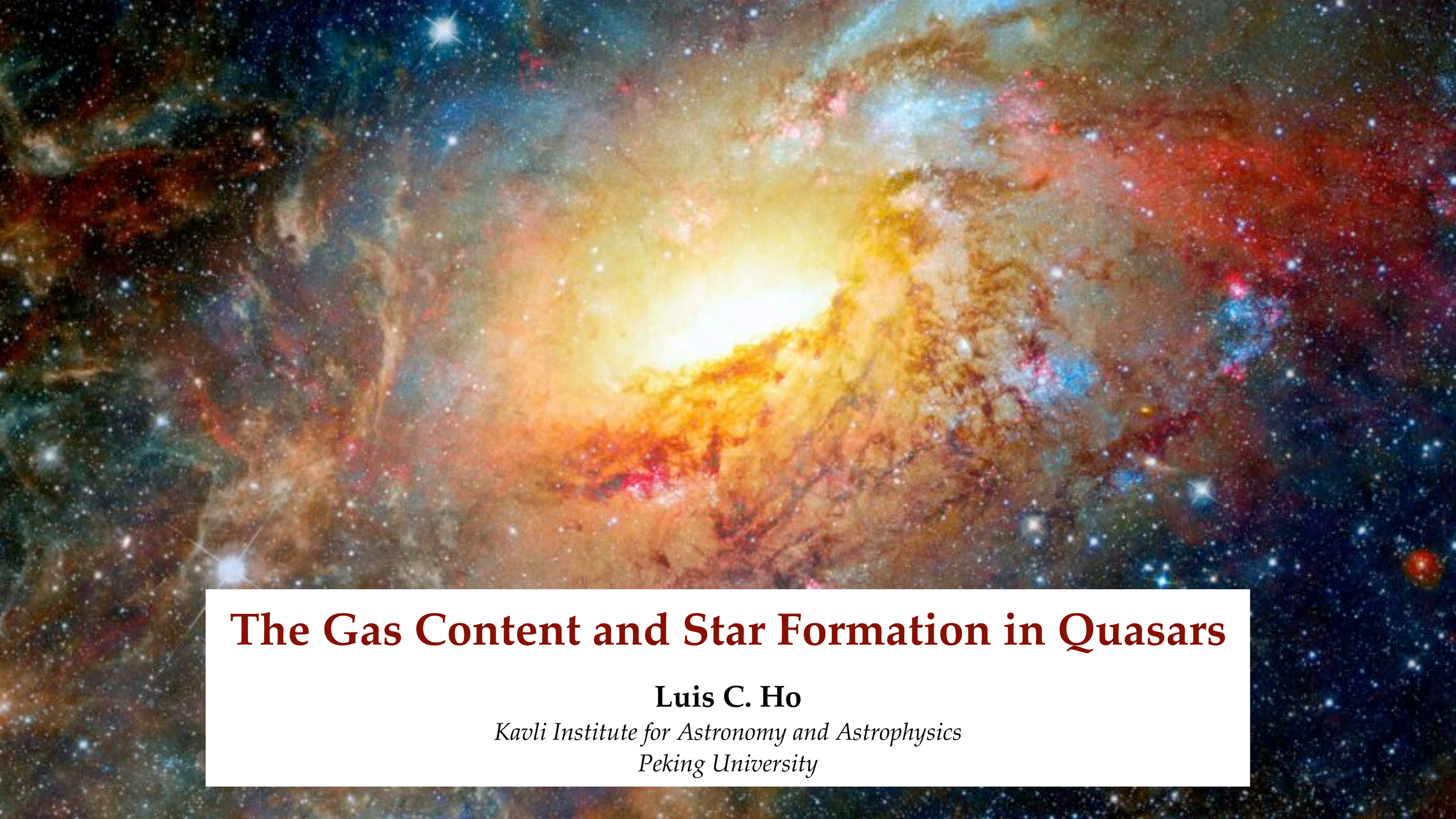
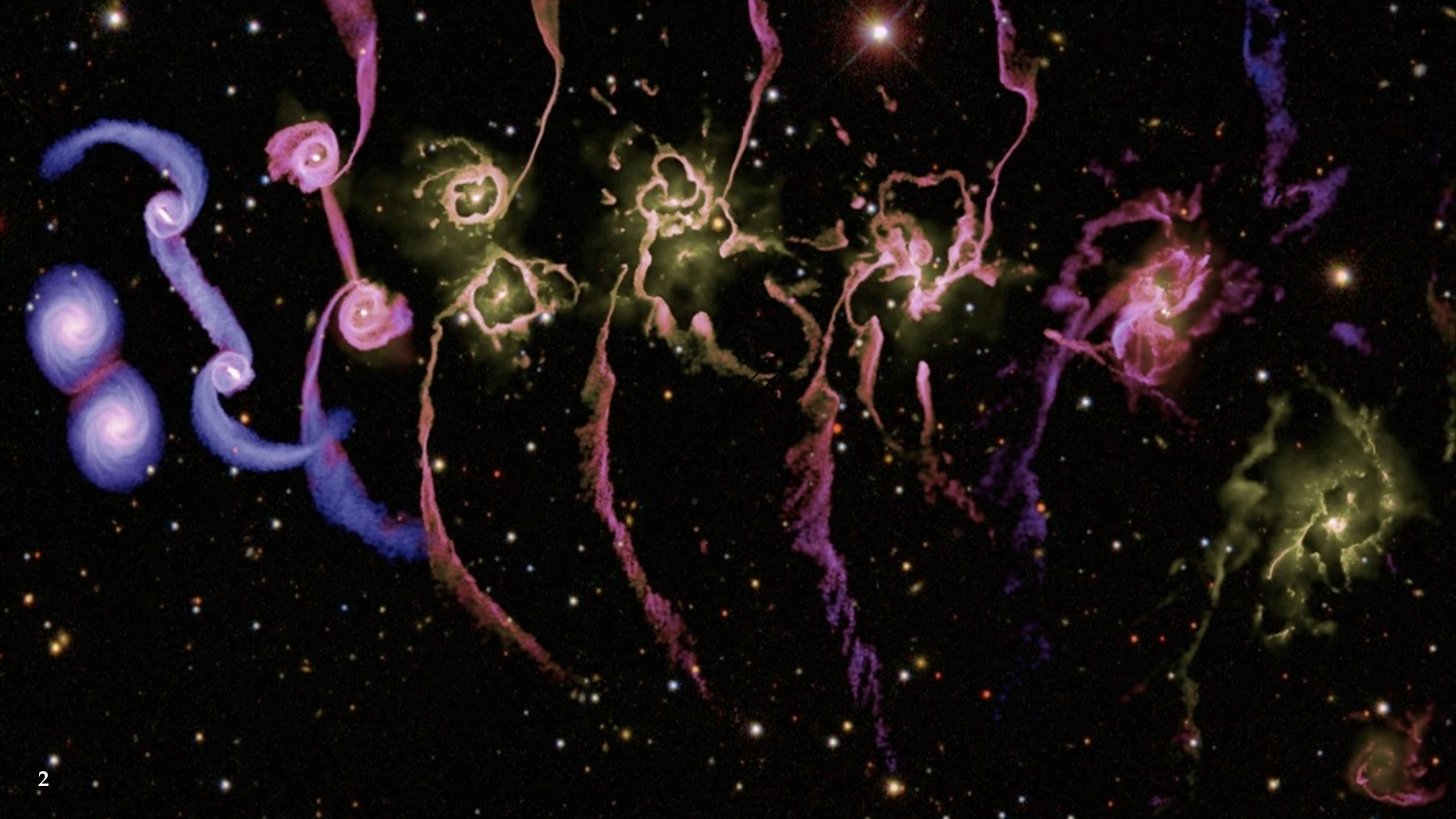
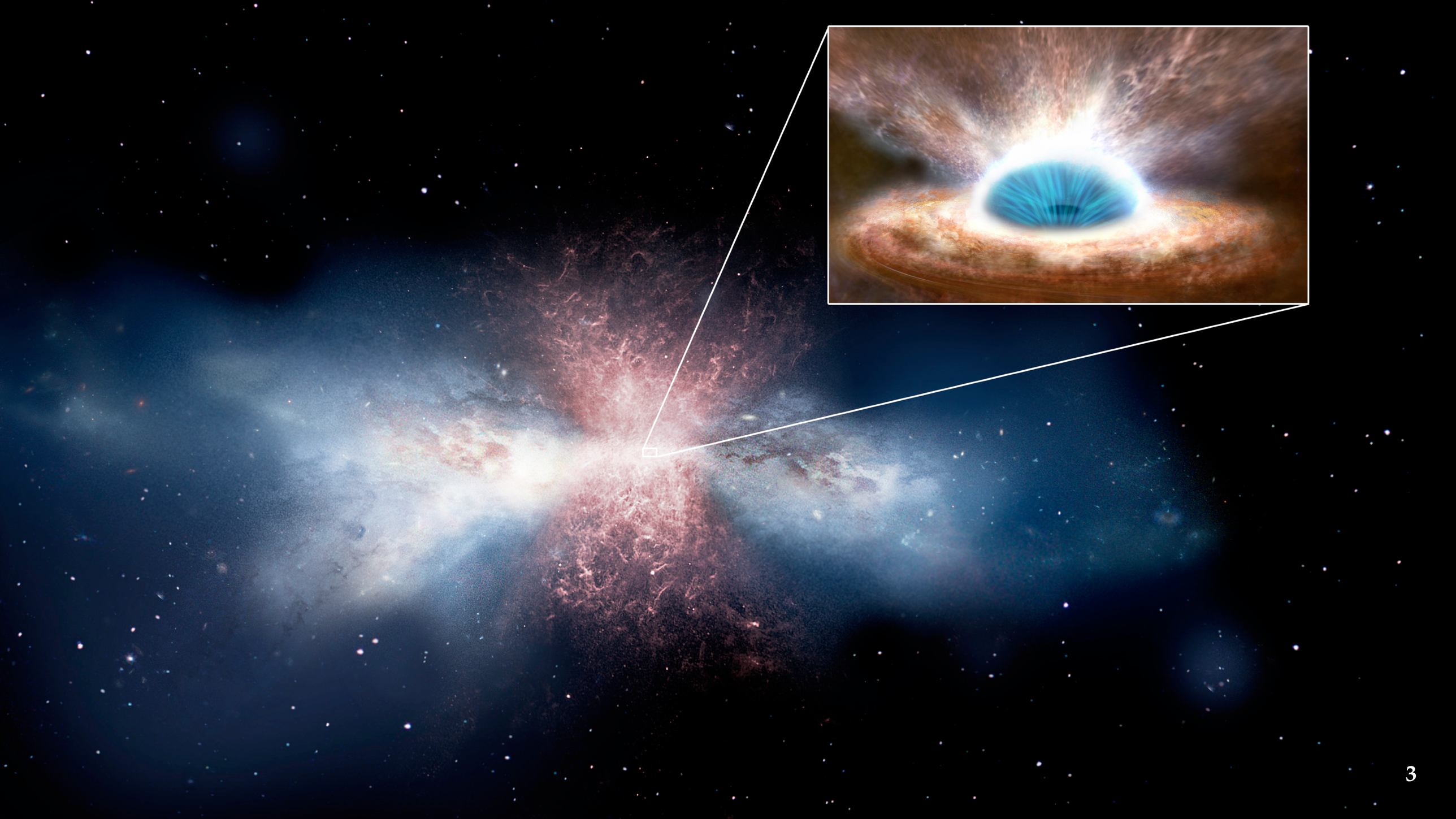


The Gas Content and Star Formation in Quasars

Luis C. Ho

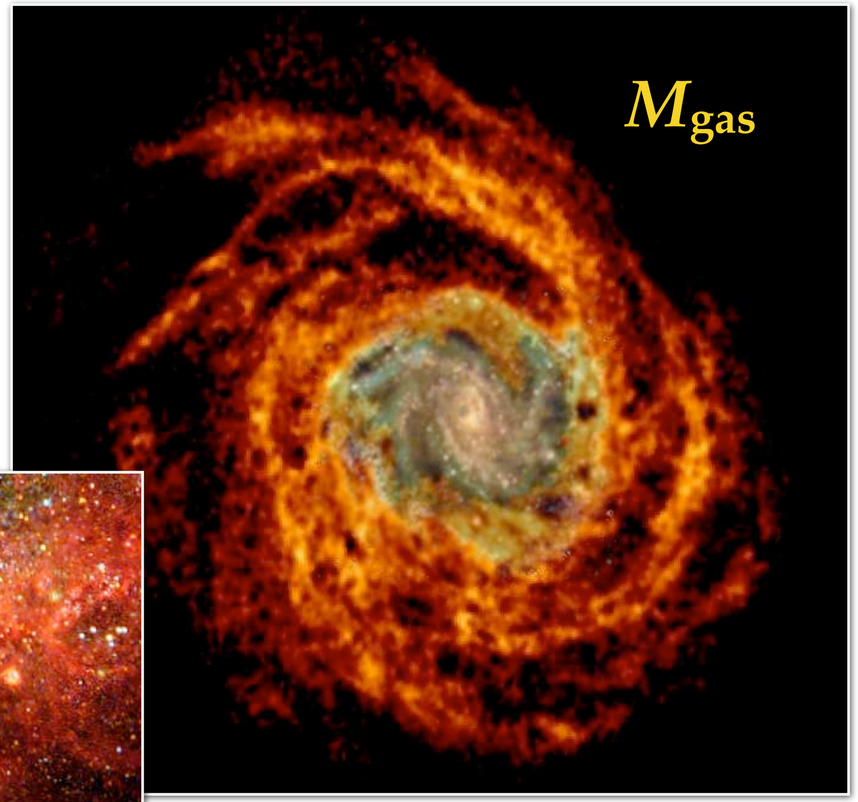
Kavli Institute for Astronomy and Astrophysics
Peking University





29

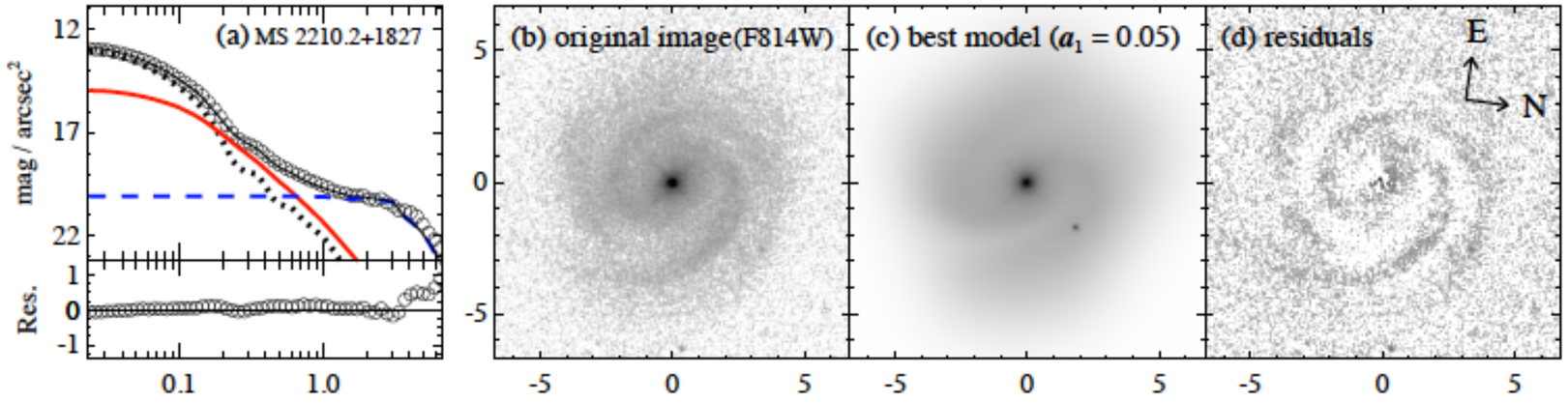
Essential Ingredients, Challenges

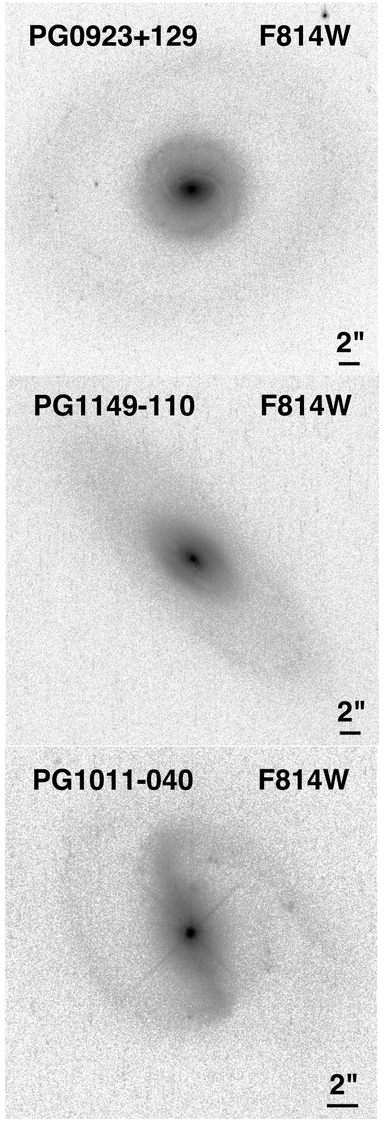


Techniques to Measure ISM and Stellar Content

Stellar Mass, Distribution, Age

- **High-resolution images with stable PSF (HST, JWST)**
  Kim, Ho et al. (2008, 2017)
- **2D decomposition (e.g., GALFIT)**
  Peng, Ho et al. (2002, 2010)
- **Multiple bands to get colors, SEDs**
  Zhao, Ho et al. (2021); Zhuang & Ho (2022, 2023)

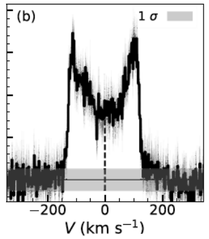




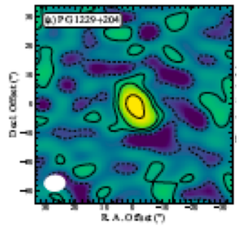
Techniques to Measure ISM and Stellar Content

Gas Properties

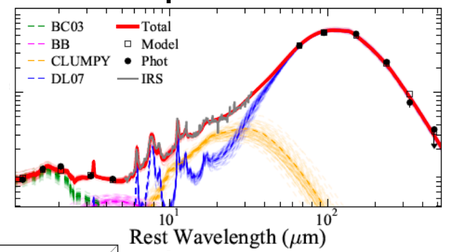
- **H I (21 cm): currently limited to $z < 0.1$**
  Ho, Darling & Greene (2008); Yu, Ho & Wang (2022)



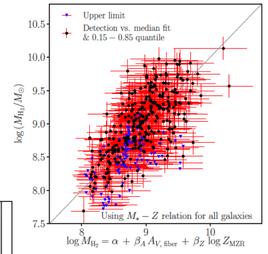
- **CO: expensive, uncertain (CO–H_2 conversion)**
  Shangguan, Ho et al. (2022a, 2022b)



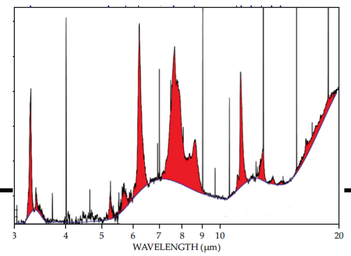
- **Dust emission: $M_{\rm gas} = M_{\rm H\,I} + M_{\rm H_2} = R_{\rm GD}\, M_{\rm dust}$; $R_{\rm GD} \propto Z \propto M_{\rm stars}$**
  Shangguan, Ho et al. (2018, 2019)



- **Dust absorption: Balmer decrement + metallicity correction**
  Yesuf & Ho (2019, 2020)



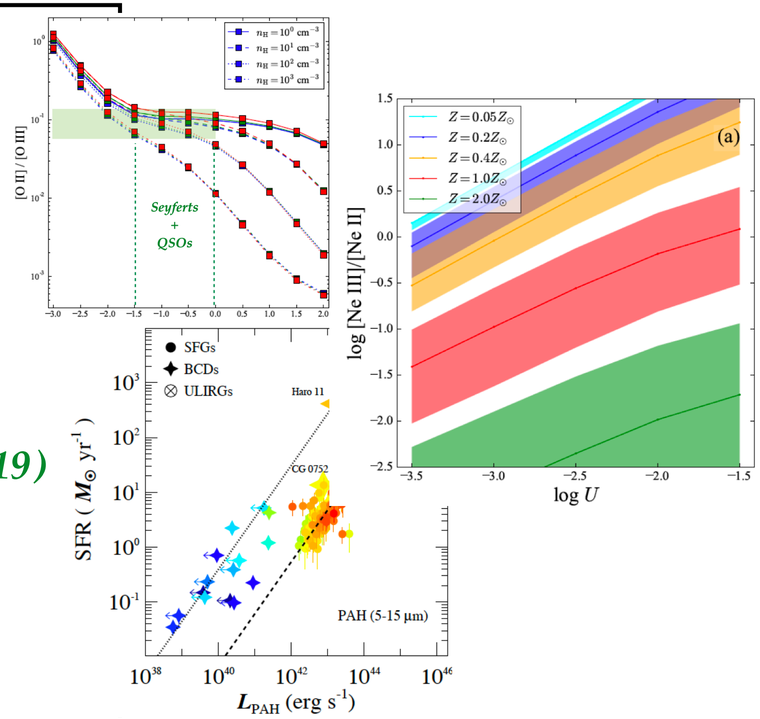
- **PAH emission: PDRs closely related to GMCs**
  Zhang & Ho (2023a)

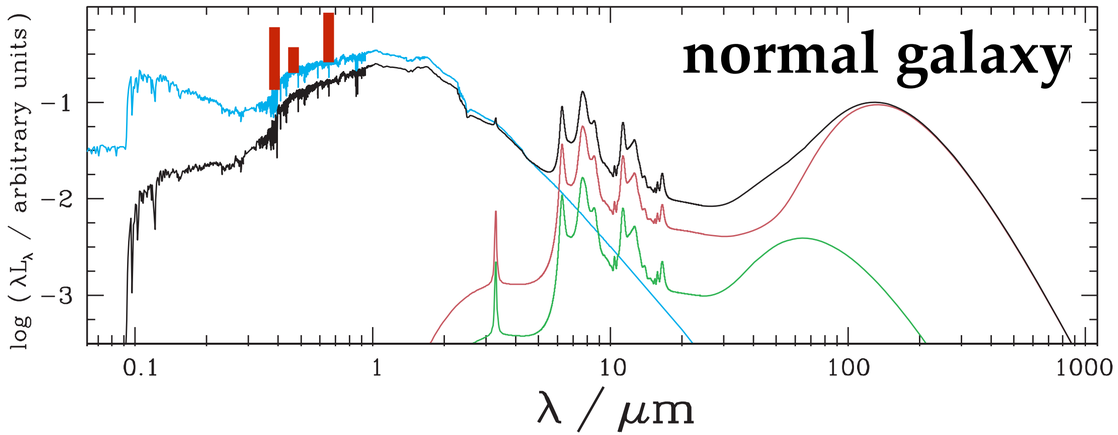


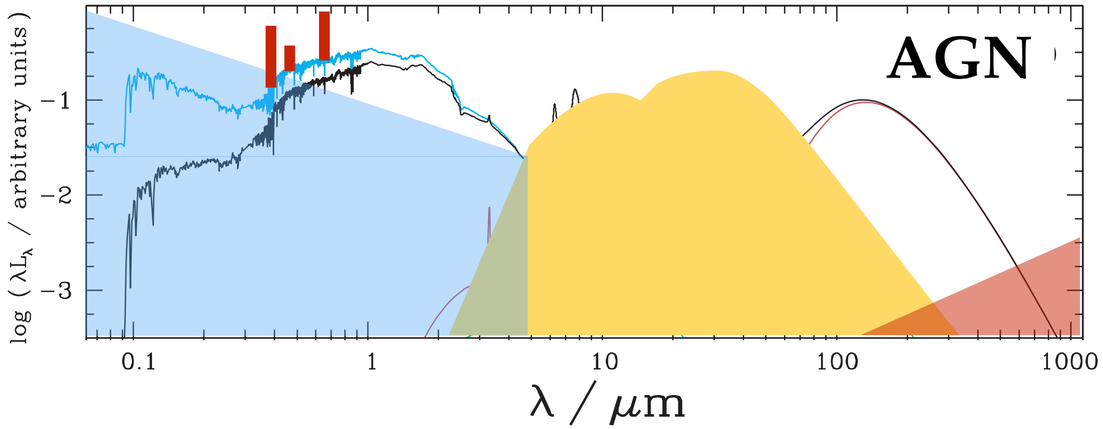
Techniques to Measure ISM and Stellar Content

Star Formation Rate, Star Formation Efficiency

- All traditional SFR estimators are suspect, AGN contamination
- New methods, new calibrations
  - ✦[O II] λ3737 *(Ho 2005; Zhuang & Ho 2019)*
  - ✦[Ne II] 12.8 μm + [Ne III] 15.6 μm *(Ho & Keto 2007; Zhuang, Ho et al. 2019)*
  - ✦PAH emission *(Xie & Ho 2019; Zhang Ho 2021, 2023)*
  - ✦FIR continuum *(Xie, Ho et al. 2021)*
  - ✦Full SED fitting *(Zhuang & Ho 2022, Li, Ho et al. 2023)*



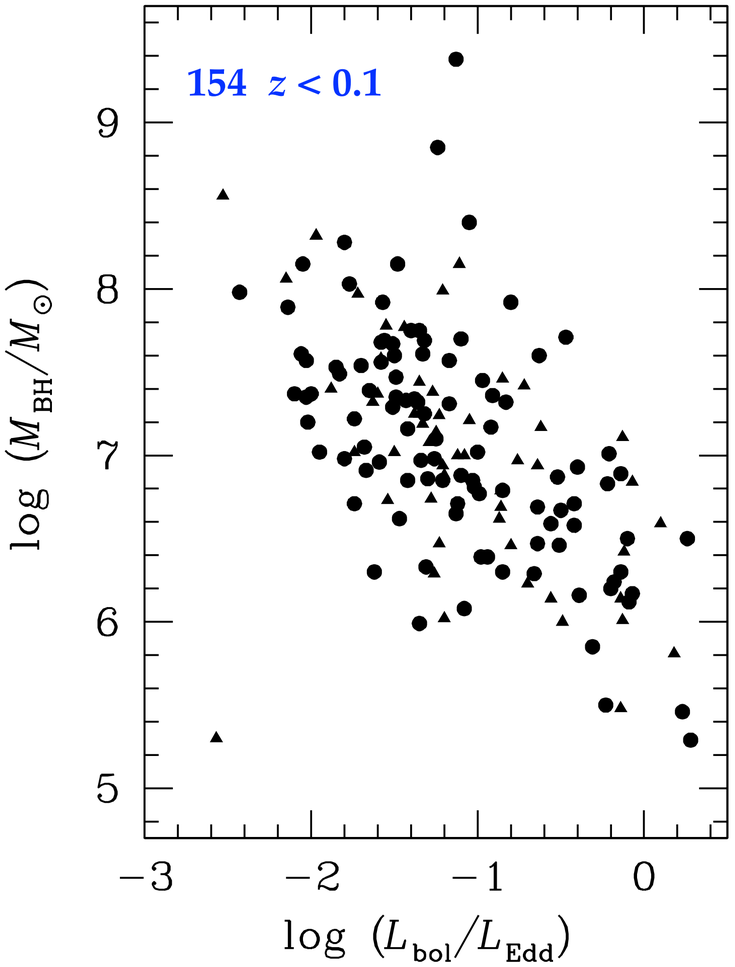


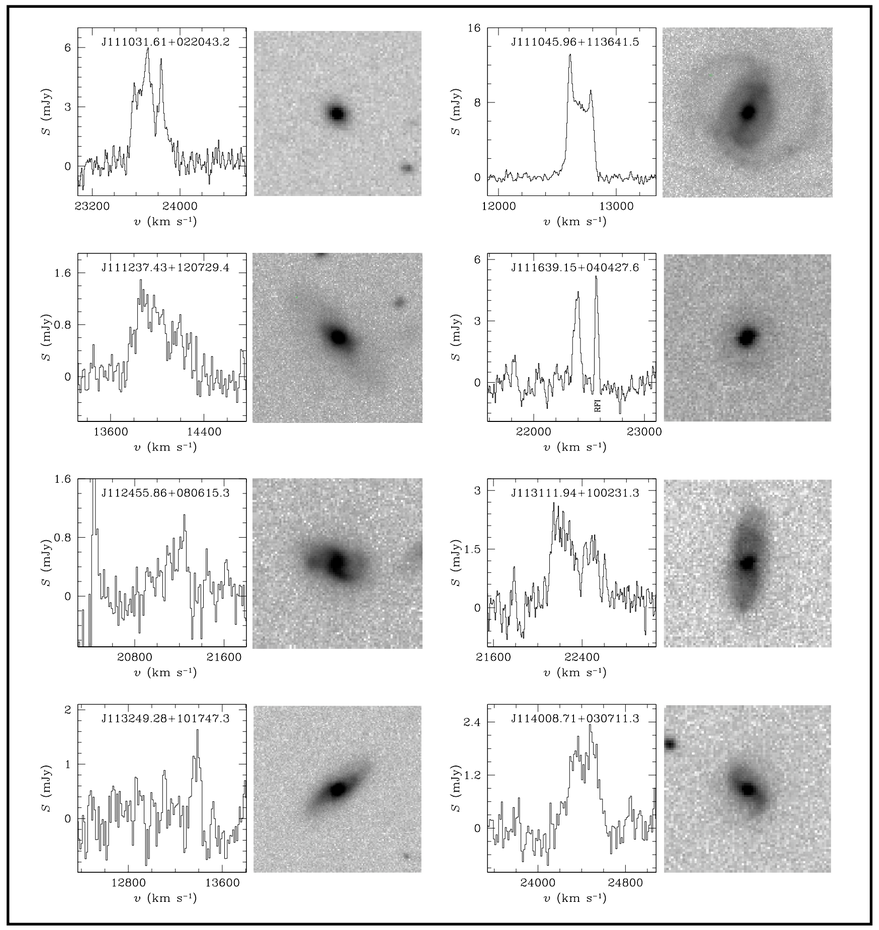


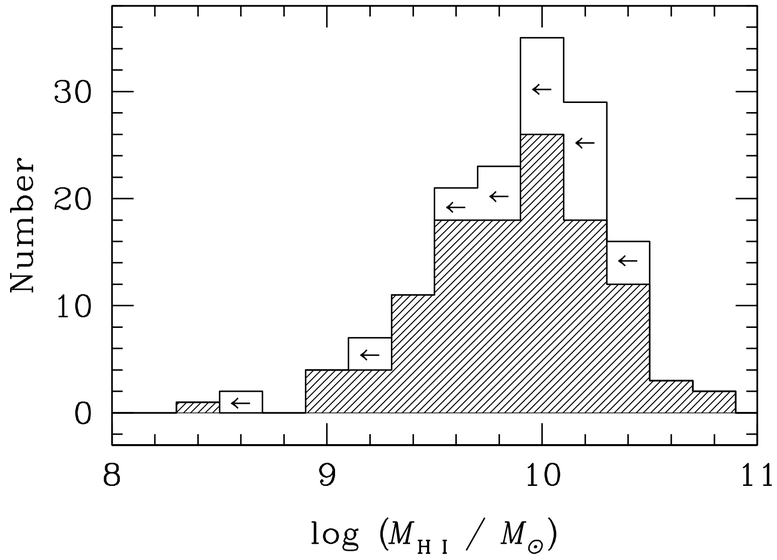
The Astrophysical Journal Suppl. Ser., **177**:103, 2008

A NEW H I SURVEY OF ACTIVE GALAXIES

LUIS C. HO[1], JEREMY DARLING[2], AND JENNY E. GREENE[3,4]





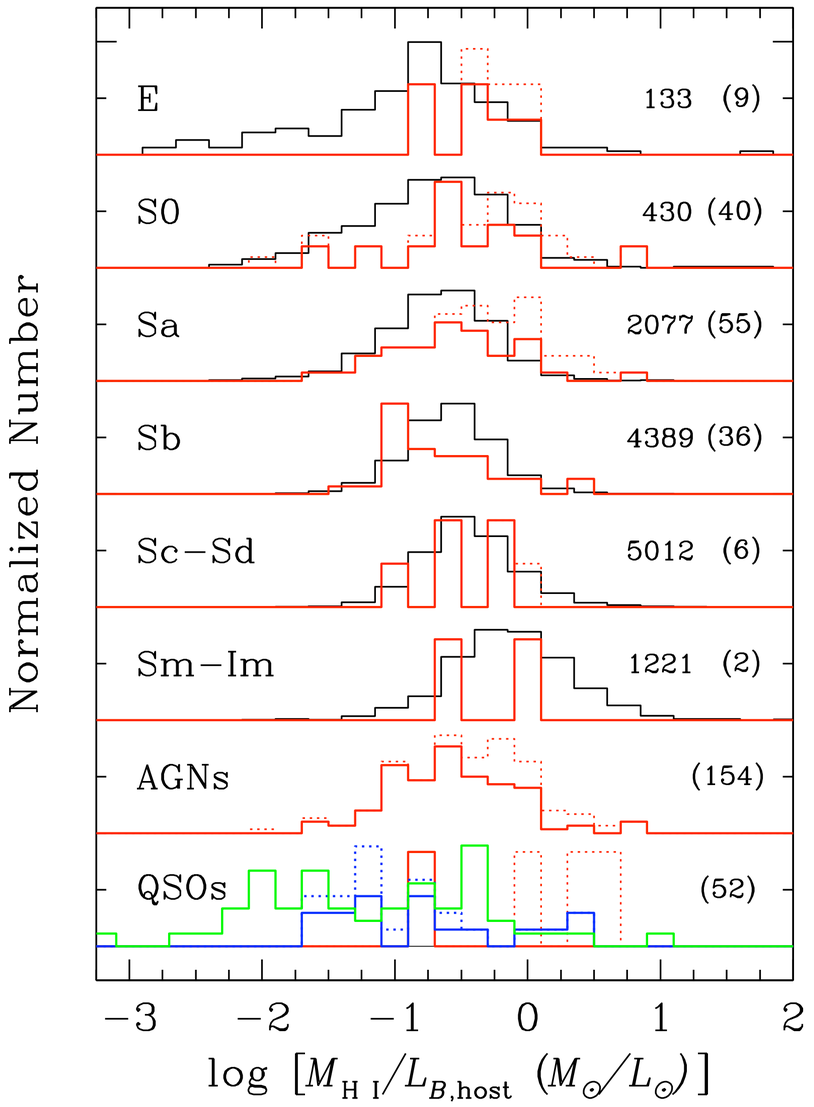


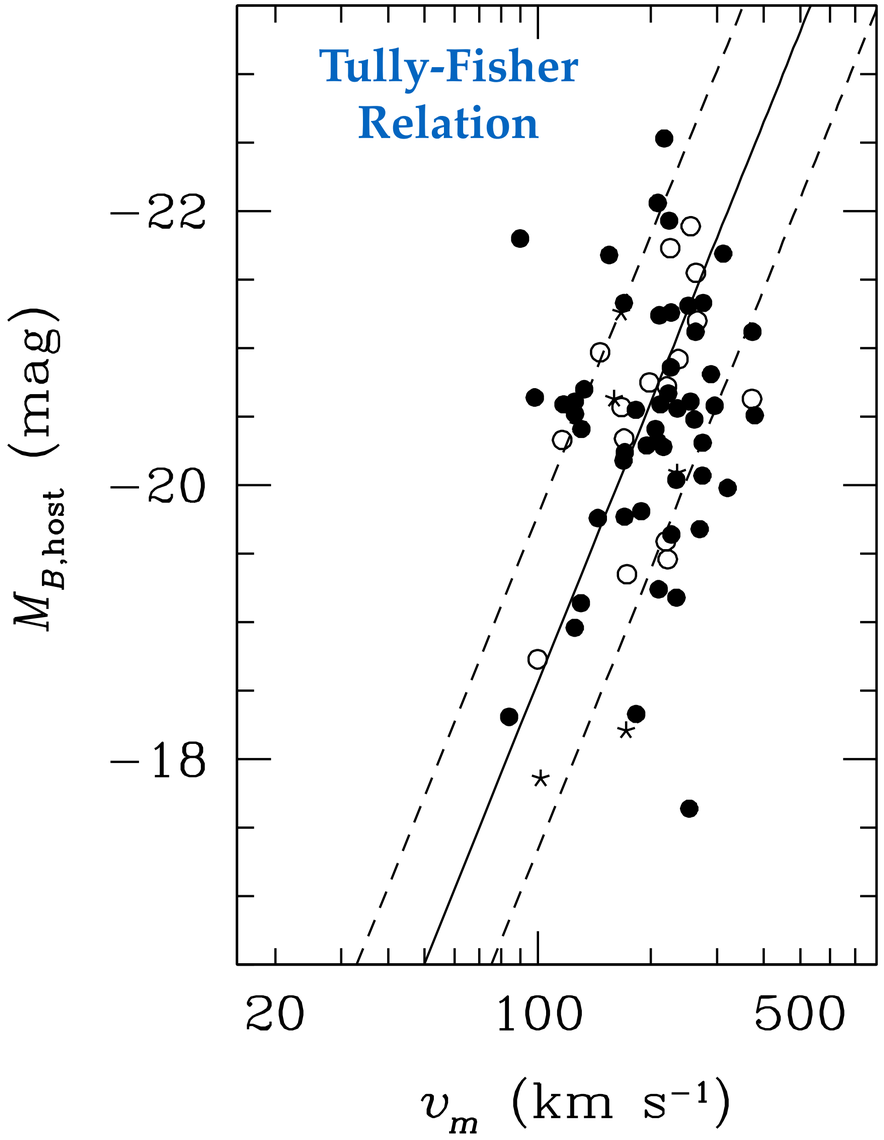
- **H I gas is common in nearby AGNs**
- **Arecibo survey: detection rate 75%**
- **Typical $M_{H\,I} \approx 10^{10}\ M_\odot$**

The Astrophysical Journal, **681**:128, 2008

PROPERTIES OF ACTIVE GALAXIES DEDUCED FROM H I OBSERVATIONS

LUIS C. HO[1], JEREMY DARLING[2], AND JENNY E. GREENE[3,4]



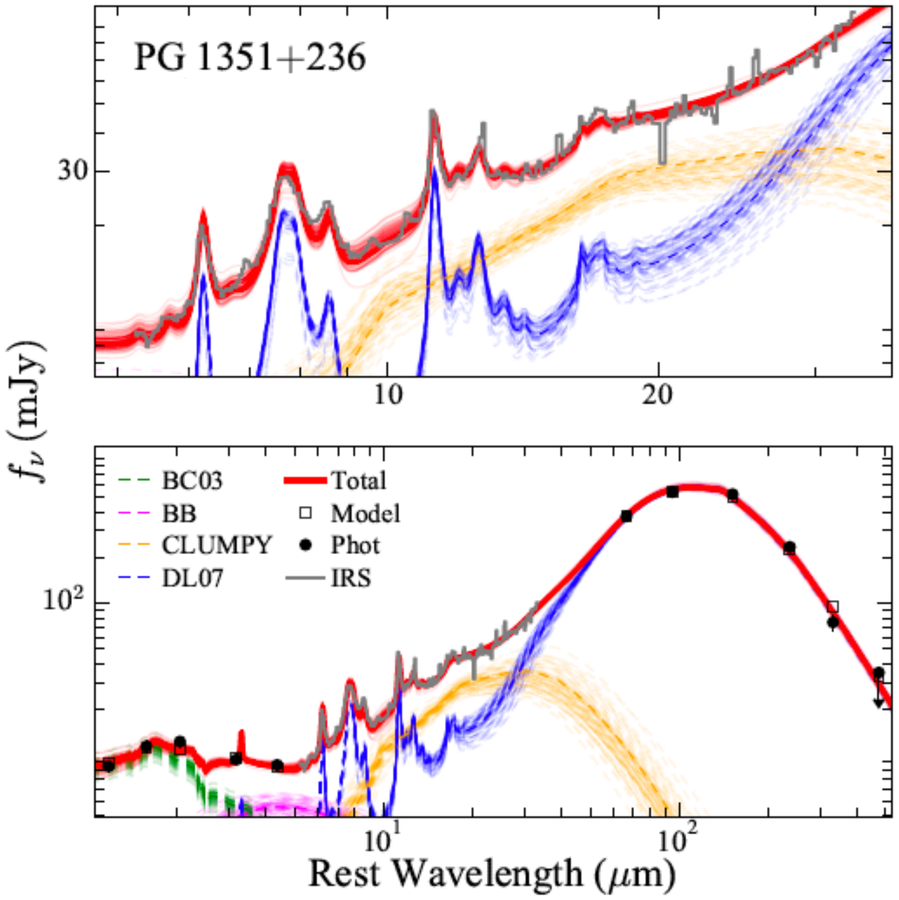


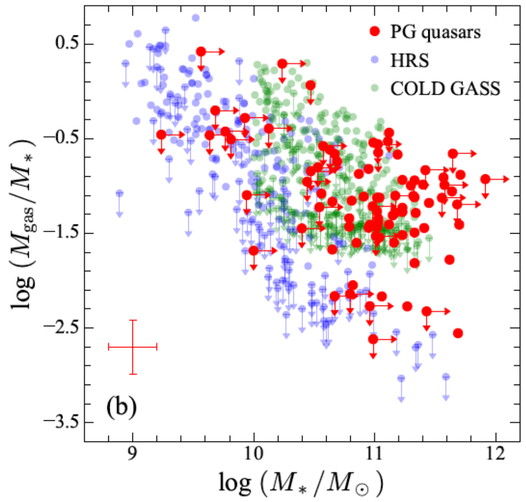
- Specific H I gas mass similar to that of normal galaxies of the same Hubble type
- H I line widths obey the Tully-Fisher relation of normal galaxies
- Implies regular spatial distribution and kinematics

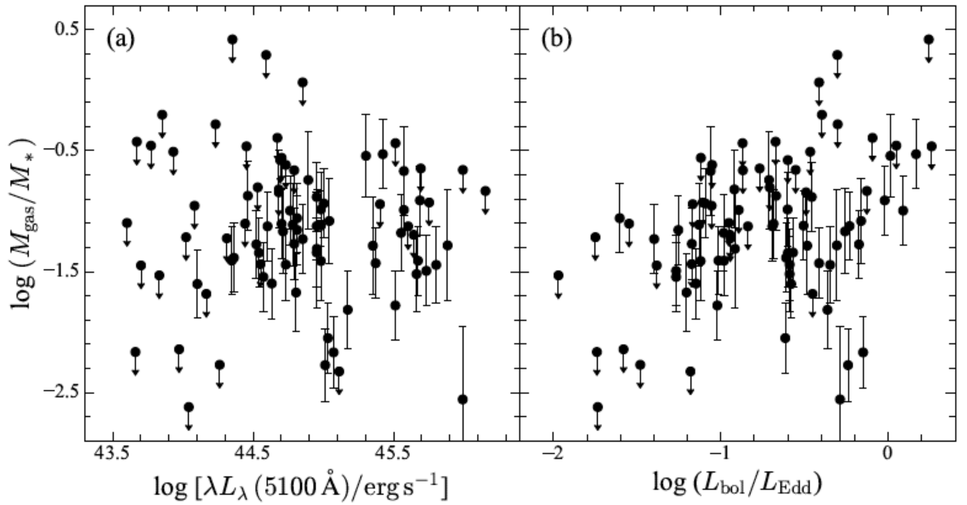
THE ASTROPHYSICAL JOURNAL, 854:158 (37pp), 2018 February 20

On the Gas Content and Efficiency of AGN Feedback in Low-redshift Quasars

Jinyi Shangguan[1,2], Luis C. Ho[1,2], and Yanxia Xie[1]





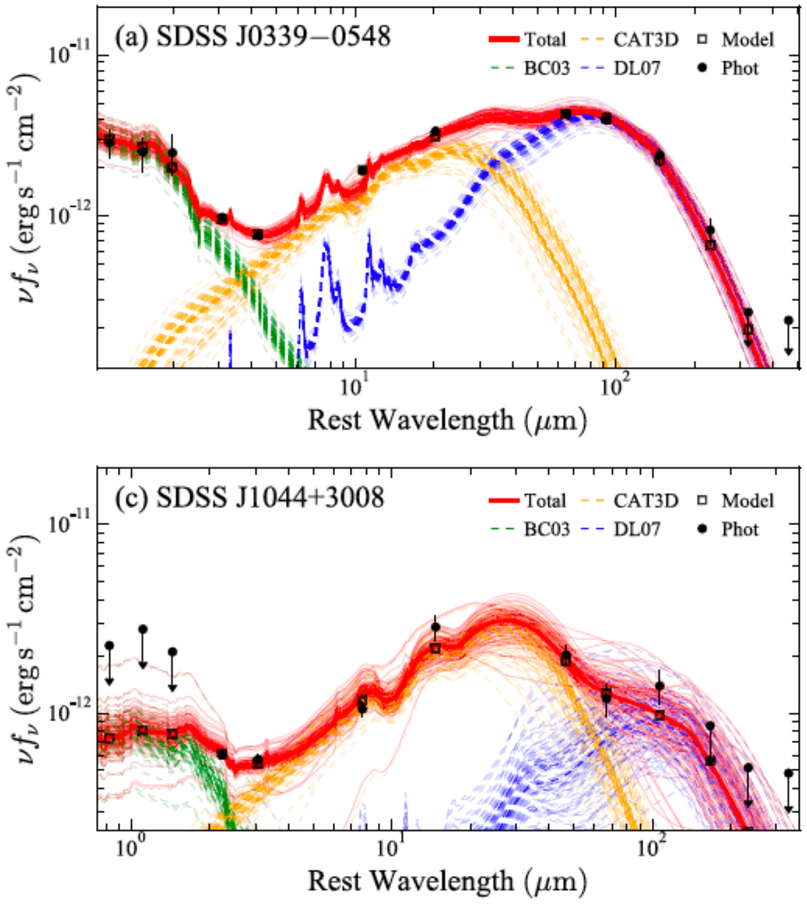


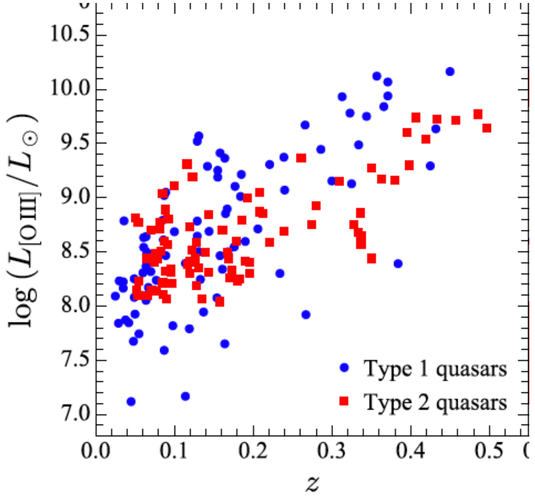
- Gas content based on the dust masses from dust emission, 1-500 μm IR SED
- Type 1 quasars ($z < 0.5$) have abundant cold gas, similar to inactive galaxies
- Gas fraction independent of AGN luminosity or Eddington ratio
- No evidence of instantaneous gas depletion by "quasar-mode" feedback

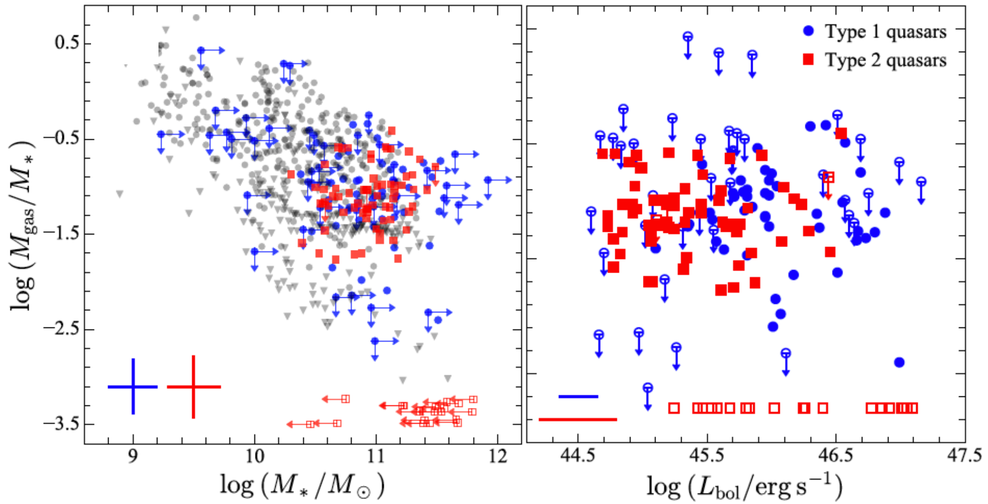
The Astrophysical Journal, 873:90 (21pp), 2019 March 1

Testing the Evolutionary Link between Type 1 and Type 2 Quasars with Measurements of the Interstellar Medium

Jinyi Shangguan[1,2] and Luis C. Ho[1,2]





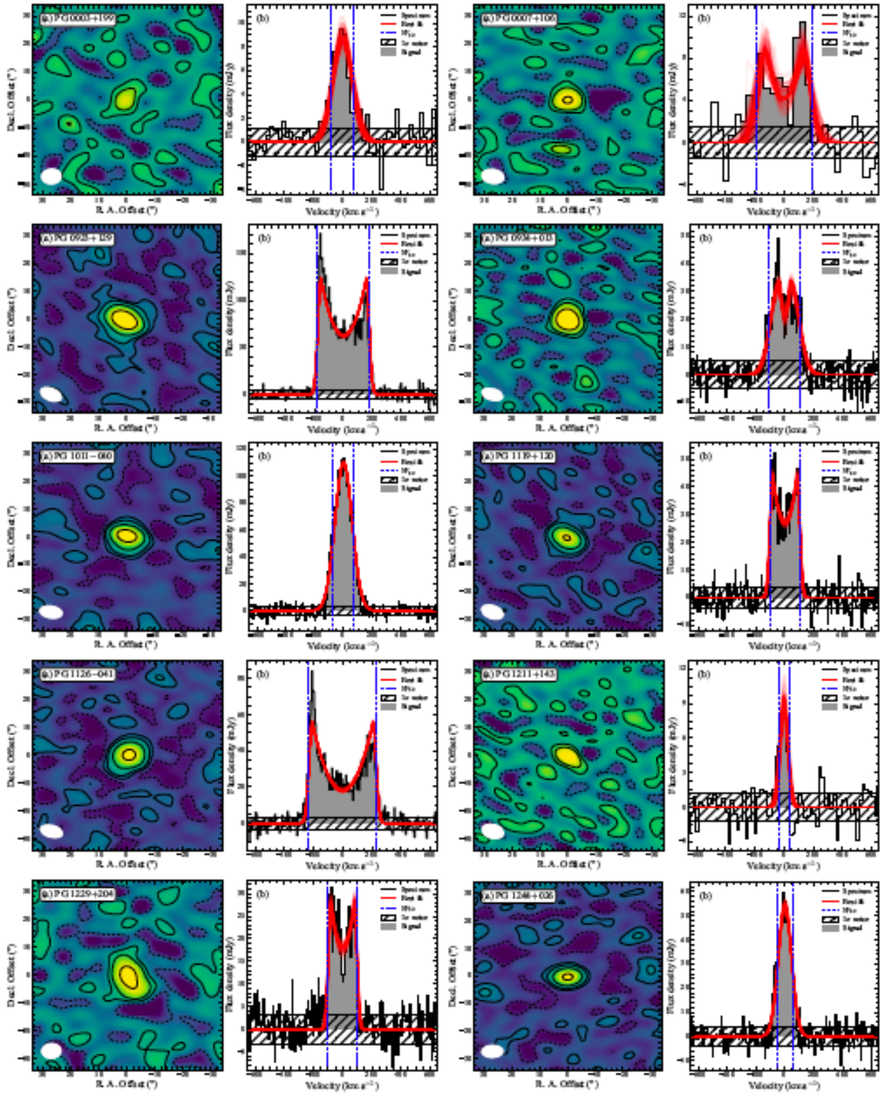


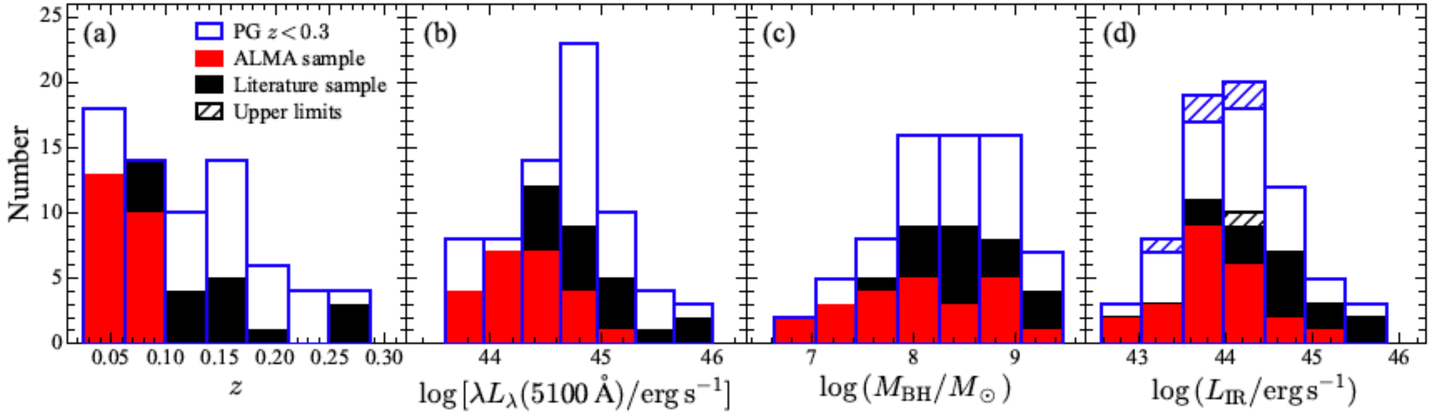
- Gas content based on the dust masses from dust emission, 1-500 μm IR SED
- Type 2 quasars ($z < 0.5$) have abundant cold gas, similar to inactive galaxies
- Gas fraction independent of AGN luminosity or Eddington ratio
- Similar to matched sample of type 1 quasars
- No evidence of instantaneous gas depletion by "quasar-mode" feedback

The Astrophysical Journal Supplement Series, 247:15 (13pp), 2020 March

An ALMA CO(2–1) Survey of Nearby Palomar–Green Quasars

Jinyi Shangguan[1,2], Luis C. Ho[2,3], Franz E. Bauer[4,5,6], Ran Wang[2,3], and Ezequiel Treister[4]



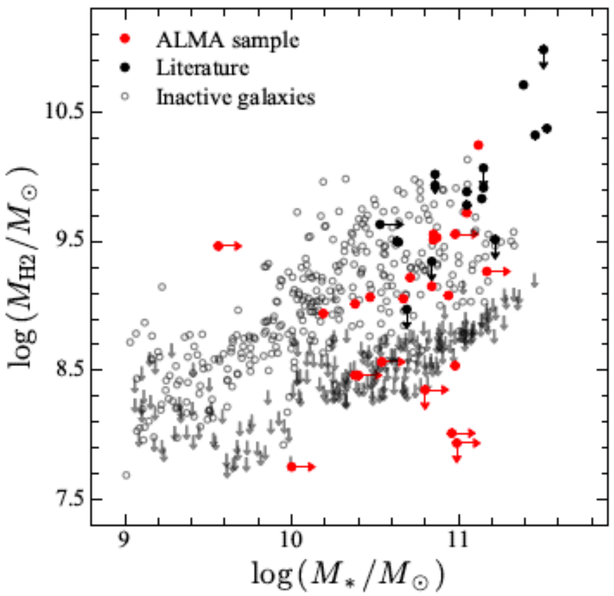


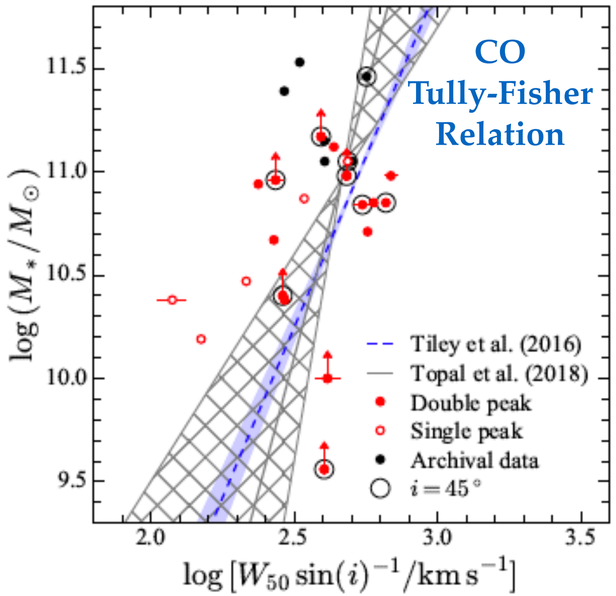
- Molecular gas content based on ALMA CO(2-1) observations
- Detection rate ~100%
- Confirms reliability of gas masses based on dust masses

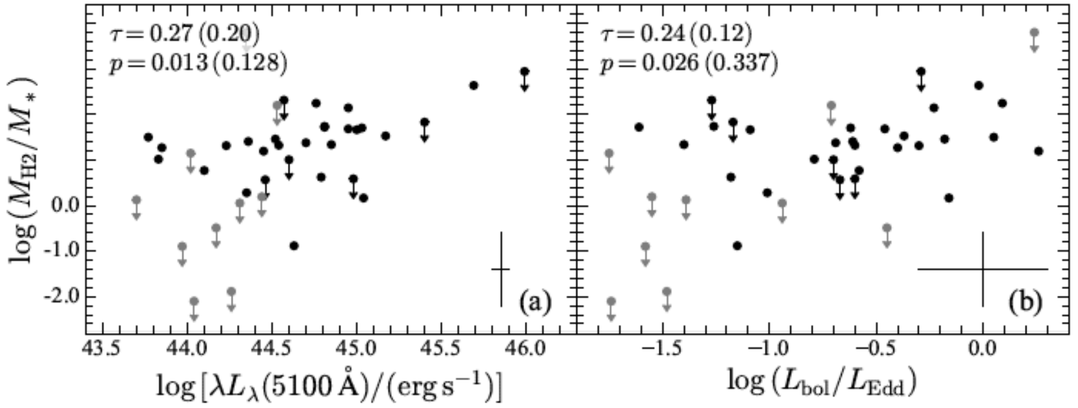
The Astrophysical Journal, 899:112 (17pp), 2020 August 20

AGN Feedback and Star Formation of Quasar Host Galaxies: Insights from the Molecular Gas

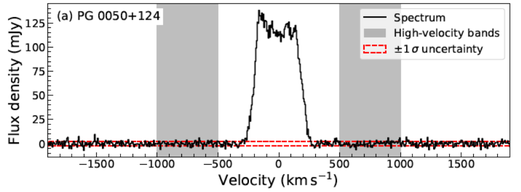
Jinyi Shangguan[1,2], Luis C. Ho[2,3], Franz E. Bauer[4,5,6], Ran Wang[2,3], and Ezequiel Treister[4]

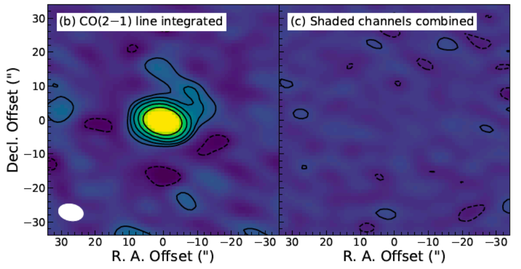


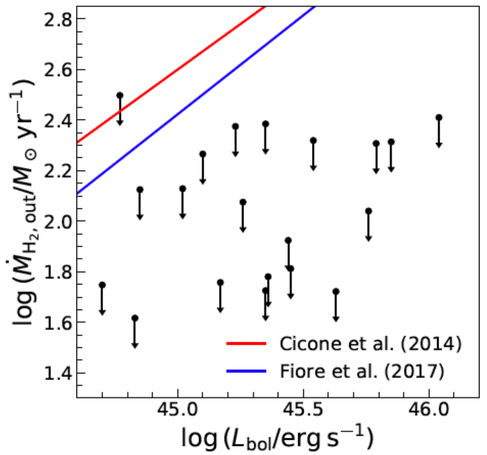




- Type 1 quasars have M_{H2} content similar to inactive galaxies
- Line widths obey the CO Tully-Fisher relation of normal galaxies, implies regular spatial distribution and kinematics
- Gas fraction independent of AGN luminosity or Eddington ratio
- No evidence of molecular outflows, stringent upper limits



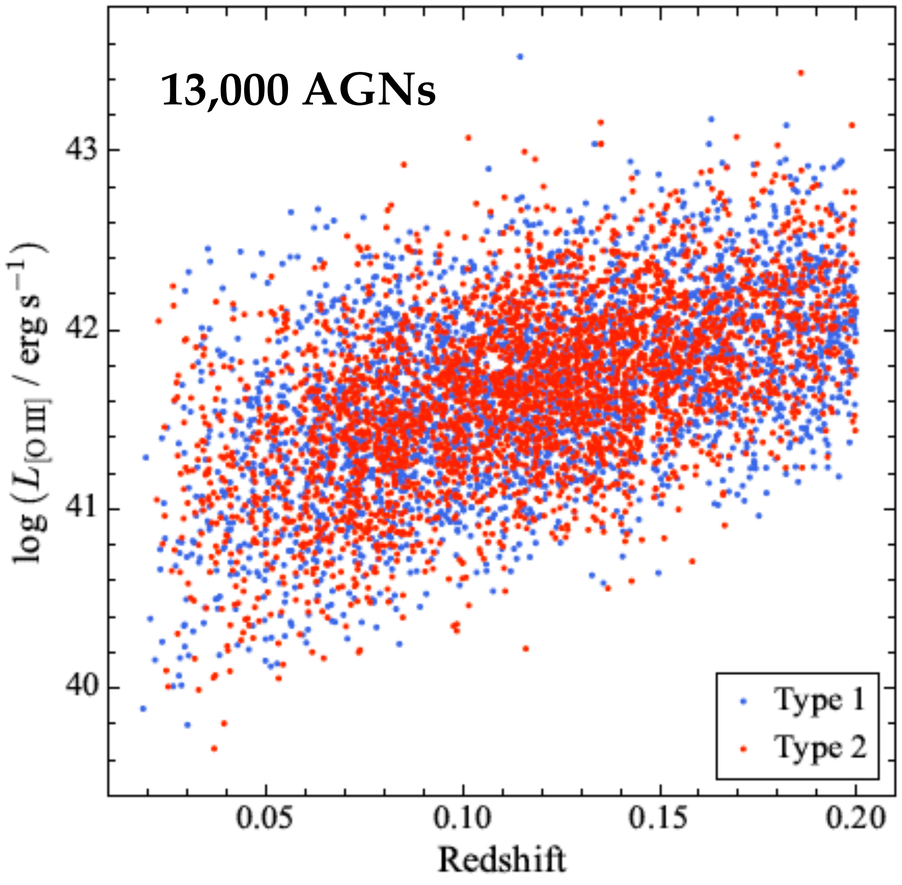


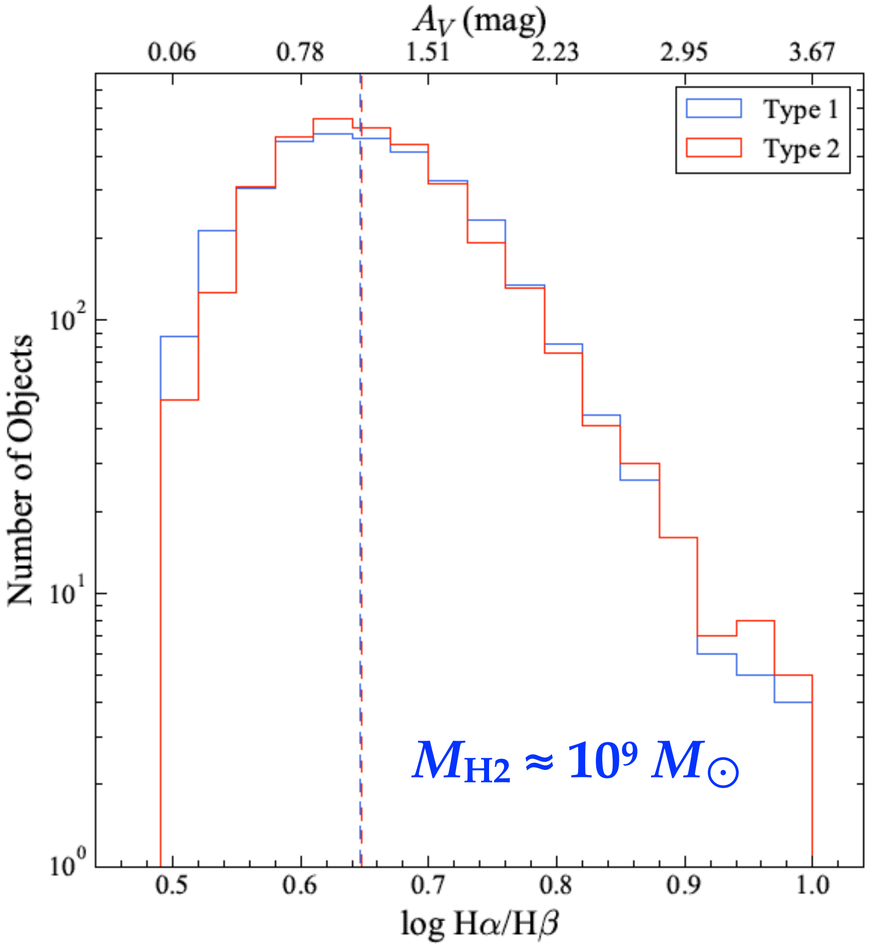


THE ASTROPHYSICAL JOURNAL, 896:108 (13pp), 2020 June 20

The Interplay between Star Formation and Black Hole Accretion in Nearby Active Galaxies

Ming-Yang Zhuang[1,2] and Luis C. Ho[1,2]



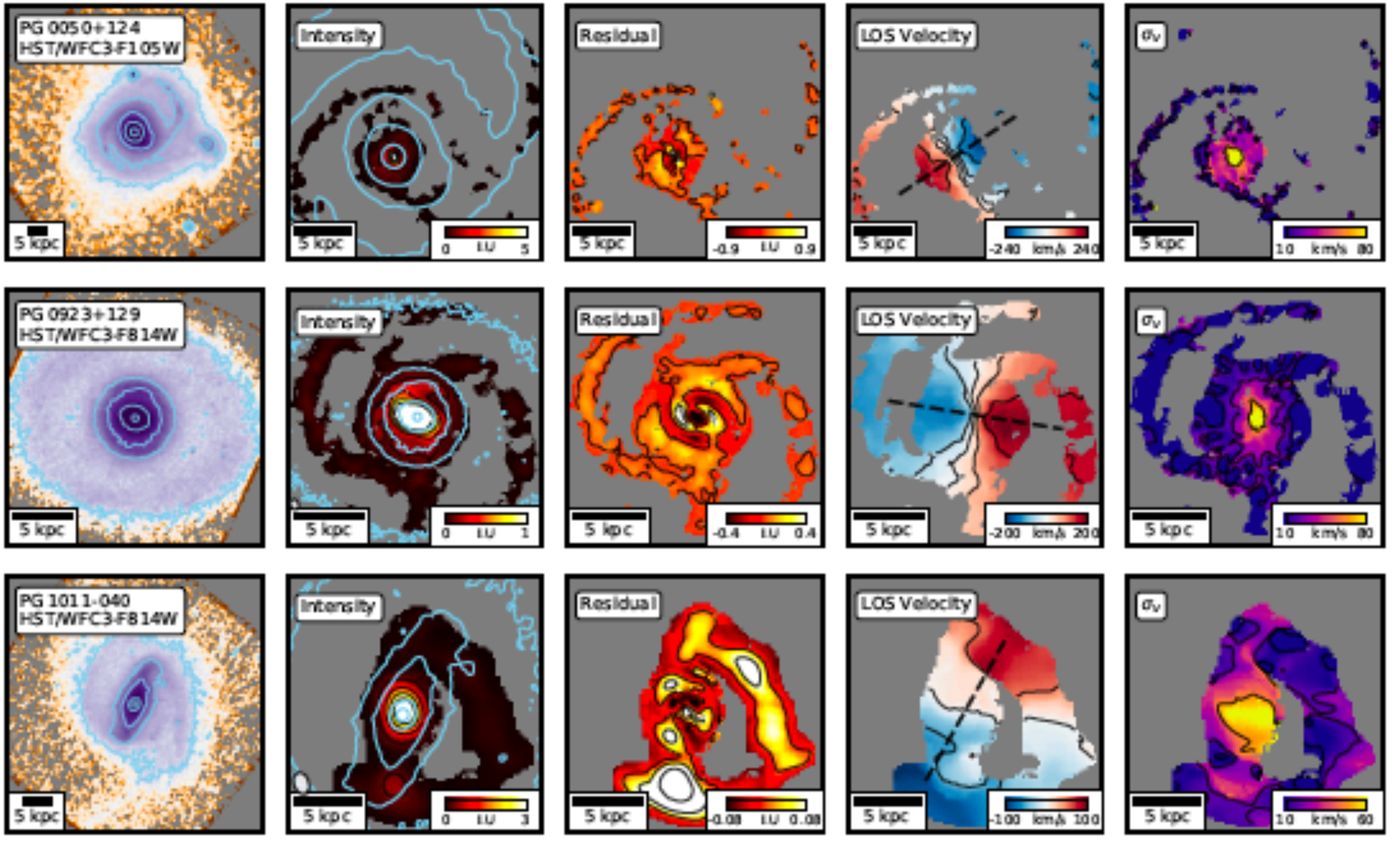


- Gas content based on the dust absorption method of Yesuf & Ho (2019)
- Both type 1 and type 2 AGNs ($z < 0.2$) have abundant molecular gas

The Astrophysical Journal, 908:231 (17pp), 2021 February 20

Compact Molecular Gas Distribution in Quasar Host Galaxies

Juan Molina[1], Ran Wang[1,2], Jinyi Shangguan[3], Luis C. Ho[1,2], Franz E. Bauer[4,5,6], Ezequiel Treister[4], and Yali Shao[7]



THE ASTROPHYSICAL JOURNAL, 908:231 (17pp), 2021 February 20

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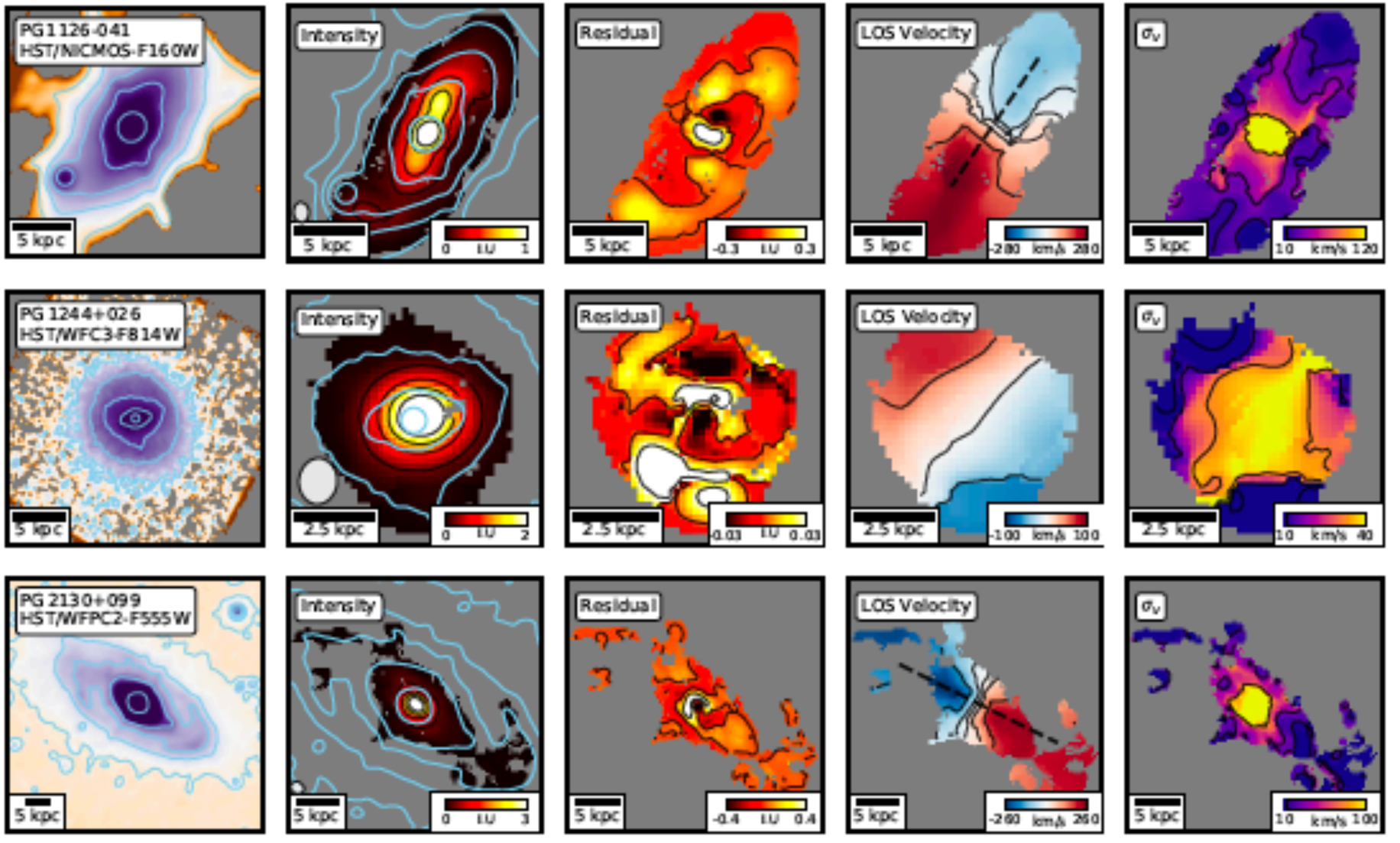

The Astrophysical Journal, 908:231 (17pp), 2021 February 20

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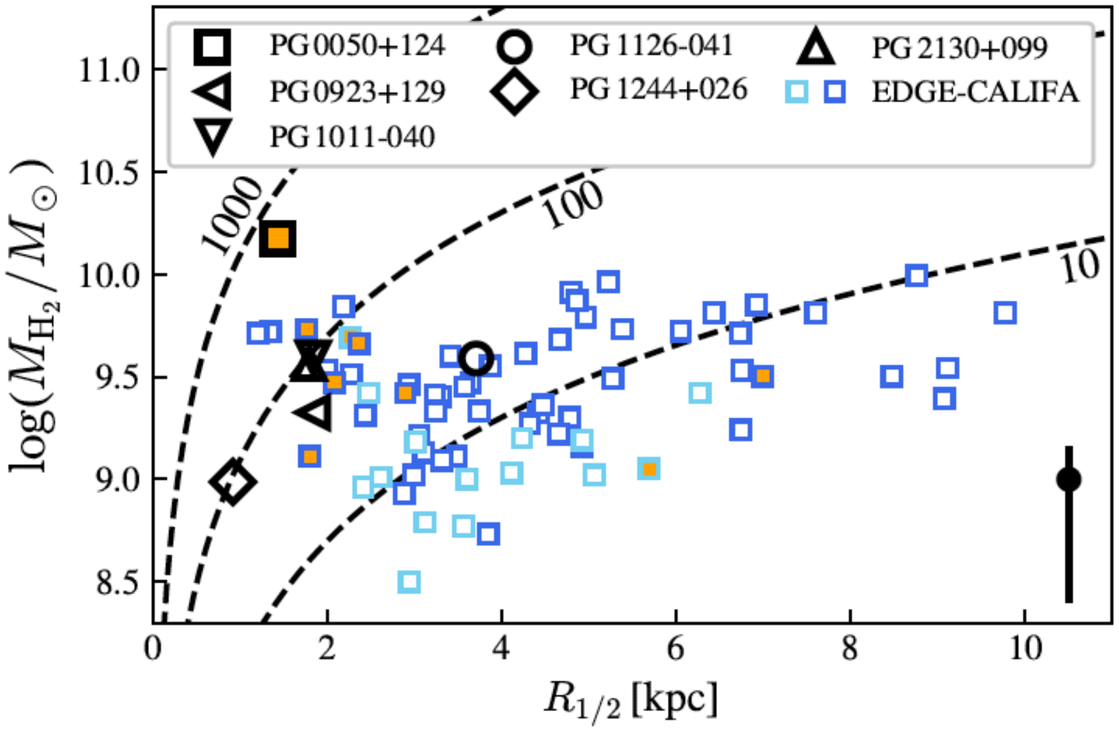
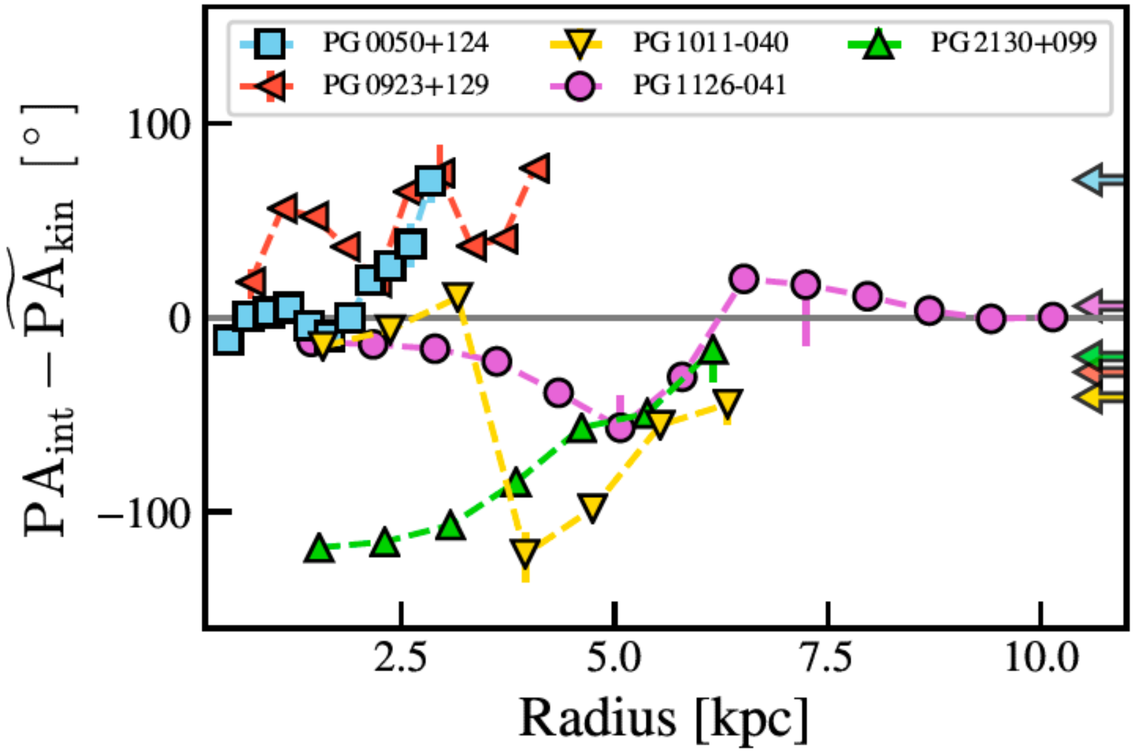




- Molecular gas is more compact (~1–2 kpc) relative to normal, star-forming galaxies
- Evidence for kinematic twisting in the centralmost regions

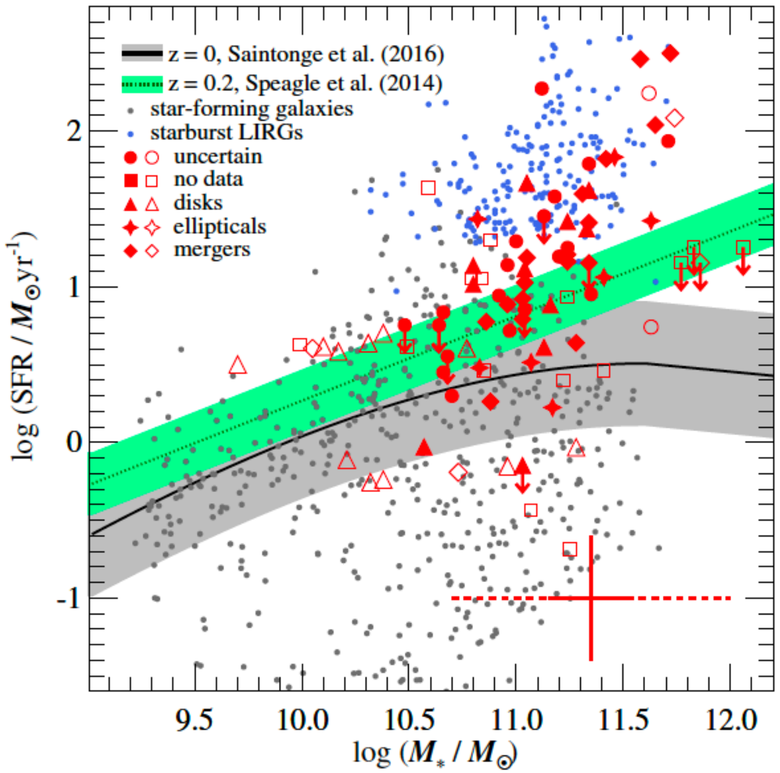
Summary I: Gas Properties

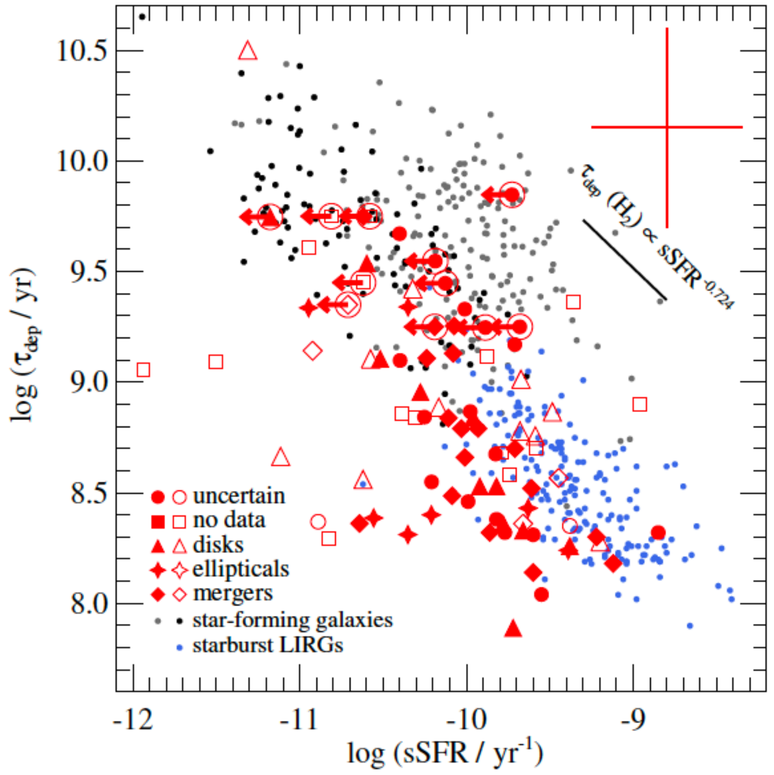
- Normal cold gas content
- Normal cold gas kinematics
- Outflows are rare
- Gas more centrally concentrated?
- Challenge to models of AGN feedback

The Astrophysical Journal, 910:124 (11pp), 2021 April 1

The Infrared Emission and Vigorous Star Formation of Low-redshift Quasars

Yanxia Xie[1], Luis C. Ho[1,2], Ming-Yang Zhuang[1,2], and Jinyi Shangguan[3]



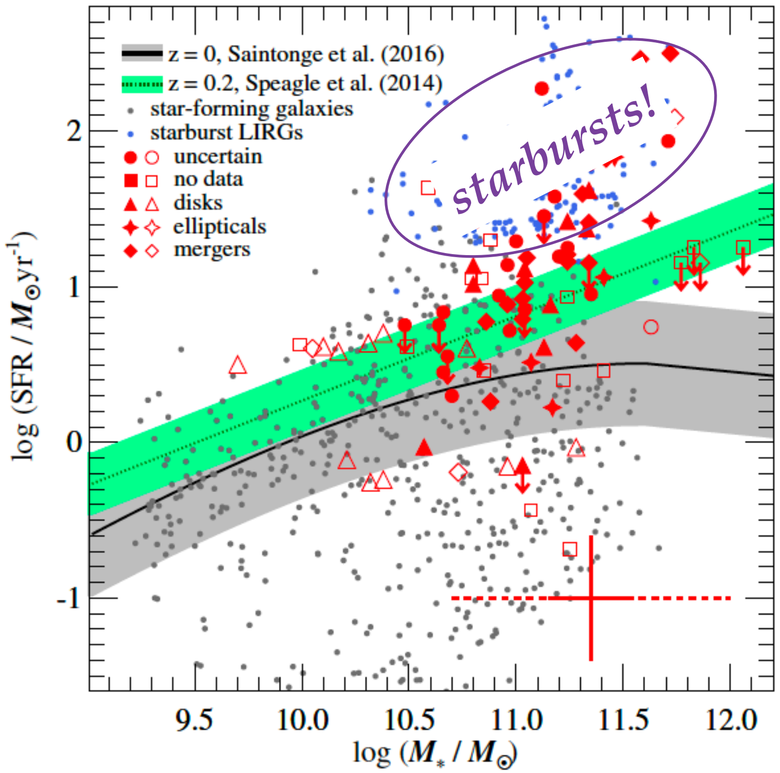


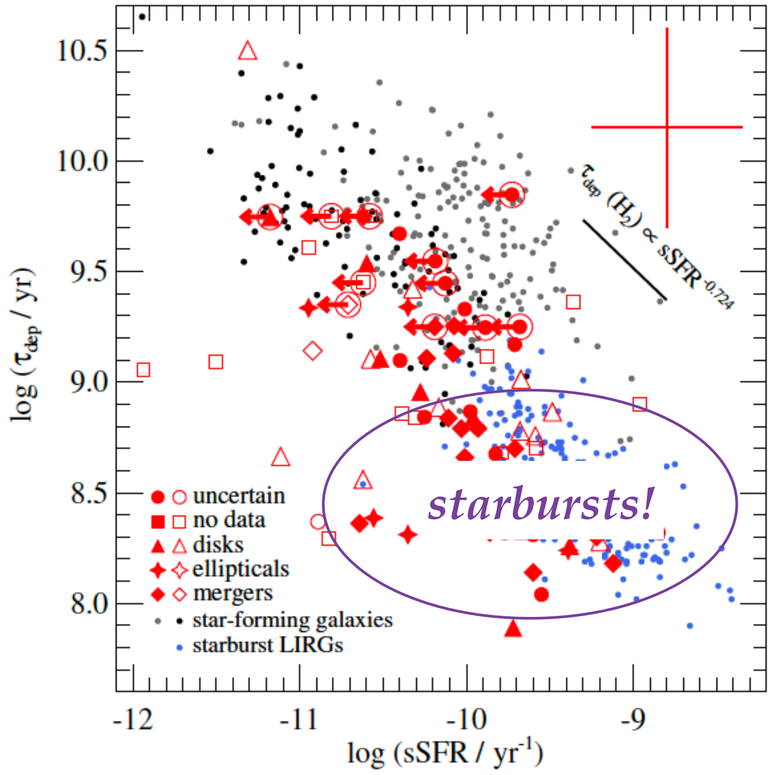
- SFRs based on FIR emission, verified with SFRs derived from [Ne II]+[Ne III] MIR lines (Ho & Keto 2007; Zhuang & Ho 2019)
- Stellar masses from HST images, gas masses from dust masses
- Most quasars lie on or above the star-forming main sequence

The Astrophysical Journal, 910:124 (11pp), 2021 April 1

The Infrared Emission and Vigorous Star Formation of Low-redshift Quasars

Yanxia Xie[1], Luis C. Ho[1,2], Ming-Yang Zhuang[1,2], and Jinyi Shangguan[3]





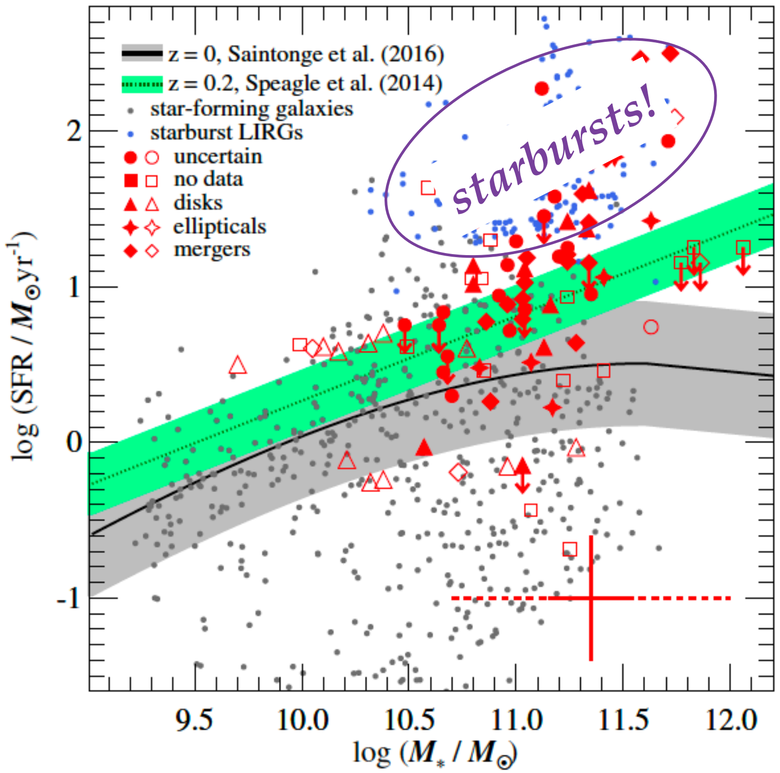
- SFRs based on FIR emission, verified with SFRs derived from [Ne II]+[Ne III] MIR lines (Ho & Keto 2007; Zhuang & Ho 2019)
- Stellar masses from HST images, gas masses from dust masses
- Most quasars lie on or above the star-forming main sequence

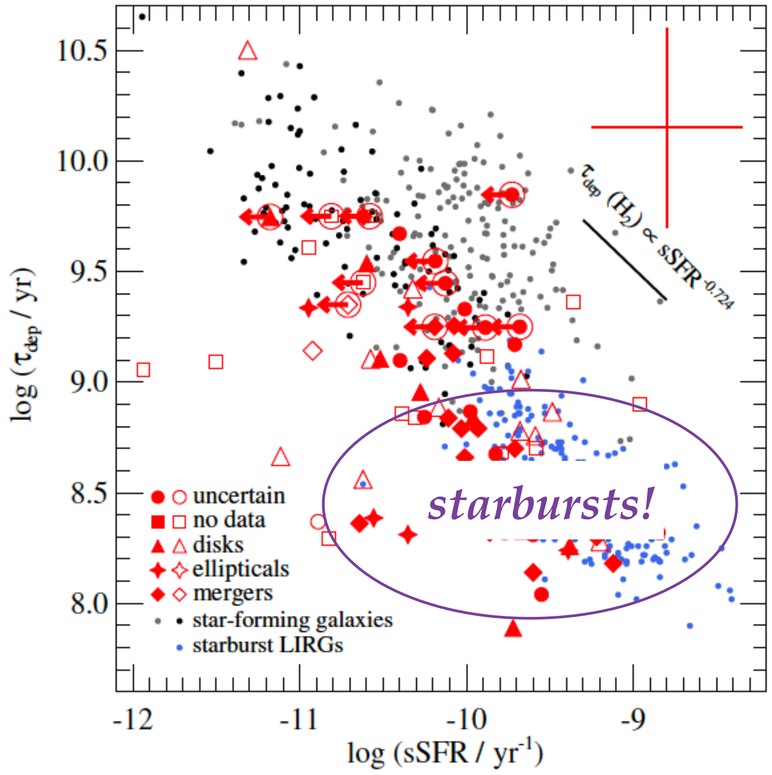
- Significant fraction of starbursts (high sSFRs and high SFEs)

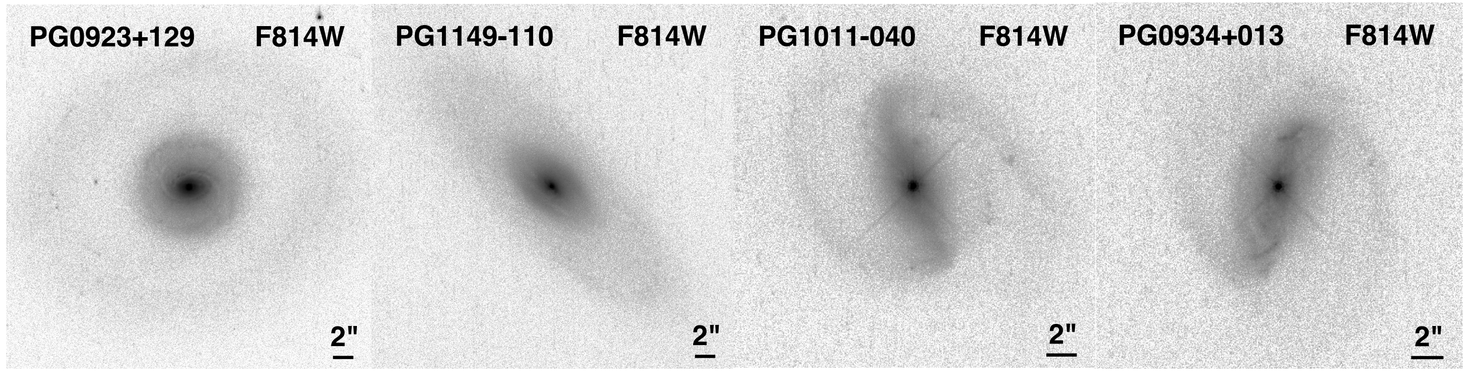
The Astrophysical Journal, 910:124 (11pp), 2021 April 1

The Infrared Emission and Vigorous Star Formation of Low-redshift Quasars

Yanxia Xie[1], Luis C. Ho[1,2], Ming-Yang Zhuang[1,2], and Jinyi Shangguan[3]







- SFRs based on FIR emission, verified with SFRs derived from [Ne II]+[Ne III] MIR lines (Ho & Keto 2007; Zhuang & Ho 2019)
- Stellar masses from HST images, gas masses from dust masses
- Most quasars lie on or above the star-forming main sequence

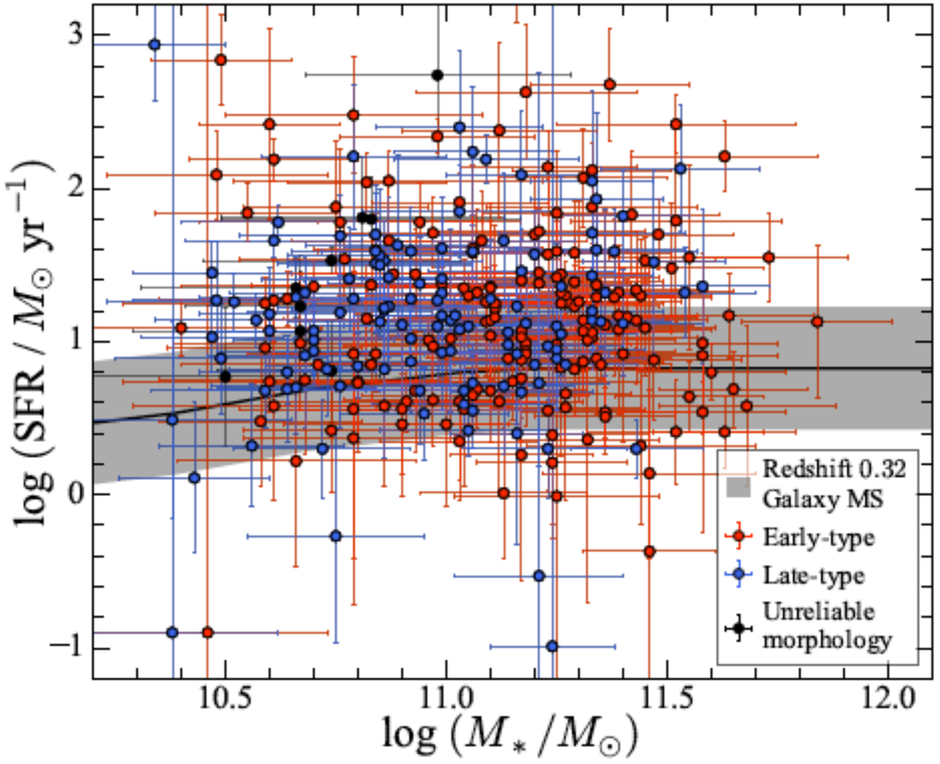
- Significant fraction of starbursts (high sSFRs and high SFEs)

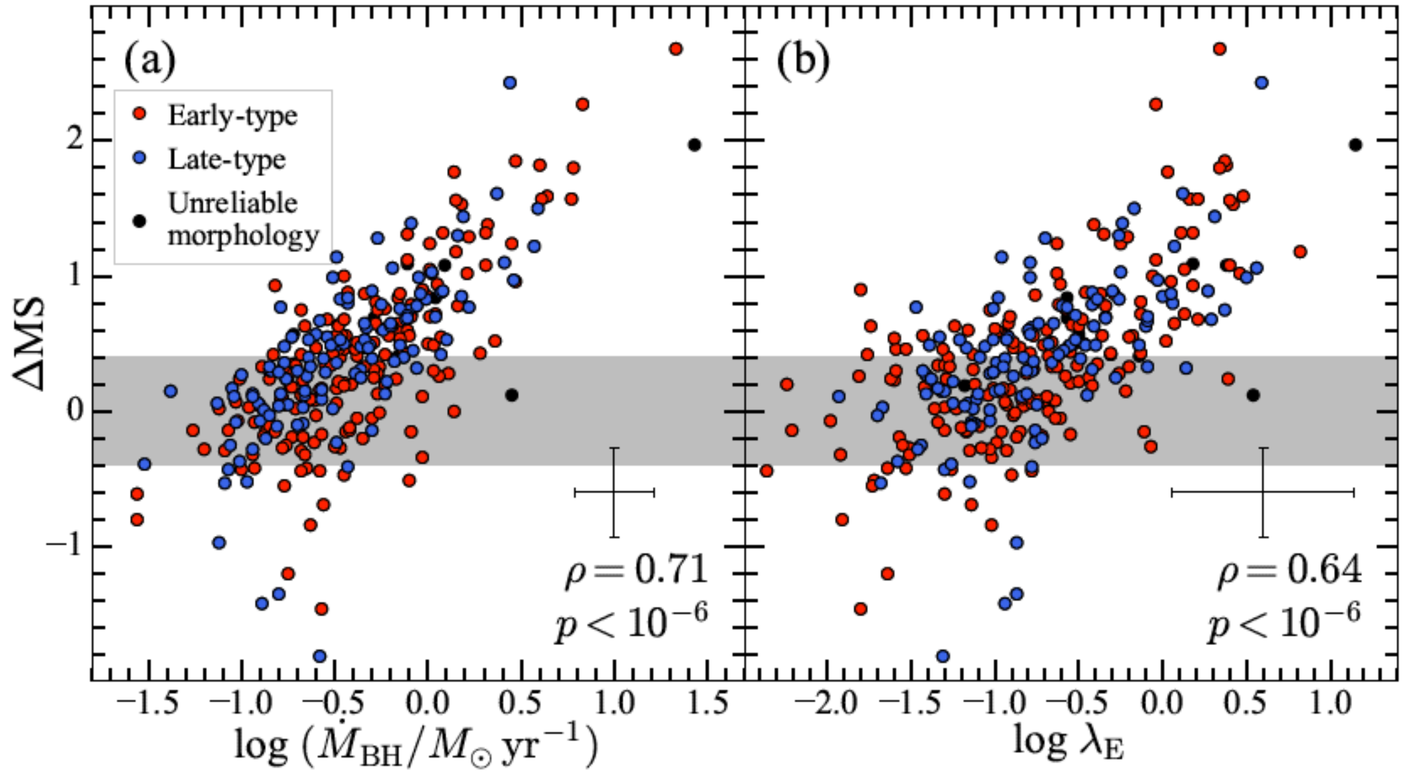
- But many are not recent mergers

The Astrophysical Journal, 934:130 (23pp), 2022 August 1

The Star-forming Main Sequence of the Host Galaxies of Low-redshift Quasars

Ming-Yang Zhuang (庄明阳)[1,2] and Luis C. Ho[1,2]





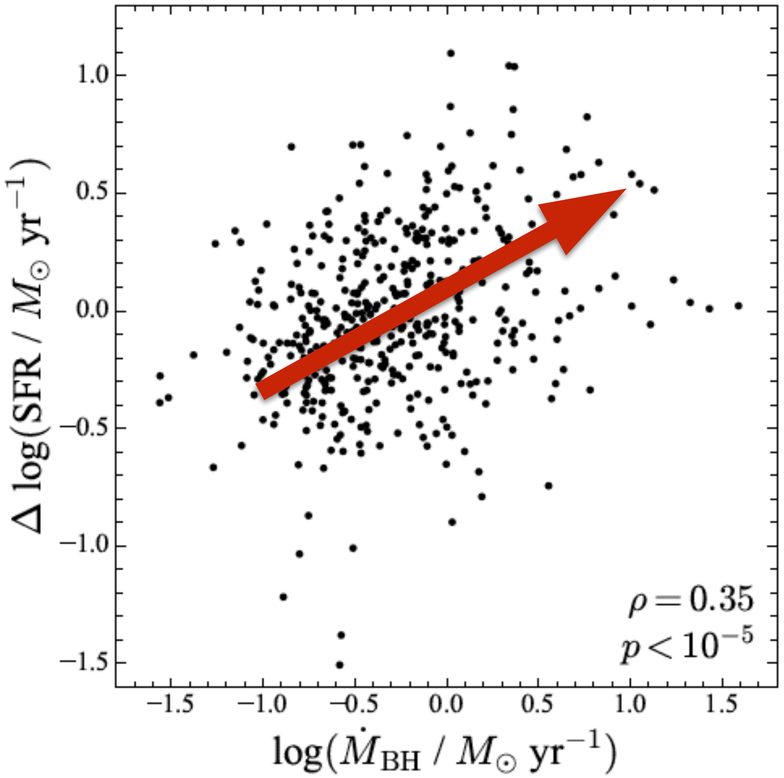
- SFRs from [O II] method of Zhuang & Ho (2019)
- Stellar masses from *grizy* PanSTARRS images
- GALFITM simultaneous multiband decomposition

- Most quasars lie on or above the star-forming main sequence
- Specific SFR increases with AGN accretion rate
- Possible evidence of positive AGN feedback?

The Astrophysical Journal, 906:38 (8pp), 2021 January 1

Black Hole Accretion Correlates with Star Formation Rate and Star Formation Efficiency in Nearby Luminous Type 1 Active Galaxies

Ming-Yang Zhuang[1,2], Luis C. Ho[1,2], and Jinyi Shangguan[3]



- SFR correlates with BH accretion rate, after accounting for mutual dependence on molecular gas mass
- Gas mass from dust absorption method of Yesuf & Ho (2019)
- SFRs from [O II] method of Zhuang & Ho (2019)

The Astrophysical Journal, 906:38 (8pp), 2021 January 1

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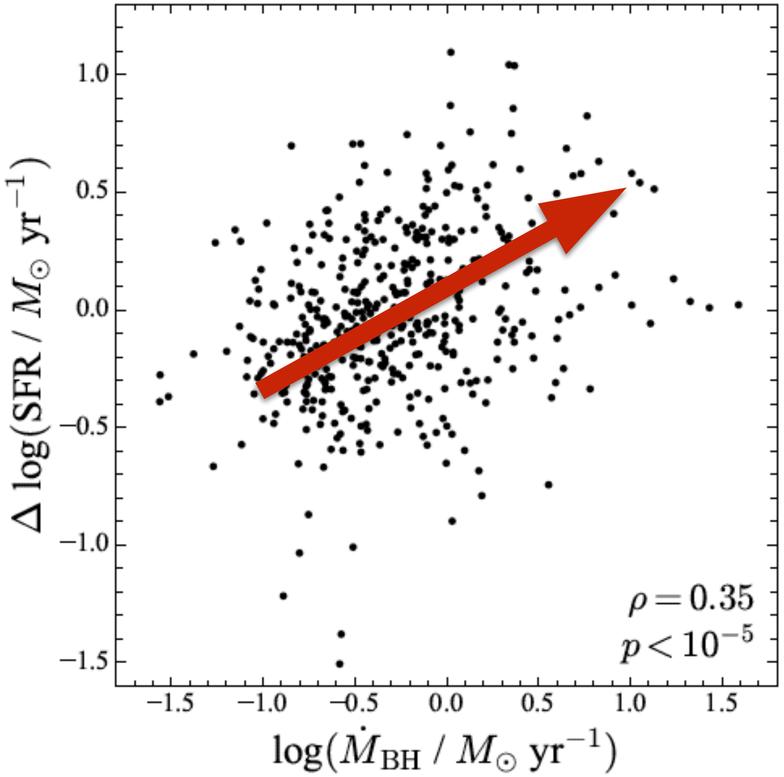
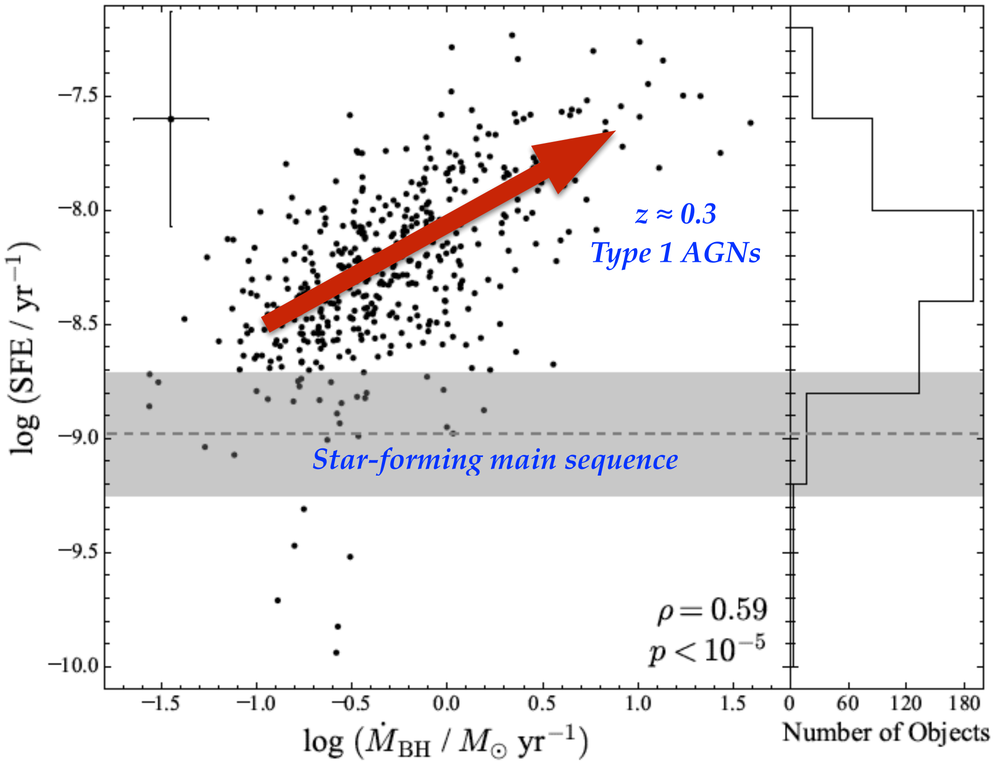




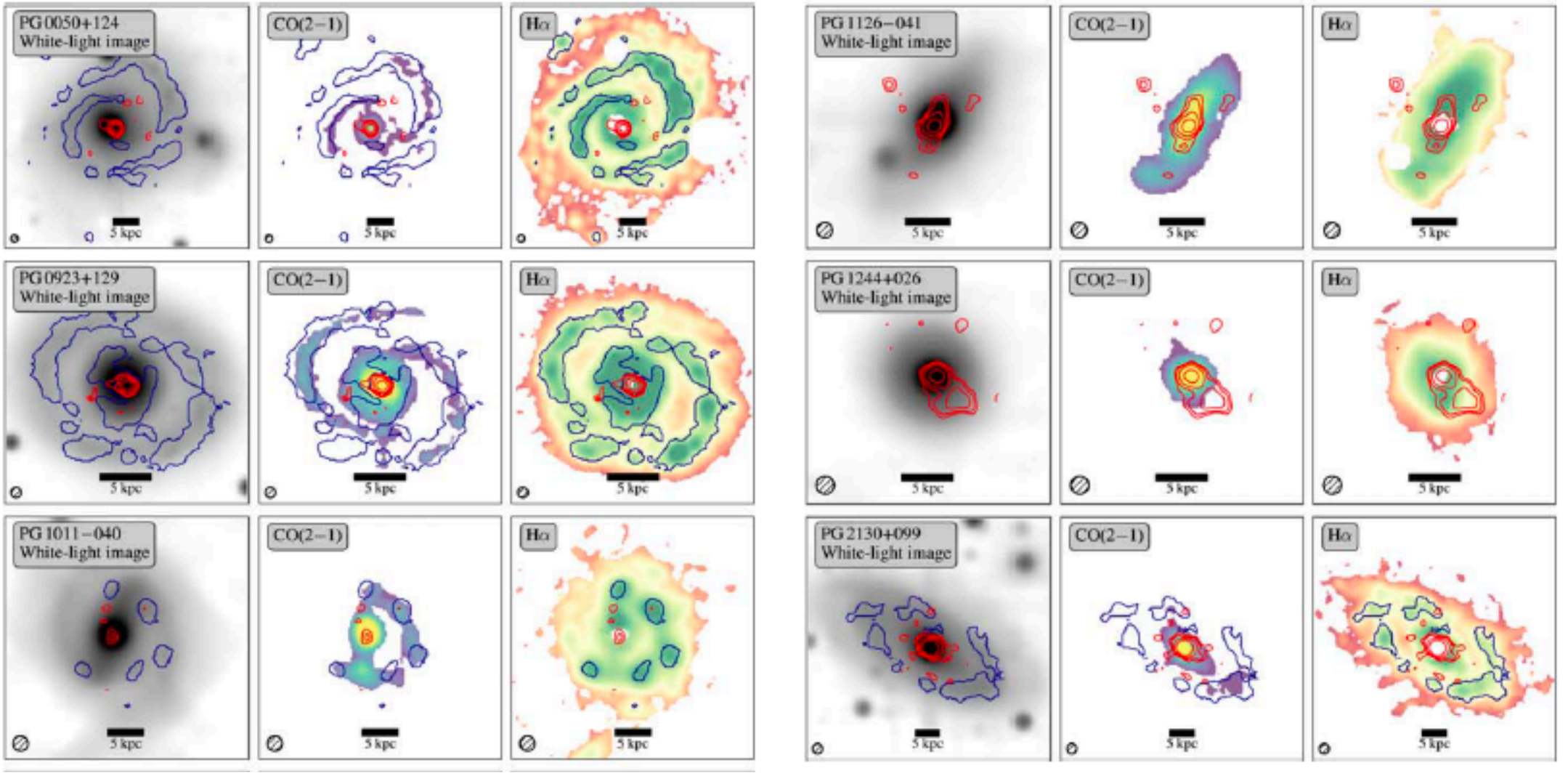
- **SFR correlates with BH accretion rate**, after accounting for mutual dependence on molecular gas mass
- Gas mass from dust absorption method of Yesuf & Ho (2019)
- SFRs from [O II] method of Zhuang & Ho (2019)

- SFE much higher than normal star-forming galaxies, consistent with starburst systems
- **SFE correlates with BH accretion rate**
- Possible evidence of positive AGN feedback?

The Astrophysical Journal, 944:30 (21pp), 2023 February 10

Enhanced Star Formation Efficiency in the Central Regions of Nearby Quasar Hosts

Juan Molina[1], Luis C. Ho[1,2], Ran Wang[1,2], Jinyi Shangguan[3], Franz E. Bauer[4,5,6], and Ezequiel Treister[4]



The Astrophysical Journal, 944:30 (21pp), 2023 February 10

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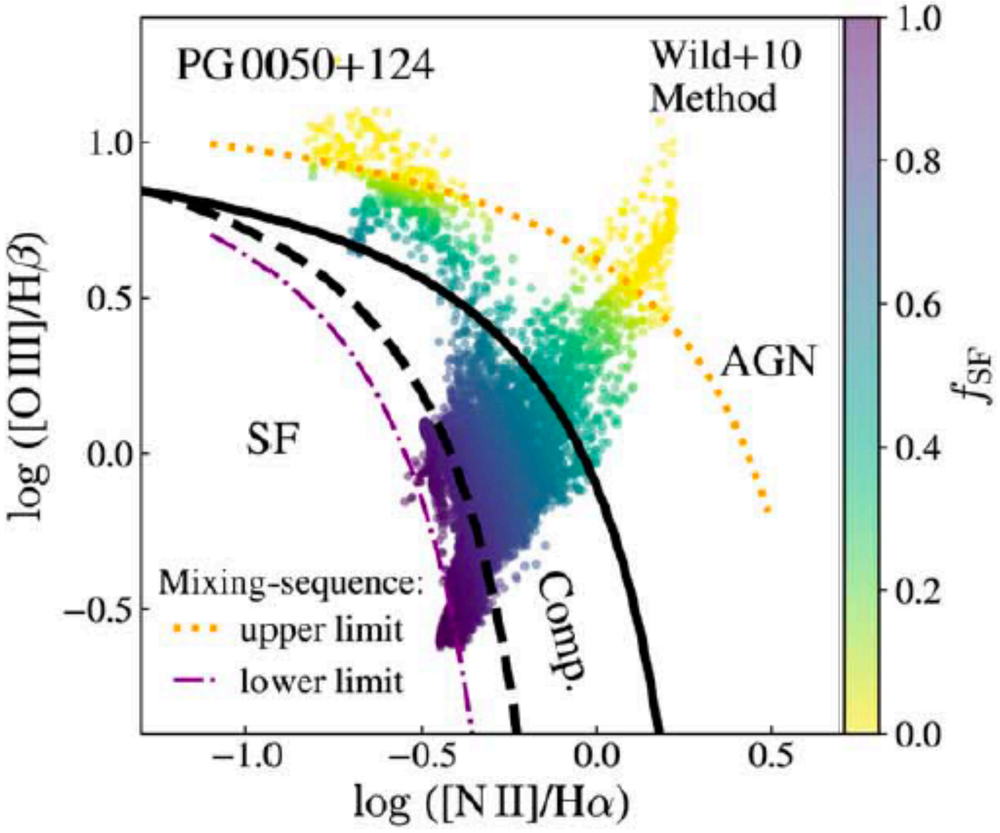

- Use mixing-sequence method to estimate distribution of spatially resolved SFRs

The Astrophysical Journal, 944:30 (21pp), 2023 February 10

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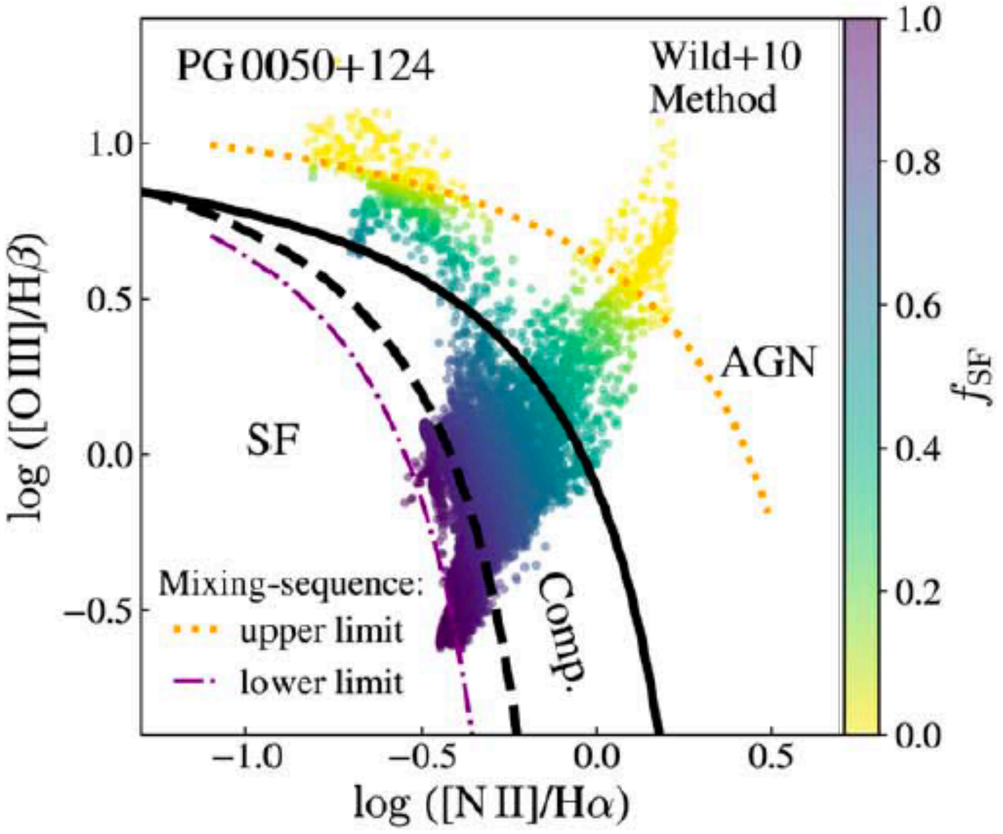
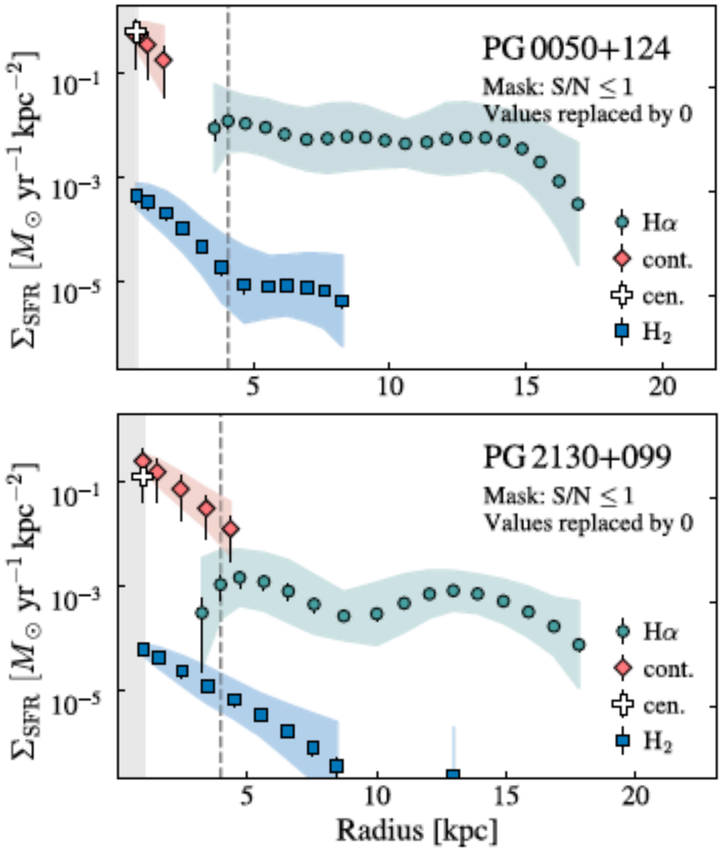
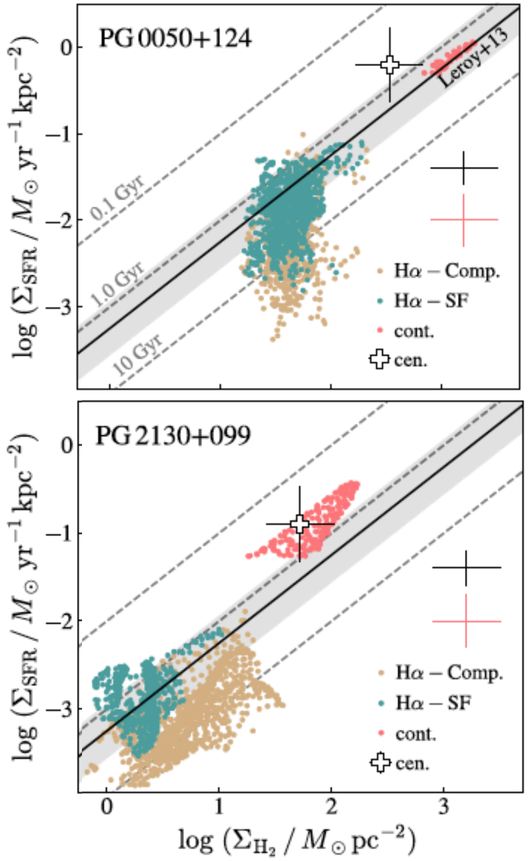






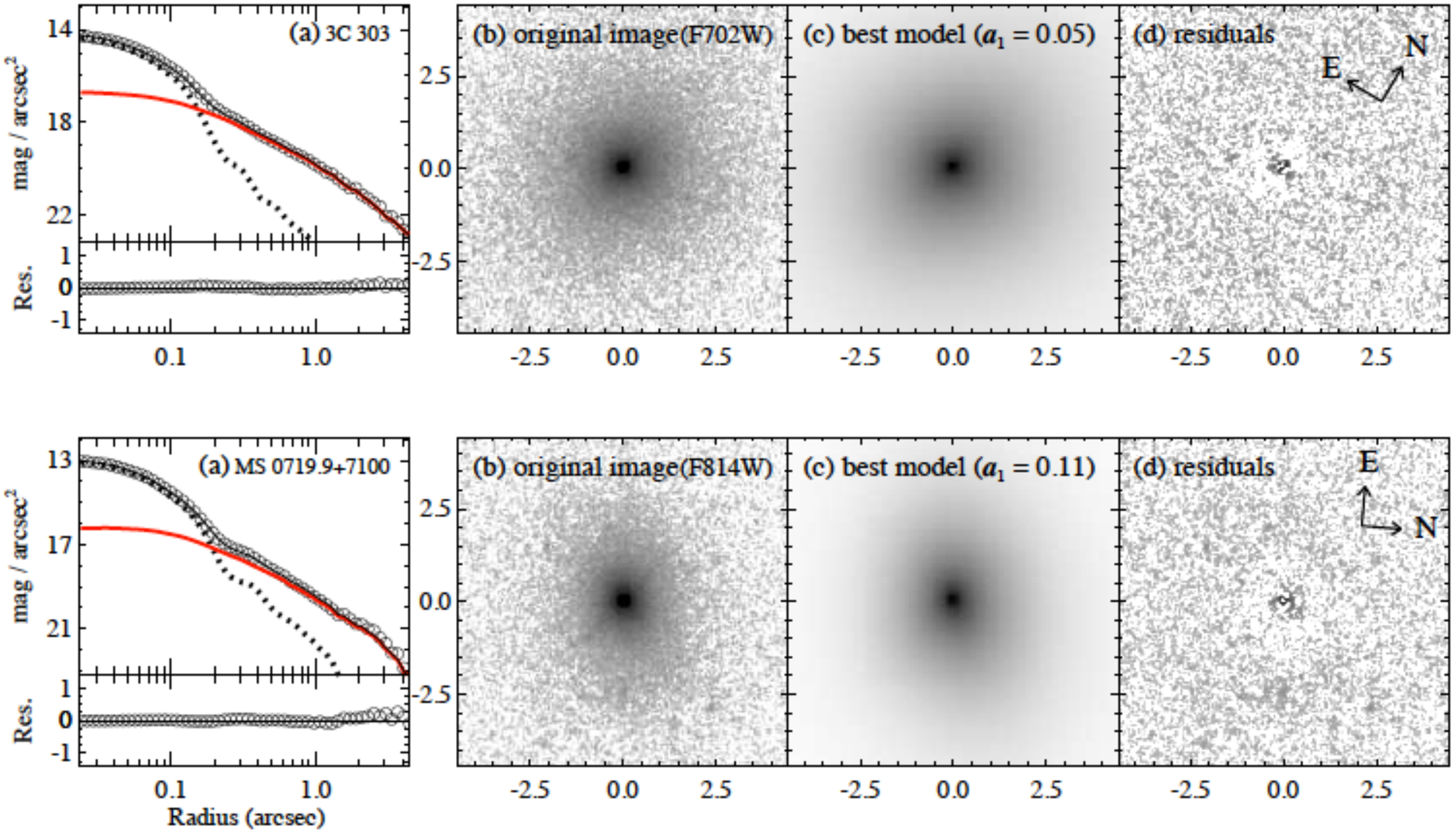
- Use mixing-sequence method to estimate distribution of spatially resolved SFRs

- Centrally peaked SFR and molecular gas distributions
- SFE enhanced in the *central* regions of the host galaxies

The Astrophysical Journal Supplement Series, 232:21 (30pp), 2017 October

Stellar Photometric Structures of the Host Galaxies of Nearby Type 1 Active Galactic Nuclei*

Minjin Kim[1,2], Luis C. Ho[3,4], Chien Y. Peng[5], Aaron J. Barth[6], and Myungshin Im[7]



- Host galaxy structure can be decomposed from AGN with detailed 2D image analysis
- Accurate bulge properties possible, but challenging
- Requires high-resolution images from HST and JWST
- Need careful treatment of PSF

The Astrophysical Journal Supplement Series, 232:21 (30pp), 2017 October

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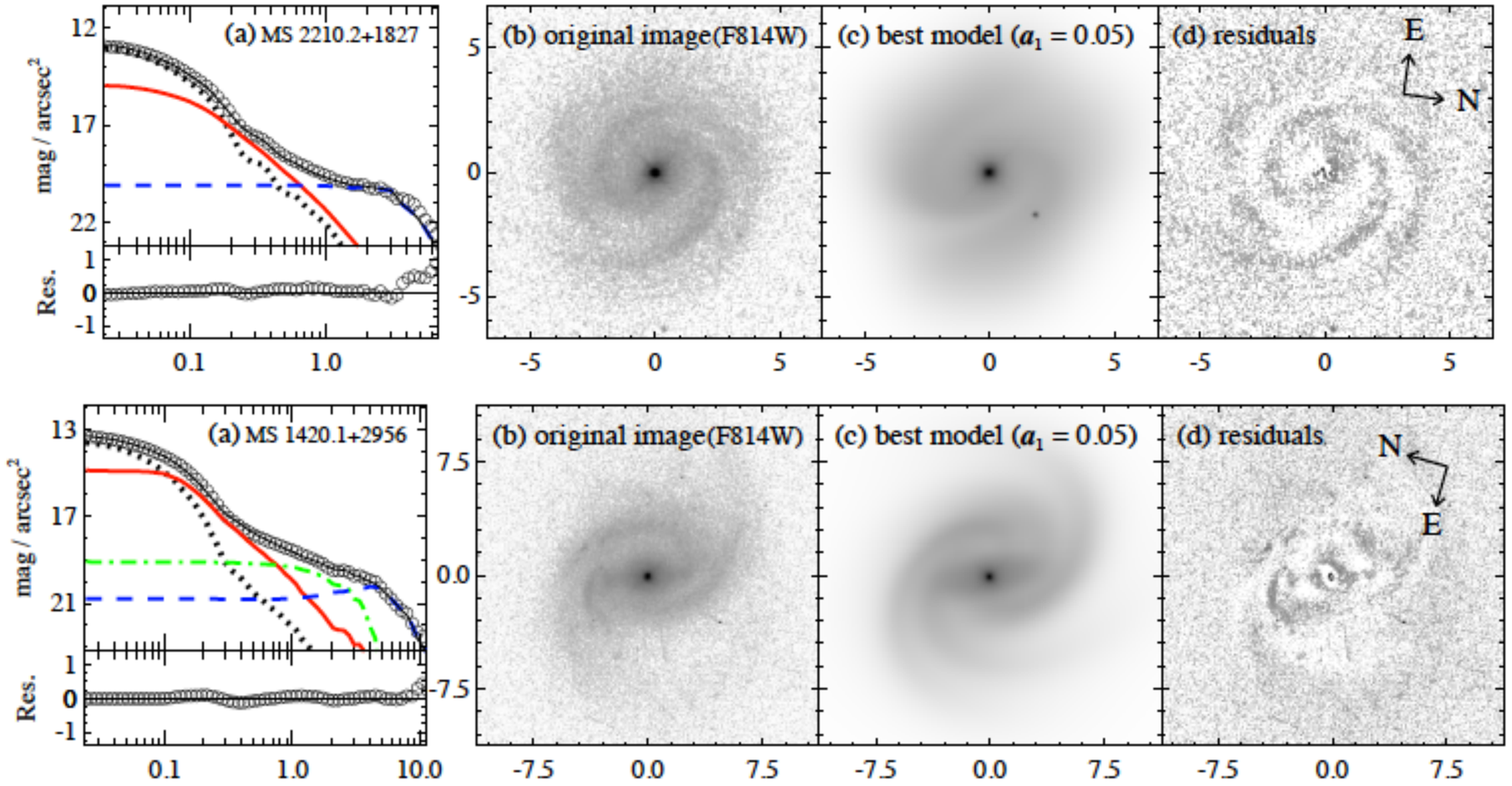

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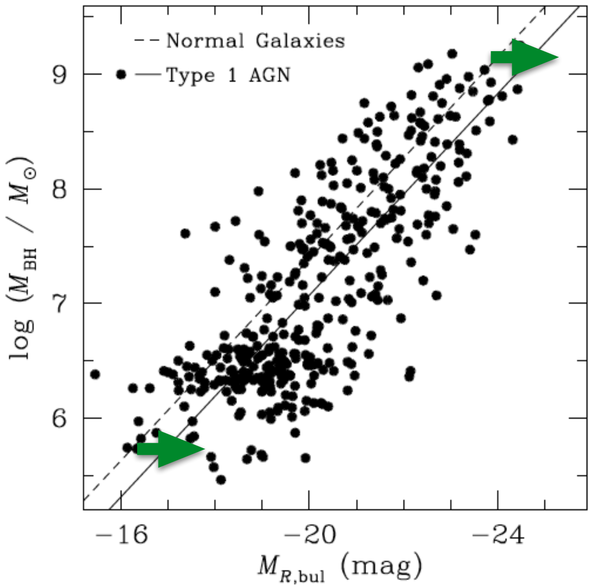
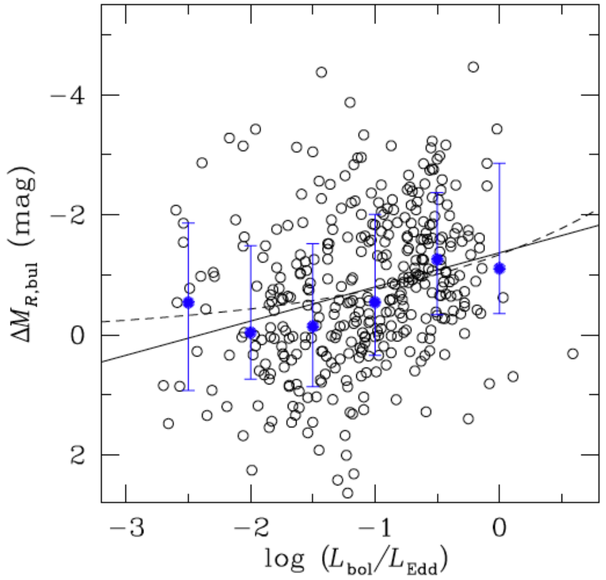
THE ASTROPHYSICAL JOURNAL, 876:35 (9pp), 2019 May 1

Evidence for a Young Stellar Population in Nearby Type 1 Active Galaxies

Minjin Kim[1,2] and Luis C. Ho[3,4]





- Bulges of AGNs overluminous cf. inactive galaxies
- Luminosity excess larger for higher Eddington ratio

The Astrophysical Journal, 876:35 (9pp), 2019 May 1

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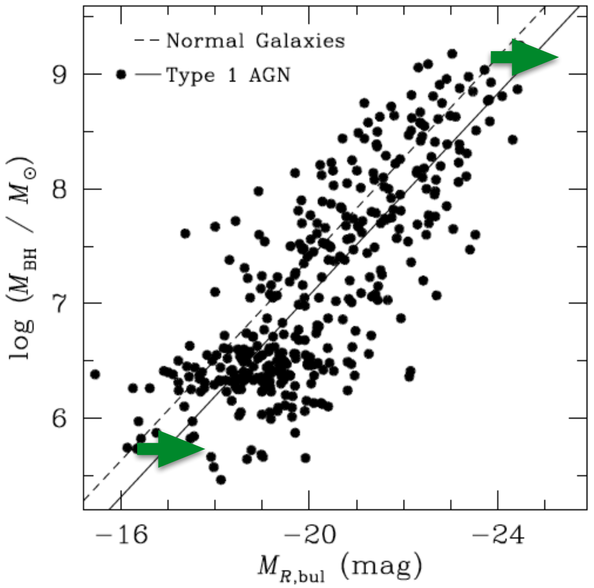

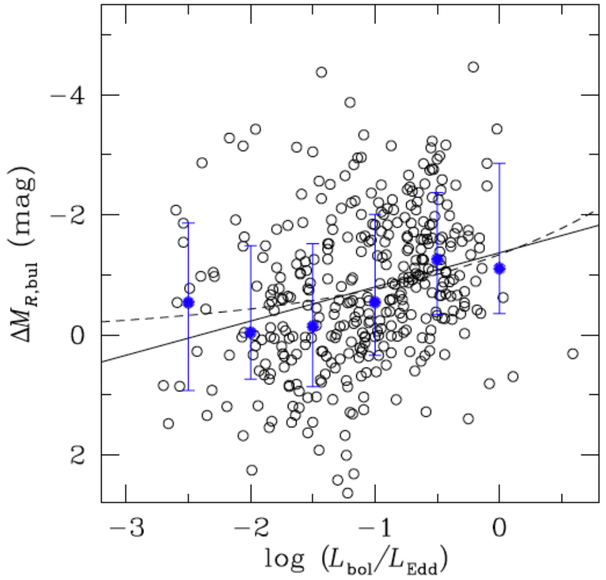

- Bulges of AGNs overluminous cf. inactive galaxies
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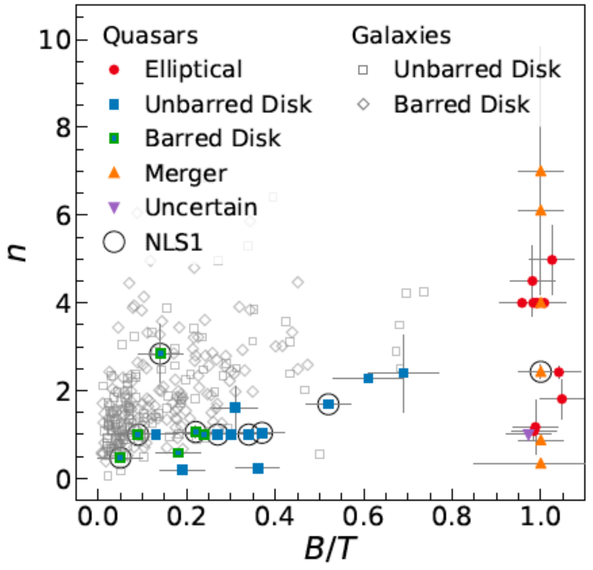
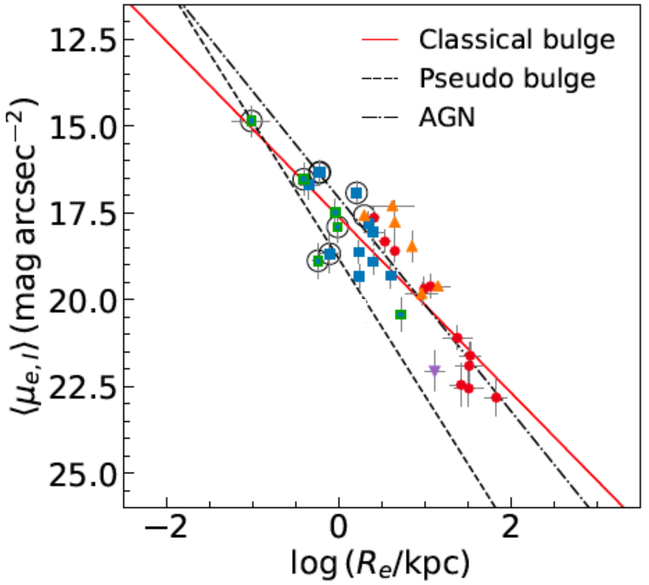
The Astrophysical Journal, 911:94 (19pp), 2021 April 20

The Diverse Morphology, Stellar Population, and Black Hole Scaling Relations of the Host Galaxies of Nearby Quasars

Yulin Zhao[1,2], Luis C. Ho[1,2], Jinyi Shangguan[1,3], Minjin Kim[4,5], Dongyao Zhao[1,6], and Hua Gao[1,2,7]



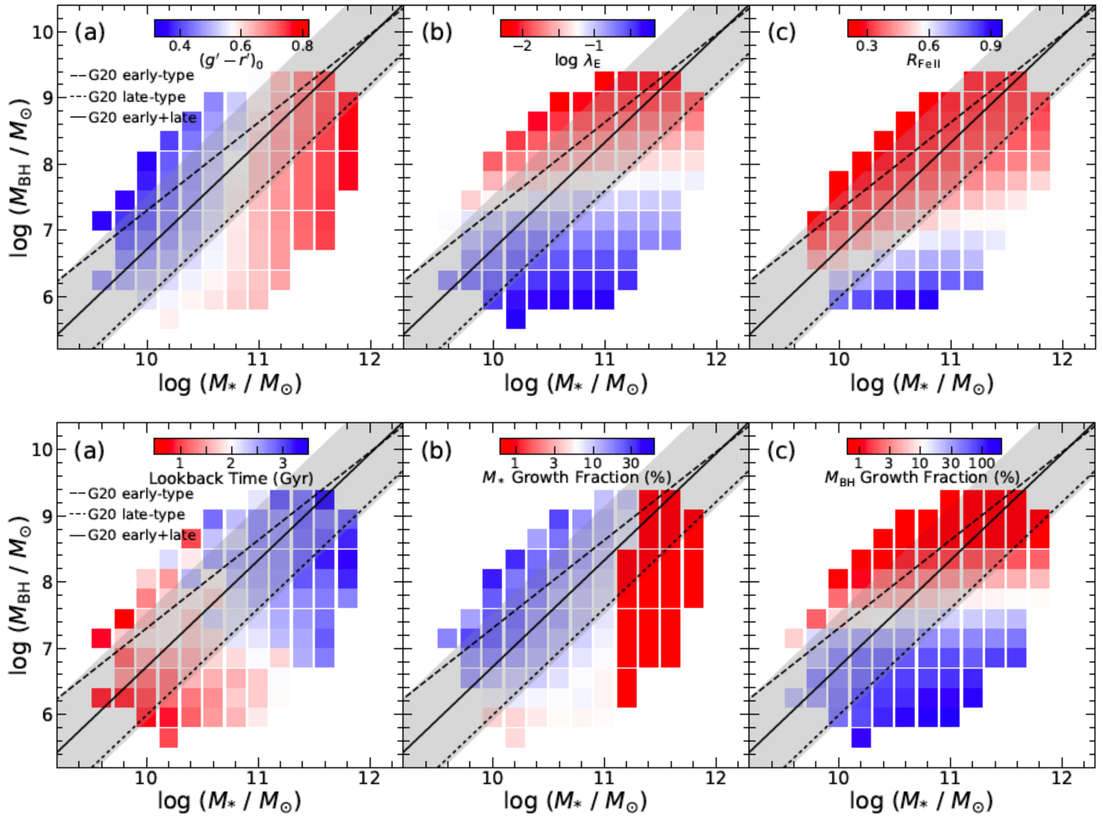


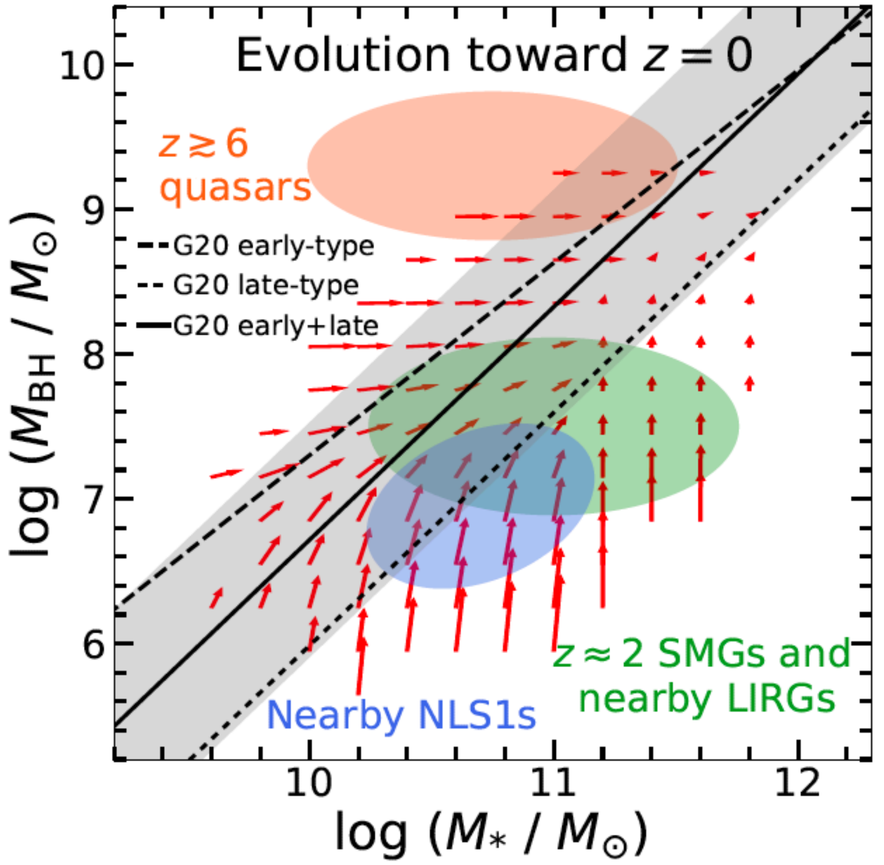
- Luminosity excess concentrated in inner region of bulge
- Consistent with younger central stellar population

NATURE ASTRONOMY 2023, in press

Evolutionary Paths of Active Galactic Nuclei and Their Host Galaxies

MING-YANG ZHUANG (庄明阳) [1,2] AND LUIS C. HO [1,2]





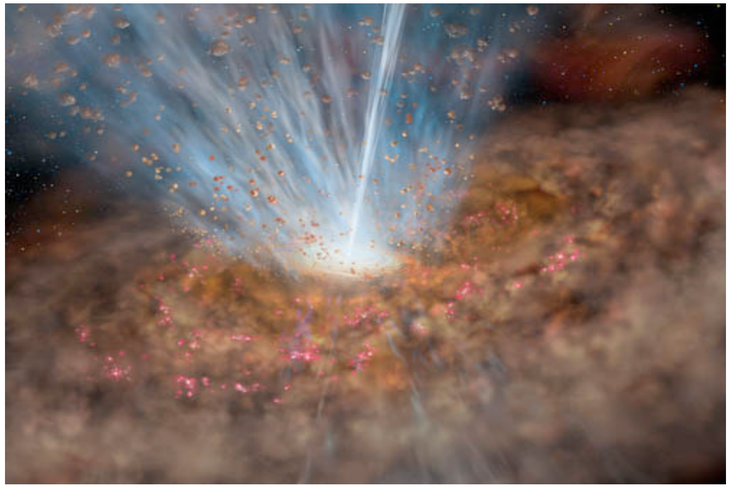
- Stellar masses from *grizy* PanSTARRS images; ~12,000 AGNs z < 0.35
- GALFITM simultaneous multiband decomposition
- Star formation history of host systematically correlated with position on BH-galaxy scaling relations

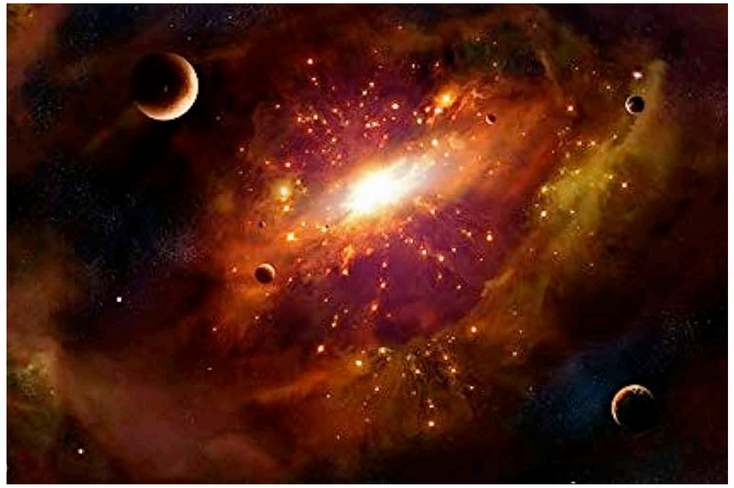
Summary II: Star Formation Properties

- Normal or enhanced SFR
- Large fraction of starbursts (high SFE)
- Star formation more centrally concentrated
- Possibly triggered internally
- SFR $\propto \dot{M}_{\rm BH}$; SFE $\propto \dot{M}_{\rm BH}$

Some Food for Thought

- Models of AGN feedback should be reevaluated
- Role of SN feedback likely under-appreciated
- Nuclear transients, circumnuclear SNe
- Evolution of stellar remnants in central regions of galaxies



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CHINA MOBILE
AQUALUNA