

# Towards large gas TPCs without xenon

Ben Monreal  
Case Western Reserve University

**Gaseous forms of  $^{76}\text{Ge}$ ,  $^{82}\text{Se}$ ,  $^{96}\text{Zr}$ ,  $^{100}\text{Mo}$ ,  $^{124}\text{Sn}$ , and  
 $^{130}\text{Te}$ : new avenues to future  $0\nu\beta\beta$  time projection  
chambers**

---

A. Avasthi,<sup>a</sup> B. Monreal,<sup>a</sup> I. Moya<sup>a</sup>

<sup>a</sup>*Department of Physics, Case Western Reserve University, Cleveland OH*

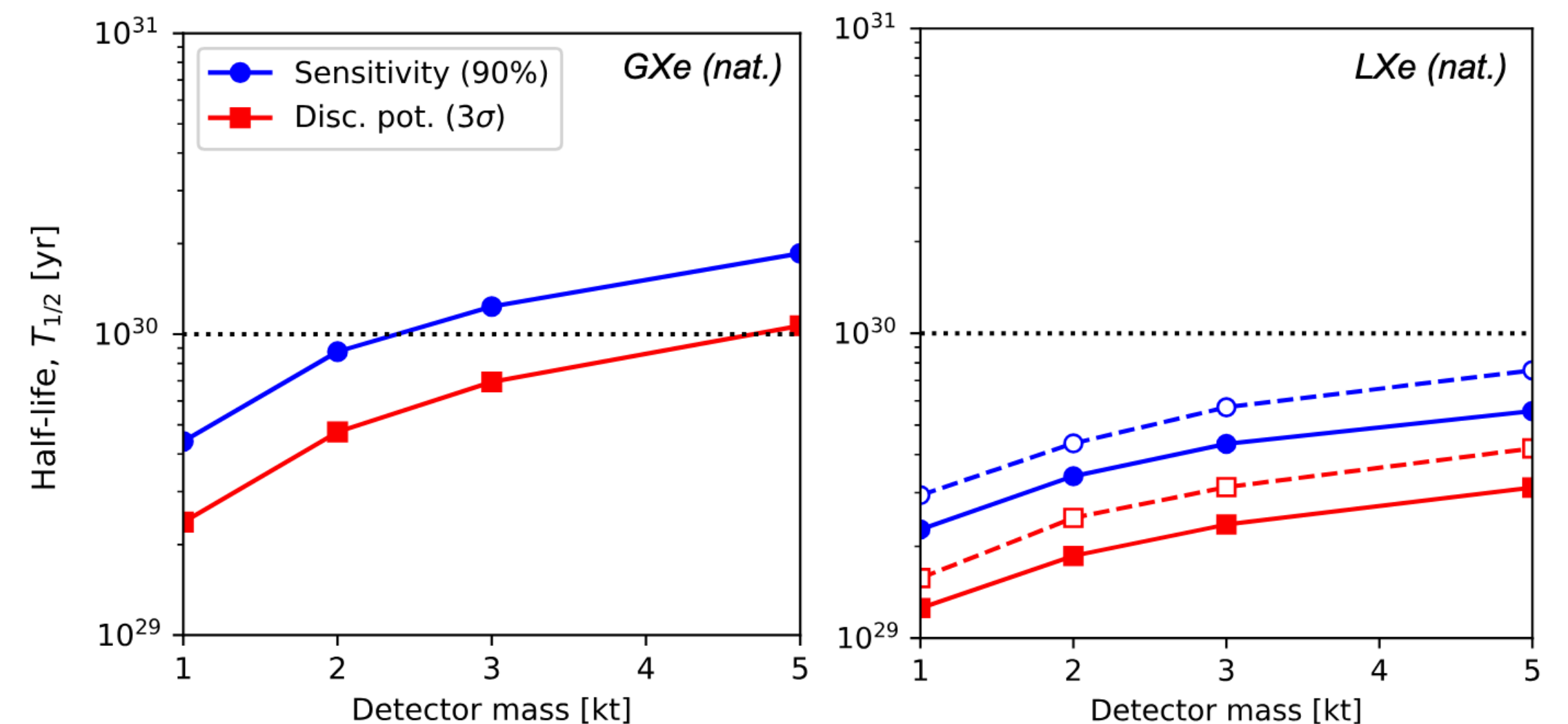
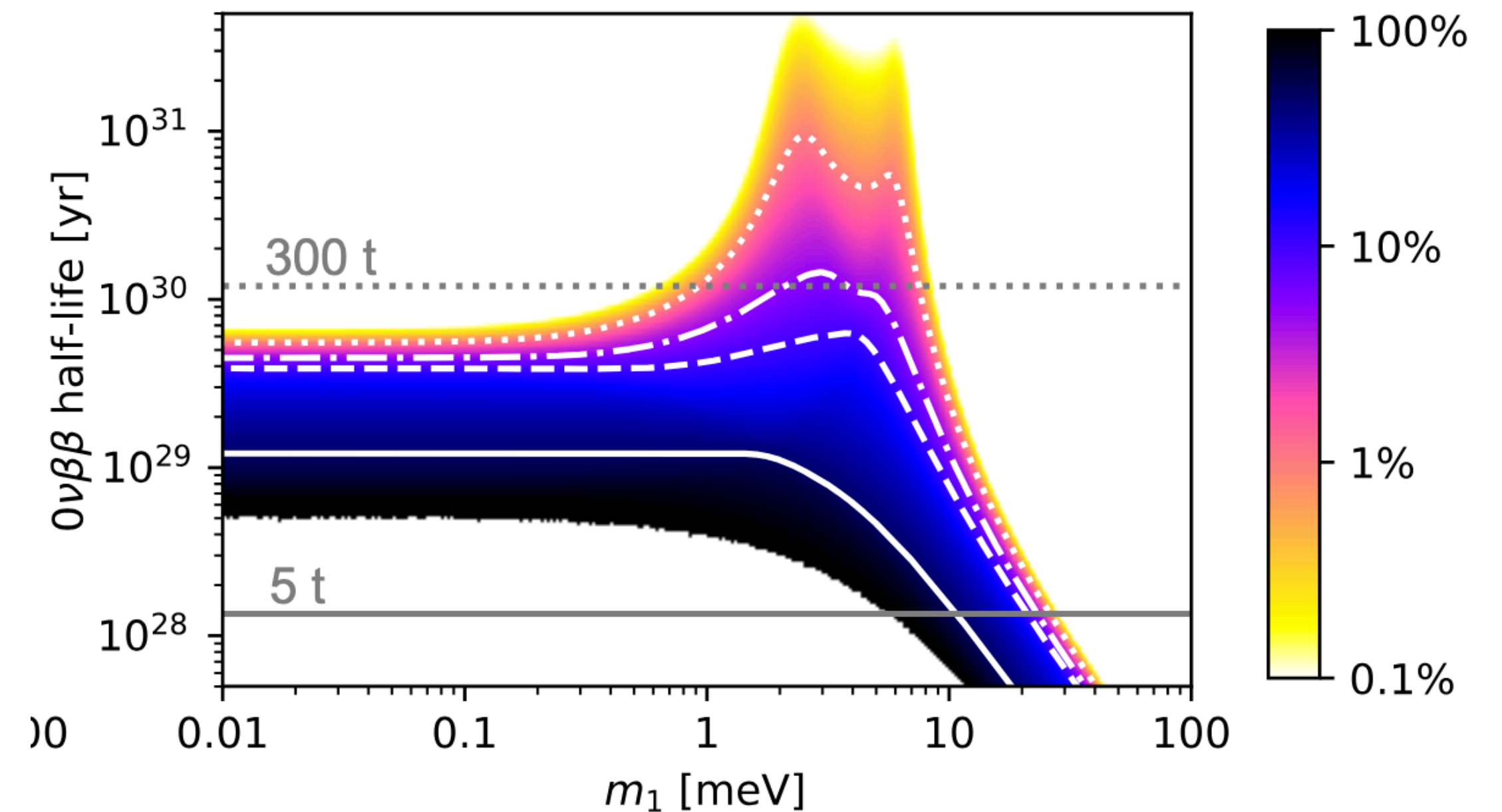
<https://arxiv.org/abs/2604.27027>

# Motivation

"I don't really understand why the approach to experimental physics always seems to be starting many orders of magnitude away from what you want and then inching slightly closer every ten years until maybe a hundred years from now someone can do something interesting" -- Matt Reece

- We are not on track to *initiating* normal-hierarchy sensitive projects in my remaining career\*
- A bluesky R&D roadmap that ends at 1 meV may be more compelling than a tightly-costed project that ends at 10 meV
- TPCs seem like the only technology with a roadmap
  - Cavern, hardware, readout is fairly safe, sane, fast
  - Materials/radio/background in might be fast & cheap in STP gases (Krishan's talk)
  - The xenon-procurement budget is unfortunately really (really) ugly

from *Kiloton-scale xenon detectors for neutrinoless double beta decay and other new physics searches*, Avasthi et al, 2110.01537 or PRD 104.112007



# How crazy is a noble- gas-free TPC?

## Electronegative gases drifting negative ions:

Negative ion drift and diffusion in a TPC near 1 bar

C.J. Martoff<sup>a,\*</sup>, R. Ayad<sup>a</sup>, M. Katz-Hyman<sup>a</sup>, G. Bonvicini<sup>b</sup>, A. Schreiner<sup>b</sup>

<sup>a</sup>Department of Physics, Temple University, Philadelphia, PA 19122, USA  
<sup>b</sup>Department of Physics & Astronomy, Wayne State University Detroit, MI 48202, USA

Received 22 August 2005; accepted 30 August 2005  
Available online 19 September 2005

CS<sub>2</sub>

NuDEX-100 Conceptual Design Report<sup>\*</sup>

SeF<sub>6</sub>

X. Cao,<sup>1</sup> Y. Chang,<sup>2</sup> K. Chen,<sup>3</sup> E. Ciuffoli,<sup>4</sup> L. Duan,<sup>4</sup> D. Fang,<sup>4</sup> C. Gao,<sup>4</sup> S. K. Ghorui,<sup>4</sup> P. Hu,<sup>2</sup> Q. Hu,<sup>4</sup> S. Huang,<sup>4</sup> Z. Huang,<sup>2</sup> L. Lang,<sup>3</sup> Y. Li,<sup>5</sup> Z. Li,<sup>4</sup> T. Liang,<sup>3</sup> J. Liu,<sup>3</sup> C. Lu,<sup>4</sup> F. Mai,<sup>4</sup> Y. Mei,<sup>6</sup> H. Qiu,<sup>4,†</sup> X. Sun,<sup>3</sup> X. Tang,<sup>5</sup> H. Wang,<sup>3</sup> Q. Wang,<sup>2</sup> L. Xiao,<sup>3</sup> M. Xiao,<sup>4</sup> J. Xin,<sup>2</sup> N. Xu,<sup>4,6</sup> P. Yang,<sup>4</sup> Y. Yang,<sup>4</sup> Z. Yang,<sup>4</sup> Z. Yu,<sup>3</sup> D. Zhang,<sup>3</sup> J. Zhang,<sup>7</sup> C. Zhao,<sup>4</sup> and D. Zhu<sup>3</sup>  
(NuDEX-100 collaboration)

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. XX, NO. XX, XXXX 2025

1

CF<sub>4</sub> → CF<sub>3</sub><sup>-</sup> or F<sup>-</sup>

Operation of a negative ion gas time projection chamber without electronegative fill gases

Lachlan J. McKie, Lindsey J. Bignell, Nicholas Adams, Victoria U. Bashu, Ferdos Dastgiri and Gregory J. Lane

## Electropositive gases drifting electrons:

Ionization parameters of Trimethylbismuth for high-energy photon detection

M. Farradèche<sup>a</sup>, G. Tauzin<sup>a</sup>, J-Ph. Mols<sup>a</sup>, J-P. Bard<sup>a</sup>, J-P. Dognon<sup>b</sup>, C. Weinheimer<sup>c</sup>, K.P. Schäfers<sup>d</sup>, V. Sharyy<sup>a</sup>, D. Yvon<sup>a,\*</sup>

<sup>a</sup>CEA, DRF, IRFU, University of Paris-Saclay, F-91191 Gif-sur-Yvette, France  
<sup>b</sup>CEA, DRF, NIMBE, University of Paris-Saclay, F-91191 Gif-sur-Yvette, France  
<sup>c</sup>Institut für Kernphysik, University of Münster, Wilhelm-Klemm-Straße 9, D-48149 Münster, Germany  
<sup>d</sup>European Institute for Molecular Imaging, University of Münster, Waldeyerstraße 15, D-48149 Münster, Germany

Bi(CH<sub>3</sub>)<sub>3</sub>

ETHYL FERROCENE IN GAS, CONDENSED, OR ADSORBED PHASES:  
THREE TYPES OF PHOTOSENSITIVE ELEMENTS FOR USE IN GASEOUS DETECTORS

G. CHARPAK, V. PESKOV, F. SAULI and D. SCIGOCKI

CERN, Geneva, Switzerland

Received 5 December 1988

Fe(C<sub>5</sub>H<sub>5</sub>)(C<sub>5</sub>H<sub>4</sub>C<sub>2</sub>H<sub>5</sub>)

Mercury-Vapor Proportional Counter: Hg(!)

C. W. McCUTCHEN

Cavendish Laboratory, Cambridge, England

(Received September 12, 1957; and in final form, August 22, 1958)

PHYSICAL REVIEW B

VOLUME 43, NUMBER 11

15 APRIL 1991-I

Free-ion yields for several silicon-, germanium-, and tin-containing liquids and their mixtures

Ge(CH<sub>3</sub>)<sub>4</sub>, etc

R. A. Holroyd

Chemistry Department, Brookhaven National Laboratory, Upton, New York 11973

S. Geer and F. Ptohos

High Energy Physics Laboratory, Harvard University, 42 Oxford St., Cambridge, Massachusetts 02138  
(Received 7 November 1990)

Di-isopropyl naphthalene, etc

Liquid scintillator time projection chamber concept

N. McConkey<sup>\*</sup>, Y.A. Ramachers

Department of Physics, University of Warwick, Coventry CV4 7AL, UK

# Our DFT study flagged 30 obscure $0\nu\beta\beta$ gases\* as probably electronegative



ORCA

<https://www.faccts.de/orca/>

$$E(\text{GeF}_4) - E(\text{GeF}_4^-) = \text{EA}$$

$$-67388.80 - -67390.27 = +1.47$$

|                   |                                              |                                         |              |     |                   |
|-------------------|----------------------------------------------|-----------------------------------------|--------------|-----|-------------------|
| $^{100}\text{Mo}$ | $\text{Mo}(\text{CO})_6$                     | Mo hexacarbonyl                         | 150          | 156 | 0.5               |
|                   | $\text{MoF}_6$                               | Mo hexafluoride                         | 17           | 34  | 3.9               |
|                   | $\text{MoO}_2\text{F}_2$                     | Mo difluoride dioxide                   | (subl 270 C) |     | 2.1               |
|                   | $\text{MoO}_2\text{Cl}_2$                    | Mo dichloride dioxide                   | 175          | ?   | 2.4               |
|                   | $\text{MoOF}_4$                              | Mo oxytetrafluoride                     | 95           | 186 | 3.28              |
|                   | $\text{MoF}_5$                               | Mo pentafluoride                        | 45           | ??  | >5                |
|                   | $\text{C}_7\text{H}_8\text{Mo}(\text{CO})_3$ | Cycloheptatriene molybdenum tricarbonyl | ~100         | ?   | 0.7 <sup>V</sup>  |
| $^{124}\text{Sn}$ | $\text{Sn}(\text{NO}_3)_4$                   | Tin(IV) nitrate                         | 91           | 98  | 3.63              |
|                   | $\text{SnCl}_4$                              | Tin(IV) chloride                        | -34          | 114 | 2.8               |
|                   | $\text{SnBr}_4$                              | Tin(IV) bromide                         | 31           | 205 | 2.23 <sup>V</sup> |
| $^{130}\text{Te}$ | $\text{TeF}_6$                               | Te hexafluoride                         | -39          | -38 | 2.3 <sup>V</sup>  |
|                   | $\text{HOTeF}_5$                             | Teflic acid                             | 39           | 60  | 2.9 <sup>V</sup>  |
|                   | $\text{Te}(\text{OH})_6$                     | Orthotelluric acid                      | 136          | ?   | 0.54 <sup>V</sup> |
|                   | $\text{B}(\text{OTeF}_5)_3$                  | Boron teflate                           | ?            | ?   | 3.2 <sup>V</sup>  |

|                  |                                         |                                  |              |                   |
|------------------|-----------------------------------------|----------------------------------|--------------|-------------------|
| $^{86}\text{Ge}$ | $\text{GeF}_4$                          | Ge tetrafluoride                 | (t.p. -15 C) | 1.47              |
|                  | $\text{GeCl}_4$                         | Ge tetrachloride                 | -49 86       | 1.0               |
| $^{82}\text{Se}$ | $\text{CSe}_2$                          | Carbon diselenide                | -44 125      | 0.57              |
|                  | $\text{CSSe}$                           | Thiocarbonyl selenide            | -75 84       | 0.38              |
|                  | $\text{SeF}_4$                          | Selenium tetrafluoride           | -13 101      | 1.8               |
|                  | $\text{SeF}_6$                          | Selenium hexafluoride            | -39 -34      | 3.32              |
|                  | $\text{SeCF}_2$                         | Selenocarbonyl fluoride          | -81 45       | 0.68              |
|                  | $\text{SeCH}_2$                         | Selenoformaldehyde               | ? ?          | 0.82              |
|                  | $\text{SeOF}_2$                         | Seleninyl fluoride               | ? 125        | 1.4               |
|                  | $\text{SeO}_2\text{F}_2$                | Selenoyl fluoride                | -99 8        | 3.3               |
|                  | $\text{SeF}_5\text{OF}$                 | Pentafluoroselenium hypofluorite | -54 -29      | 3.1 <sup>V</sup>  |
|                  | $\text{SeOCl}_2$                        | Seleninyl chloride               | 11 180       | 2.93              |
|                  | $\text{CH}_3\text{SeCH}_3$              | Dimethyl selenide                | -87 55       | 0.66              |
| $^{96}\text{Zr}$ | $\text{CH}_3\text{Se}_2\text{CH}_3$     | Dimethyl diselenide              | ?? 157       | -0.77             |
|                  | $\text{C}_{12}\text{H}_{10}\text{Se}_2$ | Diphenyl diselenide              | 60 >202      | ?                 |
|                  | $\text{Zr}(\text{BH}_4)_4$              | Zr tetraborohydrate              | 32 ?         | 0.15 <sup>V</sup> |

Our DFT study flagged  
18 obscure  $0\nu\beta\beta$   
gases\* as probably  
electropositive!

drift already seen  
in congeners

subject of  
previous drift  
studies

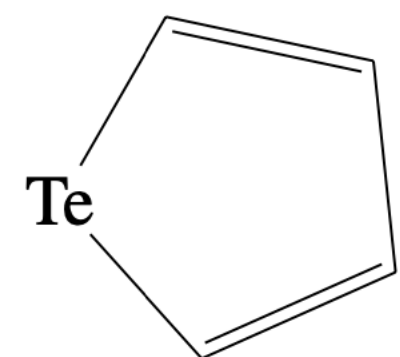
30% natural  $^{130}\text{Te}$   
abundance

endpoint above  $^{214}\text{Bi}$ ,  $^{208}\text{Tl}$

If one of these has nice drift & tolerable gain,  
how hard/easy is it to design a high-TRL TPC?

Electron-drift  $0\nu\beta\beta$  TPC gas candidates

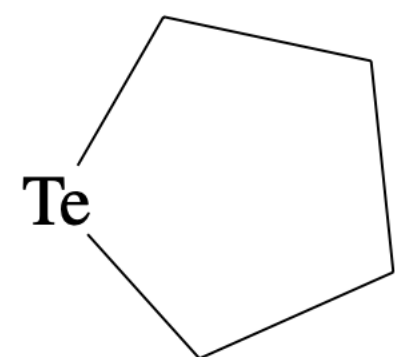
| Nuclide           | Compound                               |                                                     | m.p.<br>(C) | b.p.<br>(C) | EA<br>eV           |
|-------------------|----------------------------------------|-----------------------------------------------------|-------------|-------------|--------------------|
| $^{82}\text{Se}$  | $\text{H}_2\text{Se}$                  | Hydrogen selenide                                   | -66         | -41         | -0.93              |
|                   | $\text{CSeO}$                          | Carbonyl selenide*                                  | -122        | -23         | -0.28              |
|                   | $\text{CH}_3\text{SeH}$                | Methaneselenol                                      | -54         | 12          | -0.67              |
|                   | $\text{H}_4\text{C}_4\text{Se}$        | Selenophene                                         | -38         | 110         | -0.63              |
|                   | $\text{H}_8\text{C}_4\text{Se}$        | Selenolane                                          | ??          | 135         | -0.76              |
|                   | $\text{C}_6\text{H}_5\text{SeH}$       | Benzene selenol                                     | ??          | 183         | -0.51 <sup>V</sup> |
|                   | $\text{C}_4\text{H}_8\text{Se}_2$      | 1,4-diselenane* <sup>⬆</sup>                        | 113         | 237         | -0.58              |
|                   | $\text{C}_6\text{H}_6\text{Se}_2$      | Benzene 1,4-diselenol* <sup>⬆</sup>                 | >97         | ?           | -0.36              |
| $^{130}\text{Te}$ | $\text{H}_4\text{C}_4\text{Te}$        | Tellurophene                                        | -36         | ~148        | -0.26              |
|                   | $\text{H}_8\text{C}_4\text{Te}$        | Tellurolane                                         | ?           | ~166        | -0.34              |
| $^{76}\text{Ge}$  | $\text{GeH}_4$                         | Germane <sup>⬆</sup>                                | -165        | -88         | -1.27              |
|                   | $\text{Ge}(\text{CH}_3)_4$             | Tetramethyl germanium <sup>⬆</sup>                  | -88         | 43          | -1.02 <sup>V</sup> |
| $^{124}\text{Sn}$ | $\text{SnH}_4$                         | Stannane* <sup>⬆</sup>                              | -146        | -52         | -0.90              |
|                   | $\text{Sn}(\text{CH}_3)_4$             | Tetramethyl tin <sup>⬆</sup>                        | -54         | 75          | -0.67 <sup>V</sup> |
| $^{96}\text{Zr}$  | $((\text{CH}_3)_2\text{N})_4\text{Zr}$ | Tetrakis(dimethylamido) zirconium(IV)* <sup>⬆</sup> | 60          | 89?         | -0.75 <sup>V</sup> |
|                   | $((\text{CH}_3)_2\text{N})_4\text{Zr}$ | Zirconium(IV) tert-butoxide * <sup>⬆</sup>          | 3           | 250?        | -0.54 <sup>V</sup> |
|                   | $\text{Zr}(\text{OC}_2\text{H}_5)_4$   | Zirconium(IV)ethoxide* <sup>⬆</sup>                 | 172         | >235        | -0.79 <sup>V</sup> |
| $^{100}\text{Mo}$ | $(\text{C}_8\text{H}_{10})_2\text{Mo}$ | Bis(ethylbenzene) Mo* <sup>⬆</sup>                  | <23         | >170        | -0.76 <sup>V</sup> |



Tellurophene



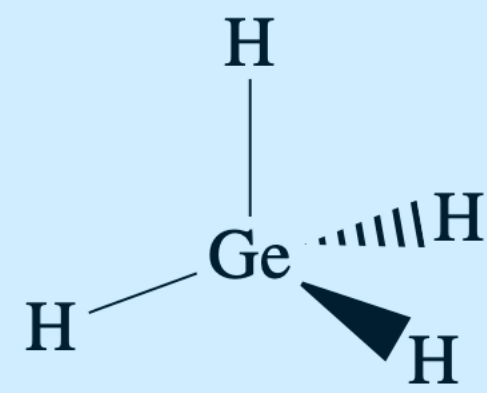
m.p. -36 C, b.p. 148 C



Tellurolane



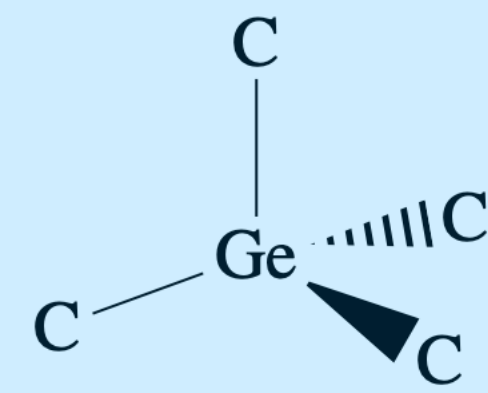
m.p. ??, b.p. 166–167 C



Germane



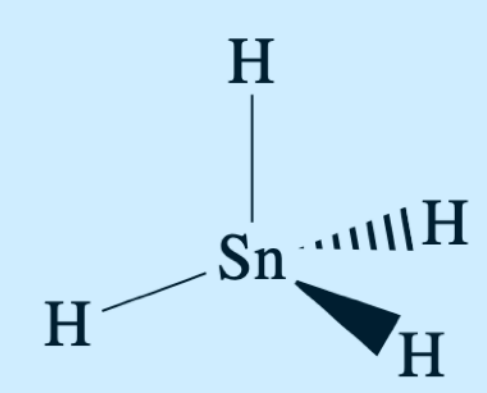
m.p -165 C, b.p. -88 C



Tetramethylgermanium



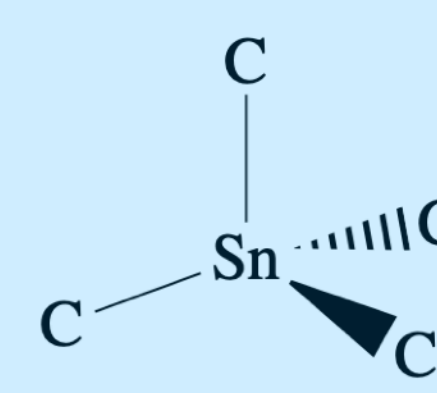
m.p. -88 C, b.p. 43 C



Stannane



m.p. -146 C, b.p. -52 C

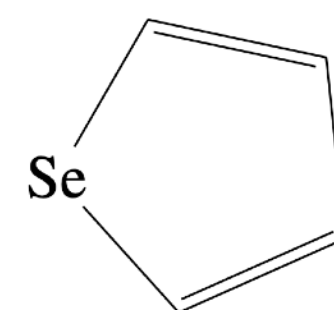
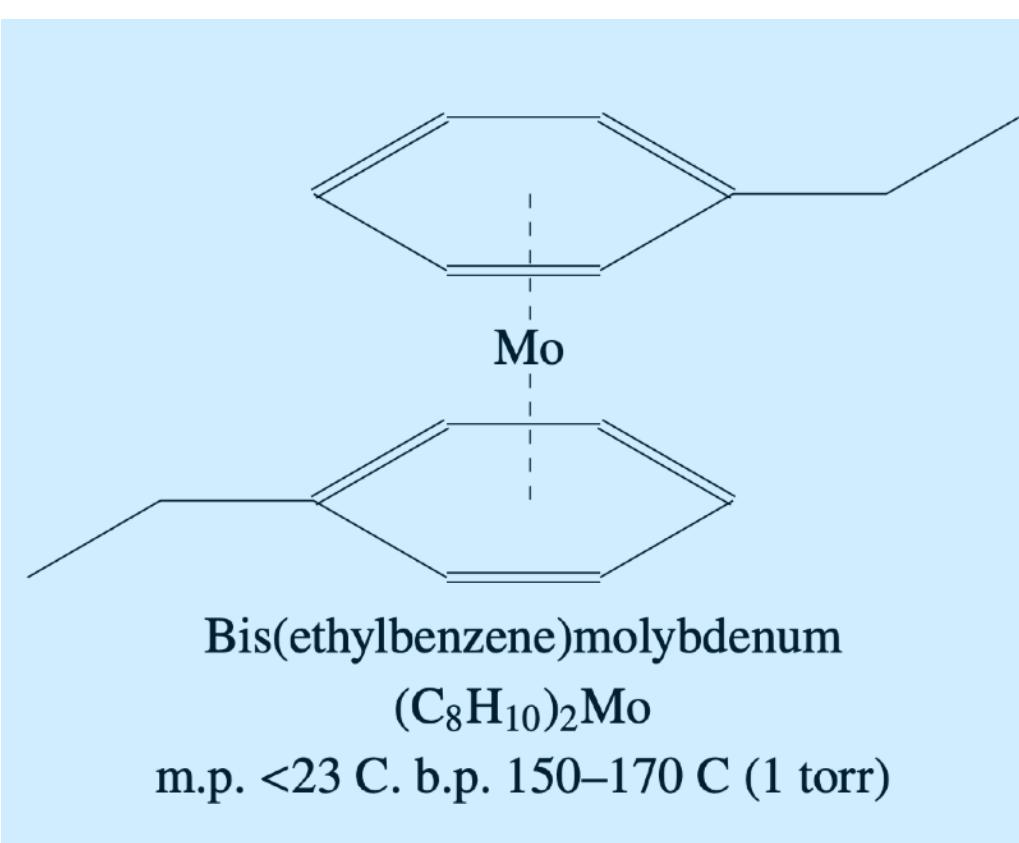


Tetramethyl tin



m.p -54 C, b.p. 75

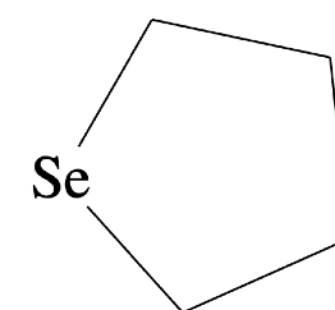
nonpolar  
species are worth  
considering for  
liquid phase



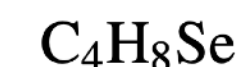
Selenophene



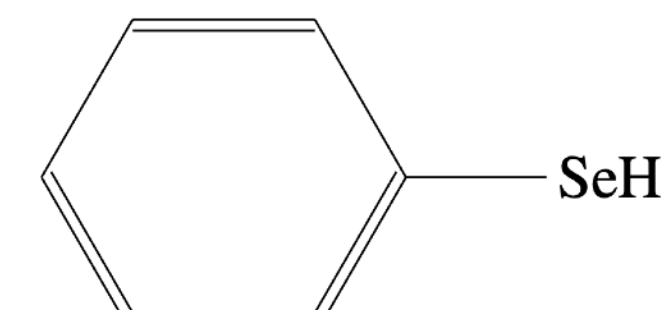
m.p -38 C, b.p. 110 C



Selenolane



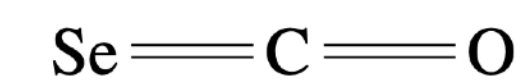
m.p. ?, b.p. 135 C



Benzeneselenenol



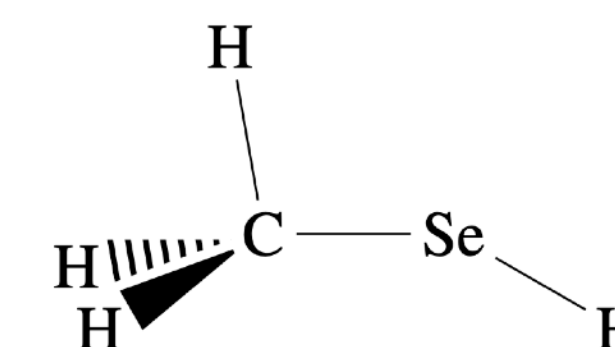
m.p. ?, b.p. 183 C



Carbonyl selenide



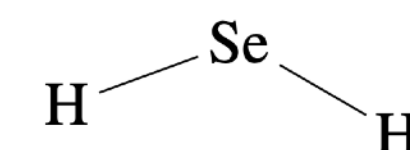
m.p. -122, b.p. -23 C



Methaneselenenol



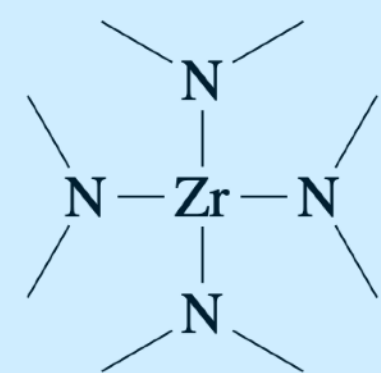
m.p. -54 C, b.p. 12 C



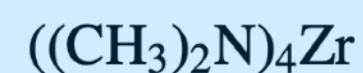
Hydrogen selenide



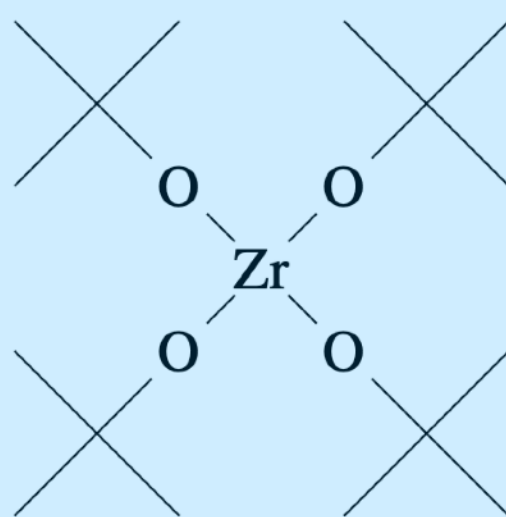
m.p. -65.73, b.p. -41.25 C



Tetrakis(dimethylamino)Zr(IV)



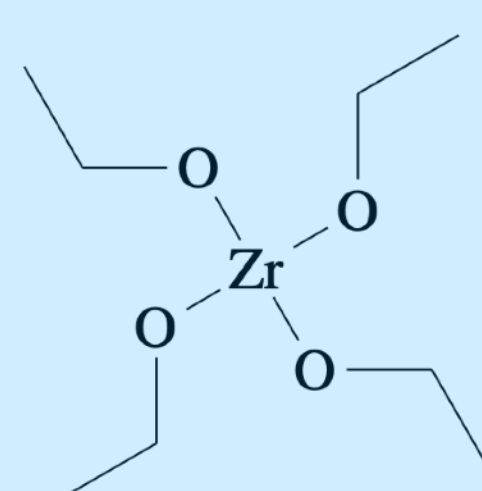
m.p. 60 C, b.p. ~89 C



Zr(IV) tert-butoxide



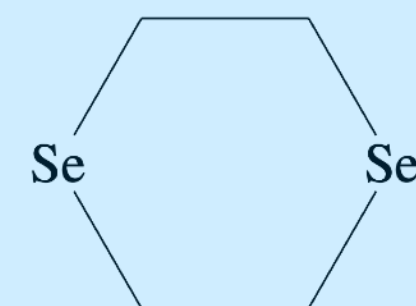
m.p. 3 C, b.p. 250 C



Zr(IV)ethoxide



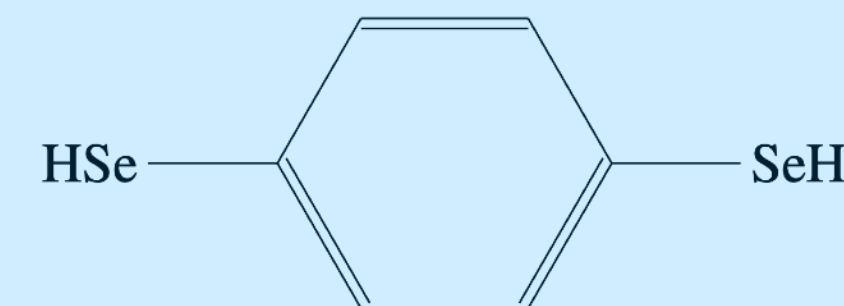
m.p. ~172 C, b.p. >235 C



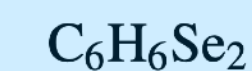
1,4-diselenane



m.p. 113 C, b.p. 237? C

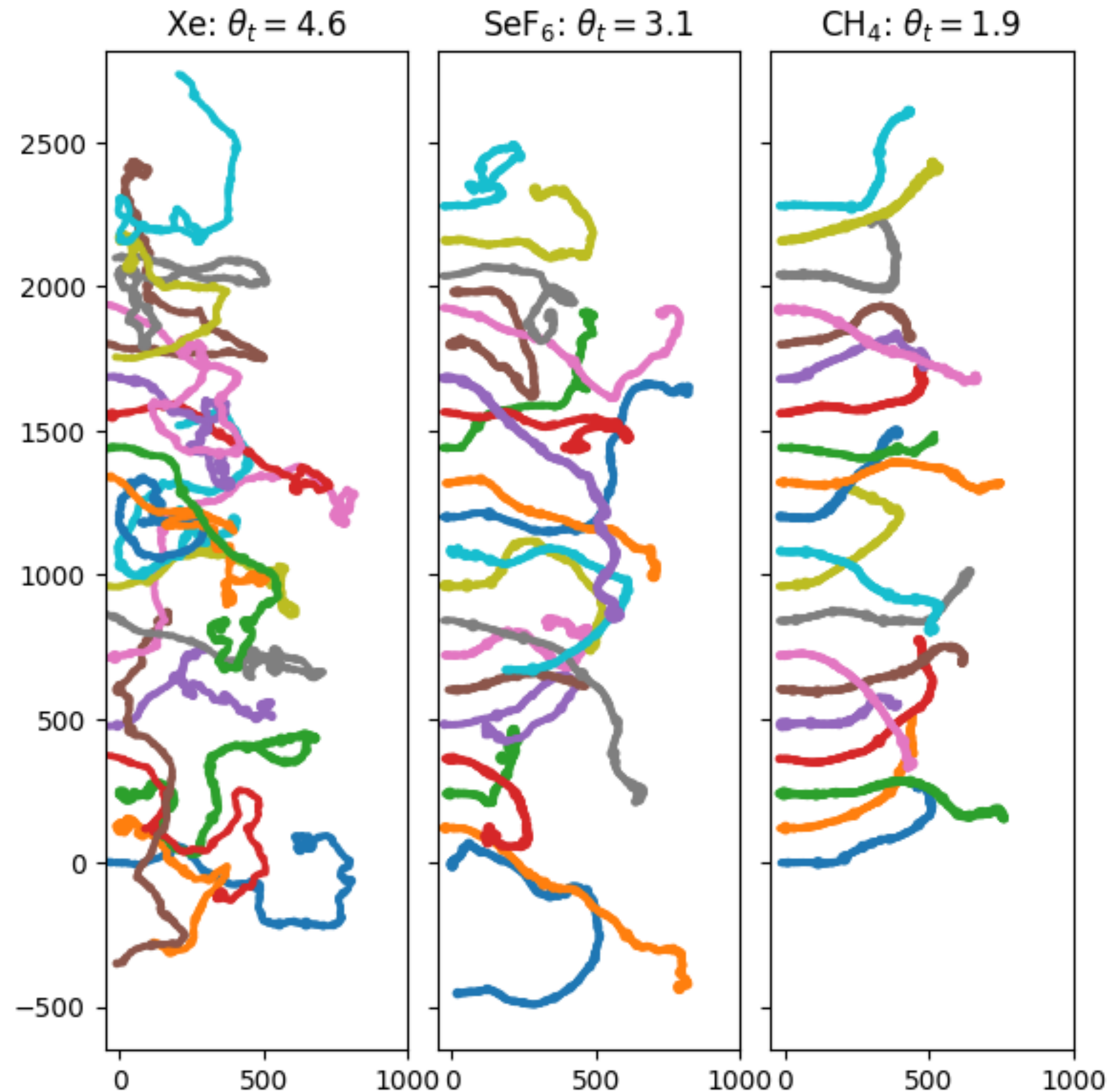


Benzene 1,4-diselenenol



m.p >97C, b.p. ? C

These are all 1 MeV stopping electrons



Angle changes due to  
high-momentum-transfer  
Mott scatters

Angle changes only due to  
many low-momentum-  
transfer ionizations

## Gas-to-gas differences in TPC tracking

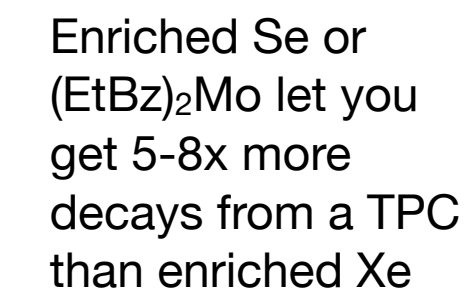
- It's easier to reconstruct a long track that crosses lots of resolution elements
  - Gas choice: prefer lower stopping power, higher  $Q_{\beta\beta}$
  - Detector design choice: operating density (prefer lower) and readout resolution (prefer higher)
- Easier to reconstruct a less-kinked track
  - Gas choice governs: prefer long radiation length. (prefer stopping power that comes from light atoms, not heavy ones)

We can assign each gas a figure-of-merit that says whether it tolerates a higher-density detector.

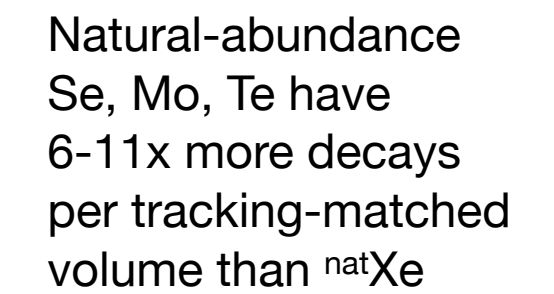
Spagetti-like tracks

"tangling factor"

nearly straight tracks



Enriched Se lets you pack 2-3x more targets into a TPC than enriched Xe



# Gas selection table (1 bar @ SuperK scale)

| Compound                                         | SuperK-like volume<br>50k m <sup>3</sup> (1 atm @ b.p.) |                         |            |                        | Scenario (a)<br>(enriched)               |                                                | Scenario (b)<br>(natural)               |                                                |
|--------------------------------------------------|---------------------------------------------------------|-------------------------|------------|------------------------|------------------------------------------|------------------------------------------------|-----------------------------------------|------------------------------------------------|
|                                                  | T<br>(C)                                                | Track<br>length<br>(cm) | $\theta_t$ | Element<br>mass<br>(T) | Targets<br>(atoms<br>$\times 10^{-28}$ ) | $0\nu\beta\beta$<br>rate<br>(y <sup>-1</sup> ) | Target<br>(atoms<br>$\times 10^{-28}$ ) | $0\nu\beta\beta$<br>rate<br>(y <sup>-1</sup> ) |
| Xenon (STP)                                      | 0                                                       | 254                     | 4.6        | 304                    | 134.9                                    | 1.7                                            | 12.0                                    | 0.2                                            |
| Hydrogen selenide                                | -41                                                     | 419                     | 3.5        | 216                    | 158.7                                    | 5.9                                            | 14.6                                    | 0.5                                            |
| Carbonyl selenide <sup>★</sup>                   | -23                                                     | 340                     | 3.2        | 200                    | 147.3                                    | 5.5                                            | 13.5                                    | 0.5                                            |
| Methane selenol                                  | 12                                                      | 435                     | 3.3        | 175                    | 129.2                                    | 4.8                                            | 11.9                                    | 0.4                                            |
| Selenophene <sup>†</sup>                         | 110                                                     | 422                     | 2.9        | 130                    | 96.2                                     | 3.6                                            | 8.8                                     | 0.3                                            |
| Selenolane <sup>†</sup>                          | 135                                                     | 435                     | 2.9        | 122                    | 90.3                                     | 3.3                                            | 8.3                                     | 0.3                                            |
| Benzeneselenol                                   | 183                                                     | 418                     | 2.8        | 109                    | 80.8                                     | 3.0                                            | 7.4                                     | 0.3                                            |
| 1,4-diselenane <sup>†★</sup>                     | 237                                                     | 344                     | 3.1        | 196                    | 144.4                                    | 5.3                                            | 13.3                                    | 0.5                                            |
| Benzene 1,4-diselenol <sup>†★</sup>              | 250*                                                    | 320                     | 3.0        | 191                    | 140.8                                    | 5.2                                            | 13.0                                    | 0.5                                            |
| Tellurophene <sup>†</sup>                        | 148                                                     | 292                     | 3.9        | 188                    | 87.5                                     | 3.5                                            | 30.2                                    | 1.2                                            |
| Tellurolane <sup>†</sup>                         | 166                                                     | 297                     | 3.9        | 181                    | 83.9                                     | 3.4                                            | 28.9                                    | 1.2                                            |
| Germane                                          | -88                                                     | 238                     | 4.1        | 251                    | 199.0                                    | 2.2                                            | 15.5                                    | 0.2                                            |
| Tetramethylgermanium                             | 43                                                      | 232                     | 3.4        | 147                    | 116.5                                    | 1.3                                            | 9.1                                     | 0.1                                            |
| Stannane <sup>★</sup>                            | -52                                                     | 202                     | 4.6        | 342                    | 166.6                                    | 3.6                                            | 9.7                                     | 0.2                                            |
| Tetramethyltin <sup>†</sup>                      | 75                                                      | 215                     | 3.9        | 217                    | 105.8                                    | 2.3                                            | 6.1                                     | 0.1                                            |
| TDMAZ <sup>†</sup>                               | 89                                                      | 216                     | 2.4        | 162                    | 101.7                                    | 3.0                                            | 2.8                                     | 0.1                                            |
| Zr(O <sup>t</sup> Bu) <sub>4</sub> <sup>†★</sup> | 250                                                     | 216                     | 2.3        | 112                    | 70.4                                     | 2.1                                            | 2.0                                     | 0.1                                            |
| Zr(OEt) <sub>4</sub> <sup>†★</sup>               | 237*                                                    | 296                     | 2.5        | 115                    | 72.2                                     | 2.1                                            | 2.0                                     | 0.1                                            |
| (EtBz) <sub>2</sub> Mo <sup>†★</sup>             | 250*                                                    | 247                     | 2.6        | 116                    | 70.4                                     | 5.9                                            | 6.8                                     | 0.6                                            |
| CaC <sub>8</sub> H <sub>20</sub> <sup>¶</sup>    | these compounds<br>are yet to be<br>invented            |                         |            |                        | 83.1                                     | 0.1                                            | 0.2                                     | 0.0                                            |
| PdC <sub>8</sub> H <sub>20</sub> <sup>¶</sup>    |                                                         |                         |            |                        | 83.1                                     | 2.5                                            | 9.8                                     | 0.3                                            |
| CdC <sub>8</sub> H <sub>20</sub> <sup>¶</sup>    |                                                         |                         |            |                        | 83.1                                     | 3.9                                            | 6.3                                     | 0.3                                            |
| NdC <sub>8</sub> H <sub>20</sub> <sup>¶</sup>    |                                                         |                         |            |                        | 83.1                                     | 7.8                                            | 4.7                                     | 0.4                                            |

- An enriched-xenon STP fill with  $1.35 \times 10^{30}$  <sup>136</sup>Xe atoms would see 1.7 events/y at  $m_{\beta\beta} = 1$  meV.

- A natural-xenon fill with  $1.2 \times 10^{29}$  <sup>136</sup>Xe atoms would see 0.2 events/y at  $m_{\beta\beta} = 1$  meV.

- AND it does so in short, tangly tracks

- Se and Mo options get higher rates with lower inventories (and easier tracking!)

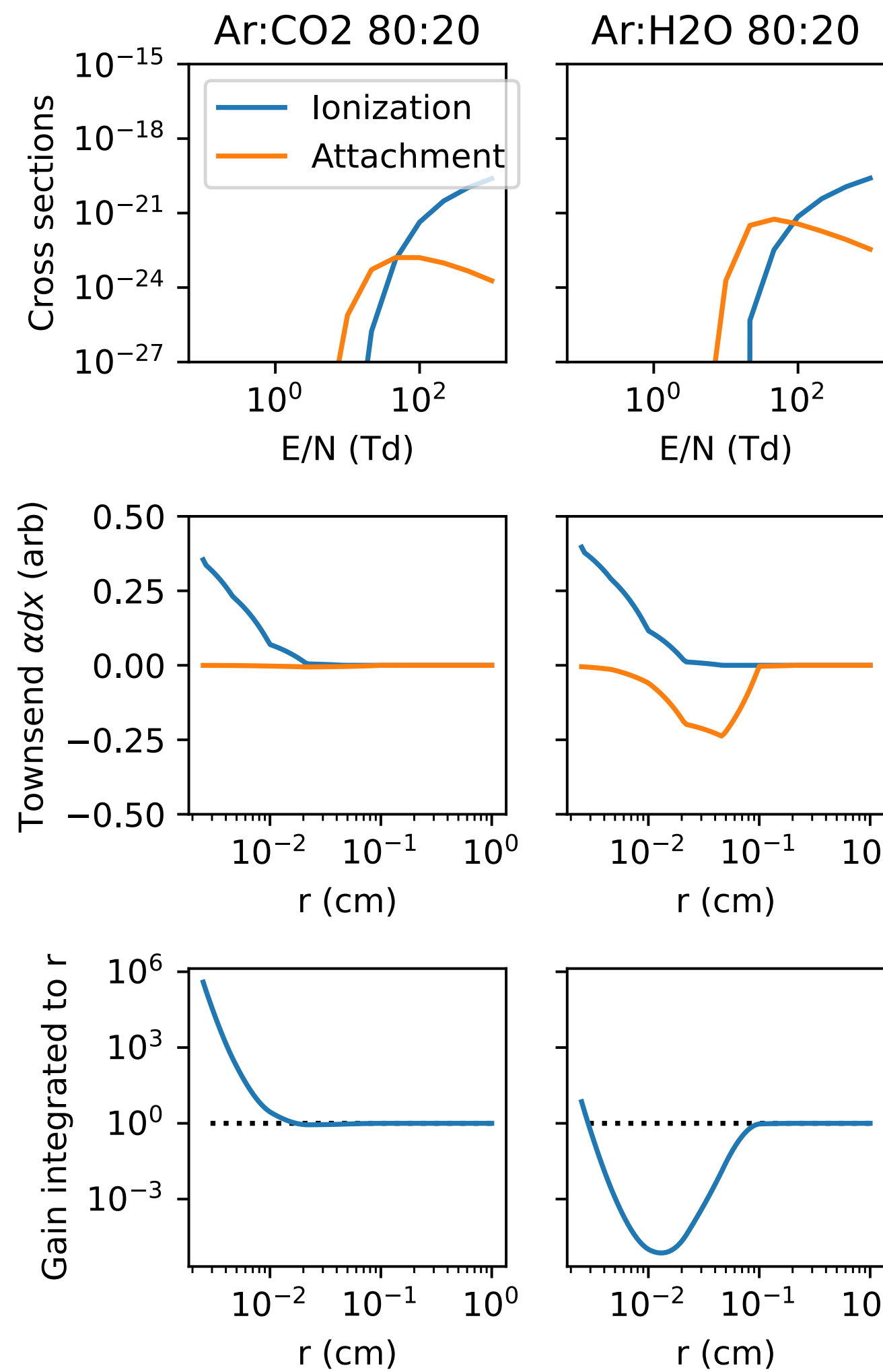
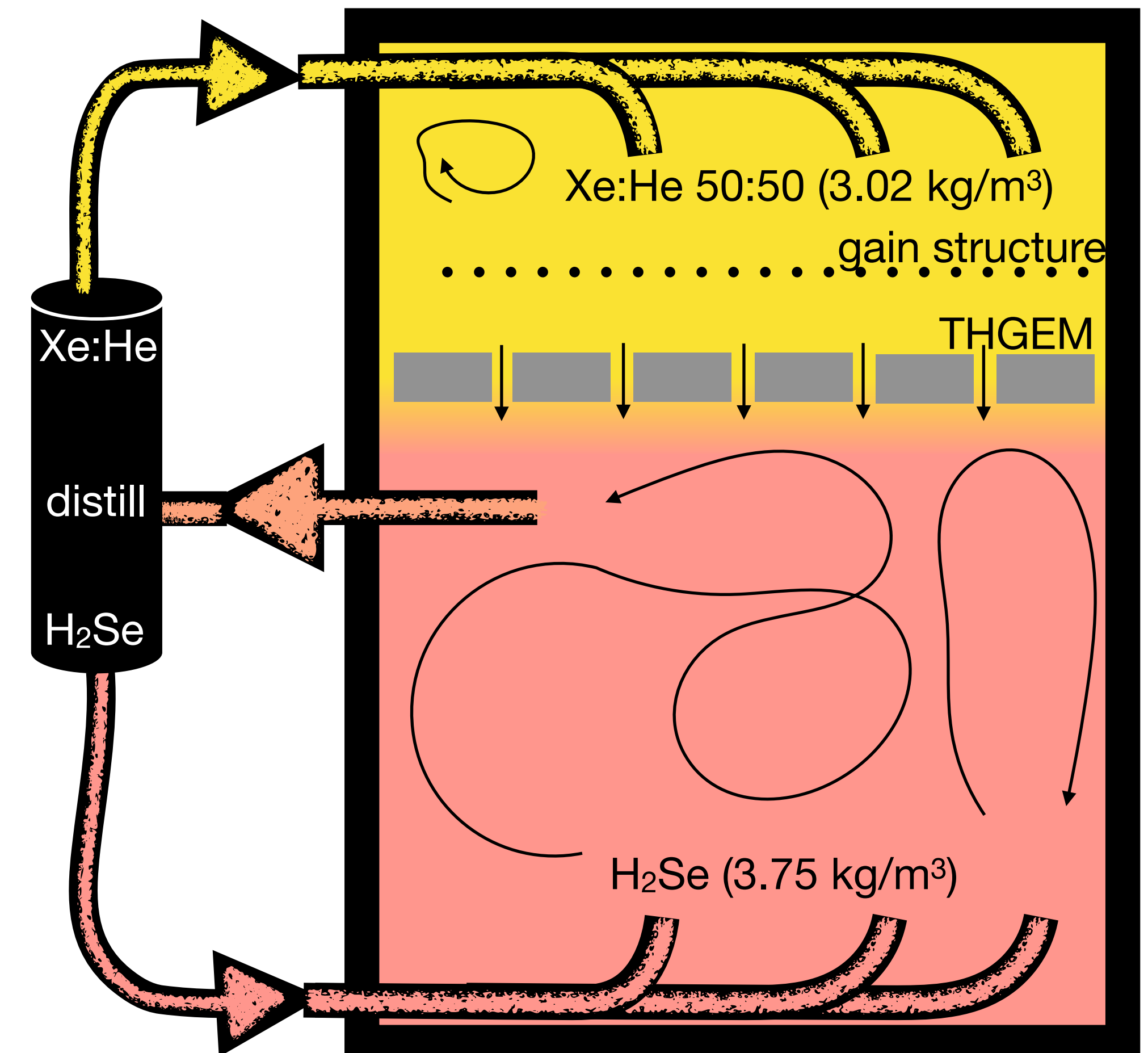
- Natural-abundance tellurophene and tellurolane get above 1 event/y!

Many gases seem plausible:

- "plan a multi-isotope campaign"
- "options for discovery followup"
- "gain/drift details will decide for us"

# Maybe we can do avalanche gain above gainless gases

- GEMs and THGEMs are good barriers to bulk gas flow. Idea: flow a light noble gas into the gain region and maintain a high-purity stratified layer.

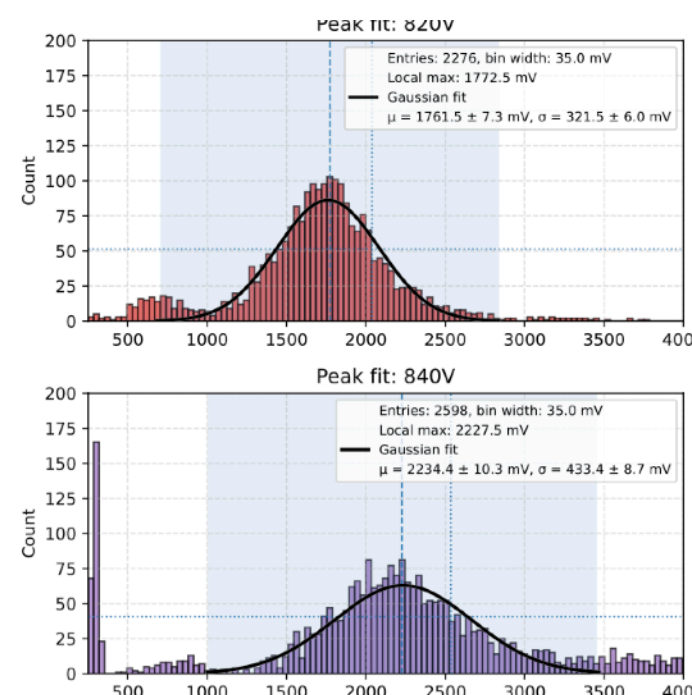


- Not all good drift gases are good gain media.

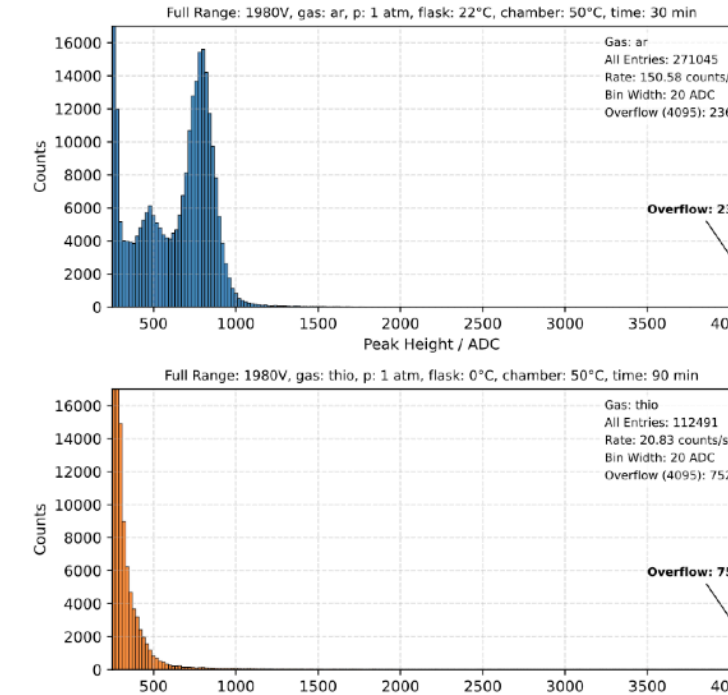
Example from LXCAT cross section data and BOLSIG++:  
CO2 vs H2O

- both good drift gases at  $E/N < 10$
- both good gain gases at  $E/N > 100$
- Difference: in the range  $10 < E/N < 100$  (few-eV electrons) H<sub>2</sub>O has much larger attachment x-sec
- $200 < r < 800 \mu\text{m}$  from a gain wire is an "electronegative wall"

(Is this correct? We humidified a warm ArCO<sub>2</sub> counter gas to 12% water and saw nice <sup>55</sup>Fe peaks.) Aneesha Avasthi PhD thesis CWRU 2026

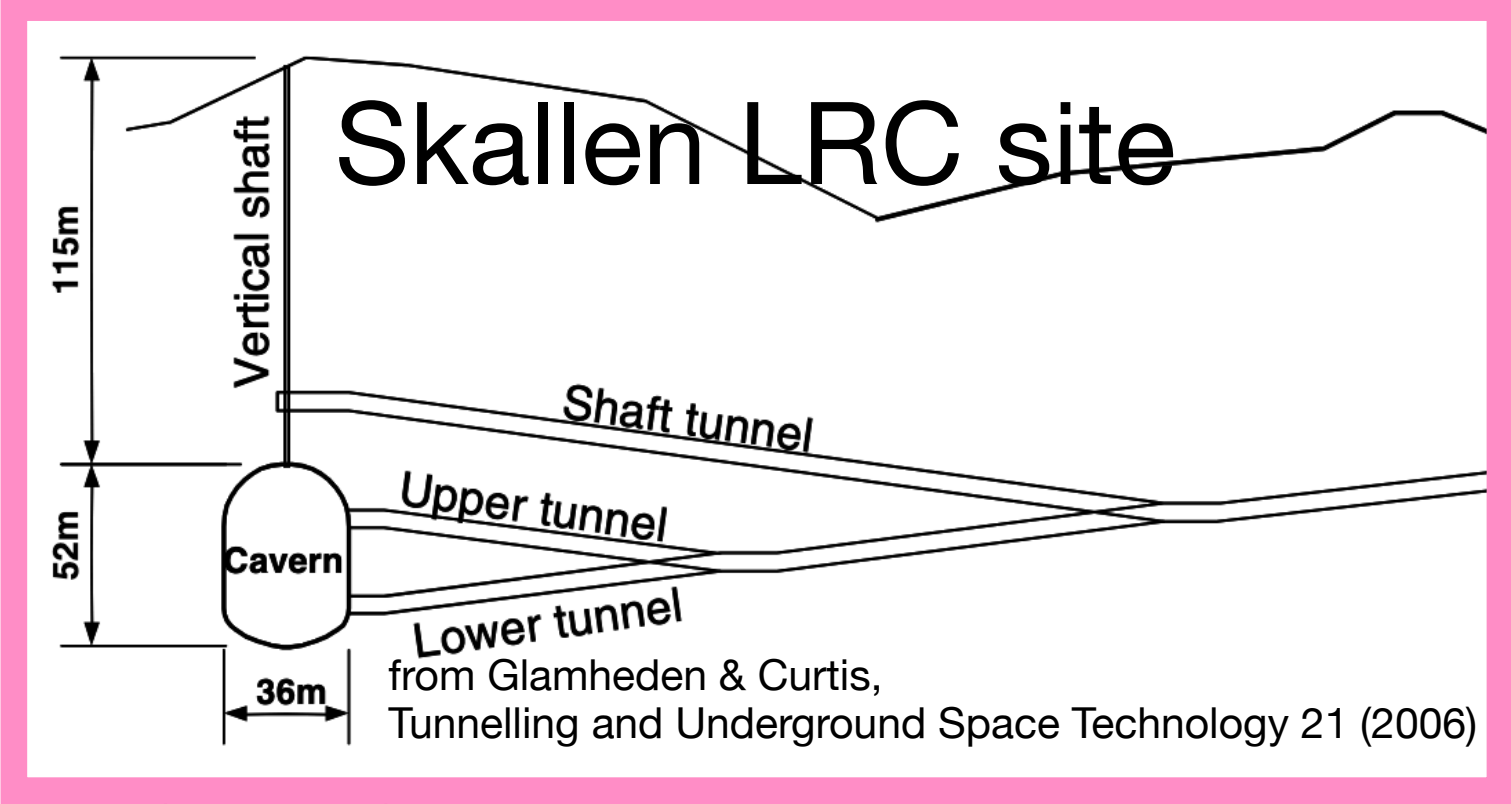


No gain was visible in thiophene but we don't know whether it was low-field attachment (with the DFT wrong) or high-field dissociation wall (as BOLSIG++'s H<sub>2</sub>O)



# What spatial and pressure scales are available?

- Please use your own lab's favorite "N copies of module V" alternative to the giant single cavern cartoons here.
- Gas TPCs don't self-shield anyway so there is less need to be monolithic.
- Many possible staging/buildout strategies with early data and



There are physics reasons to expect lower pressures (long tracks) to perform better.

If we can tolerate NEXT-like densities then the sizes are not so bad.  $10^{30}$   $^{82}\text{Se}$  atoms in 3,300 m<sup>3</sup> enriched, 50k m<sup>3</sup> natural

Don't let this scare you, a natural gas industry project in Sweden operates a SuperK-scale cavern at 200 bar.

|              | SuperK tank<br>or Skallen LRC<br>50,000 m <sup>3</sup> | SNO cavern<br>(30% LNGS Hall A)<br>12,000 m <sup>3</sup> | SNOLab Cube Hall<br>(2x KATRIN)<br>3,300 m <sup>3</sup> | Grangesberg LRC<br>(2x GERDA cryostat)<br>135 m <sup>3</sup> |
|--------------|--------------------------------------------------------|----------------------------------------------------------|---------------------------------------------------------|--------------------------------------------------------------|
| target atoms | multiple of STP density required (100% target isotope) |                                                          |                                                         |                                                              |
| $10^{29}$    | 0.08                                                   | 0.3                                                      | 1                                                       | 30                                                           |
| $10^{30}$    | 0.8                                                    | 3                                                        | 10                                                      | liquid-like                                                  |
| $10^{31}$    | 8                                                      | 30                                                       | 100 <sup>SC?</sup>                                      | —                                                            |
| target atoms | multiple of STP density required (9.2% target isotope) |                                                          |                                                         |                                                              |
| $10^{29}$    | 0.8                                                    | 3.0                                                      | 12                                                      | liquid-like                                                  |
| $10^{30}$    | 8.0                                                    | 30                                                       | 120 <sup>SC?</sup>                                      | —                                                            |
| $10^{31}$    | 80 <sup>SC?</sup>                                      | liquid-like                                              | —                                                       | —                                                            |

**Ton-scale Xenon Gas TPC for  $0\nu\beta\beta$  Search at Atmospheric Pressure**

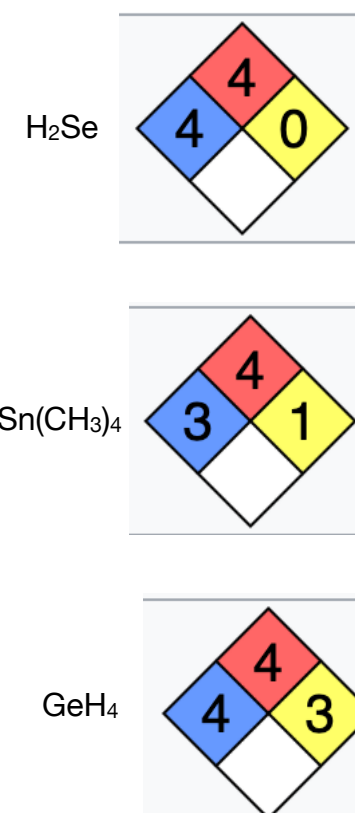
<https://arxiv.org/abs/2609.07378>

Y. Mei,<sup>1</sup> K. Mistry,<sup>1</sup> D.R. Nygren,<sup>1</sup>

# Conclusions

"I don't really understand why the approach to experimental physics always seems to be starting many orders of magnitude away from what you want and then inching slightly closer every ten years until maybe a hundred years from now someone can do something interesting" -- Matt Reece

- Is this a route to 1 meV?
- Lots of low-hanging fruit right now for an underfunded gas R&D lab with the right people/time/facilities/friends



All these gases are toxic and flammable. Please talk to real chemists and don't get anyone hurt.



"I'm skeptical of gas TPCs but have a lot of experience with liquid" start sketching some two-phase TPC ideas for 1,4-diselenane and bisethylbenzene molybdenum

"I have a colleague in computational chemistry" can they compute the electron/molecule cross sections to feed BOLSIG++ swarm calcs?

"I have a colleague in computational chemistry" can they compute the electron/molecule cross sections to feed BOLSIG++ swarm calcs?

"I have a fume hood and a proportional counter" try looking for gain in some of the safer gases or their congeners

"Our NukeEng programs have MS students who need projects" Scrape nuclear data for all the escape-peak combinatorics of  $^{83}\text{Se}$  that give two-track topologies

"The tracking software we wrote for GXeTPC topology is easy to re-train" try throwing it at these longer and less-tangled events

- "I'm a theorist"
- map out what we'd learn from various multisotope campaigns
  - what error bars do we need for the energy/angle differential rates to be interesting?

"We have some money for mine infrastructure consultants" ask a chemical engineer to sketch up how toxic gas safety would work

"I have a glovebox and a P-Chem masters' student" ask them to measure vapor pressure curves for the new gas list

"I have a glovebox and a proportional counter" try looking for gain in some of the scarier gases

"I have some 2nd-year Ph.D. students with computational skills" GEANT

GEANT

GEANT

GEANT

"We are being encouraged to collaborate with petrochemical industry people" start a conversation about lined rock caverns

"We have lots of TPC and MPGD parts lying around" try assembling a flowing-gas TPC where a GEM separates two different gases

"I have a small TPC, and there's a  $\text{GeH}_4$ -ready glovebox in the MOCVD lab upstairs" that can get interesting quickly

"I thought of a something important you missed" please email me!

**backup slides**

# Negative ion sensing

1) Collisional re-ionization in the gain region

2) Gainless negative ion sensing in CMOS

3) Laser detachment?

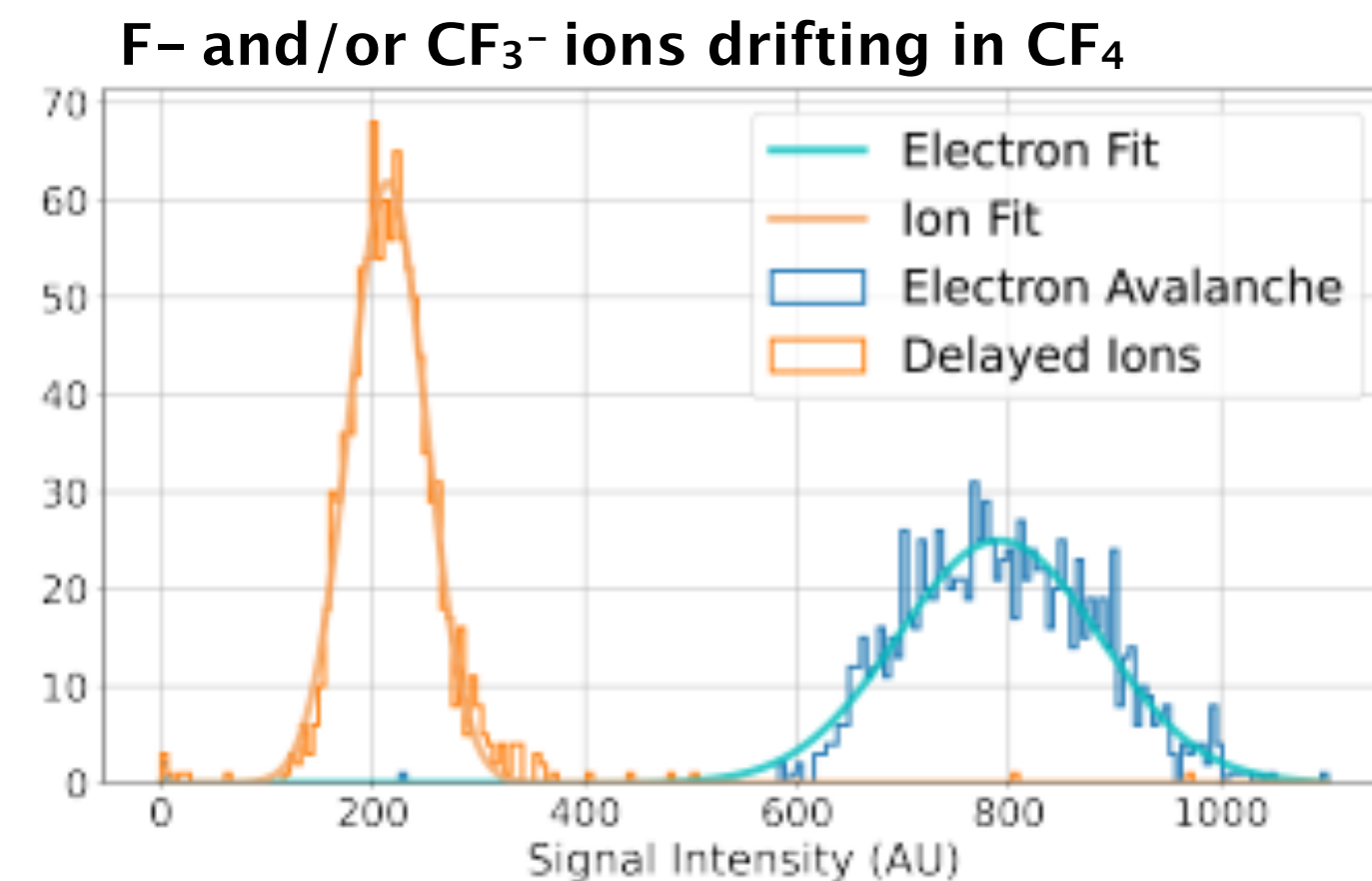


Fig. 8: Integrated signal intensity distributions for the primary, electron avalanche, and negative ion regions of the PMT waveform (see text for details) at 54 Td reduced field and 45 Torr.

Operation of a negative ion gas time projection chamber without electronegative fill gases, McKie et. al <https://arxiv.org/abs/2609.09843>

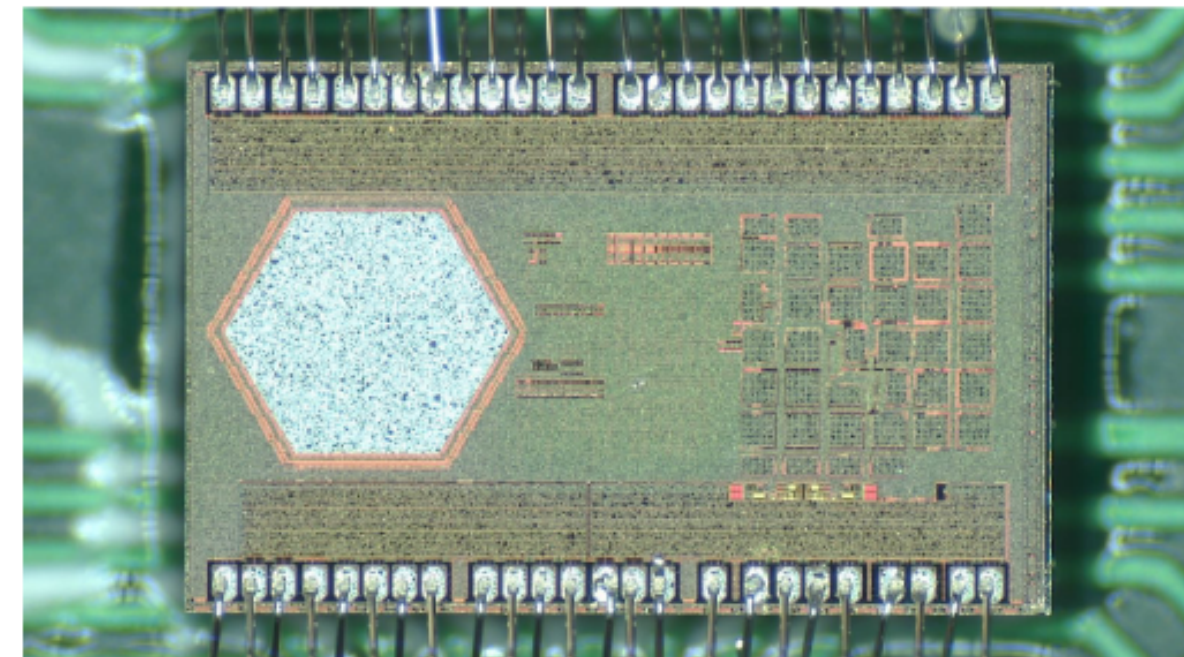
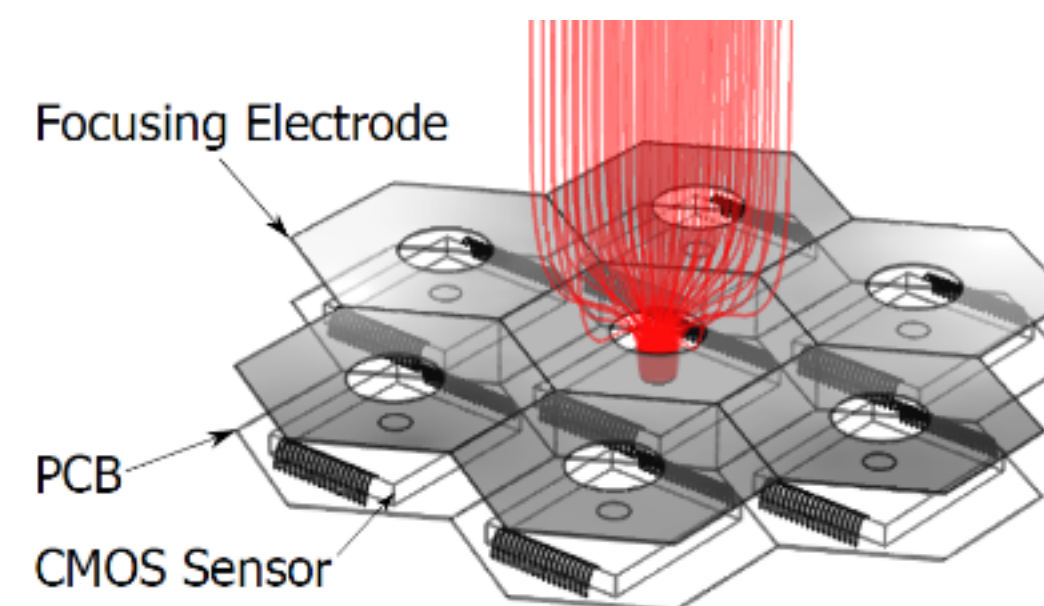
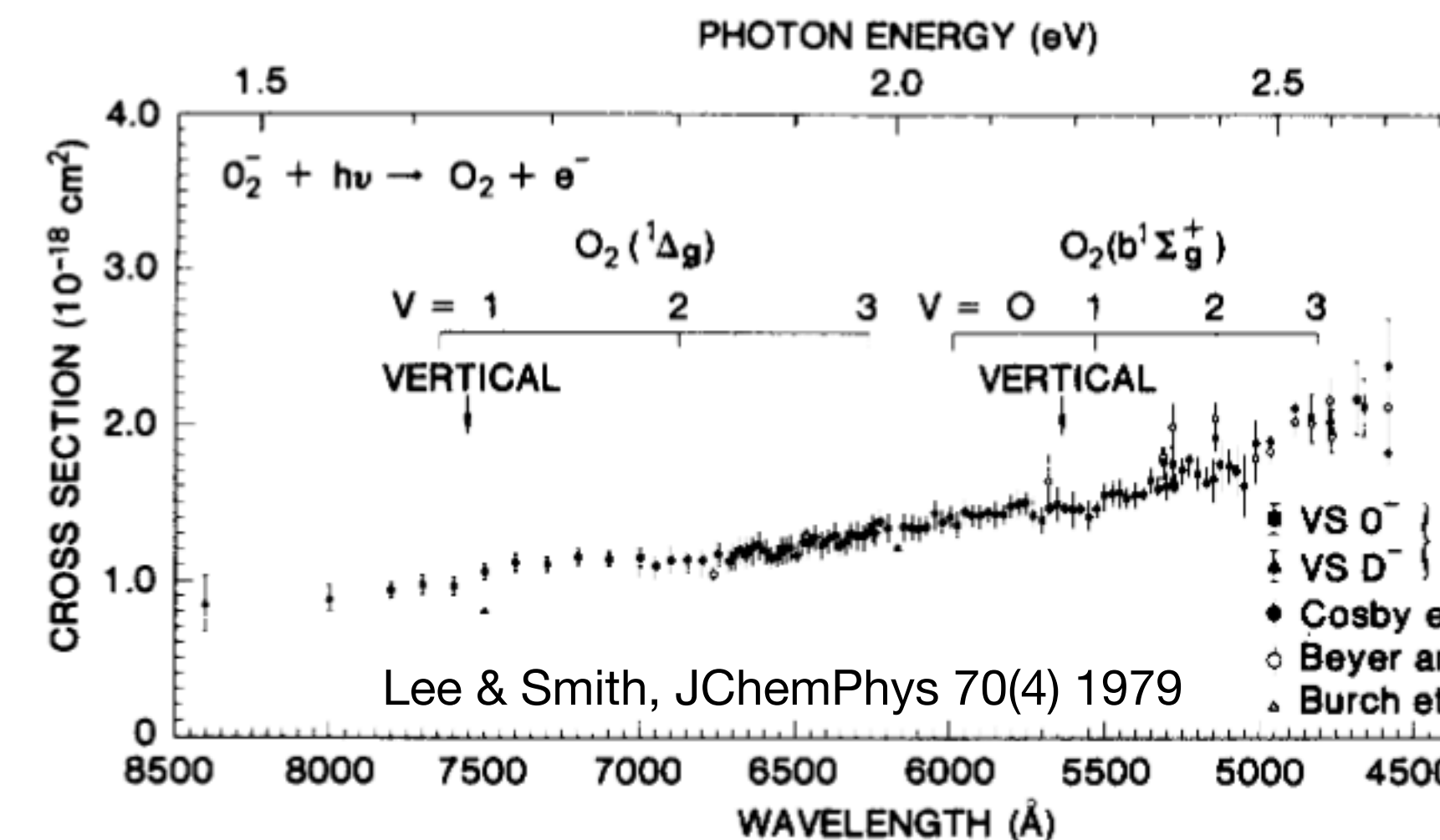


Fig. 10. Photo of the Topmetal-S sensor chip.



NVDEx-100 Conceptual Design Report, Cao et al <https://arxiv.org/abs/2304.08362>



- long distance drift species is anion (CSe<sub>2</sub><sup>-</sup>)
- Shoot kW/mm<sup>2</sup> CW laser along gain wires
- CSe<sub>2</sub><sup>-</sup> + γ → CSe<sub>2</sub> + e<sup>-</sup> with e<sup>-</sup> ready to avalanche

# Drift in liquids

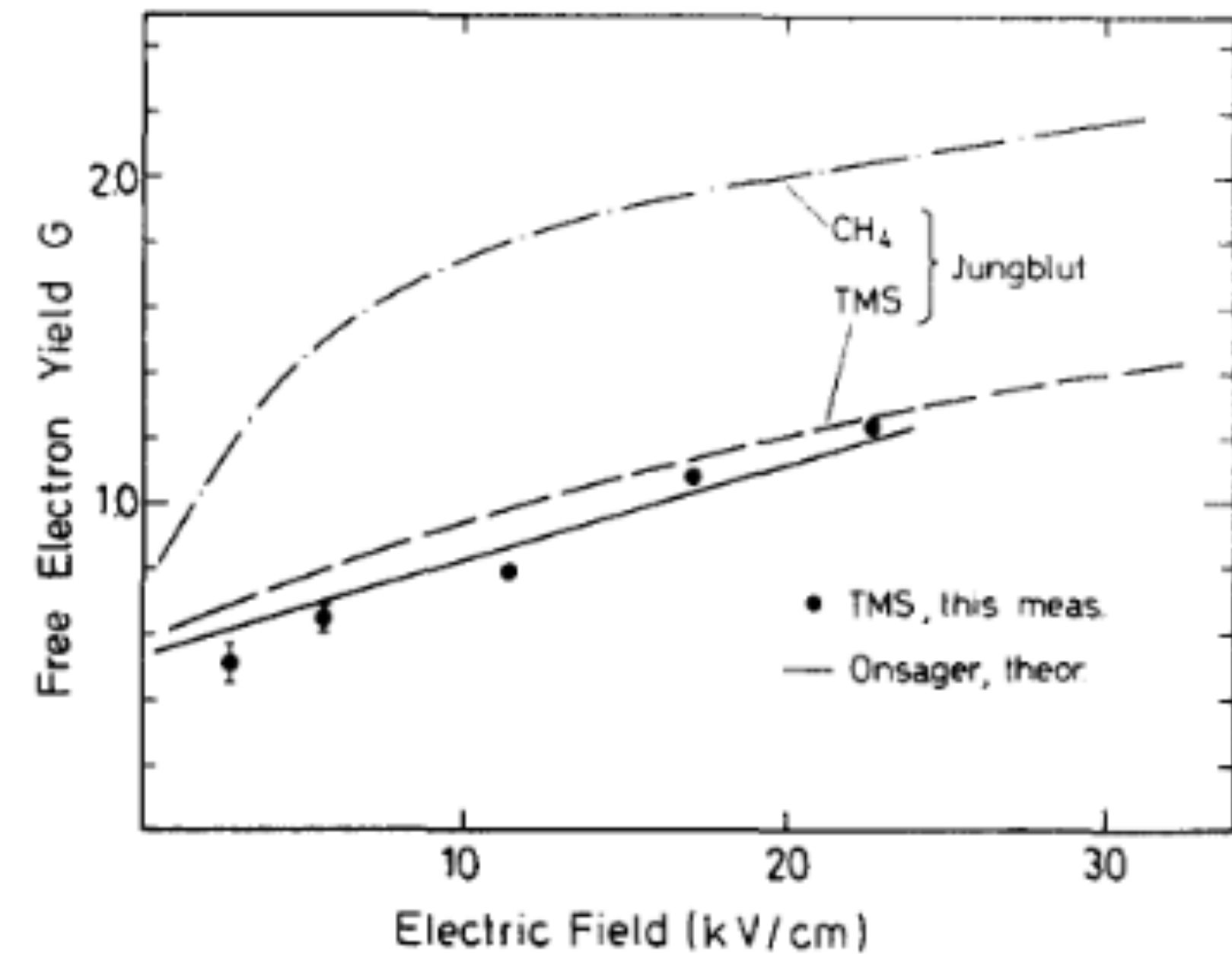
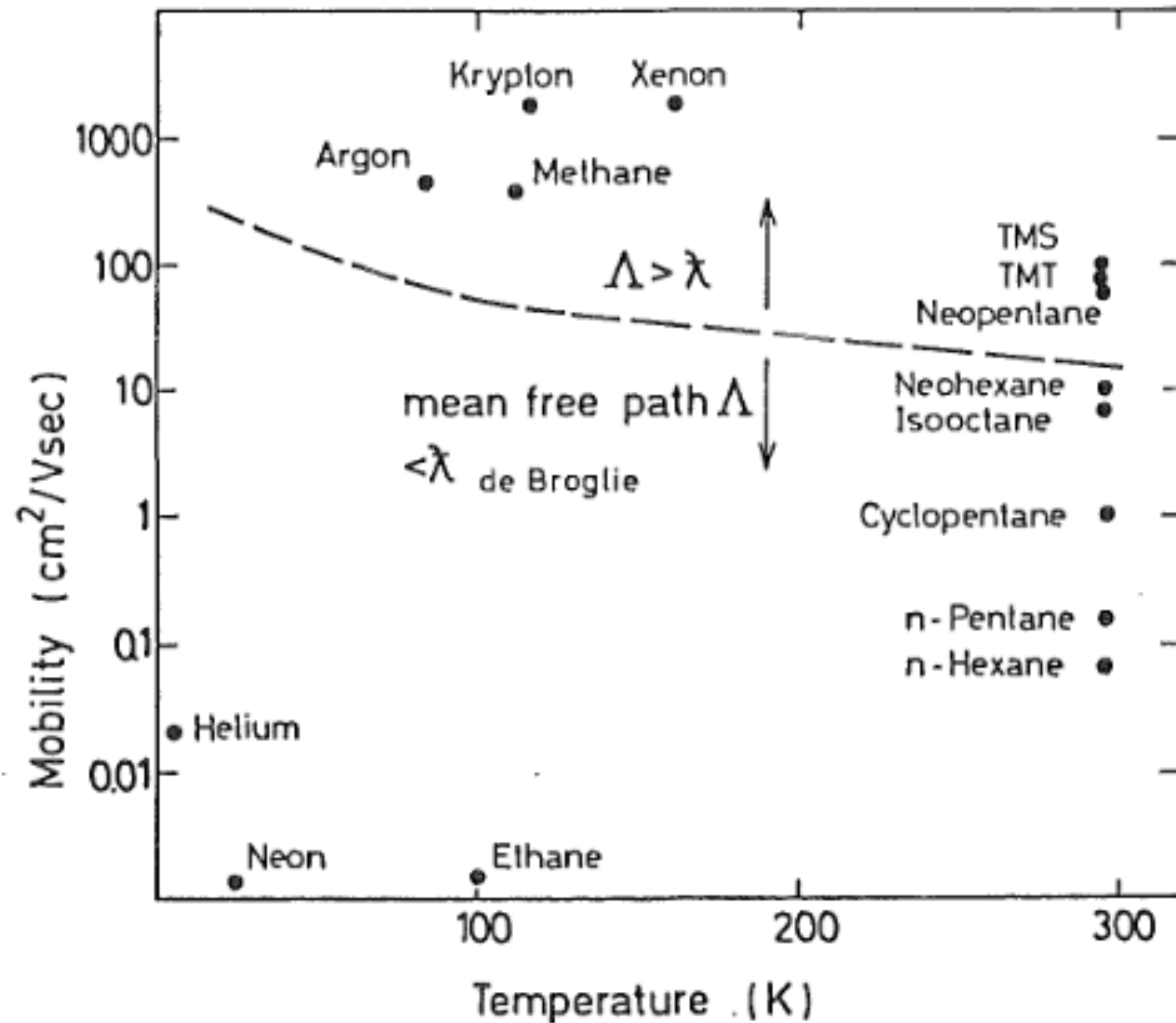


Fig. 6. Number of free electrons  $G$  yielded for 100 eV deposited ionization energy. The straight line through the measured points corresponds to Onsager's theory.

from A Liquid Ionization Chamber Using Tetramethylsilane J. Engler, H. Keim NIM 223(1) 1984