MONTE CARLO FROM SCRATCH

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EXPERIMENTS

in the lab	in the computer
we need to put a source	we also need to put a source
exposure is the main concern limited what-if tests for optimisation	zero exposure: no worries repeat as many times as we want
	we need to tell the code when to stop: 1. in space 2. in energy
detection is by disturbing its path, stopping the particle (at least partially)	perfect detection: can detect without perturbing the particle -- non-intrusive observer
to increase count rate, given the source we can't do much	to increase count rate we can -- apply shortcuts intelligently -- use multiple computers simultaneously

EXPERIMENTS

in the computer
we also need to put a source
zero exposure: no worries repeat as many times as we want
we need to tell the code when to stop: 1. in space — to avoid tracking to the end of the earth 2. in energy — to avoid tracking forever
perfect detection: can detect without perturbing the particle -- non-intrusive observer
to increase count rate we can -- apply shortcuts intelligently -- use multiple computers simultaneously

'BLACKHOLE' / 'UNIVERSE' →

TRANSPORT CUTOFF →

'BIASING' / 'VARIANCE REDUCTION' →

CLUSTER / GRID COMPUTING →

A GENERIC IRRADIATION CONDITION

FURTHER EXPERIMENTS

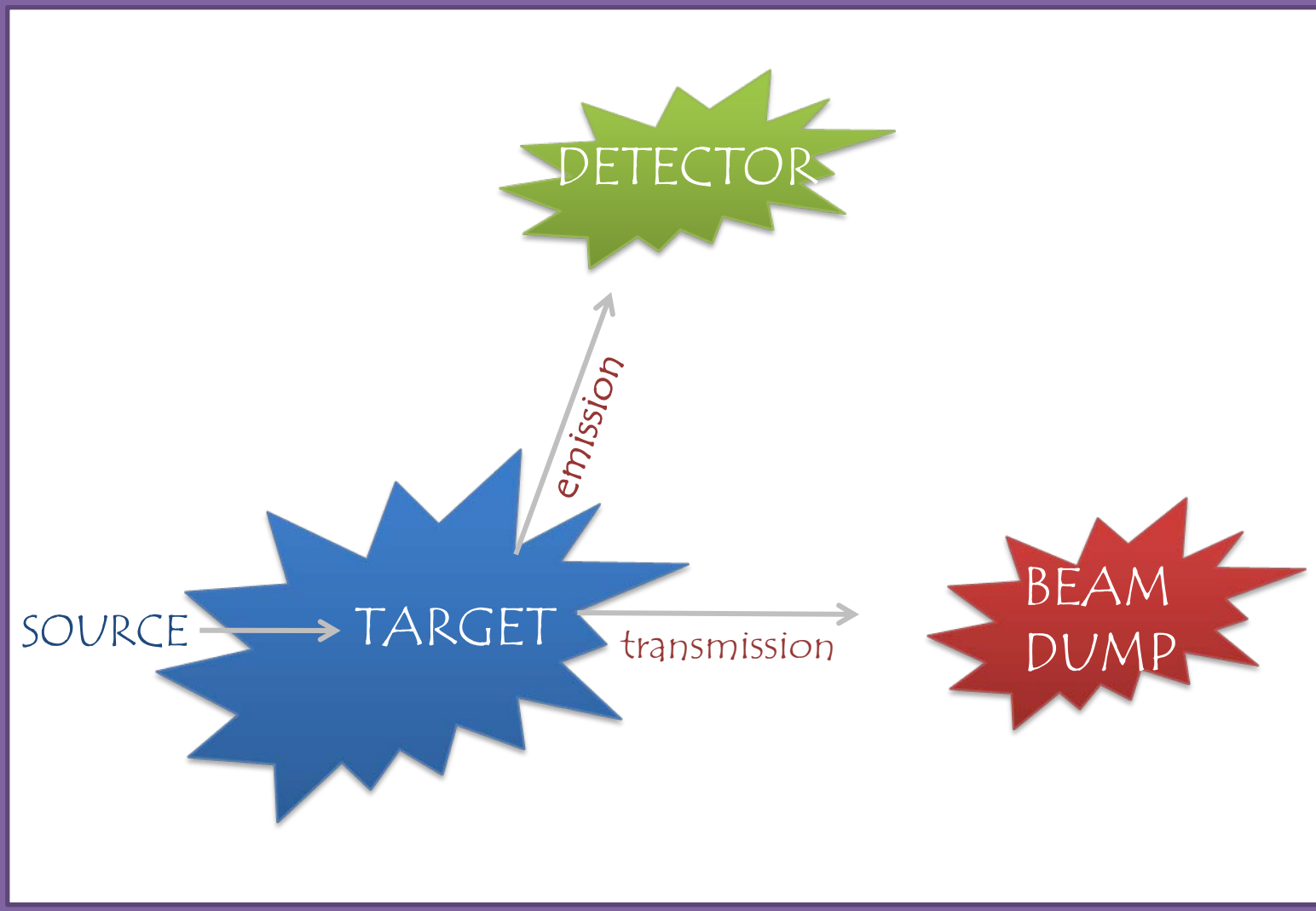
- MEASURE CROSS SECTIONS
- ORIGIN OF UNIVERSE

TO PROBE

- ANTIQUES / SAMPLES (ARCHEOLOGY/FORENSICS)
- BODY intact/parts (MEDICAL DIAGNOSIS)

TO DESTROY

- MICROBES (FOOD IRRADIATION)
- TUMOUR (RADIOTHERAPY)



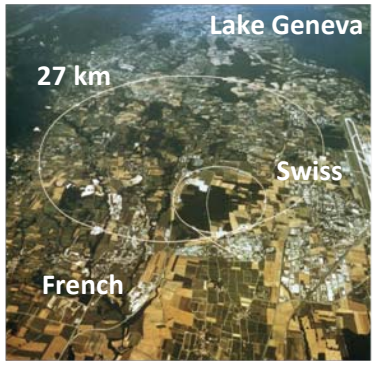
SHIELDING

THE SOURCE

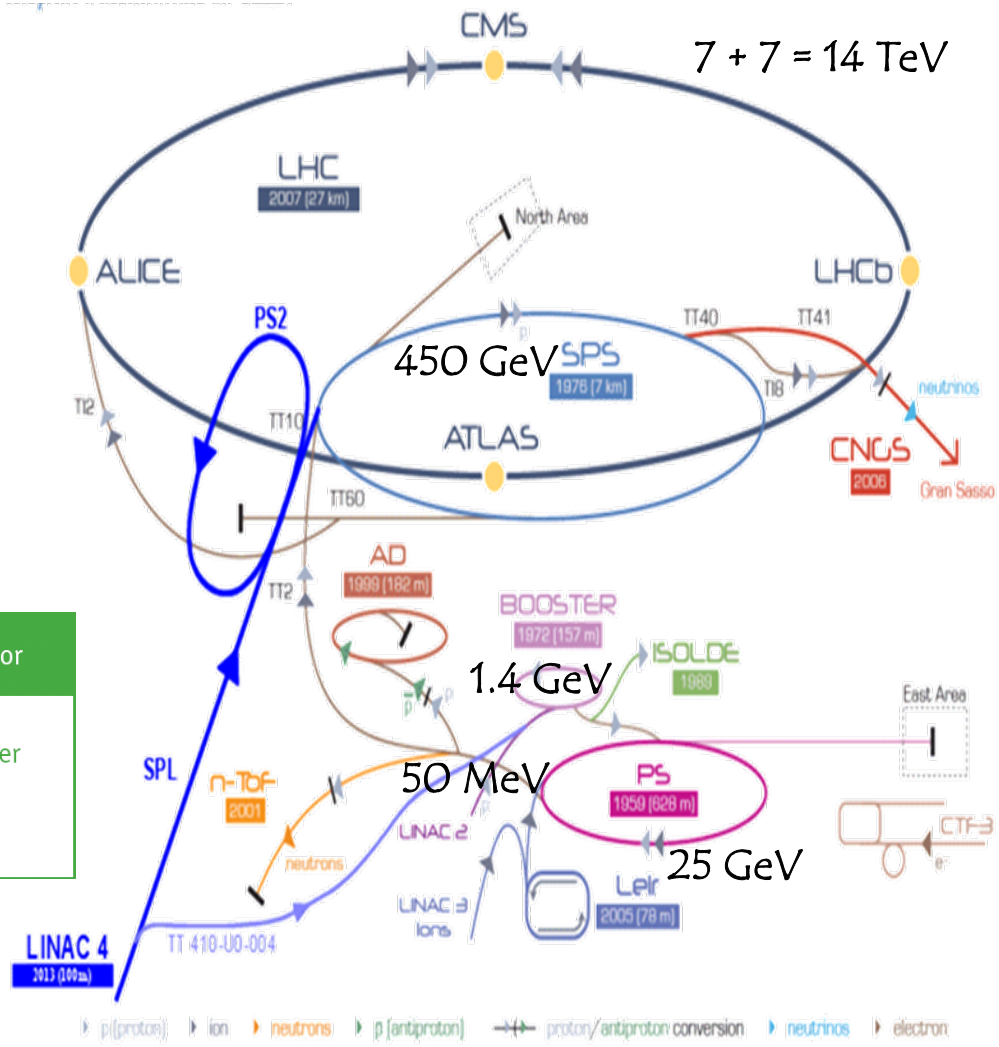
may be as simple as a point source eg. ^{60}Co, ^{137}Cs

THE SOURCE

may be as simple as a point source eg. ^{60}Co, ^{137}Cs
or may have a complex beam-line behind it

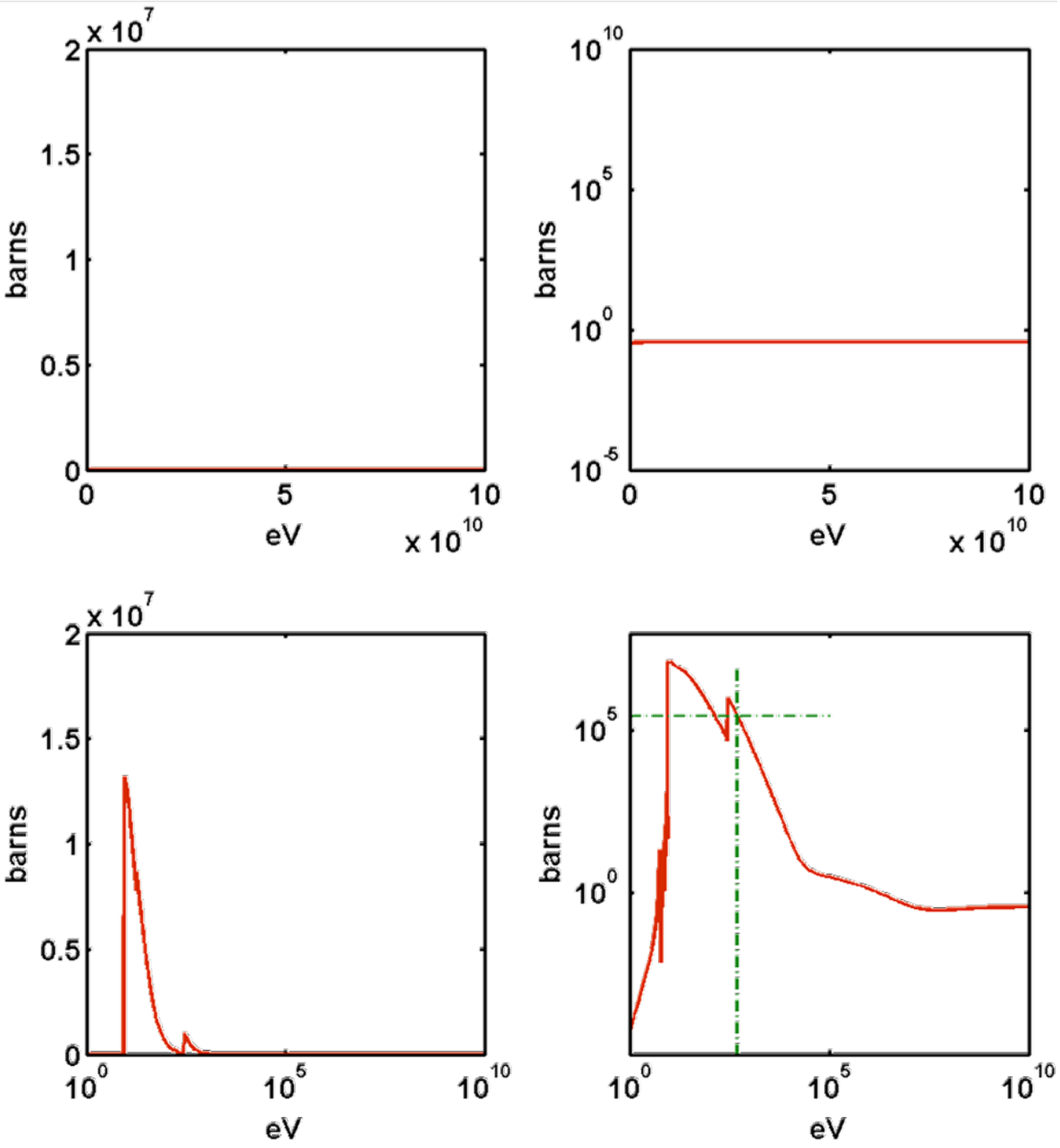


Kinetic energy of a proton (K)	Speed (%c)	Accelerator
50 MeV	31.4	Linac 2
1.4 GeV	91.6	PS Booster
25 GeV	99.93	PS
450 GeV	99.9998	SPS
7 TeV	99.9999991	LHC



an example

(which is the) photon cross-sections for carbon



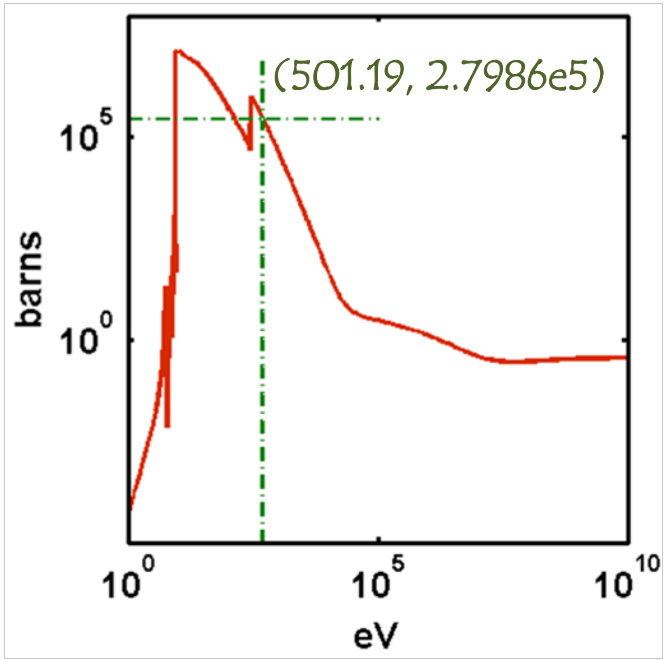
2.7986e5 barns $\rightarrow$ 2.7986e-19 cm^2 × 6.0221415e23 / 12 g × 2 g cm^{-3}

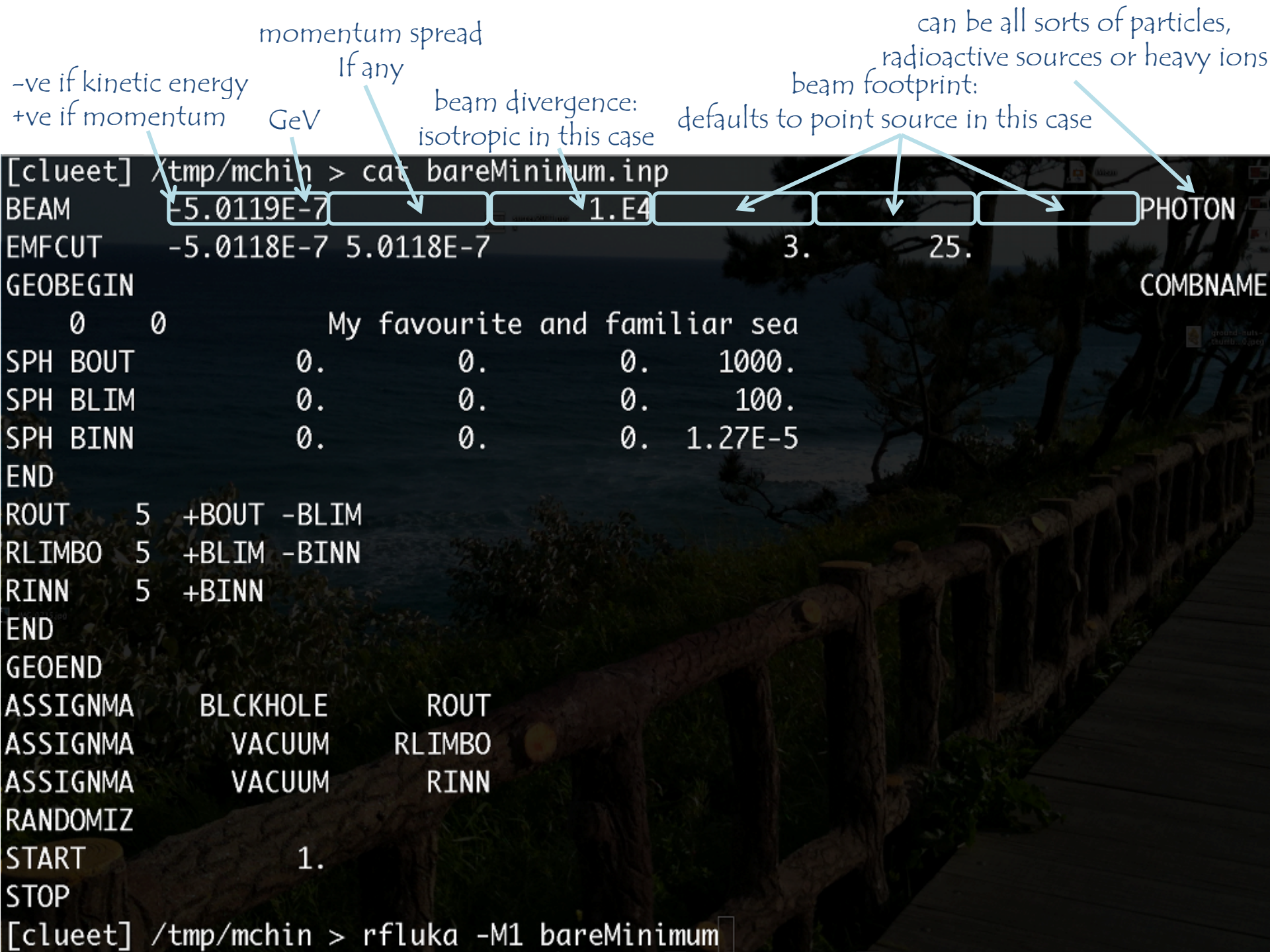
= 2.8089e4 cm^{-1} (this is the μ)

Now we can find the thickness required to get 70% transmission,

$N=N_o e^{-\mu x}$, $N/N_o = 0.7 \Rightarrow x = 1.2698e\text{-}5$ cm (< 1 microns!)

WE ARE GOING TO PUT THIS THROUGH OUR FIRST MONTE CARLO SIMULATION




momentum spread
If any
-ve if kinetic energy
+ve if momentum
GeV
beam divergence:
isotropic in this case
can be all sorts of particles,
radioactive sources or heavy ions
beam footprint:
defaults to point source in this case
[clueet] /tmp/mchin > cat bareMinimum.inp
BEAM -5.0119E-7 1.E4 PHOTON
EMFCUT -5.0118E-7 5.0118E-7 3. 25.
GEOBEGIN COMBNAME
0 0 My favourite and familiar sea
SPH BOUT 0. 0. 0. 1000.
SPH BLIM 0. 0. 0. 100.
SPH BINN 0. 0. 0. 1.27E-5
END
ROUT 5 +BOUT -BLIM
RLIMBO 5 +BLIM -BINN
RINN 5 +BINN
END
GEOEND
ASSIGNMA BLCKHOLE ROUT
ASSIGNMA VACUUM RLIMBO
ASSIGNMA VACUUM RINN
RANDOMIZ
START 1.
STOP
[clueet] /tmp/mchin > rfluka -M1 bareMinimum

```
[clueet] /tmp/mchin > cat bareMinimum.inp
BEAM       -5.0119E-7                    1.E4                                  PHOTON
EMFCUT     -5.0118E-7 5.0118E-7                          3.        25.
GEOBEGIN                                                                       COMBNAME
    0    0          My favourite and familiar sea
SPH BOUT              0.         0.         0.     1000.
SPH BLIM              0.         0.         0.      100.
SPH BINN              0.         0.         0.  1.27E-5
END
ROUT     5  +BOUT -BLIM
RLIMBO   5  +BLIM -BINN
RINN     5  +BINN
END
GEOEND
ASSIGNMA    BLCKHOLE       ROUT
ASSIGNMA      VACUUM     RLIMBO
ASSIGNMA      VACUUM       RINN
RANDOMIZ
START                 1.
STOP
[clueet] /tmp/mchin > rfluka -M1 bareMinimum
```

the geometry
shapes and sizes

the composition
without which can't
lookup cross-sections
and other properties

THE INPUT FILE

the handshake between the user and the code so that

- the code doesn't run exactly the same experiment every time
  (we don't want a calculator which calculates 1+2 each time we use it)
- users don't have to do programming and recompile the code every time

```
[clueet] /tmp/mchin > cat bareMinimum.inp
BEAM       -5.0119E-7                    1.E4                                  PHOTON
EMFCUT     -5.0118E-7 5.0118E-7                        3.        25.
GEOBEGIN                                                                       COMBNAME
    0    0          My favourite and familiar sea
SPH BOUT            0.         0.         0.     1000.
SPH BLIM            0.         0.         0.      100.
SPH BINN            0.         0.         0.  1.27E-5
END
ROUT     5  +BOUT -BLIM
RLIMBO   5  +BLIM -BINN
RINN     5  +BINN
END
GEOEND
ASSIGNMA     BLCKHOLE       ROUT
ASSIGNMA       VACUUM     RLIMBO
ASSIGNMA       VACUUM       RINN
RANDOMIZ
START               1.
STOP
[clueet] /tmp/mchin > rfluka -M1 bareMinimum
```

A SIMPLE SIMULATION

in this case

```
[clueet] /tmp/mchin > cat bareMinimum.inp
BEAM       -5.0119E-7                    1.E4                                PHOTON
EMFCUT     -5.0118E-7 5.0118E-7                        3.        25.
GEOBEGIN                                                                     COMBNAME
    0    0          My favourite and familiar sea
SPH BOUT           0.          0.          0.     1000.
SPH BLIM           0.          0.          0.      100.
SPH BINN           0.          0.          0.  1.27E-5
END
ROUT     5  +BOUT -BLIM
RLIMBO   5  +BLIM -BINN
RINN     5  +BINN
END
GEOEND
ASSIGNMA     BLCKHOLE       ROUT
ASSIGNMA       VACUUM     RLIMBO
ASSIGNMA       VACUUM       RINN
RANDOMIZ
START              1.
STOP
[clueet] /tmp/mchin > rfluka -M1 bareMinimum
```

RUN !

100% escape: zero collision and zero interaction

bareMinimum001.out

(excerpt only: 3 lines out of thousands)

```
  5.0119E-07  (100.%) GeV available per beam particle divided into
Prompt radiation      Radioactive decays
  5.0119E-07  (100.%)   0.0000E+00 ( 0.0%) GeV particles escaping the system
```

Of course!

If we surround a source with a sphere of vacuum but do not find 100% transmission, that would be worrying.

Carbon shell instead of vacuum

bareMinimum.inp

```
BEAM      -5.0119E-7                1.E4                                  PHOTON
EMFCUT    -5.0118E-7 5.0118E-7                    3.       25.
GEOBEGIN                                                                 COMBNAME
    0    0          My favourite and familiar sea
SPH BOUT          0.        0.        0.    1000.
SPH BLIM          0.        0.        0.     100.
SPH BINN          0.        0.        0.  1.27E-5
END
ROUT    5  +BOUT -BLIM
RLIMBO  5  +BLIM -BINN
RINN    5  +BINN
END
GEOEND
ASSIGNMA    BLCKHOLE      ROUT
ASSIGNMA      VACUUM    RLIMBO
ASSIGNMA      VACUUM      RINN
RANDOMIZ
START           1.
STOP
```

halfStepUp.inp

```
BEAM      -5.0119E-7                1.E4                                  PHOTON
EMFCUT    -5.0118E-7 5.0118E-7                    3.       25.
GEOBEGIN                                                                 COMBNAME
    0    0          My favourite and familiar sea
SPH BOUT          0.        0.        0.    1000.
SPH BLIM          0.        0.        0.     100.
SPH BINN          0.        0.        0.  1.27E-5
END
ROUT    5  +BOUT -BLIM
RLIMBO  5  +BLIM -BINN
RINN    5  +BINN
END
GEOEND
ASSIGNMA    BLCKHOLE      ROUT
ASSIGNMA      VACUUM    RLIMBO
ASSIGNMA      CARBON      RINN
RANDOMIZ
START          10.
STOP
```

80% escape means 80% transmission*

halfStepUp001.out

(excerpt only: 4 lines out of thousands)

```
  5.0119E-07  (100.%) GeV available per beam particle divided into
Prompt radiation       Radioactive decays
  1.0024E-07  (20.0%)   0.0000E+00 ( 0.0%) GeV electro-magnetic showers
  4.0095E-07  (80.0%)   0.0000E+00 ( 0.0%) GeV particles escaping the system
```

... but we expected 70%

*strictly for this case only, where source was started in the heart of a sphere

INCREASING THE NUMBER OF HISTORIES

halfStepUp.inp

```
BEAM      -5.0119E-7              1.E4                                  PHOTON
EMFCUT    -5.0118E-7 5.0118E-7                3.       25.
GEOBEGIN                                                                COMBNAME
    0    0          My favourite and familiar sea
SPH BOUT          0.        0.        0.    1000.
SPH BLIM          0.        0.        0.     100.
SPH BINN          0.        0.        0.  1.27E-5
END
ROUT    5  +BOUT -BLIM
RLIMBO  5  +BLIM -BINN
RINN    5  +BINN
END
GEOEND
ASSIGNMA    BLCKHOLE      ROUT
ASSIGNMA      VACUUM    RLIMBO
ASSIGNMA      CARBON      RINN
RANDOMIZ
START           10.
STOP
```

oneStepUp.inp

```
BEAM      -5.0119E-7              1.E4                                  PHOTON
EMFCUT    -5.0118E-7 5.0118E-7                3.       25.
GEOBEGIN                                                                COMBNAME
    0    0          My favourite and familiar sea
SPH BOUT          0.        0.        0.    1000.
SPH BLIM          0.        0.        0.     100.
SPH BINN          0.        0.        0.  1.27E-5
END
ROUT    5  +BOUT -BLIM
RLIMBO  5  +BLIM -BINN
RINN    5  +BINN
END
GEOEND
ASSIGNMA    BLCKHOLE      ROUT
ASSIGNMA      VACUUM    RLIMBO
ASSIGNMA      CARBON      RINN
RANDOMIZ
START           1.E8
STOP
```

70% transmission:
now we get what we estimated

oneStepUp001.out

(excerpt only: 4 lines out of thousands)

```
  5.0119E-07  (100.%) GeV available per beam particle divided into
Prompt radiation      Radioactive decays
  1.5025E-07  (30.0%)   0.0000E+00 ( 0.0%) GeV electro-magnetic showers
  3.5094E-07  (70.0%)   0.0000E+00 ( 0.0%) GeV particles escaping the system
```

LOWERING THE TRANSPORT CUTOFFS

oneStepUp.inp

```
BEAM      -5.0119E-7                1.E4                                  PHOTON
EMFCUT    -5.0118E-7 5.0118E-7                  3.       25.
GEOBEGIN                                                                 COMBNAME
    0    0          My favourite and familiar sea
SPH BOUT          0.        0.        0.    1000.
SPH BLIM          0.        0.        0.     100.
SPH BINN          0.        0.        0.  1.27E-5
END
ROUT     5  +BOUT -BLIM
RLIMBO   5  +BLIM -BINN
RINN     5  +BINN
END
GEOEND
ASSIGNMA     BLCKHOLE      ROUT
ASSIGNMA       VACUUM    RLIMBO
ASSIGNMA       CARBON      RINN
RANDOMIZ
START          1.E8
STOP
```

twoStepsUp.inp

```
BEAM      -5.0119E-7                1.E4                                  PHOTON
EMFCUT      -1.E-7     1.E-7                  3.       25.
GEOBEGIN                                                                 COMBNAME
    0    0          My favourite and familiar sea
SPH BOUT          0.        0.        0.    1000.
SPH BLIM          0.        0.        0.     100.
SPH BINN          0.        0.        0.  1.27E-5
END
ROUT     5  +BOUT -BLIM
RLIMBO   5  +BLIM -BINN
RINN     5  +BINN
END
GEOEND
ASSIGNMA     BLCKHOLE      ROUT
ASSIGNMA       VACUUM    RLIMBO
ASSIGNMA       CARBON      RINN
RANDOMIZ
START          1.E8
STOP
```

Transmission was 100% uncollided photons; electrons and (secondary) photons from Compton and photoelectric were not tracked.
No chance to bremsstrahlung.

We see photoelectric, Compton and bremsstrahlung.

^{12}C beam instead of carbon shell

twoStepsUp.inp

```
BEAM       -5.0119E-7                 1.E4                                  PHOTON
EMFCUT        -1.E-7     1.E-7                    3.       25.
GEOBEGIN                                                                   COMBNAME
    0    0          My favourite and familiar sea
SPH BOUT          0.         0.         0.      3.E4
SPH BLIM          0.         0.         0.      2.E4
SPH BINN          0.         0.         0.   1.27E-5
END
ROUT     5  +BOUT -BLIM
RLIMBO   5  +BLIM -BINN
RINN     5  +BINN
END
GEOEND
ASSIGNMA     BLCKHOLE      ROUT
ASSIGNMA       VACUUM     RLIMBO
ASSIGNMA       CARBON      RINN
RANDOMIZ
START           1.E8
STOP
```

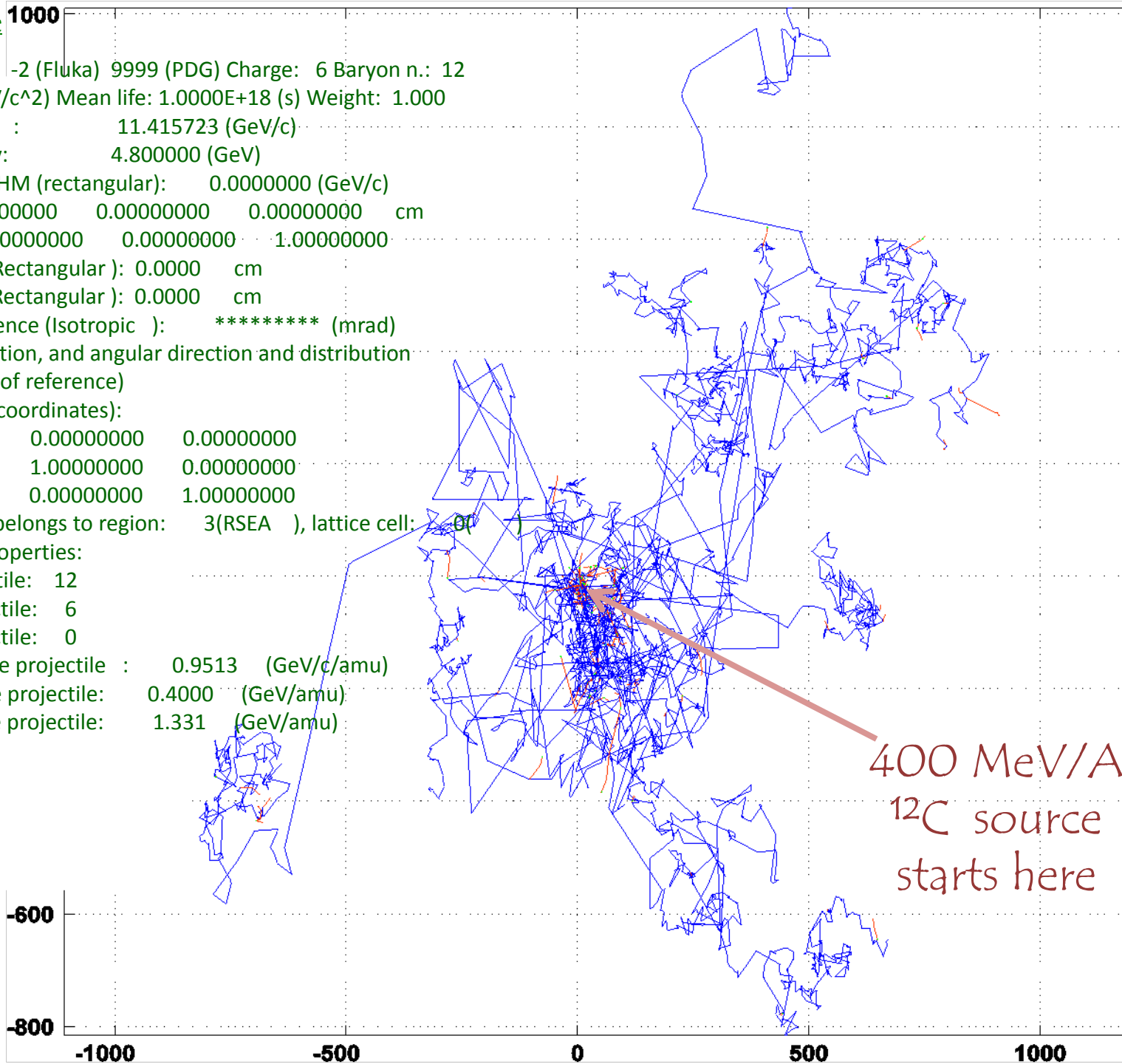
threeStepsUp.inp

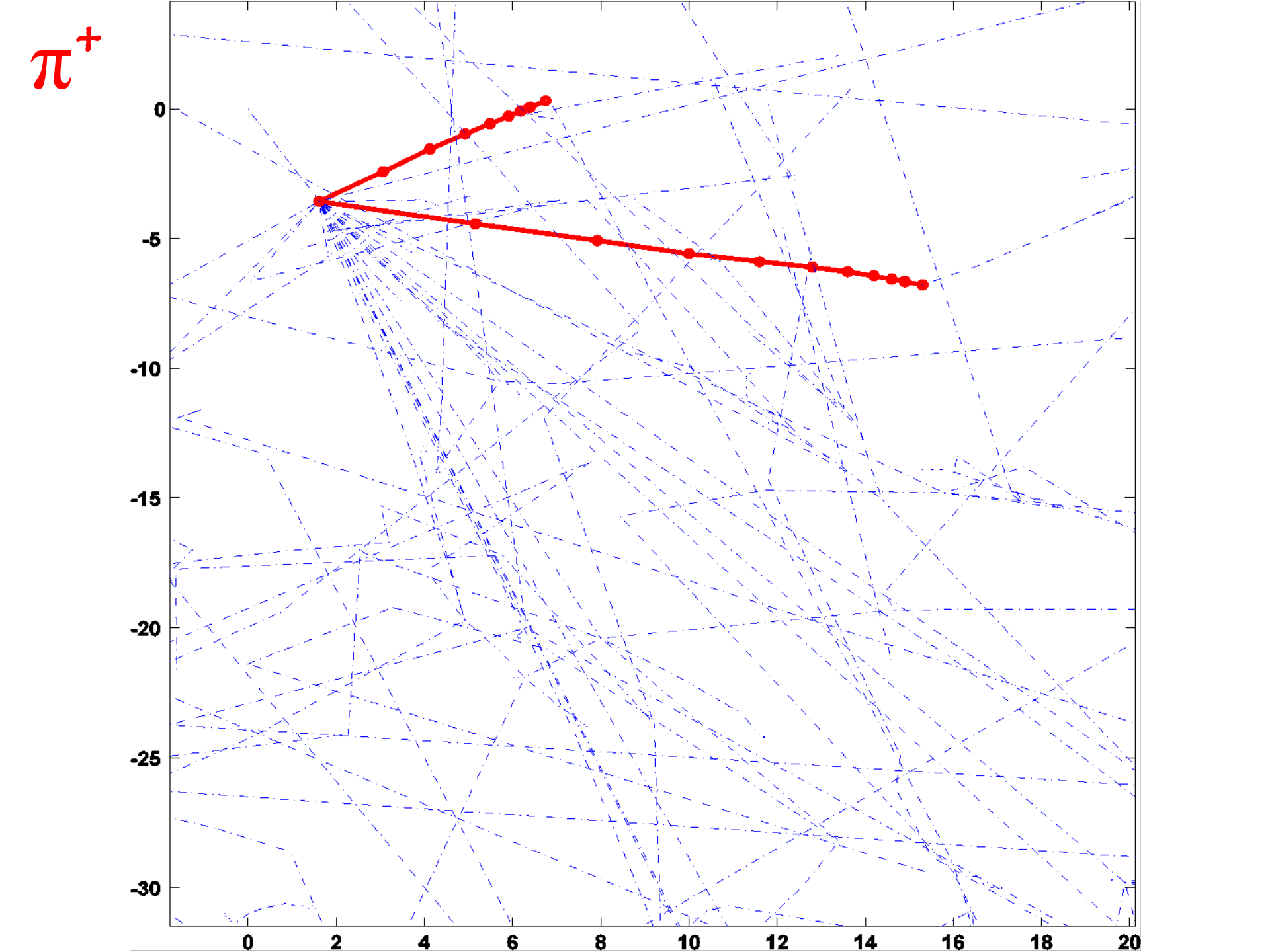
```
BEAM          -0.4                 1.E4                                  HEAVYION
HI-PROPE         6.       12.
DEFAULTS                                                                   HADROTHE
GEOBEGIN                                                                   COMBNAME
    0    0          My favourite and familiar sea
SPH BOUT          0.         0.         0.      3.E4
SPH BLIM          0.         0.         0.      2.E4
SPH BINN          0.         0.         0.       1.E4
END
ROUT     5  +BOUT -BLIM
RLIMBO   5  +BLIM -BINN
RINN     5  +BINN
END
GEOEND
ASSIGNMA     BLCKHOLE      ROUT
ASSIGNMA       VACUUM     RLIMBO
ASSIGNMA      CALCIUM      RINN
RANDOMIZ
START           1.E8
STOP
```

heavy ion transport!

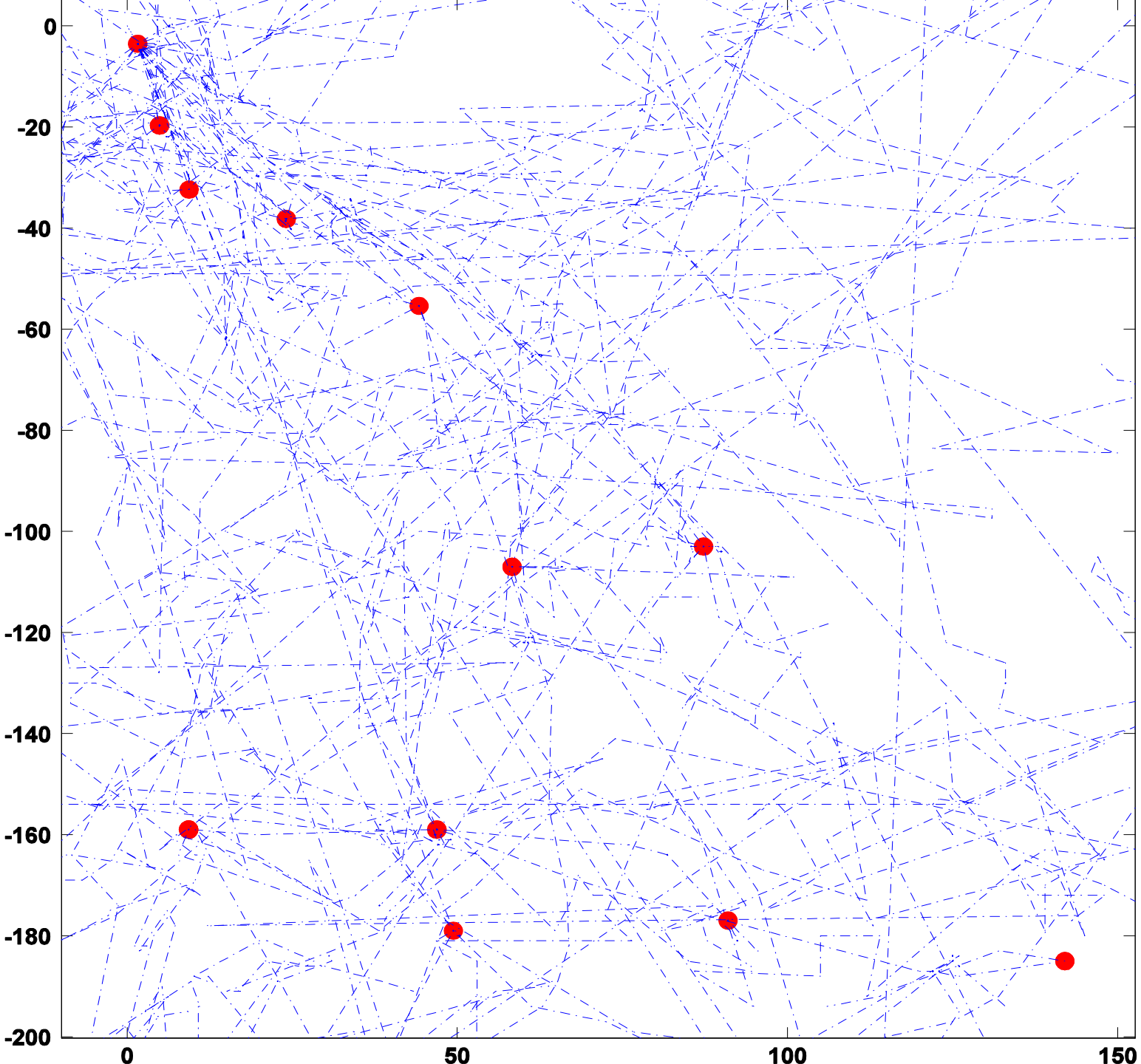
excerpt from output file

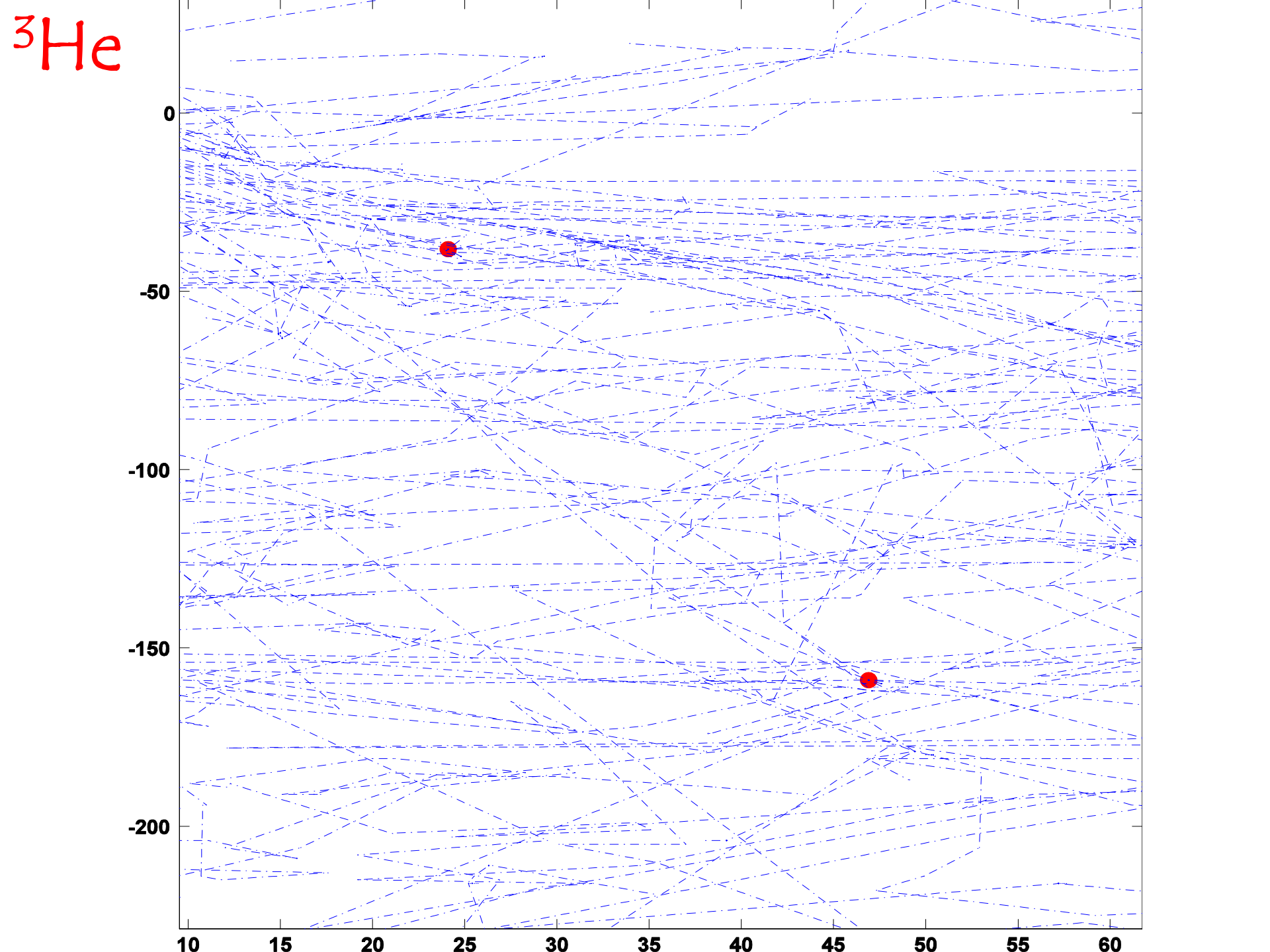
```
 Beam particle: HEAVYION Id:  -2 (Fluka)  9999 (PDG) Charge:   6 Baryon n.:  12
          Mass:  11.17     (GeV/c^2) Mean life: 1.0000E+18 (s) Weight:  1.000
 Average beam momentum      :              11.415723 (GeV/c)
 Average beam kinetic energy:              4.800000 (GeV)
 Momentum deviation at FWHM (rectangular):      0.0000000 (GeV/c)
 Beam hit position     :  0.00000000      0.00000000      0.00000000     cm
 Beam direction cosines:  0.00000000      0.00000000      1.00000000
 Beam spot FWHM X-width (Rectangular ):  0.0000     cm
 Beam spot FWHM Y-width (Rectangular ):  0.0000     cm
 Beam FWHM angular divergence (Isotropic   ):        *********  (mrad)
 (Spatial distribution, polarization, and angular direction and distribution
 are given in the beam frame of reference)
Beam reference frame (world coordinates):
   Beam X axis:   1.00000000      0.00000000      0.00000000
   Beam Y axis:   0.00000000      1.00000000      0.00000000
   Beam Z axis:   0.00000000      0.00000000      1.00000000
 The nominal beam position belongs to region:      3(RSEA    ), lattice cell:    0(
Heavy ion beam requested, properties:
 Mass   number of the projectile:   12
 Charge number of the projectile:    6
 Isomer number of the projectile:    0
 Laboratory momentum of the projectile   :      0.9513     (GeV/c/amu)
 Laboratory kin. energy of the projectile:      0.4000     (GeV/amu)
 Laboratory tot. energy of the projectile:      1.331      (GeV/amu)
```



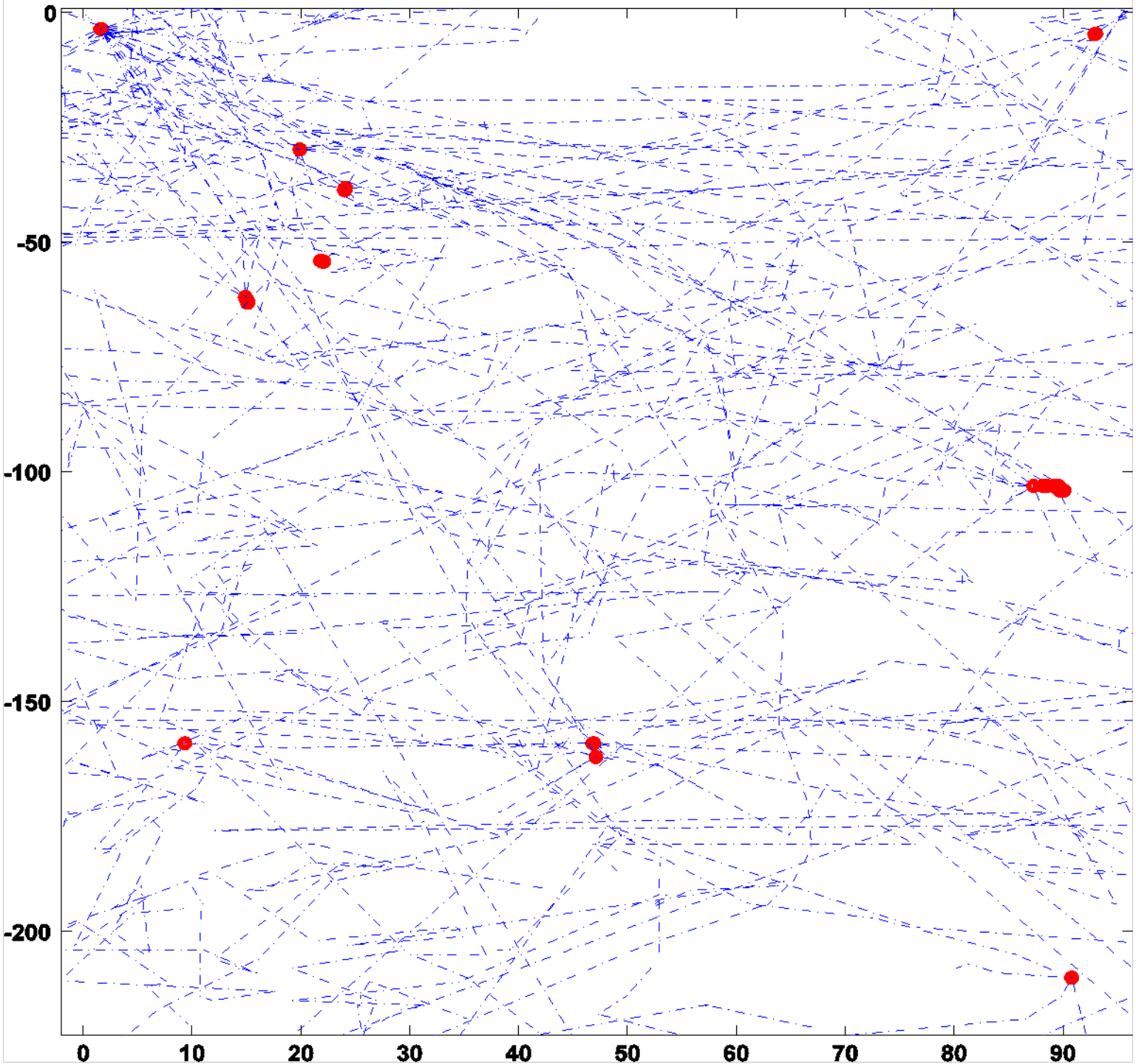

π^+
0
-5
-10
-15
-20
-25
-30
0
2
4
6
8
10
12
14
16
18
20

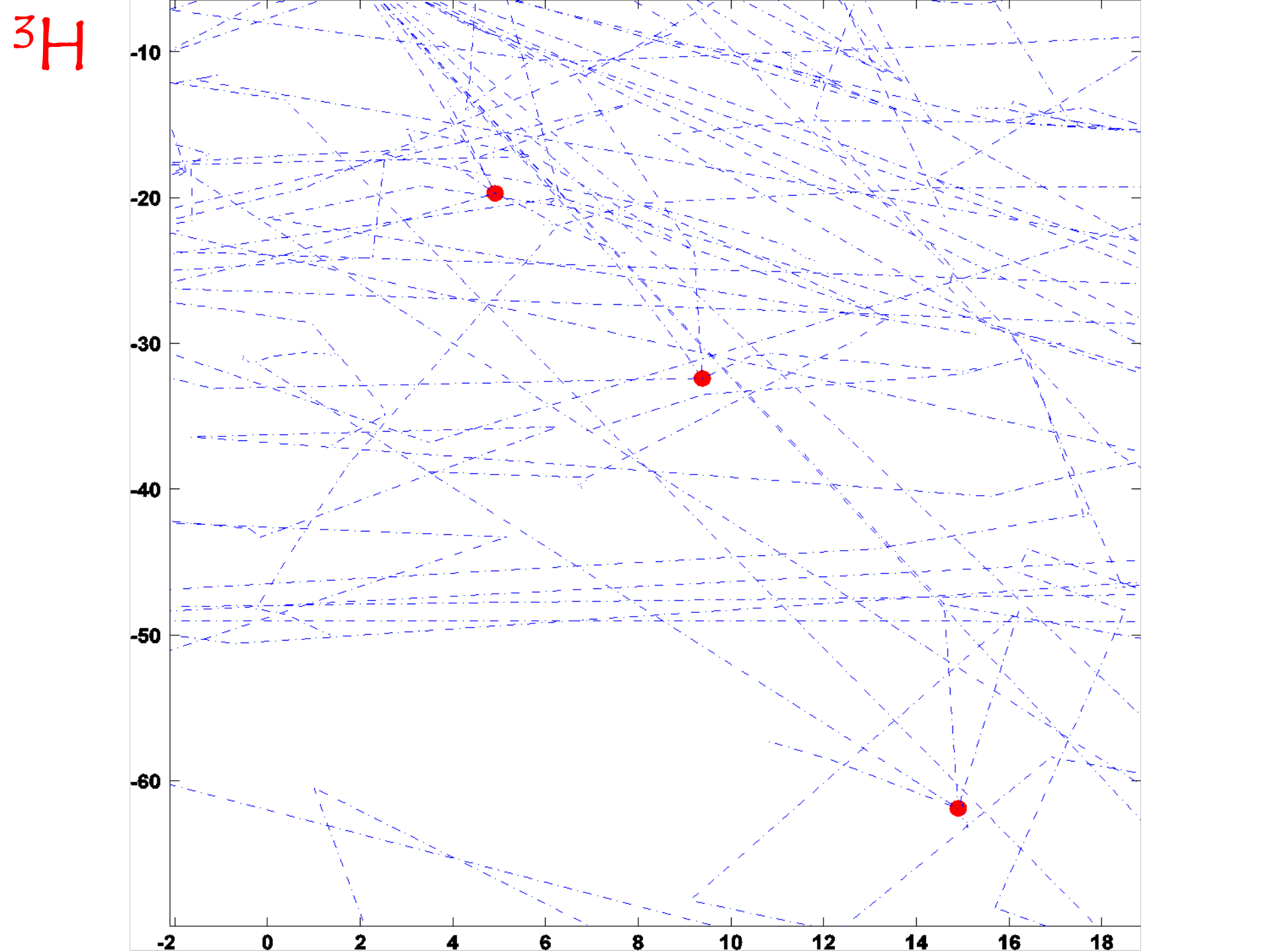
α



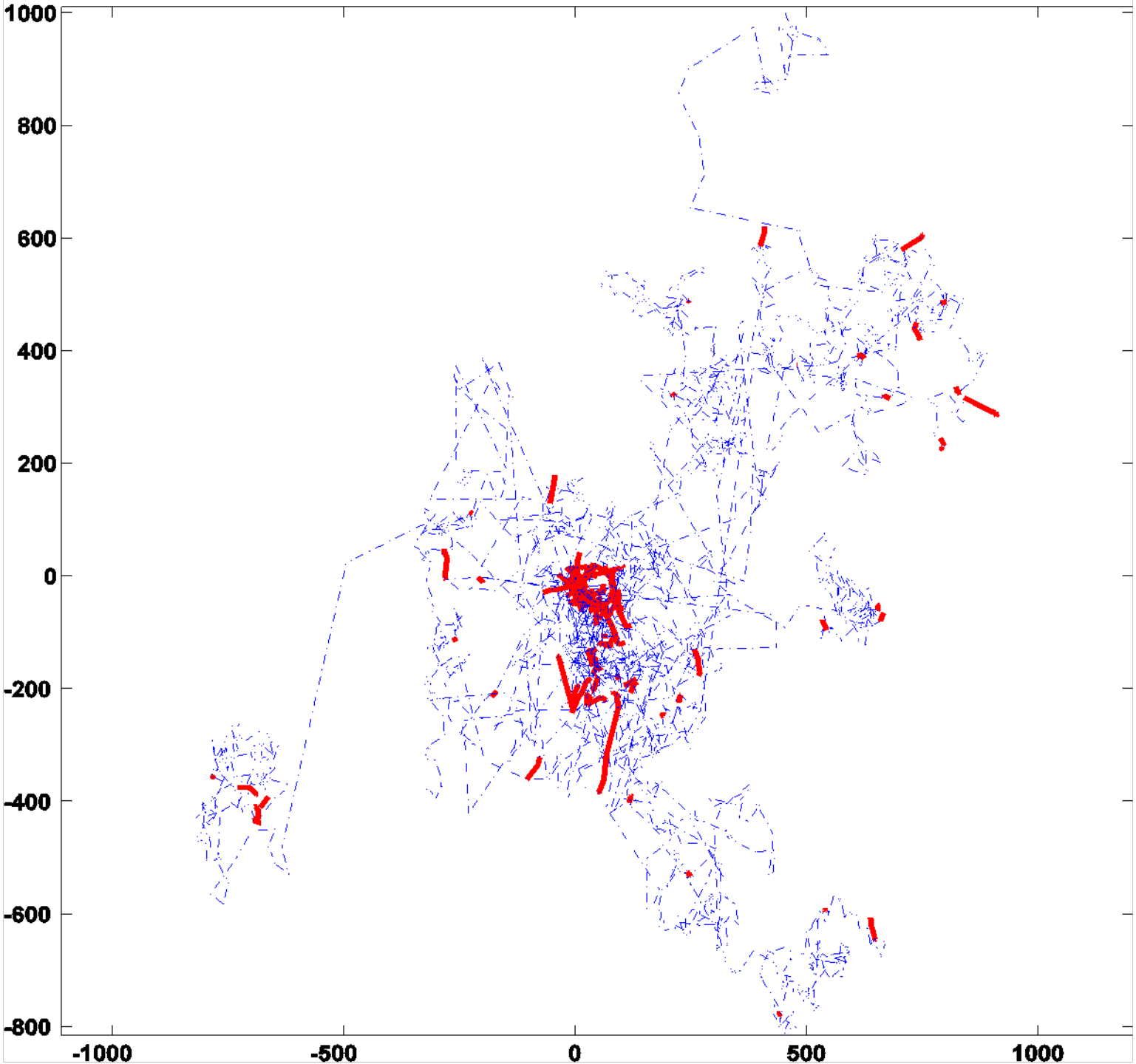

^{3}He
0
-50
-100
-150
-200
10
15
20
25
30
35
40
45
50
55
60

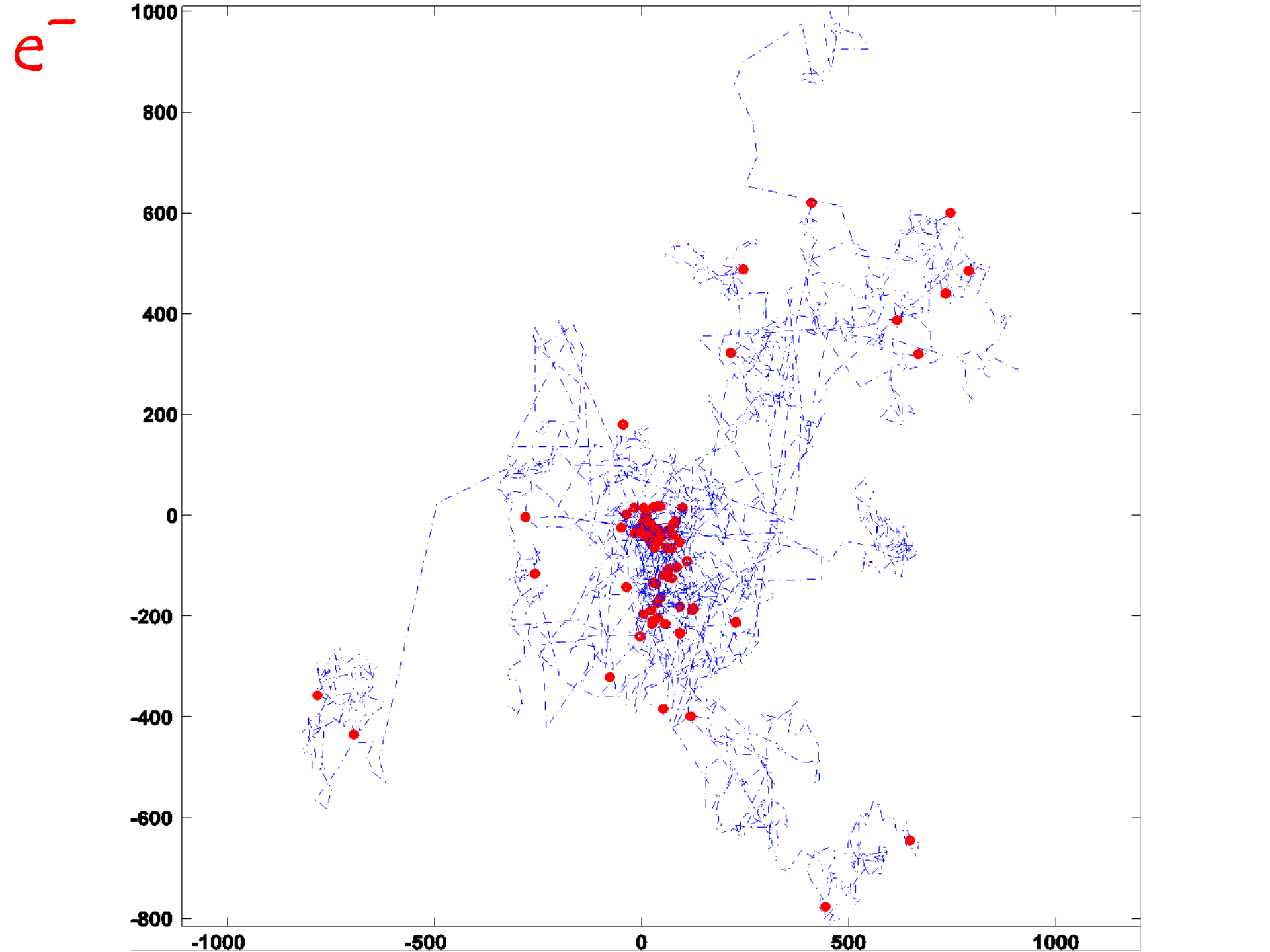
^{2}H

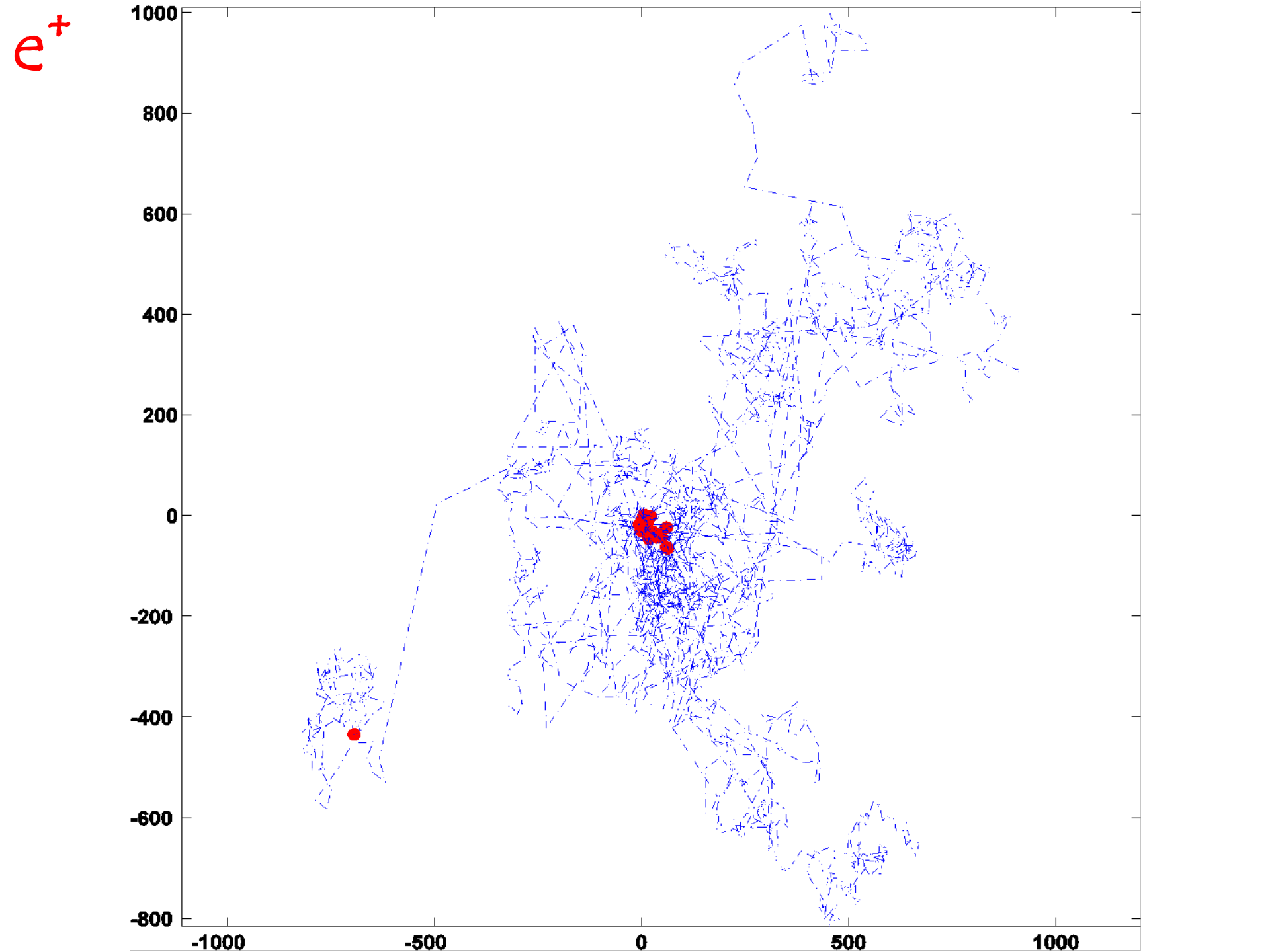



^3H
-10
-20
-30
-40
-50
-60
-2
0
2
4
6
8
10
12
14
16
18

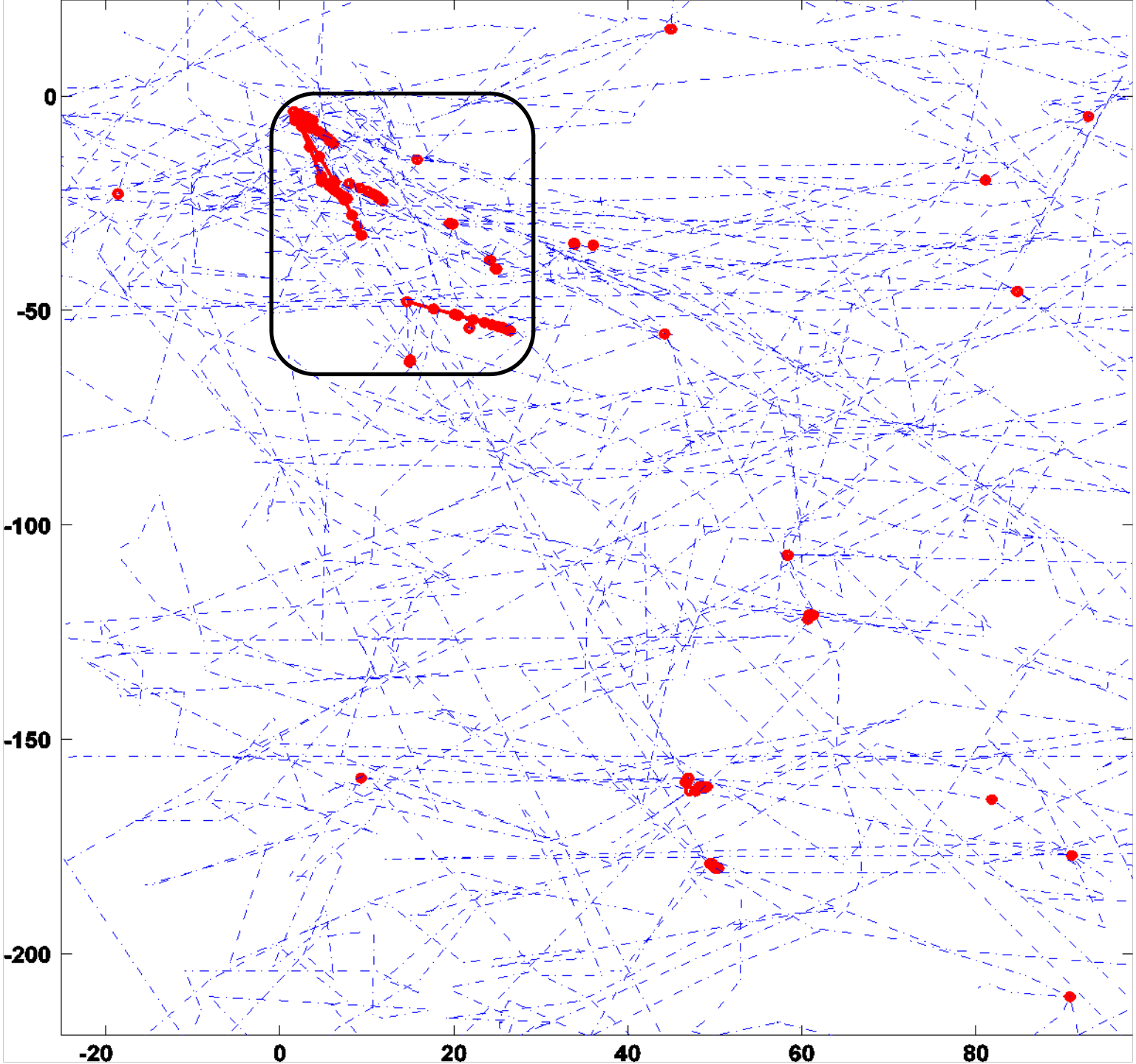
γ



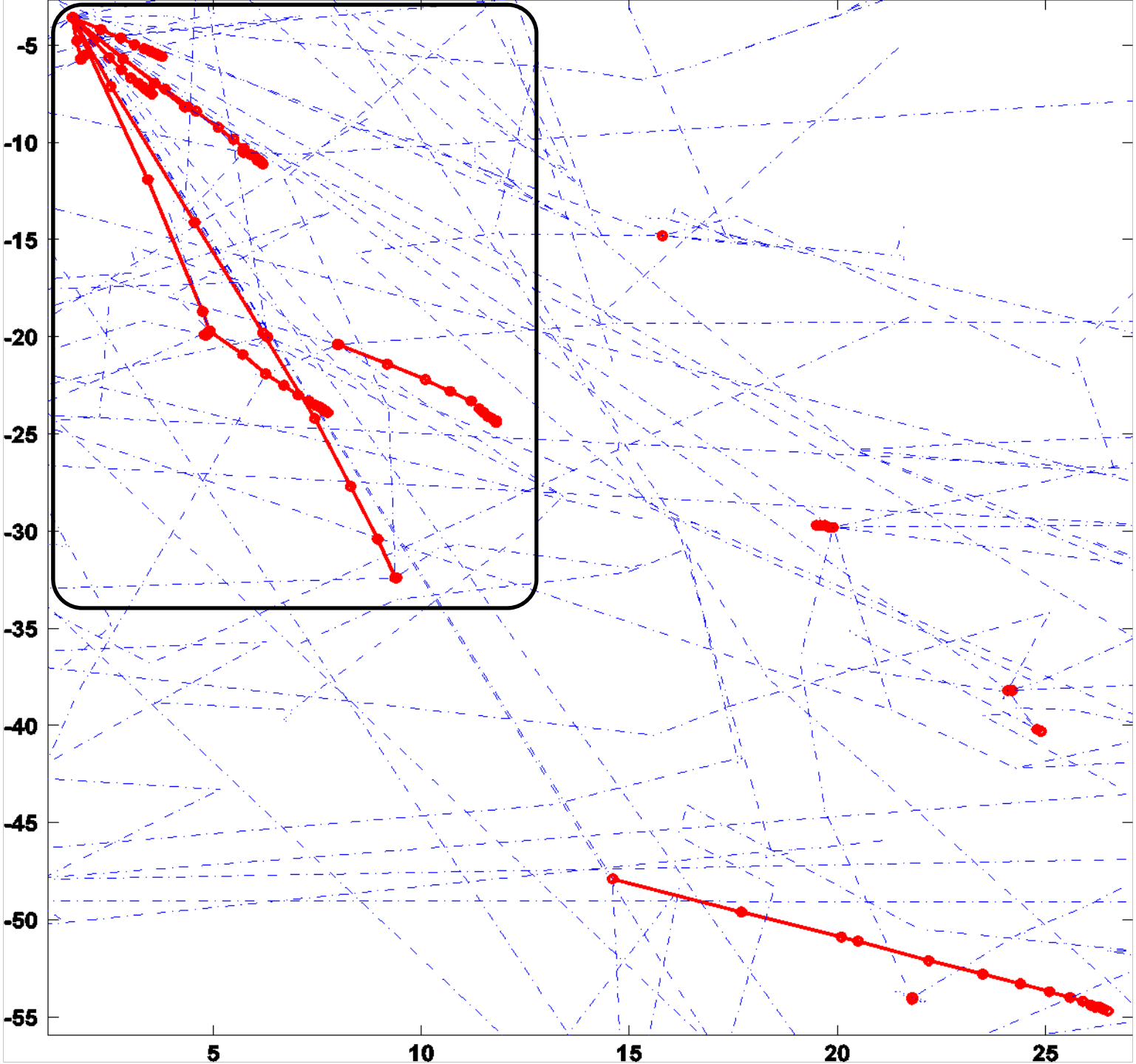

e⁻
1000
800
600
400
200
0
-200
-400
-600
-800
-1000
-500
0
500
1000


e^+
1000
800
600
400
200
0
-200
-400
-600
-800
-1000
-500
0
500
1000

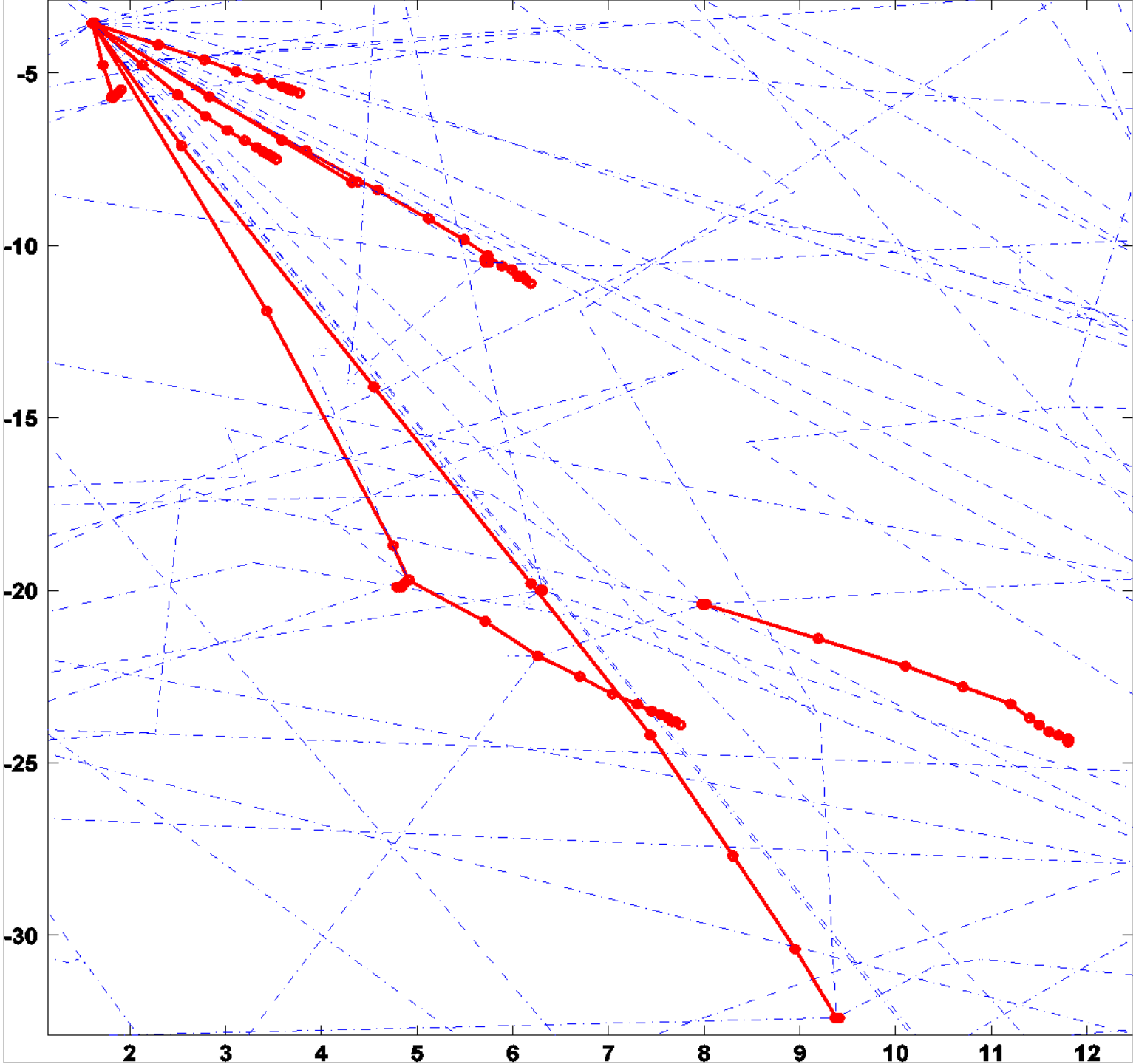
p

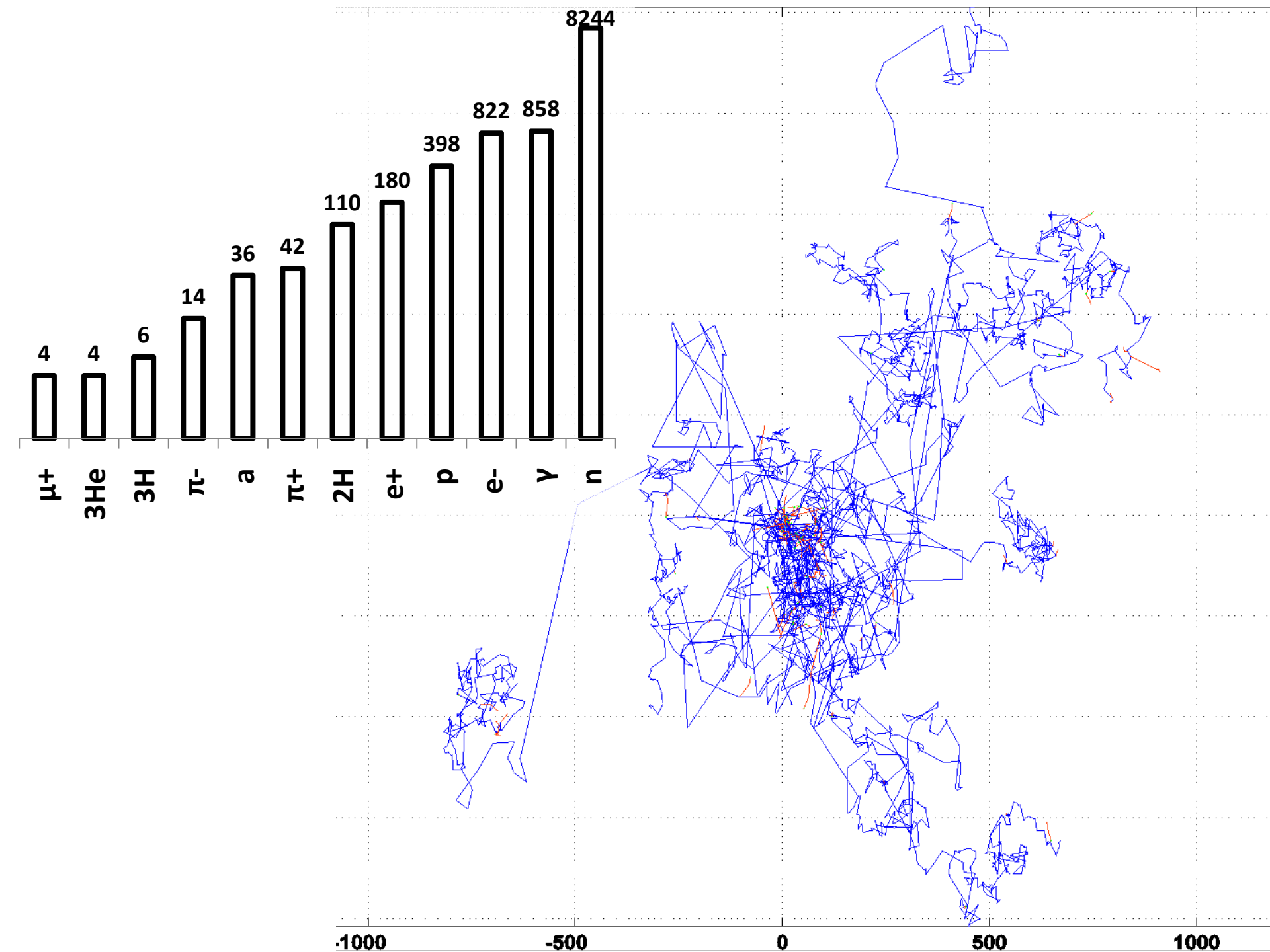


p



p



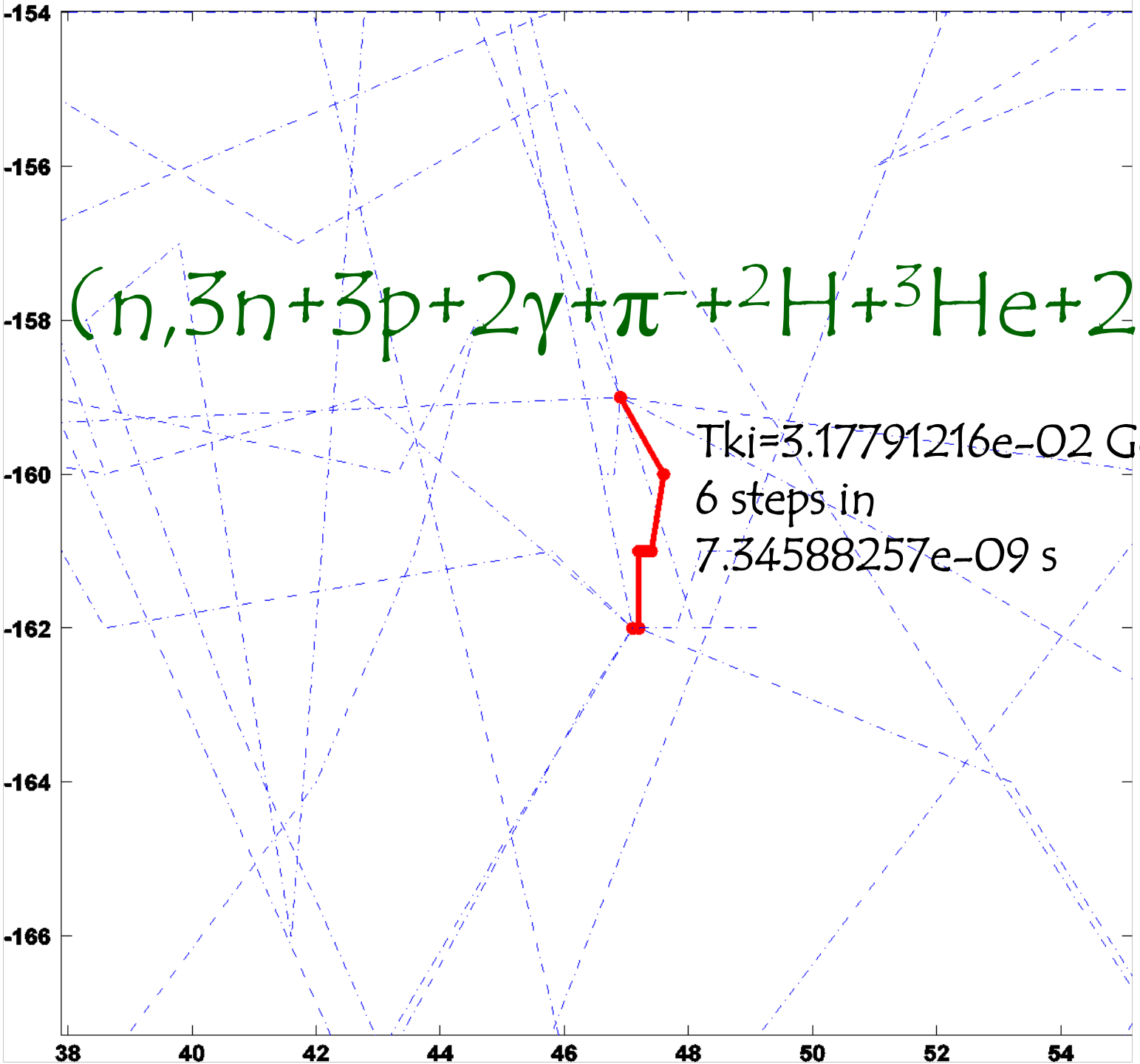

8244
858
822
398
180
110
42
36
14
6
4
4
μ+
3He
3H
π-
a
π+
2H
e+
p
e-
γ
n
-1000
-500
0
500
1000

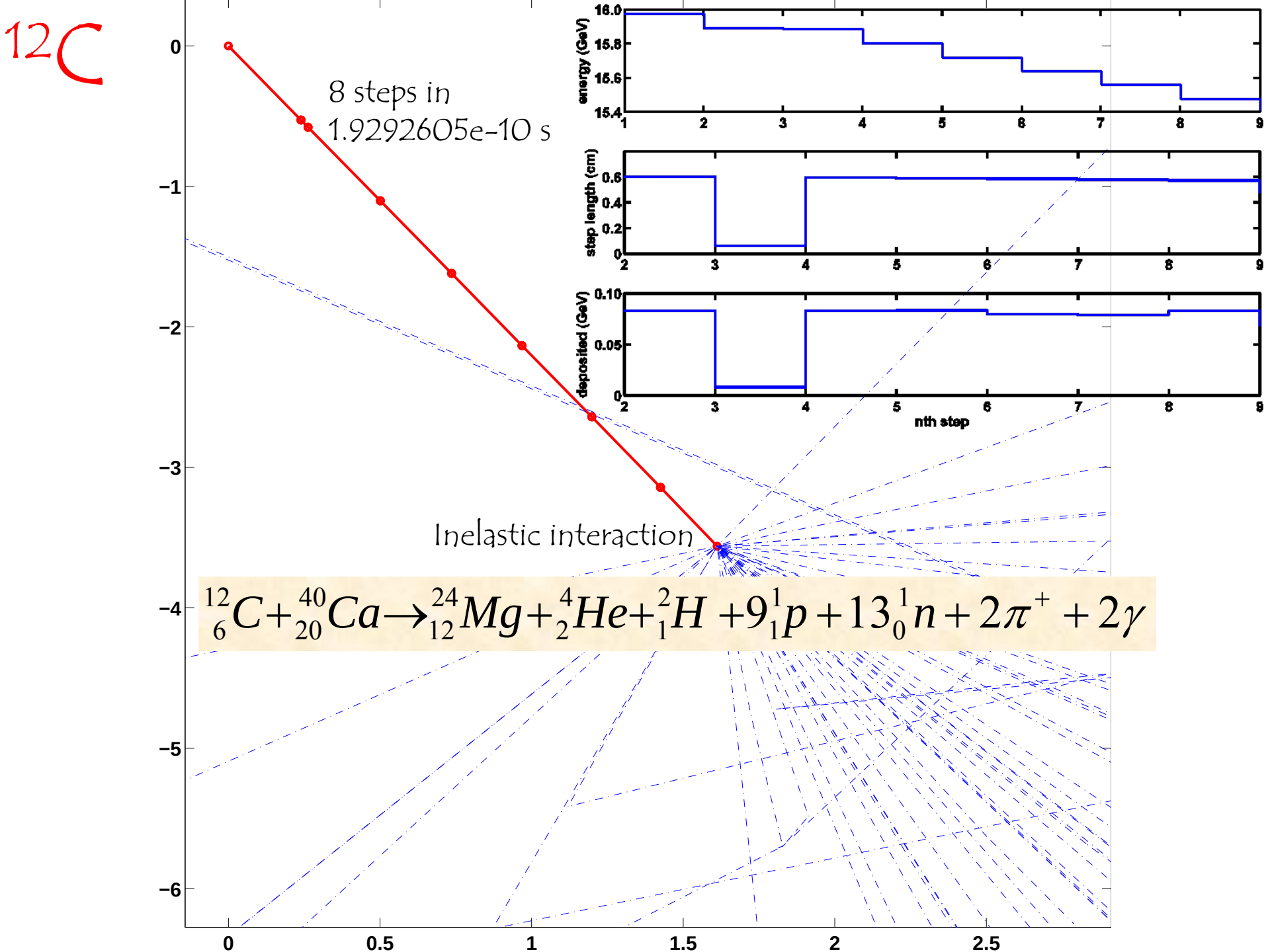
SO MANY NEUTRONS
where do they come from?

count	parent	siblings
13	$^{12}C + ^{40}Ca$	$^{24}_{12}Mg + ^{4}_{2}He + ^{2}_{1}H + 9\,^{1}_{1}p + 13n + 2\pi^{+} + 2\gamma$
5	p	n+p n+3p+3γ n+3p 2n+2p+γ
103	 n	2 to 12 siblings many $x_1n+x_2p+x_3\gamma$ 2p+4n+2γ+^{2}H 3n+3p+2γ+π^{-}+^{2}H+^{3}He+2α
3	π-	p+3n+4γ
3998	n	s o l o

HEAVY ION INTERACTION

π^-

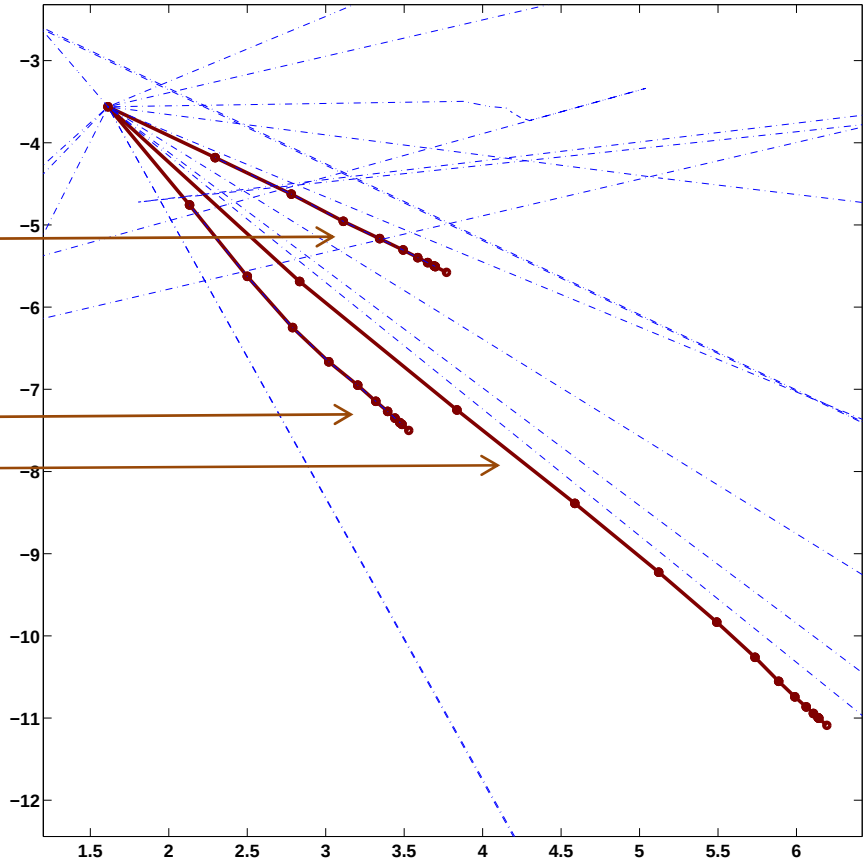

-154
-156
-158
-160
-162
-164
-166
38
40
42
44
46
48
50
52
54
(n,3n+3p+2γ+π⁻+²H+³He+2α)
Tki=3.17791216e-02 GeV
6 steps in
7.34588257e-09 s


12C
8 steps in
1.9292605e-10 s
energy (GeV)
step length (cm)
deposited (GeV)
nth step
Inelastic interaction
$^{12}_{6}C+^{40}_{20}Ca\rightarrow^{24}_{12}Mg+^{4}_{2}He+^{2}_{1}H+9^{1}_{1}p+13^{1}_{0}n+2\pi^{+}+2\gamma$

$$^{12}_{6}C + ^{40}_{20}Ca \rightarrow ^{24}_{12}Mg + ^{4}_{2}He + ^{2}_{1}H + 9^{1}_{1}p + 13^{1}_{0}n + 2\pi^{+} + 2\gamma$$

PROTONS

Tki (GeV)	what's next
2.85969377e-01	(p,2n+2p+γ)
7.94009790e-02	(p,n+3p)
6.70373663e-02	10 steps to cutoff
3.00997659e-03	1 step to cutoff
2.87470937e-01	(p,n+3p+3γ)
1.83140948e-01	(p,np)
9.14871842e-02	11 steps to cutoff
1.23939060e-01	13 steps to cutoff
5.24589885e-03	1 step to cutoff

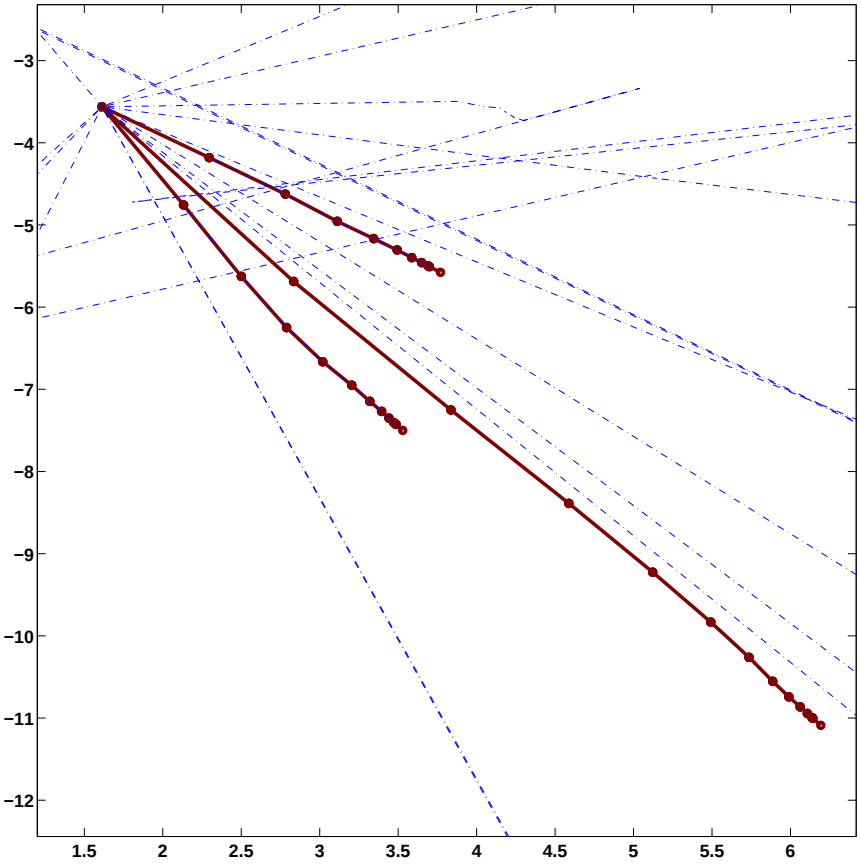


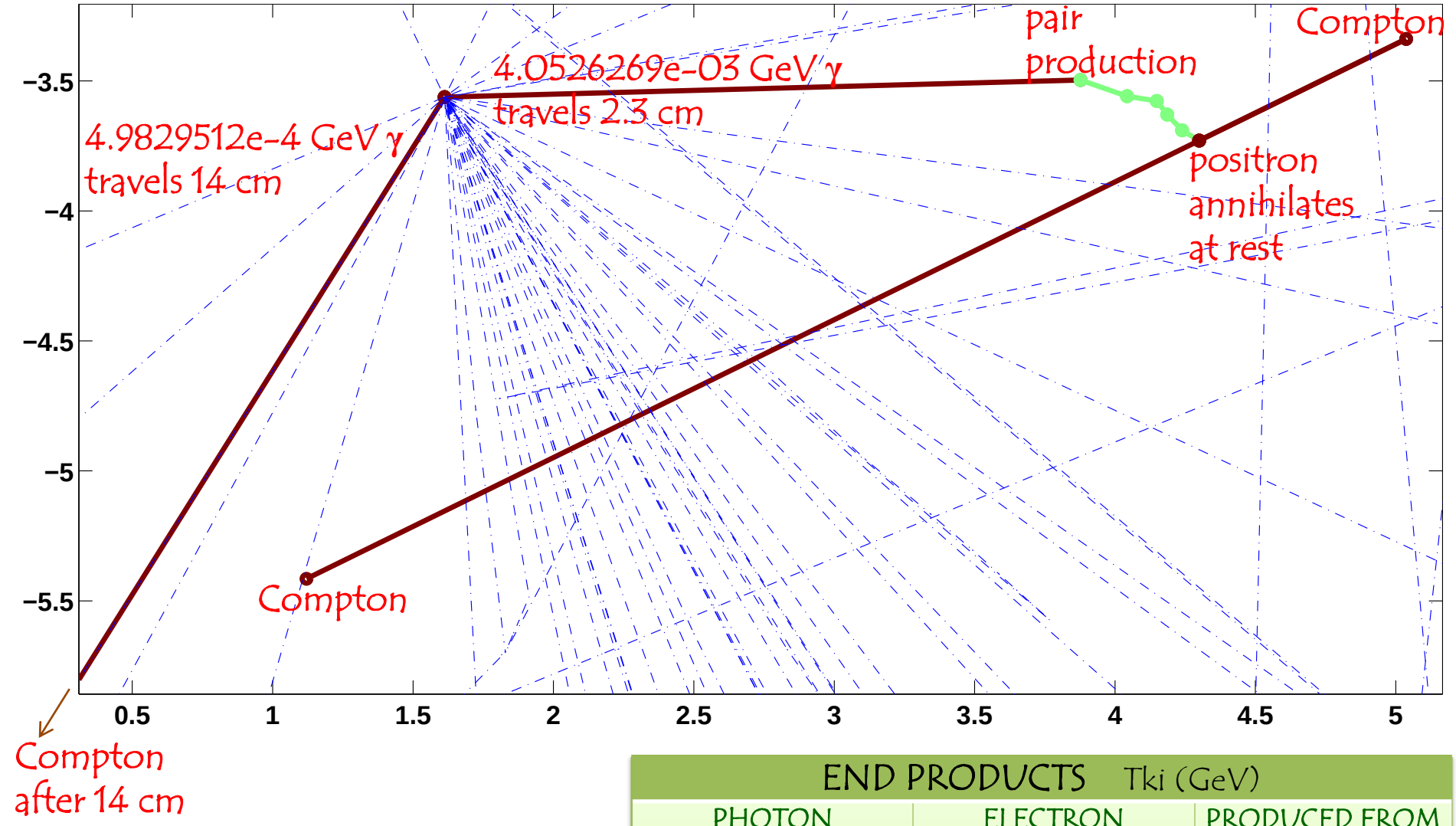
$$^{12}_{6}C + ^{40}_{20}Ca \rightarrow ^{24}_{12}Mg + ^{4}_{2}He + ^{2}_{1}H + 9^{1}_{1}p + 13^{1}_{0}n + 2\pi^{+} + 2\gamma$$

2nd generation of protons

Tki (GeV)	fate
6.08318811e-03	1 step to cutoff
2.59359460e-03	1 step to cutoff
1.59814935e-02	4 steps to cutoff
3.70376068e-03	1 step to cutoff
1.80191698e-03	1 step to cutoff
2.15159506e-02	4 steps to cutoff
1.03988886e-01	6 steps to cutoff
3.61582404e-03	1 step to cutoff
1.02260048e-02	2 steps to cutoff

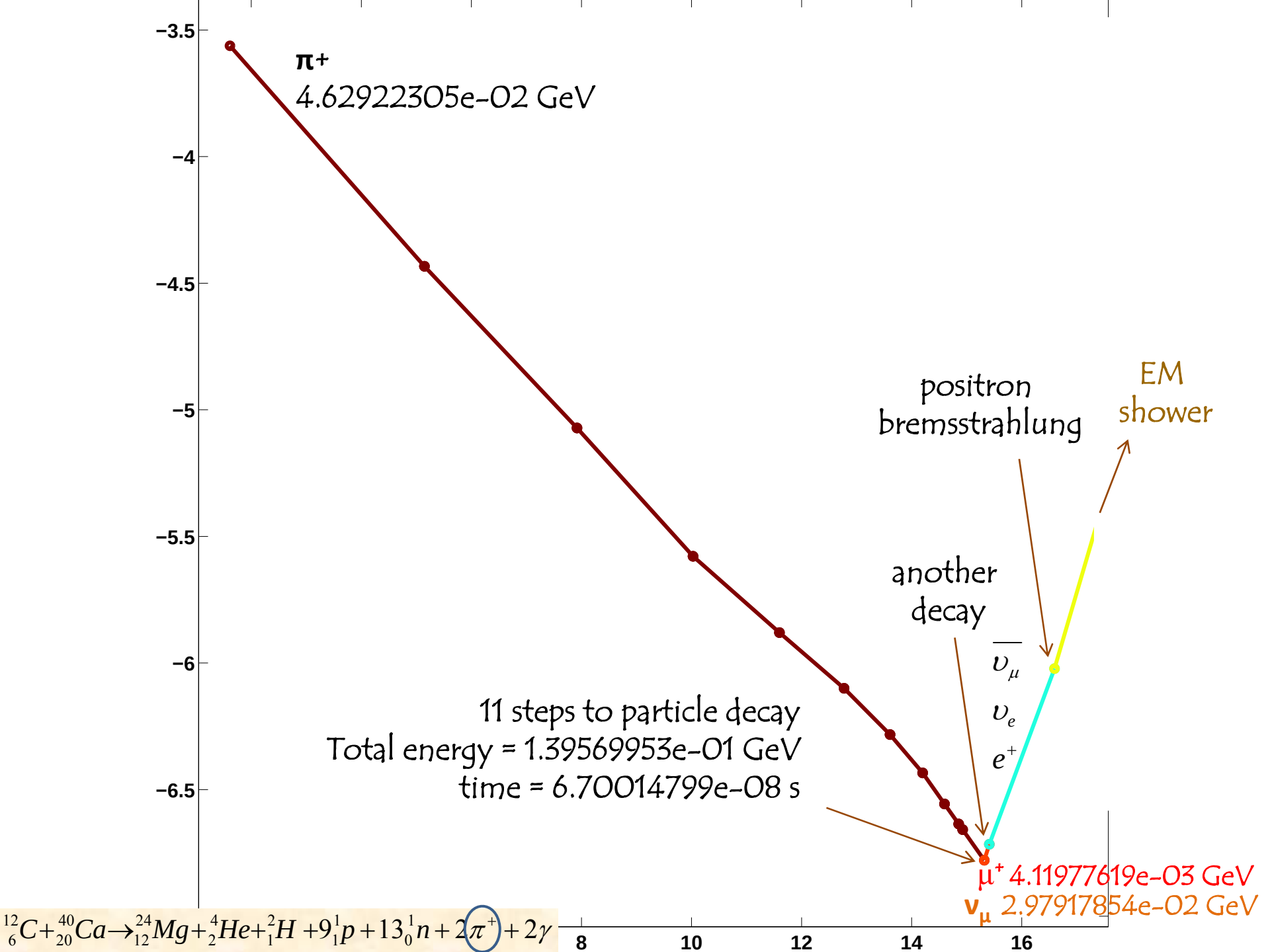
Tki (GeV)	what's next
2.85969377e-01	(p,2n+2p+γ)
7.94009790e-02	(p,n+3p)
6.70373663e-02	10 steps to cutoff
3.00997659e-03	1 step to cutoff
2.87470937e-01	(p,n+3p+3γ)
1.83140948e-01	(p,pp)
9.14871842e-02	11 steps to cutoff
1.23939060e-01	13 steps to cutoff
5.24589885e-03	1 step to cutoff

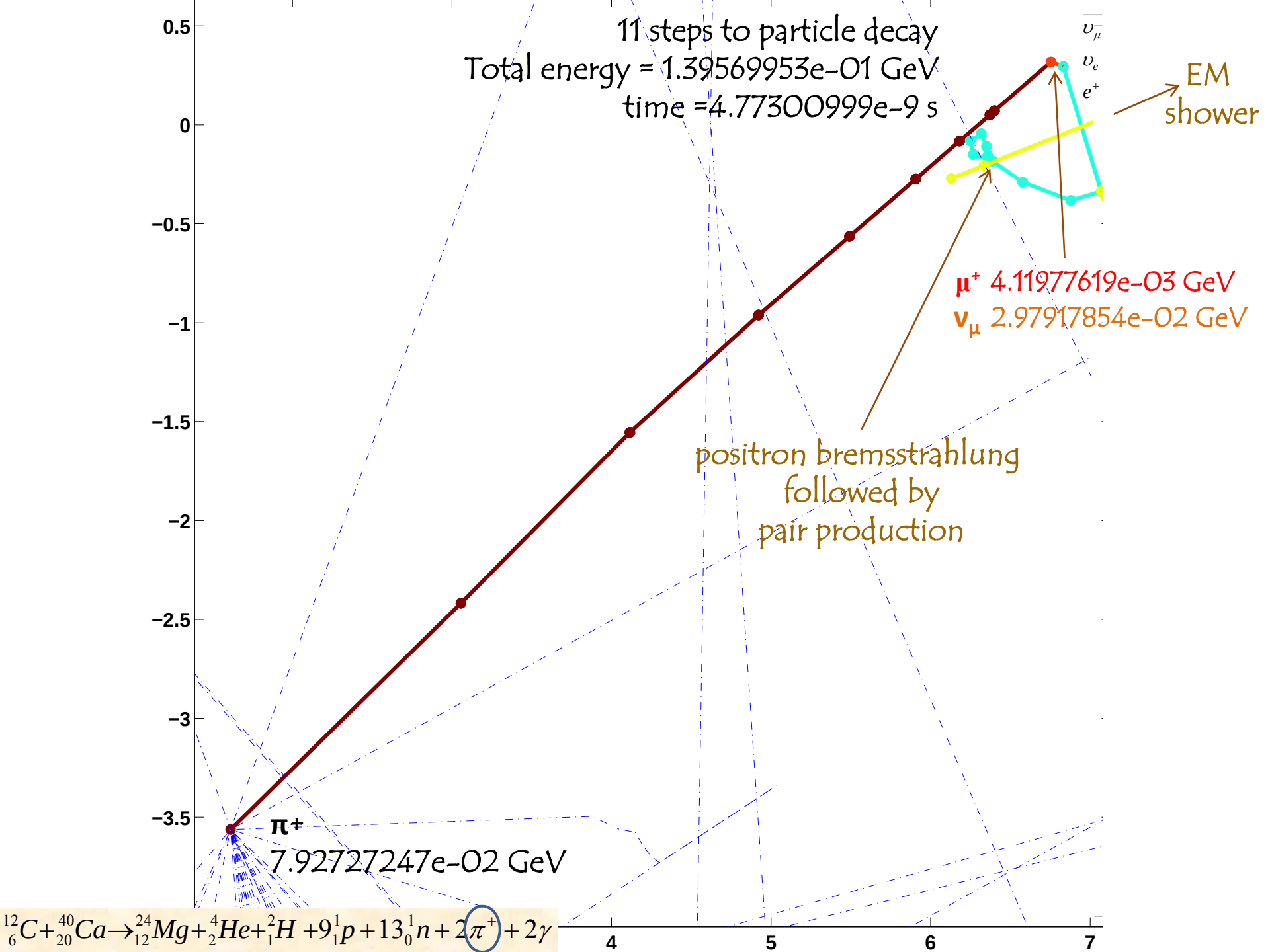


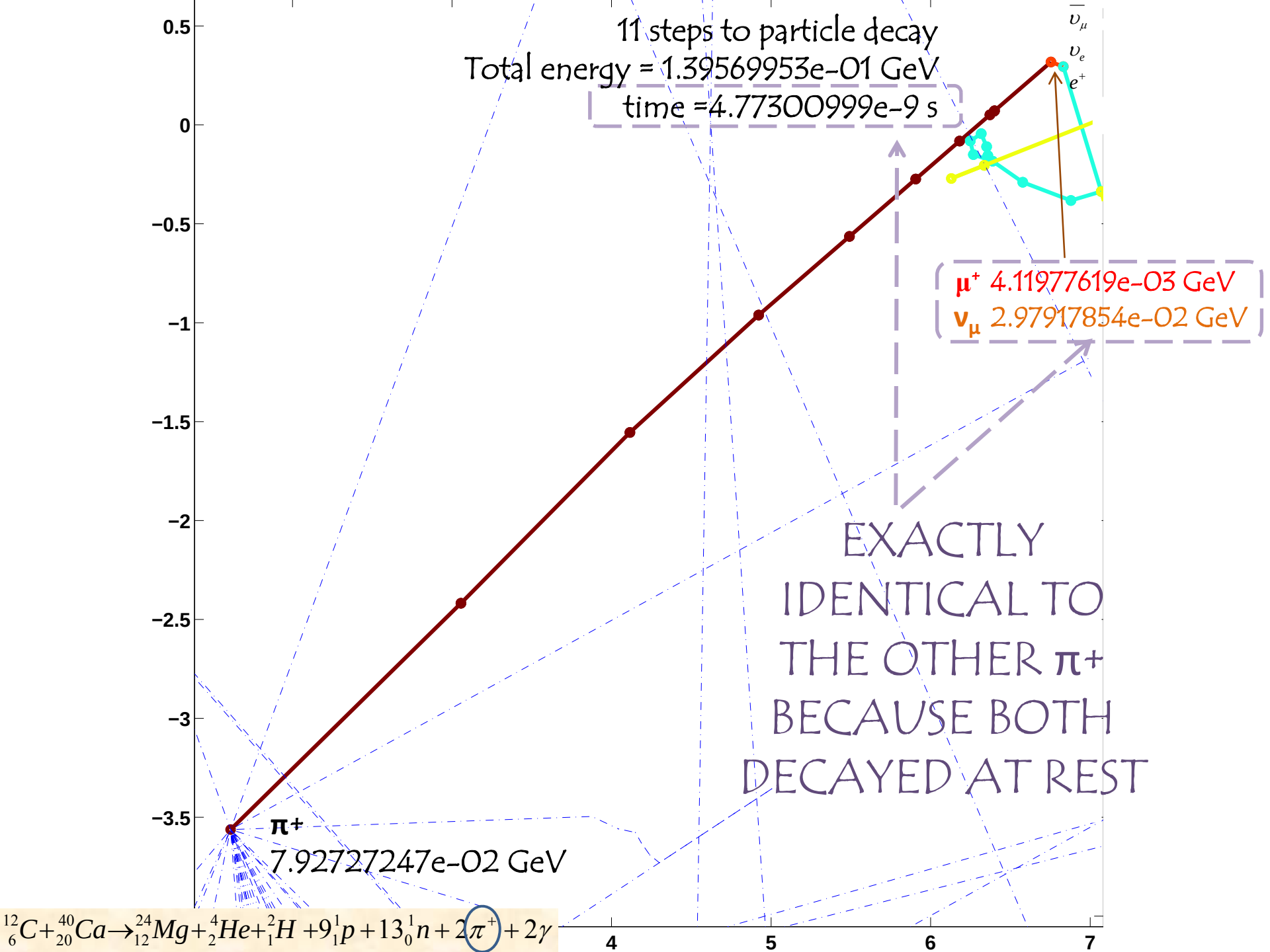


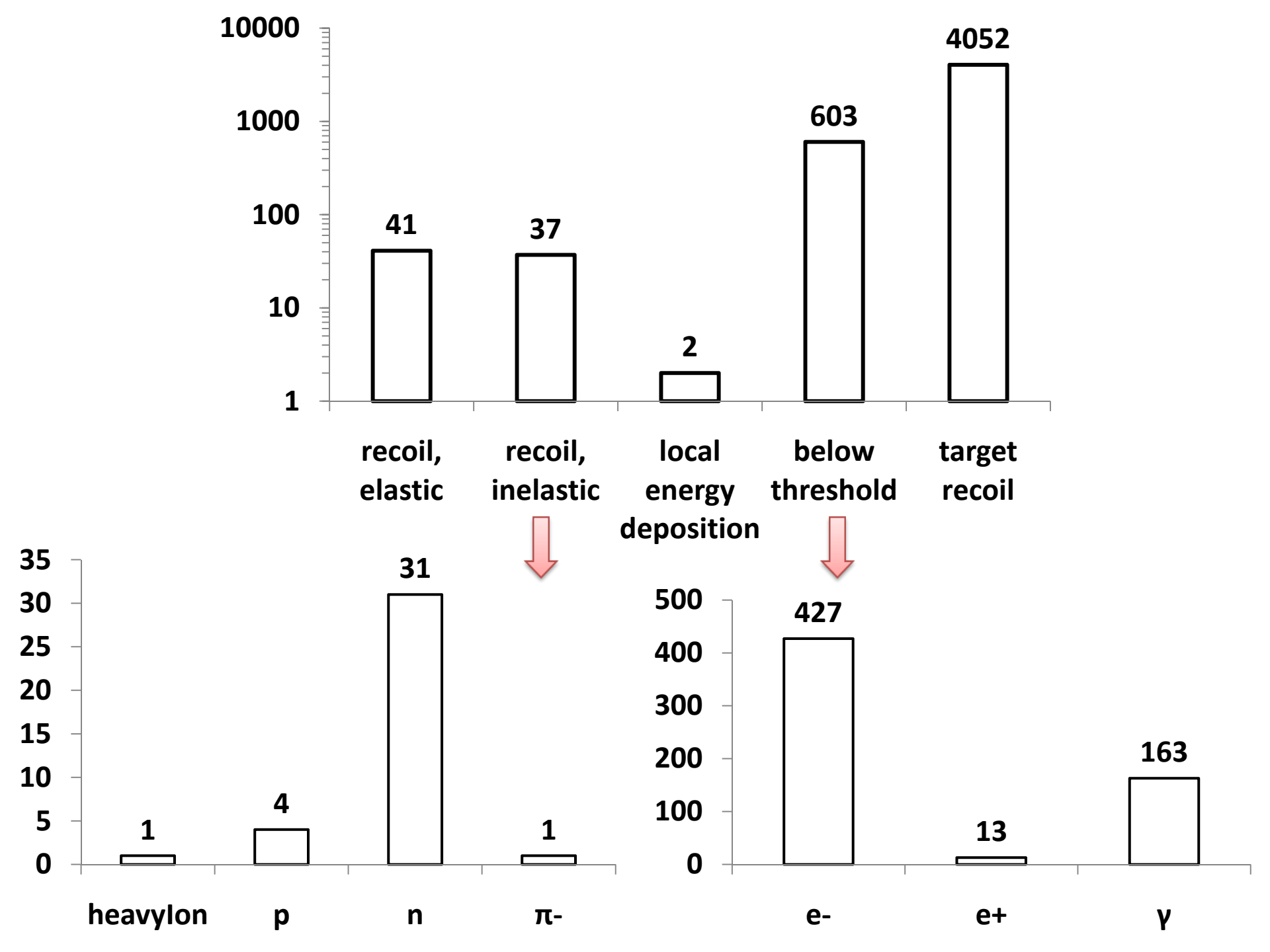
END PRODUCTS Tki (GeV)		
PHOTON	ELECTRON	PRODUCED FROM
	7.64209894e-04	pair production
2.95501173e-04	2.15497887e-04	Compton
2.53742037e-04	2.57257023e-04	
1.93167754e-04	3.05127382e-04	

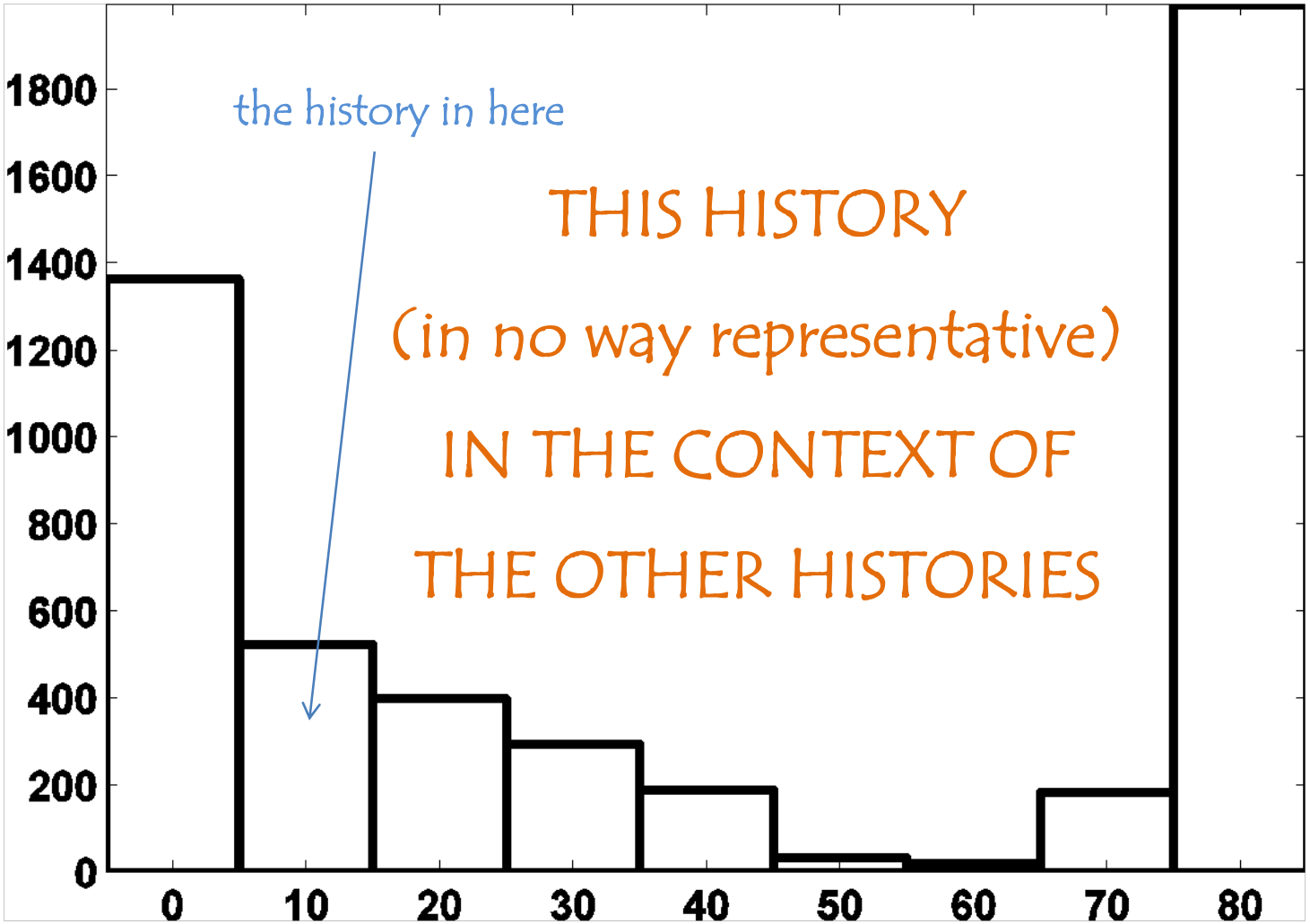
$${}^{12}_{6}C + {}^{40}_{20}Ca \rightarrow {}^{24}_{12}Mg + {}^{4}_{2}He + {}^{2}_{1}H + 9\,{}^{1}_{1}p + 13\,{}^{1}_{0}n + 2\pi^{+} + 2\gamma$$


π+
4.62922305e-02 GeV
positron
bremsstrahlung
EM
shower
another
decay
$\overline{\upsilon_\mu}$
υ_e
e^+
11 steps to particle decay
Total energy = 1.39569953e-01 GeV
time = 6.70014799e-08 s
μ+ 4.11977619e-03 GeV
νμ 2.97917854e-02 GeV
−3.5
−4
−4.5
−5
−5.5
−6
−6.5
8
10
12
14
16
$^{12}_{6}C+^{40}_{20}Ca\rightarrow^{24}_{12}Mg+^{4}_{2}He+^{2}_{1}H+9^{1}_{1}p+13^{1}_{0}n+2\pi^{+}+2\gamma$


11 steps to particle decay
Total energy = 1.39569953e-01 GeV
time =4.77300999e-9 s
$\bar{\nu}_\mu$
ν_e
e^+
EM shower
μ+ 4.11977619e-03 GeV
νμ 2.97917854e-02 GeV
positron bremsstrahlung followed by pair production
π+
7.92727247e-02 GeV
$^{12}_{6}C+^{40}_{20}Ca\rightarrow^{24}_{12}Mg+^{4}_{2}He+^{2}_{1}H+9^{1}_{1}p+13^{1}_{0}n+2\pi^{+}+2\gamma$


11 steps to particle decay
Total energy = 1.39569953e-01 GeV
time =4.77300999e-9 s
$\overline{\upsilon}_\mu$
υ_e
e^+
μ⁺ 4.11977619e-03 GeV
νμ 2.97917854e-02 GeV
EXACTLY IDENTICAL TO THE OTHER π+ BECAUSE BOTH DECAYED AT REST
π+
7.92727247e-02 GeV
$^{12}_{6}C+^{40}_{20}Ca\rightarrow^{24}_{12}Mg+^{4}_{2}He+^{2}_{1}H+9^{1}_{1}p+13^{1}_{0}n+2\pi^{+}+2\gamma$


10000
1000
100
10
1
41
37
2
603
4052
recoil, elastic
recoil, inelastic
local energy deposition
below threshold
target recoil
35
30
25
20
15
10
5
0
1
4
31
1
heavylon
p
n
π-
500
400
300
200
100
0
427
13
163
e-
e+
γ

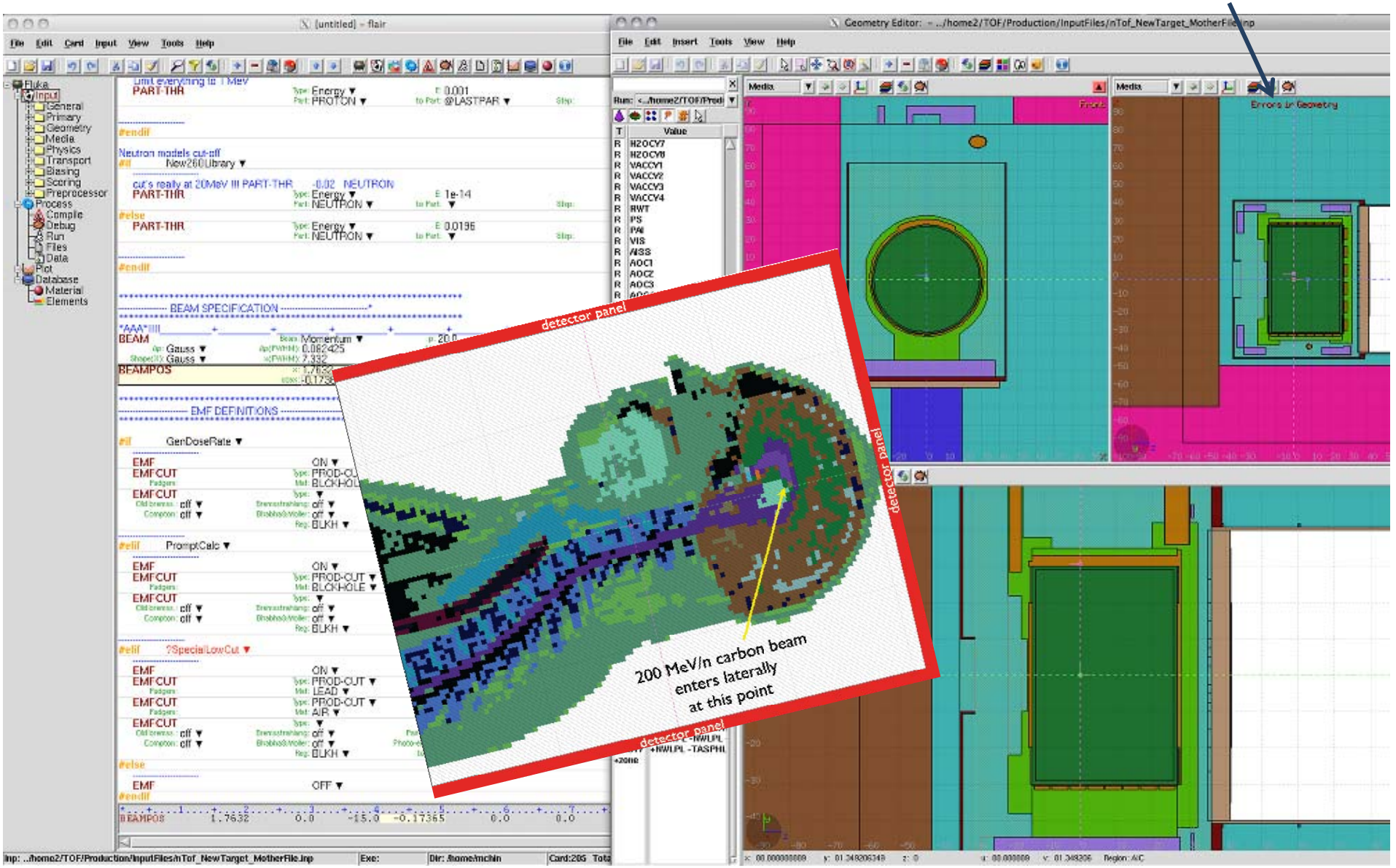


^{12}C steps before absorption / collision

USING FLUKA

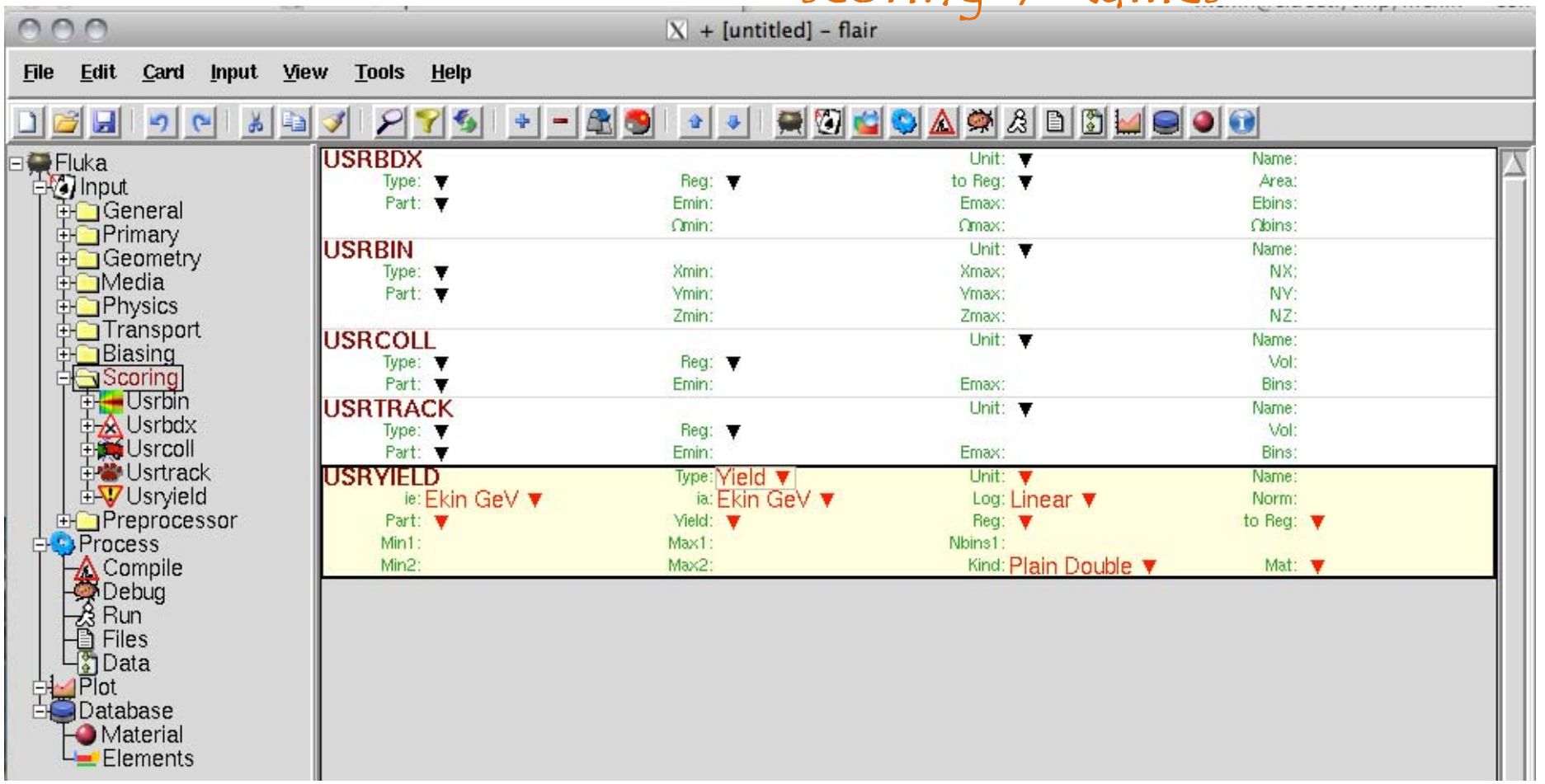
fully functional with or without GUI

automatic error detection



Asking for more answers/results: fluence / energy spectra / energy deposition / yield / dose / ...

'scoring' / 'tallies'



Asking for even more answers ... ☞ Fortran programming + re-compilation

CODES DIFFER BY

- philosophy
- physics
- software design
- licensing and permission for use

Major house-brands of General-Purpose Monte Carlo Radiation Transport Codes:

FLUKA, MCNP/MCNPX, EGSnrc,
PENELOPE, GEANT4, MARS, PHITS

MY MONTE CARLO JOURNEY STARTED RIGHT HERE!

UNIVERSITY OF SURREY

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slides available at www.marychin.org/works.html