THE STARTRACK EXPERIMENT

nanodosimetric STructure of hAdRon TRACKs

A really complicated experiment with interesting results

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  Some interesting features of the track structure of light ions

THE TRACK STRUCTURE OF IONIZING PARTICLES

1 µm

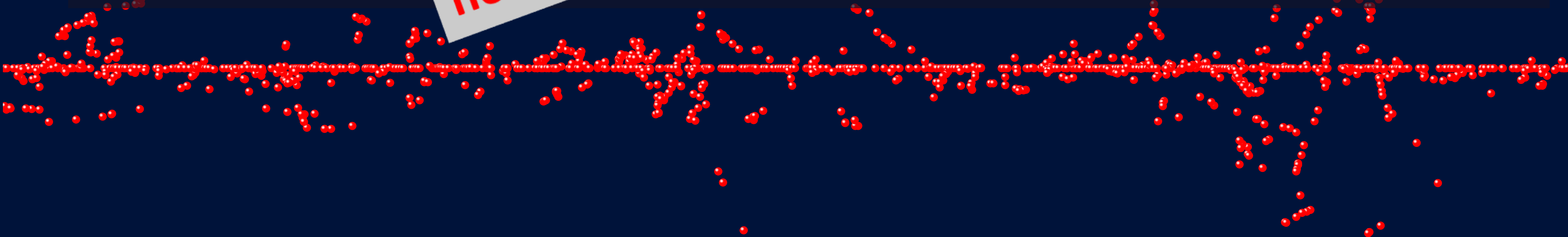
Track structure = detailed description of the interaction pattern of single particles

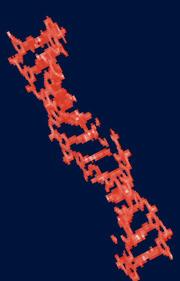
(i) **where** *the interaction takes pla… distribution of t_i)*

(ii) **which** *kind of inte… al energy deposits ε_i)*

(iii) **what** s… *e possibly formed*

not yet possible experimentally





The hypothesis: The damage to segments of the DNA is initiated to a great part by ionizing processes

Effectiveness of radiation strongly depends on the track structure

THE TRACK STRUCTURE OF IONIZING PARTICLES

← 1 μm →

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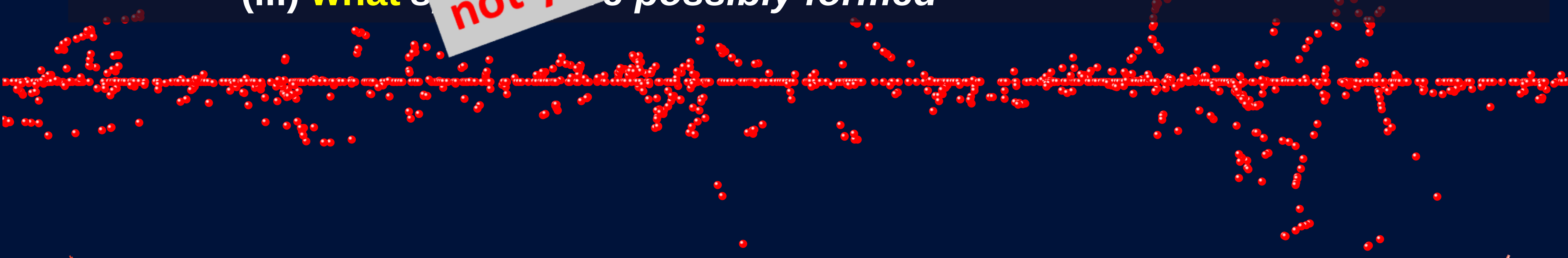
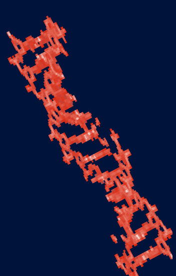
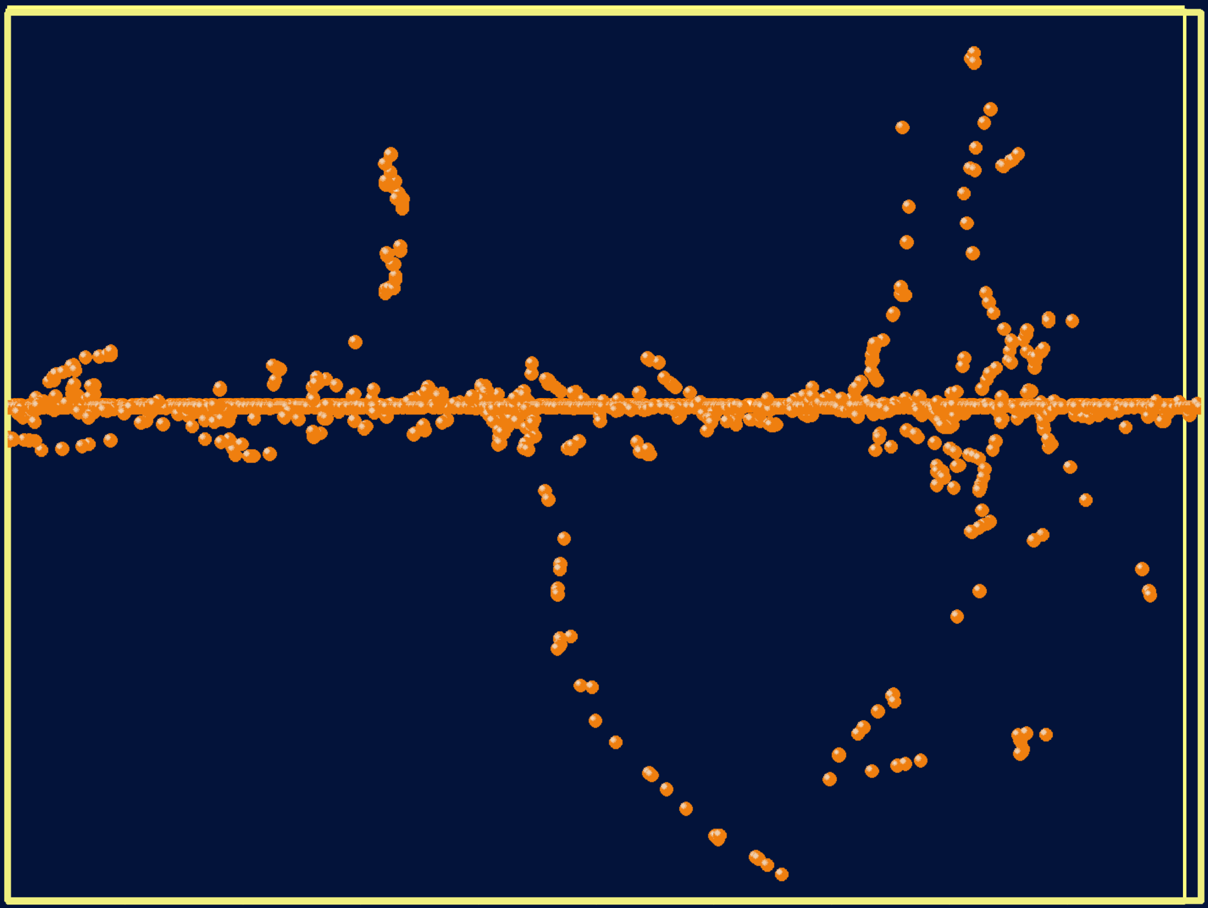




Characterization of Particle Track Structure by Measuring the frequency distribution of the number of ionizations in nanometre-sized target volumes

Effectiveness of radiation strongly depends on the track structure

THE TRACK STRUCTURE OF ENERGETIC IONS



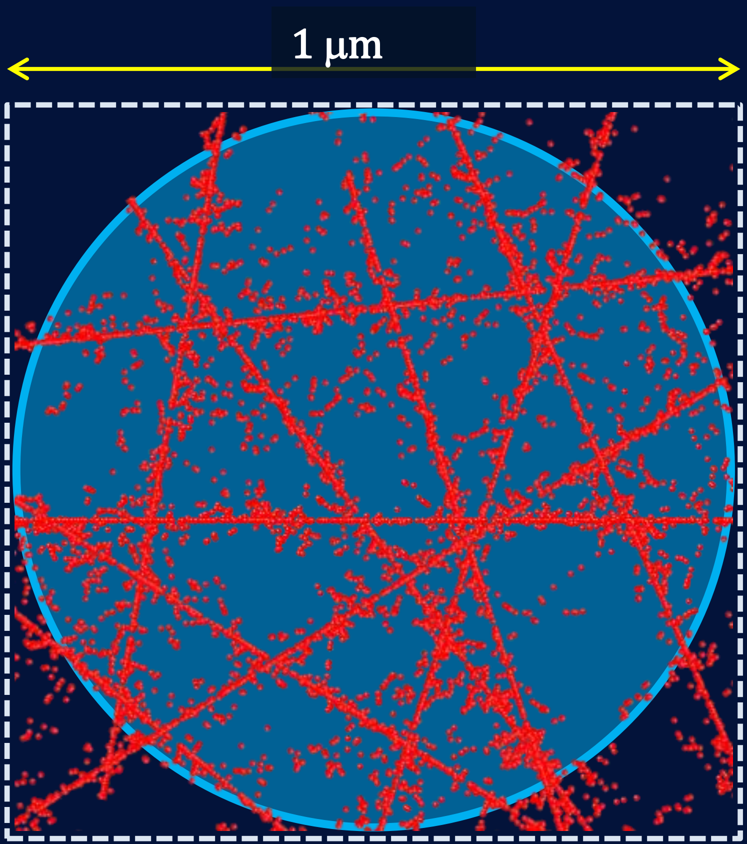
The track component due to primary-particle interactions:
Track-core region

The track component due to secondary-particle interactions:
Penumbra region

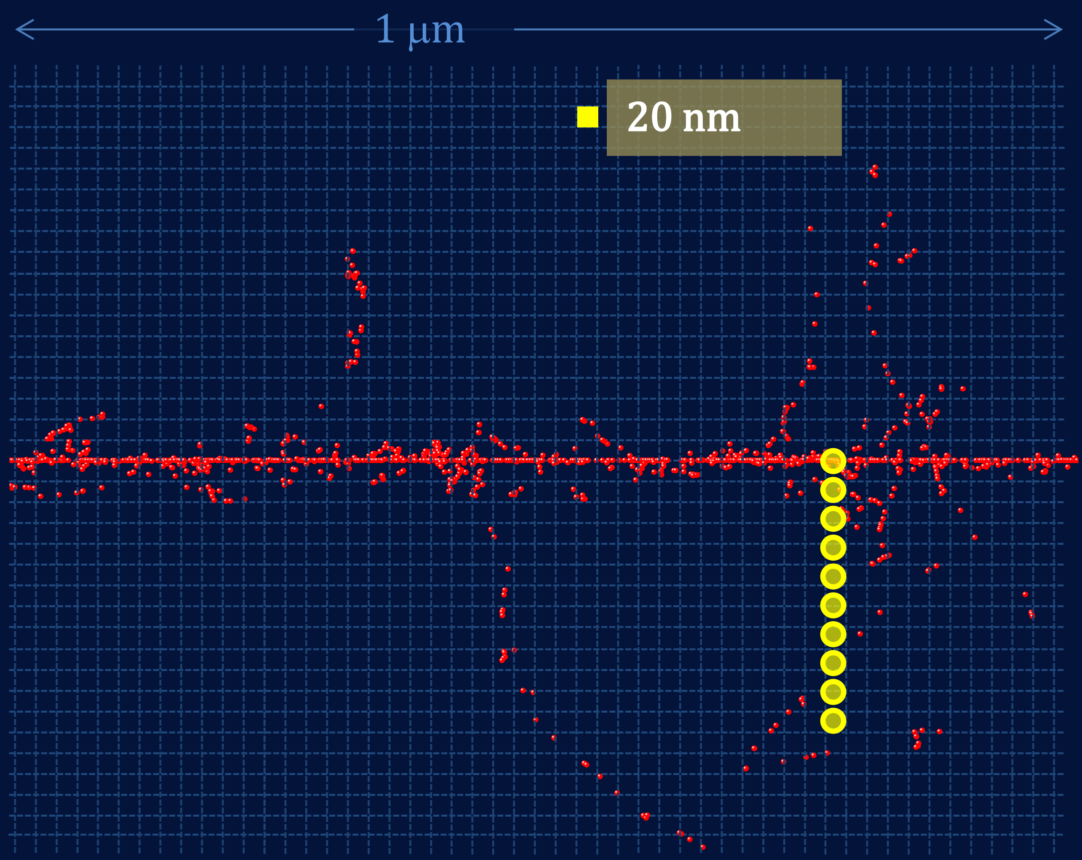
A detector to measure the track structure characteristics in the core and in the penumbra

THE PHYSICS OF THE INTERACTION

at the μm level



at the nm level

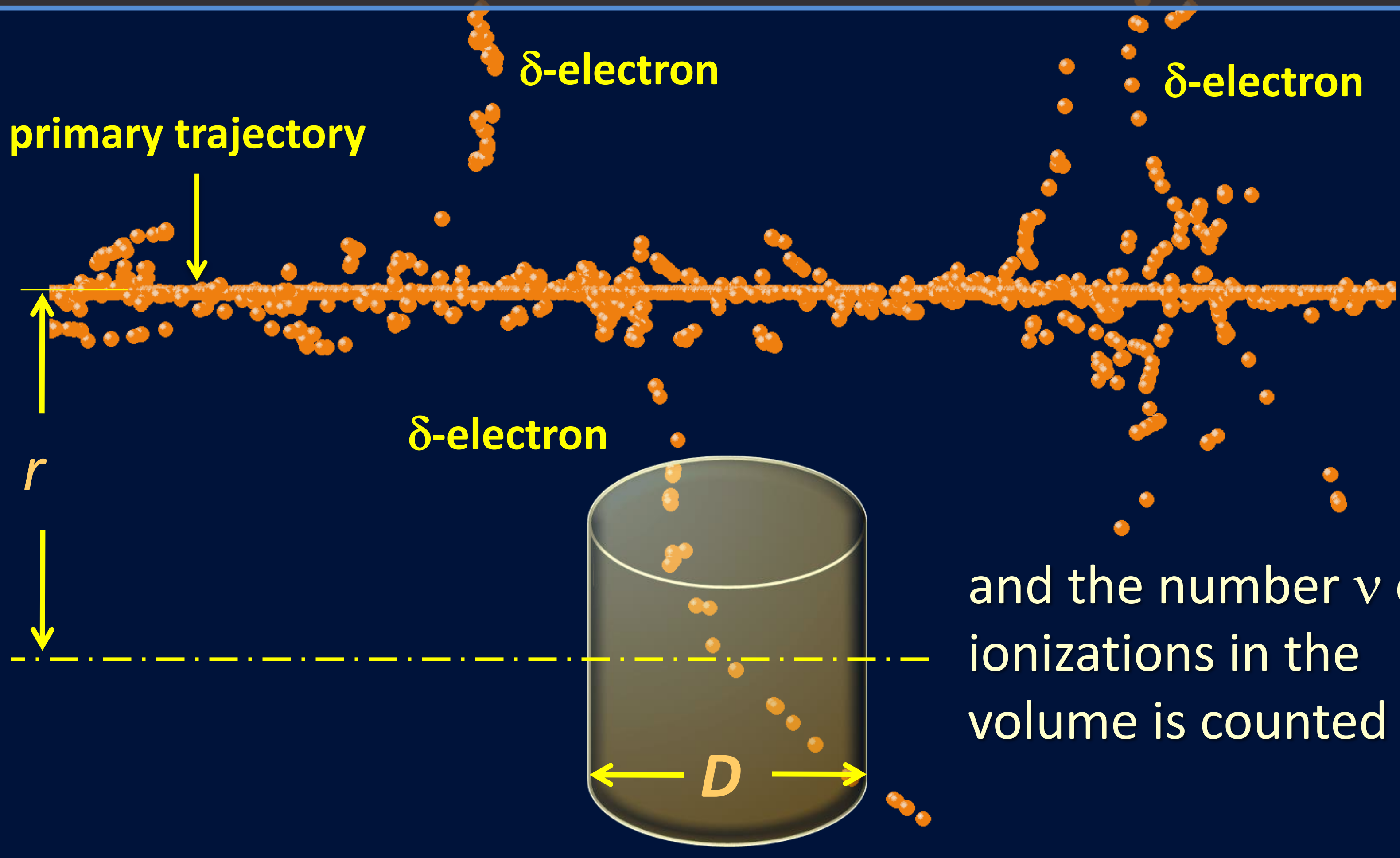


A «picture» of the track structure with a pixel of 20 nm

STARTRACK: THE EXPERIMENTAL SET UP

RATIONAL OF THE EXPERIMENT

A narrow parallel particle beam is passing a cylindrical target volume of diameter *D*, at impact parameter *r*



and the number ν of ionizations in the volume is counted

RATIONAL OF THE EXPERIMENT

A narrow parallel particle beam is passing a cylindrical target volume of diameter *D*, at impact parameter *r*

δ-electron

δ-electron

primary trajectory

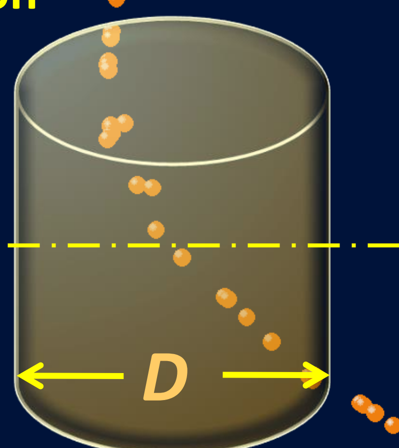
$$(\sigma_{ion})_T \cdot \rho_T \cdot D_T \,/\, M_T = (\sigma_{ion})_G \cdot \rho_G \cdot D_G \,/\, M_G$$

δ-electron

r

$$\lambda_{\text{ion}} = \frac{1}{\widetilde{N} \cdot \sigma_{\text{ion}}}$$

$$\lambda_{\text{ion}} = \frac{M}{\rho \cdot N_A \sigma_{\text{ion}}}$$



3 mbar propane, T = 25°C

$\rho_G = 5.47\text{E} - 06 \text{ g/cm}^3$

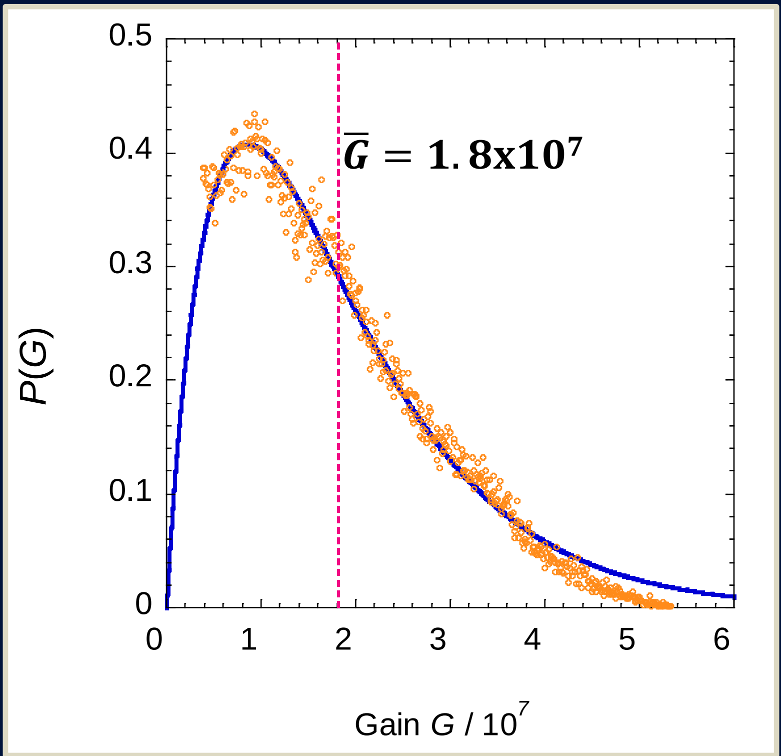
$D_G = 3.7 \text{ mm}$

$D_T = 20 \text{ nm}$

SINGLE IONIZATION (ELECTRON) COUNTING

Counting single electrons

single electron gain distribution



Small volume $\Longrightarrow$ small ν $\Longrightarrow$ high gain $\Longrightarrow$ large fluctuations

Peak amplitude $h \propto \nu$ x G

$$\left(\frac{\sigma_h}{h}\right)^2 = \left(\frac{\sigma_\nu}{\nu}\right)^2 + \left(\frac{\sigma_G}{\bar{G}}\right)^2 + \cdots$$

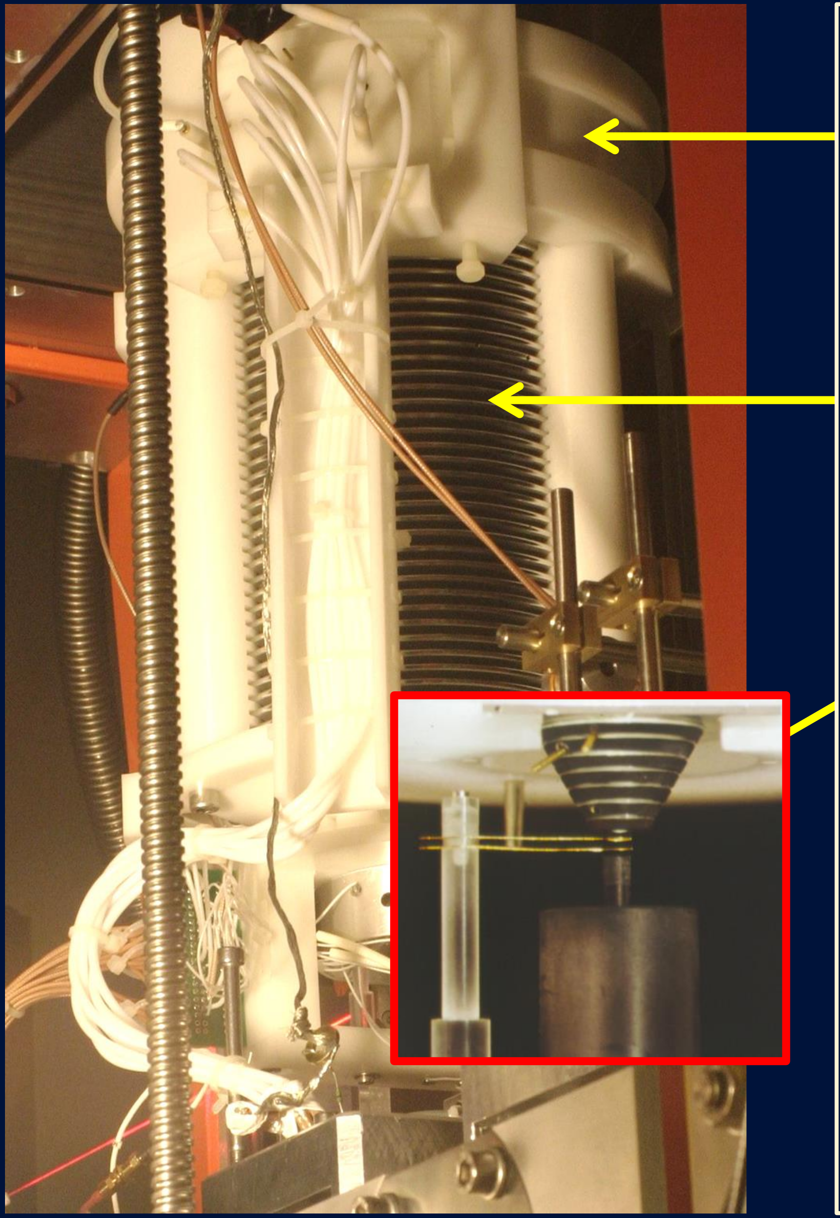
$$\left(\frac{\sigma_G}{G}\right)^2 = \frac{1}{\nu}\left(\frac{\sigma_A}{\bar{A}}\right)^2$$

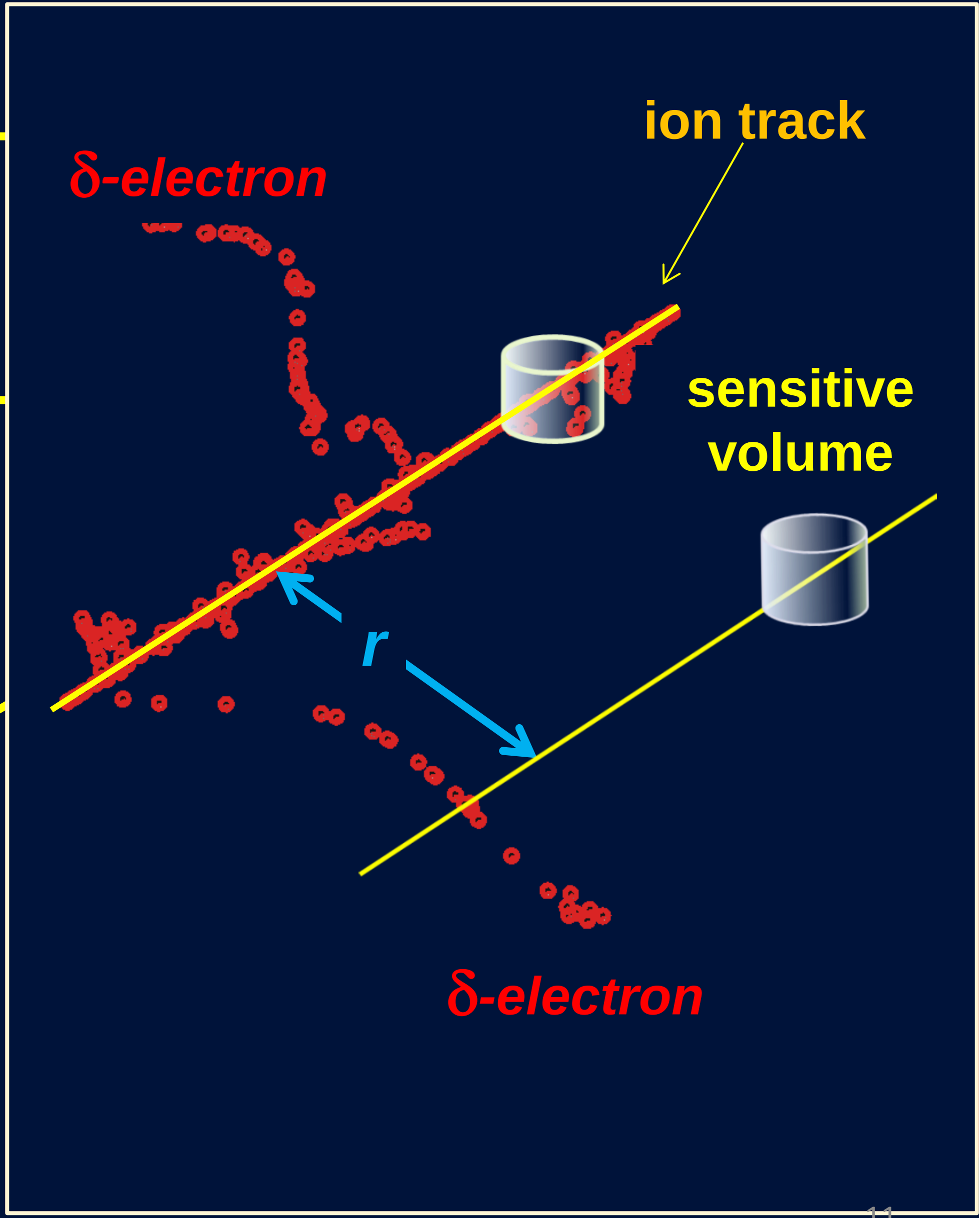
$\left(\frac{\sigma_A}{\bar{A}}\right)$ Single electron avalanche variance

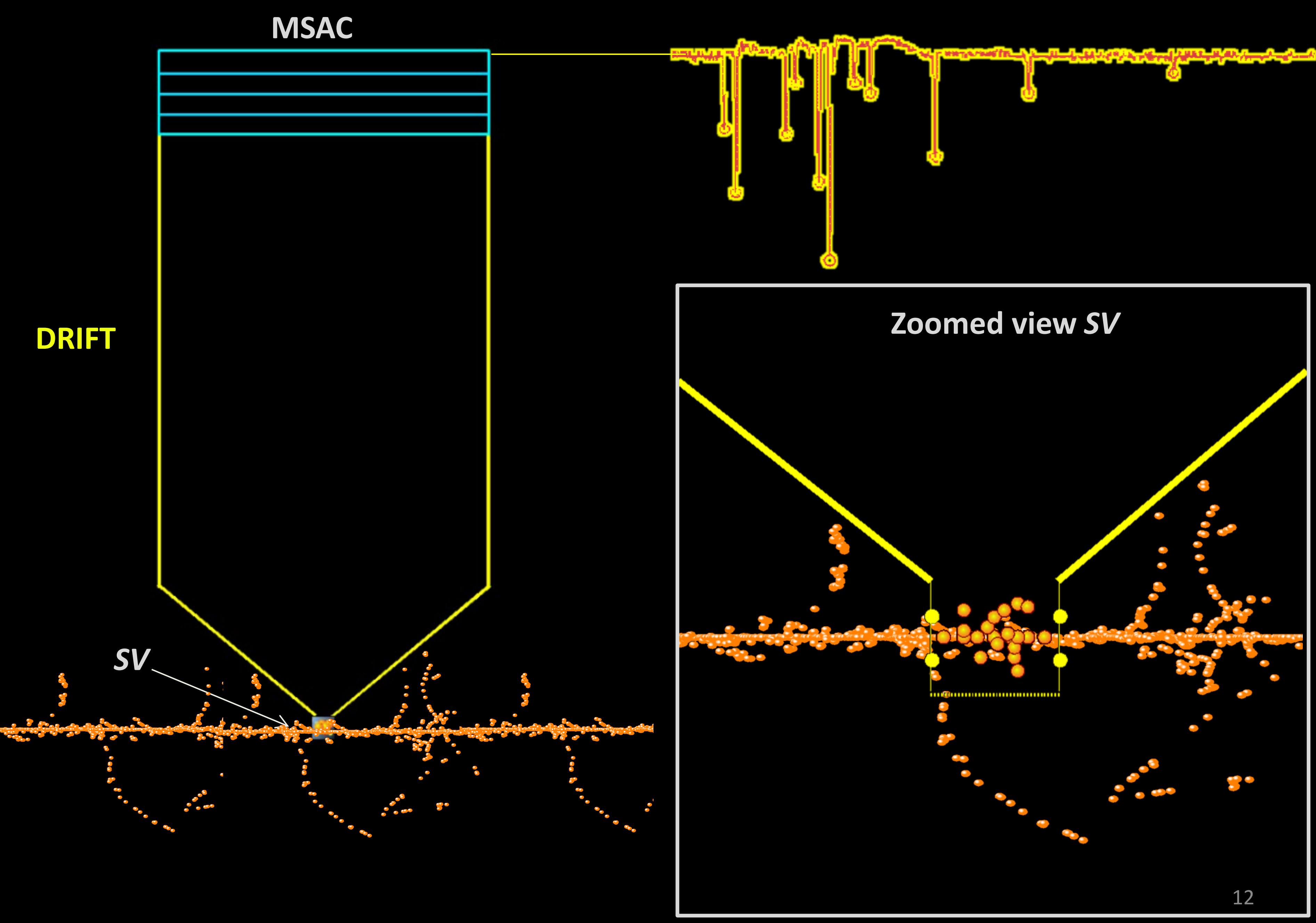
Because of the small number ν of initial electrons, the resolution of measured signal is strongly influenced by gas gain fluctuations.

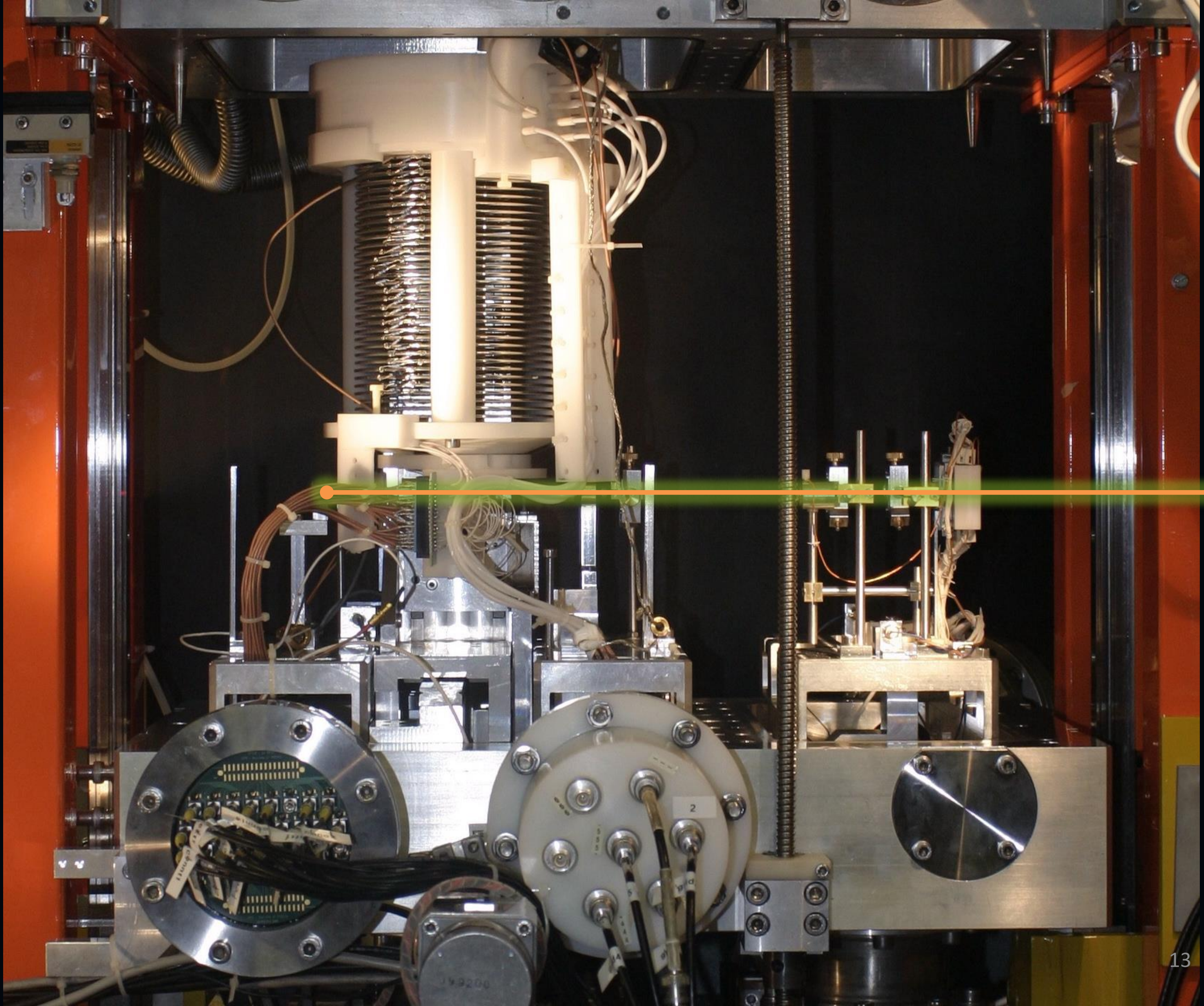
Ionization measurements based on counting of individual electrons

STARTRACK: the device

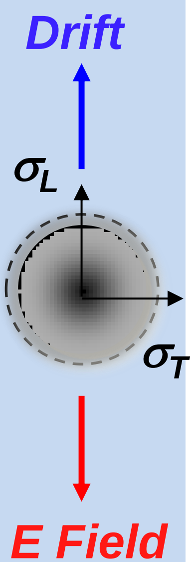


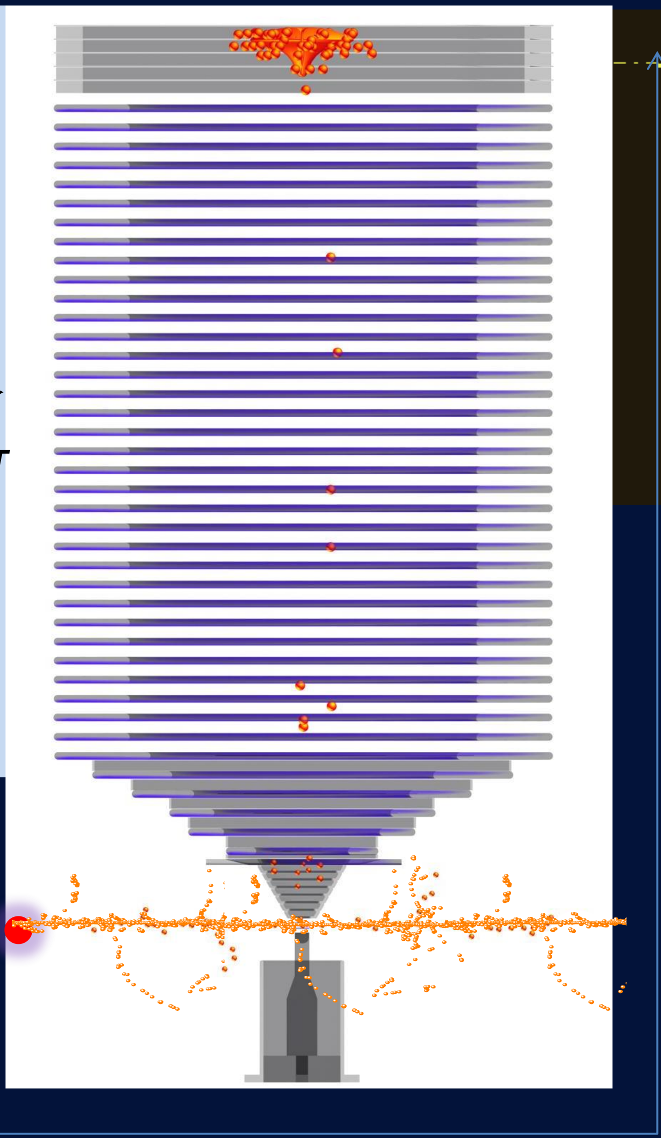


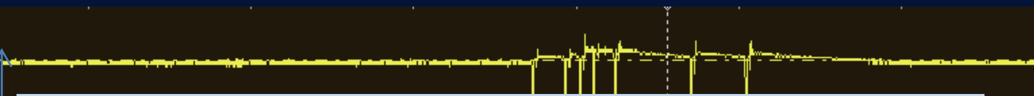

MSAC
DRIFT
SV
Zoomed view SV



SINGLE IONIZATION (ELECTRON) COUNTING







Average arrival time and std of the time distribution controlled by the drift *E* field

At low electric fields, the diffusion is symmetric.
$\sigma_L = \sigma_T$

$$\omega = \mu E \qquad \sigma = \sqrt{\frac{2D_{L,T}x}{w}} = \sqrt{\frac{2\varepsilon_K x}{eE}}$$

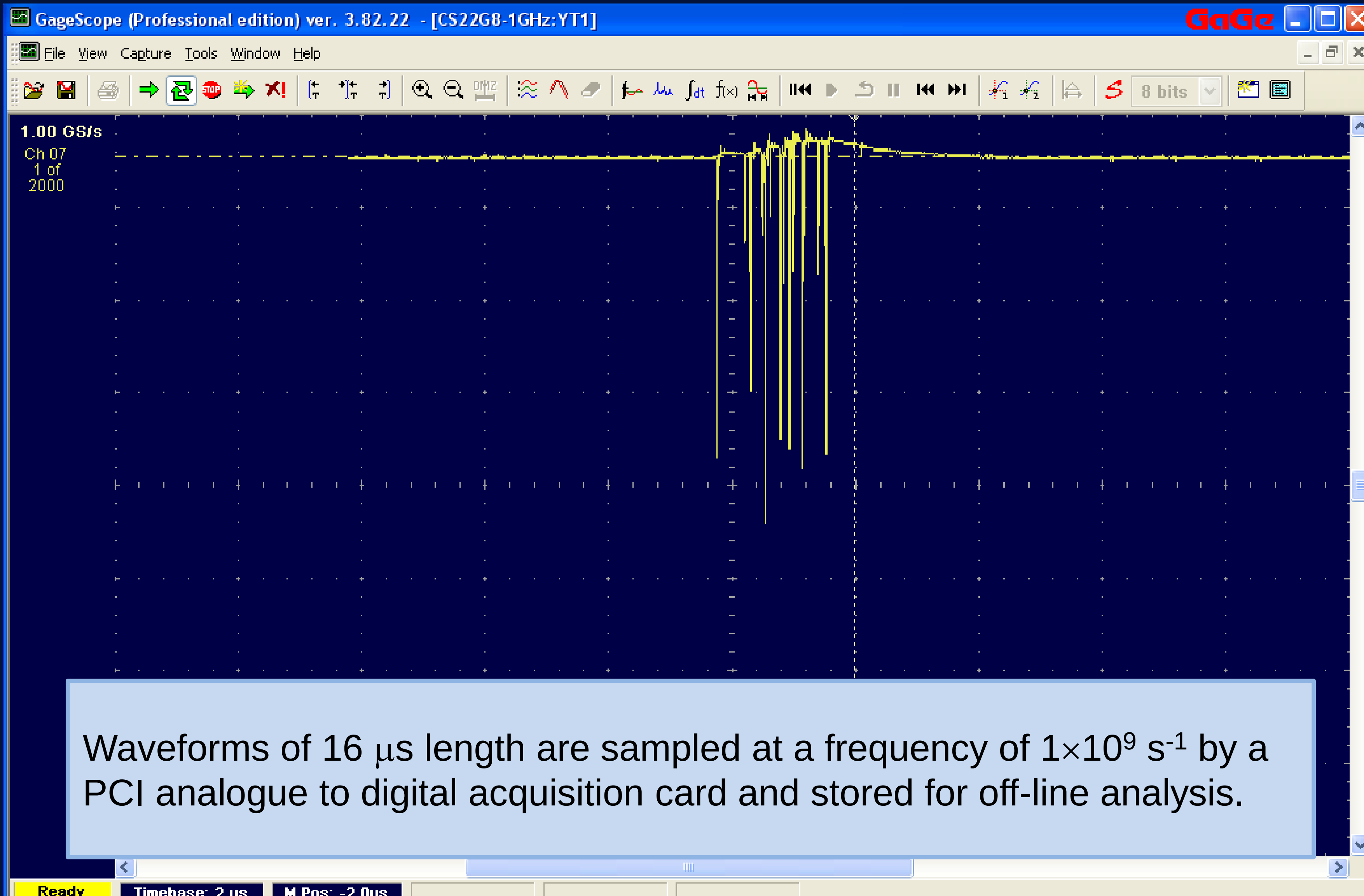
μ : mobility coefficient; $D_{L,T}$: diffusion coeff.
ε_k : characteristic energy
x: drift distance
E: electric field

Gaining factor: longitudinal diffusion

Dispersive factor: transverse diffusion

STARTRACK: DATA ACQUISITION

DATA ACQUISITION AND ANALYSIS



Waveforms of 16 μs length are sampled at a frequency of 1×10^9 s^{-1} by a PCI analogue to digital acquisition card and stored for off-line analysis.

DATA ANALYSIS: 1. CORRELATION OF RAW DATA

To increase the signal-to-noise ratio, correlation techniques are applied off-line to the raw pulse trails.

The correlation method

In this technique, each digitized primary electron track is correlated with a typical pulse

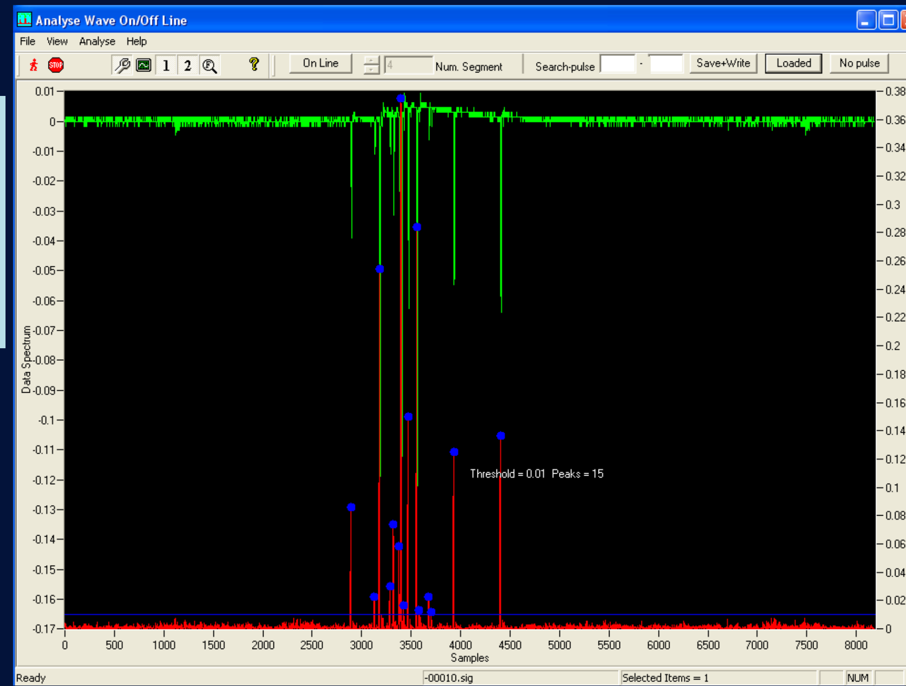
$$C_\tau = \sum_{t=0}^{N-1} f_t \, g_{t+\tau}$$

f_t Search Spectrum

g_t Data Spectrum

C_t Correlated Spectrum

- Pulses above a threshold are counted



Number of pulses	Arrival time/ns	Peak amplitude/mV
3	9500	300.3
	10250	400.8
	10800	464.6
1	11000	328.2
2	11132	25.2
	12898	56.4
…	…	…

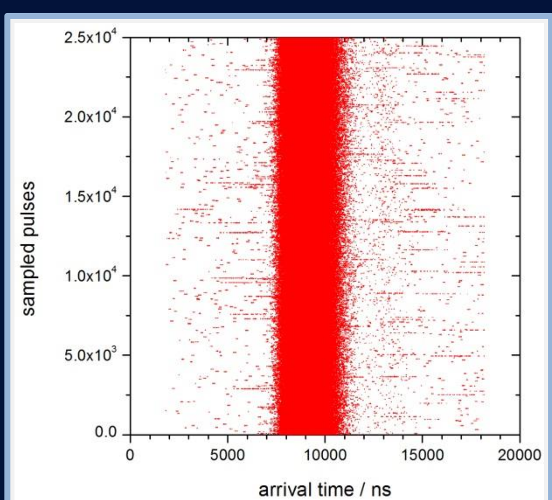
DATA ANALYSIS: 2. AMPLITUDE & TIME THRESHOLDS

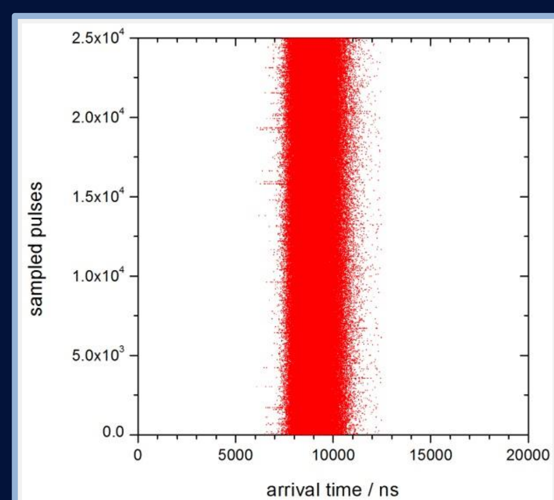
A threshold is applied to correlated pulses.

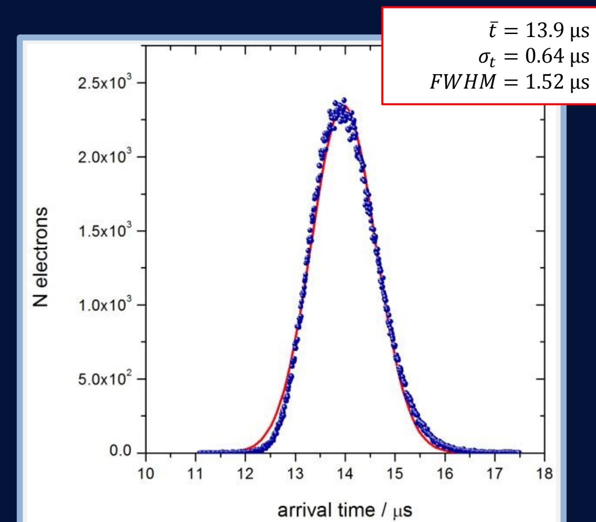
V_{thr} = 40 mV

A selective time window is applied in order to reject all the pulse trails that are not consistent with the expected drift time.

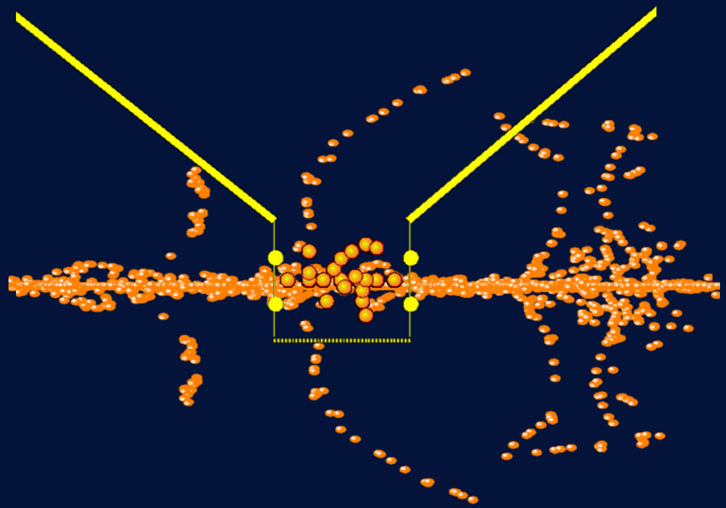
Number of pulses	Arrival time/ns	Peak amplitude/mV
3	9500	300.3
	10250	400.8
	10800	464.6
1	11000	328.2
~~2~~ 1	11132	~~2[illegible].2~~
	12898	56.4
…	…	…







DATA ANALYSIS: 3. BACKGROUND SUBTRACTION

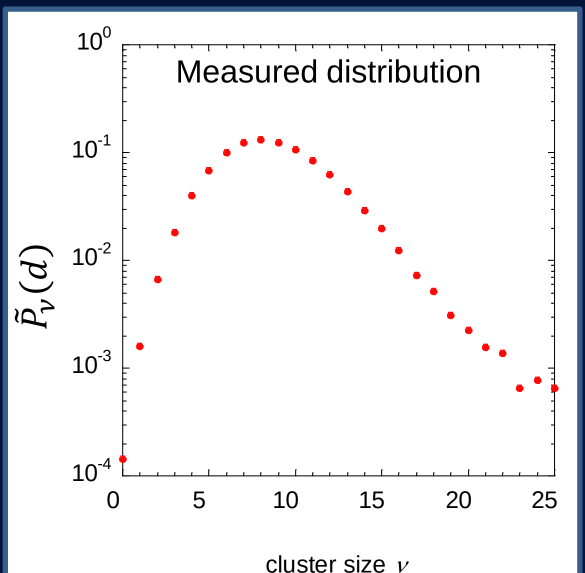


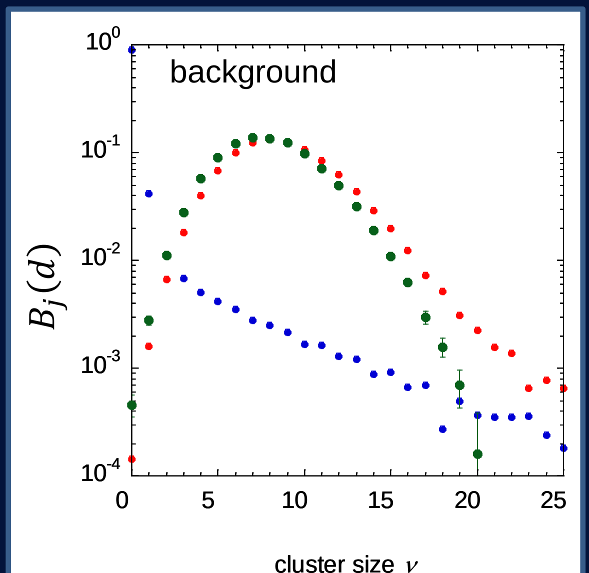
The measured cluster distribution $\tilde{P}_\nu(r)$ is the overlap of primary electron distribution $P_\nu(r)$ and a background distribution $B_\nu(r)$

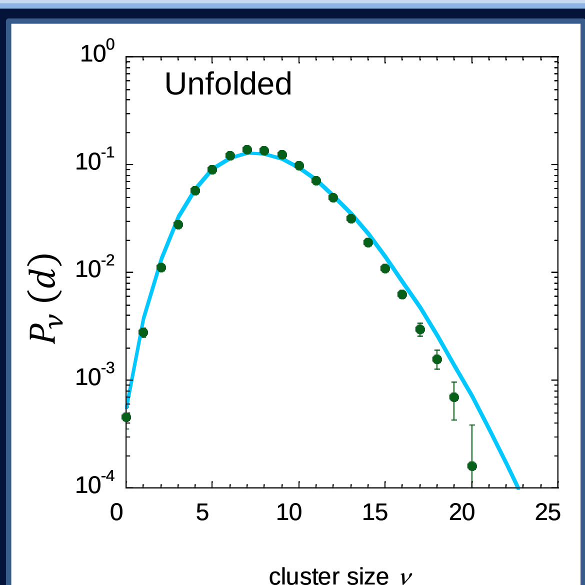
$$\tilde{P}_\nu(r) = \sum_{j=0}^{\nu} P_{\nu-j}(r)\, B_j(r)$$

Background distributions are also measured and unfolding procedure is applied

$$P_\nu\,(r) = \sum_{j=\nu}^{N_{max}} \tilde{P}_j(r)\, B_{j-\nu}(r)$$

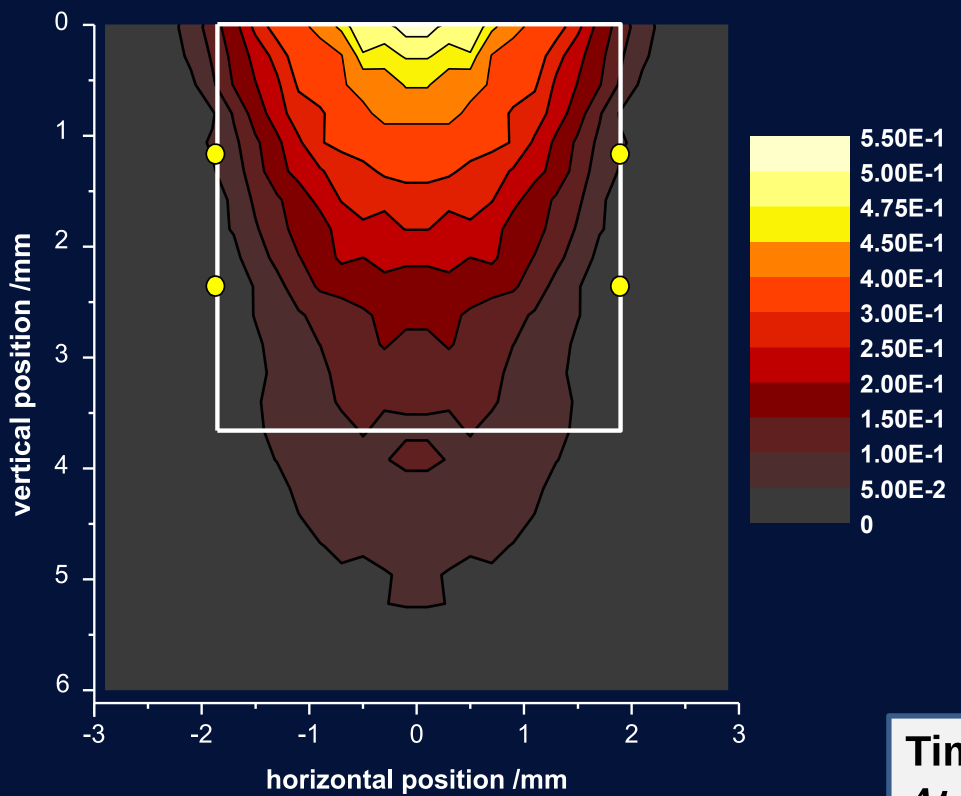




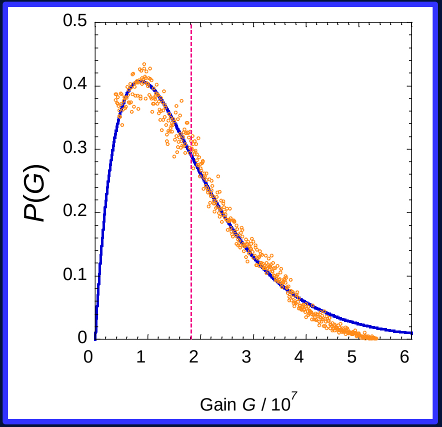


DATA SIMULATIONS

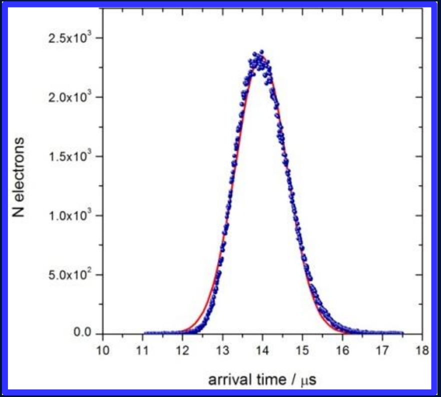
- Dedicated Monte Carlo code developed (Grosswendt).
- Response function included in the Monte Carlo code.



MSAC efficiency



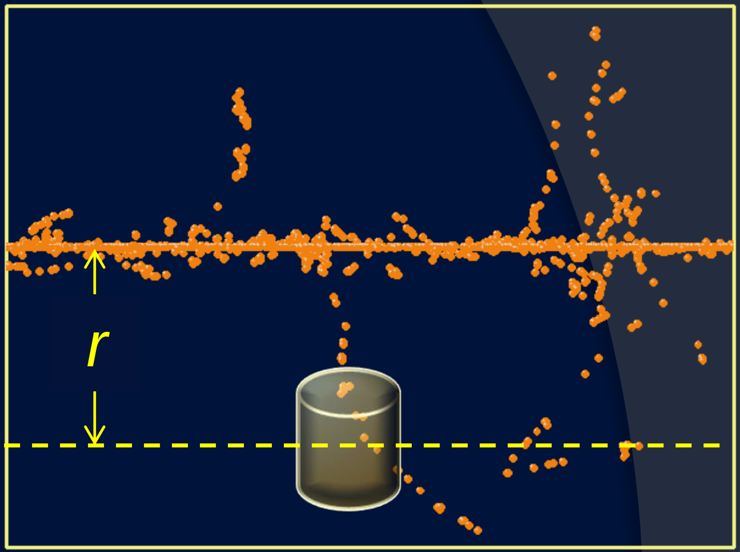
Time resolution
$\Delta t = 30\ \mathrm{ns}, \sigma_t = 700\ \mathrm{ns}$



RESULTS OF MEASUREMENTS AND SIMULATIONS

RESULTS OF MEASUREMENTS AND SIMULATIONS

$P_\nu(r)$ probability of ν ionizations at impact parameter r



$M_1 = \sum_\nu \nu \cdot P_\nu(r)$ mean cluster size

λ_{ion} Ionization mean free path of the primary ion

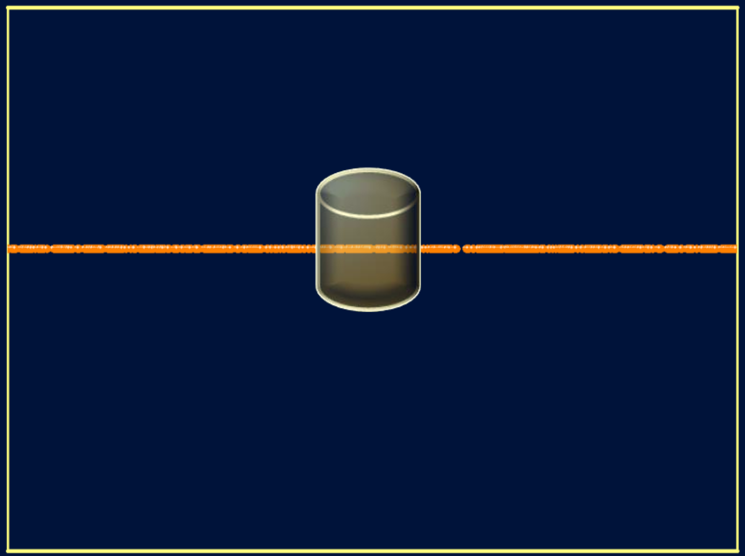
$$\lambda_{\text{ion}} \propto \frac{1}{\widetilde{N}\,\sigma_{\text{ion}}(T)}$$

D/λ_{ion} Mean number of electrons set in motion by the primary ion along a path length D

$$M_1 \propto \frac{D}{\lambda_{ion}}(m_1)$$

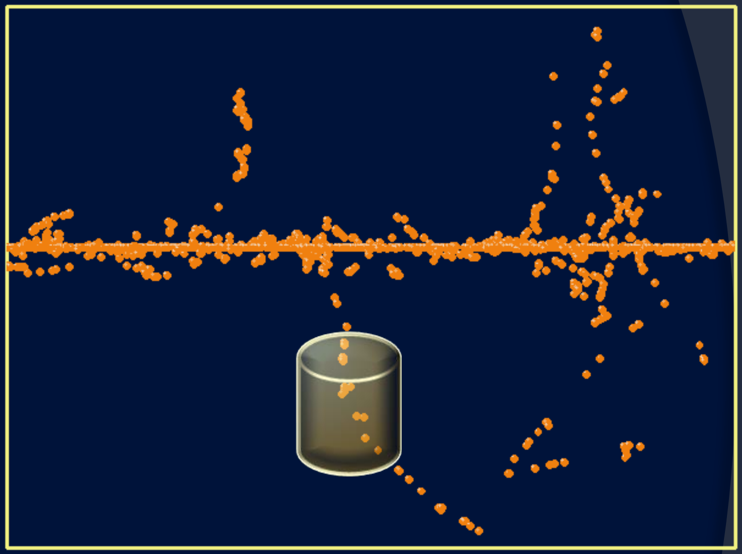
RESULTS OF MEASUREMENTS AND SIMULATIONS

CORE REGION
impact parameter *r* = 0 nm



Ionizations produced by the primary particles + ionizations produced by the secondary electrons (δ rays)

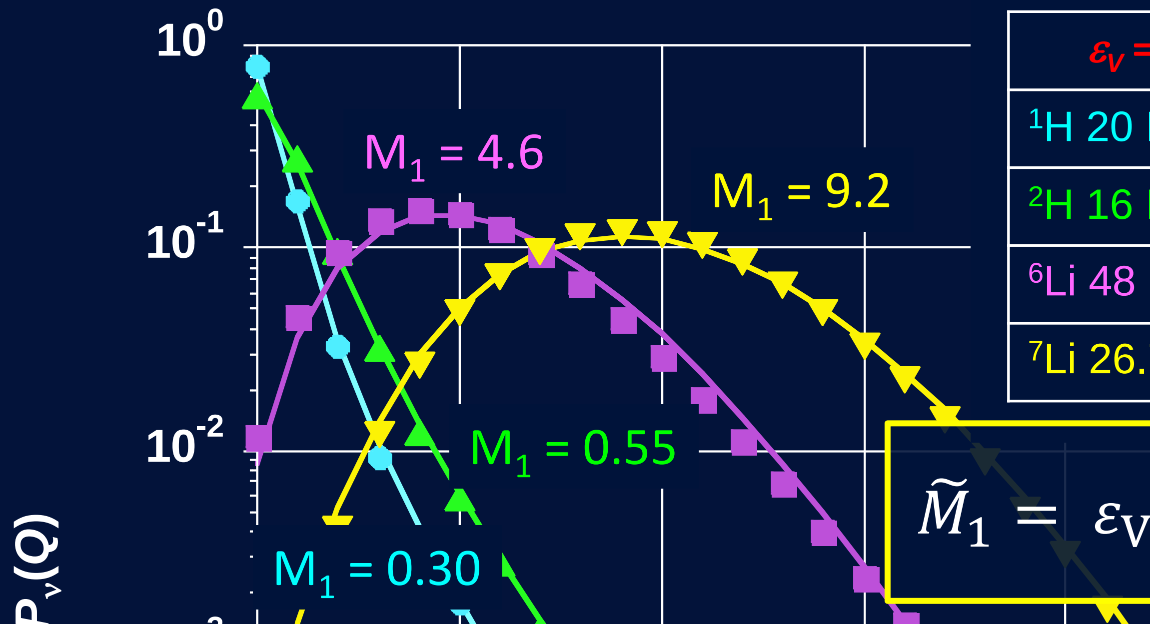
PENUMBRA REGION
impact parameter *r* > 0 nm



Ionizations produced only by δ-rays

TRACK CORE

Symbols: measurements   lines: Monte Carlo simulation



ε_V = 0.2	D/λ_{ion}	$\widetilde{M}_1$
^{1}H 20 MeV	0.97	0.19
^{2}H 16 MeV	2.1	0.43
^{6}Li 48 MeV	19	3.8
^{7}Li 26.7 MeV	36	7.3

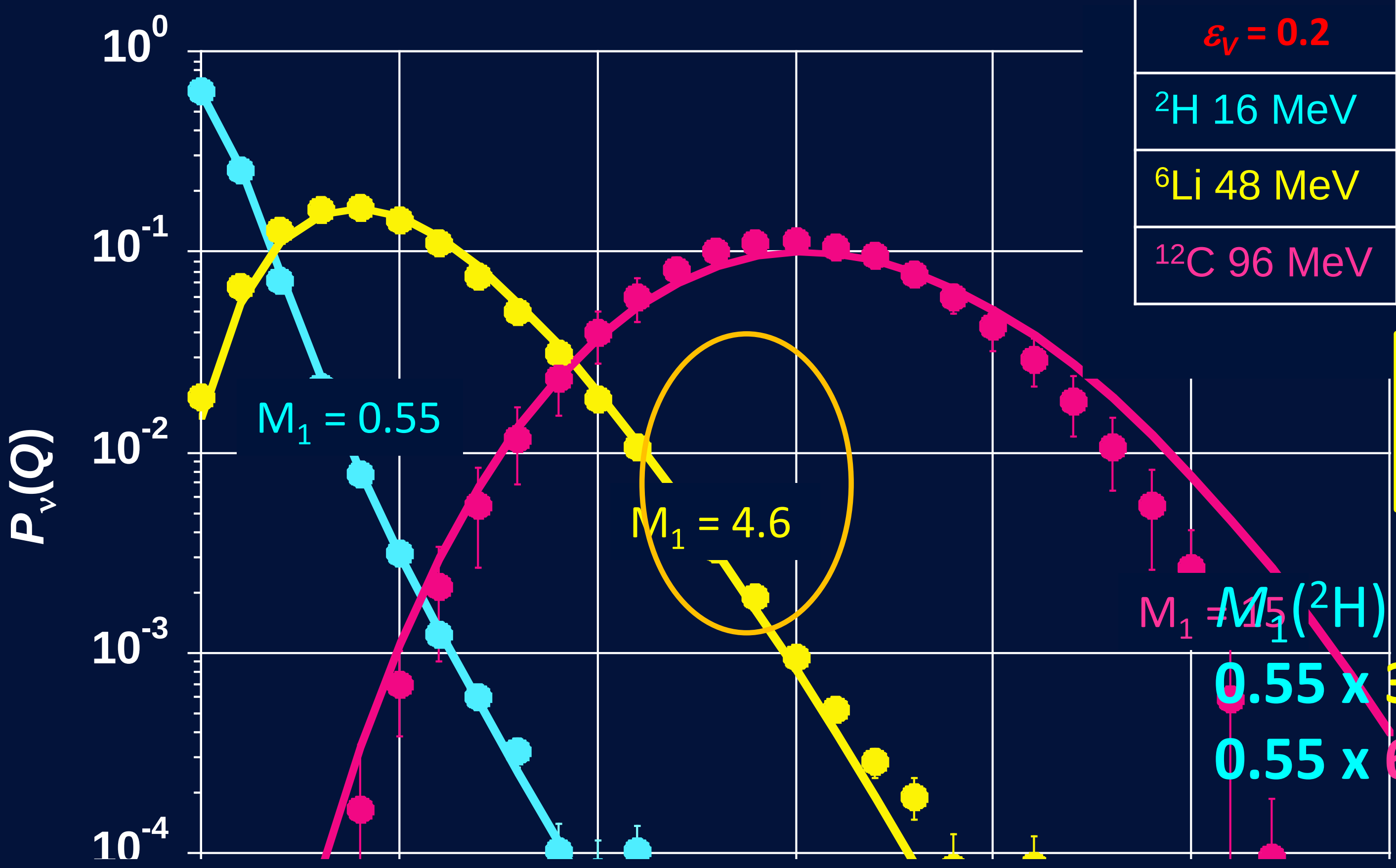
$$\widetilde{M}_1 = \varepsilon_V \cdot \frac{D}{\lambda_{ion}}$$

$$M_1 \propto \frac{D}{\lambda_{ion}}$$

Sparsely ionizing particles, like 20 MeV protons, and densely ionizing particles, like 26.7 MeV ^{7}Li-ions, show markedly different ionization patterns

With decreasing ionization mean free path length of the primary ions the distributions become peaked and shift to larger cluster sizes

TRACK CORE: same velocity, different Z



ε_V = 0.2	Z	D/λ_{ion}	$\widetilde{M}_1$
^{2}H 16 MeV	1	2.1	0.43
^{6}Li 48 MeV	3	19	3.8
^{12}C 96 MeV	6	77	15

$$M_1 \propto \frac{D}{\lambda_{ion}}$$

$M_1(^2\text{H}) = 0.55$

0.55 x 3^2 = 4.95

0.55 x 6^2 = 19.8

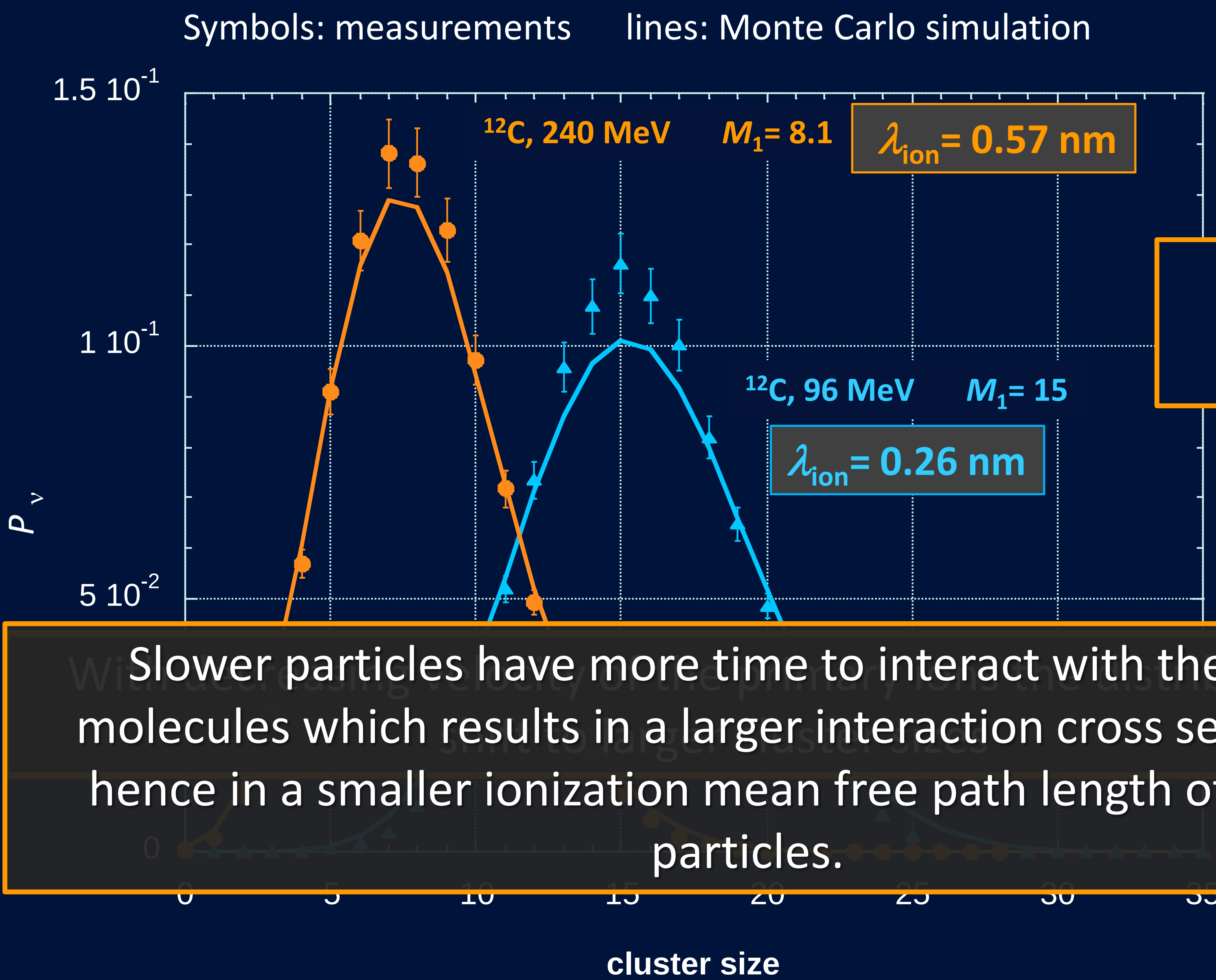
Symbols: measurements lines: Monte Carlo simulation

To improve:

1. Efficiency for large cluster **sizes**.

Cluster size ν

TRACK CORE: same *Z*, different velocities



$$M_1 \propto \frac{D}{\lambda_{ion}}$$

Slower particles have more time to interact with the target molecules which results in a larger interaction cross section and hence in a smaller ionization mean free path length of primary particles.

AGREEMENT BETWEEN MEASUREMENTS AND SIMULATIONS

Does it mean that the experimental results are correct?

NO !

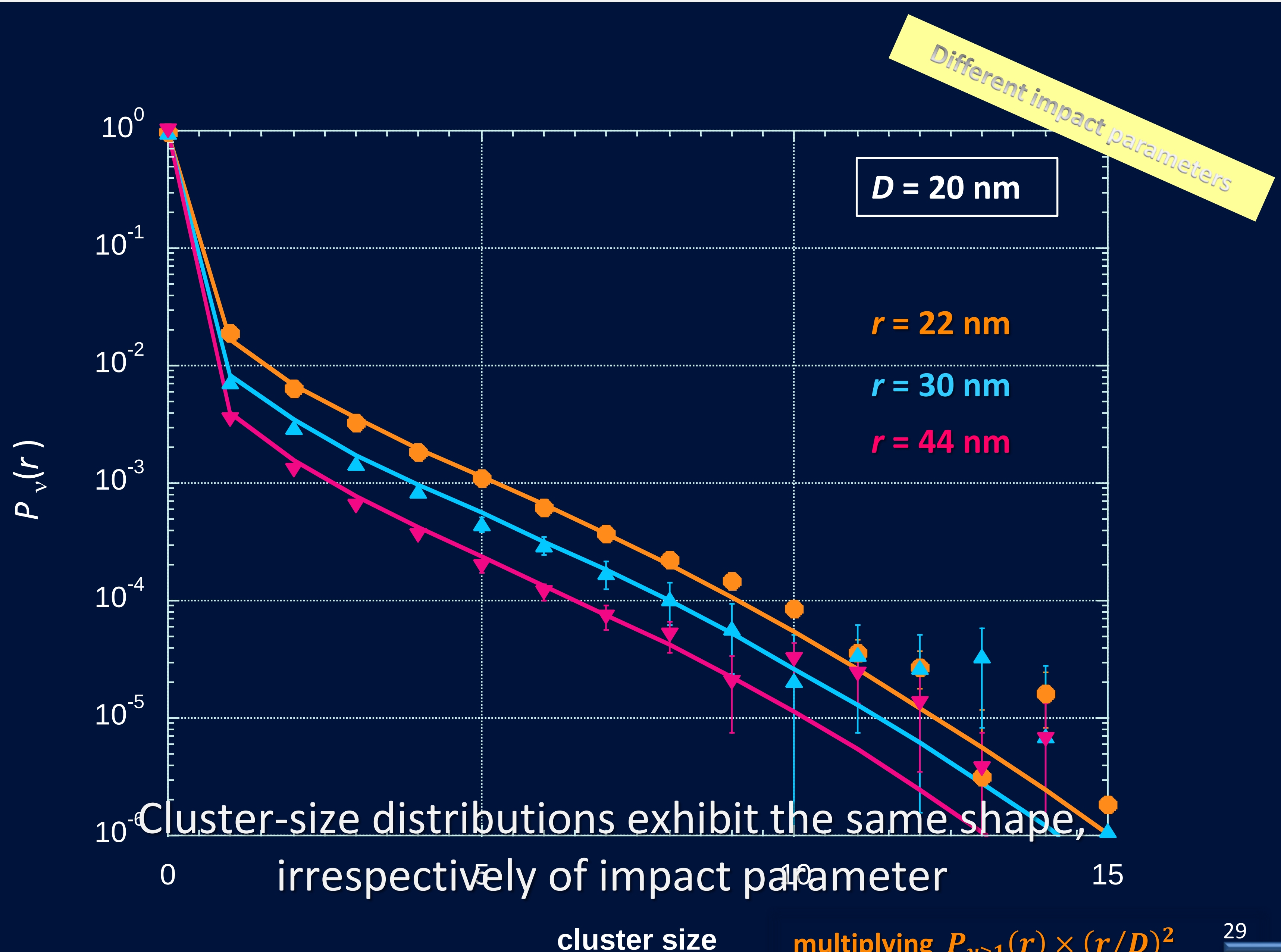
Validation of the Monte Carlo simulation code

Simulations as a tools to supplement experimental measurements

TRACK STRUCTURE in the PENUMBRA
impact parameter *r* > 20 nm

Ionizations produced only by the secondary electrons (δ rays)

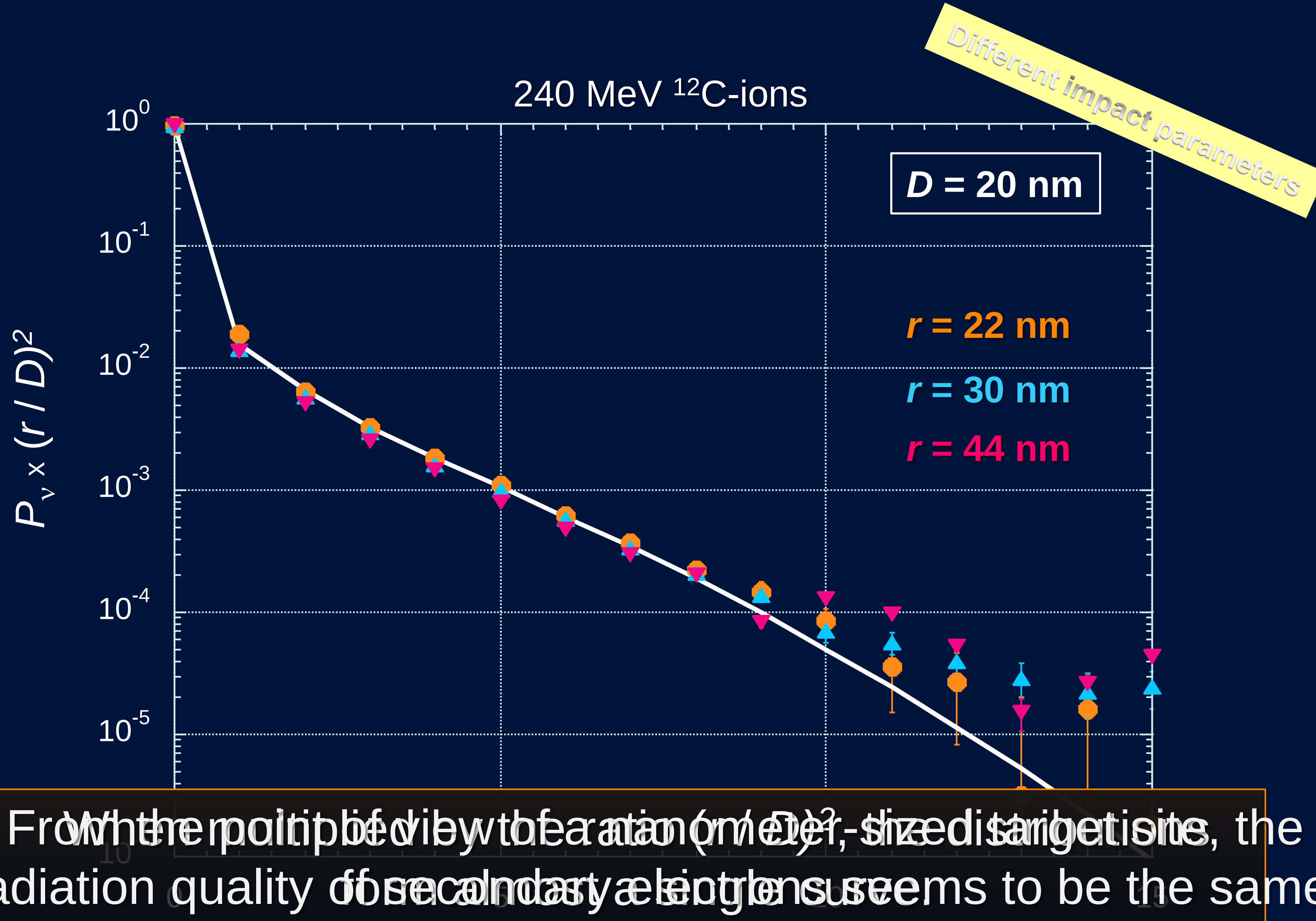
TRACK PENUMBRA: 240 MeV ^{12}C-ions, different *r*



Cluster-size distributions exhibit the same shape, irrespectively of impact parameter

multiplying $P_{\nu\geq 1}(r) \times (r/D)^2$

TRACK PENUMBRA: $P_{\nu\geq 1} \times r^2 / D^2$

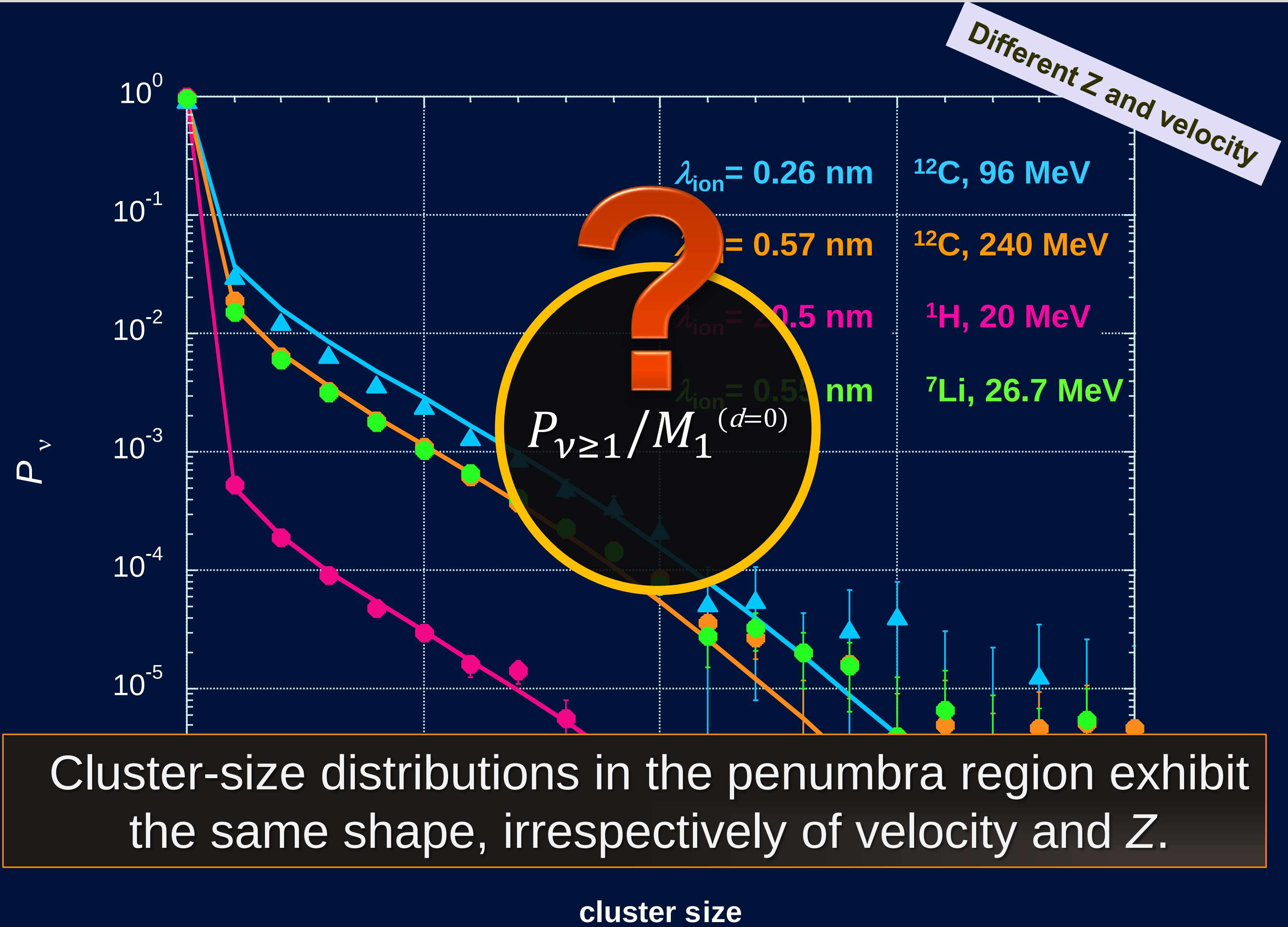


When multiplied by the ratio $(r / D)^2$, the distributions fall onto almost a single curve.

From the point of view of a nanometer-sized target site, the radiation quality of secondary electrons seems to be the same, only the probability of being hit decreases with increasing *r*.

comparing different ions

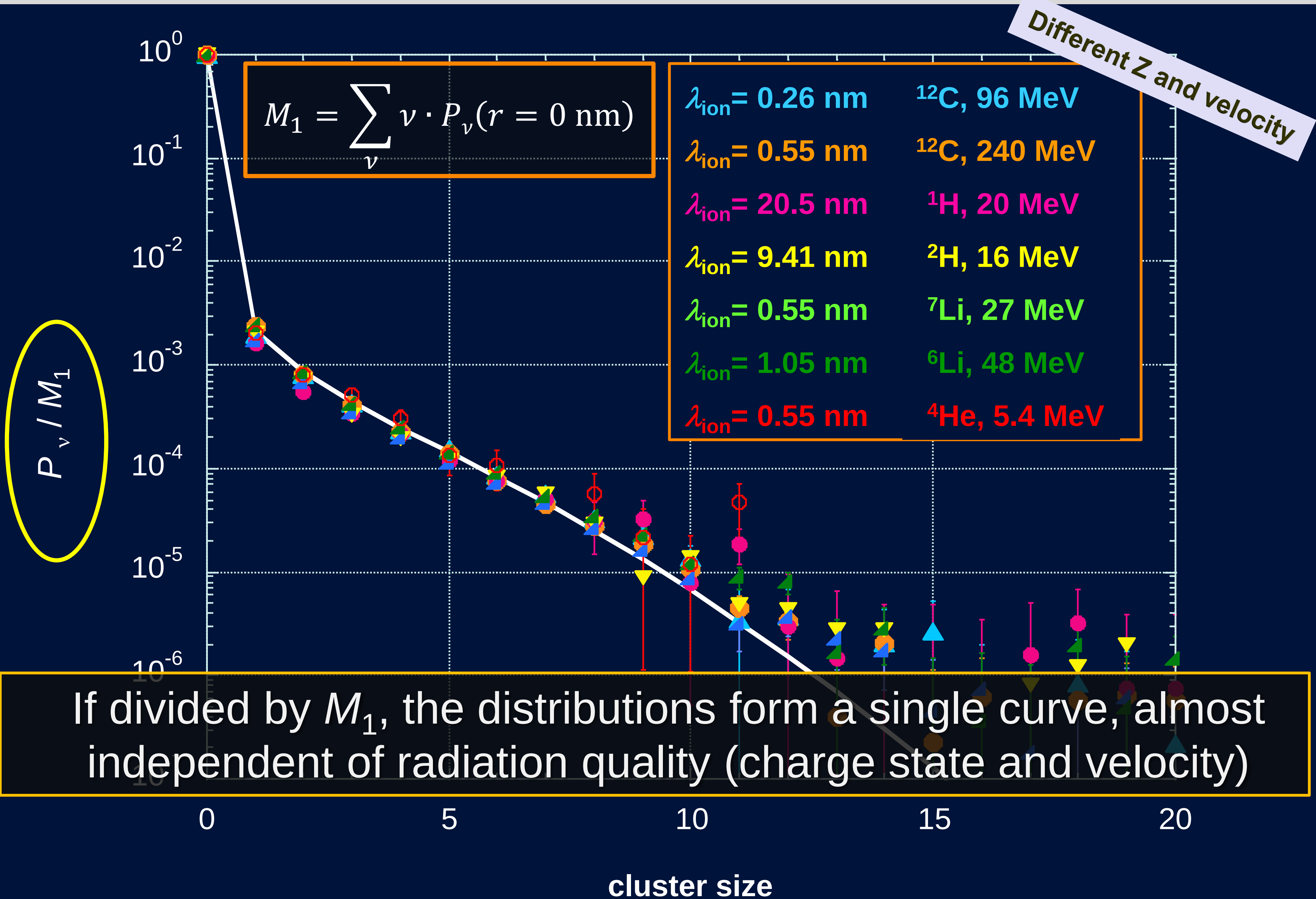
TRACK PENUMBRA: different Z and velocities



Cluster-size distributions in the penumbra region exhibit the same shape, irrespectively of velocity and *Z*.

Dividing $P_{\nu\geq1}(d) \div M_1$

TRACK PENUMBRA after dividing $P_{\nu\geq1}(Q) \div M_1$

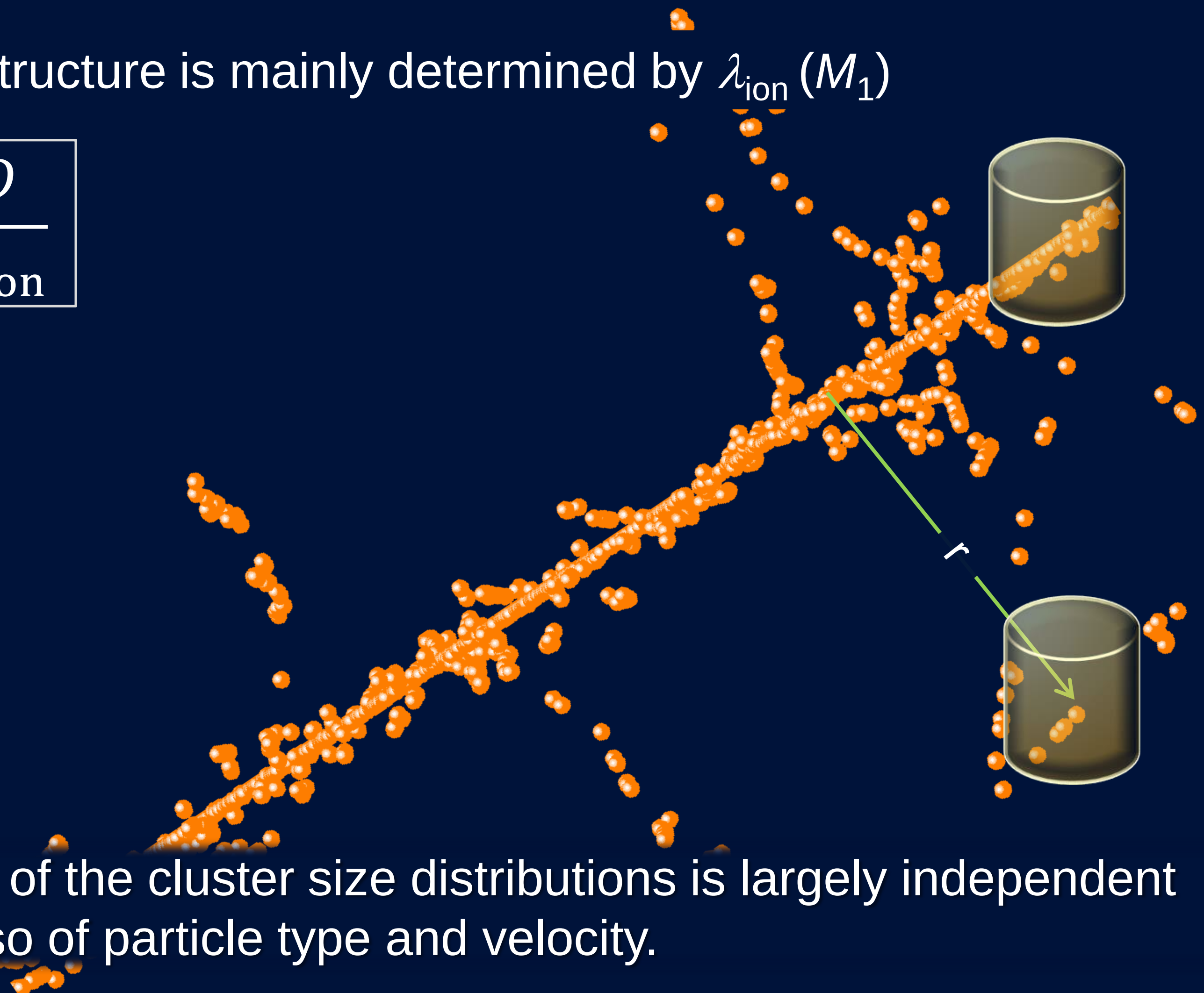


If divided by M_1, the distributions form a single curve, almost independent of radiation quality (charge state and velocity)

CONCLUSIONS

The track structure is mainly determined by λ_{ion} (M_1)

$$M_1 \propto \frac{D}{\lambda_{ion}}$$

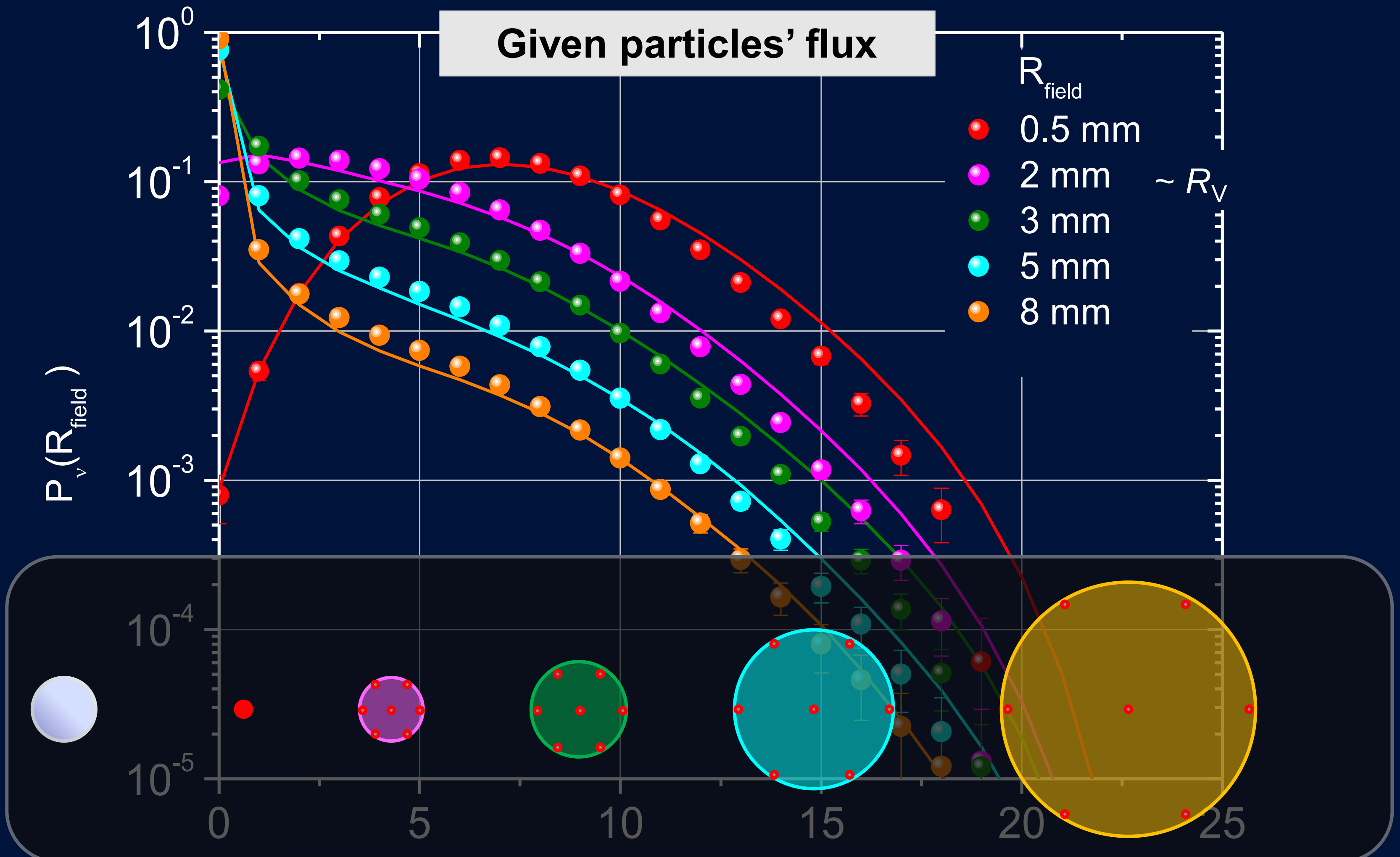


The shape of the cluster size distributions is largely independent of *r* and also of particle type and velocity.

Cluster-size distributions in nanometre-sized volumes reflect special properties of particle track structure

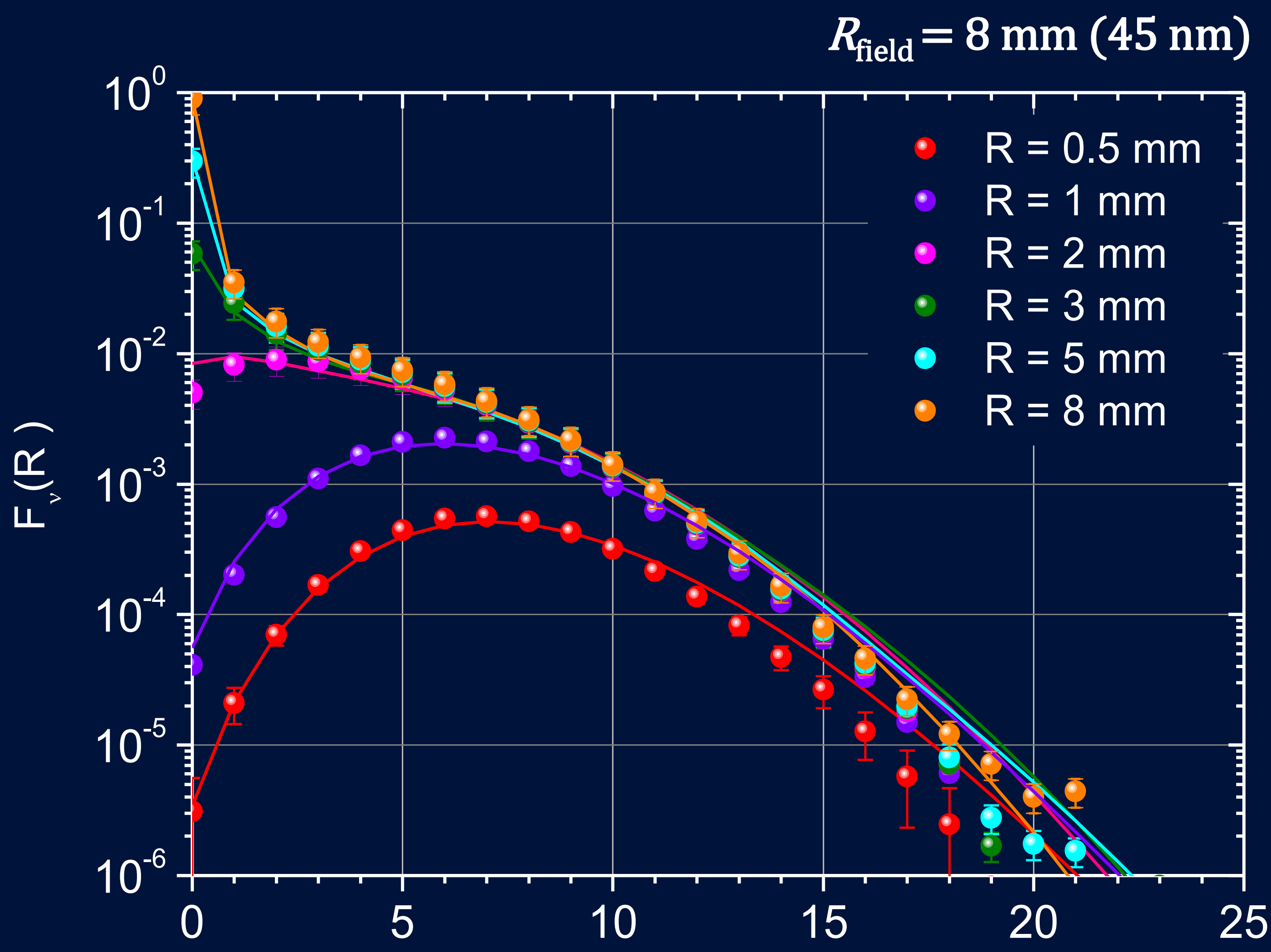
240 MeV ^{12}C-IONS HOMOGENEOUS EXTENDED BEAM

Total cluster distributions for beams of different radius R_{field}



From $R > 3$ mm (1.5 R_V) the shape is the same

240 MeV ^{12}C-IONS HOMOGENEOUS EXTENDED BEAM



Contribution from $R > 3$ mm (1.5 R_V) only increases the fraction of zeros

Challenges:
1. a practical instrument for track structure measurements.
2. a practical instrument (TEPC) for measurements at the nanometer level.