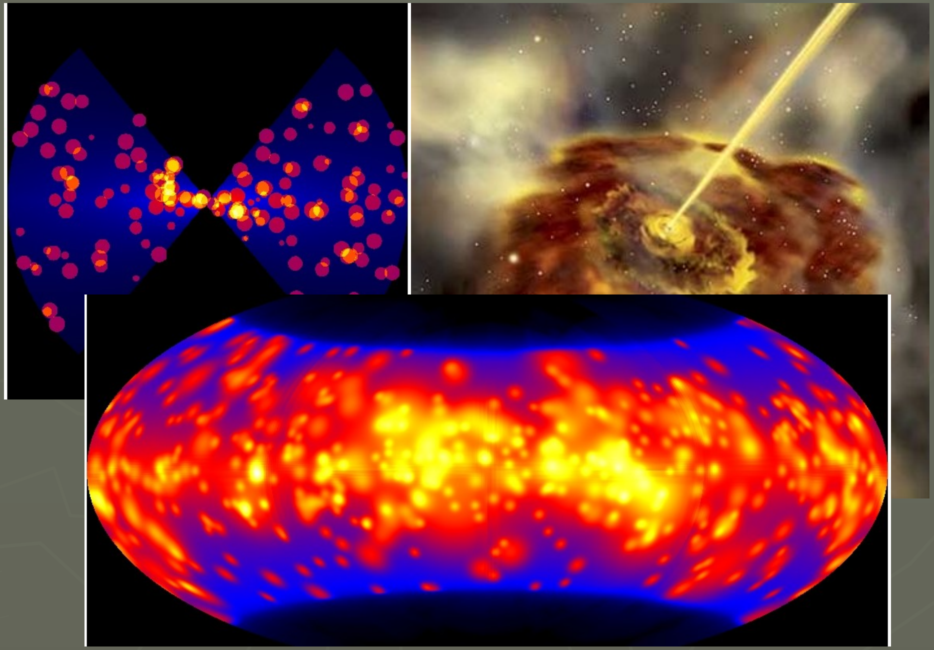
RADIATIVE TANSFER MODELING OF AGN DUSTY TORUS AS CLUMPY TWO-PHASE MEDIUM



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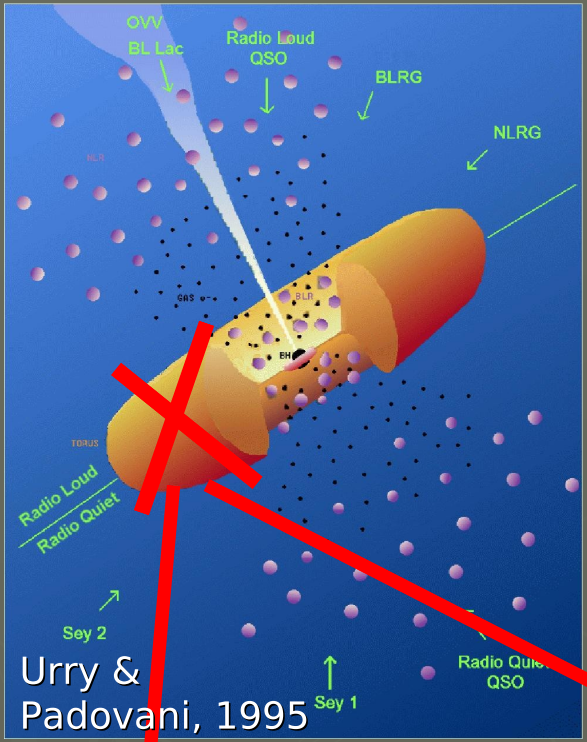
AGN DUSTY TORUS



Urry & Padovani, 1995

- 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)

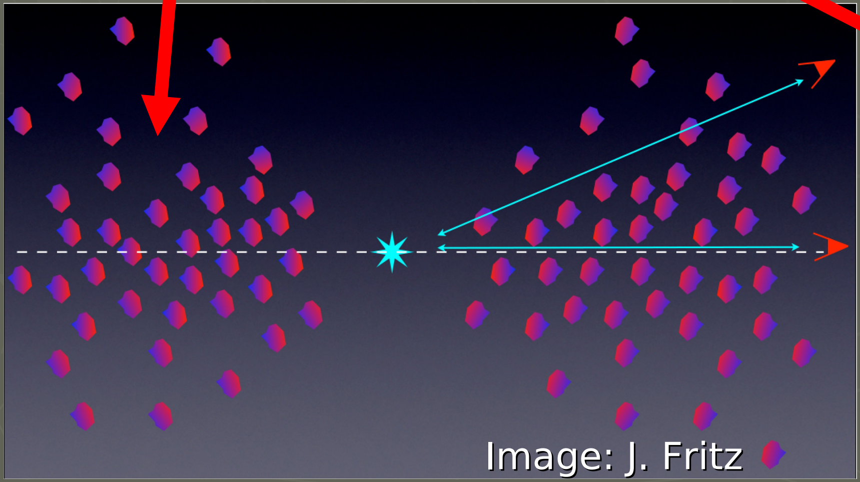
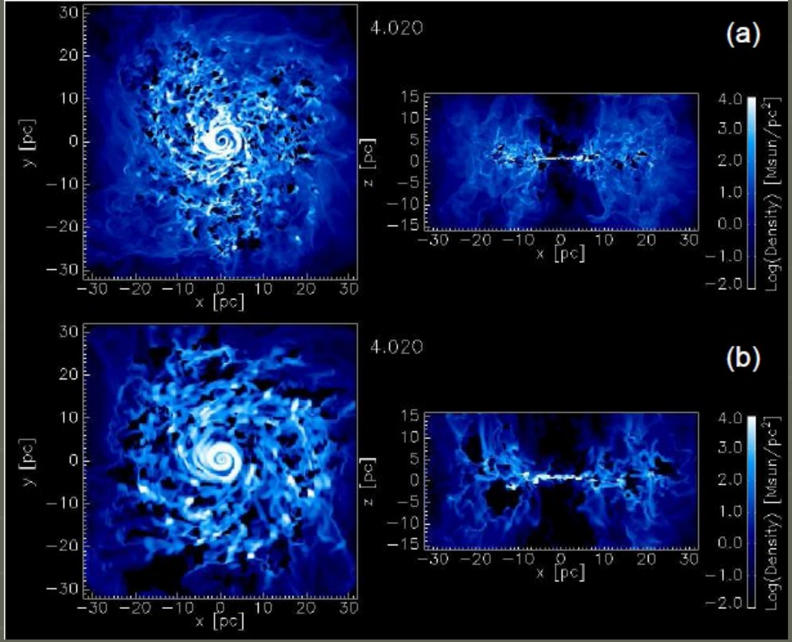
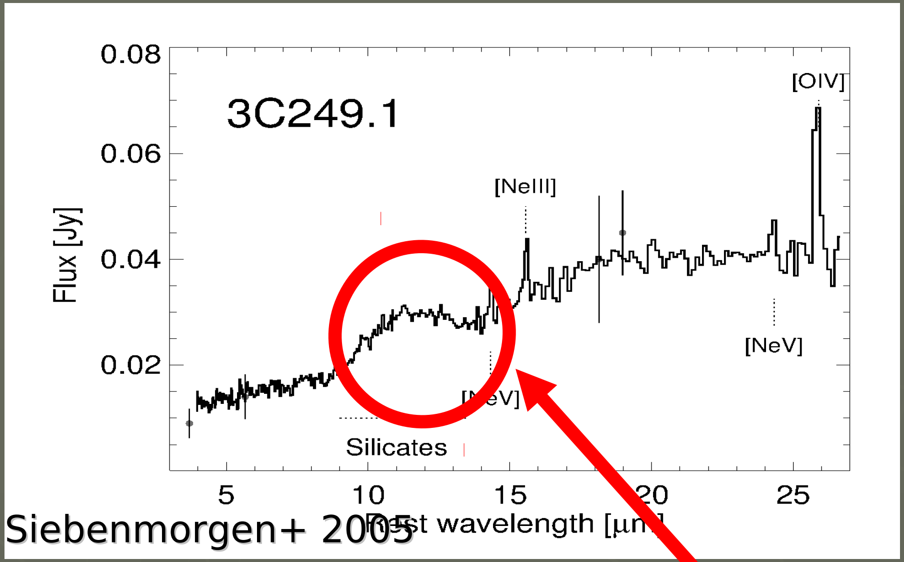


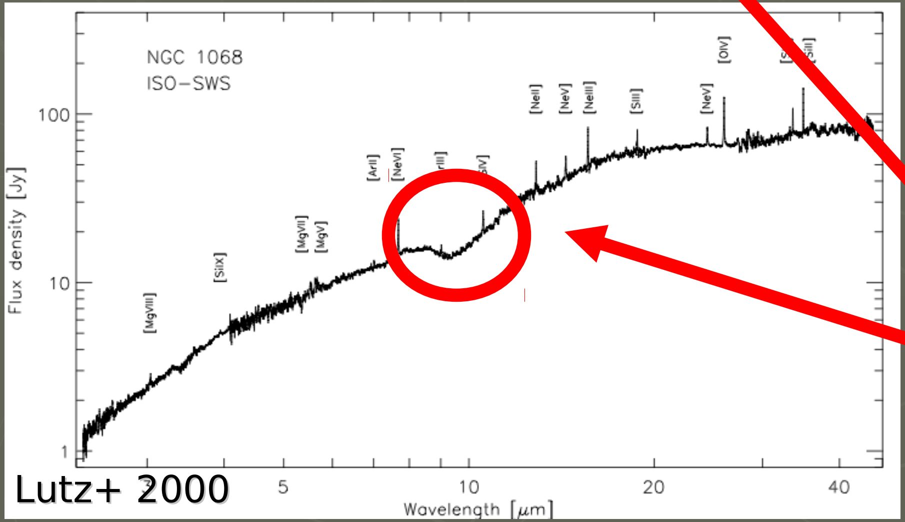
Image: J. Fritz



DUSTY TORUS EMISSION



Siebenmorgen+ 2005

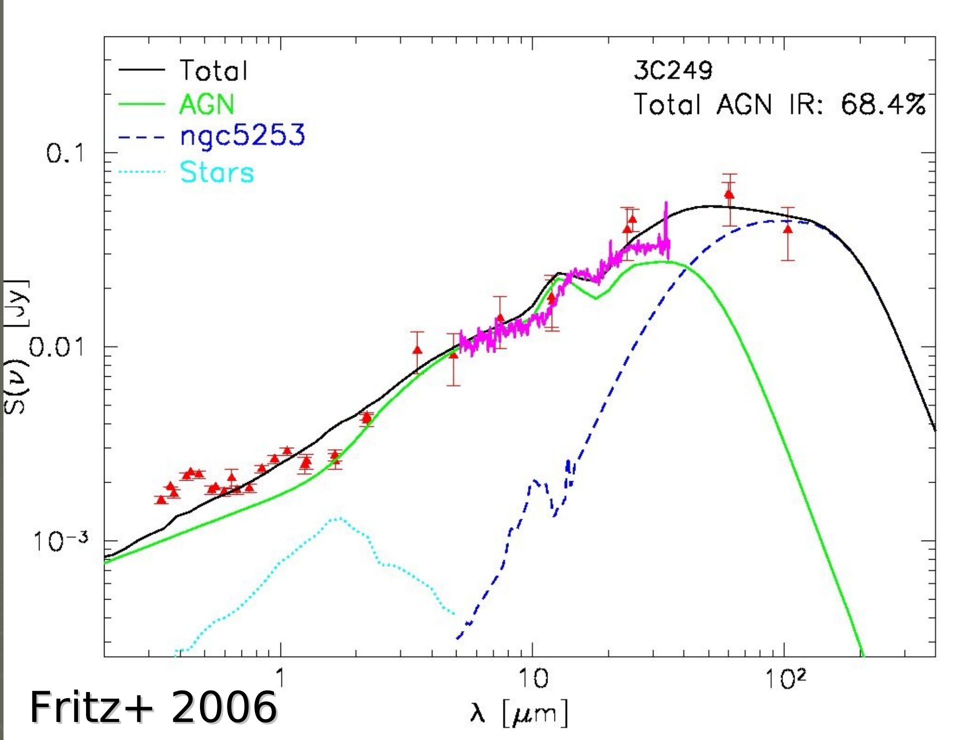


Lutz+ 2000

- Dust in the torus absorbs the incoming accretion disc radiation and re-emit it in the infrared
- Mid- to far-IR bump
- ~ 10 μm silicate feature (Si – O 'stretching' mode) –
  - Window into dust distribution and chemical compostion
  - 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) ?
  - Clumpiness suppresses intensity (Nenkova+ 2008)



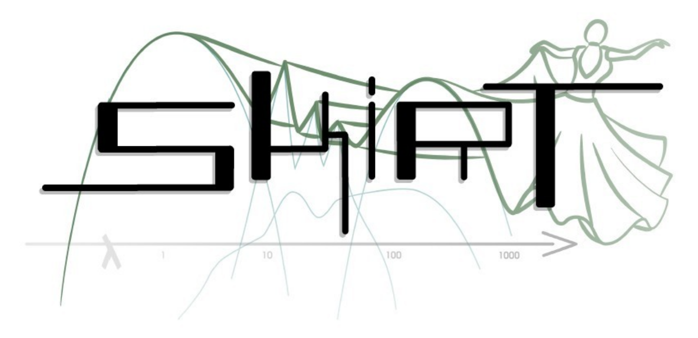
Fritz+ 2006

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

RADIATIVE TRANSFER CODE SKIRT

(Baes et al, 2003, 2011)

Stellar
Kinematics
Including
Radiative
Transfer



- 3D Monte Carlo radiative transfer code
- Developed to investigate the effects of dust extinction on the photometry and kinematics of galaxies (Baes+ 2003)
- Over the years, the code evolved into a flexible tool that can model model a variety of dusty systems, e.g:
- Variety of galaxy types (Baes+ 2010; de Looze et al. 2010)
- Post-AGB circumstellar discs (Vidal & Baes 2007)
- AGN dusty torus (Stalevski+ 2012)

RT PROBLEM

$$
\begin{aligned}
\frac{\mathrm{d}I_\lambda}{\mathrm{d}s}(\boldsymbol{r},\boldsymbol{k}) = j^{*}_{\lambda}(\boldsymbol{r}) &- \sum_{j=1}^{N_{\mathrm{pop}}} \int_{a_{\min,j}}^{a_{\max,j}} \frac{\mathrm{d}n_j}{\mathrm{d}a}(\boldsymbol{r},a)\, C^{\mathrm{ext}}_{\lambda,j}(a)\, I_\lambda(\boldsymbol{r},\boldsymbol{k})\, \mathrm{d}a \\
&+ \sum_{j=1}^{N_{\mathrm{pop}}} \int_{a_{\min,j}}^{a_{\max,j}} \frac{\mathrm{d}n_j}{\mathrm{d}a}(\boldsymbol{r},a)\, C^{\mathrm{sca}}_{\lambda,j}(a) \left[\int_{4\pi} I_\lambda(\boldsymbol{r},\boldsymbol{k}')\, \Phi_{\lambda,j}(\boldsymbol{k},\boldsymbol{k}',a)\, \frac{\mathrm{d}\Omega'}{4\pi}\right] \mathrm{d}a \\
&+ \sum_{j=1}^{N_{\mathrm{pop}}} \int_{a_{\min,j}}^{a_{\max,j}} \frac{\mathrm{d}n_j}{\mathrm{d}a}(\boldsymbol{r},a)\, C^{\mathrm{abs}}_{\lambda,j}(a)\, B_\lambda\Big(T_{\mathrm{d},j}(\boldsymbol{r},a)\Big)\, \mathrm{d}a
\end{aligned}
$$

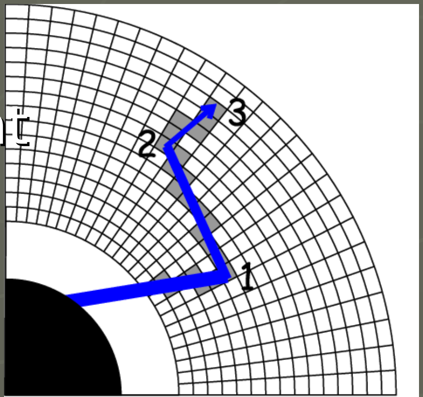
$$
\int_0^\infty C^{\mathrm{abs}}_{\lambda,j}(a)\, B_\lambda\Big(T_{\mathrm{d},j}(\boldsymbol{r},a)\Big)\, \mathrm{d}\lambda = \int_0^\infty C^{\mathrm{abs}}_{\lambda,j}(a)\, J_\lambda(\boldsymbol{r})\, \mathrm{d}\lambda
$$

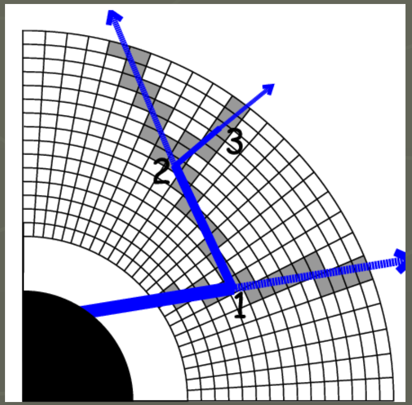
Monte Carlo radiative transfer

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



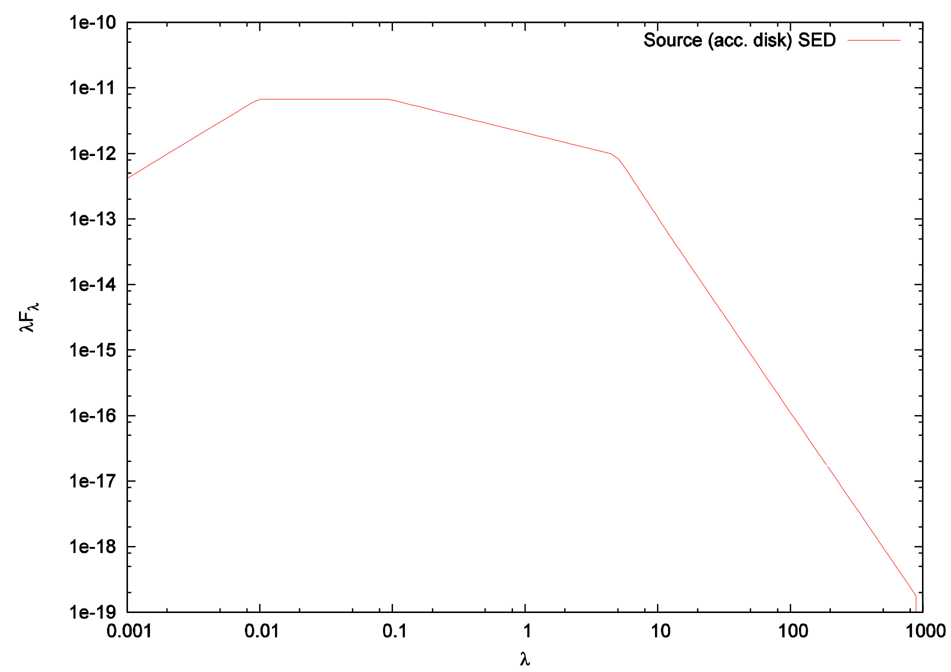


PRIMARY SOURCE: ACCRETION DISK

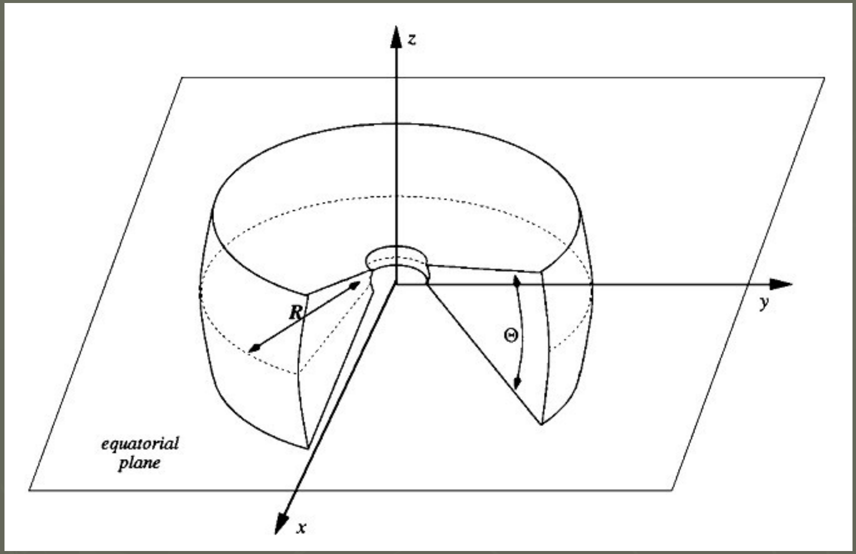
- Approx: central point-like energy source with isotropic emission

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

$L = 10^{11}\ L_o$



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

- 3D Cartesian grid of cubic cells

CLUMPY TWO-PHASE MEDIUM:

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

Smooth dust distribution:

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

+

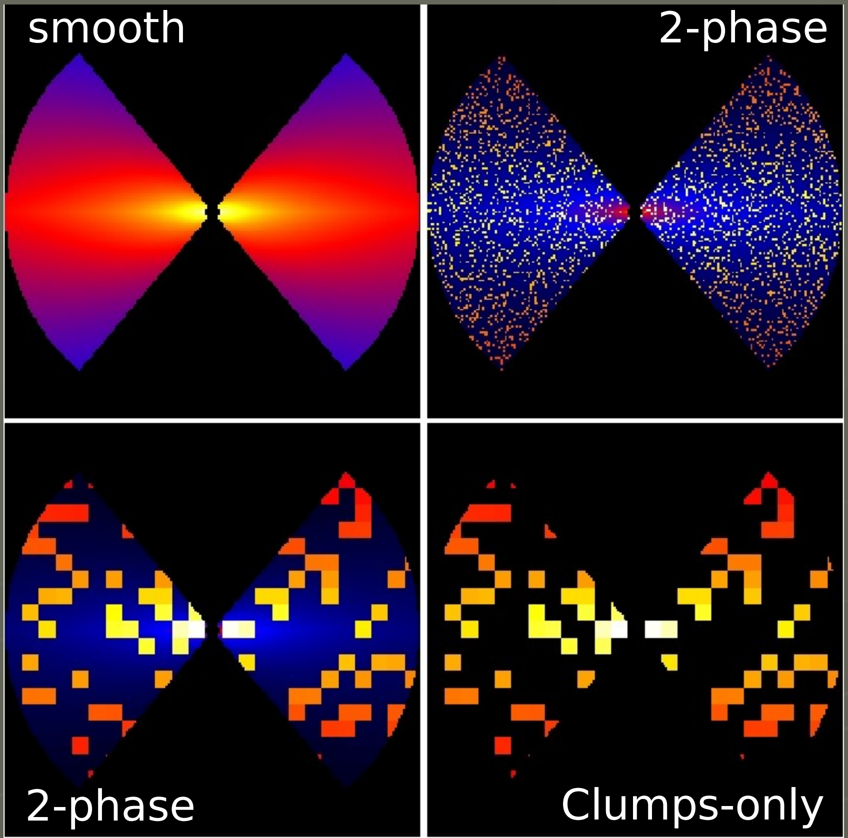
Filling factor & contrast

Two-phase medium

+

Very high contrast

Clumps-only



Dust density map (meridional plane)

CLUMPY TWO-PHASE MEDIUM:

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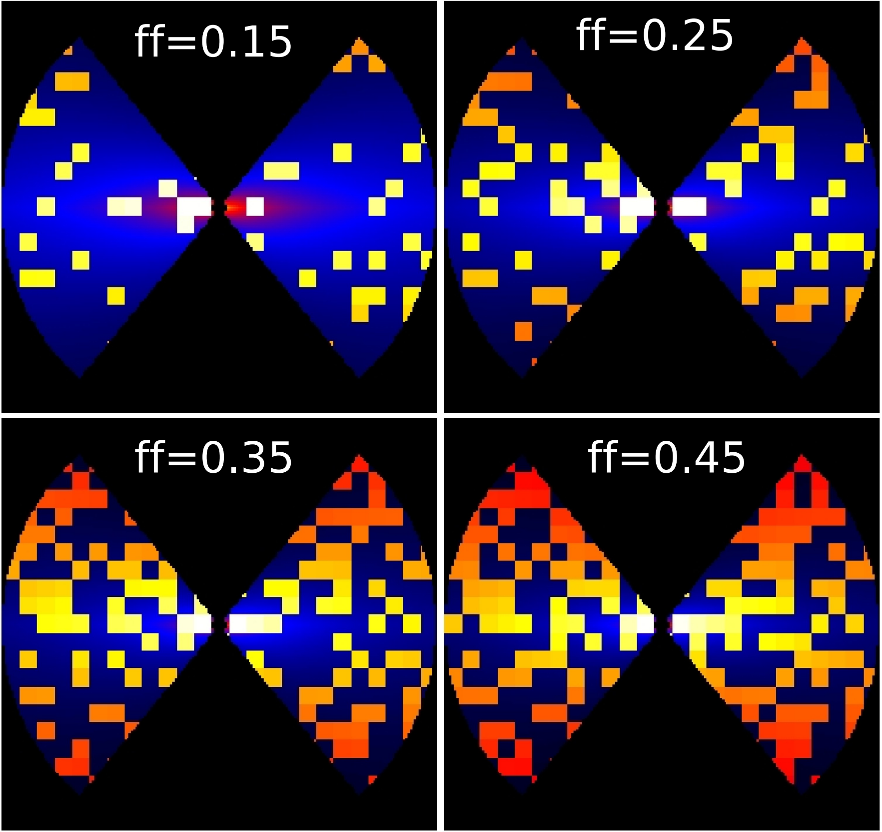
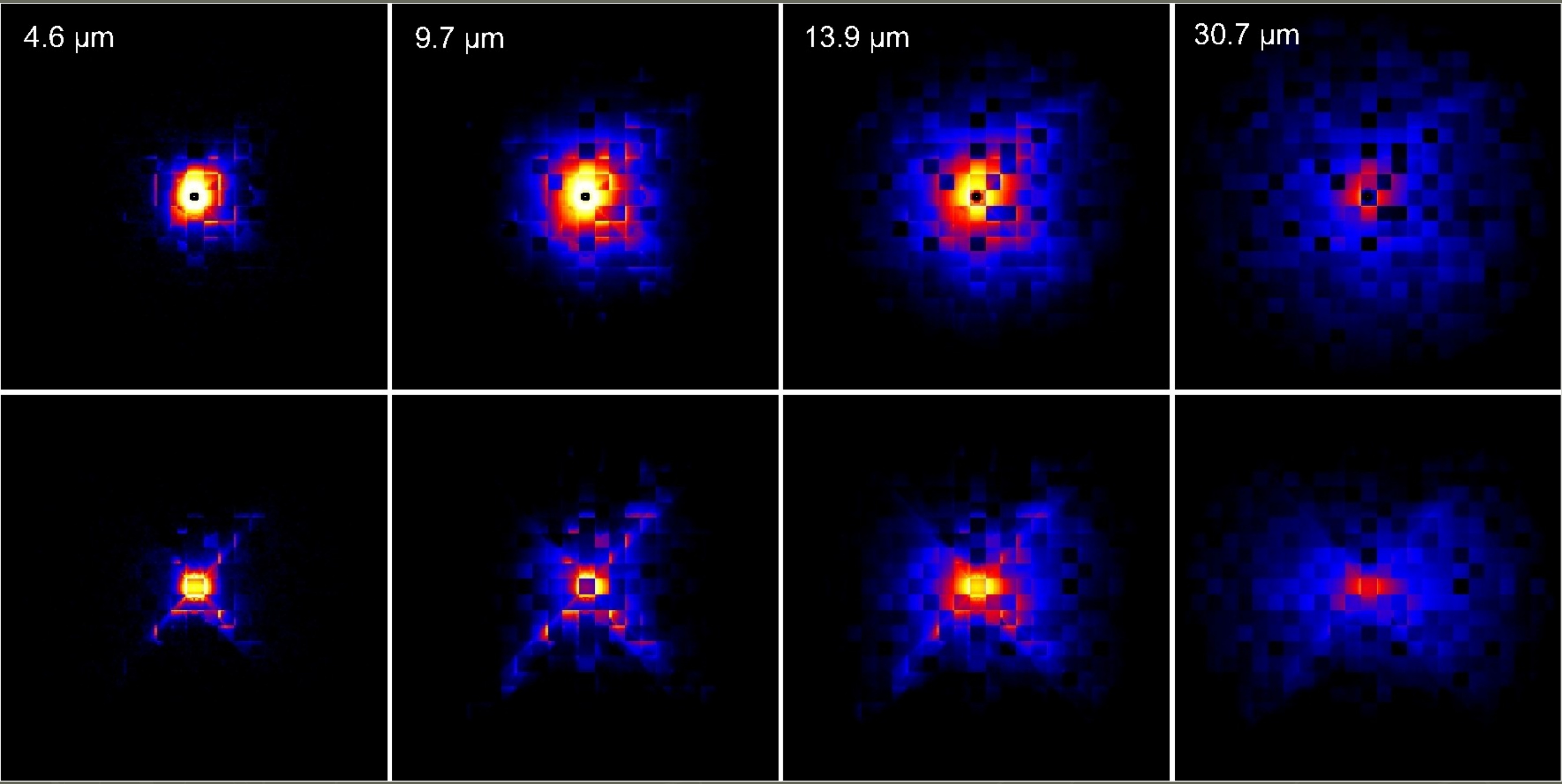
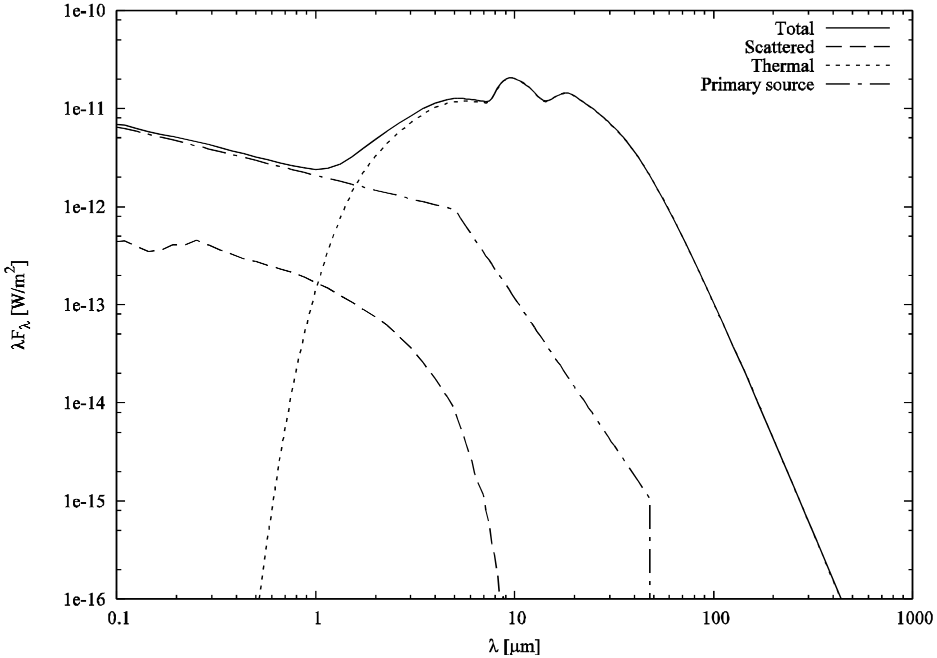

contrast=100

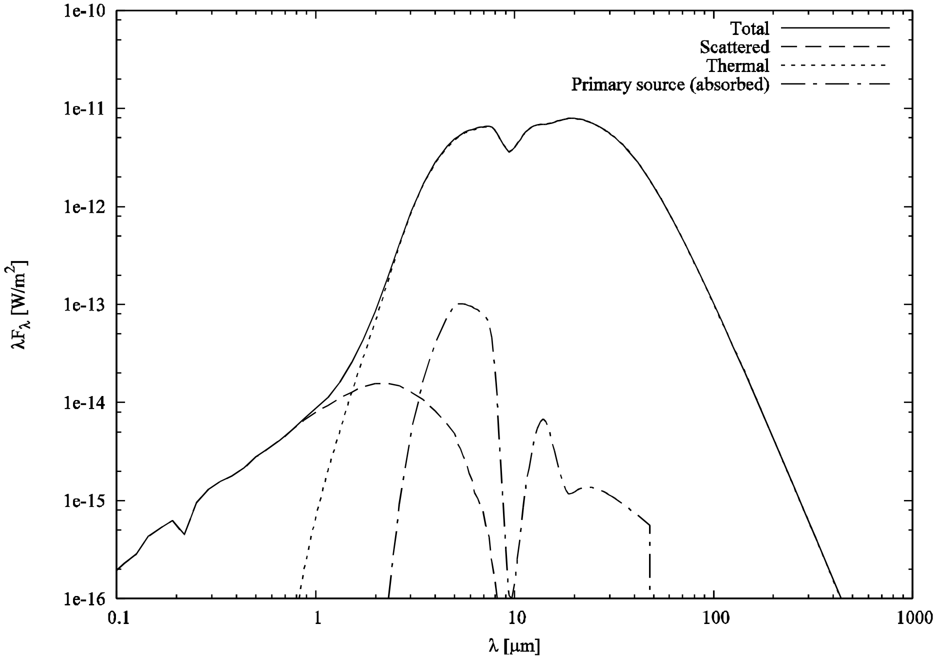
Dust density maps (meridional plane)
For different filling factorts

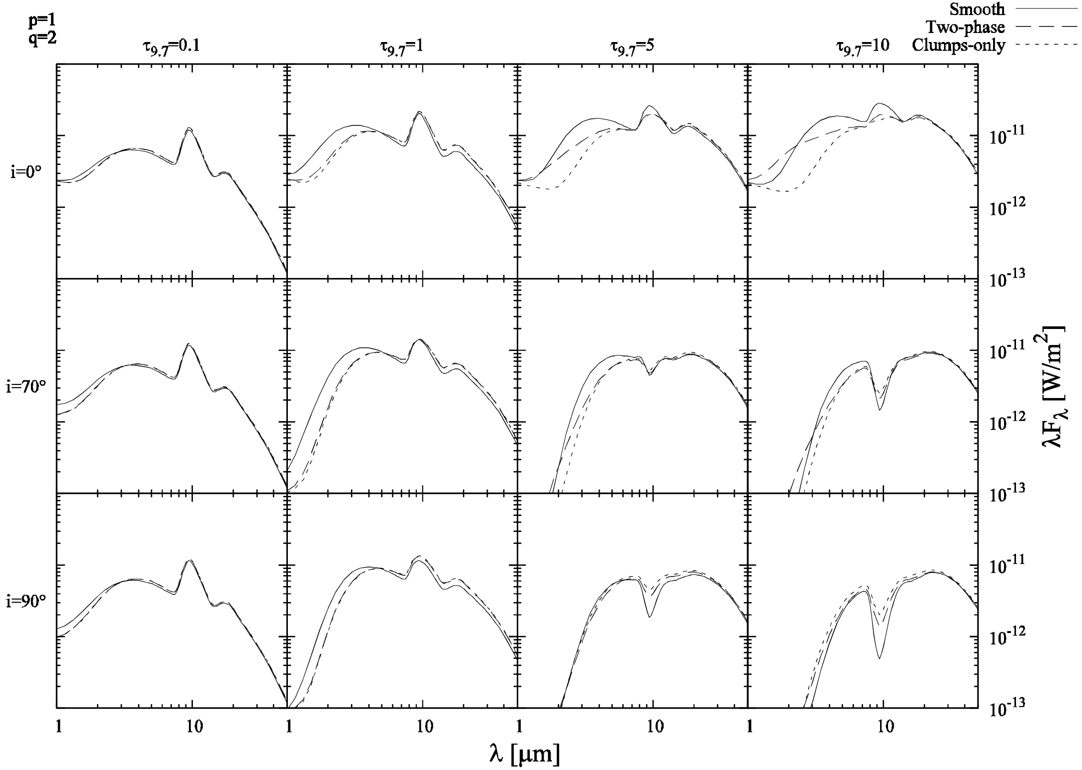
TORUS IMAGES



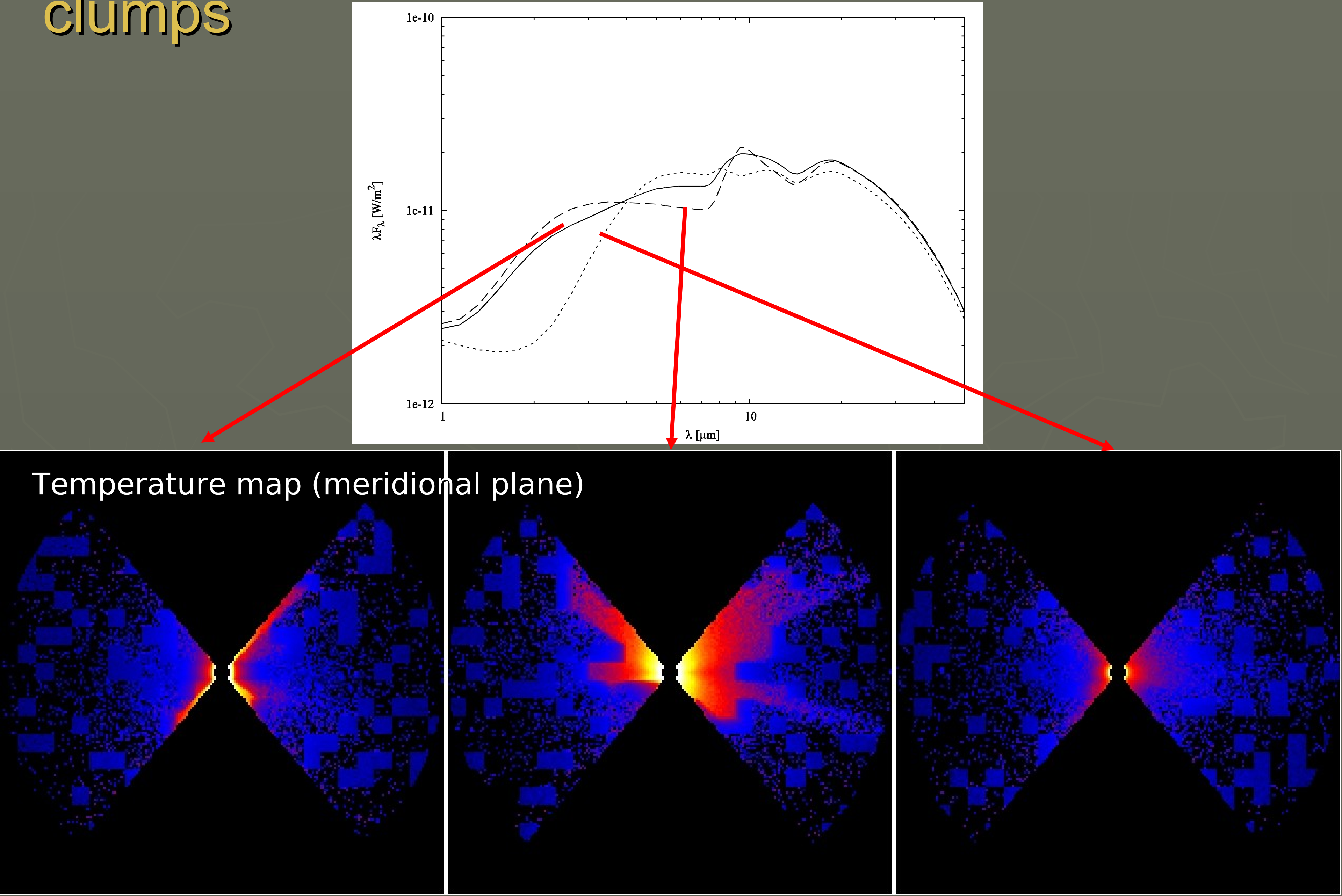
SEDs


Total
Scattered
Thermal
Primary source
1e-10
1e-11
1e-12
1e-13
1e-14
1e-15
1e-16
λF_λ [W/m^2]
0.1
1
10
100
1000
λ [μm]


Total
Scattered
Thermal
Primary source (absorbed)
1e-10
1e-11
1e-12
1e-13
1e-14
1e-15
1e-16
λF_λ [W/m^2]
0.1
1
10
100
1000
λ [μm]


Smooth
Two-phase
Clumps-only
p=1
q=2
$\tau_{9.7}$=0.1
$\tau_{9.7}$=1
$\tau_{9.7}$=5
$\tau_{9.7}$=10
i=0°
i=70°
i=90°
10^{-11}
10^{-12}
10^{-13}
λF_λ [W/m^2]
1
10
λ [μm]

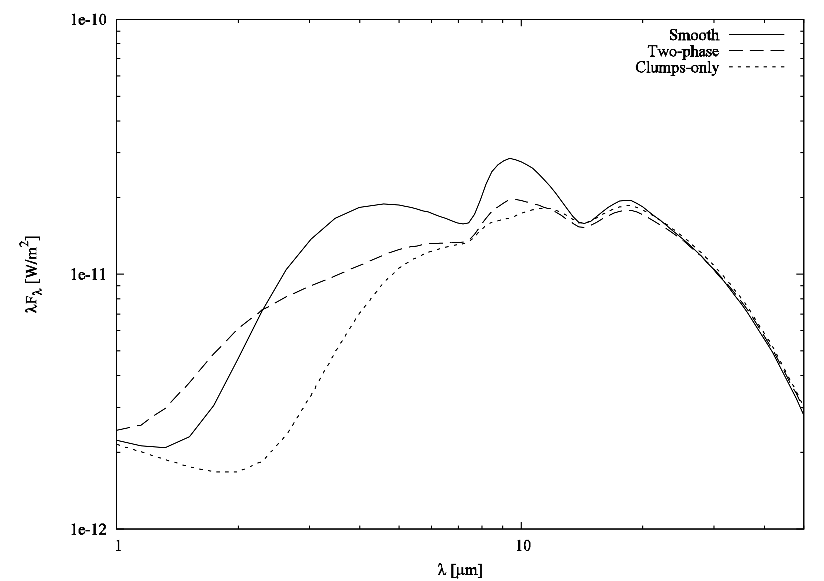
Degeneracy due to random arrangement of the clumps



Temperature map (meridional plane)

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?

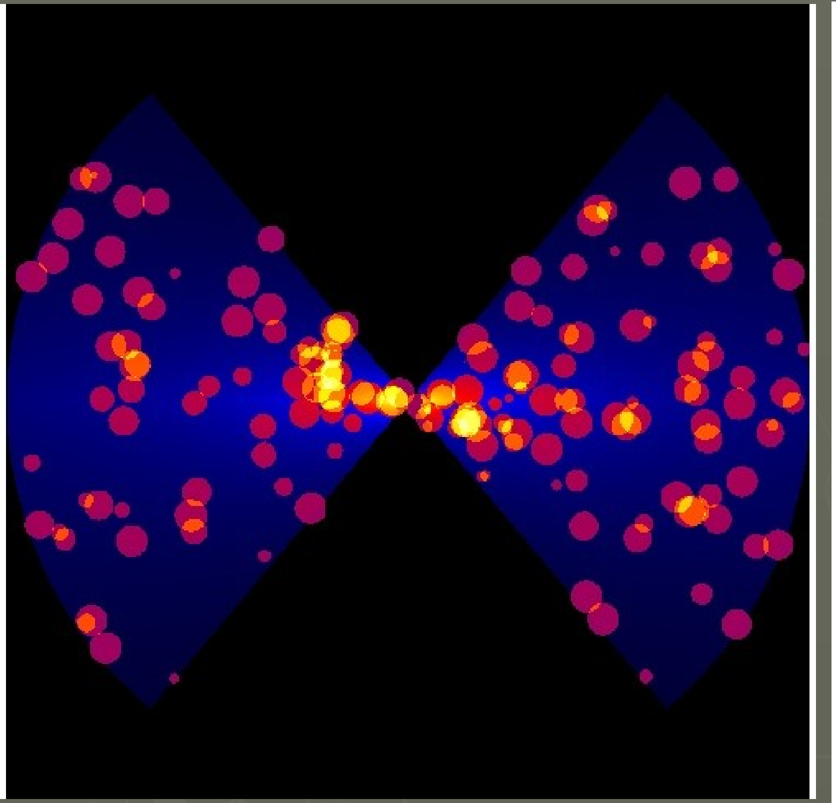
- Roseboom+ 2012: observed L_{NIR}/L_{TOTIR} ratio easily achievable in two-phase models

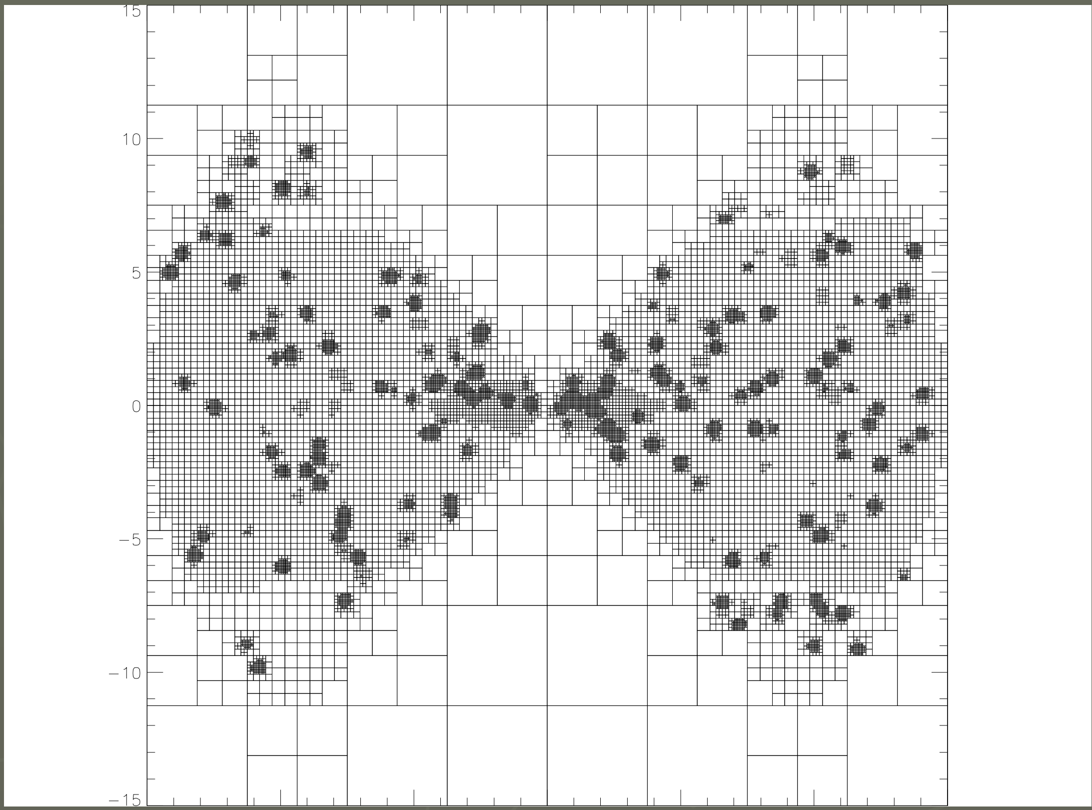
SKIRT4

(Stalevski et al. 2012, MNRAS)

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

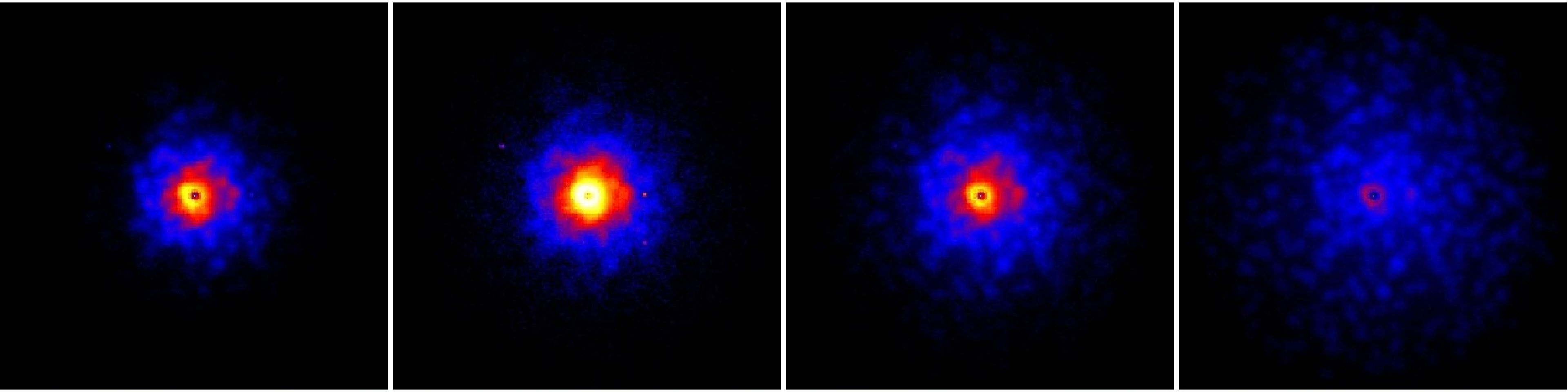
ON-GOING WORK: SKIRT5

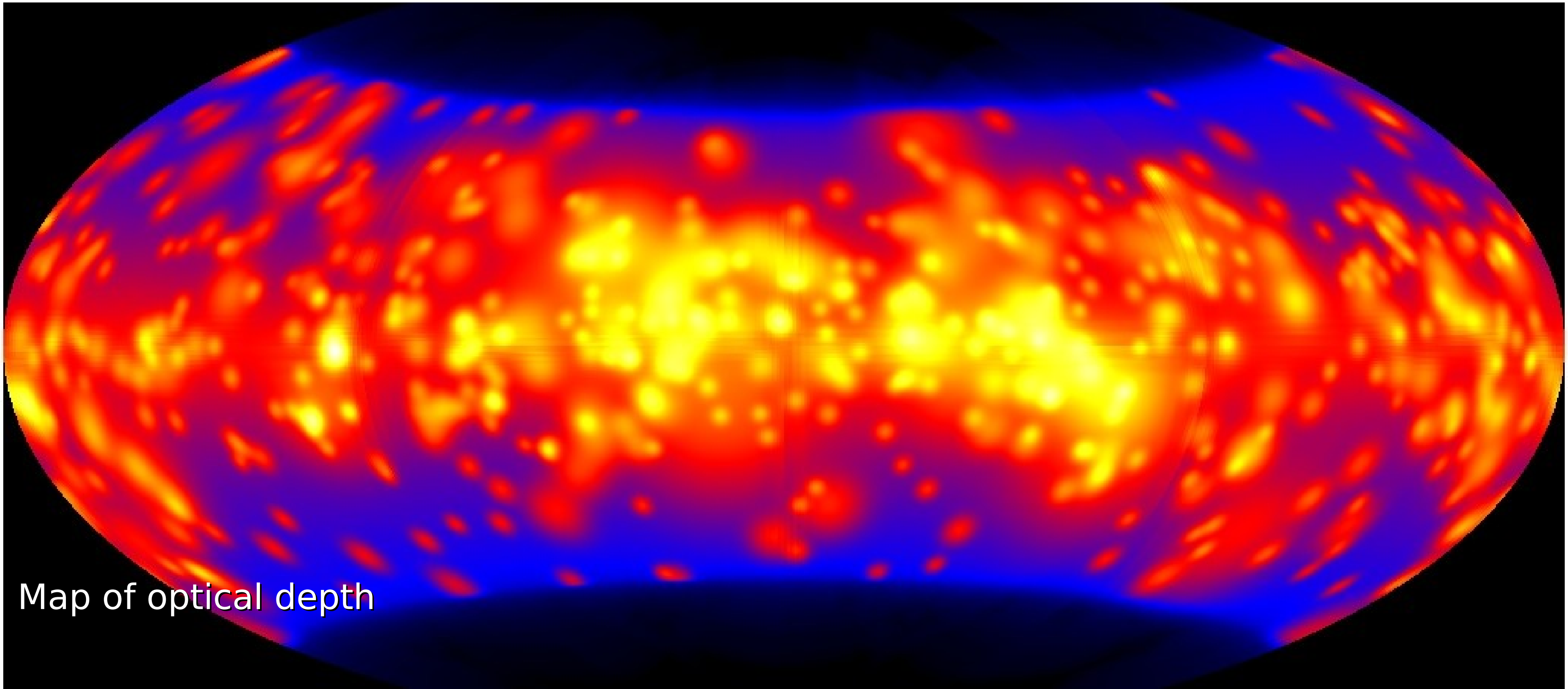




Adaptive octtree grid (Saftly et al. 2012)

ON-GOING WORK: SKIRT5

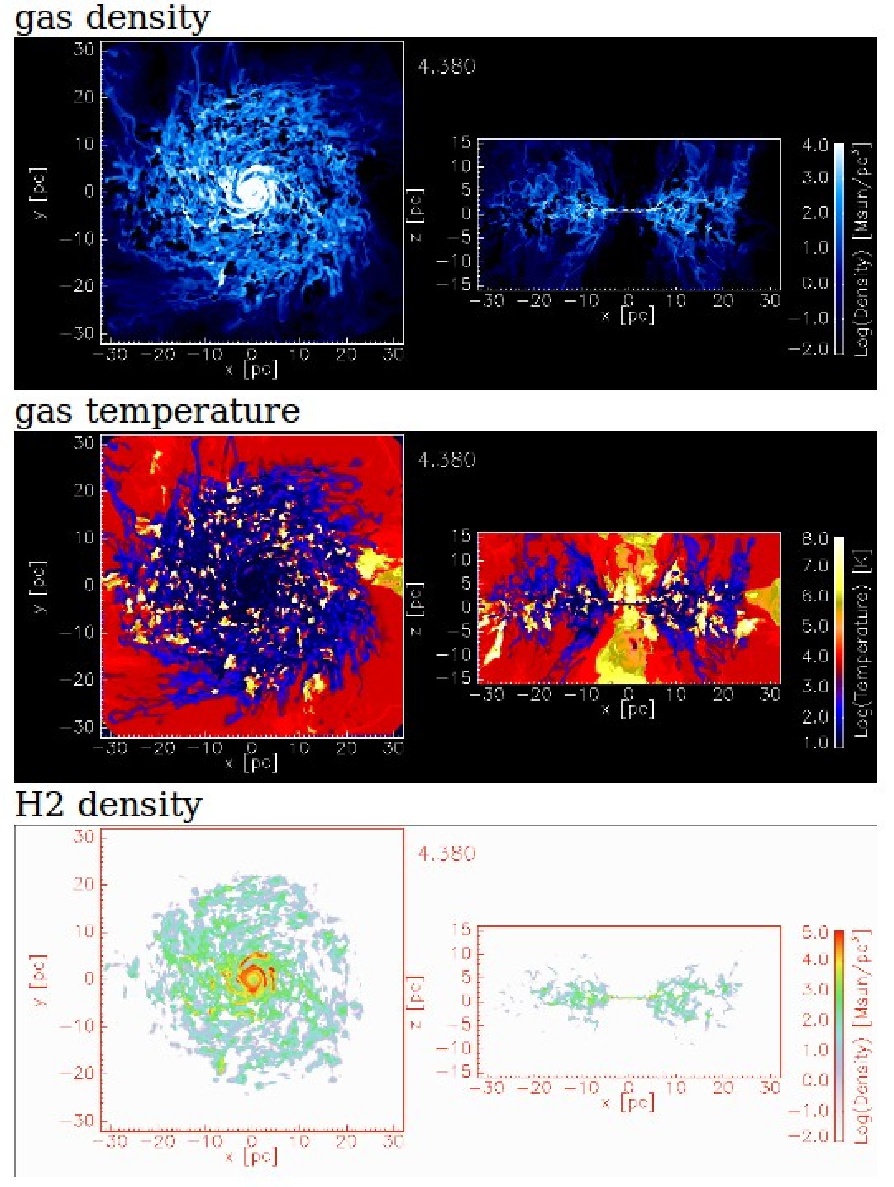




Map of optical depth

NEAR FUTURE WORK: SKIRT6

RT of multiphase, filamentary medium



Wada 2009

FUTURE WORK: Polarization in SKIRT

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

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

But not based on physically motived clumpy 3D geometries…

FUTURE WORK: Polarization in SKIRT

Including polarization into a Monte Carlo radiative transfer code is relatively straightforward

- use all Stokes parameters S = (I,Q,U,V) instead of just the intensity
- it is usually assumed that radiation is unpolarized when emitted
- scattering by dust grains polarizes the radiation: use full Mueller matrix instead of scattering phase function

$$\begin{pmatrix} I^{\text{out}} \\ Q^{\text{out}} \\ U^{\text{out}} \\ V^{\text{out}} \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} & 0 & 0 \\ S_{12} & S_{22} & 0 & 0 \\ 0 & 0 & S_{33} & S_{34} \\ 0 & 0 & -S_{34} & S_{44} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\phi & \sin 2\phi & 0 \\ 0 & -\sin 2\phi & \cos 2\phi & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} I^{\text{in}} \\ Q^{\text{in}} \\ U^{\text{in}} \\ V^{\text{in}} \end{pmatrix}$$

- Stalevski et al, 2012, MNRAS, 420, 2756

- https://sites.google.com/site/skirtorus/
  - Download model SEDs
  - Images of torus (FITS) available upon request

- SKIRT: http://users.ugent.be/~mbaes/SKIRT.html

- 9th Serbian Conference on Spectral Line Shapes in Astrophysics

  Banja Koviljaca, Serbia, May 13-17, 2013

  http://www.scslsa.matf.bg.ac.rs/