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Monte Carlo dust radiative transfer with SKIRT

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Europe
International Boundary
Road
River
National Capital
City or Town
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250
500 KM
0
250
500 Miles
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Reykjavik
Thjorsa
ICELAND
Norwegian Sea
Barents Sea
Faroe Islands
Shetland Islands
U.K.
Glasgow
Edinburgh
Belfast
IRELAND
Dublin
Cork
Liverpool
Manchester
Birmingham
Bristol
London
Atlantic Ocean
North Sea
NETHERLANDS
Antwerp
DENMARK
Arhus
Copenhagen
Malmo
Goteborg
NORWAY
Bergen
Oslo
Trondheim
SWEDEN
Osterdalalven
Stockholm
Gulf of Bothnia
FINLAND
Turku
Helsinki
Tallinn
ESTONIA
Riga
LATVIA
Liepaja
Daugavpils
LITHUANIA
Vilnius
Baltic Sea
Gdansk
RUSSIA
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BELARUS
Berlin
Warsaw
POLAND
Lodz
Krakow
Prague
CZECH REP
L'viv
Kiev
UKRAINE
Kharkiv
Donets'k
Dnipropetrovs'k
Rostov
Odesa
MOLDOVA
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Bratislava
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Casablanca
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Aleppo
Euphrates
Tigris
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IRAQ
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Ahvaz
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Tabriz
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AZ.
Aras
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Black Sea
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Lake Onega
Sukhona
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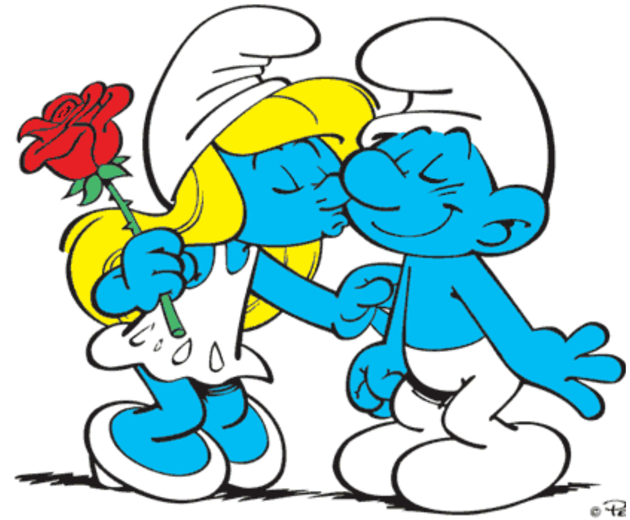
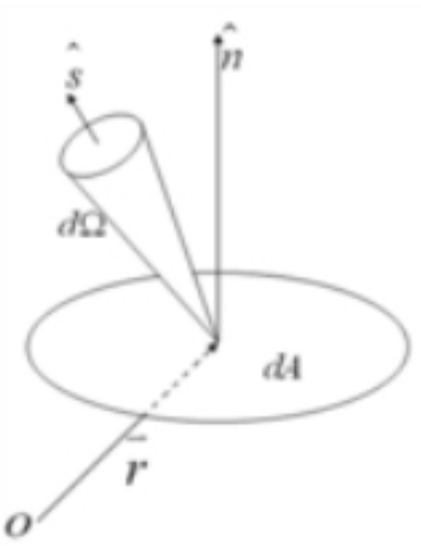
Yekaterinburg
Chelyabinsk
Ufa
RUSSIA
Pechora
Ob'
Irtysh
Tobol

Belgium ???



The radiative transfer problem

The general radiative transfer problem describes the interaction between radiation and matter. It is a very general problem with applications in all sciences…



Generally described by the following equation (RTE)

$$\boxed{\frac{\mathrm{d}I}{\mathrm{d}s}(\boldsymbol{x},\boldsymbol{n},\lambda) = -\kappa(\boldsymbol{x},\lambda)\,\rho(\boldsymbol{x})\,I(\boldsymbol{x},\boldsymbol{n},\lambda) + j(\boldsymbol{x},\boldsymbol{n},\lambda)}$$

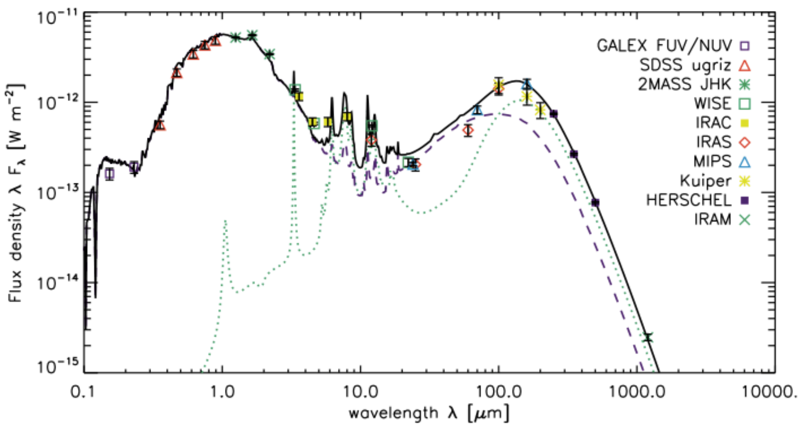
Rate of change of the intensity of the radiation field

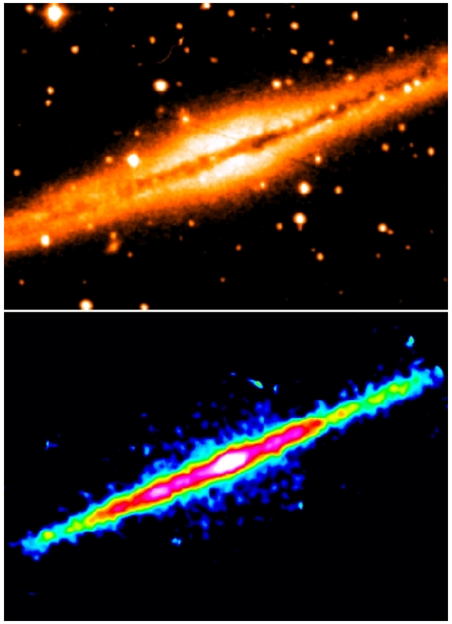
Sinks: removal of radiation due to interaction with matter

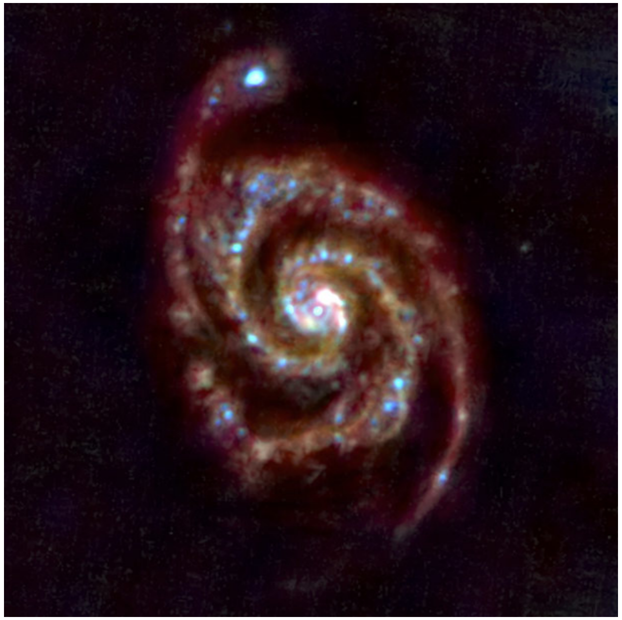
Source terms: creation of radiation

Starlight and interstellar dust

- dust is very efficient in absorbing and scattering UV/optical radiation
- re-emits thermal energy in the MIR, FIR and submm
- 30 to 50% of the starlight in the Universe is absorbed by dust !







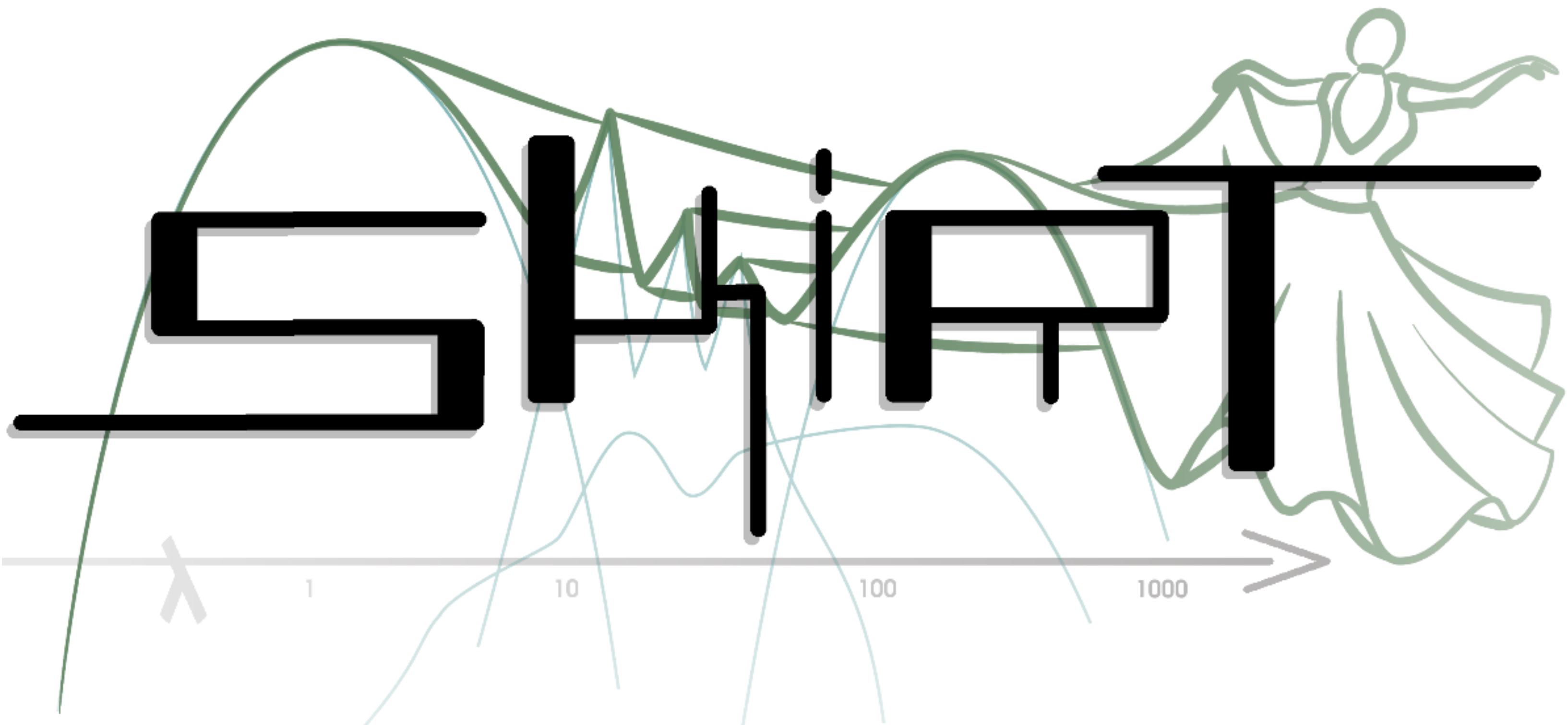
Fritz et al. 2012

A tough problem…

- 6D problem: 3 space + 2 direction + 1 wavelength dimension.
  100 grid points in every dimension implies 10^{12} points…
- strongly non-linear problem
- non-local problem
  - in space: propagation of photons across the domain
  - in direction: scattering couples the intensity in all directions
  - in wavelength: absorption/re-emission changes wavelength
- often to be used to model observed data
  - problem of fitting data (i.e. optimization problem)
  - projection effects

SKIRT

(Stellar Kinematics Including Radiative Transfer)



Baes et al. 2003, 2011

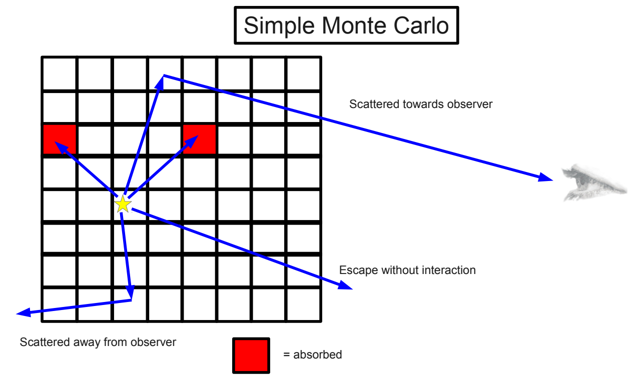
Monte Carlo radiative transfer

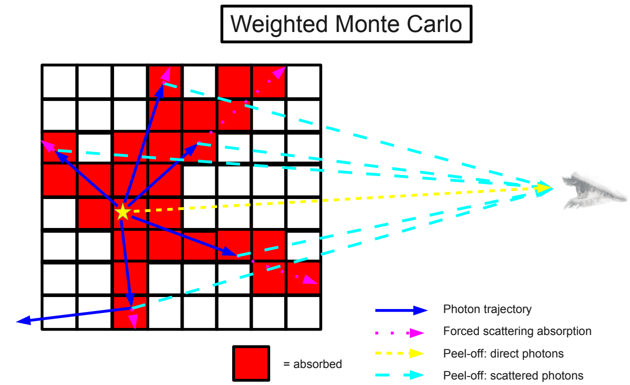
- probabilistic simulation method (does not "solve" the radiative transfer equation)
- A large number of photon packages are followed **individually** through the dusty medium.
- The trajectory of each photon package is determined by (pseudo) random numbers.
- The radiation field is reconstructed by classifying the photon packages by position, propagation direction, wavelength…

Weighted Monte Carlo RT

SKIRT is a weighted Monte Carlo code: contains many dirty/clever tricks to make the simulations more efficient. For example

- **biased emission**: preferentially shoot photons to interesting directions
- **forced scattering**: don't waste photons that leave the system without interacting
- **peel-off technique**: drastically increase the signal-to noise in observed images/ SEDs
- **continuous absorption**: absorb along the ray instead of at one single location
- **polychromatism**: shoot photon packages that contain photons at many different wavelengths

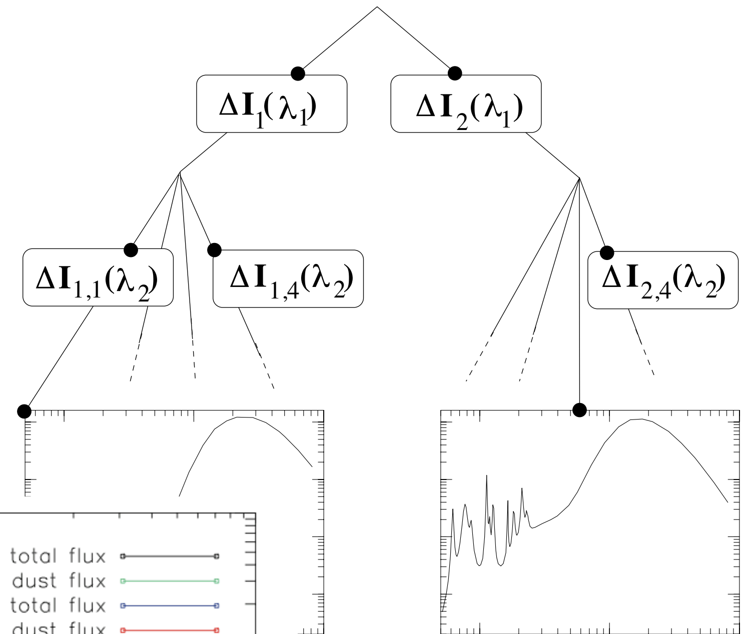




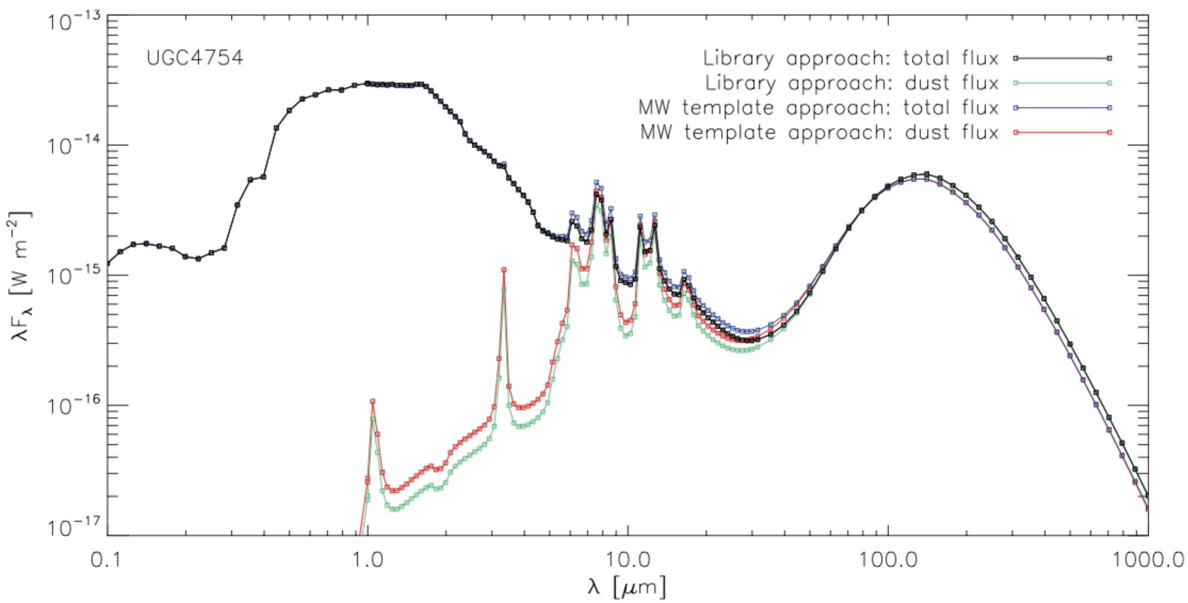
Non-equilibrium dust emission

Different approaches possible

- brute force calculation
- template approach
- dynamical library approach

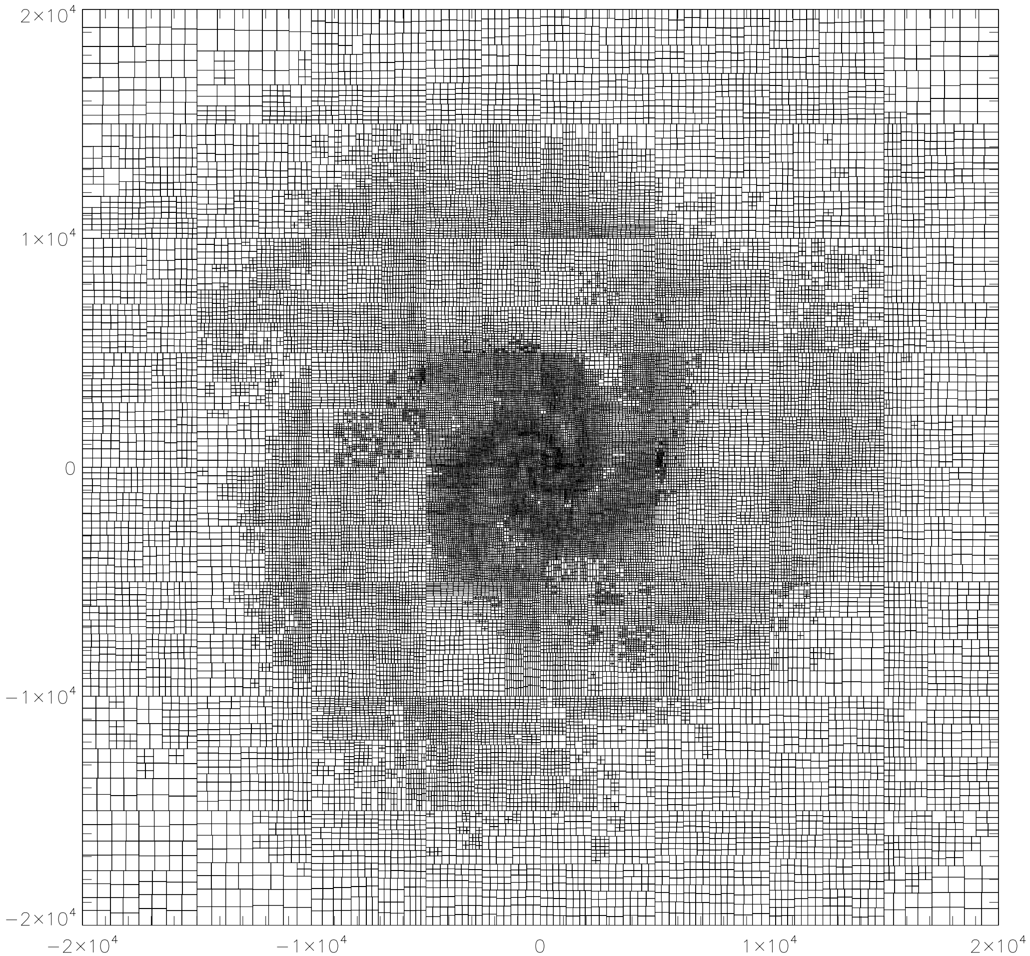


Juvela & Padoan 2003



Baes et al. 2011

Adaptive grids



Recently added octtree grid

- Geometric or barycentric subdivision
- Neighbor search to speed up calculation of photon paths

Goal: limit number of dust cells for complex models

- Face-on spiral galaxies
- Compact dust clumps
- Results from hydro-dynamic simulations

Saftly et al. in prep

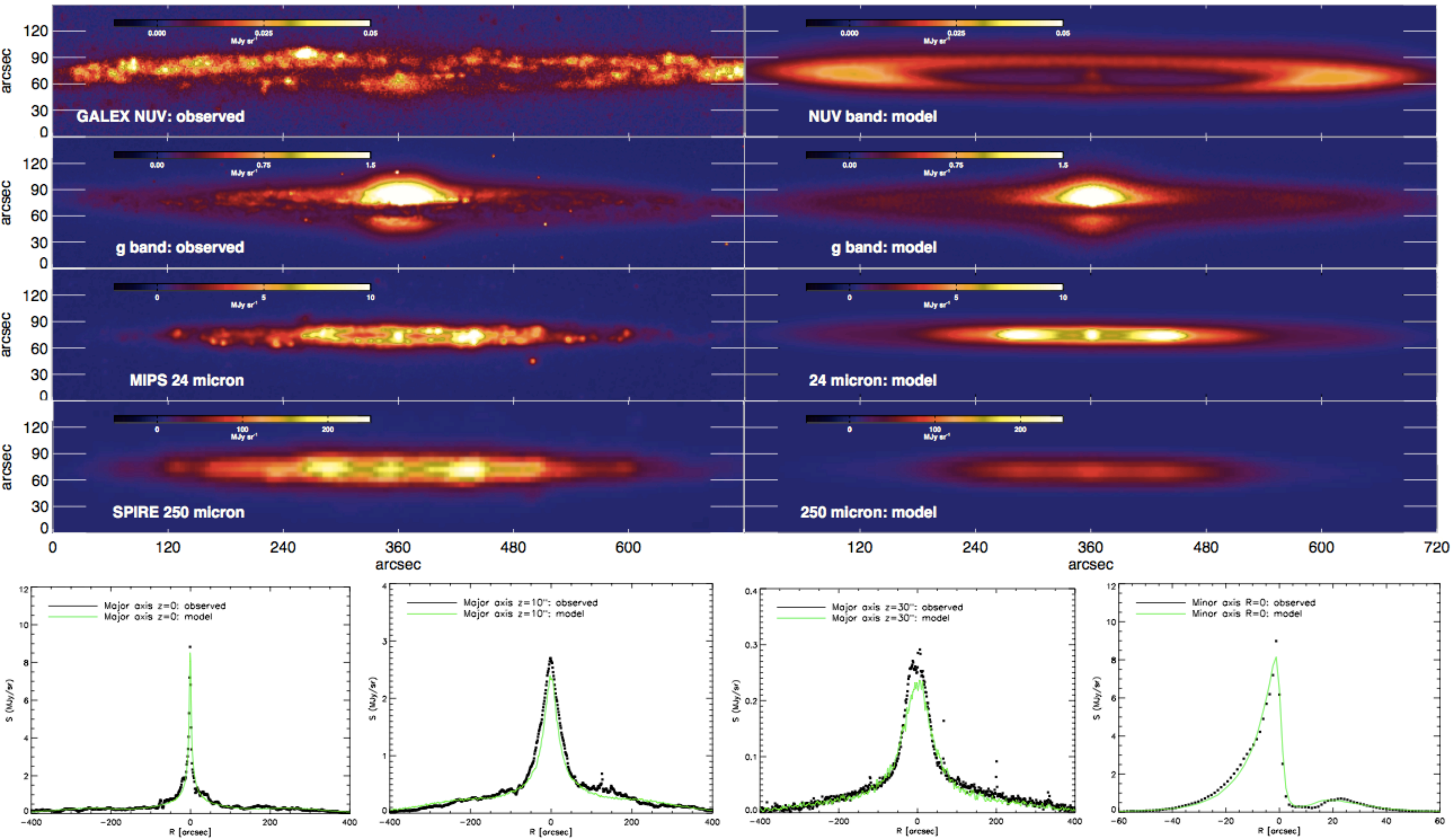
Inverse radiative transfer

Model a particular real galaxy by fitting radiative transfer models to observational data (SED, images,…).

Major complications

- Star-dust geometry: large number of parameters to be fitted
    - Intrinsic geometry
    - Orientation
    - Dust properties
- Run-time for a single simulation (i.e. a single point in the multi-dimensional parameter space) is considerable
- Memory requirements as well…
- Monte Carlo noise makes fitting more complicated

Baes et al. 2011
De Looze et al. 2012a



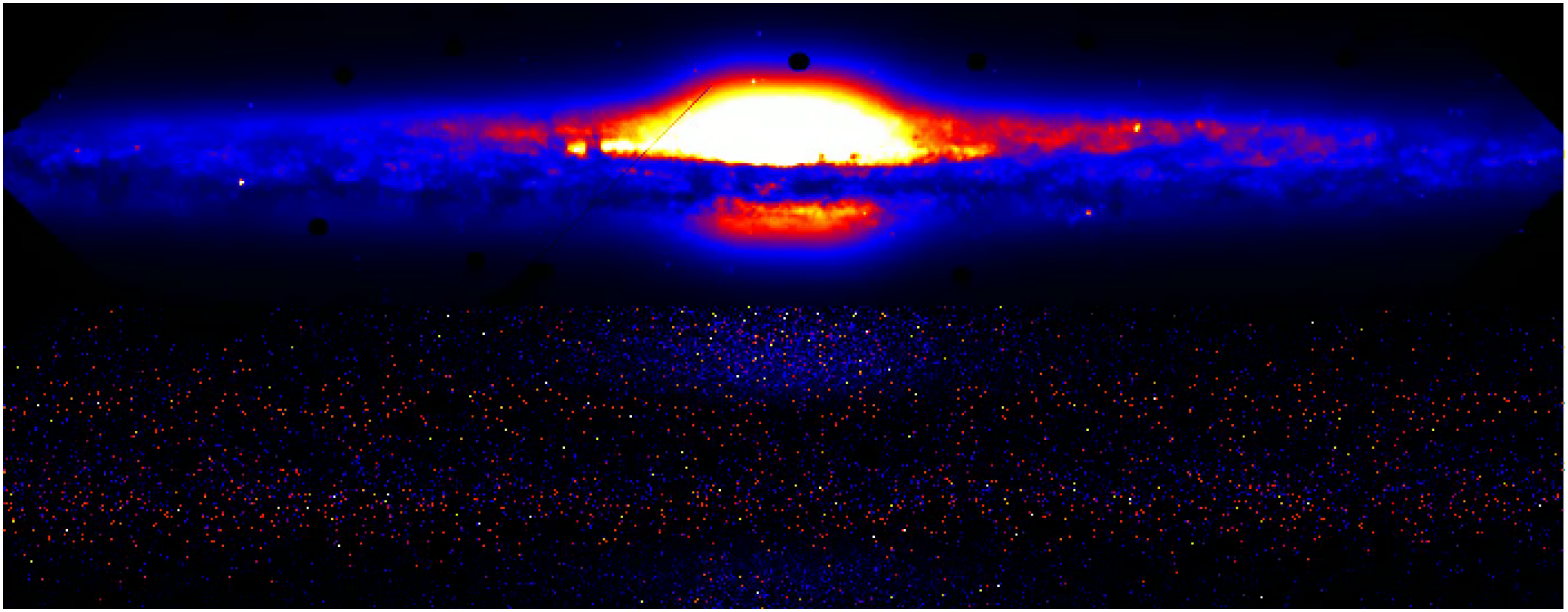
De Looze et al. 2012b

FitSKIRT

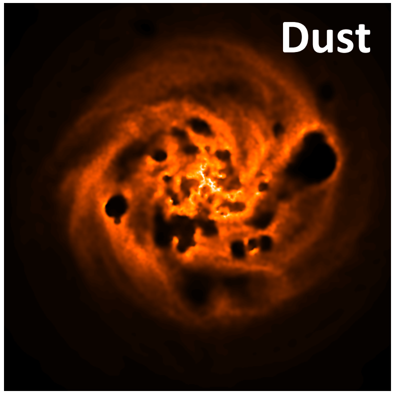
Tool to fit parametric 3D models to a set of UV/optical/NIR images.

- couples the SKIRT radiative transfer code to a genetic algorithm optimization routine
- (almost) fully automated and unbiased

De Geyter et al. 2012, submitted

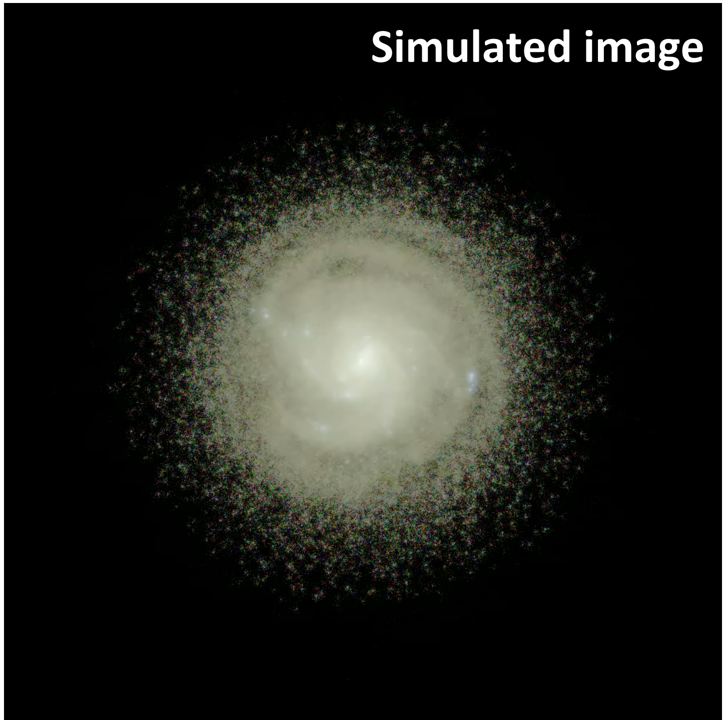


Realistic imaging of simulated galaxies



Rahimi & Kawata 2012

Building an adaptive dust density grid from the heavily overlapping SPH gas particles requires special care to limit computation time (this galaxy has 410k star particles and 190k gas particles)



Major challenges for the future:

- Derive appropriate recipe to calculate dust distribution from the SPH gas properties (density, metallicity, temperature)
- Resolution effects !
- Parallellization…

EAGLE

- Forthcoming large-scale cosmological hydrodynamic simulation
- includes stars, gas, dark matter, star formation, AGN and SN feedback,…

  → *tens of thousands* of simulated galaxies !!

Camps et al., in prep

- Objective: validate physical assumptions by comparing simulation results with the observable universe
- But: simulation provides information not always directly available to observers
- Solution: generate images from the simulation data, and analyze those with the same methods used by observers

If you are simulating dusty galaxies, AGNs, circumstellar discs, molecular clouds… and you want to know how these systems look at UV to submm wavelengths, come and talk to me.

Thanks to my collaborators…

Thank you for your attention !

Peter Camps
Seb Vandewoude
Jacopo Frtiz
Gert De Geyter
Waad Saftly
Ilse De Looze
Marko Stalevski
Joris Verstappen