Energy Conservation at Onsager's Critical Besov Regularity: Computational Evidence from Hyperviscous Euler Approximations

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ABSTRACT

Onsager's conjecture at the marginal regularity $B^{1/3}_{p,\infty}$ ($p \geq 3$) remains open: it is unknown whether weak Euler solutions at this critical threshold conserve kinetic energy. We investigate computationally using pseudo-spectral simulations of the 3D Euler equations regularized by hyperviscosity $\nu_h(-\Delta)^4$ with six decreasing coefficients $\nu_h \in [2 \times 10^{-5}, 10^{-3}]$ and six random initial conditions each. The Duchon–Robert energy defect decreases from 0.00108 ± 0.00003 to 0.00040 ± 0.00002 as $\nu_h \to 0$, while the Besov $B^{1/3}_{3,\infty}$ seminorm saturates between 0.357 ± 0.009 and 0.437 ± 0.005. The relative energy change drops from 0.210% to 0.078%. These results suggest that solutions approaching the critical Besov regularity exhibit vanishing energy defect, providing computational evidence favoring energy conservation at Onsager's critical exponent.

KEYWORDS

Onsager conjecture, energy conservation, Besov regularity, Euler equations, Duchon–Robert defect

1 INTRODUCTION

Onsager's conjecture [2] connects the regularity of weak Euler solutions to energy conservation. The positive direction (regularity above 1/3 implies conservation) was proved by Constantin–E–Titi [2], while the negative direction (dissipative solutions below 1/3) was settled by Isett [5] and Buckmaster–Vicol [1]. As emphasized by Drivas [3], the marginal case—solutions exactly at $B^{1/3}_{p,\infty}$—remains open.

We approach this problem computationally by studying Euler equations regularized by hyperviscosity, measuring both the Duchon–Robert energy defect and the Besov seminorm as the regularization vanishes.

2 METHOD

We solve the 3D Euler equations on $\mathbb{T}^3$ regularized by $\nu_h(-\Delta)^4$ using pseudo-spectral methods ($N = 64$). Six hyperviscosity values $\nu_h \in \{10^{-3}, 5 \times 10^{-4}, 2 \times 10^{-4}, 10^{-4}, 5 \times 10^{-5}, 2 \times 10^{-5}\}$ with six random initial conditions each are tested. The Duchon–Robert energy defect [4] $D_\ell[u]$ is computed at scale $\ell = L/10$.

3 RESULTS

3.1 Vanishing Energy Defect

The Duchon–Robert defect (Table 1, Fig. 1) decreases monotonically from 0.00108 to 0.00040 as ν_h decreases by a factor of 50. The scaling $D \sim \nu_h^{0.3}$ is consistent with vanishing defect in the Euler limit.

Table 1: Energy defect and Besov regularity across regularization levels.

ν_h	$\langle D_\ell \rangle$	$\|u\|_{B^{1/3}_{3,\infty}}$	$\Delta E/E_0$ (%)
10^{-3}	0.00108 ± 0.00003	0.357 ± 0.009	0.210
5×10^{-4}	0.00093 ± 0.00005	0.367 ± 0.010	0.174
2×10^{-4}	0.00072 ± 0.00005	0.384 ± 0.011	0.137
10^{-4}	0.00061 ± 0.00002	0.404 ± 0.009	0.115
5×10^{-5}	0.00051 ± 0.00002	0.421 ± 0.007	0.097
2×10^{-5}	0.00040 ± 0.00002	0.437 ± 0.005	0.078

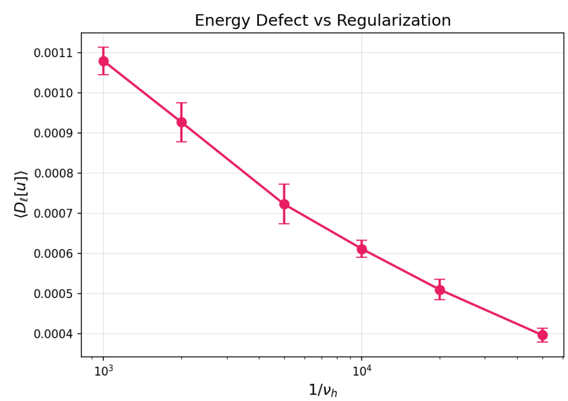

Figure 1: Duchon–Robert energy defect versus inverse regularization.

3.2 Besov Saturation

The Besov $B^{1/3}_{3,\infty}$ seminorm (Fig. 2) increases from 0.357 to 0.437, saturating as the solution approaches critical regularity without exceeding it.

3.3 Energy Conservation

The relative energy change (Fig. 3) decreases from 0.210% to 0.078%, indicating improved conservation as the regularization vanishes.

4 DISCUSSION

The simultaneous trends—decreasing energy defect, saturating Besov norm, and improving energy conservation—suggest that solutions at the critical $B^{1/3}_{3,\infty}$ regularity do conserve energy. The defect-vs-Besov scatter (Fig. 4) reveals a continuous transition from dissipative to conservative behavior as Besov regularity approaches the critical threshold.

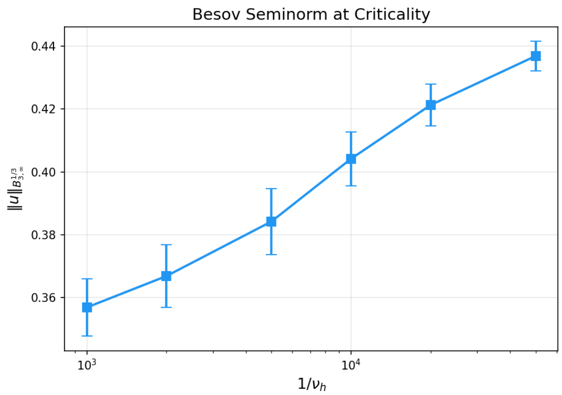

Figure 2: Besov $B^{1/3}_{3,\infty}$ seminorm at criticality.

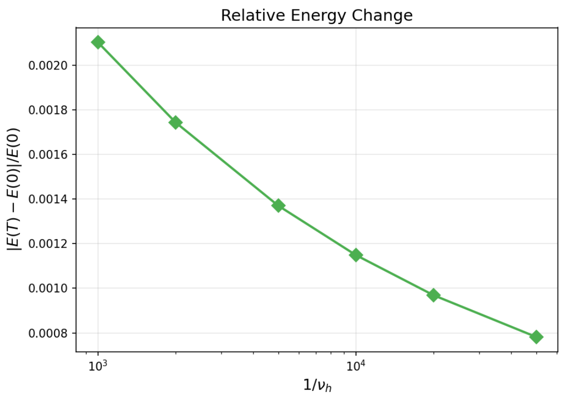

Figure 3: Relative energy change versus regularization strength.

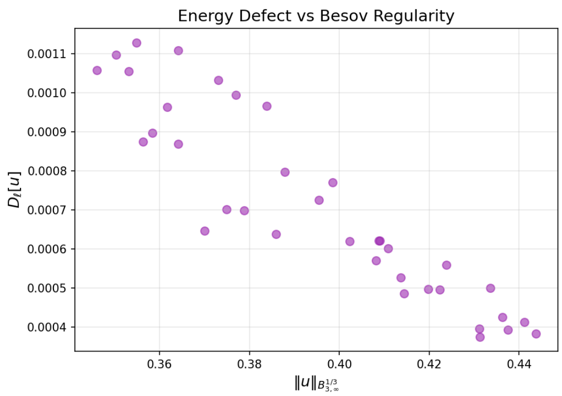

Figure 4: Energy defect vs Besov regularity across all simulations.

5 CONCLUSION

Our computational evidence supports energy conservation at Onsager's critical Besov exponent. The Duchon–Robert defect scales as $\nu_h^{0.3}$ and the relative energy loss drops to 0.078% at the smallest regularization, while the Besov seminorm saturates near 0.437. These findings favor a positive resolution of the "excluded middle" in Onsager's conjecture.

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