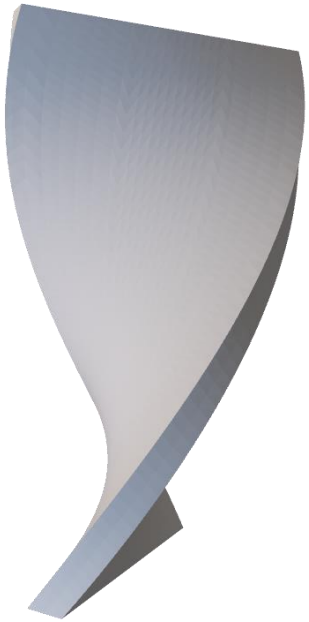
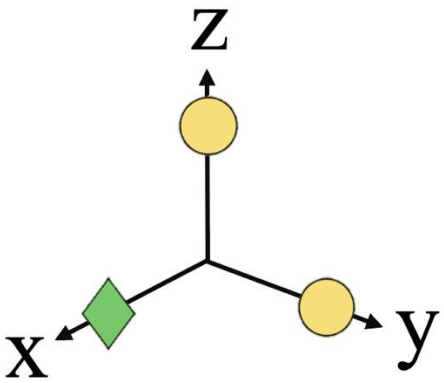
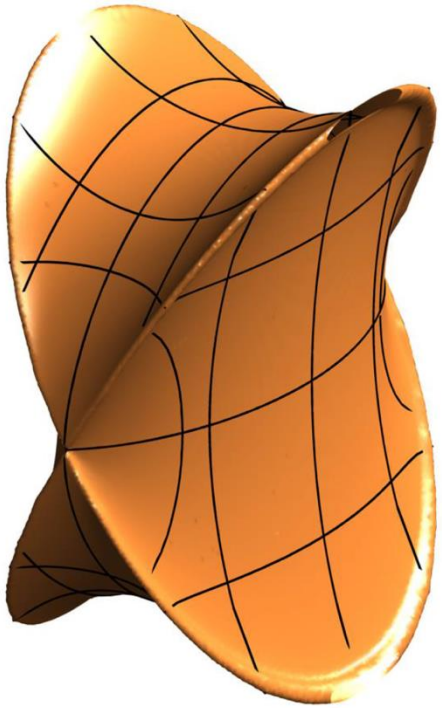
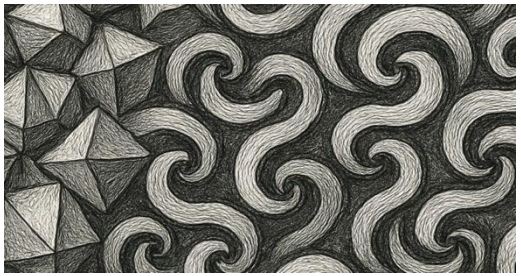
Chiral Design for Laminar and Turbulent Sedimentation







Greg Voth
Wesleyan University,
Middletown, CT, USA



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Meera Das, Undergraduate


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Arjun Menezes, Undergraduate


Darcy Collins, Undergraduate
Samitha Sanjuka, Graduate Student

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US National Science Foundation,
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Applications

Chiral Particles in Fluids

- Microorganisms
- Microrobotics
- Ice crystals in clouds
- Flocs and marine snow
- Control of alignment in colloidal suspensions

Chiral optical response of

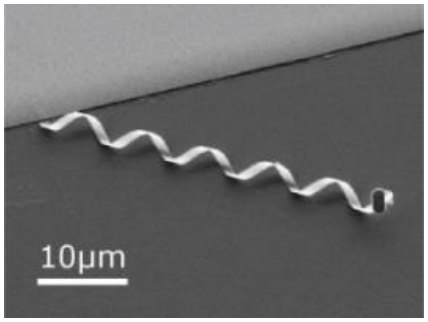
- Molecules
- Metamaterials

Chiral phases of liquid crystals

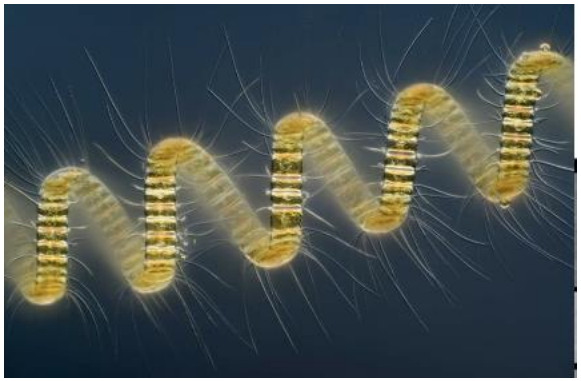
Chiral Elastic Materials

Unifying idea:
Translation-Rotation Coupling
(vector to pseudo-vector)

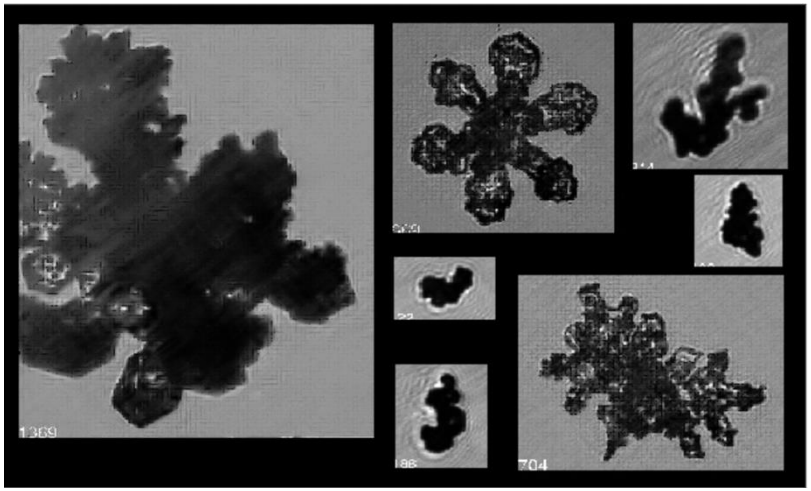
Namba Group, Osaka



Multi-scale robotics lab, ETH Zurich

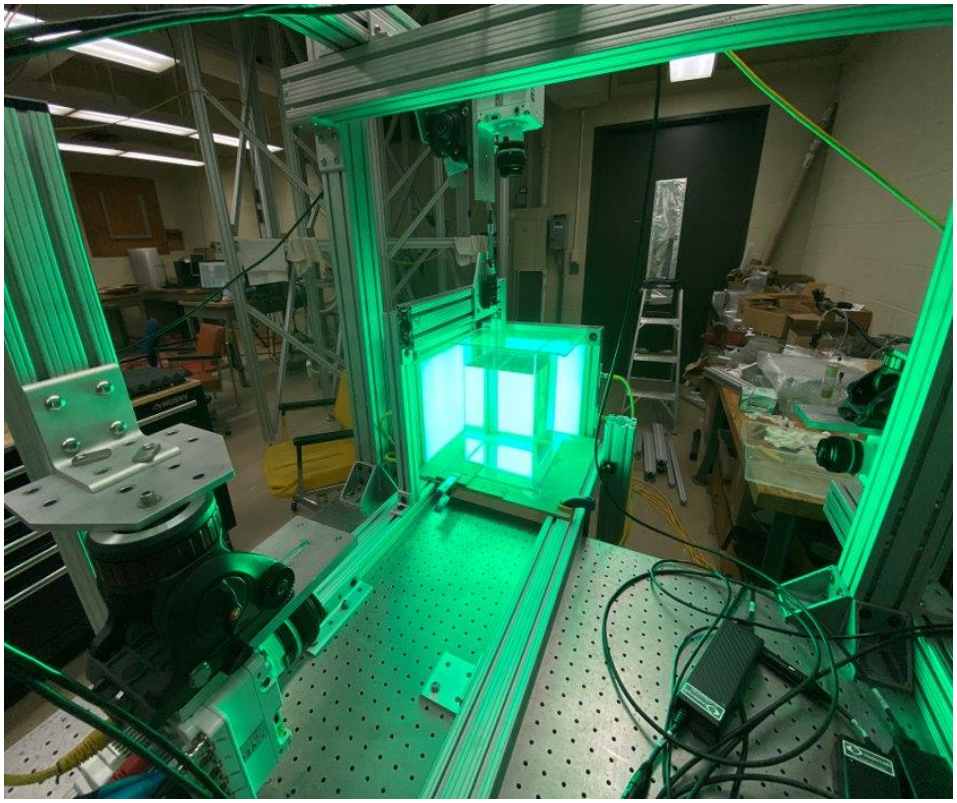


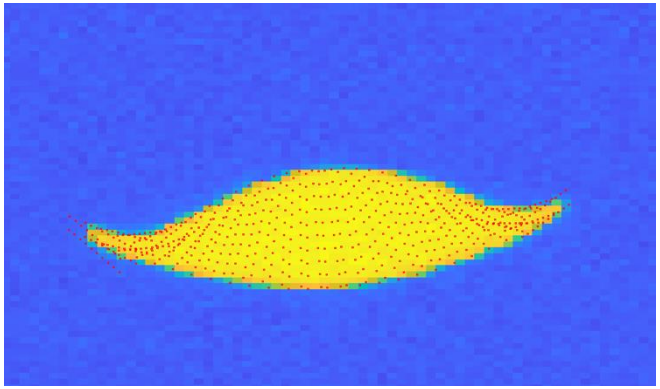
Wim van Egmond



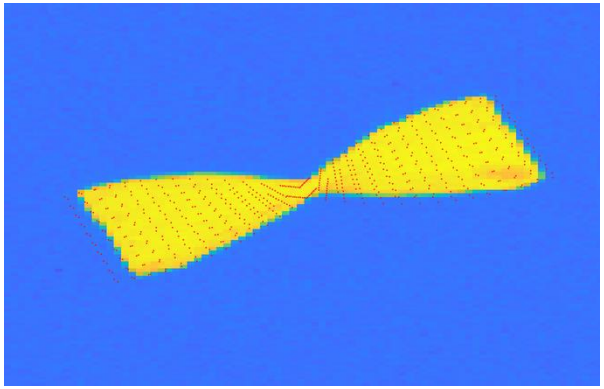
University of Manchester, Center for Atmospheric Science

Experimental 3D Tracking
Silicon oil 1000 cSt
Small Tank:
20cm x 20cm x 30cm
(length, width, height)

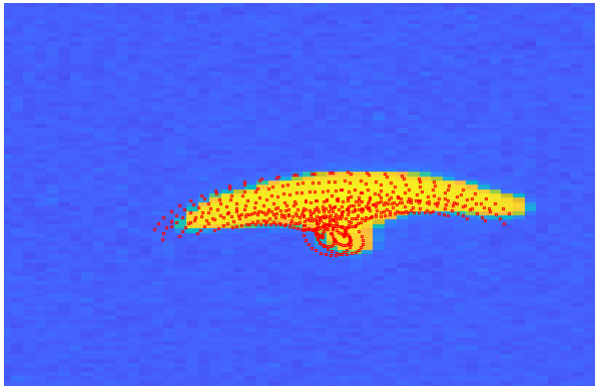




Side Camera 1

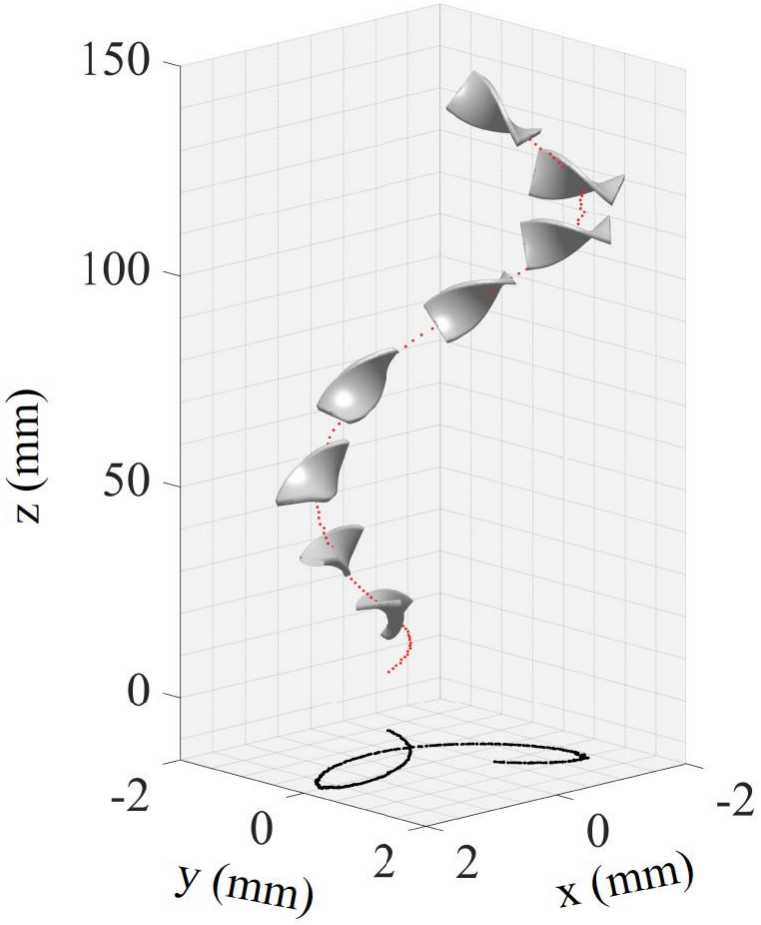


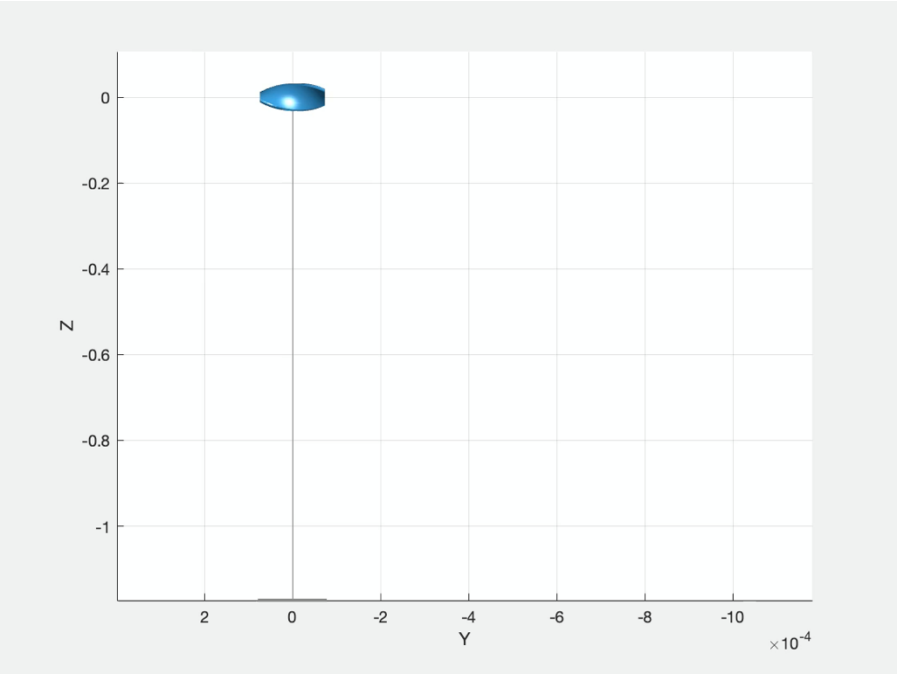
Top Camera



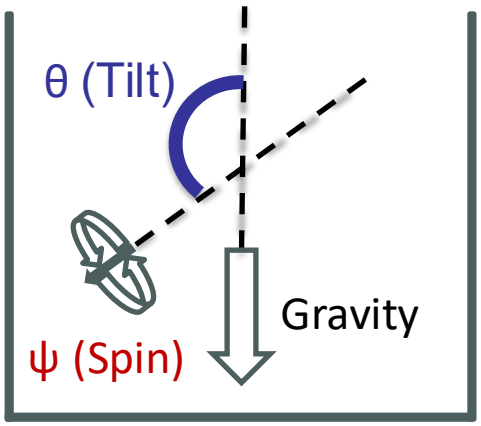
Side Camera 2

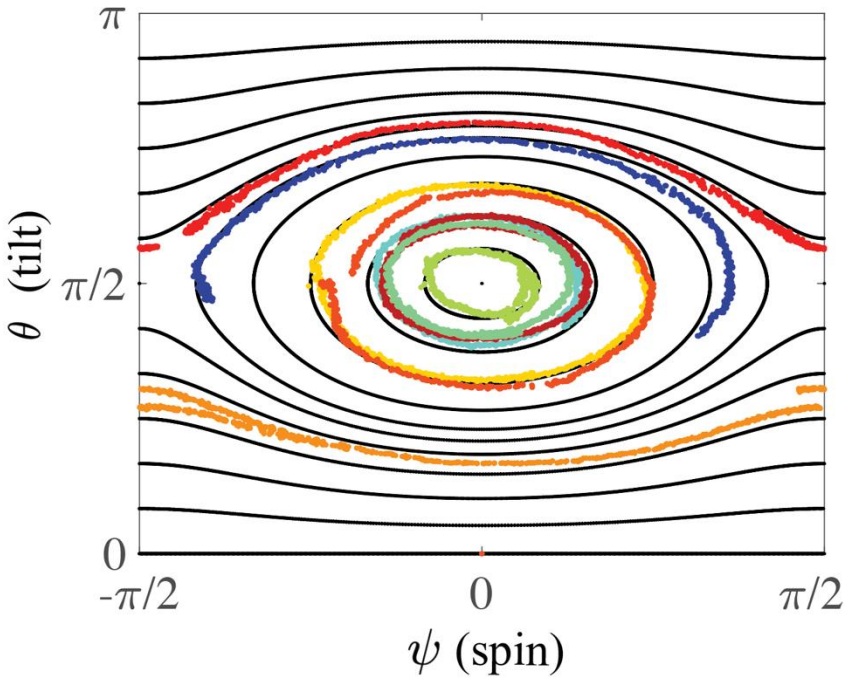
Sedimenting Helical Ribbon

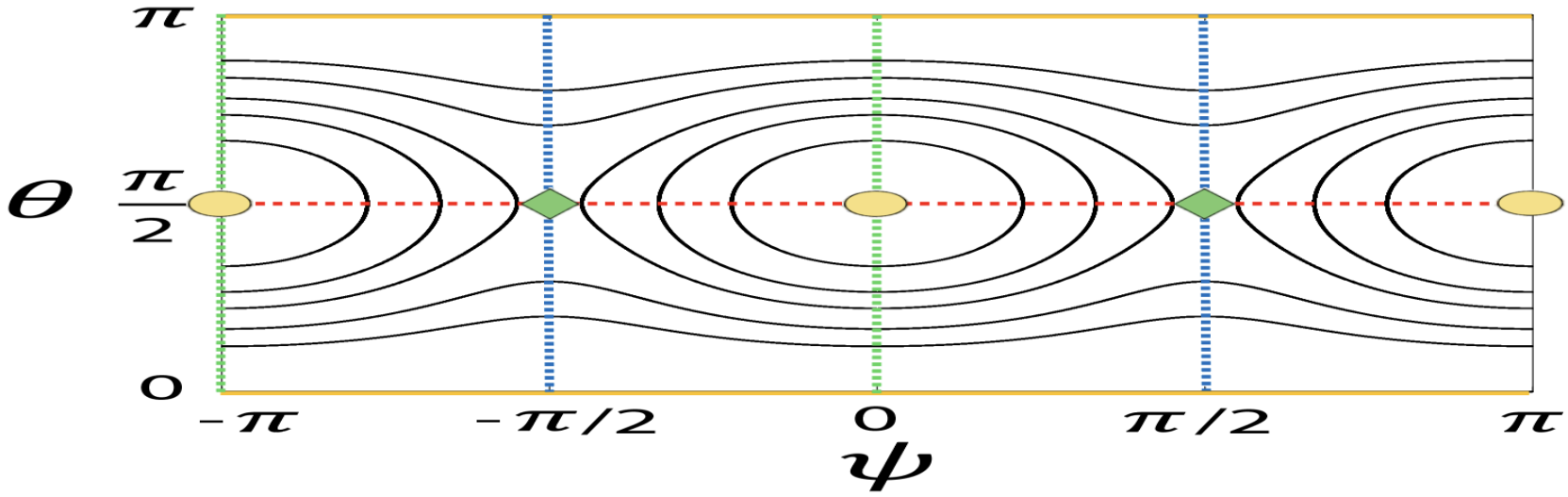




Huseby et al, Phys. Rev. Fluids (2025)
Miara et al, Comm. Phys. (2024)
Joshi et al, Phys. Rev. Lett. (2025)

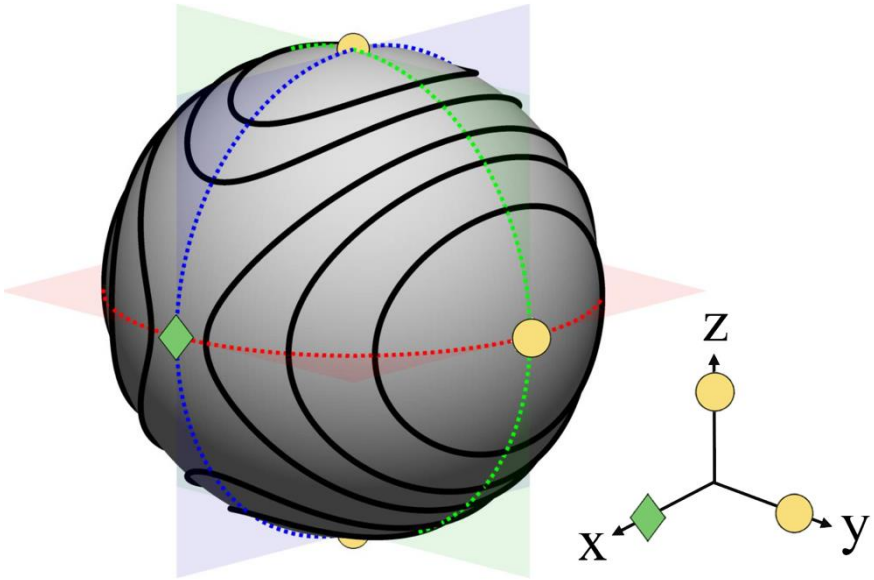

θ (Tilt)
Gravity
ψ (Spin)

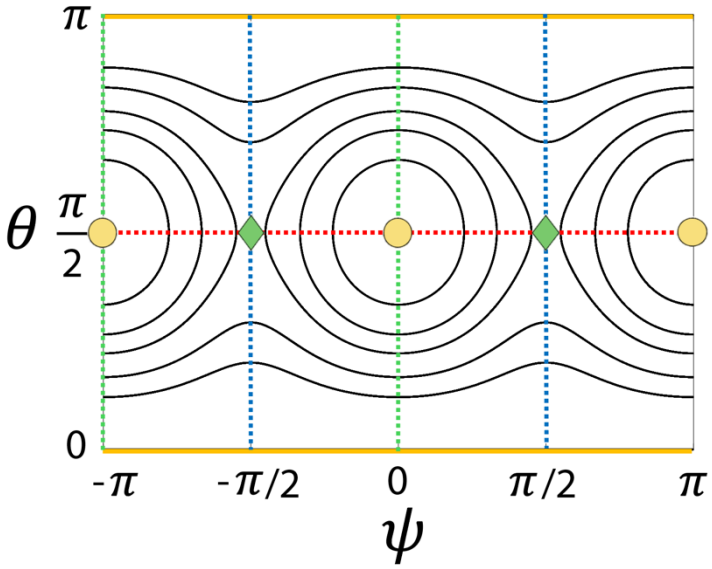

π
θ (tilt)
π/2
0
-π/2
0
π/2
ψ (spin)


π
θ
π/2
0
−π
−π/2
0
π/2
π
ψ

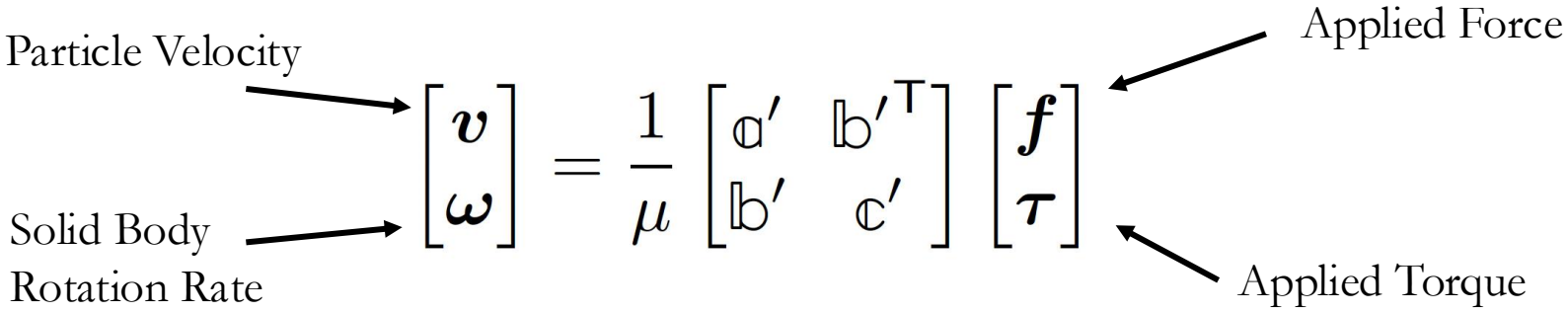
Dynamics of the gravity vector in body coordinates: Co-centered case

Witten and Diamant Rep. Prog. Physics (2020)
Gonzalez et al, JFM (2004)

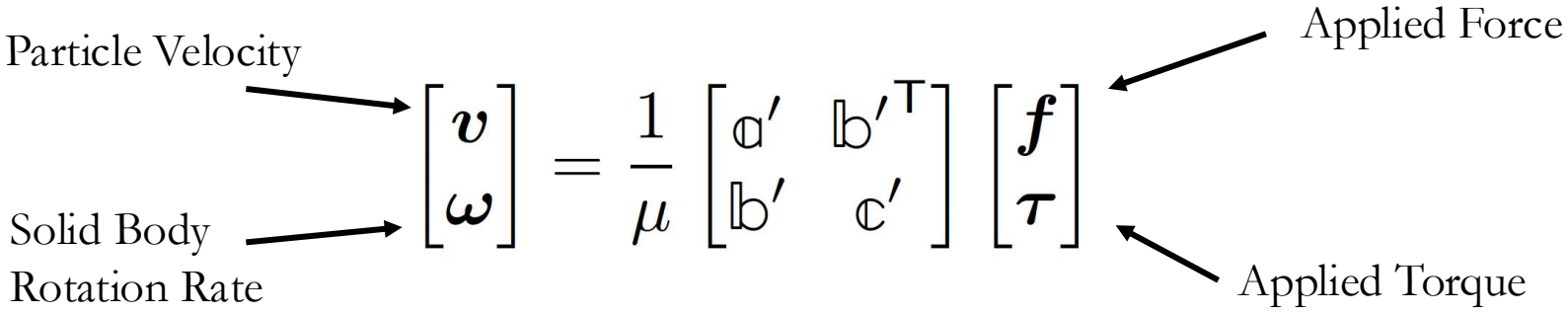




Mobility Tensors in Stokes Flow



Mobility Tensors in Stokes Flow



$$\begin{bmatrix} \boldsymbol{v} \\ \boldsymbol{\omega} \end{bmatrix} = \frac{1}{\mu} \begin{bmatrix} \mathbb{a}' & \mathbb{b}'^{\mathsf{T}} \\ \mathbb{b}' & \mathbb{c}' \end{bmatrix} \begin{bmatrix} \boldsymbol{f} \\ \boldsymbol{\tau} \end{bmatrix}$$

Resistance Tensors in Stokes Flow

$$\begin{bmatrix} \boldsymbol{f} \\ \boldsymbol{\tau} \end{bmatrix} = \mu \begin{bmatrix} \mathbb{A} & \mathbb{B}^{\mathsf{T}} & \mathbb{G} \\ \mathbb{B} & \mathbb{C} & \mathbb{H} \end{bmatrix} \begin{bmatrix} \boldsymbol{u}^{\infty} - \boldsymbol{v} \\ \boldsymbol{\Omega}^{\infty} - \boldsymbol{\omega} \\ \mathbb{S}^{\infty} \end{bmatrix}$$

Mobility Tensors in Stokes Flow

Particle Velocity

Solid Body Rotation Rate

Applied Force

Applied Torque

$$\begin{bmatrix} \boldsymbol{v} \\ \boldsymbol{\omega} \end{bmatrix} = \frac{1}{\mu} \begin{bmatrix} \mathbb{a}' & \mathbb{b}'^{\mathsf{T}} \\ \mathbb{b}' & \mathbb{c}' \end{bmatrix} \begin{bmatrix} \boldsymbol{f} \\ \boldsymbol{\tau} \end{bmatrix}$$

$$\frac{d}{dt}\hat{\boldsymbol{g}} = \boldsymbol{\omega} \times \hat{\boldsymbol{g}}$$

$$\frac{d}{dt}\hat{\boldsymbol{g}} = \frac{|f|}{\mu}(\mathbb{b}_f \hat{\boldsymbol{g}}) \times \hat{\boldsymbol{g}}$$

Gonzalez et al, JFM 2004

$\mathbb{b}_f$ is the translation-rotation coupling tensor around the center of force

- The co-centered case is when the center of force is the center of mobility. Then $\mathbb{b}_f$ is symmetric and the fixed points are the orthogonal eigenvectors.
- Translation theorem relates $\mathbb{b}_m$ (around the center of mobility) to $\mathbb{b}_f$

$$\mathbb{b}_f = \mathbb{b}_m + \mathbb{c} \times \boldsymbol{r}$$

Center of Force Offset

Geometric Symmetry and Parity-Time Reversal Symmetry

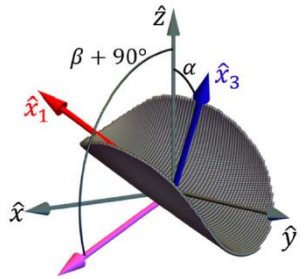
$\mathbb{b}$ is symmetric under orthogonal transformation $\mathbb{R}$ if it satisfies

$$\mathbb{b} = \det(\mathbb{R})\, \mathbb{R}\, \mathbb{b}\, \mathbb{R}^T$$

Brenner, Chem. Eng. Sci. (1964)
Fries, Einarson, and Mehlig, Phys. Rev. Fluids (2017)
Sundberg et al, arXiv:2512.17822 (2025)

Geometric symmetries occur when $\mathbb{R}$ leaves the geometry invariant.

It is not recognized widely enough that a reflection symmetry is not enough to ensure $\mathbb{b}=0$. Chirality is neither necessary nor sufficient for translation-rotation coupling.



Miara et al, Comm. Phys. (2024)

A Parity-Time reversal symmetry occurs when $\mathbb{R}$ is a special reflection that converts $\mathbb{b}$ to -$\mathbb{b}$

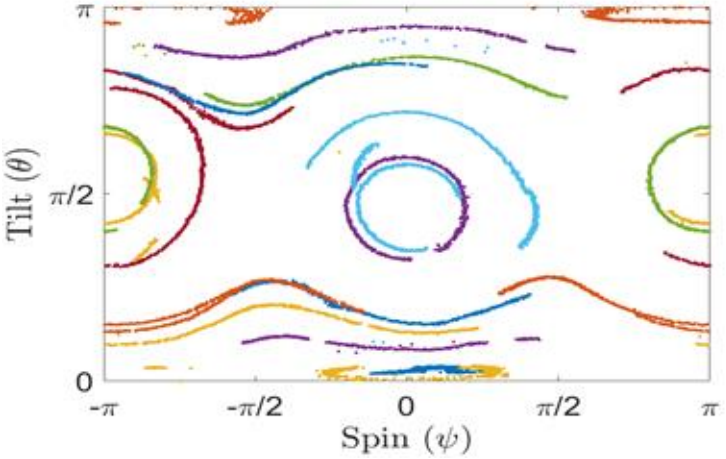
$$\frac{d}{dt}\hat{\boldsymbol{g}} = \frac{|f|}{\mu}(\mathbb{b}_f\hat{\boldsymbol{g}}) \times \hat{\boldsymbol{g}}$$

Co-centered particles always have 3 planes of Parity-Time reversal symmetry along whose normals are the three eigenvectors of $\mathbb{b}$.
A general particle has no PT symmetries.

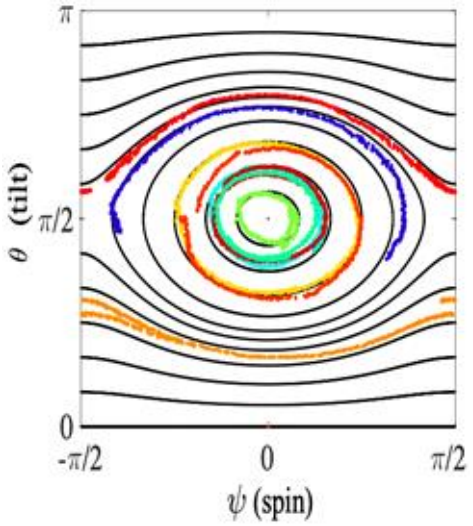
Actual Early Data

Form2 3D Printer

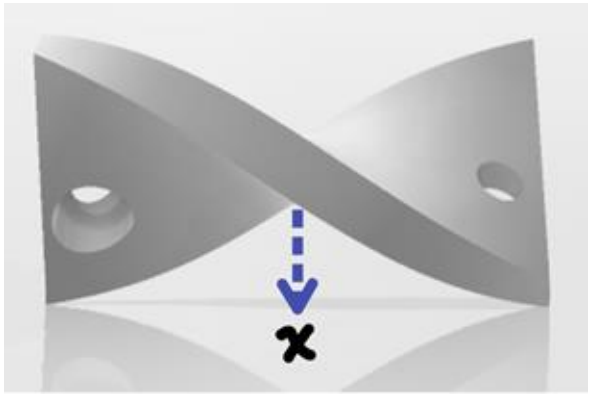
Printed on FormLabs Printer

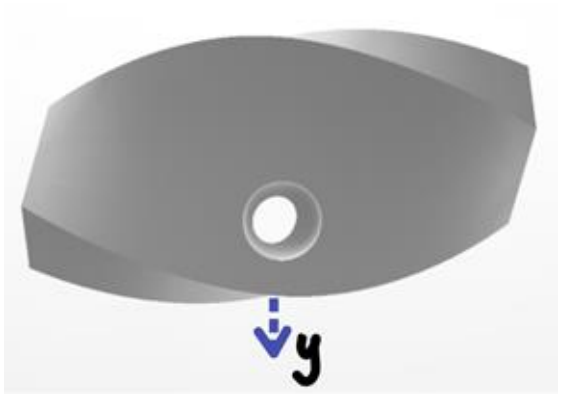


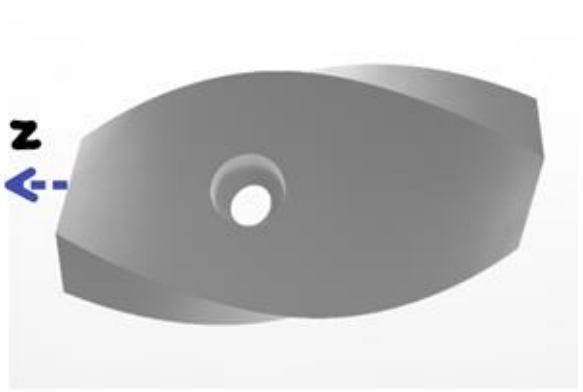
Printed by Boston Microfabrication

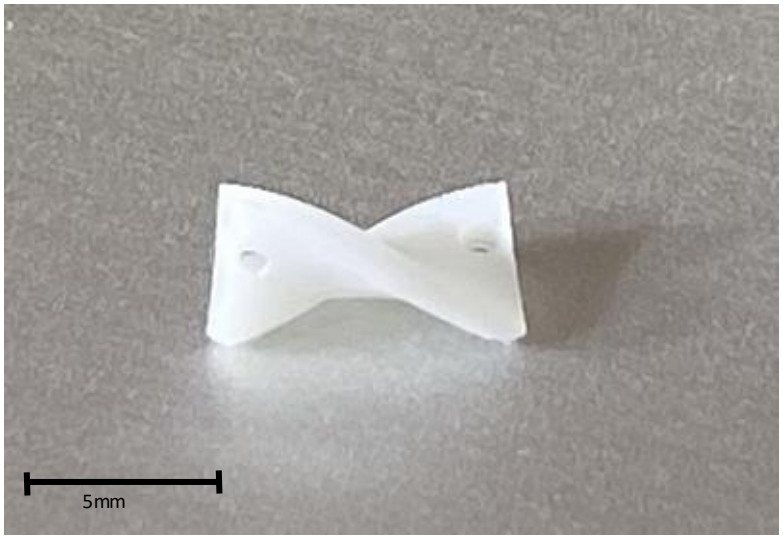


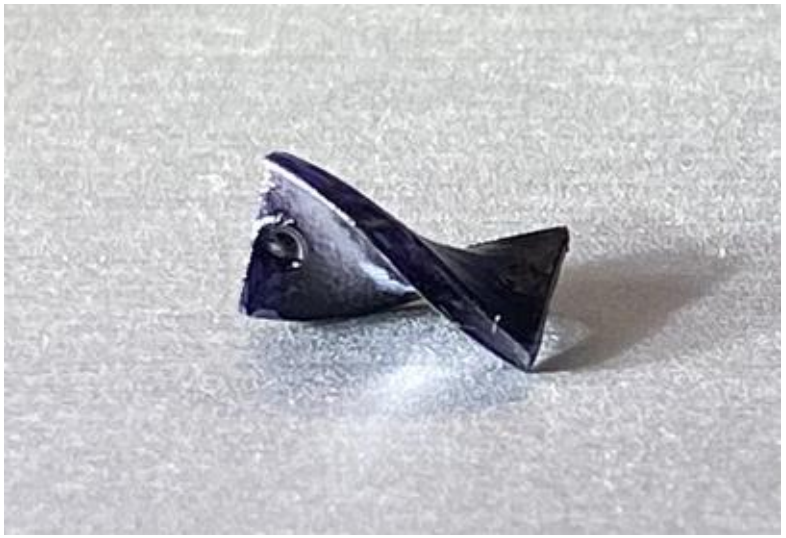
Controlling Center of Mass Offset



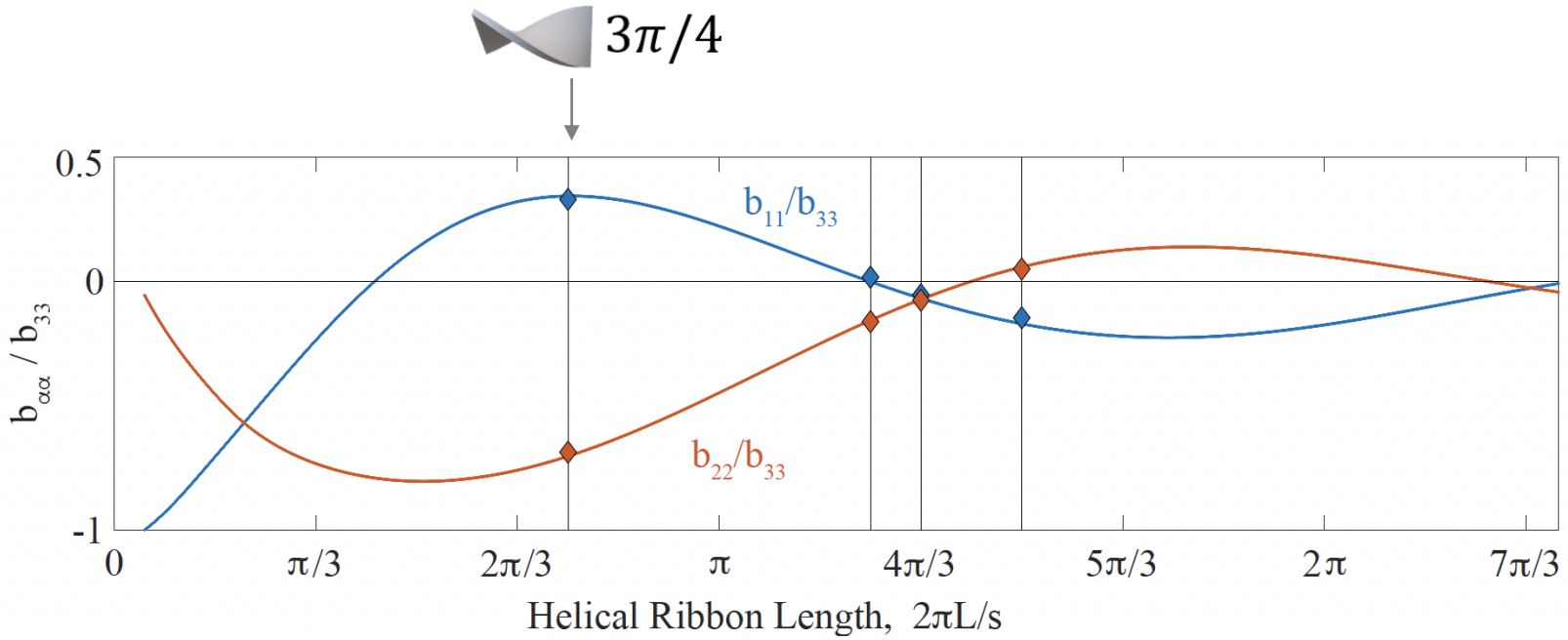


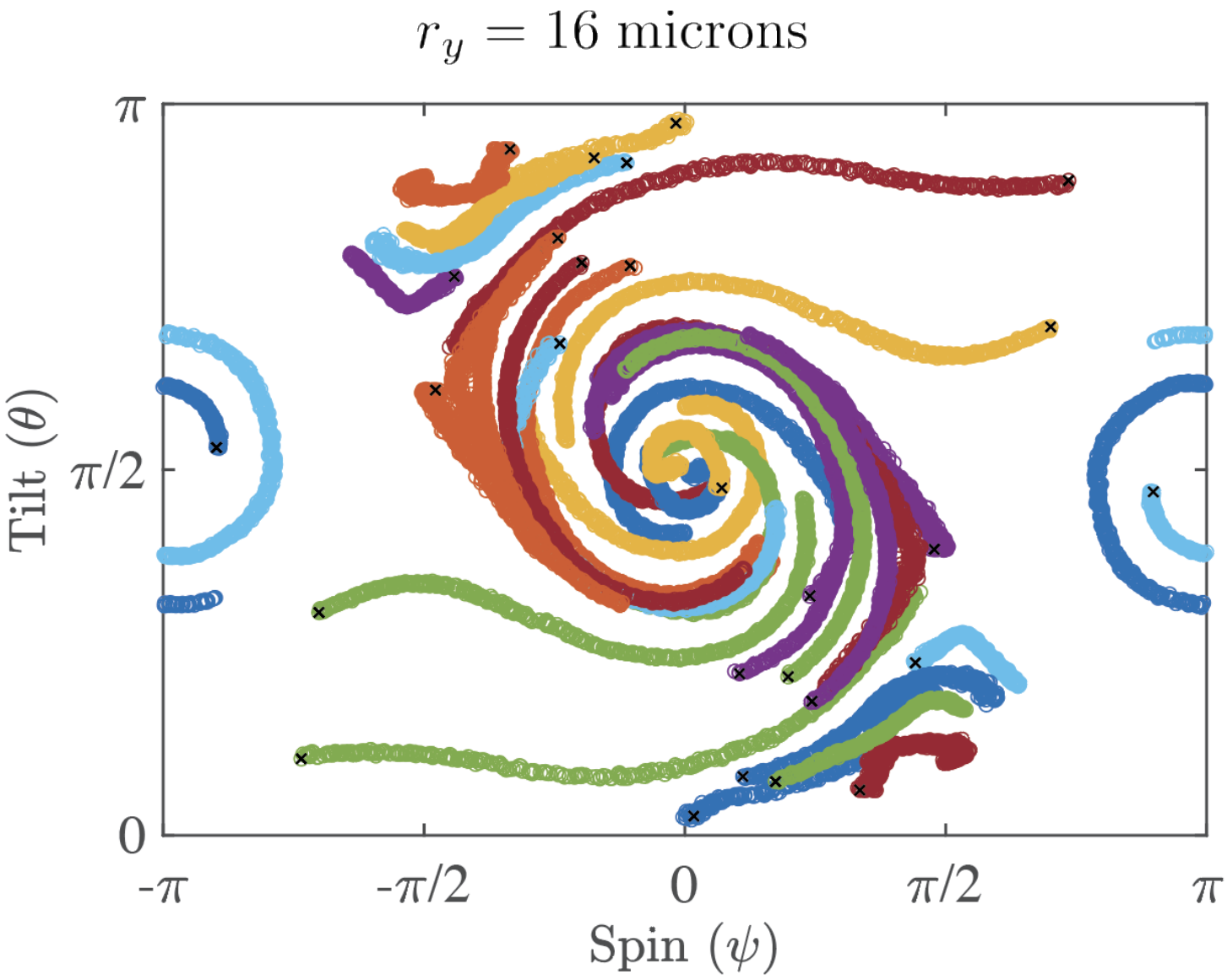


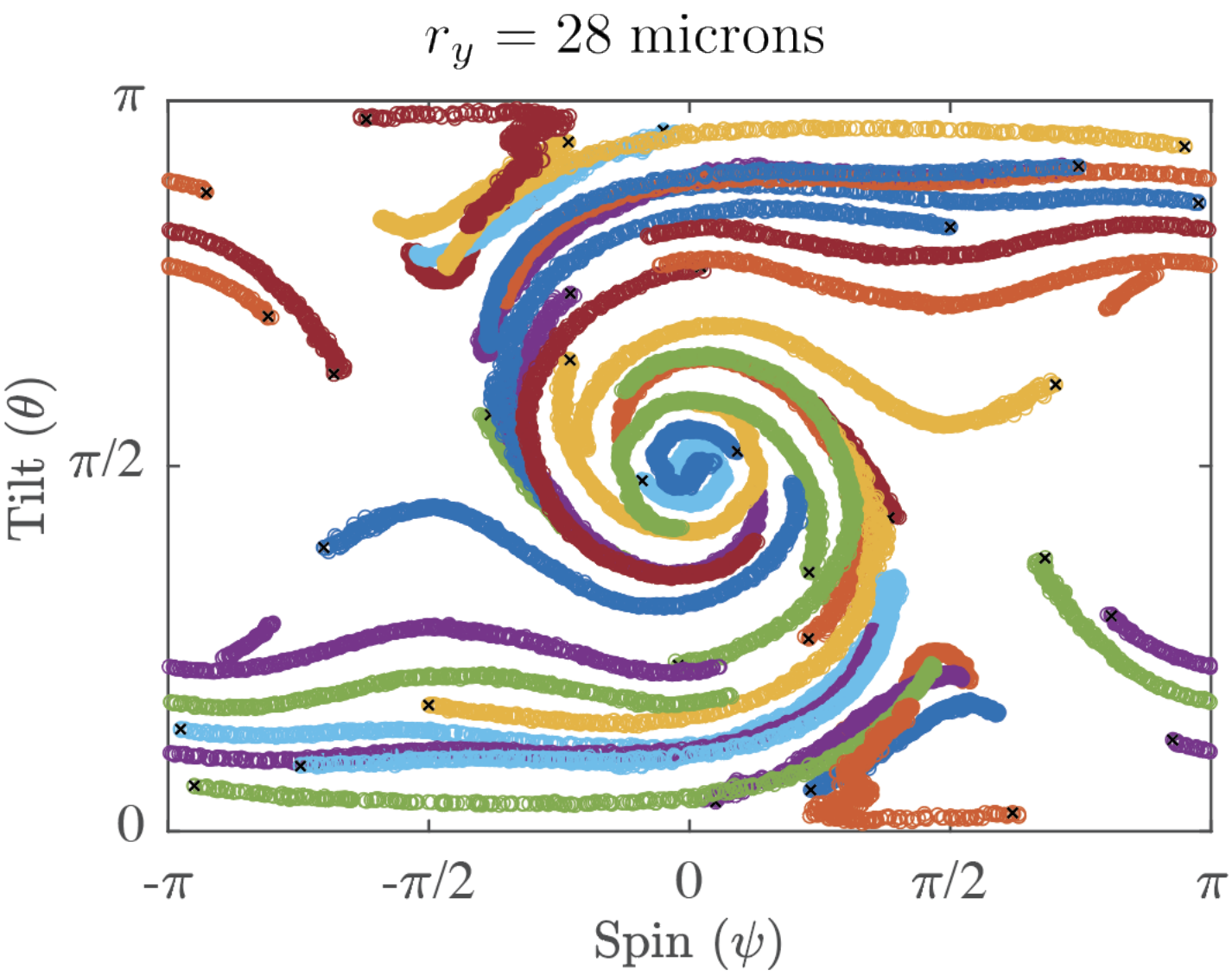


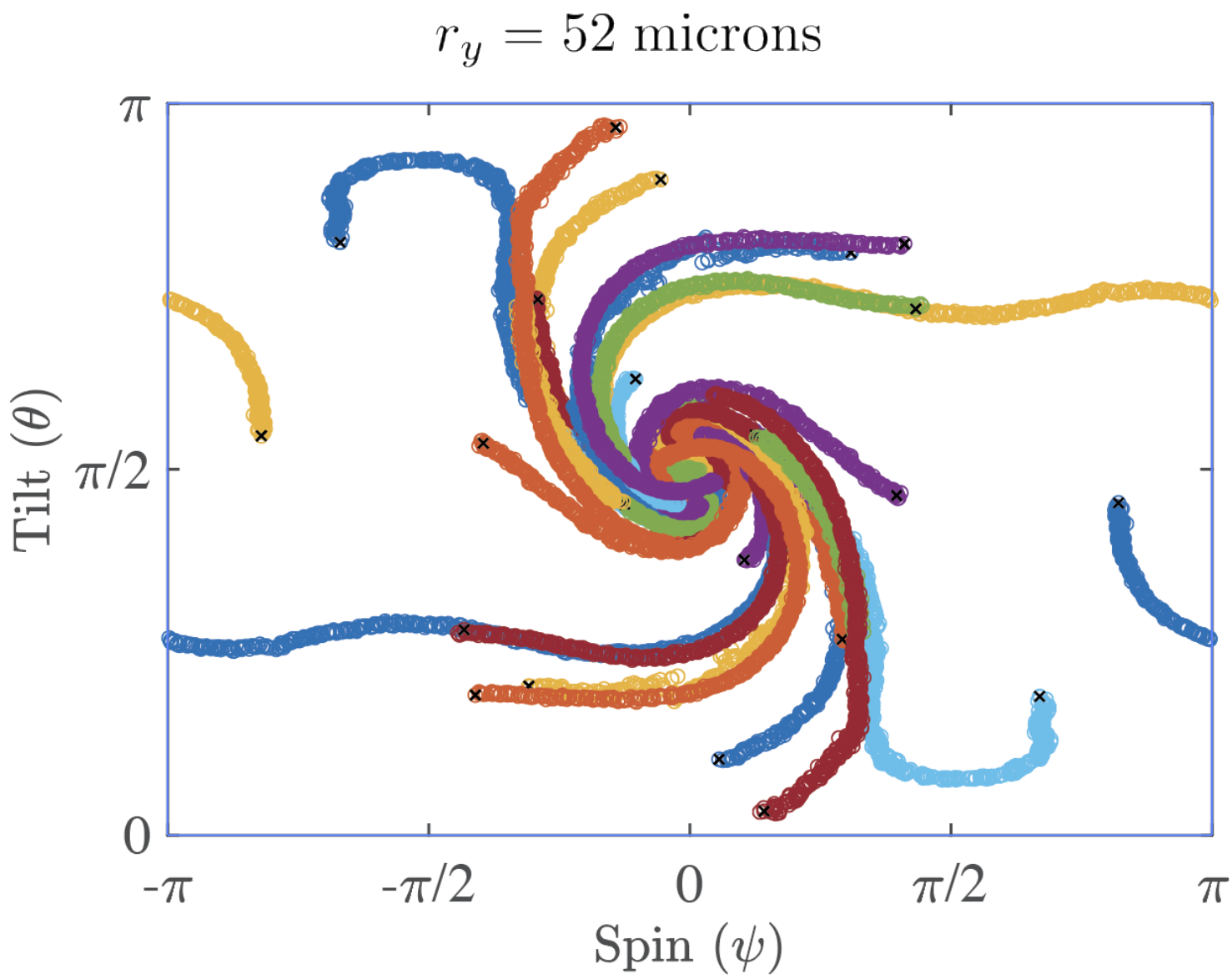


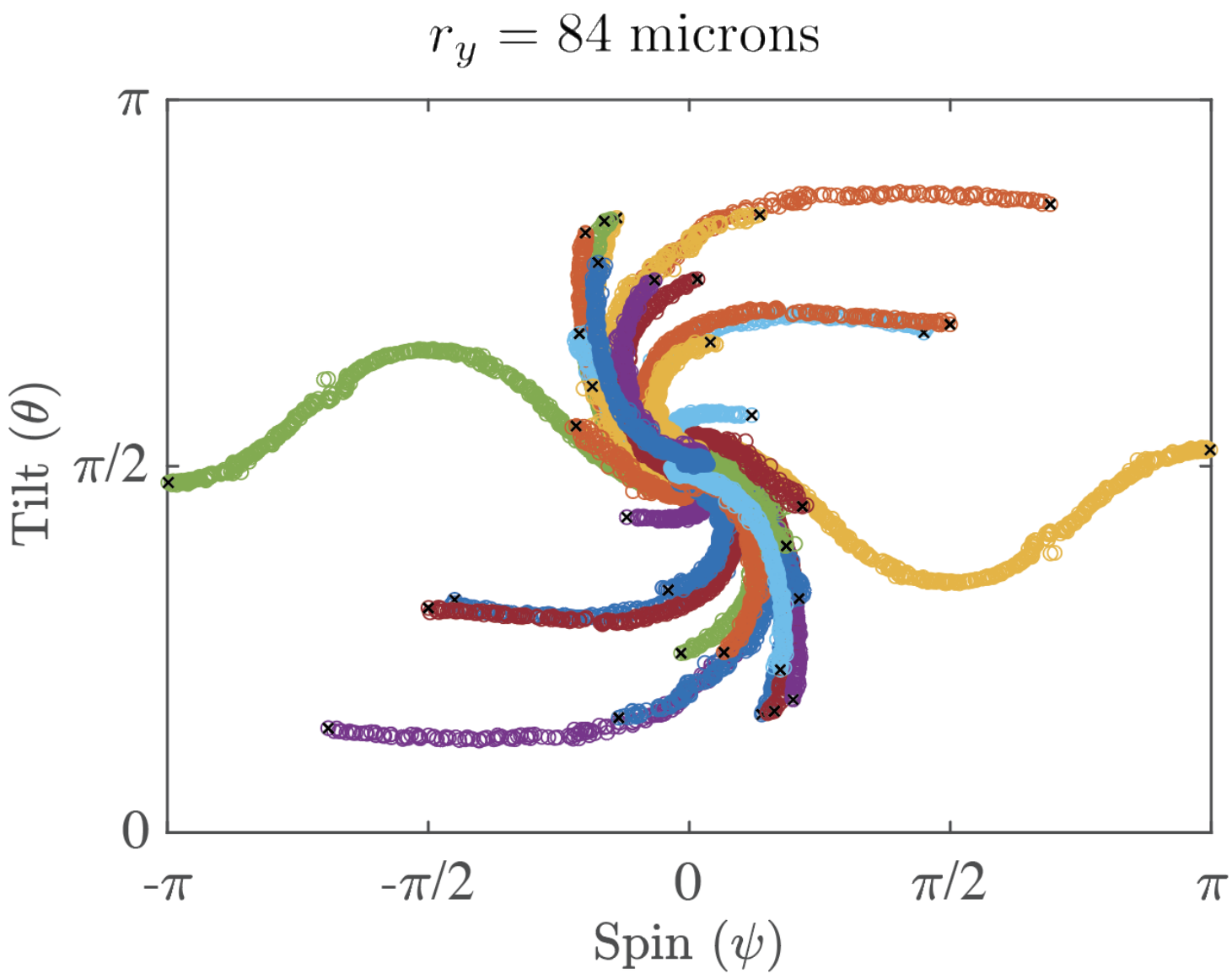
Geometry is Constant

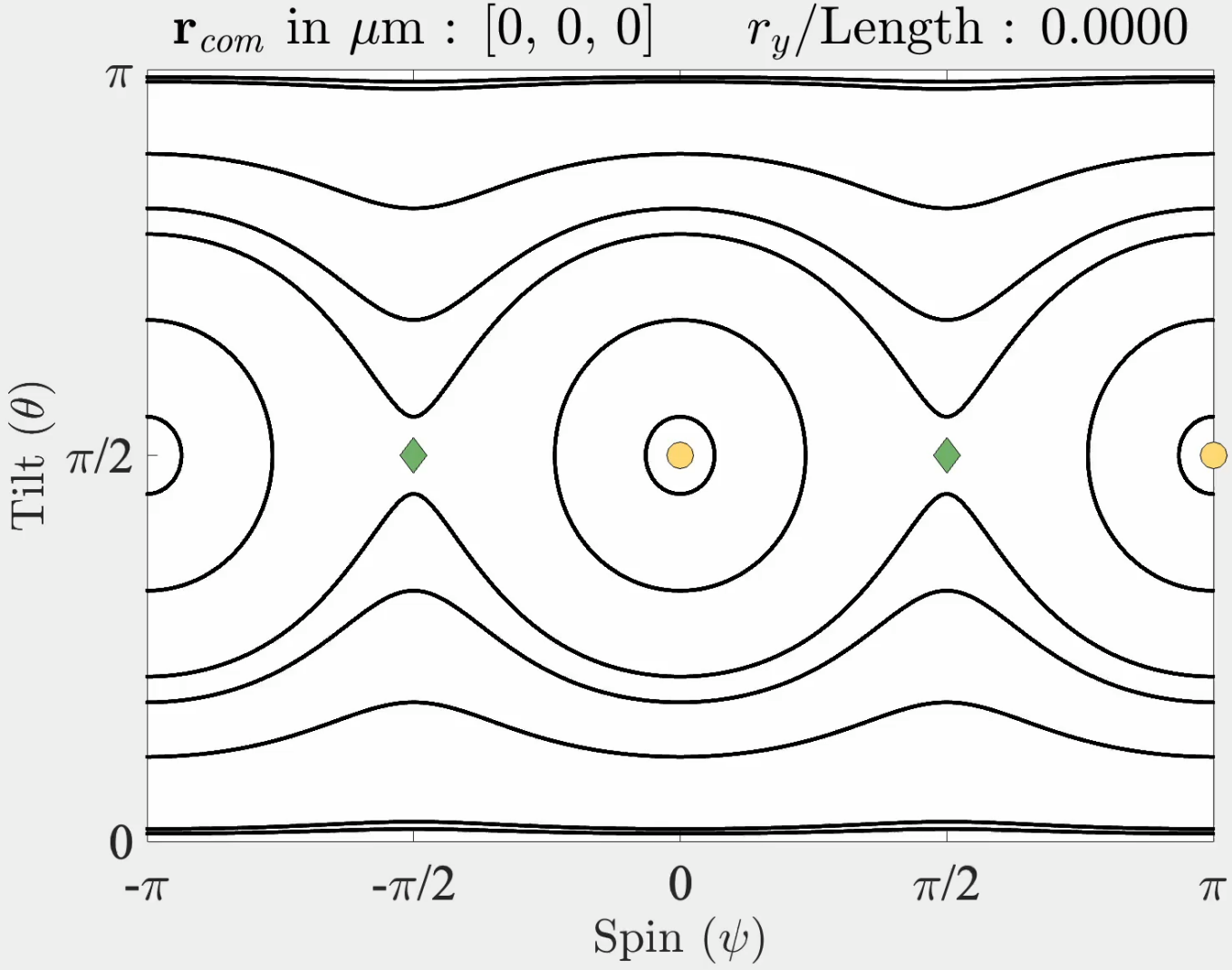



$r_y = 16$ microns
π
$\pi/2$
0
Tilt (θ)
$-\pi$
$-\pi/2$
0
$\pi/2$
π
Spin (ψ)

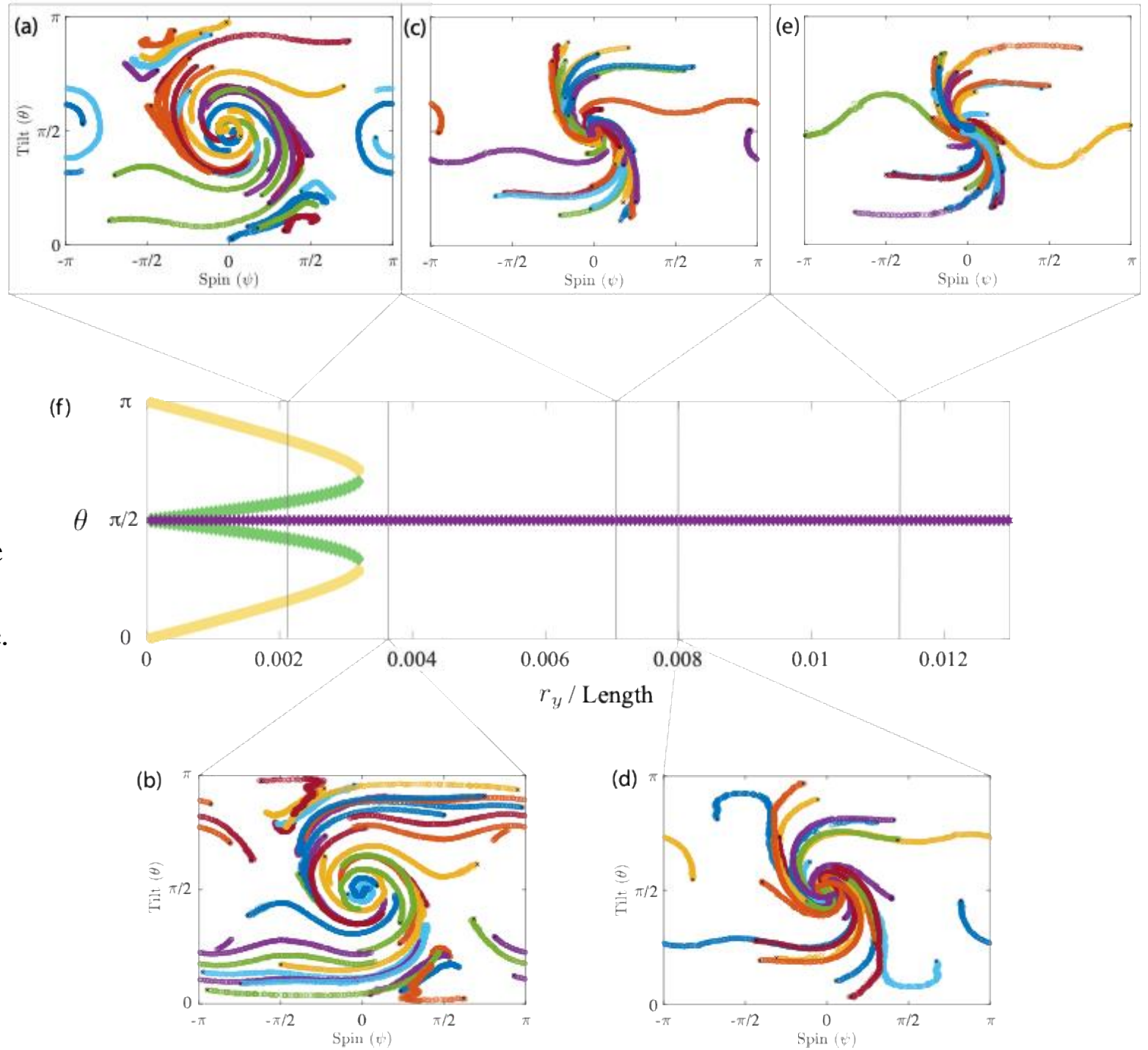

$r_y = 28$ microns
π
$\pi/2$
0
Tilt (θ)
$-\pi$
$-\pi/2$
0
$\pi/2$
π
Spin (ψ)


$r_y = 52$ microns
π
$\pi/2$
0
Tilt (θ)
$-\pi$
$-\pi/2$
0
$\pi/2$
π
Spin (ψ)


$r_y = 84$ microns
π
$\pi/2$
0
Tilt (θ)
$-\pi$
$-\pi/2$
0
$\pi/2$
π
Spin (ψ)


$\mathbf{r}_{com}$ in μm : [0, 0, 0]
r_y/Length : 0.0000
π
$\pi/2$
0
Tilt (θ)
-π
-$\pi/2$
0
$\pi/2$
π
Spin (ψ)

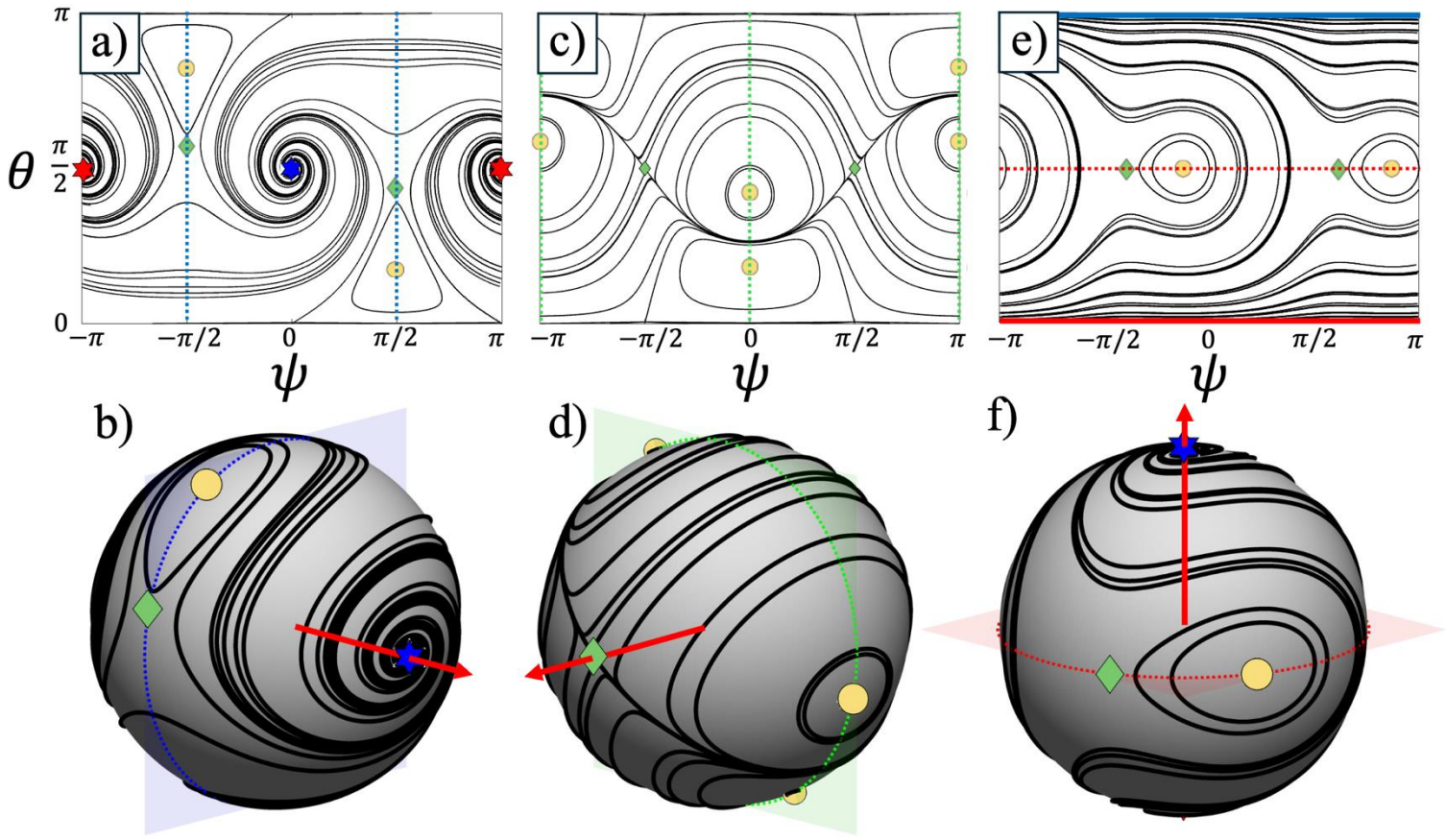
Offset of the Center of Force in y direction: minor axis of the co-centered reference particle.



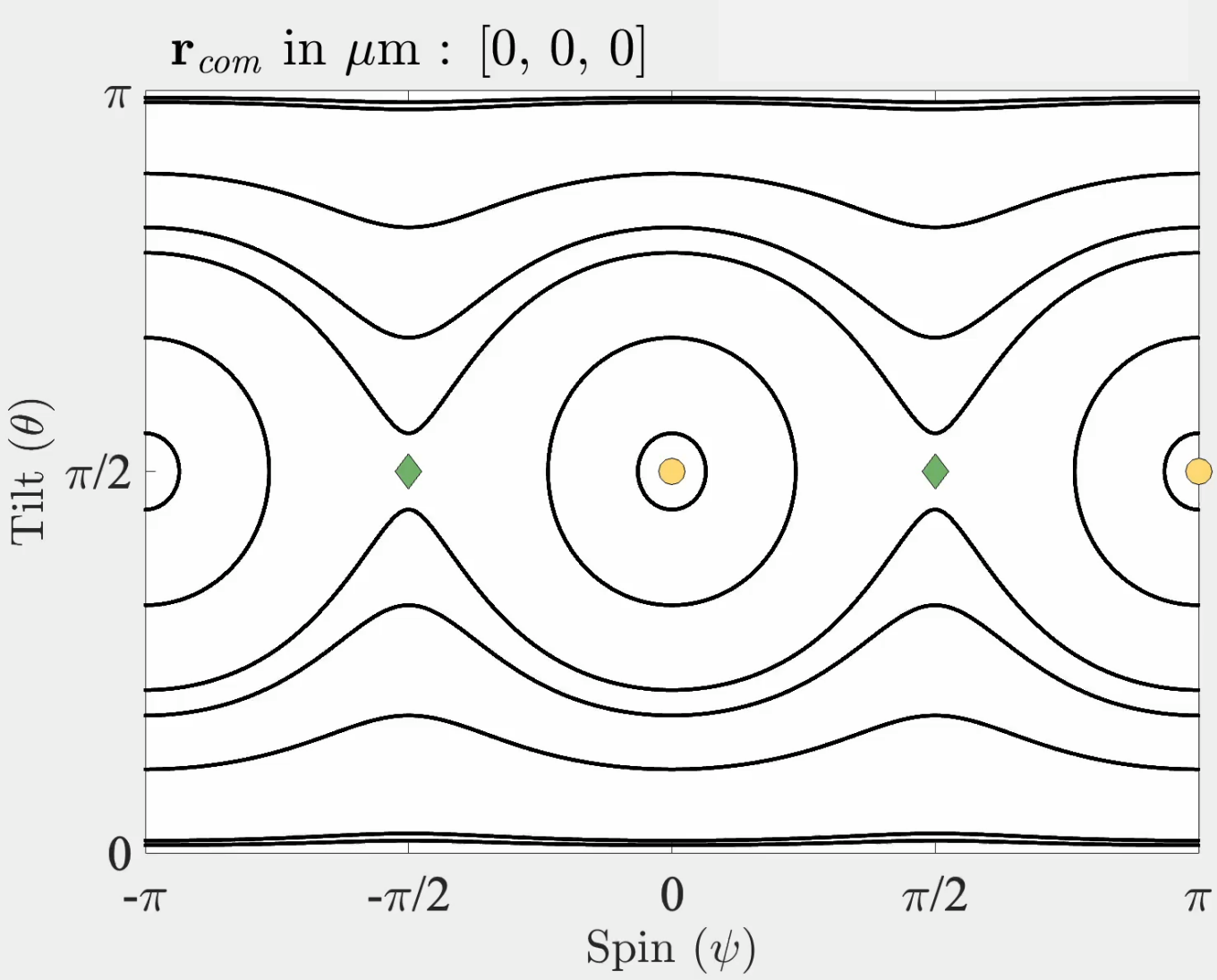
Minor Axis

Intermediate Axis

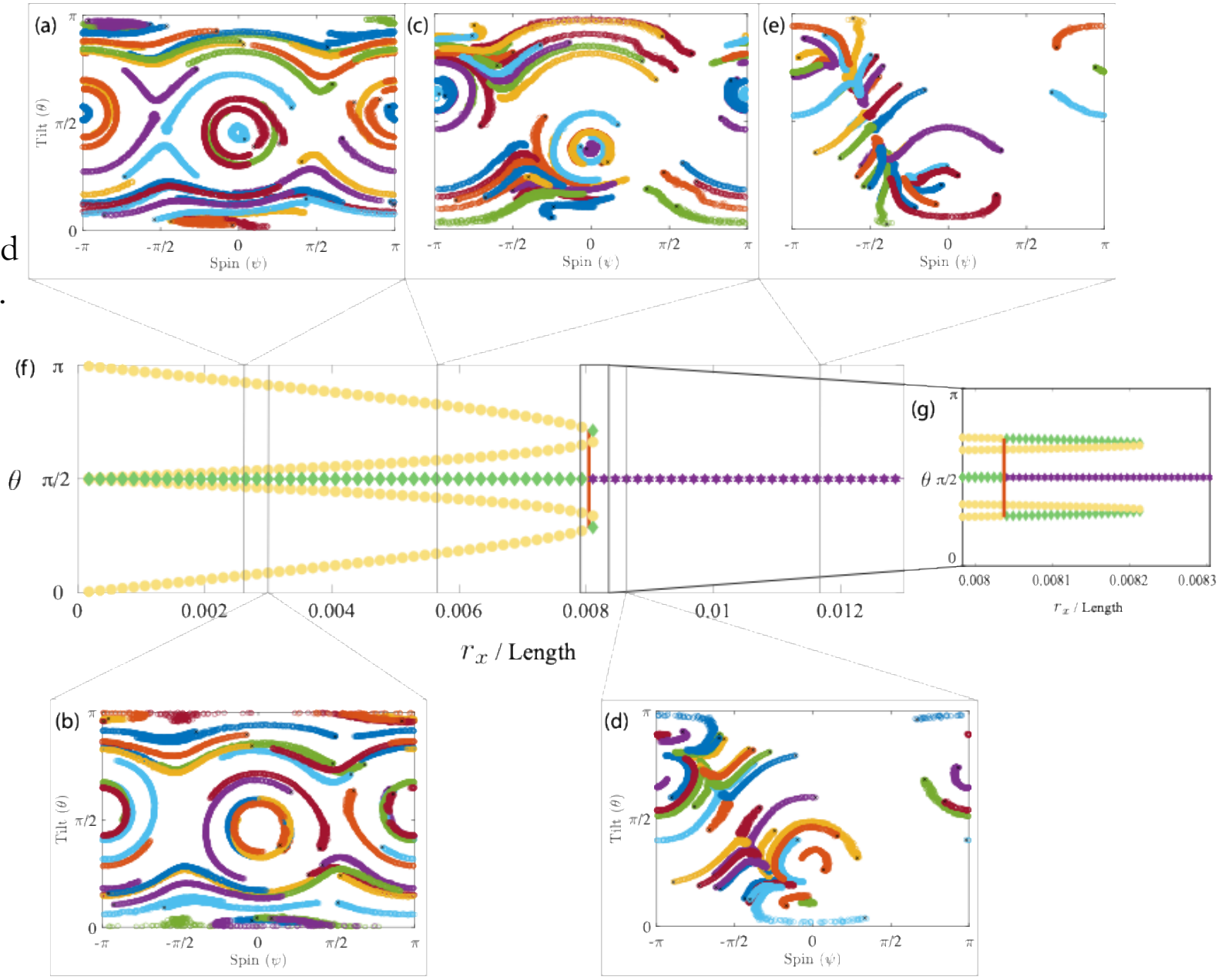
Major Axis



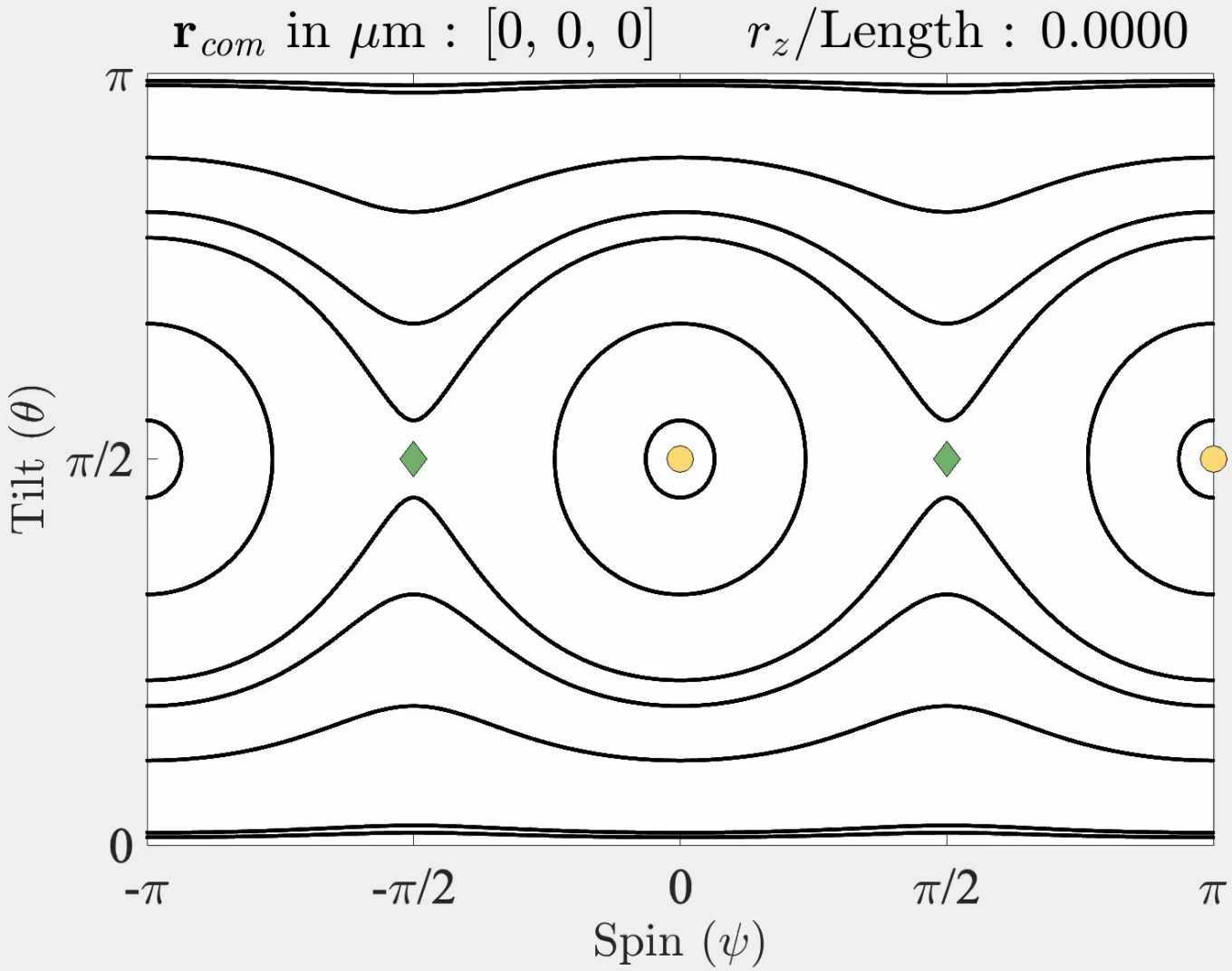
Intermediate Axis (r_x)



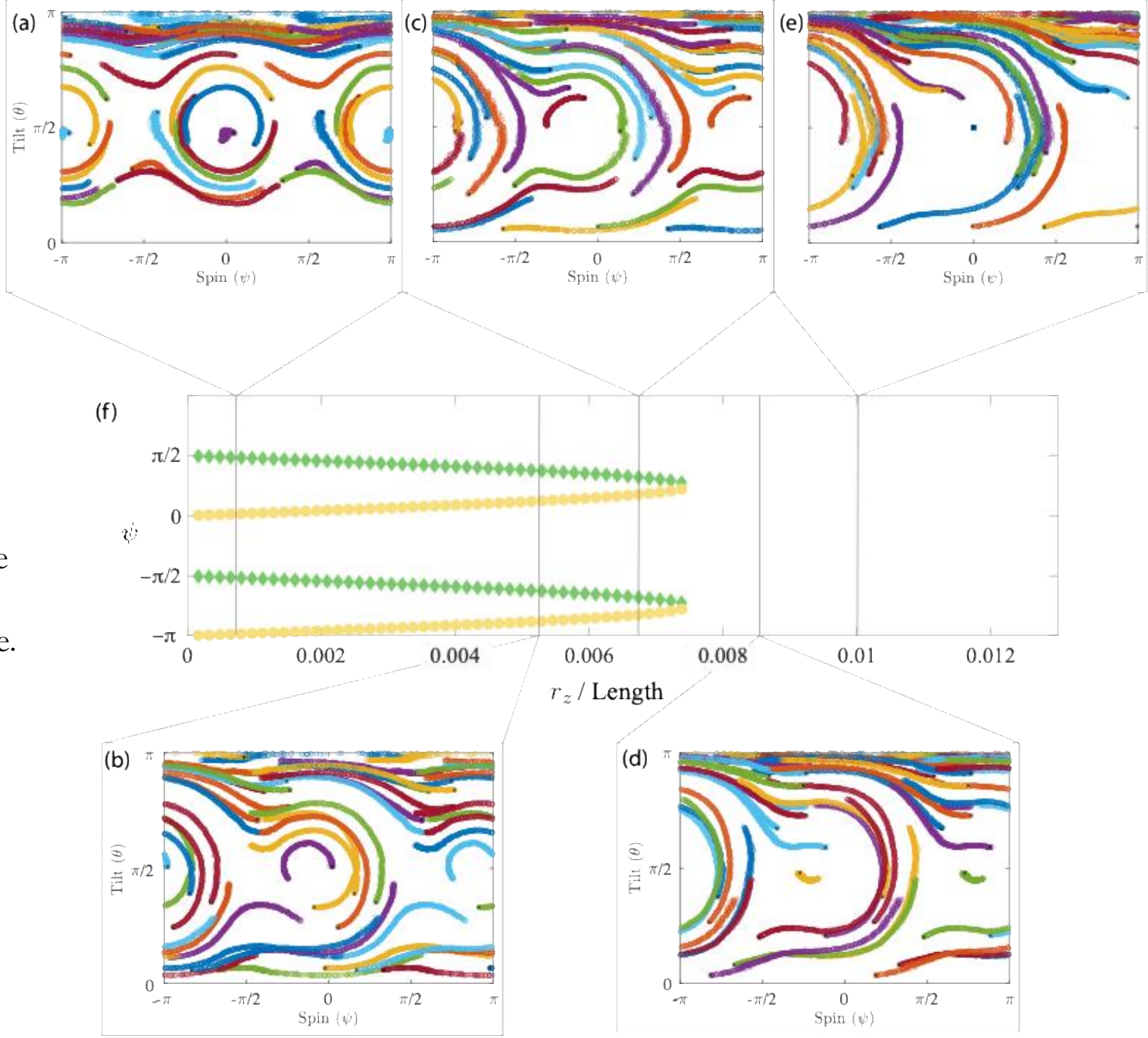
Offset of the Center of Force in x direction: intermediate axis of the co-centered reference particle.



Major Axis


$\mathbf{r}_{com}$ in μm : [0, 0, 0]
r_z/Length : 0.0000
π
$\pi/2$
0
Tilt (θ)
$-\pi$
$-\pi/2$
0
$\pi/2$
π
Spin (ψ)

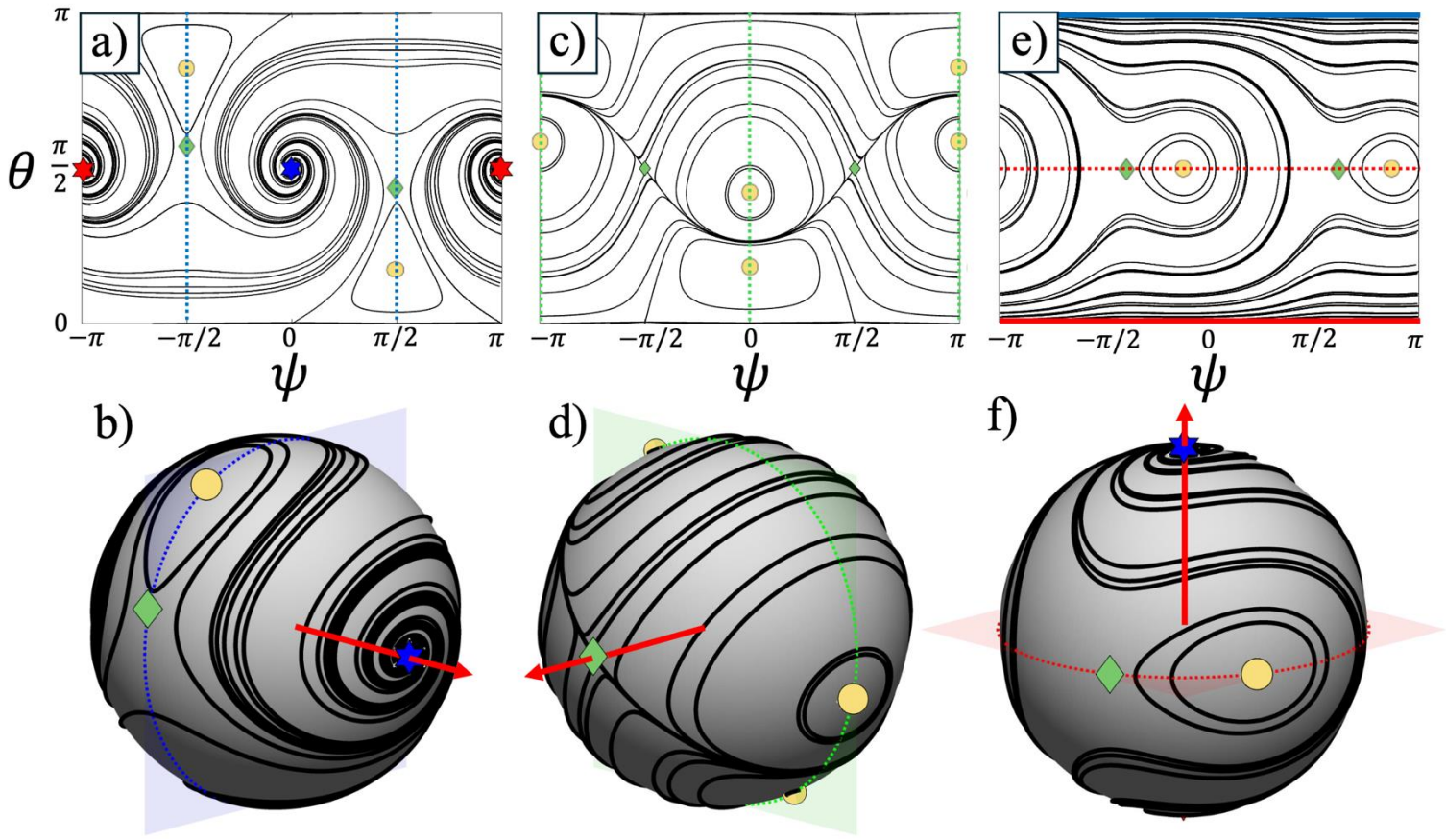
Offset of the Center of Force in z direction: major axis of the co-centered reference particle.



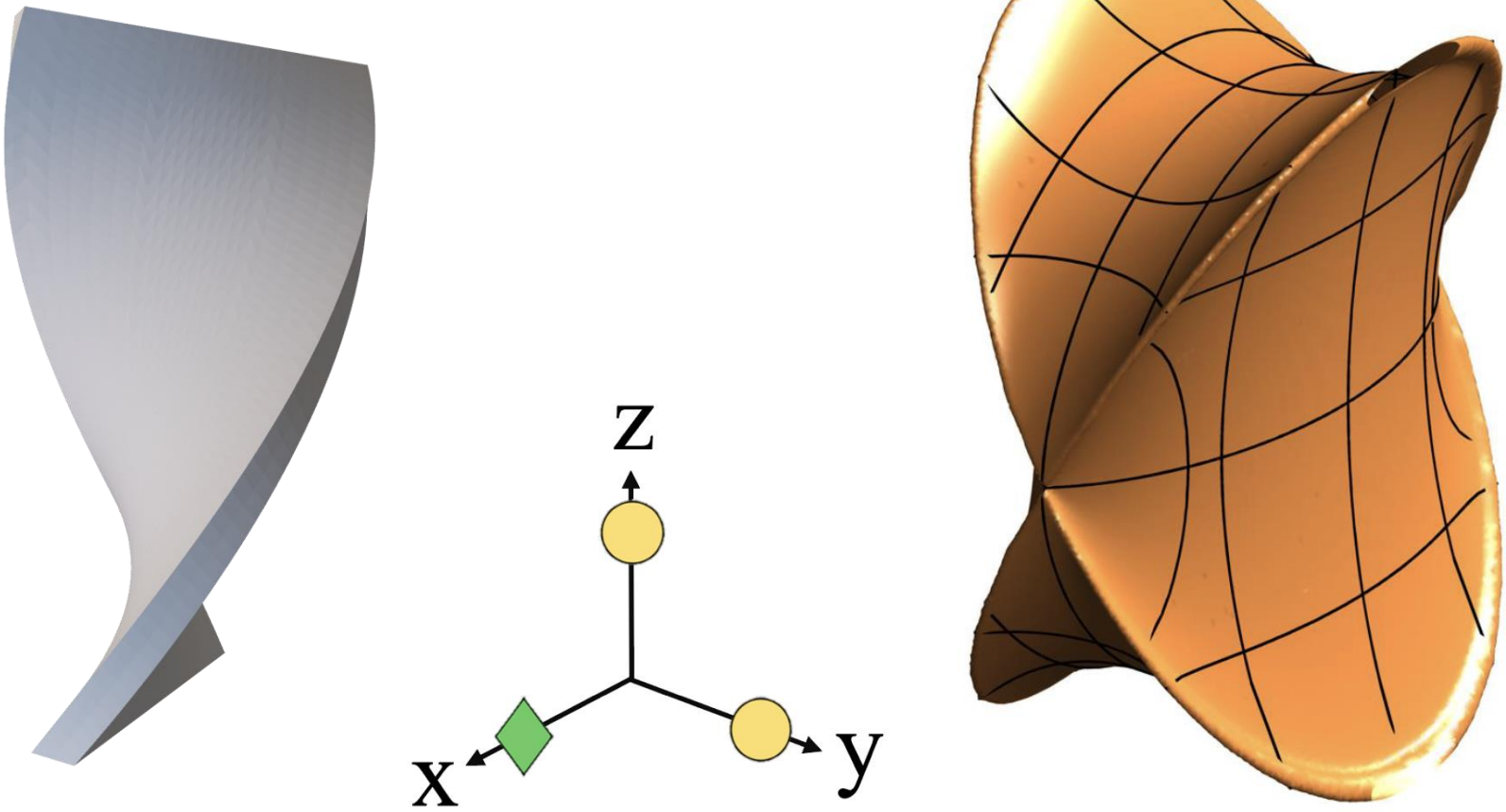
Minor Axis

Intermediate Axis

Major Axis

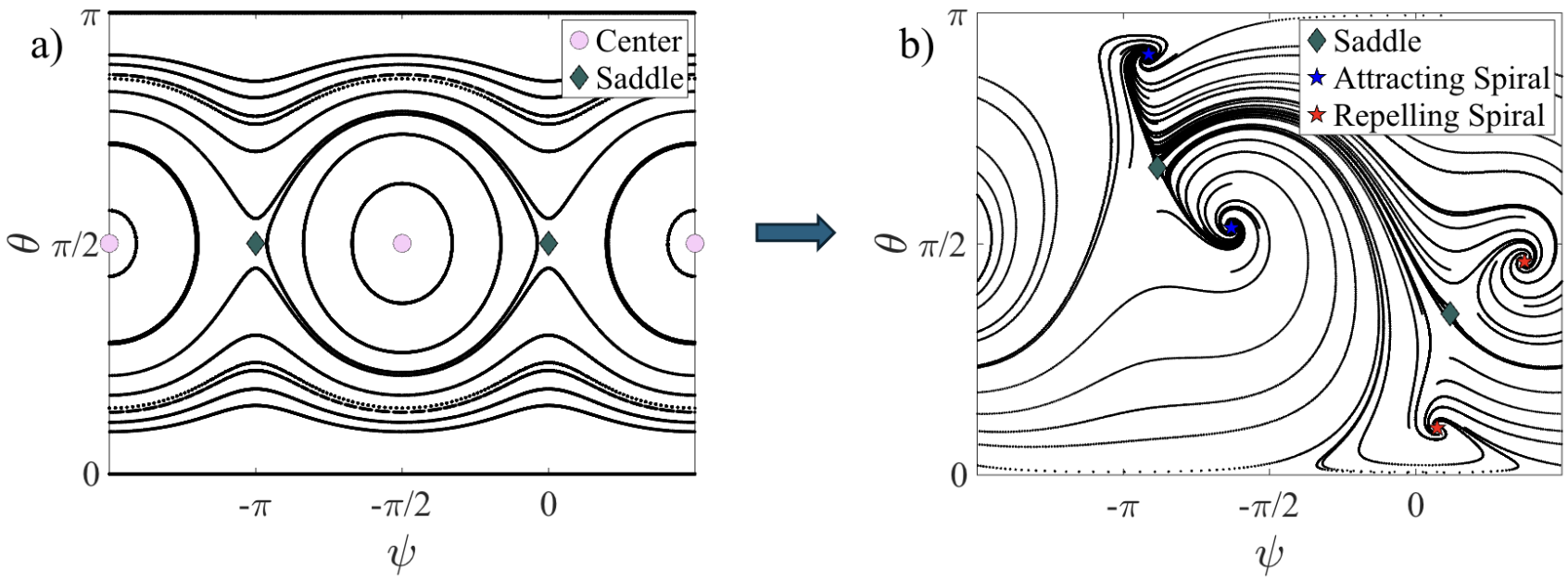


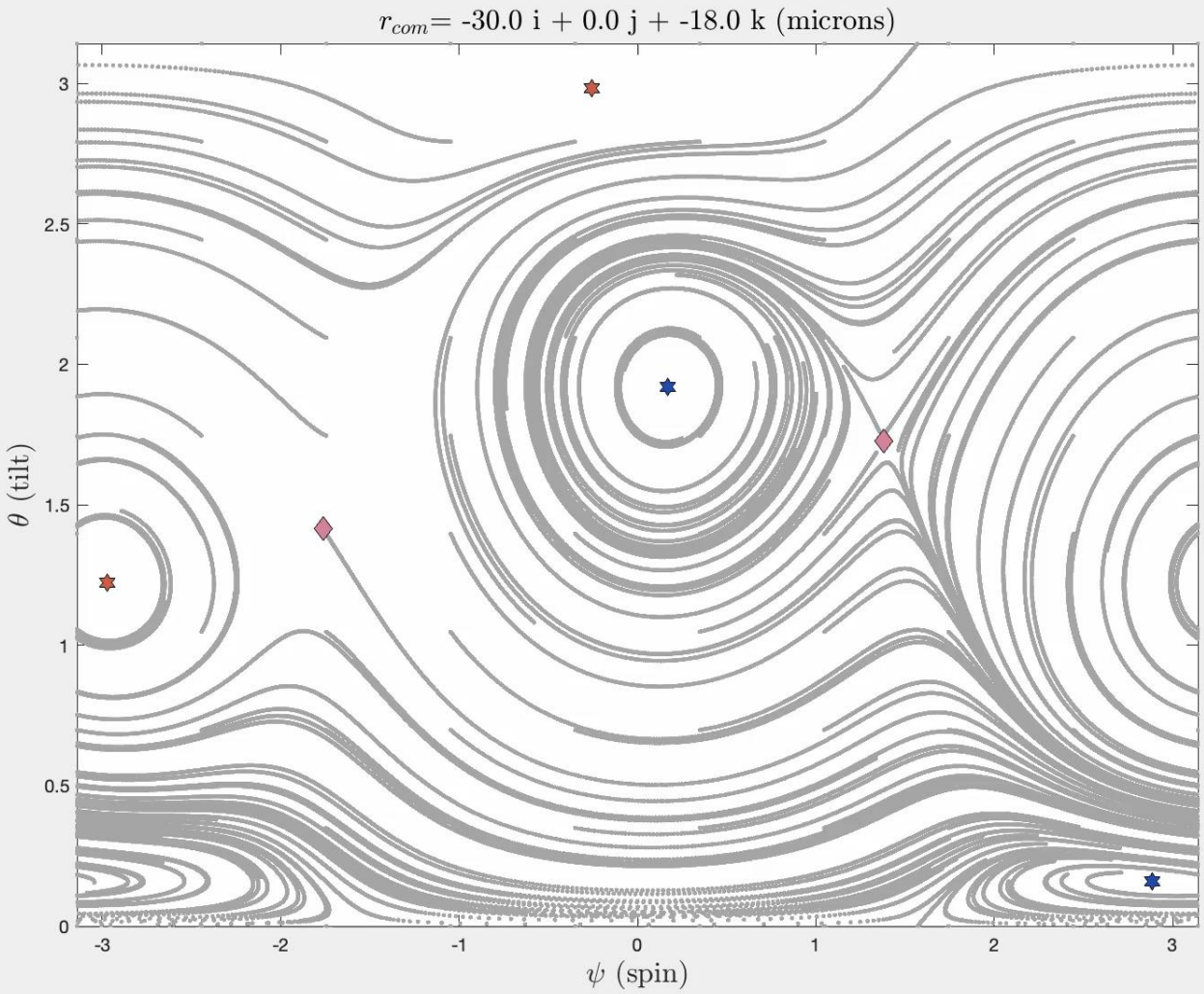
Moving the Center of Force in Arbitrary Directions: Alignment Bifurcation Surface



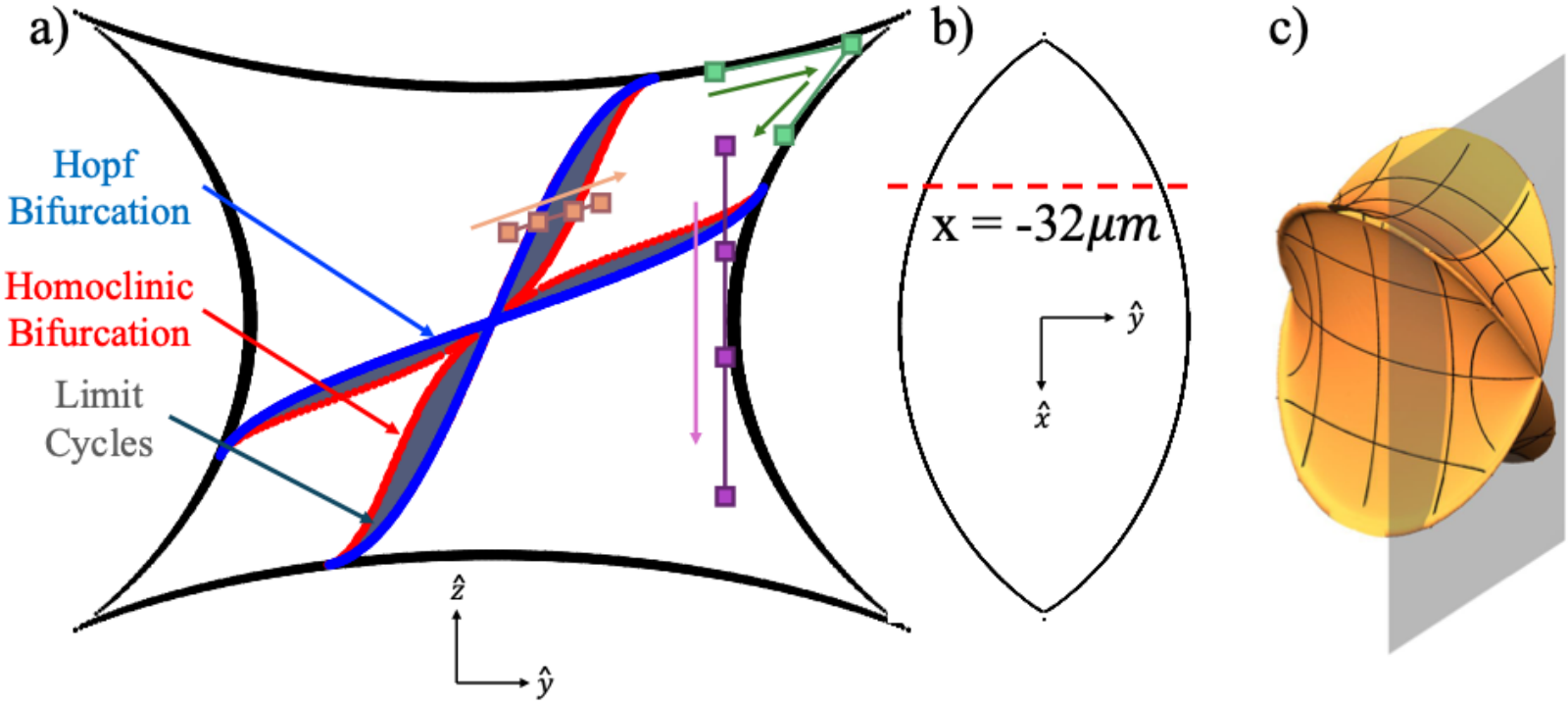
Surface in the space of center of force offsets that separates 6 fixed points (inside) from 2 fixed points (outside)

Inside the Alignment Bifurcation Surface




r_{com}= -30.0 i + 0.0 j + -18.0 k (microns)
θ (tilt)
ψ (spin)
0
0.5
1
1.5
2
2.5
3
-3
-2
-1
0
1
2
3

Bifurcations inside the Alignment Bifurcation Surface: Limit Cycles

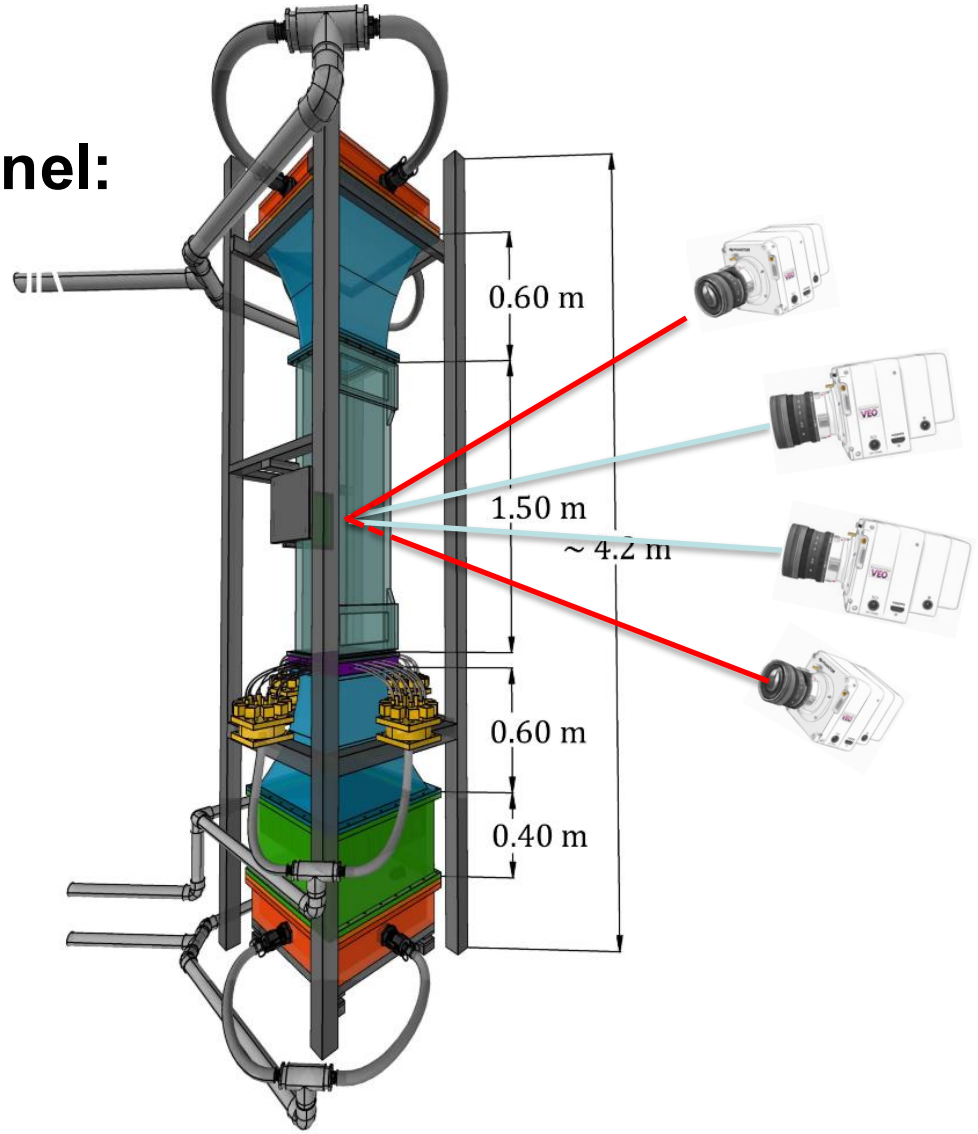


Chiral Particles in Turbulence

Wesleyan Vertical Water Tunnel:

- 30 cm x 30 cm cross section in the test section
- Active random jet-array system allows control of the turbulence using the sunbathing algorithm (Variano and Cowen, JFM 2008)
- Can generate turbulence up to $Re_\lambda = 400$

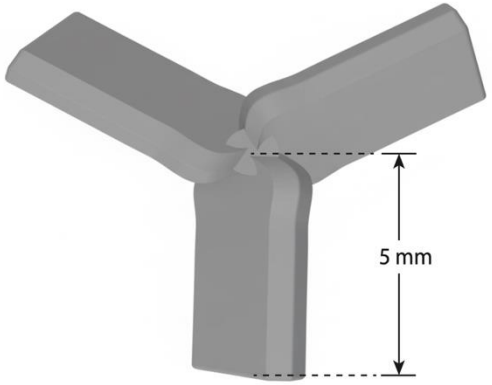
$$\eta \approx 0.3\,\mathrm{mm}$$



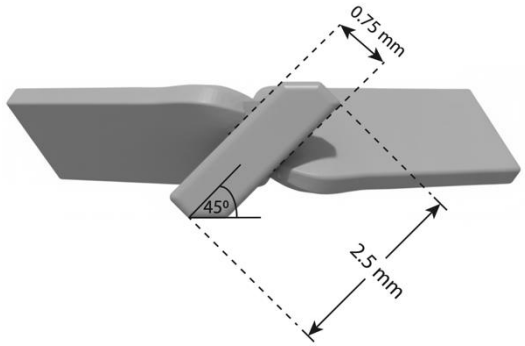
A. Roy, et al, J. of Non-Newtonian Fluid Mech (2023).

3-Blade Propeller

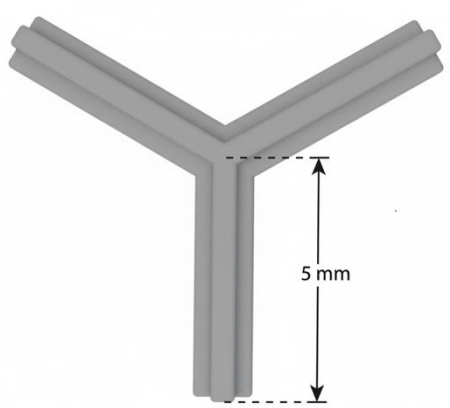
Top view

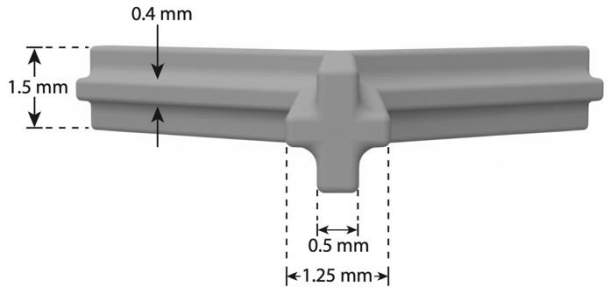


Side view



Achiral Particle





- Chosen to approximately match sedimentation rates in both vertical and horizontal orientations

$$\frac{D}{\eta} \approx 33 \qquad \mathrm{Chiral}(\mathrm{Re}_p \approx 475) \qquad \mathrm{Achiral}(\mathrm{Re}_p \approx 410)$$

Raw Data: High Turbulence Configuration $(\mathrm{Re}_\lambda \approx 354)$

z

g

Chiral Particles

Achiral Particles

Raw Data: Low Turbulence Configuration $(\mathrm{Re}_\lambda \approx 53)$

z

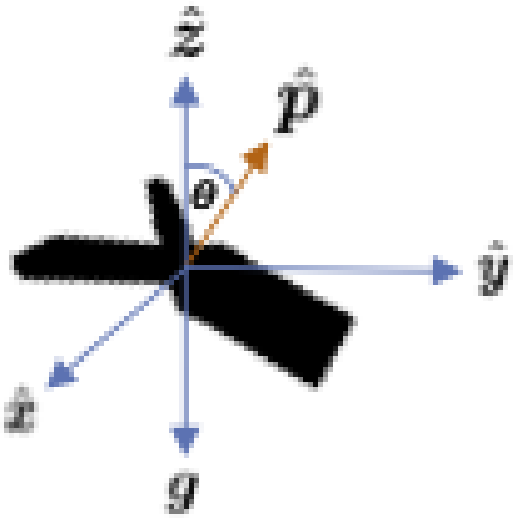
g

Chiral Particles

Achiral Particles

Conditional Orientations

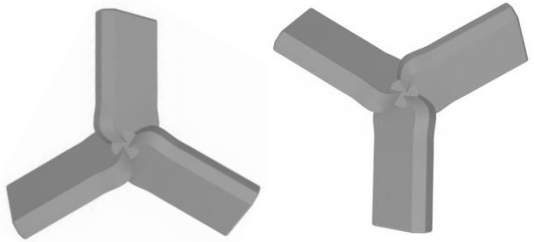
$$p_z = \hat{\boldsymbol{p}} \cdot \hat{\boldsymbol{z}}$$



When $p_z = 1$

→ Horizontal orientation

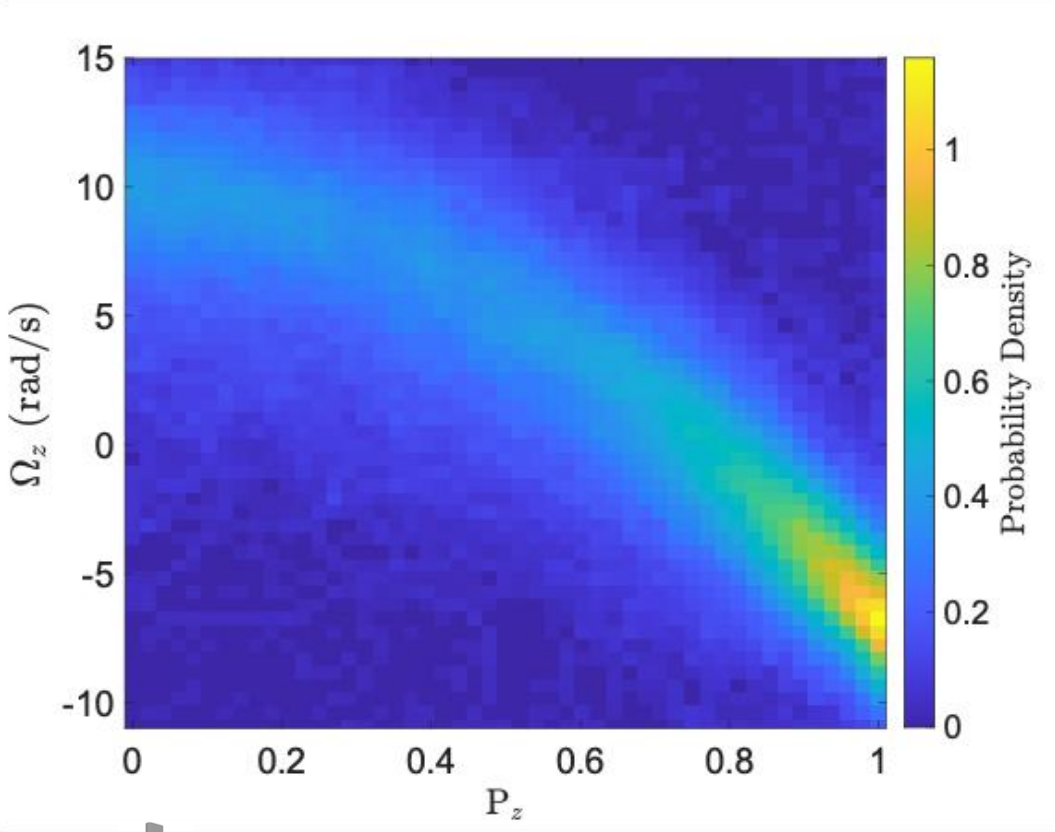
When $p_z = 0$



→ Vertical orientation

- Consider $\boldsymbol{\Omega}_z$ which is the vertical component of the solid body rotation rate

Vertical component of the solid body rotation rate (Ω_z)



Vertical Orientation

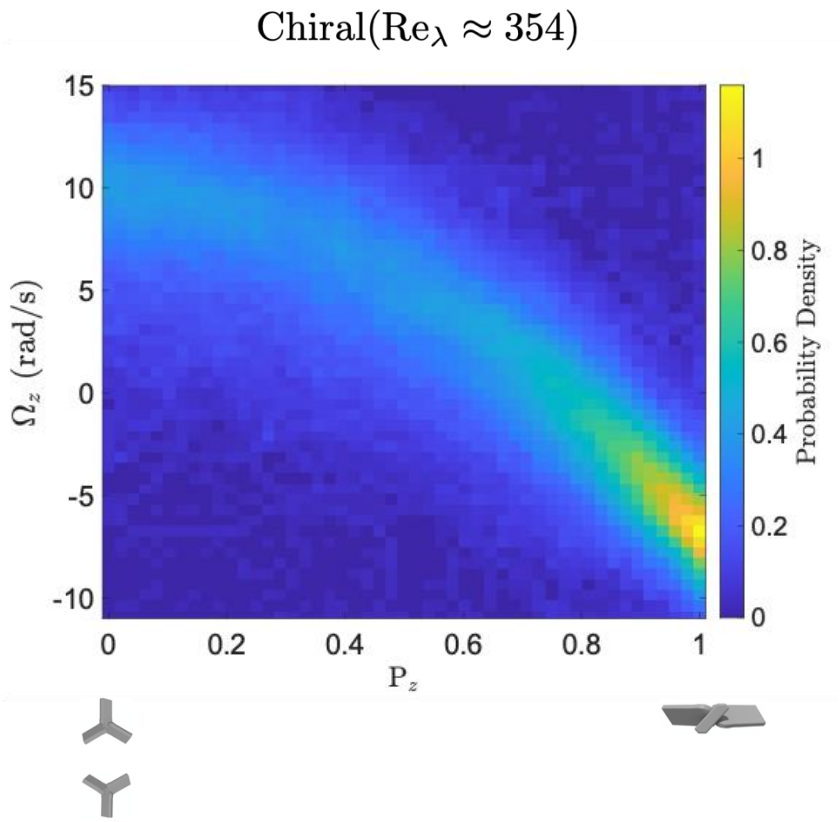
Left - Handed

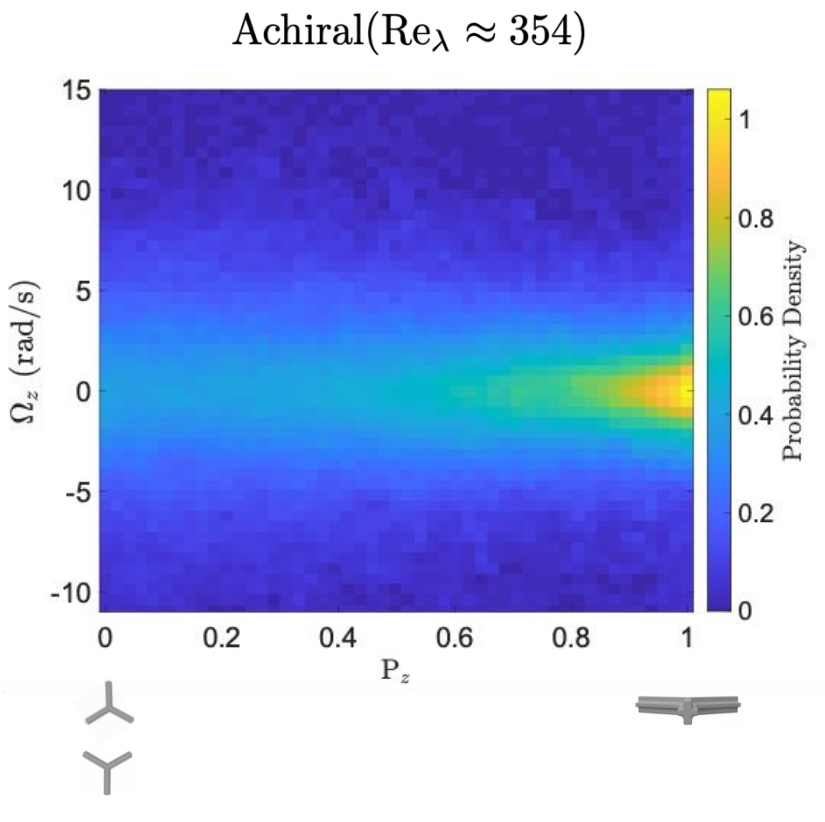
Horizontal Orientation

RIGHT - Handed

$(\mathrm{Re}_\lambda \approx 354)$

Joint PDFs of $\boldsymbol{\Omega}_z$ and P_z for Chiral and Achiral Particles

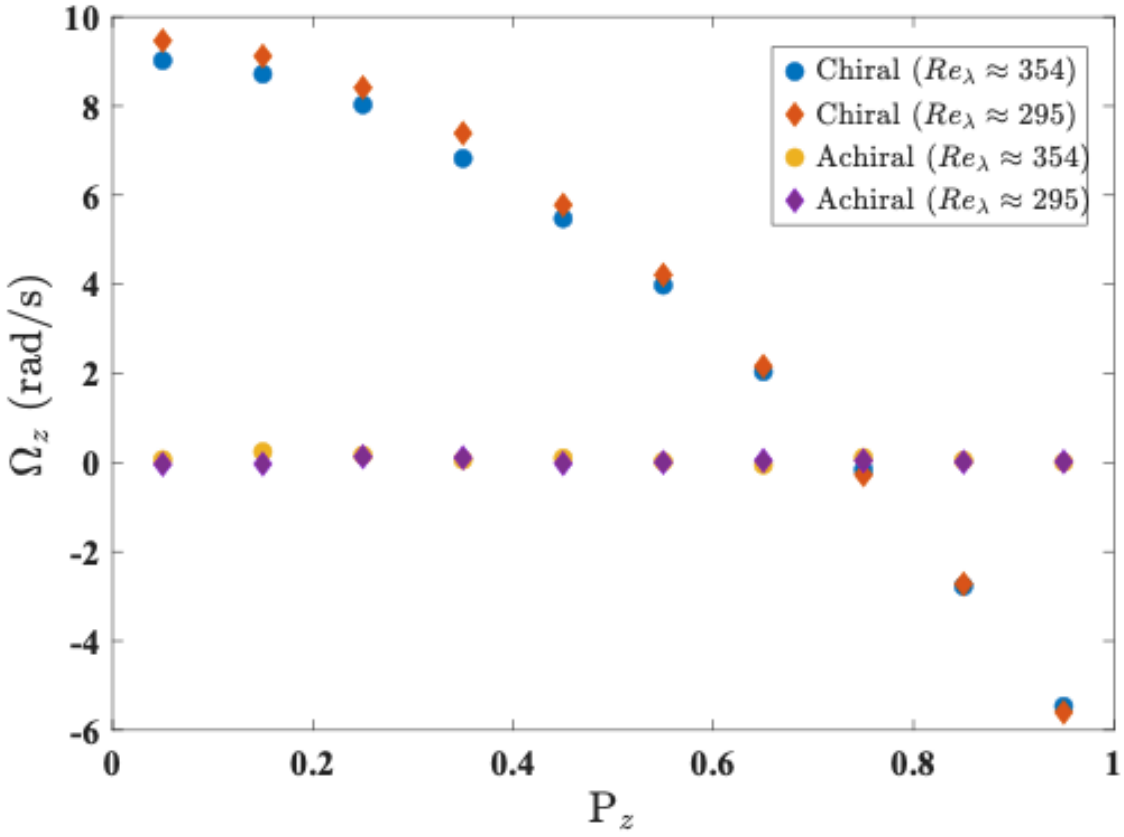




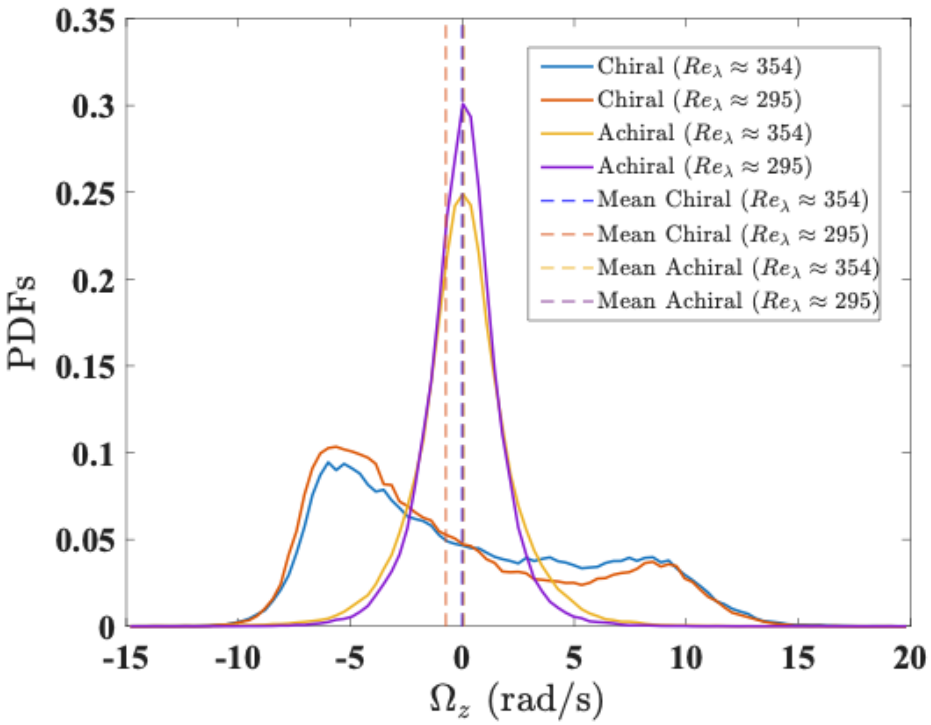
Left - Handed

RIGHT - Handed

Chiral vs Achiral Particles



Rotation rates including all orientations



Chiral:

$\bar{\Omega}_z\ (\mathrm{Re}_\lambda \approx 354) = \text{-}0.0043\ \mathrm{rad/s}$
$\bar{\Omega}_z\ (\mathrm{Re}_\lambda \approx 295) = \text{-}0.7353\ \mathrm{rad/s}$

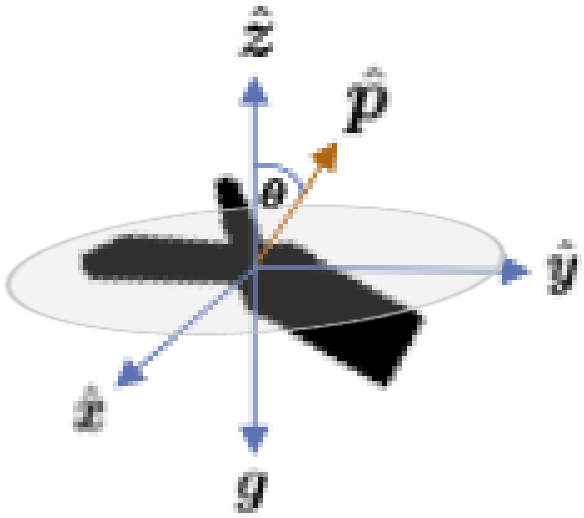
Achiral:

$\bar{\Omega}_z\ (\mathrm{Re}_\lambda \approx 354) = 0.0576\ \mathrm{rad/s}$
$\bar{\Omega}_z\ (\mathrm{Re}_\lambda \approx 295) = 0.0259\ \mathrm{rad/s}$

"***Particle chirality does not matter in strong turbulence***"
Piumini, Assen, Lohse, and Verzicco
JFM (2024)

Flapper, Sader, Lohse, Huisman
ARXIV:260.01941

What about rotation rates in x-y plane?



Now consider:

- $\boldsymbol{\Omega_{h\parallel}}$ is the horizontal component of rotation rate in the plane containing $\hat{p}$ and $\hat{z}$ (horizontal component in the direction of tilt)

Joint PDFs of $\boldsymbol{\Omega}_{h\|}$ *vs* $\mathbf{P}_z$