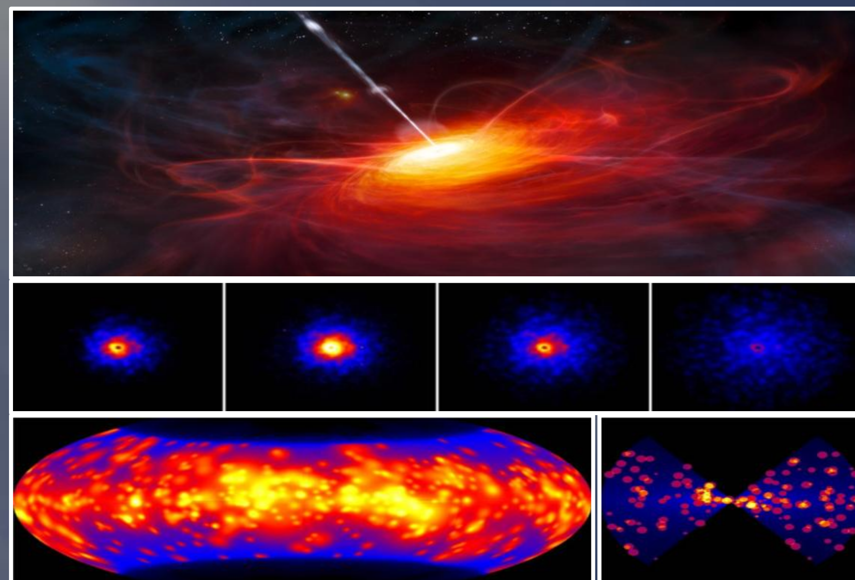
INFRARED EMISSION OF THE AGN DUSTY TORUS: RADIATIVE TRANSFER MODELING WITH SKIRT



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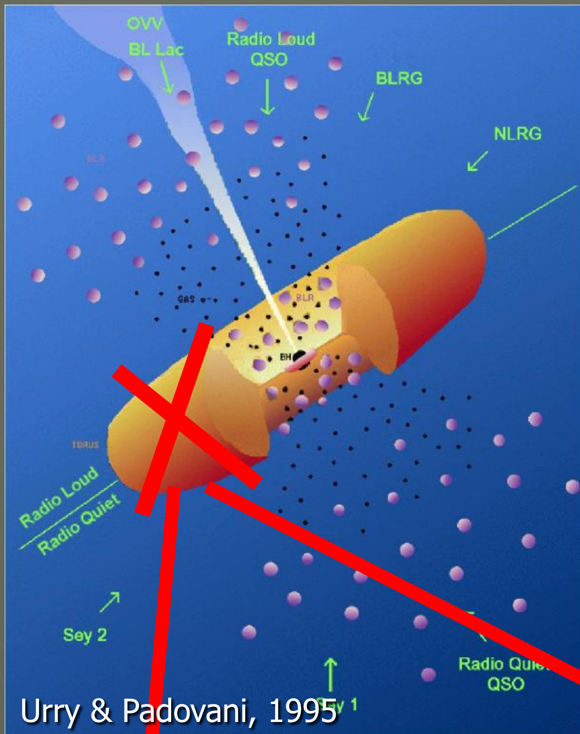
DUSTY TORUS

- Smooth, homogenous torus problems:
  - Survival of dust grains ?
  - Dynamical stability ?

- → The torus consists of a large number of optically thick clumps orbiting around the central engine (Krolik & Begelman 1988).

- Hydrodynamical simulations → ISM around AGN is a multiphase filamentary structure (Wada & Norman 2002; Wada 2009, 2012)



Urry & Padovani, 1995

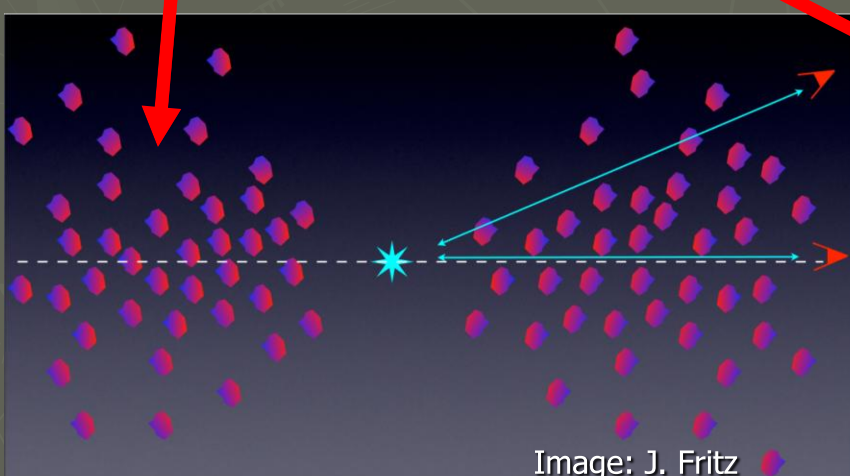
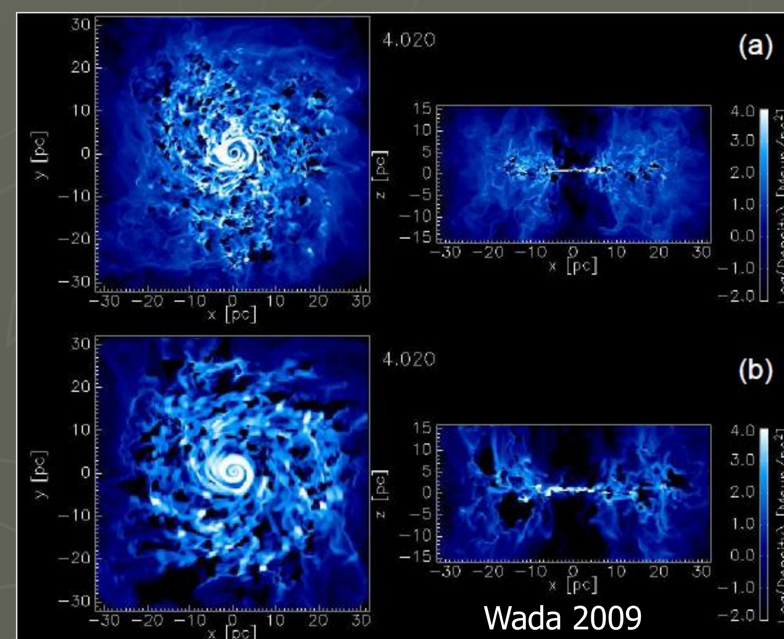
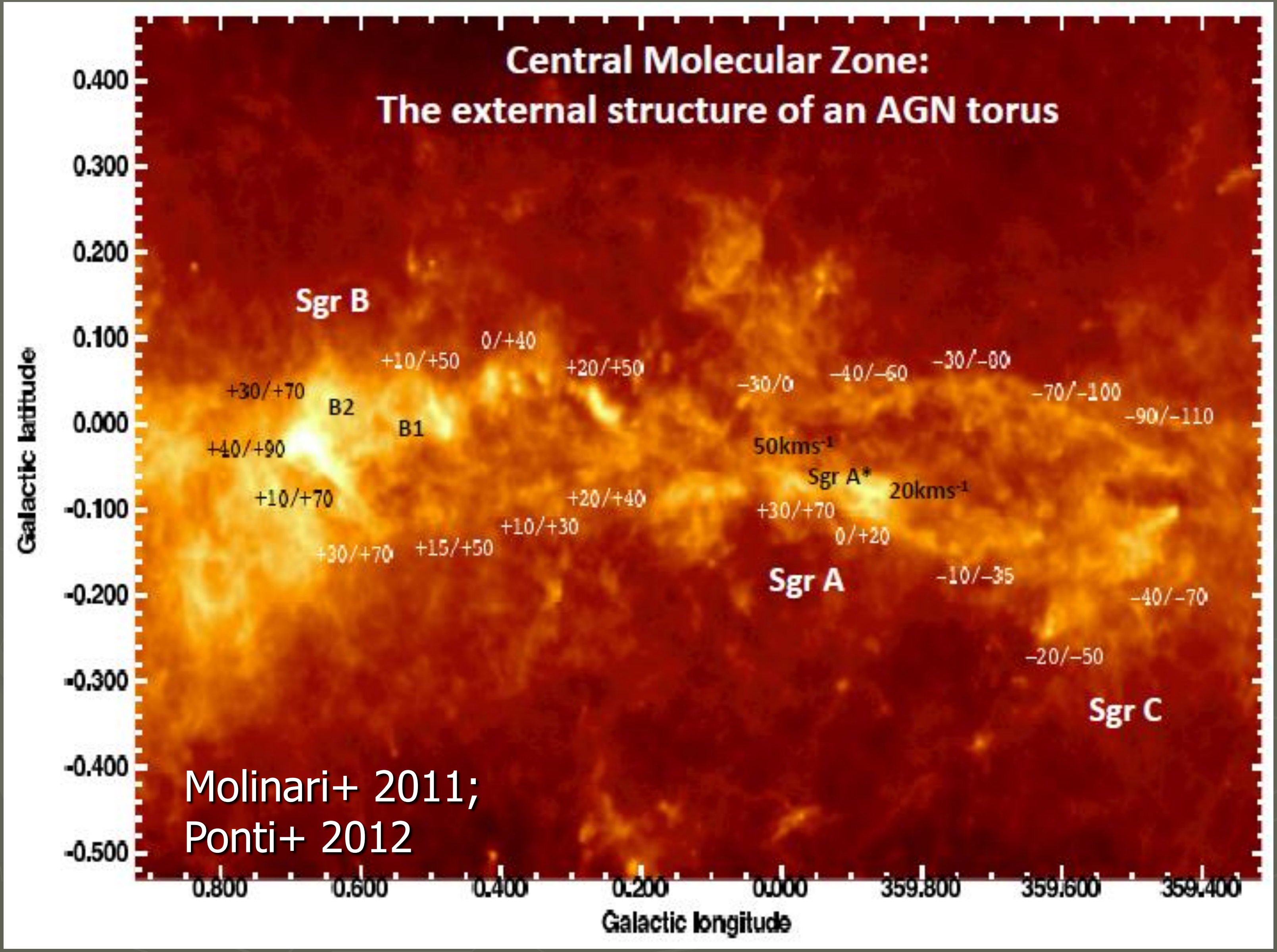


Image: J. Fritz

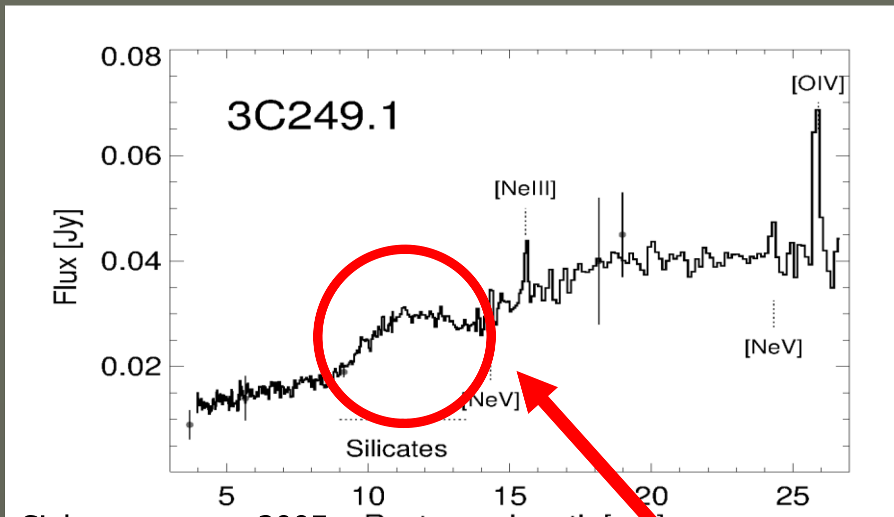


Wada 2009

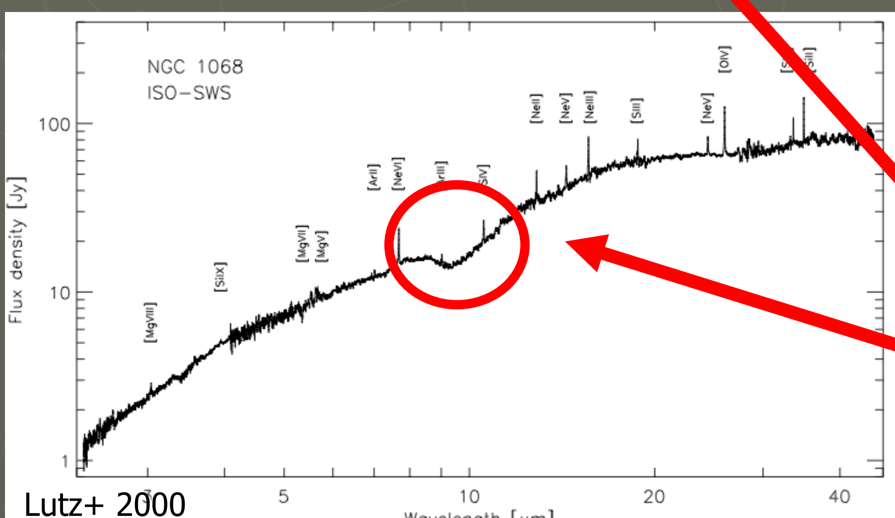
DUSTY TORUS: Isolated clumps + interclump dust ?



DUSTY TORUS EMISSION



Siebenmorgen+ 2005

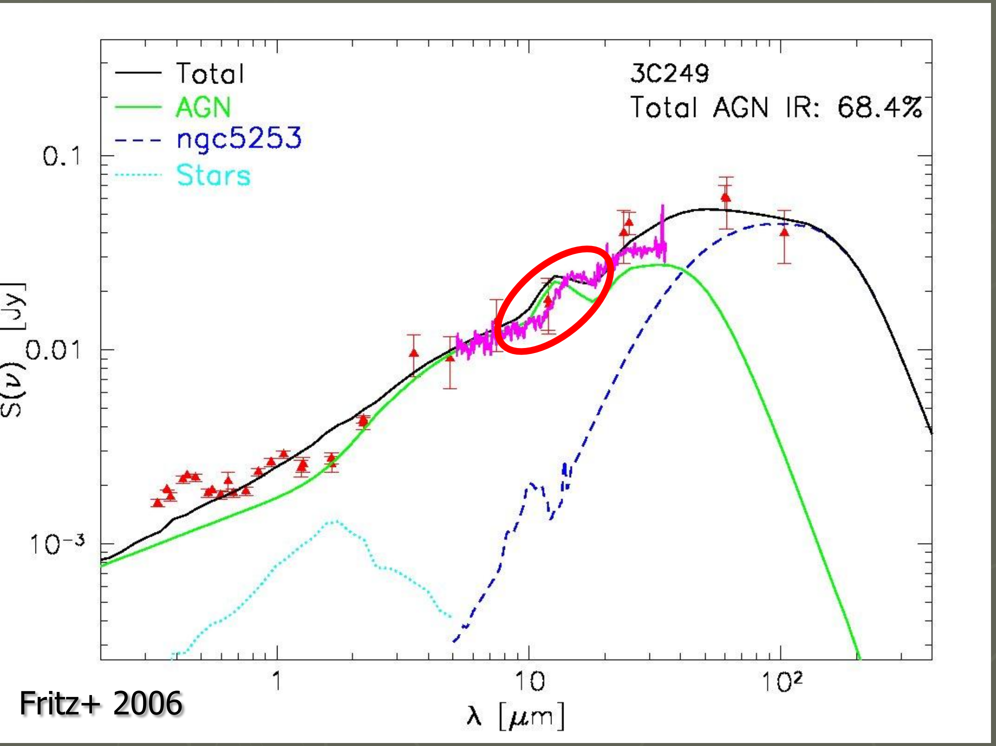


Lutz+ 2000

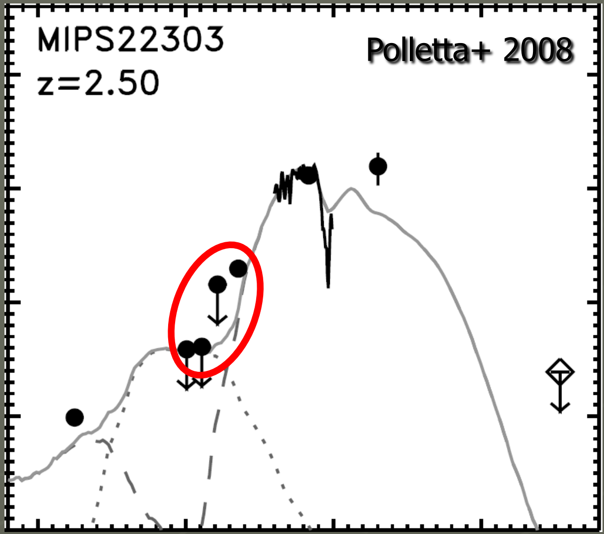
- Dust in the torus absorbs the incoming accretion disc radiation and re-emits it in the infrared
- Mid- to far-IR bump
- ~ 10 μm silicate feature (Si – O 'stretching' mode) –
  - Window into dust distribution and chemical composition
  - In emission in type 1 AGN
  - In absorption in type 2 AGN

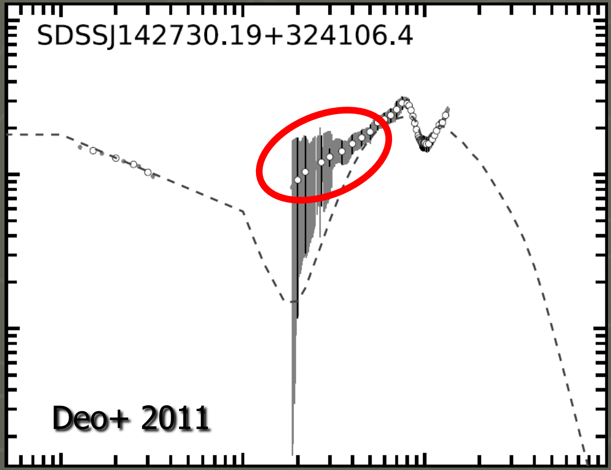
SOME OUTSTANDING ISSUES

- Intensity and position of the 10 μm silicate feature. Different chemical composition, emissivity properties, geometrical effects (Nikutta+ 2009) ?



- NIR excess when fitting observed SEDs (Polletta+ 2008; Mor+ 2009; Ramos Almeida+ 2009; Mor & Netzer, 2012; Deo+ 2011)





MODEL: dusty torus as a clumpy two-phase medium (Isolated clumps + interclump dust)

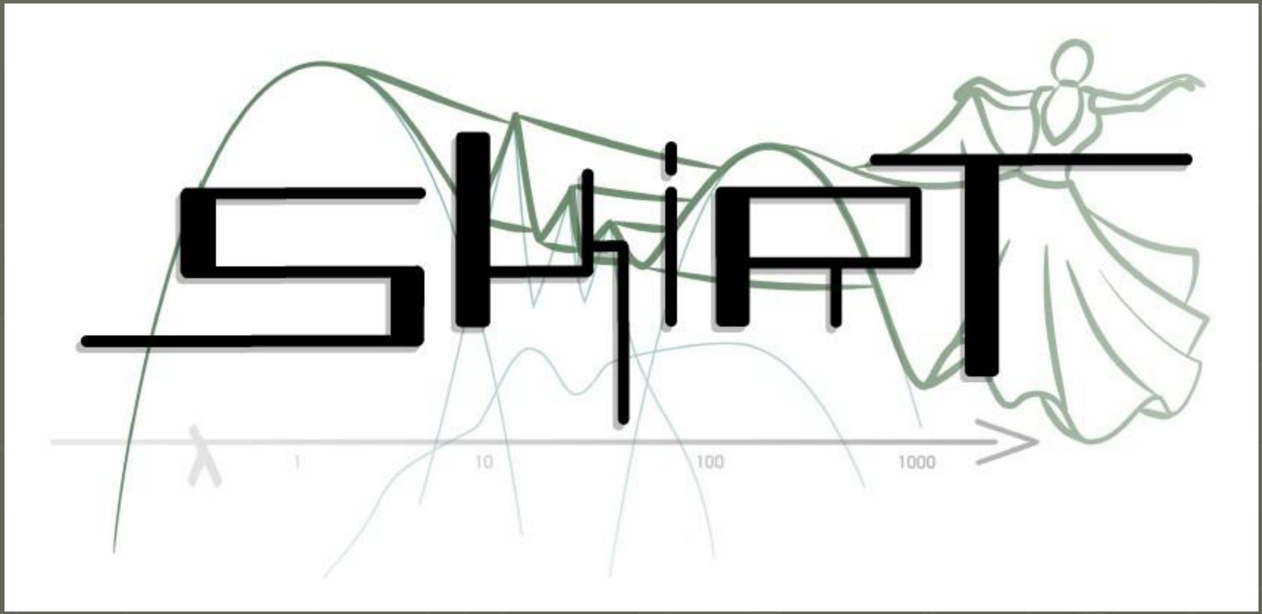
- A step further toward a more realistic model - dusty torus as a clumpy two-phase medium
- Calculate a grid of model spectral energy distributions (SEDs)
- Analyze model SEDs and their observable properties, the influence of different parameters
- Compare smooth, 2-phase and clumps-only SEDs

RADIATIVE TRANSFER CODE SKIRT

(Baes+ 2003, 2011)

- Developed to investigate the effects of dust extinction on the photometry and kinematics of galaxies (Baes+ 2003)

Stellar
Kinematics
Including
Radiative
Transfer



SKIRT people

Maarten Baes

Sebastiaan Vandewoude

is a mathematics master stude
implementing and testing differ
efficiency of various ways to mo

Jacopo Fritz

works as a Herschel postdoc on
and the HELGA survey of the Ar
AGNs (modeling the infrared SE

Edgardo Vidal Pérez

is a PhD student working on the observation and modelling of circumstellar discs around post-AGB stars. He is using near- and mid-infrared interferometric data from the VLTI instruments AMBER and MIDI to probe these discs on the smallest scales, and using the SKIRT radiative transfer code to model these observations in order to gain insight in their physical structure. This research is a collaboration between UGent and KUL.

Joris Verstappen

a PhD student working on a FWO project grant. His research topics are the study of the dust energy balance in edge-on spiral disk galaxies through the comparison of SKIRT simulations with multi-wavelength observations, the extension of the SKIRT code with very small grains and PAHs, and the data reduction of Herschel PACS data for the HeViCS, HELGA and HEROES surveys.

Ilse De Looze

works as a PhD student on a PRODEX studentship. Her research interests are observing and modelling different samples of galaxies at infrared, submm and radio wavelengths. Among others, she has detected dwarf ellipticals with Herschel, has constructed a multi-wavelength radiative transfer model for the Sombrero galaxy, she is mapping the dust in NGC205, and contributing actively to the HeViCS and HELGA projects.

Marko Stalevski

is a PhD student on a PhD program jointly organized by UGent and the University of Belgrade, Serbia. He is a research associate at Astronomical Observatory of Belgrade where he is participating in the "Astrophysical spectroscopy of extragalactic objects" and "Gravitation and large scale structure of the Universe" programs. His research interest include AGN dusty tori and accretion disks and gravitational lensing.

Waad Saftly

is a PhD student working on the SKIRT radiative transfer code. She is implementing more advanced grid structures in the code, which will enable the user to run powerful simulations with a large dynamical range. She will be using this updated SKIRT code to investigate the multi-wavelength properties of simulated galaxies, including merging galaxies.

Gert De Geyter

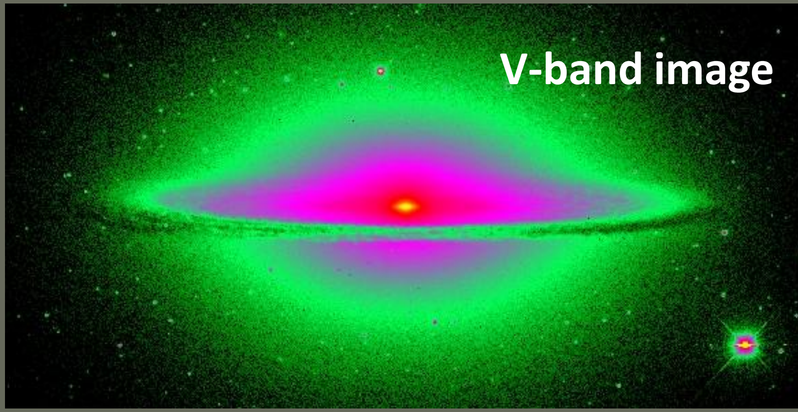
works on the implementation of FitSKIRT, a tool that is designed to fit dust radiative transfer models to optical images of dusty galaxies, with the goal to recover the intrinsic distribution of both stars and dust in the galaxy. The tool uses a genetic algorithm library on top of the SKIRT code. He will apply this tool on edge-on spiral and dust-lane elliptical galaxies in the frame of the HEROES and FRIEDL projects.

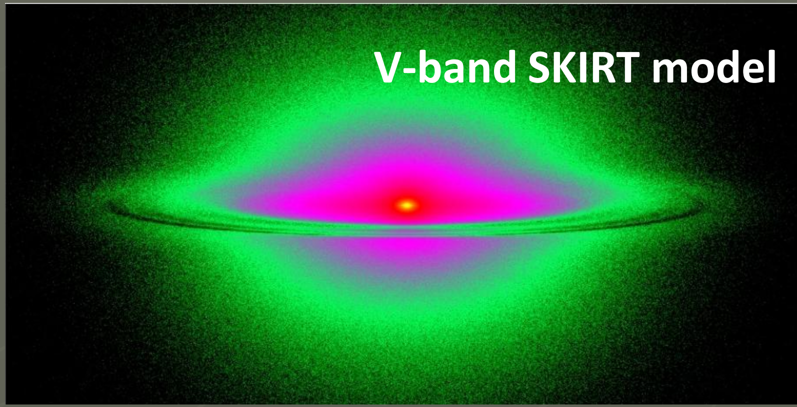
Peter Camps

returned to the university to start a second career as a PhD student, after developing commercial publishing software for about thirty years. He now works on the SKIRT radiative transfer code with a dual focus: improving the development process and the user experience, and implementing a framework that uses the result of a hydrodynamic simulation as an input model for SKIRT.

RADIATIVE TRANSFER CODE SKIRT

- 3D continuum Monte Carlo radiative transfer code
- A flexible tool that can model model a variety of dusty systems
- Full treatment of absorption, multiple anisotropic scattering and thermal dust re-emission
- Stochastic heating of small grains and PAH molecules
- Any 3D geometry without limitations
- A variety of galaxy types (Baes+ 2010; de Looze et al. 2010), circumstellar discs (Vidal & Baes 2007), AGN dusty tori (Stalevski+ 2012a, 2012b) …even human heart!





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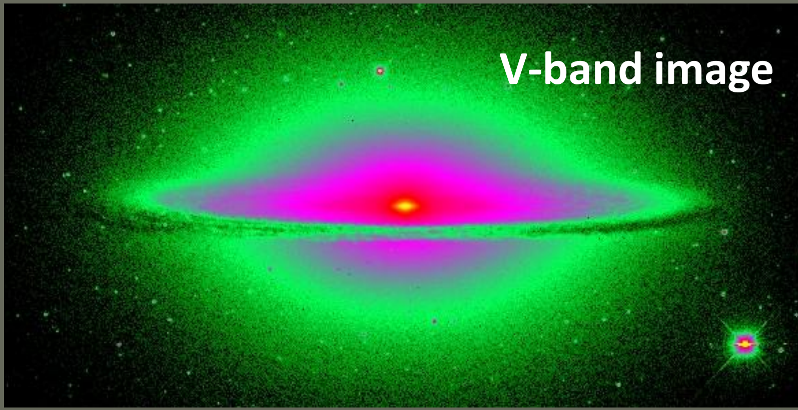
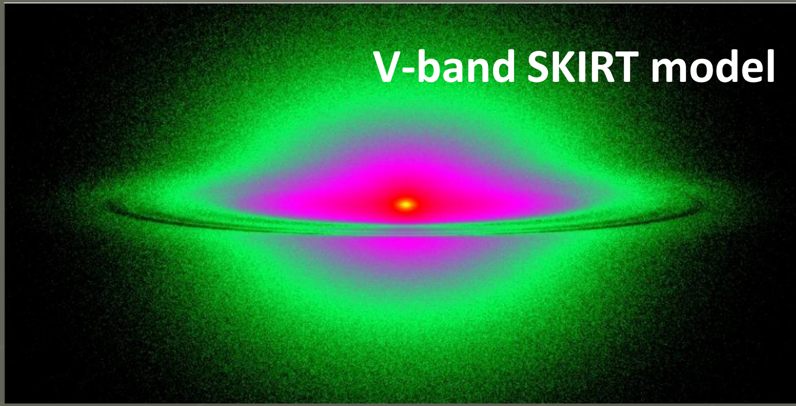
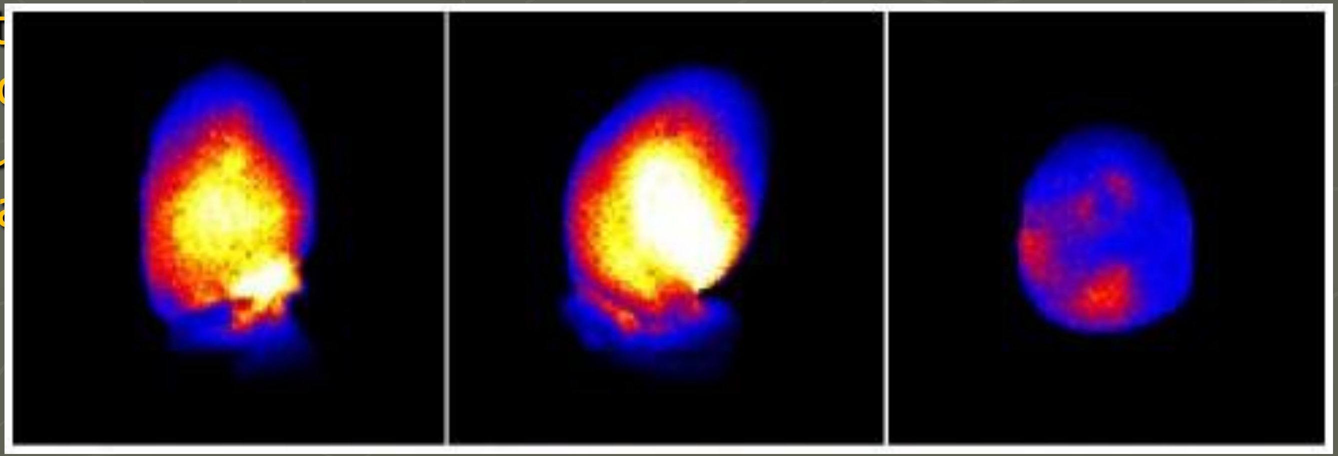






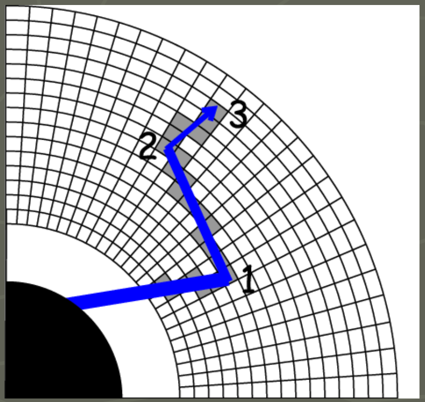
MONTE CARLO RADIATIVE TRANSFER

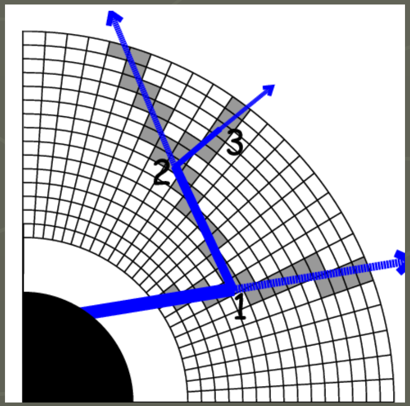
A large number of photon packages are followed **individually** through the dusty medium.

The trajectory of each photon package is determined by (pseudo) random numbers.

Clever tricks to make MCRT simulations efficient

- continuous absorption
- immediate re-emission
- frequency distribution adjustment
- peeling-off technique

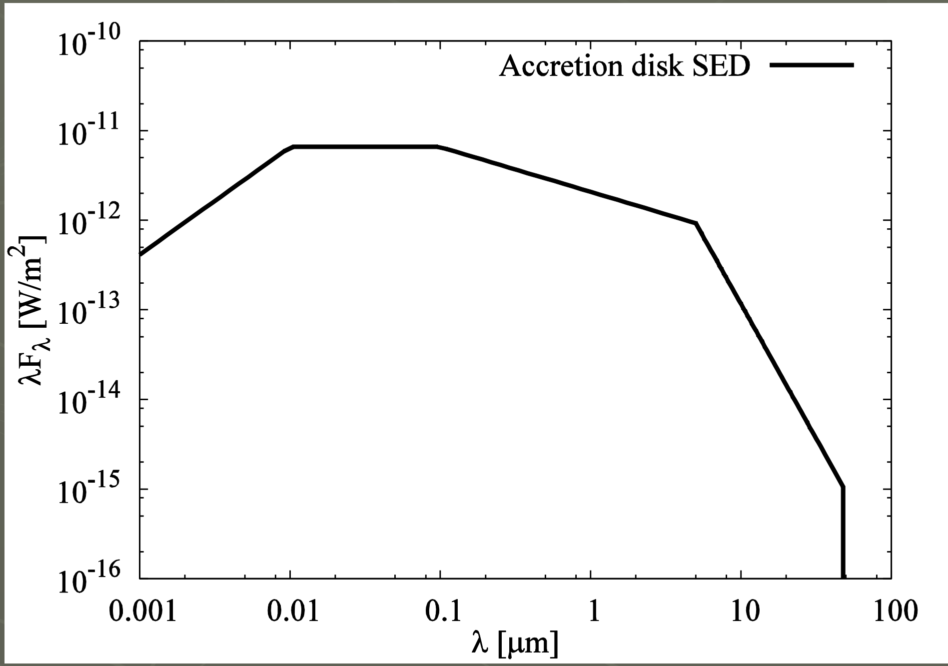




PRIMARY SOURCE: ACCRETION DISK

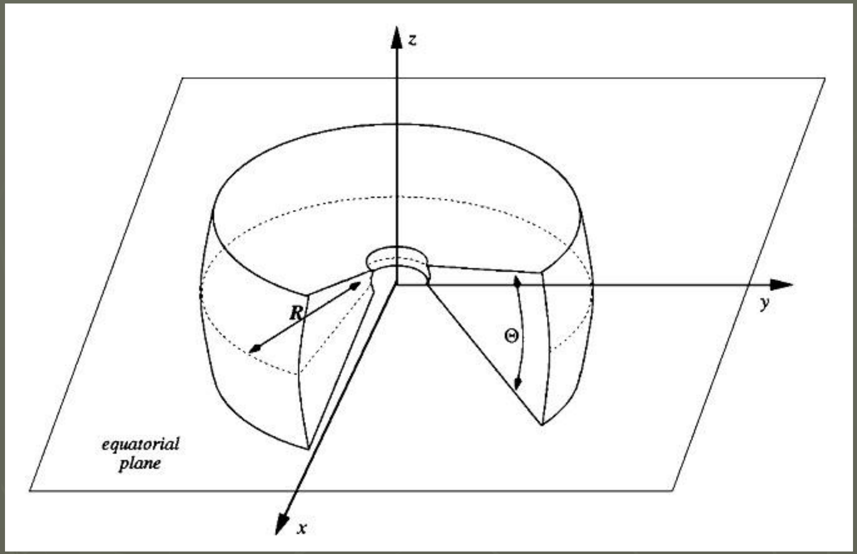
- Approx: central point-like energy source with
  - Isotropic emission
  - Anisotropic emission

$$\lambda L(\lambda) \propto \begin{cases} \lambda^{1.2} & 0.001 < \lambda < 0.01 \quad [\mu m] \\ \lambda^{0} & 0.01 < \lambda < 0.1 \quad [\mu m] \\ \lambda^{-0.5} & 0.1 < \lambda < 5 \quad [\mu m] \\ \lambda^{-3} & 5 < \lambda < 1000 \quad [\mu m] \end{cases}$$



$L = 10^{11}\ L_o$

TORUS MODEL



$$R_{min} \simeq 1.3 \cdot \sqrt{L_{46}^{AGN}} \cdot T_{1500}^{-2.8} \qquad [pc],$$

- Dust mixture: silicate and graphite dust grains
- Dust grain size - MRN distribution:

$$dn(a) = Ca^{-3.5} da$$

a: 0.005 – 0.25 μm

- Dust is distributed on a 3D Cartesian grid of a large number of cubic cells

CLUMPY TWO-PHASE MEDIUM:

High-density clumps + low-density dust between the clumps

Smooth dust distribution:

$$\rho\,(r,\theta) = r^{-p} e^{-\gamma|cos(\theta)|}.$$

+

Filling factor & contrast

↓

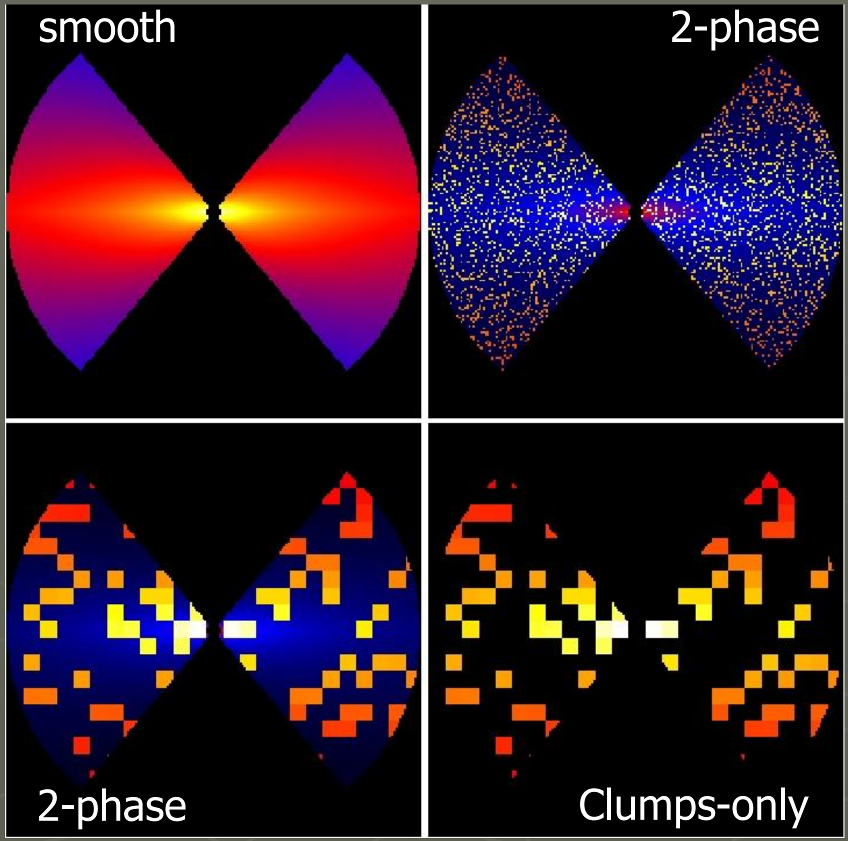
Two-phase medium

+

Very high contrast

↓

Clumps-only



Dust density map (meridional plane)

CLUMPY TWO-PHASE MEDIUM:

High-density clumps + low-density dust between the clumps

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+

Filling factor & contrast

↓

Two-phase medium

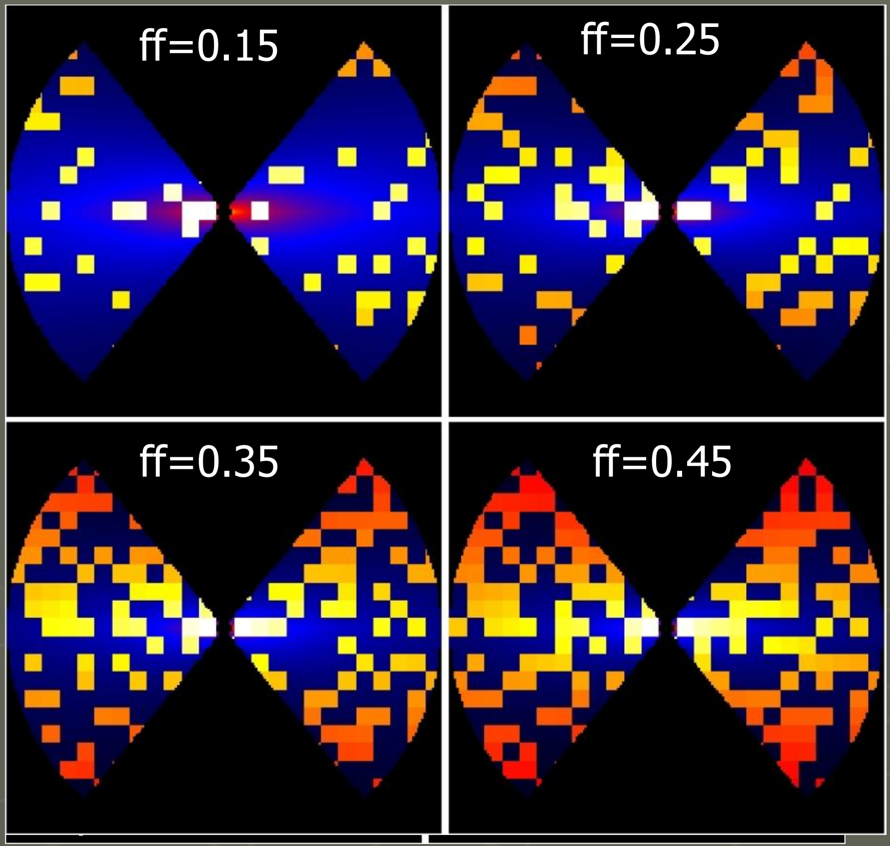
+

Very high contrast

↓

Clumps-only

contrast=100



Dust density maps (meridional plane)
For different filling factorts

CLUMPY TWO-PHASE MEDIUM:

High-density clumps + low-density dust between the clumps

Smooth dust distribution:

$$\rho\left(r,\theta\right) = r^{-p} e^{-\gamma |cos(\theta)|}.$$

+

Filling factor & contrast

↓

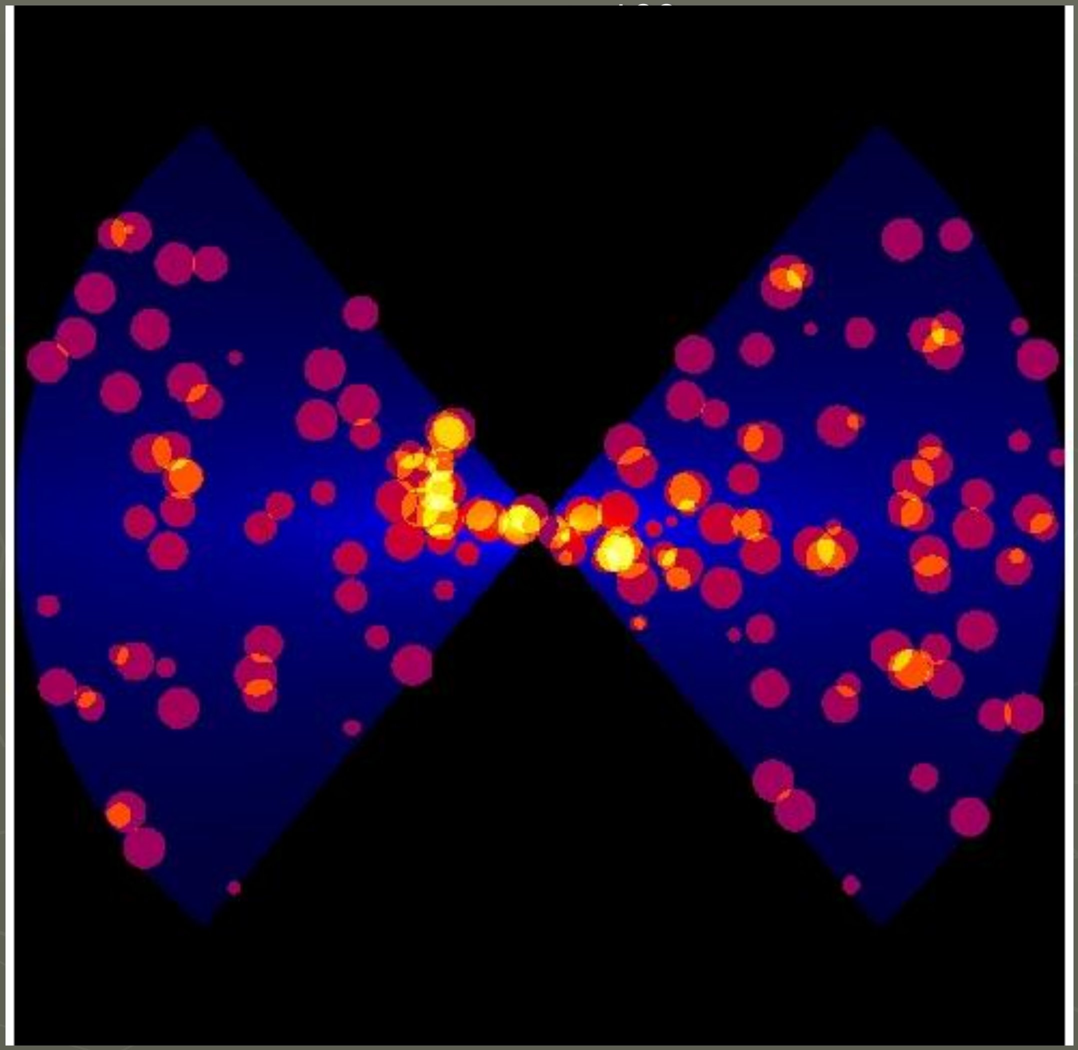
Two-phase medium

+

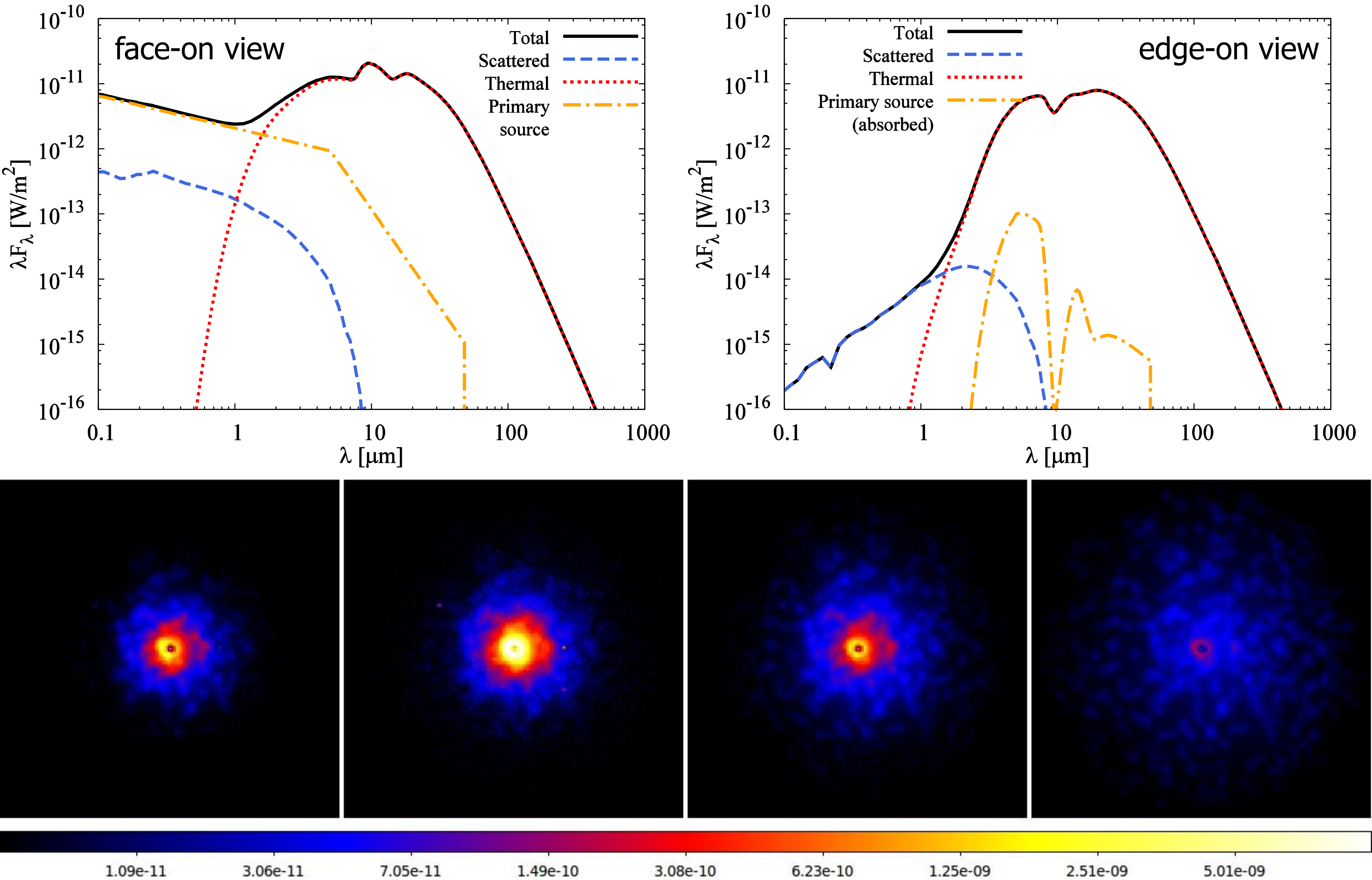
Very high contrast

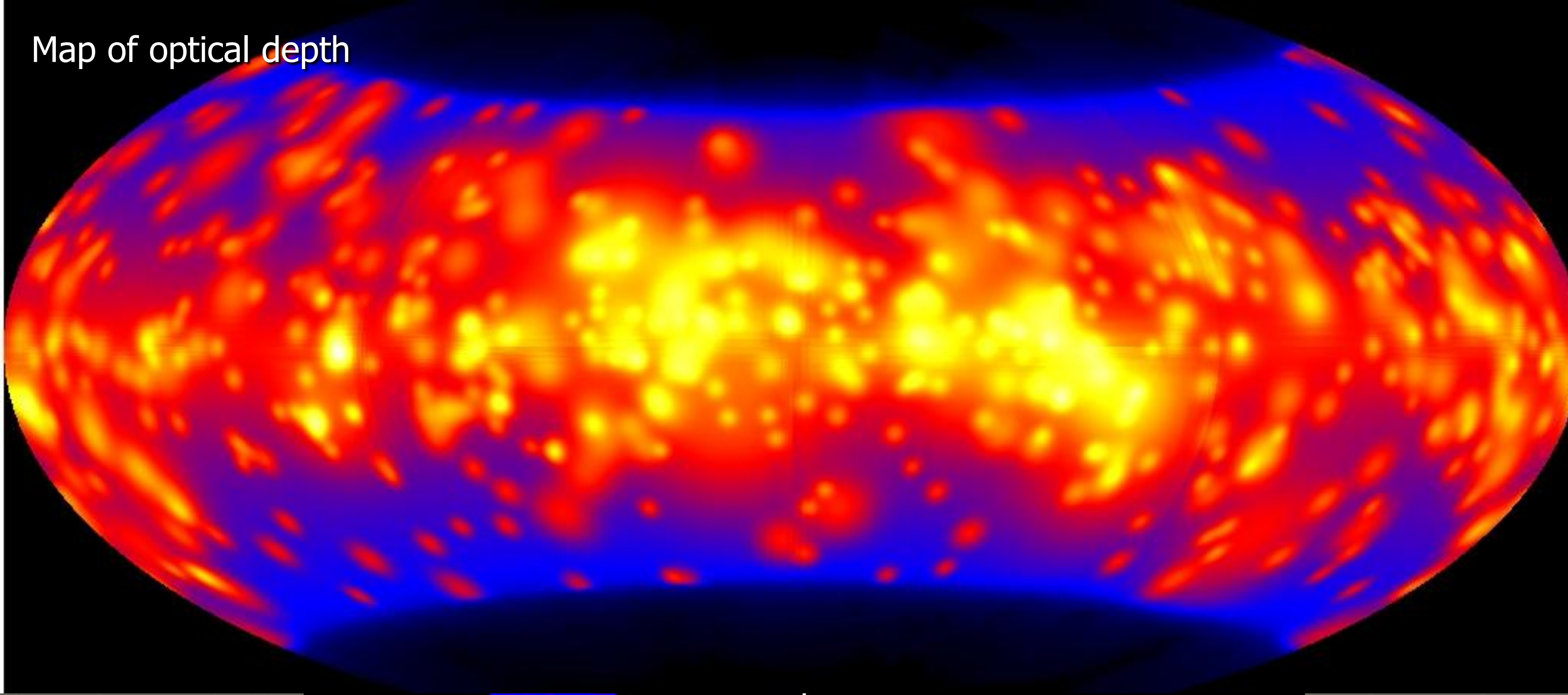
↓

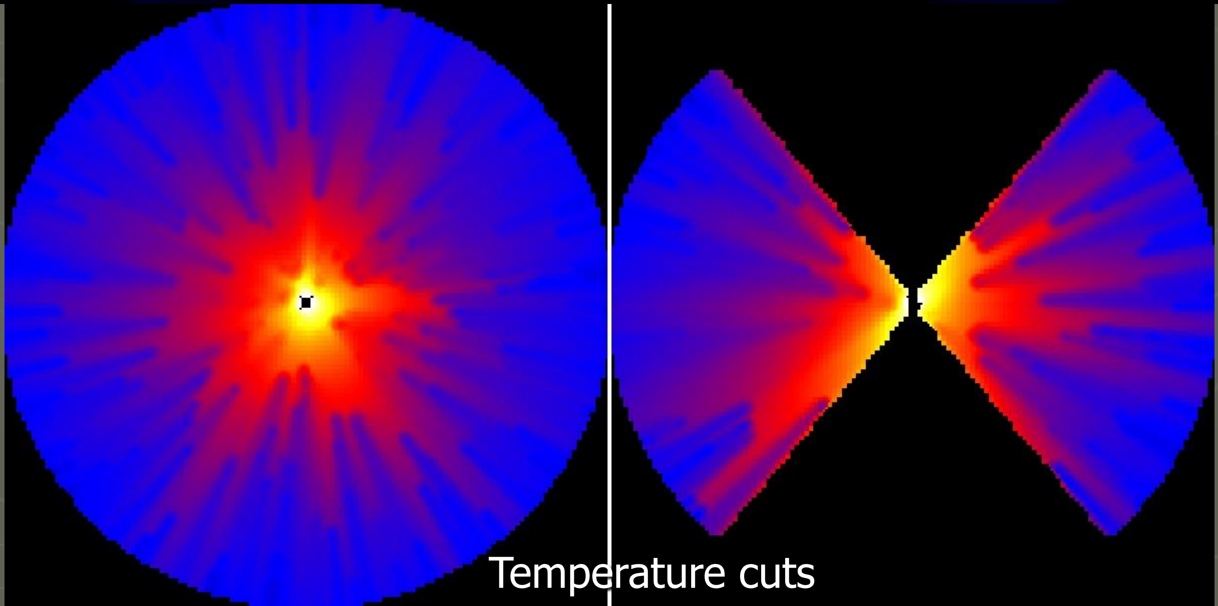
Clumps-only



DUSTY TORUS SEDs

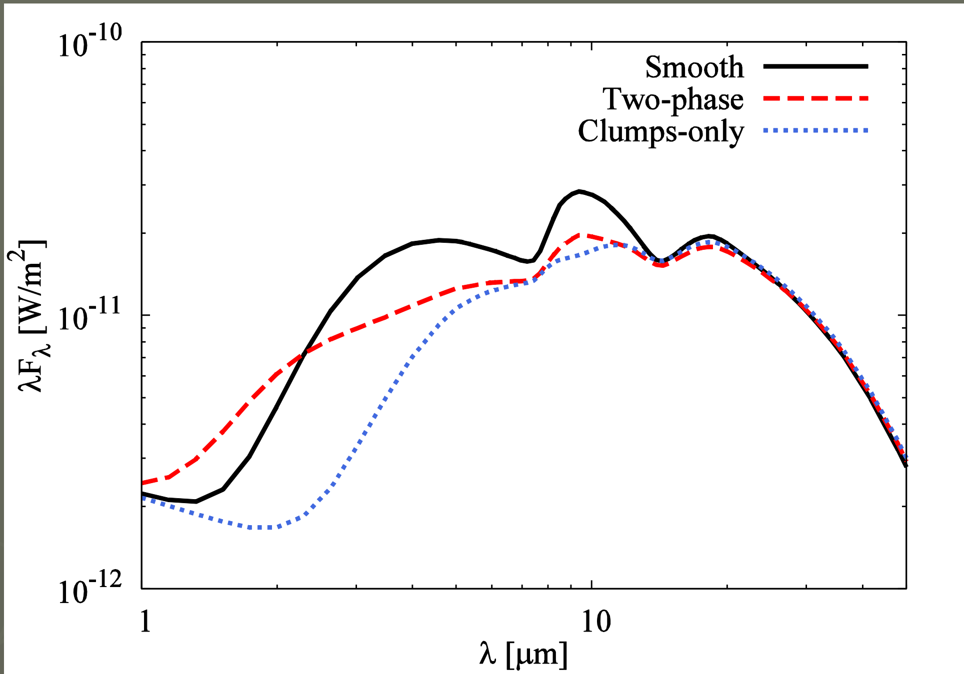



Map of optical depth

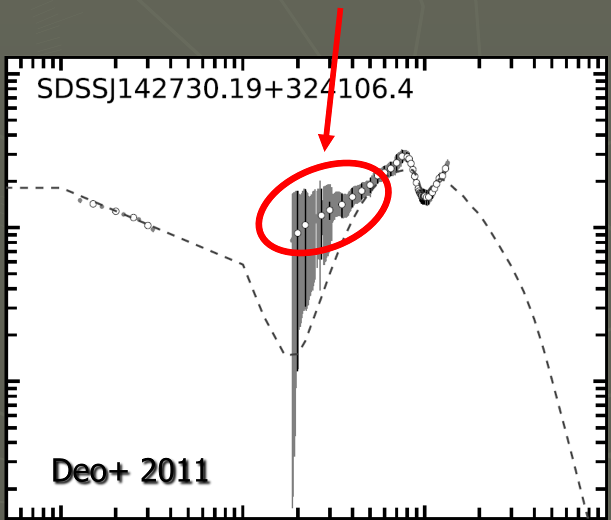

Temperature cuts

Silicate feature and NIR excess

- 10 μm silicate feature attenuated in the clumpy models. But smooth models are able to reproduce almost the same range of the silicate feature strength



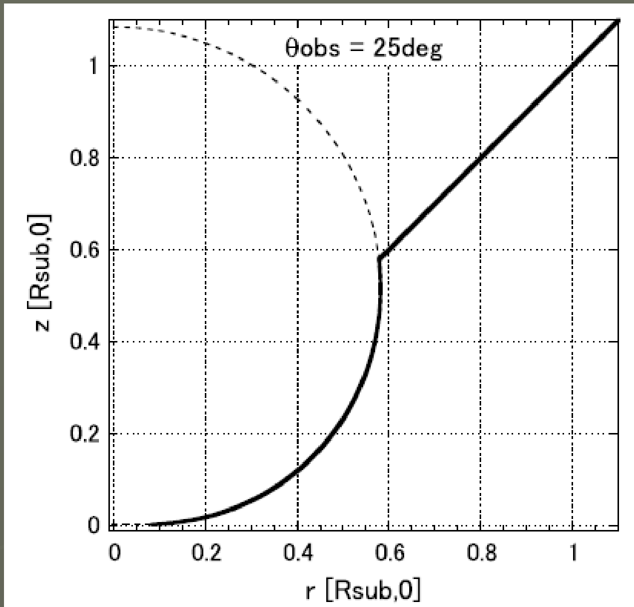
- Two-phase models: more pronounced NIR emission + attenuated silicate feature: a natural solution to the NIR excess problem?



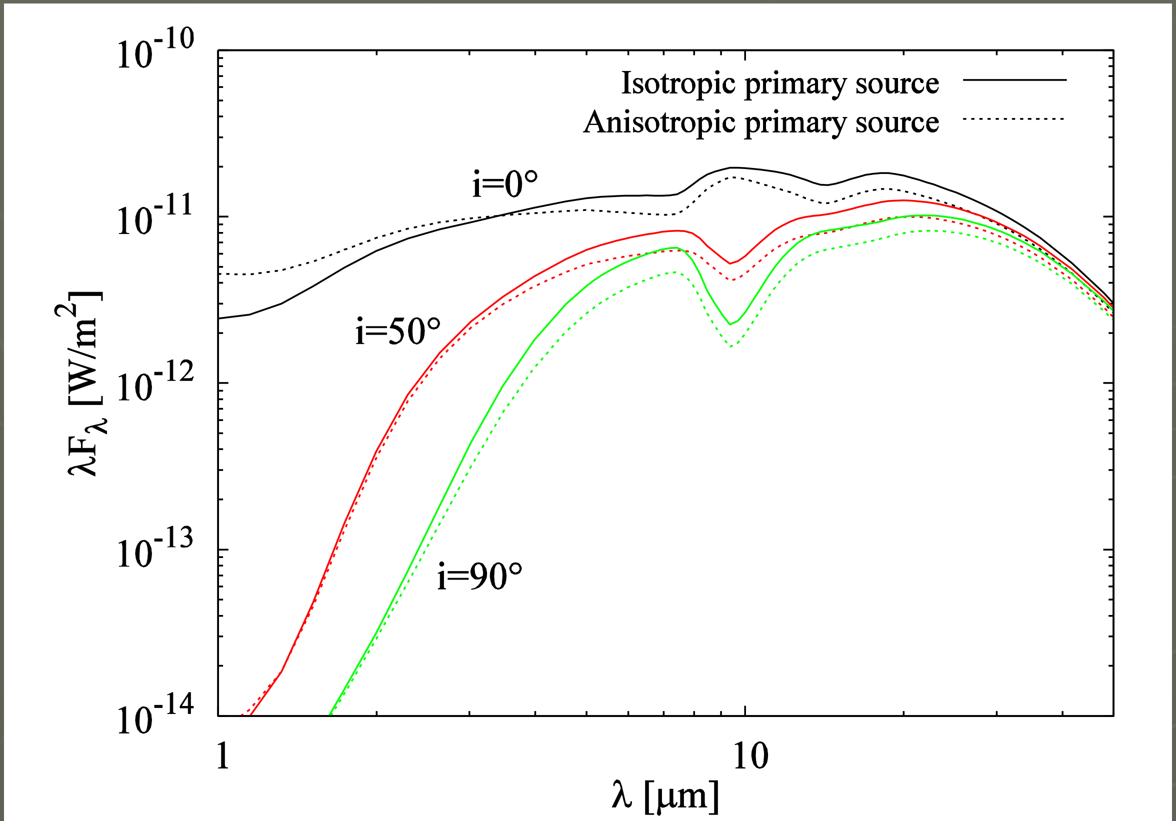
- Roseboom+ 2012: observed L_{NIR}/L_{TOTIR} ratio easily achievable in two-phase models

ANISOTROPIC PRIMARY SOURCE

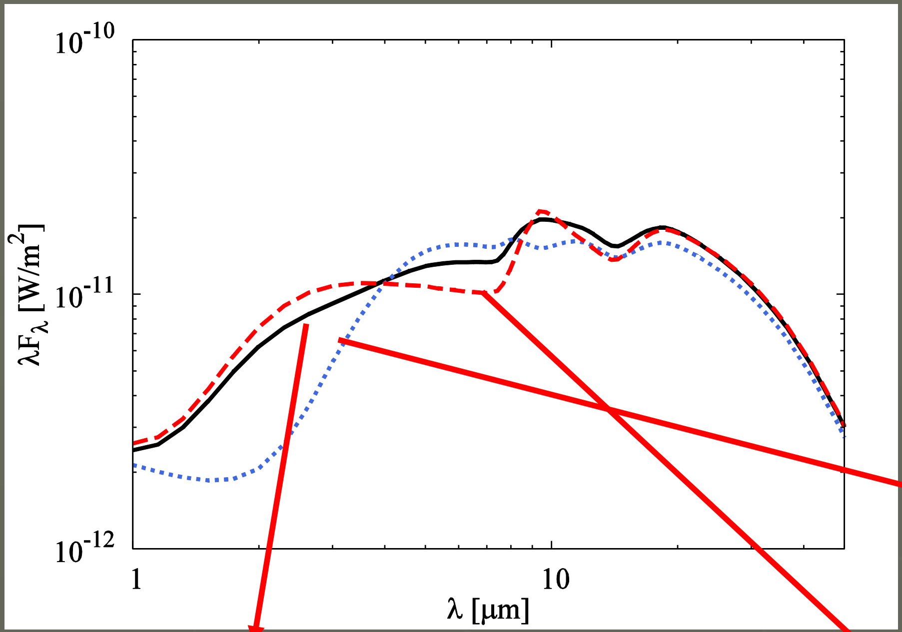
$$F \propto \cos\theta(1 + 2\cos\theta)$$



Kawaguchi & Mori 2010

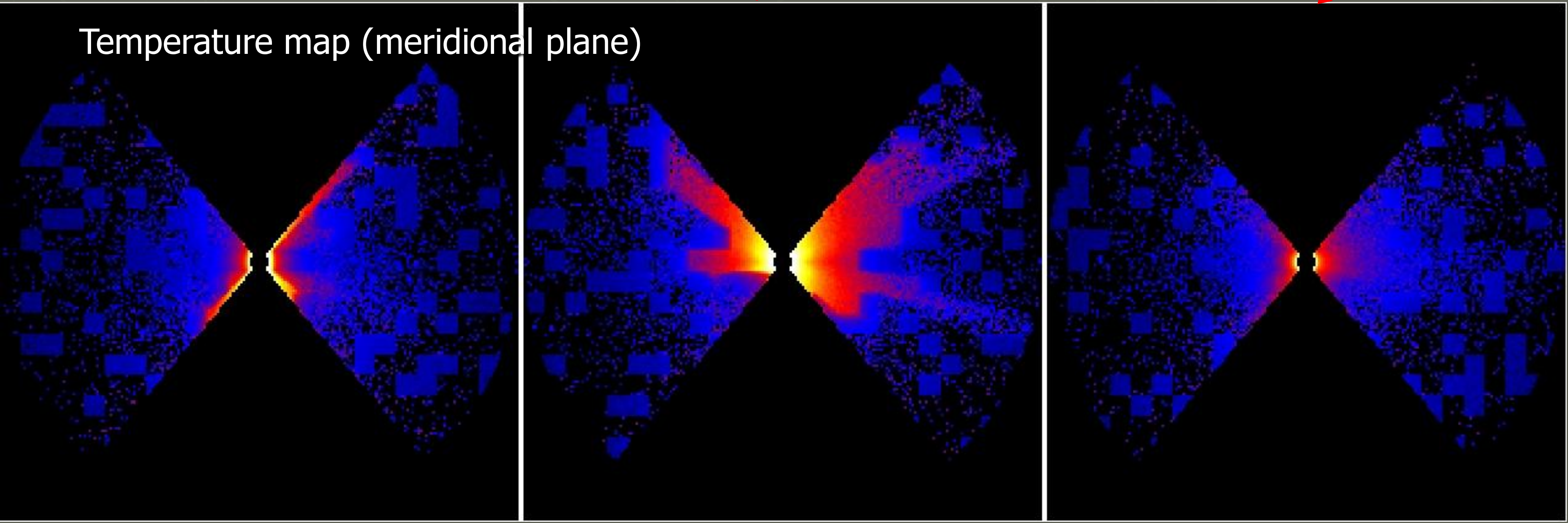


Influence of random arrangement of the clumps



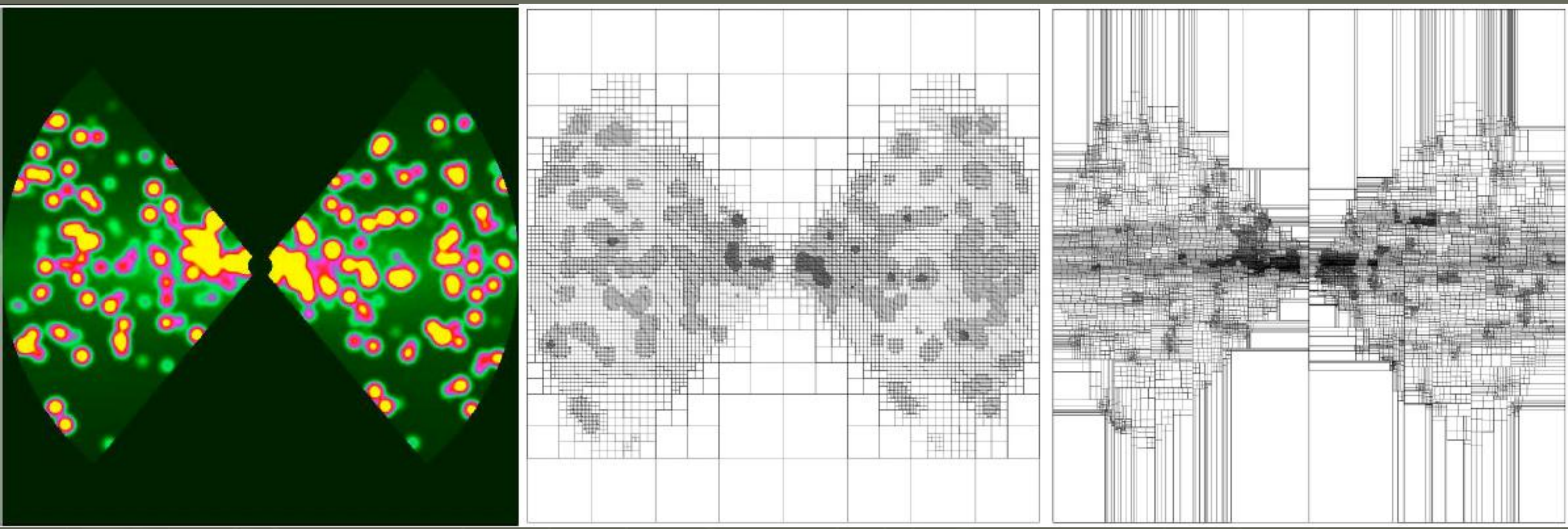
BUT:

- EXTREME EXAMPLES!
- More models for better statistic
- Clumps should be smaller in the inner region (tidal shearing)



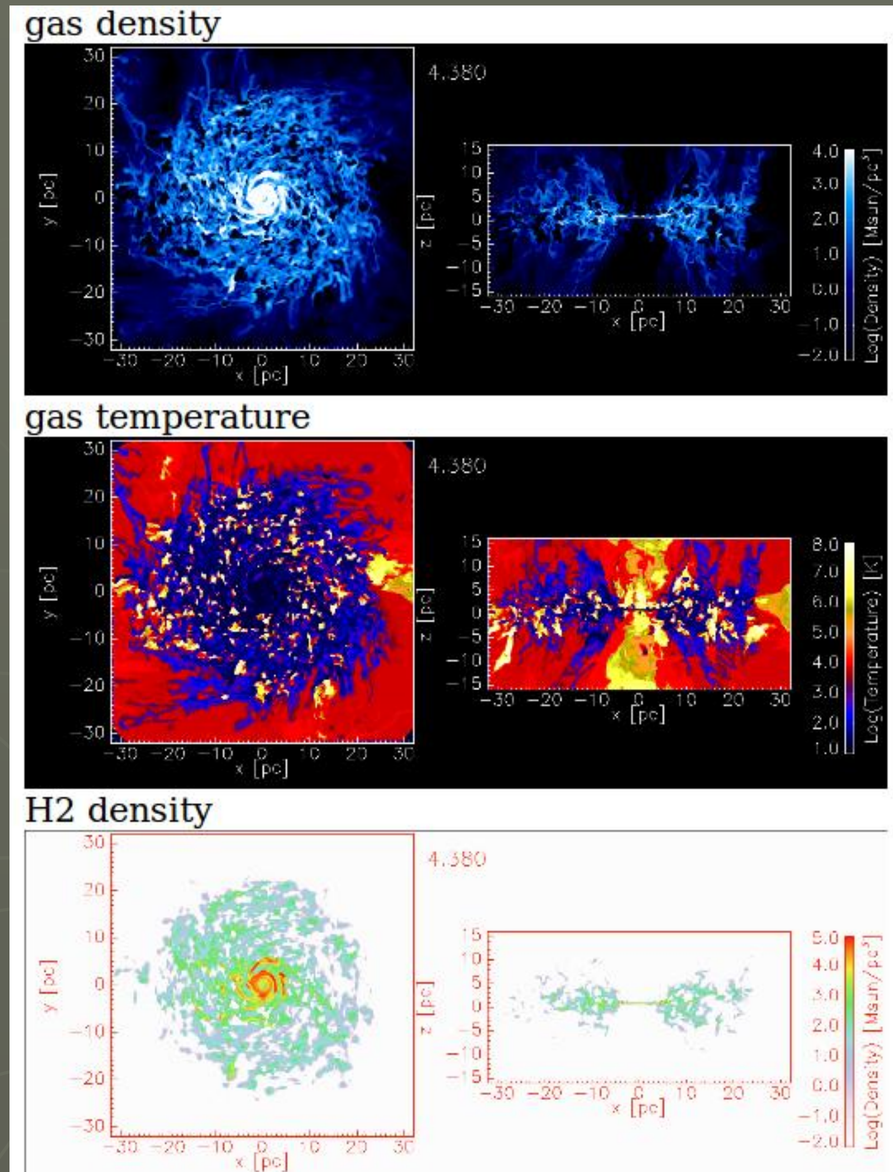
SKIRT6

Adaptive octree grid (Saftly+ 2013)



ON-GOING WORK: SKIRT6

RT of multiphase filamentary medium



Wada 2009

ON-GOING WORK: Including polarization in SKIRT

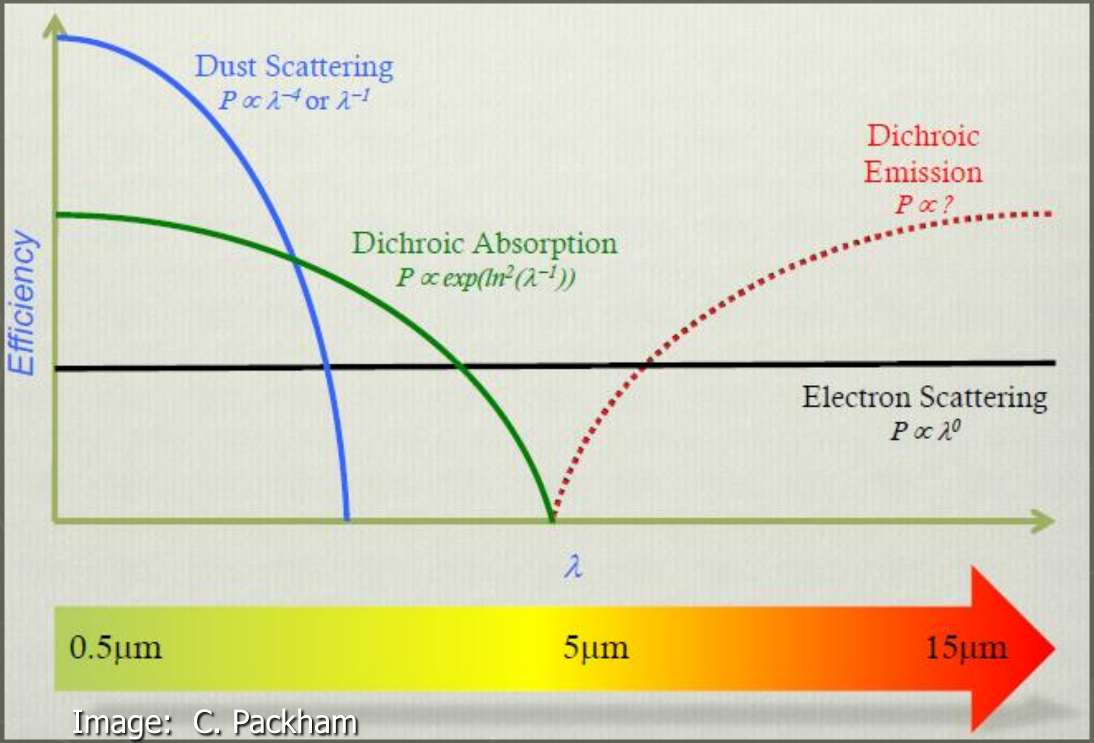
- Observed polarization properties can constrain geometry of different scattering regions in AGN:
  - Dusty torus
  - Equatorial scattering region
  - Polar outflows

Due to:

- Scattering on dust grains
- Scattering on electrons
- Grain alignment

Polarization studies of AGN and based on Monte Carlo radiative transfer studies have been done before (e.g. Goosmann & Gaskell 2007, Marin+ 2012)

But not based on a clumpy 3D geometries…



Stalevski+ 2012, MNRAS, 420, 2756

https://sites.google.com/site/skirtorus/

A grid of model SEDs available for download

Images of torus (FITS) available upon request

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