Hidden Supermassive Black Holes in Star-Forming Galaxies

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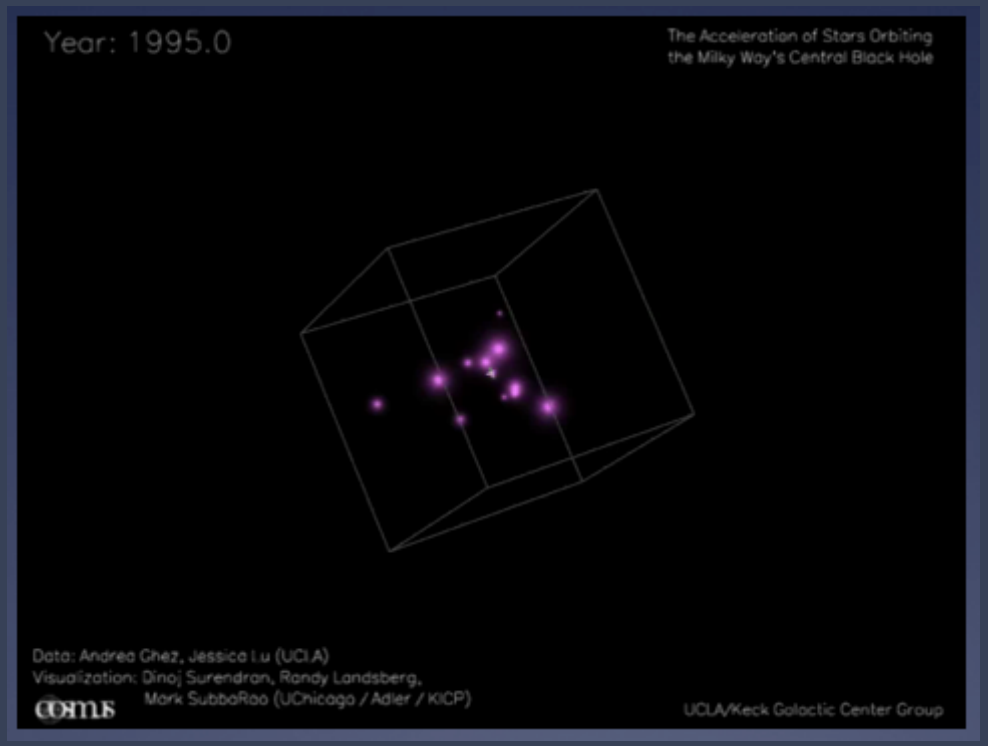
Outline

- Intro: Active Galactic Nuclei / supermassive black holes
- MEx AGN diagnostic
- AGN fraction (& obscuration) in star-forming galaxies
- Challenges at high redshifts

Supermassive Black Holes are:

- **Massive: 10^6 – 10^9 $M_\odot$ (3-4x10^6 $M_\odot$ in Milky Way)**

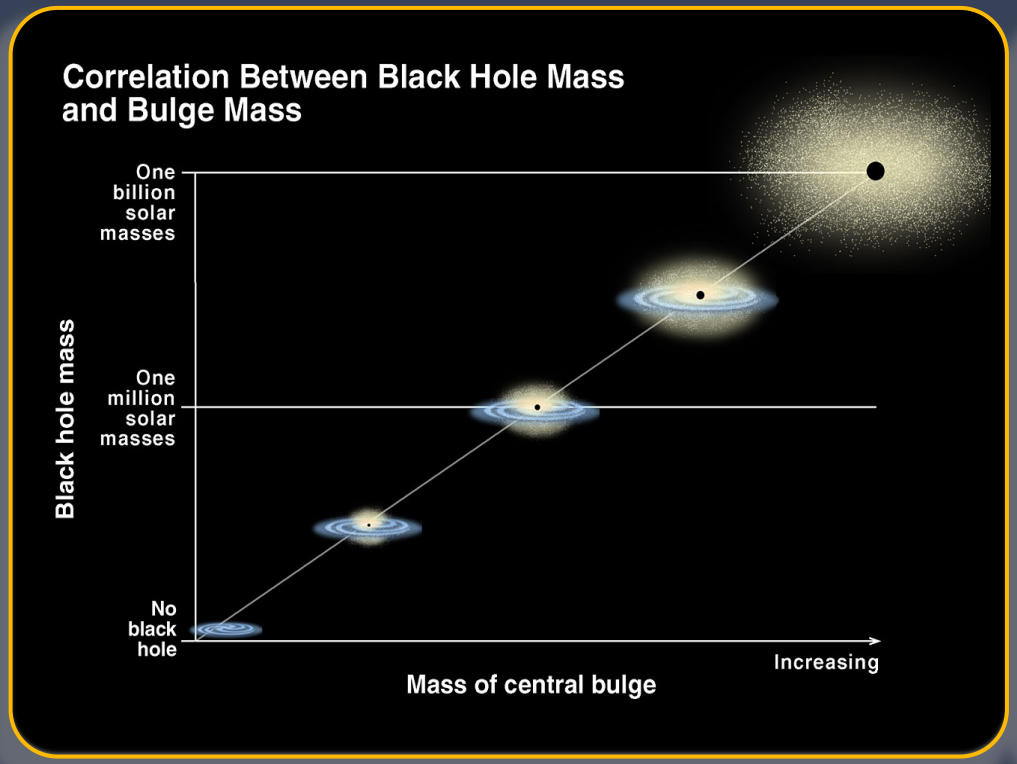


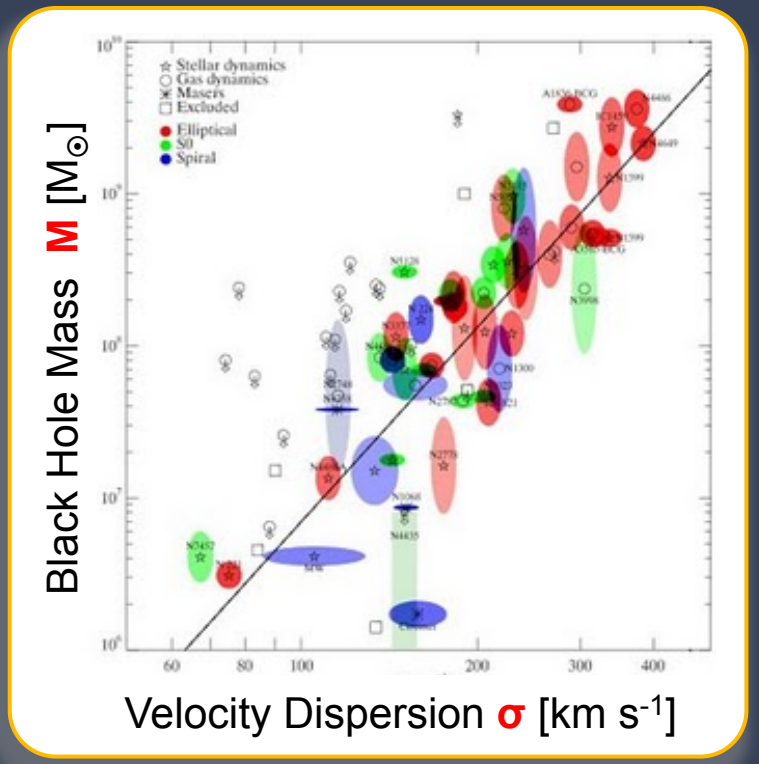
(Ghez et al. 2000; Genzel; +follow-up for 16 years in Gillensen et al. 2008)

Supermassive Black Holes are:

- Massive: 10^6 – 10^9 $M_\odot$ (3-4x10^6 $M_\odot$ in Milky Way)
- Common (in ~all galaxies) but not always ‘active’
- **Aware of their host galaxy’s mass**

- Black-Hole Mass – Galaxy Velocity Dispersion (M-σ) relation
  (e.g., Magorrian+ 1998; Ferrarese & Merritt 2000; Haring & Rix 2004)





Gultekin et al. 2009

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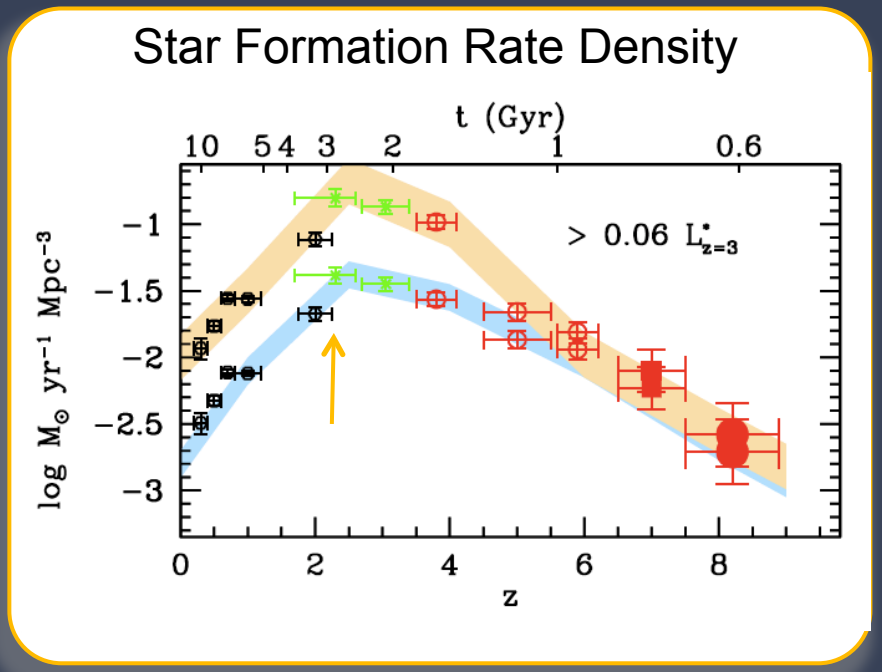
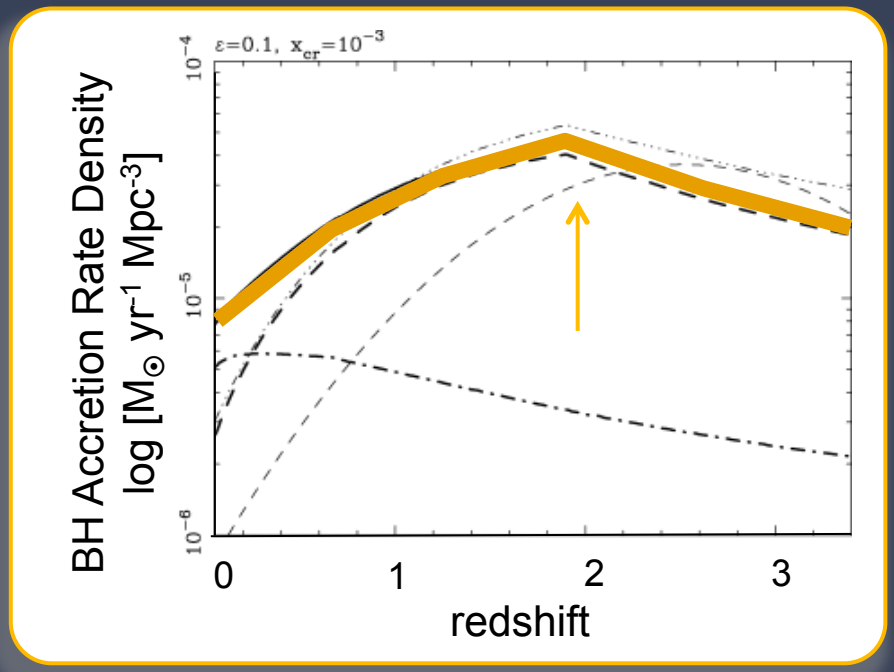
- Common (in ~all galaxies) but not always 'active'
- Aware of their host galaxy's mass
- **Growing at the same epoch as galaxies**

- Star formation history and black hole accretion history peaked at z~2 and declined steeply since z=1



Bouwens et al. 2010 (also see Hopkins+04)



Merloni et al. 2004 (also see Barger et al. 2001)

- Star formation rate / black hole accretion rate ~ constant *when taking volume-averages* (z=1-2, Mullaney+ 2012; also seen as sBAR tracking sSFR by Bongiorno+ 2012)

Supermassive Black Holes are:

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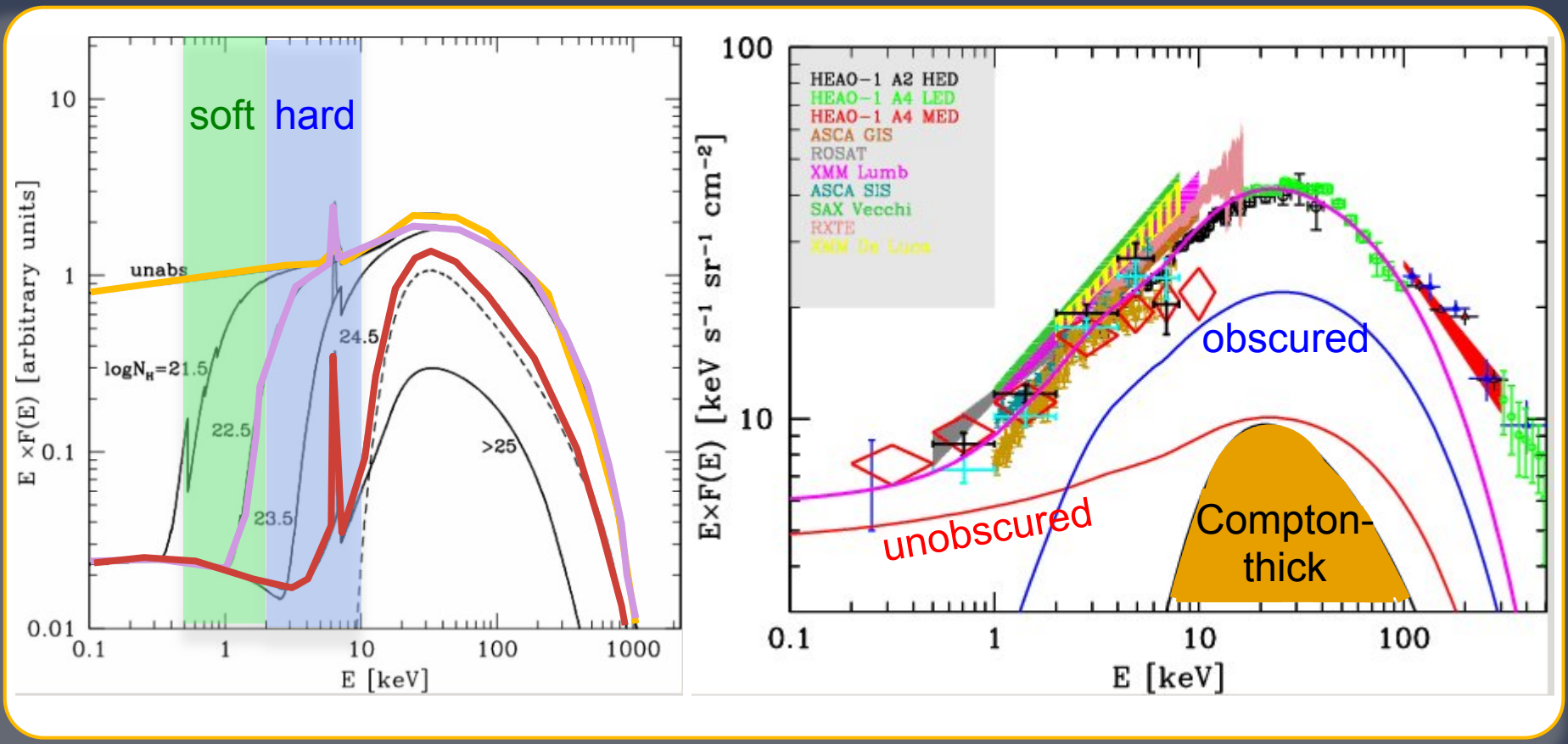
- Aware of their host galaxy's mass
- Growing at the same epoch as galaxies
- **(can be) Hidden even while 'active'**

  (from the Cosmic X-ray Backgroud: e.g., Gilli+ 2007; Comastri+ 95; Mushotzky+ 2000; Alexander+ 03; Bauer+ 04; Treister & Urry 2005)

Cosmic X-ray Background



Gilli+ 2007

(also see Comastri+ 95; Mushotzky+ 2000; Alexander+ 03; Bauer+ 04; Treister & Urry 2005)

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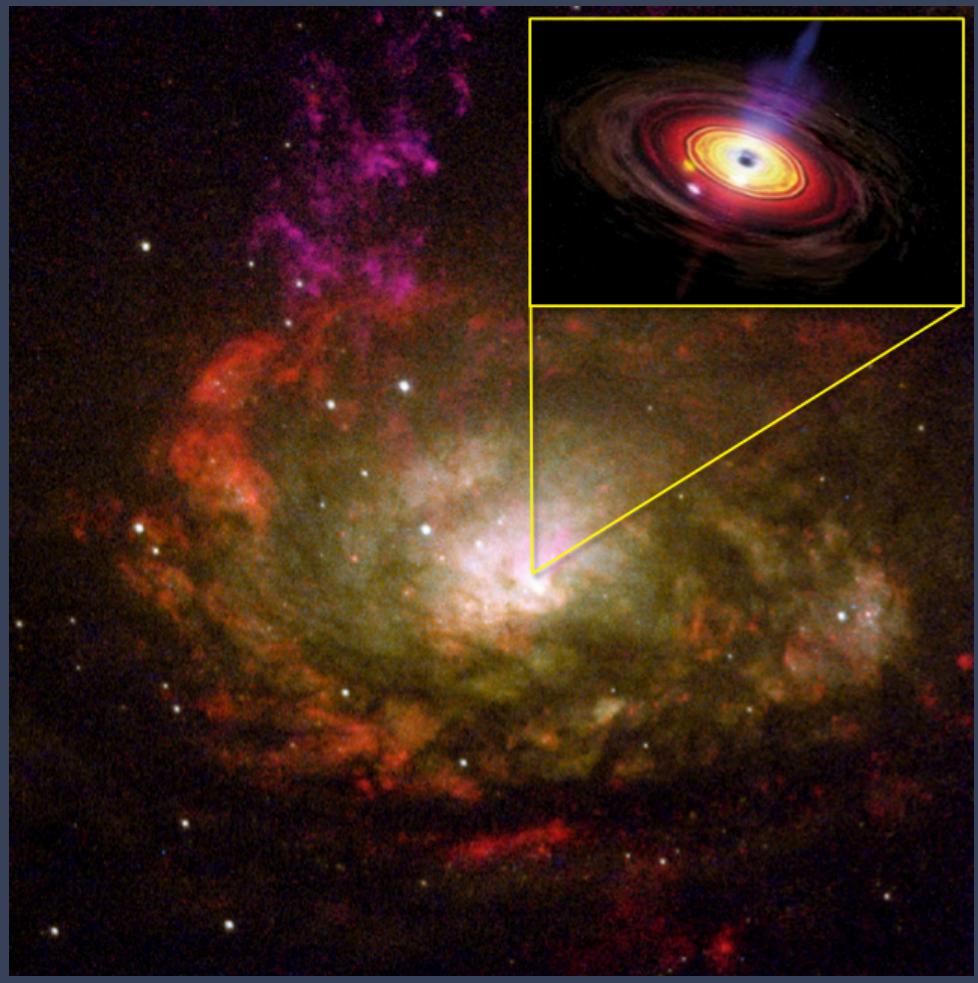
- (can be) Hidden even while ‘active’

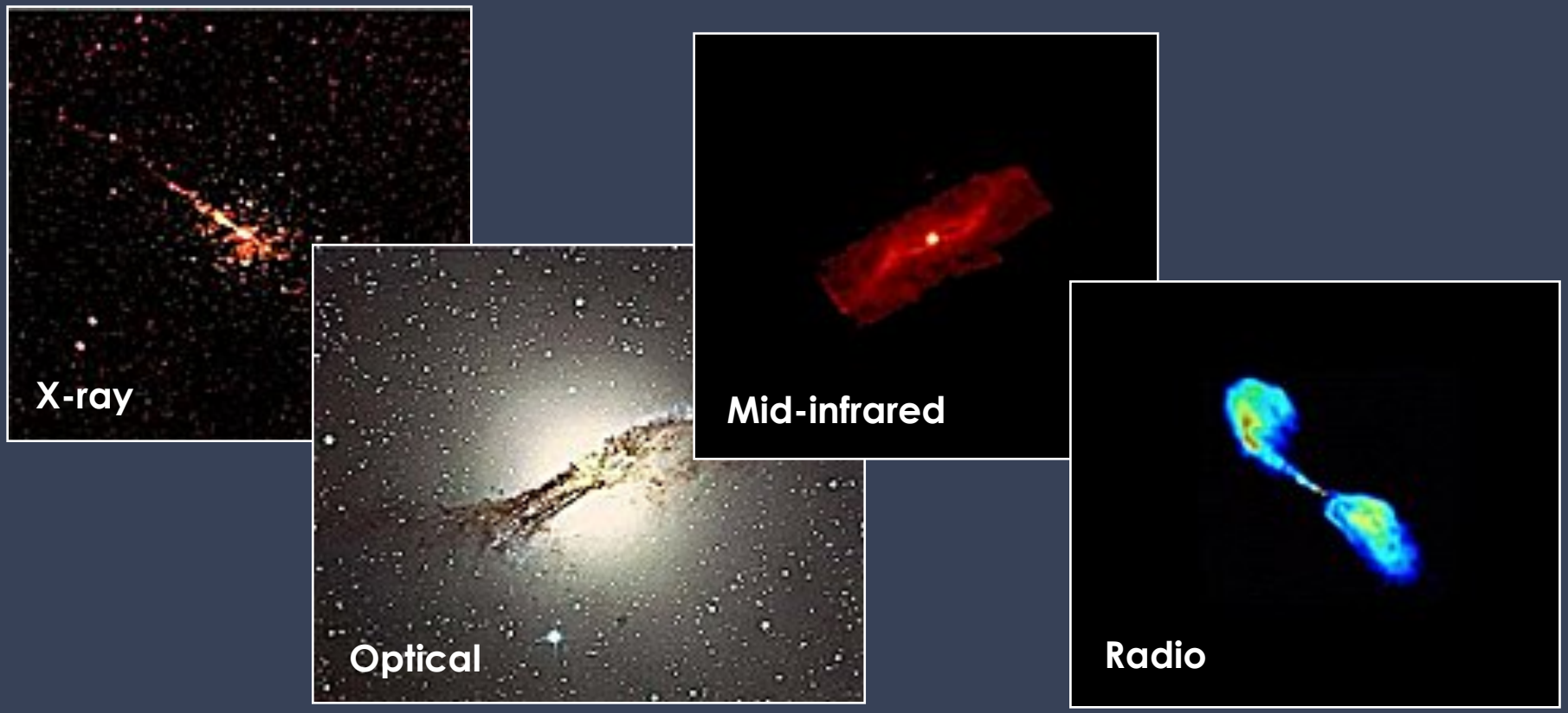
Open Issues

- What is the main triggering mechanism for AGN?
- What is the *multiscale* connection between the growth of stars and black holes in galaxies?
- Is there redshift evolution in our ability to find AGN?



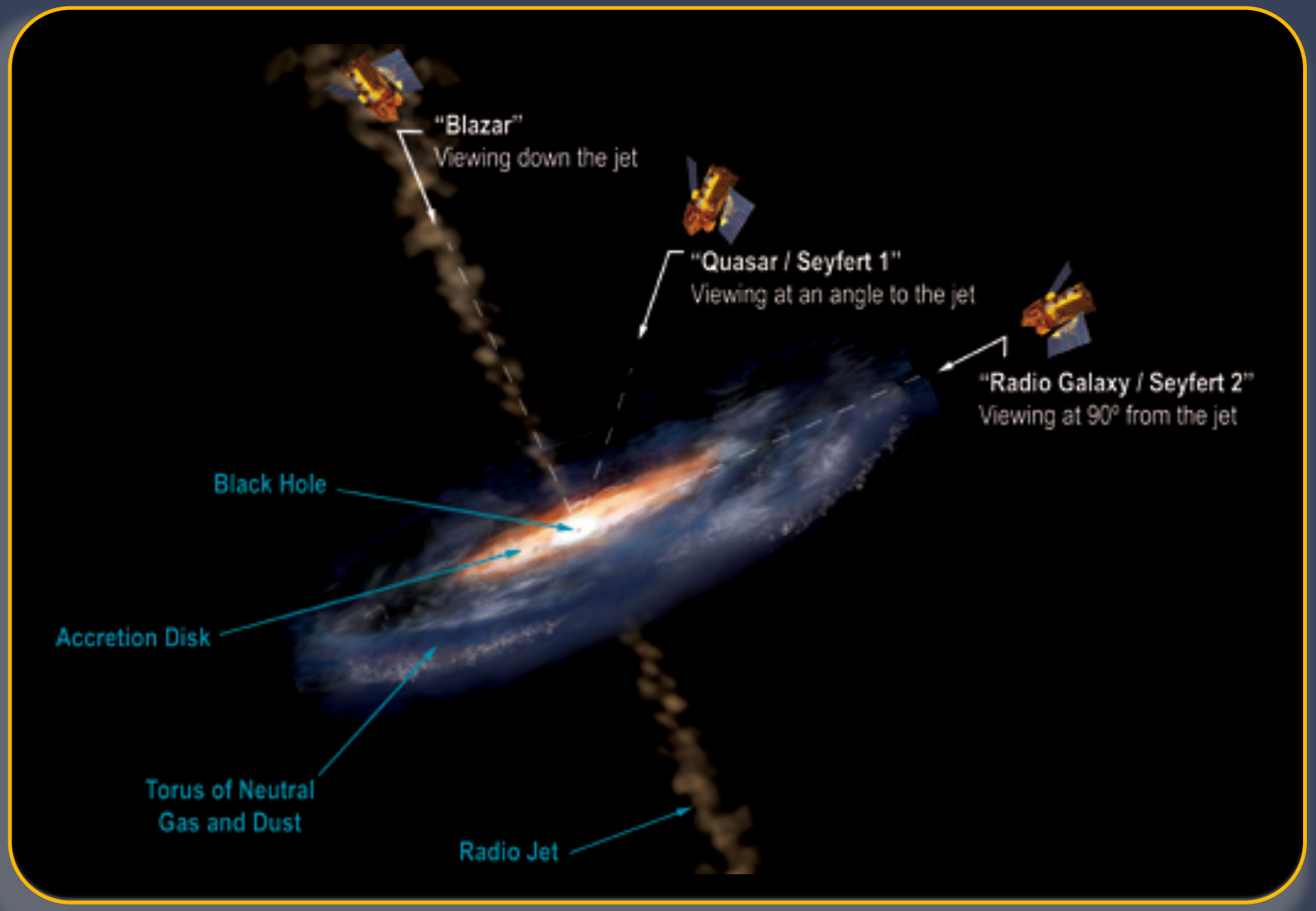
→ We need to identify all the growing black holes!

AGN Identification

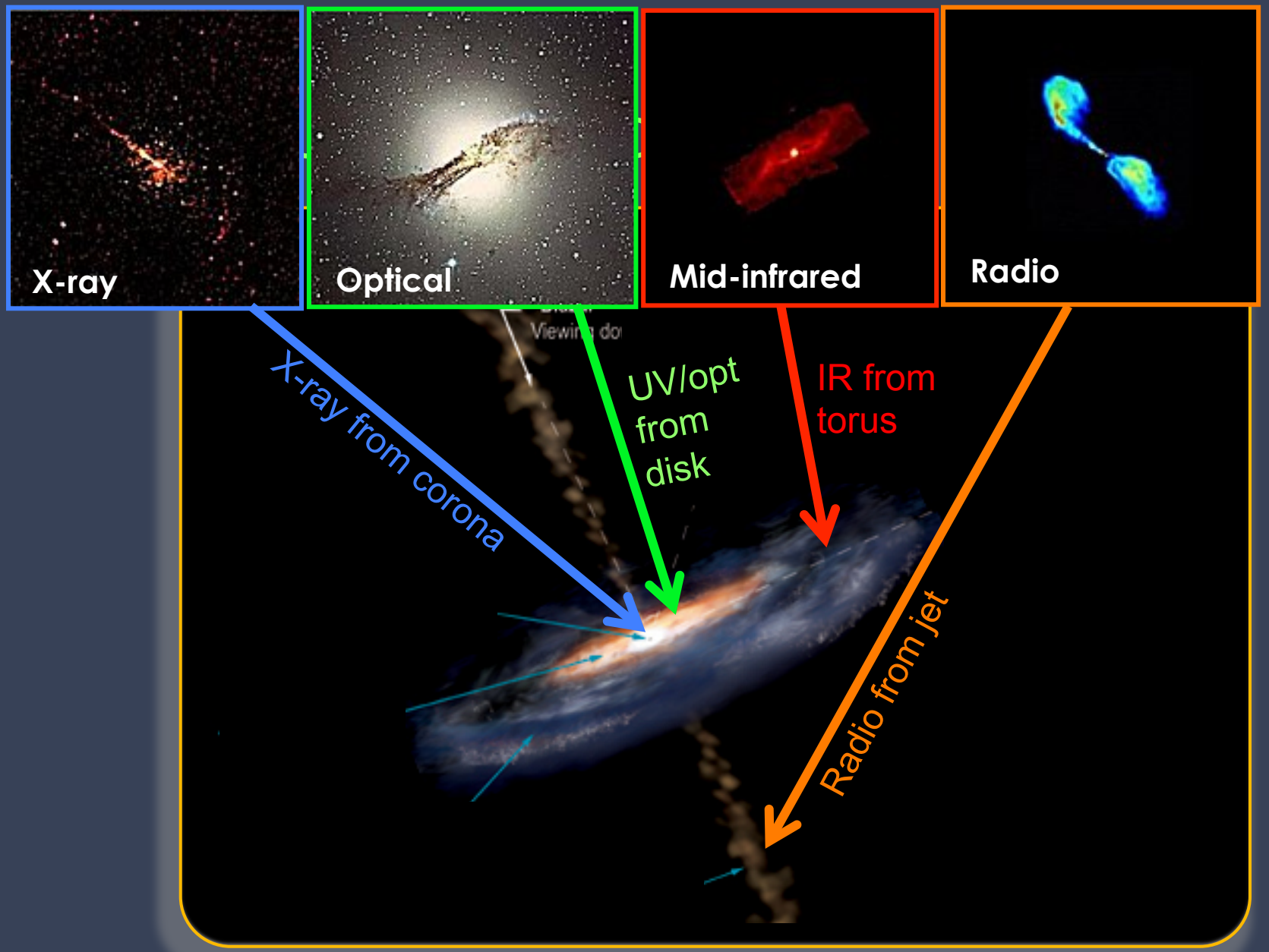


slide credits: Dave Alexander

AGN Unified Model

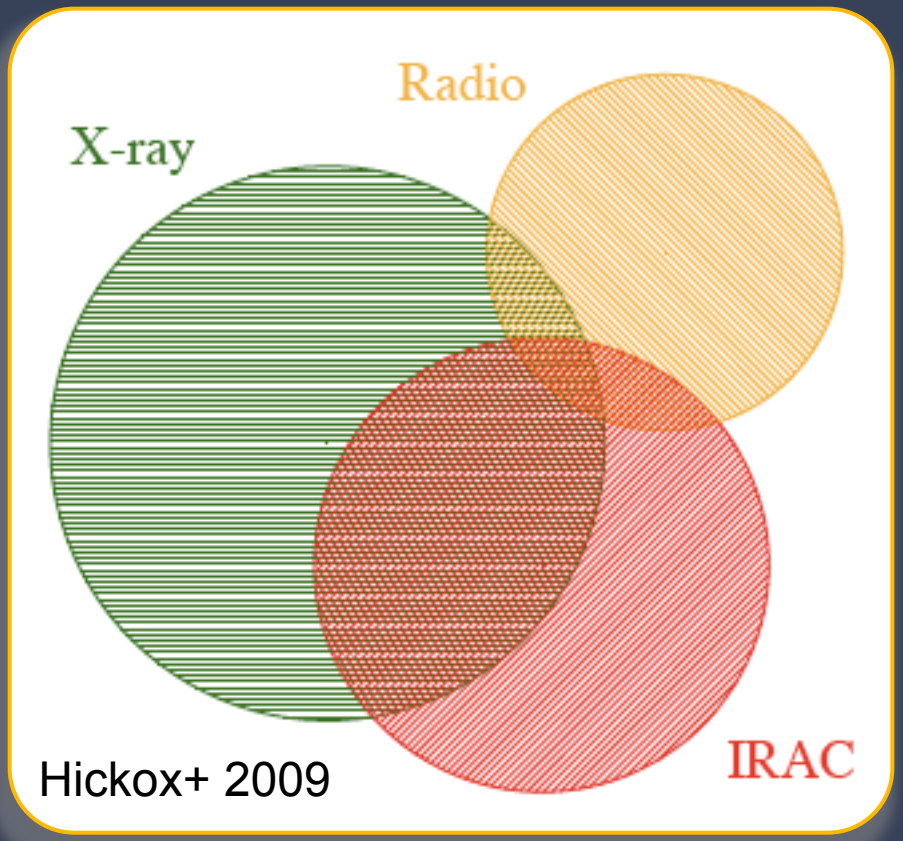


(also see: Antonucci 1984; Urry & Padovani 1995)

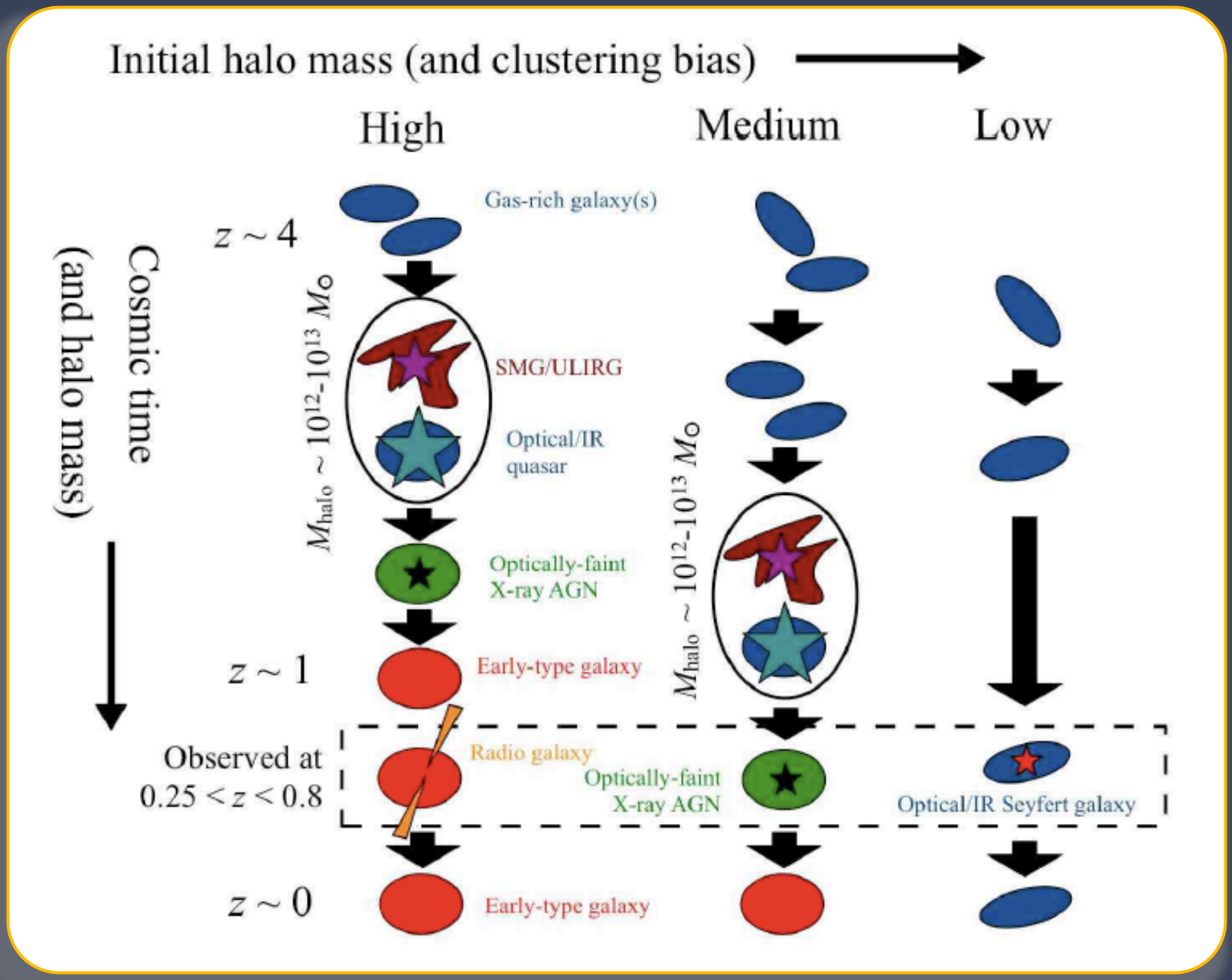


slide credits: Dave Alexander

AGN Finding Methods



Hickox+ 2009


Initial halo mass (and clustering bias)
High
Medium
Low
Cosmic time
(and halo mass)
z ~ 4
z ~ 1
z ~ 0
Gas-rich galaxy(s)
SMG/ULIRG
Optical/IR
quasar
Optically-faint
X-ray AGN
Early-type galaxy
Radio galaxy
Optically-faint
X-ray AGN
Optical/IR Seyfert galaxy
Early-type galaxy
Observed at
0.25 < z < 0.8
M_halo ~ 10^12-10^13 M_o
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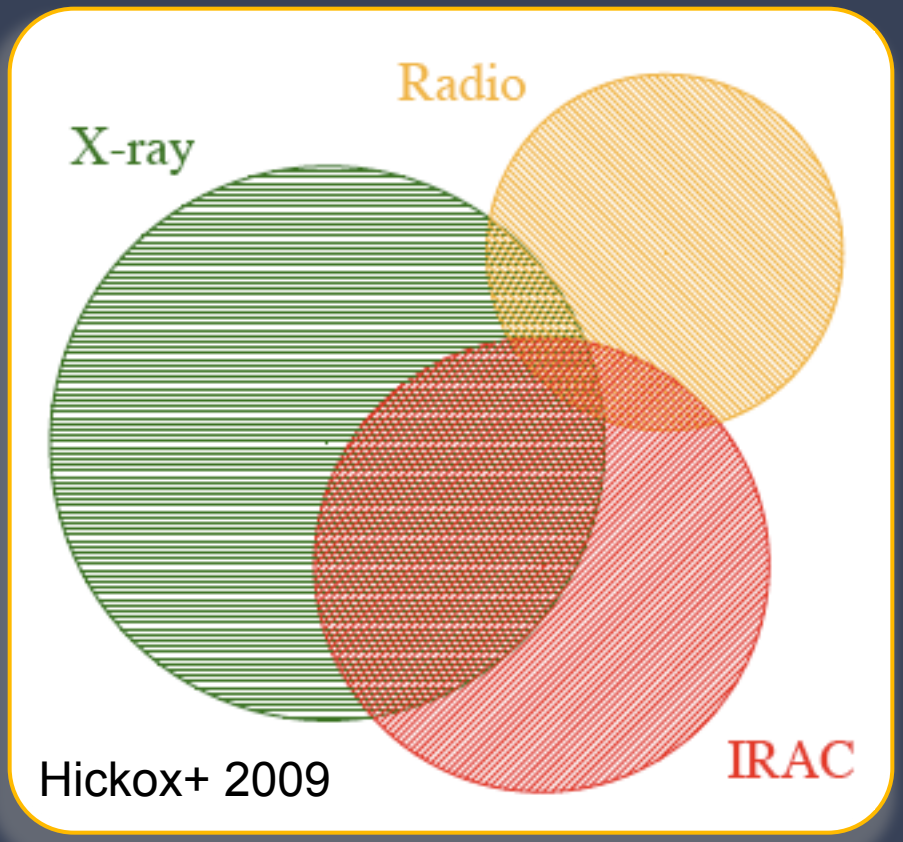
Hickox+ 2009

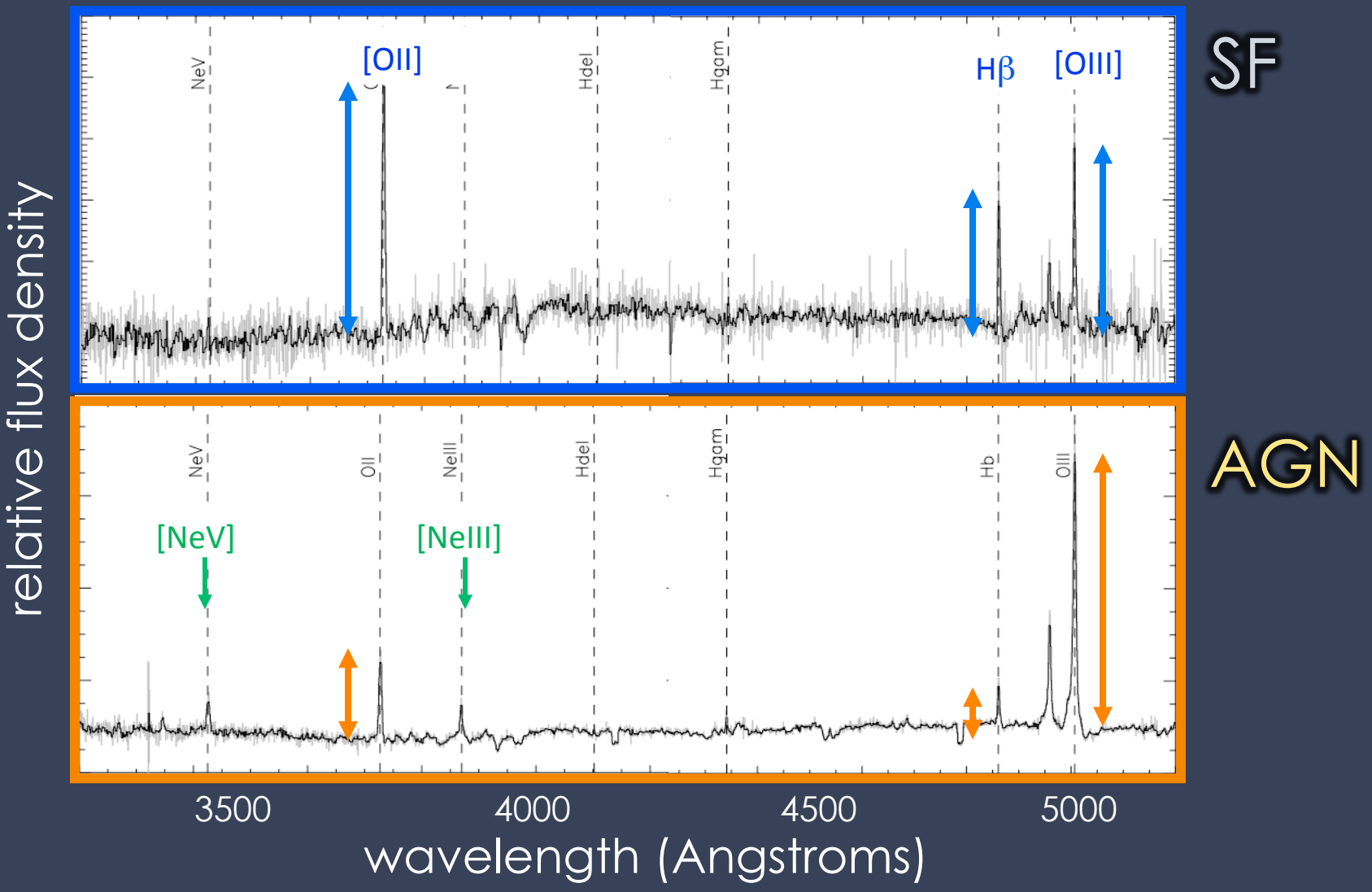
AGN Finding Methods



Hickox+ 2009

+1

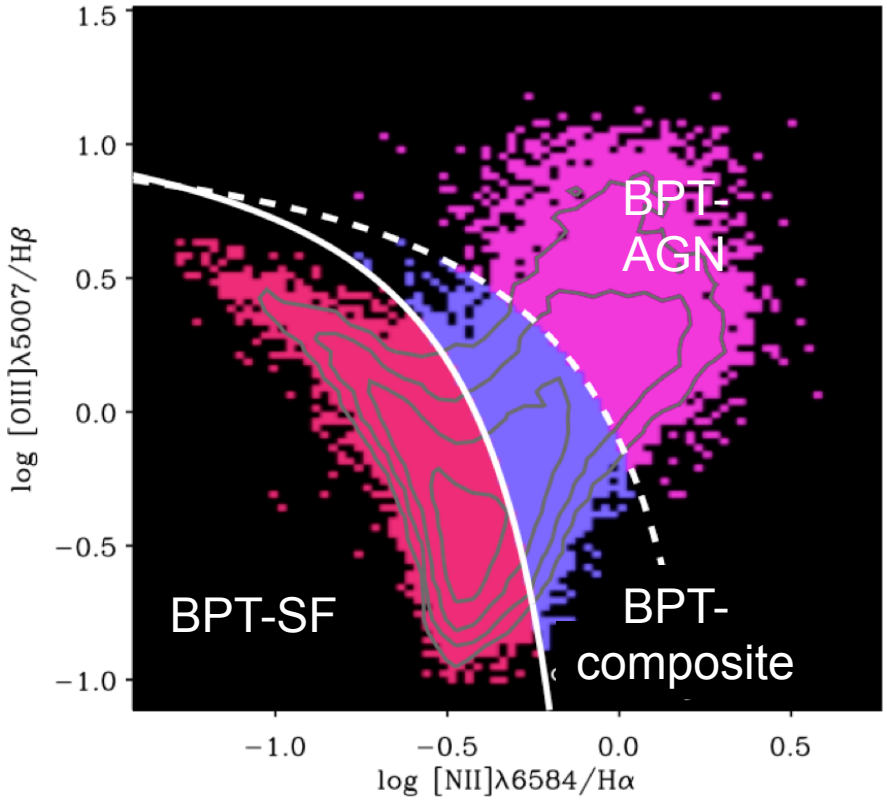
Example Spectra (stacks)



BPT Diagnostic (Baldwin, Phillips & Terlevich 81)

1- Empirical & theoretical dividing lines (Kauffmann+ 03, Kewley+ 01, Kewley+ 06)

2- Useable out to z~0.4 with optical spectra

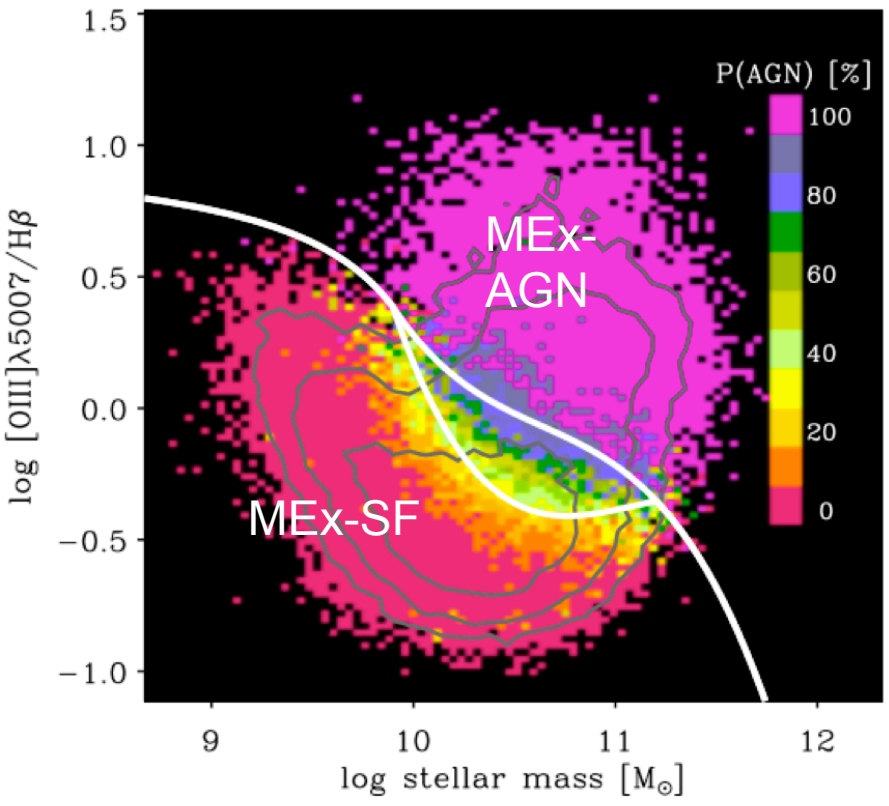


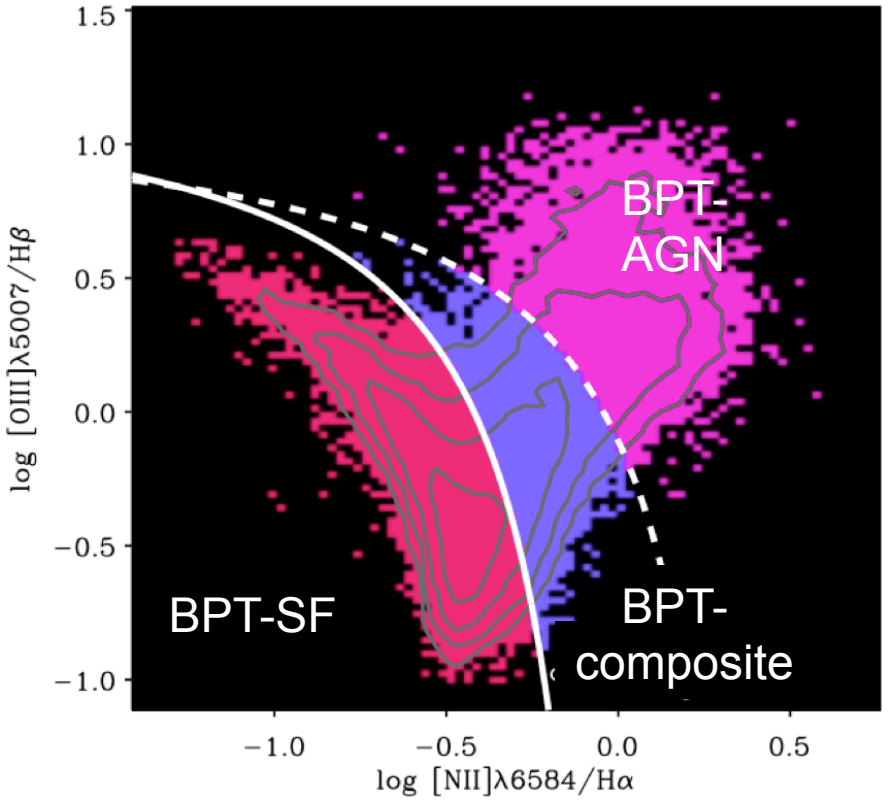
(adapted from Juneau+ 2011)

Mass-Excitation (MEx) Diagnostic

1- Empirical dividing Lines (from >100,000 SDSS galaxies at 0.05<z<0.1)

2- Probabilistic approach → P(AGN) = probability of presence of AGN

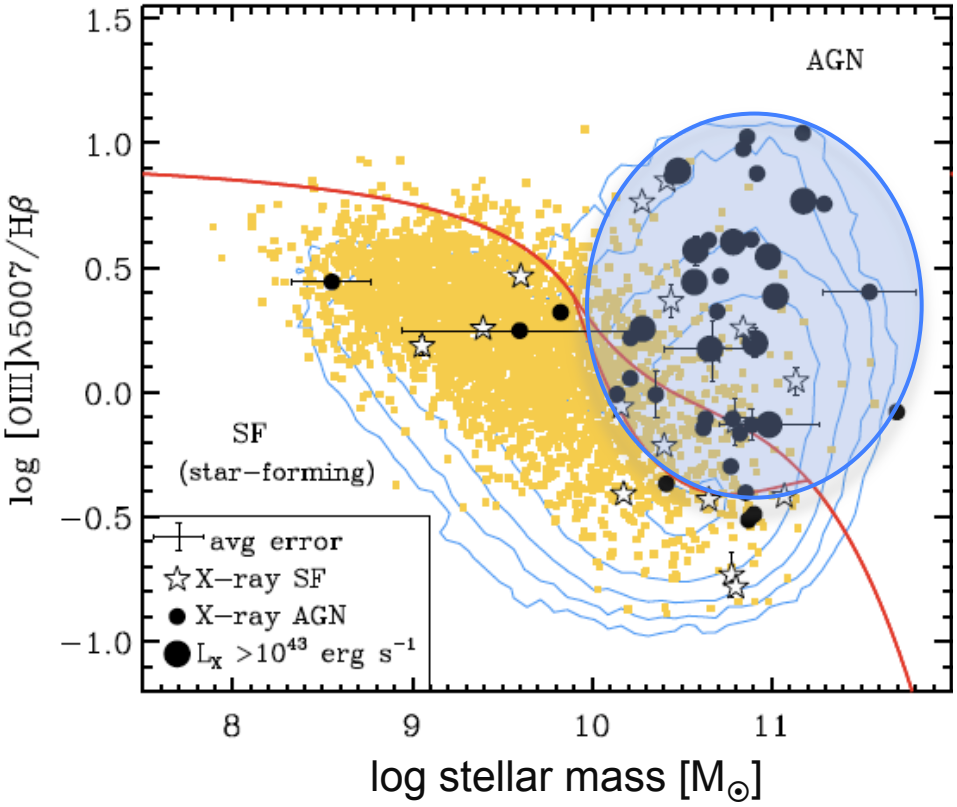




(adapted from Juneau+ 2011)

MEx confirmed up to z=1 with X-ray data

Mass-Excitation (MEx) diagnostic



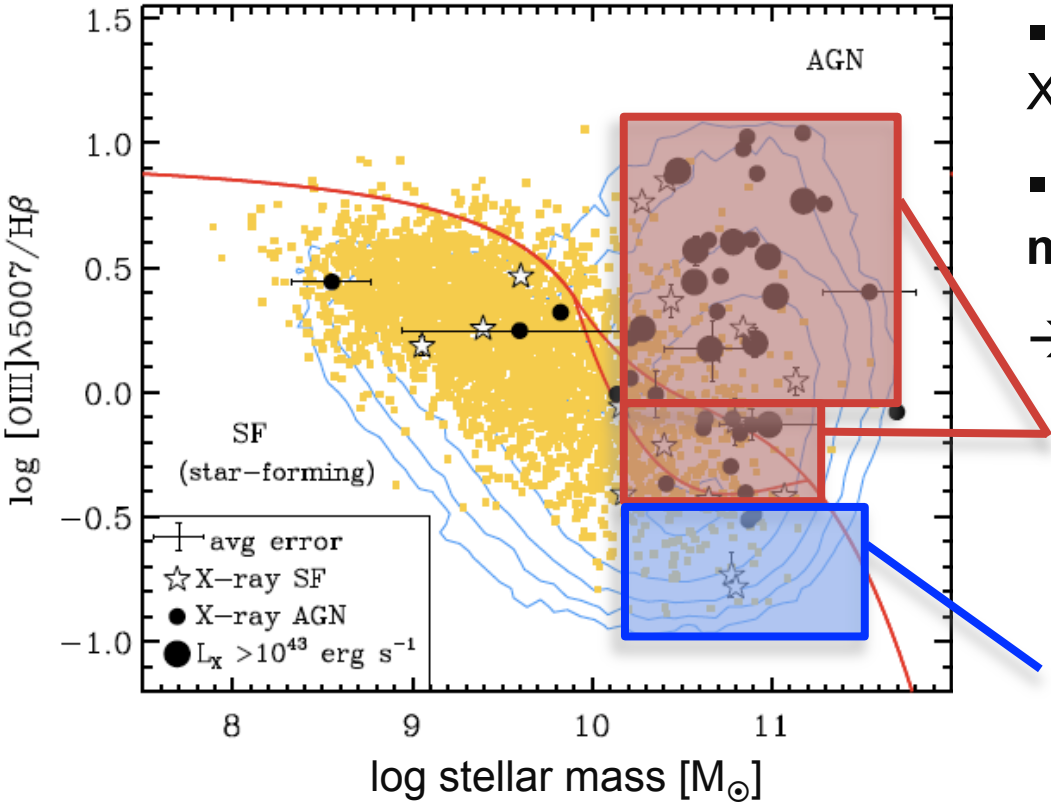
- MEx diagram identifies 85% of X-AGN that have emission lines

Sample: 3,386 galaxies at **0.3<z<1** with [OIII]λ5007, Hβ & stellar mass in **GOODS-North** & **EGS**
Chandra X-ray: 2 Msec in GOODS-N (Alexander+ 03); 200 ksec in EGS (Nandra+05, Laird+09)

Juneau et al (2011)

MEx confirmed up to z=1 with X-ray data

Mass-Excitation (MEx) diagnostic



- MEx diagram identifies 85% of X-AGN that have emission lines
- Additional AGN **missed or misclassified in the X-rays**

→ **X-ray stacking**

MEx-AGN
- *Chandra*'s soft & hard bands yield a flat X-ray spectral index (Γ~0.6): **some obscured AGN!**

MEx-SF
- Only soft band detection: **consistent with SF**

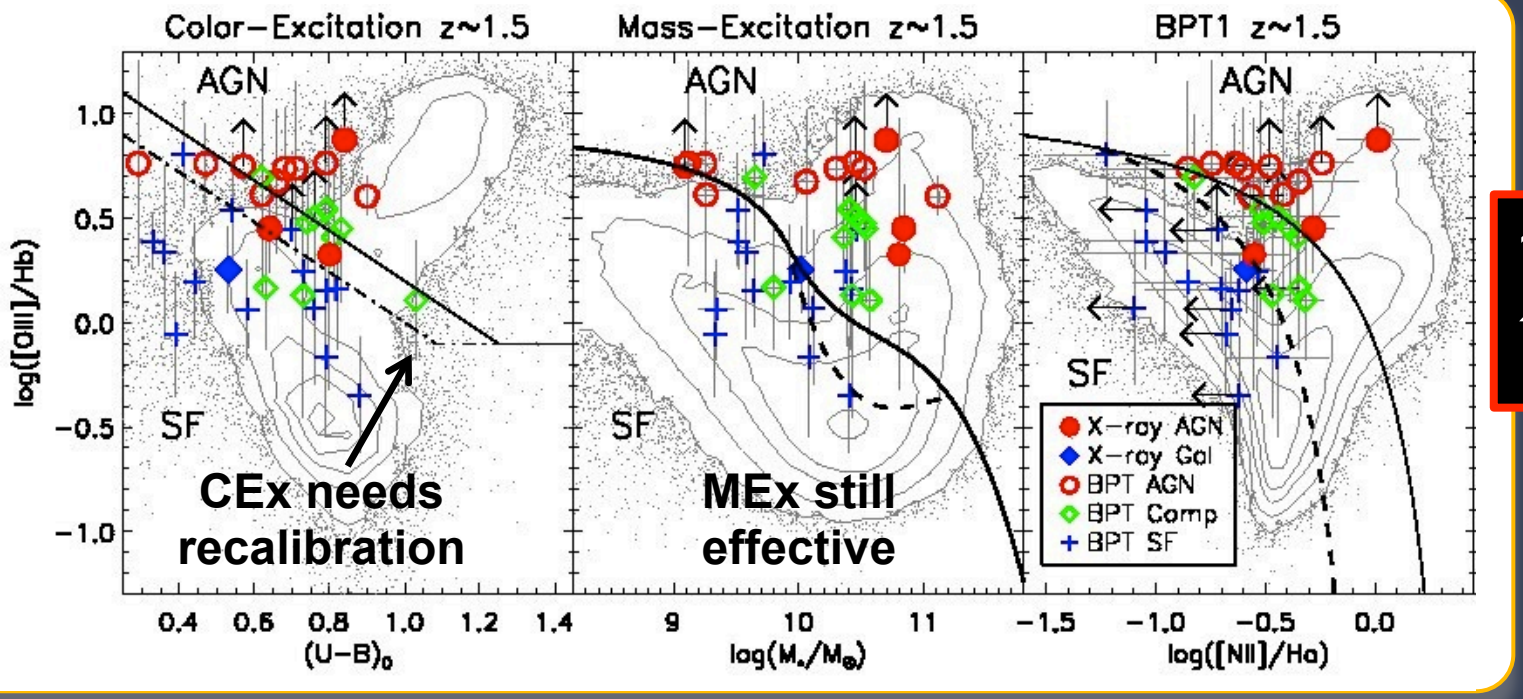
Sample: 3,386 galaxies at **0.3<z<1** with [OIII]λ5007, Hβ & stellar mass in **GOODS-North** & **EGS**
Chandra X-ray: 2 Msec in GOODS-N (Alexander+ 03); 200 ksec in EGS (Nandra+05, Laird+09)

Juneau et al (2011)

AGN diagnostics at z~1.5

Sample: emission-line galaxies at z~1.5
→ low-mass galaxies without strong bulges (some clumpy)

AGN: X-ray (Chandra 4Ms) & BPT (WFC3 + MOSFIRE)



~50% host X-ray/BPT AGNs!

Trump et al (2013)

MEx Diagnostic Diagram: Summary

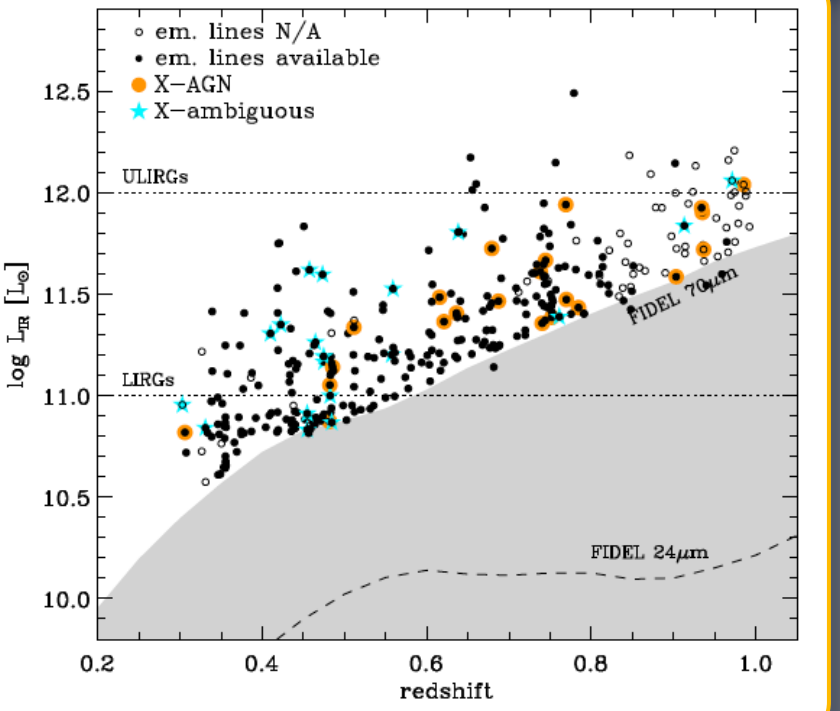
- Calibrated with >10^5 low-redshift SDSS galaxies ($0.05 < z < 0.1$)
- Consistent with previous studies that found AGN hosts to be massive (e.g., Kauffmann+03, Brusa+09, Mullaney+11) but may be selection effect (Aird+10, Bongiorno+12)
- Probabilistic approach with built-in uncertainty and applicable as statistical weights
- Tested *directly* up to z=1 with independent X-ray data (detections AND stacking; Juneau+2011) and up to z=1.5 with NIR spectra (Trump+2013)
- Caveat: Don't we expect evolutionary effects?

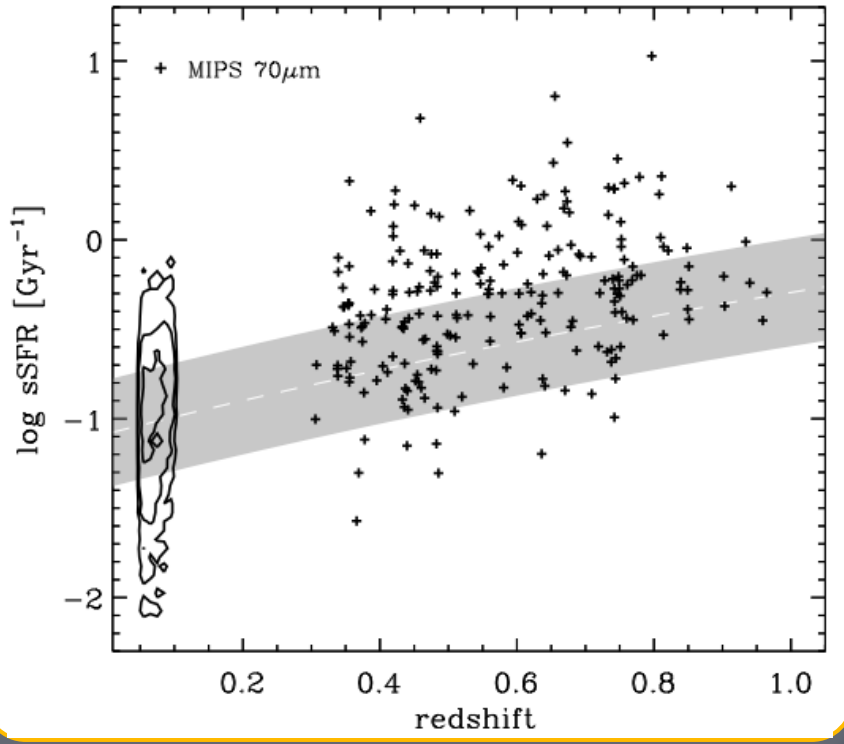
Now we have an AGN diagnostic complementary to X-rays → search for AGN in star-forming galaxies

AGN in star-forming galaxies: Sample

- Selection from the Far-IR Deep Extragalactic Legacy survey (FIDEL, PI: M. Dickinson; catalog in Magnelli+2011)
- 70 μm-selected sample in GOODS-N and EGS: 2.5mJy (3 σ) with *Spitzer*/MIPS

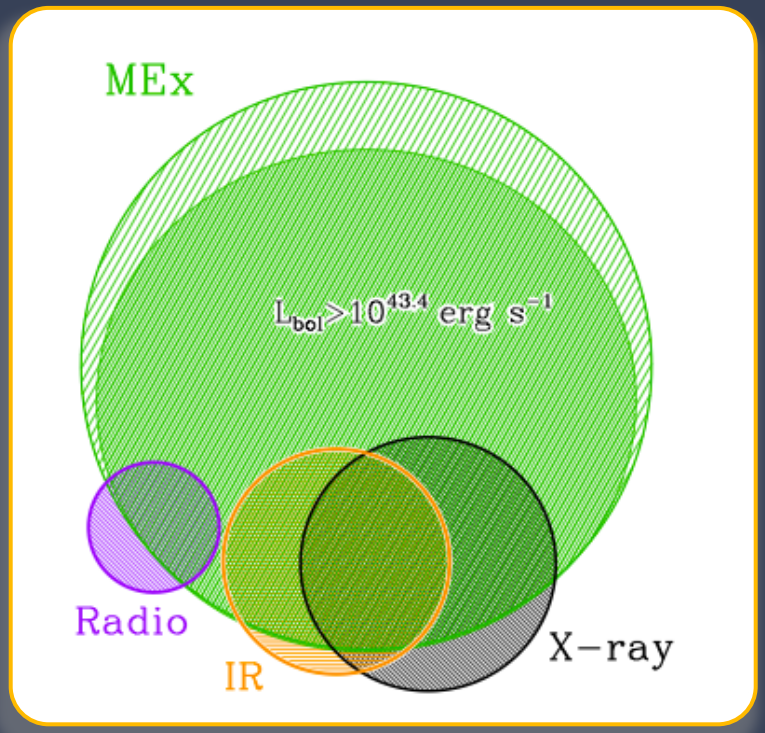
  → LIRGs at z~1 (typical star-forming galaxies → major contributors to the cosmic star formation rate; e.g., Le Floc' h+ 2005, Magnelli+ 2009)



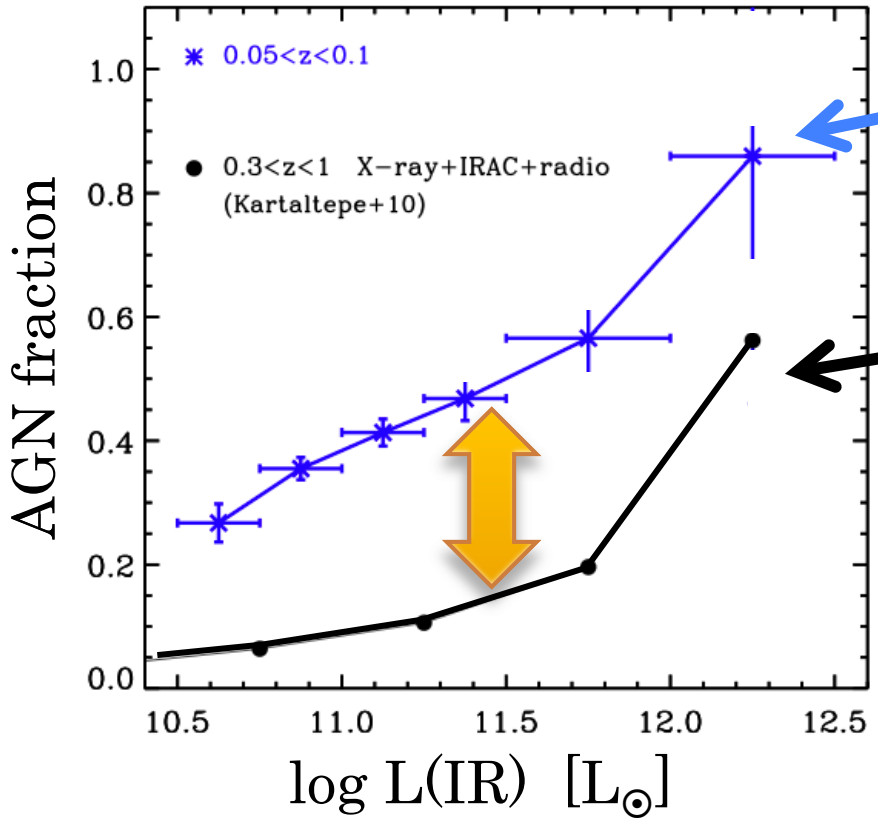


AGN Finding Methods

- X-ray ($L_X > 10^{42}$ erg/s *or* HR > -0.1; similar to Bauer+04)
- Optical emission lines (MEx diagram; Juneau+ 11)
- IRAC colors (Stern+ 05)
- Radio-excess (Sargent+ 10; Del Moro+ 12)



Occurrence of AGN



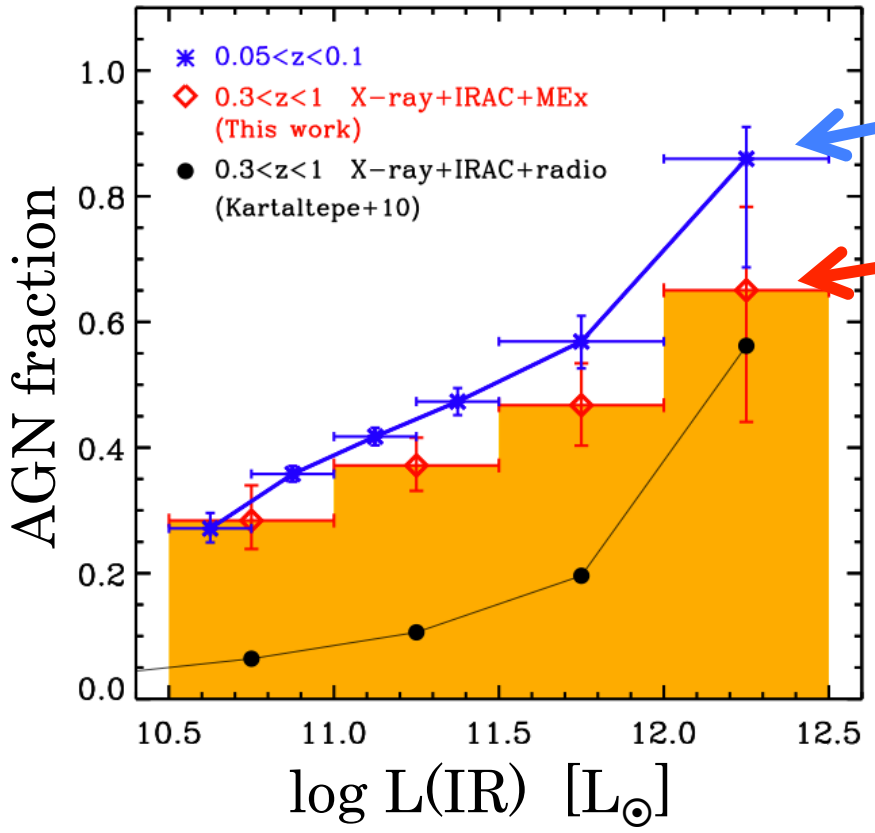
low-z (<0.1) FIR galaxies
(SDSS + IRAS 60 μm or AKARI 90 μm)

0.3< z <1 FIR galaxies
(MIPS 70 μm; also see Symeonidis+10)

X-ray, IR, radio AGN

AGN fraction is *high* in IR galaxies, up to ~100% in ULIRGs ($L_{IR}>10^{12}$ $L_{\odot}$; e.g., Veilleux +1995, Yuan+2010)

Occurrence of AGN



low-z (<0.1) FIR galaxies
(SDSS + IRAS 60 μ m or AKARI 90 μ m)

0.3< z <1 FIR galaxies
(MIPS 70 μ m)

→ X-ray, IR, radio & **MEx** AGN

AGN fraction in intermediate-redshift galaxies are very similar to that in nearby (z~0.07) galaxies (Juneau et al. 2013)

Three AGN Categories

- X-ray unabsorbed AGN (L_X(2-10keV) > 10^{42} erg/s)
- X-ray absorbed AGN (infer L_X > 10^{42} erg/s from [OIII])
- weak AGN (L_X <10^{42} erg/s intrinsically)

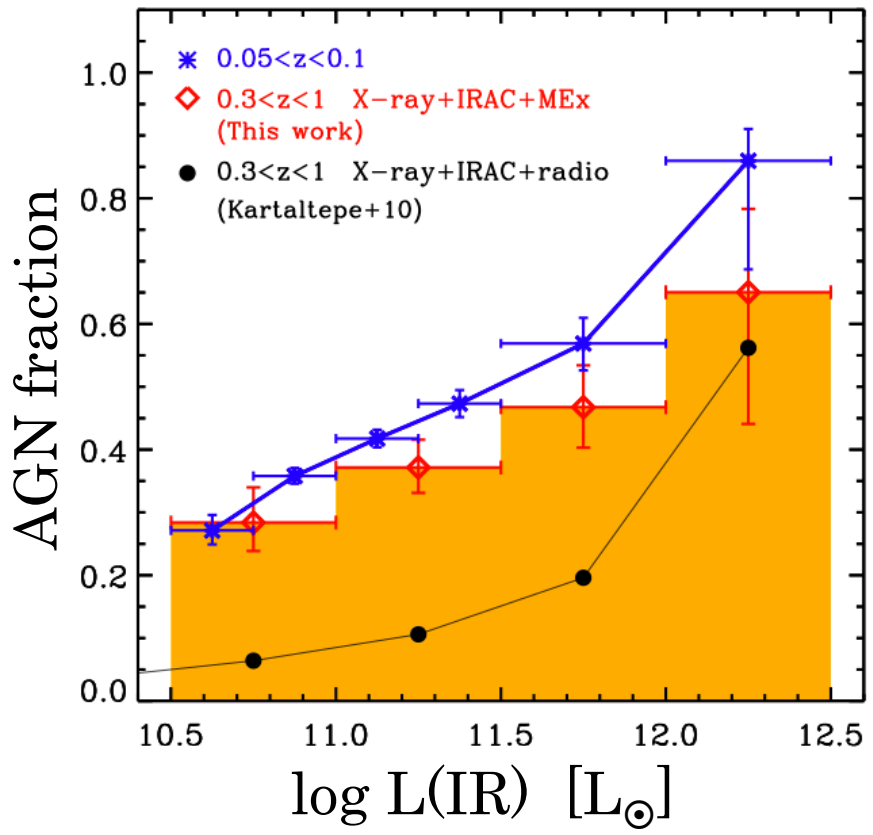
Missed in deepest X-ray surveys
(e.g., 2 Msec *Chandra* Deep Field North)

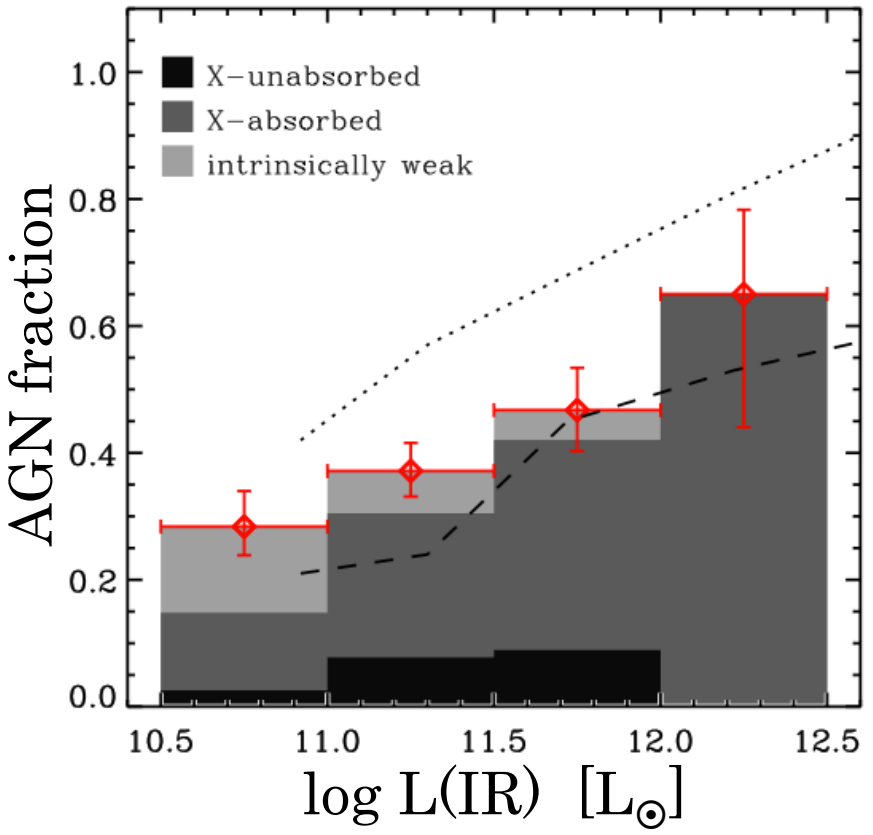
Note: The X-ray absorption is *inferred* and not measured.

Results

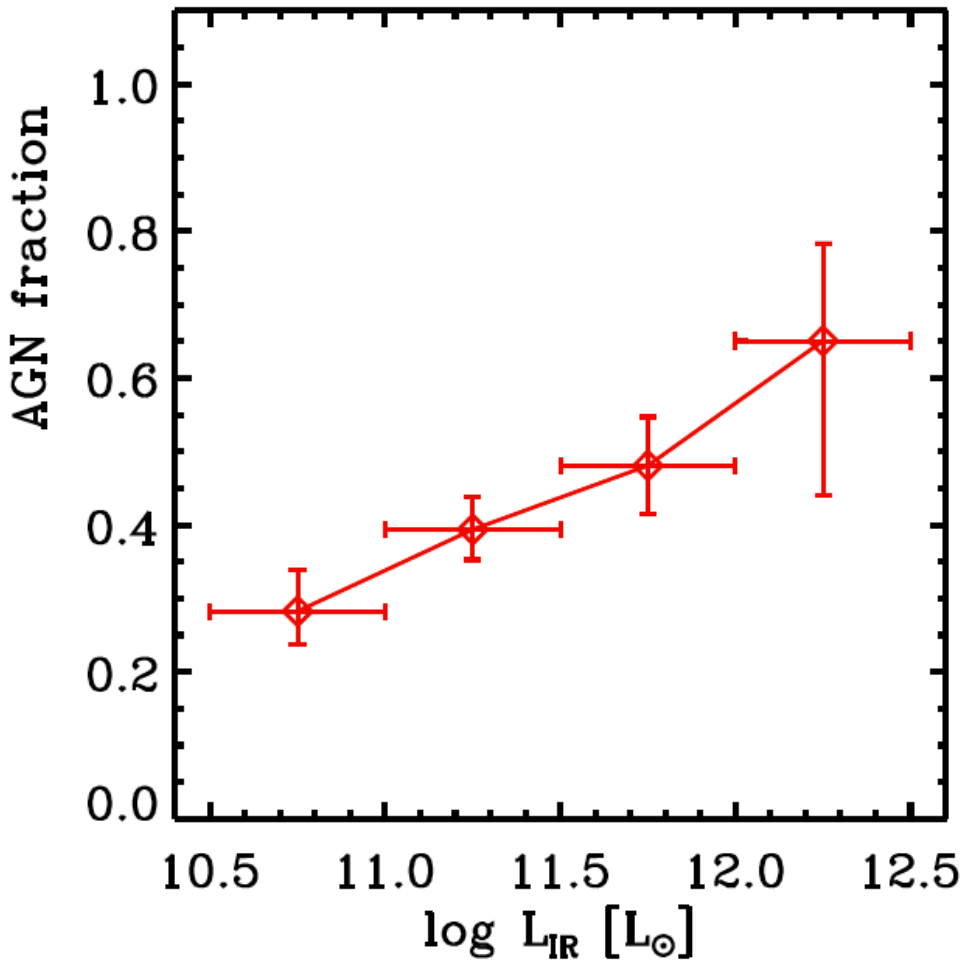
- We find that 37% of 70μm-selected galaxies host an AGN* (Juneau+ 2013) * 30% excluding the 'weak' AGNs
- Previous studies found ~10-20% for similar L_{IR} and redshift ranges (e.g., Kartaltepe+ 10, Symeonidis+ 10)
- We have a more complete census of AGN:
  - X-ray unabsorbed AGN: 7%
  - X-ray absorbed AGN: 22%
  - weak AGN: 8%

Occurrence of AGN





f(Star Formation Rate)



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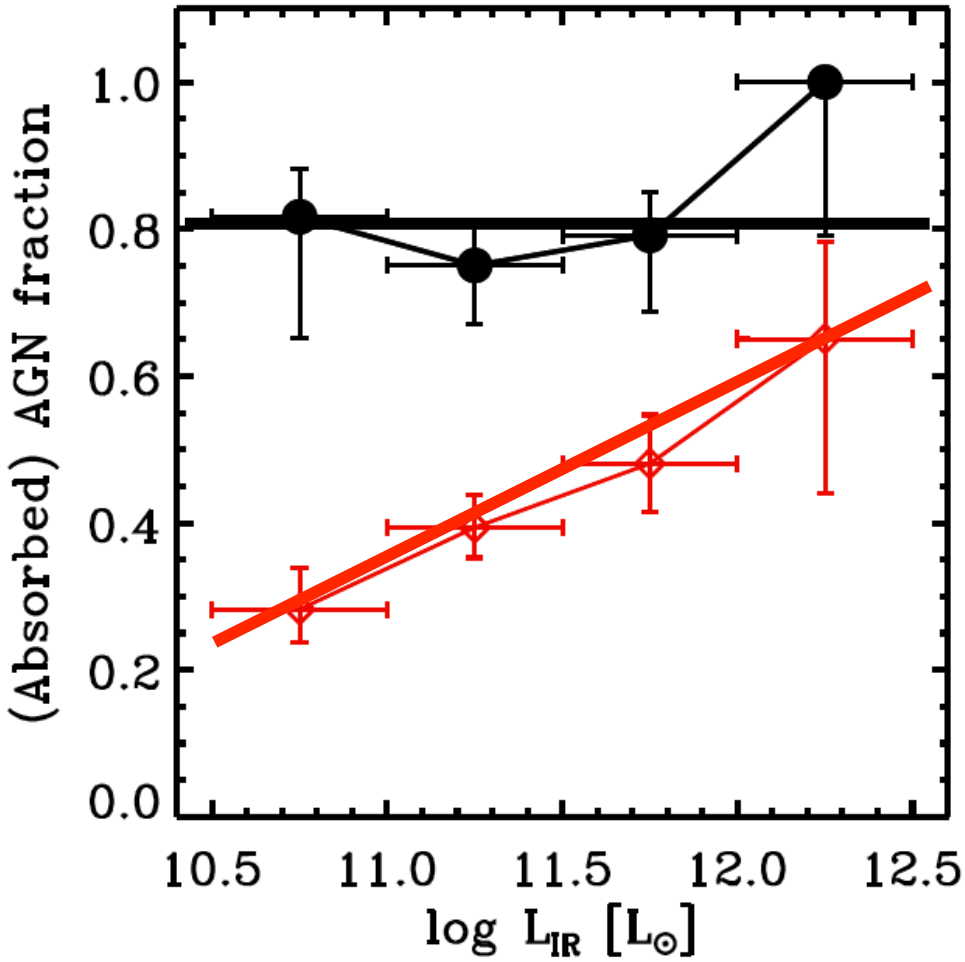
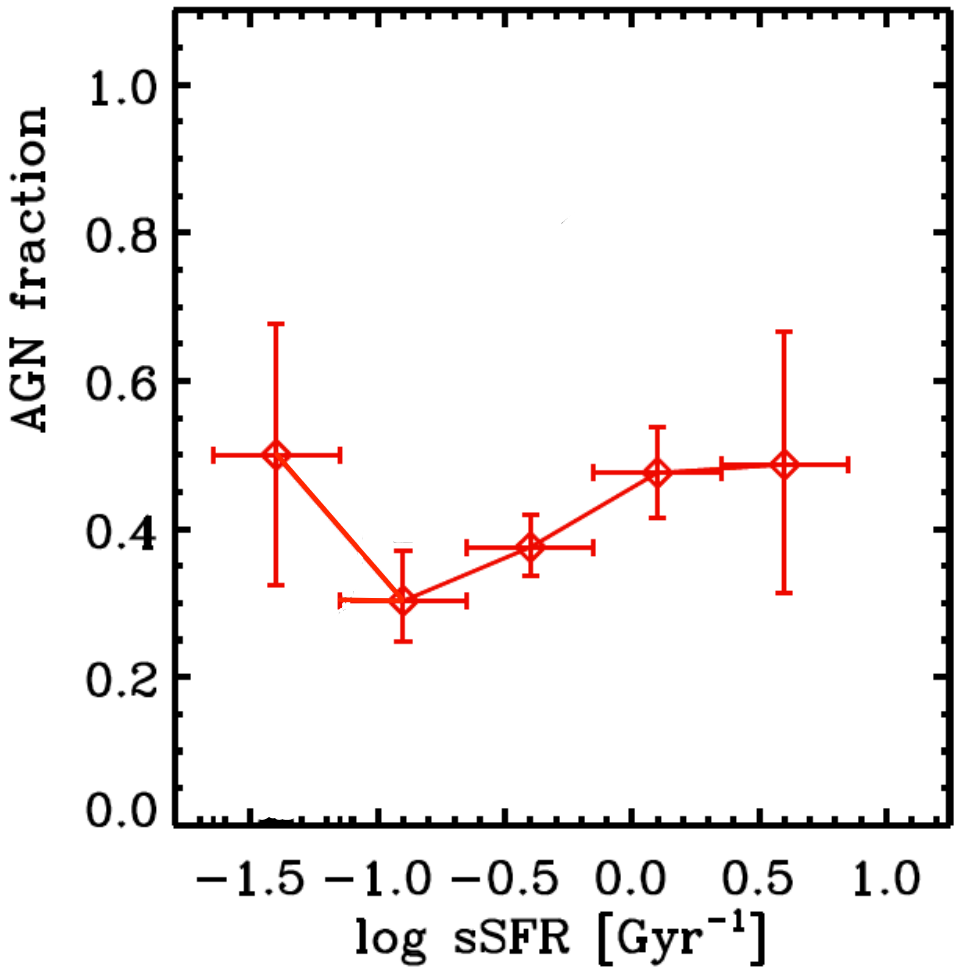


f(SSFR = SFR/M_*)



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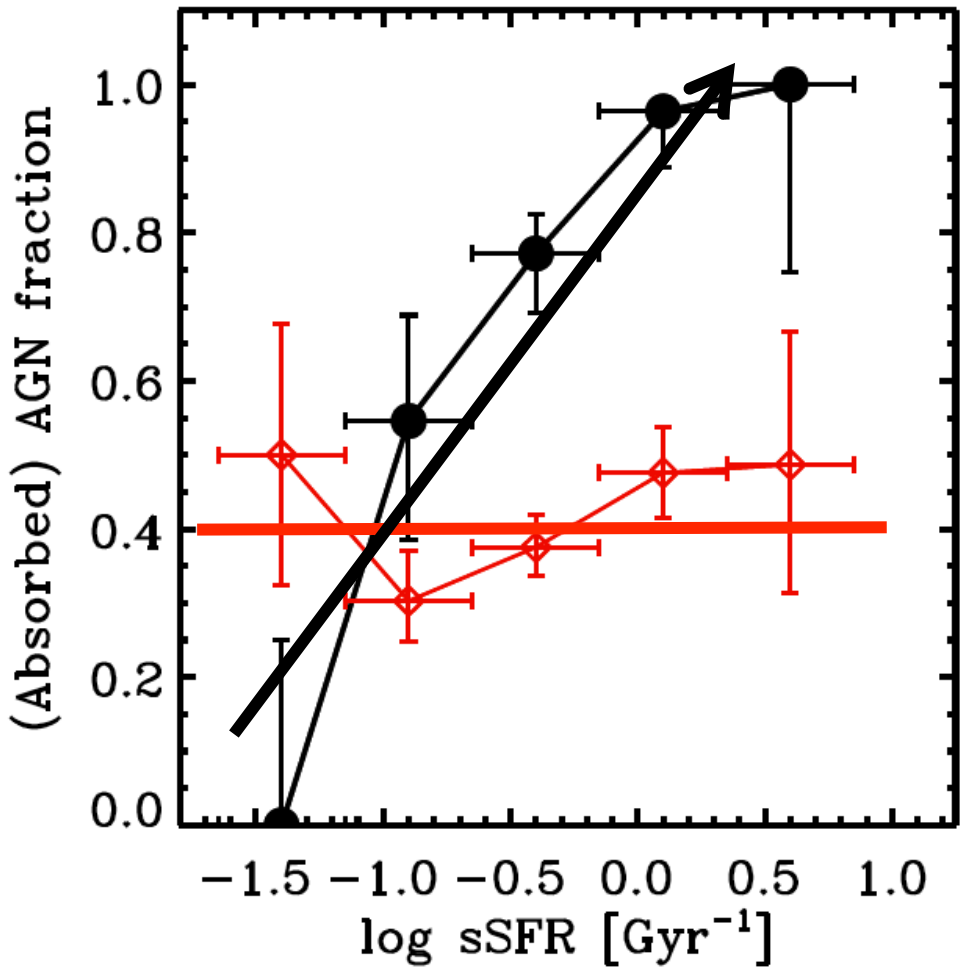
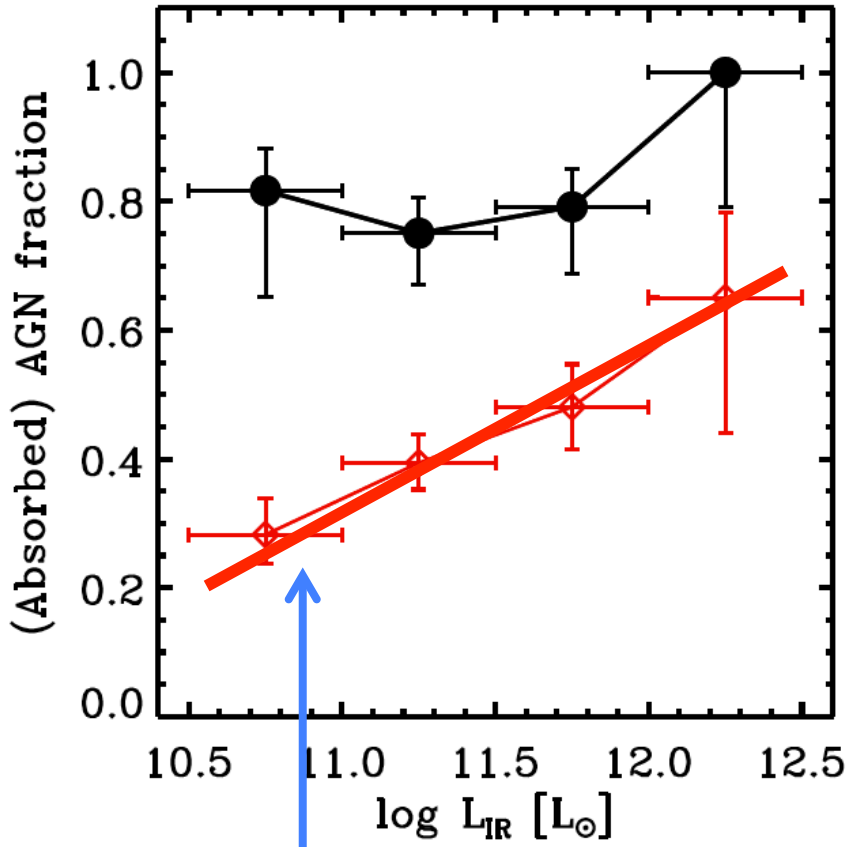
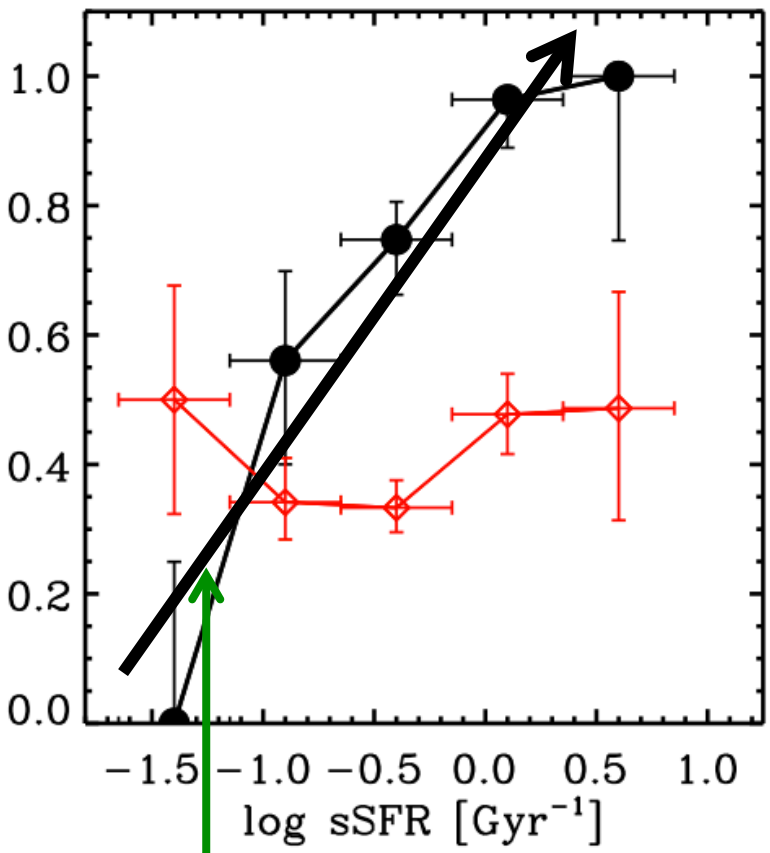

(Absorbed) AGN fraction
1.0
0.8
0.6
0.4
0.2
0.0
−1.5 −1.0 −0.5 0.0 0.5 1.0
log sSFR [Gyr^{-1}]

f(Star Formation Rate)

f(SSFR = SFR/M_*)





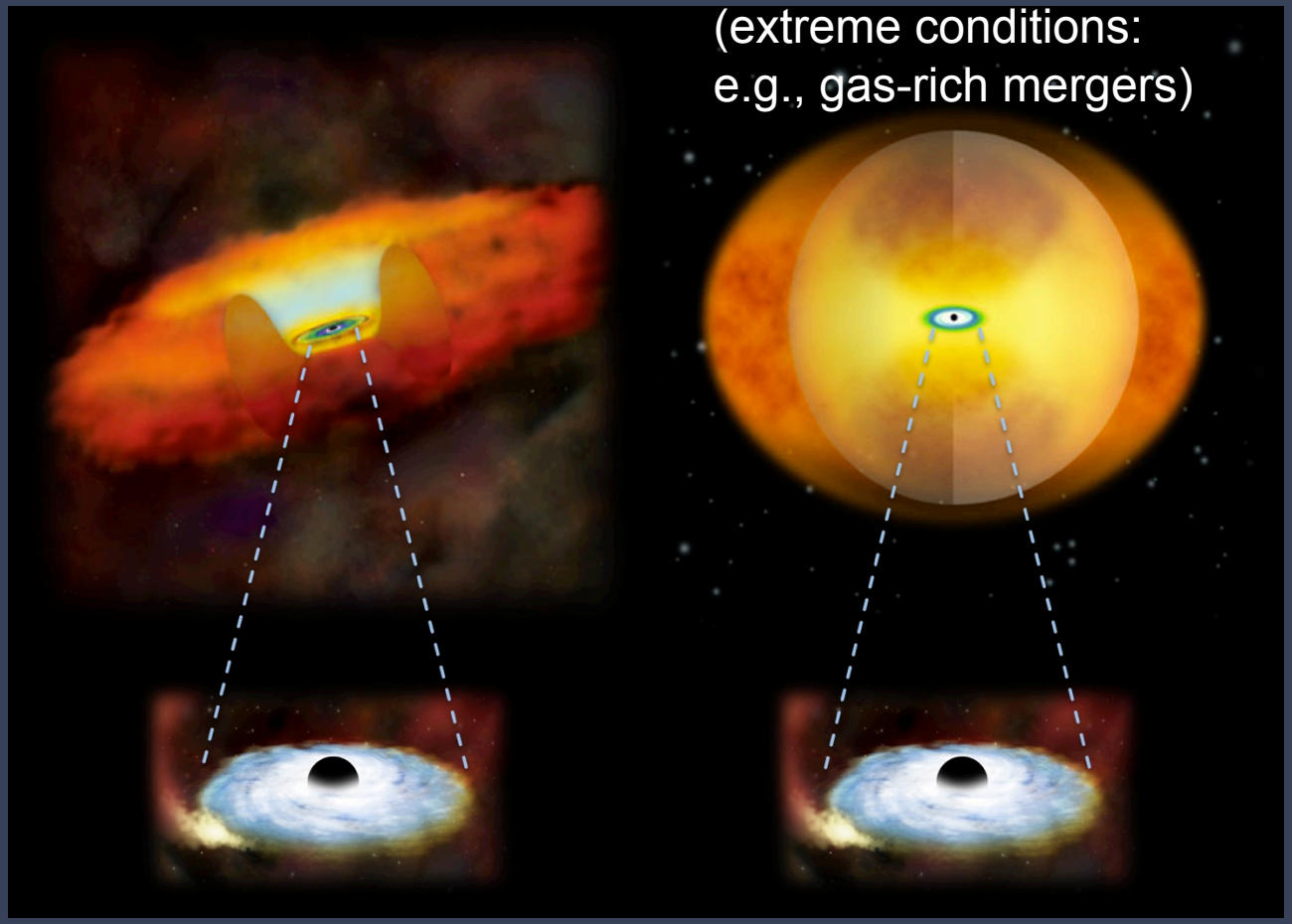
AGN *triggering* knows about L_{IR}
(~SFR, ~total gas mass)

AGN *obscuration* knows about sSFR
(~gas fraction, ~gas geometry)

AGN obscuration scenarios

Torus obscuration

Host obscuration
(extreme conditions:
e.g., gas-rich mergers)



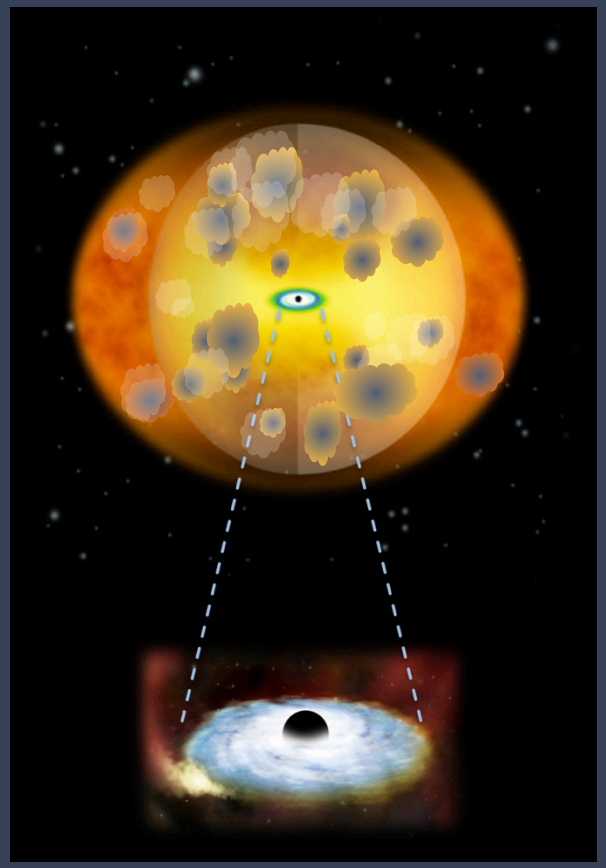
"Buried" AGN, missing X-ray AND optical signatures

Image credits: NASA (lower & upper left). NAOJ, Naomi Ishikawa (upper right)

AGN obscuration scenarios

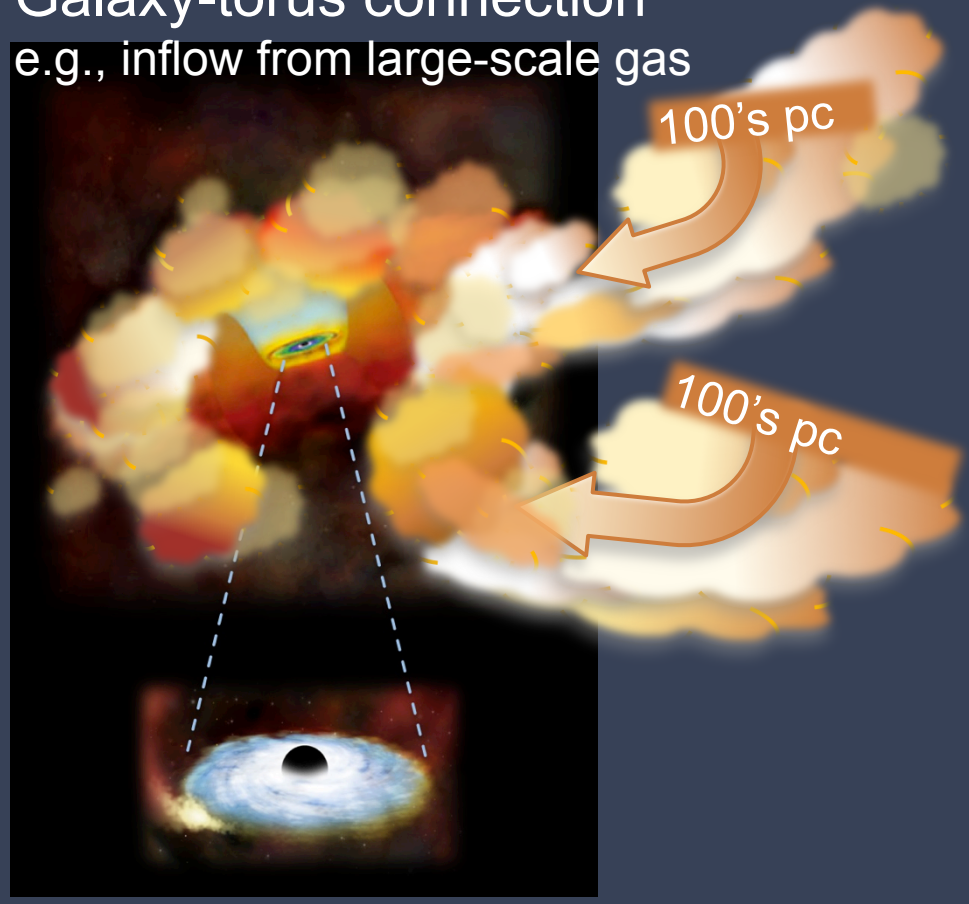
… 2 additional possibilities

"Patchy" host obscuration



Galaxy-torus connection

e.g., inflow from large-scale gas



Summary

- AGN identification:
  - MEx diagram (Juneau+11) statistically confirmed *out to z~1*
  - X-ray absorbed AGN (including Compton-Thick candidates)
- High incidence of AGN in *star-forming* galaxies (30-37%; Juneau+13)
  - Similar to low-z sample f(SFR) → higher AGN fraction at high z (in qualitative agreement w/ e.g., Brusa+09, Bongiorno+12)
  - Likely X-ray absorbed
- Connection between sSFR and black hole obscuration
  - Does not strictly follow the AGN *Unified Model*