

Xe - M_x mixtures for the NEXT EL TPC

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NEXT Collaboration

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LIBPhys - Coimbra

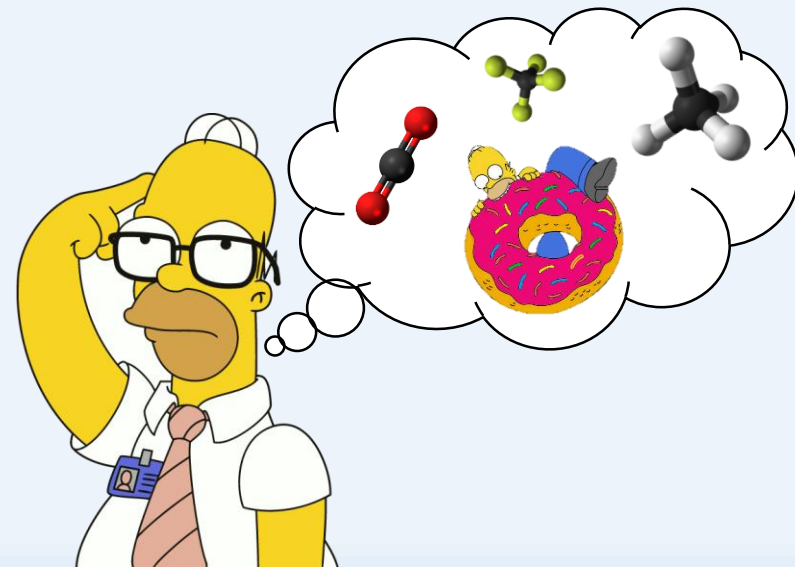
University of Coimbra

8th SYMPOSIUM ON LARGE TPCS FOR LOW-
ENERGY RARE EVENT DETECTION

December / 2016

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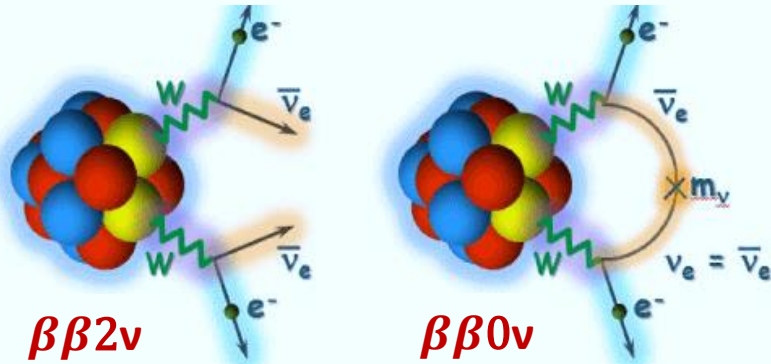
1. Introduction
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Introduction

1. Neutrinos absolute mass?
2. Majorana particles? ($\nu = \bar{\nu}$)

Answer: **neutrinoless double beta decay**

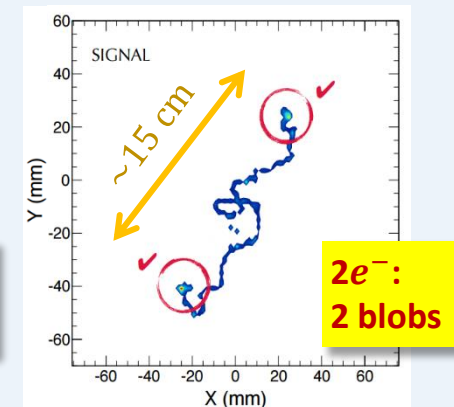
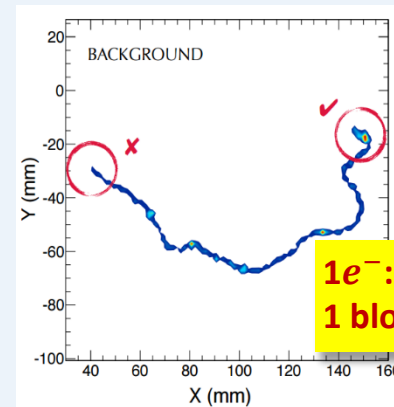
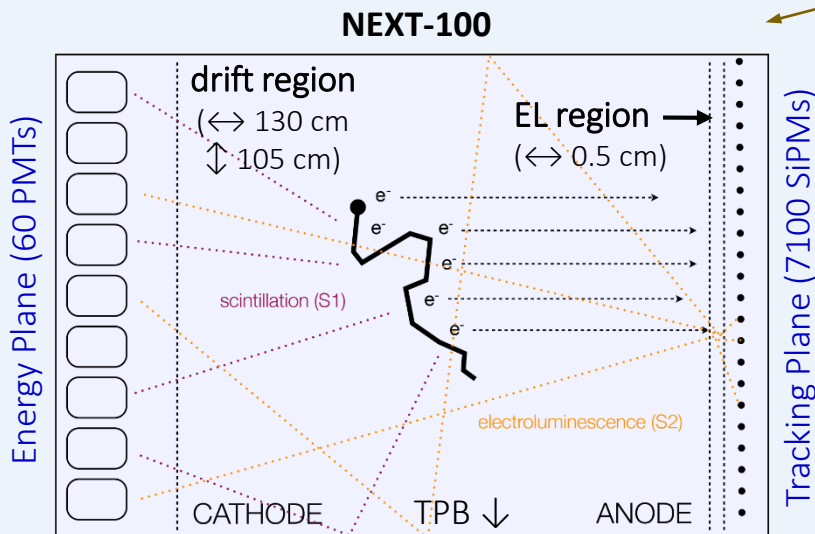


Neutrino Experiment with
a Xenon Time Projection
Chamber (TPC)

NEXT-100 detector: 100 kg of ^{136}Xe gas at 15 bar
High-pressure Xe (**HPXe**) electroluminescence (**EL**) TPC
with separated readouts for **calorimetry** and **tracking**

NEXT key features:

- 1) **Excellent R_E** \rightarrow 0.5 – 0.7 % at $Q_{\beta\beta}$ (2.457 MeV)
- 2) **Scalability** \rightarrow towards the ton scale
- 3) **Topological signature** \rightarrow background rejection



NEXT – improving the spatial resolution

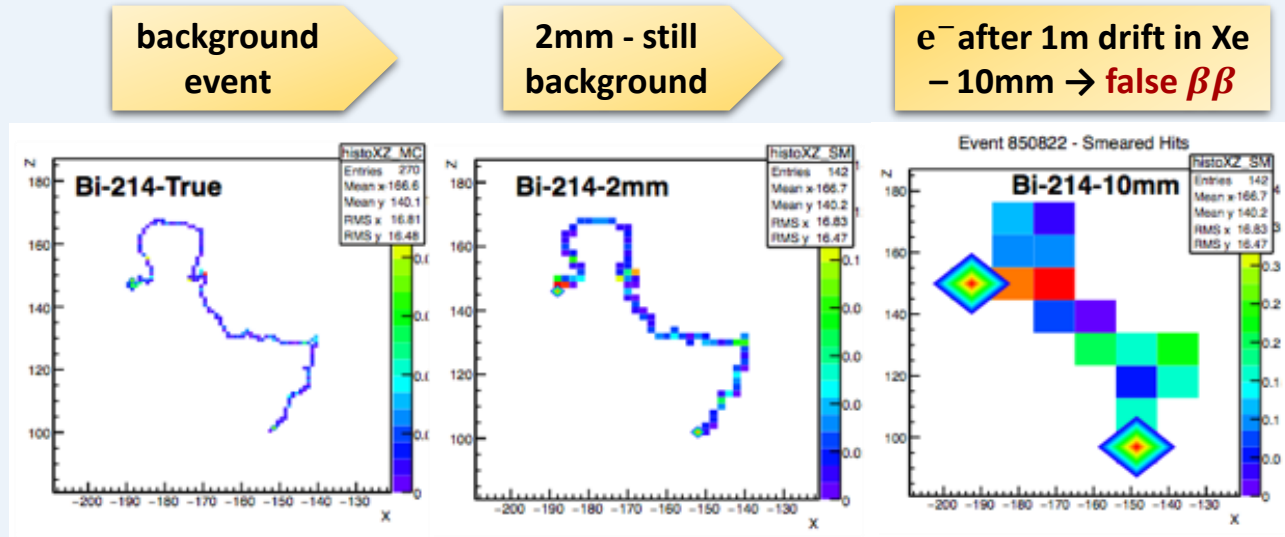
❖ Improve topological signature...

1. Longitudinal resolution:

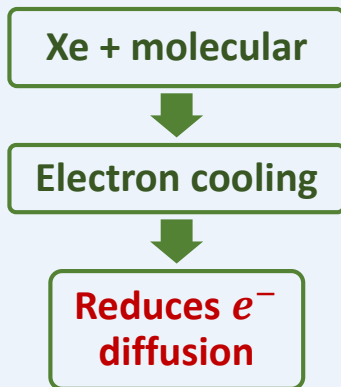
- $D_L(\text{Xe}) \sim 4.5 \text{ mm/m}$
- EL gap (5mm) \rightarrow 1.5 mm

2. Transversal resolution:

- $D_T(\text{Xe}) \sim 10 \text{ mm/m}$
- SiPMs pitch + barycenter algorithm \rightarrow 1 mm



❖ reducing electron diffusion:

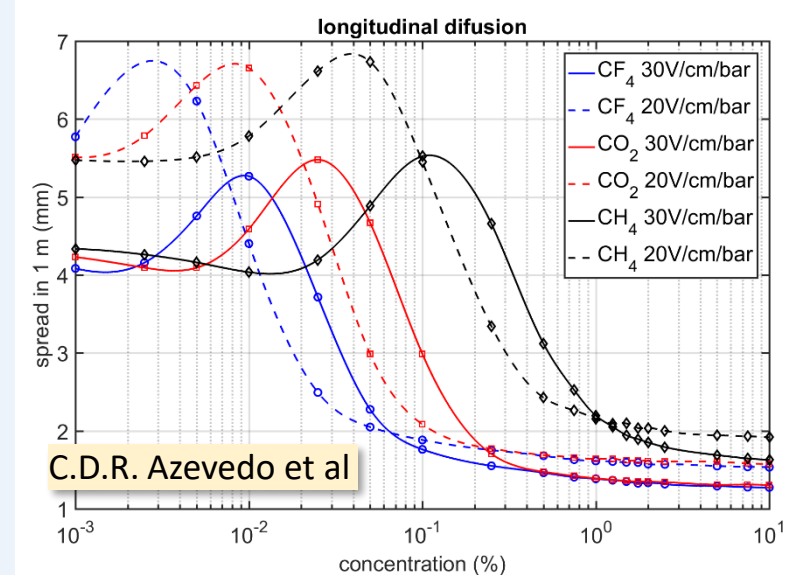
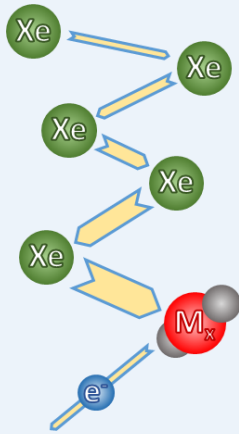
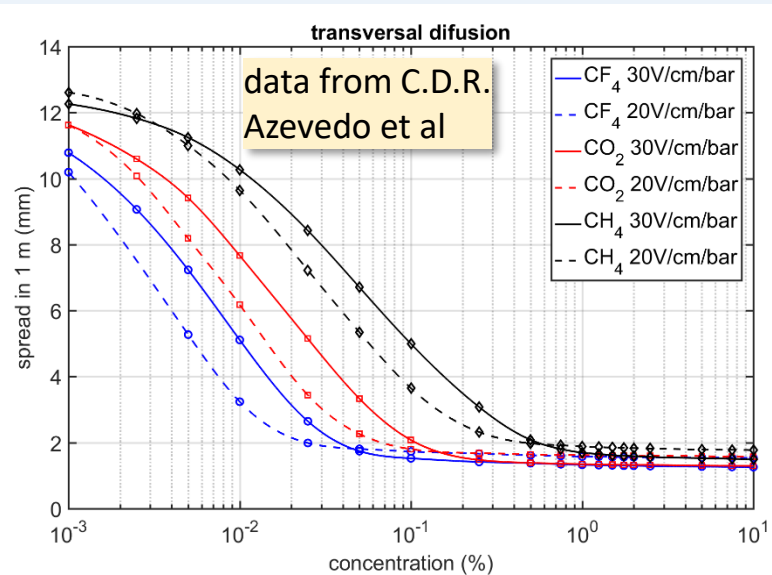


It also degrades:

- S1 and S2 yield
- Energy resolution

Additive & concentration

1) **Xe – M_x reduces e⁻ diffusion:** e⁻ cooled by vibrational excitation modes of M_x



2) **Xe – M_x degrades S1, S2 and R_E:**



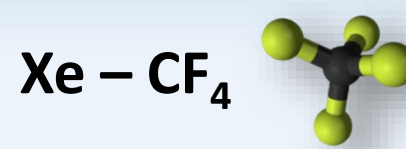
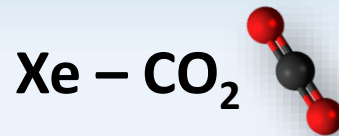
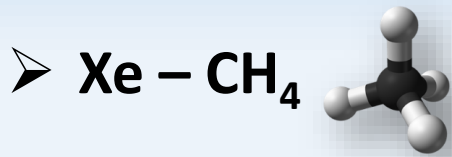
- e⁻ cooling → lower Y at same E (S2)
- quenching by M_x (S1, S2)
- attachment/recombination: in drift or EL regions (S2)
- lower transparency to VUV (S1, S2)

3) **Xe – M_x technical issues:**

- **stable & compatible** (with detector and purification system)
- **of easy handling and cleaning**



Experimental setup



➤ Driftless Gas Scintillation Proportional Counter (GSPC) with $EL_{\text{gap}} = 25\text{mm}$

▪ Electroluminescence and R_E (@ ~1.1 bar)

➤ Gas Residual Analyzer (RGA)

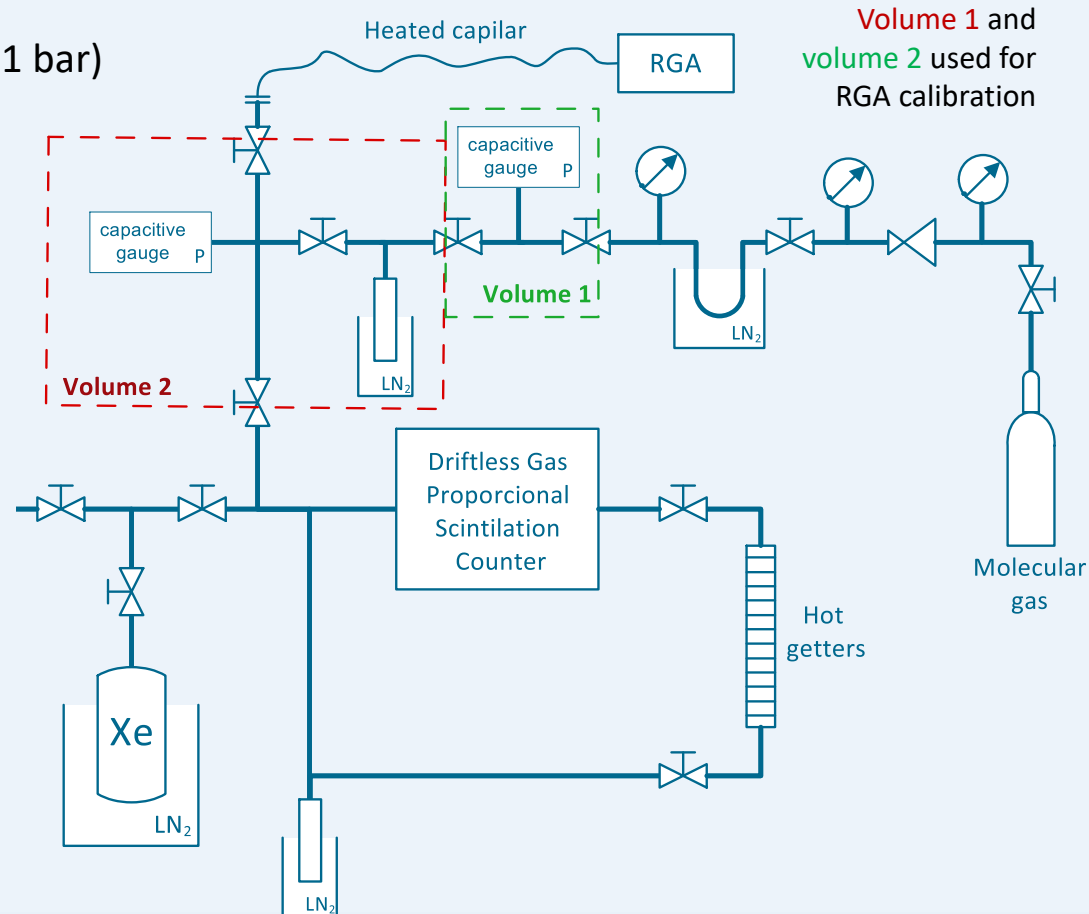
▪ real-time mixture concentration

➤ Gas purified by SAES hot getters

▪ Pure Xe at 250° C

▪ Xe – CH₄ and CF₄ at 120° C

▪ Xe – CO₂ at 80° C



Energy resolution ($R_E = FWHM / \text{centroid}$)

$$R_E = 2.35 \sqrt{\frac{F}{\bar{N}_e} + \frac{Q}{\bar{N}_e} + \frac{1}{k \cdot \bar{N}_e \cdot \bar{N}_{EL}} \left(1 + \frac{\sigma_G^2}{G^2} \right)}, \bar{N}_e = \frac{E}{w_i}$$

σ in primary charge production
 $\bar{N}_e \rightarrow$ primary e^-

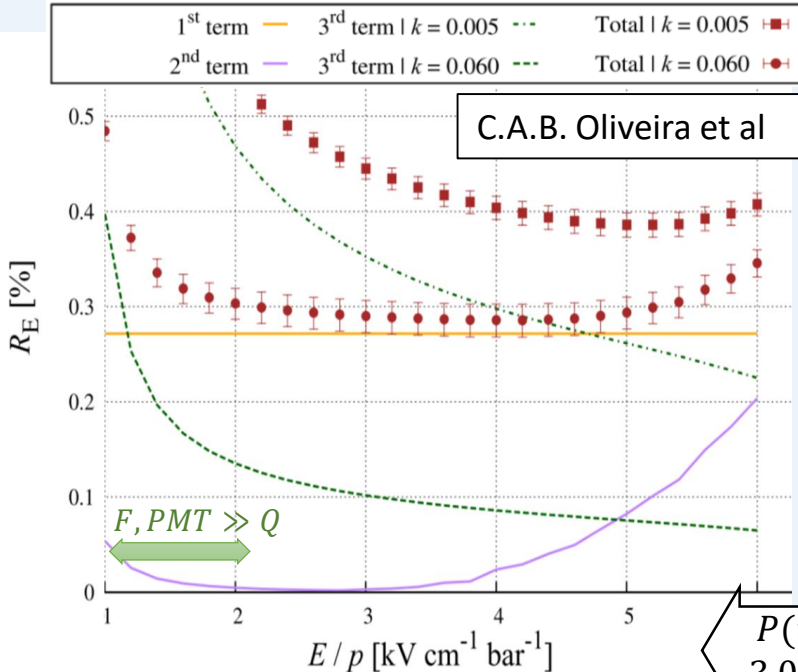
σ in EL photon production

σ in PMT signal
 $k \rightarrow$ light collection efficiency
 $\sigma_G \rightarrow$ fluctuations in PMT gain
 $\bar{N}_{EL} \rightarrow$ EL emitted photons

$$R_E^2 \propto (N_{EL})^{-1}$$

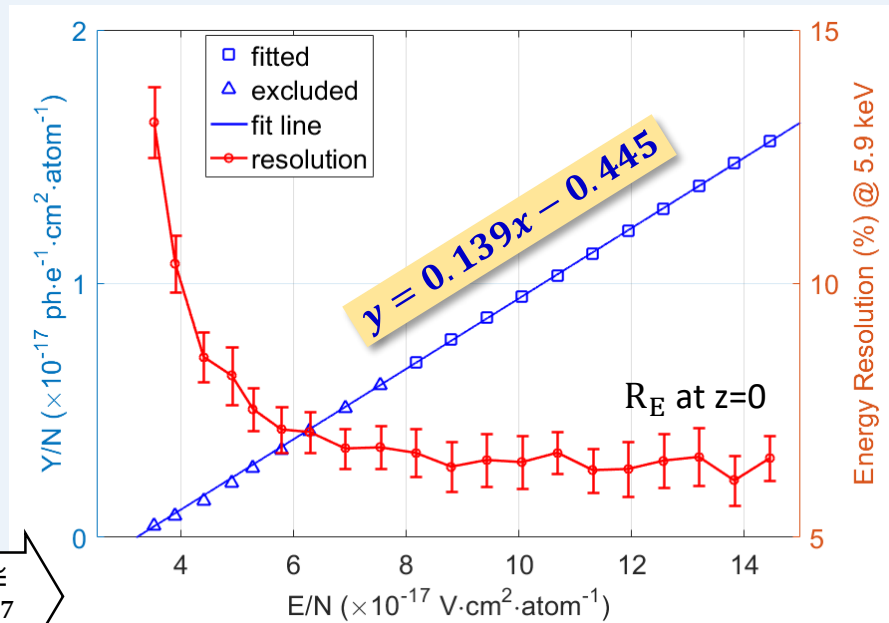
for E/N: $F, PMT \gg Q$

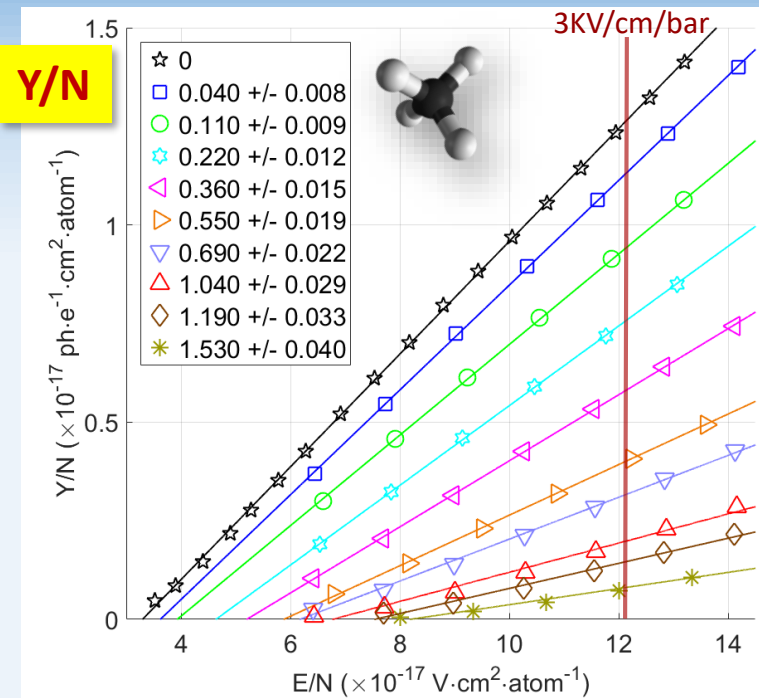
F and PMT contribution are determined using data from pure Xe



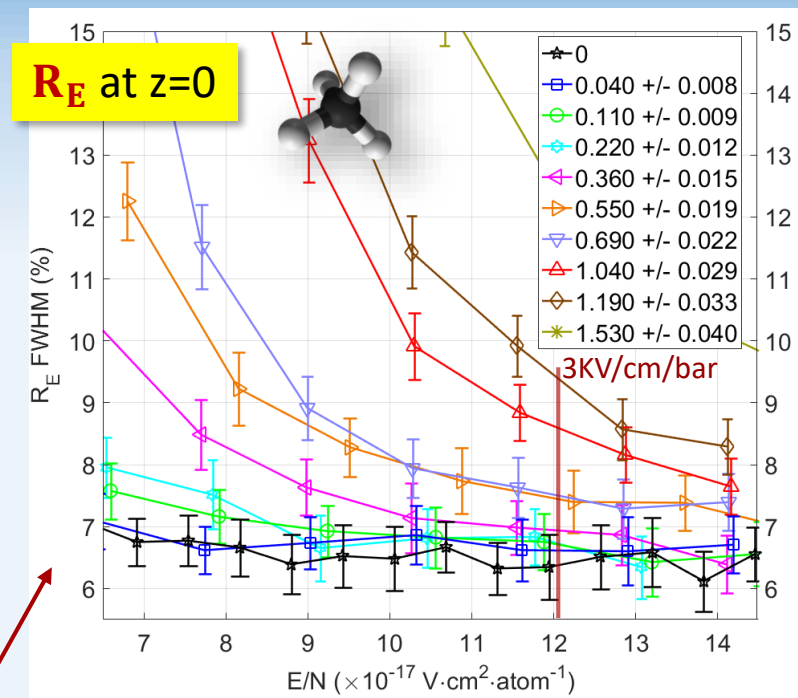
$$\frac{P(\text{torr})}{N} \cong 3.034 \times 10^{-17}$$

EL Yield (Y) & R_E in a driftless GSPC (pure Xe)

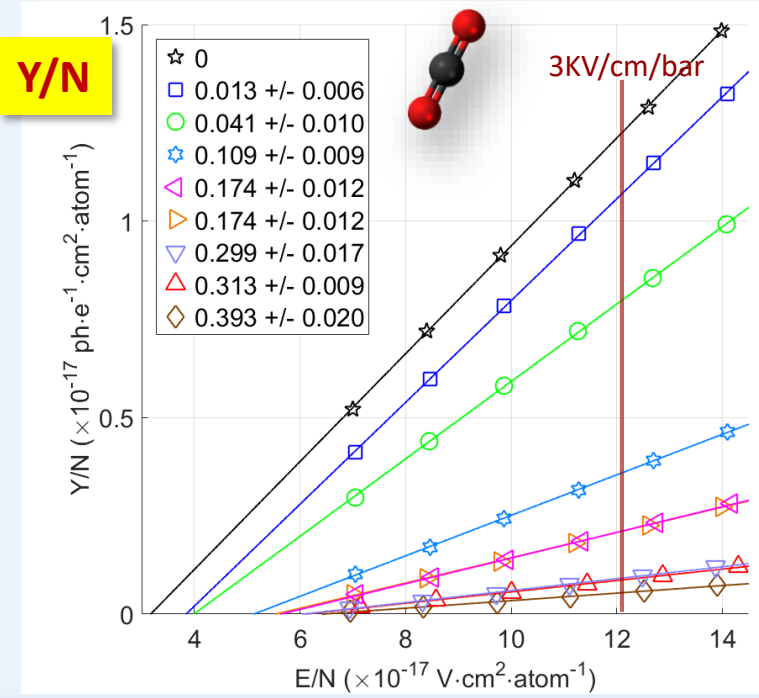




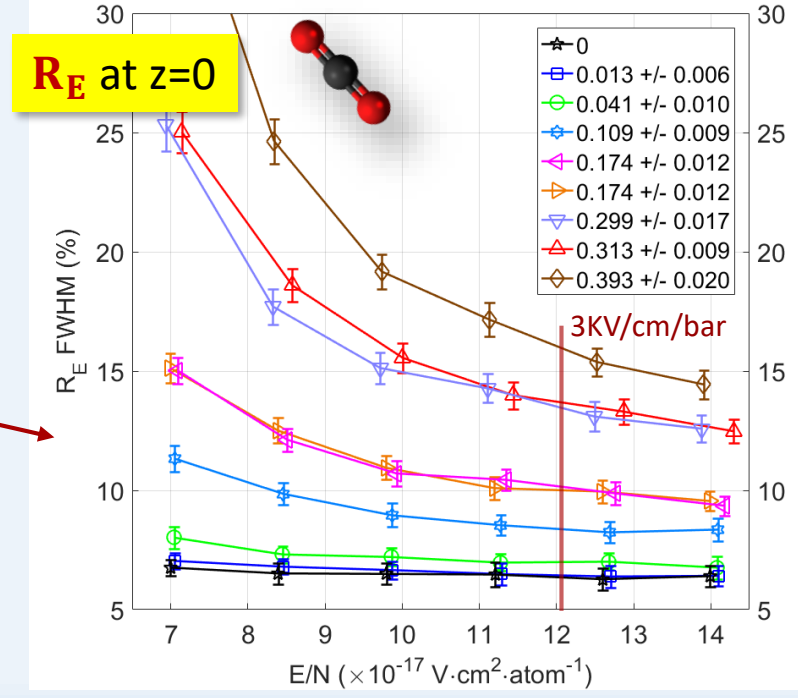
R_E estimated for zero x-ray penetration →
(driftless GSPC pulse-height distribution is left-tailed, exp + gauss)



EL threshold increases and slope decreases



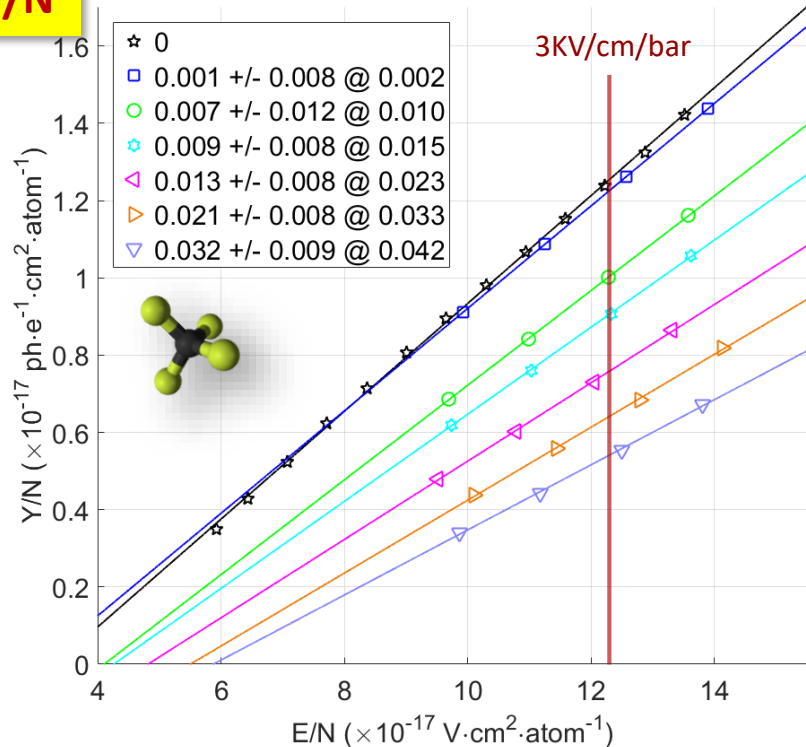
Stronger E/N → better R_E
favoured in CH4



$P(\text{torr})/N \cong 3.034 \times 10^{-17}$

The CF₄ case

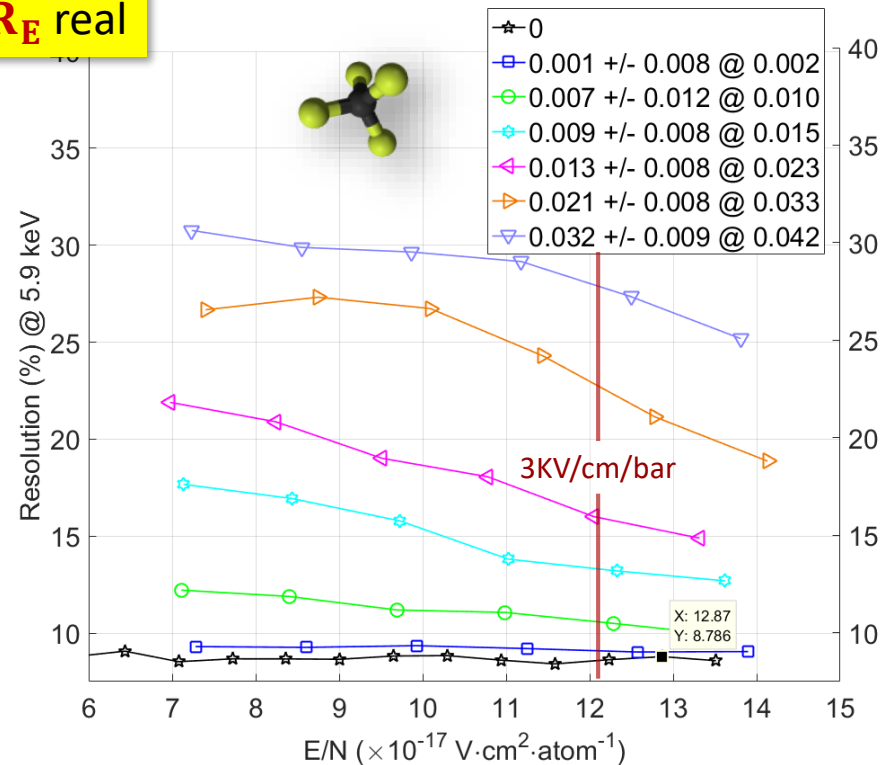
Y/N



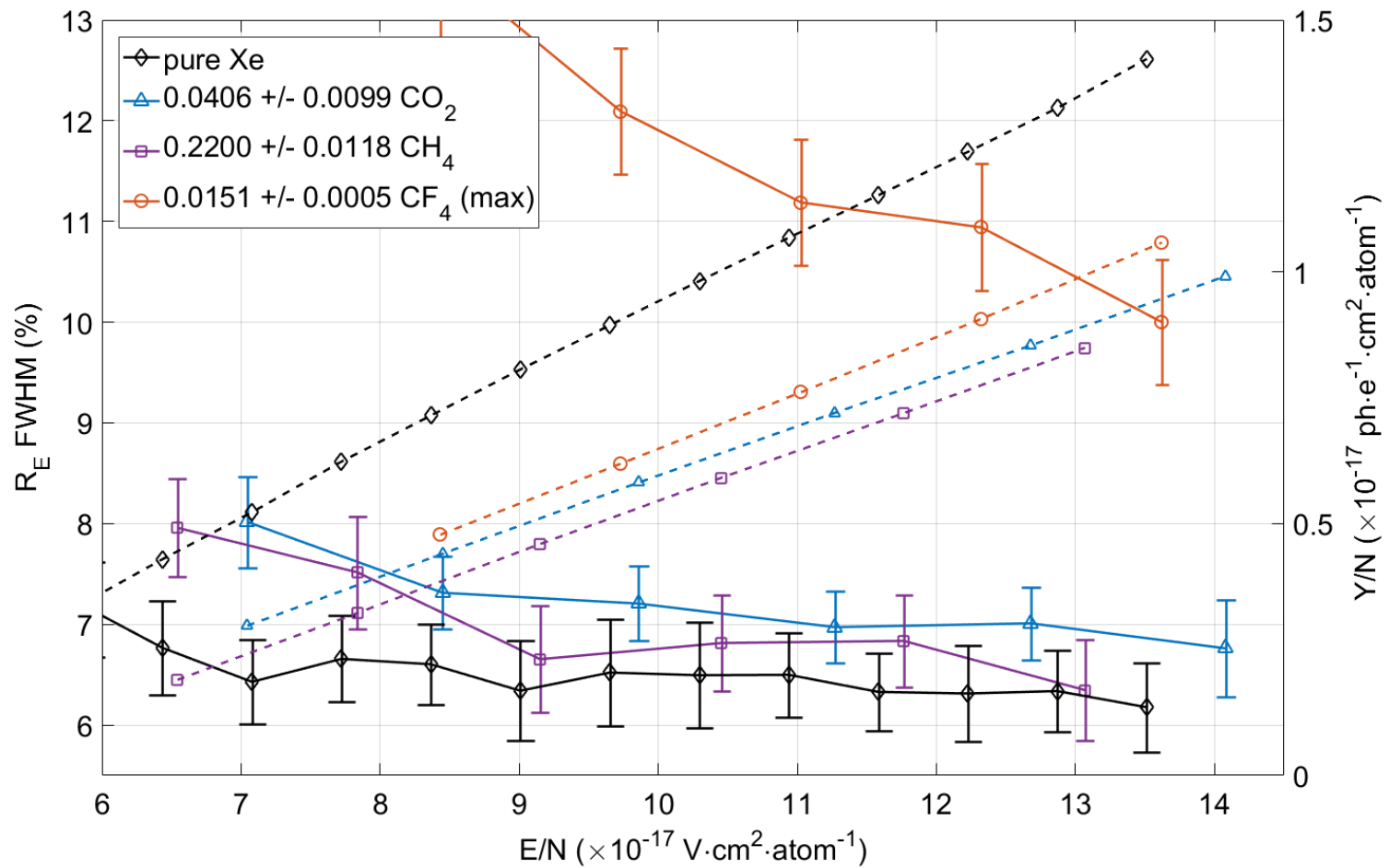
- EL Y well preserved if compared with R_E
- Lower R_E dependence on E/N

- Here, the real R_E is showed (because the CF₄ high attachment resulted in some right-tailed spectrums)
- But, in next slides previous z=0 extrapolation adopted although ignoring right-tailed spectrums

R_E real



Comparison: Y and R_E for the same $D_{3D} = \sqrt[3]{D_L \times D_T \times D_T} \sim 2.75 \text{ mm/m}$

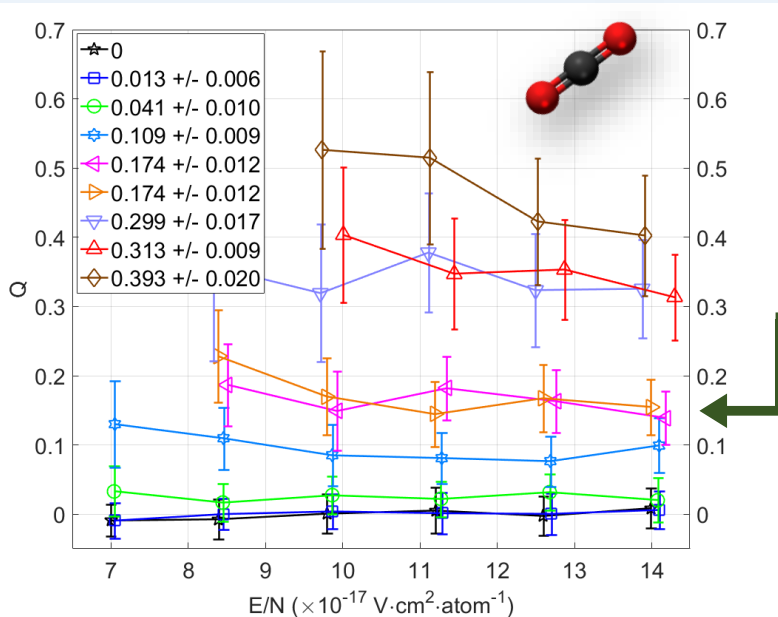
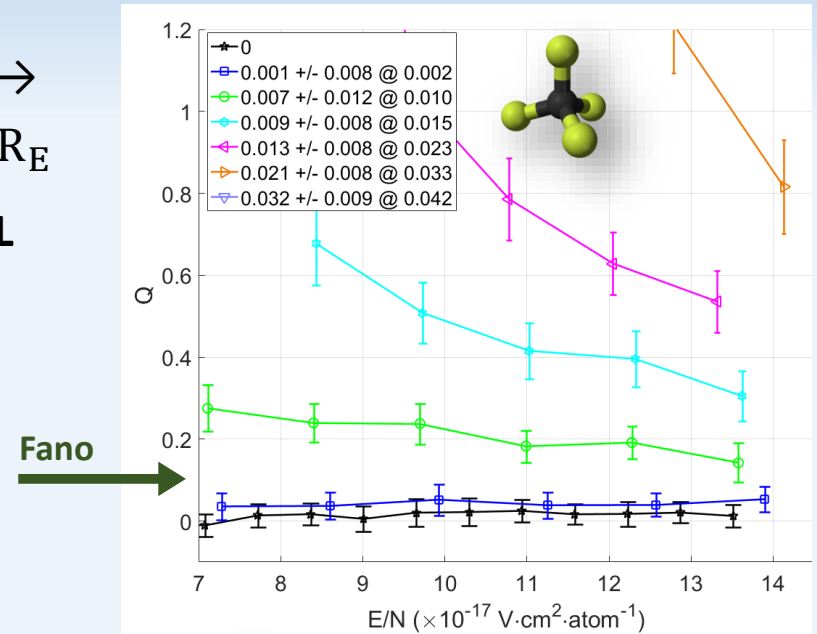


- **CO_2 have a good R_E** (but it degrades abruptly for higher concentrations)
- **CH_4 have the best R_E , even with the worst Y**
- **CF_4 have the best Y , but a terrible R_E**

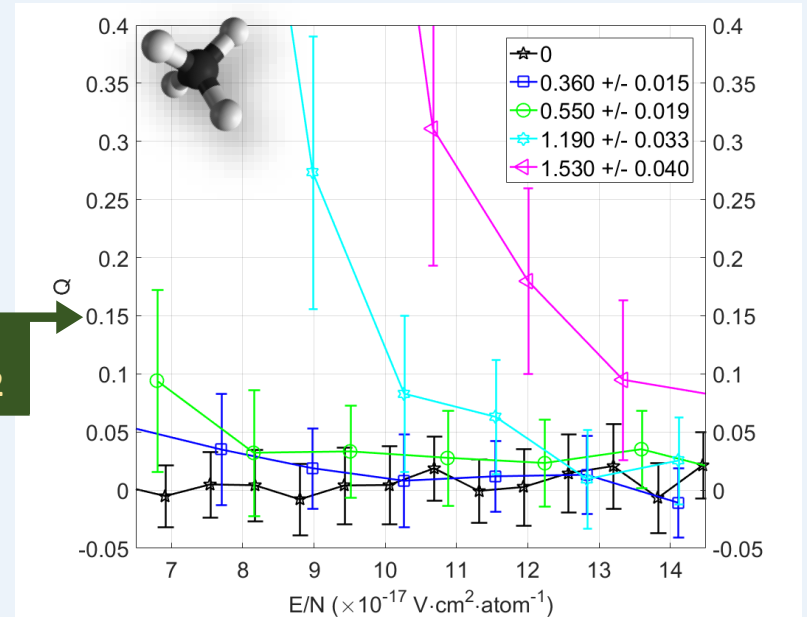
Concerning Q

- Using F , k and σ_G/G estimated with **pure Xe** \rightarrow PMT and Fano contributions are subtracted to R_E
- The Q (relative fluctuations in the number of **EL photons**) is estimated
 - CH4: Q negligible ($\ll F$)
 - CO2: $Q \sim \frac{1}{2}$ Fano (for conc. in ROI)
 - CF4: $Q \gg$ Fano (high attachment)

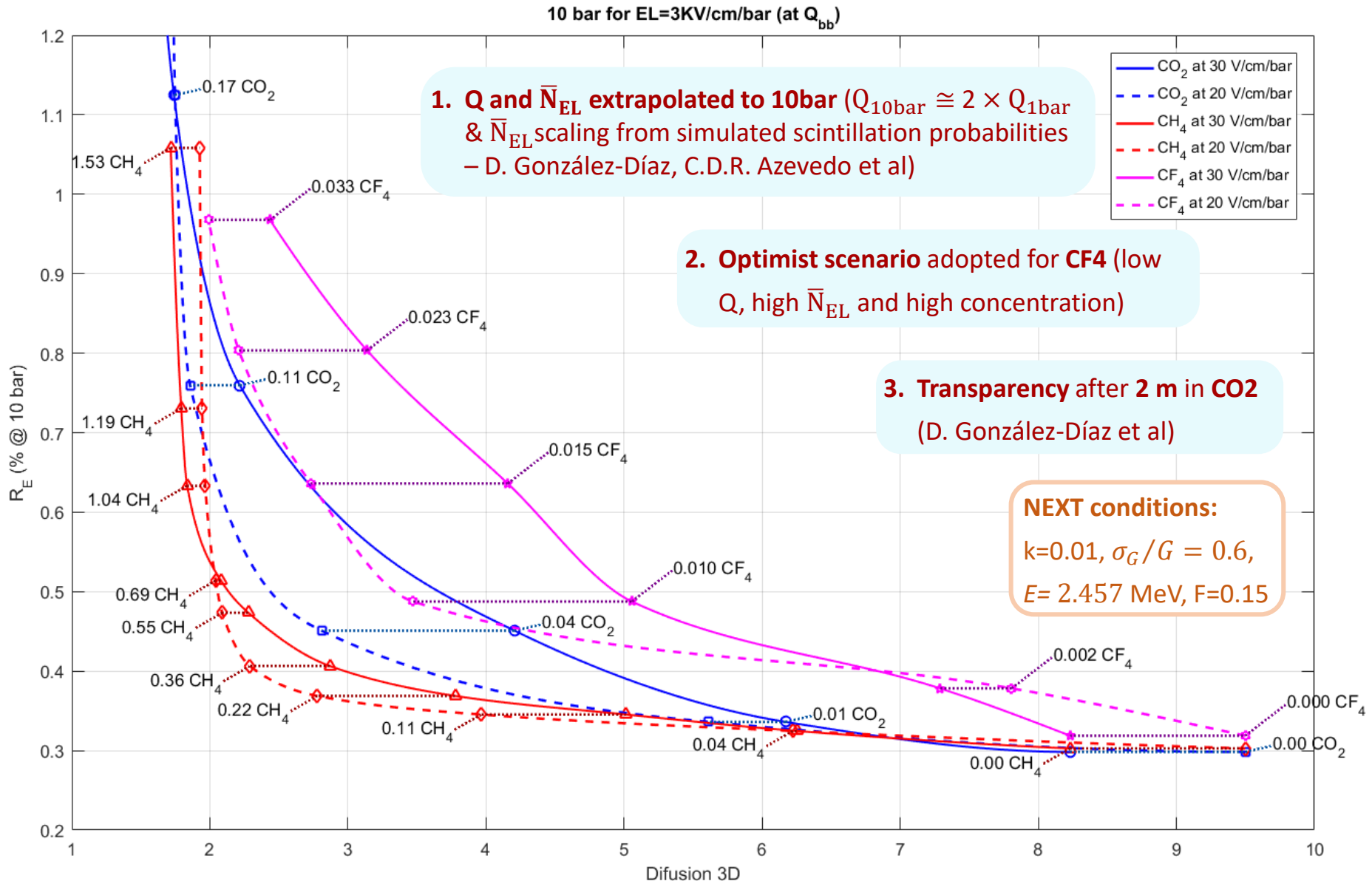
\downarrow Same method as in CO2 and CH4, but **ignoring right-tailed pulse distributions**



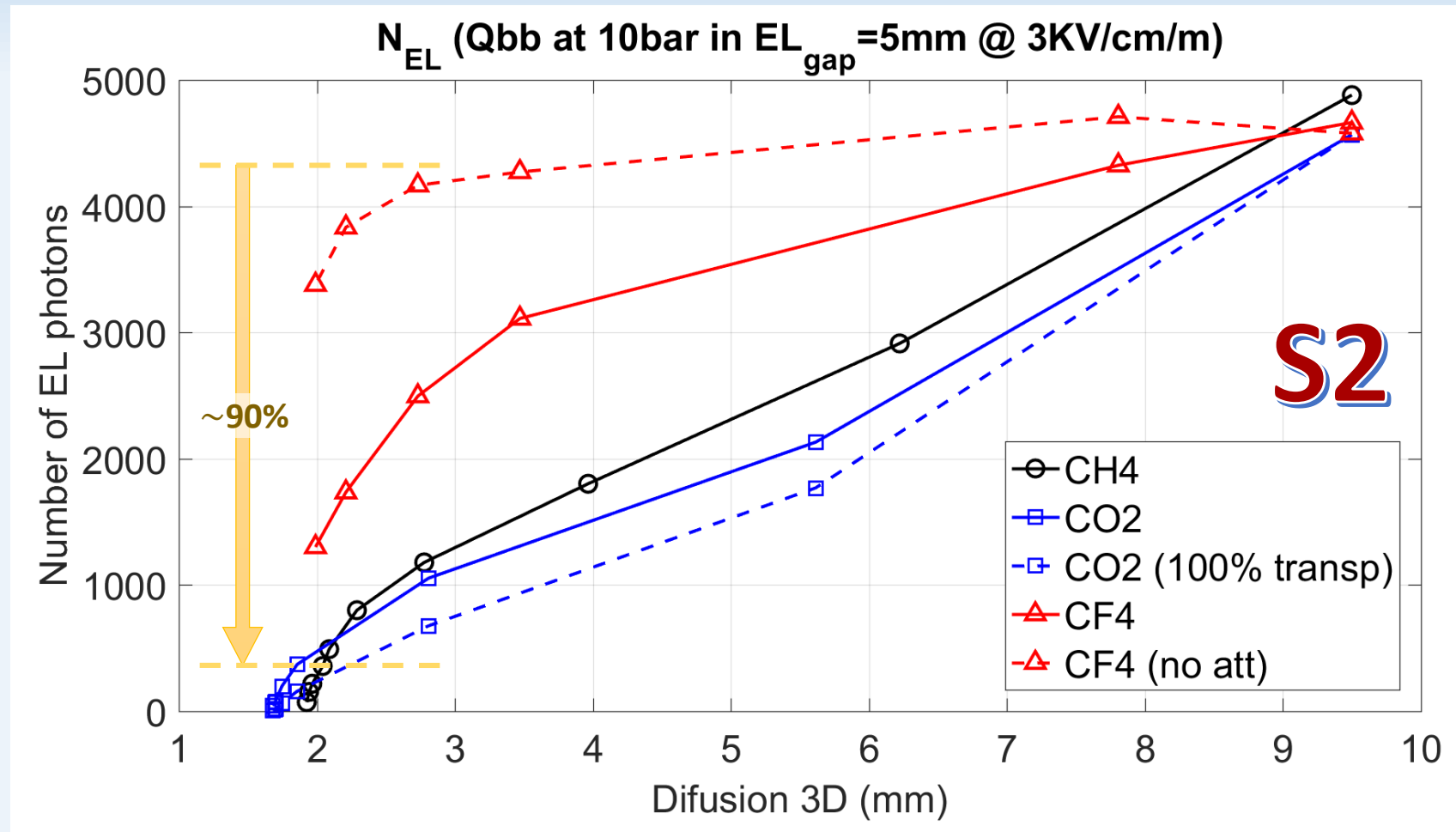
Fano
 0.15 ± 0.02



The compromise R_E vs D_{3D} – CO_2 , CH_4 and CF_4



N_{EL} vs D_{3D} – CO_2 , CH_4 and CF_4

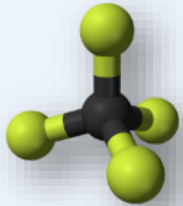


S1

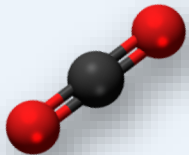
~80% light lose expected in CO_2 and CH_4 (almost 0% for CF_4) from simulated scintillation probability (D. González-Díaz et al, same simulations are in agreement with experimental data for S2 at 1bar)

Conclusion:

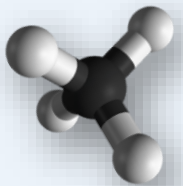
Xe – M_x may improve **spatial resolution** in a EL optical TPC, keeping **S1, S2** and **R_E**



Low quenching, high transparency → **S1** and **S2** slightly affected
High attachment → **R_E** extremely degraded (dominated by Q)
Stable, but concentrations (~100ppm) too low to handle and measure



S1 and S2 affected by quenching and transparency
Good **R_E** (attachment still low) in concentration ROI
Absorbed by hot getters and transformed CO (CO₂ specific cold getters)

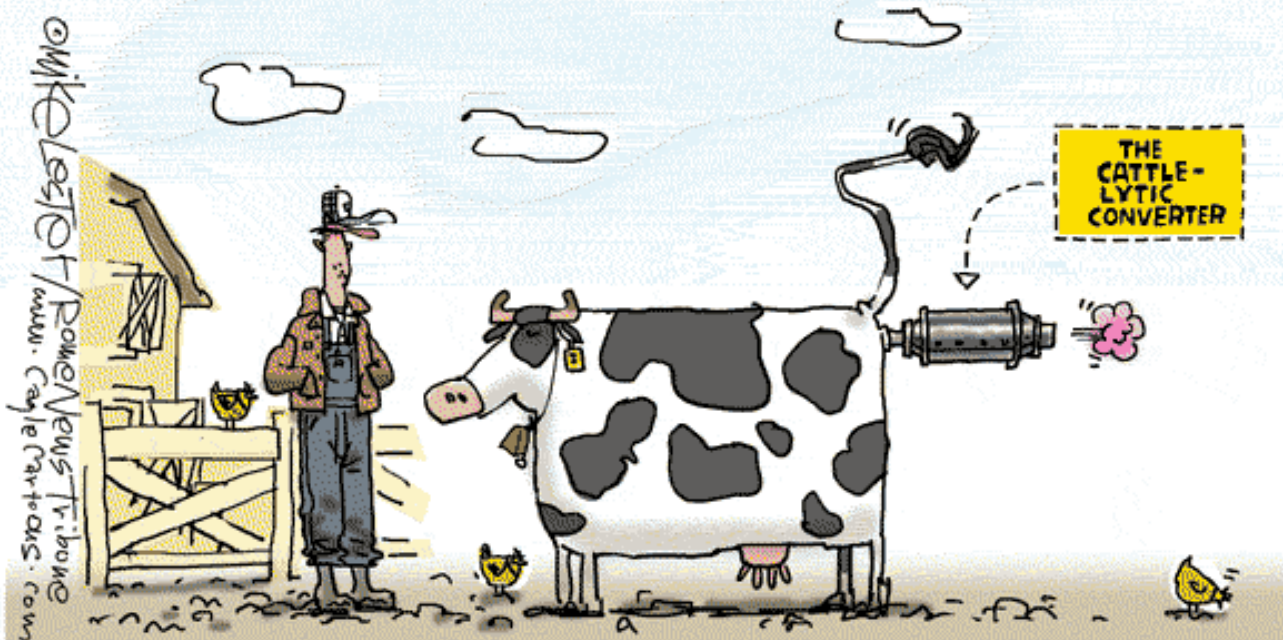


S1 and S2 affected by the high quenching
Excelente **R_E** (Q~0), if E/N is increased (as EL threshold) S2 improved and **R_E** almost the same as in pure Xe
Stable & high concentrations (~4000ppm), easy to handle and measure

Thank you for your time

U-N REPORT IDENTIFIES "COW EMISSIONS" ARE MORE DAMAGING TO PLANET THAN CO₂ FROM CARS... SOLUTION?

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References

1. Gómez Cadenas, J.J. et al. “Present Status and Future Perspectives of the NEXT Experiment.” *Advances in High Energy Physics* 2013 (2014).
2. C.D.R. Azevedo, L.M.P. Fernandes, E.D.C. Freitas et al., “An homeopathic cure to pure Xenon large diffusion,” *Journal of Instrumentation*, vol. 11, C02007–C02007, (2016). doi:10.1088/1748-0221/11/02/C02007.
3. C.A.B. Oliveira, M. Sorel, J. Martin-Albo et al., “Energy resolution studies for NEXT,” *Journal of Instrumentation*, vol. 6, P05007–P05007, (2011). doi:10.1088/1748-0221/6/05/P05007.
4. C.M.B. Monteiro, L.M.P. Fernandes, J.A.M. Lopes et al., “Secondary scintillation yield in pure xenon,” *Journal of Instrumentation*, vol. 2, P05001–P05001, (2007). doi:10.1088/1748-0221/2/05/P05001.
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6. J. Escada, T.H.V.T. Dias, F.P. Santos et al., “A Monte Carlo study of the fluctuations in Xe electroluminescence yield: pure Xe vs Xe doped with CH₄ or CF₄ and planar vs cylindrical geometries,” *Journal of Instrumentation*, vol. 6, P08006–P08006, (2011). doi:10.1088/1748-0221/6/08/P08006.
7. C.D.R. Azevedo, D. González-Díaz et al., “Microscopic simulation of Xenon-based gaseous optical TPCs in the presence of molecular additives,” (2016)

Backup

Conclusion: mixture purification

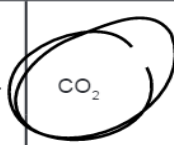
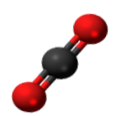
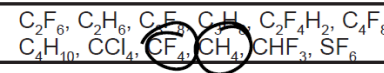


❖ Purifying the Xe - M_x gas:

Specialized cold getters could be used to purify Xe + CO₂/CH₄/CF₄
 This getters absorbs the main contaminants: **CO**, H₂O, O₂, and H₂...
However they don't absorb N₂

Radon?

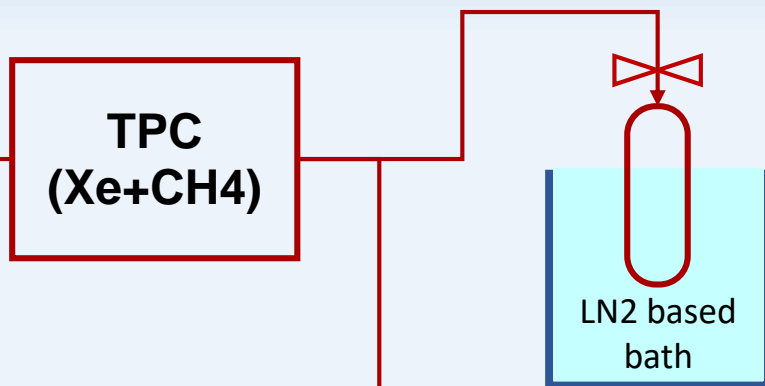


Purification and Removal Capabilities

Media	Gases Purified	Impurities Removed	Outlet Performance	Regenerable	Dangerous Goods (DG) Classification
804	 CO ₂ 	H ₂ O, O ₂ , CO, H ₂ Volatile Acids, Refractories, Condensable Organics (>100amu), Volatile Base Non-Condensable Organics (>45 amu)	< 1 ppbV < 5 pptV < 100pptV	YES	DG - UN2881 Class 4.2
905	  	H ₂ O, O ₂ , CO, CO ₂ , H ₂ NMHCs*	< 1 ppbV	YES	DG - UN2881 Class 4.2

Conclusion: remove M_x from the Xe

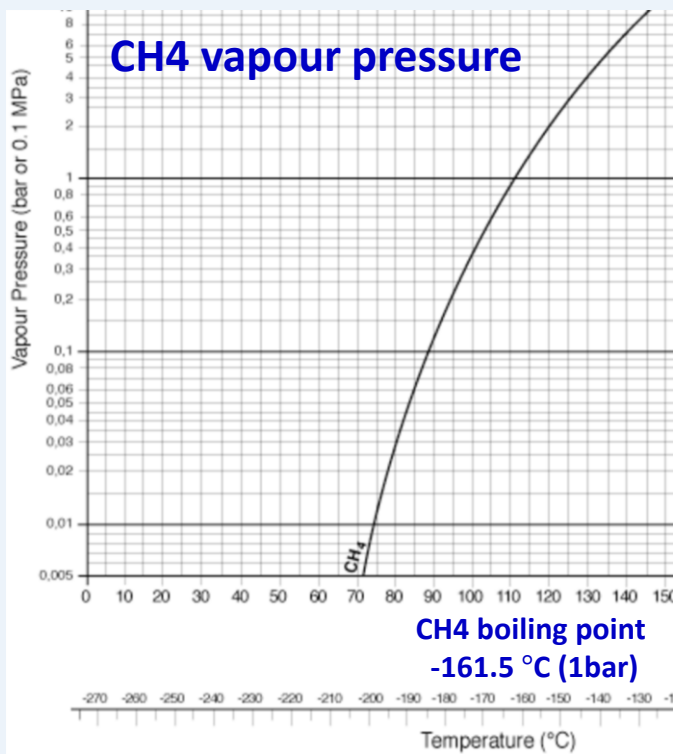
CH₄
pumped
out



Cooling baths

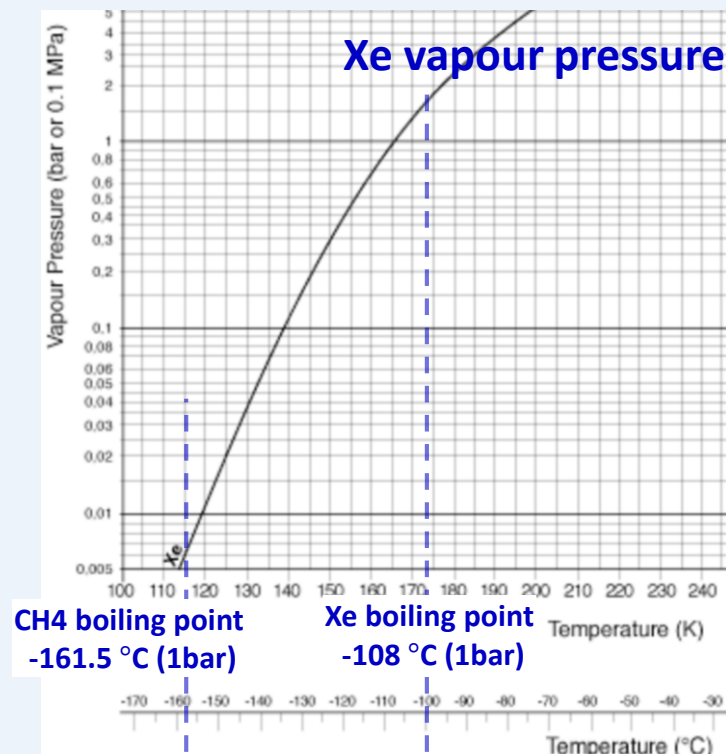
Temp.
(°C)

		Temp. (°C)
Liquid N ₂	Ethanol	-116
Liquid N ₂	Ethyl bromide	-119
Liquid N ₂	Acetaldehyde	-124
Liquid N ₂	Methylcyclohexane	-126
Liquid N ₂	n-Propanol	-127
Liquid N ₂	n-Pentane	-131
Liquid N ₂	1,5-Hexadiene	-141
Liquid N ₂	Isopentane	-160
Liquid N ₂	(none)	-196

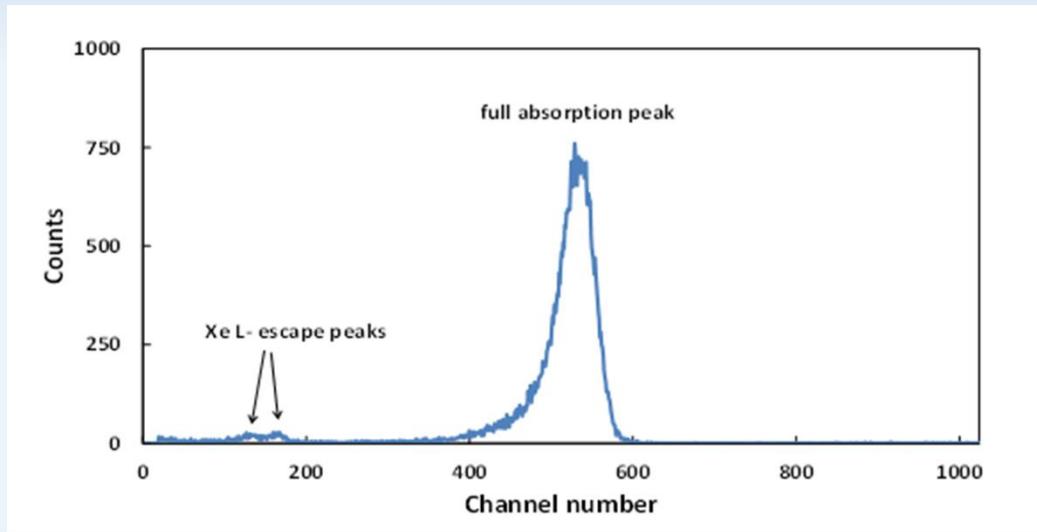


**Hot
getters**

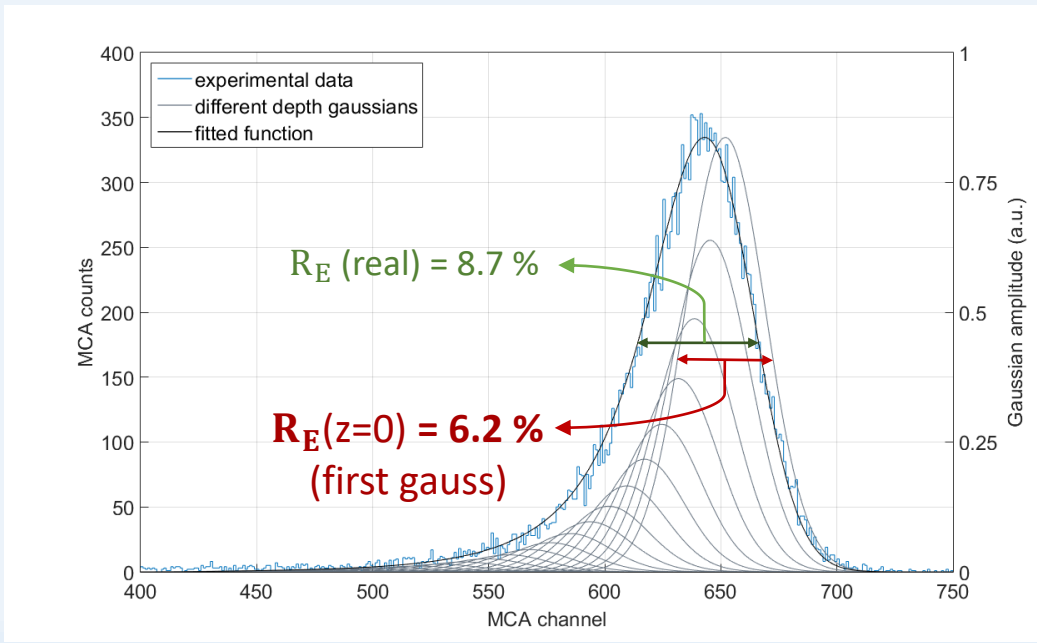
To remove
remaining CH₄
(small
concentration
will not saturate
getters)



The pulse height distribution, of a driftless GPSC



← pulse height distribution of 5.9-keV (^{55}Fe) x-rays absorbed in a **driftless** GPSC filled with pure Xe (at ~ 800 torr)

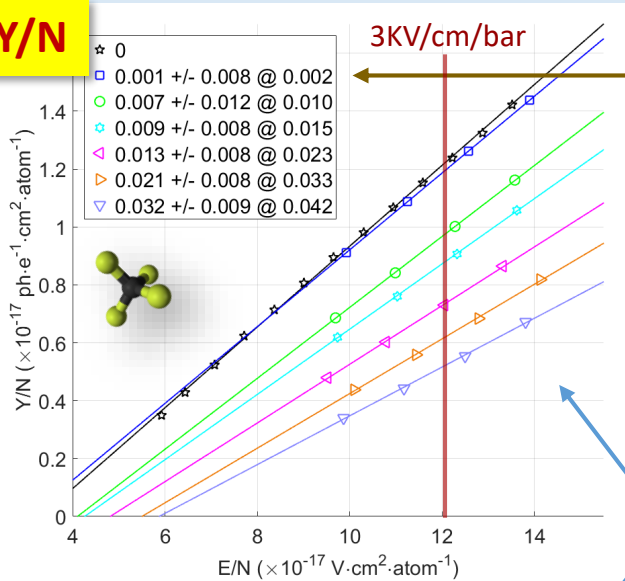


← Different depth (z) absorbed x-rays \rightarrow **left-tailed** pulse-height distribution (gaussian & exponential absorption)

R_E is estimated for zero x-ray penetration (FWHM/E of the first gauss)

The CF₄ case

Y/N



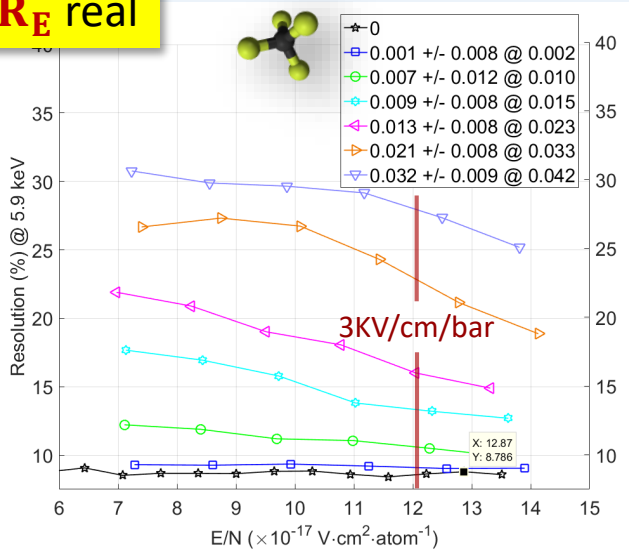
Huge **uncertainty** in low RGA's measurements:

Initial/max values from P-V calculation are also shown

! There is not a systematic error – RGA's calibration was successfully tested after taking data !

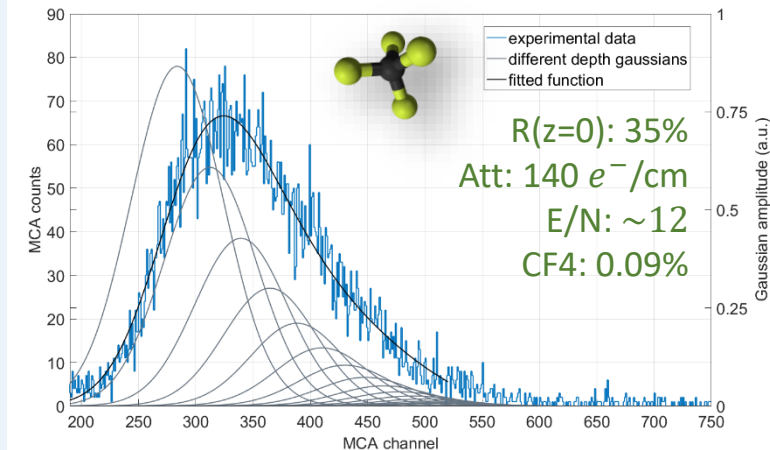
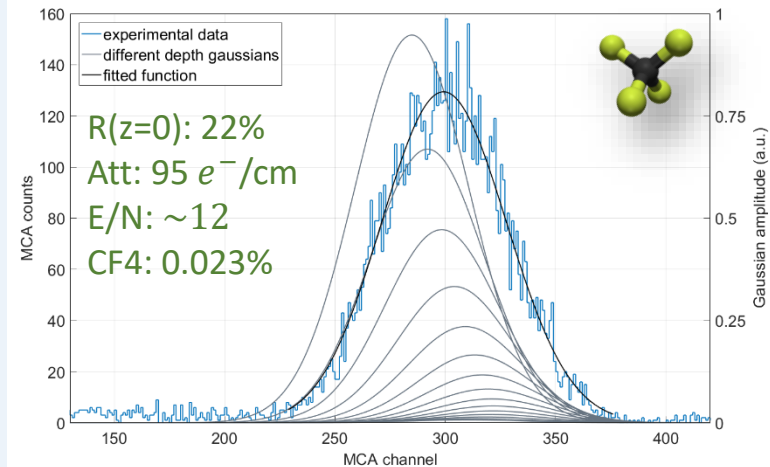
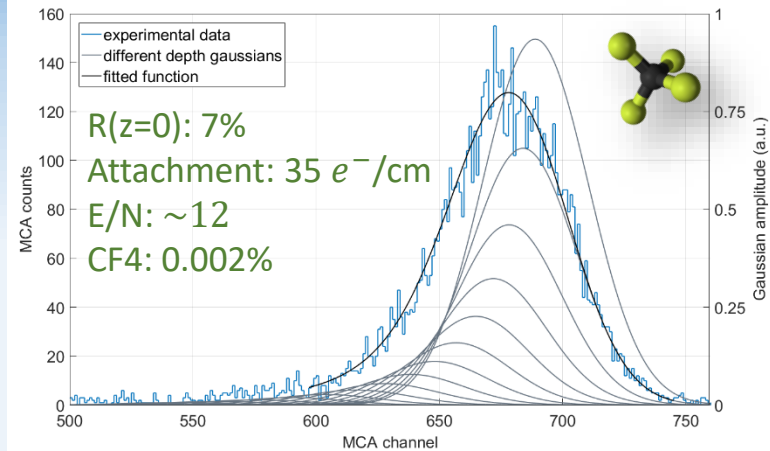
- EL Y well preserved if compared with R_E
- Lower R_E dependence on E/N

R_E real



With 1 more free fitting parameter (attachment), R_E (z=0) extrapolation could be not reliable:

- ← Here, the real driftless GSPC R_E
- ↓ Next, previous z=0 extrapolation used but ignoring right-tailed spectrums



What about NEXT - $Q_{\beta\beta}$ at 10 bar, $EL_{gap} = 5\text{mm}$

$$R_E = 2.35 \sqrt{\frac{F}{\bar{N}_e} + \frac{Q}{\bar{N}_e} + \frac{1}{\bar{N}_{ep}} + \frac{\sigma_G^2}{\bar{N}_{ep} G^2}}$$


$$\bar{N}_e = \frac{E_x}{w_{ion}} = \frac{2.457\text{MeV}}{22\text{ eV}},$$

$$F \sim 0.15 \mp 0.02$$

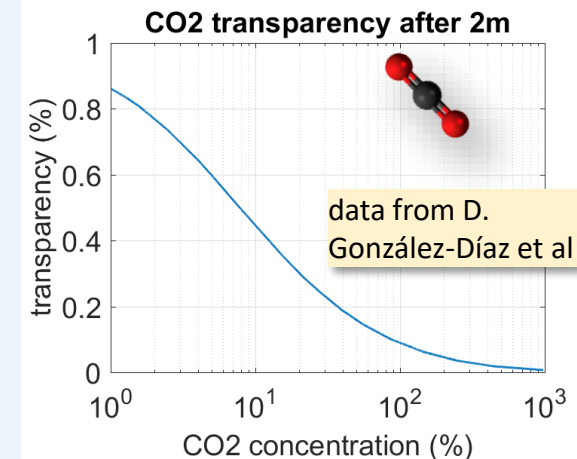
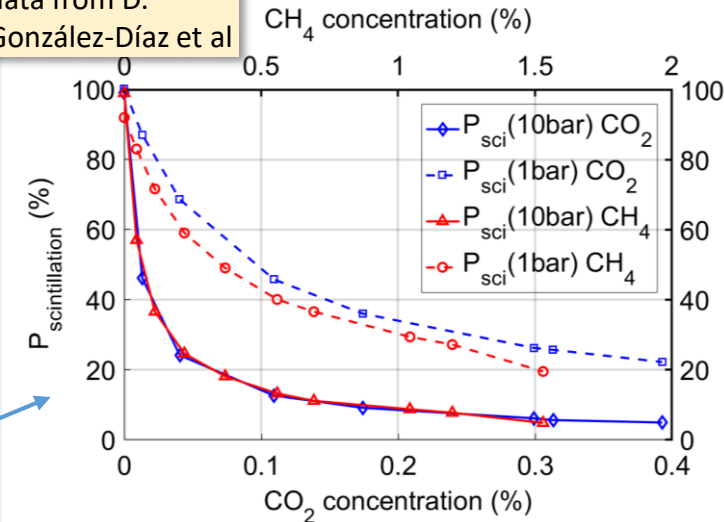
$$\bar{N}_{ep} = k \cdot \bar{N}_e \cdot \bar{N}_{EL}$$

Expected features in NEXT-100:

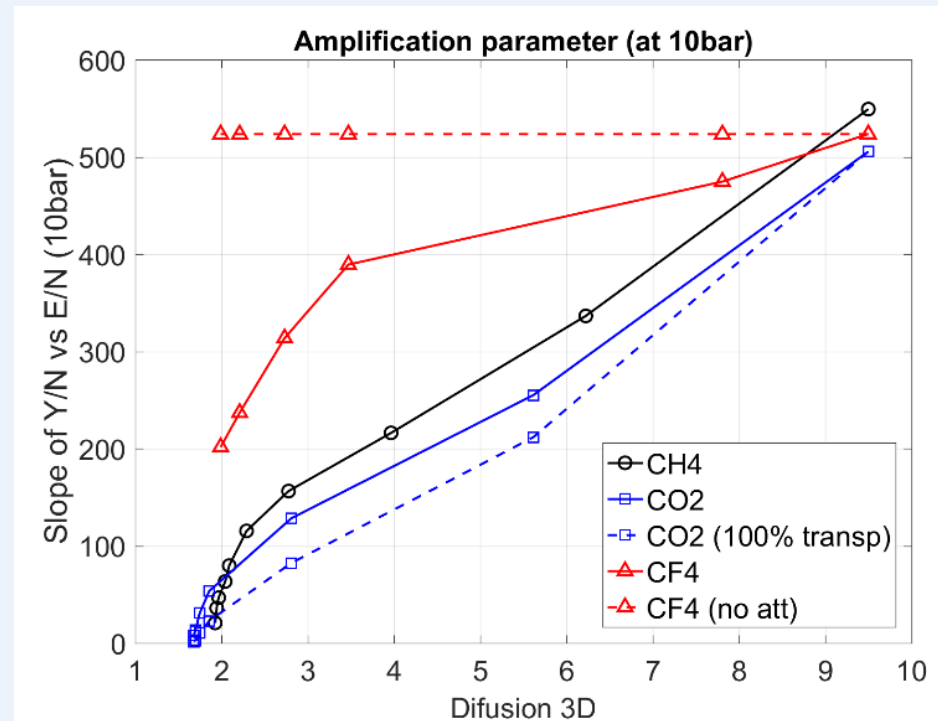
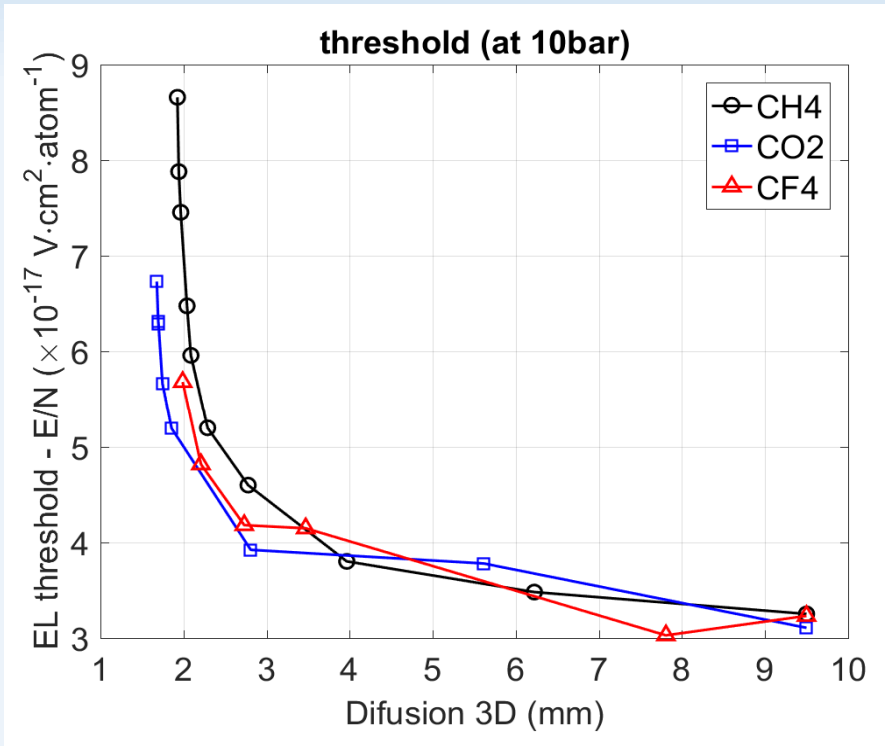
- EL photon collection efficiency (k) = **0.01**
- Relative fluctuations in PMT's gain (σ_G/G) = **0.6**

1. **$Q(10\text{bar}) \cong 2 \times Q(1\text{bar})$** since $\frac{10\text{bar}}{1\text{bar}} \times \frac{5\text{mm gap}}{25\text{mm gap}}$,
if dominated by attachment \rightarrow in **CH4** $Q(1\text{bar}) = Q(10\text{bar})$
2. **$\bar{N}_{EL}(10\text{ bar}) \cong \bar{N}_{EL}(1\text{ bar}) \times P_{scint}(10\text{bar})/P_{scint}(1\text{bar})$**
from simulations (Diego-Azevedo), when reduction in Y is due to e^- cooling (threshold) and quenching, ie. in **CH4** and **CO2**
3. For **CF4** the more optimist scenario is adopted: **Q for max(E/N), max/initial concentrations** adopted, 
and **$\bar{N}_{EL}(10\text{ bar}) \cong \bar{N}_{EL}(1\text{ bar}) - 20\%$** lower at 10bar in ROI ($2 \times$ att)
4. **Transparency to EL photons after 2 m in CO2** \rightarrow
100% in CH4 and CF4

data from D.
González-Díaz et al



The compromise N_{EL} vs D_{3D} – CO_2 , CH_4 and CF_4



Preliminary results: CO₂ and CH₄

$$P(\text{torr})/N \cong 3.034 \times 10^{-17}$$

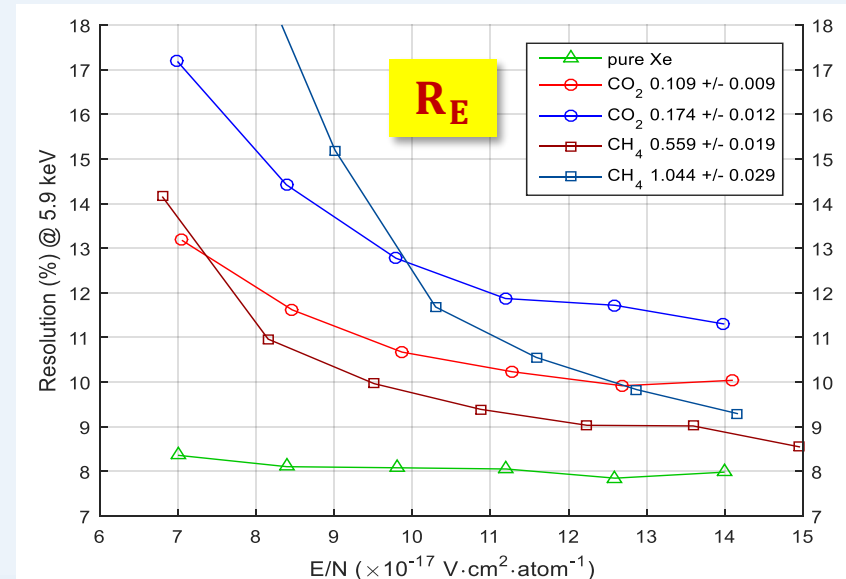
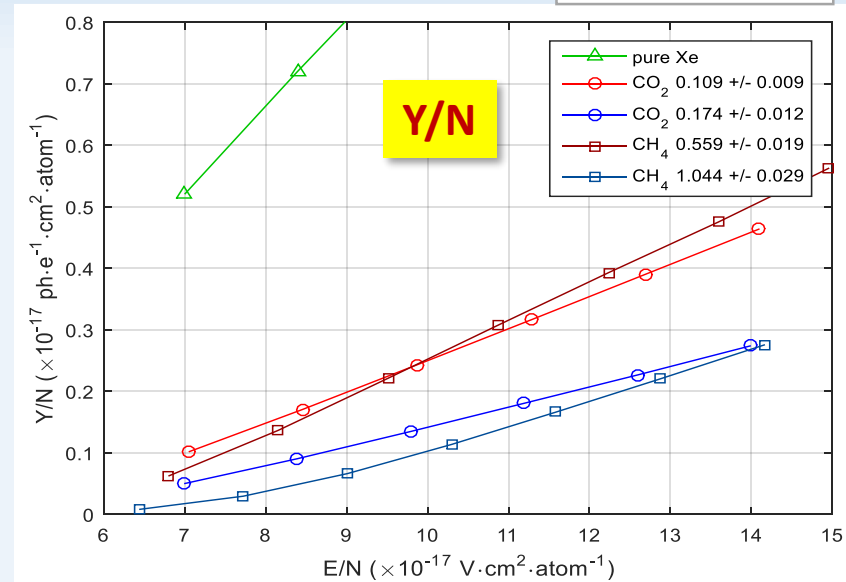
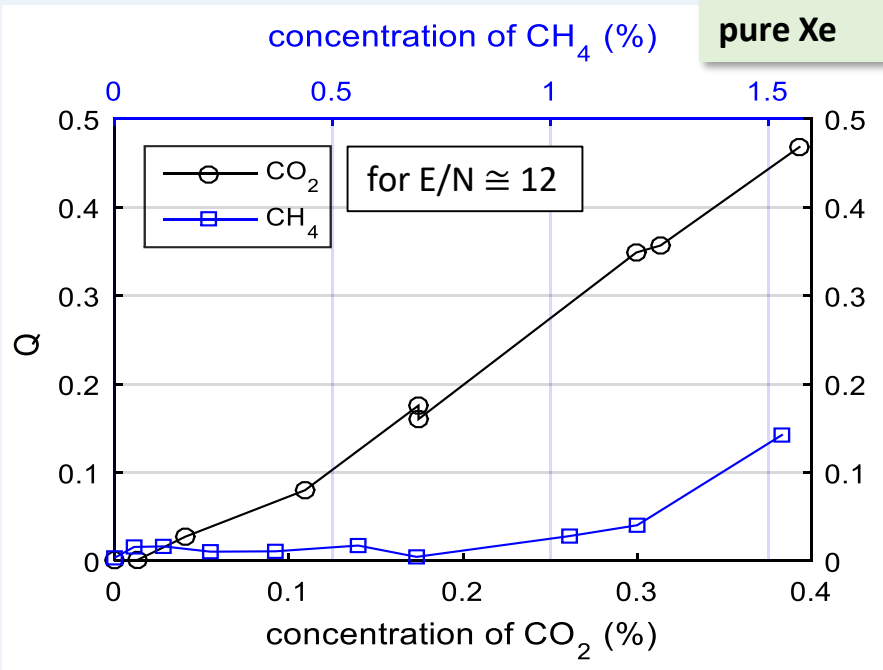
❖ Which mixture is best for NEXT?

$D_L @ D_T$ (mm/ \sqrt{m}) CO₂ CH₄

➔ ~ 3 (28%) @ 2.8 (77%) ~0.11 % ~0.55 %
 ~2.2 (47%) @ ~2.6 (78%) ~0.17 % ~1.04 %

❖ Subtracting Fano and PMT contributions (preliminary)

using estimated F and k in pure Xe

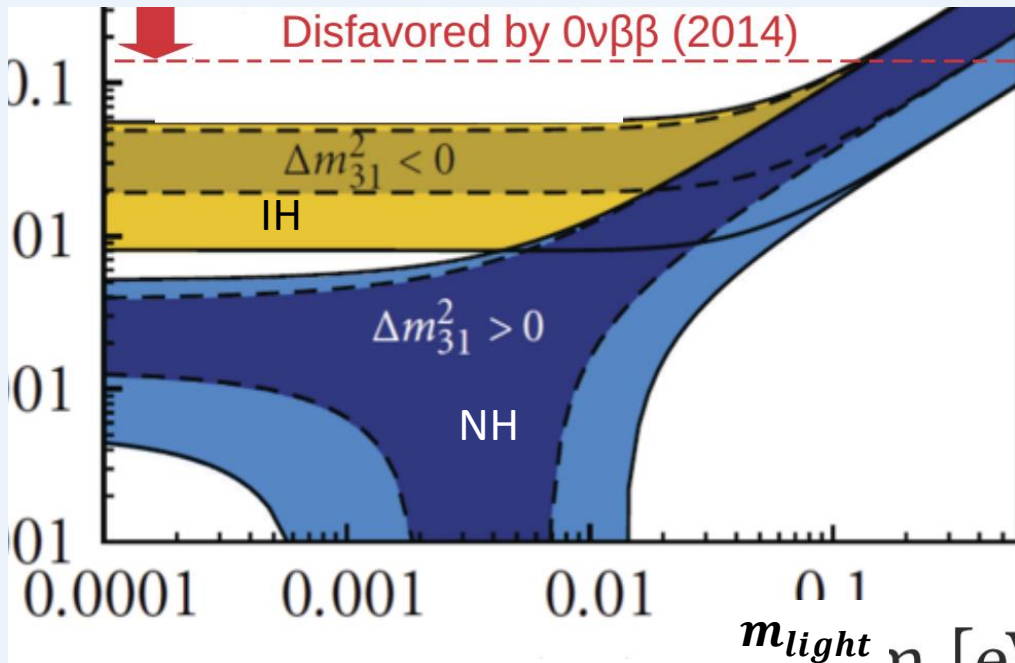


Neutrino mass and $\beta\beta 0\nu$ rate

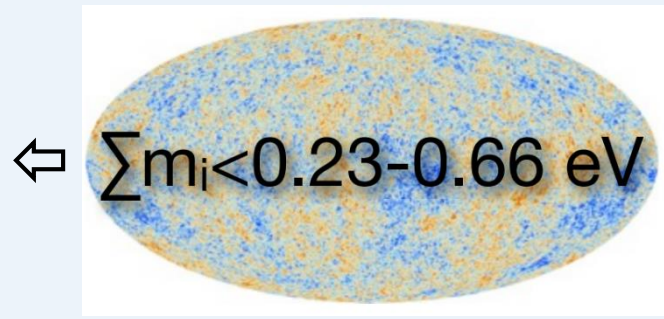


$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu} |M^{0\nu}|^2 m_{\beta\beta}^2 \quad \& \quad m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right|$$

High source of uncertainty \leftarrow Nuclear Matrix of Elements (NME)



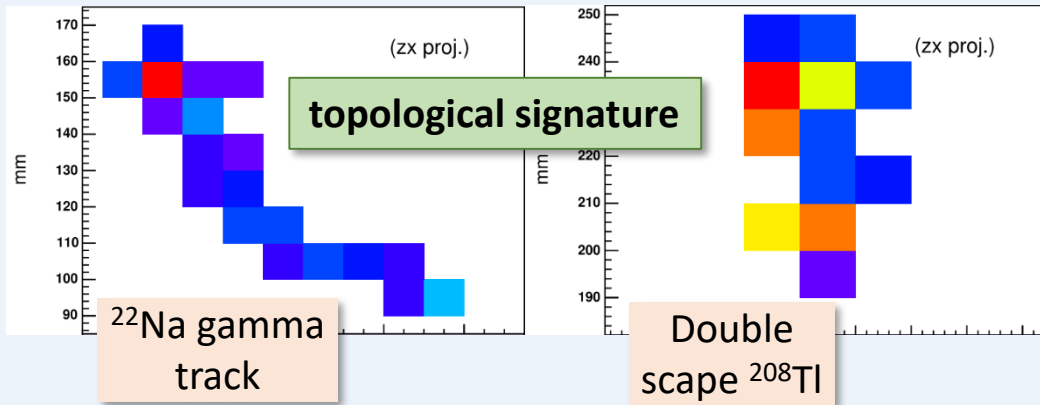
\Downarrow experiments combined results : $< 130-310$ meV (different systematic error)



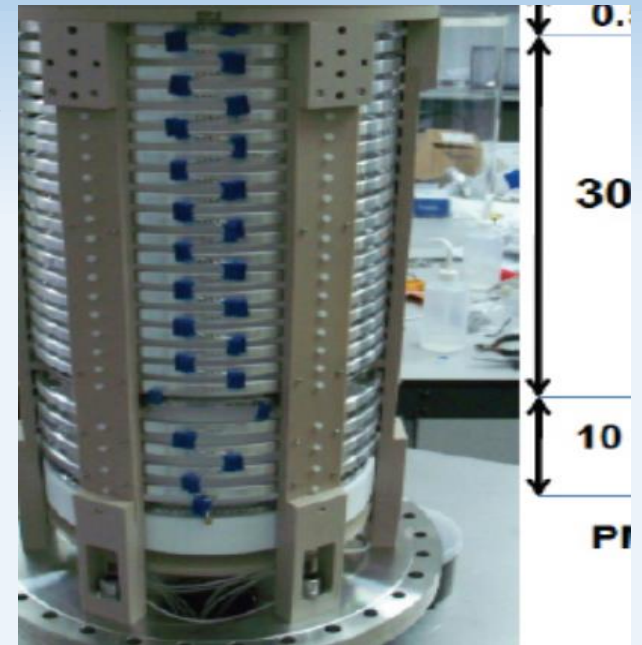
NEXT – prototypes

NEXT-DEMO ~1.5 kg @ 10 bar

➤ Demonstrate NEXT technology

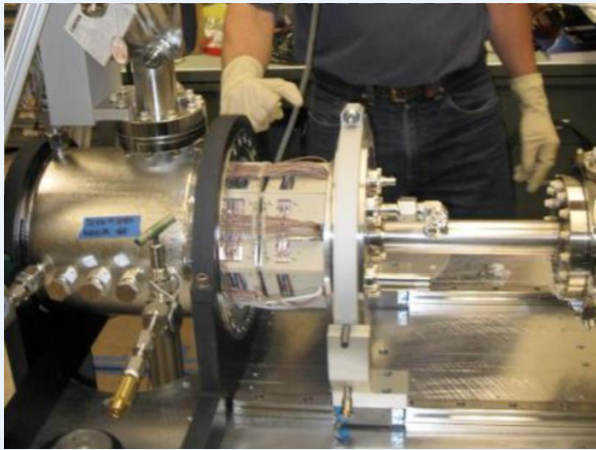


$R_E \sim 0.7\% \rightarrow$
at $Q_{\beta\beta}$



NEXT-DBDM ~1 kg @ 10 – 15 bar

➤ Study R_E in HPXe



$\leftarrow R_E \sim 0.5\%$
at $Q_{\beta\beta}$

NEXT phase I – NEW ~10 kg of ^{136}Xe

- NEXT-100 at scale 1:2 @ 20% of photosensors
- 1^o radiopure underground detector

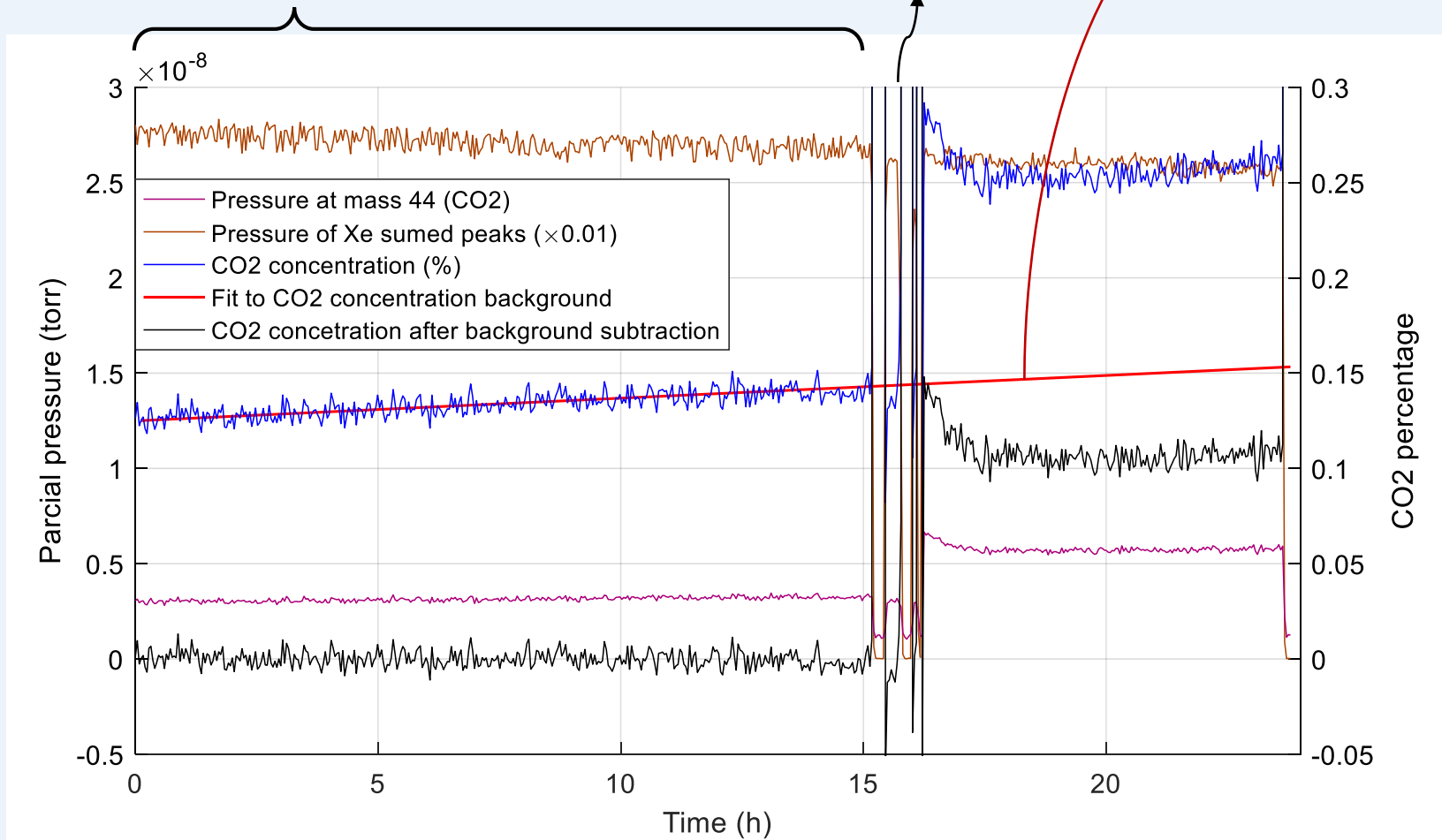


RGA's Calibration

Background measurement –
CO2 reading after V2 is filled
with pure Xe

CO2 added here,
then CO2 + Xe
are liquefied

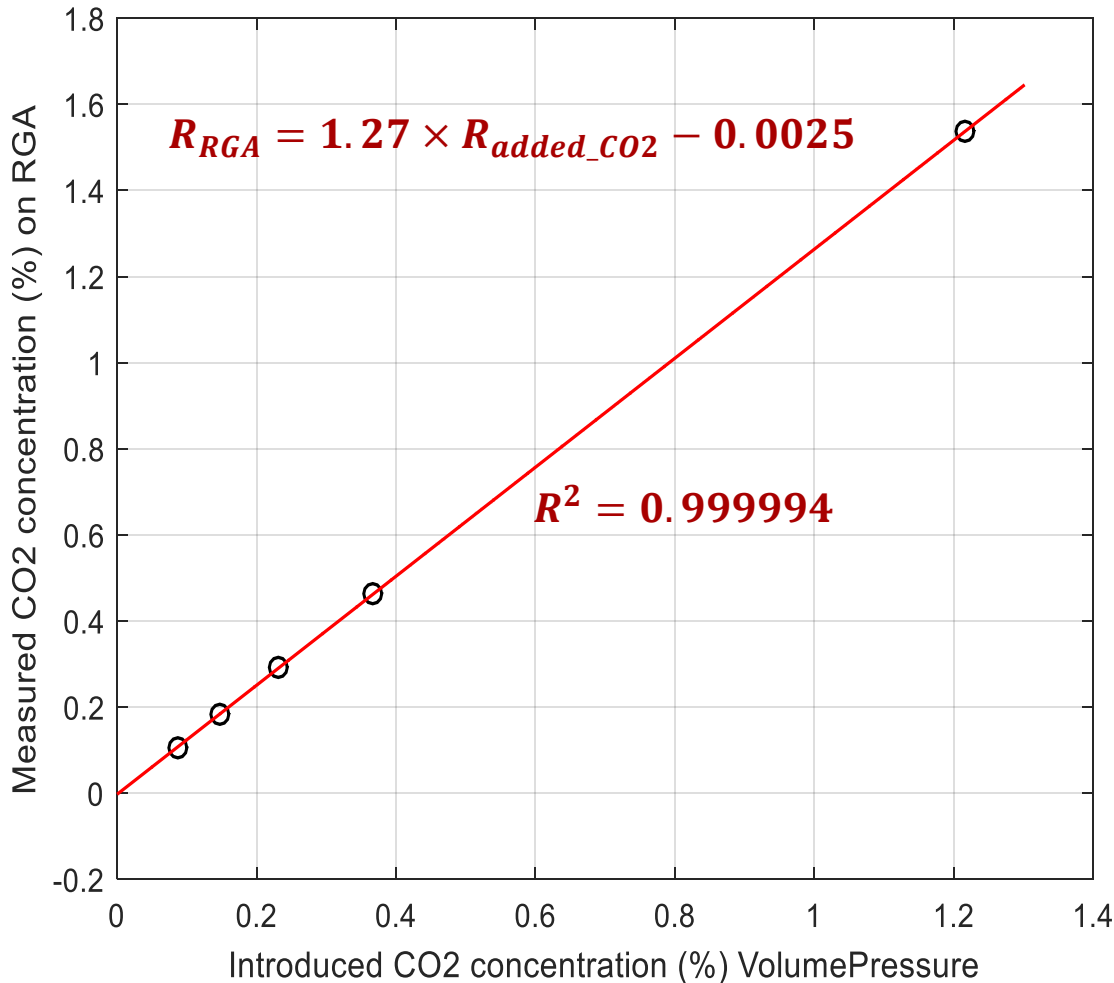
For CO2 background
estimation after
mixing



↑ RGA's example spectrum of a calibration point (0.088 %)

RGA's Calibration

➤ Calibration line:



← As expected RGA's response is **linear**, at least within ROI

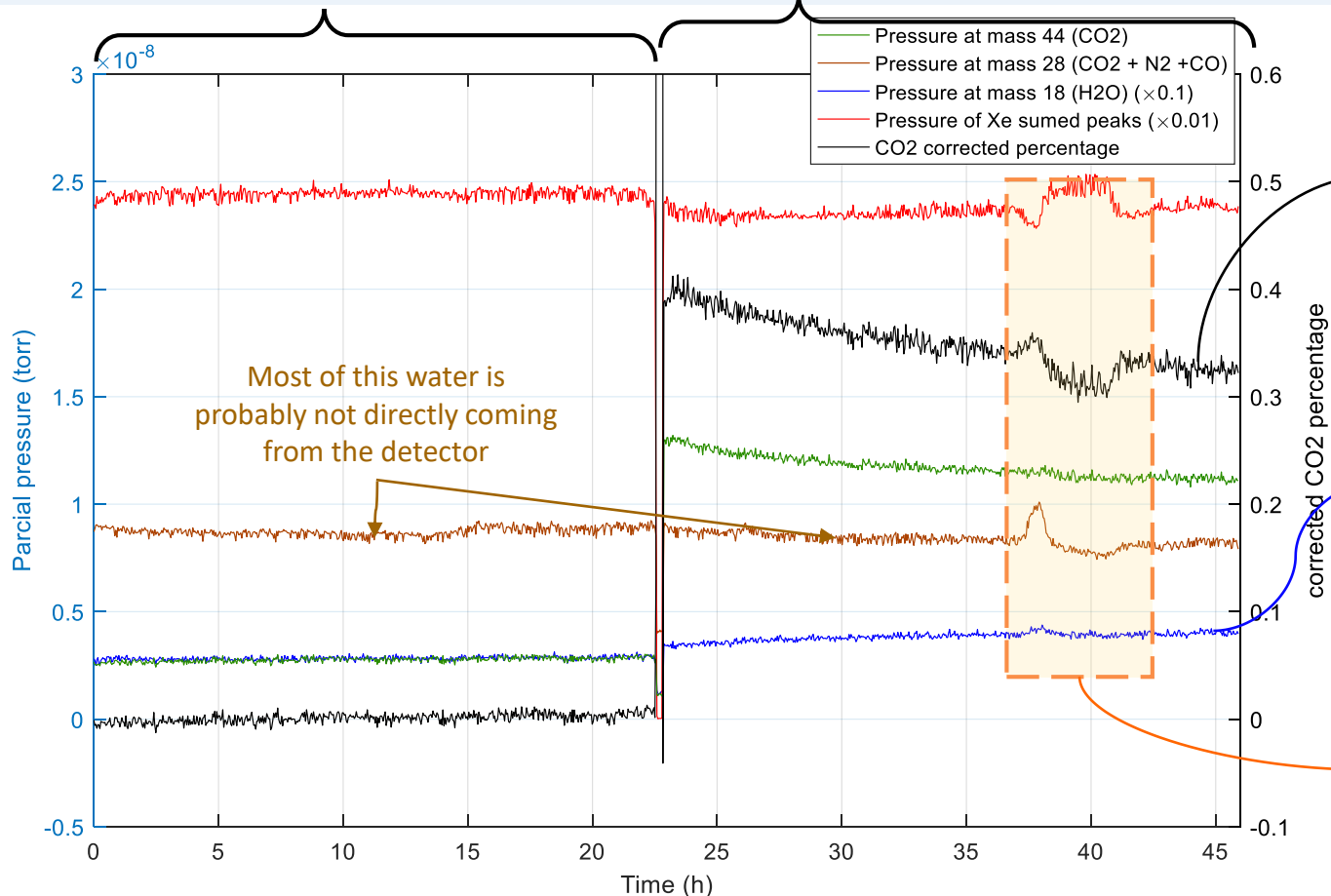
- Several methods were used to extrapolate the background of CO2 after mixing, this one showed the best R^2
- This background estimation method will be also used in main mixtures

Results – RGA's example spectrum $\rightarrow CO_2/(Xe + CO_2) = 0.44\%$

1) Pure Xe with getters at 250° C is recorded for background quantification at the beginning of each mixture $\rightarrow CO_2/(Xe + CO_2) \approx 0.1\%$ changing at each mixture

2) Getters are set to 80° C one hour before CO₂ is introduced \rightarrow for a more efficient mixing, Xe + CO₂ are liquefied after adding the CO₂.

➤ 0.44 % introduced (estimated from volume-pressure calculation) – 0,33 % @ after 21h (estimated from RGA data)



CO₂ percentage in relation to Xe + CO₂ \rightarrow corrected using RGA's calibration line

- EL measure was done in the last hour (44h – 45h)

Partial pressure at mass 28 rises in time after adding CO₂ \rightarrow 28 is the main peak of N₂ and CO, and a secondary peak of CO₂ ($\sim 5\%$ \rightarrow obtained in calibration)

A typical non-explained perturbation \rightarrow usually, these perturbations are stronger in H₂O and Xe, and often periodic (T=24h)

Results – CO production

➤ **Pressure at mass 28 rises after adding CO2** → **Mass 28 is a combination of:**

If the growth at 28 was just coming from CO2, it would not be continually rising
Is this due to CO production?

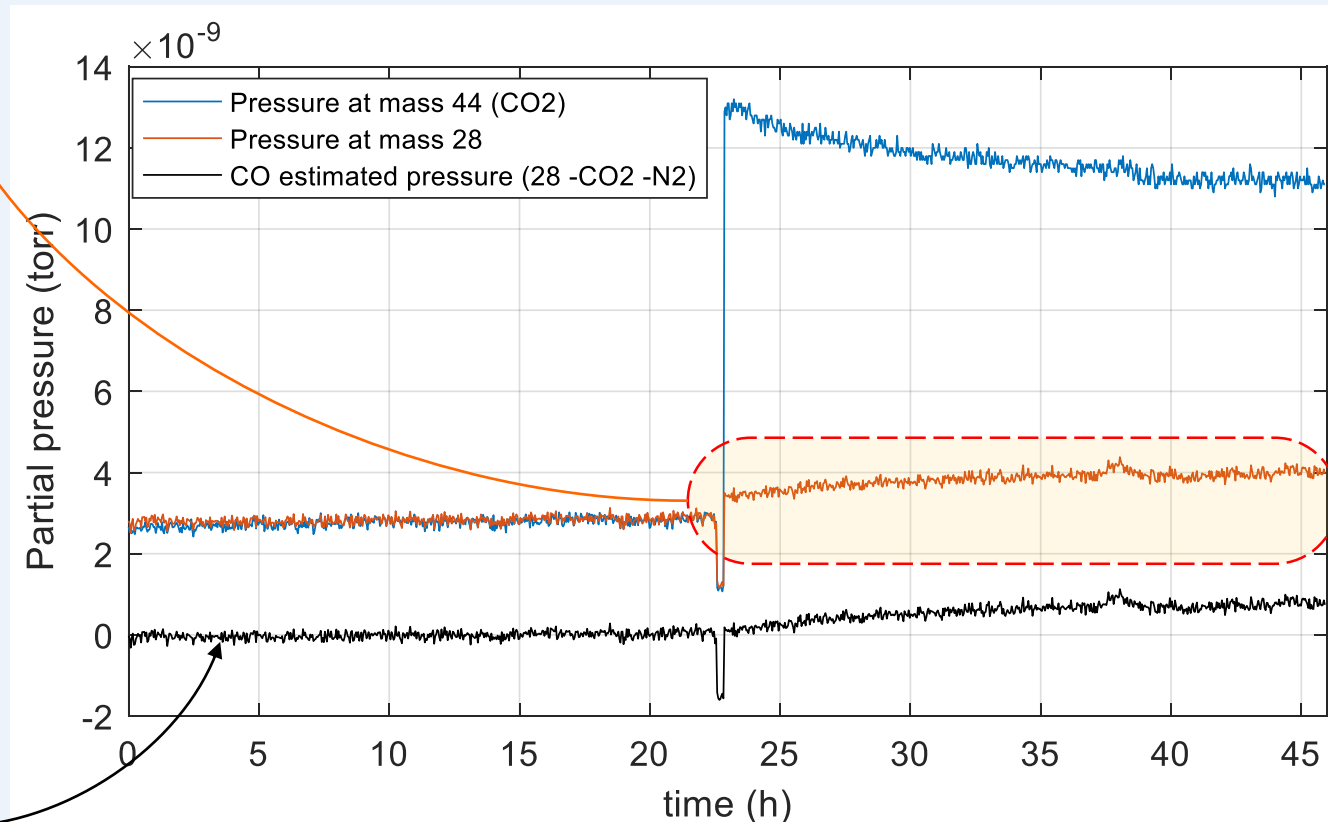
- Nitrogen (major fragmentation peak)
- CO (major fragmentation peak)
- CO2 (secondary fragmentation peak)

Assuming:

- N2 keeps constant after adding CO2
- Experimental cracking pattern of CO2 obtained during calibration
- CO is zero before CO2

We can:

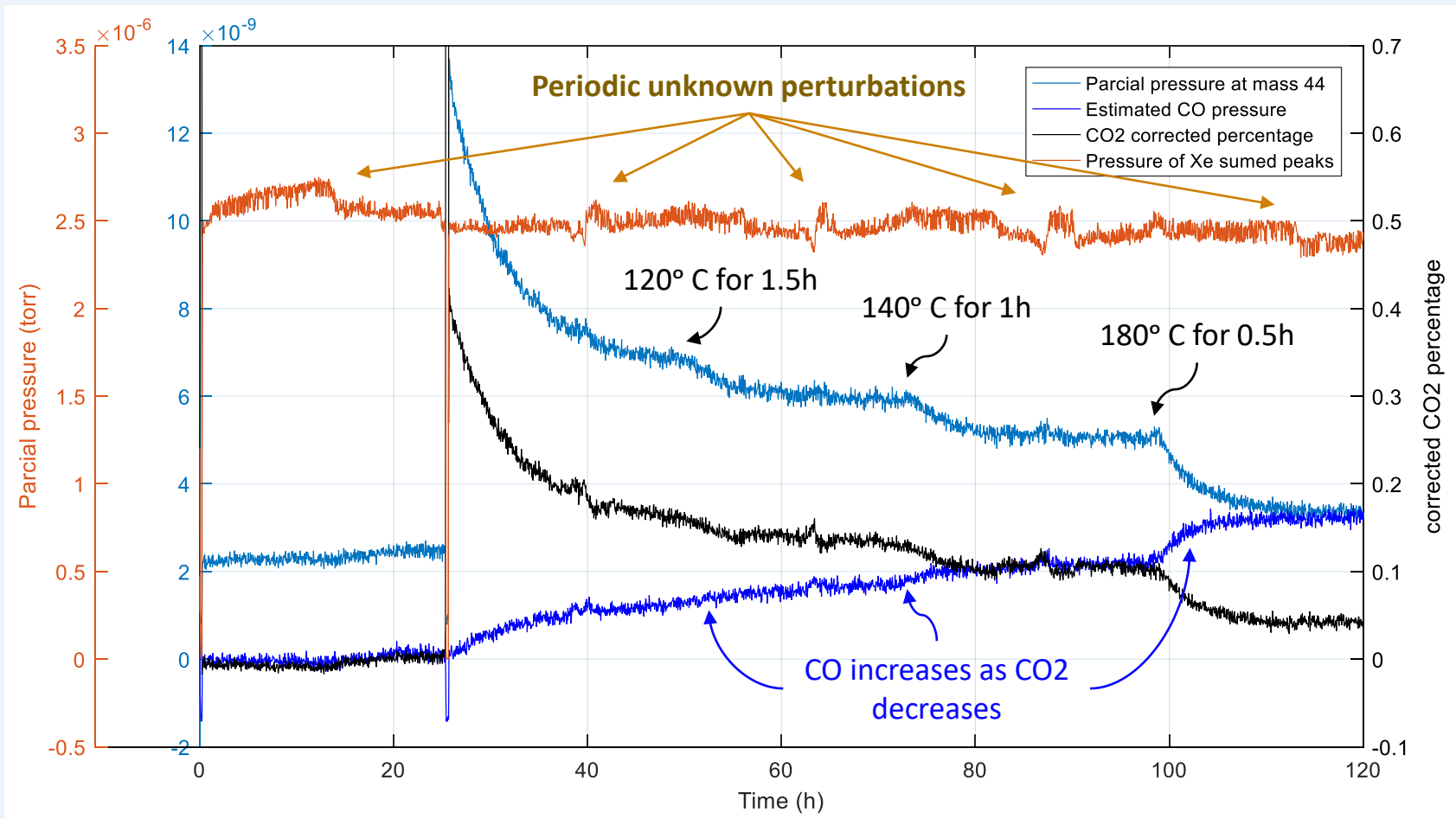
Estimate CO pressure at mass 28 by subtracting CO2 and N2 contributions



Results – Getters' temperature & CO

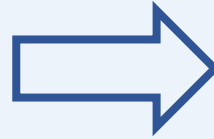
- **Two different mixtures became stable at 0.18 %** → in the last one we **raised up** the temperature of getters in order to absorb CO₂ → **however CO have raised even more as the getters' temperature was increased.**

Temperatures were raised up just for some time, then they are cooled down to 80° C again

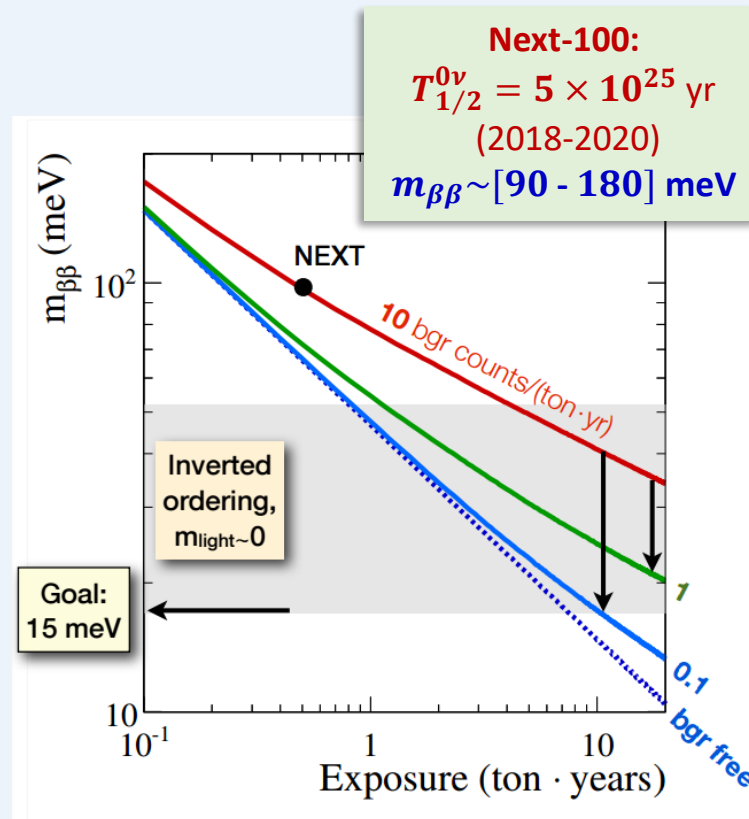


NEXT – towards the inverted hierarchy

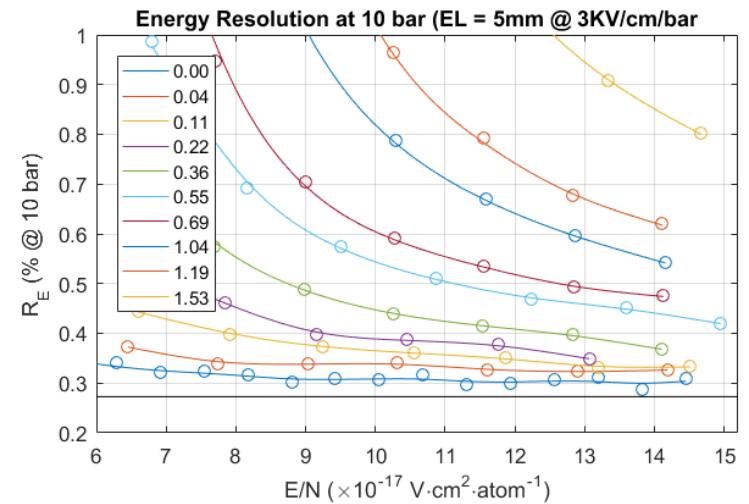
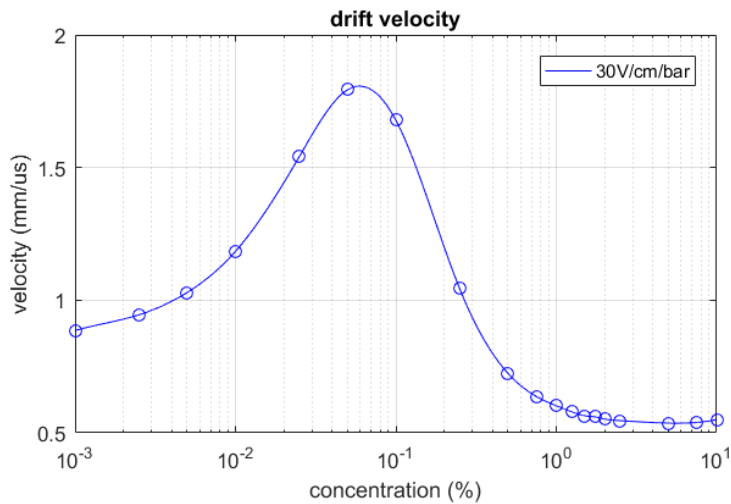
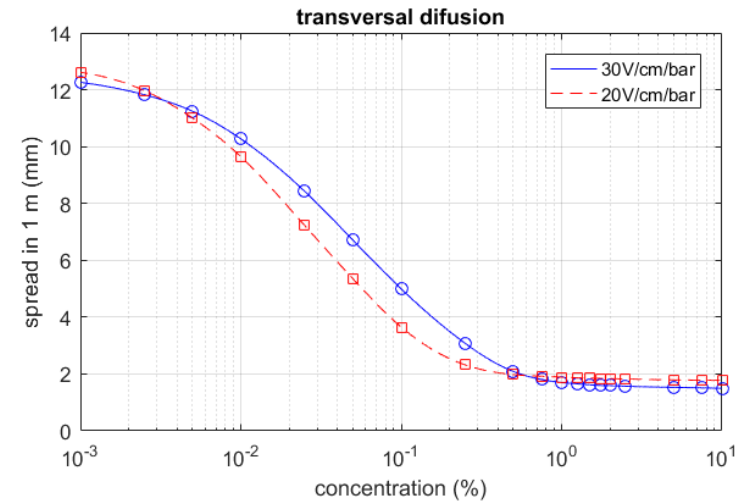
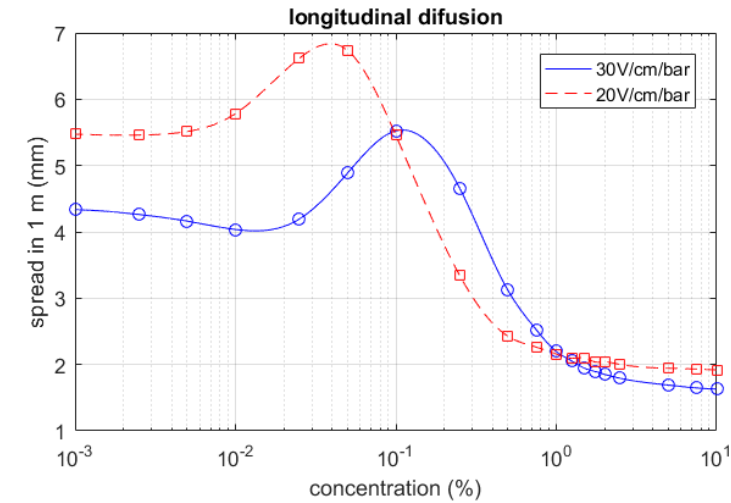
$\beta\beta 0\nu$ **unlikely** with current experiments



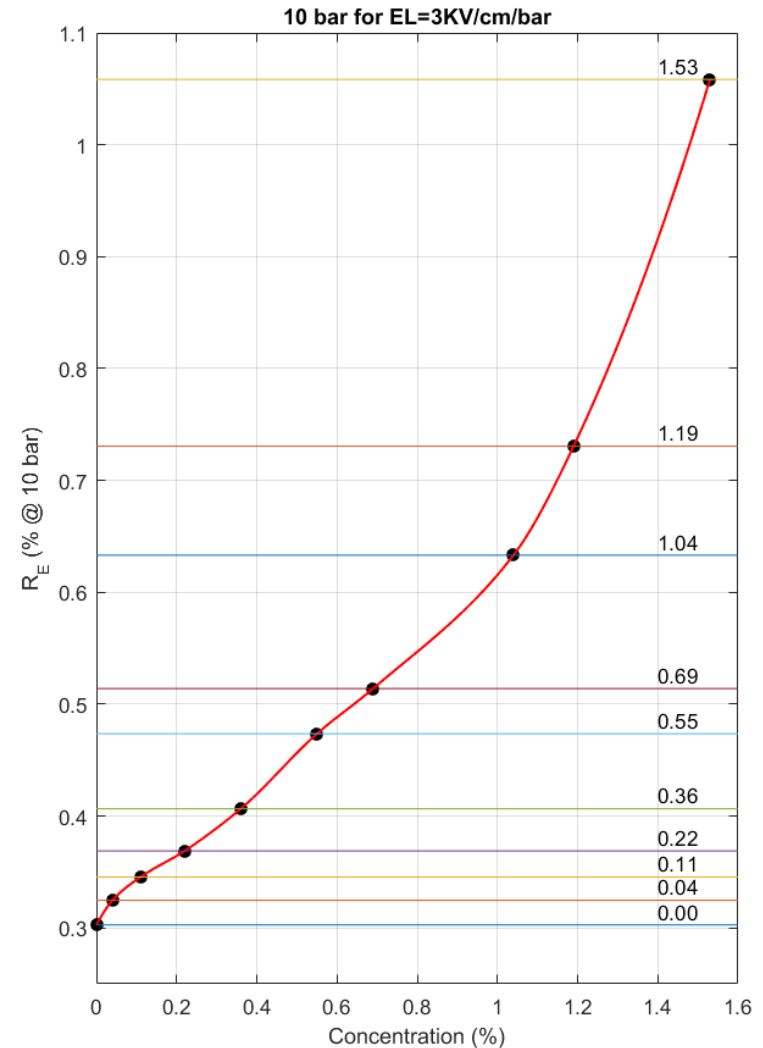
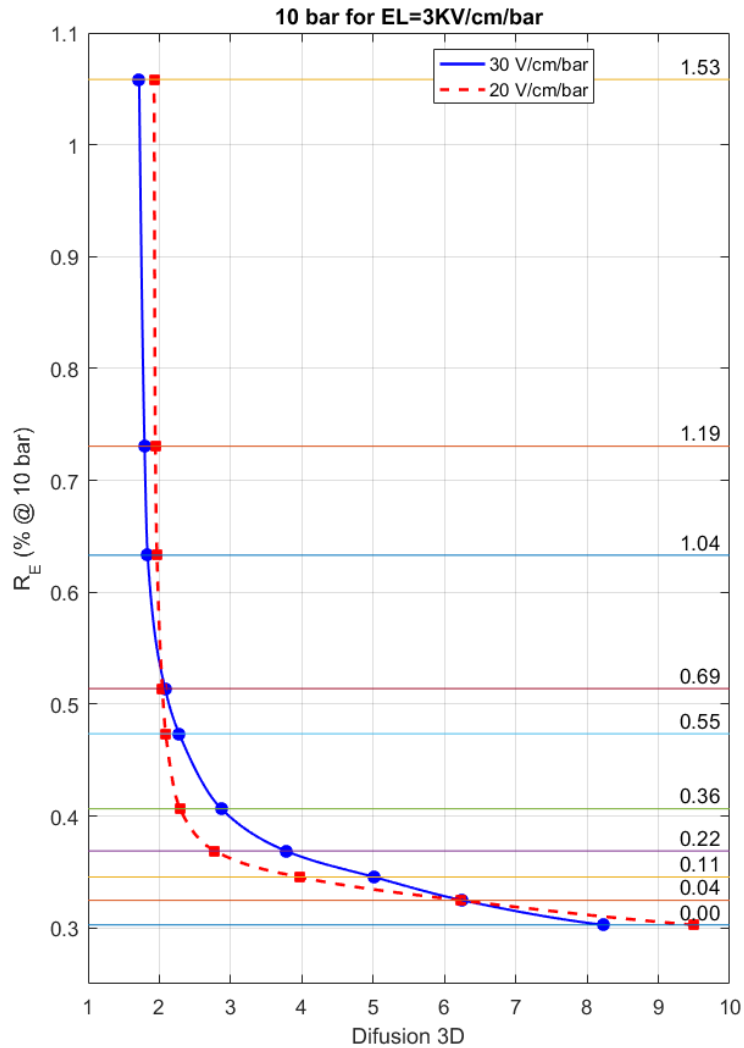
Ton scale + background reduction/rejection



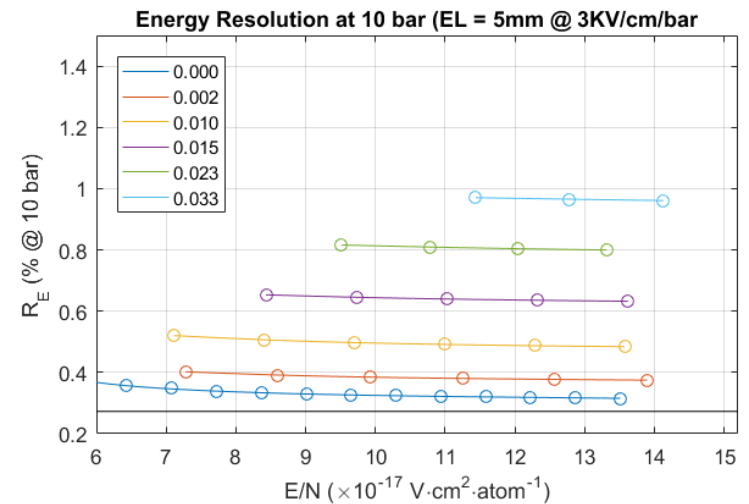
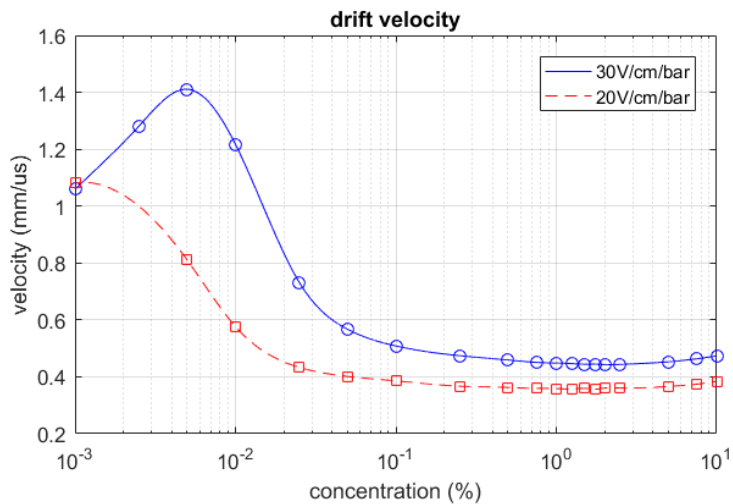
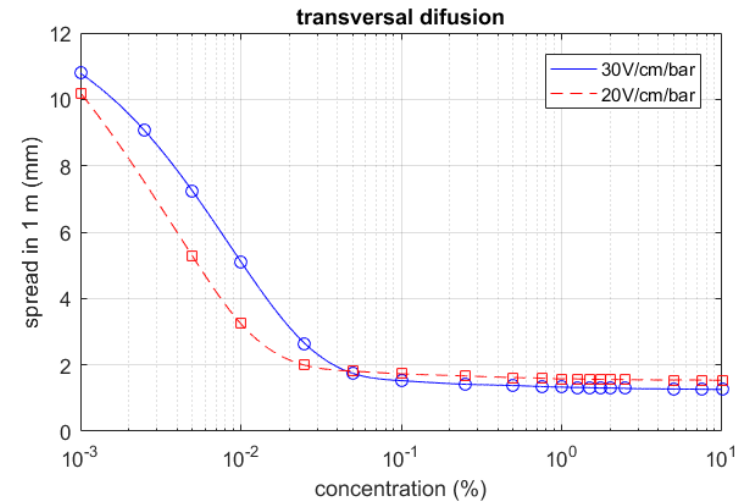
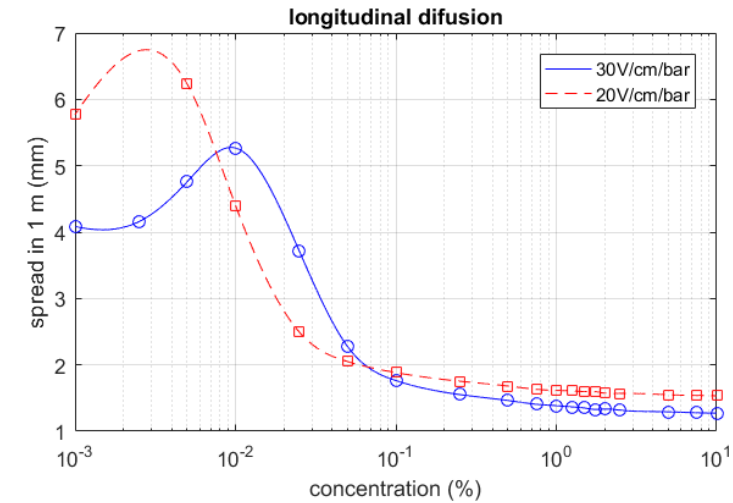
R (3KV), Dt, Dl and v in CH₄



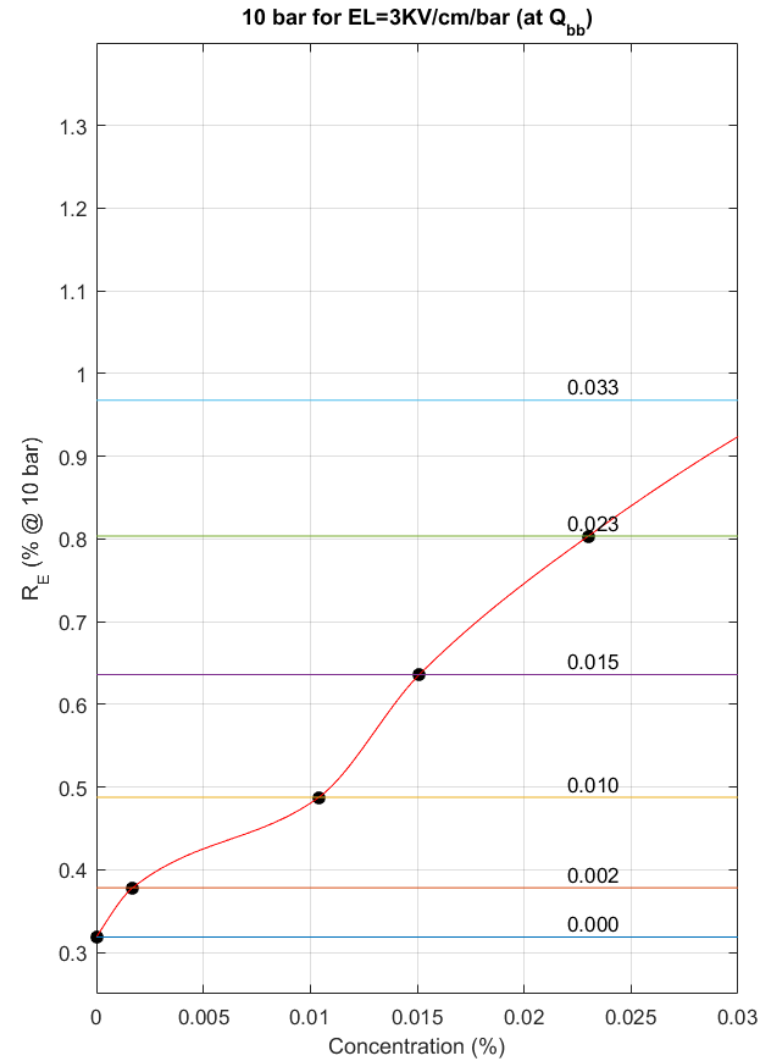
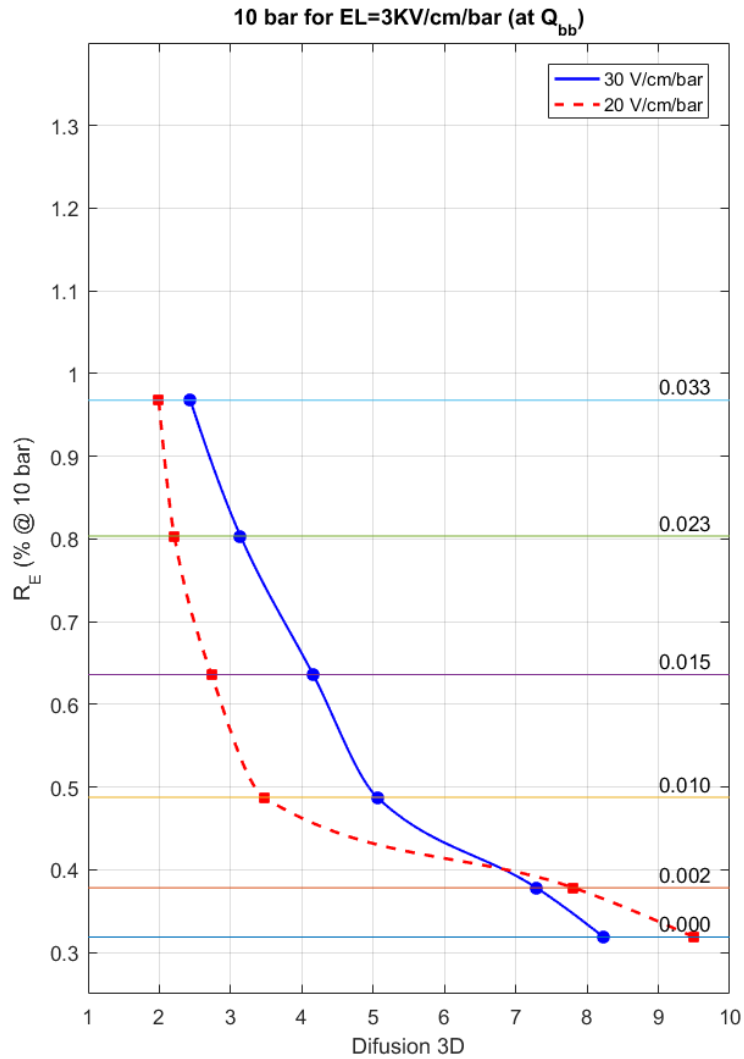
R (3KV) vs D3d and concentration in CH₄



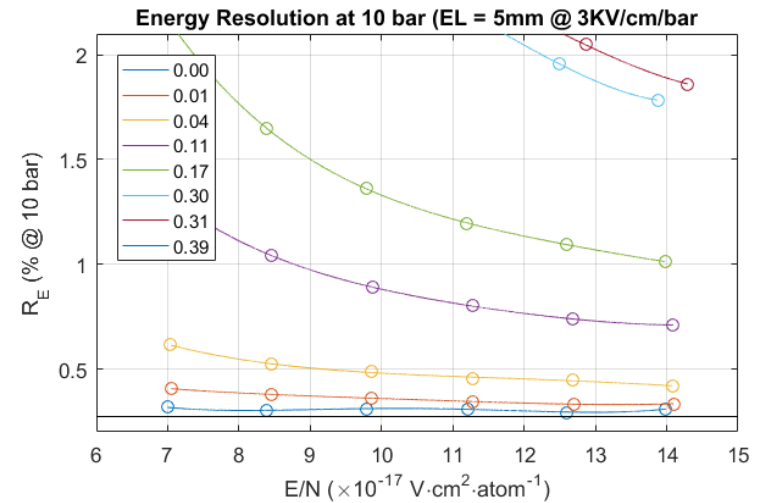
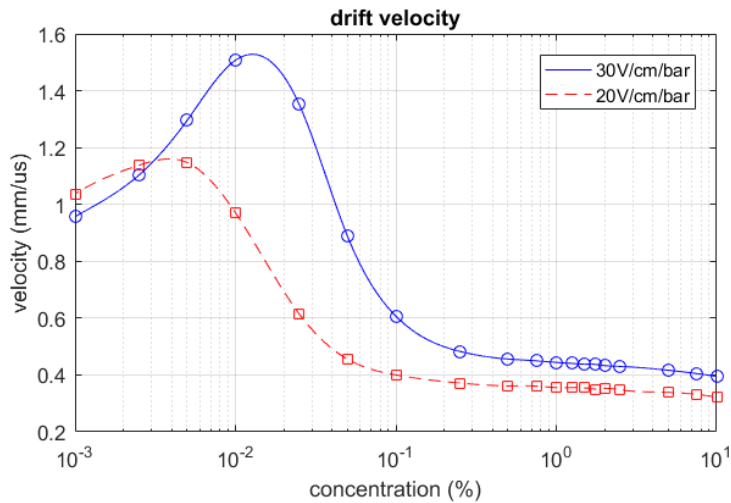
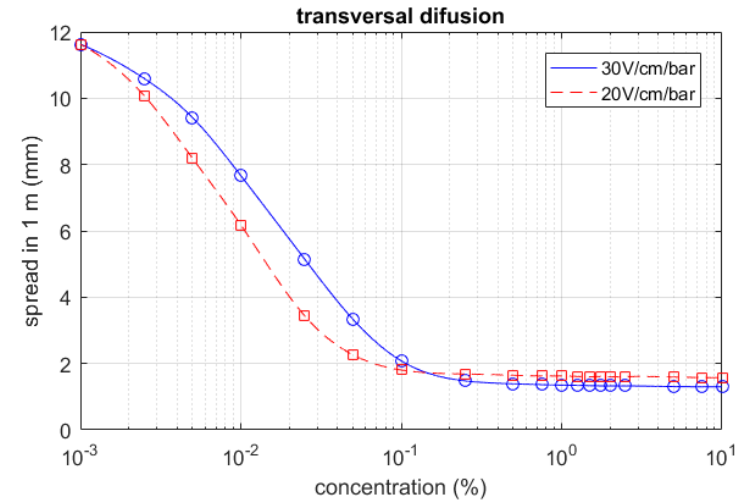
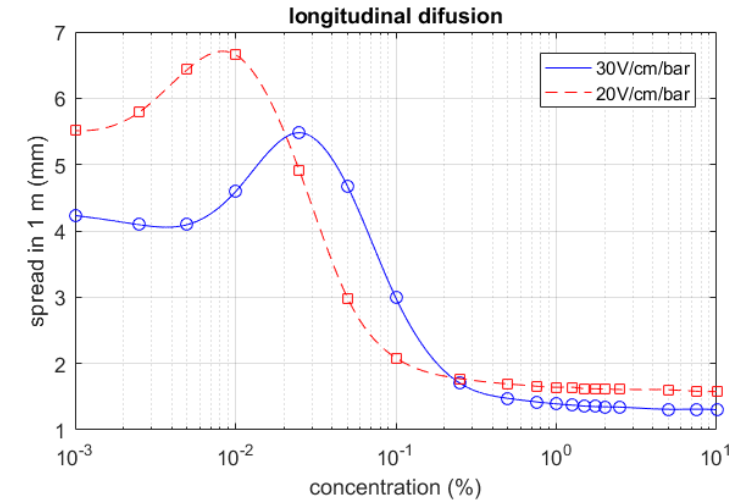
R (3KV), Dt, Dl and v in CF₄



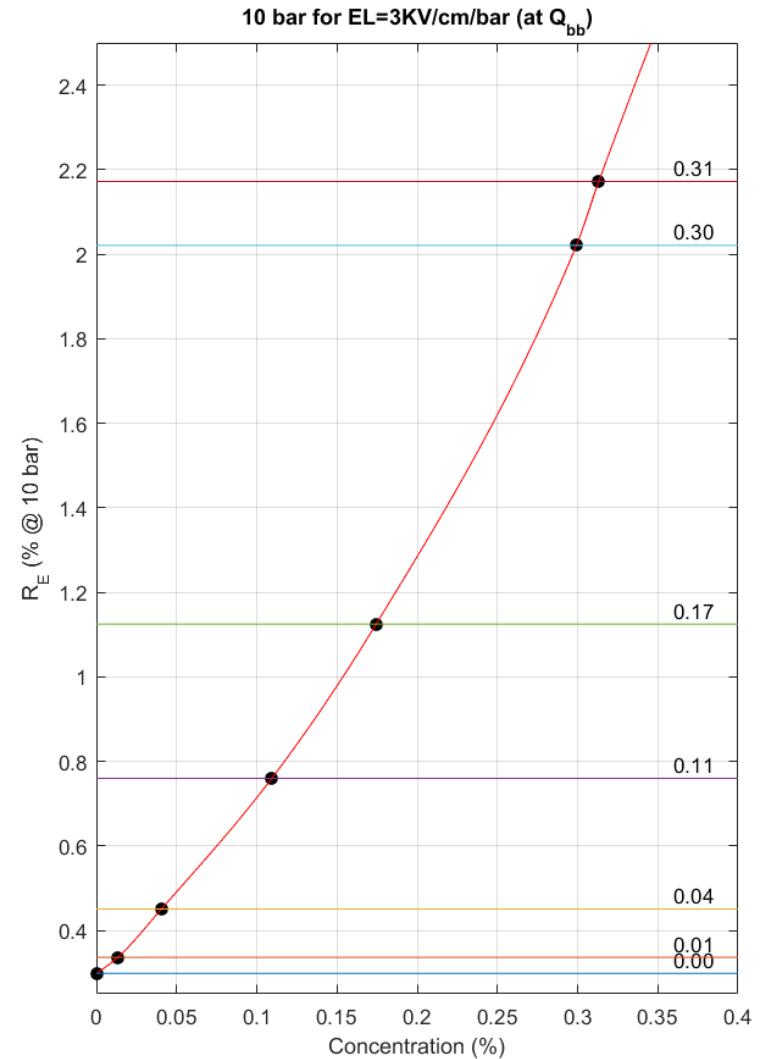
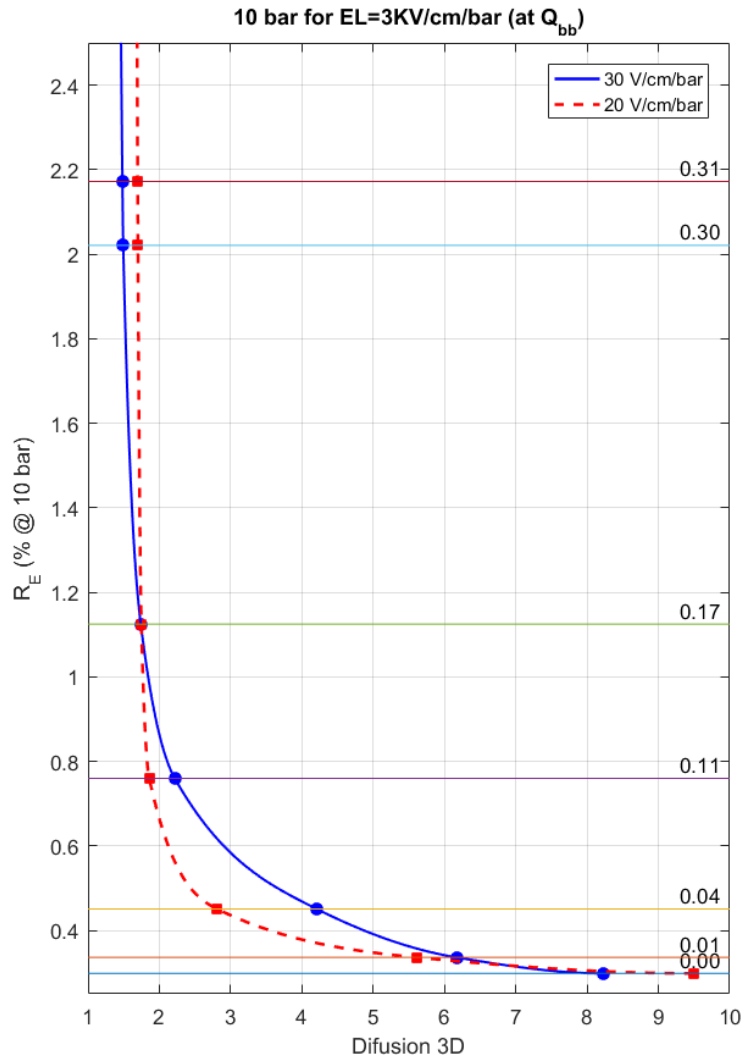
R (3KV), Dt, Dl and v in CH₄



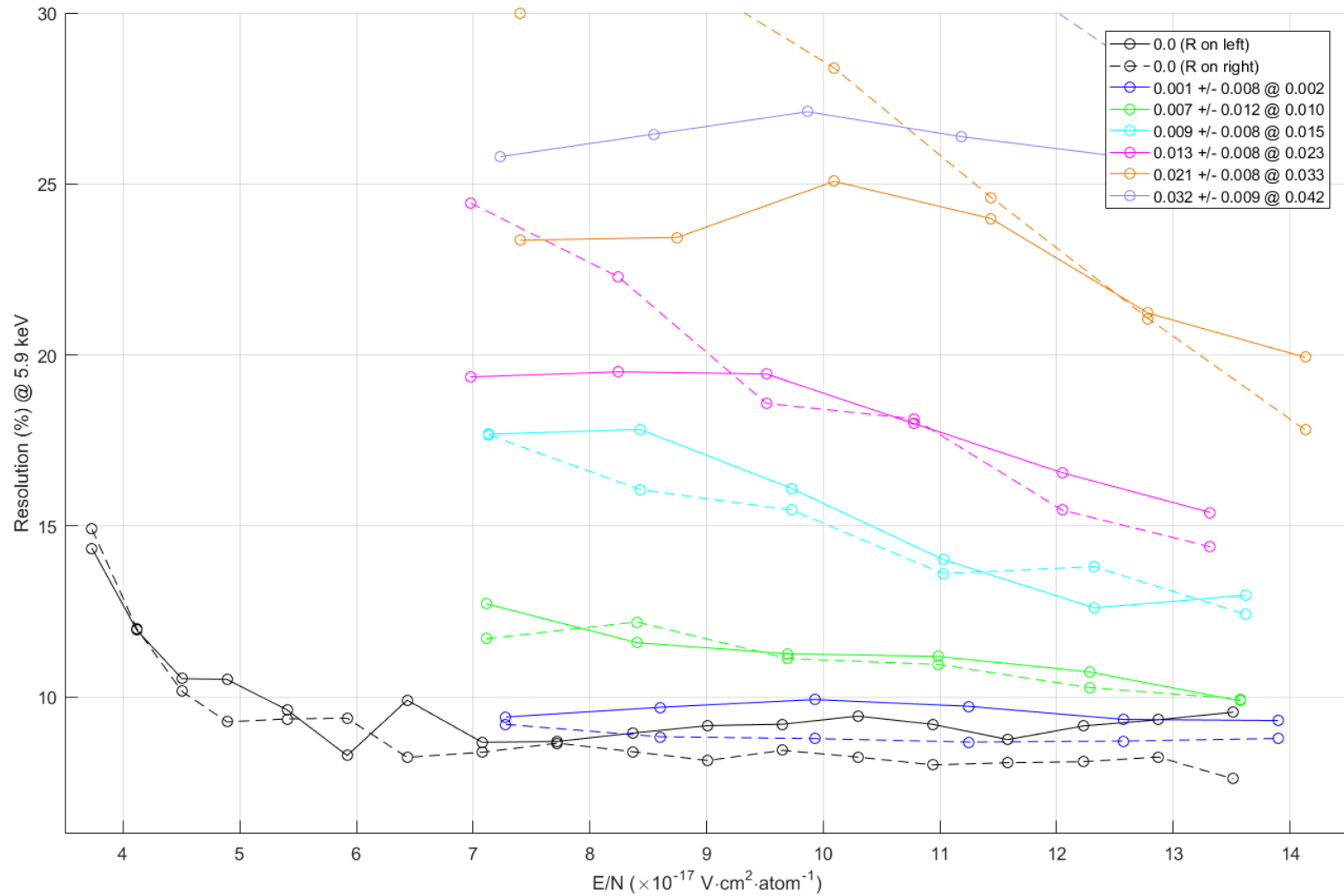
R (3KV), Dt, Dl and v in CO₂



R (3KV), Dt, Dl and v in CO₂



CF₄ right-left real R



R(z=0) without attachment - CF₄

