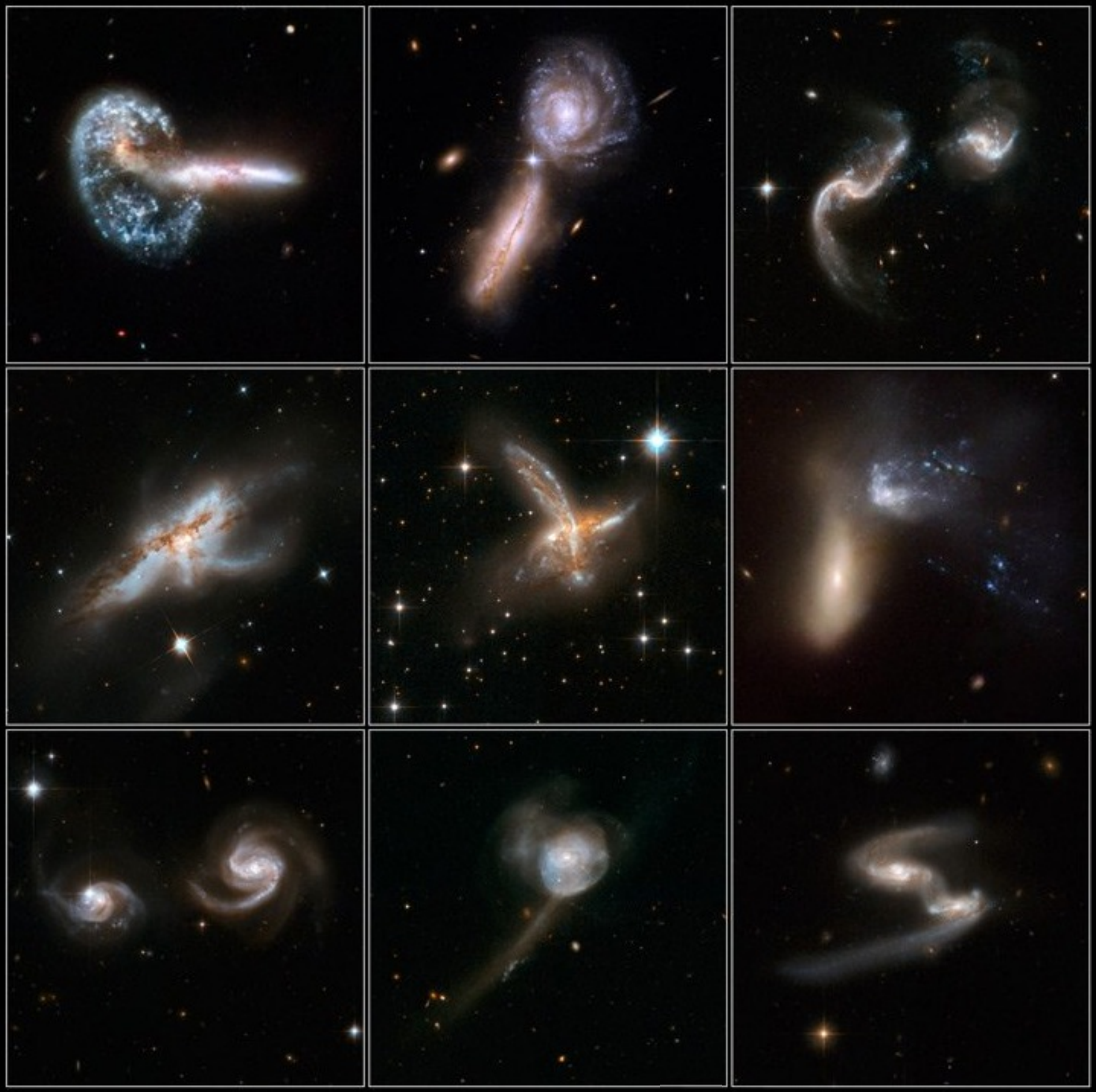
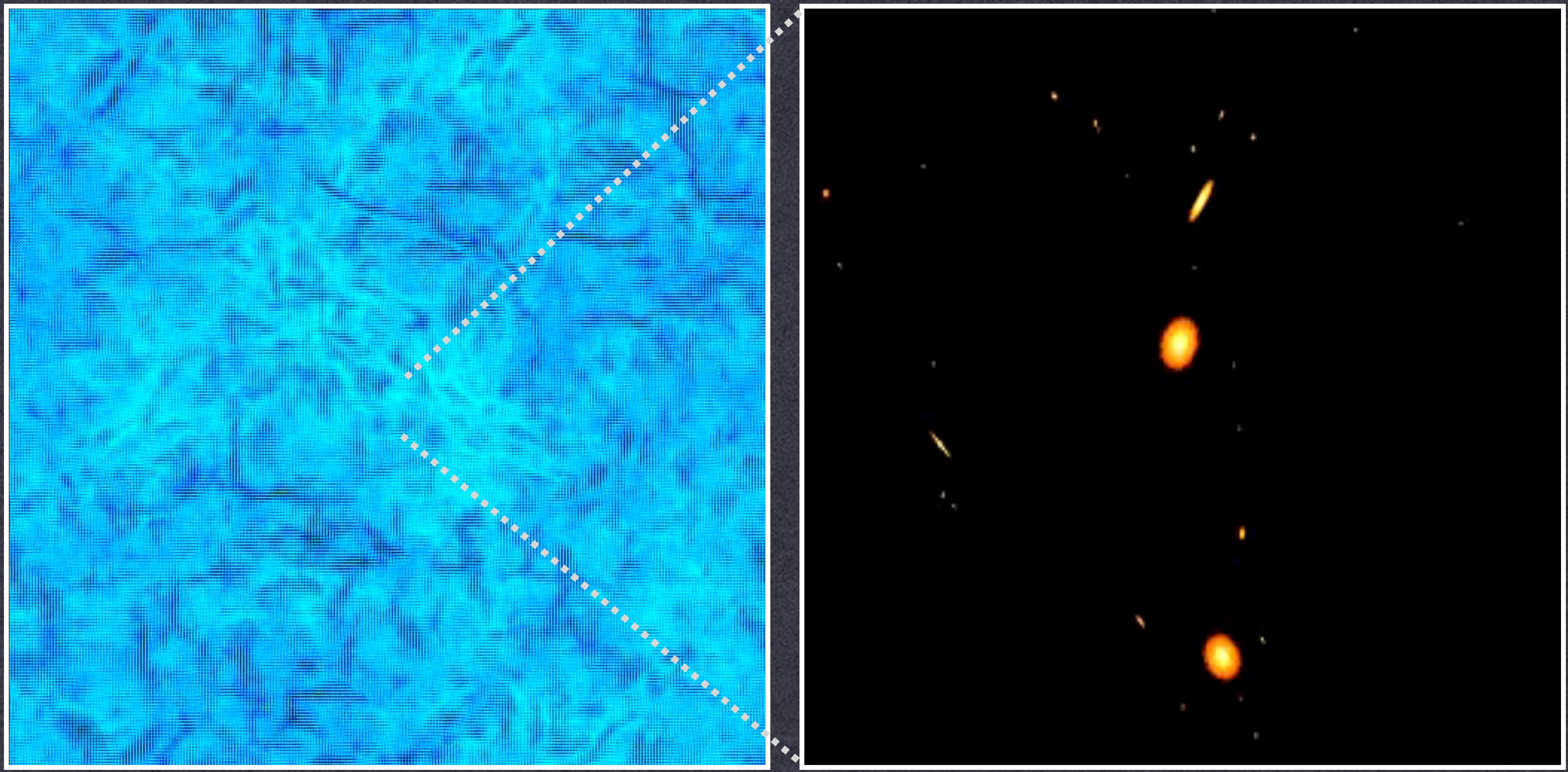
# Merger-Induced Black Hole Accretion & Star Formation: Observations vs. Simulations



Hai Fu

P. Bode, UPenn

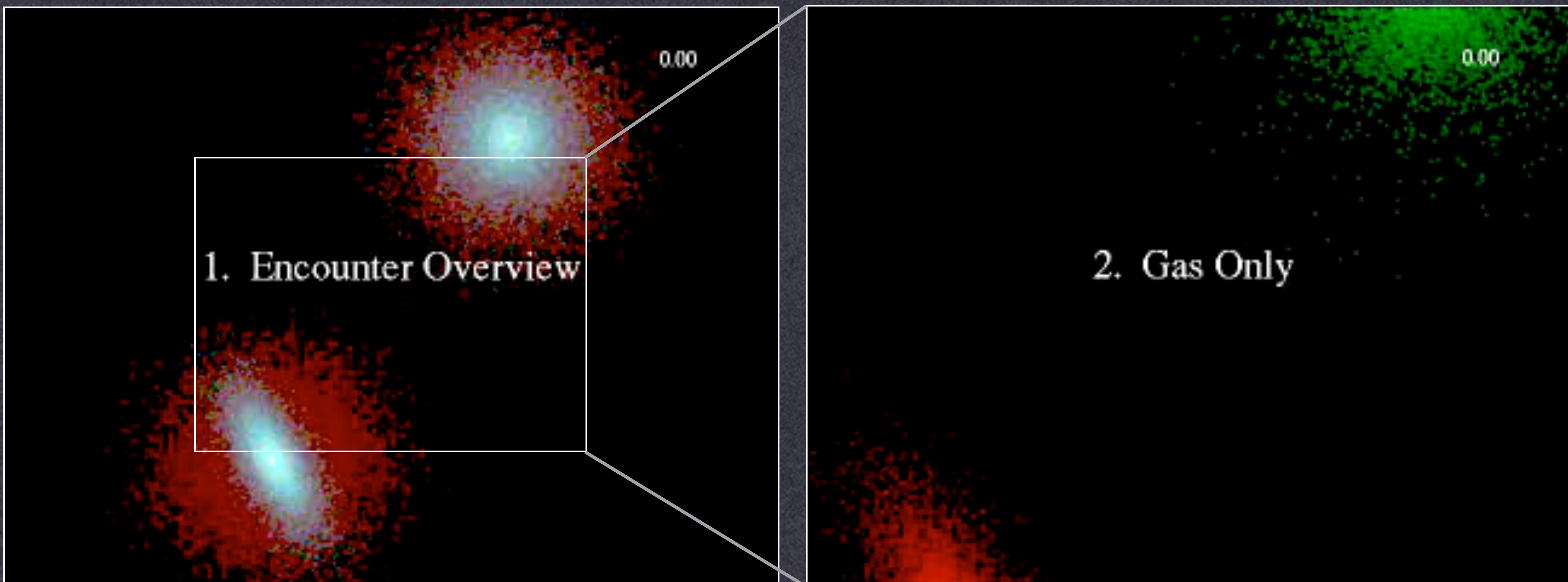
J. Dubinski, CITA



# Hierarchical Structure Formation

DM, Stars, Gas

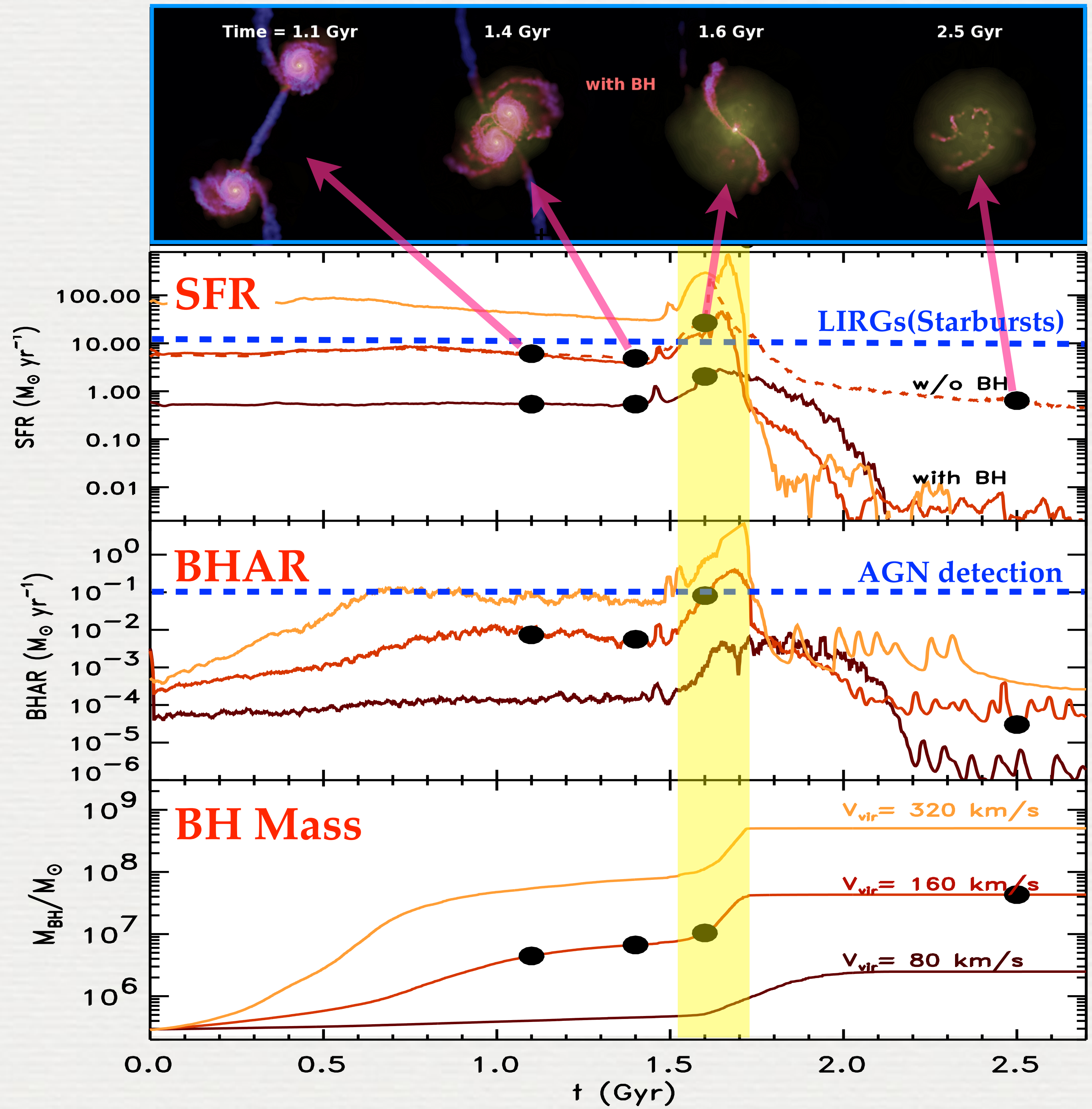
Gas Only



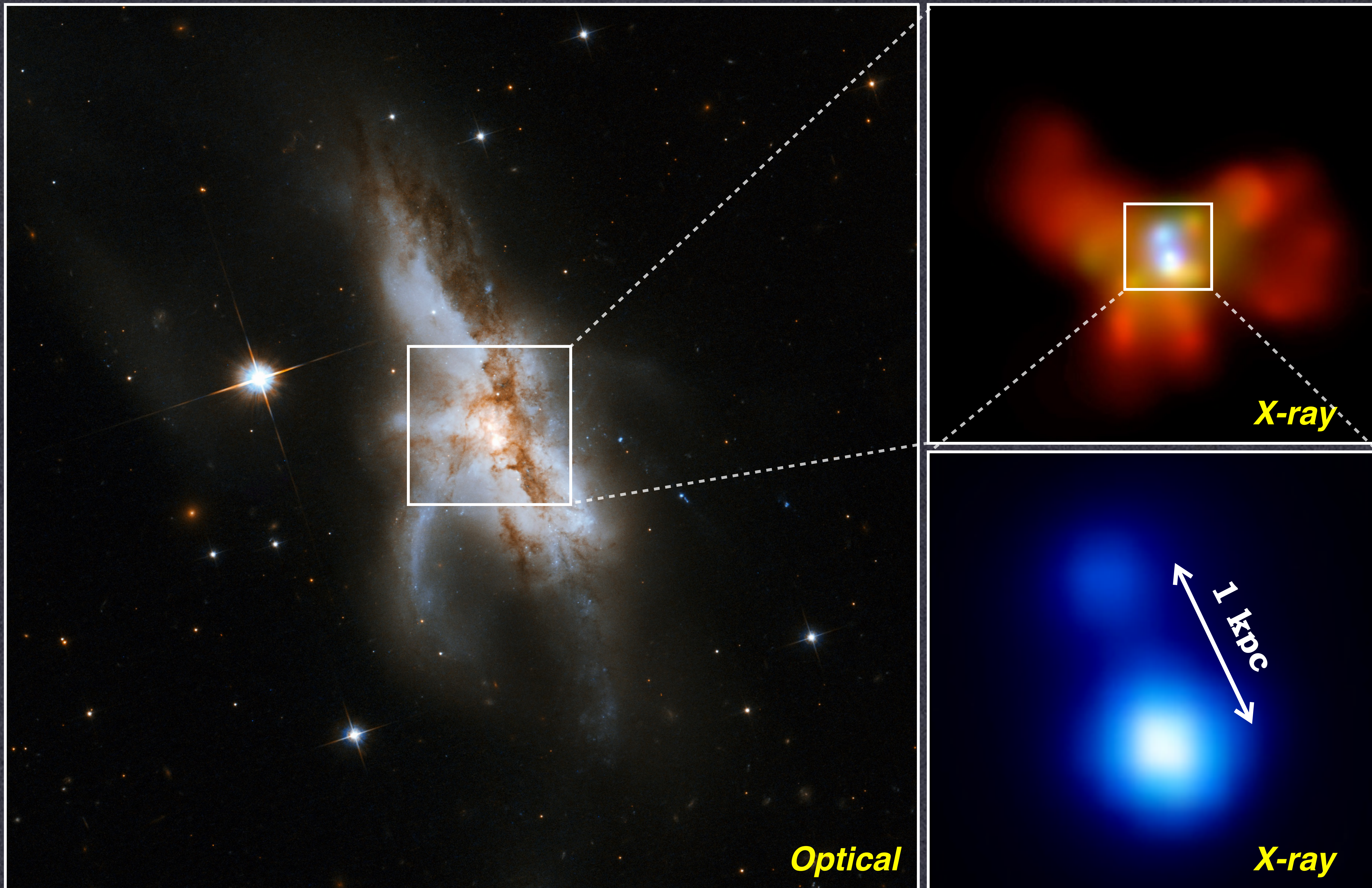

Barnes & Hernquist (1996)

# 1:1 Merger of Gas-Rich Spirals

*Di Matteo et al. (2005)*




# 1:1 Merger of Gas-Rich Spirals

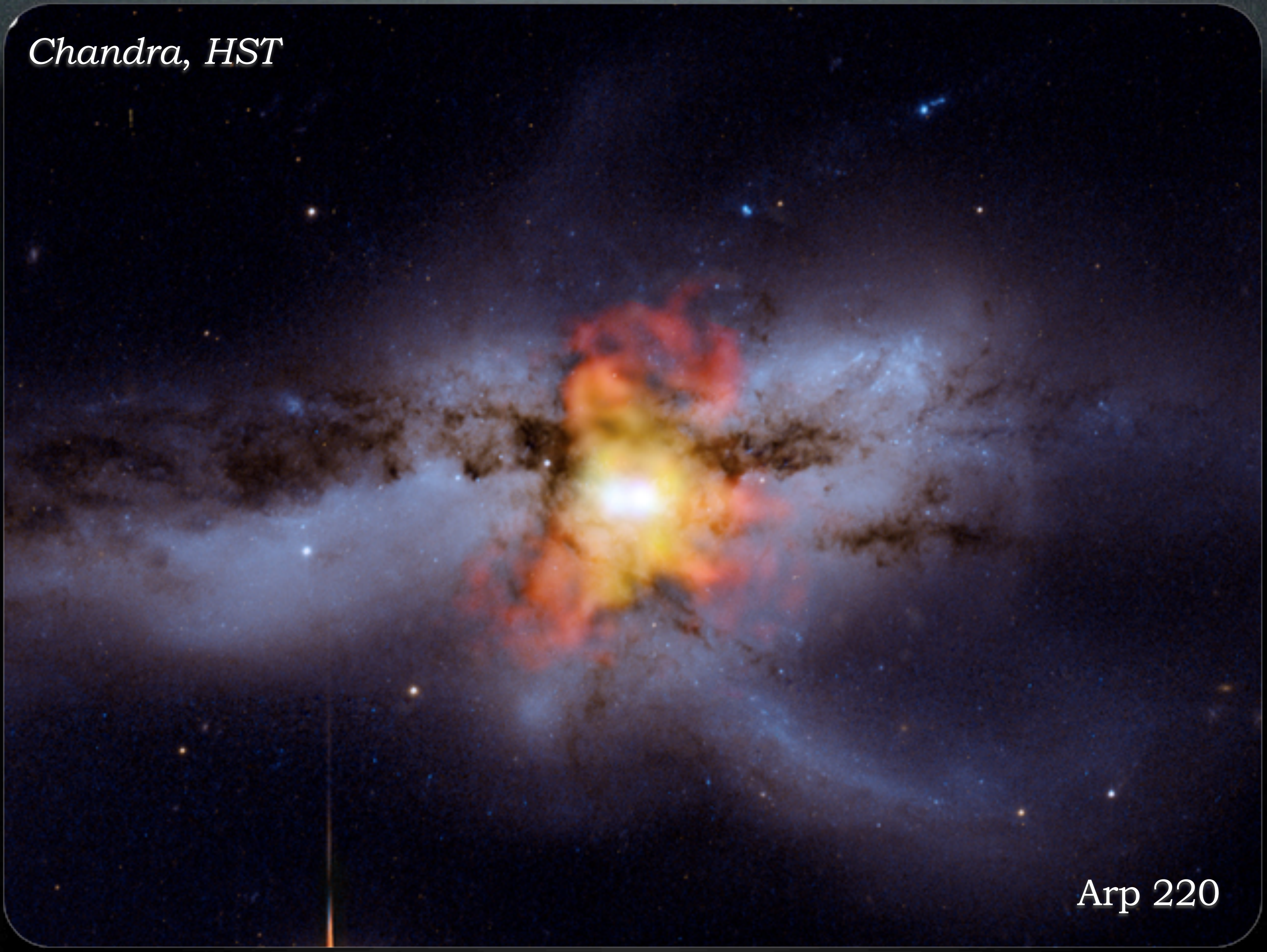



# NGC 6240: a Binary AGN & a Starburst in a Merger

Komossa et al. (2003)


# Binary AGNs

Fu et al. (2011a, 2011b, 2012a)



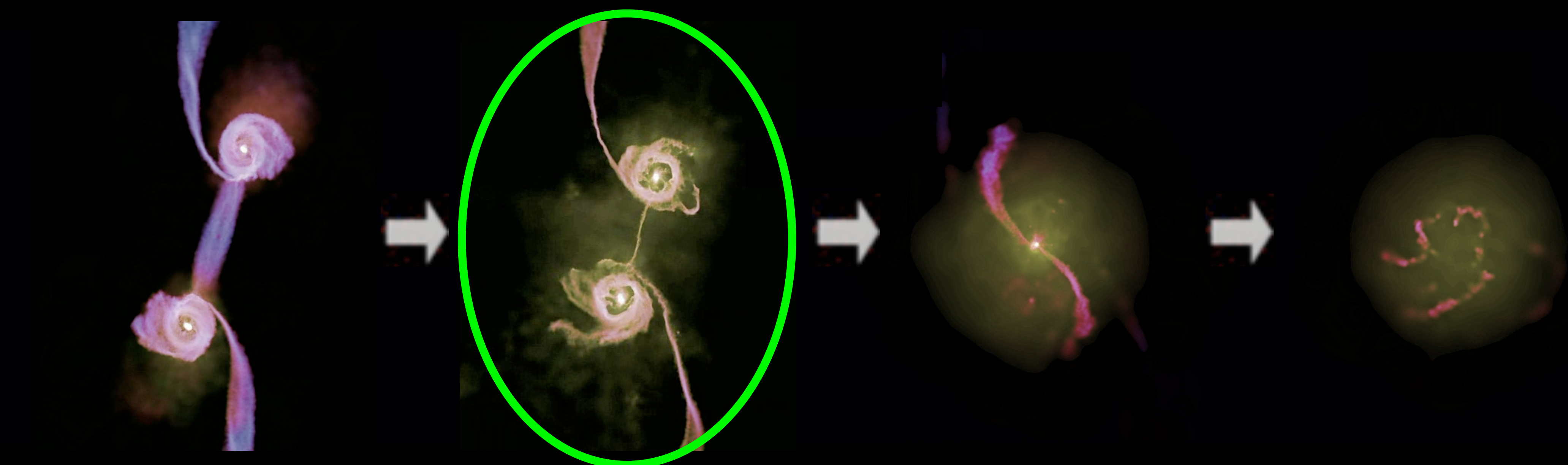

# BH Accretion in Starbursts

Fu et al. (2010)

Binary AGNs

10-100 kpc ↔ few kpc

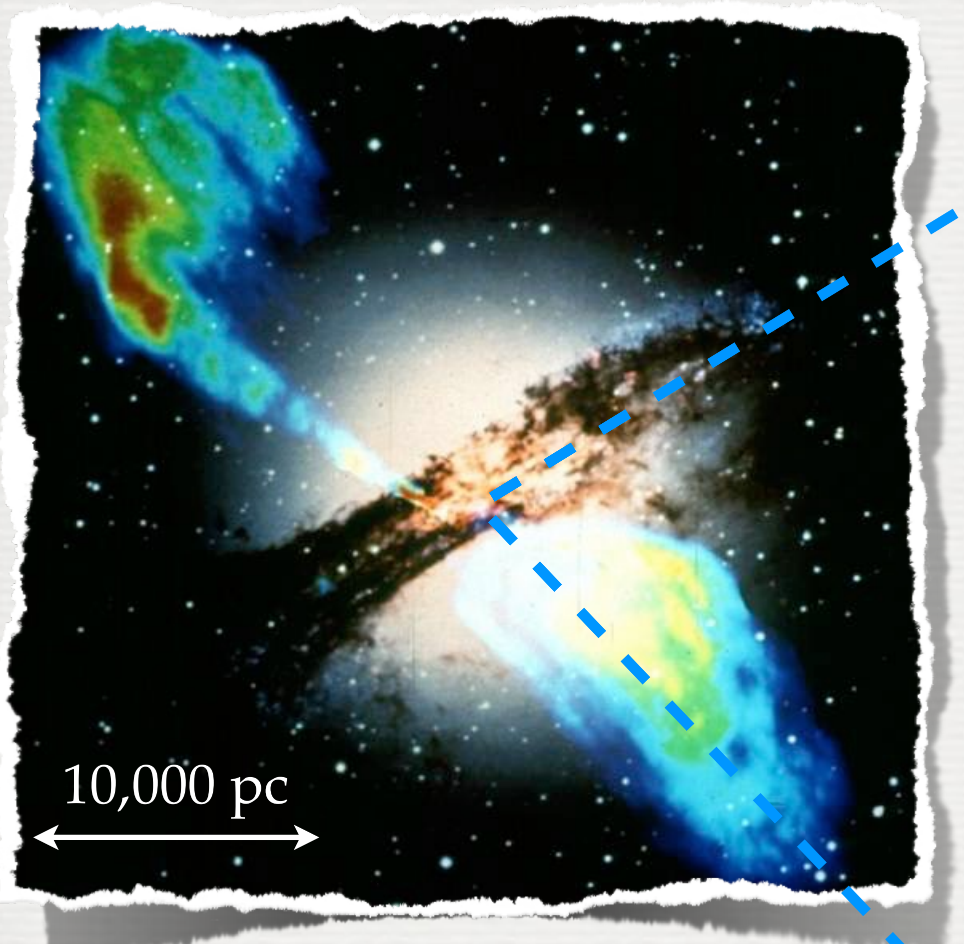
After 1st passage | Before the merge | Peak AGN activities | Coalesced



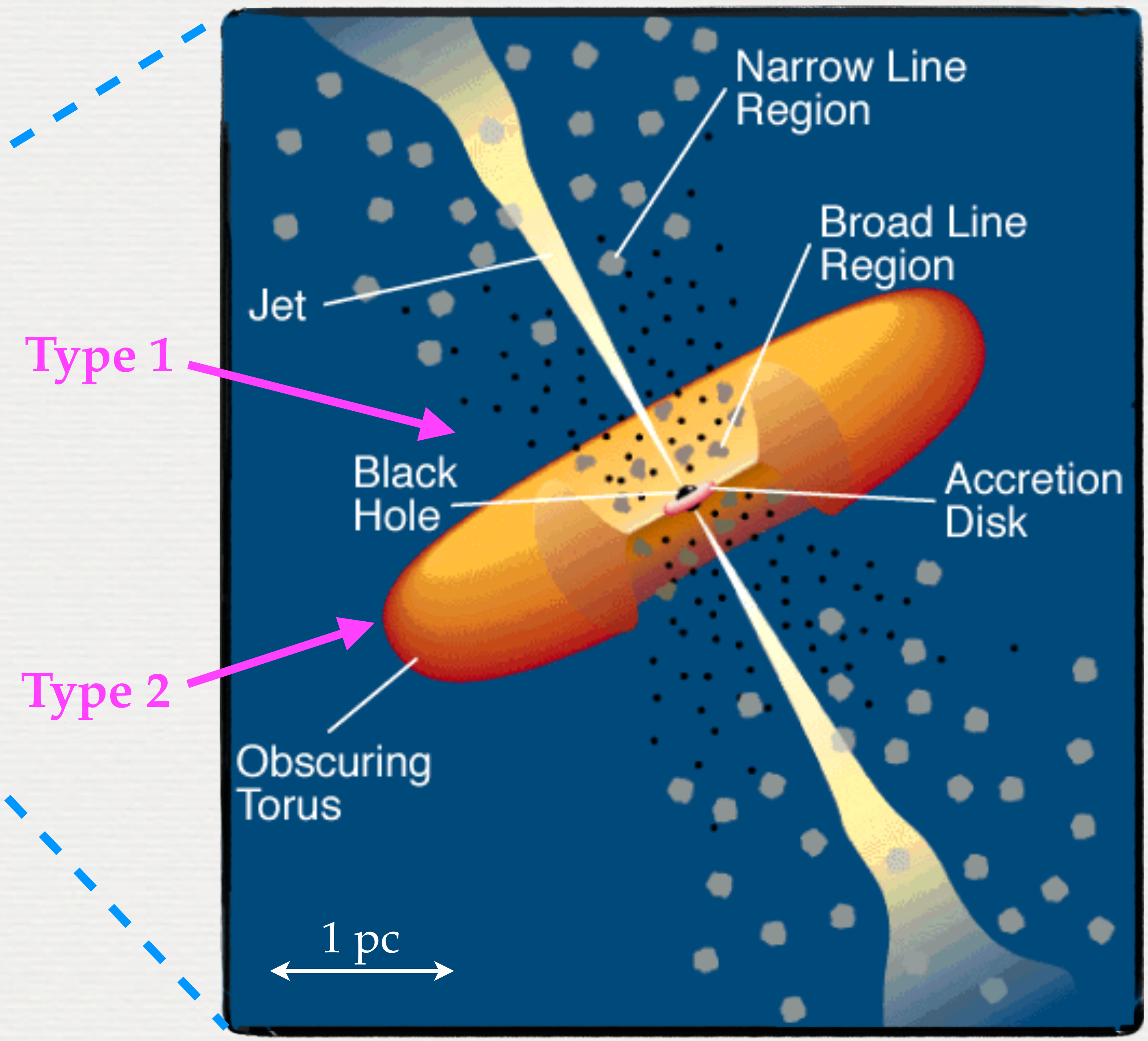
**Gas density, color coded w/ temperature**

*simulation: Di Matteo et al. (2005)*

# AGN Central Engine

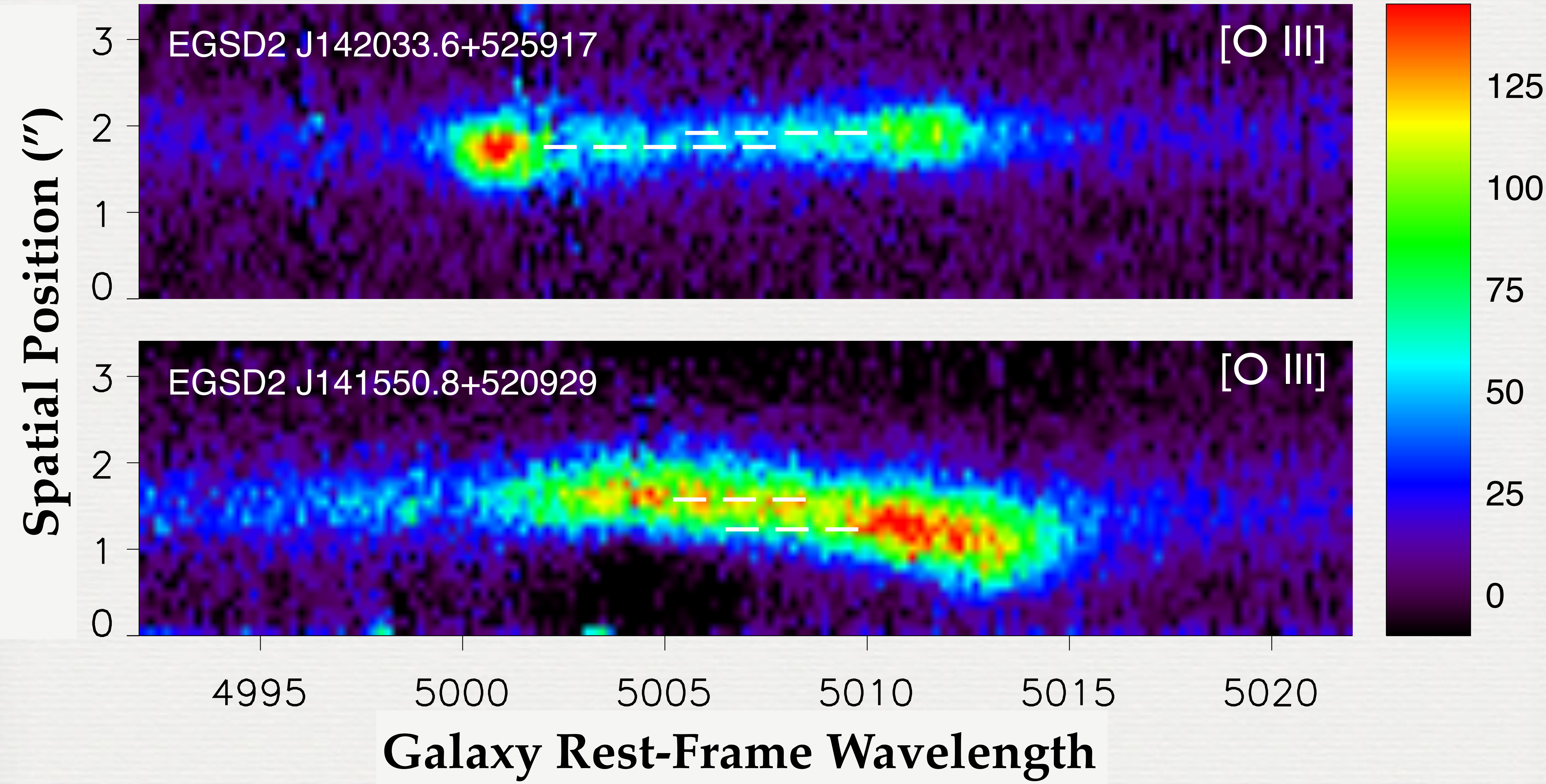



Centaurus A



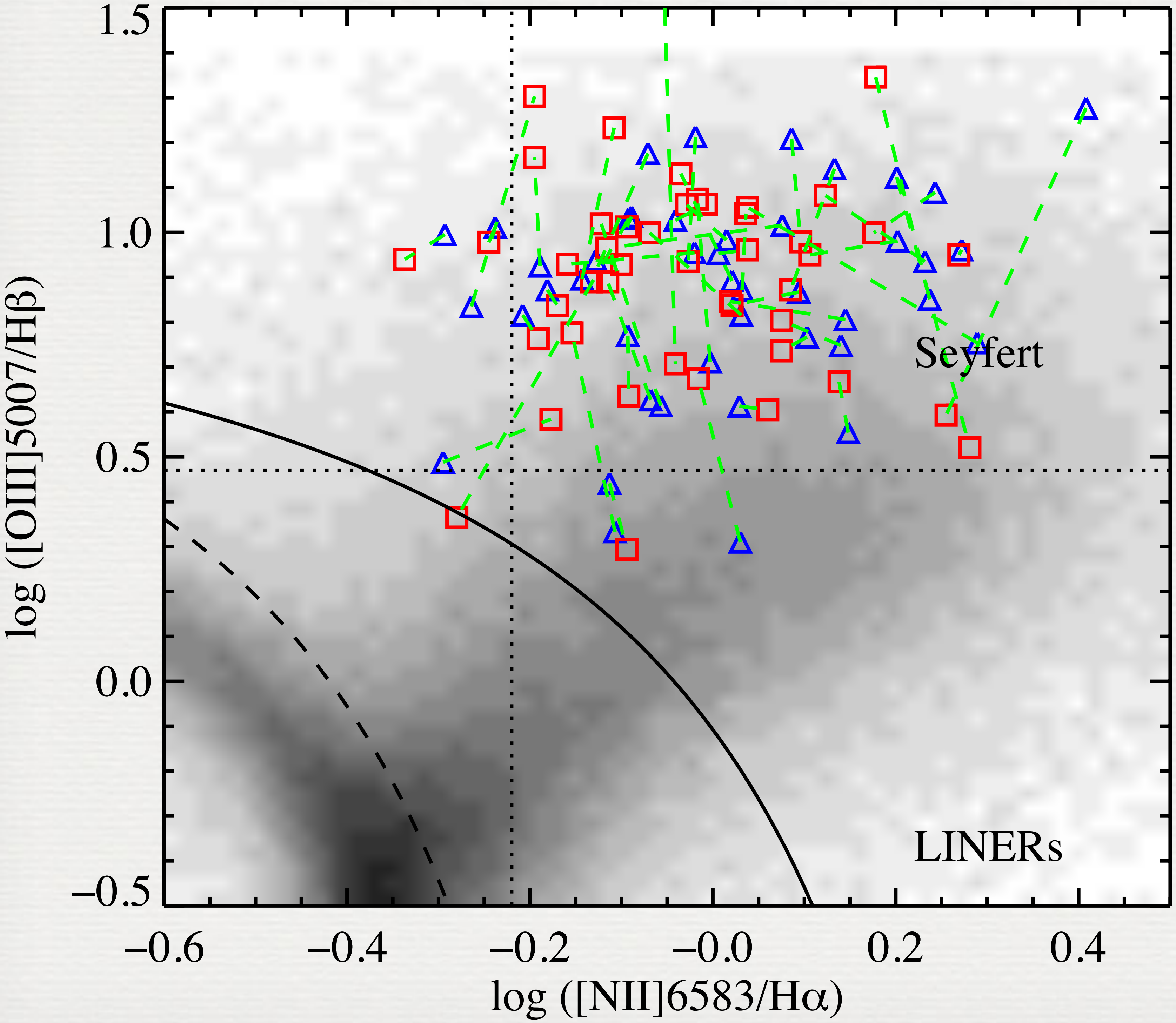

*Urry & Padovani 1995*

# Double-Peaked [O III] AGNs: DEEP2




*Gerke et al. (2007)*
*Comerford et al. (2009)*

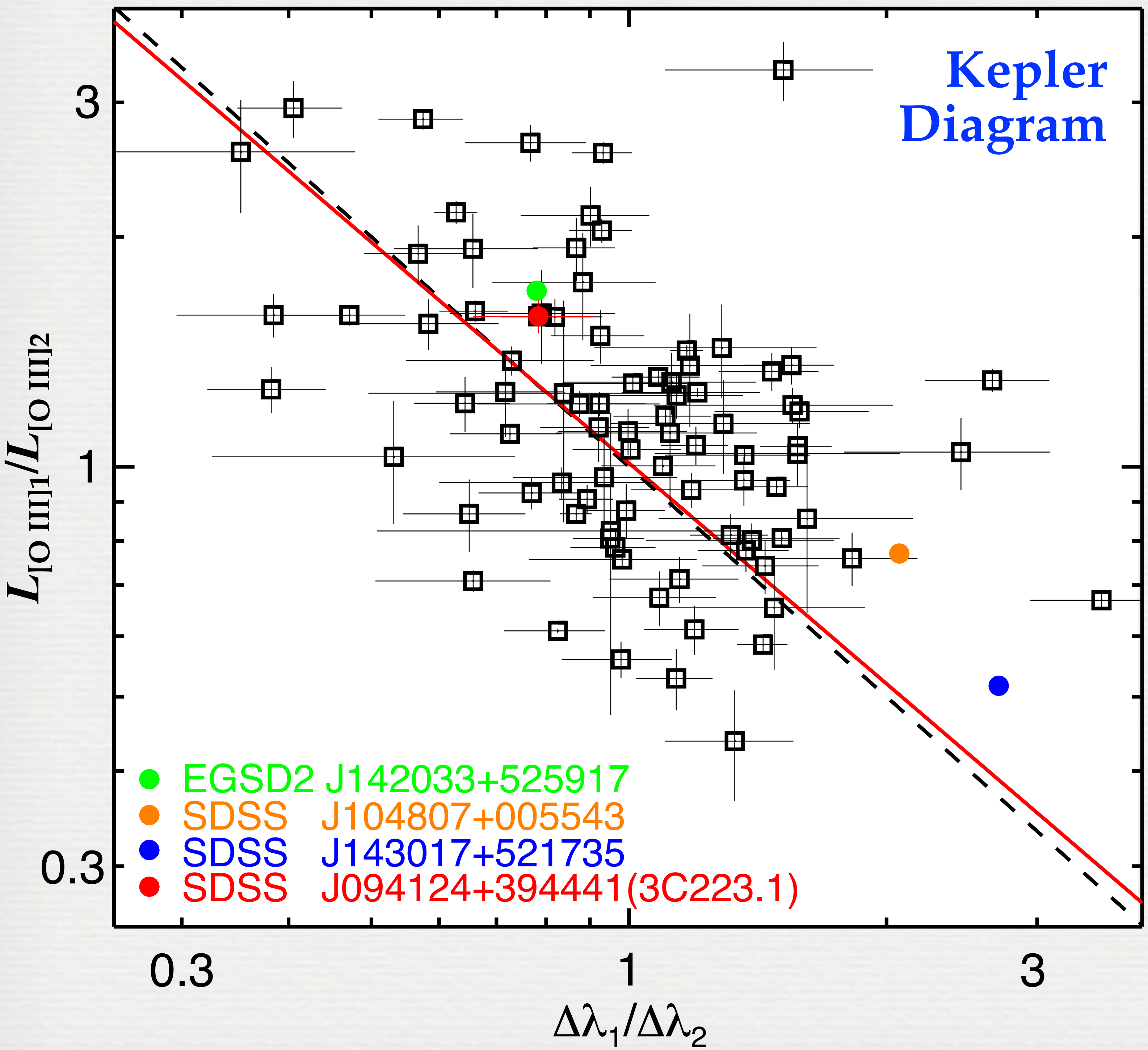
# Double-Peaked [O III] AGNs: SDSS




- 271 double-peaked [O III] AGNs from the SDSS at $z < 0.7$ (1% of SDSS AGNs)
- 41 Ty-1 & 230 Ty-2, $\Delta V > 250$ km/s
- Both components appear photoionized by AGNs

*Wang et al. (2009)*
*Liu et al. (2010)*
*Smith et al. (2010)*

# Are Double-Peaked AGNs Binaries?




- Observed:

  $L1_{[O\ III]}/L2_{[O\ III]} \propto V2/V1$

- Interpretation:

  Assuming same Bolometric corr.:

  $L1_{[O\ III]}/L2_{[O\ III]} \propto L1_{bol}/L2_{bol}$

  Assuming same Eddington ratio:

  $L1_{bol}/L2_{bol} \propto M1_{BH}/M2_{BH}$

  Magorrian Relation:

  $M1_{BH}/M2_{BH} \propto M1^*/M2^*$

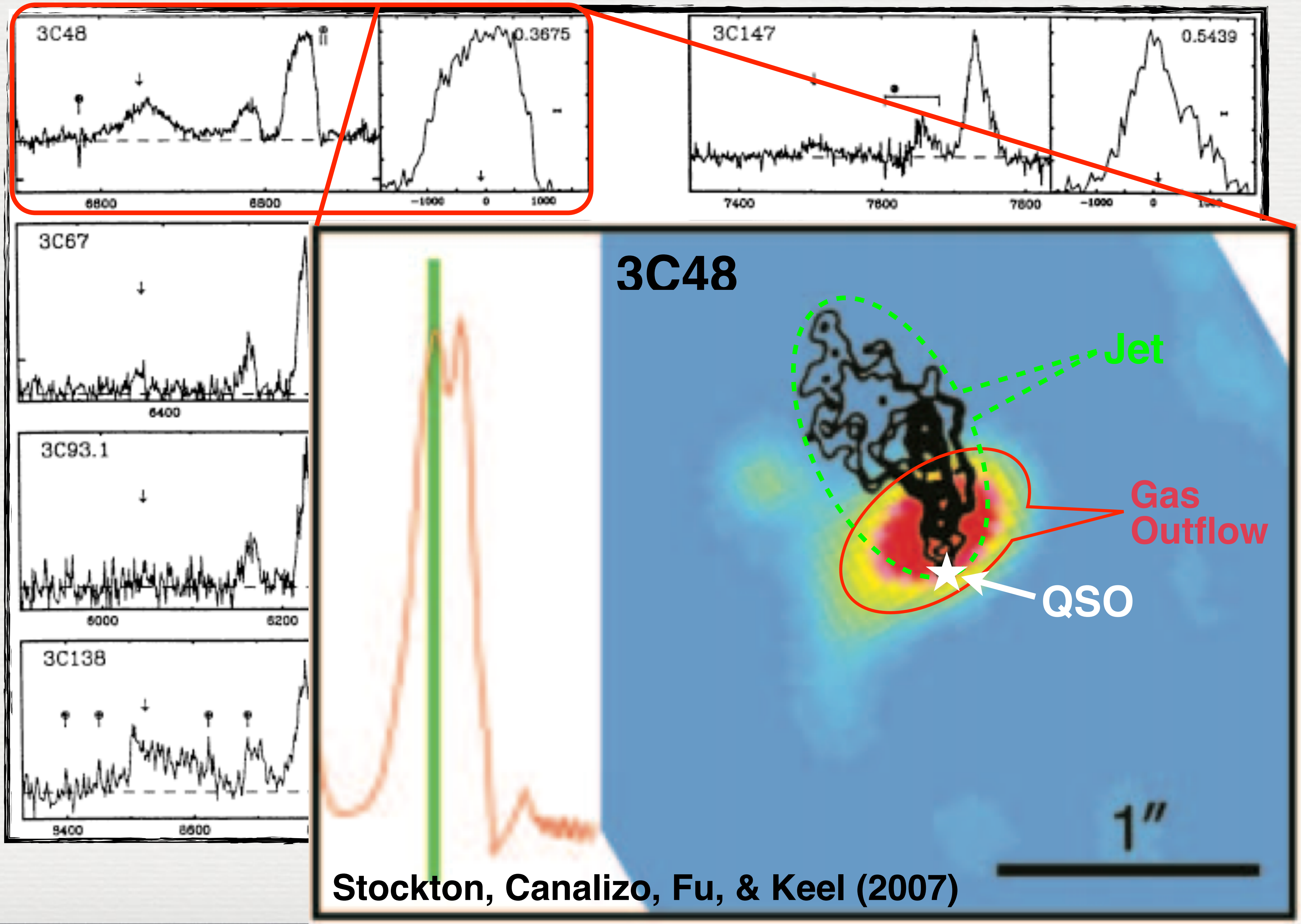
  Kepler's law:

  $M1^*/M2^* = V2/V1$

  ⇨ $L1_{[O\ III]}/L2_{[O\ III]} \propto V2/V1$

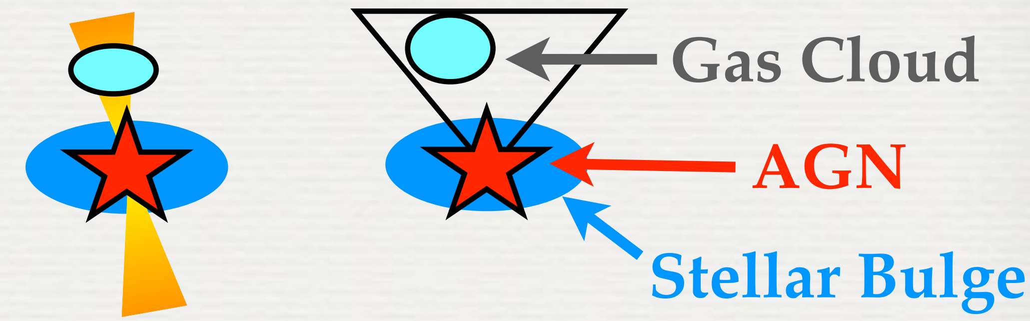
*Wang et al. (2009)*

# Double-Peaked [O III]: Jet-Driven Outflow

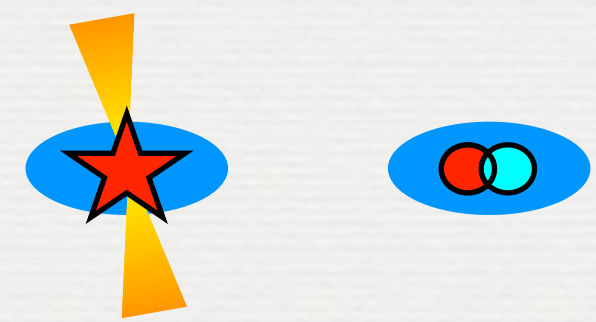


# Possible Double-Peaked Scenarios

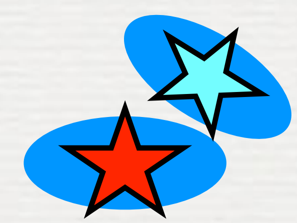
Spatially Resolved:
Outflows



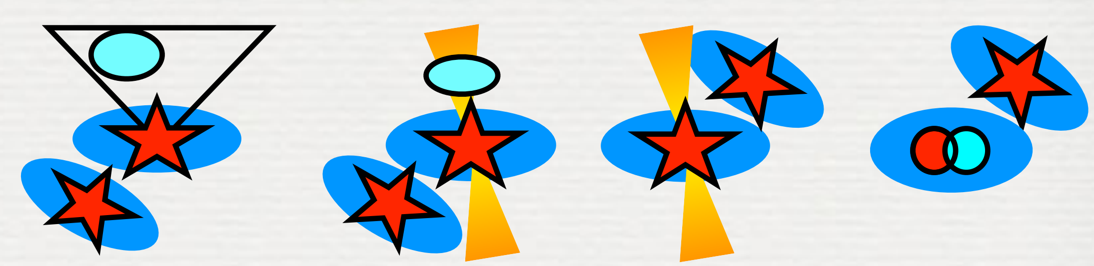

Spatially Unresolved:
Polar Outflows/Peculiar NLRs



Spectrally Resolved Binaries:



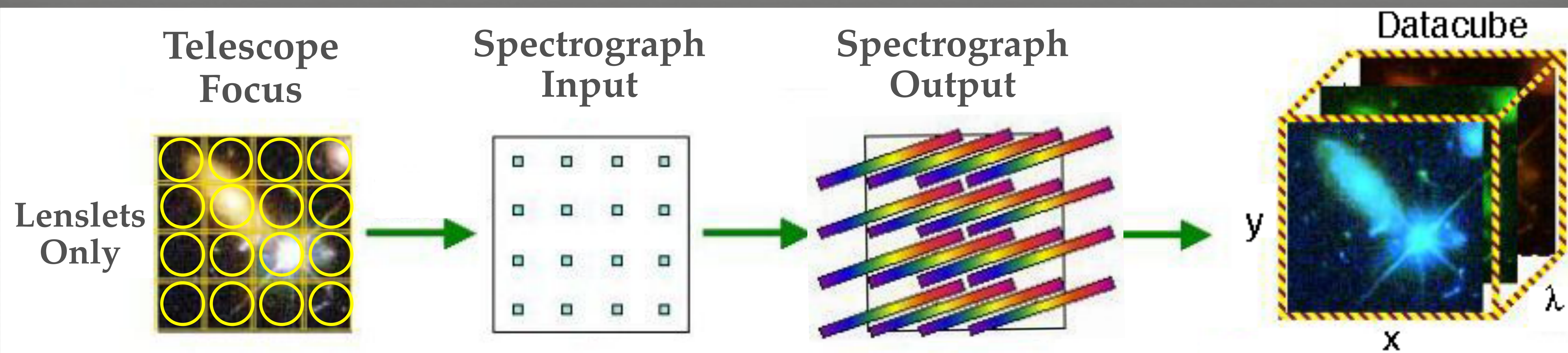
Spectrally Unresolved Binaries:
*selected because of outflow/NLR*



# Follow-up Observations

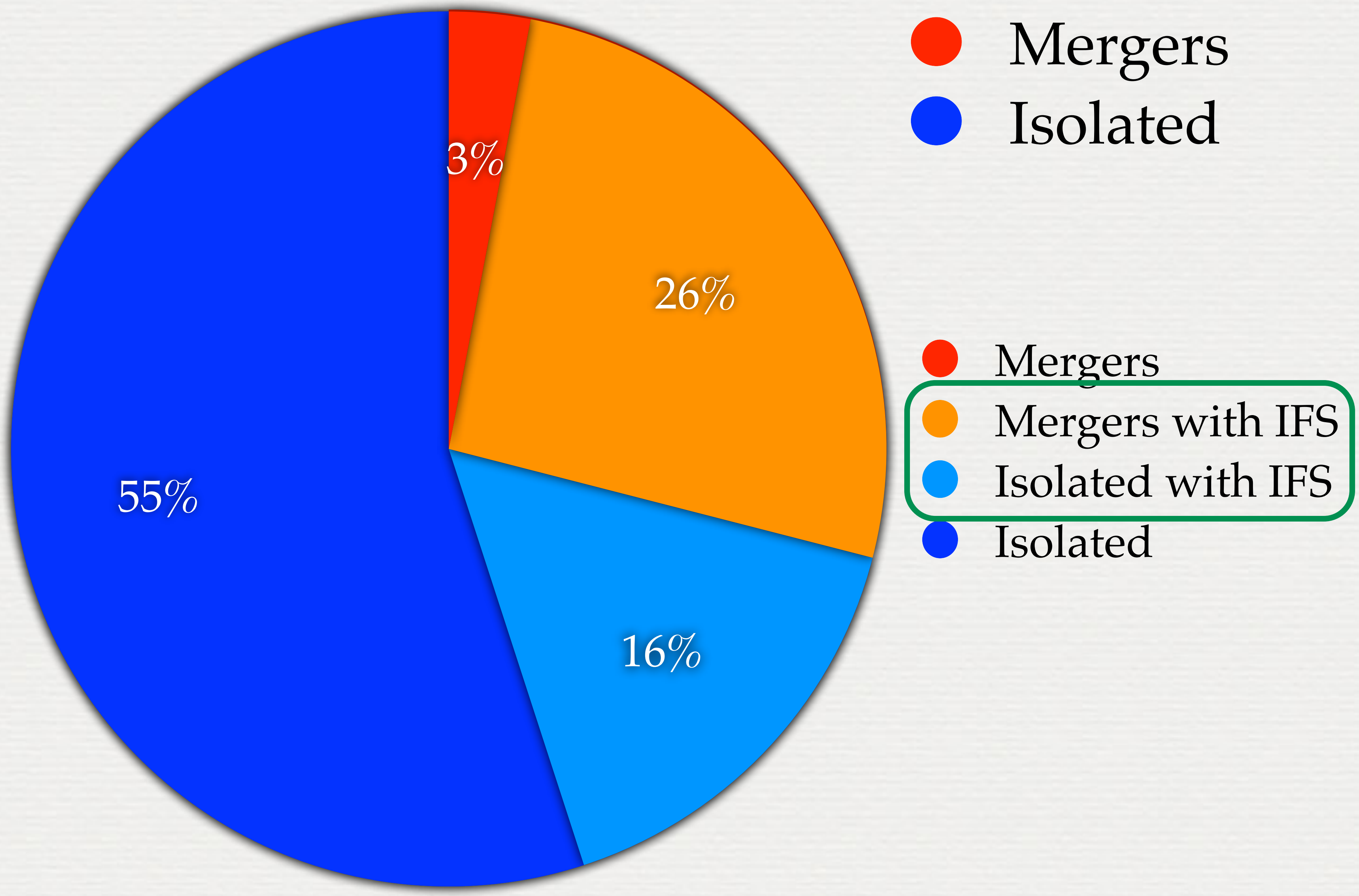
## Keck Laser Guide Star Adaptive Optics (LGSAO)


## UH 2.2m SNIFS & Keck OSIRIS+LGSAO

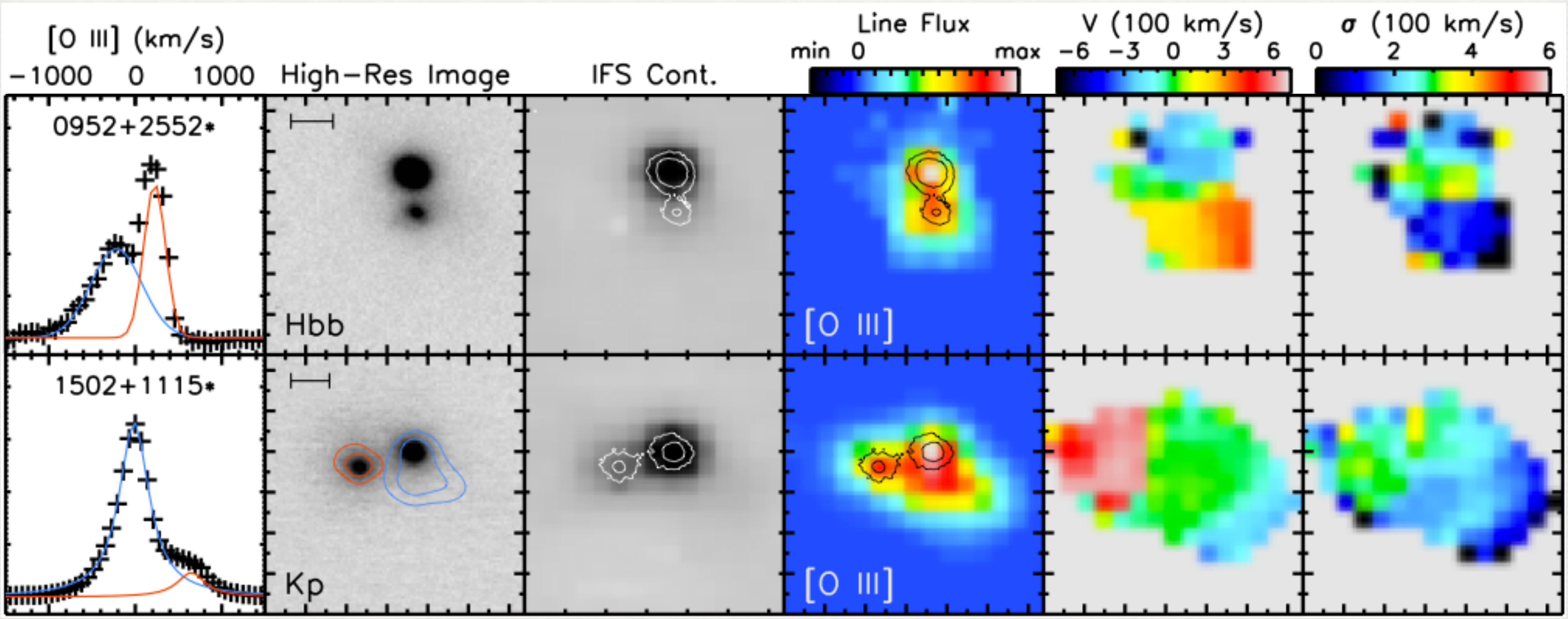



*Fu et al. (2011a, 2012a)*

# Follow-up Observations



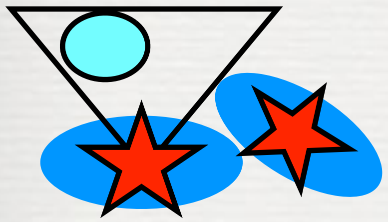
# Spectrally Resolved Binaries

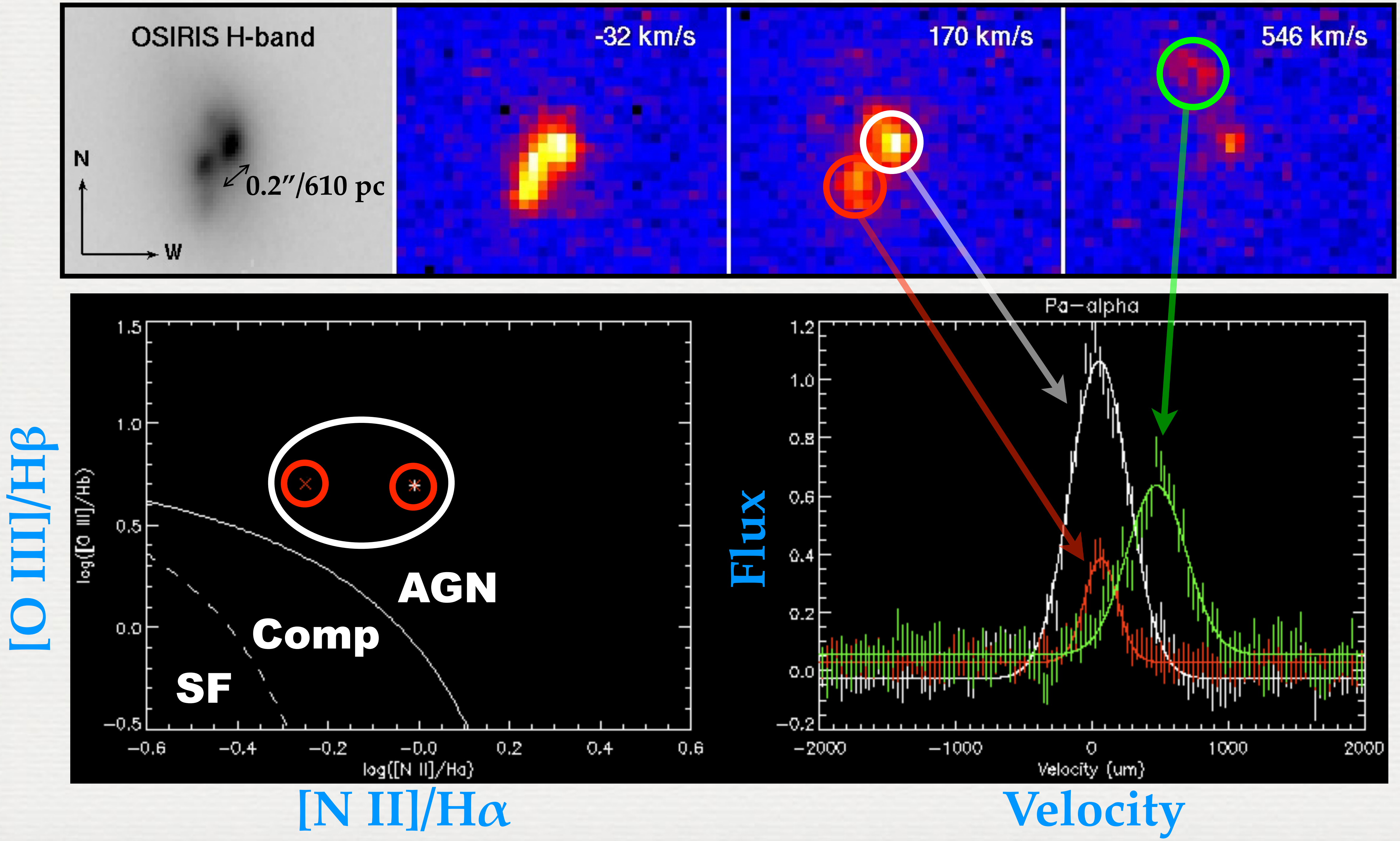


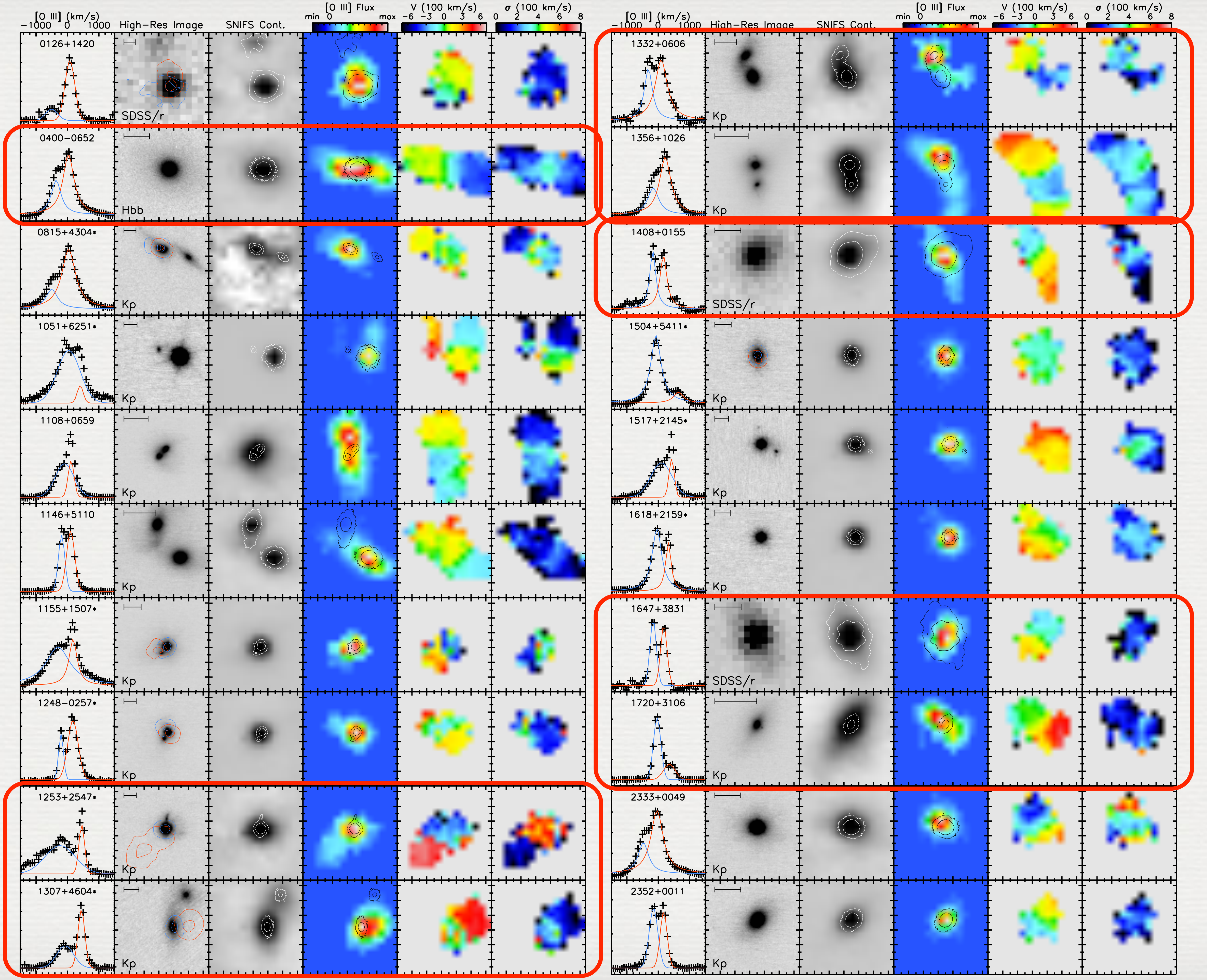

*Fu et al. (2012a)*

# Spectrally Unresolved Binaries

Selected because of outflows

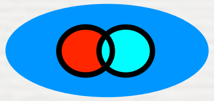


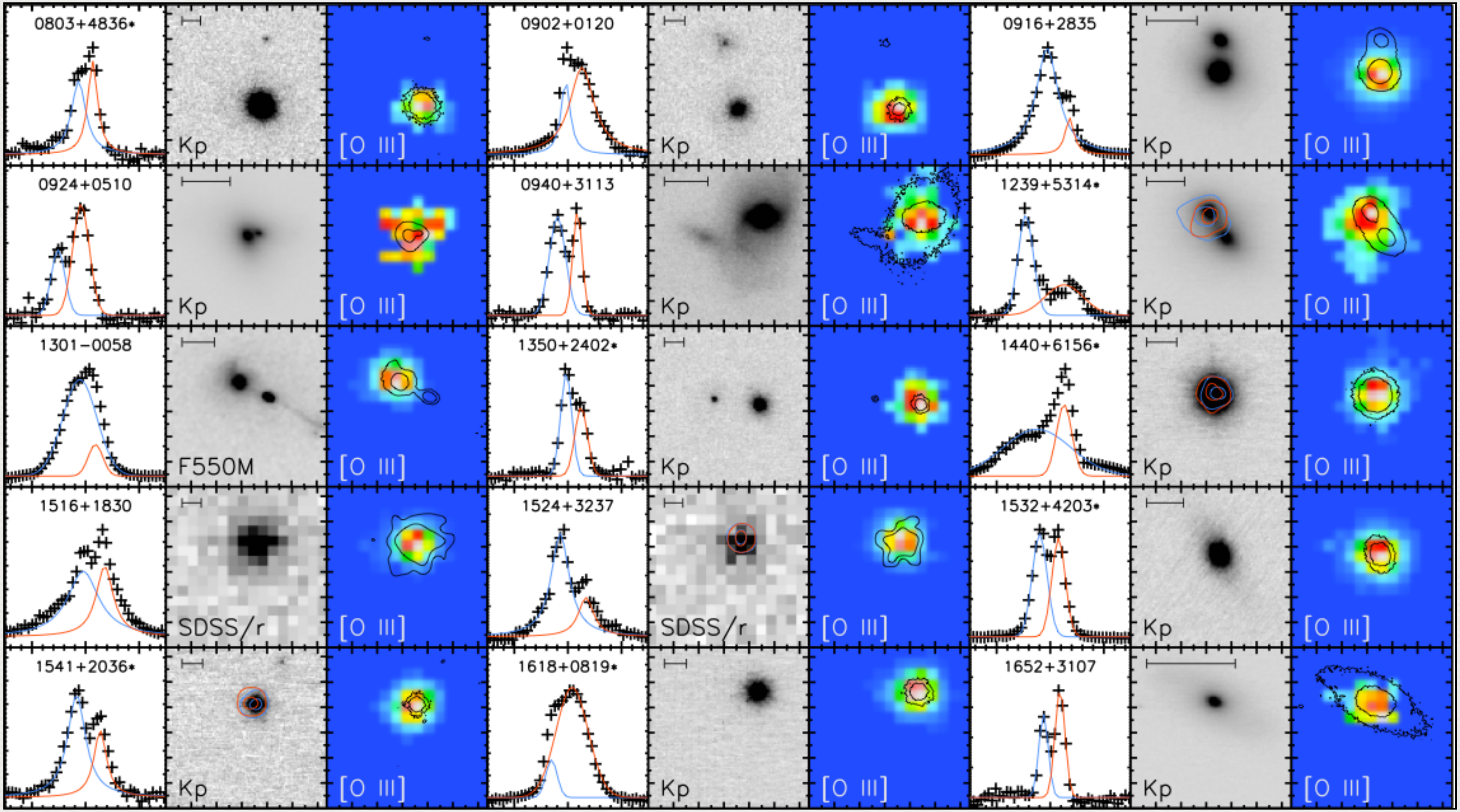




[O III] (km/s)
−1000 0 1000
High−Res Image
SNIFS Cont.
[O III] Flux
min 0 max
V (100 km/s)
−6 −3 0 3 6
σ (100 km/s)
0 2 4 6 8
0126+1420
SDSS/r
0400−0652
Hbb
0815+4304*
Kp
1051+6251*
Kp
1108+0659
Kp
1146+5110
Kp
1155+1507*
Kp
1248−0257*
Kp
1253+2547*
Kp
1307+4604*
Kp
1332+0606
Kp
1356+1026
Kp
1408+0155
SDSS/r
1504+5411*
Kp
1517+2145*
Kp
1618+2159*
Kp
1647+3831
SDSS/r
1720+3106
Kp
2333+0049
Kp
2352+0011
Kp

# Single AGNs:
## Spatially unresolved outflows/NLRs

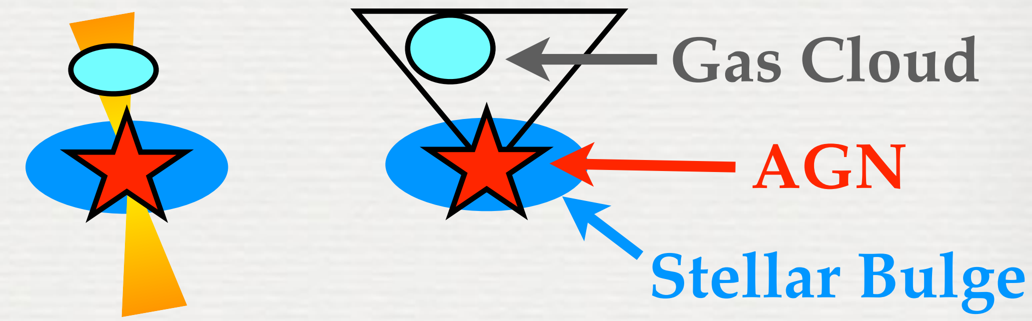




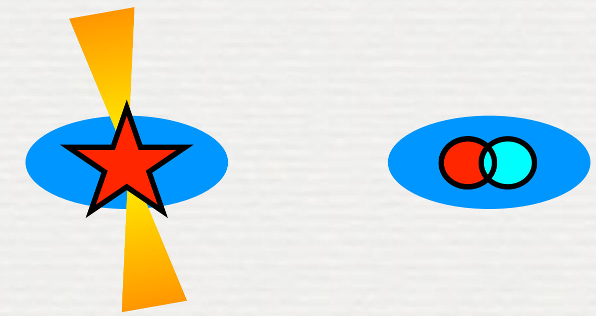

*Fu et al. (2012a)*

# Constituents of Double-Peaked AGNs

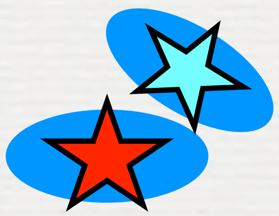
Spatially Resolved (50%):
Outflows



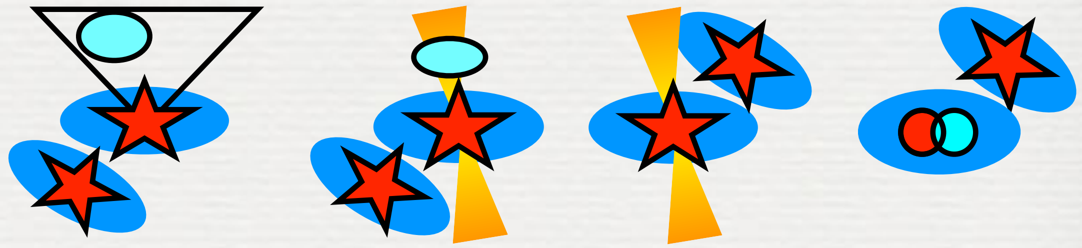

Spatially Unresolved (46%):
Polar Outflows/Peculiar NLRs



Spectrally Resolved Binaries (2%):



Spectrally Unresolved Binaries (2%):
*selected because of outflow/NLR*



# Implications:

## (1) Binary Fraction and Duty Cycle

- ~0.02% of AGNs are spectrally resolved binaries
  - ➢ *Binary Fraction* × *Completeness* = 0.02%
- ~0.02% of AGNs are spectrally unresolved binaries but are double-peaked b/c of outflows/NLRs
  - ➢ *Binary Fraction* × (1−*Completeness*) × *Double-Peaked Fraction* = 0.02%
    *Double-Peaked Fraction* = 1%

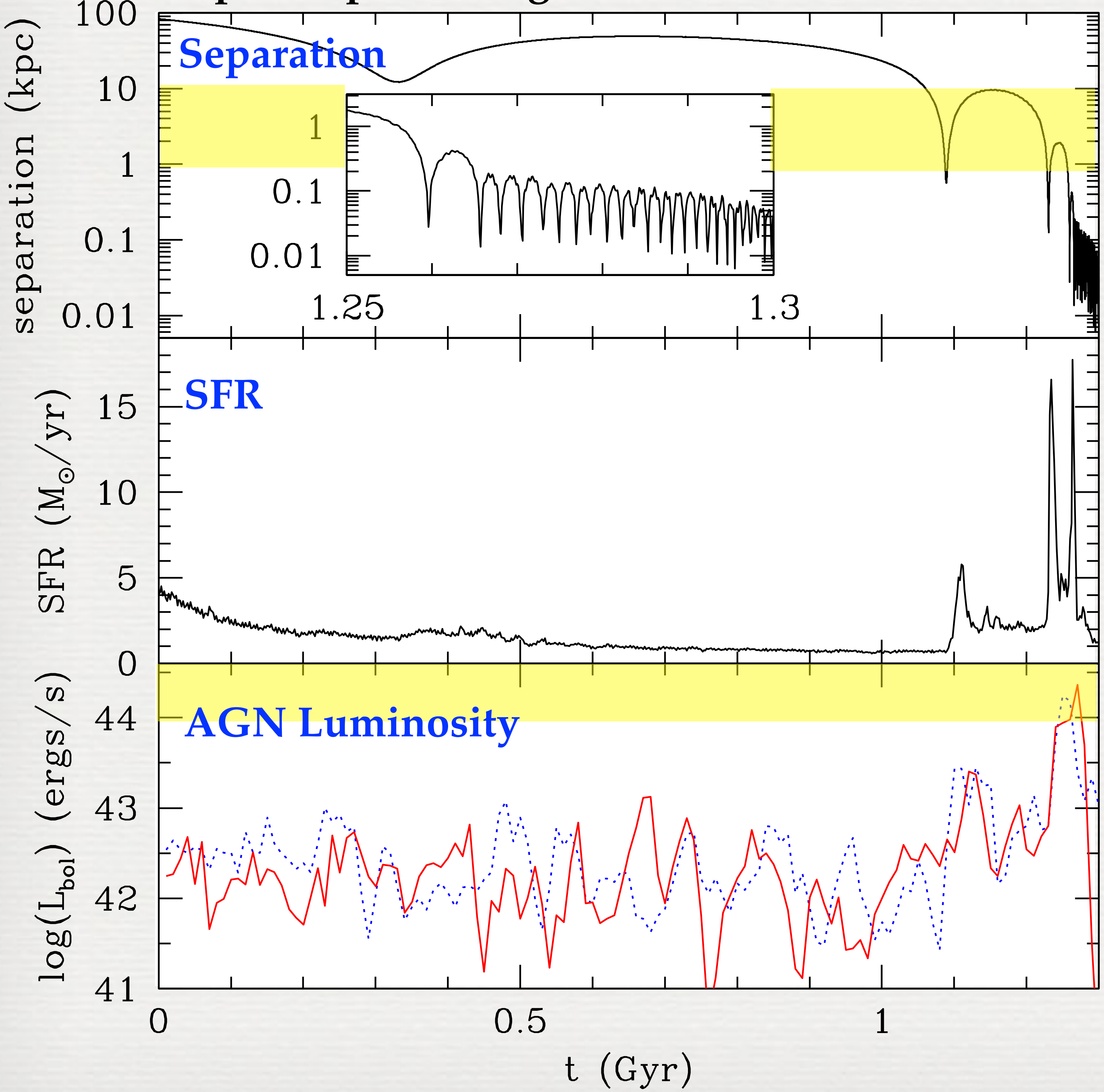
☑ ~2% of all AGNs are binaries: *Binary Fraction ~ 2%*
~1% of binaries are spectrally resolved: *Completeness ~ 1%*

☑ AGN duty cycle increases by ~15× in kpc-scale mergers

We expect 1% of the AGNs in mergers are binaries (1% Duty Cycle: Shankar+09)
However, we observed 4 binaries in 26 AGNs in mergers (15%)
*(Note that <30% of AGNs are in mergers according to our LGSAO survey)*

# How many binary AGNs are observable?

**1:2 Spiral-Spiral Merger** *(Van Wassenhove et al. 2012)*



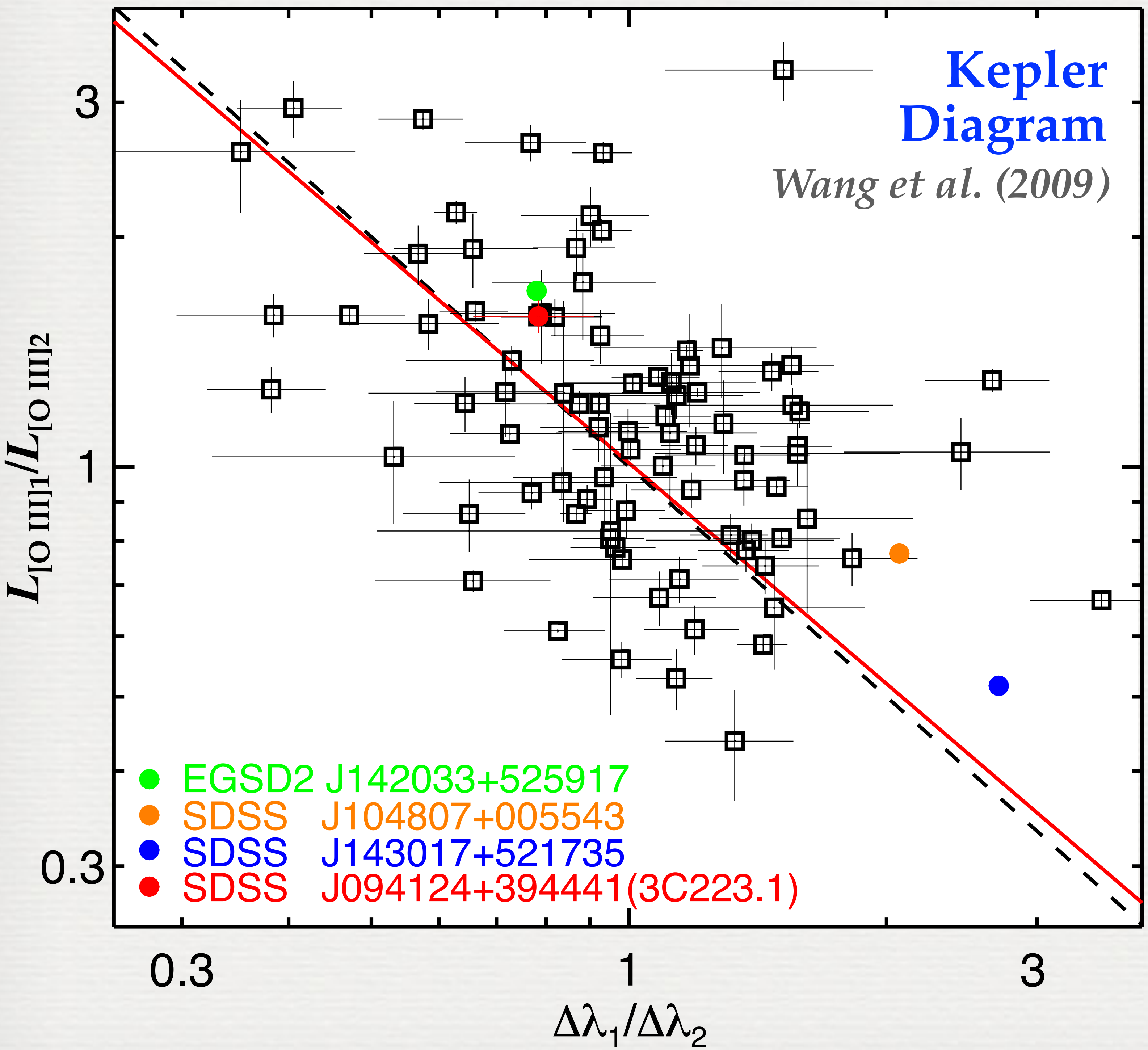

- Simulation:
  kpc-scale binary AGN is observed in 16% of the time when either BH is an AGN (i.e. $L_{bol} > 10^{44}$ erg/s)

- Observation:
  4 binaries in 26 AGN that are mergers (~15%)

- Merger fraction is ~5% at $z \sim 0.5$ (*Hopkins et al. 2010*)
  ➯ **binary fraction in all AGNs is ~0.8%**

# Implications:

## (2) Interpreting the "Kepler" Diagram




- Observed:

  $L1_{[O\,III]}/L2_{[O\,III]} \propto V2/V1$

- My interpretation:

  Similar [OIII]/Hβ ratio:

  $L1_{[O\,III]}/L2_{[O\,III]} \propto M1_{gas}/M2_{gas}$

  Bipolar outflow:

  $M1_{gas}/M2_{gas} = V2/V1$

  ⇨ $L1_{[O\,III]}/L2_{[O\,III]} \propto V2/V1$

- Wang+09's Interpretation:

  $L1_{[O\,III]}/L2_{[O\,III]} \propto L1_{bol}/L2_{bol}$

  $L1_{bol}/L2_{bol} \propto M1_{BH}/M2_{BH}$

  Kepler's law:

  $M1_{BH}/M2_{BH} = V2/V1$

  ⇨ $L1_{[O\,III]}/L2_{[O\,III]} \propto V2/V1$

# Implications:

## (3) Radiation-Pressure Driven Outflow?

- *Radiation Pressure:*

  $\dot{p}_{rad} = \tau\, L_{bol}/c$

  *Bolometric Luminosity:*

  $L_{bol} = 3500 L_{[O III]} = \epsilon \dot{M}_{BH} c^2$

  $0 < \tau < 1$: *the optical depth.*

- *Average p Injection Rate:*

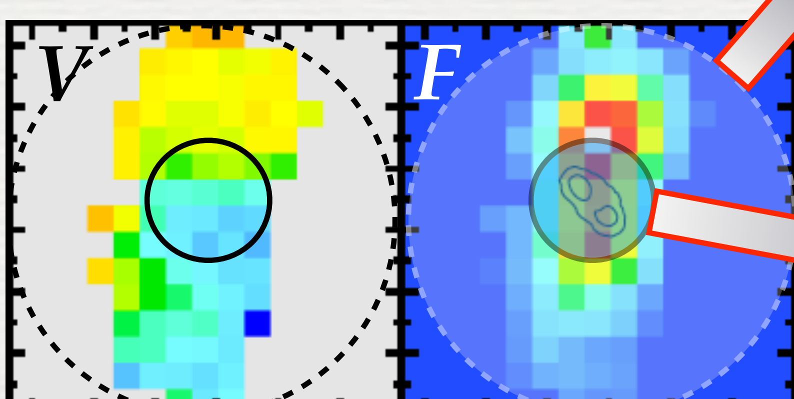
  $\dot{p}_{gas} = M_{gas} V_{gas} / t$

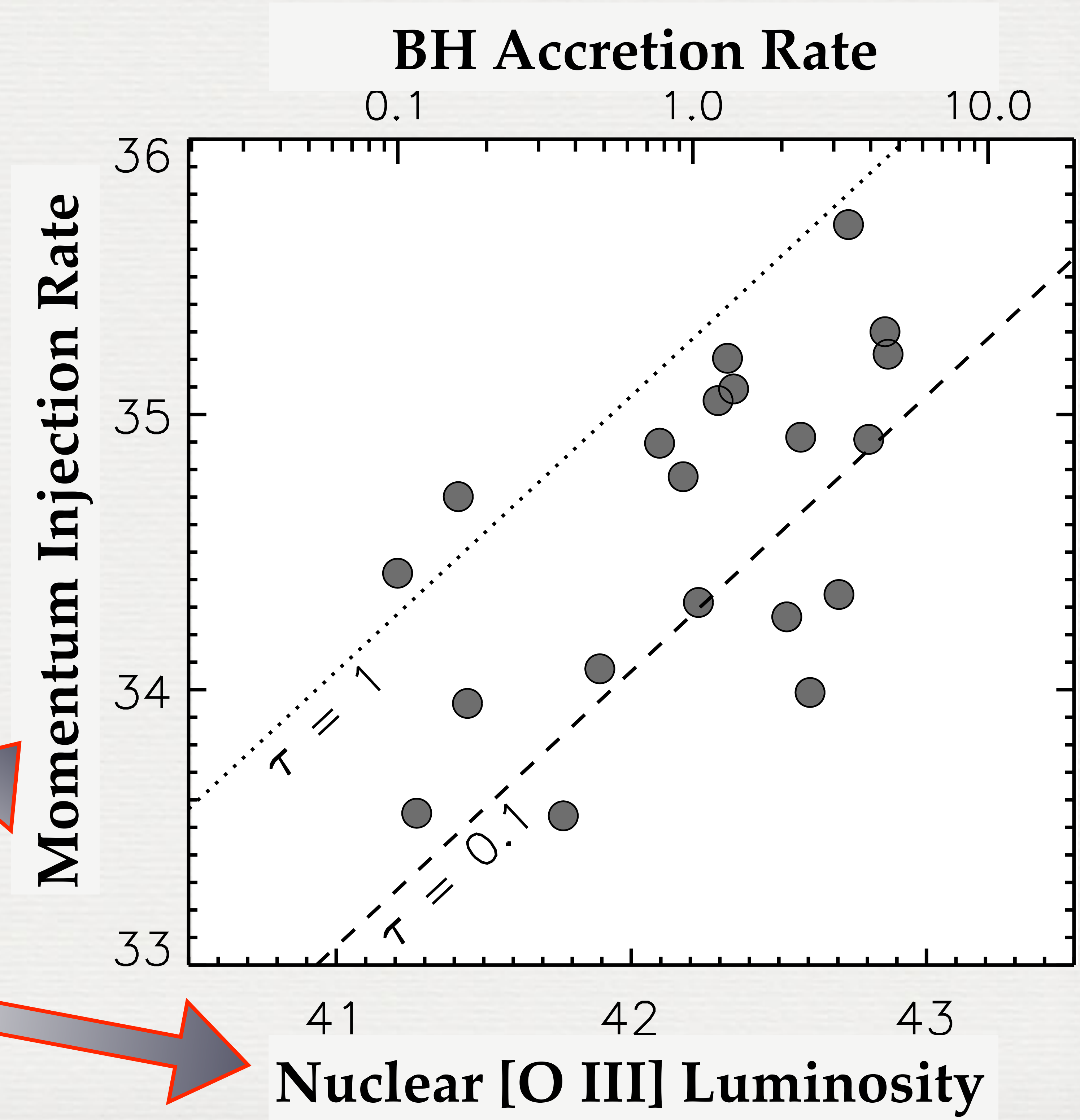
  *Gas Momentum:*

  $p_{gas} = M_{gas} V_{gas} \propto L_{[O III]} V_{gas}$

  *Dynamical Timescale:*

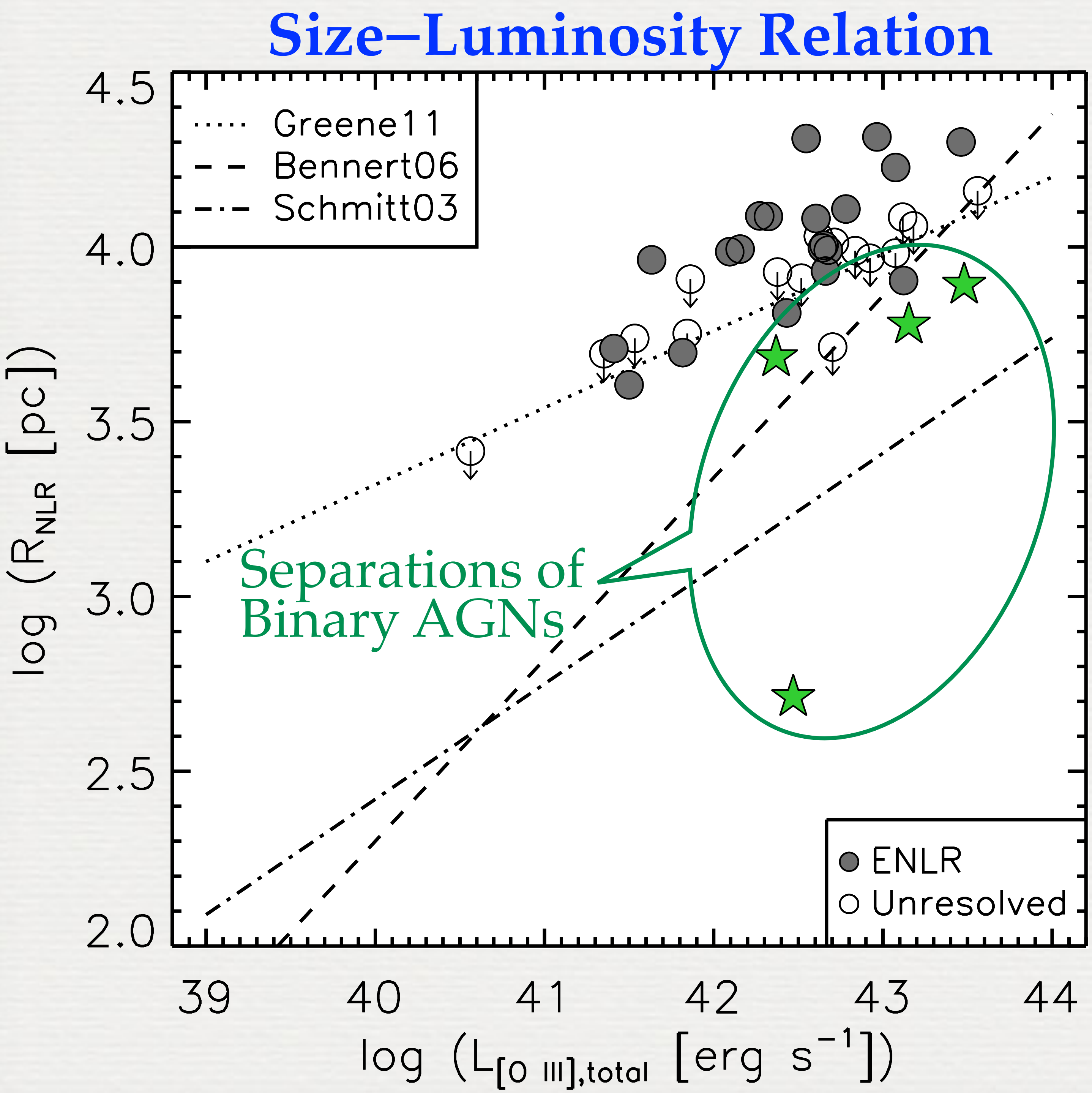
  $t = R_{NLR}/\max(V_{gas})$



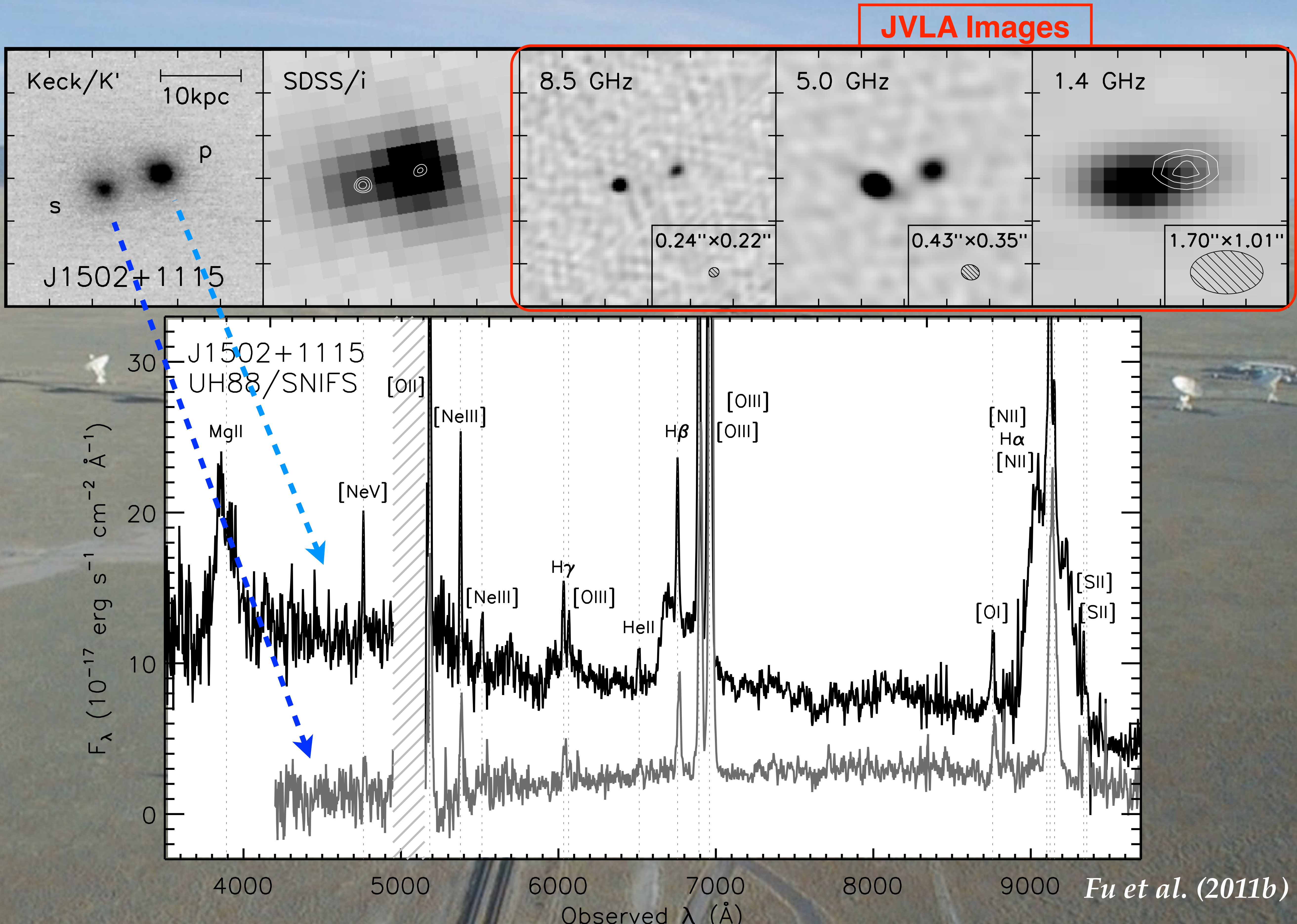
# Implications:

## (4) ``Strömgren Spheres" of AGNs




- $\log(R_{NLR}) = \alpha \log(L_{[O\ III]})$+c
  $\alpha$ ~ 0.5 implies constant $U$ (ionization parameter):
  $U \propto L_{[O\ III]}/R^2$
- Separation < $R_{NLR}$ implies that one of the merging components may not have an active nucleus

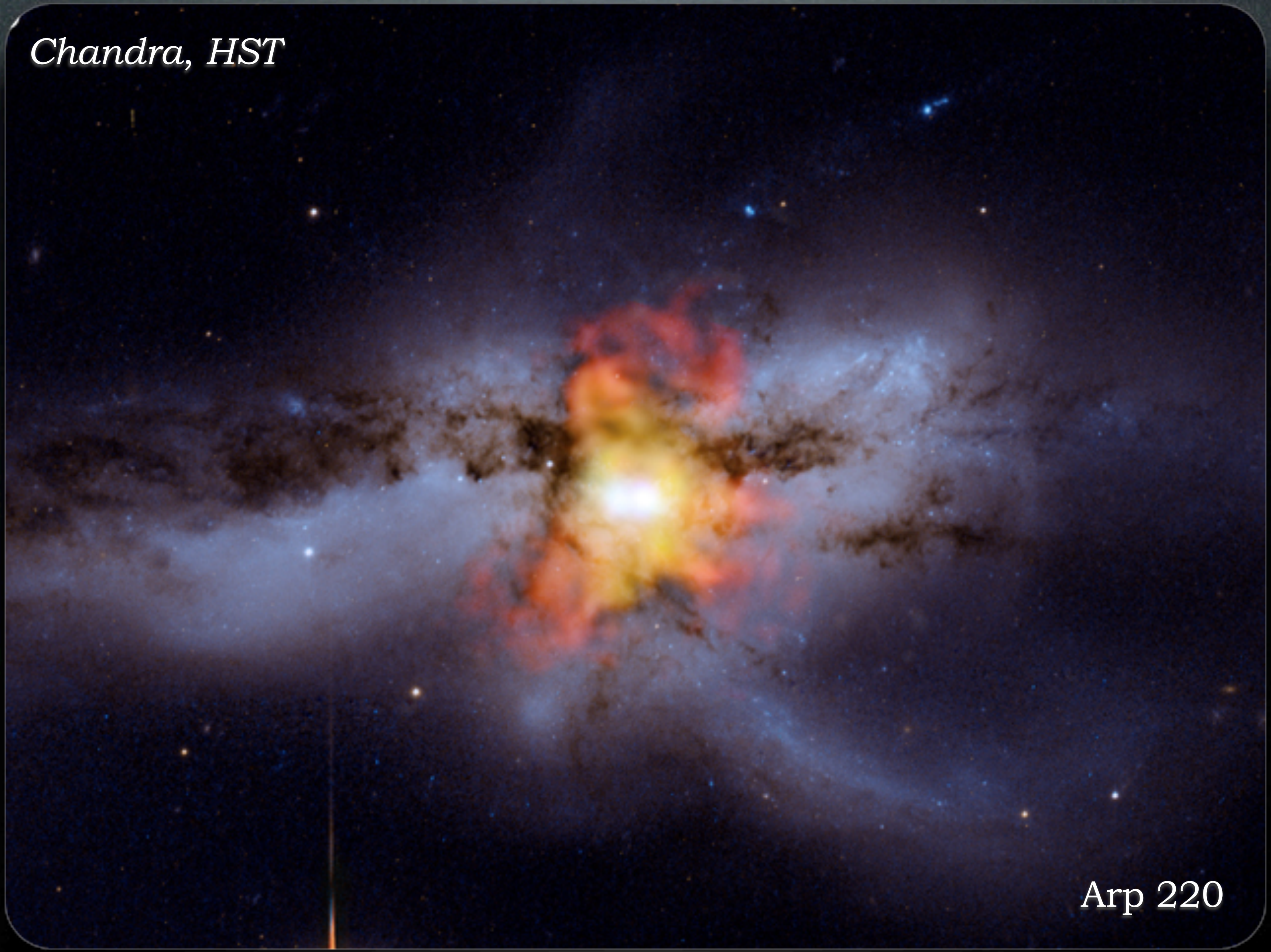
*Fu et al. (2012a)*




Fu et al. (2011b)

# Summary

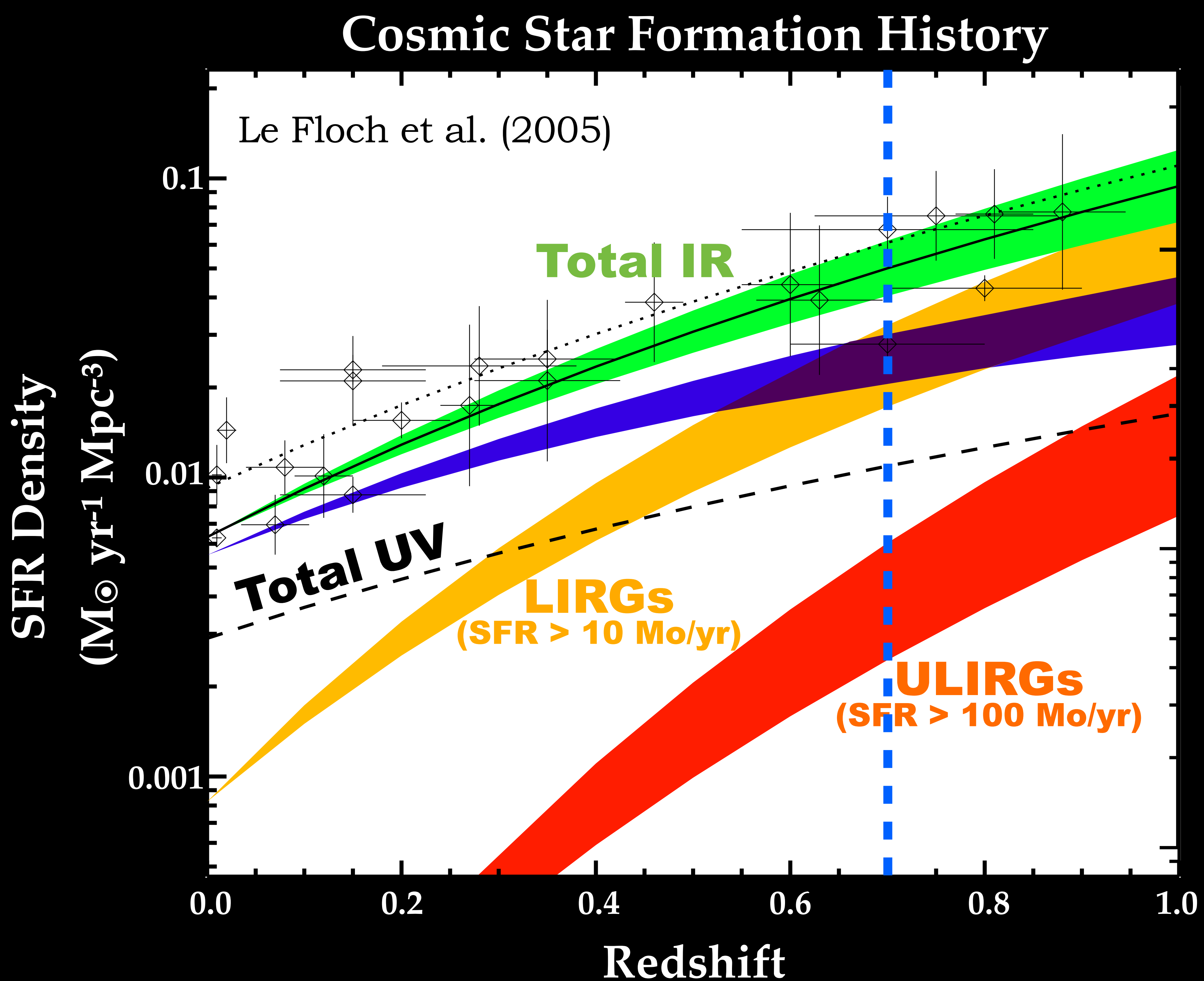
- ~2% of AGNs are kpc-scale binaries, consistent with simulations of 2:1 S-S mergers. But hints that AGN merger fraction is ~2× higher than $L^{\star}$ galaxies.
- Duty cycle increases by >15× in kpc-scale mergers.
- ~1% of binaries are spectrally resolved ($\Delta V > 250$ km/s).
- Double-peaked selection is extremely incomplete: 98% are radiation-driven outflows or peculiar NLRs.
- Optically-selected binary AGNs need confirmations.



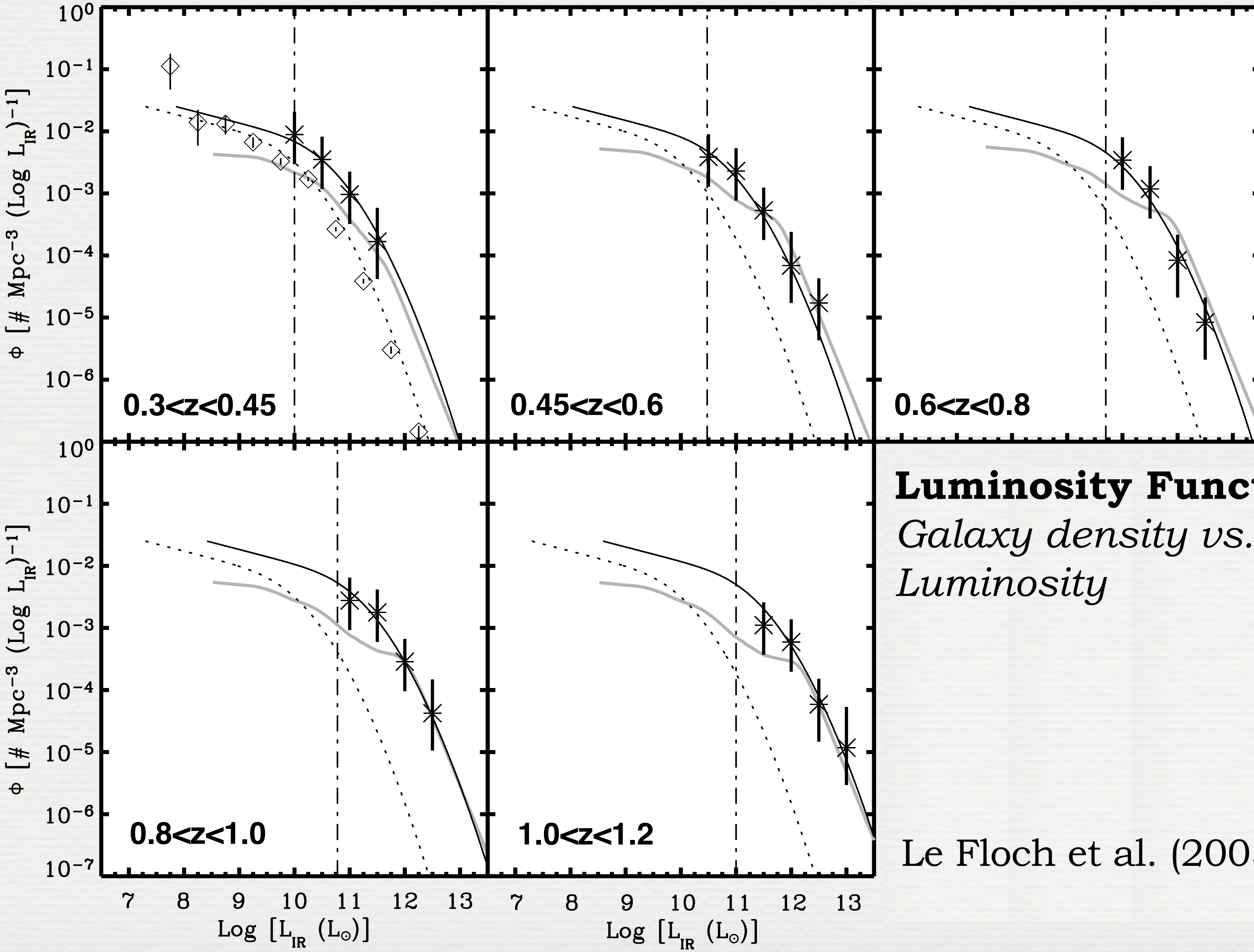

# BH Accretion in (U)LIRGs

**Fu et al. (2010)**

# Luminous Infra-Red Galaxies (LIRGs)



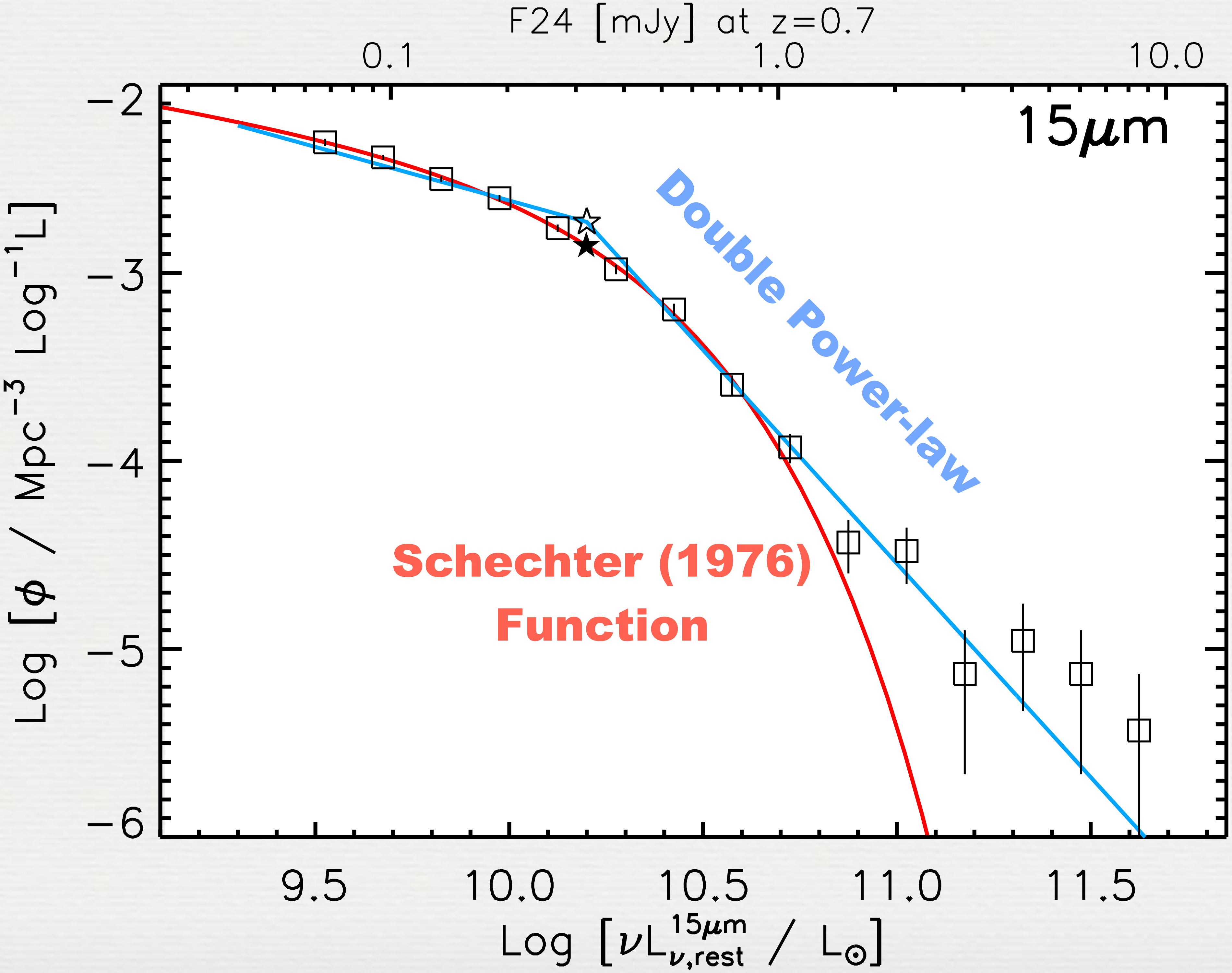
# Total IR Luminosity Functions



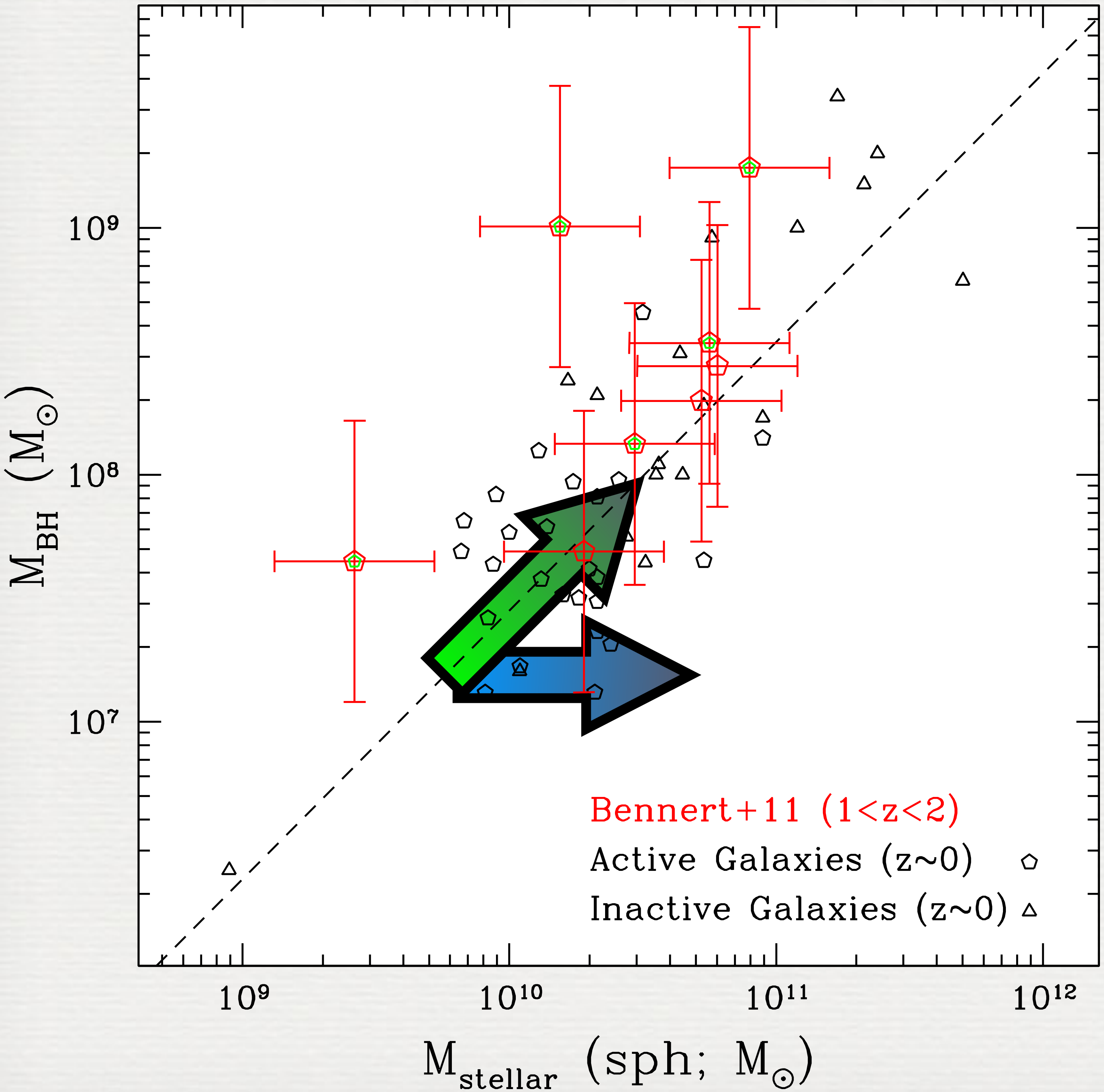

**Luminosity Function:**
*Galaxy density vs. Luminosity*

Le Floch et al. (2005)

# Shape of mid-IR Luminosity Functions



# The Magorrian Scaling Relation




- Magorrian relation:

  $M^*/M_{BH} \approx 1000$

  given ~50% of M* recycled

  ➪ $\langle SFR/\dot{M}_{BH}\rangle \approx 2000$

- Energy conversion:

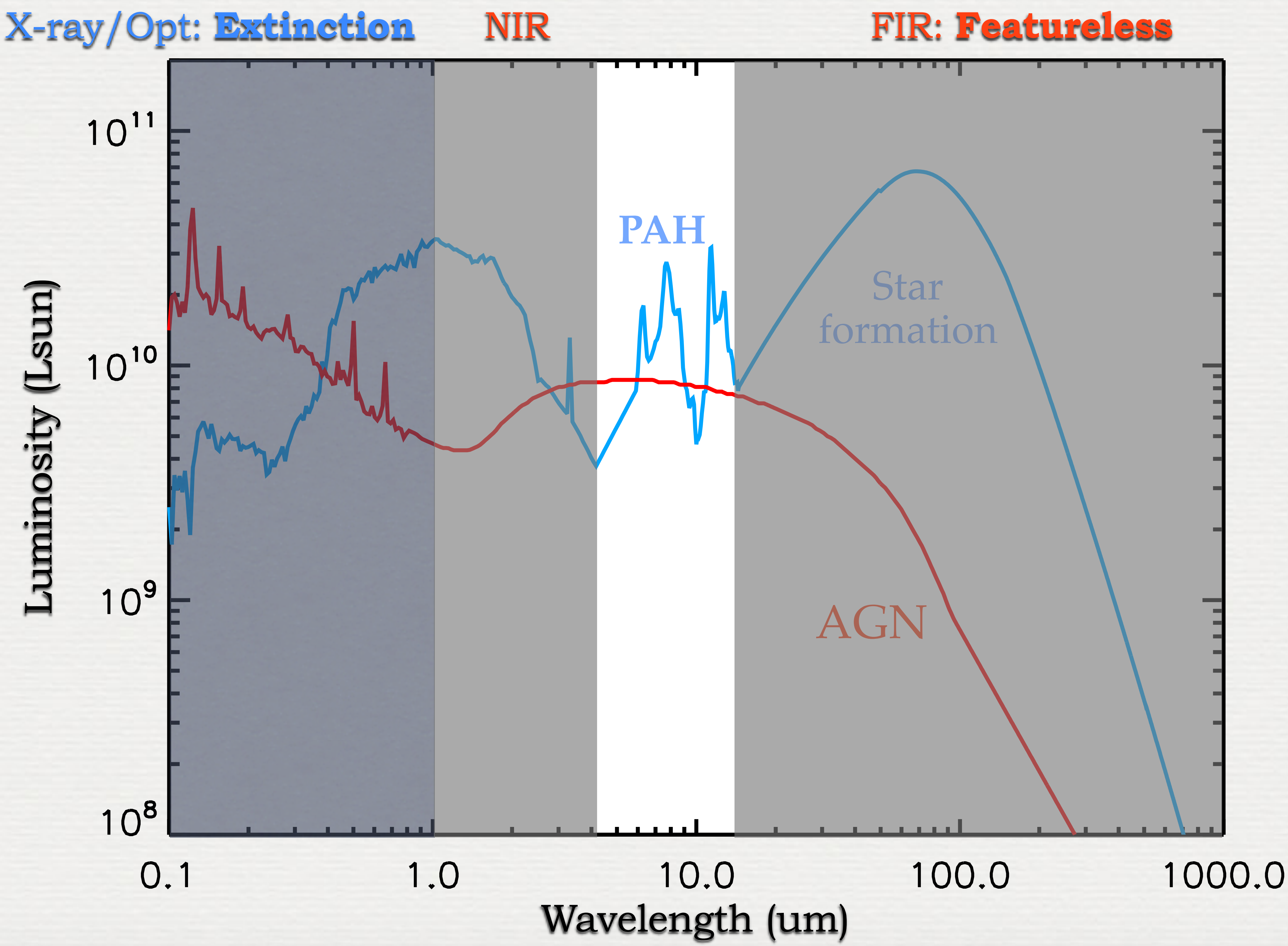
  $L_{AGN}/L_\odot = 2{\times}10^{12}\ \dot{M}_{BH}/M_\odot\ yr^{-1}$

  $L_{SF}/L_\odot = 10^{10}\ SFR/M_\odot\ yr^{-1}$

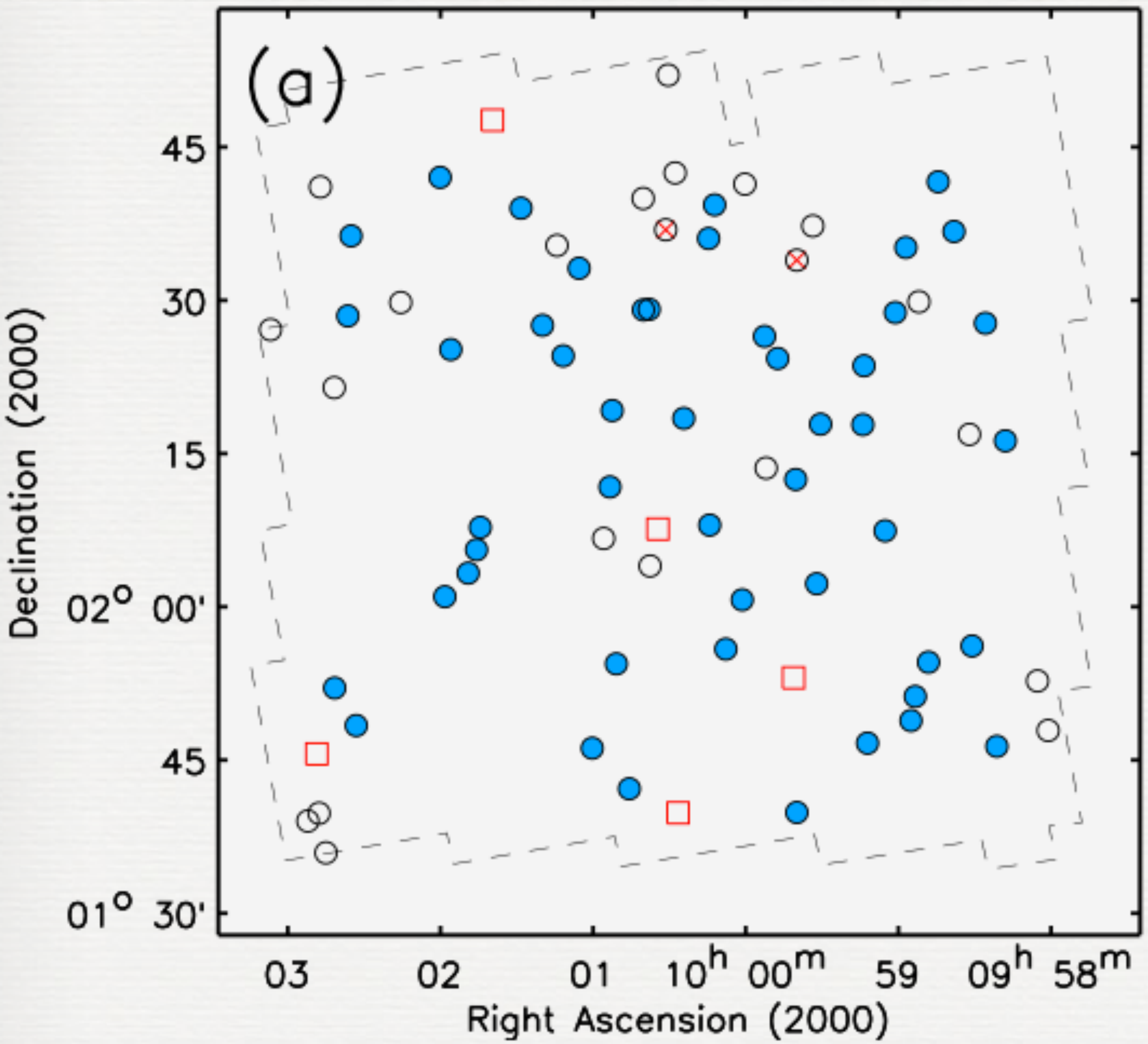
  ➪ $L_{AGN}/L_{SF} \approx 10\%$

*Häring & Rix (2004)*
*Bennert et al. (2010)*

# Why Mid-Infrared Spectroscopy?



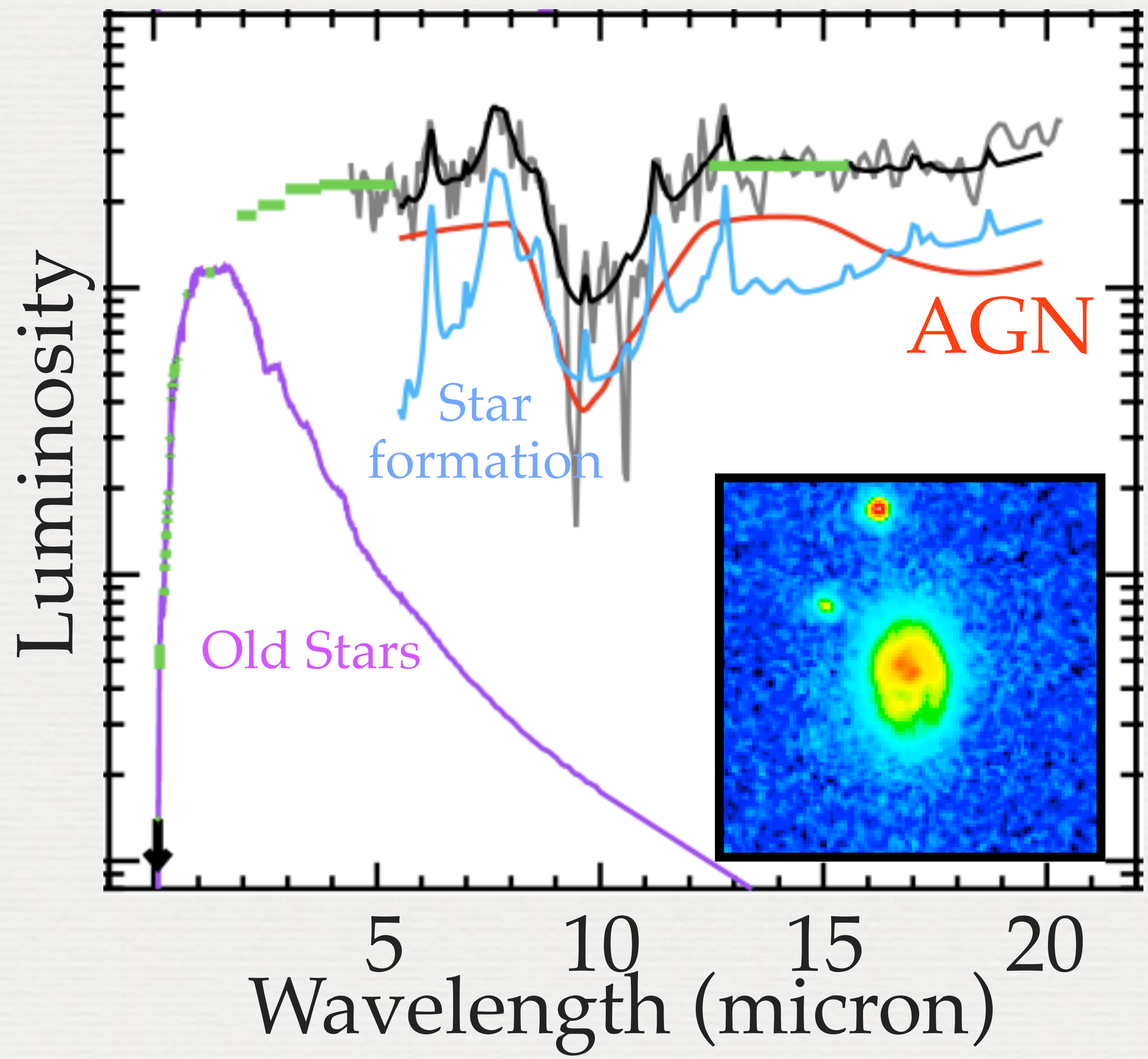
# COSMOS *Spitzer*/IRS Sample




- ☑ $0.6 < z < 0.8$
- ☑ F24 > 0.7 mJy
- ☑ Inside *HST* Field
- ☑ Completeness: 68% (48/70)
- ☑ Area: 1.12 sq deg

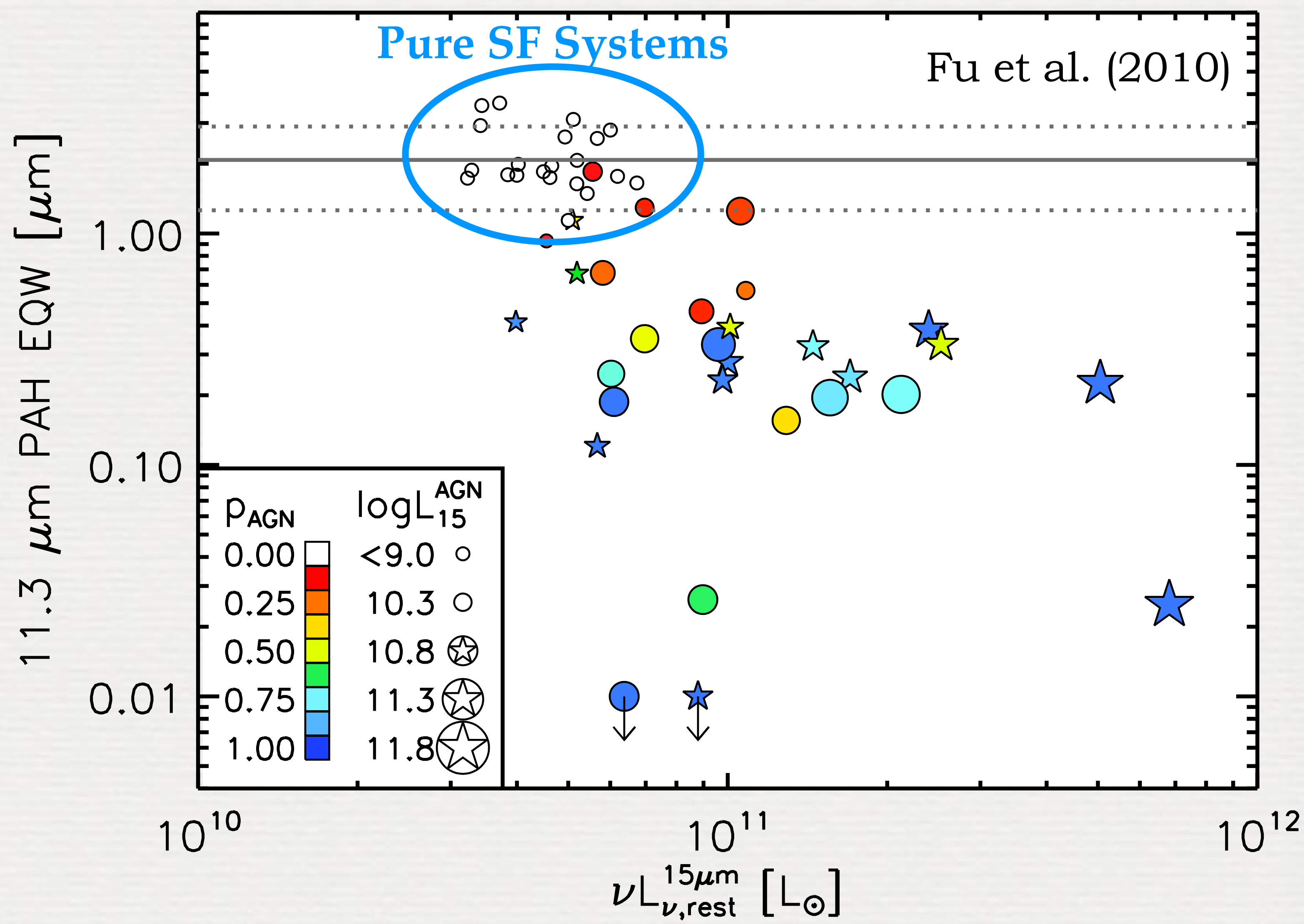
# AGN/Star Formation Decomposition

- AGN: power-law
- Star Formation: templates from Rieke et al. (2009)
- Modified Galactic Center Extinction Curve (Smith et al. 2007)



# PAH EQW vs. 15um Luminosity

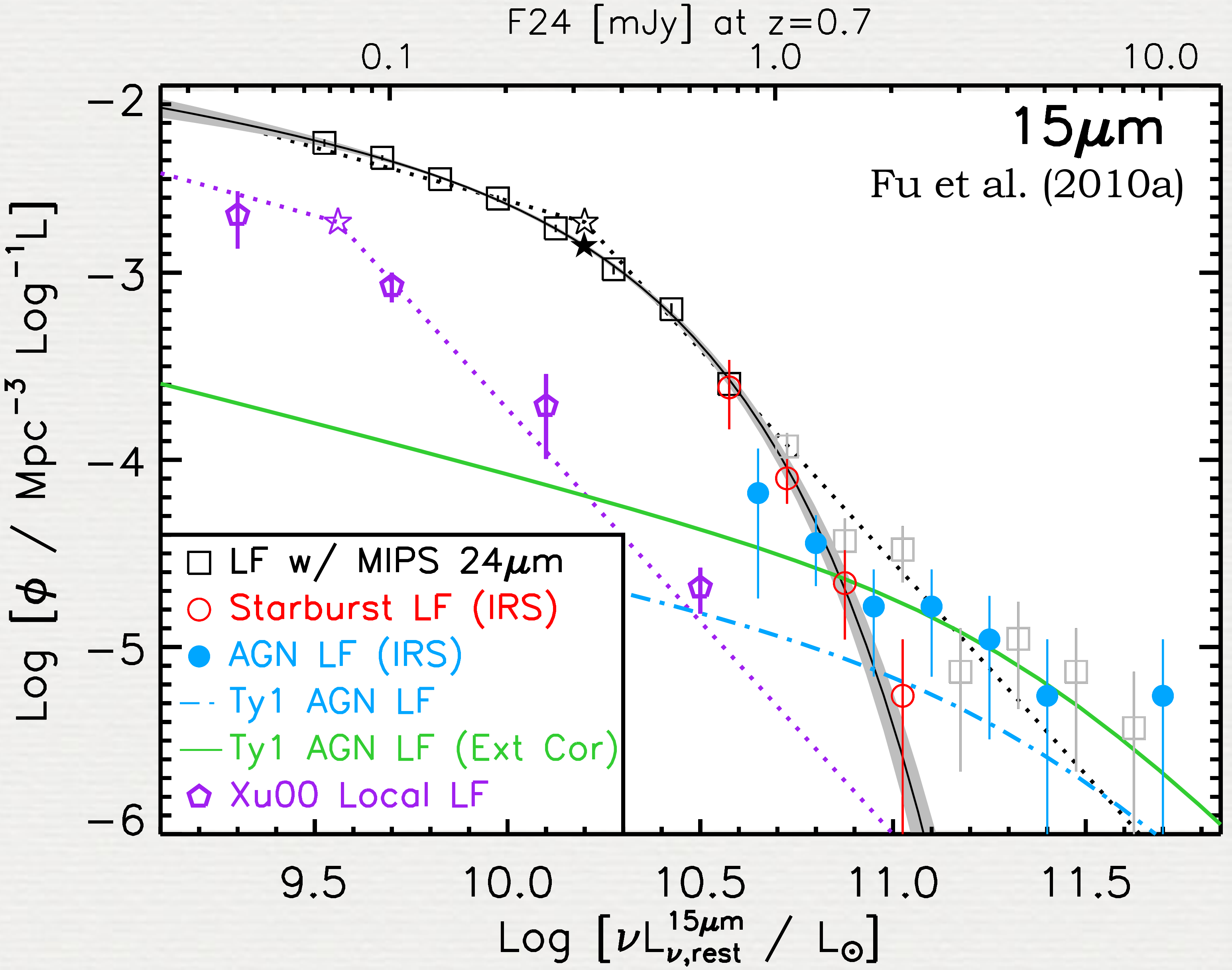
- AGNs dominate at high 15um luminosity
- PAH equivalent widths decrease because of dilution from the AGN continuum



# The Decomposed 15μm LF

- **Star-forming LF**:
  Schechter profile extends to $\phi = 10^{-5}$ Mpc$^{-3}$ dex$^{-1}$

- **AGN LF:**
  shallow bright-end slope



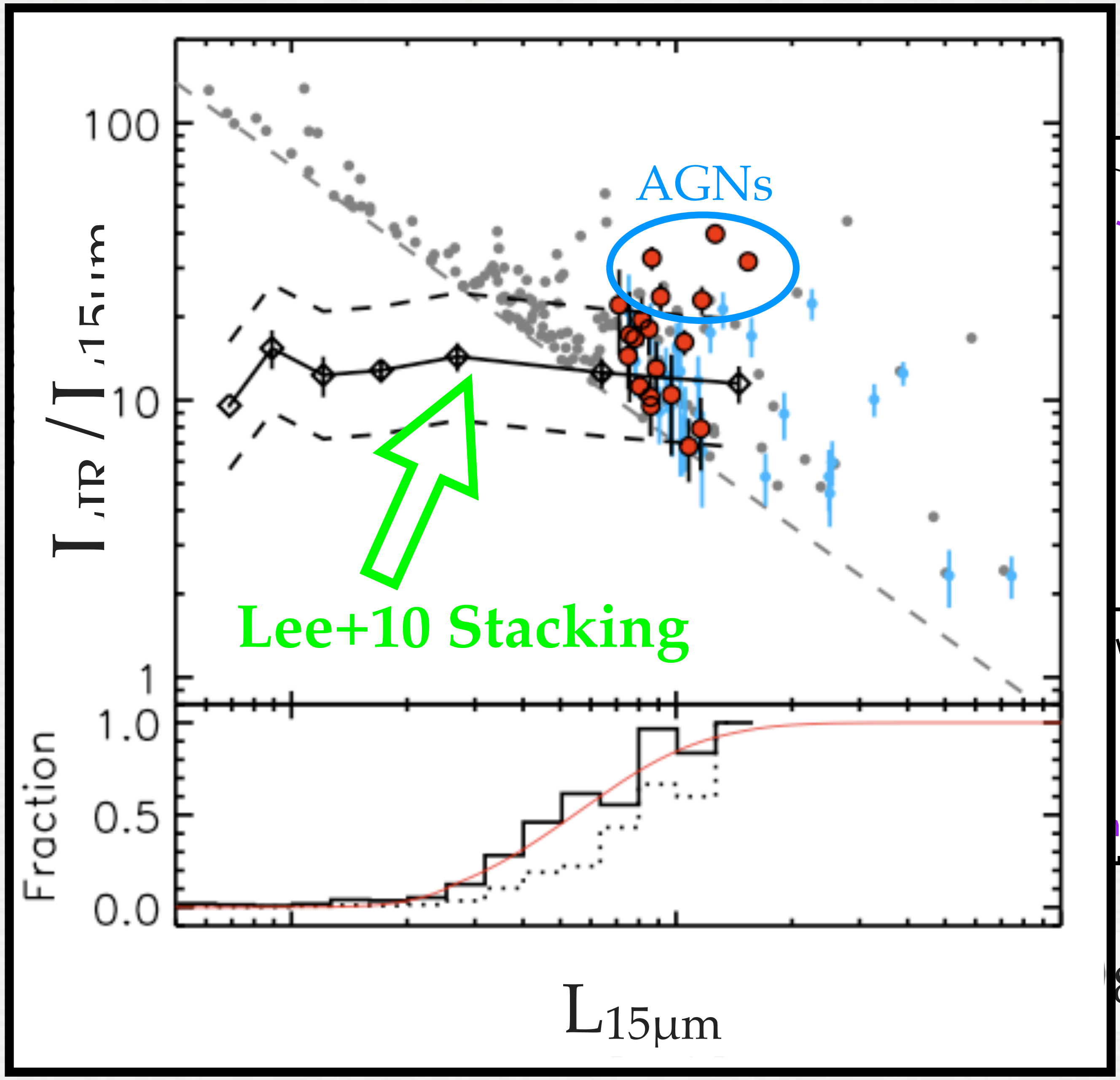
# Black Hole Accretion in (U)LIRGs at z~0.7

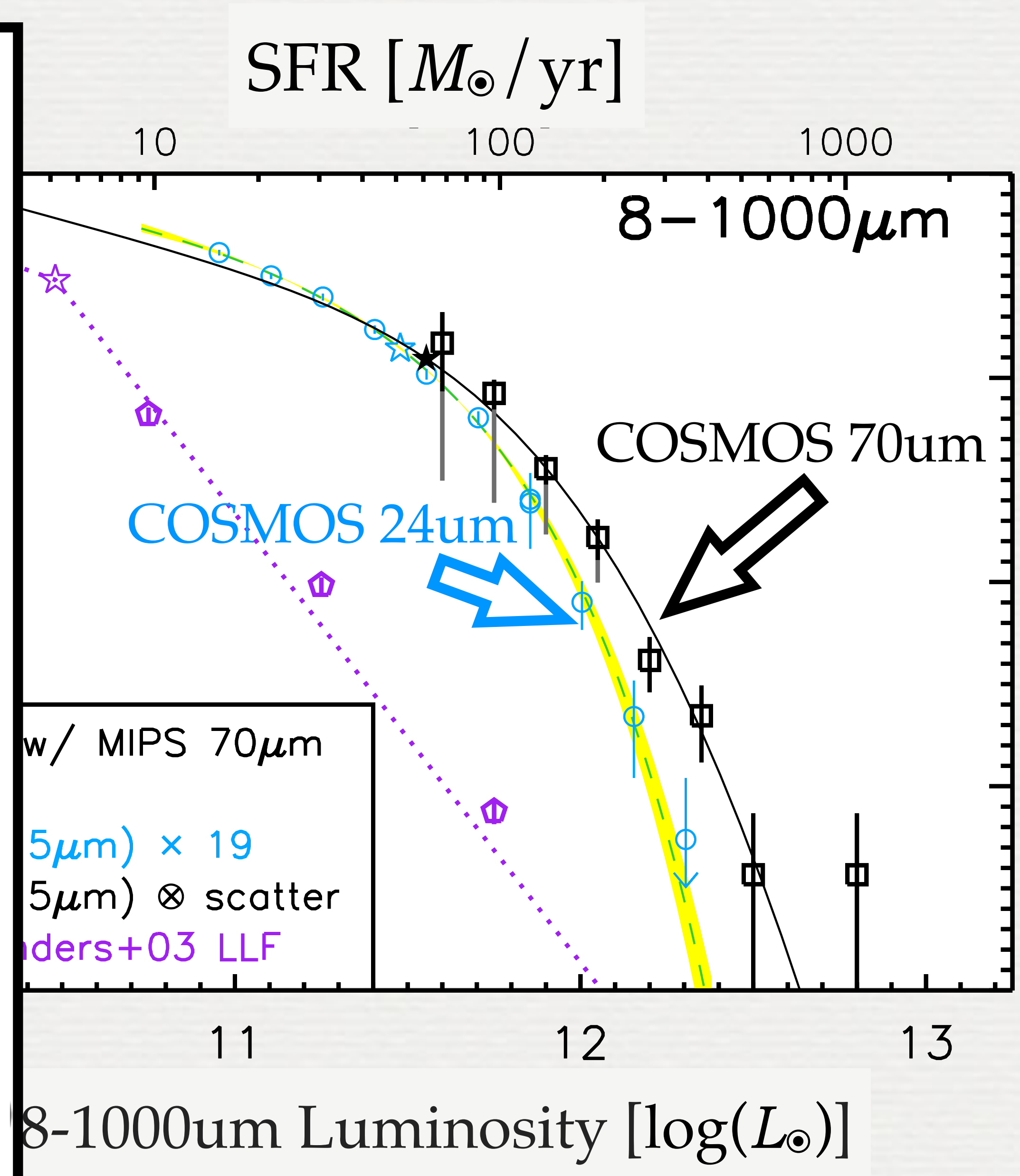
- $L_{15}$(AGN) ➪ $L_{bol}$ ➪ $\dot{M}_{BH}$: $L_{bol}/L_{\odot} = 2\times10^{12}\,\dot{M}_{BH}/M_{\odot}\,yr^{-1}$
  $L_{15}$(SF) ➪ $L_{IR}$ ➪ SFR: $L_{IR}/L_{\odot} = 10^{10}\,SFR/M_{\odot}\,yr^{-1}$

- 31/48 have $L_{15}$(SF) > $3\times10^{10}\ L_{\odot}$
  7/31 have $L_{15}$(AGN) > $3\times10^{10}\ L_{\odot}$
  ➪ AGN Duty Cycle = 7/31 = 23%

➡ $\Sigma\ \dot{M}_{BH}/\Sigma$ SFR × DutyCycle = $4.6\times10^{-3}$ × 23% = $10^{-3}$
$M_{BH}/M_{Bulge}$ @ z~0 ~= $M_{BH}/M_{Galaxy}$ @ z~1.5
~= $[1.0\text{-}2.5]\times10^{-3}$ (*Häring & Rix 2004, Jahnke et al. 2009*)

# Comparison with the 70μm-derived SFR Function




Fu et al. (2010)

# Summary

- Mid-IR spectra nicely separates AGN and star formation
- BH accretion in the (U)LIRG phase preserves the $M_{BH}$–$M_{gal}$ scaling relation.
- SF luminosity functions are Schechter; AGNs LFs are double power-laws.
- AGN may produce >50% of the FIR flux
  ⇨ *Spitzer*/IRS + *Herschel* (*coming soon*)