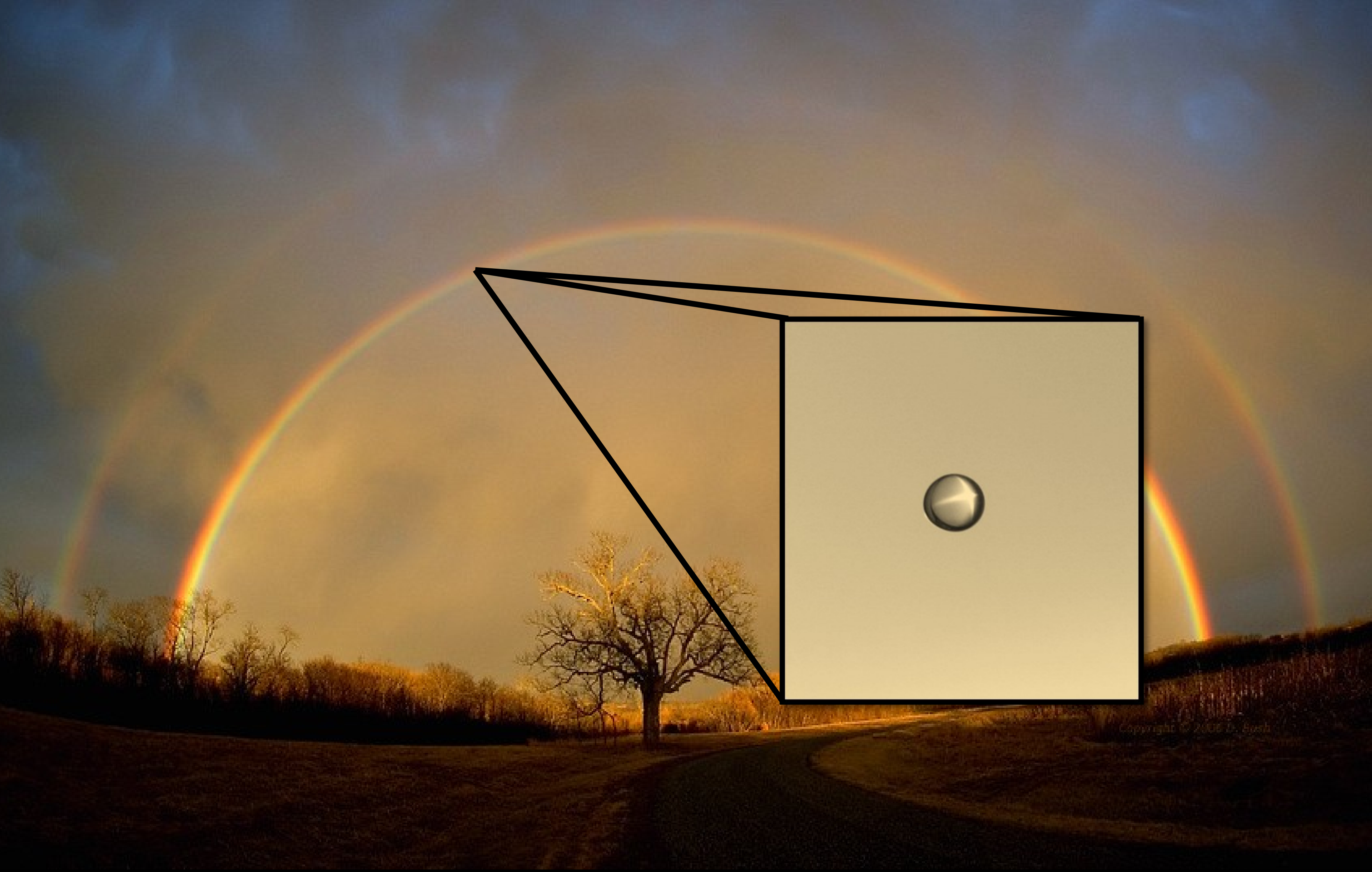
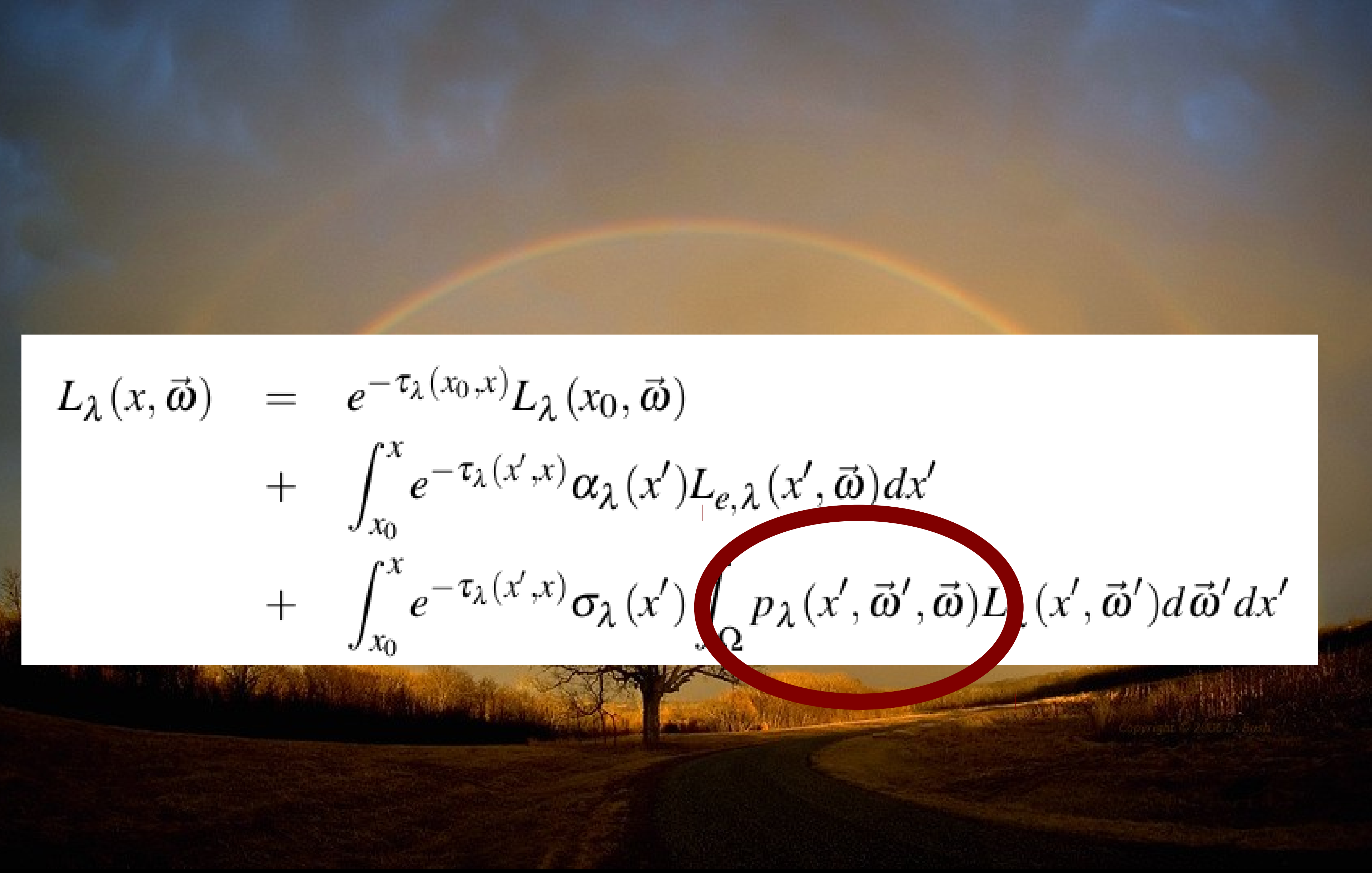
PHYSICALLY BASED SIMULATION OF RAINBOWS

Iman Sadeghi[1], Adolfo Munoz[2], Philip Laven[3], Wojciech Jarosz[4], Francisco Seron[2], Diego Gutierrez[2], Henrik Wann Jensen[1]

[1] UC San Diego
[2] Universidad de Zaragoza
[3] Horley, UK
[4] Disney Research Zurich

8/8/2012





$$
\begin{aligned}
L_\lambda(x,\vec{\omega}) &= e^{-\tau_\lambda(x_0,x)} L_\lambda(x_0,\vec{\omega}) \\
&+ \int_{x_0}^{x} e^{-\tau_\lambda(x',x)} \alpha_\lambda(x') L_{e,\lambda}(x',\vec{\omega})\, dx' \\
&+ \int_{x_0}^{x} e^{-\tau_\lambda(x',x)} \sigma_\lambda(x') \int_\Omega p_\lambda(x',\vec{\omega}',\vec{\omega}) L_\lambda(x',\vec{\omega}')\, d\vec{\omega}'\, dx'
\end{aligned}
$$

APPEARANCE OF RAINBOWS

Primary Bow

APPEARANCE OF RAINBOWS

Double Rainbow

APPEARANCE OF RAINBOWS

Double Rainbow / Alexander Dark Band

APPEARANCE OF RAINBOWS

Red Bow at Sunset

APPEARANCE OF RAINBOWS

Multiple Supernumerary Arcs

APPEARANCE OF RAINBOWS

Fog Bow

APPEARANCE OF RAINBOWS

Twinned Bow

APPEARANCE OF RAINBOWS

Twinned Bow

APPEARANCE OF RAINBOWS

Twinned Bows

WATER DROP SHAPES

- Gravity vs. surface tension vs. air resistance

WATER DROP SHAPES

- Gravity vs. surface tension vs. air resistance

WATER DROP SHAPES

- Gravity vs. surface tension vs. air resistance

Misconception Small Drops

WATER DROP SHAPES

- Gravity vs. surface tension vs. air resistance

Misconception Small Drops Large Drops

APPEARANCE OF RAINBOWS

- Refraction
- Dispersion
- Interference
- Diffraction

APPEARANCE OF RAINBOWS

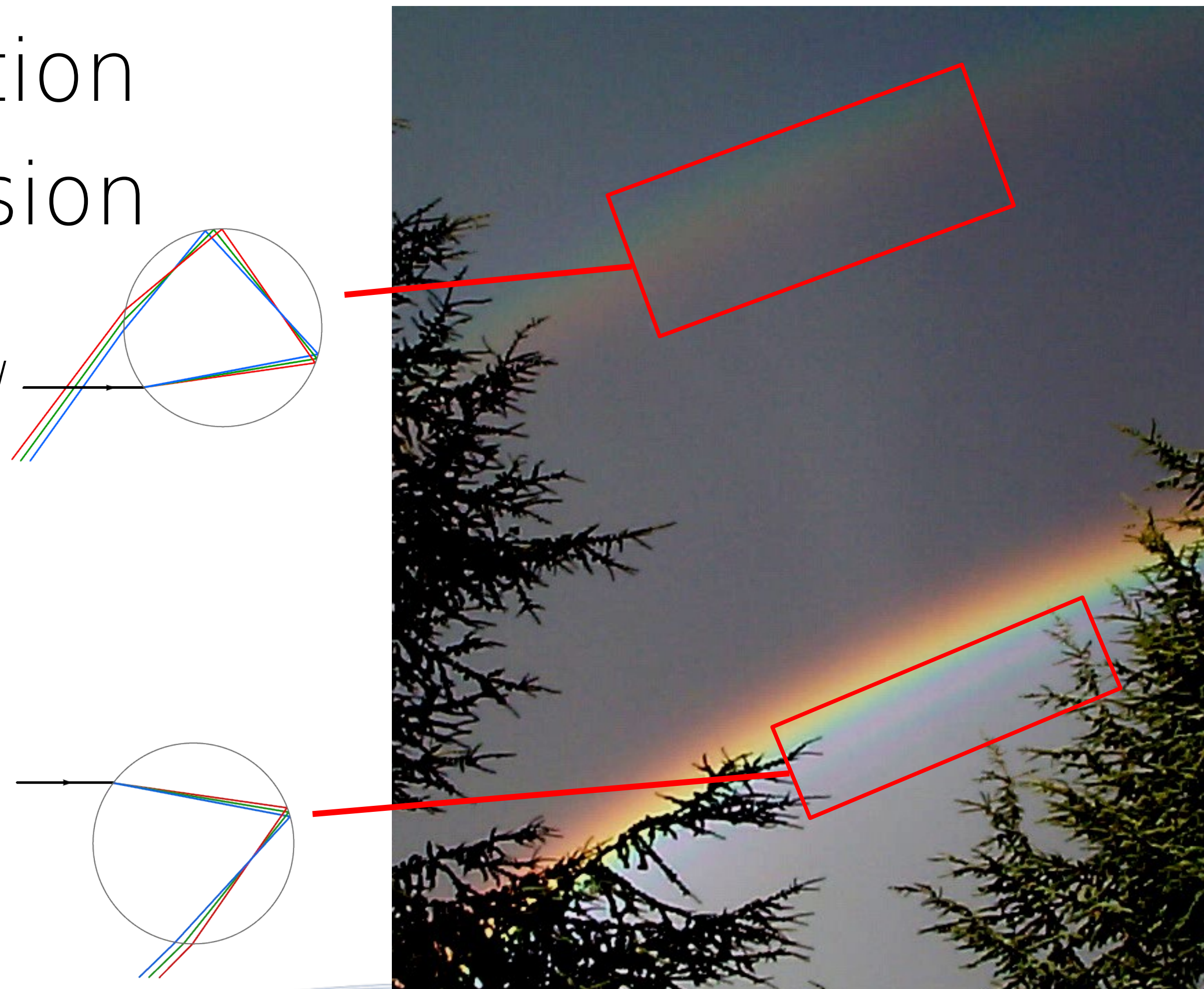
- Refraction
- Dispersion
- Interference
- Diffraction

APPEARANCE OF RAINBOWS

- Refraction
- Dispersion

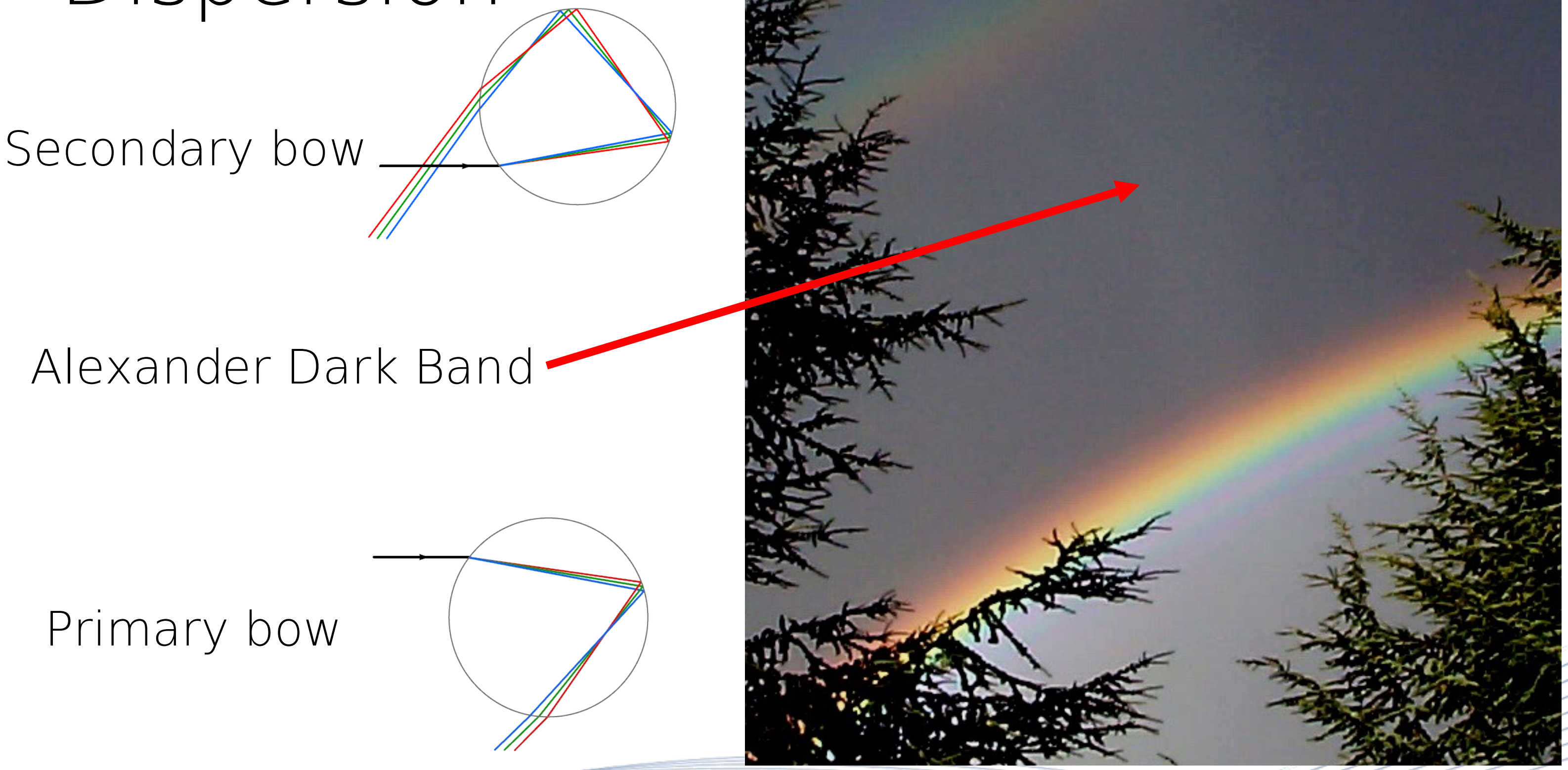
Secondary bow

Primary bow



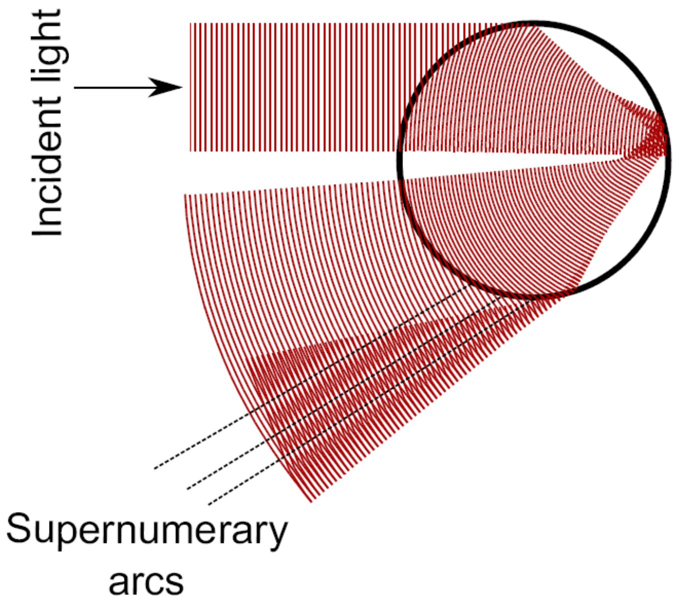
APPEARANCE OF RAINBOWS

- Refraction
- Dispersion



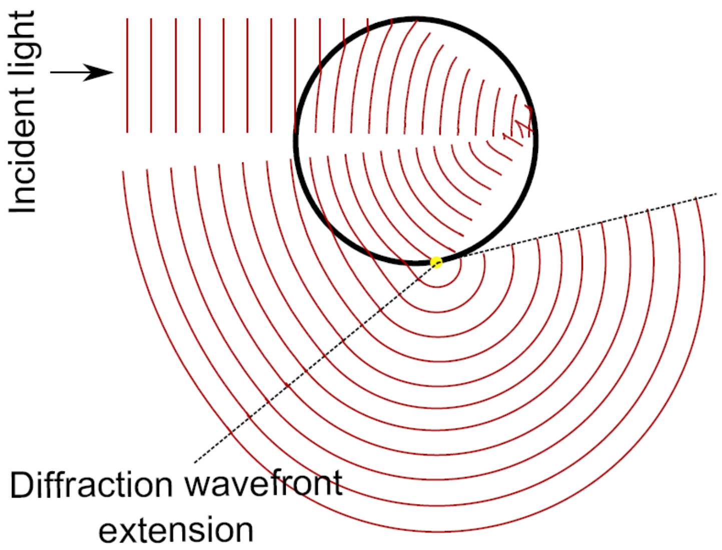
APPEARANCE OF RAINBOWS

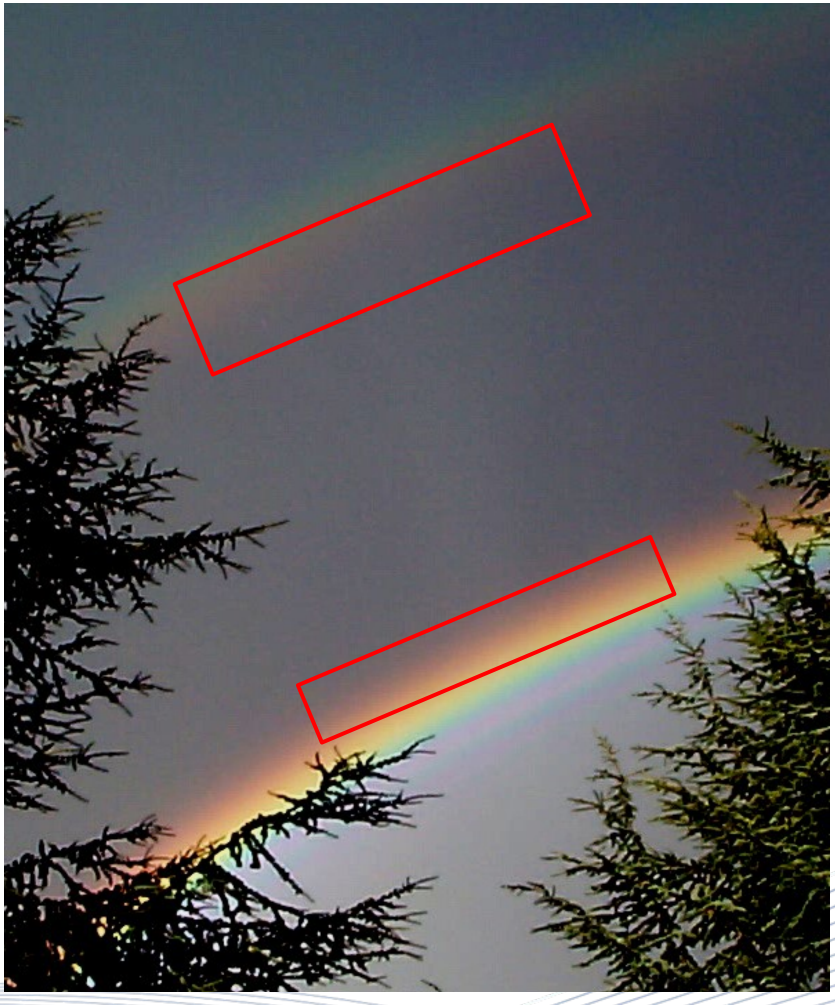
- Interference



APPEARANCE OF RAINBOWS

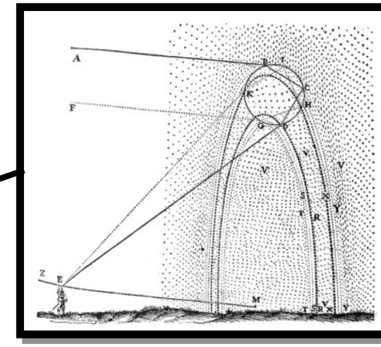
- Diffraction

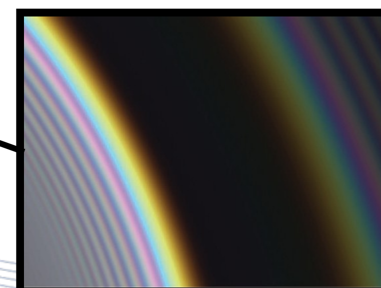




PREVIOUS WORK

- Ray Optics
  - Aristotle 384-322 BC
  - Descartes 1637
  - ...
  - Musgrave 1989
  - Frisvad et al. 2007
- Lorenz-Mie Theory
  - Jakel and Walter 1997
  - Lee 1998
  - Laven 2003, 2004
  - Riley et al. 2004
  - Gedzelman 2008
- FDTD Methods
  - Yang and Liou 1995 (Ice halos)





PREVIOUS WORK

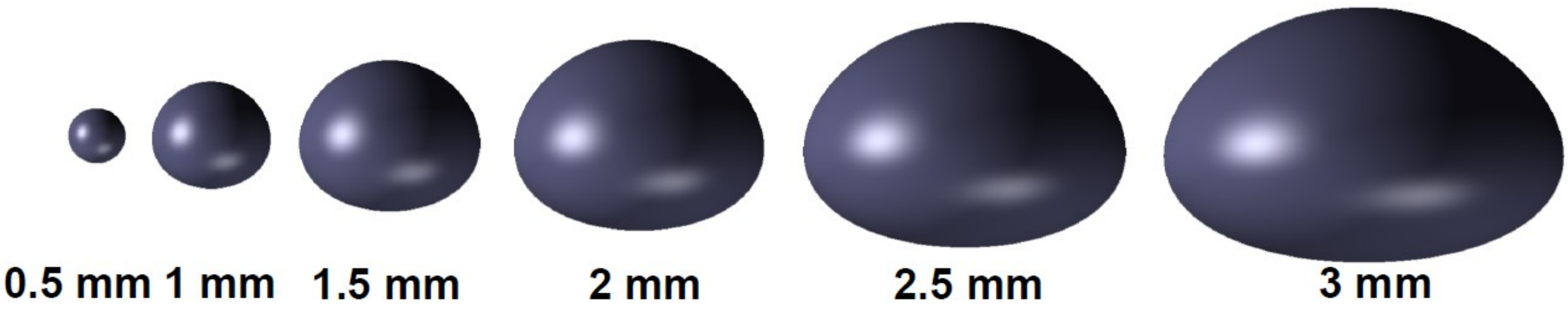
	Interference/ Diffraction	Physically Based Drops	Practical
Ray Optics	✗	✗	✓
Lorenz-Mie	✓	✗	✓
FDTD	✓	✓	✗
Our Goal	✓	✓	✓

OUR APPROACH

- Model physically based shape of water drops
- Compute the scattering profile of a water drop
- Use the scattering profile in rendering

PHYSICALLY BASED SHAPES

- Based on [Beard and Chuang 1987]



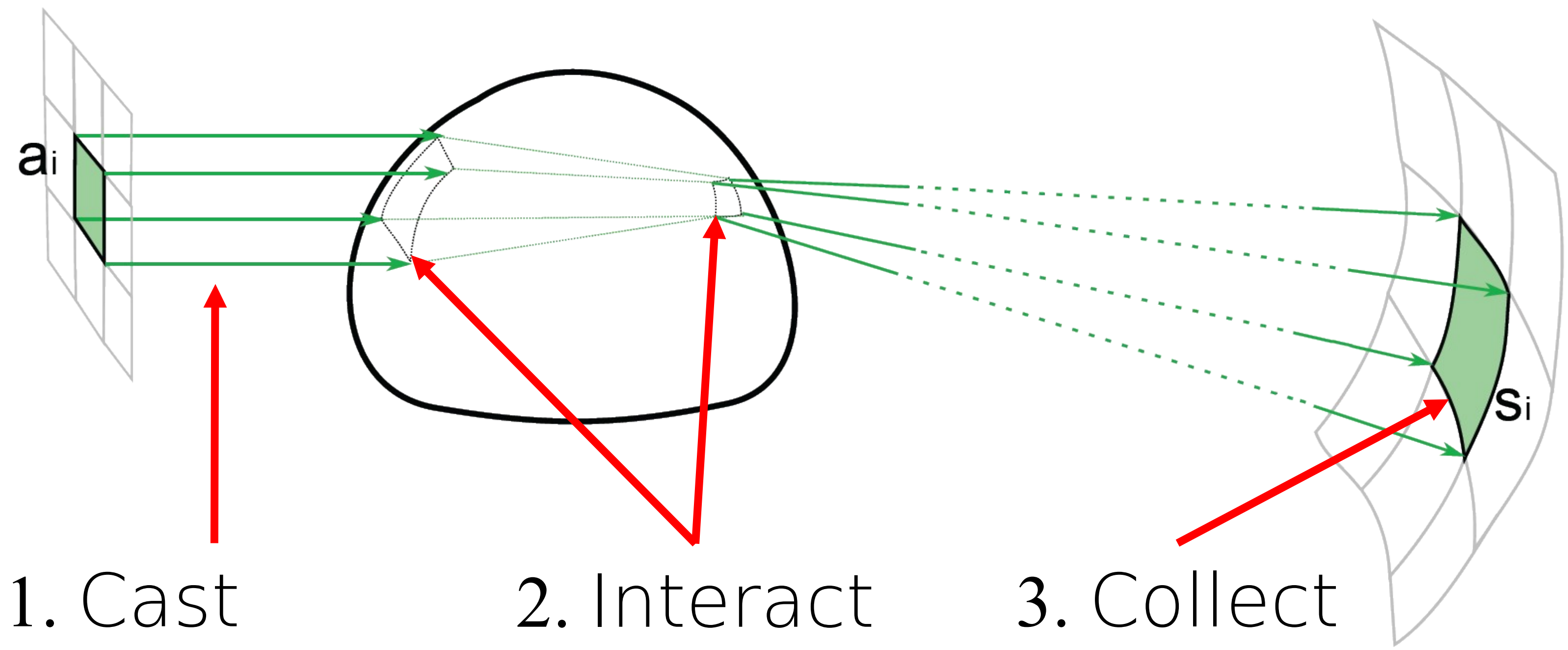
- Considered:
  - Surface tension
  - Hydrostatic pressure
  - Aerodynamic pressure

SCATTERING PROFILE SIMULATION

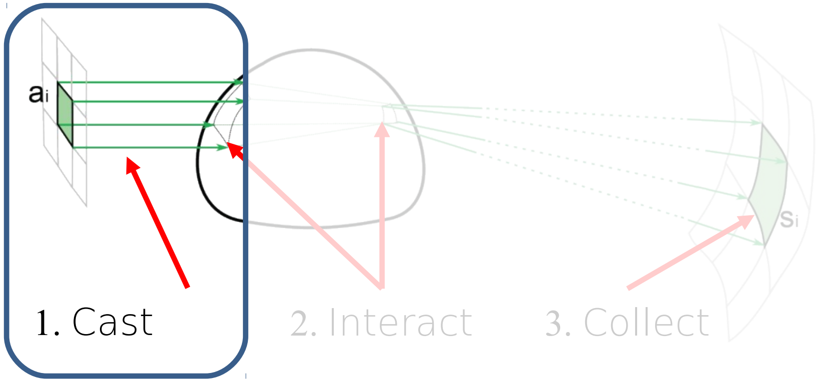
- Key ideas
  - Ray tracing
    - ✓ Arbitrary geometry
    - ✗ Interference
  - Keep track of the phase of light
    - ✓ Interference

SCATTERING PROFILE SIMULATION

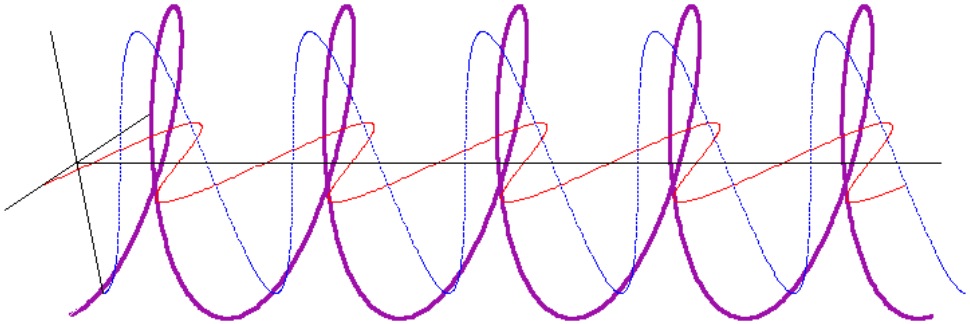
- Algorithm (per wavelength)



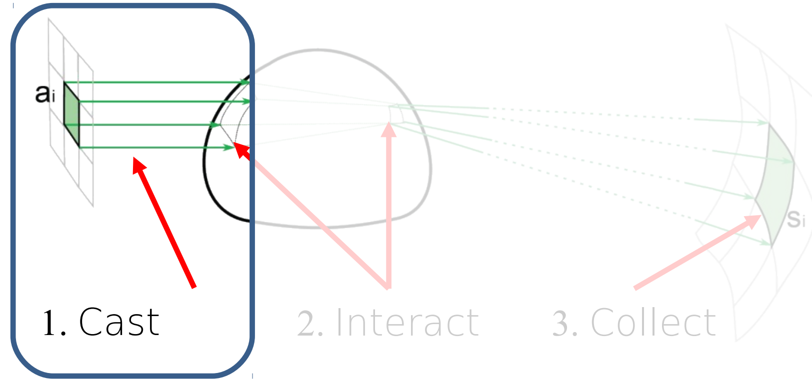
SCATTERING PROFILE SIMULATION



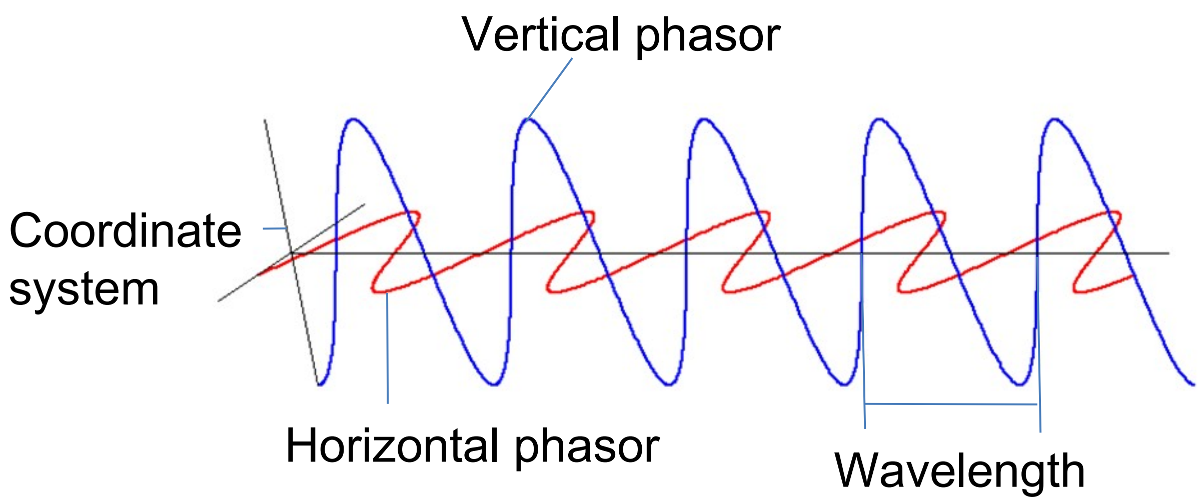
- 1. Cast
  - Electromagnetic wave information



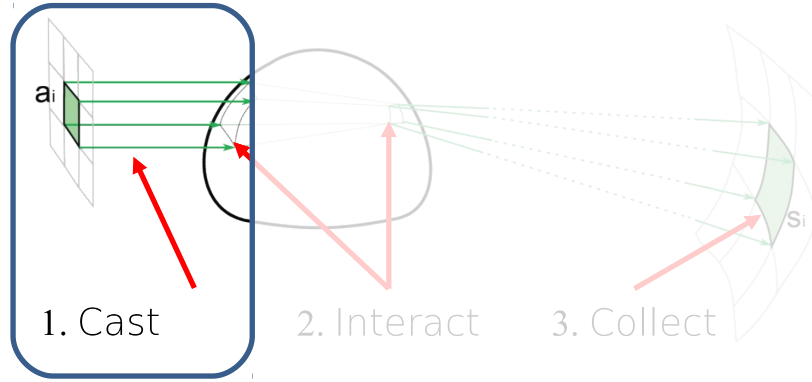
SCATTERING PROFILE SIMULATION



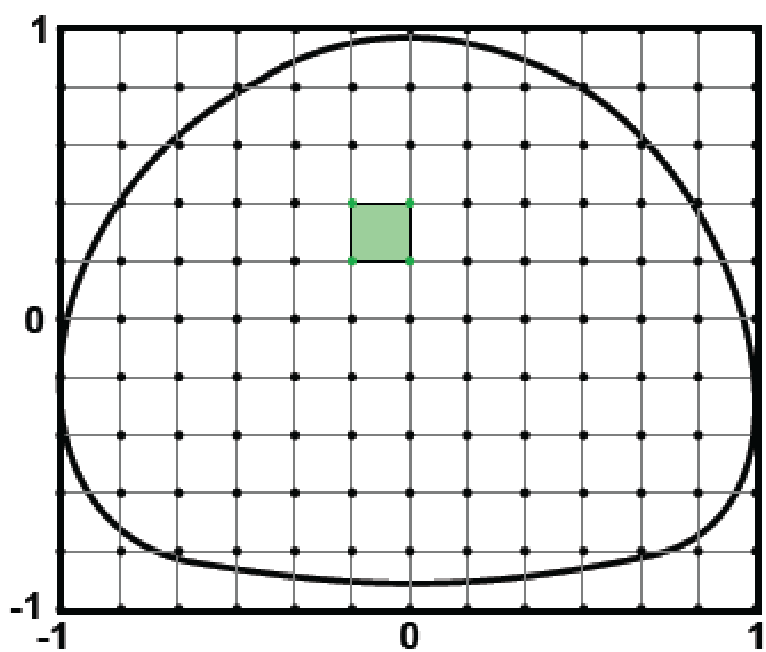
- 1. Cast
  - Electromagnetic wave information



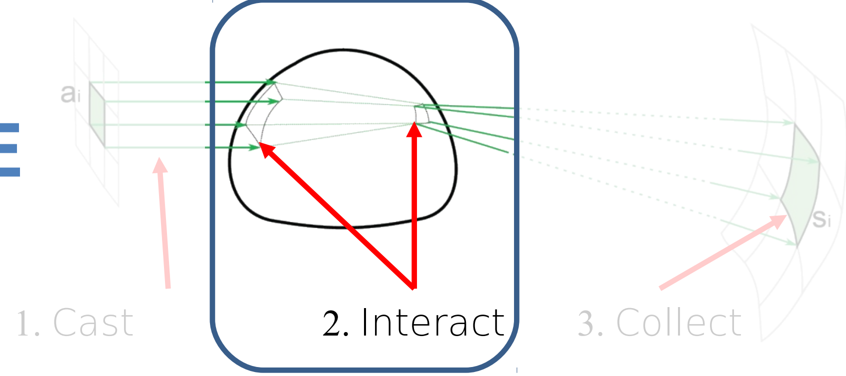
SCATTERING PROFILE SIMULATION



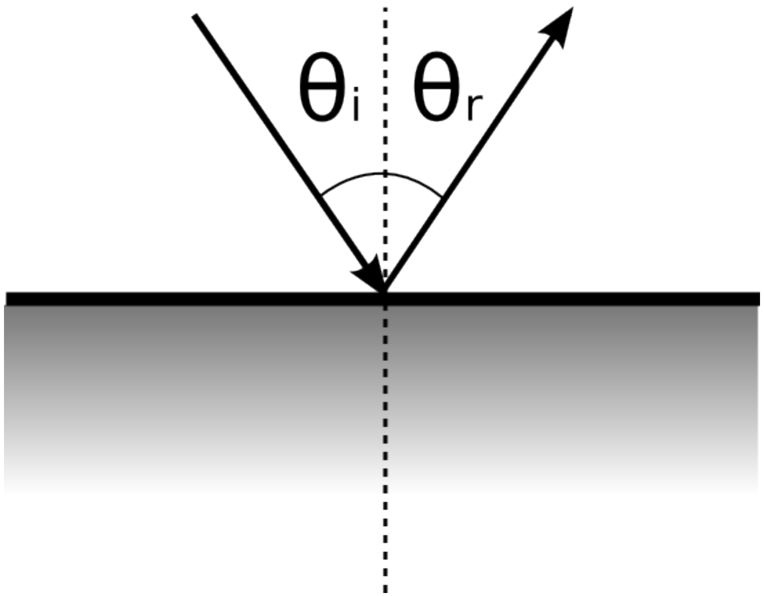
- 1. Cast
  - From a reference plane
  - Grid of rays



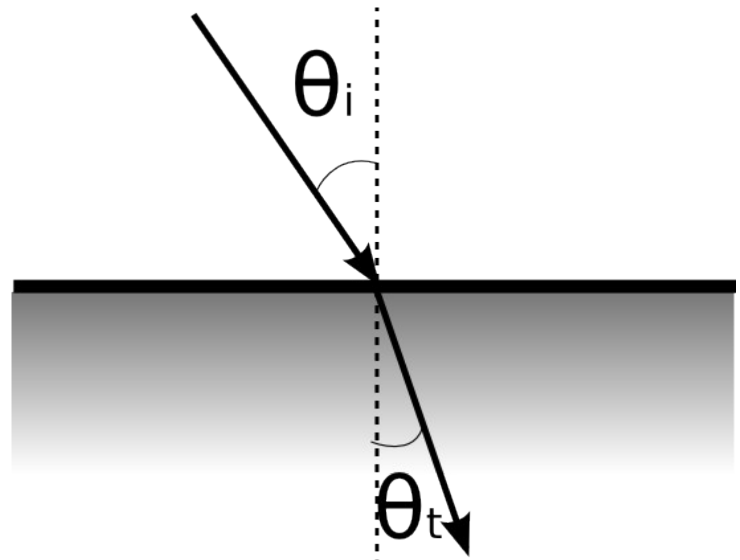
SCATTERING PROFILE SIMULATION



- 2. Interact
  - Geometric optics

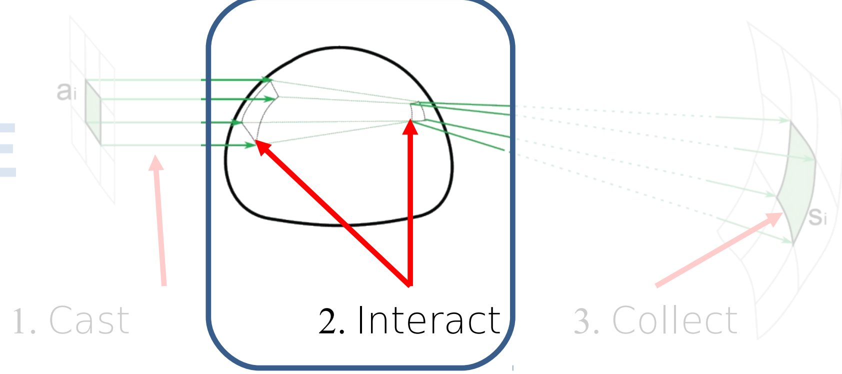


Reflection: law of reflection



Refraction: Snell's law

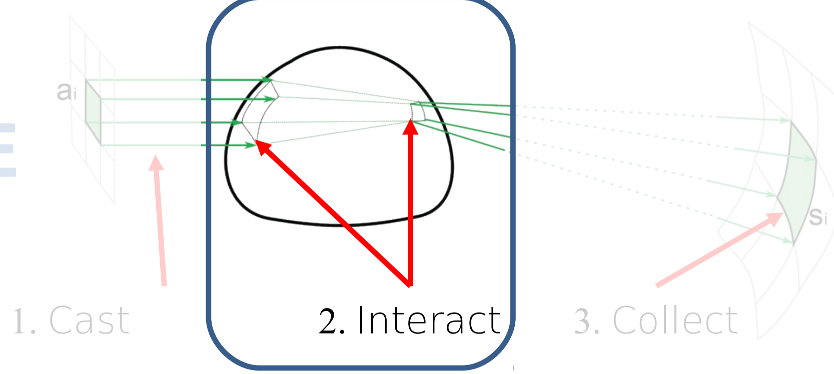
SCATTERING PROFILE SIMULATION

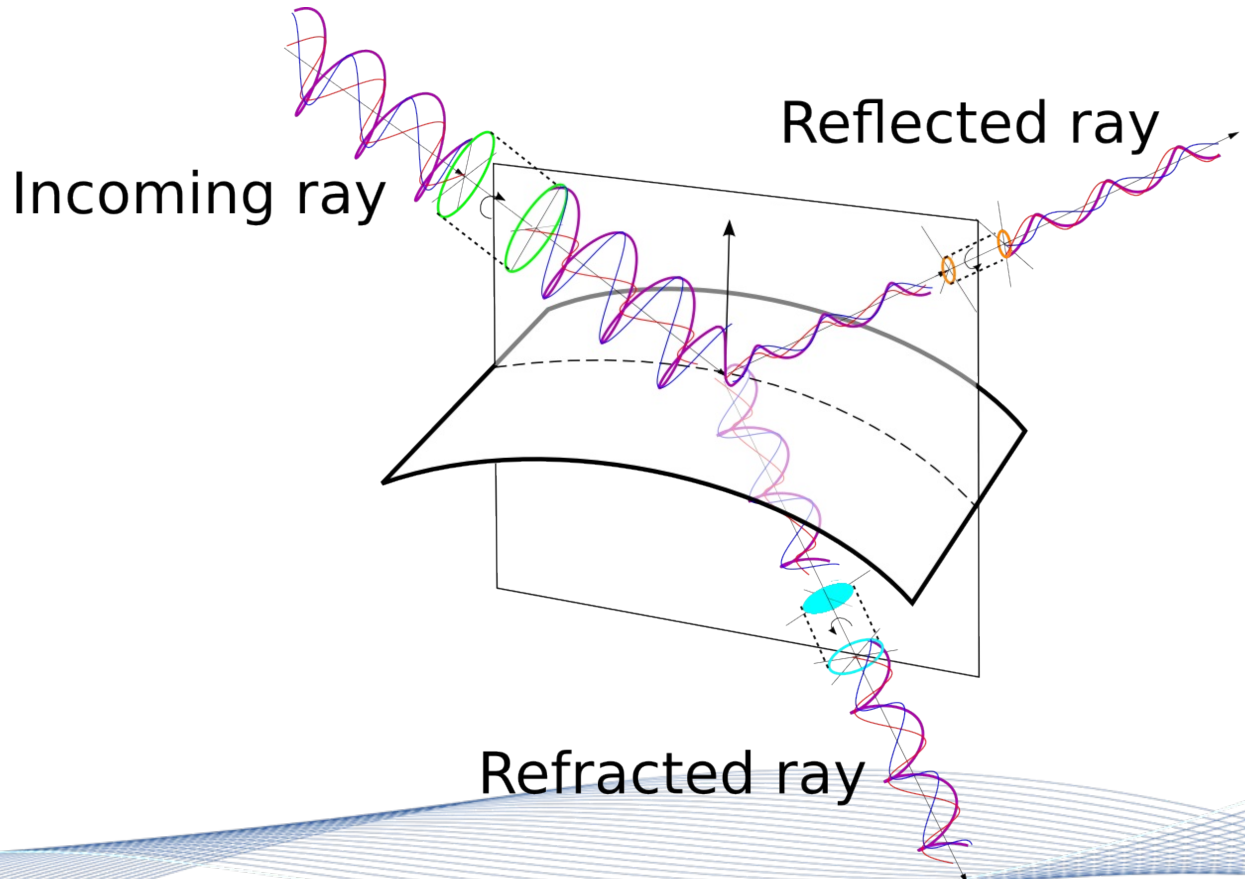


- 2. Interact
  - Fresnel coefficients
  - Focal lines
  - Optical path

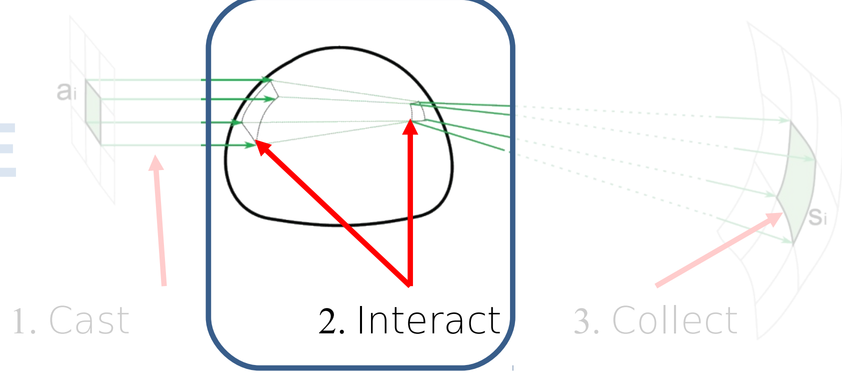
SCATTERING PROFILE SIMULATION

- 2. Interact
  - Fresnel coefficients

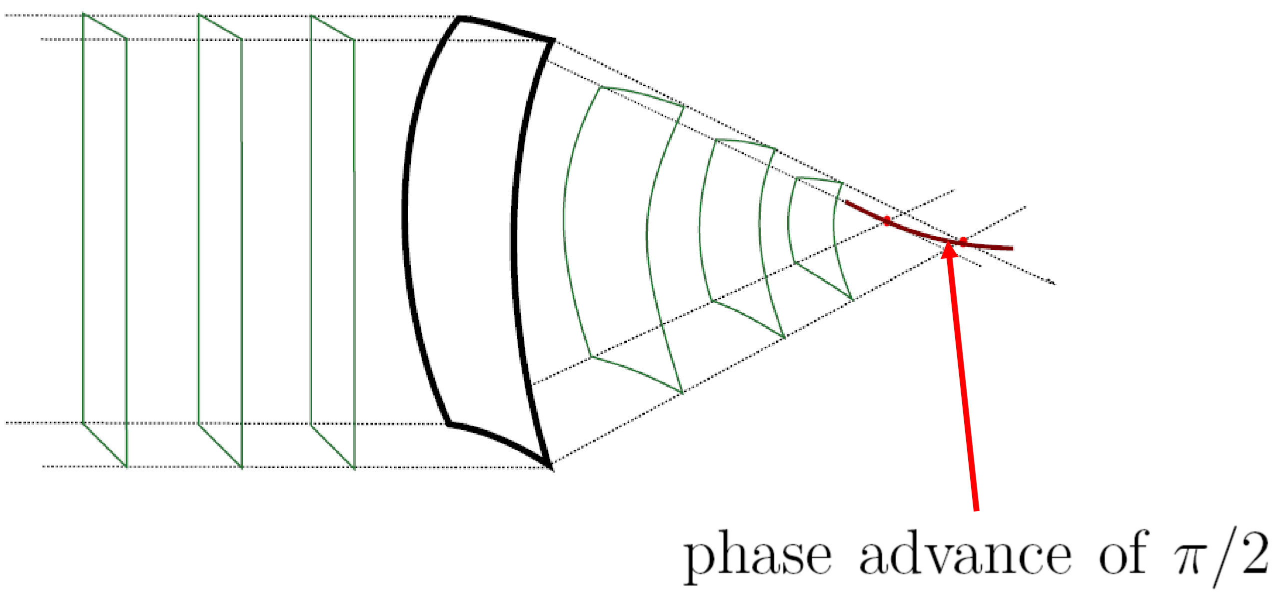




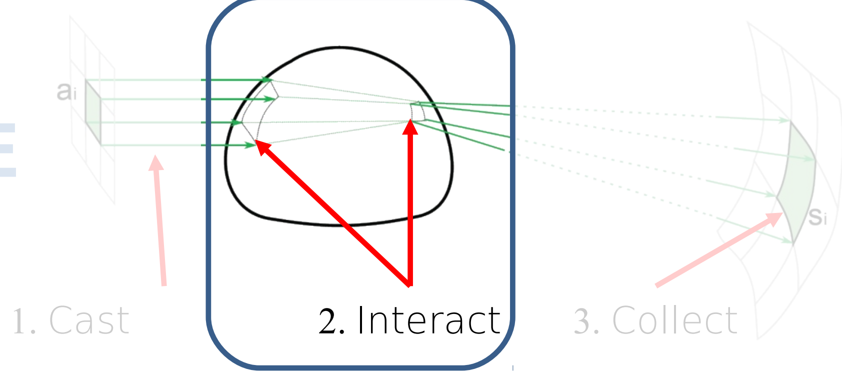
SCATTERING PROFILE SIMULATION



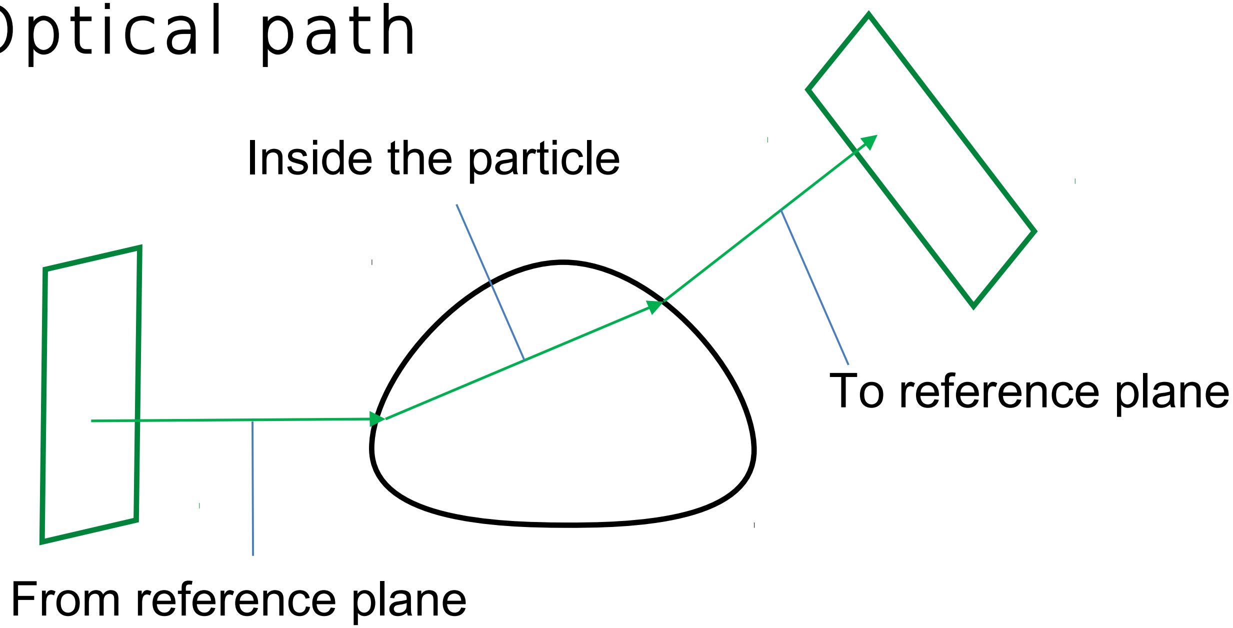
- 2. Interact
  - Fresnel coefficients
  - Focal lines



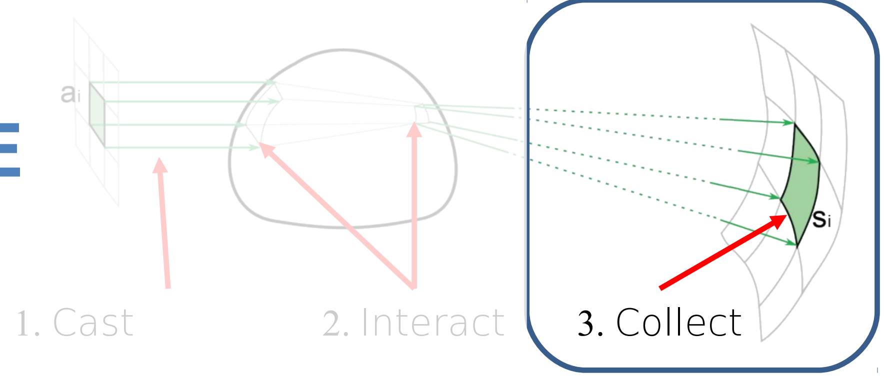
SCATTERING PROFILE SIMULATION



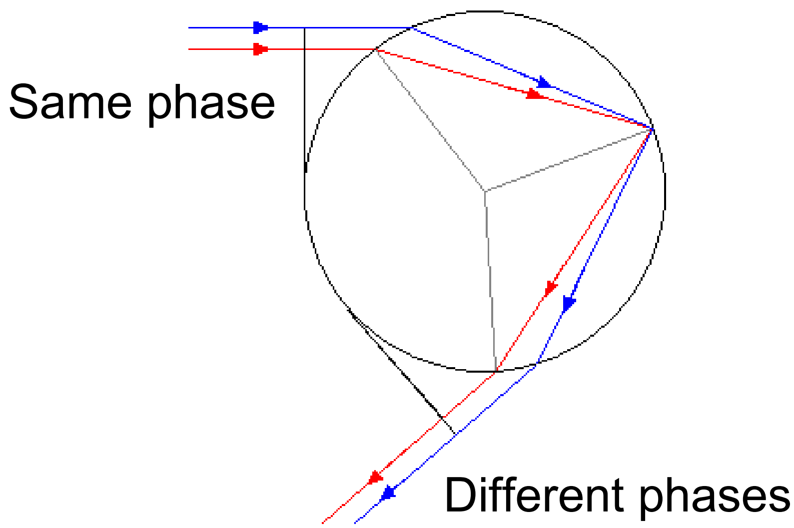
- 2. Interact
  - Fresnel coefficients
  - Focal lines
  - Optical path



SCATTERING PROFILE SIMULATION

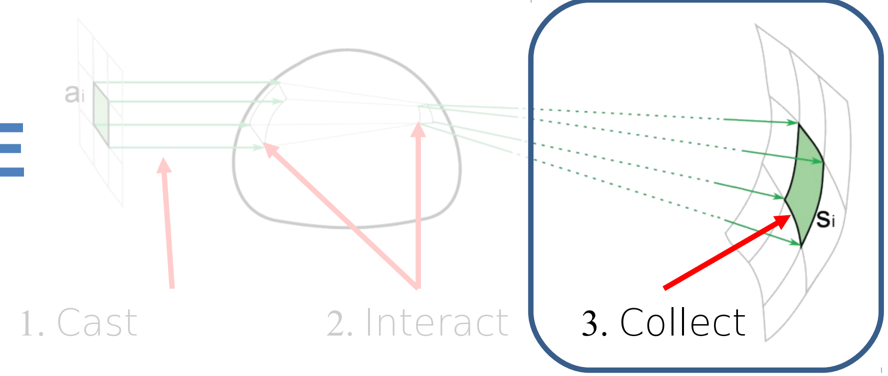


- 3. Collect
  - Computing interference

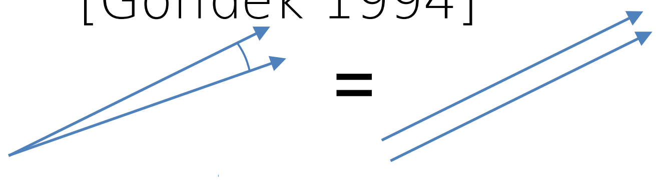


  - Probability of finding interfering paths is ~ 0

SCATTERING PROFILE SIMULATION

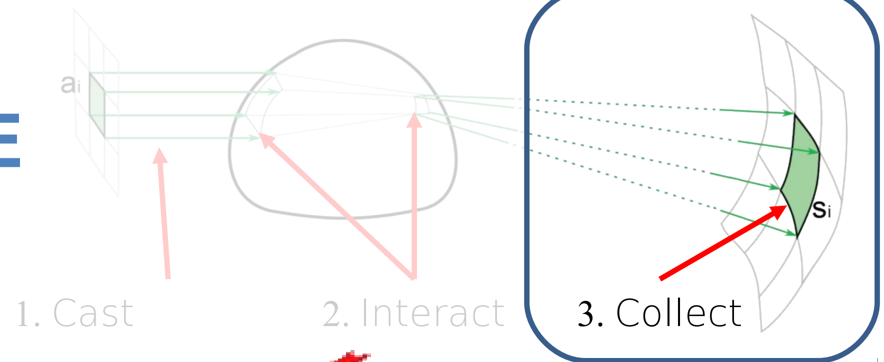


- 3. Collect
  - Finding rays exiting the same direction:
    - Idea: Establish a small angular threshold [Gondek 1994]



    - Another idea: Use a density estimation kernel (as in Photon Mapping)

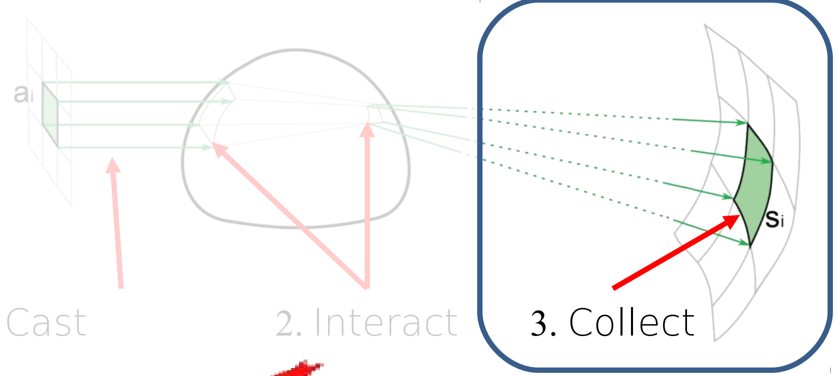
SCATTERING PROFILE SIMULATION



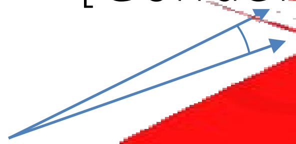
- 3. Collect
  - Fi[illegible]ding rays exiting th[illegible]me direction:
    - Ide[illegible]blish a s[illegible]gular threshold [Gondek [illegible]

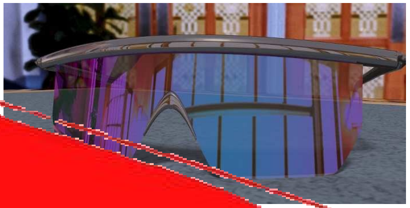
    - Another idea: Use a density estimation kernel (as in Photon Mapping)

SCATTERING PROFILE SIMULATION



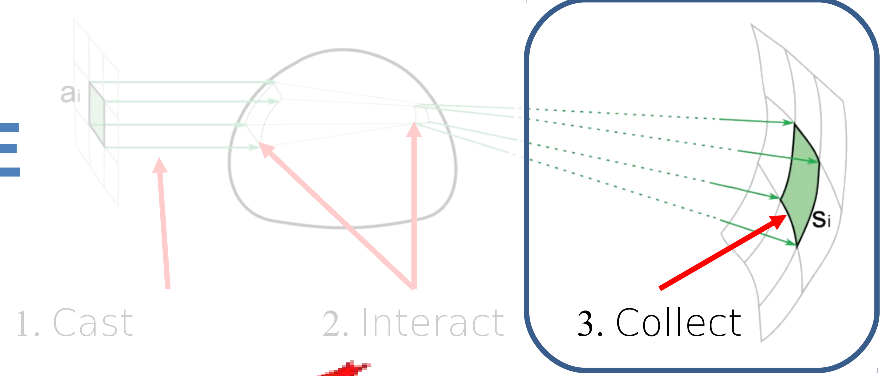
- 3. Collect
  - Fi[illegible]ding rays exiting th[illegible]me direction:
    - Ide[illegible]tablish a s[illegible]gular threshold [Gondek 1[illegible]



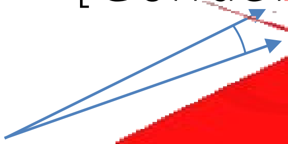


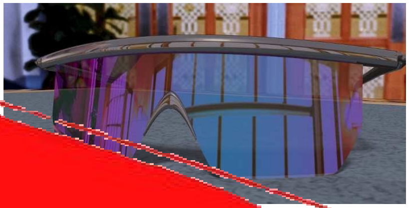
    - Better idea: Use a density estimation kernel (as in Photon Mapping)

SCATTERING PROFILE SIMULATION



- 3. Collect
  - Fi ding rays exiting th me direction:
    - Ide tablish a s gular threshold [Gondek 19



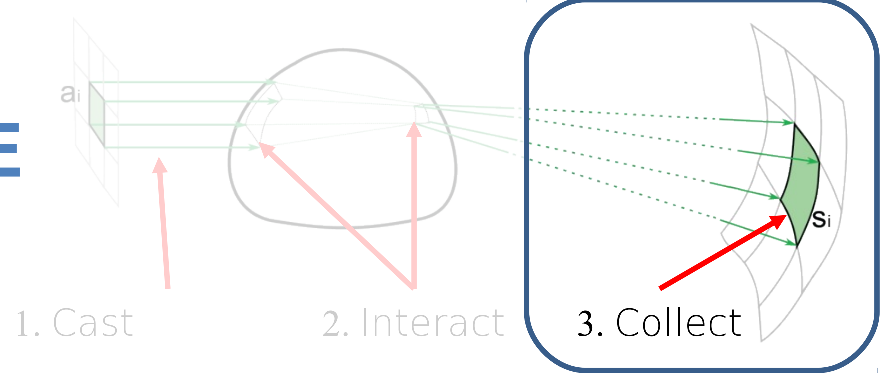


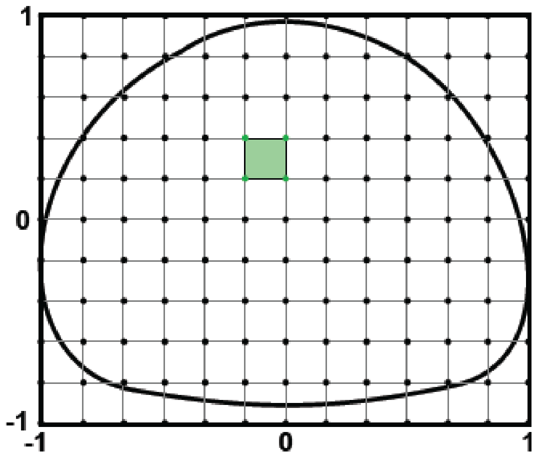
    - Another idea: Use a density estimation kernel (as in Photon Mapping)

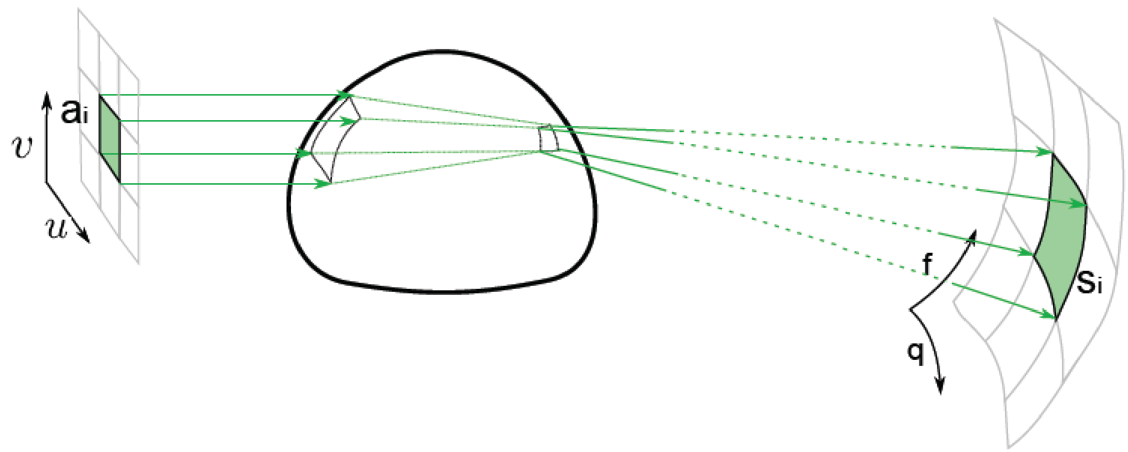
Small angle variation → High optical path variation → High phase variation → Simulate for eternity

SCATTERING PROFILE SIMULATION

- 3. Collect

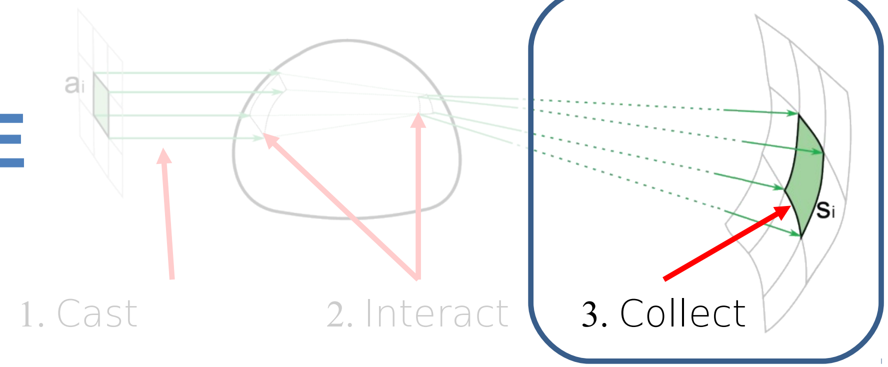


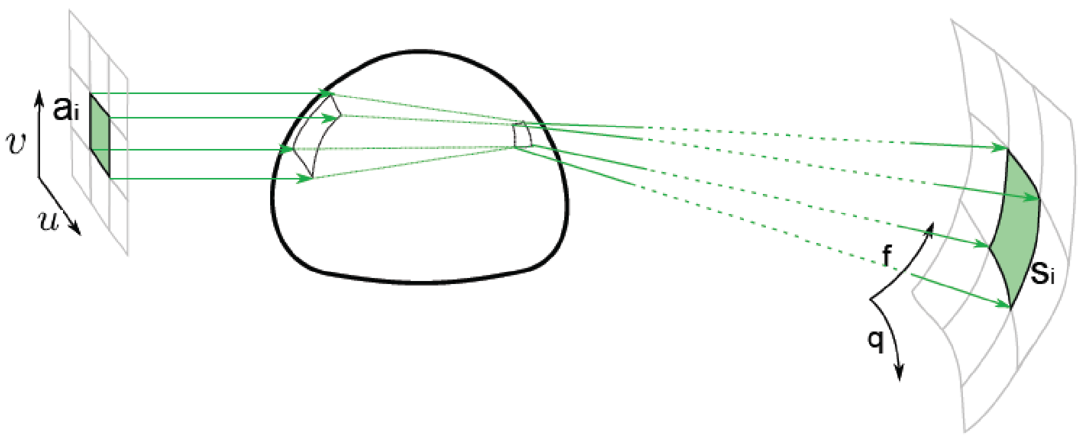


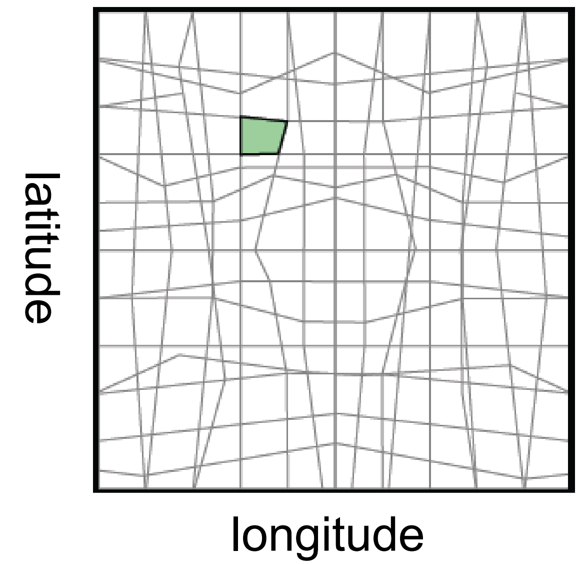


SCATTERING PROFILE SIMULATION

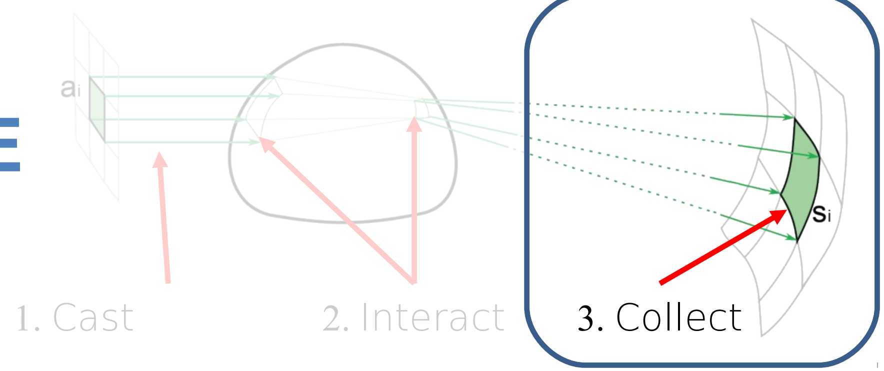
- 3. Collect



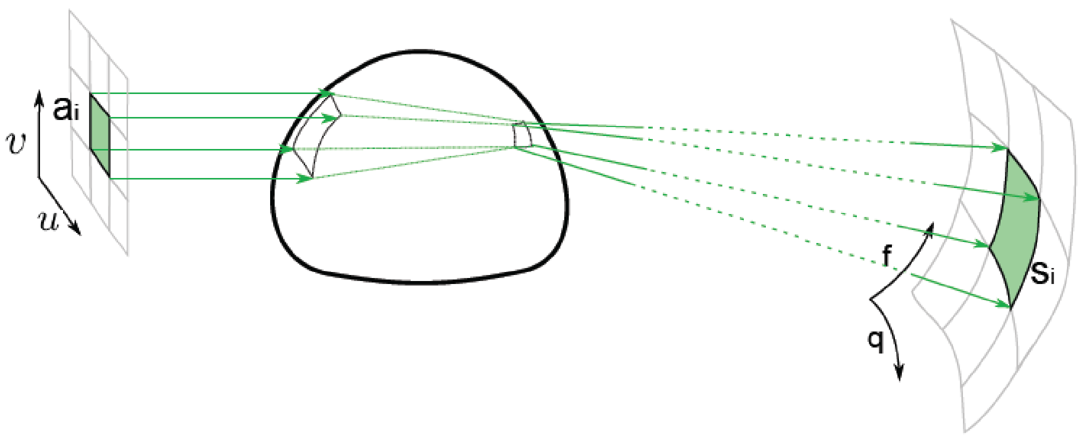


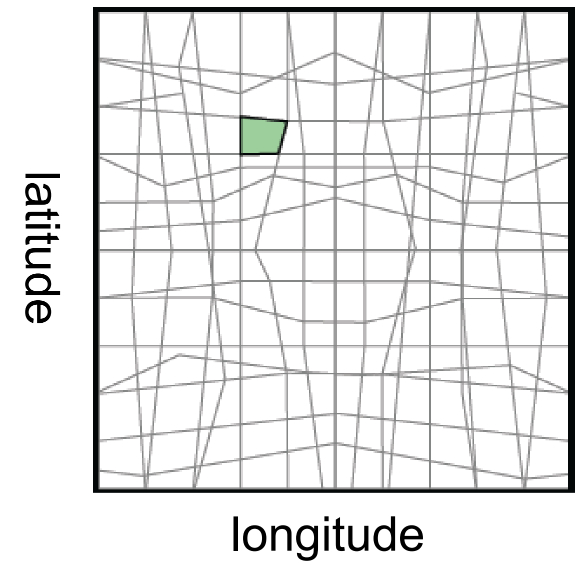


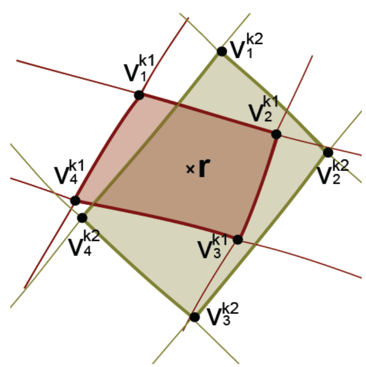
SCATTERING PROFILE SIMULATION



- 3. Collect

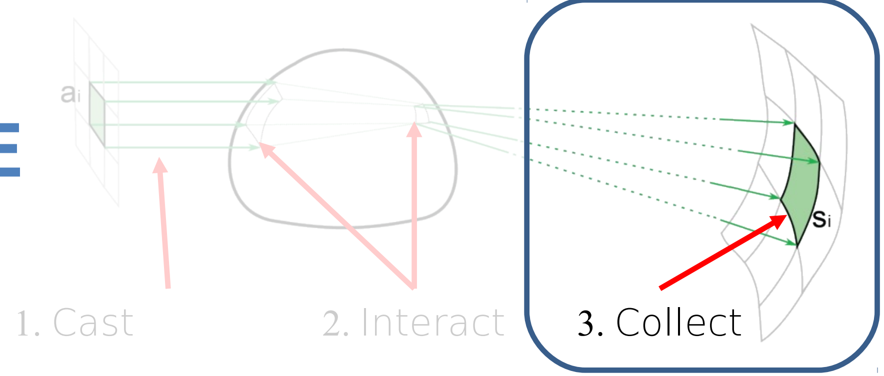




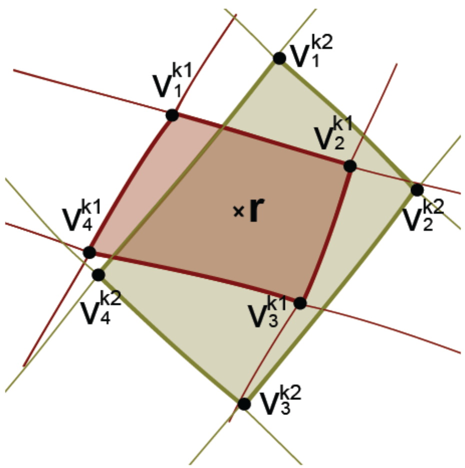


Per-patch interpolation
Phasor addition

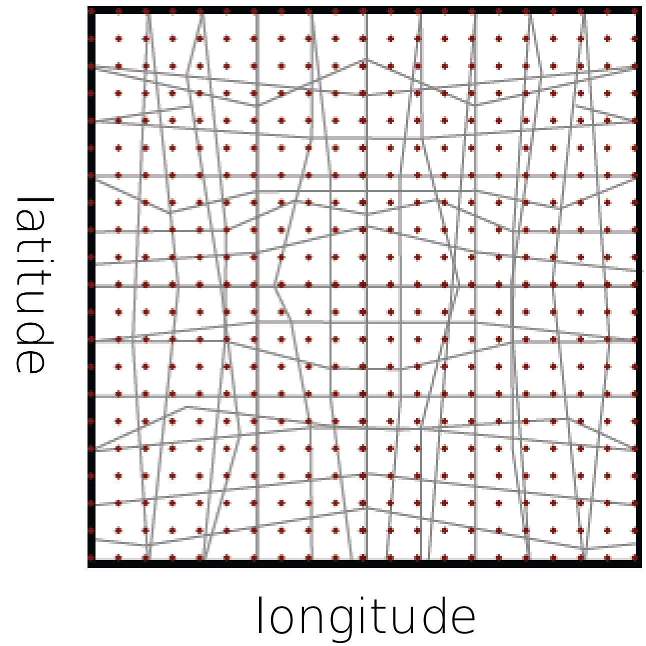
SCATTERING PROFILE SIMULATION



- 3. Collect
  - Query and tabulate data (per wavelength)

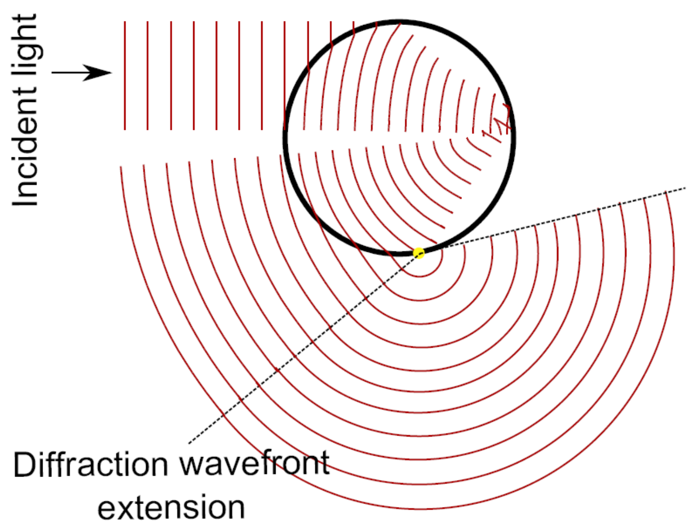


Per-patch interpolation
Phasor addition



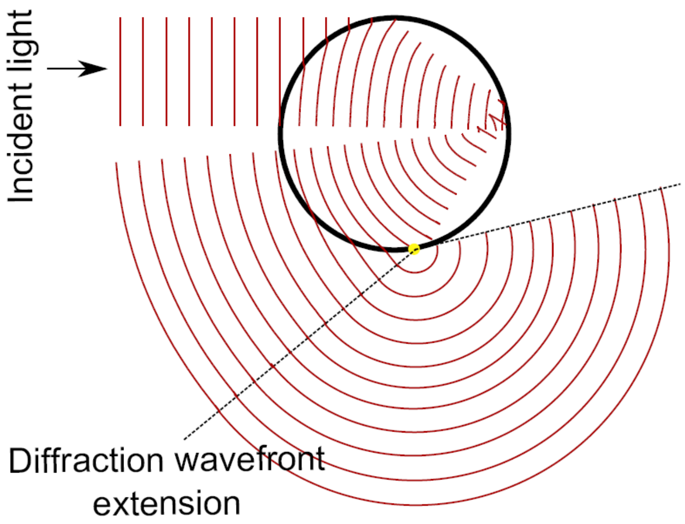
SCATTERING PROFILE SIMULATION

- Diffraction



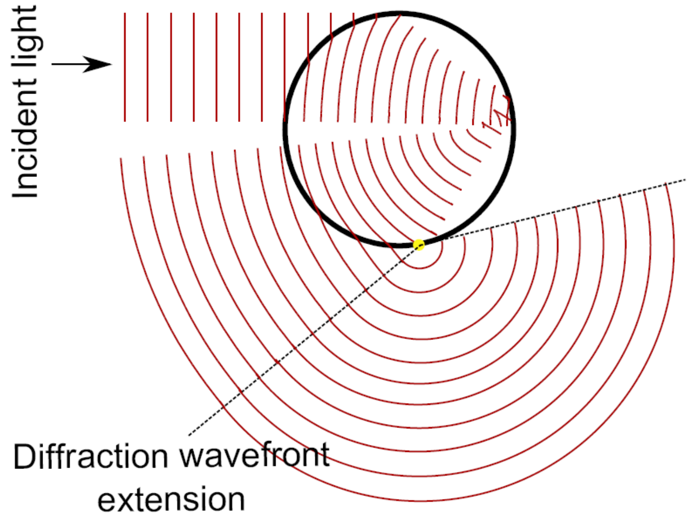
SCATTERING PROFILE SIMULATION

- Diffraction approximation



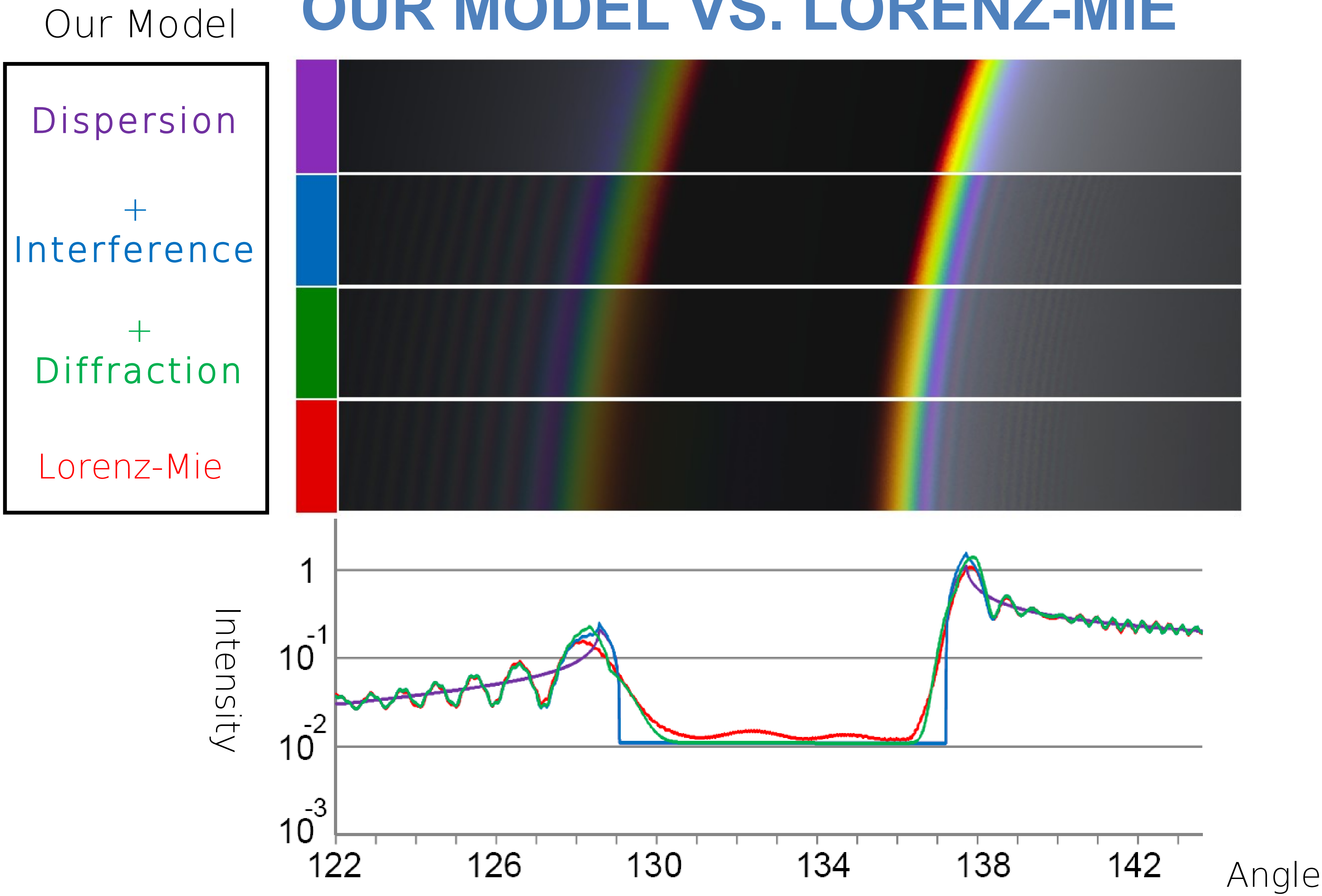
SCATTERING PROFILE SIMULATION

- Diffraction approximation
  - Smooth sharp transitions



Radius (mm)	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
σ (degrees)	0.70	0.45	0.30	0.25	0.22	0.20	0.18	0.17	0.16	0.15

OUR MODEL VS. LORENZ-MIE



OUR MODEL VS. LORENZ-MIE

(a) Our model
(b) Lorenz-Mie

(a)

(b)

Spherical (0.4mm)

Nonspherical (0.5mm)

OUR MODEL VS. LORENZ-MIE

Spherical (0.4mm) Nonspherical (0.5mm)

(a) Our model
(b) Lorenz-Mie

MATCHING PHOTOGRAPHS

Double Rainbow

MATCHING PHOTOGRAPHS

Double Rainbow / Alexander Dark Band

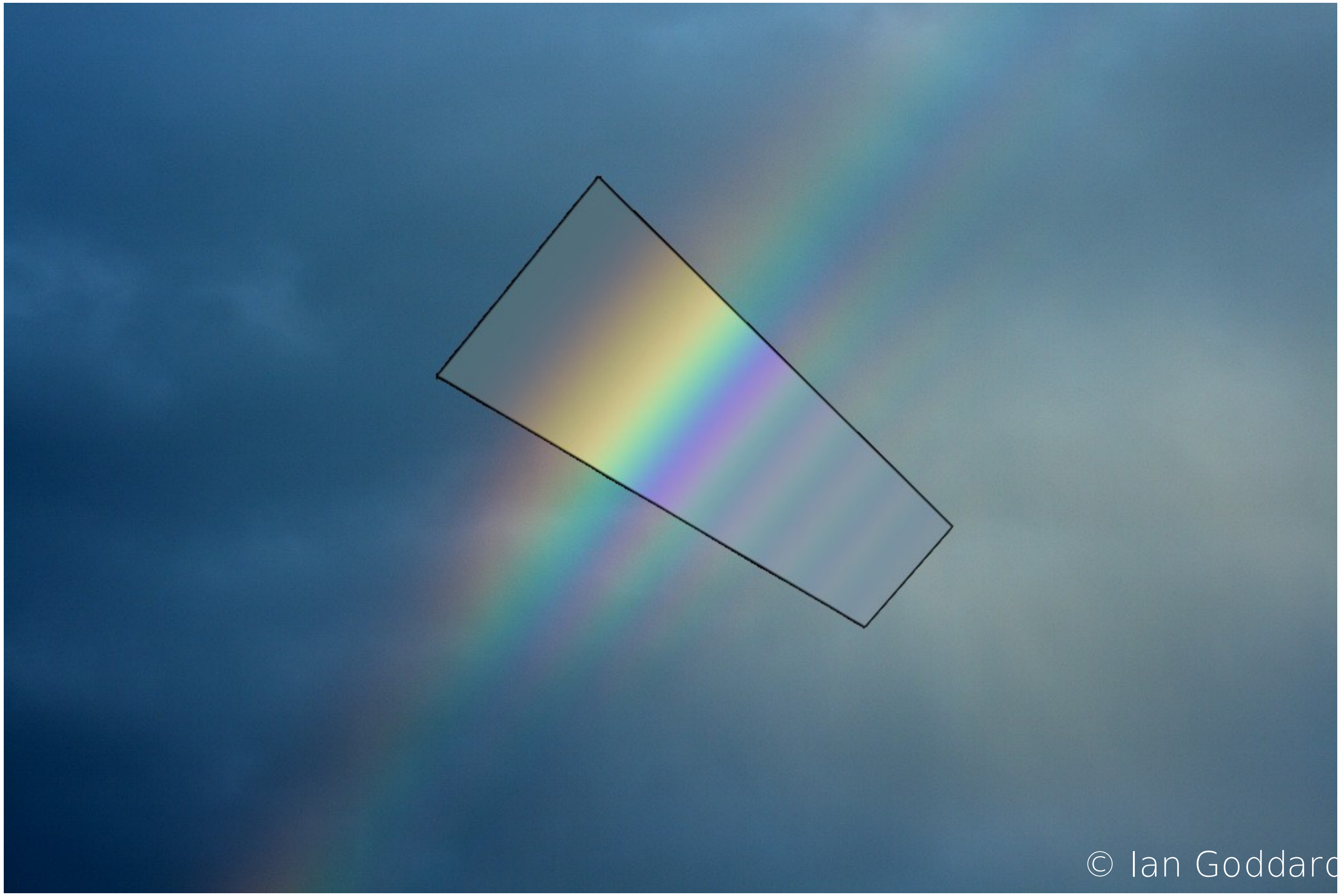
MATCHING PHOTOGRAPHS

Double Rainbow with Supernumerary Arcs

MATCHING PHOTOGRAPHS

Red Bow at Sunset

MATCHING PHOTOGRAPHS



Multiple Supernumerary Arcs

MATCHING PHOTOGRAPHS

Fog Bow

MATCHING PHOTOGRAPHS

Photograph

Rendering
(0.4 mm & 0.45 mm)

Twinned Bow

SUMMARY

- Rainbow simulation from physically based shapes
  - Match Lorenz-Mie for spheres.
  - Not limited to spheres.
- Matched photographs of real rainbows
  - Double rainbows, supernumerary arcs, fogbows, red bows, etc.
  - First comprehensive simulation of twinned bows

FUTURE WORK

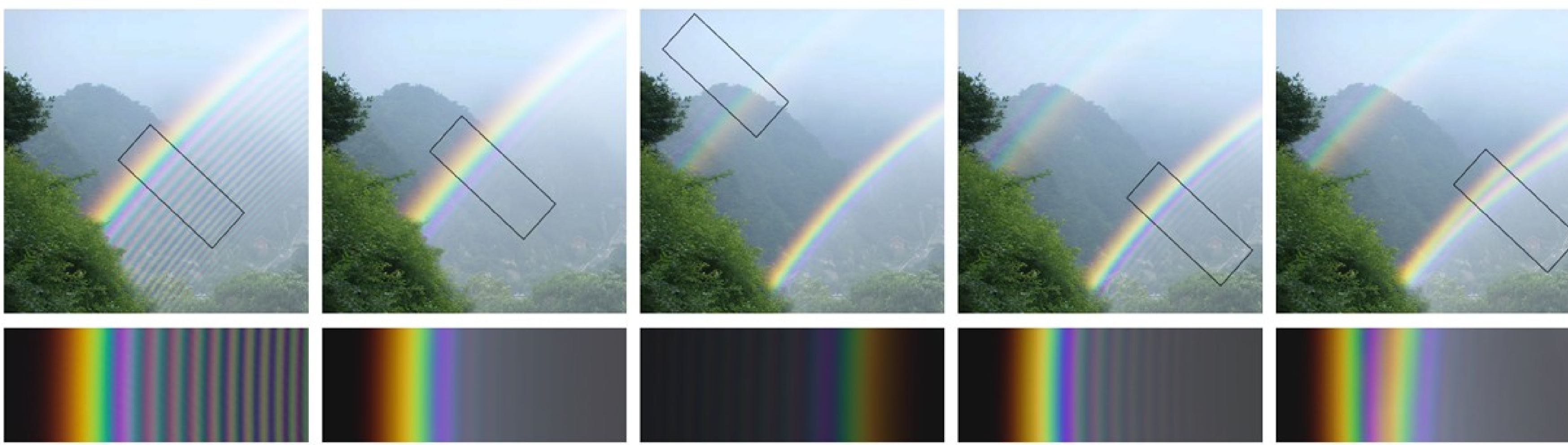
- Automate photo matching
- Simulation of other phenomena
- Diffraction Approximation
- GPU implementation

THANK YOU!

Physically-Based Simulation of Rainbows

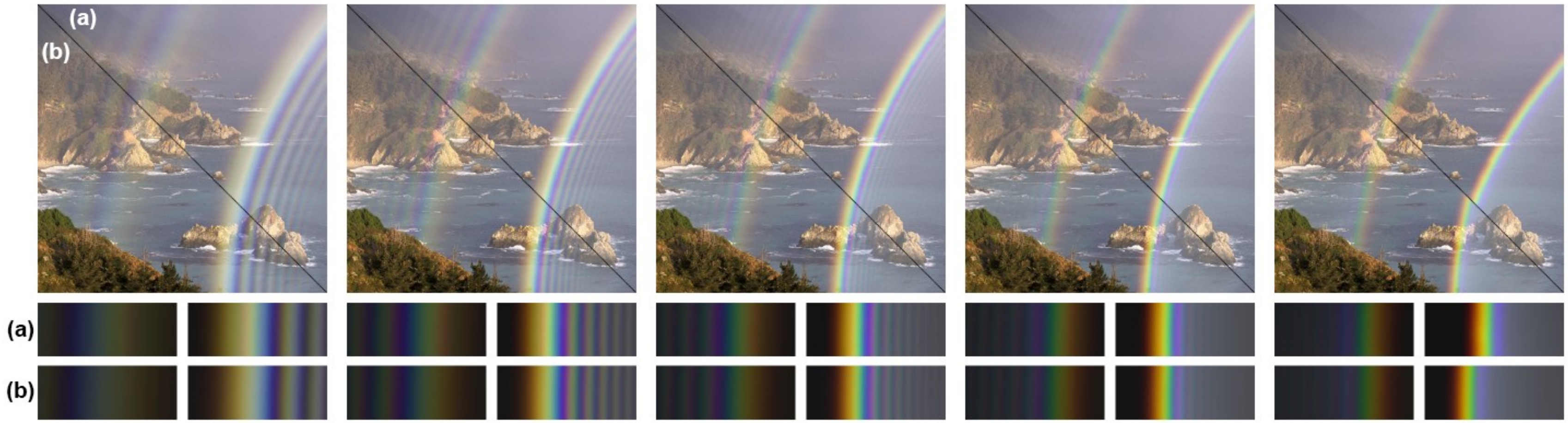
Iman Sadeghi[1] Adolfo Munoz[2] Philip Laven[3] Wojciech Jarosz[1,4]
Francisco Seron[2] Diego Gutierrez[2] Henrik Wann Jensen[1]

[1]University of California, San Diego [2]Universidad de Zaragoza [3]Geneva [4]Disney Research, Zürich



OUR MODEL VS. LORENZ-MIE

(a) Our model (b) Lorenz-Mie



0.1 mm 0.2 mm 0.3 mm 0.4 mm 0.5 mm

Spherical

Nonspherical

OUR MODEL VS. LORENZ-MIE

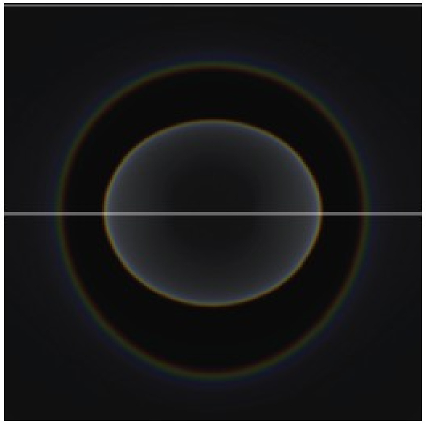
(left half) Lorenz-Mie (right half) Our model

0.4 mm 0.5 mm 0.6 mm 0.7 mm

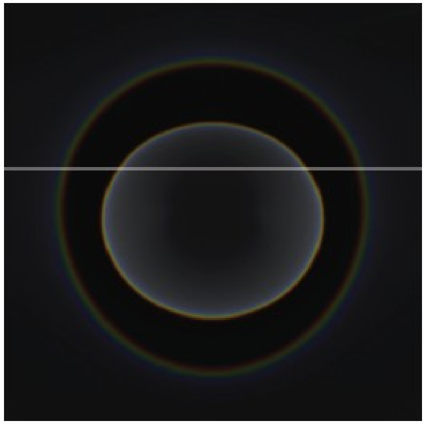
Spherical Nonspherical

Sun's inclination 25°

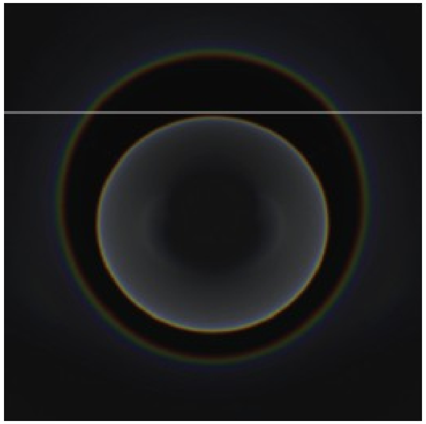
SUN'S INCLINATION



0°



20°



40°

Sun's inclination

NON-SPHERICAL WATER DROPS

0.4 mm 0.5 mm 0.6 mm 0.7 mm

Sun’s inclination 0^{o}