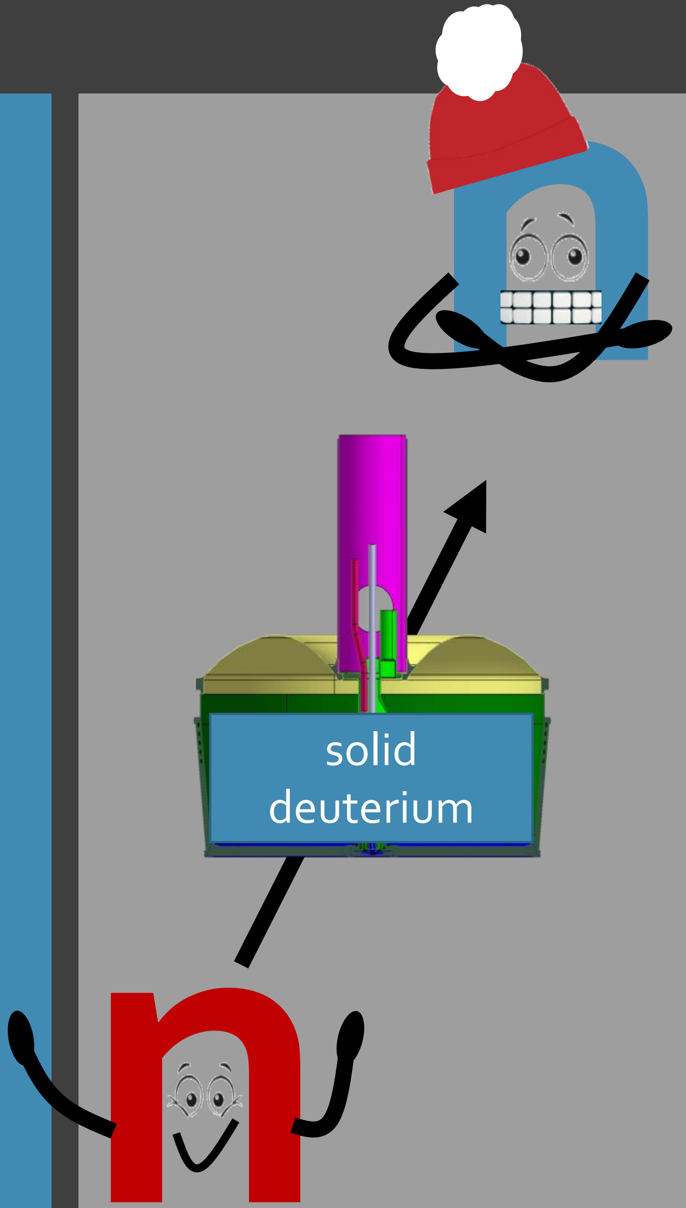
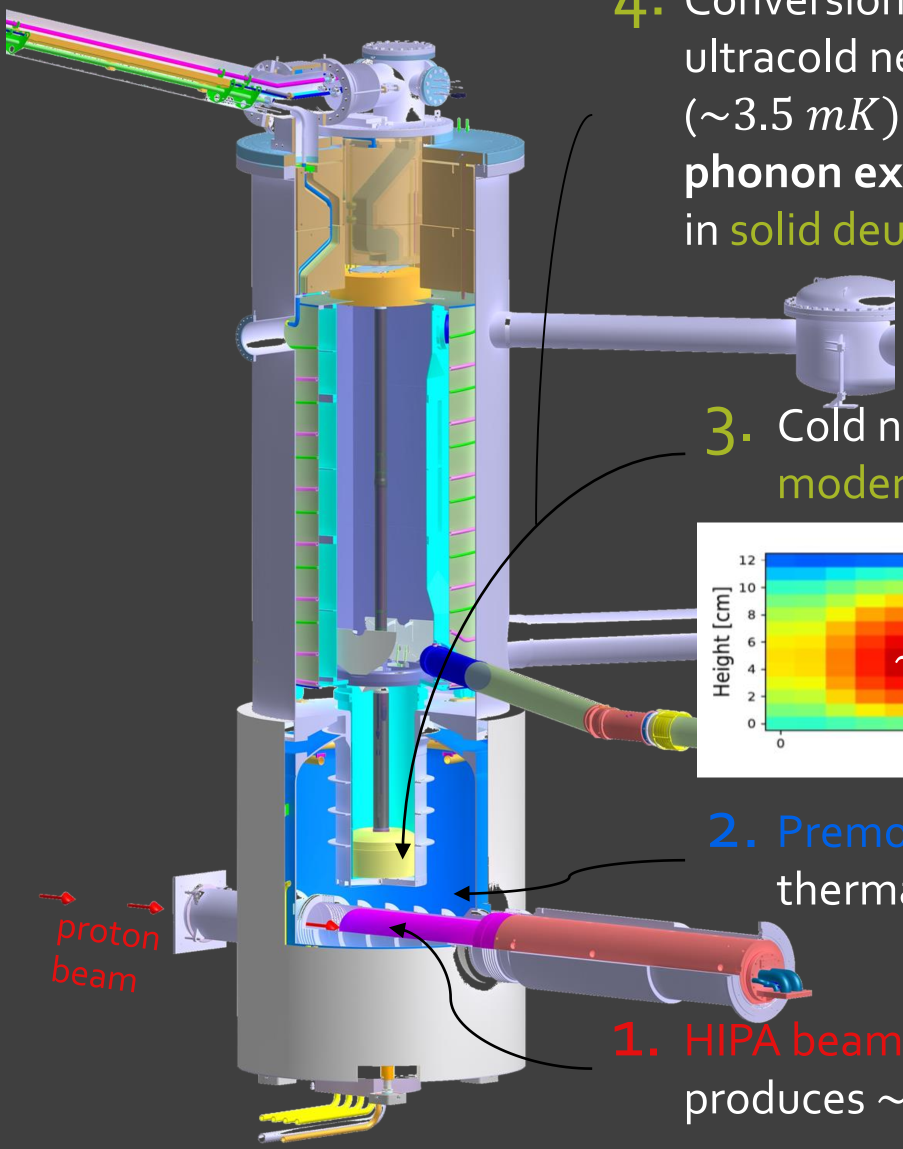
Ultracold neutron (UCN) production and extraction from solid deuterium

Ingo Rienäcker, PSI UCN group, LTP Seminar 27.04.2020

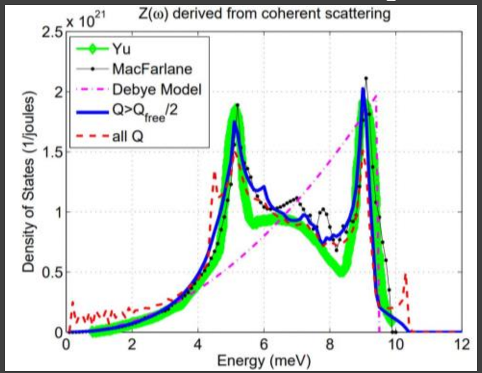


The PSI ultracold neutron source



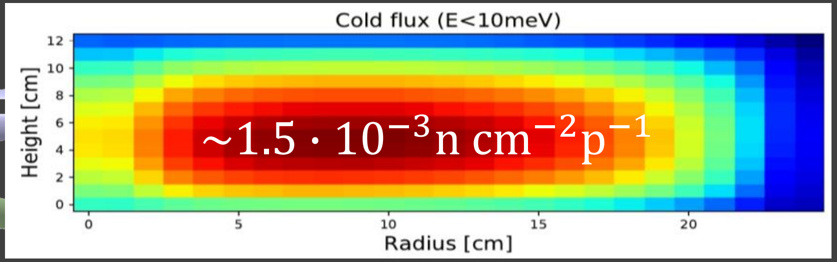
4. Conversion to ultracold neutrons ($\sim 3.5\ mK$) by **phonon excitation** in solid deuterium

Phonon density of states
(accessible states of occupation)



C.-Y. Liu, A.R. Young, C. Lavelle, and D. Salvat, arxiv 1005.1016, 2010

3. Cold neutron flux ($\sim 21K$) density from moderation in solid deuterium at 5K



MCNP simulation

2. Premoderation in heavy water thermalizes neutrons at room temperature

1. HIPA beam on Pb spallation target (up to 8s) produces ~8 free neutrons per proton

Ultracold neutron lifetime in solid deuterium

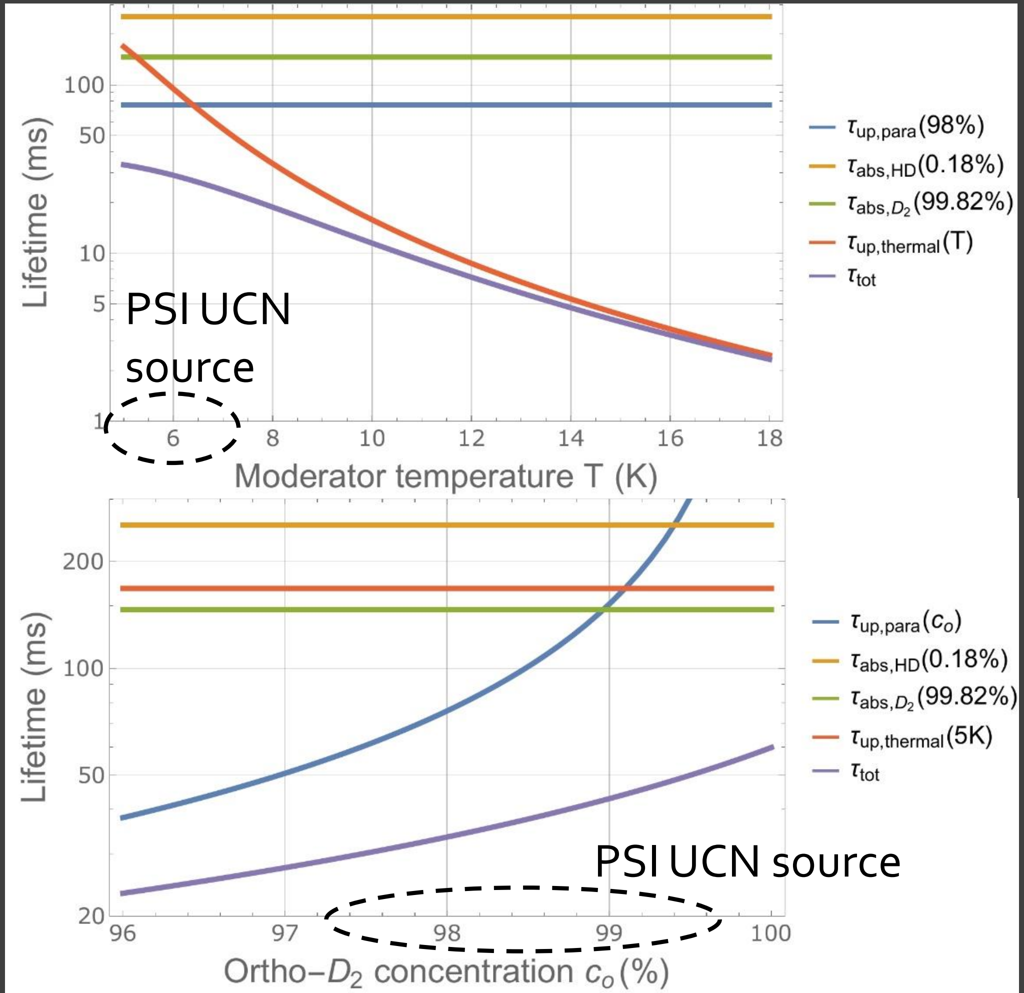
UCN are lost by:

- Neutron capture by deuterons
- Neutron capture by protons
  Solution: Reduce hydrogen contamination
- Thermal (phonon) up-scattering
  Solution: Cool moderator to low temperatures
- Up-scattering on J=1⟶0 transition of D_2 angular momentum eigenstate
  Solution: Increase J=0 D_2 concentration

$\rightarrow \quad \tau \approx 30 \text{ ms}$

$\rightarrow \quad MFP = \tau\langle v\rangle \approx 6 \text{ cm}$

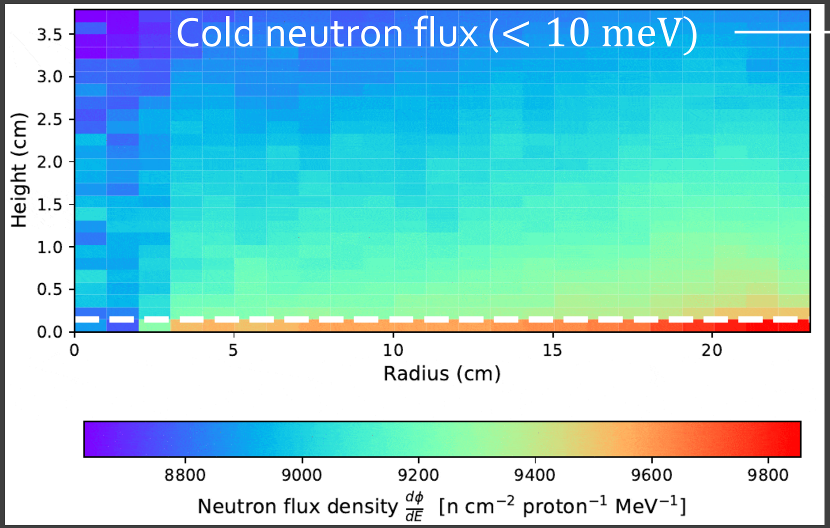
UCN lifetime $\tau = (\rho_{sD_2}\sigma_{loss}v)^{-1}$

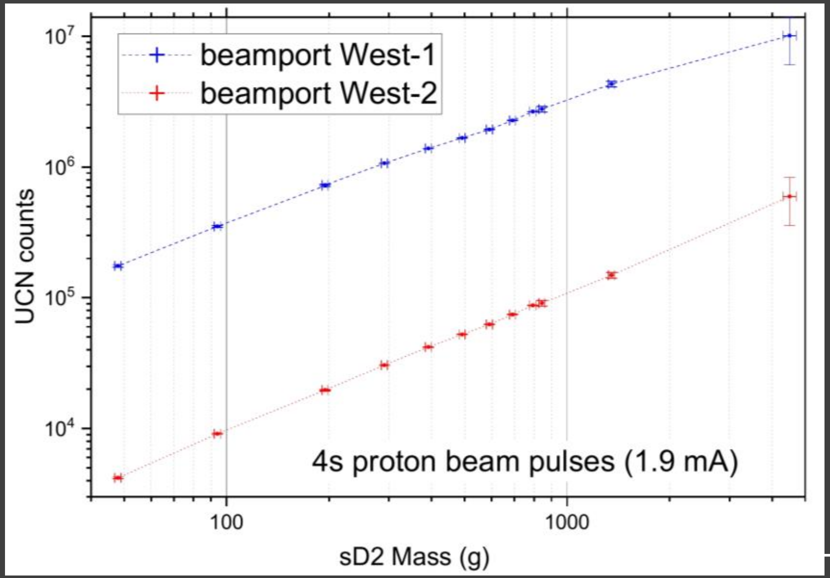


[C.-Y. Liu, A.R. Young, S.K Lamoreaux, Phys. Rev. B, Vol62]

[NIST Centre for Neutron Research, Neutron News, Vol. 3, No. 3, 1992]

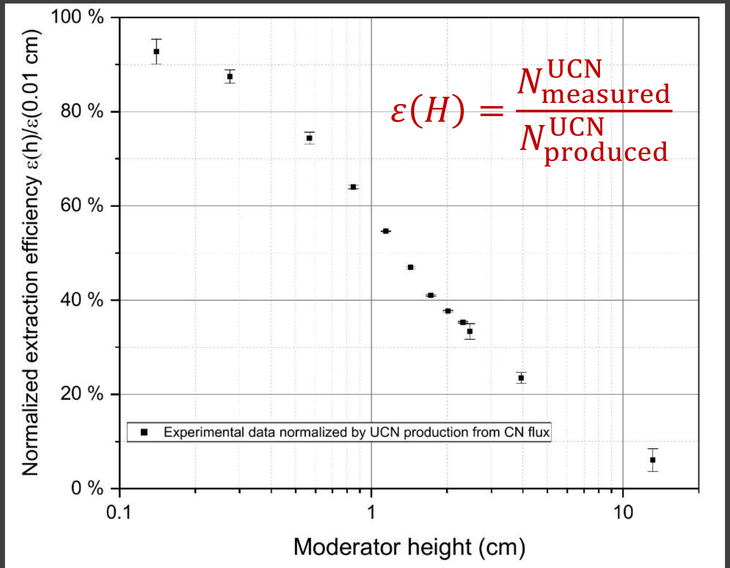
Ultracold neutron extraction from solid deuterium





phonon creation (down-scattering) cross section

$$\frac{dN^{\mathrm{UCN}}}{dE_{\mathrm{UCN}}}(H) \sim \int_0^H dz\, \rho_{\mathrm{sD}_2} \int dE\, \frac{d\phi}{dE}(z)\, \frac{d\sigma}{dE_{\mathrm{UCN}}}(E)$$

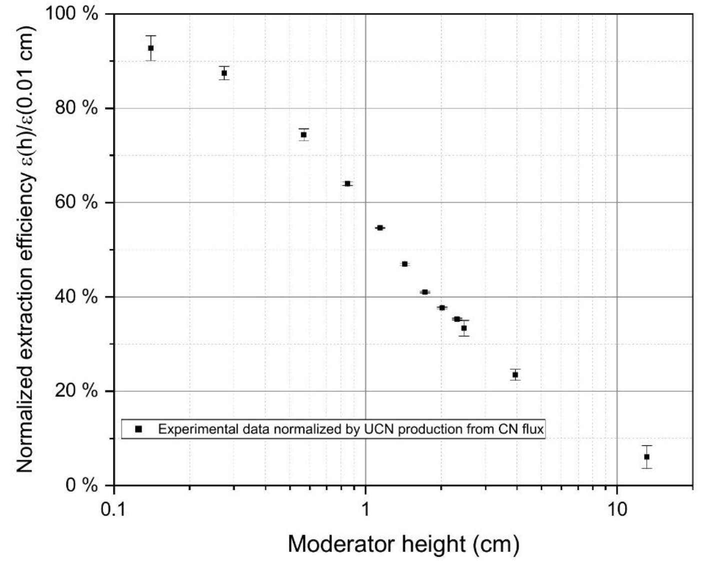


$$\varepsilon(H) = \frac{N^{\mathrm{UCN}}_{\mathrm{measured}}}{N^{\mathrm{UCN}}_{\mathrm{produced}}}$$

$$N^{\mathrm{UCN}}_{\mathrm{measured}}(H)$$

Ultracold neutron extraction from solid deuterium

- Discrepancy between expected ($MFP \approx 6\mathrm{cm}$) and measured ($\sim 1\mathrm{cm}$) output



- Elastic neutron scattering → Increases time of flight of the UCN inside the solid deuterium

Neutron scattering from crystals

scattering length $b_i = \bar{b} + \delta b_i$

$$V_{Fermi} = \frac{2\pi\hbar^2}{m} \sum_i b_i \delta^{(3)}(\boldsymbol{r} - \boldsymbol{R}_i)$$ (low energy s-wave scattering in the Born approximation)

$$\sigma \sim |\langle f | V_{\mathrm{Fermi}} | i \rangle|^2 \sim \sum_{i,j} \overline{b_i b_j} e^{-i\boldsymbol{Q}\cdot(\boldsymbol{R}_i - \boldsymbol{R}_j)} = \bar{b}^2 \sum_{i,j} e^{-i\boldsymbol{Q}\cdot(\boldsymbol{R}_i - \boldsymbol{R}_j)} + \sum_i (\overline{b^2} - \bar{b}^2)$$

Coherent scattering — **Incoherent scattering**

[R. Golub, D. Richardson, S.K. Lamoreaux, Ultra-Cold Neutrons, Adam Hilger, 1991]

[I.I.Gurevich, L.V.Tarasov, Low-energy neutron physics, North-Holland Publishing Company, 1968]

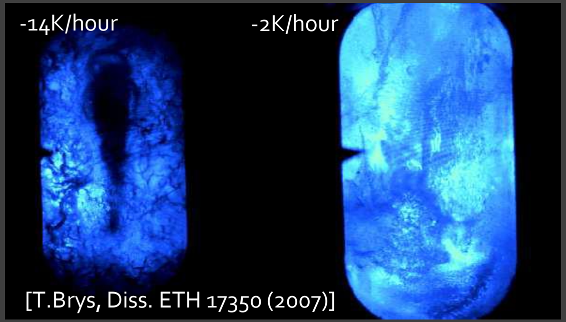
- σ
  - σ_{coh}
    - $\sigma_{\mathrm{coh}}^{el}$ — Neutron optics (refractive index) (no Bragg scattering since $2d \sin\theta \ll \lambda$)
    - $\sigma_{\mathrm{coh}}^{inel}$
  - σ_{inc}
    - $\sigma_{\mathrm{inc}}^{inel}$
    - $\sigma_{\mathrm{inc}}^{el}$

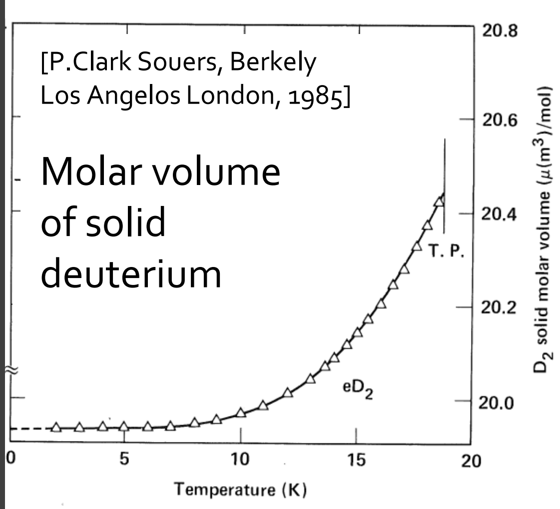
$\sigma_{\mathrm{coh}}^{inel}$, $\sigma_{\mathrm{inc}}^{inel}$: Phonon up/down-scattering

$\sigma_{\mathrm{inc}}^{el}(\mathrm{sD2})$ = 4.04 barn → $MFP \approx$ 8.2 cm

[NIST Centre for Neutron Research, Neutron News, Vol. 3, No. 3, 1992]

Elastic neutron scattering on defects in solid deuterium

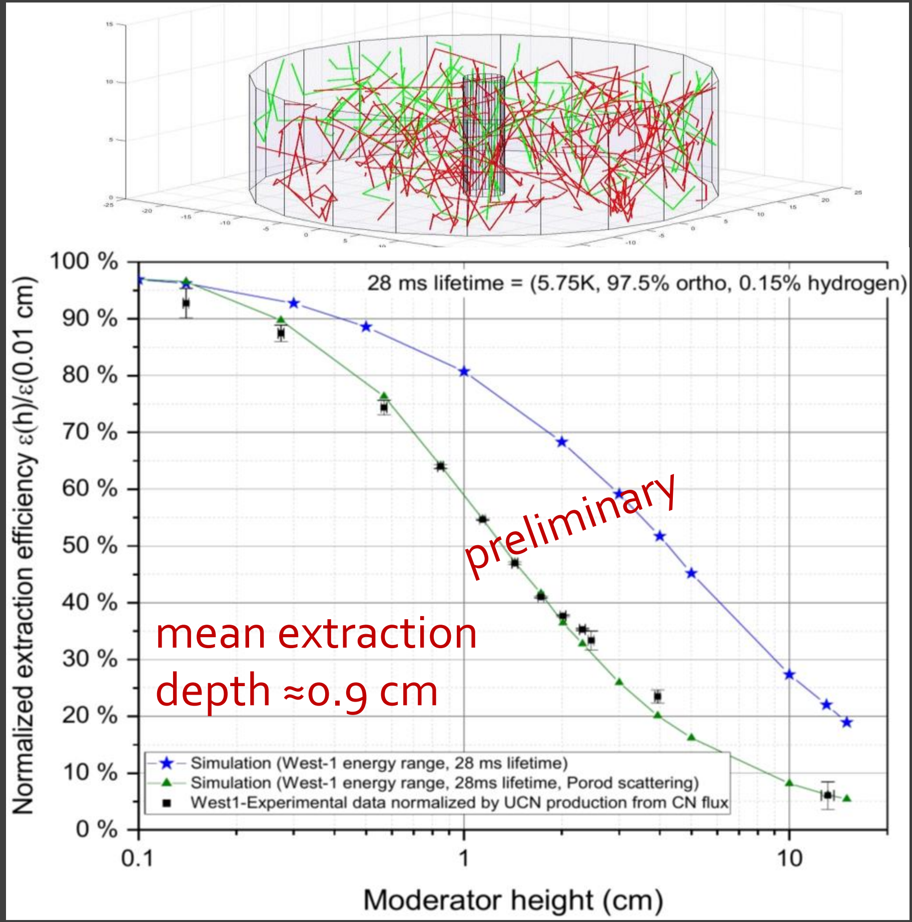




Cooling of solid deuterium leads to thermal stress and the formation of defects

Neutron scattering on smooth interfaces

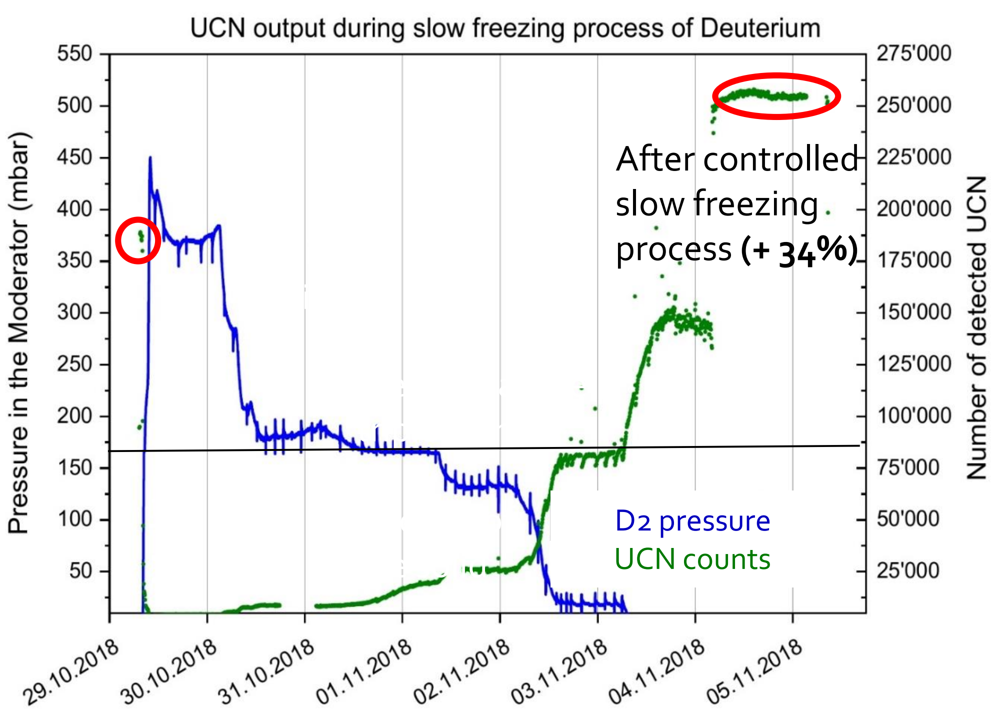
$$\frac{d\sigma}{d\Omega} = \frac{P}{Q^4} \quad \left(\text{for } Q = \frac{4\,\pi\,\sin\theta/_2}{\lambda} \gg \frac{2\,\pi}{D}\right)$$



Conclusion:

How to improve the ultracold neutron extraction

- Slow deuterium freezing and cooling procedure reduces thermal stress and can improve the ultracold neutron extraction



- Potentially a new moderator geometry adjusted to the low extraction depth (separate into moderator/converter chamber)