



Proxima  
Fusion

# ConStellaration: A dataset of QI-like stellarator plasma boundaries and optimization benchmarks

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39th Conference on Neural Information Processing Systems | Datasets & Benchmarks Track  
(NeurIPS 2025).



# Fusion is the ultimate source of clean energy

Fusion is the process that powers the stars.

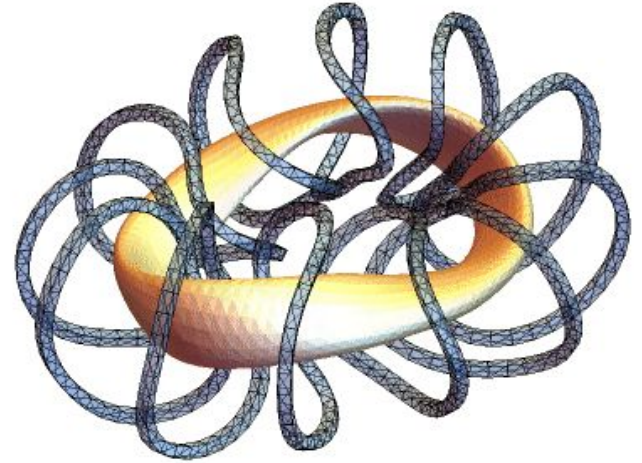
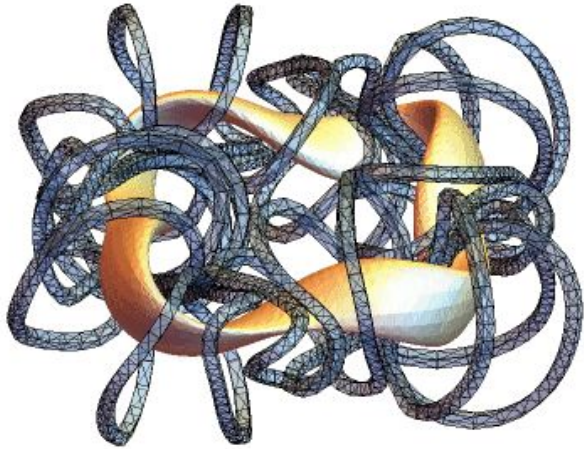
Fusion power is the opposite of nuclear fission – by fusing light atoms together, mass is transformed into energy.

One approach to achieving fusion is via magnetic confinement of plasma.

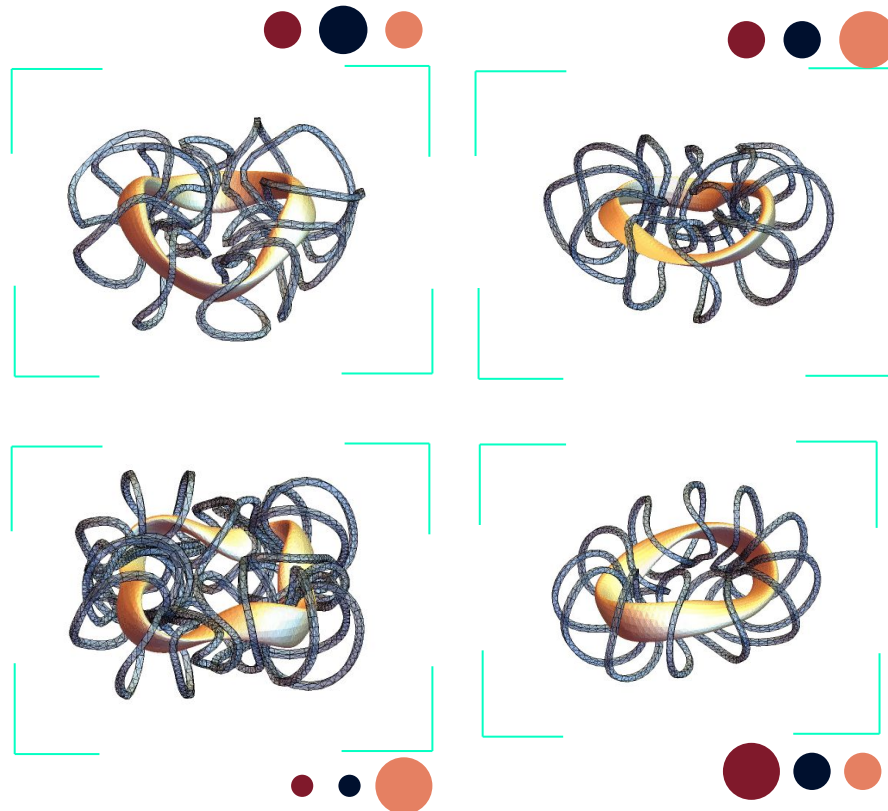
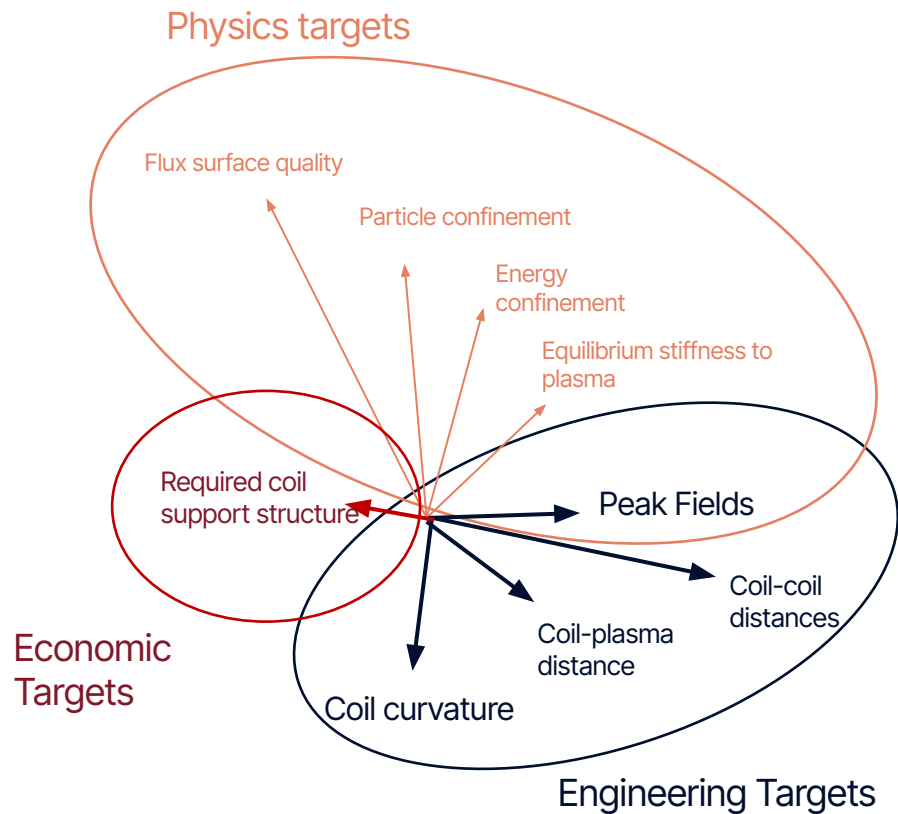
# Stellarator optimization

## What are we looking for?

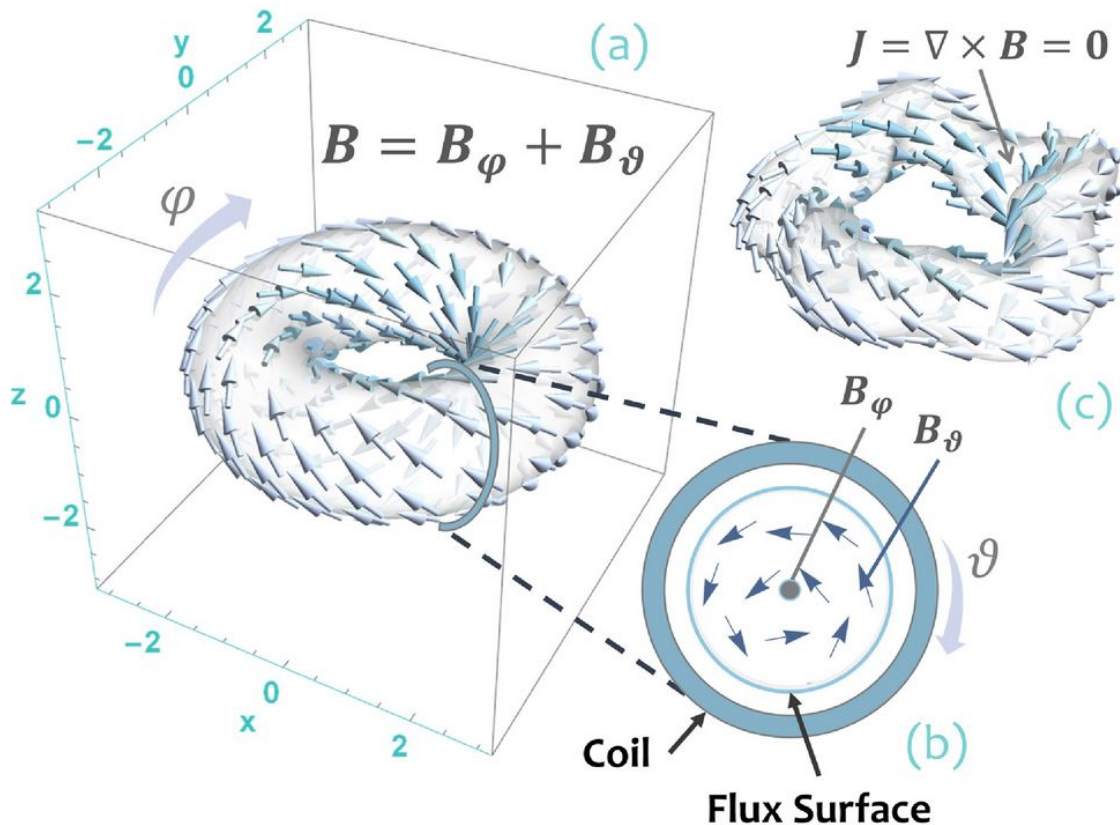
# Stellarator optimization: identifying core plasma and magnet geometries that meet target criteria



# Trade-offs exist between objectives



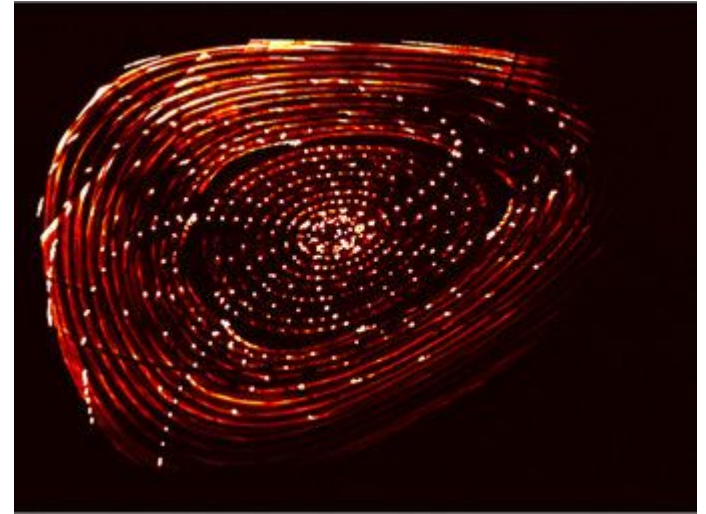
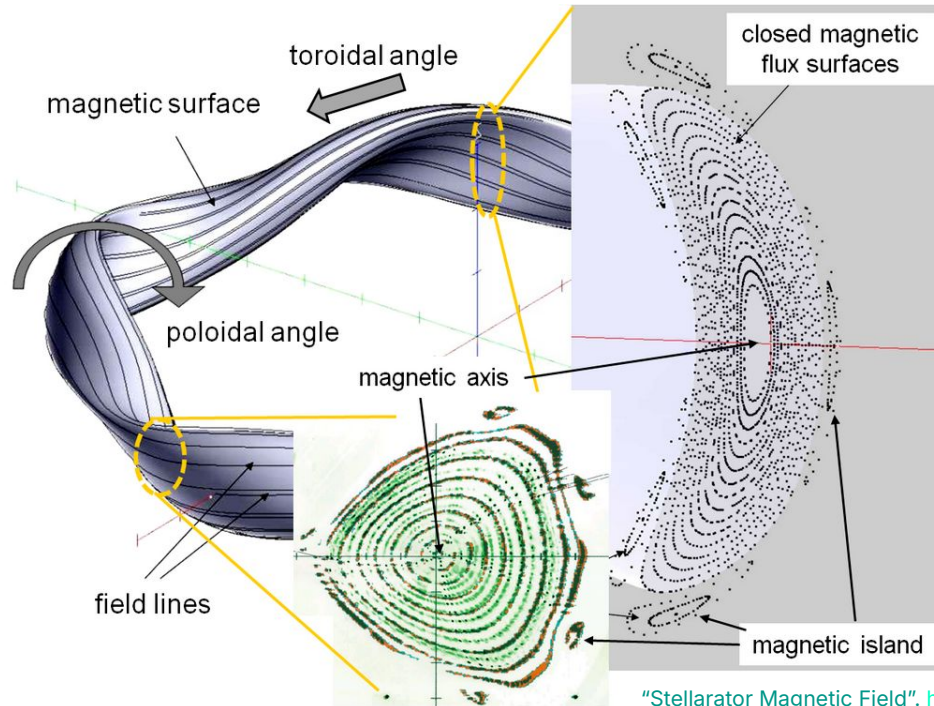
# What do plasma shapes (flux surfaces) represent?



Imagine the magnetic field as water flowing through space. **Flux surfaces are like invisible pipes guiding the flow.** The magnetic field never pierces through these surfaces—it always glides along them (i.e., it lies tangential to them).

The surfaces shape can be derived via the knowledge of the magnetic field.

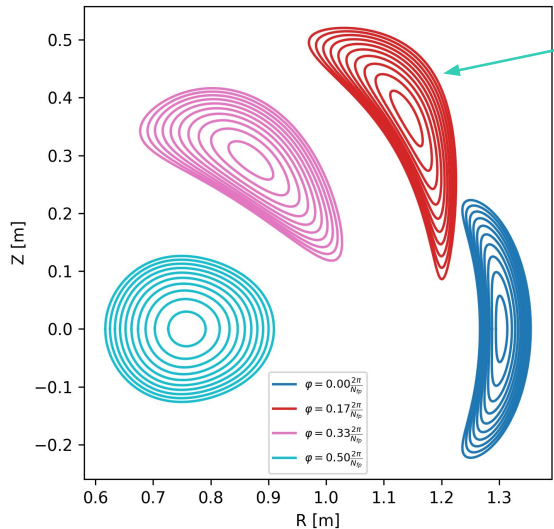
# An important goal of stellarator optimization is to achieve nested magnetic flux surfaces to avoid radial transport



In **simulation** and in the **experiment!**

"Stellarator Magnetic Field". [https://commons.wikimedia.org/wiki/File:Stellarator\\_magnetic\\_field.png](https://commons.wikimedia.org/wiki/File:Stellarator_magnetic_field.png)  
 "Confirmation of the topology of the Wendelstein 7-X magnetic field to better than 1: 100,000." Nature communications 7.1 (2016): 13493.

# Core plasma boundary optimization



The **last surface** in the onion represents your **design space** and the boundary condition for the PDE.

$X$  is parameter space in which the shape lives

$$\min_{\mathbf{x} \in X} f_1(\mathbf{x}), f_2(\mathbf{x}), \dots, f_N(\mathbf{x})$$

$$\text{s.t. } \mathbf{J}(\mathbf{x}) \times \mathbf{B}(\mathbf{x}) = \nabla p$$

$$\text{s.t. } g_1(\mathbf{x}), g_2(\mathbf{x}), \dots, g_M(\mathbf{x})$$

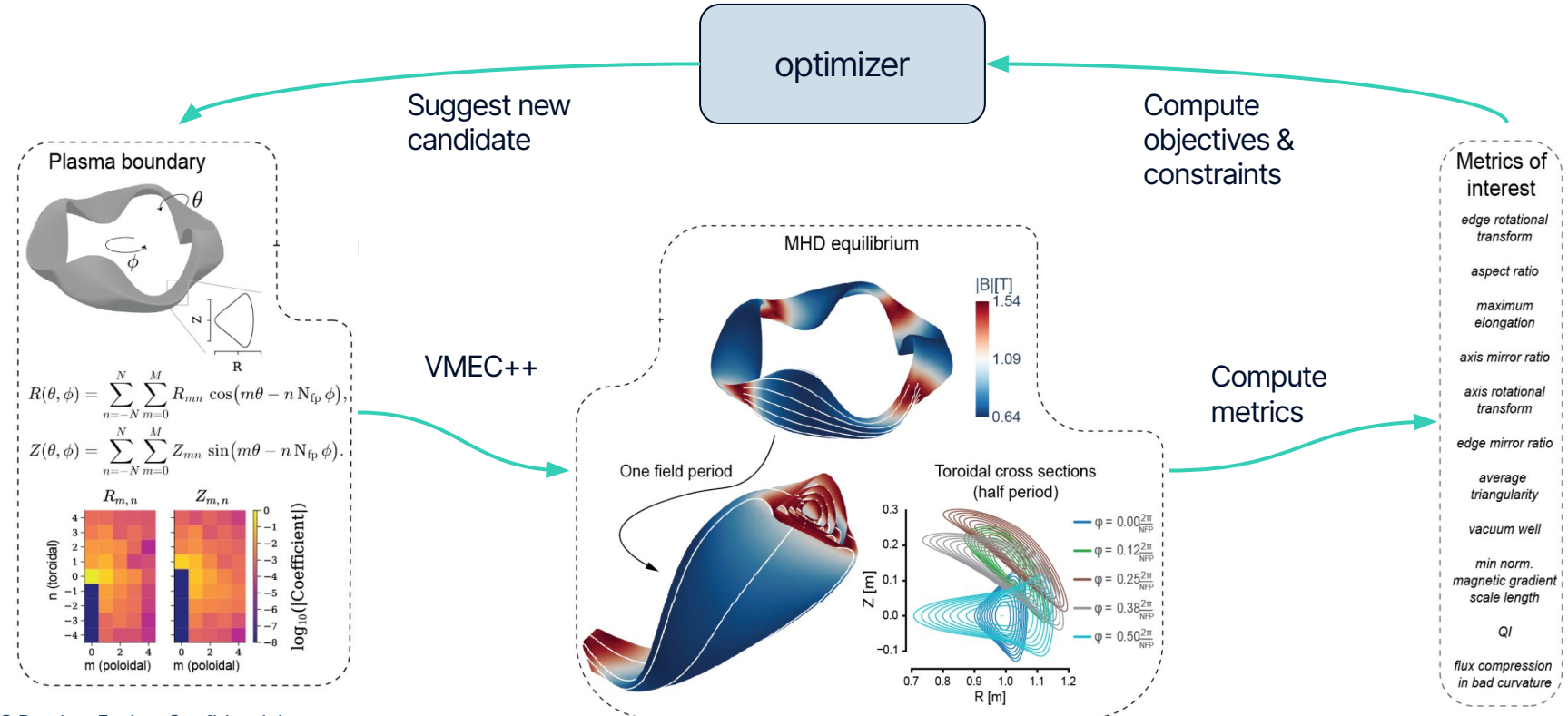
Ideal-MHD  
PDE systems  
of equations

**Design space:** the shape of one (assumed to exist) flux surface.

**Forward model:** solution of a PDE system (the ideal-Magnetohydrodynamics model) that describes the equilibrium magnetic field inside that flux surface (the flux surface is the boundary condition for the PDE).

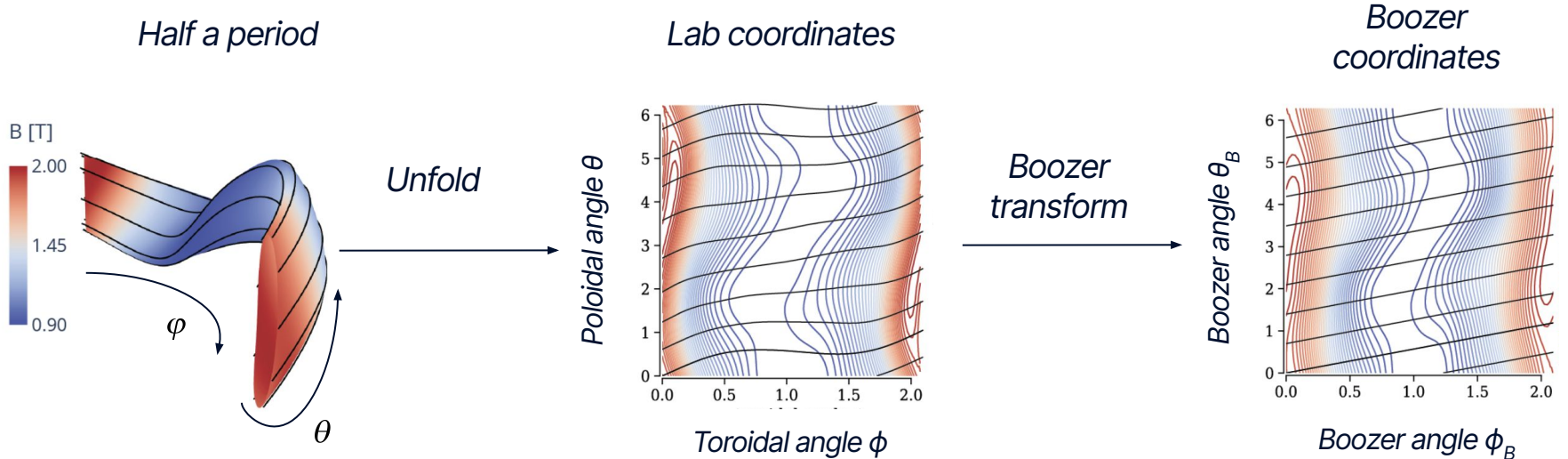
**Objectives and constraints:** physics (and engineering) properties of interest that depend only on the solution of the PDE system.

# Plasma boundary optimization using VMEC++ in the loop.

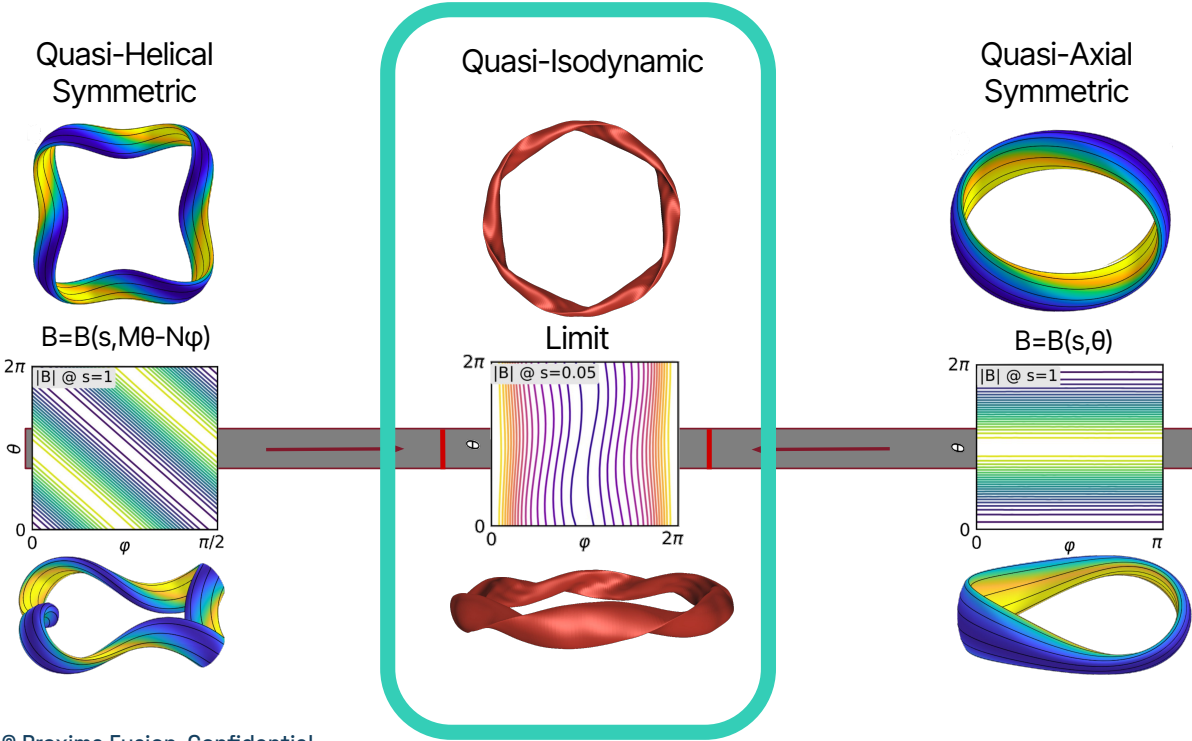


# Additional background: Stellarators can be designed to possess symmetries that live in a space of transformed coordinates

Introducing **Boozer coordinates**  
(aka the coordinate system that particles "see")



# Additional Background "Quasi-symmetry" (or the more general *Omnigenity*) improves confinement of trapped particles.



*Quasi-symmetry*: when  $|B|$  depends on linear combination of  $\phi_B$  and  $\theta_B$

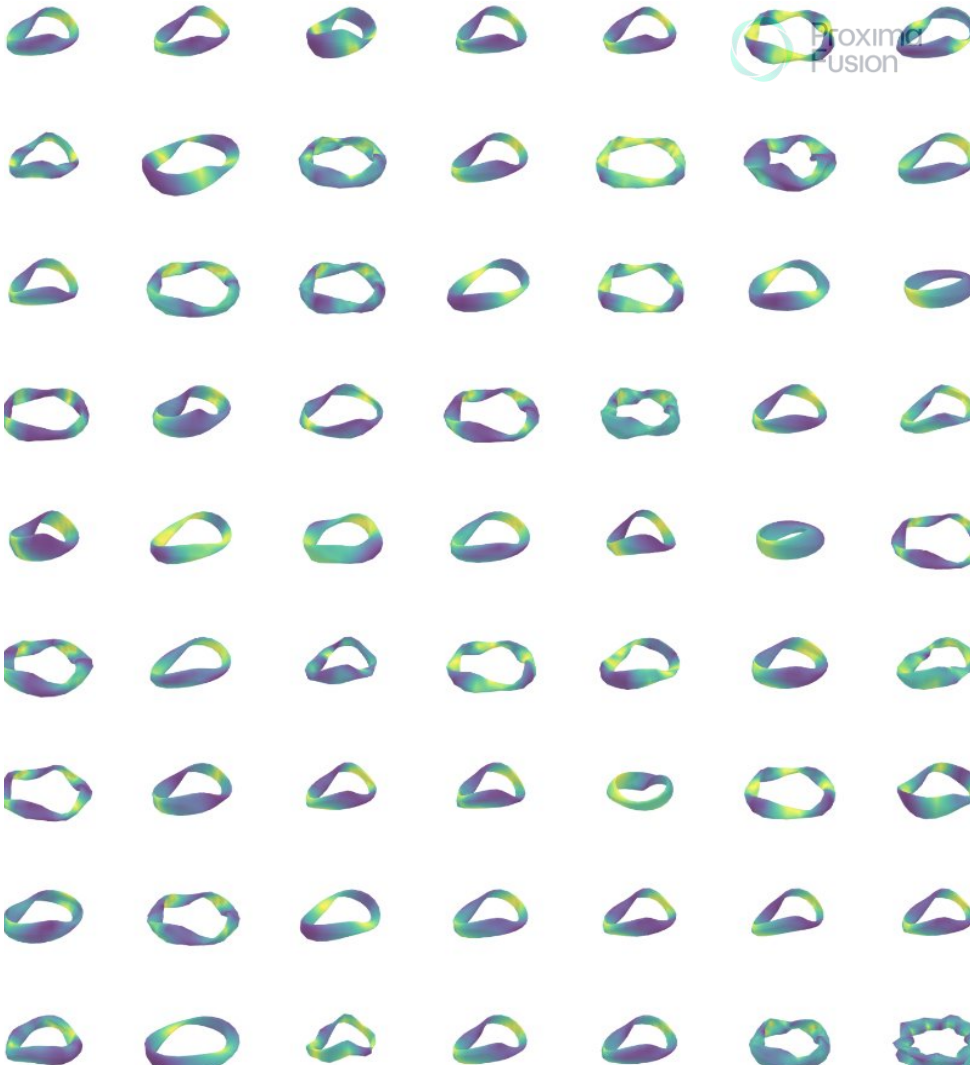
Omnigenity (a relaxation of *Quasi-symmetry*) improves confinement of trapped (bouncing) particles.

*QI* is a one type of Omnigenous stellarator kinds

# The ConStellaration challenge

# What is ConStellaration?

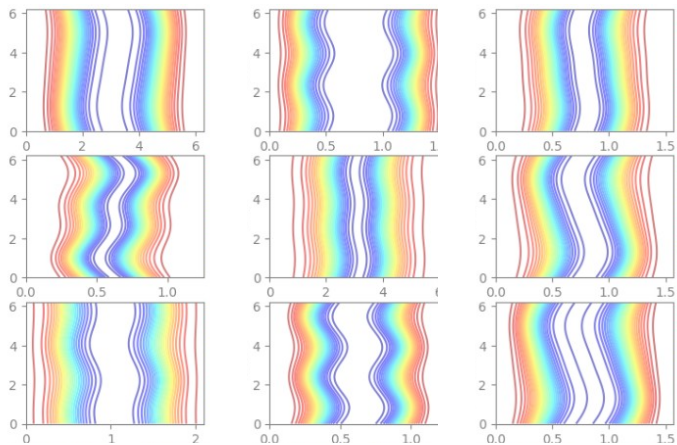
- A ~160k dataset of QI-like stellarator plasma boundaries + equilibria + metrics:  
<https://huggingface.co/datasets/proxima-fusion/constellation>
- Three optimization benchmarks with tools and baselines:  
<https://github.com/proximafusion/constellation>
- A public leaderboard of the challenge with 🤖:  
<https://huggingface.co/spaces/proxima-fusion/constellation-bench>
- Paper: <https://arxiv.org/abs/2506.19583>, accepted at NeurIPS



# How do we sample diverse boundaries that are physics relevant (QI)?

## 1. We sample *ideal* target QI fields

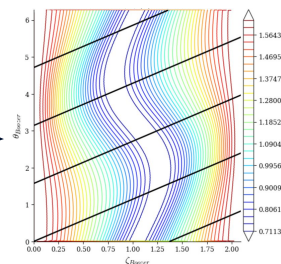
- Using a direct parameterization of these
- We also sample number of field periods, aspect ratio, rotational transform



A sample

## 2. We run an optimization to match the target boozer field

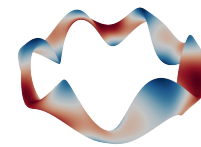
Target



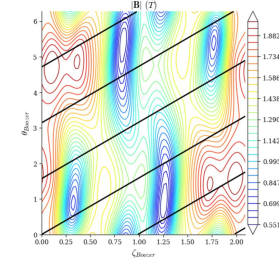
$\neq$

To minimize

Initial guess



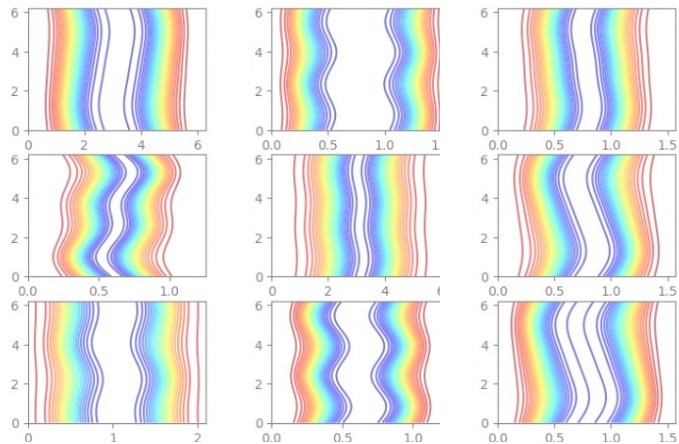
Boozer transform



# How do we sample diverse boundaries that are physics relevant (QI)?

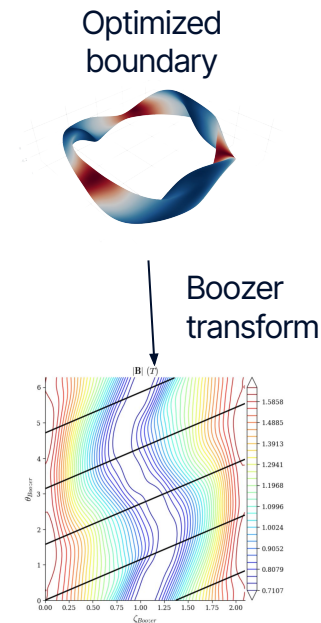
## 1. We sample *ideal* target QI fields

- Using a direct parameterization of these
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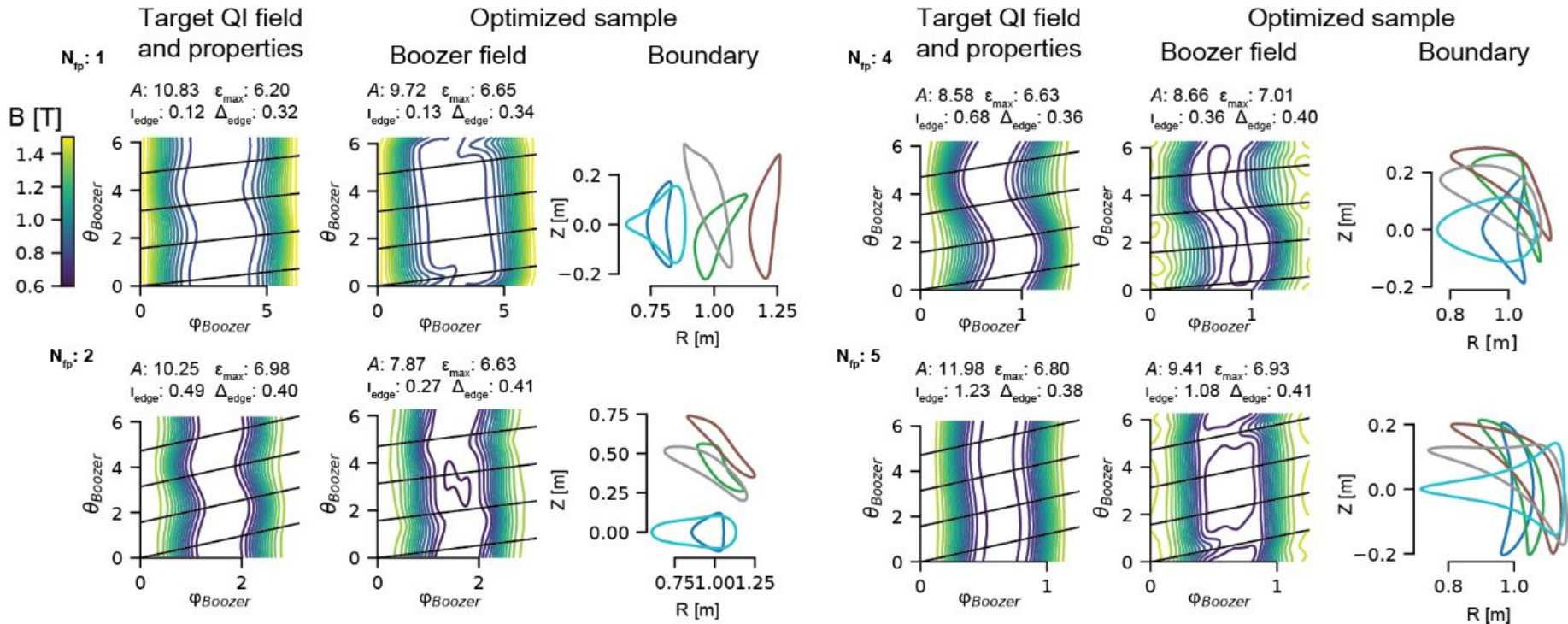


A sample

## 2. We run an optimization to match the target boozer field



# We obtained diverse QI-like samples



# Optimization benchmarks

# 1. Geometric Problem

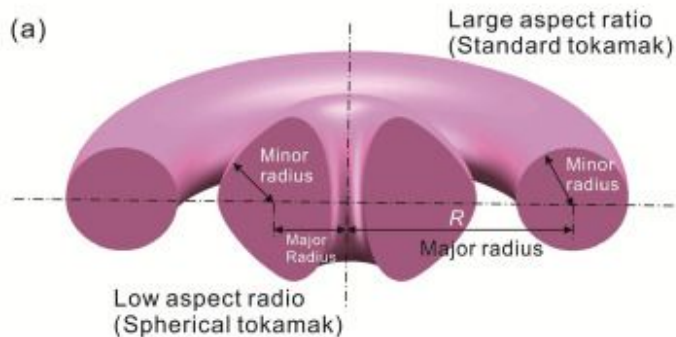
$$\min_{\Theta} \epsilon_{\max}$$

$$\text{s.t. } A \leq A^*,$$

$$\bar{\delta} \leq \bar{\delta}^*,$$

$$\tilde{t} \geq \tilde{t}^*.$$

- **Minimize max. elongation:** “stretching” of the longest cross-section
- **Constraints** for compactness
  - **Aspect ratio:** major radius / minor radius → keep it compact
  - **Edge rotational transform** → keep it twisted enough
  - **Triangularity** → keep it compact



## 2. Simple-to-build QI

$$\min_{\Theta} \tilde{L}_{\nabla B}$$

$$\text{s.t. } \tilde{t} \geq \tilde{t}^*, \quad QI \leq QI^*$$

$$\Delta \leq \Delta^*, \quad A \leq A^*$$

$$\epsilon_{\max} \leq \epsilon_{\max}^*$$

- **Maximize** proxy for **coil simplicity**
- **Constraints** to achieve **QI** field
  - **Geometry** → keep it compact
    - Aspect ratio: major radius / minor radius
    - Edge rotational transform
    - Triangularity
    - Max. elongation
  - **Mirror ratio:** How much the cross section area changes toroidally
  - **“QI”-ness:** how close the field is to perfect QI

# 3. MHD-stable QI (multi-objective)

$$\min_{\Theta} (-\tilde{L}_{\nabla B}, A)$$

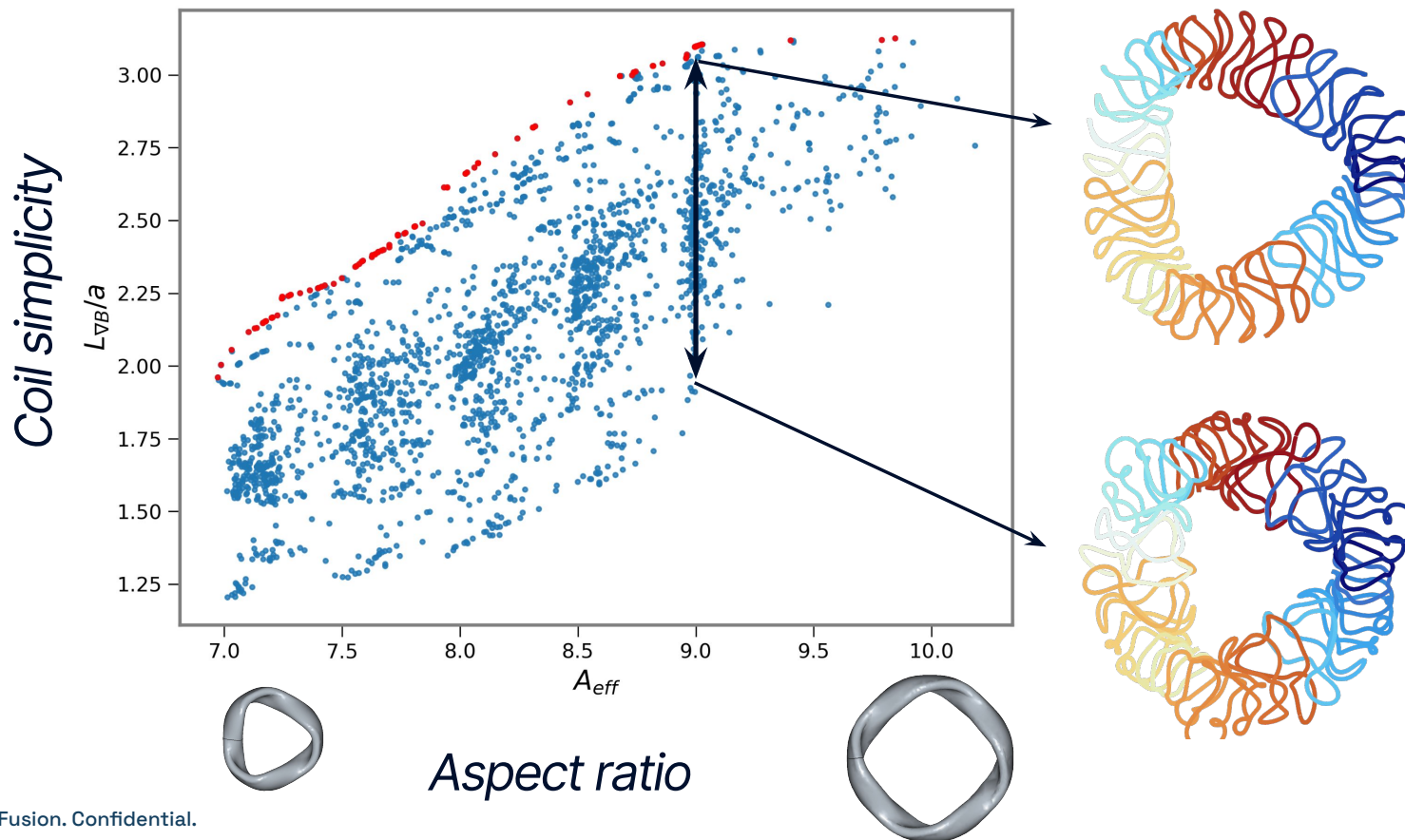
$$\text{s.t. } \tilde{t} \geq \tilde{t}^*, \quad QI \leq QI^*$$

$$\Delta \leq \Delta^*, \quad W_{\text{MHD}} \geq 0$$

$$\langle \chi_{\nabla r} \rangle \leq \langle \chi_{\nabla r} \rangle^*$$

- Two **objectives**
  - **Coil simplicity**
  - **Aspect ratio**
- **Constraints** for **QI field** and **stability**
  - **Geometry** -> compactness
  - **Magnetic field** -> QI-ness
  - **Stability**
    - MHD plasma stability
    - Turbulent transport

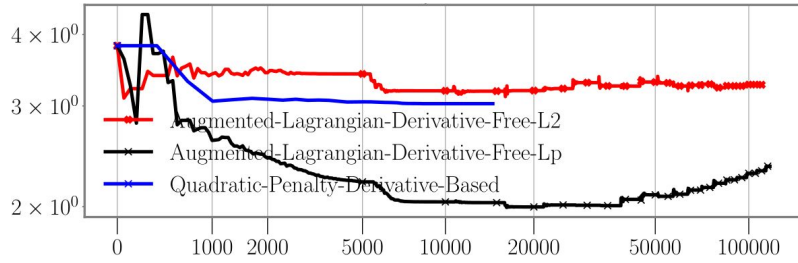
# Multi-objective: We want to meet all constraints while improving coil simplicity and compactness



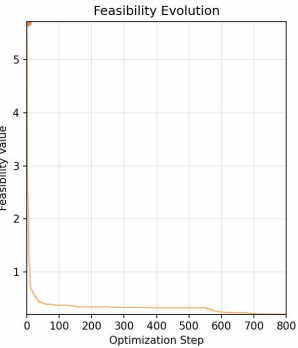
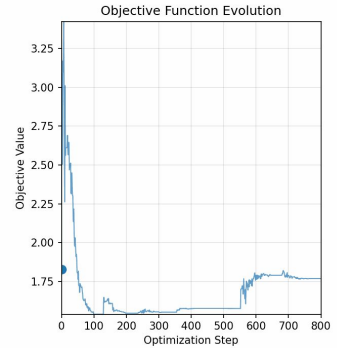
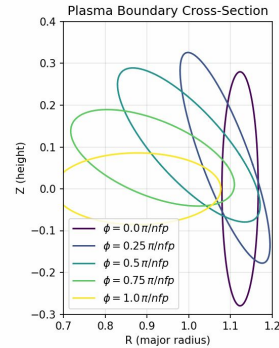
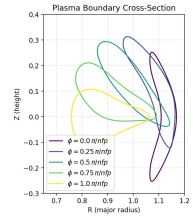
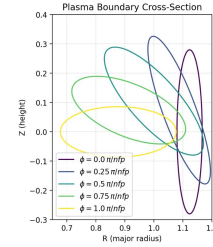
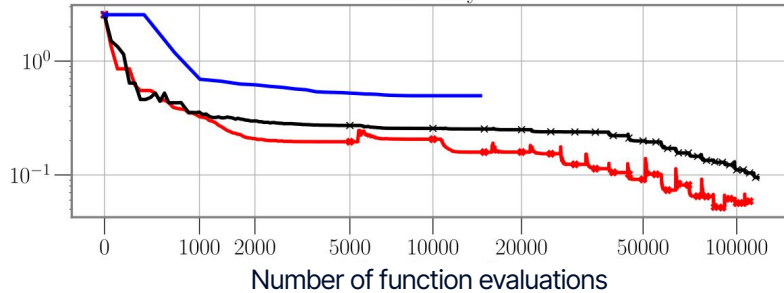
# Optimization Baselines

# We generated baselines with the Augmented Lagrangian Method using gradient-free evolutionary strategies

Objective ( $\uparrow$ )



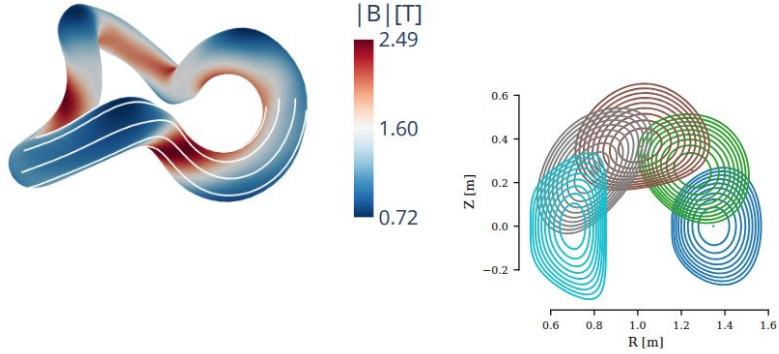
Constraint violation ( $\downarrow$ )



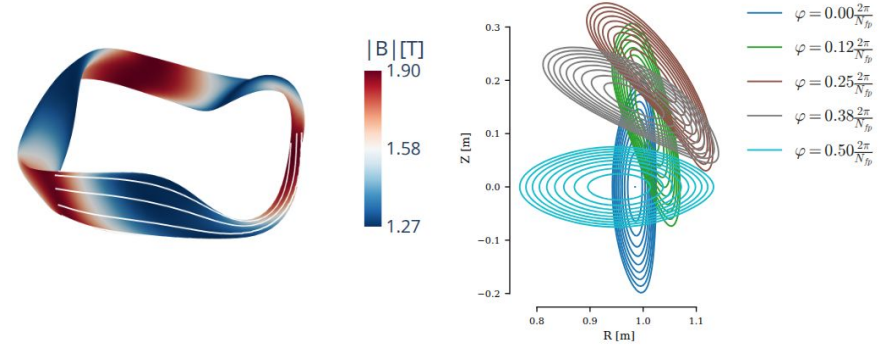
[https://github.com/proximafusion/constellation/tree/main/optimization\\_examples](https://github.com/proximafusion/constellation/tree/main/optimization_examples)

# Baseline results

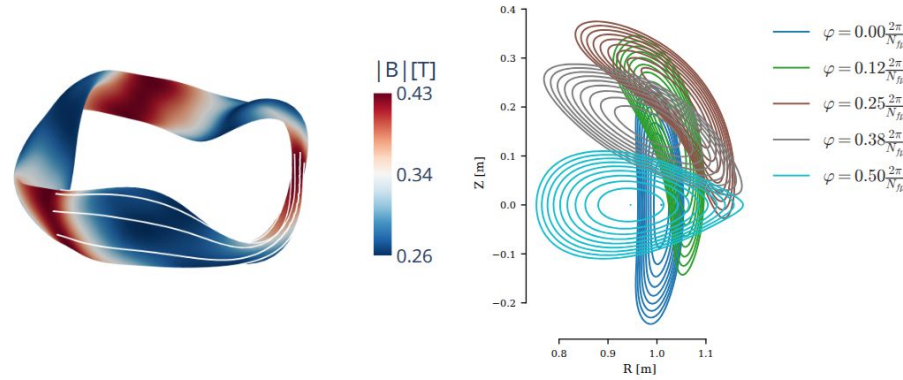
## Geometric Problem



## Simple to build QI



## MHD stable QI



# Our baselines have already been beaten 🎉!

## *Simple-to-build QI design*

submission time	problem type	user	score	full results
2025-09-02T10:31:19.976883	simple_to_build	<a href="#">DMCXE</a>	0.49853602632198885	<a href="#">link</a>
2025-08-14T09:57:47.488429	simple_to_build	<a href="#">NianRan1</a>	0.4367098218770565	<a href="#">link</a>
2025-08-14T09:59:30.532373	simple_to_build	<a href="#">NianRan1</a>	0.4367098218770565	<a href="#">link</a>
2025-07-01T19:59:48.038381	simple_to_build	<a href="#">scadena-pf</a>	0.4307230550411947	<a href="#">link</a>

## *Multi-objective MHD stable designs*

submission time	problem type	user	score	full results
2025-08-12T09:00:48.480632	mhd_stable	<a href="#">NianRan1</a>	103.02479639835846	<a href="#">link</a>
2025-07-02T07:38:21.817193	mhd_stable	<a href="#">scadena-pf</a>	129.796069251409	<a href="#">link</a>
2025-08-12T07:53:37.758128	mhd_stable	<a href="#">NianRan1</a>	133.50051029413004	<a href="#">link</a>

# Conclusions

# Conclusions

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- Effective stellarator optimization involves scientific and engineering targets and trade-offs.
- We believe that a larger community can contribute to the problem of stellarator optimization.
- We open sourced tools, data, and benchmarks to enable people to contribute better approaches.
- We have an open leaderboard to track progress



# Thank you!

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Clean energy, for good

