On the Relevance of Atmospheric Particles for Laminar-Turbulent Transition in Hypersonic Flight

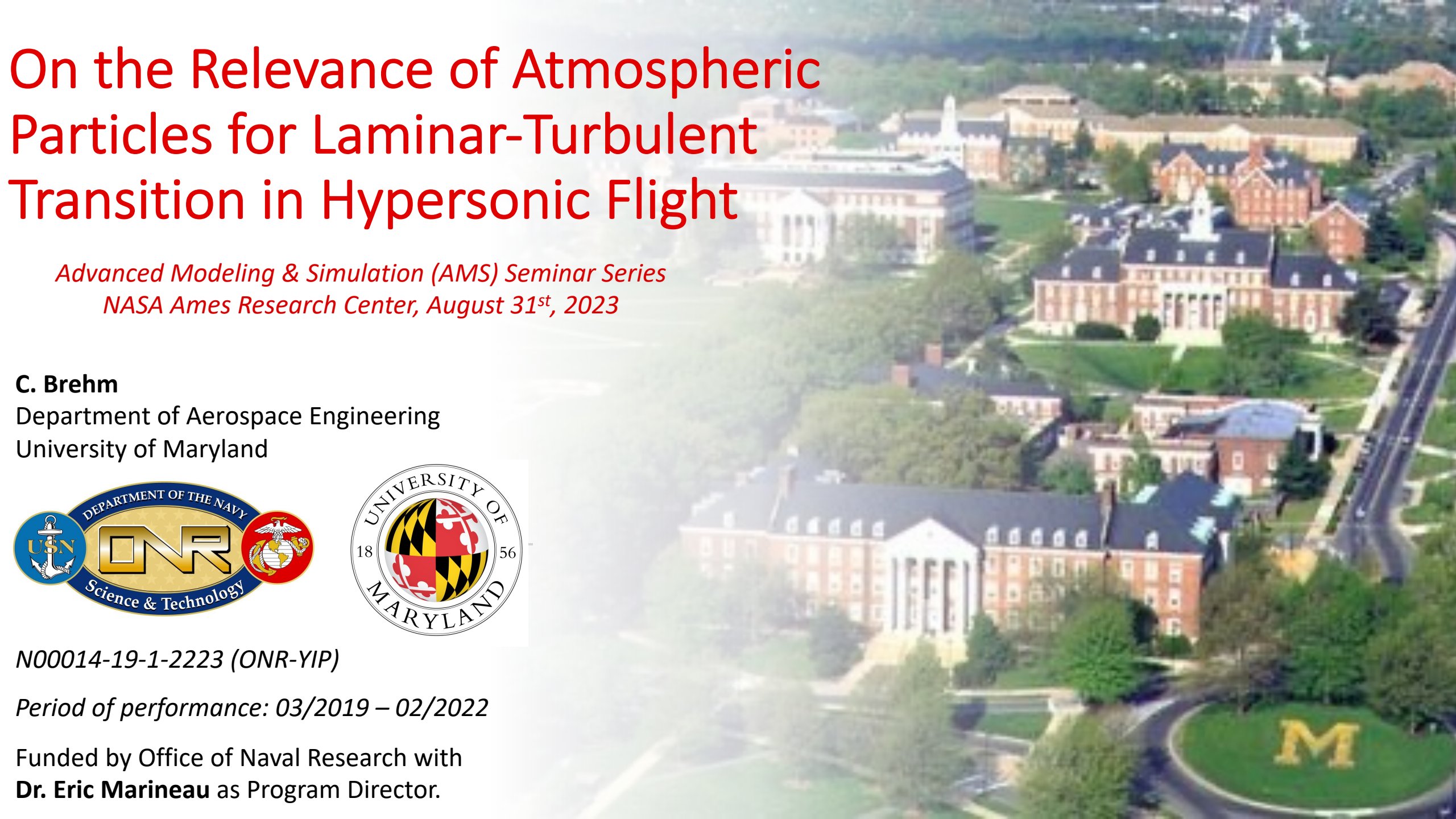
Advanced Modeling & Simulation (AMS) Seminar Series
NASA Ames Research Center, August 31st, 2023

C. Brehm
Department of Aerospace Engineering
University of Maryland

N00014-19-1-2223 (ONR-YIP)

Period of performance: 03/2019 – 02/2022

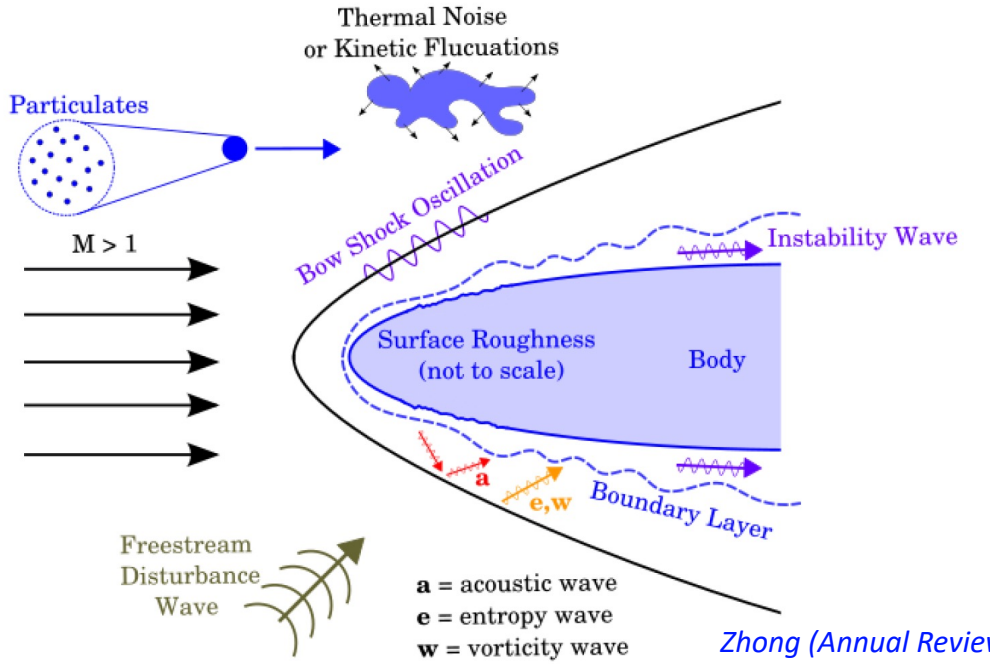
Funded by Office of Naval Research with
Dr. Eric Marineau as Program Director.



Background

- Different disturbance sources are present in the environment which can introduce low disturbances into the boundary layer (i.e., natural transition), namely freestream turbulence, surface roughness, vibrations, kinetic fluctuations, temperature spot, **particulates**, etc.

Disturbance Sources in Free-Stream Environment

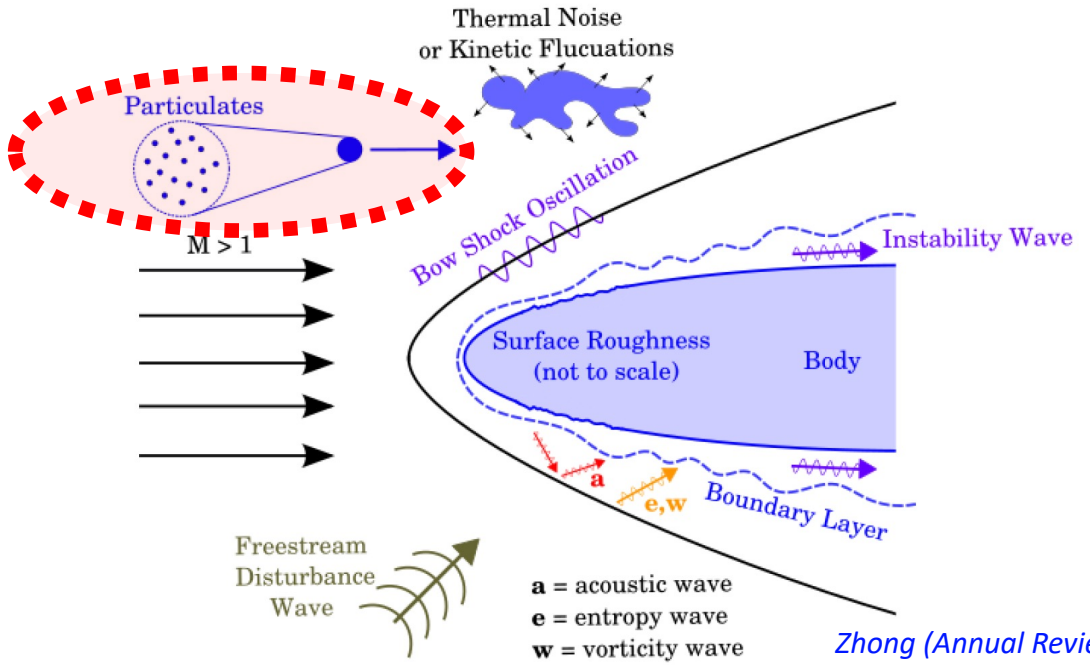


Zhong (Annual Review 1988)

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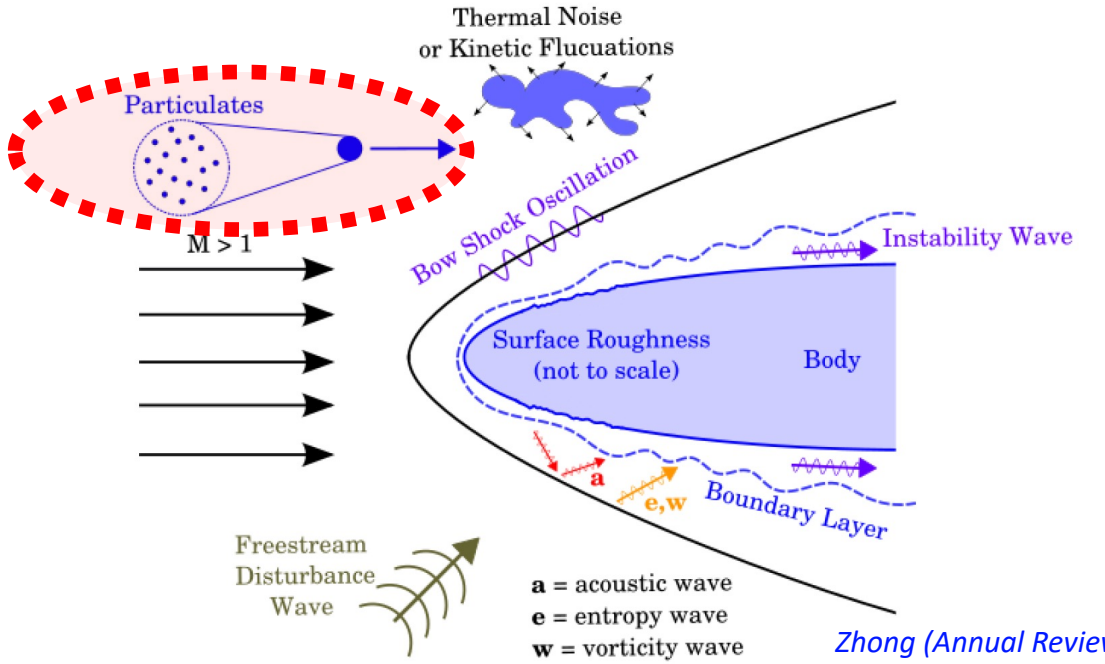


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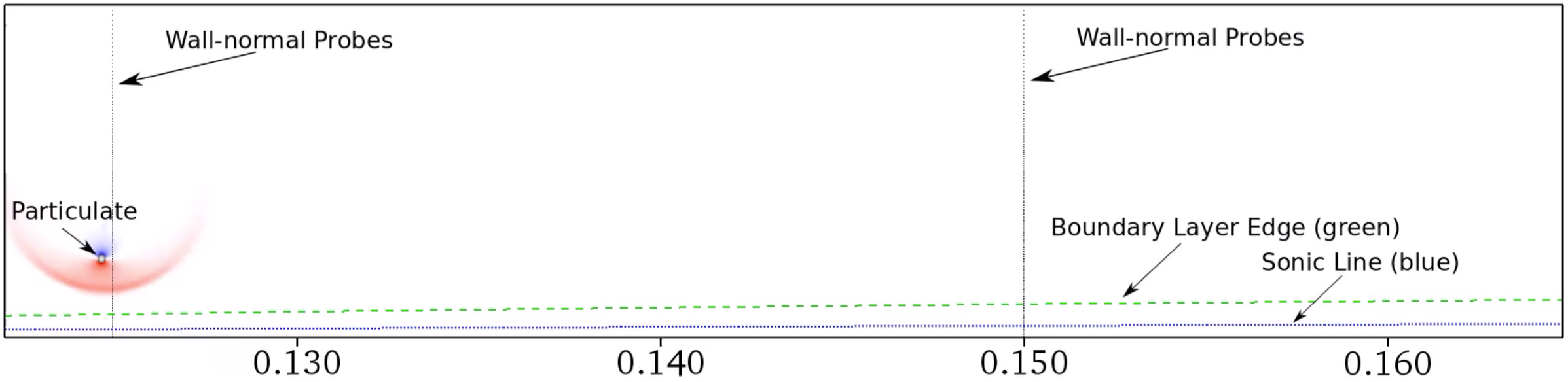
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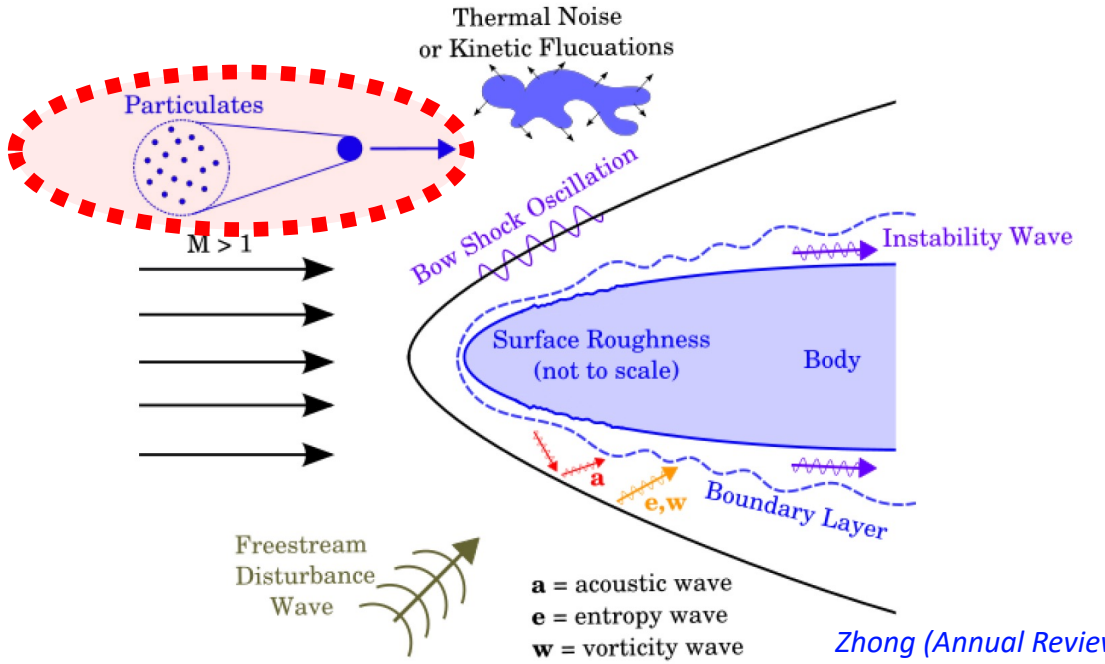
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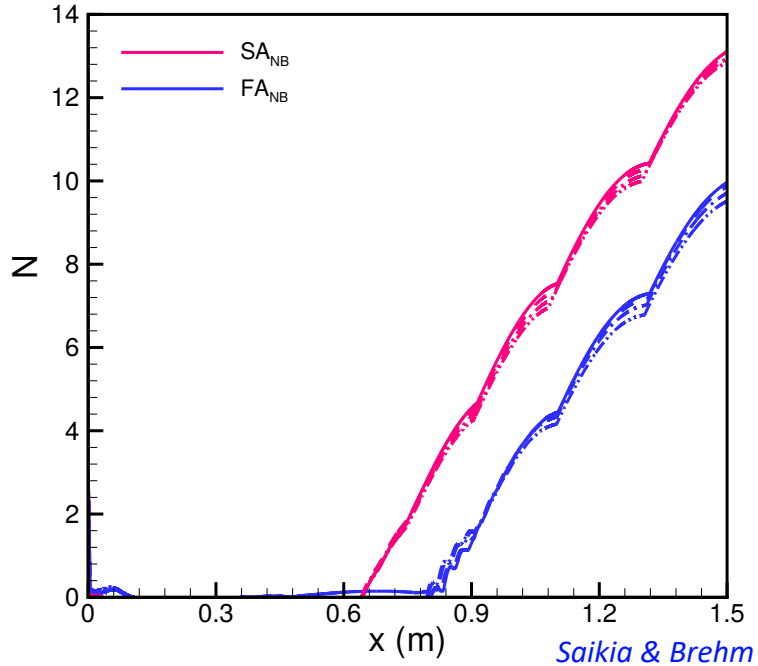
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- Particles can introduce small-scale disturbances inside the boundary layer generating wavepackets, which propagate in the downstream direction, may amplify and lead to transition.
- Modeling particle-induced transition is challenging due to the need to accurately model the particle-flow interactions.

Disturbance Sources in Free-Stream Environment



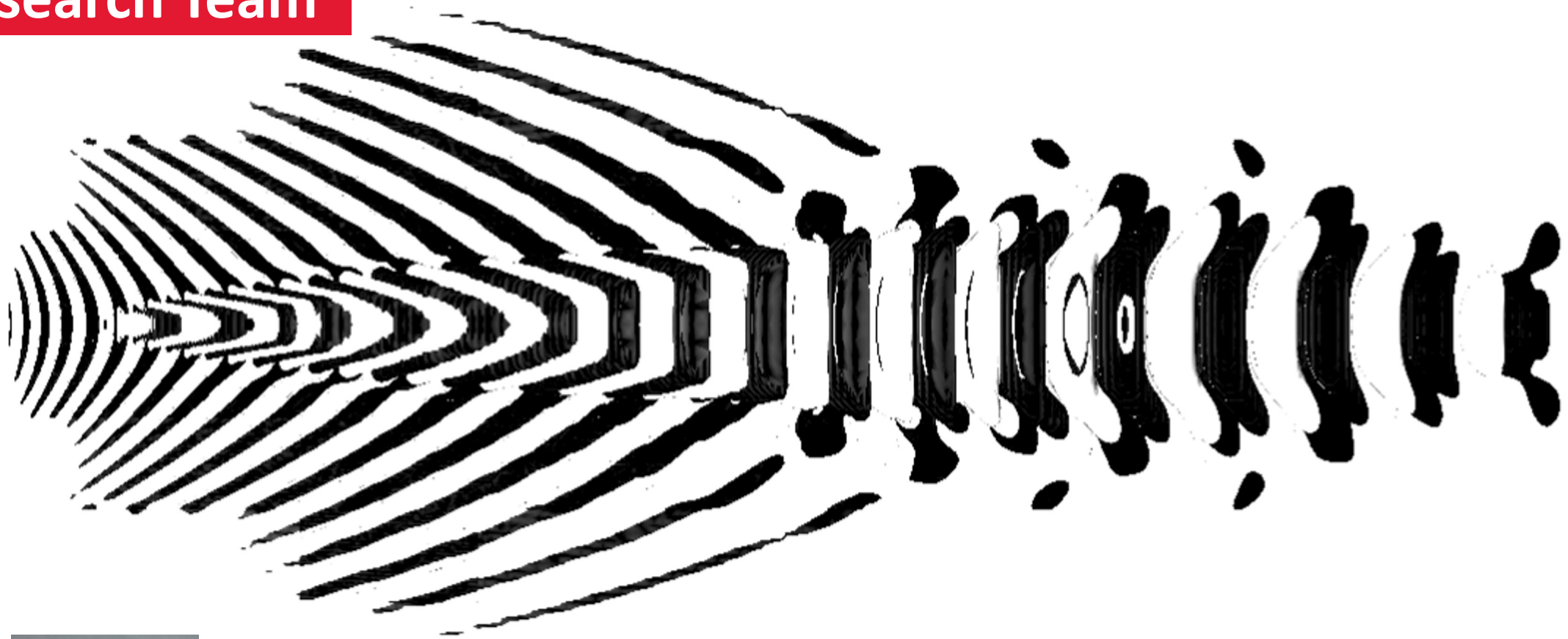
Zhong (Annual Review 1988)

Receptivity Study for Slow vs Fast Acoustic Waves



Saikia & Brehm (2023)

Research Team





C. Brehm
Associate Prof. (UMD)



V. Russo
PhD student (UK)



S. Al Hasnine
PhD student (UMD)



O. Browne
(STC/NASA Ames)

Other Contributors:

- **Prof. Anatoli Tumin (UofA)** for fruitful discussions and guidance on bi-orthogonal decomposition of the disturbance flow field.
- **Ibrahim Guven's research team (VCU)**
- **Savio Poovathingal's research team (UK)**

Publications

- *"Fully-Resolved Particulate-Induced Transition Simulations for High-Speed Boundary-Layers with an Immersed Boundary Method ,"* O. M. F. Browne, S. Hasnine, V. Russo, and C. Brehm, AIAA SciTech, Orlando, Florida, January 6, 2020.
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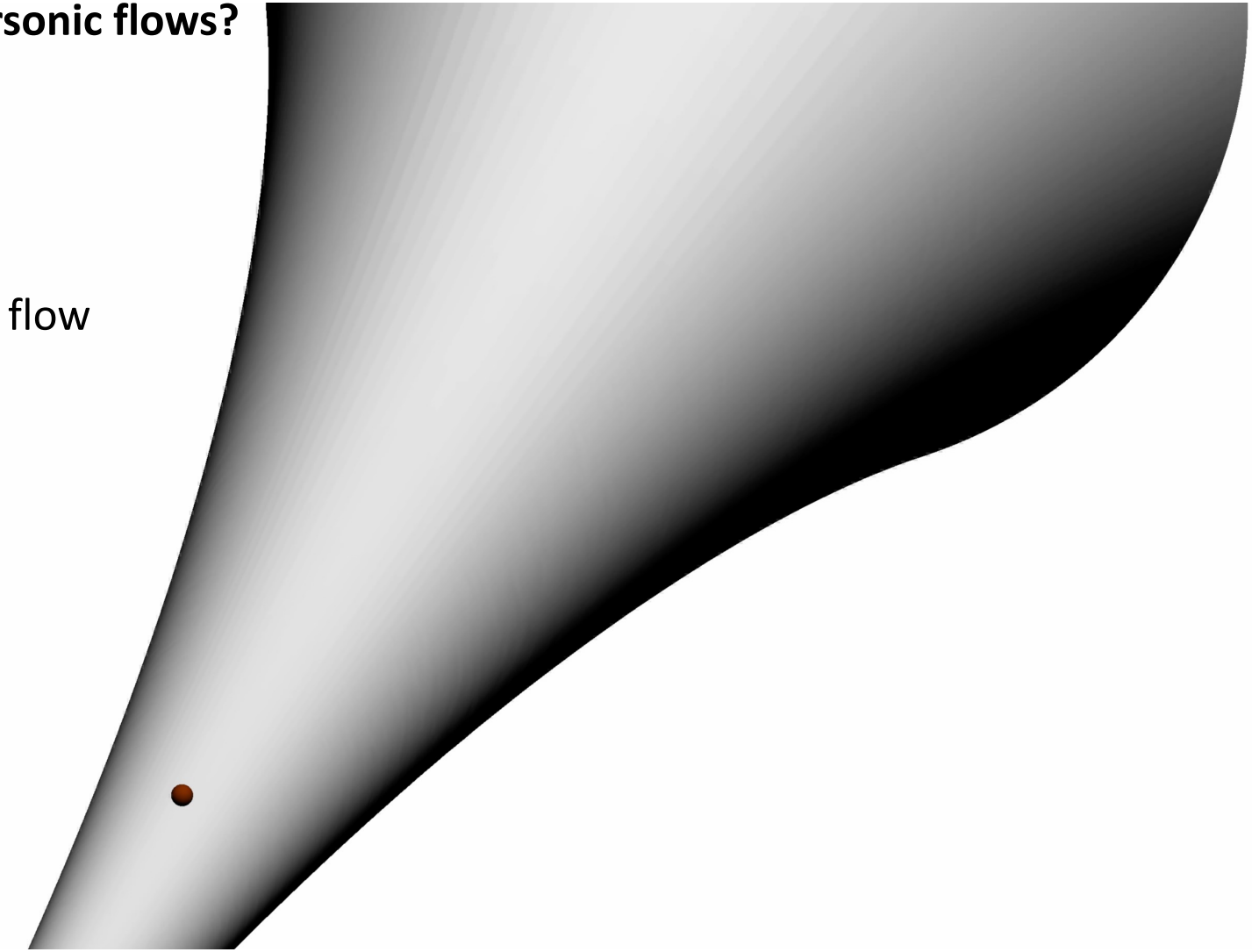
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Relevance of Particle-Induced Transition for Hypersonic Flight

What are the key parameters that need to be considered when assessing particle-induced transition for hypersonic flows?

- ❑ Particle sizes in the atmosphere
- ❑ Particle concentration
- ❑ Required particle flux to maintain turbulent flow
- ❑ Receptivity mechanisms seeding
  - disturbance amplitude
  - instability mechanisms
- ❑ Particle Modeling



Relevance of Particle-Induced Transition for Hypersonic Flight

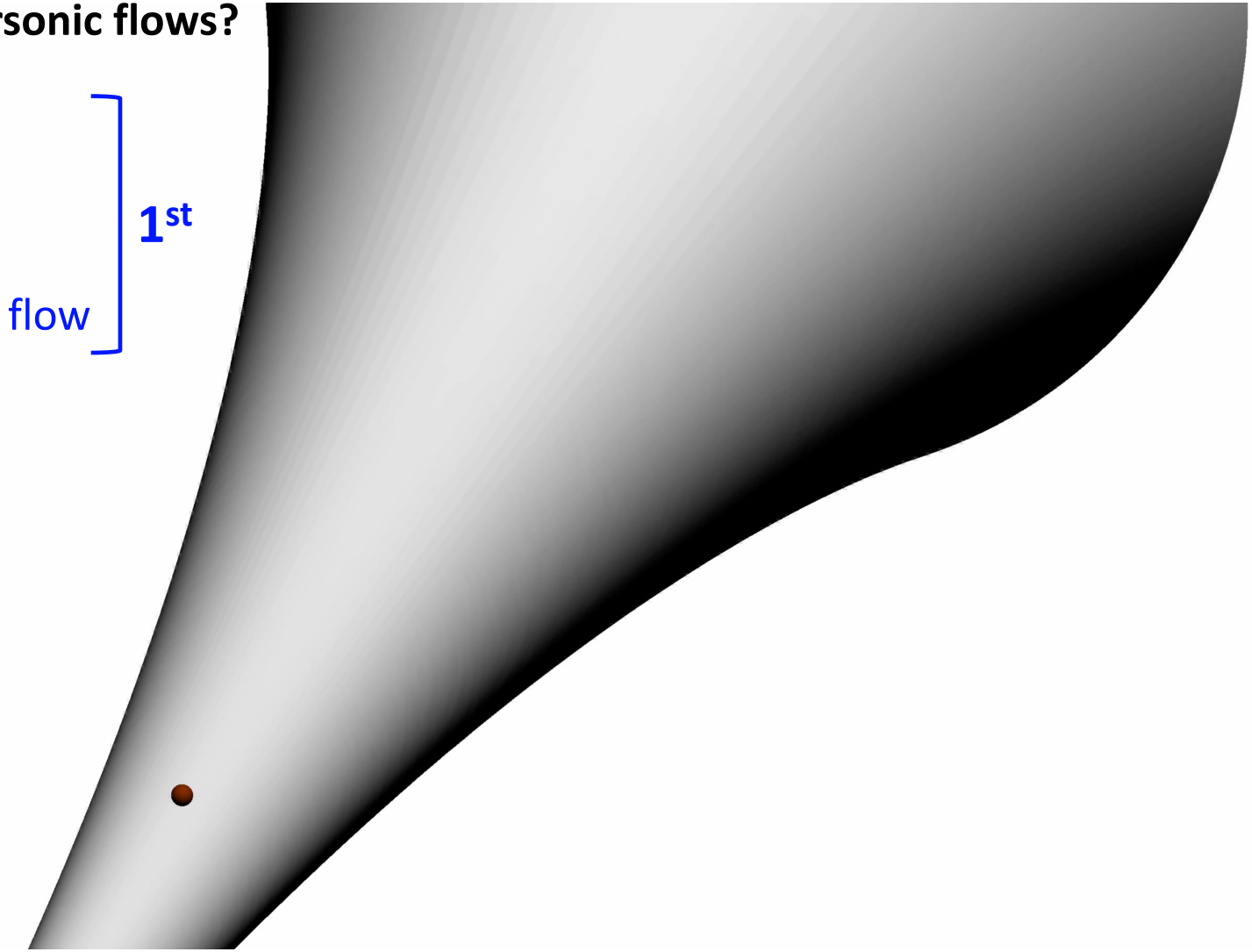
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1st

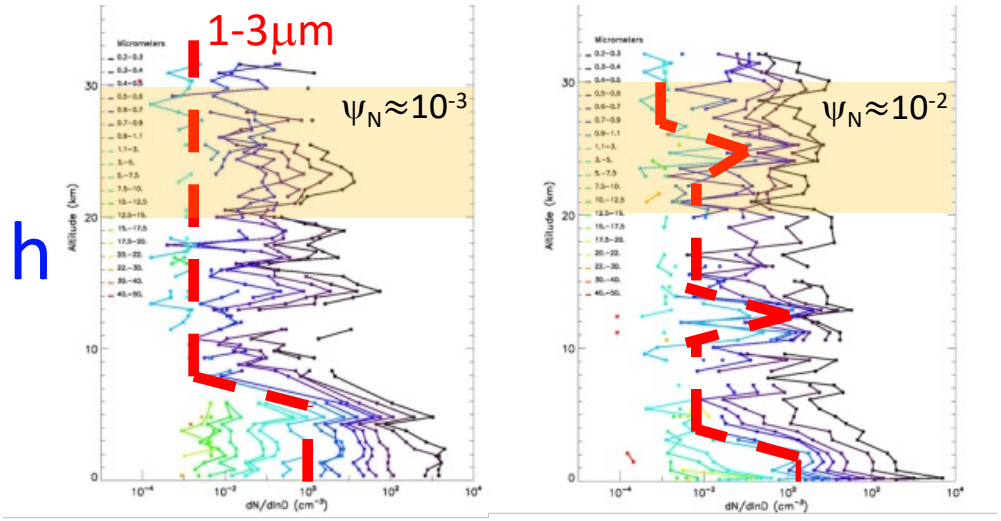
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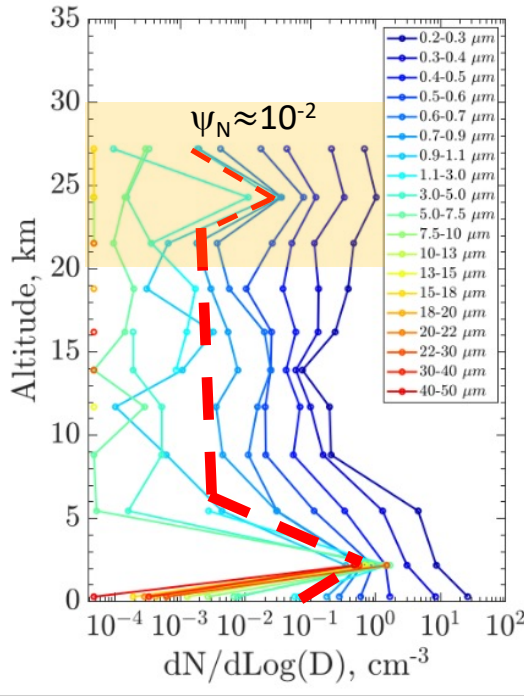
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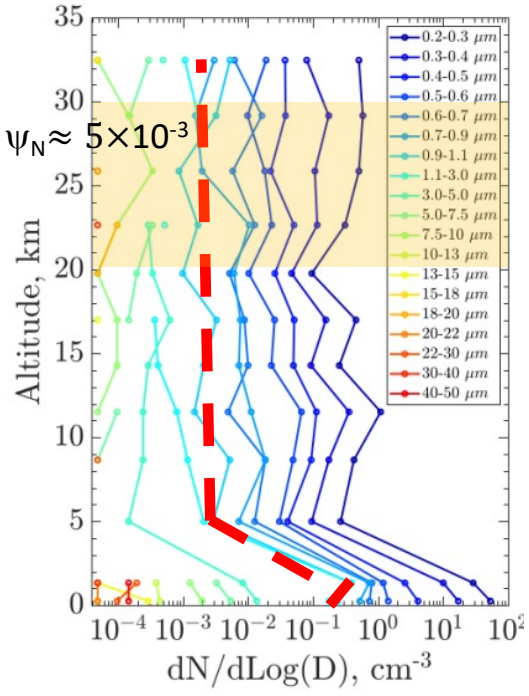


Particle Sizes and Concentration in the Atmosphere

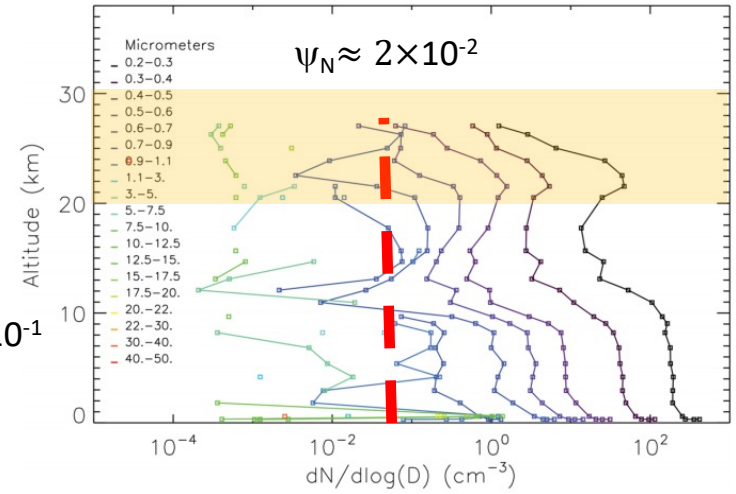
LOAC: a small aerosol optical counter/sizer for ground based and balloon measuremets of the size distribution and nature of atmospheric particles - part 2, J. Renard et al., Atmos. Meas. Tech. Discuss, 2015







High-altitude balloon measurements of atmospheric particulates, J. B. Habeck, J. A. Flaten, G. V. Candler, AIAA Scitech 2020

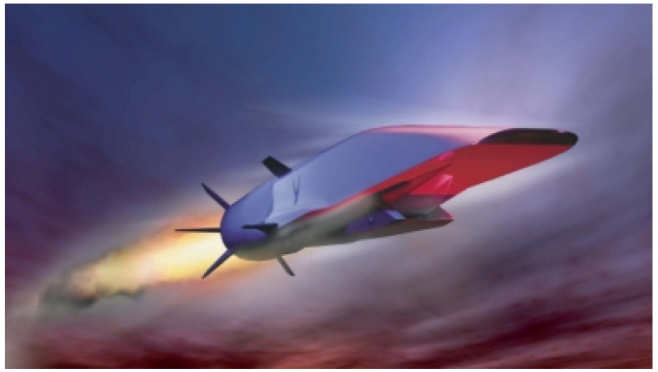


Measurements of aerosols and charged particles on the BEXUS18 stratospheric balloon, E. Brattich et al., Annales Geophysicae 2019

ψ_N=dN/dLog(N)

Required Particle Flux

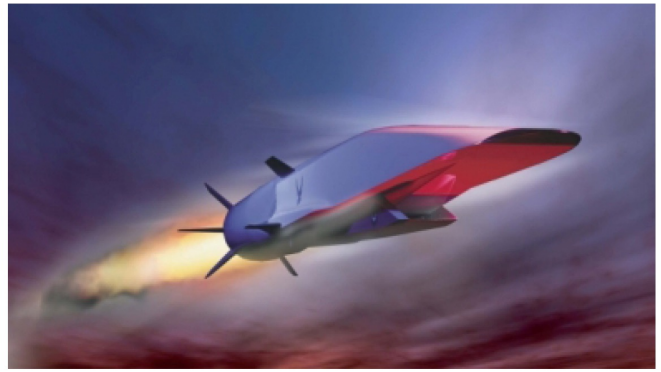
- Hypersonic vehicle travels with M=6-10 or v=1784-2974 m/s



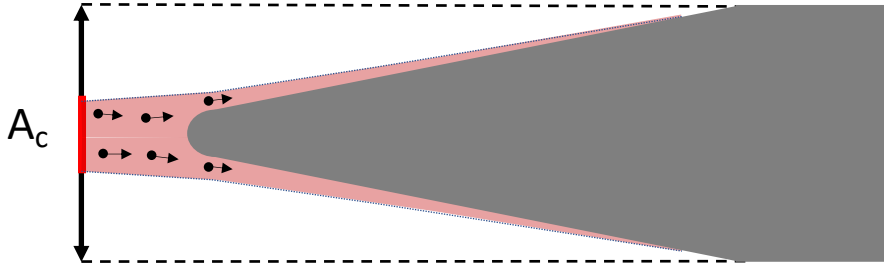


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- Hypersonic vehicle travels with M=6-10 or v=1784-2974 m/s
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  - Bolt and HiFire-5: A_c=0.1m^2
  - ICBM has cross-section diameter of D=1.56m or A_c=1.9m^2
- Volume/s = v $\times$ A_c ~ 2000 m^3/s



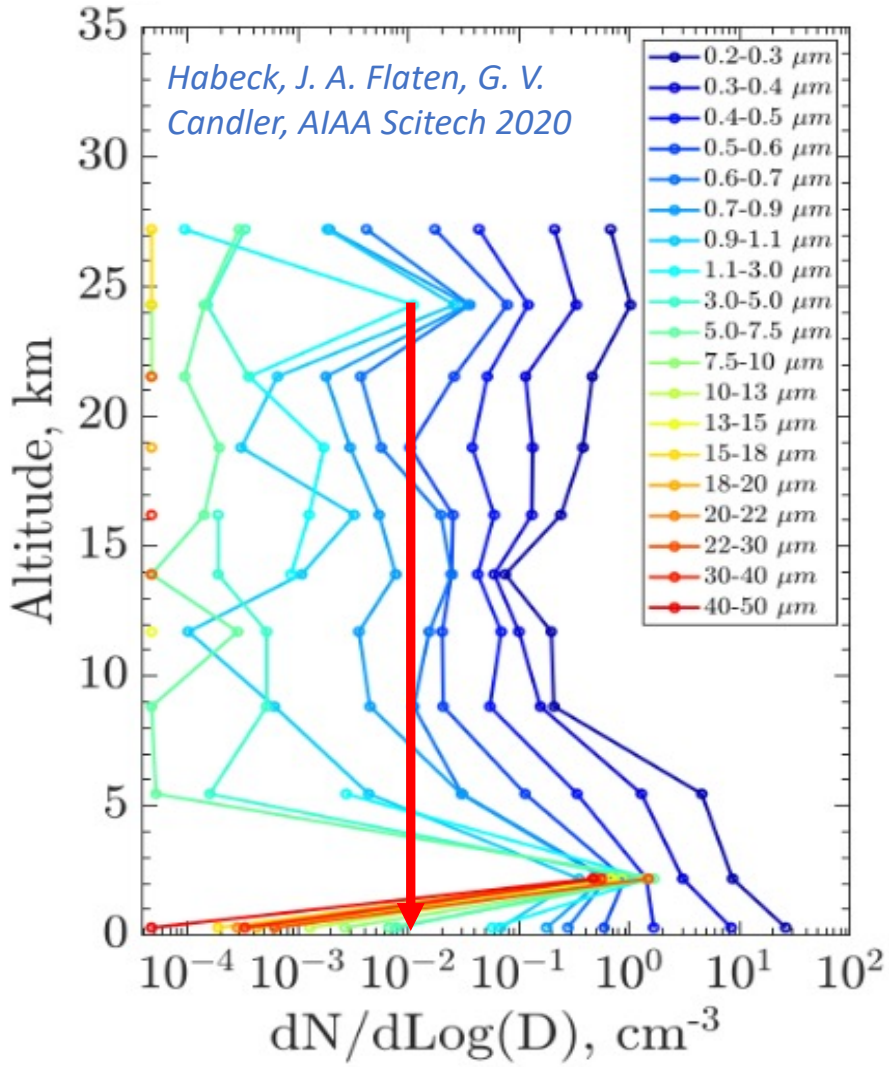






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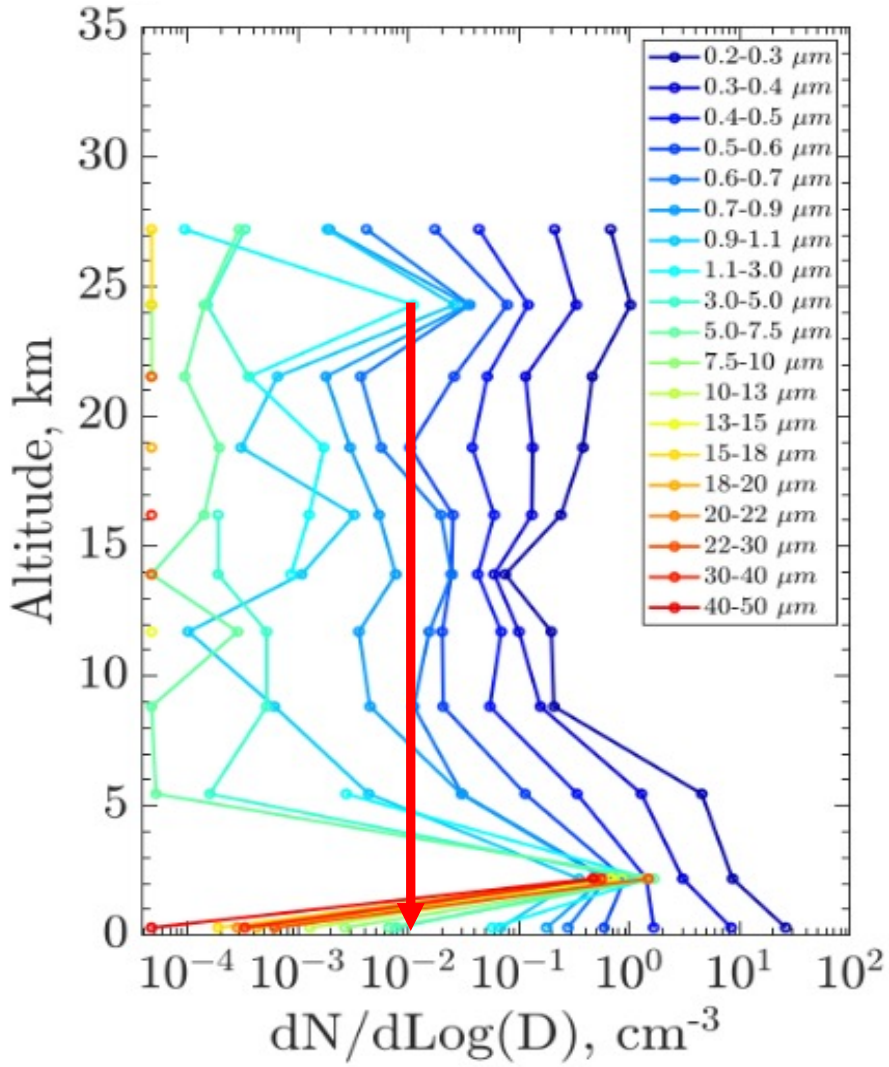
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- dN/dLog(D)=1e-2, D_u = 3μm, D_l = 1.1μm, Log(D_u)-Log(D_l)=0.44
  - **dN=0.0044 particles/cm³**



$$\frac{dN}{dLog(D)} = \frac{\text{number concentration } [cm^{-3}]}{Log(D_{upper}) - Log(D_{lower})}$$

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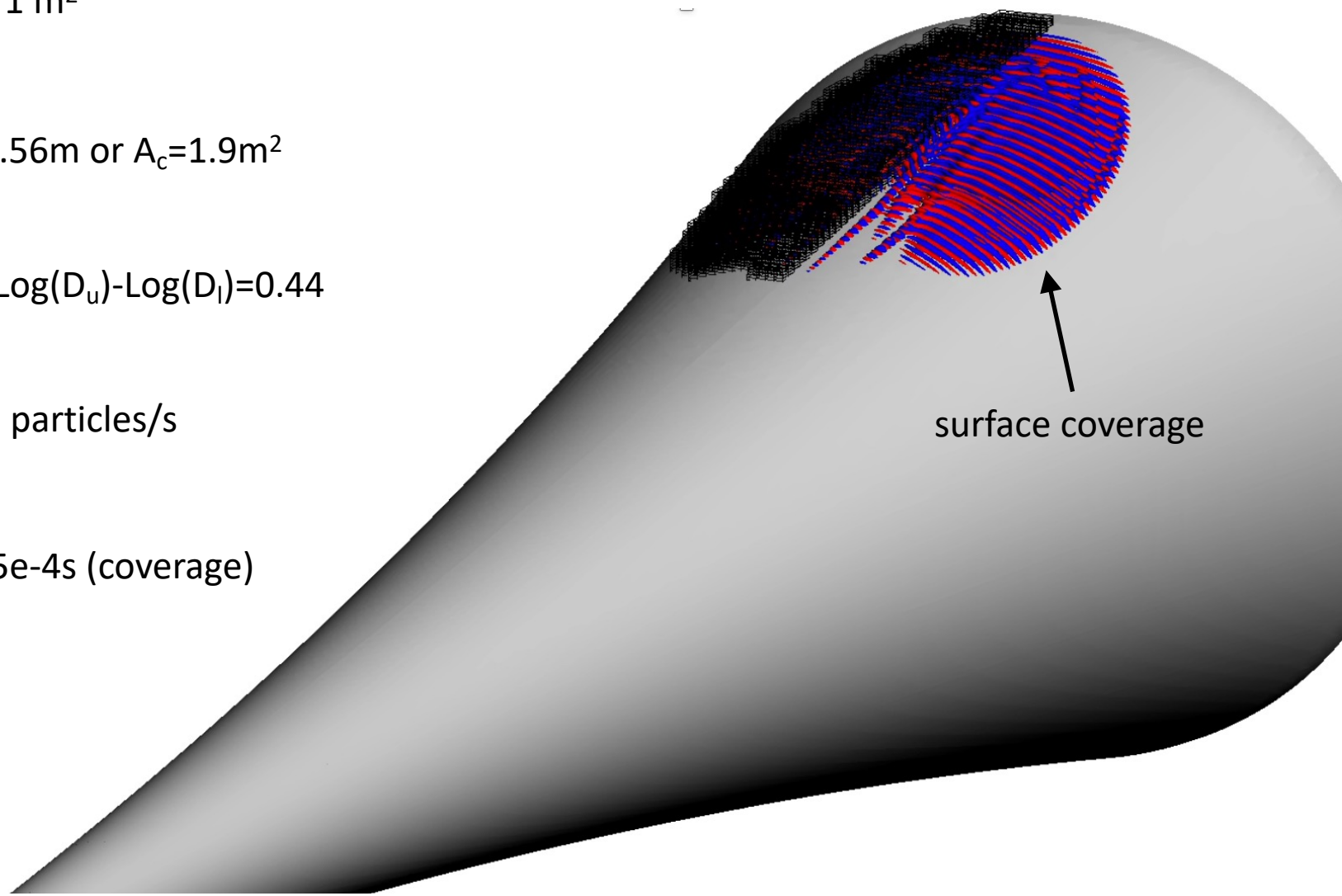
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- Number of particles per second, N_t ~ 9e6 particles/s



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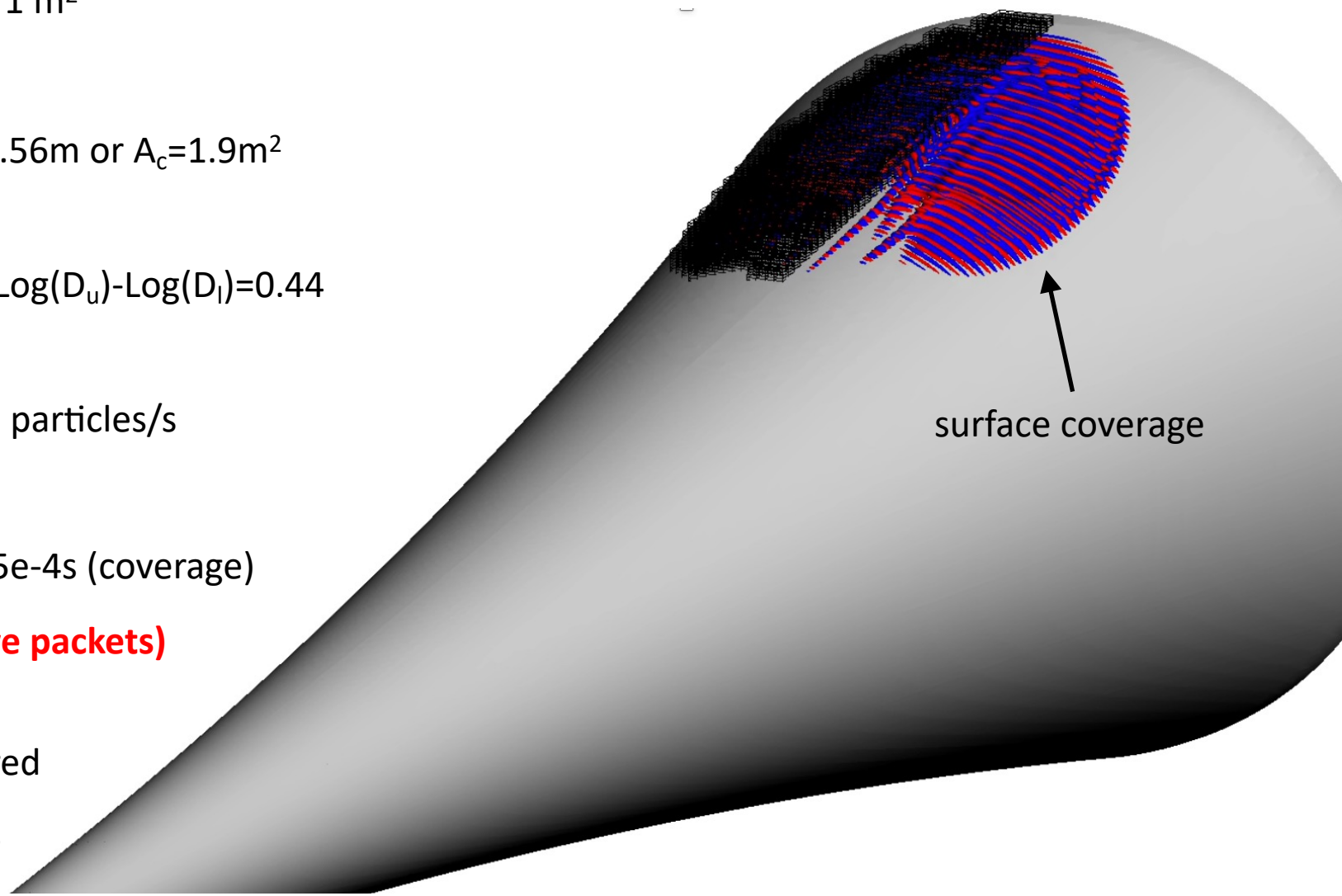
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- Wavepacket travels at c_g~2000m/s ~ Δt=5e-4s (coverage)



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- **N_t x Δt = 4,500 particles (or induced wave packets)**
  - Only fraction of cross-section is relevant and surface coverage needs be considered
  - ~50 particles even at dN/dLog(D)=1e-3 and 1/10 of cross-section



Relevance of Particle-Induced Transition for Hypersonic Flight

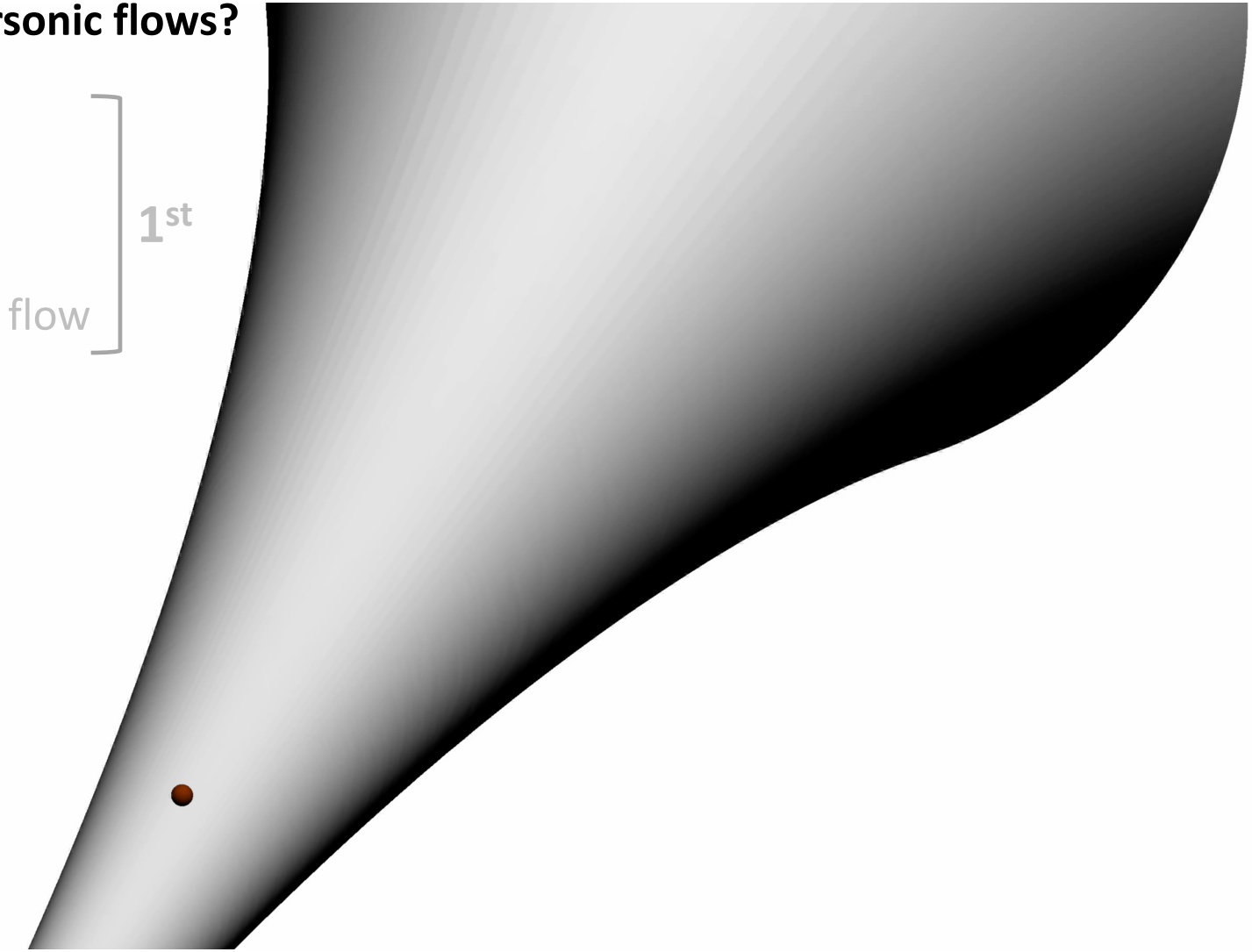
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1st

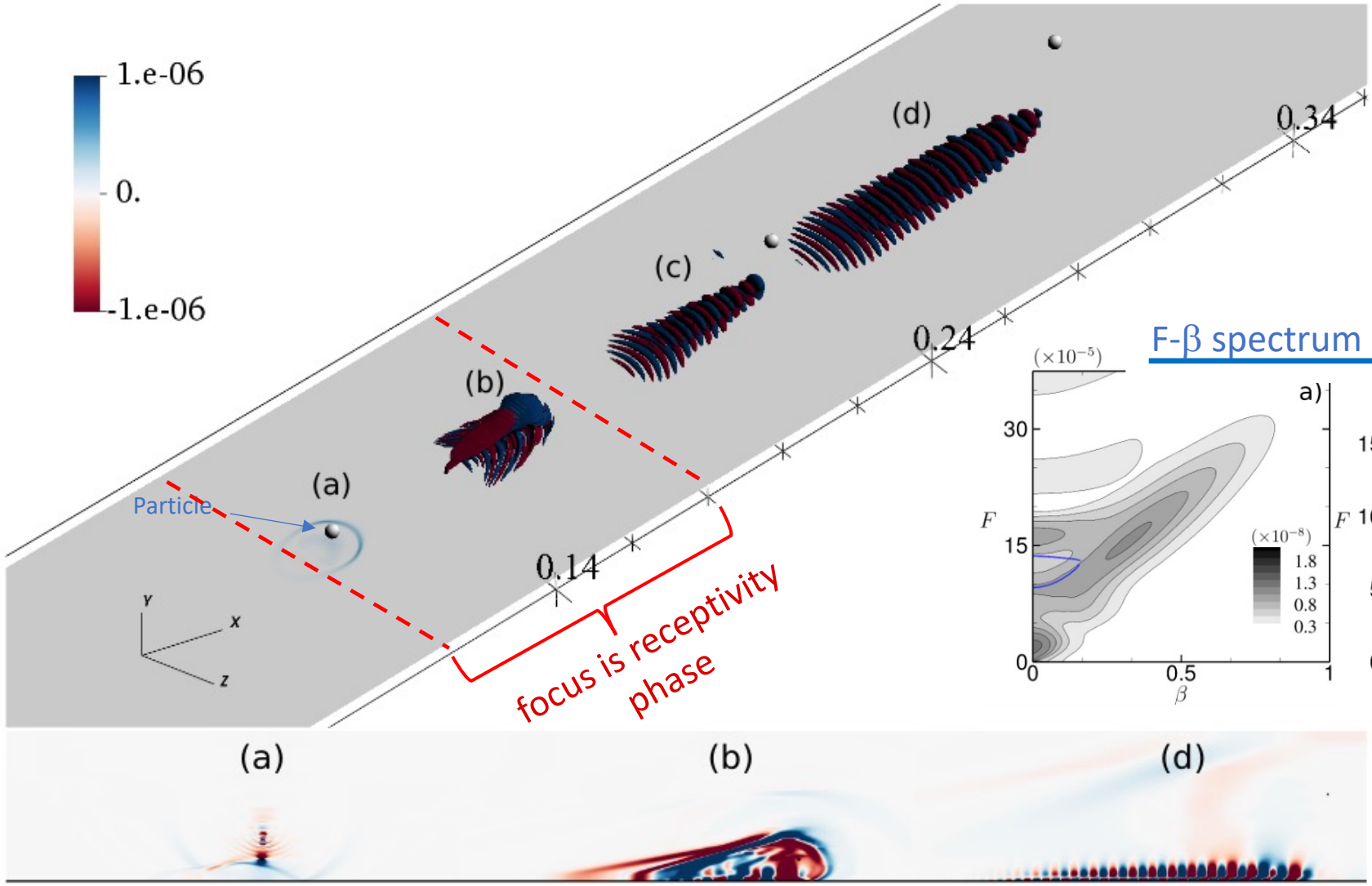
- ❑ **Receptivity mechanisms seeding**
  - **disturbance amplitude**
  - **instability mechanisms**
- ❑ **Particle Modeling**

2nd



Receptivity Mechanisms

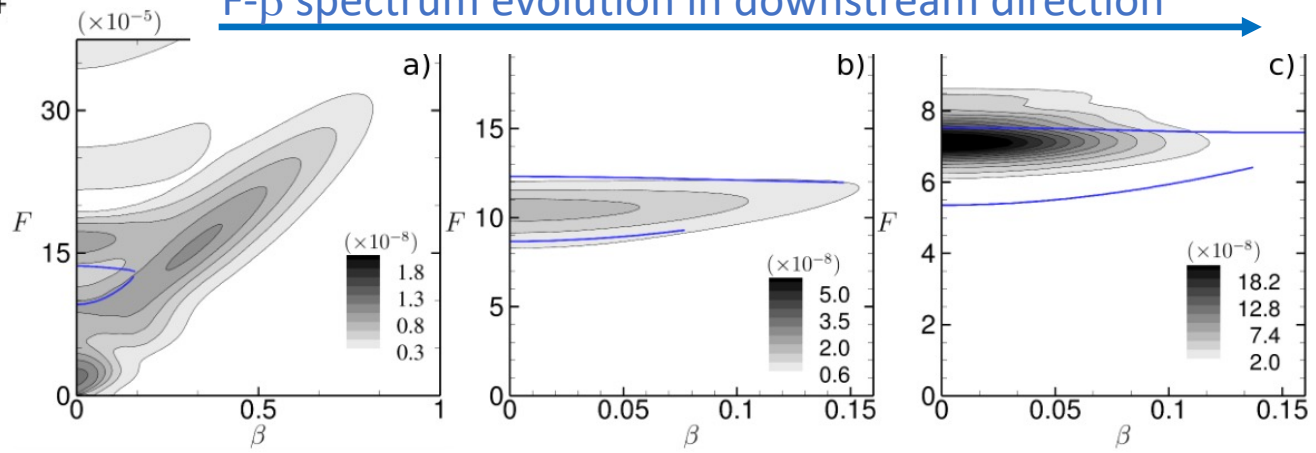
Wavepacket generated by a particle impinging on a M=5.35 boundary layer flow



Freestream conditions for M=5.35 flat plate BL.

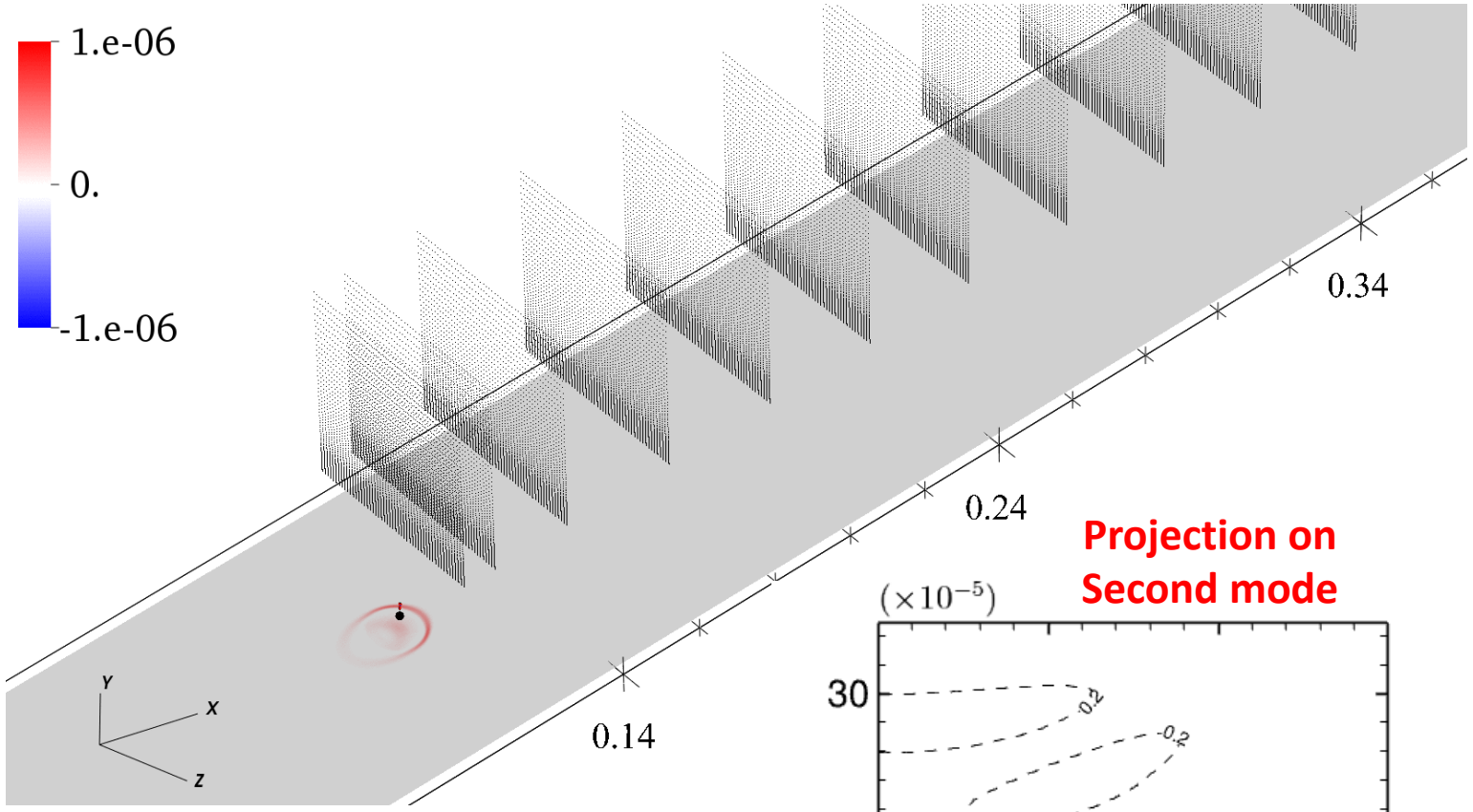
M_∞	5.35
$Re_\infty(1/m)$	13.678×10^6
$p_\infty(N/m^2)$	1.298×10^3
$T_\infty(K)$	63.923
$U_\infty(m/s)$	857.633

F-β spectrum evolution in downstream direction

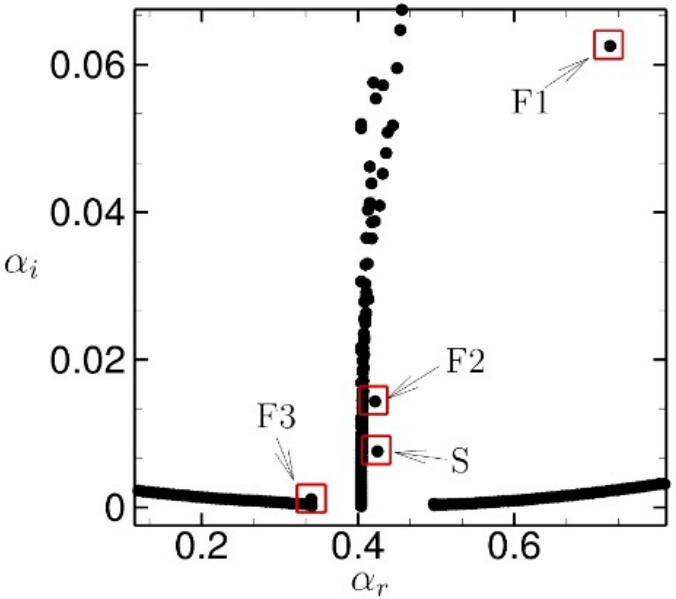


Disturbance spectra of p_w generated by a 10μm particle a) x=0.138m, b) x=0.17m and c) x=0.463m. The blue line marks the neutral curve.

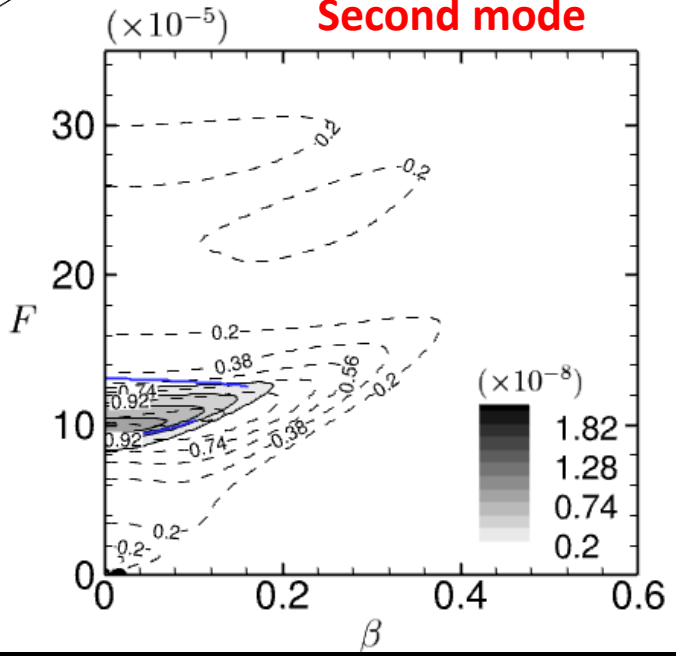
Receptivity Mechanisms



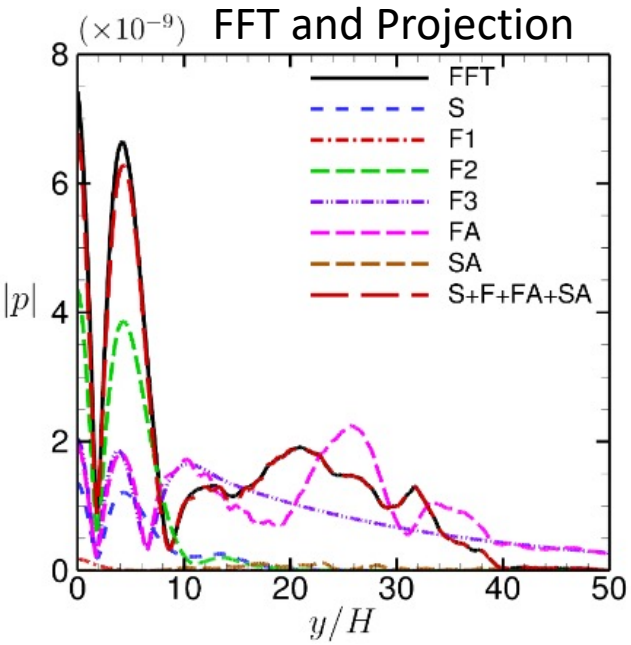
Global EV Spectrum



Projection on Second mode



FFT and Projection

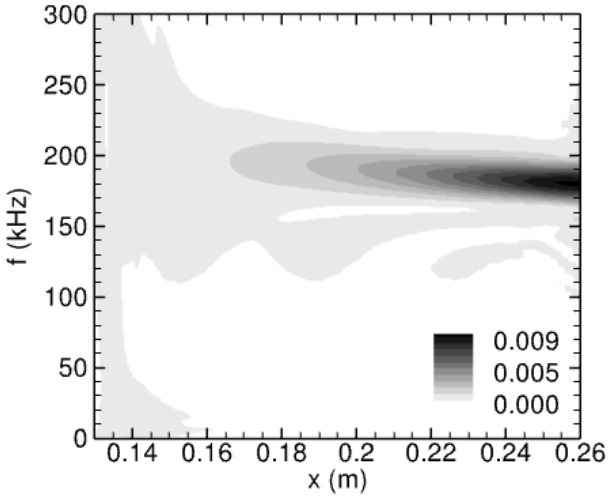


- Excitation of a wide range of discrete and continuous modes
- Only small fraction of disturbance energy arrives in instability mode

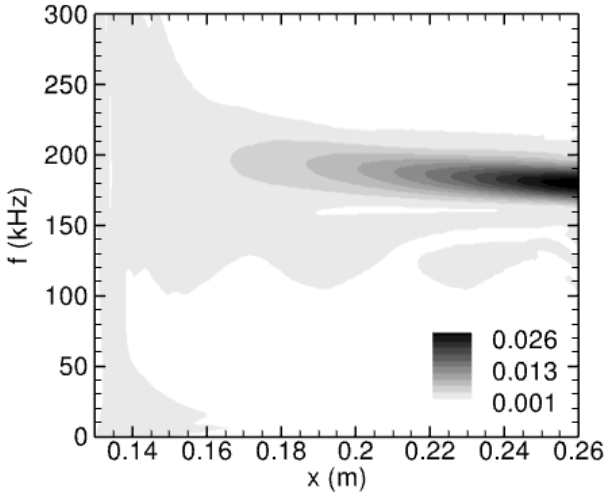
Disturbance Amplitude

M = 5.35 Flat Plate, β=0

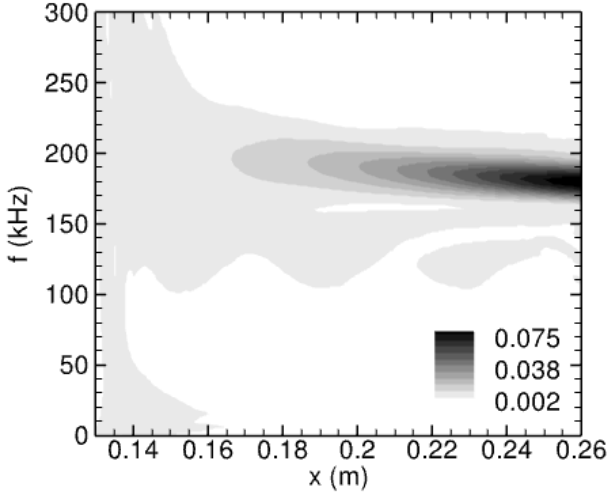
$R_p = 5\mu m$



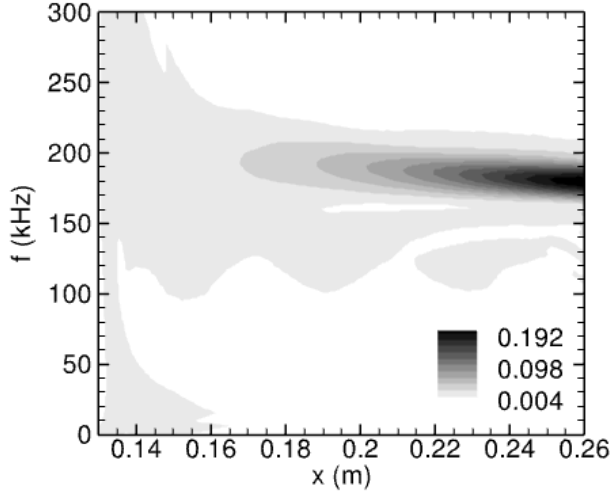
$R_p = 10\mu m$

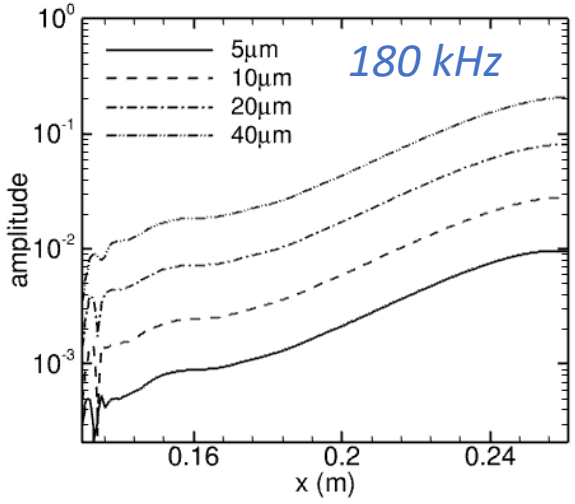


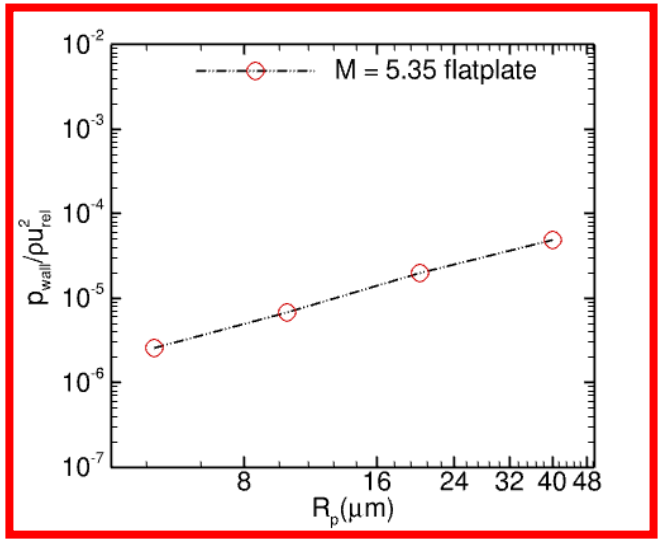
$R_p = 20\mu m$



$R_p = 40\mu m$



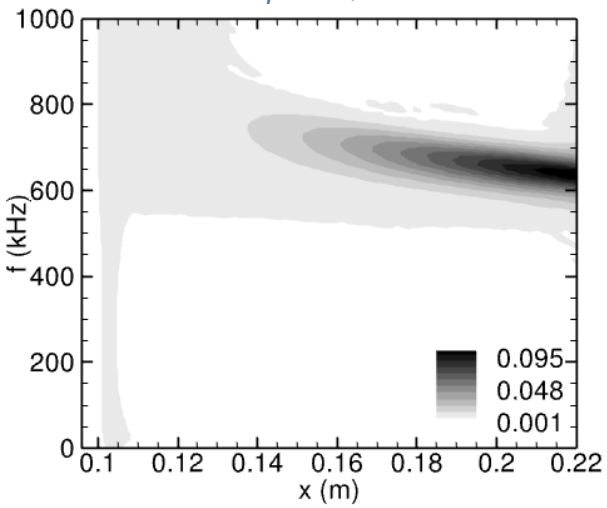




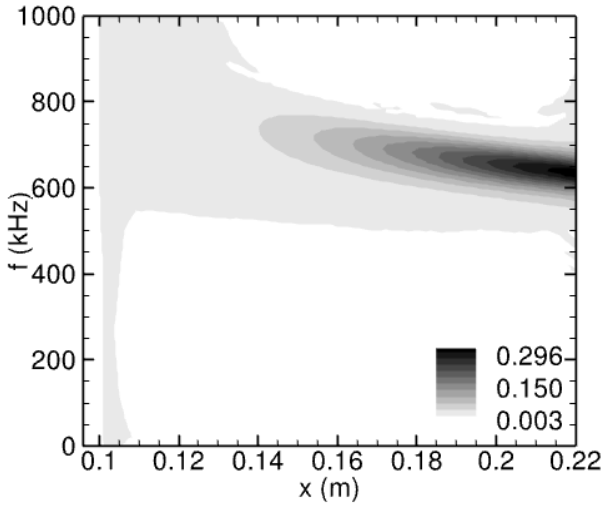
Disturbance Amplitude

M = 9.5 7^o Wedge, β=0

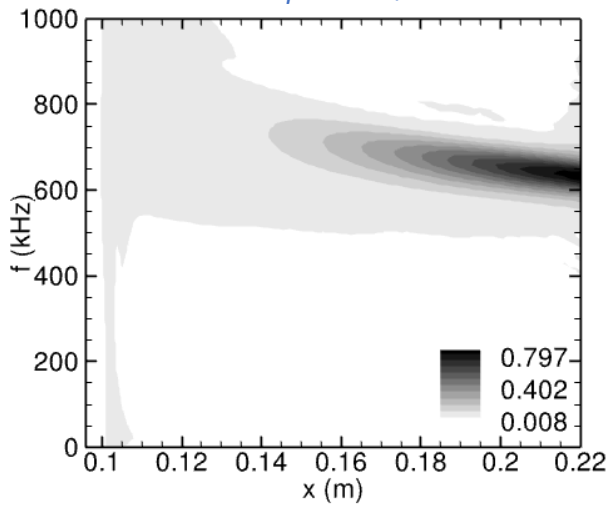
$R_p = 5\mu m$



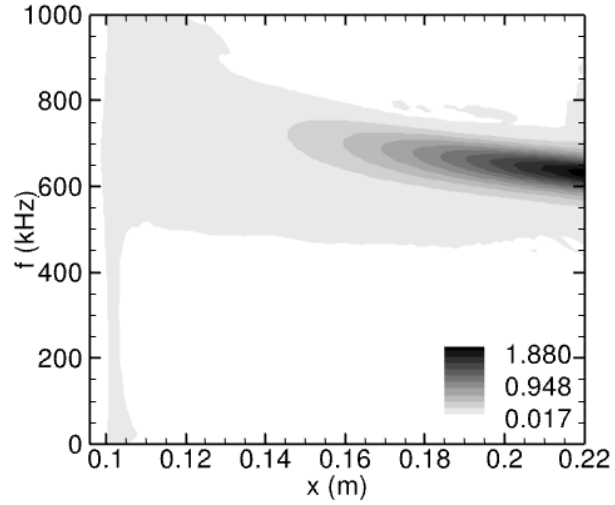
$R_p = 10\mu m$

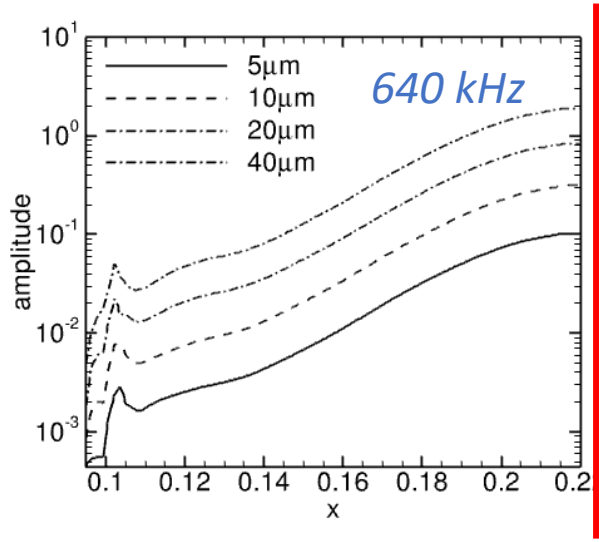


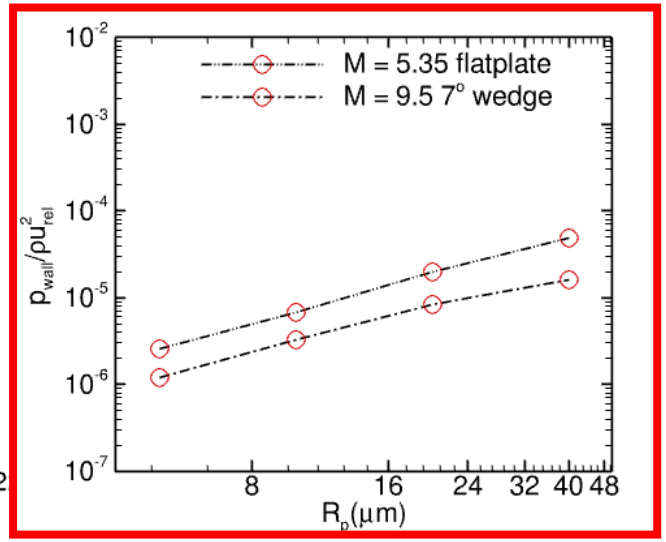
$R_p = 20\mu m$



$R_p = 40\mu m$



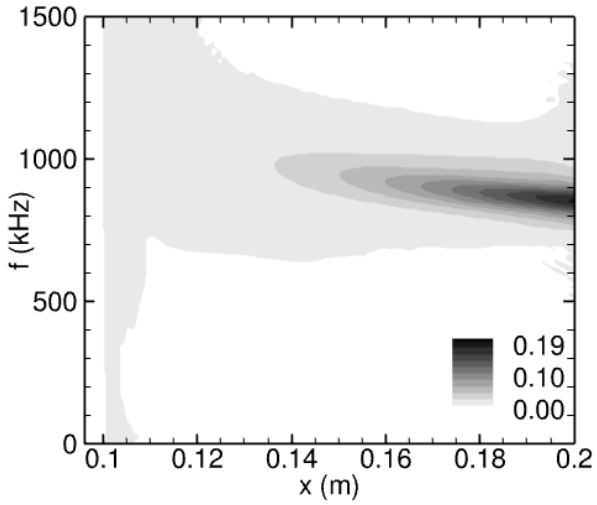




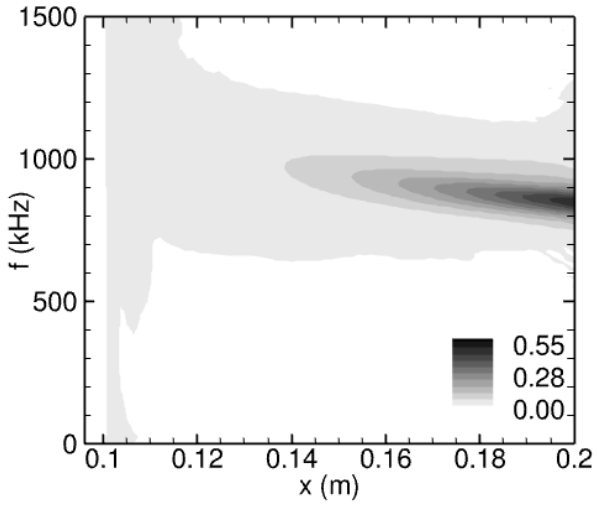
Disturbance Amplitude

M = 9.5 *10.5°* Wedge, β=0

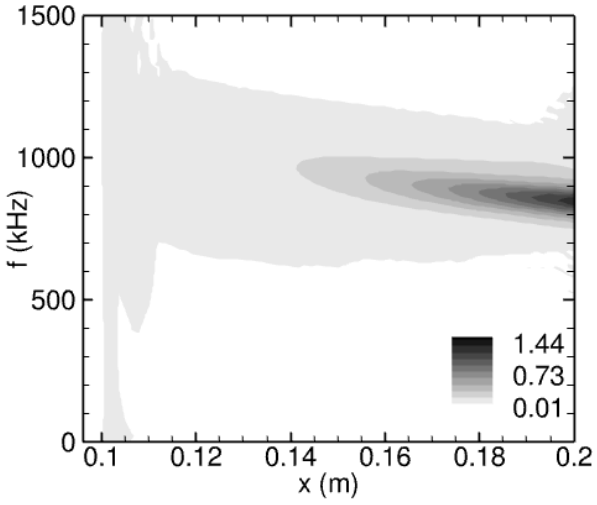
R_p = 5μm



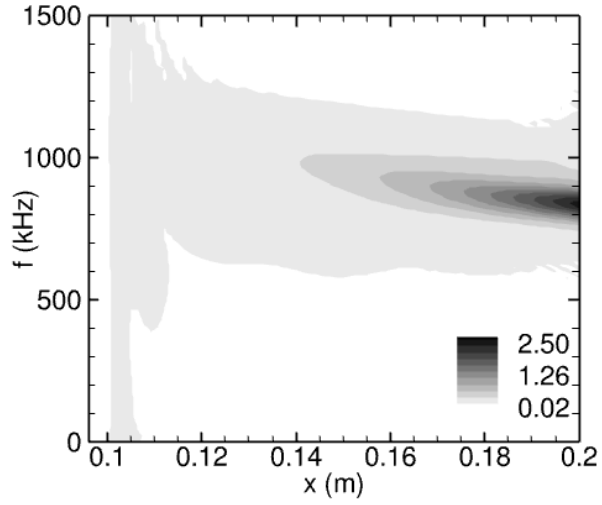
R_p = 10μm

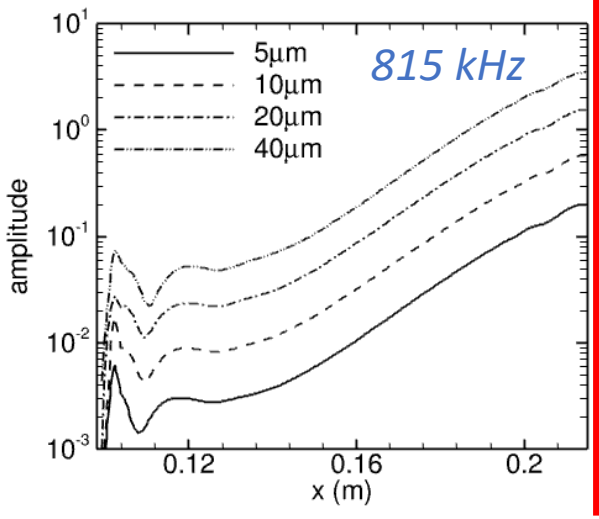


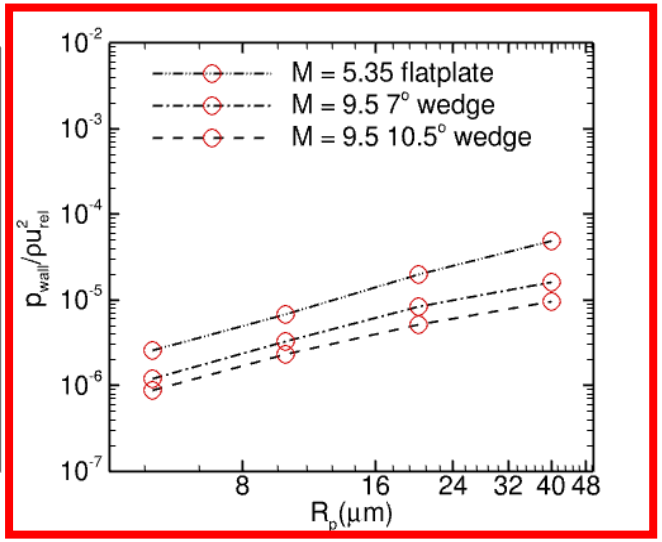
R_p = 20μm



R_p = 40μm



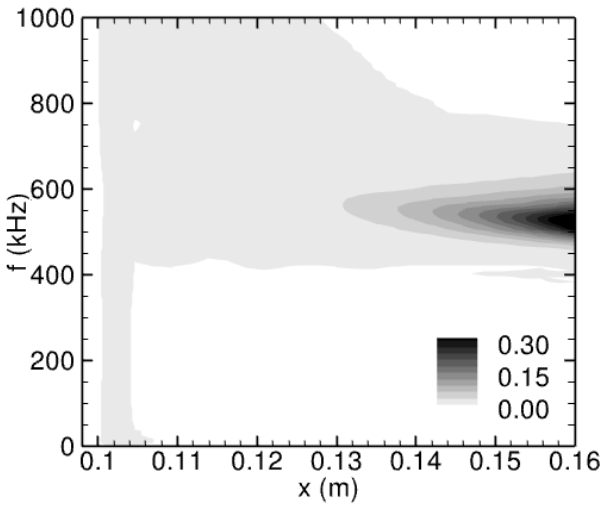




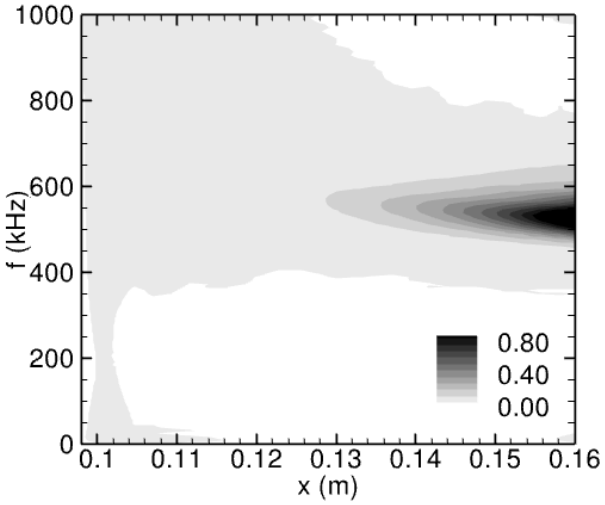
Disturbance Amplitude

M = 9.5 *14°* Wedge, β=0

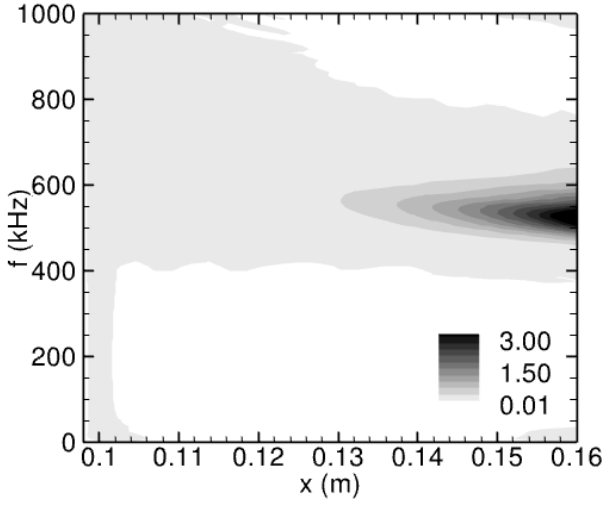
R_p = 5μm



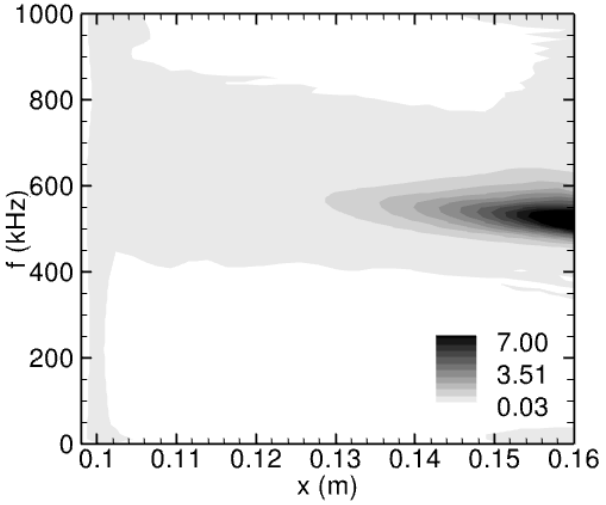
R_p = 10μm

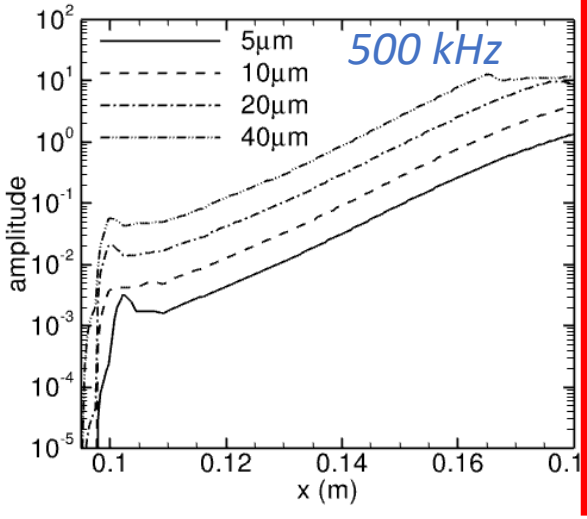


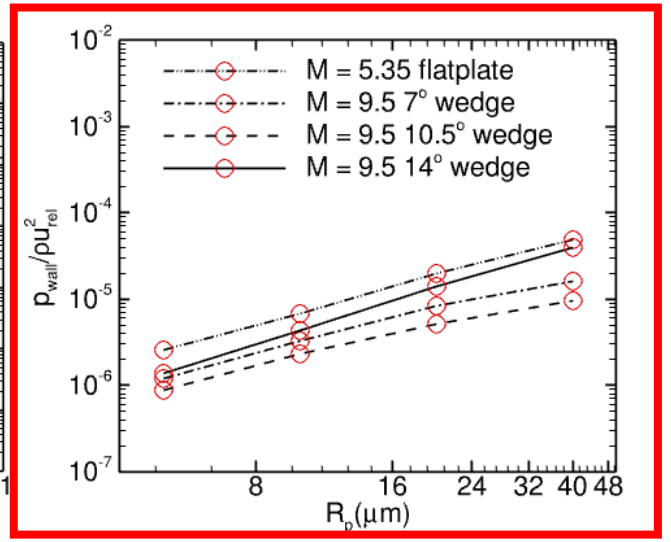
R_p = 20μm



R_p = 40μm

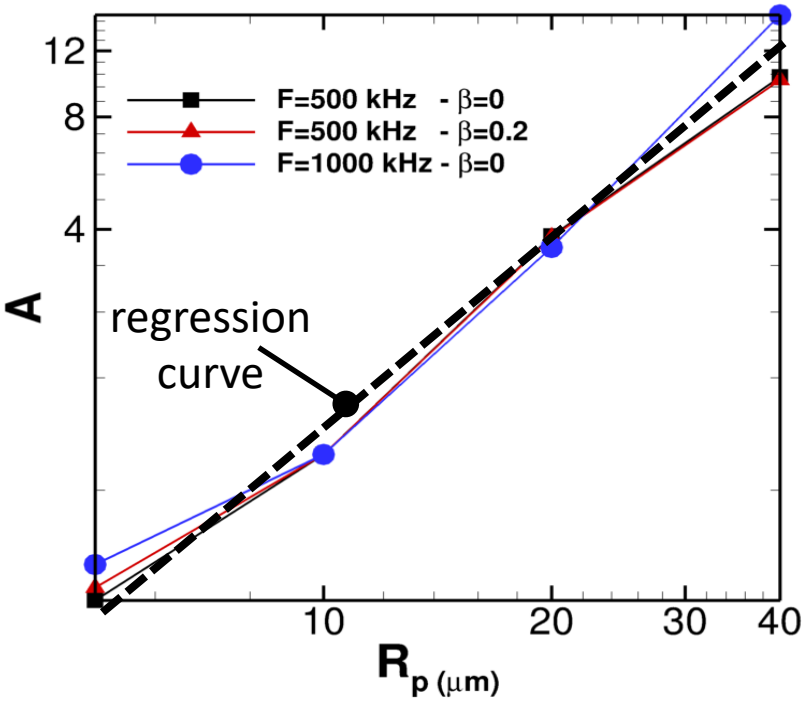




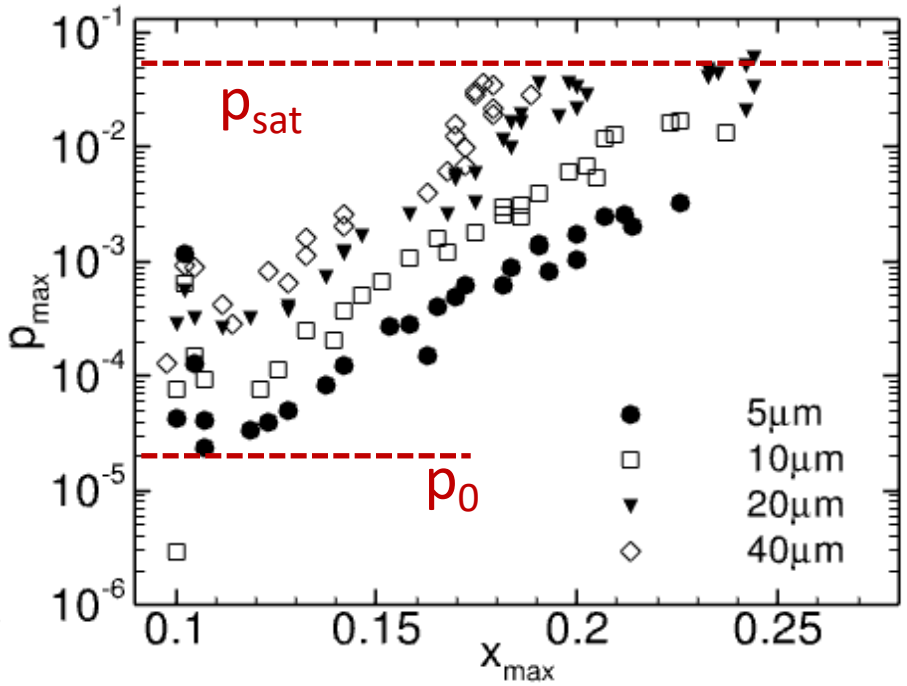


Disturbance Amplitude

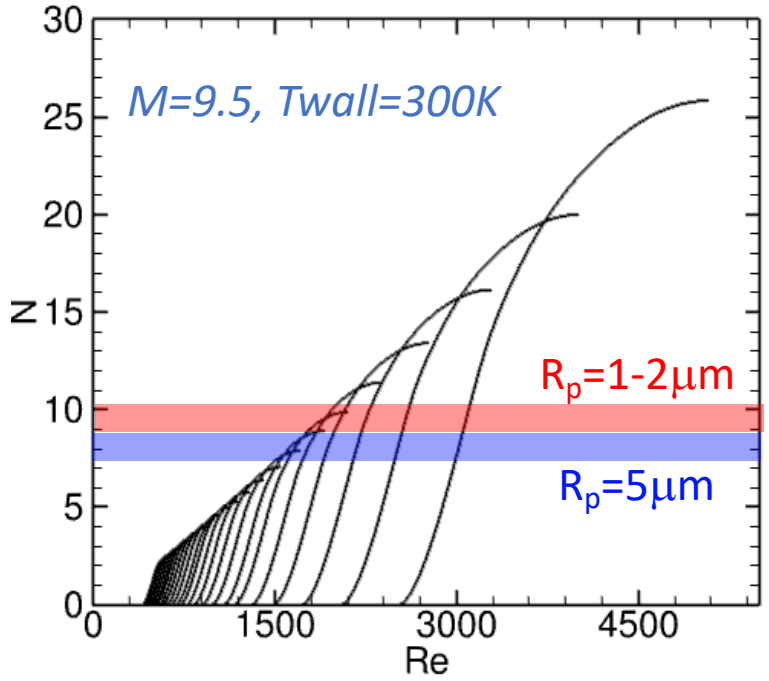
Disturbance Amplitude vs. Particle Radius



Maximum Disturbance Pressure



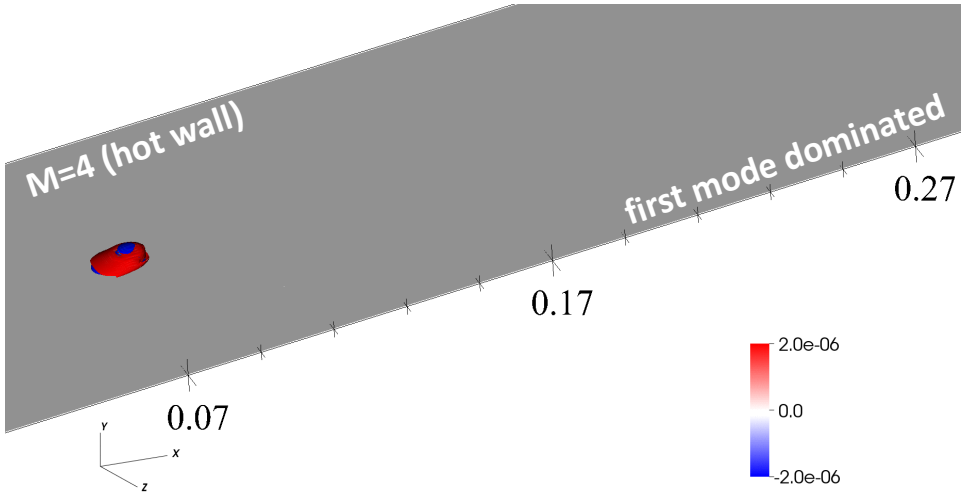
N-Factor Curves

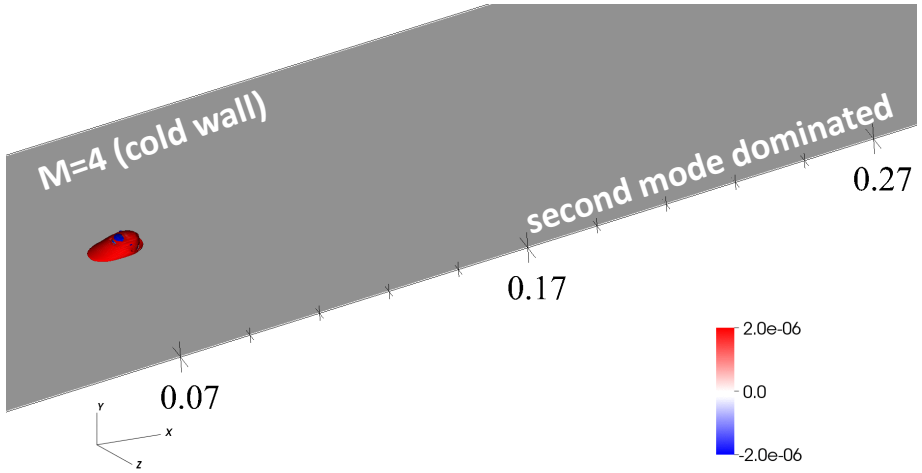


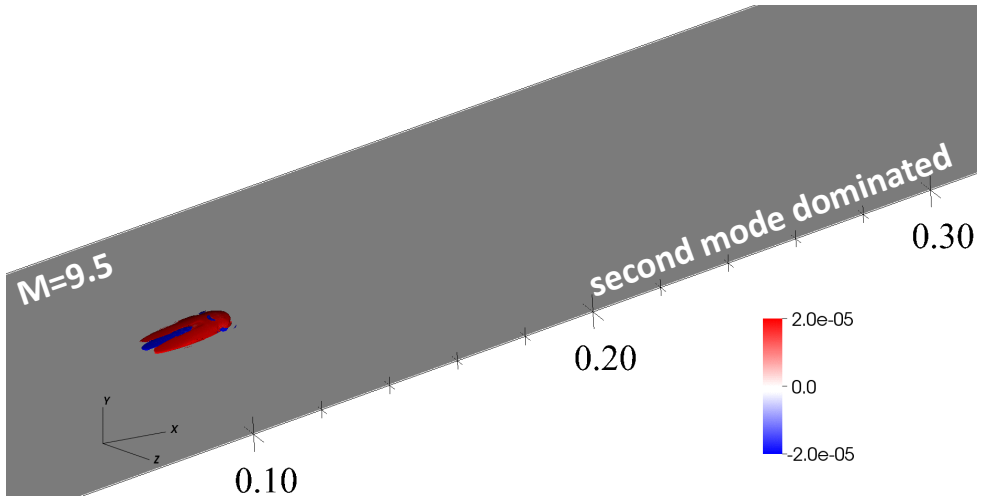
- For R_p=5μm, $p_0/p_{sat}=10^{-3}$ in vicinity of impingement location
  → N≈7-8 is sufficient to transition the flow
- Based on various studies R_p=1-2μm introduce sufficient disturbance amplitudes to transition the flow for N-factors of N≈9-10

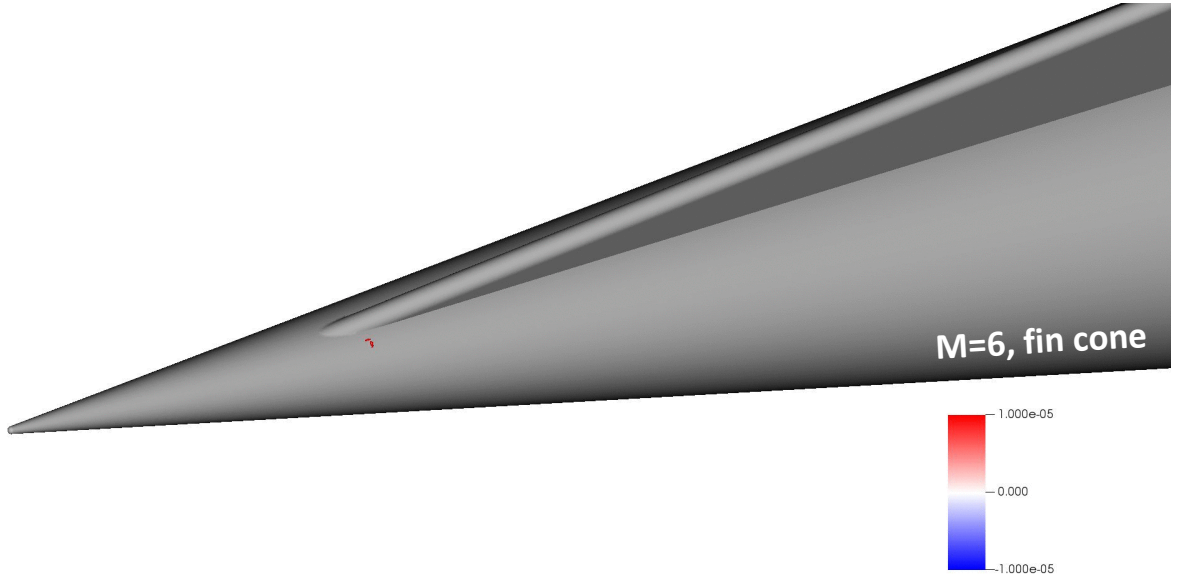
Receptivity Mechanisms

Different Particle-Induced Transition Scenarios

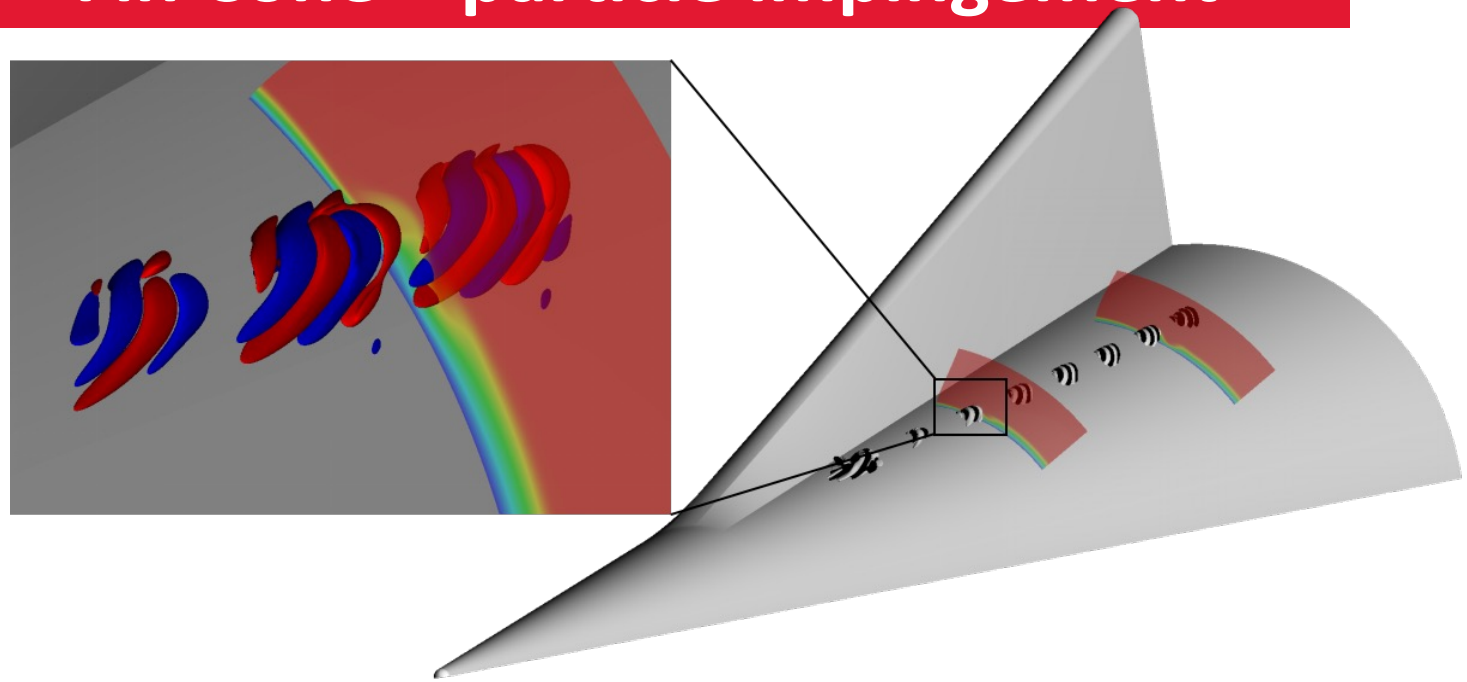




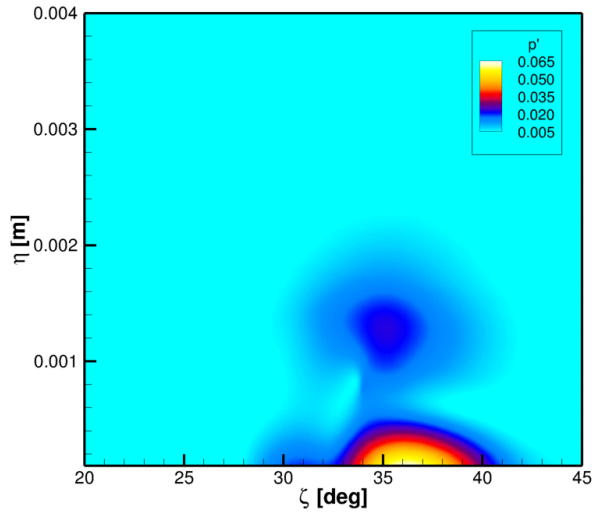




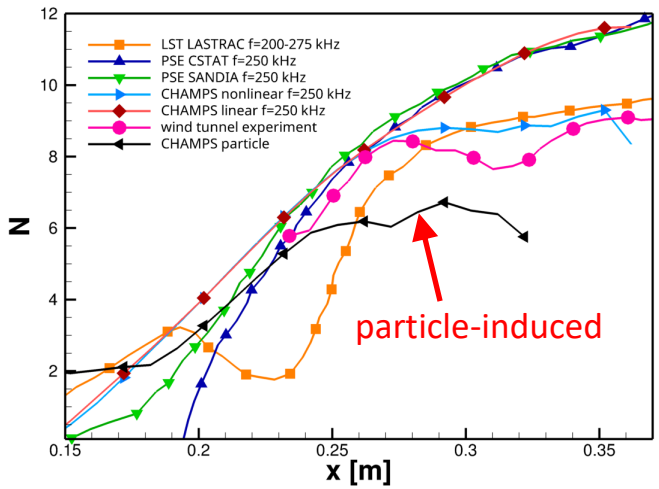
Fin Cone – particle impingement



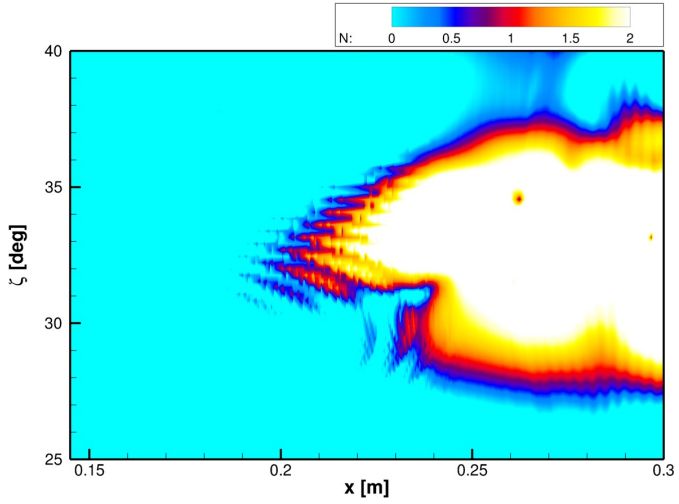
Disturbance Field



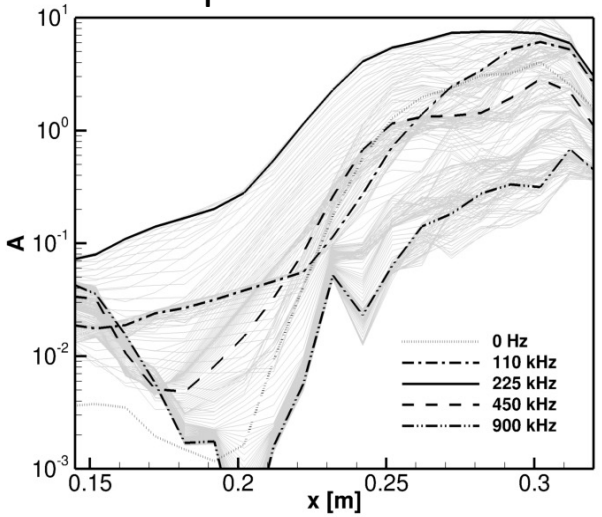
N-Factor Comparison



N-Factor on the Surface

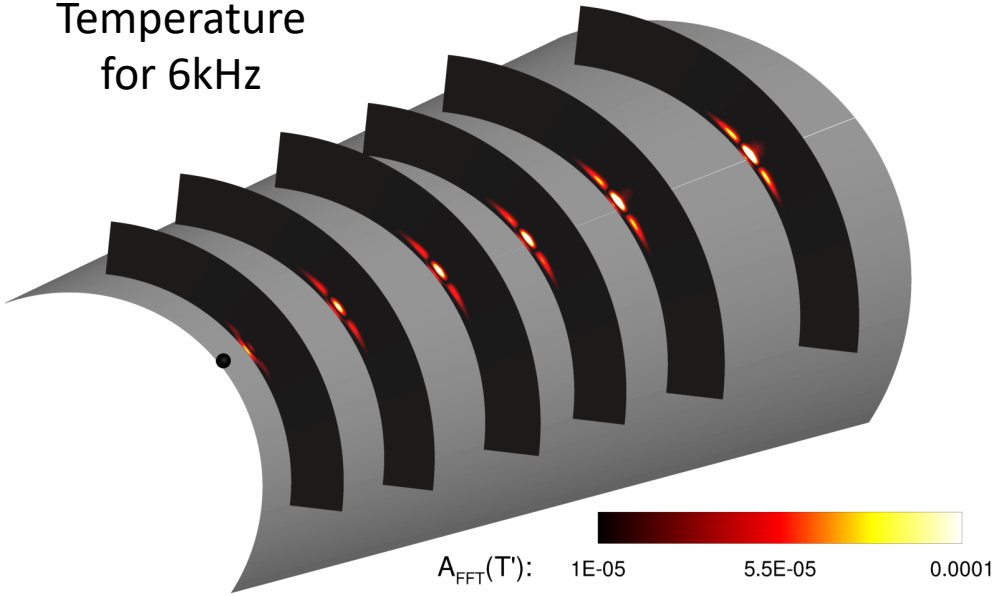


Amplitude Curves



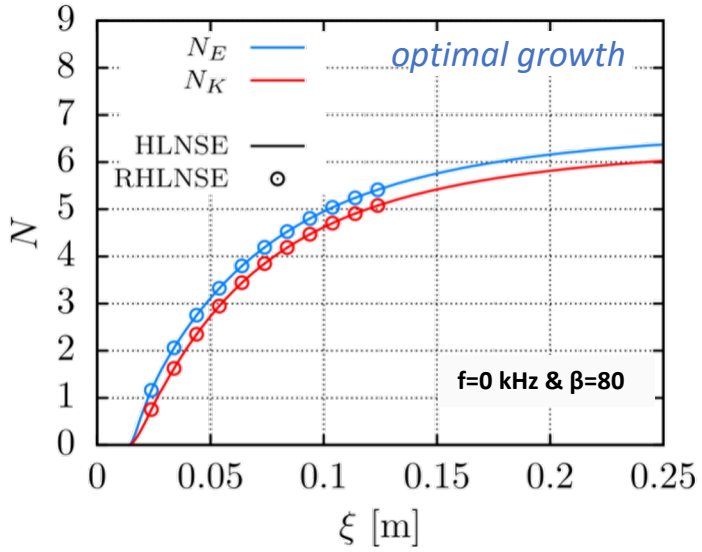
Non-Modal growth

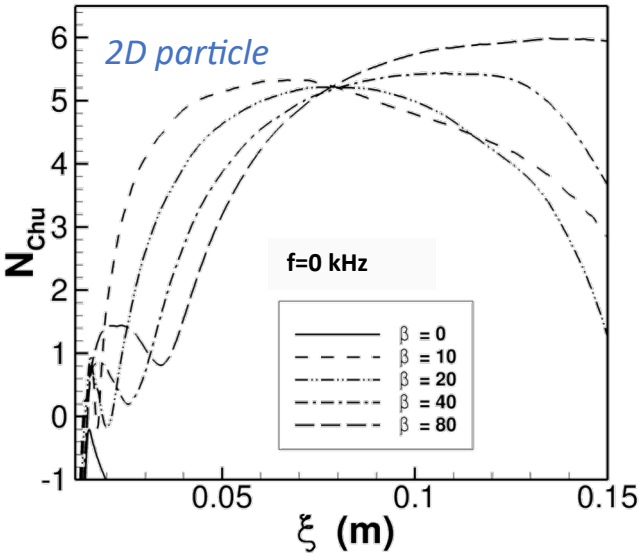
Temperature for 6kHz



"Fully-Resolved Particulate-Induced Transition of Blunt Cone in Hypersonic Flow," Russo et al., AIAA Paper 2021.

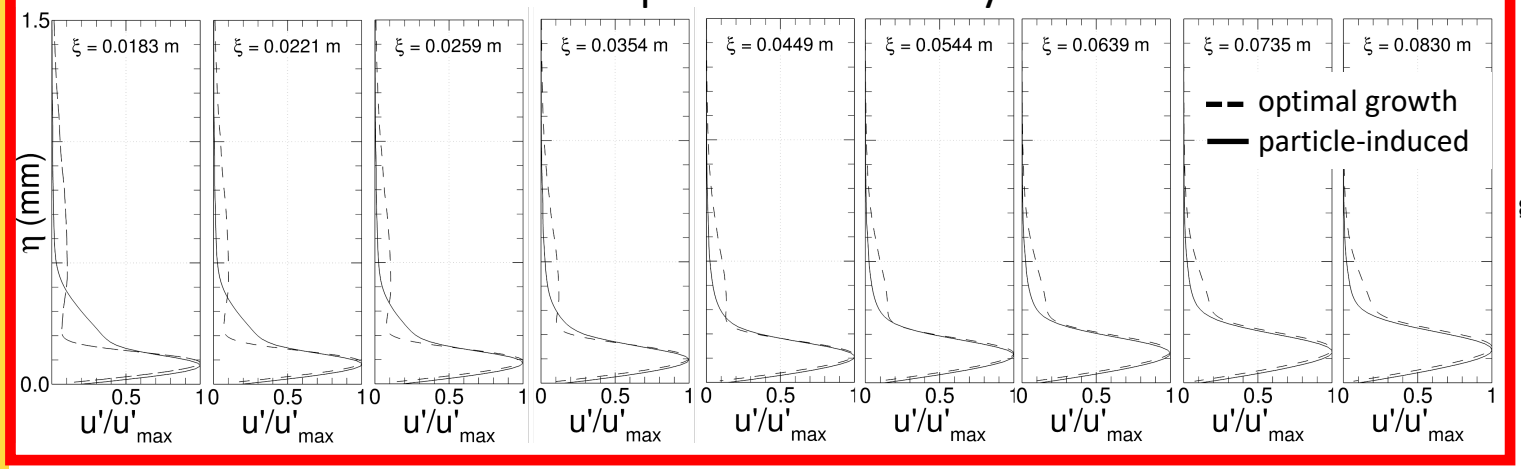
N-Factor



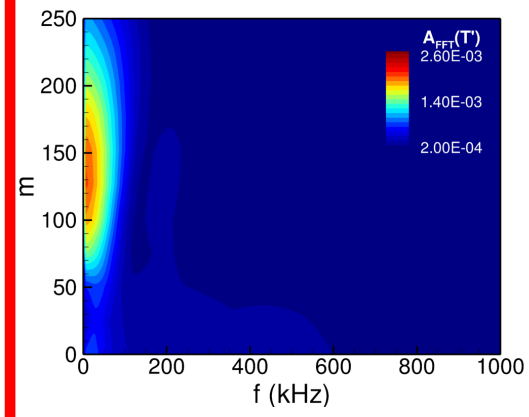


Paredes et al. (2019)

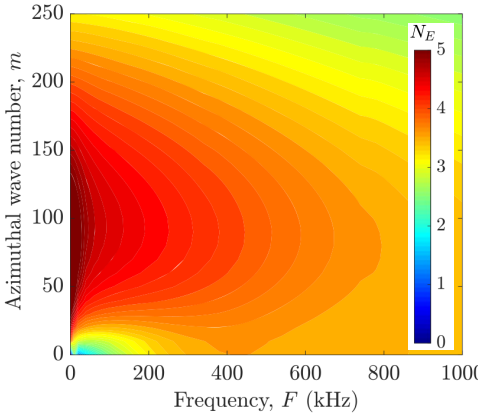
Comparison of Velocity Streaks



Particle-Induced



Optimal Growth



Paredes et al. (2019)

Relevance of Particle-Induced Transition for Hypersonic Flight

What are the key parameters that need to be considered when assessing particle-induced transition for hypersonic flows?

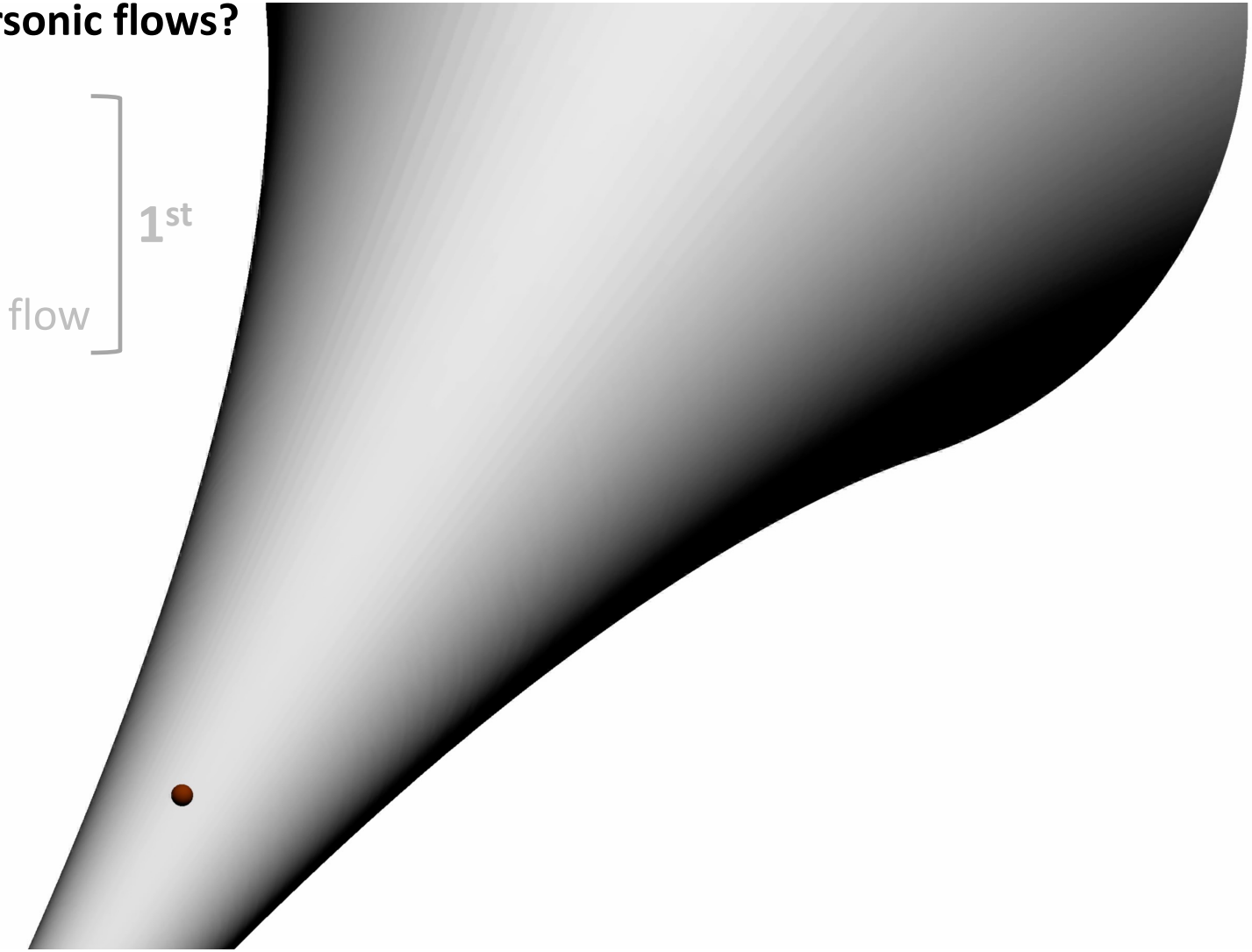
- ❑ Particle sizes in the atmosphere
- ❑ Particle concentration
- ❑ Required particle flux to maintain turbulent flow

1st

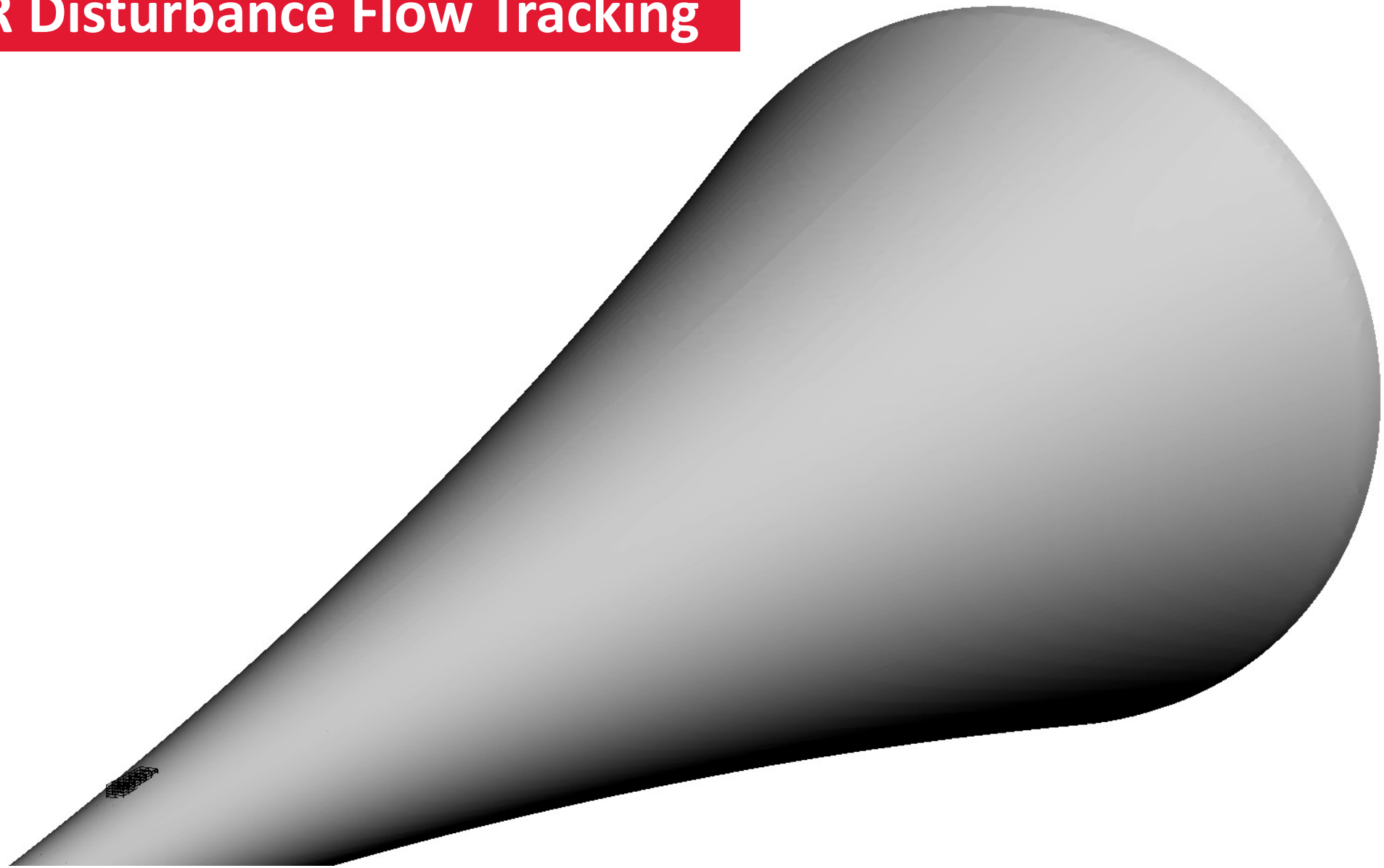
- ❑ Receptivity mechanisms seeding
  - disturbance amplitude
  - instability mechanisms

2nd

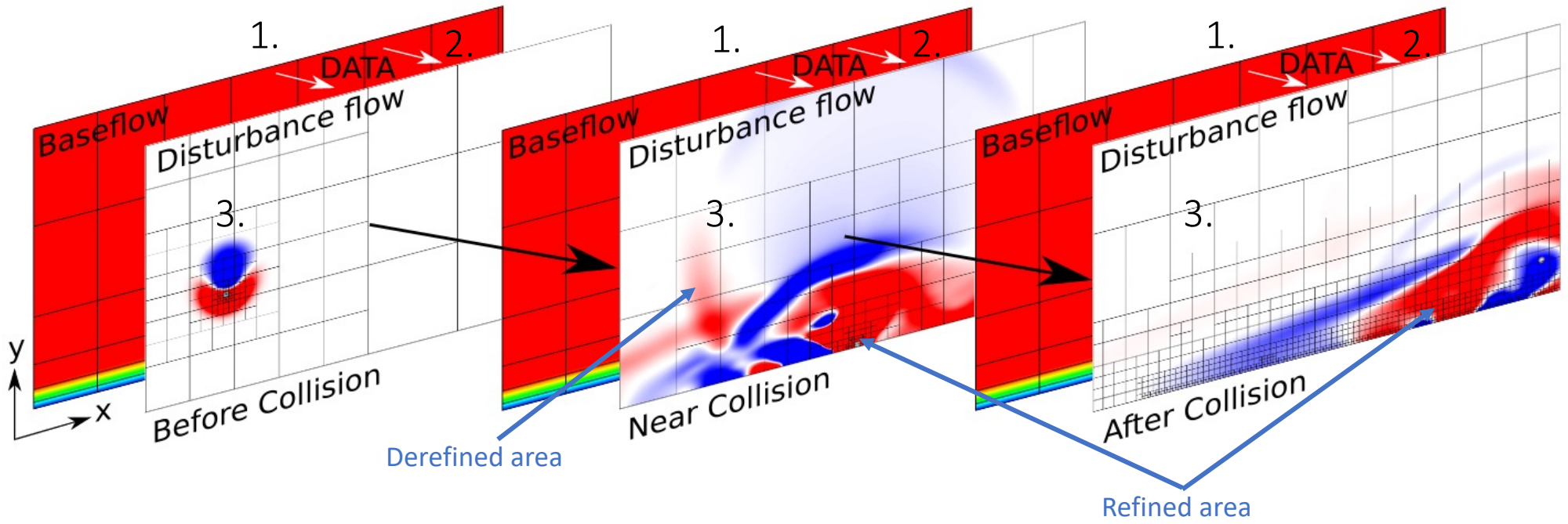
- ❑ **Particle Modeling**



AMR Disturbance Flow Tracking



AMR Disturbance Flow Tracking



1. Compute the baseflow on static mesh by solving CNSE.
2. Interpolate the baseflow onto disturbance flow mesh/AMR mesh.
3. Solve the LDE and Particulate Model in disturbance flow mesh/AMR mesh to get the disturbance flow field.
4. The refinement and derefinement of the disturbance flow mesh/AMR mesh depends on sensitivity parameter: $\varphi = \max\left(\frac{|\phi_1'|}{\max(|\phi_1'|)}, \frac{|\phi_2'|}{\max(|\phi_2'|)}, \dots\dots\right)$ based on tracking variable $\phi'(x, t, Q')$. *[Browne et al. (2019a, 2019b, 2020)]*

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Particle Modeling

Governing equations in nonlinear disturbance flow form including nonlinear particle flow source term:

$$\frac{\partial \tilde{\mathbf{W}}}{\partial t} + \frac{\partial \tilde{\mathbf{E}}(\bar{\mathbf{W}}, \tilde{\mathbf{W}})}{\partial x} + \frac{\partial \tilde{\mathbf{F}}(\bar{\mathbf{W}}, \tilde{\mathbf{W}})}{\partial y} + \frac{\partial \tilde{\mathbf{G}}(\bar{\mathbf{W}}, \tilde{\mathbf{W}})}{\partial z} = -\mathbf{S}(\bar{\mathbf{W}}, \tilde{\mathbf{W}})$$ *(assuming continuum flow assumption)*

Particulate model:

$$\frac{d\mathbf{x}_p}{dt} = \mathbf{v}_p \quad \& \quad m_p \frac{d\mathbf{v}_p}{dt} = \mathbf{D}_p$$

$$\mathbf{D}_p = -\frac{1}{2} C_D \rho \left|\mathbf{v}_p - \mathbf{v}\right| (\mathbf{v}_p - \mathbf{v}) \pi R_p^2$$

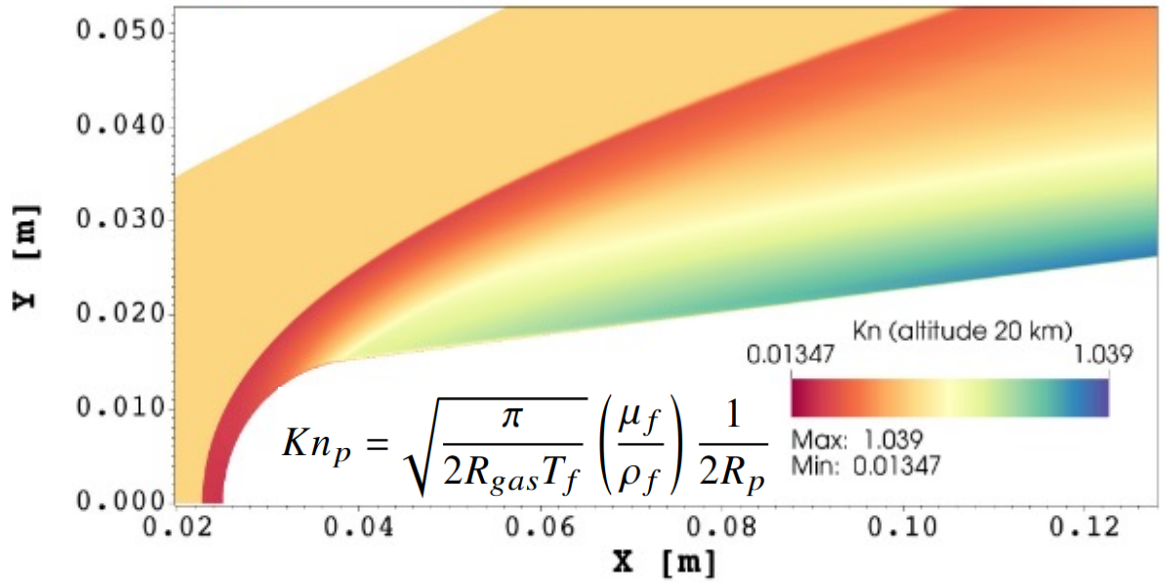
PSIC

Various drag correlations are available in the literature including the rarified flow regime (Loth et al., etc.)

Additional forces may be relevant (*Regele et. al. 2014*):

- Pressure gradient force, $\mathbf{F}_{pg} = -V_p \frac{\partial p}{\partial \mathbf{x}}$
- Added mass force, $\mathbf{F}_{am} = C_a V_p \rho \left(\frac{D\mathbf{v}}{Dt} - \frac{d\mathbf{v}_p}{dt} \right)$
- Viscous unsteady (Basset) force, $\mathbf{F}_{vu} = 3D_p^2 \sqrt{\pi \rho \mu} \int_0^t \kappa_{vu} \frac{\frac{D\mathbf{v}}{Dt} - \frac{d\mathbf{v}_p}{d\chi}}{\sqrt{t - t'}}$

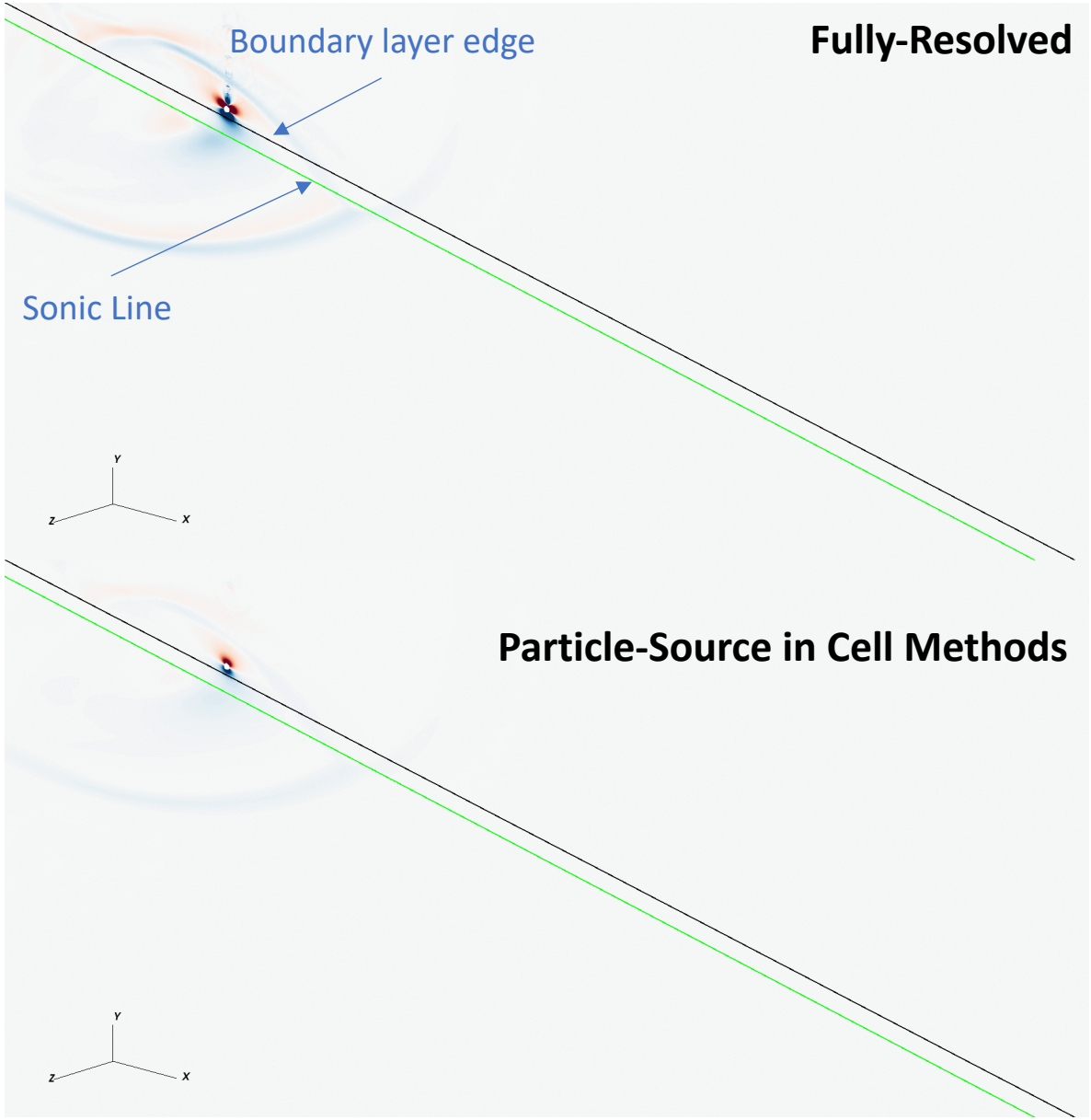
Knudsen number contours computed for $R_p = 1\mu m$ around a 7° cone, $M_\infty = 5.9$, & R_n=15.24 mm at h=20 km



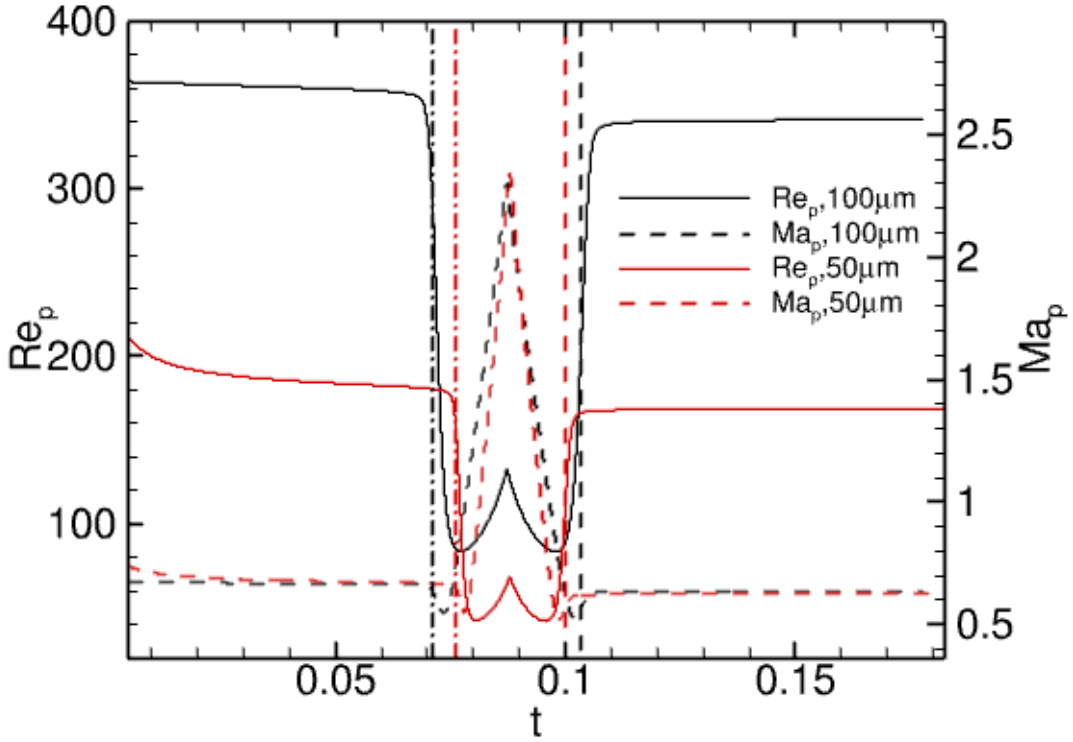
"An Assessment of the Particle Modeling Fidelity for Particle-Induced Transition Simulations", Hasnine et al., AIAA Paper 2022.

Impingement

Fully-Resolved vs. PSIC Approach



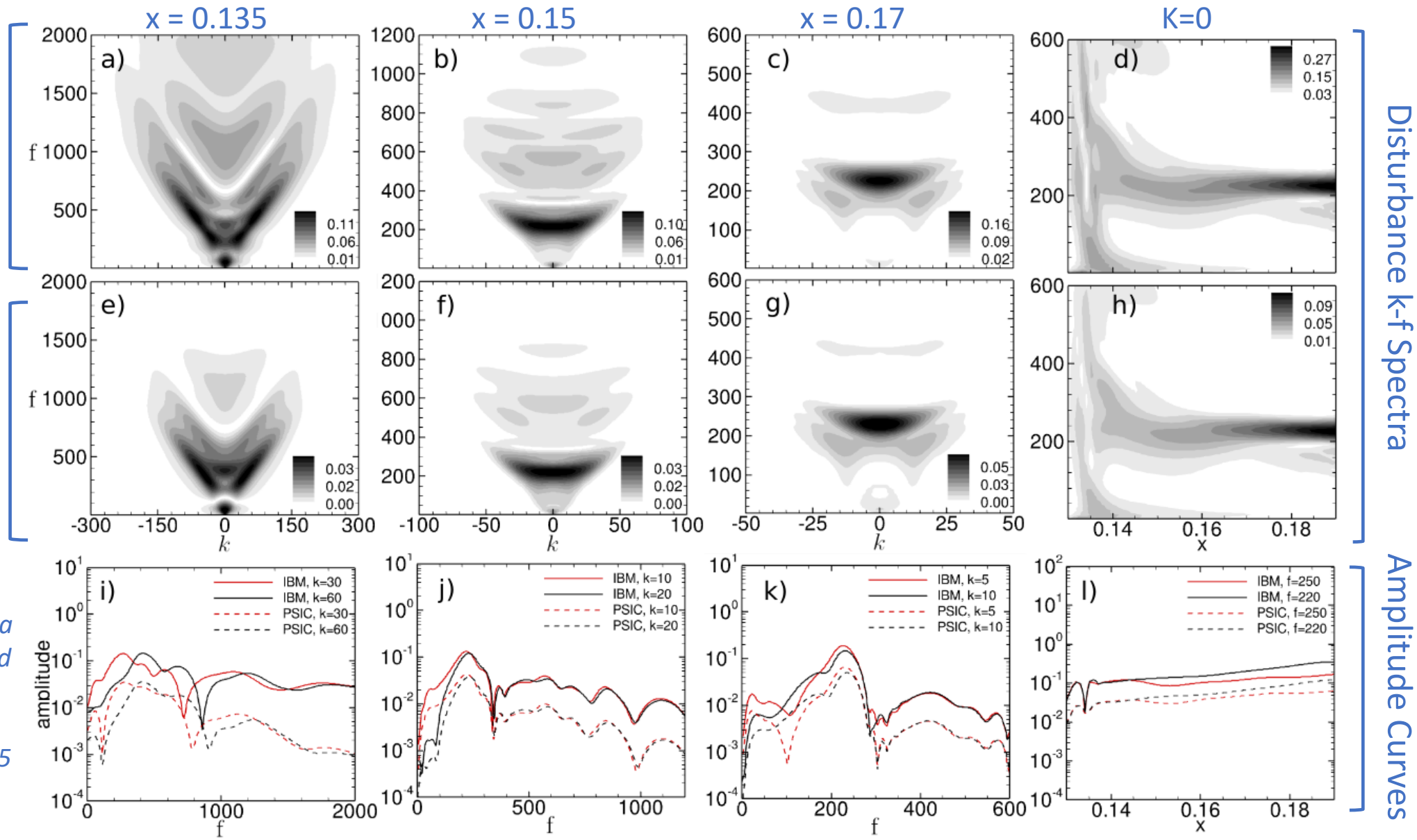
Particle Re and Ma for the 100 micron and 50 micron particle. Time normalized by U_∞ .



- Particle speed changes from subsonic to supersonic inside boundary layer

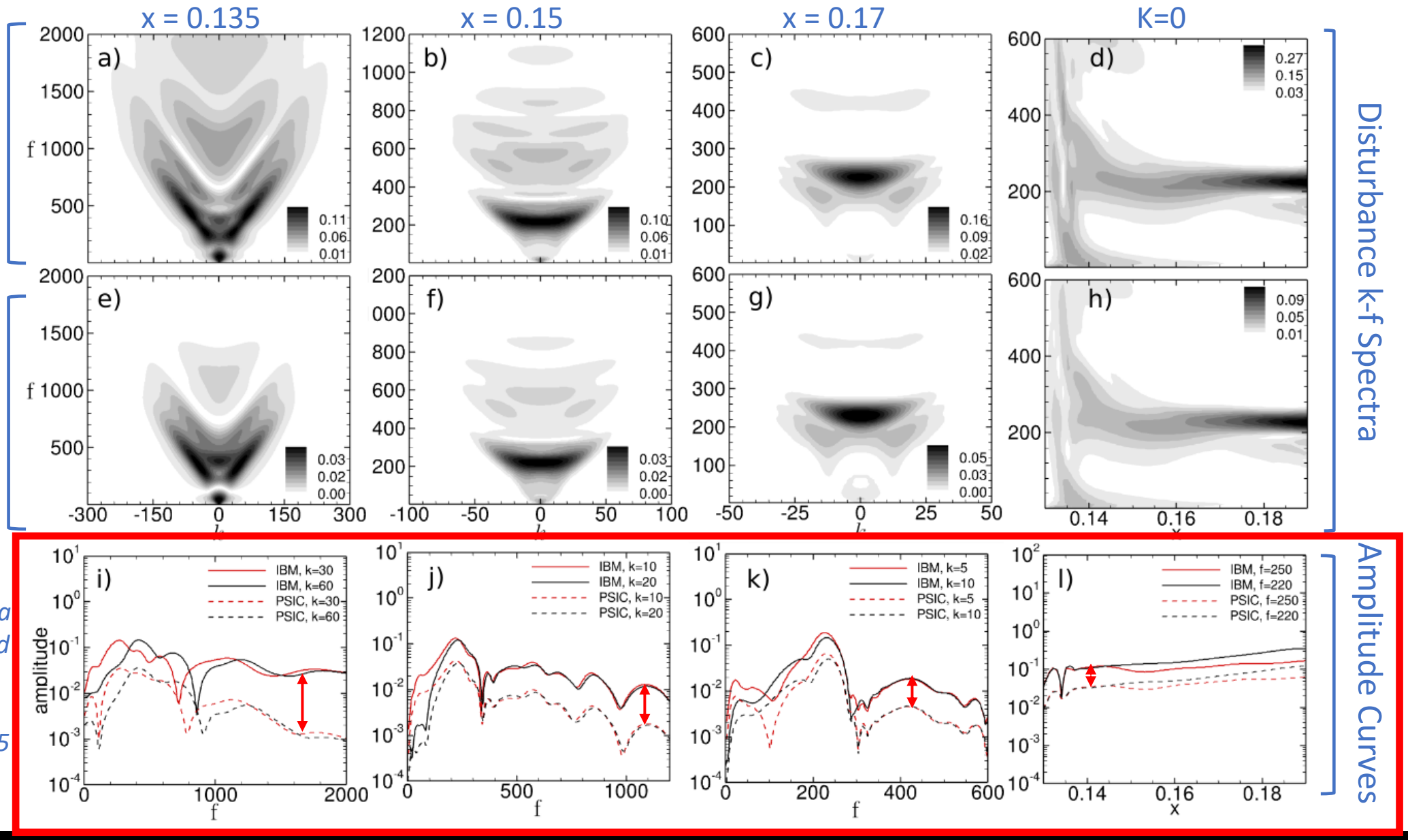
"An Assessment of the Particle Modeling Fidelity for Particle-Induced Transition Simulations", Hasnine et al., AIAA Paper 2022.

Fully-Resolved vs. PSIC Approach



Rp= 50 micron, Disturbance spectra of (a,b,c,d) IBM and (e,f,g,h) PSIC simulations at a,e) x=0.135, b,f) x=0.15 and c,g) x=0.17, d,h) k=0

Fully-Resolved vs. PSIC Approach

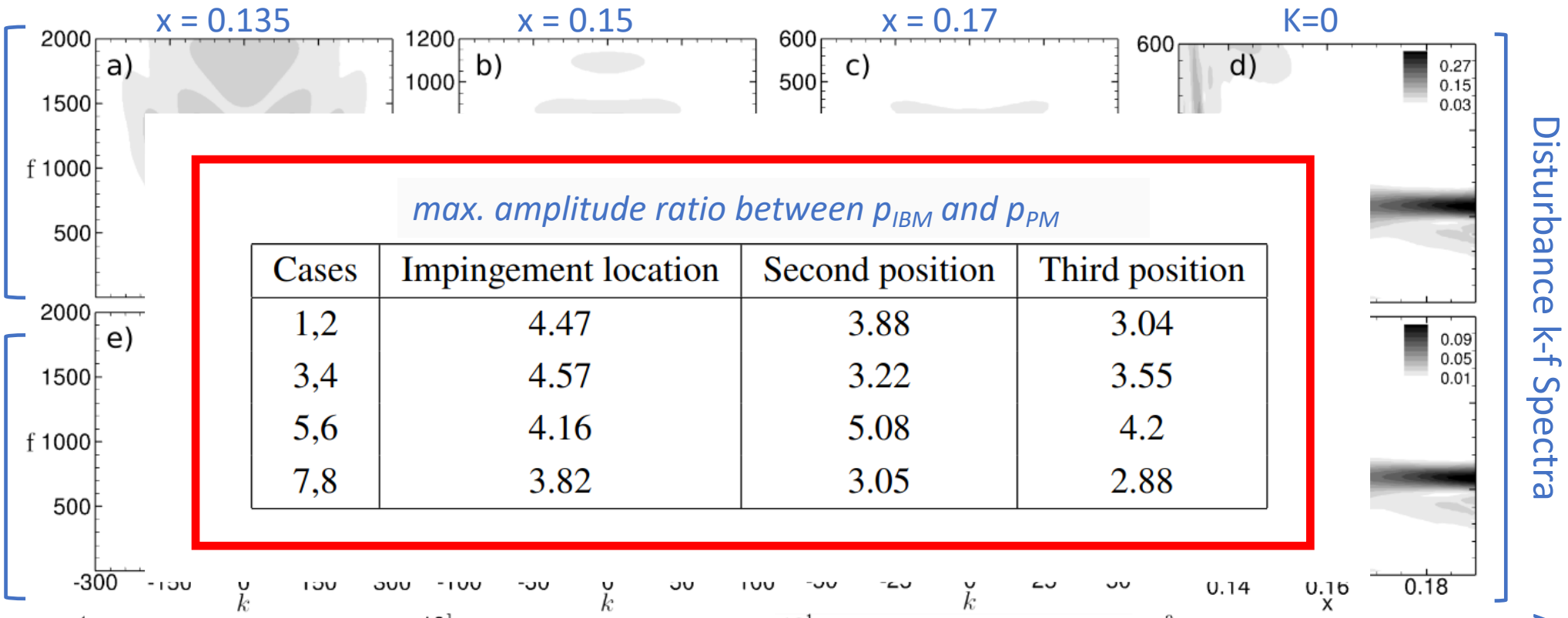


Rp= 50 micron, Disturbance spectra of (a,b,c,d) IBM and (e,f,g,h) PSIC simulations at a,e) x=0.135, b,f) x=0.15 and c,g) x=0.17, d,h) k=0

Fully-Resolved vs. PSIC Approach

Fully-Resolved

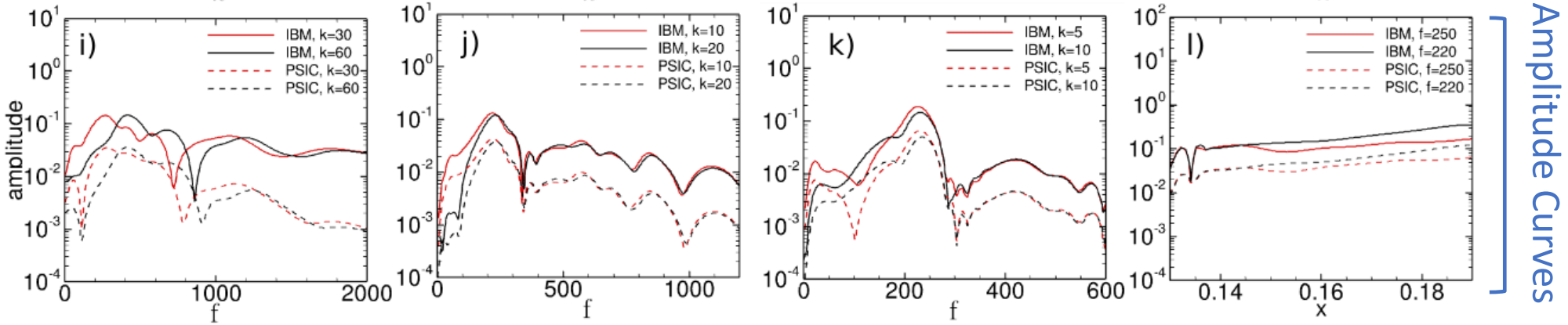
PSIC



max. amplitude ratio between p_{IBM} and p_{PM}

Cases	Impingement location	Second position	Third position
1,2	4.47	3.88	3.04
3,4	4.57	3.22	3.55
5,6	4.16	5.08	4.2
7,8	3.82	3.05	2.88

Disturbance k-f Spectra



Amplitude Curves

Rp= 50 micron, Disturbance spectra of (a,b,c,d) IBM and (e,f,g,h) PSIC simulations at a,e) x=0.135, b,f) x=0.15 and c,g) x=0.17, d,h) k=0

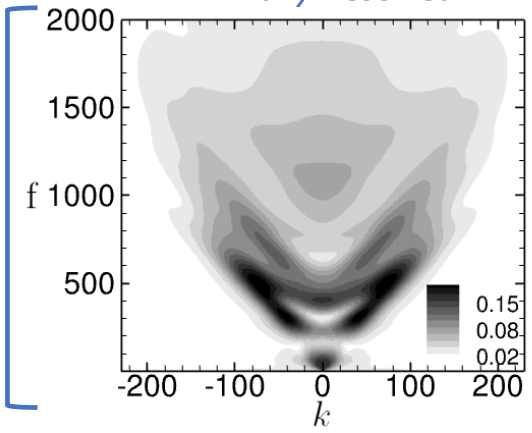
Fully-Resolved vs. PSIC Approach

Adjusted force in PSIC simulation (R_p= 100 micron)

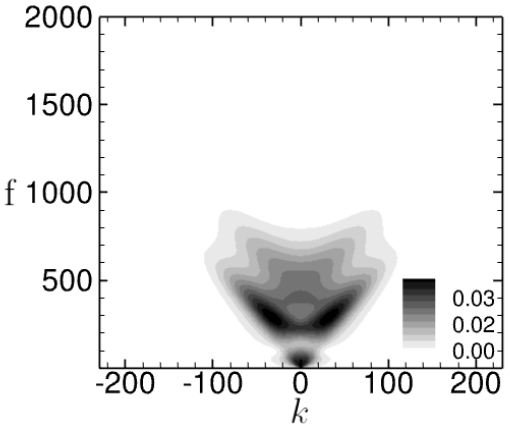
@ impingement location (x=0.135)

amplitude distributions for K=0

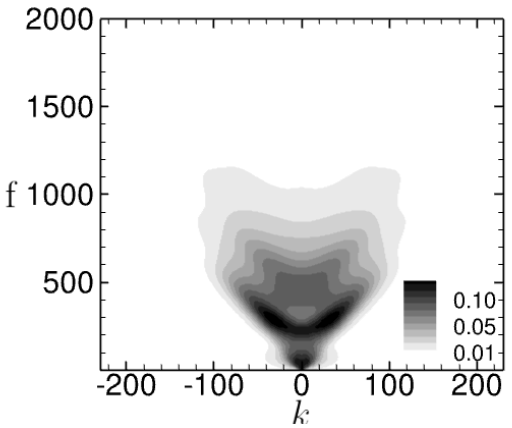
k-f Spectrum
Fully-Resolved



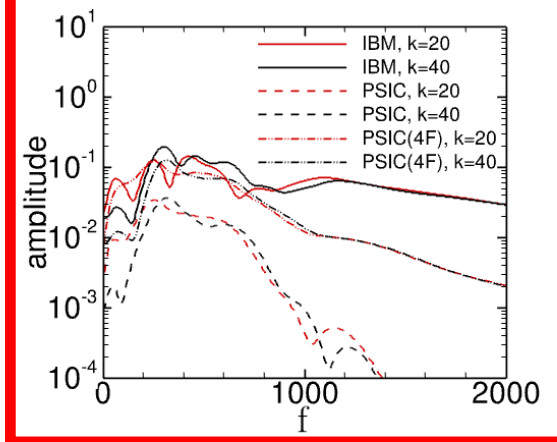
k-f Spectrum
PSIC

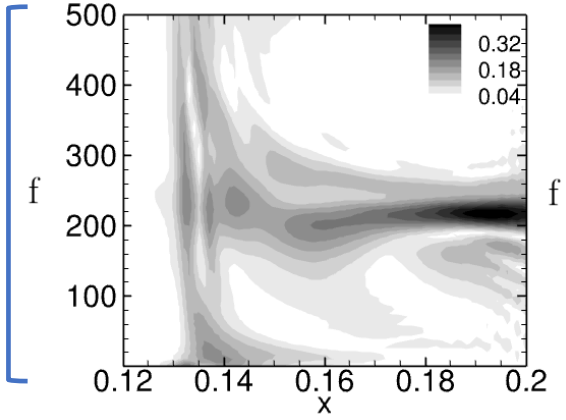


k-f Spectrum
PSIC Adjusted Force

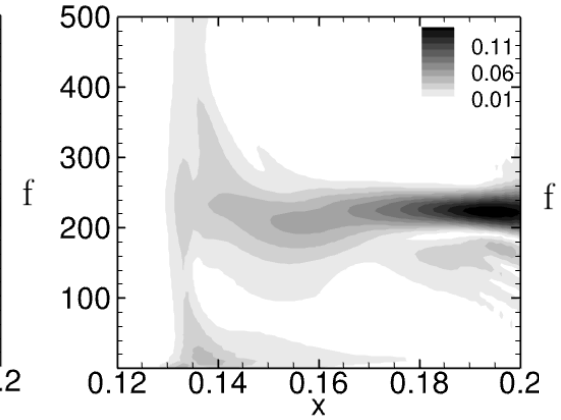


Amplitude Plot

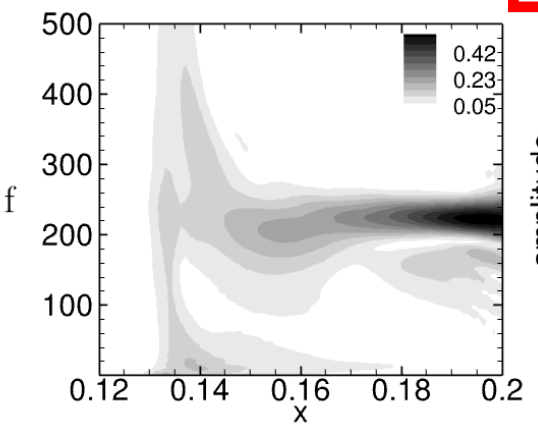




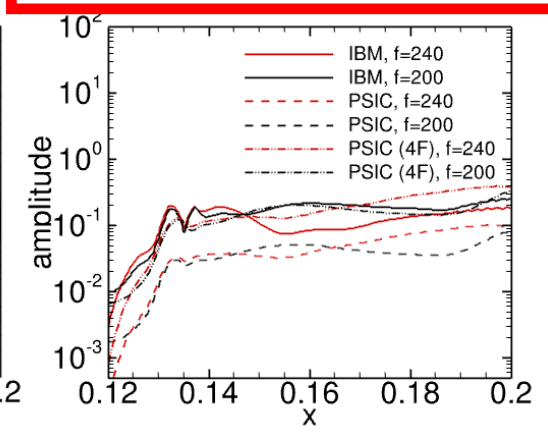
Amplitude Plot
Fully-Resolved



Amplitude Plot
PSIC



Amplitude Plot
PSIC Adjusted Force

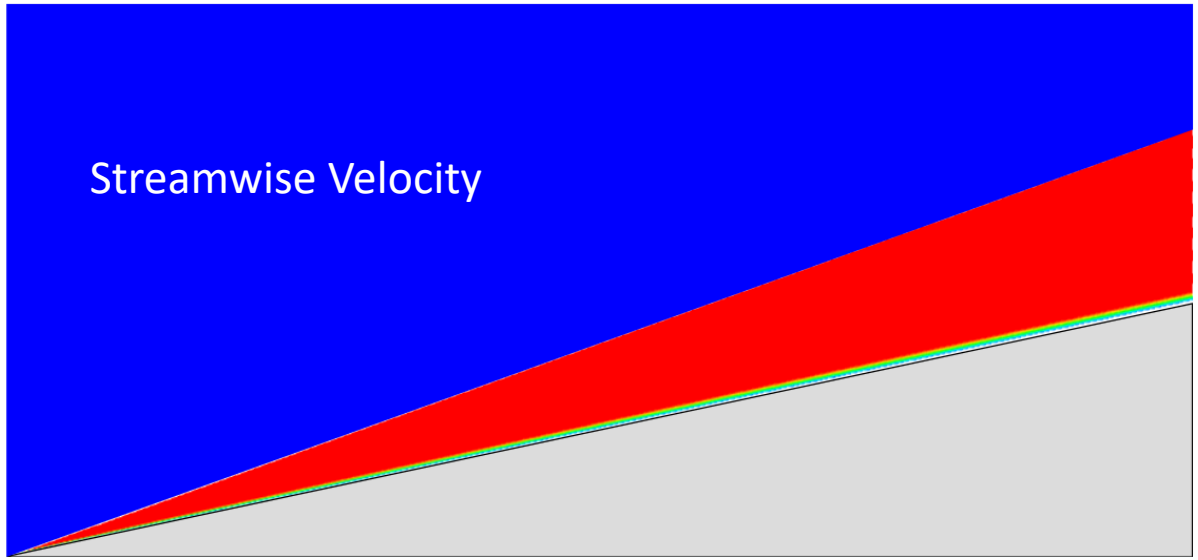


Curves

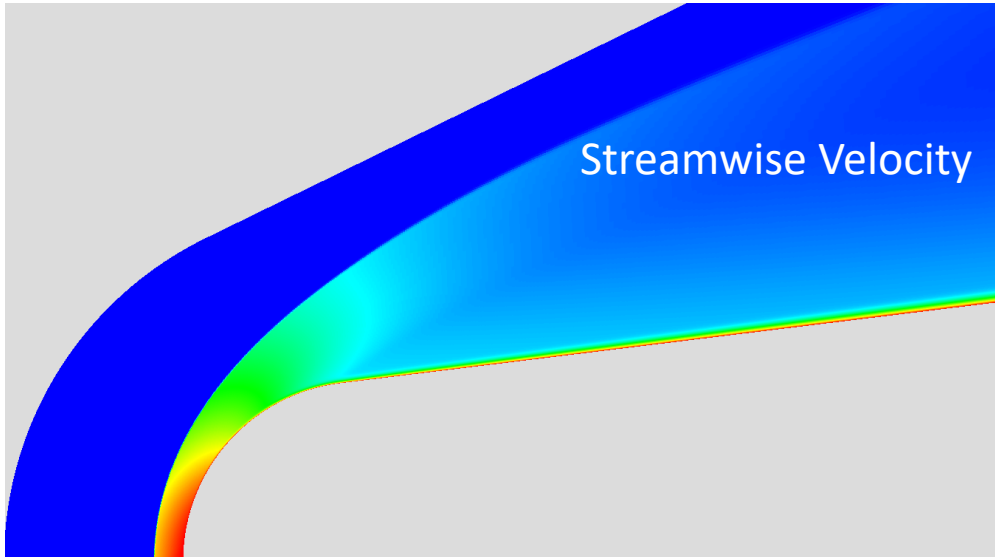
Particle-Induced Transition Model — Summary

Chosen Flow Conditions and Geometries

M=9.5 14° Wedge Fedorov (2013), Browne et al. (2019)



M=5.07 HIFiRE-1 7° Cone Li et al. (2015)



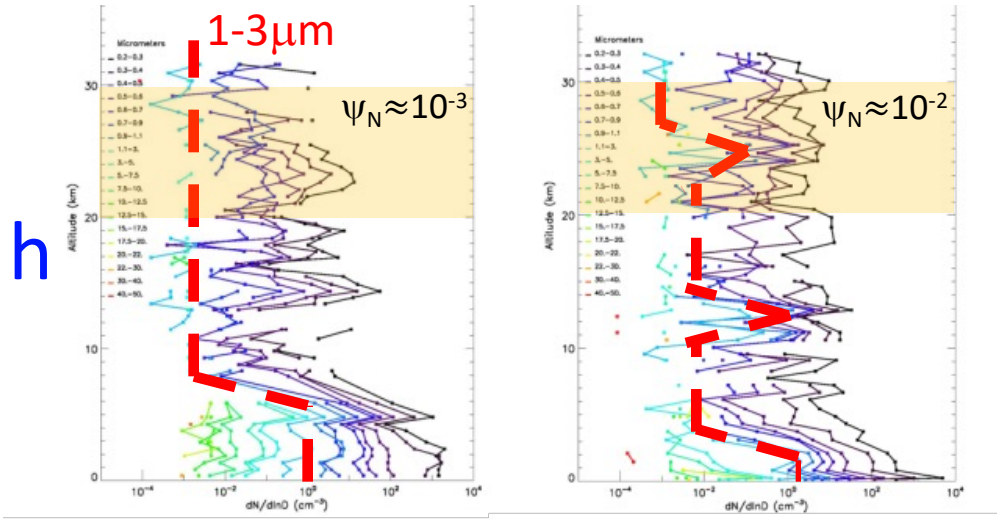
Flow Conditions

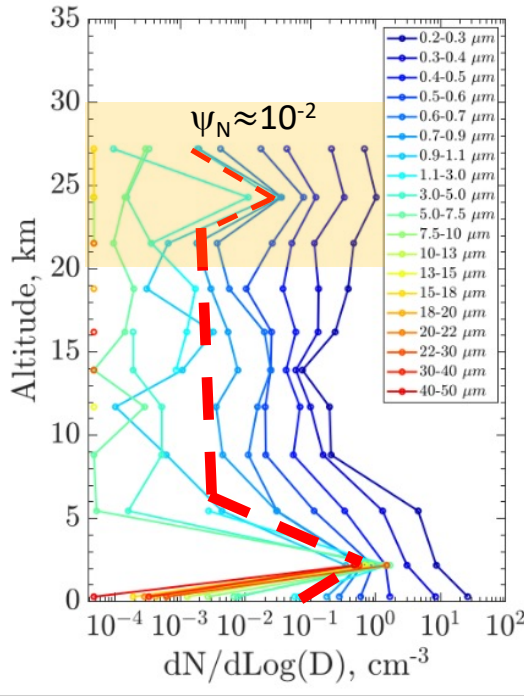
Case	Altitude (km)	M_∞	$Re_\infty (1/m)$	$p_\infty (N/m^2)$	$T_\infty (K)$	$U_\infty (m/s)$
14^o Wedge	26	9.5	1.126×10^7	2090.7	222.84	2842.13
HIFiRE-1	16.75	5.07	1.846×10^7	9851.9	201.0	1441.2

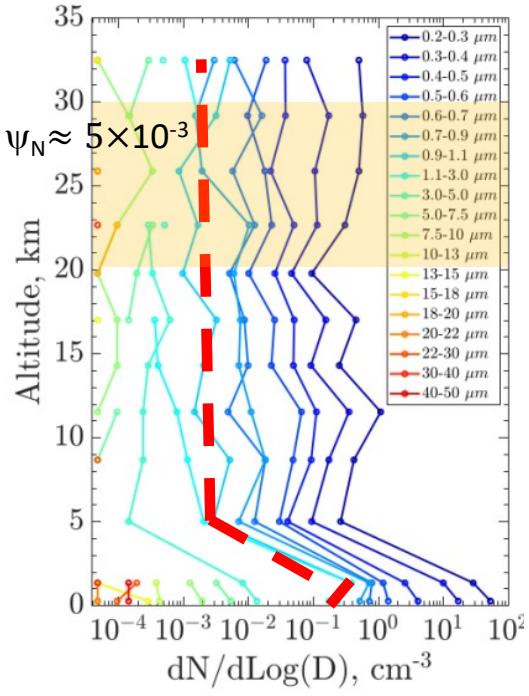
Freestream conditions are based on the US standard atmosphere model (1976)

Particle Sizes and Concentration in the Atmosphere

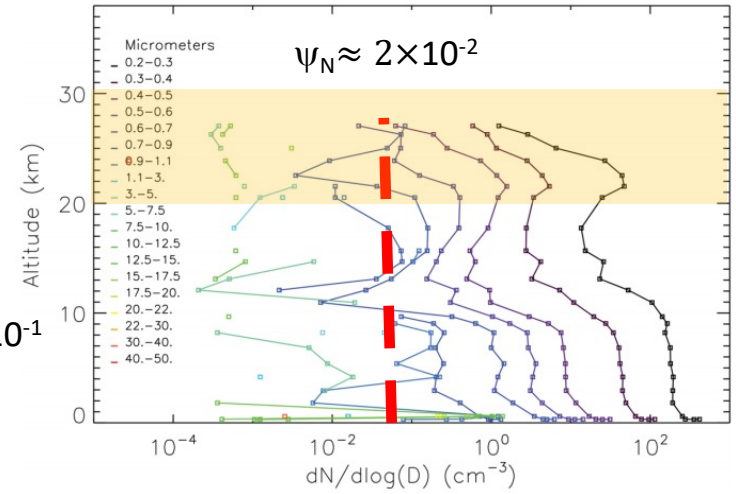
LOAC: a small aerosol optical counter/sizer for ground based and balloon measuremets of the size distribution and nature of atmospheric particles - part 2, J. Renard et al., Atmos. Meas. Tech. Discuss, 2015







High-altitude balloon measurements of atmospheric particulates, J. B. Habeck, J. A. Flaten, G. V. Candler, AIAA Scitech 2020



Measurements of aerosols and charged particles on the BEXUS18 stratospheric balloon, E. Brattich et al., Annales Geophysicae 2019

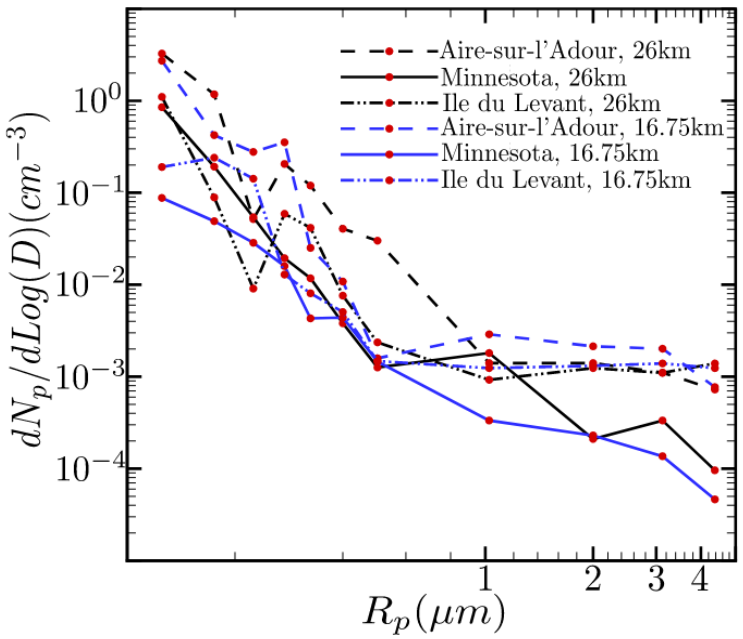
ψ_N=dN/dLog(N)

Particle-Induced Transition Model — Summary

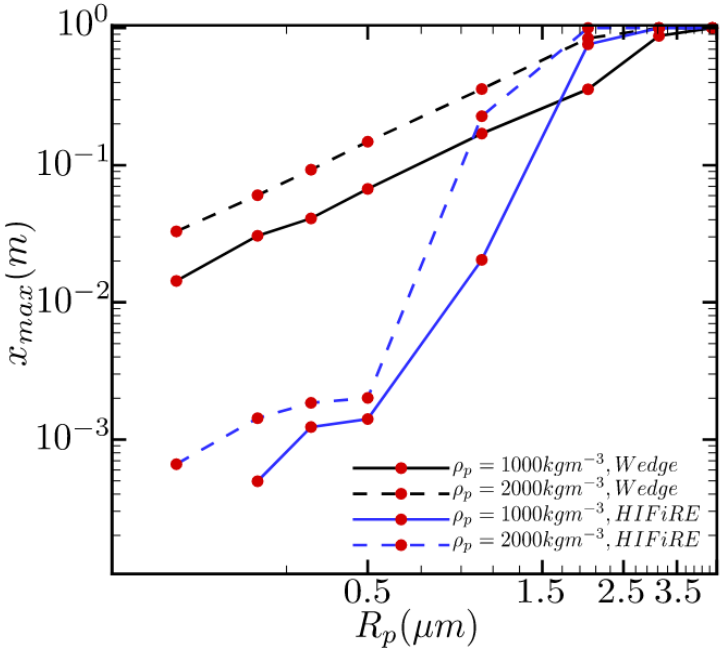
Summary of Particle induced transition model:

1. Seed random particles in domain based on given concentration and properties

Particle Concentration



Maximum Impact Location

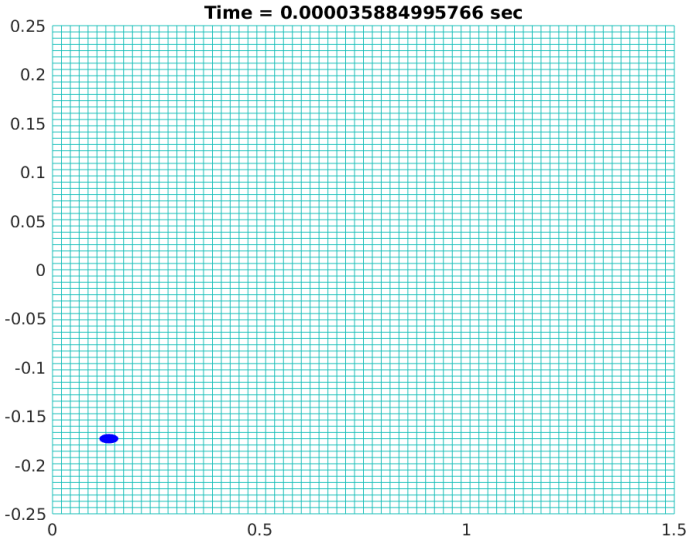


Particle-Induced Transition Model — Summary

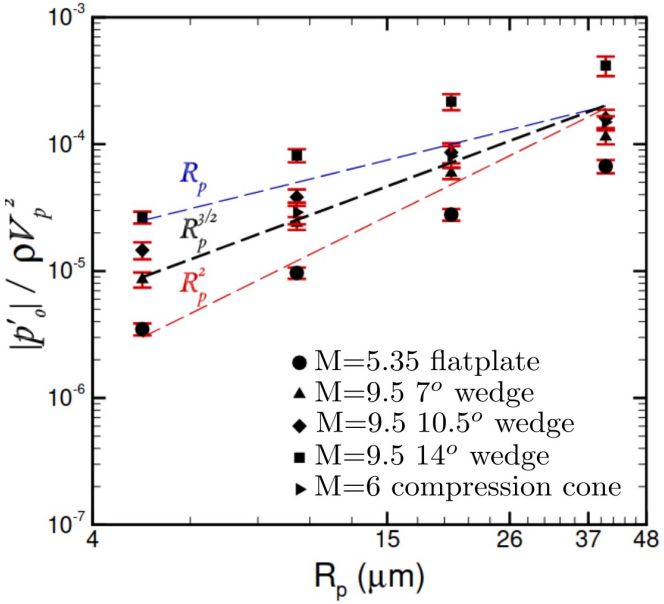
Summary of Particle induced transition model:

1. Seed random particles in domain based on given concentration and properties
2. Wavepackets generated with initial disturbance amplitude A_0 at impingement location

Wavepacket generated at the particle impingement location



A_0 Pressure Amplitude vs. R_p

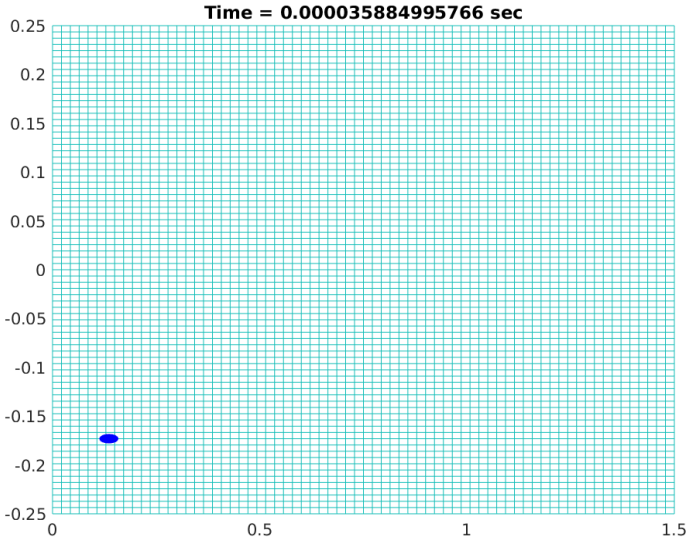


Particle-Induced Transition Model — Summary

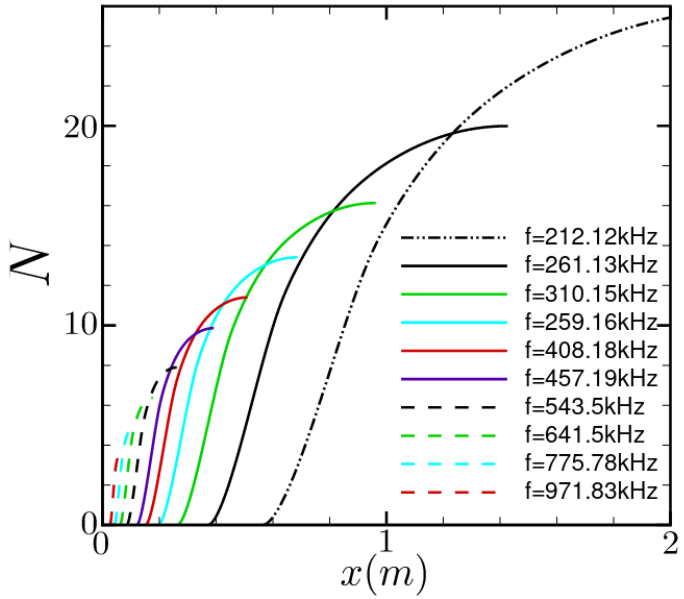
Summary of Particle induced transition model:

1. Seed random particles in domain based on given concentration and properties
2. Wavepackets generated with initial disturbance amplitude A_0 at impingement location
3. Amplification due to linear growth (here LST)

Wavepacket generated at the particle impingement location



Instability Growth

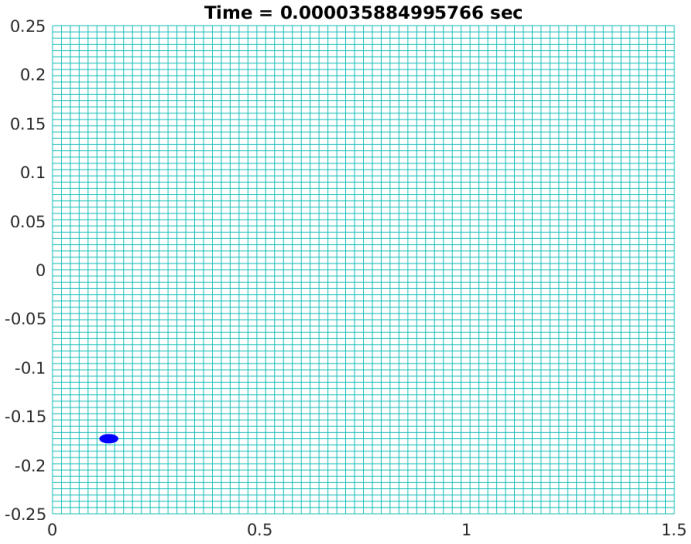


Particle-Induced Transition Model — Summary

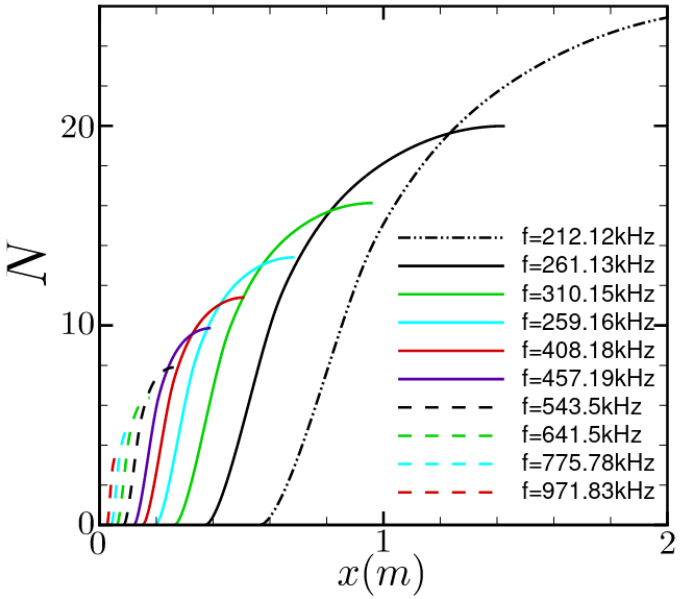
Summary of Particle induced transition model:

1. Seed random particles in domain based on given concentration and properties
2. Wavepackets generated with initial disturbance amplitude A_0 at impingement location
3. Amplification due to linear growth (here LST)
4. Wavepacket spreads with given spreading rate

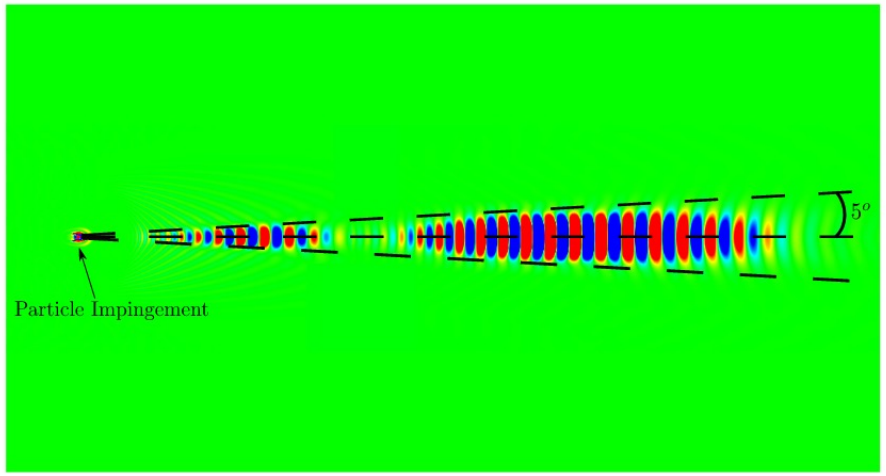
Wavepacket generated at the particle impingement location



Instability Growth



Developing Wavepacket

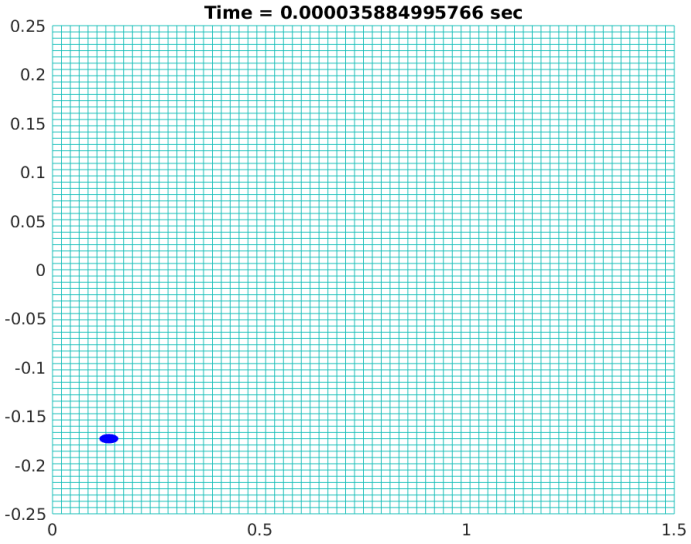


Particle-Induced Transition Model — Summary

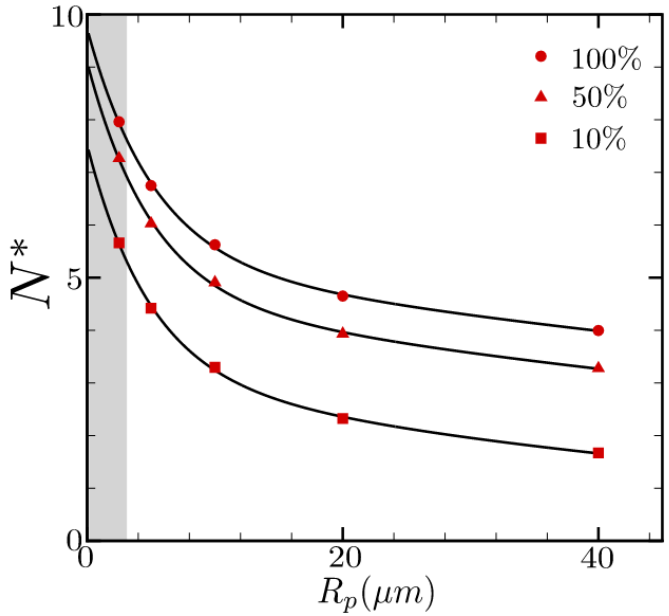
Summary of Particle induced transition model:

1. Seed random particles in domain based on given concentration and properties
2. Wavepackets generated with initial disturbance amplitude A_0 at impingement location
3. Amplification due to linear growth (here LST)
4. Wavepacket spreads with given spreading rate
5. Critical N-factor based on assumed saturation amplitude (nonlinear regime neglected)

Wavepacket generated at the particle impingement location



Critical N-factor

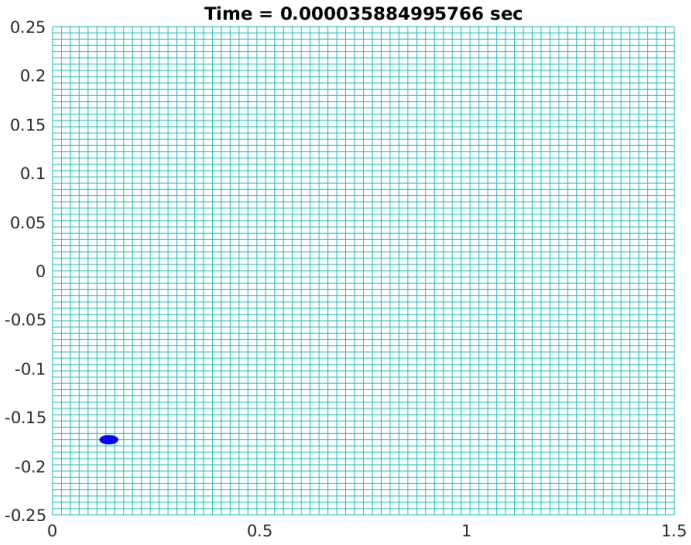


Particle-Induced Transition Model — Summary

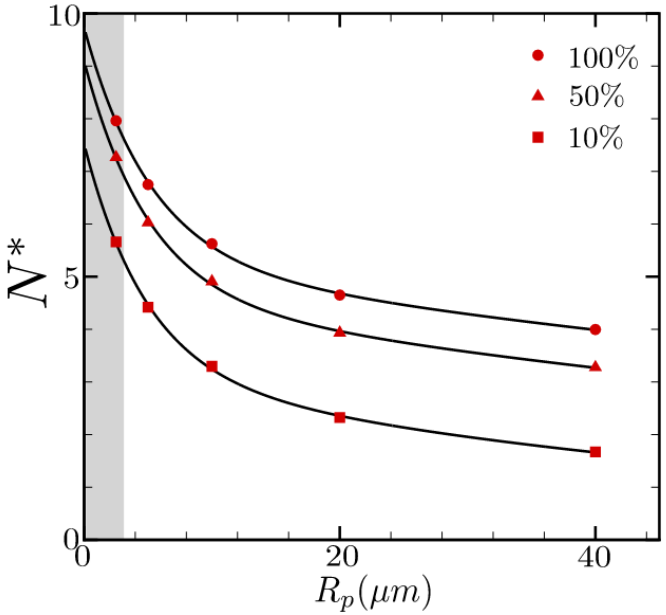
Summary of Particle induced transition model:

1. Seed random particles in domain based on given concentration and properties
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4. Wavepacket spreads with given spreading rate
5. Critical N-factor based on assumed saturation amplitude (nonlinear regime neglected)
6. Turbulent flow region is generated and turbulent region spreads with assumed spreading rate

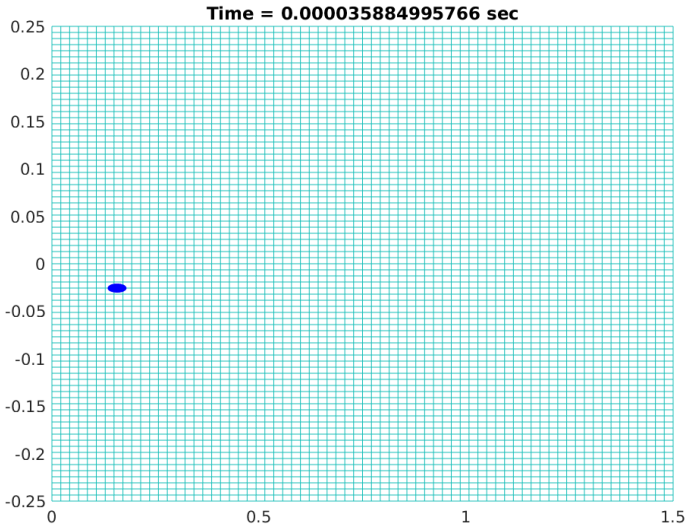
Wavepacket generated at the particle impingement location



Critical N-factor



Turbulent flow region

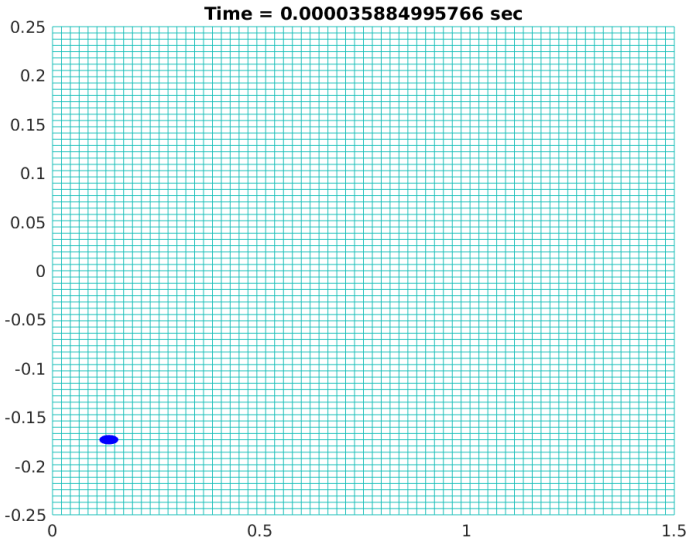


Particle-Induced Transition Model — Summary

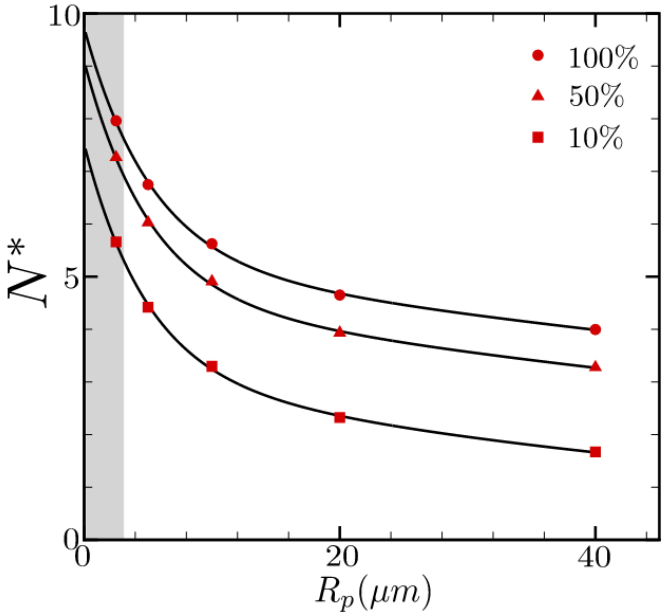
Summary of Particle induced transition model:

1. Seed random particles in domain based on given concentration and properties
2. Wavepackets generated with initial disturbance amplitude A_0 at impingement location
3. Amplification due to linear growth (here LST)
4. Wavepacket spreads with given spreading rate
5. Critical N-factor based on assumed saturation amplitude (nonlinear regime neglected)
6. Turbulent flow region is generated and turbulent region spreads with assumed spreading rate
7. Compute transitional and turbulent intermittency factors

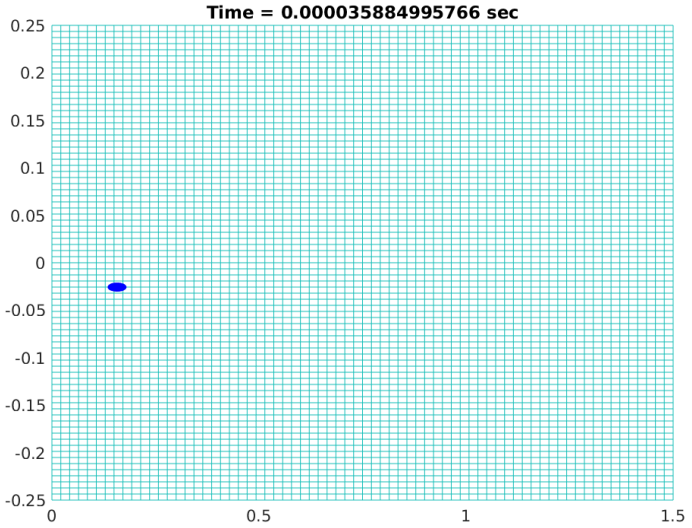
Wavepacket generated at the particle impingement location



Critical N-factor

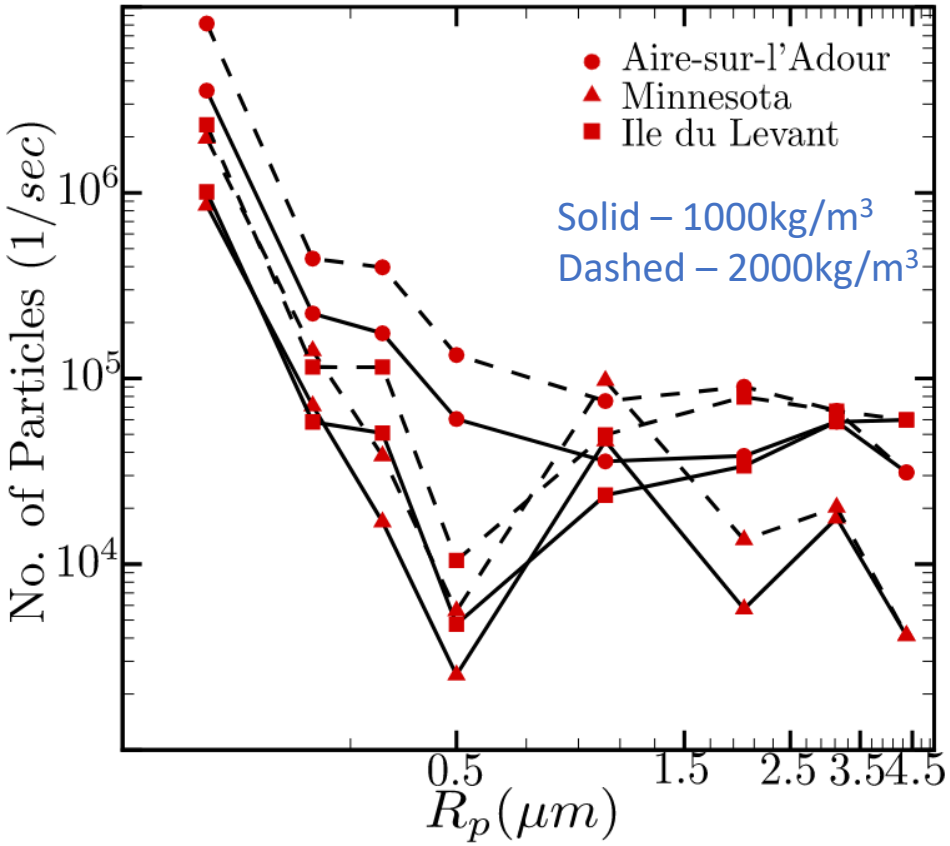


Turbulent flow region

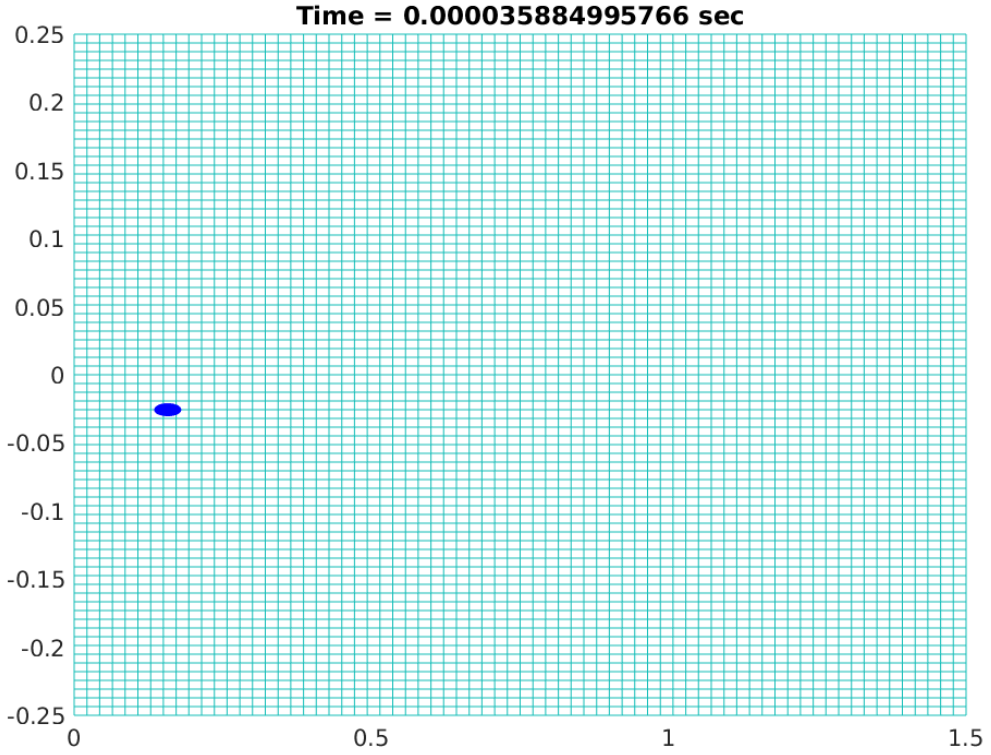


Particle-Induced Transition Simulation for 14° Wedge

Number of Particles Per Second



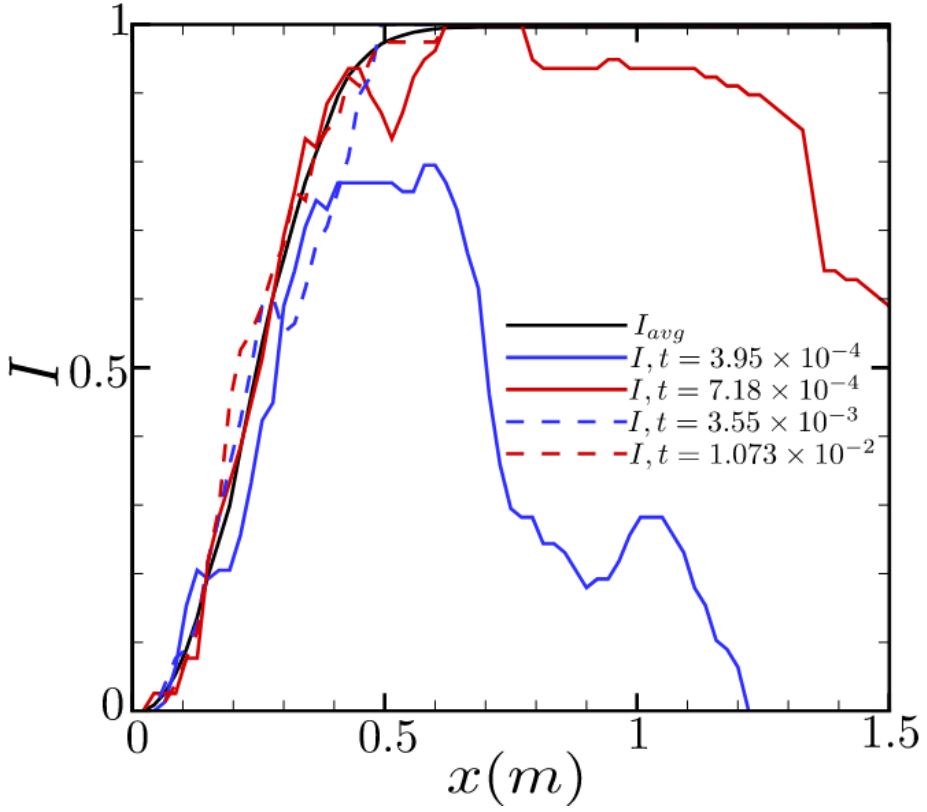
Visualization of Transitional and Turbulent Regions



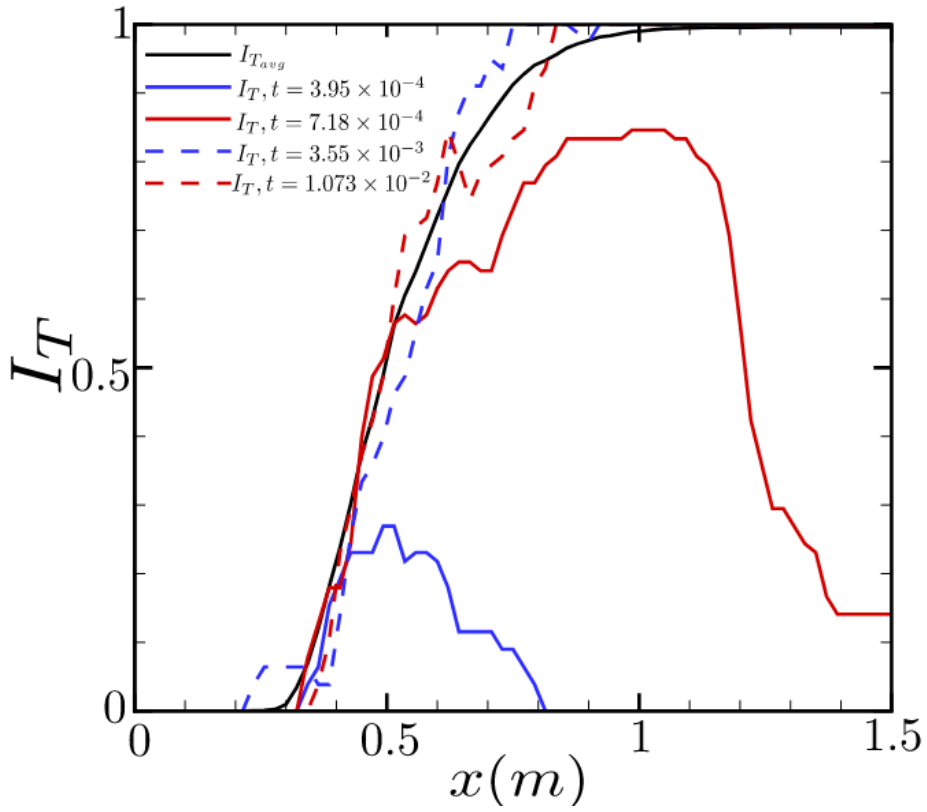
Note, particles are introduced randomly up to the maximum impact location.

Instantaneous Intermittency Factors for 14º Wedge

Transitional Intermittency



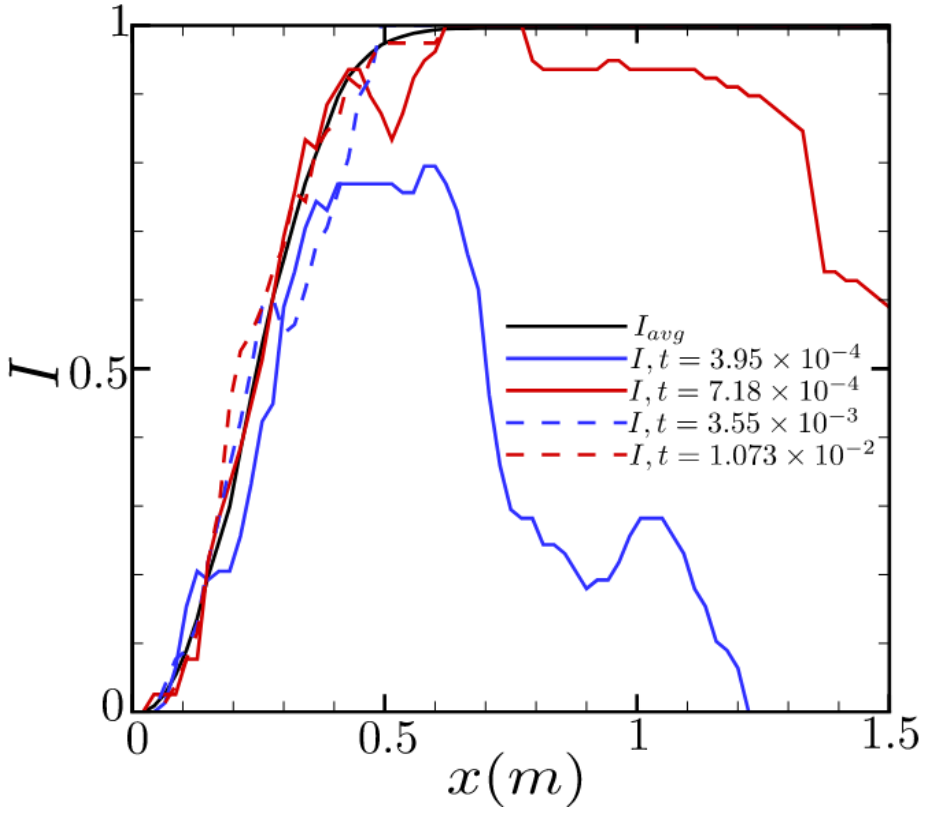
Turbulent Intermittency



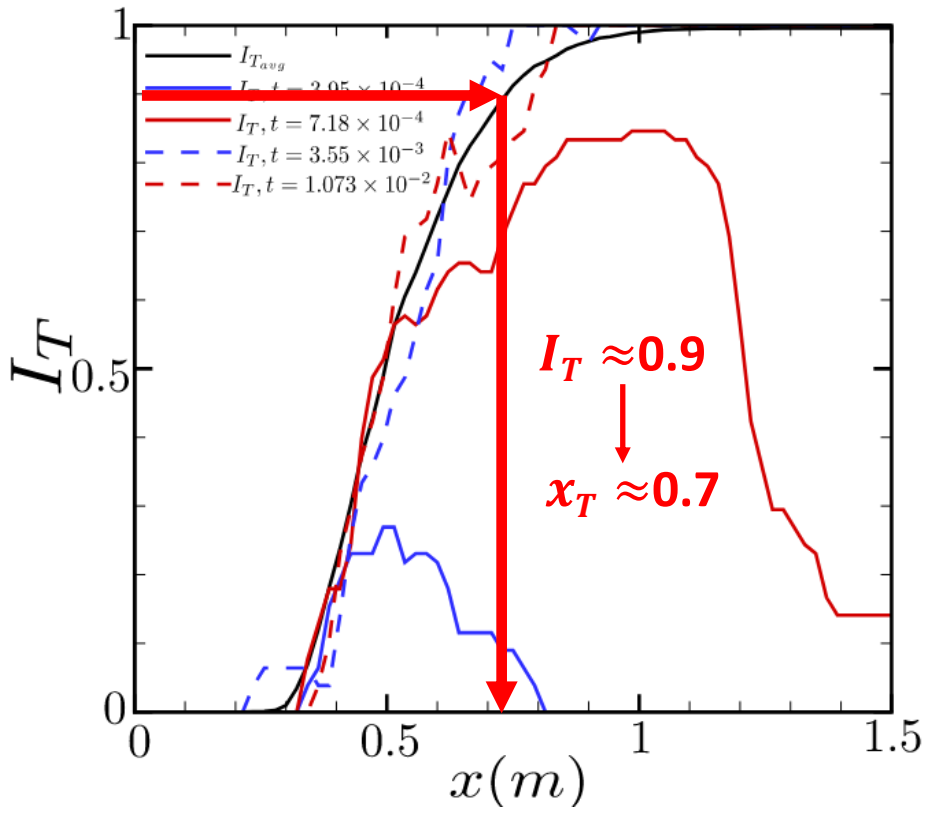
- Averaging of intermittency factor is performed from three flow through to ten flow through times.
- Intermittency reaches statistical convergence after around five flow through times.

Instantaneous Intermittency Factors for 14° Wedge

Transitional Intermittency



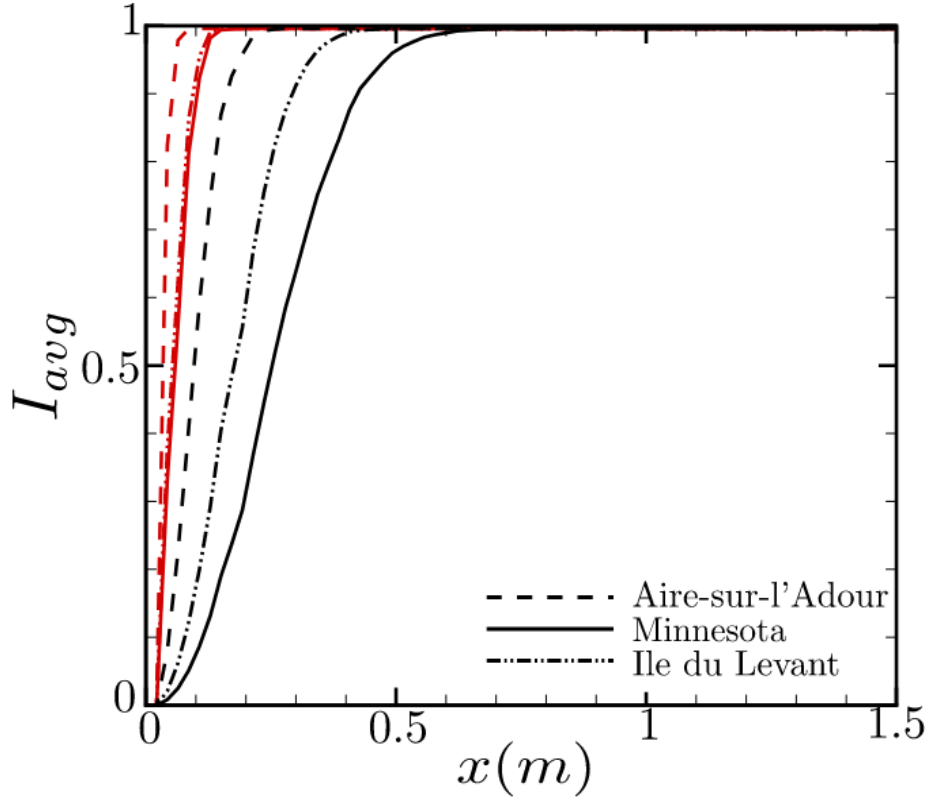
Turbulent Intermittency



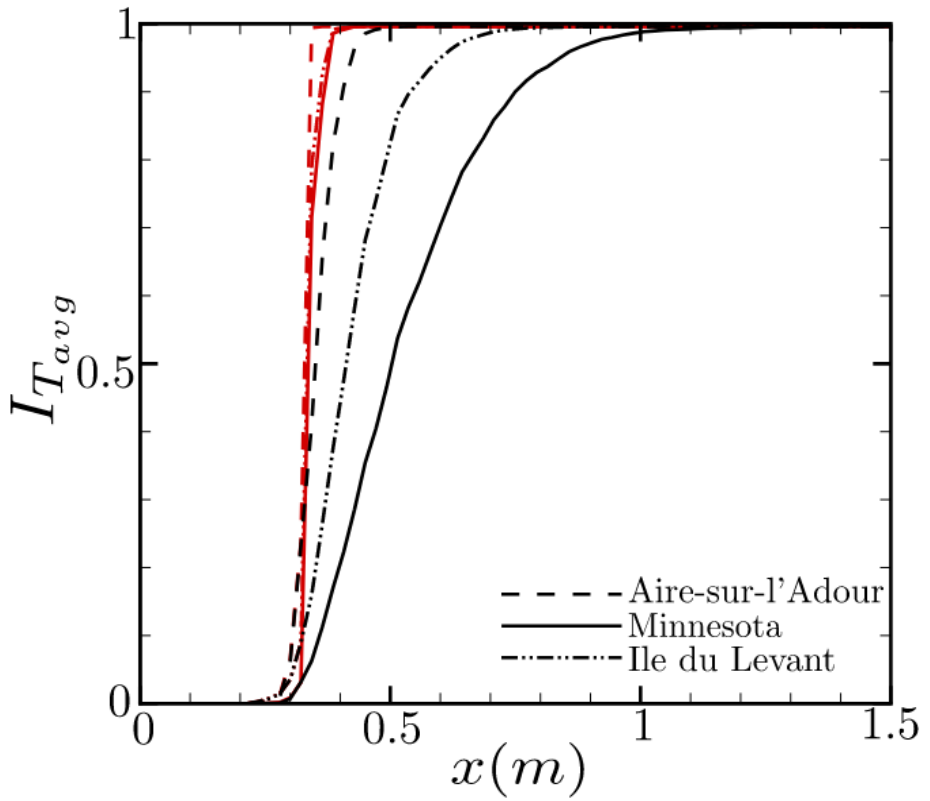
- Averaging of intermittency factor is performed from three flow through to ten flow through times.
- Intermittency reaches statistical convergence after around five flow through times.

Time-Averaged Intermittency Factors for 14° Wedge

Transitional Intermittency



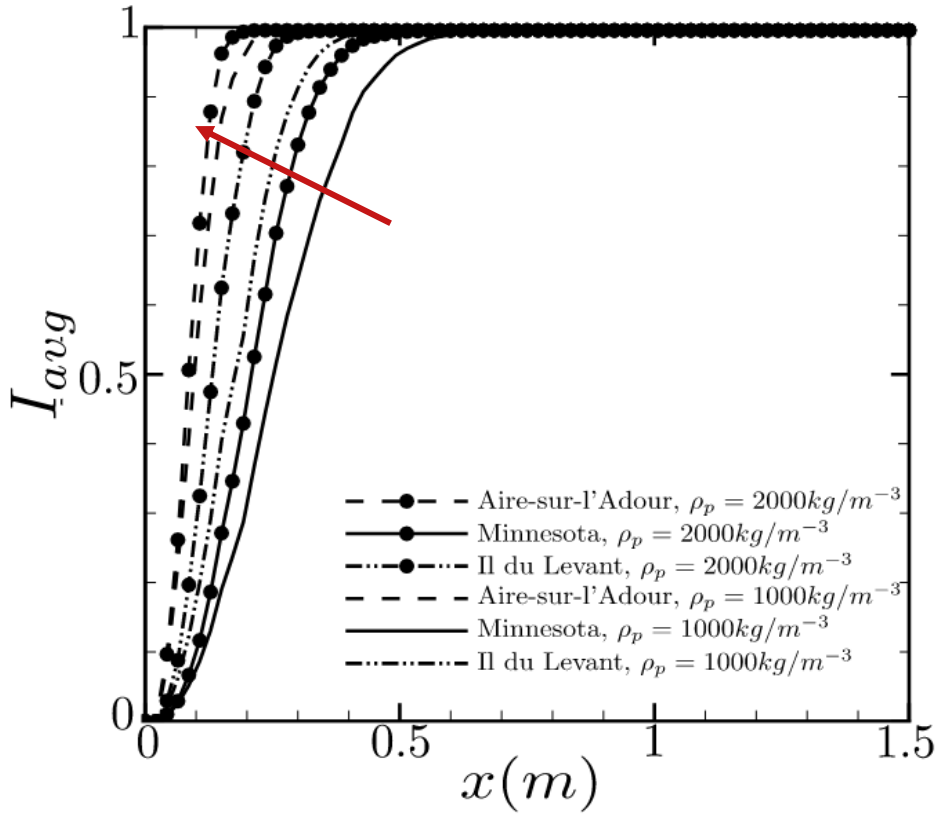
Turbulent Intermittency



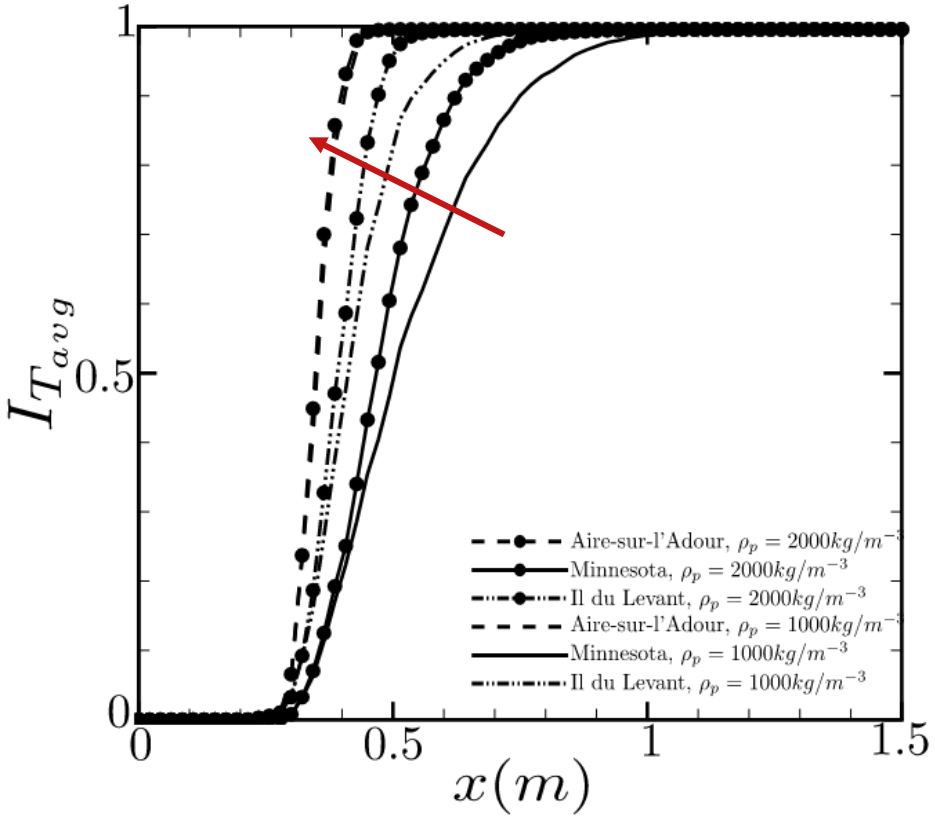
- Red curves are for all the 11 bins and black curves are for the 0.5-0.6 bin and above
- Transition is reached for all particle concentrations with earliest transition observed for the Aire-sur-l'Adour.

Effect of Particle Density

Transitional Intermittency



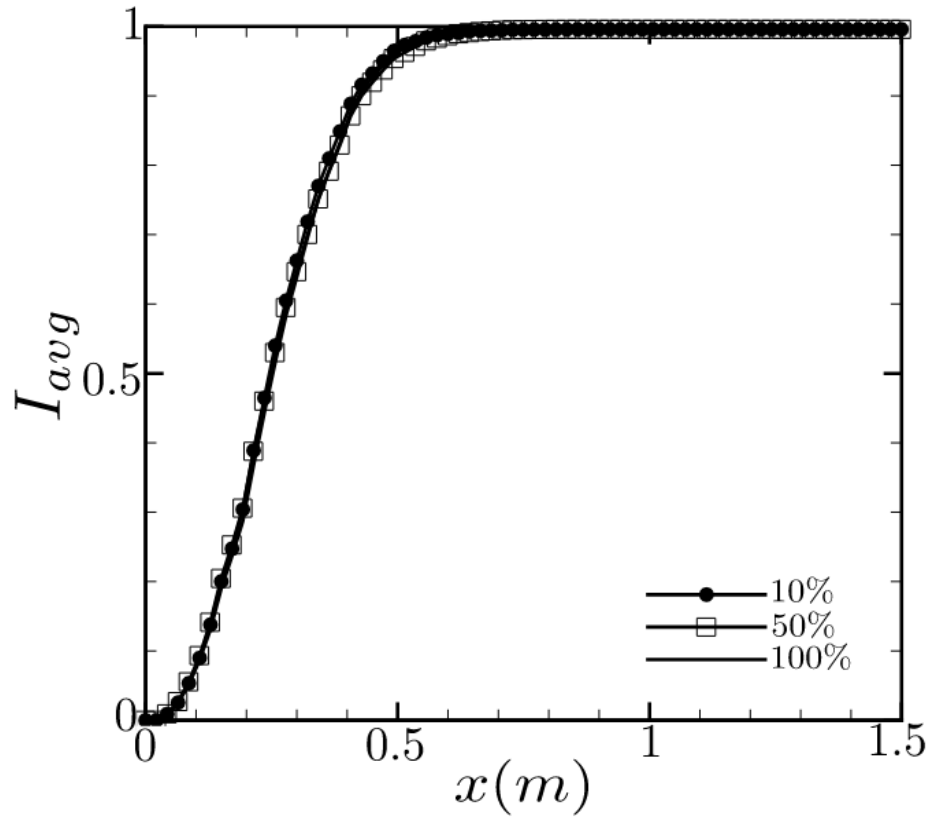
Turbulent Intermittency



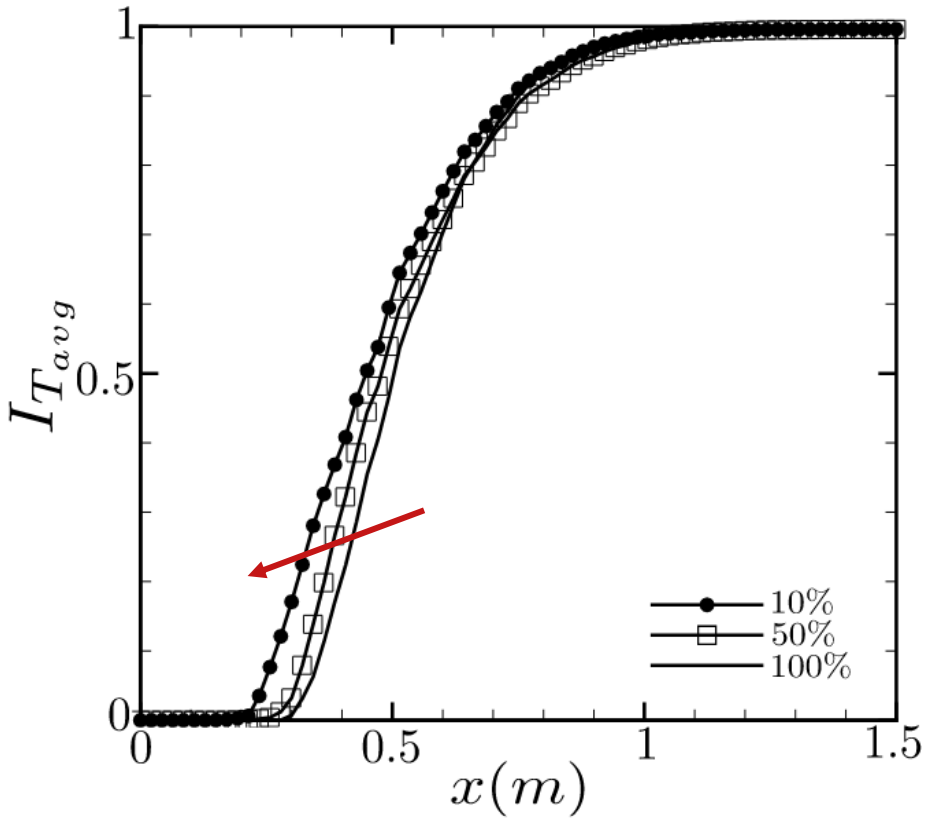
- As the density of the particle increases the transition is observed early.

Effect of Saturation Amplitude

Transitional Intermittency



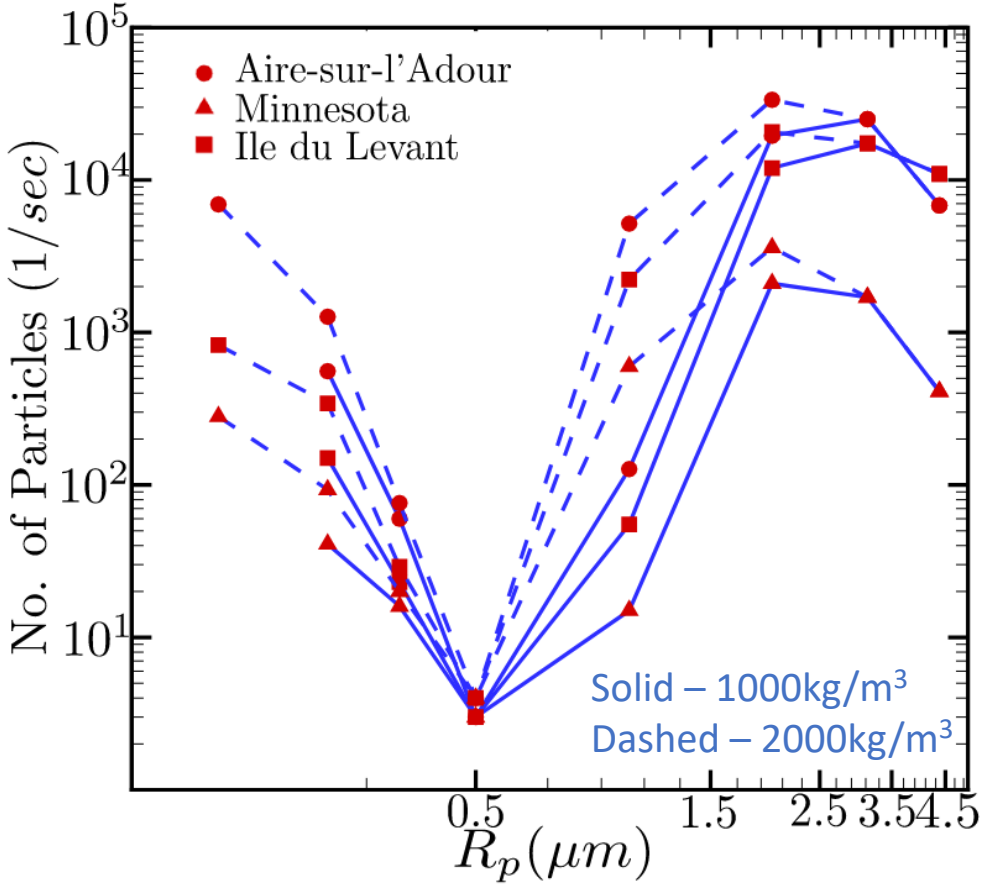
Turbulent Intermittency



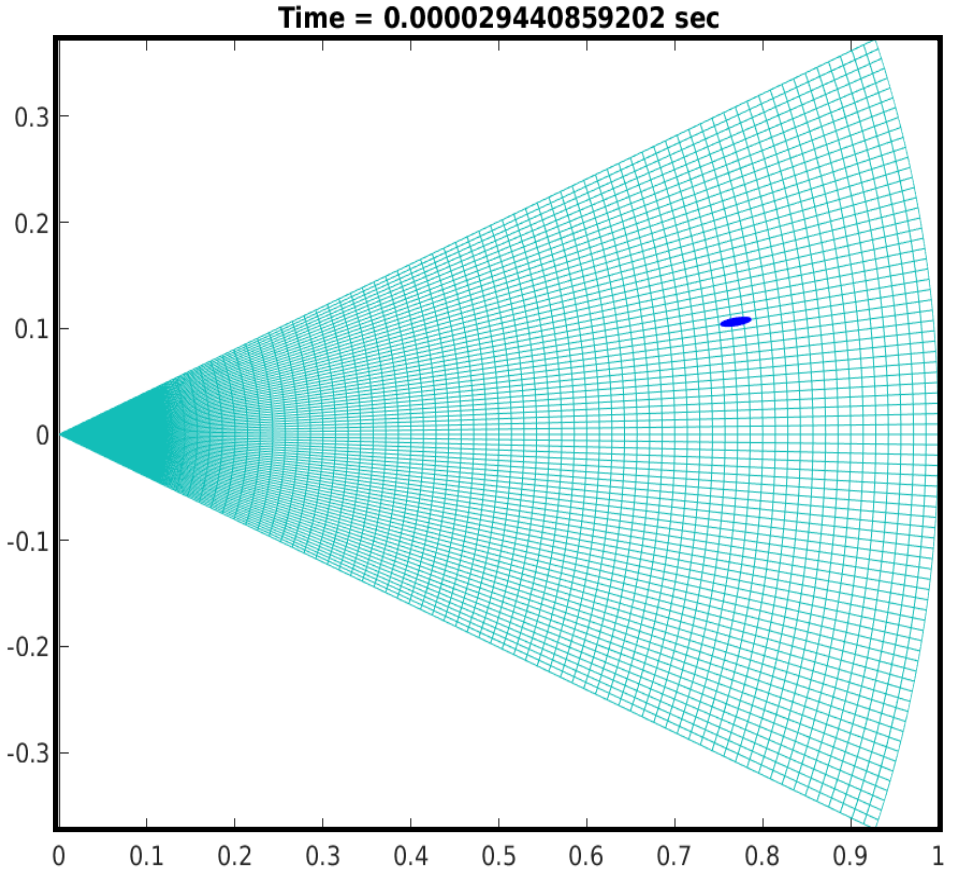
- As the saturation level decreases the turbulent intermittency factor shifts to an upstream position, indicating an earlier onset of transition
- Mild effect on transition location

Particle-Induced Transition Simulation for HIFiRE-1

Number of Particles Per Second



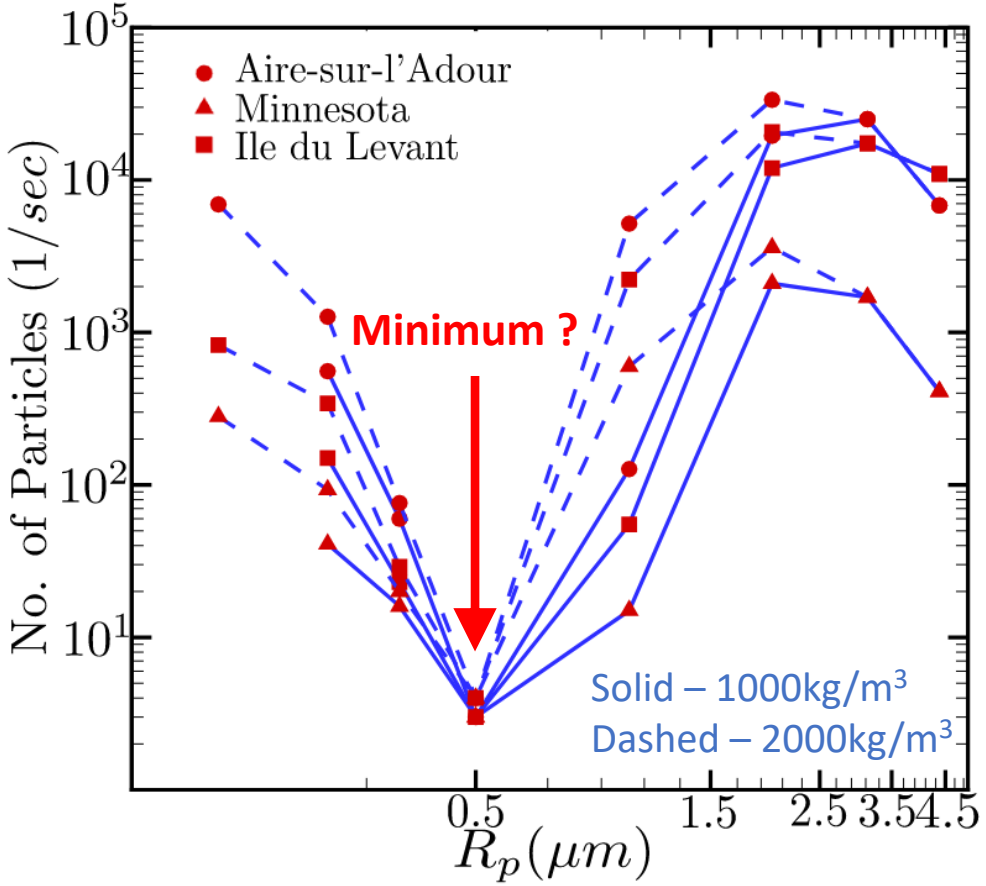
Visualization of Transitional and Turbulent Regions



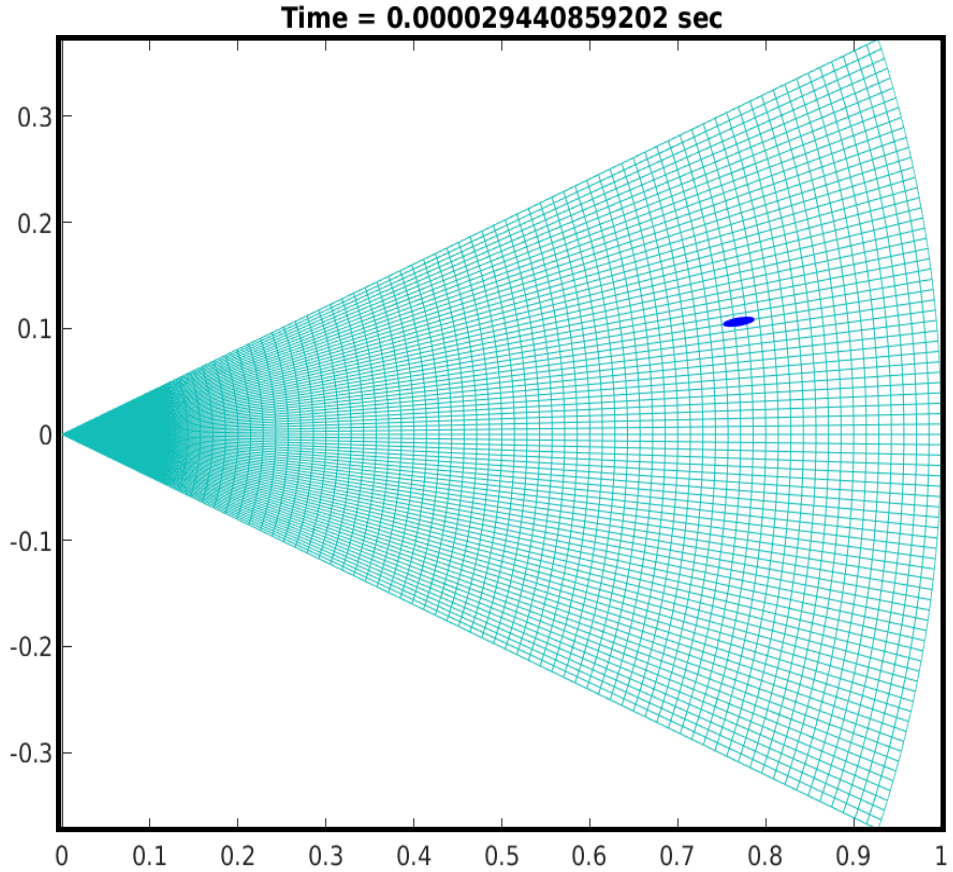
Note, particles are introduced randomly up to the maximum impact location.

Particle-Induced Transition Simulation for HIFiRE-1

Number of Particles Per Second



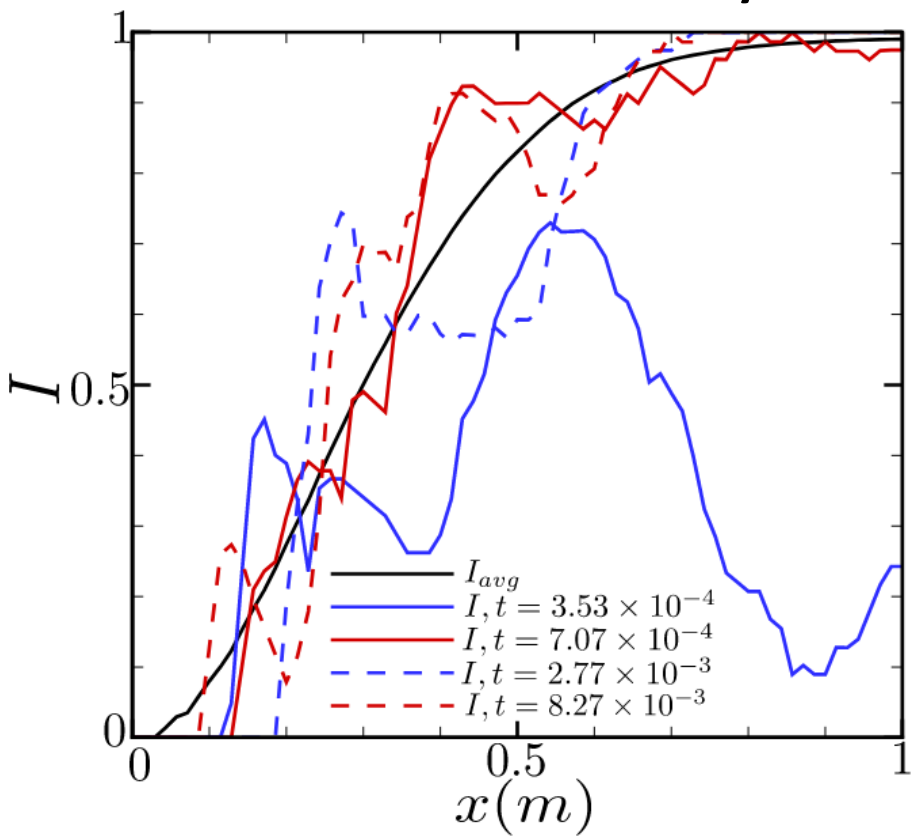
Visualization of Transitional and Turbulent Regions



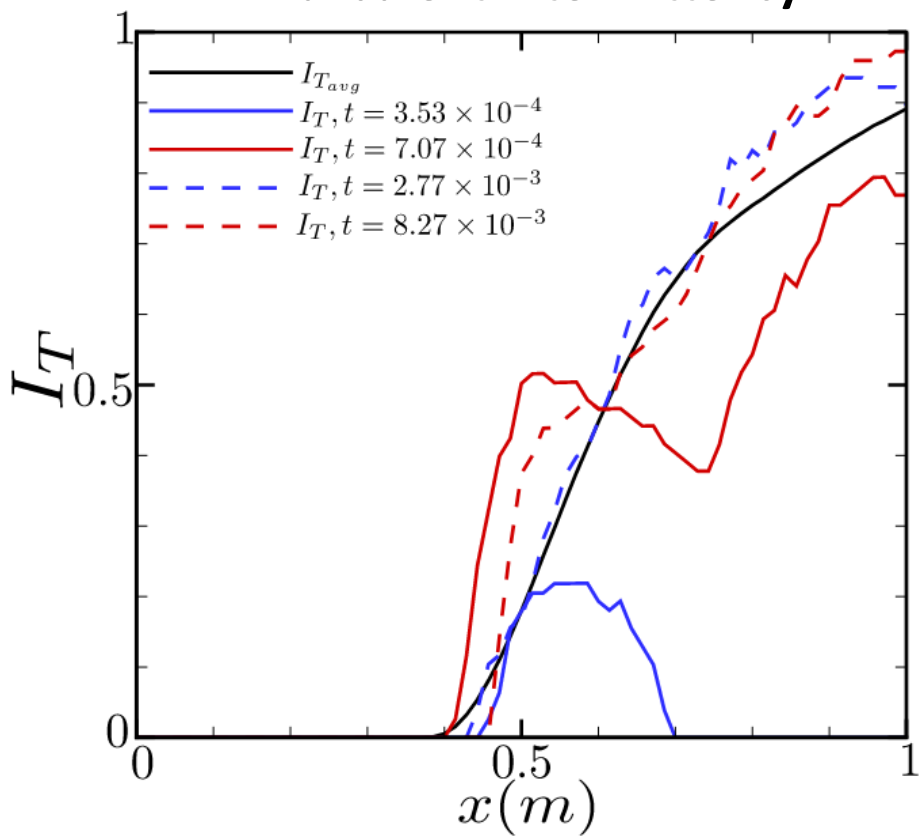
Note, particles are introduced randomly up to the maximum impact location.

Instantaneous Intermittency Factors for HIFiRE-1

Transitional Intermittency

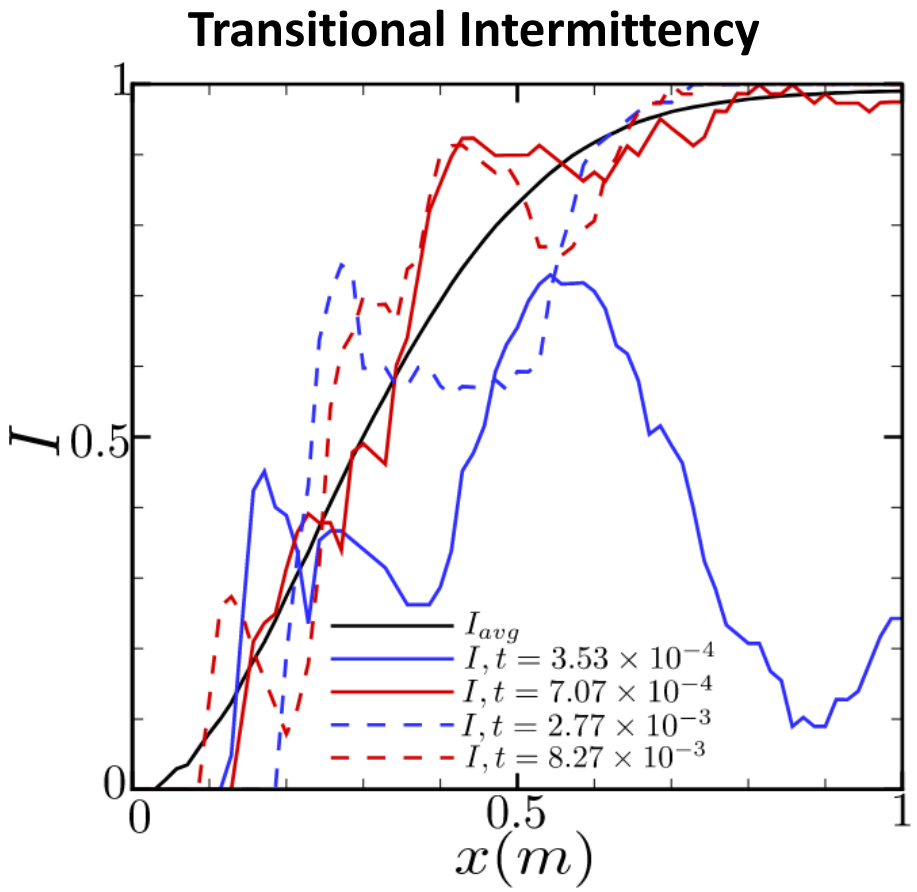


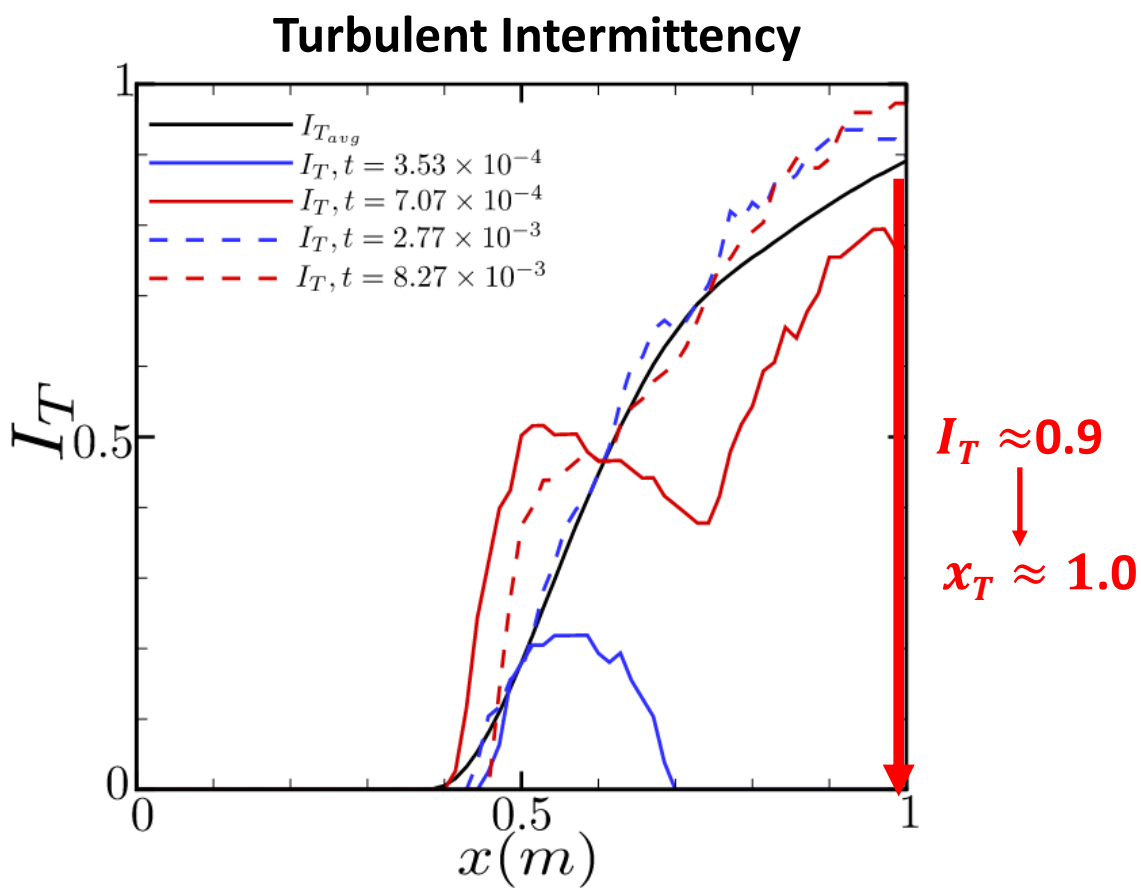
Turbulent Intermittency



- Averaging of intermittency factor is performed from three flow through to ten flow through times.
- Intermittency reaches statistical convergence after around five flow through times.

Instantaneous Intermittency Factors for HIFiRE-1

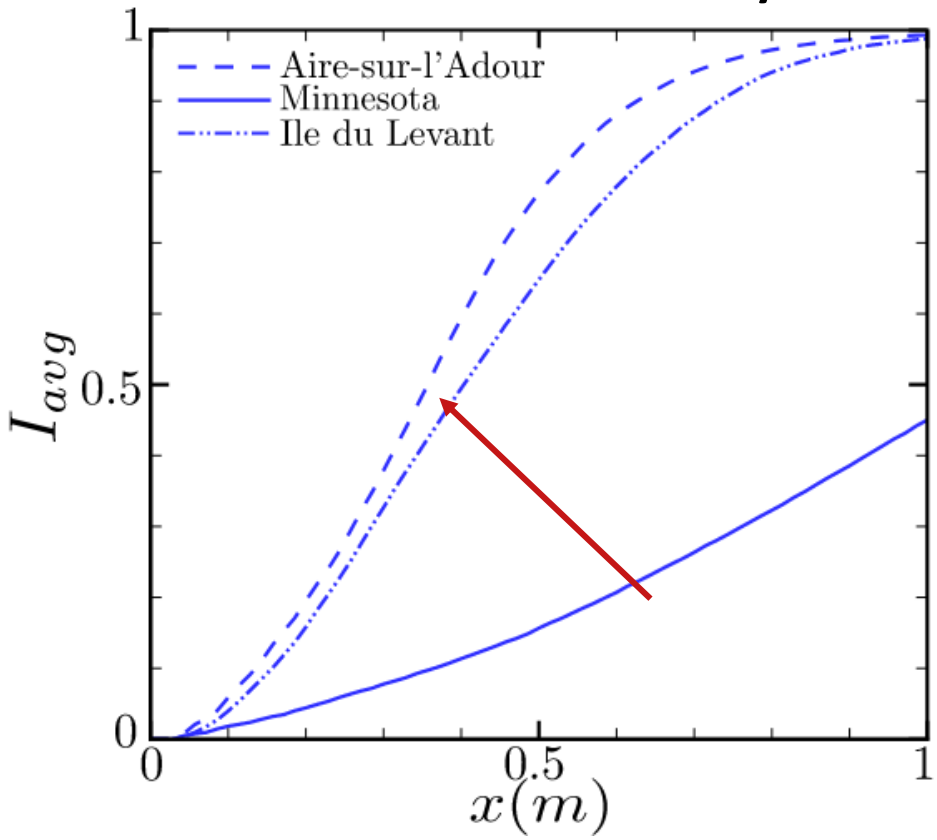




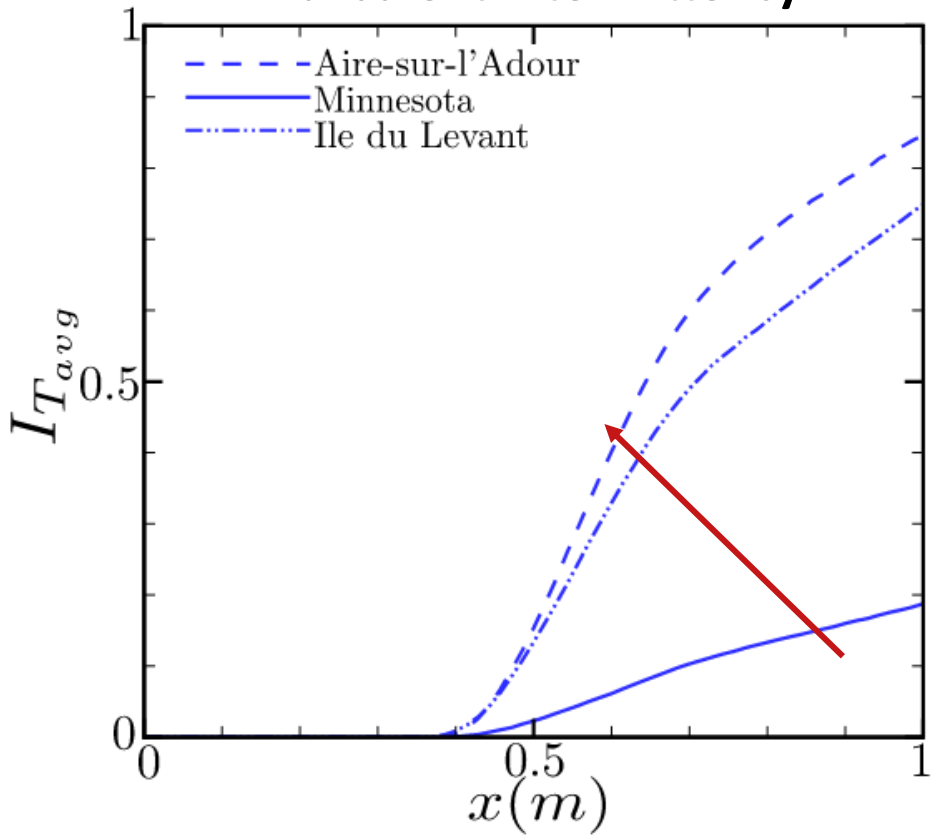
- Averaging of intermittency factor is performed from three flow through to ten flow through times.
- Intermittency reaches statistical convergence after around five flow through times.

Time-Averaged Intermittency Factors for HIFiRE-1

Transitional Intermittency



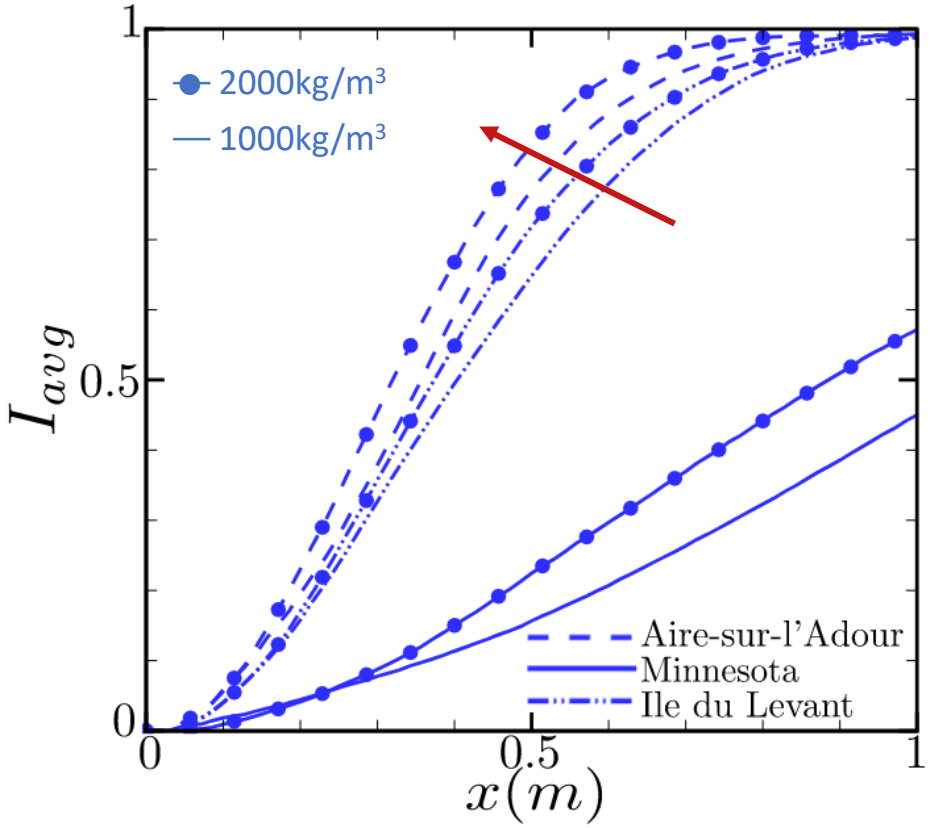
Turbulent Intermittency



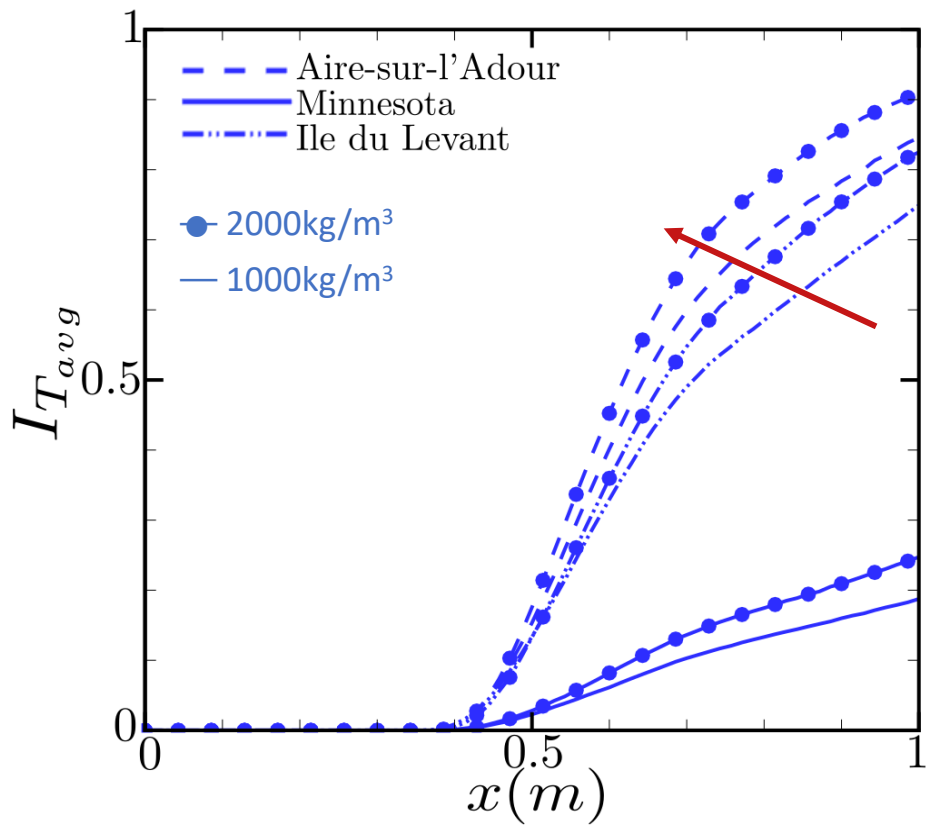
- Highest intermittency is observed for the Aire-sur-l'Adour data but fully turbulent flow is barely reached at x=1m

Effect of Density

Transitional Intermittency



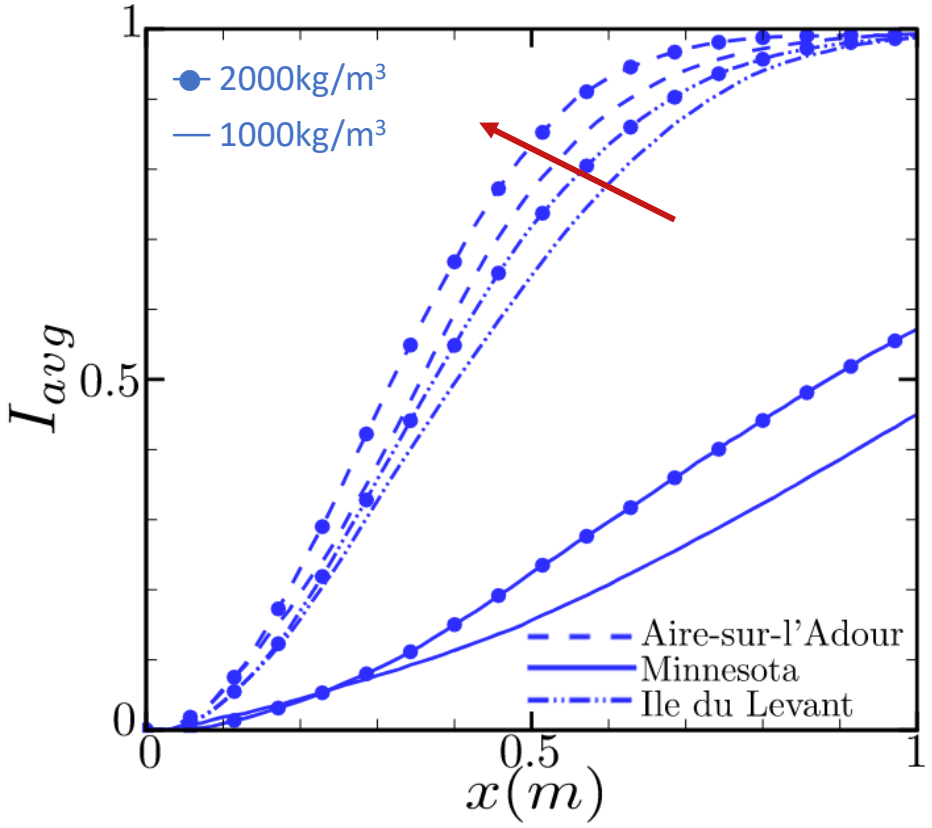
Turbulent Intermittency



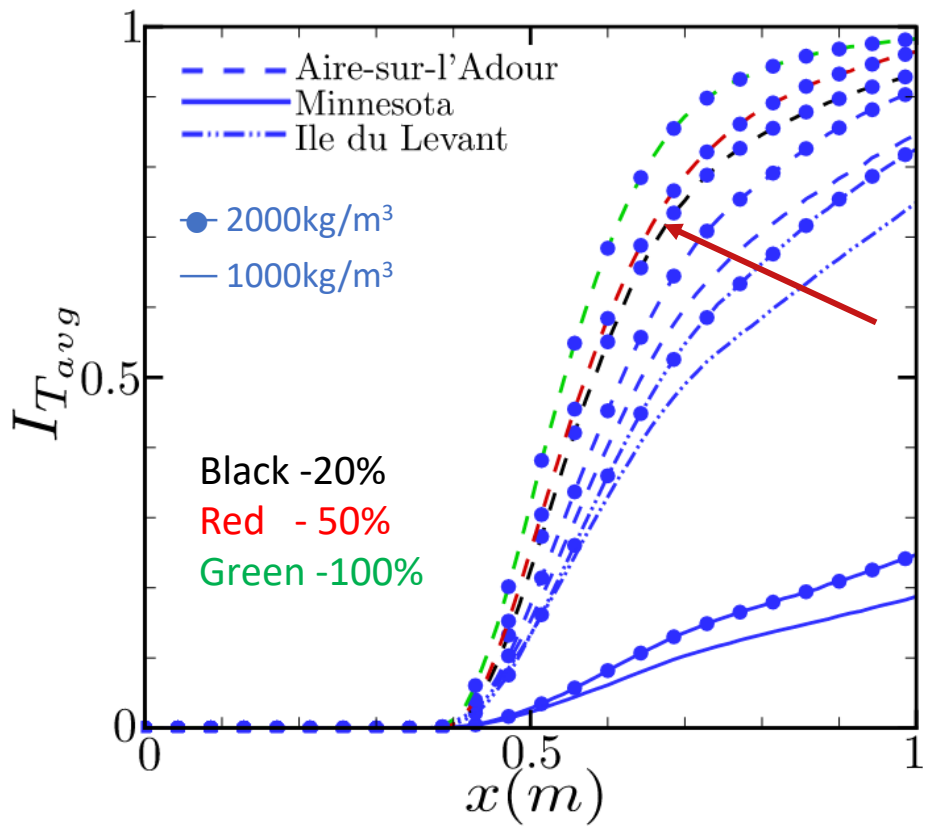
- As the density of the particle increases the curves shifts upstream.

Effect of Density

Transitional Intermittency



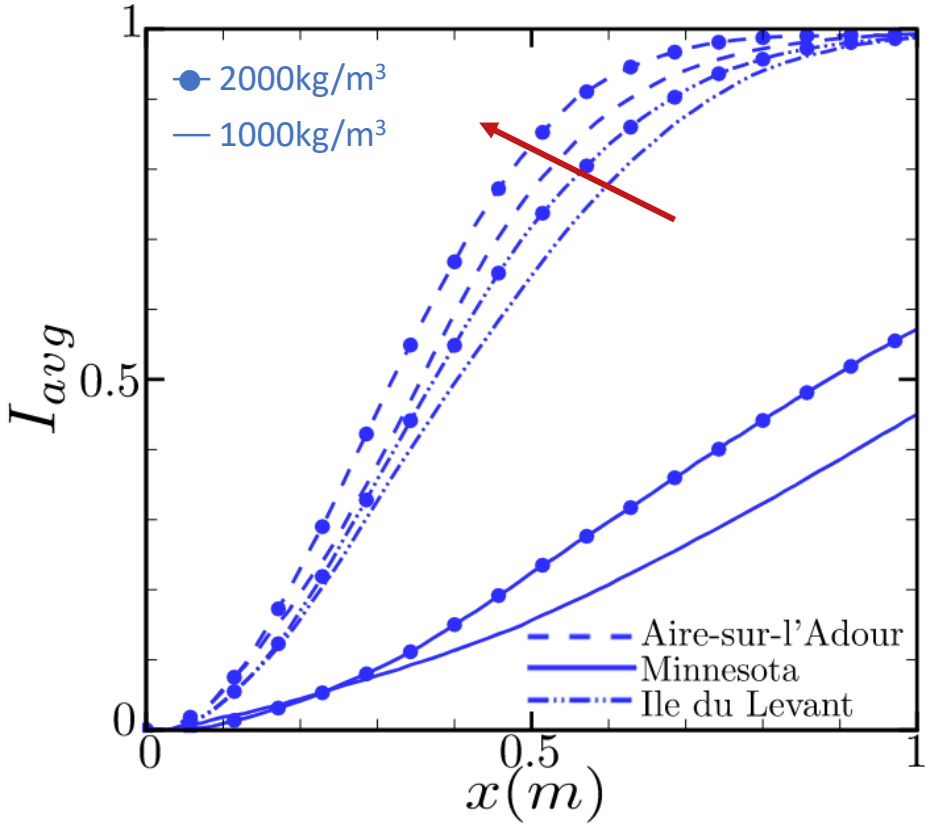
Turbulent Intermittency



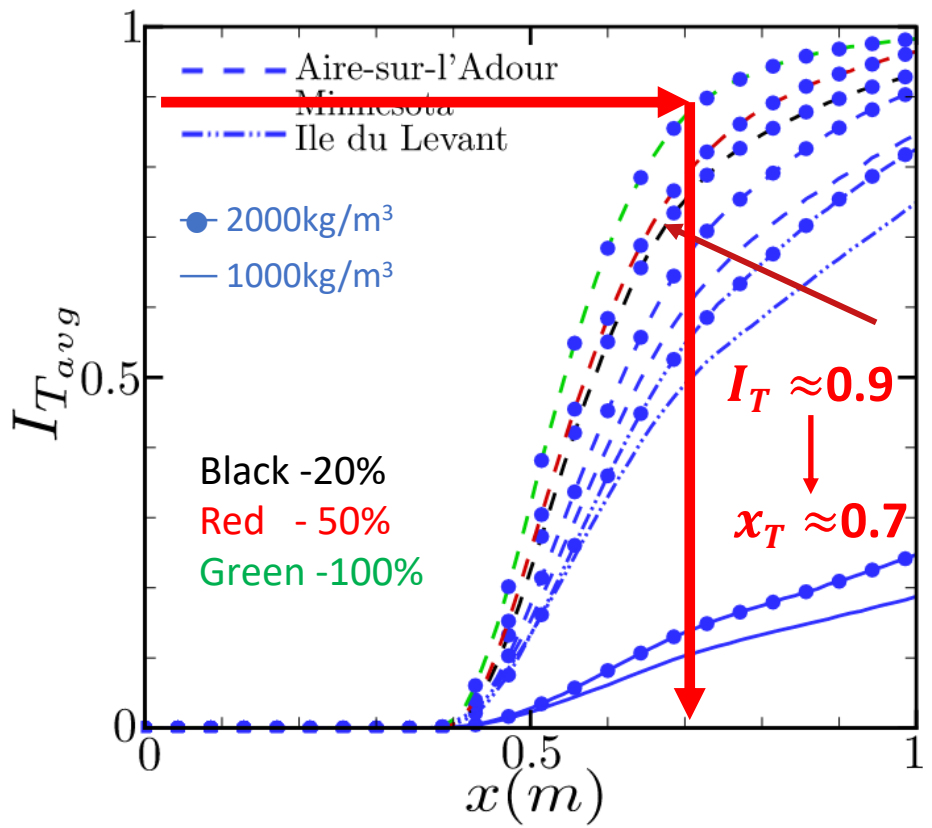
- The turbulent flow is reached at x=0.7m when doubling the particle concentration for the Aire-sur-l'Adour condition.

Effect of Density

Transitional Intermittency



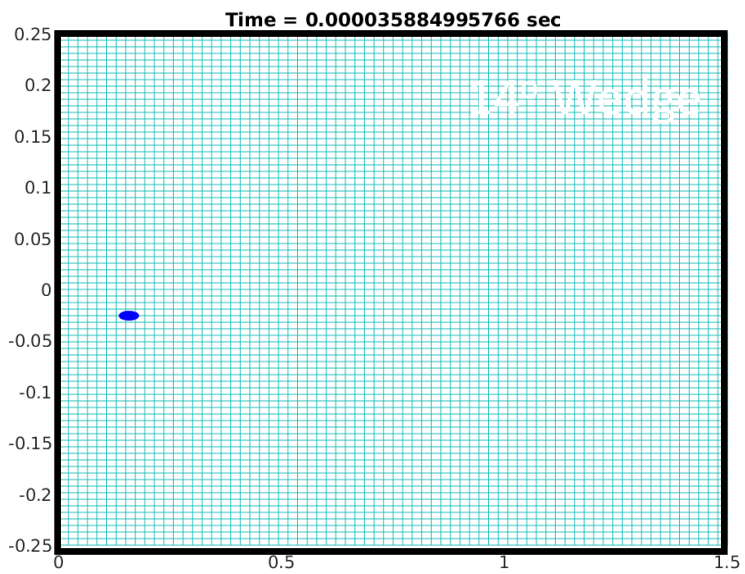
Turbulent Intermittency

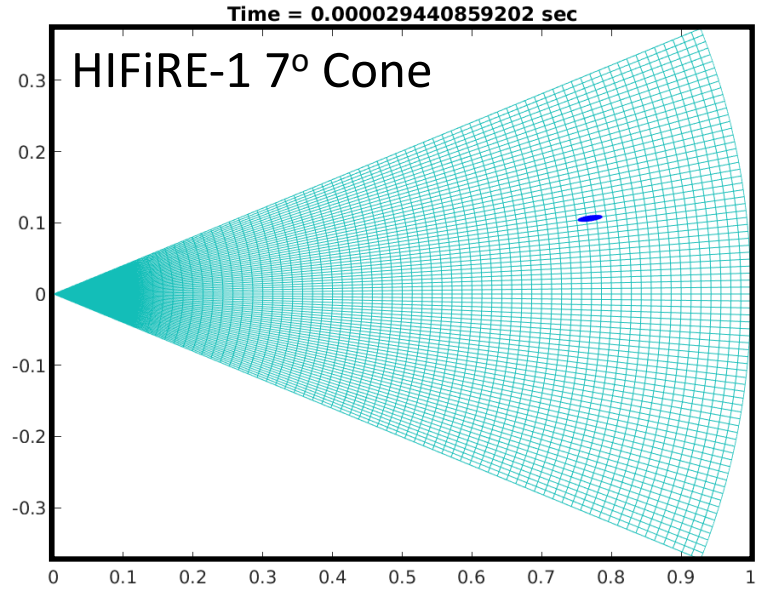


- The turbulent flow is reached at x=0.7m when doubling the particle concentration for the Aire-sur-l'Adour condition.

Conclusions

- A model for particle-induced transition model for hypersonic boundary layer flows has been presented considering relevant flow conditions and particle properties.
- The model has been applied to a M=9.5 over a 14° wedge and HIFiRE-1 7° cone considering the stability characteristics of the flow, different particle concentrations, particle density and saturation levels.
- For all particle concentrations considered transition to turbulence has been observed for the M=9.5 14° wedge within the domain of interest.
- For HIFiRE-1, the current results are not fully conclusive but particle-induced transition cannot be ruled out.





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Summary

- Particles can be an important disturbance source for laminar-turbulent transition for hypersonic vehicle during free flight
  - Particles with sufficient size are present in the atmosphere
  - Particle concentration/flux can maintain turbulence on the vehicle
  - Disturbance amplitude is large enough to cause transition (N≈10)
  - Particles can excite a wide range of modal and non-modal instability mechanisms

- Particle modeling is difficult to perform
  - Fully-resolved approach is too expensive (even worse when continuum flow assumption is not valid)
  - Disturbance amplitude appears to be under-predicted with popular PSIC approach