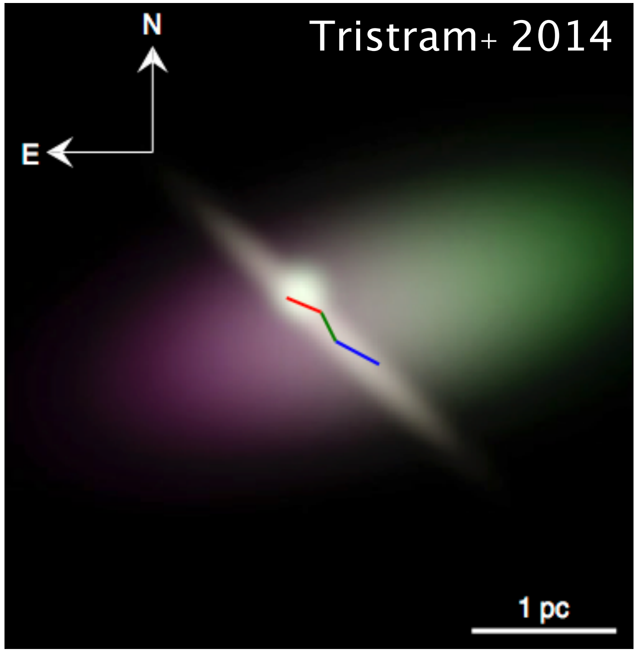
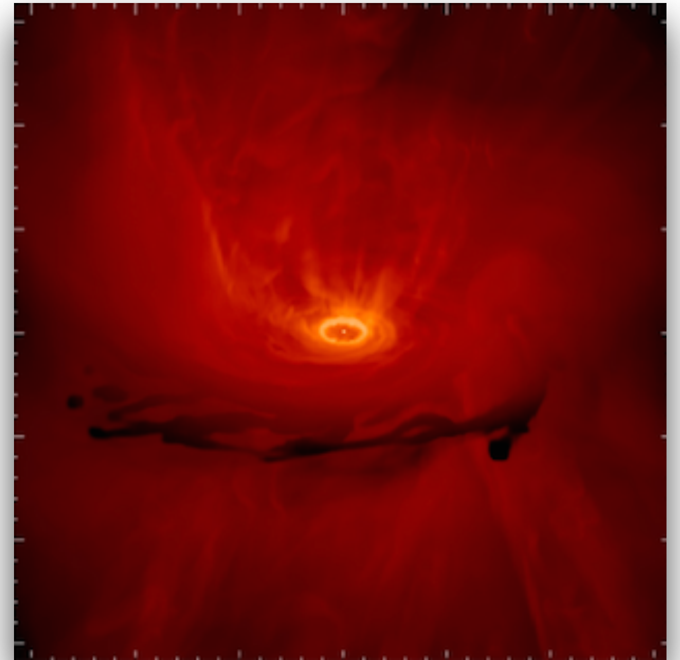
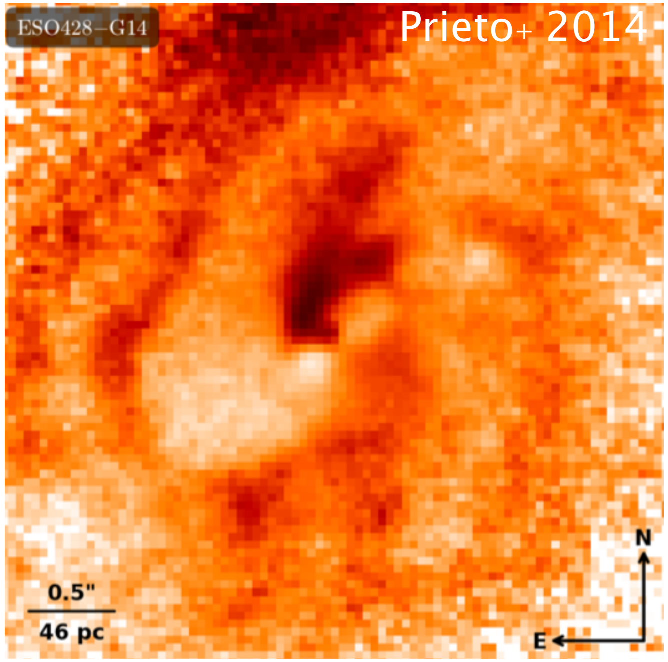
# Obscuring structures in nearby Seyfert galaxies



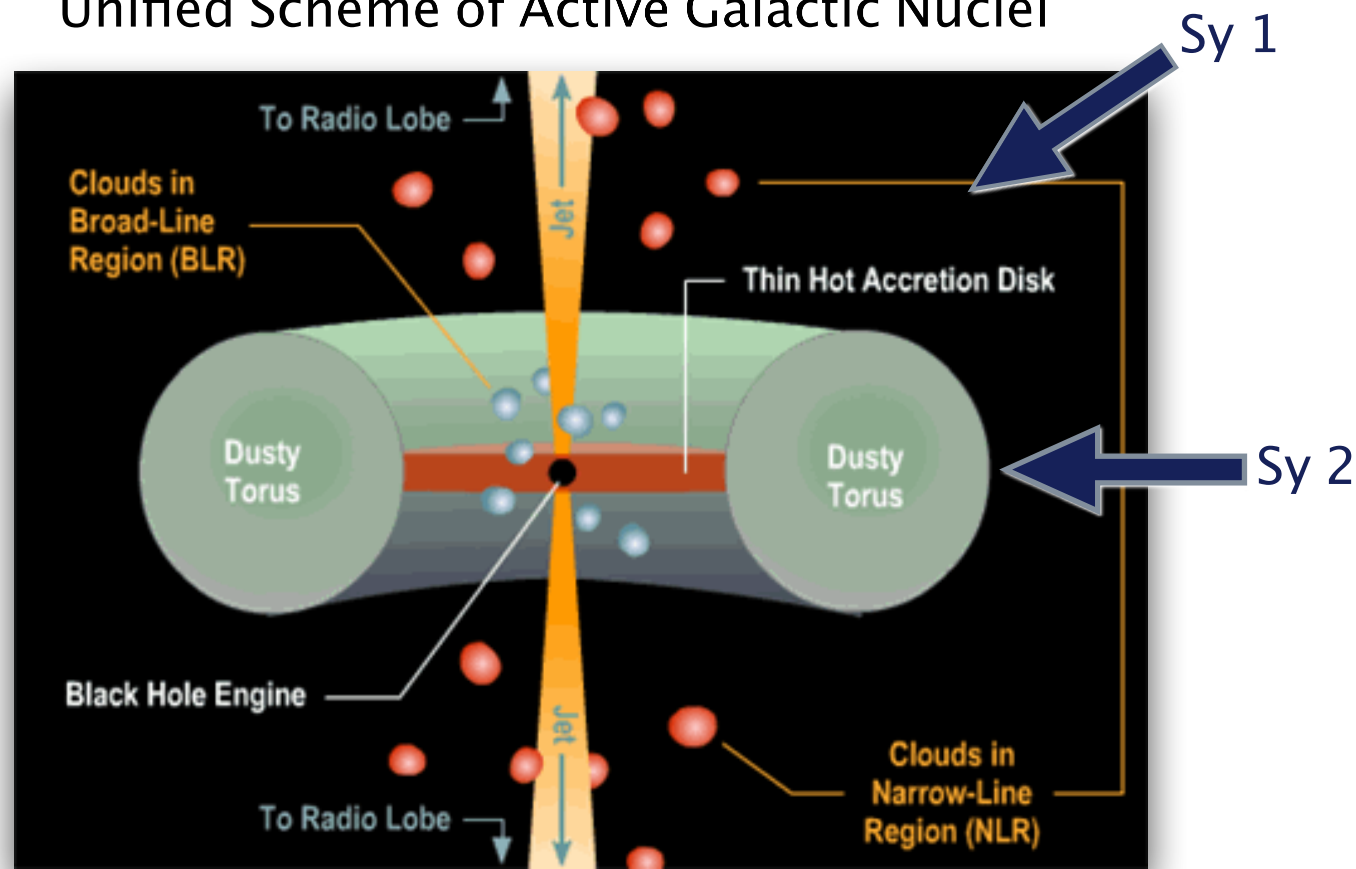



Marc Schartmann, Konrad Tristram, Keiichi Wada, Almudena Prieto, Andreas Burkert, Leonard Burtscher, Ric Davies and many other…

# Seyfert Galaxies & The Unified Scheme

- otherwise normal spiral galaxies light up, when enough gas is accreted onto the centre
- core luminosity comparable to stars of whole galaxy

Unified Scheme of Active Galactic Nuclei




- central black hole ($10^6$ to $10^{10}$ $M_\odot$)
- accretion disc
- obscuring torus
- (hidden) broad line region
- narrow line region
- ionization cones
- jet emission
- contribution of obscuring material further out(?)

# Seyfert Galaxies & The Unified Scheme

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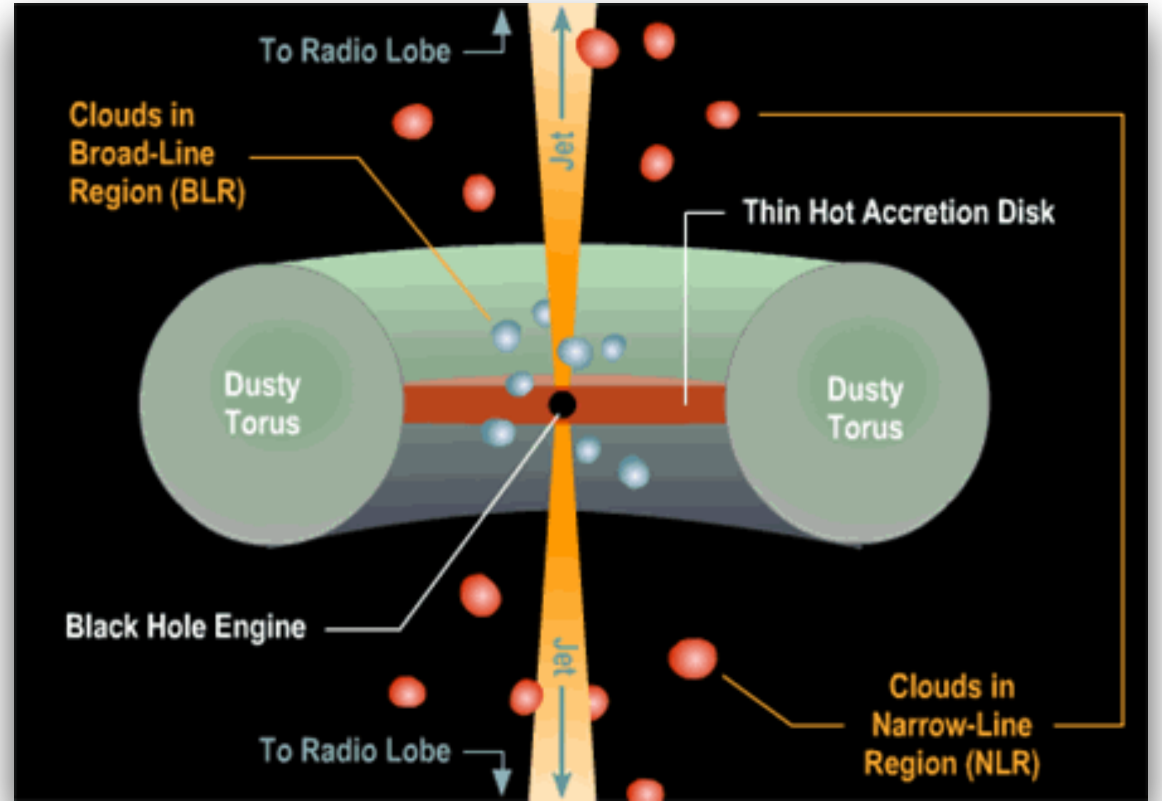
Unified Scheme of Active Galactic Nuclei

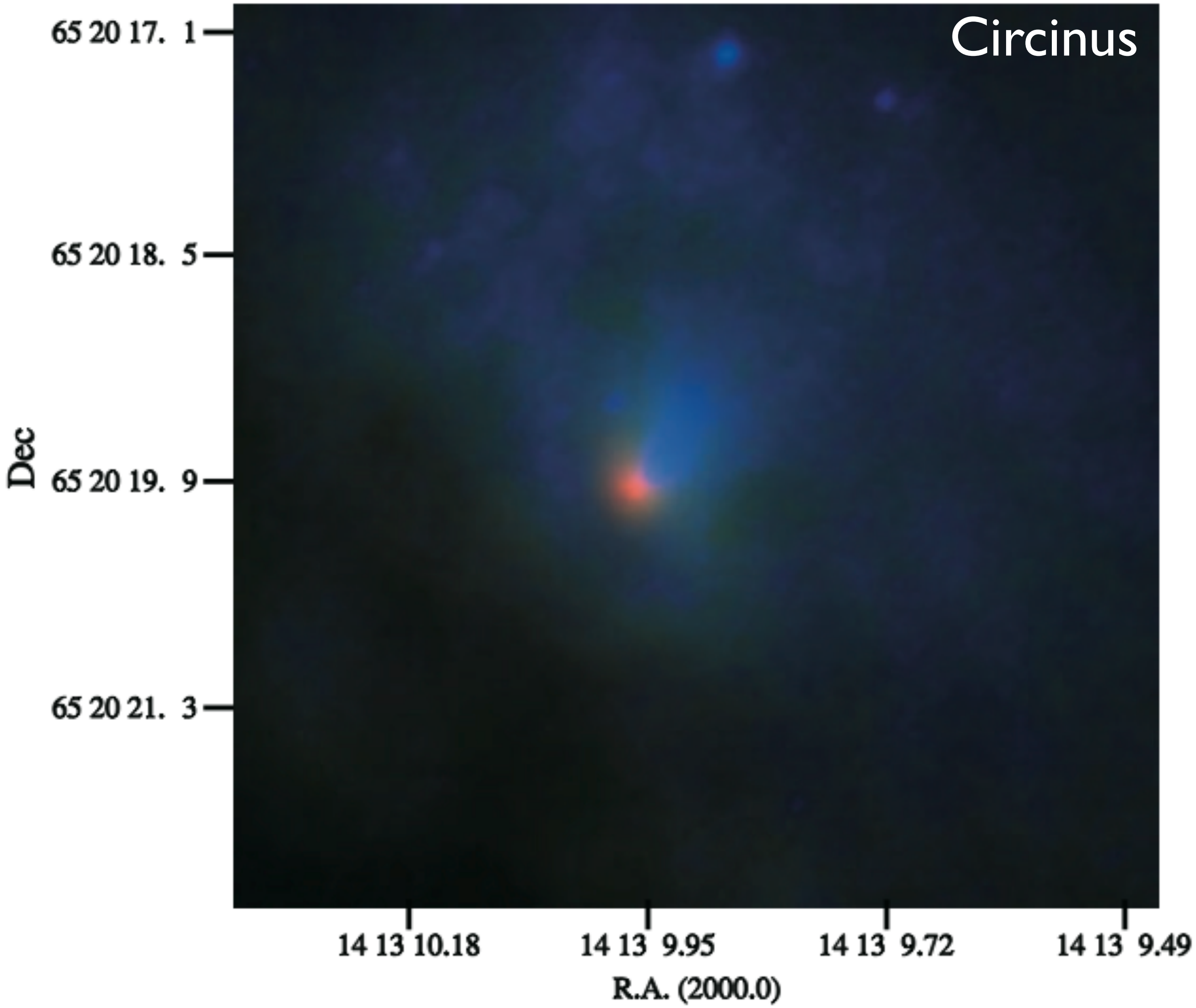



many open questions remain:

- same tori in Sy1 / Sy2?
- what is the geometry of the torus?
- what is the dynamical state
- what is the driver of turbulence?

Idea: better understand the distribution of gas and dust near galactic nuclei

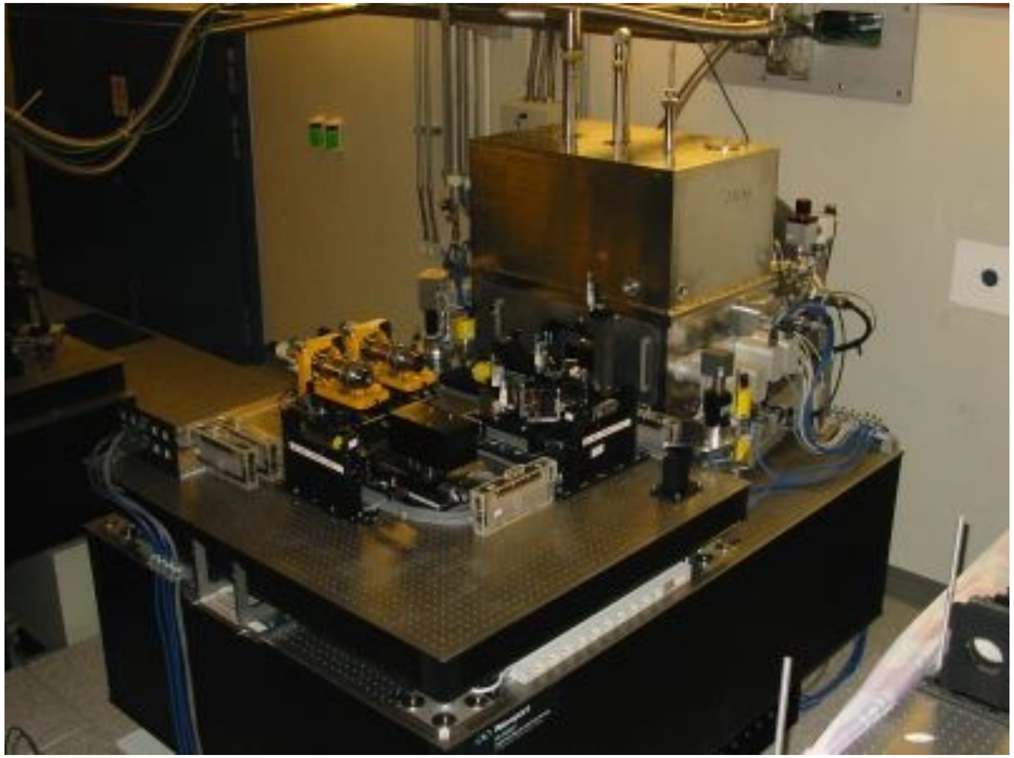
Prieto+ 2004




True-color image combining HST WFPC2-PC F814W (blue) and NACO J ( green) and $K_s$ (red ) bands

- nuclear IR dust emission unresolved in single-dish observations
- need for interferometric methods
- emission of hot dust (~300-1000K)
- N-band, MIDI

MIDI@VLTI



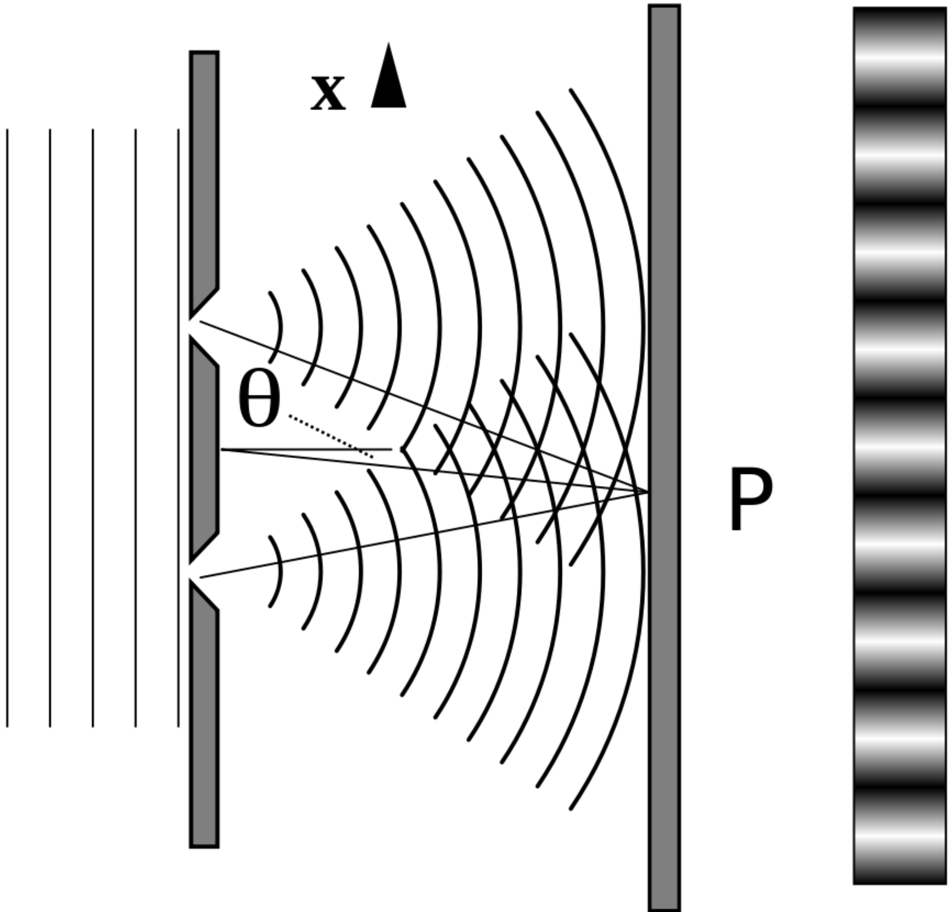
ESO

- basically Young's experiment
- correlated flux = flux in the fringes
- visibilities:

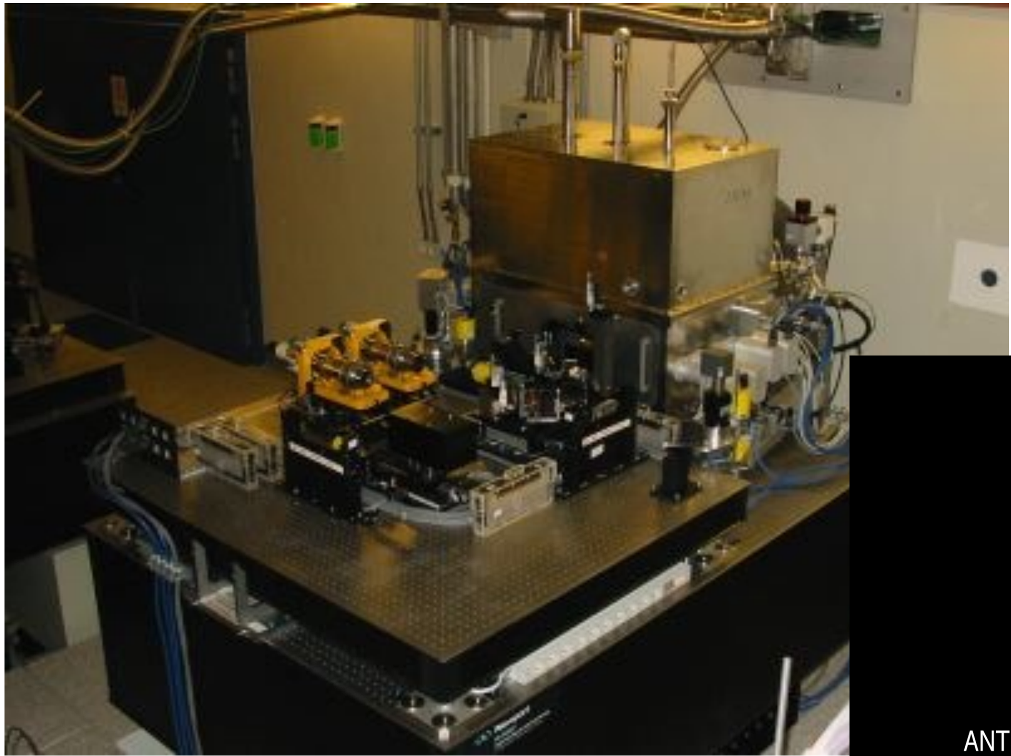
$$V = F_{corr} / F_{tot}$$

- resolution:

$$\boldsymbol{\alpha} = \lambda / 2\ BL$$

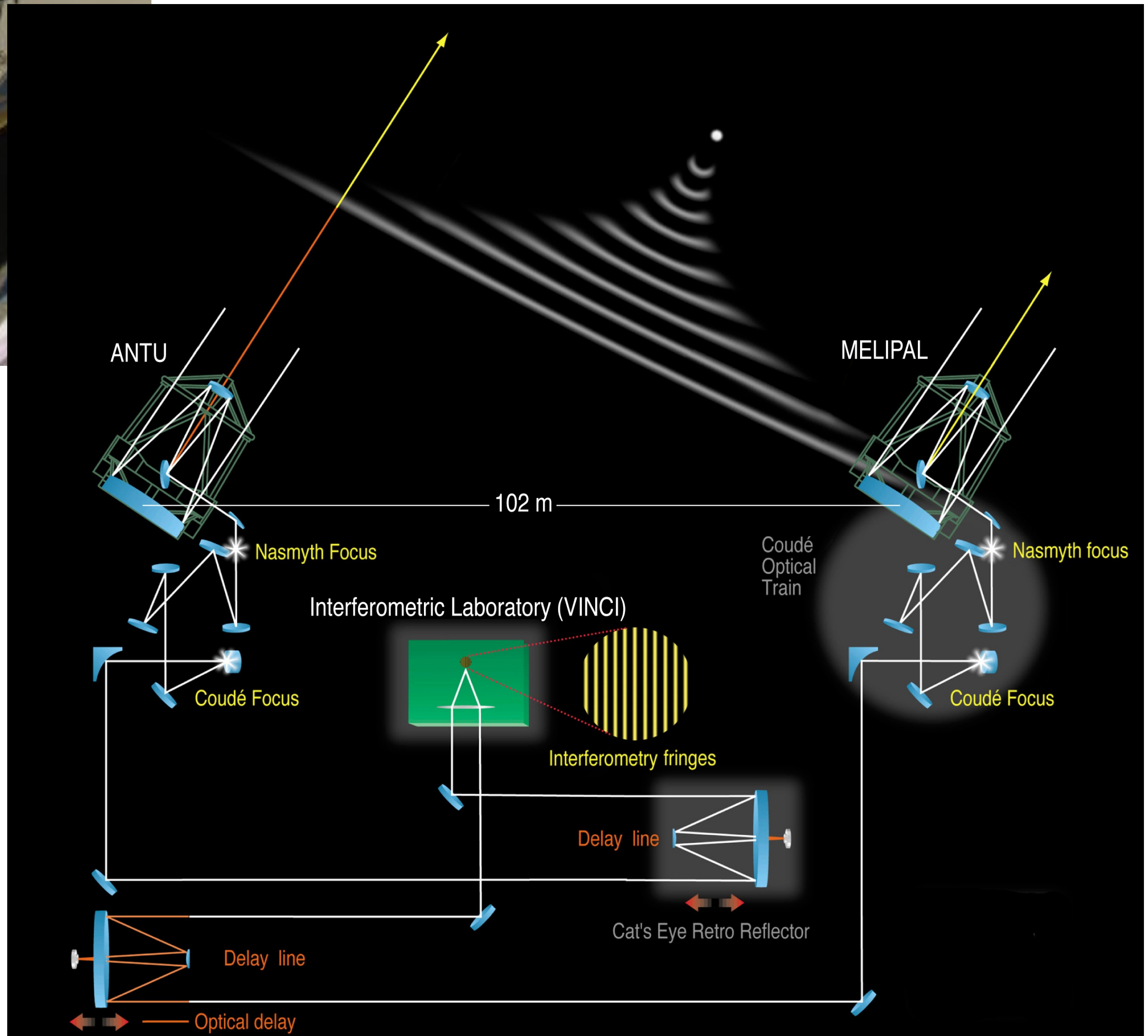



Wikipedia



# MIDI@VLTI

VLT Interferometer




- basically Young's experiment
- correlated flux = flux in the fringes
- visibilities:

$$V = F_{corr} / F_{tot}$$

- resolution:

$$\alpha = \lambda / 2\, BL$$

# MIDI observations of the Circinus galaxy

General Properties

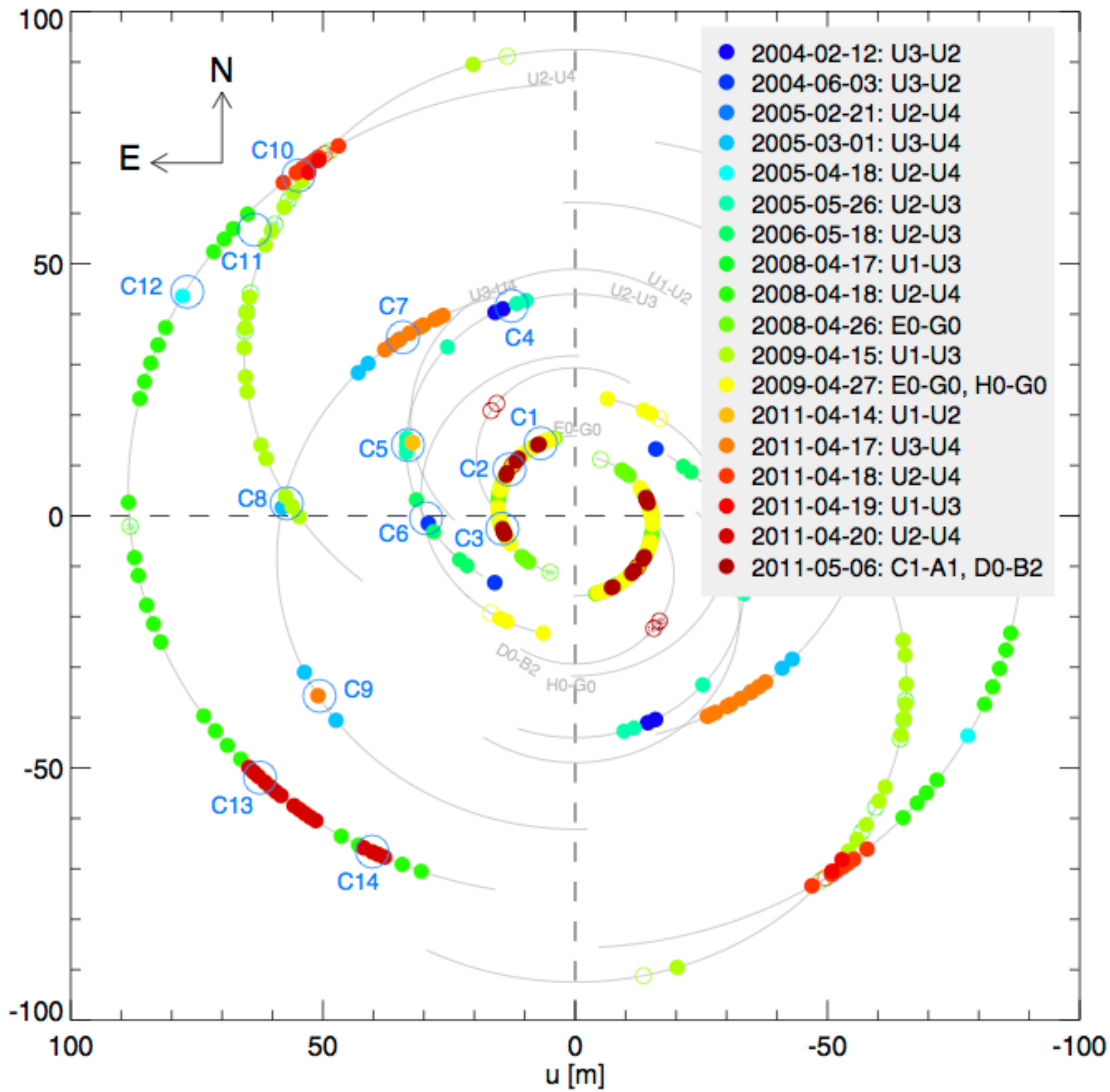
credit: Wilson (University of Maryland), HST

- spiral galaxy SA(s)b
- inclination 65 degrees
- Seyfert 2 galaxy
- black hole mass: 4 x$10^6$ $M_\odot$
- distance ~ 4 Mpc,
- 1pc ~ 50 mas
- circum-nuclear starbursts

Tristram+ 2014

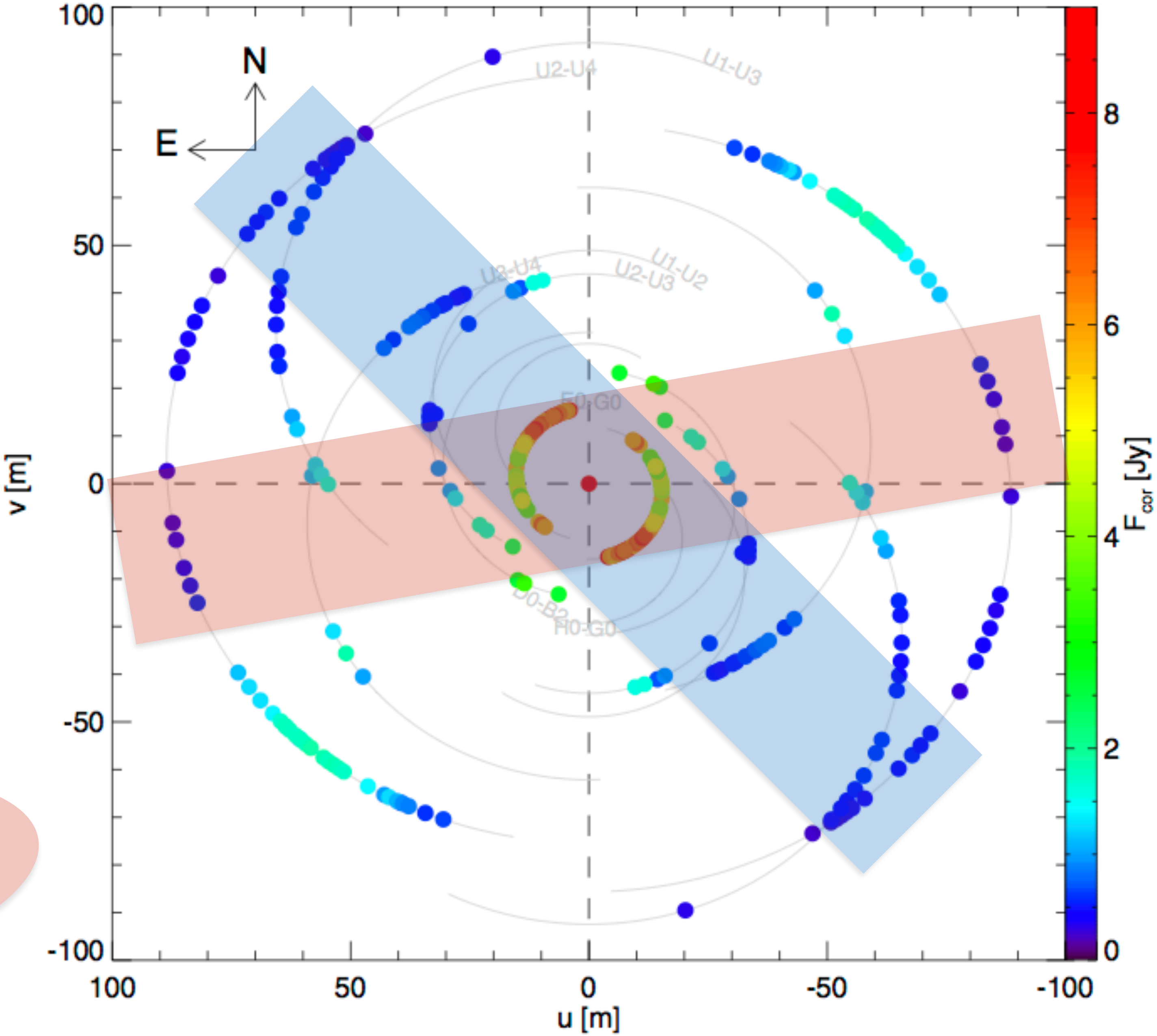
Circinus: UV coverage

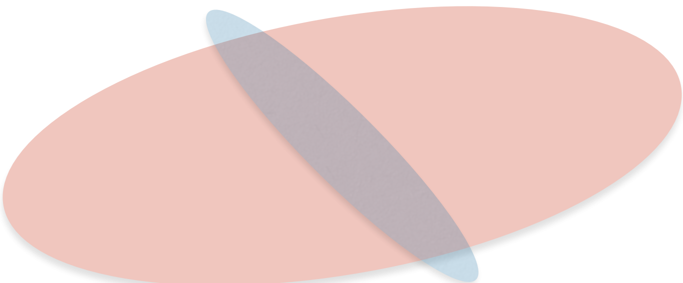
- 152 useful measurements
- telescope combinations where the projected baseline length remains roughly constant
- directly infer source size in different directions



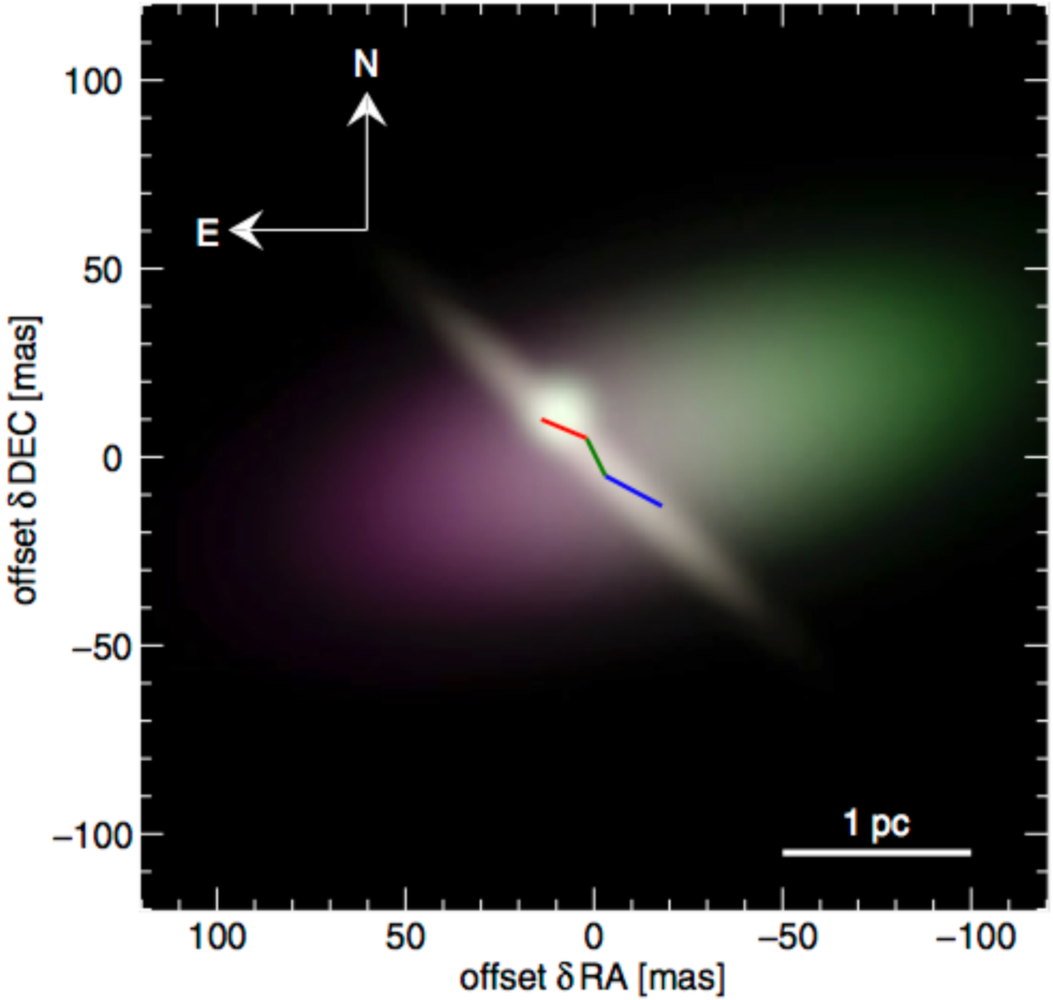
correlated fluxes at 12 micron

- spatial scales ~150mas: moderately elongated emission along PA~100°
- on smaller scales: strong elongation along PA~45°



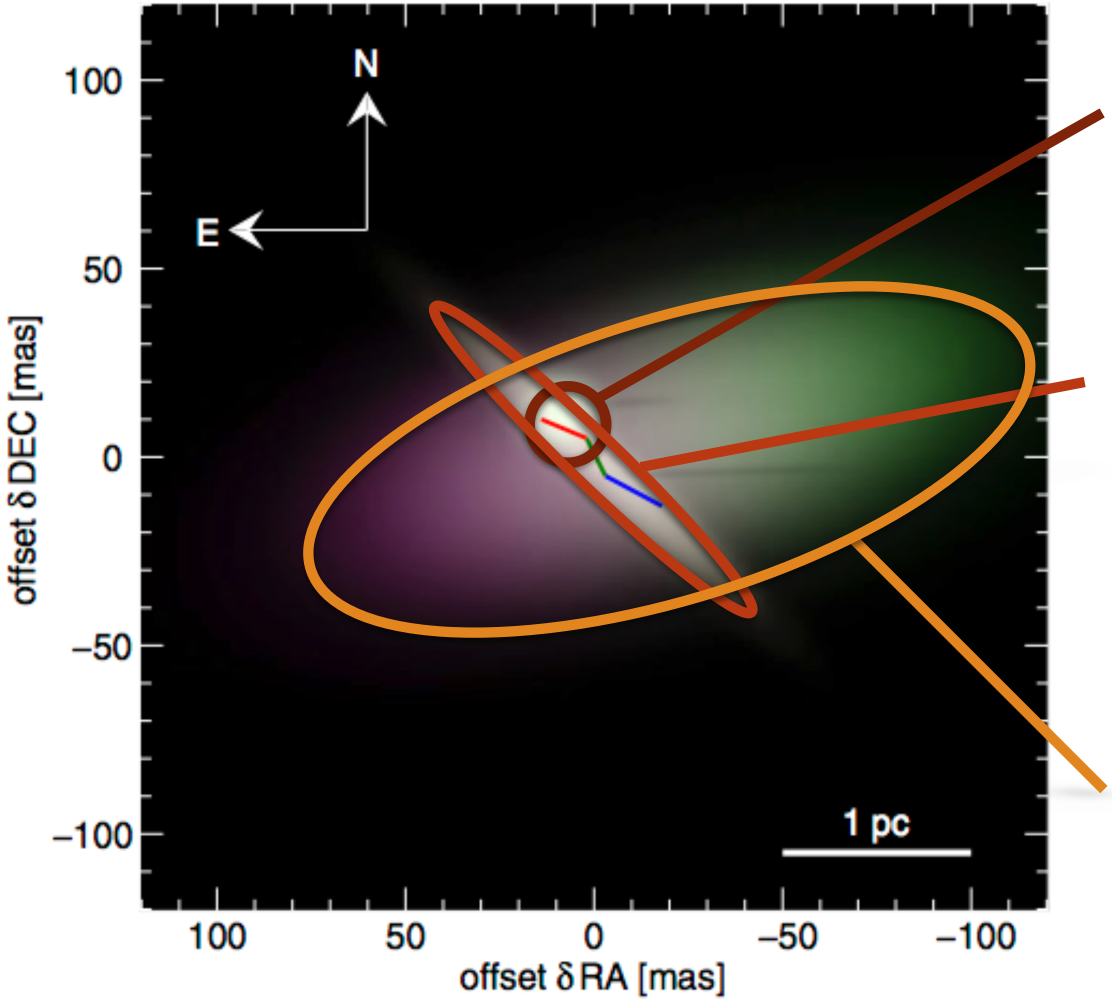



Circinus: 3-component dust emission
(Gaussian black bodies)




- model with 3 Gaussian black bodies
- false color image of the 3-component model
- maser disk
- increasing silicate absorption from green to violet: 27 per arcsec
- in line with large-scale optical depth gradient due to inclination

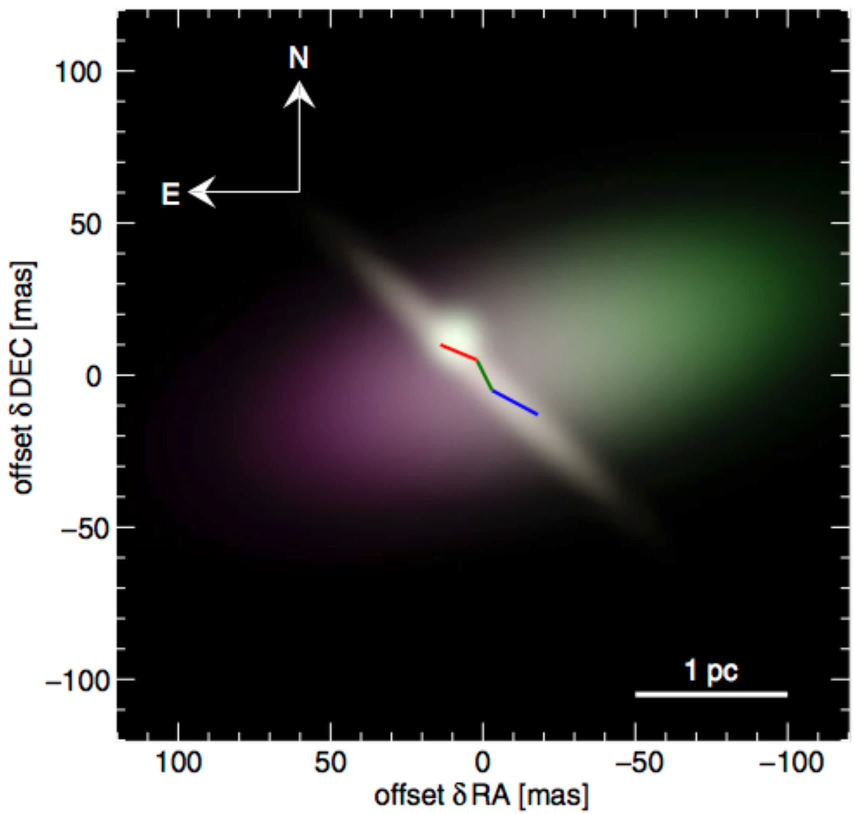
# Circinus: 3-component dust emission (Gaussian black bodies)



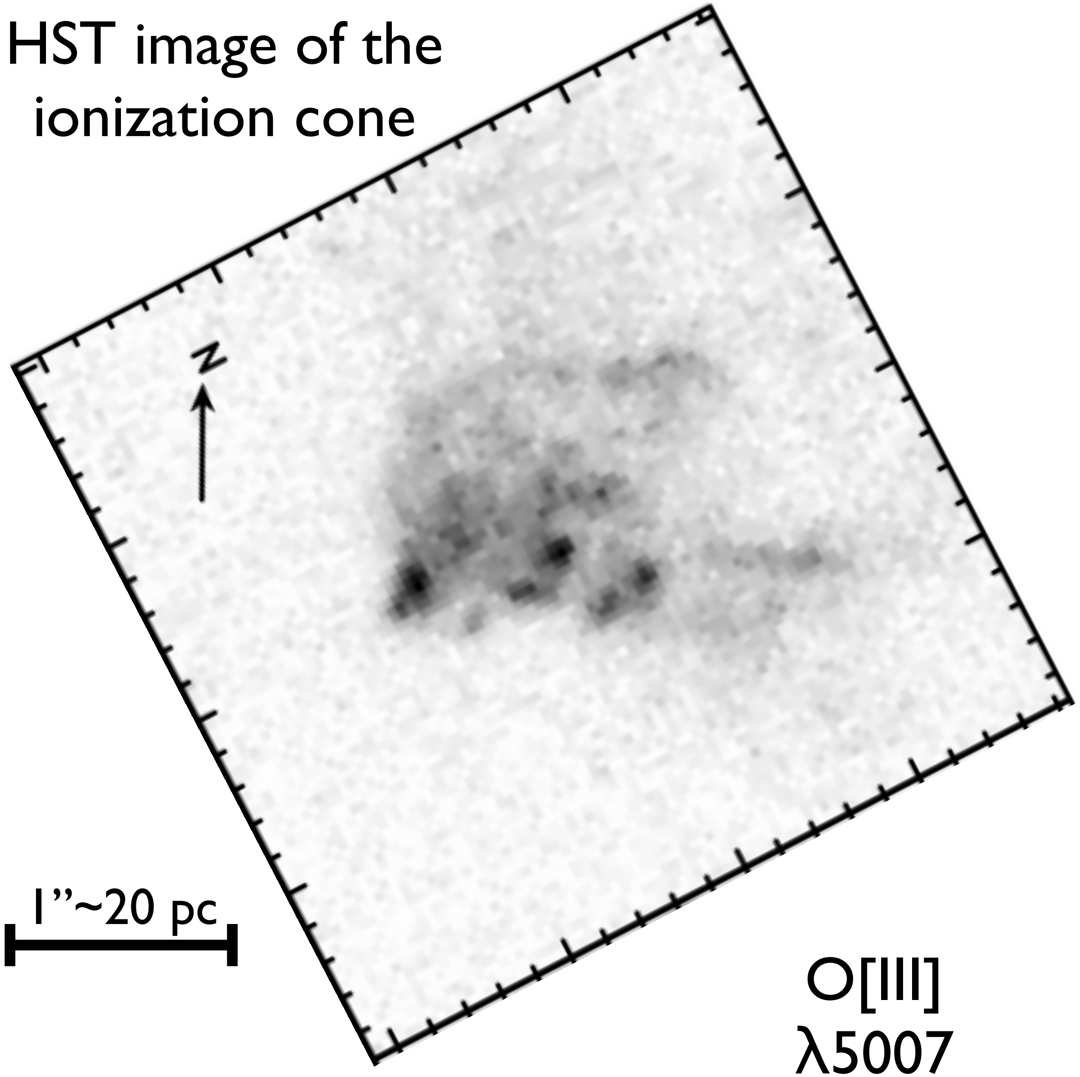

| | |
|---|---|
| Size: | $\Delta_1$ = 12 ± 2 mas |
| Silicate depth: | $\tau_1$ = 1.2 ± 0.2 |
| Temperature: | $T_1$ = 317 ± 22 K |
| Covering factor: | $f_1$ = 0.5 ± 0.3 |
| Size: | $\Delta_2$ = 57 ± 15 mas |
| Axis ratio: | $r_2$ = 0.16 ± 0.04 |
| Position angle | $\alpha_2$ = 46 ± 3° |
| Silicate depth: | $\tau_2$ = 1.9 ± 0.4 |
| Temperature: | $T_2$ = 290 ± 22 K |
| Covering factor: | $f_2$ = 0.6 ± 0.3 |
| Size: | $\Delta_3$ = 93 ± 12 mas |
| Axis ratio: | $r_3$ = 0.45 ± 0.07 |
| Position angle: | $\alpha_3$ = 107 ± 8° |
| Silicate depth: | $\tau_3$ = 2.4 ± 0.6 |
| Temperature: | $T_3$ = 304 ± 30 K |
| Covering factor: | $f_3$ = 0.3 ± 0.2 |

all components T ~ 300 K

comparison to other observations




HST image of the ionization cone

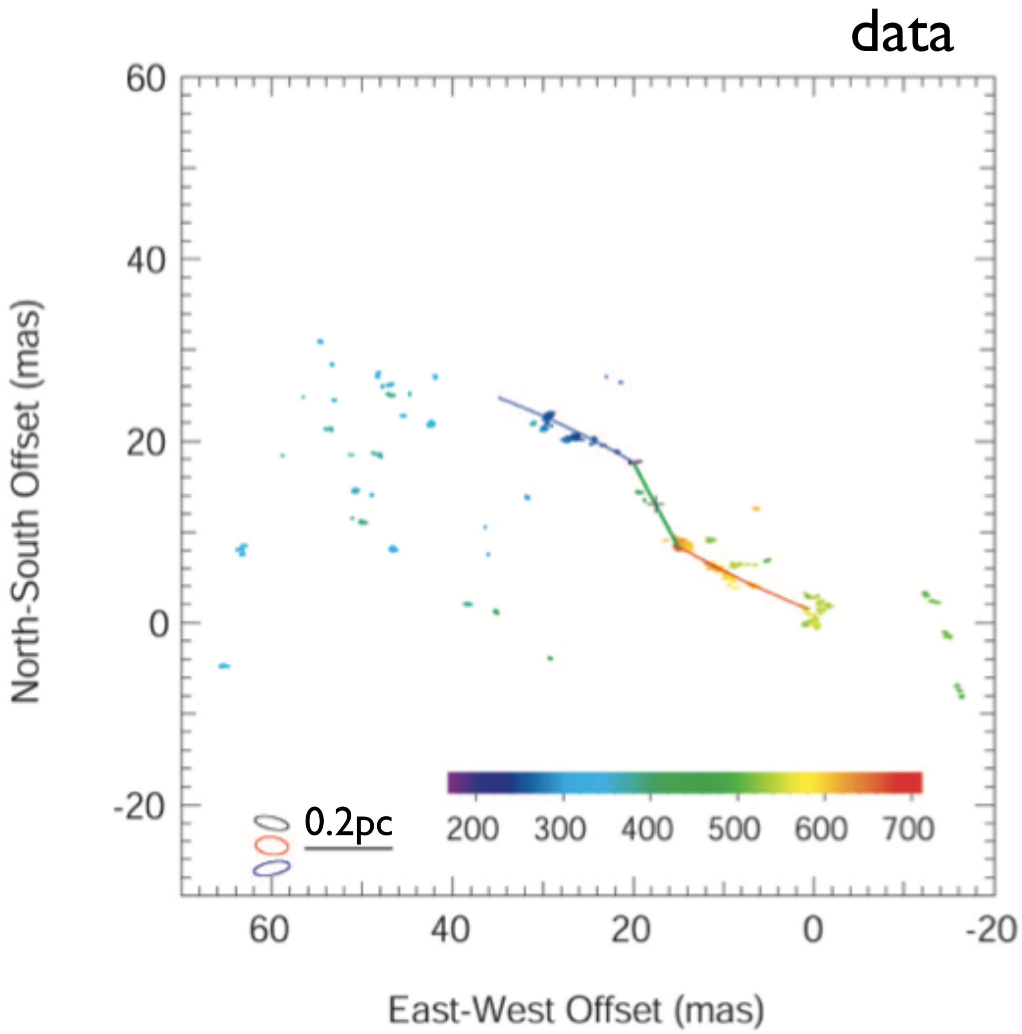


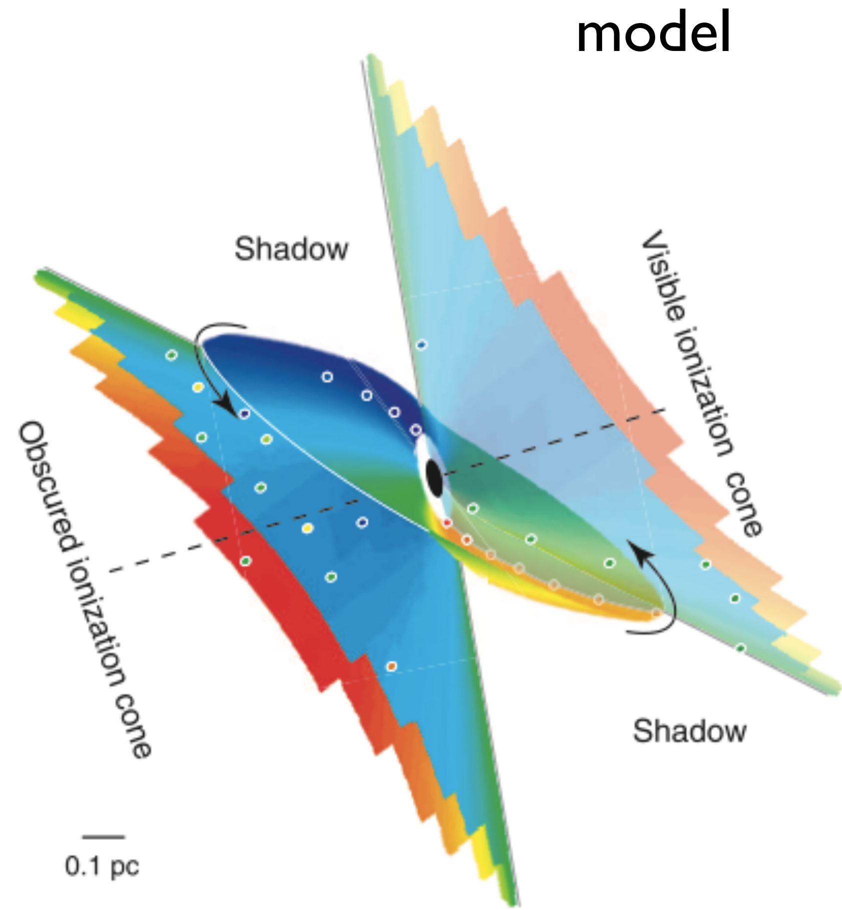

1"~20 pc

O[III] λ5007

Wilson+ 2000

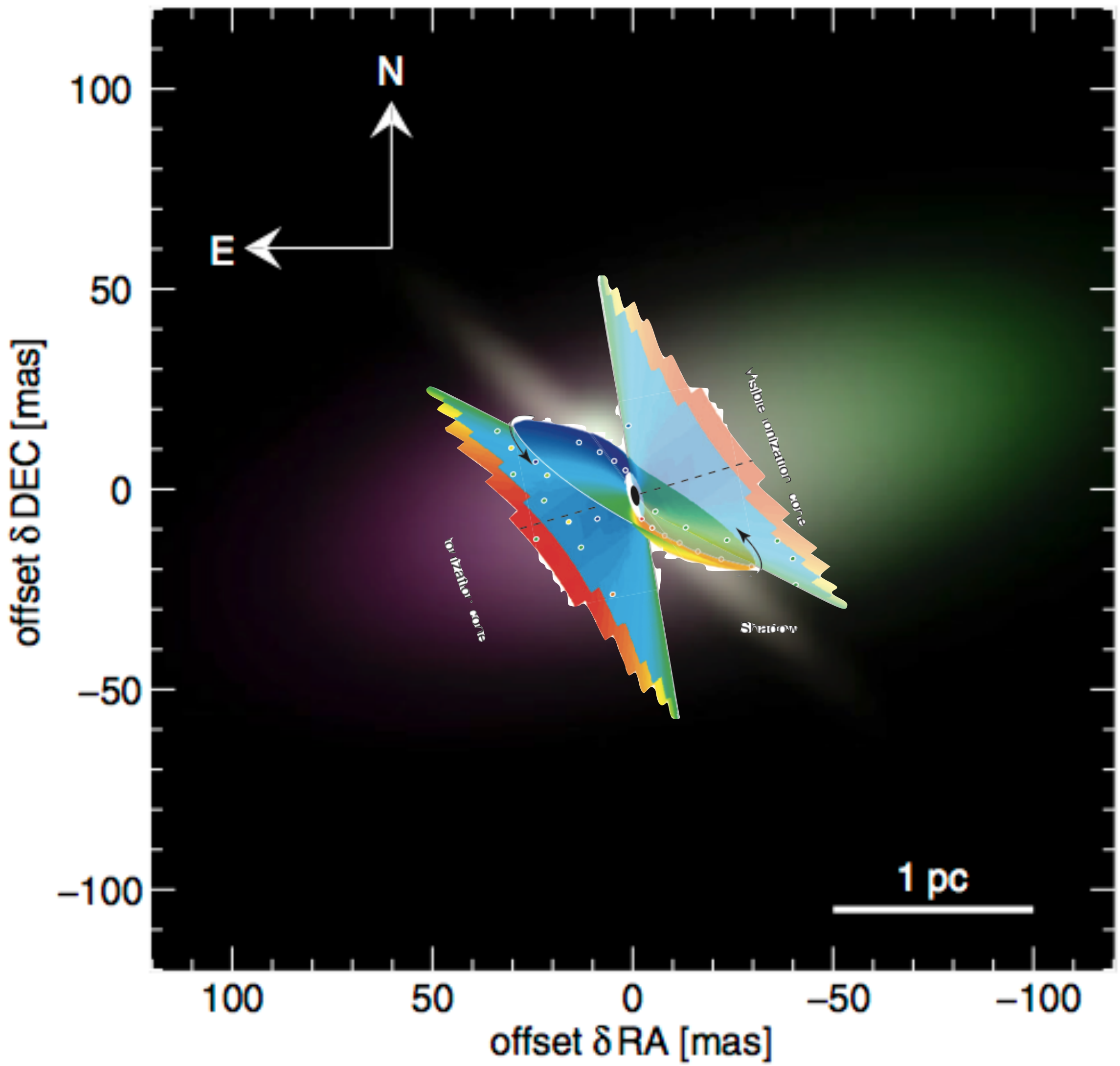
## $H_2O$ maser emission



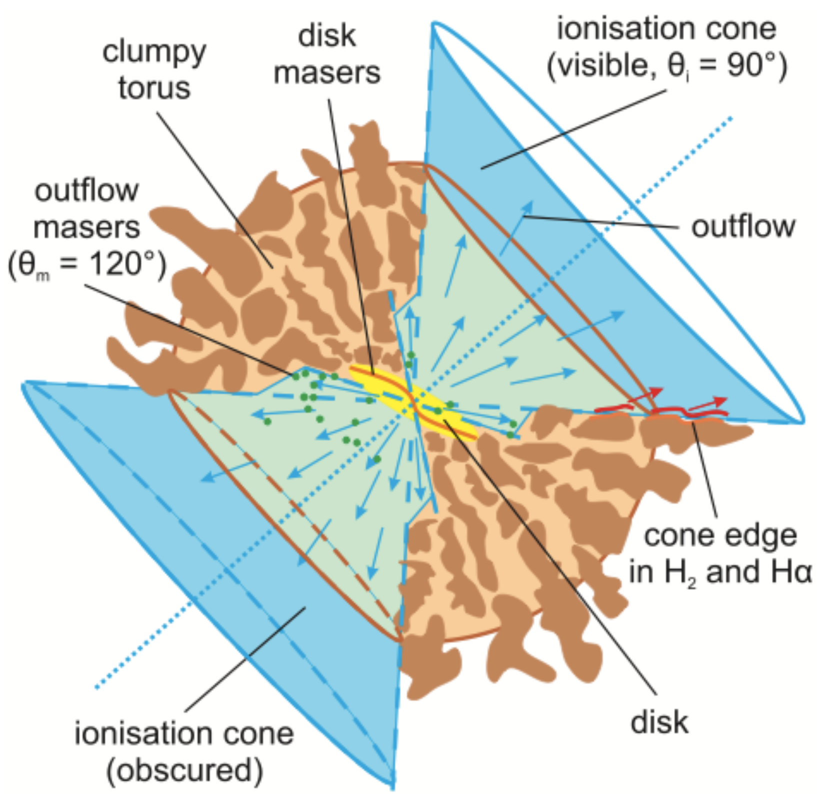




- maser disk in Keplerian rotation
- outflow maser spots

Greenhill+ 2003



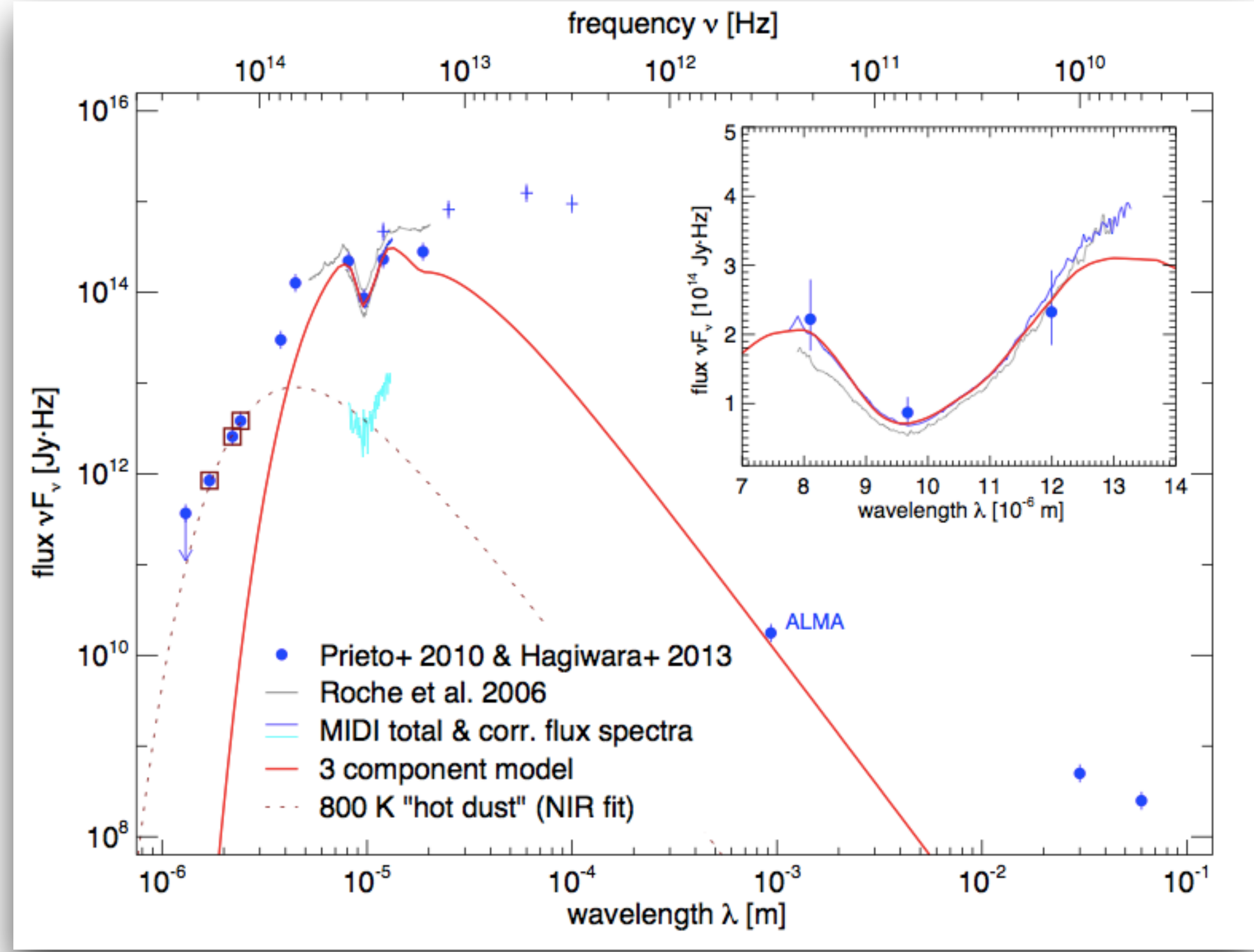

Greenhill+ 03, Tristram+ 07/14



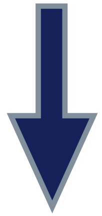

- in good agreement with the model derived from MIDI data

- multi-component structure: dense disk, filamentary torus, point source and emission / outflow within the cones

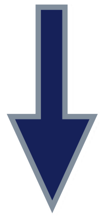
Tristram+ 2014




- high spatial resolution spectral energy distribution
- additional constraint



challenge for modelers: simultaneously fit SED plus interferometric observations

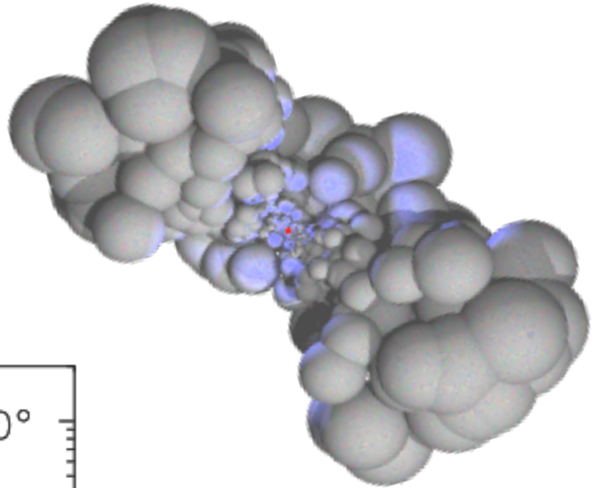


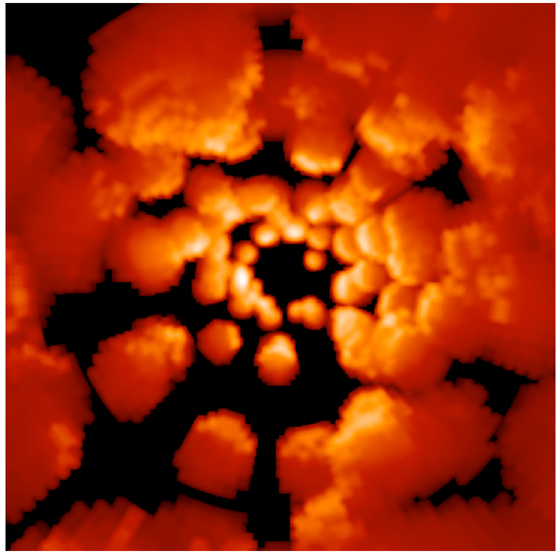
clumpy torus models

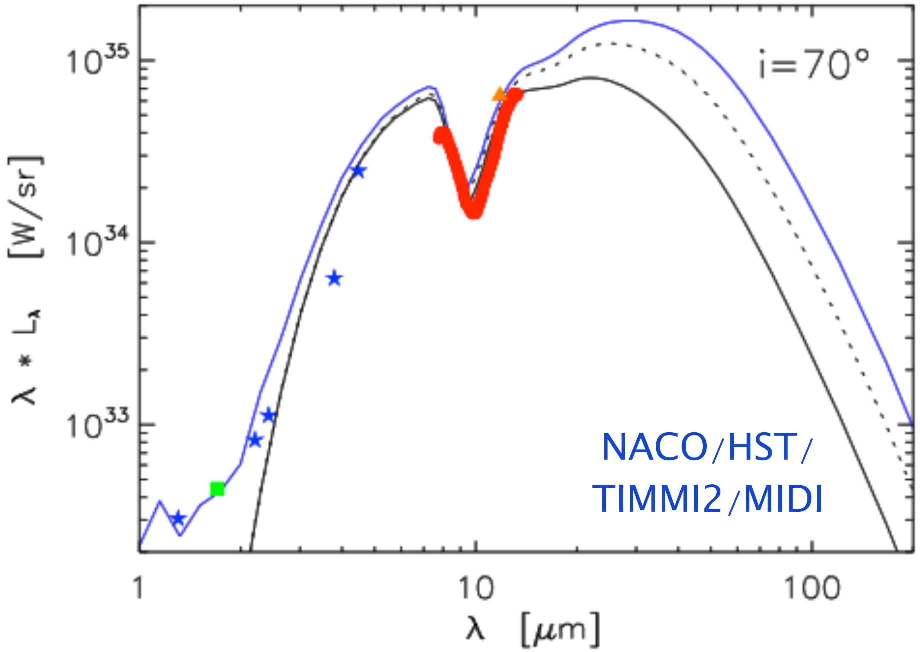
# 3D Radiative Transfer models for Clumpy tori

- distribute clumps in a 3D geometry
- simultaneously account for high spatial resolution data as well as interferometric data
- good idea of torus structure

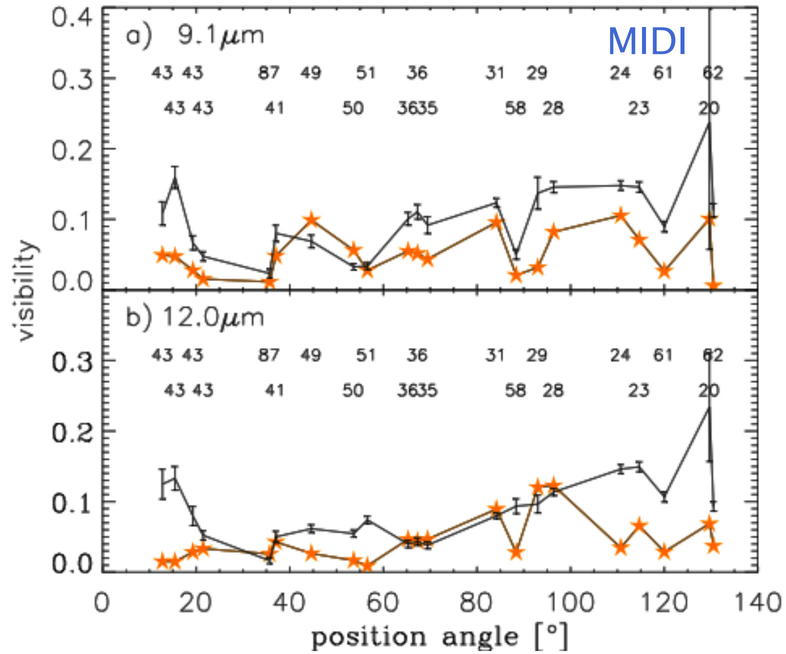
Schartmann+ 2008








Circinus galaxy, Tristram+ 2007



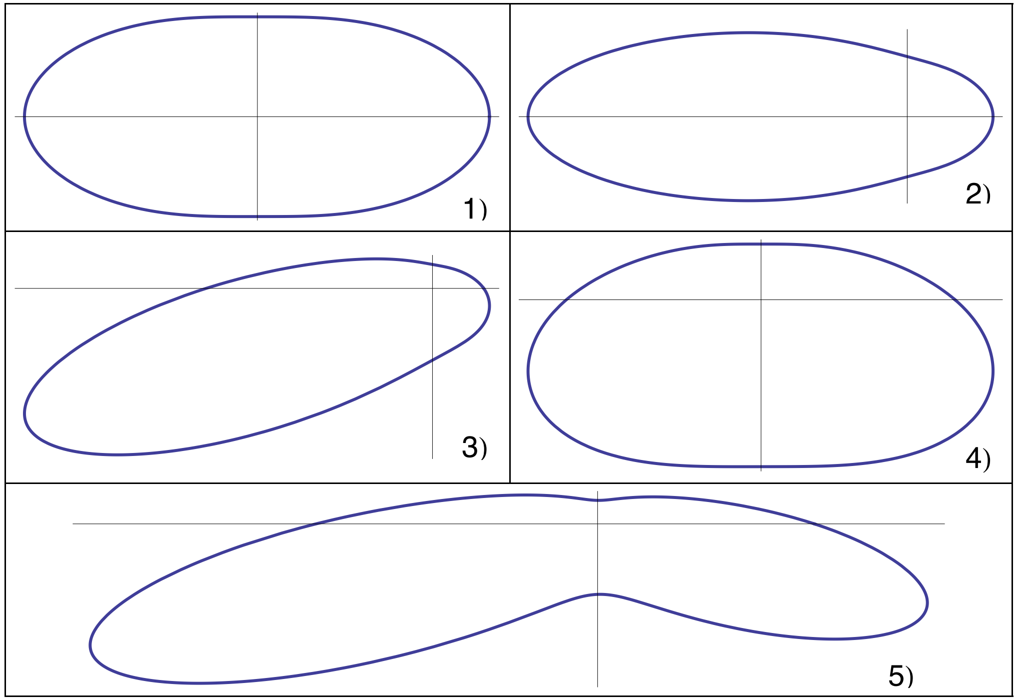

- ambiguities
- toy models
- dynamical stability

→ need for physical models

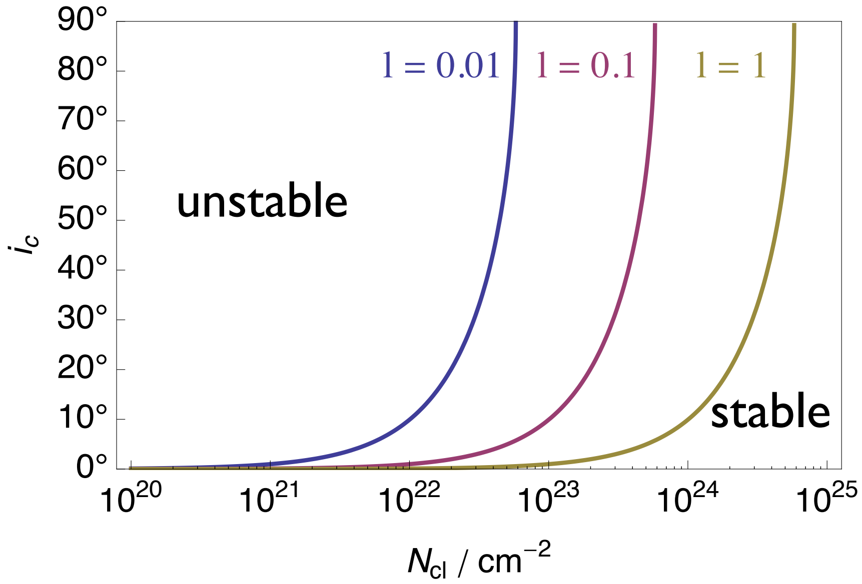
# Dynamical models of clumpy AGN tori

## Cloud orbits under the influence of gravity plus radiation pressure

- cos(theta) radiation characteristic
- all orbits closed
- derive orbit structure



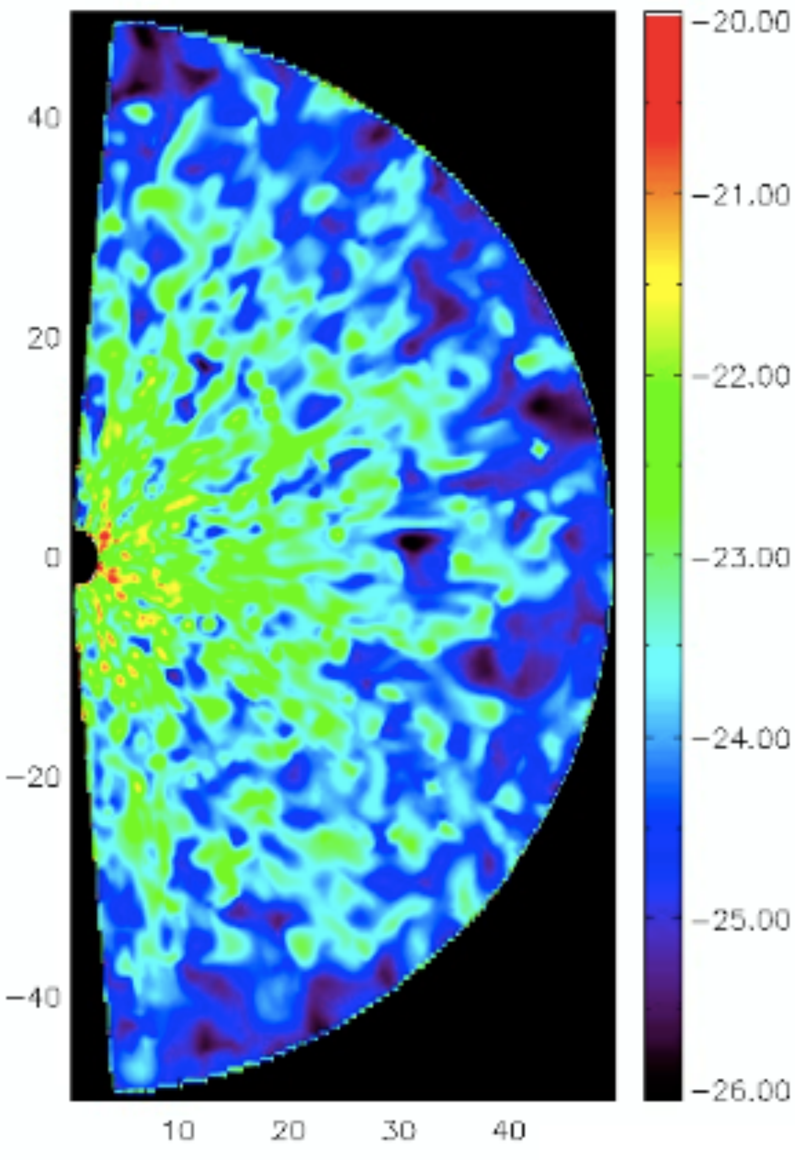

orbit families




- torus/BLR opening angle for constant cloud column density
- slightly differs from non-dynamical approach

Plewa et al., 2013

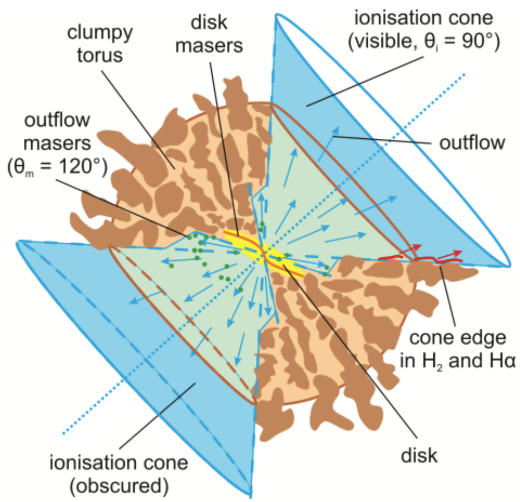
# Tori fueled by nuclear star clusters

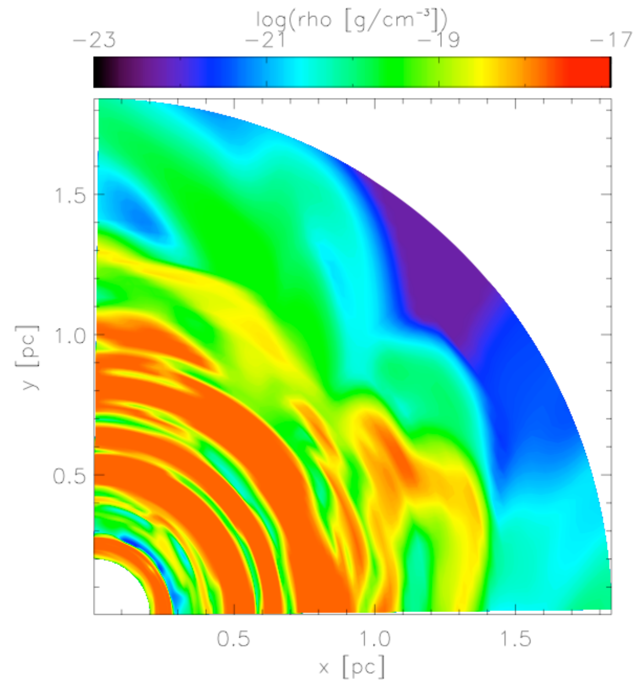



Schartmann+ 2009/2010

AGN fueled by post-starburst evolution

- many nearby Seyferts harbor young NSC
- after violent phase of SN II explosions
- slow winds can be accreted
- two-component structure: filamentary large scale distr. & disk/torus
- seems to work for some nearby Seyfert galaxies (Davies+ 2007)
- typically leads to two-component structures



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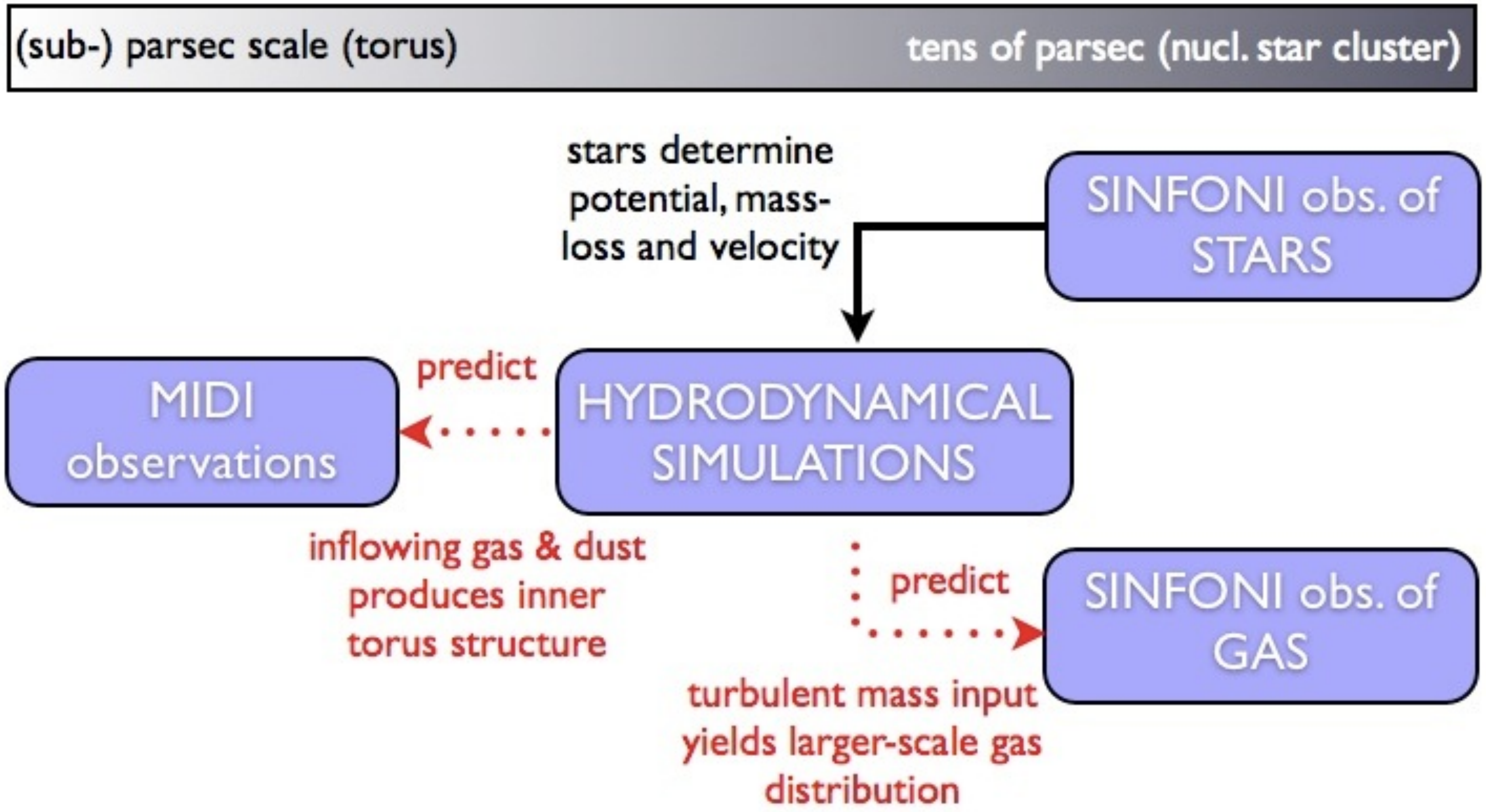


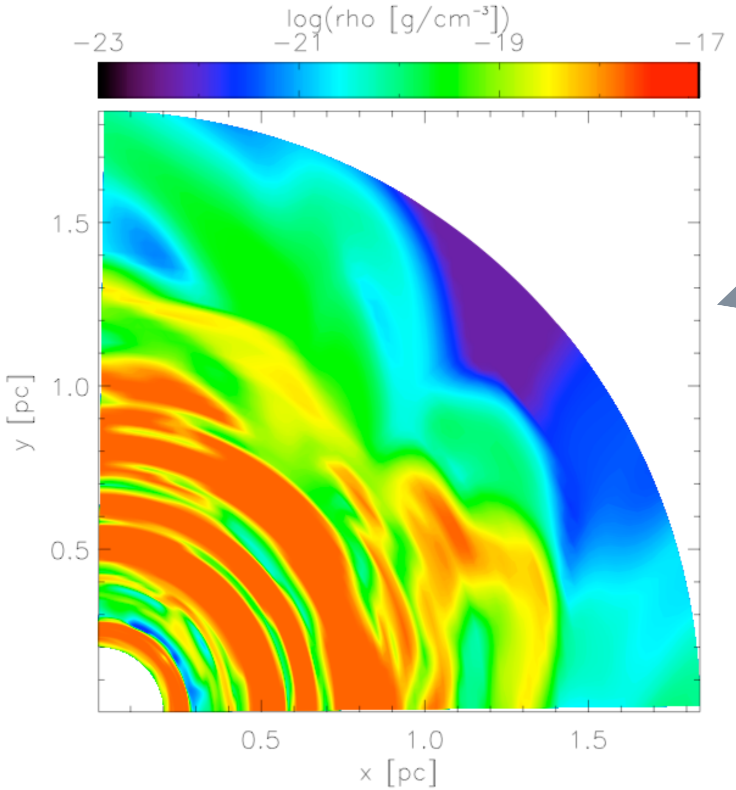

- Sample of nearby Seyfert galaxies, for which SINFONI and MIDI observations are/will be available
- hydrodynamical simulations combine large and small scale observations
- many details not understood

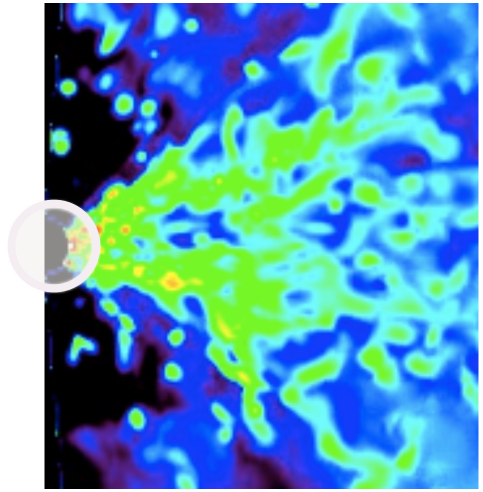
→

- use as basic model
- investigate various physical processes / regions separately

# Nuclear Disk/Torus Evolution

Schartmann+ 2010



- maser disc in NGC 1068: 0.65 to 1.1pc (Greenhill & Gwinn 1997)
- evolution of thin disk component
- 1D effective disc model: viscous evolution, SF sink and source term

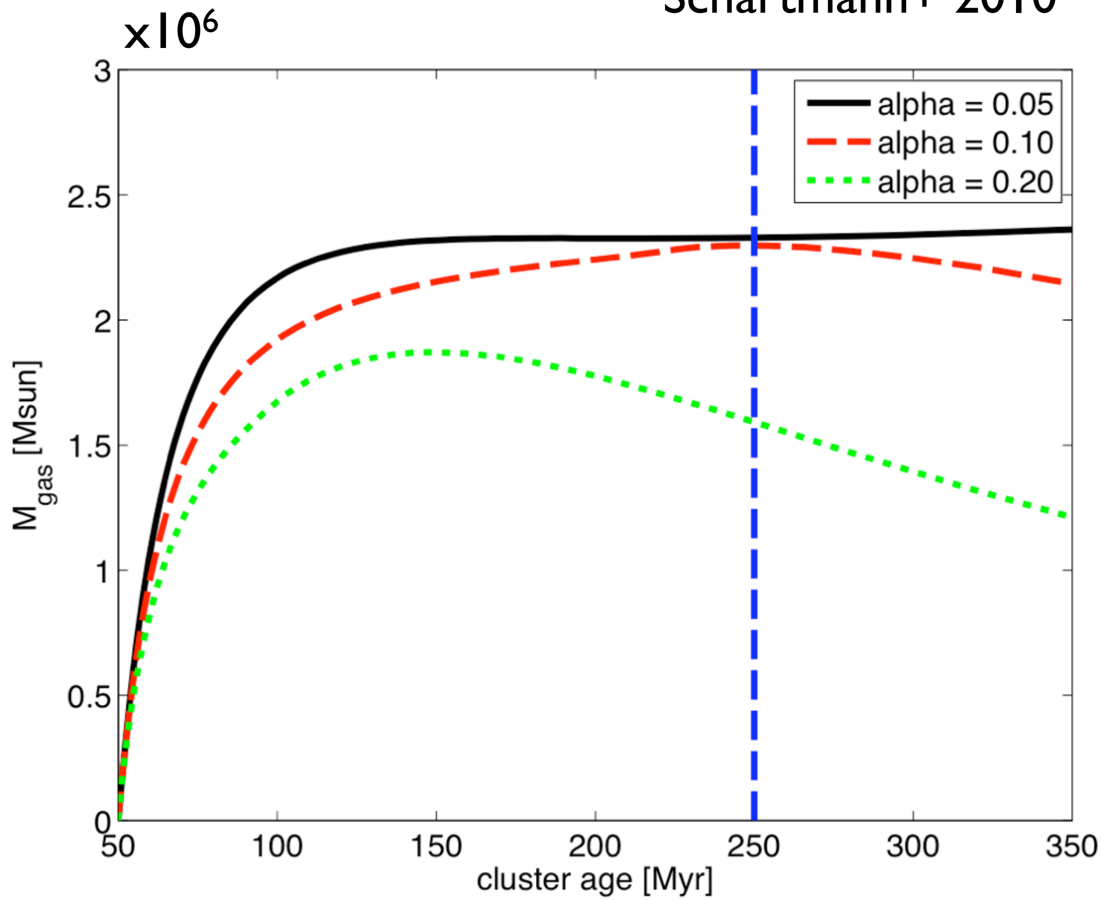
$$\frac{\partial}{\partial t}\Sigma(t,R)+\frac{1}{R}\frac{\partial}{\partial R}\left[\frac{\frac{\partial}{\partial R}\left(\nu\Sigma(t,R)R^{3}\Omega'(R)\right)}{\frac{d}{dR}\left(R^{2}\Omega\right)}\right]=\dot{\Sigma}_{\mathrm{input}}(t,R)-\dot{\Sigma}_{\mathrm{SF}}(t,R)$$

Lin & Pringle, 1987

→ connect with observations (mass, size, ...), verify scenario

# Nuclear Disk/Torus Evolution

Schartmann+ 2010



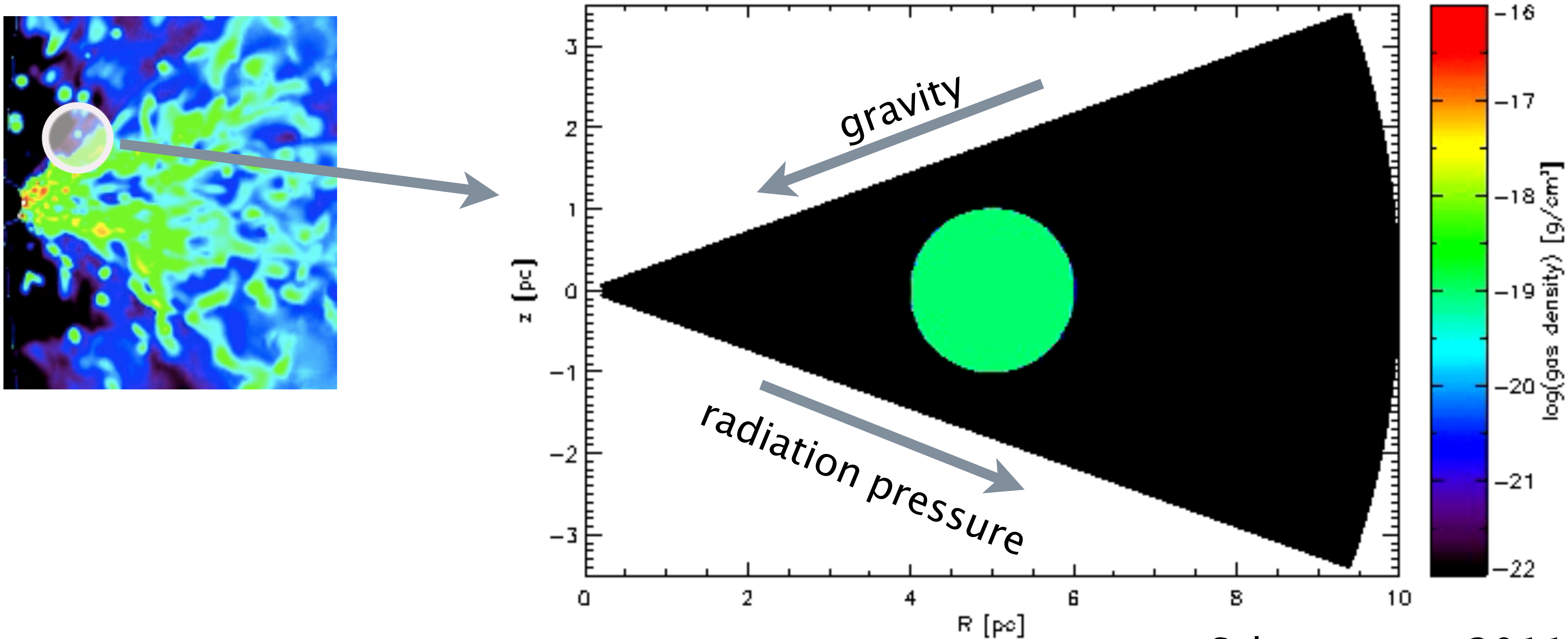

alpha viscosity value unclear:

observations of fully ionized discs:
0.1 to 0.4 (King 2007)

→ alpha parameter study

- Models reproducing maser observations in NGC 1068: ~$10^6$ $M_{sun}$ in clumpy disc model (Kumar 1999)

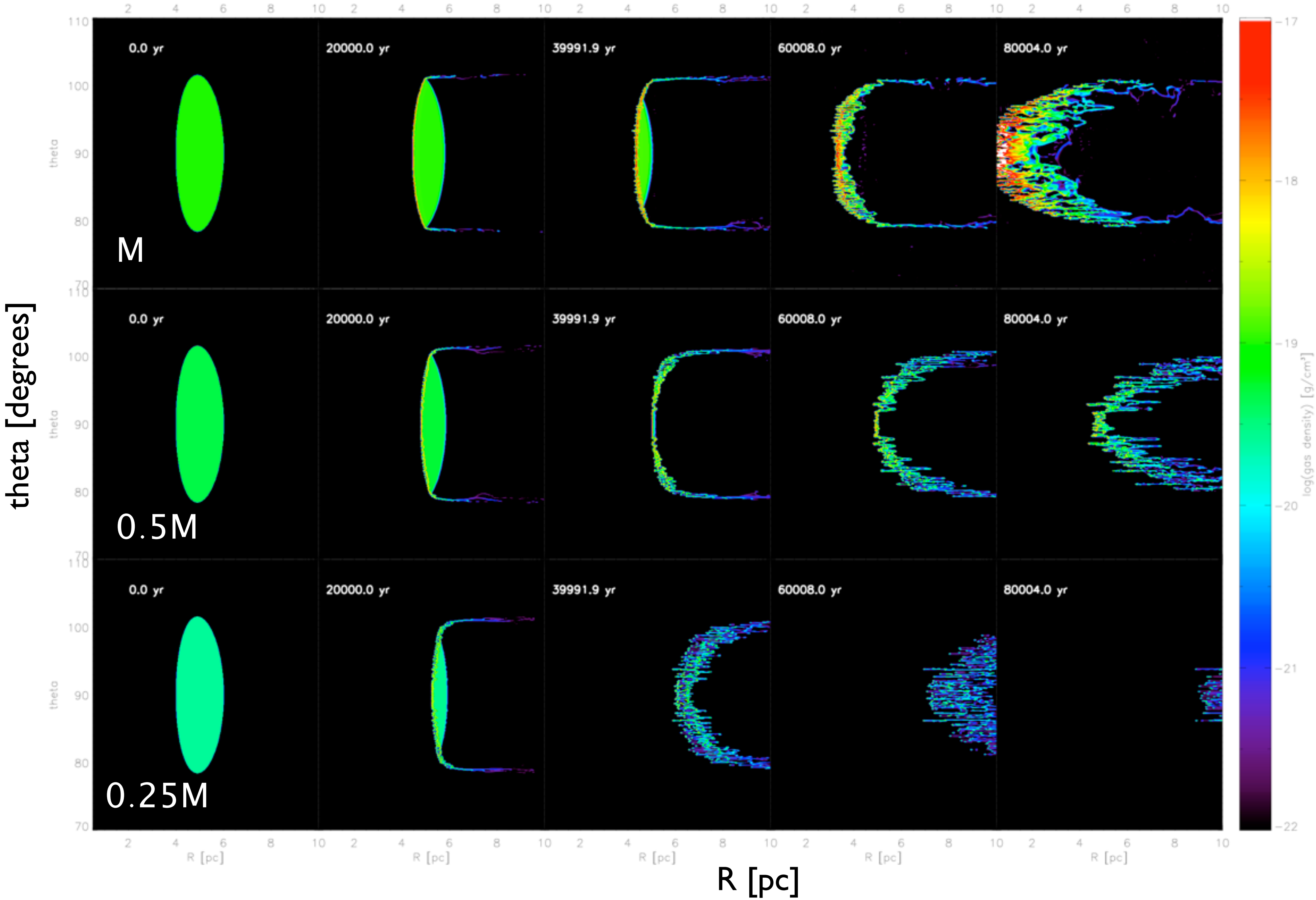
# Radiation pressure feedback




Schartmann+ 2011

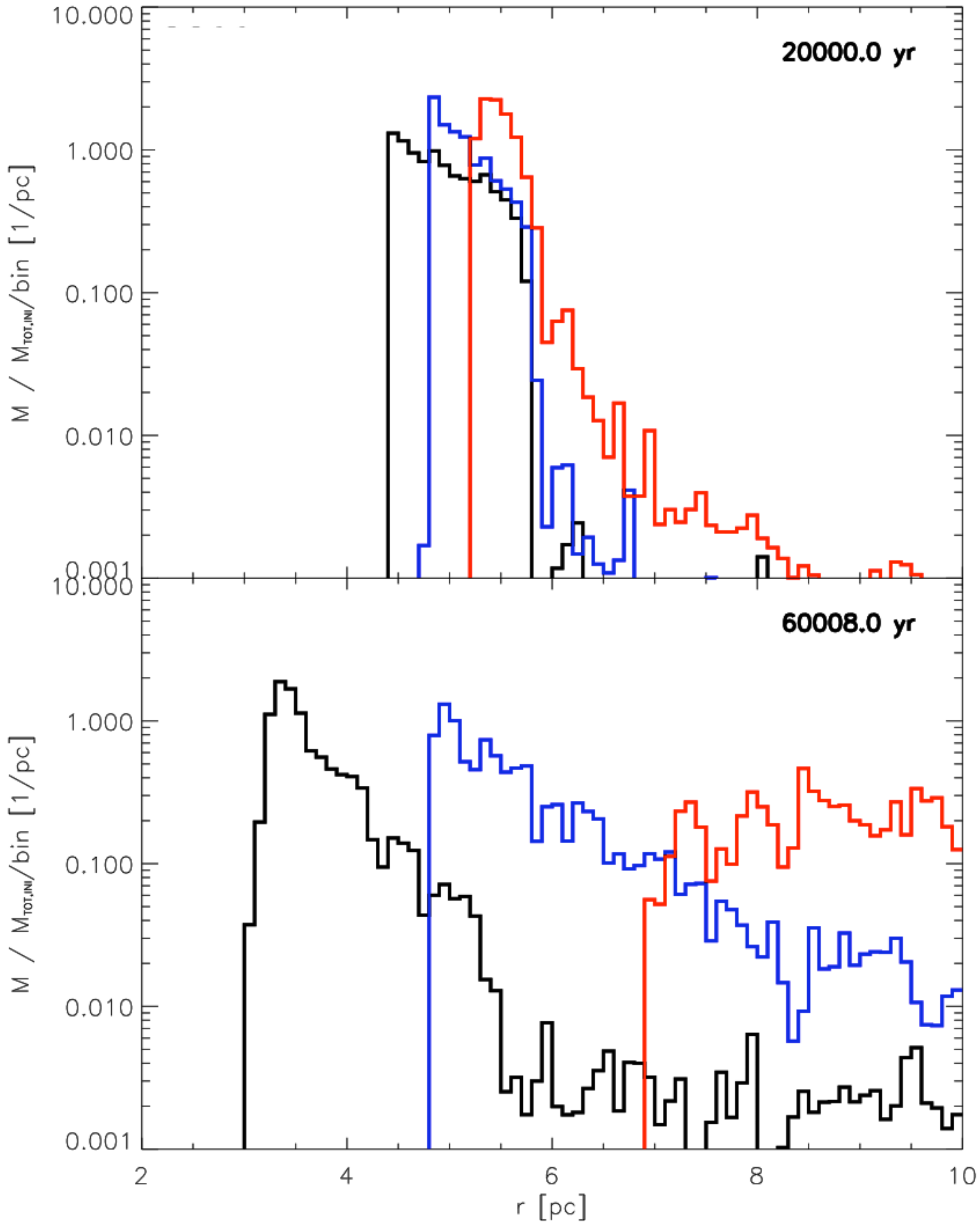
- frequency resolved rad. transfer + gravity
- standard galactic gas/dust mixture
- accretion disc spectrum
- gas and dust dynamically, but not thermally coupled
- dust present for $T_{gas} < T_{sputt}$

# Radiation pressure feedback



# Radiation pressure feedback

cloud density study - mass
on shells

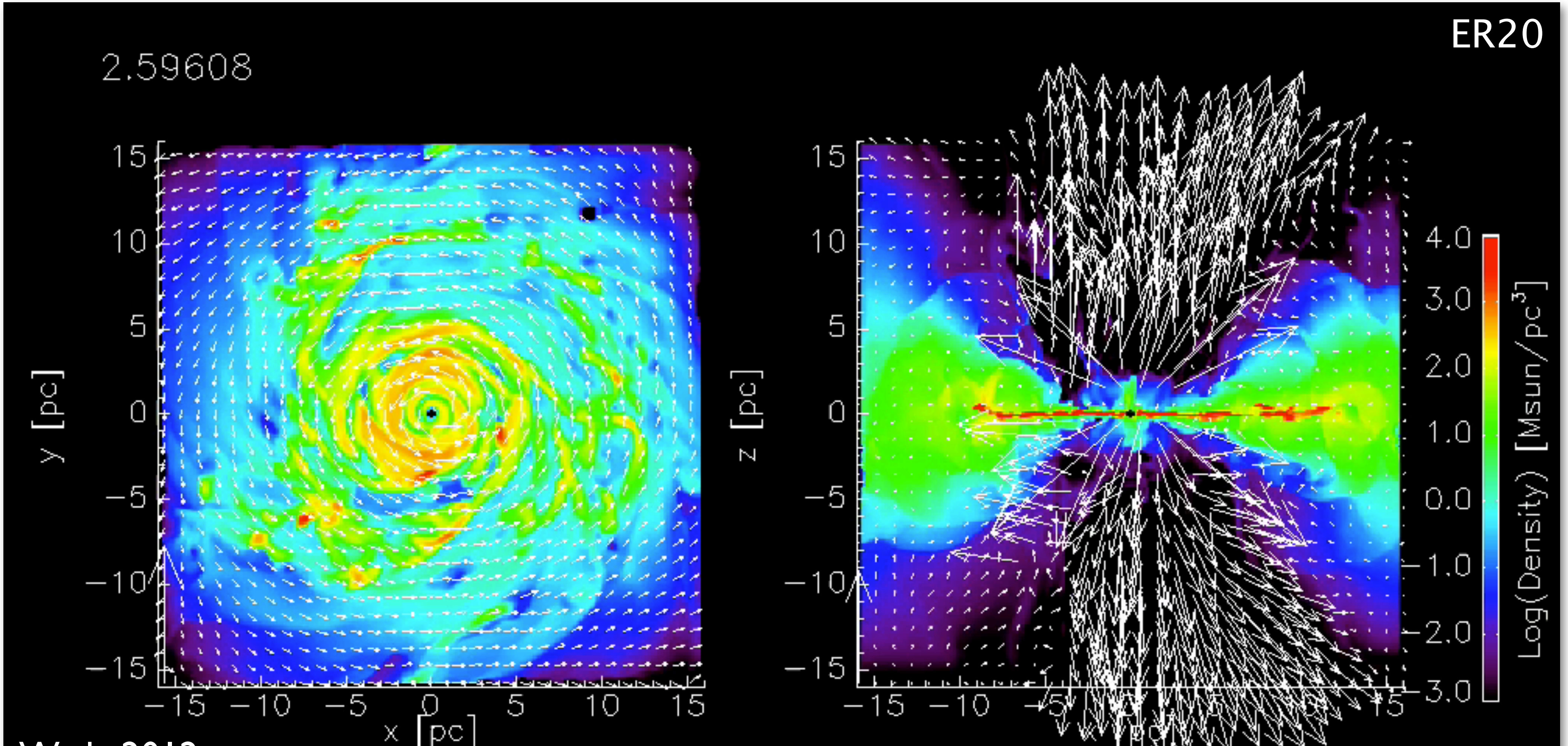



M
0.50 x M
0.25 x M

# Radiation-driven AGN tori

- self-gravitating gas disc ($10^6$ M$_\odot$)
- central SMBH ($10^7$ M$_\odot$)
- fixed DM and stellar potential

- X-ray heating, dust radiation pressure
- ray-tracing method
- 3 Eddington ratios: 0.01, 0.1, 0.2
- 0.125pc resolution
- $32^3$ pc box




Wada 2012

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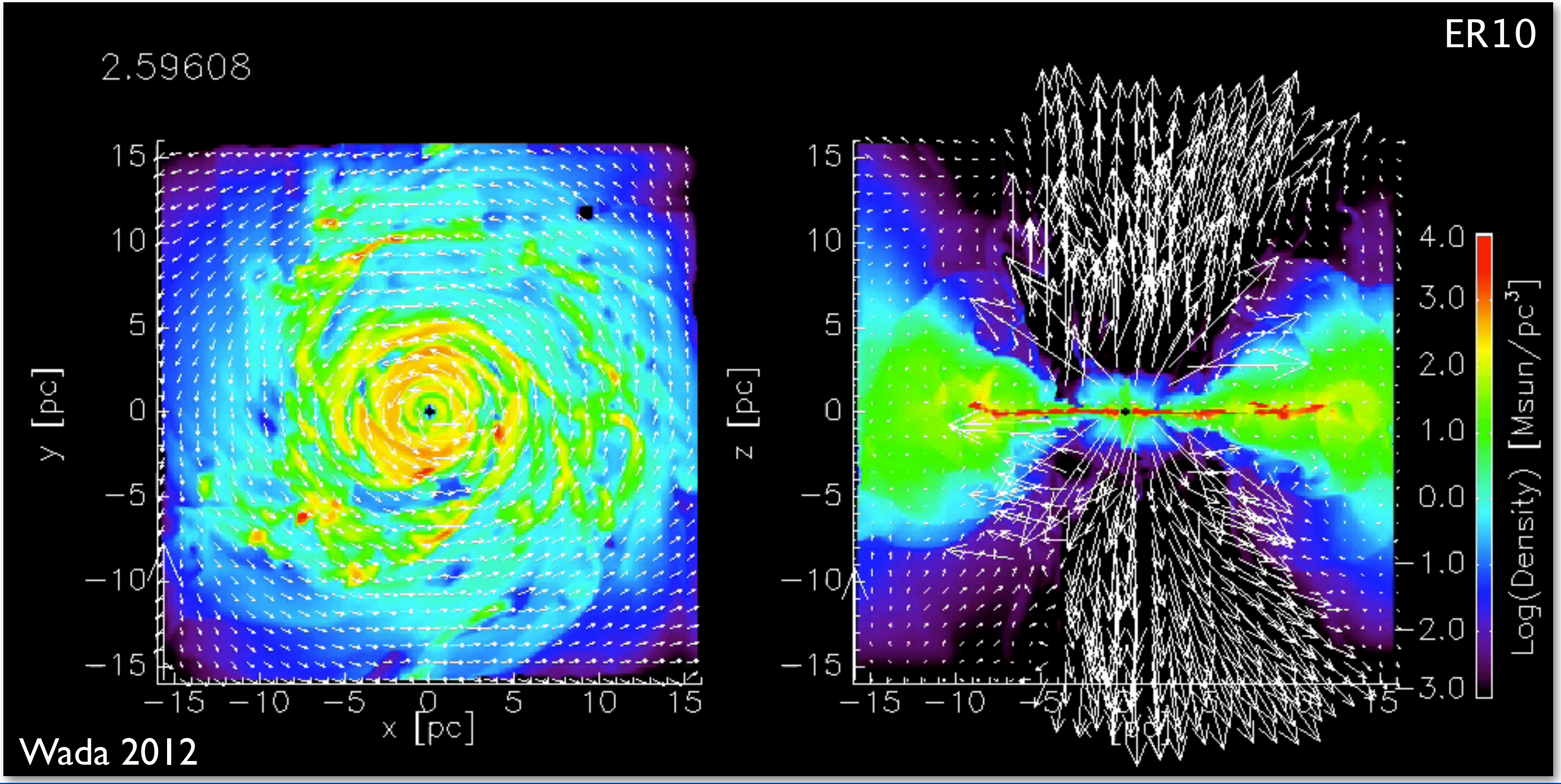

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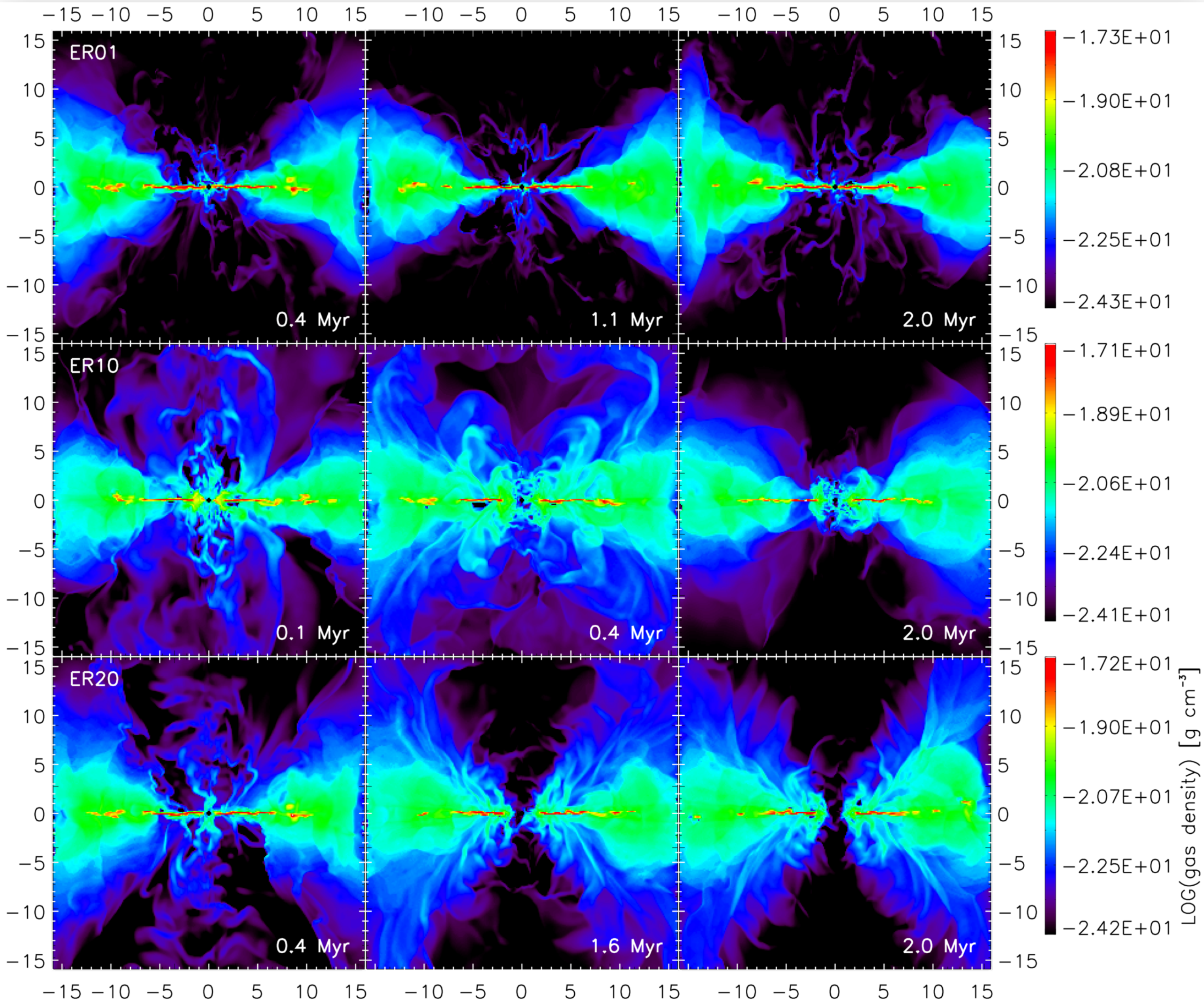



gas density distribution

X-ray heating and radiation pressure

$0.01\ L_{Edd}$

- thin disk
- tenuous outflow

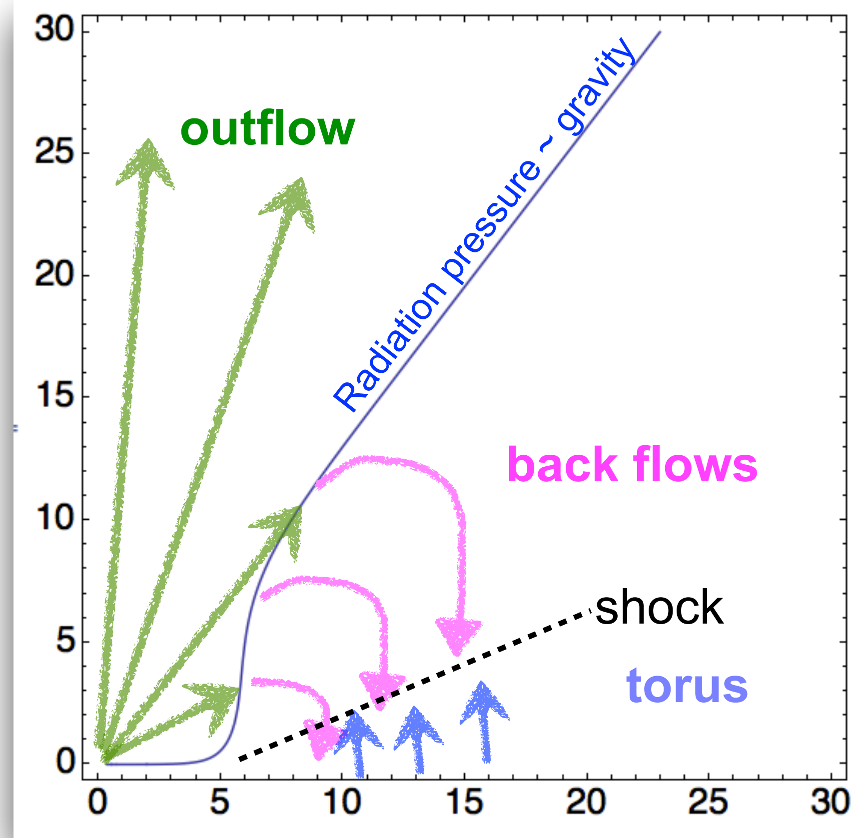
$0.10\ L_{Edd}$

- dense, puffed-up structure
- outflow ceases

$0.20\ L_{Edd}$

- dense, puffed-up structure
- tenuous outflow

# "Radiation pressure driven fountain"



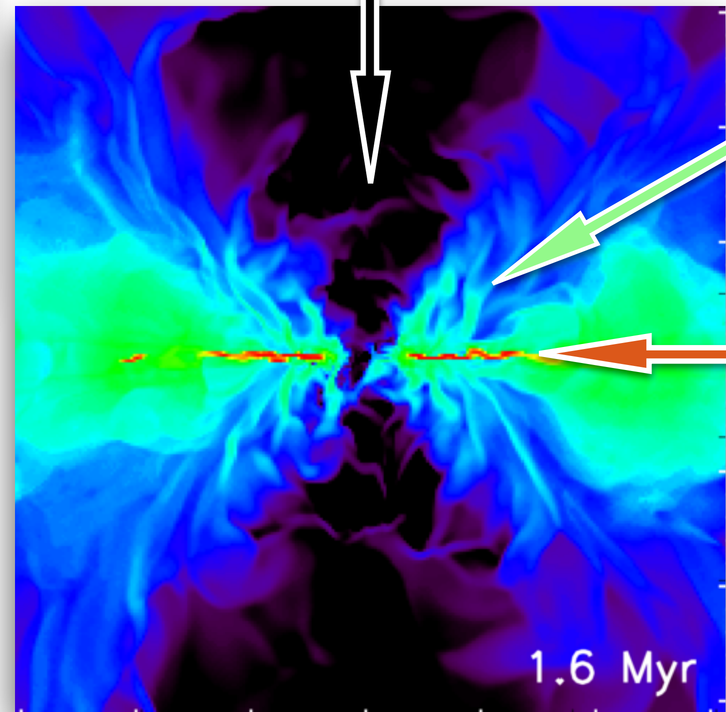

Wada 2012

3-component obscuring structure replaces the classical "torus":

+ hot, dusty, low density outflow

+ puffed-up "torus"

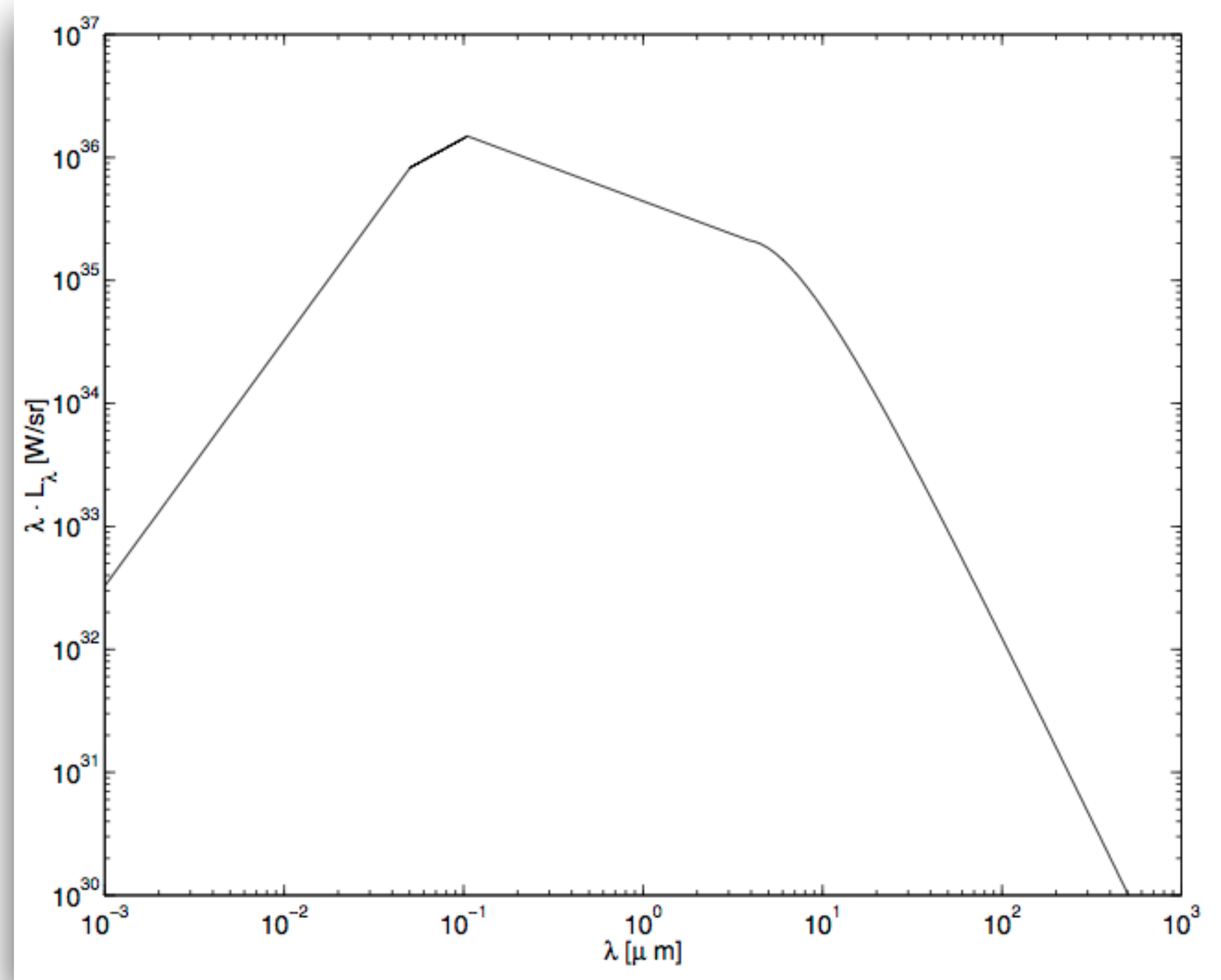
+ thin disk



# Dust Continuum Radiative Transfer & RADMC-3D

$$\frac{1}{c}\frac{\partial I_\nu(\vec{x},\vec{n})}{\partial t} + \vec{n}\cdot\vec{\nabla} I_\nu(\vec{x},\vec{n}) = \frac{1}{4\pi}\rho_d(\vec{x})\, j_\nu(\vec{x},T) - \rho_d(\vec{x})\,\{\kappa_{\nu,\mathrm{abs}}(T) + \kappa_{\nu,\mathrm{sca}}(T)\}\, I_\nu(\vec{x},\vec{n}) + \rho_d(\vec{x}) \int_{4\pi} d\Omega'\, \Phi(\vec{n},\vec{n}')\,\kappa_{\nu,\mathrm{sca}}(T)\, I_\nu(\vec{x},\vec{n}')$$

- solve radiative transfer equation with 3D Monte-Carlo code RADMC-3D (Dullemond et al.)
- primary source SED, point-like




work in progress,
comments welcome…

# Dust Continuum Radiative Transfer & RADMC-3D

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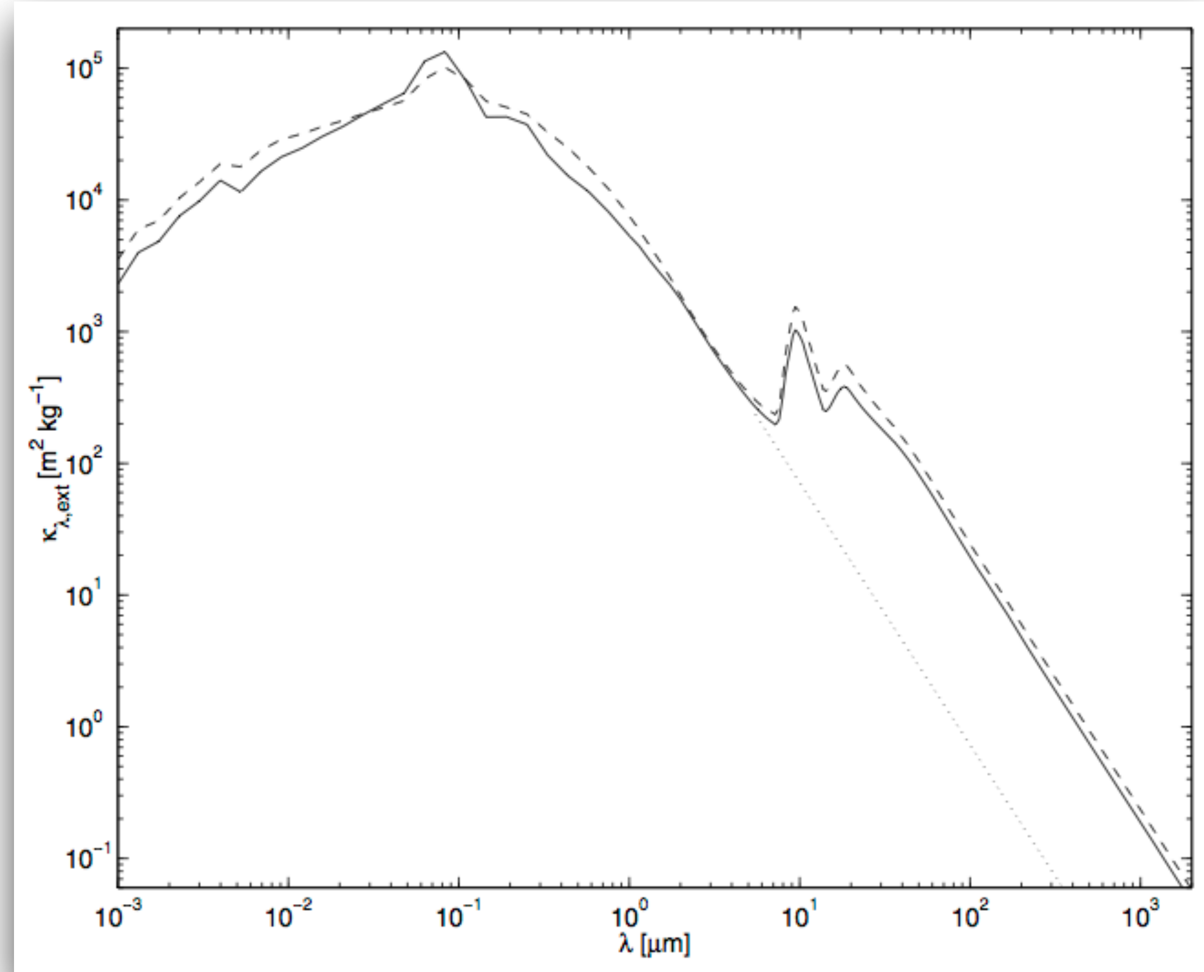
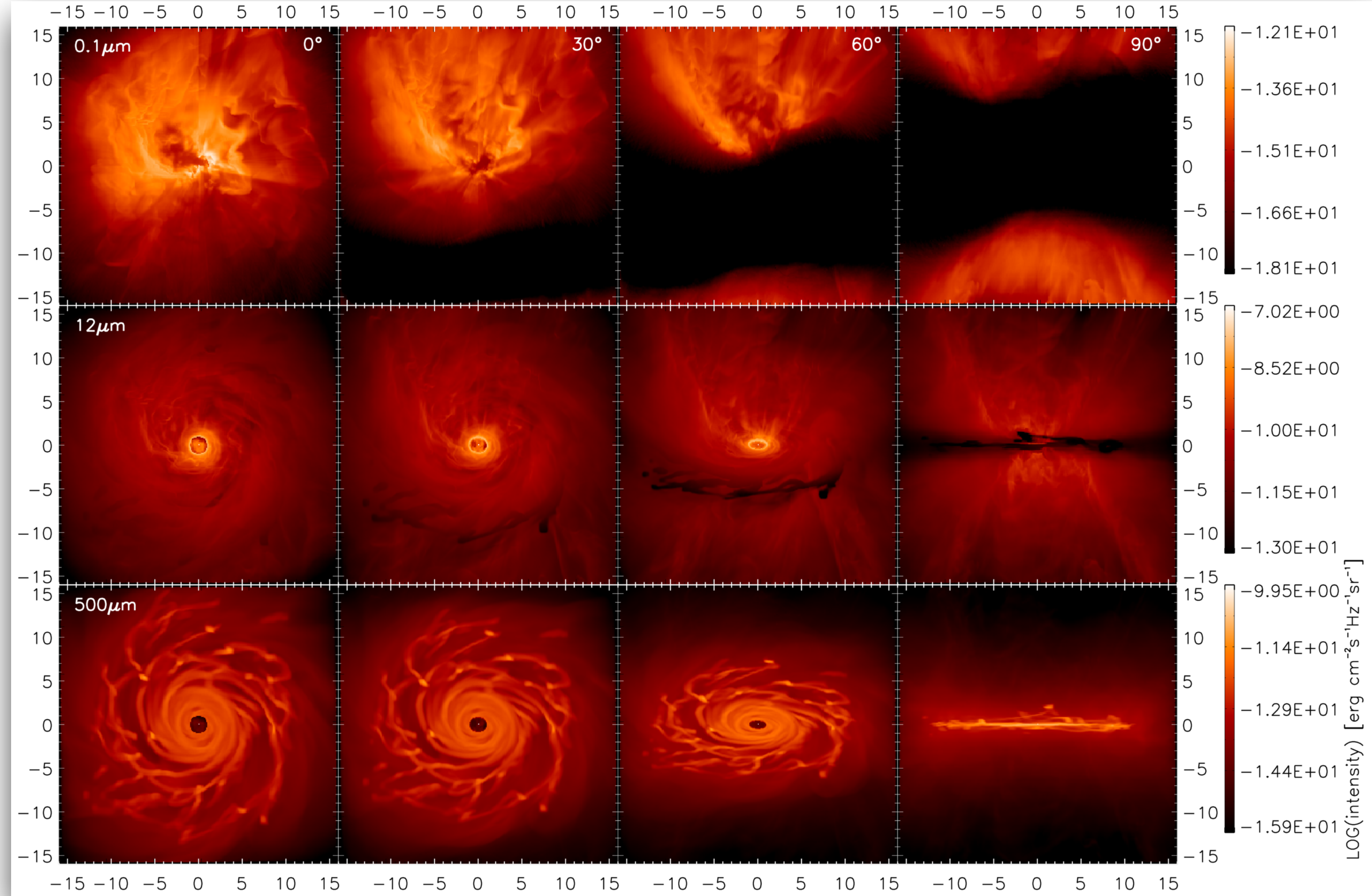
- solve radiative transfer equation with 3D Monte-Carlo code RADMC-3D (Dullemond et al.)
- primary source SED, point-like

- local ISM dust model: 62.5% silicate, 37.5% graphite
- spectral features
- cut at $r_{in}$=1pc



# Wavelength-dependent appearance

20% $L_{Edd}$




- scattered light within the cone

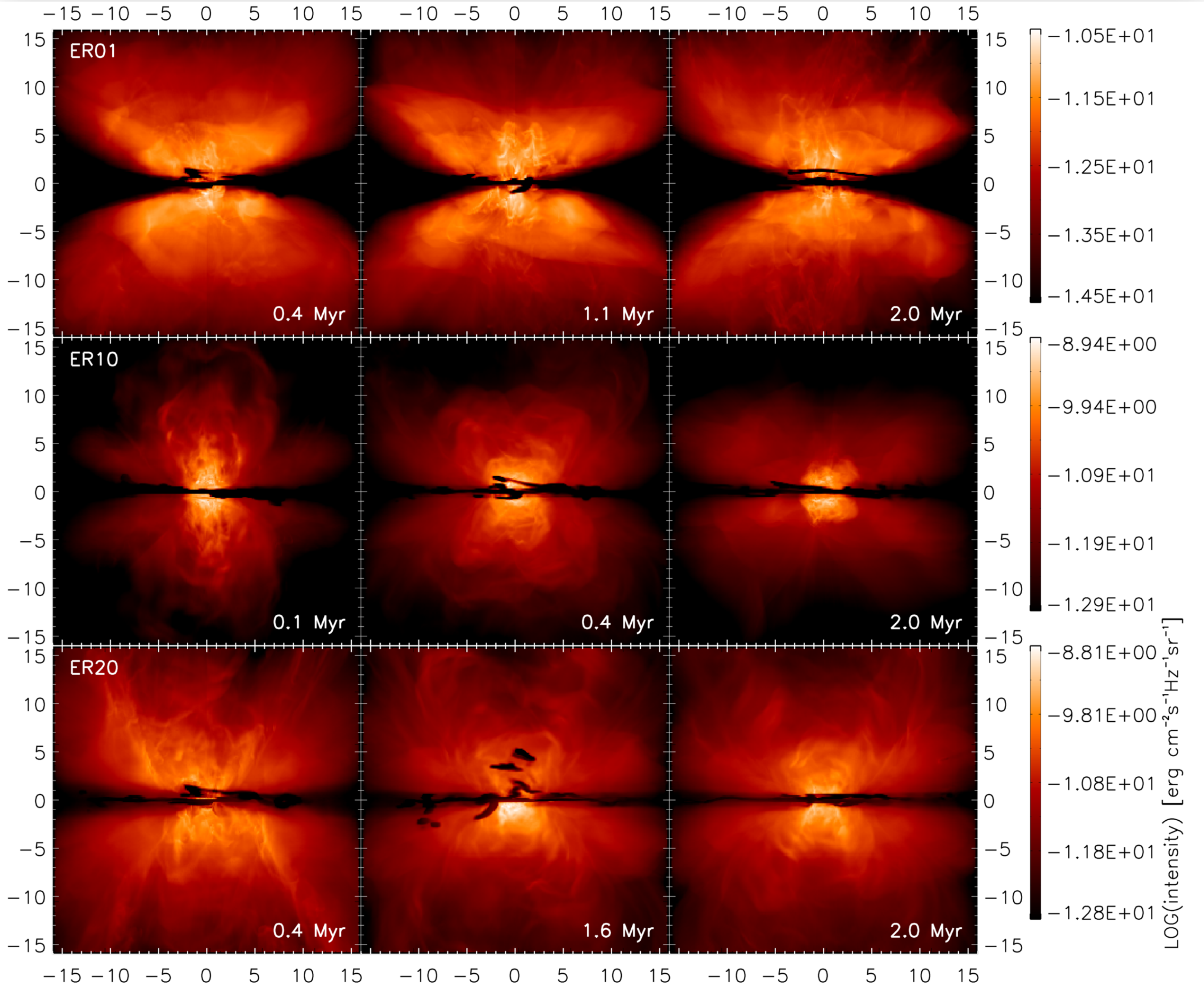
- cone edge
- inner disk rim
- clumpy disk in absorpt.

- cold filaments and clumpy disk

- orders of magnitude different intensity levels

# Time evolution of MIR images

12 micron




- filamentary outflow
- wide opening angle

- ceasing outflow
- vert. elongation changes to spherical shape

- vertical elongation
- low density cone

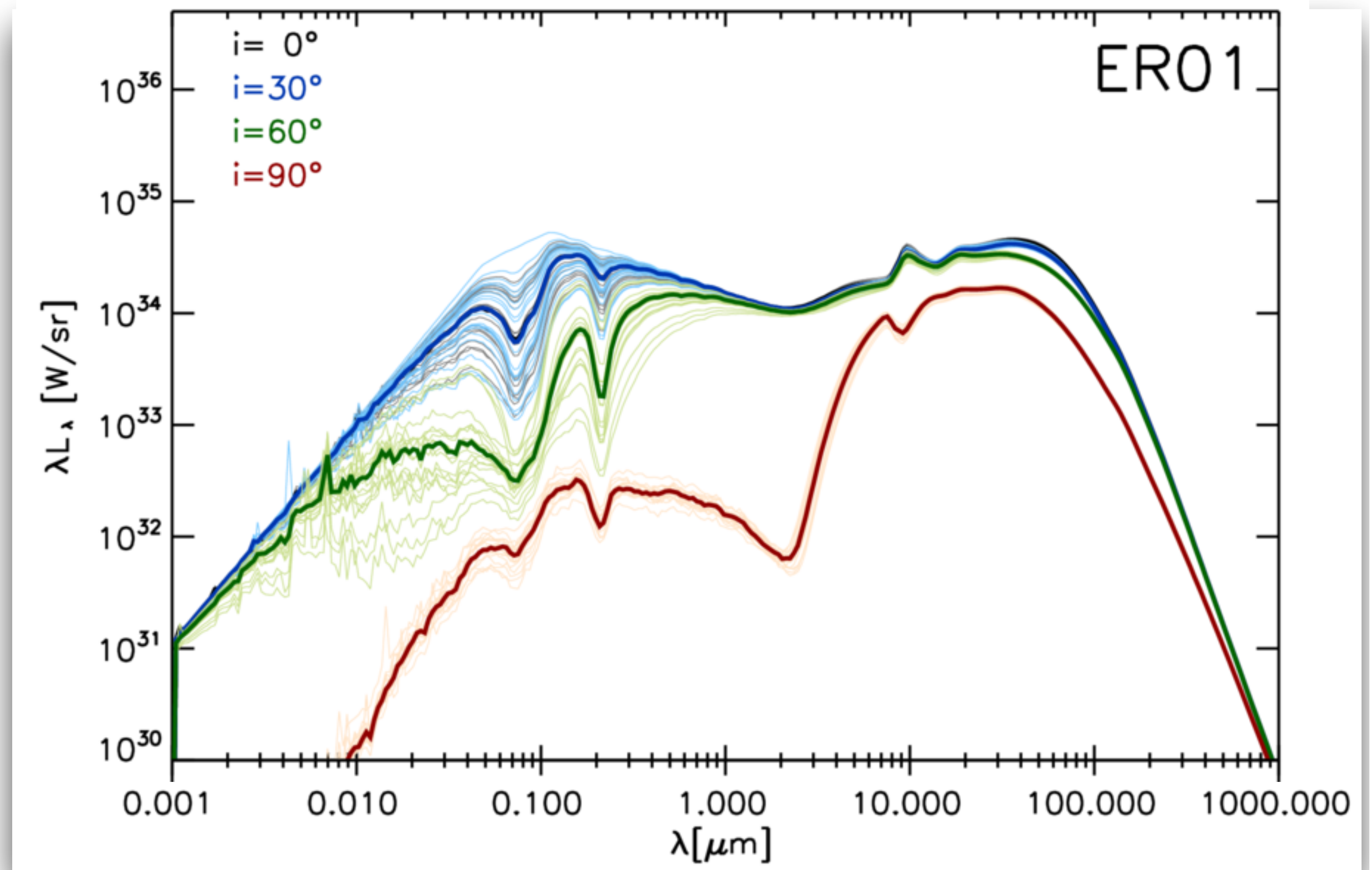
# Spectral Energy Distributions

1% Eddington

- “Big Blue Bump”, IR re-emission bump
- spectral features
- evolution for ~ 2 Myr

- 0,30 and 60 very similar
- large differences to edge-on view

typical for a thin disk

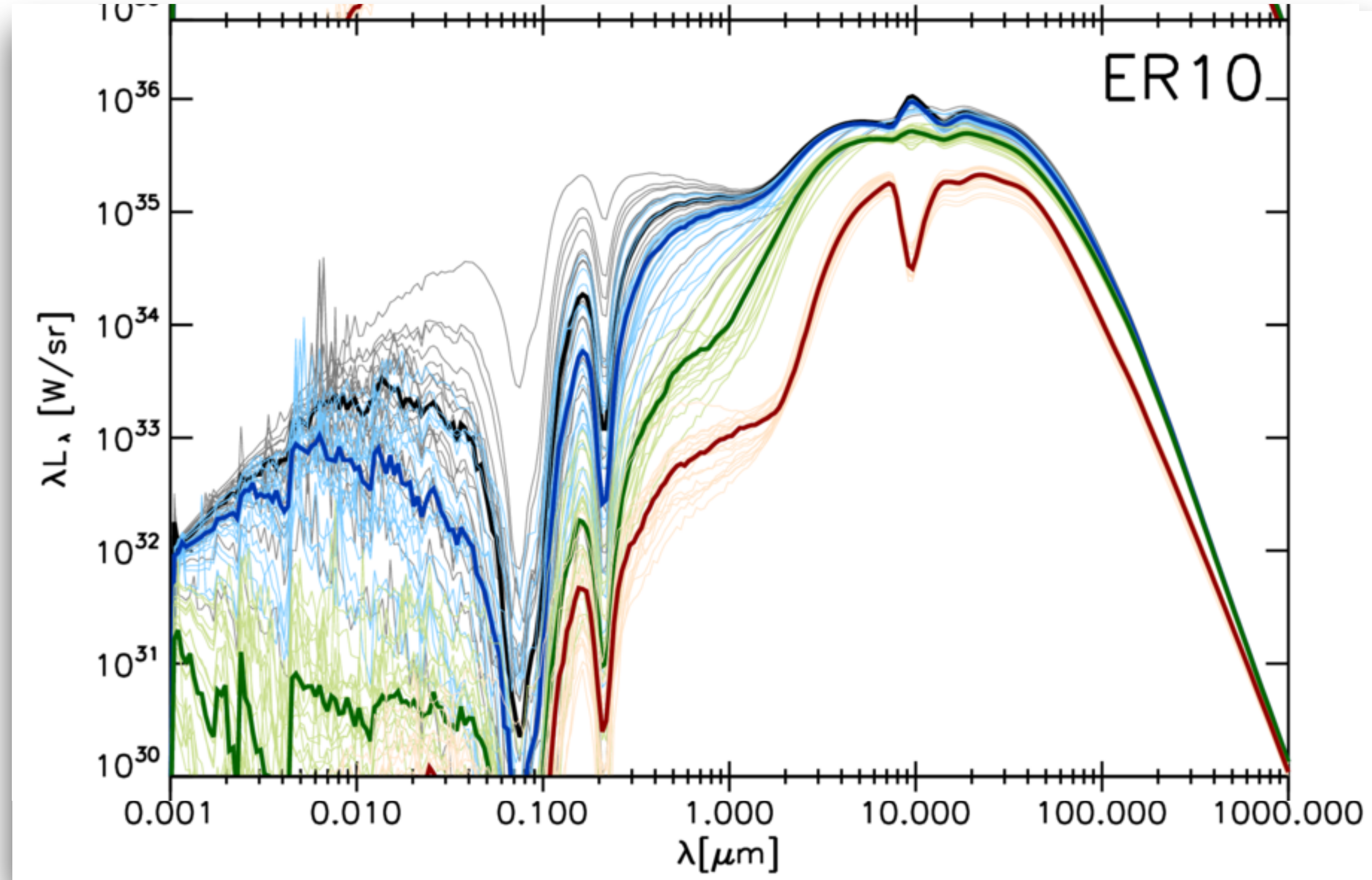


# Spectral Energy Distributions

10% Eddington

- much larger differences between inclination angles
- strong absorption in the visible
- deep silicate absorption features

- ceased wind
- (completely) dust enshrouded AGN

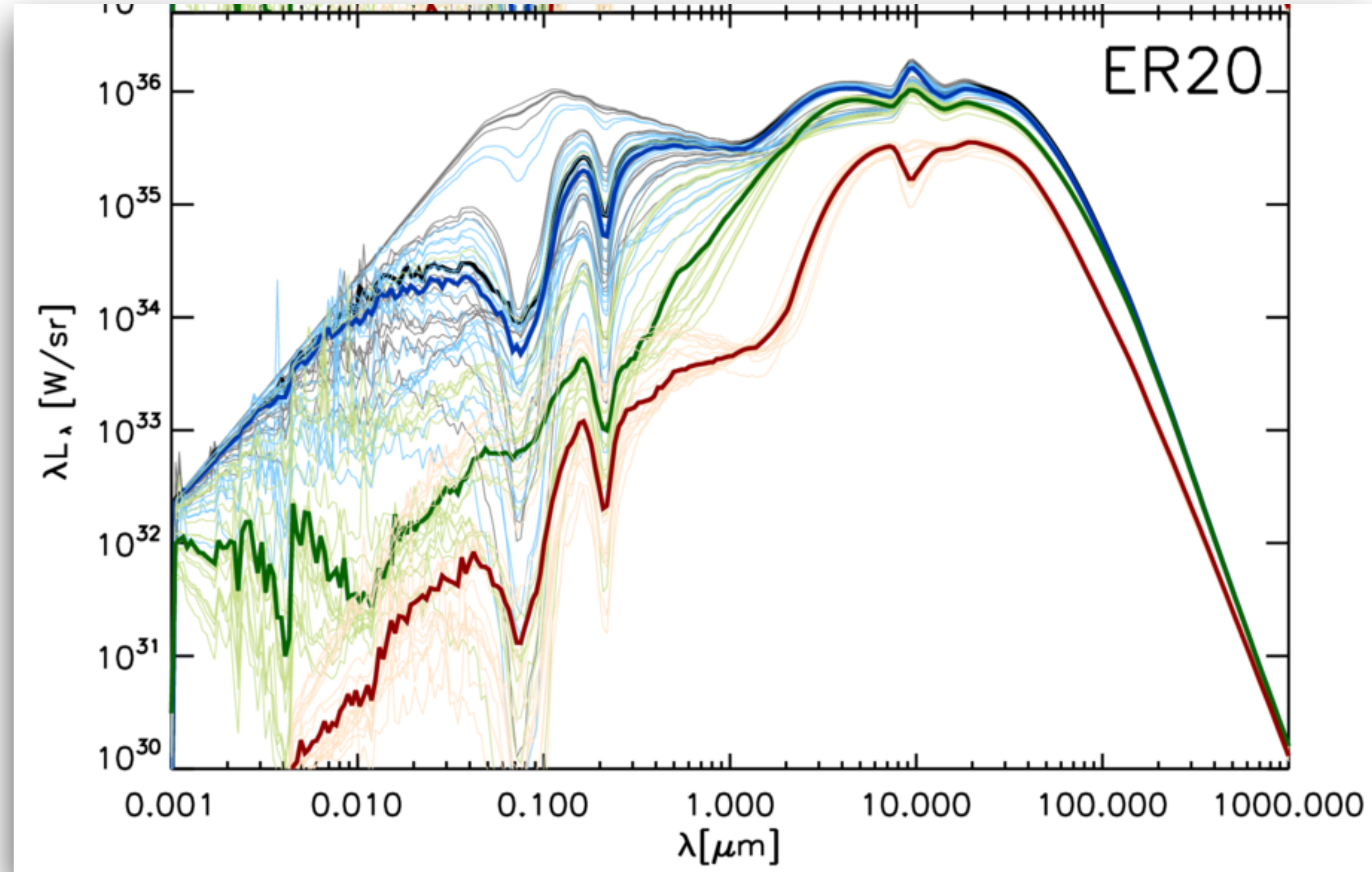


# Spectral Energy Distributions

20% Eddington

- large differences between inclination angles
- large variety of absorption in the visible
- moderately deep abs. features in IR

three-component system: disk plus low density outflow plus puffed-up structure

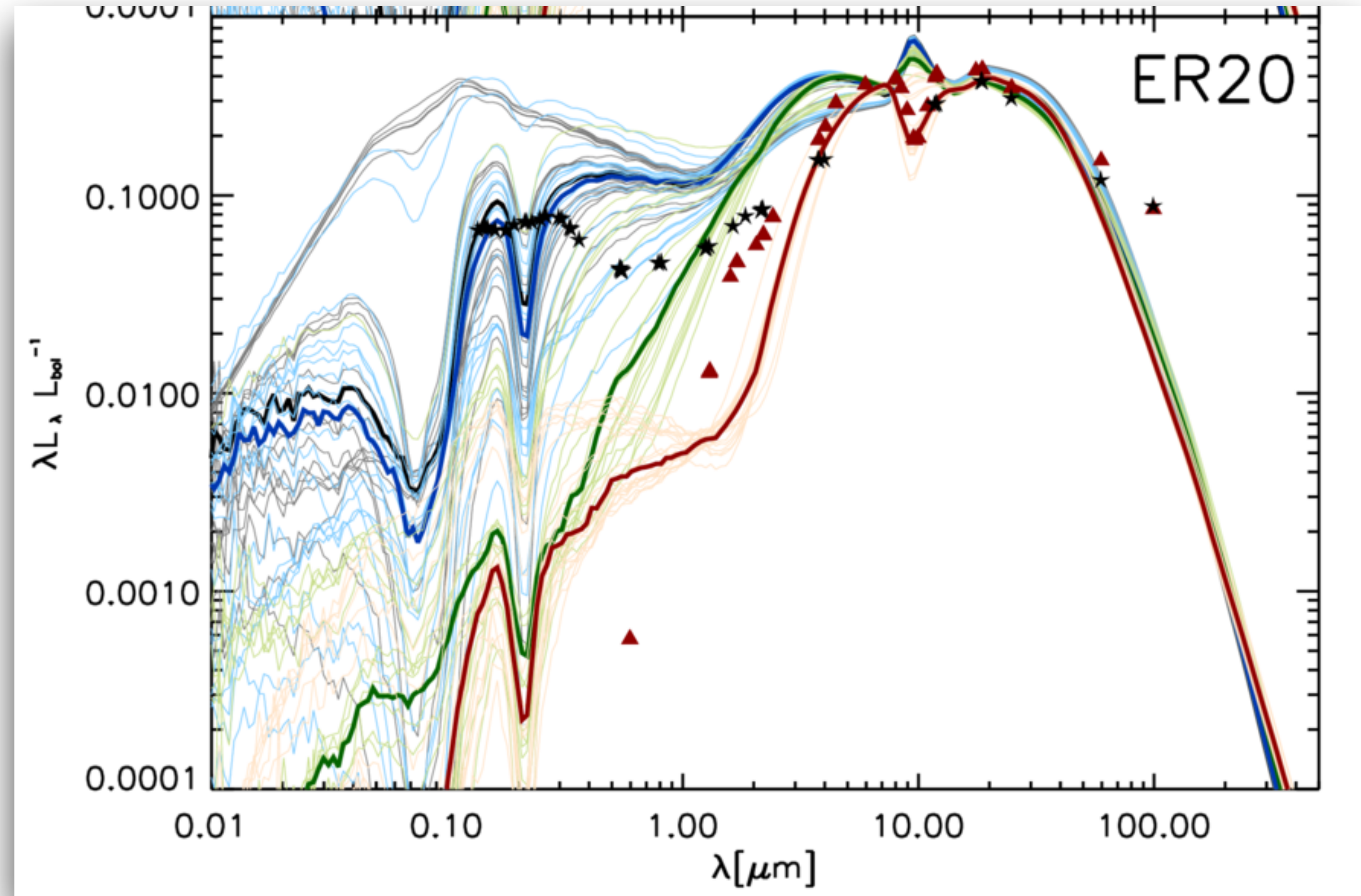


# Comparison to observed SEDs

20% Eddington

- Seyfert galaxy templates (Prieto et al. 2010)
- type I - black stars
- type 2 - red triangles
- normalised to total bolometric luminosity

- edge-on case: overall good agreement
- face-on case: reasonable agreement at short and long wavelengths
- too much flux at NIR wavelengths (outflow, resolution?)

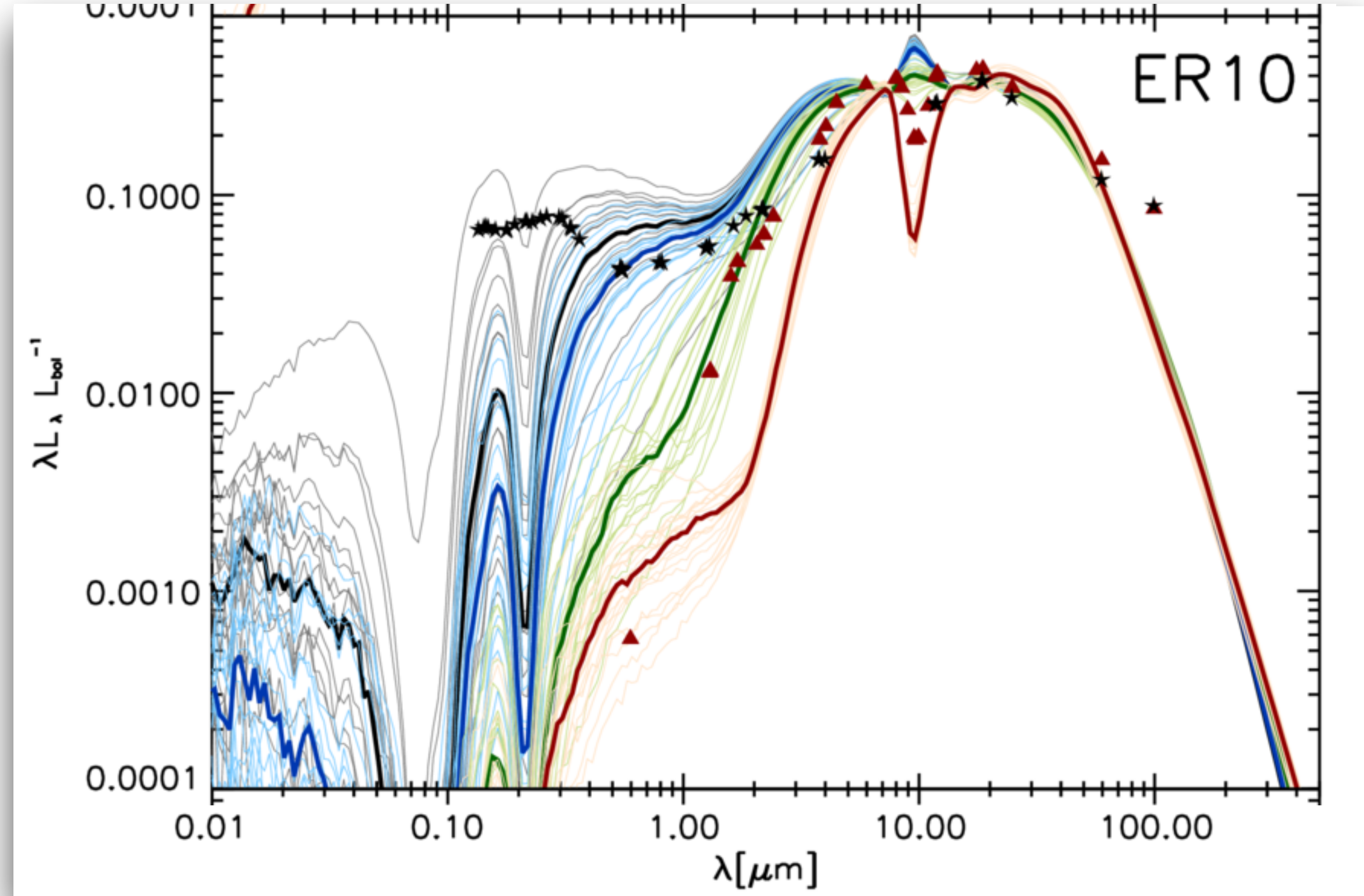


# Comparison to observed SEDs

10% Eddington

- Seyfert galaxy templates (Prieto et al. 2010)
- type I - black stars
- type 2 - red triangles
- normalised to total bolometric luminosity

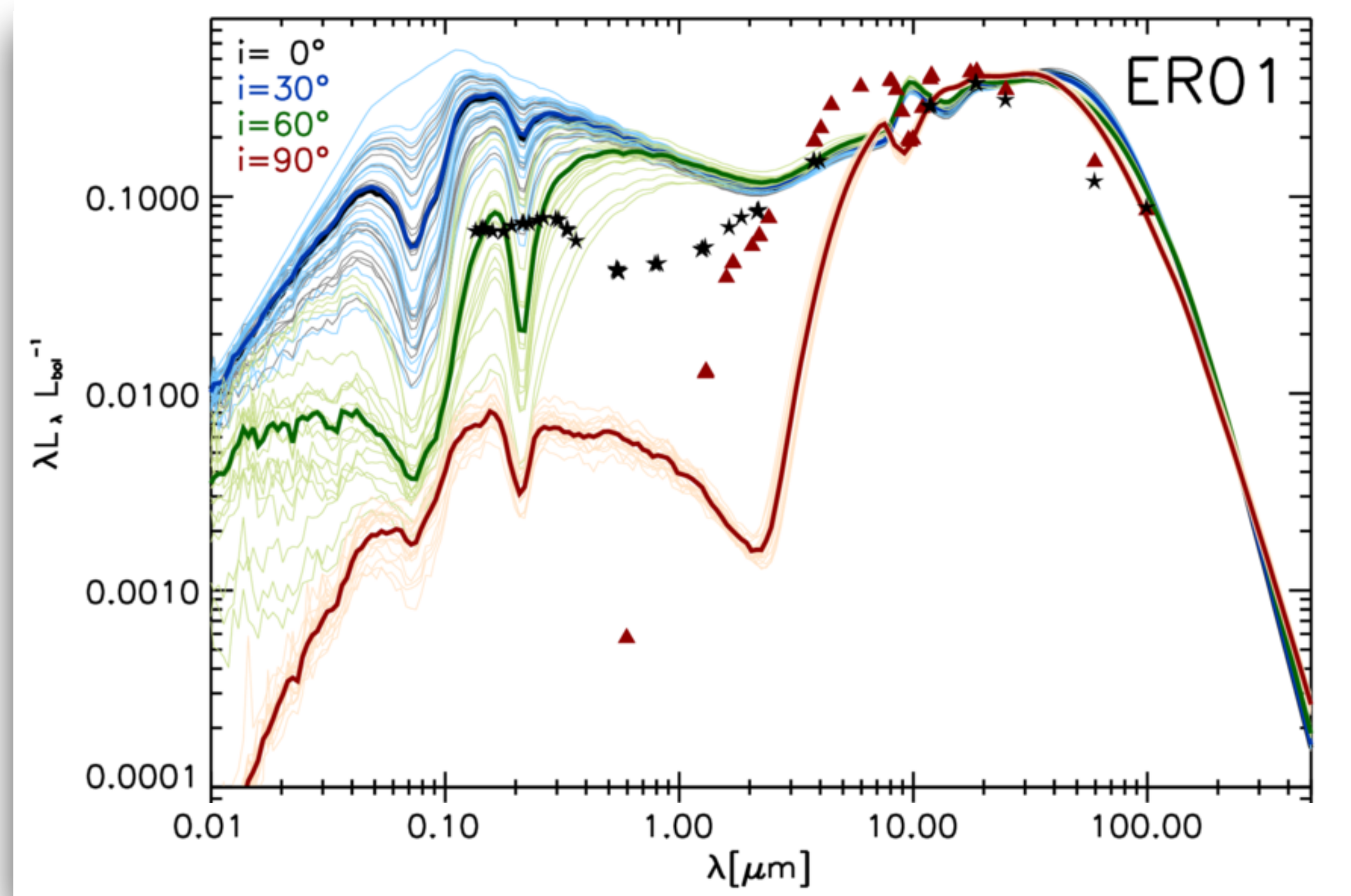
- edge-on case: similarly good agreement, but too strong silicate absorption
- face-on case: too much extinction at short wavelengths



# Comparison to observed SEDs

1% Eddington

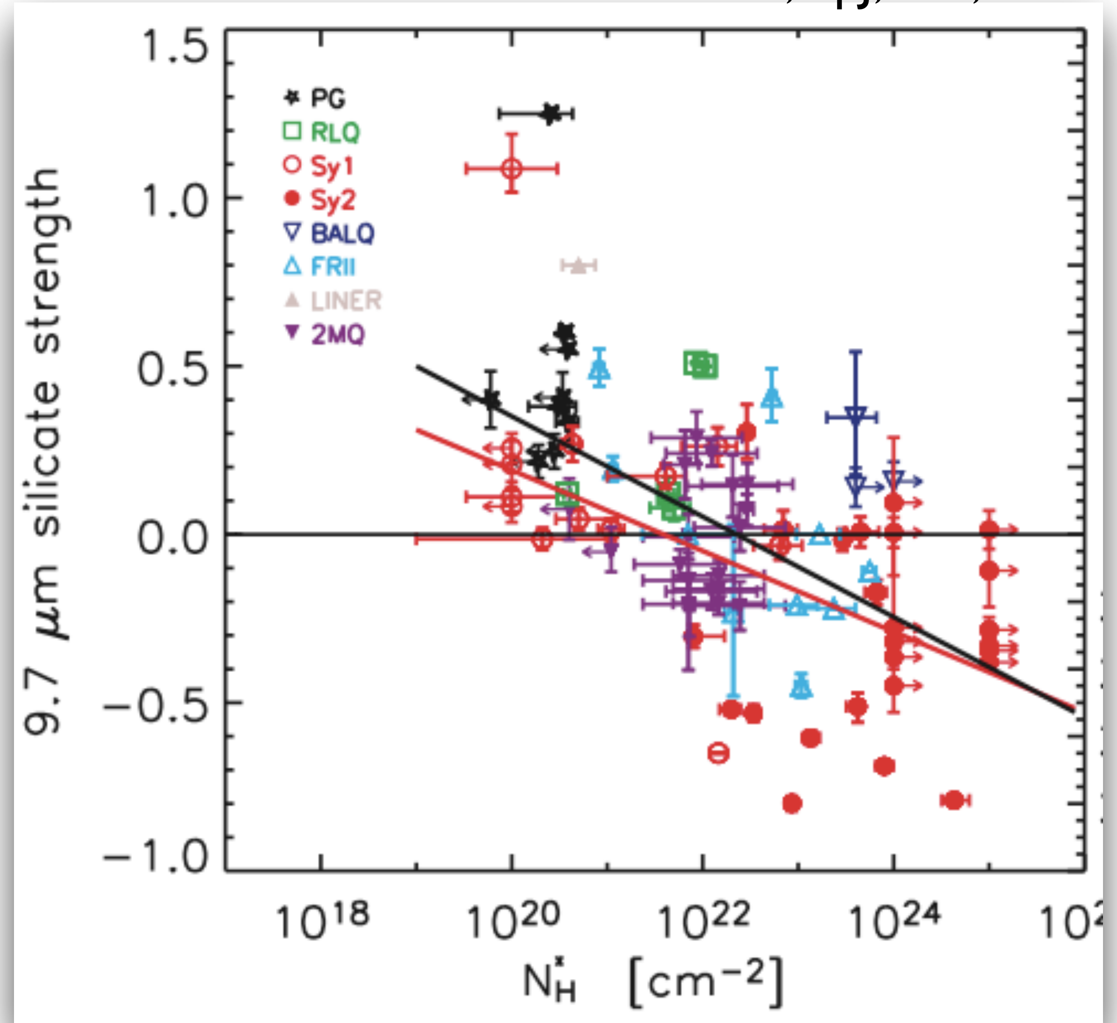
- Seyfert galaxy templates (Prieto et al. 2010)
- type I - black stars
- type 2 - red triangles
- normalised to total bolometric luminosity




- neither explains face-on nor edge-on case very well

# Comparison with observations: silicate feature vs gas column density

Shi et al. 2006, ApJ, 653, 127




- red line = Seyfert sub-sample
- black line = all objects
- NH probes single line of sight
- silicate feature = mixture of emission and absorption components within the beam
- linear relation found with large amount of scatter
- interpreted as being the result of clumpiness

# Comparison with observations: silicate feature vs gas column density

ER20 - stars

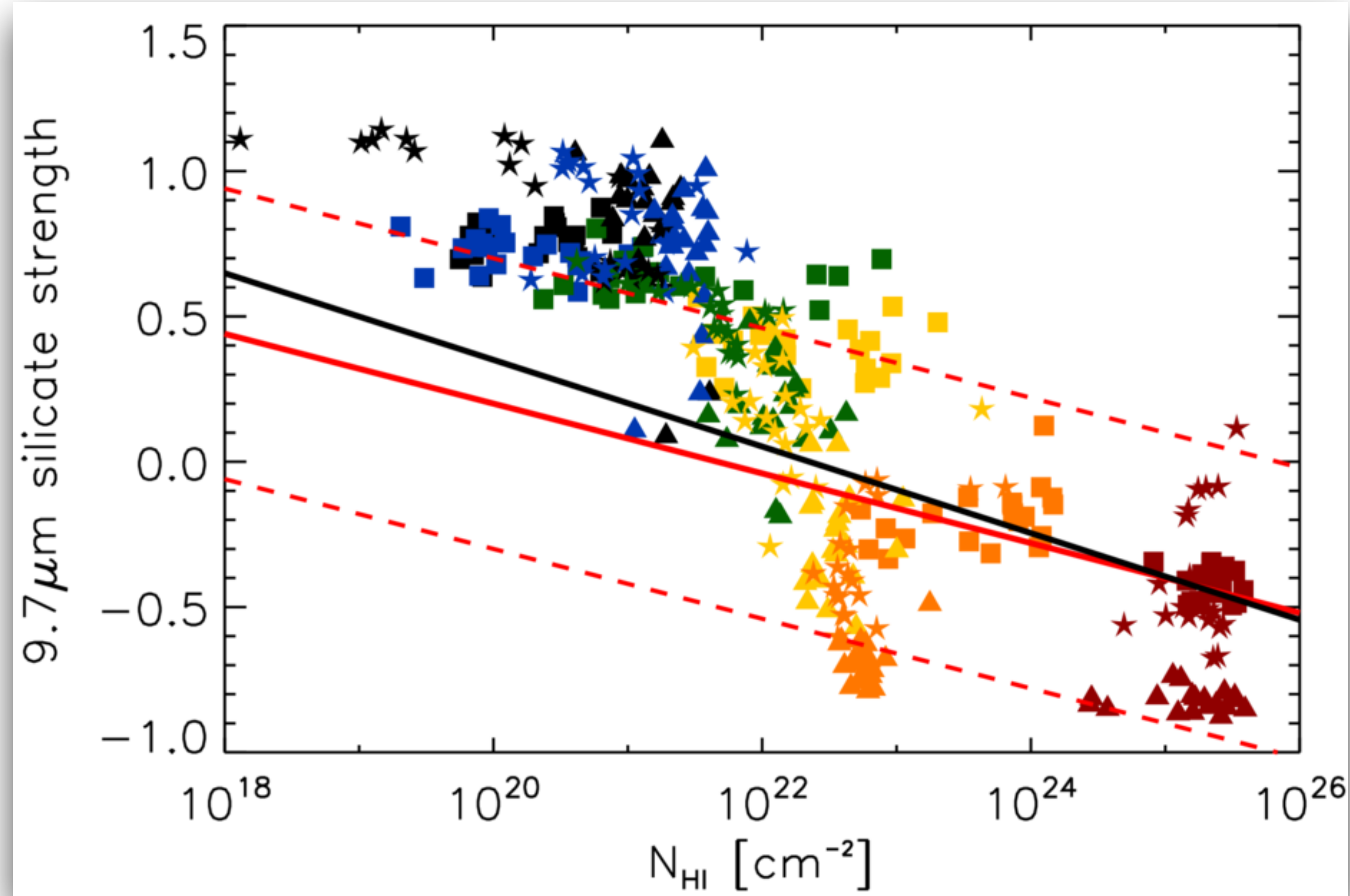
- overall best match

ER01 - squares

- too little scatter

ER10 - triangles

- 90: compactness problem



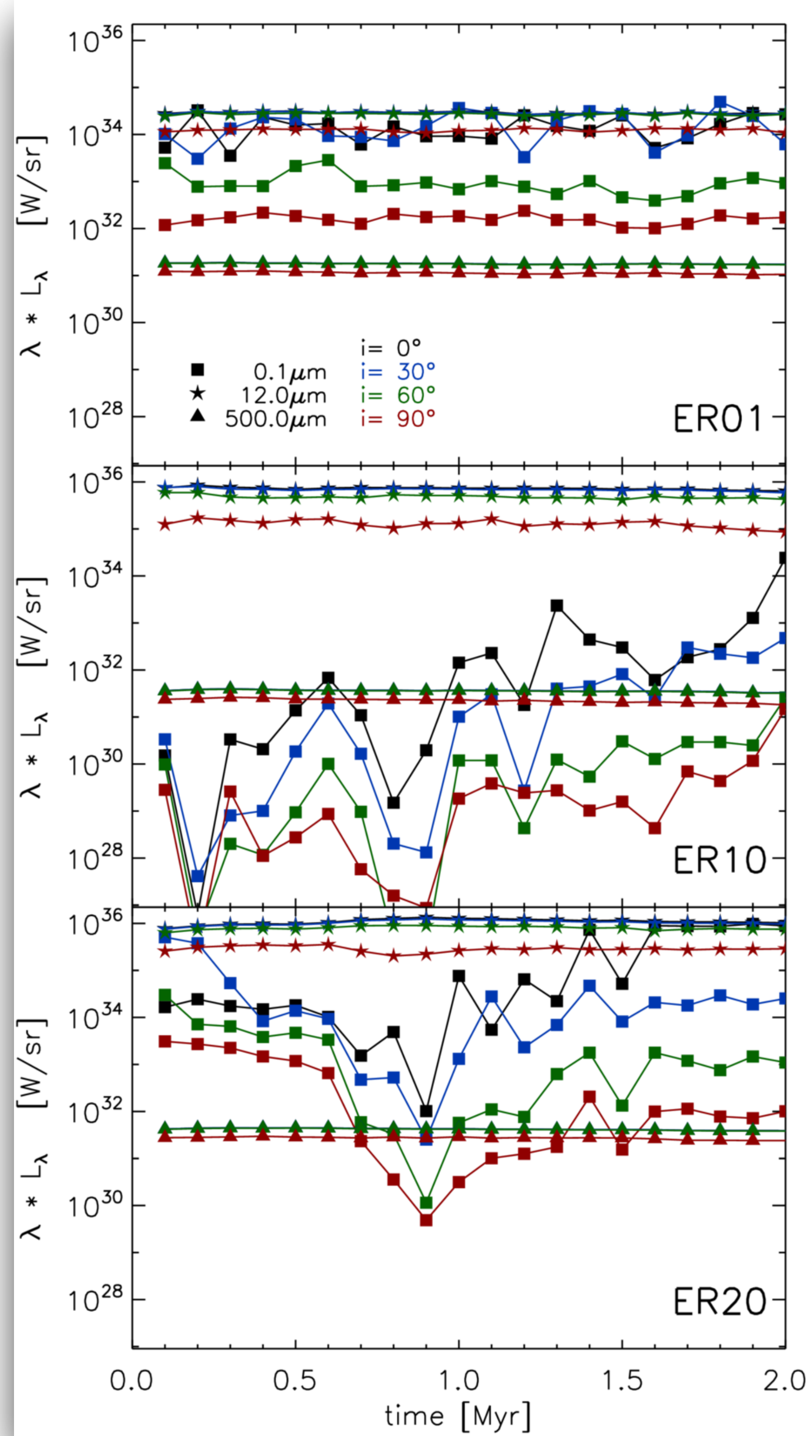

too strong silicate feature emission → missing clumpiness in central region?

# Seyfert Light Curves

- 500 micron (triangles): cold, dense disk, optically thin, in quasi-steady state

  → no time evolution

- at shorter wavelengths, the curves for the inclination angles split up
- the strongest evolution visible for 0.1 micron (max of opacity): scattering plus primary
    - ER01: constant (low density lifted dust)
    - ER10: rising trend, decreasing optical depth in cone (no steady state)
    - ER20: episode of strong and dense outflows

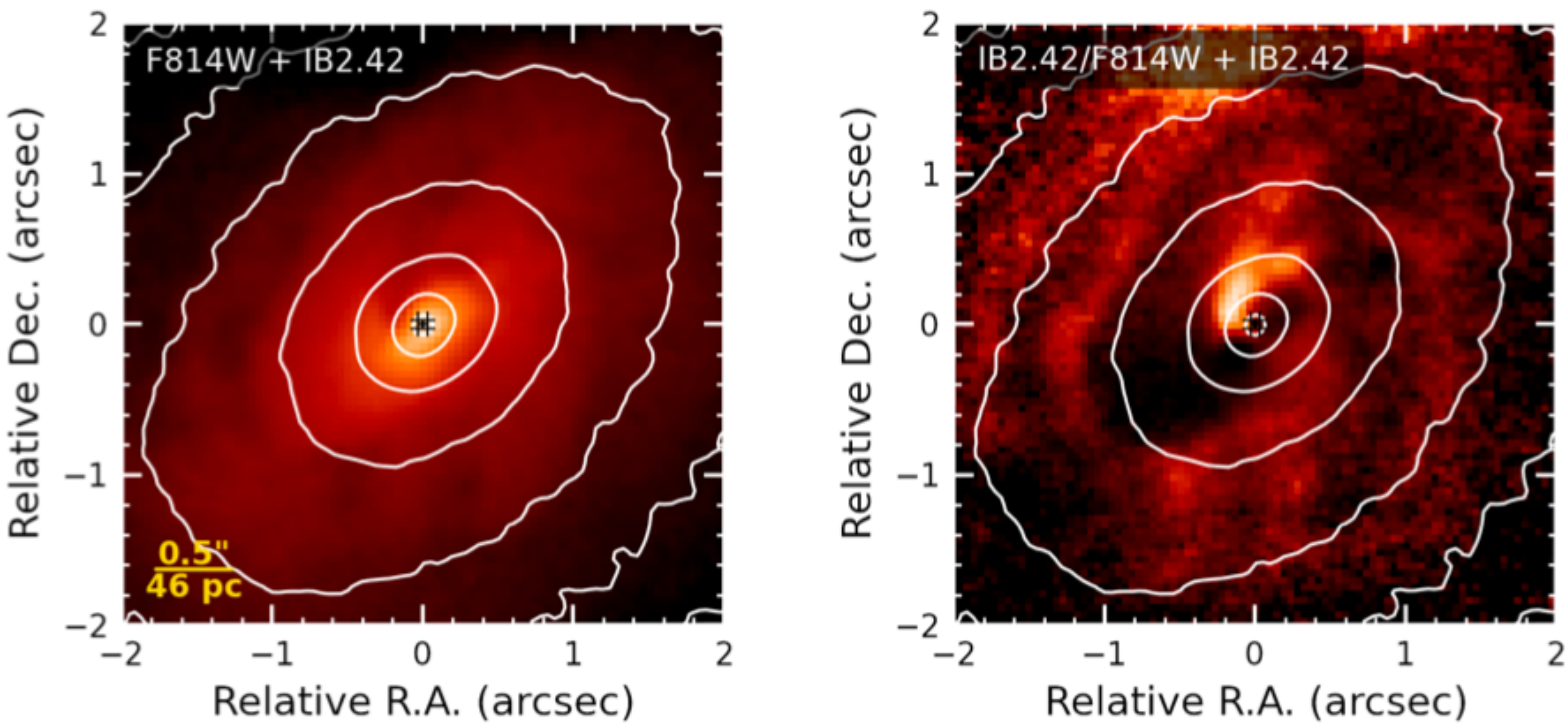


# Obscuration on larger scale

Prieto+ 2014

ESO 428-G14

- very accurate registration of the images with point sources
- K-band source identified as the nucleus
- additional nuclear obscuration by intersection of filaments spiraling towards nucleus (even traced further out towards kpc scale - fueling channels?)
- Hα fills region between dominant dust spirals



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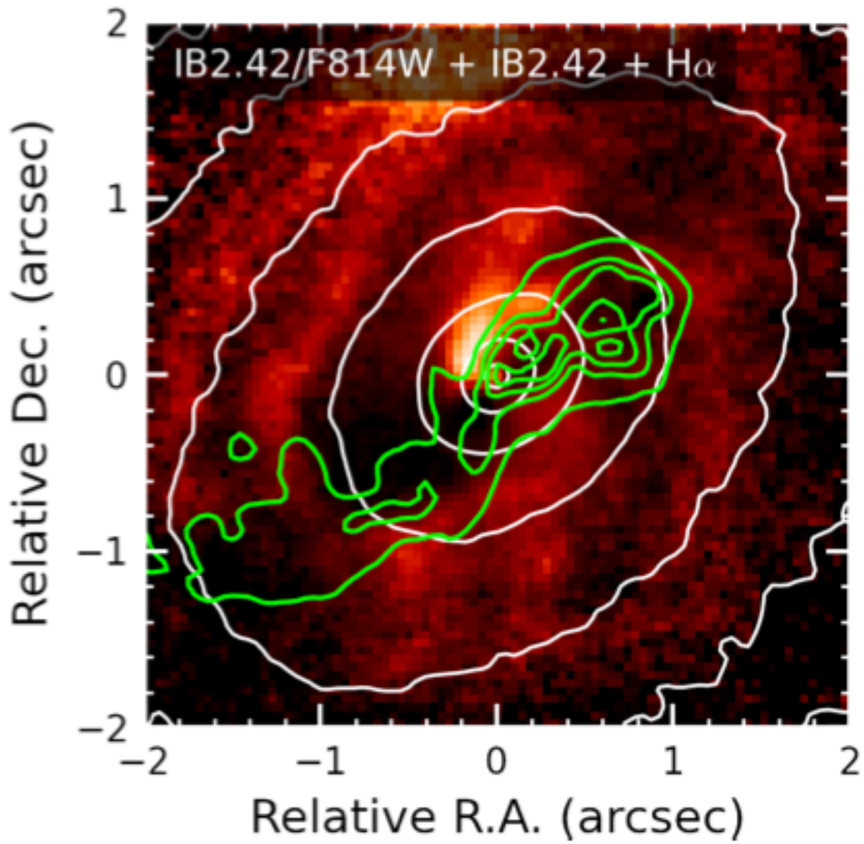
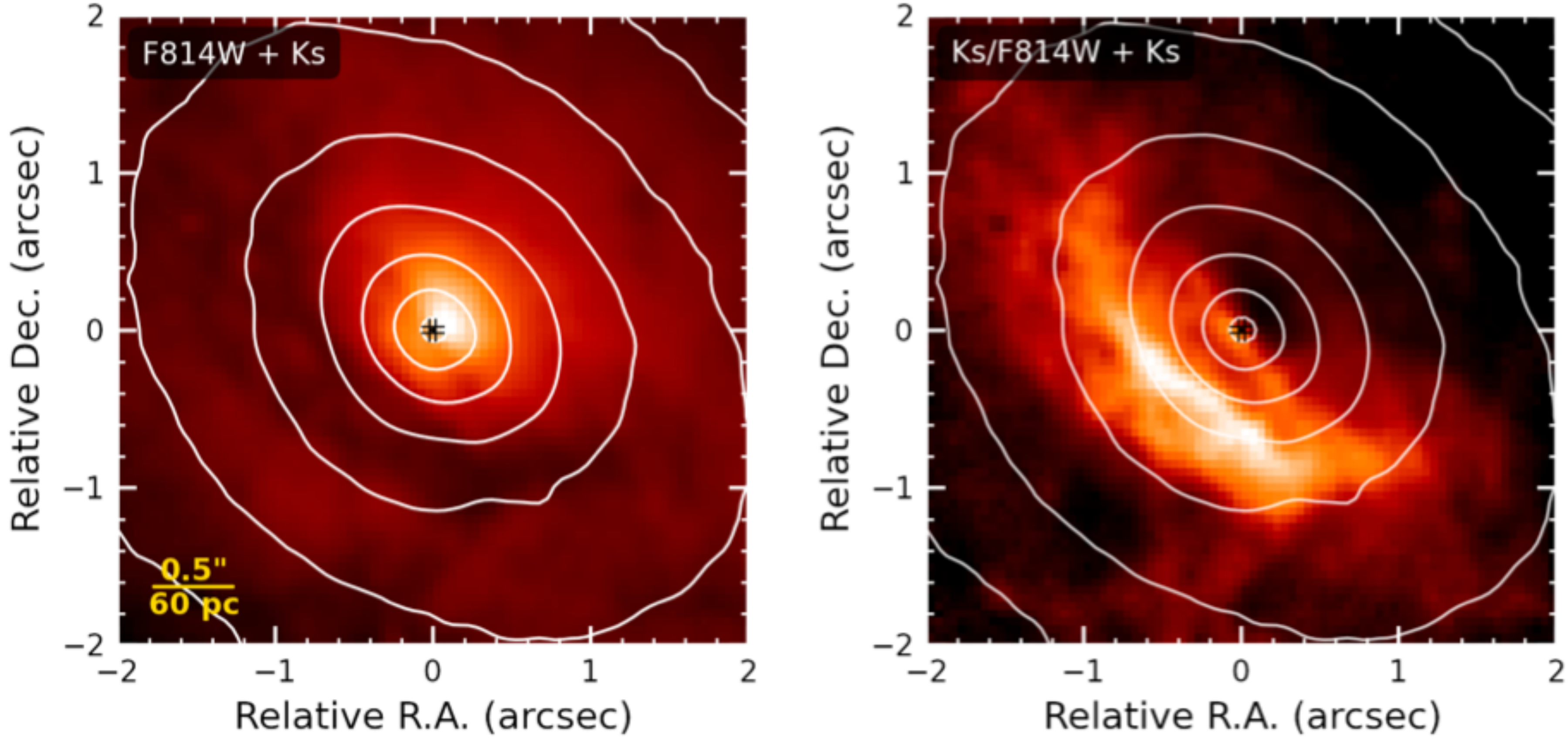


# Obscuration on larger scale

Prieto+ 2014

NGC 3169

- LLAGN (Ho et al. 1995): galaxy light dominates nuclear emission
- thin dust lane crossing the centre
- conical ionized gas emission peaks close to K-band source
- apparent collimation of the ionized gas could be caused by the larger scale dust morphology
- reminiscent of 0.01 Eddington case shown above



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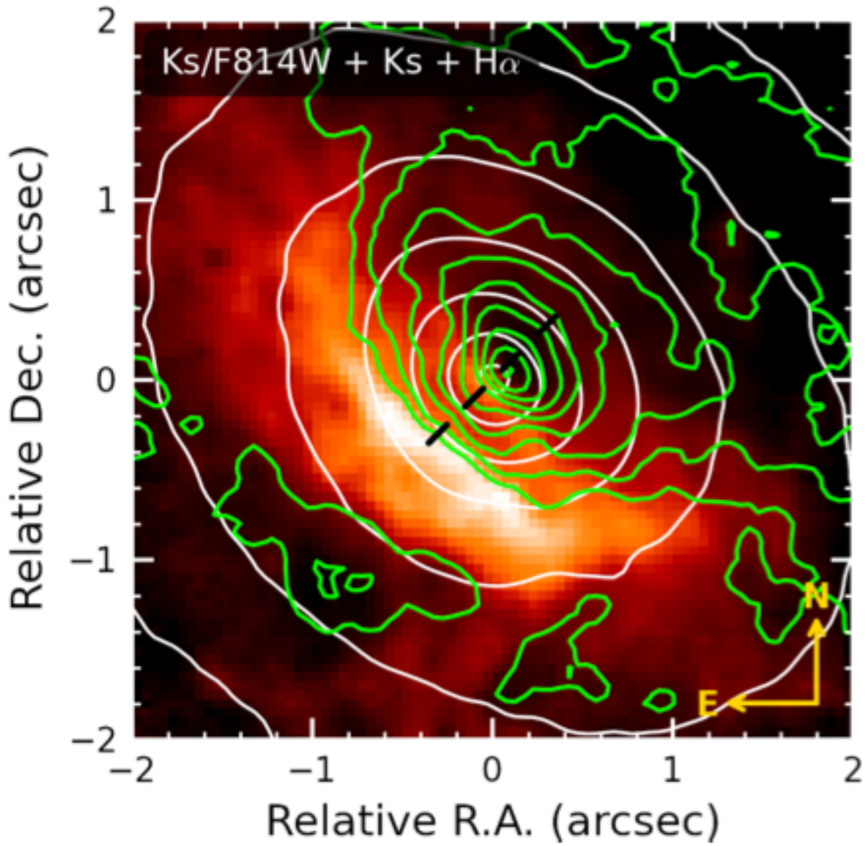
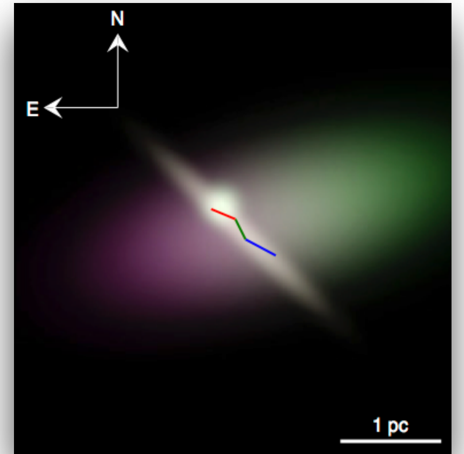
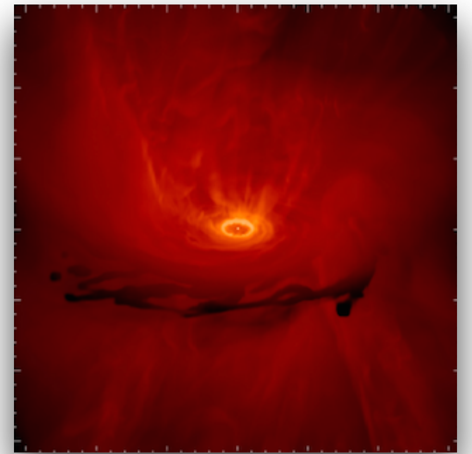
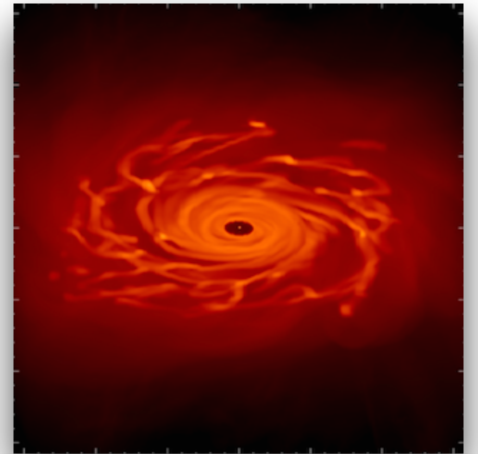
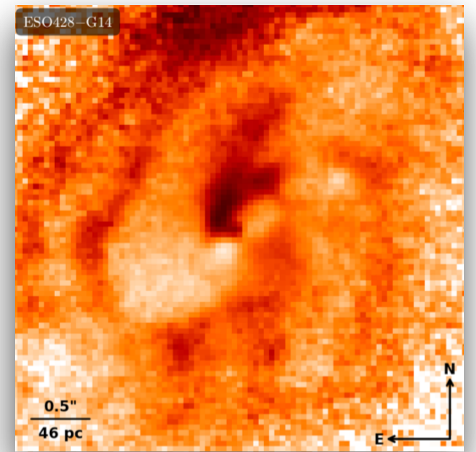


# Summary I

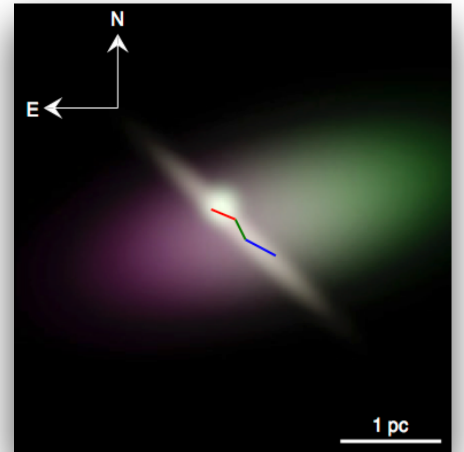
- hot / warm dust emission parsec-sized; need interferometry to resolve them
- Circinus: warm disk + warm torus + dust in cone; silicate gradient visible ==> asymmetric appearance even on pc-scale
- clumpy torus models can simultaneously account for high-spatial resolution SEDs and interferometric data
- need for physical torus models reproducing similar morphology
- radiation pressure important ingredient
- X-ray heating plus radiation pressure on dust able to maintain geometrical thickness by invoking a “fountain” process (Wada 2012)
- dust continuum radiative transfer calculations to connect to available and future observations

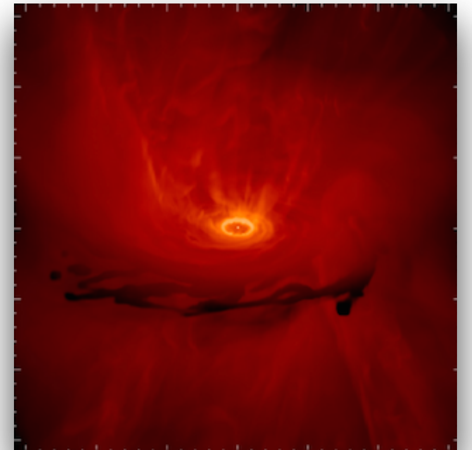
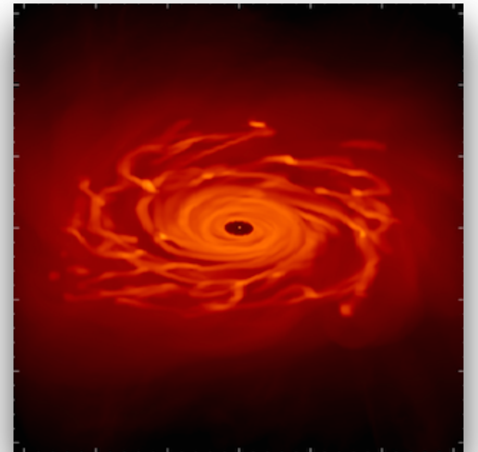
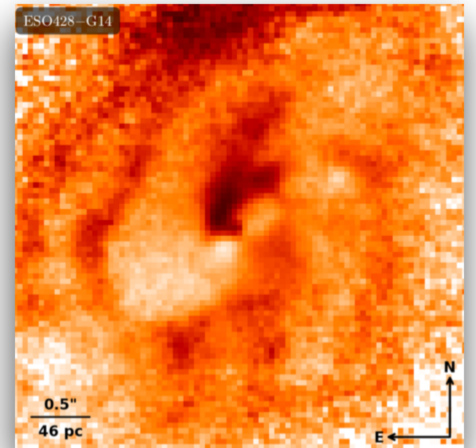


# Summary II

- best agreement with observations is found for models which show a three-component obscuring structure: a dense disk and a puffed-up structure in combination with a tenuous outflow component
- strong morphological differences between MIR and FIR images
- might be testable with ALMA observations (work in progress)
- some nearby Seyferts show significant dust extinction on larger scales (10-100pc)
- might cause the collimation of the ionization cone in some cases, especially for low luminosity AGN



# Thanks for your attention!