The background of the slide features a traditional Japanese ink wash painting style. It depicts a misty mountain range in the distance and several willow branches with small, dark buds or blossoms in the foreground on the right side. The overall color palette is muted, consisting of various shades of beige, tan, and brown.

*Heavy ion simulation in
Geant4 with JQMD code*

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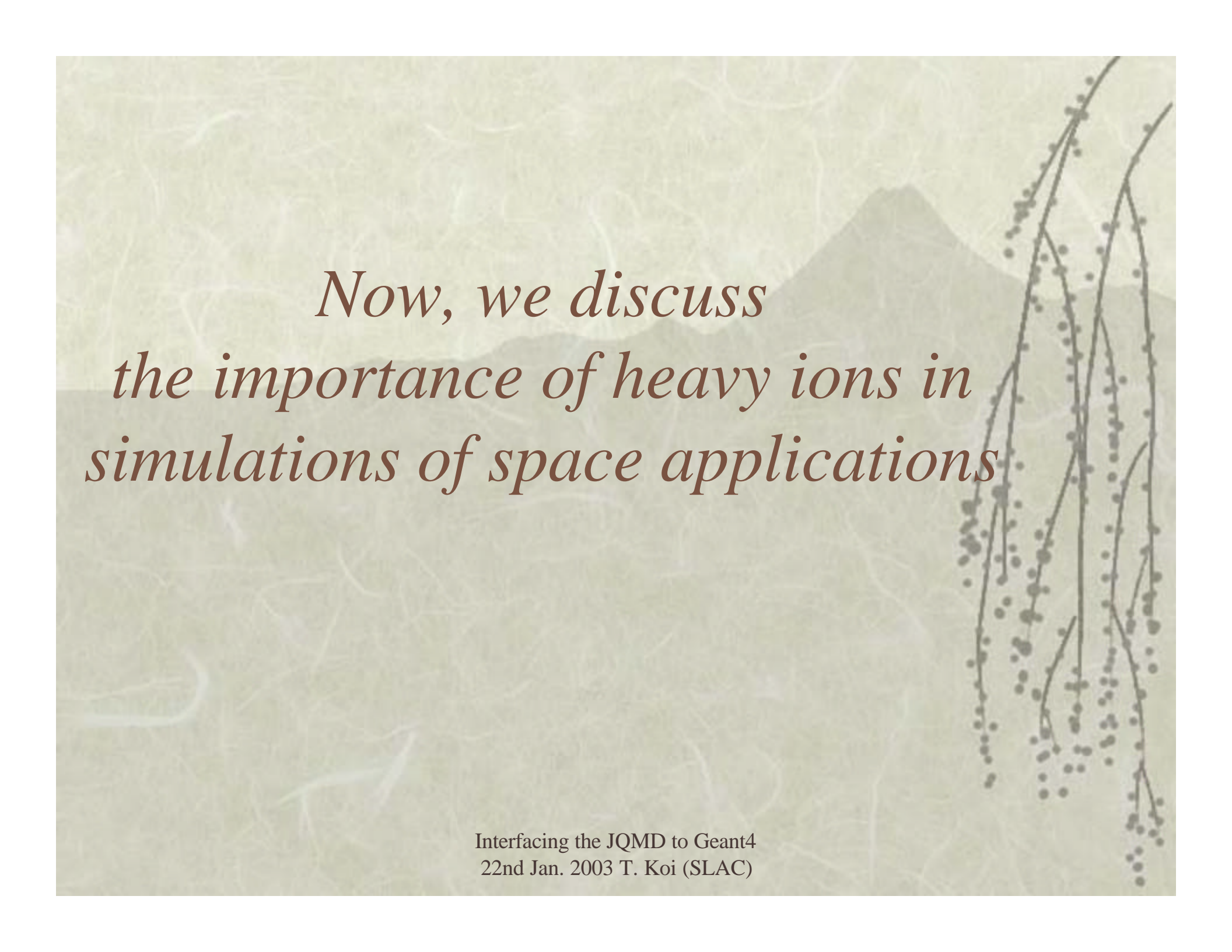
Outline

- ❖ Introducing joint activity of SLAC and JAERI for interfacing Fortran code of JQMD to Geant4
 - To satisfy the urgent need for beam test simulation of a SLAC experiment.
- ❖ Contents
 - Importance of heavy ions for simulations in space applications
 - What is JQMD
 - Interfacing JQMD to Geant4
 - Demonstration
 - Summary

We tried to connect Fortran code of JQMD to Geant4 which is written in C++.

Advantages of this method are

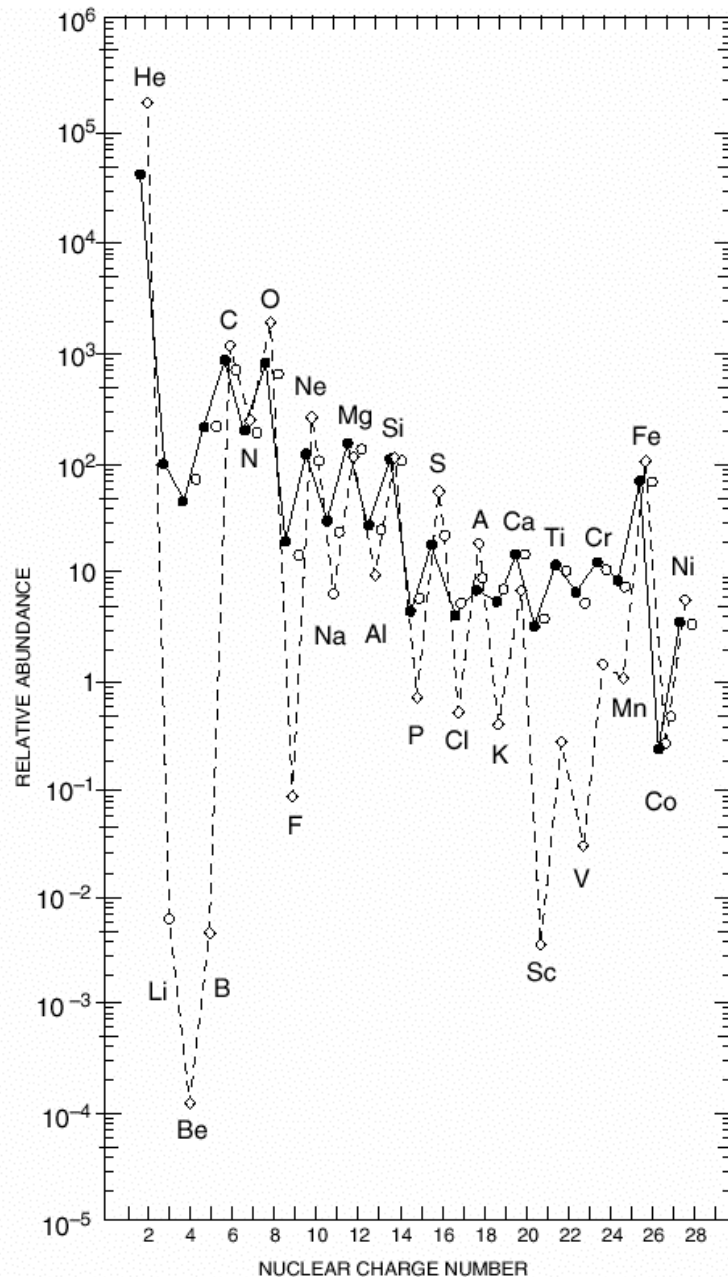
- ❖ It is more convenient interfacing to Fortran code directly than re-writing the code in C++.
- ❖ In the process of re-writing, new bugs may enter into the code. We can avoid this situation.
- ❖ Once the interface is established, the Fortran code and Geant4 can be updated independently.
- ❖ No copyright problems associated with re-writes.

The background of the slide features a soft, sepia-toned landscape. In the distance, a range of mountains is visible under a pale sky. In the foreground on the right side, a branch of a willow tree hangs down, adorned with numerous small, dark berries. The overall aesthetic is calm and naturalistic.

*Now, we discuss
the importance of heavy ions in
simulations of space applications*

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Relative abundances of elements in cosmic rays and solar system Simpson (1983)

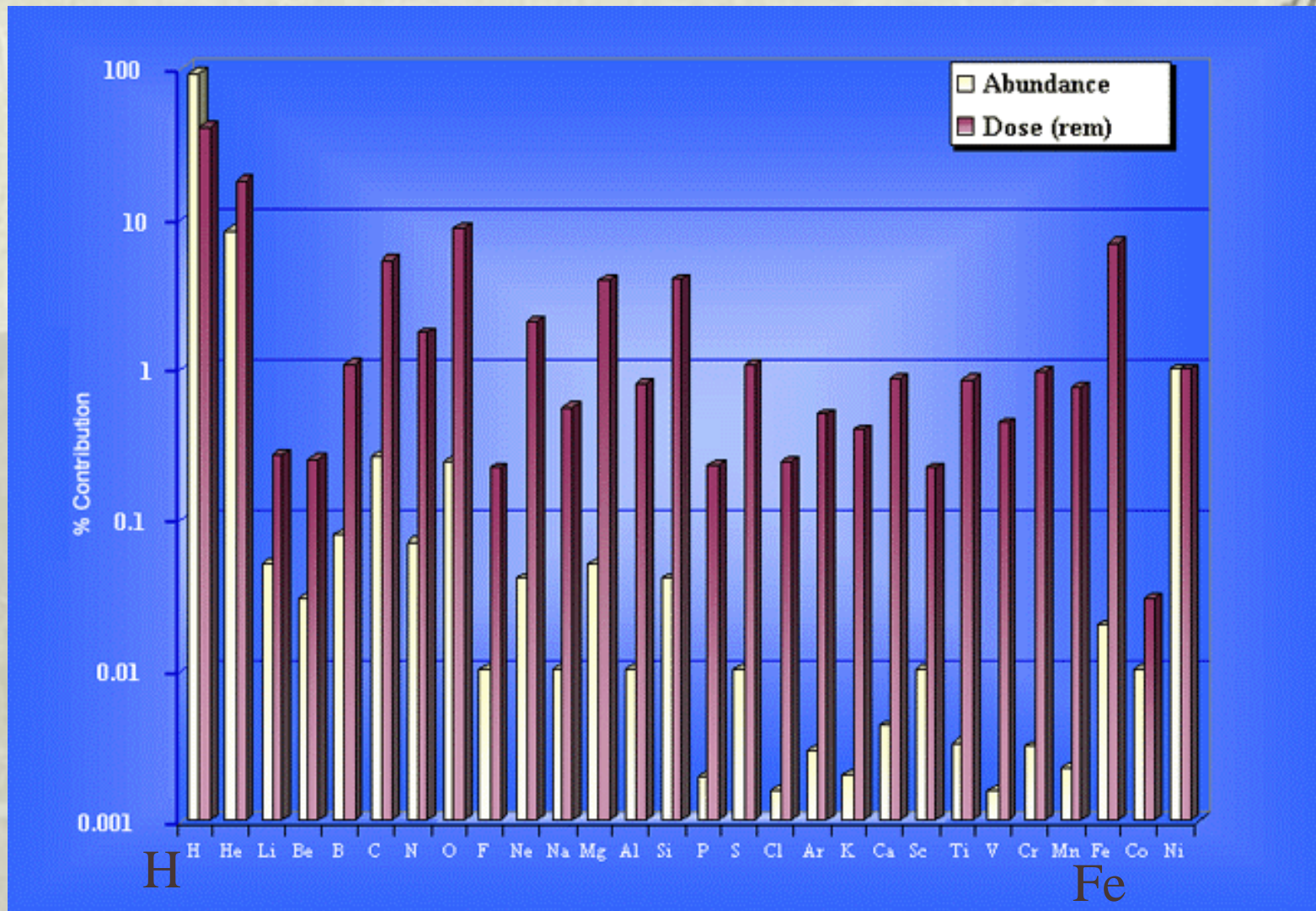


solid line: cosmic rays
open circle: high energy
close circle: low energy
dashed line: the solar system

Many kinds of heavy ion are contained
in cosmic rays.

90% of cosmic rays are protons, up to
10% are heavier nuclei.

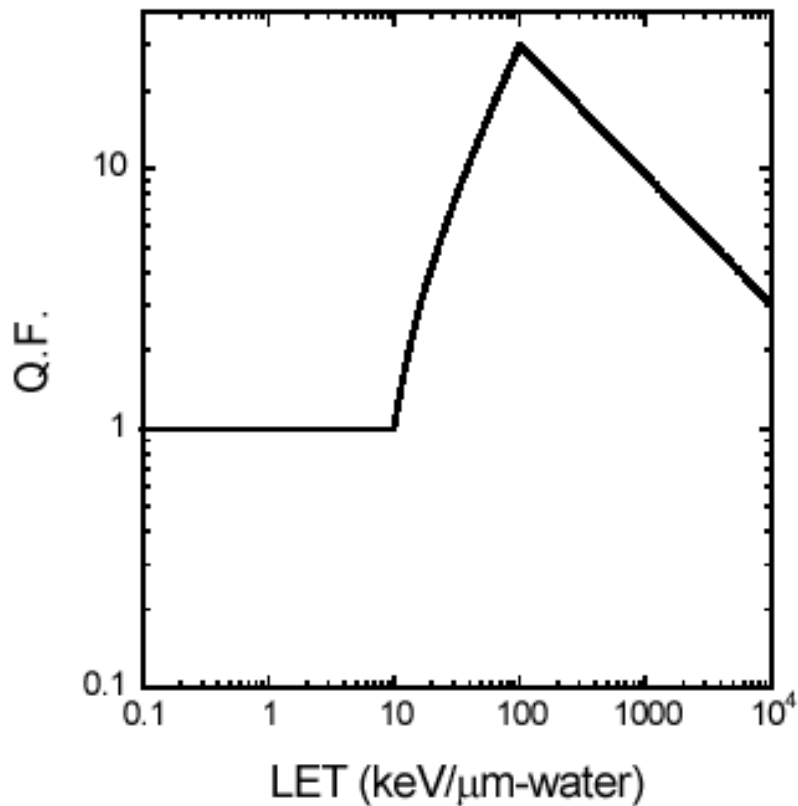
Comparison between Abundance and Dose(rem)



❖ From Web page of Space Radiation Health Project / JSC / NASA

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QL relation in ICRP pub. 60



- ❖ Biological radiation damage is not a linear function of LET (dE/dx).
- ❖ Minimum ionization level of Iron ion is located around the top of QL function.

HZE particles

- ❖ HZE (high energy and high charge) particles are less abundant, however they possess significantly higher ionizing power with a greater potential for radiation-induced damage not only for astronauts but also electronic instruments onboard spacecraft.

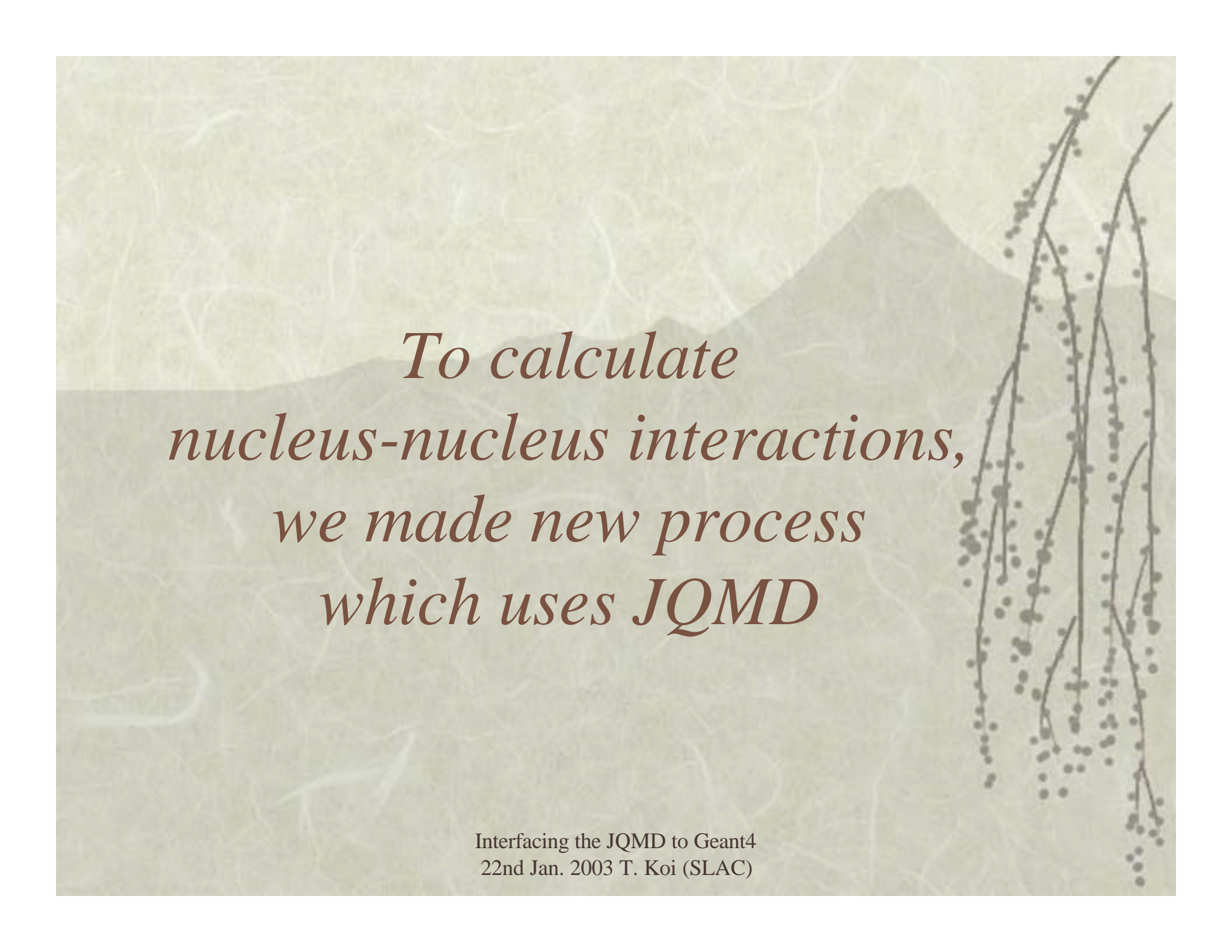
Secondary Particles

- ❖ Many neutrons, protons, gamma rays, mesons and fragmented heavy ions are produced by interaction between primary cosmic rays and shielding material of spacecraft.
- ❖ Some secondary particles have larger penetration power than the primary particle.
- ❖ Radiation weighting factor of neutrons is high.

These secondary particles are also important for the radiation environment in spacecraft.

Heavy ions in Geant4

- ❖ Definition of heavy ions
- ❖ Processes available in Geant4
 - Transportation
 - Several physical processes for heavy ions, for example, ionization process can be applied to heavy ions.

The background of the slide features a light beige, textured paper-like surface. In the upper right, a dark silhouette of a mountain range is visible. On the right side, a dark, thin branch of a willow tree hangs down, adorned with numerous small, dark, round buds.

*To calculate
nucleus-nucleus interactions,
we made new process
which uses JQMD*

Interfacing the JQMD to Geant4
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JQMD

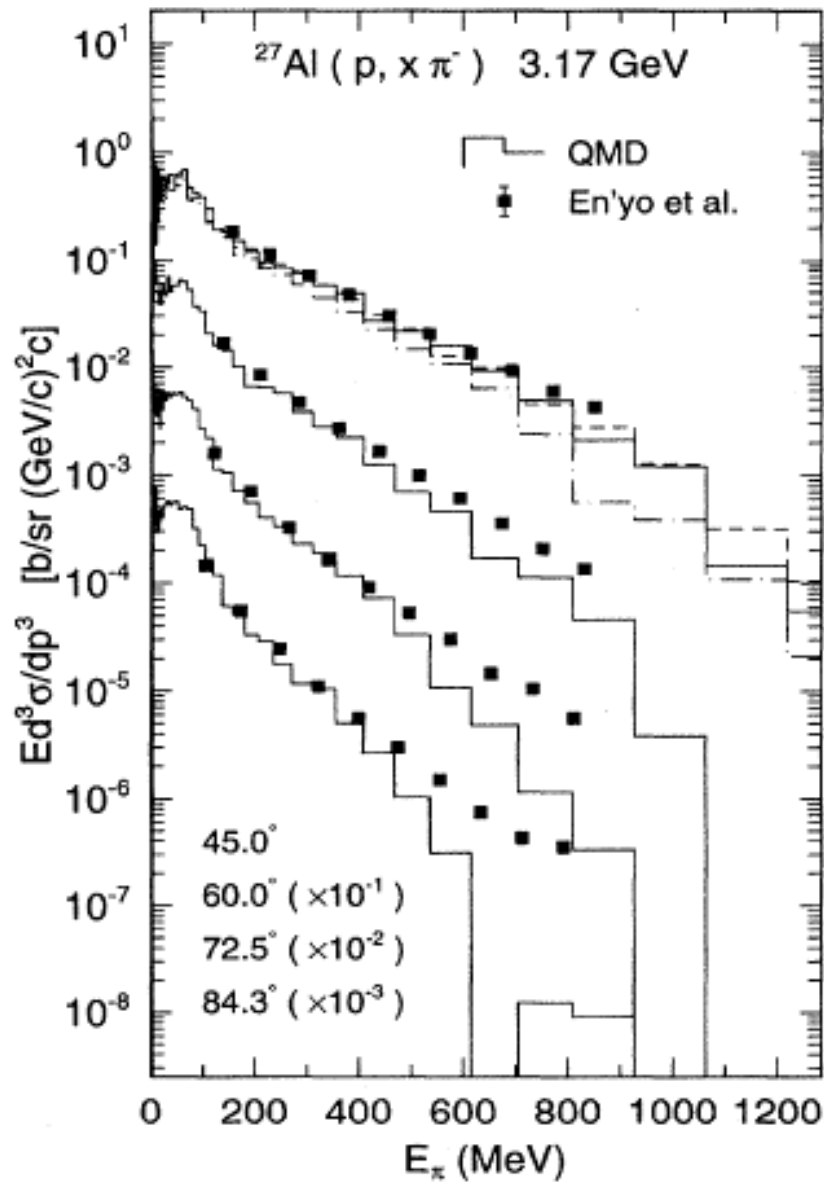
- ❖ QMD (Quantum Molecular Dynamics) is quantum extension of classical molecular-dynamics model.
- ❖ QMD model is widely used to analyze various aspects of heavy ion reactions
- ❖ JQMD (Jaeri QMD) is a QMD code developed by JAERI
(Japan Atomic Energy Research Institute).
- ❖ Written in Fortran

JQMD (cont.)

- ❖ Energy Range of JQMD
several 10 MeV/N ~ about 3 GeV/N
- ❖ Projectile particle species
nucleon (including proton) and pion
- ❖ SDM (Statistical Decay Model)
JQMD includes SDM, i.e., evaporation
and fission decays occur for excited nucleus
- ❖ Detailed description of JQMD is given in
Niita et al, Physical Review C 52 (1995) 2620
- ❖ PHITS code niita@hadron03.tokai.jaeri.go.jp

Pi-minus from 3.17 GeV on Al

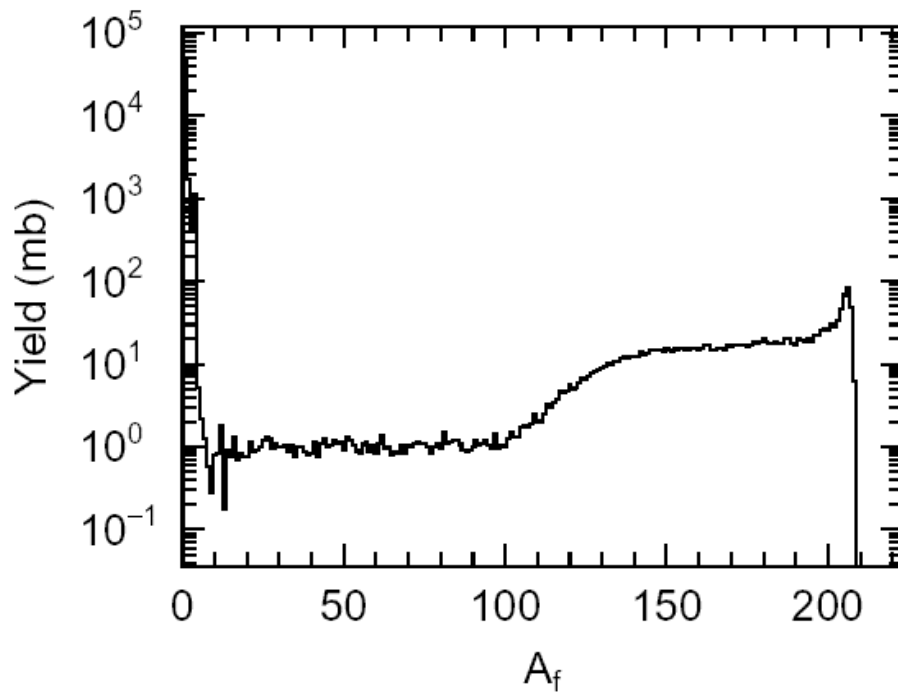
Niita et al,
Physical Review
C 52 (1995) 2620



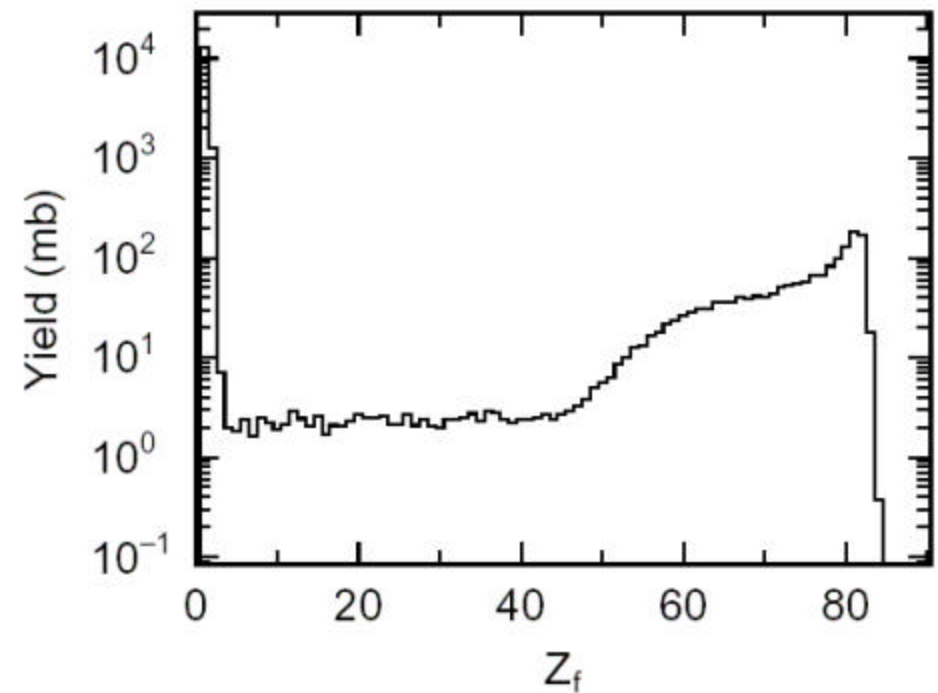
Fragment Ions Production

3.17 GeV p on Pb

Mass Distribution of SDM

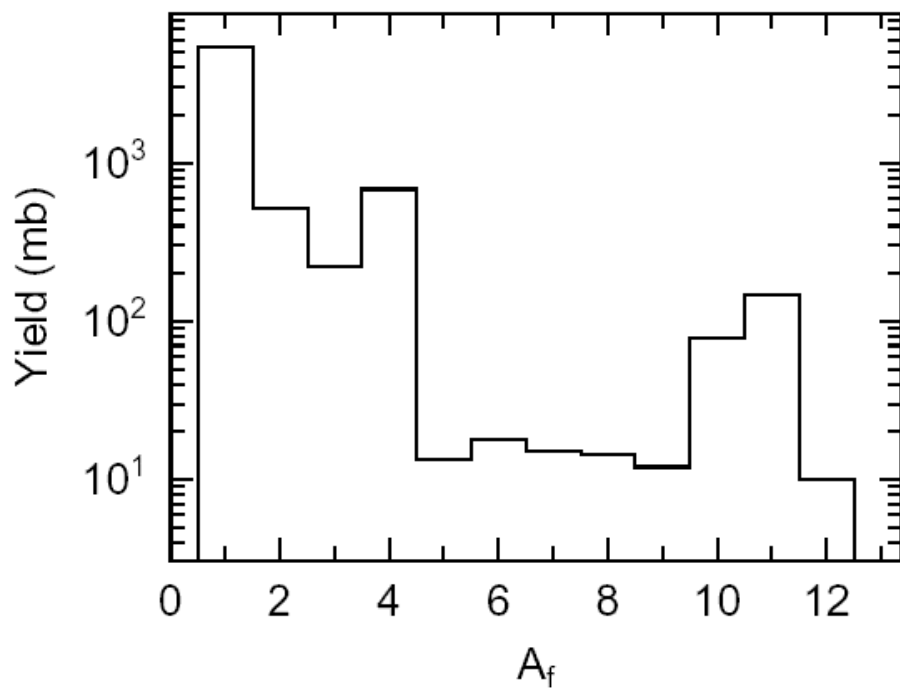


Charge Distribution of SDM

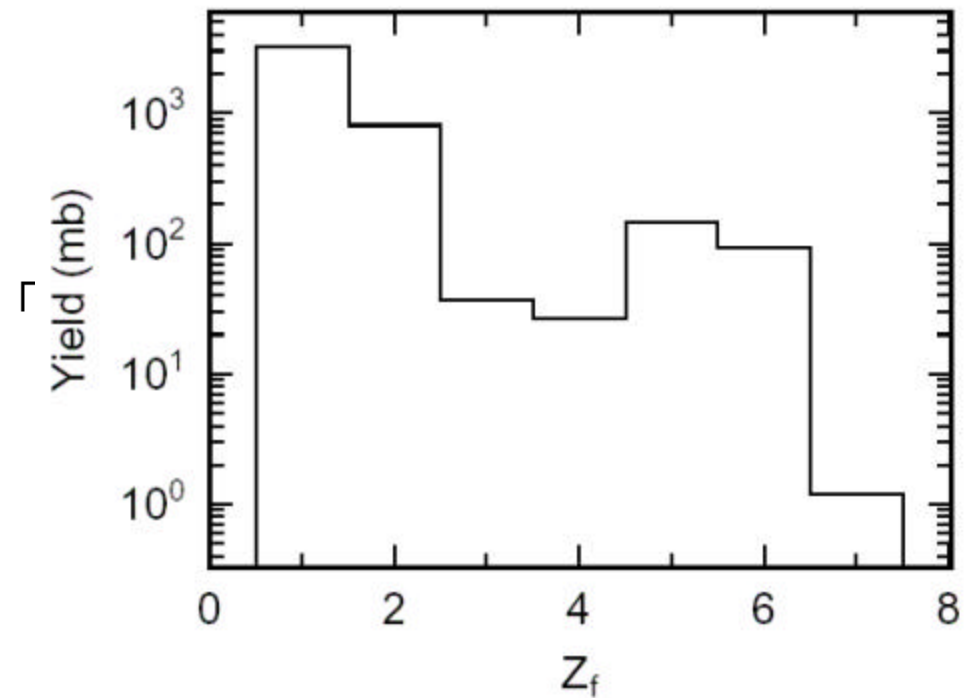


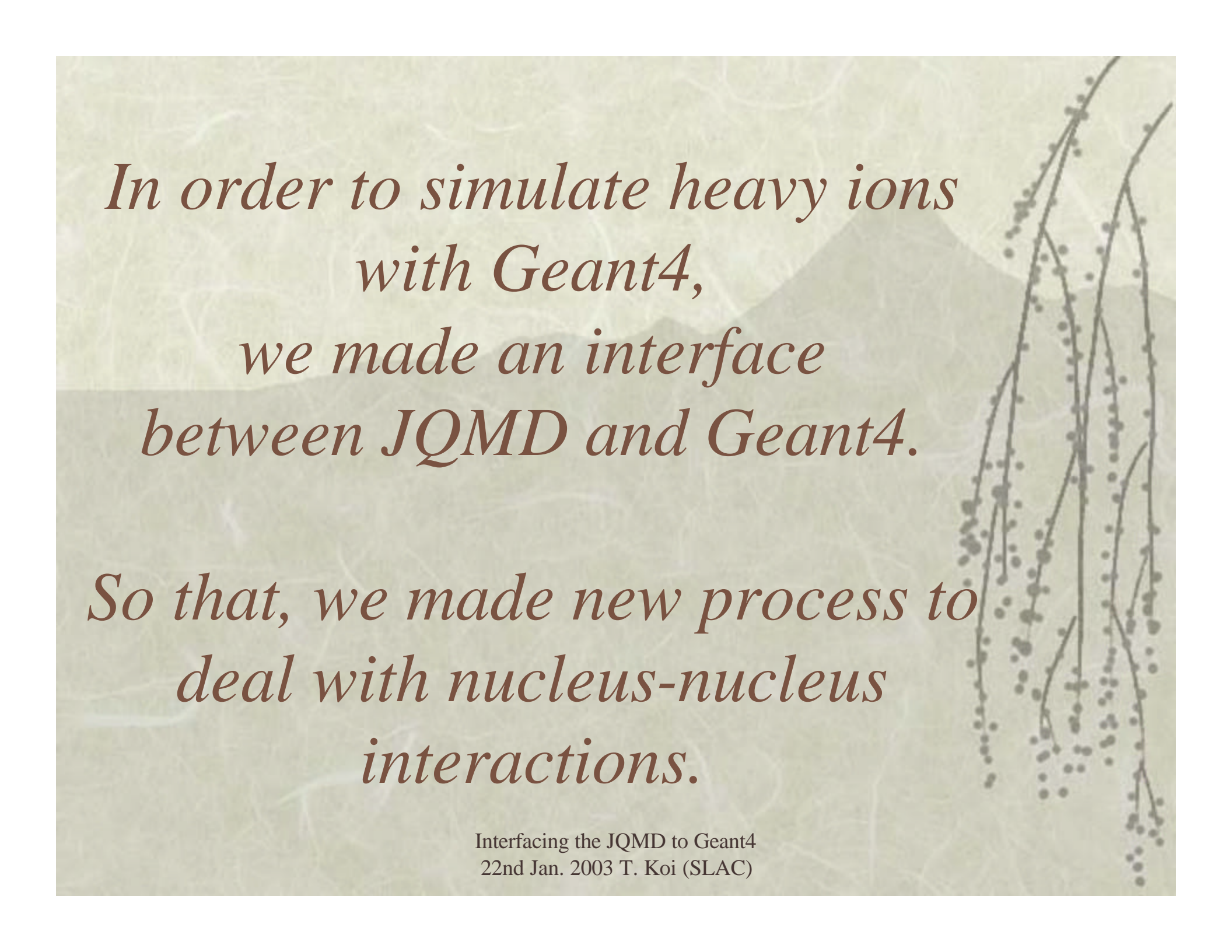
Fragment Ions Production 1 GeV/N C on C

Mass Distribution of SDM



Charge Distribution of SDM





*In order to simulate heavy ions
with Geant4,
we made an interface
between JQMD and Geant4.*

*So that, we made new process to
deal with nucleus-nucleus
interactions.*

What Does a Process Do in Geant4

- ❖ Decides when and where an interaction will occur (GetPhysicalInteractionLength)
 - Cross section
- ❖ Generates the final state (DoIt)
 - Reaction model

Cross Section for heavy ions

GetCrossSection()

❖ Tripathi Formula

- NASA Technical Paper 3621 (1997)
- G4TripathiCrossSection

❖ Shen Formula

- Nuclear Physics. A 491 (1989) 130
- JQMD2G4ShenCrossSection

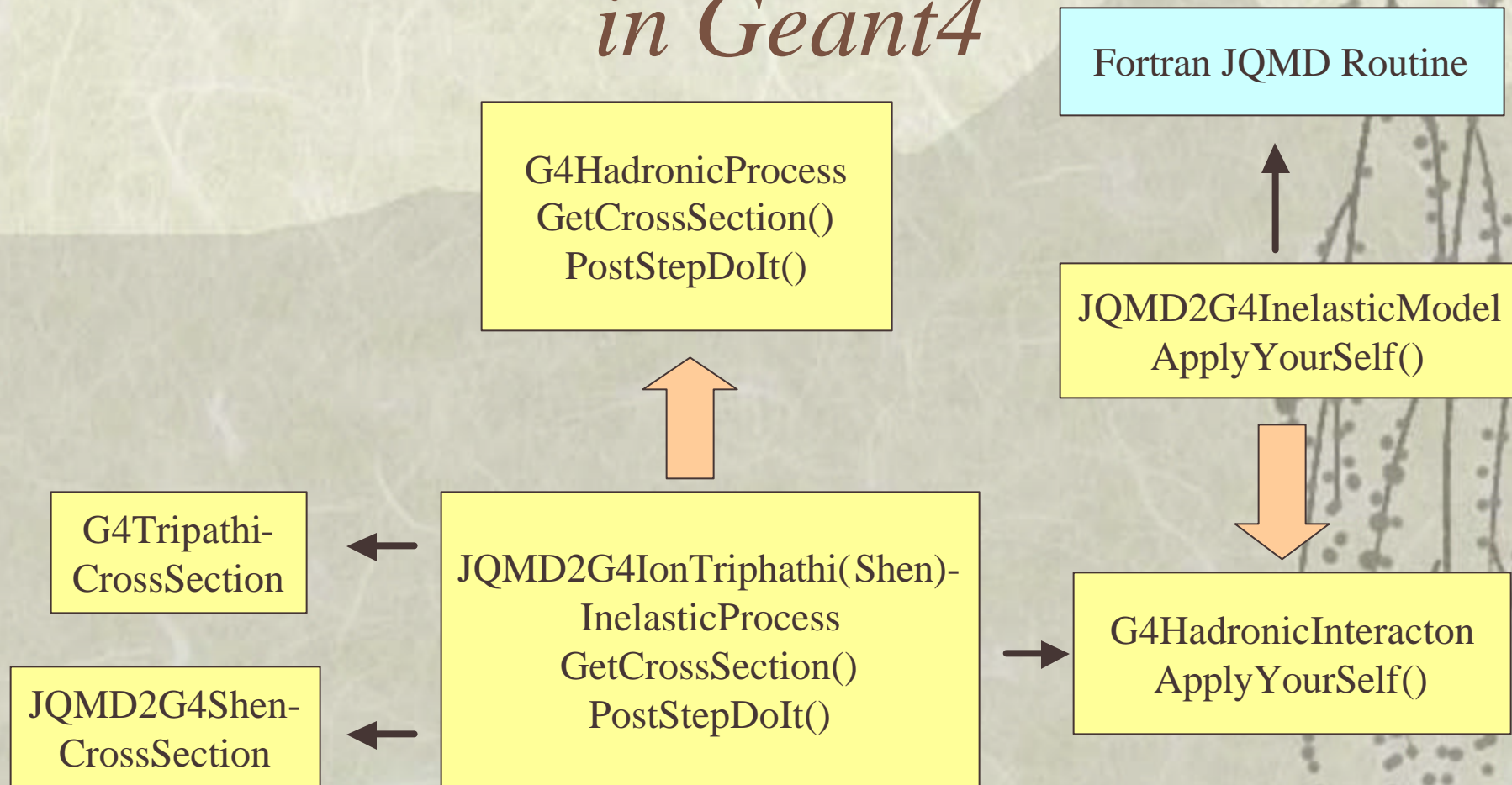
Reaction for heavy ions
ApplyYourself()

JQMD2G4IonInelasticModel

In this class,

Fortran JQMD Routine is called.

Framework of Ion Interactions in Geant4



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Using Fortran routines from C++

- ❖ Tested system
 - OS: Red Hat Linux 7.2 (6.2)
 - Compiler: gcc-2.95.3 (2.91.66 with egcs-1.1.2)
- ❖ We did not test this interface in other OS and compilers. Perhaps small modifications will be required.

Demonstrations

- ❖ N03HJQMD
- ❖ ICRU Sphere

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Simulation snapshot 1

The image shows a simulation snapshot in a Cygwin/XFree86 environment. The main window, titled "viewer-1 (OpenGLImmediateX)", displays a 3D visualization of particle tracks. The tracks are represented by numerous green and blue lines radiating from a central point, with a white grid overlaid on the scene. A mouse cursor is visible in the upper left corner of the viewer window.

The terminal window, titled "xterm", displays the following simulation output:

```
1 3 5 5 1 5 2 1
1 5 6 2 11 3 2
1 2 2 4 4 2 5 3 2
1 1 3 5 6 9 5 3 2 1
2 4 7 3 5 5 4 5 1 1
2 2 3 2 3 2 4 1 1
1 2 4 2 2 3
2 4 1 3 3
1
1

** T = 80,00 (fm/c), Edif = 0,0043 (MeV/A), [ N, R, P ] (207, 0, 0)
1 [207 ] ( 82,125, 0 ) { 0,258 }
2 [ 1 ] ( 1, 1, 0, 0 ) Free Particles

1 1 1 1 3 1
2 1 2 4 5 3 3
2 3 3 3 5 3 7 1 1
1 2 4 4 3 3 3 6 3 1
1 1 3 6 7 210 6 2 1
2 2 8 3 6 3 4 1 2
1 4 1 6 4 7 1 2
1 4 2 2 1
3 4 2 1 1
1 1 1

1

** T = 90,00 (fm/c), Edif = 0,0048 (MeV/A), [ N, R, P ] (209, 0, 0)
1 [205 ] ( 81,124, 0 ) { 0,000 }
4 [ 1 ] ( 2, 2, 0, 0 ) Free Particles
--> End of event: 0
Absorber: total energy: 2,79248 GeV total track length: 64,9952 cm
Gap: total energy: 106,982 MeV total track length: 22,9903 cm

10 hits are stored in ExN03HJQMDColorHitsCollection.
Run terminated.
Run Summary
Number of events processed : 1
User=14,562s Real=16,422s Sys=0,015s
/vis/viewer/update
Idle>
```


Simulation snapshot 2

The image shows a simulation snapshot in a Cygwin/XFree86 environment. The main window, titled "viewer-1 (OpenGLImmediateX)", displays a particle detector visualization. The detector consists of a series of vertical strips, and a particle track is shown as a blue line with green and red segments, indicating its path through the detector. The track enters from the left and interacts with the strips, creating a complex pattern of green and red lines.

The terminal window, titled "xterm", displays simulation parameters and results. The parameters are:

```
** T = 80.00 (fm/c), Edif = 0.0070 (MeV/A), [ N, R, P ]
```

The results for the first event are:

```
1 [197] ( 81,116, 0 ) { 0.762 }
2 [ 2 ] ( 1, 1, 0 ) { 1.226 }
3 [ 2 ] ( 2, 0, 0 ) { 0.000 }
19 [ 1 ] ( 5, 13, 0, 1 ) Free Particles
```

The terminal also shows a list of hits for the first event:

```
1
2 1 4 1
1 1 3 2 3 1 1
2 2 3 3 3 8 6
1 3 5 5 6 2 4 2 1 1
1 1 6 4 2 6 4 8 5 2 1
1 1 4 6 6 9 2 4 2
2 1 5 7 3 3 2 1 1
1 1 1 2 1 2 1 2 2
1 3 1 1
1 1 1
1 1 1
```

The parameters for the second event are:

```
** T = 90.00 (fm/c), Edif = 0.0076 (MeV/A), [ N, R, P ] (219, 0, 1)
```

The results for the second event are:

```
1 [196] ( 80,116, 0 ) { 0.691 }
2 [ 2 ] ( 1, 1, 0 ) { 1.354 }
3 [ 2 ] ( 2, 0, 0 ) { 0.000 }
20 [ 1 ] ( 6, 13, 0, 1 ) Free Particles
```

The terminal also shows the total energy and track length for the second event:

```
---> End of event: 0
Absorber: total energy: 5.23144 GeV total track length: 28.3196 cm
Gap: total energy: 439.642 MeV total track length: 19.7565 cm
```

The terminal also shows the number of hits stored in the collection:

```
10 hits are stored in ExN03HJQMDCalorHitsCollection.
```

The terminal also shows the run summary:

```
Run terminated.
Run Summary
Number of events processed : 1
User=7.375s Real=8.297s Sys=0.016s
/vis/viewer/update
Idle>
```

Simulation snapshot 3

Cygwin/XFree86

viewer-0 (OpenGLImmediateX)

xterm

```
1 1 1 2 4 3 3 3 1
  3 6 4 4 1 1
  3 3 6 5 3 2 1
  1 4 2 3 1
    1 1
  2 1
```

(fm/c), Edif = 0,0085 (MeV/A), [N, R, P]

```
( 46, 69, 0 ) { 1,756 }
( 4, 4, 0 ) { 6,425 }
( 9, 7, 0, 0 ) Free Particles
```

1

1

1

```
1 1
  1 4 2
  1 2 5 1 1
  1 3 2 4 4 1 1
  1 5 4 2 3 4 2 1
  1 3 3 3 7 1
  4 7 5 5 2 3 1
  2 3 2 1 1 1
  2 1
```

1

(fm/c), Edif = 0,0093 (MeV/A), [N, R, P] (139, 0, 0)

```
( 45, 67, 0 ) { 1,174 }
( 4, 4, 0 ) { 6,046 }
( 10, 9, 0, 0 ) Free Particles
```

event: 0

total energy: 7.4e+02 MeV total track length: 7.4e+02 m

1 hits are stored in JQMDN01CalorHitsCollection.

Run terminated.

Run Summary

Number of events processed : 1

User=2,8s Real=3,4s Sys=0s

/vis/viewer/update

/vis/viewer/update

Idle>

Conclusions

- ❖ We successfully developed the interface between JQMD and Geant4.
- ❖ With this interface, we can simulate heavy ions in complex Geant4 geometries.
- ❖ Preliminary test results agree well with data. Much more validation to be done.

Further Studies planned in

- ❖ Ionization loss and multiple scattering processes dedicated to heavy ions
- ❖ Additional Cross Section tables
- ❖ Performance tuning