UNIVERSITEIT GENT

Dust radiative transfer in galaxies

Maarten Baes

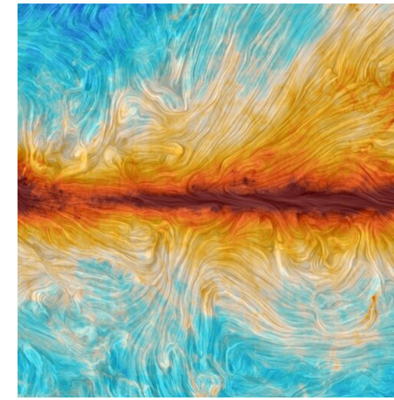
Fifth Pan Dust Conference, Tucson, 10-14 November 2025

Interaction between dust and radiation

Dust absorption: extremely efficient at UV and blue wavelengths

Dust scattering: extremely efficient at UV and blue wavelengths

Dust emission: thermal re-emission of absorbed energy at MIR to mm wavelengths



Polarization: due to scattering, absorption or emission of aligned grains

Dust radiative transfer

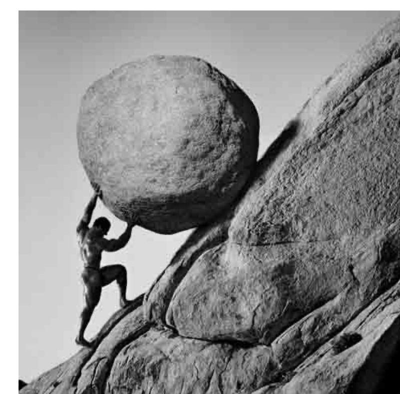
primary emission extinction (absorption + scattering)

$$\frac{\mathrm{d}I}{\mathrm{d}s}(\boldsymbol{x},\boldsymbol{k},\lambda) = \boxed{j^{\star}(\boldsymbol{x},\lambda)} - \boxed{\kappa^{\mathrm{ext}}(\boldsymbol{x},\lambda)\,\rho(\boldsymbol{x})\,I(\boldsymbol{x},\boldsymbol{k},\lambda)}$$
$$+ \boxed{j^{\mathrm{th}}(\boldsymbol{x},\lambda)} + \boxed{\kappa^{\mathrm{sca}}(\boldsymbol{x},\lambda)\,\rho(\boldsymbol{x}) \int I(\boldsymbol{x},\boldsymbol{k}',\lambda)\,\Phi(\boldsymbol{x},\boldsymbol{k},\boldsymbol{k}',\lambda)\,\mathrm{d}\Omega'}$$

dust emissivity scattering emissivity

Difficult to solve ?

- partial integrodifferential equation in 6D
- nonlocal (in all dimensions) and nonlinear
- dust emissivity is not known a priori
- we have omitted time dependence and polarization



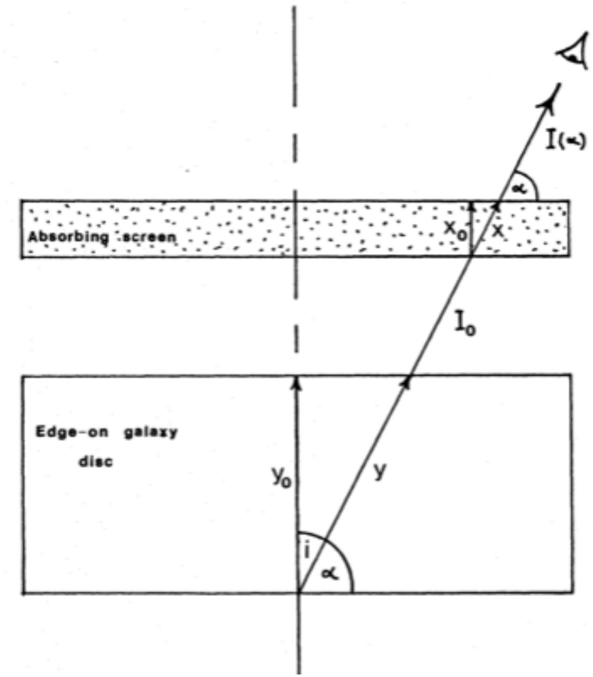
Can we simplify the radiative transfer problem ?

Attractive options to simplify the RT problem:

- plainly ignore dust
- neglect/approximate scattering
- use a screen geometry
- …

Shown by many authors since the late 1980s that these simplifications are never satisfactory.

Witt et al. 1992: "…much previous work on the effects of dust on stellar radiation has been simplistic, wrong, and usually both !"



Disney et al. 1989; Witt et al. 1992; Byun et al. 1994; Baes & Dejonghe 2001

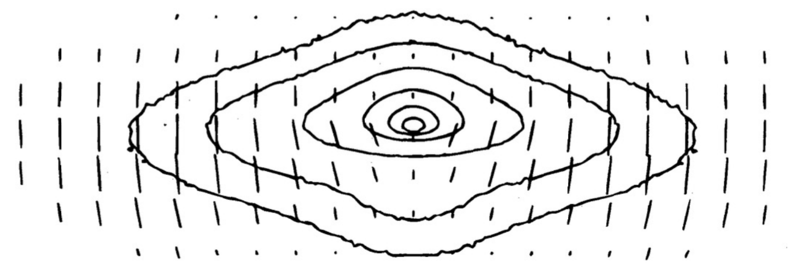
Dust radiative transfer in galaxies in 1990s

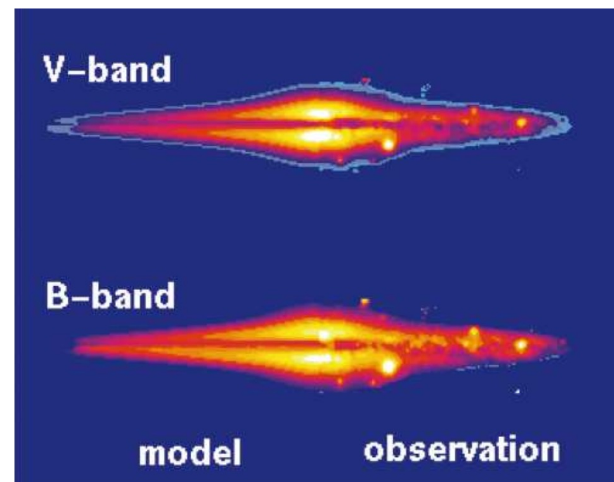
First RT models in a “realistic” 2D galaxy geometry:

- treatment of absorption, scattering, and scattering polarization
- first attempts to fit RT models to observed images of edge-on galaxies

Different solution methods:

- Monte Carlo RT
- ray-tracing





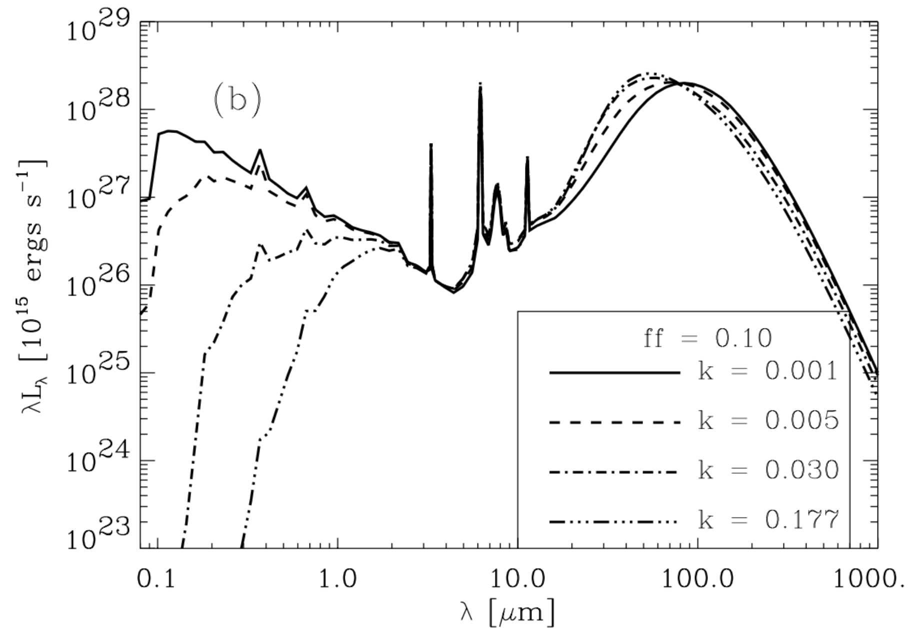
Byun et al. 1994; Bianchi et al. 1996; Xilouris et al. 1997, 1998; Witt et al. 1997

Dust radiative transfer in galaxies in 2000s

Improvement on different aspects

- inclusion of thermal dust emission (equilibrium and stochastically heated dust grains)
- transition from 2D to 3D
- inclusion of inhomogeneous dust geometries
- more advanced grids

Shift to Monte Carlo RT as the preferred method



Witt & Gordon 2000; Bianchi et al. 2000; Popescu et al. 2000, 2011; Gordon et al. 2001; Misselt et al. 2001

Current state-of-the-art dust radiative transfer

Methods and numerics

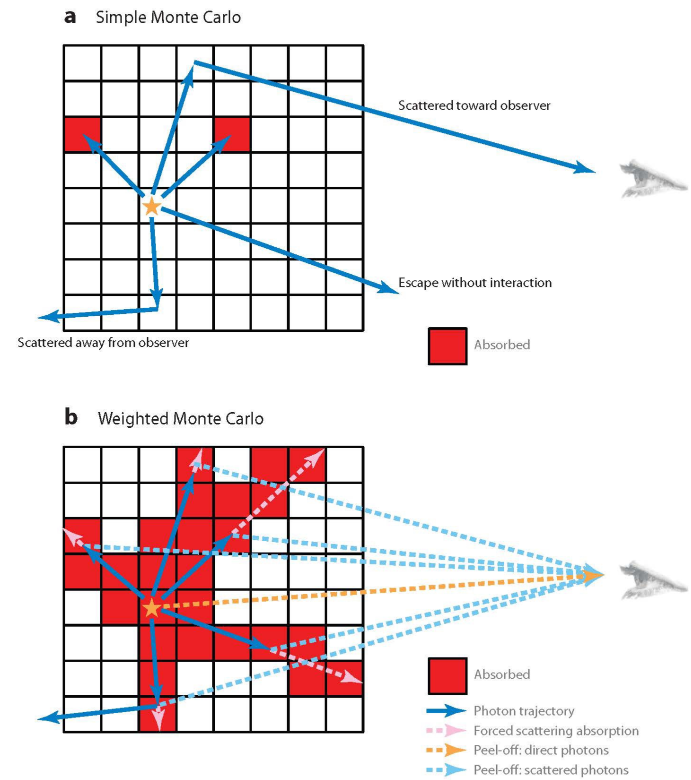
- Monte Carlo method rules
- MC optimization tricks: weighted MCRT
- parallelization is useful

Physics included

- “full” dust treatment
- codes often also include other physics (NLTE line RT, X-ray RT…)

No geometric limitations

- arbitrary 3D geometries
- hierarchical and unstructured grids



Steinacker et al. 2013

Three-Dimensional Dust Radiative Transfer*

Jürgen Steinacker,[1,2] Maarten Baes,[3] and Karl D. Gordon[4,3]

[1]UJF-Grenoble 1/CNRS-INSU, Institut de Planétologie et d'Astrophysique de Grenoble (IPAG), UMR 5274, Grenoble, F-38041, France; email: stein@mpia.de

[2]Max-Planck-Institut für Astronomie, D-69117 Heidelberg, Germany

[3]Sterrenkundig Observatorium, Universiteit Gent, B-9000 Gent, Belgium; email: maarten.baes@ugent.be

[4]Space Telescope Science Institute, Baltimore, Maryland 21218; email: kgordon@stsci.edu

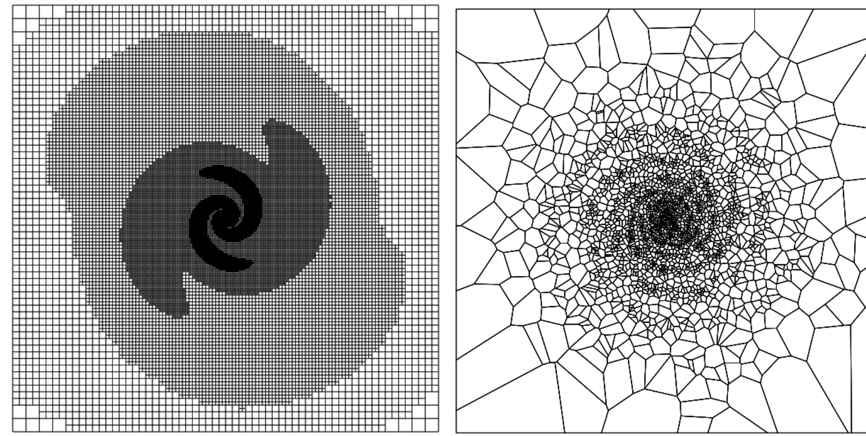
Steinacker et al. 2013

Code name	Type[b]	Reference	Main application
SKIRT	MC	Baes et al. (2003, 2011)	Galaxies, AGNs
(no name)	MC	Bethell (2004, 2007)	Star-forming (SF) clouds
TRADING	MC	Bianci, Ferrara & Giovanardi (1996); Bianchi (2008)	Galaxies
RADISHE	MC	Chakrabarti et al. (2007), Chakrabarti & Whitney (2009)	Galaxies
(no name)	MC	Doty, Metzler & Palotti (2005)	SF clouds
RADMC-3D	MC	Dullemond (2012)	SF disks
MOCASSIN	MC	Ercolano, Barlow & Storey (2005)	Photoionized regions
(no name)	MC	Fischer, Henning & Yorke (1994)	SF disks
(no name)	MC	Gonçalves, Galli & Walmsley (2004)	SF clouds
STOKES	MC	Goosmann & Gaskell (2007)	AGNs
DIRTY	MC	Gordon et al. (2001), Misselt et al. (2001)	Galaxies, nebulae
TORUS	MC	Harries (2000), Harries et al. (2004)	SF disks
(no name)	MC	Heymann & Siebenmorgen (2012)	SF disks, AGNs
SUNRISE	MC	Jonsson (2006); Jonsson, Groves & Cox (2010)	Galaxies
CRT	MC	Juvela & Padoan (2003), Juvela (2005)	SF clouds
(no name)	MC	Lucy (1999, 2005)	Supernovae
MCMax	MC	Min et al. (2009, 2011)	SF disks
STSH	MC	Murakawa et al. (2008)	SF disks
MCTRANSF	MC	Niccolini, Woitke & Lopez (2003), Niccolini & Alcolea (2006)	SF disks
mcsim mpi	MC	Ohnaka et al. (2006)	Carbon stars
MCFOST	MC	Pinte et al. (2006)	SF disks
HYPERION	MC	Robitaille (2011)	SF clouds
PHAETHON	MC	Stamatellos et al. (2004, 2005)	SF cores
STEINRAY	FD	Steinacker et al. (2003)	SF disks
	RayT	Steinacker et al. (2006)	SF cores
(no name)	FD	Stenholm, Stoerzer & Wehrse (1991)	SF disks, AGNs
HO-CHUNK	MC	Whitney & Wolff (2002)	SF disks
MC3D	MC	Wolf & Henning (2000, 2003b)	SF disks, SF cores, AGNs
(no name)	MC	Wood & Reynolds (1999), Bjorkman & Wood (2001)	SF disks, galaxies
(no name)	RayT	Xilouris et al. (1997), Misiriotis et al. (2000)	Galaxies

Discretization of the dusty medium

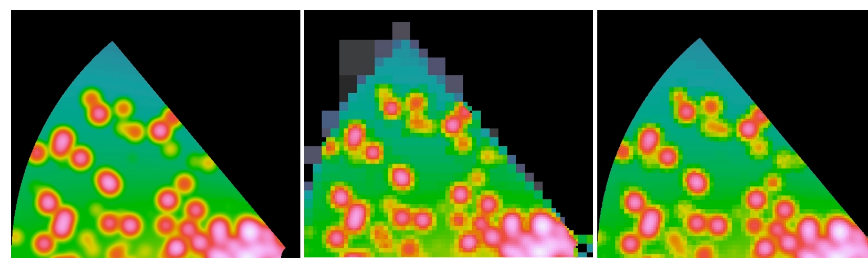
Required grid specifications

- reduce number of cells as much as possible
- large dynamic range
- traversing grids should be efficient



Modern MCRT codes: different grid types and ray-tracing algorithms

- hierarchical grids
- Voronoi grids
- tetrahedral grids



Kurosawa & Hillier 2001; Niccolini & Alcolea 2006; Bianchi 2008; Camps et al. 2013 ; Saftly et al. 2013, 2014; Lauwers et al. 2024

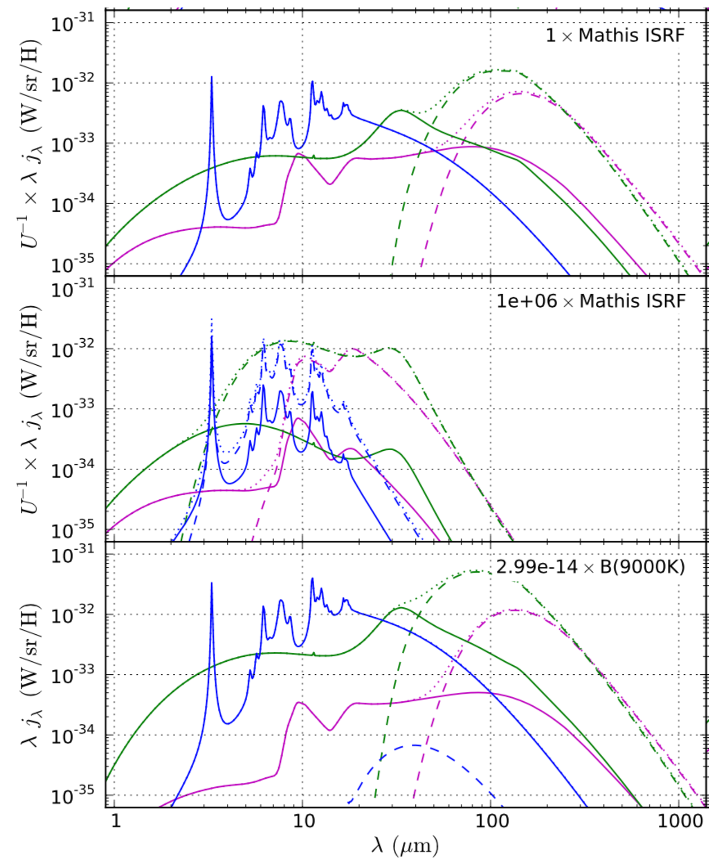
Calculation of thermal dust emission

If we know the distribution and properties of stars and dust, we can in principle

- determine ISRF in every cell
- calculate the dust temperature distribution
- predict the thermal emission at infrared-submm wavelengths

Computationally expensive

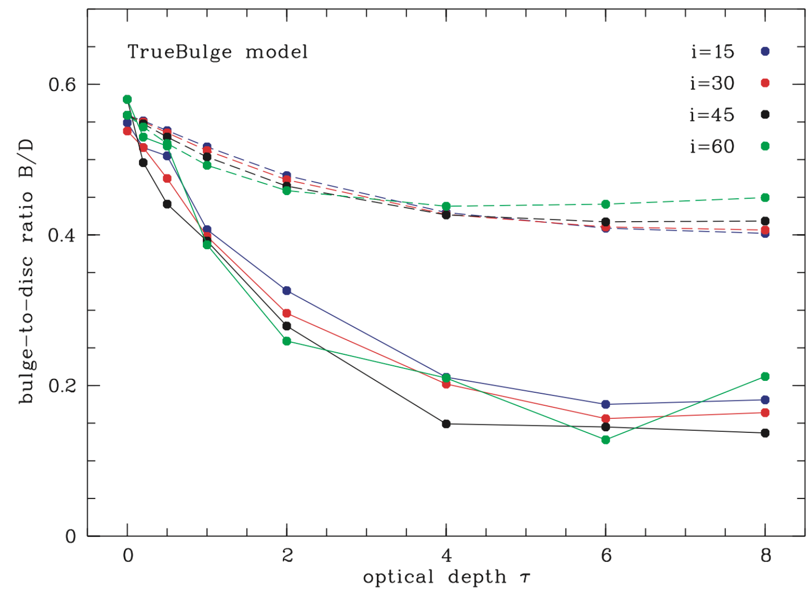
- separate calculations for each cell, each dust grain type, and each grain size bin
- sometimes iteration is required



Camps et al. 2015

Dust RT based on simple toy models

Useful to investigate the systematic effect of dust attenuation

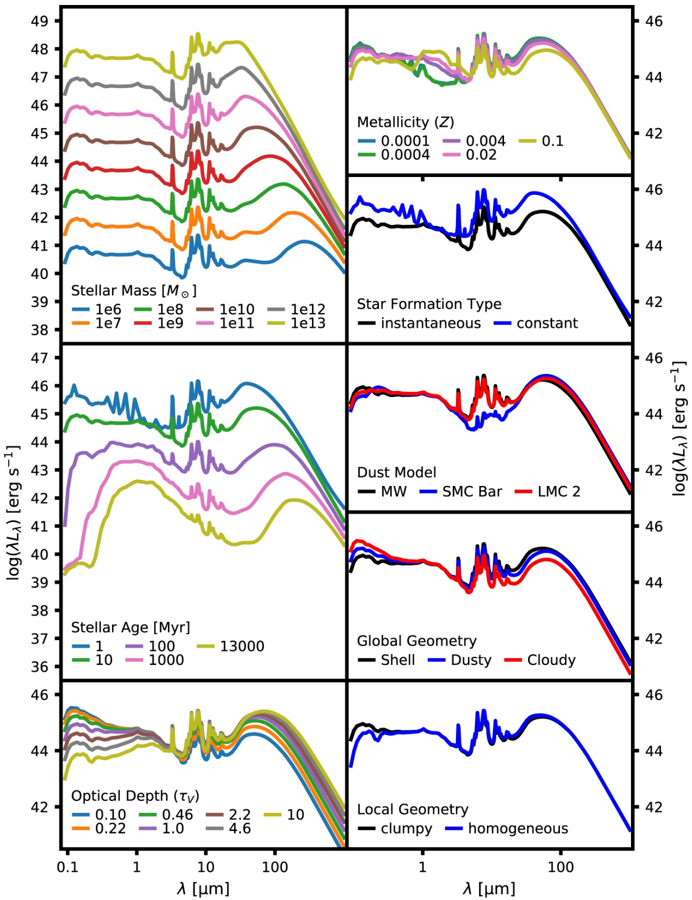


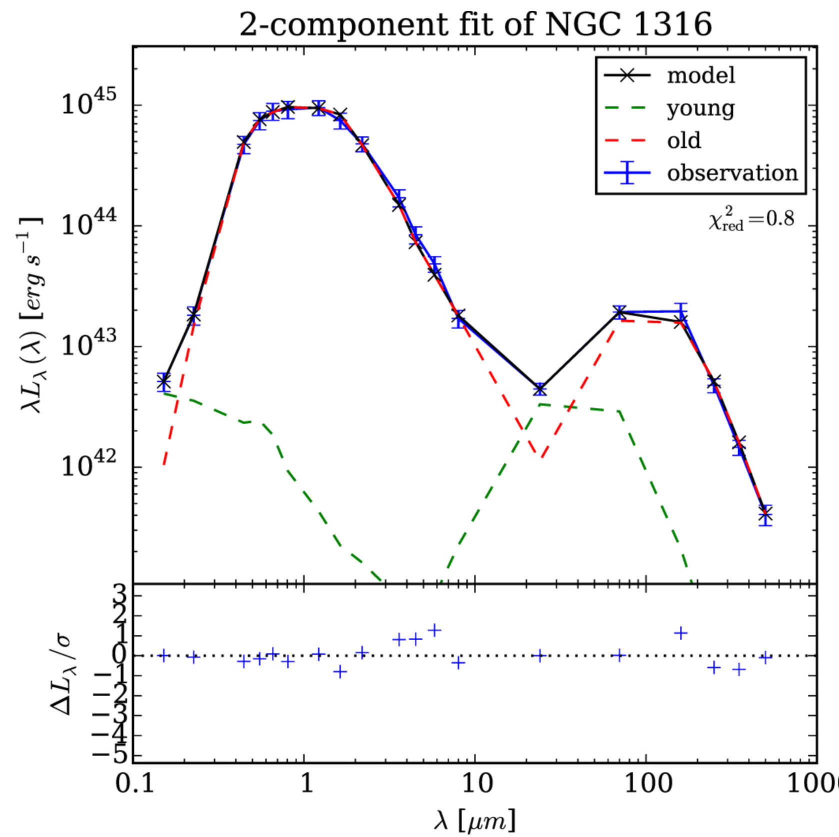
General observations

- most apparent observables are affected by dust (fluxes, apparent sizes, bulge fractions, kinematics…)
- star-dust geometry (including clumpiness) is crucial
- scattering cannot be approximated

Witt & Gordon 2000; Tuffs et al. 2004; Pierini et al. 2004; Gadotti et al. 2010; Pastrav et al. 2013

Libraries of galaxy RT models



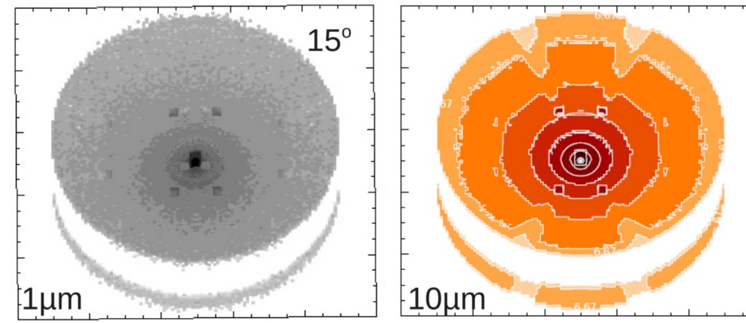


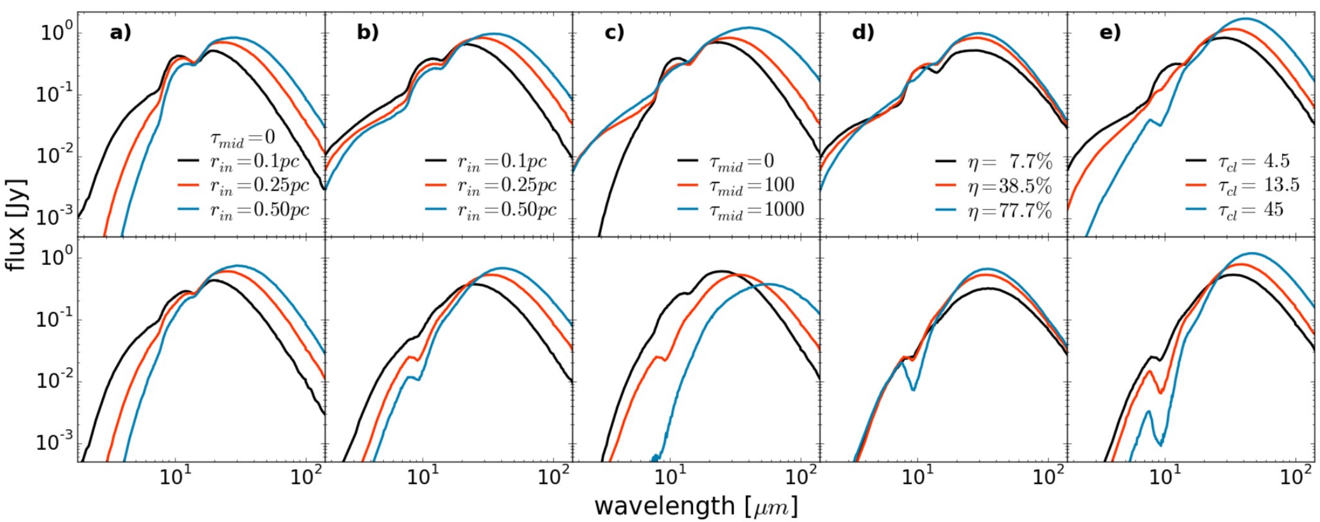
Law et al. 2018, 2021; Efstathiou et al. 2022; Varnava & Efstathiou 2024

Libraries of AGN RT models

Libraries of 2D smooth and 3D clumpy and two-phase torus models

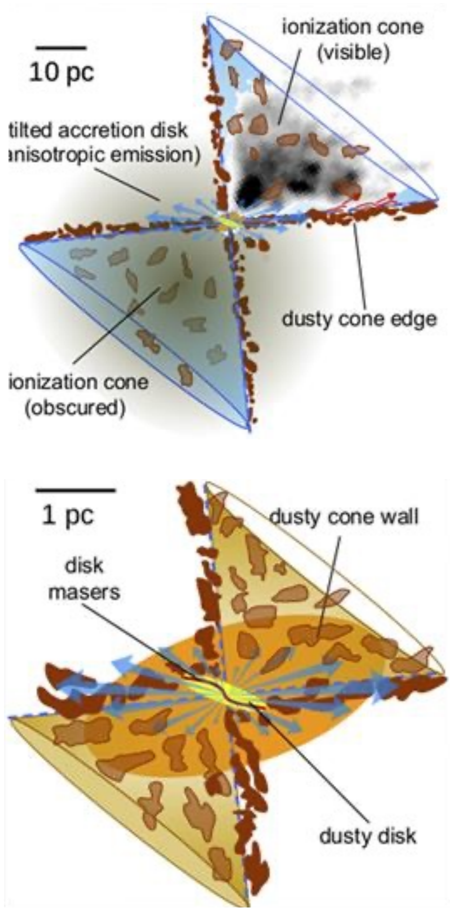
- included in many SED fitting codes
- widely used to interpret AGN SEDs

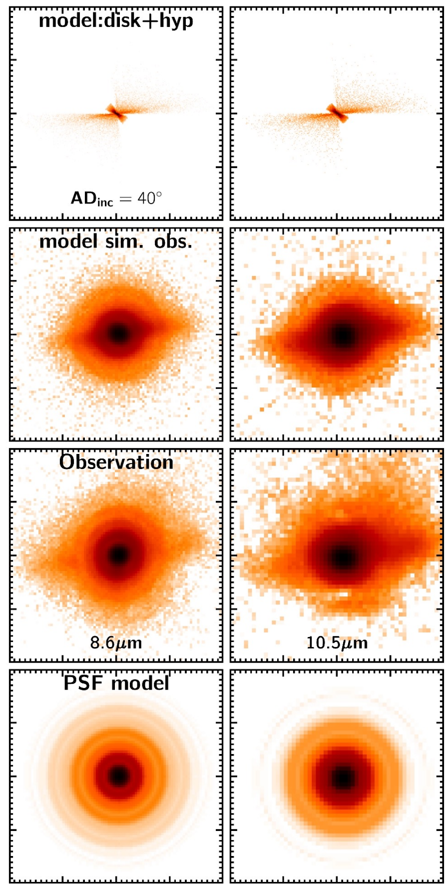


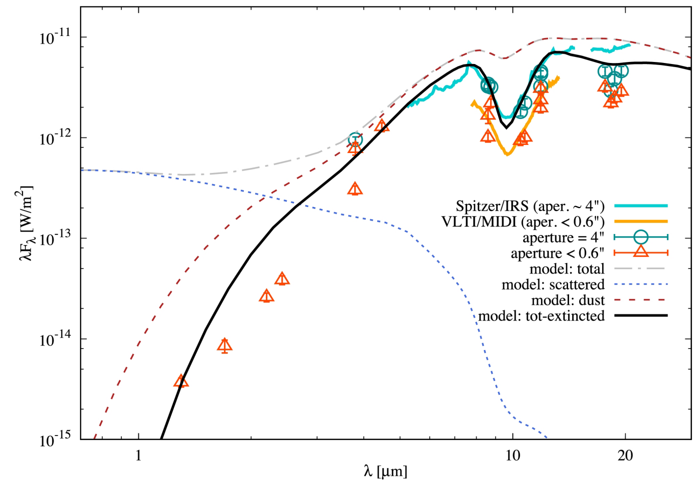


Fritz et al. 2006
Nenkova et al. 2008
Stalevski et al. 2012, 2016
Siebenmorgen et al. 2015
Hönig & Kishimoto 2017
Nikuta et al. 2021
Reyes-Amador et al. 2025

A radiative transfer model for Circinus







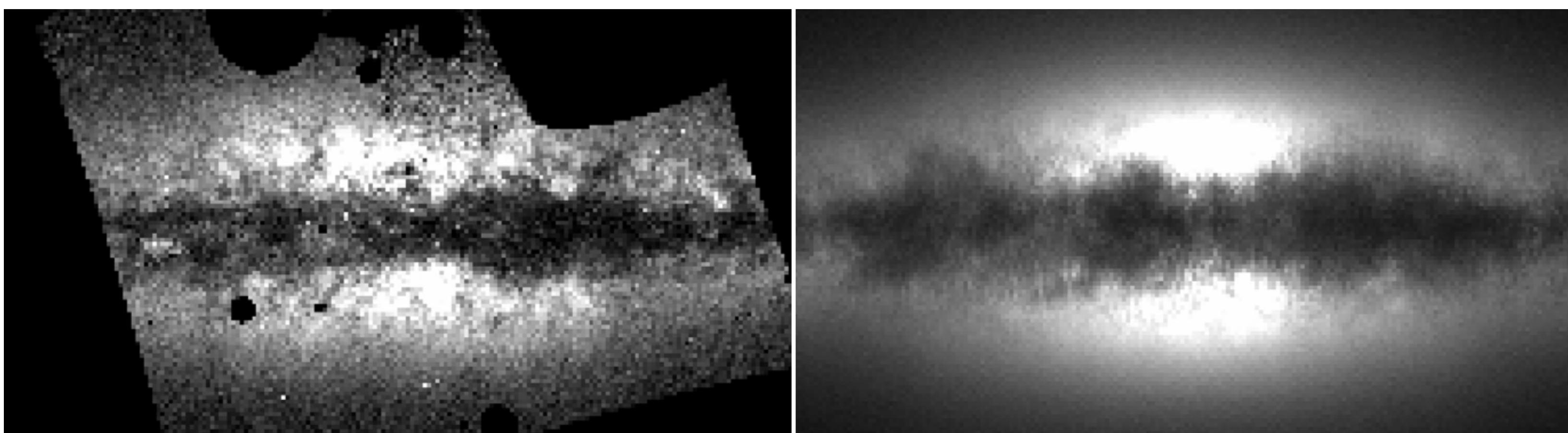
Toy model for can explain wide set of data including SED, imaging, interferometry, polarization…

Stalevski et al. 2017, 2019, 2023
Kakkad et al. 2023
Isbell et al. 2023

Fitting RT models to observed images

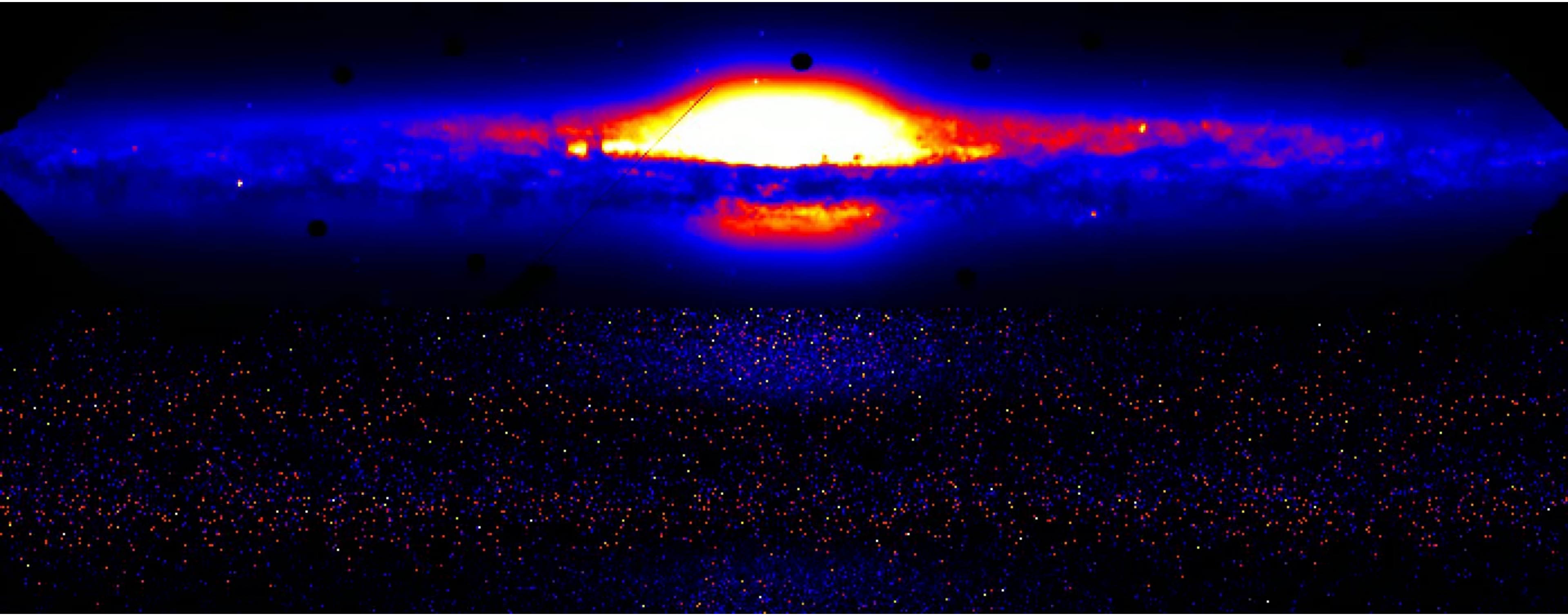
Challenging problem:

- simple galaxy model easily contains 10+ free parameters
- individual image generation is costly
- RT models have MC noise: make gradient optimization methods challenging
- most efforts focused on edge-on spirals: clear dust attenuation signature



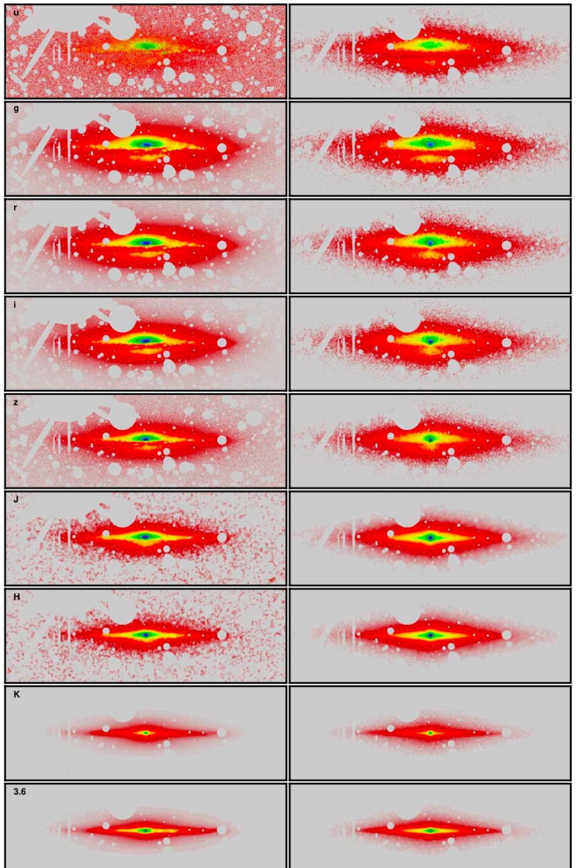
Schechtman-Rook et al. 2012

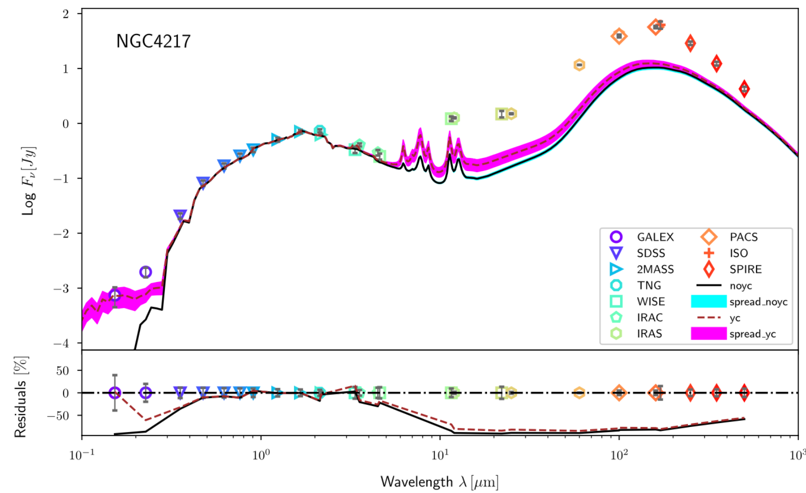
Fitting RT models to observed images



De Geyter et al. 2013, 2014

Dust energy balance in edge-on spiral galaxies





FIR fluxes inferred from 2D RT models fit to UV-NIR images underestimate the observed fluxes. Probably due to small- and large-scale dust structures.

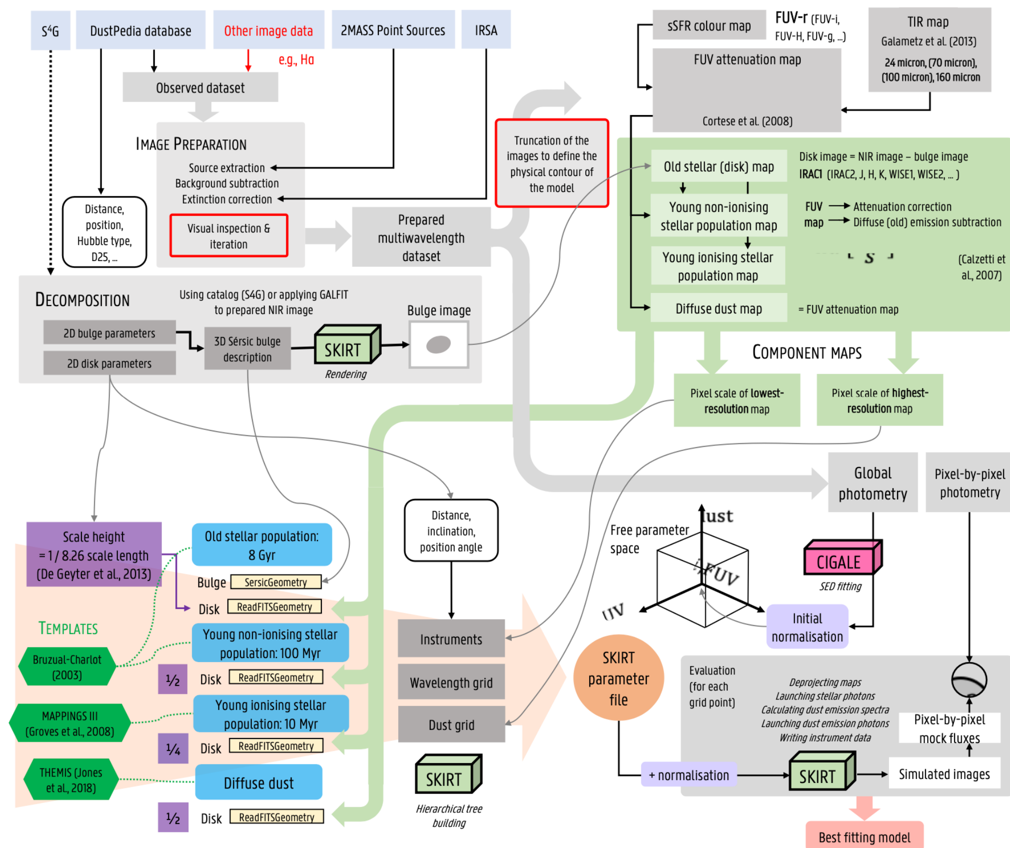
De Geyter et al. 2015; Saftly et al. 2015; Mosenkov et al. 2016, 2018

Fitting RT models to images of face-on galaxies

Fitting parametrized RT models to face-on galaxies is almost impossible

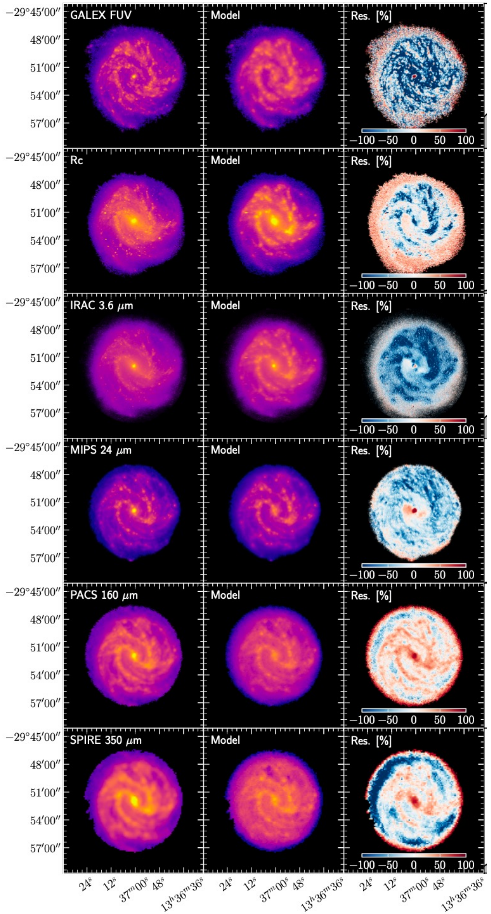
Alternative approach: construct model based on

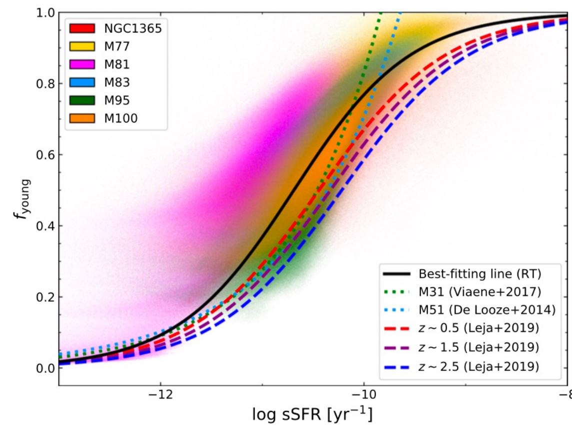
- deprojecting images
- adding vertical structure



De Looze et al. 2014
Williams et al. 2019
Verstocken et al. 2020
Viaene et al. 2020
Nersesian et al. 2020a,b

Fitting RT models to images of face-on galaxies



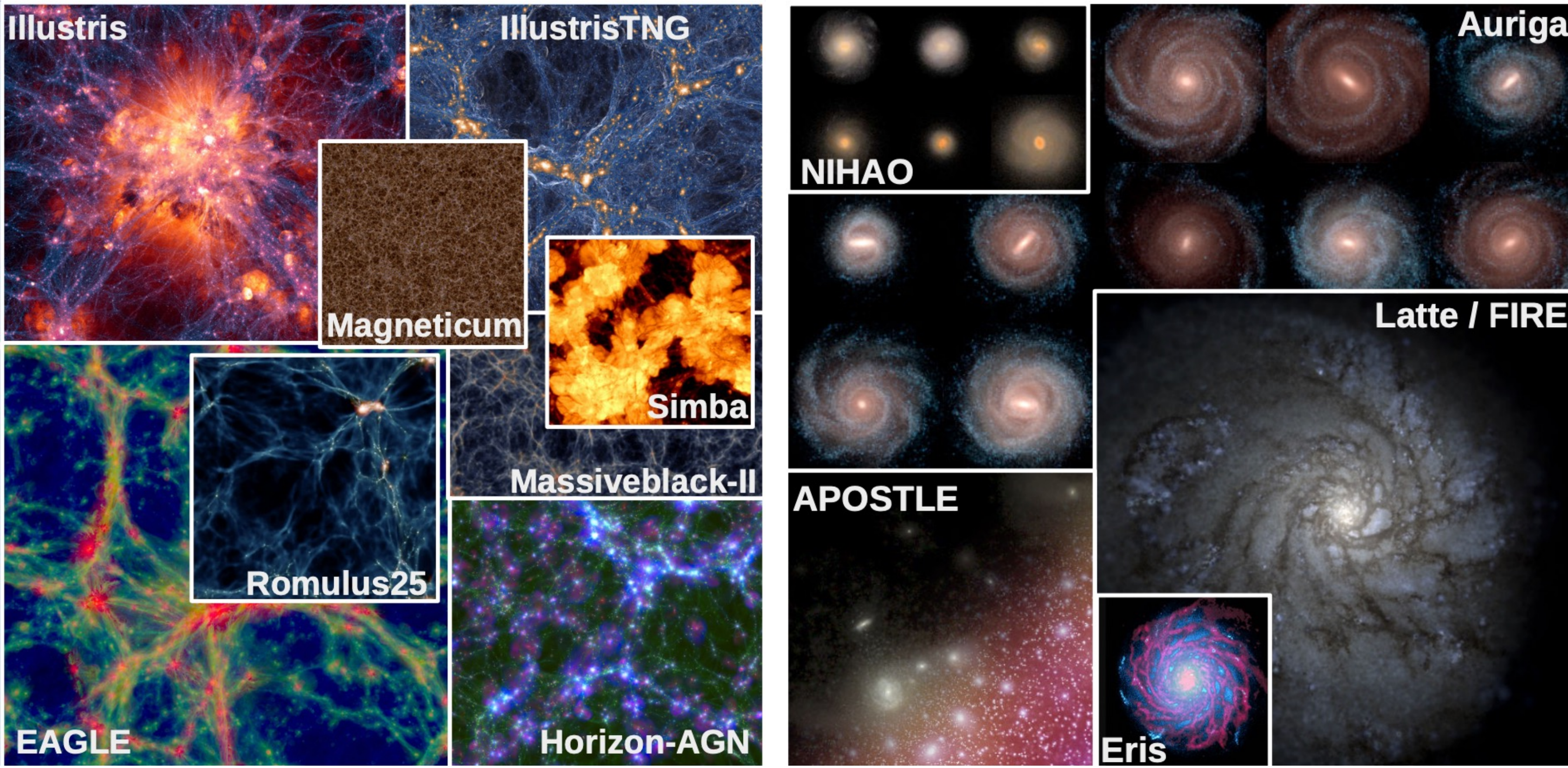


De Looze et al. 2014
Williams et al. 2019
Verstocken et al. 2020
Viaene et al. 2020
Nersesian et al. 2020a,b

Global results based on limited number of models

- 30 to 40% of the stellar emission absorbed by dust
- dust heating dominated by young stellar population
- old population can contribute up to 50%

Cosmological galaxy formation simulations



Vogelsberger et al. 2019

Comparison of simulated and observed galaxies

Numerical simulations

- predict the 3D distribution of particles/cells with associated properties
- easy to calculate physical galaxy properties (stellar mass, SFR…)

Astronomical observations

- measure 2D distribution of light on plane of the sky
- yield fluxes, images, SEDs, polarization maps…

Forward radiative transfer modelling allows apples-to-apples comparison, including crucial aspects such as morphology, kinematics…

Inserting the dust

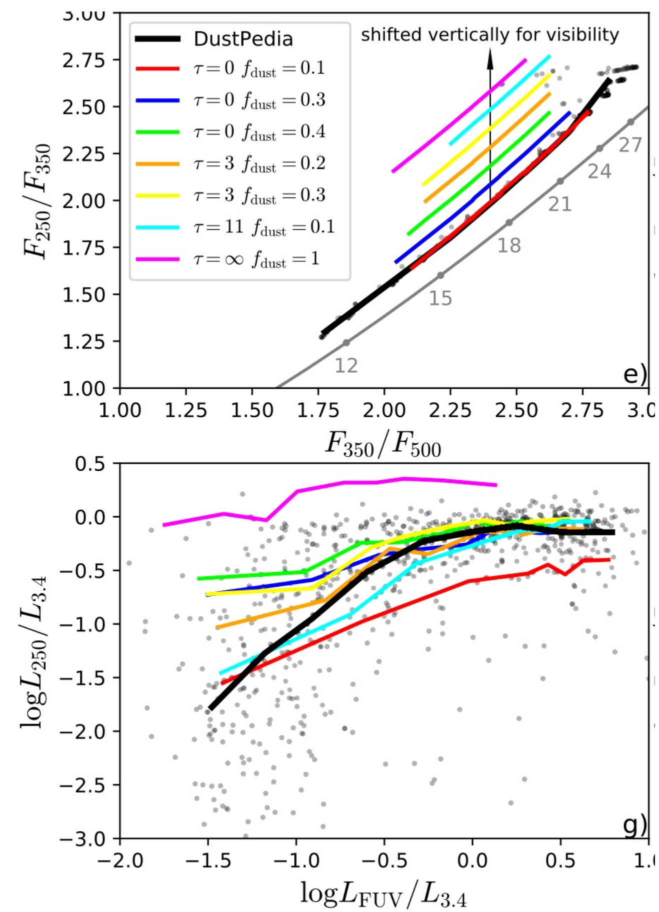
Large-volume cosmological volumes typically do not include dust as a separate hydrodynamical species

Solution: use a proxy/recipe to insert dust in the simulated galaxies based on ISM properties

Common approach: assume fixed dust-to-metal ratio (calibrate against observational data)

Note: some recent cosmological simulation include dust physics (see later)

Trčka et al. 2022

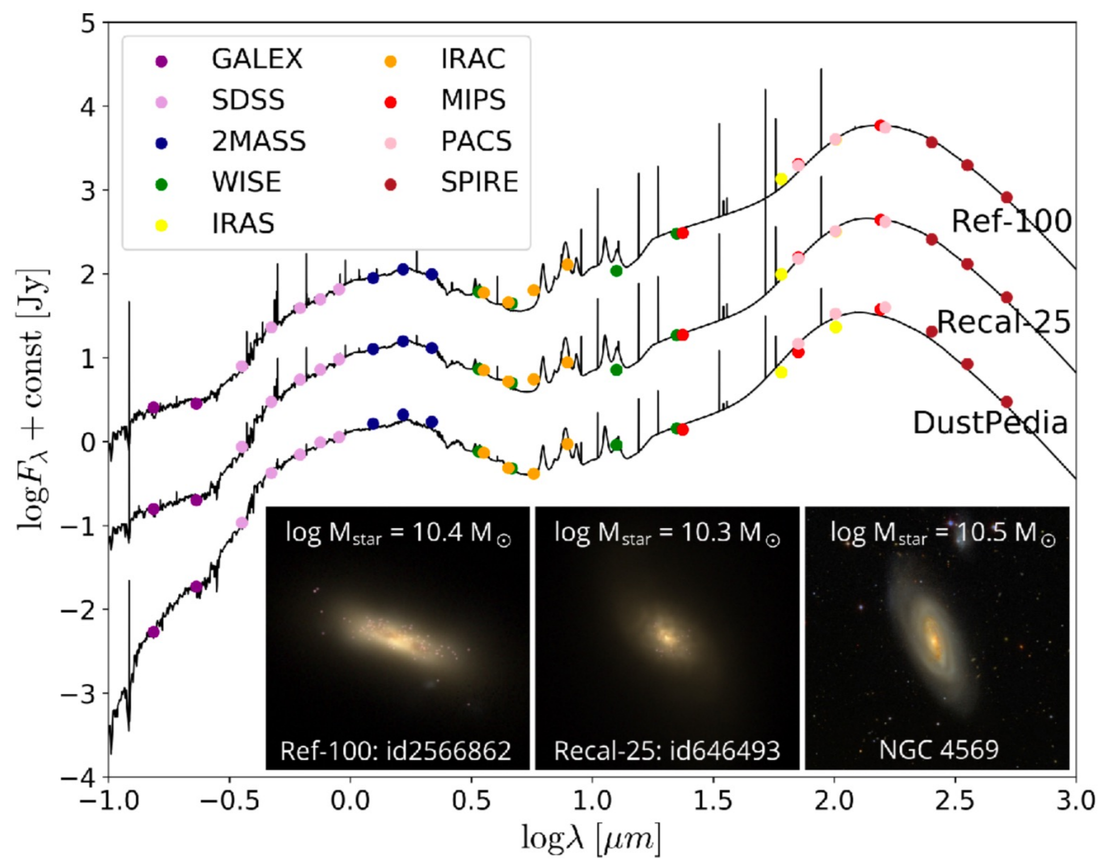


Integrated broadband fluxes and SEDs

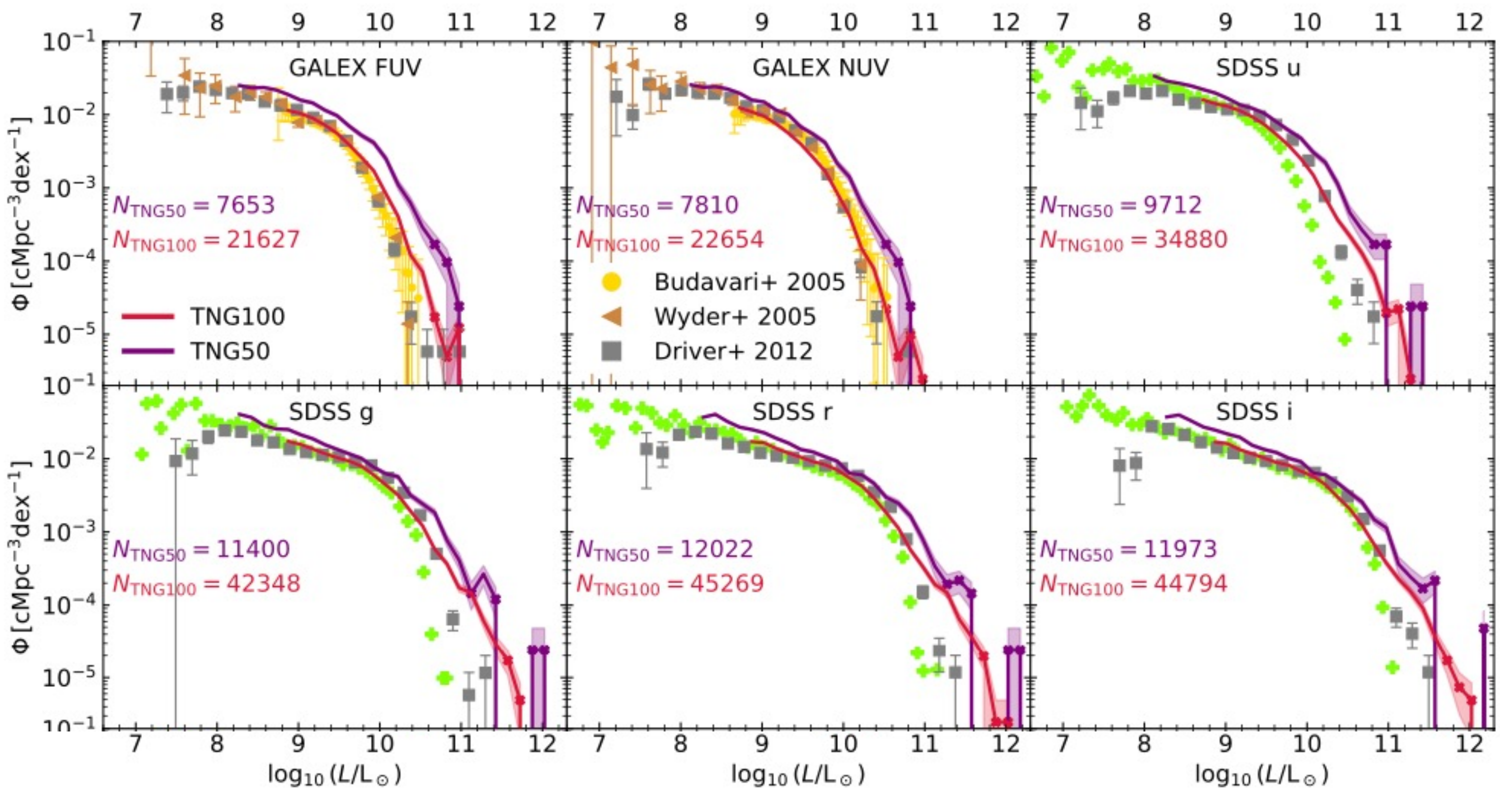
Methodology applied to generate synthetic UV-mm SEDs for 10,000s of galaxies from different simulations

Relatively cheap (not that many photon packets are required for global fluxes)

Jonsson et al. 2010
Camps et al. 2016, 2018
Trayford et al. 2017
Trčka et al. 2020, 2022
Vogelsberger et al. 2020
Gebek et al. 2024, 2025

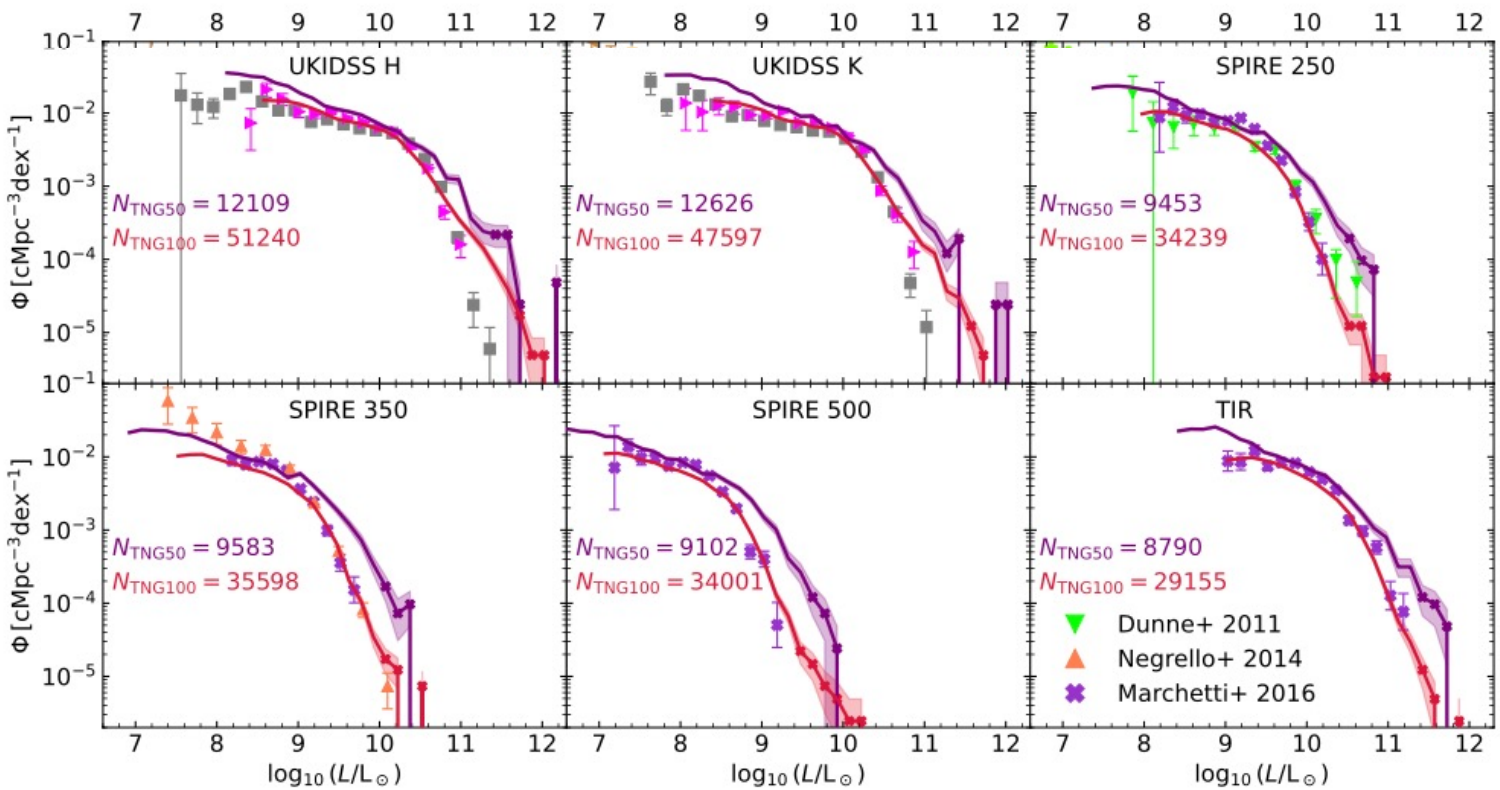


Luminosity functions at z ≈ 0



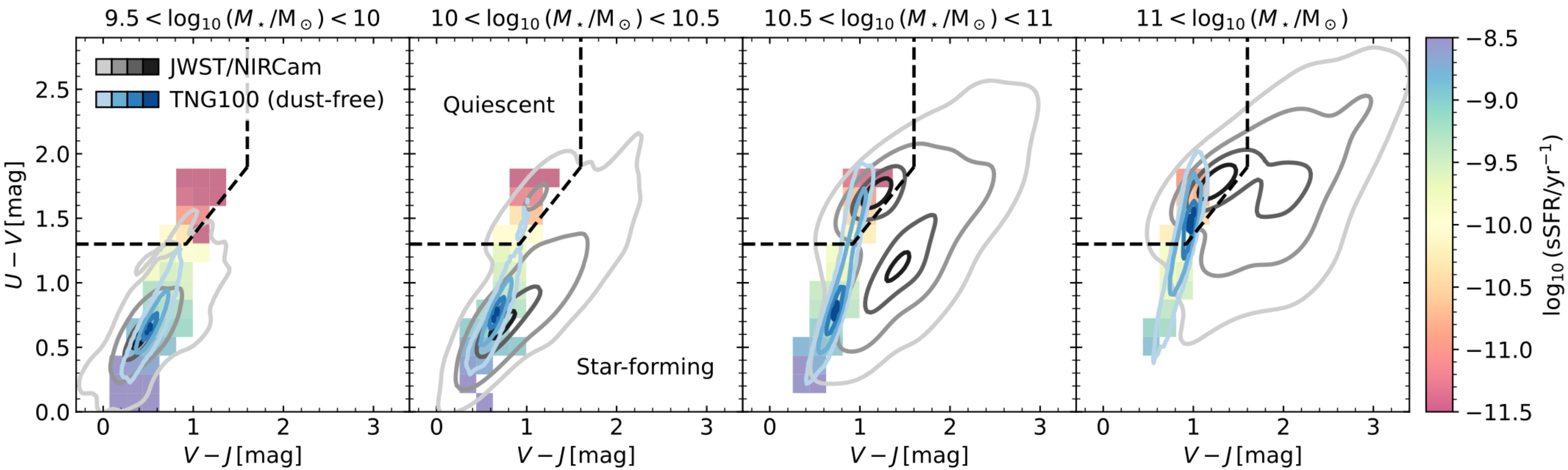
Trčka et al. 2022
Gebek et al. 2024

Luminosity functions at $z \approx 0$



Trčka et al. 2022
Gebek et al. 2024

UVJ diagram at Cosmic Noon ($z \approx 2$)



Impossible to explain the red colours of massive galaxies

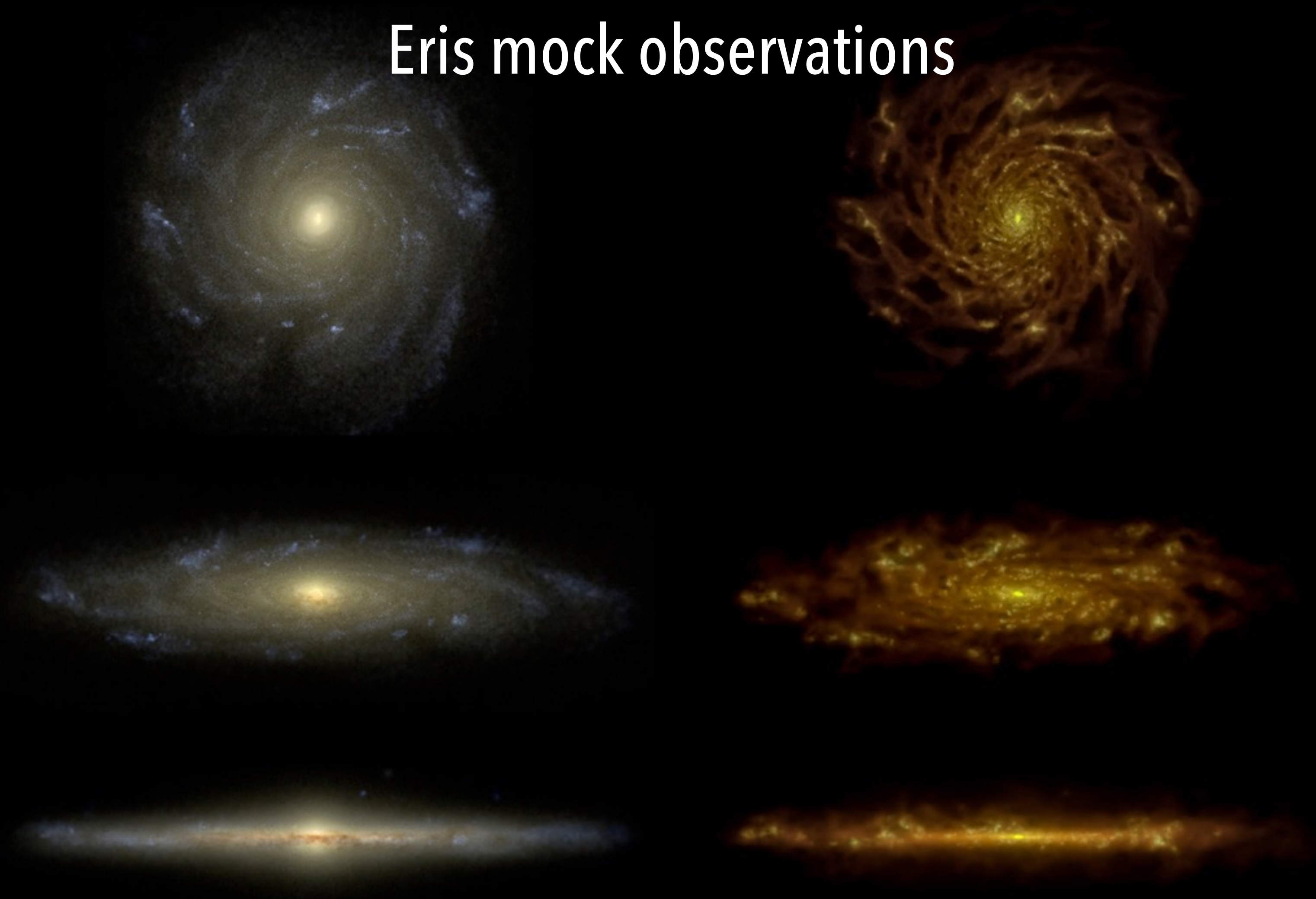
- models with fixed dust-to-metal ratio cannot get explain V – J colours
- possible solution: dust screens around the populations < 1 Gyr

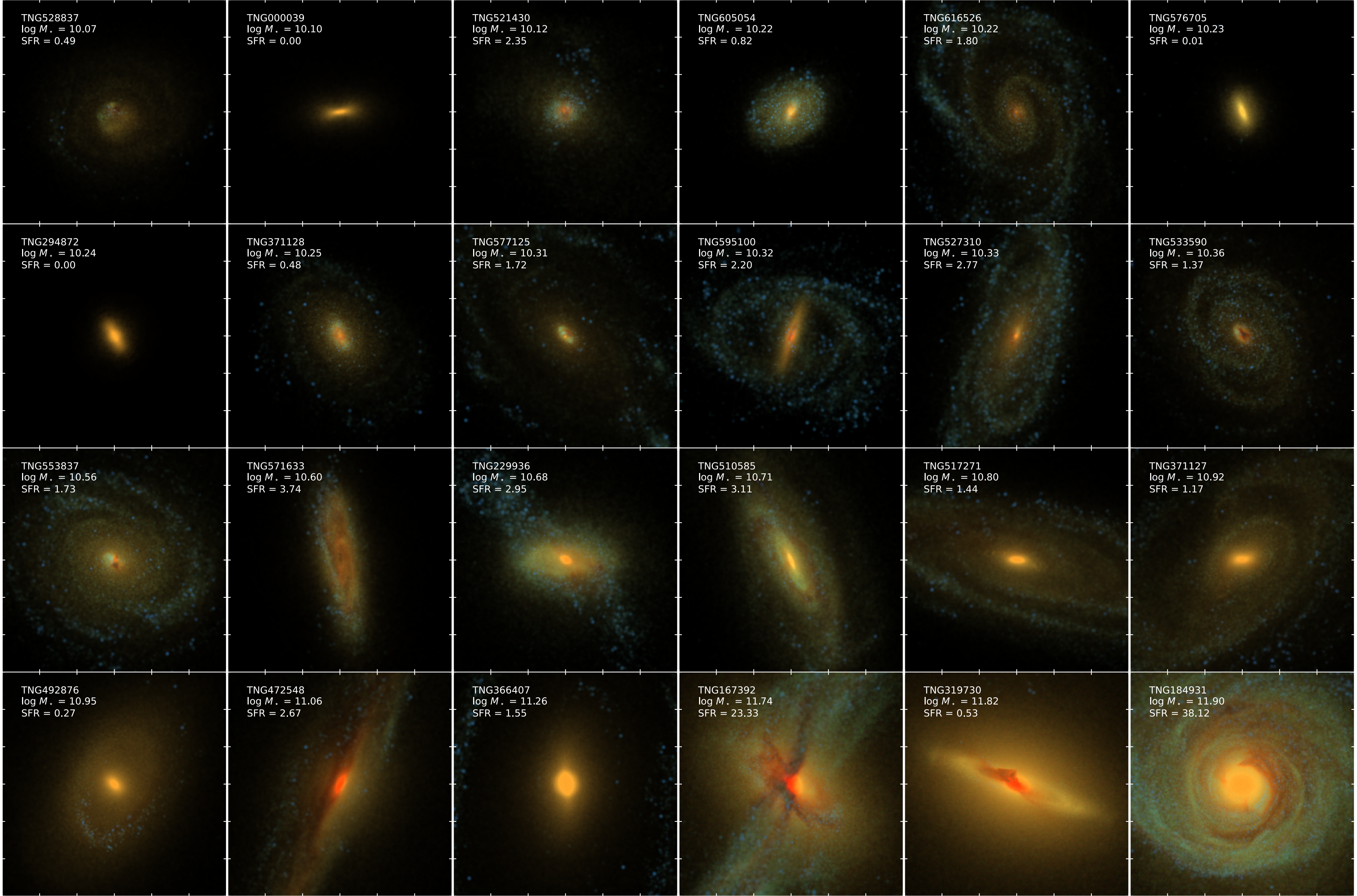
Gebek et al. 2025

Eris mock observations

Saftly et al. 2015
Verstocken et al. 2017

Eris mock observations



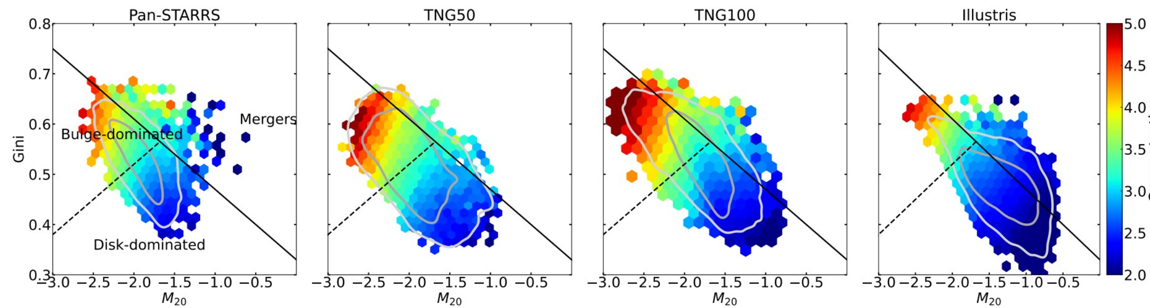


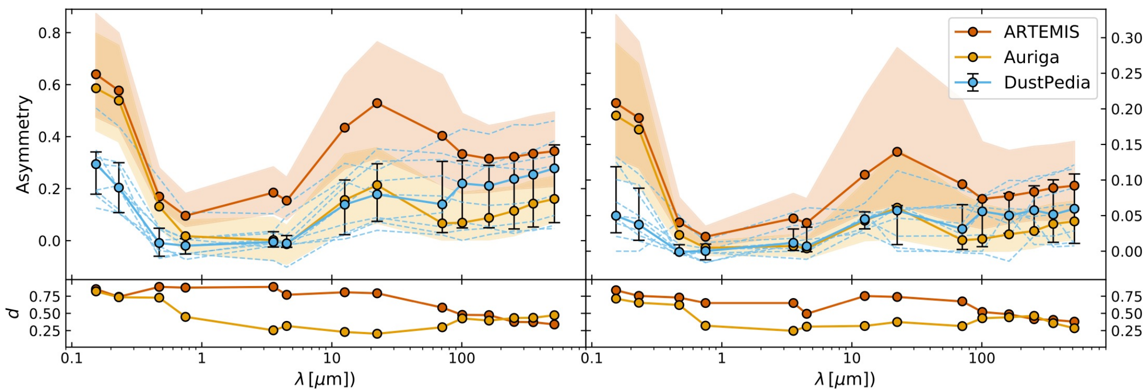
Baes et al. 2024

Morphology of simulated galaxies

Galaxy morphology is critical test to cosmological simulations (not used in the calibration of the subgrid physics recipes)

Interesting: can be measured over the entire UV–mm wavelength range.



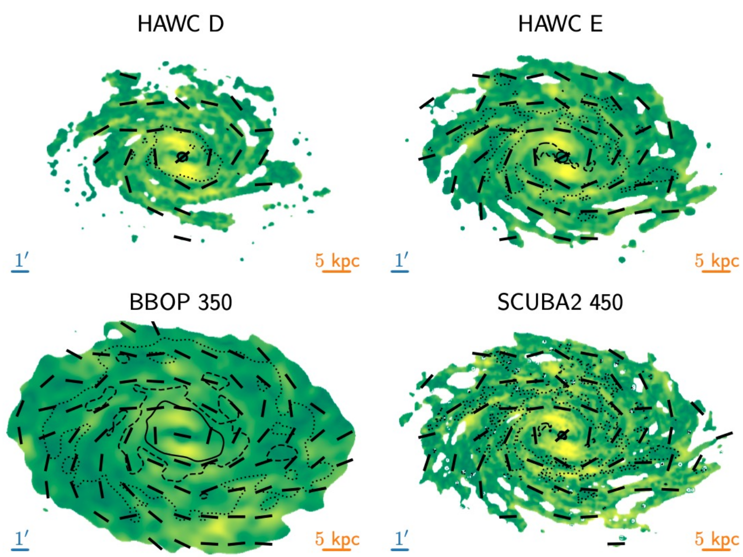


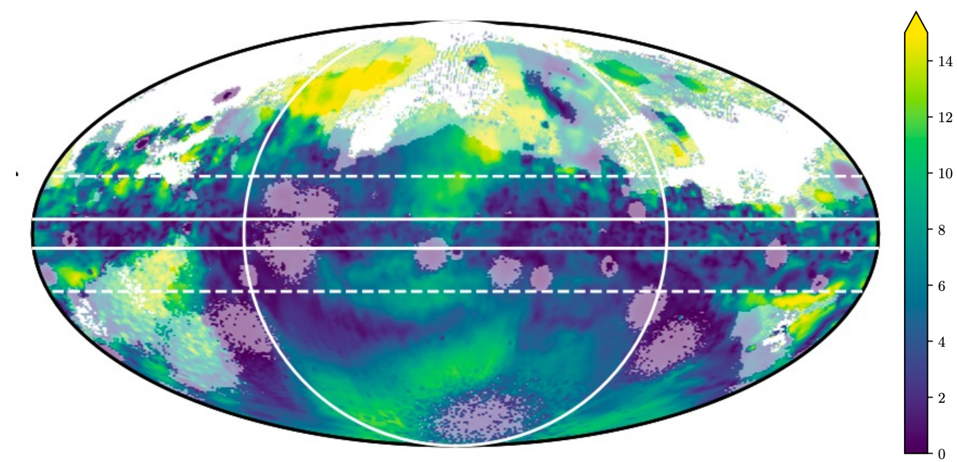
Bignone et al. 2017; Rodriguez-Gomez et al. 2019; Kapoor et al. 2021; Camps et al. 2022; Bottrell et al. 2024; Bokona Tulu et al. 2025

Dust polarimetry

Far-infrared polarimetry

- due to thermal emission from aligned nonspherical dust grains
- opportunity to study galaxy magnetic fields and physics of dust grains
- let's hope for PRIMA !





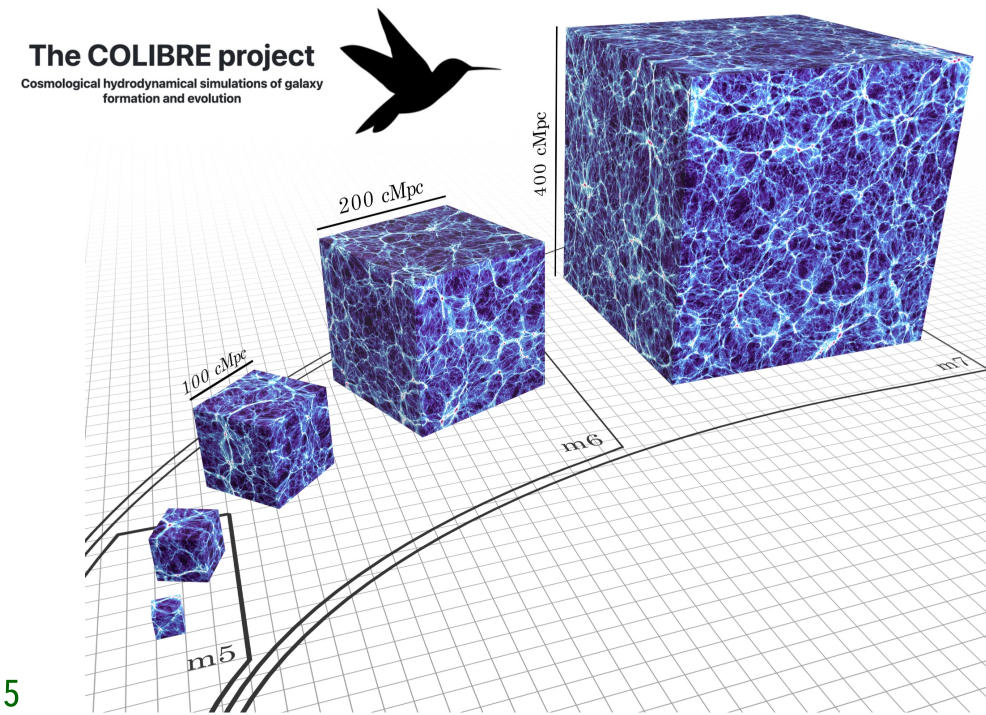
Vandenbroucke et al. 2021

New generation of cosmological simulations

Limitation on RT modelling of simulated galaxies from large-volume simulations: no cold ISM and no dust medium.

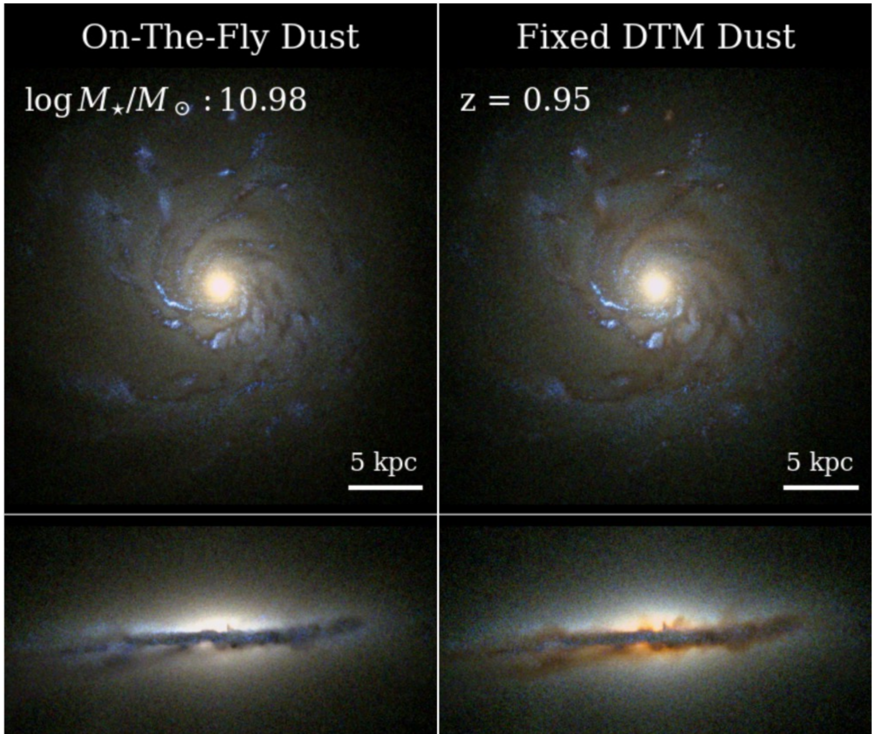
New generation of simulations now includes:

- physics of the cold ISM (cooling down to 10 K)
- dust physics (creation, destruction and evolution of dust grains)



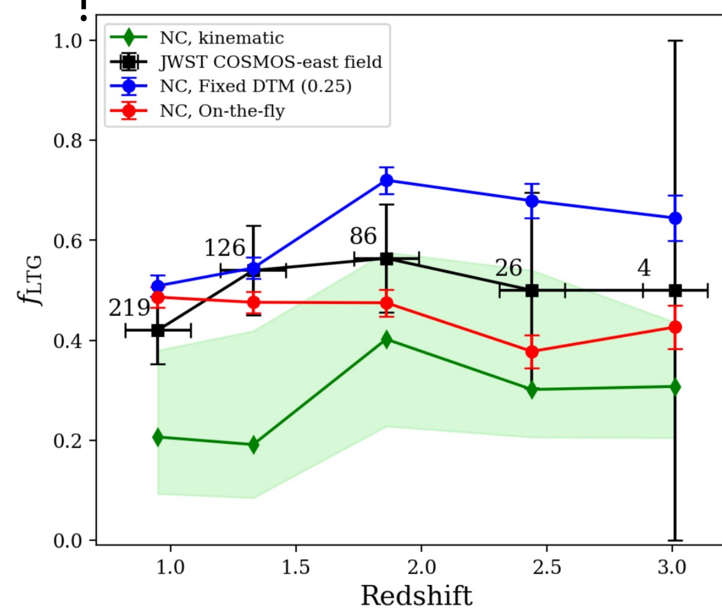
Schaye et al. 2025

Morphology of Cosmic Noon galaxies in NewCluster



Byun et al. 2025

Dust-to-metal ratio not constant.
Morphology of galaxies depends on star-dust geometry !



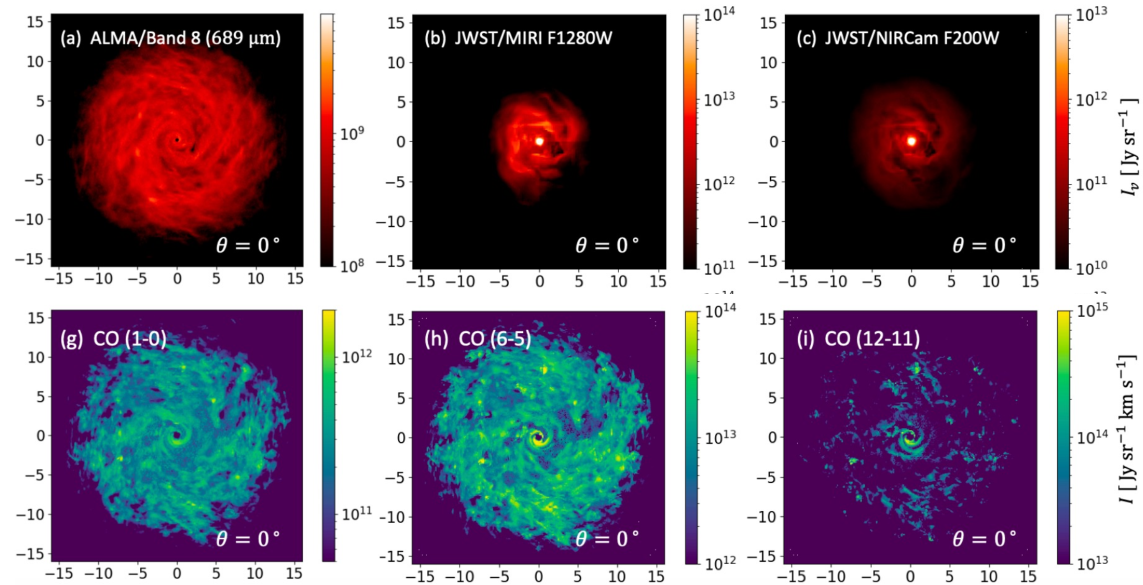
Some challenges for dust RT in the coming decade

Uncertainties on output from MCRT

- statistical diagnostics exist, but are rarely applied in full
- challenge to calculate realistic error bars on secondary emission
- challenge for postprocessing hydro-sims: errors due to limited particle sampling

Coupling dust and gas RT

- full NLTE line RT is tough…
- on-the-fly dust physics models can still improve



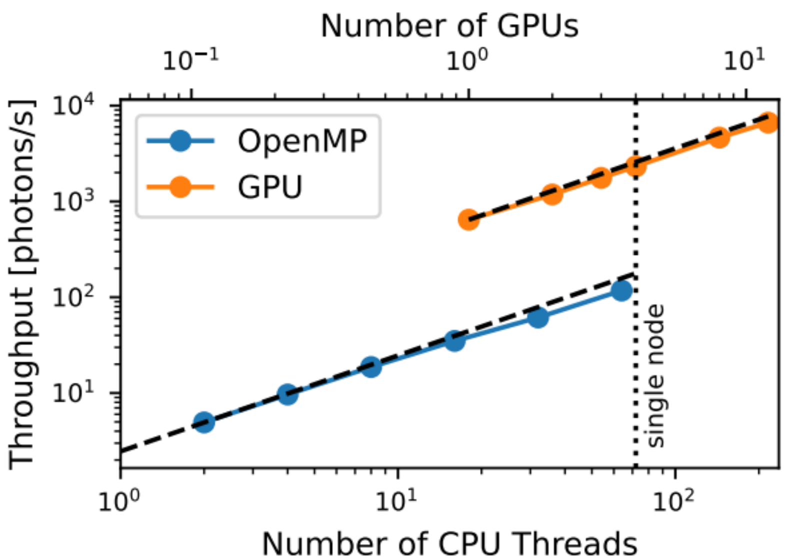
Matsumoto et al. 2023

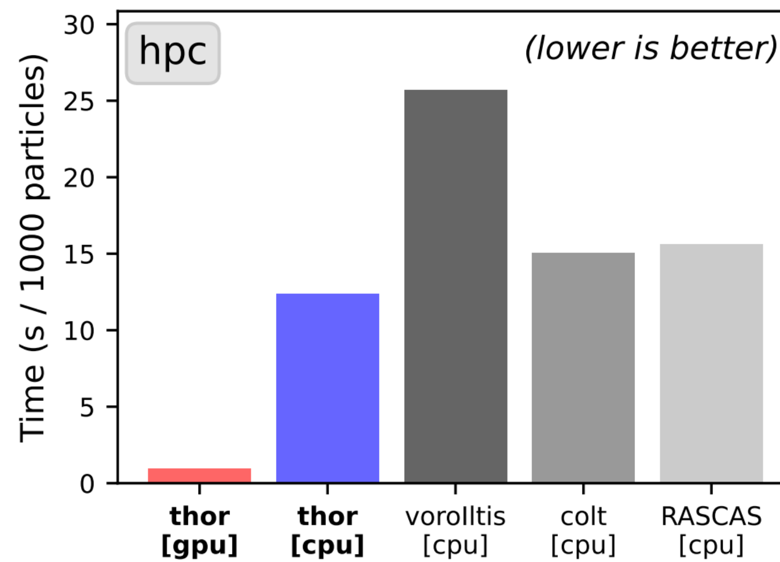
Some challenges for dust RT in the coming decade

Transition from CPU to GPU

- computer power is shifting from CPU to GPU
- Monte Carlo radiative transfer on GPU seem hard (lot of branching)
- some interesting developments…

Byrohl & Nelson 2025

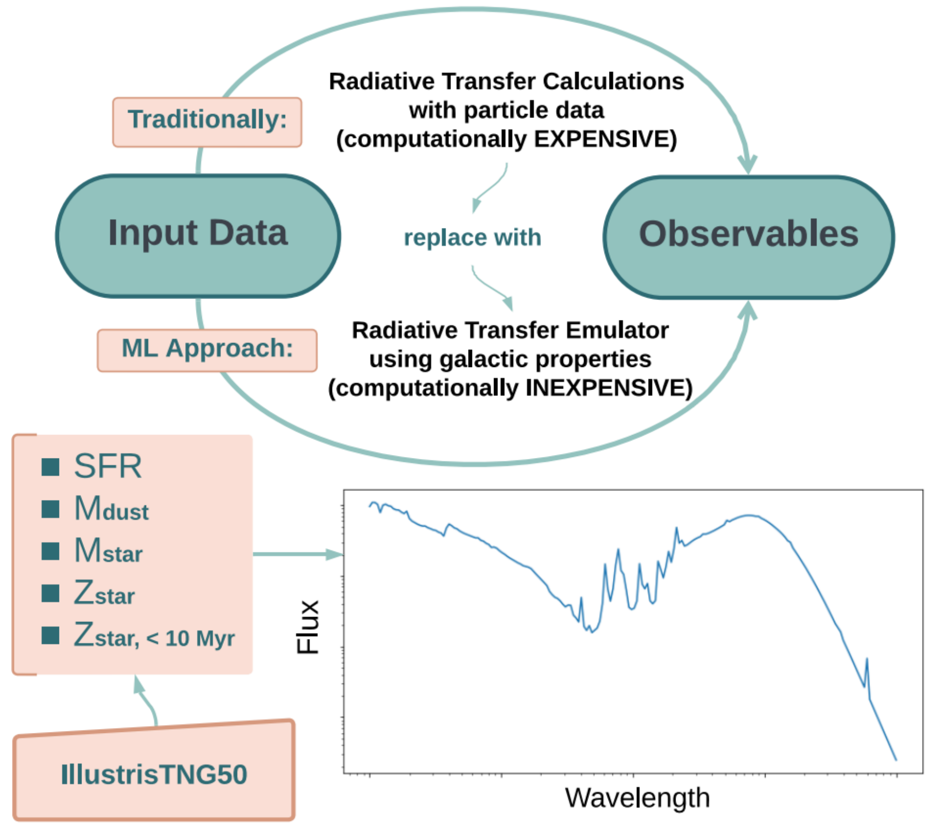




Some challenges for dust RT in the coming decade

Optimization and emulation

- next generation of hydrosims are massive
- more optimization techniques are required: e.g. adaptive/dynamic grids
- interesting avenue: emulating RT using ANNs and deep learning



Sethuram et al. 2023
Su et al. 2025

Summary

Dust radiative transfer is a complex problem

- do it the right way: don't simplify/approximate the problem
- modern Monte Carlo codes can solve RT problems in arbitrary 3D geometry

Plenty of dust radiative transfer applications on galaxy-wide scales

- systematic investigation of dust effects on apparent galaxy properties
- fitting dust RT models to images and SEDs
- postprocessing of simulated galaxies: apples-to-apples comparison of galaxy formation simulations and observational data

Some challenges in dust radiative transfer

- beating MC noise: uncertainty calculation, optimization, transition to GPUs
- coupling dust and gas radiative transfer