ZoRo: a laboratory experiment to explore the effects of rotation, ellipticity and flows in planetary seismology

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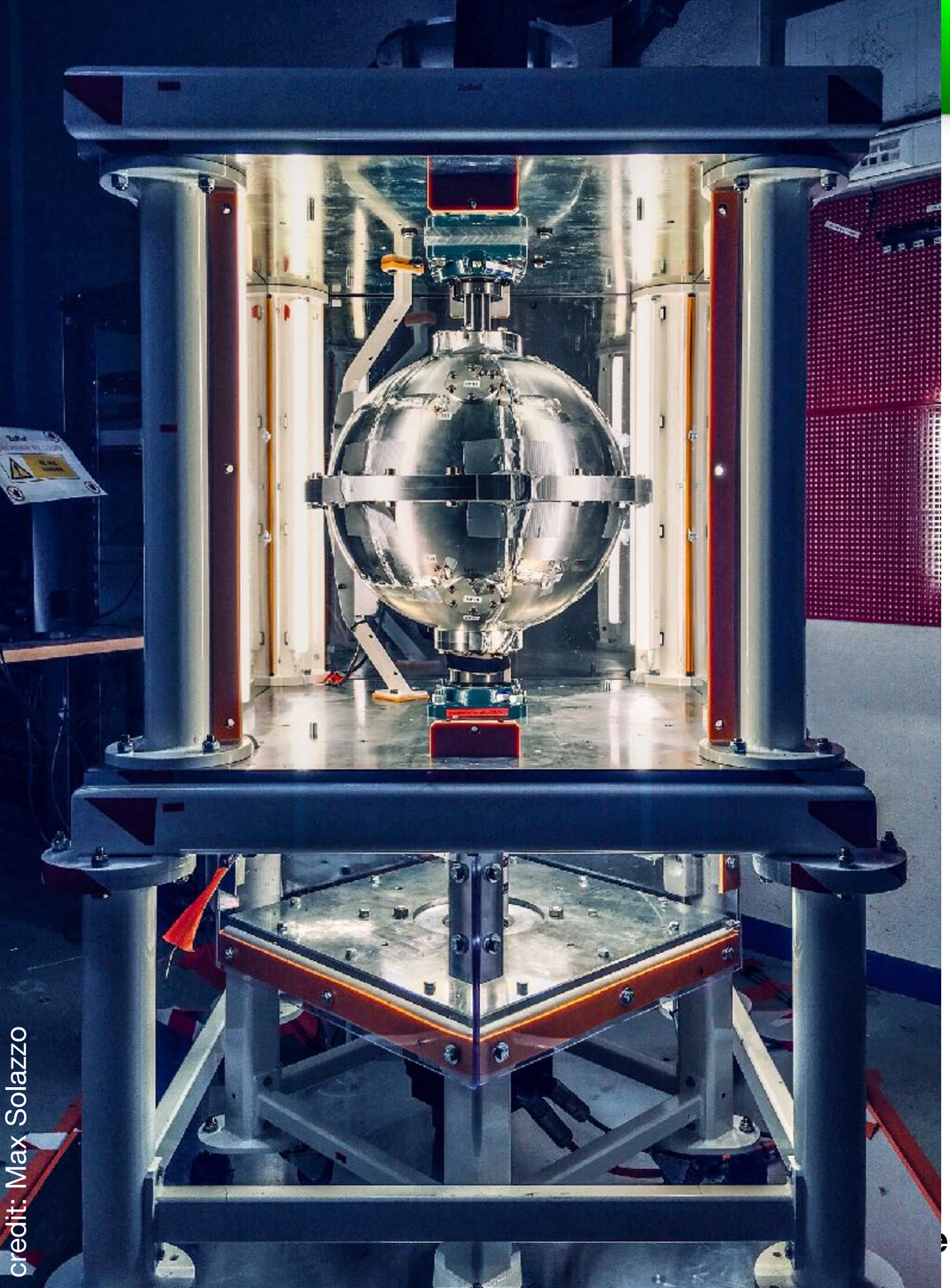
ISTerre, Univ. Grenoble Alpes, CNRS, Grenoble

Journées SF2A, June 23rd 2026

The ZoRo experiment



credit: Max Solazzo

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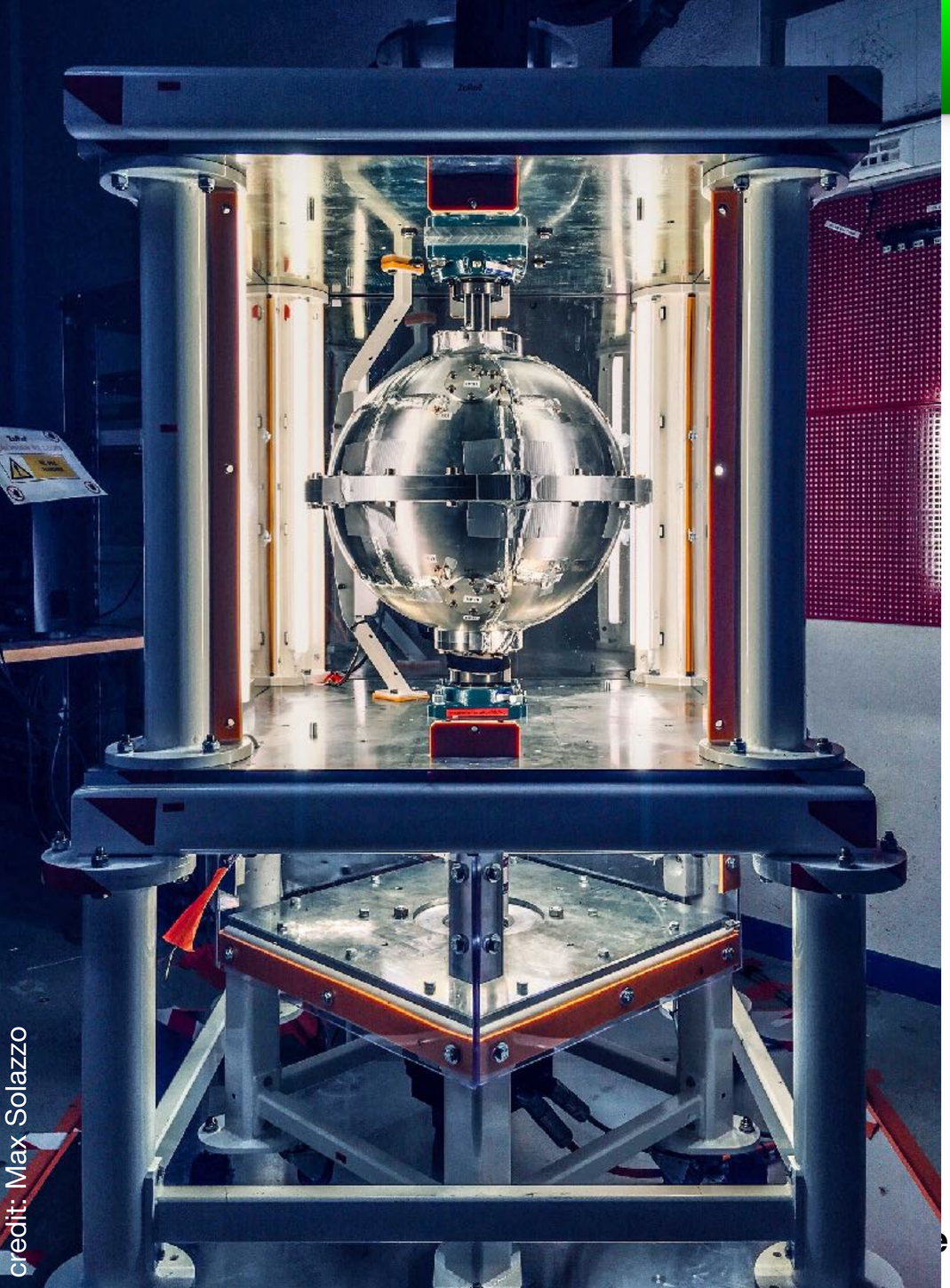

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A gas-filled rapidly rotating spheroid, equipped for acoustic diagnostics.

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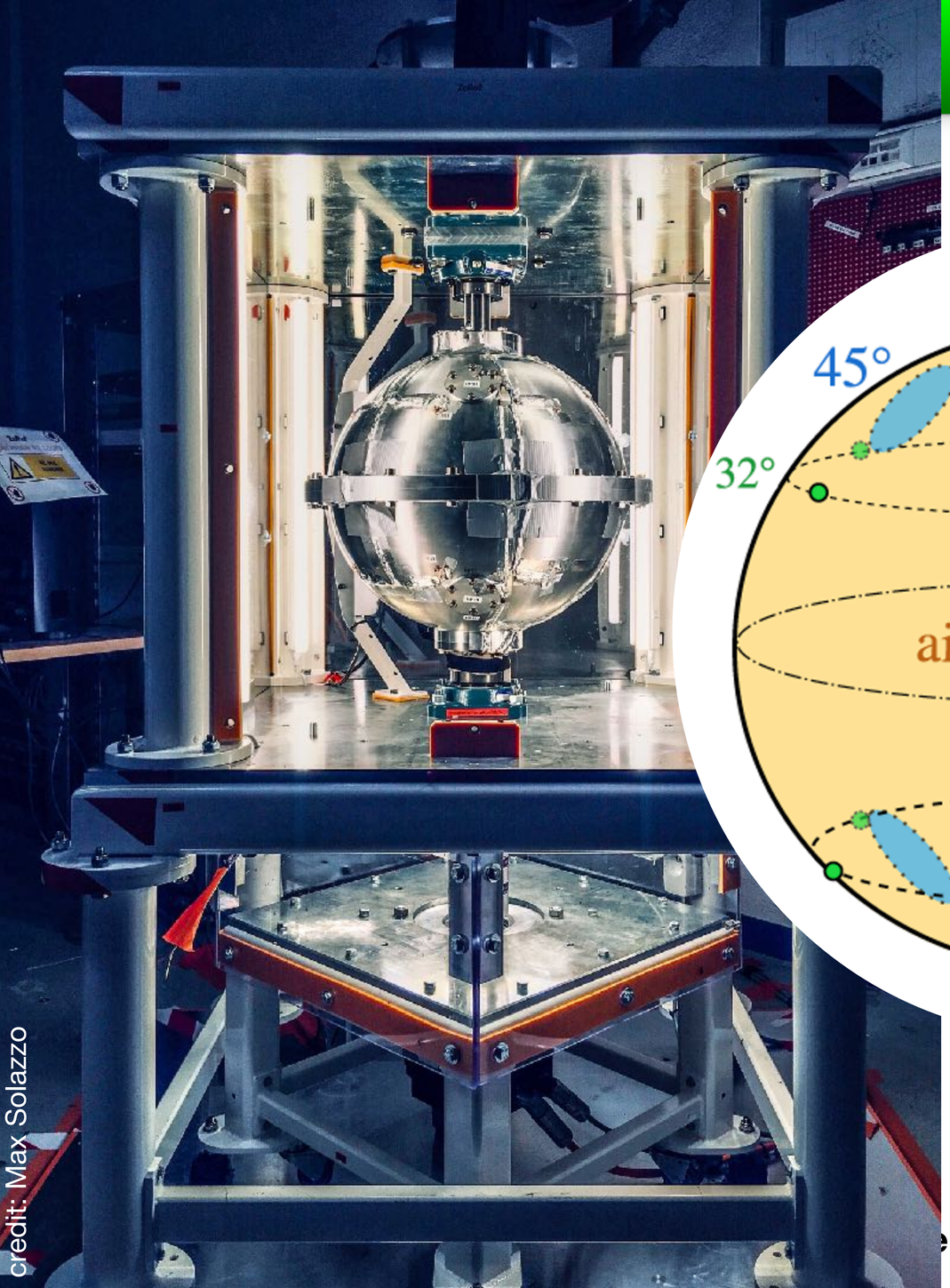

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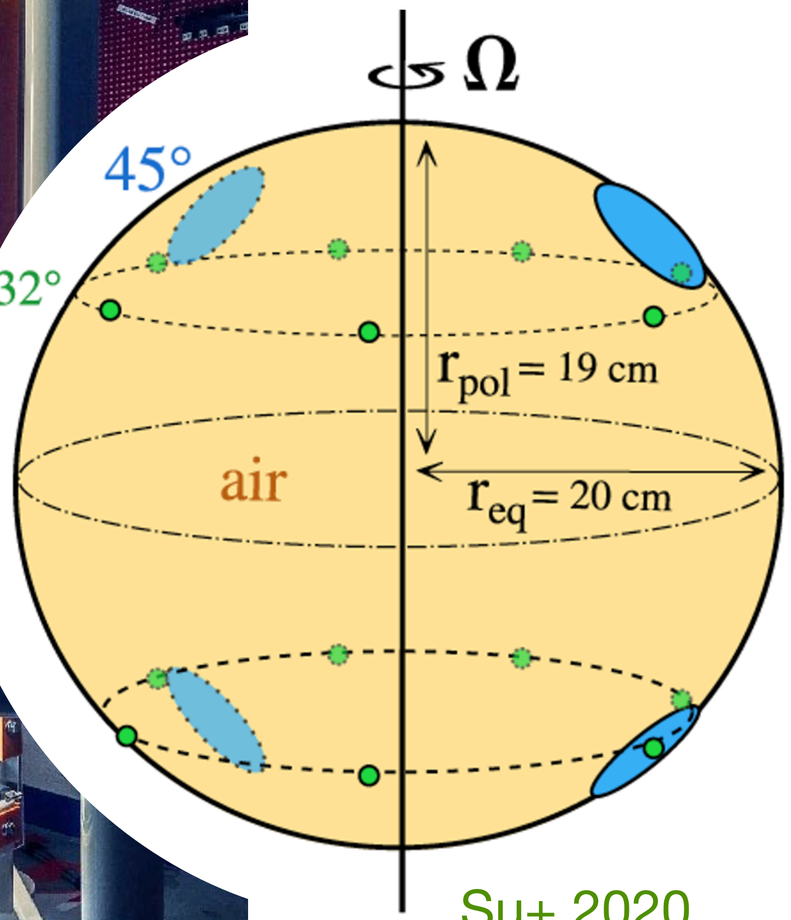

Su+ 2020

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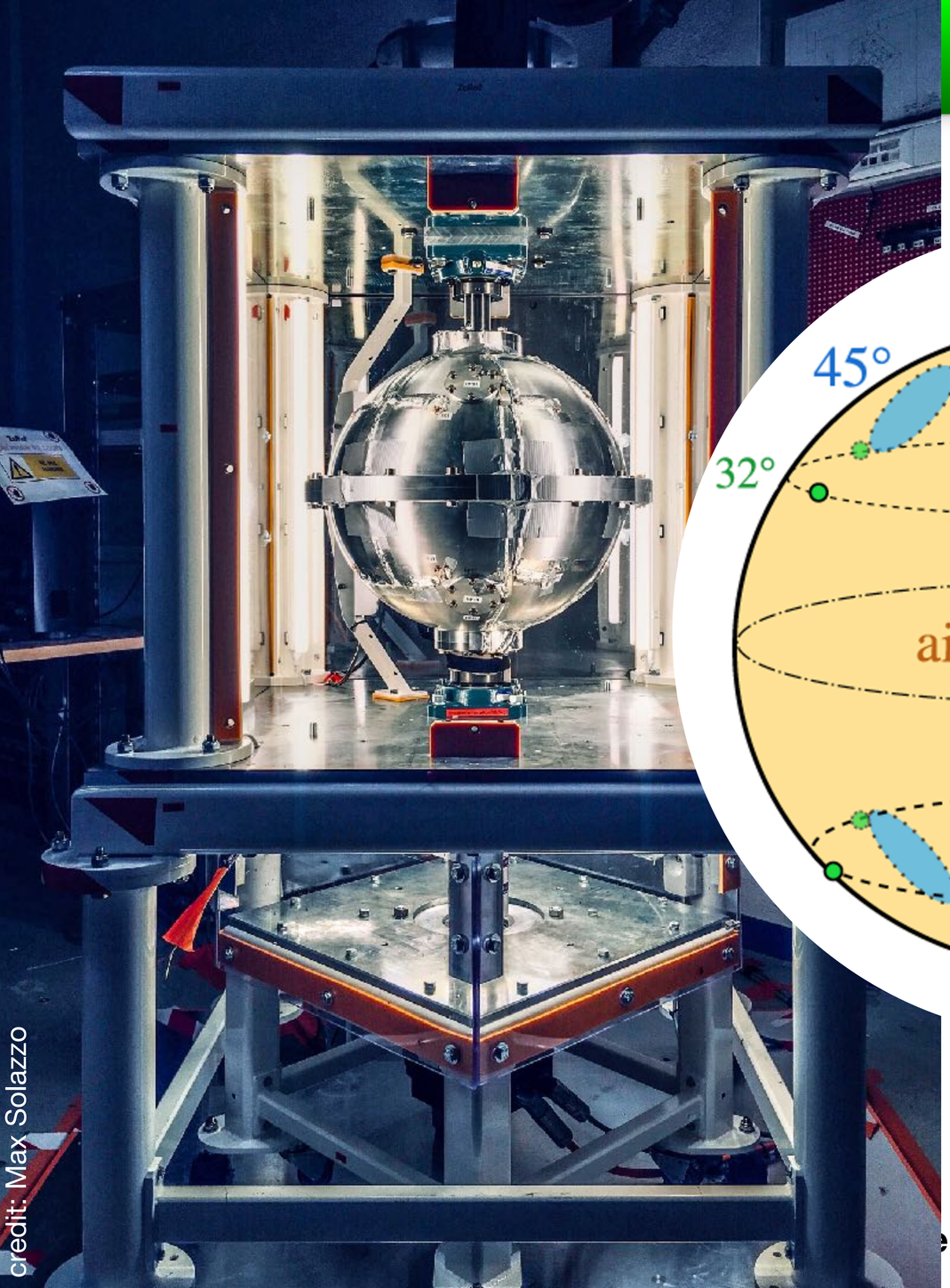

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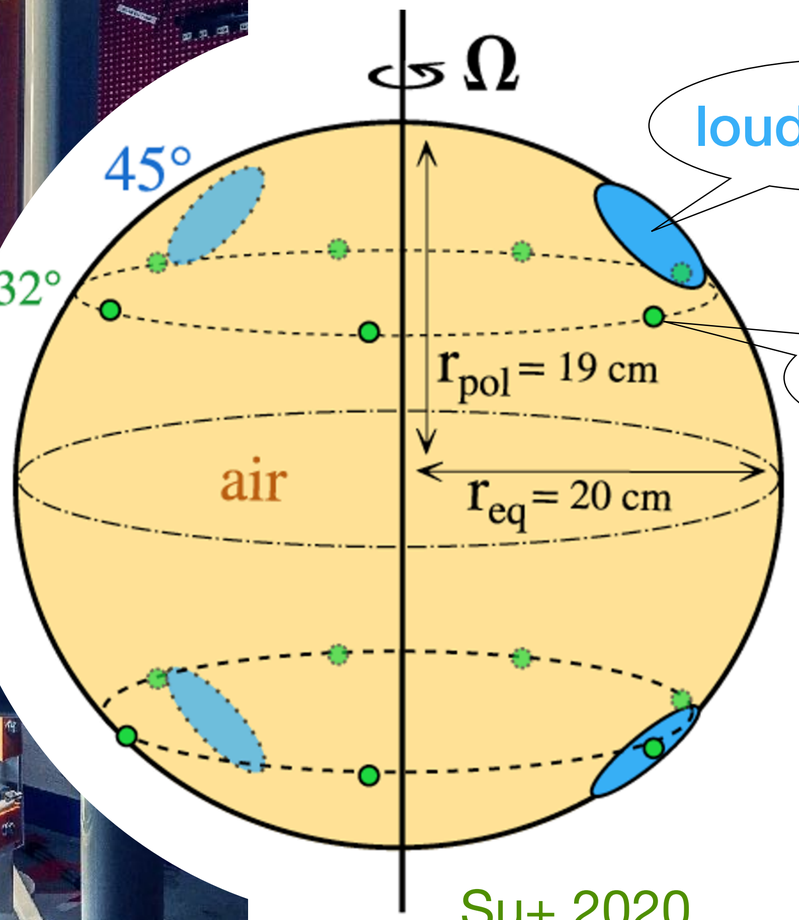

loudspeaker

microphone

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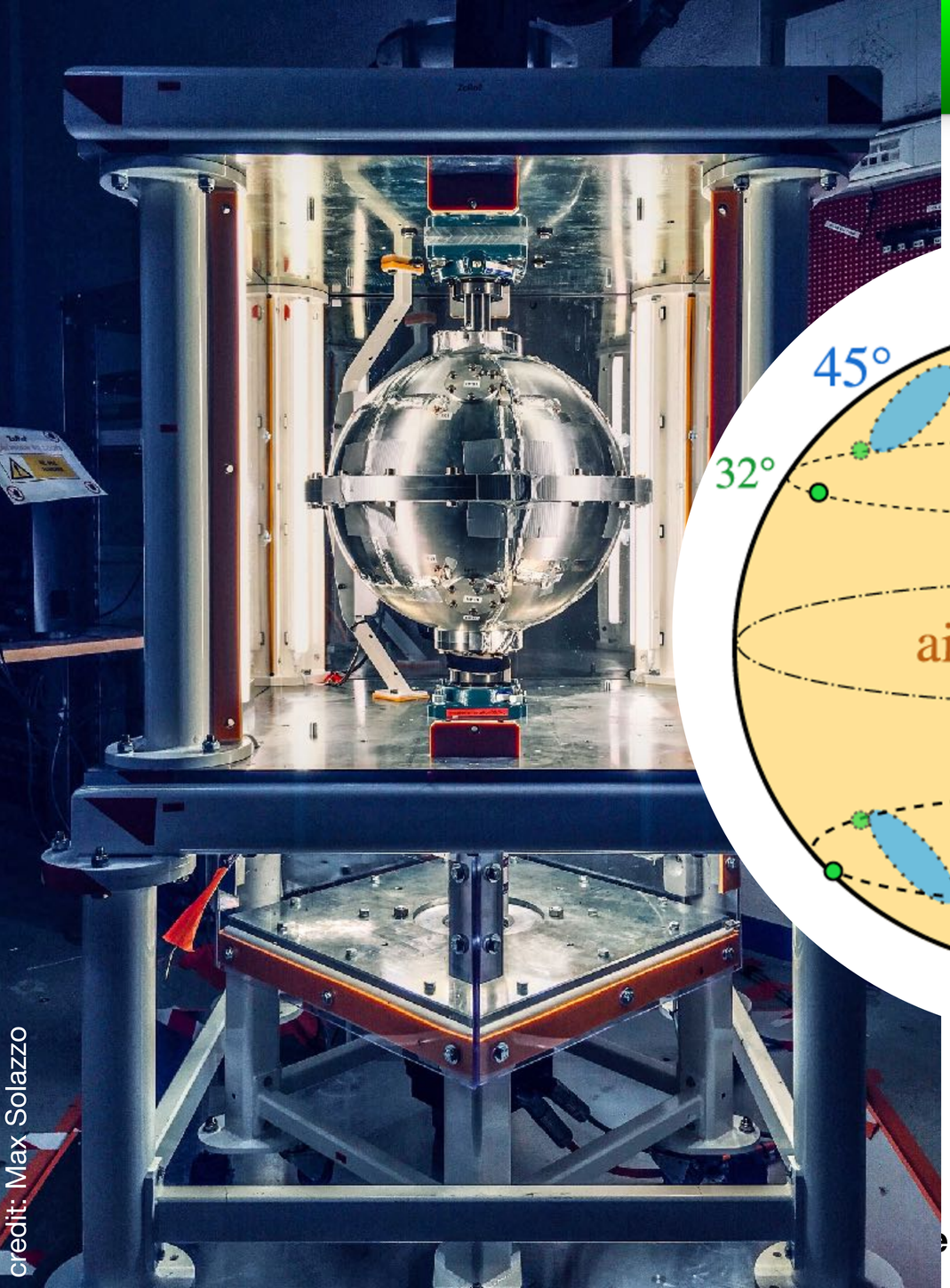

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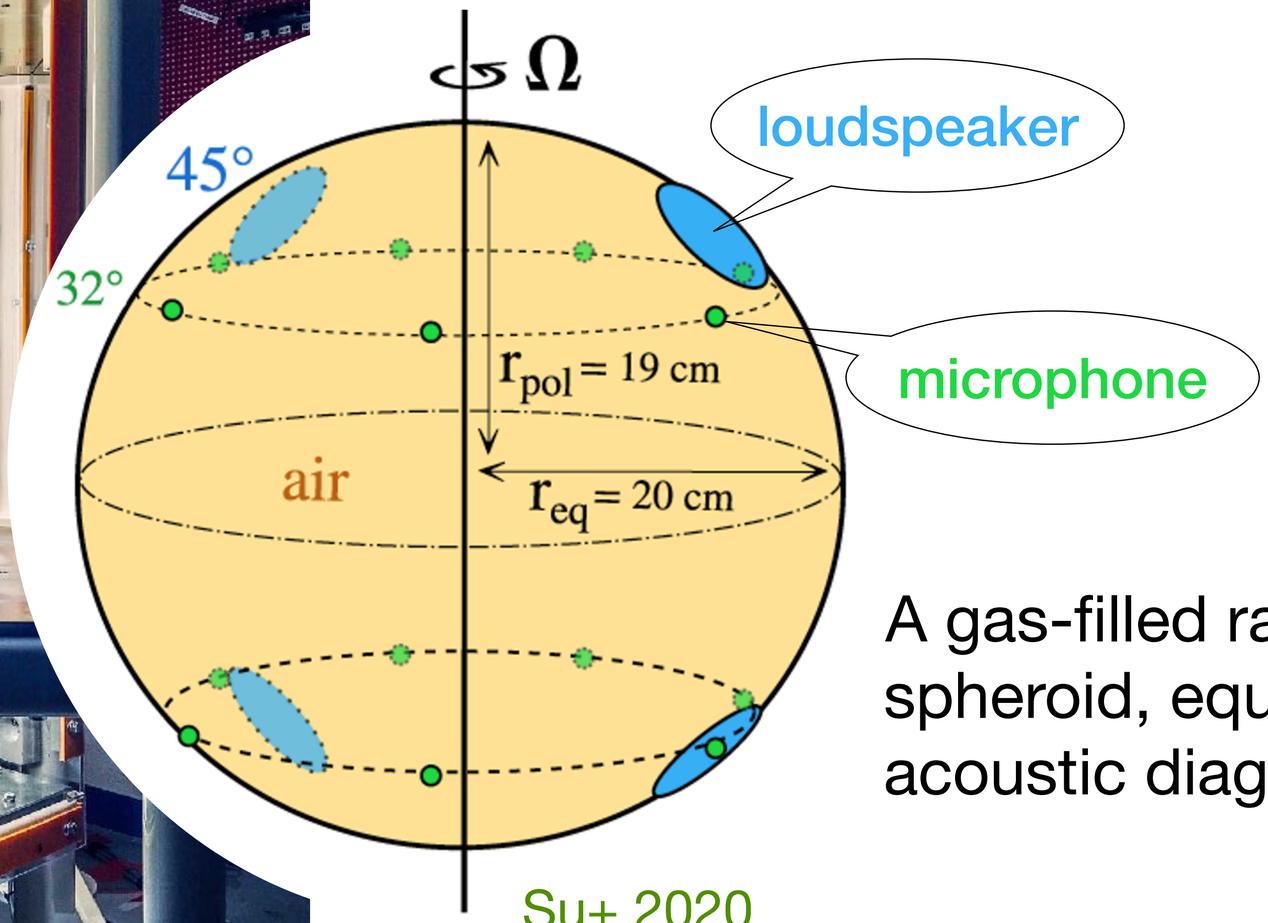

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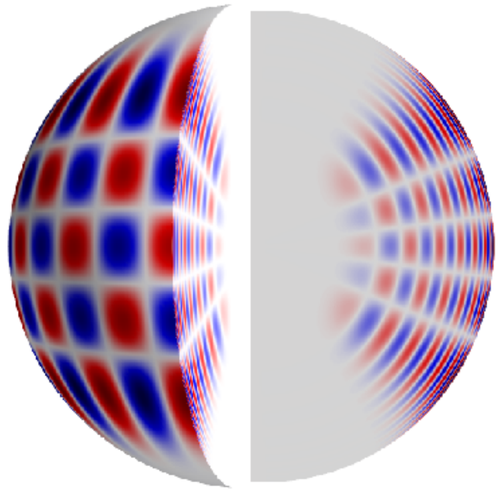

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Three examples

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2. Flow inversion: recovering Greenspan's libration flow.

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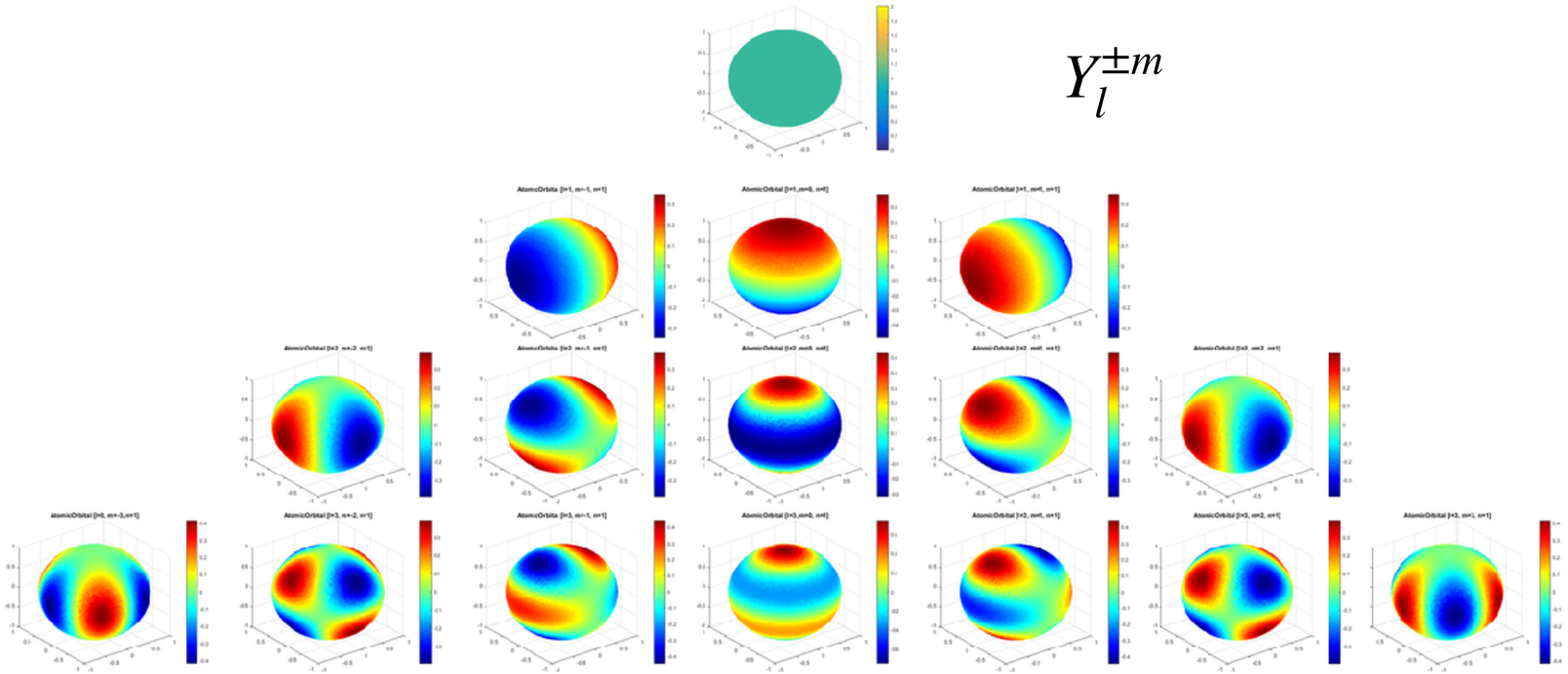

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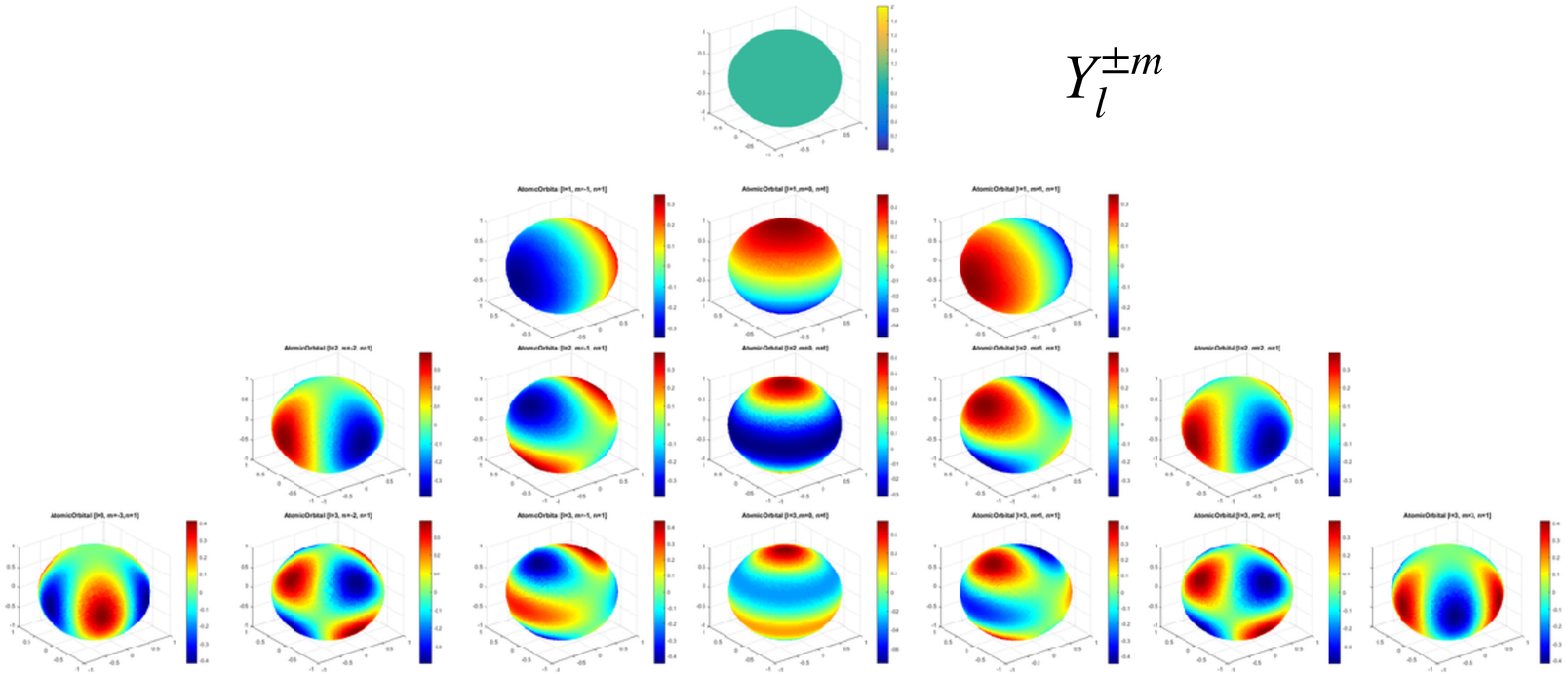

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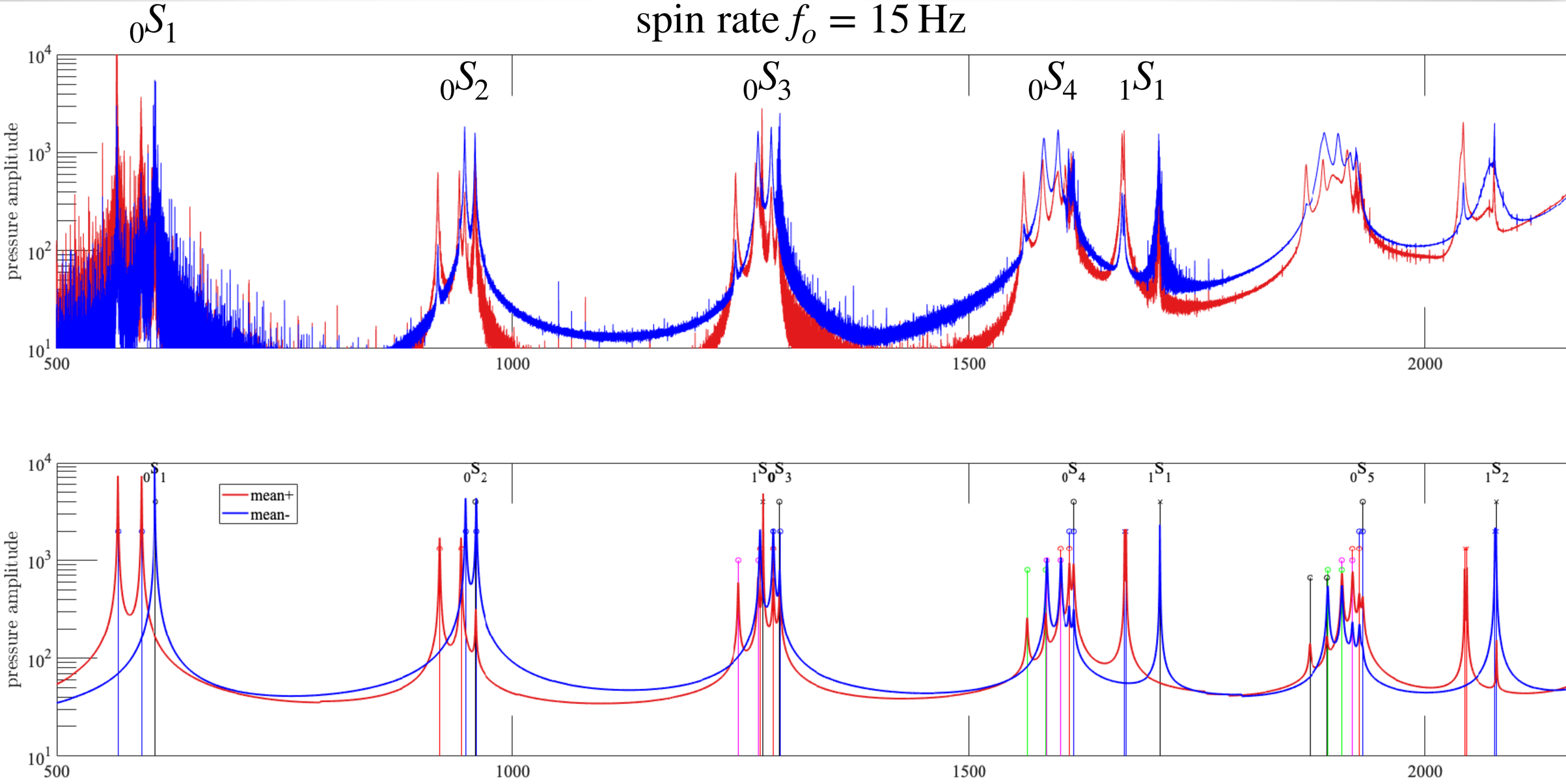
The music of ZoRo : measured and synthetic power spectra



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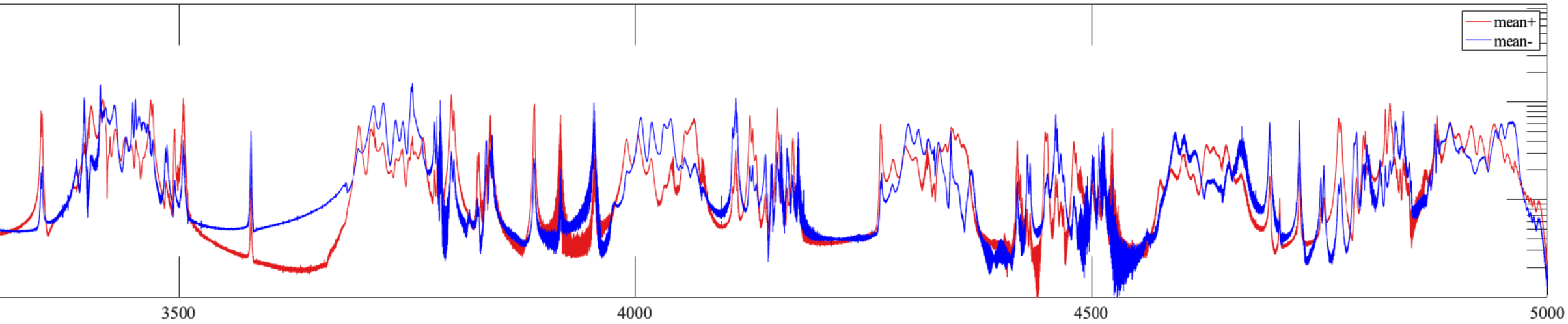
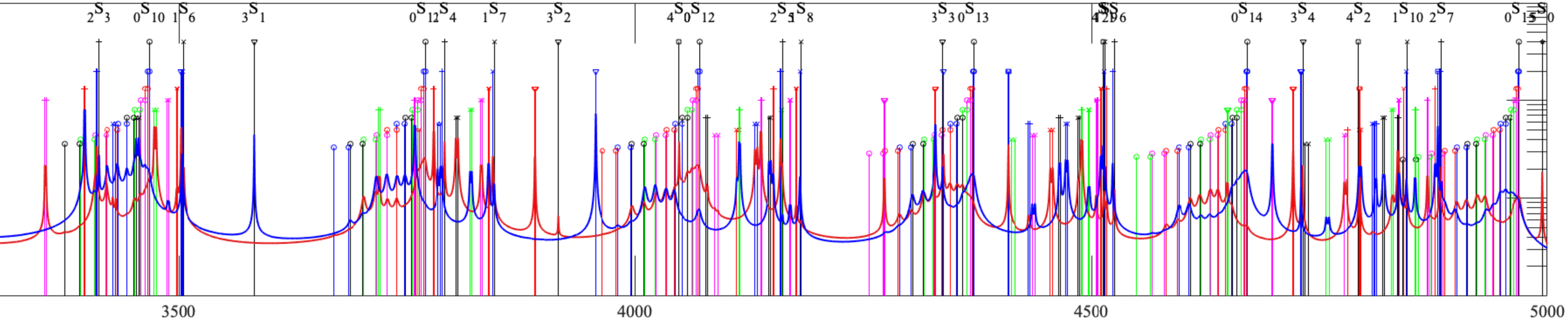
spin rate $f_o = 15\,\mathrm{Hz}$





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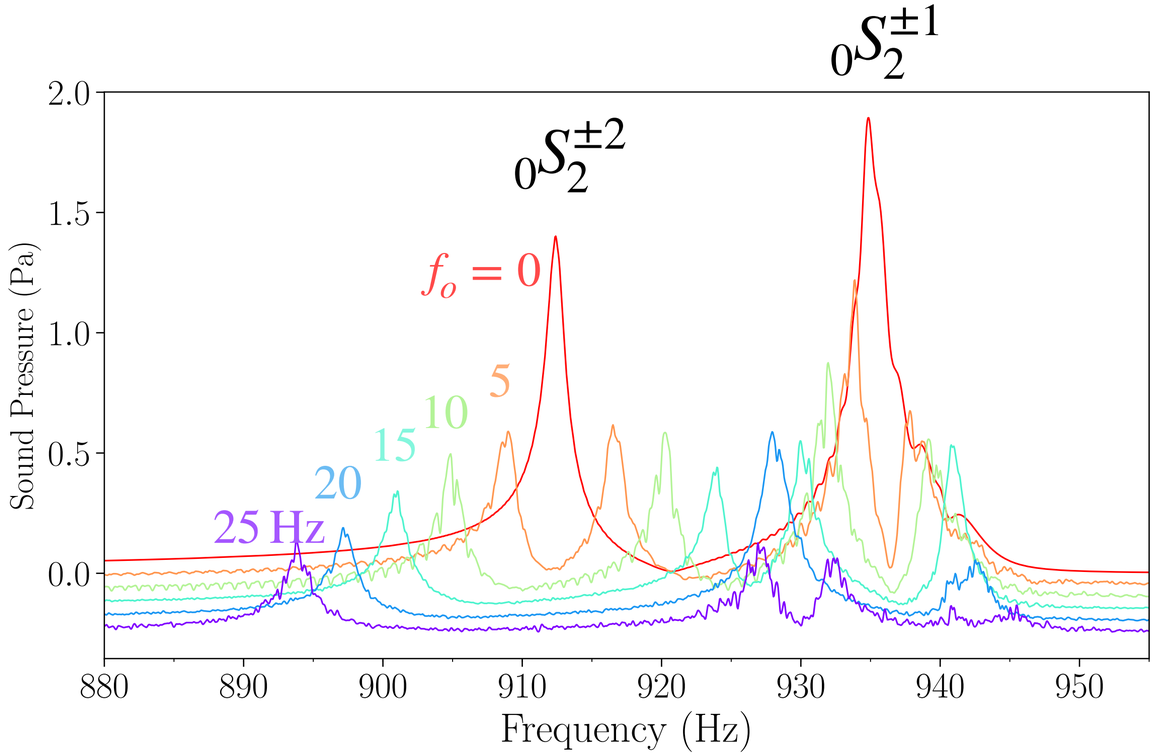

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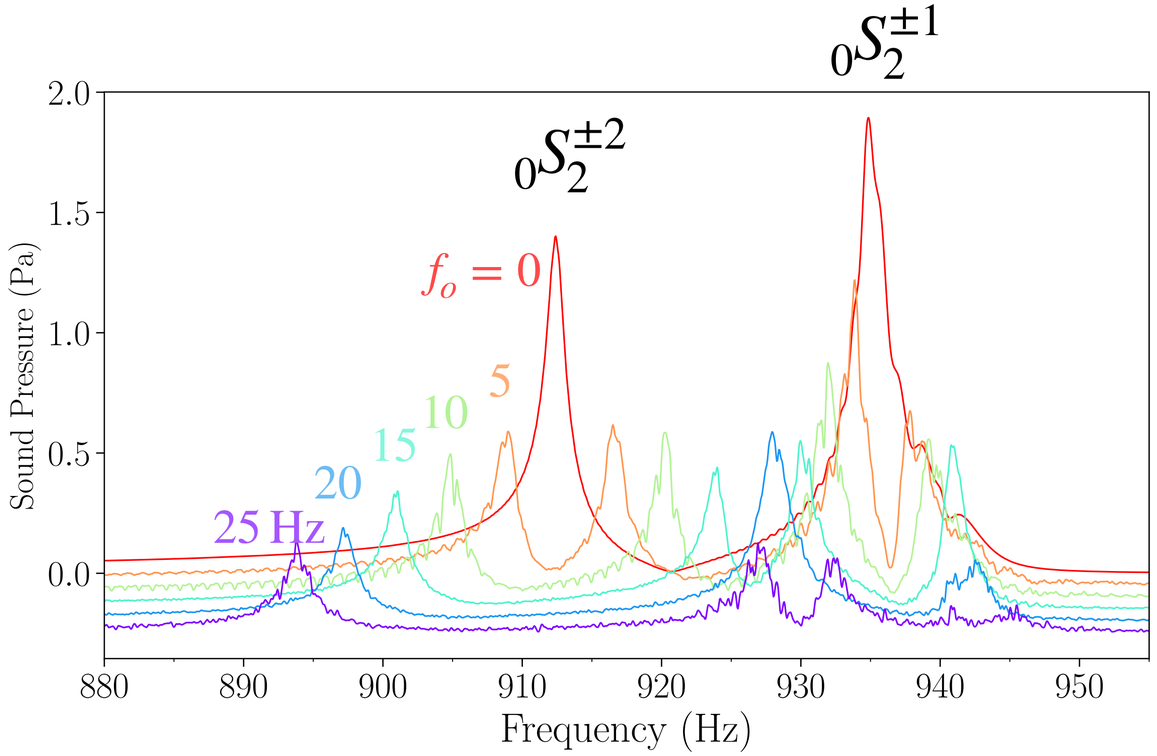

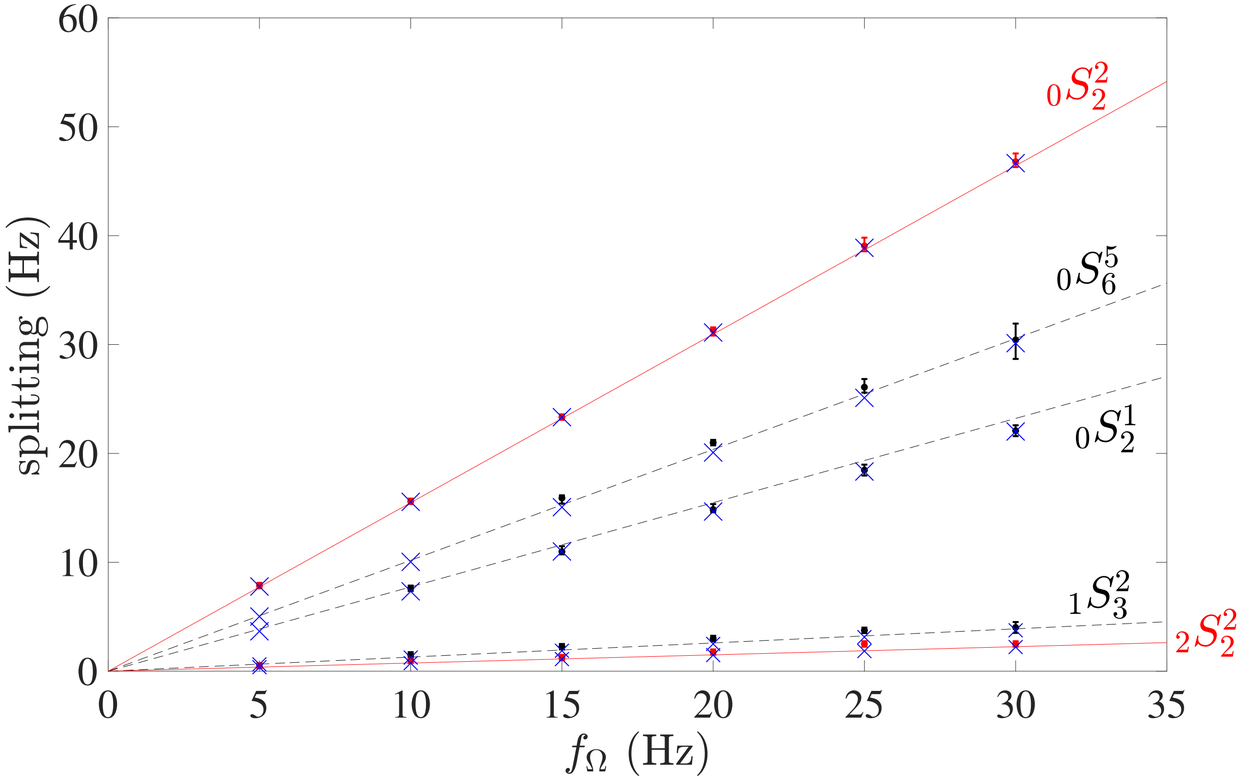

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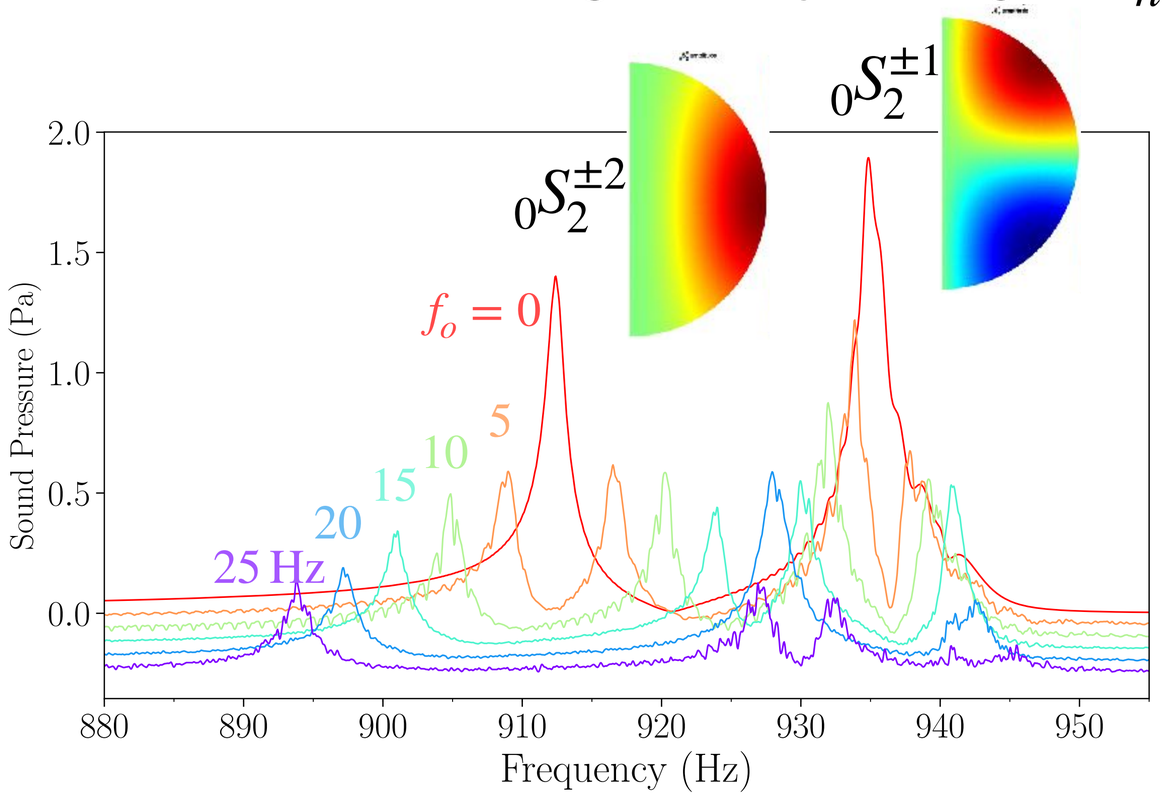
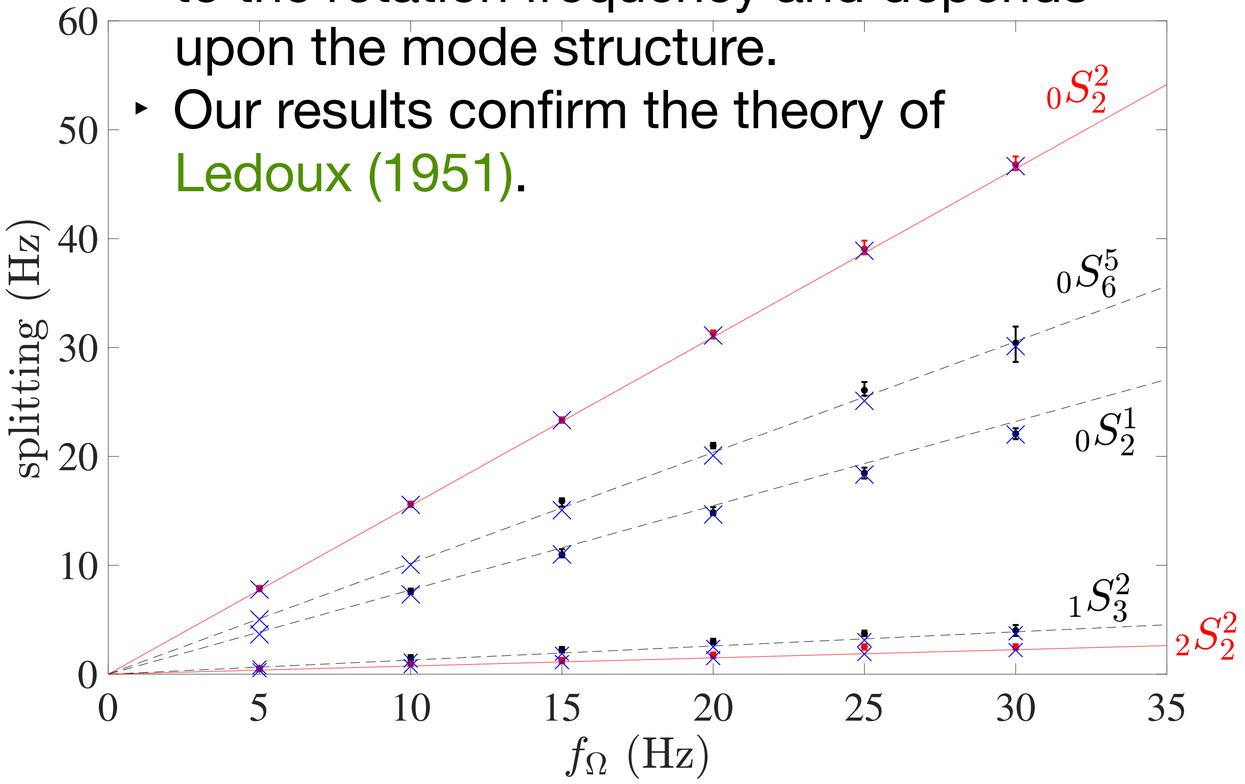


- The frequency splitting is **proportional** to the rotation frequency and depends upon the mode structure.
- Our results confirm the theory of Ledoux (1951).



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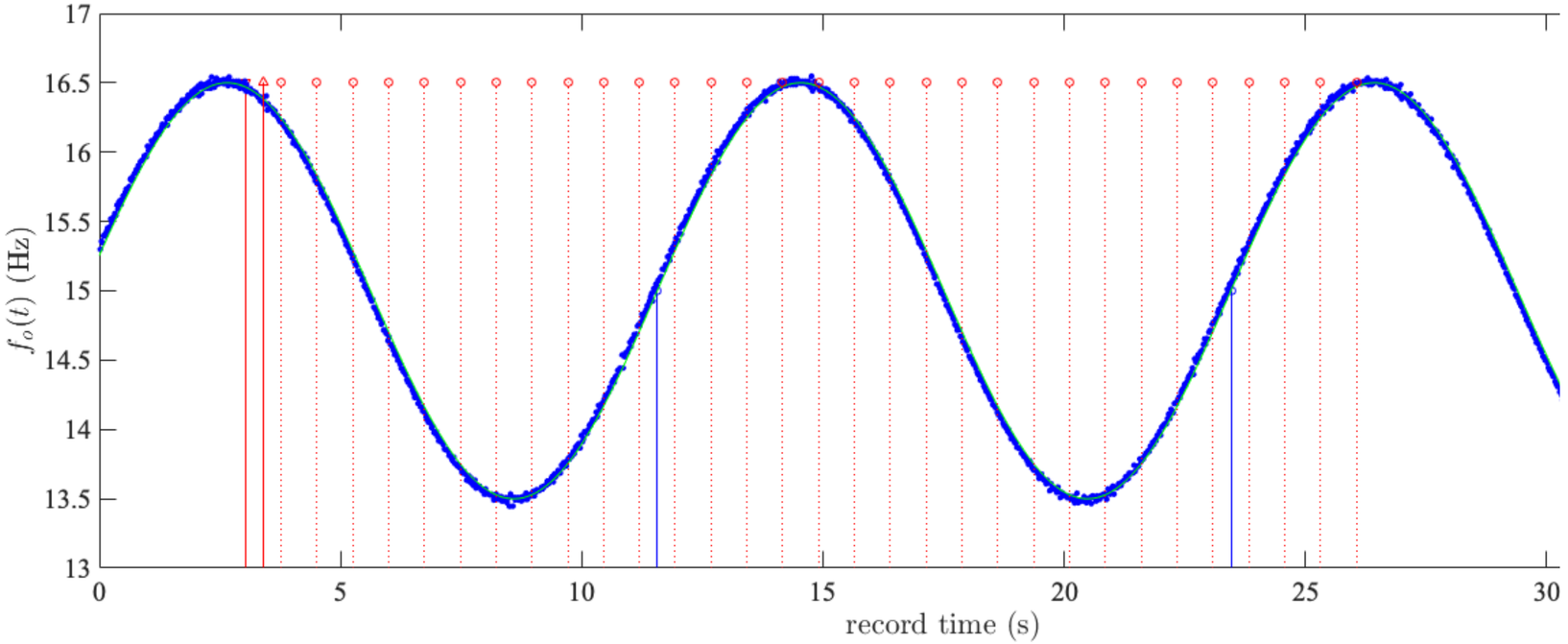
Libration flow: $f_{shell}(t) = f_o + \Delta f \sin(2\pi f_{lib} t)$



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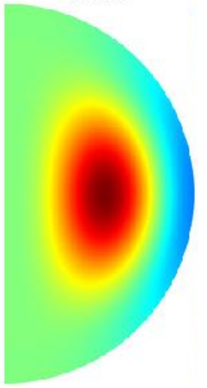
- We trigger **libration** flows in ZoRo and test the model of Greenspan (1968).
- The splitting then **varies** in time.
- We **repeat** a very **short chirp** targeting a **specific** doublet, here ${}_1S_3^{\pm 3}$.



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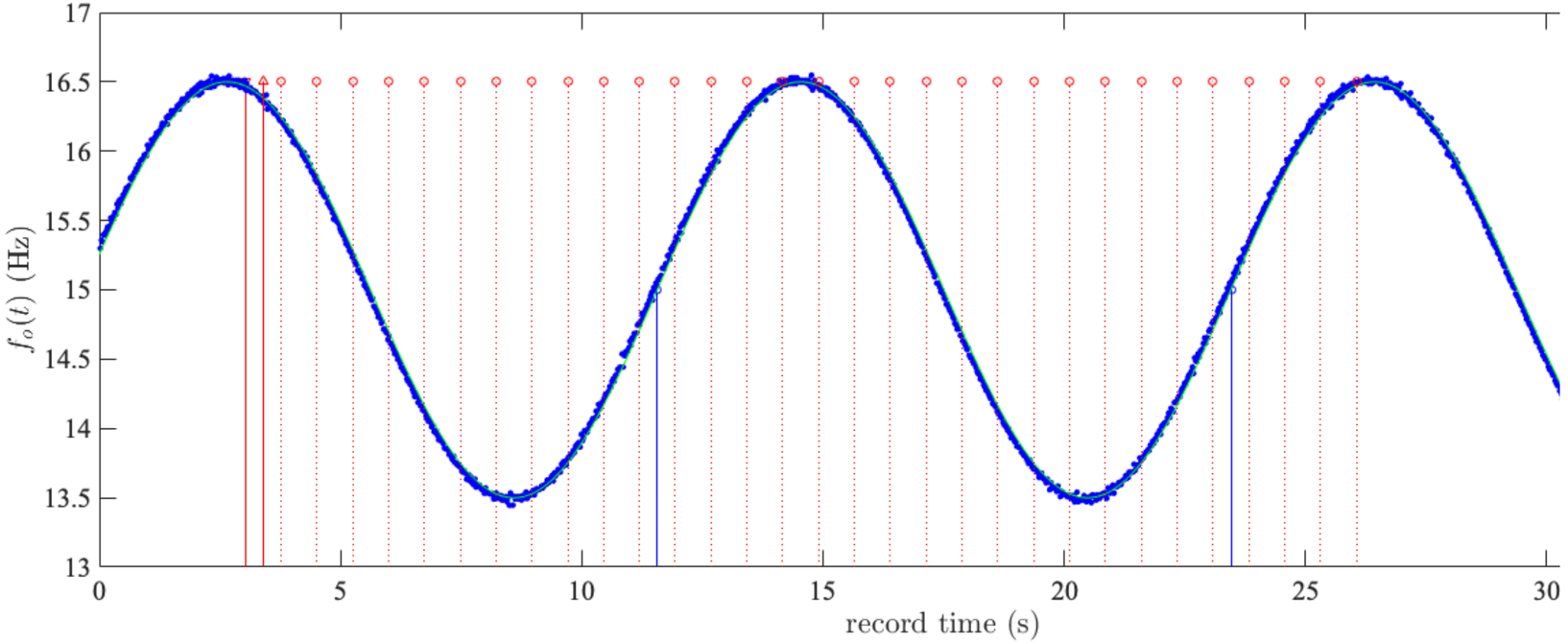

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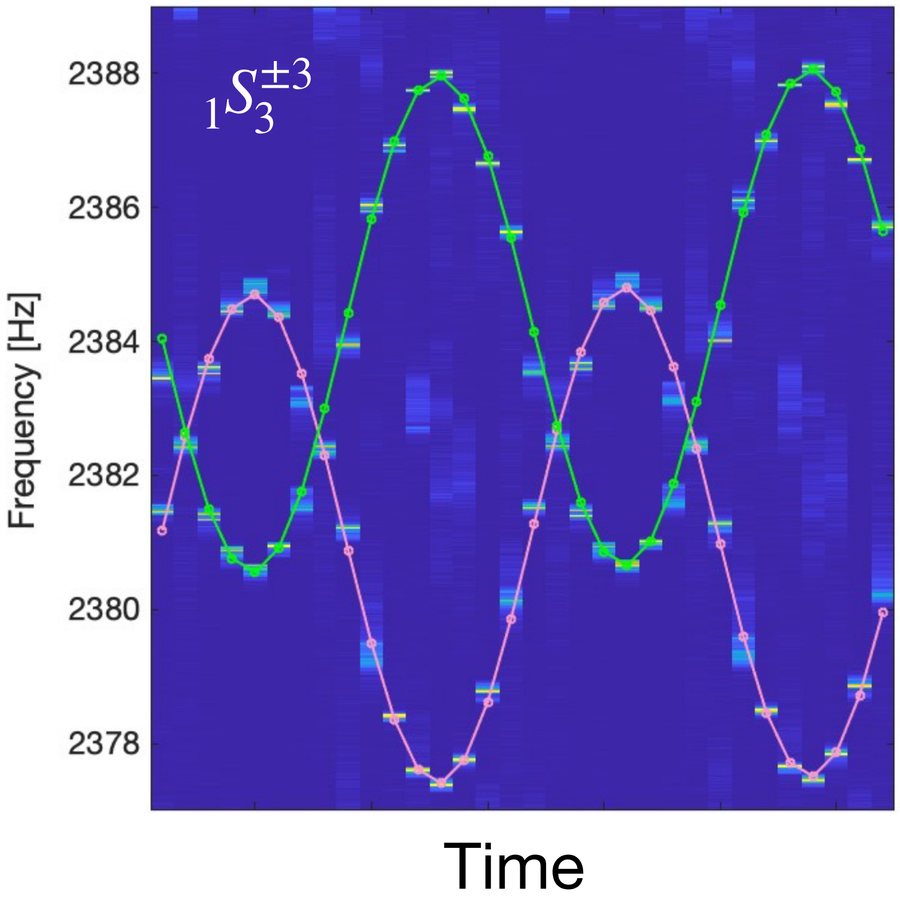
- We recover the frequencies of the two singlets by a non-linear high-resolution analysis in the **time-domain**.



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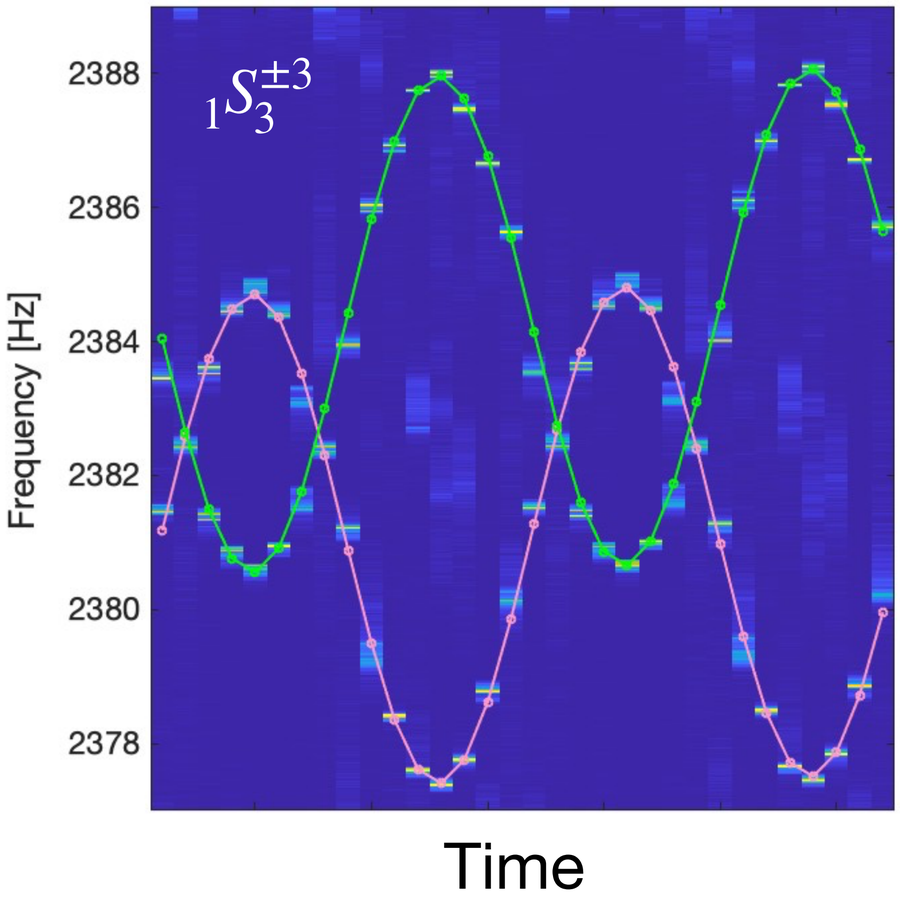
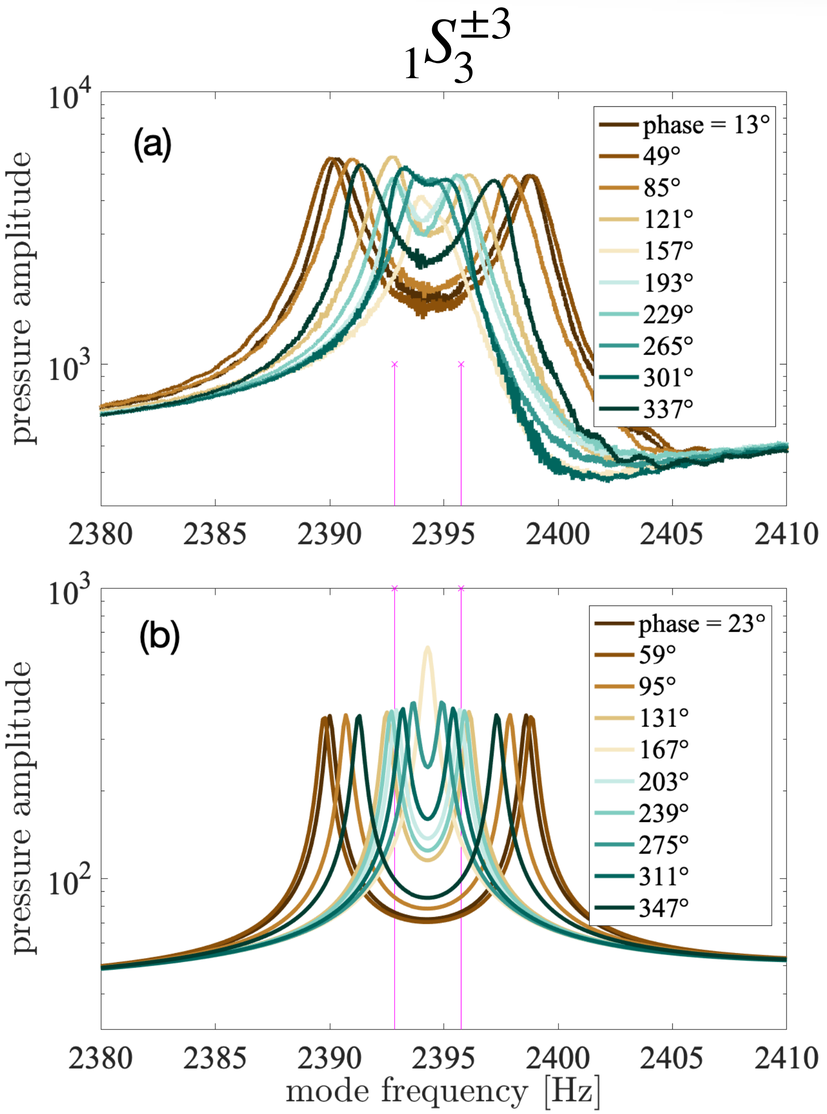


- Or we **repeat complete** long chirps and measure the splitting for **different libration** phases.



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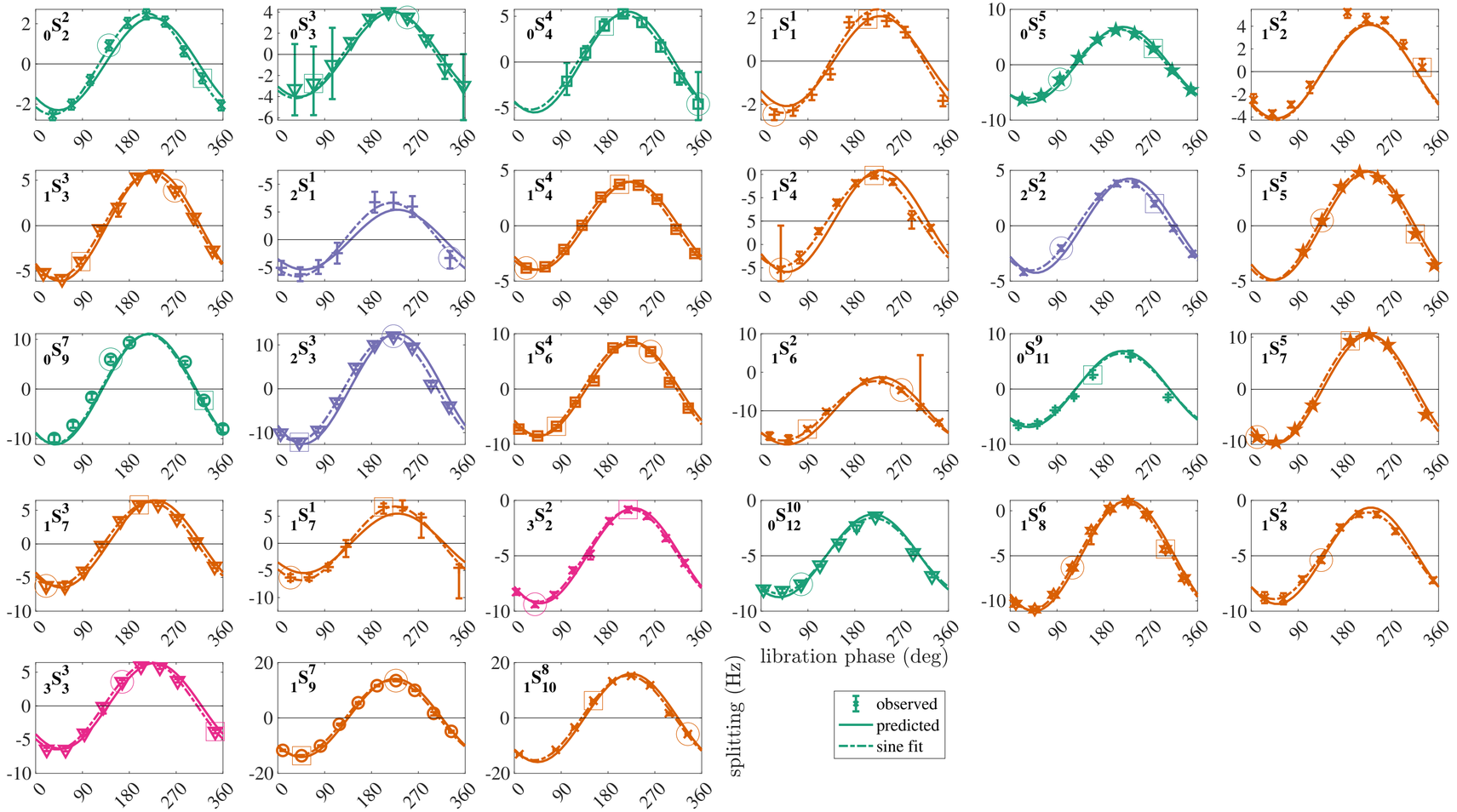

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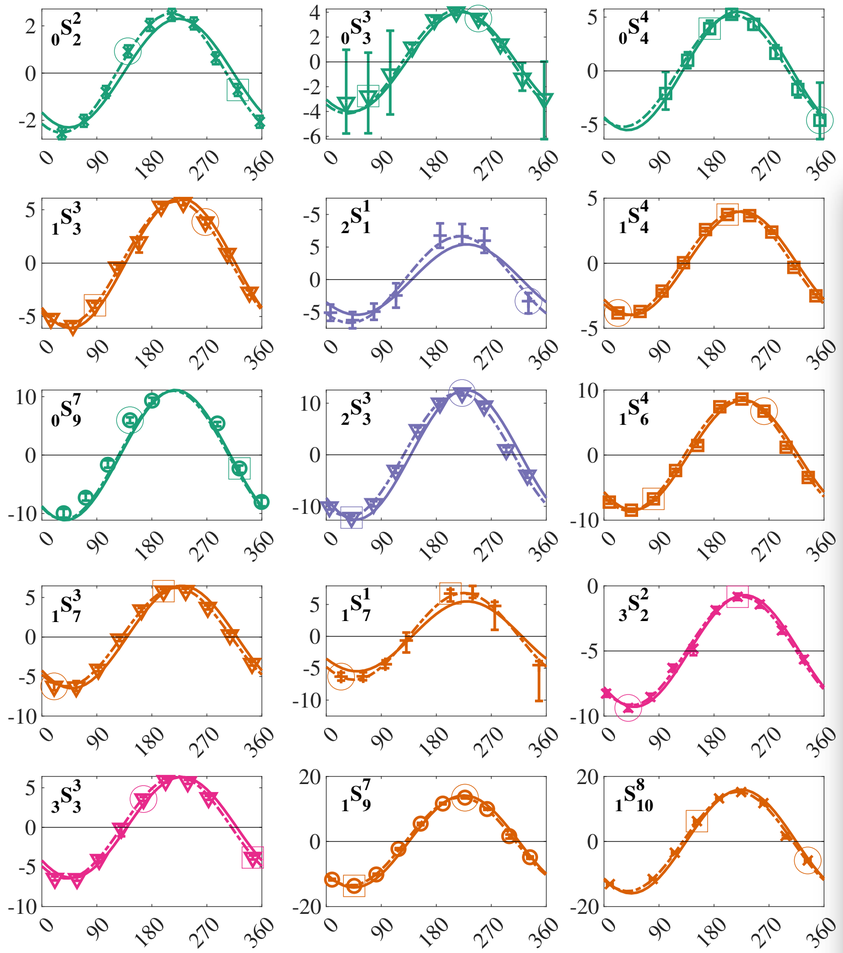

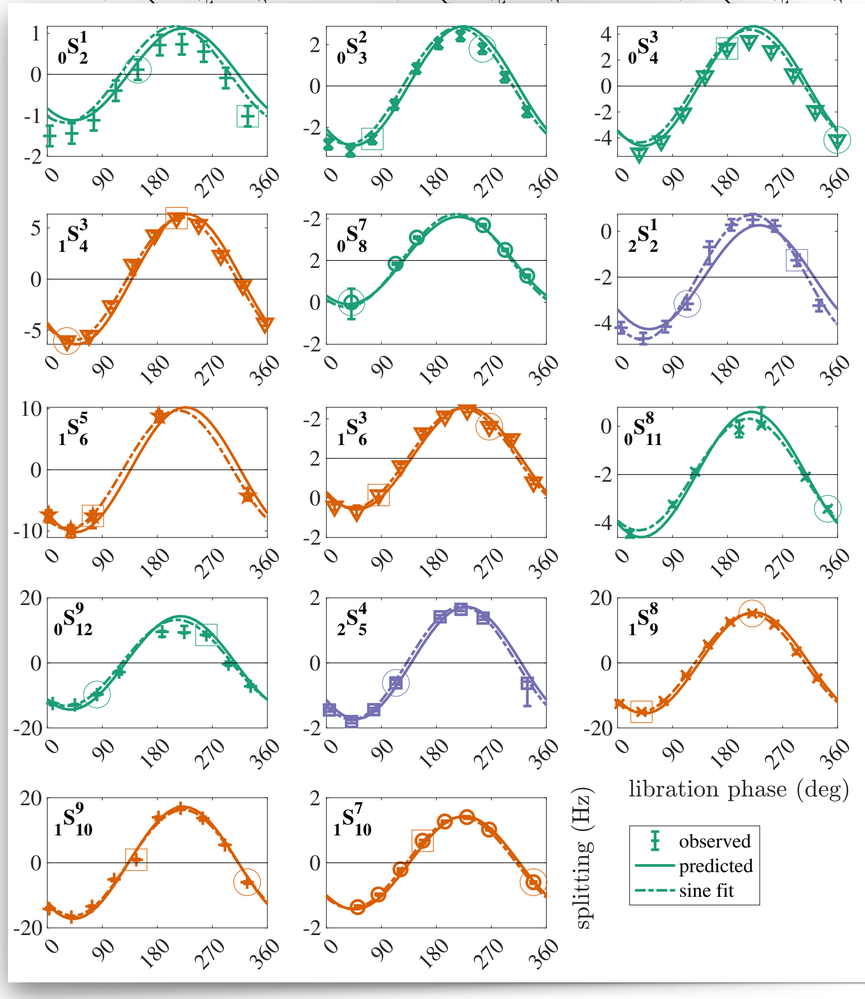

- We thus collect the splitting of more than **50 doublets**.

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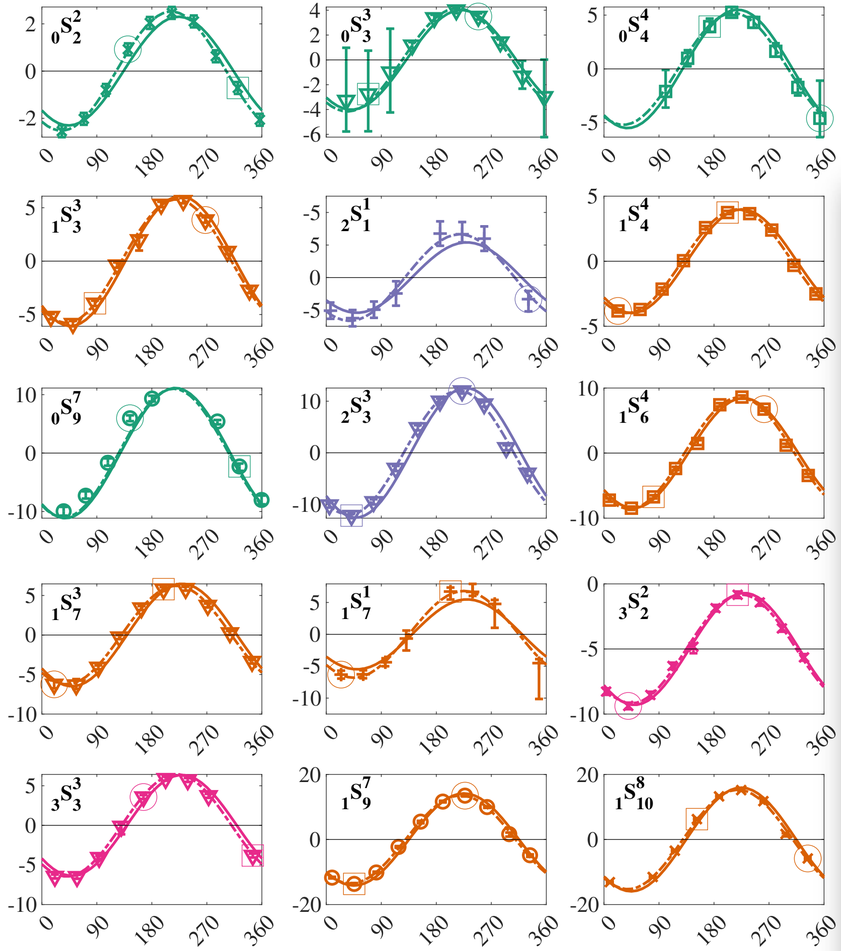

- Greenspan's flow is well **recovered** by inversion.

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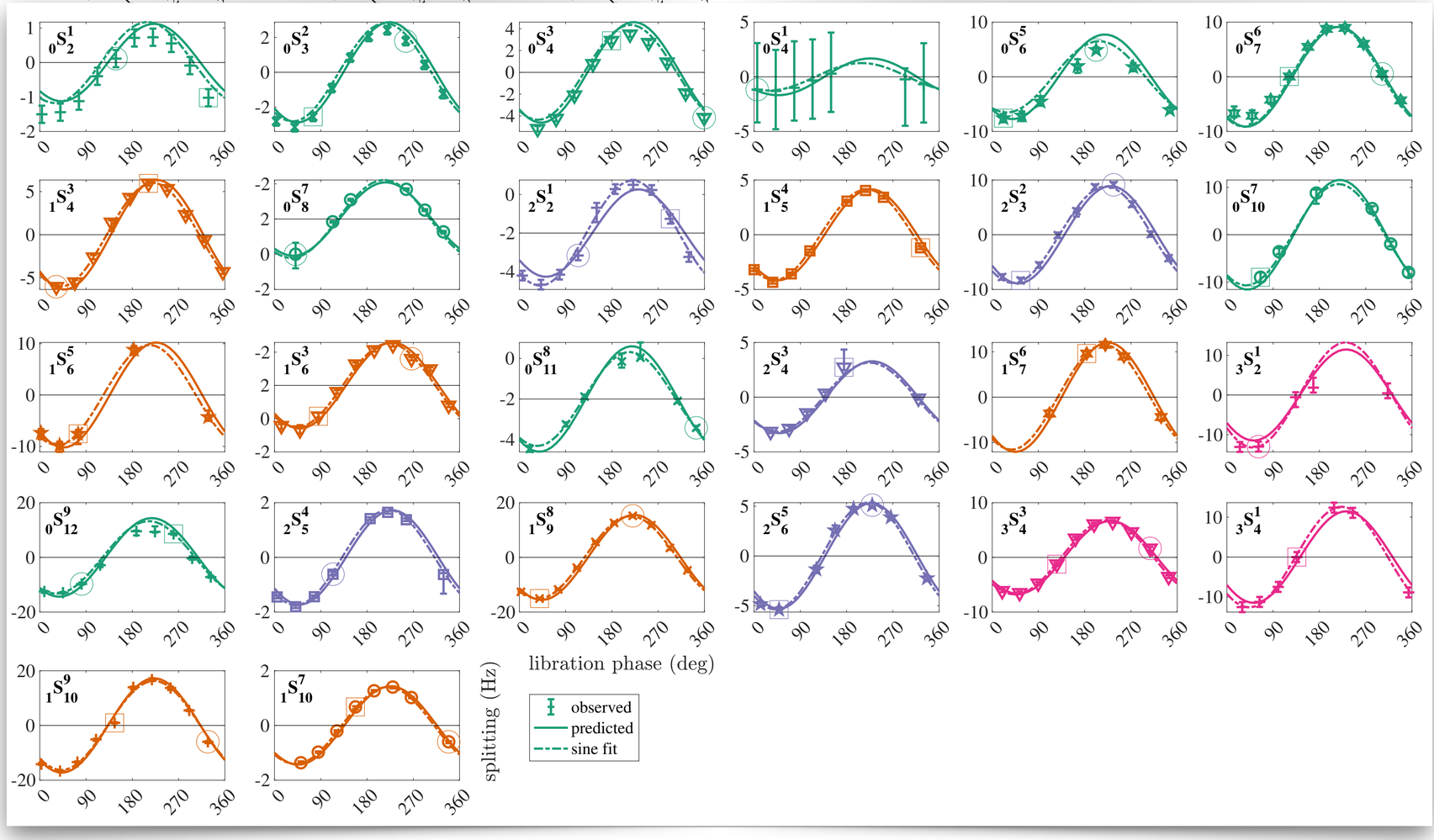
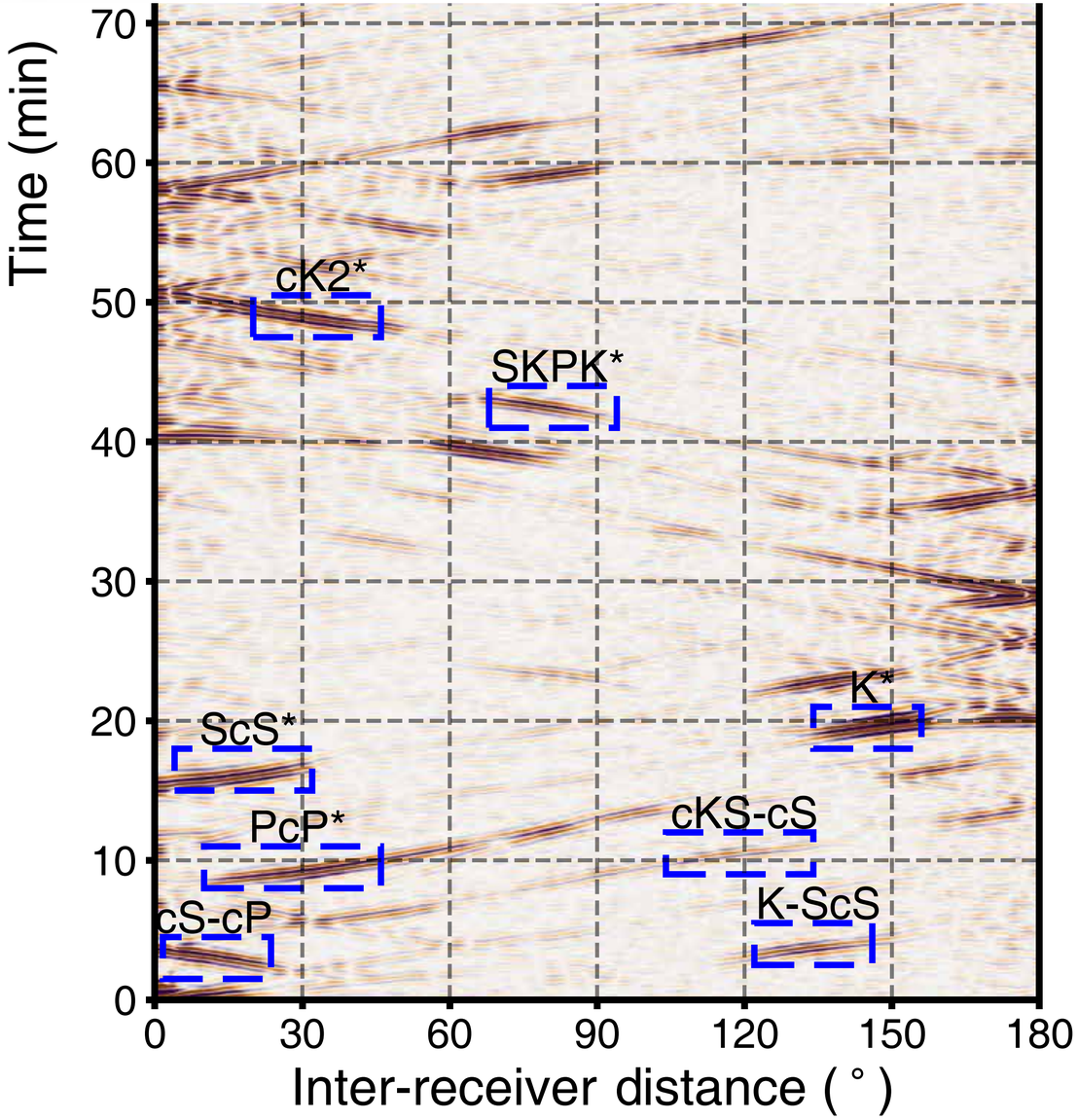


3. Global Cross-correlograms and ellipticity

Ma & Tkalcic, 2024



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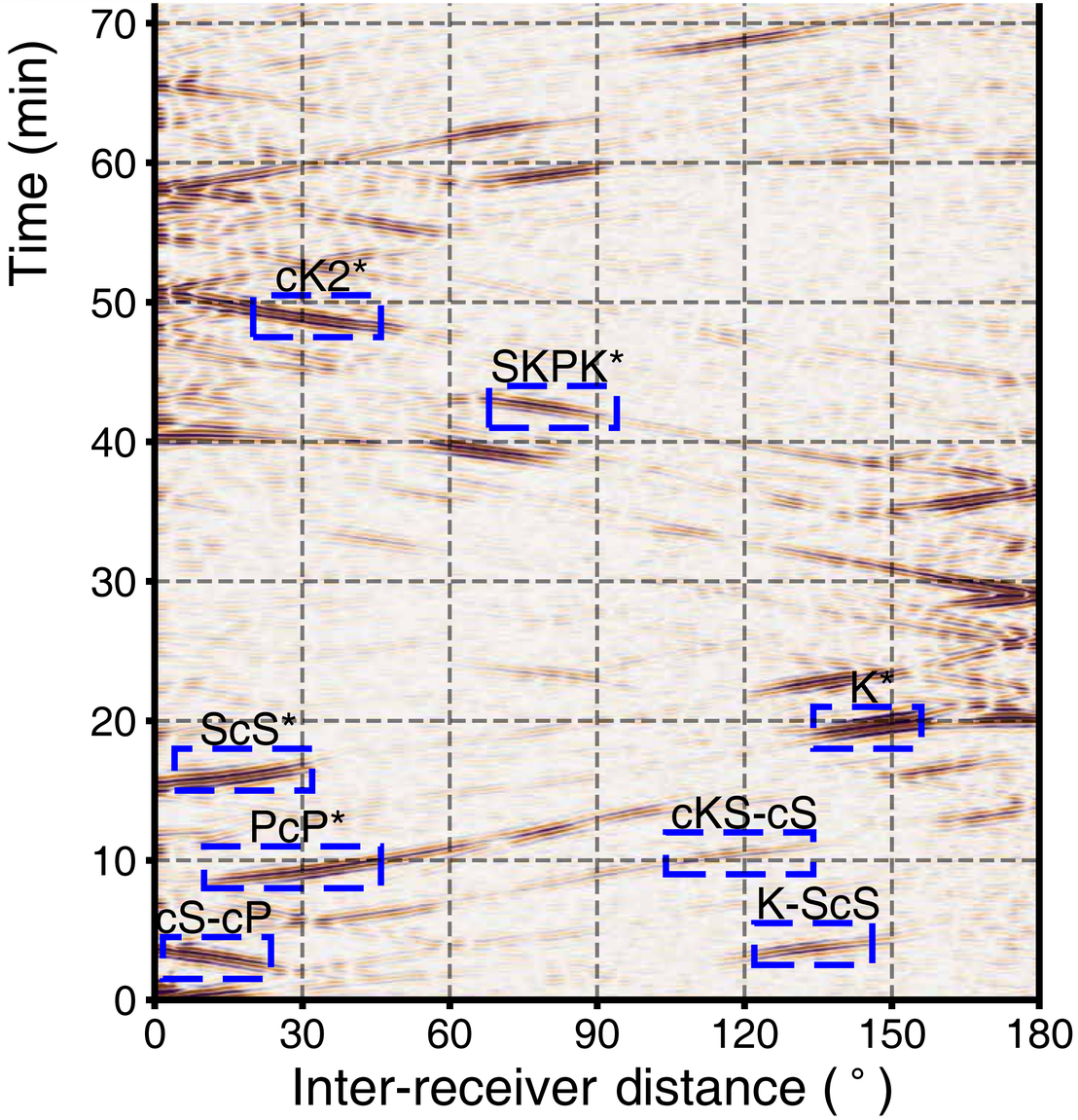

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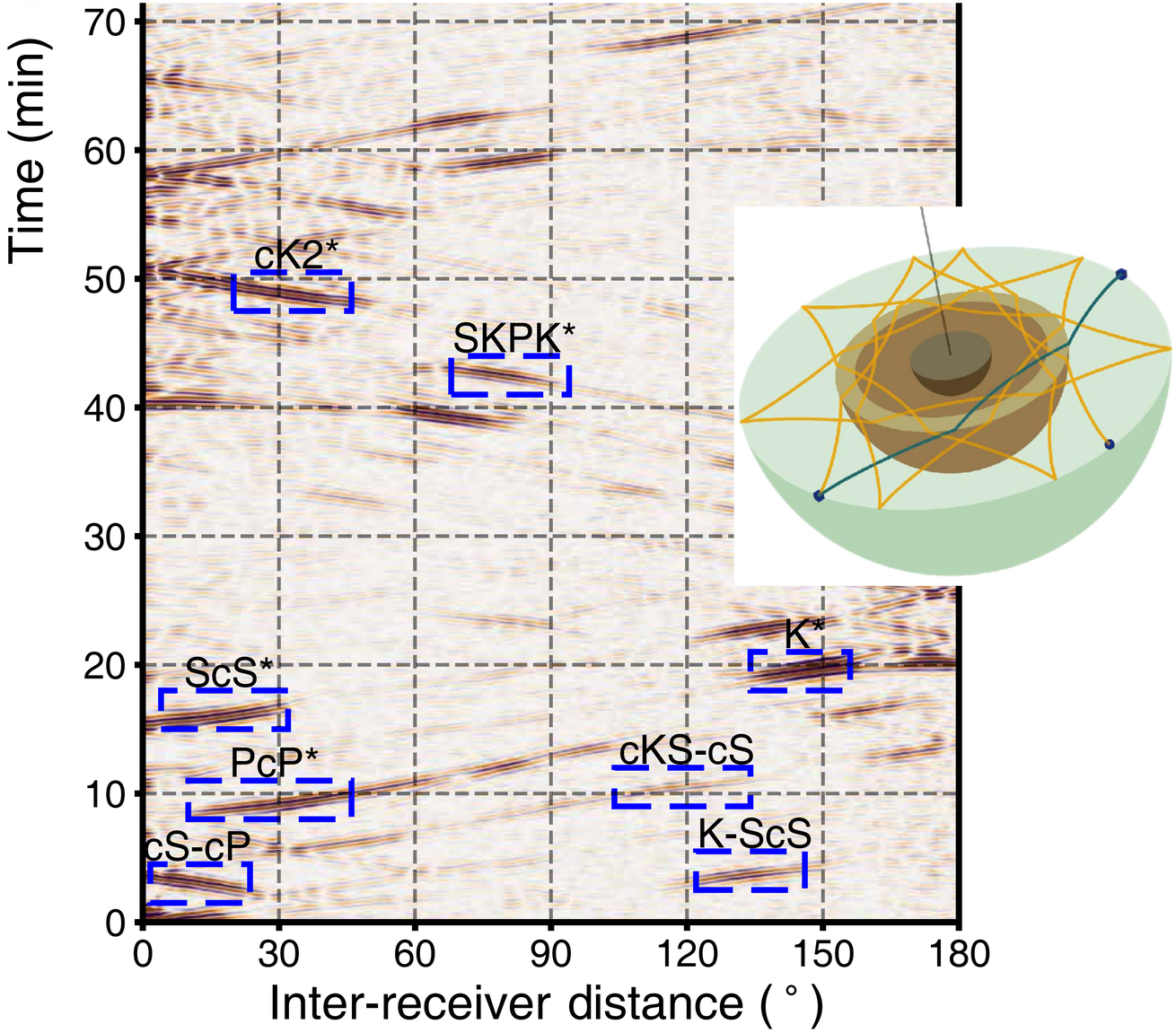

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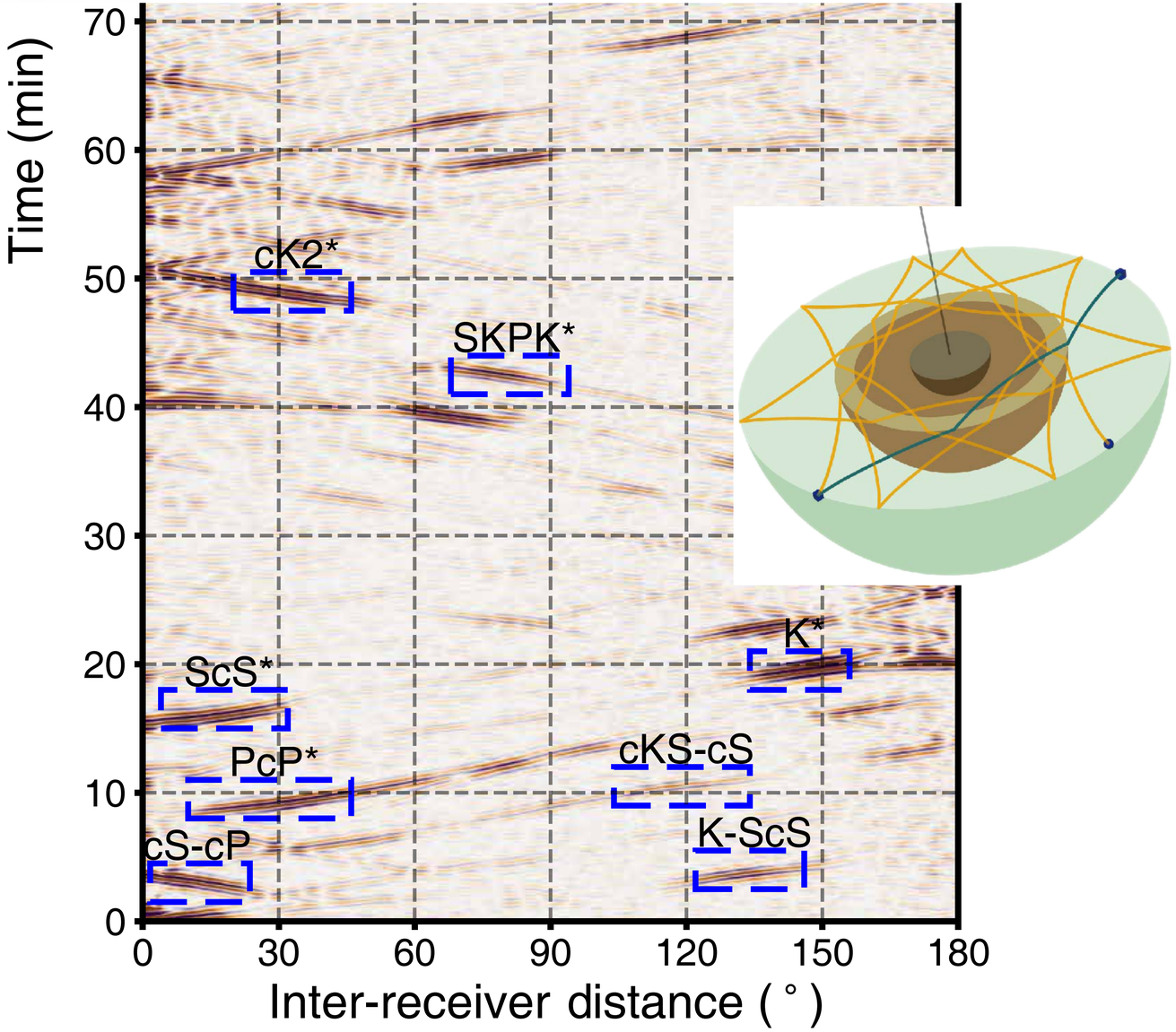

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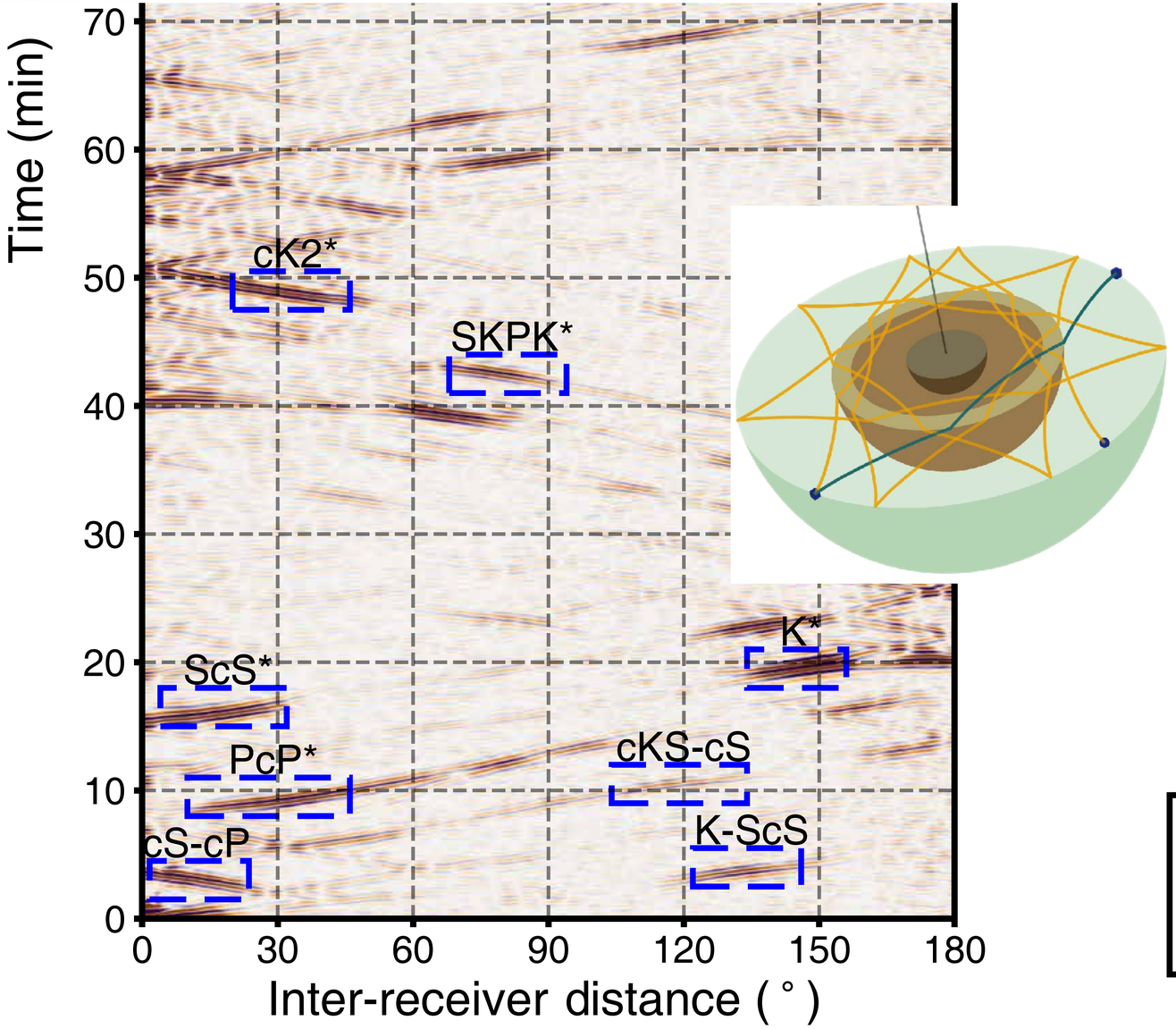

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How do **ellipticity** and **rotation** affect the Earth's **global cross-correlogram**?

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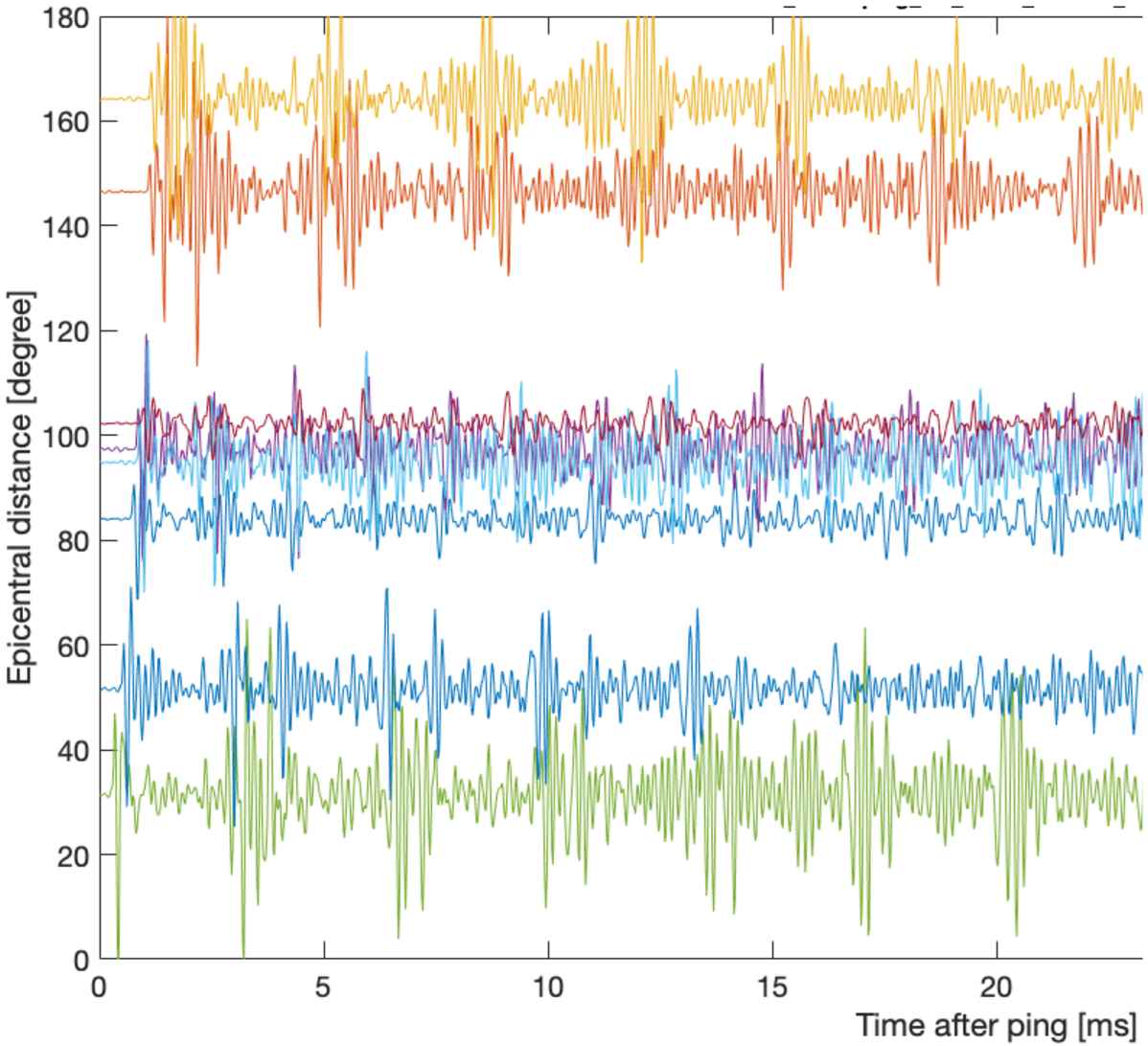

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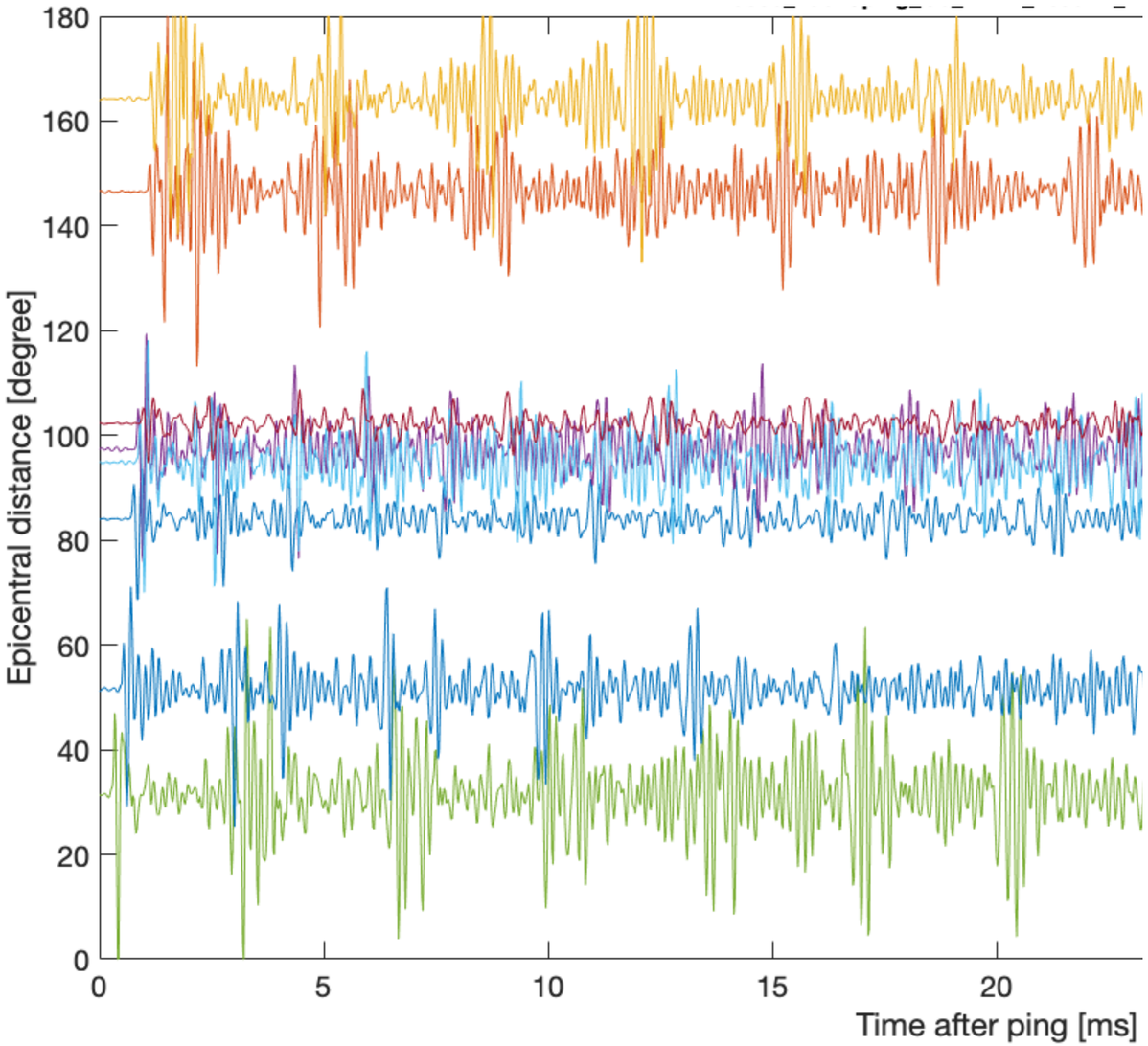

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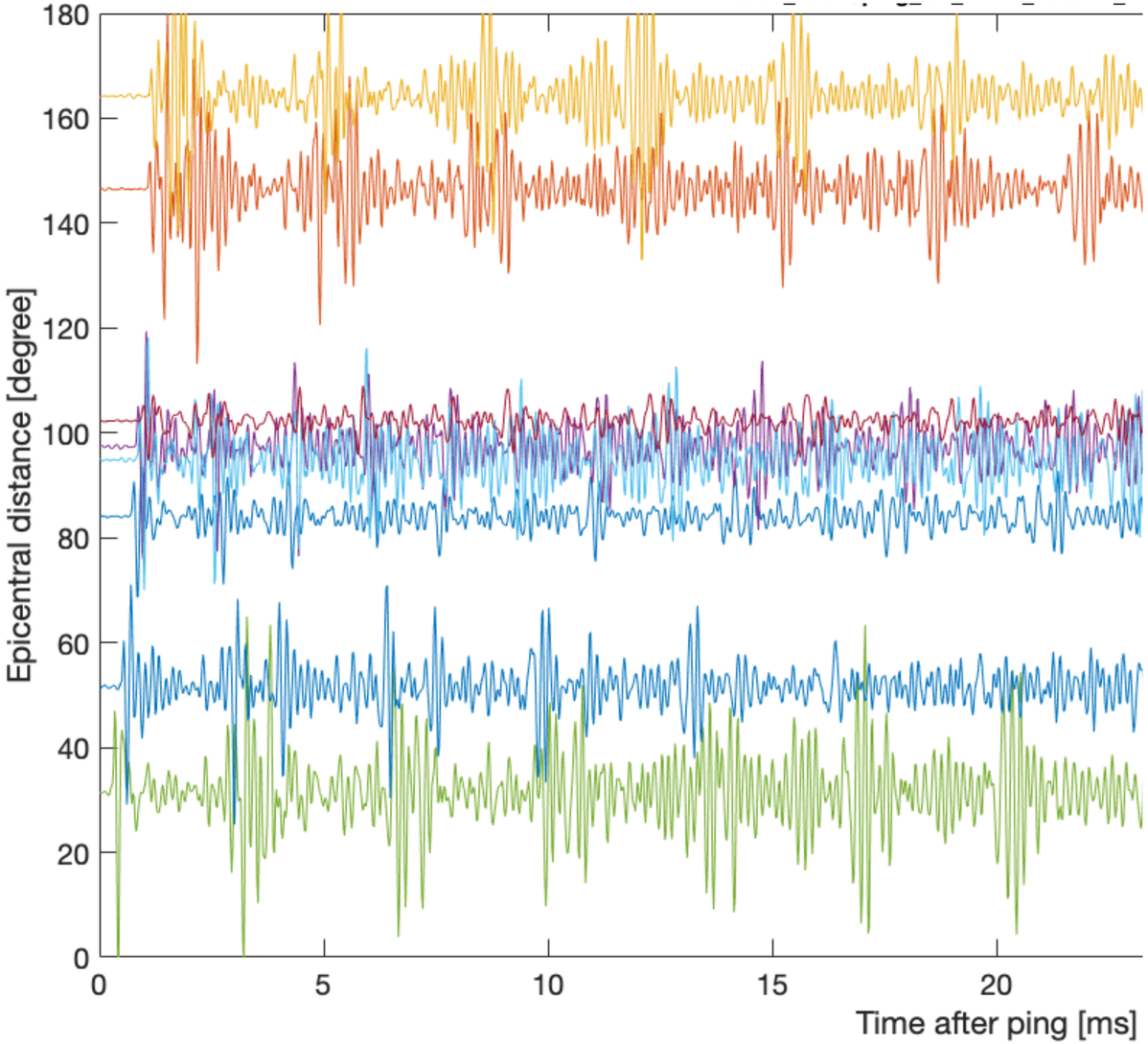

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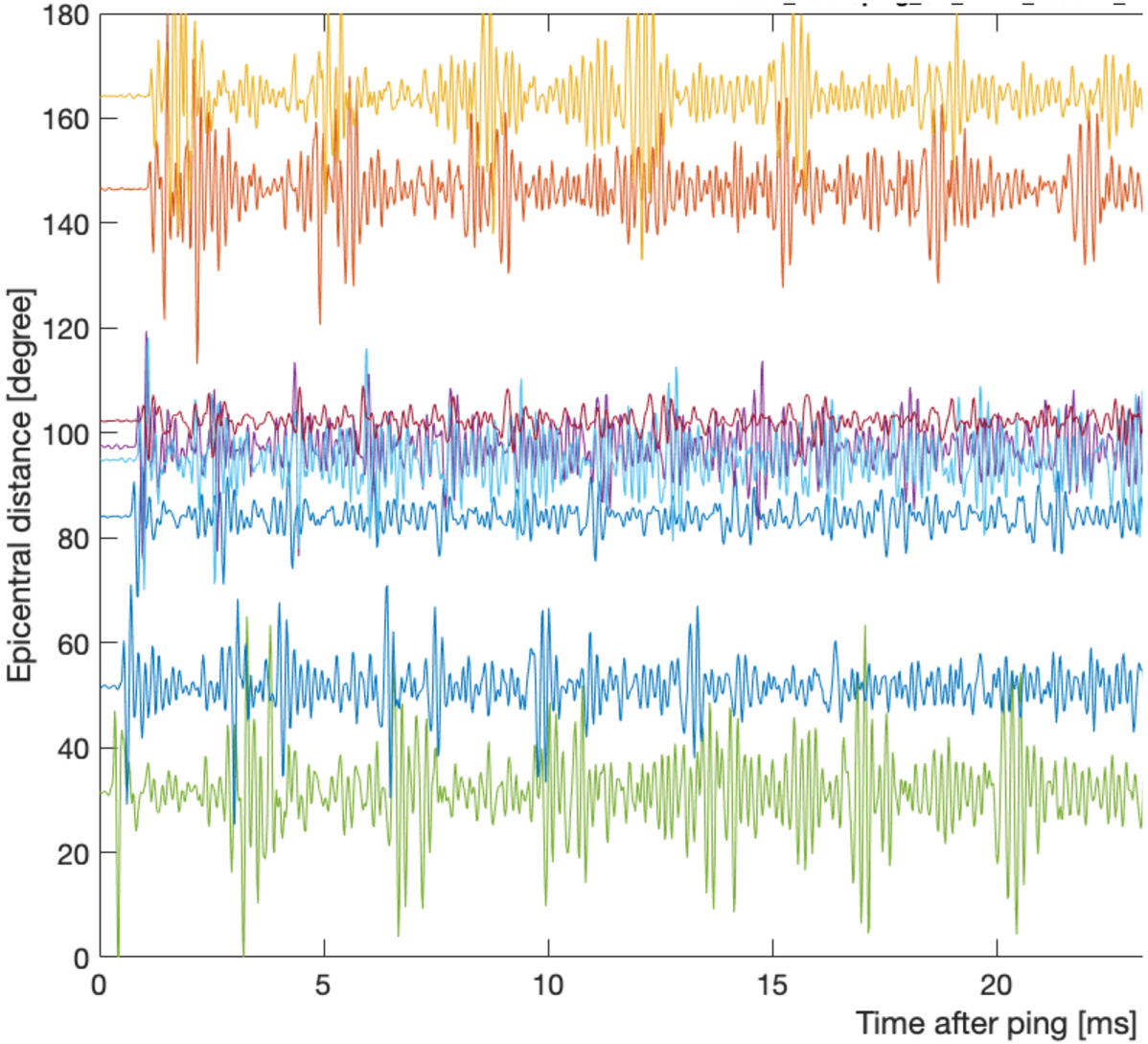

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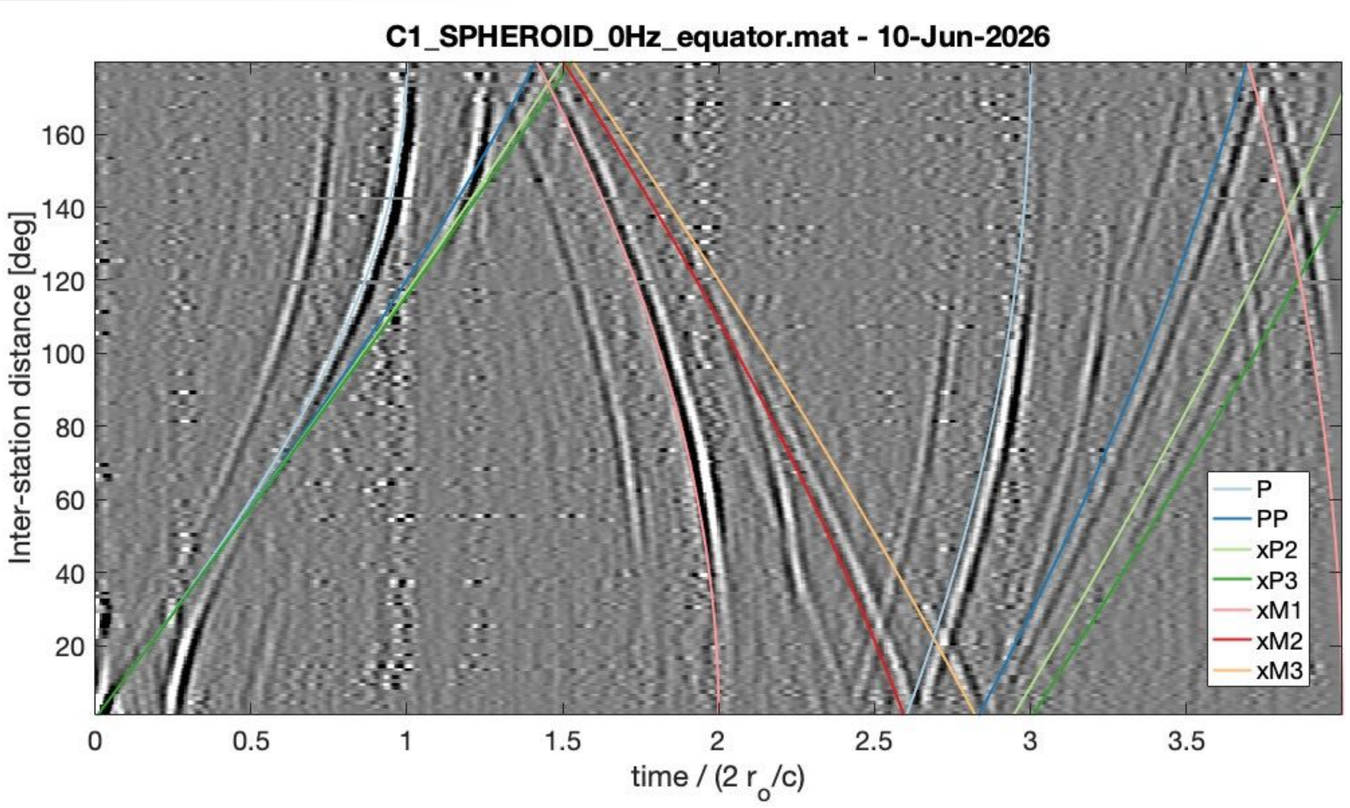

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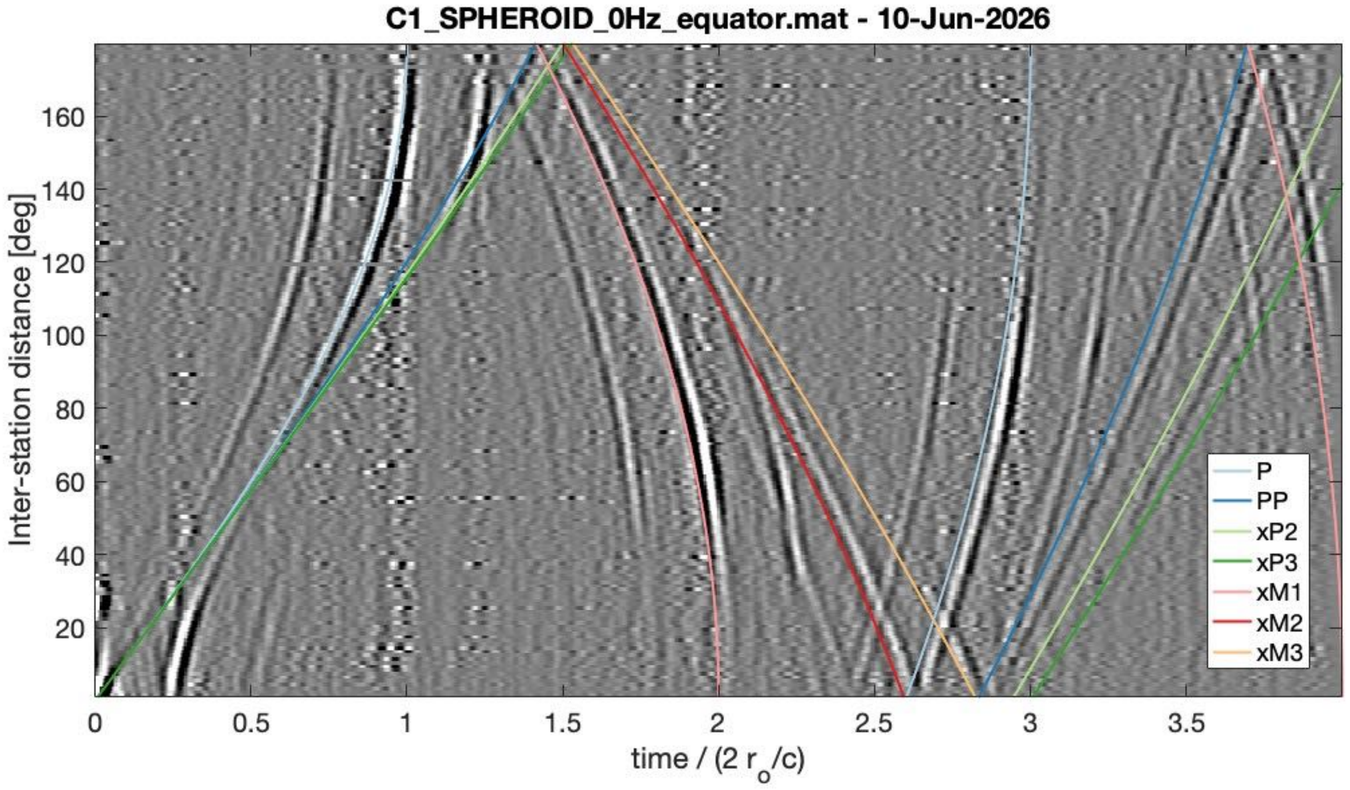

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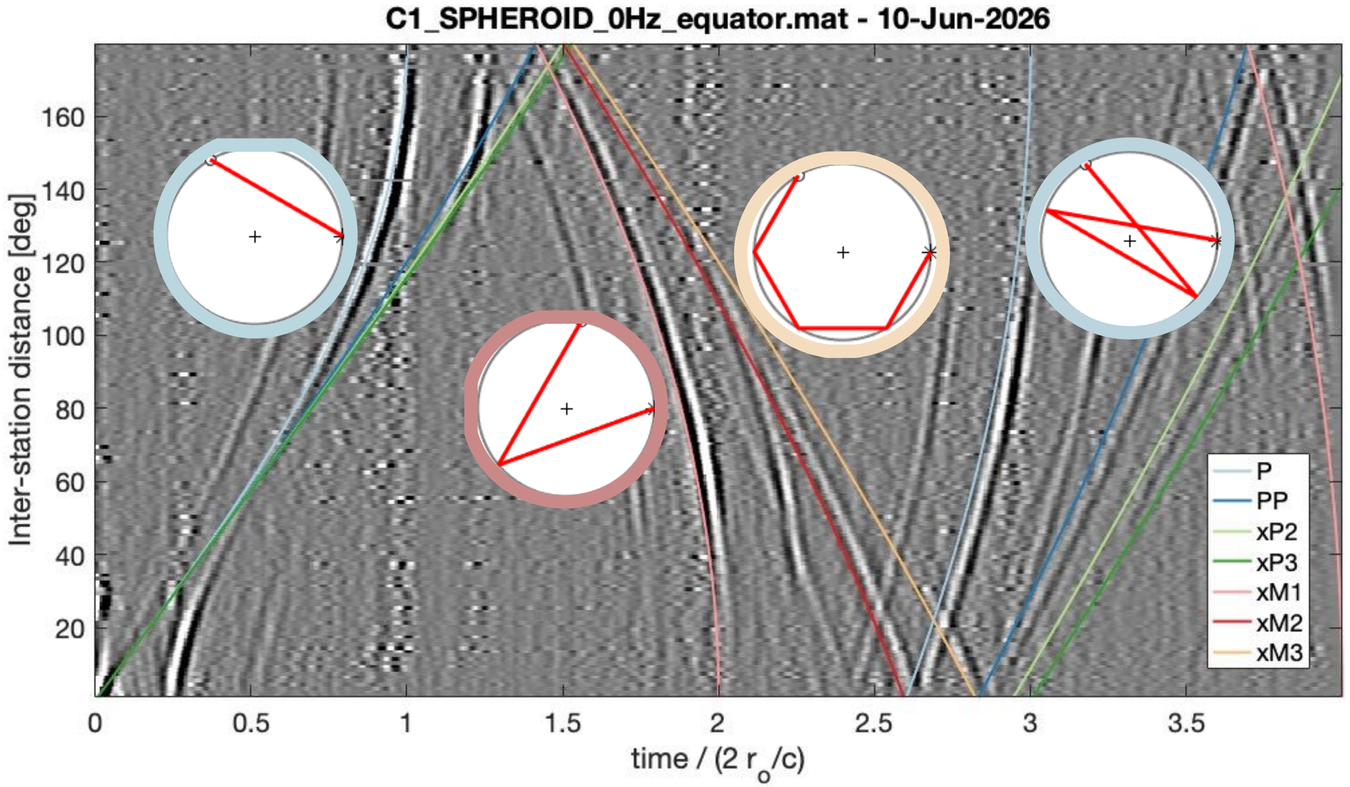

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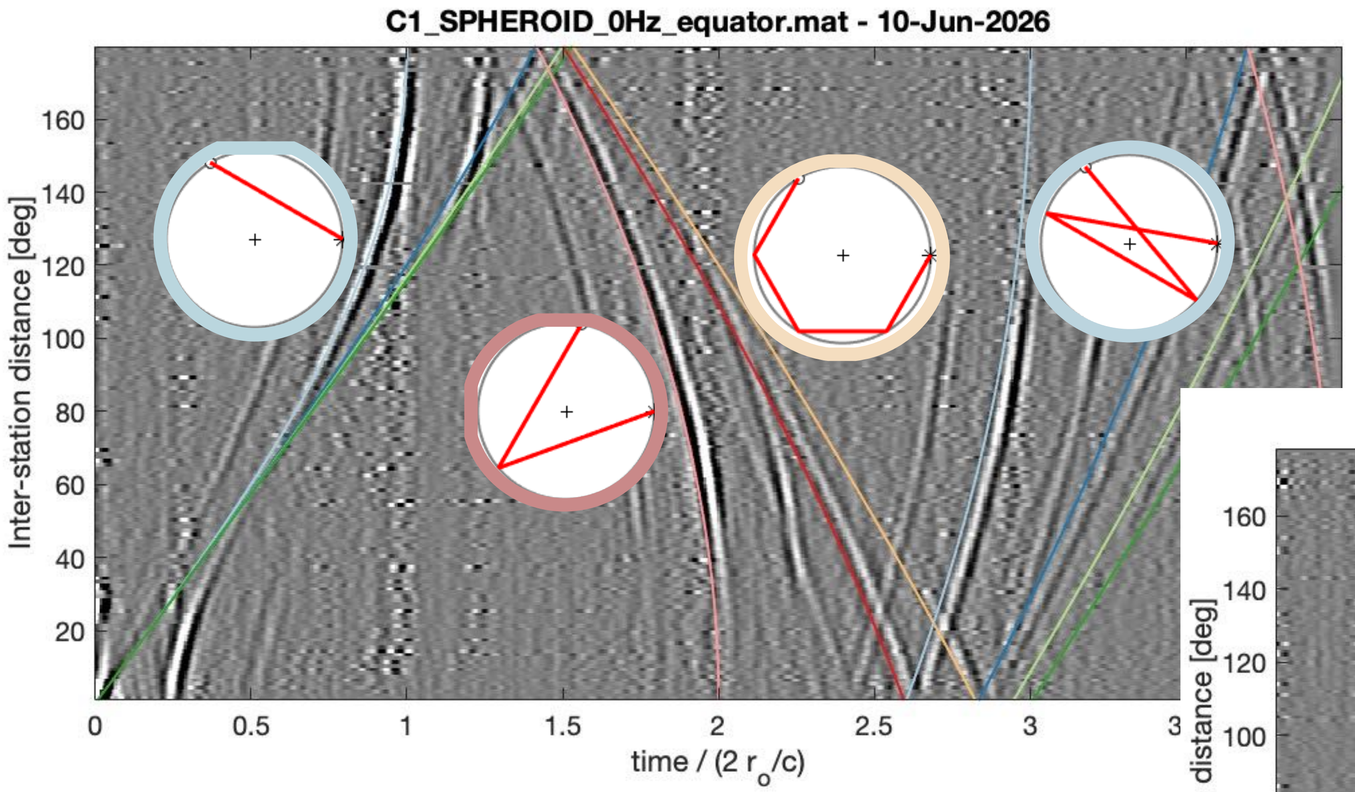

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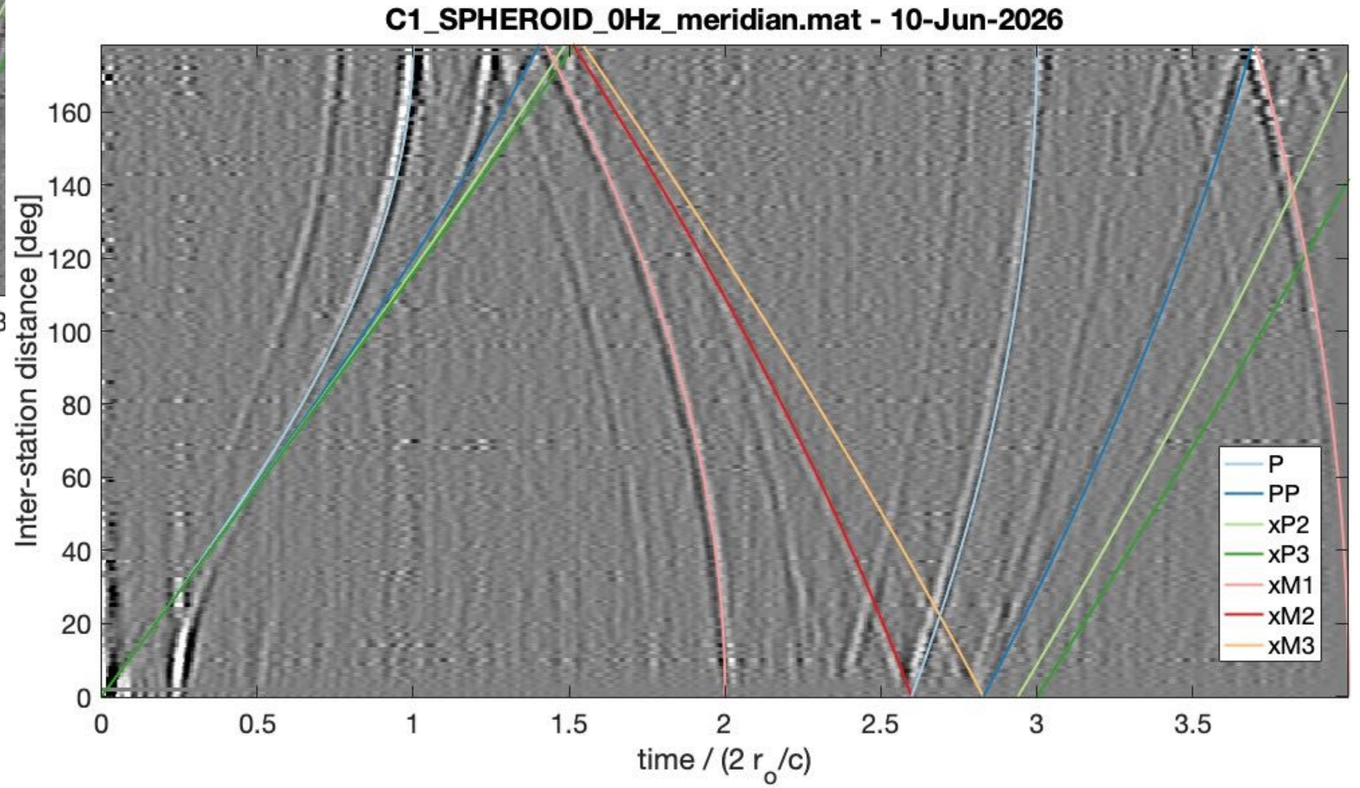
- **Equatorial** cross-correlograms **differ** from **meridian** ones in several aspects.



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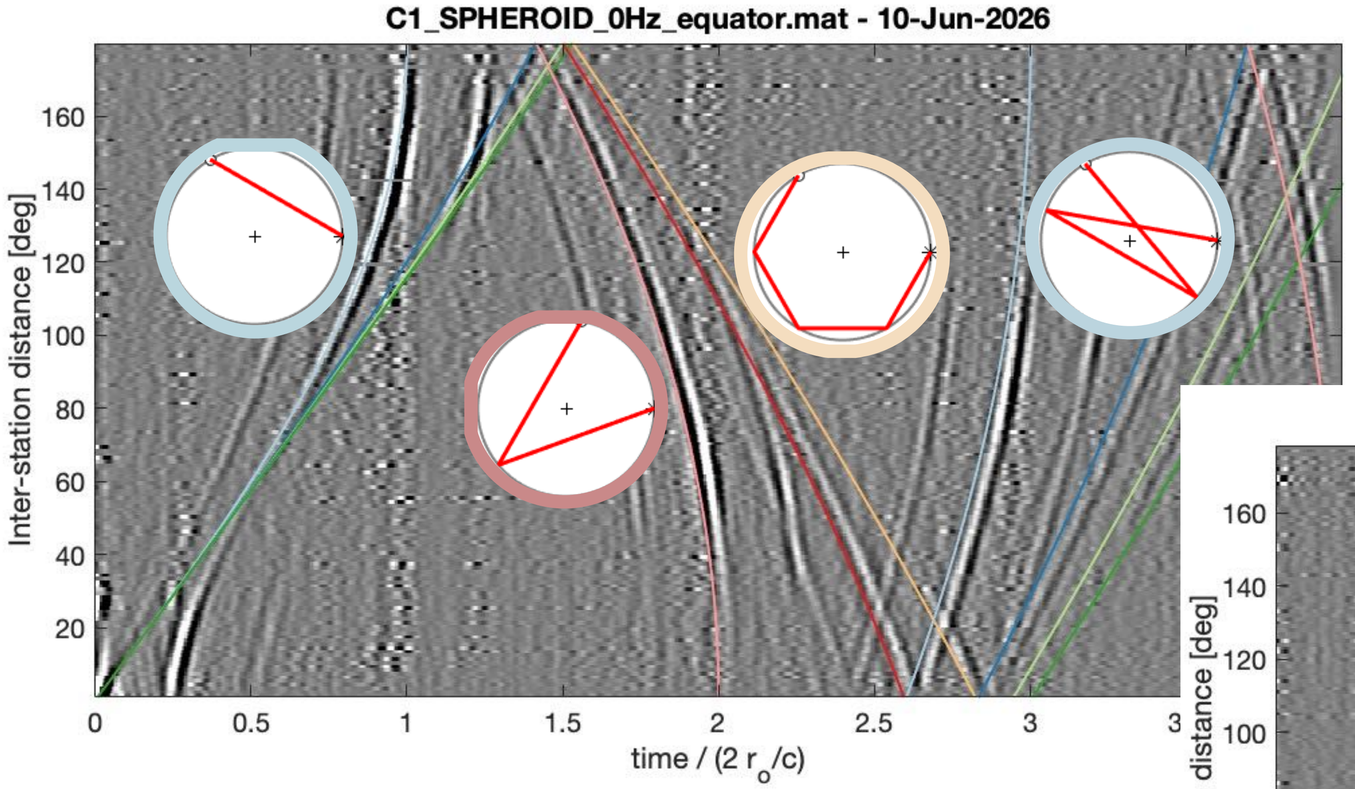
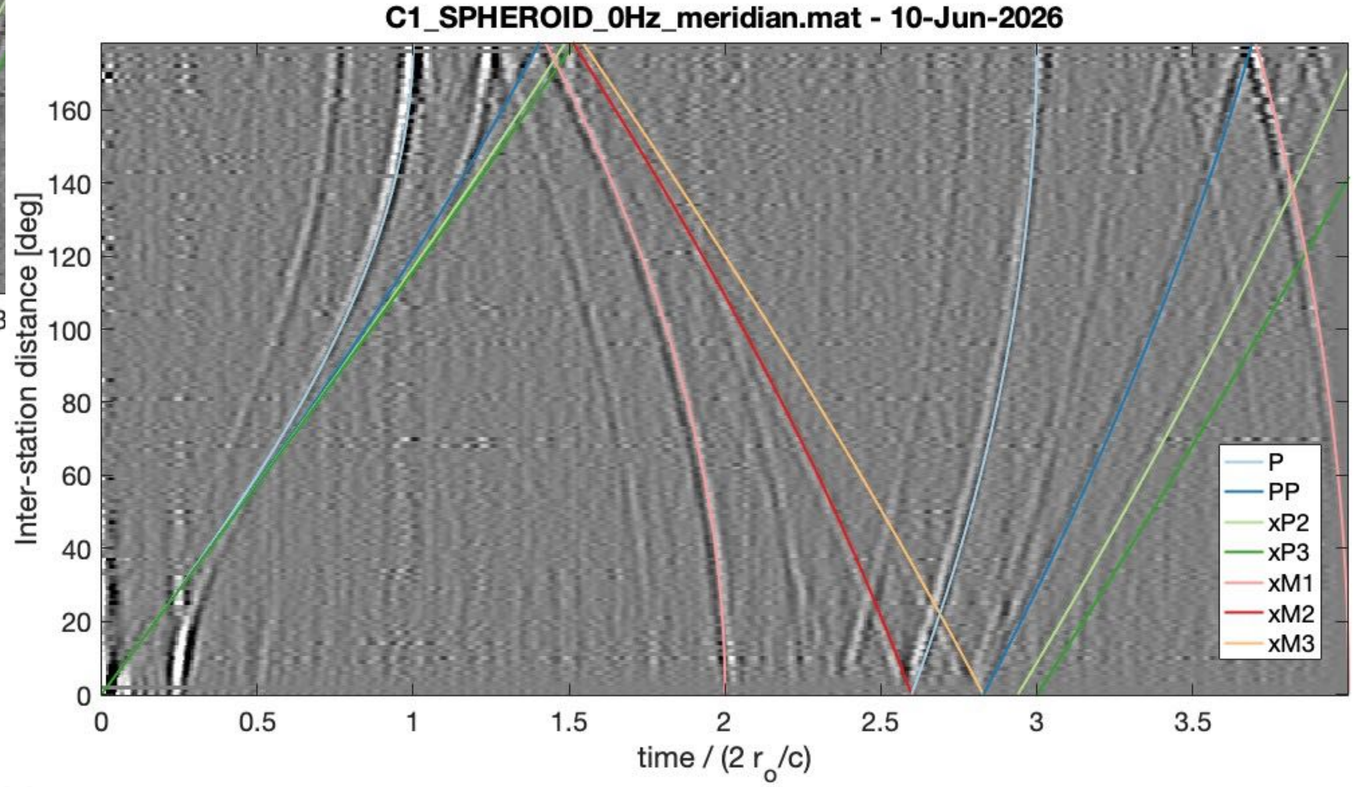


- **Features** clearly show up, aligning with theoretical body wave **travel-time curves**.
- **Equatorial** cross-correlograms **differ** from **meridian** ones in several aspects.
- *On-going work!…*

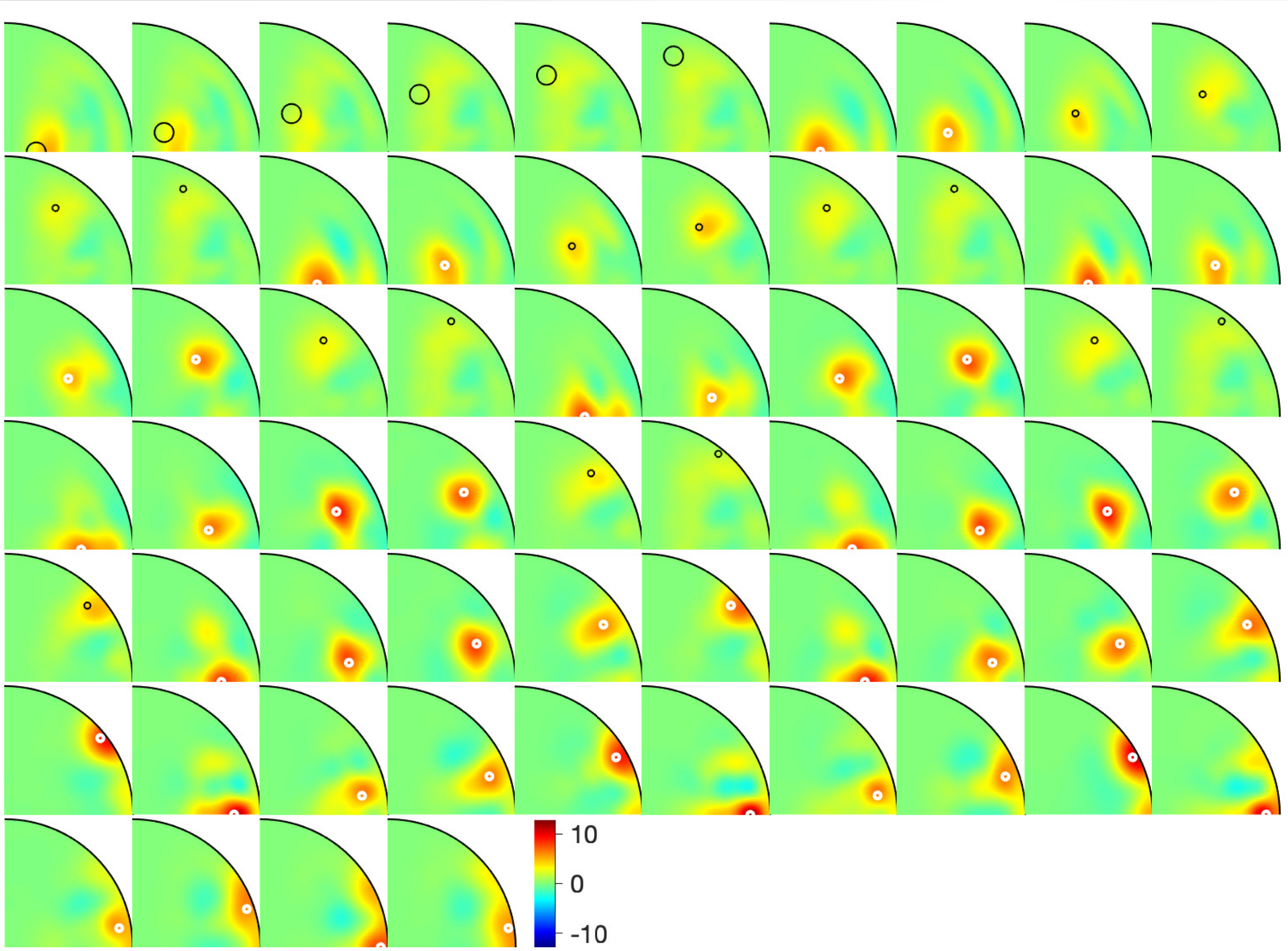


Thank you

References

- Modal Acoustic Velocimetry in libration-driven flows, Nataf H-C, S. Su, P. Roux, P. Cardin, D. Cébron & Y. Do. *Experiments in Fluids*, **66** (10), 185, 2025.
- Acoustic modes of rapidly rotating ellipsoids subject to centrifugal gravity, Vidal J. & D. Cébron, *J. Acoustic. Soc. Amer.*, **150** (2), 1467-1478, 2021.
- Compressible fluid modes in rigid ellipsoids: towards modal acoustic velocimetry, Vidal J., S. Su & D. Cébron, *J. Fluid Mech.*, **885**, A39, 2020.
- Acoustic and inertial modes in planetary-like rotating ellipsoids, Vidal J. & D. Cébron, Proc. of the Royal Society A, **476**, 20200131, 2020.
- Acoustic spectra of a gas-filled rotating spheroid, Su S., D. Cébron, H-C. Nataf, P. Cardin, J. Vidal, M. Solazzo & Y. Do, *European J. Mech. B/Fluids*, **84**, 302-310, 2020.
- Helioseismology in a bottle: Modal acoustic velocimetry, Triana S.A., D.S. Zimmerman, H.-C. Nataf, A. Thorette, V. Lekic & D.P. Lathrop, *New Journal of Physics*, **16**, 113005, 2014.

Resolution kernels for libration flow



2. Recovering Greenspan's libration flow

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- Frequency splitting of *singlets* ${}_nS_l^{-m}$ and ${}_nS_l^{+m}$ can also be produced by fluid **flow**.
- We trigger **libration** flows in ZoRo and test the model of Greenspan (1968).

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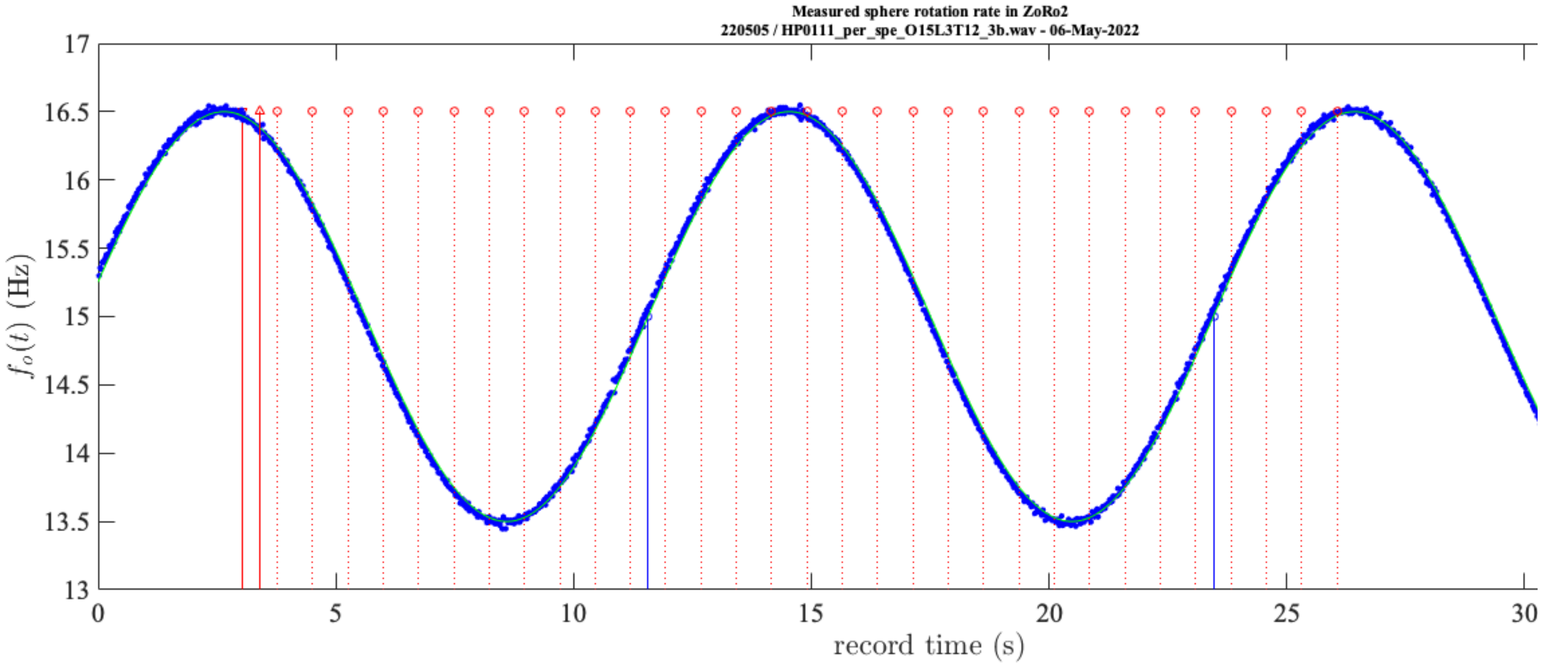
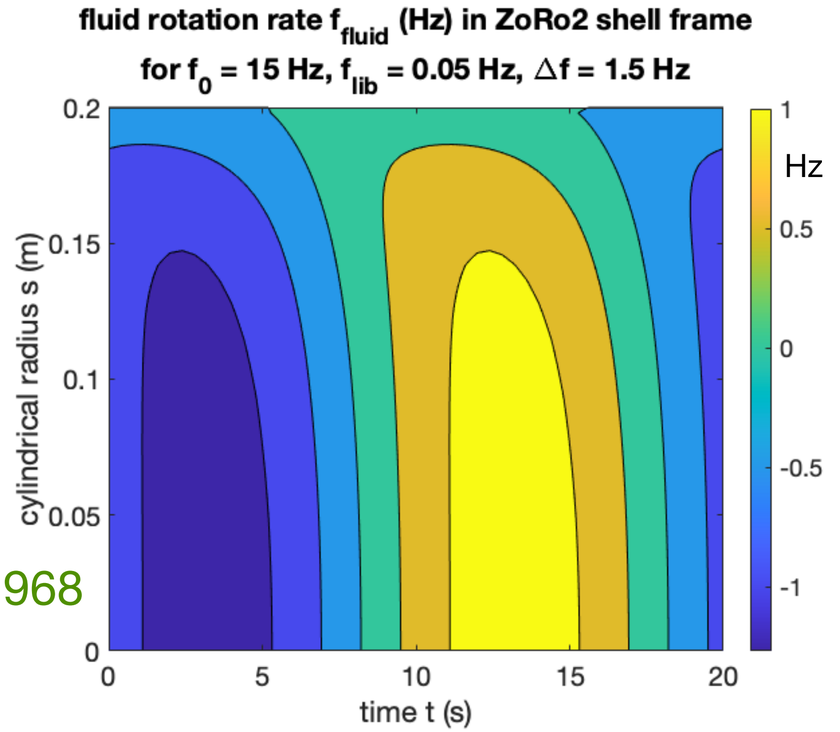


Libration flow: $f_{shell}(t) = f_o + \Delta f \sin(2\pi f_{lib} t)$

Greenspan, 1968



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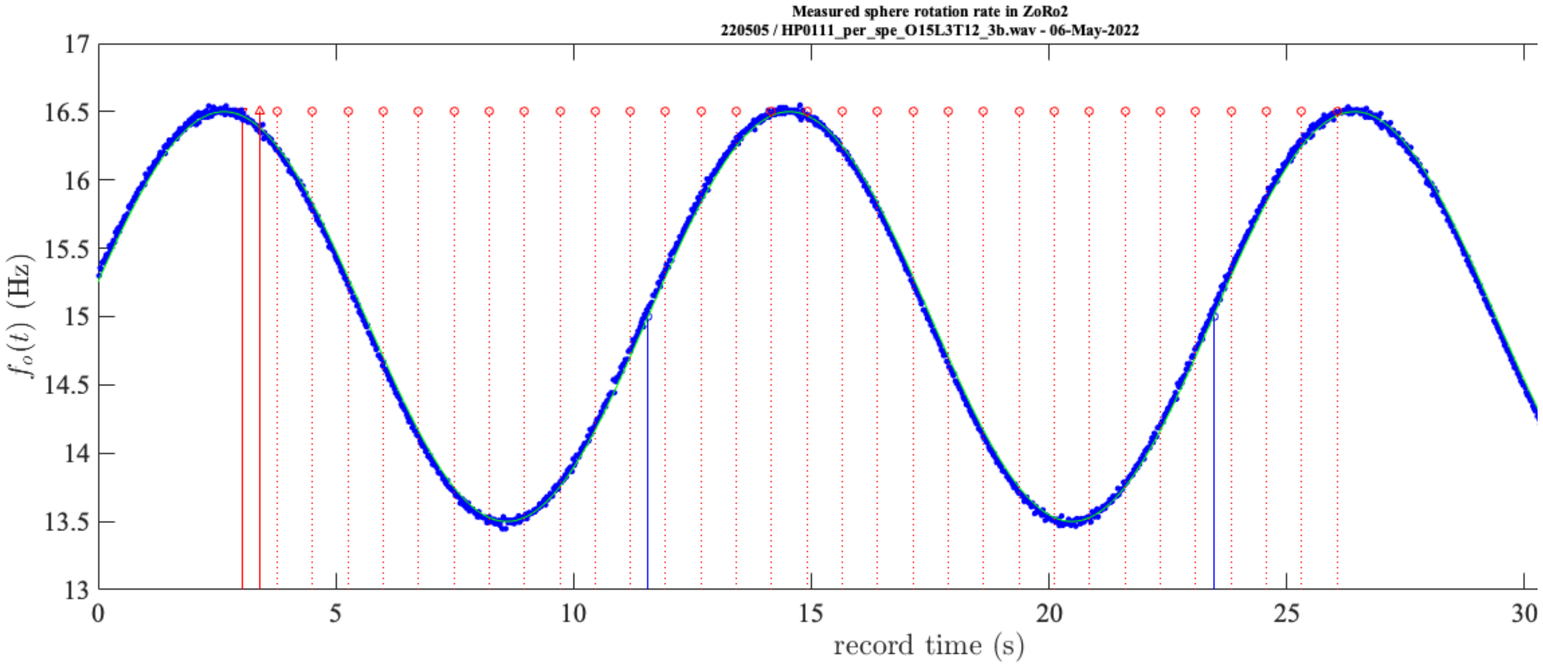
- Frequency splitting of *singlets* ${}_nS_l^{-m}$ and ${}_nS_l^{+m}$ can also be produced by fluid **flow**.
- We trigger **libration** flows in ZoRo and test the model of Greenspan (1968).
- The splitting then **varies** in time.
- We **repeat** a very **short chirp** targeting a **specific** doublet, here ${}_1S_3^{\pm 3}$.



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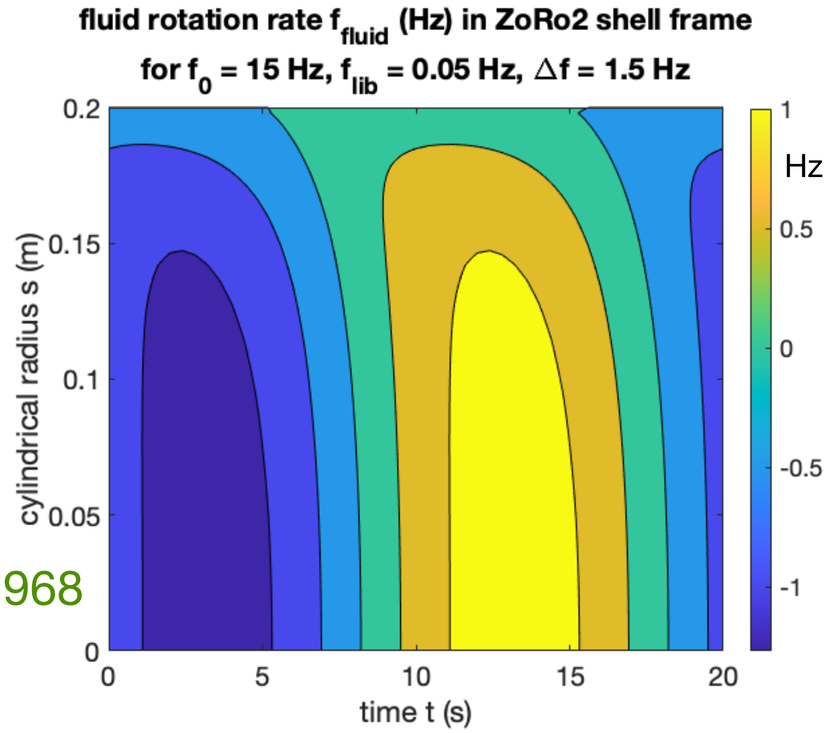
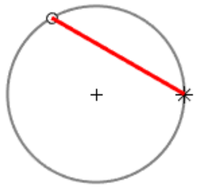
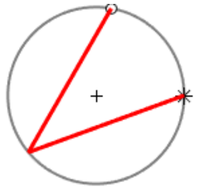
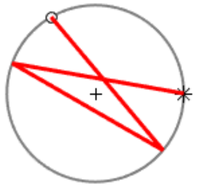




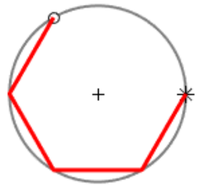
xP0
120°



xM1
80°



xP0_2
120°



xM3
120°