Nuclear obscuration properties in AGN

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Credit: NASA / JPL-Caltech
Physical scales of nuclear dust

- Torus: a few to tens of parsecs.
- Polar dust: up to a few hundred parsecs.
- Circumnuclear disk (CND): a few tens/hundreds parsecs.
How does the torus look like: observations

Tristram+2014
- 3 component model of the Circinus dust emission
- Disk and polar dust

Hönig+2013
- Disk and polar dust in MIR and NIR
- NGC 3783

García-Burillo+2016
- Dust and torus in NGC 613
- CO(3-2) and arcsec scale

Combes+2018
- Disk/Torus and Polar dust
- COLD DUST/GAS

HOT/WARM DUST
How does the torus look like: models

- Pier & Krolik 1992
- Schartmann+2008
- Hönig & Kishimoto 2017
- Wada 2012, 2016

Circinus Galaxy
Hubble Space Telescope *WFC2

Gas

Dust
How does the torus look like: observations

Smooth $\rightarrow$ Clumpy
Observationally supported (e.g. X-rays; Markowitz+2014; Marinucci+2016; Liu+2018).

Excess above 20 keV
August 2014

December 2012

Marinucci+2016

Liu+2018

Changing-look AGN in optical more likely due to intrinsic variability (Tuesday talks).
How does the torus look like: observations

Some AGN show a significant fraction of MIR emission along the polar direction.


How does the torus look like: observations

MIR emission of Seyfert galaxies = point source + faint extended emission (inner ~400 pc) in 80% of X-ray selected sample (García-Bernete et al. 2016).
Simplest torus models (e.g. CLUMPY) reproduce NIR+MIR SED of most Seyfert galaxies, but some of them show NIR excess (e.g. NGC 3783).

1) Polar dust (Hönig+2013; Tristram+2014)
2) Graphite-rich dusty clouds @inner torus wall (Mor & Netzer 2012)
3) Host galaxy

García-Bernete et al. in preparation
Simplest torus models (e.g. CLUMPY) reproduce NIR+MIR SED of most Seyfert galaxies, but some of them show NIR excess (e.g. NGC 3783).

1) Polar dust (Hönig+2013; Tristram+2014).
2) Graphite-rich dusty clouds @inner torus wall (Mor & Netzer 2012).
3) Host-galaxy - NIR bump strongly correlated with hard X-rays (García-Bernete et al. 2017).
How does the torus look like: models

Torus $\rightarrow$ Inflowing disk (NIR) + outflowing wind (MIR)
See e.g. Wada 2012, 2016; Hönig & Kishimoto 2017

Hönig & Kishimoto+2017
CAT3D-WIND
Radiative transfer model

Wada+2016
Radiation-driven fountain
Multi-phase hydrodynamic model
How does the torus look like: models

Torus  ➔  Inflowing disk (NIR) + outflowing wind (MIR)
See e.g. Wada 2012, 2016; Hönig & Kishimoto 2017

Hönig & Kishimoto+2017

CAT3D–WIND SED parameter space

NGC3783

CAT3D SED parameter space

NGC3783

Hönig & Kishimoto+2017
How does the torus look like: observations

- **Tristram+2014**
  - 3 component model of the Circinus dust emission
  - Disk
  - Polar dust

- **Hönig+2013**
  - Disk
  - MIR
  - NGC 3783

- **García-Burillo+2016**
  - Cold Dust/Gas
  - Hot/Warm Dust

- **Combes+2018**
  - NGC 613
  - Dust Torus
  - CO(3-2)
  - Arcsec
Dust and molecular torus now detected in several AGN.

ALMA 432 µm view (0.05-0.07" resolution) of central 2"

- Dust and molecular gas torus (major axis 7-10 pc).
- Torus M_{\text{GAS}} \sim 10^5 M_\odot
- CND (300 pc x 200 pc) with recent SF activity.

First direct detection of the torus: NGC1068

García-Burillo+2016 also Gallimore+2016; Imanishi+2016,2018
Dust and molecular torus now detected in several AGN.

ALMA 432 µm view (0.05-0.07'' resolution) of central 2''
• Dust and molecular gas torus (major axis 7-10 pc).
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First direct detection of the torus: NGC1068

García-Burillo+2016 also Gallimore+2016; Imanishi+2016,2018
Large tori detected with ALMA

NGC5506

NGC6300

García-Burillo & GATOS 2019 in prep.
Large tori detected with ALMA

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Radius (pc)</th>
<th>S(CO)dV (Jy km/s)</th>
<th>Mass$^a$ ($10^7 M_\odot$)</th>
<th>inc(°) torus</th>
<th>PA(°) torus</th>
<th>inc(°)$^b$ gal</th>
<th>Beam (pc)</th>
<th>logNH$_2$ (cm$^{-2}$)</th>
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<td>14±3</td>
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Combes, García-Burillo et al. 2018

Seyfert - Log L$_{bol}$ $\sim$ 42.5
Large tori detected with ALMA

Combes, García-Burillo et al. 2018

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$^a$ Mass of CO(3-2) torus
$^b$ Incidence in the galaxy plane
Large vs small torus (hot vs cold)

Near/mid-infrared
hot dust
$r<10$ pc

Far-infrared/sub-mm
cold dust
$10<r<30$

Schartmann+2008
with the obscuring tori having similar properties in all AGN independent of AGN luminosity, redshift, Eddington ratio, etc.
Distinguishing among covering factors

- Geometrical covering factor \( f_2 \) = function of torus angular width and number of clouds along equatorial direction.

\[
N_{LOS}(i) = N_0 e^{-\frac{(90-i)^2}{\sigma_{torus}^2}}
\]

\[
P_{esc} \approx e^{-N_{LOS}}
\]

\[
\beta = 90 - i
\]

\[
f_2 = 1 - \int_0^{\pi/2} P_{esc}(\beta) \cos(\beta) d\beta.
\]

Ramos Almeida 2014

Elitzur 2012
Distinguishing among covering factors

- Geometrical covering factor \((f_2)\) = function of torus angular width and number of clouds along equatorial direction.

- Dust reprocessing efficiency-derived covering factor = \(C_T \propto \frac{L_{IR}}{L_{bol}}\)
  - Torus anisotropy needs to be accounted for (Stalevski et al. 2016).
Distinguishing among covering factors

- Geometrical covering factor \( (f_2) \) = function of torus angular width and number of clouds along equatorial direction.

- Dust reprocessing efficiency-derived covering factor = \( C_T \propto L_{IR}/L_{bol} \)

- Fraction of obscured AGN \( (f_{obs}) \) as proxy for the covering factor of gas+dust.

\[ f_{obs} \text{ always smaller for large column densities } (N_H > 10^{23} \text{ cm}^{-2}) \text{ - dense gas surrounding the nuclei mostly concentrated on a thin disk (Wada 2015).} \]

Ramos Almeida & Ricci 2017

70% of local AGN obscured (Ricci+2015)

X-ray obscuration produced by multiple absorbers @different spatial scales.
Different covering factor for Type 1 and Type 2 AGN

Sy2/absorbed AGN tori have larger covering factors than Sy1/unabsorbed AGN - X-ray selected samples of AGN.

García-Bernete+2019, in preparation
The Obscured AGN fraction

Obscured fraction ($f_{\text{obs}}$) usually derived from X-ray column densities ($N_{\text{H},i}$) and optical class (type 1 broad vs. type 2 narrow lines).

Dependence with AGN luminosity? with redshift?

Samples of X-ray selected AGN: different estimations of covering factor, different sample sizes, different spatial resolutions.

Covering factor practically constant for Seyfert-like luminosities.

587 X-ray selected AGN
SED Spectral decomposition
Low-angular resolution data

24 X-ray selected AGN
Near-IR and mid-IR nuclear SEDs
High-angular resolution data
Covering Factors vs Luminosity

Samples of X-ray selected AGN: different estimations of covering factor, different sample sizes, different spatial resolutions.

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Real vs simulated data - larger scatter in $L_{\text{IR}} - L_{\text{X}}$ explains luminosity dependence of covering factor.
Missing AGN in X-ray (<10keV) surveys

Less obscured AGN at high luminosities?

- A non-negligible fraction of X-ray undetected luminous, heavily obscured (high covering factors) type-2 AGN (at energies < 10 keV).

- Weak luminosity dependence (solid line).
Missing AGN in X-ray (<10keV) surveys

Less obscured AGN at high luminosities?

- Luminosity dependence of the obscuring fraction vanishes when using MIR-(e.g. Assef+2015) and radio-selected samples (e.g. Willott+2000).

- X-ray observations of e.g. infrared-selected samples needed to uncover missing sources.

![AGN obscuration vs luminosity](image.png)

Lawrence & Elvis 2010
Complete samples of X-ray selected AGN: different estimations of covering factor, different sample sizes, different spatial resolutions.

Covering factor practically constant for Seyfert-like luminosities.

587 X-ray selected AGN
SED Spectral decomposition
Low-angular resolution data

Real vs simulated data - larger scatter in \( L_{IR} - L_X \) explains luminosity dependence of covering factor.
Torus disappearance at low luminosities?

Combes+2018

NGC1326 - Log $L_{bol}$ ~ 41.2

NGC1433 - Log $L_{bol}$ ~ 40.5

Izumi+2017

NGC1097 - Log $L_{bol}$ ~ 41.9

Band 7 continuum

CO(3-2)
Torus disappearance at low luminosities?

Consistent with MIR studies of low-luminosity AGN (González-Martín+2015, 2017) - no torus below Log \( L_{\text{bol}} \sim 41 \) — lower \( L_{\text{bol}} \) than theoretically predicted (Elitzur 2012).
Eddington ratio dependence of the covering factor

Ricci+2017, Nature
Redshift dependence of the covering factor

The intrinsic fraction of obscured AGNs increases with redshift.
Redshift dependence of the covering factor

The intrinsic fraction of obscured AGNs does not increase with redshift.
Host galaxy dependence of the covering factor

- Different sample selection implies different host galaxies — different SMBH stages?

  - Radio-loud AGN - massive ellipticals.
  - X-ray AGN - higher fraction of spiral galaxies as compared to optically-selected AGN (Koss+2011).
  - IR AGN - less massive galaxies, more mergers = highly obscured AGN (Donley+2018).

Hickox+2009

Alexander & Hickox+2012
Host galaxy dependence of the covering factor


Type-1/type-2 different phases of AGN evolutionary sequence.

Villarroel & Korn 2014

Alexander & Hickox+2012

Photometric sample

Cristina Ramos Almeida

Puerto Varas, Torus2018
Host galaxy dependence of the covering factor

Claudio's talk
Host galaxy dependence of the covering factor

Claudio’s talk

Cristina Ramos Almeida

Puerto Varas, Torus2018
What’s next?

• Statistics needed to infer general torus properties (X-ray and IR-selected samples with covering factors derived in different manners).

• Detailed studies of nearby AGN required to improve our understanding of torus physics.

• ALMA observations of AGN (dust continuum, molecular & neutral gas) to understand the multi-phase nature of the torus.

• Matched control samples/twin galaxies to study the properties of dust and gas - need to understand the duty cycles.
The future

ALMA

VLTI

JWST

eROSITA

E-ELT

Athena
The ALMA view of nearby AGN: lessons learnt and future prospects

Aims and scope

It is now well established that growing supermassive black holes (SMBHs) play a fundamental role in the evolution of their host galaxies. Feedback from active SMBHs can affect the galaxies interstellar medium in various forms: consuming, heating, sweeping out and/or disrupting the gas available to form new stars. Unfortunately, directly studying the influence of active galactic nuclei (AGN) feedback on galaxy evolution is extremely challenging because of the short timescales of nuclear activity. Therefore, to directly probe the AGN-host galaxy connection we need to look at the structure and kinematics of the parsec-scale gas and dust surrounding the accreting SMBHs.

Our knowledge of the nuclear environment of AGN has increased tremendously since ALMA started scientific operations seven years ago. The combination of angular resolution and sensitivity provided by ALMA permits to peer into the central region of nearby AGN and, for the first time, obtain images of the parsec-scale dusty torus. Thanks to ALMA we also have advanced in our understanding of the gas flow cycle, in particular how the molecular gas reservoirs of the galaxies (100-200 parsecs) are connected with the torus and AGN central