Lecture on Radiative Transfer

1st FARGO3D Workshop

USACH

CIRAS | CENTER FOR INTERDISCIPLINARY RESEARCH IN ASTROPHYSICS AND SPACE SCIENCES

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Overview

Today

- Aim and motivation
- What / why / how
- Basics
  - Radiative transfer equation
  - Assumptions
- Why is radiative transfer hard?
  - Ways of solving the RT equation

Tomorrow

- What are important things that we learn from observations that can inform our simulations?
- Dusty media (opacities, masses, etc)
  - What dominates the opacities, and hence, what we see?
- Gas kinematics (line emission and absorption)
- Scattering and polarized light

Aim and Motivation

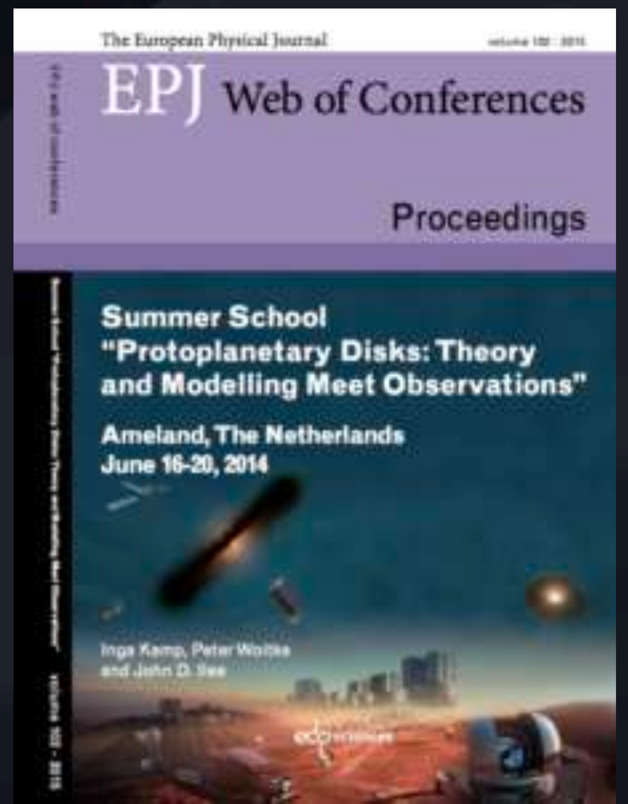
Lecture on Radiative Transfer (RT)

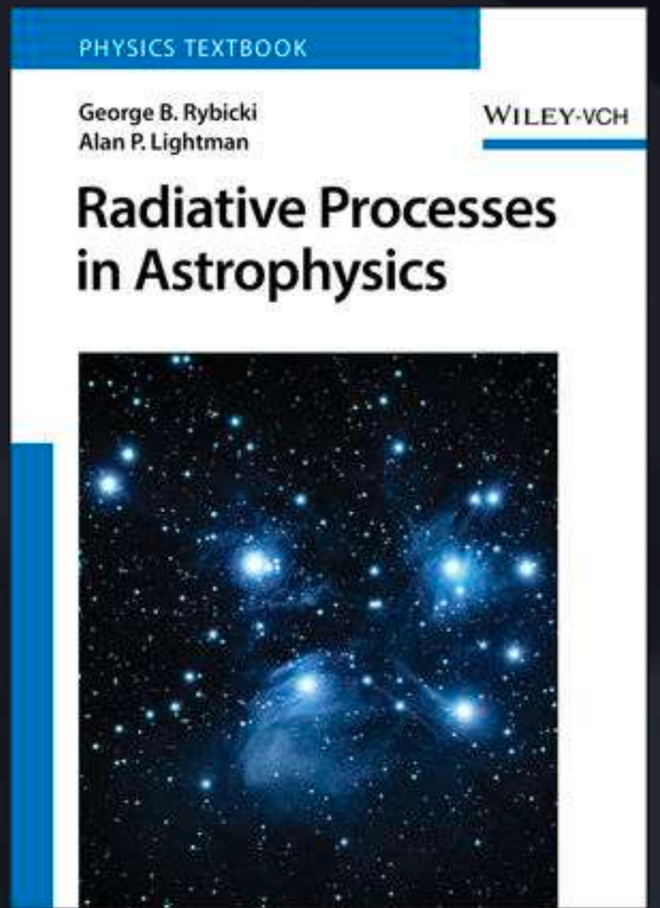
- to give an overview with enough background to understand more specialised literature, and to understand what's going on when we perform RT calculations this week

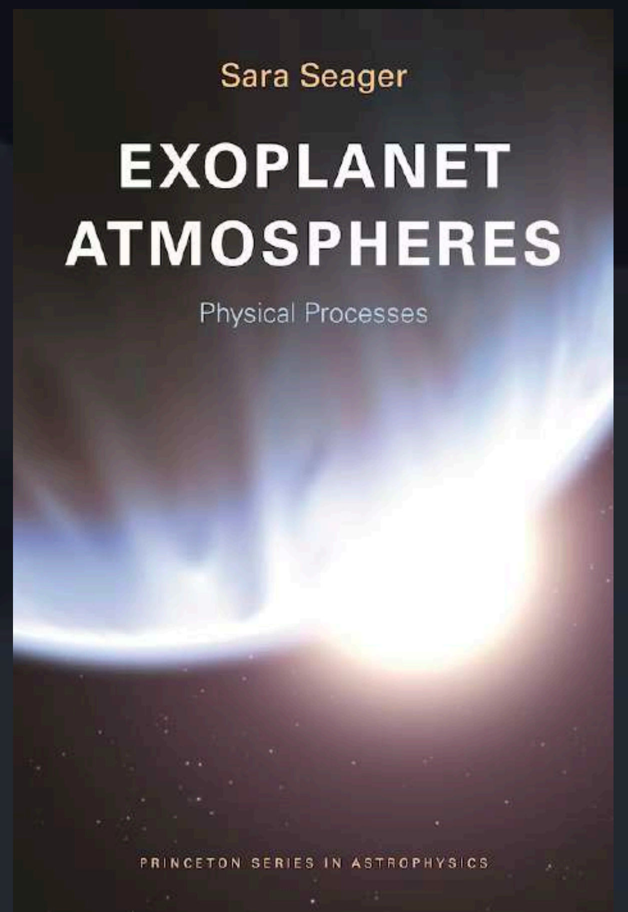
Resources

Books, lectures and videos

1. **Radiative transfer in astrophysics (Master/PhD Course) by Kees Dullemond** 🔗
2. Exoplanet Atmospheres by Sara Seager
3. Radiative Processes in Astrophysics by Rybicki and Lightman.
4. Summer School "Protoplanetary Disks: Theory and Modelling Meet Observations" 🔗







Aim and Motivation

Lecture on Radiative Transfer (RT)

- to give an overview with enough background to understand more specialised literature, and to understand what's going on when we perform RT calculations this week

- *"Astrophysics is a kind of experimental physics in which the experiments were not designed by us, but by Nature, and which we can only observe from a distance."*
  —Kees Dullemond

- *How do we decode the information encrypted in the light we receive?*

Image Credit: NASA, ESA, CSA, STScI

What is radiative transfer?

A discipline? A process? A theory? A phenomenon? A tool?

- Radiative transfer is essentially a theory, allows you to study how radiation travels and interacts with a medium.

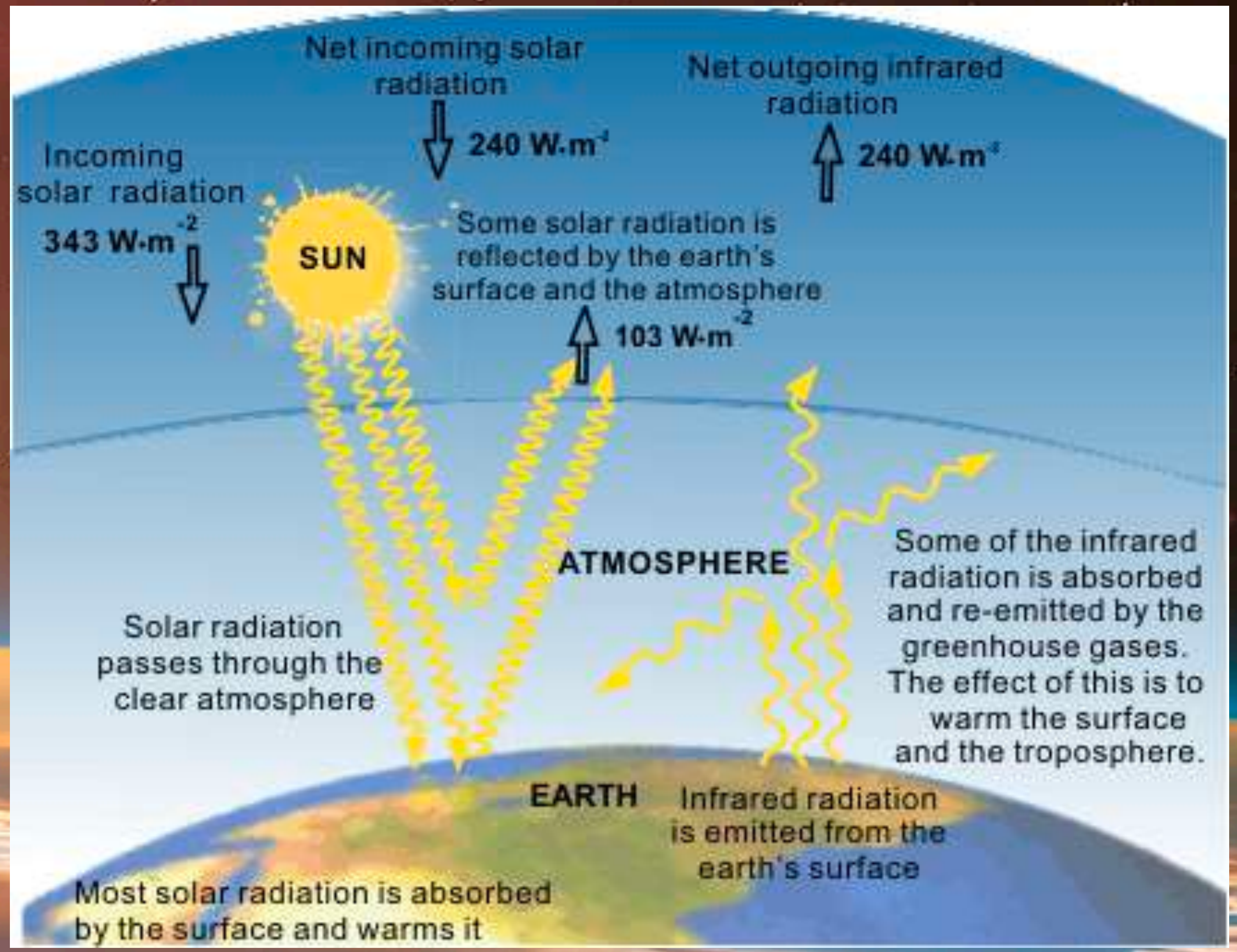
- It's a **macroscopic description** of the interaction between light and matter. Pre-dates quantum mechanics.

- Complex interplay between absorption, emission and scattering of photons.

Solar Radiation and Earth's Atmosphere

Climate Science

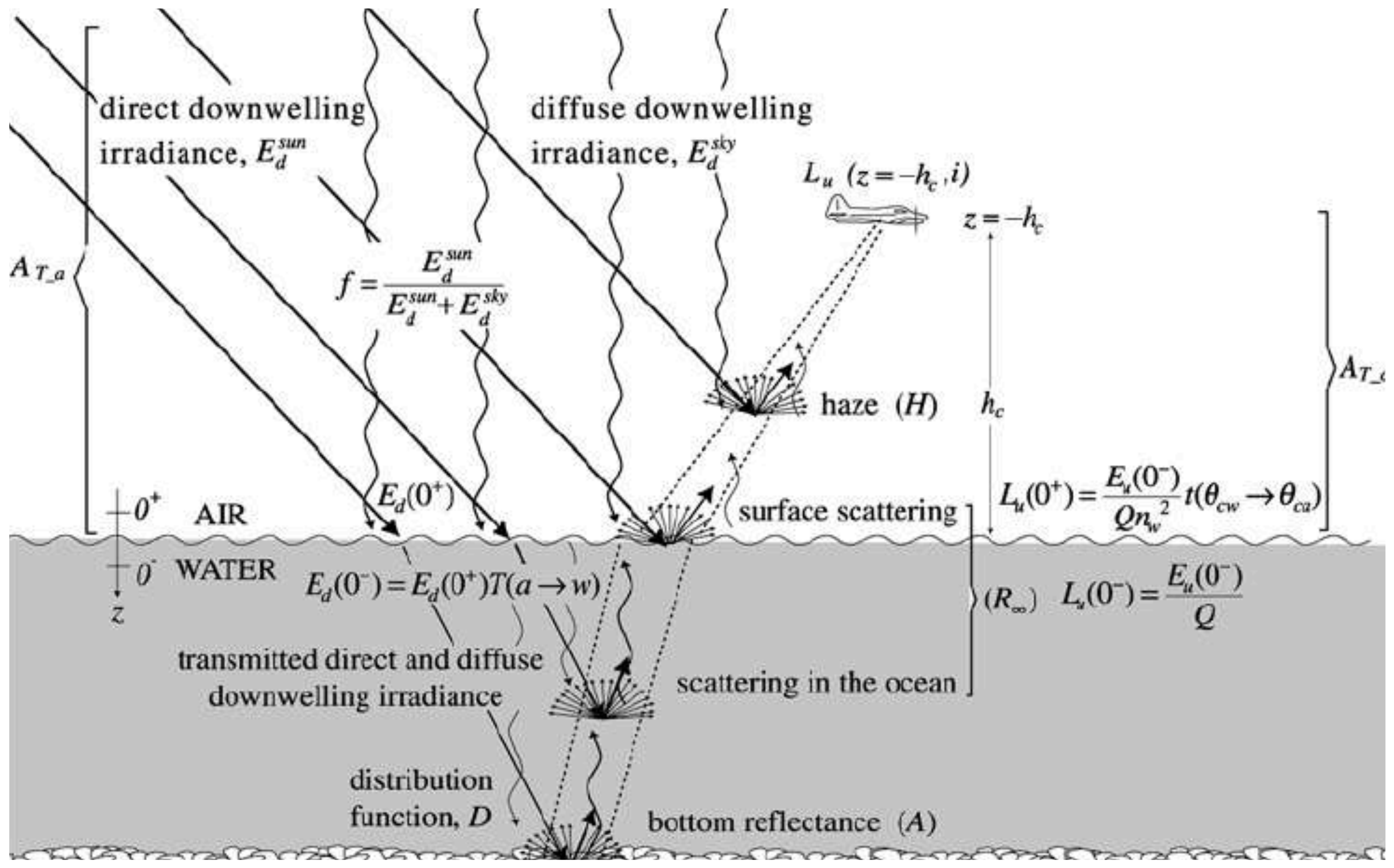
- Radiative transfer is fundamental in understanding how solar radiation is absorbed and re-emitted by the Earth's surface and atmosphere, crucial in climate models and studies of global warming and the climate crisis.



Light absorption and scattering in ocean waters.

Oceanography

- Radiative transfer is used to study how light penetrates ocean layers, which is important for understanding oceanic heat content, plant life distribution, and underwater visibility.



“Atmospheric perspective” in paintings

Art

- Atmospheric perspective, a concept often used in art, is the effect where objects at a distance appear less distinct and usually “colder” than objects close by. This phenomenon is a direct consequence of the radiative transfer of light as it travels through the Earth's atmosphere.

Special FX in movies

Tech & Innovation

wētāFX HOME FILMS+ AWARDS TECH & RESEARCH CAREERS LEARNING ABOUT SEARCH

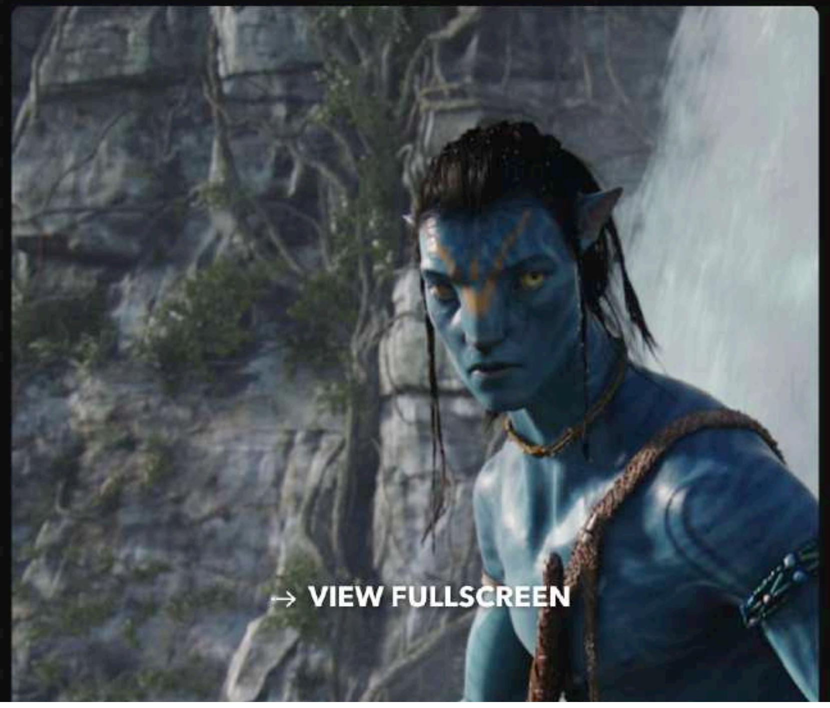
Home › Tech & Research › Technology › Physically-base…

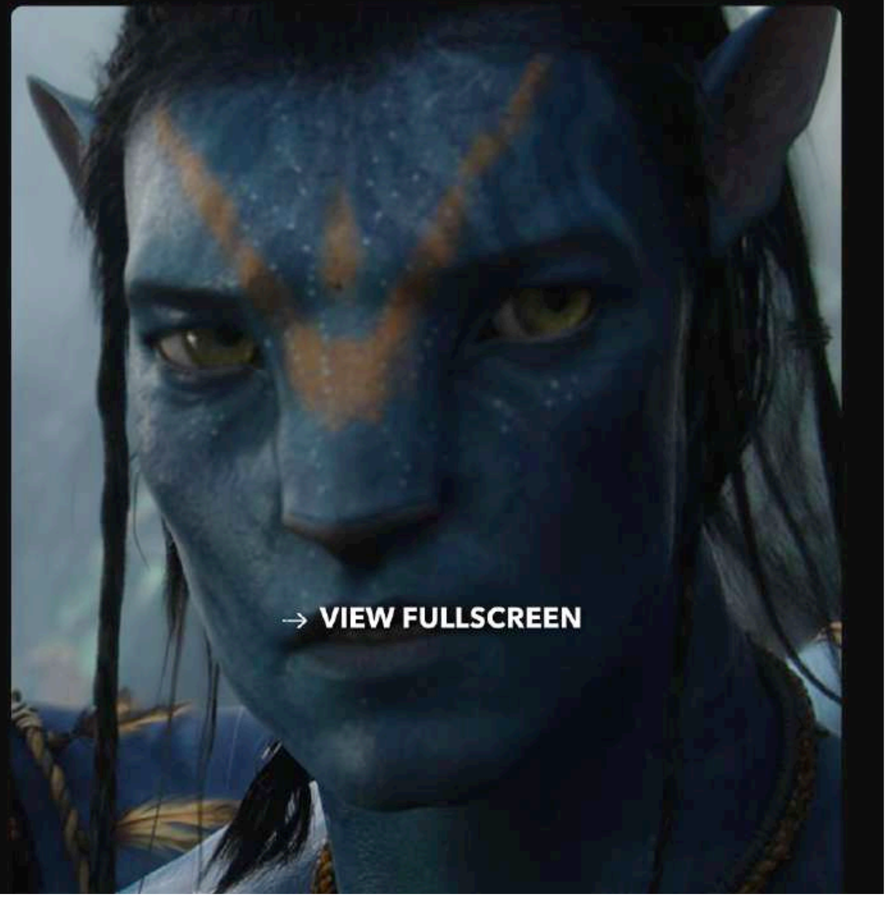
PHYSICALLY-BASED SHADING

SHARE

SHADING IS THE PROCESS OF CALCULATING HOW LIGHT INTERACTS WITH SURFACES: WHAT THE OBJECT ACTUALLY LOOKS LIKE WHEN LIGHT SHINES ON (OR THROUGH) IT.

This is incredibly complex, especially for things like hair or skin – where the light is partially shining through the surface. Weta's approach to shading is to look to real-world physics. The shading models for different surfaces are based on the actual physical properties of those surfaces. Our in-house renderers, Manuka and Gazebo, use real-world physics to calculate how light interacts with each surface – down to the level of calculating wavelengths of light separately.





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KEY PUBLICATIONS

2023
ARXIV.ORG
ROBUST AVERAGE NETWORKS FOR MONTE CARLO DENOISING
Javor Kalojanov (Unity/Wētā Digital), Kimball Thurston (Wētā FX)
Video illustration here.
AVAILABLE FROM ARXIV.ORG

2020
ACM TRANSACTIONS GRAPH TOG
MODEL PREDICTIVE CONTROL WITH A VISUOMOTOR SYSTEM FOR PHYSICS-BASED CHARACTER ANIMATION
Haegwang Eom (Visual Media Lab, KAIST and Weta Digital), Daseong Han (Handong Global University), Joseph S Shin (Handong Global University and KAIST), Junyong Noh (Visual Media Lab, KAIST)
AVAILABLE FROM THE ACM DL

2020
ACM TRANSACTIONS GRAPH TOG
SIMPLE AND SCALABLE FRICTIONAL CONTACTS FOR THIN NODAL OBJECTS
Gilles Daviet
AVAILABLE FROM THE ACM DL

2020
ACM TRANSACTIONS GRAPH TOG
WAVE CURVES: SIMULATING LAGRANGIAN WATER WAVES ON DYNAMICALLY DEFORMING SURFACES
Tomáš Skřivan (IST Austria), Andreas Söderström (Sweden), John Johansson (Weta Digital), Christoph Sprenger (Weta Digital), Ken Museth (Weta Digital), Chris Wojtan (IST Austria)
AVAILABLE FROM THE ACM DL

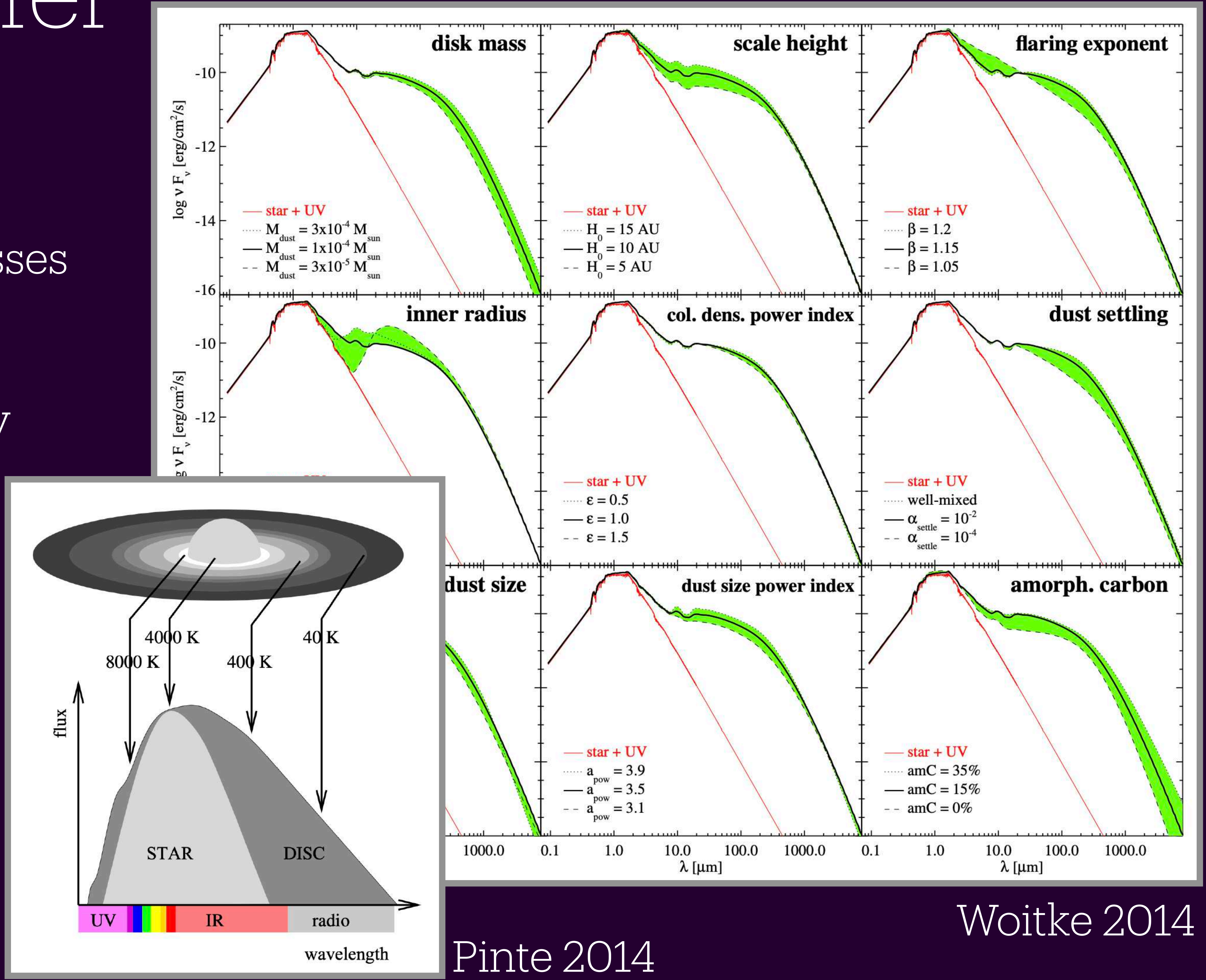
2020
ACM SIGGRAPH 2020 COURSES
ML/DL ROUNDUP
Andrew Glassner
AVAILABLE FROM THE ACM DL

2020
RENDERING COURSES 2020
ADVANCES IN MONTE CARLO RENDERING: THE LEGACY OF JAROSLAV KŘIVÁNEK
Alexander Keller (NVIDIA), Pascal Gautron (NVIDIA), Jiří Vorba (Weta Digital), Iliyan Georgiev (Autodesk), Martin Šik (Chaos Czech), Eugene d'Eon (NVIDIA), Pascal Grittmann (Saarland University), Petr Vévoda (Charles University Prague), and Ivo Kondapaneni (Charles University Prague)
PDF

Radiation Transfer

Key issue in astrophysics

- Involves the main cooling processes and also heating processes
- A lot of the chemistry is driven by radiation
- **Link between theory and observations (diagnostic RT).**



Woitke 2014

Pinte 2014

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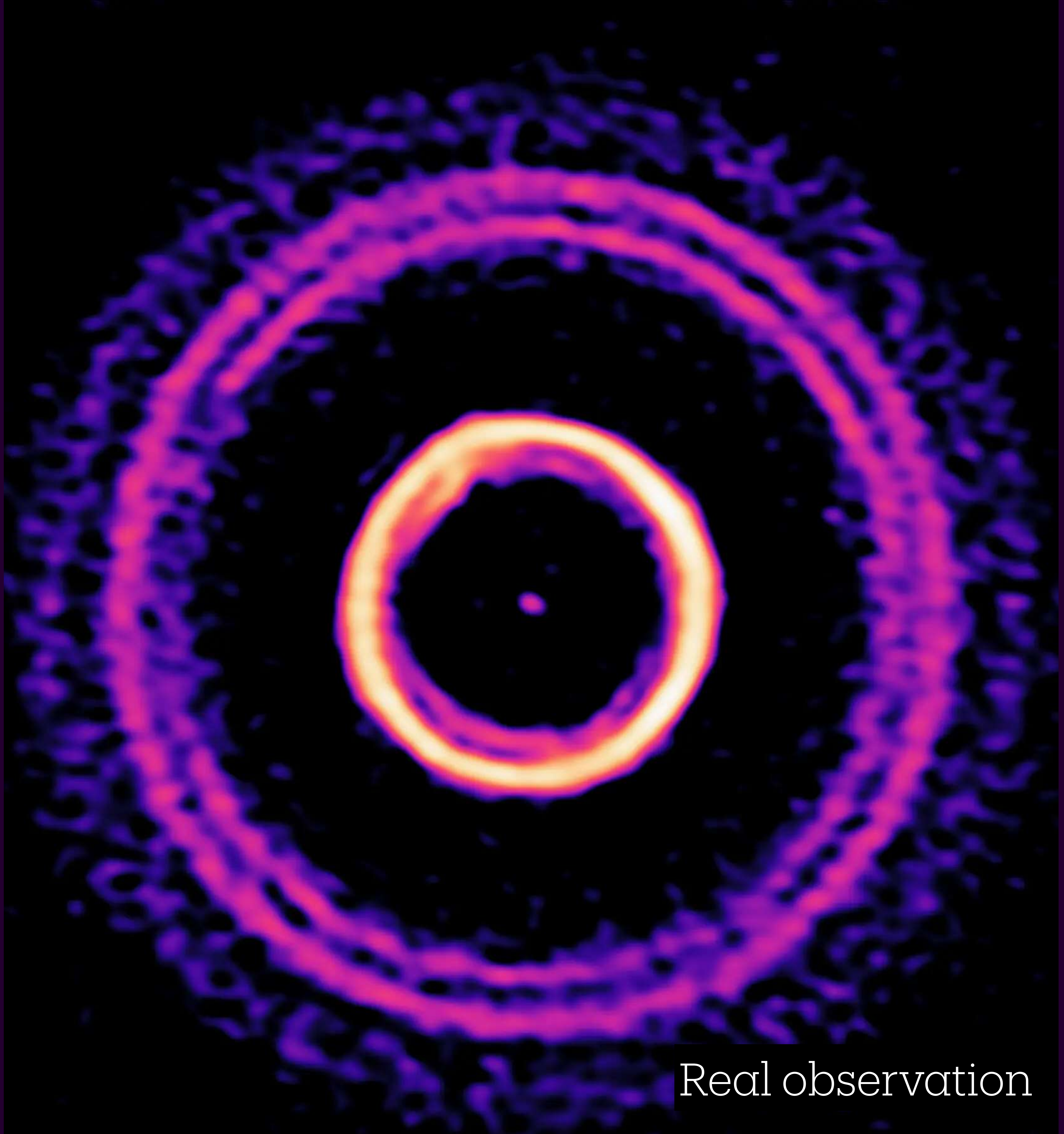

HD169142, Pérez et al. (2019)

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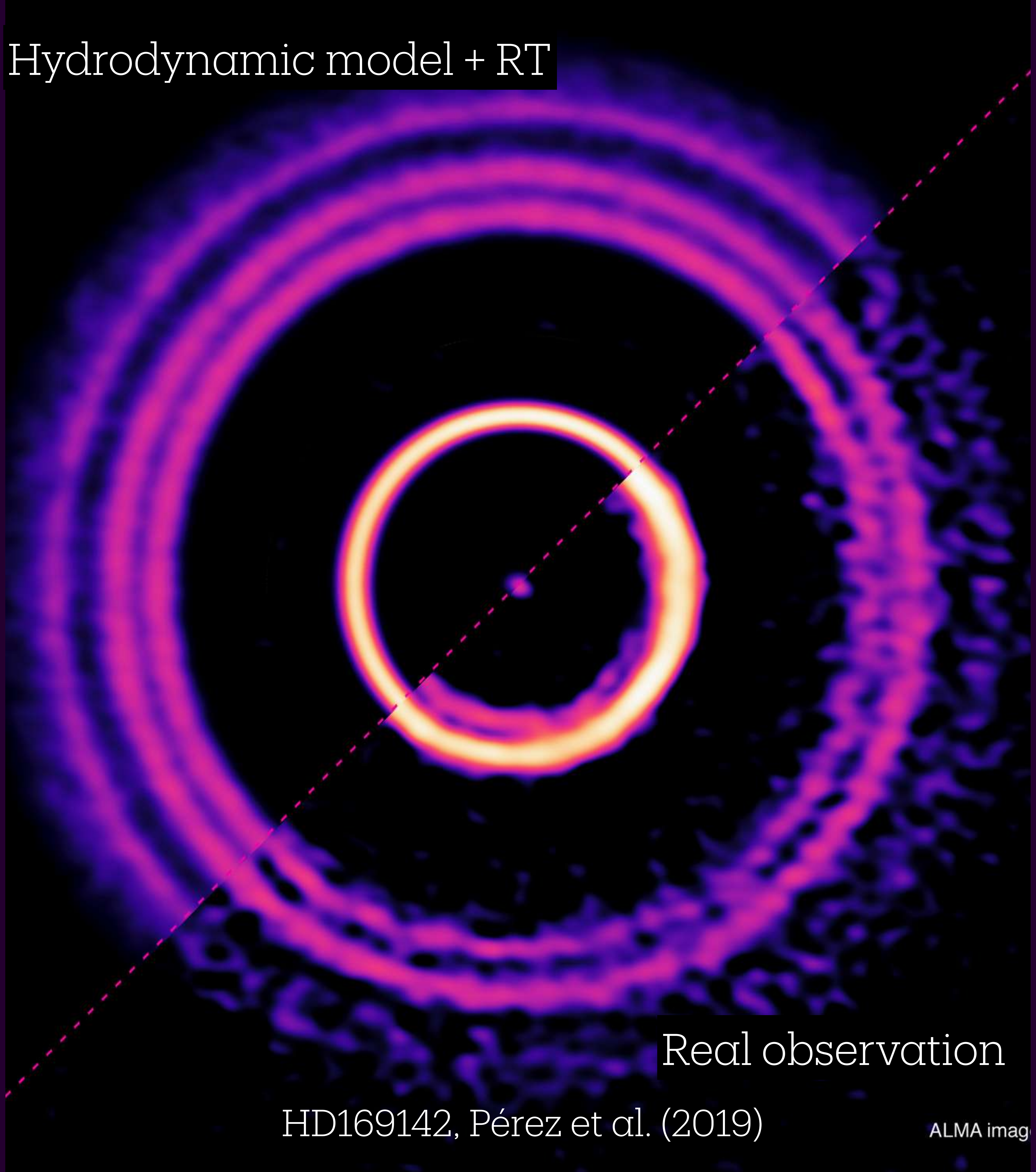


Radiation transfer approximation

- good news: we do not need to solve Maxwell's equations
- the laws of geometric optics apply sometimes.
- we can use the particle description of electromagnetic radiation and ignore diffraction (except…)
- For a diluted medium (like nebulae or some parts of protoplanetary disks)
  - Index of refraction is set to 1. —> Light travels strictly in straight lines
  - In case of scattering, light travels in straight lines between two events


Imagine a beam of light (I)
Source terms (j)
(add to the emission)
Absorption $(-\alpha I)$
(dust/planets/rebel scum)
Δs
$\Delta I = -\text{absorption} + \text{emission}$
$\Delta I = -\alpha I \Delta s + j \Delta s$
$\frac{\Delta I}{\Delta s} = -\alpha I + j$
$\frac{dI}{ds} = -\alpha I + j$

Radiation transfer equation

The radiative transfer equation is nothing more than injecting photons into a ray, and removing photons from that same ray.

$$I = I(\nu, x, y, z, \mathbf{n})$$

$$\frac{dI}{ds} = -\alpha I + j + \text{scattering}$$

opacity

Radiation transfer equation

The radiative transfer equation is nothing more than injecting photons into a ray, and removing photons from that same ray.

$$I_\nu(s_1) = I_\nu(s_0)\, e^{-\tau_\nu}$$

$$\frac{dI_\nu}{ds} = -\,\rho\kappa_\nu I_\nu$$

$$\tau_\nu(s_0, s_1) = \int_{s_0}^{s_1} \rho\kappa_\nu ds$$

mass weighted opacity

$$\alpha_\nu = \rho\kappa_\nu$$

Radiation transfer equation

Case of a medium in thermal equilibrium

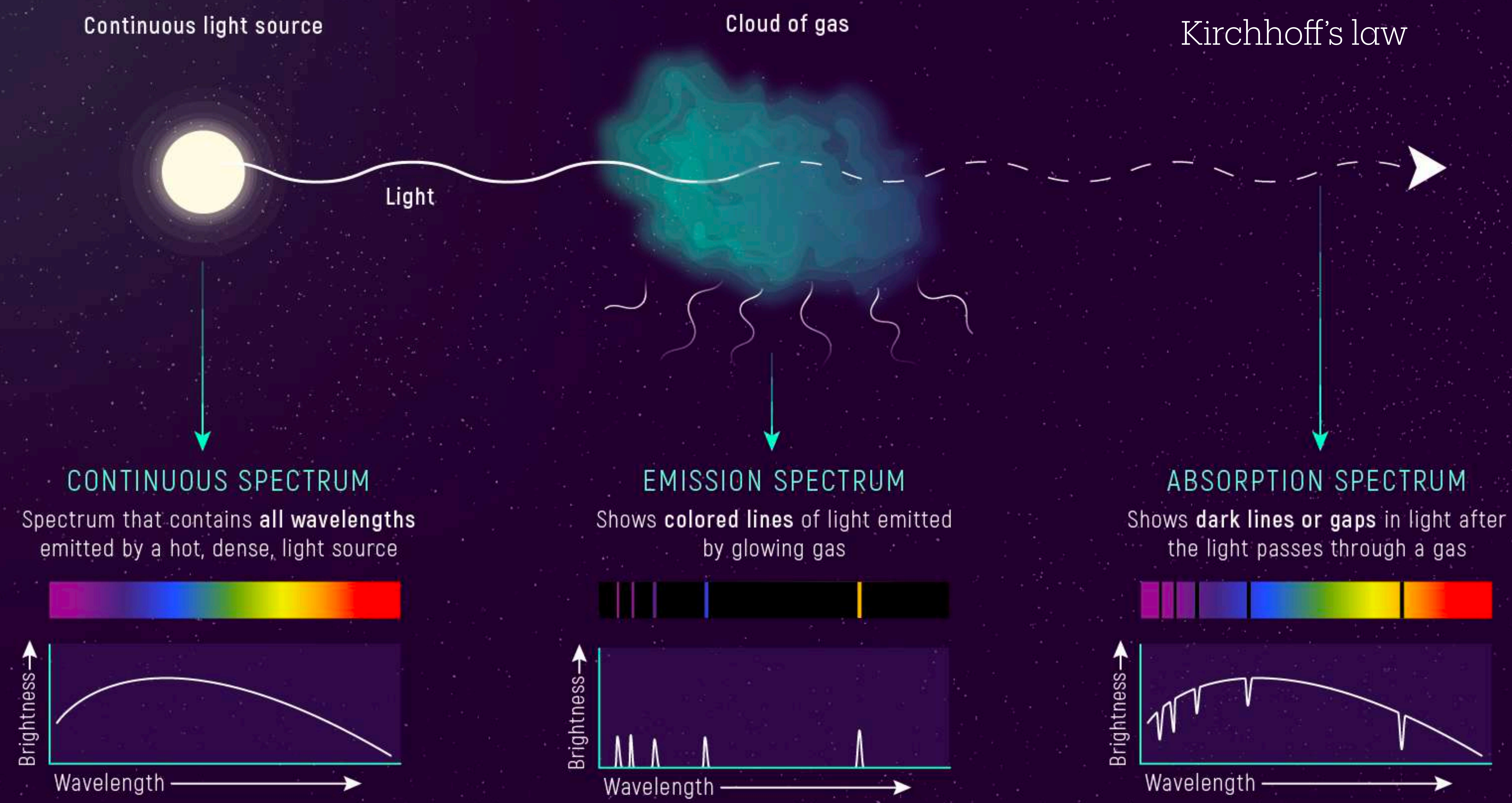
$$I_\nu = B_\nu(T)$$

$$\frac{dI_\nu}{ds} = -\alpha_\nu I_\nu + j_\nu = -\alpha_\nu B_\nu(T) + j_\nu = 0$$

$$\frac{j_\nu}{\alpha_\nu} = B_\nu(T)$$

Kirchhoff's law

Kirchhoff's law



NASA, ESA, Leah Hustak (STScI)

Radiation transfer equation in LTE

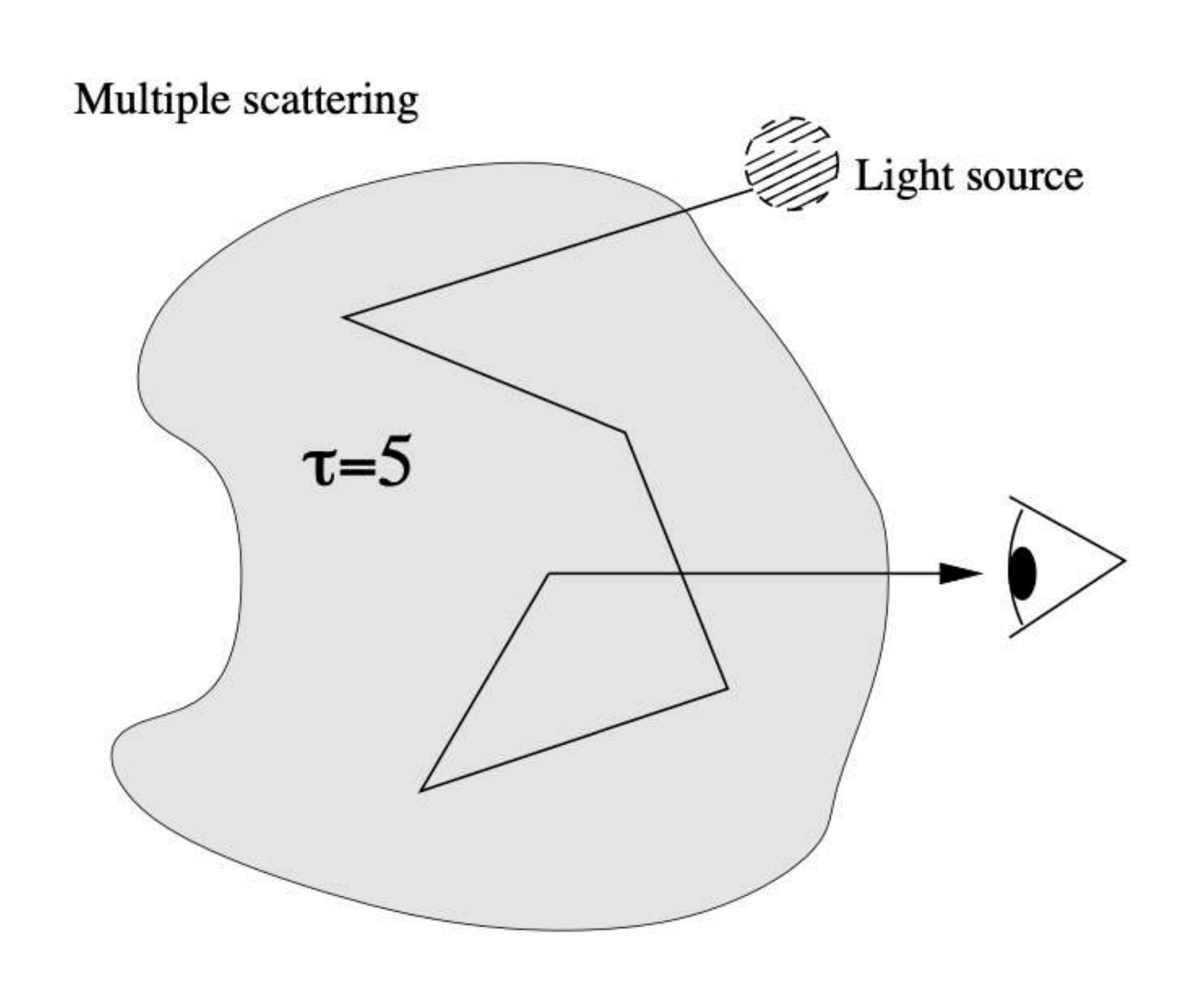
$$\frac{dI_\nu}{ds} = \rho\kappa_\nu[B_\nu(T) - I_\nu]$$

- To solve the RT for a given medium, we need to put the problem on a grid.
- Choose the right spatial resolution.
- Use a stable numerical integration scheme.
- Use all the appropriate approximations.

Why is it difficult then?

chicken-or-egg problem

- There is a lot of “input physics”.
- To compute I(x) we need to know j(x) and α(x), and to compute j(x) and α(x) we need to know I(x).
- We cannot solve the problem for each ray separately
- Add the fact that we can have multiple scattering events.



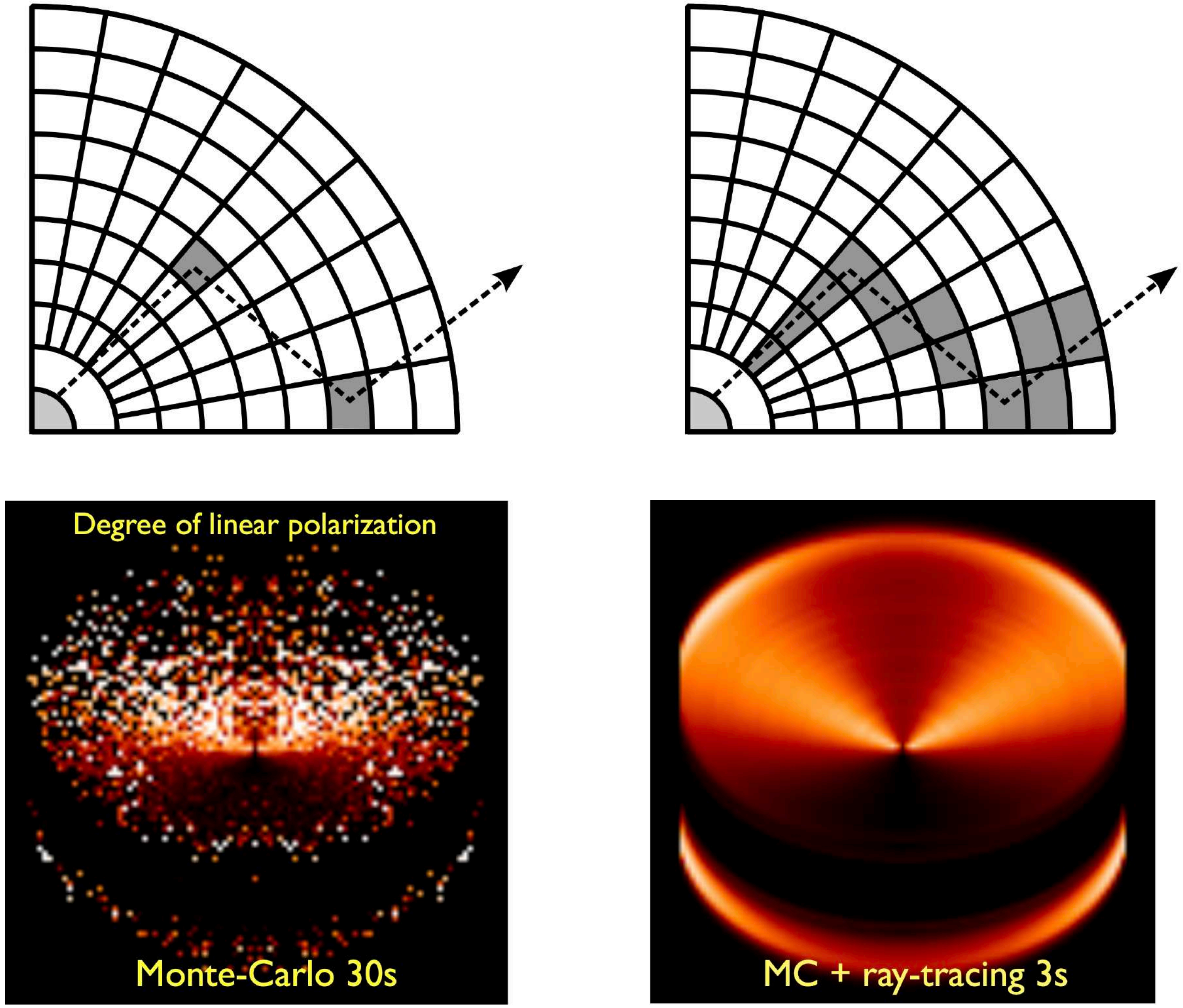
Ways of solving the RT equation

Monte Carlo method

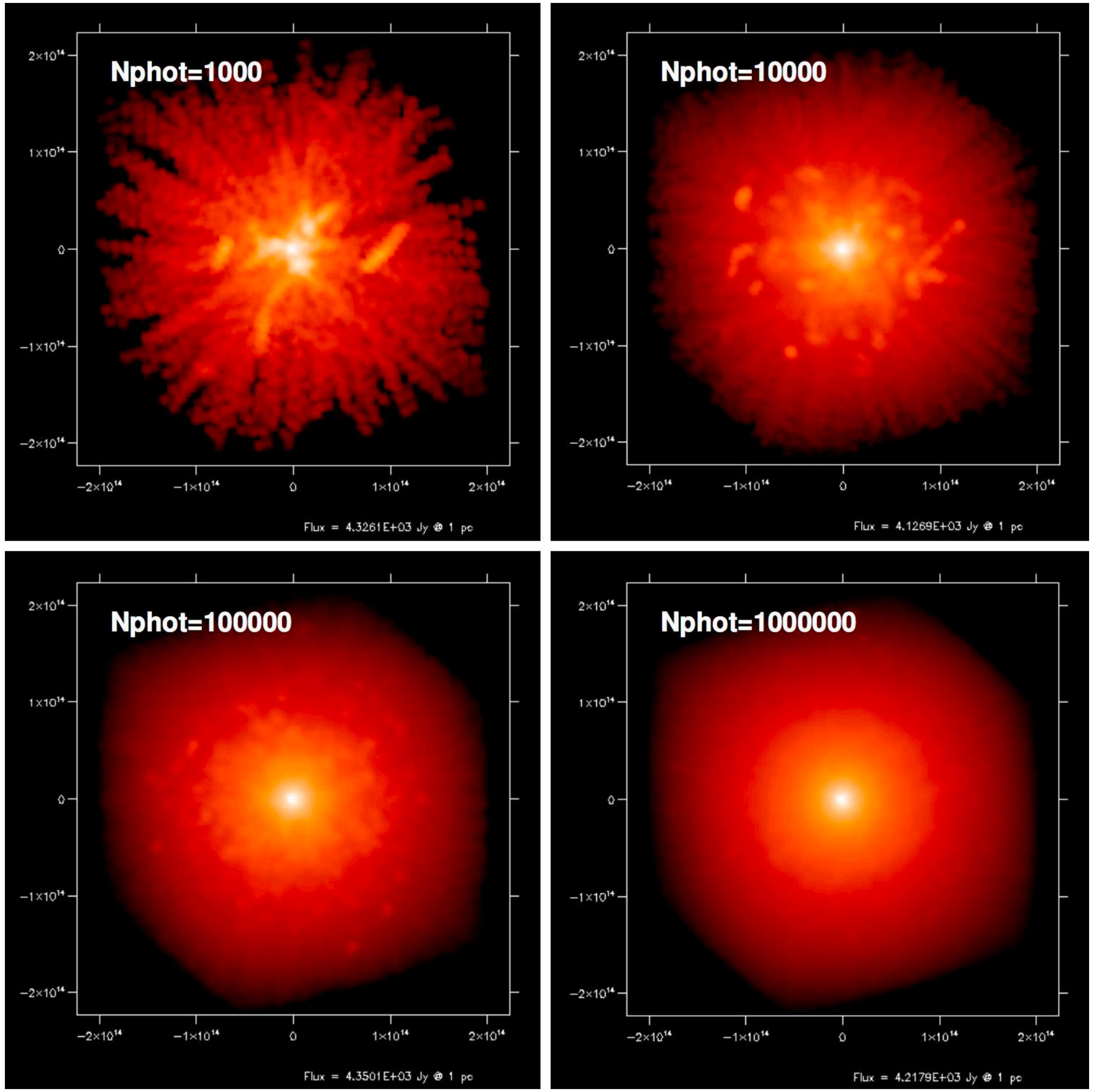
- Exact analytical solutions to basic problems (like multiple scattering) are rare and limited to simple geometries.
- One of the main methods that allows a general solution of the RT problem is the **Monte Carlo** method.
- follow the path of a photon from one scattering event to the next and use random numbers to decide in which direction and how far the photon will proceed.
- Repeat for millions of photons.

- we want to predict what we would observe if we look the cloud.

Monte Carlo examples



From Pinte (2014)



From radmc3d's manual

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- Gas kinematics (line emission and absorption)
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