Westfälische Wilhelms-Universität Münster

SEARCH AND DISCOVER

THE HUNT FOR RARE DECAYS OF ^{124}Xe & TRACE DETECTION OF KRYPTON IN XENON

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GRK 2149

2. Retreat / Körbecke 2016

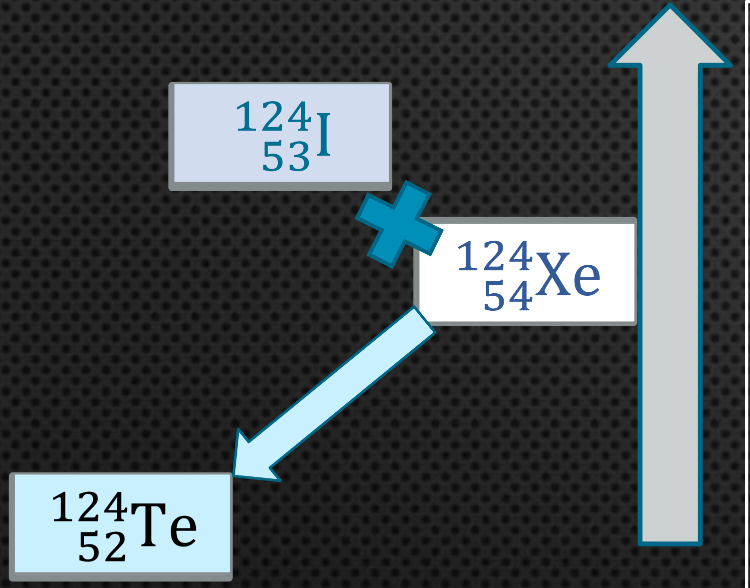
THE HUNT FOR RARE DECAYS OF ^{124}Xe

TRACE DETECTION OF KYPTON IN XENON

THE HUNT FOR RARE DECAYS OF ^{124}XE

TRACE DETECTION OF KYPTON IN XENON

DECAYS OF ^{124}Xe



- Abundance of 0.095 % in natural xenon
- β-decay into ^{124}I energetically forbidden
- Double β-decay into ^{124}Te predicted
- Q-Value of 2856.73(12) keV allows several decay modes

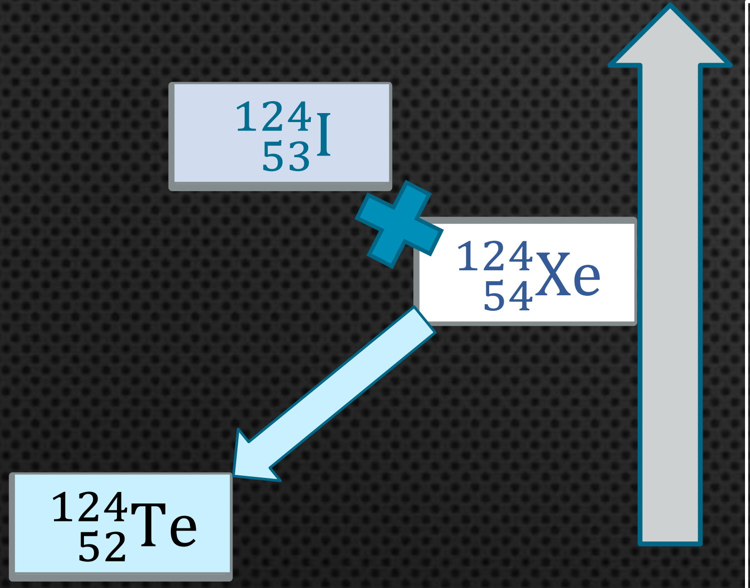
$$^{124}\text{Xe} + 2e^- \rightarrow {}^{124}\text{Te}^* + 2\nu_e \qquad (2\nu\text{DEC})$$

$$^{124}\text{Xe} + e^- \rightarrow {}^{124}\text{Te}^* + e^+ + 2\nu_e \qquad (2\nu\beta^+\text{EC})$$

$$^{124}\text{Xe} \rightarrow {}^{124}\text{Te} + 2e^+ + 2\nu_e \qquad (2\nu 2\beta^+)$$

Processes predicted by Standard Model

DECAYS OF ^{124}Xe



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$^{124}\mathrm{Xe} + 2e^- \rightarrow {}^{124}\mathrm{Te}^* + 2\nu_e$		$(2\nu\mathrm{DEC})$
$^{124}\mathrm{Xe} + e^- \rightarrow {}^{124}\mathrm{Te}^* + e^+ + 2\nu_e$		$(2\nu\beta^+\mathrm{EC})$
$^{124}\mathrm{Xe} \rightarrow {}^{124}\mathrm{Te} + 2e^+ + 2\nu_e$		$(2\nu 2\beta^+)$

Processes predicted by Standard Model

Nuclear matrix element (NME)

$$T_{\frac{1}{2}}(2\nu) \sim a_{2\nu} F_{2\nu} |(M_{2\nu})|^2$$

Dimensional factor $\sim yr^{-1}$

Phase-space factor $\sim Q^{\geq 5}$

Depending on NME model

Theoretical half-life predictions	Decay mode
~10^{27} yr	$2\nu 2\beta^+$
$10^{22} - 10^{24}$ yr	$2\nu\beta^+$EC
$10^{21} - 10^{23}$ yr	2νDEC

Winter, Rolf G. Phys.Rev. 100 (1955) 142-144 J. Suhonen 2013 *J. Phys. G: Nucl. Part. Phys.* **40** 075102

THE XENON DARK MATTER PROJECT

Dual-phase xenon detectors with extremly low background designed for dark matter search located at Laboratori Nazionali del Gran Sasso (LNGS)

- International collaboration (140 physicists)
- Successfully explores parameter space for potential dark matter particles (WIMPs)
- Different stages with the upcoming XENON1T to become the most sensitive dark matter detector in the world
- **Suitable for other rare event searches**

www.xenon1t.org

XENON100

2011/12

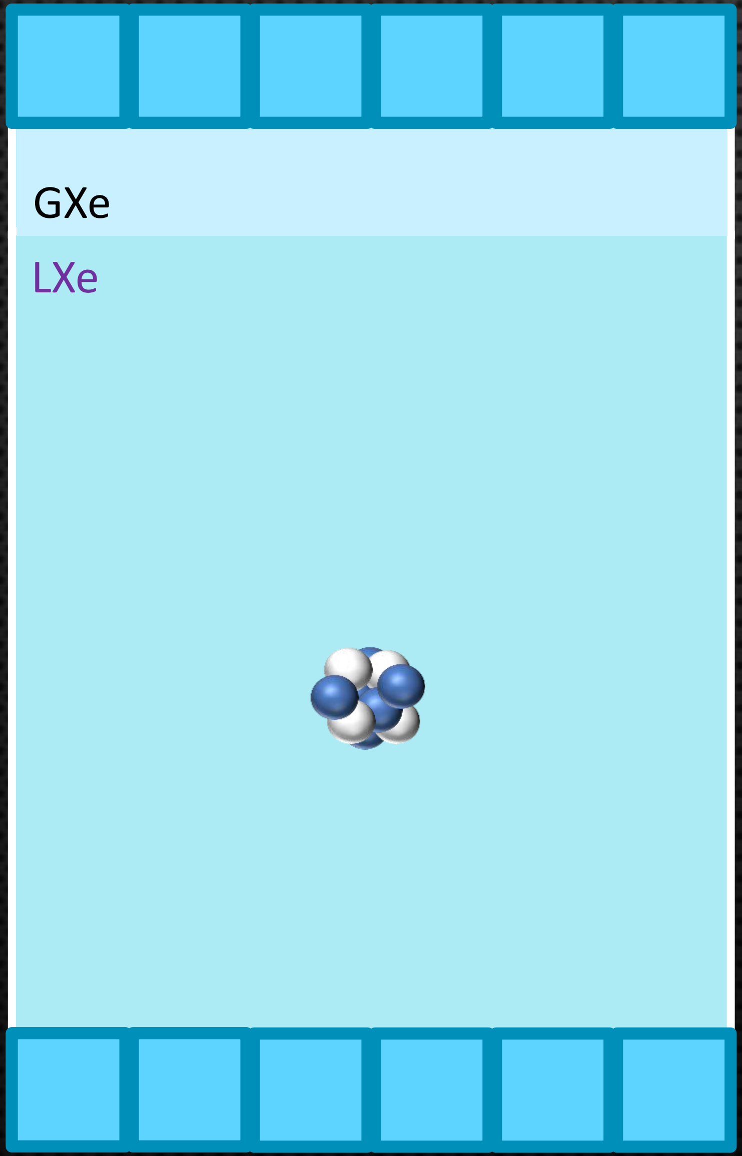
2016

XENON1T

Analysis of 225 live days will be shown in this talk

Will provide data this year.
Sensitivity study shown in this talk

DUAL-PHASE XENON TPC



An energy deposition in xenon results in
Scintillation & Ionization

Anti-correlated simultaneous production of electrons and photons

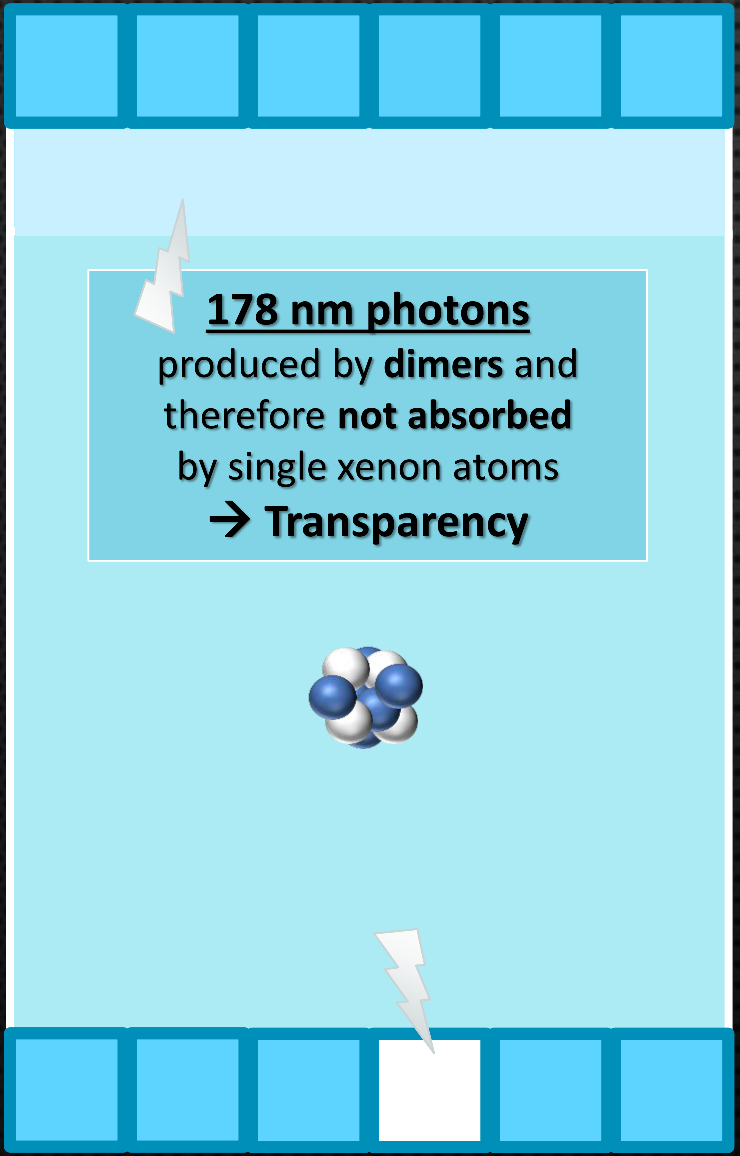
Number of photons and electrons is proportional to the deposited energy
→ **Energy calibration**

Different light and charge yields depending on interaction
→ **Particle discrimination**

If electrons completly recombine they also produce only direct scintillation light
→ **How to make use of both channels?**

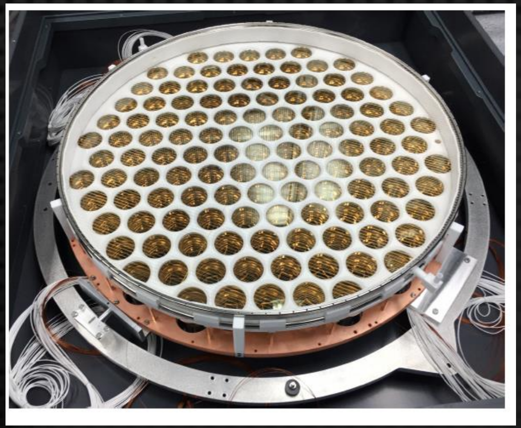
XENON100 Collaboration (Aprile, E. et al.) Astropart.Phys. 35 (2012) 573-590c

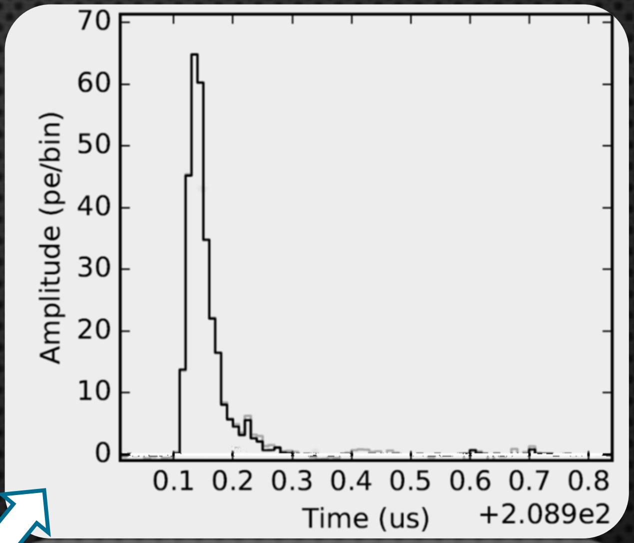
DUAL-PHASE XENON TPC



The photons are detected with photomultipliers optimized for VUV-light (quantum efficiency 25% - 40%)

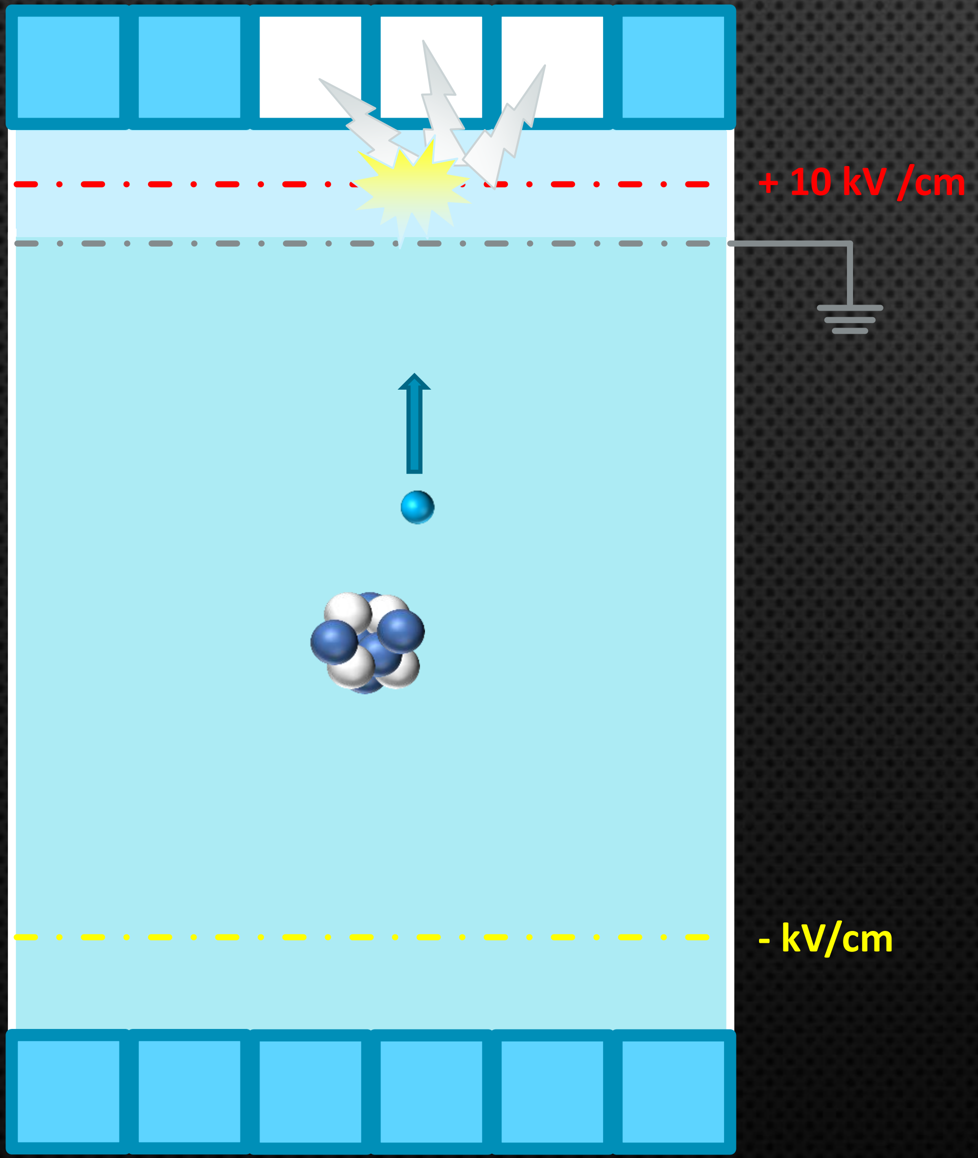
Photomultiplier tubes (PMTs)





Fast light signal from the emitted photons with a width of a few 100 ns
→ **S1**

DUAL-PHASE XENON TPC

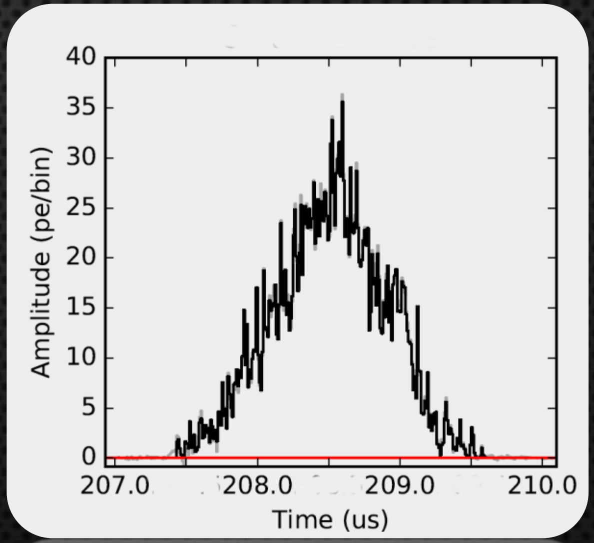


By applying an electric field (~kV/cm) the electrons generated by ionization are removed from the interaction site

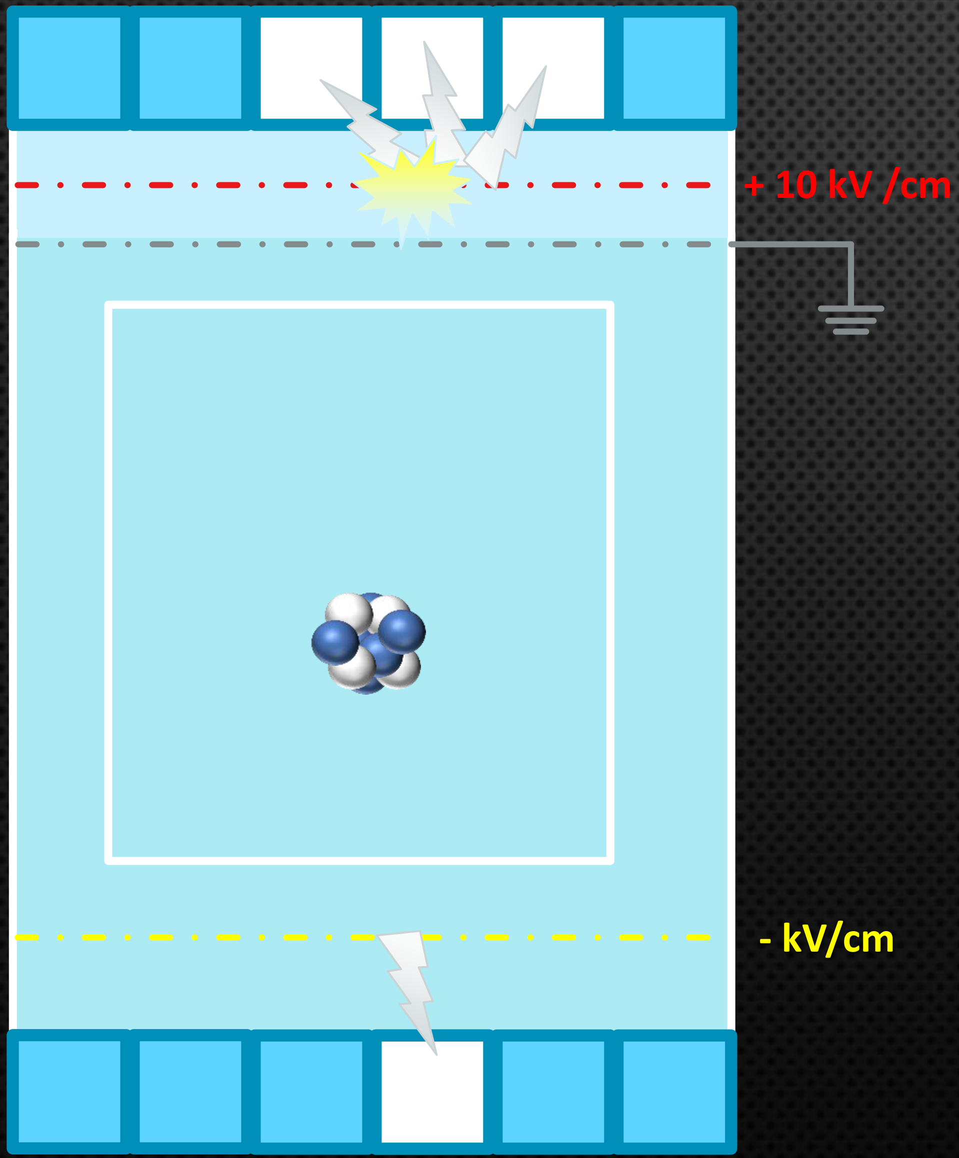
They are drifted with a constant velocity (~mm/µs) towards the gas phase

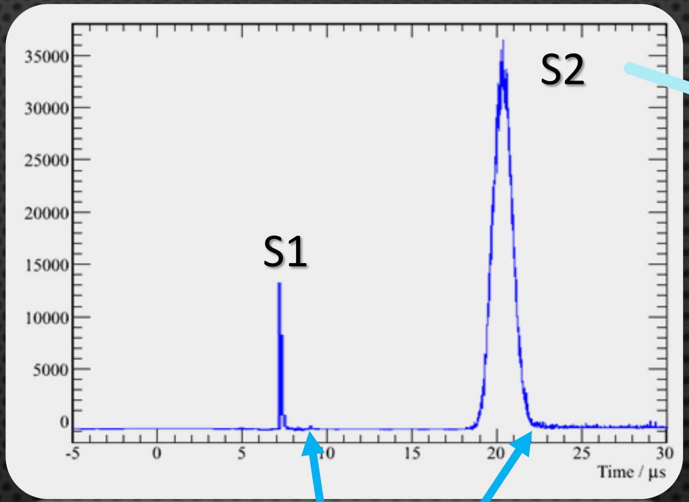
There they are pushed and accelerated by a secondary strong field (10 kV/cm) and produce a spreadout light signal by proportional scintillation („electroluminescence“)

→ **S2**

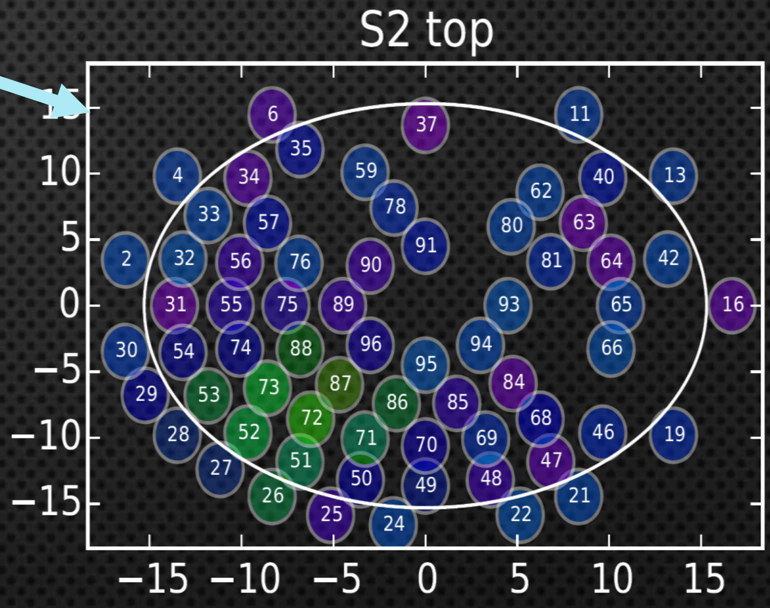


DUAL-PHASE XENON TPC





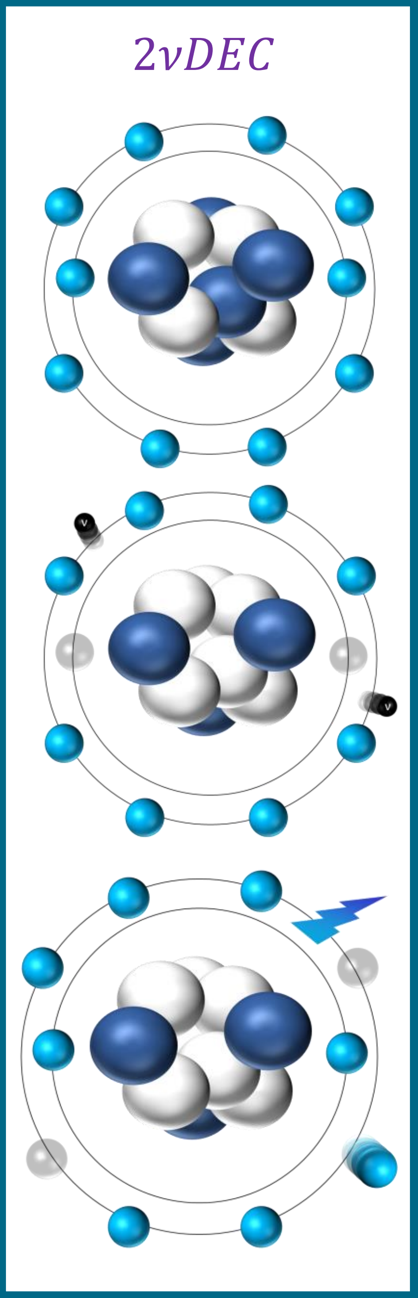
x,y – position reconstruction via pattern (O(mm) resolution)



From the time difference of the S1 and S2 signals one obtains a precise depth information (z) with a resolution of O(0.1 mm)

3D-reconstruction possible

- Discrimination of double scatters
- Selection of a fiducial volume with reduced external background



WHY SEARCH FOR DOUBLE ELECTRON CAPTURE WITH THIS DETECTOR?

Expected signal for two K-shell electron capture

64.33 keV

Due to the small range (<0.5 mm) and time difference (~10^{-15} s) the individual X-rays (Auger electrons) at cannot be resolved

- Source = Detector
- High self-shielding capacity
- 3D vertex reconstruction allows for selection of a fiducial volume
- Careful screening of materials and active removal of radioactive krypton

Extremely low background experiment with keV-scale optimized sensitivity

Data is for „free“ as it is the same as for the dark matter search

Nesterenko, D.A. et al. Phys.Rev. C86 (2012) 044313

ANALYSIS OF XENON100 DATA

Phys.Rev.Lett. 109 (2012) 181301

In D.-M. Mei, I. Marshall, W.-Z. Wei, and C. Zhang Phys. Rev. C **89**, 014608 a study is carried out by non-collaboration members without insight to the data
→ **Limit was overestimated**

Study on real data!

224.6 live days
Same dataset used for several analyses regarding dark matter

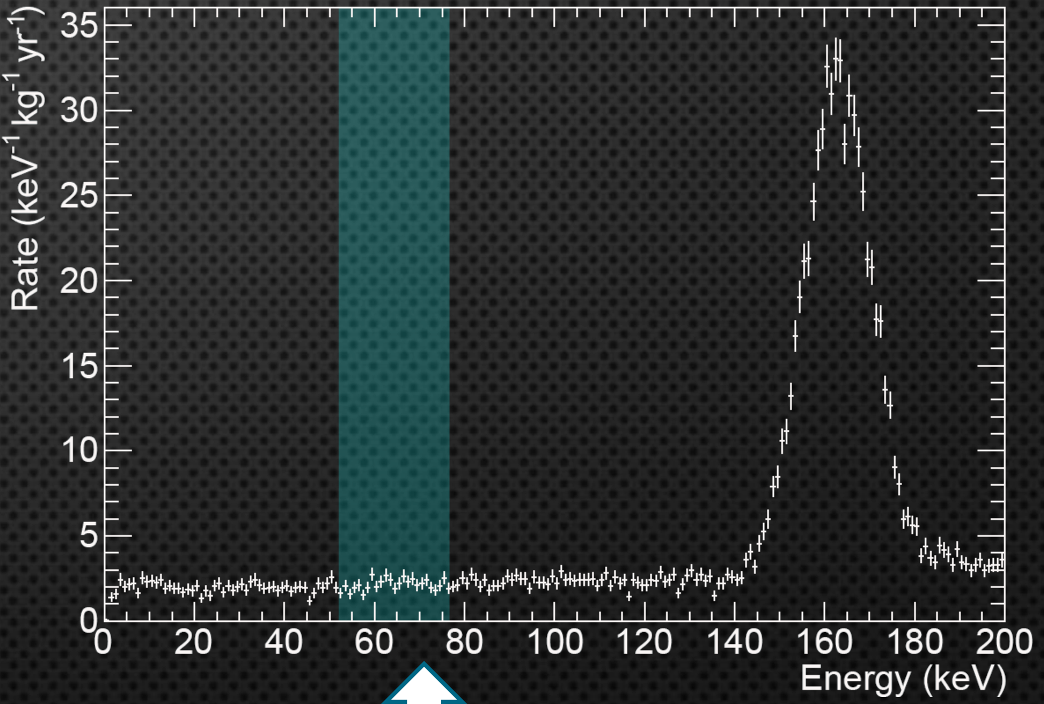
Derive an energy scale based on the combination of the two signals (S1 & S2) using neutron activation lines induced by ^{241}AmBe

Energy resolution of 4.1keV @ 64.33 keV

Select 34 kg fiducial volume, corresponding to 29 g of ^{124}Xe (0.095%)

Apply data quality and selection cuts and estimate their acceptance using ^{232}Th & ^{60}Co calibration sources

Plot it!



ANALYSIS OF XENON100 DATA

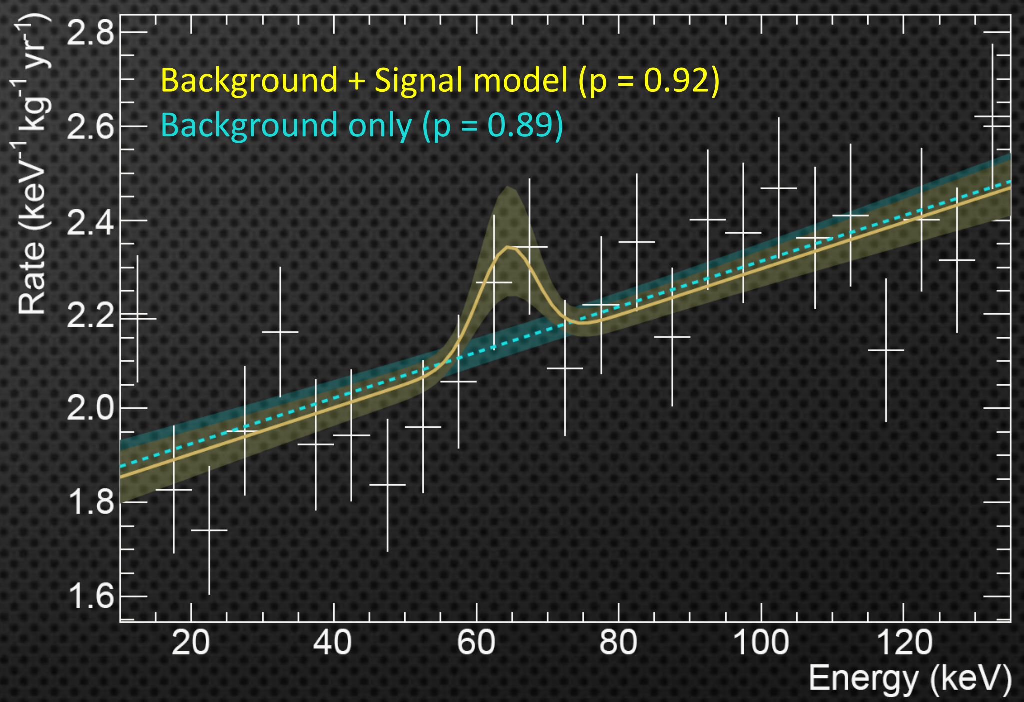
Expected signal:
single energy peak at
64.33 keV

Γ: decay rate
η: ^{124}Xe abundance
mt: exposure
N_A: Avogadro´s constant
M_{XE}: molar mass of xenon
σ_{sig}: peak width
μ_{sig}: peak position
f_{bkg}: linear background

Bayesian fit from 10 keV to 135 keV with two models:

Linear background only
Linear background and a Gaussian signal

$$f_{sig} = \frac{\Gamma \eta \epsilon m t N_A}{\sqrt{2\pi}\,\sigma_{sig} M_{XE}} \cdot e^{-\frac{(E-\mu_{sig})^2}{2\sigma_{sig}^2}} + f_{bkg}$$



ANALYSIS OF XENON100 DATA

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Bayesian fit from 10 keV to 135 keV with two models:

Linear background only

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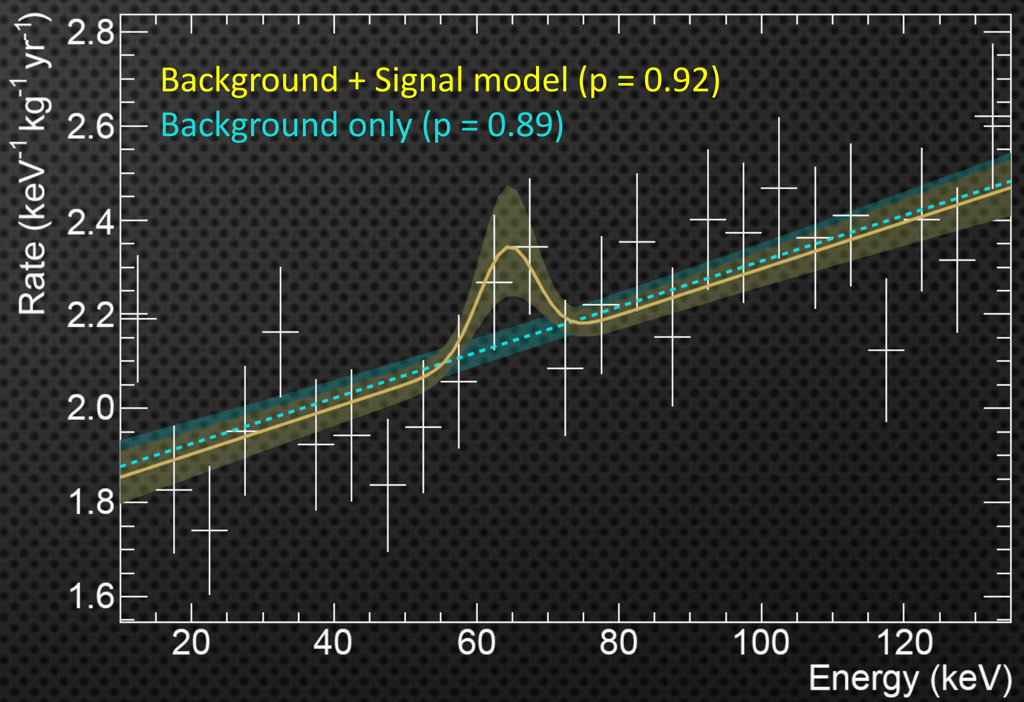


Use knowledge about parameters
Implement systematical uncertainties as Gaussian priors
Evaluate signal significance with Bayes factor (BF)

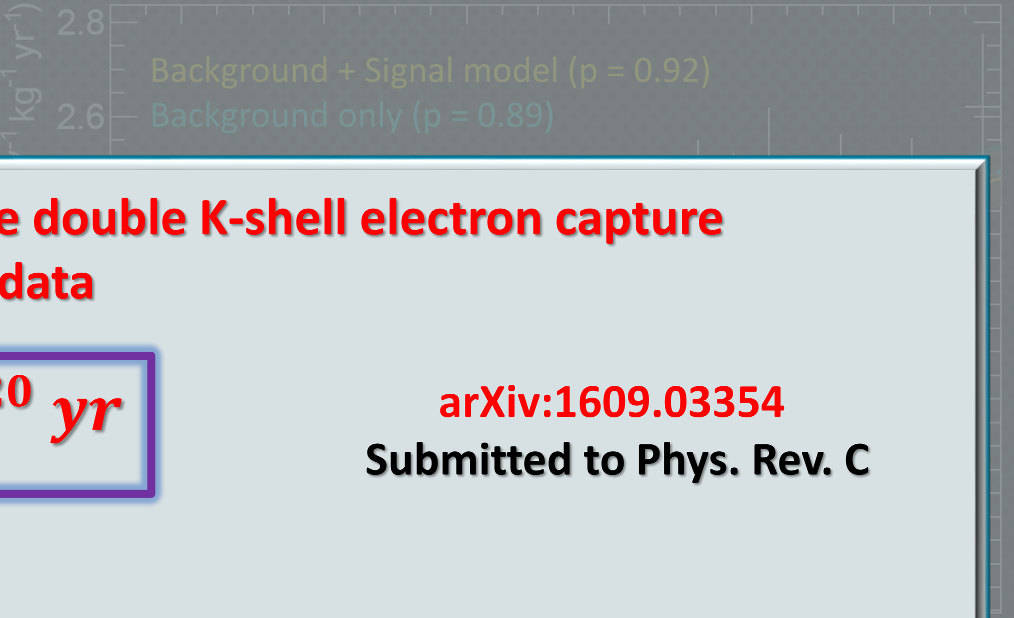
→ $BF = \frac{P(f_{bkg}|\vec{D})}{P(f_{sig}|\vec{D})} = 1.2$ → Favors background only model → Calculate lower limit on the half-life

A. Caldwell, D. Kollar, and K. Kroninger, Comput. 438 Phys. Commun. 180, 2197 (2009).

ANALYSIS OF XENON100 DATA

Expected signal: single energy peak at

Bayesian fit from 10 keV to 135 keV with two models:



Result on the 90% lower credibility limit of the double K-shell electron capture from XENON100 data

$$\boldsymbol{T_{\frac{1}{2}} > 6.5 \; x \; 10^{20} \; yr}$$

arXiv:1609.03354
Submitted to Phys. Rev. C

<u>Other results on the half-life</u>

XMASS (Abe et al.): $> 4.7 \cdot 10^{21}\ yr$
Gavrilyuk et al. : $> 2.0 \cdot 10^{21}\ yr$

This result supersedes the obtained limit by Mei et al. $(> 1.6 \cdot 10^{21} yr)$

Implement systematical uncertainties as Gaussian priors
Evaluate signal significance with Bayes factor (BF)

$$BF = \frac{P(f_{bkg}|\vec{D})}{P(f_{sig}|\vec{D})} = 1.2$$

Favors background only model

Calculate lower limit on the half-life

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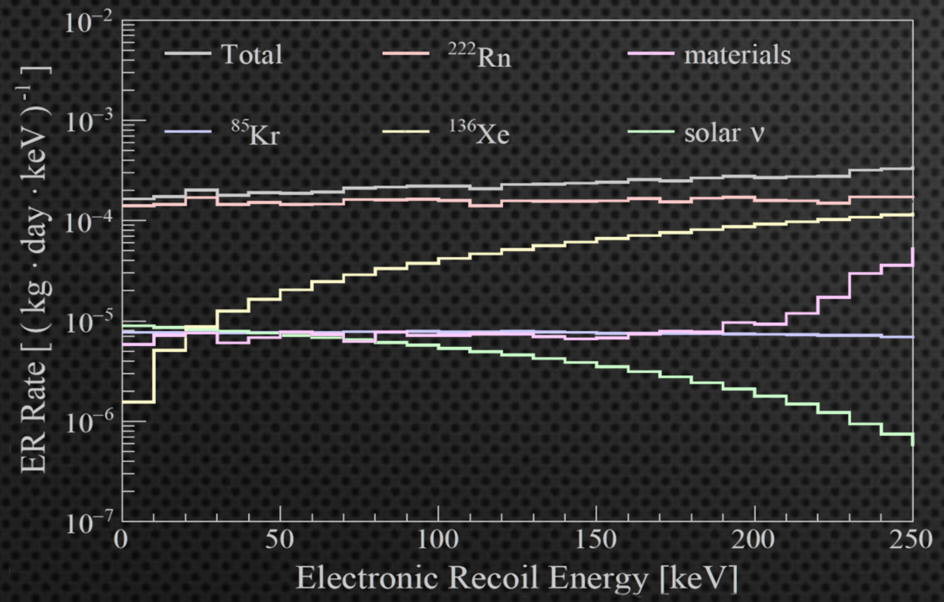
XENON1T – THE NEXT STEP

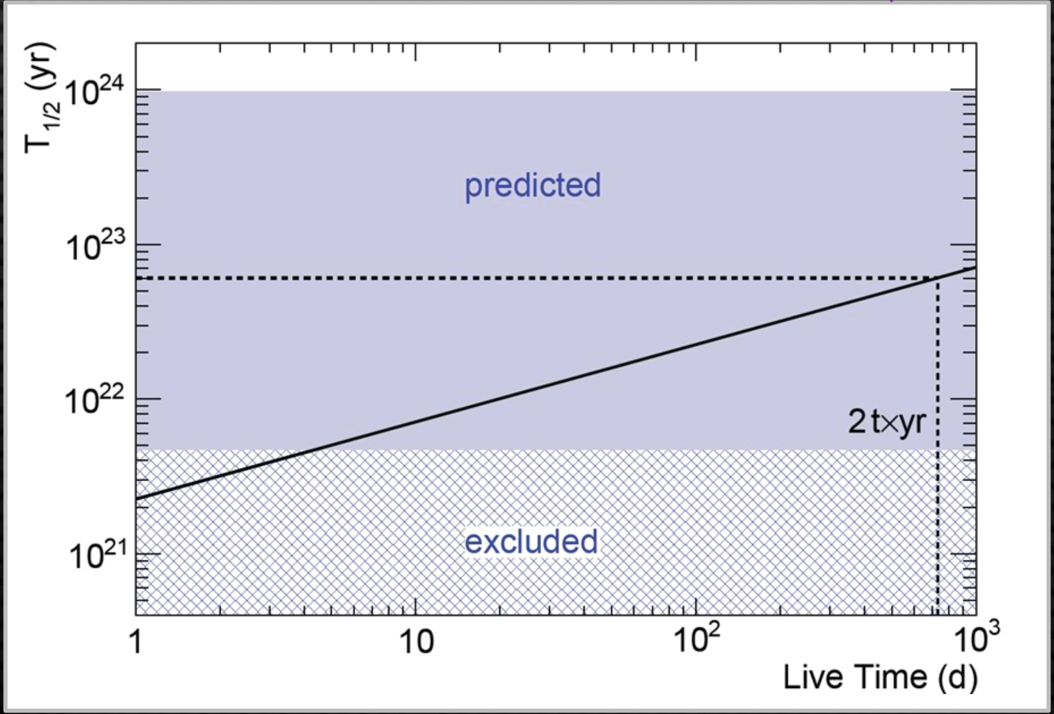
30 x less background



XENON Collaboration (Aprile, E. et al.) JCAP 1604 (2016)

- Located in Hall B at LNGS underground laboratory
- Immersed in a water tank providing an active muon veto
- Built to improve the existing dark matter search sensitivity by 2 orders of magnitude
- > 3.2 t of xenon in total with 2 t of LXe in the active volume

2 kg of ^{124}Xe



Assuming the same light yield as XENON100 (pessimistic) and a fiducial volume of 1 ton (1kg of ^{124}Xe):

5 live days to achieve the highest sensitivity
2 live years to be sensitive up to $6.1 \cdot 10^{22}$ yr half-life @ 90 % C.L.

Additionally: Due to improved detector technology the search for high energy signals (e.g. $2\nu EC\beta^+, 0\nu DEC$) becomes possible

FIRST DATA EXPECTED THIS YEAR

STAY TUNED…

THE HUNT FOR RARE DECAYS OF ^{124}Xe

TRACE DETECTION OF KYPTON IN XENON

THE HUNT FOR RARE DECAYS OF ^{124}Xe

TRACE DETECTION OF KYPTON IN XENON

Background ^{85}Kr

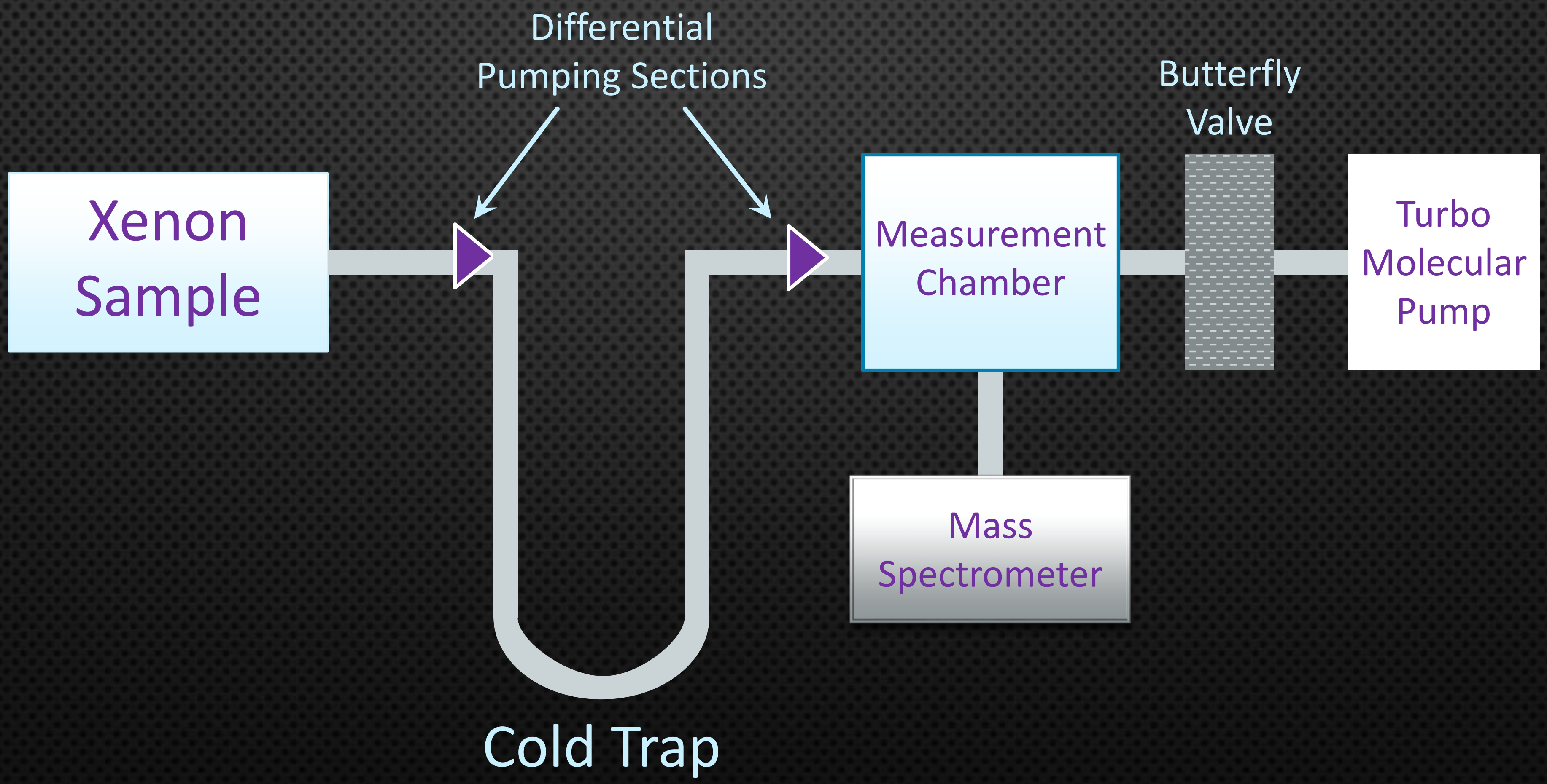
- Beta decay of ^{85}Kr into ^{85}Rb is a significant intrinsic background for XENON1T
- Determination of the ^{85}Kr concentration in xenon is of crucial importance for knowledge of the signal background
- Ratio of ^{85}Kr to natural krypton is at 10^{-11}, while natural krypton is aimed to be below <0.2 ppt in the used xenon

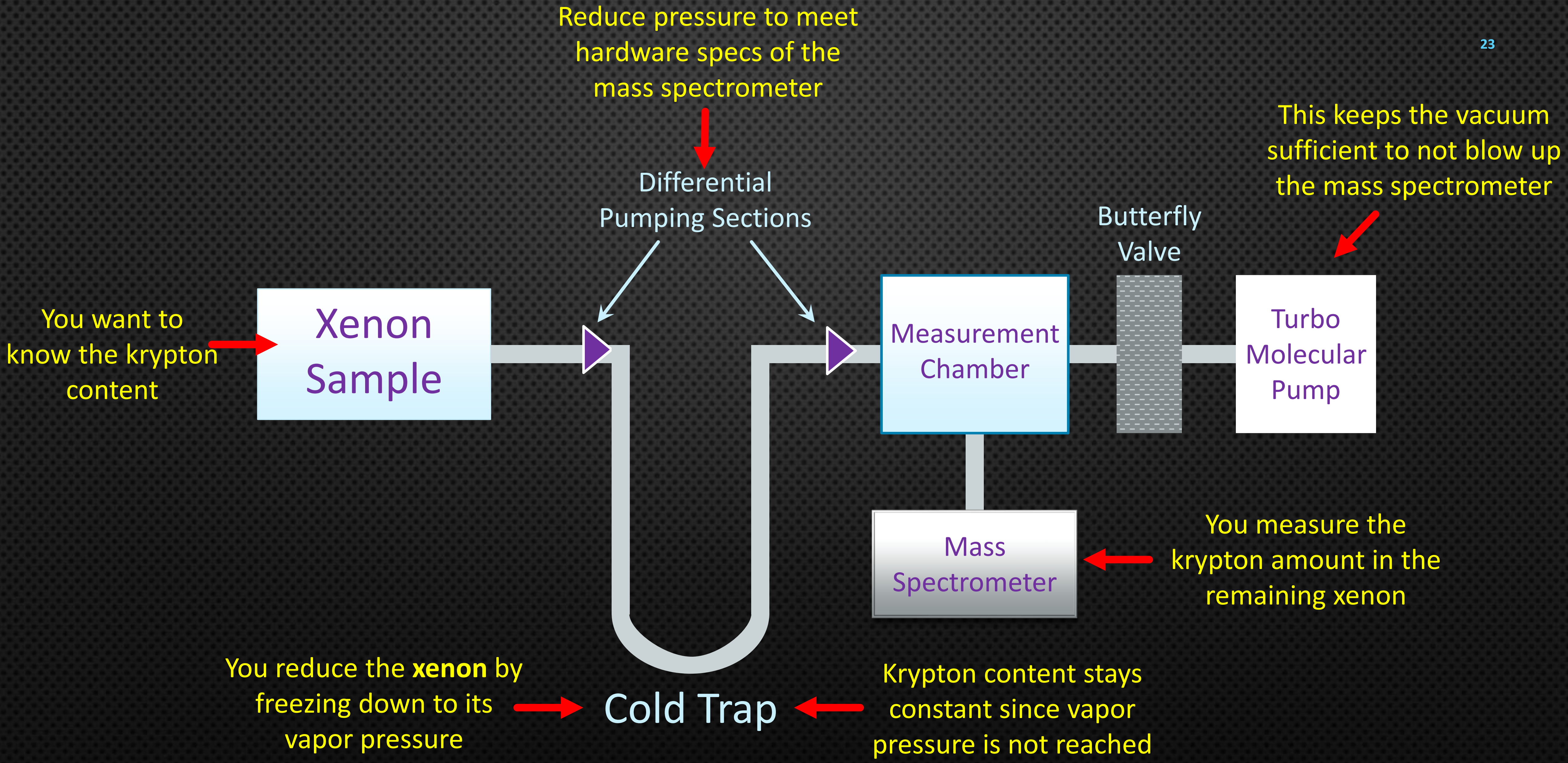
Background ^{85}Kr

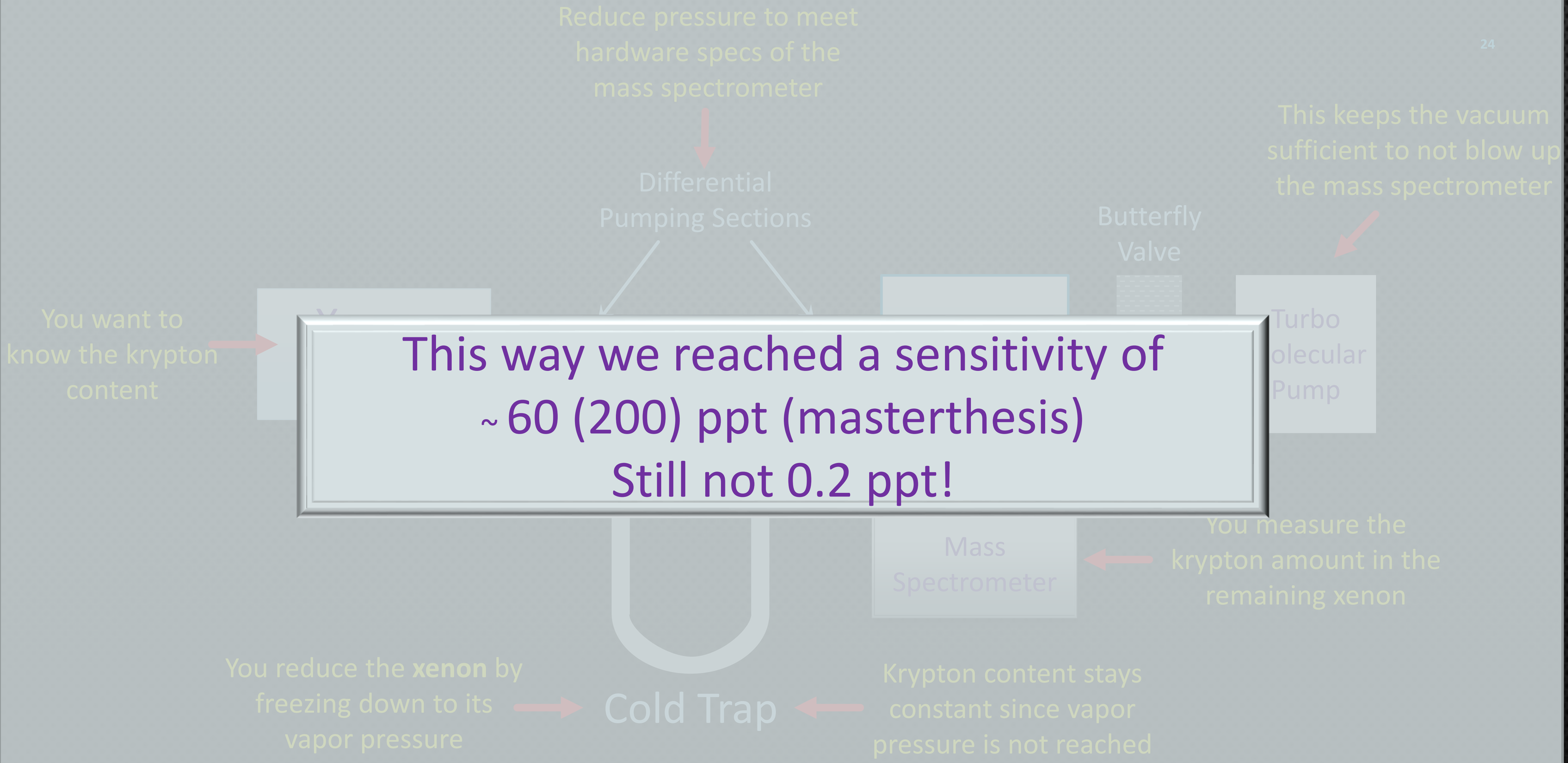
- Beta decay of ^{85}Kr into ^{85}Rb is a significant

Measuring the Krypton concentration at the sub-ppb level is not trivial!

- while natural krypton is aimed to be below <0.2 ppt in the used xenon

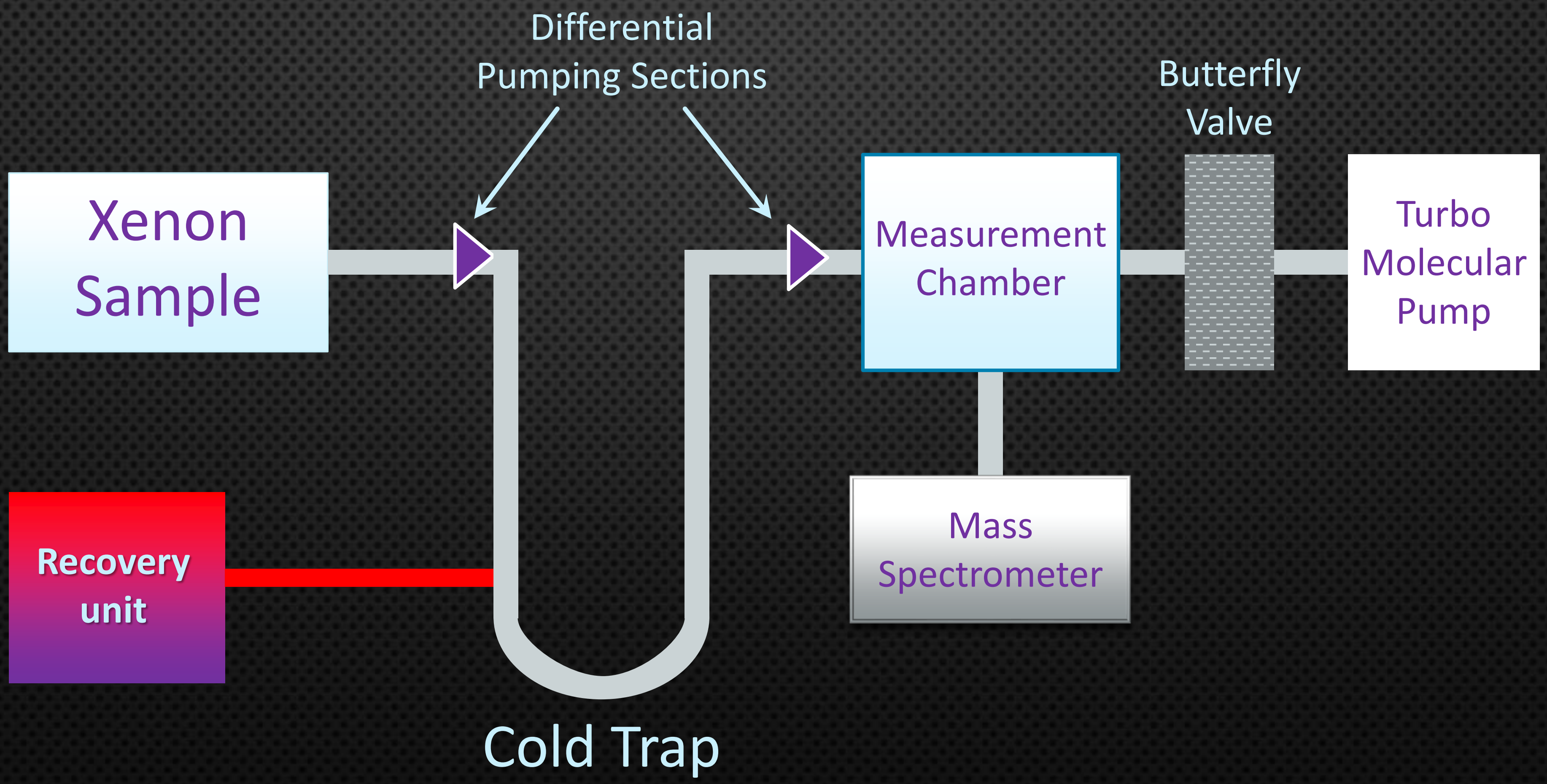

Differential
Pumping Sections
Butterfly
Valve
Xenon
Sample
Measurement
Chamber
Turbo
Molecular
Pump
Mass
Spectrometer
Cold Trap


Reduce pressure to meet hardware specs of the mass spectrometer
Differential Pumping Sections
This keeps the vacuum sufficient to not blow up the mass spectrometer
Butterfly Valve
You want to know the krypton content
Xenon Sample
Measurement Chamber
Turbo Molecular Pump
Mass Spectrometer
You measure the krypton amount in the remaining xenon
You reduce the **xenon** by freezing down to its vapor pressure
Cold Trap
Krypton content stays constant since vapor pressure is not reached



This way we reached a sensitivity of ~60 (200) ppt (masterthesis)

Still not 0.2 ppt!


Differential
Pumping Sections
Butterfly
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Sample
Measurement
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Recovery
unit
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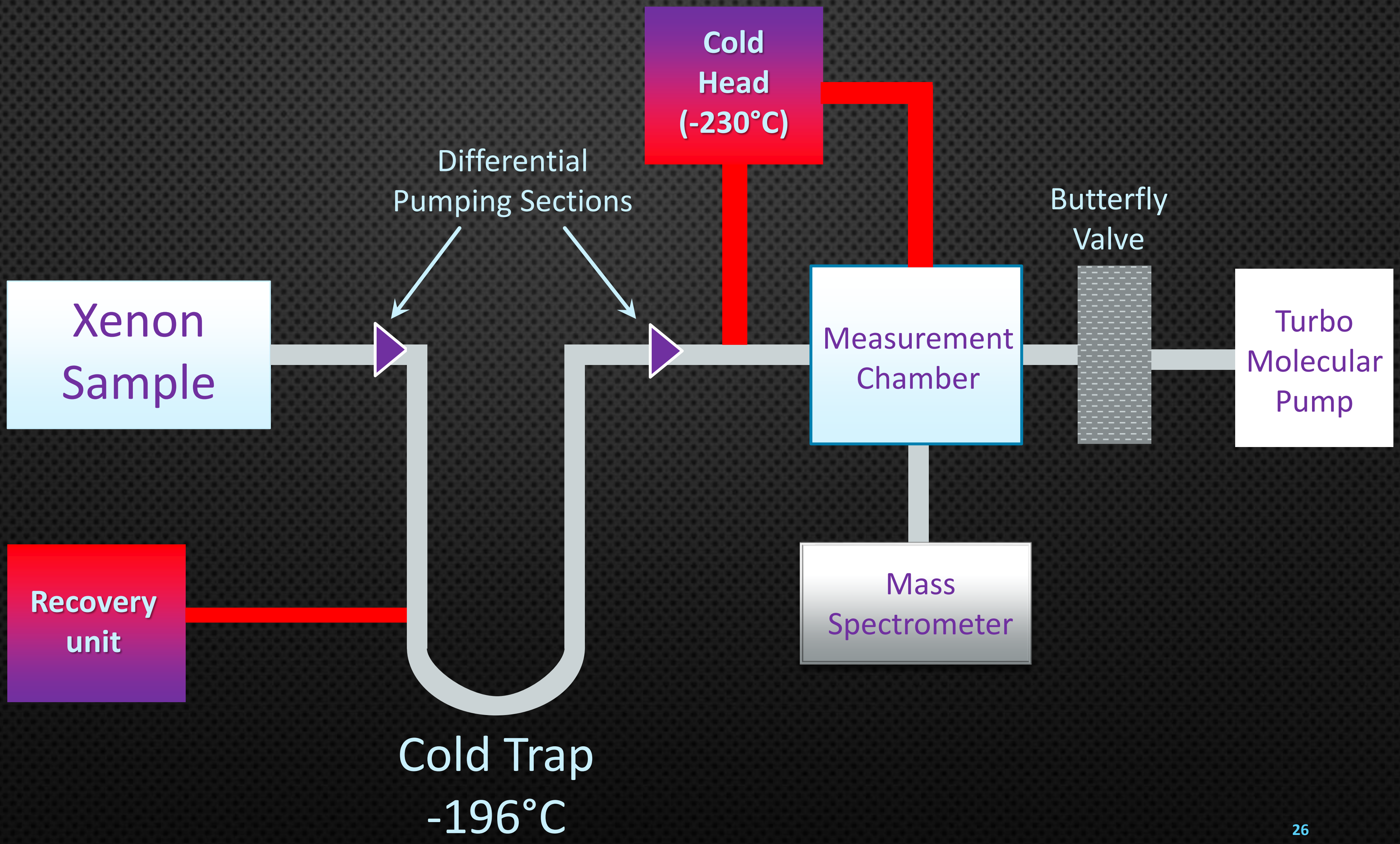
Spectrometer
Cold Trap


Cold
Head
(-230°C)
Differential
Pumping Sections
Butterfly
Valve
Xenon
Sample
Measurement
Chamber
Turbo
Molecular
Pump
Recovery
unit
Mass
Spectrometer
Cold Trap
-196°C

Analysis ongoing

Promising preliminary results

Project finished soon

^{124}Xe

Questions?

Kr