Structure of AGN Tori in Merging Galaxies Revealed by Mid-infrared and X-ray Observations

Yamada+19, ApJ

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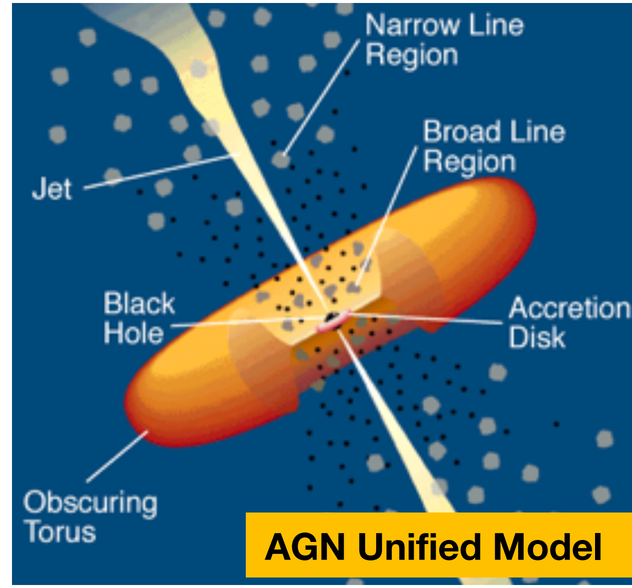
Galaxy Evolution Workshop 2019 @ Kavli IPMU

Major merger scenario

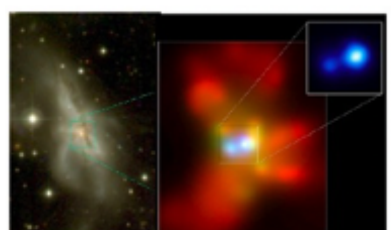
- Tight correlations between BH mass and bulge mass => Coevolution?
- Mass accretion onto a SMBH is observable as an **AGN.**



Urry & Padovani 1995

- The gas and dust need to lose ~99% of their angular momentum. => **A merger of gas-rich galaxies** is a key mechanism!!

Galaxy merger



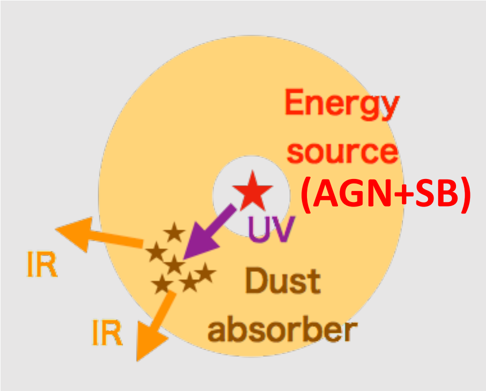
Ultra-/luminous infrared galaxies (U/LIRGs)

Elliptical galaxies

@ Hopkins+08

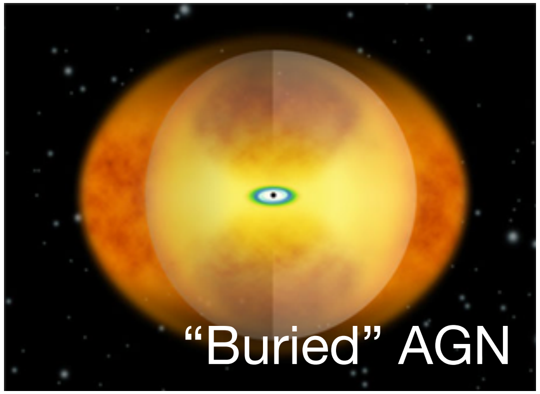
Obscured AGNs in U/LIRGs

- **U/LIRG (Ultra-/Luminous Infrared Galaxy)**
  - Large IR luminosity ($L_{IR} > 10^{12}/10^{11}\ L_{\odot}$)
  - Many of them are interacting galaxies.



- During the final phase of a merger, rapid accretion onto the SMBHs takes place when nucleus is deeply enshrouded by gas and dust (= "buried" AGN; e.g., Hopkins+06).

- However, it is difficult to test the scenario of merger-driven SMBH growth, because of thick obscuration.
  => **X-rays and Mid-IR** are useful!!

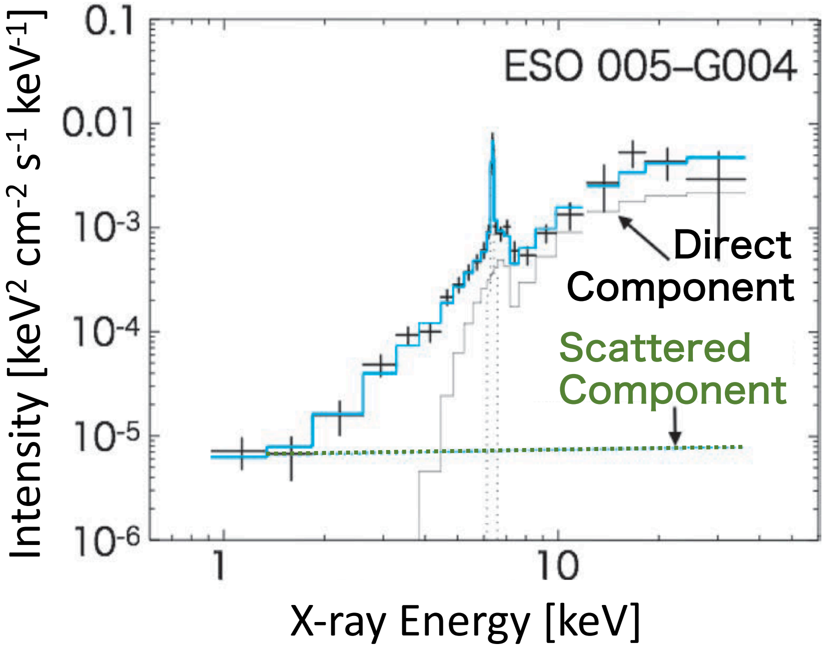


https://www.subarutelescope.org/Pressrelease/2006/02/15/j_index.html#fig1

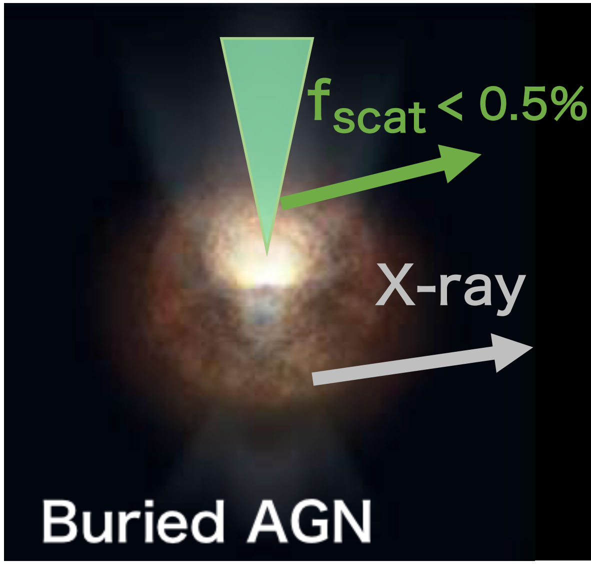
Identification of buried AGNs ① : X-ray

- **Broadband X-ray spectra** enable us to identify buried AGNs.

  e.g.) Intensity of X-rays scattered by the NLR gas relative to that of the direct component.
  (Scattering fraction: f_{scat})



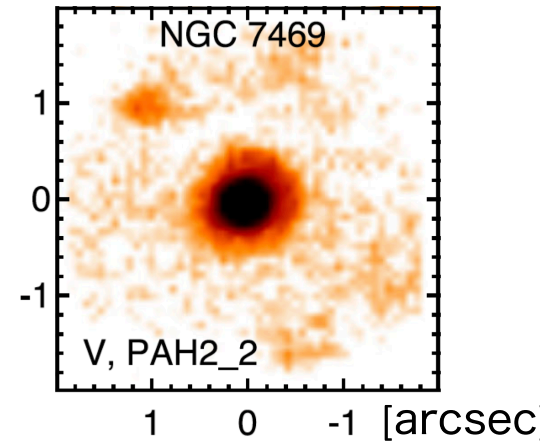
- To apply this method, however, we need X-ray spectra with sufficiently high quality. Such objects are very limited.



Upper：http://www.asj.or.jp/geppou/archive_open/2015_108_12/108_822.pdf

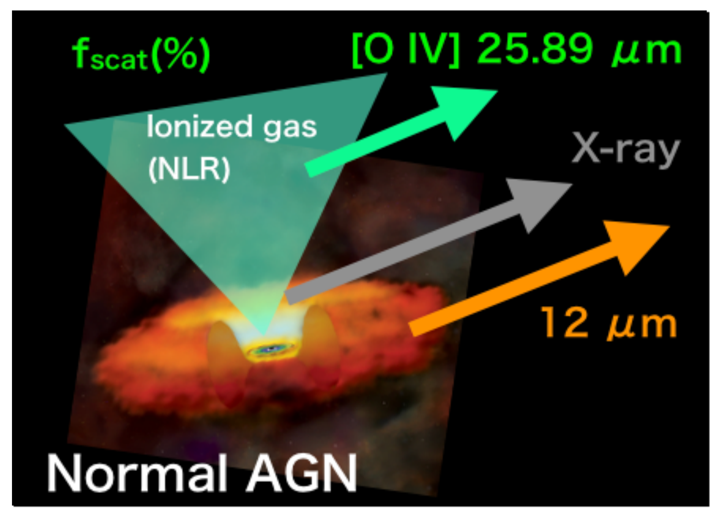
Identification of buried AGNs ② : Mid-IR

- Mid-IR luminosity should be proportional to the bolometric AGN luminosity times the torus covering fraction.



- To make the contamination from the star formation as small as possible, we adopt the **nuclear (subarcsecond scale) 12 μm** luminosity. (Asmus+14, 15)

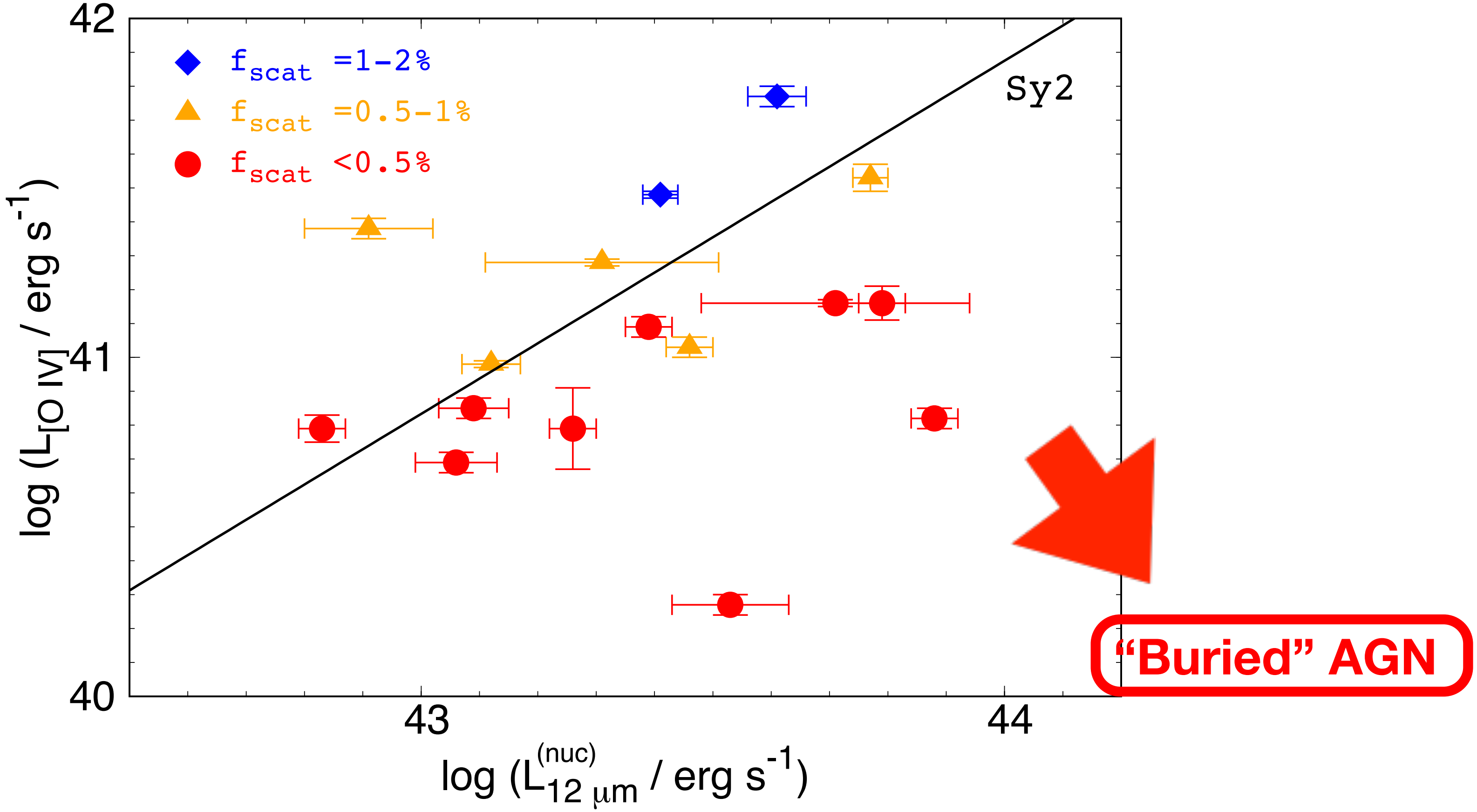
- We propose new diagnostics that use the [O IV] 26 μm (Inami+13) and nuclear 12 μm luminosity ratio for identifying “buried” AGNs!!



$L_{[O\ IV]}/L^{(nuc)}_{12\ \mu m}$ ratio as diagnostics of buried AGNs

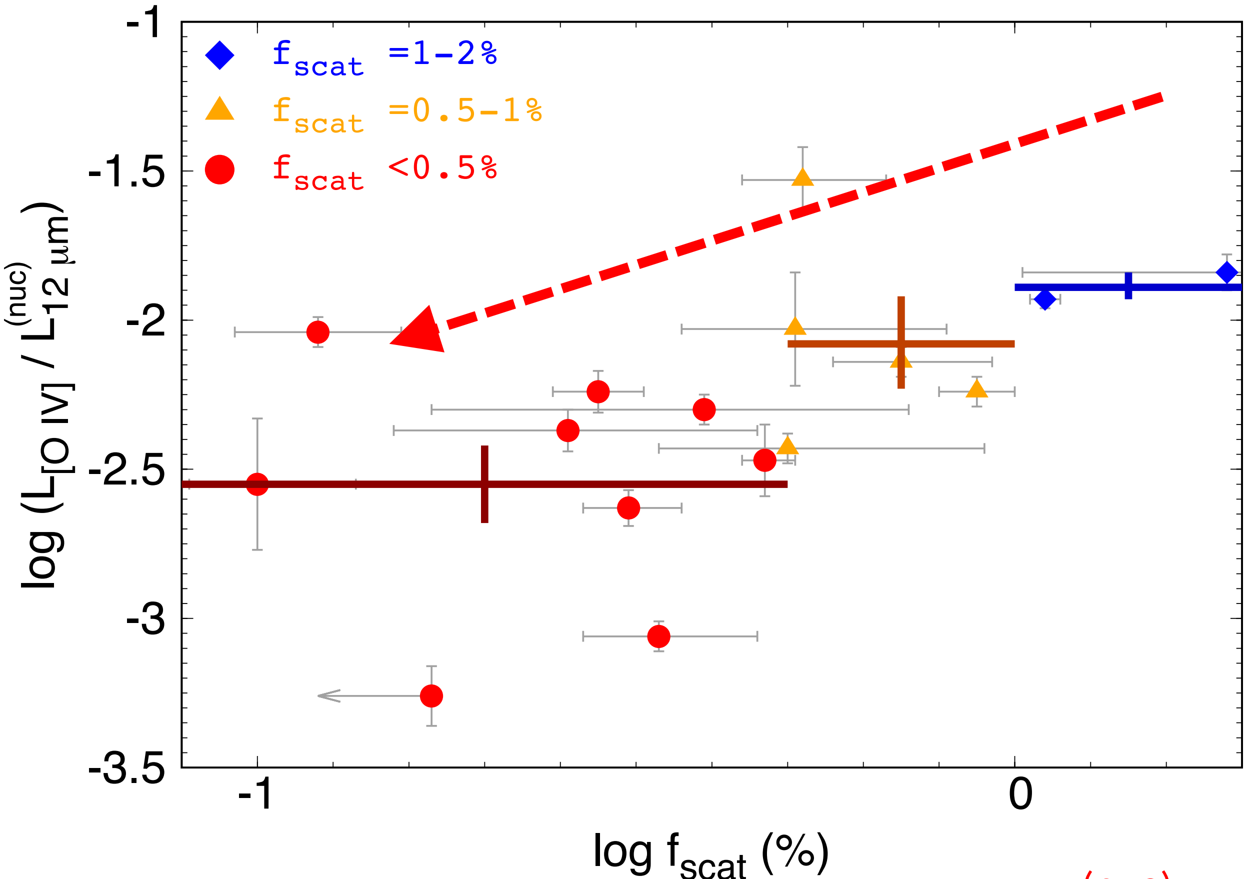
- To justify that the $L_{[O\ IV]}/L^{(nuc)}_{12\ \mu m}$ ratio is a good indicator for the buried AGNs, we first investigate the correlation between **$L_{[O\ IV]}/L^{(nuc)}_{12\ \mu m}$ and f_{scat}.**

- We use **16 Compton-thin AGNs** observed by Suzaku (e.g., Kawamuro+16).



$L_{[O\ IV]}/L^{(nuc)}_{12\ \mu m}$ vs. f_{scat}

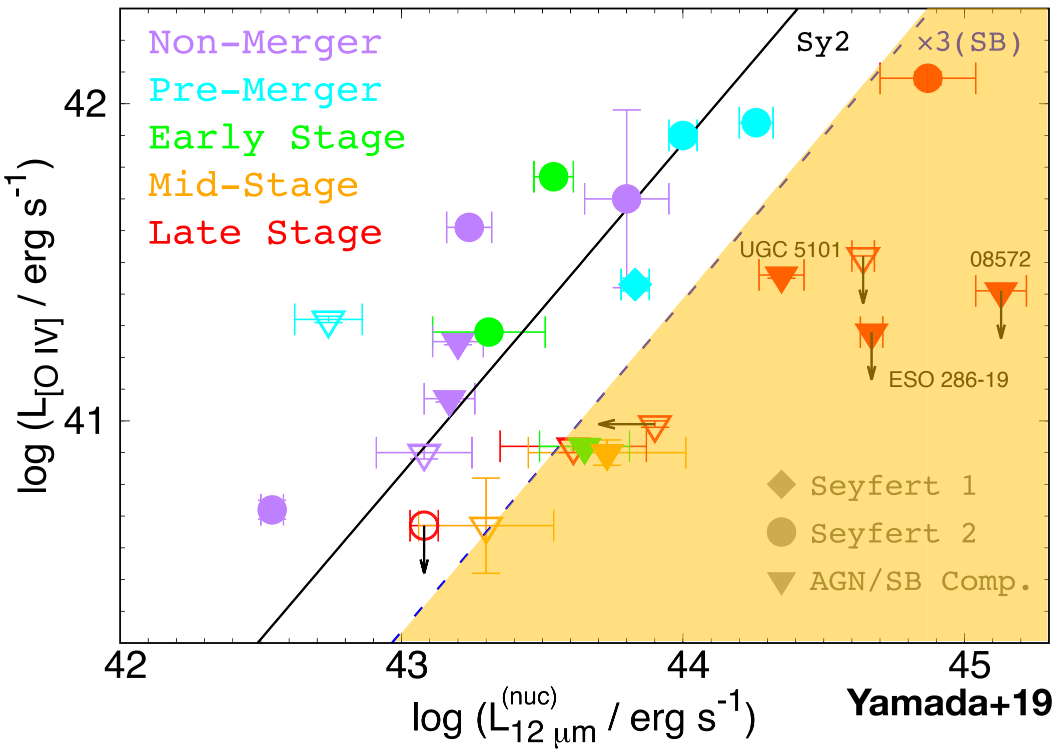
- The $L_{[O\ IV]}/L^{(nuc)}_{12\ \mu m}$ ratio as a function of f_{scat}, together with their average and standard error in three f_{scat} bins.



=> Buried AGNs tend to have lower $L_{[O\ IV]}/L^{(nuc)}_{12\ \mu m}$ ratios.

Application to U/LIRGs

- Next, we apply this $L_{[O\ IV]}/L^{(nuc)}_{12\ \mu m}$ method to **23 local U/LIRGs** hosting AGNs (Armus+09).

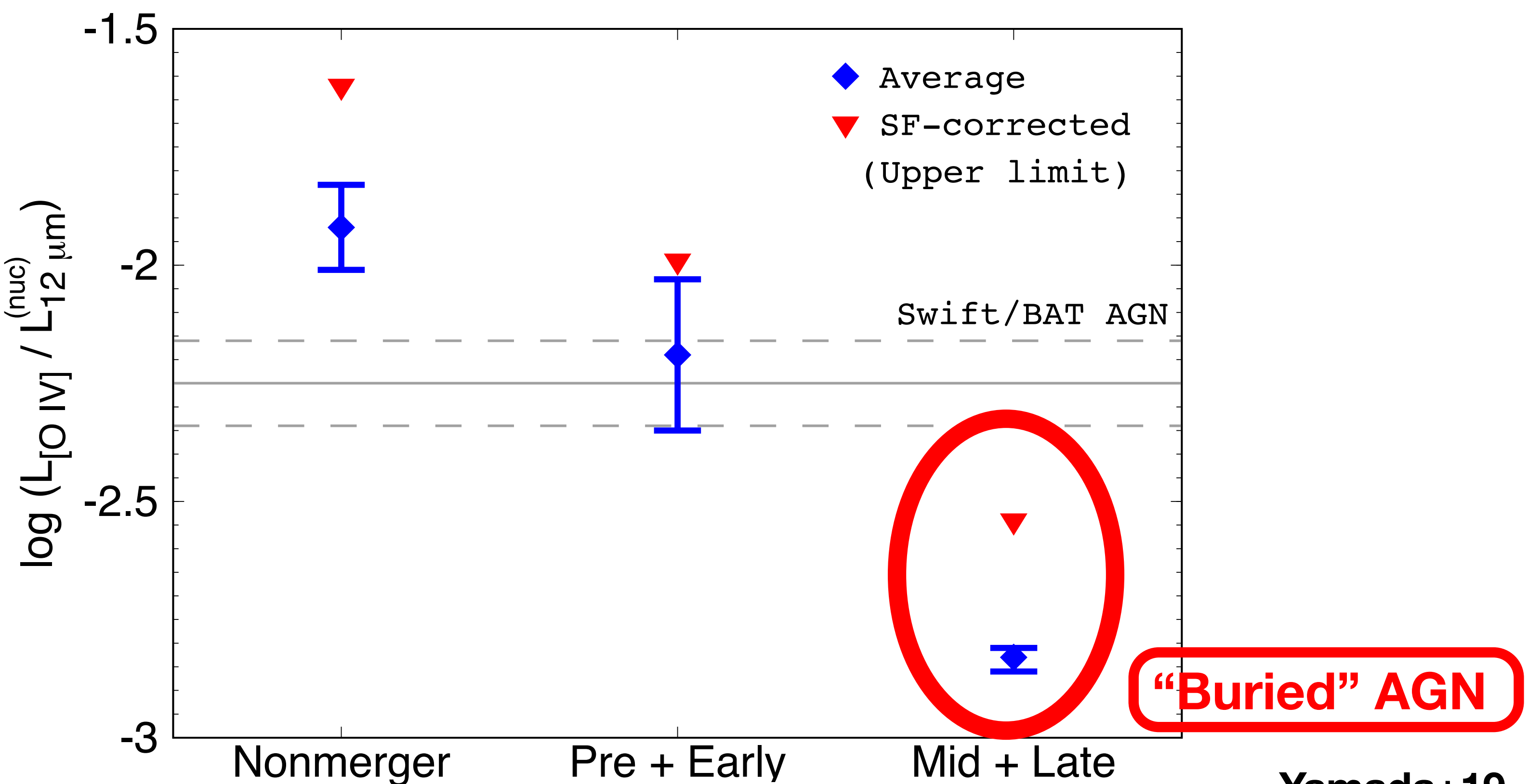


- We only use the AGNs whose contribution to the Mid-IR luminosity greater than 1/3 (filled symbols), and exclude starburst-dominant ones.

- AGNs in most of mid- to late-stage mergers are buried, while those in earlier stage ones and non-mergers are not.

Buried AGNs fraction with merger stage

- $L_{[O\ IV]}/L^{(nuc)}_{12\ \mu m}$ ratios tend to decrease with merger stage.
  => The fraction of buried AGNs in U/LIRGs increases as the galaxy-galaxy interaction becomes more significant.



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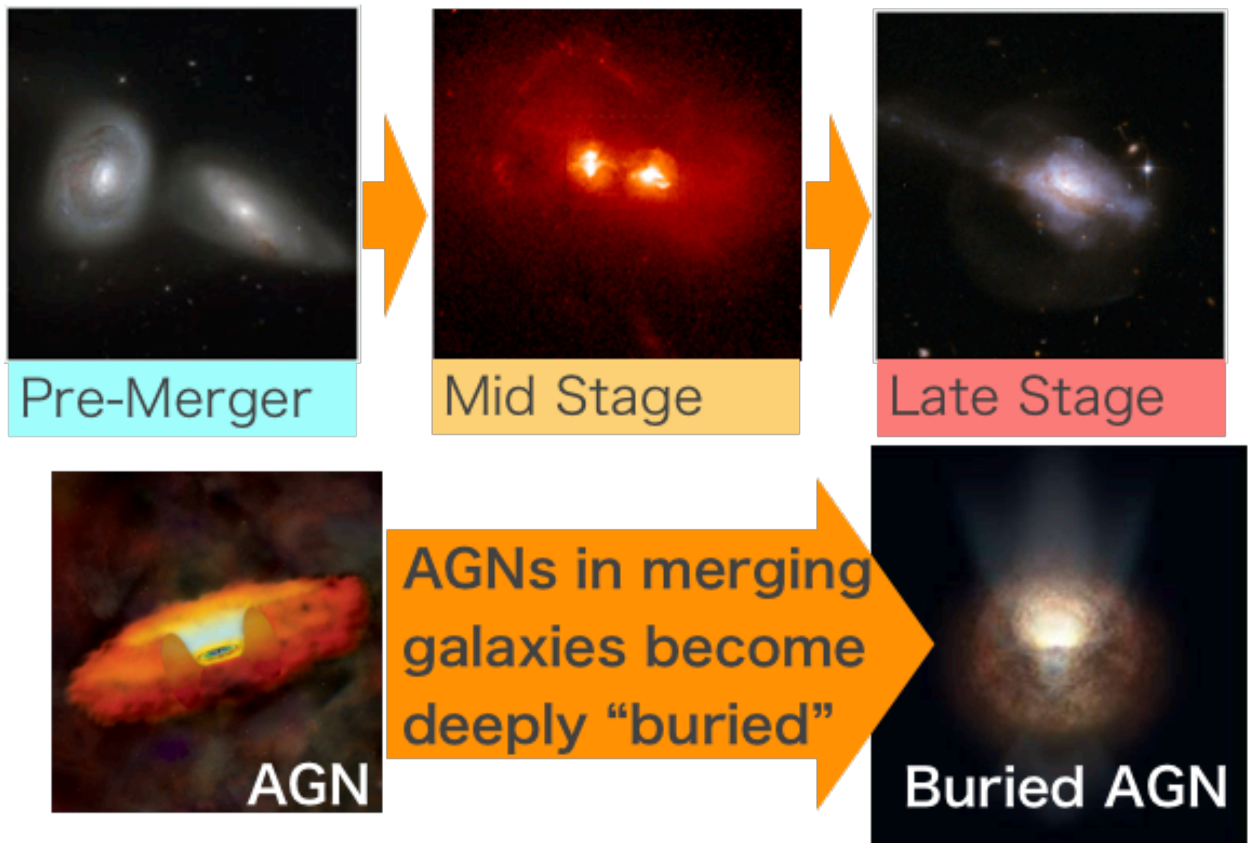

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To confirm such an evolutional scenario, it is important to investigate the torus properties and f_{scat}(%) by using the broadband X-ray spectral analysis.

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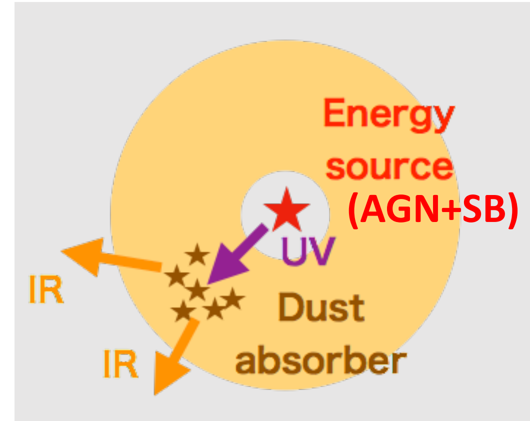
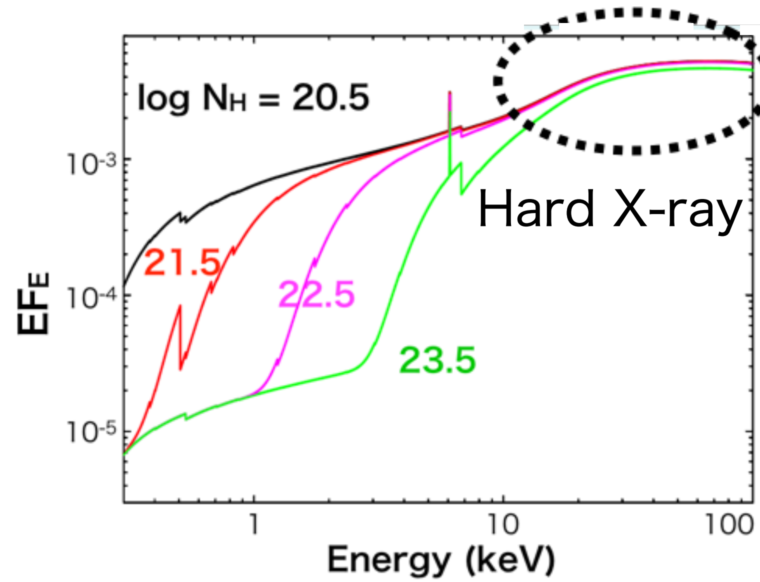
X-ray observations of U/LIRGs

- U/LIRG
  AGNs (and SB) are hidden by gas and dust.

- Hard X-rays (> 10 keV) are useful due to high penetrating power against obscuration.
  => hydrogen column density (N_H), torus structure, and f_{scat}

- NuSTAR (3-79 keV) observations revealed the properties of obscured AGNs (e.g., Ricci+17)



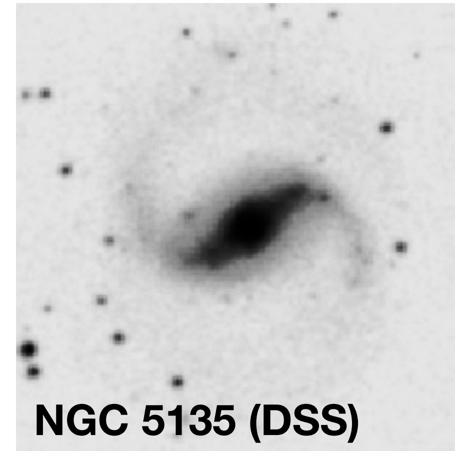


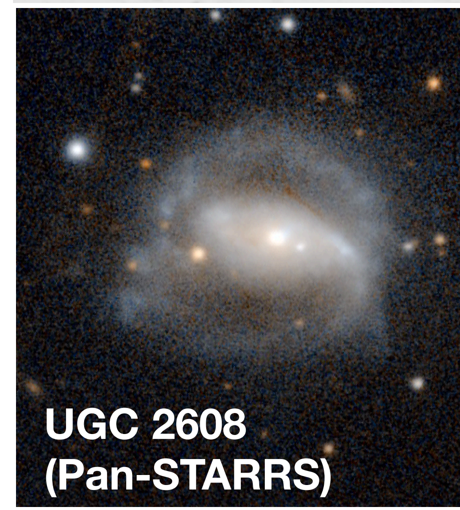
X-ray observations of Nonmerger LIRGs

- Are the buried AGNs triggered by mergers?
  => "Nonmerger" LIRGs are the best targets.
  (NGC 5135, UGC 2608)

- We analyze broadband (0.4-70 keV) X-ray spectra using the data from NuSTAR, Chandra, XMM-Newton, and Suzaku.

- To investigate the torus properties, we adopt the X-ray clumpy torus model (Tanimoto+19).

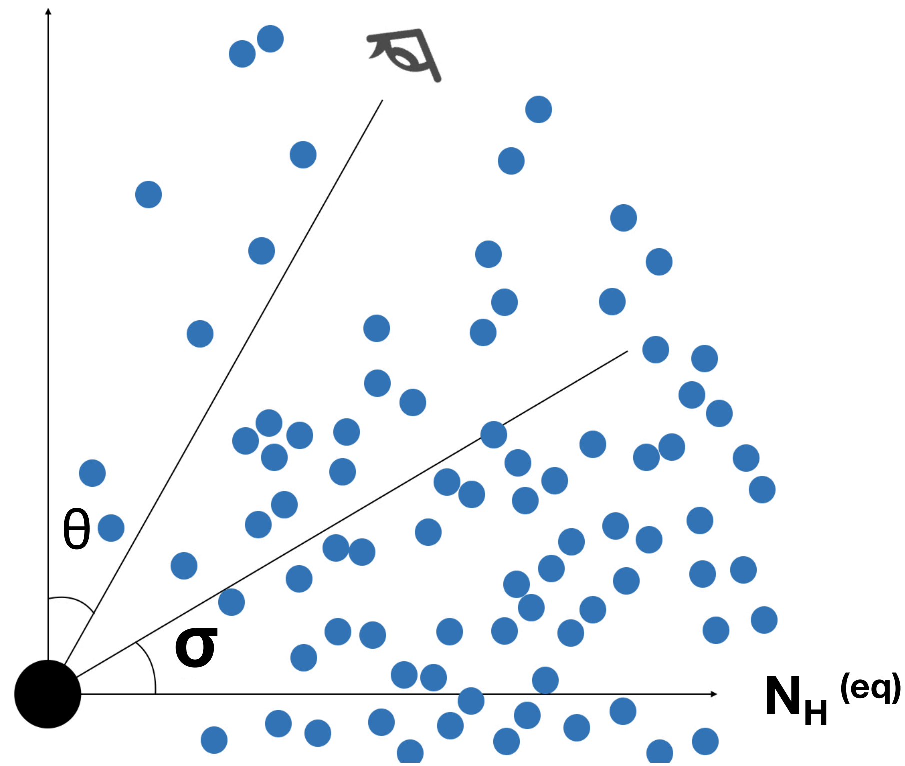




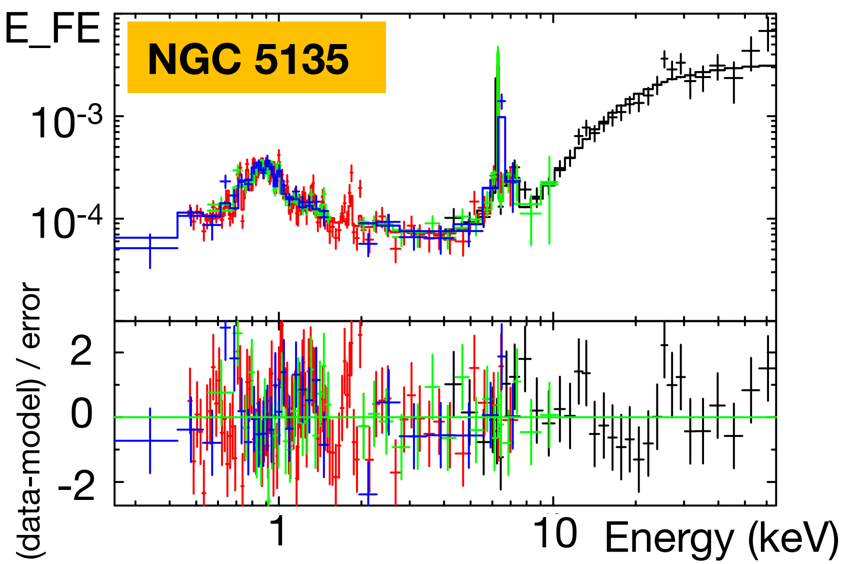
X-ray clumpy torus model : XCLUMPY

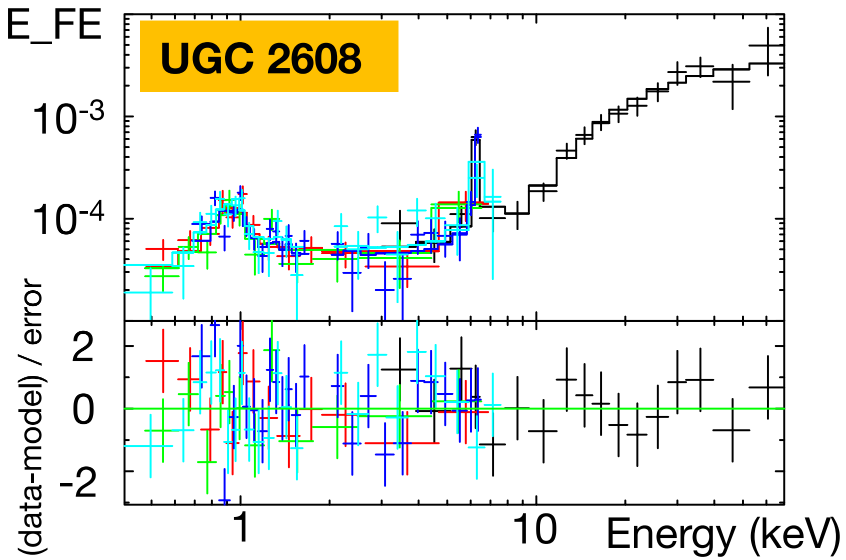
- **XCLUMPY model (Tanimoto+19)**
  - geometry : the same **clump distribution** as that of the CLUMPY model in the infrared band (Nenkova+08).
  - Radial distribution : Power law

- Free Parameter
  - column density : $\boldsymbol{N_H}$ **[cm^{-2}]**
  - torus angular width : $\boldsymbol{\sigma}$ **[°]**
  - inclination : θ (=80°; fixed)



Broadband X-ray spectral analysis





	NGC 5135	UGC 2608
Column density (N_H)	～ 5 x 10^24 [cm-2]	～ 5 x 10^24 [cm-2]
Torus angular width (σ)	< 19 [degree]	< 34 [degree]
Scattering fraction (f_scat)	0.9—3.7 [%]	0.5—2.6 [%]

- We find that both of AGNs in these two Nonmerger LIRGs are not deeply “buried” ($\sigma \lesssim 30$, $f_{scat} > 0.5\%$).

  -> consistent with the results from the $L_{[O\ IV]}/L_{12\mu m}$ diagnostics.

Summary

- In order to identify buried AGNs, we propose new diagnostics that use the ratio between [O IV] 26 μm and nuclear 12 μm luminosities.

- By applying the criteria for 23 local U/LIRGs, we find that the fraction of buried AGNs in U/LIRGs increase with merging stage. (Yamada+19, ApJ)

- Also, the broadband X-ray spectral analysis of two AGNs in nonmerger LIRGs indicate that they are not deeply buried.