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# Overview of possible NNbarX Configurations and Staging

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# Sensitivity of NNbarX

$$P_{n\rightarrow\bar{n}}\left(t\right)=\frac{\alpha^2}{\alpha^2+V^2}\cdot\sin^2\left(\frac{\sqrt{\alpha^2+V^2}}{\hbar}\cdot t\right)$$

where $\alpha$-mixing amplitude; $t$ - neutron observation time; $V$-potential different for $n$ and $\bar{n}$

For "vacuum oscilations": $P_{n\rightarrow\bar{n}} = \left(\frac{\alpha}{\hbar}\times t\right)^2 = \left(\frac{t}{\tau_{n\bar{n}}}\right)^2$

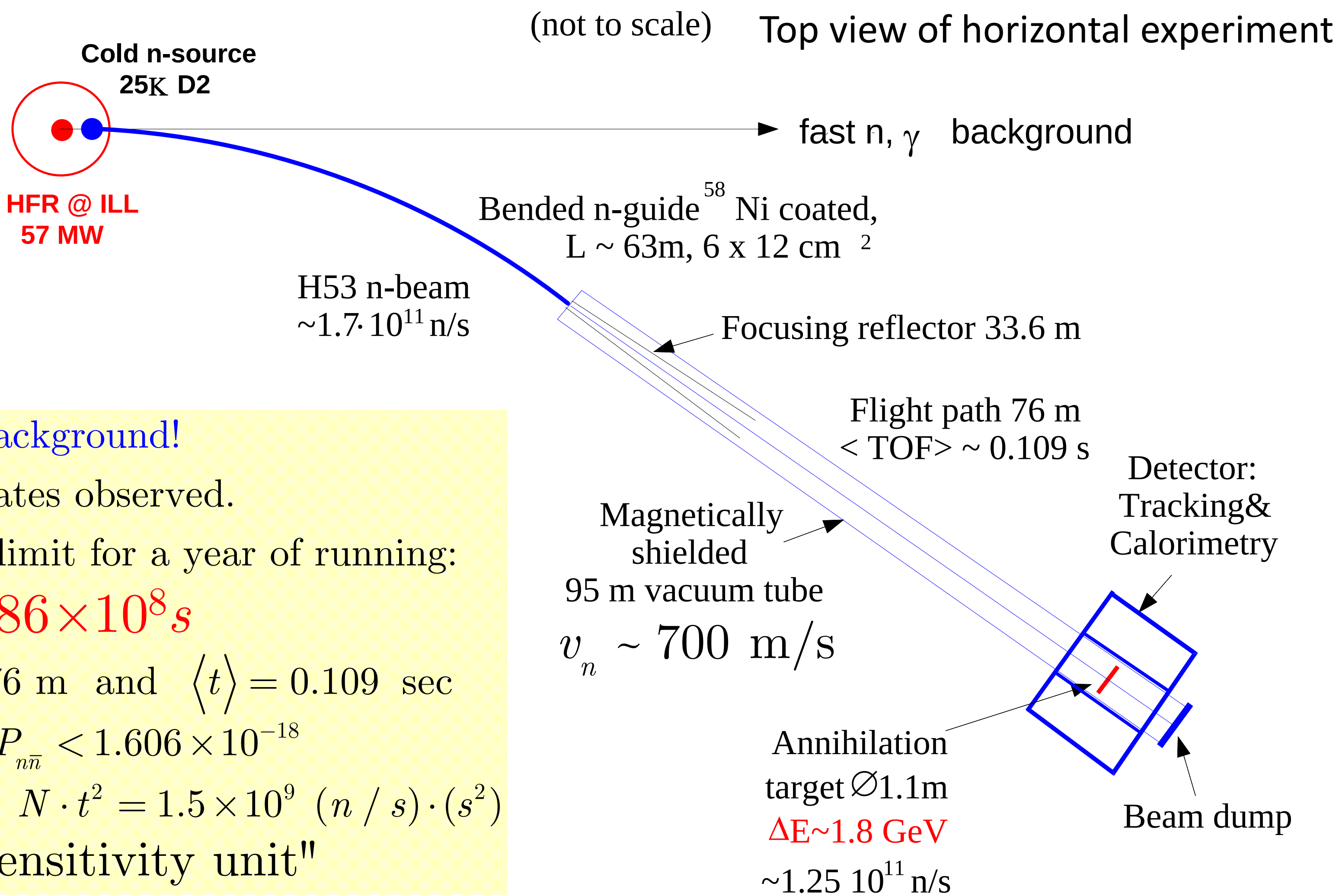
$$\text{Sensitivity} = \text{Figure of merit} = N_n \cdot \overline{t^2}$$

Improvement factor of oscillation time $\tau_{n\bar{n}}$: $\sqrt{\text{Sensitivity}} = \sqrt{N_n} \times t$

# Previous n-nbar search experiment with free neutrons

## At ILL/Grenoble reactor in 89-91 by Heidelberg-ILL-Padova-Pavia Collaboration

**Z. Phys., C63 (1994) 409**




No GeV background!

No candidates observed.

Measured limit for a year of running:

$\tau_{n\bar{n}} > 0.86 \times 10^8 s$

with L ~ 76 m and $\langle t \rangle = 0.109$ sec

measured $P_{n\bar{n}} < 1.606 \times 10^{-18}$

sensitivity: $N \cdot t^2 = 1.5 \times 10^9 \ (n/s) \cdot (s^2)$

$\doteq$ "ILL sensitivity unit"

$$1 \text{ ILL unit of sensitivity} \doteq 1.5\times 10^{9}\ n\cdot s$$

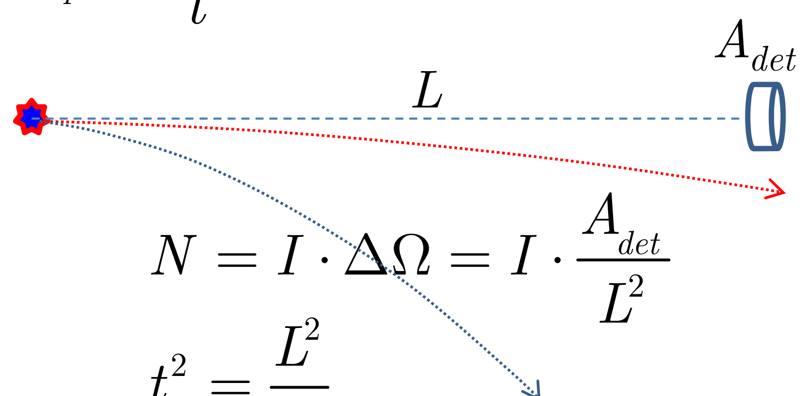
| $\tau$ | ILL units | |
|---|---|---|
| $0.86\times10^{8}$ s | 1u | ←Free neutrons at ILL (1994) |
| $3.45\times10^{8}$ s | 16u | ←Super-K now, 22.5kt, 4 years |
| $5.5\times10^{8}$ s | 40u | ←Goal of NNbarX Demonstrator |
| $7.5\times10^{8}$ s | 76u | ←Hyper-K 500kt, 10 years |
| $1\times10^{10}$ s | 13,500u | ←Goal of staged NNbarX |
| $1\times10^{11}$ s | 1,350,000u | ←Theory wish |

How to reach this sensitivity
with optimization of performance
vs cost ? It is the question
of our study for Snowmass'13

# Some simple facts

$$S = N_n \times \overline{t^2}$$

- Need many neutrons: reactor or spallation source ← Produced as ~ 2 MeV
- Slowest possible neutrons with maximum observation time ← Even moderated to 300K $v_n$ ~ 2,200 m/s with broad Maxwell-Boltzmann spectrum
- Earth magnetic field shielding: $2\mu B < \frac{\hbar}{t} \quad \rightarrow \quad B < 1 - 10 \ nT$
- Required vacuum : $\overline{U_{opt}} < \frac{\hbar}{t} \quad \Rightarrow \quad \text{Pressure} < 10^{-5} \ \text{Pa}$
- Distance ? Doesn't matter →
- Gravity effect on horizontal beam → cutoff for most valuable slowest n




$$N = I \cdot \Delta\Omega = I \cdot \frac{A_{det}}{L^2}$$

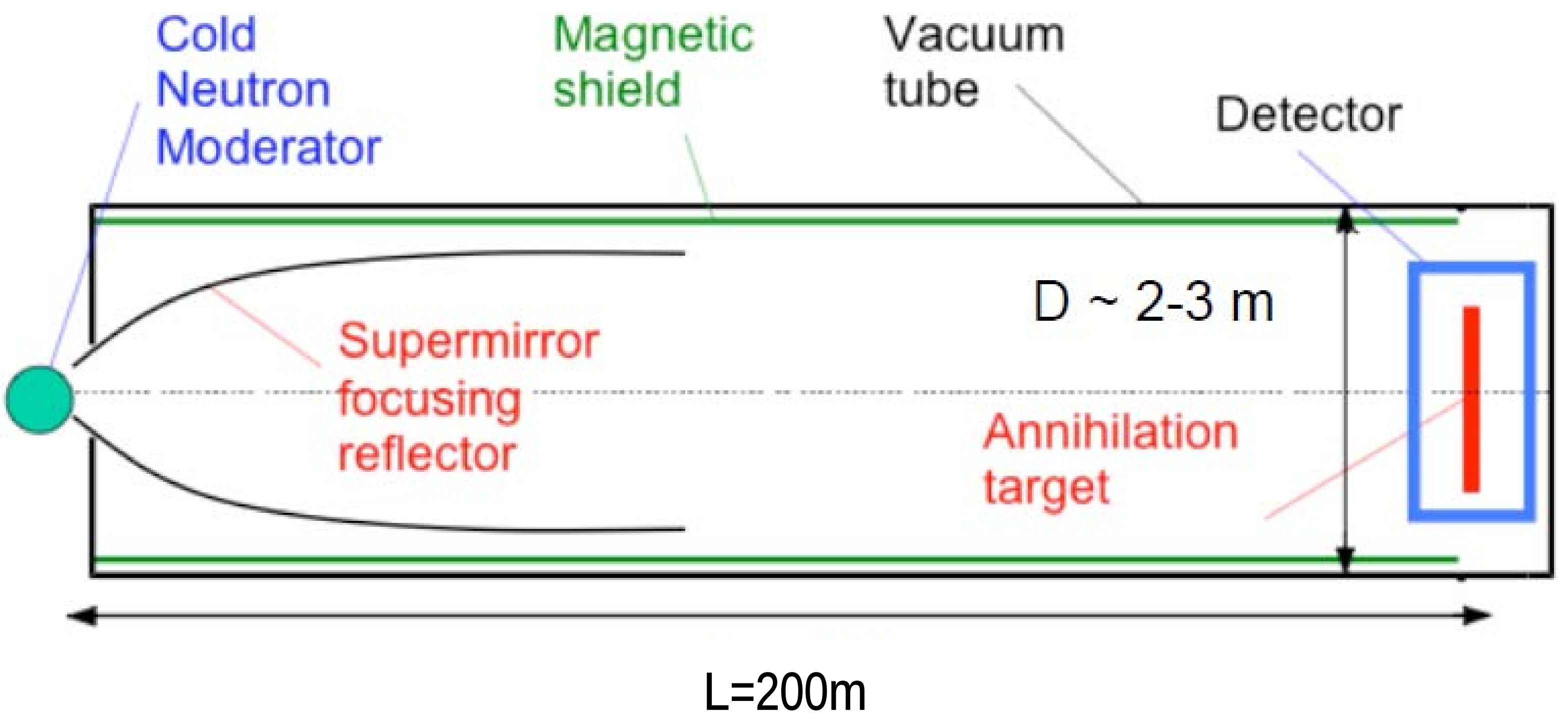
$$t^2 = \frac{L^2}{v_n^2}$$

# Possible improvements in sensitivity

- Dedicated source (advantage of Project X)
- Efficient source coupling to experiment
- Maximize source and target parameters
- Slower Neutrons ("Cold" $\rightarrow$ "Very Cold" $\rightarrow$"Ultra Cold")
- Focusing neutrons by efficient ("high-m") mirror reflection
- Maintain low background
- Neutron manipulation by gravity

Various factors are correlated. Performance optimization should include cost as a parameter.

# *Advanced Scheme of ILL-like experiment*

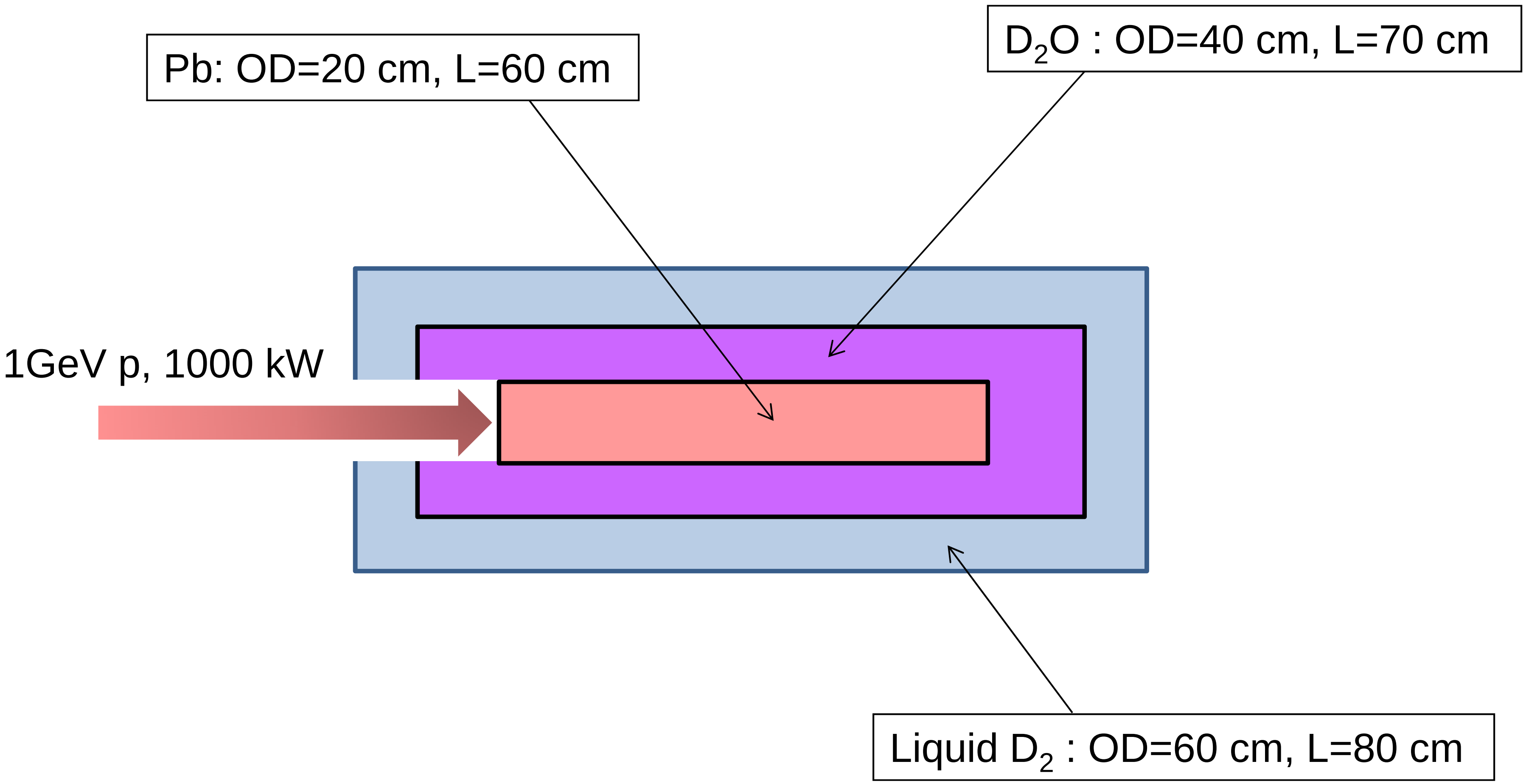



**With solid angle intercepted by focusing reflector the Sensitivity ~ $L^2$**

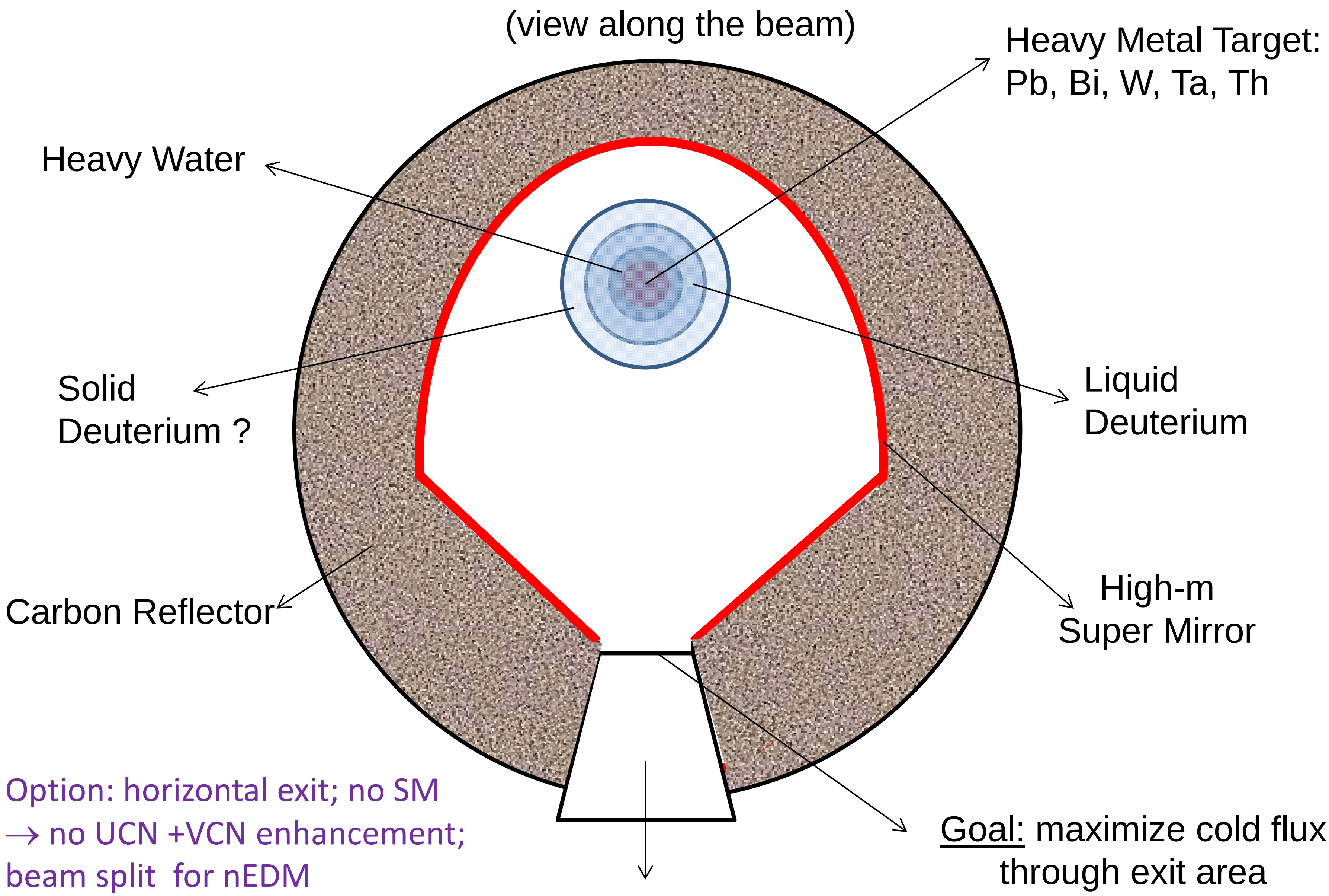
**No need for curved guide to reduce prompt background due to pulsed nature of spallation source**

# Generic configuration of 4$\pi$-emitting source target

for simulations and optimization

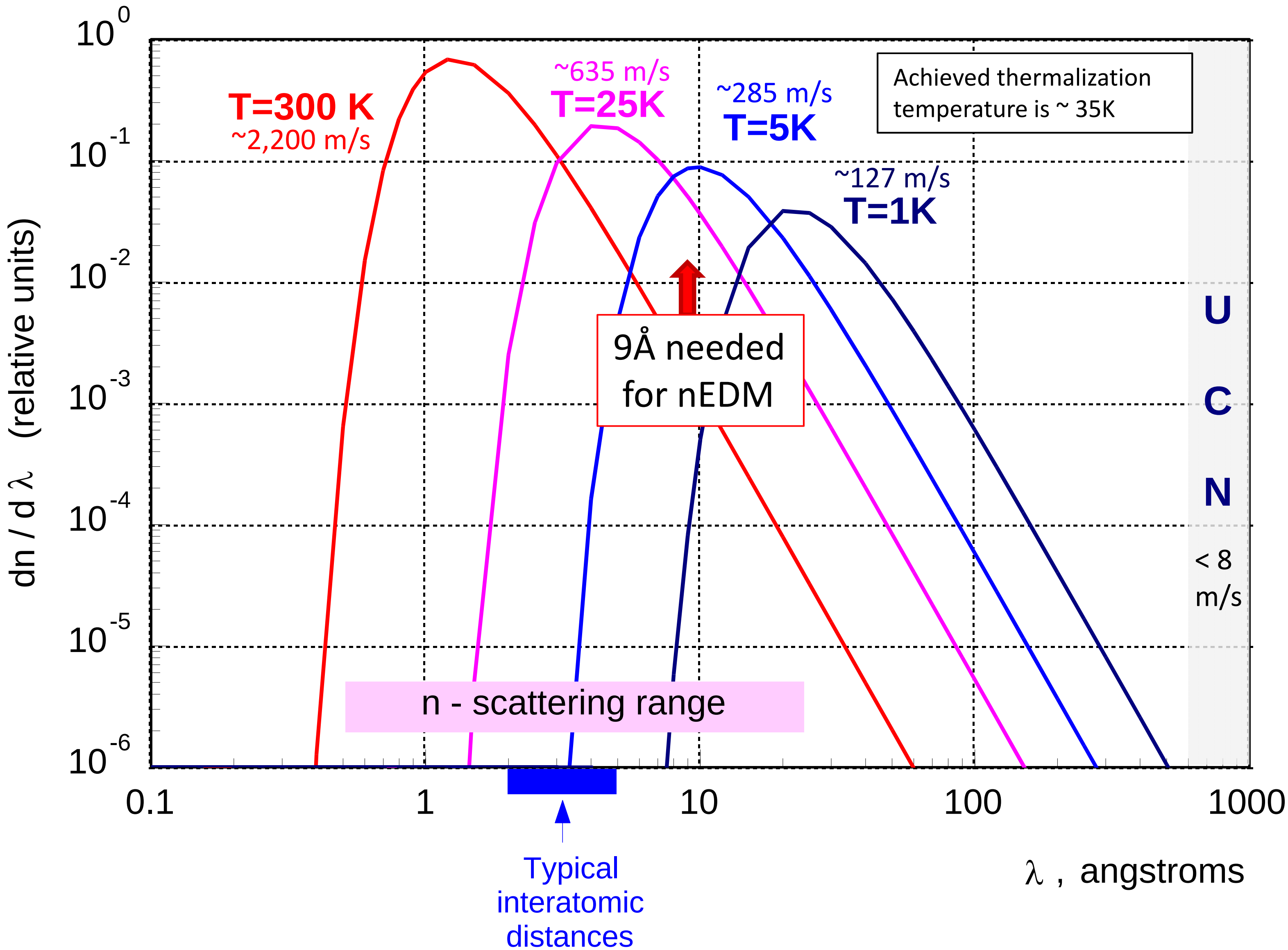


# Dedicated spallation target with enhanced vertical Cold&VCN&UCN production




Option: horizontal exit; no SM
→ no UCN +VCN enhancement;
beam split for nEDM

# Maxwellian spectra of thermalized neutrons at temperature T



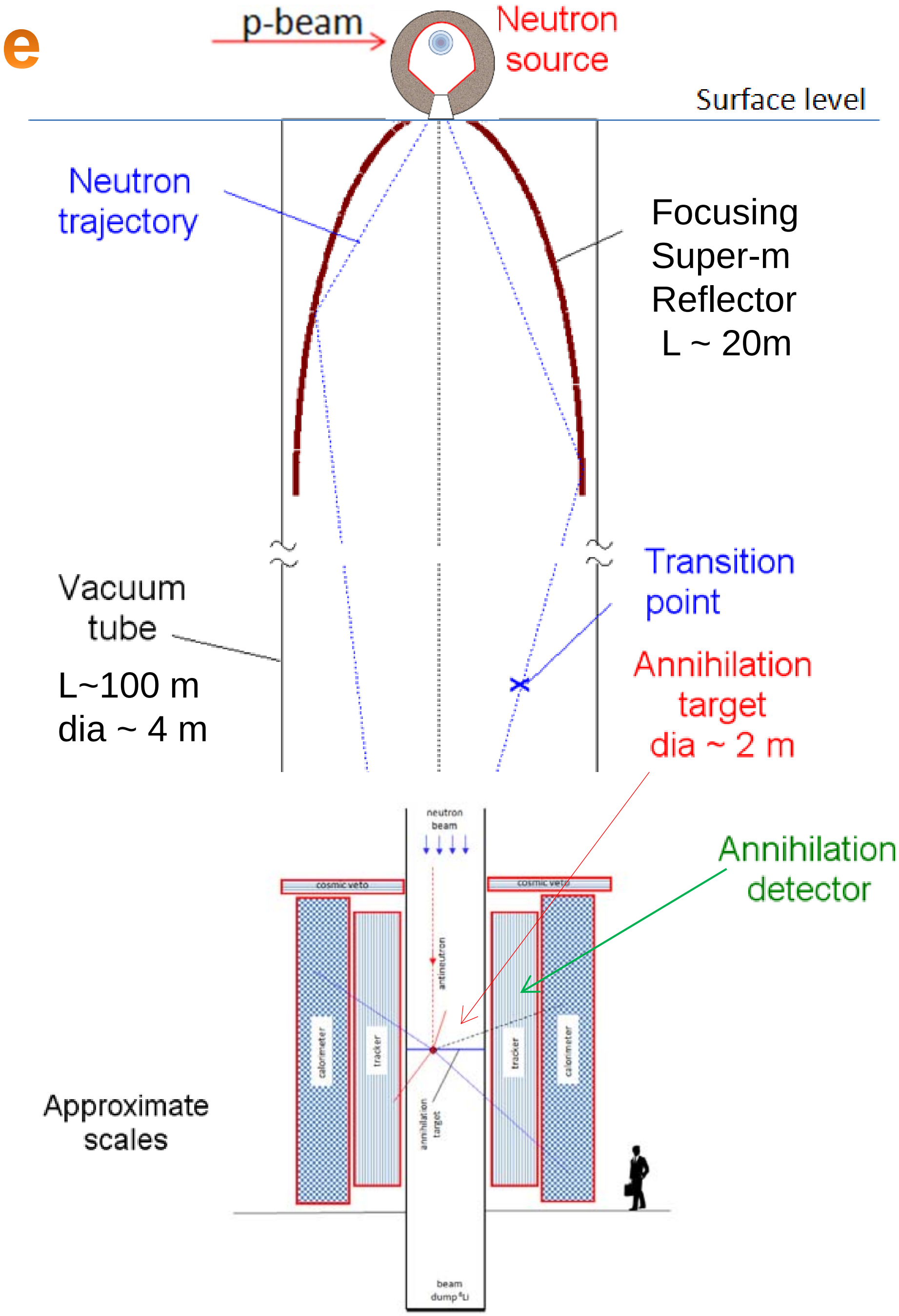
# Top-Down vertical scheme

- Can combine most of improvements;
- CW or pulsed;
- Max UCN (<10 m/s) enrichment will be most advantageous;
- Cold and VCN are also used;
- Ultimate combination of all improvements should boost the sensitivity by factor > 1,000 u times several years of operation

$$h = v_0 t + \frac{1}{2} g t^2$$

$$105\ \mathrm{m} = 100\ \mathrm{m/s} \cdot 1\ \mathrm{s} + 4.9\ \mathrm{m/s^2} \cdot 1^2\ \mathrm{s}^2$$

$$105\ \mathrm{m} = 10\ \mathrm{m/s} \cdot 3.7\ \mathrm{s} + 4.9\ \mathrm{m/s^2} \cdot 3.7^2\ \mathrm{s}^2$$

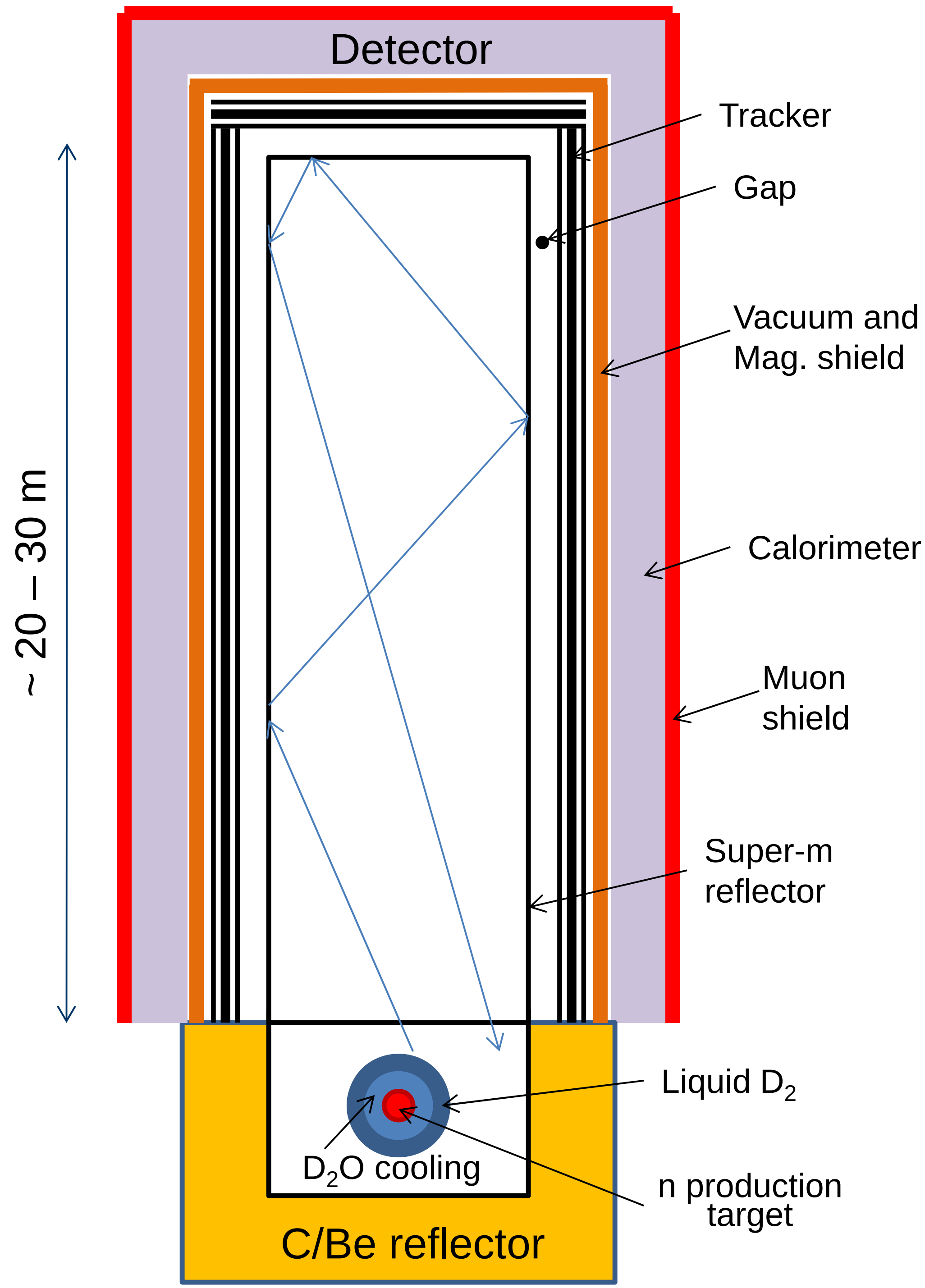


# Bottom – UP scheme using VCN source

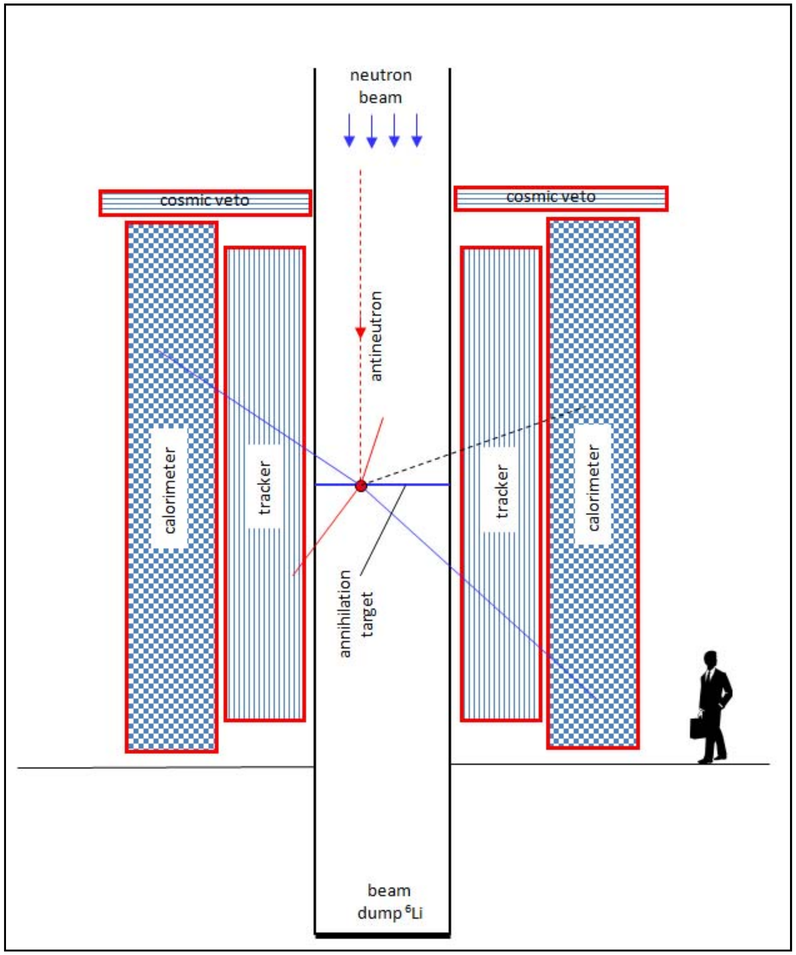
Feature: large detector around VCN trap.

Suitable for low-intensity Cold + VCN source. Several orders of magnitude higher detector counting rate.
No strong cosmic background separation constraints.

Slow pulse operation with time veto during pulse for detector can help for beam background reduction.
E.g. 1 ms pulse with repetition rate of 10 Hz
→ ~ 1% loss of efficiency



# Annihilation Detector



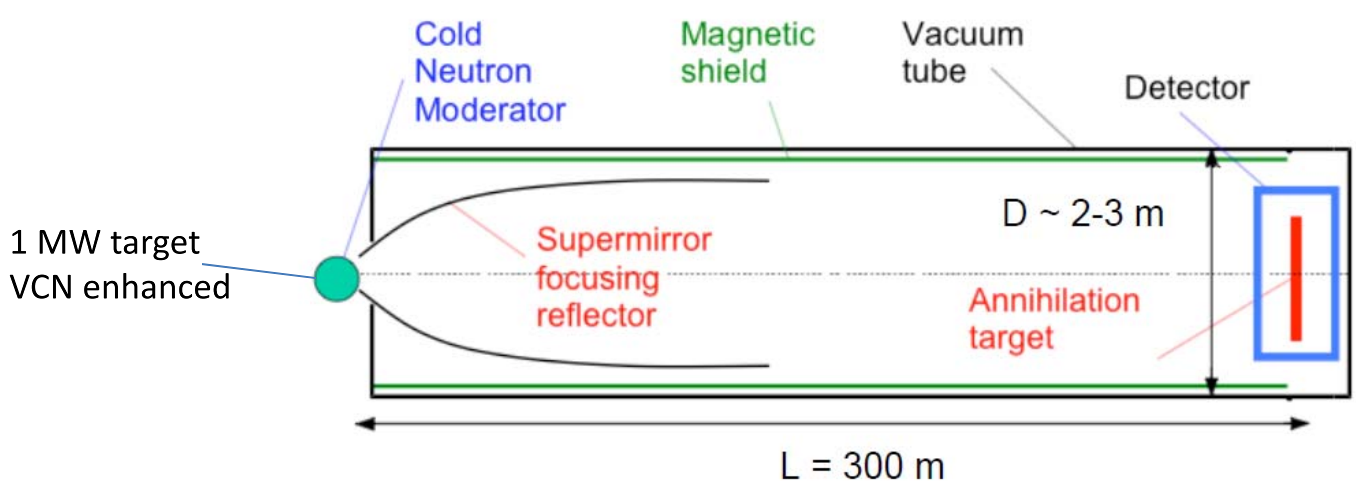

Annihilation feature: $\overline{n} + C \rightarrow \langle 5\pi \rangle$

- Use ideas of backgroundless ILL detector;
- Can be Vertical and Horizontal;
- Tracker for vertex to thin carbon target;
- Calorimeter for trigger and energy reco;
- TOF before and after tracker to remove vertices of particles coming from outside;
- Cosmic veto;
- Intelligent shielding to minimize (n,$\gamma$) emission.

# Demonstrator for PX Stage 1

Essential improvement in sensitivity is possible with straightforward extension of the existing technology in ILL-like horizontal scheme at PX Stage 1 with 1 MW target:

- Will demonstrate operation of 1 MW VCN-enhanced dedicated spallation target;
- Non-expensive scheme delivering sensitivity above Super-K n-nbar limits;
- Test and demonstrate critical technology of neutrons manipulation with super-mirrors;
- Test detector technologies, performance, and rates;
- Test Monte-Carlo simulation tools;
- Determine shielding  necessary for trigger and DAQ;
- Demonstrate backgroundless operation of the detector.



# Goals of R&D prior to Snowmass'13

Simulation and engineering study of configuration options with possible optimization of performance and cost for Demonstrator and Ultimate Sensitivity NNbarX experiment.

Deliverable information to support comparison of various options

| Options | Sensitivity | Cost | Issues |
|---|---|---|---|
| … | | | |
| … | | | |