Lectures: M-Th

- **Lecture 1:** Starburst-AGN Connection
- **Lecture 2:** Ultraluminous Infrared Galaxies
- **Lecture 3:** Feedback Processes and Impact on Galaxy Formation and Evolution
- **Lecture 4:** Elemental Abundances as Tracers of Star Formation

Lecture #1:
Starburst – AGN Connection

S. Veilleux (U. Maryland)

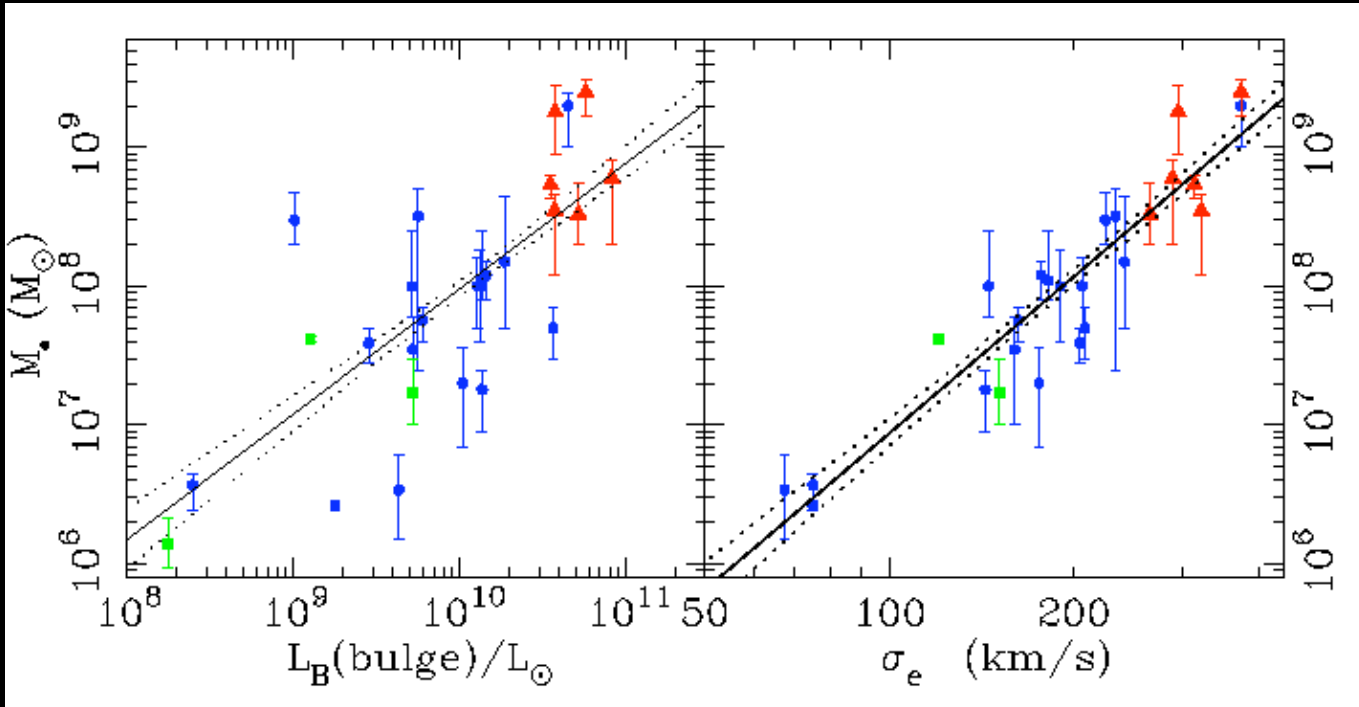
Plan

- Introduction
  - Black Hole – Galaxy Host relation
  - Feedback
- Star Formation Diagnostics
- Evidence for Starburst-AGN connection in:
  - Low-luminosity AGN
  - High-luminosity AGN
- Summary

Relevant Reviews

- **Kennicutt 1998, ARAA, 36, 189–232**
- **Veilleux 2000, astro–ph/0012121**

SMBH – Host Galaxy Relation



(Gebhardt et al. 2000)

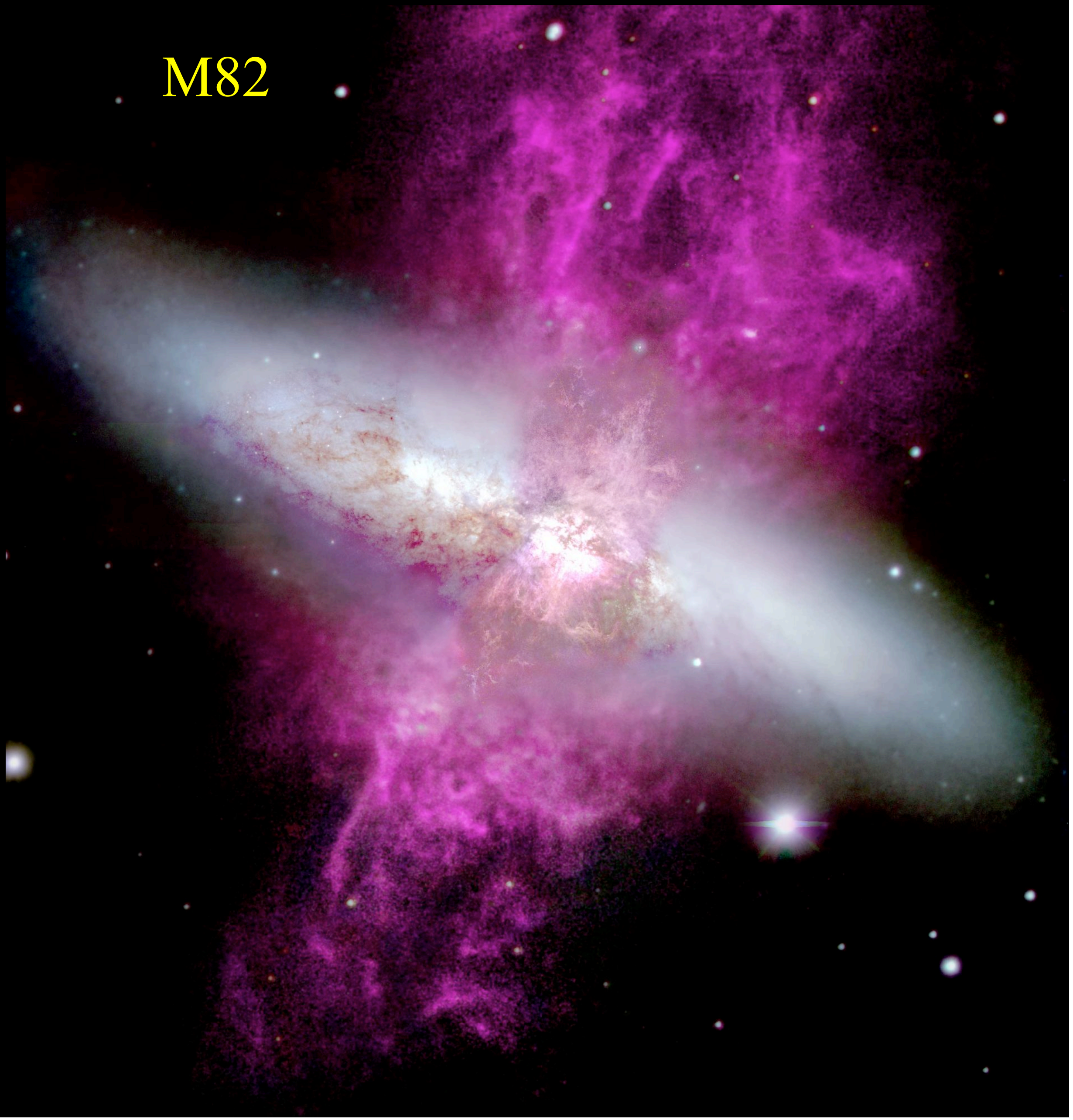
There is a close connection between SMBH and spheroids:

M(SMBH) ~ 0.001 M(bulge) $^{1.0}$ ***~ 1.3 x 10***^{8} ***M***$_{sun}$ ***(***σ_e***/200 km s***$^{-1}$***)***$^{4.0}$

→ **Causal connection between spheroid/galaxy formation (starburst) and BH growth (quasar activity)?**

Negative Feedback from Galactic Winds

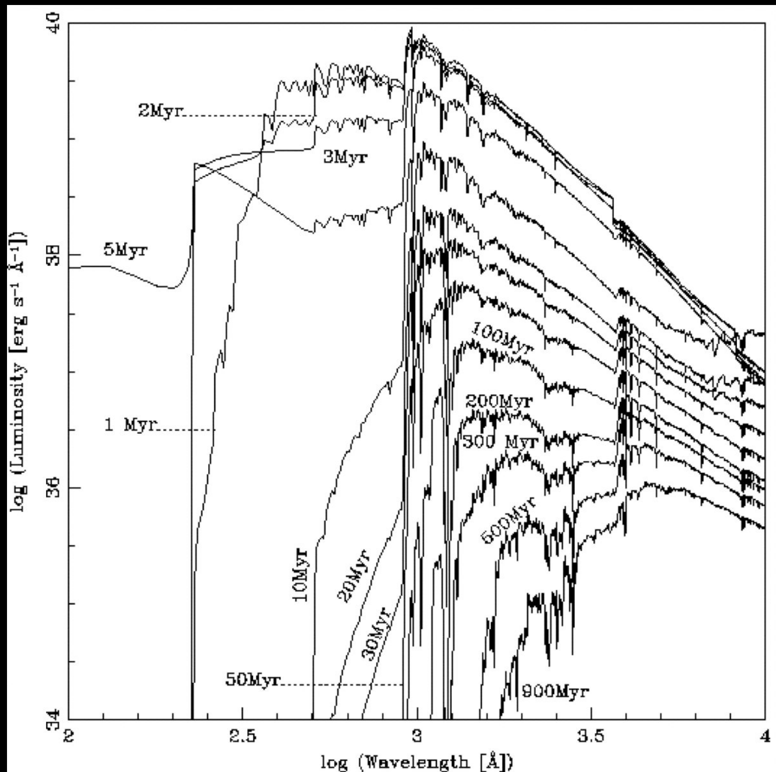
- Gas/radiation pressure from a starburst- and/or AGN-driven wind may help shut off the fuel supply to the BH and terminate star formation in the surrounding galaxy
  (e.g., Murray+05)



Star Formation Diagnostics: UV Continuum

- UV (1500 – 2800 Å) continuum scales linearly with luminosity of young stars and therefore with SFR
- For solar abundances and Salpeter "Initial Mass Function" (≡ IMF, 0.1 – 100 M_{sun}):

$$SFR\ (M_{sun}\ /\ yr) = 1.4 \times 10^{-28}\ L_{u}\ \text{(ergs / s / Hz)}$$



(Leitherer et al. 1999)

Star Formation Diagnostics:
Recombination Lines

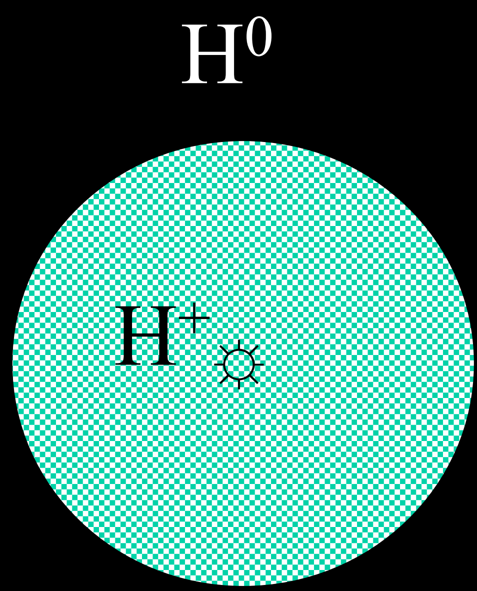
- Strömgren sphere around HII regions:

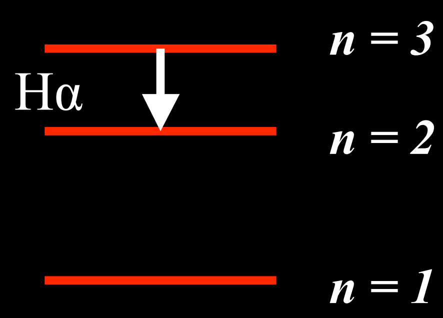
  # of ionizations = # of recombinations

- The nebular lines effectively re-emit the integrated stellar luminosity of galaxies shortward of the Lyman limit (≥ 13.6 eV)

- For solar abundances and Salpeter IMF (0.1 – 100 M_{sun}):

  SFR **(*M_{sun}* / *yr*) = *7.9 x 10^{-42} $L_{H\alpha}$*** (ergs / s)

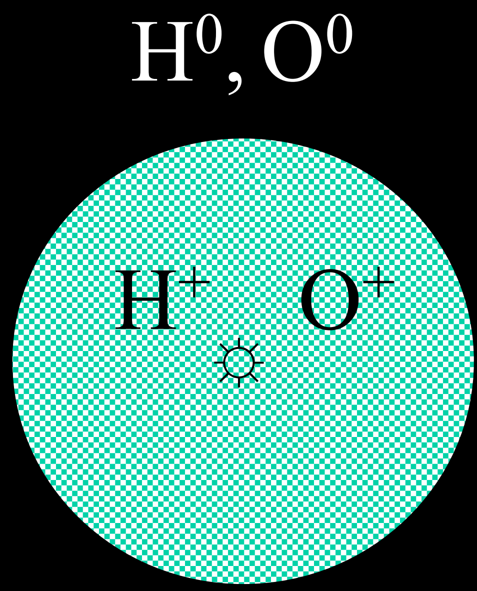




Star Formation Diagnostics: Forbidden Lines

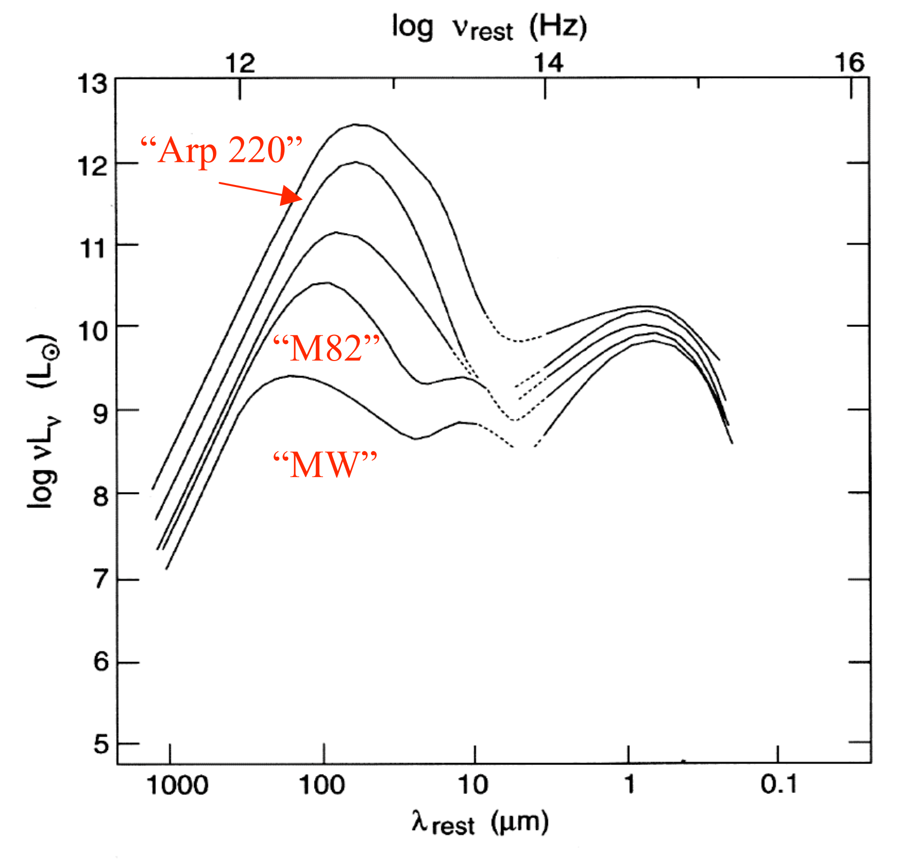
- **Hα is redshifted out of the visible window beyond *z* ~ 0.5**
- **Hβ and higher order Balmer emission lines are weak and stellar absorption more strongly influences the emission-line fluxes**
- **Strongest emission feature in the blue is [O II] λλ3727 forbidden-line doublet.**
- **Strength of [O II] is sensitive to abundance and ionization state of the gas**
- **Rough calibration:**

  $SFR\ (M_{sun}\ /\ yr) = (1.4 \pm 0.4)\ \times 10^{-41}\ L_{[O\ II]}$ (ergs / s)



Star Formation Diagnostics: Far–Infrared Continuum

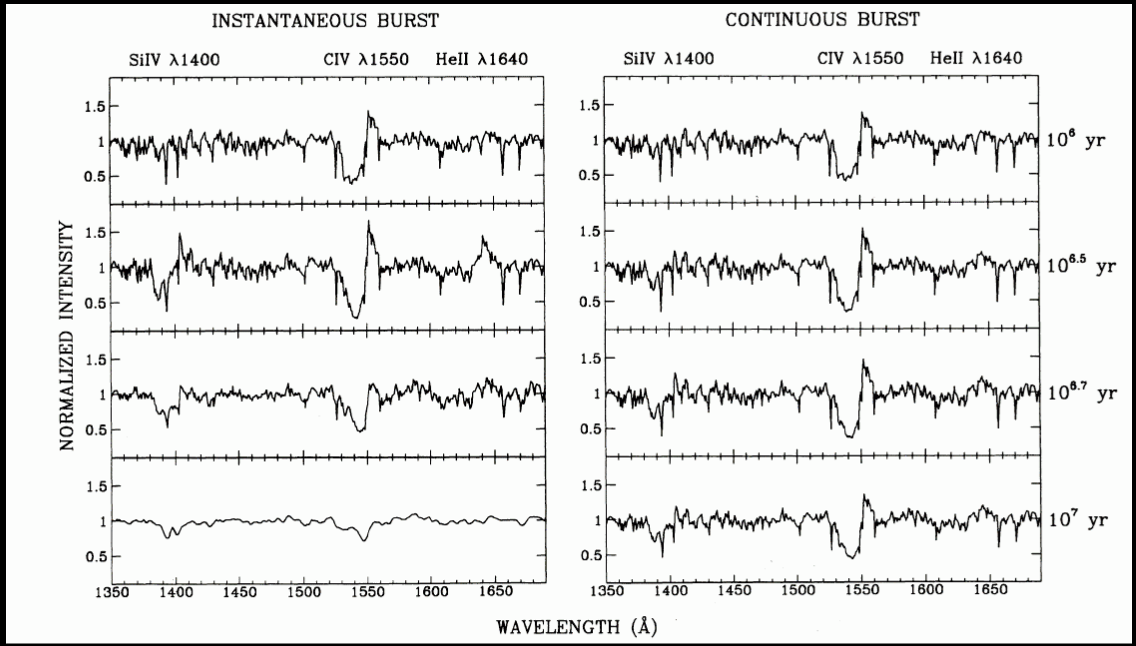
- A significant fraction of the bolometric luminosity of a galaxy is absorbed by interstellar dust and re-emitted in the thermal IR (10 – 300 μm)
- The absorption cross-section of the dust is strongly peaked in the UV, so in principle the FIR emission scales with SFR
- Limiting case: dust cocoon surrounding star-forming galaxy



SFR (M_{sun} / yr) = 4.5 x 10^{-44} L_{FIR} (ergs / s)

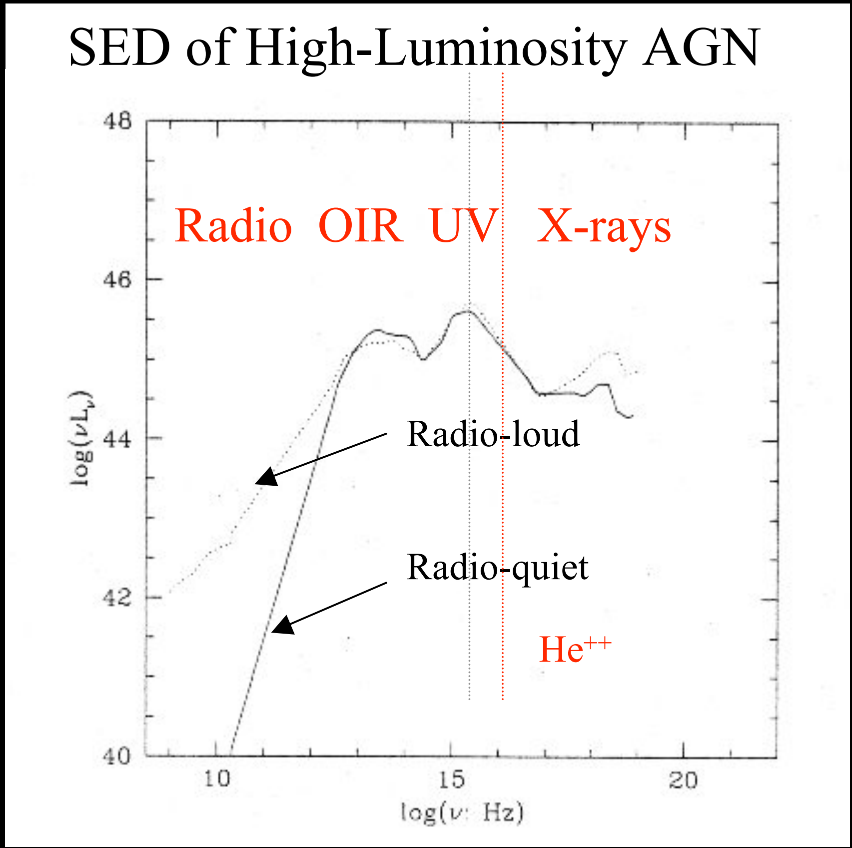
Star Formation Diagnostics
AGN Contamination

- **Optical/UV continuum:** **Use strengths of stellar atmospheric features to quantify starburst**
  - **Optical: Balmer series, Ca I Triplet λλλ8498, 8542, 8662**
  - **UV: Si IV λ1400, CIV λ1550, He II λ1640…**

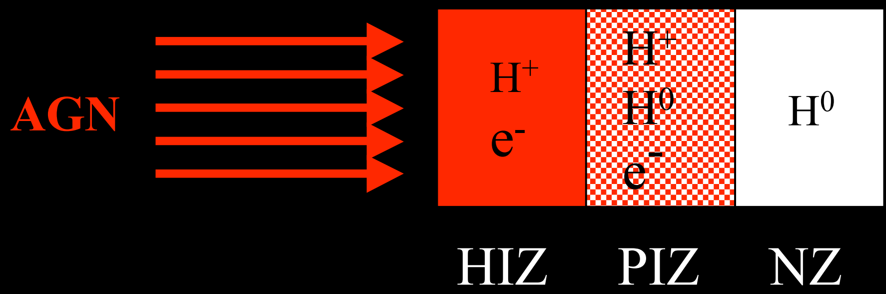


(Robert et al. 1993)

Star Formation Diagnostics: AGN Contamination



(Elvis et al. 1994)

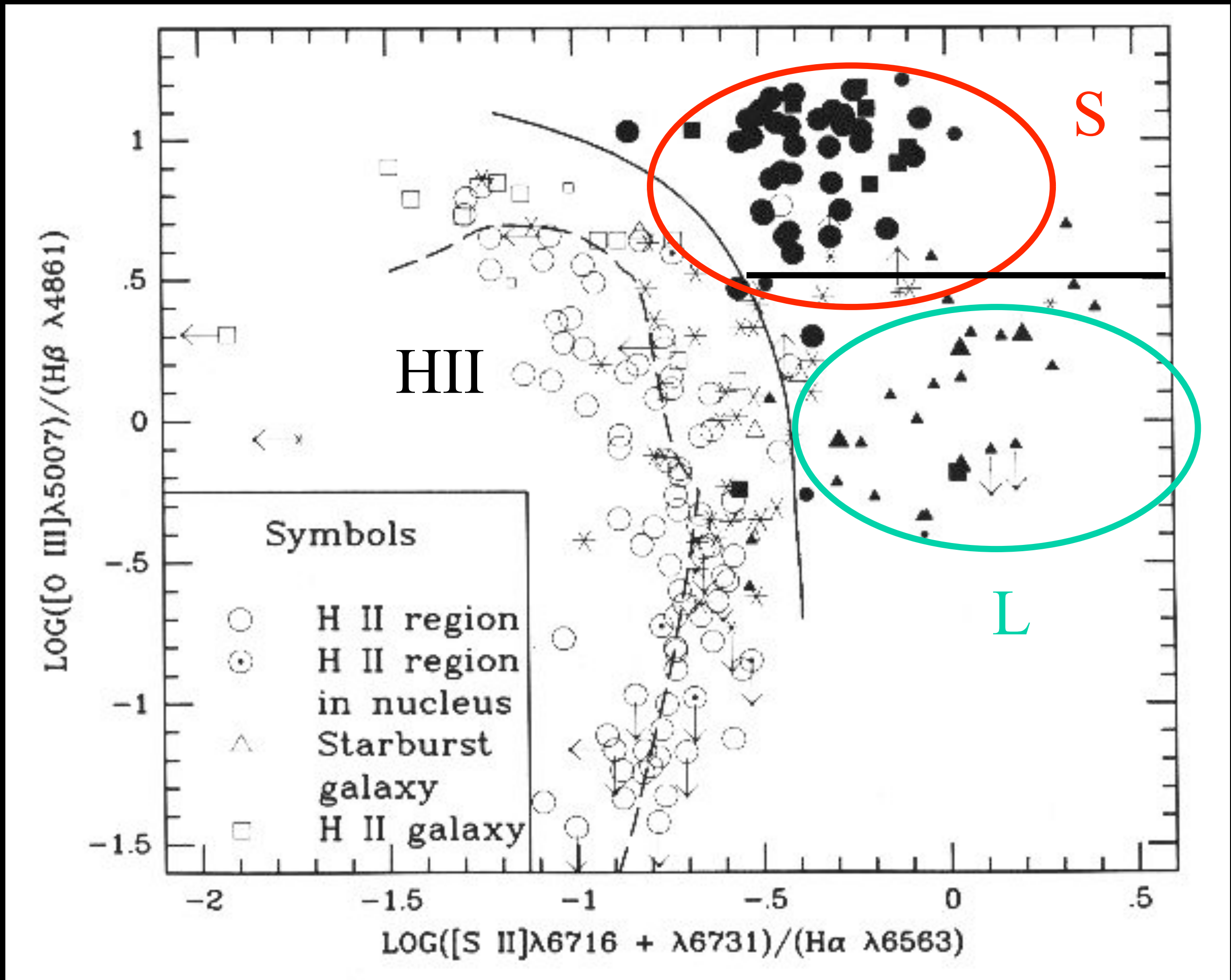


Emission lines

- The ionizing spectra of all but the hottest O stars cut off near the He II edge (54.4 eV)
- AGNs emit high-energy γ's
  - Emission of high ionization lines from material near AGN
  - Existence of partially ionized zones in material photoionized by AGN ($\sigma_\nu \sim \nu^{-3}$)
    - → Enhancement of collisionally excited low-ionization lines in AGN relative to those in HII

Optical Diagnostic Diagrams

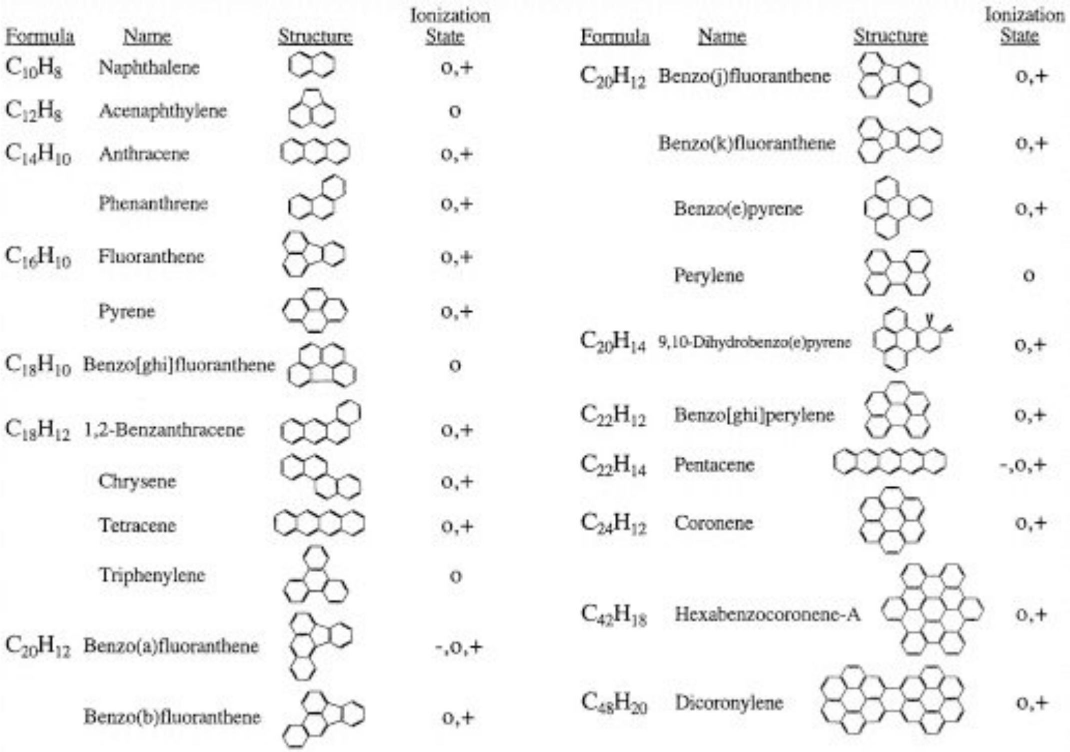
(SV & Osterbrock 1987)



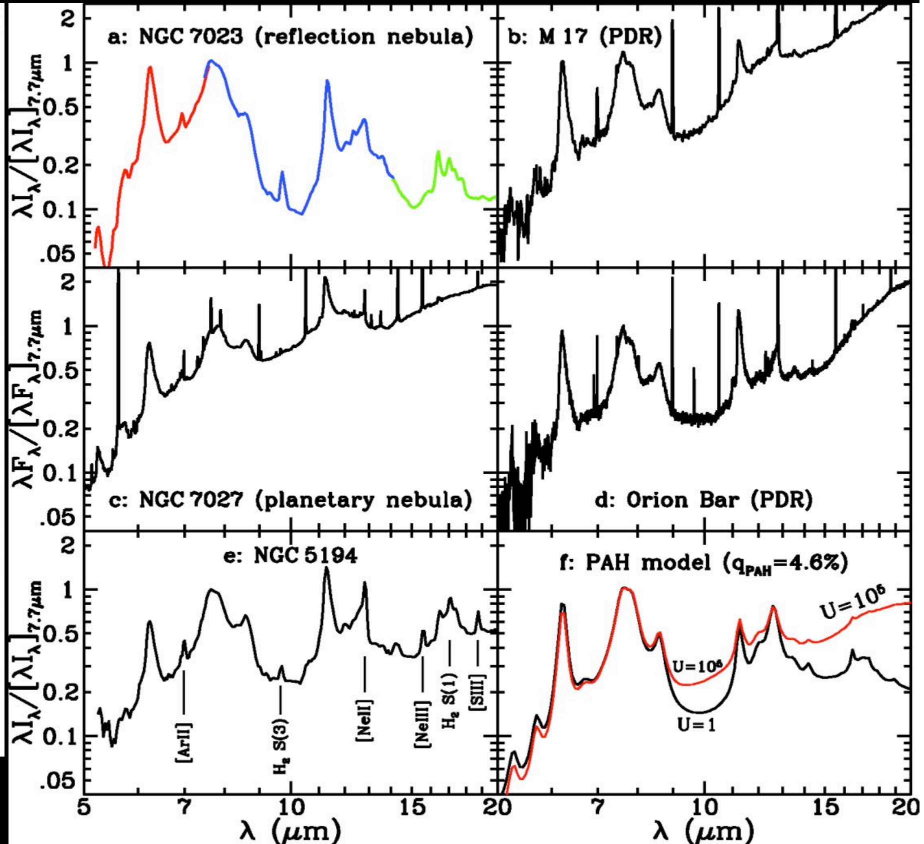
- Line ratios involve emission lines of similar wavelengths to minimize sensitivity to reddening

Star Formation Diagnostics: AGN Contamination

PAH = Polycyclic Aromatic Hydrocarbon



Formula	Name	Structure	Ionization State
$C_{10}H_8$	Naphthalene		o,+
$C_{12}H_8$	Acenaphthylene		o
$C_{14}H_{10}$	Anthracene		o,+
	Phenanthrene		o,+
$C_{16}H_{10}$	Fluoranthene		o,+
	Pyrene		o,+
$C_{18}H_{10}$	Benzo[ghi]fluoranthene		o
$C_{18}H_{12}$	1,2-Benzanthracene		o,+
	Chrysene		o,+
	Tetracene		o,+
	Triphenylene		o
$C_{20}H_{12}$	Benzo(a)fluoranthene		-,o,+
	Benzo(b)fluoranthene		o,+
$C_{20}H_{12}$	Benzo(j)fluoranthene		o,+
	Benzo(k)fluoranthene		o,+
	Benzo(e)pyrene		o,+
	Perylene		o
$C_{20}H_{14}$	9,10-Dihydrobenzo(e)pyrene		o,+
$C_{22}H_{12}$	Benzo[ghi]perylene		o,+
$C_{22}H_{14}$	Pentacene		-,o,+
$C_{24}H_{12}$	Coronene		o,+
$C_{42}H_{18}$	Hexabenzocoronene-A		o,+
$C_{48}H_{20}$	Dicoronylene		o,+

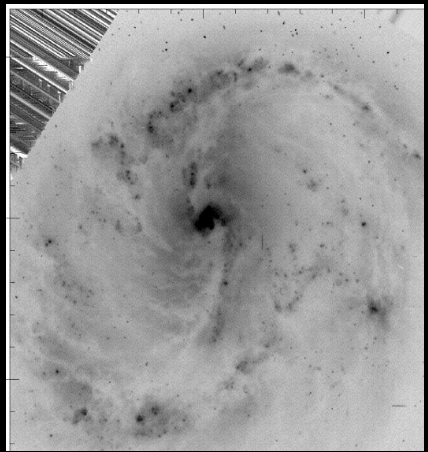
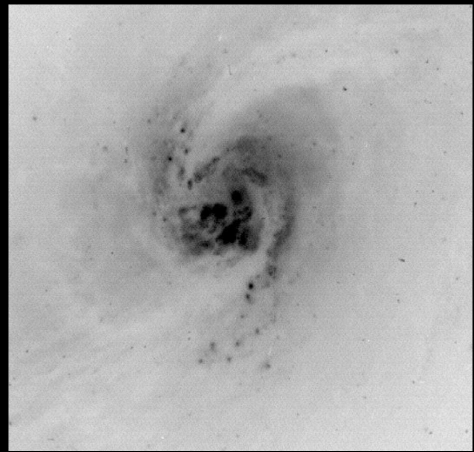
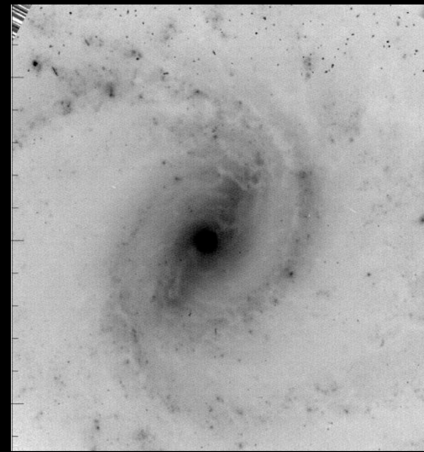


MIR PAH features are stronger in starbursts than in AGN

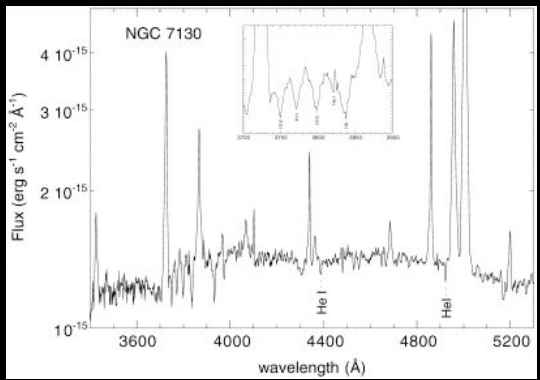
Low-Luminosity AGN

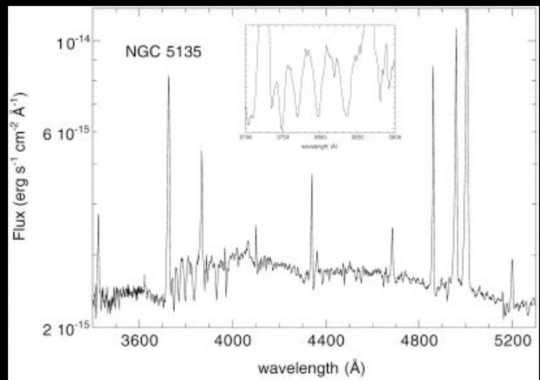
(Gonzalez Delgado + 98; also Muñoz Marín + 07)

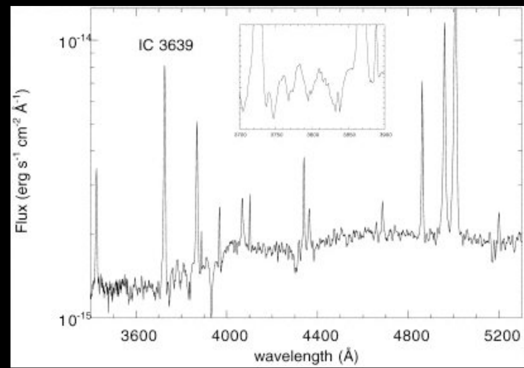
UV

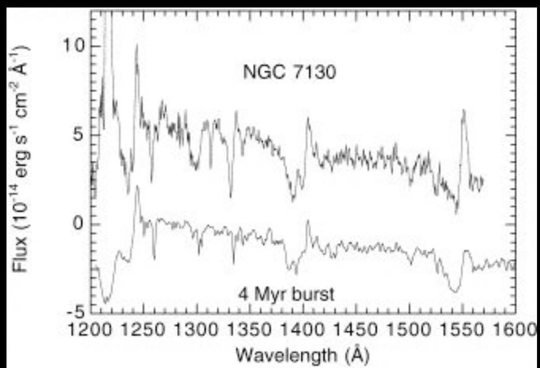
OPT

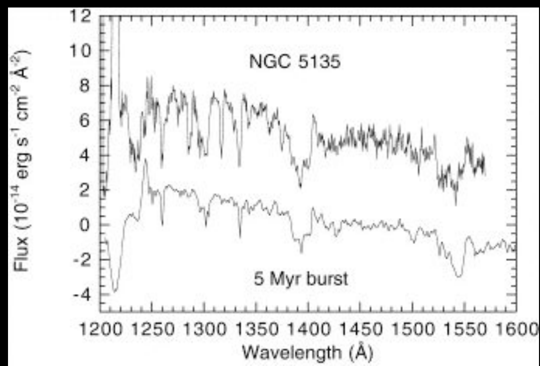


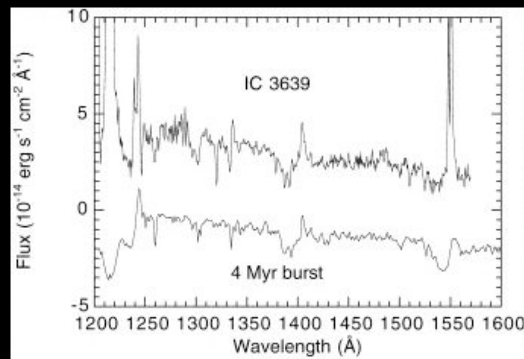




UV

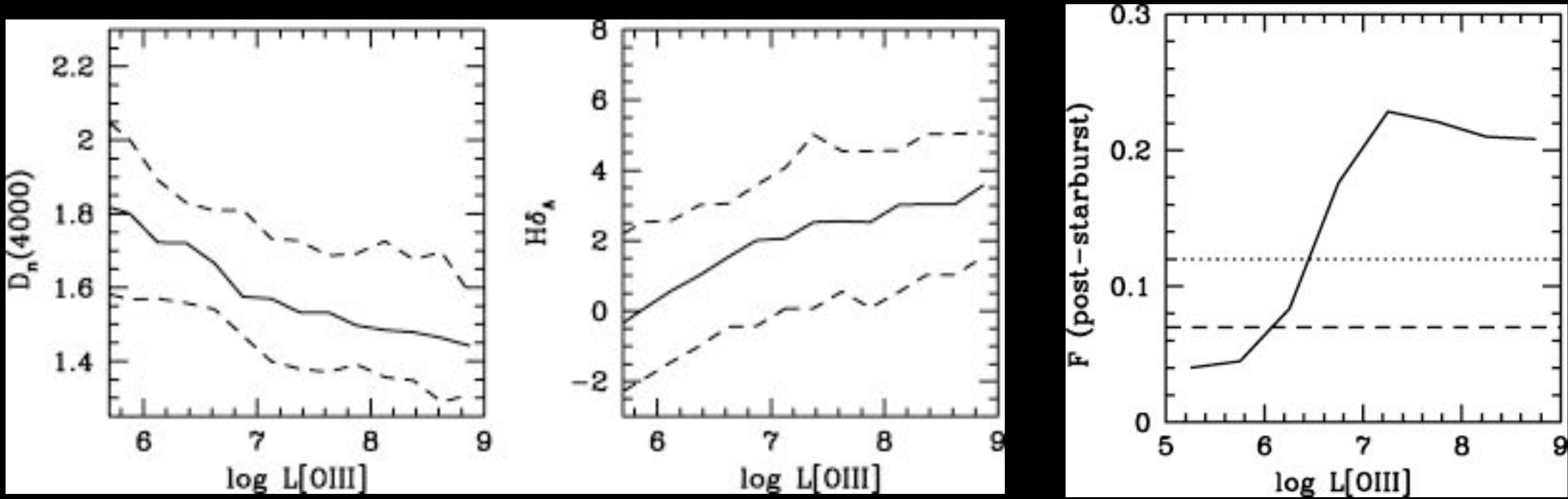






Low-Luminosity AGN: SDSS

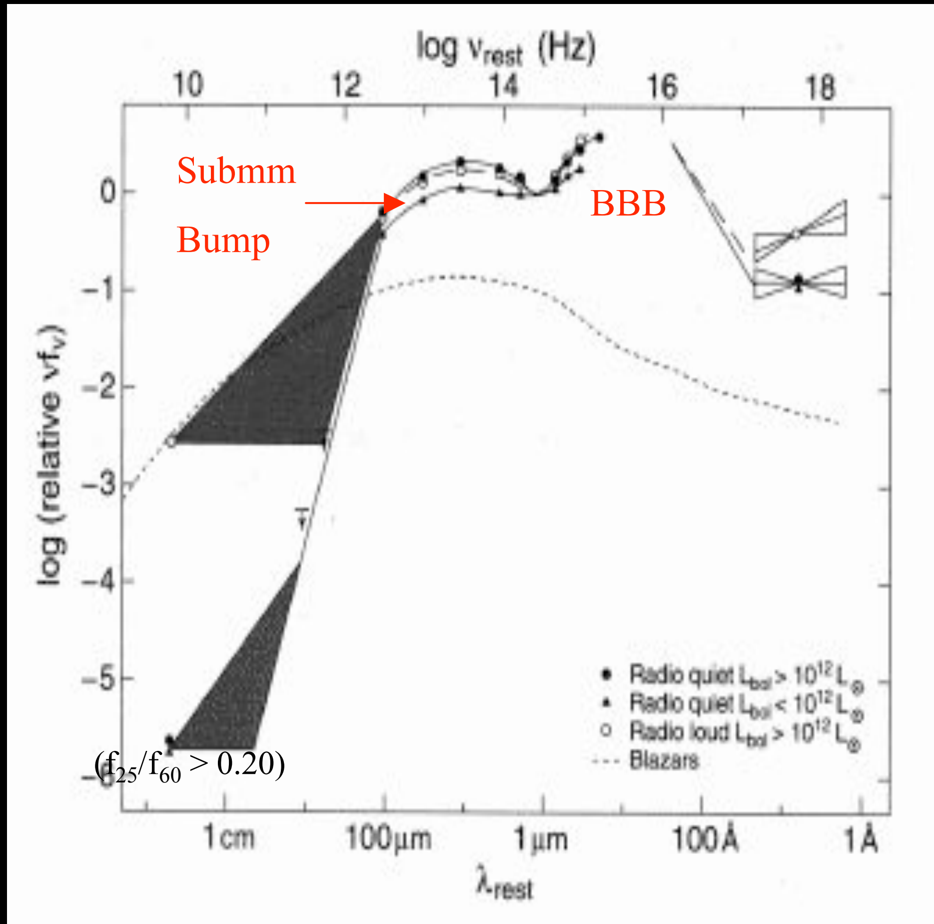
(Kauffmann et al. 2003)



- Sample: 22 623 narrow-line AGN with 0.02 < z < 0.3
- The hosts of low-luminosity AGN have stellar populations similar to normal early types
- The hosts of high-luminosity AGN have much younger mean stellar ages
- Young (< 1 Gyr) stellar population is a general property of AGN with high [O III] luminosity
- The young stars are spread out over scales of at least several kpc

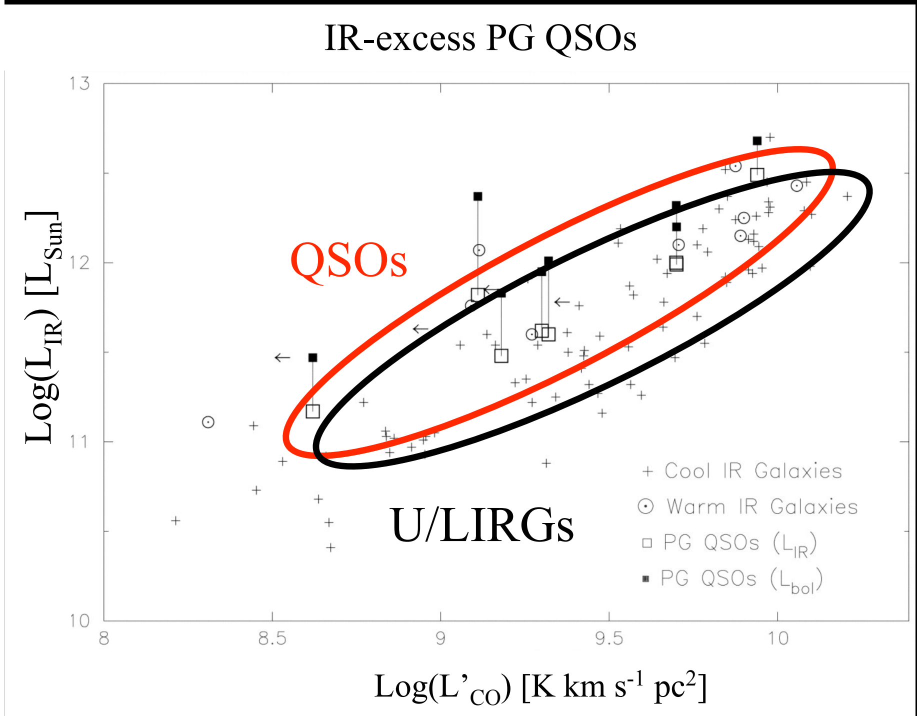
(see also R. Davies' lectures)

Starbursts in Local Quasars



(~ 20 – 30% show an IR excess: $L_{IR}/L_{BBB} > 0.4$)

Starbursts in Local Quasars

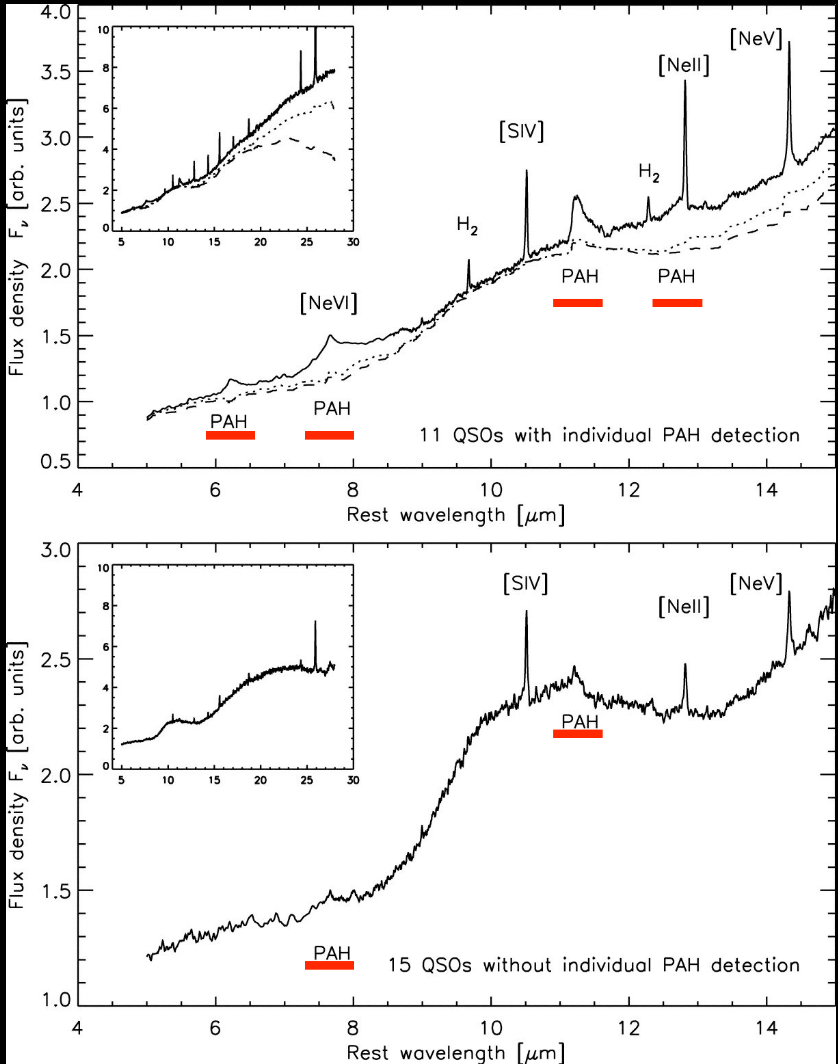


(Evans et al. 2001)

- $M(H_2) \sim 10^9$ – few x 10^{10} M_{Sun}
- M(dust) $\sim 10^6$ – few x 10^8 M_{sun}
- $M(H_2)$/M(dust) ~ Galactic
- IR-excess QSOs tend to have larger dust and H_2 masses

Starbursts in Local Quasars

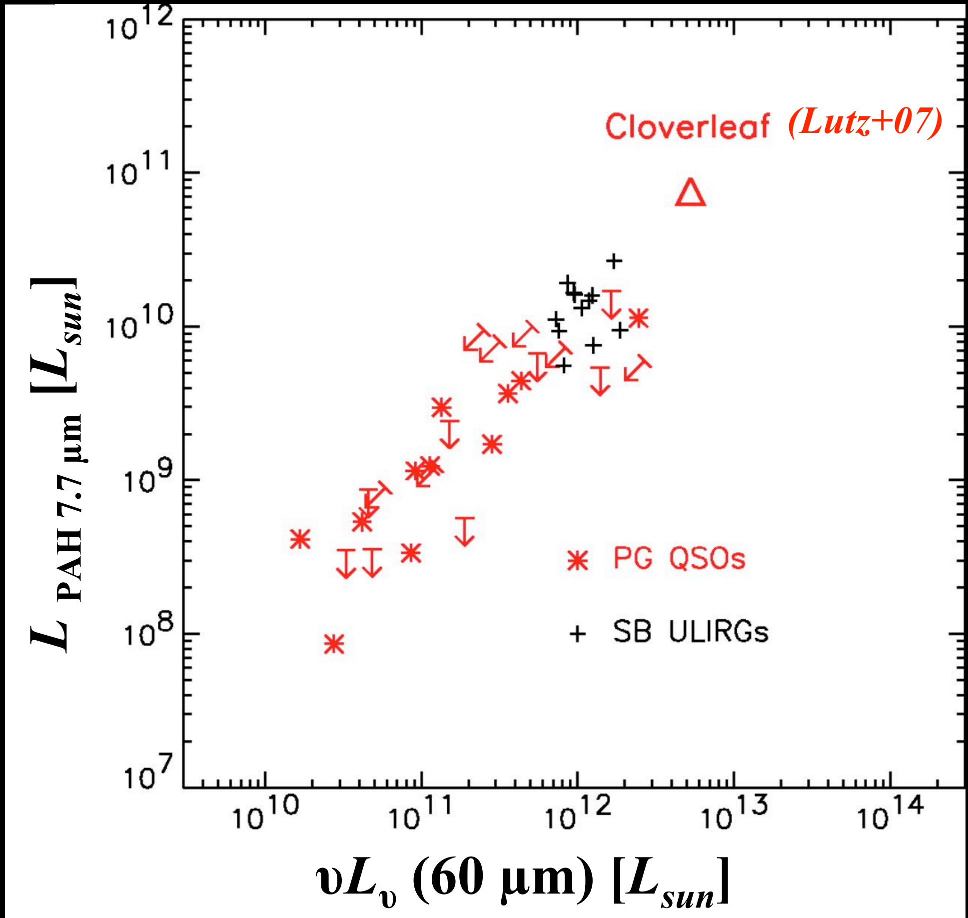
(Schweitzer et al. 2006)



- **PAH emission detected in 11 of 26 PG QSOs**
- **PAH emission is detected in average spectrum of other 15 PG QSOs**

Starbursts in Local Quasars

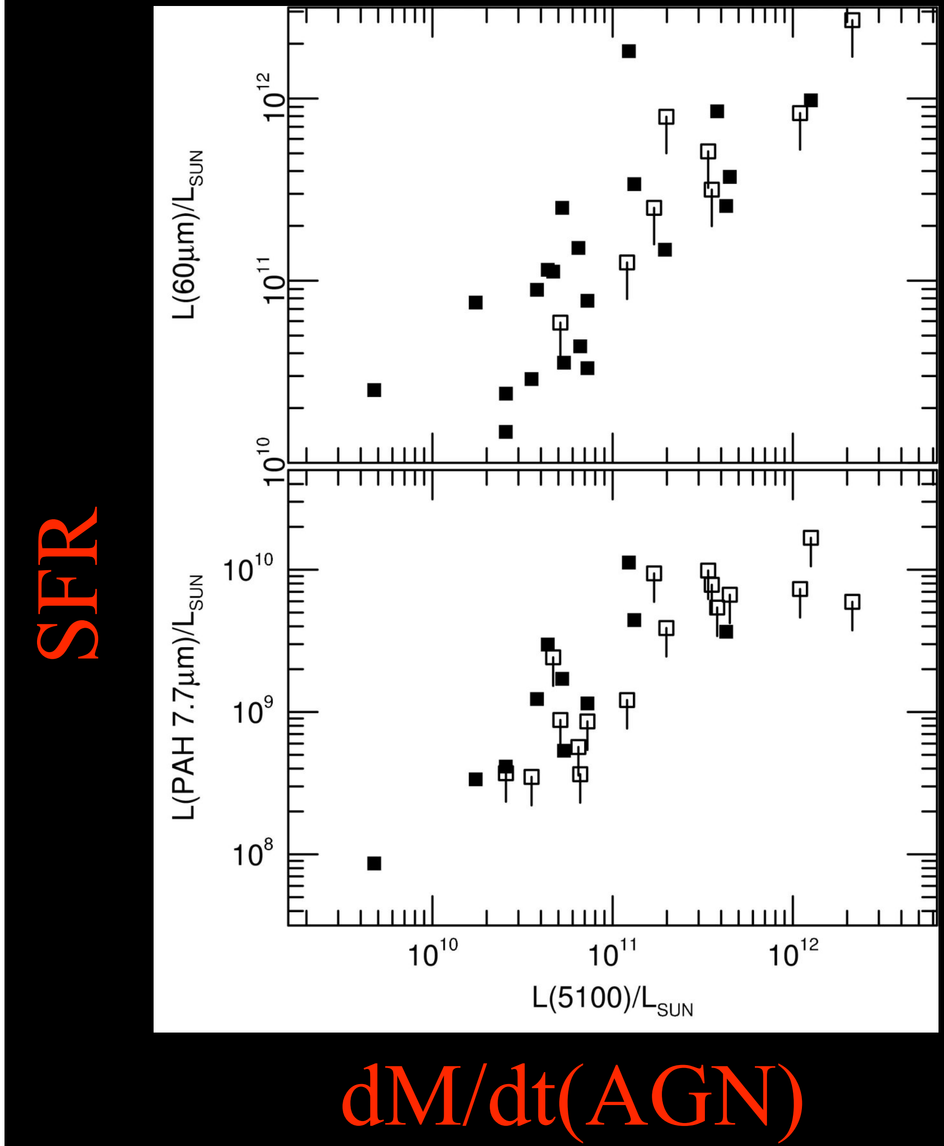
(Schweitzer et al. 2006)



- Strength of PAHs in quasars is consistent with FIR luminosity being produced primarily by U/LIRG-like starbursts (2 – 300 M_{sun} / yr)

Starbursts in Local Quasars

(Netzer et al. 2007)

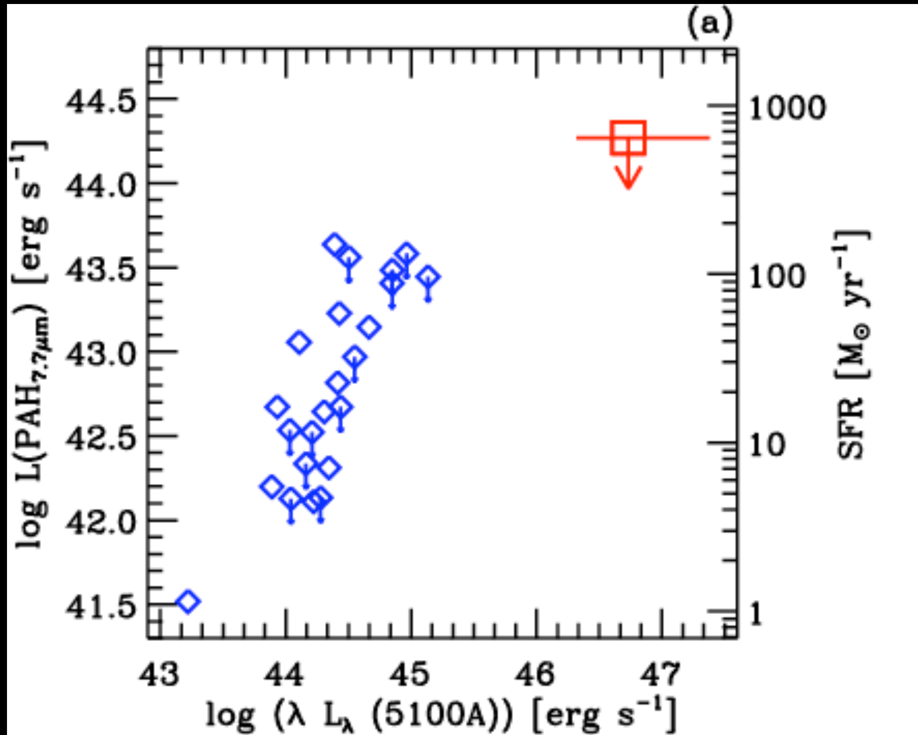


- Strength of starburst correlates with that of QSO

→ strong starburst – AGN connection!

Starbursts in High-z Quasars

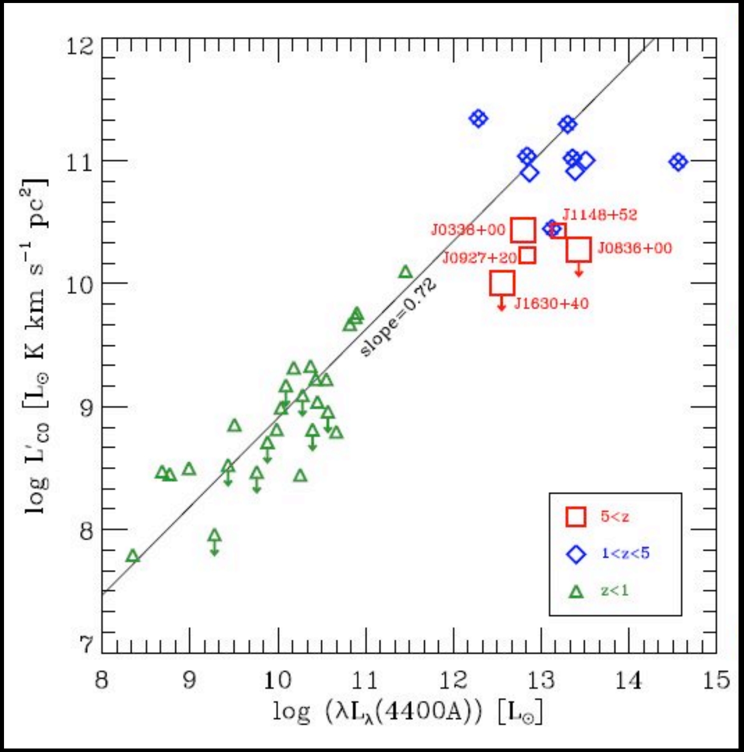
(Maiolino et al. 2007)



- Luminous, high-z QSOs do not show evidence for PAH emission
- The correlation between star formation rate and AGN power appears to “saturate” at high luminosities

Molecular Gas in High-z Quasars

(Maiolino et al. 2007b)



- Flattening of CO emission vs nuclear optical emission
- Less fuel at high z

Summary

- The tight SMBH – spheroid relation seen at low redshift must imply a tight starburst – AGN connection over the history of the Universe
- Starbursts often coexist with active SMBH
- There is a tight starburst – AGN relation in high-luminosity AGN but not in low-luminosity AGN
  - BH fueling in low-luminosity AGN is stochastic and does not necessarily scale with the surrounding starburst
  - BH fueling in high-luminosity AGN is likely induced by a major merger of galaxies that also produces a major nuclear starburst event
  - A lack of “fuel” (= molecular gas) may explain the apparent break in the starburst-AGN connection at very high AGN luminosities