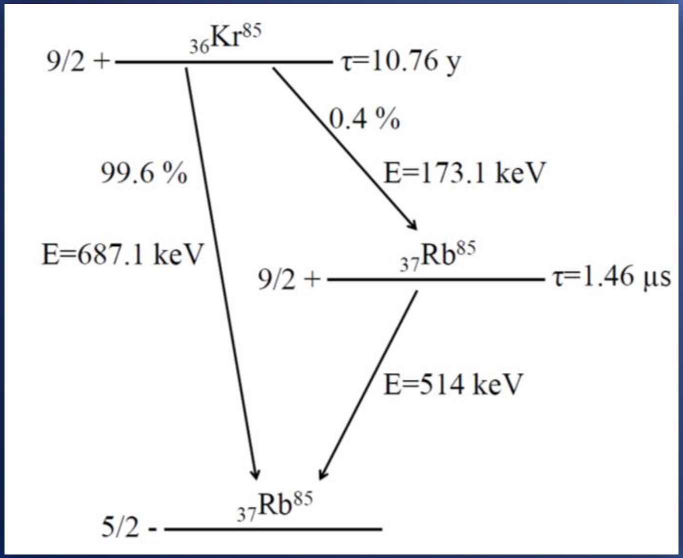
Krypton in Xenon

Determination of krypton concentration in cryogenic distilled xenon gas with a quadrupole mass spectrometer following a cold-trap at a temporarily reduced pumping speed

by Alexander Fieguth (WWU Münster)

Krypton is a radioactive background

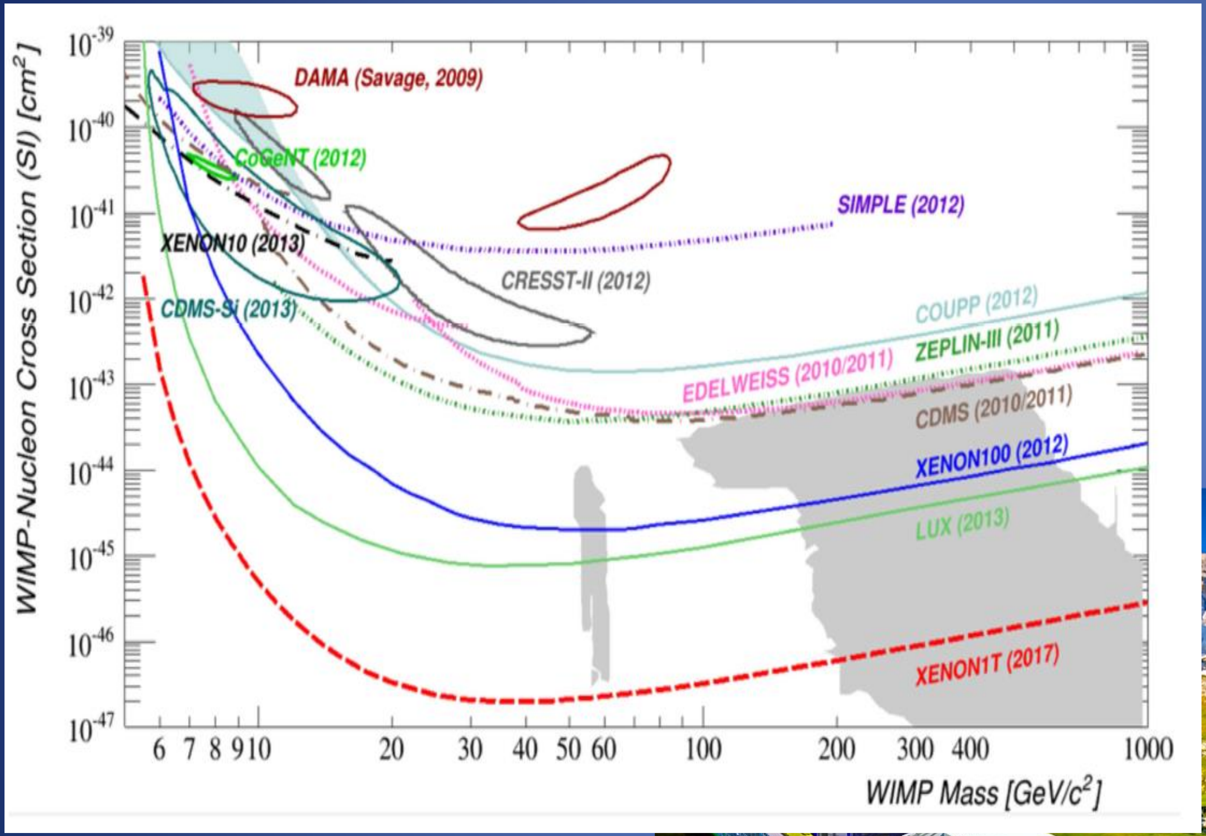
- Krypton-85 decays via β-decay with an endpoint energy of 687 keV
- Trace amounts of ^{85}Kr are abundant in the atmosphere due to nuclear bomb tests and nuclear reprocessing

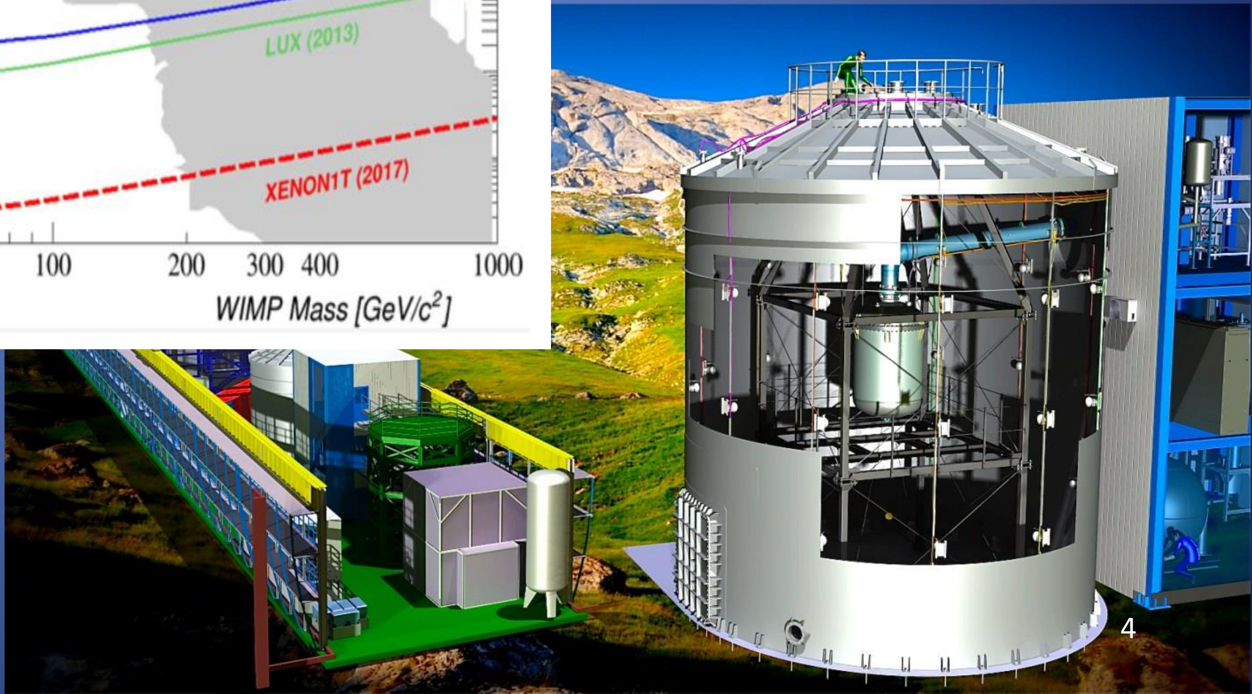


Xenon extraction from atmosphere leads to natural krypton contamination!

$$\frac{^{85}Kr}{^{nat}Kr} \sim 10^{-11}$$

XENON Dark Matter Project

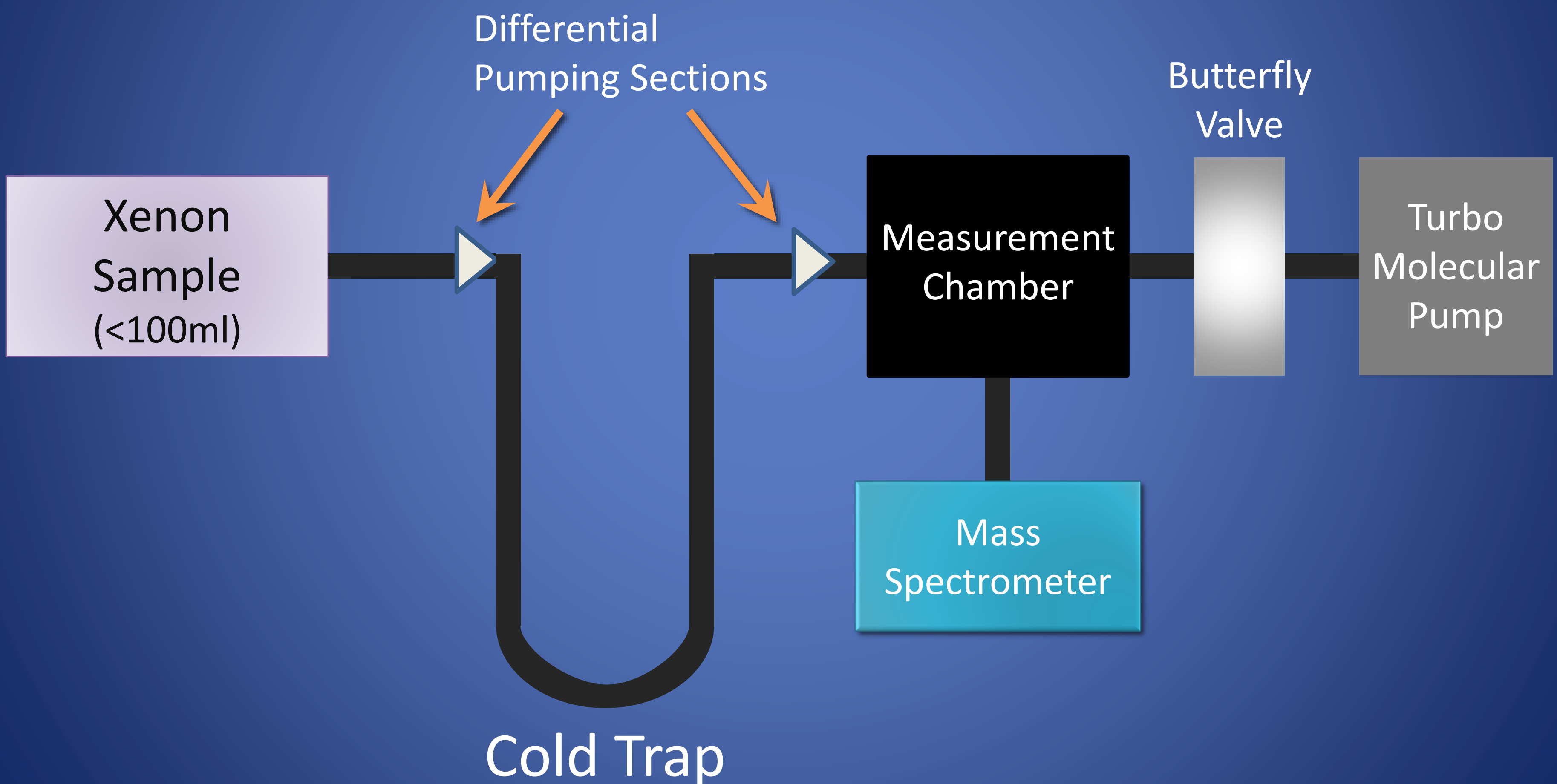




XENON1T / XENONnT requirements

- Commercial xenon has a krypton content at the ppm to ppb level
- Removal of krypton is done by cryogenic distillation (see talk of M. Murra)
- Desired concentration is in the sub-ppt range
- Knowledge of the content is necessary for background event expectation due to krypton
- Measurement of the krypton concentration in this regime is not trivial

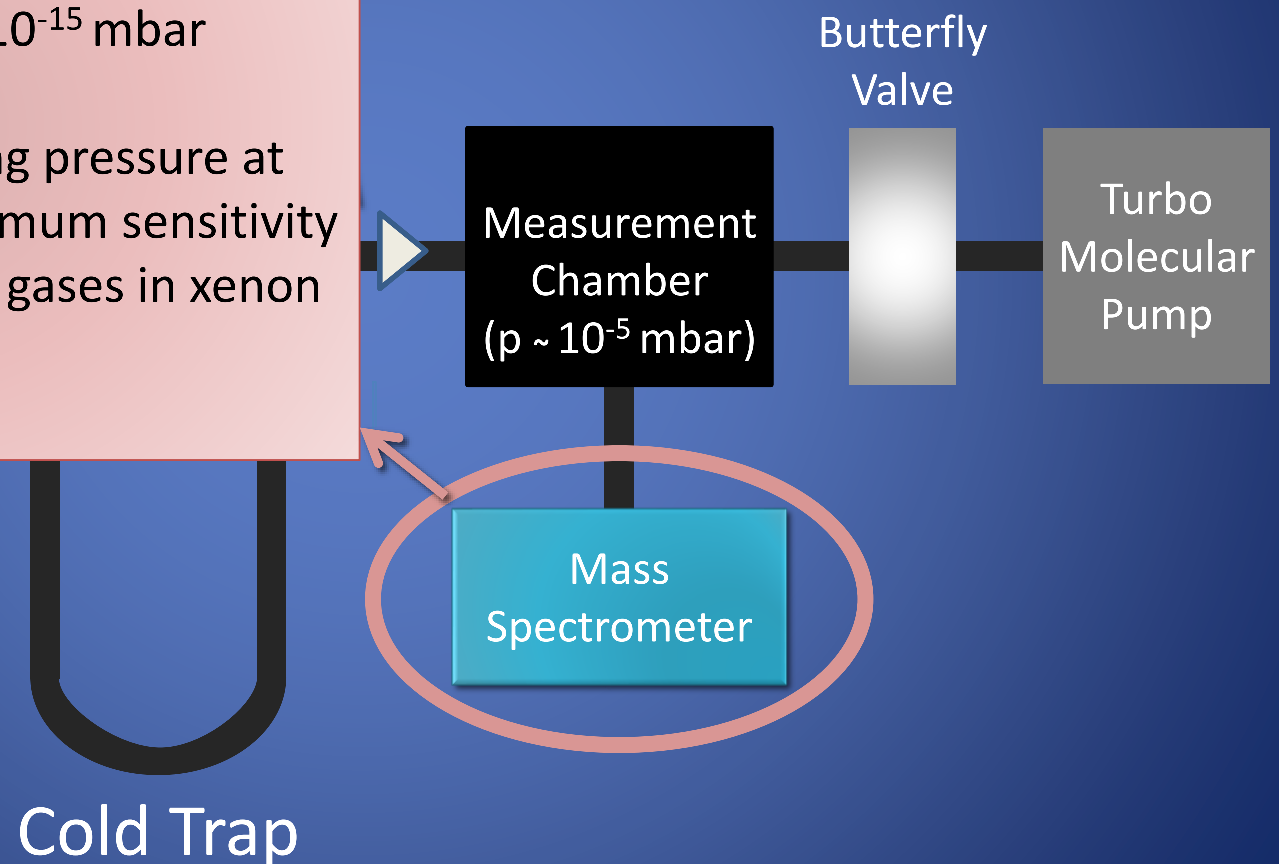
Measurement setup



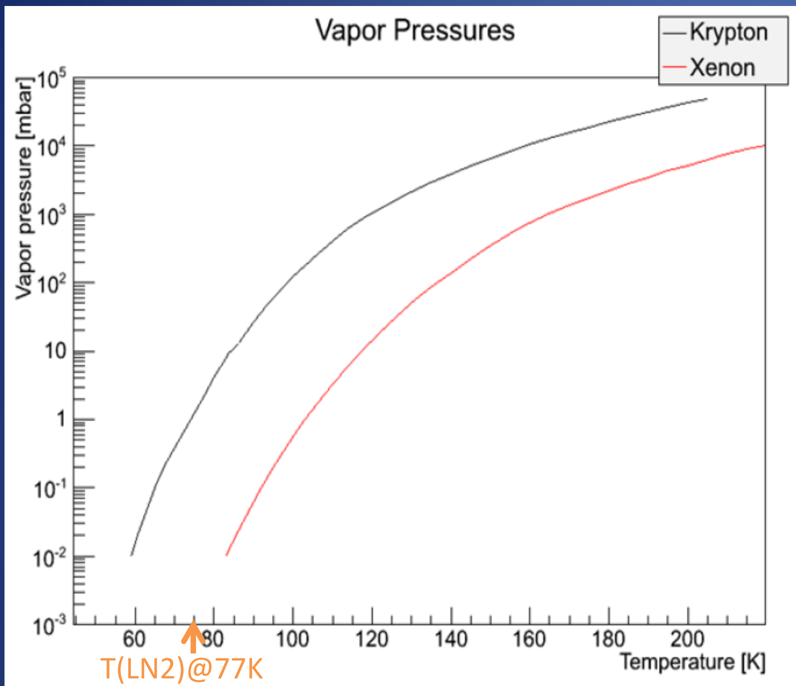
A.Dobi et al. Nucl.Instrum.Meth. A665 (2011) 1-6 & **E.Brown et al., JINST** 8 (2013) P02011

Mass spectrometer

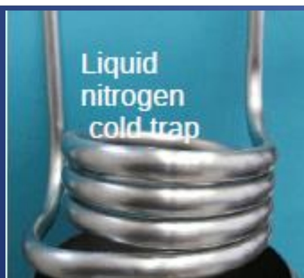
- Using a commercial residual gas analyzer with a partial pressure sensitivity down to ~10^{-15} mbar
- Limitation of operating pressure at 10^{-5} mbar sets a maximum sensitivity when detecting trace gases in xenon at ppb level



Cold trap

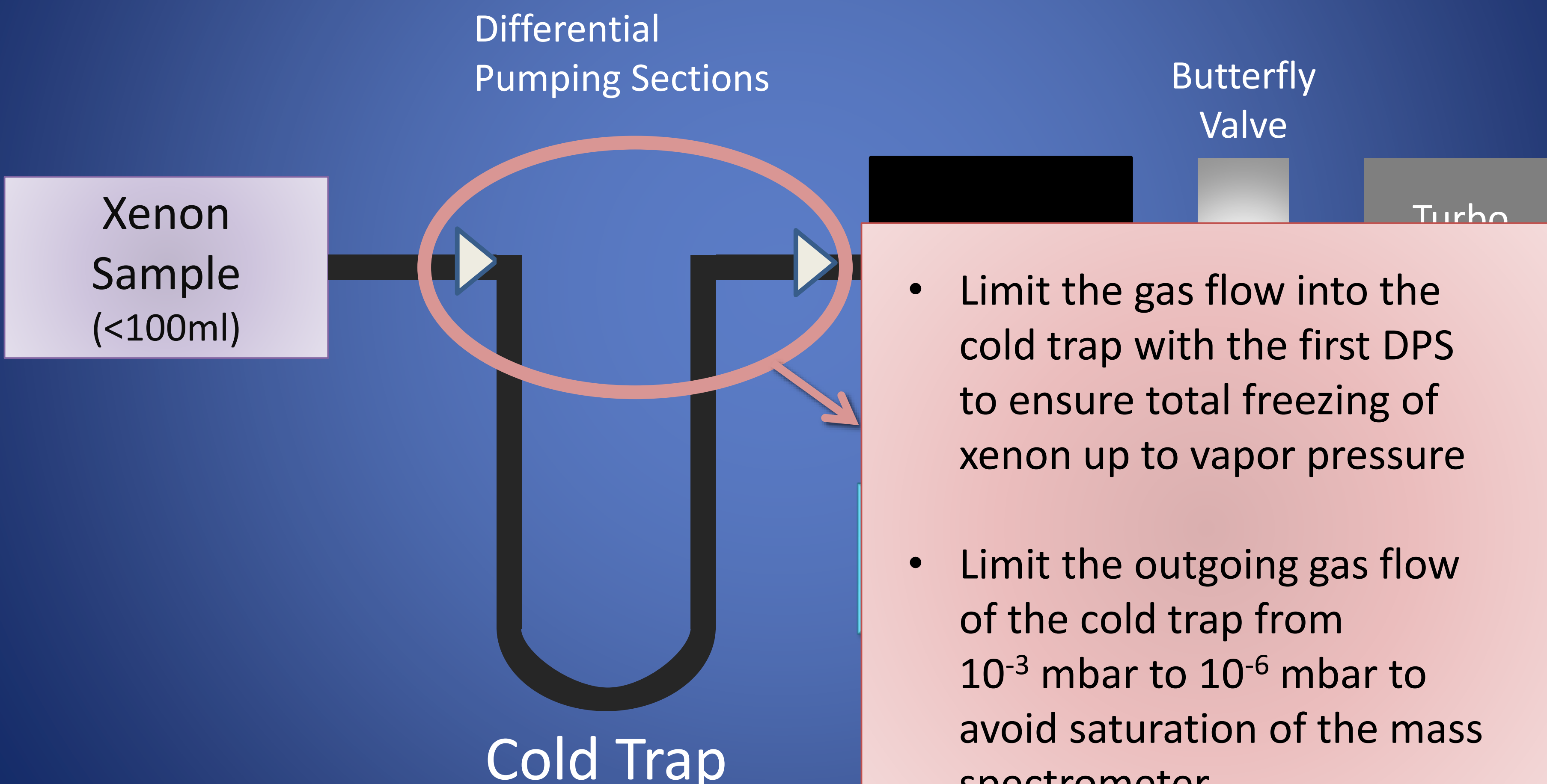


- Cool the stainless steel coil in a liquid nitrogen dewar down to 77K
- Xenon should freeze to the walls until the pressure reaches the vapor pressure of about 3×10^{-3} mbar at 77K
- Due to its low concentration krypton should pass unaffected and therefor the krypton concentration is enhanced



Mass Spectrometer

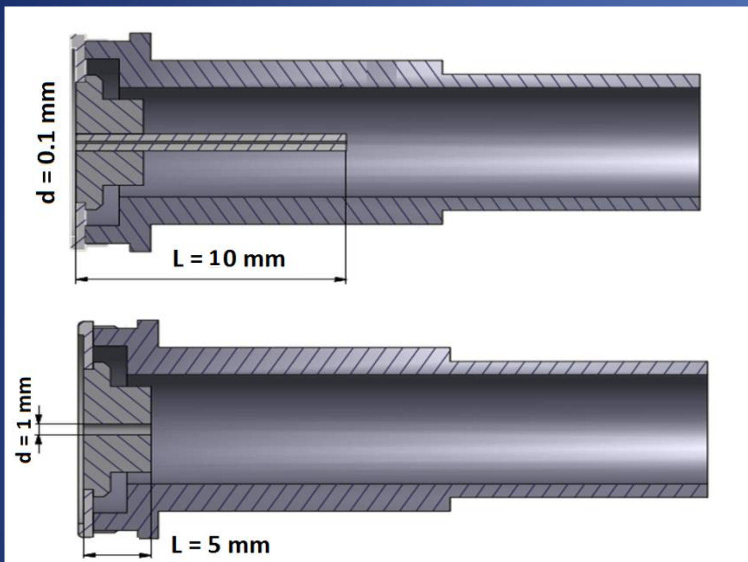
Differential pumping sections (DPS)

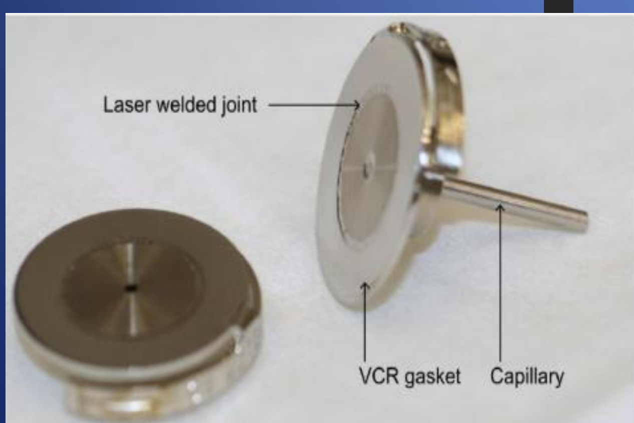


- Limit the gas flow into the cold trap with the first DPS to ensure total freezing of xenon up to vapor pressure

- Limit the outgoing gas flow of the cold trap from 10^{-3} mbar to 10^{-6} mbar to avoid saturation of the mass spectrometer

Differential pumping sections (DPS)





ial
Sections

Butterfly
Valve

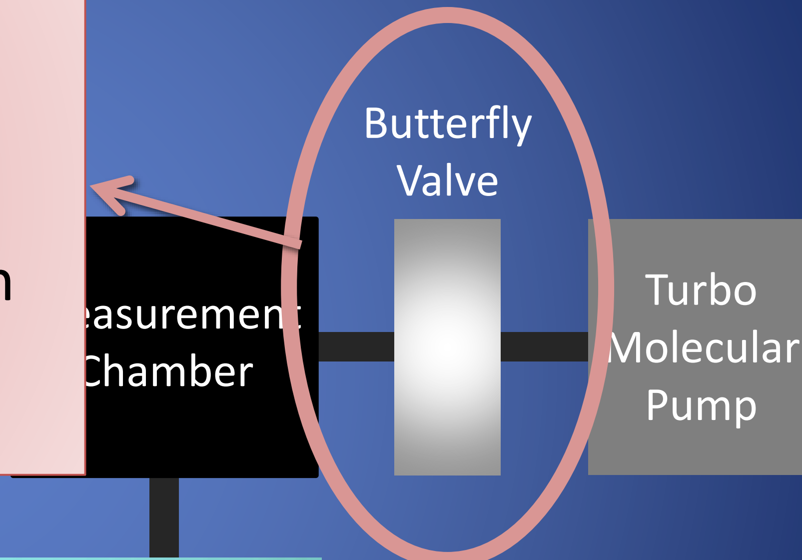
Turbo

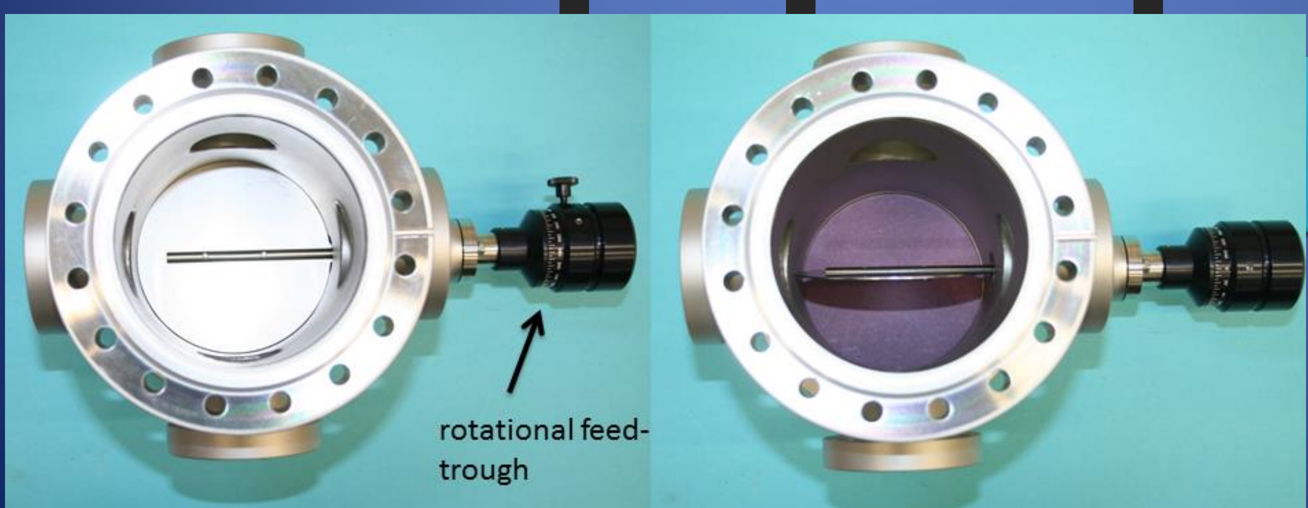
d Trap

- Limit the gas flow into the cold trap with the first DPS to ensure total freezing of xenon up to vapor pressure
- Limit the outgoing gas flow of the cold trap from 10^{-3} mbar to 10^{-6} mbar to avoid saturation of the mass spectrometer

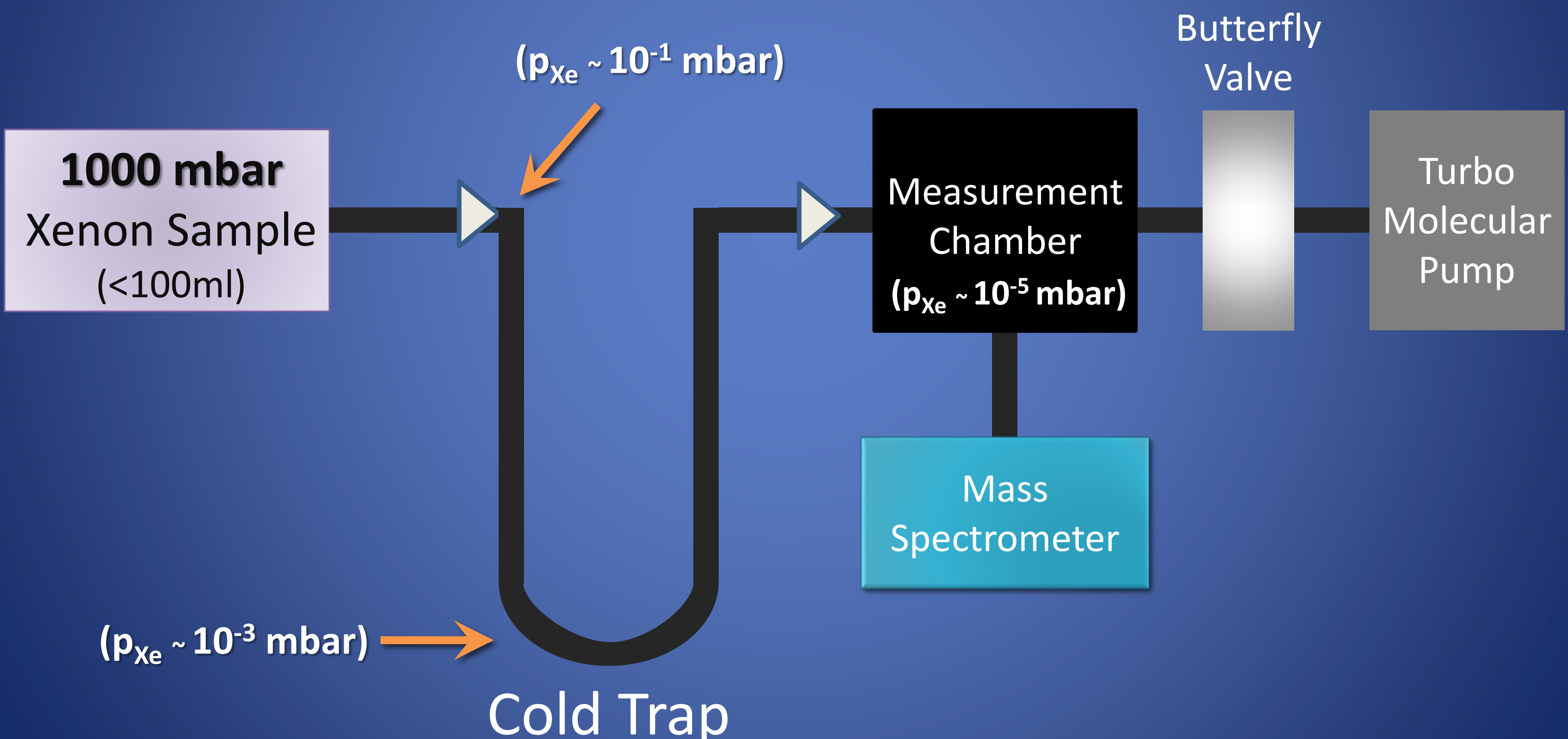
Custom made butterfly valve

- Using a custom made butterfly valve allows to have a dynamic range of effective pumping speed (from 300 l/s down to 6l/s) and therefore a regulation of gas load going to the mass spectrometer





Measurement setup



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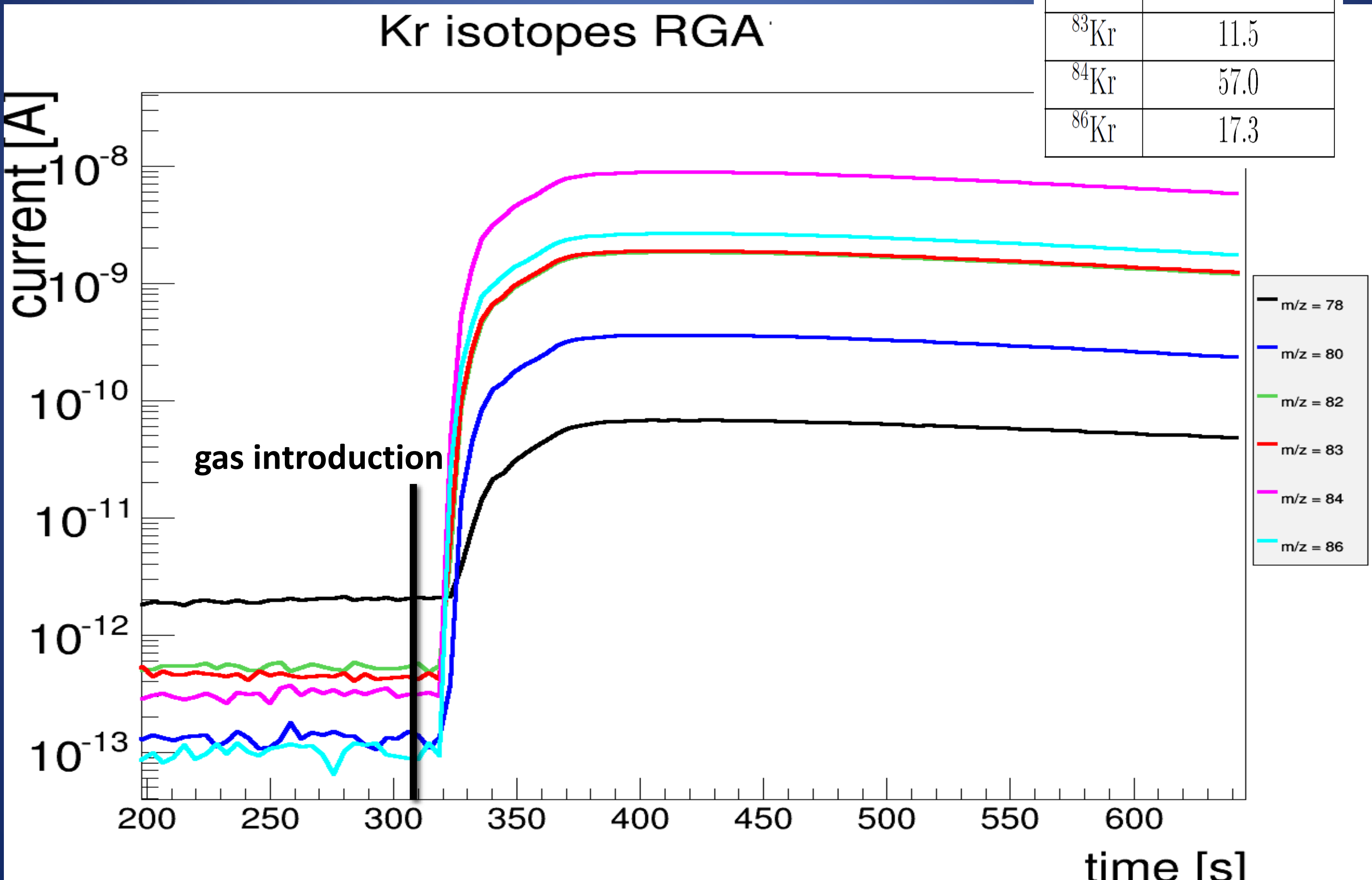
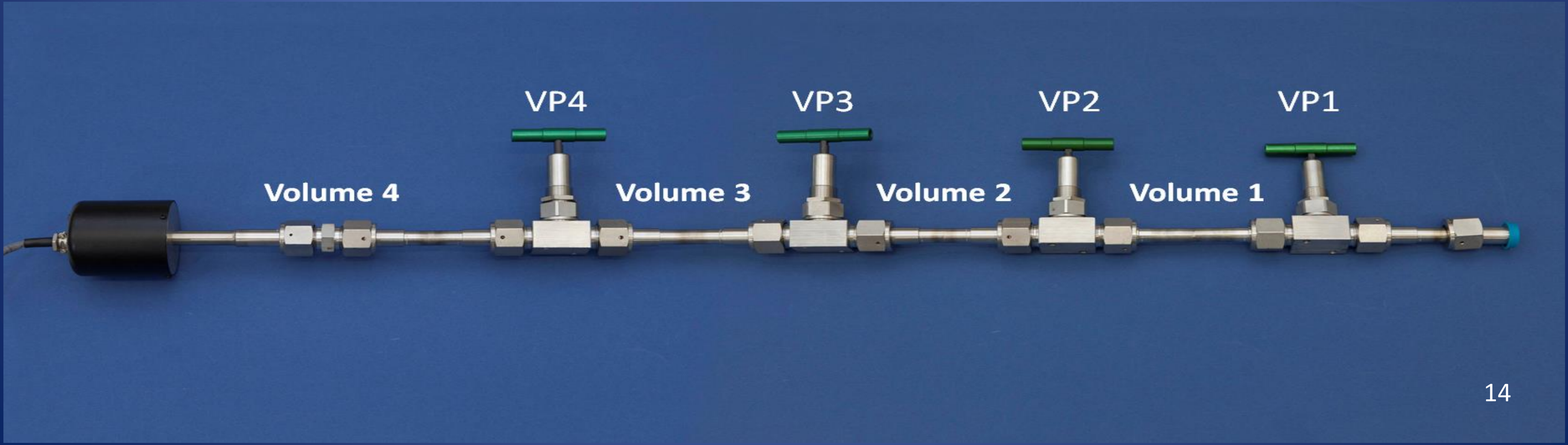
Example signal

Isotope	Abundance in %
^{78}Kr	0.35
^{80}Kr	2.25
^{82}Kr	11.6
^{83}Kr	11.5
^{84}Kr	57.0
^{86}Kr	17.3

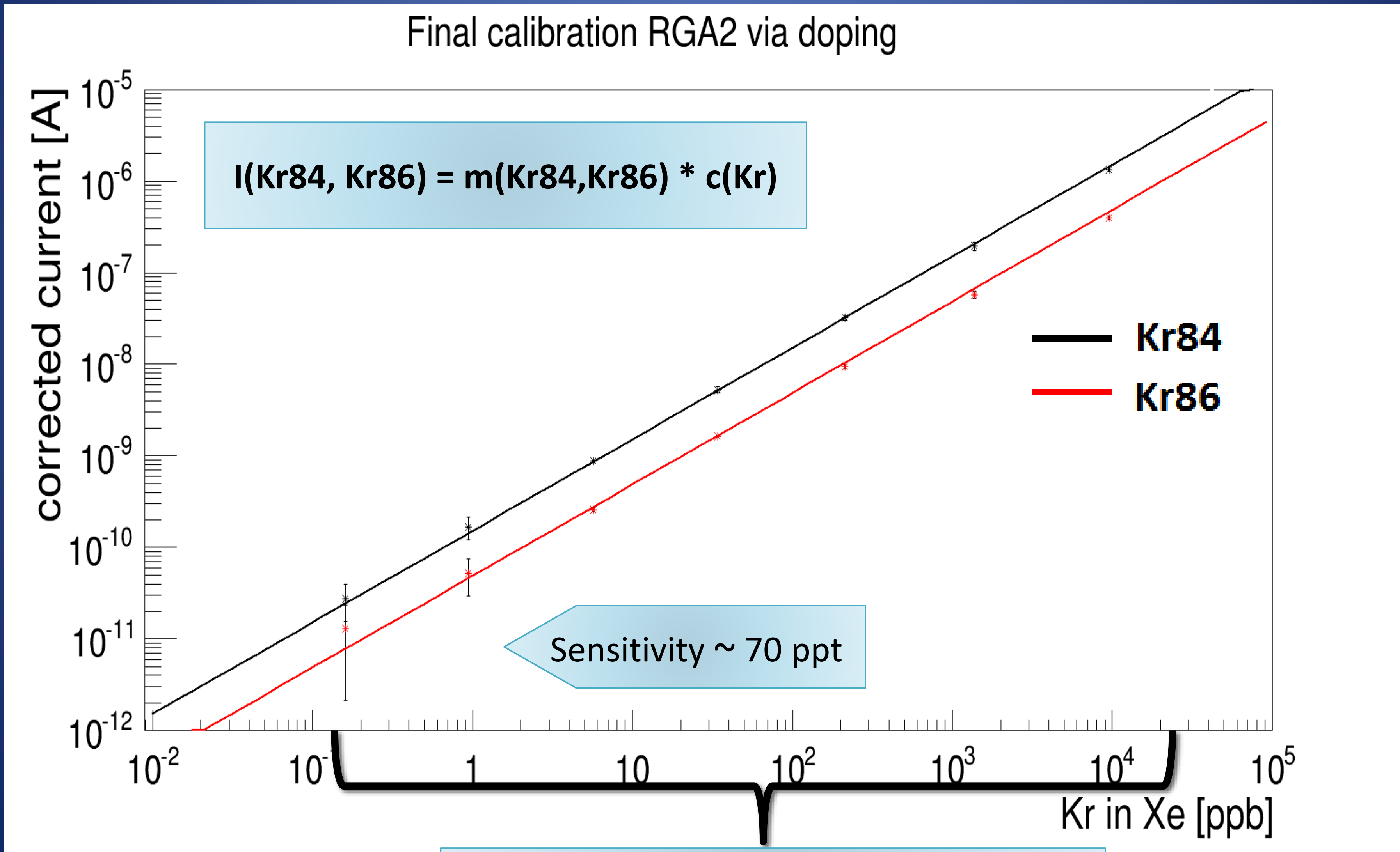


Calibration

- Artificially enhance the krypton concentration in xenon gas samples
- Using volume expansion for mixtures with known concentrations (“doping”)
- Advantage of a running distillation column allows for gas mixtures down to ppt



Calibration



Dynamic range over 6 orders of magnitudes

Measuring krypton at the sub-ppt level?

- For measurements on the sub-ppt level other methods are available (ATTA, GC-RGMS, Low-level counting (LLC))
- These methods are offline-methods, as they post-analyze a taken sample off-site

→ Purpose of this system is fast characterization and online analysis

Applications

- Fast screening of gas bottles designated for the XENON1T experiment down to sub-ppb on-site (installed in 2015)
- Characterization and controlling of the distillation column online at processing

Measured a separation factor > 125 000 with artificially doped gas (see talk M. Murra)

Thank you for your attention

This work is supported by DFG.

Beyond the limit?!

- Increasing the amount of krypton relative to xenon in a reproducible way (change input flow -> increase DPS conductance)

- Decrease of the background or an better understanding of the background behavior

- Investigating the influence of other impurities on the sensitivity limit

Background ^{85}Kr

- Beta decay of ^{85}Kr into ^{85}Rb is a significant intrinsic background for XENON1T
- Determination of the ^{85}Kr concentration in xenon is of crucial importance for knowledge of the signal background
- Ratio of ^{85}Kr to natural krypton is at 10^{-11}, while natural krypton is aimed to be

  below <0.5 ppt in the used xenon

Background ^{85}Kr

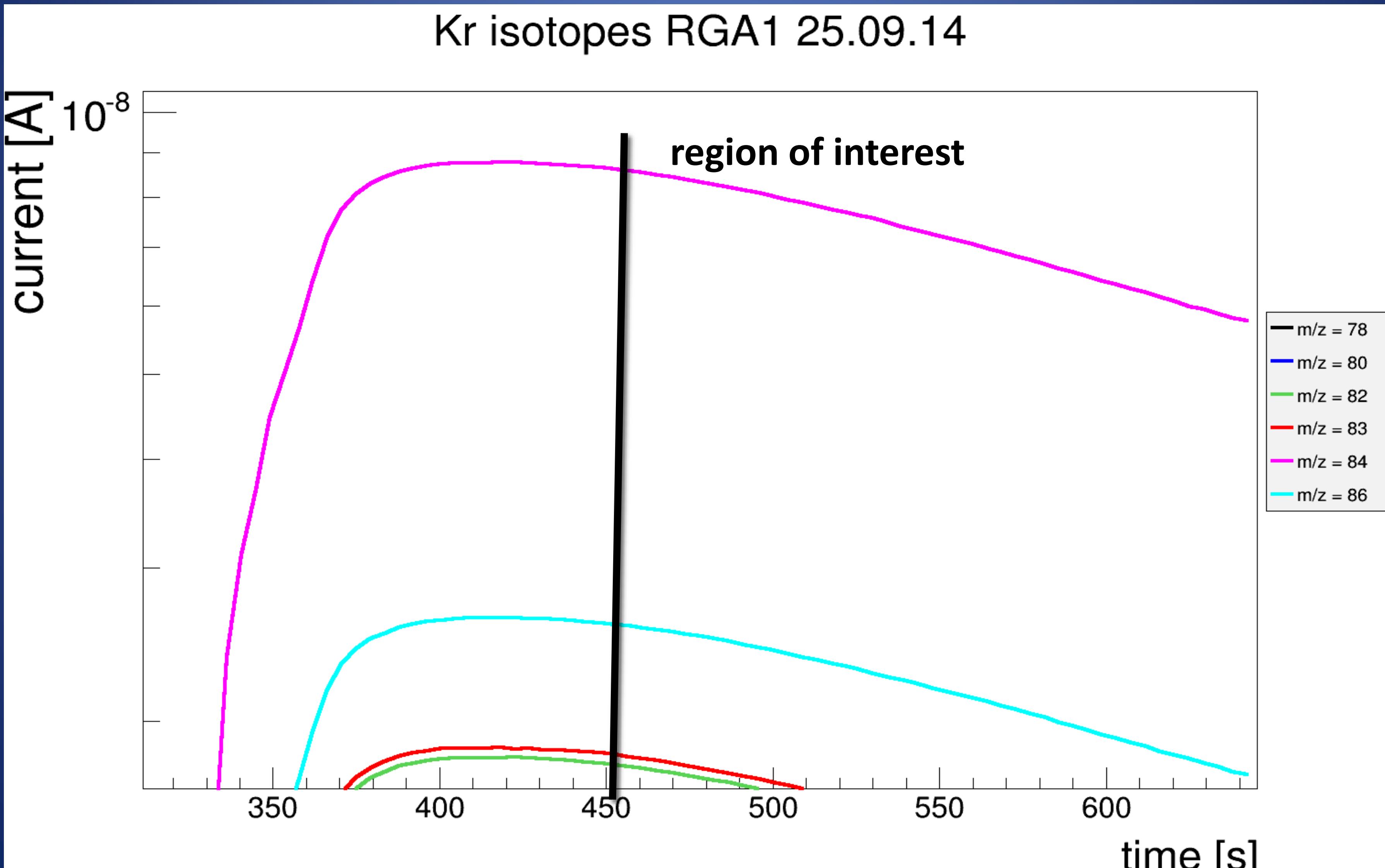
- Beta decay of ^{85}Kr into ^{85}Rb is a significant intrinsic background for Xenon1T

<u>Measuring the Krypton concentration at the sub-ppb level is not trivial!</u>

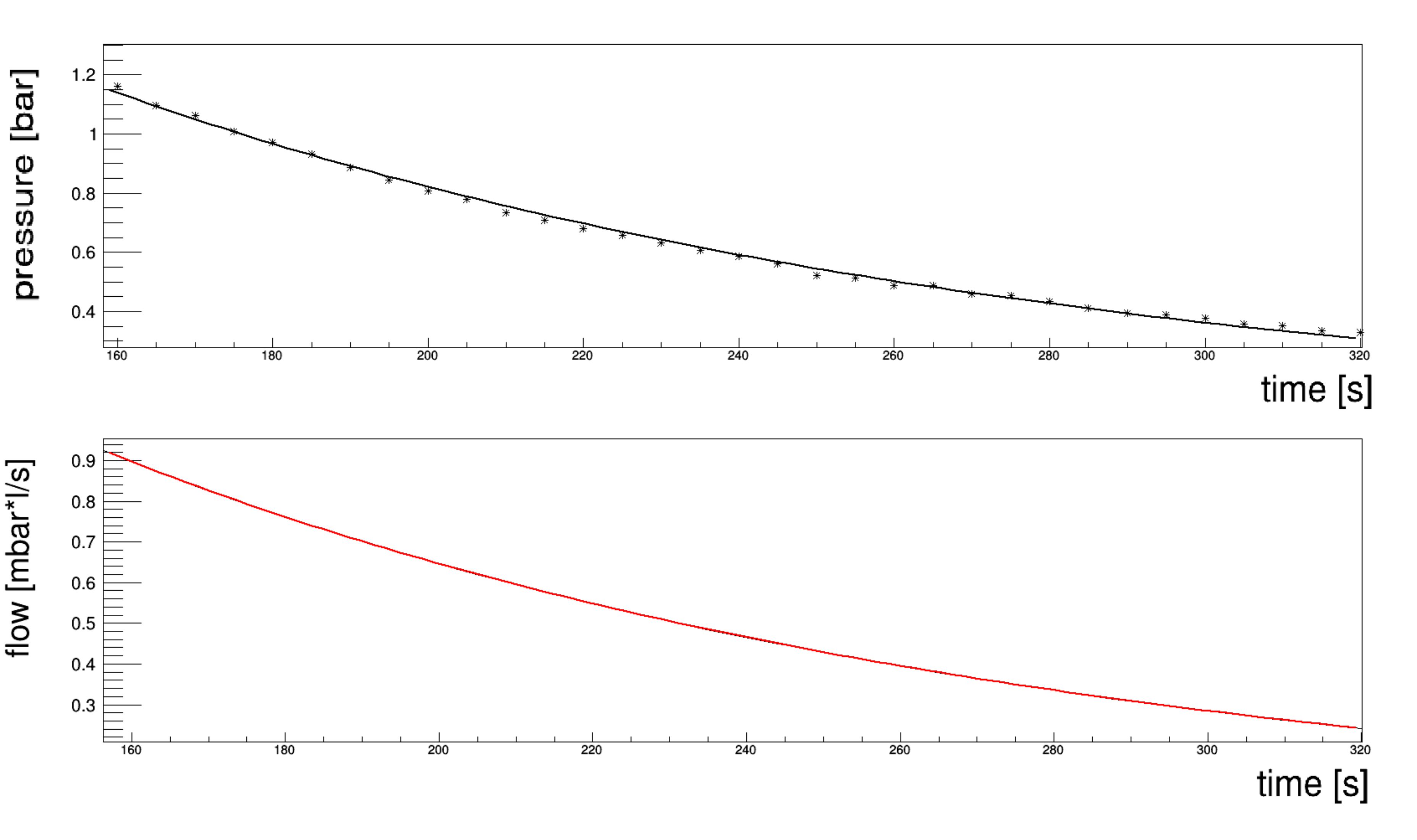
Possible offline methods used for Krypton detection are e.g. LLC, ATTA, GC-RGMS

- while natural Krypton is aimed to be below <0.5 ppt in the used xenon

Example signal (~ 6ppm)



Flow correction



Isotopic fraction (~ 6ppm)

Isotope	Abundance in %
^{78}Kr	0.35
^{80}Kr	2.25
^{82}Kr	11.6
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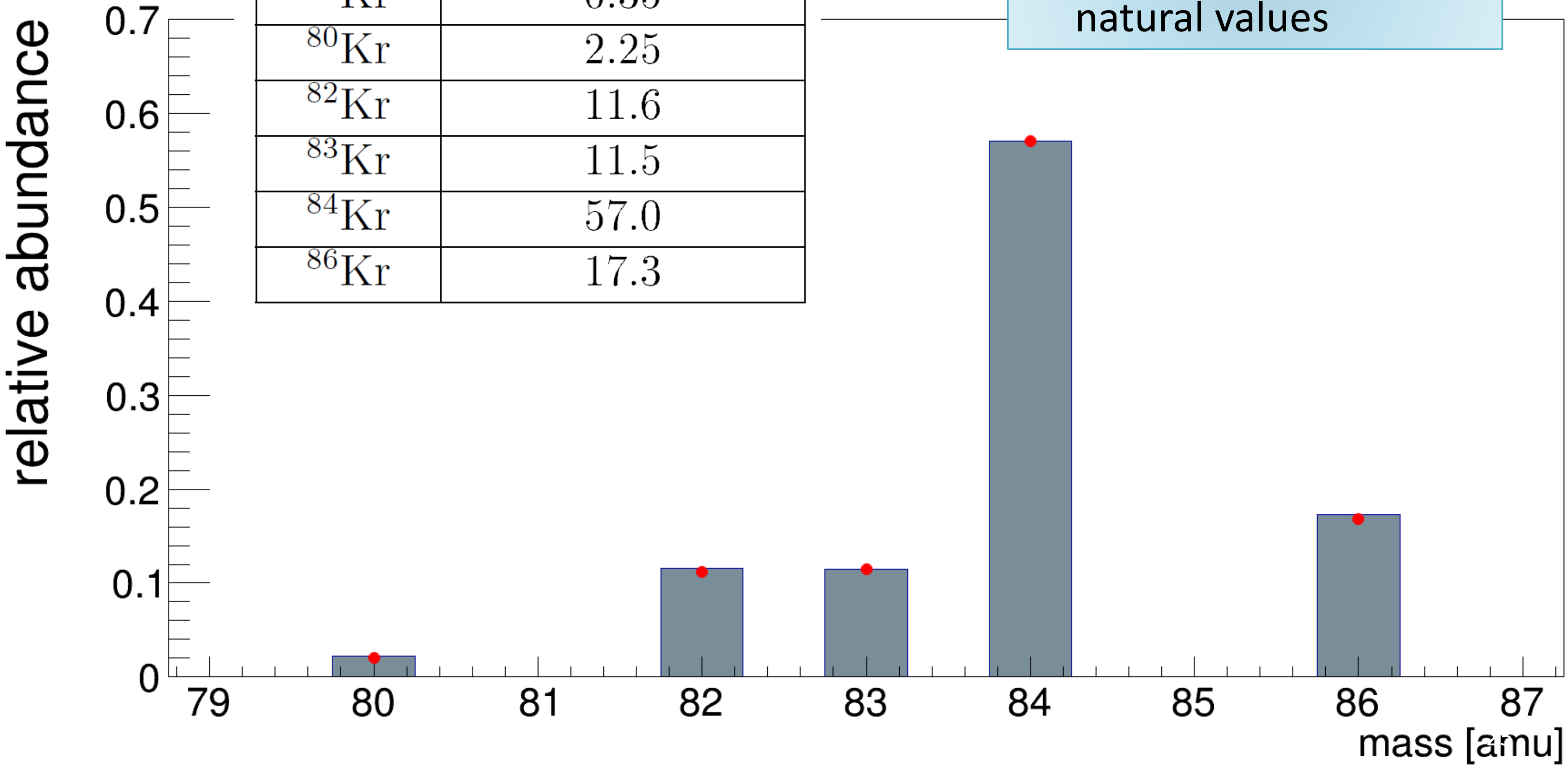
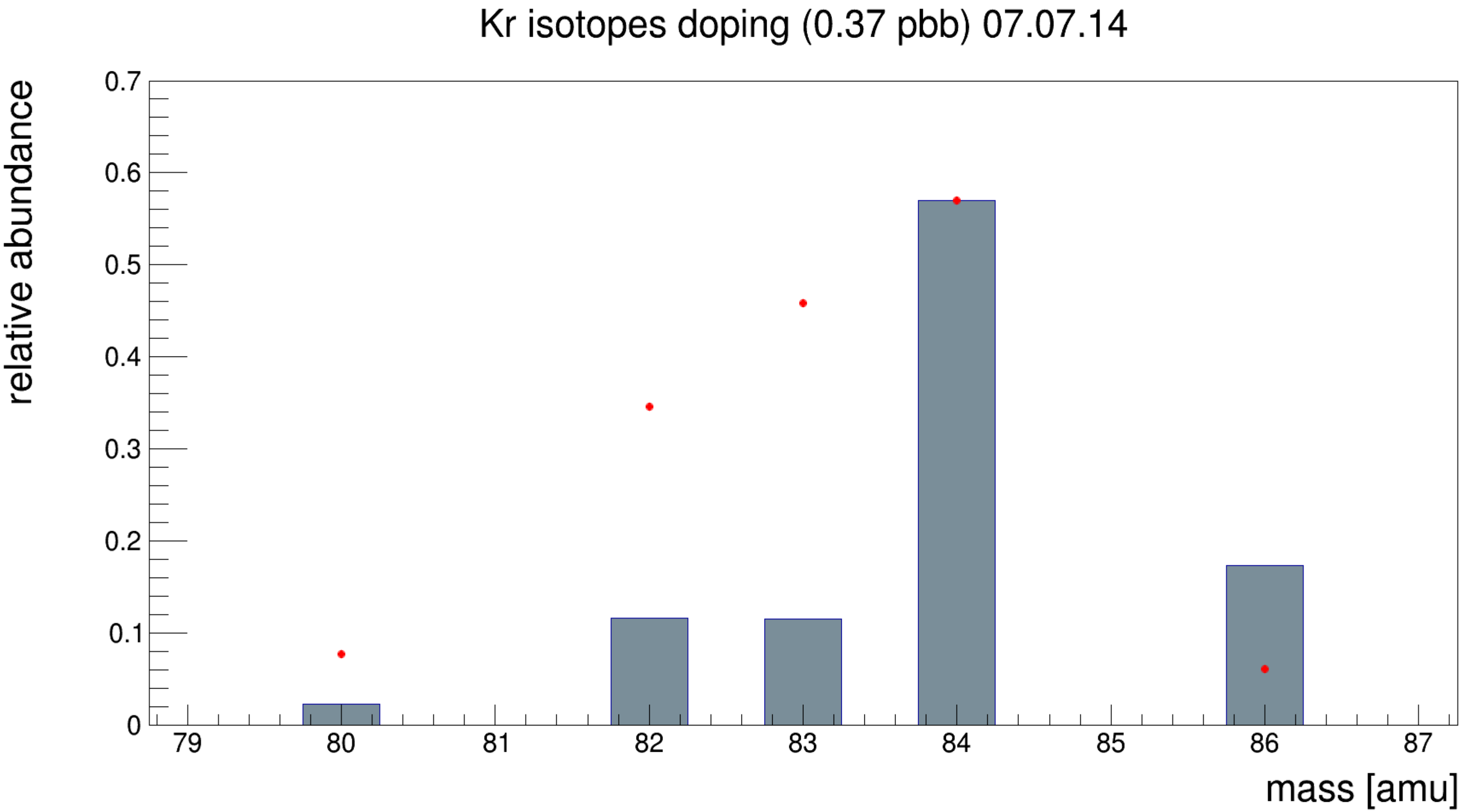
Isotopic abundance is **matching** with natural values



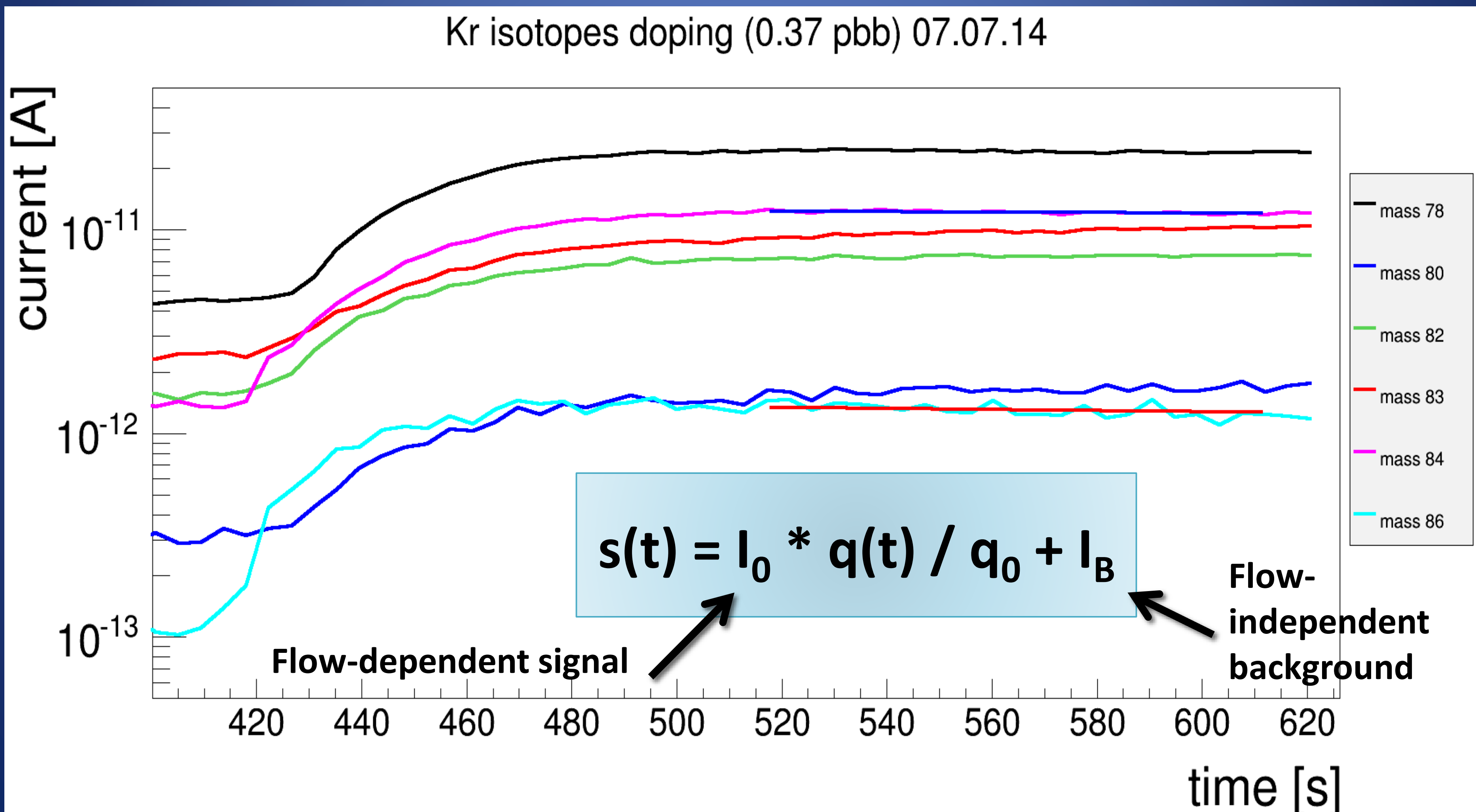
Isotopic fraction low doping (~0.3 ppb)

NO MATCH!

→ Background?



Analysis with background fit



Volume 1 – Volume 3	Volume 4
2300 mbar xenon	200 mbar krypton

Volume 1 – Volume 3

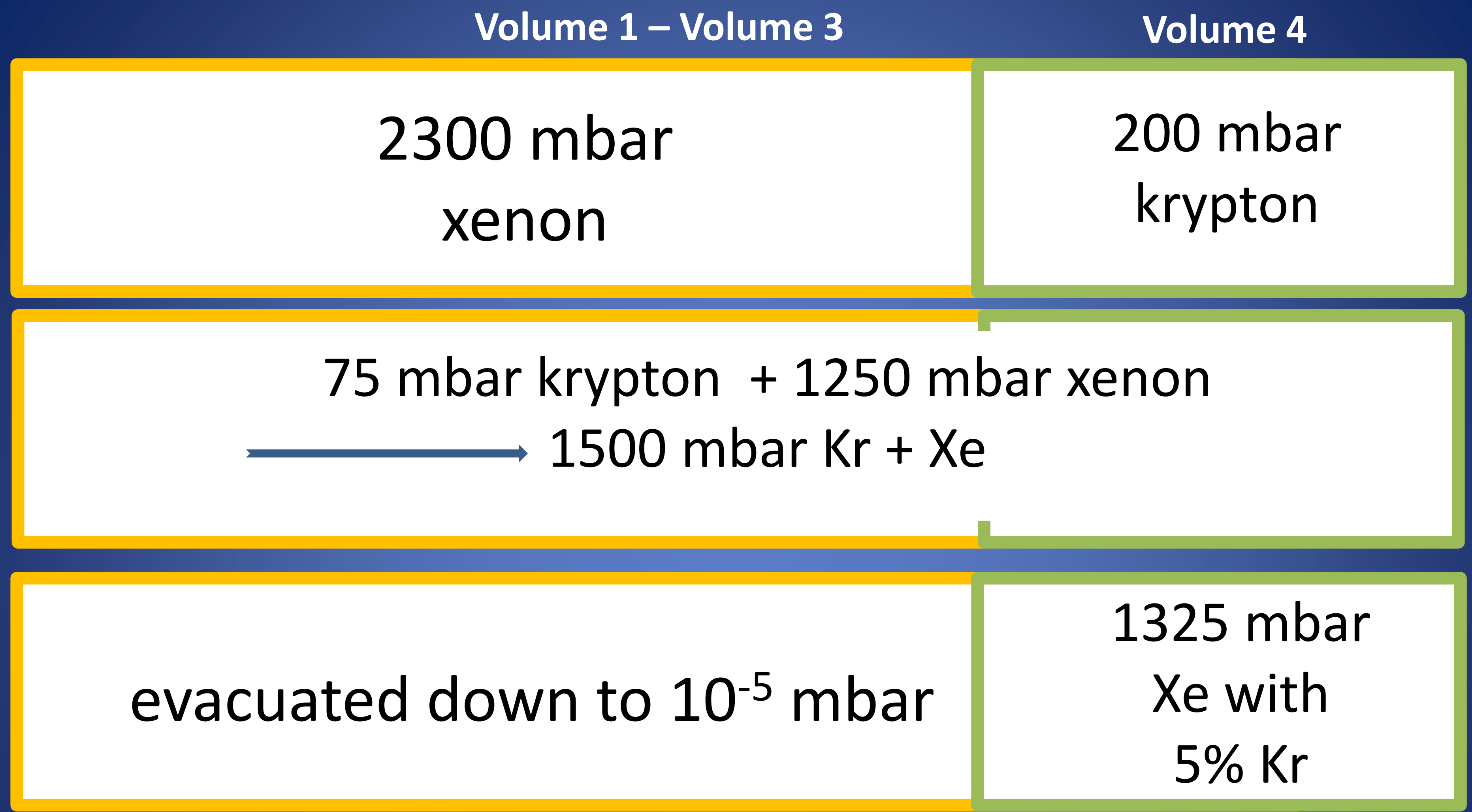
Volume 4

2300 mbar xenon

200 mbar krypton

75 mbar krypton + 1250 mbar xenon

$\longrightarrow$ 1500 mbar Kr + Xe


Volume 1 – Volume 3
Volume 4
2300 mbar
xenon
200 mbar
krypton
75 mbar krypton + 1250 mbar xenon
1500 mbar Kr + Xe
evacuated down to 10^{-5} mbar
1325 mbar
Xe with
5% Kr

Volume 1 – Volume 3	Volume 4
2300 mbar xenon	200 mbar krypton

75 mbar krypton + 1250 mbar xenon $\longrightarrow$ 1500 mbar Kr + Xe

Volume 1 – Volume 3	Volume 4
evacuated down to 10^{-5} mbar	1325 mbar Xe with 5% Kr

570 mbar xenon with 5% krypton

Volume 1 – Volume 3

Volume 4

2300 mbar xenon

200 mbar krypton

75 mbar ...pton + 1250 mbar xenon

...0 mbar Kr + Xe

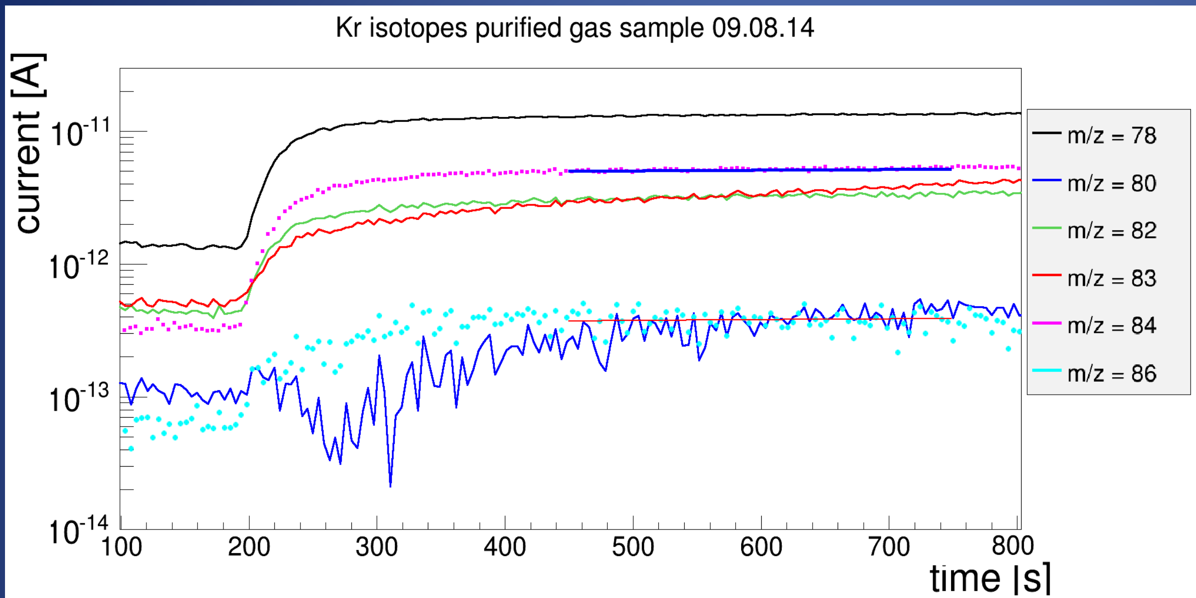
Mixing time is in order of hours!

evacuate... ...wn t... ...5 mbar

1325 mbar Xe with 5% Kr

570 mbar xenon with 5% krypton

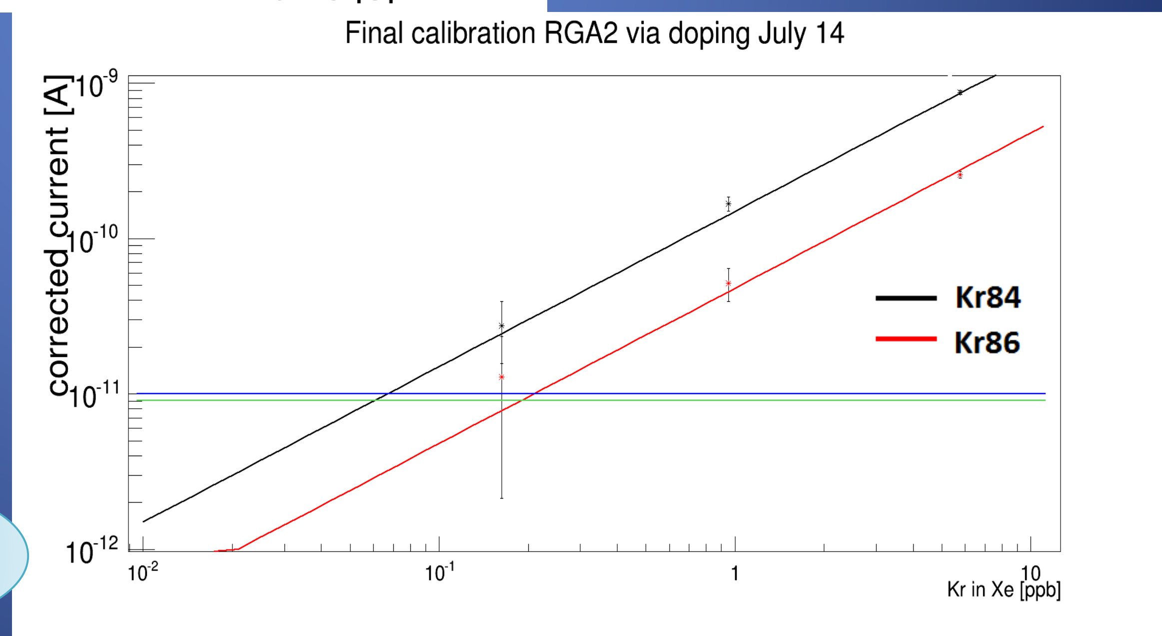
Sensitivity limit



Idea: Use ultrapure gas (sub-ppt) for an estimation of a 1σ-sensitivity limit -> Only background signals!

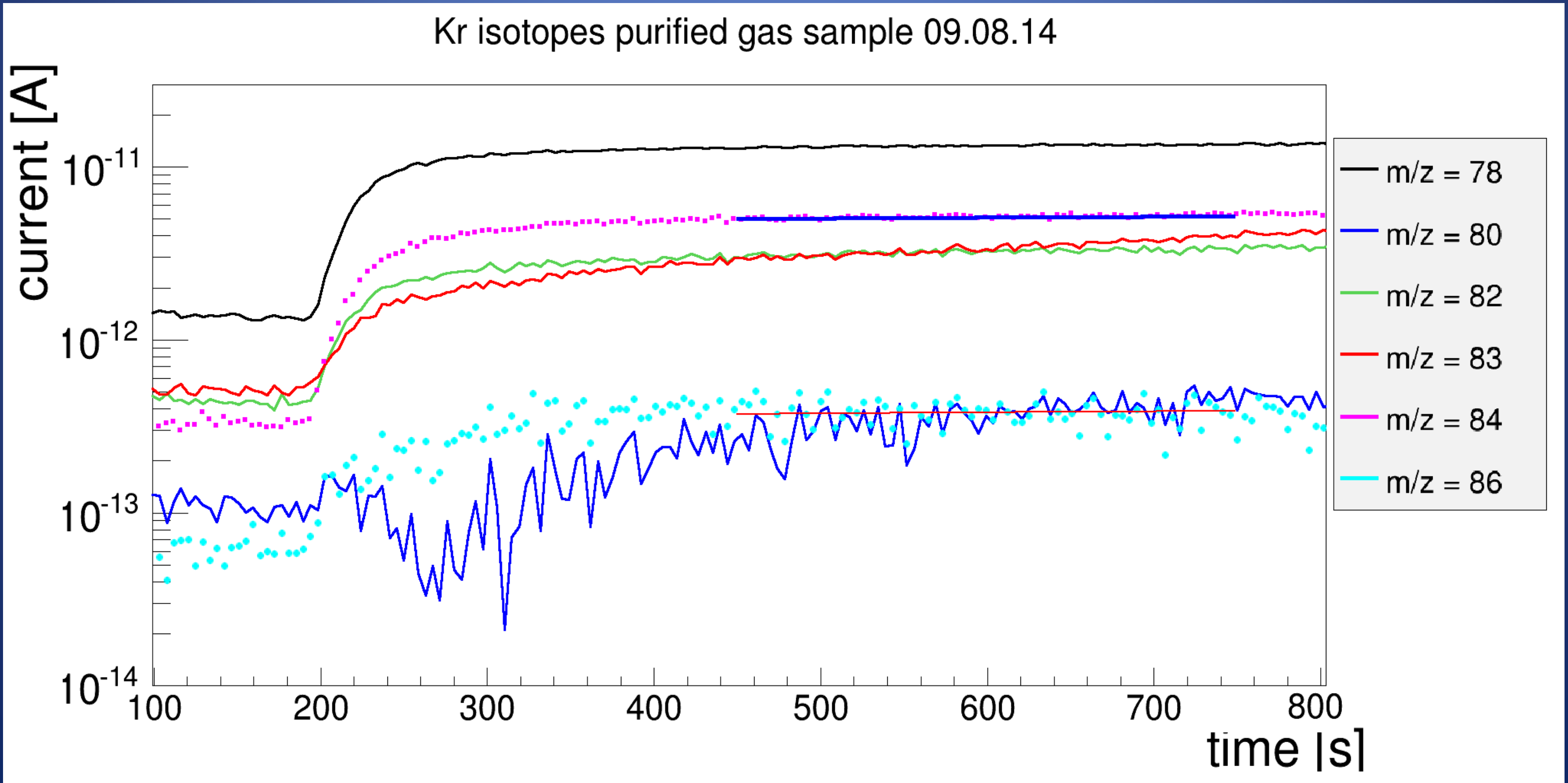
- Deviation of the background signal limits conservatively the detection sensitivity

67 ppt



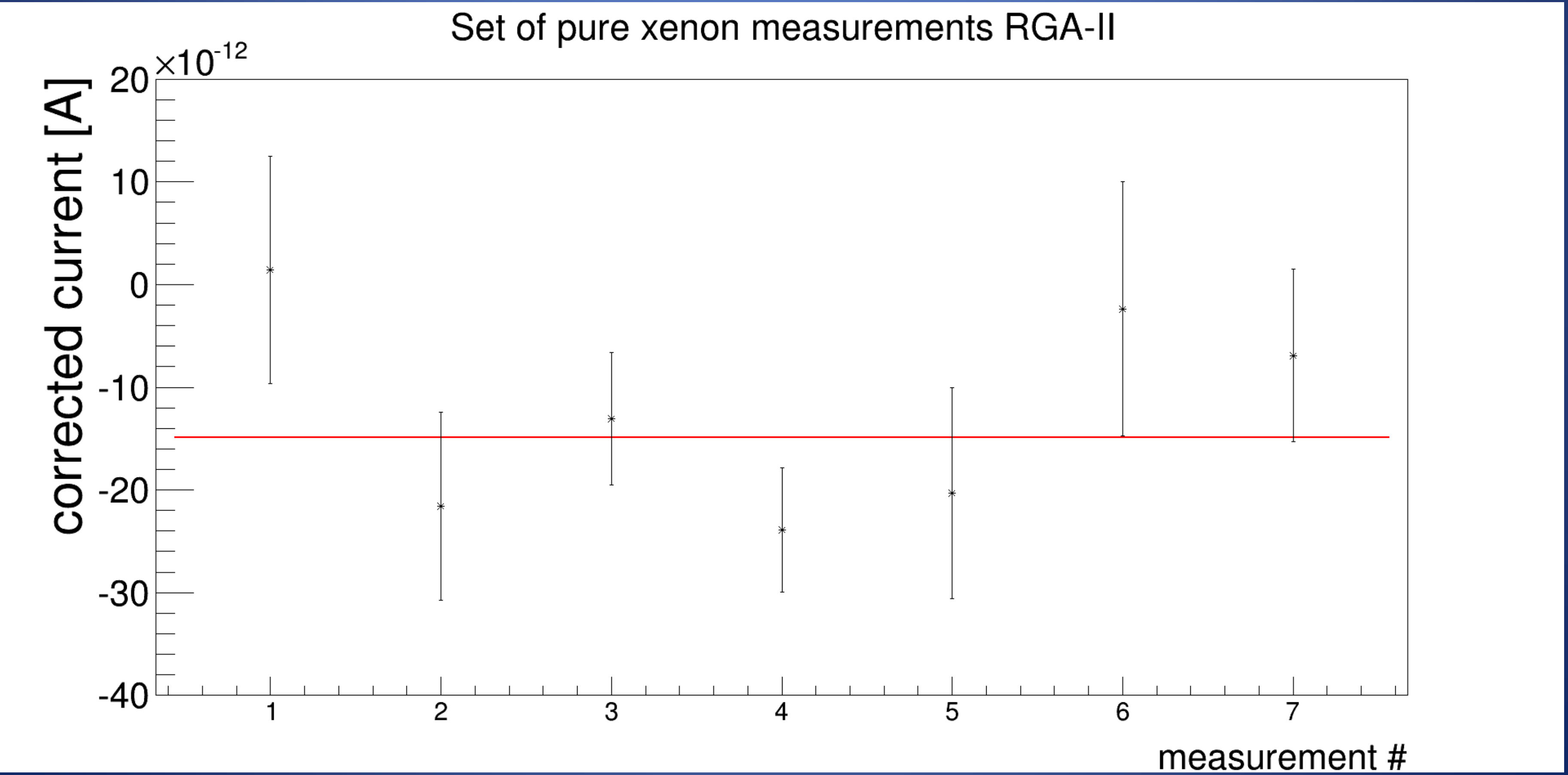
Sensitivity limit

- Idea: Use ultrapure gas (sub-ppt) for an estimation of a 1σ-sensitivity limit -> Only background signals!

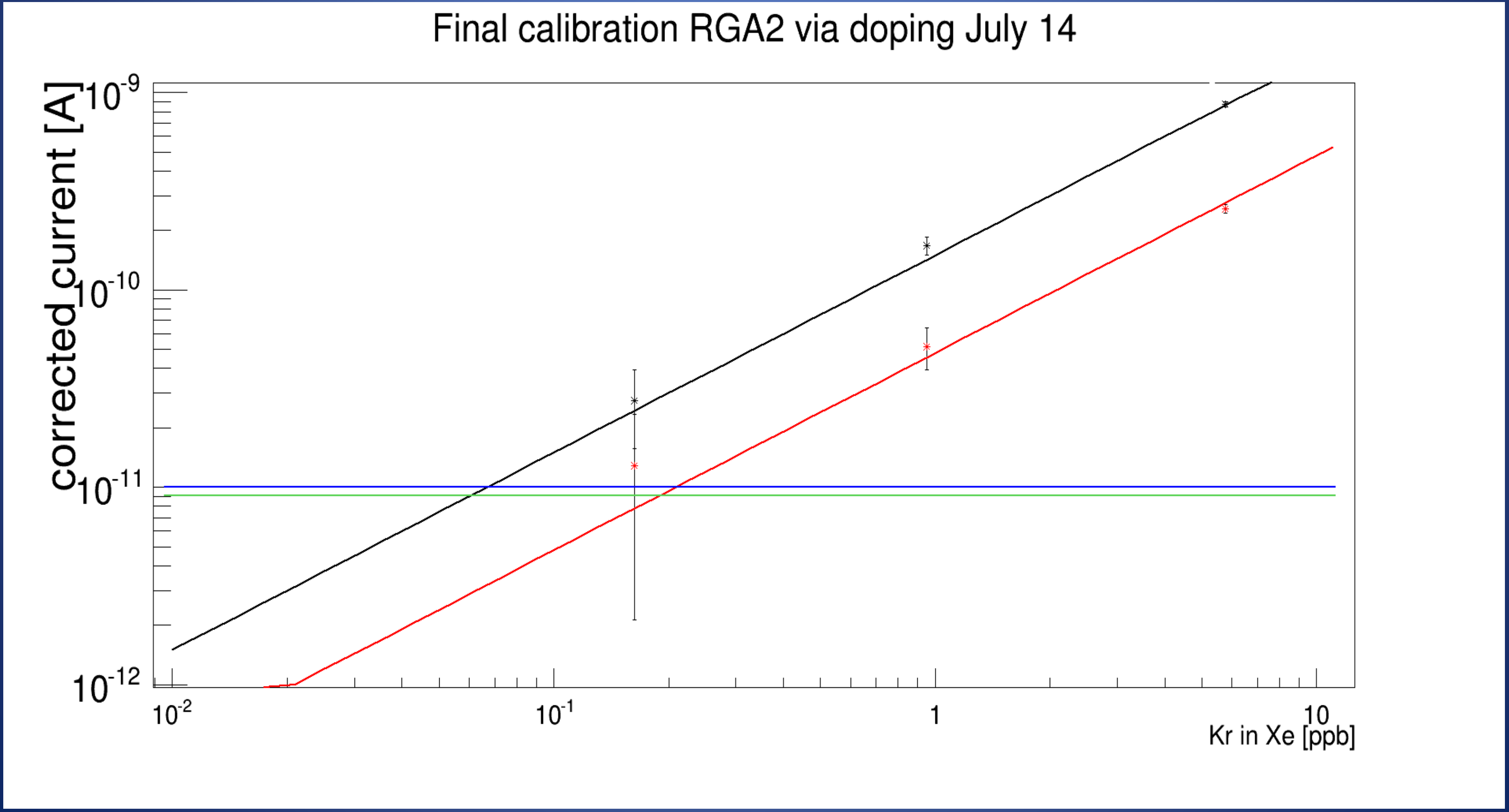


Sensitivity limit

- The uncertainty of the pure measurements determine the minimum detectable signal



Sensitivity limit



Background ^{85}Kr

- Beta decay of ^{85}Kr into ^{85}Rb is a significant intrinsic background for XENON1T
- Determinati… …tation in xenon is of cru…
- R… natural kr… below <0.5 ppt in the used xenon
- Natural krypton abundance is measured and the ^{85}Kr concentration is derived from this value
- Can be removed along with cryogenic distillation

Sensitivity is limited above the desired value of 0.5 ppt

→ **Make use of fast results and minimal consumption advantages for other applications!**