Improving the Proportional Scintillation Signal of Liquid Argon by Xenon Doping

CPAD, March 18th, 2021

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Motivation

- Single-phase liquid argon is the workhorse target medium for low cross-section physics
  - ICARUS T600, MicroBoone, DUNE, and many others*

- For the lowest energy events, dual-phase xenon is the most successful medium
  - Nuclear recoils yield measured to 300 eV **
  - Electronic recoils resolved down to 186 eV ***

Property	Gas scintillation wavelength	Gas scintillation lifetime	Liquid phase ionization energy	Ease of purification	Kinetic match to light particles
Argon	128 nm	~ 3.2 μs	14.3 eV	Easier	A = 39.95
Xenon	178 nm	~ 22 ns	12.13 eV	Difficult	A = 131.29

- Argon light is more difficult to produce and more difficult to sense

* K. Majumdar, K. Mavrokoridis, arXiv:2103.06395 ** B.G. Lenardo et al., arXiv:1908.00518 *** D.S. Akerib et al., arXiv:1709.00800

Motivation – Physics

- WIMP dark matter detection
  - Darkside-20K / GADMC
  - Especially important for extending the reach of ionization-only analysis

- Neutrino physics via the CEνNS channel*
  - Sterile neutrino searches
  - Neutrino magnetic moment searches
  - Non-standard interactions and new light mediators
  - Flavor-blind observation of supernovae, including potential insight into the mass hierarchy**

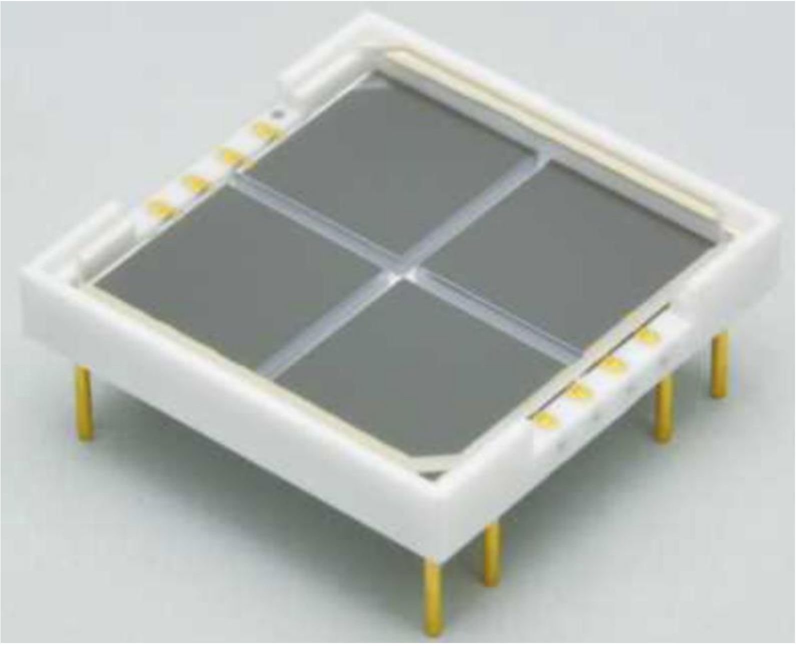
- Anti-proliferation technology
  - Reactor fuel cycle monitoring with CEνNS***

* O.G. Miranda et al., arXiv:2003.12050 ; L.J. Flores et al. arXiv:2002.12342 ; C. Blanco et al. arXiv:1901.08094

** P. Agnes et al., arXiv:2011.07819 ; *** C. Hagmann and A. Bernstein, arXiv:nucl-ex/0411004

Motivation – Technology

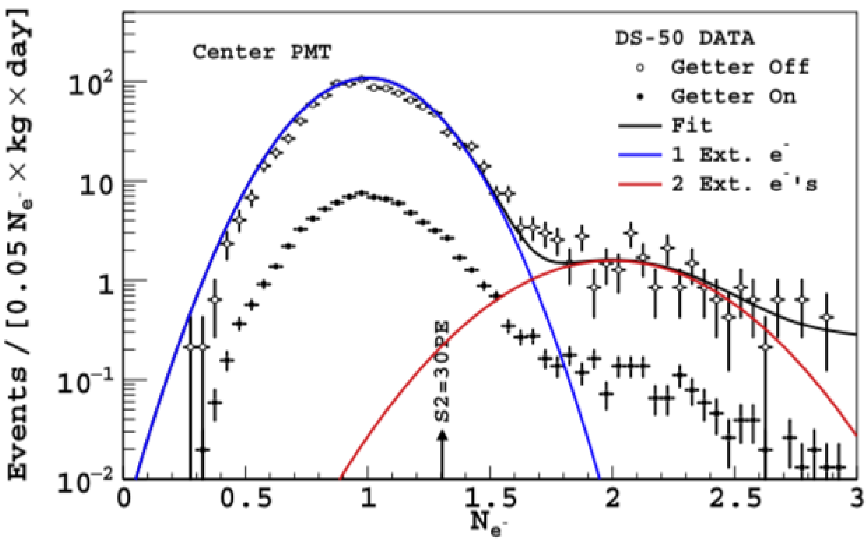
- Underground argon infrastructure*
  - Urania plant (330 kg / day) under construction at the Kinder-Morgan Doe Canyon facility, Colorado, USA
  - Aria cryogenic distillation column for purification under construction in the Seruci Mine, Sardinia, Italy
- VUV SiPM development
  - Durable, compact, and radiopure relative to PMTs
  - Numerous cryogenic amplification schemes**



* W. Bonivento doi:10.1088/1742-6596/1468/1/012234

** M. D'Incecco et al. arXiv: 1706.04213 ; A. Falcone et al., arXiv: 2001.09051

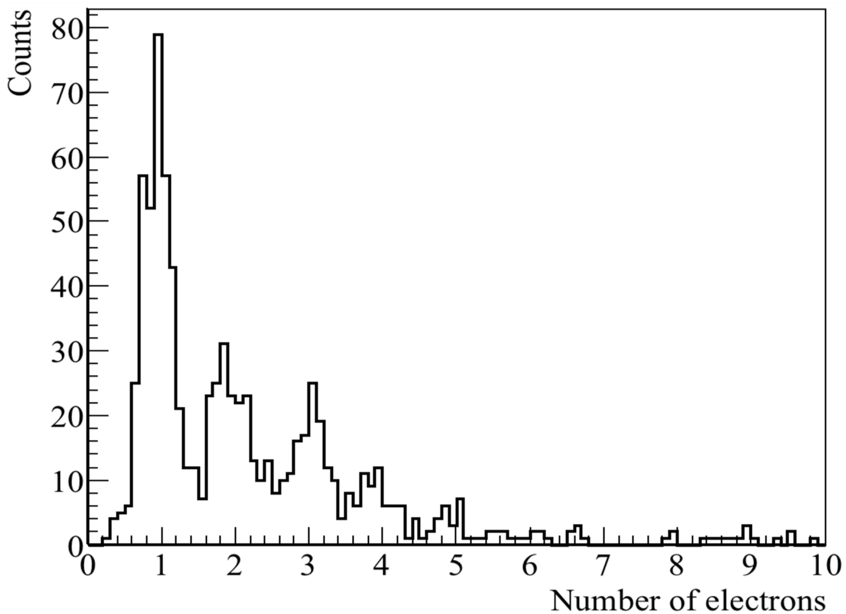
Single electron spectra: Xenon and Argon



DarkSide50 SE spectrum
PRL, 121, 081307 (2018)

23 PMT photoelectrons / extracted electron

Measurement of wavelength-shifted argon S2 light



XeNu detector SE spectrum
J. Xu, Magnificent CEνNS workshop (2020)

72 PMT photoelectrons / extracted electron

Direct measurement of xenon S2 light

Chemistry of S2 light production

Pure Ar

Fast e^- + Ar → slow e^- + Ar^*

Threshold 11.8 eV

Inelastic collision of electron with argon

Ar^* + Ar → Ar_2

Argon finds a ground state atom and forms a metastable excimer molecule

Ar_2 → 2 Ar + $h\nu$

128 nm; 2 - 3 μs lifetime

Excimer molecules decompose and emit photons

Chemistry of S2 light production

Ar + Xe

Fast e^- + Ar → slow e^- + Ar* — Inelastic collision of electron with argon

Threshold 11.8 eV

Fast e^- + Xe → slow e^- + Xe* — Inelastic collision of electron with Xenon

Threshold 8.4 eV

Ar* + Ar → Ar_2

Ar* + Xe → ArXe

Xe* + Xe → Xe_2

Argon and xenon form metastable excimer molecules

Ar_2 → 2 Ar + hν ← 128 nm; 3.2 μs lifetime

ArXe → Xe + Ar + hν ← 147 nm; 300? ns lifetime

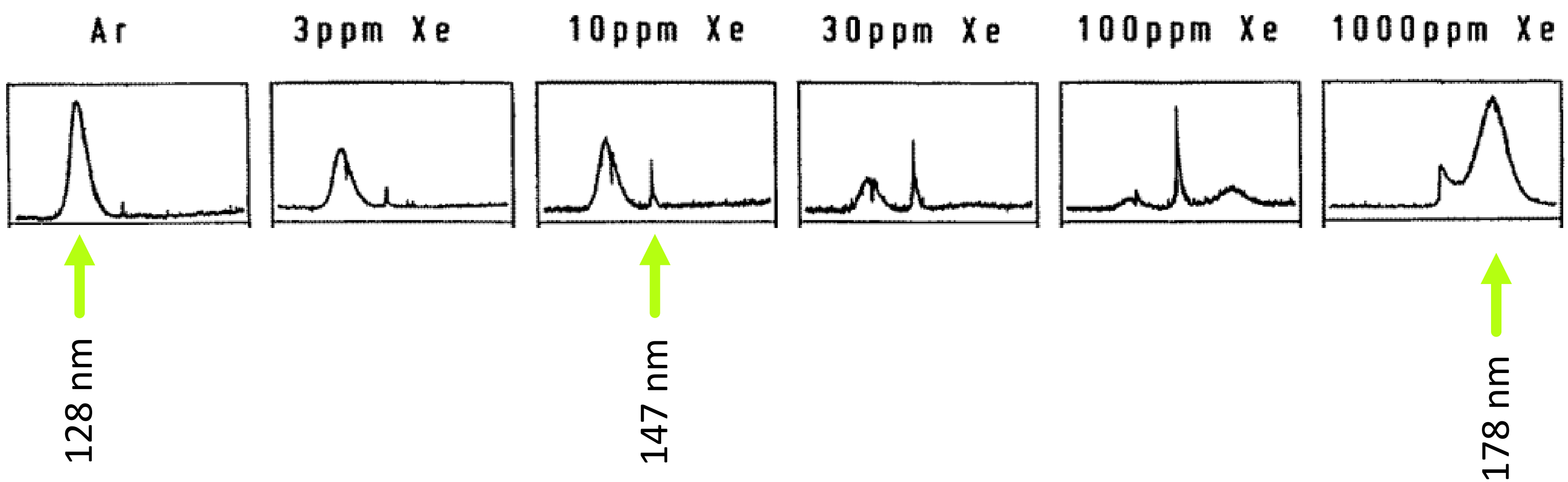
Xe_2 → 2 Xe + hν ← 178 nm; 22 ns lifetime

Excimer molecules decompose and emit photons

Conclusion: New reactions allow for more light production with longer wavelengths and faster timing.

Energy transfer in Ar Xe gas mixtures

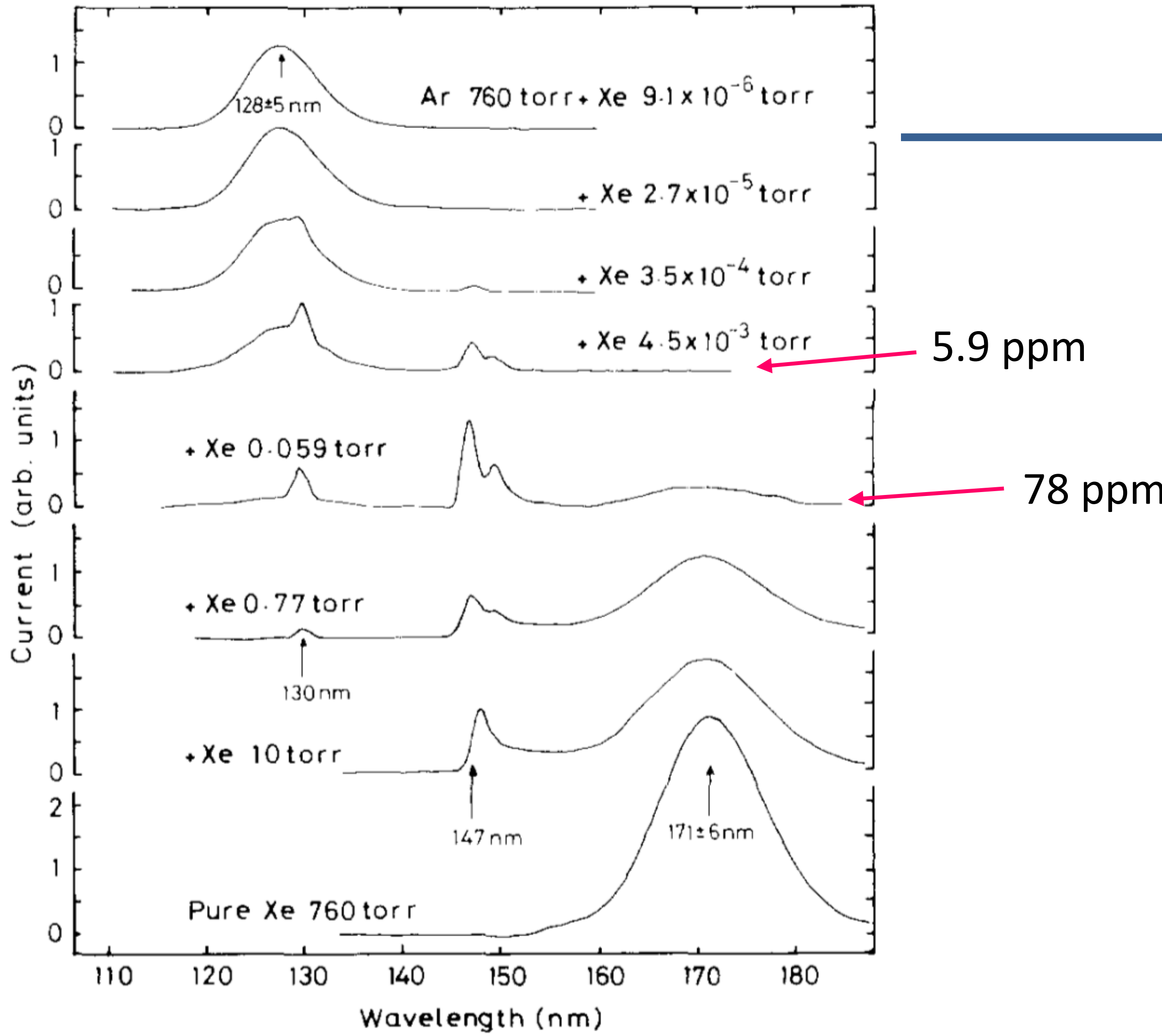
Emission spectra of xenon-doped argon gas mixtures at 1.4 bar under excitation by ^{32}S heavy ion beam



T. Efthimiopoulos et al. J. Phys. D: Appl. Phys. ***30*** *1746 (1997)*

Energy transfer in Ar Xe gas mixtures

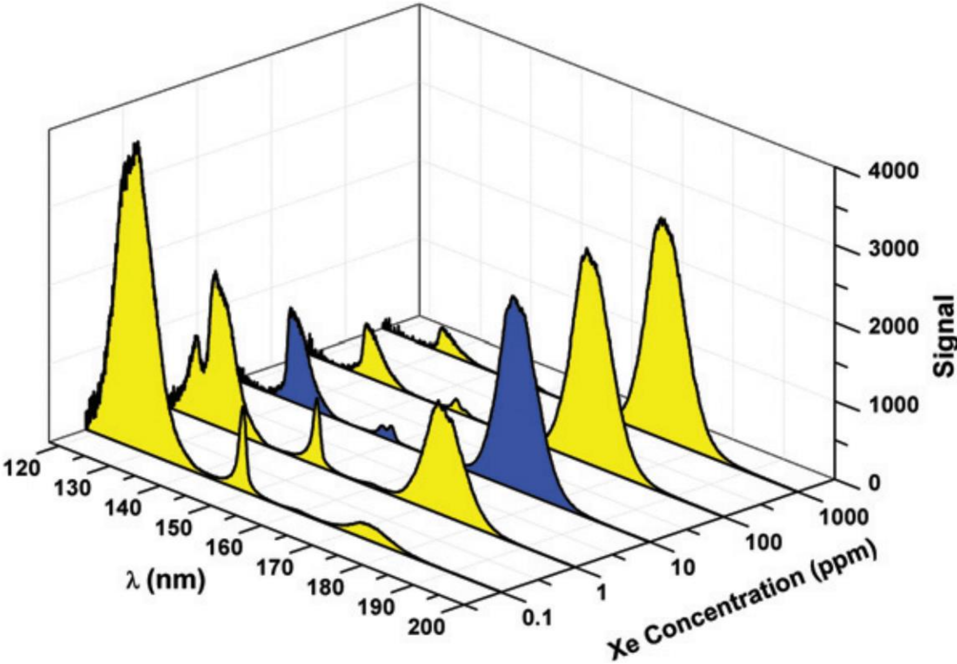
Emission spectra of xenon-doped argon gas mixtures at 1 atm in a gas proportional counter



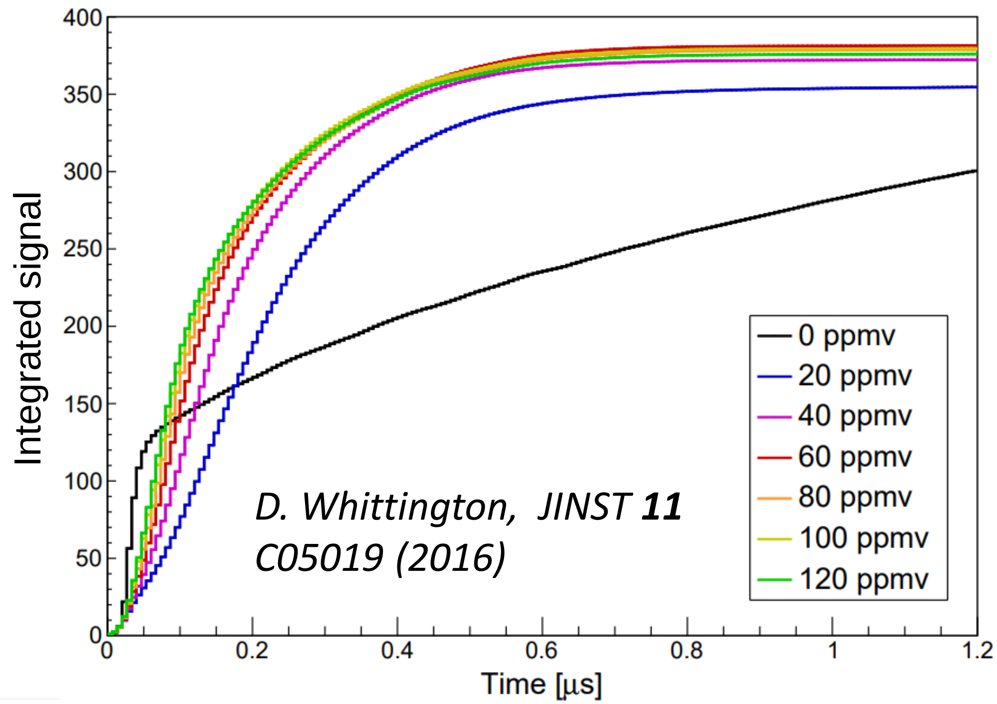
We expect a most of the S2 light will be wavelength shifted to 147 nm by ~ 50 ppm of Xe addition to Ar gas

T. Takahashi et al.
*NIM **205** 591-596 (1983)*

Energy transfer in Ar Xe *liquid* mixtures



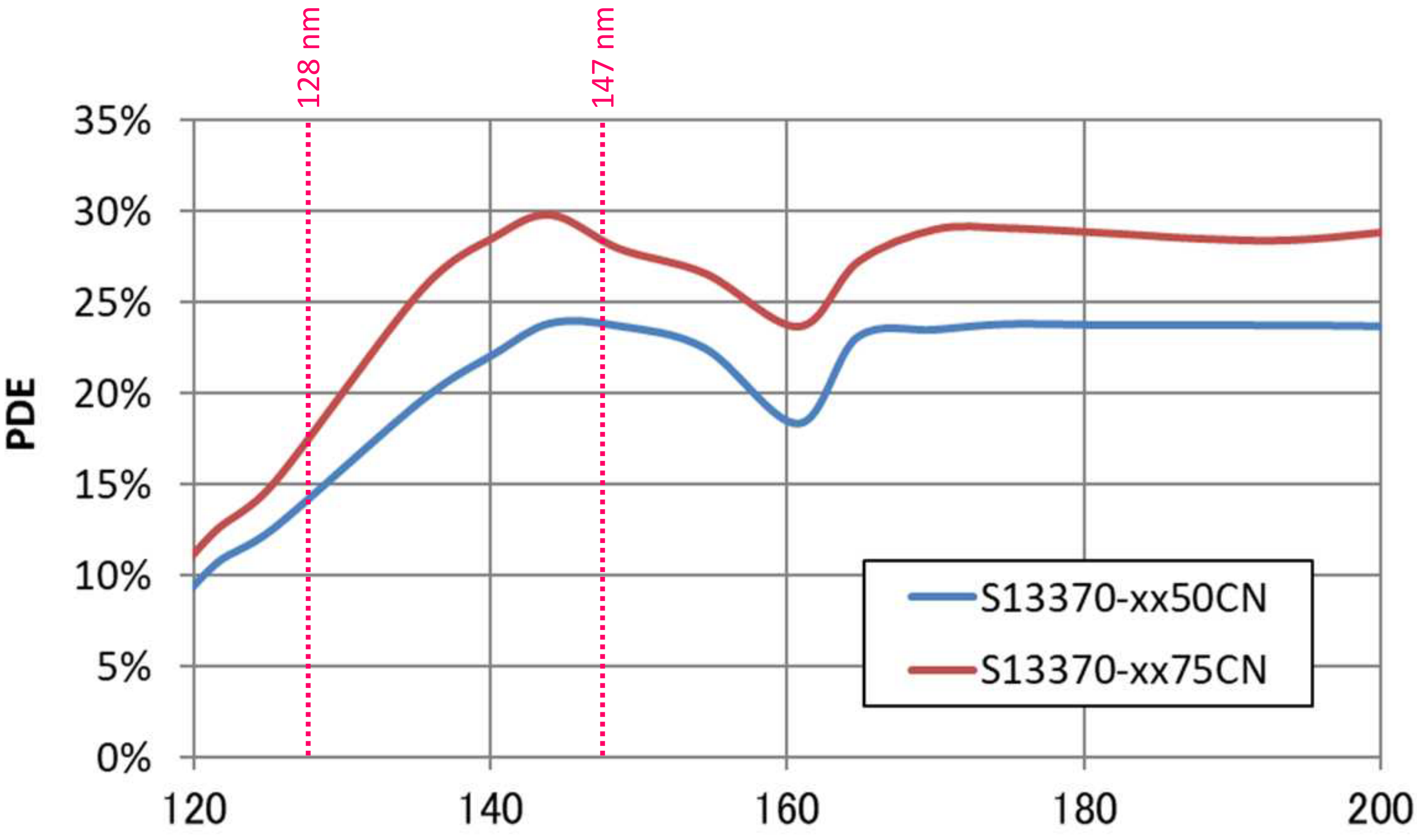
A. Neumeier et al.
*EPL **109** 12001 (2015)*



*D. Whittington, JINST **11** C05019 (2016)*

C. Galbiati et al. arXiv: 2009.06238
Review talk: Andrea Zani, CPAD 2018

SiPM sensitivity to VUV light



QE of 147 nm detection is about 60% higher than 128 nm detection

Yuto Ohashi, Hamamatsu Photonics K.K. CHEF Conference (2019)

S2 Light Measurement Improvement by Addition of Xenon To Argon

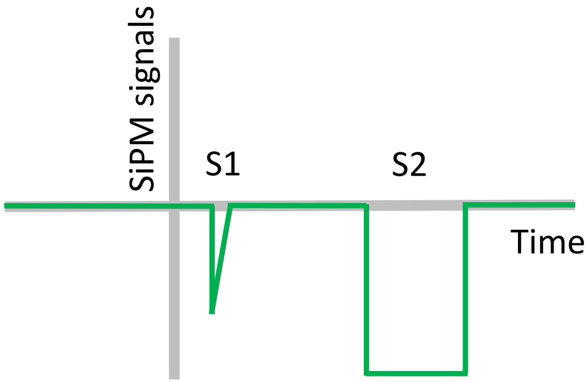
Improvements in light production and sensing of the S2 pulse

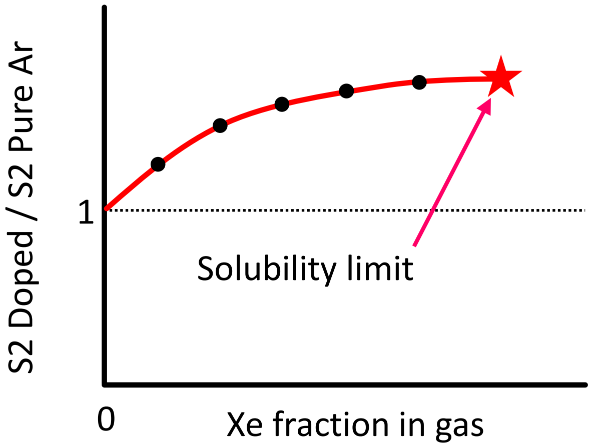
- Xe – containing excimers emit at longer wavelengths that are more efficiently measured.
- Xe – containing excimers emit their light faster, shortening pulse duration.
- Xe* has a lower threshold for excitation → more excitations per drift electron

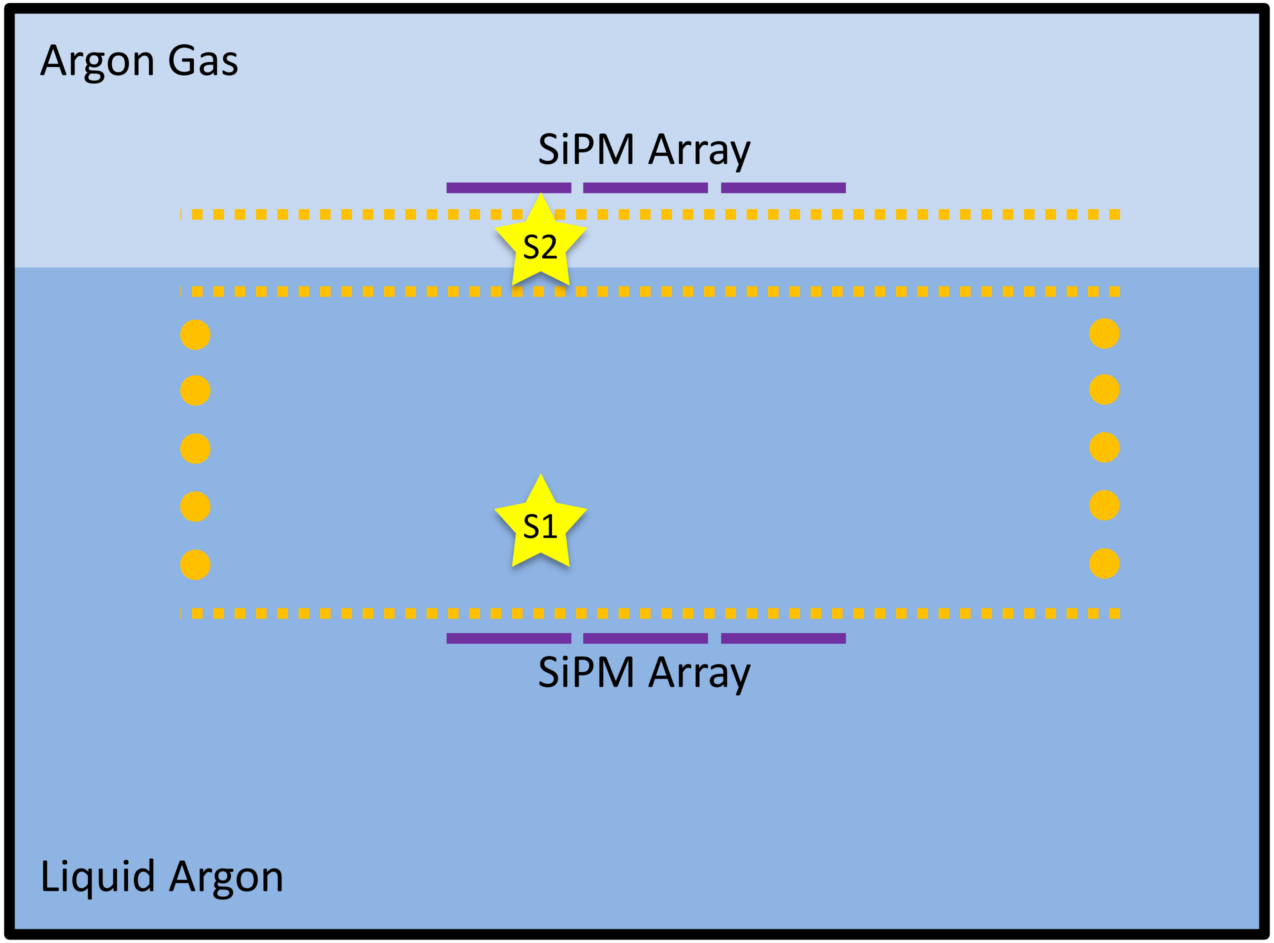
Improvements in ionization yield of the liquid (speculative)

- Xenon has a lower ionization energy that argon → more electrons per unit deposited energy
- Xenon may be ionized by the Penning process $Ar^* + Xe \rightarrow Ar + Xe^+ + e^-$

Xenon-Doped Argon S2 Experiment

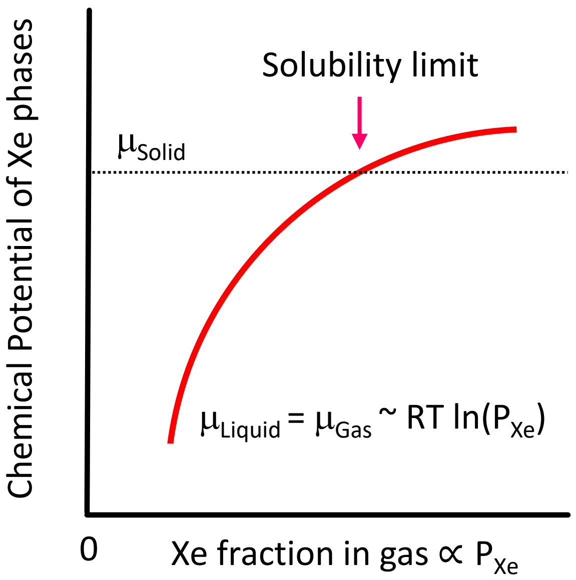


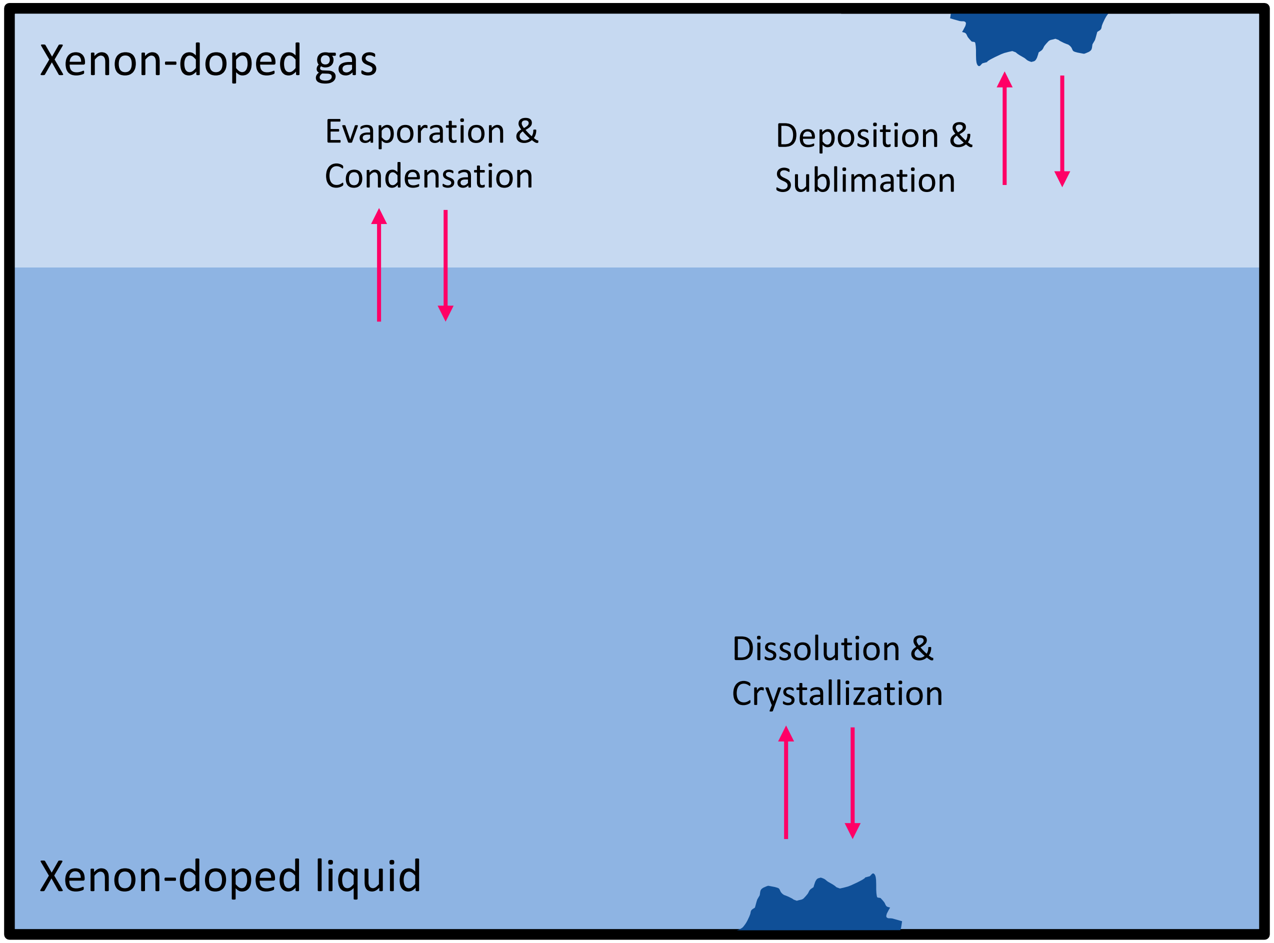




Detector Vessel

Solubility considerations

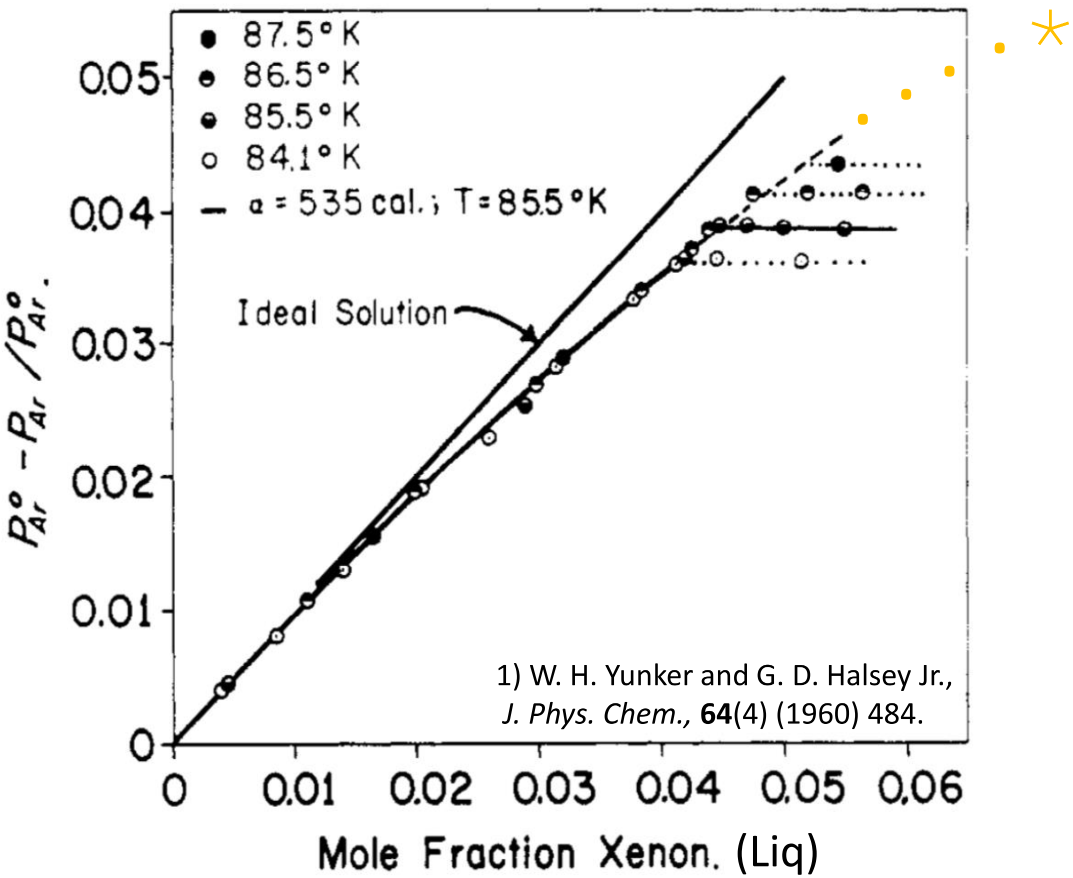




Detector Vessel

Solubility considerations

Extrapolating to
100 / T = 1.054 from plot at right
Predicts n^{Sat} = 7.1% at 2 bar



1) W. H. Yunker and G. D. Halsey Jr., *J. Phys. Chem.*, **64**(4) (1960) 484.

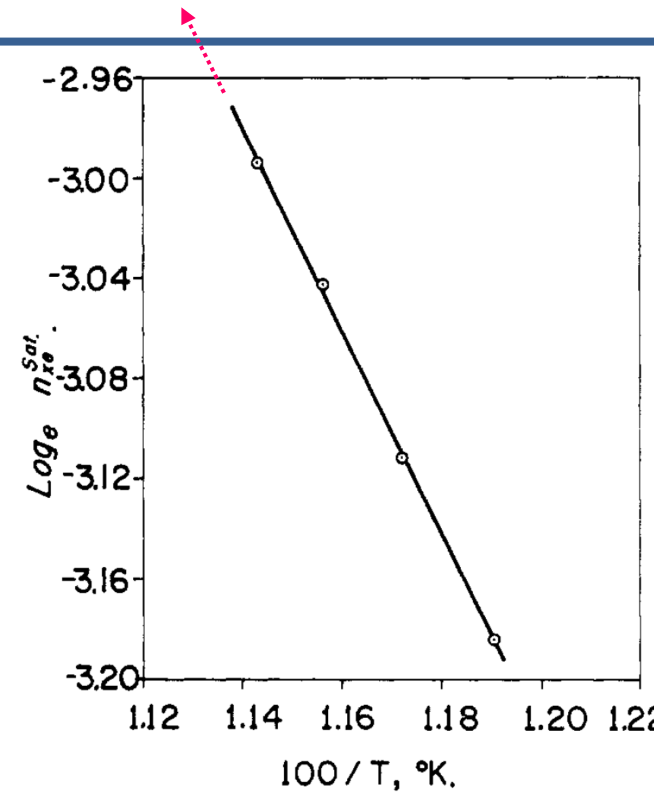


Fig. 2.—Ln n^{Sat}_{xe} *vs.* 100/T °K.

Temp. (°K.)	α (cal./mole)
84.0	560 ± 55
85.5	536 ± 39
86.5	504 ± 39
87.5	504 ± 20
Av.	535 ± 58

Henry's law

$$\mathrm{H^{cc}} = \frac{\textit{Xenon number fraction in liquid}}{\textit{Xe number fraction in gas}}$$

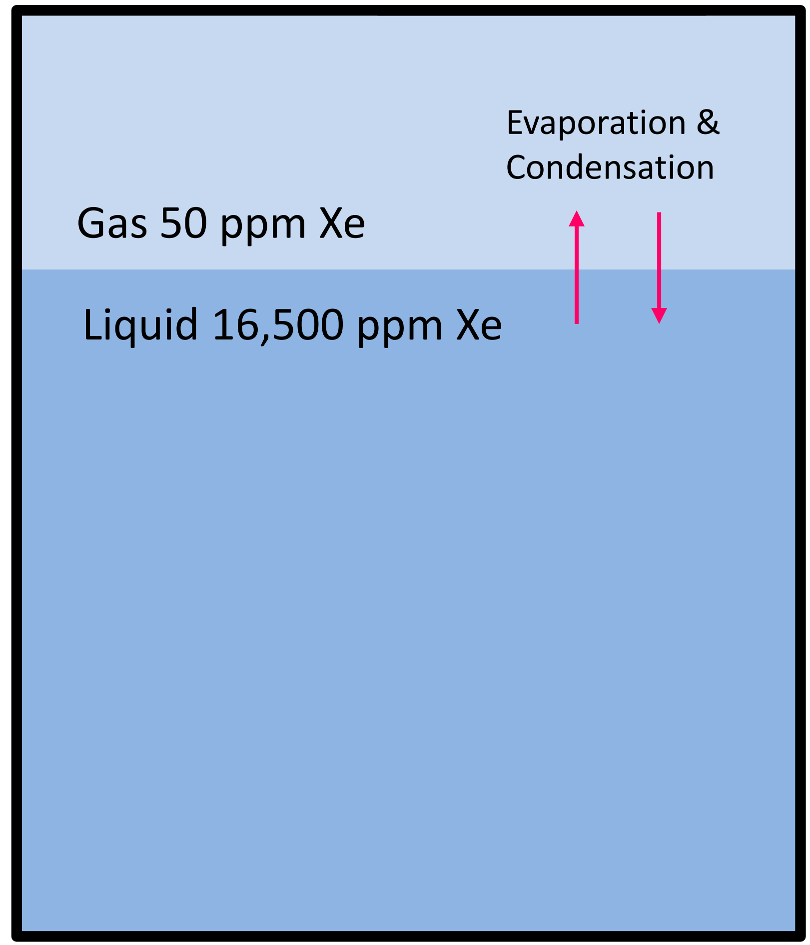
From solubility data we estimate

$$\mathrm{H^{cc}} \sim 250 - 450 \text{ at 2 bar}$$

Assume $\mathrm{H^{cc}}$ = 330

Then 50 ppm in gas implies
1.65% liquid doping at 2 bar
(23% of solubility limit)

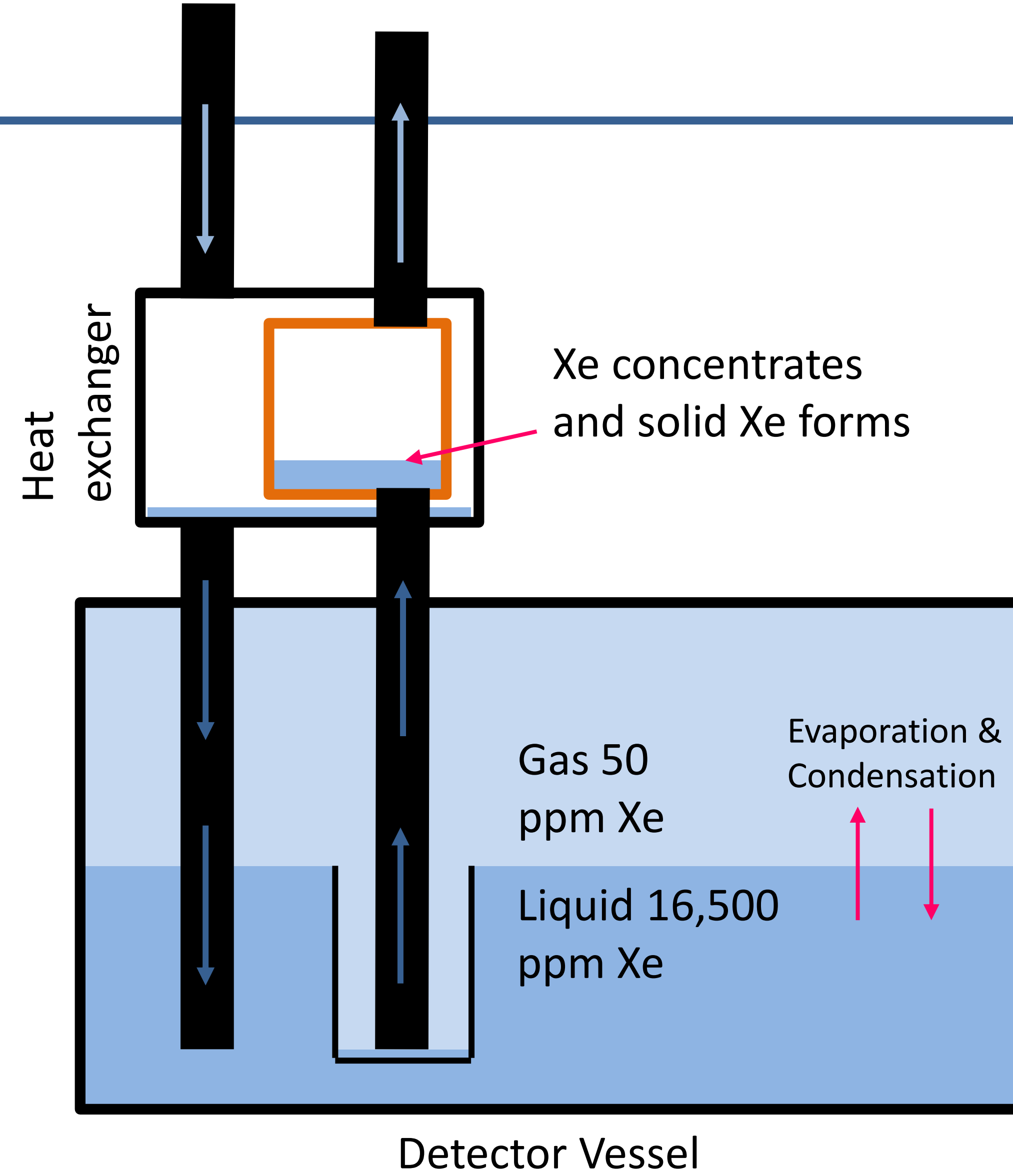
Distillation effects are very strong;
this affects circulation design



Detector Vessel

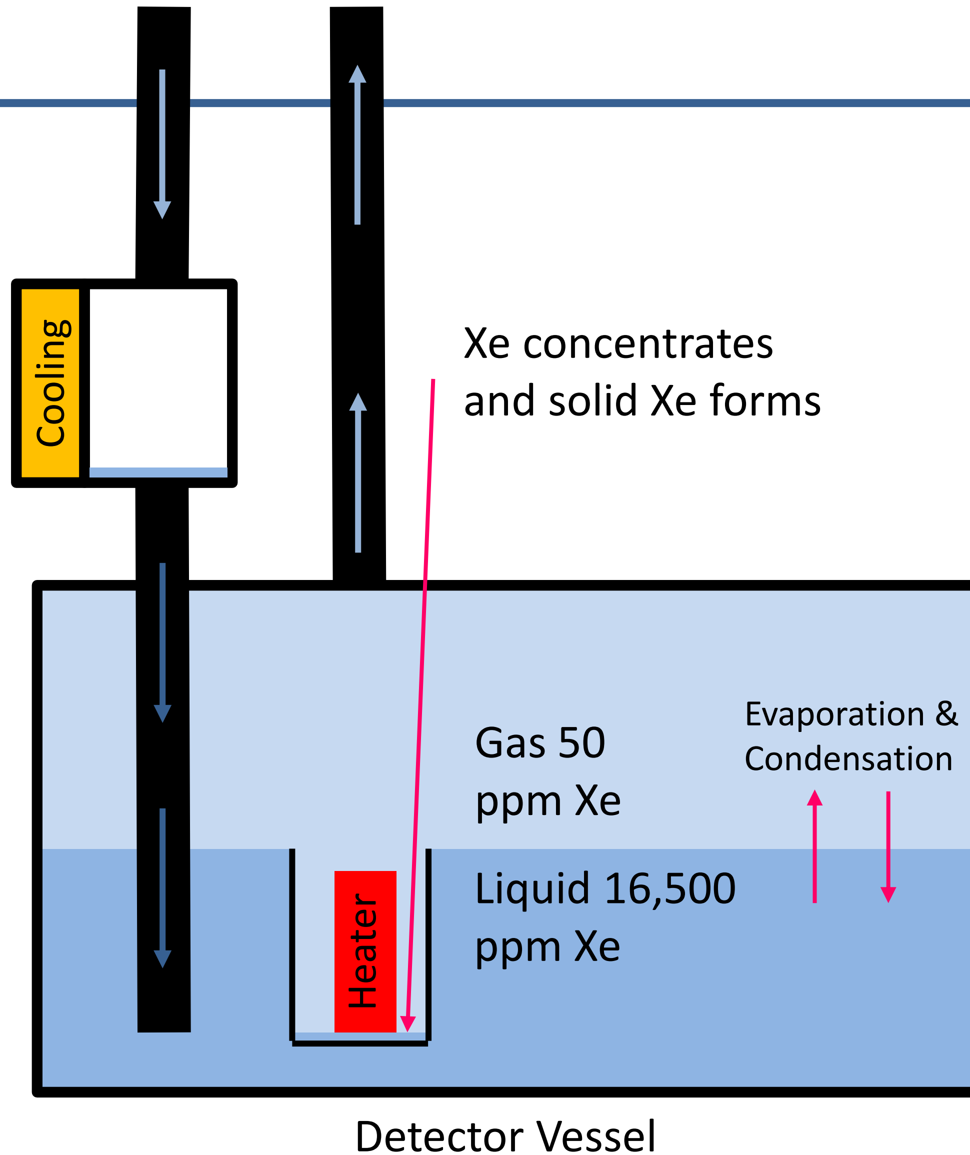
Design approach

Conventional phase-change heat exchanger method fails

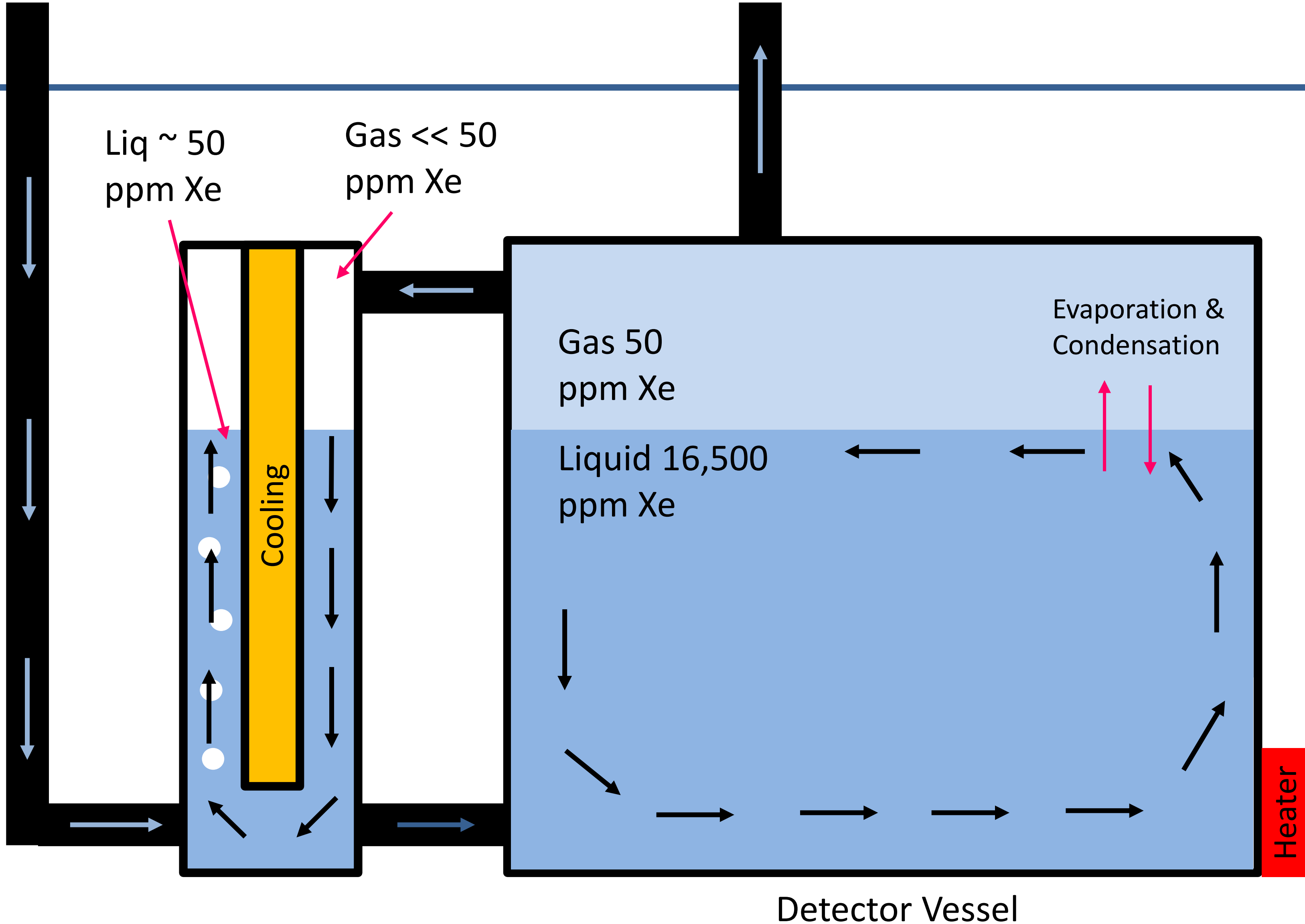


Design approach

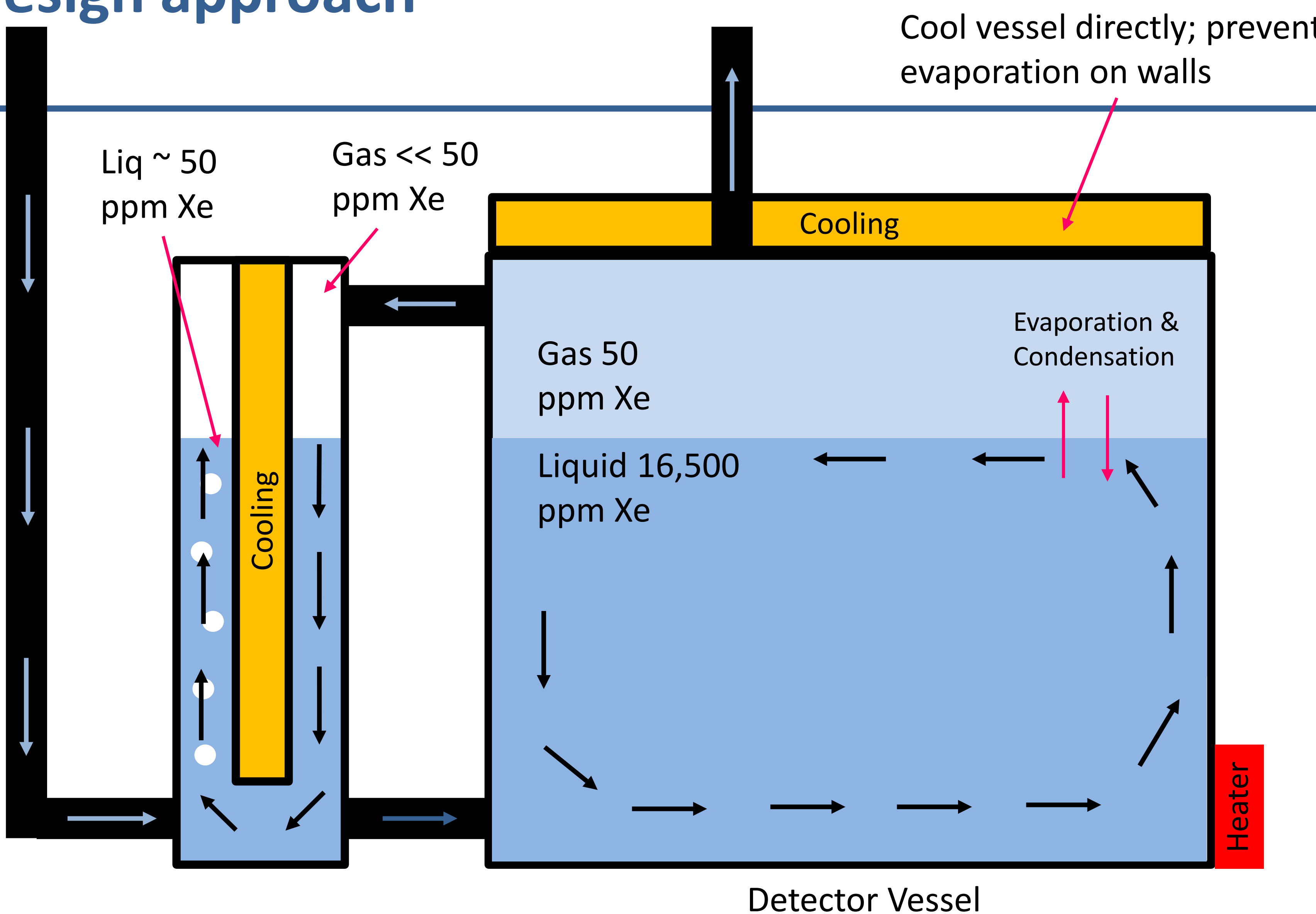
Heated weir method fails



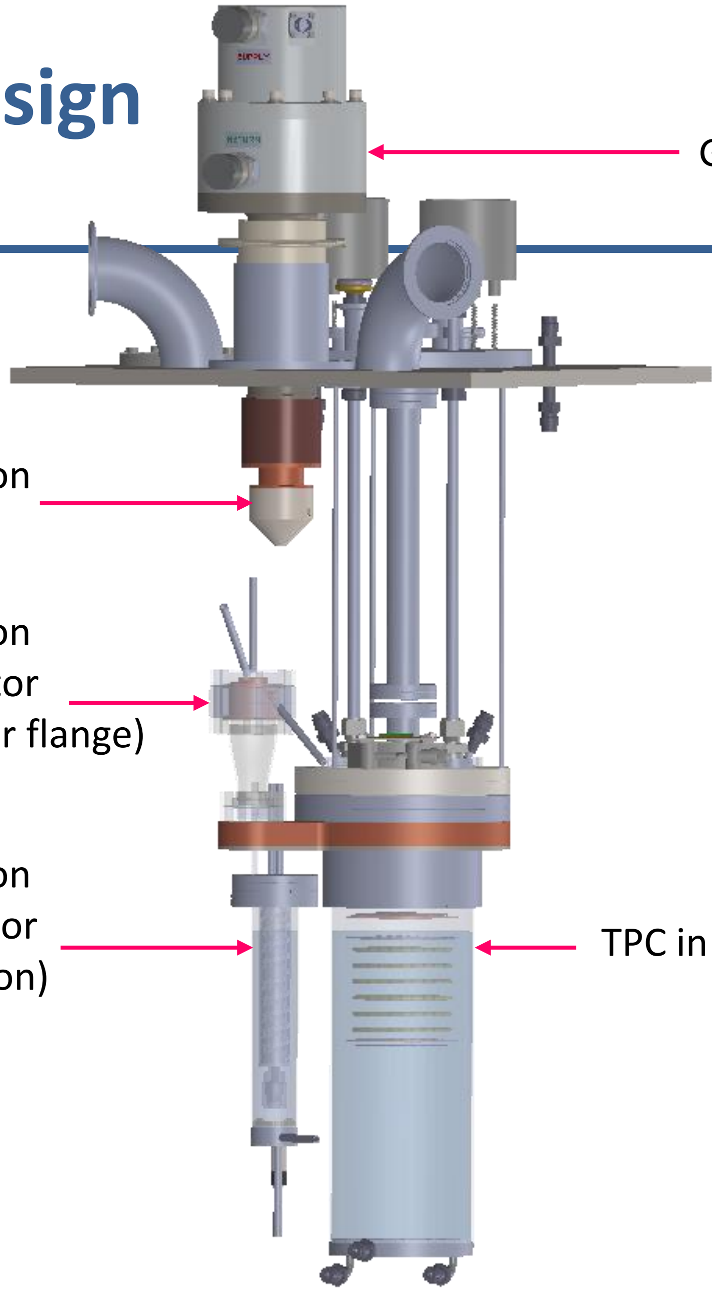
Design approach



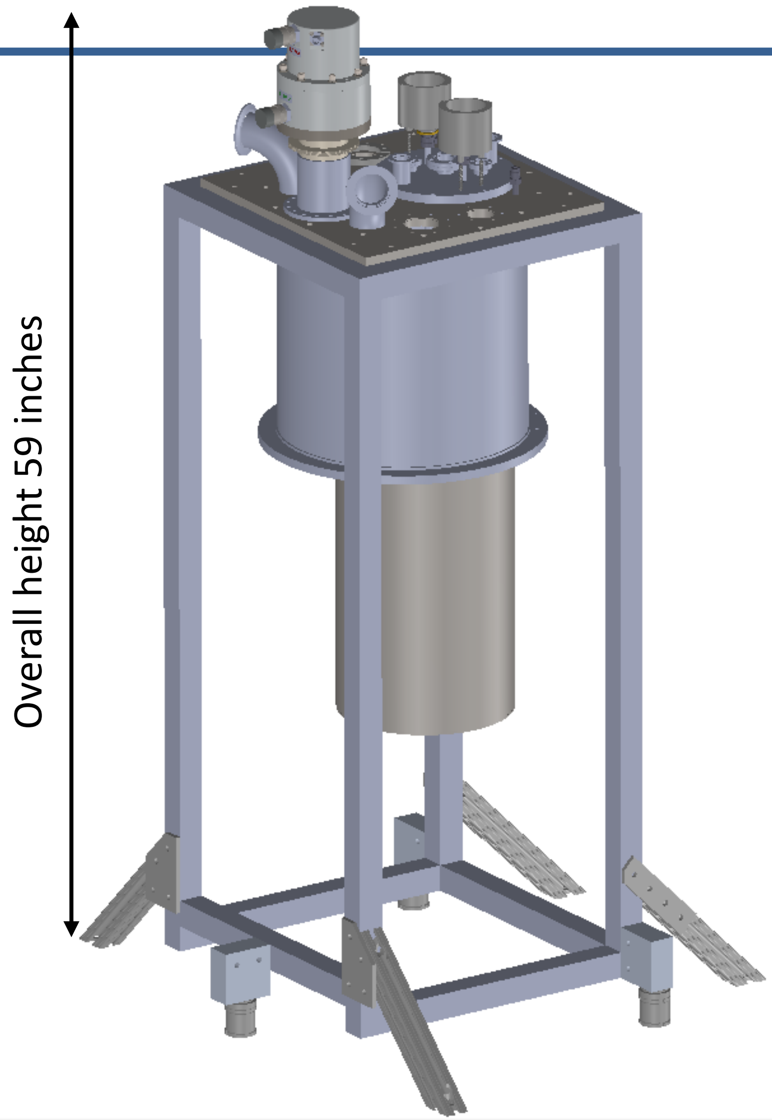
Design approach

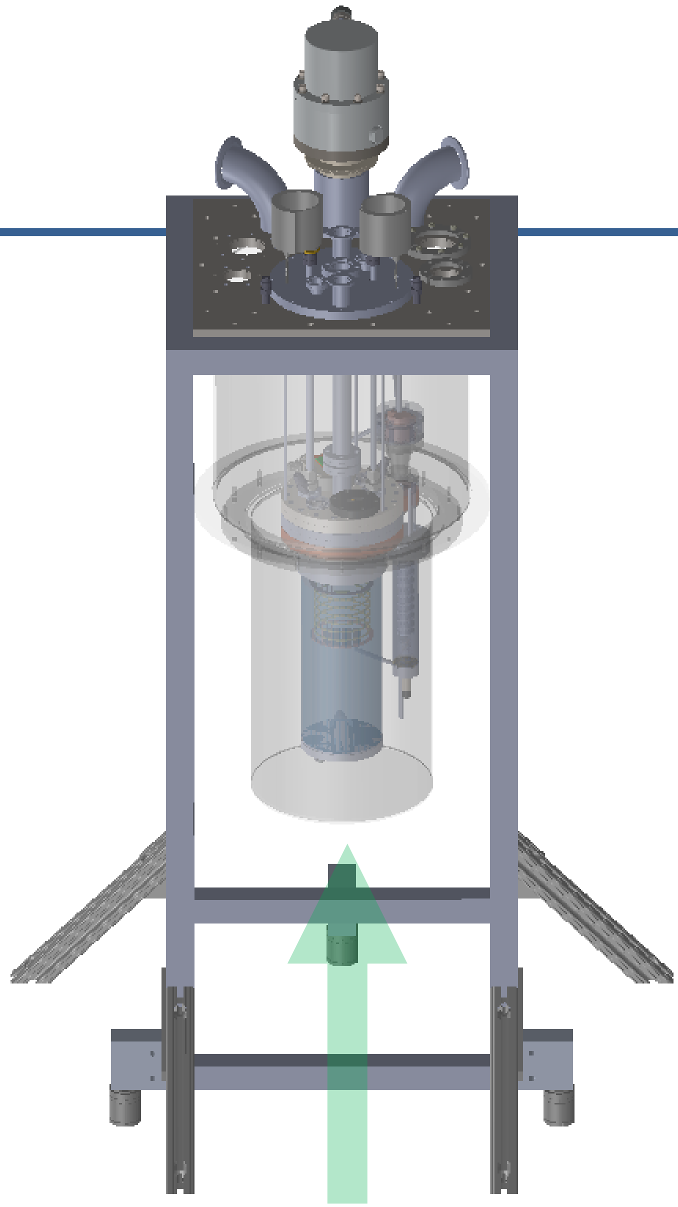


Detector design



Detector design





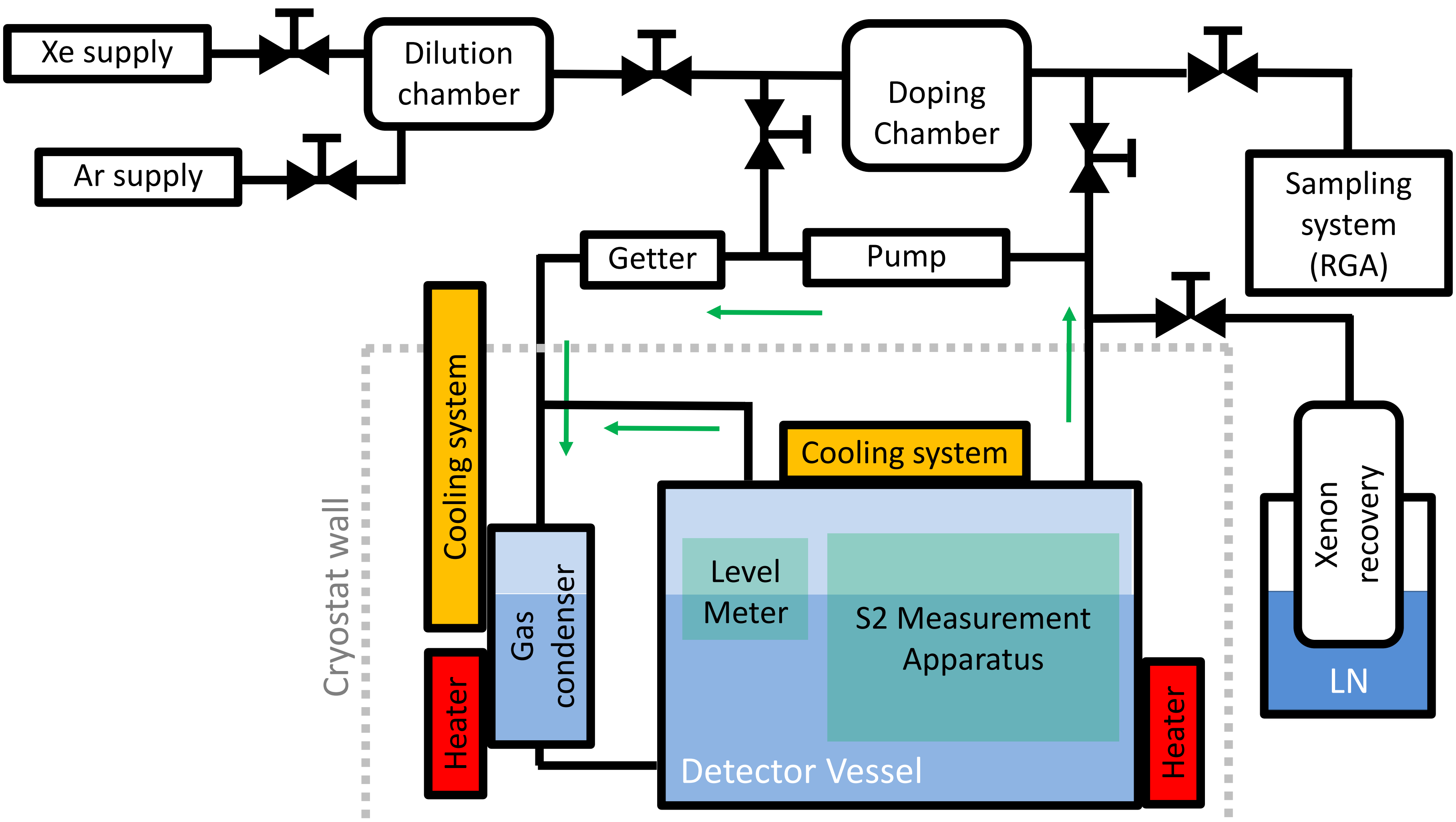
Low obstruction path for neutron scattering measurements

Lawrence Livermore National Laboratory

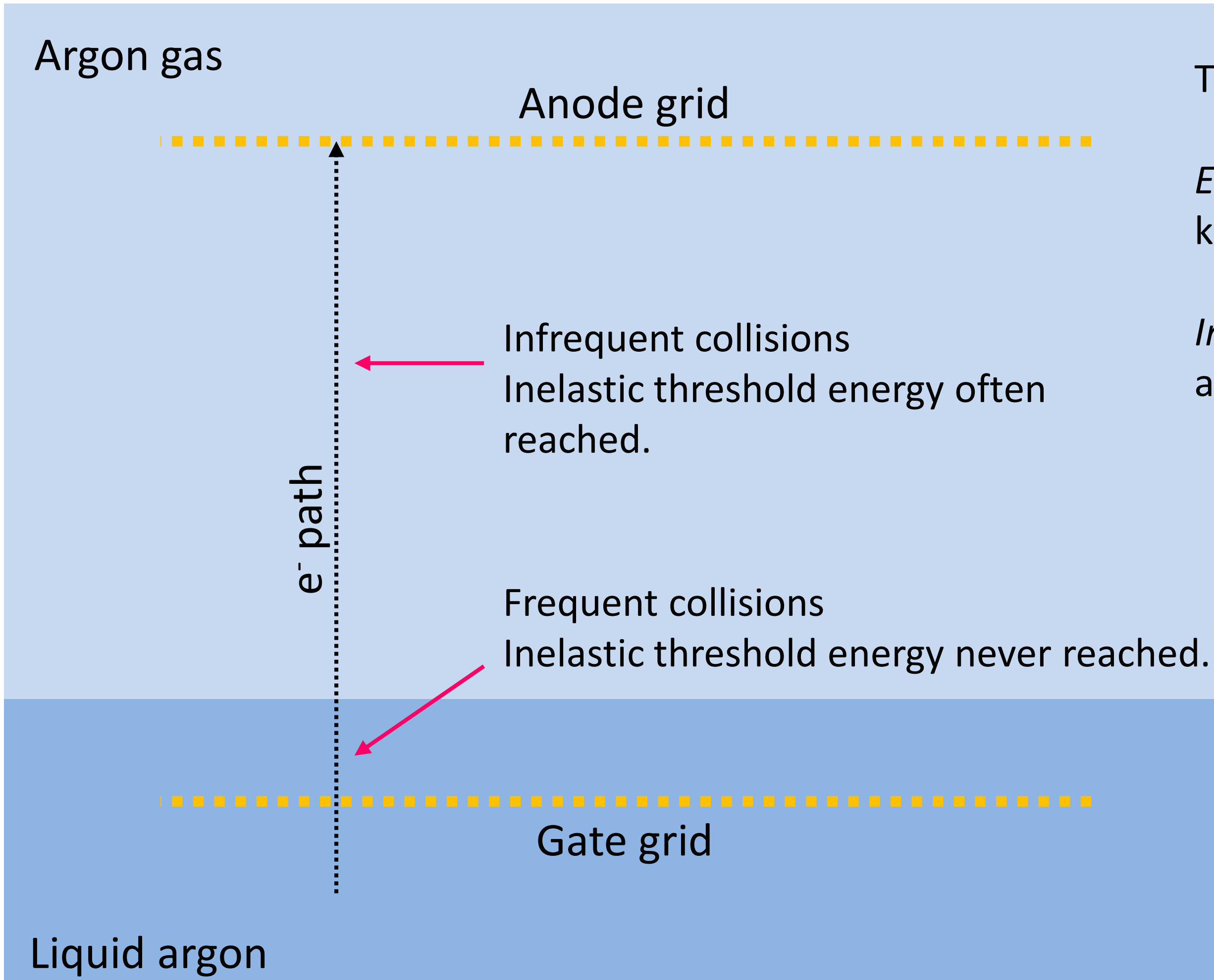
Prepared by LLNL under Contract DE-AC52-07NA2

Detector design

Xenon-Doped Argon Circulation Scheme



Chemistry of S2 light production



Two collision types:

Elastic collisions only add to the kinetic energy of the recoiling atoms.

Inelastic collisions raise the recoiling atoms to an excited electronic state.