Xe - M_x mixtures for the NEXT EL TPC

Carlos A.O. Henriques [a], C.D.R. Azevedo, D. Gonzalez-Diaz,
C.M.B. Monteiro, L.M.P. Fernandes, J.J. Gómez-Cadenas,
NEXT Collaboration

[a] henriques@gian.fis.uc.pt

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University of Coimbra

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

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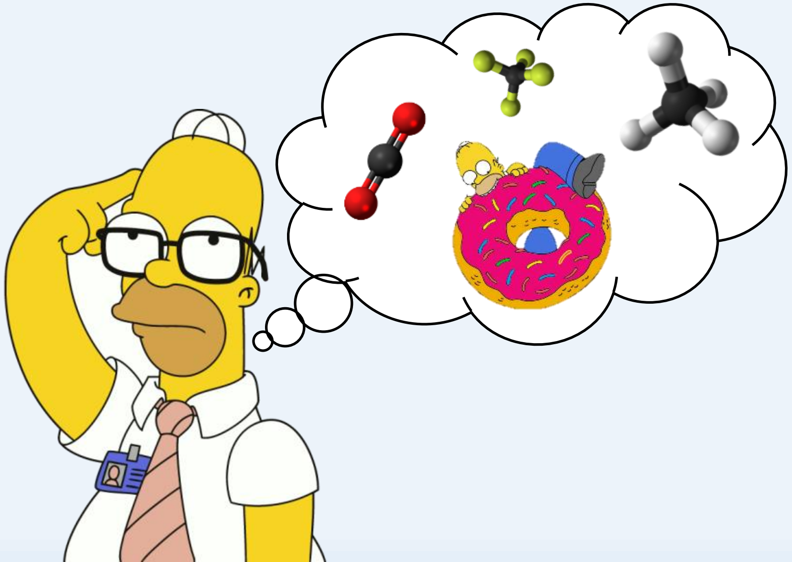
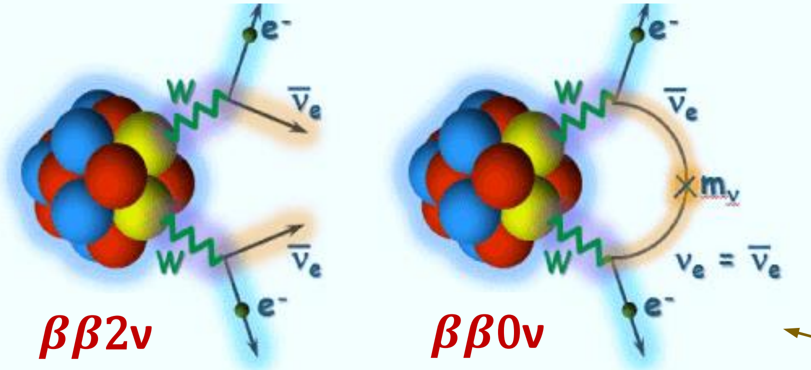


Introduction

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

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

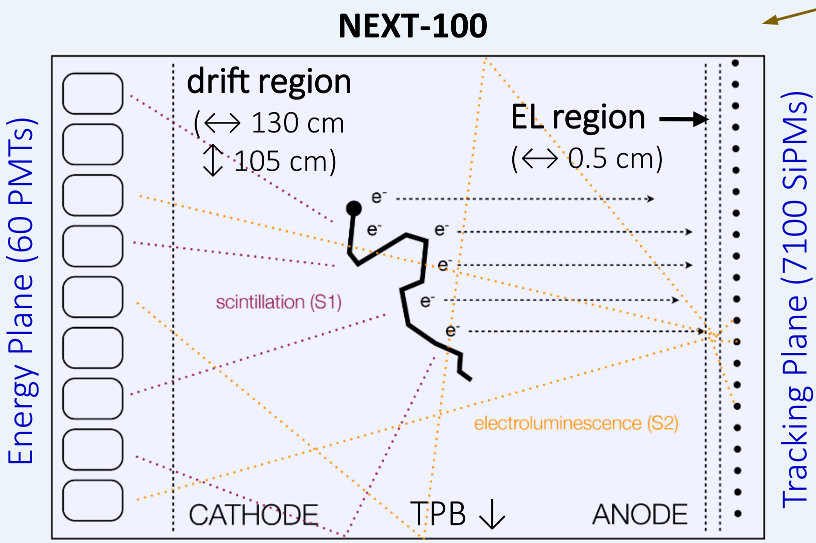
High-pressure Xe (**HPXe**) electroluminescense (**EL**) **TPC** with separated readouts for **calorimetry** and **tracking**

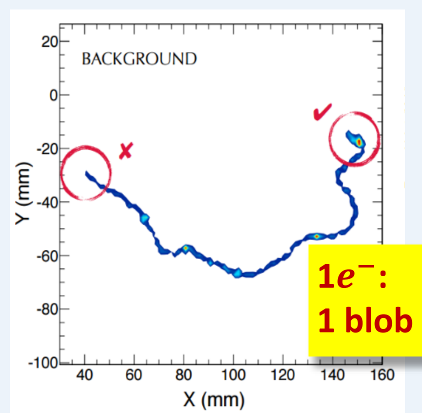
NEXT key features:

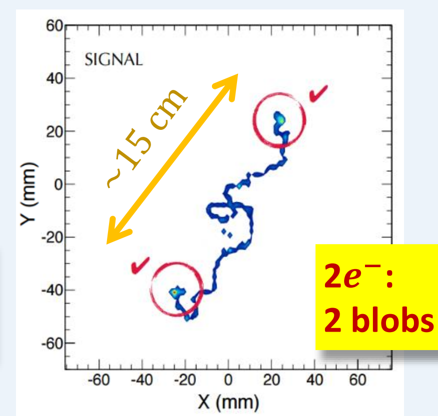
1) **Excellent R_E** → 0.5 – 0.7 % at $Q_{\beta\beta}$ (2.457 MeV)

2) **Scalability** → towards the ton scale

3) **Topological signature** → background rejection





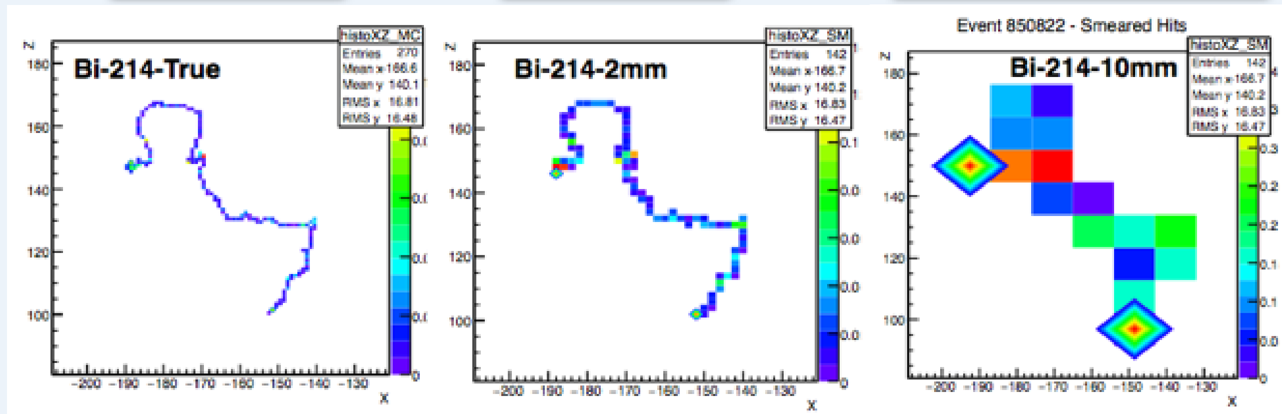


NEXT – improving the spatial resolution

❖ **Improve topological signature…**

1. **Longitudinal resolution:**
   - D_L (Xe) ~ 4.5 mm/m
   - EL gap (5mm) → 1.5 mm
2. **Transversal resolution:**
   - D_T (Xe) ~ 10 mm/m
   - SiPMs pitch + barycenter algorithm → 1 mm

background event → **2mm - still background** → **e^- after 1m drift in Xe – 10mm → false $\beta\beta$**



❖ **reducing electron diffusion:**

Xe + molecular

↓

Electron cooling

↓

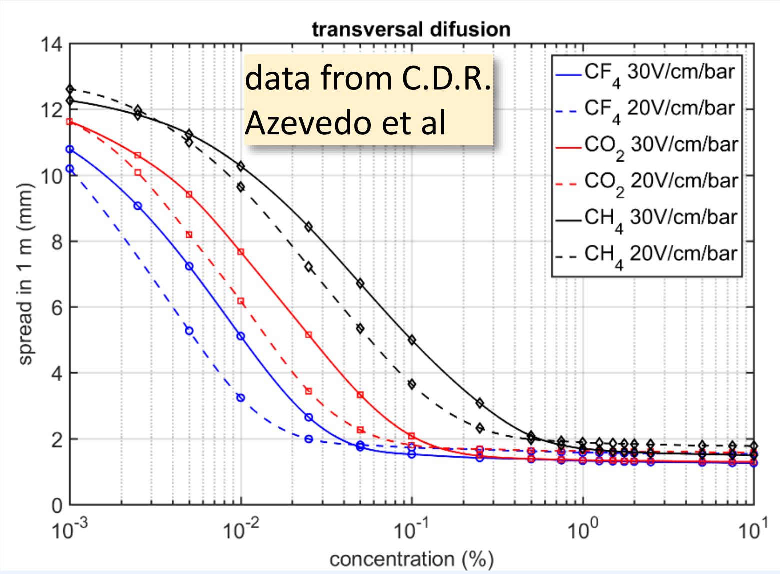
Reduces e^- diffusion

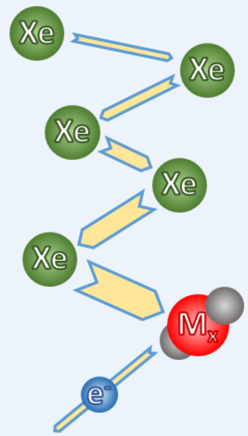
It also degrades:

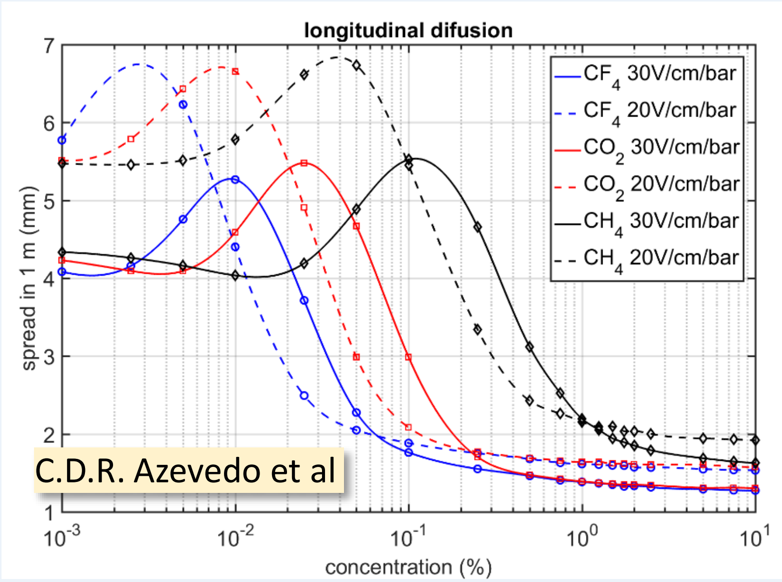
- **S1 and S2 yield**
- **Energy resolution**

Additive & concentration

1) Xe – M_x reduces e^- diffusion: e^- cooled by vibrational excitation modes of M_x







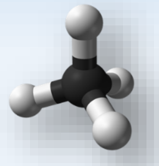
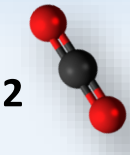
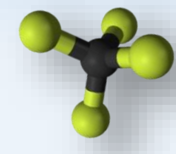
2) Xe – M_x degrades S1, S2 and R_E:

- ***e^-* coolling** → 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**

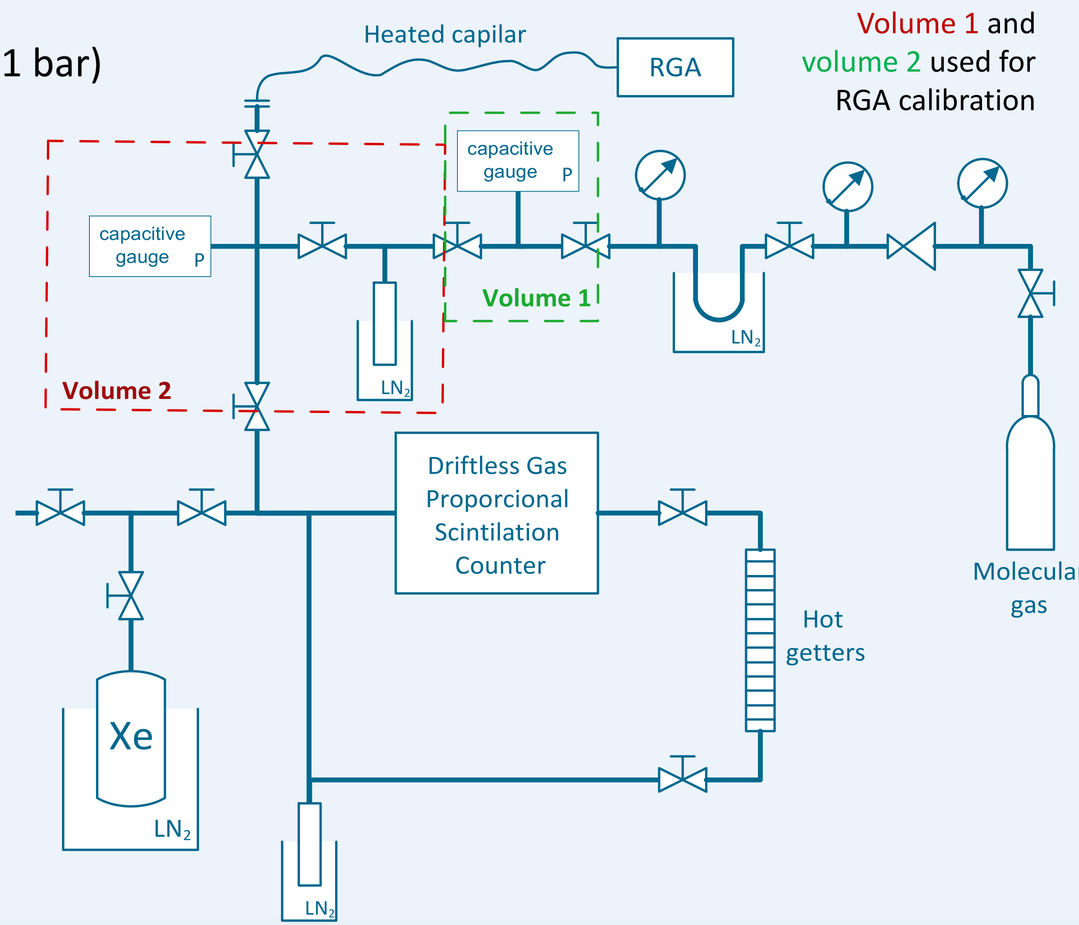
Experimental setup

- **Xe – CH_4**  **Xe – CO_2**  **Xe – CF_4** 

- **Driftless Gas Scintillation Proportional Counter (GSPC) with $\mathbf{EL_{gap} = 25mm}$**
  - Eletroluminescence 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 – CH_4 and CF_4 at 120° C
  - Xe – CO_2 at 80° C



Energy resolution $(R_E = {}^{FWHM}/_{centroid})$

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

σ in primary charge production
N_e → primary e^-

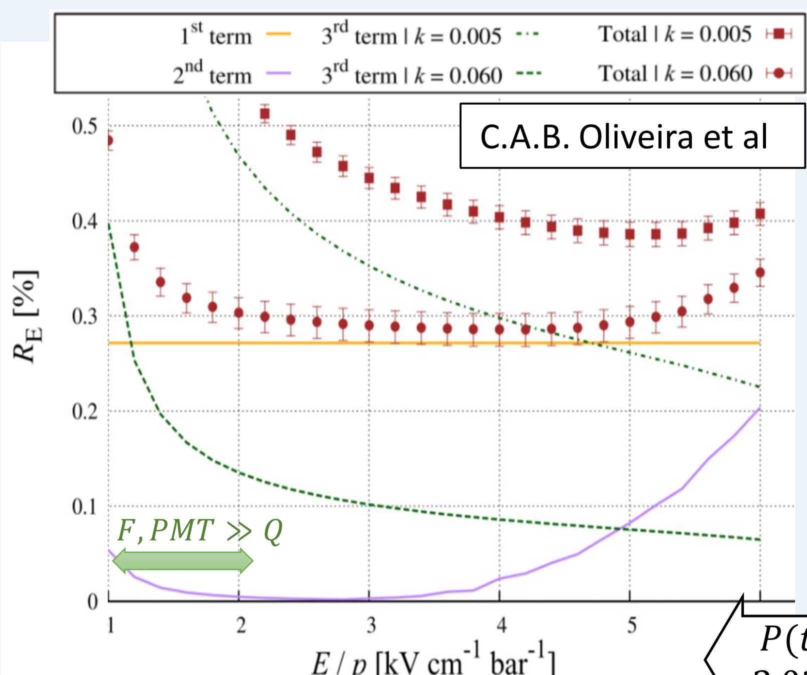
σ in EL photon production

σ in PMT signal
k → light collection efficiency
σ_G → fluctuations in PMT gain
N_{EL} → EL emitted photons

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

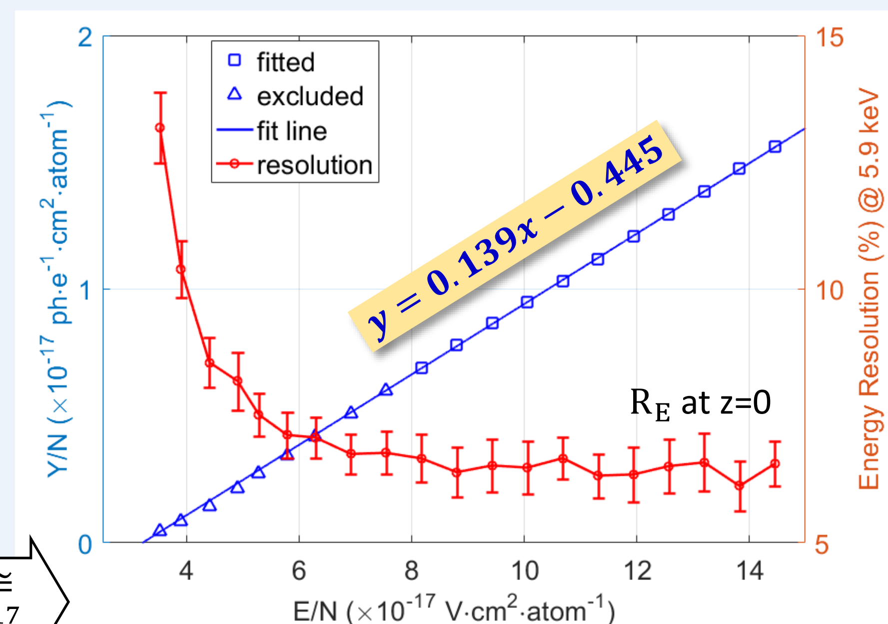
for E/N: $F, PMT \gg Q$

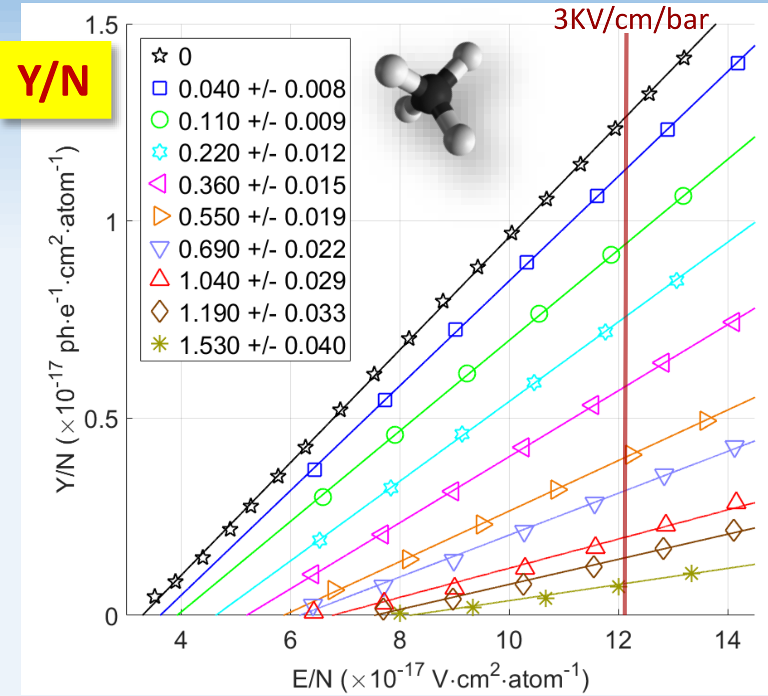
F and **PMT** contribution are determined using data from pure Xe



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

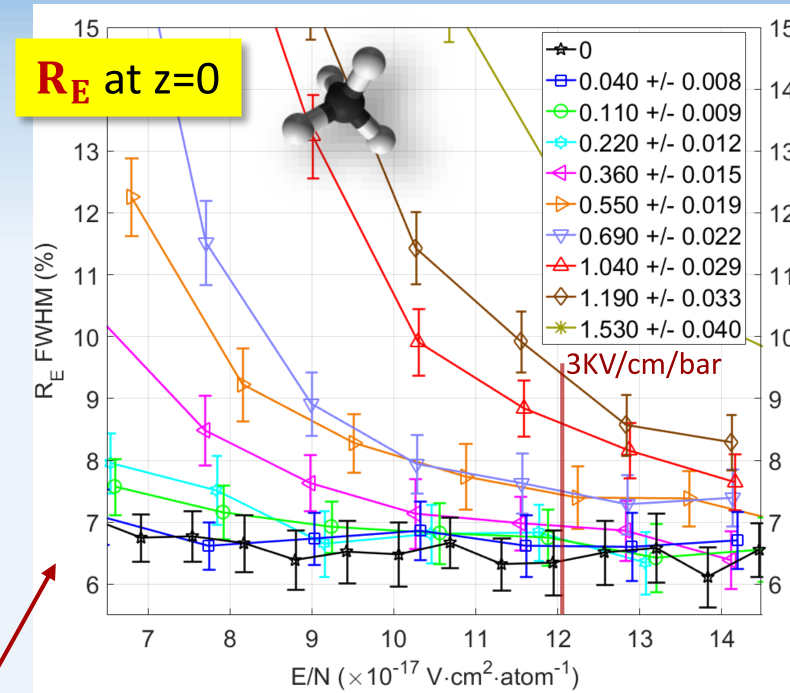
EL Yield (Y) & R_E in a driftless GSPC (pure Xe)



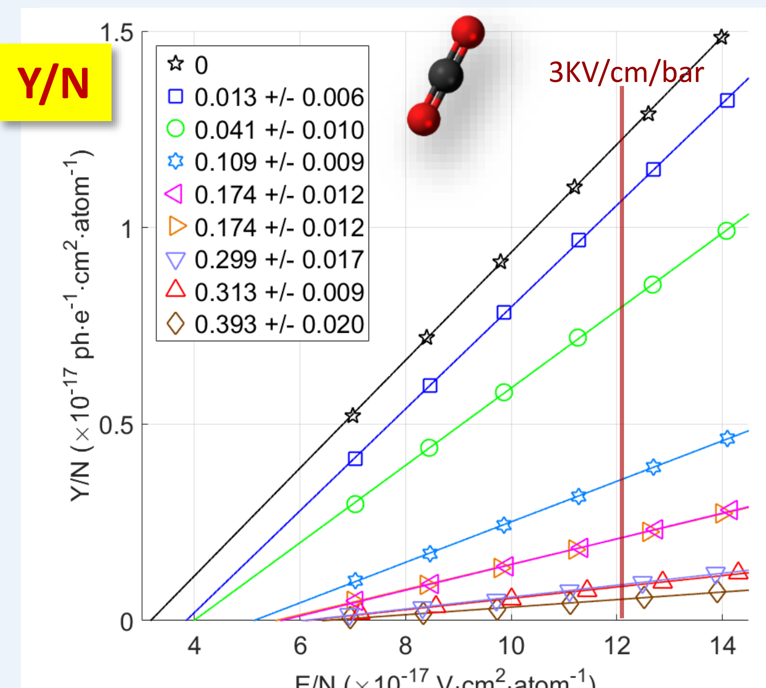


R_E **estimated for zero x-ray penetration →**

(driftless GSPC pulse-height distribution is left-tailed, exp + gauss)



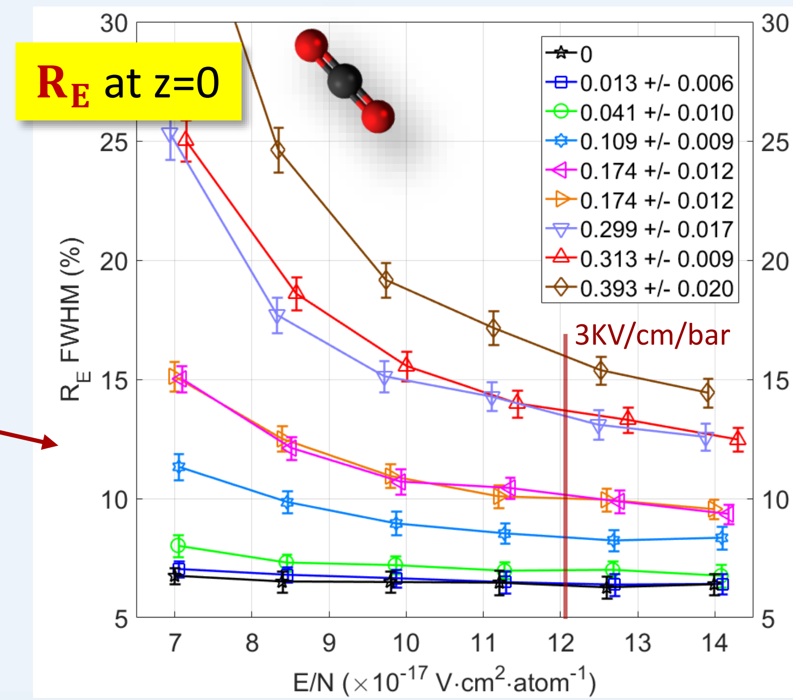
EL threshold increases and **slope** decreases



Stronger E/N → better R_E

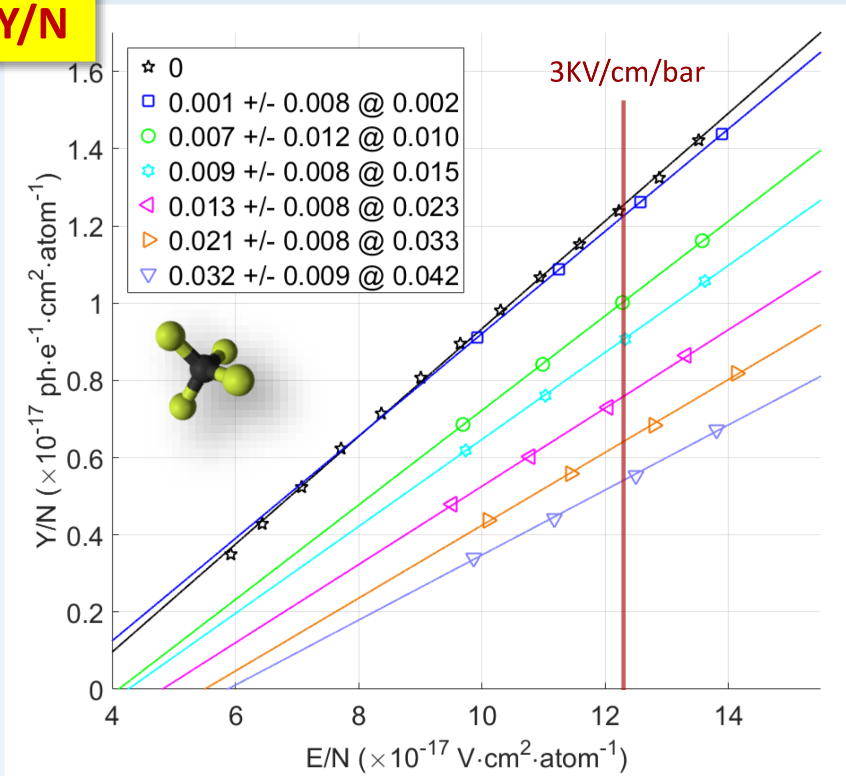
favoured in CH4

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



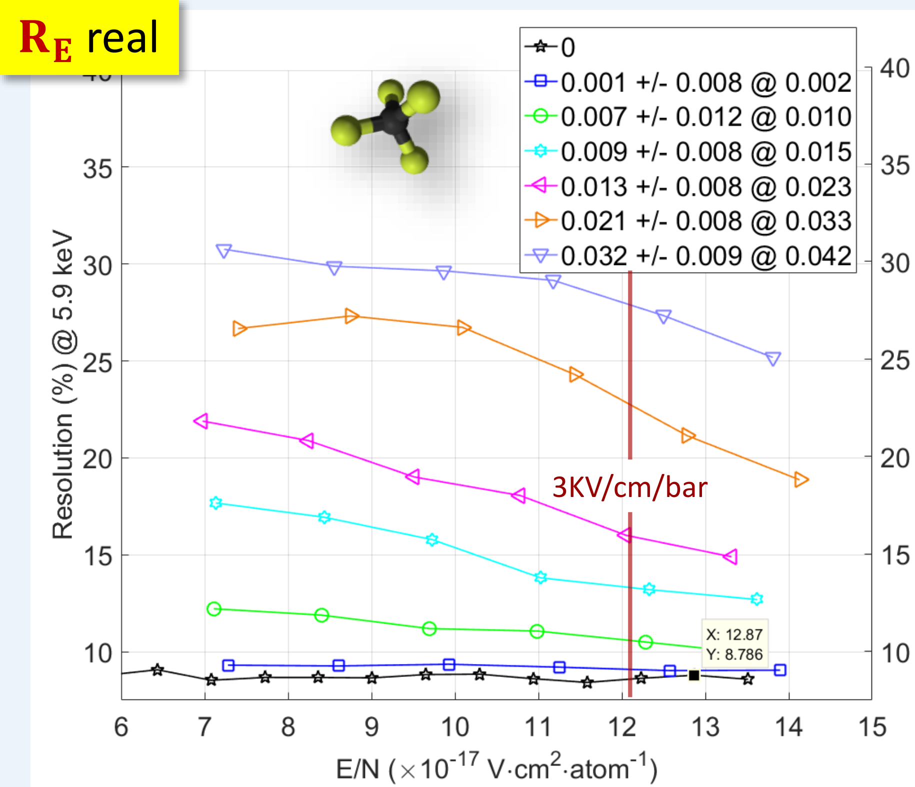
The CF_4 case

Y/N



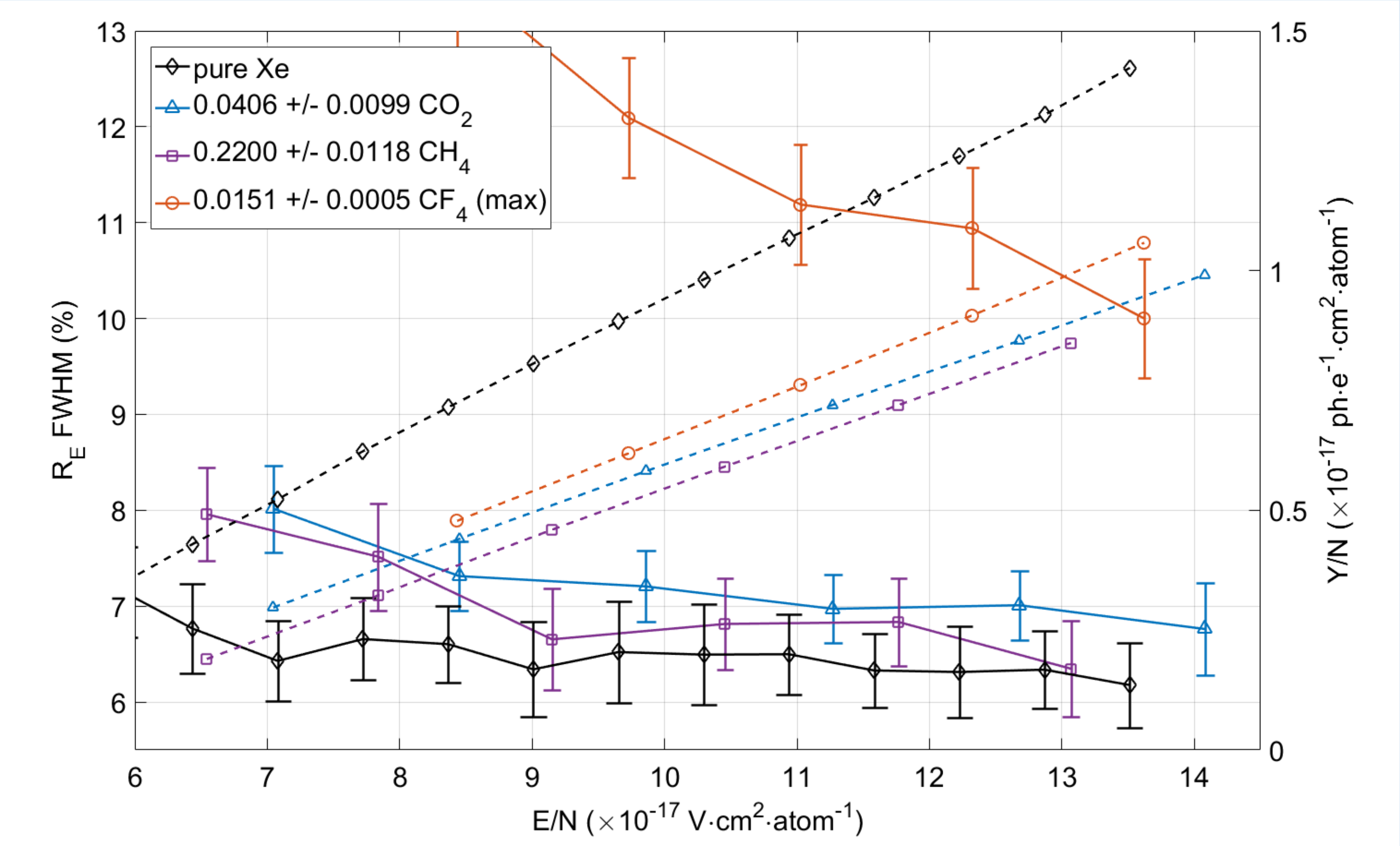
- Here, the real $\mathbf{R_E}$ is showed (because the CF4 high attachment resulted in some right-tailed spectrums)
- But, in next slides previous z=0 extrapolation adopted although ignoring right-tailed spectrums

$\mathbf{R_E}$ real



- **EL Y** well preserved if compared with $\mathbf{R_E}$
- Lower $\mathbf{R_E}$ dependence on E/N

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



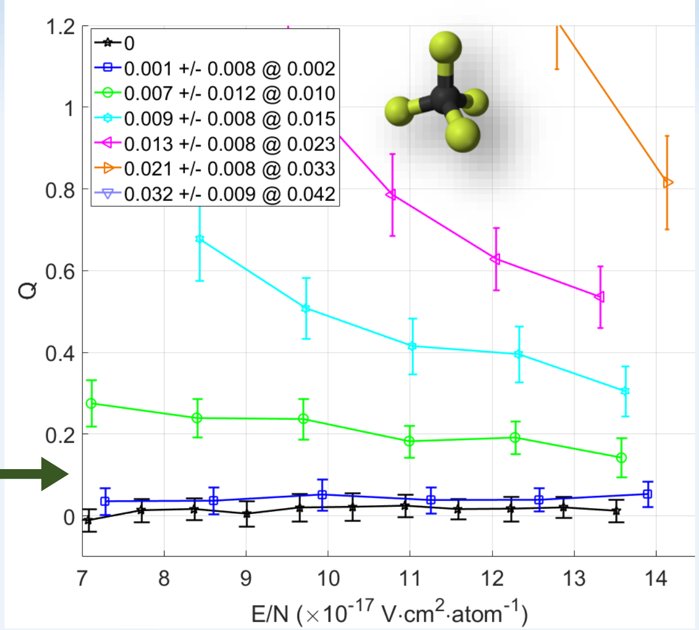
- **CO2 have a good R_E** (but it degrades abruptly for higher concentrations)
- **CH4 have the best R_E, even with the worst Y**
- **CF4 have the best Y, but a terrible R_E**

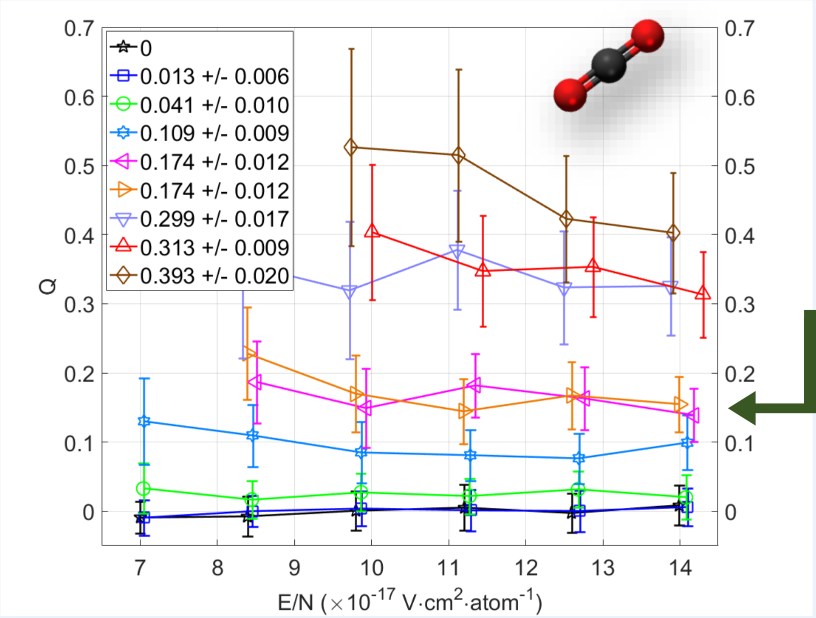
Concerning Q

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

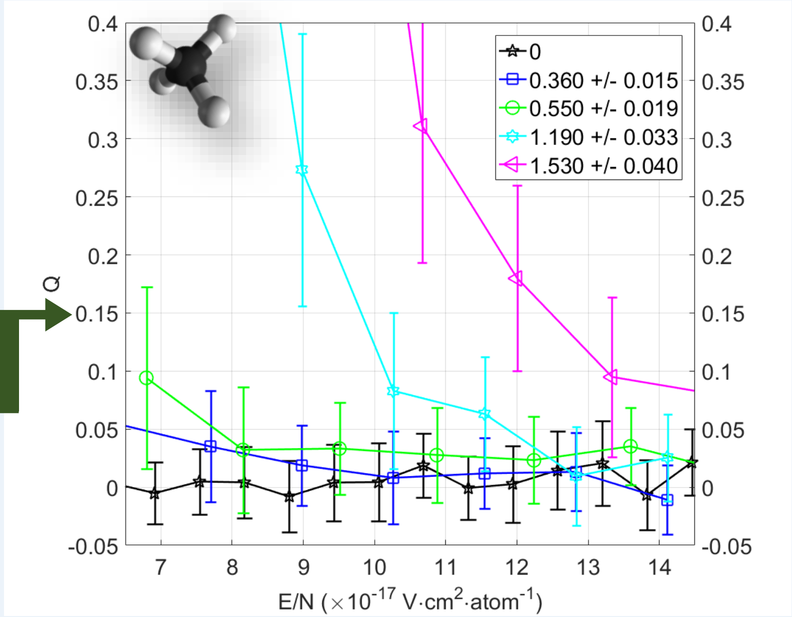
1. Using ***F***, ***k*** and $\boldsymbol{\sigma_G / G}$ estimated wirh **pure Xe** → PMT and Fano contributions are subtracted to $\mathrm{R_E}$
2. The **Q** (relative fluctuations in the number of **EL photons**) is estimated
   - CH4: Q negligible (≪ F)
   - CO2: Q ~ ½ Fano (for conc. in ROI)
   - CF4: Q ≫ Fano (high attachment)

Fano

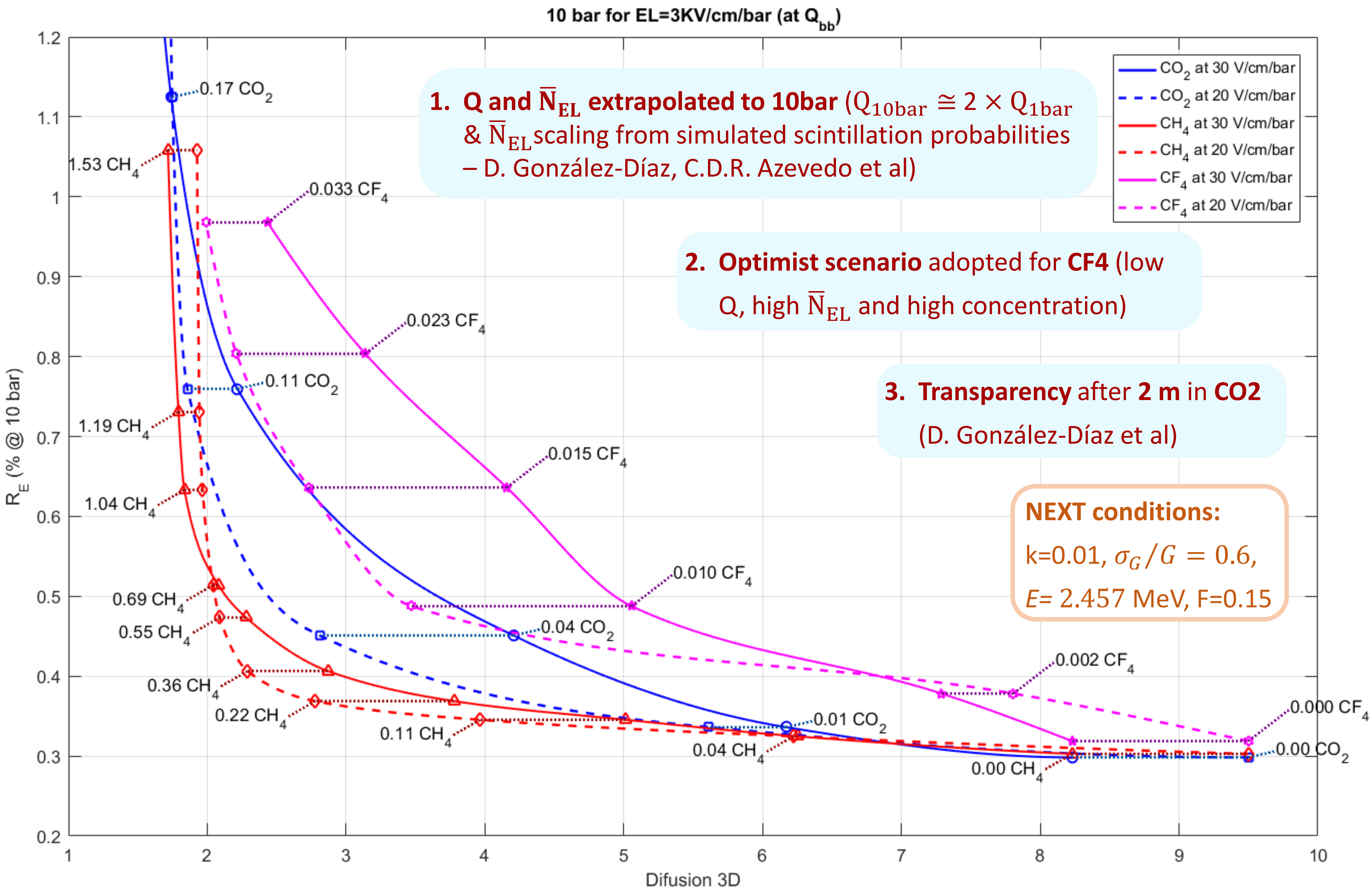




Fano
0.15 ± 0.02



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



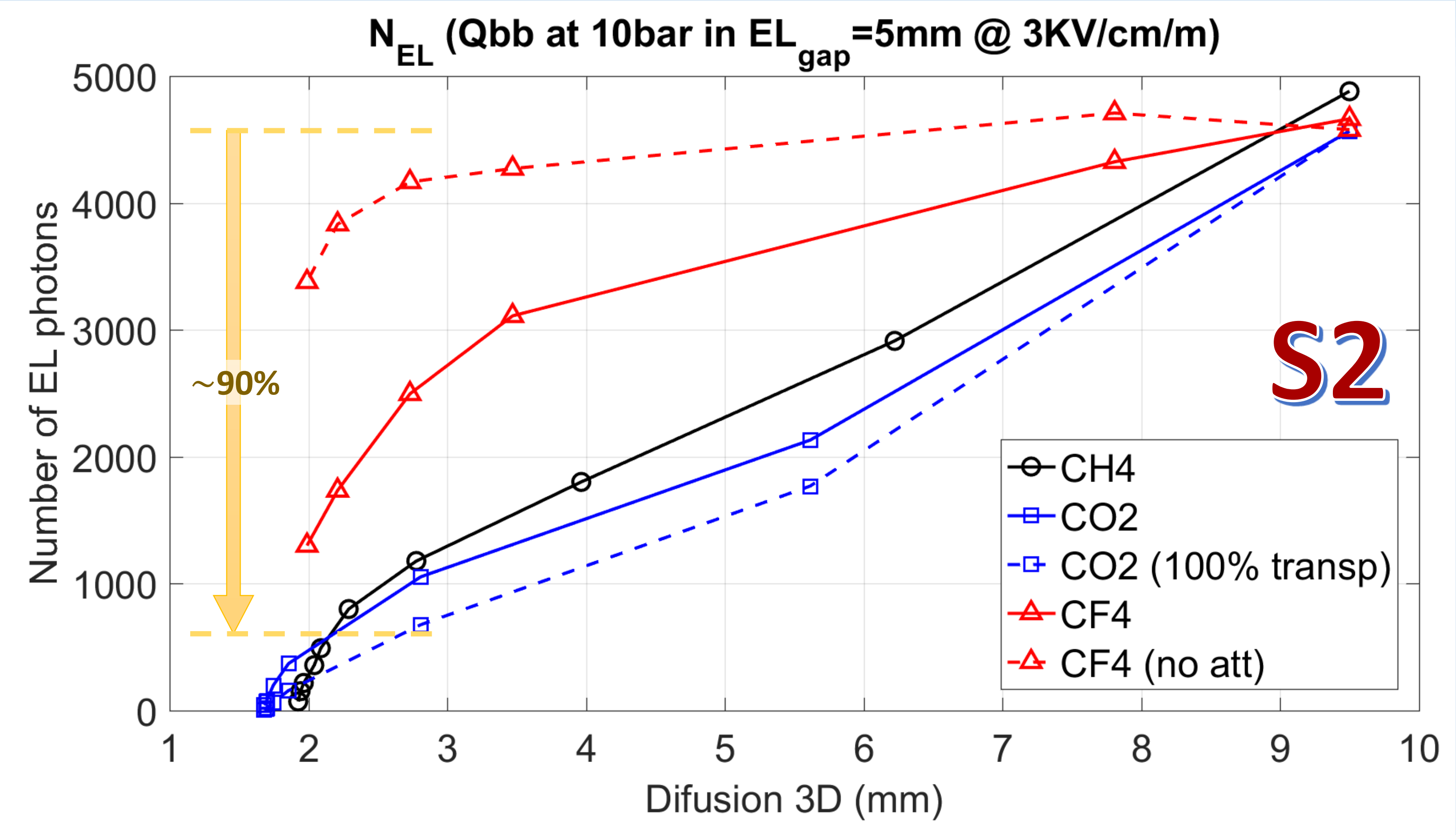
1. **Q and $\overline{N}_{EL}$ extrapolated to 10bar** ($Q_{10bar} \cong 2 \times Q_{1bar}$ & $\overline{N}_{EL}$ scaling from simulated scintillation probabilities – D. González-Díaz, C.D.R. Azevedo et al)

2. **Optimist scenario** adopted for **CF4** (low Q, high $\overline{N}_{EL}$ and high concentration)

3. **Transparency** after **2 m** in **CO2** (D. González-Díaz et al)

NEXT conditions:
k=0.01, $\sigma_G/G = 0.6$,
E= 2.457 MeV, F=0.15

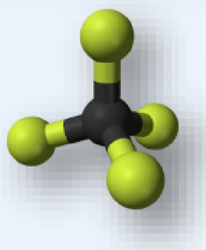
N_{EL} vs D_{3D} – CO_2, CH_4 and CF_4



S1

~80% light lose expected in CO2 and CH4 (almost 0% for CF4) **from simulated** scintillation probability (D. González-Díaz et al, same simulations are in agreement with experimental data for S2 at 1bar)

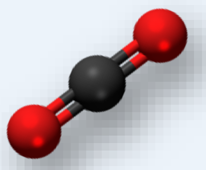
Conclusion:



Low quenching, high transparency → **S1** and **S2** slightly affected

High attachment → $\mathbf{R_E}$ extremely degraded (dominated by Q)

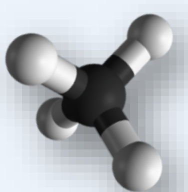
Stable, but concentrations (~100ppm) too low to handle and measure



S1 and S2 affected by quenching and transparency

Good $\mathbf{R_E}$ (attachment still low) in concentration ROI

Absorbed by hot getters and transformed CO (CO2 specific cold getters)



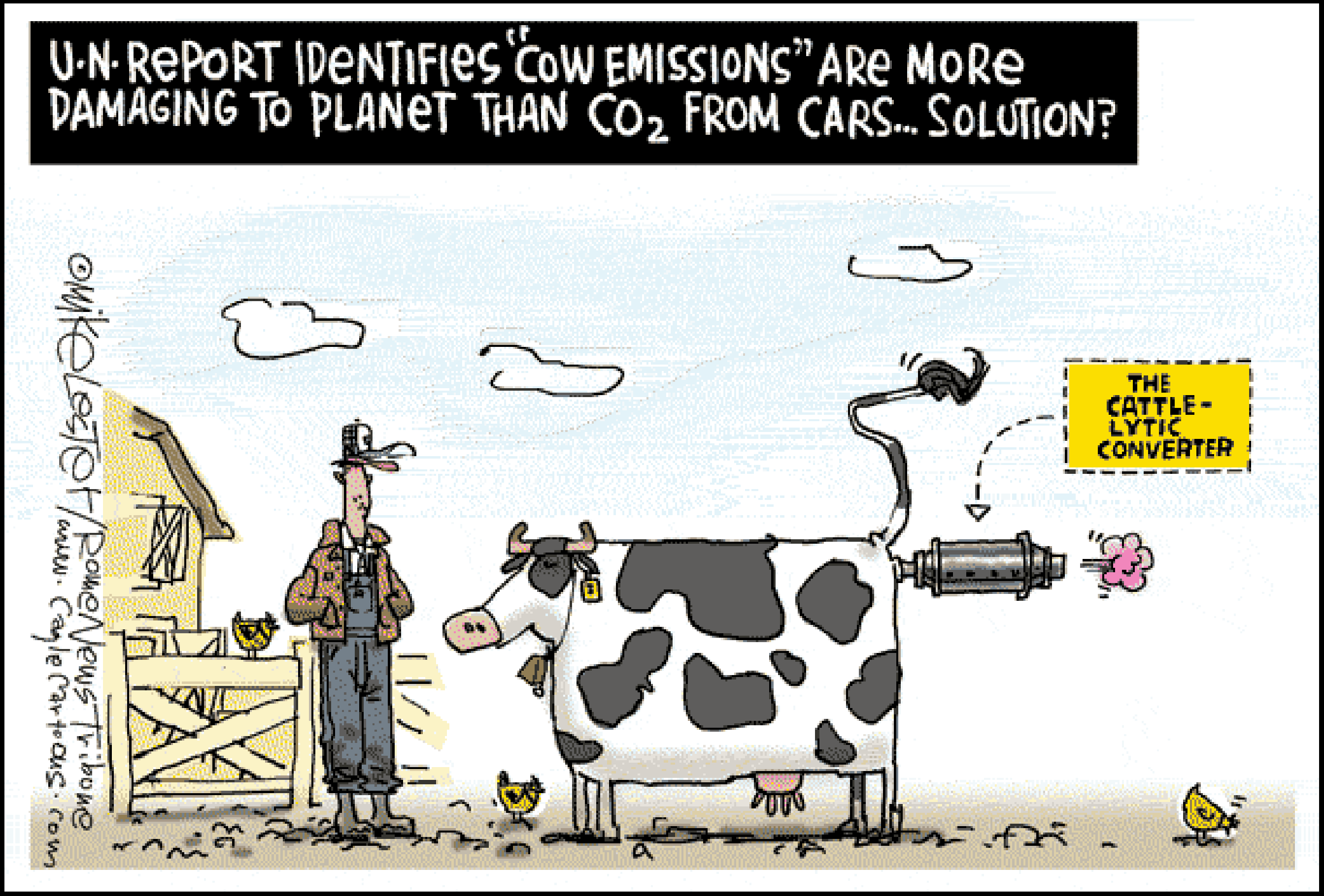
S1 and S2 affected by the high quenching

Excelente $\mathbf{R_E}$ (Q~ 0), if E/N is increased (as EL threshold) S2 improved and $\mathbf{R_E}$ almost the same as in pure Xe

Stable & high concentrations (~4000ppm), easy to handle and measure

Xe – M_x may improve **spatial resolution** in a EL optical TPC, keeping **S1, S2** and $\mathbf{R_E}$

Thank you for your time



References

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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.
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5. L.M.P. Fernandes, E.D.C. Freitas, M. Ball et al., "Primary and secondary scintillation measurements in a Xenon Gas Proportional Scintillation Counter," *Journal of Instrumentation*, vol. 5, P09006–P09006, (2010). doi:10.1088/1748-0221/5/09/P09006.
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…

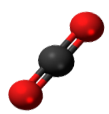
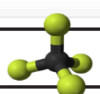
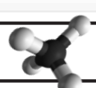
  However they don't absorb N2

  Radon?

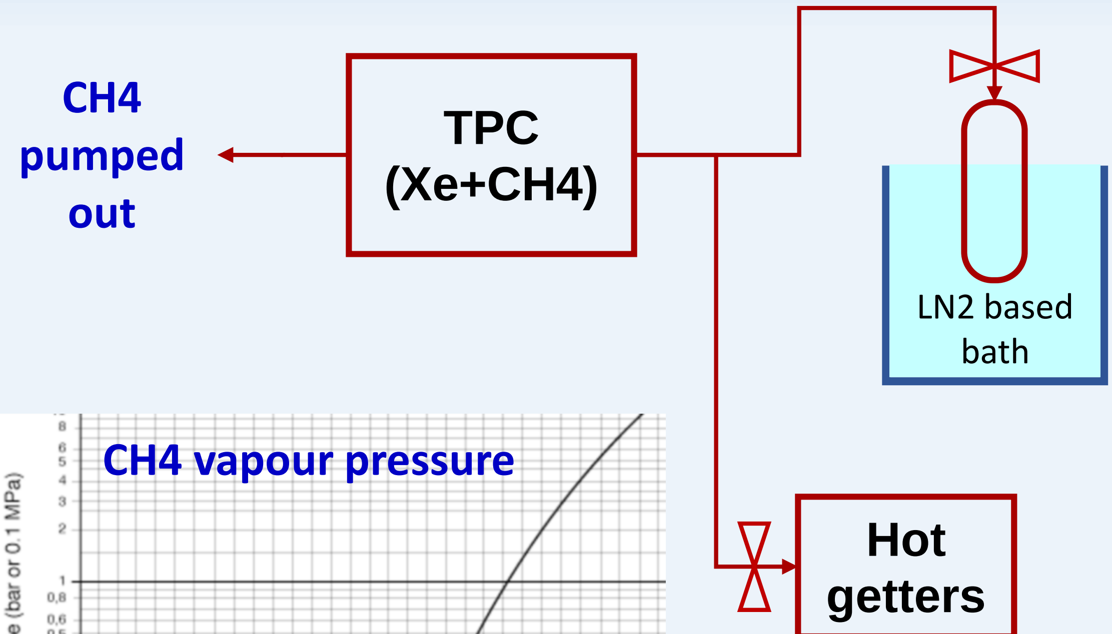
MICRO TORR

saes group

Purification and Removal Capabilities

Media	Gases Purified	Impurities Removed	Outlet Performance	Regenerable	Dangerous Goods (DG) Classification
804	CO_2 	H_2O, O_2, CO, H2	< 1 ppbV	YES	DG - UN2881 Class 4.2
		Volatile Acids, Refractories, Condensable Organics (>100amu), Volatile Base	< 5 pptV		
		Non-Condensable Organics (>45 amu)	< 100pptV		
905	C_2F_6, C_2H_6, C_3F_8, C_3H_8, $C_2F_4H_2$, C_4F_8, C_4H_{10}, CCl_4, CF_4, CH_4, CHF_3, SF_6  	H_2O, O_2, CO, CO_2, H_2 NMHCs*	< 1 ppbV	YES	DG - UN2881 Class 4.2

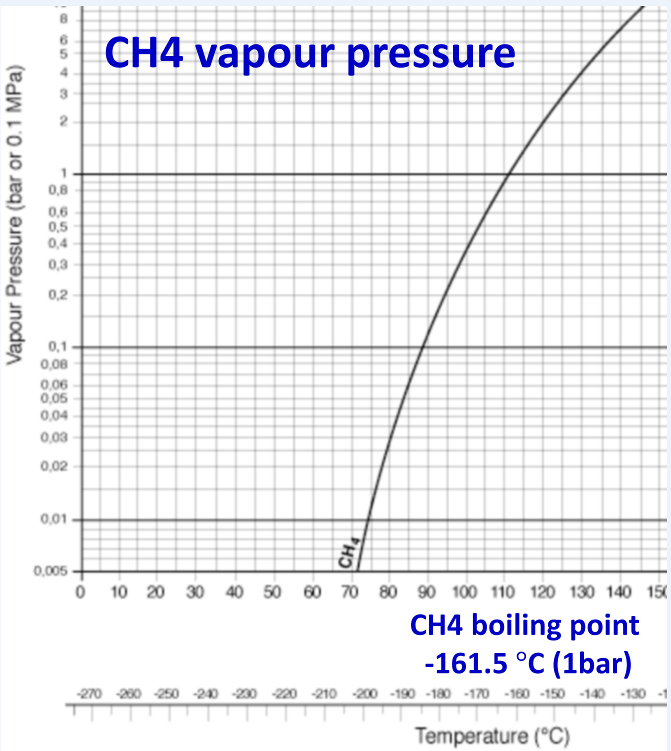
Conclusion: remove M_x from the Xe

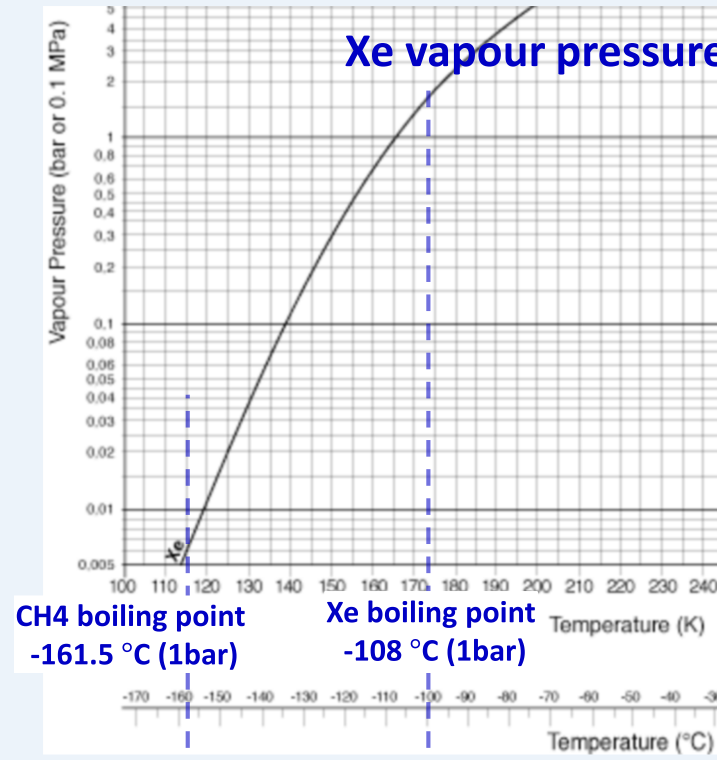


To remove remaining CH4 (small concentration will not saturate getters)

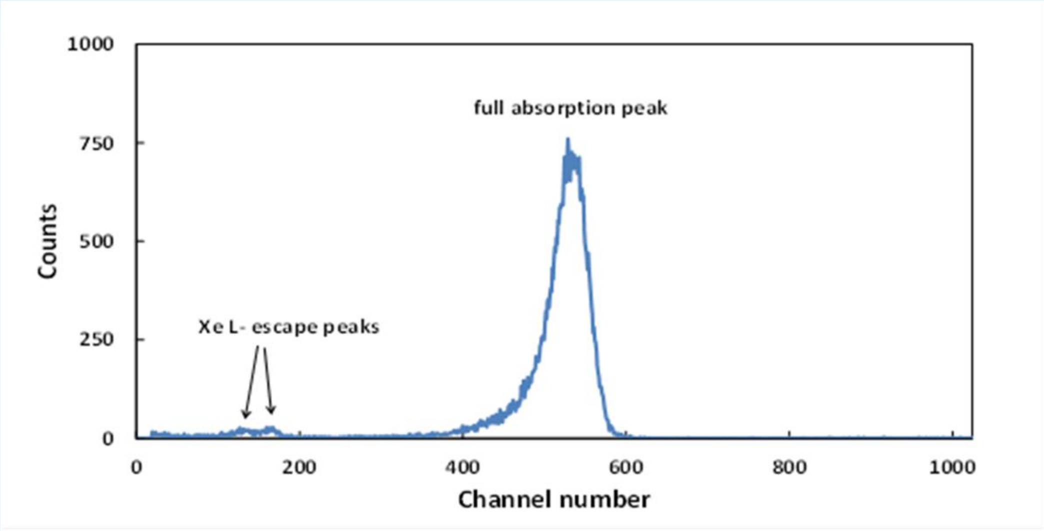
Cooling baths

		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

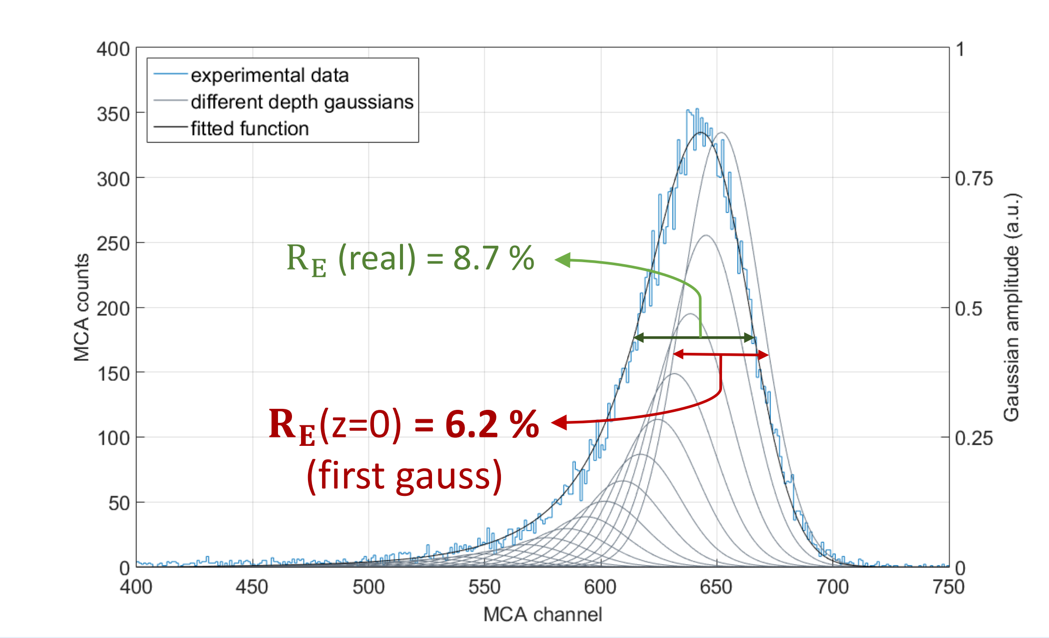




The pulse height distribution, of a driftless GSPC



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

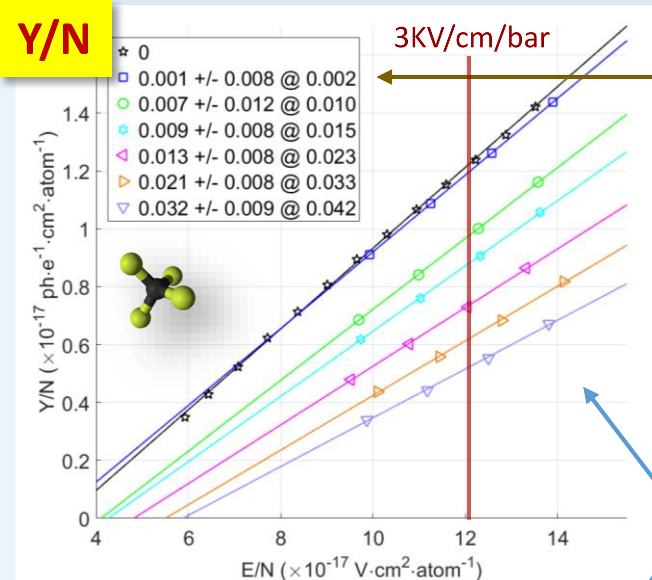


← Different depth (z) absorbed x-rays → **left-tailed** pulse-height distribution (gaussian & exponential absorption)

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

The CF_4 case

Y/N



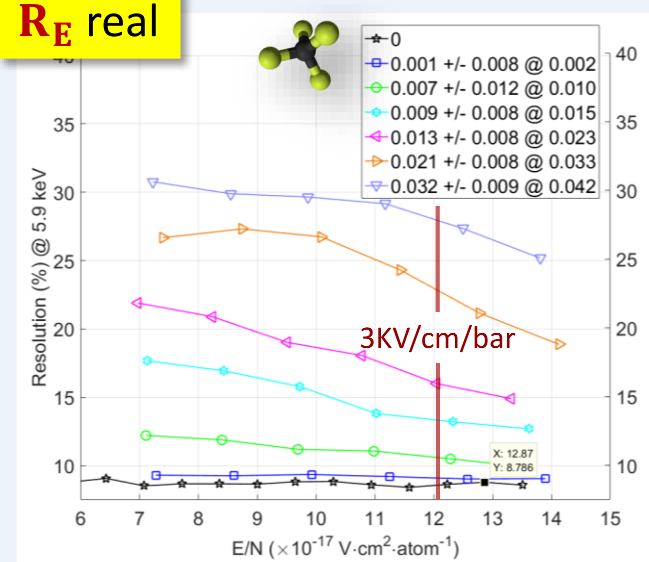
Huge **uncertainty** in low RGA's measurements:

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 $\mathbf{R_E}$
- Lower $\mathbf{R_E}$ dependence on E/N

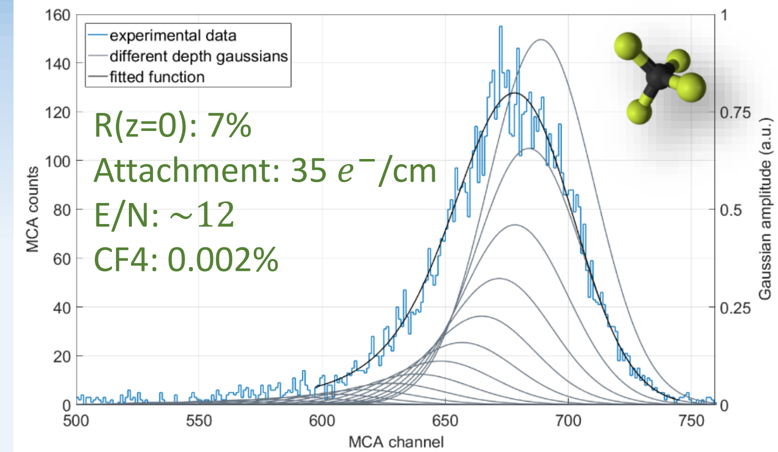
$\mathbf{R_E}$ real

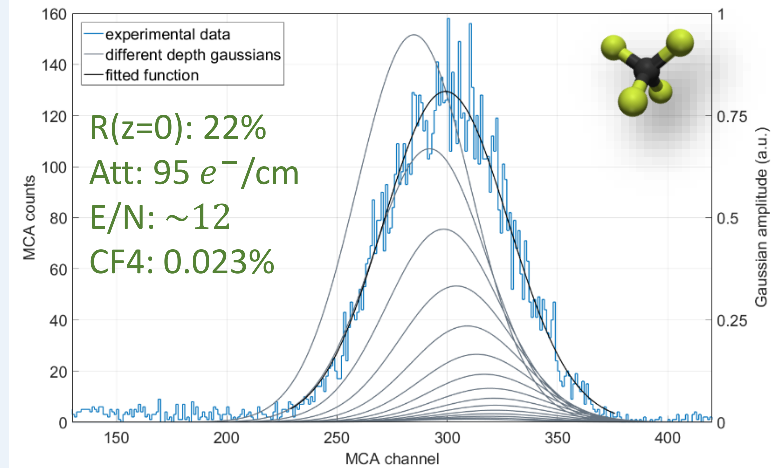


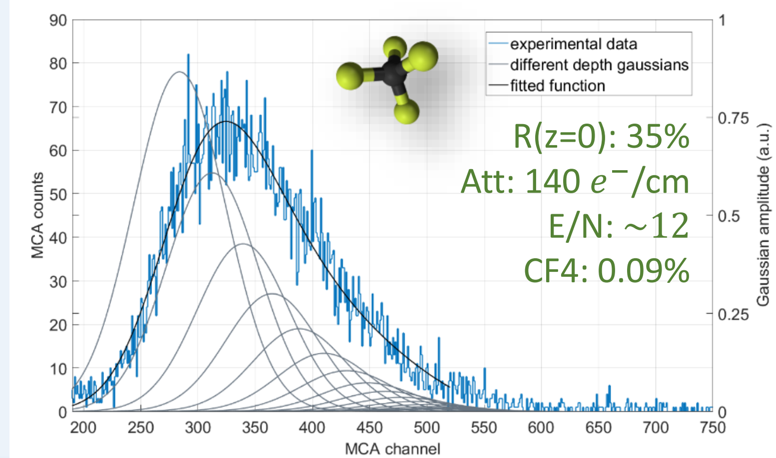
With 1 more free fitting parameter (attachment), $\mathbf{R_E}$ **(z=0)** extrapolation could be not reliable:

← Here, the real driftless GSPC $\mathbf{R_E}$

↓ Next, previous z=0 extrapolation used but ignoring right-tailed spectrums







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

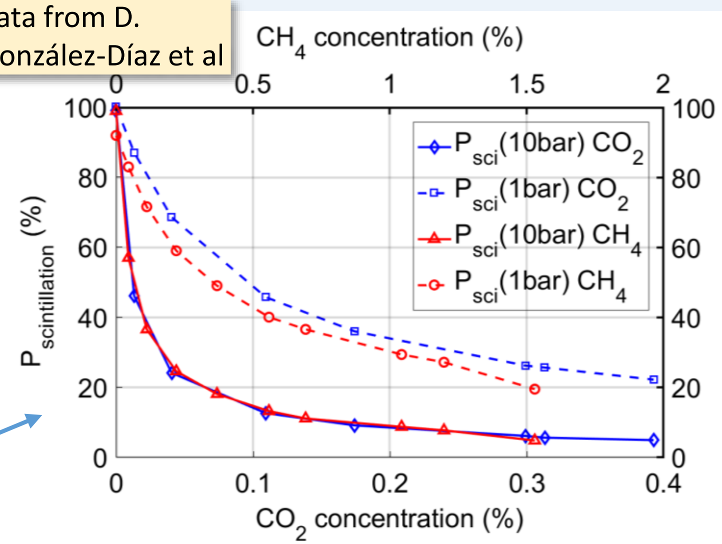
$$R_E = 2.35\sqrt{\frac{F}{\overline{N}_e} + \frac{Q}{\overline{N}_e} + \frac{1}{\overline{N}_{ep}} + \frac{\sigma_G^2}{\overline{N}_{ep}G^2}}$$

$$\overline{N}_e = \frac{E_x}{w_{ion}} = \frac{2.457\text{MeV}}{22\text{ eV}}, \quad F \sim 0.15 \mp 0.02, \quad \overline{N}_{ep} = k \cdot \overline{N}_e \cdot \overline{N}_{EL}$$

Expected features in NEXT-100:

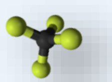
- EL photon collection efficiency **(k) = 0.01**
- Relative fluctuations in PMT's gain **(σ_G/G) = 0.6**

data from D. González-Díaz et al

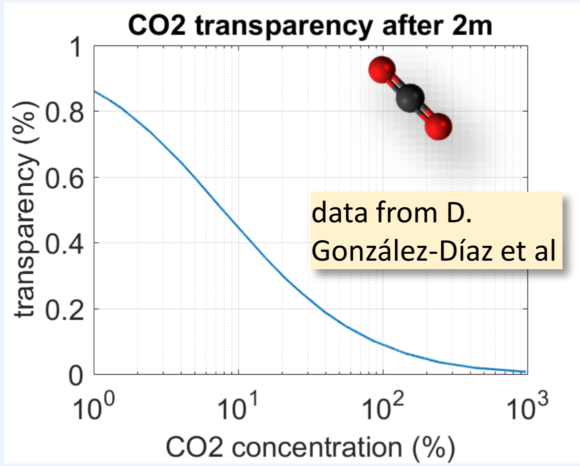


1. **Q(10bar) ≅ 2 × Q(1bar)** since $\frac{10bar}{1bar} \times \frac{5mm\ gap}{25mm\ gap}$,
   if dominated by attachment → **in CH4 Q(1bar) = Q(10bar)**

2. $\overline{\mathbf{N}}_{\mathbf{EL}}$**(10 bar)** ≅ $\overline{\mathbf{N}}_{\mathbf{EL}}$**(1 bar)** × $\mathbf{P_{scint}(10bar)/P_{scint}(1bar)}$
   from simulations (Diego-Azevedo), when reduction in Y is due to e^- cooling (threshold) and quenching, ie. in **CH4** and **CO2**

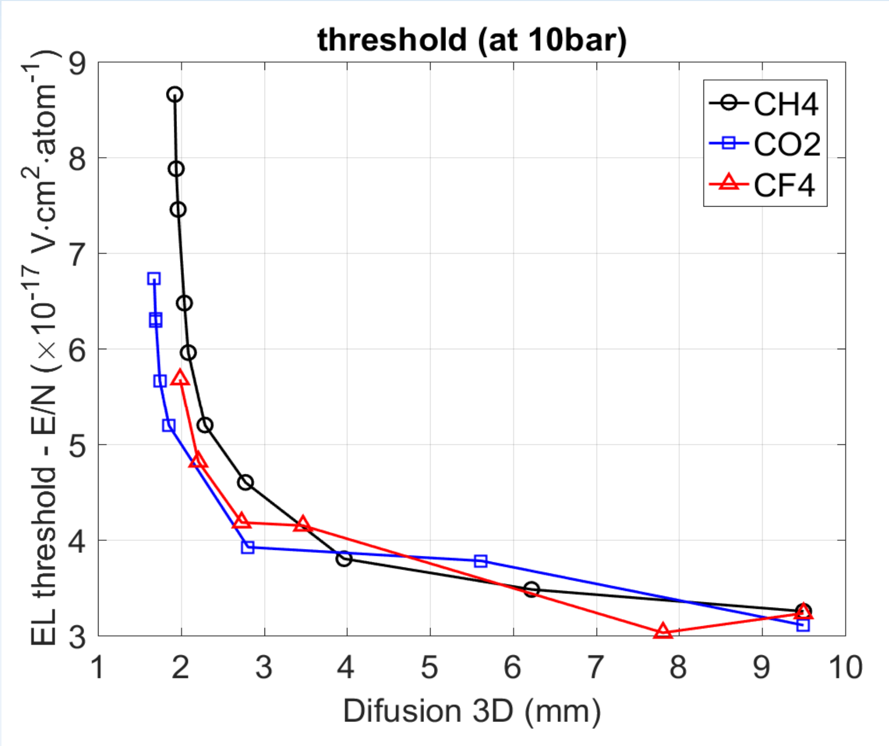
3. **For CF4** the more optimist scenario is adopted: **Q for max(E/N), max/initial concentrations** adopted,
   
   and $\overline{N}_{EL}$**(10 bar)** ≅ $\overline{N}_{EL}$**(1 bar)** – 20% lower at 10bar in ROI (2 × att)

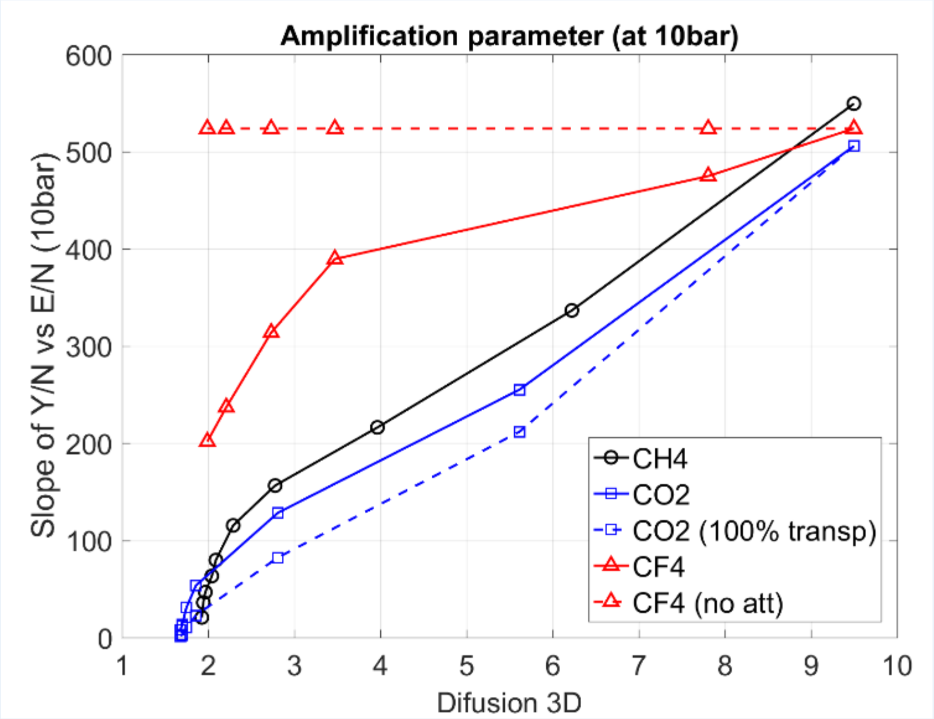
4. **Transparency** to EL photons after 2 m in **CO2**
   100% in CH4 and CF4



data from D. González-Díaz et al

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





Preliminary results: CO_2 and CH_4

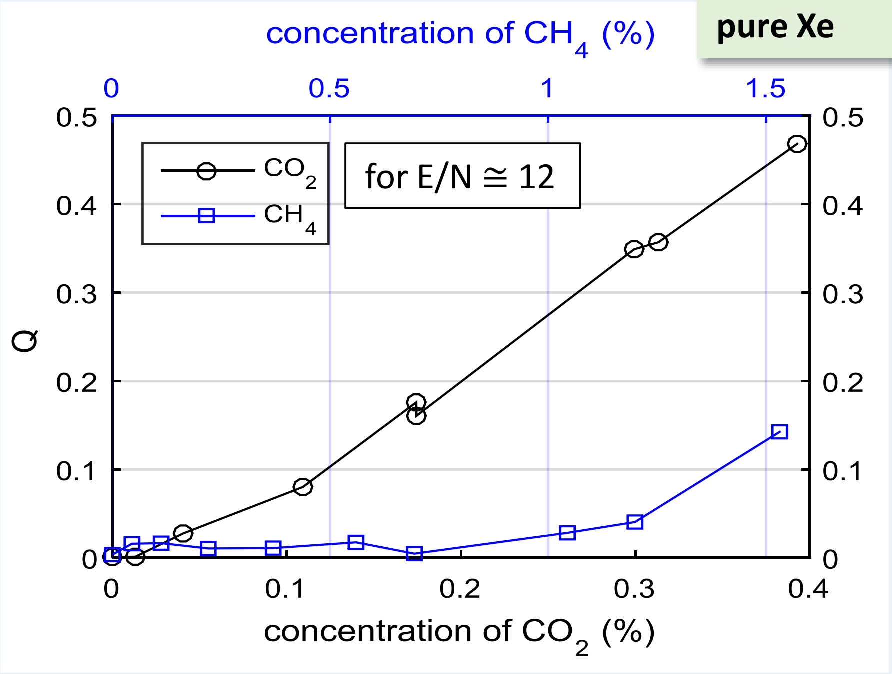
$P(torr)/N \cong 3.034 \times 10^{-17}$

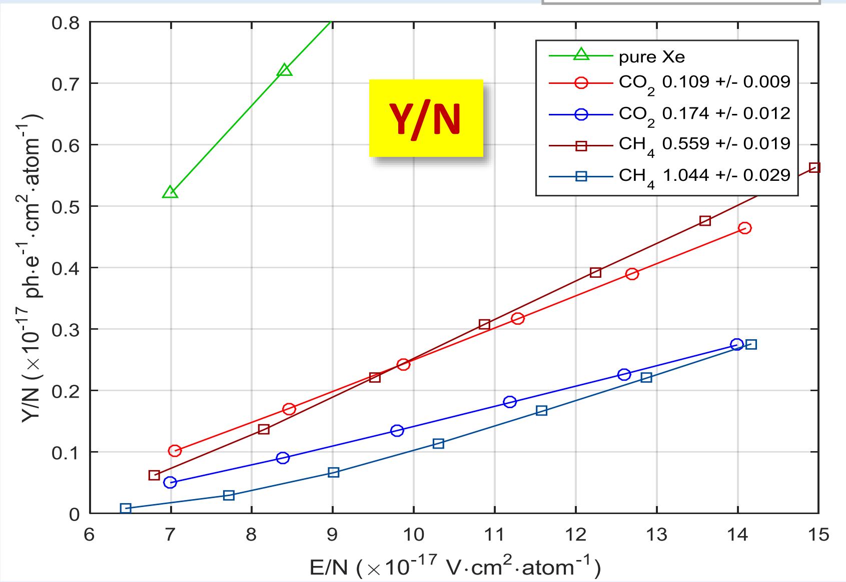
❖ **Which mixture is best for NEXT?**

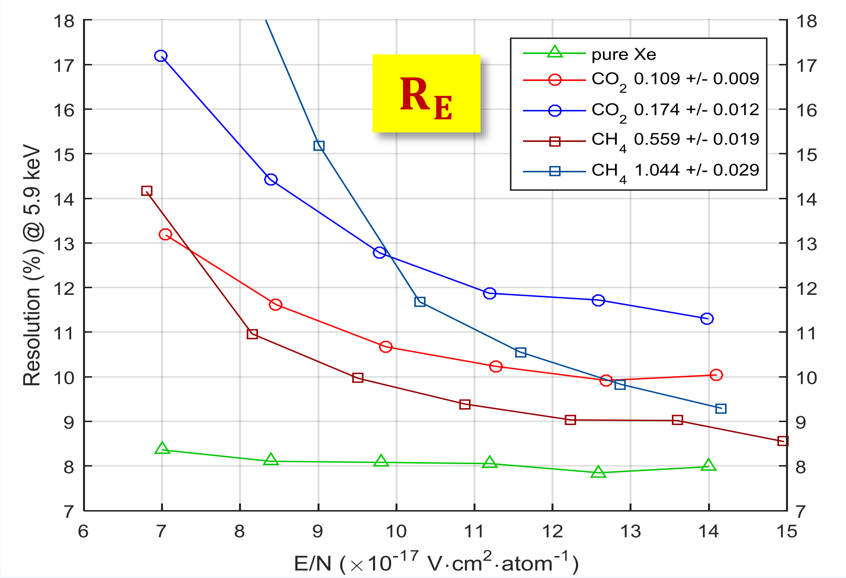
D_L @ D_T $(mm/\sqrt{m})$	CO_2	CH_4
~ 3 (28%) @ 2.8 (77%)	~0.11 %	~0.55 %
~2.2 (47%) @ ~2.6 (78%)	~0.17 %	~1.04 %

❖ **Subtracting Fano and PMT contributions** (preliminary)

using estimated ***F*** and ***k*** in **pure Xe**







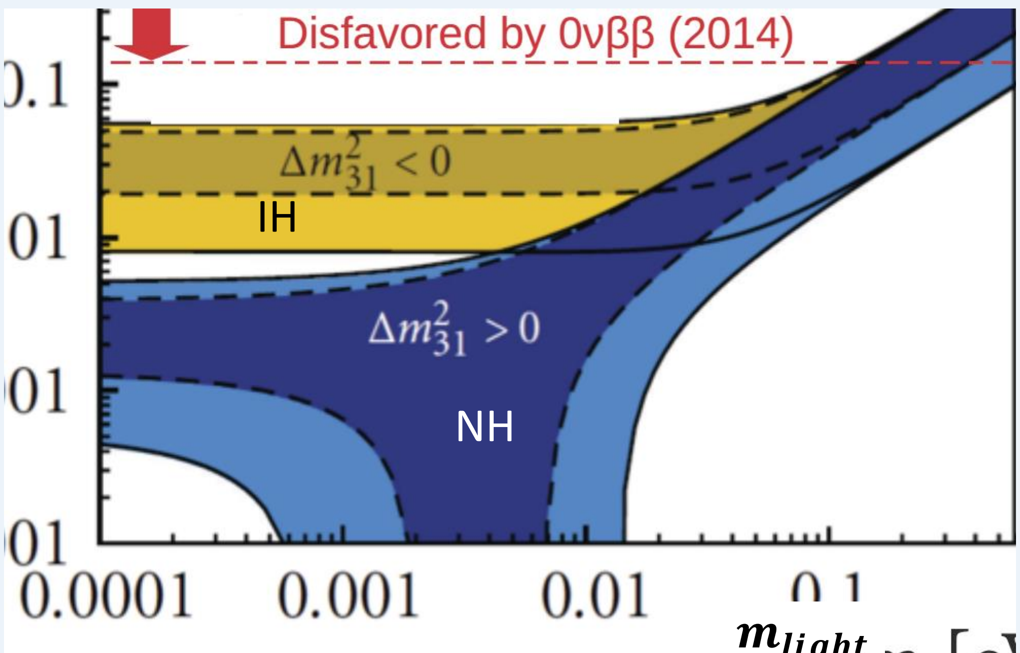
Neutrino mass and ββ0ν rate

$\beta\beta 0\nu$ **decay rate** → $m_{\beta\beta}$ → $m_{\nu_1}, m_{\nu_2}, m_{\nu_3}$

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

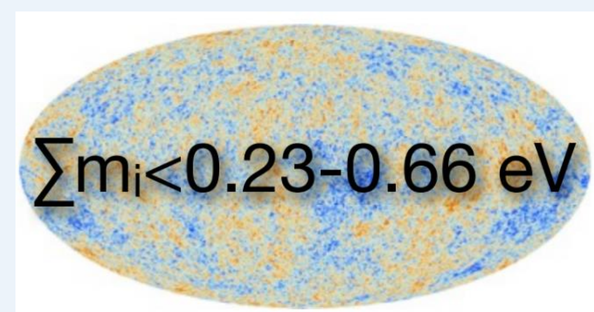
⇩

High source of uncertainty ← Nuclear Matrix of Elements (NME)



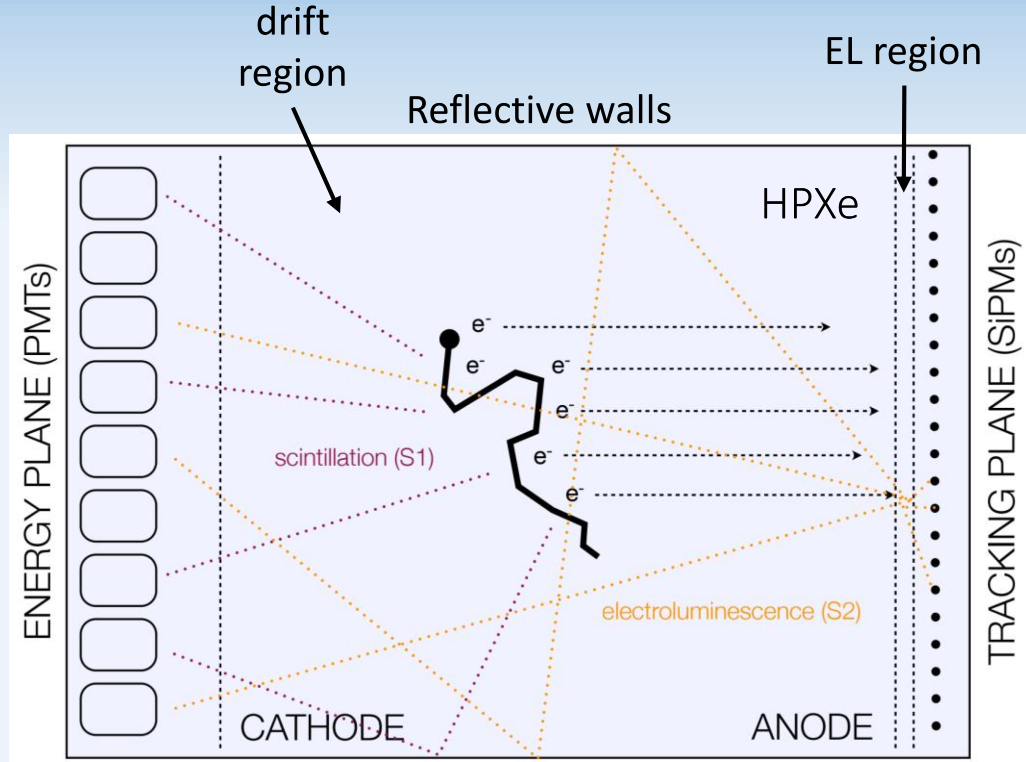
⇩ **experiments combined results : < 130-310 meV**
(different systematic error)

⇦

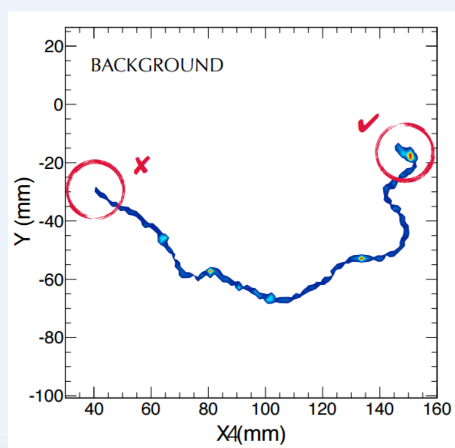


NEXT – concept

1. ^{136}Xe decays → $2e^-$
2. Primary electrons (P_{e^-}) + Primary scintillation (S1)
3. S1 at the energy plane → t_0
4. Pe^-drift towards EL region
   ($\sim 1\ mm/\mu s$ @ $\sim 0.5\ \ KV/cm/bar$)
5. P_{e^-} accelerated in EL region
   → electroluminescence (S2)
   ($\sim 4\ \ KV/cm/bar$) (S2 $\sim 2\ \mu s$)
6. S2 by tracking plane + t_0
   → 3D event topology
7. S2 by energy plane
   → precise energy of event

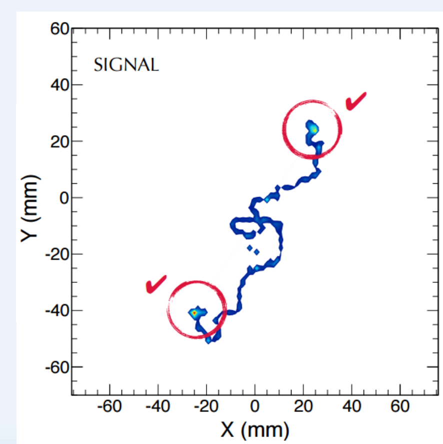


↓ **Topology signature** (simulation) ↓



Single gamma
($1e^-$):
← **1 blob**

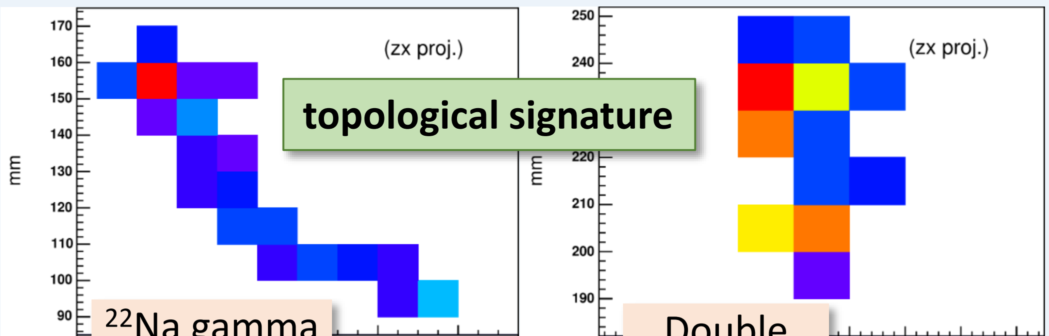
$\beta\beta$ decay
($2e^-$):
2 blobs →



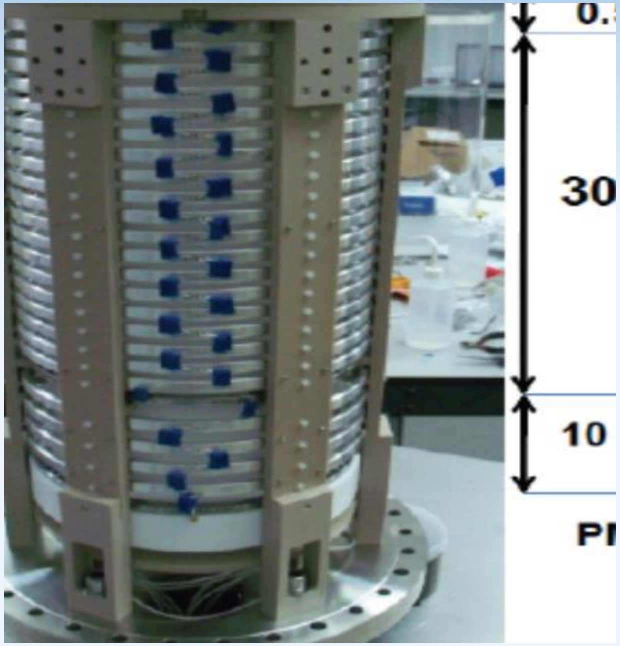
NEXT – prototypes

NEXT-DEMO $\sim 1.5\ kg$ @ $10\ bar$

➢ Demonstrate NEXT technology

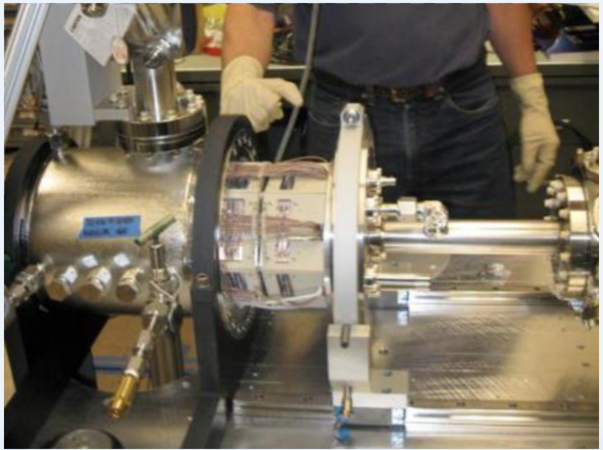


$R_E \sim 0.7\%$ → at $Q_{\beta\beta}$



NEXT-DBDM $\sim 1\ kg$ @ $10 - 15\ bar$

➢ Study R_E in HPXe



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

NEXT phase I – NEW $\sim 10\ kg$ of ^{136}Xe

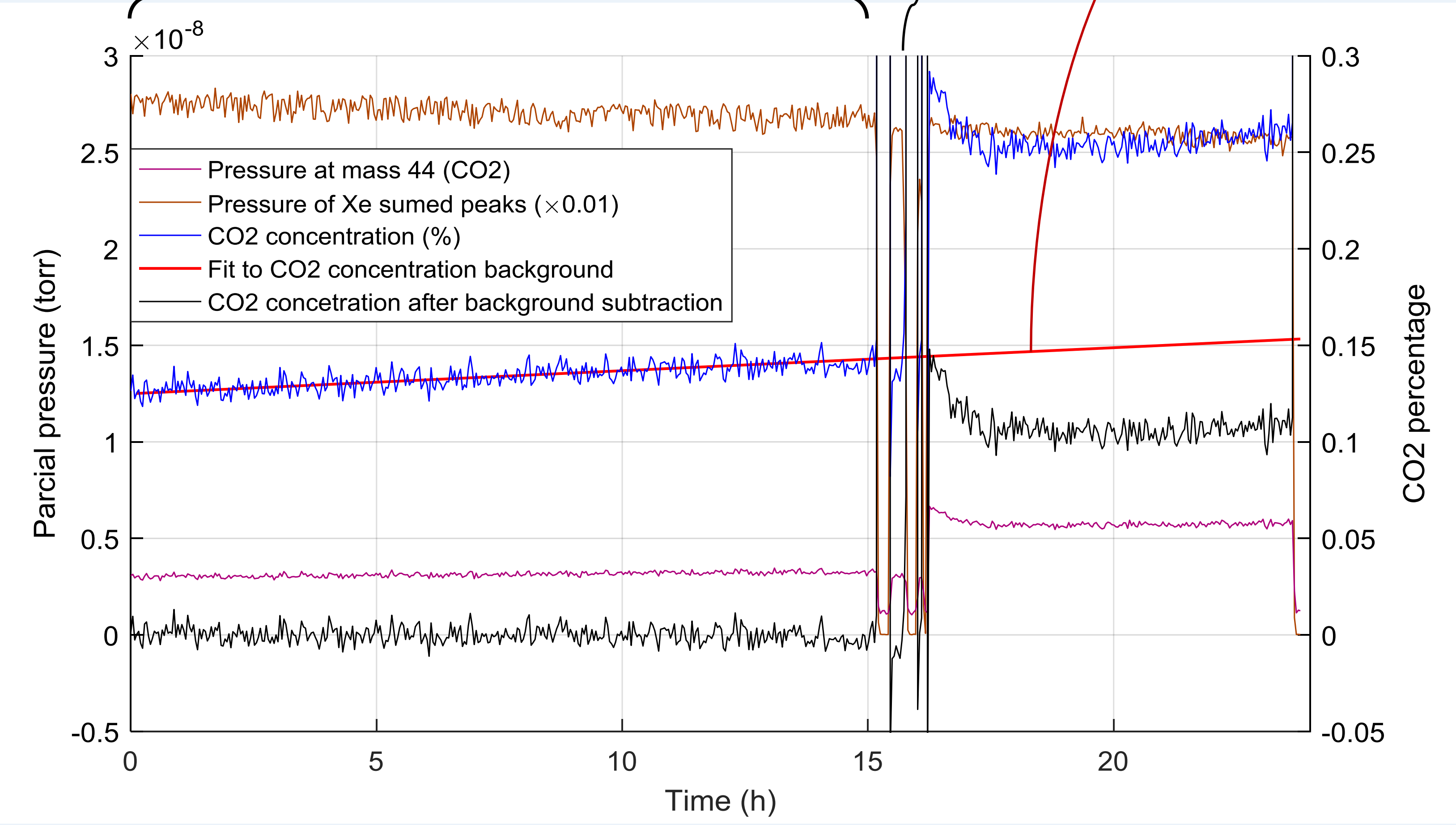
- **NEXT-100 at scale 1:2** @ 20% of photosensors
- 1º radiopure underground detector

RGA's Calibration

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

CO2 added here, then CO2 + Xe are liquefied

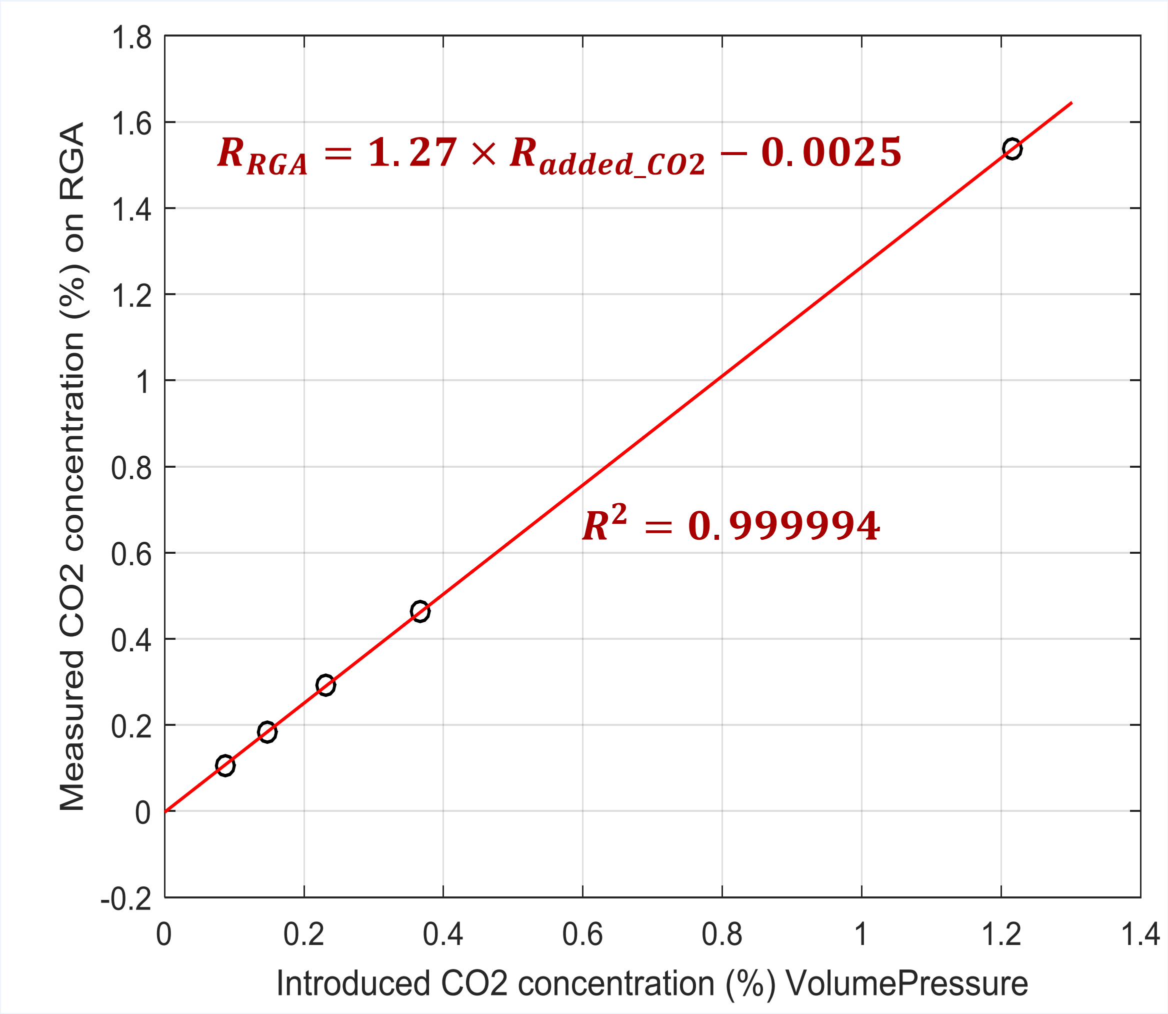
For CO2 background estimation after mixing



↑ 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

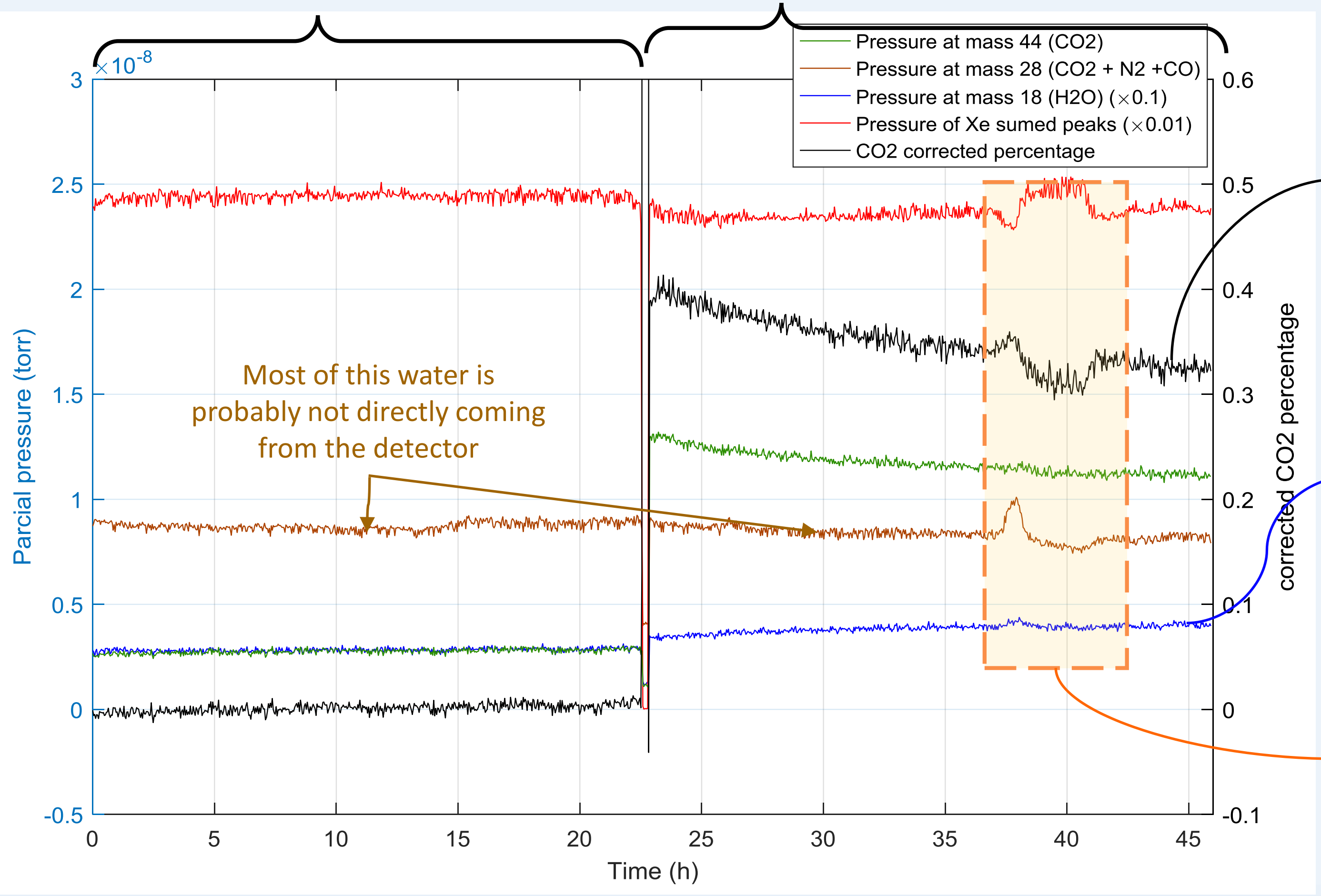
- Several methods were used to extrapolate the background of CO_2 after mixing, this one showed the best R^2
- This background estimation method will be also used in main mixtures

Results – RGA's example spectrum → $CO2/(Xe + CO2) = 0.44\%$

1) Pure Xe with getters at 250° C is recorded for background quantification at the beginning of each mixture → $CO2/(Xe + CO2) \approx 0.1$ % changing at each mixture

2) Getters are set to 80° C one hour before CO2 is introduced → 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 → 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 → 28 is the main peak of N2 and CO, and a secondary peak of CO2 (~5 % → obtained in calibration)

A typical non-explained perturbation → 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:**
  - Nitrogen (major fragmentation peak)
  - CO (major fragmentation peak)
  - CO2 (secondary fragmentation peak)

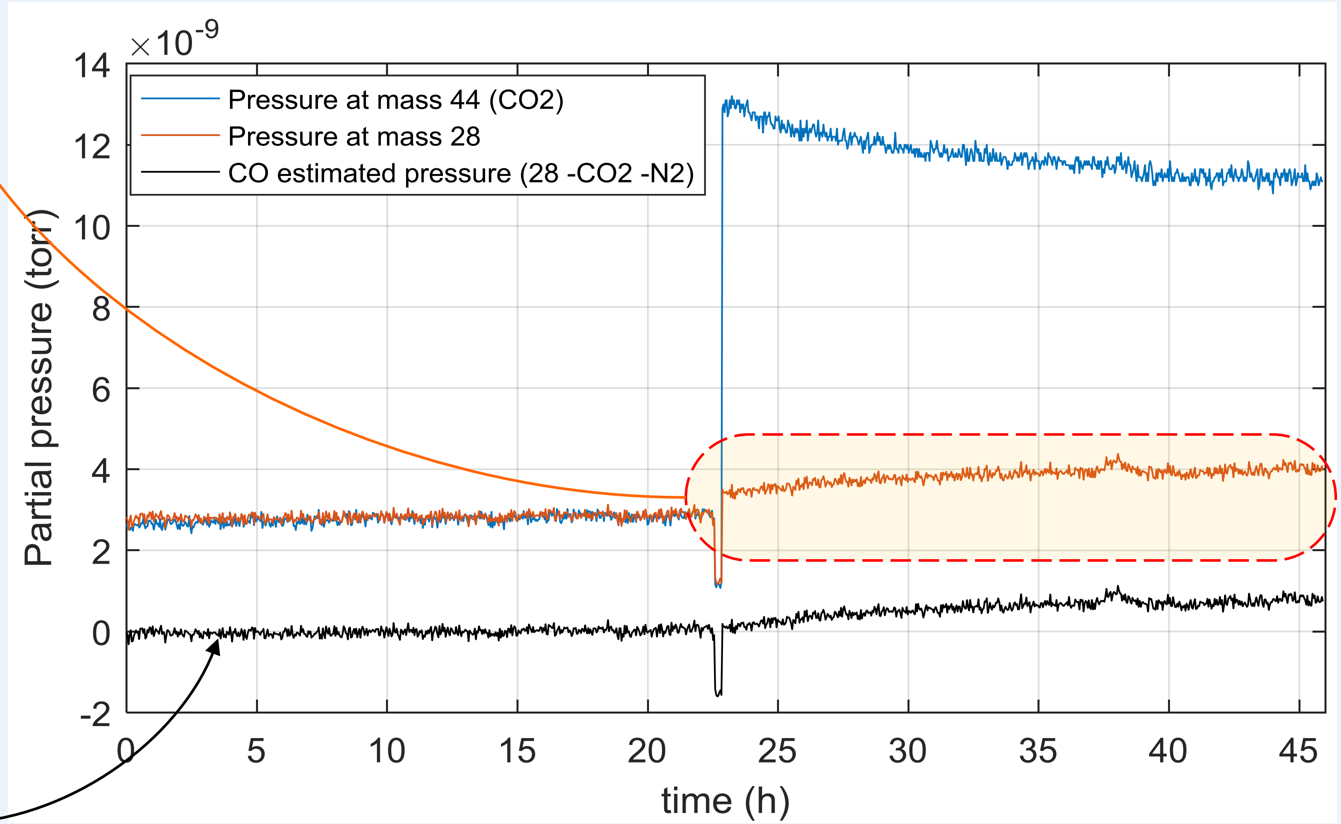
If the growth at 28 was just coming from CO2, it would not be continually rising
Is this due to CO production?

Assuming:

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

We can:

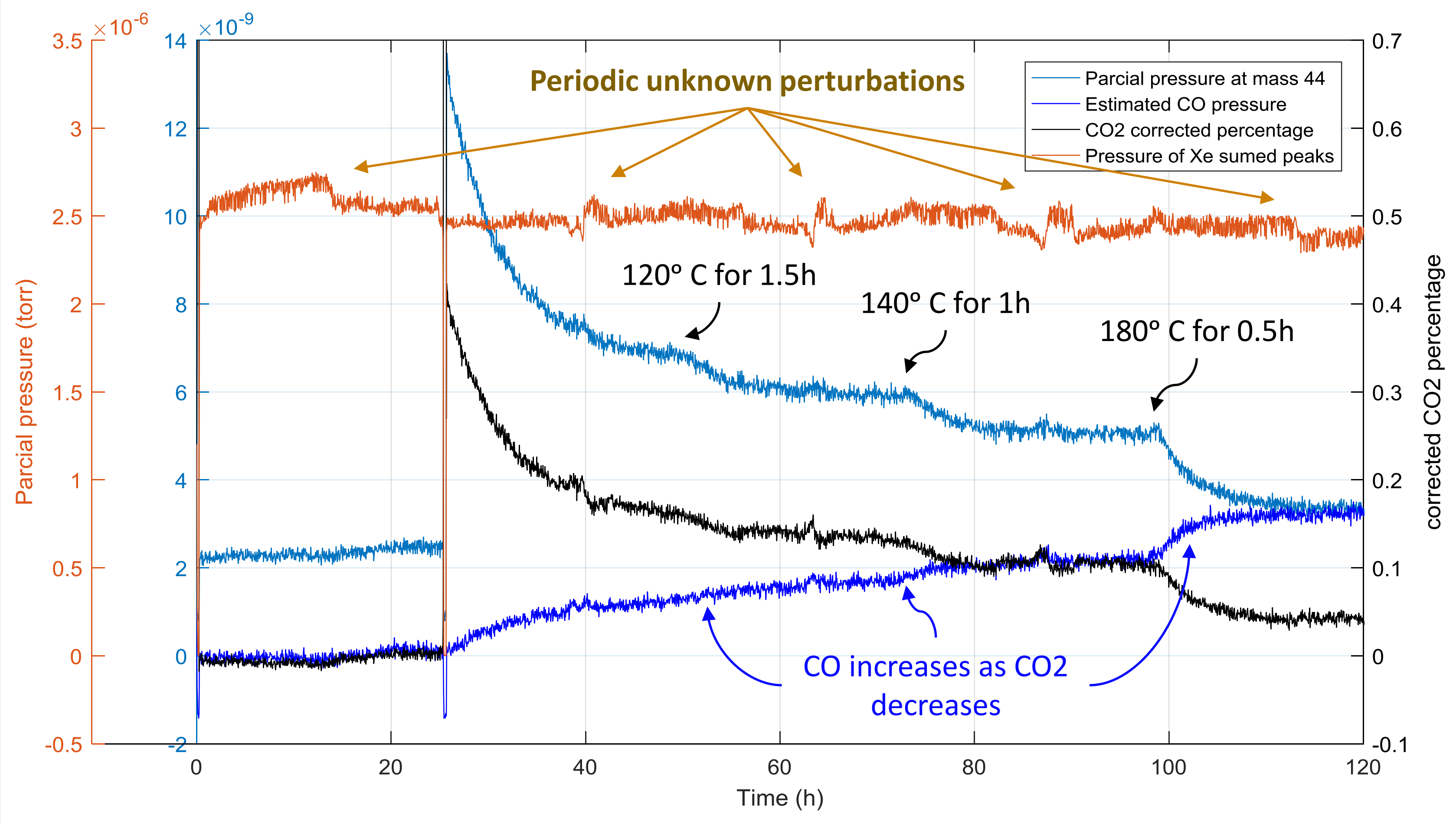
Estimate CO pressure at mass 28 by subtracting CO2 and N2 contributions



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.**

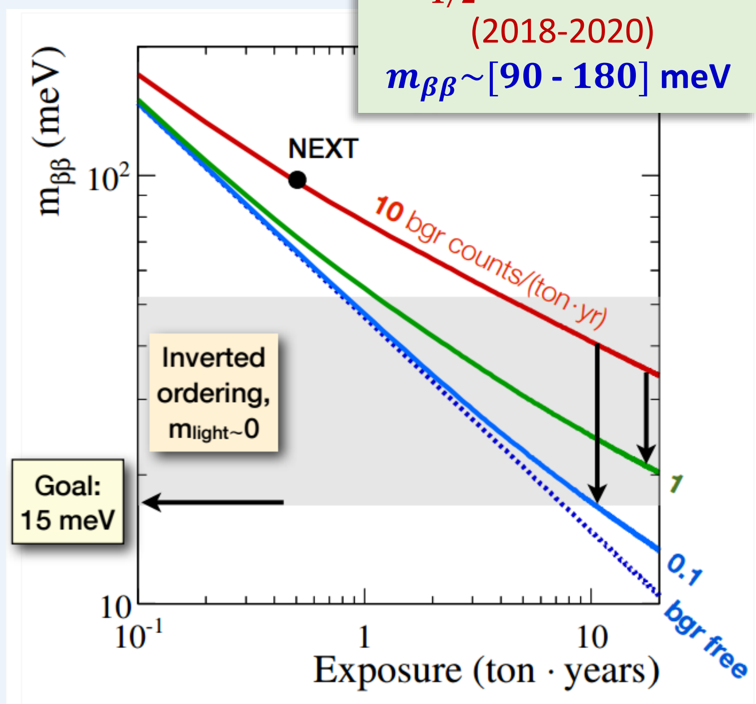
Temperatures were raised up just for some time, then they are cooled down to 80° C again



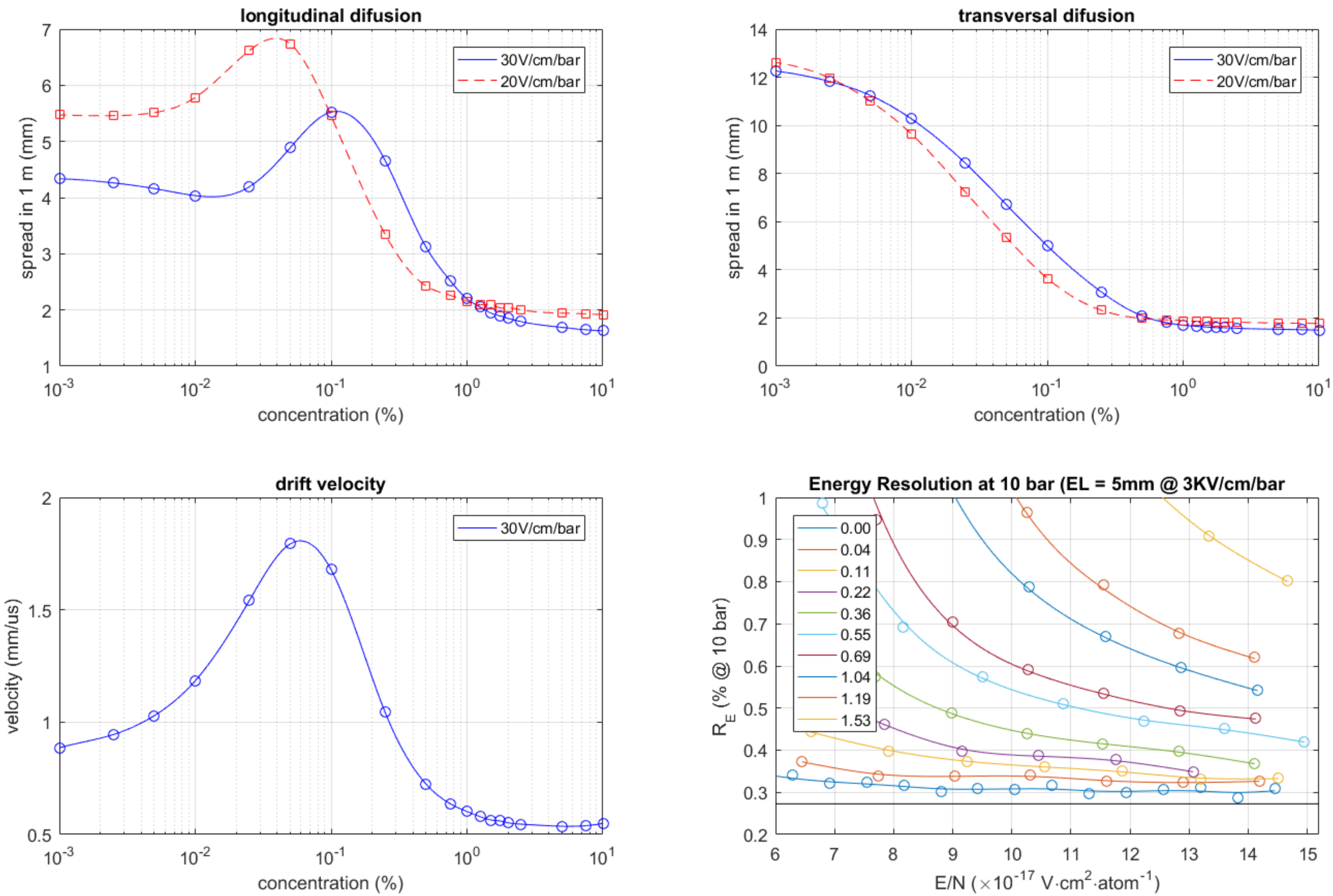
NEXT – towards the inverted hierarchy

ββ0ν **unlikely** with current experiments ⇒ **Ton scale + background reduction/rejection**

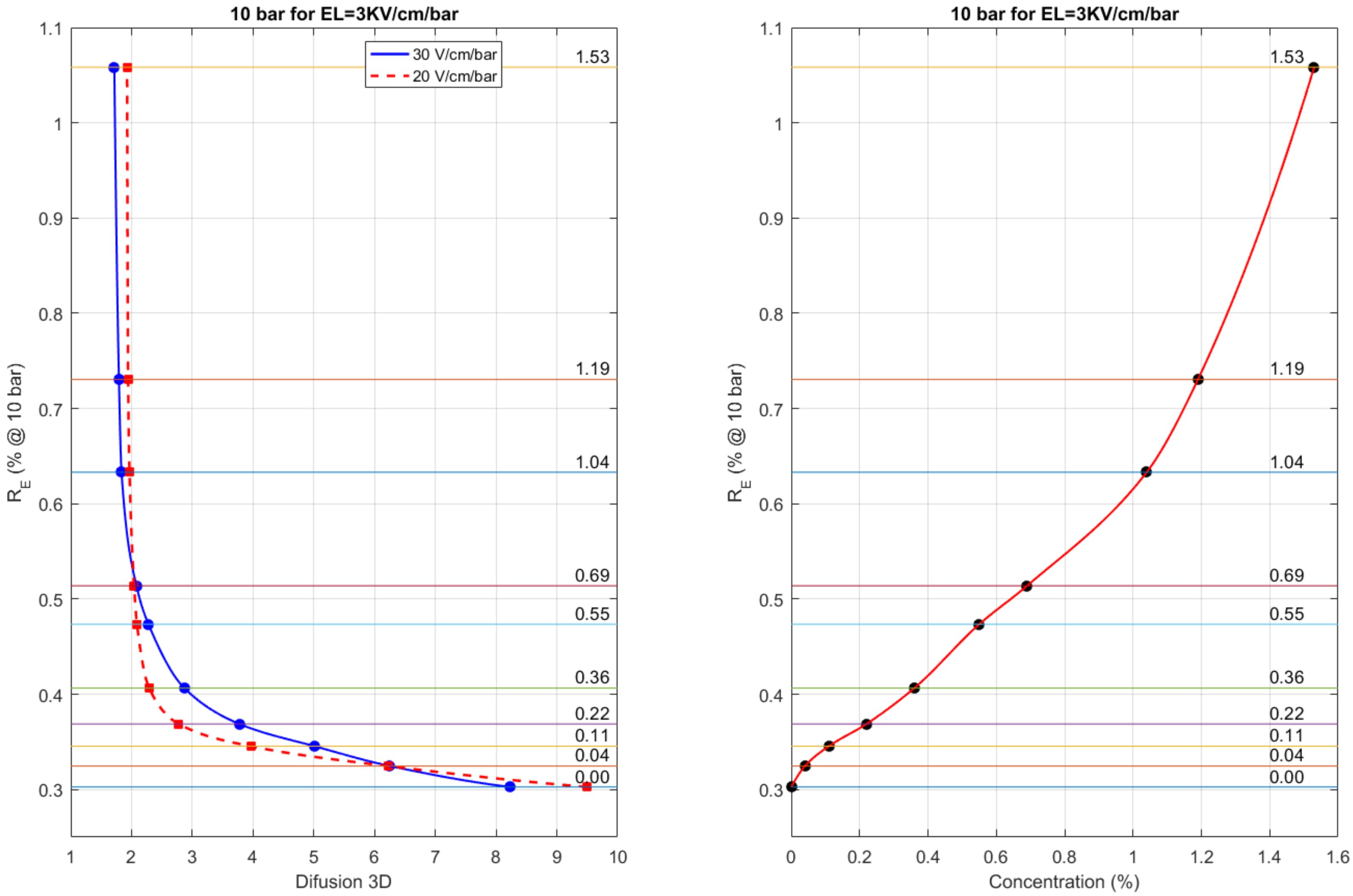
Next-100:
$T_{1/2}^{0\nu} = 5 \times 10^{25}$ yr
(2018-2020)
$m_{\beta\beta} \sim [90 - 180]$ meV



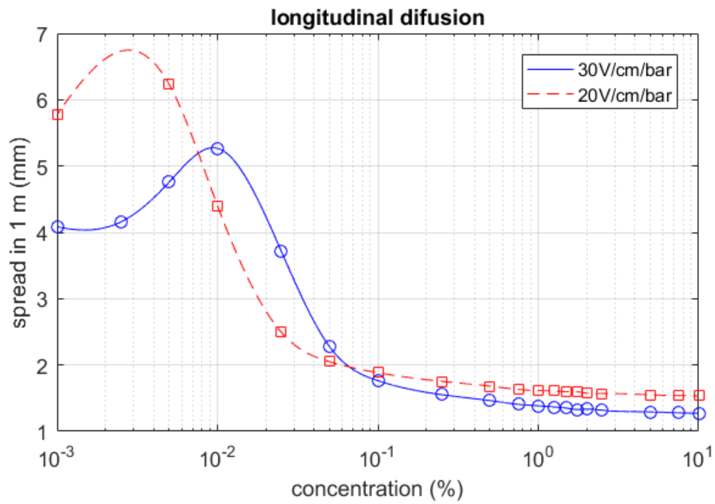
R (3KV), Dt, Dl and v in CH_4

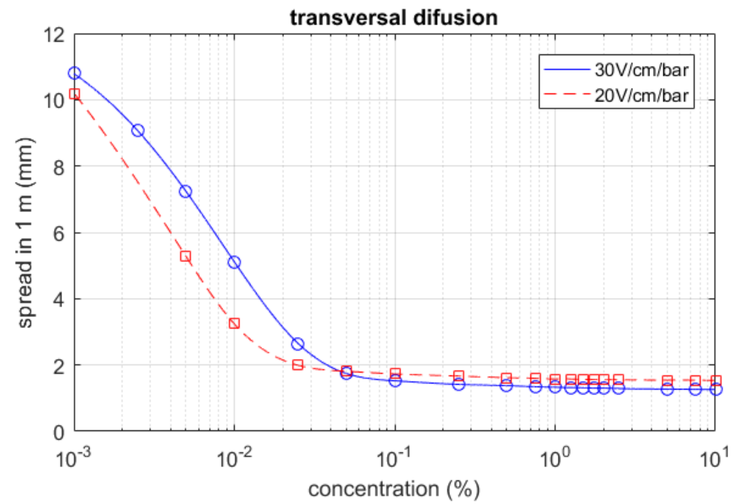


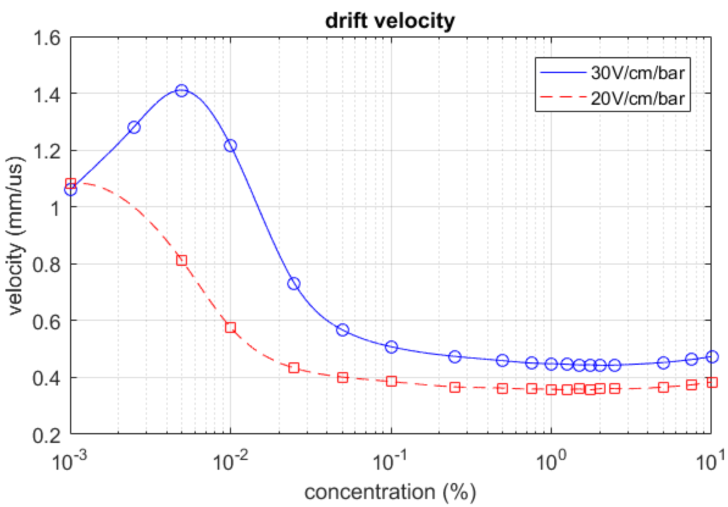
R (3KV) vs D3d and concentration in CH_4

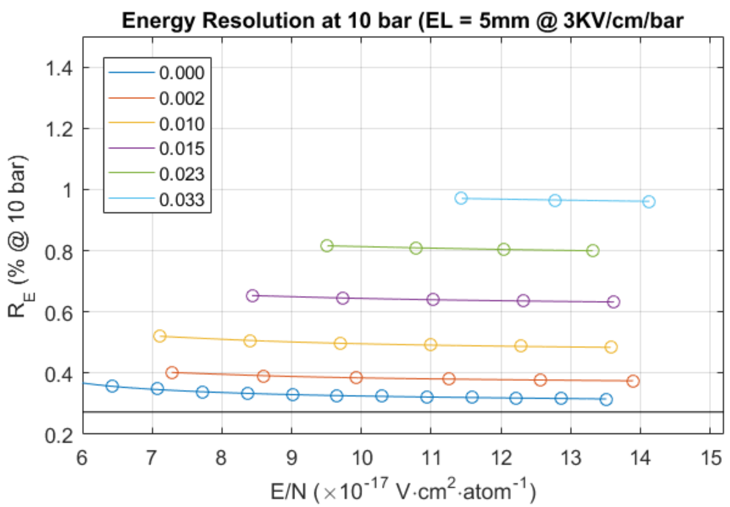


R (3KV), Dt, Dl and v in CF_4

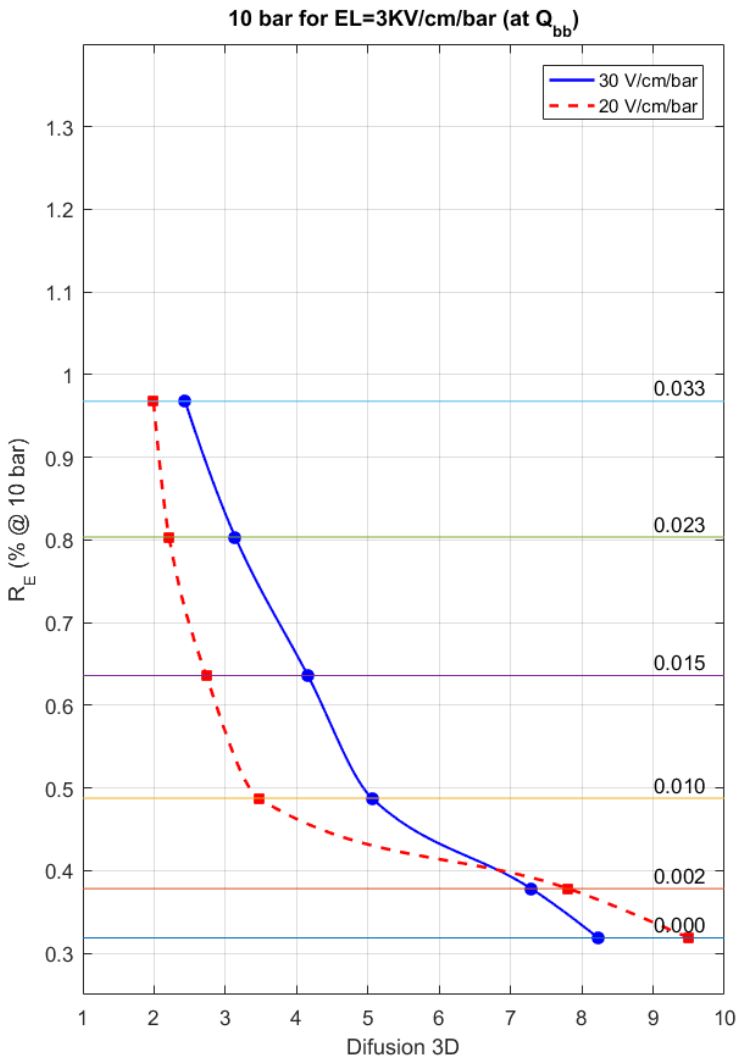


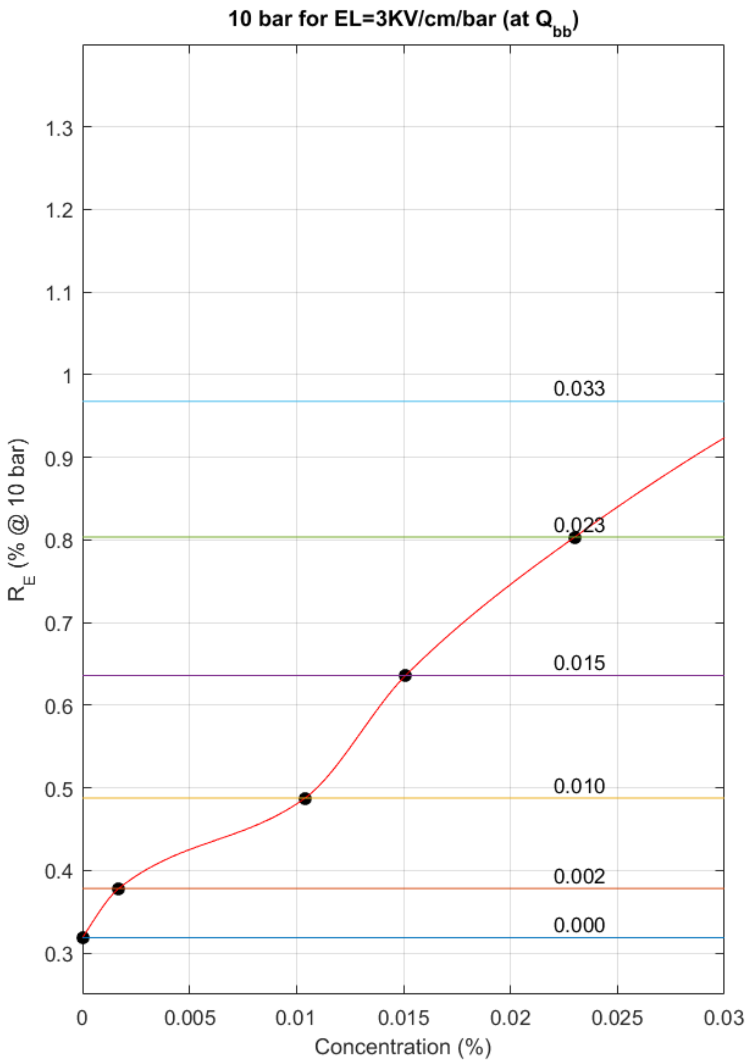




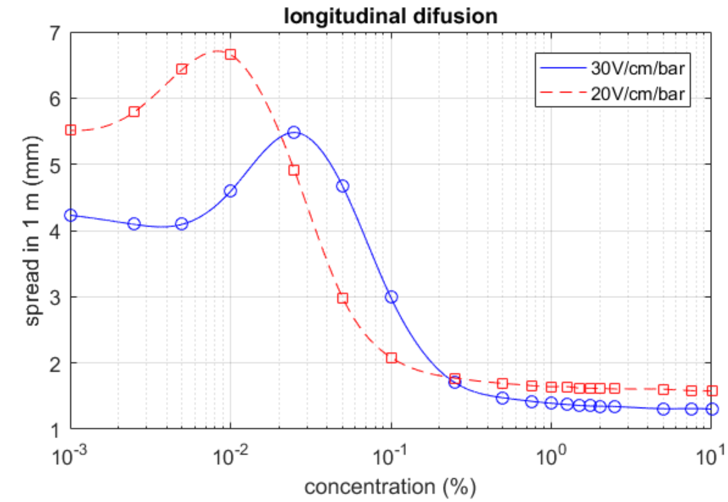


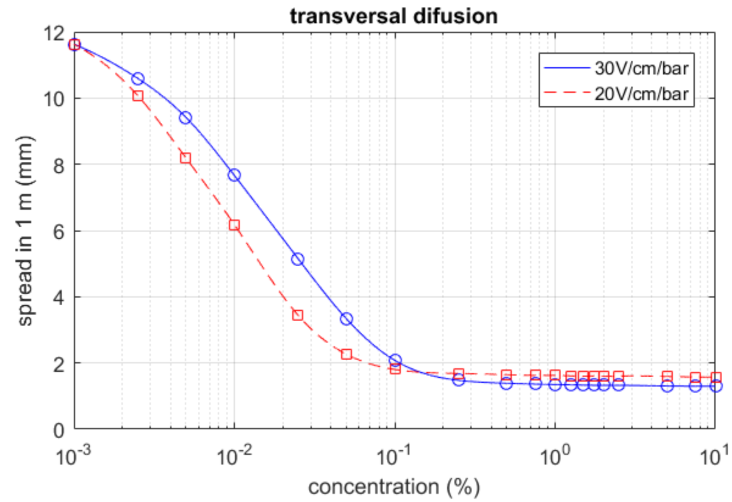
R (3KV), Dt, Dl and v in CH_4

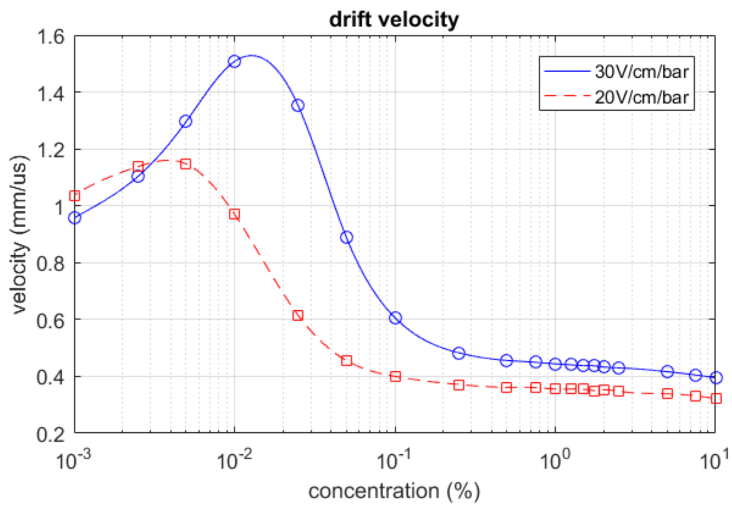


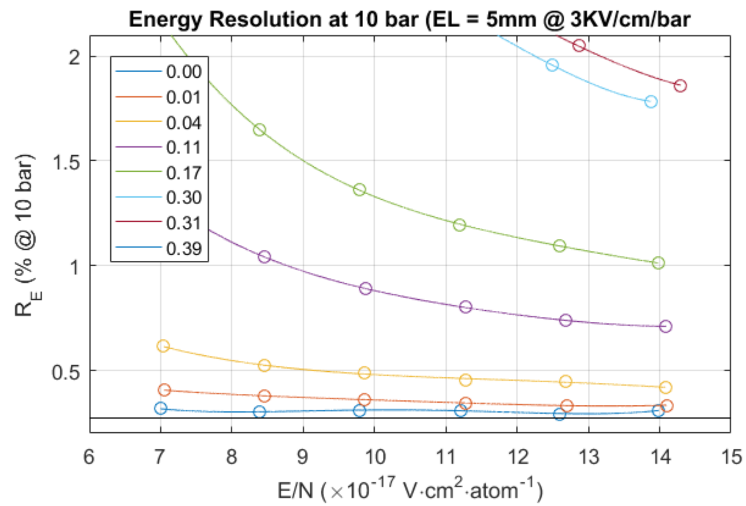


R (3KV), Dt, Dl and v in co_2

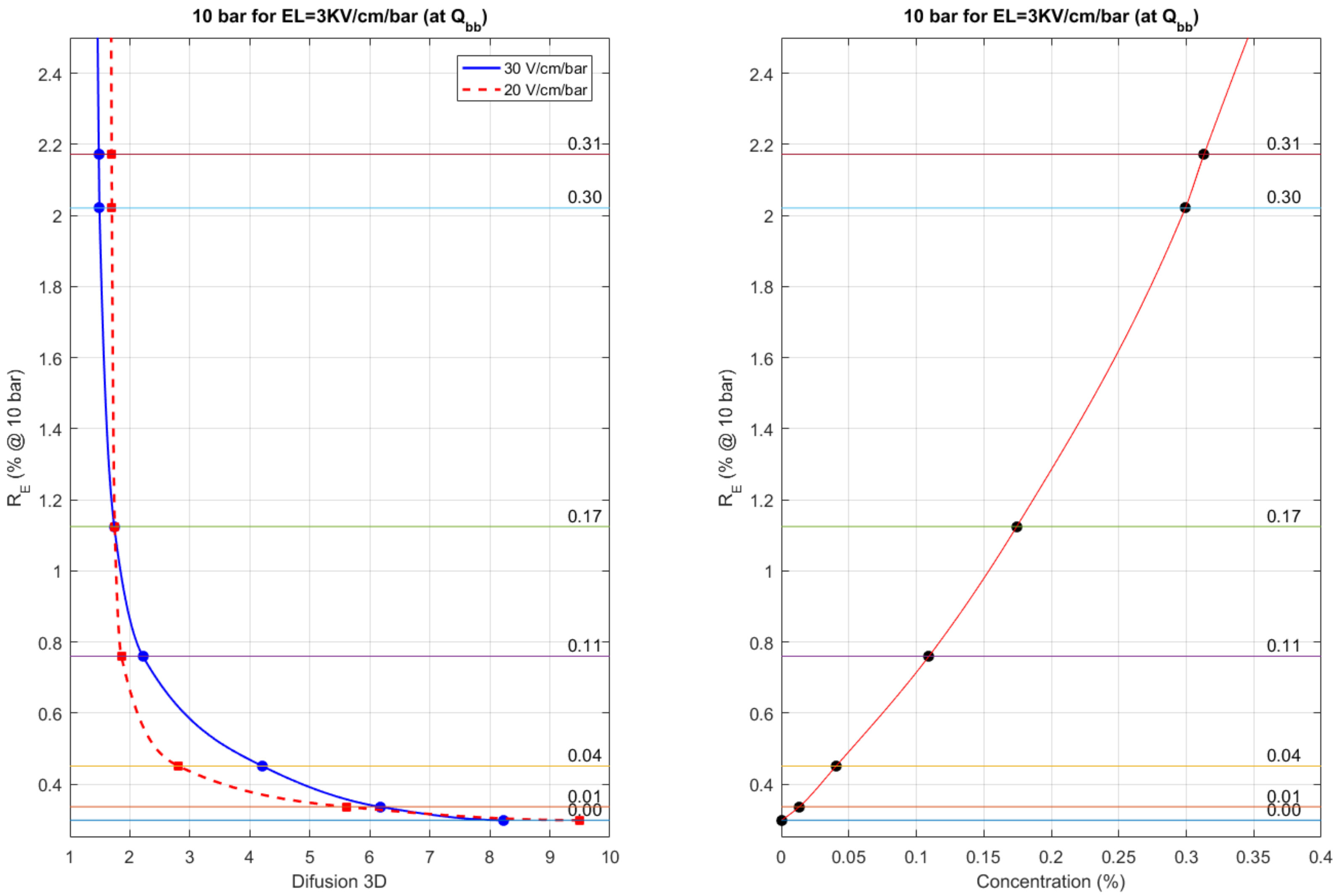




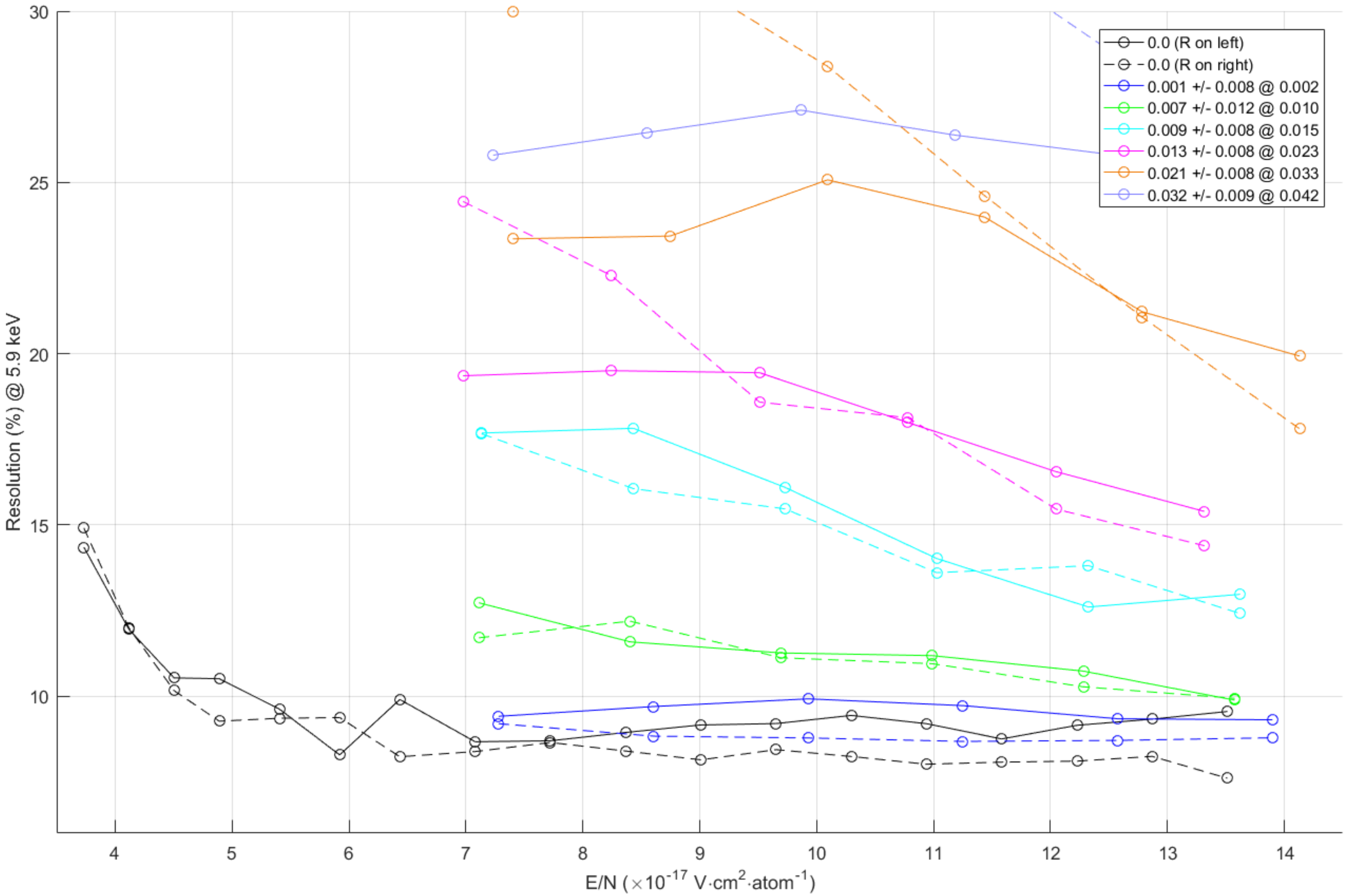




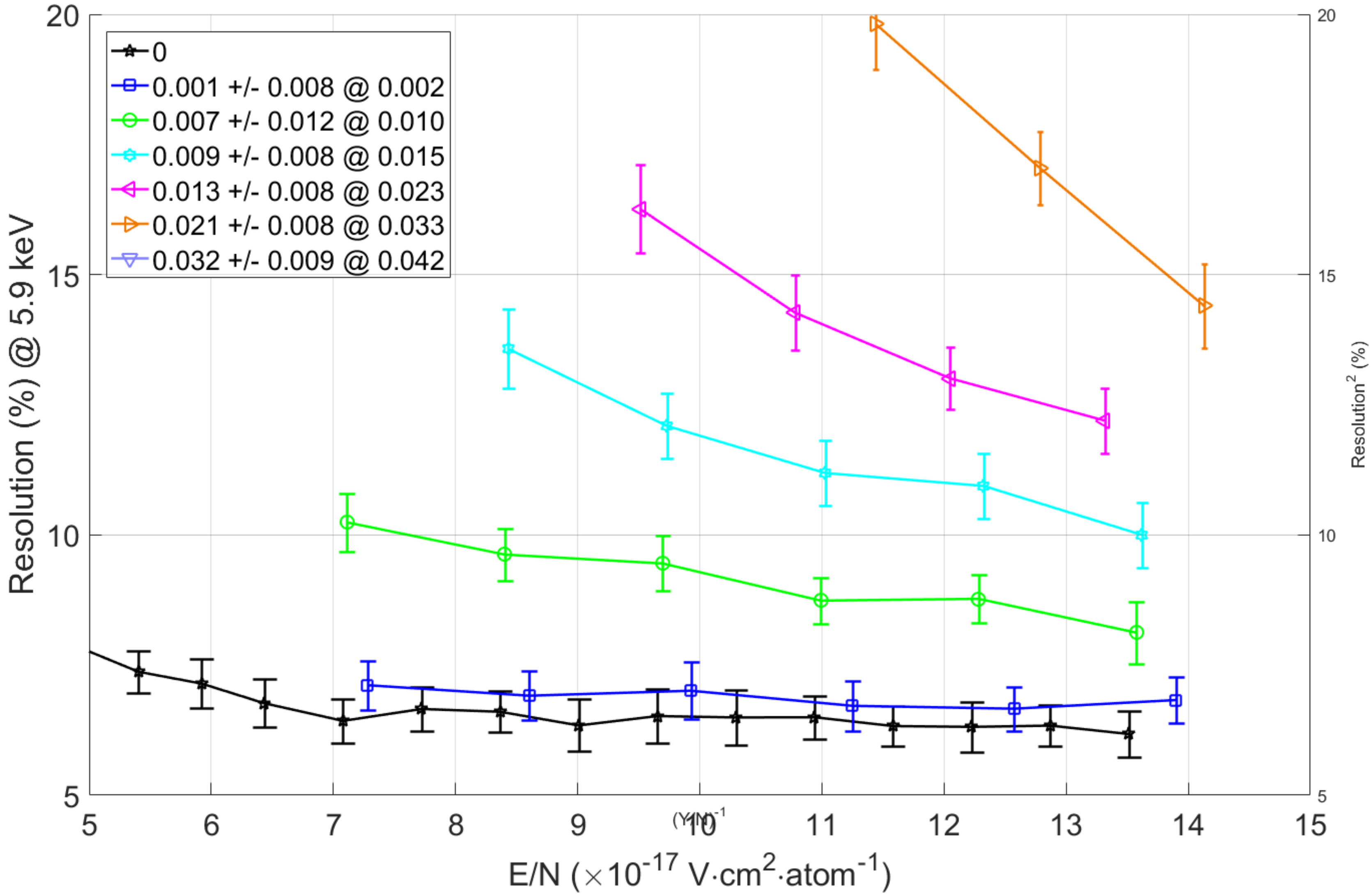
R (3KV), Dt, Dl and v in co_2

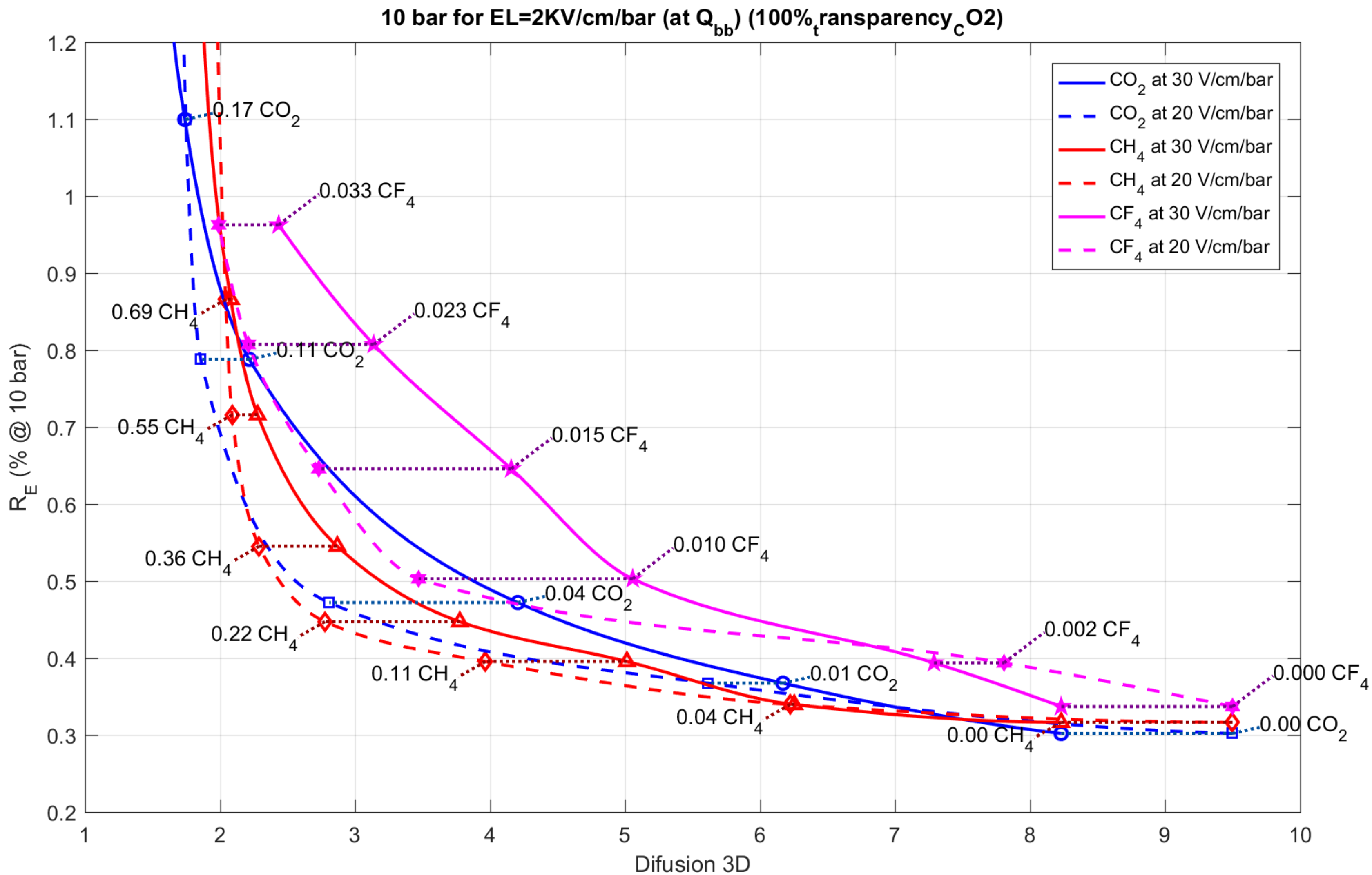


CF_4 right-left real R

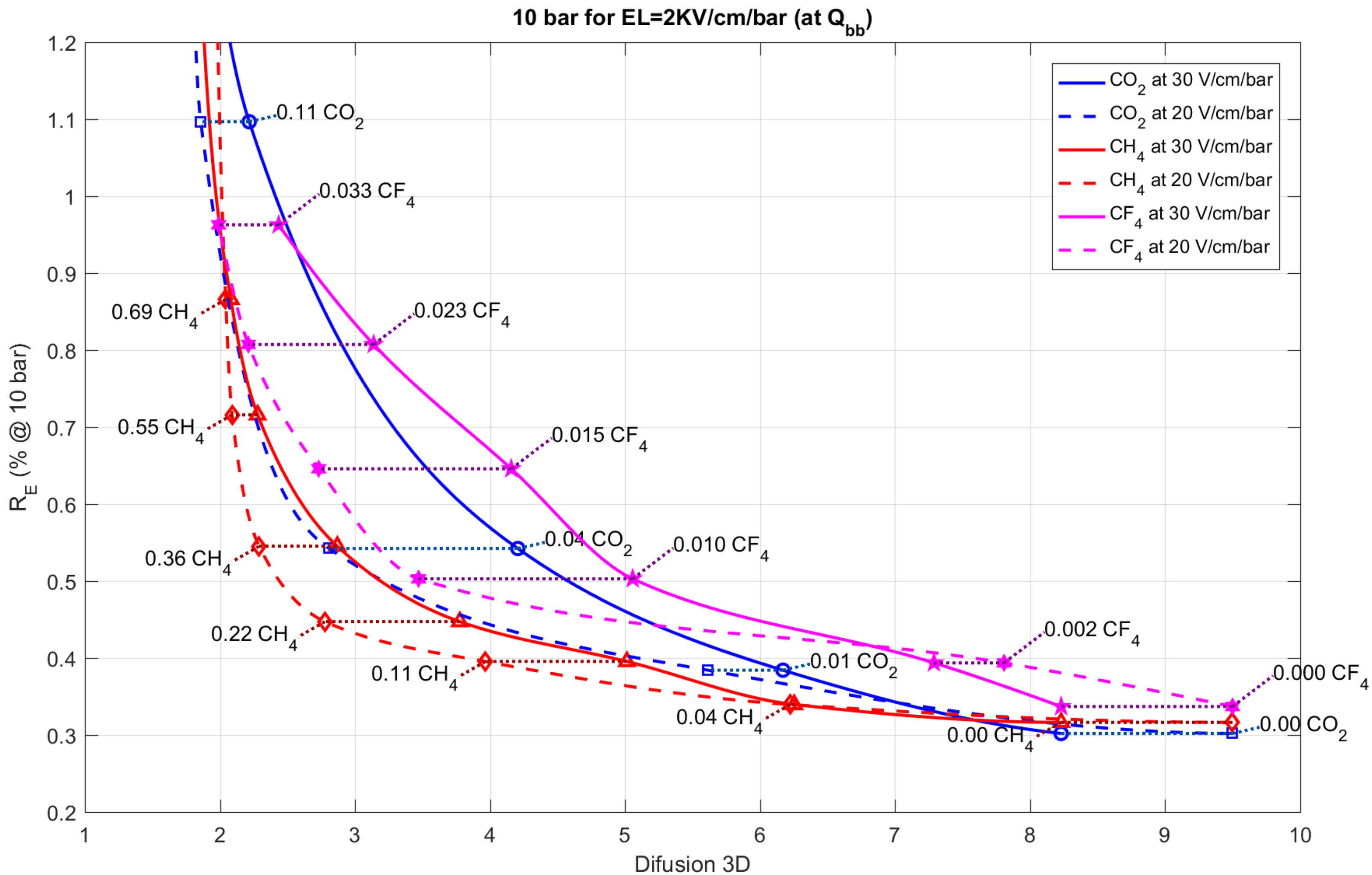


R(z=0) without attachment - CF_4

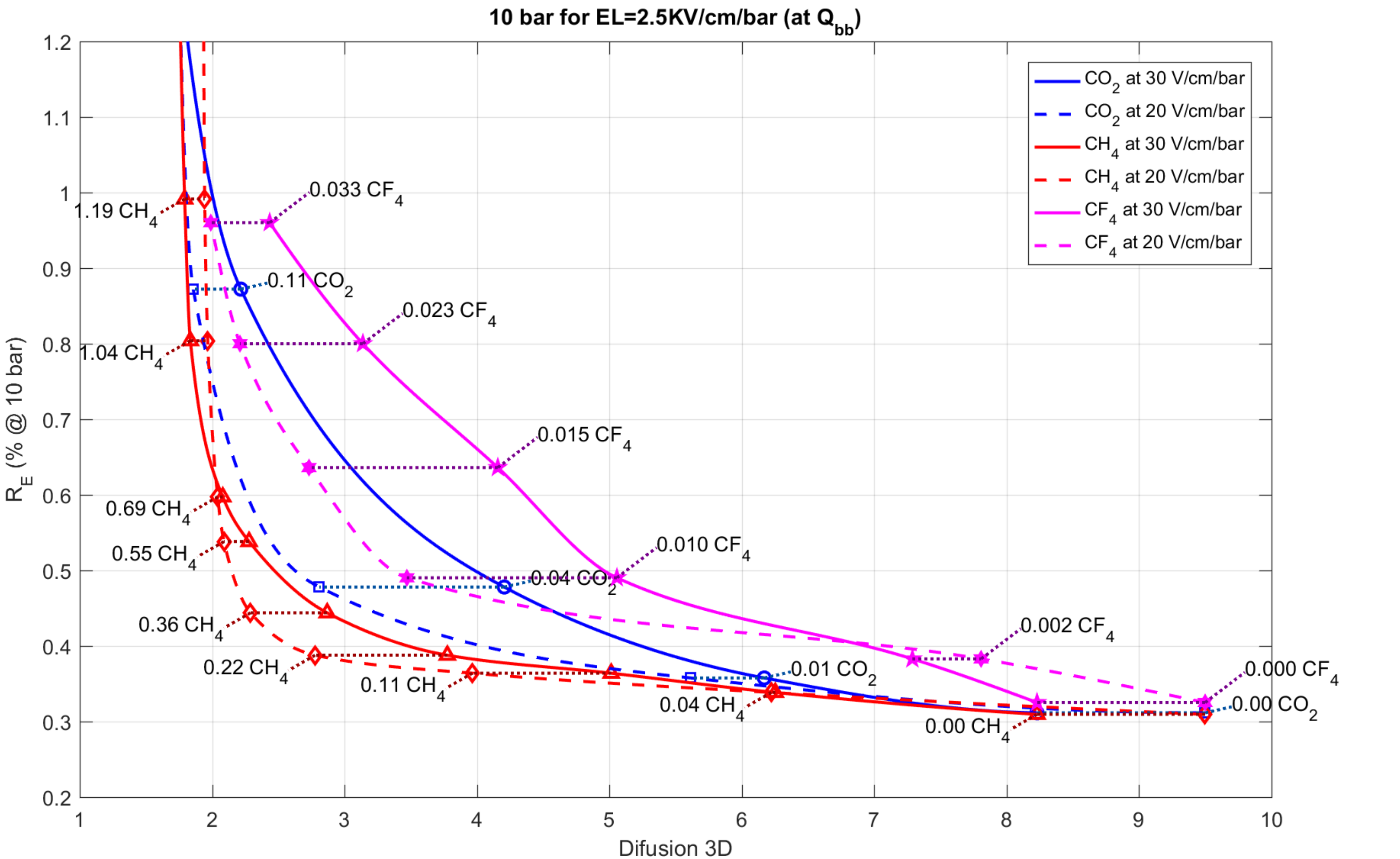




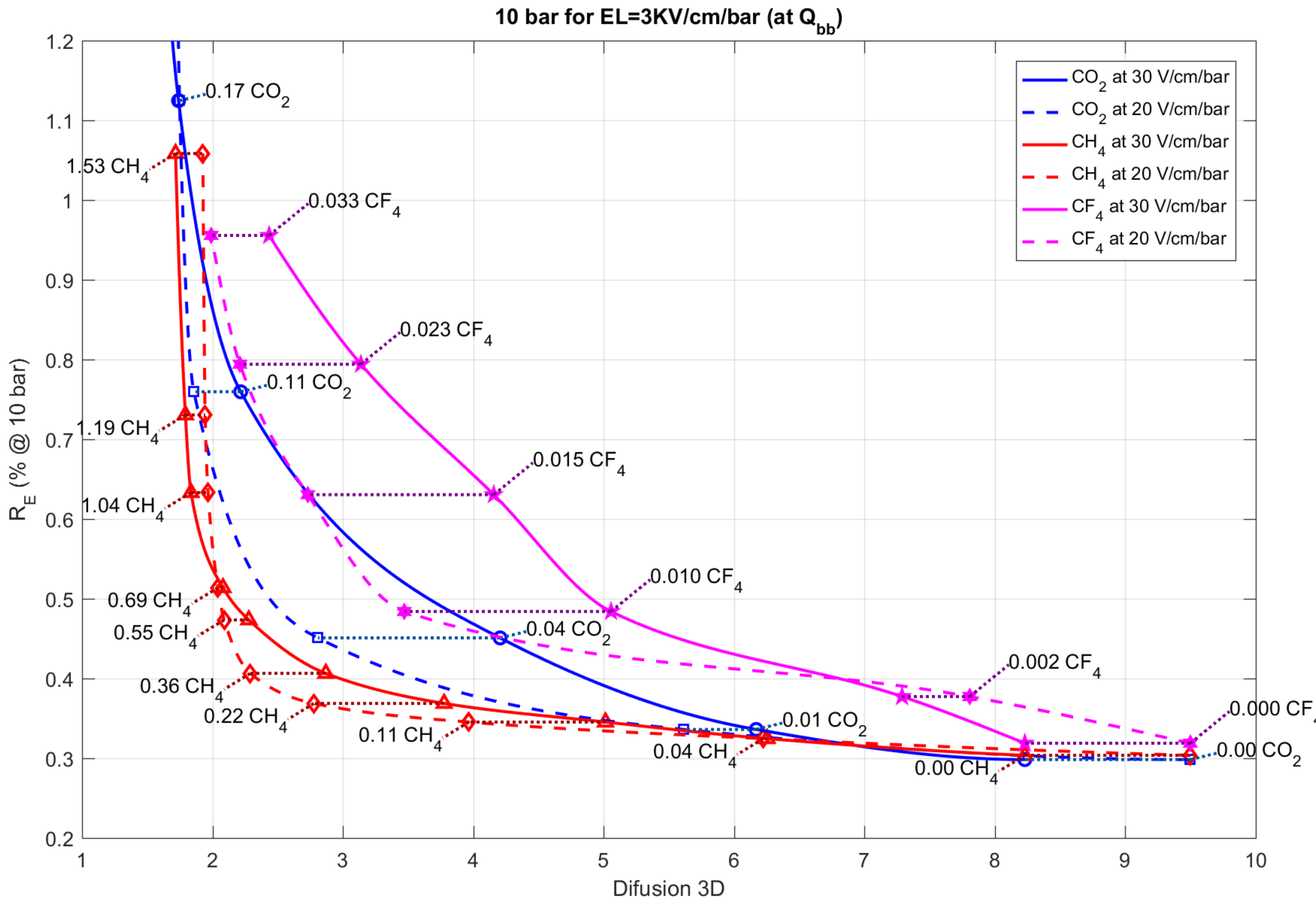
10 bar for EL=2KV/cm/bar (at Q_bb) (100%_transparency_CO2)
CO2 at 30 V/cm/bar
CO2 at 20 V/cm/bar
CH4 at 30 V/cm/bar
CH4 at 20 V/cm/bar
CF4 at 30 V/cm/bar
CF4 at 20 V/cm/bar
0.17 CO2
0.033 CF4
0.69 CH4
0.023 CF4
0.11 CO2
0.55 CH4
0.015 CF4
0.36 CH4
0.010 CF4
0.04 CO2
0.22 CH4
0.002 CF4
0.11 CH4
0.01 CO2
0.000 CF4
0.04 CH4
0.00 CO2
0.00 CH4
R_E (% @ 10 bar)
Difusion 3D
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
1
2
3
4
5
6
7
8
9
10

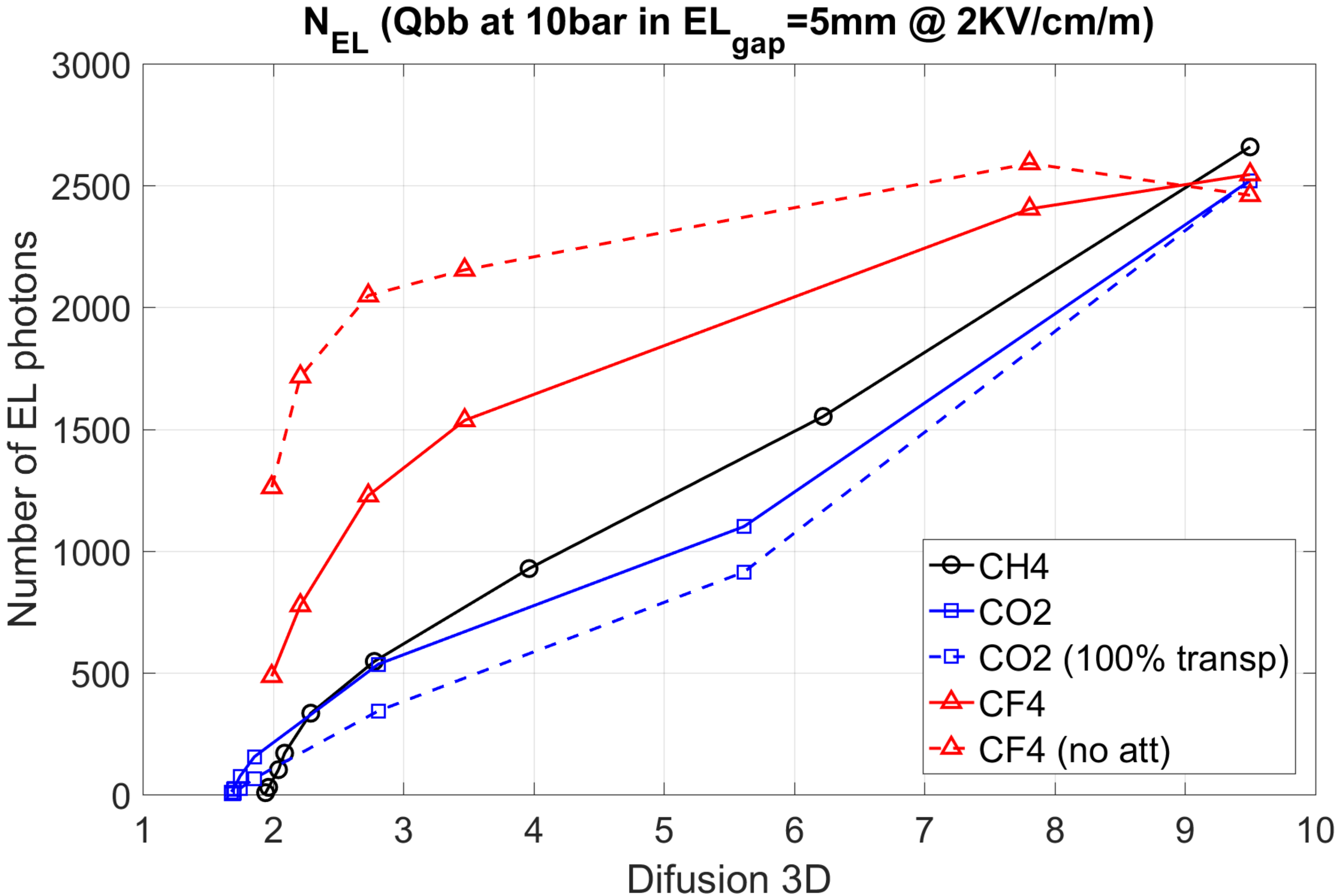


10 bar for EL=2KV/cm/bar (at Q_bb)
R_E (% @ 10 bar)
Difusion 3D
CO2 at 30 V/cm/bar
CO2 at 20 V/cm/bar
CH4 at 30 V/cm/bar
CH4 at 20 V/cm/bar
CF4 at 30 V/cm/bar
CF4 at 20 V/cm/bar
0.11 CO2
0.04 CO2
0.01 CO2
0.00 CO2
0.033 CF4
0.023 CF4
0.015 CF4
0.010 CF4
0.002 CF4
0.000 CF4
0.69 CH4
0.55 CH4
0.36 CH4
0.22 CH4
0.11 CH4
0.04 CH4
0.00 CH4

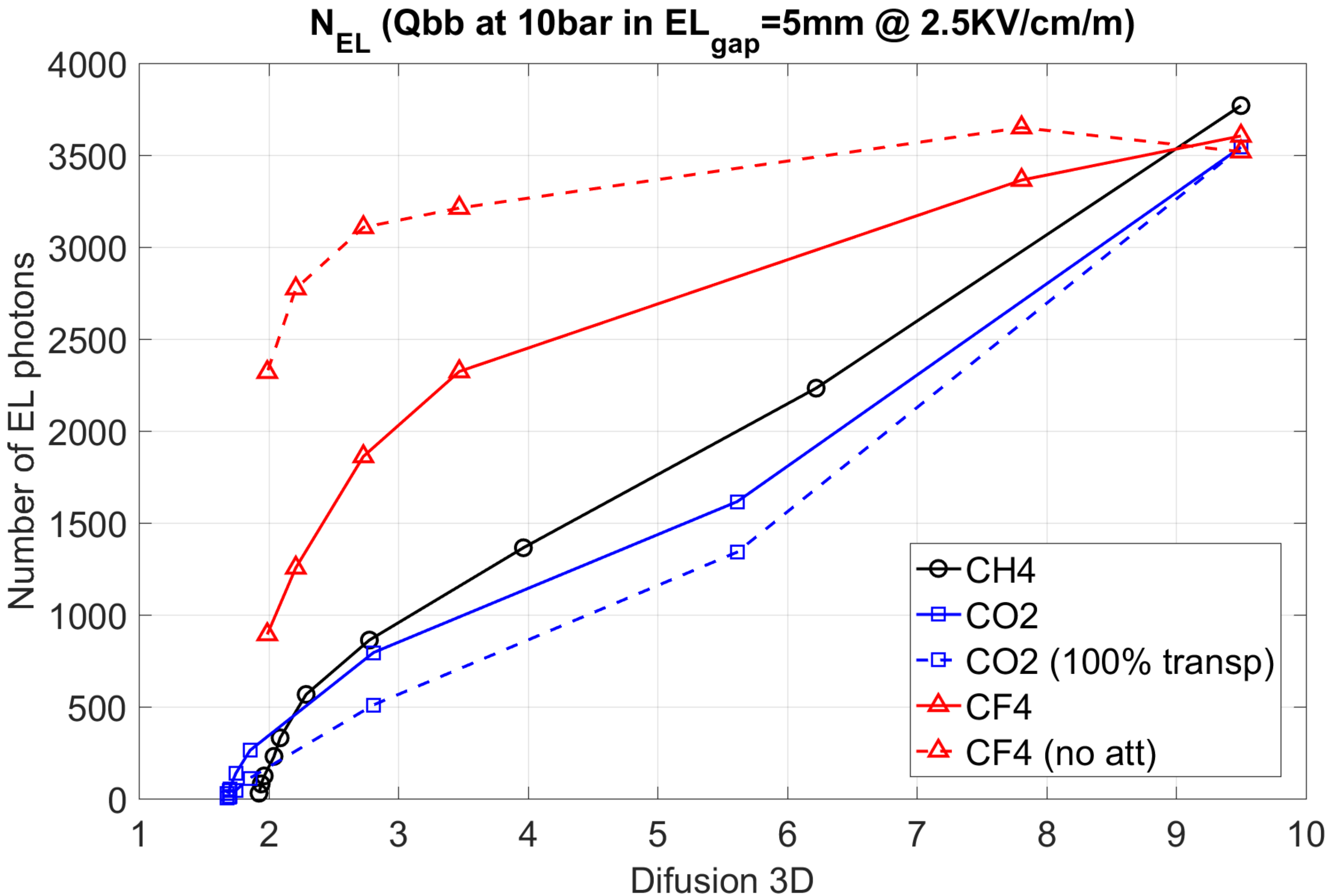


10 bar for EL=2.5KV/cm/bar (at Q_bb)
CO2 at 30 V/cm/bar
CO2 at 20 V/cm/bar
CH4 at 30 V/cm/bar
CH4 at 20 V/cm/bar
CF4 at 30 V/cm/bar
CF4 at 20 V/cm/bar
1.19 CH4
0.033 CF4
0.11 CO2
0.023 CF4
1.04 CH4
0.015 CF4
0.69 CH4
0.55 CH4
0.010 CF4
0.04 CO2
0.36 CH4
0.002 CF4
0.22 CH4
0.11 CH4
0.01 CO2
0.000 CF4
0.04 CH4
0.00 CO2
0.00 CH4
R_E (% @ 10 bar)
Difusion 3D

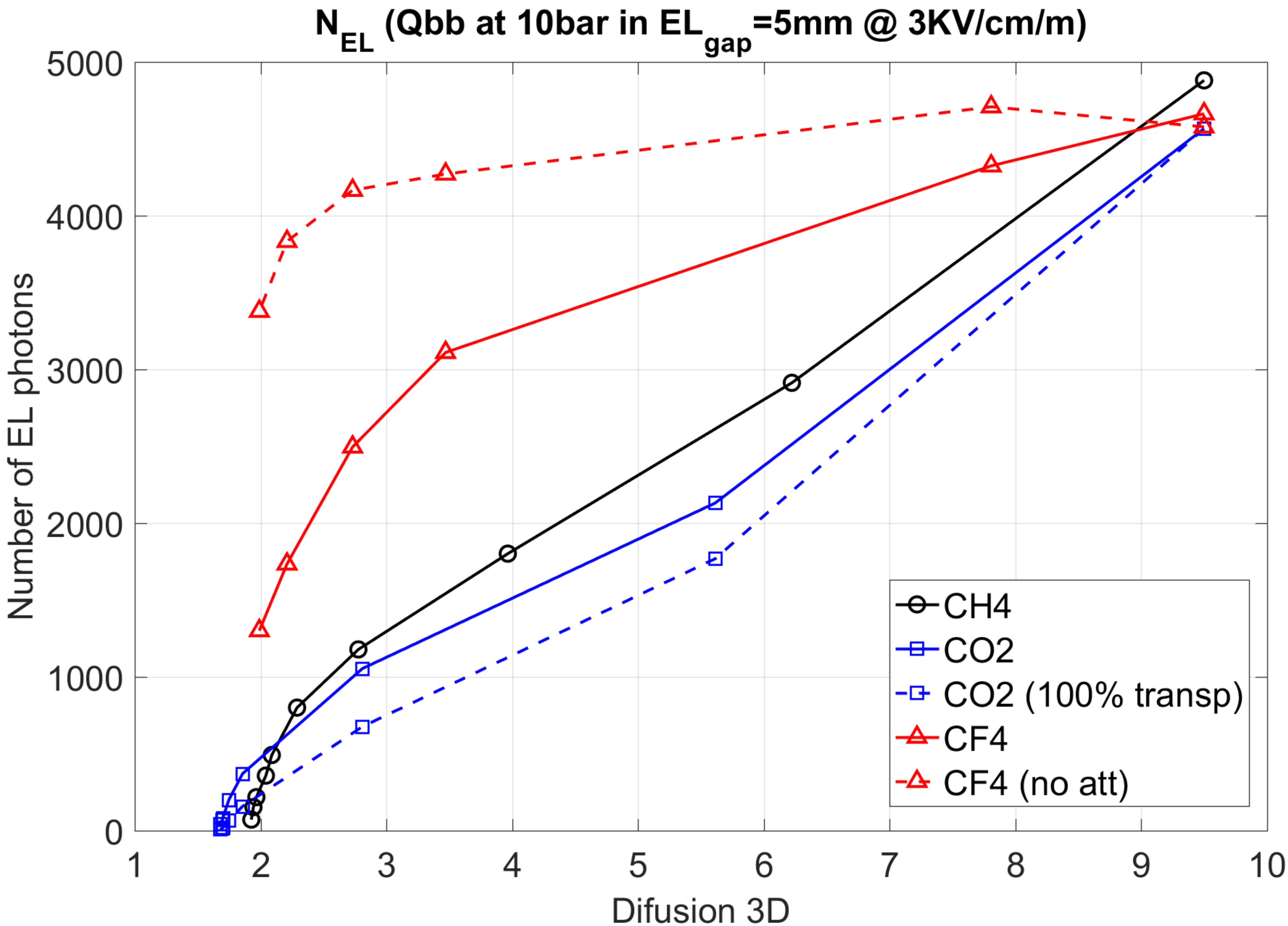

10 bar for EL=3KV/cm/bar (at Q_bb)
R_E (% @ 10 bar)
Difusion 3D
CO2 at 30 V/cm/bar
CO2 at 20 V/cm/bar
CH4 at 30 V/cm/bar
CH4 at 20 V/cm/bar
CF4 at 30 V/cm/bar
CF4 at 20 V/cm/bar
0.17 CO2
0.11 CO2
0.04 CO2
0.01 CO2
0.00 CO2
1.53 CH4
1.19 CH4
1.04 CH4
0.69 CH4
0.55 CH4
0.36 CH4
0.22 CH4
0.11 CH4
0.04 CH4
0.00 CH4
0.033 CF4
0.023 CF4
0.015 CF4
0.010 CF4
0.002 CF4
0.000 CF4



N_{EL} (Qbb at 10bar in EL_{gap}=5mm @ 2KV/cm/m)
3000
2500
2000
1500
1000
500
0
Number of EL photons
1
2
3
4
5
6
7
8
9
10
Difusion 3D
CH4
CO2
CO2 (100% transp)
CF4
CF4 (no att)



N_EL (Qbb at 10bar in EL_gap=5mm @ 2.5KV/cm/m)
Number of EL photons
Difusion 3D
0
500
1000
1500
2000
2500
3000
3500
4000
1
2
3
4
5
6
7
8
9
10
CH4
CO2
CO2 (100% transp)
CF4
CF4 (no att)



N$_{EL}$ (Qbb at 10bar in EL$_{gap}$=5mm @ 3KV/cm/m)
Number of EL photons
0
1000
2000
3000
4000
5000
1
2
3
4
5
6
7
8
9
10
Difusion 3D
CH4
CO2
CO2 (100% transp)
CF4
CF4 (no att)