The dusty environment of AGN under the microscope —

Lessons learned from the first 10 years of mid-IR interferometry

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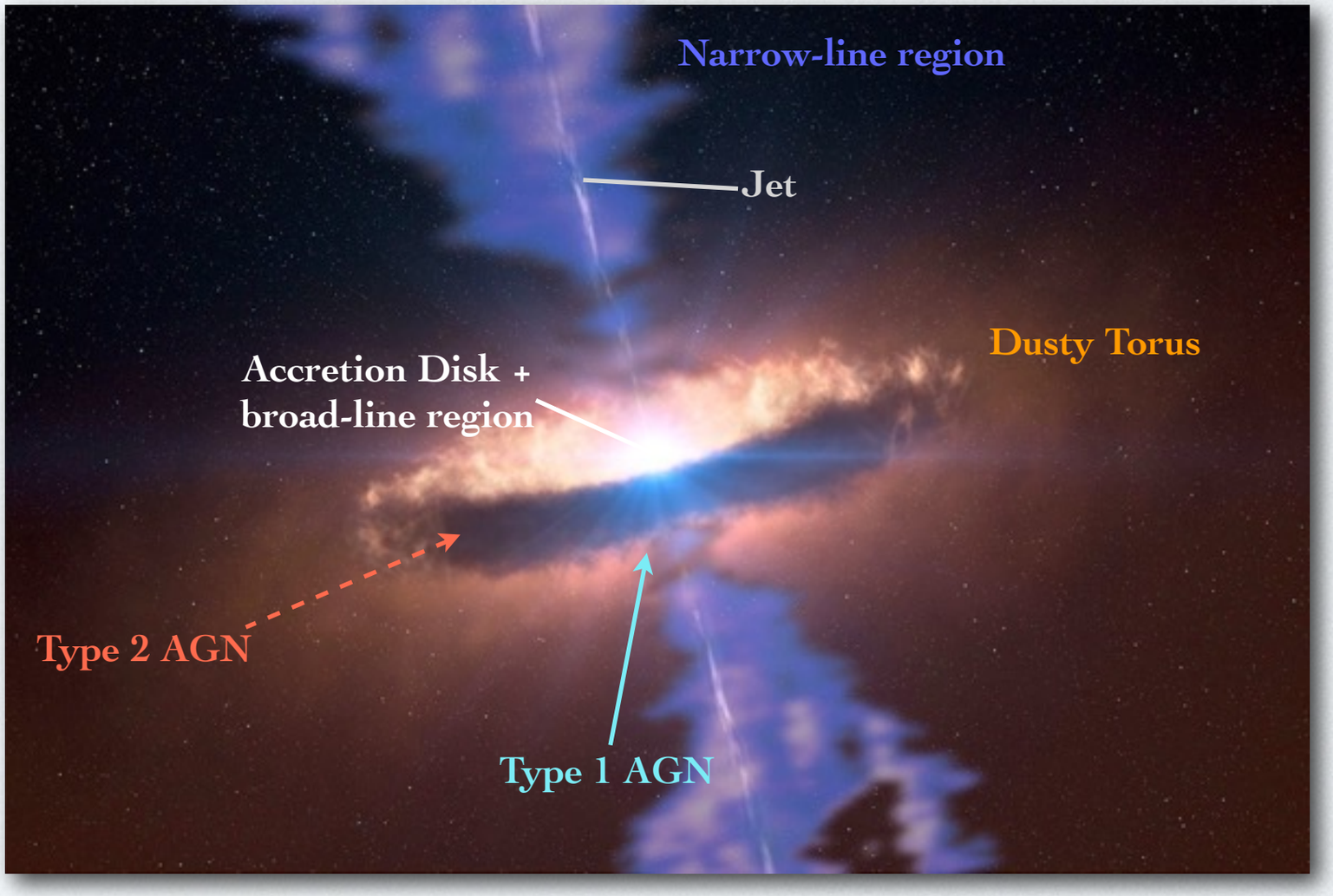
Overview

- **Prelude: What we thought we know**
  - state of the art before IR interferometry came in
- **Interferometry of AGN**
  - our tools and some numbers
- **The beginning: Dust tori are clumpy!**
  - early results
- **What kind of tori are there?**
  - have a more detailed look
- **The era of samples (finally…)**
  - a comprehensive view
- **Surprises…**

Prelude:
What we thought we know…

AGN structure



- in the IR we see the **dusty torus**
- cornerstone of **AGN unification**
- Typical scaling: **few pc ~ 10 milliarcseconds**

Obs. & phys. constraints

- basic framework:

  dusty, obscuring (τ_v>1), geometrically-thick

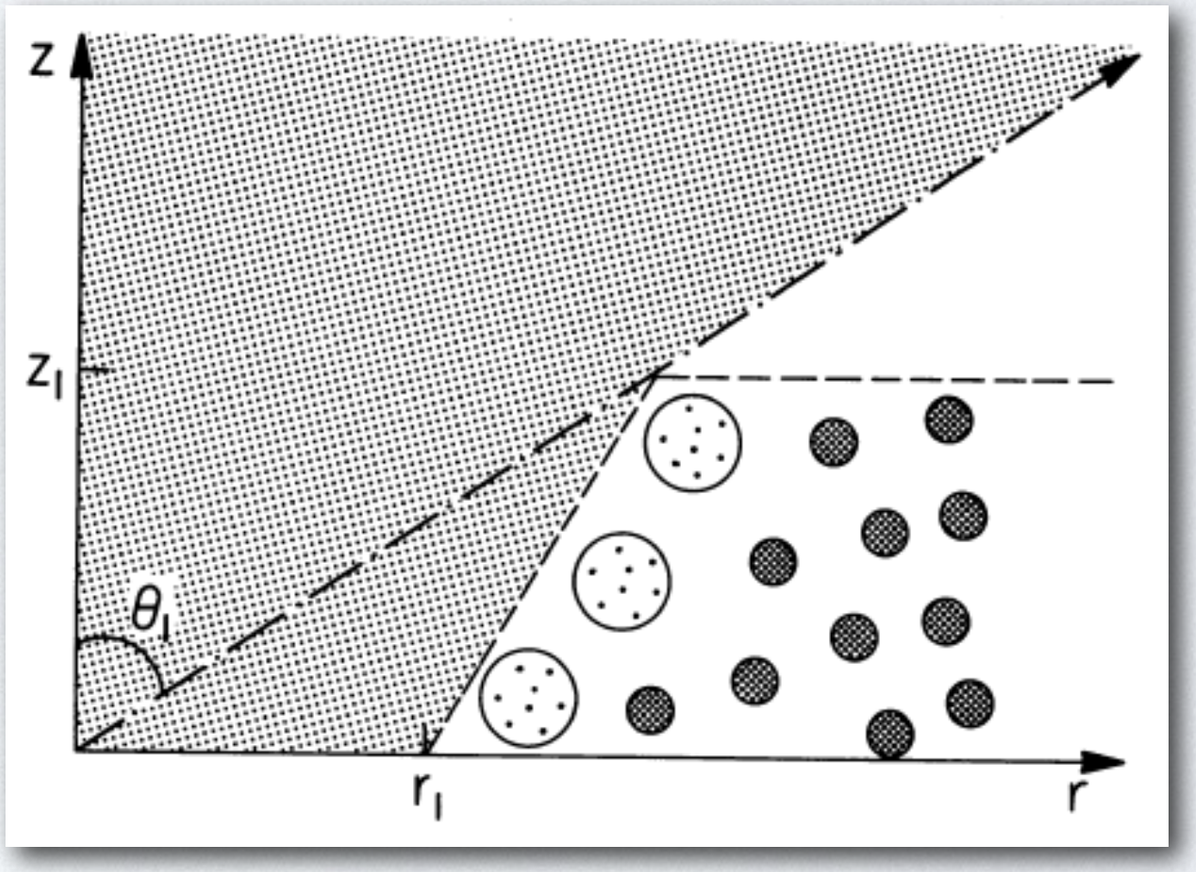
- Further constraints:

  - **(sub-)parsec-scaled** (dust radiative equilibrium)
  - **inhomogeneous** ("clumpy"):

    → observational: e.g. velocity dispersion, CO emissivity, X-ray column variability, ...

    → theoretical: e.g. SG instability, shear, radiation pressure, ...

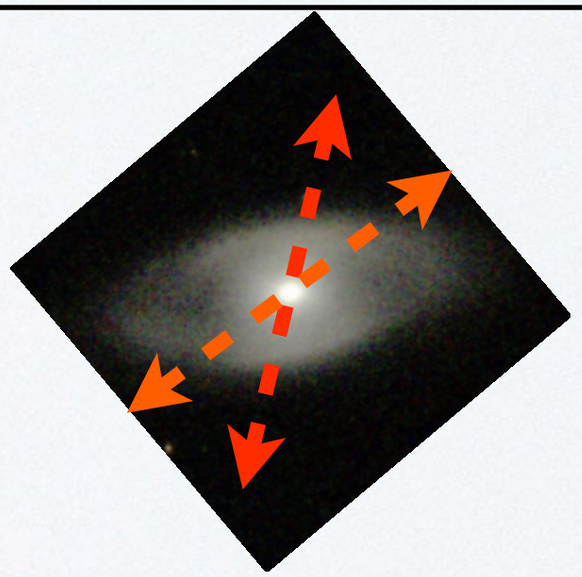
Krolik & Begelman 1986, 1988; Barvainis 1987; Pier & Krolik 1992a; Tacconi et al. 1994; Risaliti et al. 2002; ...

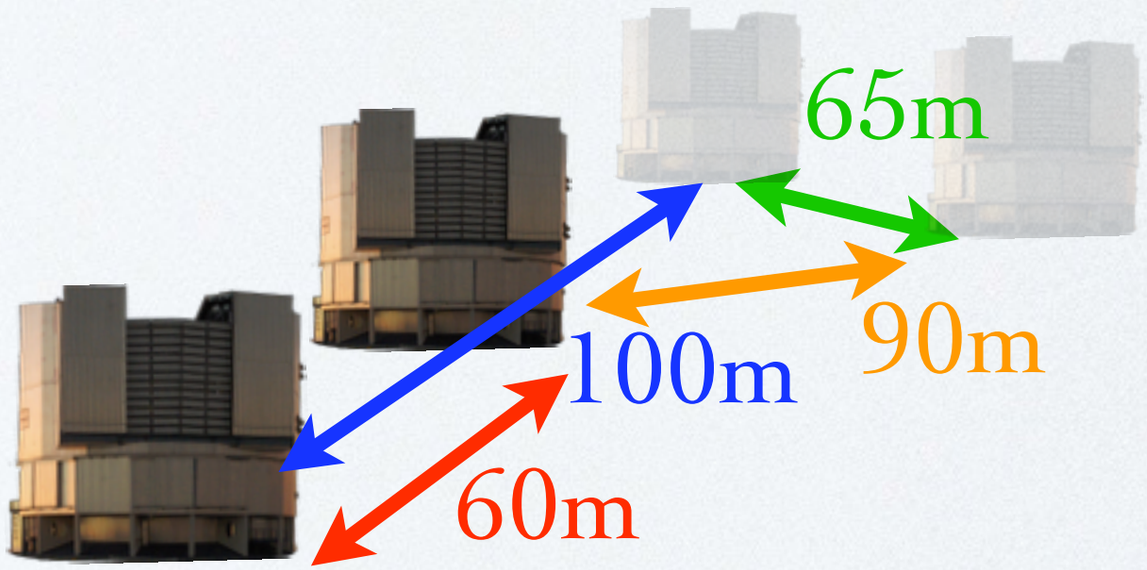


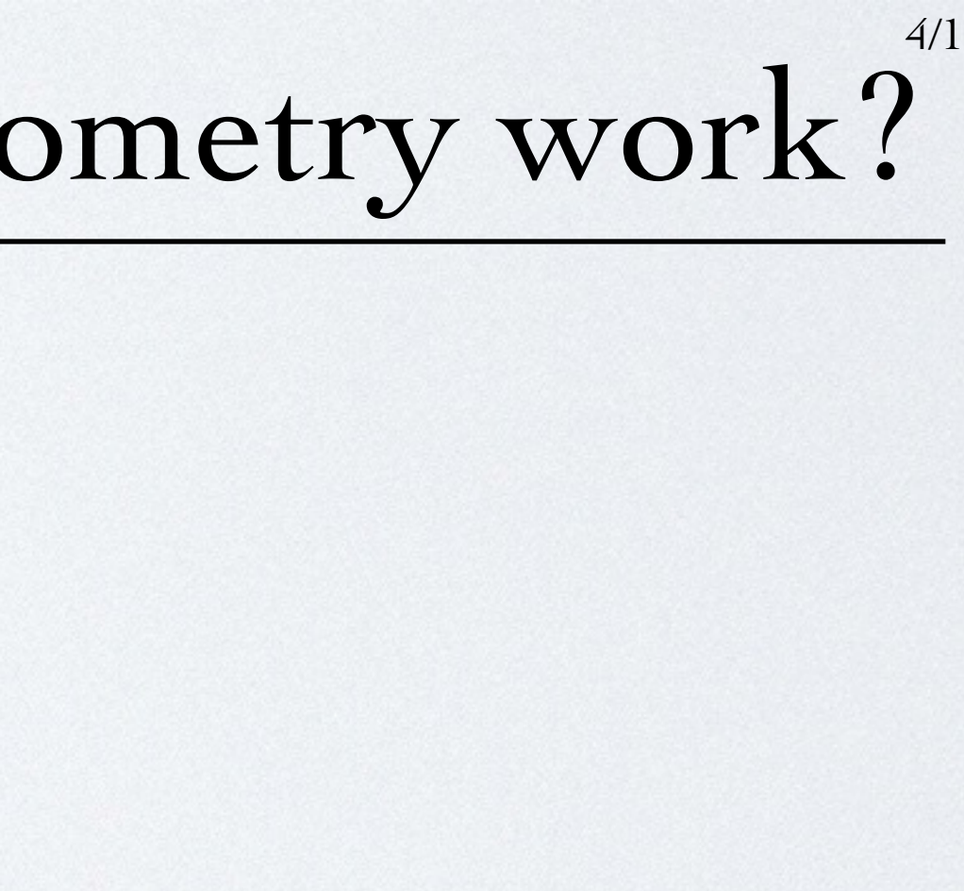
Krolik & Begelman 1986

Interferometry of AGN

How does IR interferometry work?







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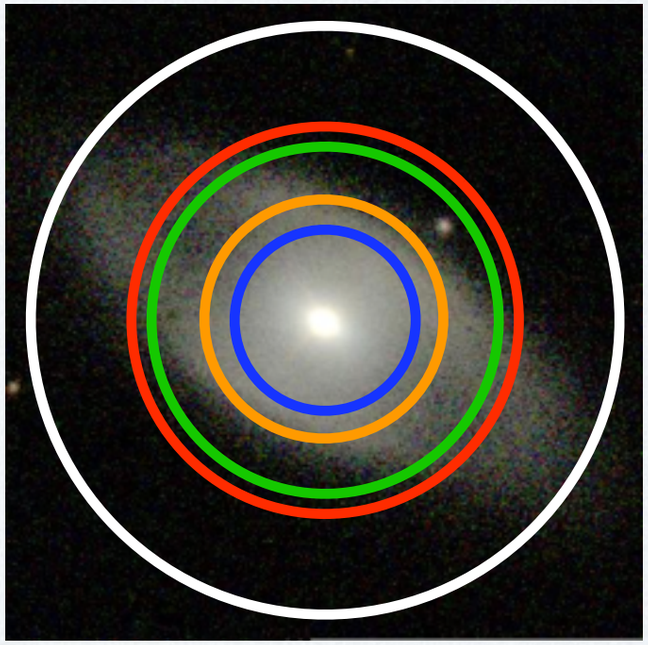
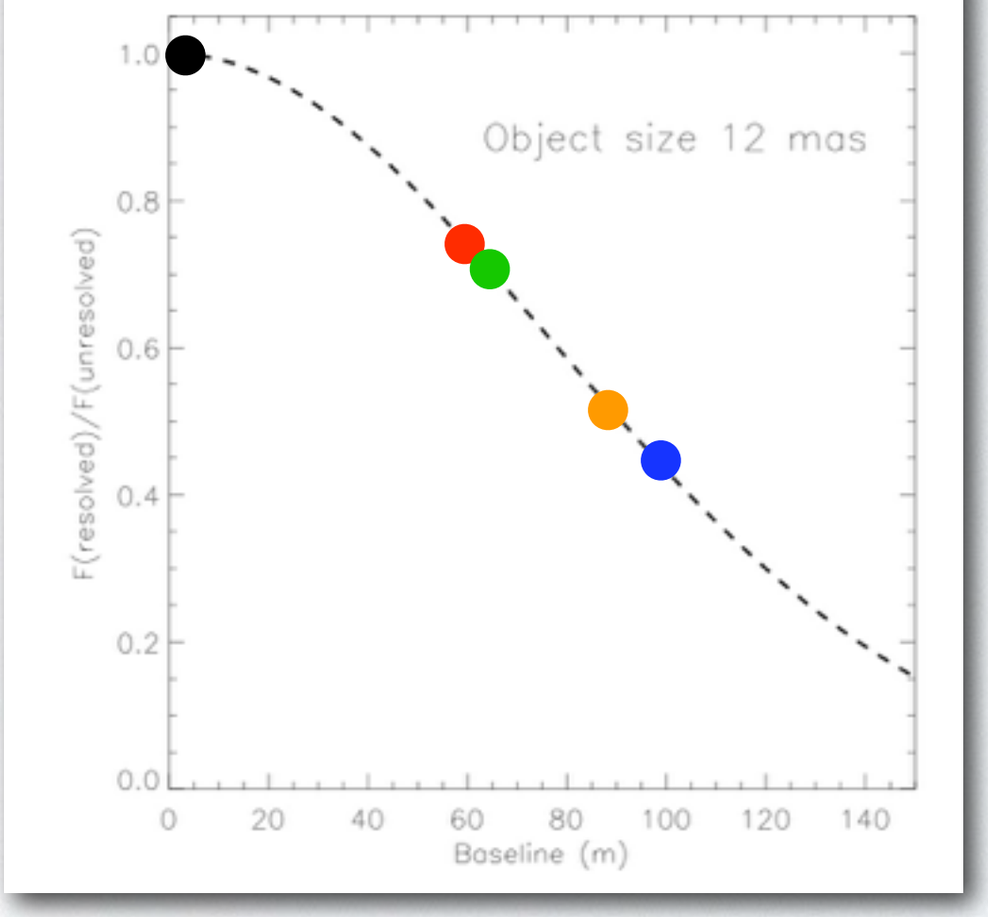
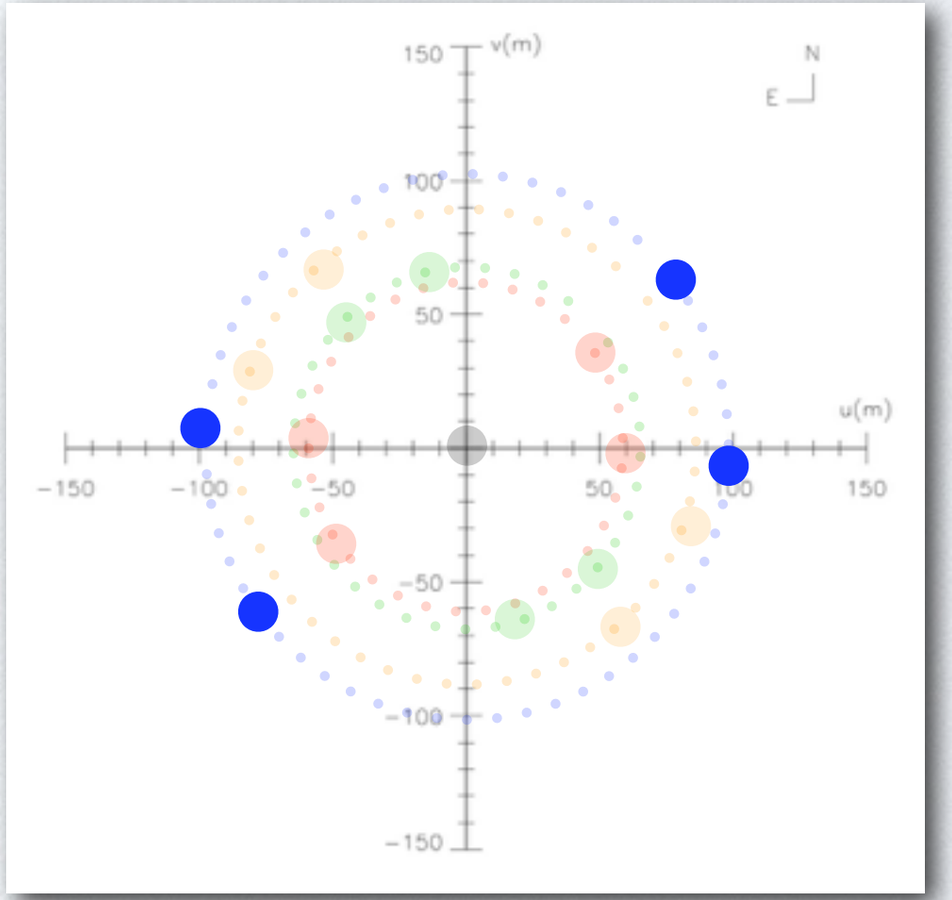




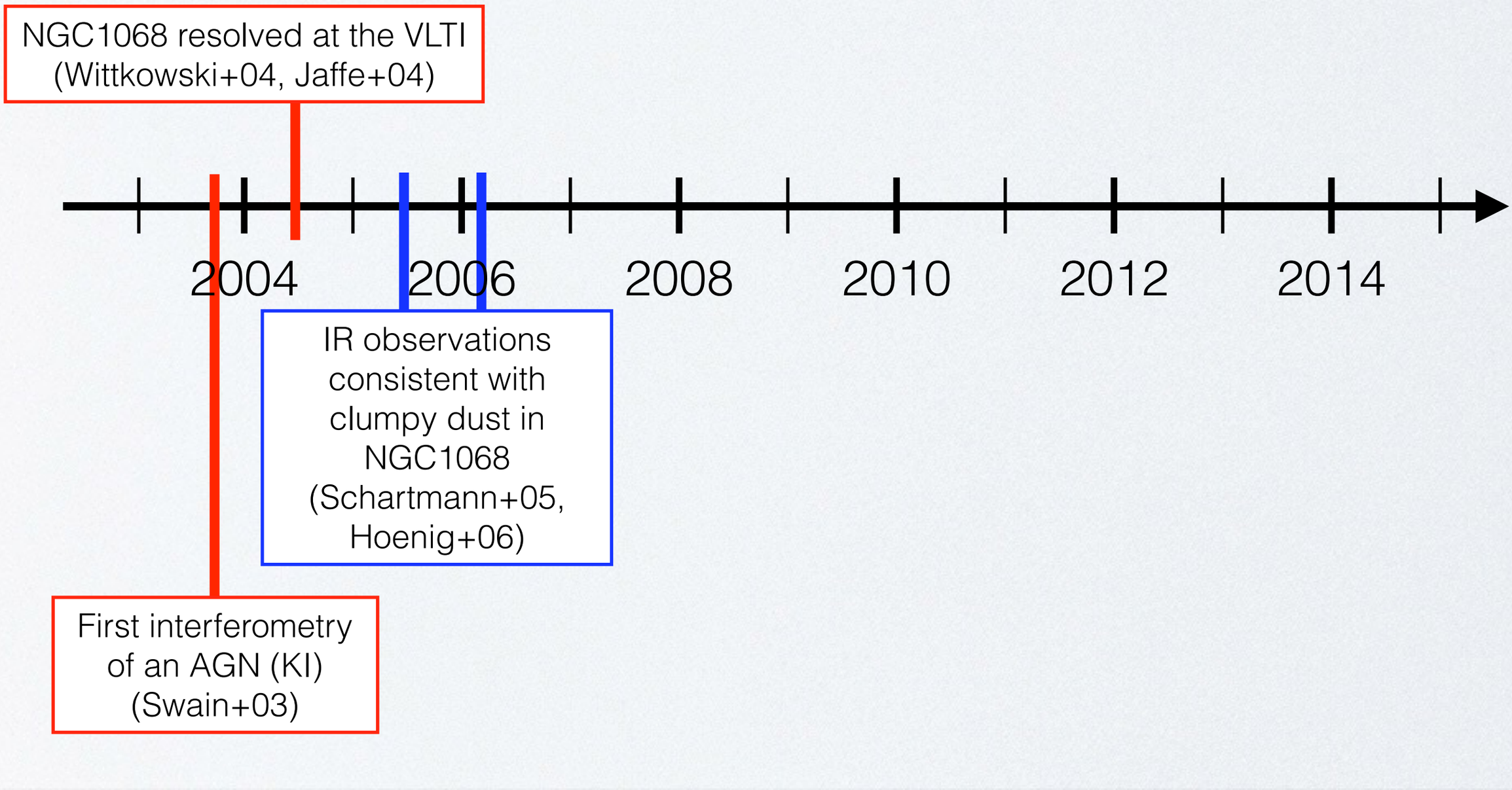


IR interferometry of AGN

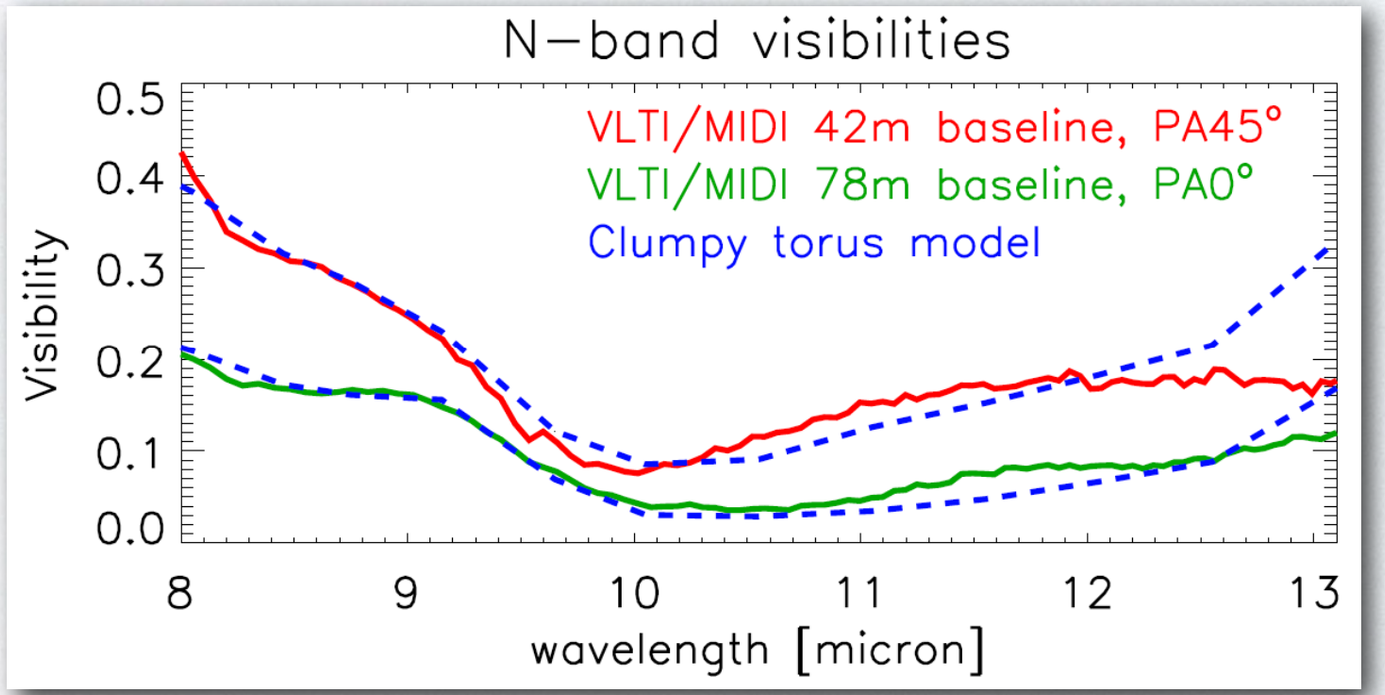
- We are always **one step behind** stellar interferometry...
  ... but we are **catching up**!
- **40 objects** successfully observed (plus 5+ with limits)
  → construction of useful samples
- 9 objects with **closure phases** in near-IR (→ images next)
- 3+ objects with additional **time-domain resolution**

The beginning:
Dust tori are clumpy!

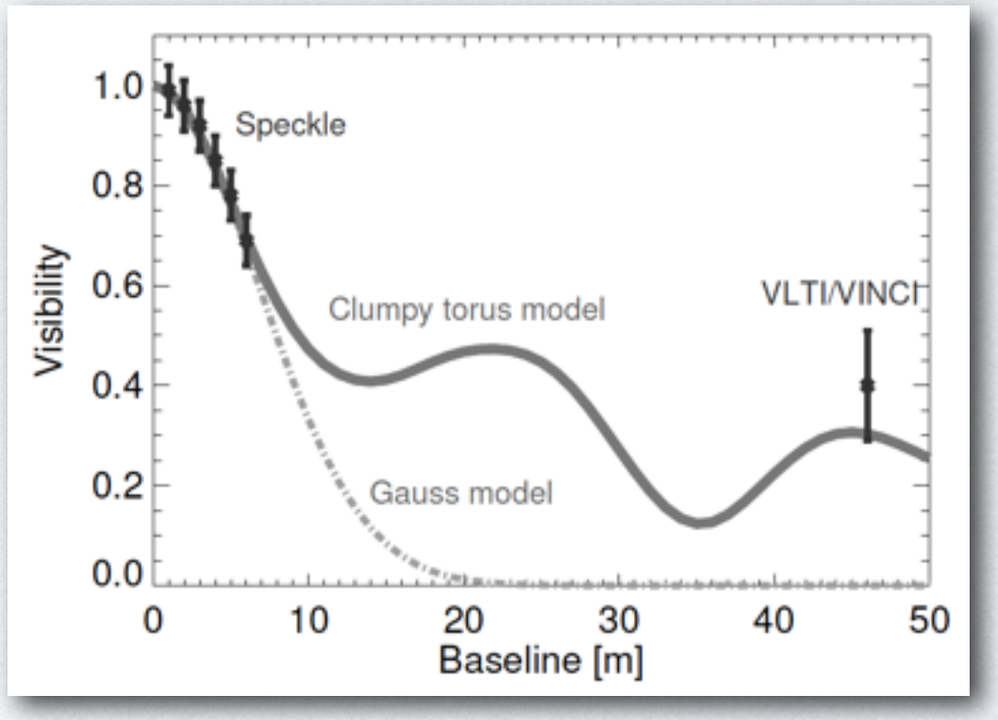
AGN interferometry time line



The torus is clumpy (indeed)



Jaffe et al. 2004; Hoenig et al. 2007

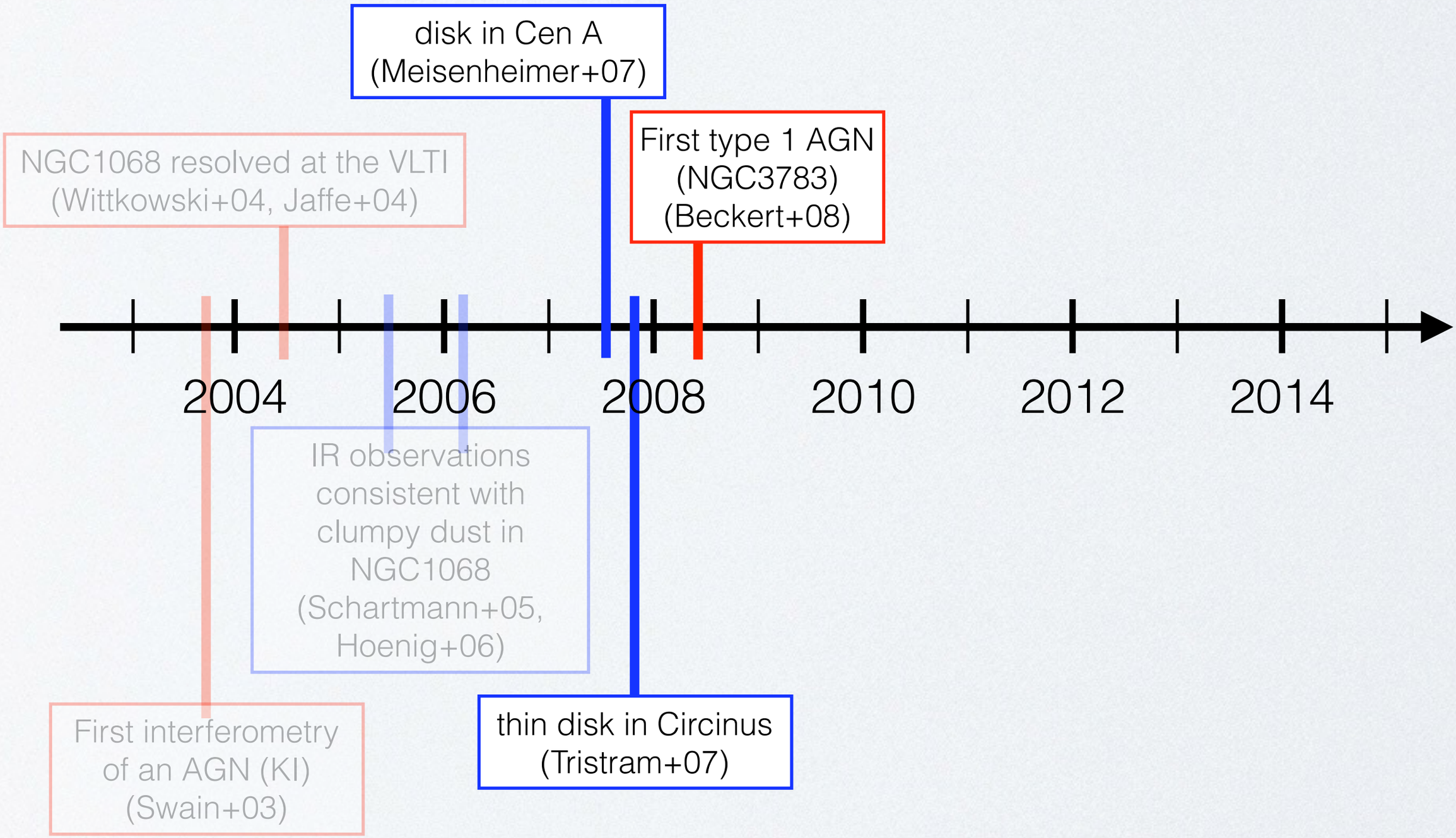


Wittkowski et al. 2004; Hoenig et al. 2007

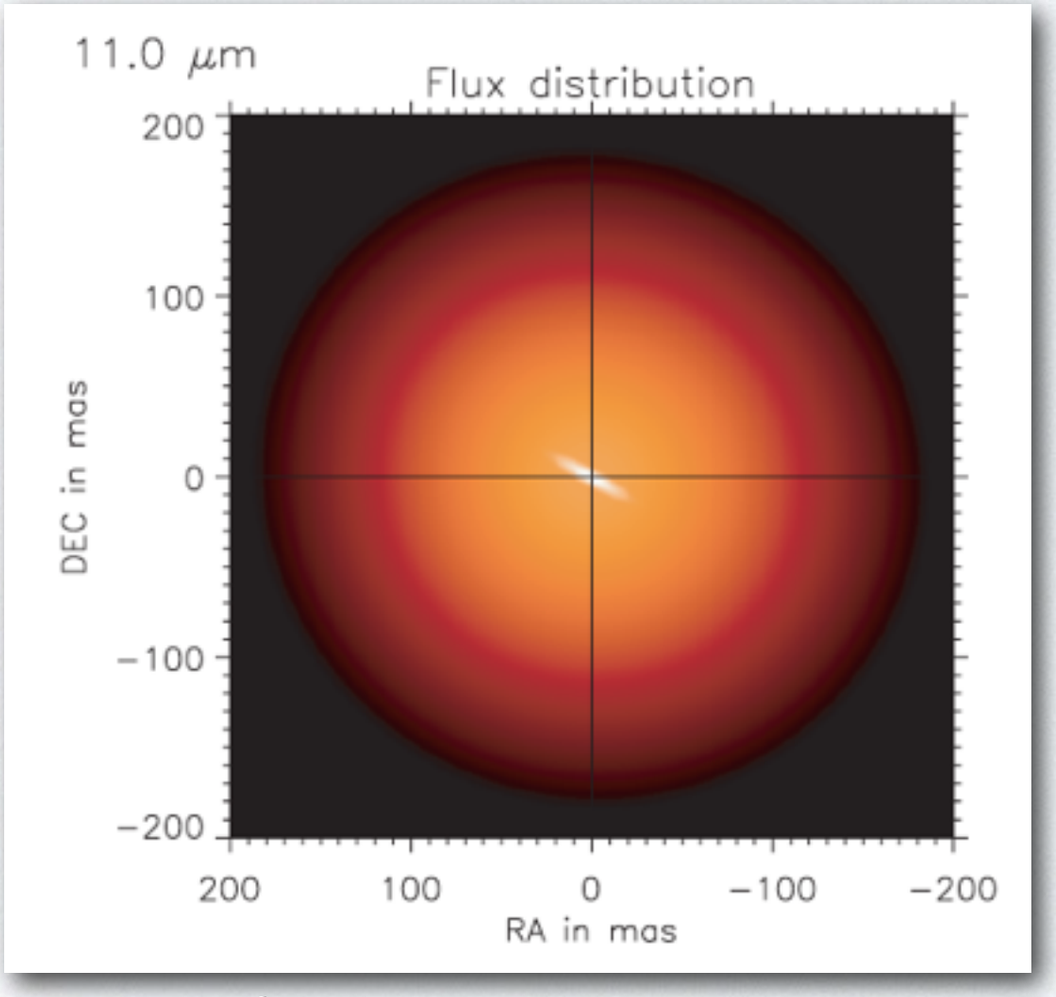
- NGC 1068 in K- and N-bands: **strong silicate absorption**
- Consistent with **clumpy torus models**, not consistent with smooth dust models (see also Schartmann+05, Hoenig+06; Schartmann+08)
- **compact region + extended region** along jet
- NGC 4151: <0.1pc → **torus or accretion disk?**

What kind of tori are there?

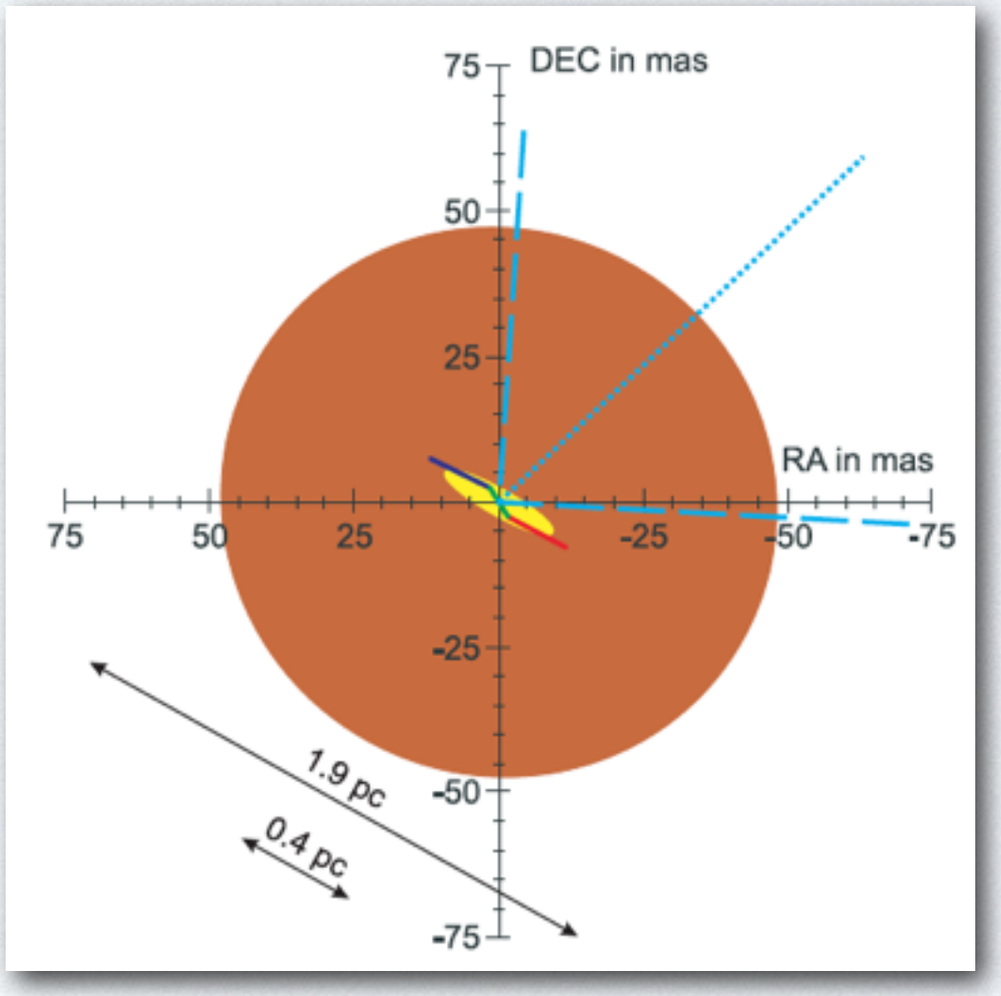
AGN interferometry time line



Circinus



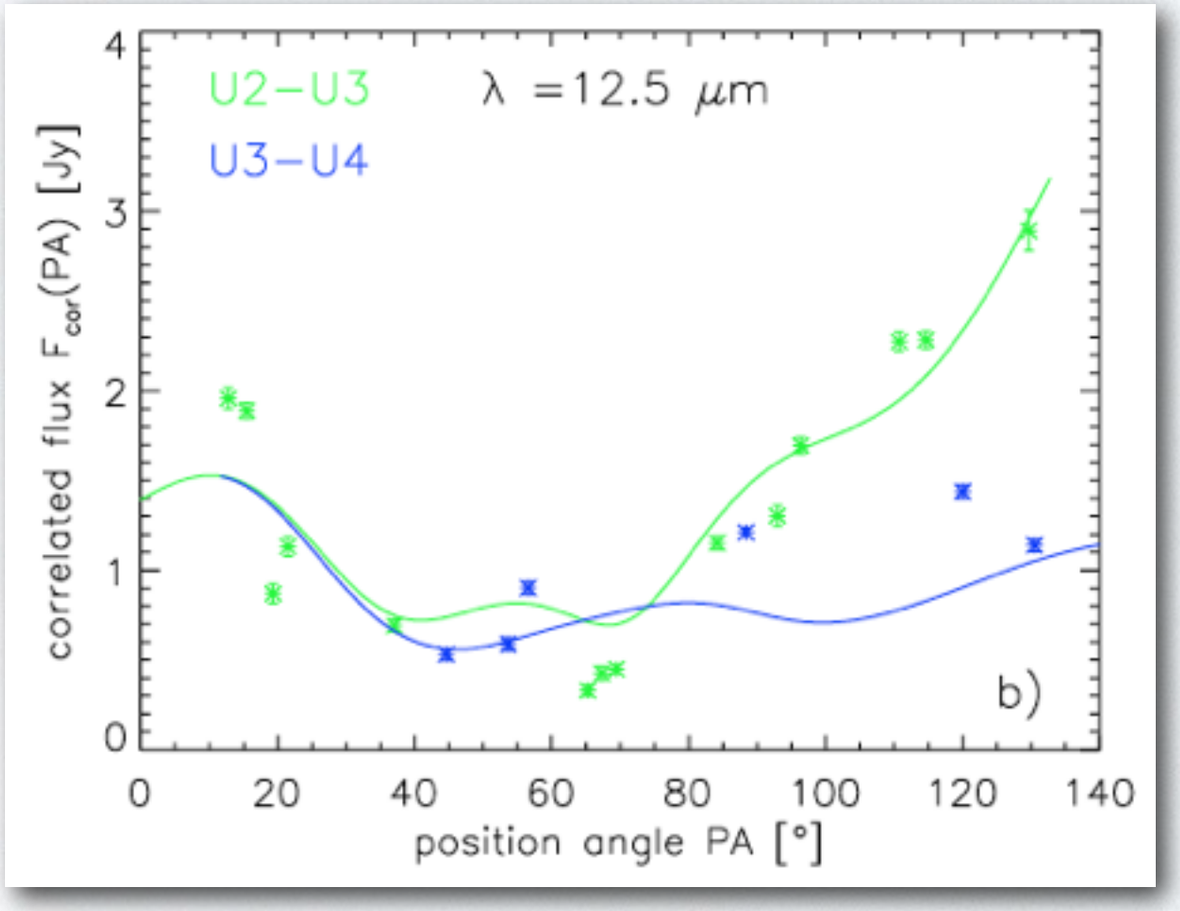
Tristram et al. 2007



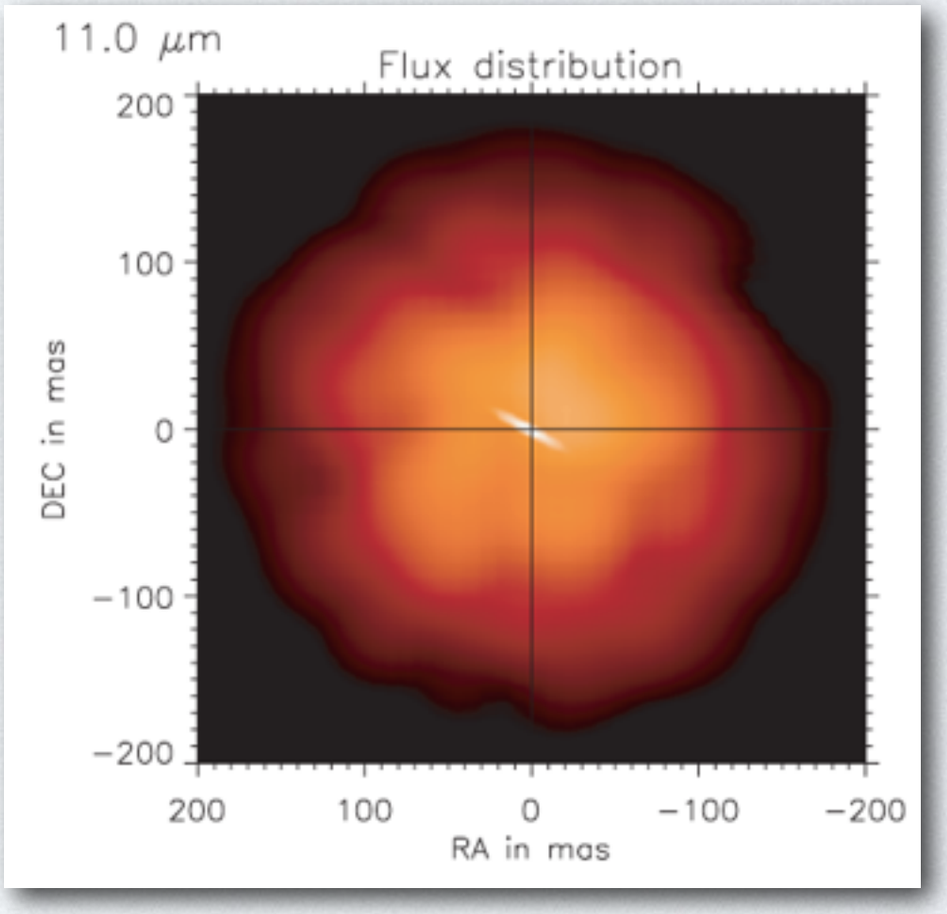
Tristram et al. 2007

- geometrically thin **disk + "halo"**
- disk aligned with **maser disk** and perpendicular to NLR

Circinus



Tristram et al. 2007

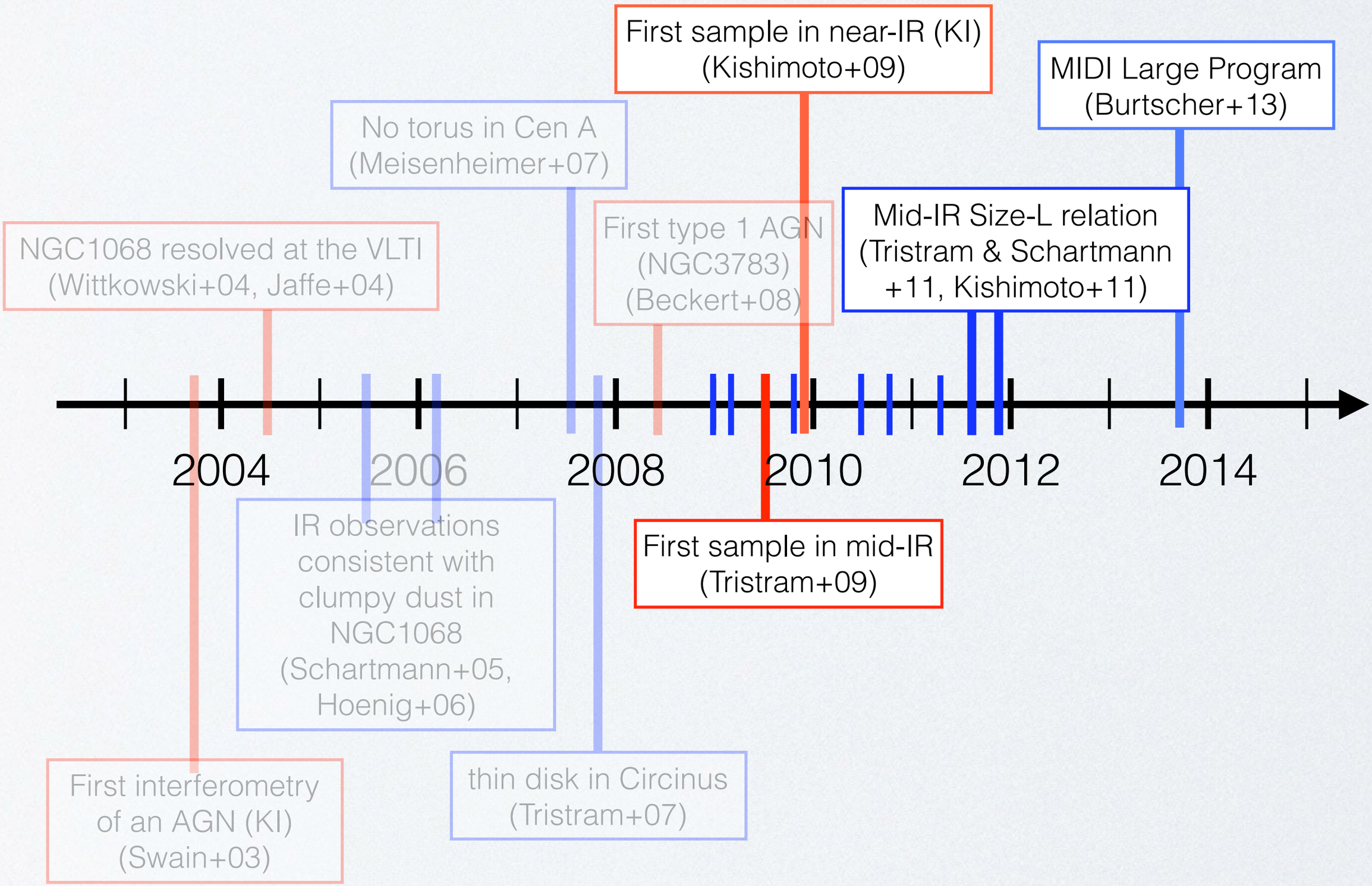


Tristram et al. 2007

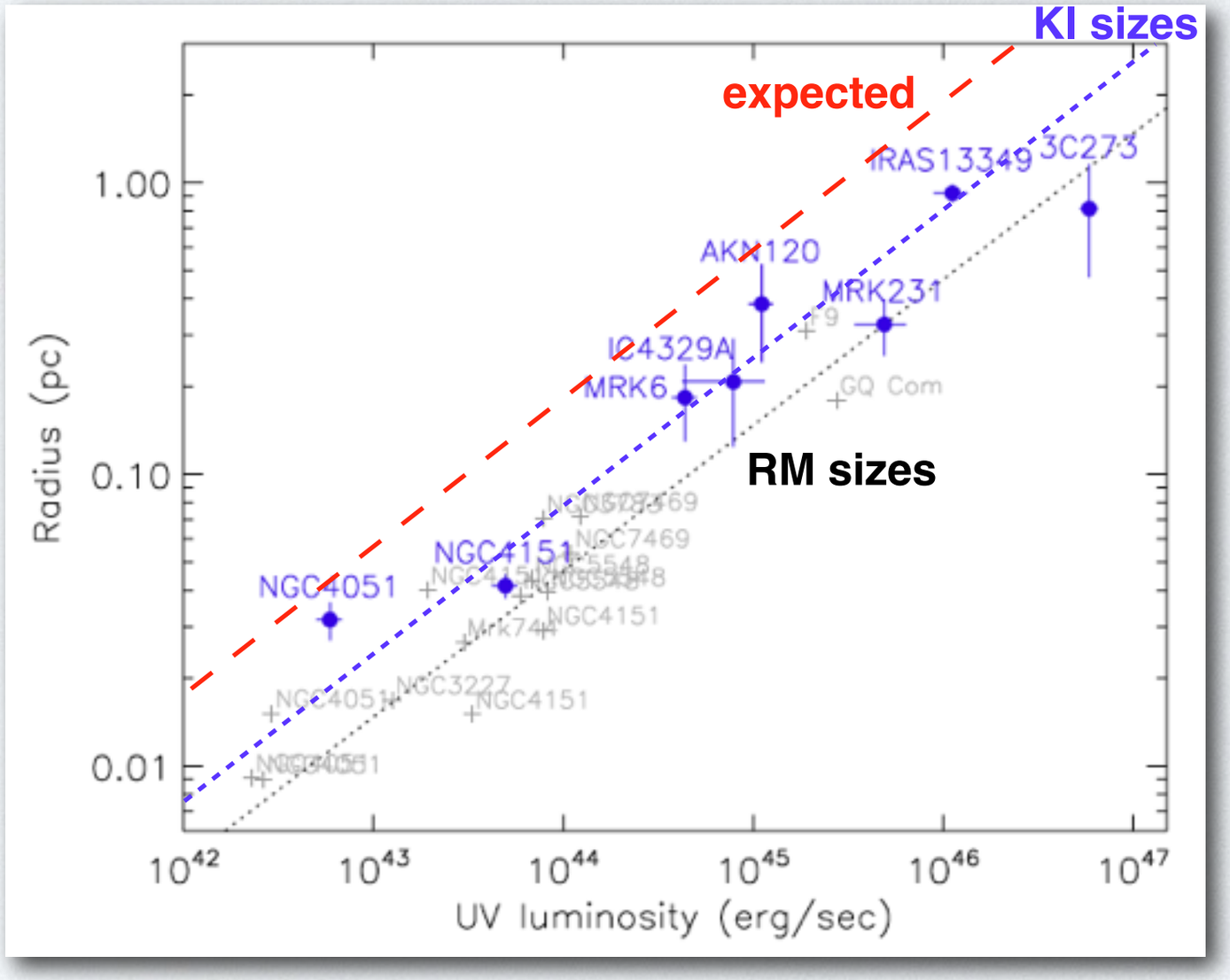
- geometrically thin **disk + "halo"**
- disk aligned with **maser disk** and perpendicular to NLR
- need for **clumpiness**
- **"halo" dominates** emission

The era of samples (finally…)

AGN interferometry time line



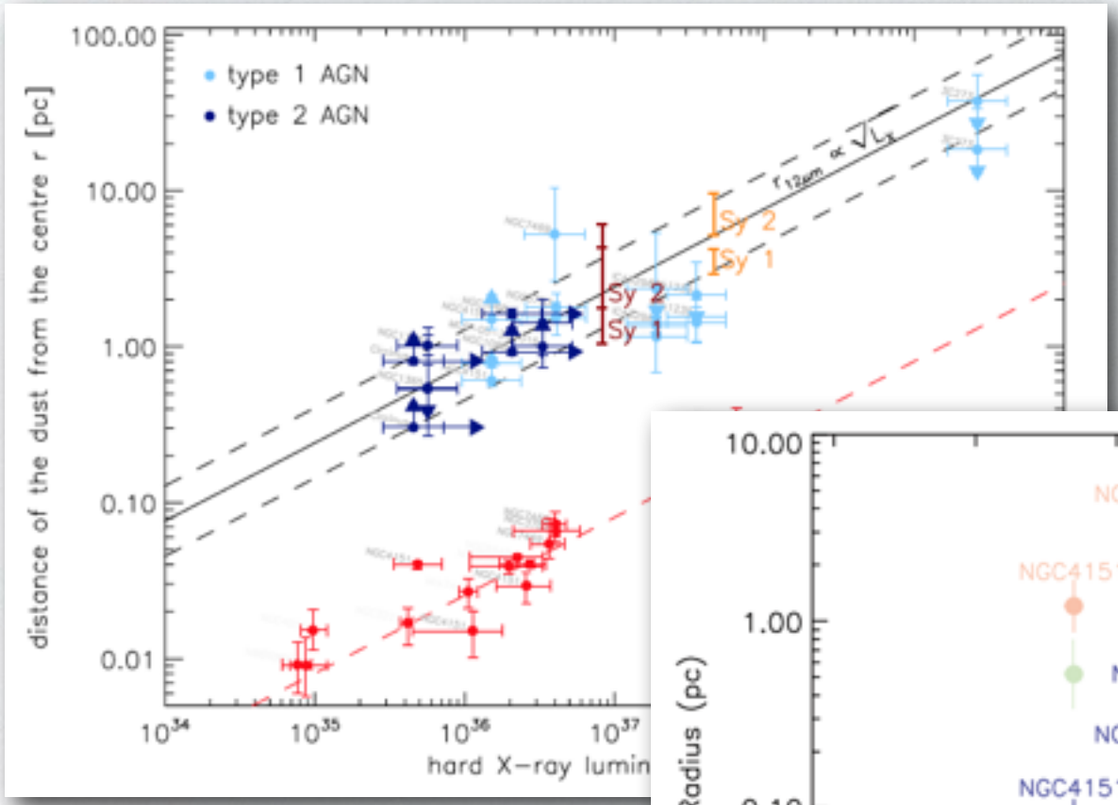
The sublimation radius is small!



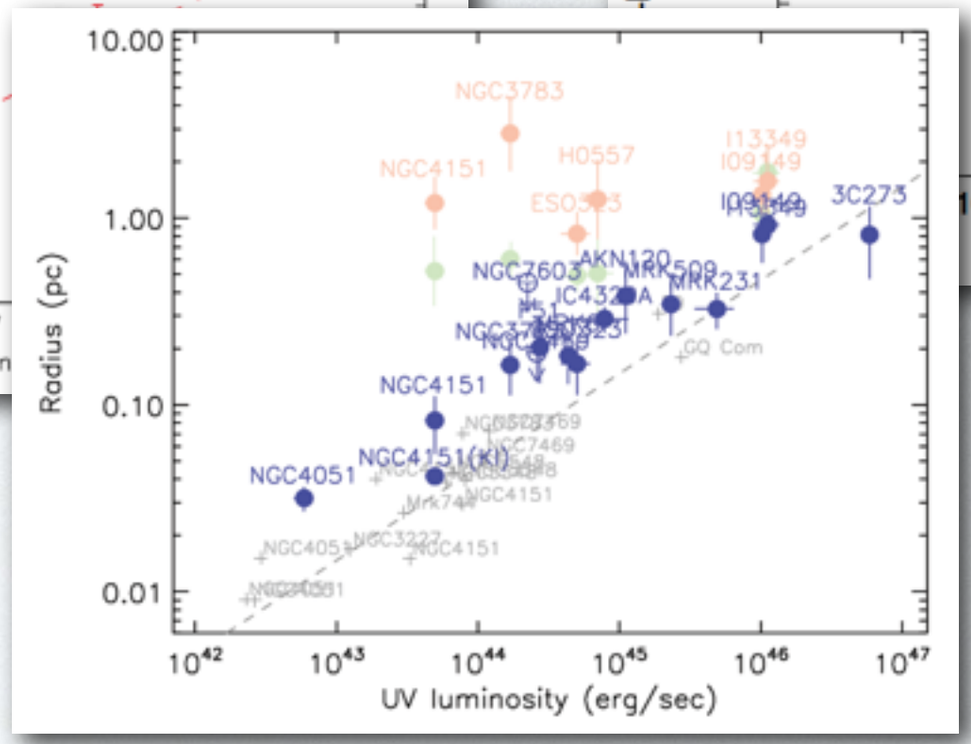
Kishimoto et al. 2011a

- inner radius of torus **scales with $L^{1/2}$** (as expected from dust)
- brightness and colour **temperatures ~ 1500 K** (as expected from dust)
- absolute sizes are **smaller than expected by factor ~3 (large grains)**
- surf. emissivity ~0.05 - 1→ **surf. cov. factor ~0.1, near-BB emission**

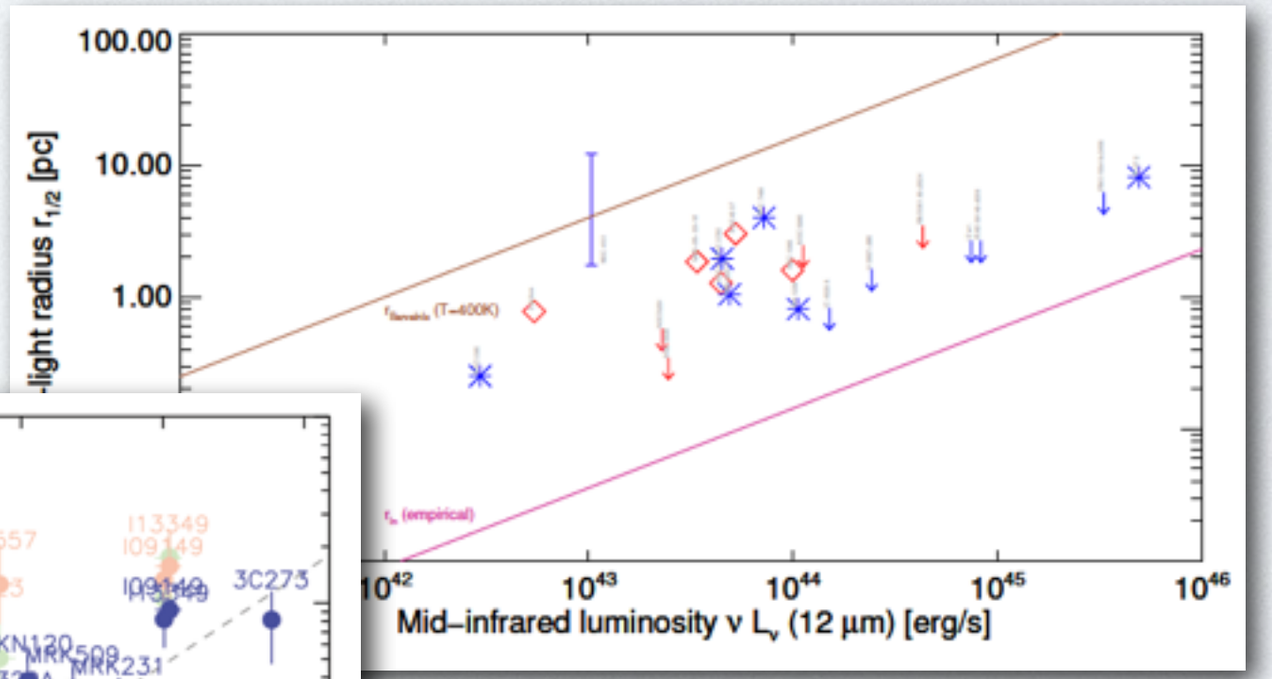
Size-L relation in the mid-IR?



Tristram & Schartmann 2010



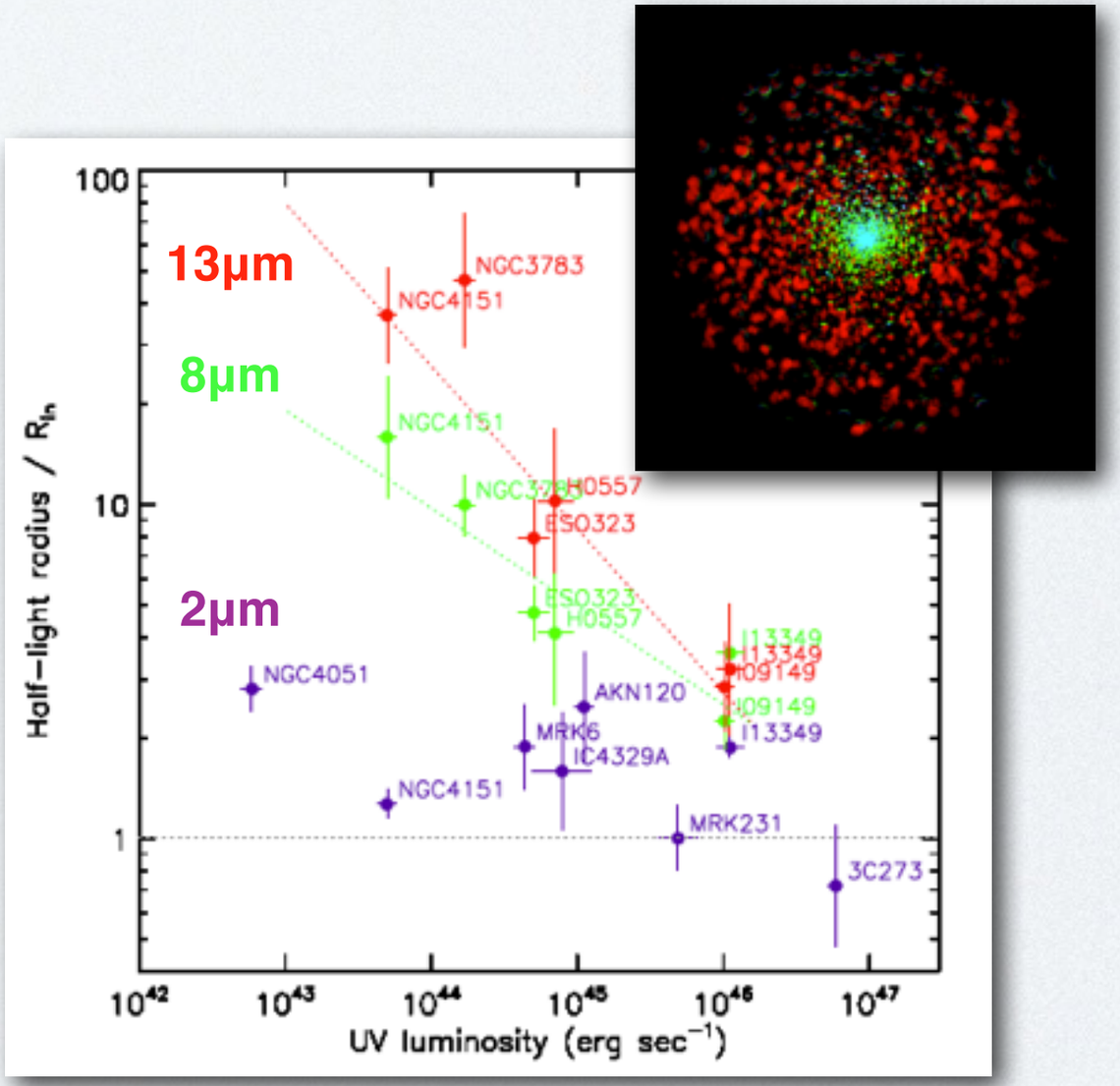
Kishimoto et al. 2011b



Burtscher et al. 2013

- the mid-IR is **quite diverse** in terms of size
- results are **model-dependent**

Some are compact, some extended

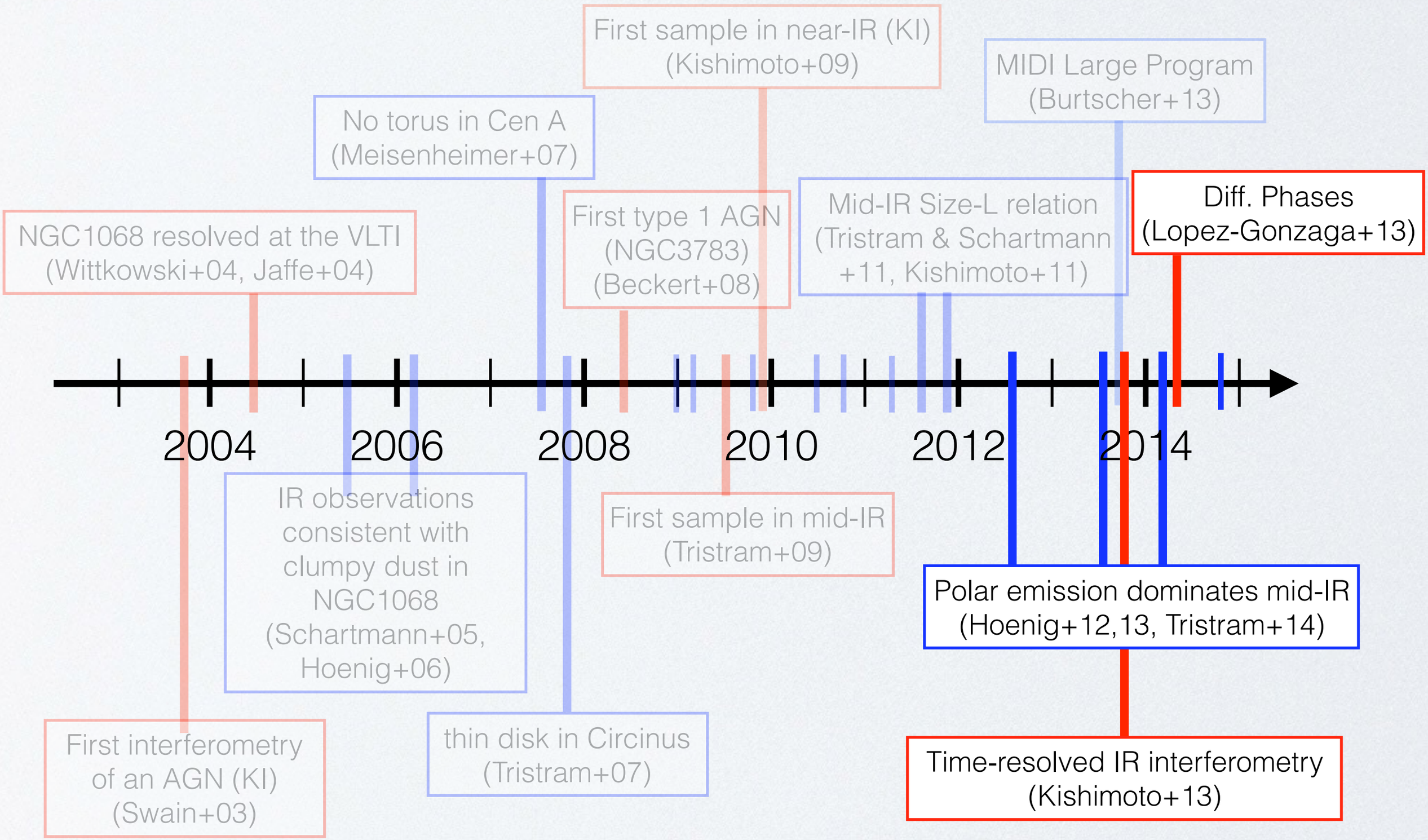


Kishimoto et al. 2011b

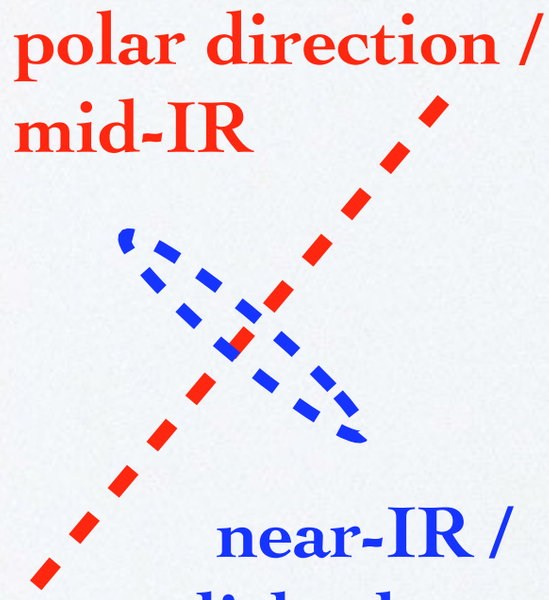
- there are objects **"lacking" cooler dust**
- other objects are **dominated by cooler emission** → **L-dependence?**

Surprises…

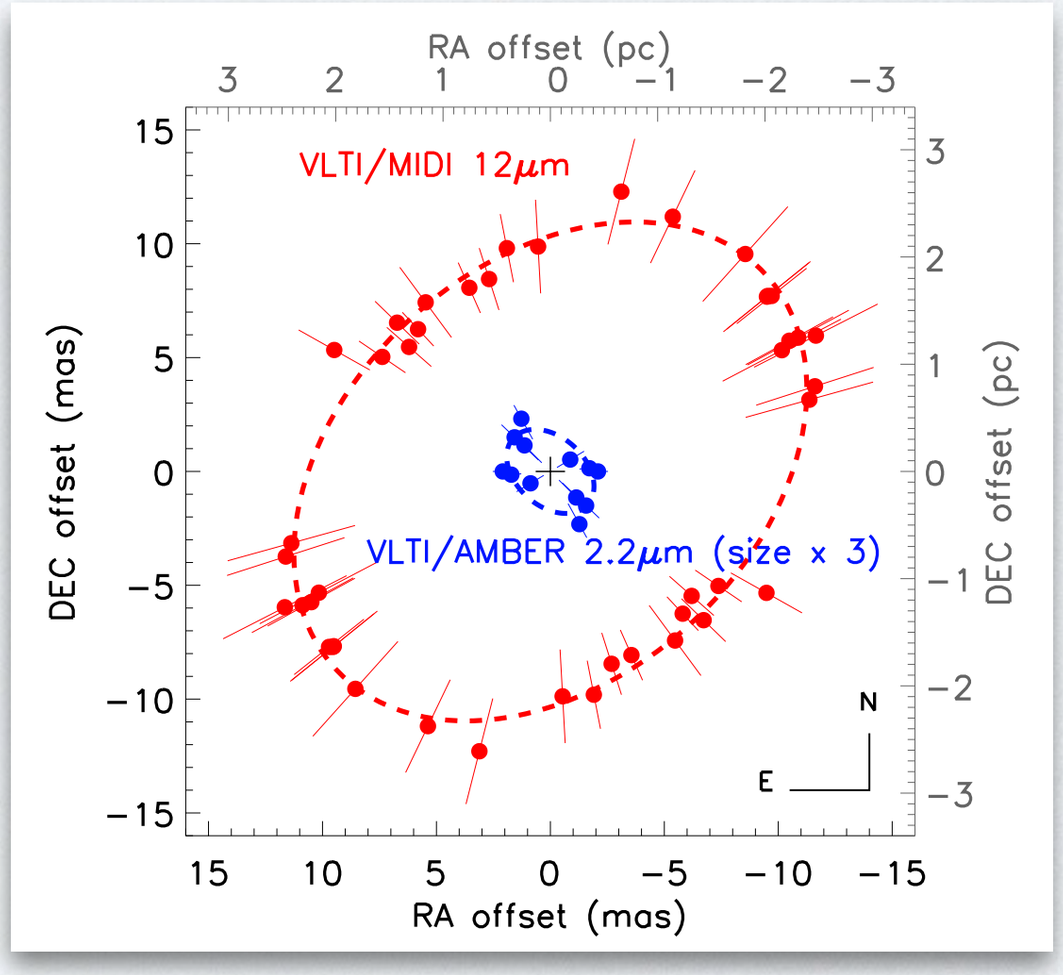
AGN interferometry time line



IR emission from the polar region



Hoenig et al. 2013



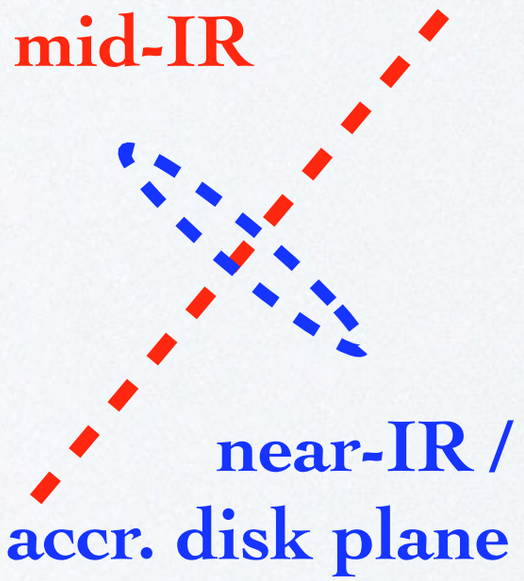
- VLTI: significant mid-IR emission from **polar region**
  (Raban+09, Hoenig+12,13, Burtscher+13, Tristram+14)

  → **60-80%** of pc-scale emission

- **not predicted** by models

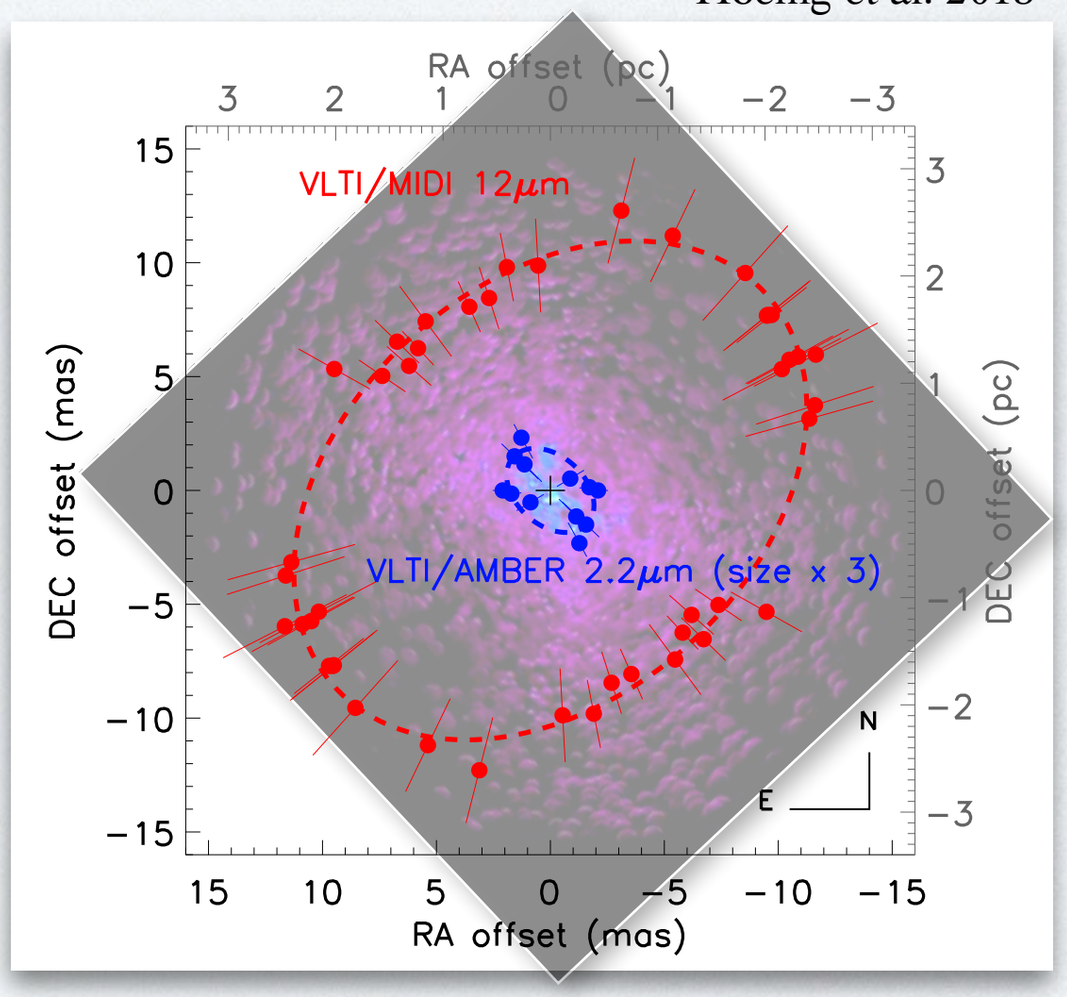
IR emission from the polar region

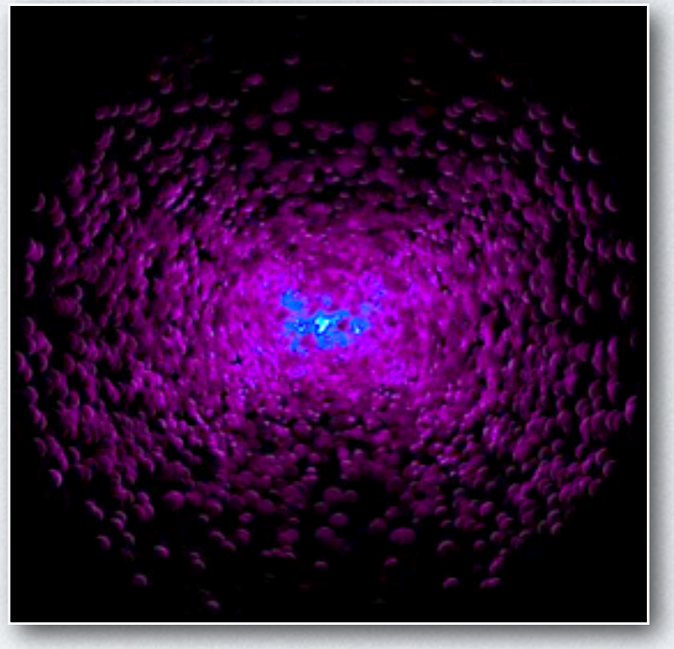
polar direction / mid-IR



near-IR / accr. disk plane

Hoenig et al. 2013





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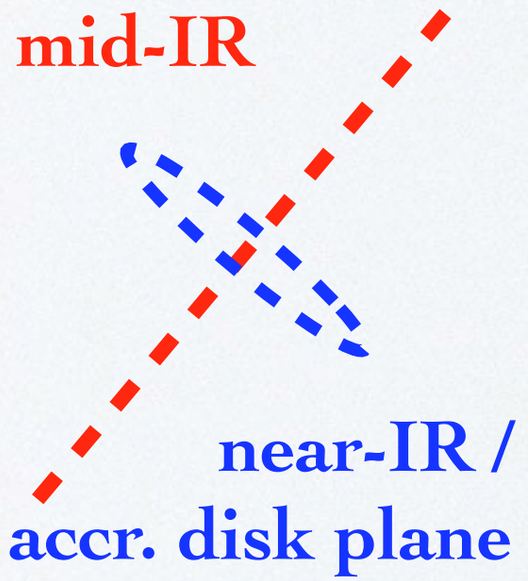

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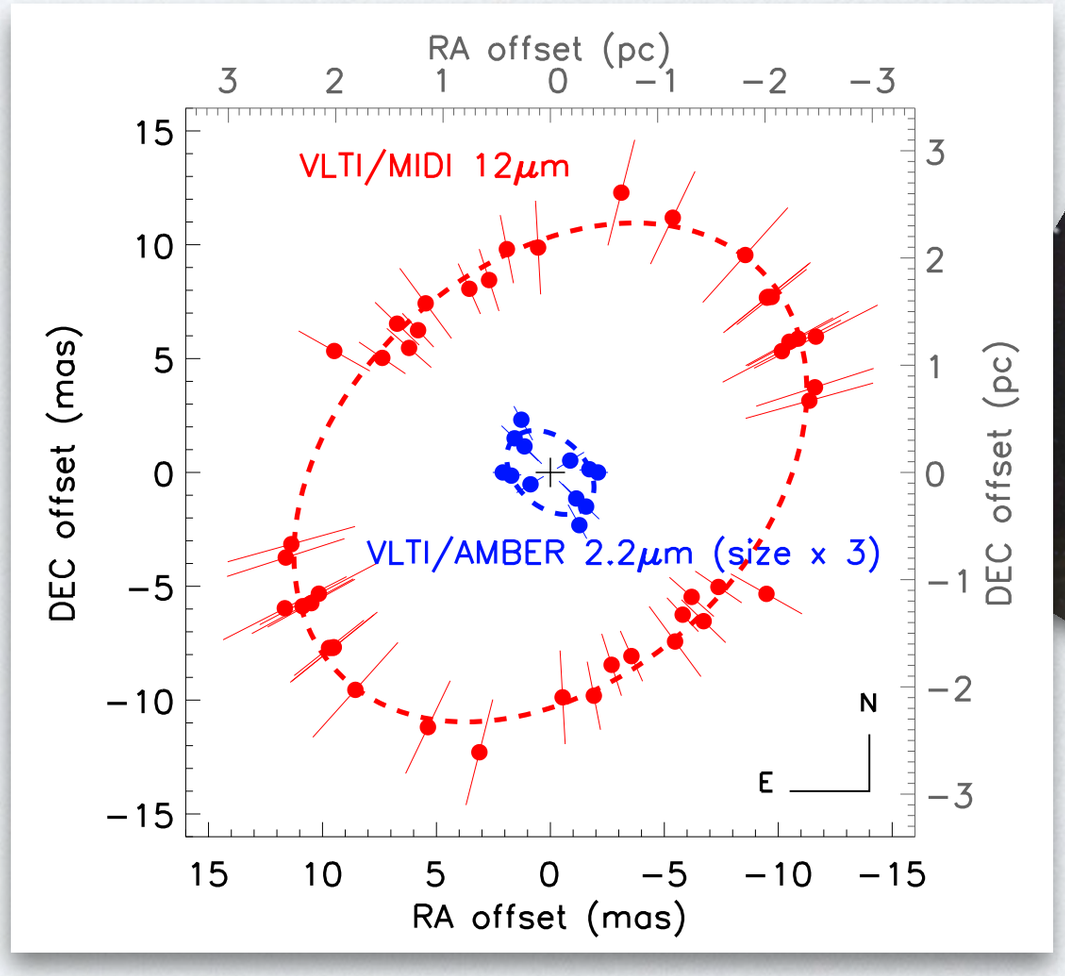

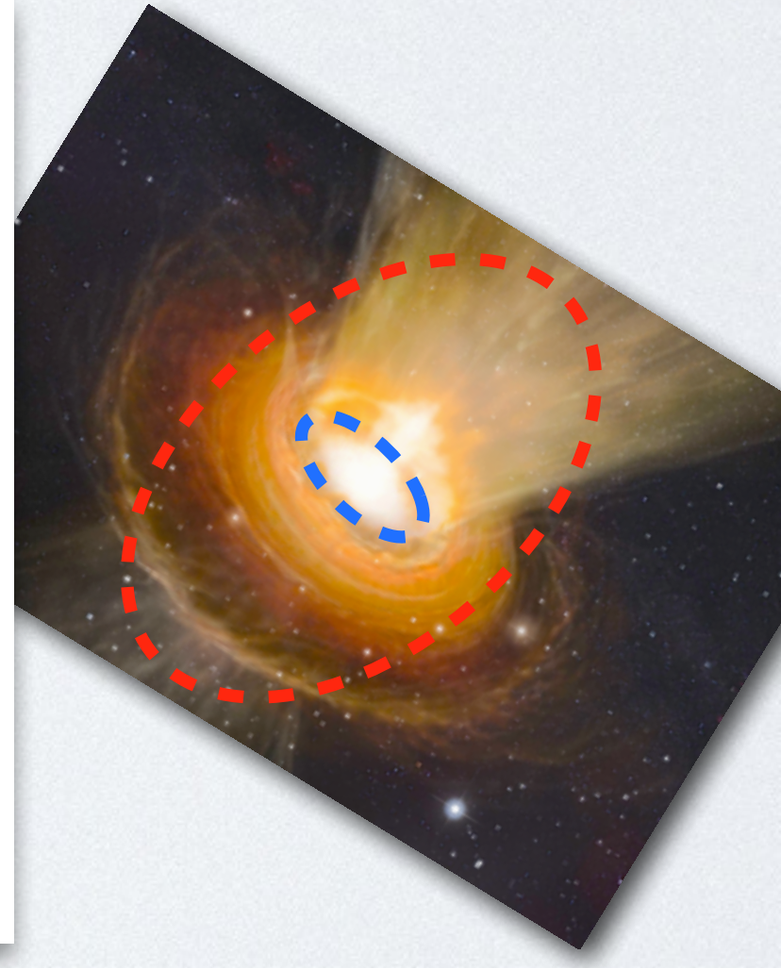

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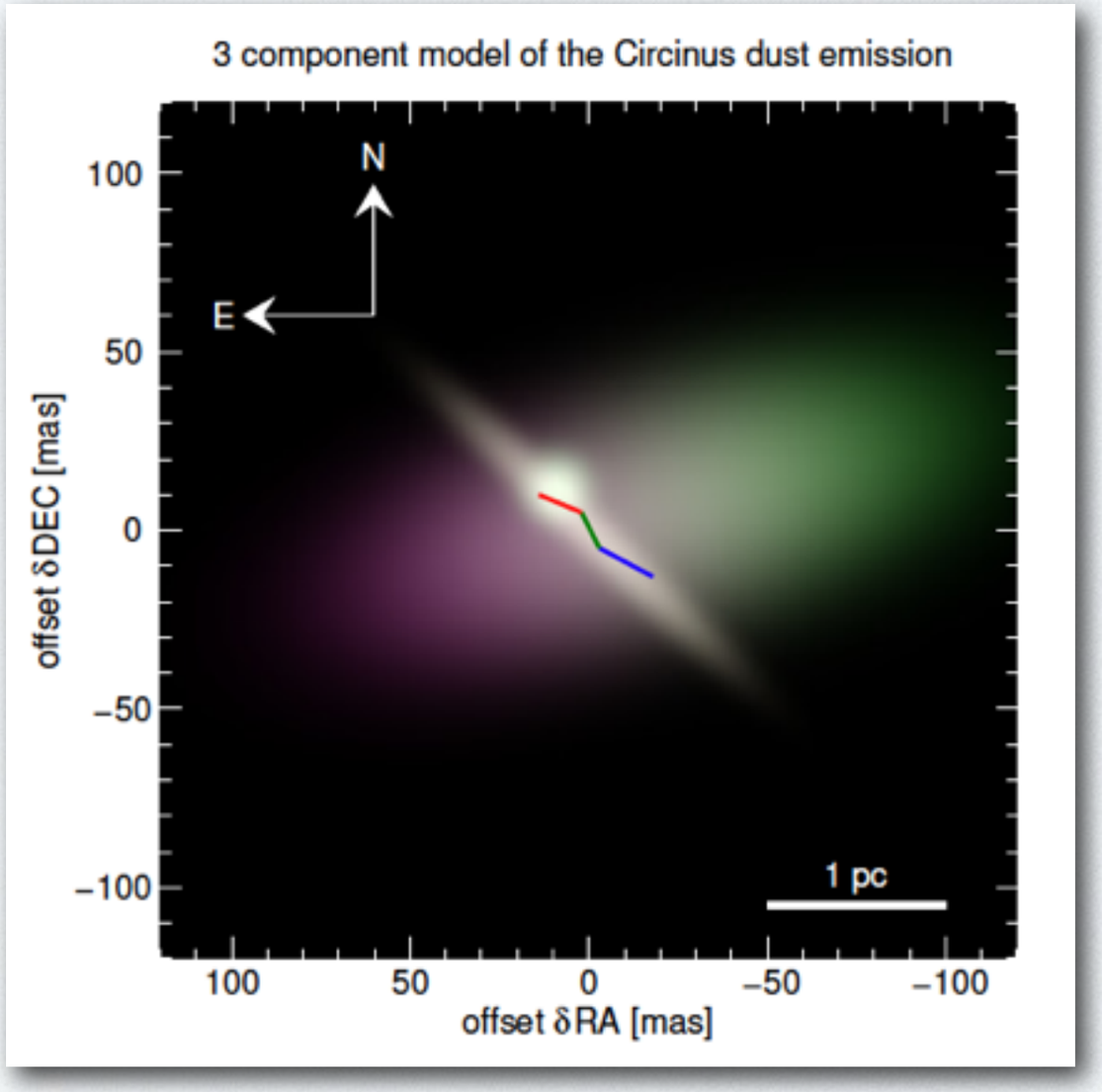
A dense IR-emitting disk



Tristram et al. 2014

- Circinus/NGC 1068: non-polar component in **"disk"**
  (Tristram+14, Lopez-Gonzaga+14 → see **Noel's talk!**)
- coincident with **maser disks**
- has equivalent in **RHD models** (Wada 12, Schartmann+14)

Summary and next steps

- **What we learned…**
  - dusty structure are **clumpy**
  - they IR emission is **quite diverse → why?**
  - their main emitting dust component is **not ISM → large grains**
  - it is probably **not the torus everyone expected → disk + wind?**

- **What is coming up…**
  - find a new paradigm for the dusty structure **→ MATISSE**
  - **direct black hole mass** from resolved BLR

"After languishing for a decade largely through lack of data, this field should now see a revival, as it is refreshed by detailed infrared imaging. The dynamical problems guessed at years ago can be brought into clearer focus" — Julian Krolik, Nature News & Views, 2004

"The most impressive recent results [regarding AGN unification] are due to IR interferometry. […] Long-baseline interferometry is the way of the future" — Hagai Netzer, ARA&A, 2015