Advantages of Operating your TPC at the Drift Velocity Maximum and the Properties of P2

Philip Hamacher-Baumann

ND-GAr: HPgTPC+ECAL Weekly Meeting

2022

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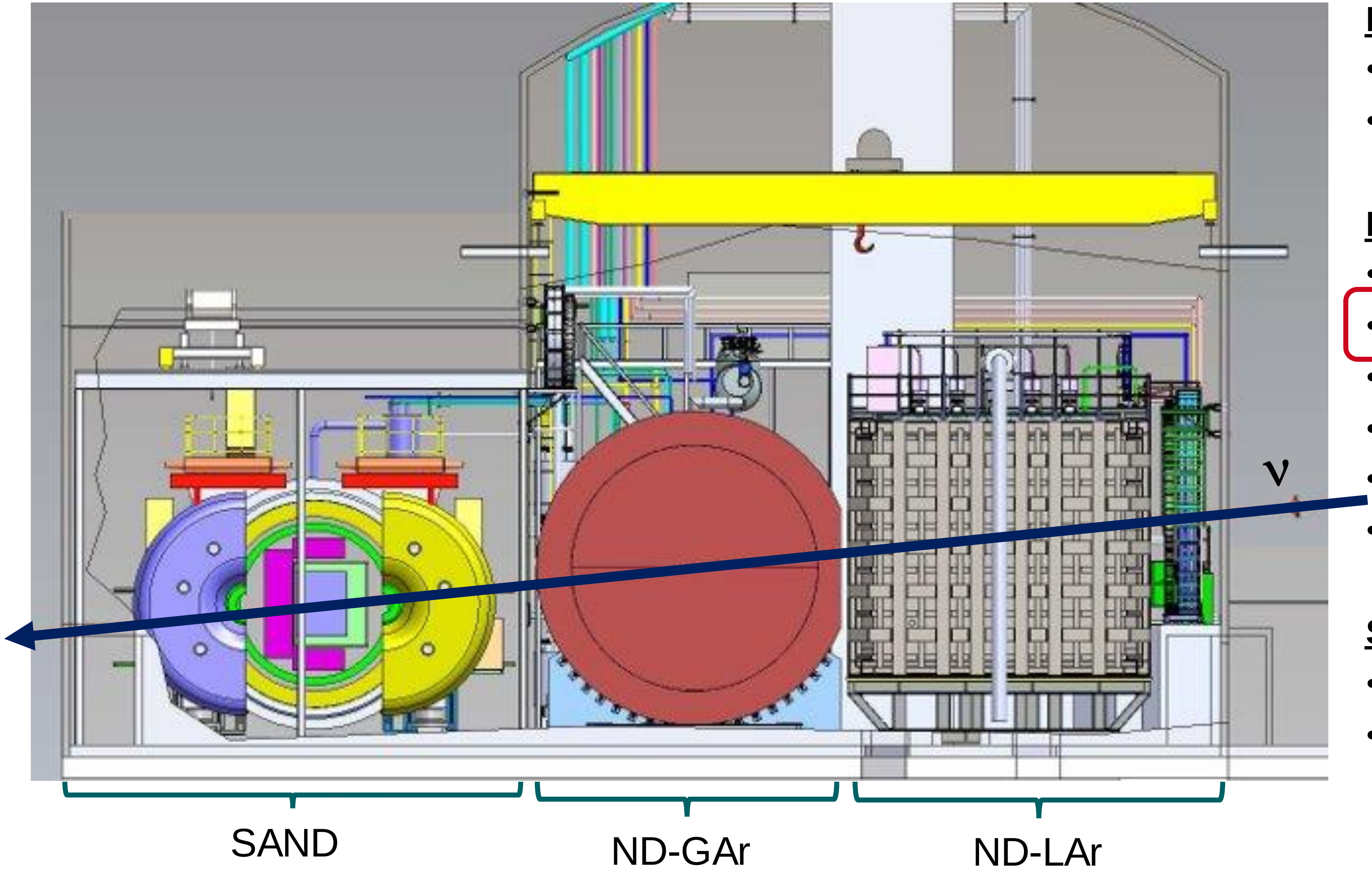
The DUNE Near Detector



ND-LAr

- Liquid Argon TPC
- Not magnetized

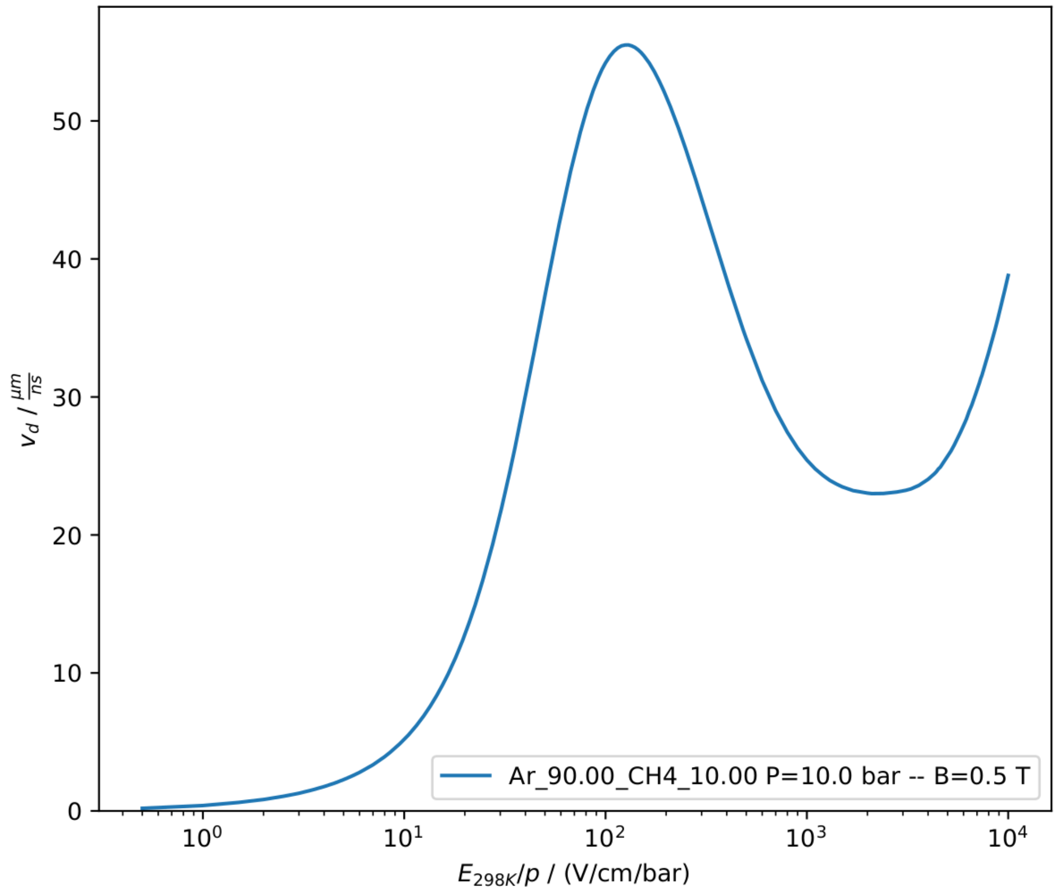
ND-GAr

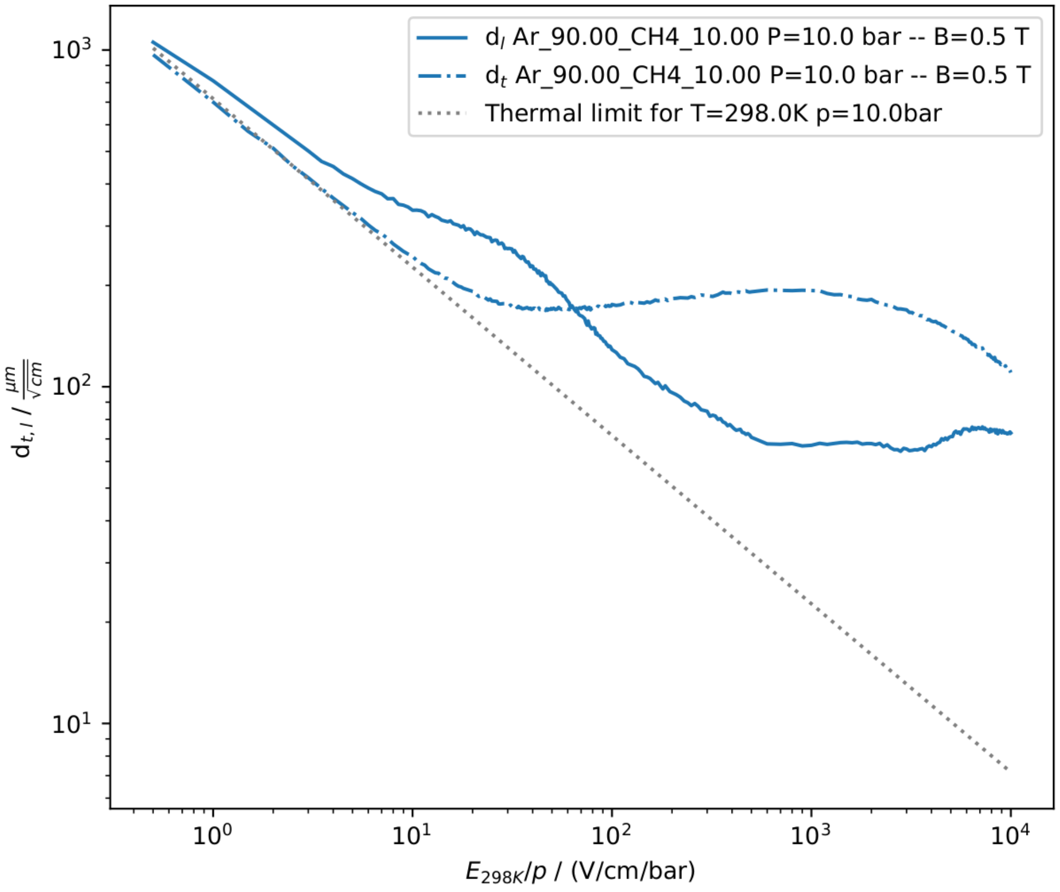
- High pressure TPC
- *Baseline mixture P10 (Ar + 10% CH_4)*
- Magnetized + contains an ECAL
- Spectrometer for particles leaving ND-LAr
- Additional ν-Ar measurements
- *Very low tracking threshold*

SAND

- Permanently on-axis beam monitor
- Magnetized

Properties of P10 under ND-GAr Conditions





Maximum in v_d at 130 V/cm/bar
= 1300 V/cm at 10 bar

Diffusion very low across all fields

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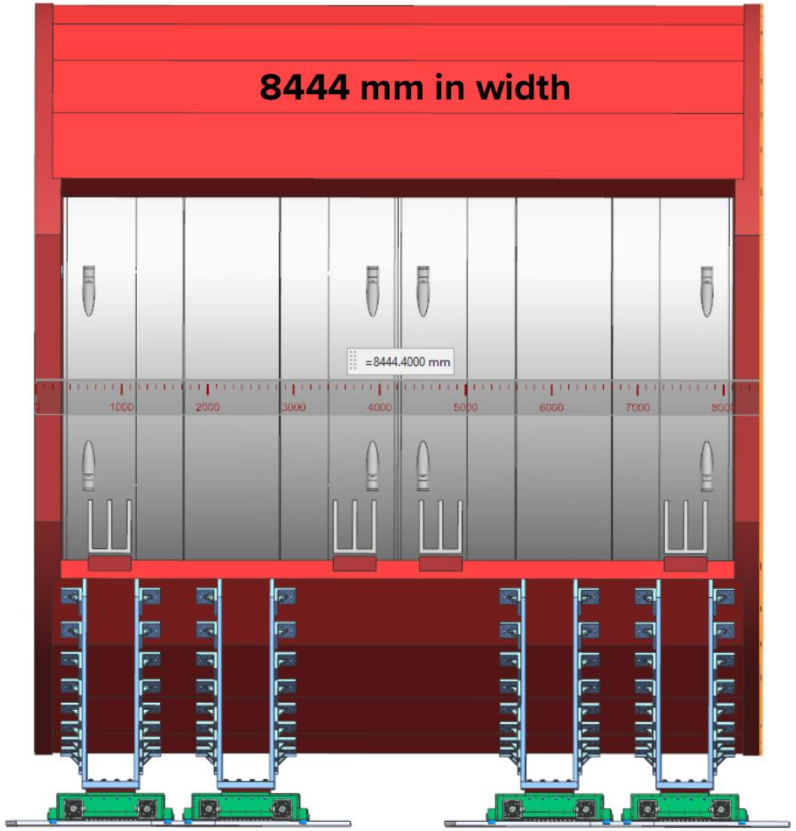
TPC Gas in DUNE's ND-GAr Detector



Drift distance *5m* or *2.5m*

Maximum in v_d for most stable for operation, at *2.5 m* drift:

- P10: 130 V/cm/bar -> 325 kV on cathode
- P2: 50 V/cm/bar -> 125 kV on cathode

And twice that for single anode 5m drift.

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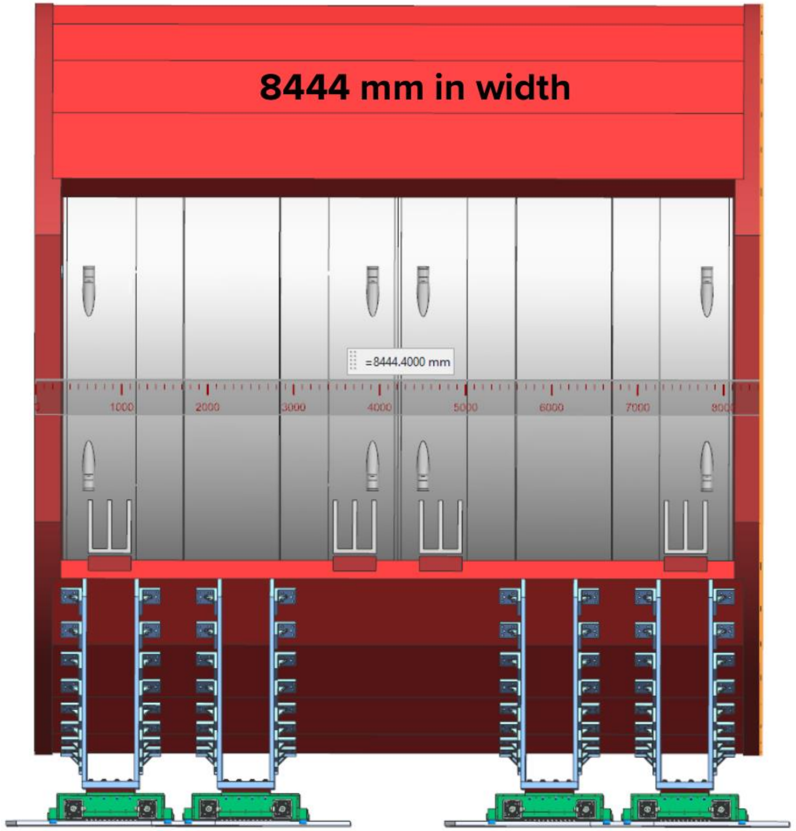
TPC Gas in DUNE's ND-GAr Detector



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And twice that for single anode 5m drift.

Maybe we don't need to operate at the drift velocity maximum then?

Advantages of Operating at the Drift Velocity Maximum

Short Reminder: Density Scaling in Gaseous Detectors

Most experienced at atmospheric conditions

Swarm parameters depend on T and p (+ also E)

- averages of microscopic e- atom/molecule collisions
- change in mean free path affects all parameters

All swarm parameters depend on the gas density.

n~p/T

magnitude	scaling ($n = N/N_0$)
electron, ion drift velocity v_d	$v_d(E/n)$
electron, ion diffusion coefficients $D^*_{L,T}$	$\frac{1}{\sqrt{n}} D^*_{L,T}(E/n)$
attachment coefficient η	$n \cdot \eta(E/n)$ *a
Light transparency $\mathcal{T}$	$\exp(-n\Pi_a L^*)$
scintillation probability P_{scin}	$\frac{1}{1+n\tau k}$
particle range R	R/n
Fano factor F_e, W_I, W_{ex}	$\sim$ constant
charge multiplication coefficient α	$n \cdot \alpha(E/n)$ *b
secondary scintillation coefficient Y	$n \cdot Y(E/n)$ *b

arxiv:1710.01018 [3]

Note:
B~B/n

Perks of Operation at Drift Velocity Maximum: Density Control

Pressure control:

No problem – TPC in pressure vessel

High flow, high precision dome regulators

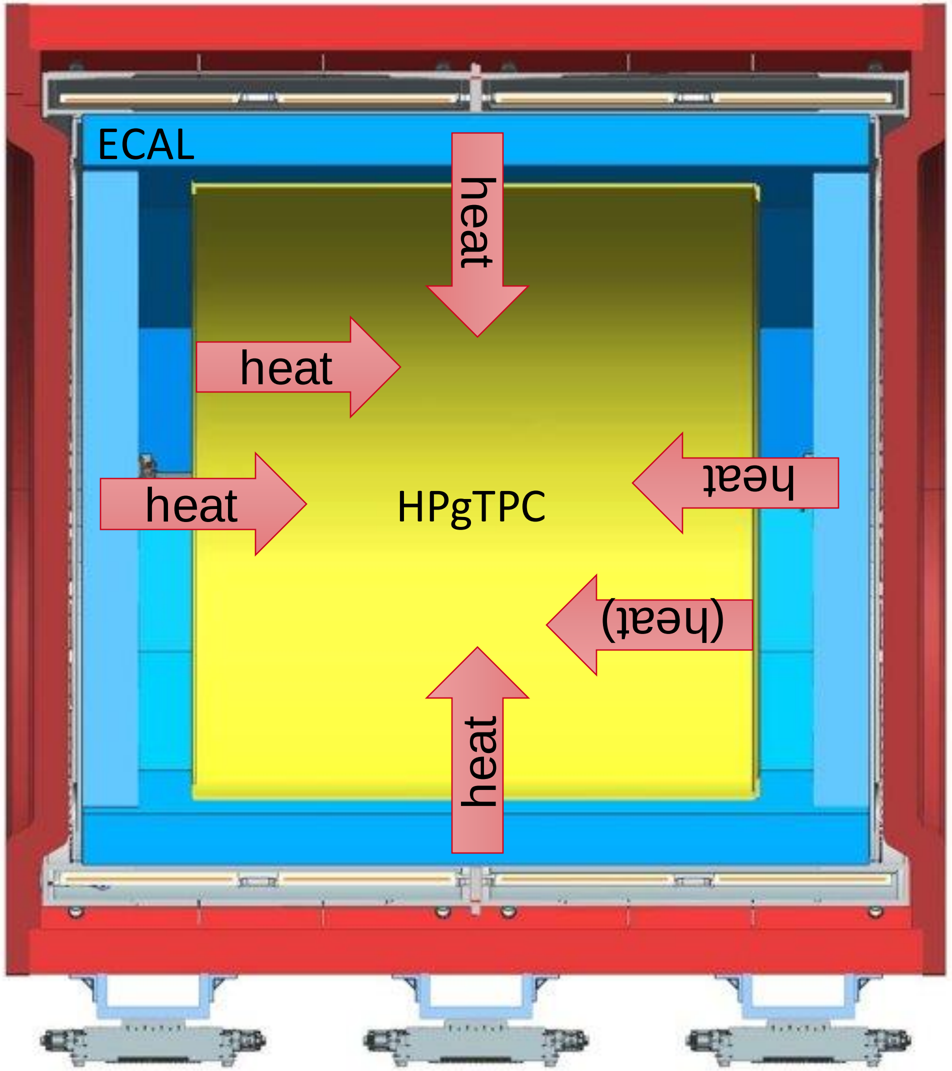
Various spring-loaded regulators

Perks of Operation at Drift Velocity Maximum: Density Control

<u>Pressure control:</u>
No problem – TPC in pressure vessel

<u>Temperature control:</u>
Electronics / ECAL *inside* of vessel
Could mean large temperature gradients

Q:
Without any temperature control, what is the spread of v_d at a constant E/p?
Assume T from 0°C to 60°C



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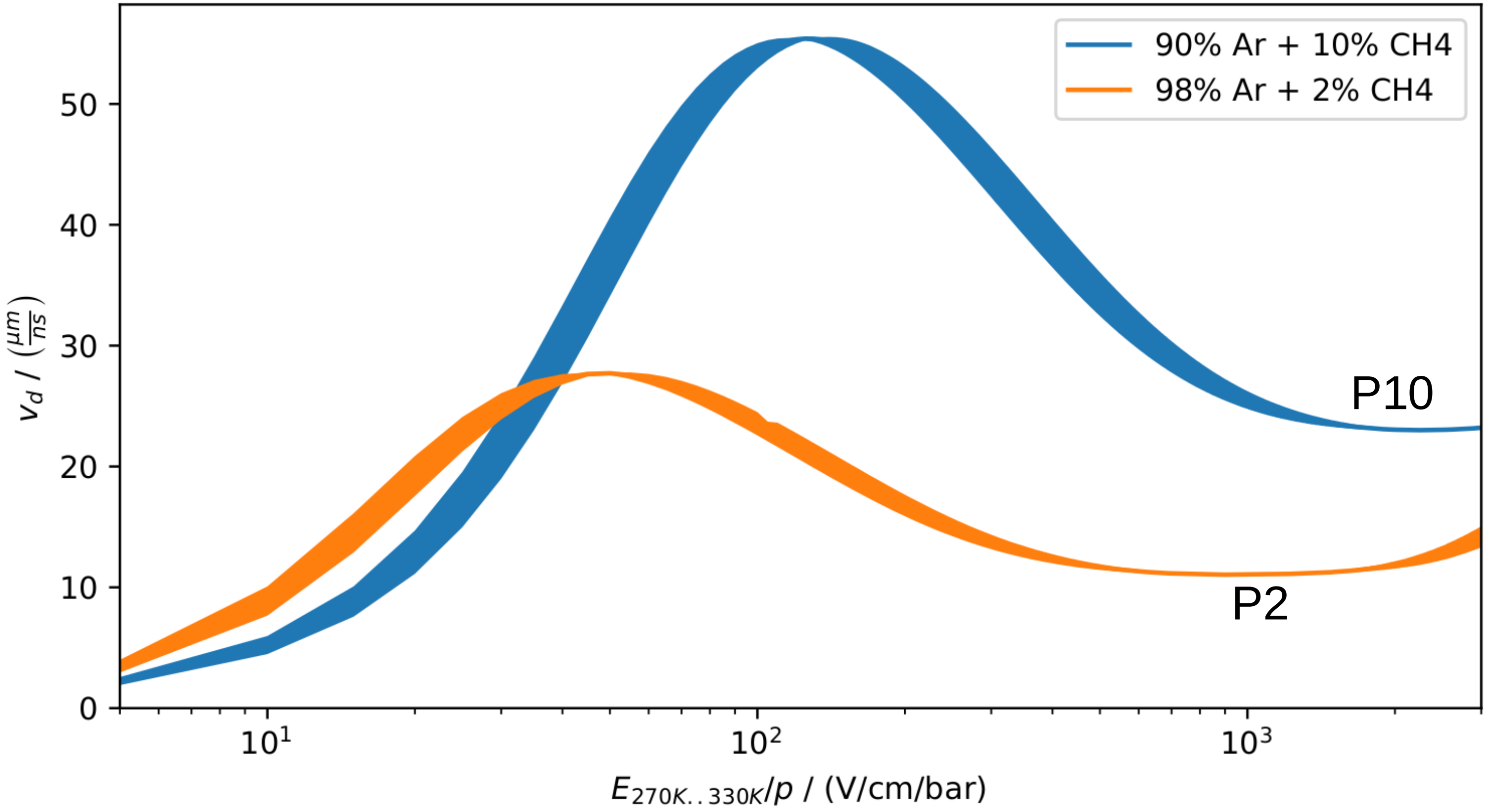
A:
Basically negligible at v_d^{max}!
Ignoring T elsewhere can add *O*(10cm) error!



Height of v_d curve at constant E/p is resulting temperature error.

Perks of Operation at Drift Velocity Maximum: Density Control

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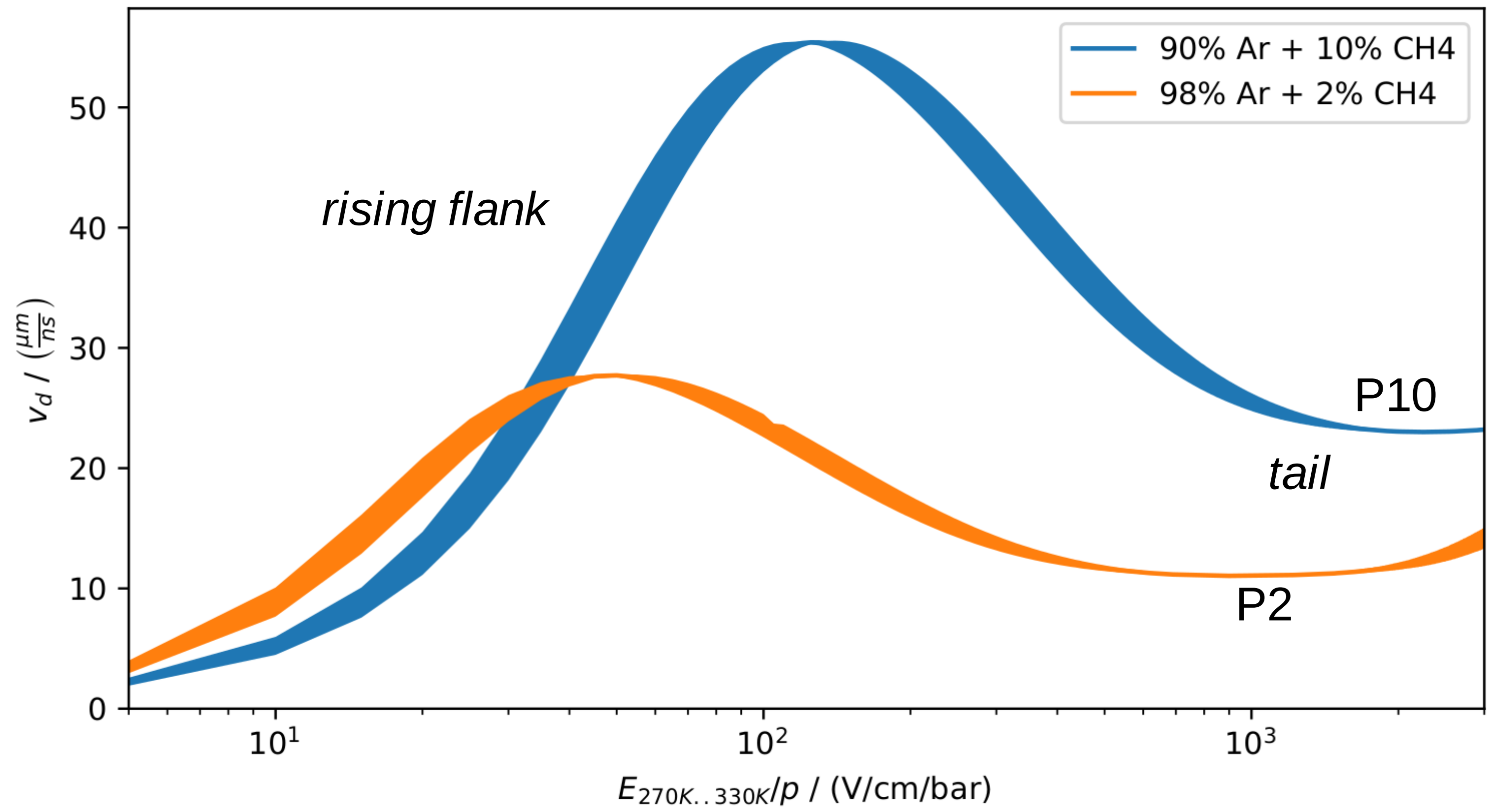


Height of v_d curve at constant E/p is resulting temperature error.

Perks of Operation at Drift Velocity Maximum: Impact of Outgassing

1.5 bar P10

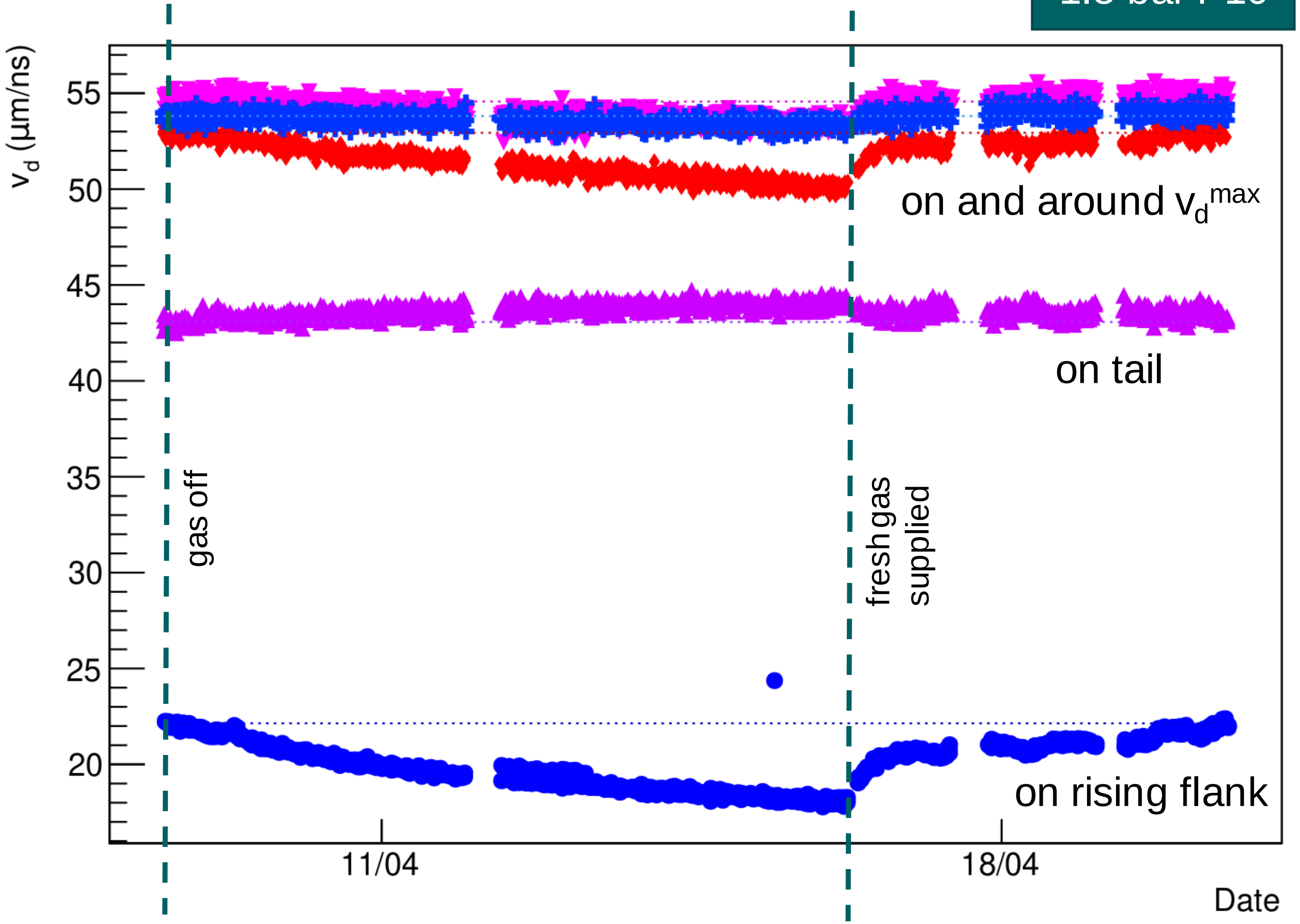
Estimating effect of gas purity in HPGMC:

1. Completely shut off gas
2. Repeat measurements
3. Watch for deterioration

Outgassing accumulates quicker at low pressures

- At 1.5bar, the change in v_d is:
  - -20% at lowest field
  - **-2% at v_d^{max}**
  - +2% for highest field

Sum of e⁻-gas xsec *lowest* around v_d^{max}, yet influence of impurities is **not higher**, but **lower** through this!



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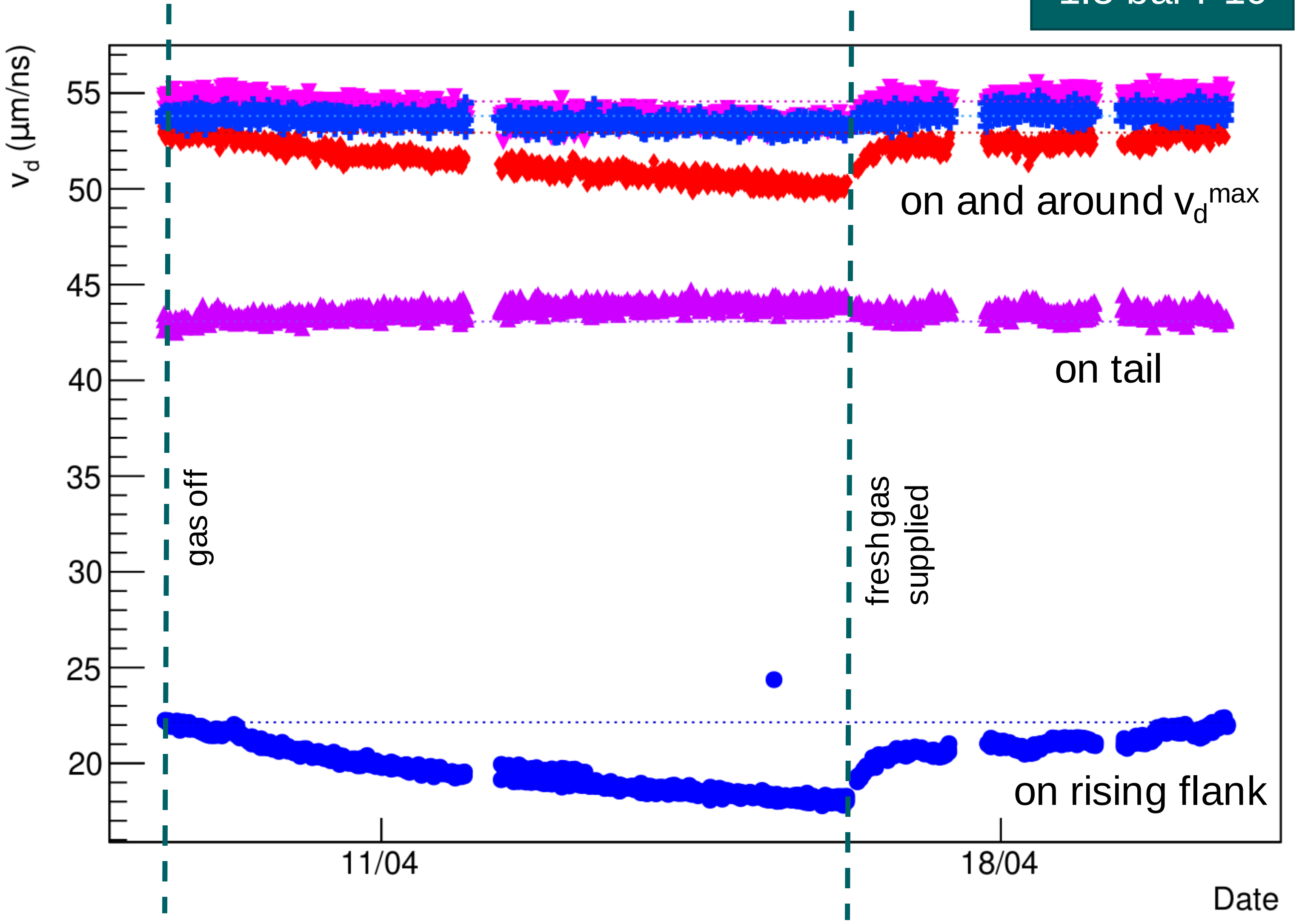
So how can we get ND-GAr to operate at a v_d maximum?



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Ar:CH_4 Mixtures with low CH_4 Fraction

Properties of Argon:Methane Mixtures at $E_{drift}(v_d^{max})$: Drift Velocity

Which value do we want?

Common shape of $Ar:CH_4$ mixtures

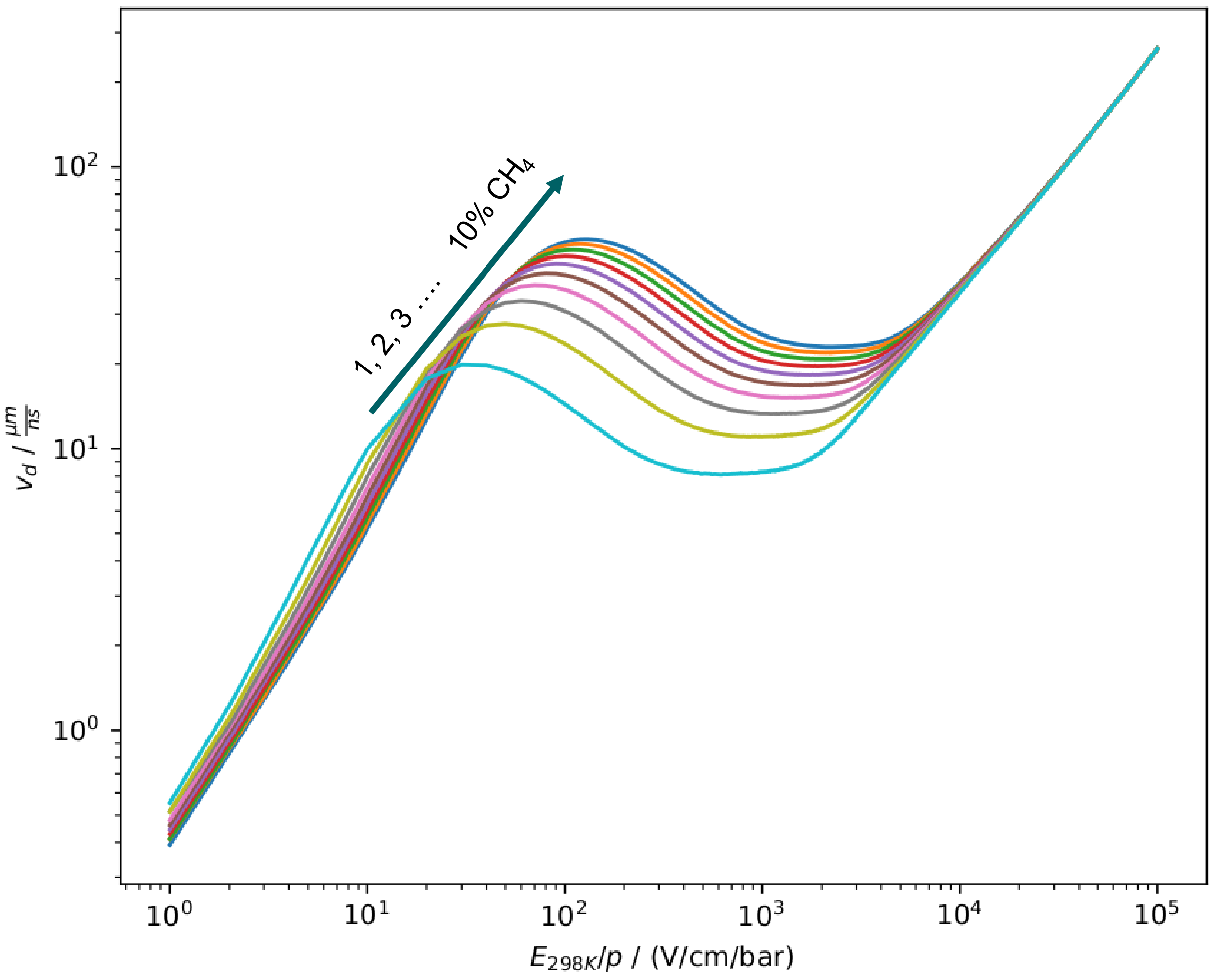
- CH_4 content scales v_d and shifts E/p
- High CH_4 = high v_d^{max}
- And vice-versa

Drift velocity determines "pile-up" between spills

- Beam arrives at ~1Hz
- Spills never overlap: $1^{\mu m}/_{ns} = 1000^{m}/_{s}$

Each spill has a substructure

- 1µs spacing (my guess?)
- Separatable with v_d=2500(5000)$^{\mu m}/_{ns}$ = unreachable



No real v_d criteria derivable from beam, can go solely by cathode voltage argument (2% CH_4).

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Properties of Argon:Methane Mixtures at $E_{drift}(v_d^{max})$

Like E/p scaling, magnetic field also scales B~B/n

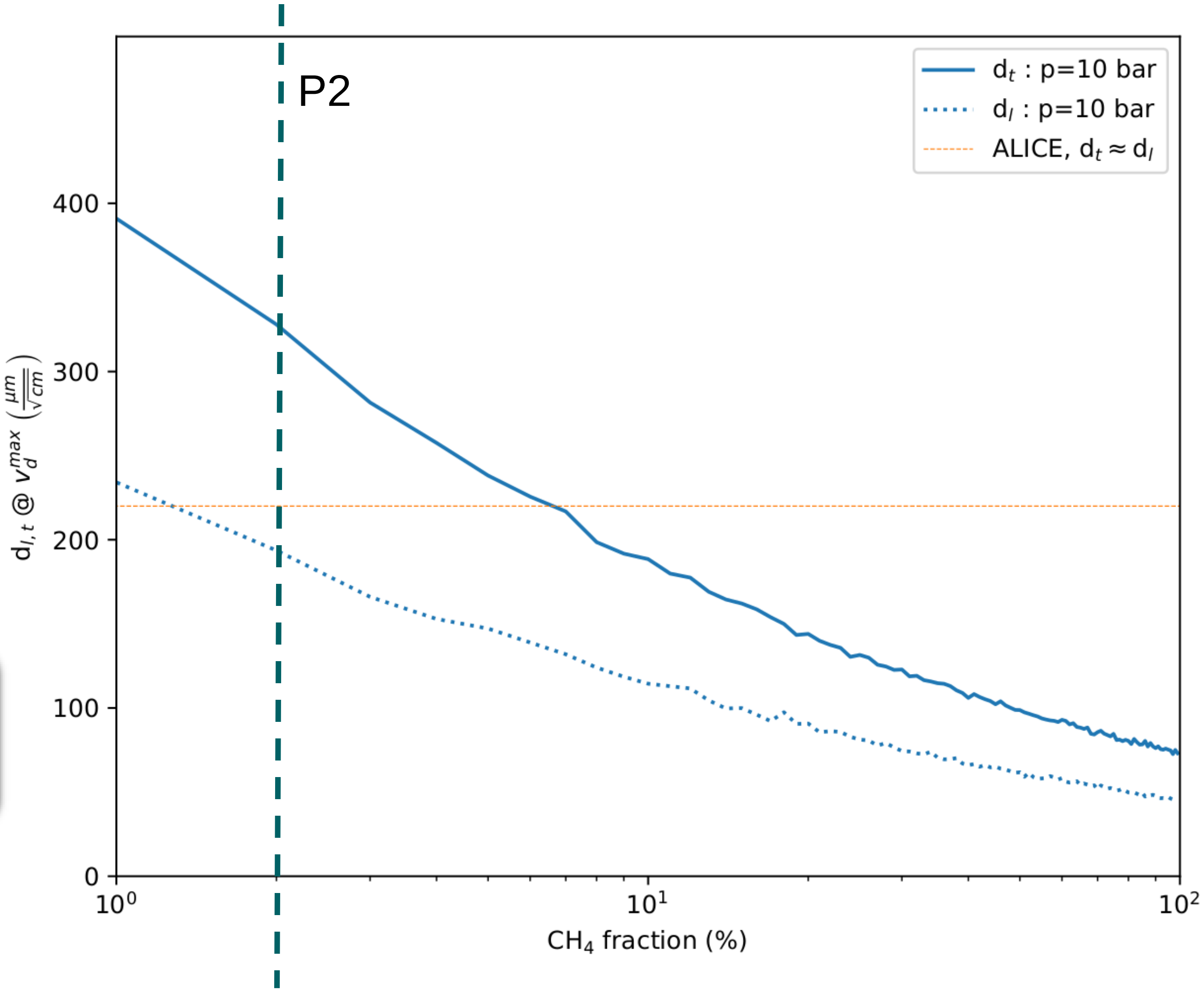
- 10 bar and 0.5 T only reduced d_t by ~1%
- B field still mandatory for sign selection

Longitudinal diffusion below ALICE reference

Transversal diffusion is larger:

- Point charge spread after 250cm (500cm): 5.5 mm (7.8mm)
- ½ to 1 pad size

Diffusion heavily suppressed by pressure scaling - even for P2 and low fields.



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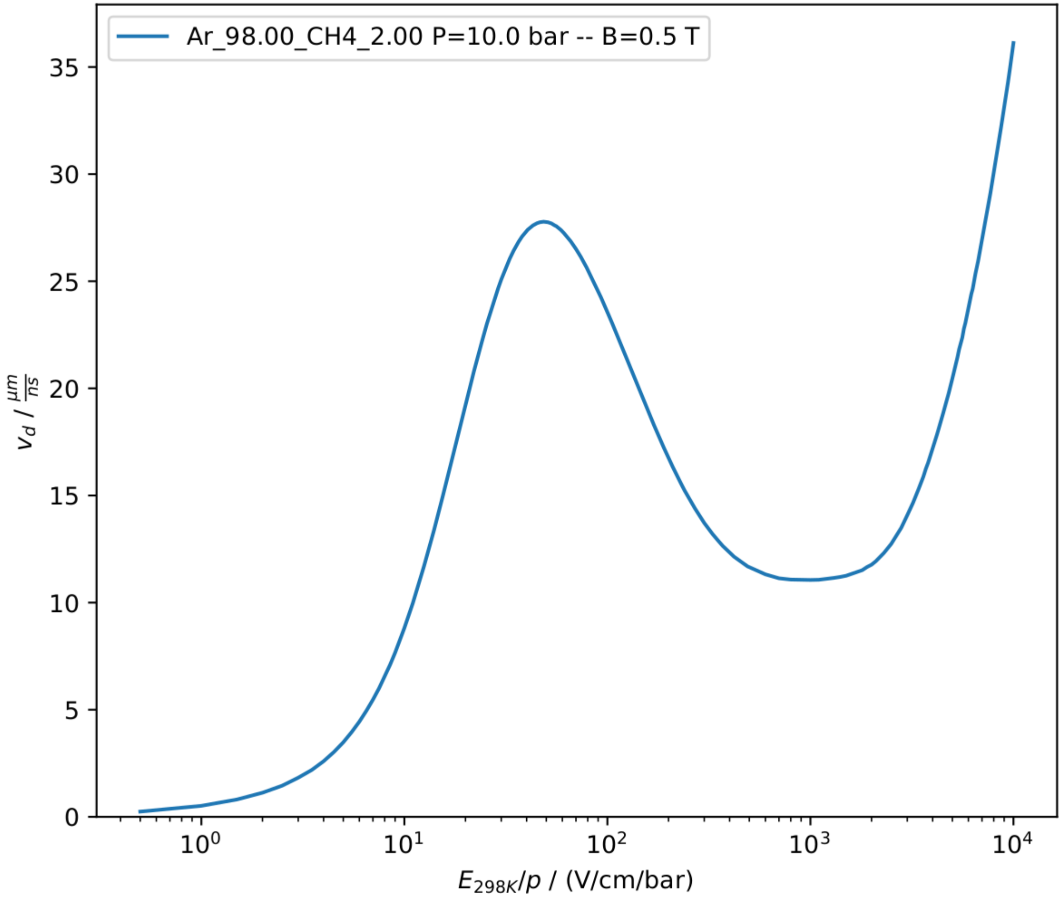
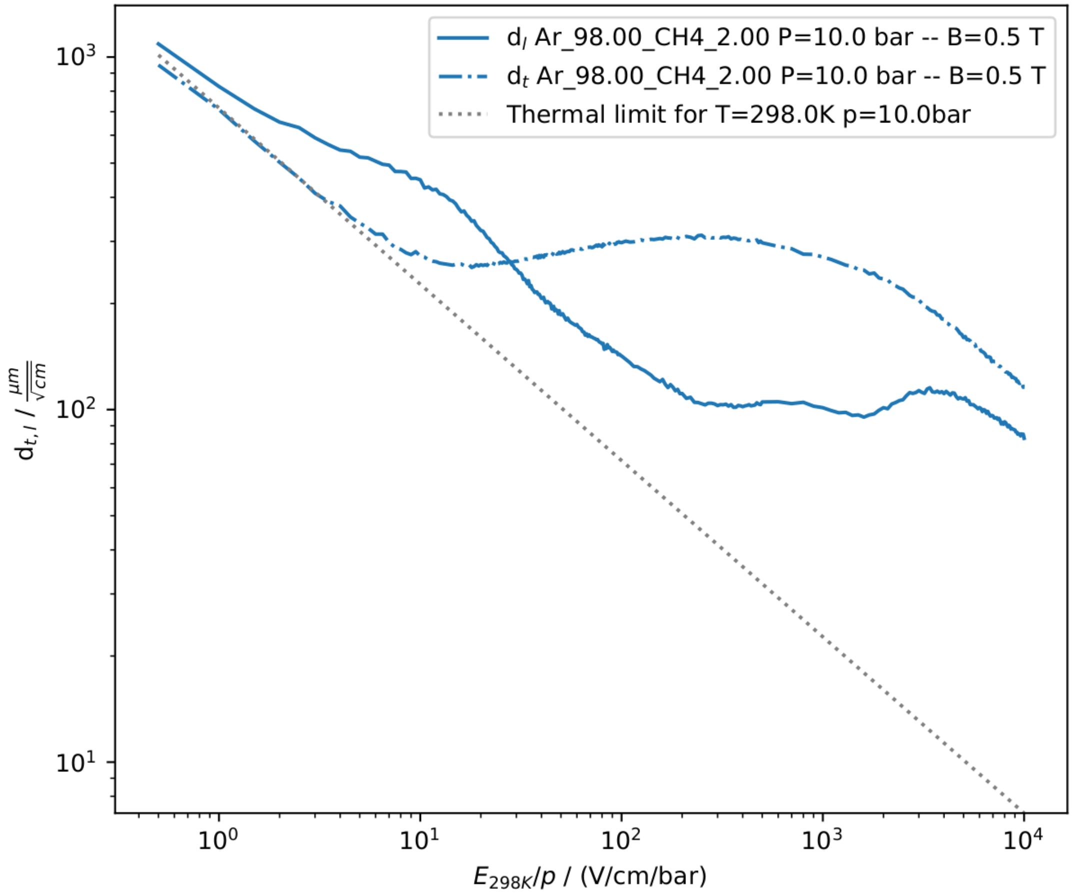
Properties of P2 under ND-GAr Conditions





Maximum in v_d at 50 V/cm/bar
= 500 V/cm at 10 bar

Diffusion very low across all fields

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Gas Gain on Wire(s)

- Townsend multiplication happens a few wire-radii above wire
- ALICE Anode Wires have 20µm diameter
- MWPC and single wire look the same 100µm scale
  - Use a Single Wire Proportional Counter as proxy

magnitude	scaling ($n = N/N_0$)
electron, ion drift velocity v_d	$v_d(E/n)$
electron, ion diffusion coefficients $D^*_{L,T}$	$\frac{1}{\sqrt{n}} D^*_{L,T}(E/n)$
attachment coefficient η	$n \cdot \eta(E/n)$ ^{*a}
charge multiplication coefficient α	$n \cdot \alpha(E/n)$ ^{*b}
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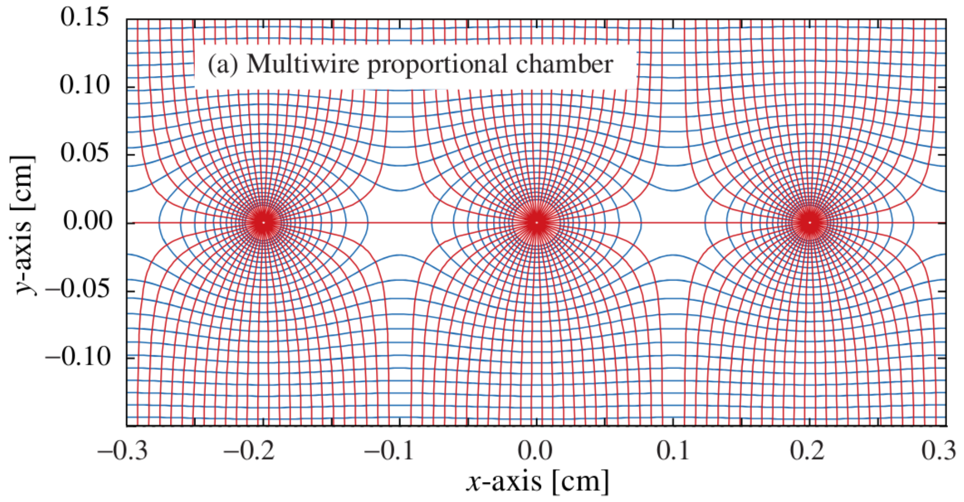
arxiv:1710.01018 [3]



First Townsend coefficient

- Both electric field and value scaling
- 10x pressure does not mean 10x anode voltage scaling

Gas gain **not** linearly proportional to pressure.

Gas Gain on Wire(s)

Ye et al. "Gas amplification in high pressure proportional counters" [1]

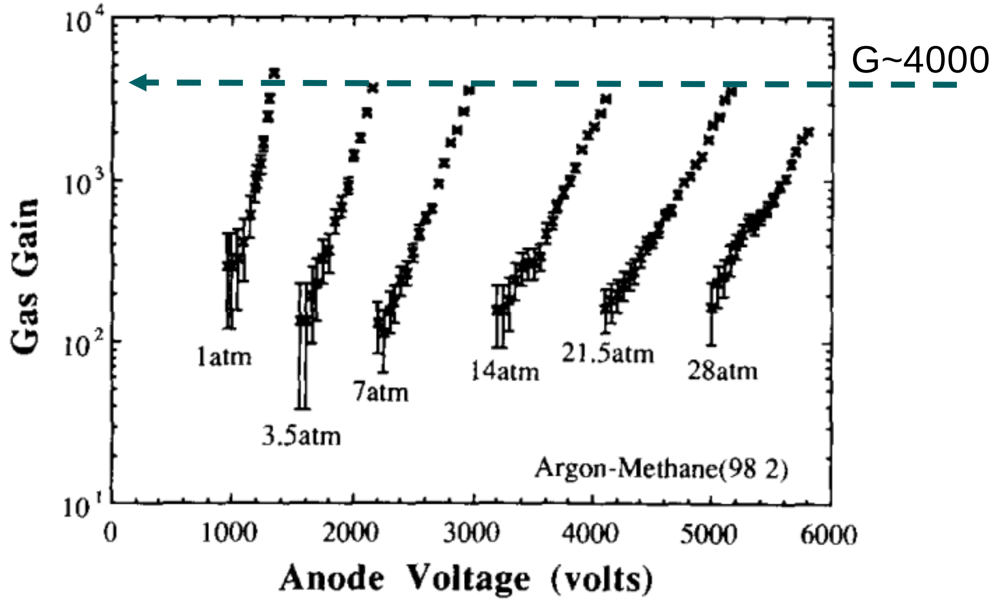


Fig. 4. Gas gain, using the current method, as a function of applied anode voltage for argon–methane (98:2) at various pressures.

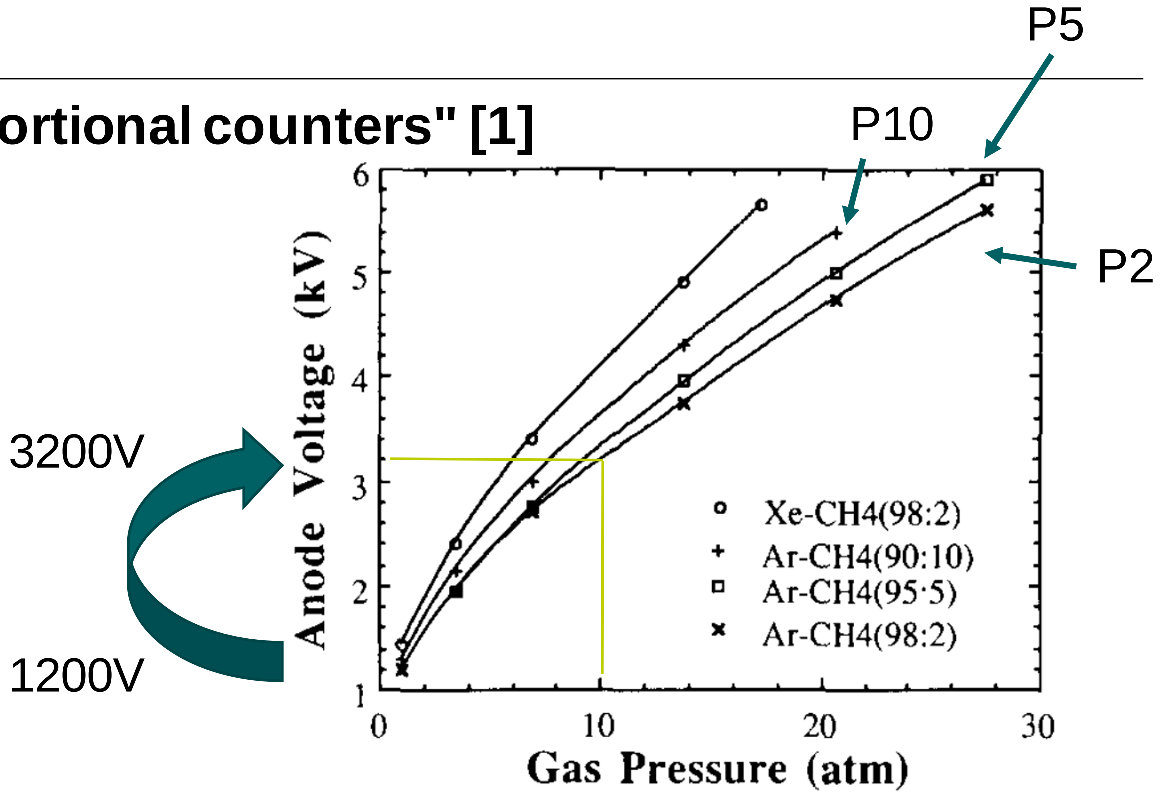


Fig. 7. Anode voltage required for a gas gain of 10^3 as a function of the gas pressure.

- Maximum gain appears constant up to >20 bar
- Constant gain under 10x pressure increase with ~2.5x voltage increase
- Lower-CH_4 mixtures require less anode voltages

Additional Benefit

Less methane, less inflammable!

Ar:CH_4 in air
- below ~ 4% CH_4 or
- above ~17% CH_4

will not ignite.

Fermilab has its own rules.

Table 12.1 Limits of inflammability of some gases and vapours in air that are of interest for particle detectors, from two different sources (vol. % of total mixture)

Compound	Formula	Limits of inflammability of gas or vapour			
		[LEW 61]		[CER 96]	
		Lower	Upper	Lower	Upper
Methane	CH_4	5.3	15.0	4.4	16.9
Ethane	C_2H_6	3.0	12.5	2.4	14.6
Propane	C_3H_8	2.2	9.5	1.8	10.4
Butane	C_4H_{10}	1.9	8.5	1.4	8.9
Isobutane	$i\text{-}C_4H_{10}$	1.8	8.4	1.55	8.4
Pentane	C_5H_{12}	1.4	7.8		
Isopentane	$i\text{-}C_5H_{12}$	1.4	7.6		
2,2-dimethylpropane	C_5H_{12}	1.4	7.5		
Hexane	C_6H_{14}	1.2	7.5		
Ethylene	C_2H_4	3.1	32.0		
Propylene	C_3H_6	2.4	10.3		
Methylalcohol	CH_3OH	7.3	36.0		
Isopropylalcohol	C_3H_7OH	2.0	12.0		
Diethylether	$C_4H_{10}O$	1.9	48.0		

From [2]

Conclusion

~~Many~~ Only benefits of operating a TPC at the drift velocity maximum!

- Temperature and pressure fluctuations almost negligible
- Diffusion low due to pressure scaling
- Resilience of swarm parameters against impurities

Reducing the CH_4 content in the DUNE ND-GAr gas mixture puts v_d^{max} at an achievable cathode voltage

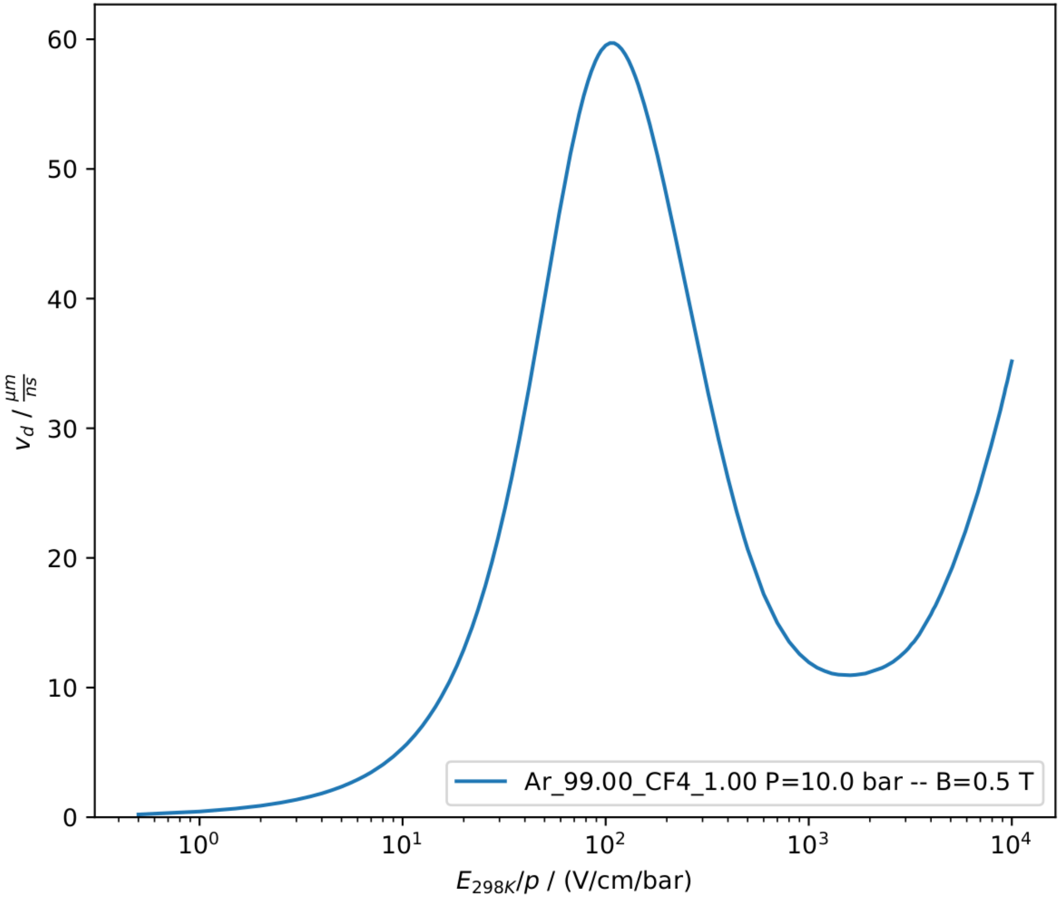
- **[+]** P2 has earlier onset of gas multiplication than P10
- **[+]** Large Ar content in both cases, $^{dE}/_{dx}$ should look very similar
- **[–]** P2 shows no primary scintillation

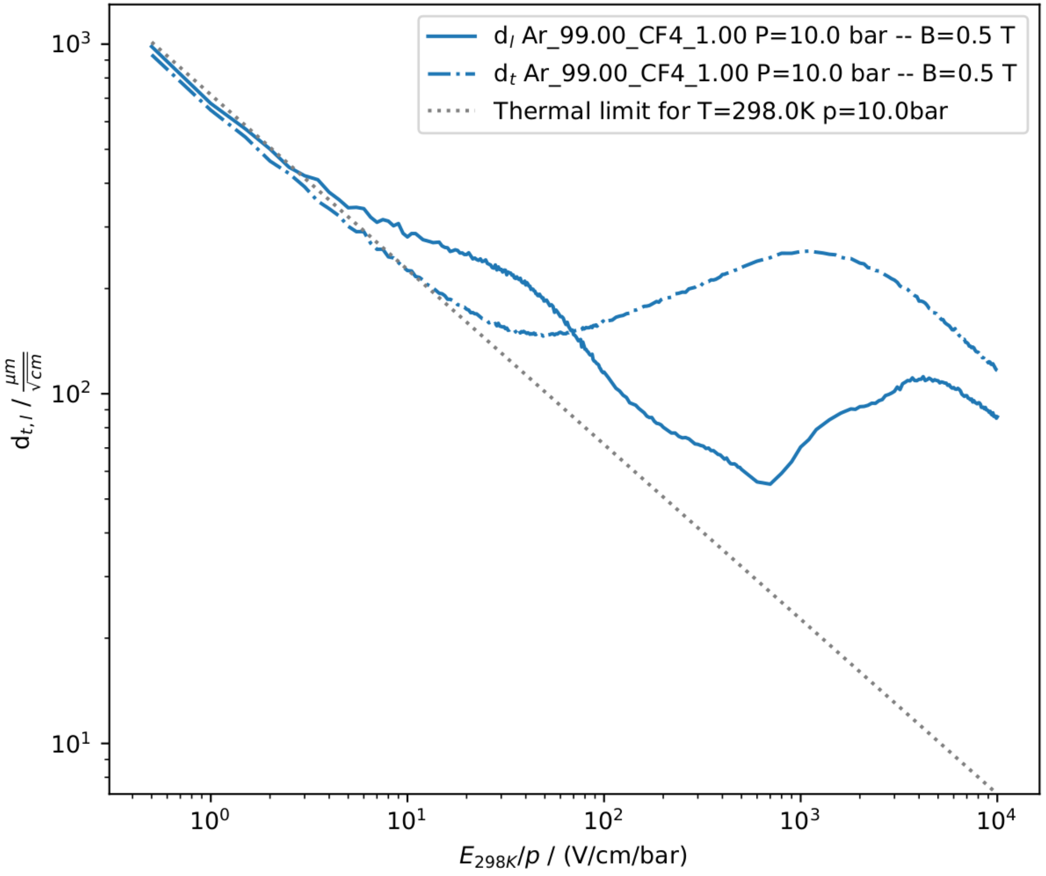
Source(s):

1. Z. Ye, R. Sood, D. Sharma, R. Manchanda, and K. Fenton. Gas amplification in high pressure proportional counters. Nucl. Instrum. Meth. A, 329(1-2):140–150, May 1993. doi: 10.1016/0168-9002(93)90929-c.
2. W. Blum, W. Riegler, and L. Rolandi. Particle Detection with Drift Chambers. Particle Acceleration and Detection. Springer, 2nd edition, 2008. ISBN 9783540766834. doi: 10.1007/978-3-540-76684-1.
3. D. González-Díaz, F. Monrabal, and S. Murphy. Gaseous and dual-phase time projection chambers for imaging rare processes. Nucl. Instrum. Meth. A, 878:200–255, jan 2018. doi: 10.1016/j.nima.2017.09.024.

Thank you!

Properties of 1% CF_4 in Ar under ND-GAr Conditions

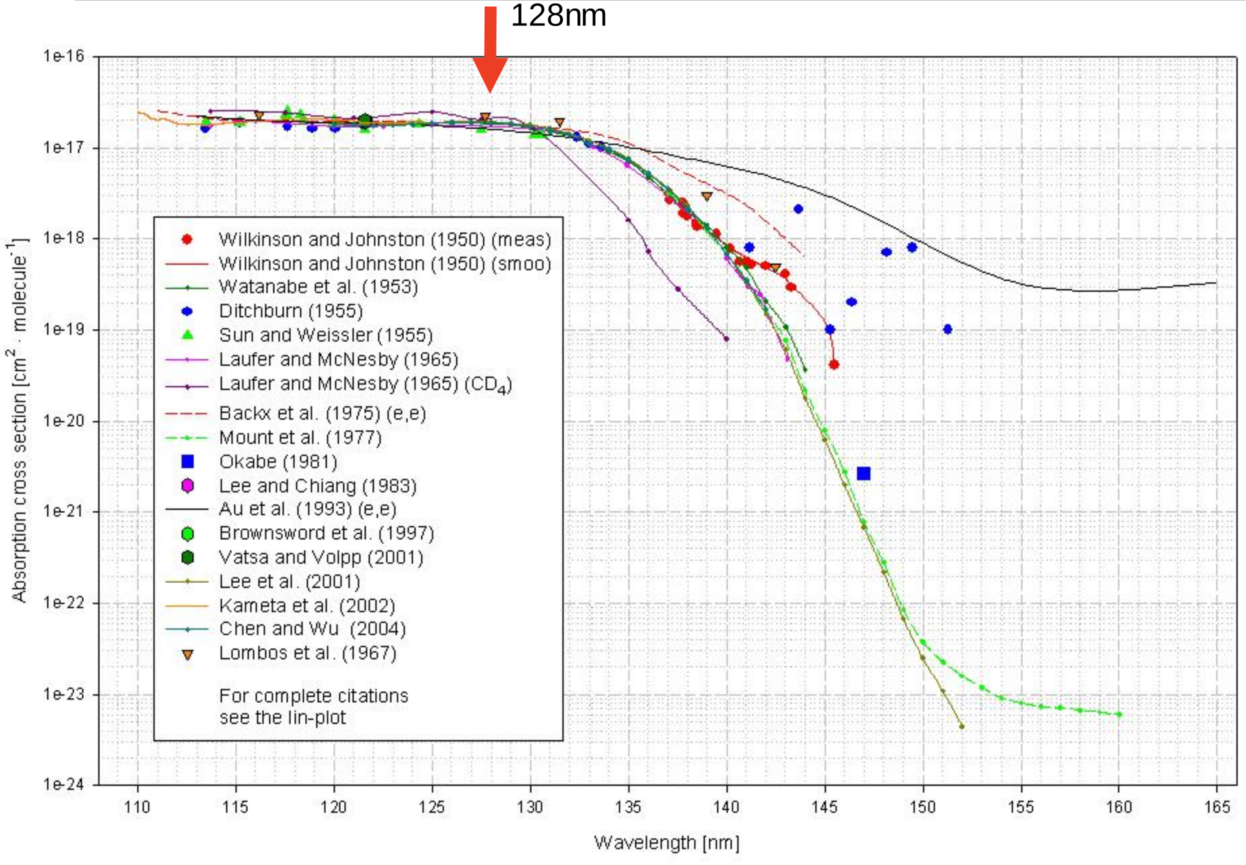




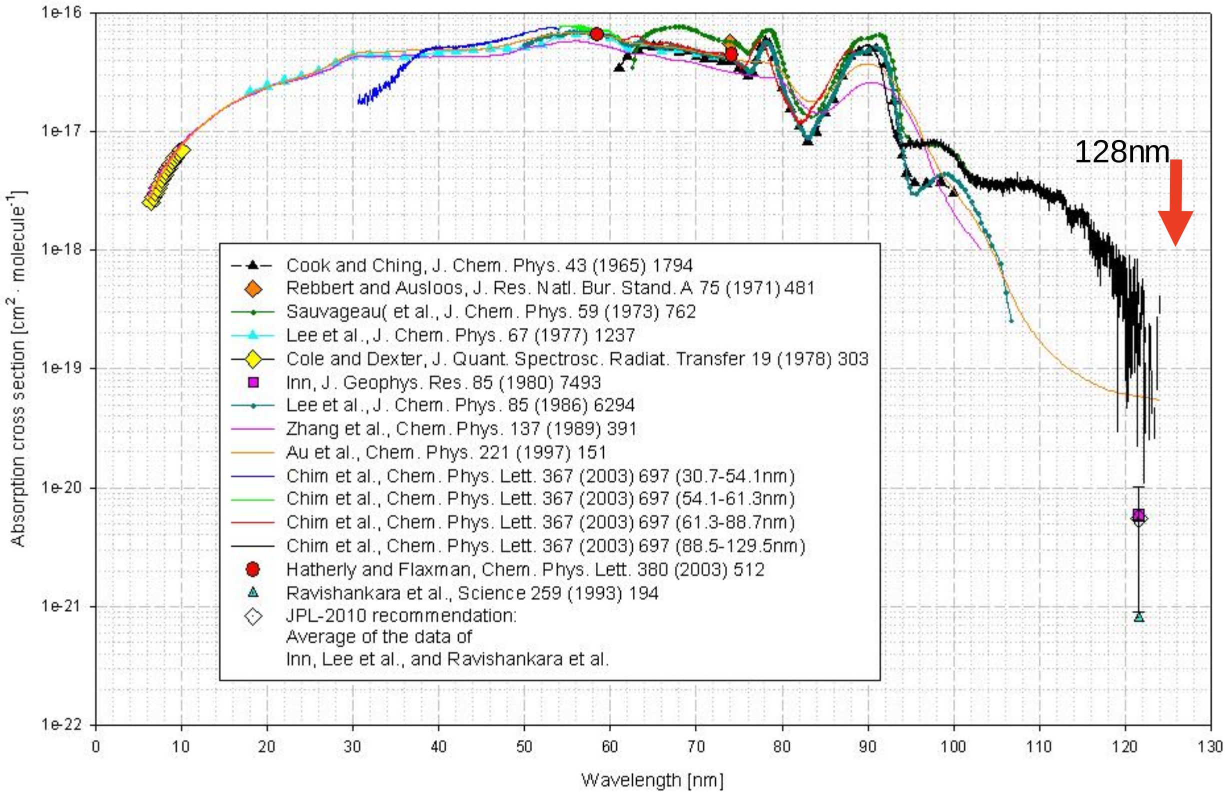
Maximum in v_d at 105 V/cm/bar
= 1050 V/cm at 10 bar

Diffusion very low across all fields
(values below 5 V/cm/bar suspicious)

VUV Absorption Cross-sections of CH_4 and CF_4



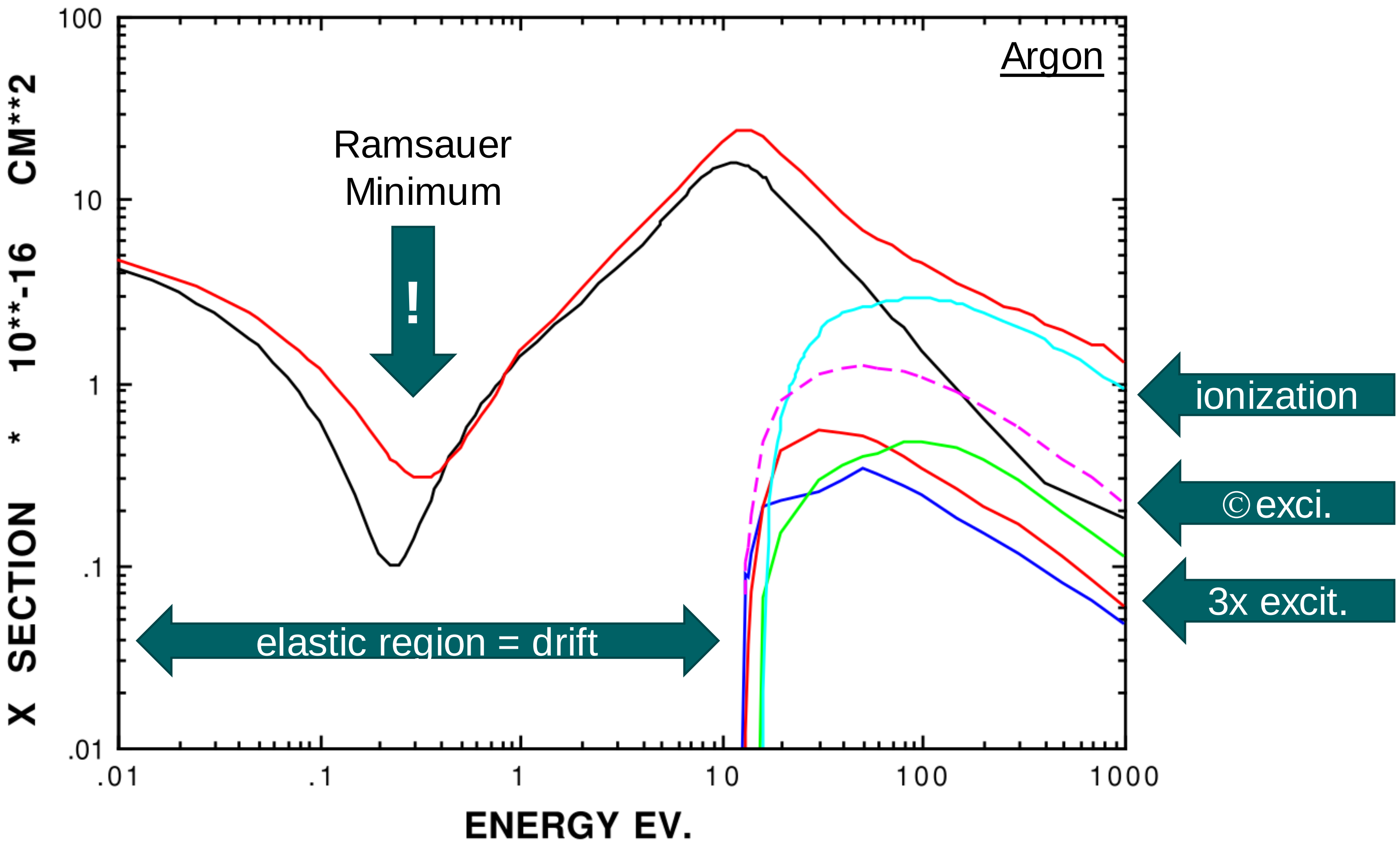
Absorption cross sections of methane CH_4 at room temperature (110-165 nm)



VUV absorption cross sections of tetrafluoromethane CF_4 at room temperature

From http://satellite.mpic.de/spectral_atlas/cross_sections/

Electron Scattering Cross Sections: Argon



Free electrons gain energy by acelleration in electric field

Scattering on gas components

Elastic
- Ramsauer Minimum at 0.2-0.3eV

Excitation
- Threshold ~10eV

Ionization
- Threshold ~10eV

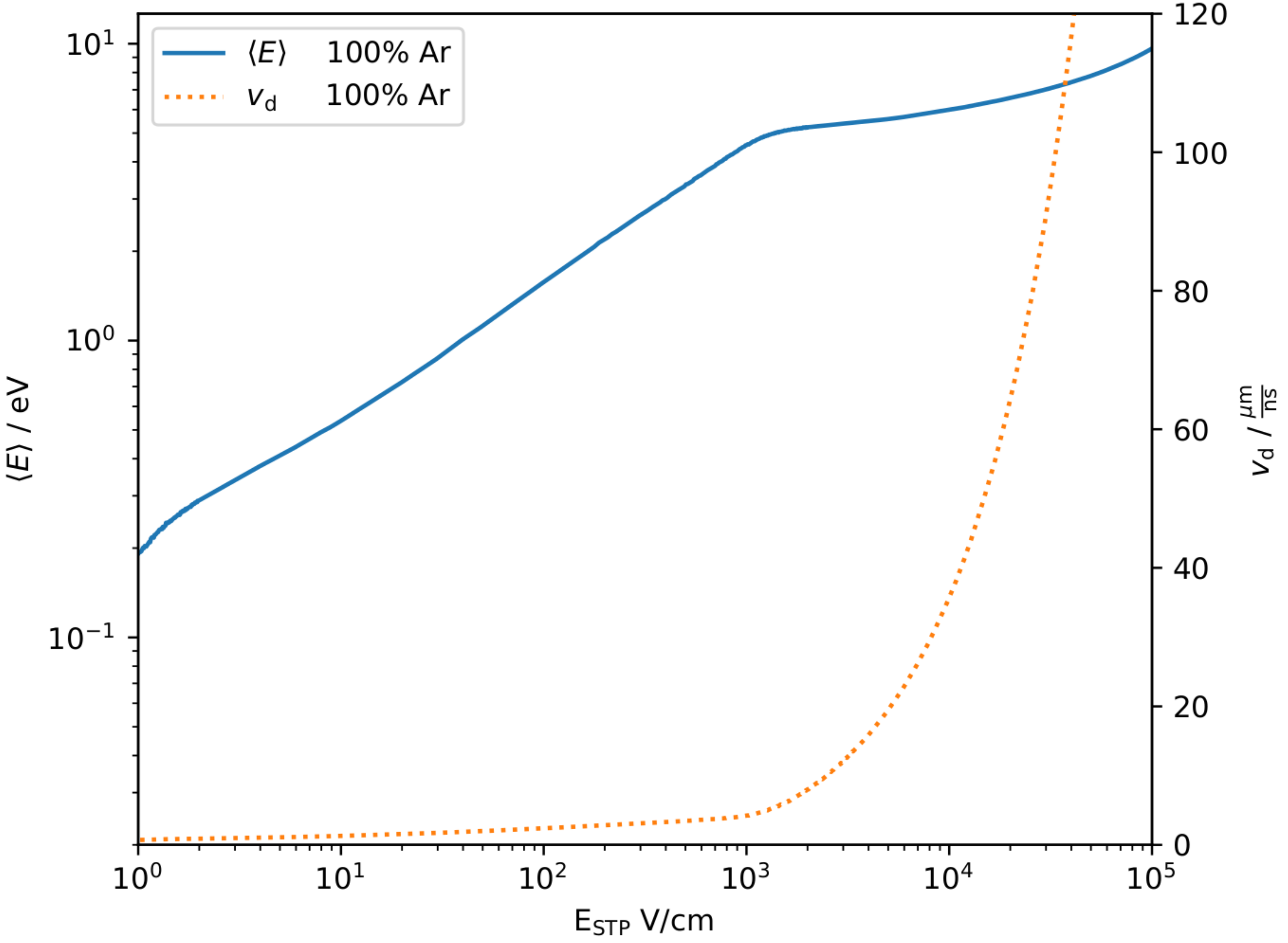
Drifting Electrons in Pure Argon

(Don’t do it.)

Pure argon is a very slow drifter.

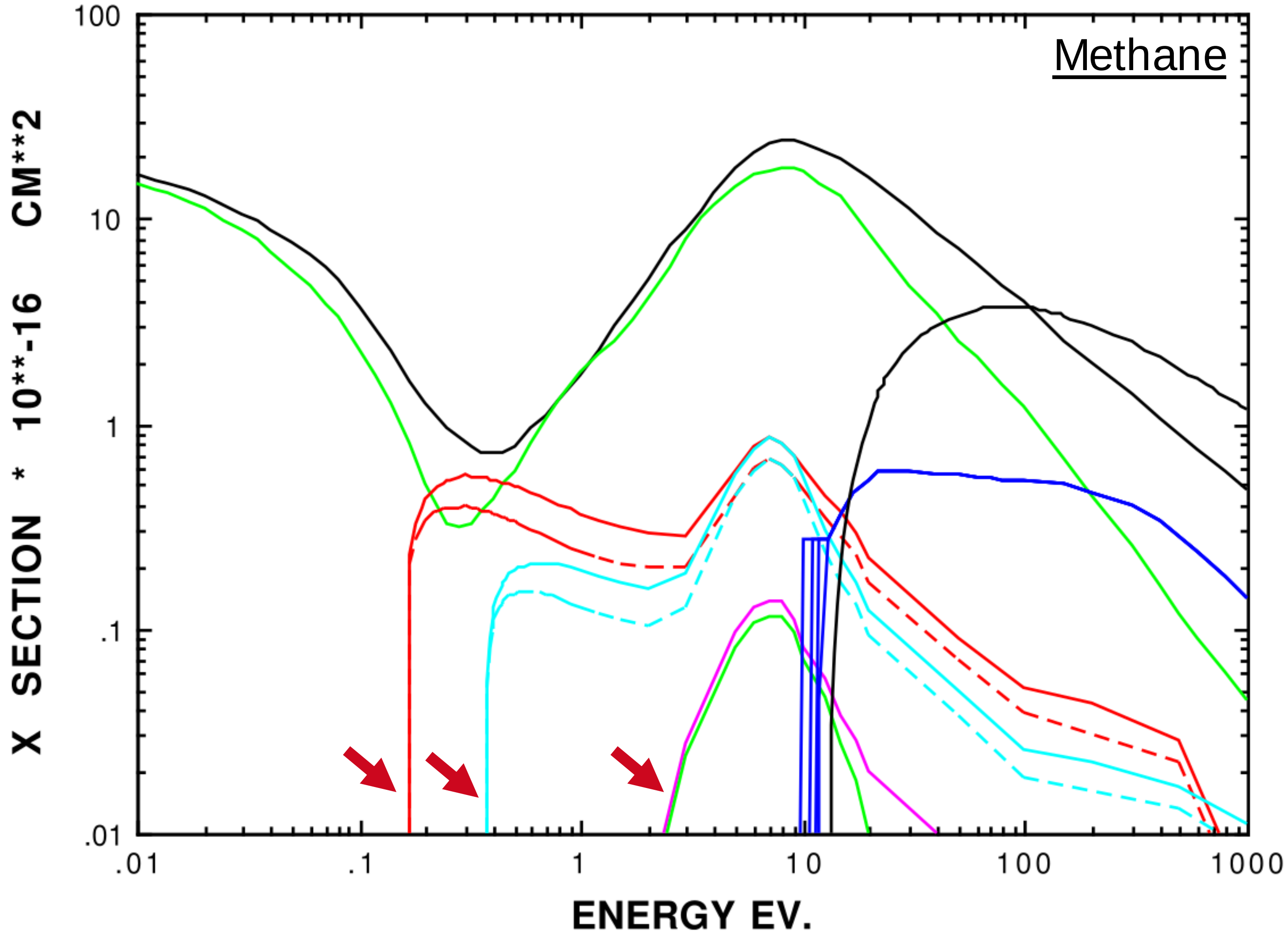
Electrons gain energy unhindered
- Large diffusion

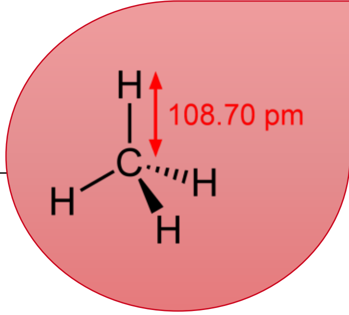
Excitation and ionization limit energy gain eventually.



NB: Gas multiplication in pure Ar is unstable.

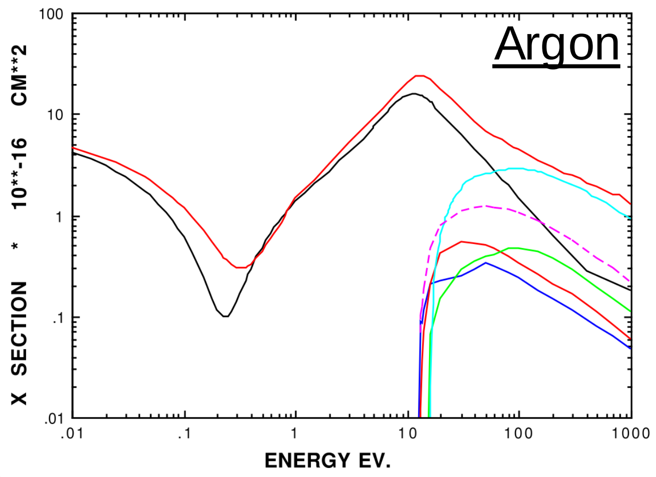
Electron Scattering Cross Sections: Methane



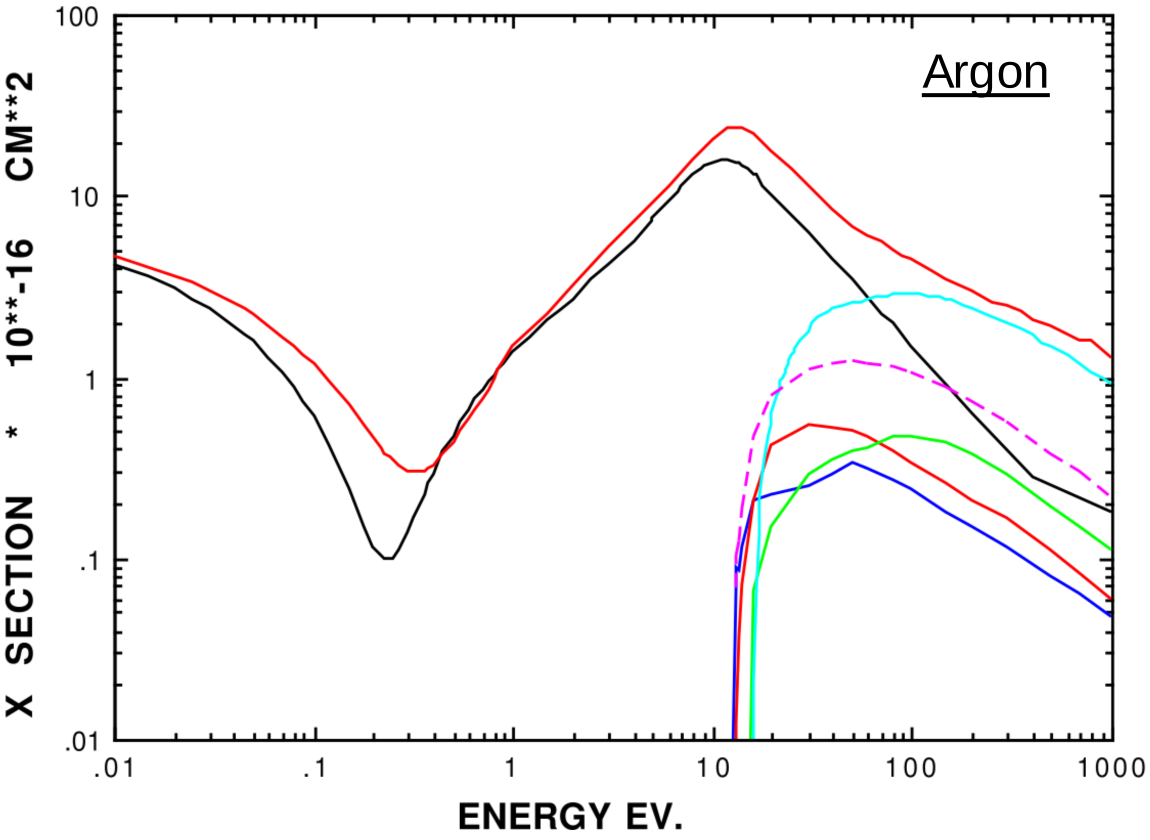


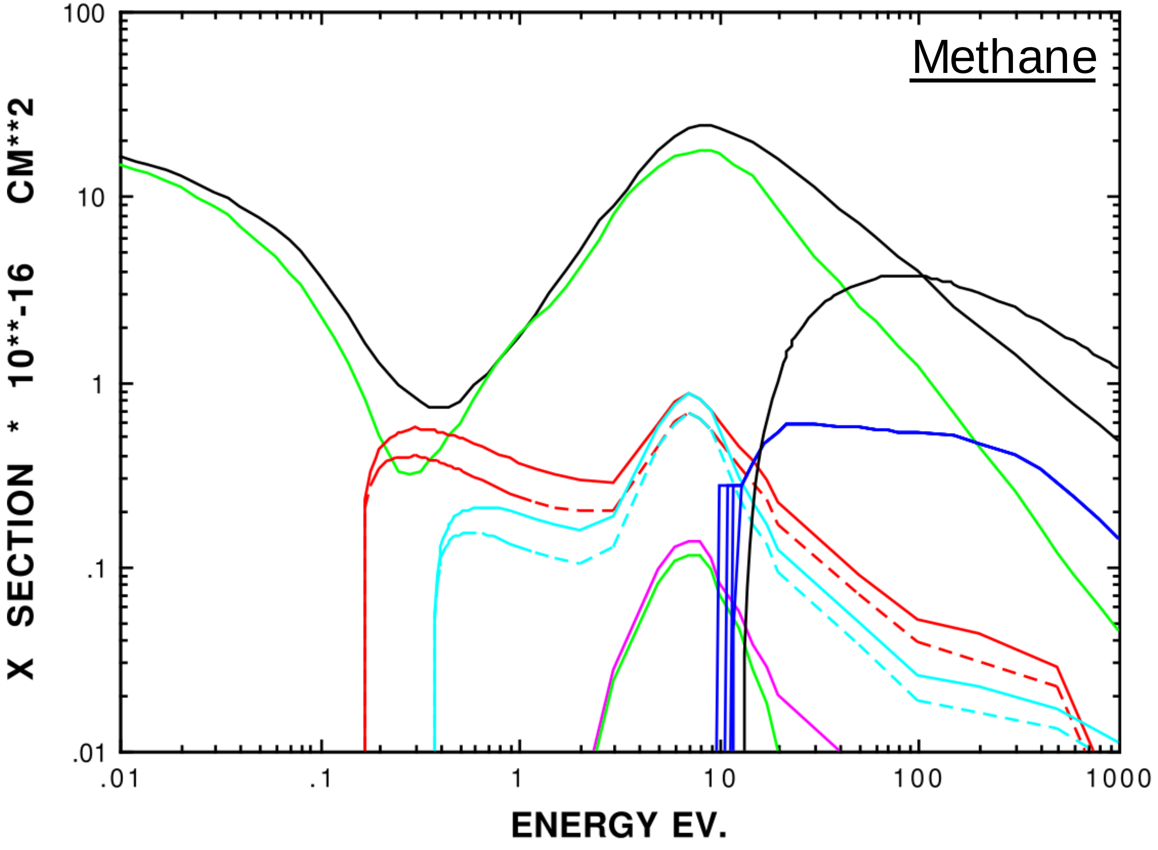
Additional rotational and vibrational degrees of freedom:

- Inelastic collisions = *cooling* effect
- Threshold ~ 0.2 eV



Electron Scattering Cross Sections: Argon + Methane





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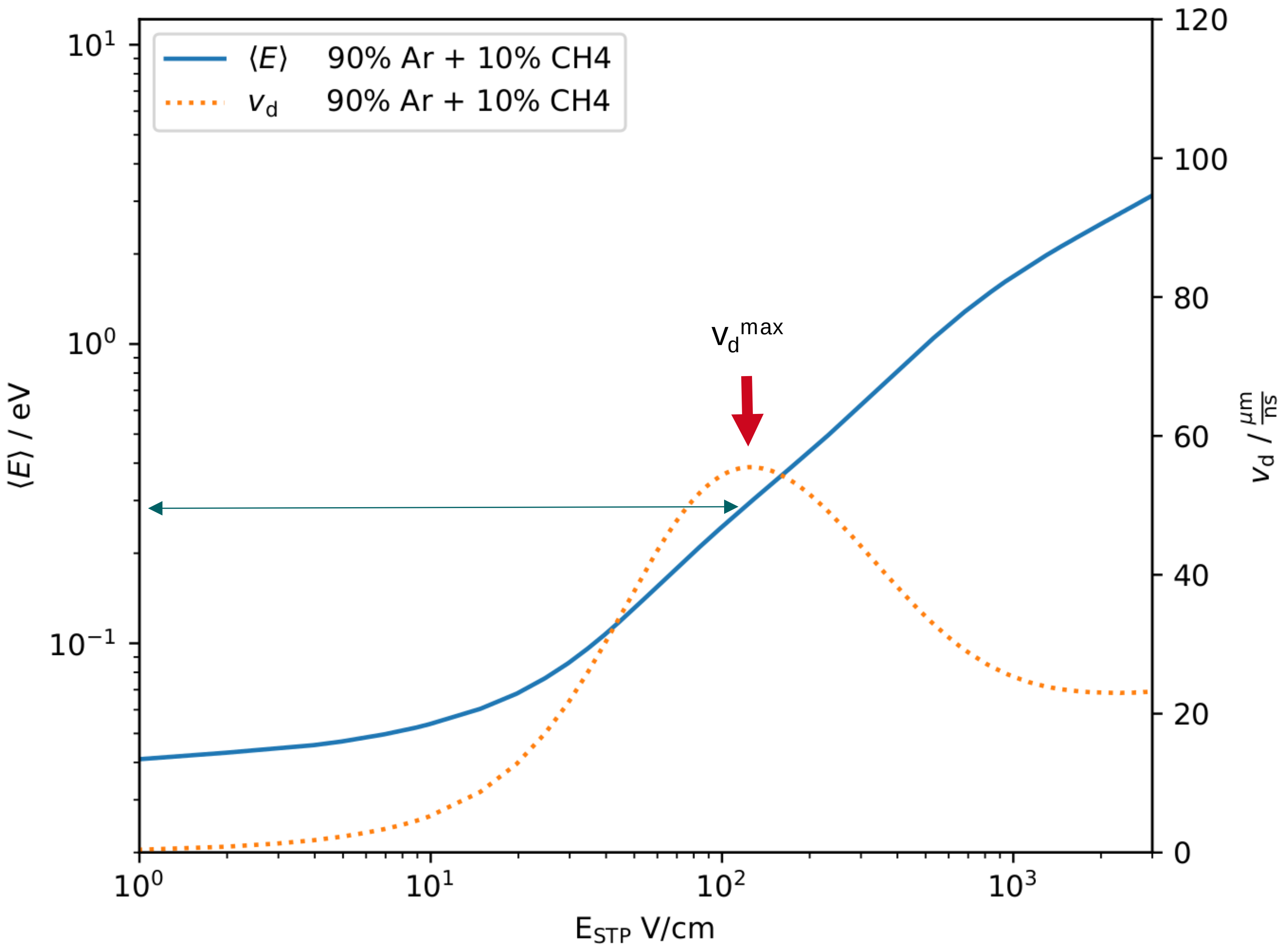
Electron Scattering Cross Sections: Argon-based Mixtures

Drift velocity maximum coincides with Ramsauer minimum of argon!



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Drifting Electrons in Pure CH_4

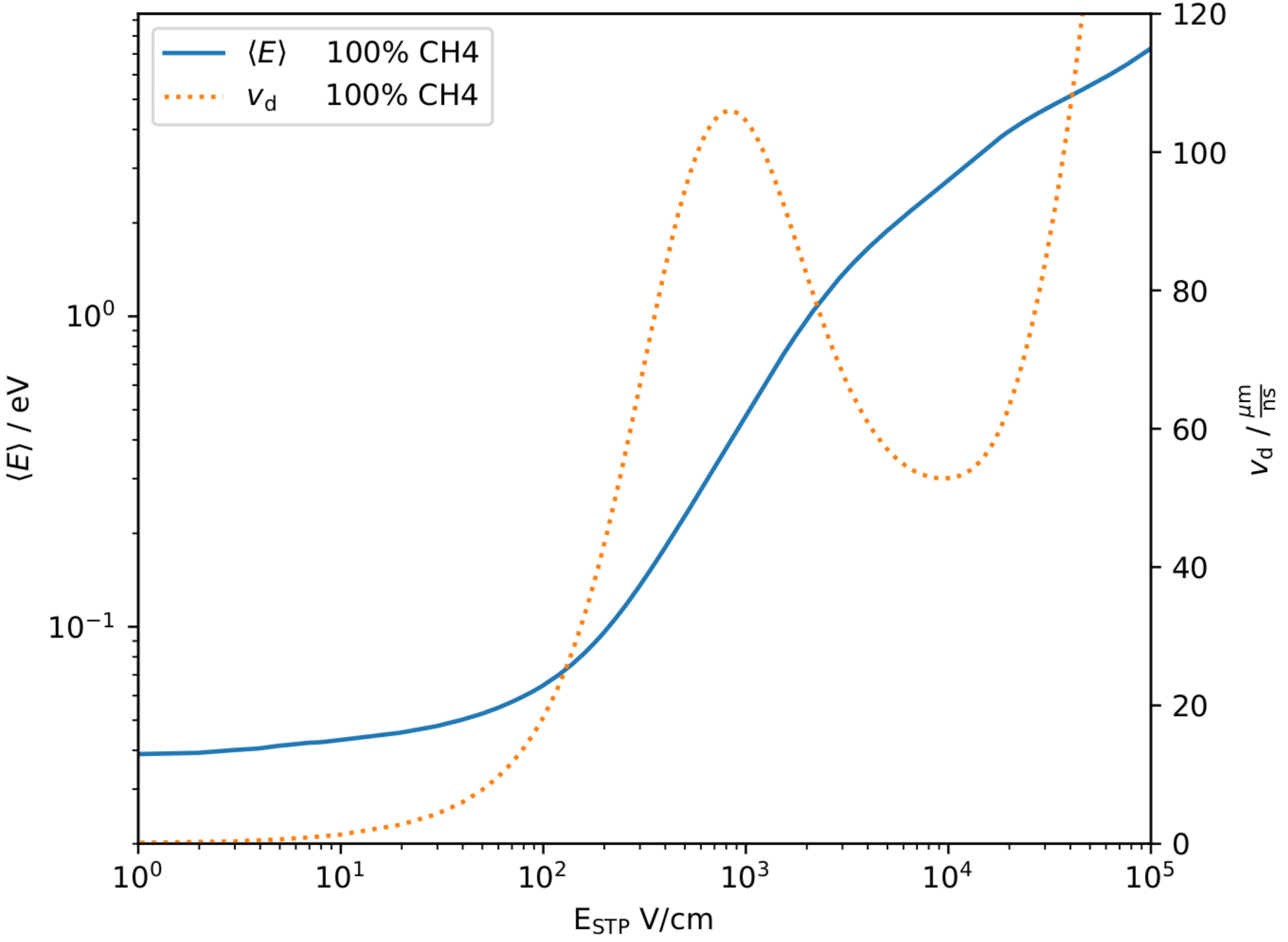
Pure methane is a very fast drifter, but only at high fields

- Saturated v_d (maximum)
- Very interesting for TPC operators

Electrons cooled to thermal limit up to ~100 V/cm

- **Lowest** diffusion

Avalanche multiplication possibly, but at very high fields.



Effect of Additional Quencher

- Electrons fall into Ramsauer minimum at higher fields
- Shift of v_d^{max} to higher E

- Same behaviour could be caused by accumulating impurities with low-threshold inelastic xsec contributions

- Unclear what impurity present
- H_2O and N_2 in sensible concentrations cannot explain shift