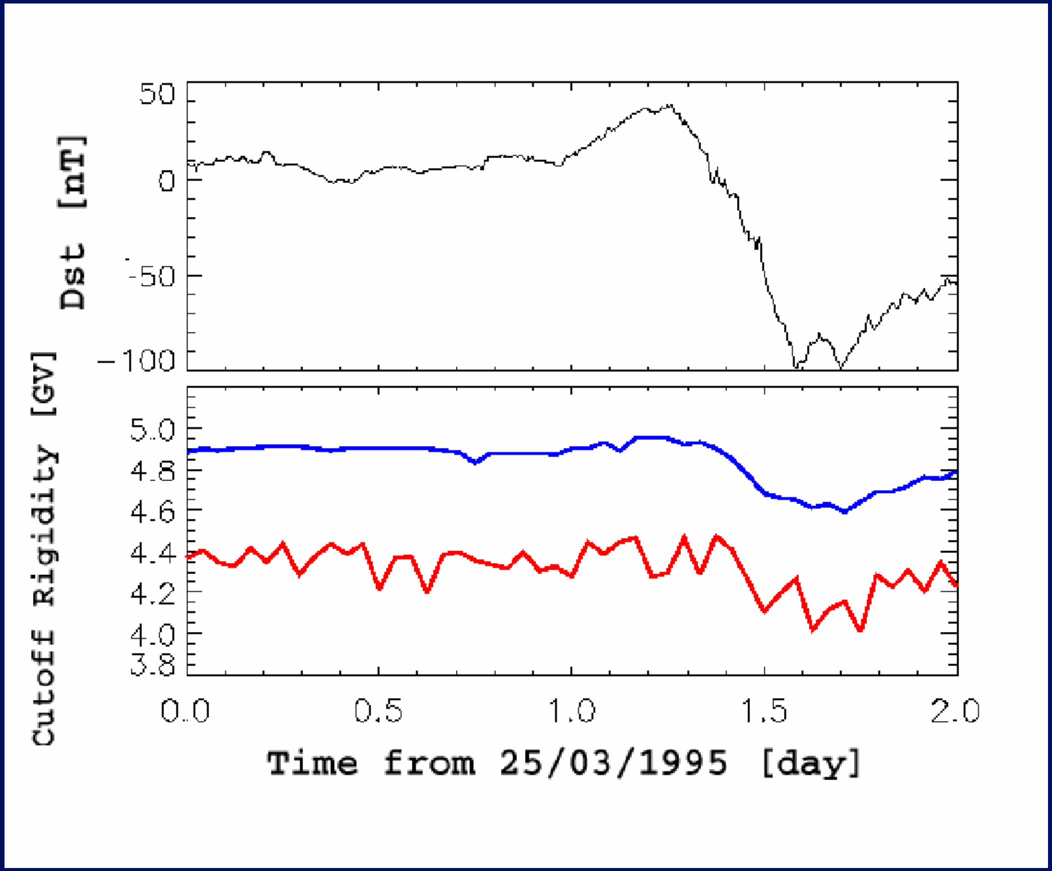
# Dynamic rigidity cut-off calculations

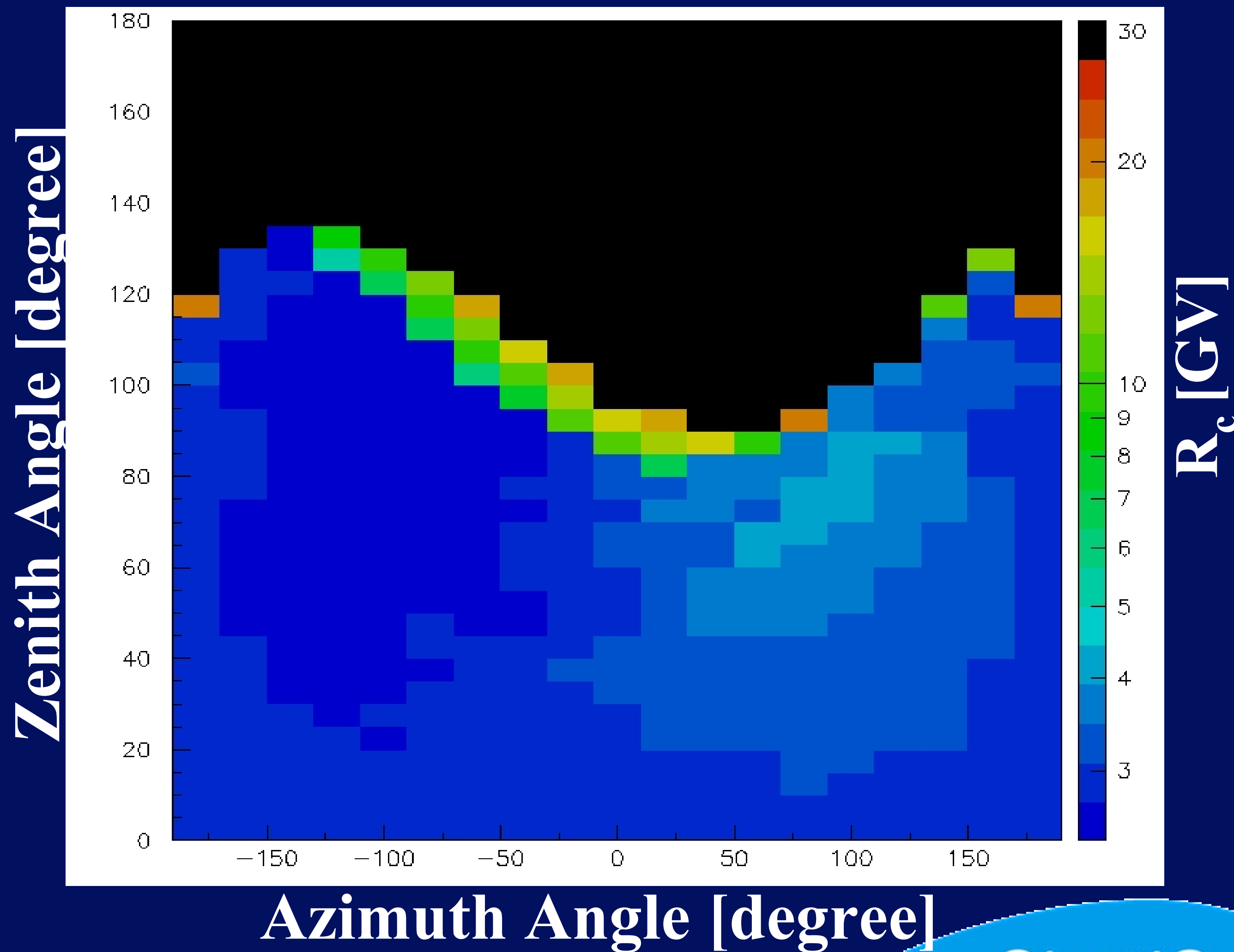



The lower panel of this figure represents the time variation of the main (blue line) and effective (red line) cutoff rigidities at the Jungfraujoch neutron monitor station, Switzerland, for the March 26th 1995 magnetic storm.

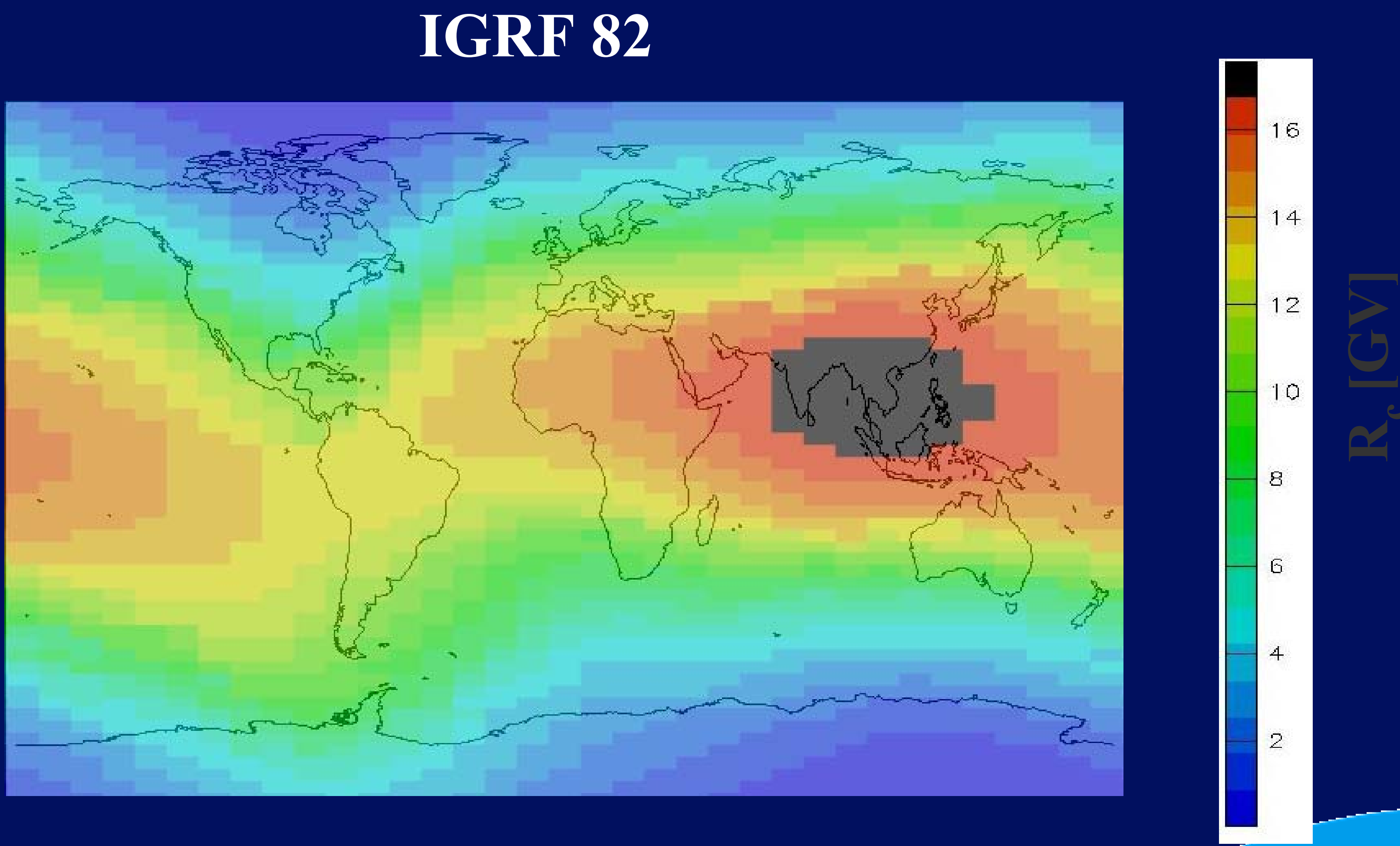
The top panel represents the variation of the Dst index. In this simulation the magnetosphere was modeled by the IGRF and the Tsyganenko 2001 models.

# Cutoff vs Direction

**400 km, 50 N, 0 E**
**Tsyganenko 89**
**25 March 1995**
**0 UT**



# Cutoff Rigidities Map



# *ATMOCOSMICS*

- Propagation of  cosmic rays through the Earth's atmosphere
- With or without the magnetic field
- Build-in atmosphere model
- Build-in model for cosmic-ray radiation model
- Visualisation
- Computing flux of secondaries at any altitude
- Energy deposited vs altitude
- Cosmogenic nuclides production

Code and Documents:

http://reat.space.qinetiq.com/septimess/atmcos

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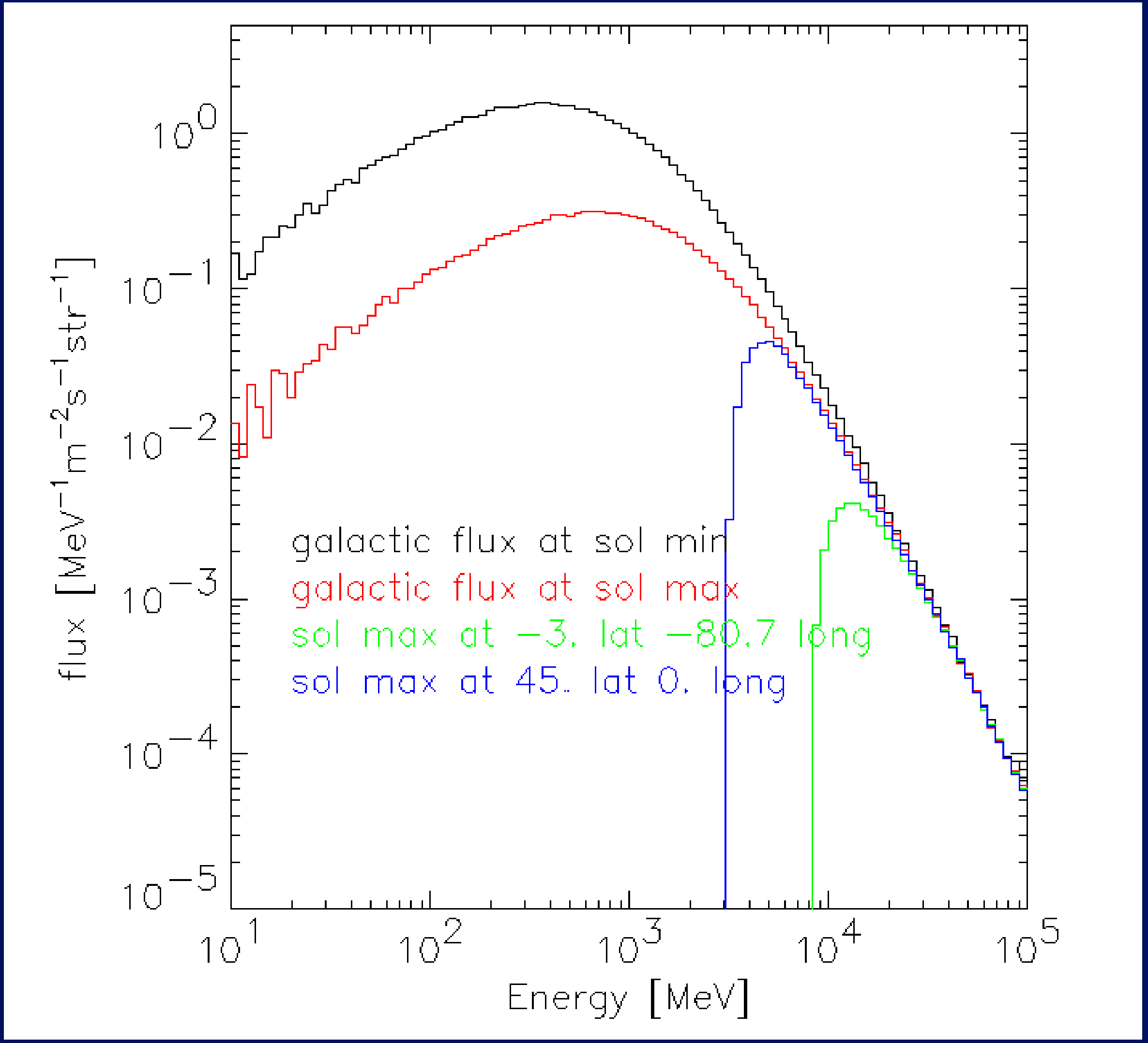
# Atmosphere

- Geometry:
  - Divided in successive  homogenous layer
  - Flat or spherical layers
- Composition model:
  - MSISE90 and NRLMSISE2000
  - Table model
  - Oxygen, Nitrogen, Ar,.....

# Primary incident particle generator

- Derived from G4GeneralParticleSource (GPS)
- User defined spectrum
- Cut-off rigidity in function of direction or fixed
- Isotropic galactic cosmic ray proton and alpha particle
    - Solar minimum
    - Solar maximum
    - Modulation parameter (Garcia Munoz 1975)

# Galactic proton flux at 1AU

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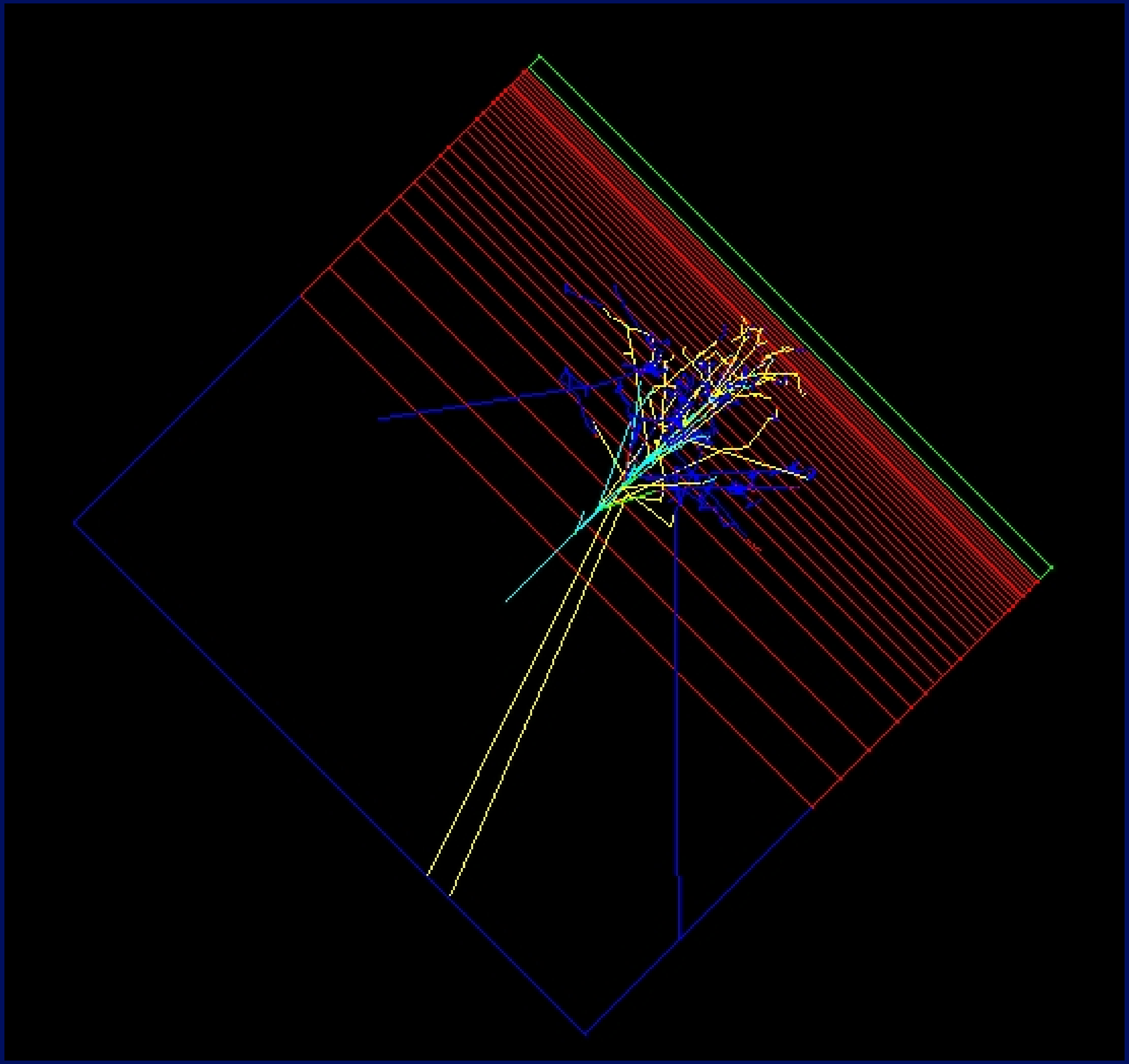
# Physics

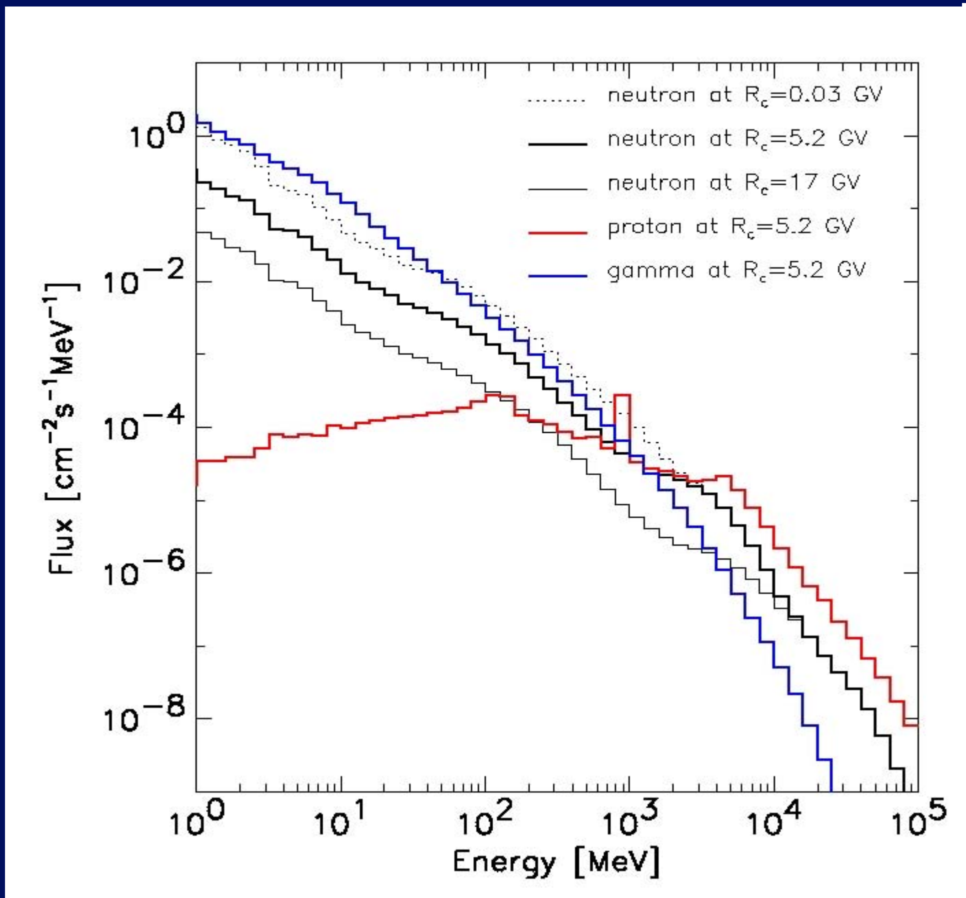
- Electromagnetic physics:
  - G4Std, G4LowEnergy
- Hadronic physics:
  - G4NeutronHP (neutron <20 MeV)
  - G4Precompound
  - G4Binary cascade, G4HETC
    - Bug #607
  - G4QGSP, G4LHEP,.....

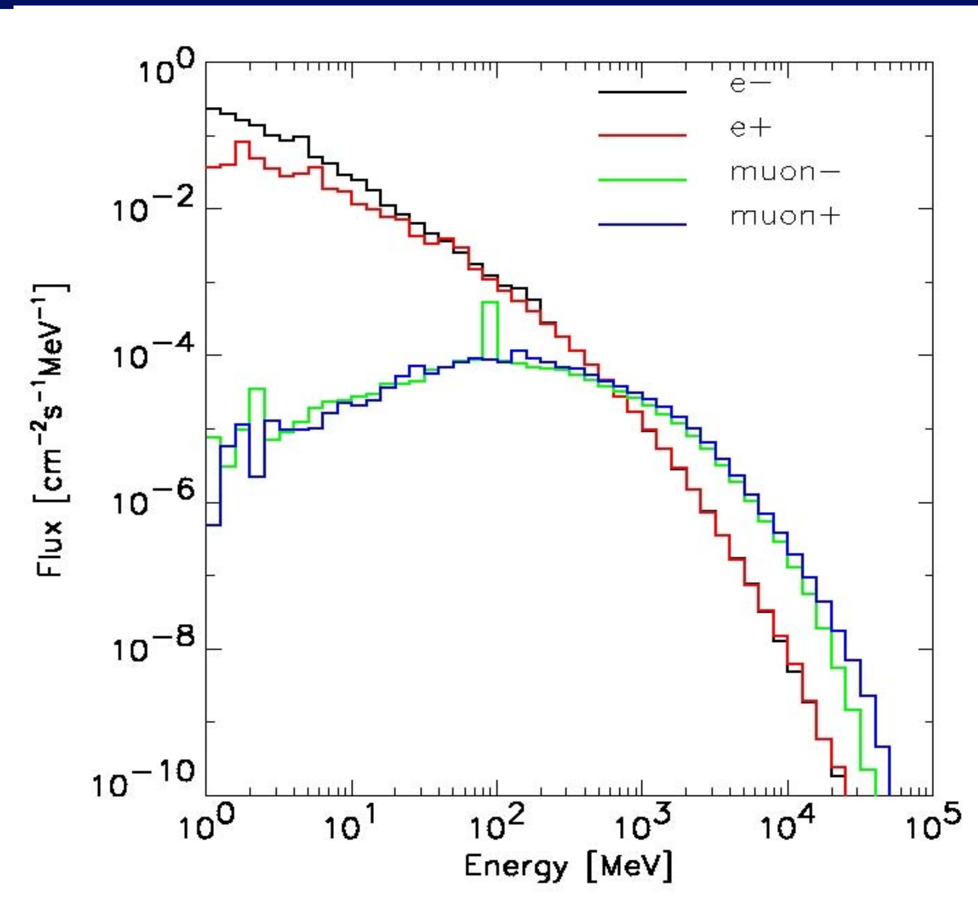
# Visualisation



**2 GeV protons interacting with atmosphere**

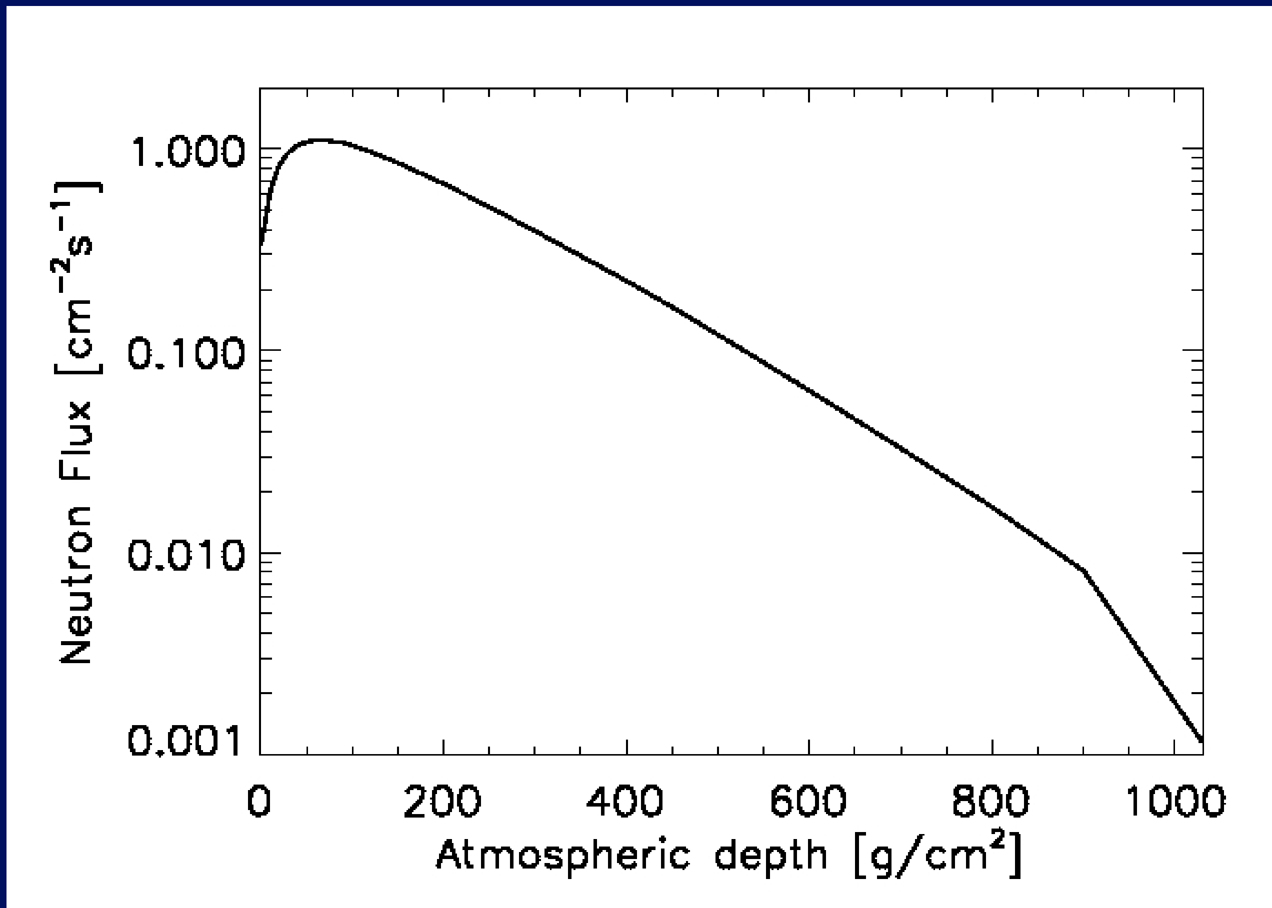
# Simulated flux at 16 km (100 g/cm2)




Primary spectrum: galactic proton at solar minimum

# Simulated neutron flux (1-10 MeV)




**Primary spectrum: galactic proton at solar minimum Rc=3.2 GV**

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# GoF Toolkit

A project to develop a
**statistical analysis system,**
to be used in Geant4 testing

Main application areas in Geant4:

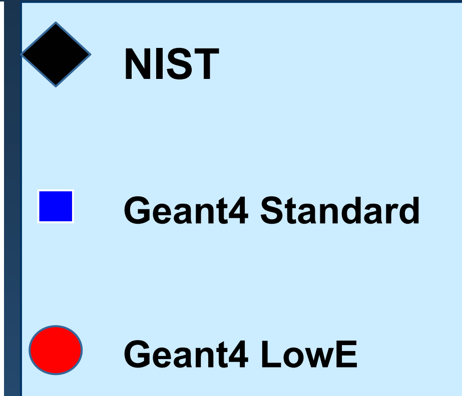
- physics validation
- regression testing
- system testing

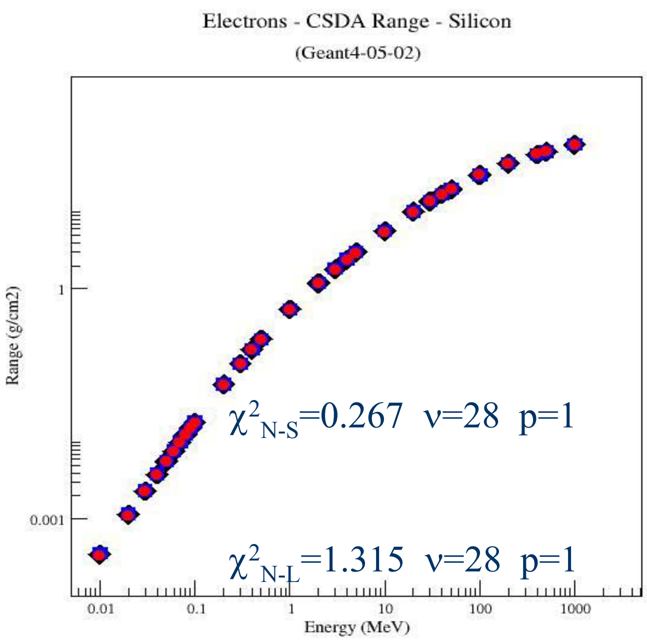
Provide tools for the **statistical comparison** of distributions

- equivalent reference distributions *(for instance, regression testing)*
- experimental measurements
- data from reference sources
- functions deriving from theoretical calculations or from fits

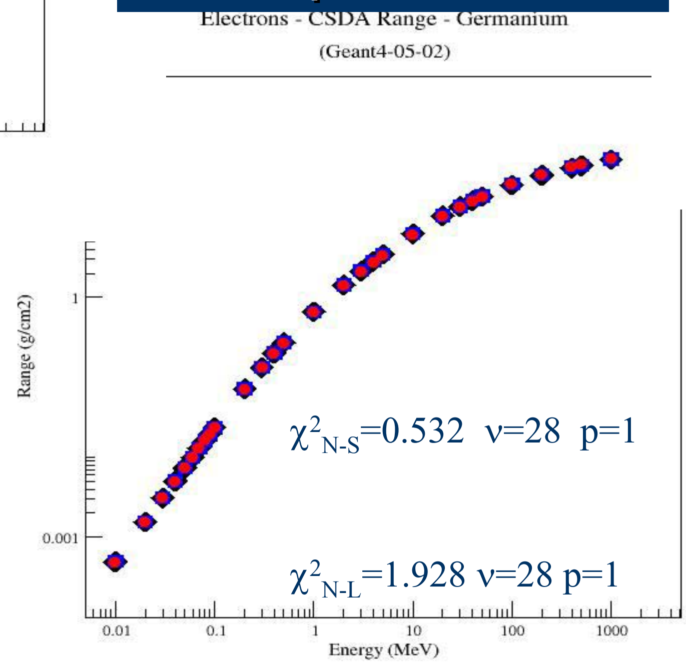
Interest in other areas, not only Geant4

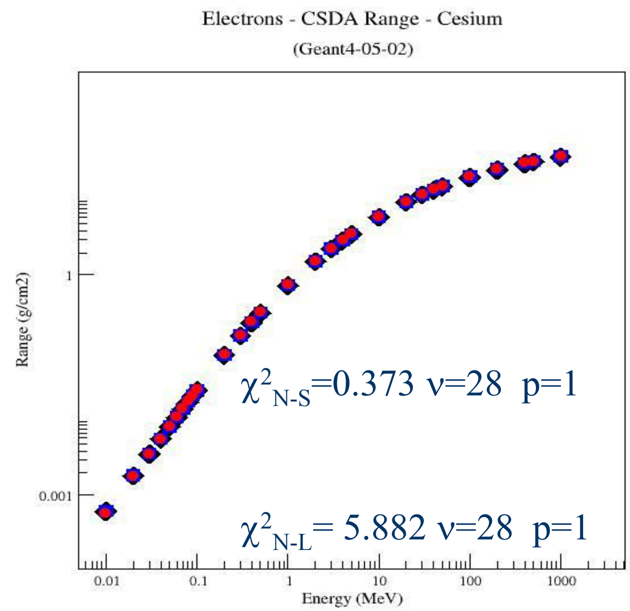
# Microscopic validation of Geant4 physics




Chi-squared test

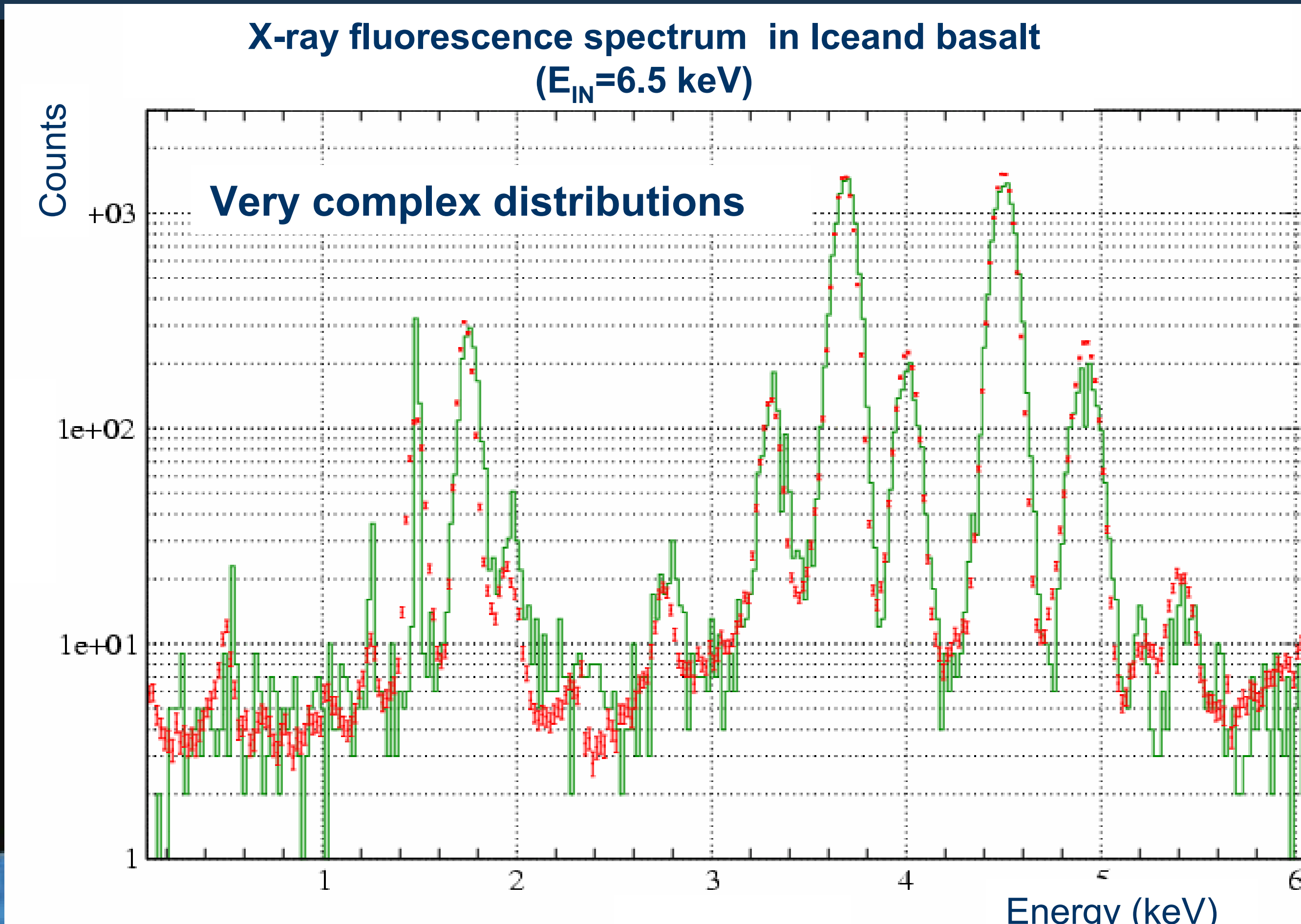



Many tests of Geant4 electromagnetic physics performed!

More results documented at http://www.ge.infn.it/geant4/TandA

# Test beam at Bessy
# Bepi-Colombo mission




$\chi^2$ not appropriate

**(< 5 entries in some bins, physical information would be lost if rebinned)**

**Anderson-Darling**

$A_c$ (95%) =0.752

A.Mantero, M.Bavdaz, A.Owens, A.Peacock, M.G.Pia
*Simulation of X-ray Fluorescence and Application to Planetary Astrophysics, IEEE-NSS 2003*

# G4HDS: Geant4 hadronic data set

- G4HDS: data format for store and manage data such as cross sections of hadronic interaction in the Geant4 framework
- Will be used by HARP in its hadron productions data
- Comprehensive reference list of experimental hadron c-s data
  - A limited number of data set have been converted to G4HDS format
- Utilities for
  - input and update data
  - Retrieve and search
- SpaceHad01:Application developed to test Geant4 hadronic cross section evaluation

All available from the Geant4 repository!

# New G4GeneralParticleSource

- Design iteration
  - Split into 7 classes
  - Tree structured commands
- New feature
  - Multiple sources definition
- Bug fixing
  - Biasing
  - Integral spectrum
  - Beam profile
- Released in Geant4-06-01-ref-01
  http://reat.space.qinetiq.com/gps

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# Summary (I)

- All instruments of future ESA science missions are susceptible to energetic particle radiation effects
- Geant4 is largely ready to face the energetic particle transport simulation demands from ESA future science missions, but
  - New physics will be required. E.g. for XUES
    - Scattering of charged particles in x-ray mirror system
    - Low energy threshold: < 50 eV
    - Charge transfer in pn-CCDs and DEPFETs
    - Thermal transfer in STJ array and TES
  - Geometry
  - ...

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# Summary (II)

- Simulations of the test-mass experiments: novel application of G4, proved to be very demanding in physics.
  - Need experiments (data) to validate
  - Proved to be an very important tool in the mission design phase
- SINTEGRAL simulations will be a big challenge to Geant4, isotope production and radioactive decay in particularly.
- The statistical test toolkit, an invaluable tool not just to Geant4!

# Summary (III)

- GPS: has been proved to be essential to Geant4 space applications and beyond.
- G4HDS: great for hadron physics validations; a foundation for the implementation of a c-s based process.
- Geant4 based tools for space application tools
  - MAGNETOCOSMICS: important application in radiation environment modeling. Will be used and made available by SPENVIS
  - ATMOCOSMICS: atmospheric radiation modeling for LEO missions and the study of terrestrial and atmospheric radiation effects

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