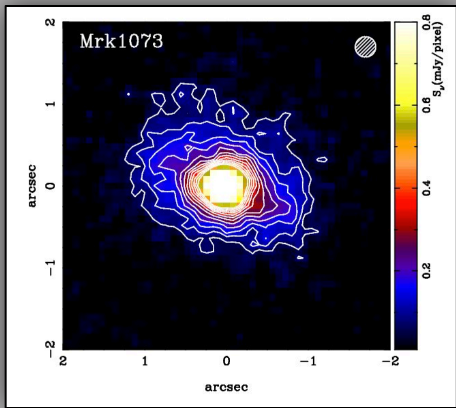
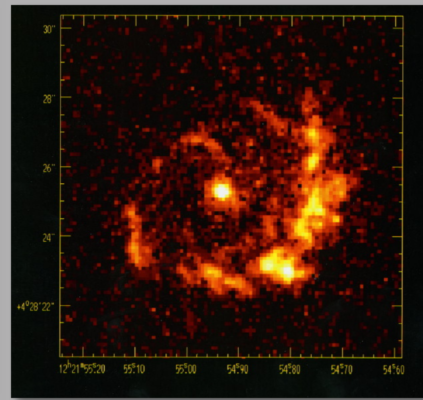
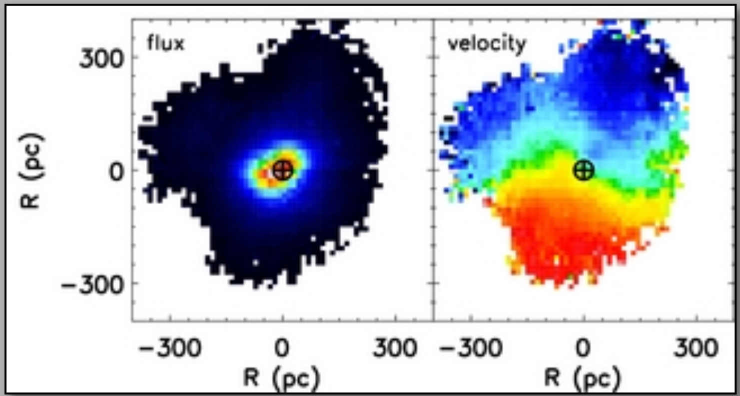




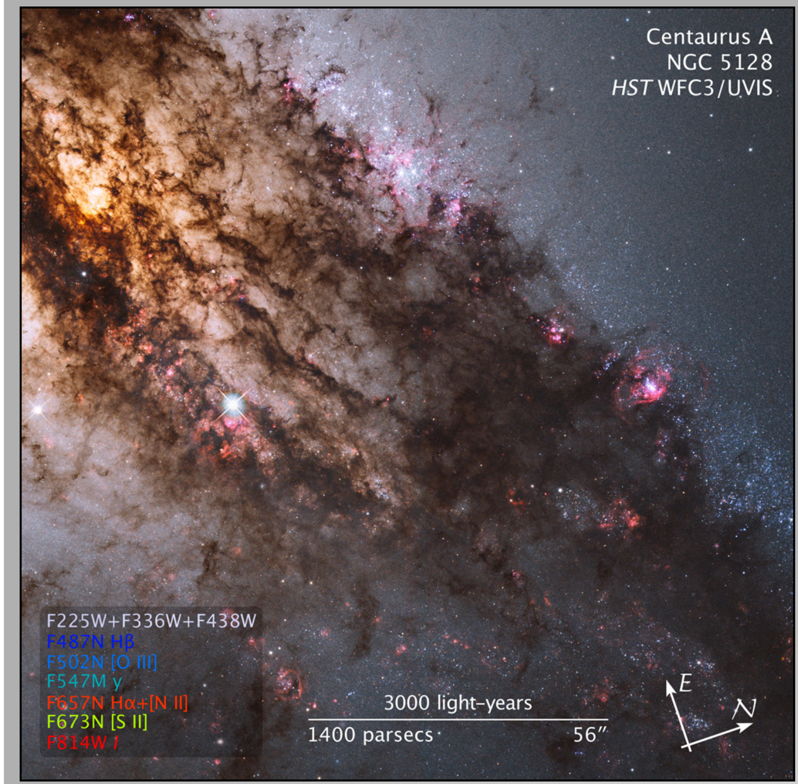


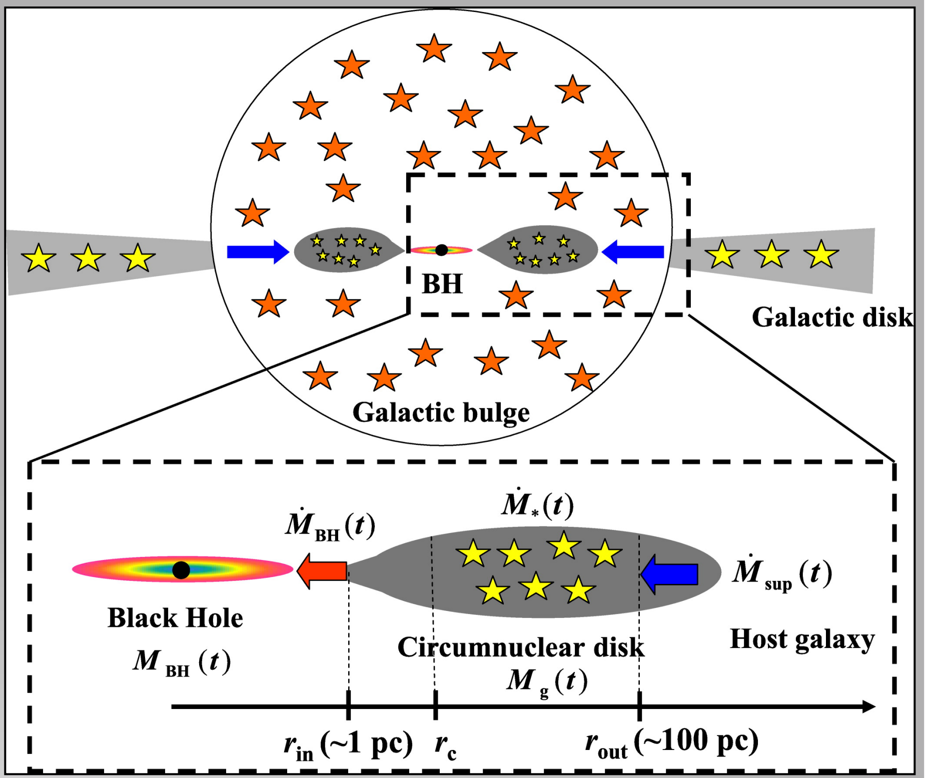
Connecting the AGN and star formation phenomena on nuclear (~100pc or less) scales

Almudena Alonso Herrero
Instituto de Física de Cantabria, Spain

Nuclear star formation activity in AGN

Gas transported from kpc-scales to nuclear region is predicted to form a reservoir, i.e., a circumnuclear disk, in the central 100 pc around a BH because gravitational torques might not be efficient at r<100pc

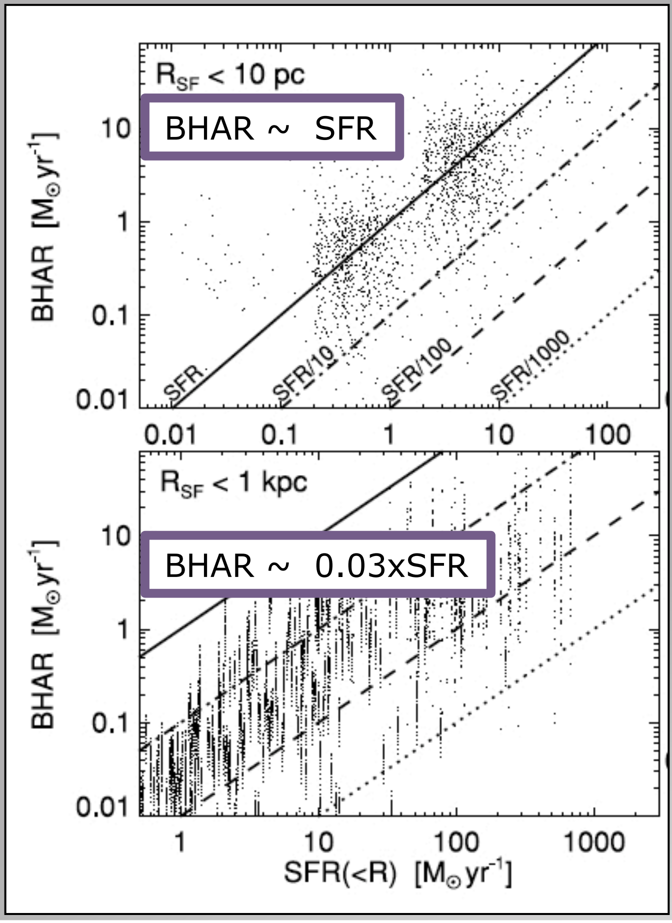


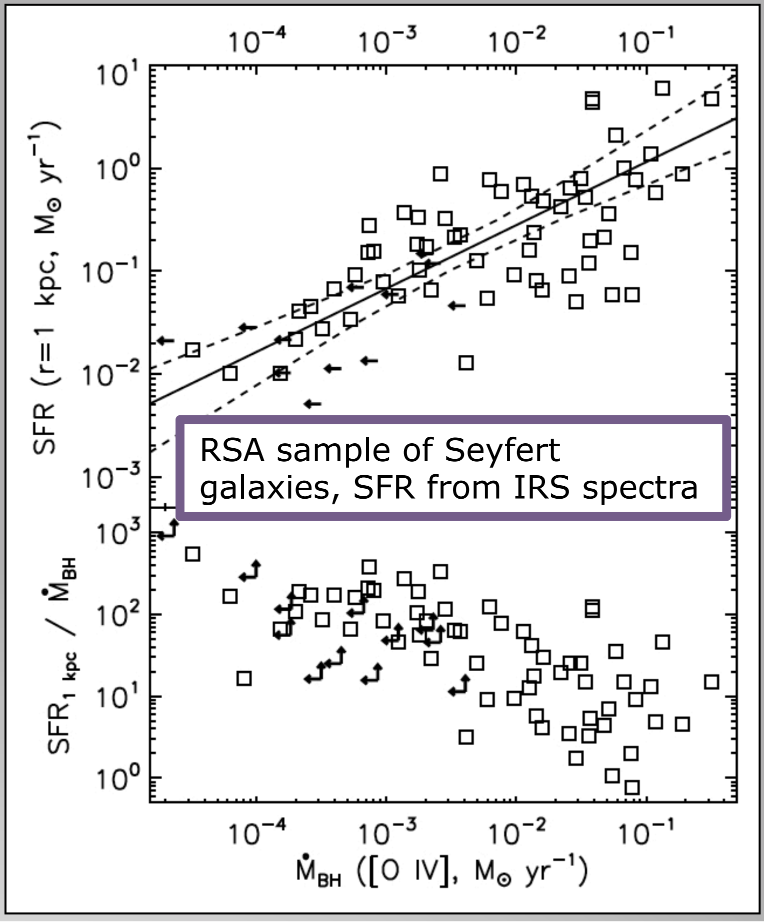


Model for a circumnuclear disks in AGN:
Kawakatu & Wada 2008

See García-Burillo et al. 2005, Combes review talk

Star formation activity is related to the BH Accretion Rate





Simulations predict a tighter relation on smaller physical scales: Hopkins & Quataert 2010

Empirical where SF is measured on kpc scales: Diamond-Stanic & Rieke 2012

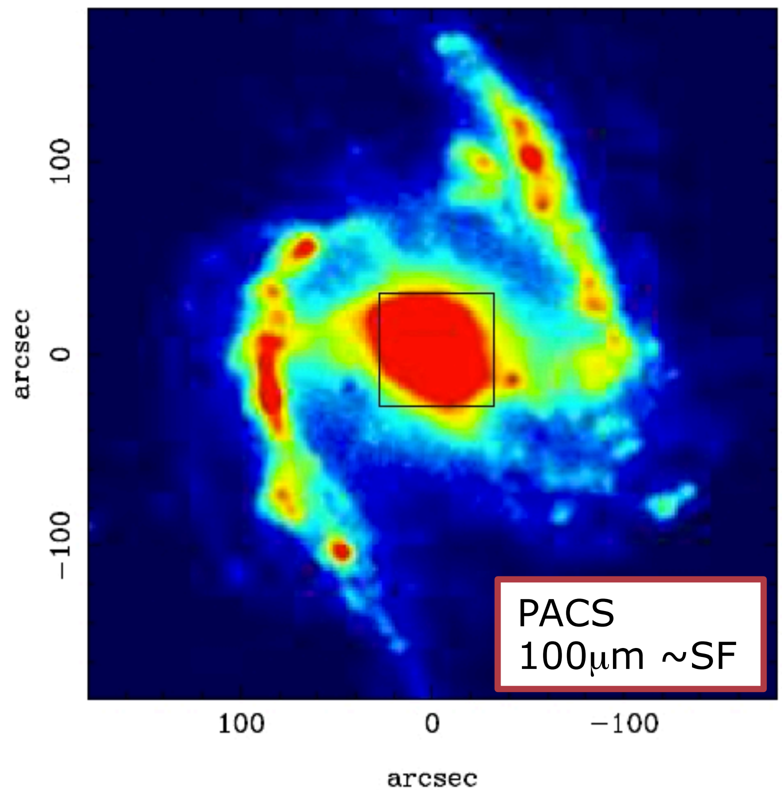
See also e.g., Kauffmann et al. 2003, Shi et al. 2006, **talks by: Chen, Azadi, La Massa, Thacker**

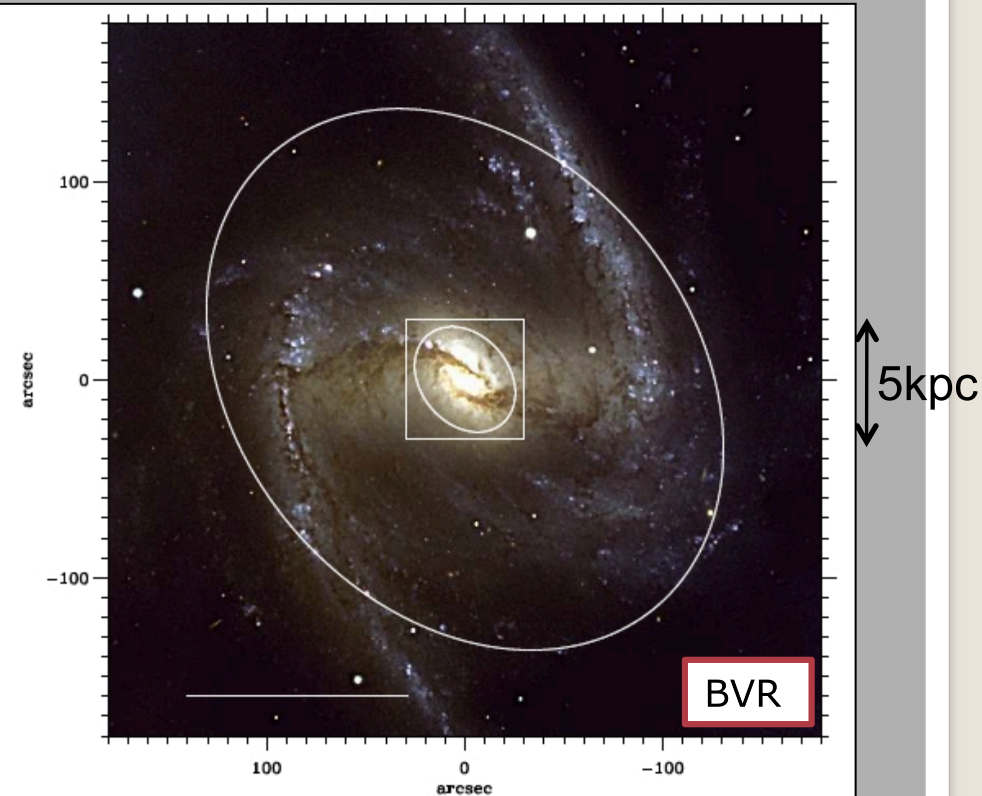
Open questions

- ★ Plenty of evidence of SF in the nuclei and host galaxies of local type 2 AGN, how about type 1 AGN?
- ★ How do we detect and quantify nuclear SF, especially in type 1 AGN?
- ★ Is there SF at distances of less than ~ 100pc from AGN?
- ★ Is the nuclear SF a function of the AGN luminosity (i.e., black hole accretion rate)?
- ★ Are nuclear SF and active black hole accretion coeval processes?
- ★ What is the role of nuclear SF in obscuring the AGN? Relation between SF and nuclear gas disks and the dusty torus?

Nuclear vs. Circumnuclear SF in AGN

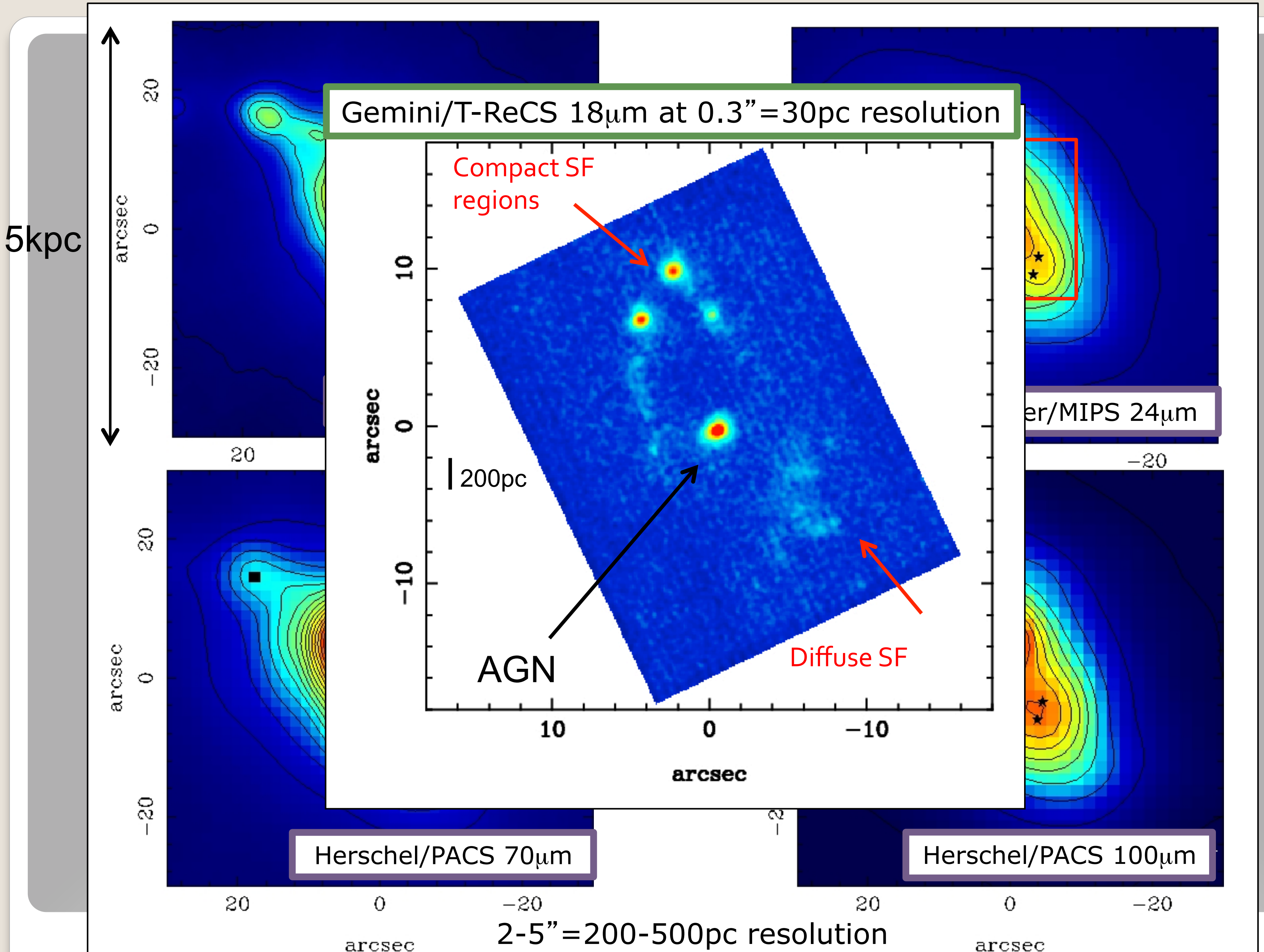
Nearby Seyfert galaxy NGC1365, D=21Mpc, 1¨~100pc, $L_{2\text{-}10keV}=10^{42}$erg/s





Alonso-Herrero et al. 2012

Elmegreen et al. 2009



Alonso-Herrero et al. 2012

Outline of the talk

1. On-going/recent SF tracers and results in the nuclear regions (physical scales of 100 pc or less) of AGN (mostly Seyfert galaxies) and caveats
   - −UV emission
   - -Hydrogen recombination lines (Hβ, Hα, Paβ, Paα, Brγ)
   - -Modeling of stellar populations
   - -IR emission, PAH features
   - -σ-drops

2. SFR vs. BHAR on nuclear scales

3. Co-evolution of nuclear SF and BH growth?

4. Nuclear SF and relation to molecular gas, torus, obscuration, etc

5. Summary

A few words about SF tracers

★**UV** – Calibration based on direct stellar light. Youngest stellar populations emit most of their energy in the UV (< 0.3μm). **If there's no extinction,** best SFR indicator over time scales **100-300 Myr** (O and B stars)

$$\mathrm{SFR(UV)} = 3.0 \cdot 10^{-47} \lambda L(\lambda)$$

★**Hα, Paα, Brγ** – Calibration based on number of ionizing photons. Only stars $M>20M_{\odot}$ emit sufficient $Q(H^0)$. If stars formed instantaneously then it probes ages **up to 10Myr**

$$\mathrm{SFR}(Q(\mathrm{H}^o)) = 7.4 \cdot 10^{-54} Q(\mathrm{H}^o)$$

$$\mathrm{SFR}(\mathrm{H}\alpha) = 5.5 \cdot 10^{-42} L(\mathrm{H}\alpha)$$

★**Infrared** – Calibration based on reprocessed emission when ionizing UV photons are absorbed and re-emitted in the IR. Assuming constant SFR for **100Myr**

$$\mathrm{SFR(TIR)} = 2.8 \cdot 10^{-44} L(\mathrm{TIR})$$

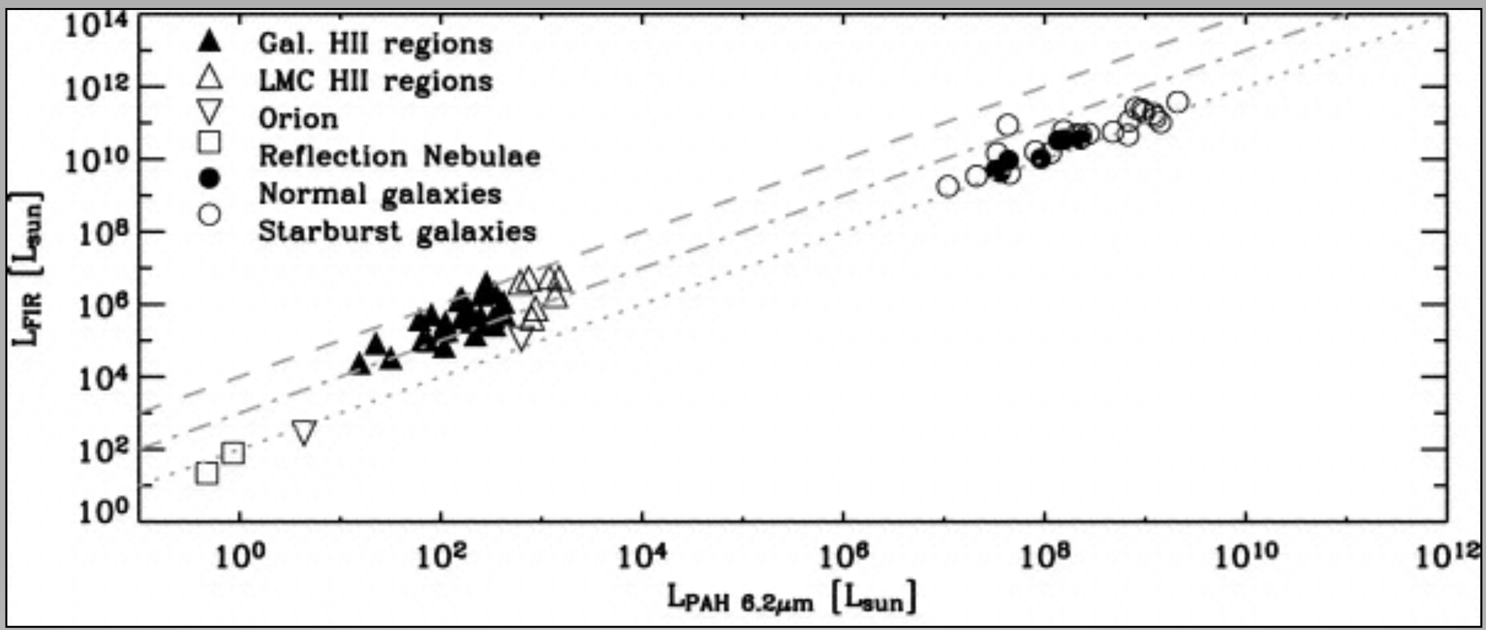
$$\begin{aligned} \mathrm{SFR}(24)_{\mathrm{global}} &= 2.04 \cdot 10^{-43} L(24) && (4 \cdot 10^{42} \le L(24) \le 5 \cdot 10^{43}) \\ &= 2.04 \cdot 10^{-43} L(24) && \\ &\times [2.03 \cdot 10^{-44} L(24)]^{0.048} && (L(24) > 5 \cdot 10^{43}) \end{aligned}$$

Kennicutt 1998, Calzetti's review
http://ned.ipac.caltech.edu/level5/Sept12/Calzetti/Calzetti1_2.html and refs therein

PAH emission as a SF tracer in SB and AGN

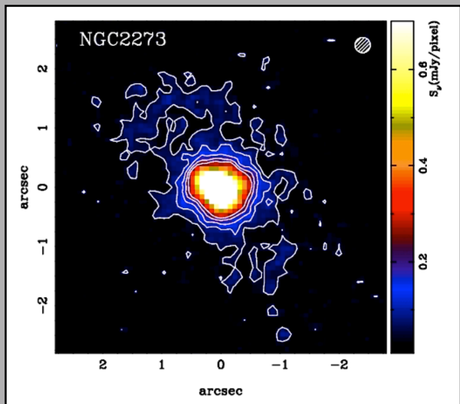
PAH emission is related to L_{IR} for high metallicity HII regions and SBs.

PAHs are better suited as a tracer of B stars than as a tracer of massive SF. They probe star formation activity **time scales of up to 100Myr.**



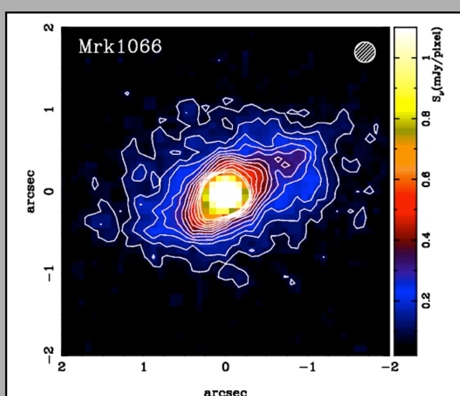
Peeters et al. (2004). See also e.g.: Brandl et al. (2006), Smith et al. (2007), Bernard-Salas et al. (2009), Díaz-Santos et al. (2010), Diamond-Stanic & Rieke (2012)

PAH emission in Nuclear and Circumnuclear regions of AGN

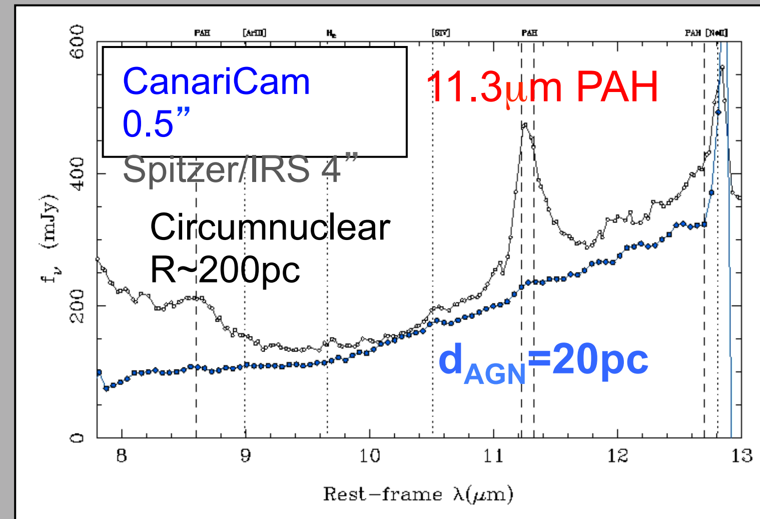


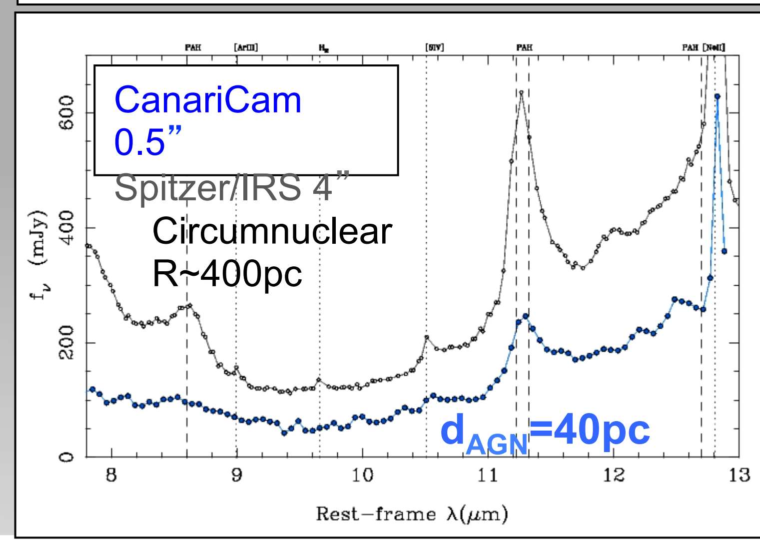
NGC2273

GTC/CanariCam 8.7μm, **0.26-0.4”** **resolution:** Alonso-Herrero et al. (2014)



Mrk1066

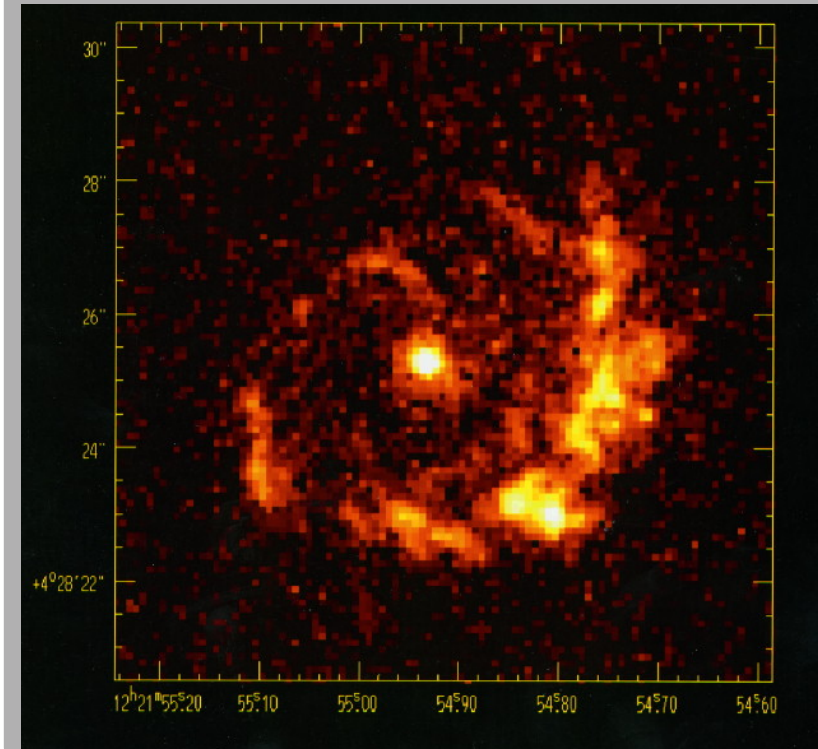




See also: Roche et al. 1991, Clavel et al. 2000, Laurent et al. 2000, Siebenmorgen et al. 2004, Deo et al. 2009, Wu et al. 2009, Diamond-Stanic & Rieke 2010, 2012, Hönig et al. 2010, Díaz-Santos et al. 2010, LaMassa et al. 2012, González-Martín et al. 2013, Sales et al. 2013, Esquej et al. 2014, Ramos Almeida et al. 2014, Mori et al. 2014, **E. Hatziminaglou’s talk**

UV emission in the nuclear regions of Seyferts

NGC4303 – UV image, bright spiral structure (r~230pc) plus UV core
Colina et al (1997)



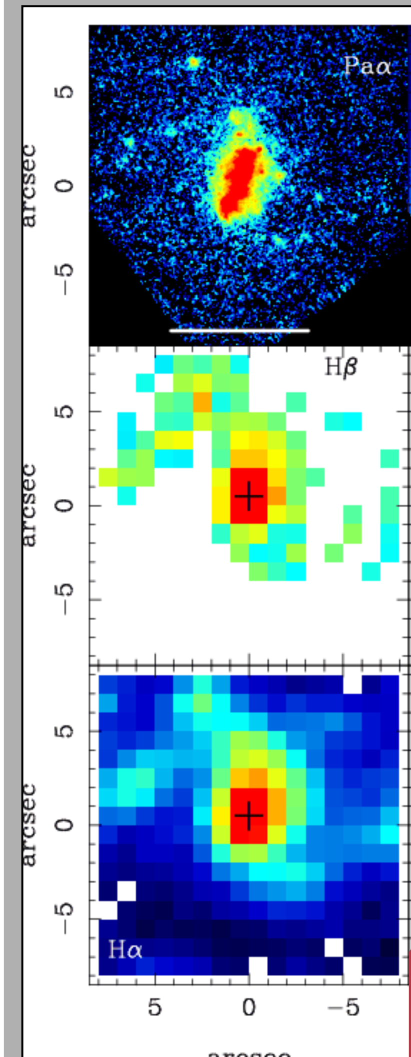
Seyfert 1 nuclei are compact
Most Seyfert 2 nuclei show resolved nuclear UV emission

Extended UV emission seen in imaging data:

(i) *Stellar continuum* due to young/intermediate age massive star clusters and the underlying older stellar population of the galaxy.
(ii) *Nebular continuum*, morphology as ionized gas.
(iii) *Emission lines from ionized gas.*
(iv) *Light from the AGN,* which can be scattered by free electrons or dust.

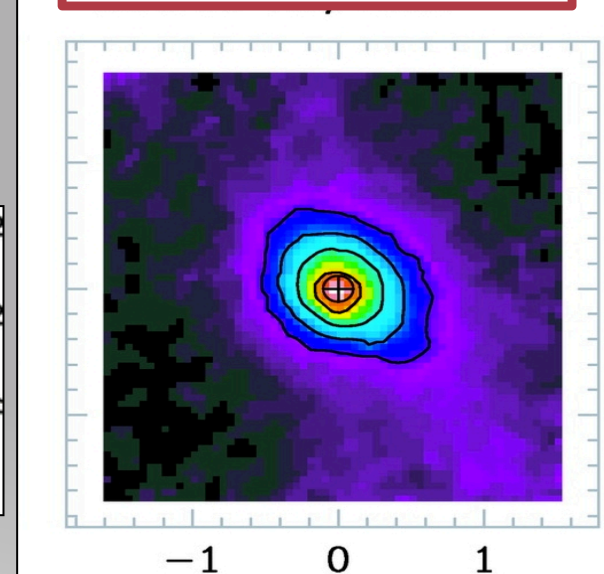
E.g., Colina et al. 1997a,b, González Delgado et al. 1998, Muñoz-Marín et al. 2007, 2009

Nuclear and Circumnuclear Hβ, Hα, Brγ, Paα emission in Seyfert galaxies

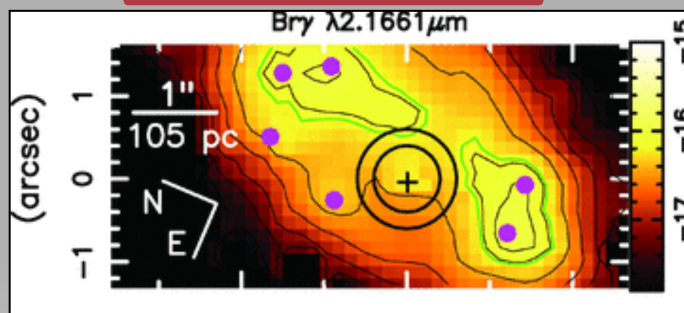


Nuclear rings, disks, mini-spirals detected in hydrogen recombination lines.

NGC2992 – narrow Brγ
Davies et al (2007)



NGC7582 – Brγ
Riffel et al (2009)

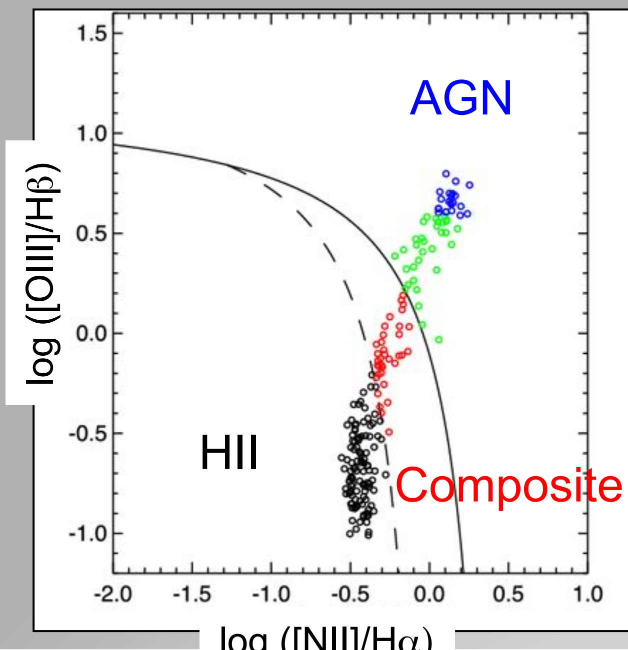


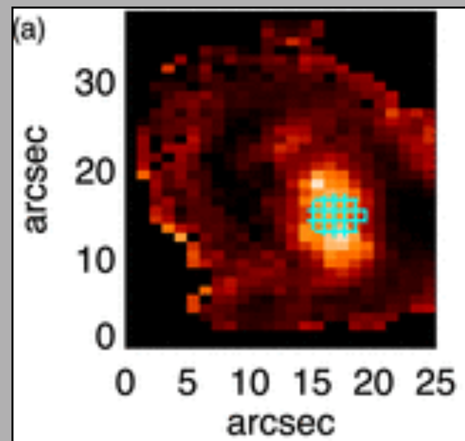
NGC6701 – Paα, Hβ, Hα
Alonso-Herrero et al. (2009)

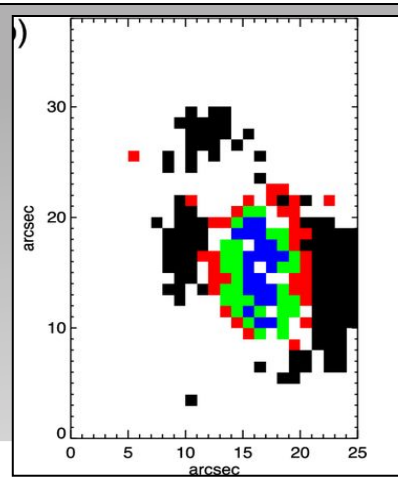
Bergmann et al. 1996, González Delgado et al. 1997, Ferruit et al. 2000, Knapen et al. 2004, Müller-Sanchez et al. 2006, Dumas et al. 2007, Davies et al. 2006, 2007, Alonso-Herrero et al. 2006,2009, Riffel et al. 2008,2009,2010, Bedregal et al. 2009, Stoklasova et al. 2009, R. L. Davies et al. 2014

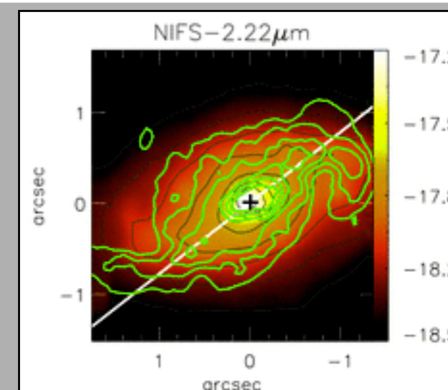
AGN contamination to hydrogen recombination lines

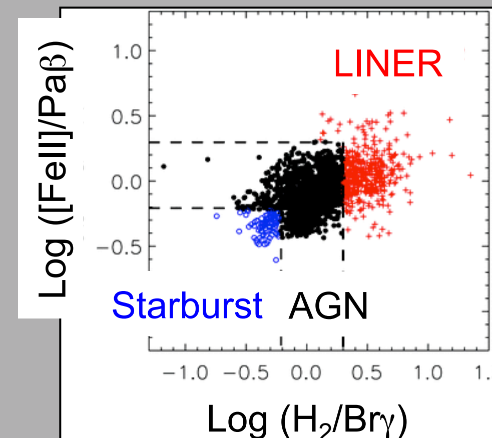
Even for type 2 AGN, in central 1-2” there is strong contribution from NLR emission to hydrogen recombination line

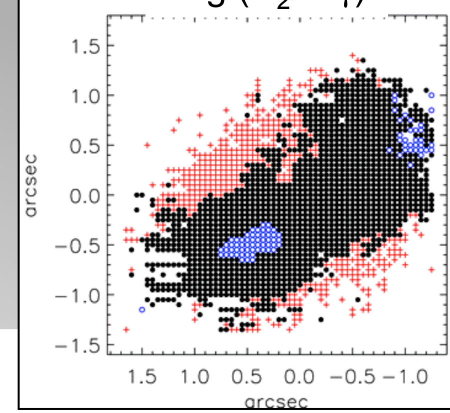










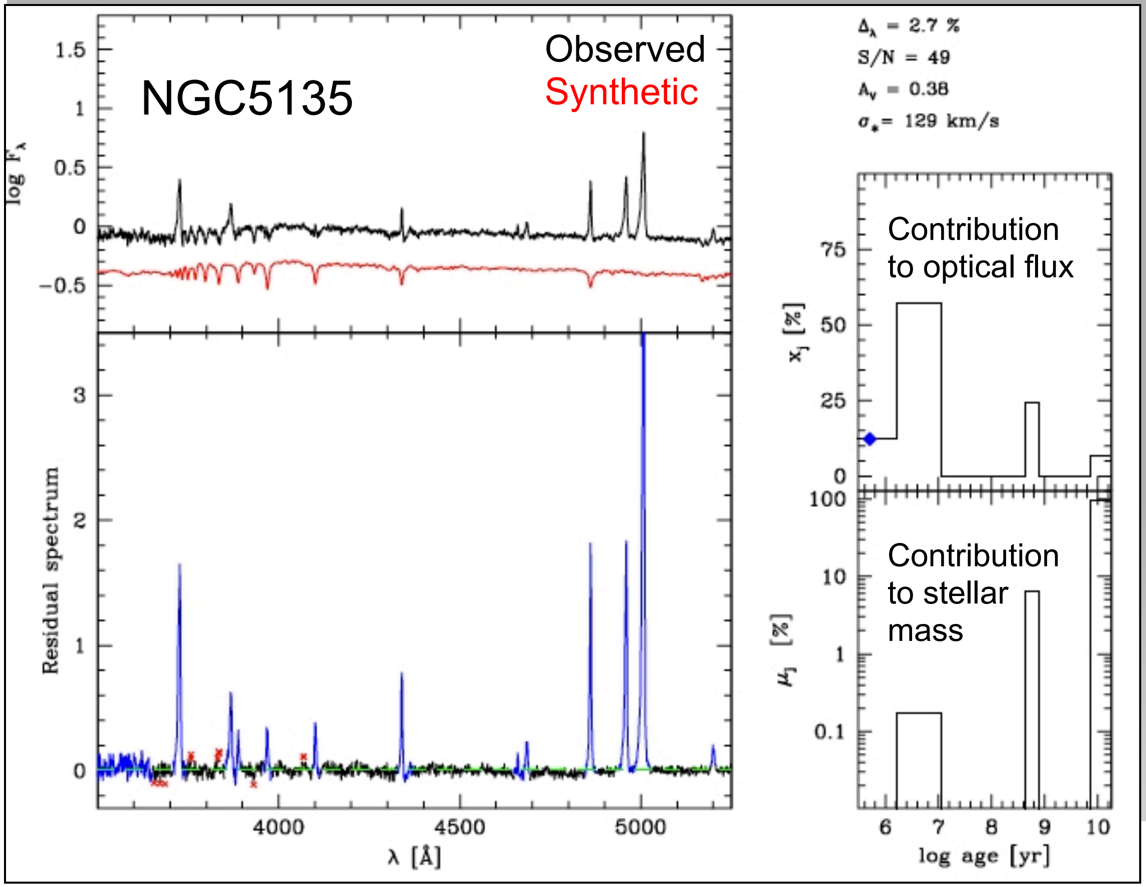


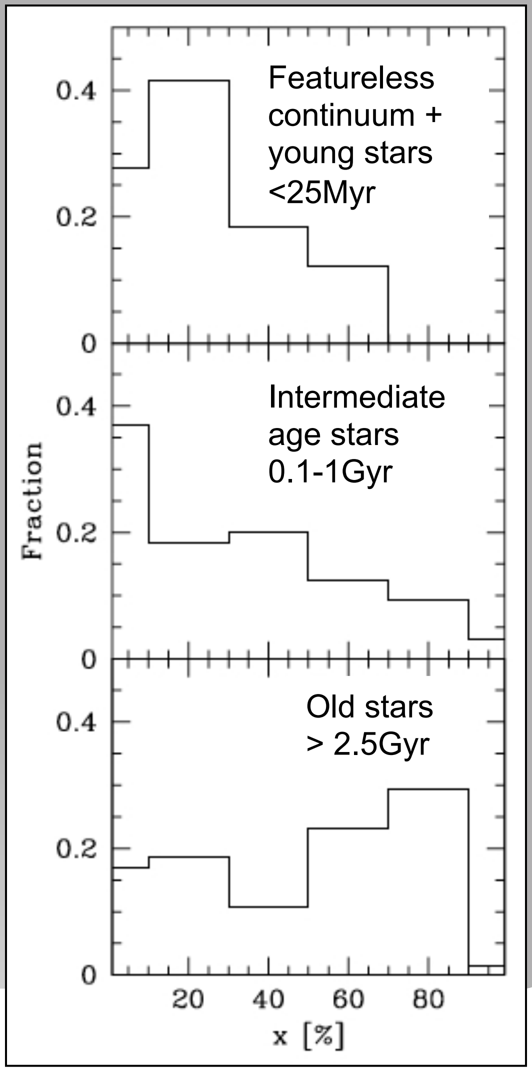
NGC7130: Rebecca Davies et al. 2014

Mrk1066: Riffel et al. 2010

Stellar Populations in Seyfert 2 nuclei: optical

Between 1/3 and half of nearby Seyfert 2 nuclei (~200pc) have experienced **significant SF in the recent past.**





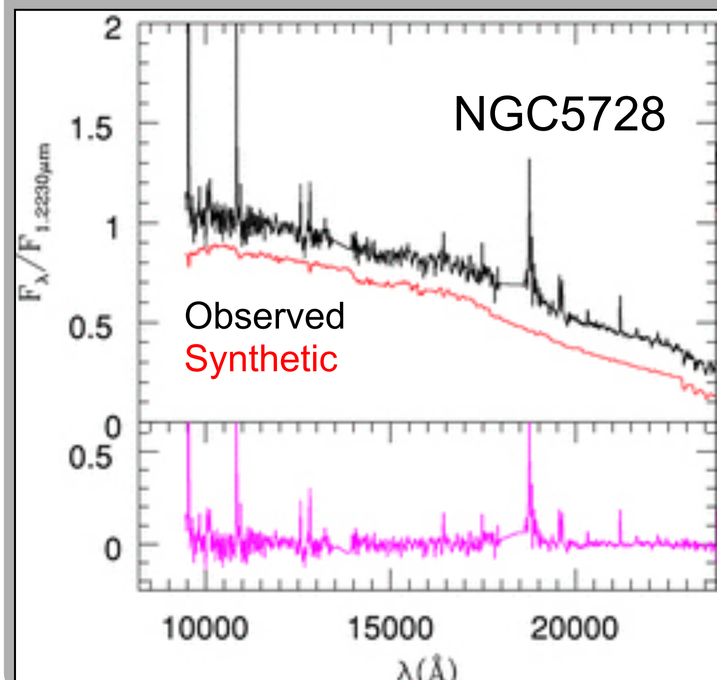
Fits to 3000-5000Å spectra: Cid Fernandes et al. 2004

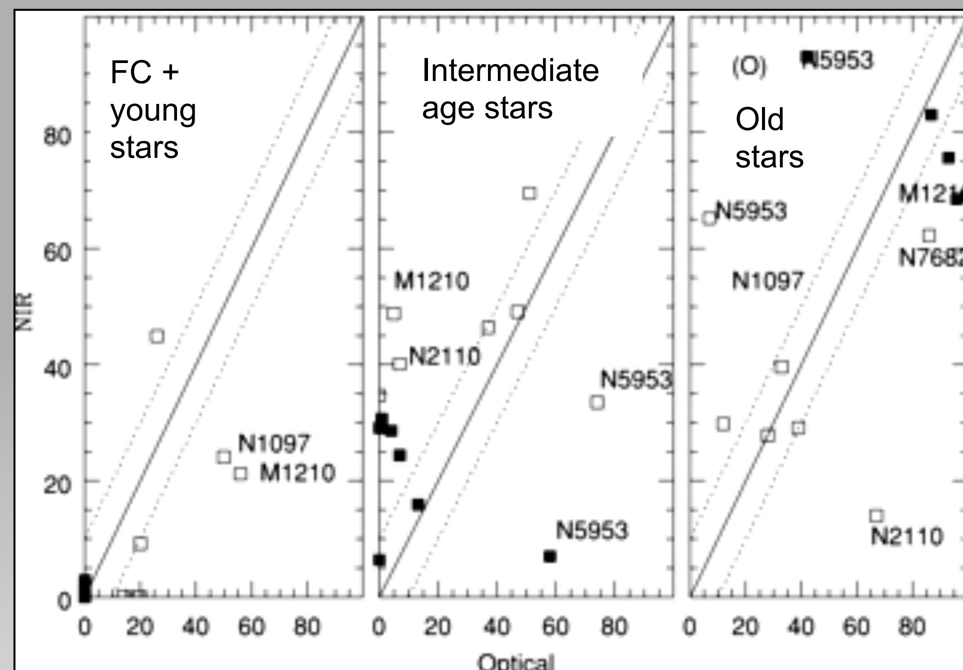
See also: Cid Fernandes et al. 1998, González Delgado et al. 1998,2001,2004, Raimann et al. 2003

Stellar Populations in nuclear regions of Seyferts: near-IR

Near-IR good choice to study the stellar populations of Sy 1s and 2s, as opposed to the usually heavily attenuated optical range.

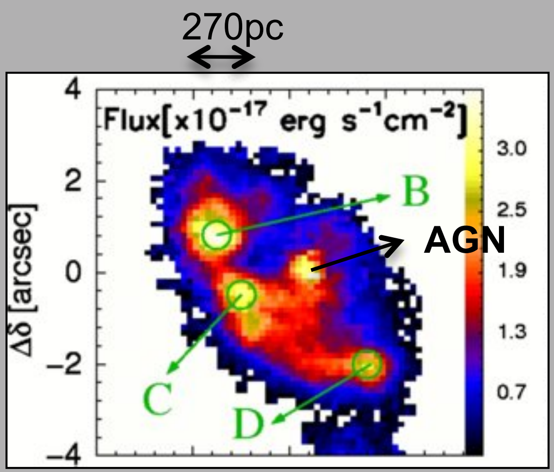
Good agreement between results in optical and near-IR.



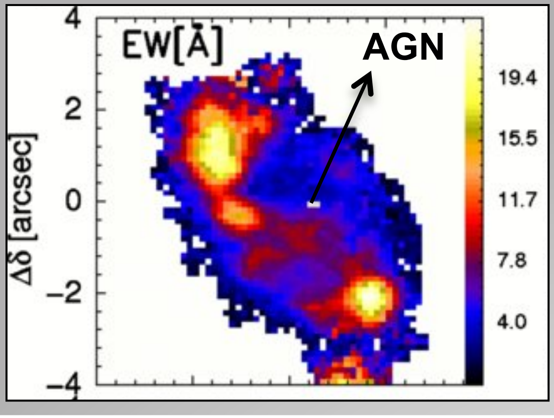


Riffel et al. 2009

Stellar Populations in nuclear regions of Seyferts: near-IR



NGC5135 – Brγ
Bedregal et al. (2009)



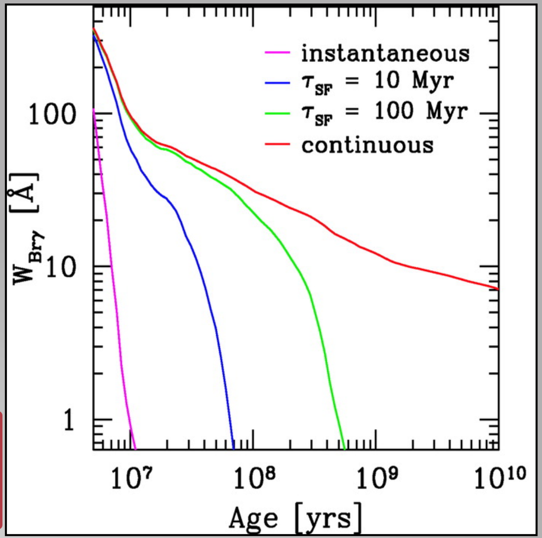
Hot dust emission at ~2μm is present in most Sy 1 and 2 nuclei, but with a smaller contribution in Sy 2.

Evidence of recent (10 - 300Myr) SF in the central regions of Seyfert galaxies based on small EW of Brγ line.

SF as close as 10pc from the AGN.

SF episodes are probably short-lived.

Models – Davies et al. (2007)



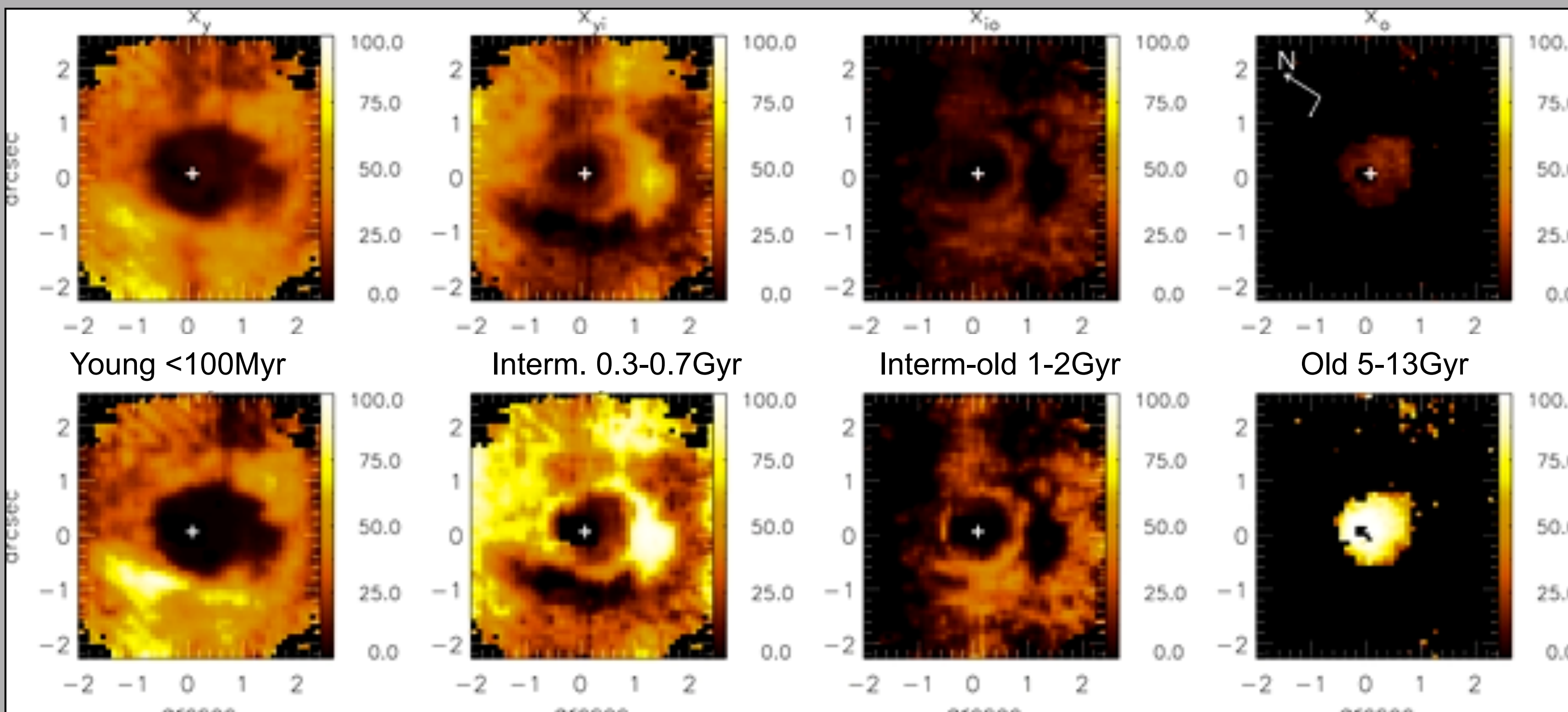
See e.g., Thatte et al. 1997, Ivanov et al. 2000, Davies et al. 2006,2007, Riffel et al. 2006,2007,2009a,b, Bedregal et al. 2009, Ramos Almeida et al. 2009, Friederich et al. 2010, Storchi-Bergmann et al. 2012

Stellar pops. in nuclear region of NGC1068

Two episodes of recent SF:

First started 300 Myr ago, extending over most of the nuclear region

Second started 30 Myr ago, in a ring-like structure at r=100 pc, which is coincident with an expanding ring of H_2 emission.

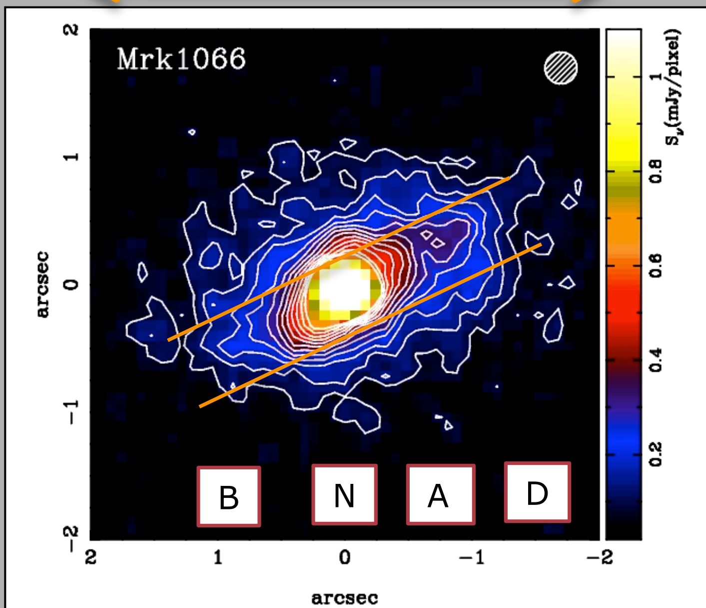


280pc

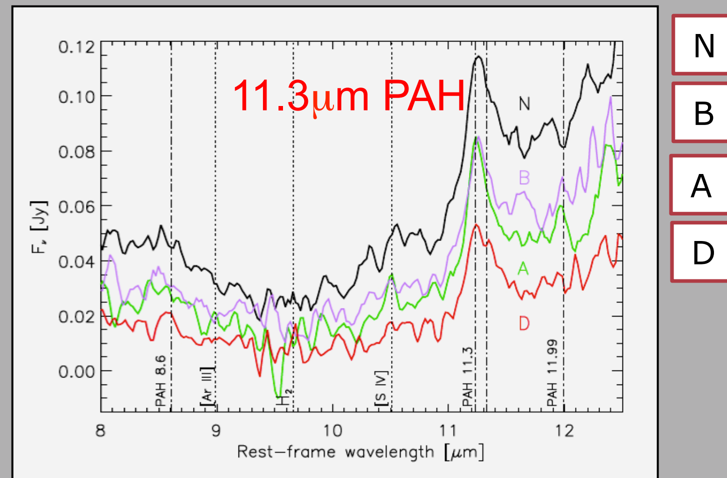
Storchi-Bergmann et al. 2012

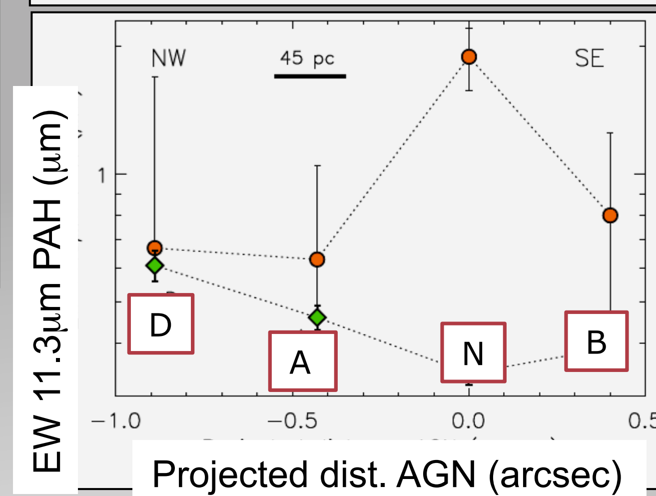
11.3μm PAH feature emission in Mrk1066

900pc



GTC/CanariCam 8.7μm at 0.3” angular resolution





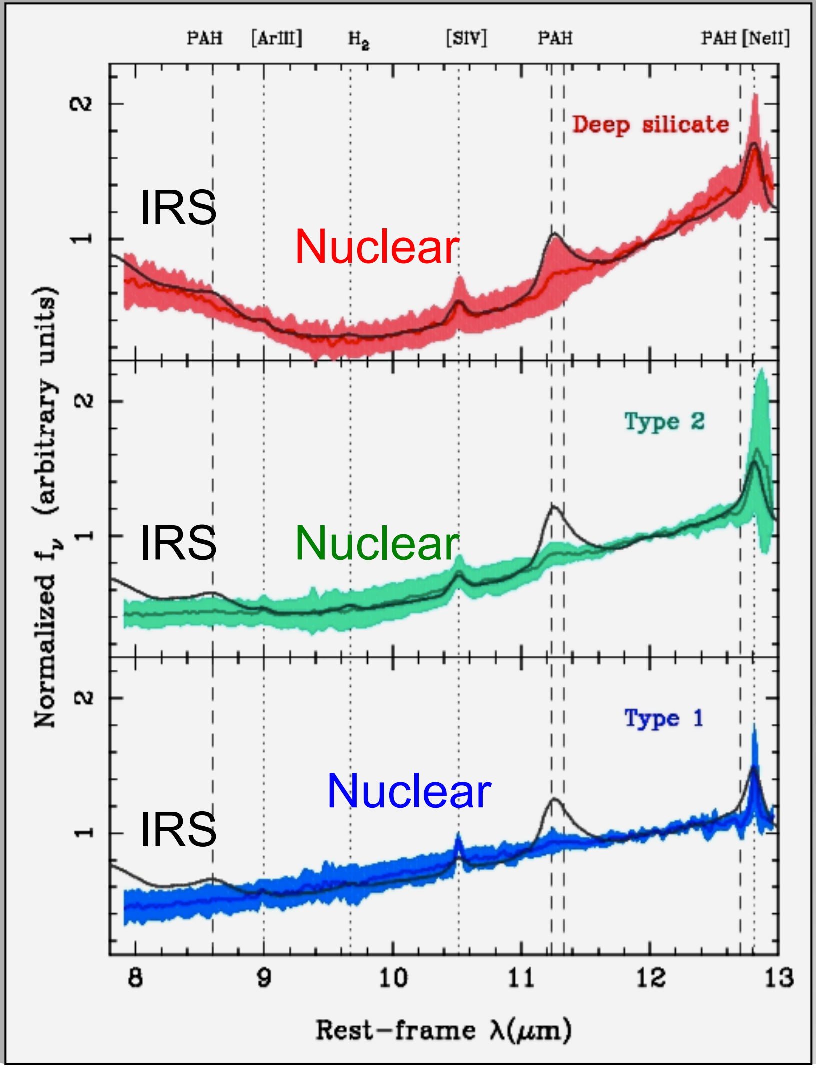
AGN emission corrected

Observed

AGN continuum emission dilutes EW(11.3μm PAH) but not its luminosity

Ramos Almeida et al. 2014

Nuclear mid-IR spectra of RSA Seyferts



Ground based mid-IR spectroscopy of 24 Seyfert 1s and 2s in RSA sample probing central 100pc (median).

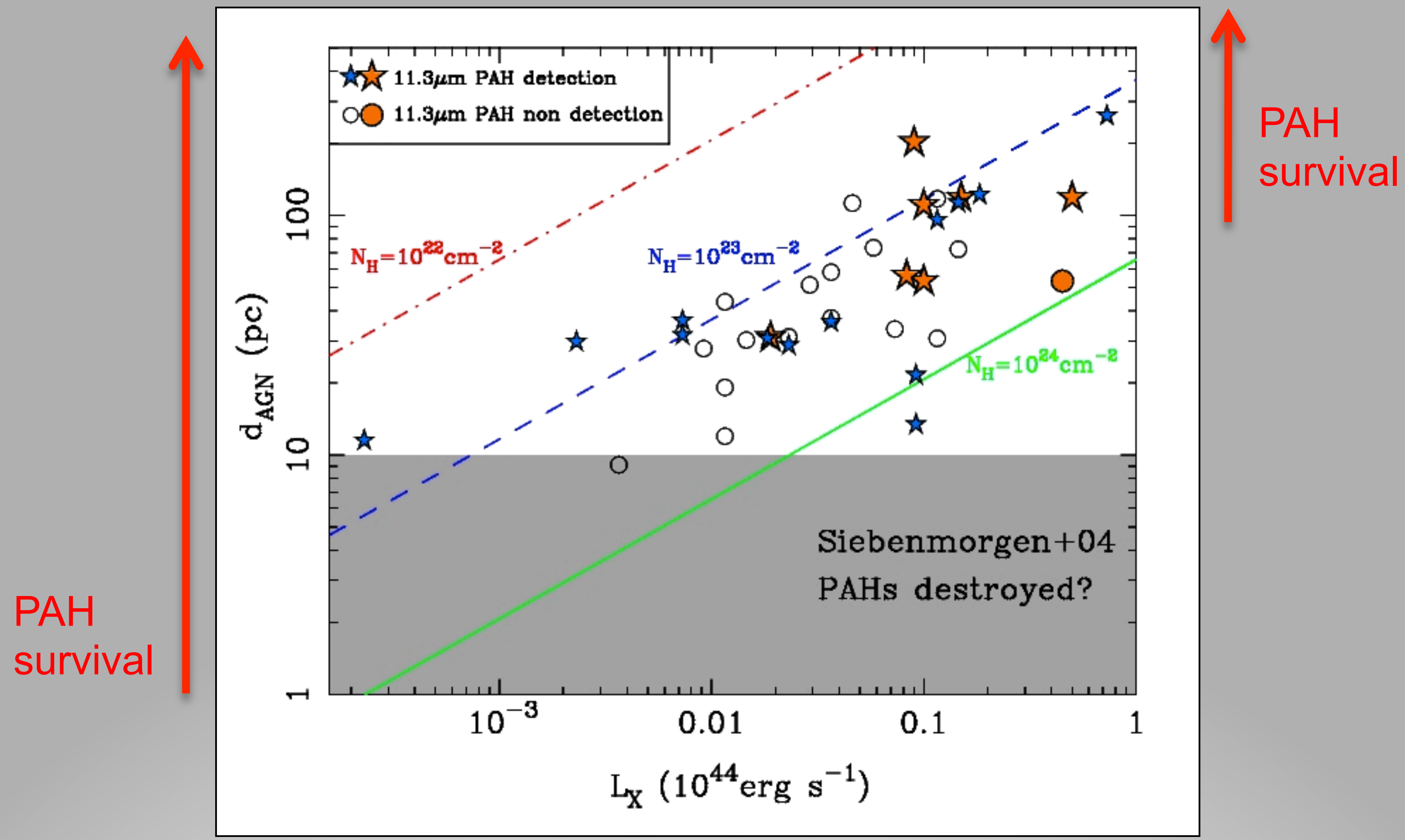
11.3μm PAH emission 11.3μm PAH emission detected in nuclear spectra of 50% of Seyfert 1s and 2s.

Similar EW of PAH feature in median Seyfert 1s and 2s ~ same SF.

Detection of 11.3μm PAH emission indicates the presence of stellar populations with ages <100Myr as close as 10pc from the AGN.

Alonso-Herrero et al. 2014 and Esquej et al. 2014. For PAH emission in nuclear regions of AGN see also: Roche et al. 2006, Díaz-Santos et al. 2010, Hönig et al. 2010, Sales et al. 2013, González-Martín et al. 2013, Ramos Almeida et al. 2014, Mori et al. 2014

Nuclear PAH molecules survive to d_{AGN}>10pc

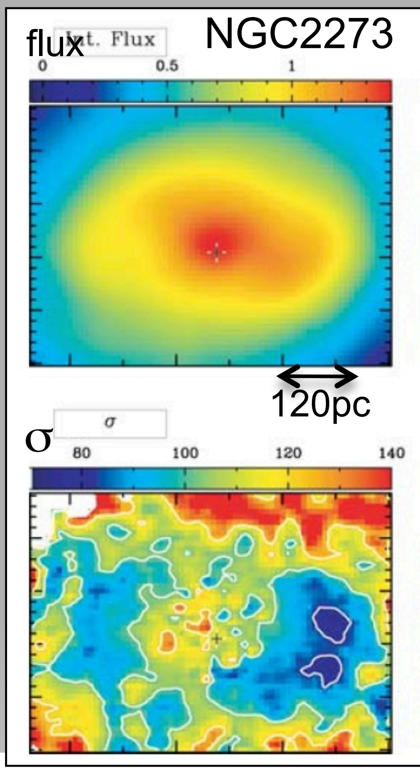


Alonso-Herrero et al. 2014

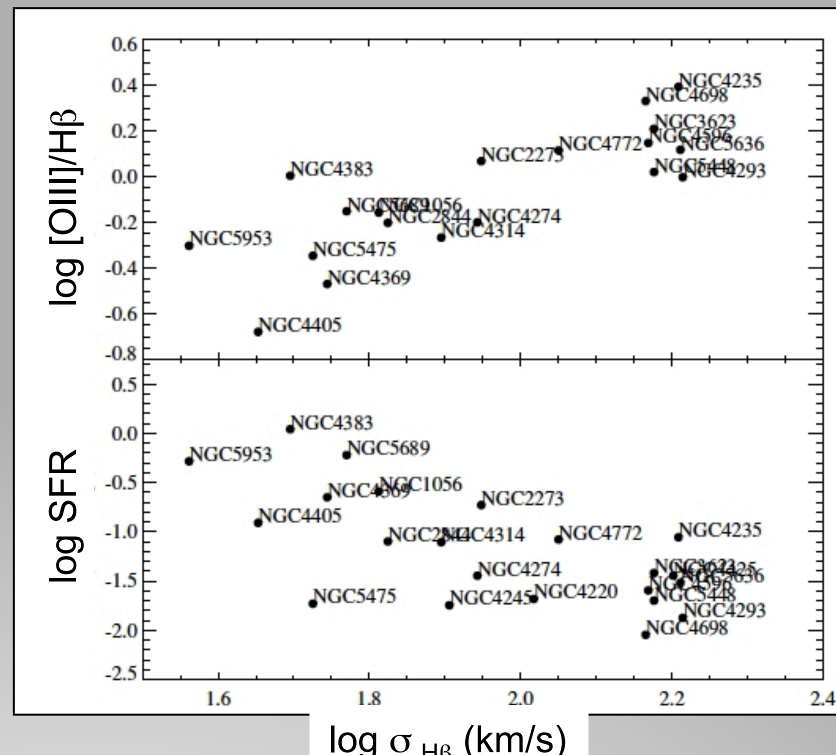
σ-drops in nuclear regions of Seyferts

Believed to be inflow-induced SF in a dynamically cold disk of gas, inner dust system of spiral arms or nuclear ring-like morphologies.

Higher rate of Seyferts among the σ-drop hosts.



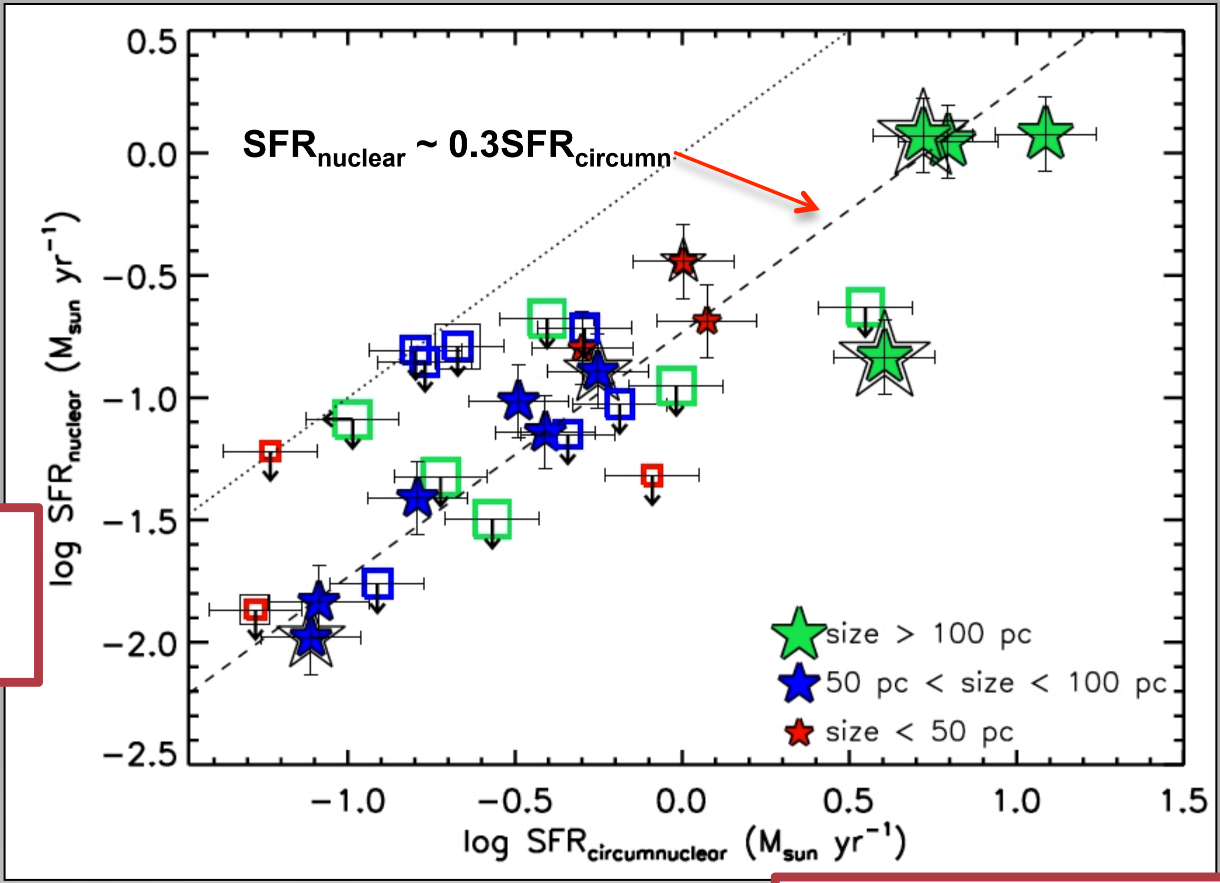
Barbosa et al. 2006



The SAURON project Sa galaxies: Falcón Barroso et al. 2006

See also: Elmsellen et al. 2006, Comeron et al. 2008, Riffel et al. 2011, Storchi-Bergmann et al. 2012

Nuclear vs. Circumnuclear SF in Seyferts



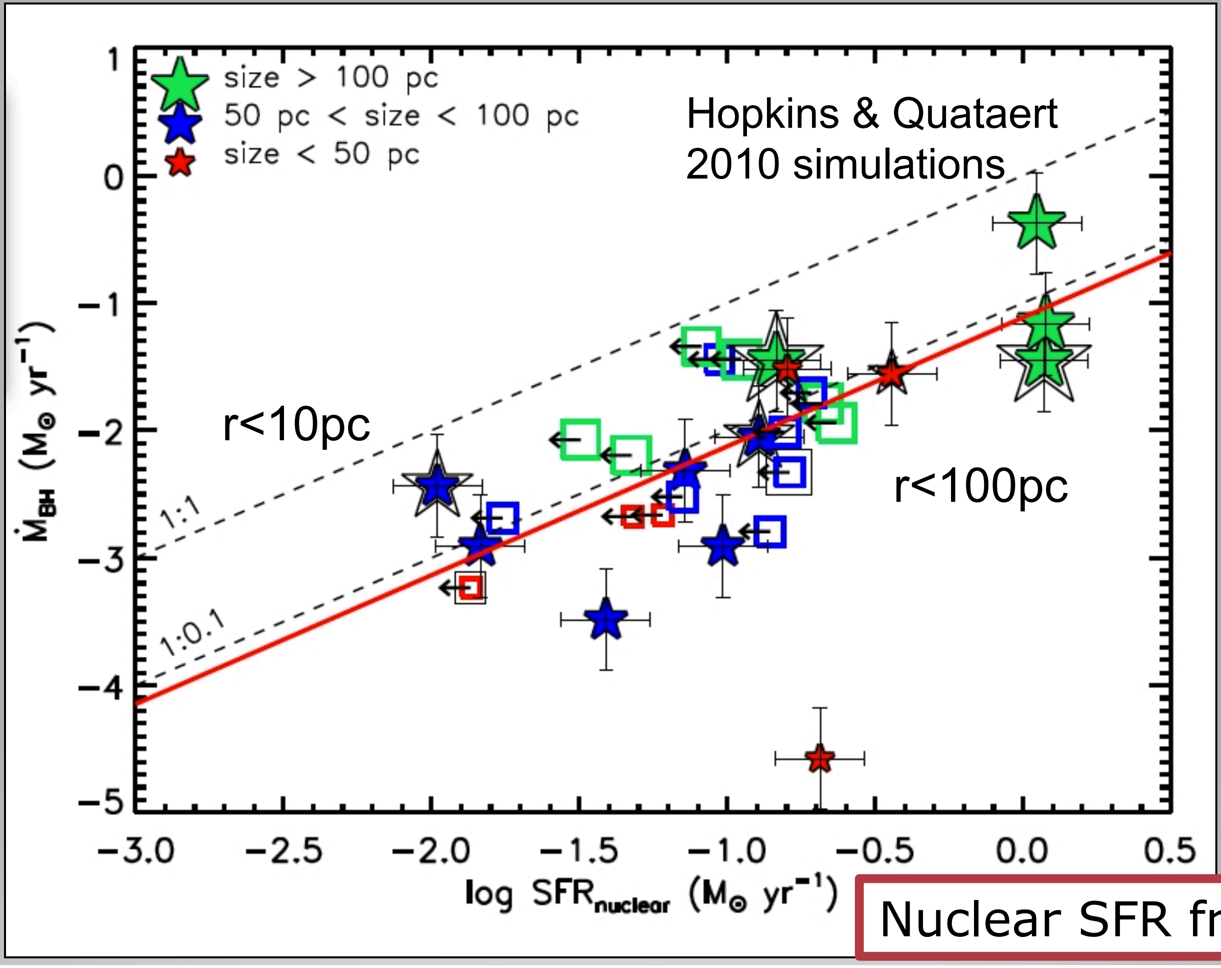
Nuclear (~100pc) SFR from L_{PAH}

Circumnuclear (~1kpc) SFR from L_{PAH}

Esquej et al. 2014

Black Hole Accretion Rate vs. nuclear SFR

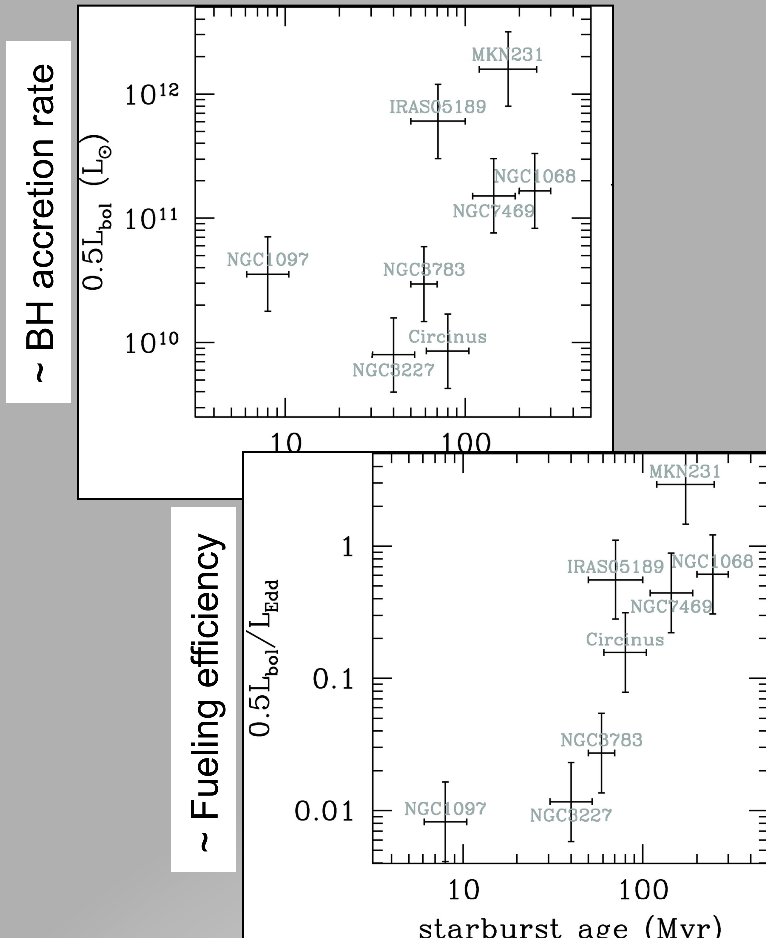
BHAR from L_X with a BC

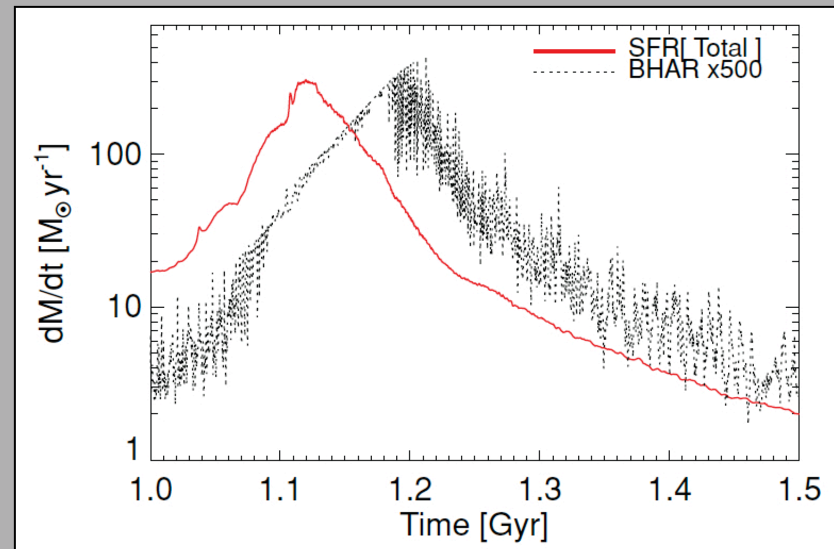


Nuclear SFR from L_{PAH}

Esquej et al. 2014

Delays between peaks of nuclear SF and BH growth





Peak of AGN activity occurs ~50–200 Myr after onset of SF activity

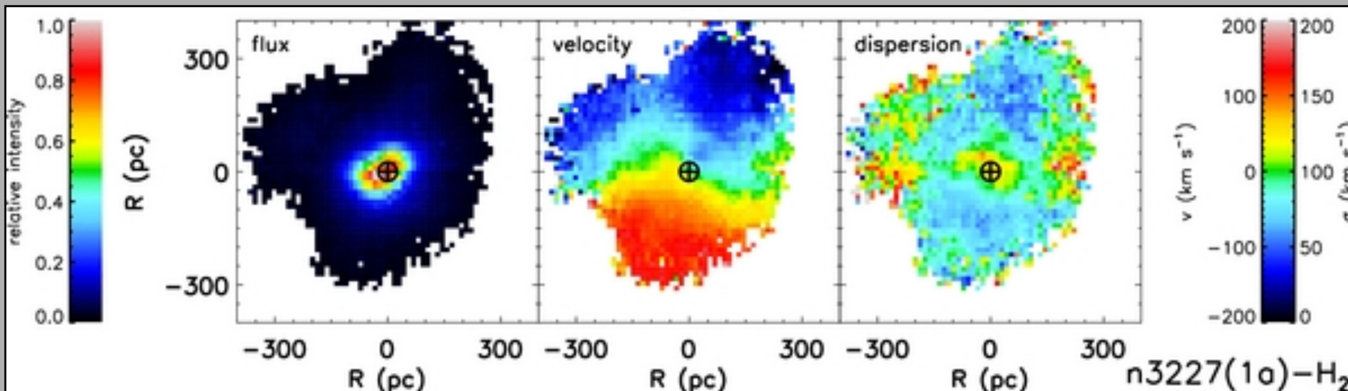
Stellar feedback feeds AGN?

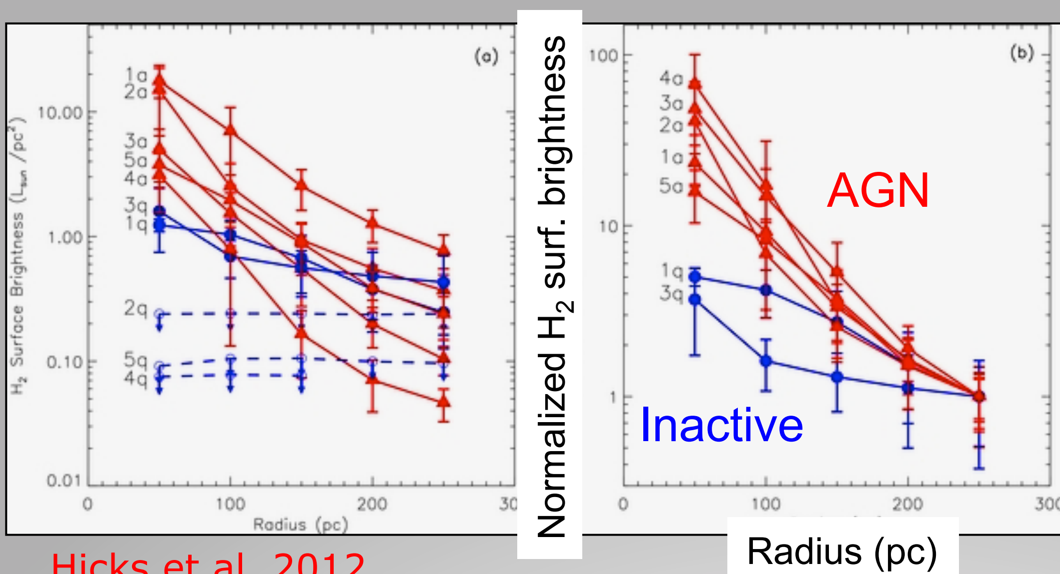
Observational evidence: Davies et al. 2007

Numerical simulations: Hopkins 2012

On large scales (host galaxy, kpc-scales): Schawinksi et al. 2009, Wild et al. 2010, Alonso-Herrero et al. 2013, **talk by Wild**

Molecular gas (H_2) in the nuclear regions





Hicks et al. 2012

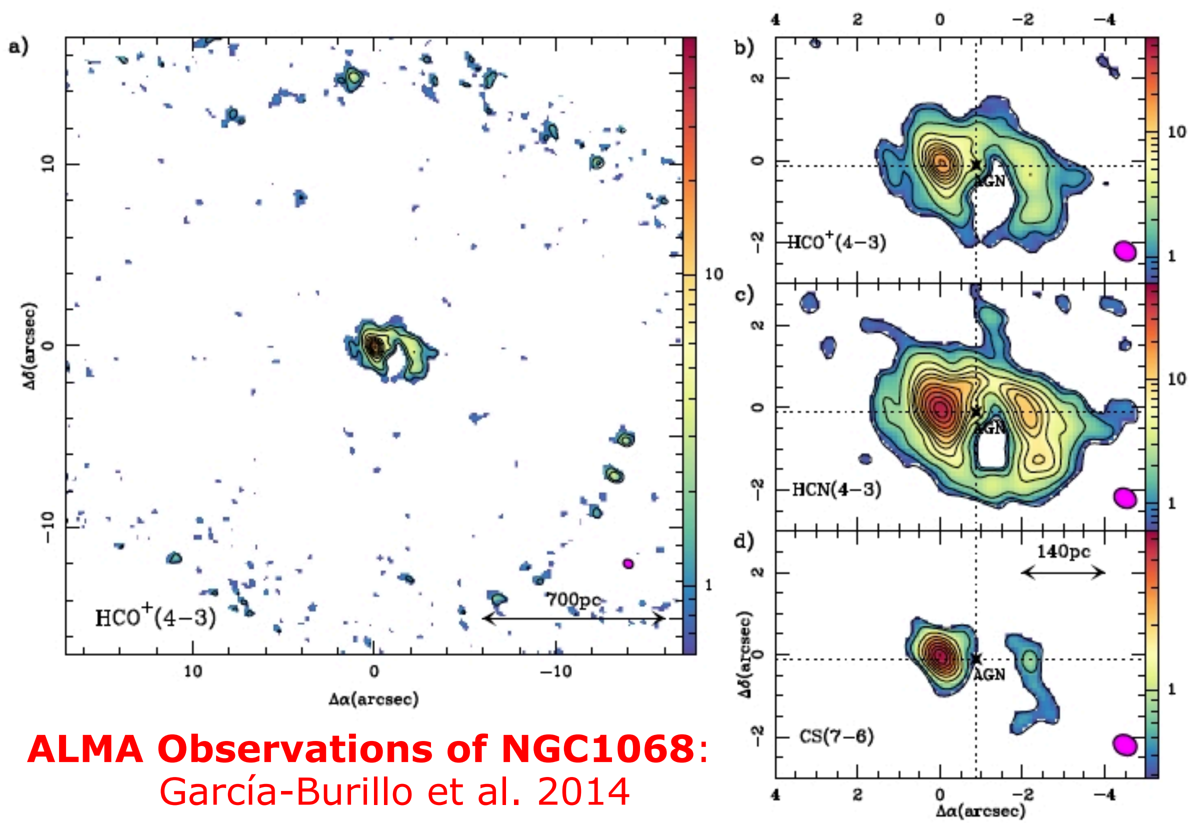
Rotating thick H_2 disks.

Seyfert nuclei (central 200pc) show enhanced H_2 emission compared to inactive galaxies.

H_2 at 2.12μm traces warm (T~1000K) gas and a small fraction of total M_{gas}.

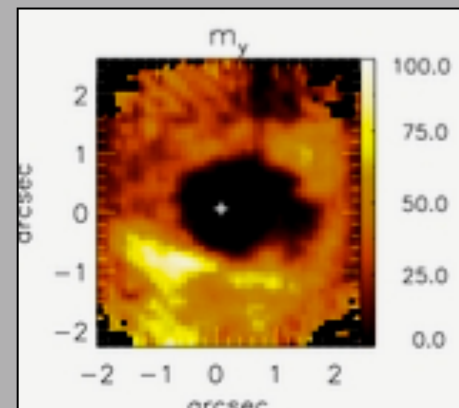
See also Hicks et al. 2009, Riffel et al. 2010, 2012, Storchi-Bergmann et al. 2012, Mazzalay et al. 2013a,b, Müller-Sanchez et al. 2013, Davies talk

Dense molecular gas in the nuclear regions



ALMA Observations of NGC1068:
García-Burillo et al. 2014

These transitions probe cold T~10-100K and dense n(H_2)~ 10^5-10^6 cm^{-3} gas.



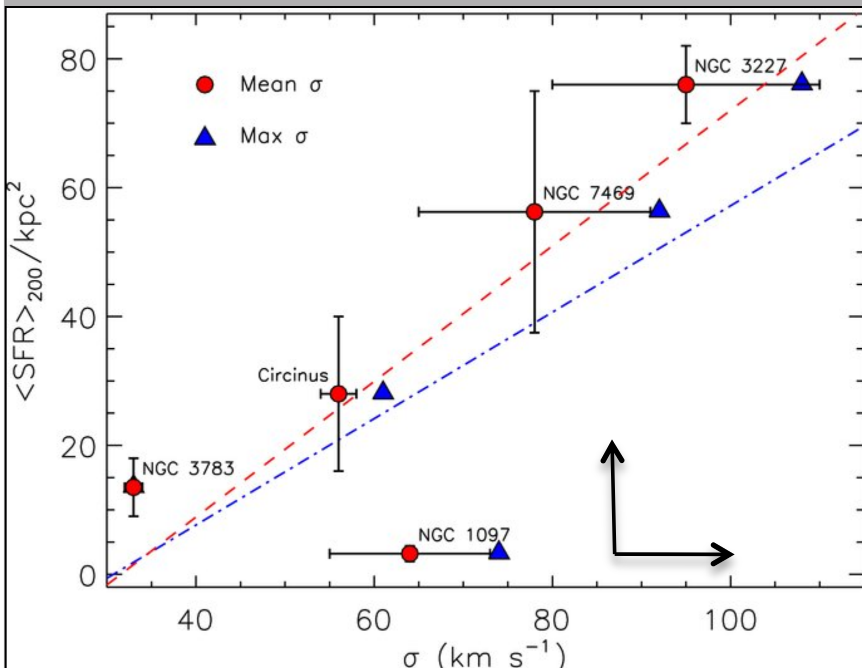
Young stars in NGC1068:
Storchi-Bergmann et al. 2012

There's dense molecular gas in central 50-100pc regions of Seyfert galaxies but not clear if conditions are suited for on-going SF in nuclear regions.

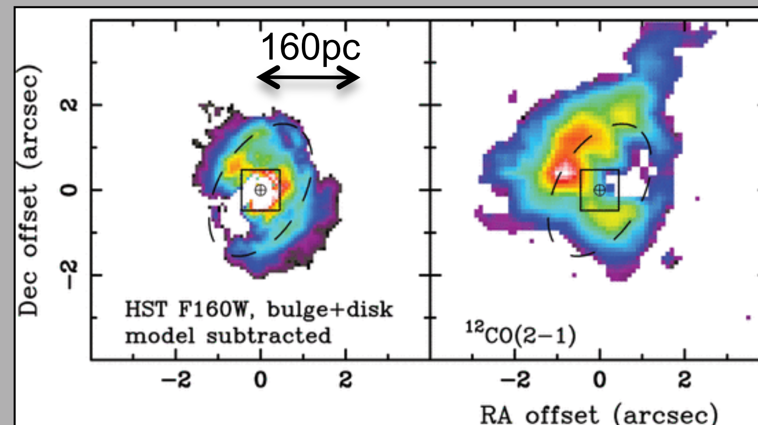
See also Matsushita et al. 2007, Krips et al. 2011, Sani et al. 2012, Izumi et al. 2013, Combes et al. 2013, Imanishi et al. 2013, Fathi et al. 2013, Combes review talk

Relation between nuclear SF, obscuration, torus?

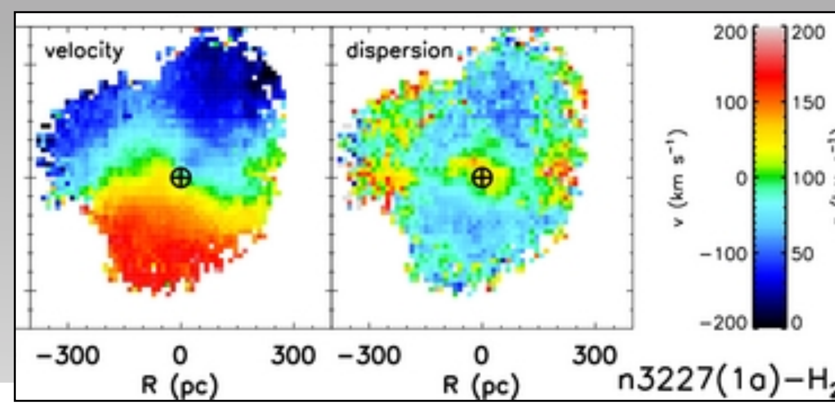
Molecular gas within central ~100 pc of Sy's is in a rotating, thick ($z_o/R \sim 1$) disk-like distribution spatially mixed with the nuclear stellar population.



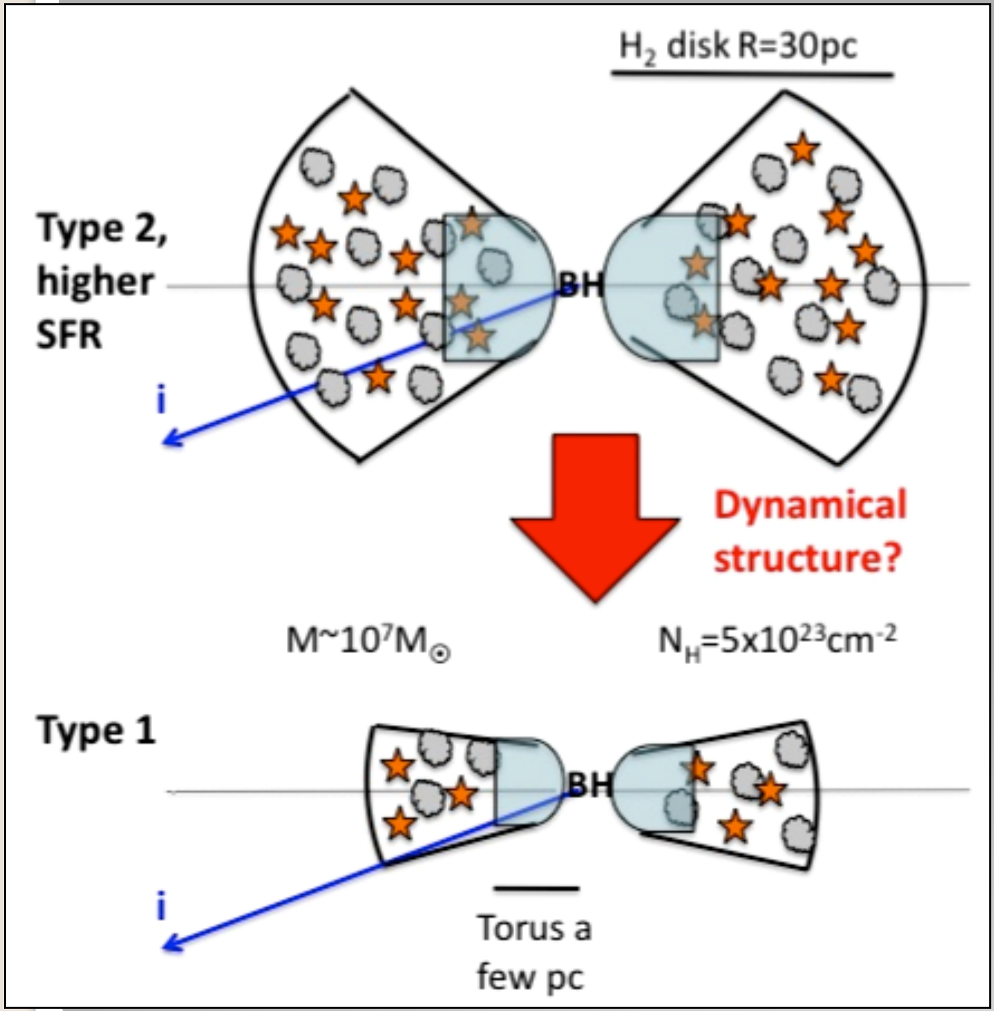
Hicks et al. 2009



Sani et al. 2012



But molecular line ratios indicate that the clouds are not self-gravitating and hence cannot form stars Lin & Davies poster!



Nuclear SF likely to play a role in obscuring the AGN.

Molecular gas disks might be the external part of the AGN torus.

Higher SF activity would be able to support the vertical extent of the torus and AGN would be more likely classified as a type 2 AGN.

Lower (decreasing) SFR would result in a thinner disk and a more likely classification as type 1 AGN.

Consistent with lower covering factors in Seyfert 1s and Seyfert 2s Ramos Almeida et al. (2011)

Conclusions

- ★ Evidence of nuclear SF in the nuclear regions of type 1 & 2 AGN -mostly local Seyferts because we can reach <100pc with current instrumentation.
- ★ Nuclear SF in Seyferts is not on-going. Recent starbursts took place 10-300Myr ago.
- ★ It is hard to quantify nuclear SF, especially in type 1 AGN, but near-IR stellar population synthesis and PAH features are promising indicators!
- ★ Recent SF detected as close as ~ 10pc from AGN.
- ★ Nuclear SF (over 100Myr) appears to be related to the AGN luminosity (i.e., black hole accretion rate), however, nuclear SF and active BH accretion do not appear to be coeval.
- ★ There is some evidence that nuclear SF plays a role in obscuring the AGN. Nuclear gas disks (r~30pc) where SF took place recently might be related to the outer parts of the dusty torus.