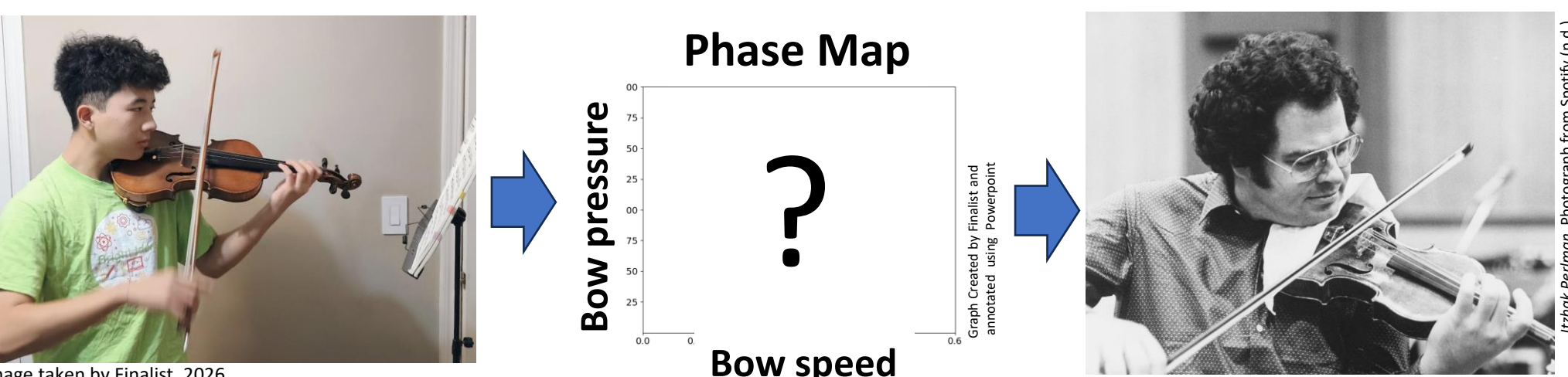


Motivation: How can I play more expressively?



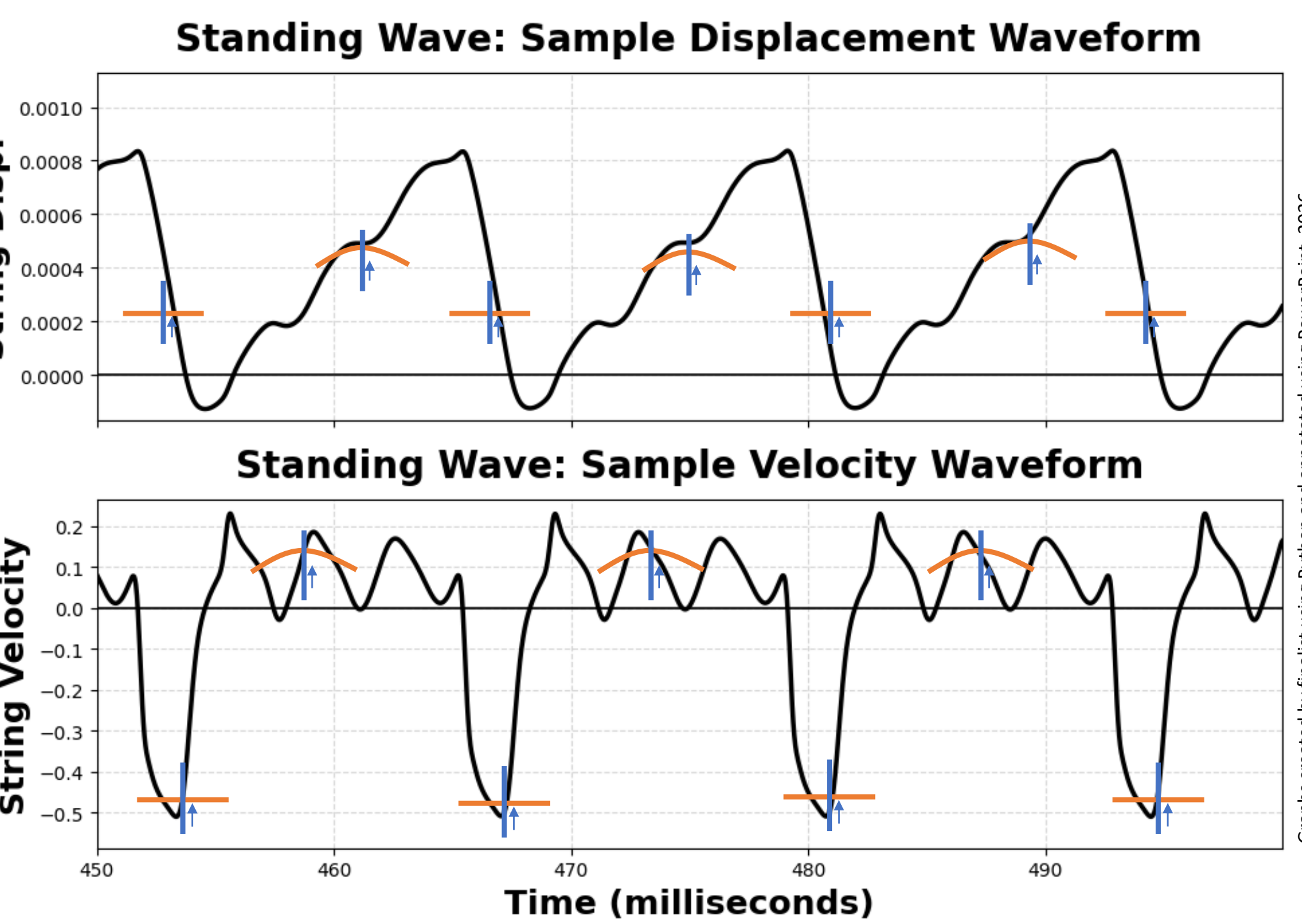
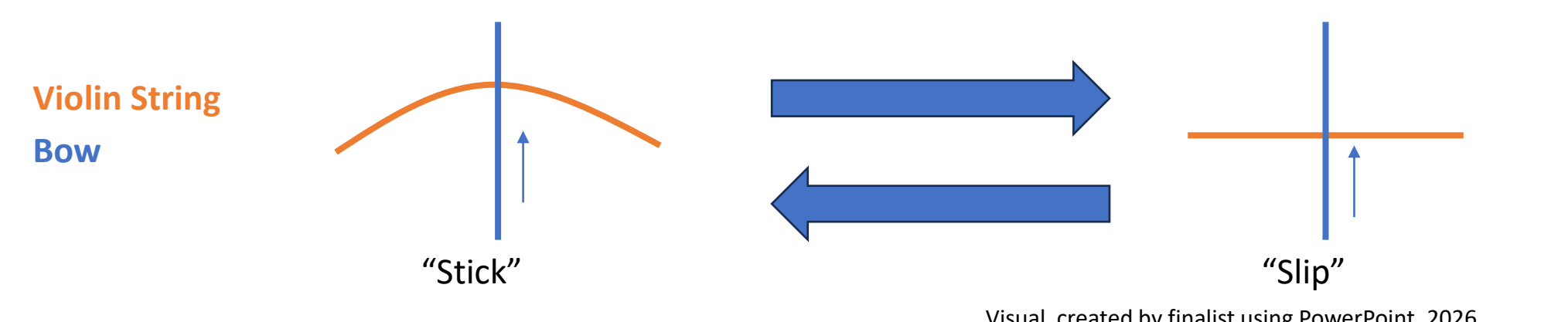
- What does my violin teacher mean when she encourages me to play more expressively?
- Emotion needs imperfection: A moving violin performance isn't perfectly smooth. It relies on slight roughness and changing tones.
- We know how violin strings work, and we know what sounds emotional, but we don't fully understand how the two connect.
- I use a computer model to study how pushing a violin's sound to the edge of stability creates the rich, emotional tones we hear.

Background

A. How does a violin make sound?

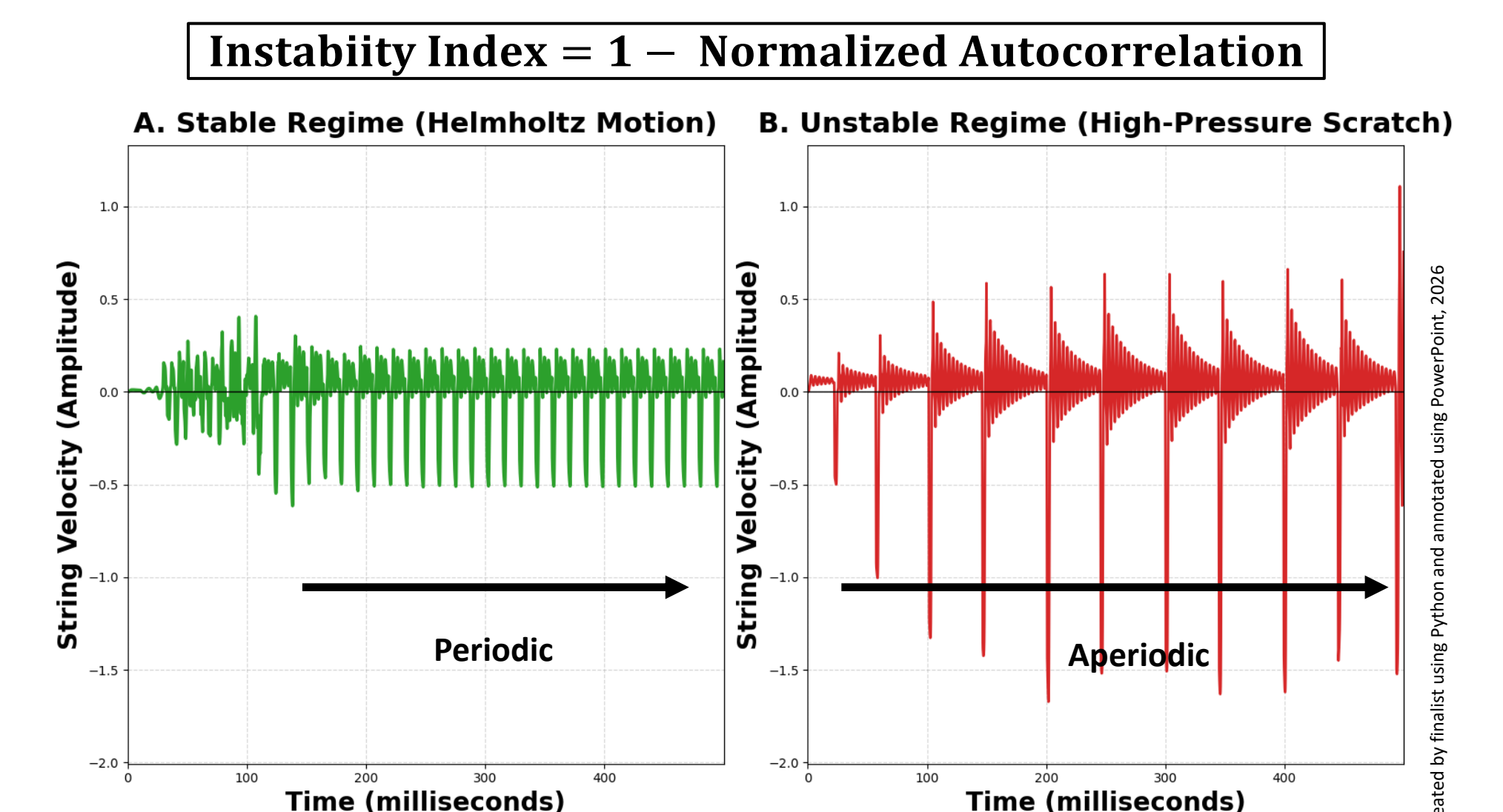
Def. Sound: a wave of pressure propagating throughout the air, triggered by a mechanical vibration

- Bow friction makes the violin string “stick” and “slip”
- This in turn creates a vibration in the string which propagates through the air.



B. What is stable playing?

- Stable regime: Smooth sound.
- Unstable Regime: Rough sound
- In my project I define an Instability Index



C. Expressivity Index: How can expressivity be quantified?

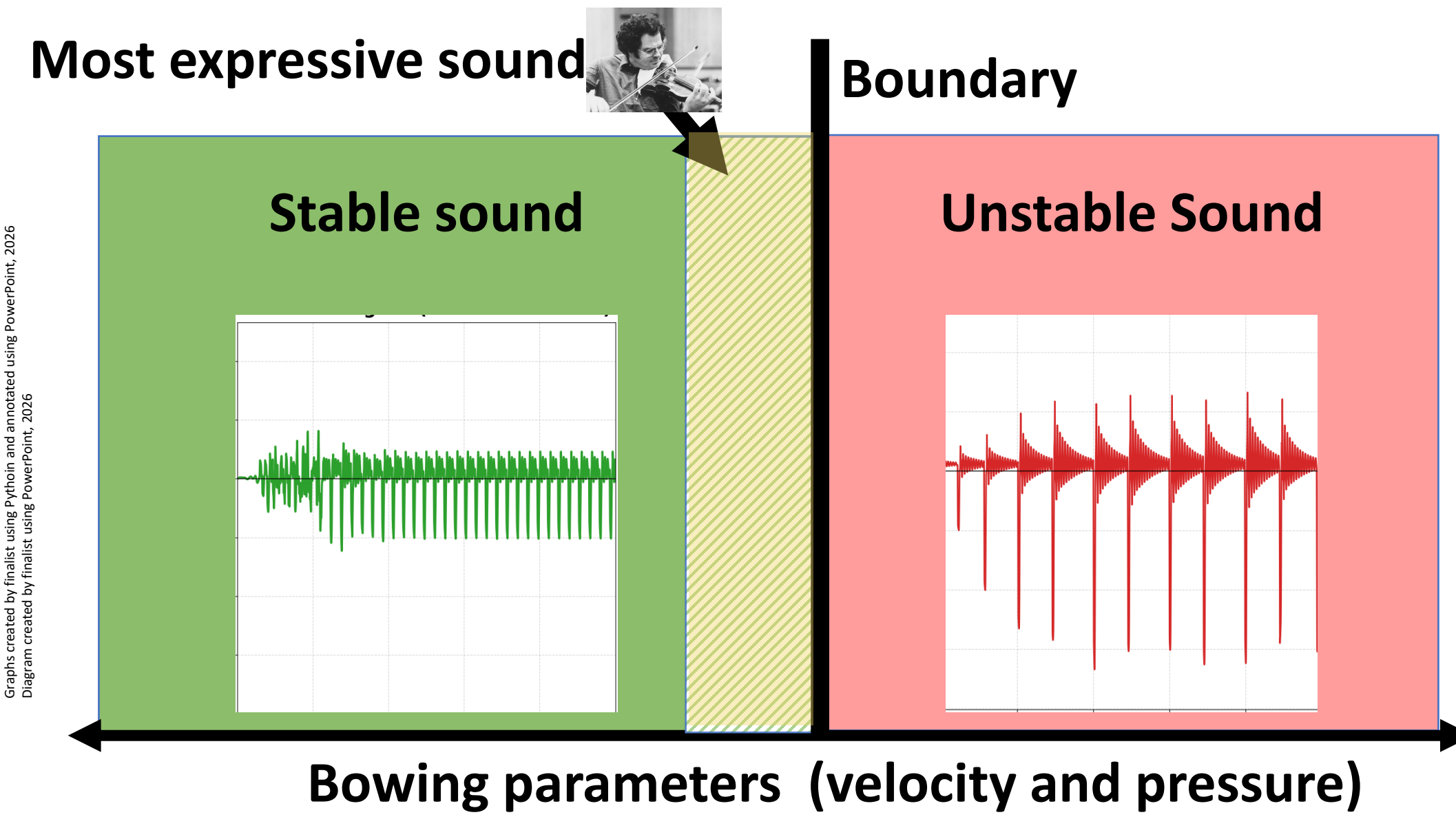
- Expressivity is what makes violin sound feel emotional or “alive” rather than mechanical, linked to “tone color” (timbre)
- Using metrics that describe a “soloistic” tone: “brightness”, “crunch”, and “texture”, I define an Expressivity Index:

Expressivity Index = “brightness” + “crunch” + “texture” – “energy penalty” – “harmonic penalty”

| Characteristic                           | Definition                                                |
|------------------------------------------|-----------------------------------------------------------|
| Brightness (Spectral Centroid)           | How much high frequency energy present (center of mass)   |
| Crunch (Harmonic Saturation)             | How much energy being pushed to higher overtones          |
| Texture (Microvariability)               | How many microscopic imperfections                        |
| Energy Penalty (Root Mean Square energy) | Penalizes little amplitude                                |
| Harmonic Penalty                         | Penalizes spectral energy lying outside of harmonic bands |

# Modeling Violin Expression: Timbral Dynamics at the Instability Boundary

Hypothesis: Expressivity Index Is Greatest Near Instability Boundary.



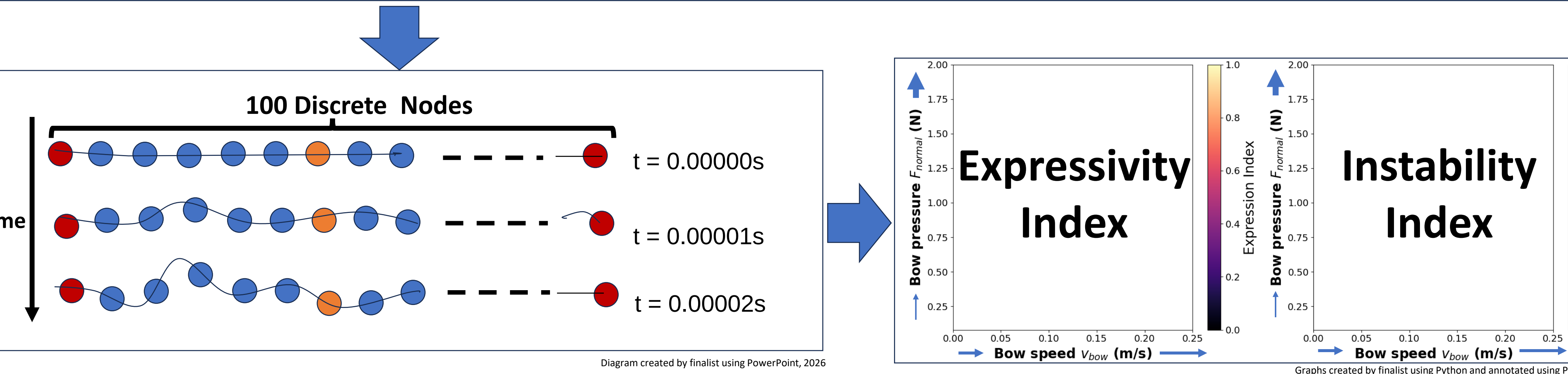
I hypothesize that the Expressivity Index is greatest near the boundary between stability and instability, where the sound is stable.

- Intuition: emotional violin performances aren't smooth!

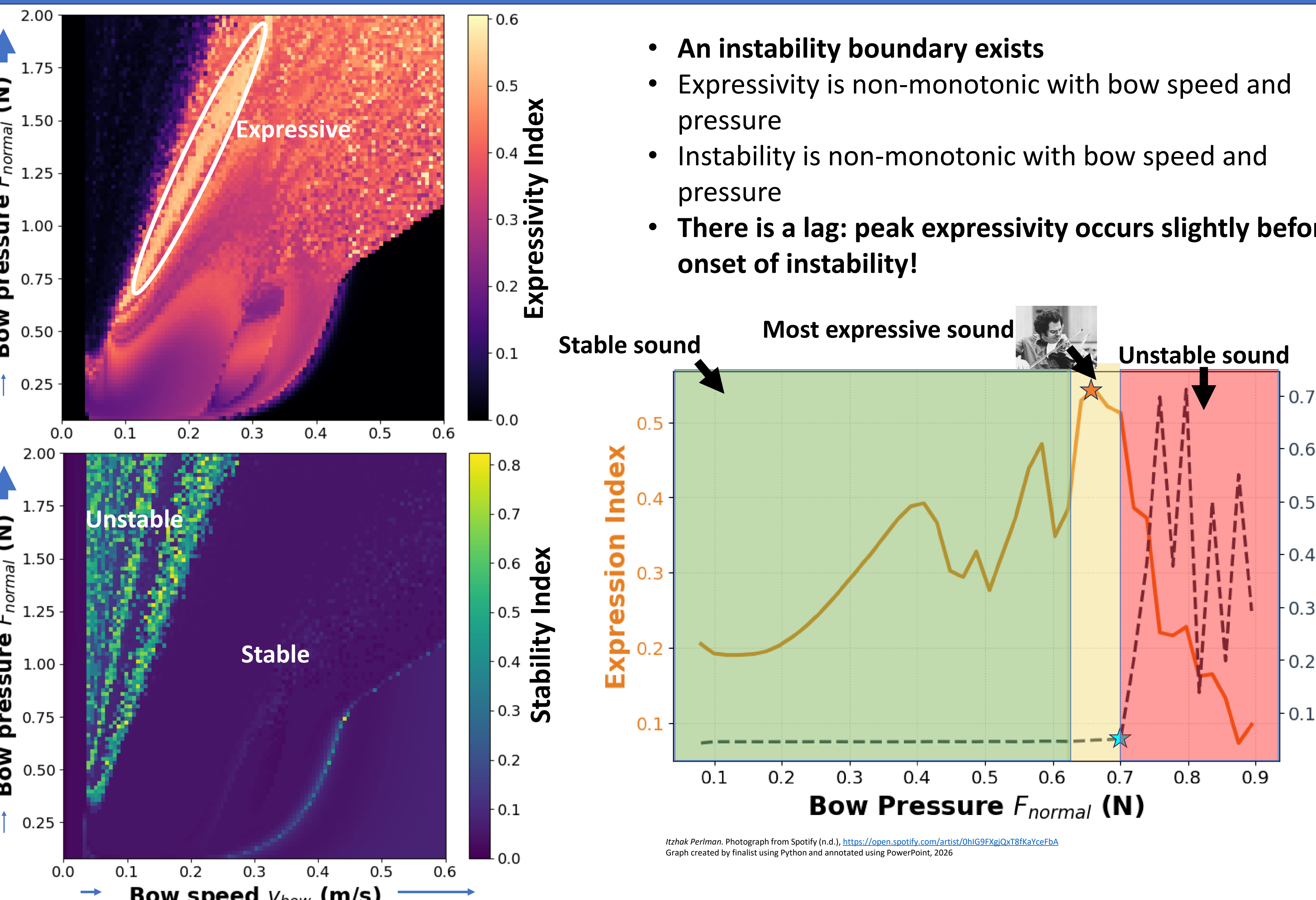
Model and Methods: Expressivity and Instability Index Values for a Simulated Violin Wave Equation

$$\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2} - \gamma \frac{\partial u}{\partial t} + \sigma \frac{\partial^3 u}{\partial t \partial x^2} + \frac{F_{bow}}{\rho} \delta(x - x_{bow})$$

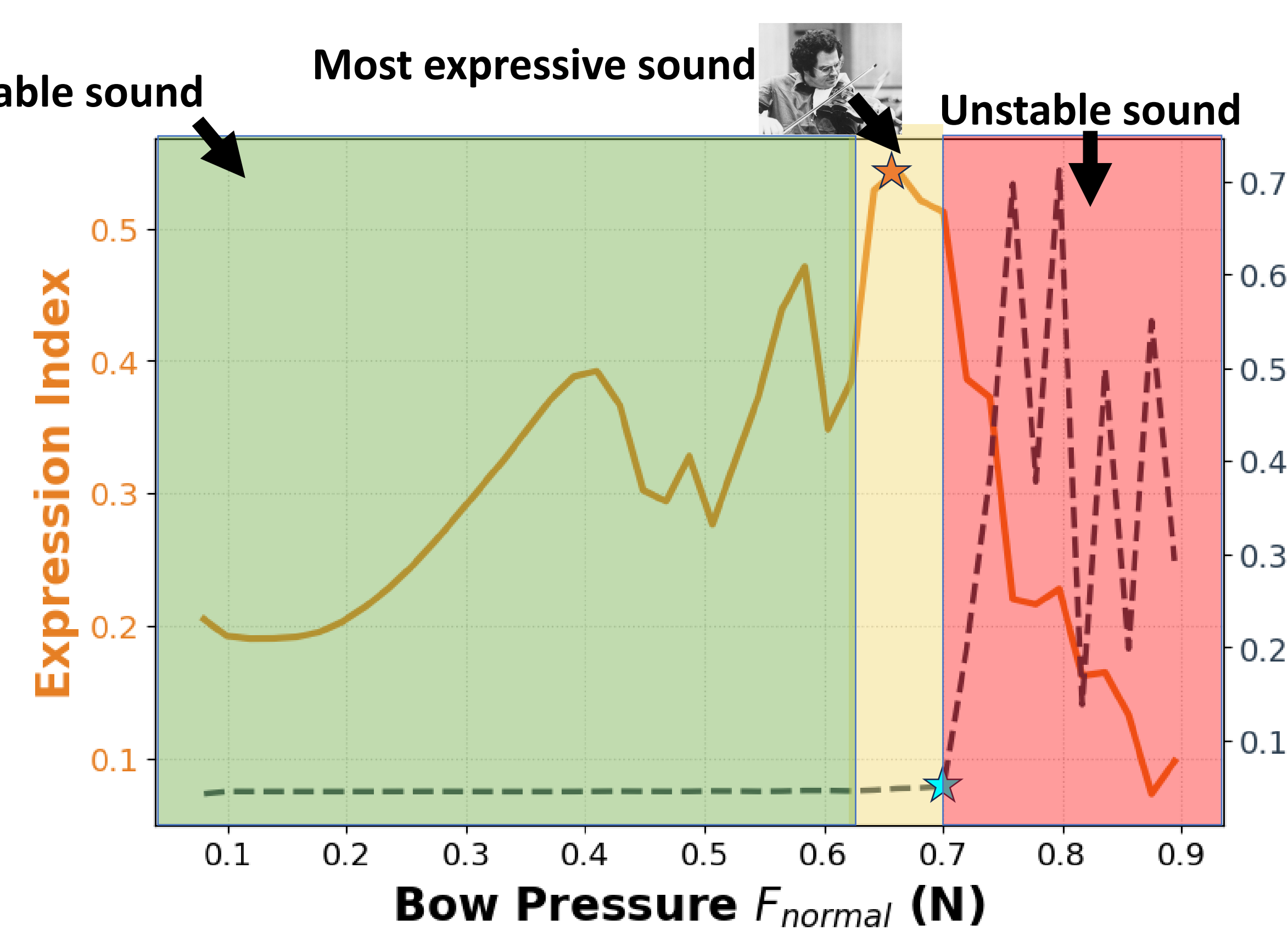
u: string displacement  
x: position  
t: time  
c: wave speed  
γ: damping coeff.  
σ: high-frequency damping coeff.  
F<sub>bow</sub>: bow force  
ρ: string linear density  
x<sub>bow</sub>: bow position  
δ: local force (Dirac delta funct.)



Results: Expressivity Index Peaks Near the Instability Boundary



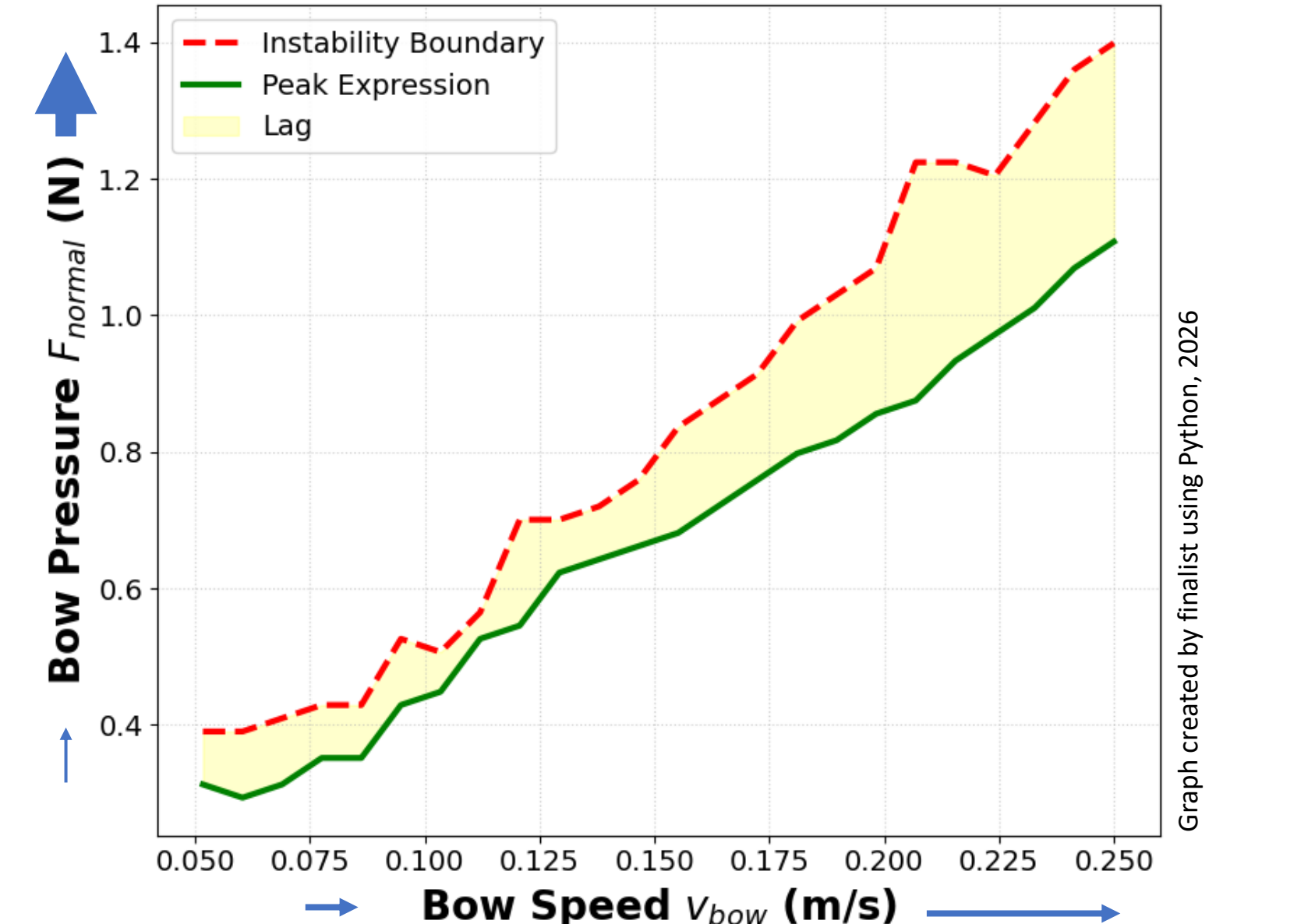
- An instability boundary exists
- Expressivity is non-monotonic with bow speed and pressure
- Instability is non-monotonic with bow speed and pressure
- There is a lag: peak expressivity occurs slightly before onset of instability!



Results: Optimal Bow Pressure Changes with Speed

Optimal Bow Speed and Pressure Grow Linearly

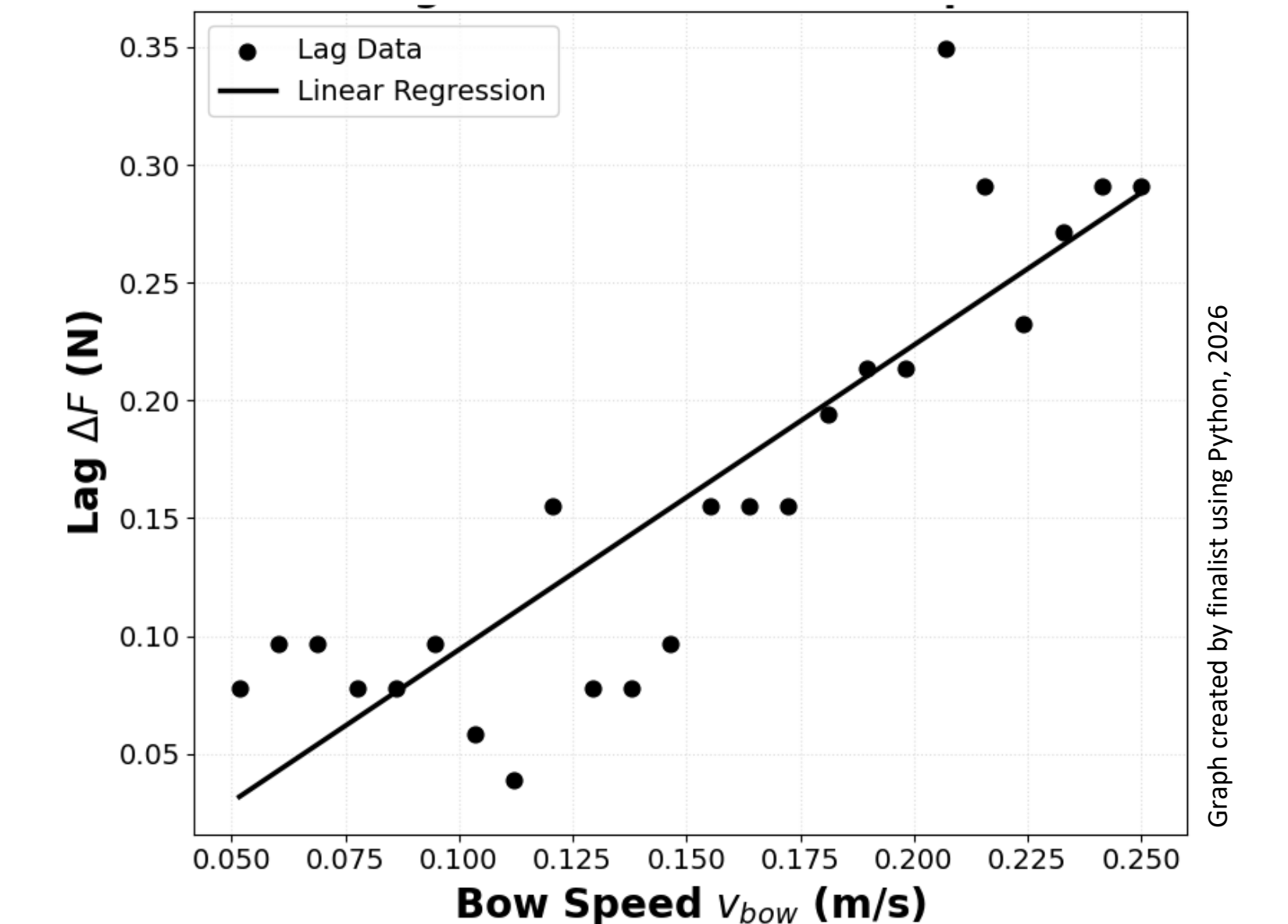
(r = 0.7372, p = 2.2325 × 10<sup>-18</sup>, m = 0.1115 [(m/s)/N])



- The optimal bow pressure changes linearly as bow speed increases, suggesting violinists need to adapt to play expressively
- Peak Expressivity Index always occurs before the instability boundary

Lag Between Peak Expressivity and Instability Boundary Increases with Bow Speed

(r = 0.8748, p = 2.27 × 10<sup>-8</sup>, m = 1.2931 [Ns/m])



- The lag between the peak Expressivity Index value and Instability Boundary increases for higher bow speeds
- This suggests a larger safe expressive playing zone for higher bow speeds

Discussion and Future Work

Why This Project?

- Quantifies violin Expressivity by linking bowing physics to sound stability and timbre.

Key Findings

- Expressivity peaks near and before stability boundaries
- Optimal bow pressure changes linearly with bow speed, suggesting violinists need to adapt to play expressively
- Higher bow speeds may have a larger safe expressive playing zones

Limitations

- Simplified model
- Expressiveness index is a proxy derived from the model, not a direct measure of human perception

Future Work

- Systematically validate the model's predictions using professional recordings
- Conduct a perception study to validate expressivity predictions
- Stiffness, vibrato, damped boundaries, torsional vibrations, moving bow position

## Applications: Quantifying Complex Behavior Near Stability Boundaries

- Index can be used as a biomarker for tipping point in ecology
- Neural activity is highest near a critical boundary
- Flow approaches a transition to turbulence

Key References

Bilbao, S. (2009). Numerical sound synthesis. John Wiley & Sons.

Body Resonators. (2025). Stanford University. [https://ccrma.stanford.edu/~jos/nmr/Body\\_Resonators.html](https://ccrma.stanford.edu/~jos/nmr/Body_Resonators.html)

Desvages, C. (2018). Physical modelling of the bowed string and applications to sound synthesis (Doctoral dissertation, University of Edinburgh). [https://www.acoustics.ed.ac.uk/wp-content/uploads/Theses/Desvages\\_Charlotte\\_PhDThesis\\_UniversityOfEdinburgh\\_2018.pdf](https://www.acoustics.ed.ac.uk/wp-content/uploads/Theses/Desvages_Charlotte_PhDThesis_UniversityOfEdinburgh_2018.pdf)

Finite Difference Method Python Numerical Methods. (n.d.). Python Numerical Methods. <https://pythonnumericalmethods.studentorg.berkeley.edu/notebooks/chapter23.03-Finite-Difference-Method.html>

Jing, Y., Wang, T., & Clement, G. T. (2012). A k-space method for moderately nonlinear wave propagation. IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 59(8), 1664–1673. <https://doi.org/10.1109/TUFFC.2012.2372>

McIntyre, M. E., Schumacher, R. T., & Woodhouse, J. (1983). On the oscillations of musical instruments. The Journal of the Acoustical Society of America, 74(5), 1325–1345. <https://doi.org/10.1121/1.390157>

Tzanetakis, G., & Cook, P. (2002). Musical genre classification of audio signals. IEEE Transactions on Speech and Audio Processing, 10(5), 293–302. <https://doi.org/10.1109/tsa.2002.800560>

Wolfe, J. (n.d.). Violin acoustics: An introduction. University of New South Wales. <https://www.phys.unsw.edu.au/jw/violintro.html>