Predicting RNA solvation shell using enhanced sampling molecular dynamics simulations

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Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

Funding (PRIN): *Hunting metal ions within cryo-EM derived RNA structures*

Our first CASP experience

June 11, 2024

Hello!

We (David Case, Rhiju Das, Rachael Kretsch, and Wah Chiu, along with the CASP organizers) are reaching out to you because of your interest and expertise in molecular dynamics simulation of macromolecules, especially their behavior in explicit water.

As part of the CASP16 experiment, we are piloting a water and ion prediction category.

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- (previously measured cryo EM map)

Task:
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- validated against unpublished cryo EM map

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💪 Dear Olivier, dear Elisa,
did you plan holidays already?

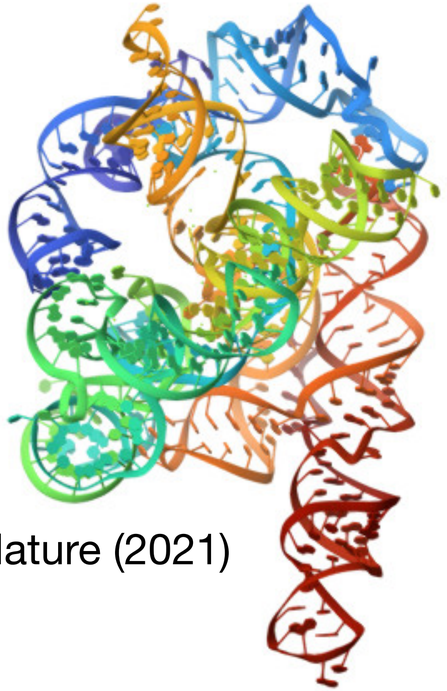
The system

T. thermophila group I self-splicing intron PDB: 7EZ0
387 nucleotides

GROMACS with:

- AMBER (χOL3 + TIP3P)
- Grotz & Schwierz (micro Mg, 2021)
- Mamatkulov & Schwierz (Na, Cl, 2018)

RNA + 27 PDB Mg^{2+} + 151 Mg^{2+} + 121 Na^{+} + 91 Cl^{-} + 85730 water
Rect. box with 2 nm buffer and restrained rotations



Su et al, Nature (2021)

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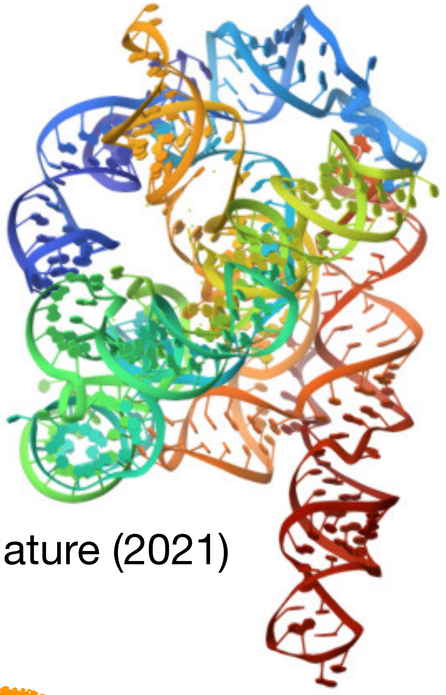
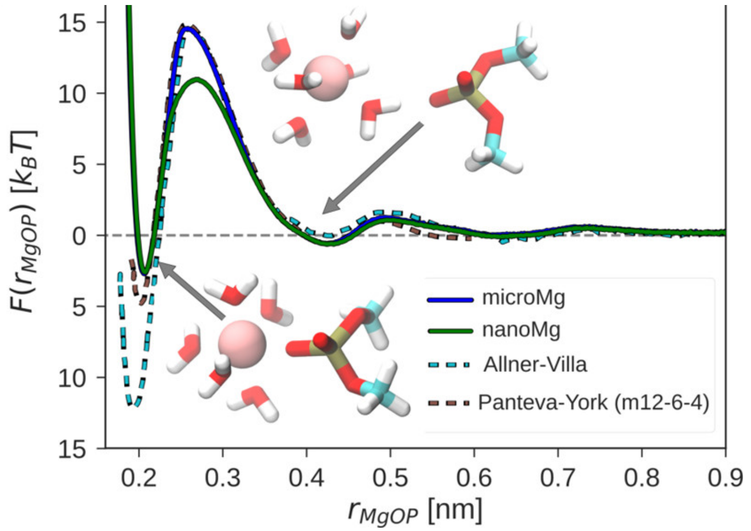


Su et al, Nature (2021)

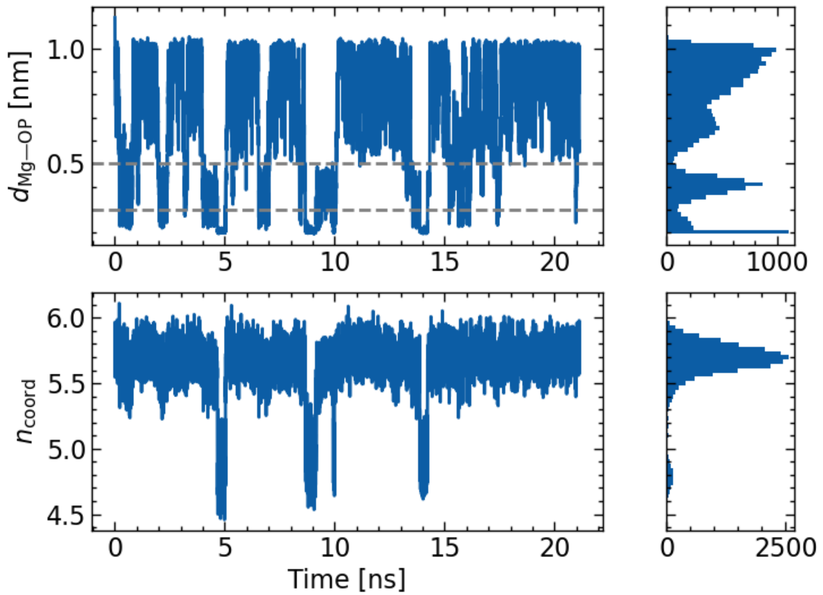
Coordination shell rearrangement happens on the μs time scale (as it should)

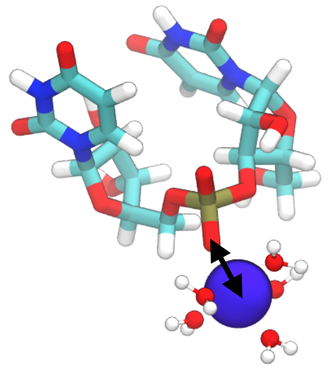
Table 3. Properties of Water Exchange from Simulations and Experiments[a]

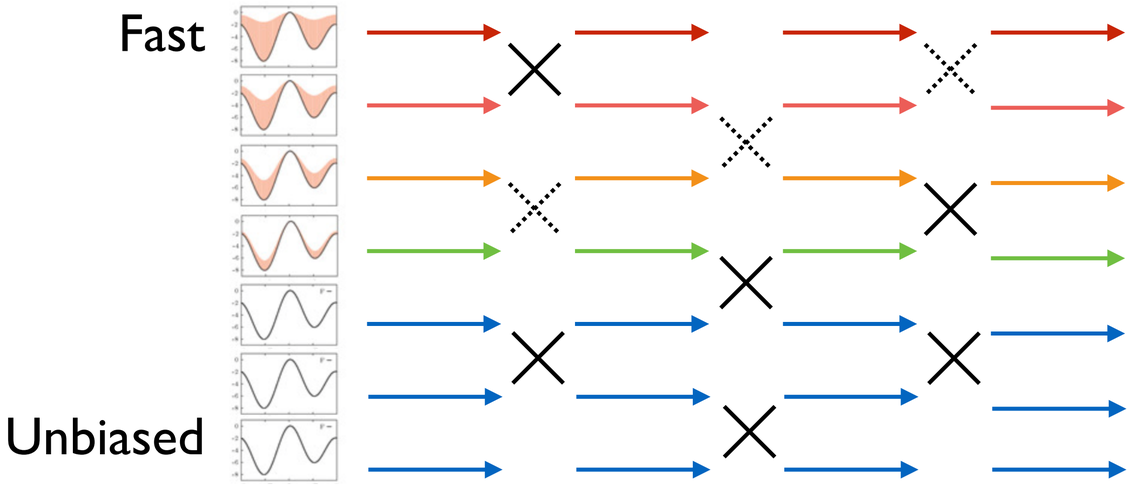
	N	k [s^{-1}]
microMg	376 ± 56	$(8.04 \pm 1.20) \times 10^5$



Ad hoc biasing + replica exchange





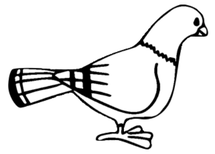


Biased variables:
- Distance from closest phosphate O
- Number of coordinated water O

Manually designed attractive potential on barriers to convince "reluctant" Mg^{2+}

Ladder of 16 replicas
(5 unbiased + 11 biased)
Growing accelerating prefactor
5 "ground replicas" provide unbiased sampling

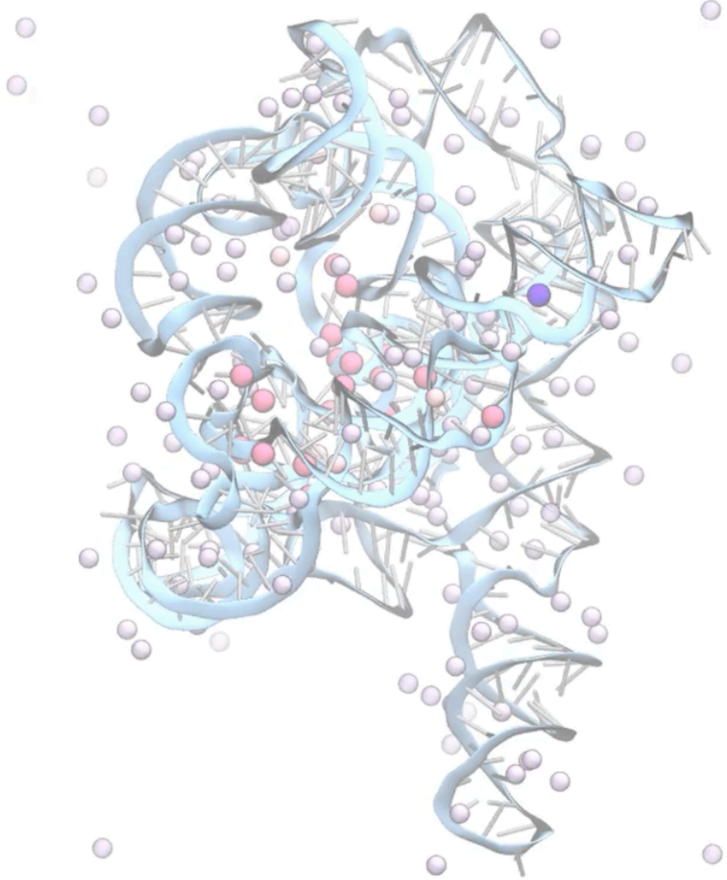
Inspired on Cunha & Bussi, RNA (2017)
Implemented using PLUMED



Inspired on Curuksu & Zacharias, JCP (2009)
+ Gil-Ley & Bussi, JCTC (2014)

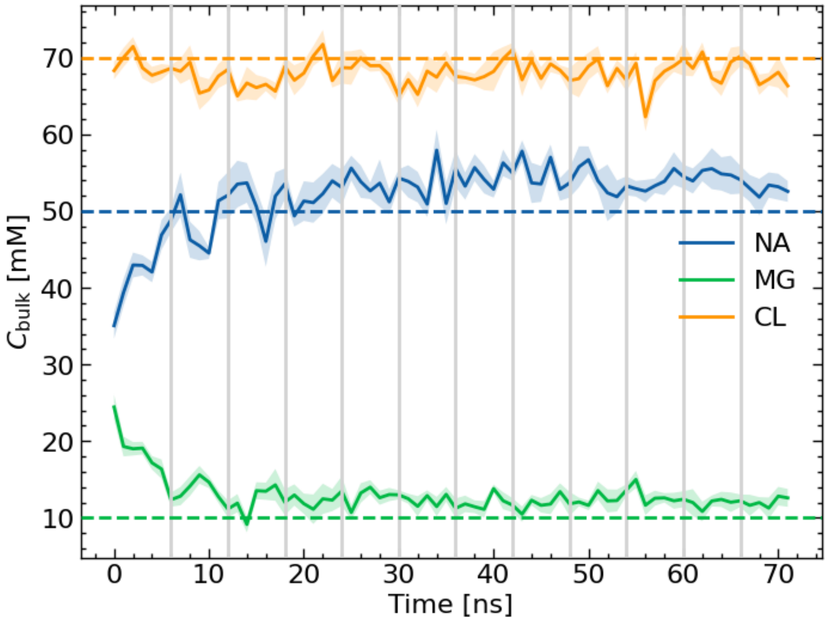
Fast forward

Before



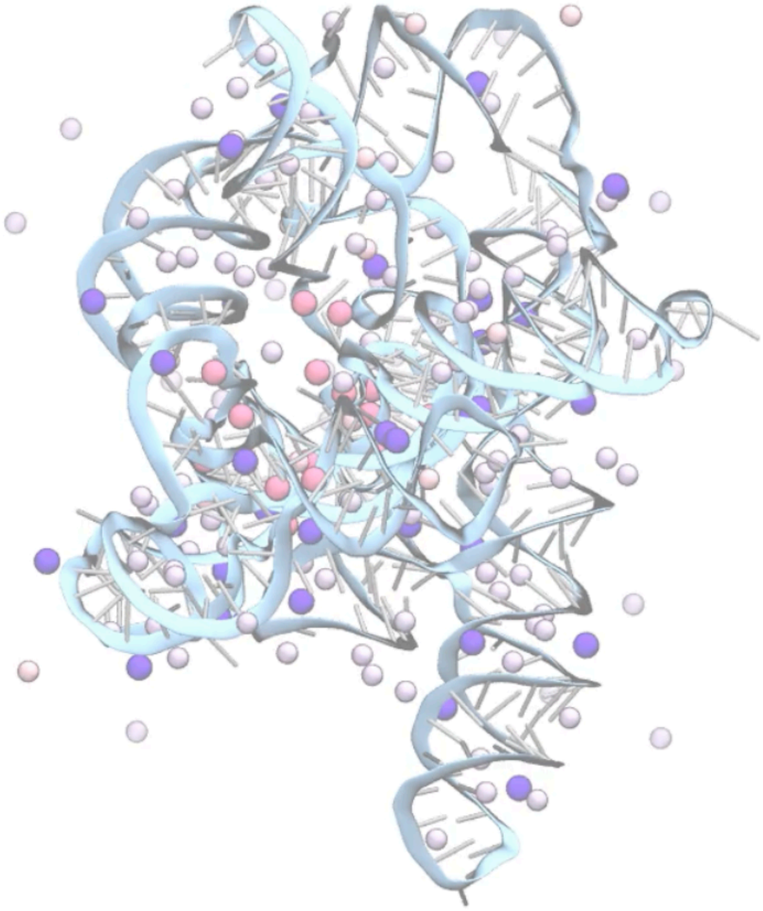
- not directly bound
- in 7EZ0
- predicted

⏭️ ~160 ns per replica
~ 10 days



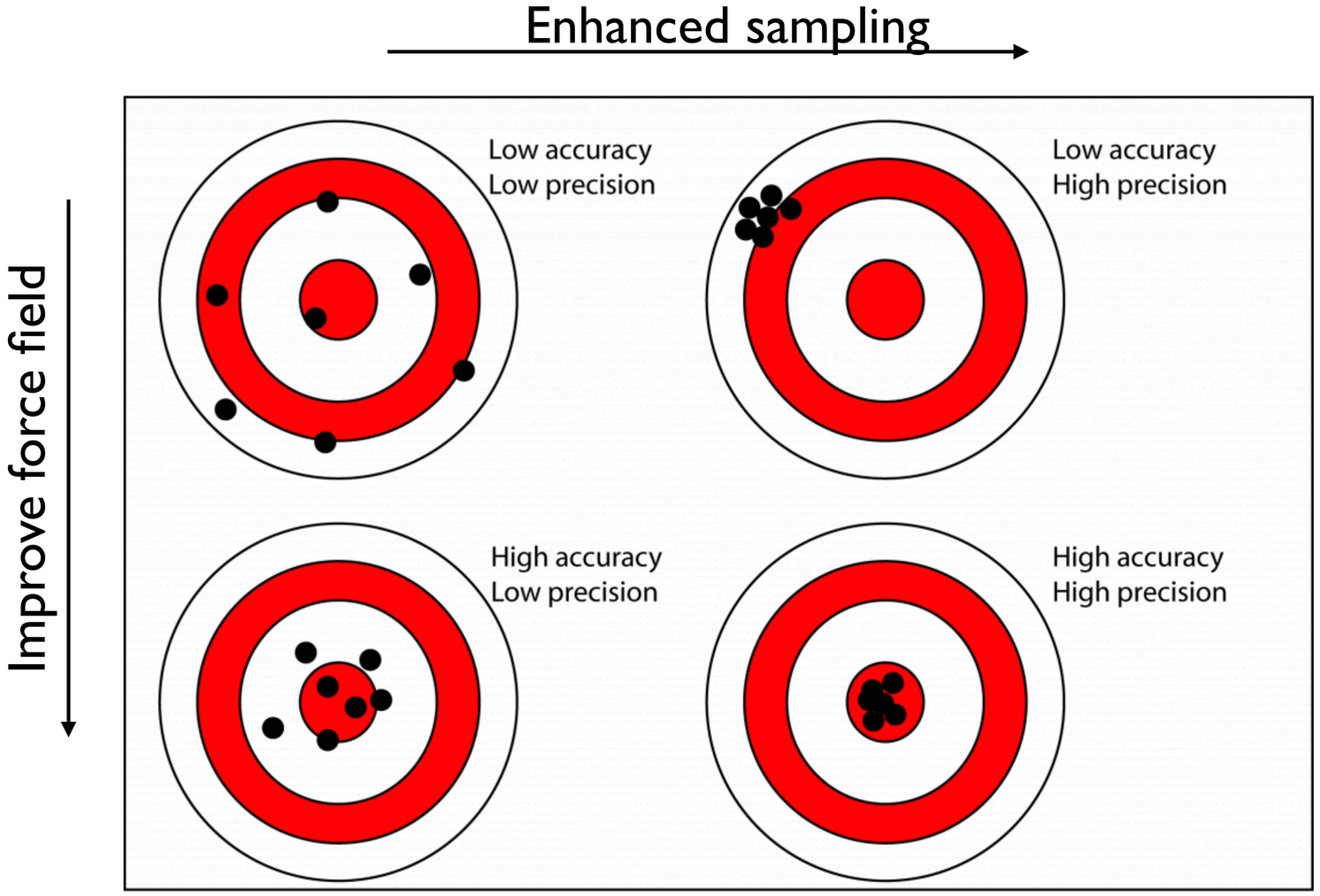
Adjust number of Mg^{2+} to match experimental concentration in bulk

After



No movie in pdf, but this is an ensemble!

Self-assesment

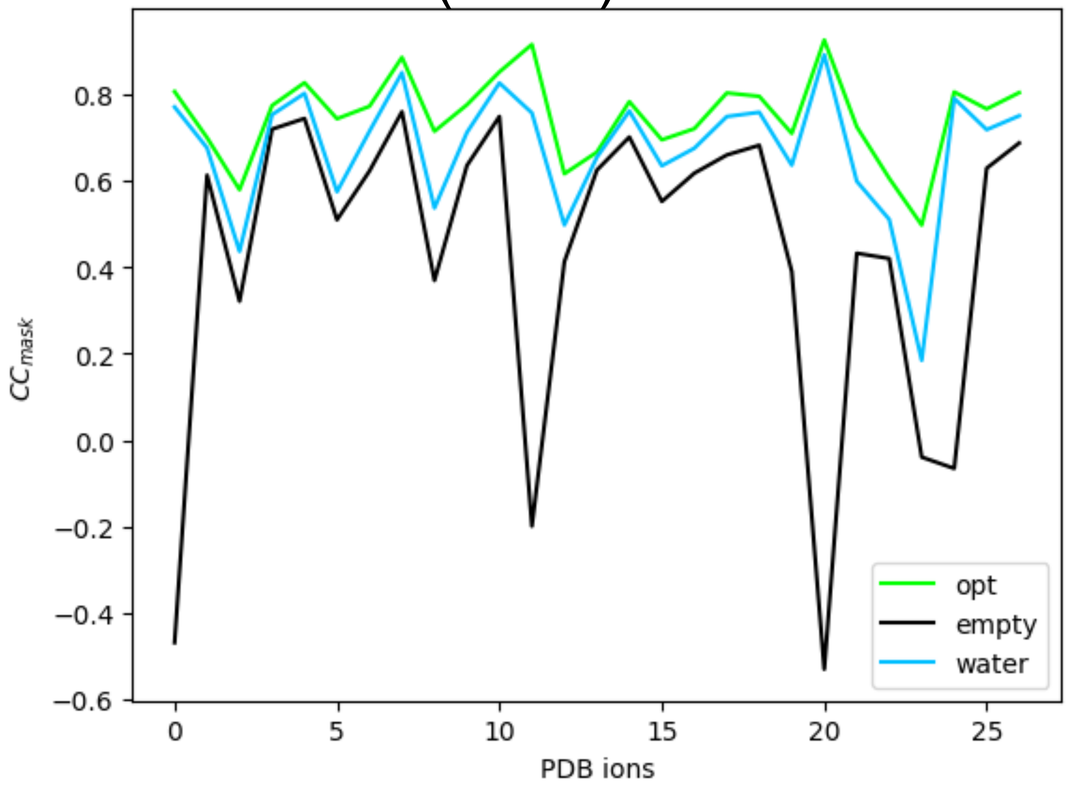


Precision: internal consistency (e.g. dependence on simulation length)

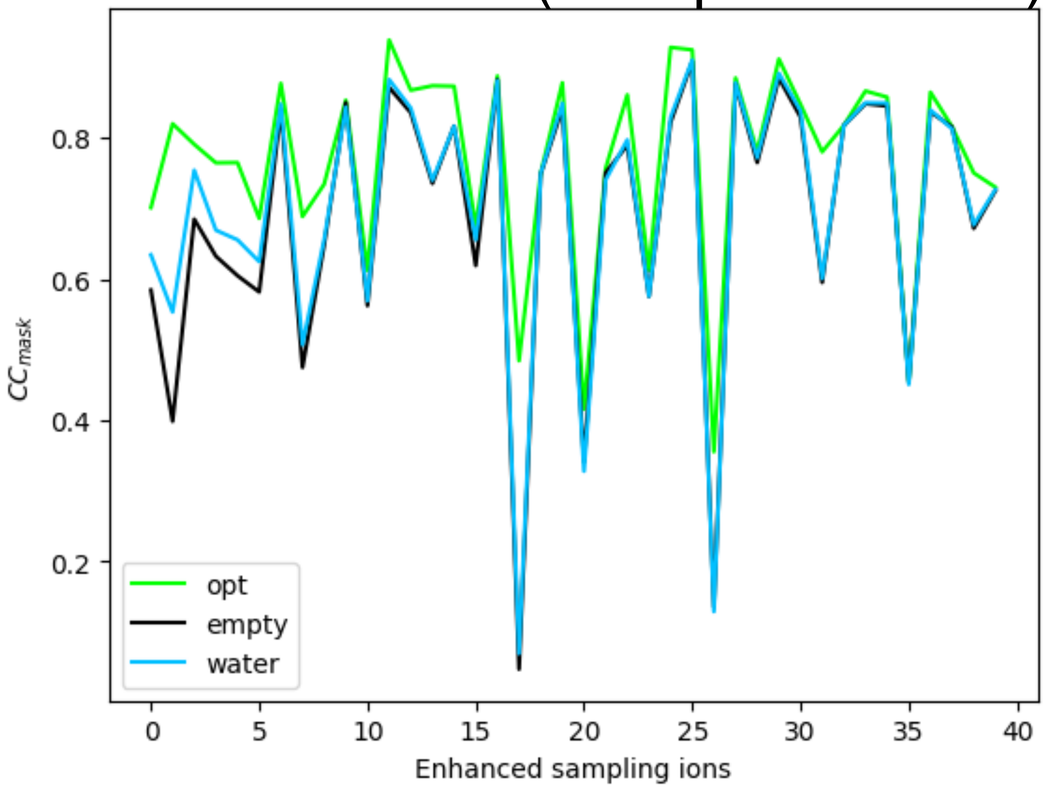
Accuracy: are experimental data sensitive to ion placement?

Validate predicted Mg^{2+} sites

PDB sites (7EZ0)



New sites (occupied > 50%)



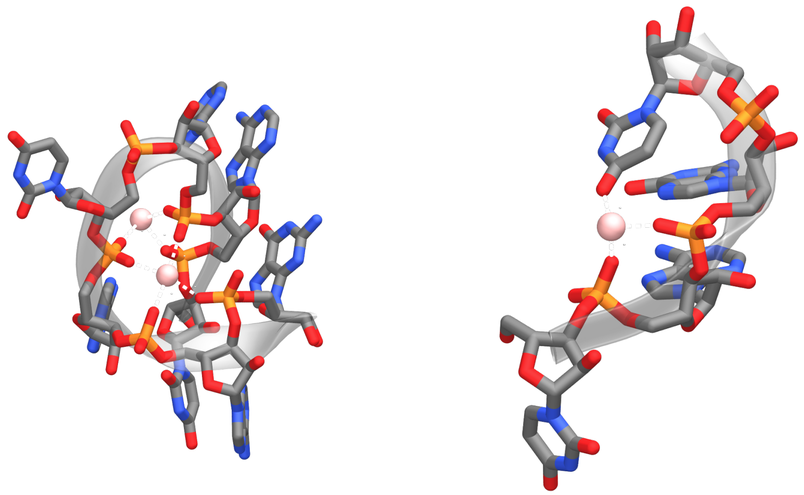
- PDB sites are confirmed by cryo-EM data
- All predicted sites are compatible with data, many are supported by data

(Tests done with public 7EZ0 map)

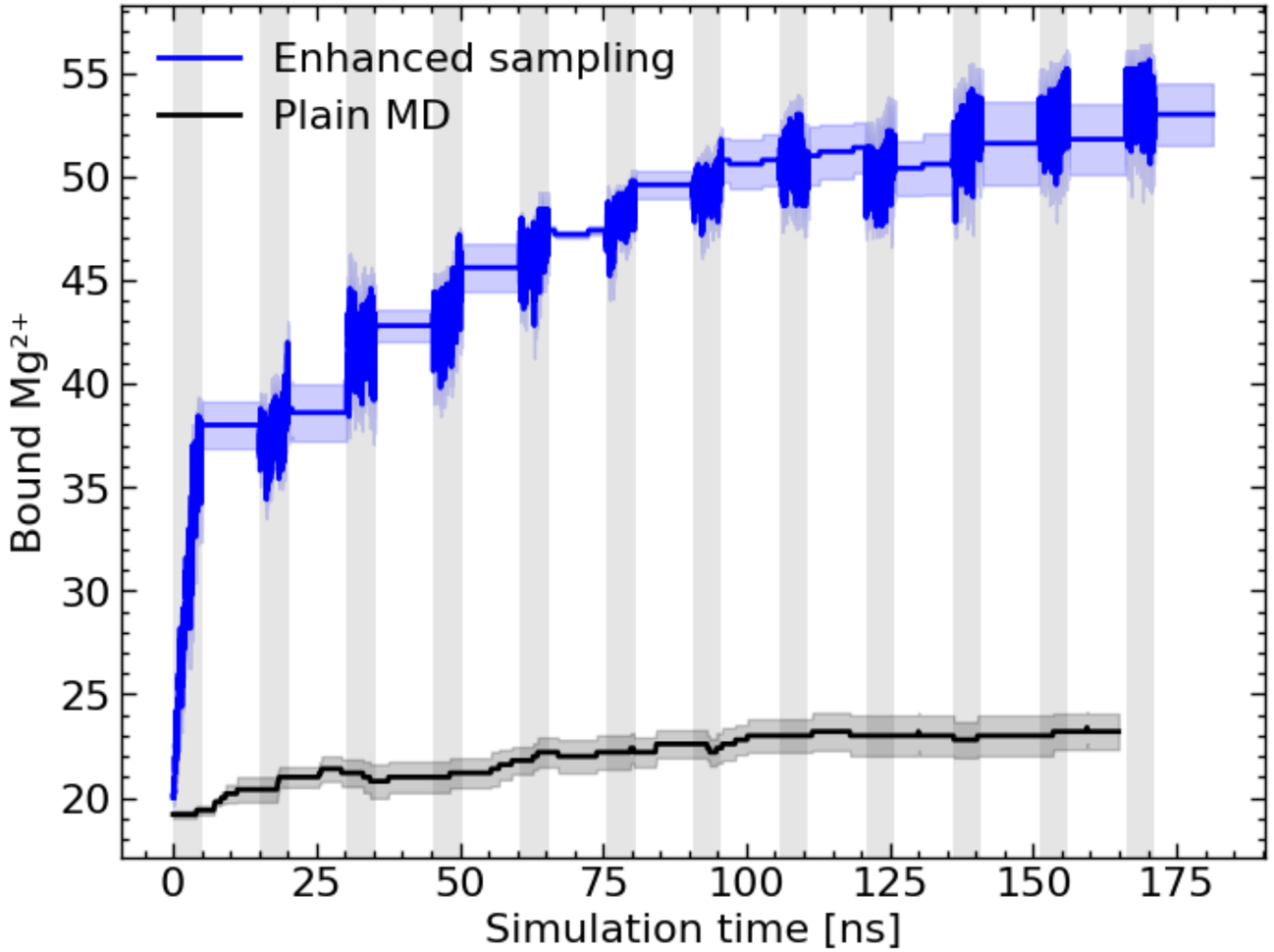
What went well 😀

Enhanced sampling worked!

Meanwhile, we further improved the method and can address deeply bound Mg^{2+} (tested on small motifs)



On CASP target



Olivier Languin-Cattoën et al, in preparation

What went wrong 😢

Validation is challenging, result depends on which criterion we use

Interplay of water/ion dynamics and RNA dynamics

Preliminary scoring by Rachael Kretsch is good, but we don't know yet if prediction is accurate enough and why

What's next 🧐

Run our protocol using:

- Multiple systems with high resolution cryo-EM maps *
- Test multiple RNA/water/Mg^{2+} force fields*

- Optimize/cherry pick force-field parameters to maximise correlation with experiment
- Use resulting Mg^{2+} ensembles to train DL methods (discussed with S.-J. Chen)

* can easily do one per week, if Rhiju Das sends us the structures 😀