Recent Advances in Compressible Multiphase Flows
Explosive Dispersal of Particles

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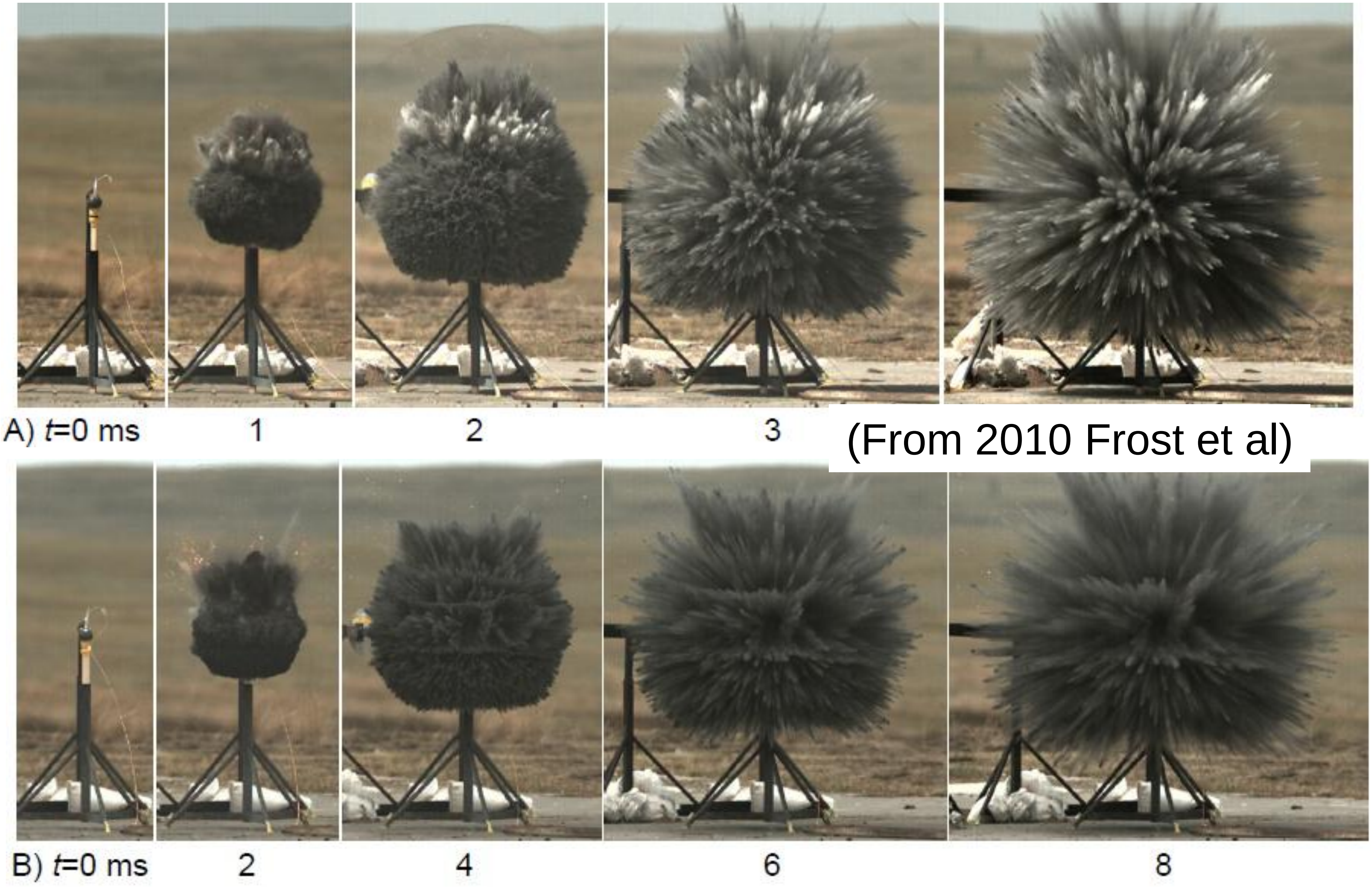
(NSF, AFRL, NDEP, ONR, Sandia)

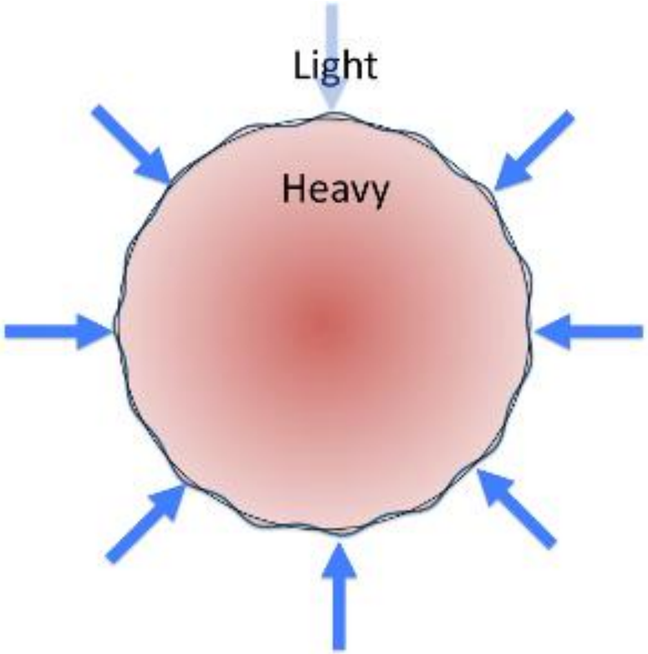
Multiphase Spherical Explosion



(From 2010 Frost et al)

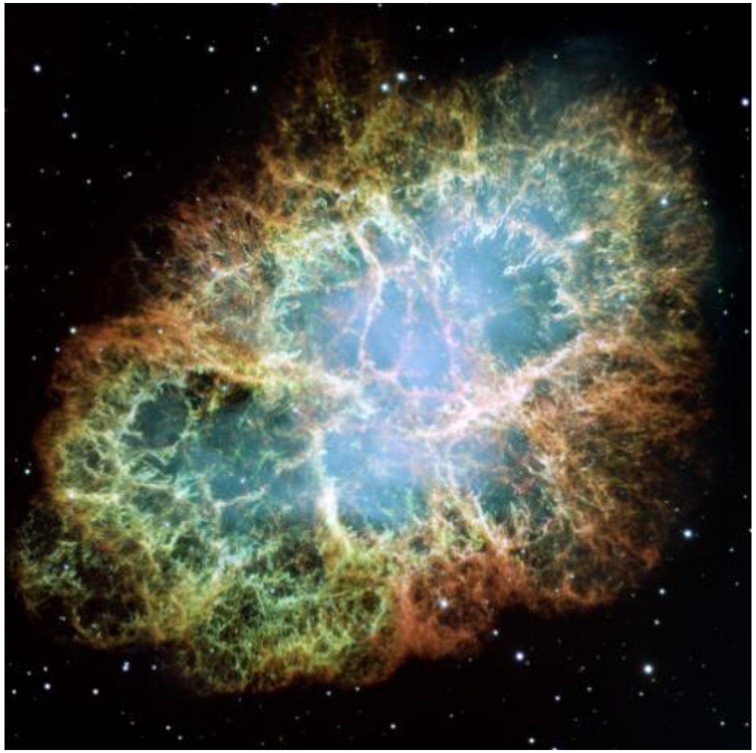
Rapidly Expanding Spherical Interface

Inertial Confinement Fusion

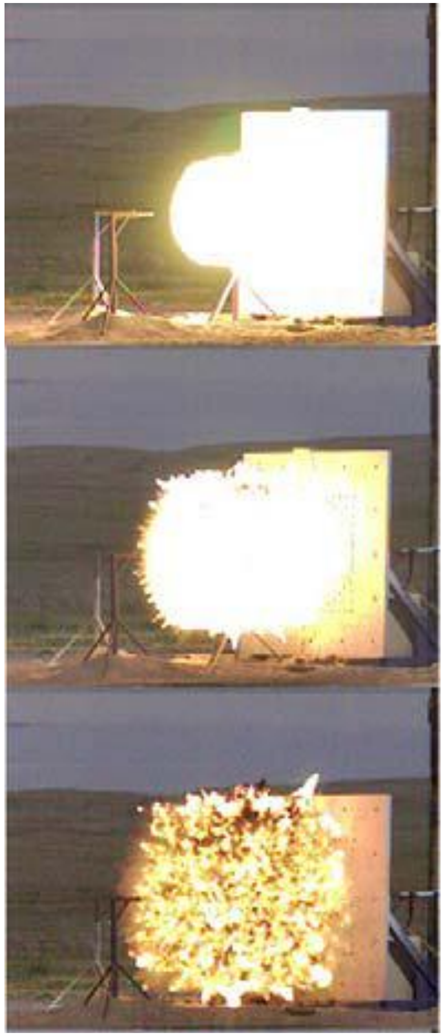


Bubble collapse – Sonoluminescence

Supernovae



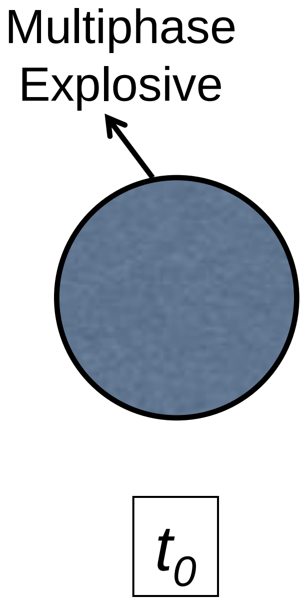
Spherical Explosion



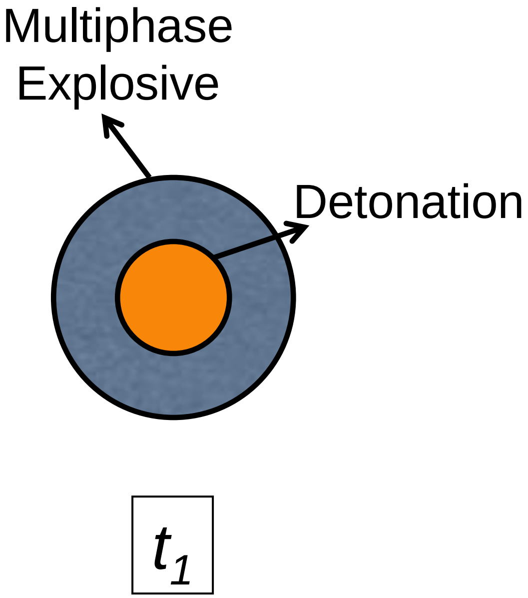
Outline

- Introduction to compressible multiphase flow
- Challenges & current status
- Rigorous compressible BBO & Maxey-Riley equations
- Finite Re and Ma extension & validation
- Shock-particle-curtain interaction
- Summary

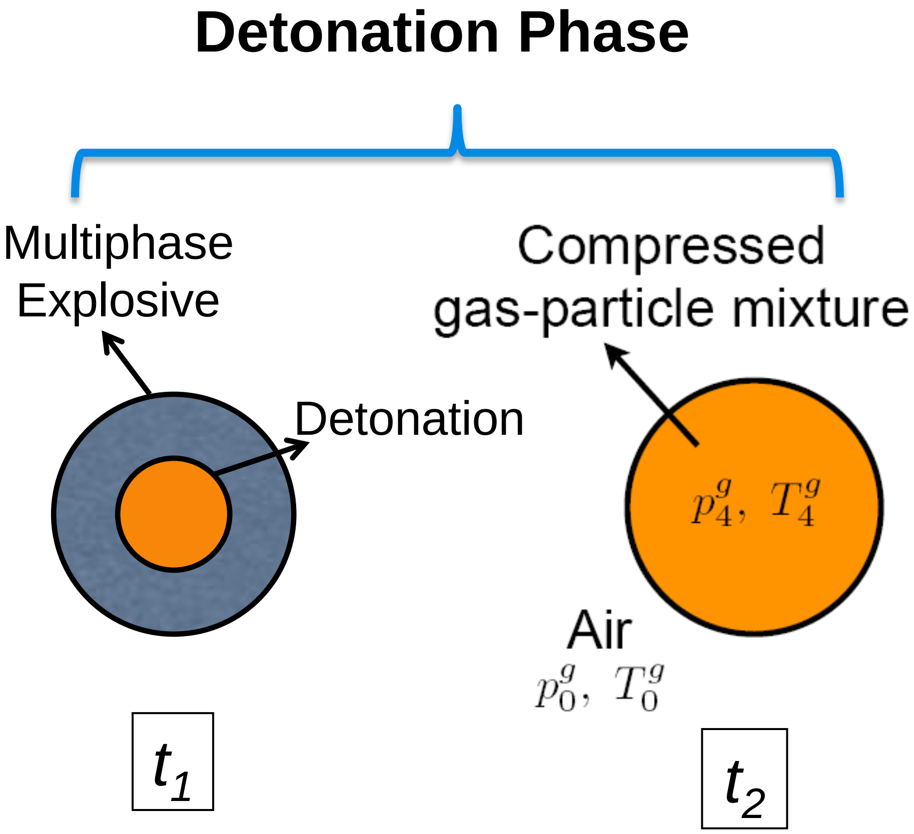
Spherical Explosion – Basic Physics



Spherical Explosion – Basic Physics



Spherical Explosion – Basic Physics



Detonation Phase

Multiphase Explosive

Detonation

Compressed gas-particle mixture

$p_4^g, \; T_4^g$

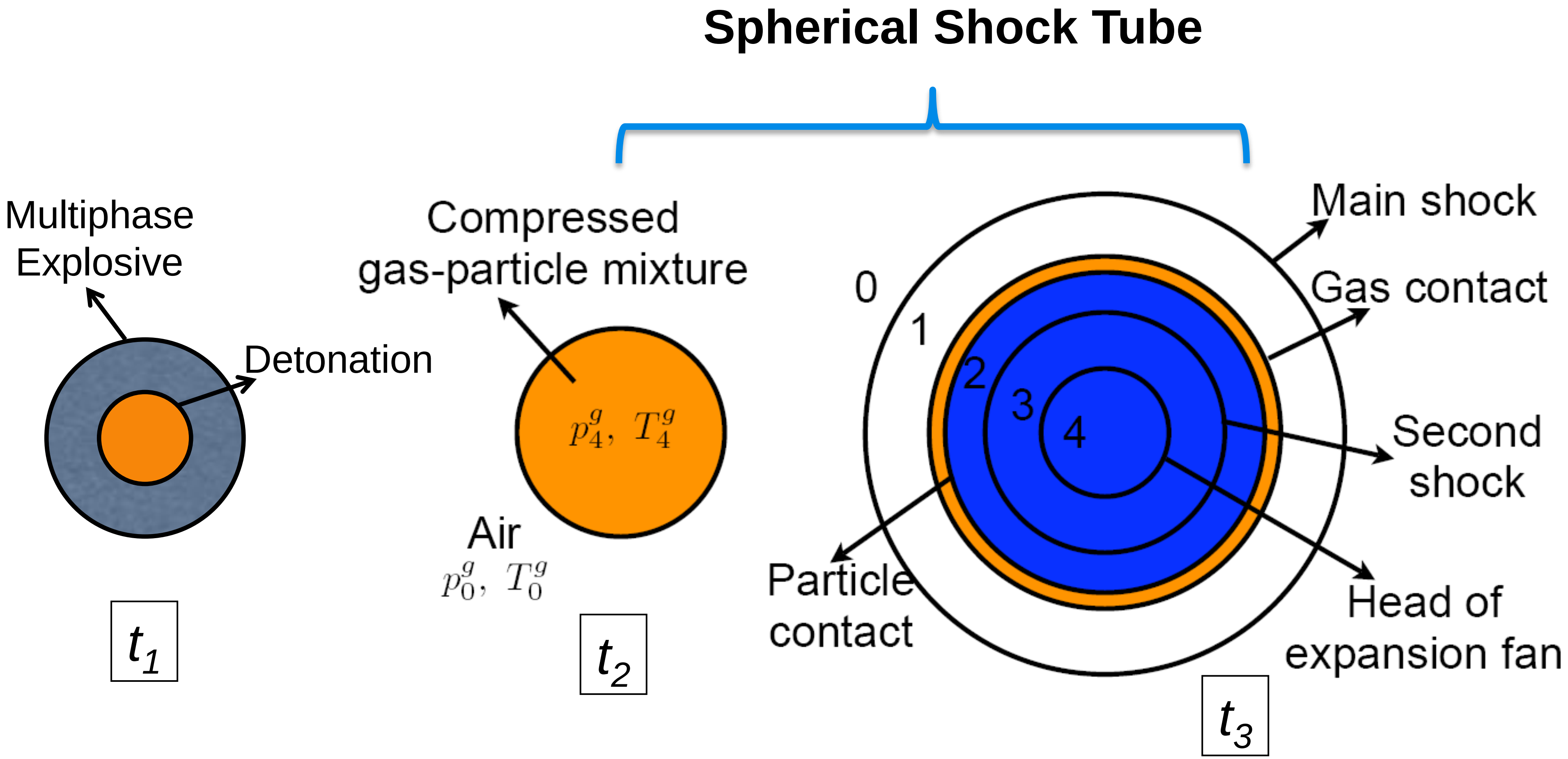
Air

$p_0^g, \; T_0^g$

t_1

t_2

Spherical Explosion – Basic Physics



Spherical Shock Tube

Multiphase Explosive

Detonation

t_1

Compressed gas-particle mixture

$p_4^g,\ T_4^g$

Air

$p_0^g,\ T_0^g$

t_2

0

1

2

3

4

Main shock

Gas contact

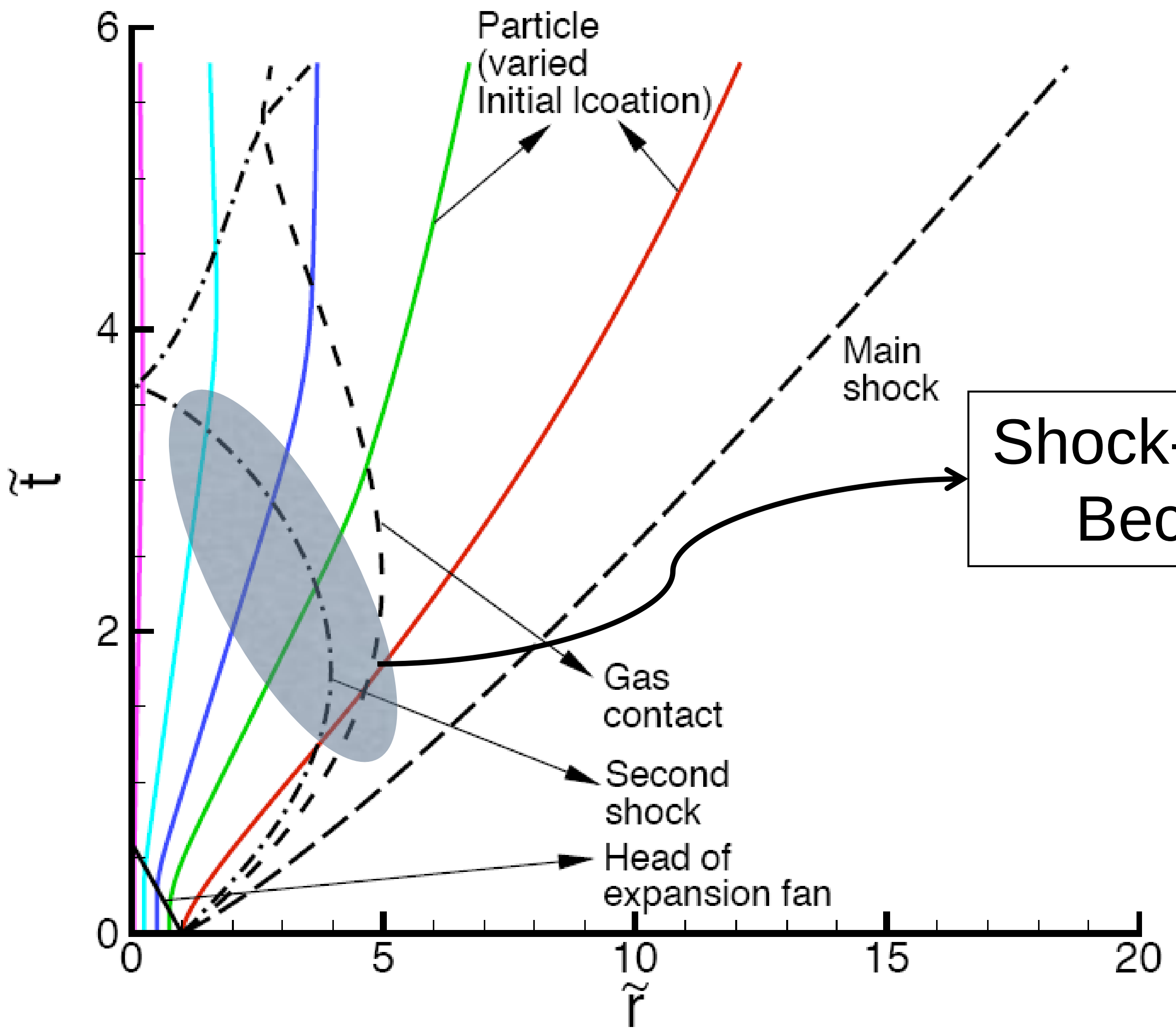
Second shock

Head of expansion fan

Particle contact

t_3

Spherical Shock Tube – With Particles



Shock-particle interaction
Becomes important

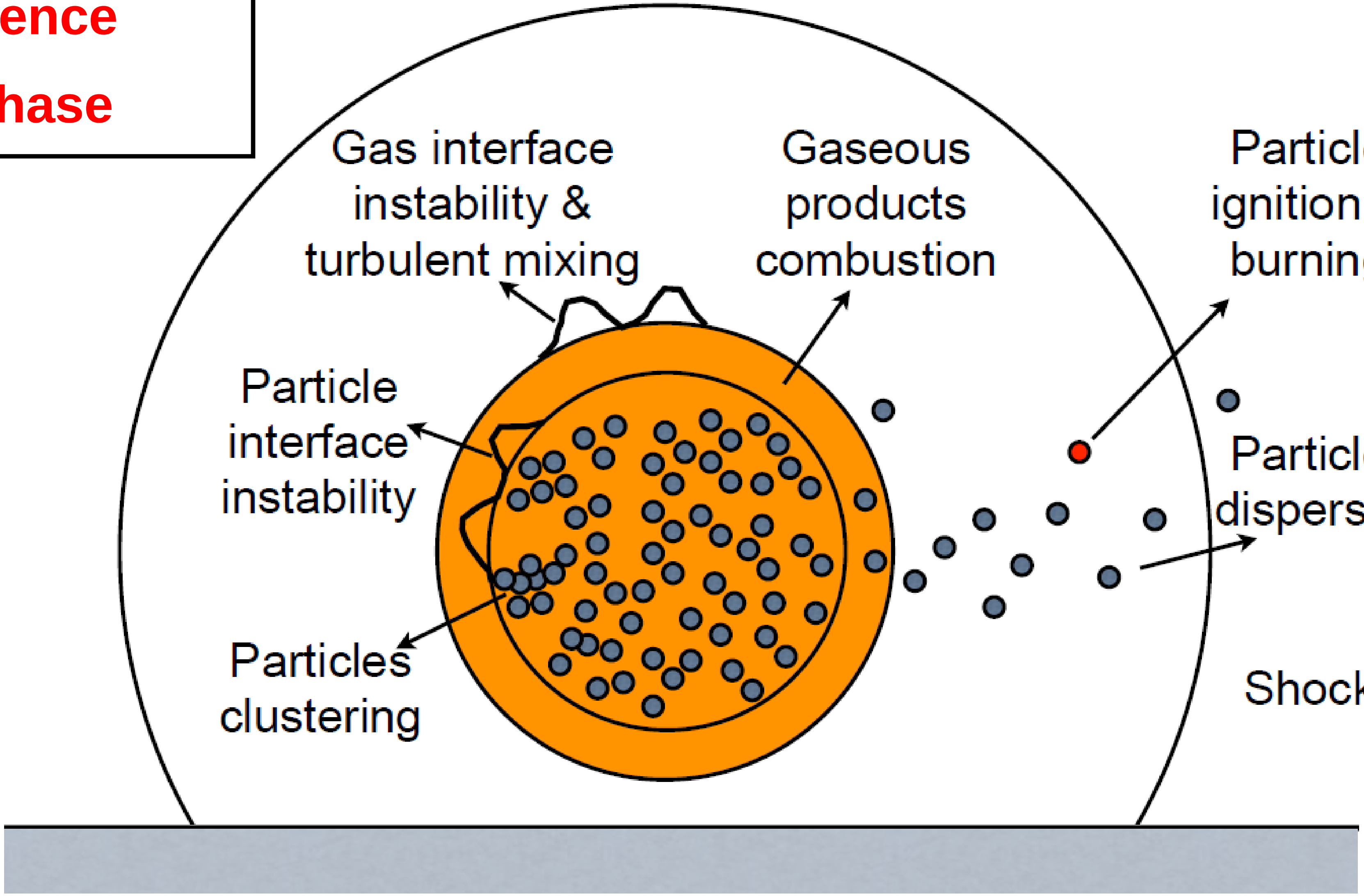
Compressibility effect
always important

Challenges

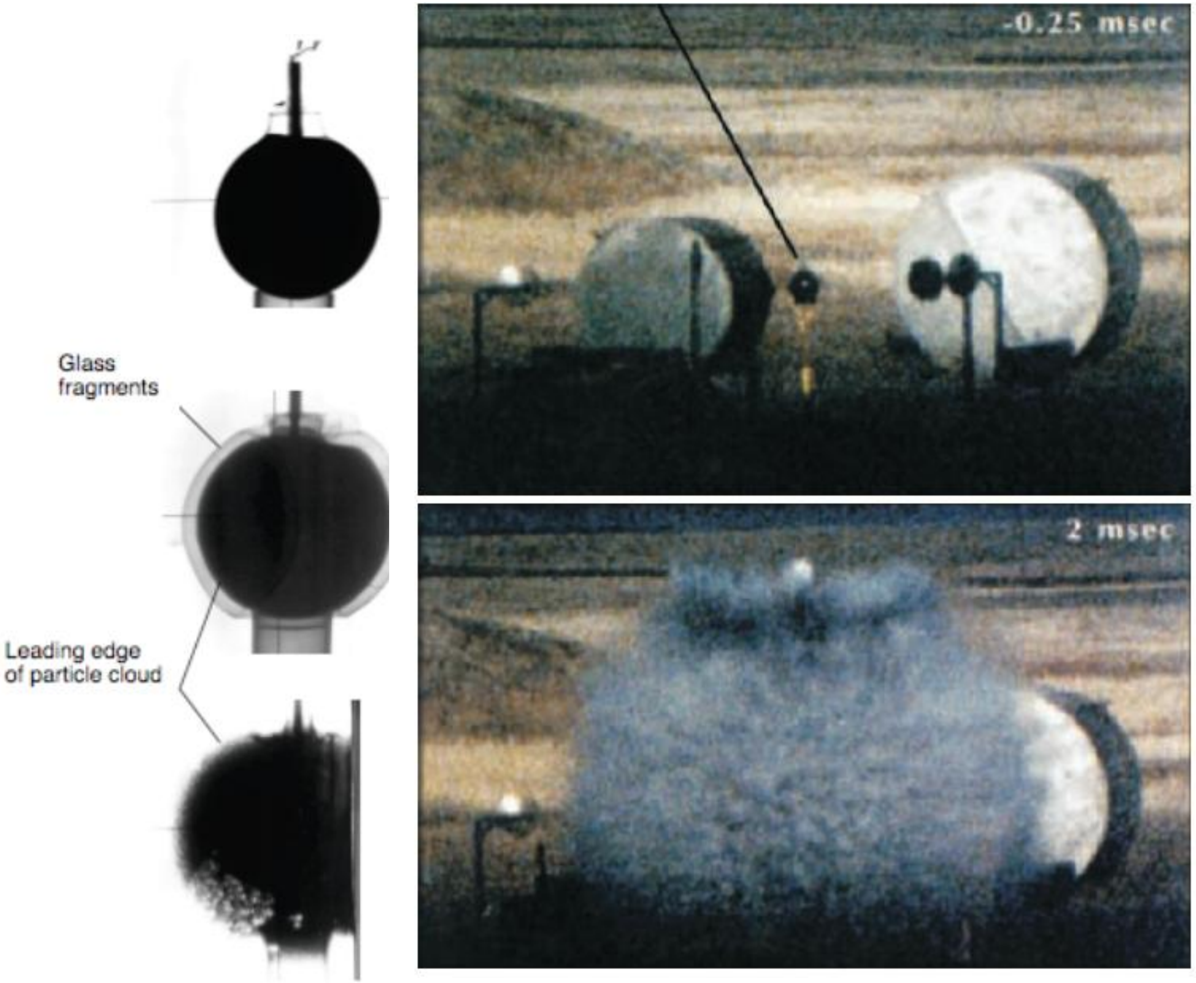
Compressibility

Turbulence

Multiphase



Approach - Macroscale



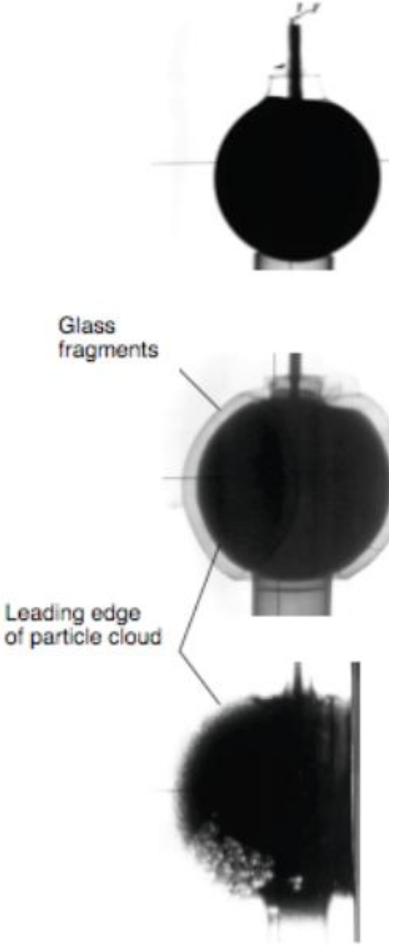
Zhang et al. *Shock Waves* **10**:431 (2001)

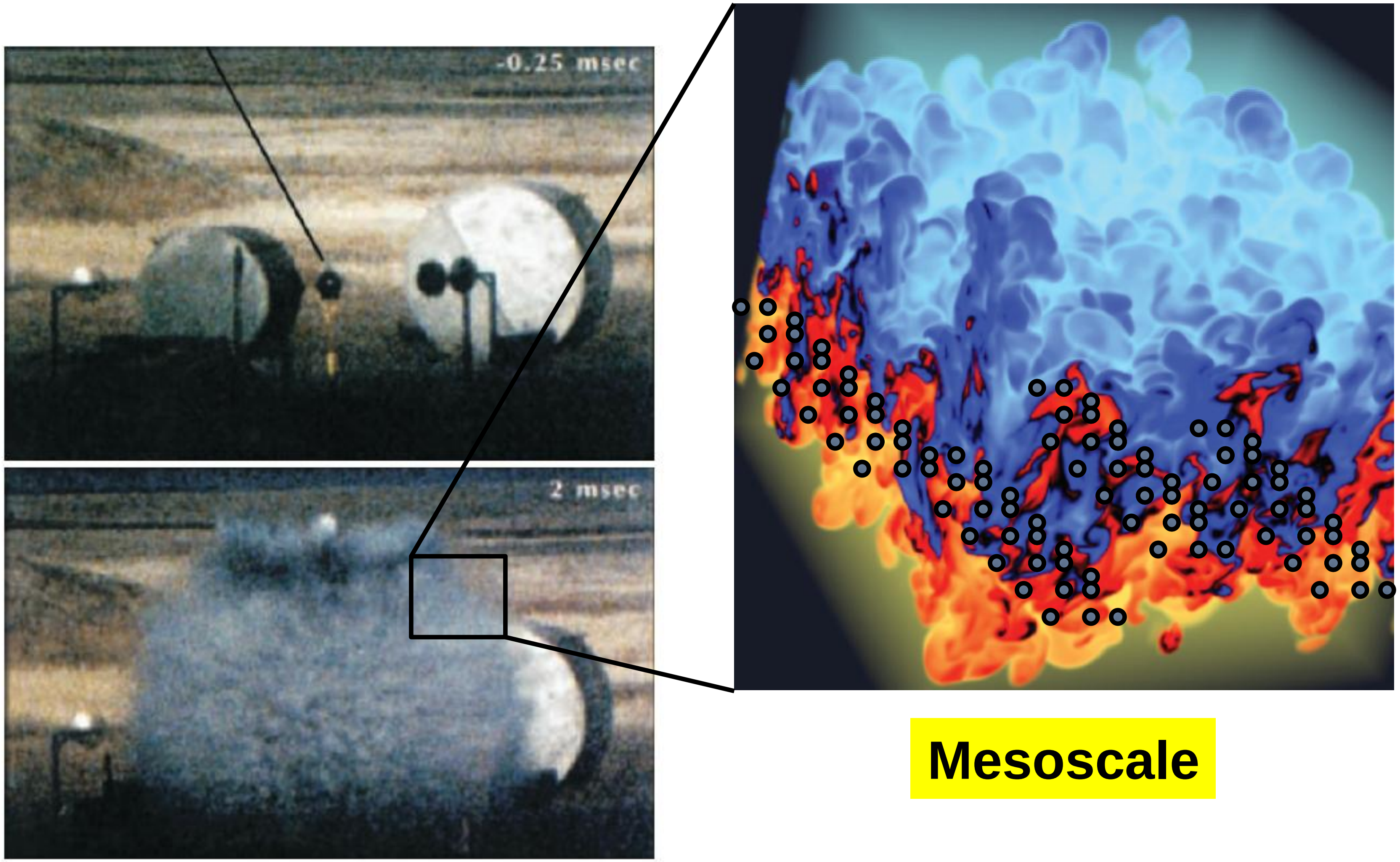
Macroscale

- Gas phase
  - Unsteady RANS
  - LES
- Particulate phase
  - Point particles (Lagrangian)
  - Second fluid (Eulerian)
- Approximations
  - RANS/LES closure
  - Inter-phase coupling

Approach - Mesoscale

Macroscale





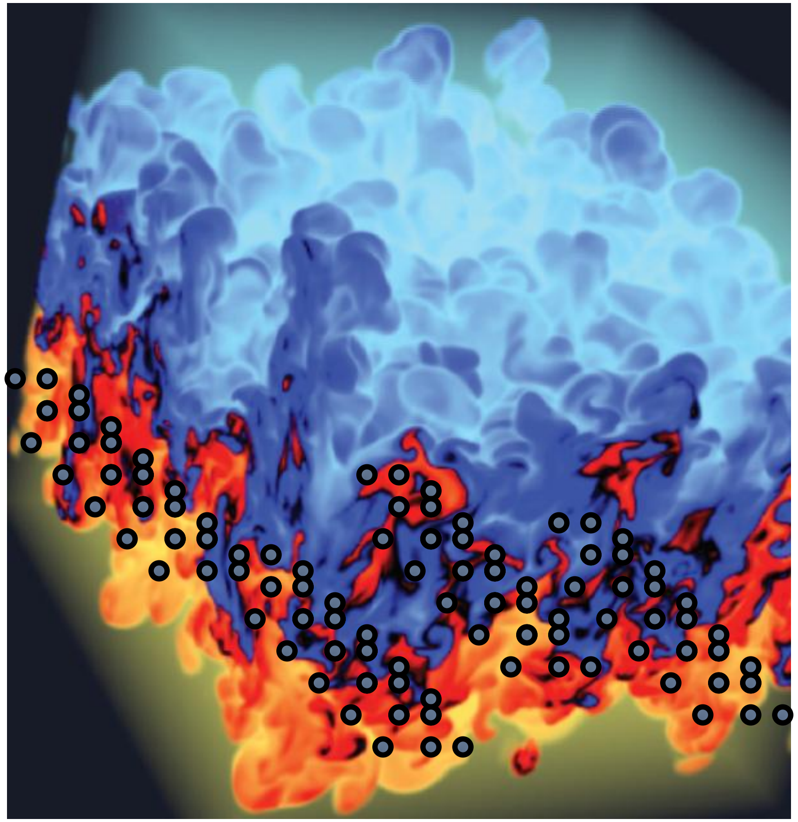
Mesoscale

Zhang et al. *Shock Waves* **10**:431 (2001)

Approach - Mesoscale

Maesoscale

- Gas phase
  - DNS possible !!
- Particulate phase
  - Extended particles (Lagrangian)
  - Second fluid (Eulerian)
- Approximations
  - Inter-phase coupling

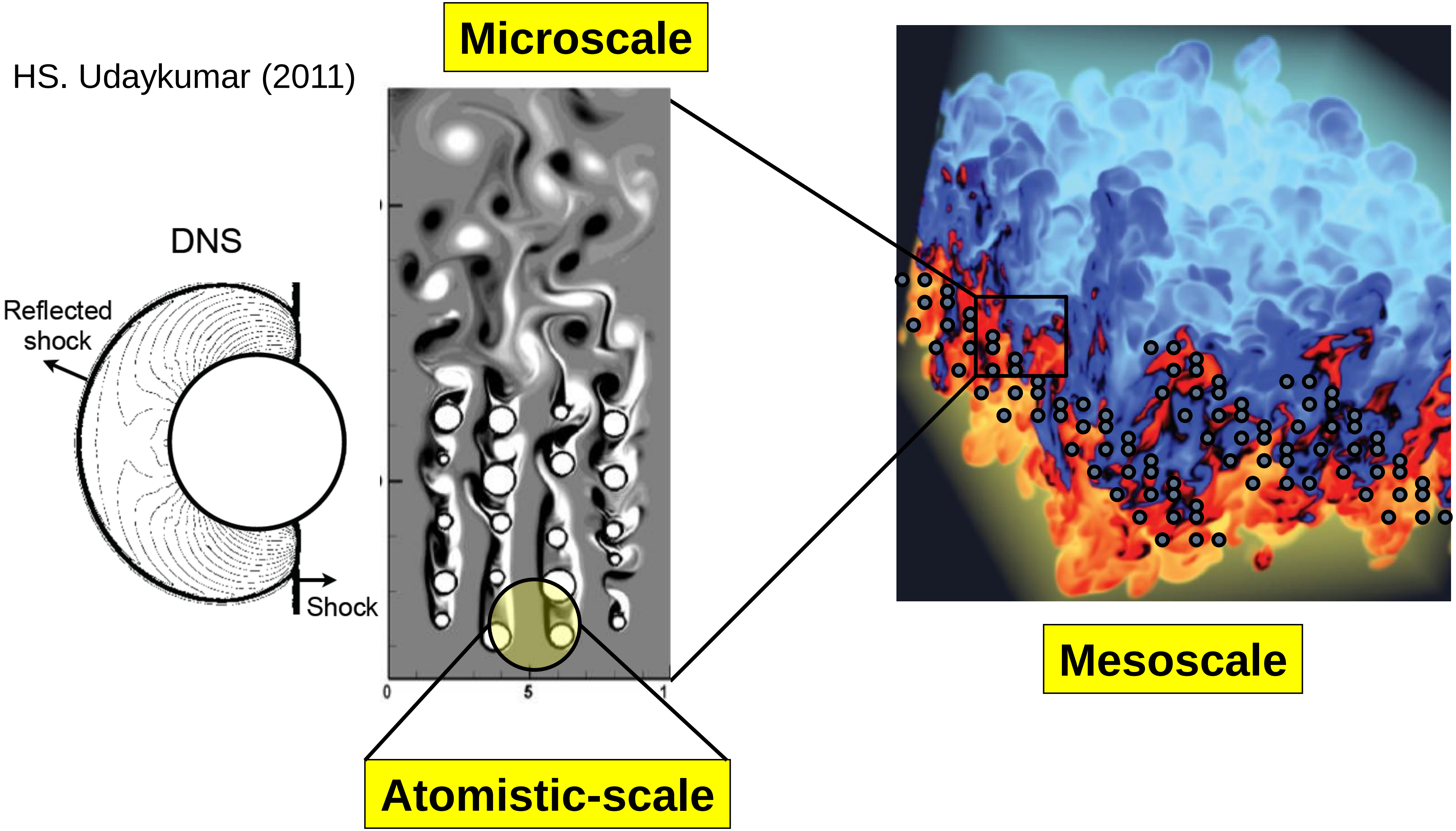


Mesoscale

Zhang et al. *Shock Waves* **10**:431 (2001)

Multi-scale Problem

HS. Udaykumar (2011)

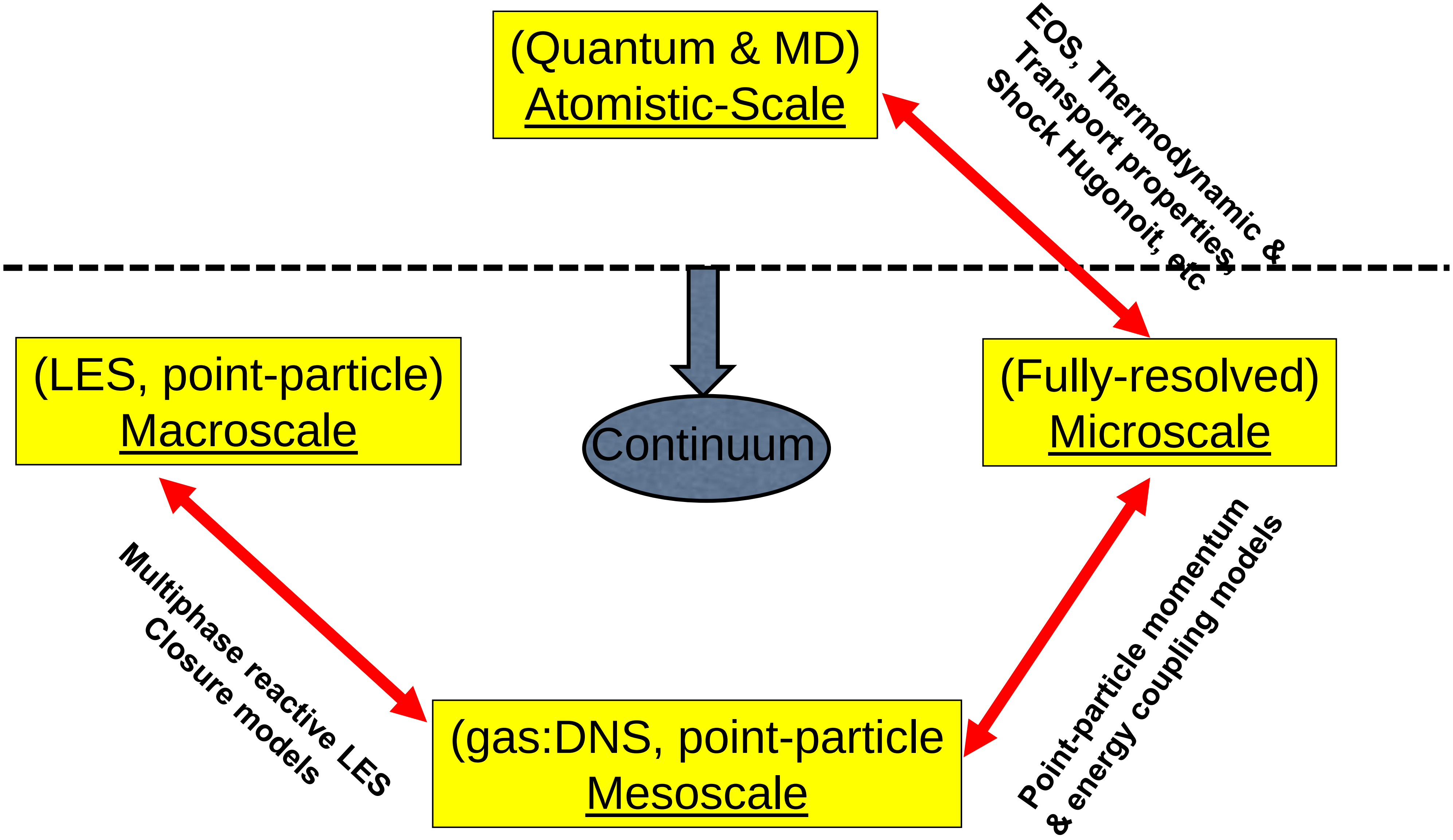


Microscale

Mesoscale

Atomistic-scale

Physics-Based Coupling Between Scales



(Quantum & MD)
Atomistic-Scale

EOS, Thermodynamic &
Transport properties,
Shock Hugonoit, etc

(LES, point-particle)
Macroscale

Continuum

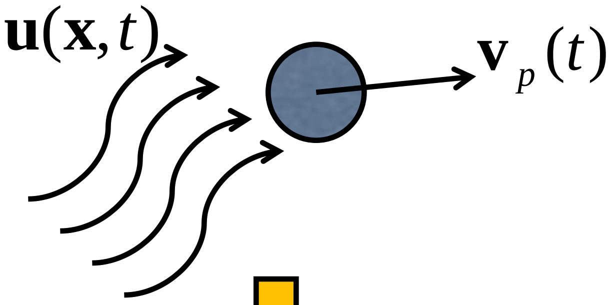
(Fully-resolved)
Microscale

Multiphase reactive LES
Closure models

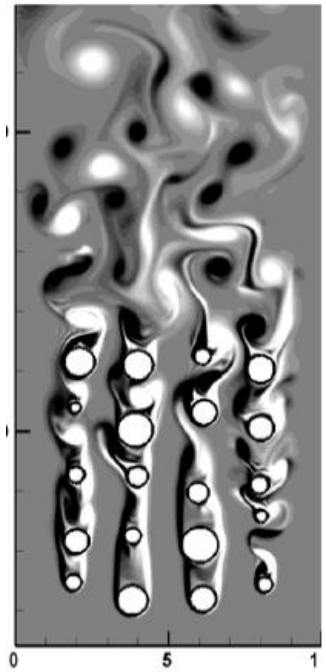
Point-particle momentum
& energy coupling models

(gas:DNS, point-particle
Mesoscale

Point-Particle Coupling Models



Models we currently use: Incompressible, moderate Re, quasi-steady, nearly uniform flows



What we need to use:

- Strong nonuniformity
  - Shocks, contacts, slip lines
- Highly unsteady
  - Both gas and particle acceleration
- Very large Mach and Reynolds numbers
- Particle-particle interaction (volume fraction effect)
- Particle deformation
- Other effects: polydispersity, turbulence, etc.

Modeling Approach

1. Establish the form of equation of particle motion in the limit Re→0 and M→0
2. Extend the model to finite Re, finite M, finite volume fraction, etc
3. Validate against high quality experiments
4. Extend modeling approach to particle deformation, heat transfer, etc

Equation of Particle Motion - Background

	Incompressible **Re → 0**
Steady & uniform	Stokes (1851)
Unsteady & uniform	Basset (1888), Boussinesq (1885) & Oseen (1927)
Steady & non-uniform	Faxen (1924)
Unsteady & non-uniform	Maxey & Riley (1983), Gatignol (1983)

Equation of Particle Motion - Background

	Incompressible **Re → 0**	**Compressible** **Re → 0, M → 0**
Steady & uniform	Stokes (1851)	Stokes (1851)
Unsteady & uniform	Basset (1888), Boussinesq (1885) & Oseen (1927)	Zwanzig & Bixon (1970) Parmar *et al.* Proc Roy Soc (2008), PRL (2010a)
Steady & non-uniform	Faxen (1924)	
Unsteady & non-uniform	Maxey & Riley (1983), Gatignol (1983)	Bedeaux & Mazur (1974) Parmar *et al*. JFM (2012)

- Rigorous compressible BBO equation of motion
- Rigorous compressible MRG equation of motion

Physics Based Force Model

$$m_p \frac{d\mathbf{v}_p}{dt} = \boxed{\mathbf{F}_{qs}} + \boxed{\mathbf{F}_{sg}} + \boxed{\mathbf{F}_{am}} + \boxed{\mathbf{F}_{vu}} + \text{ other}$$

- Quasi-steady
  - Dependent only on instantaneous relative velocity
  - Parameterized in terms of Re and M
- Stress gradient force
  - Due to undisturbed ambient flow
- Added-mass force
  - Dependent on relative acceleration
- Viscous unsteady force
  - Dependent on relative acceleration

$\Big\}$ Unsteady Mechanisms

Basset-Boussinesq-Oseen Equation

$$
\begin{aligned}
m_p \frac{d\mathbf{v}_p}{dt} &= 3\pi\mu d(\mathbf{u}-\mathbf{v}_p) \\
&+ \mathbb{V}\rho \frac{D\mathbf{u}}{Dt} \\
&+ \boxed{C_m}\,\mathbb{V}\rho\left(\frac{D\mathbf{u}}{Dt}-\frac{d\mathbf{v}_p}{dt}\right) \\
&+ \frac{3}{2}d^2\rho\sqrt{\pi\nu}\int_{-\infty}^{t}\boxed{K_v(t-\xi)}\left(\frac{D\mathbf{u}}{Dt}-\frac{d\mathbf{v}_p}{dt}\right)d\xi
\end{aligned}
$$

Incompressible
Uniform

$$C_m = \frac{1}{2}$$

$$K_v(t-\xi) = \frac{1}{\sqrt{t-\xi}}$$

Finite Re, Finite Ma Momentum Coupling

$$f = f_{qs} + f_{pg} + f_{am} + f_{vu}$$

- Quasi-steady: $f_{qs} = \frac{\overline{u^g}^s - u^p}{\tau^p} \frac{\boxed{C_D(\mathrm{Re}^p, \mathrm{M}^p)}\,\mathrm{Re}^p}{24}$
- Pressure-gradient: $f_{pg} = \frac{1}{\rho^p} \overline{\left(\rho^g \frac{Du^g}{Dt} \right)}^v$
- Added-mass:

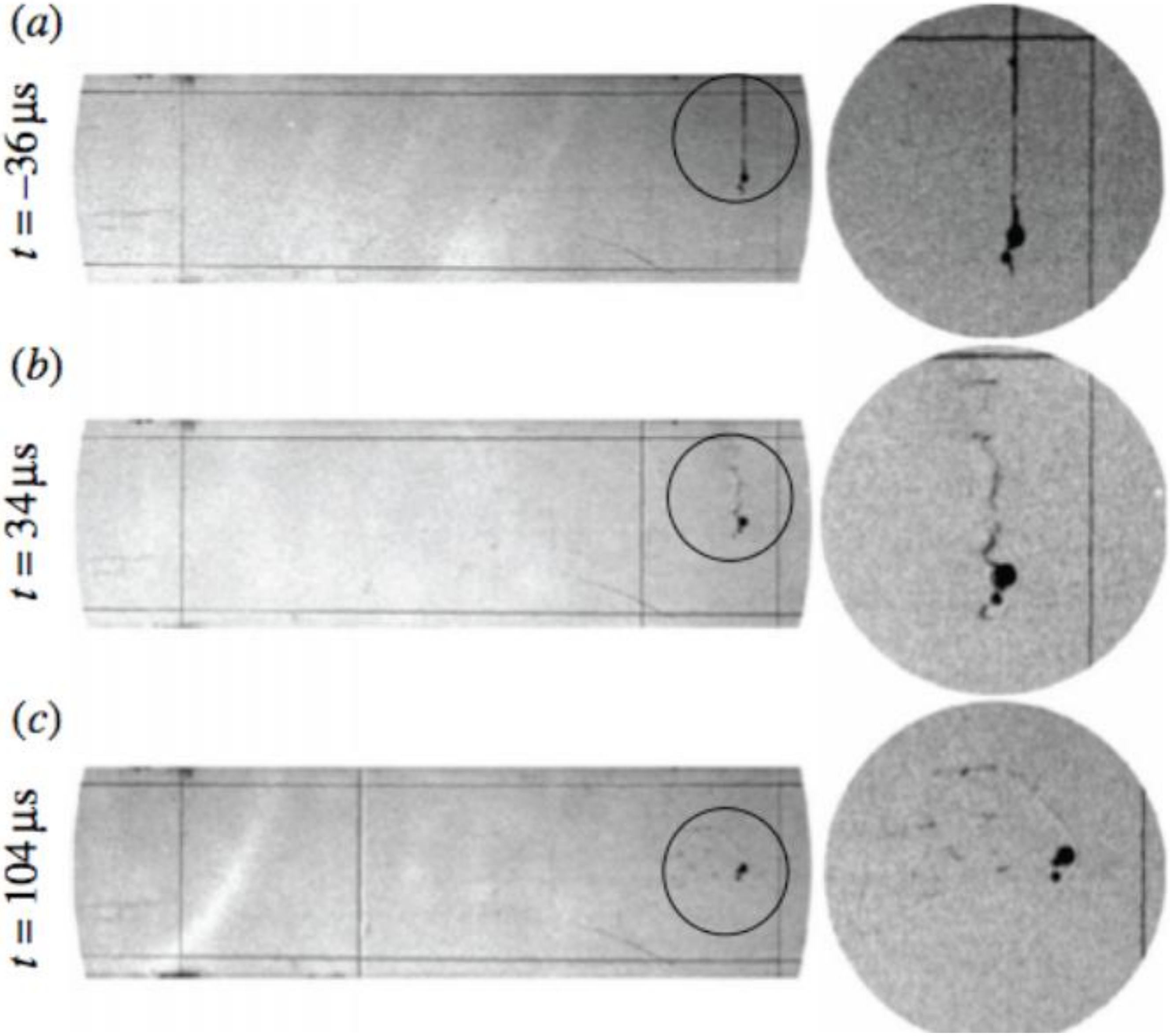
$$f_{am} = \frac{1}{\rho^p} \int_{-\infty}^{t} \boxed{K_{am}(t-\chi, \mathrm{M}^p)} \left(\overline{\frac{D}{Dt}}^v \boxed{\overline{(\rho^g u^g)}^v} - \frac{d}{dt} \overline{(\rho^g u^p)}^v \right) d\chi$$

- Viscous-unsteady: Mei & Adrian (1992)

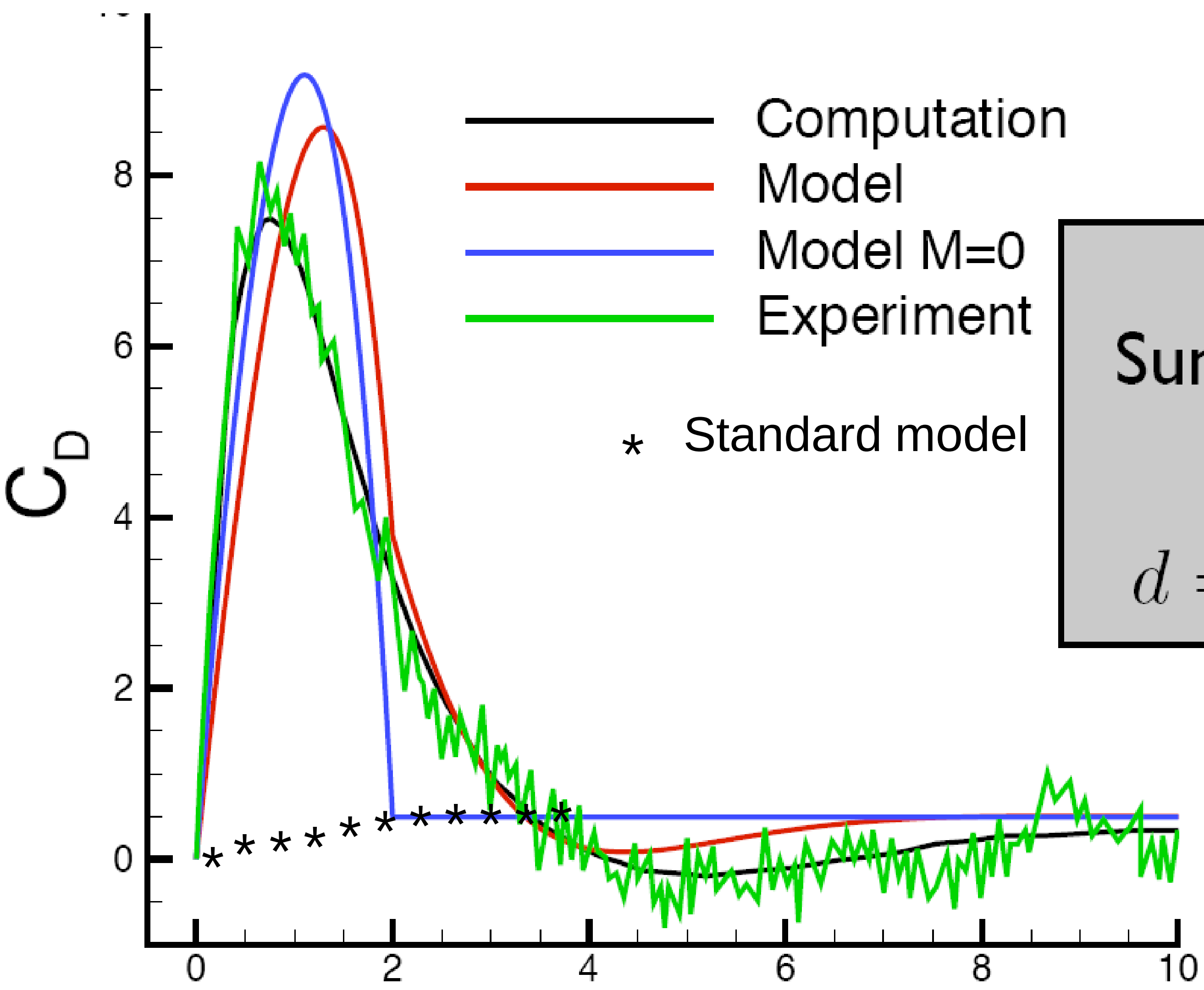
$$f_{vu} = \frac{1}{\rho^g \tau^p} \int_{-\infty}^{t} \boxed{K_{vu}(t-\chi, \mathrm{Re}^p, \mathrm{M}^p)} \left(\overline{\frac{D}{Dt}}^s \overline{(\rho^g u^g)}^s - \frac{d}{dt} \overline{(\rho^g u^p)}^s \right) d\chi$$

Parmar *et al.* Proc Roy Soc (2008); Phys. Rev. Let. (2010), JFM (2012)

Validation: Shock-Particle Interaction



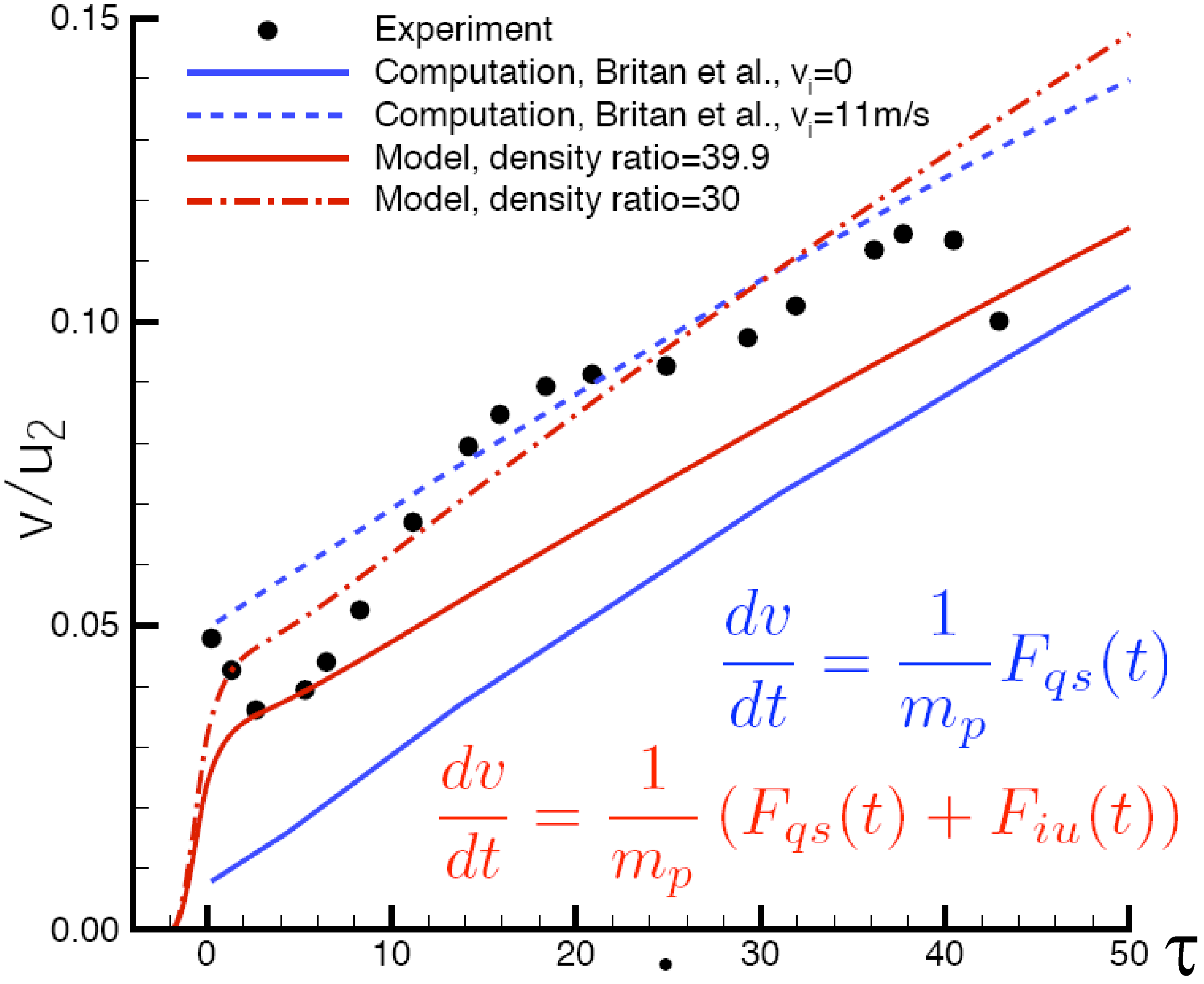
Validation – Short Time Peak Force



Data:
Sun et al. (2005)
$M_s = 1.22$
$d = 8 \times 10^{-3}\,\mathrm{m}$

- Parmar, Haselbacher, Balachandar, *Shock Wave*, 2009

Validation - Impulsive Motion of a Particle



$$\frac{dv}{dt} = \frac{1}{m_p} F_{qs}(t)$$

$$\frac{dv}{dt} = \frac{1}{m_p} \left(F_{qs}(t) + F_{iu}(t)\right)$$

$$\tau_s' = \tau_s - 2$$

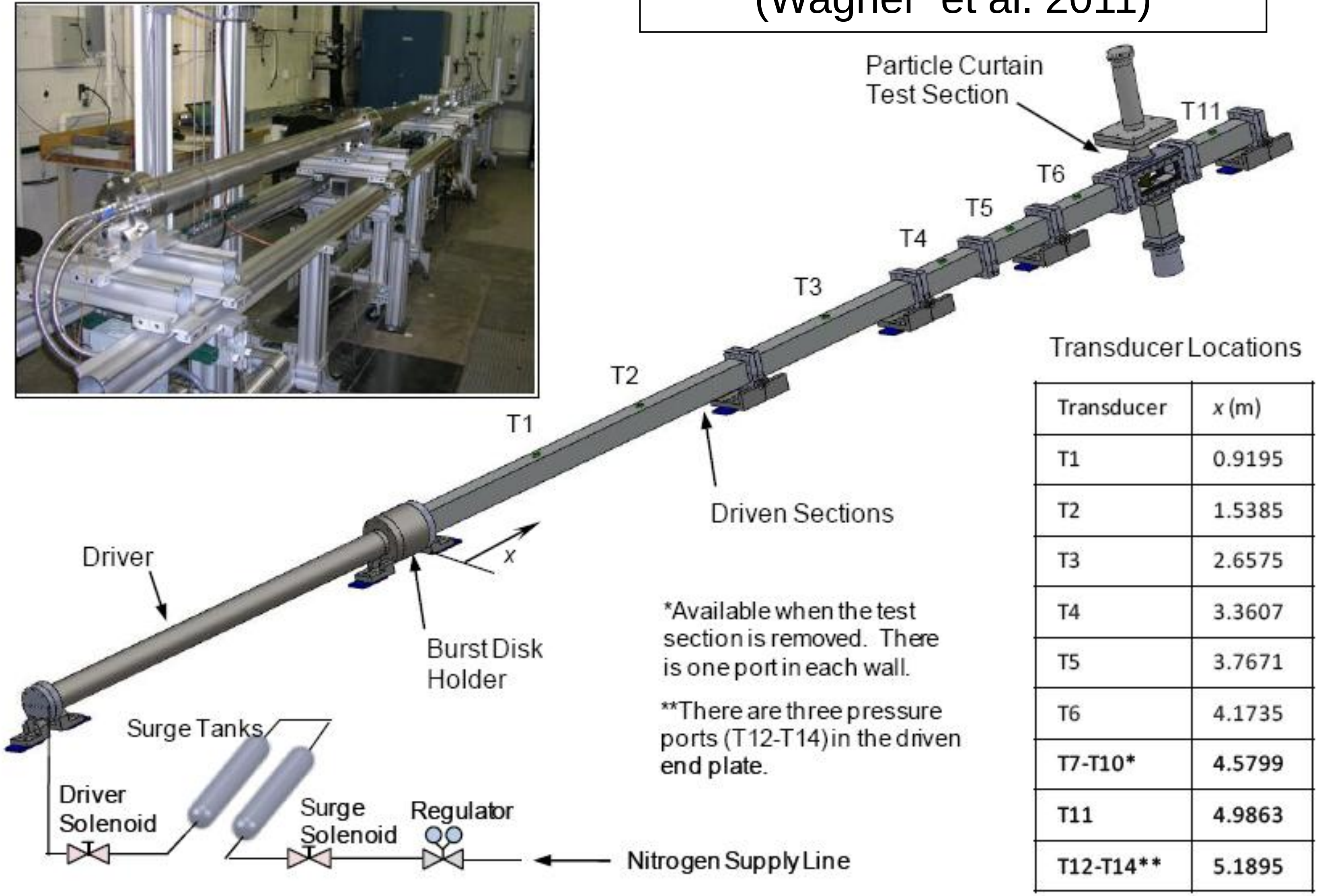
Data:
Britan et al. (1995)

$$d = 3.8 \times 10^{-2}\,\mathrm{m}$$
$$\rho_p = 89.4\,\mathrm{kg/m^3}$$

- Parmar, Haselbacher, Balachandar, *Shock Wave*, 2009

Sandia Mutiphase Shock Tube Facility

Sandia Multiphase Shock Tube
(Wagner et al. 2011)



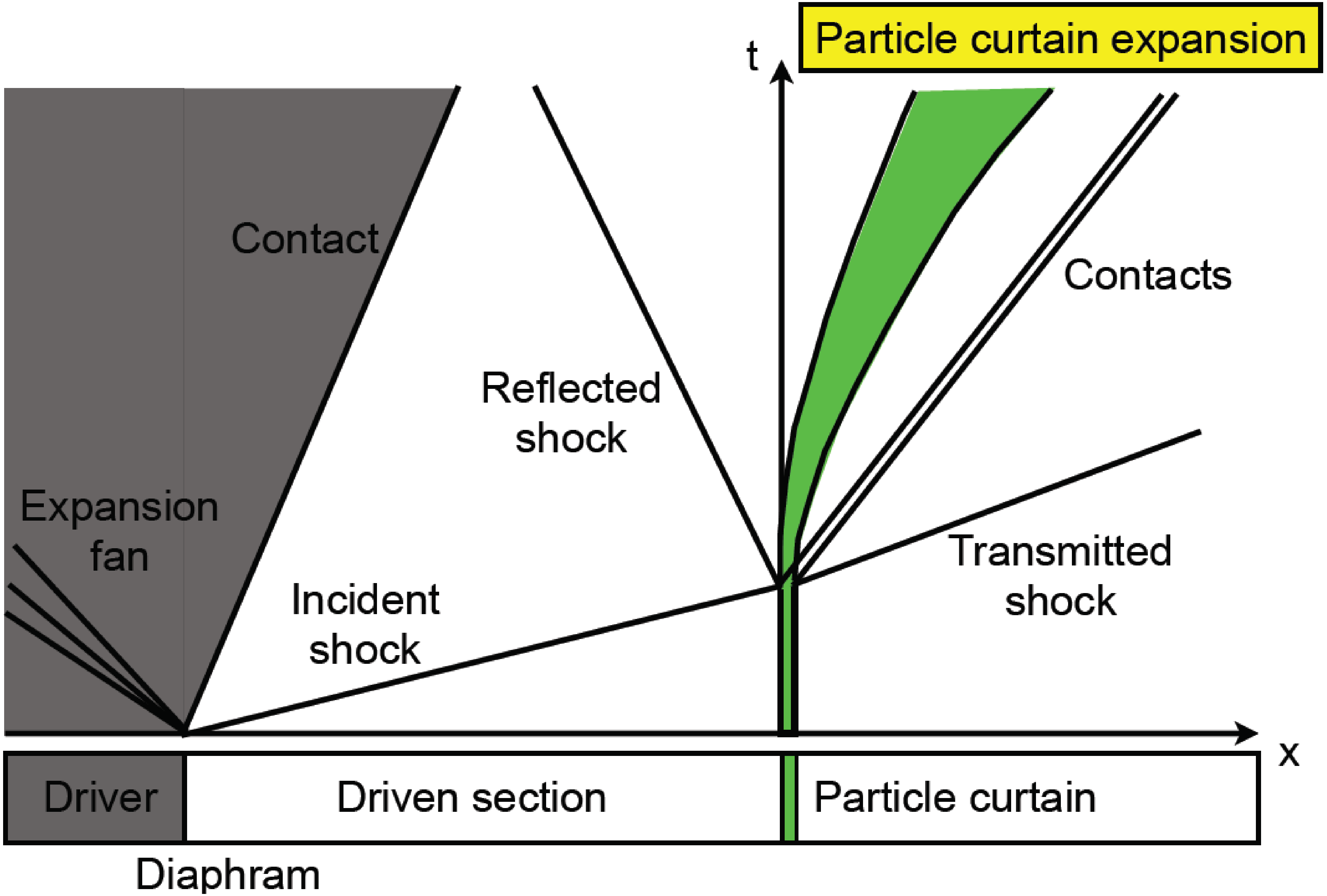
*Available when the test section is removed. There is one port in each wall.

**There are three pressure ports (T12-T14) in the driven end plate.

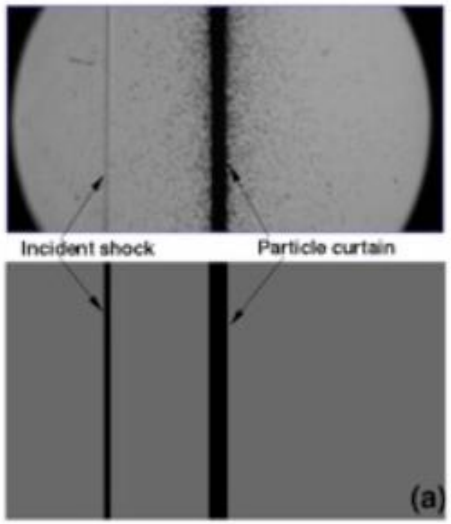
Transducer Locations

Transducer	*x* (m)
T1	0.9195
T2	1.5385
T3	2.6575
T4	3.3607
T5	3.7671
T6	4.1735
T7-T10*	4.5799
T11	4.9863
T12-T14**	5.1895

Shock-Curtain Interaction



Schlieren Images (M = 1.92)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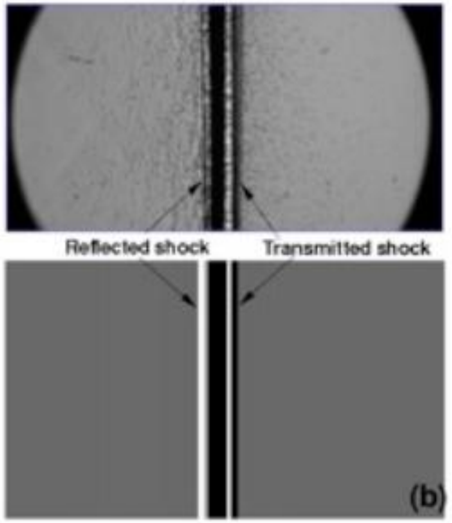
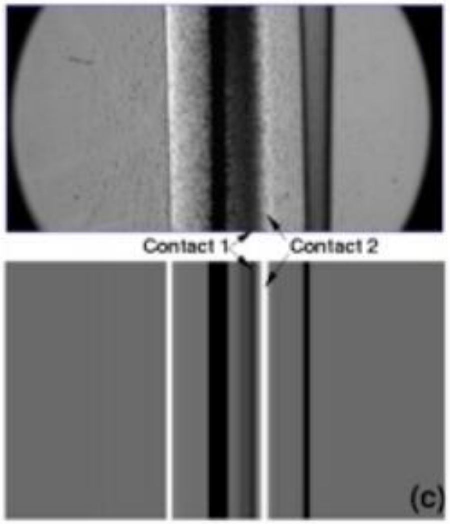

t=5us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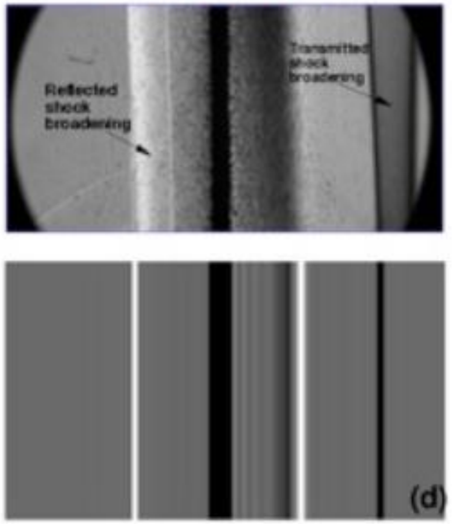
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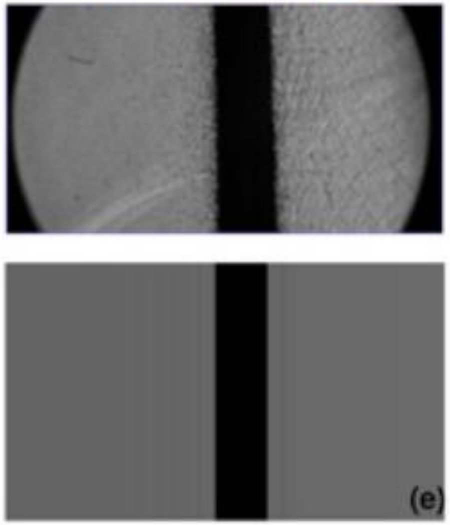
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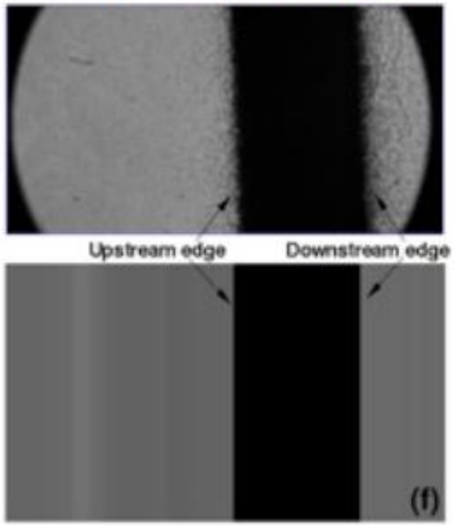
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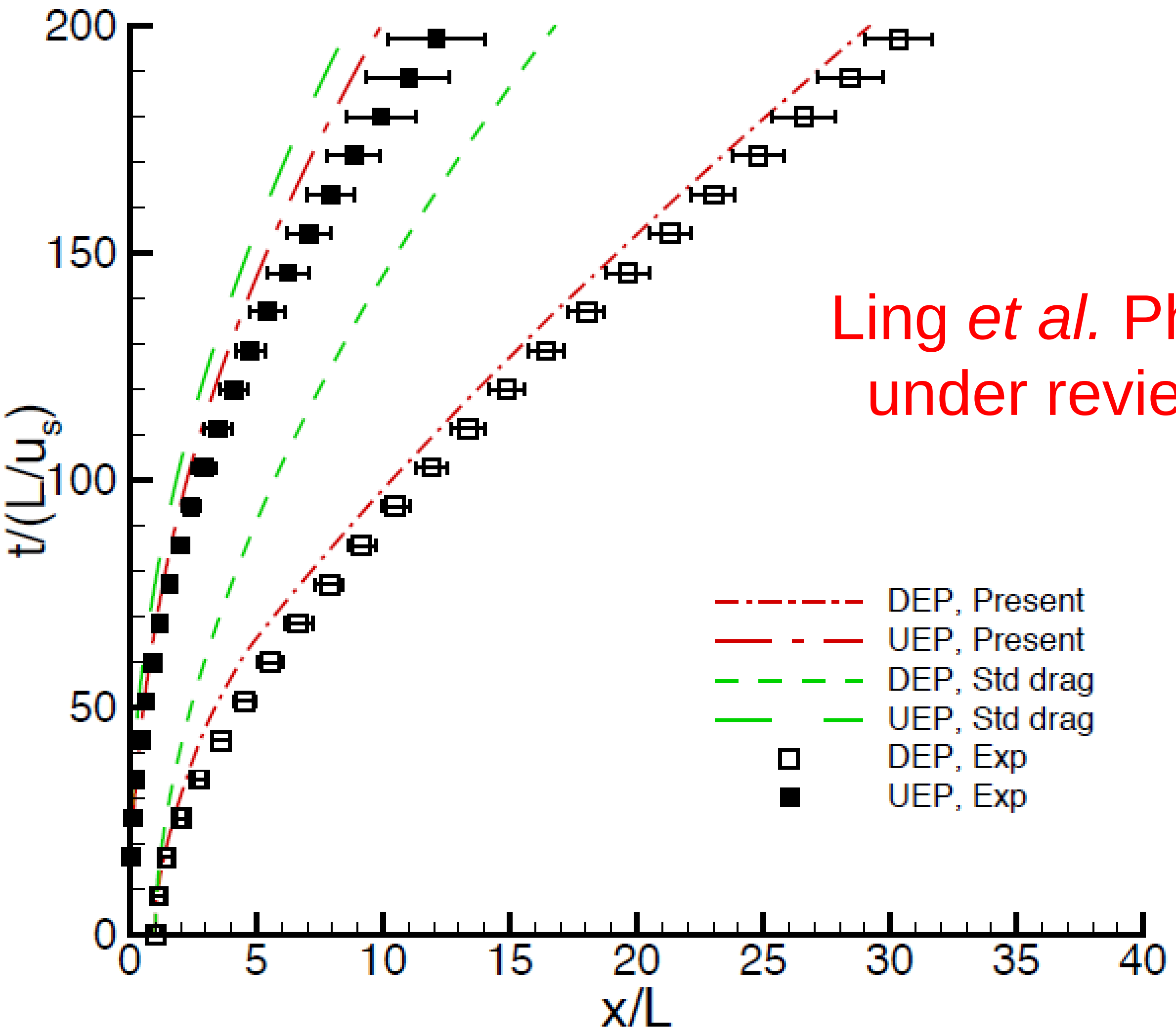
New vs Standard Drag Model



Ling *et al.* Phys. Fluids under review (2012)

- Standard model seriously under predicts both curtain location and curtain width

Summary

- Compressible multiphase flow has interesting new physics. Standard drag will not be adequate.
- Unsteady effects are very important
  - Contrary to conventional gas-particle wisdom
  - In terms of peak forces for deformation & fragmentation
  - In terms of peak heating & ignition
  - In case of two-way coupling with cluster of particles
- Physics-based modeling is the only viable option
  - But requires step-by-step validation

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