A better constraint on neutron-antineutron oscillations … without a new experiment

- Neutron-antineutron oscillations (just an introduction),
- Antineutron guides (are they possible?...),
- First option (PF1B at ILL, with Cold Neutrons (CNs)),
- Main option (ESS, with CNs),
- Advantages of Very Cold Neutrons (VCNs) (do they justify the construction of a VCN source?),
- Finally, how to get a better constraint without a new experiment?

Neutron-antineutron oscillations, **motivation**

$$n - \bar{n} \qquad\qquad \Delta B = 2$$

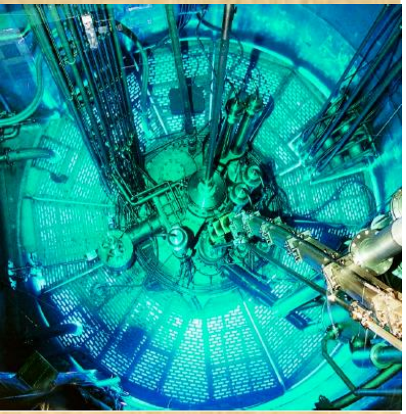
An **observation** of neutron-antineutron oscillations, which violate both Baryon and Baryon-Lepton conservation, would constitute a scientific discovery of fundamental importance to **physics and cosmology**.

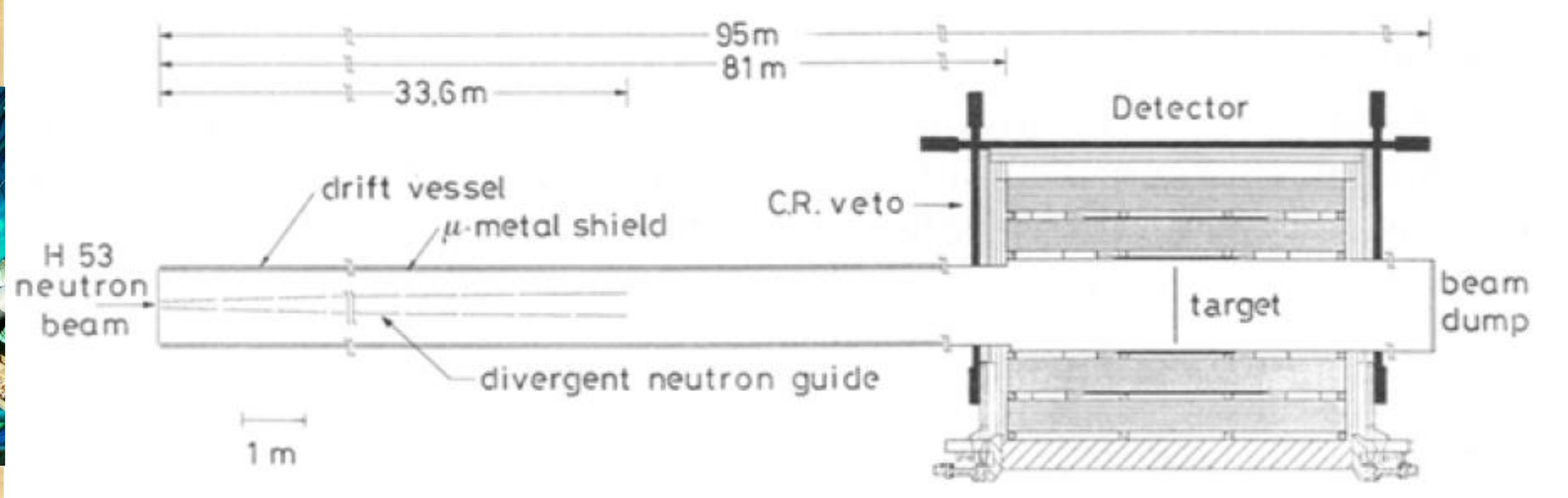
A stringent **upper bound** on its transition rate would make an important contribution to our understanding of the Baryon asymmetry of the universe by eliminating the **post-sphaleron baryogenesis** scenario in the light quark sector.

Neutron-antineutron oscillations, experiment

The best existing experimental constraint to free-neutron neutron-antineutron oscillations: M. Baldo-Ceolin *et al*, *A new experimental limit on neutron-antineutron oscillations*, Zeit. Phys. C 63 (1994) 409

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





The most recent review of experimental options: A. Addazi *et al*, *New high-sensitive searches for neutrons converting into antineutrons and/or sterile neutrons at the HIBEAM/NNBAR experiment at the European Spallation Source*, J. Phys. G 48 (2021) 070501

Antineutron guides

Proposal (presented for the first time at QUARKS-2018): V.V. N. *et al*, *Experimental approach to search for free neutron-antineutron oscillations based on coherent neutron and antineutron mirror reflection*, Phys. Rev. Lett. 122 (2019) 221802;

Low-energy antineutrons are reflected in analogy to neutrons (from optical Fermi potential of the surface material)

$$b_{\bar{n}A} \sim 1.54\sqrt[3]{A} - i$$

A characteristic lifetime of antineutrons in the guide is **1-3 s**

Element	$b_{\bar{n}A}$ [fm]	$U_{\bar{n}}$ [neV]	$\tau_{\bar{n}}$ [s]
C	$3.5 - i$	$103 - i29$	1.7
Mg	$3.5 - i$	$39 - i11$	1.0
Si	$3.7 - i$	$48 - i13$	1.2
Ni	$4.7 - i$	$111 - i24$	2.3
Cu	$4.7 - i$	$104 - i22$	2.2
Zr	$5.3 - i$	$59 - i11$	1.8
Mo	$5.3 - i$	$89 - i16$	2.3
W	$6.5 - i$	$106 - i16$	3.0
Pb	$6.7 - i$	$57 - i8.6$	2.3
Bi	$6.7 - i$	$49 - i7$	2.1

Antineutron guides

This is a development of the quasi-free-neutron method: **Cold Neutrons** are allowed to **bounce** from the neutron guide walls. An antineutron would travel along the same trajectory, without annihilating and/or loosing coherence of the two states, for **extended periods of time**.

This is a direct analogy to the proposed earlier experiments with **ultracold neutrons** [M.V. Kazarnovski *et al*, JETP Lett. 32 (1980) 82; K.G. Chetyrkin *et al*, Phys. Lett. B 99 (1981) 358; H. Yoshiki, R. Golub, Nucl. Phys. A 501 (1989) 869],

However:

Antineutron guides

We:

- Extend this approach to **higher neutron energies (CNs instead of UCNs)**, thus largely increasing statistics and experiment sensitivity,
- Point out the conditions for suppressing the **phase difference** for neutrons and antineutrons at reflection ("clock non-reset"),
- Underline the importance of setting **low transverse momenta** of neutrons (suppressed annihilation of antineutrons),
- and make **certain choices for the nuclei** composing the guide material (to achieve the goals stated above).

Antineutron guides

ESS (the host institute, which is going to set up a new advanced search for neutron-antineutron oscillations) organized a workshop dedicated to our proposal ("**Clock non-reset**", on neutron scattering and the phase-shift, ESS, Lund, Sweden, 22.06.2020)

Conclusion: the proposal changes "rules of the game in the field"

Before: "UCNs guides" are **not competitive** because of low intensity and "reset of the clock" at each bounce
After: "CNs guides" provide the **most sensitive** method and transparent theoretical interpretation of results

The arguments are summarized in: V.V. N. *et al*, *Comment on B.O. Kerbikov "The effect of collisions with the wall on neutron-antineutron transitions"* … Phys. Lett. B 795 (2020) 135357

Antineutron guides

For **the same installation length**, advantages include

- **Smaller transversal sizes**,
- **Lower costs**,
- **Larger statistics** (higher accuracy).

For **a larger length**,

a large **gain in sensitivity**. In terms of the oscillation probability, the gain increases quadratically with the length (and still a large reductions of costs).

Antineutron guides

Reliability of the interpretation of results is based just on **quantum mechanics**: a wave is reflected from a sufficiently sharp potential step.

No precision data on antineutron-nuclear scattering length is needed as long as the lifetime of antineutrons in the guide (typically **1-3 s**) is much longer than the time-of-flight (typically **0.05-0.4 s**) – concrete estimations are given below.

Nevertheless, a (very) conservative analysis of the antineutron-nuclear scattering lengths is also available: K.V. Protasov *et al*, *Theoretical analysis of antineutron nucleus data needed for antineutron mirrors in neutron-antineutron oscillation experiments*, Phys. Rev. D 102 (2020) 075025

First option (PF1B at ILL)

V. Gudkov et al, *A possible neutron-antineutron oscillation experiment at PF1B at the Institut Laue Langevin*, Symmetry 13 (2021) 2314

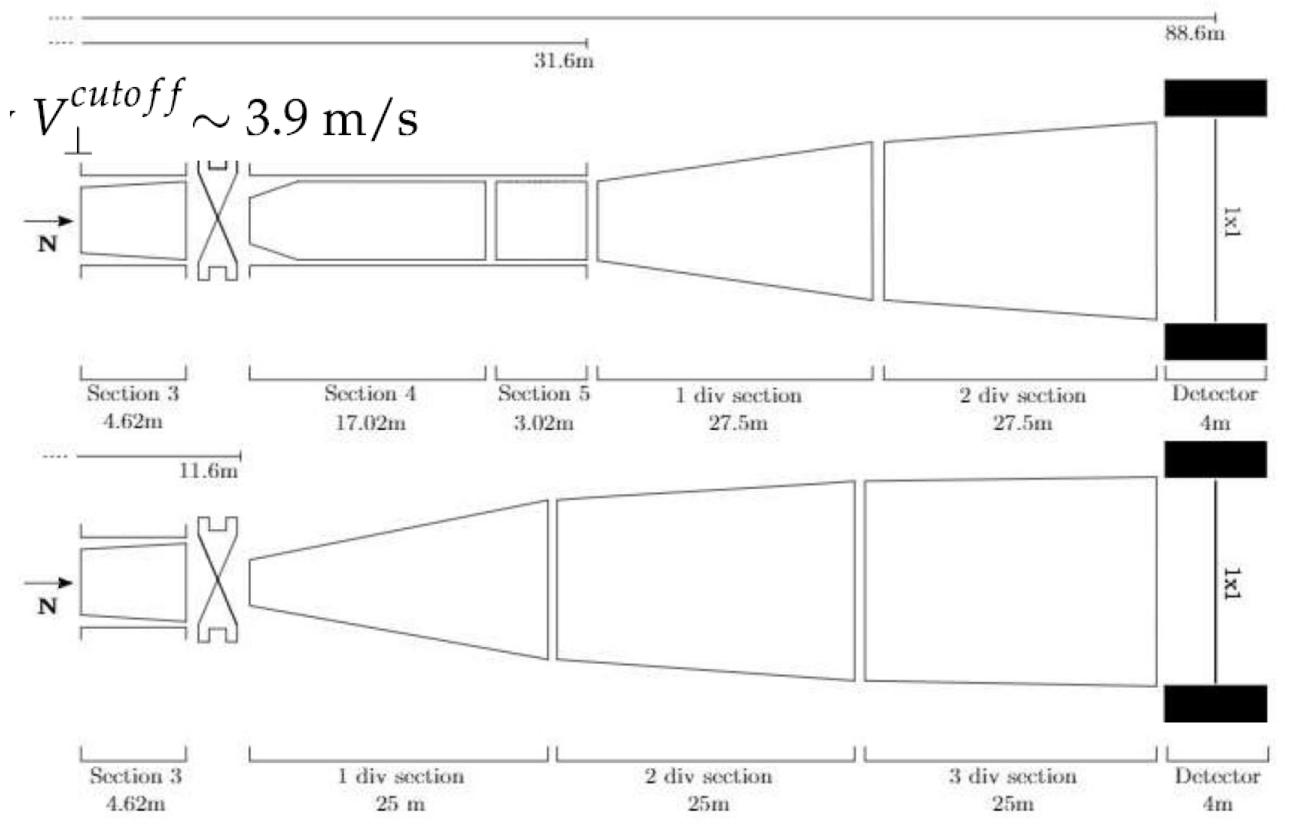
$$V_F(\bar{n}\mathrm{Cu}) \equiv V_0 - iW = 94 - i27\ \mathrm{neV},$$

A Cooper guide. Both the real and imaginary parts of the scattering length are decreased/increased by 5 standards deviations

The **overall gain** factor over the best existing limit is **3-10 times** (as a function of the chosen configuration)

- Background: **below 1 event**
- Systematics: **virtually absent**

$$V_{\perp}^{cutoff} \sim 3.9\ \mathrm{m/s}$$



Main option (ESS)

ESS ("**green field facility**") would provide a **much higher sensitivity** (the experiment design and sensitivity are going to be analyzed soon in detail)

Gain factor (compared to PF1B) include:

- A significantly larger **length** (**quadratic** increase in sensitivity),
- A significantly larger **solid angle** of extracted neutrons (also **quadratic** increase in sensitivity)

These factors would give an **additional** (conservative) **gain of >100**
Lower costs due to the smaller guide and detector sizes, **smaller backgrounds** from the spallation source, compared to the design without the antineutron guide

Main option (ESS)

An uncertainty in the experiment sensitivity estimation is associated with the **uncertainty in the scattering length** of slow antineutrons on the guide wall material.

-for **PF1B**, the time of flight is 0.05 s, much shorter than antineutron storage times, thus it is **negligible**,

-for **ESS**, the time of flight is 0.4 s, $\Delta \mathrm{Im} b_{\bar{n}A} / \mathrm{Im} b_{\bar{n}A} = \Delta \mathrm{Im} a_{\bar{n}A} / \mathrm{Im} a_{\bar{n}A} \sim 0.1$

$\tau_{\bar{n}} / \tau_{\mathrm{obs}} \sim 5.$, and the systematic uncertainty in the estimation of the oscillation time is as small as **0.5%**.

Conclusion: systematics is also virtually absent.

Advantages of VCNs

As the observation time at ESS would be still significantly smaller than the lifetime of antineutrons in the guide, one could try to use **the advantages of the method to its maximum** and decrease the mean neutron velocity.

- Sensitivity increases as the **square** of observation time,
- Neutron flux decreases as the **square** of neutron velocity,
- Thus **sensitivity is the same for the same phase-space density**.

However, a **dedicated VCN source** would significantly increase the phase-space density and might give an additional factor of **10**!

A possible implementation at ESS

The design kindly provided by Luca Zanini

The proposal:

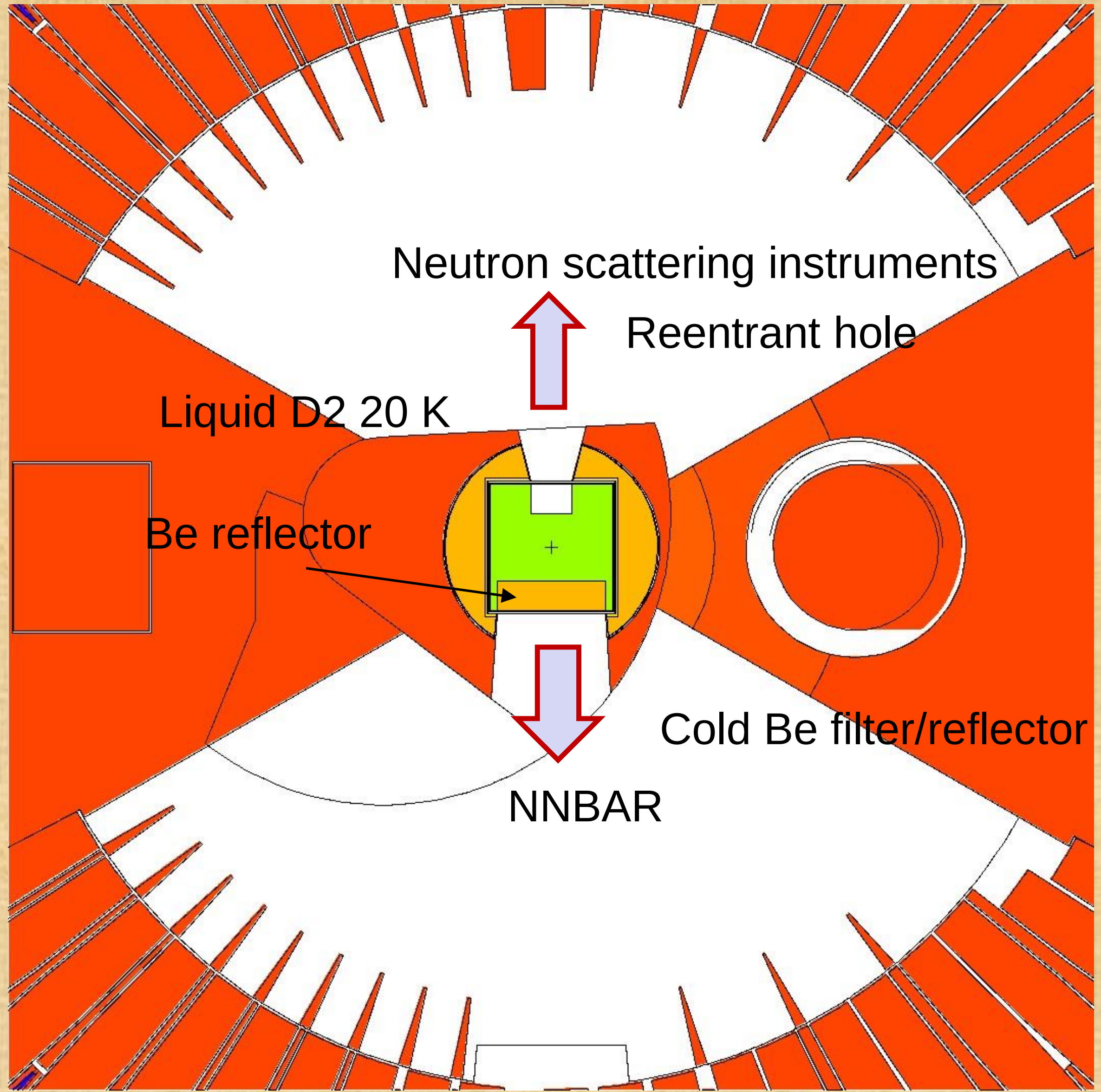
to replace

Be reflector by

solid-deuterium

VCN converter,

Or to put on top of the reflector



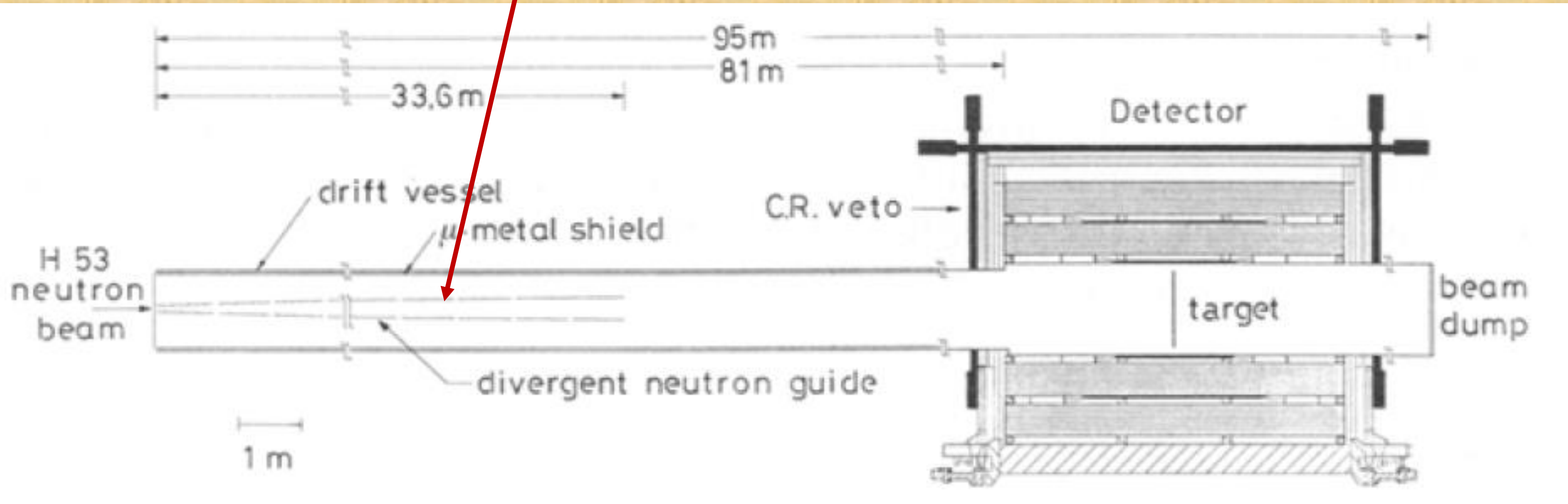
A possible implementation at ESS

- An **optimum position** (close to the maximum CN flux),
- An **optimum** (for VCN production) **incident neutron velocity**,
- A **large cross-section** – thus a large **total VCN flux**,
- The thickness (**say, 5 cm**) is a compromise between the heat load to solid deuterium and the VCN extraction depth,
- No problems with neutron scattering on the **density inhomogeneity** (an important problem for UCNs but virtually absent for VCNs),
- The technology of first **efficient VCN reflectors** based of **fluorinated diamond nano-powders** has been developed.

A better constrain without a new experiment

Well, the talk is nearly finished. Where is the promised new constraint???

Please, look carefully:



This is a figure from the original publication M. Baldo-Ceolin *et al*, *A new experimental limit on neutron-antineutron oscillations*, Zeit. Phys. C 63 (1994) 409

A better constrain without a new experiment

Referee remark to our article [V. Gudkov et al, *A possible neutron-antineutron oscillation experiment at PF1B at the Institut Laue Langevin*, Symmetry 13 (2021) 2314] :

"…In the experiment at PF1 instrument, a 33.6 m long focusing reflector coated with nickel was used. Could using a new approach based on a n/nbar guide lead to the case that the sensitivity of the previous experiment is underestimated?..."

(from the high quality of other critical remarks of this referee, I think, I can guess who is this referee…)

A very preliminary constraint is at least

$\tau_{n\bar{n}} > 1.0 \cdot 10^8\ s$ instead of $\tau_{n\bar{n}} > 0.86 \cdot 10^8\ s$

A more serious analysis is going to be done in the nearest future, and the number could still improve.