INTERNATIONAL CENTRE *for* THEORETICAL SCIENCES
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Particle Collisions in Turbulence

The Role of Structures in the Flow

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17th May, 2021

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Extreme Dissipation and Intermittency in Turbulence

EUROMECH COLLOQUIUM (Virtual)

Preamble

Suspensions of small, heavy particles in a turbulent flow is commonplace

Preamble

Suspensions of small, heavy particles in a turbulent flow is commonplace

EXAMPLE

https://www.youtube.com/watch?v=oH45yZvswO4

ATMOSPHERIC SCIENCE

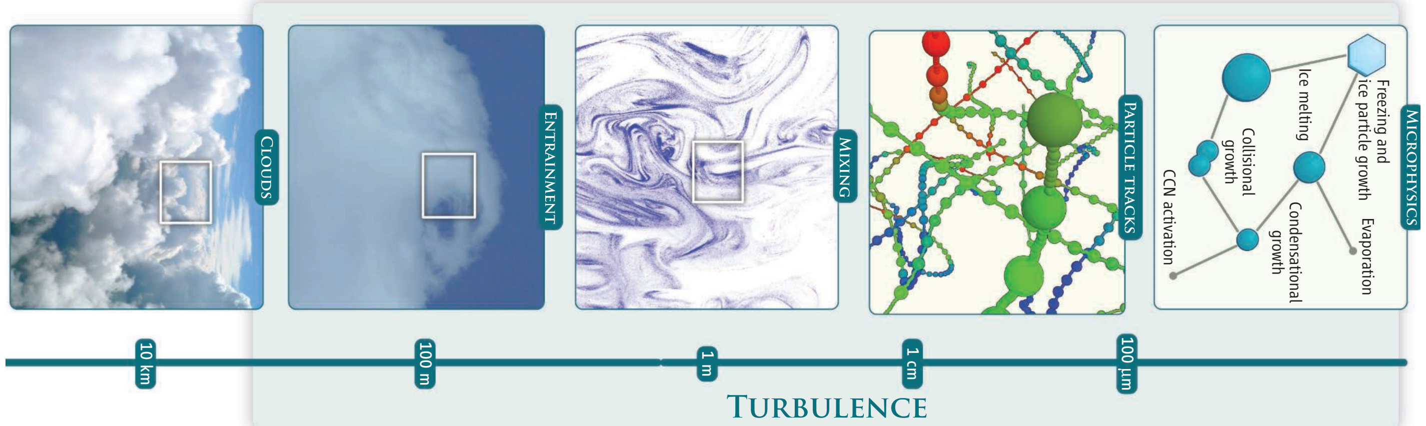
Science

Can We Understand Clouds Without Turbulence?

Advances at the interface between atmospheric and turbulence research are helping to elucidate fundamental properties of clouds.

E. Bodenschatz,[1,2] S. P. Malinowski,[3] R. A. Shaw,[4] F. Stratmann[5]

19 FEBRUARY 2010 VOL 327 SCIENCE www.sciencemag.org



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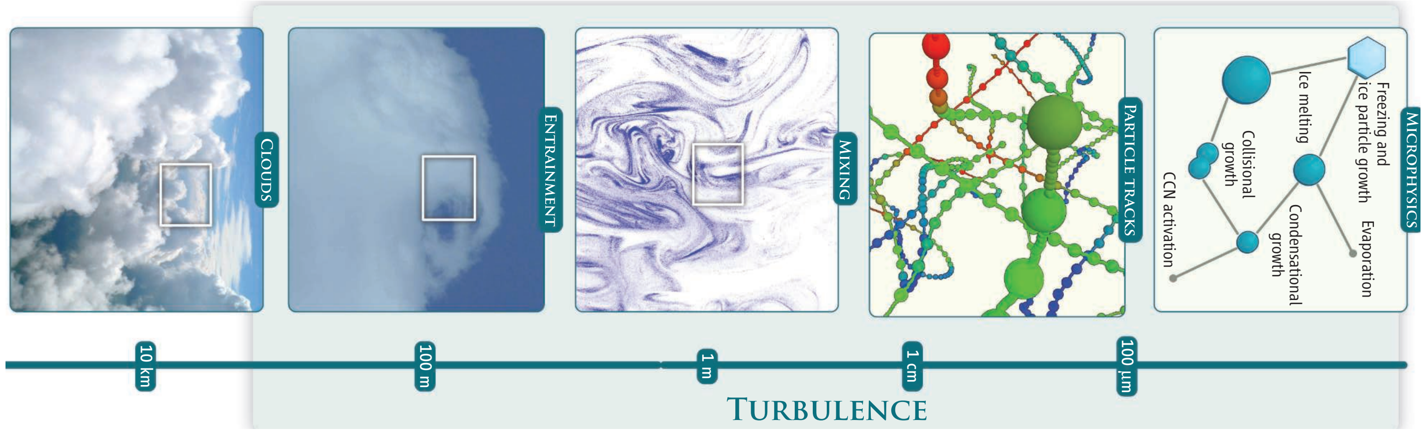

Important questions relate to *collisions* and *coalescences*

Preamble

Suspensions of small, heavy particles in a turbulent flow is commonplace

The Carrier Turbulent Flow

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = \nu \nabla^2 \mathbf{u} - \nabla P + \mathbf{f}$$

$$\nabla \cdot \mathbf{u} = 0$$ **Incompressibility**

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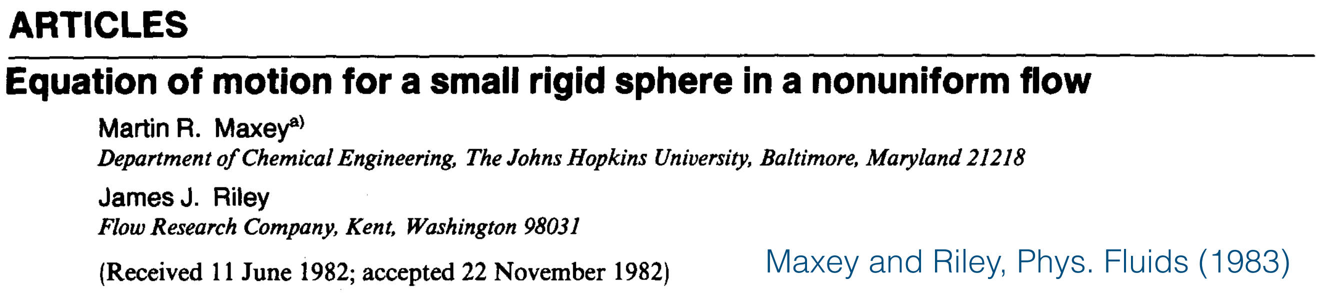
The Particle



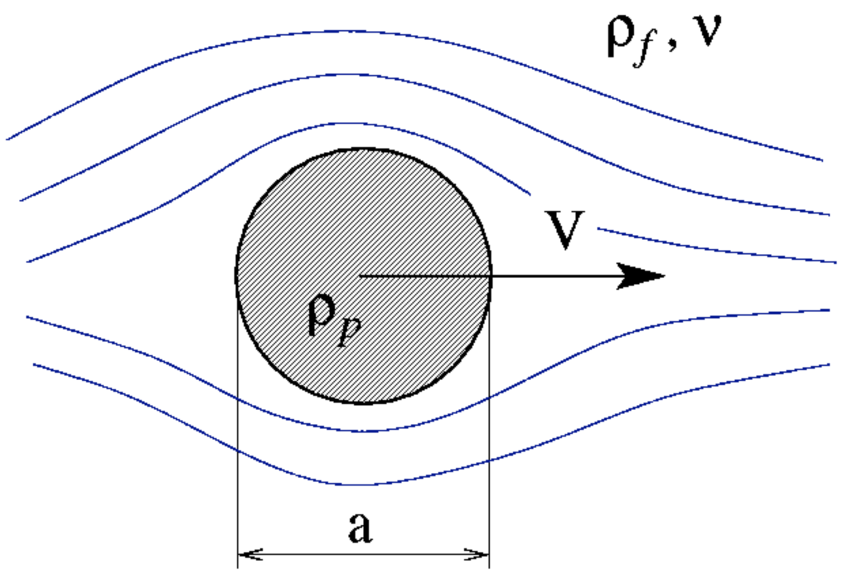
ARTICLES

Equation of motion for a small rigid sphere in a nonuniform flow

Martin R. Maxey[a]
Department of Chemical Engineering, The Johns Hopkins University, Baltimore, Maryland 21218
James J. Riley
Flow Research Company, Kent, Washington 98031

(Received 11 June 1982; accepted 22 November 1982)

Maxey and Riley, Phys. Fluids (1983)



$$m_p \frac{d\mathbf{v}}{dt} = m_p \mathbf{g} + \oint_s \sigma \cdot \hat{\mathbf{n}} dS$$

Basset, *Treatise on Hydrodynamics (1888)*
Boussinesq. *Theorie Analytique de la Chaleur (1903)*
Oseem, *Hydrodynamik* (1927)
Tchen, PhD thesis, Delft (1947)
Corrsin and Lumley, Appl. Sci. Res. (1956)

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Incompressibility

The Particle

$$\frac{d\mathbf{x}}{dt} = \mathbf{v}$$

$$\frac{d\mathbf{v}}{dt} = \mathbf{g} - \frac{1}{\tau_p}(\mathbf{v} - \mathbf{u})$$

The linear Stokes drag model

Preamble

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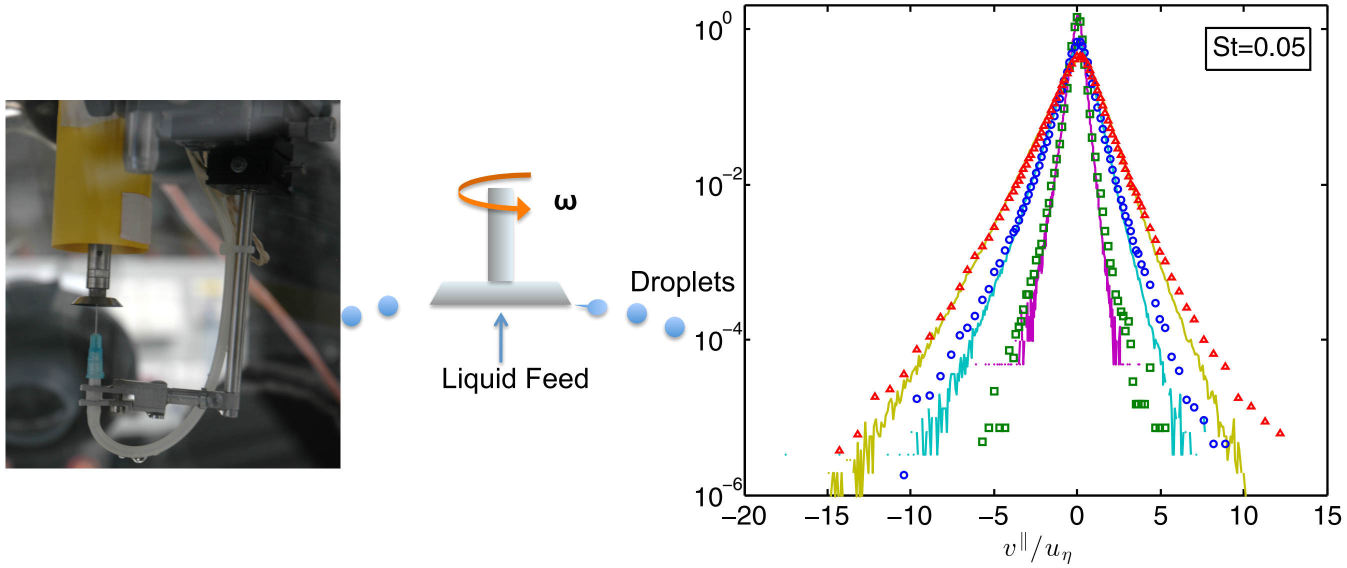
$$\frac{d\mathbf{x}}{dt} = \mathbf{v}$$

$$\frac{d\mathbf{v}}{dt} = \mathbf{g} - \frac{1}{\tau_p}(\mathbf{v} - \mathbf{u})$$

Is this approximate form valid?



Saw, Bewley, Bodenschatz, Ray, and Bec, Phys. Fluids Lett. (2016)

Working Equations

The Carrier Turbulent Flow

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u} = \nu\nabla^2\mathbf{u} - \nabla P + \mathbf{f}$$

$$\nabla\cdot\mathbf{u} = 0$$

$$\text{Characteristic timescale} : \tau_\eta = \sqrt{\frac{\nu}{\varepsilon}}$$

$$\text{Characteristic lengthscale} : \eta = \left(\frac{\nu^3}{\varepsilon}\right)^{1/4}$$

The Particle

$$\frac{d\mathbf{x}}{dt} = \mathbf{v}$$

$$\frac{d\mathbf{v}}{dt} = \mathbf{g} - \frac{1}{\tau_p}(\mathbf{v} - \mathbf{u})$$

$$\text{Characteristic timescale} : \tau_p = \frac{2a^2\rho_p}{9\nu\rho_f}$$

$$\text{Characteristic lengthscale} : a$$

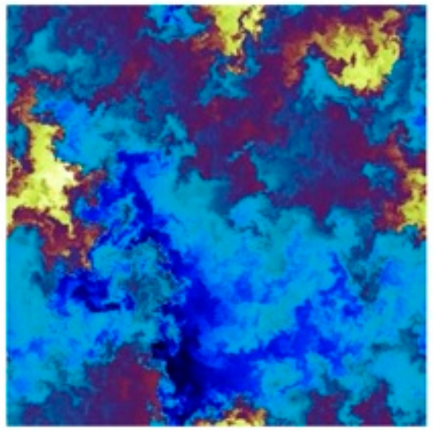
Non-Dimensional Number

$$St = \frac{\tau_p}{\tau_\eta}$$

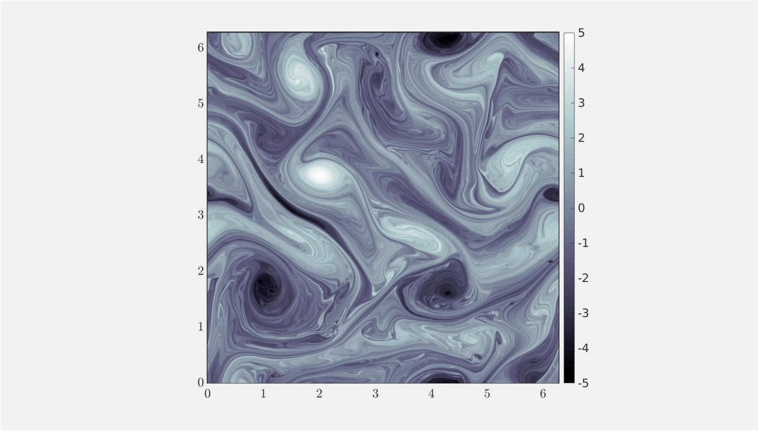
Fingerprints

Turbulent Flows

- **Irreversible and intermittent**
- **Multiple length and time scales**
- **Exotic structure: Vortices and straining regions**



Celani, *et al.*, Phys. Fluids (2001)



M. Gupta and R. Singh

Fingerprints

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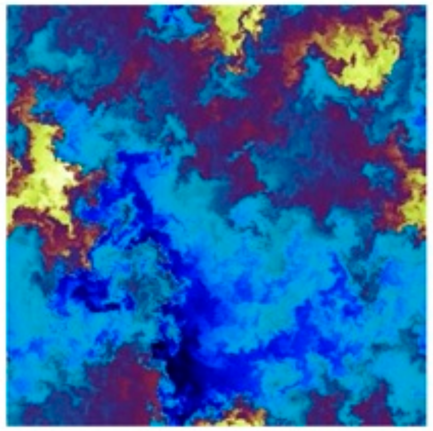

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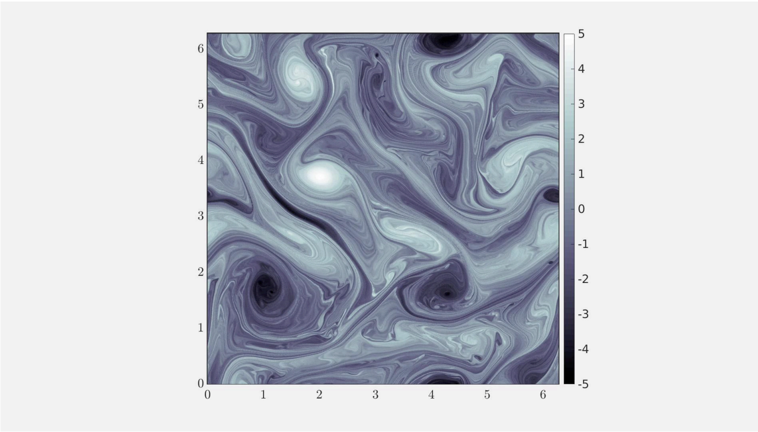
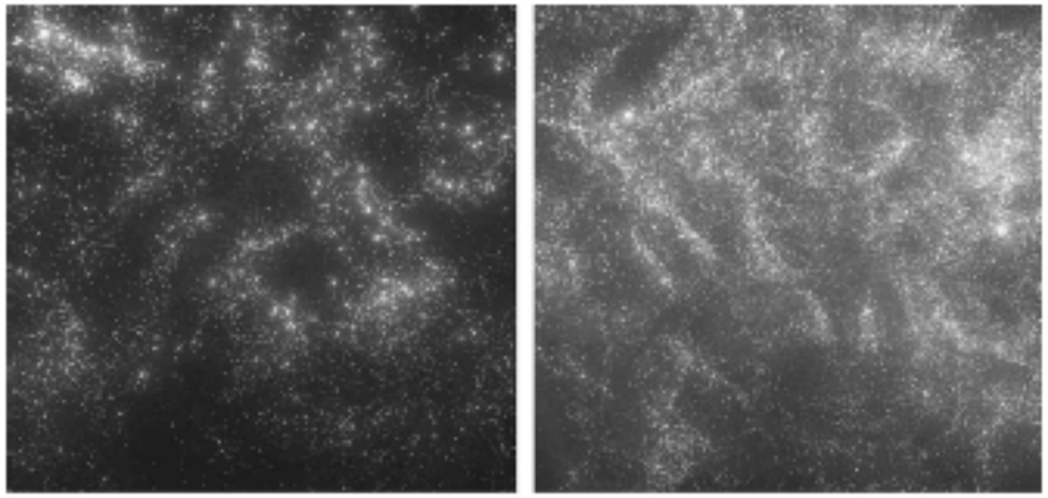
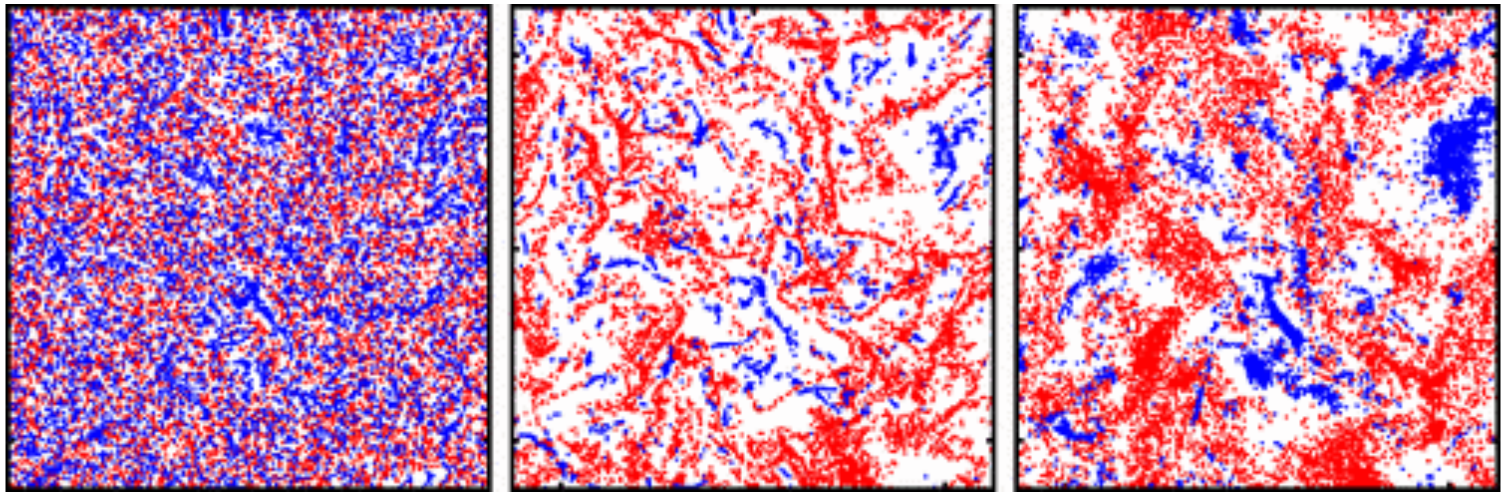


M. Gupta and R. Singh

Inertial Particles

- Dissipative dynamics: Phase space contraction
- Spatial distribution strongly inhomogeneous: Preferential Concentration
- Maximum clustering achieved for finite values of the Stokes number
- Uniform distribution in the small and large Stokes number asymptotics





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E. Calzavarini, *et al.*, Phys. Rev. Lett., **101** (2008).

Longmire and Eaton, J. Fluid Mech. (1992)
Bec, Phys. Fluids (2003)
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Bec, Celani, Cencini, and Musacchio Phys. Fluids (2005)

Chun, *et al.*, J. Fluid Mech. (2005)
Bec, *et al.*, Phys. Rev. Lett. (2007)
Monchaux, Bourgoin, and Cartellier, Int. J. Multiphase Flows, (2012)
Gustavsson and Mehlig, Adv. Phys. (2016)

Conventional Wisdom: Rate of Collisions

The rate of collisions depends on the relative velocity of particles at contact

Saw, Bewley, Bodenschatz, Ray, and Bec, Phys. Fluids 26, 111702 (2014)
James & Ray, Sci. Rep. 7, 12231 (2017)
Bhatnagar, Gustavsson, and Mitra, Phys. Rev. E 97, 023105 (2018)
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Tracers

- Determined by fluid velocity gradients: Increases with increasing Reynolds number
- Disregards whether the local velocity gradient arises from rotation or strain

Saffman & Turner, J. Fluid Mech. 1, 16 (1956)

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Inertial Particles

- Preferentially concentrate: Increases local particle density
- Sling effect: Large relative velocities through caustics
- Ideas as true for smooth random flows as it is for turbulent flows

Falkovich, Fouxon, and Stepanov, Nature 419, 151 (2002)
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Wilkinson, Mehlig, Östlund, and Duncan, Phys Fluids 19, 113303 (2007)

Bec, S. Musacchio, and Ray, Phys. Rev. E 87, 063013 (2013)
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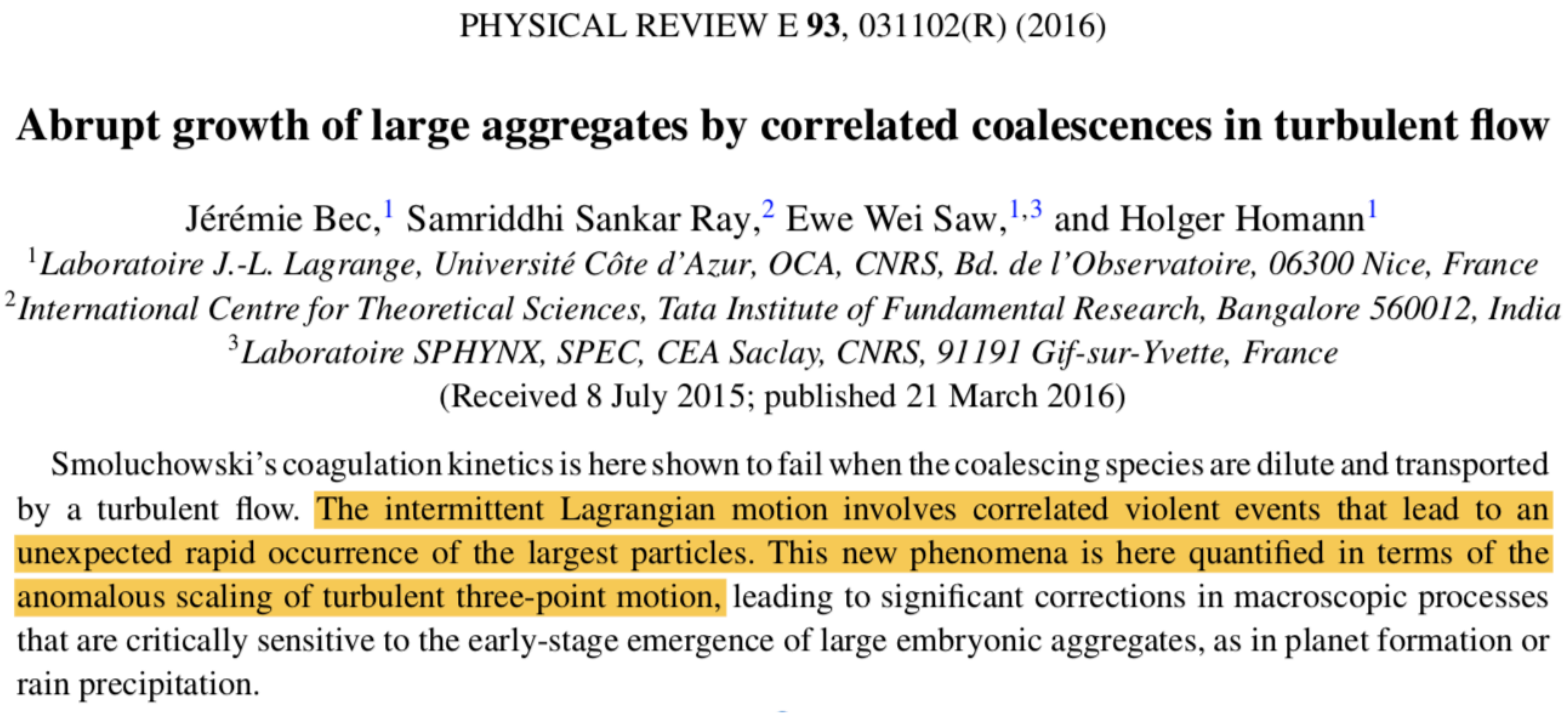
These effects do not necessarily imply that collisions sense the structures of turbulence

A Link



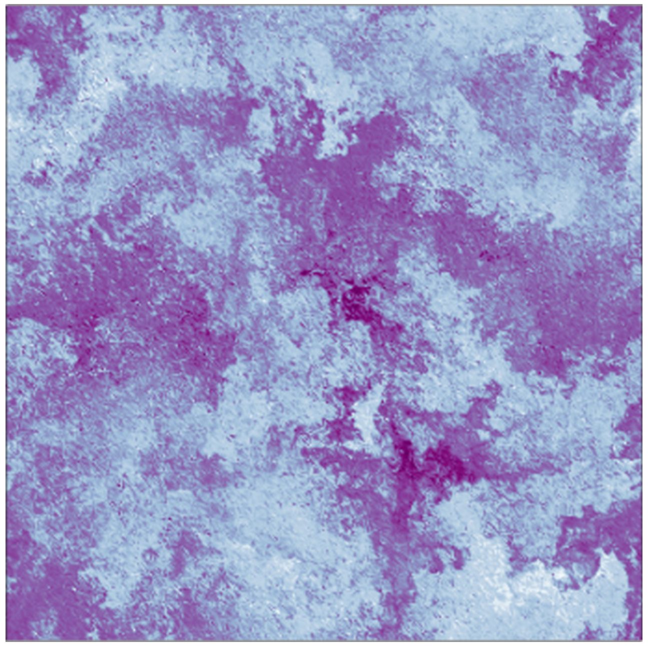
PHYSICAL REVIEW E **93**, 031102(R) (2016)

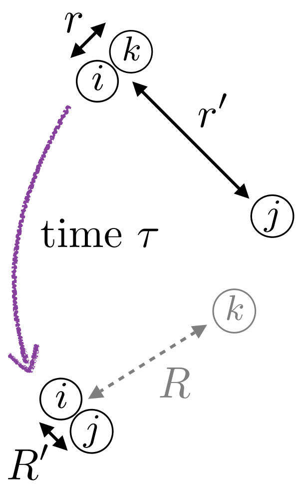
Abrupt growth of large aggregates by correlated coalescences in turbulent flow

Jérémie Bec,[1] Samriddhi Sankar Ray,[2] Ewe Wei Saw,[1,3] and Holger Homann[1]
[1] *Laboratoire J.-L. Lagrange, Université Côte d'Azur, OCA, CNRS, Bd. de l'Observatoire, 06300 Nice, France*
[2] *International Centre for Theoretical Sciences, Tata Institute of Fundamental Research, Bangalore 560012, India*
[3] *Laboratoire SPHYNX, SPEC, CEA Saclay, CNRS, 91191 Gif-sur-Yvette, France*

(Received 8 July 2015; published 21 March 2016)

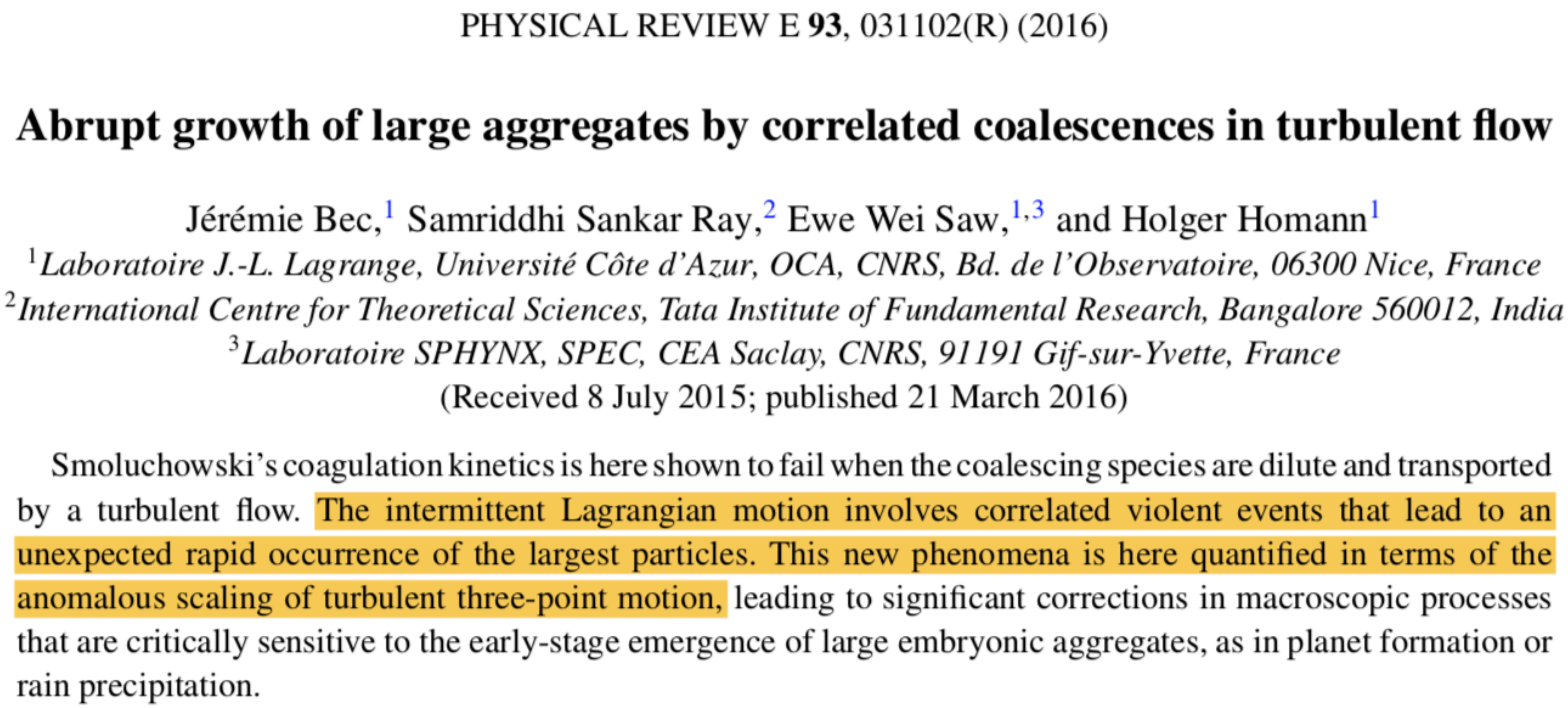
Smoluchowski's coagulation kinetics is here shown to fail when the coalescing species are dilute and transported by a turbulent flow. The intermittent Lagrangian motion involves correlated violent events that lead to an unexpected rapid occurrence of the largest particles. This new phenomena is here quantified in terms of the anomalous scaling of turbulent three-point motion, leading to significant corrections in macroscopic processes that are critically sensitive to the early-stage emergence of large embryonic aggregates, as in planet formation or rain precipitation.





Lagrangian evolution of fluid elements: Scaling and geometry tied together

A Link



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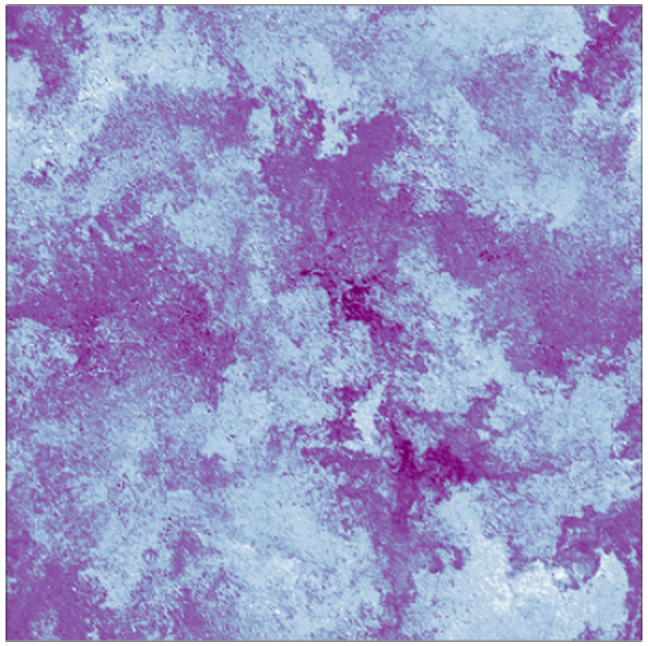

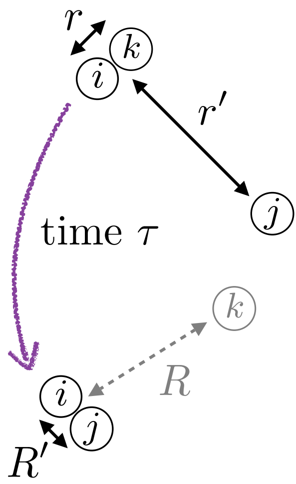

Lagrangian evolution of fluid elements: Scaling and geometry tied together

The implied correlation between the structure of the flow and droplet collisions and coalescences remained an open one: Evidence suggests that flow structures matter, but how and when?

The Question

What is the effect of structures in a flow on collisions and coalescence of droplets?

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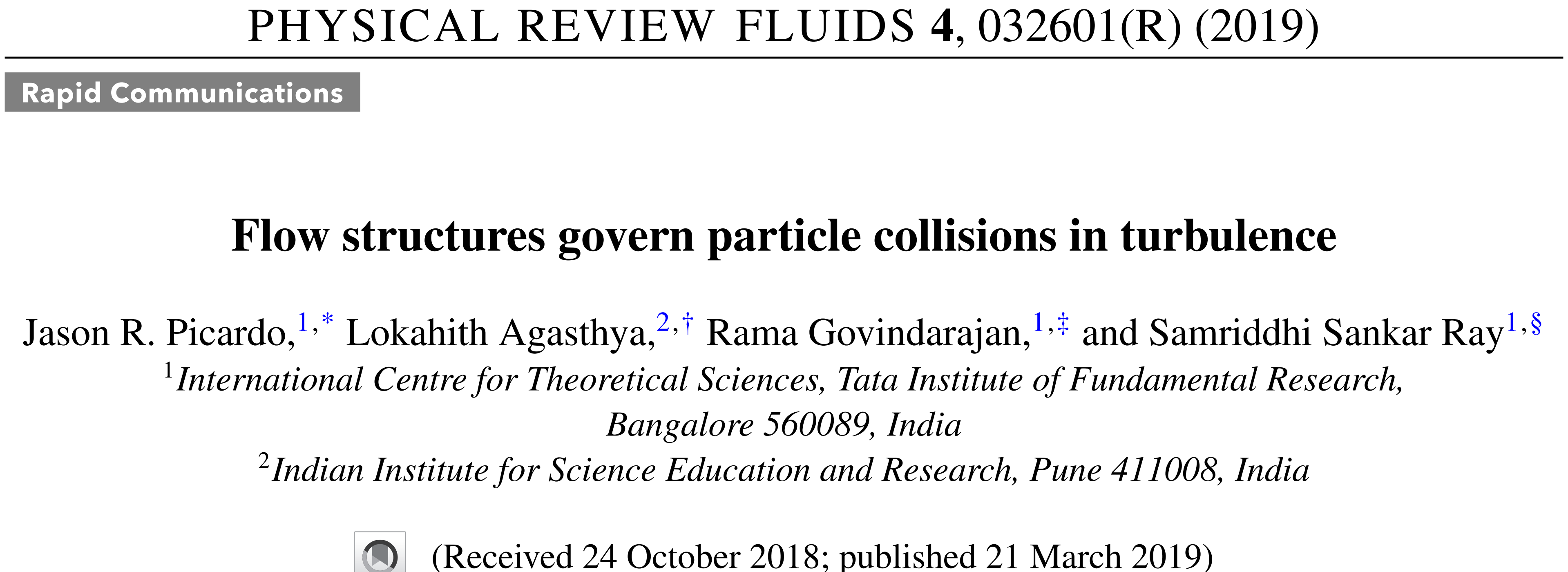

PHYSICAL REVIEW FLUIDS **4**, 032601(R) (2019)

Rapid Communications

Flow structures govern particle collisions in turbulence

Jason R. Picardo,[1,*] Lokahith Agasthya,[2,†] Rama Govindarajan,[1,‡] and Samriddhi Sankar Ray[1,§]

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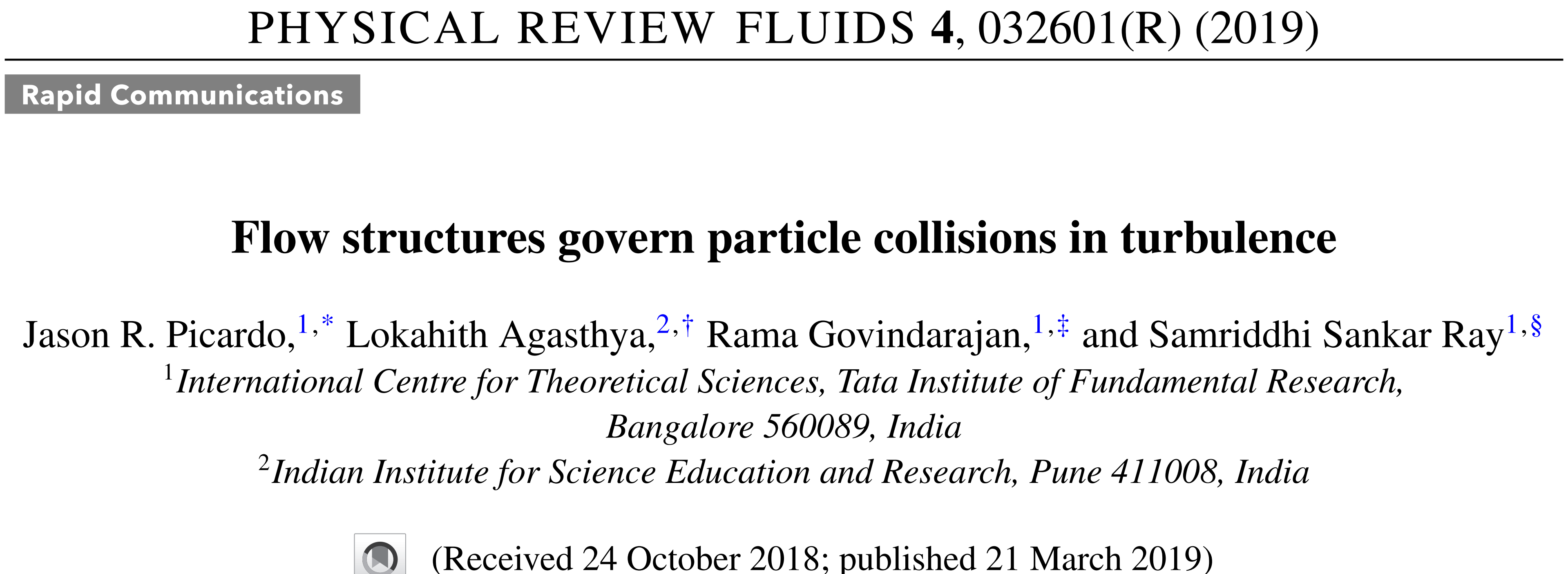
The Answer

- Straining regions more effective at generating collisions



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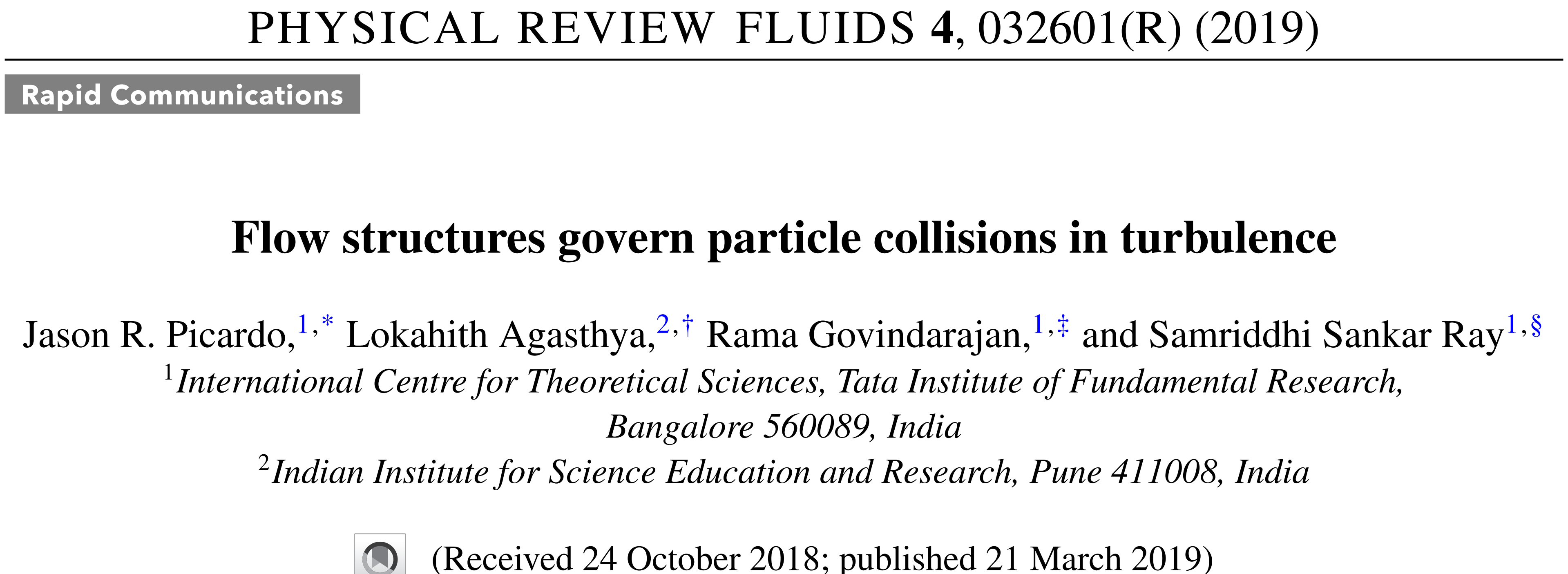
The Answer

- Straining regions more effective at generating collisions
- Intense vorticity and strain, cohabiting as vortex-strain worm-rolls, conspire to generate violent collisions.



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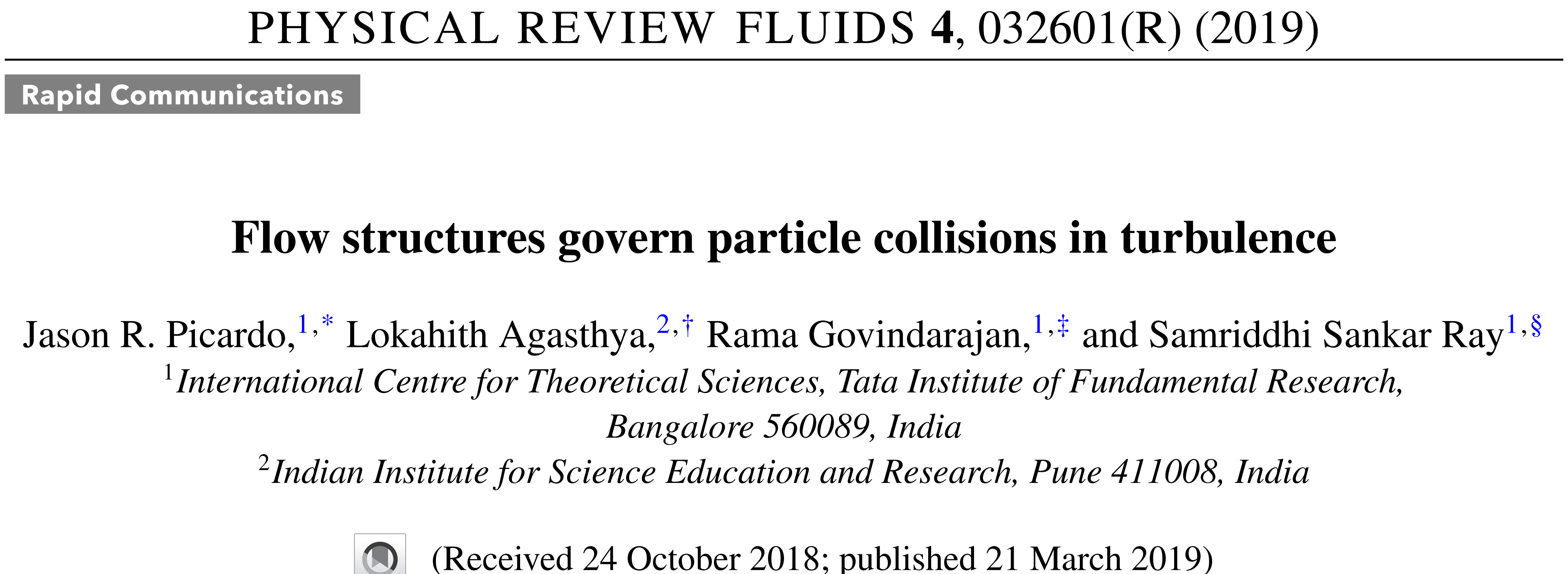
Key Message: These effects are not *just* due to preferential concentration



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The Tools

Identifying structures in the fluid

Velocity gradient tensor

$$\mathcal{A} = \tau_\eta \nabla \mathbf{u}$$

$$\mathcal{S} = \frac{\mathcal{A} + \mathcal{A}^{\mathrm{T}}}{2} \qquad \mathcal{R} = \frac{\mathcal{A} - \mathcal{A}^{\mathrm{T}}}{2}$$

Symmetric: Strain

Antisymmetric: Rotation

Dubief & Delcayre, J. Turbul. 1, N11 (2000)
Blackburn, Mansour, and Cantwell, J. Fluid Mech. 310, 269 (1996)
Chong, Perry, and Cantwell, Phys. Fluids A 2, 765 (1990)

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$$\mathcal{Q} = \frac{\mathcal{R}^2 - \mathcal{S}^2}{2}$$

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$\mathcal{Q} > 0$ [Vorticity] $\mathcal{Q} < 0$ [Strain]

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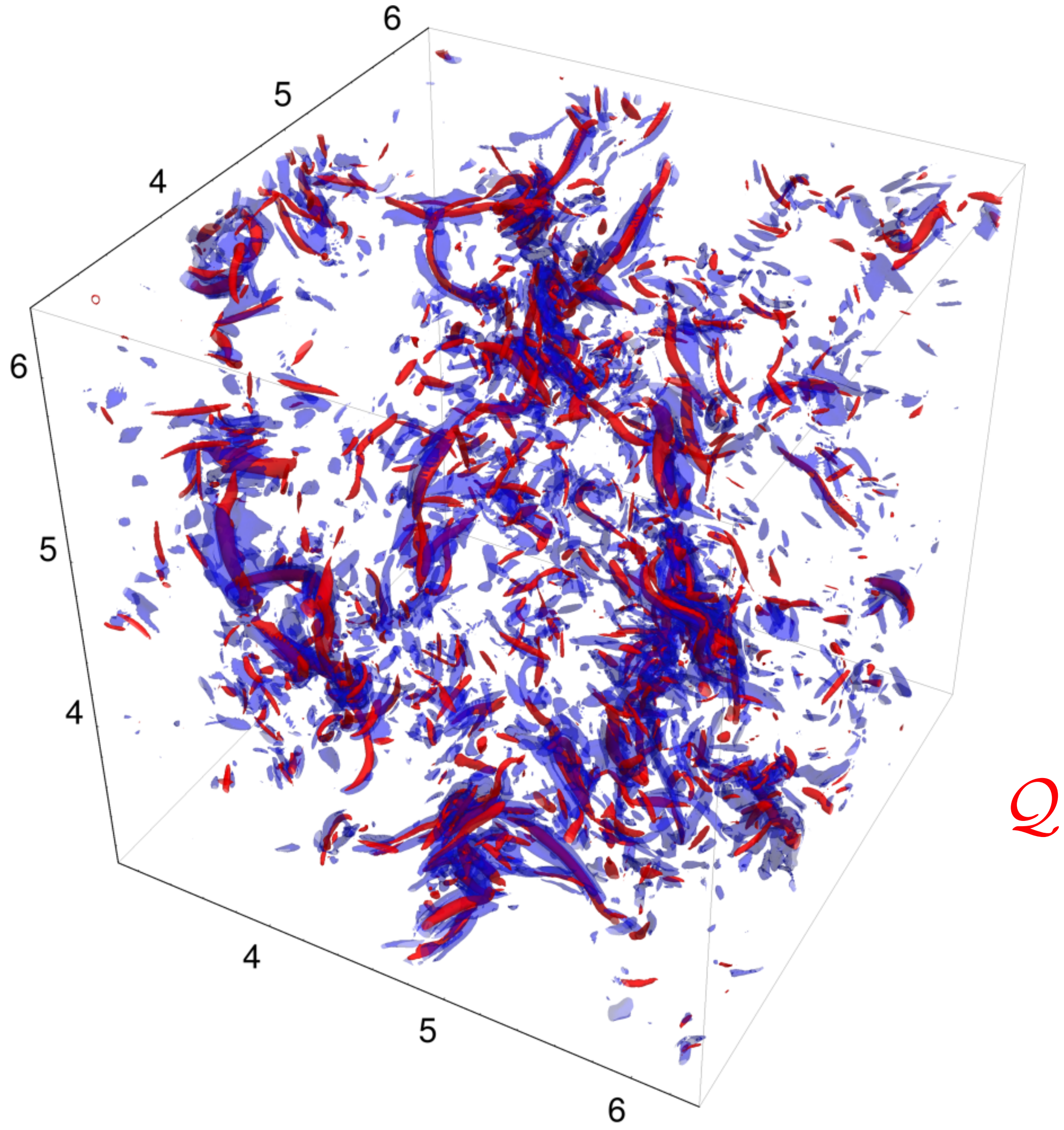

Picardo, Agasthya, Govindarajan, and Ray, Phys. Rev. Fluids (Rapids) 4, 032601(R) (2019)

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Direct Numerical Simulations

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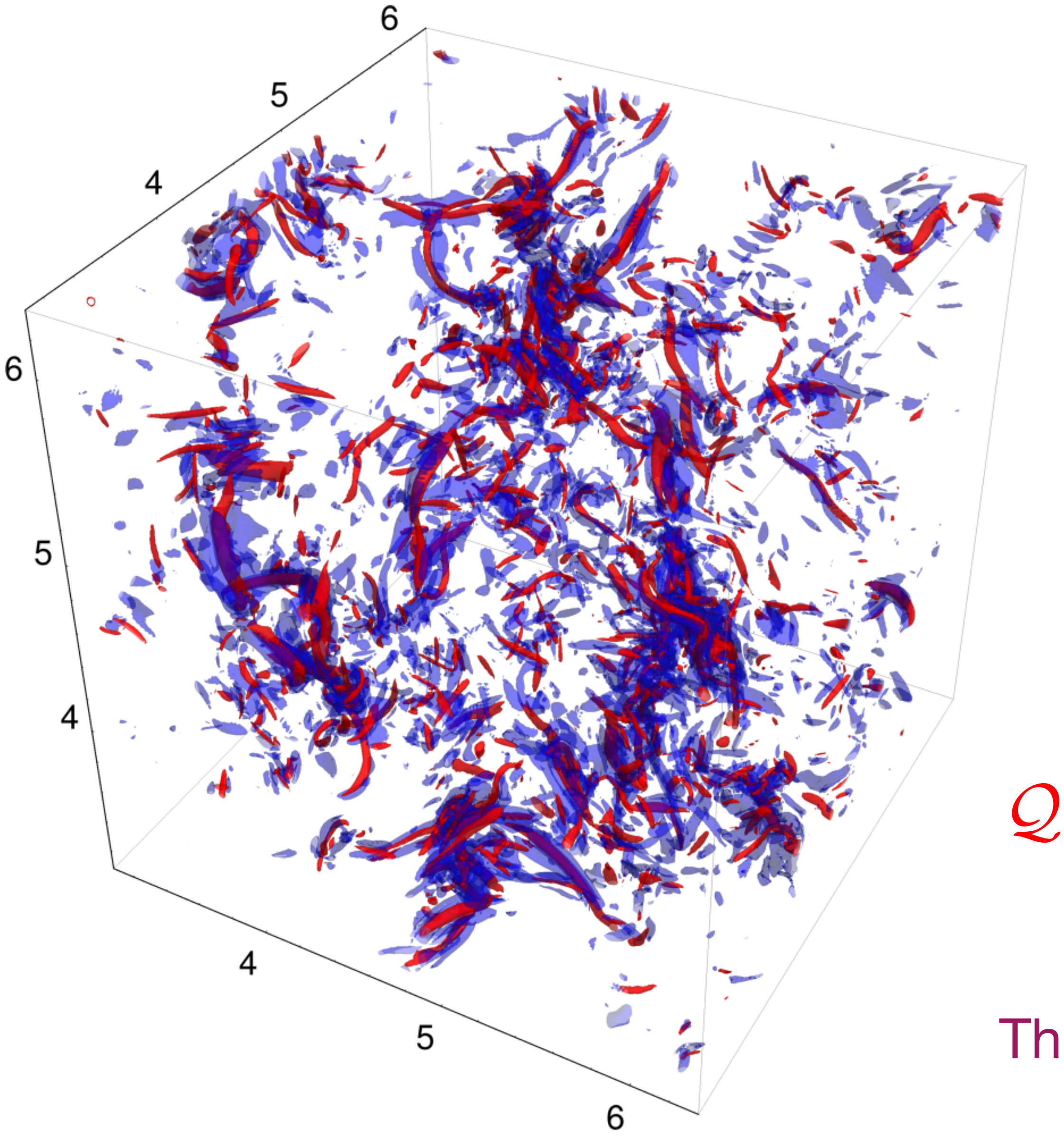
The Tools

Identifying structures in the fluid

Vortex-strain worm-rolls



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These can be measured along the particle trajectories

Ireland, Bragg, and Collins, J. Fluid Mech. 796, 617 (2016)

Picardo, Agasthya, Govindarajan, and Ray, Phys. Rev. Fluids (Rapids) 4, 032601(R) (2019)

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Direct Numerical Simulations

Begin with tracers

Saffman-Turner hypothesis: Collisions should occur uniformly between any two regions that possess the same velocity gradient magnitude

Saffman & Turner, J. Fluid Mech. 1, 16 (1956)

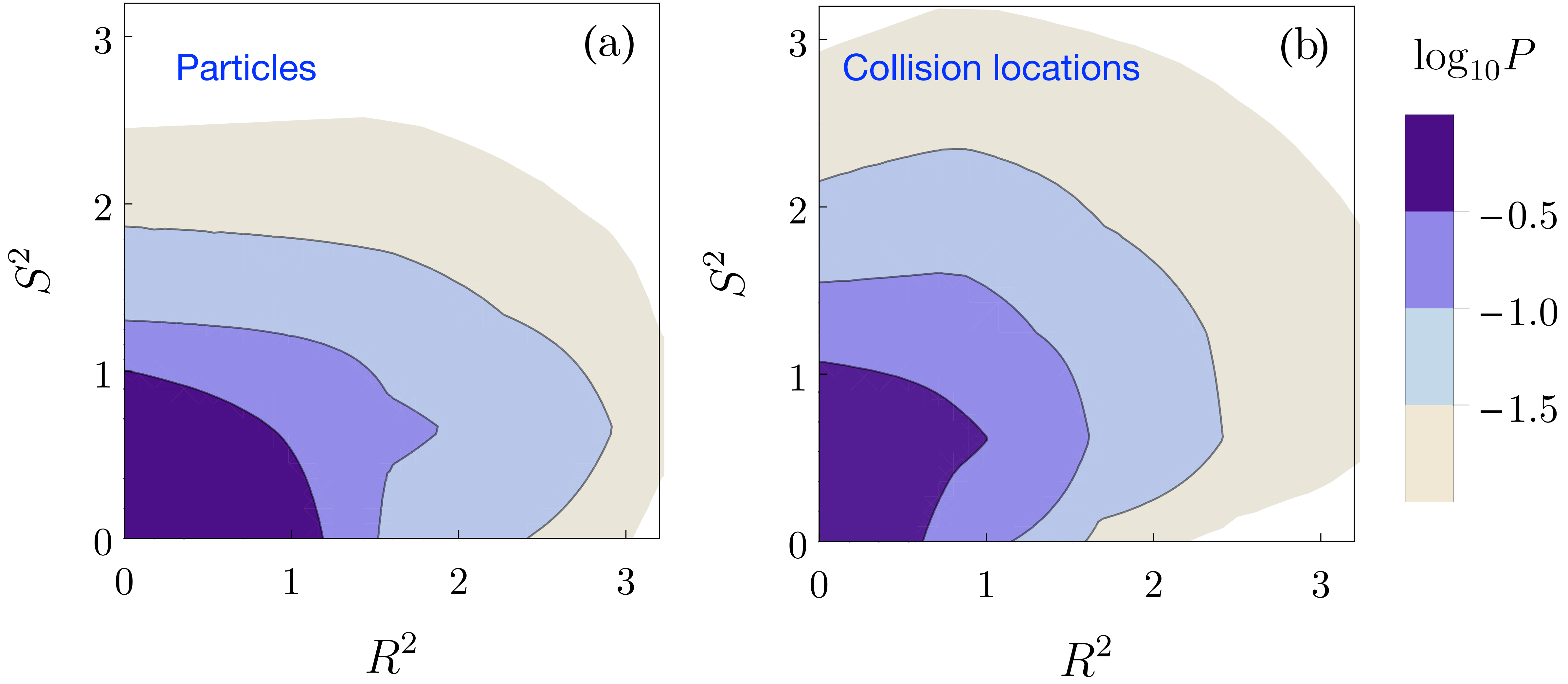
Picardo, Agasthya, Govindarajan, and Ray, Phys. Rev. Fluids (Rapids) 4, 032601(R) (2019)

Begin with tracers

Saffman-Turner hypothesis: Collisions should occur uniformly between any two regions that possess the same velocity gradient magnitude

Saffman & Turner, J. Fluid Mech. 1, 16 (1956)

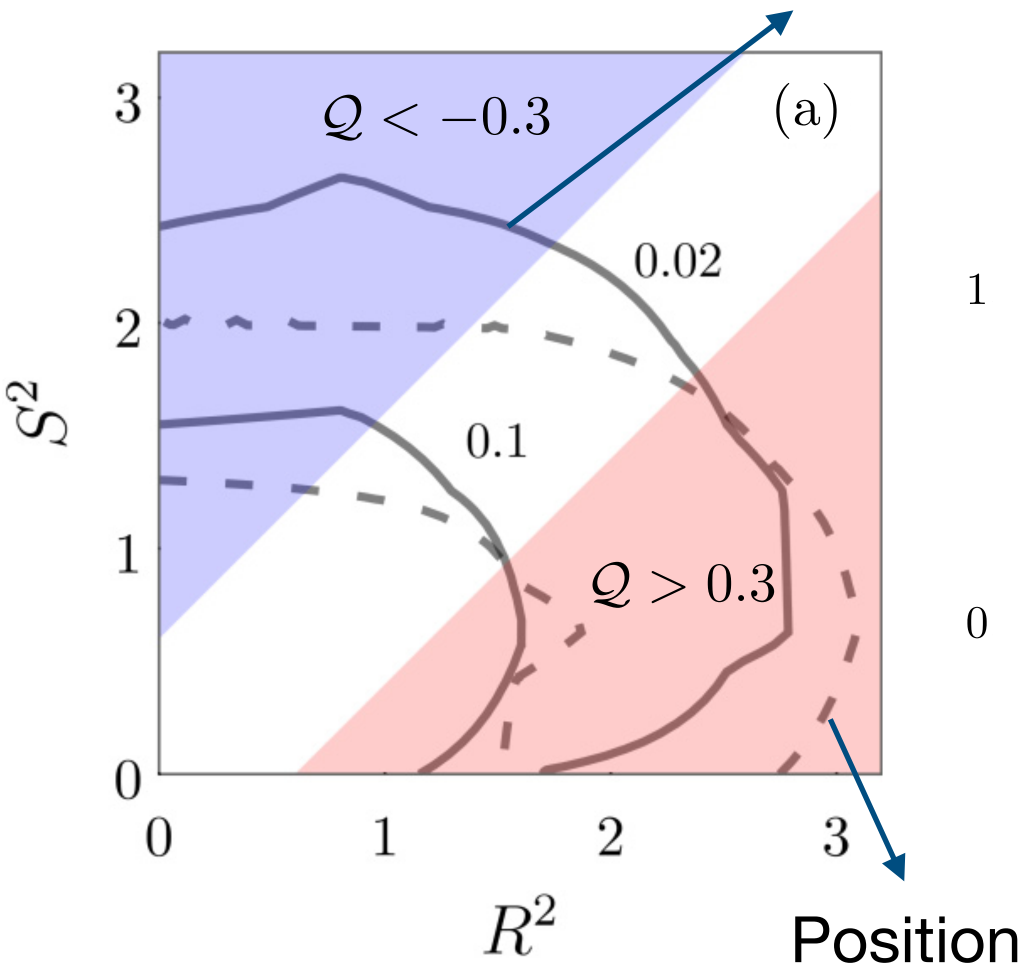
Discrepancy: Flow structures that are intrinsically more effective at causing collisions.



Collisions *over sample* straining regions relative to where particles reside

Picardo, Agasthya, Govindarajan, and Ray, Phys. Rev. Fluids (Rapids) 4, 032601(R) (2019)

Still with tracers



Collisions

Positions

Take home messages

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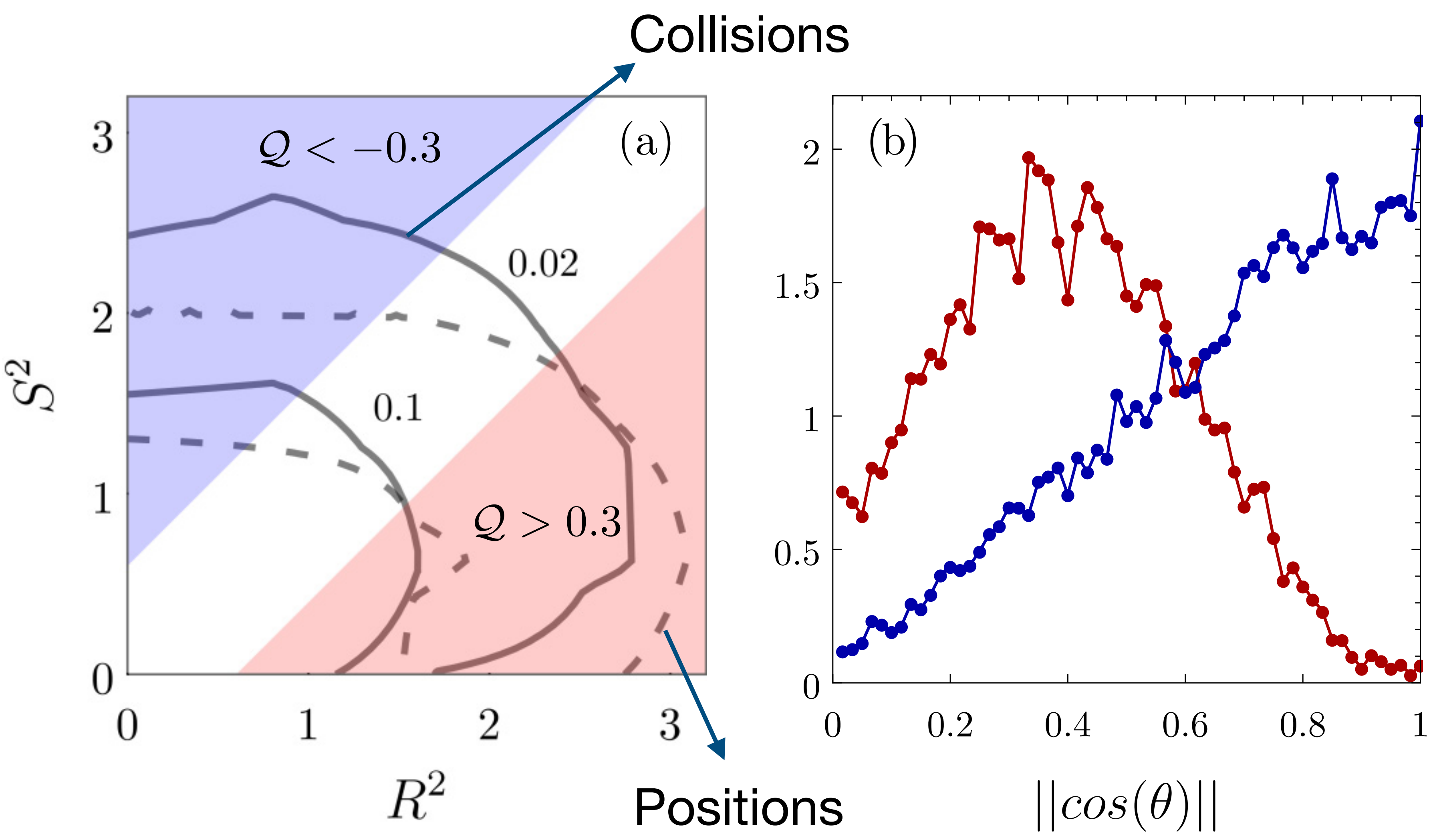

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- Collisions *head-on* or *rear-end* in straining regions; perpendicular in vortical regions

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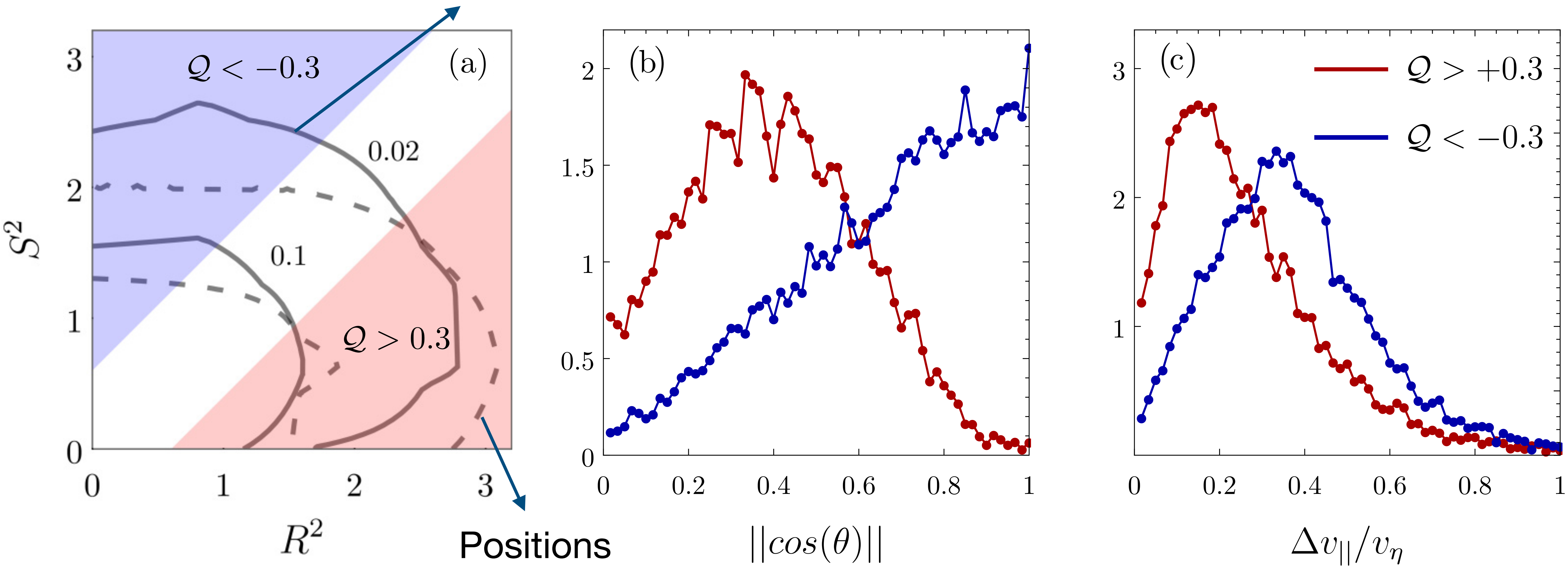

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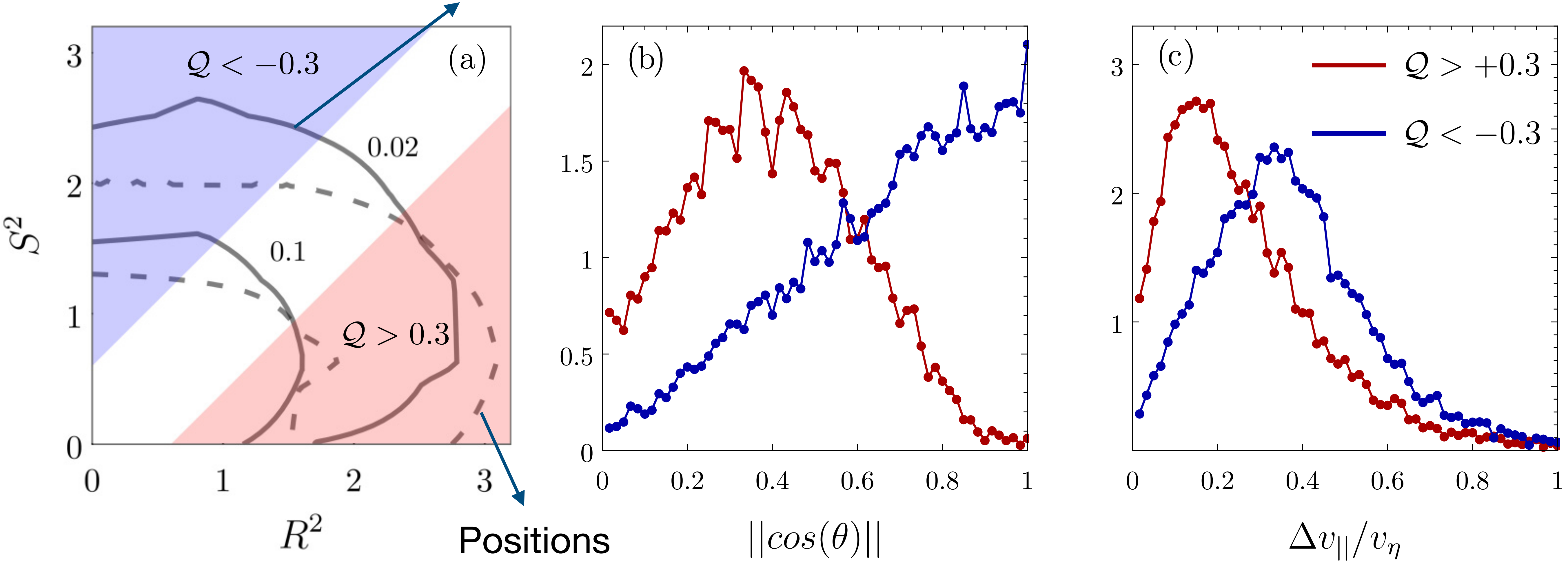

Collisions

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In a given time interval, fewer particles will collide in vortical regions compared to straining regions

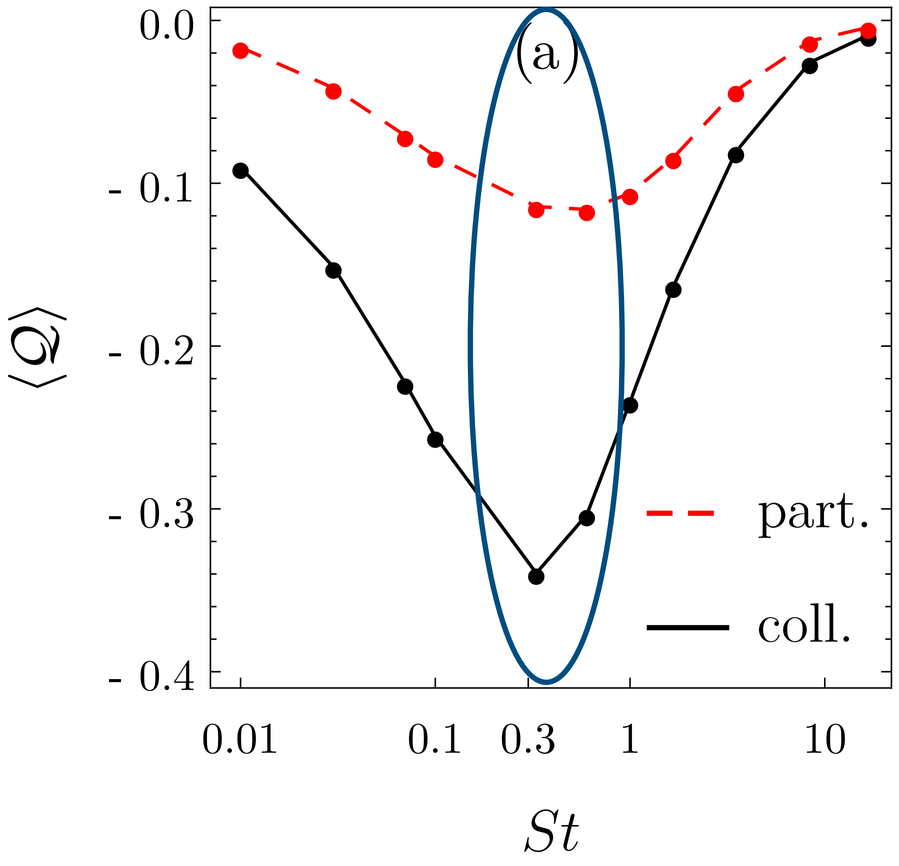
Picardo, Agasthya, Govindarajan, and Ray, Phys. Rev. Fluids (Rapids) 4, 032601(R) (2019)

Inertial Particles

How does particle inertia affect this picture?

Picardo, Agasthya, Govindarajan, and Ray, Phys. Rev. Fluids (Rapids) 4, 032601(R) (2019)

Inertial Particles



- Large Stokes: Particle dynamics decorrelated from the flow
- St ~ 0.3: Strongest effect for strain-dominated collisions

Perrin & Jonker, Phys. Rev. E 89, 033005 (2014)
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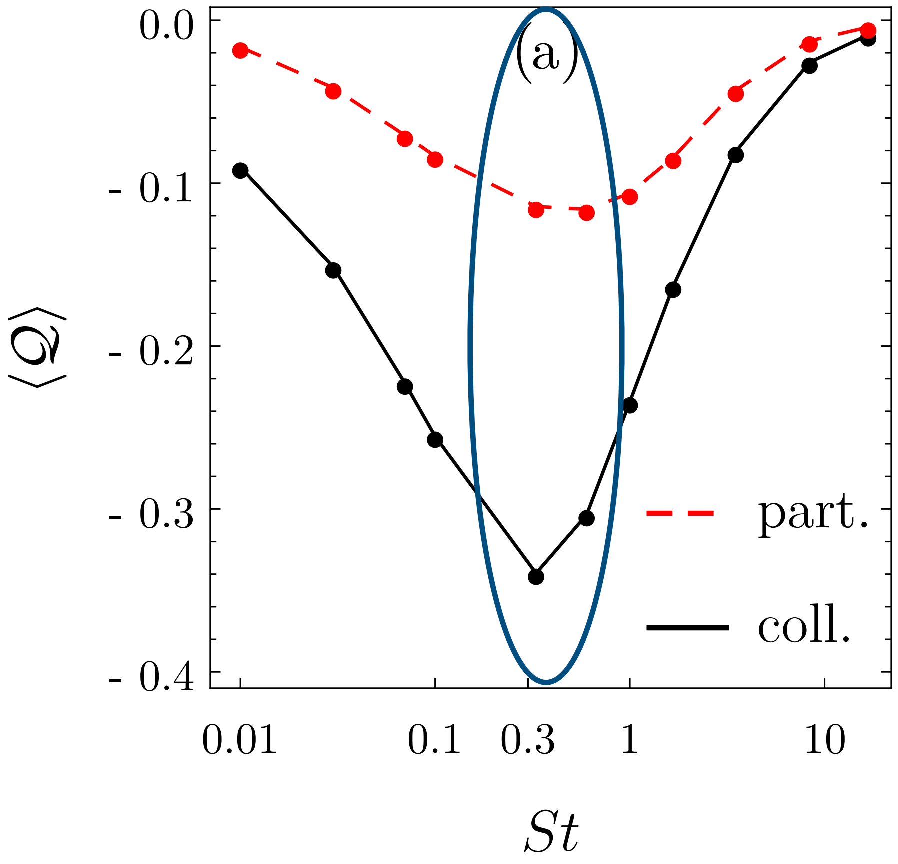

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Possible Explanations

- Preferential Concentration: Higher number of collisions

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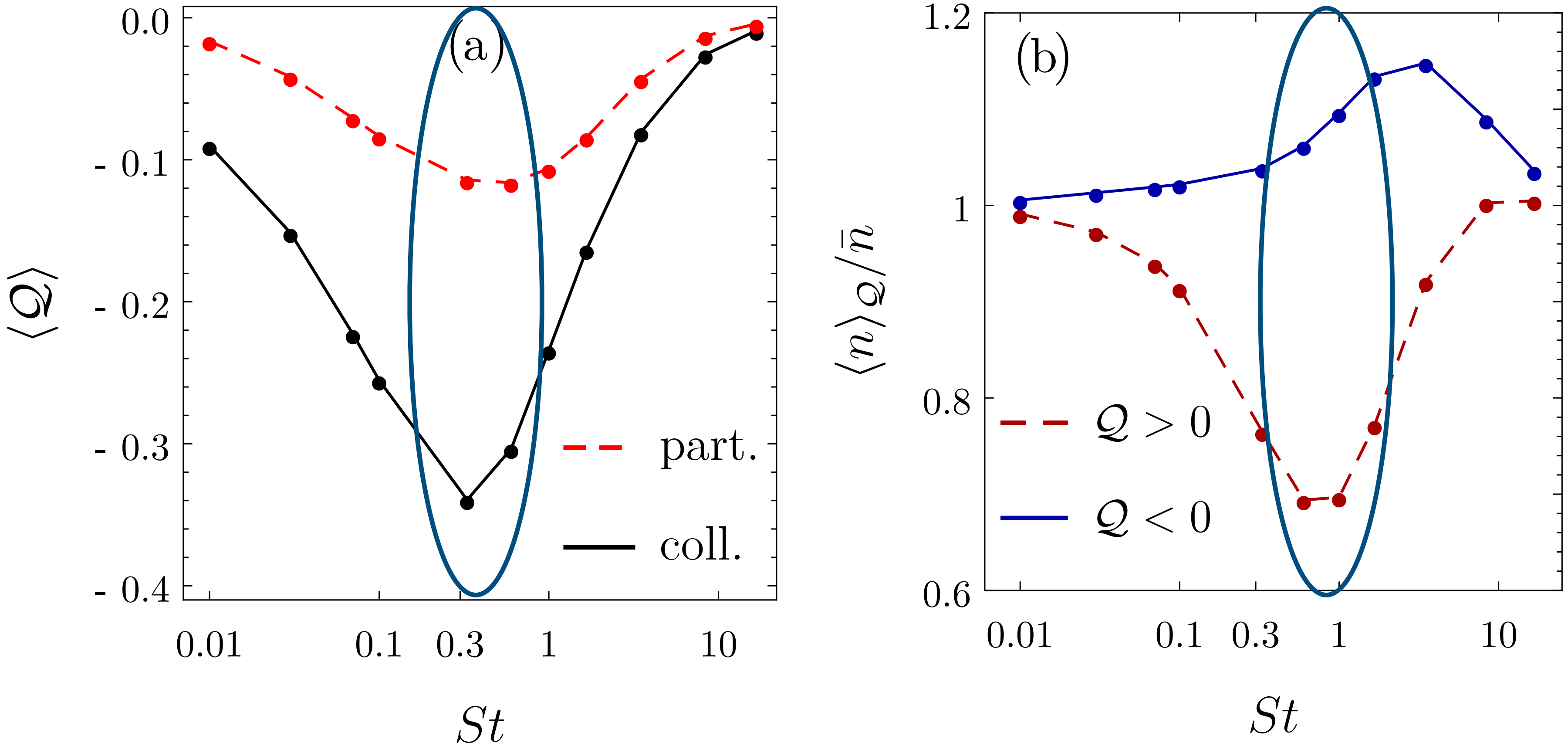

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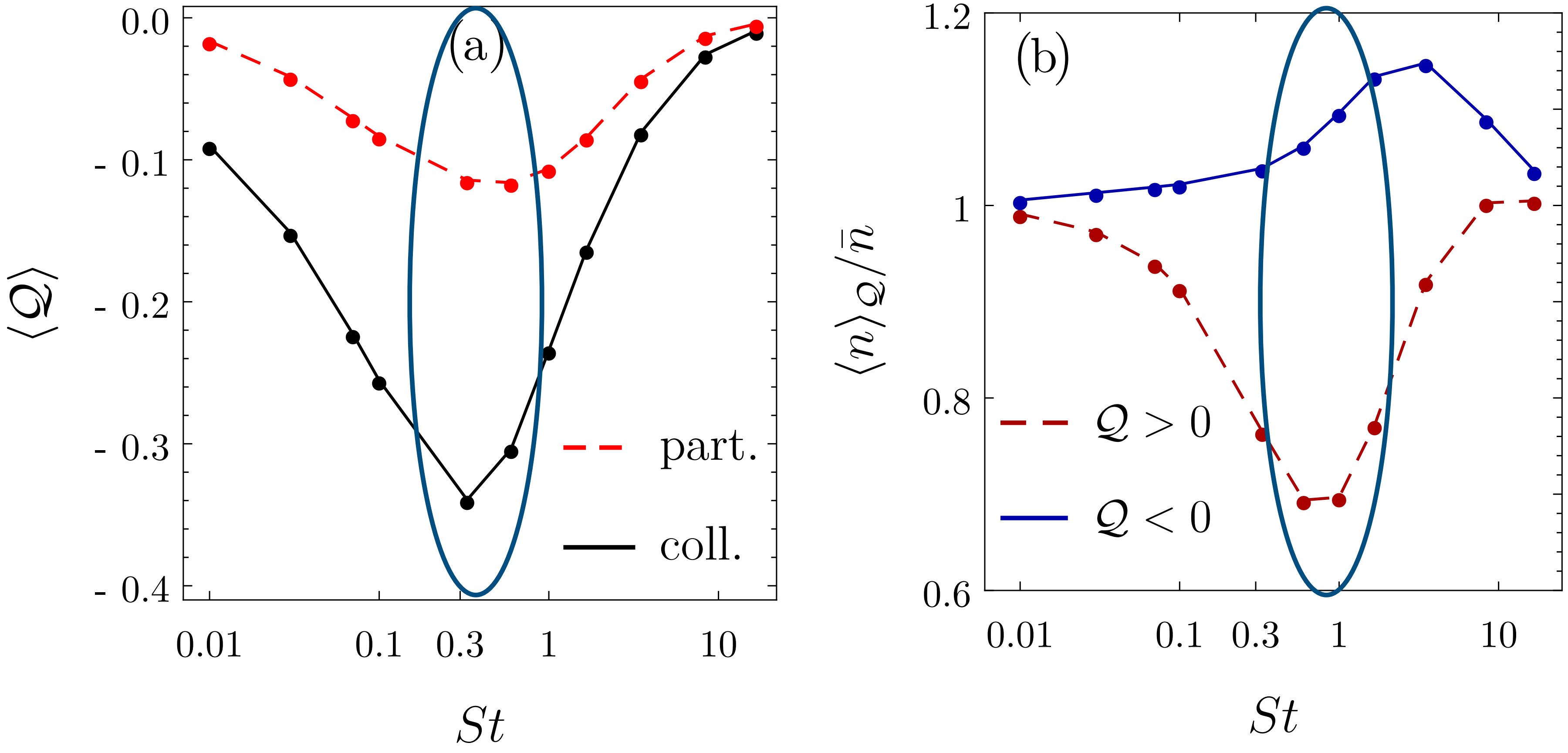

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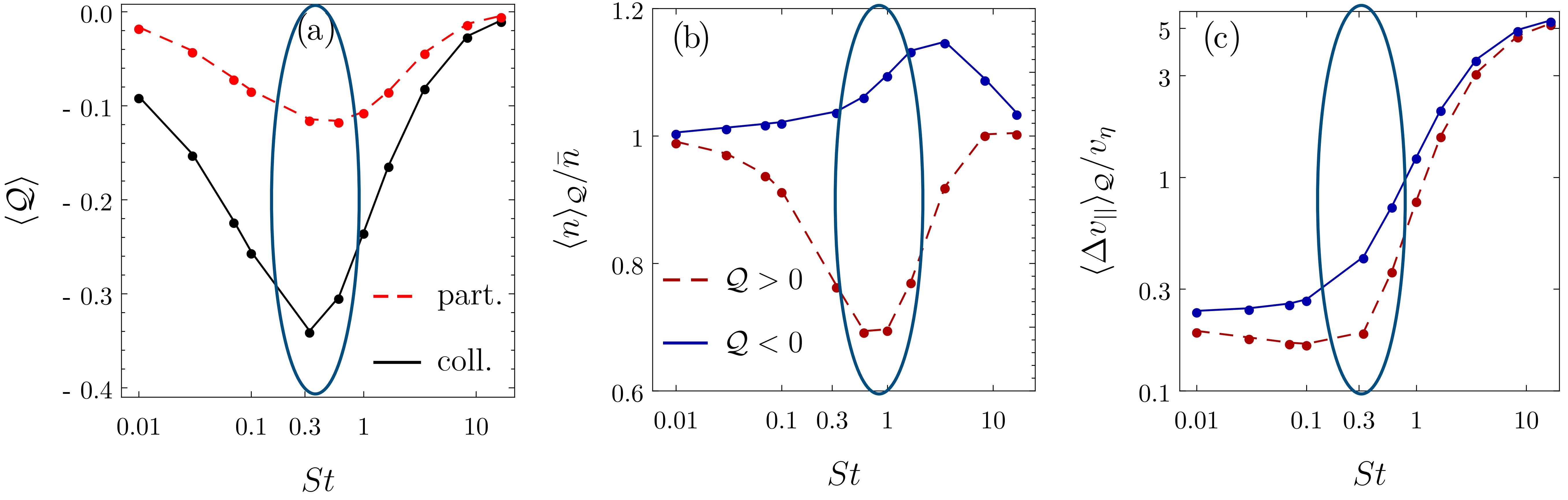

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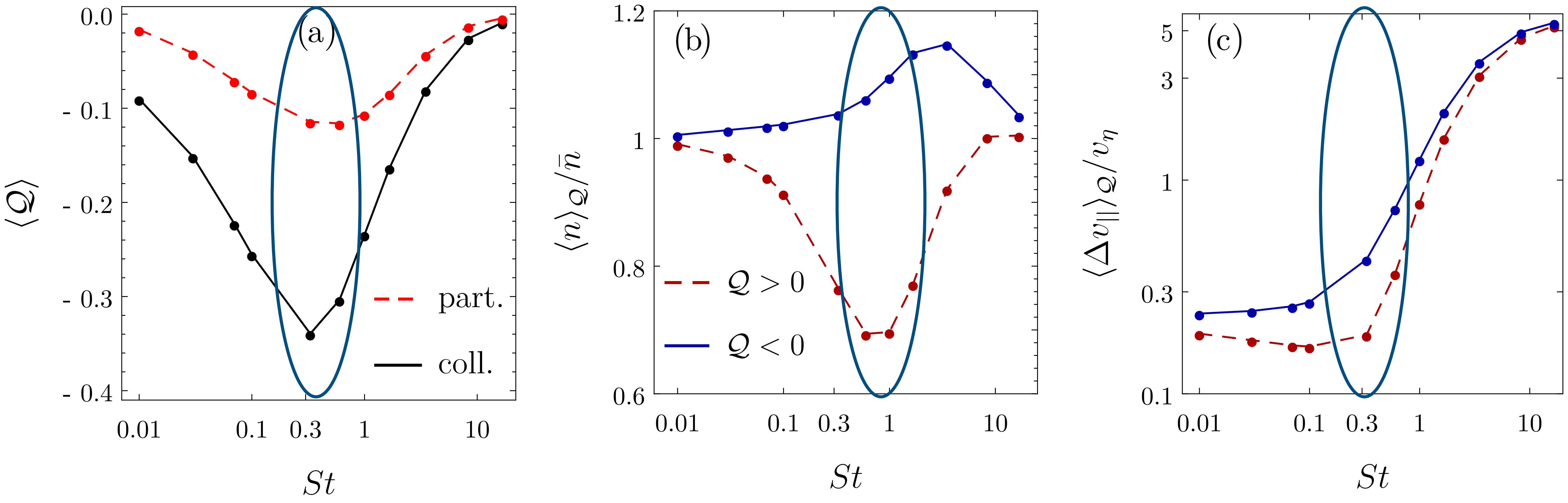

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Larger approach rates due to flow structures and not preferential concentration seems to be the primary driver for collisions

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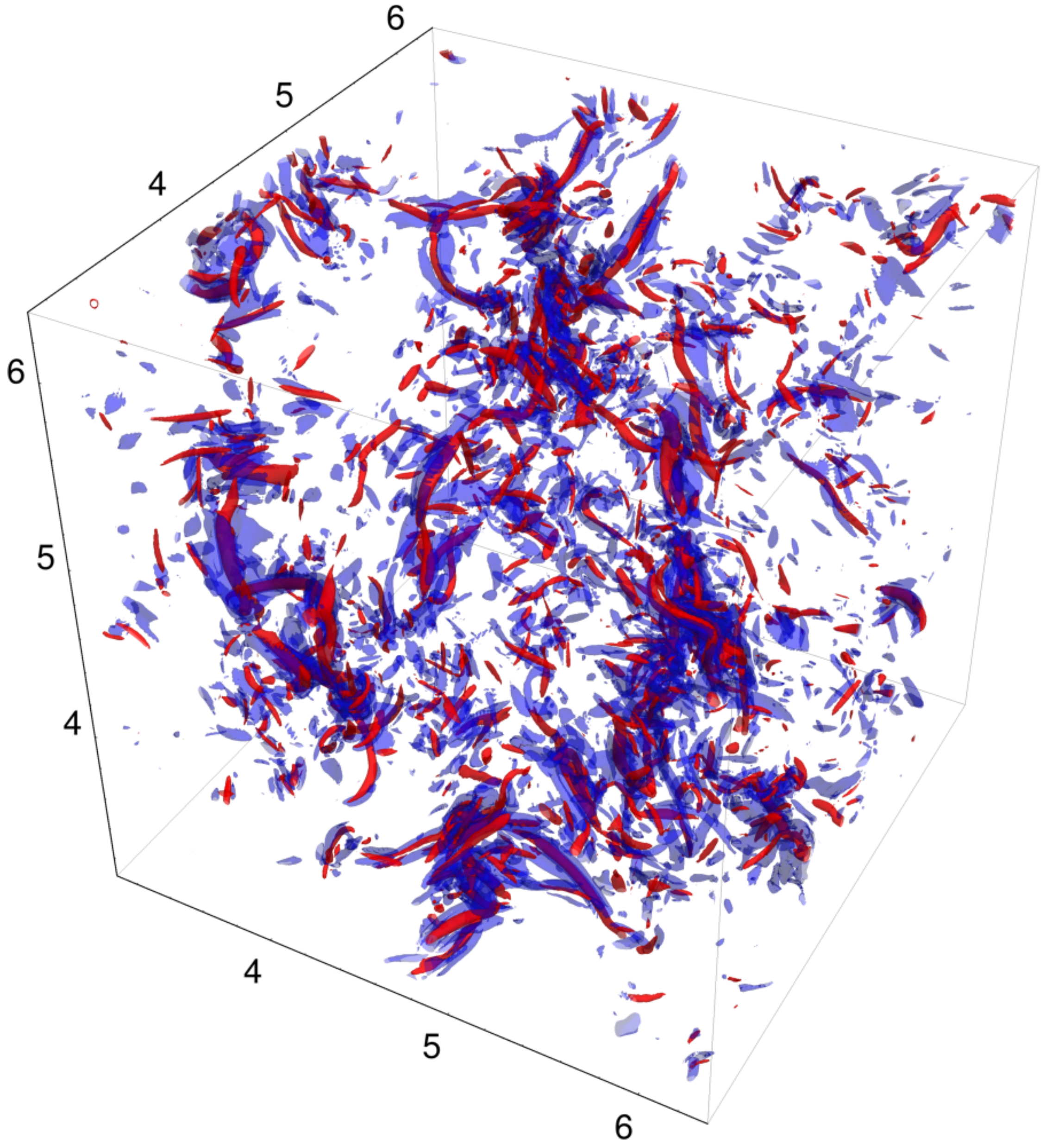
Can vortical and straining regions conspire to enhance collisions?

Picardo, Agasthya, Govindarajan, and Ray, Phys. Rev. Fluids (Rapids) 4, 032601(R) (2019)

The conspiracy of vortex-strain worm-rolls



Geometry of the flow lead to particles in intense vortex tubes to be ejected into strong straining sheets leading to collisions

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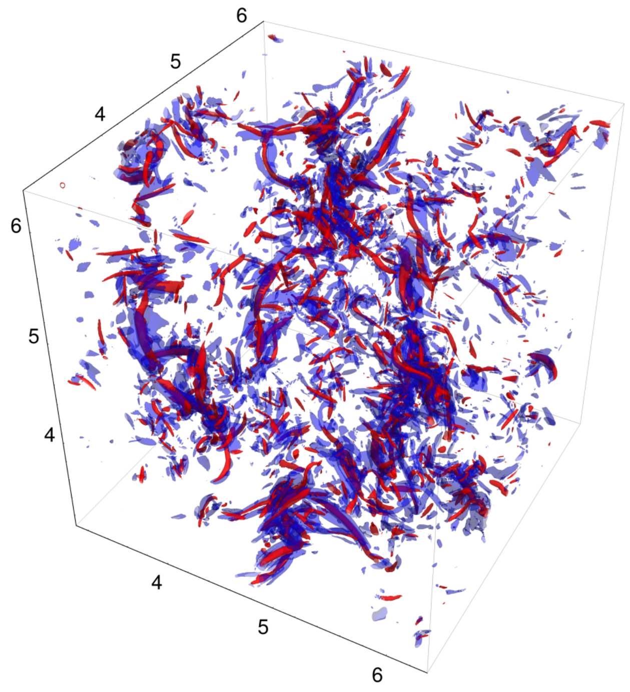

Geometry of the flow lead to particles in intense vortex tubes
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Use backward-in-time Lagrangian calculations to trace where colliding particles come from

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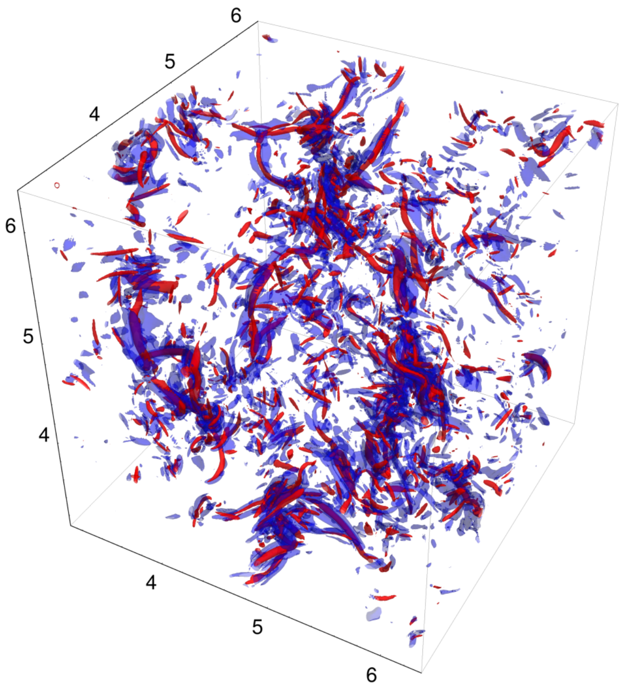

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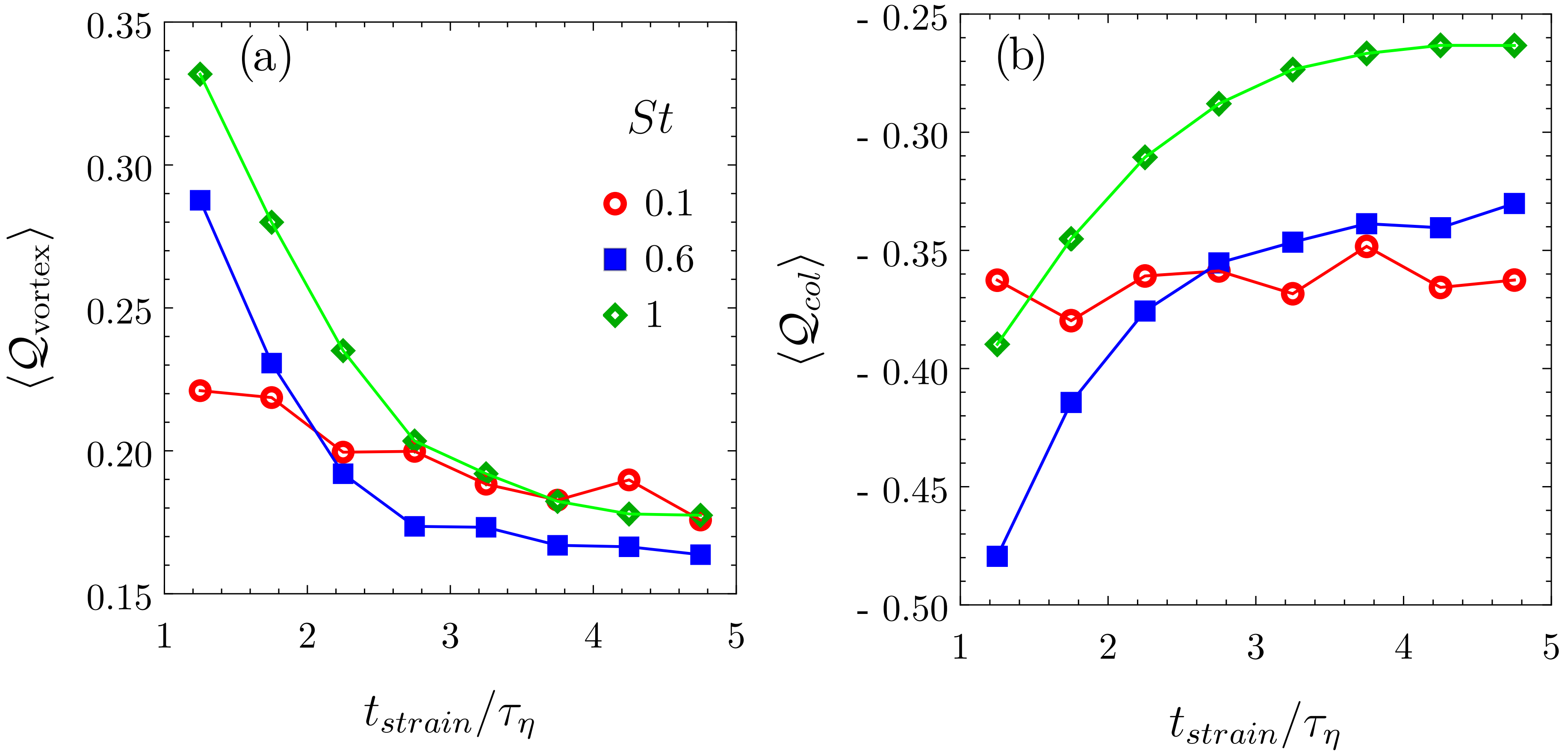
Particles that collide quickly originate in intense vortices and collide in regions of intense strain



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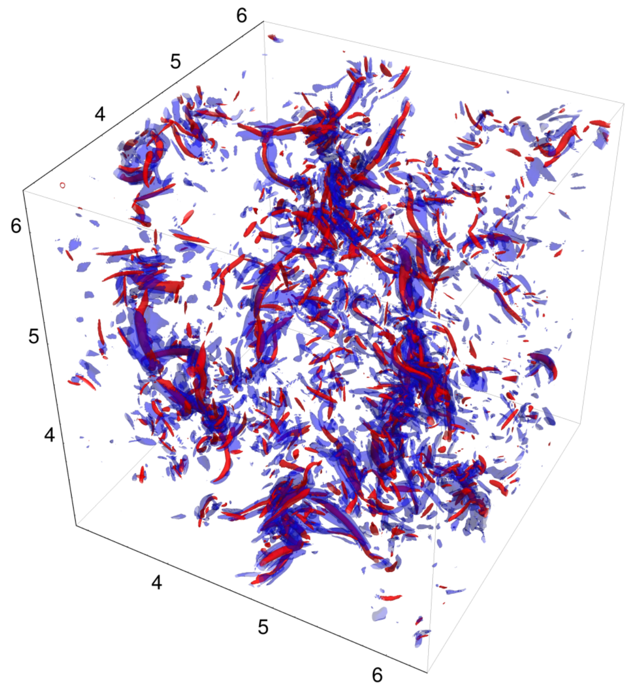

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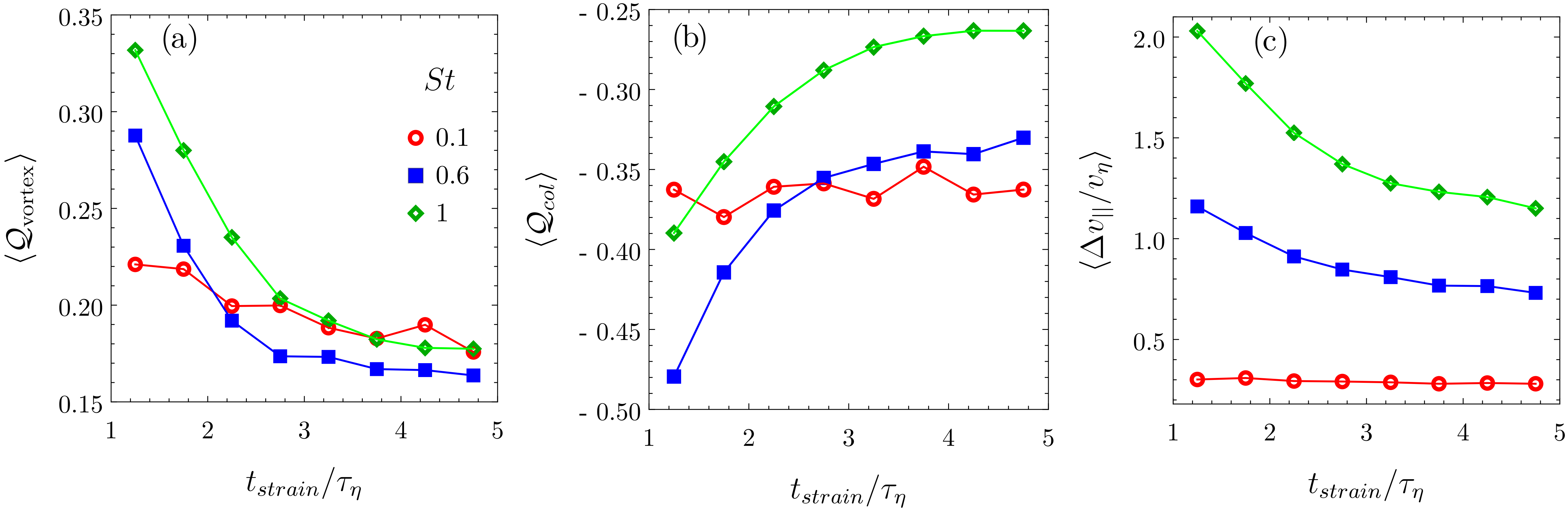
Collisional velocities systematically larger when they structures conspire



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Conclusions & Perspective

Summary

- Straining regions more effective at generating collisions: Larger proportion of *head-on* or *rear-end* collisions
- A larger fraction of the velocity gradient in straining zones is translated into the particle approach velocity.
- Intense vorticity and strain, cohabiting as vortex-strain worm-rolls, conspire to generate violent collisions.
- Preferential concentration, caustics and other mechanisms only a part of the story: Turbulence matters!

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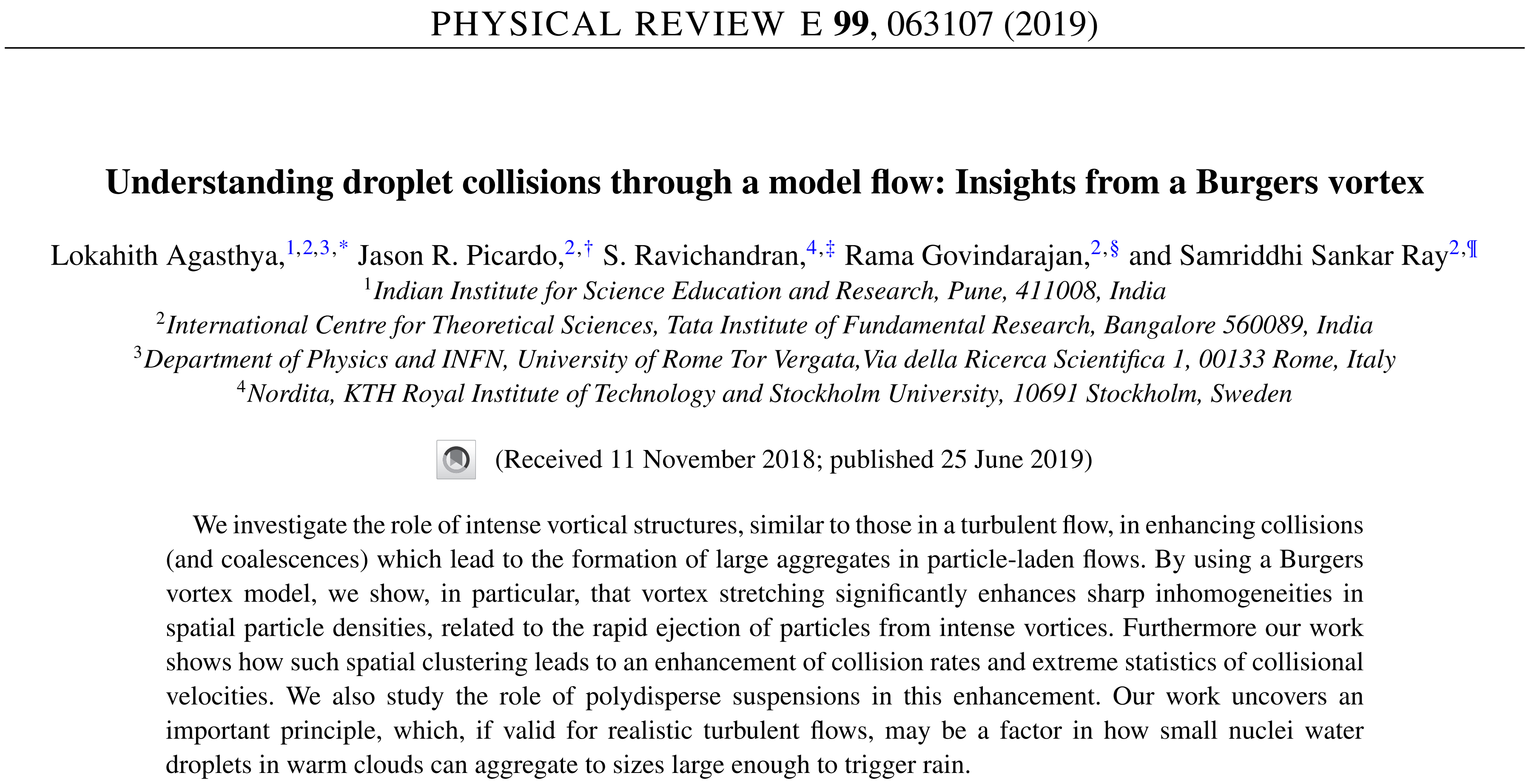

PHYSICAL REVIEW E **99**, 063107 (2019)

Understanding droplet collisions through a model flow: Insights from a Burgers vortex

Lokahith Agasthya,[1,2,3,*] Jason R. Picardo,[2,†] S. Ravichandran,[4,‡] Rama Govindarajan,[2,§] and Samriddhi Sankar Ray[2,¶]
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[2]*International Centre for Theoretical Sciences, Tata Institute of Fundamental Research, Bangalore 560089, India*
[3]*Department of Physics and INFN, University of Rome Tor Vergata,Via della Ricerca Scientifica 1, 00133 Rome, Italy*
[4]*Nordita, KTH Royal Institute of Technology and Stockholm University, 10691 Stockholm, Sweden*

(Received 11 November 2018; published 25 June 2019)

We investigate the role of intense vortical structures, similar to those in a turbulent flow, in enhancing collisions (and coalescences) which lead to the formation of large aggregates in particle-laden flows. By using a Burgers vortex model, we show, in particular, that vortex stretching significantly enhances sharp inhomogeneities in spatial particle densities, related to the rapid ejection of particles from intense vortices. Furthermore our work shows how such spatial clustering leads to an enhancement of collision rates and extreme statistics of collisional velocities. We also study the role of polydisperse suspensions in this enhancement. Our work uncovers an important principle, which, if valid for realistic turbulent flows, may be a factor in how small nuclei water droplets in warm clouds can aggregate to sizes large enough to trigger rain.

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Open Questions

- How are collisions affected when structures change?
- Modification of flow structures by new physical interactions: Examples include condensation, small-scale moti elastic feedback from polymer additives.
- Role of gravitational settling

Bec, Homann, and Ray, Phys. Rev. Lett. 112, 184501 (2014)

Picardo, Agasthya, Govindarajan, and Ray, Phys. Rev. Fluids (Rapids) 4, 032601(R) (2019)