ALMA molecular line observations of ULIRGs to scrutinize deeply buried AGNs

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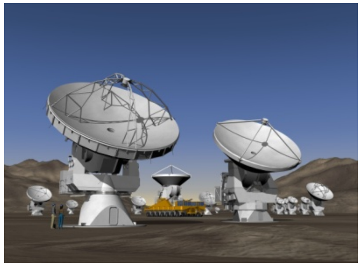
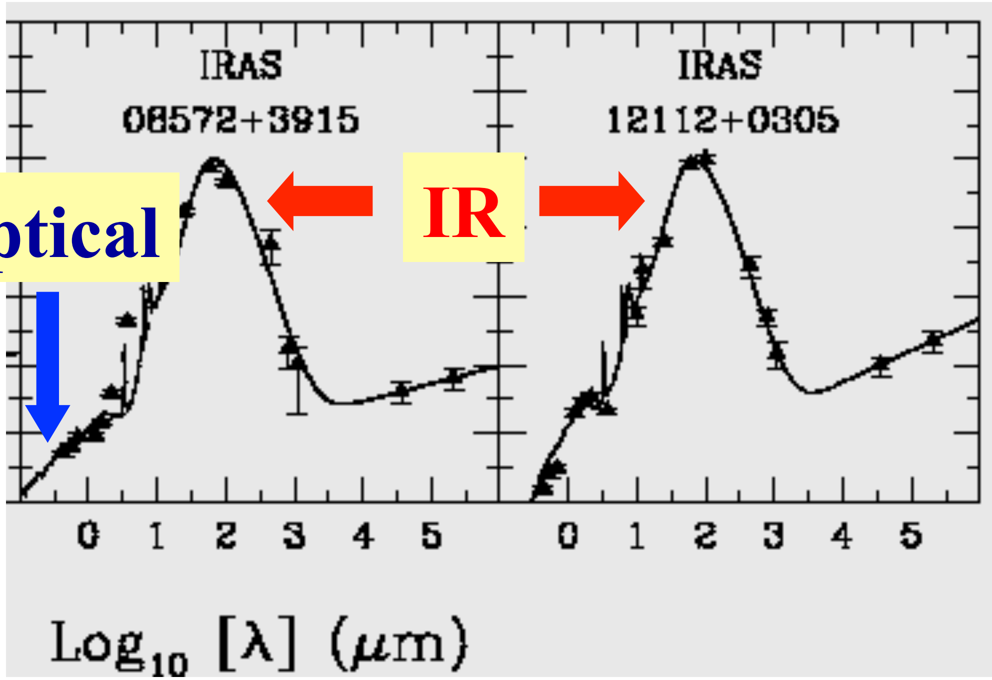
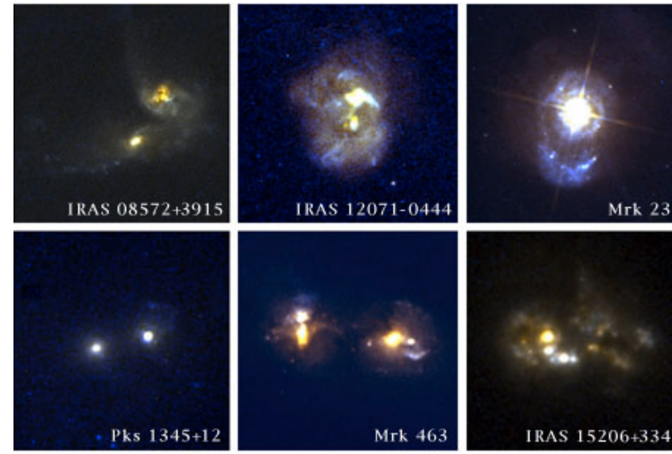
ALMA



ULIRGs

$L_{IR} > 10^{12}$ Lsun



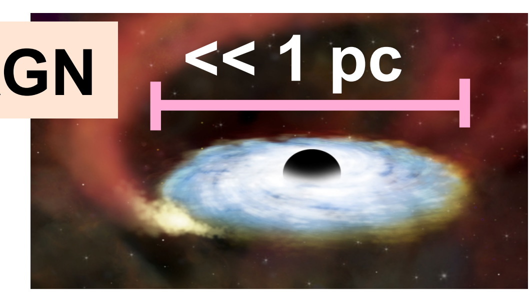


J.Surace

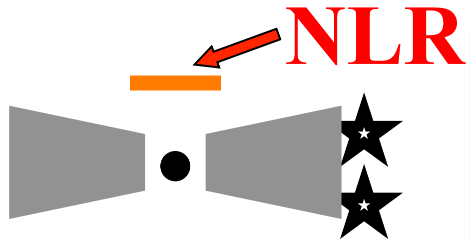
Energy sources are hidden behind dust

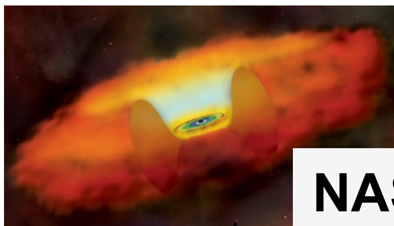
Starburst (SB)

AGN



AGNs in ULIRGs are buried





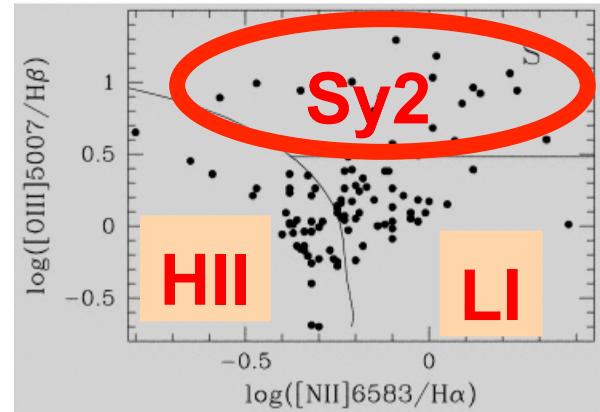
NASA

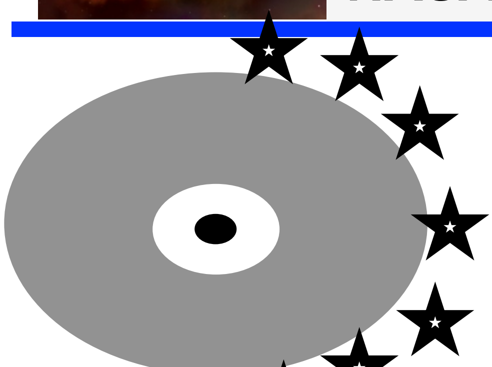
AGNs surrounded by torus

Sy2

Optically identifiable

Veilleux+99

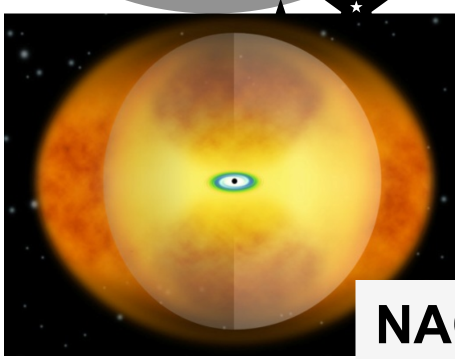




Large amounts of gas and dust concentrated at ULIRG's nuclei

Hopkins+06

Buried AGNs are elusive



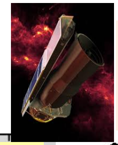
NAOJ

>70% ULIRG = non-Sy

Veilleux+99;Yuan+10

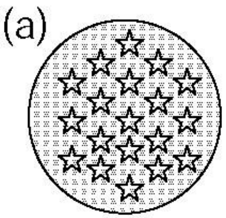
Buried AGN search in ULIRGs

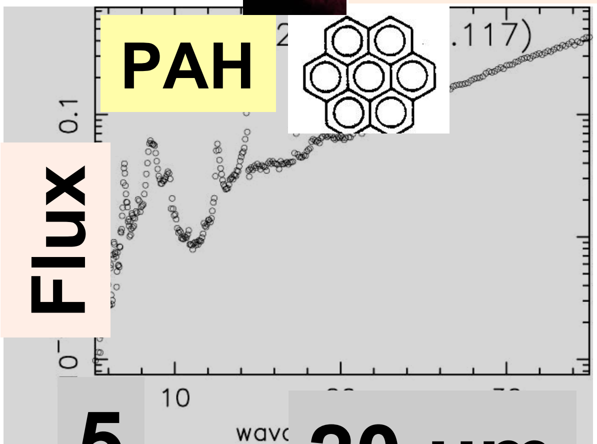
IR (3-35 μm)



Spitzer

Starburst





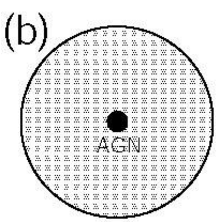
PAH

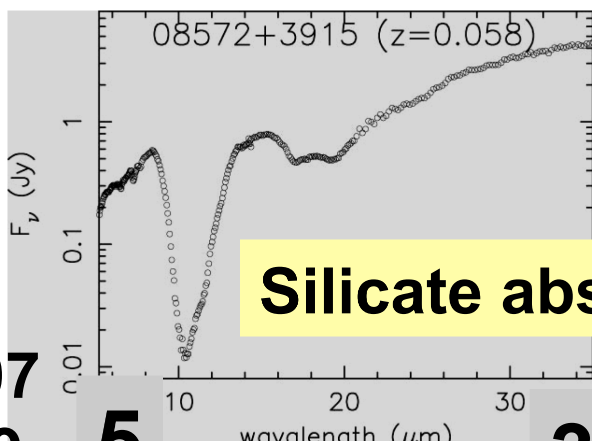
Flux

5

20 μm

Buried AGN





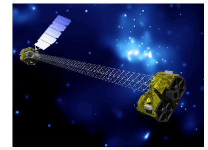
Silicate abs.

5

35

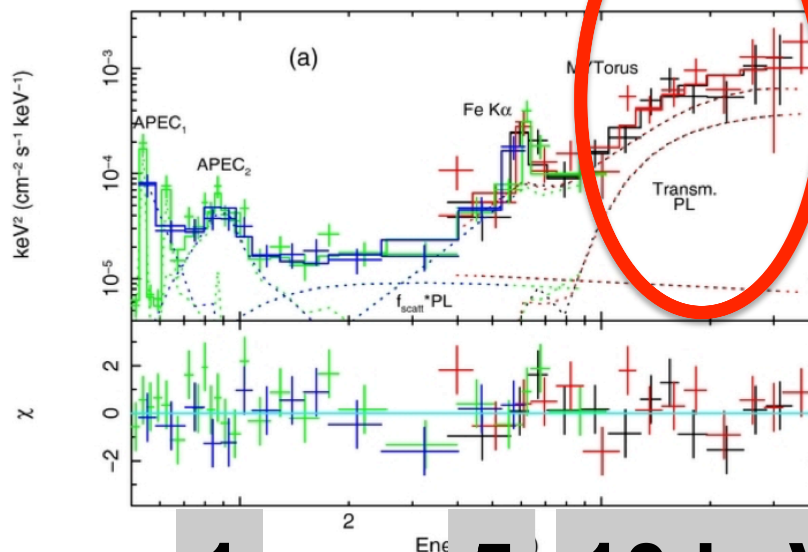
Imanishi+07
Veilleux+09

X-ray (>10 keV)



NuSTAR

>10 keV excess



1

5

10 keV

Gandhi+14 ApJ 792 117

Why (sub)millimeter ?

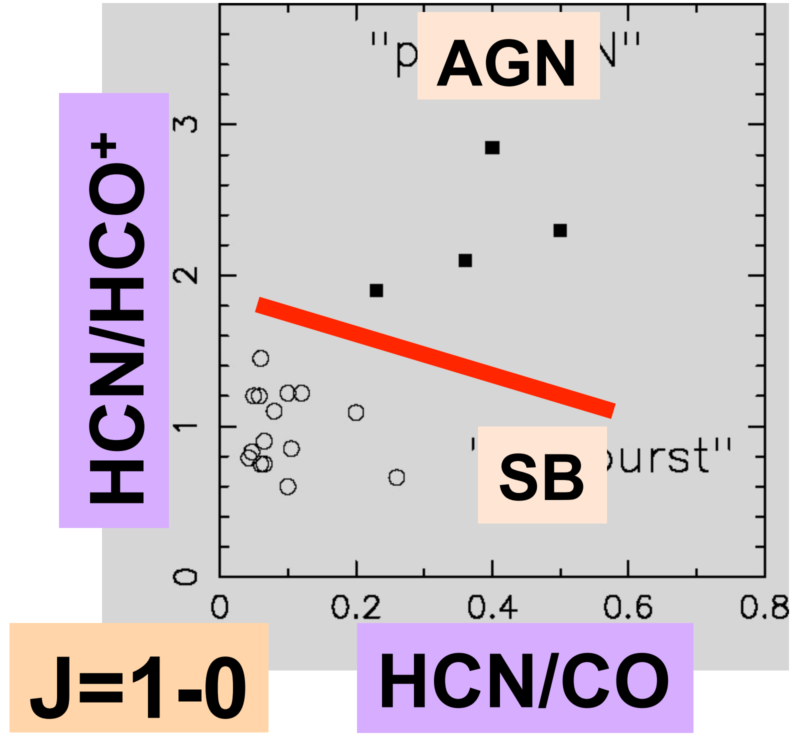
$$N_H/\text{tau}(\lambda) = 1.2 \times 10^{25} (\lambda/400\ \mu m)^2$$

(Hildebrand 83)

Tau (20 um)	Tau(X-ray @ 10 keV)	Tau (850 um)
1		0.003
	1	0.03

(Sub)mm buried AGN search in ULIRGs

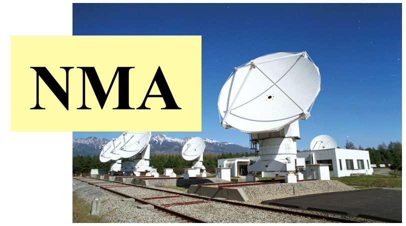
1. **Molecular line flux ratio**

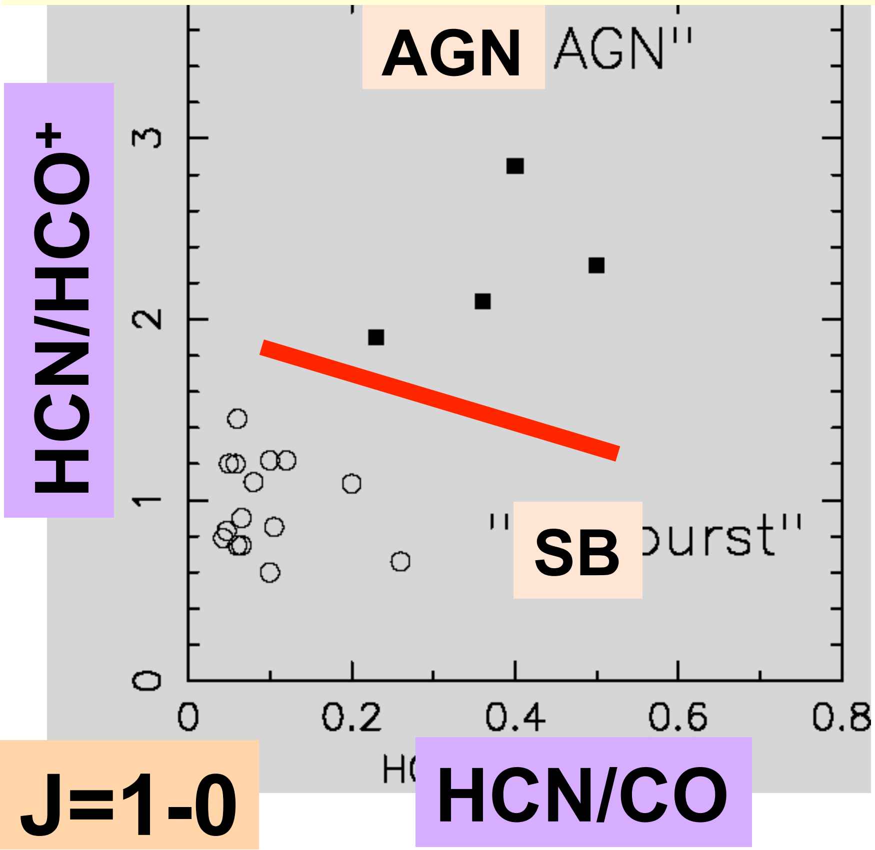


Kohno astro-ph/0508420

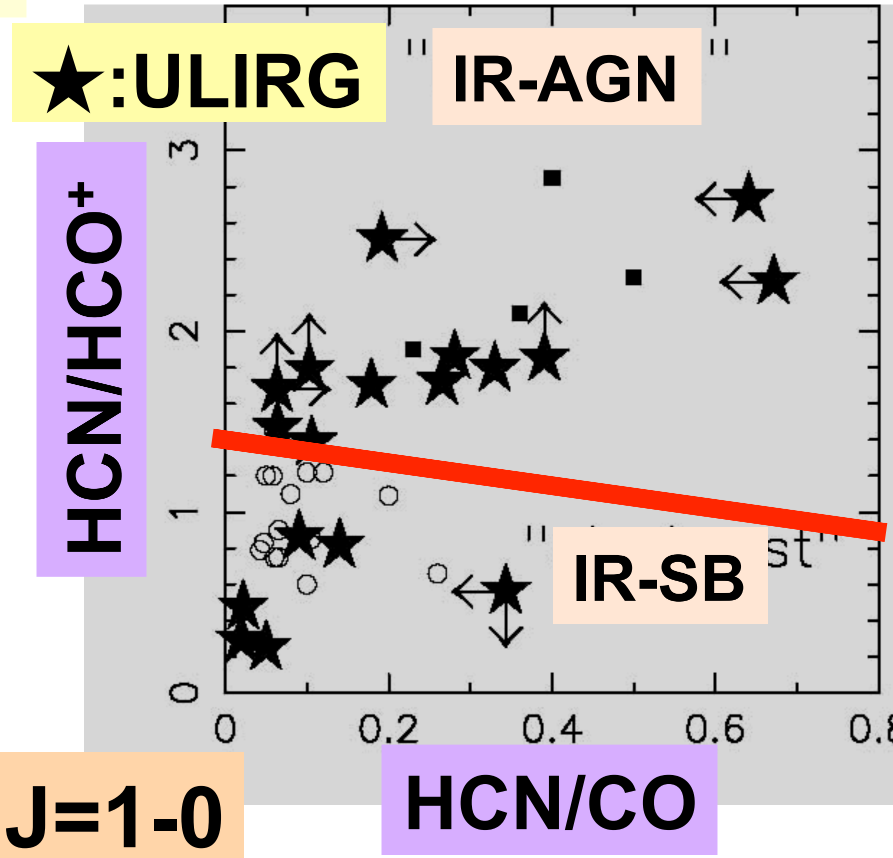
2. **Vibrationally-excited emission line**

Molecular gas at mm (small dust extinction)





J=1-0



J=1-0

Kohno astro-ph/0508420

Imanishi+09 AJ 137 3581
See Izumi+16 for latest result

z<0.06 only

contamination by host gas

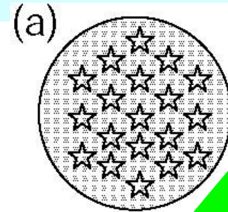
ALMA
J=3-2,4-3

- **Applicable to higher-z**
- **Less contamination by host gas**

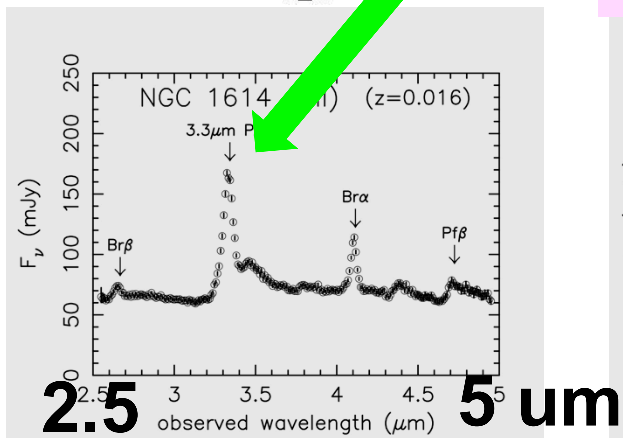
IR spectroscopic classification (AKARI satellite)

Imanishi+08 PASJ 60 S489
Imanishi+10 ApJ 721 1233

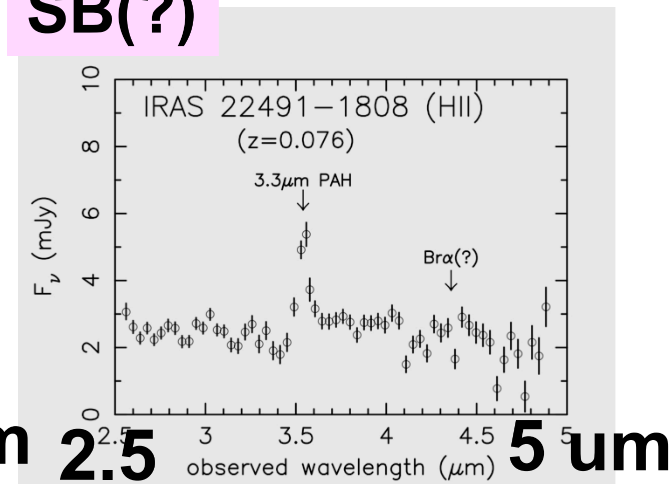
SB



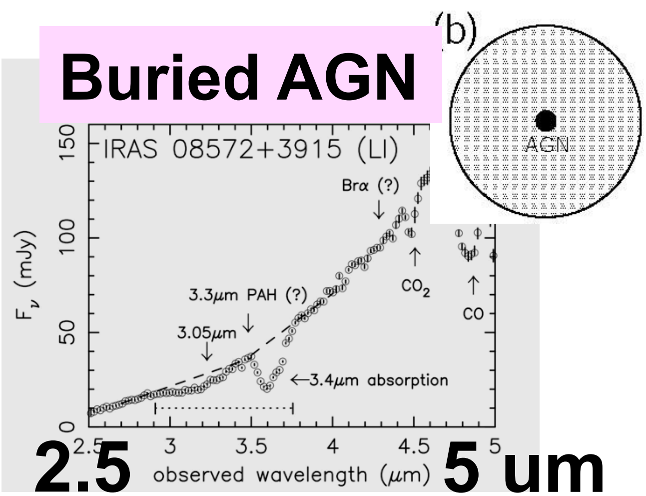
PAH



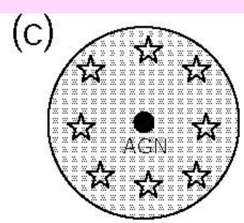
SB(?)

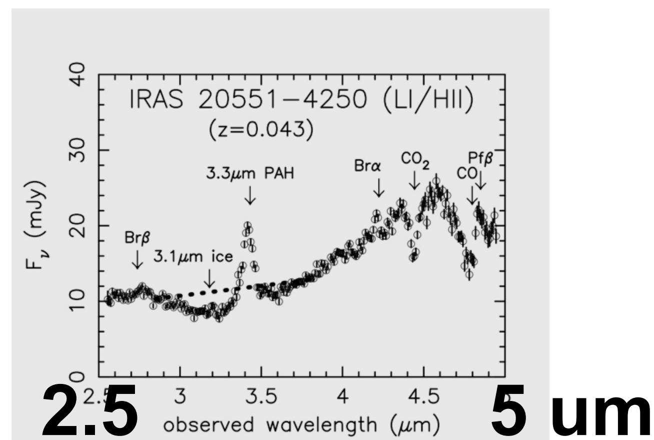


Buried AGN

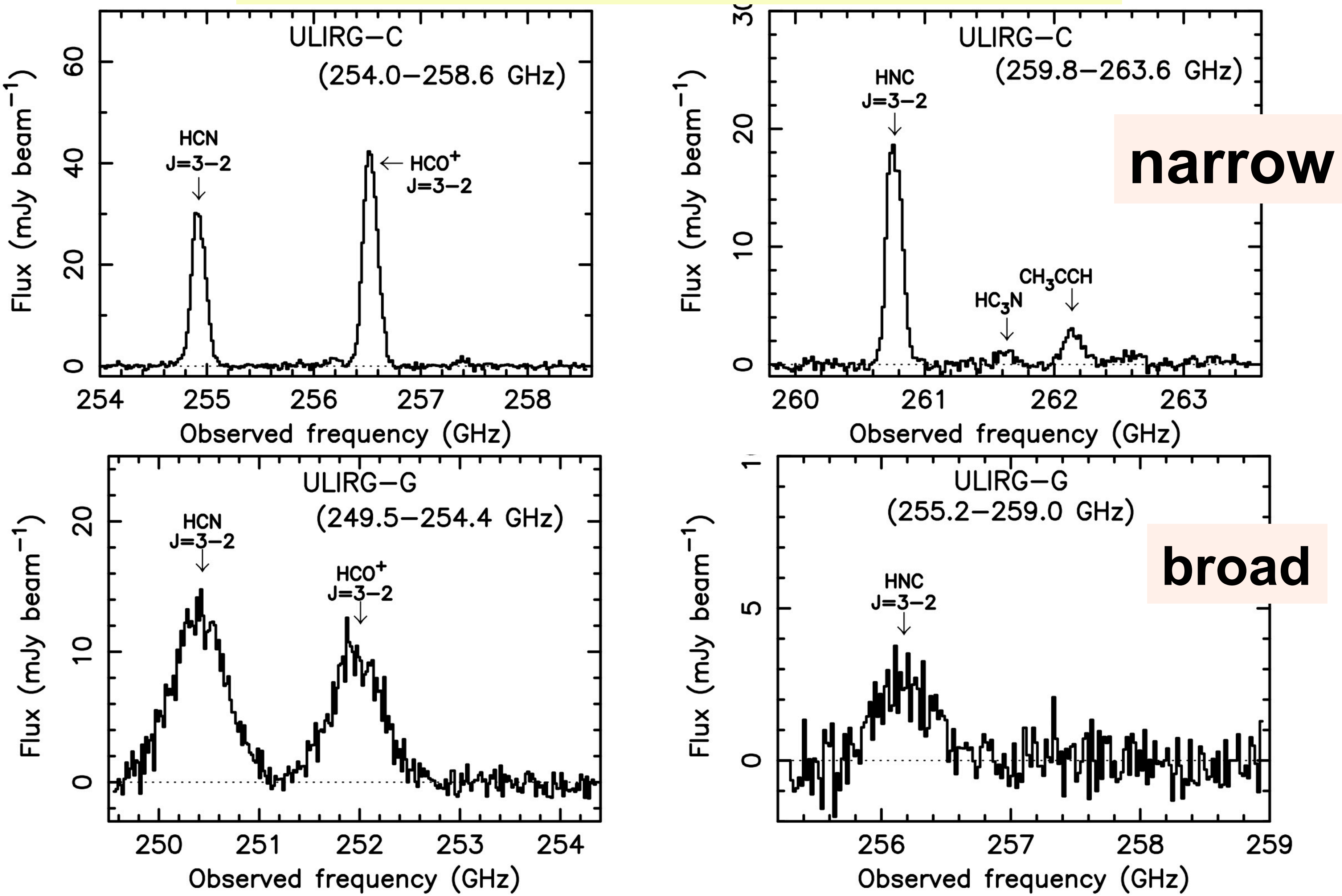


B-AGN+SB



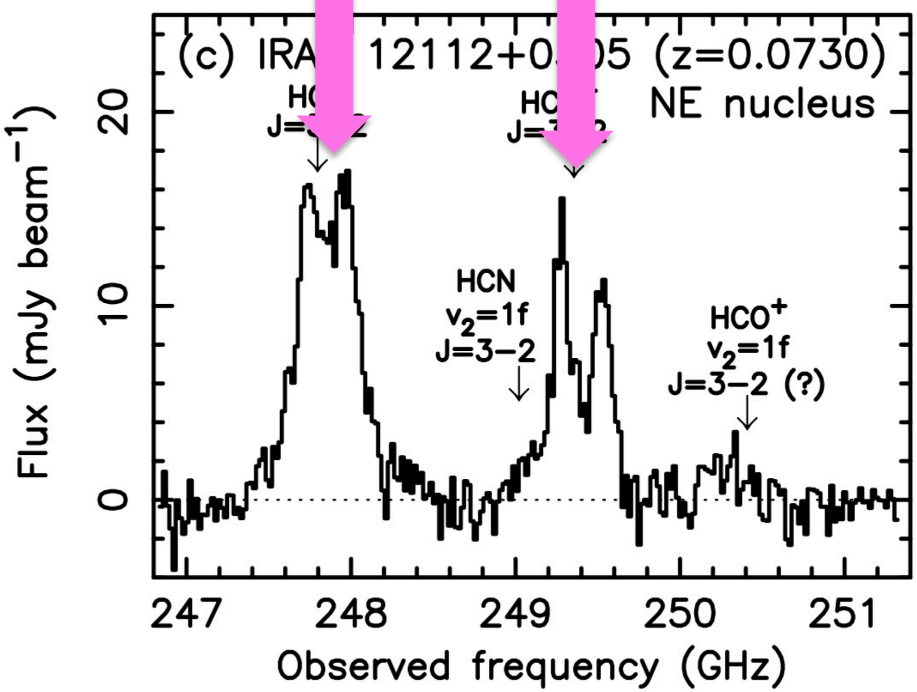


ALMA example spectra (I)



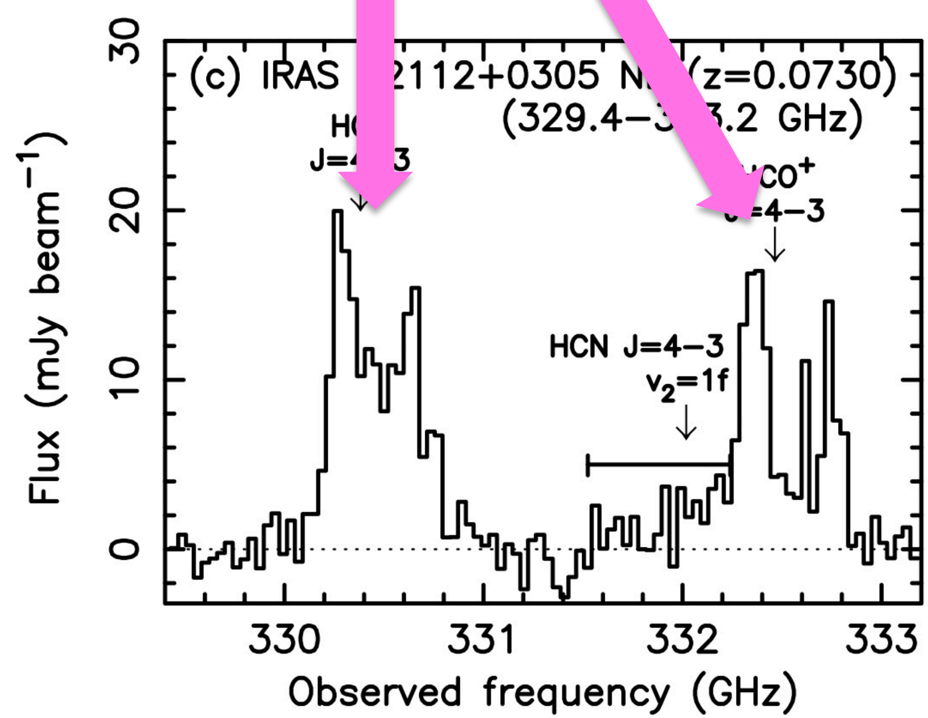
ALMA example spectra (II)

HCN, HCO+ J=3-2



Imanishi+16b

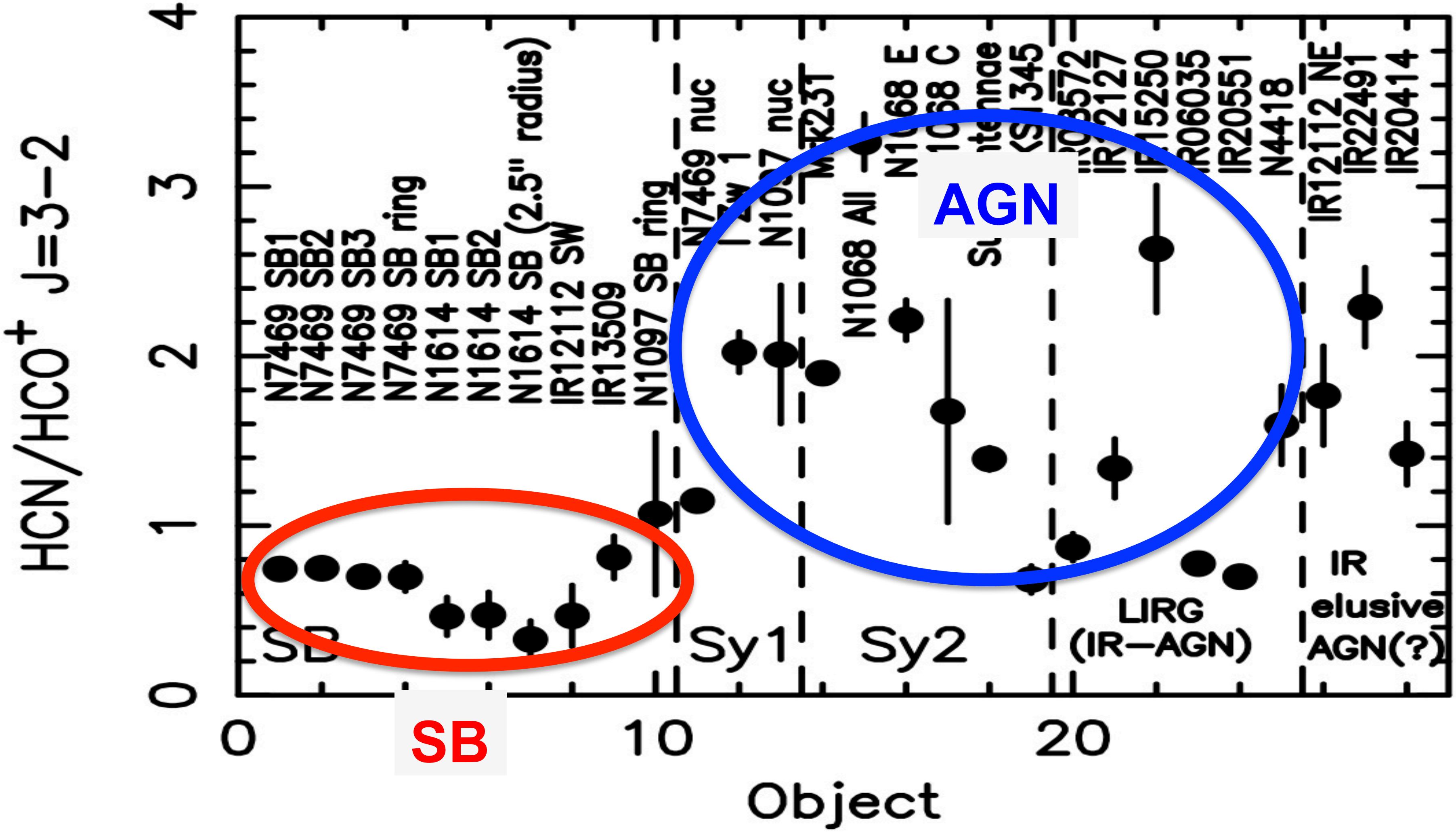
HCN, HCO+ J=4-3



Imanishi+17b (in prep)

Double-peaked → Rotating disk ?

HCN-to-HCO$^+$ flux ratios at J=3-2: AGN > SB

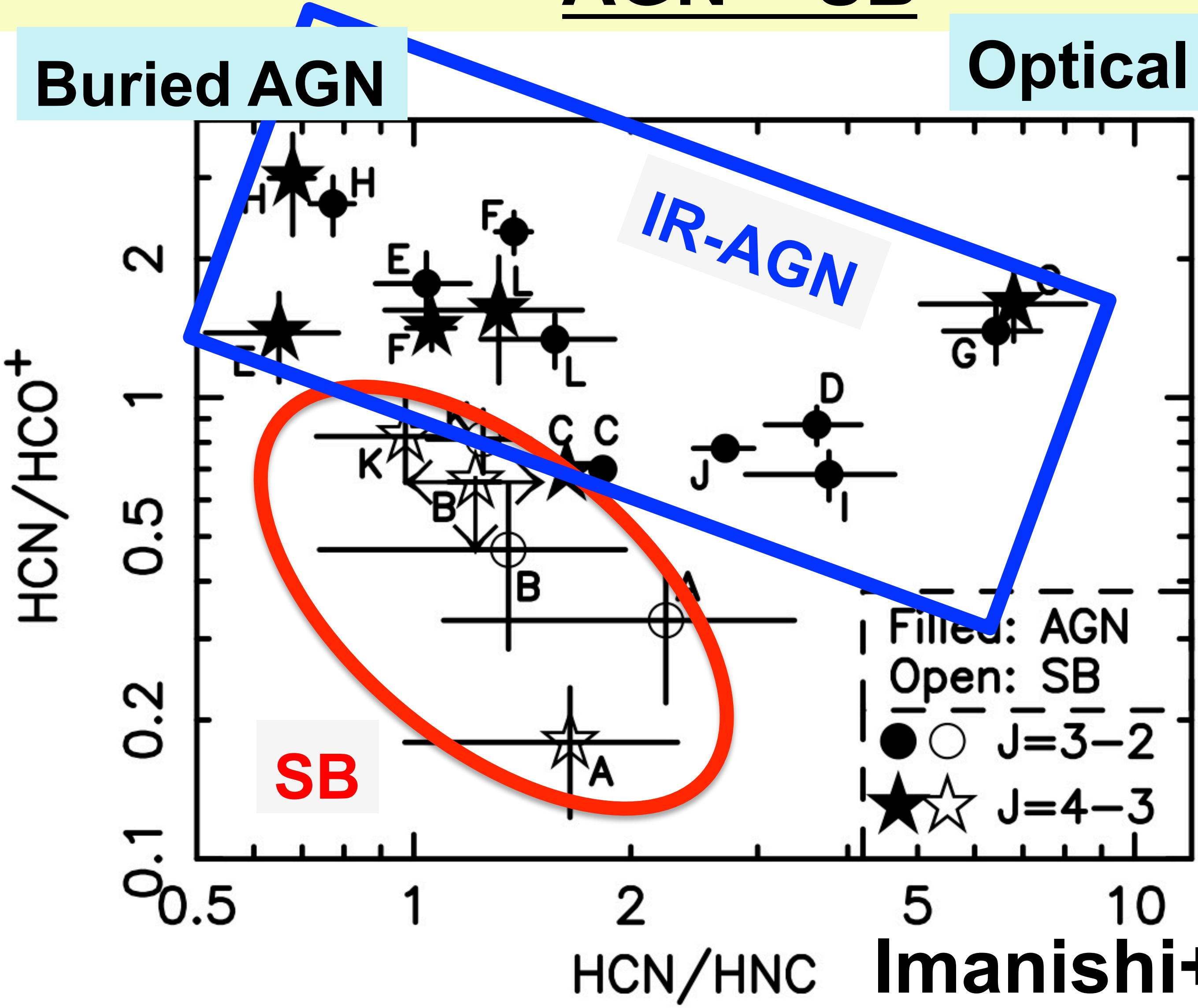


Imanishi+16c AJ 152 218 (modified)

HCN-to-HCO+ flux ratios at J=3-2 and J=4-3 : AGN > SB

Buried AGN

Optical Sy

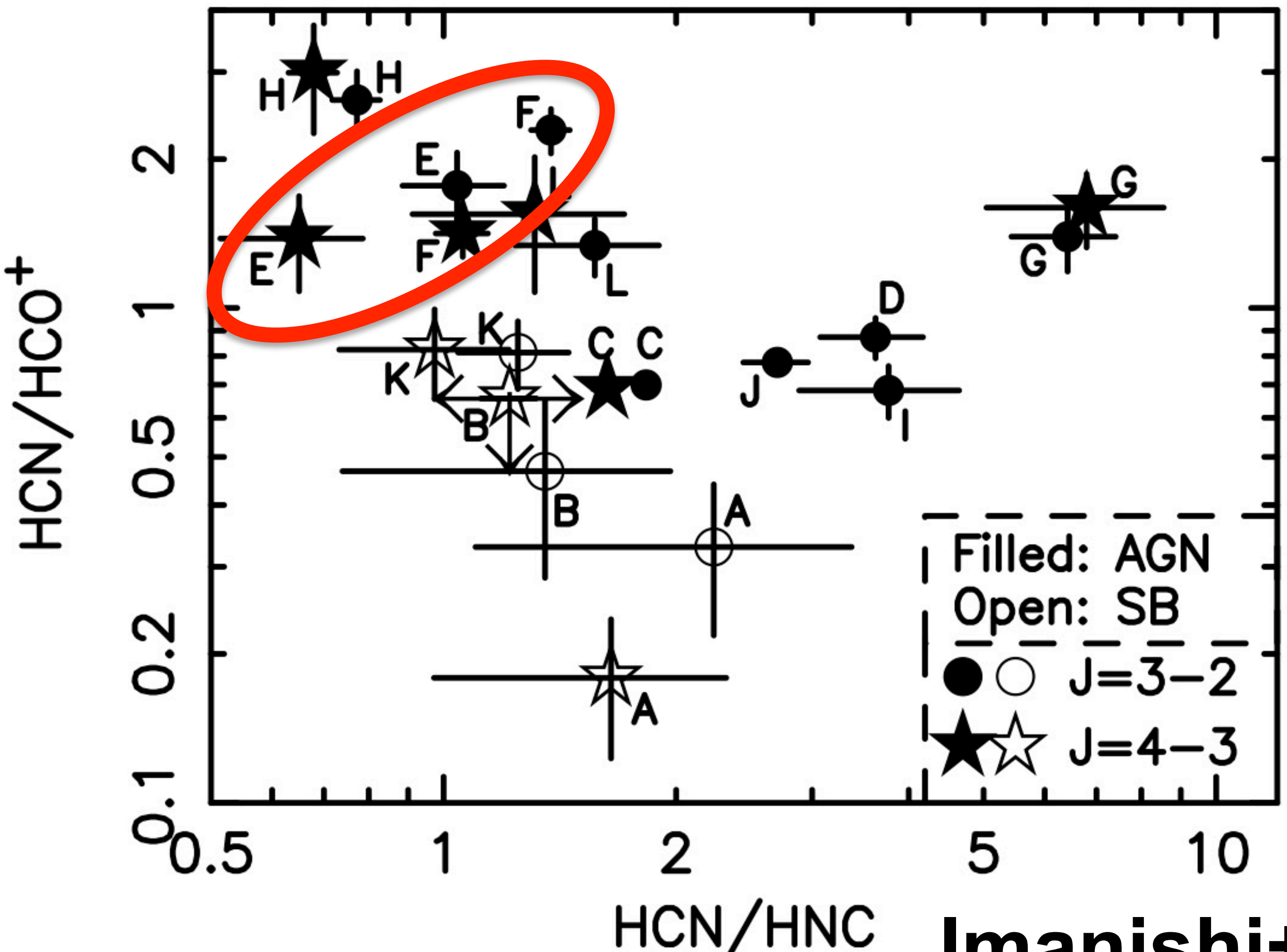


C,D,G,H,I,J: IR-AGN

A, B, K: SB

Imanishi+17b (in prep)

Some IR non-AGN show high HCN/HCO^+ flux ratios



C,D,G,H,I,J: IR-AGN

A,B,K: SB

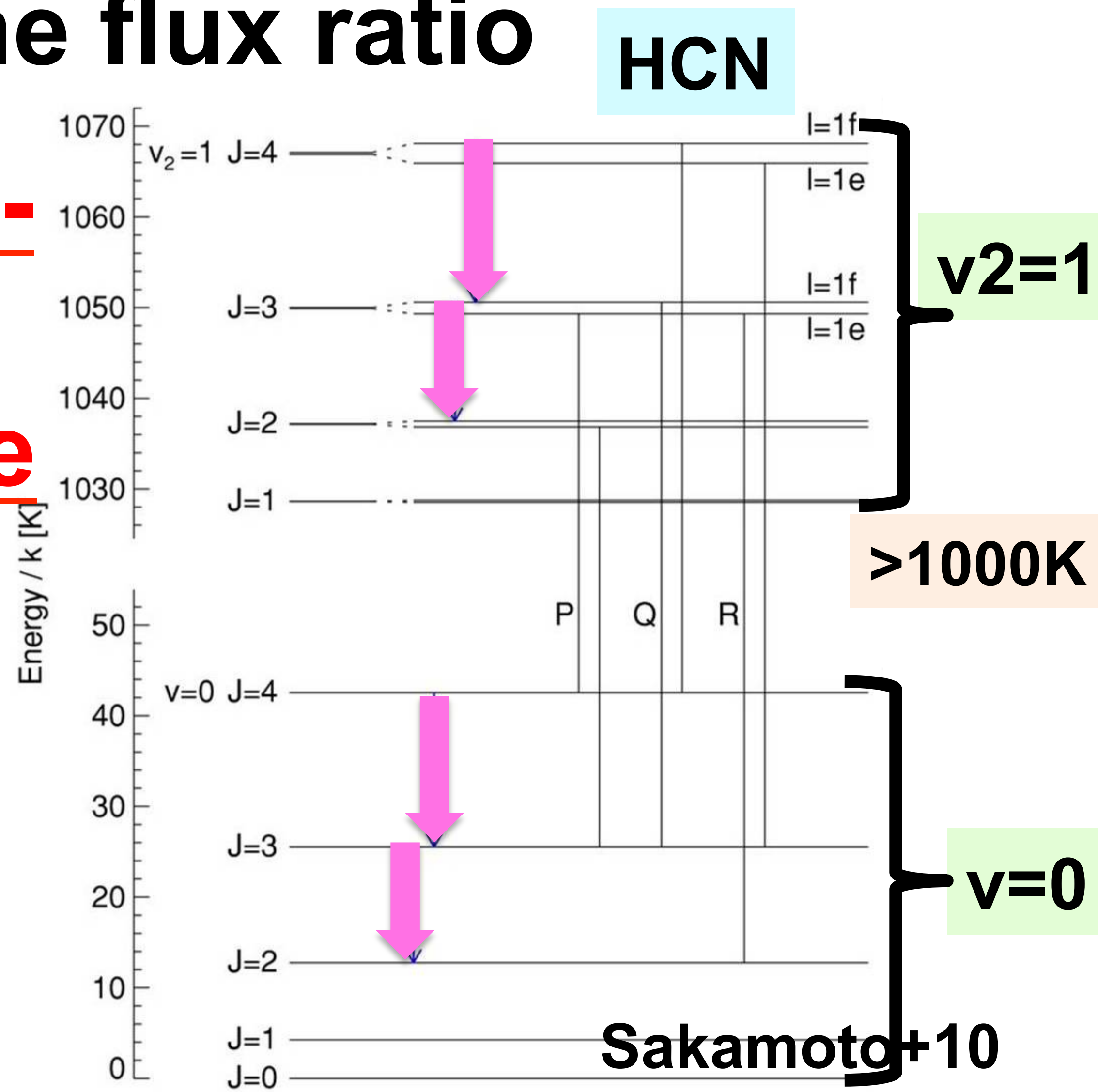
E,F: ULIRG (IR no-AGN)

Imanishi+17b (in prep)

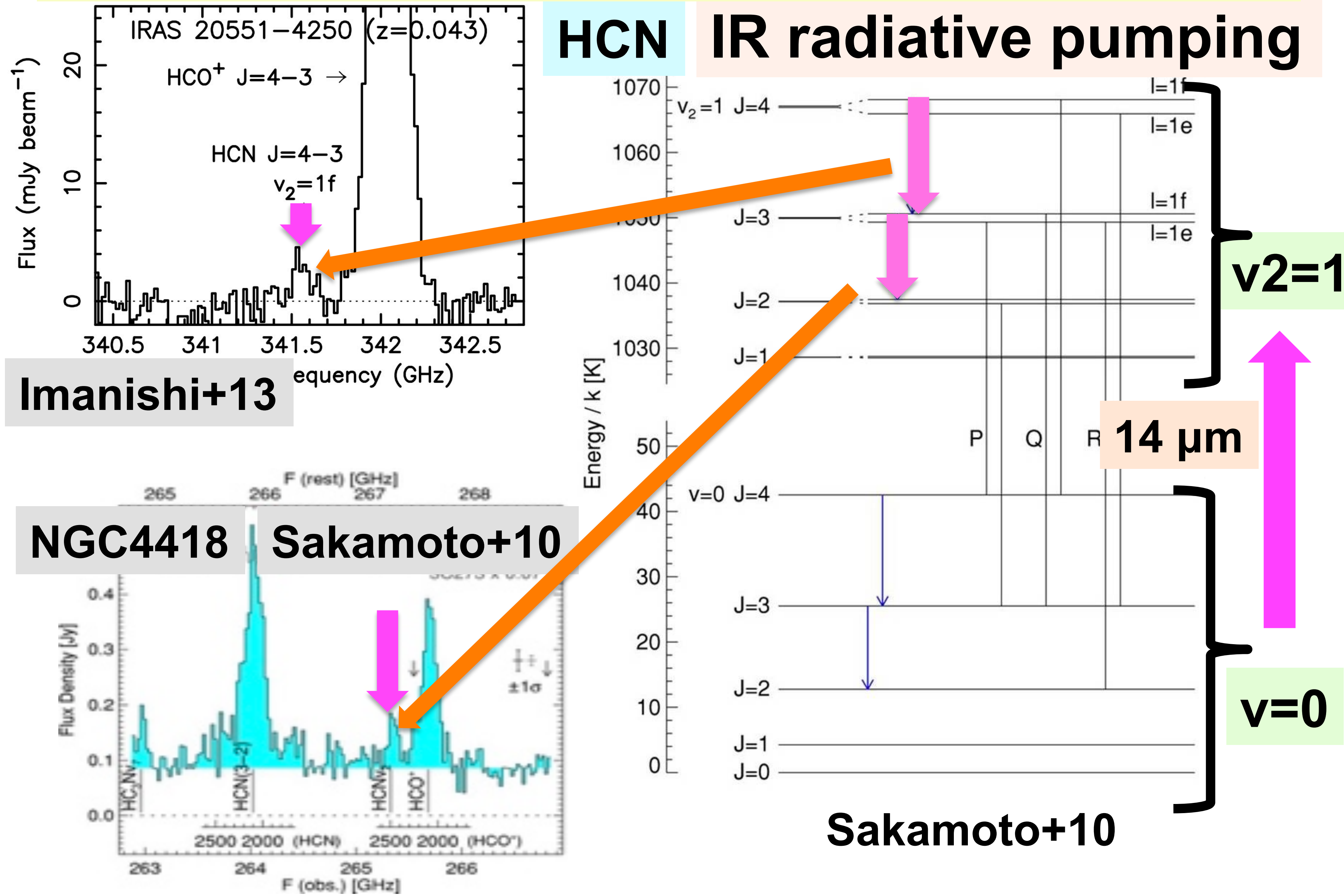
(Sub)mm buried AGN search in ULIRGs

1. Molecular line flux ratio

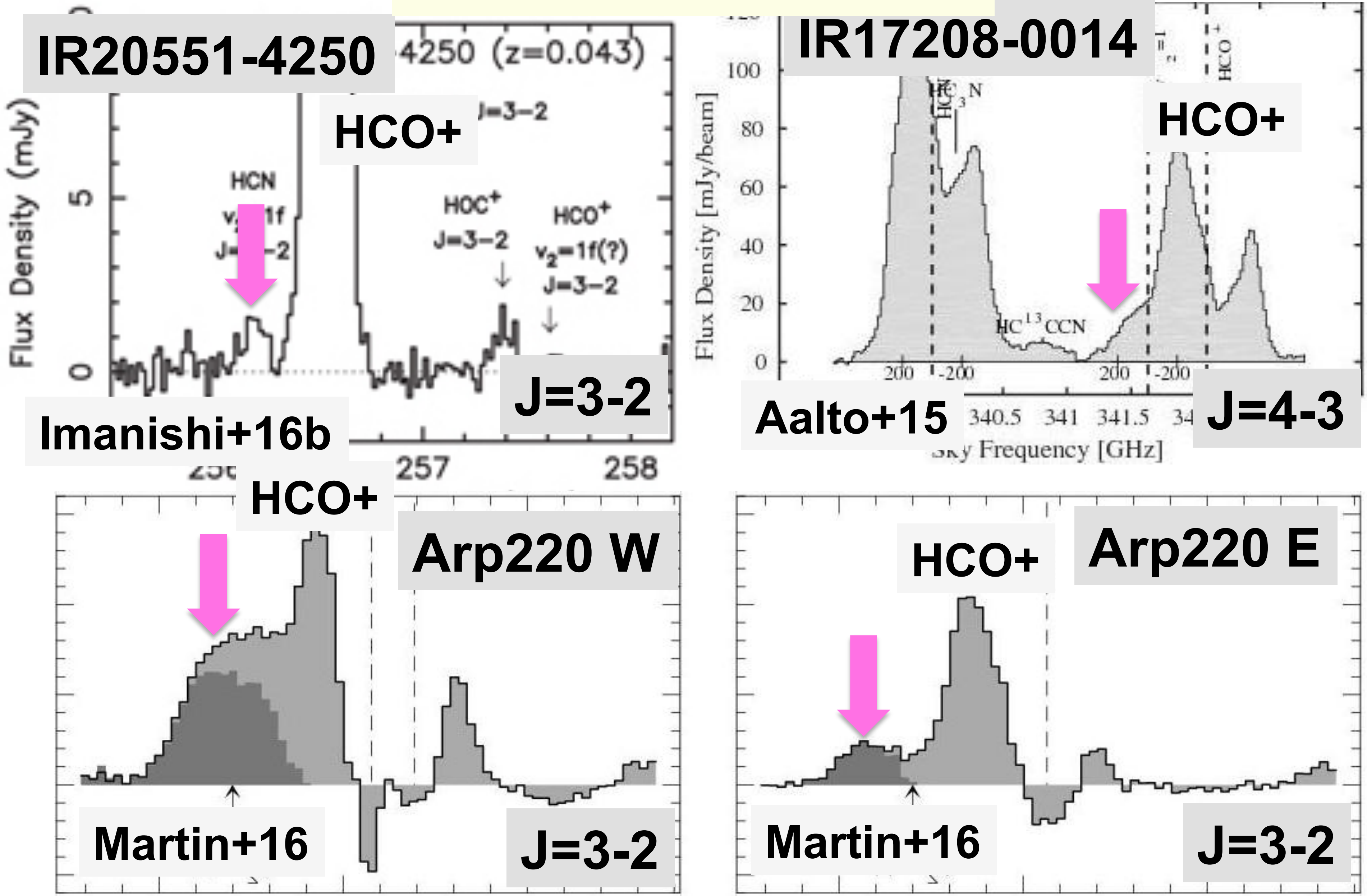
2. Vibrationally-excited emission line



Vibrationally-excited HCN lines (HCN-VIB)



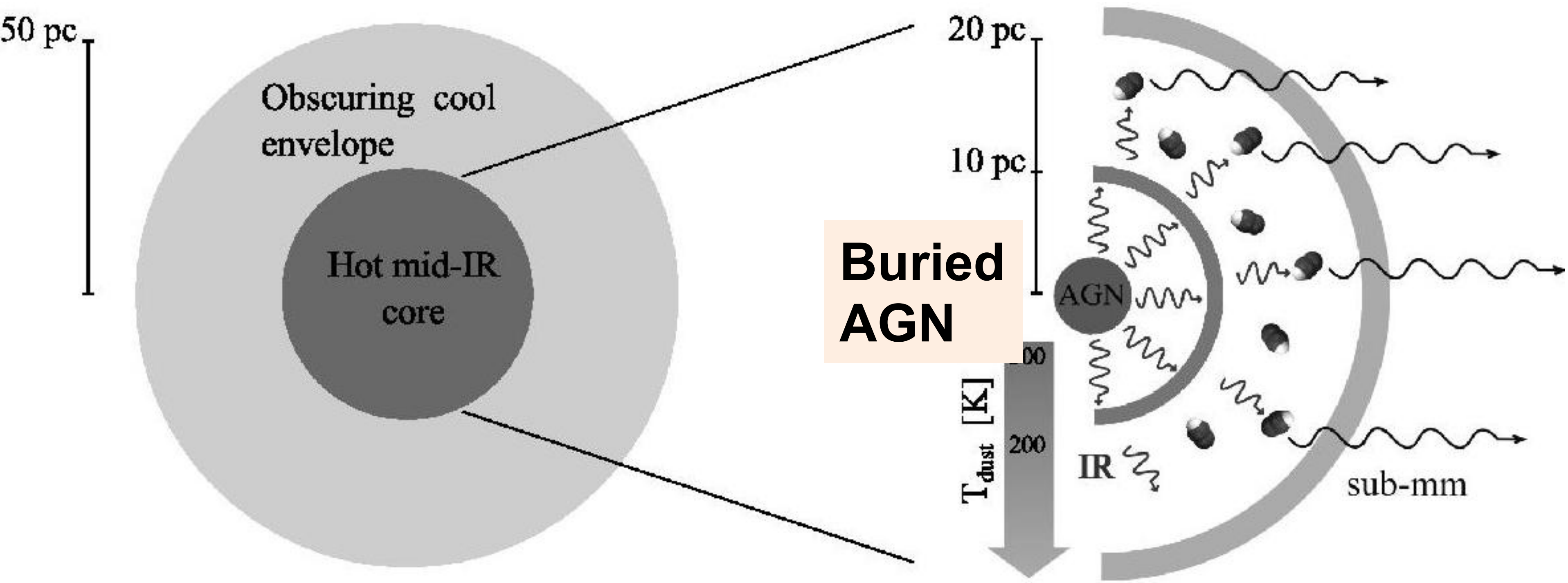
HCN-VIB in ULIRGs



HCN-VIB: Vibrationally-excited (v2=1f) HCN

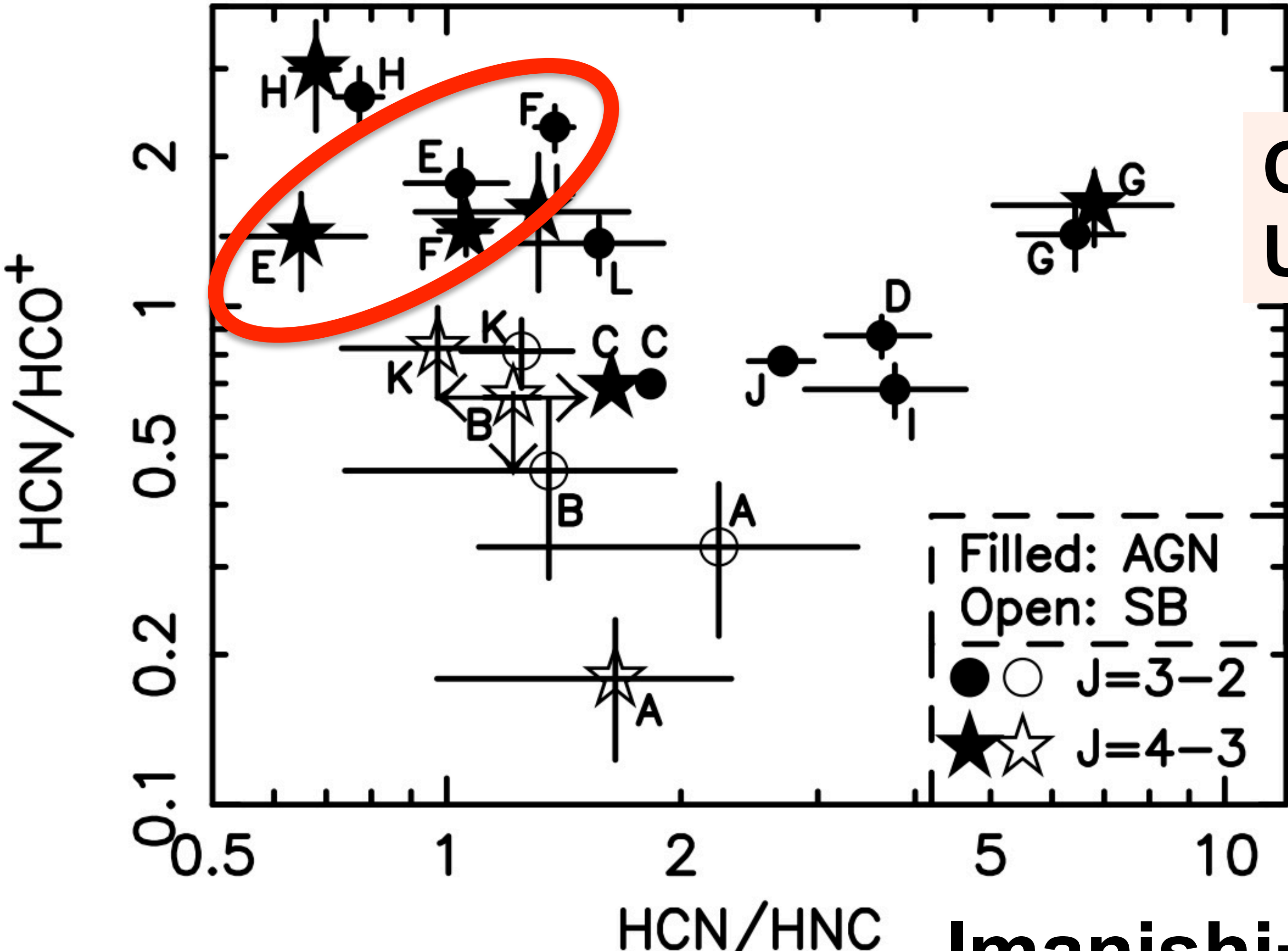
→ **mid-infrared (14 um) continuum**

→ **AGN-heated hot dust (?)**



Aalto+15 A&A 584 A42

Some IR non-AGN show high HCN/HCO^+ flux ratios



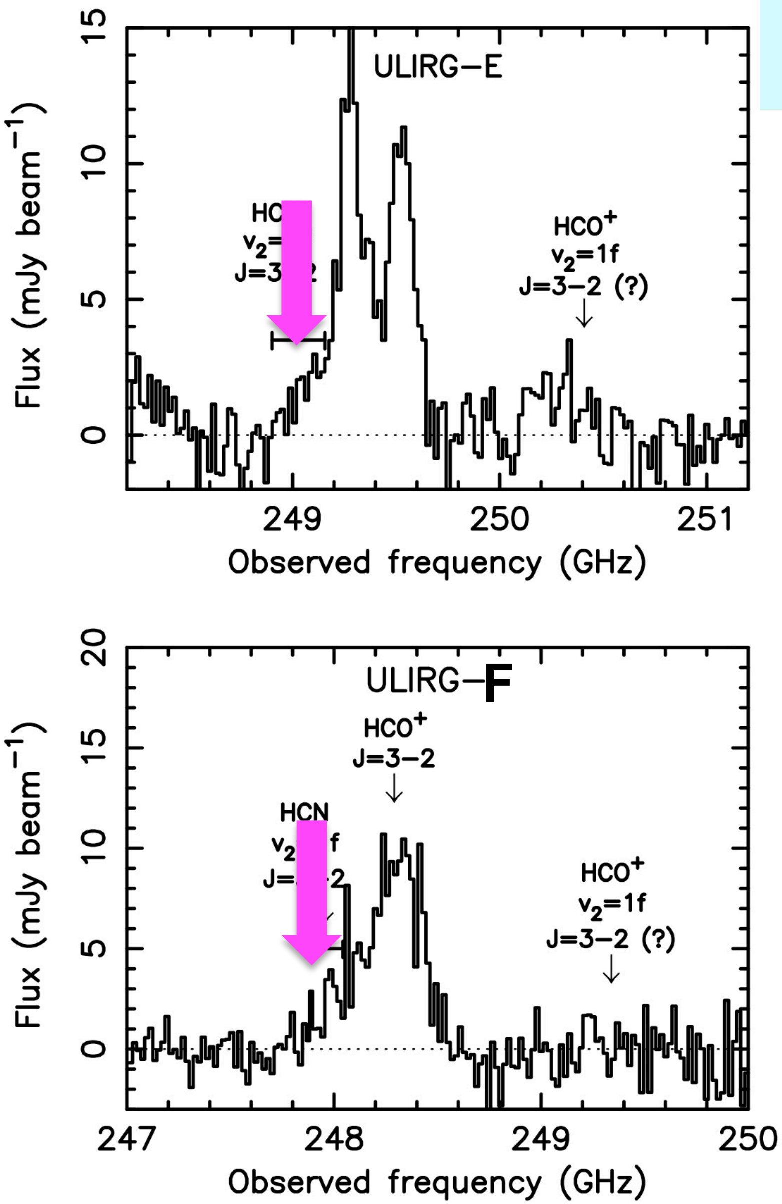
C,D,G, H, I, J: ULIRG (IR-AGN)

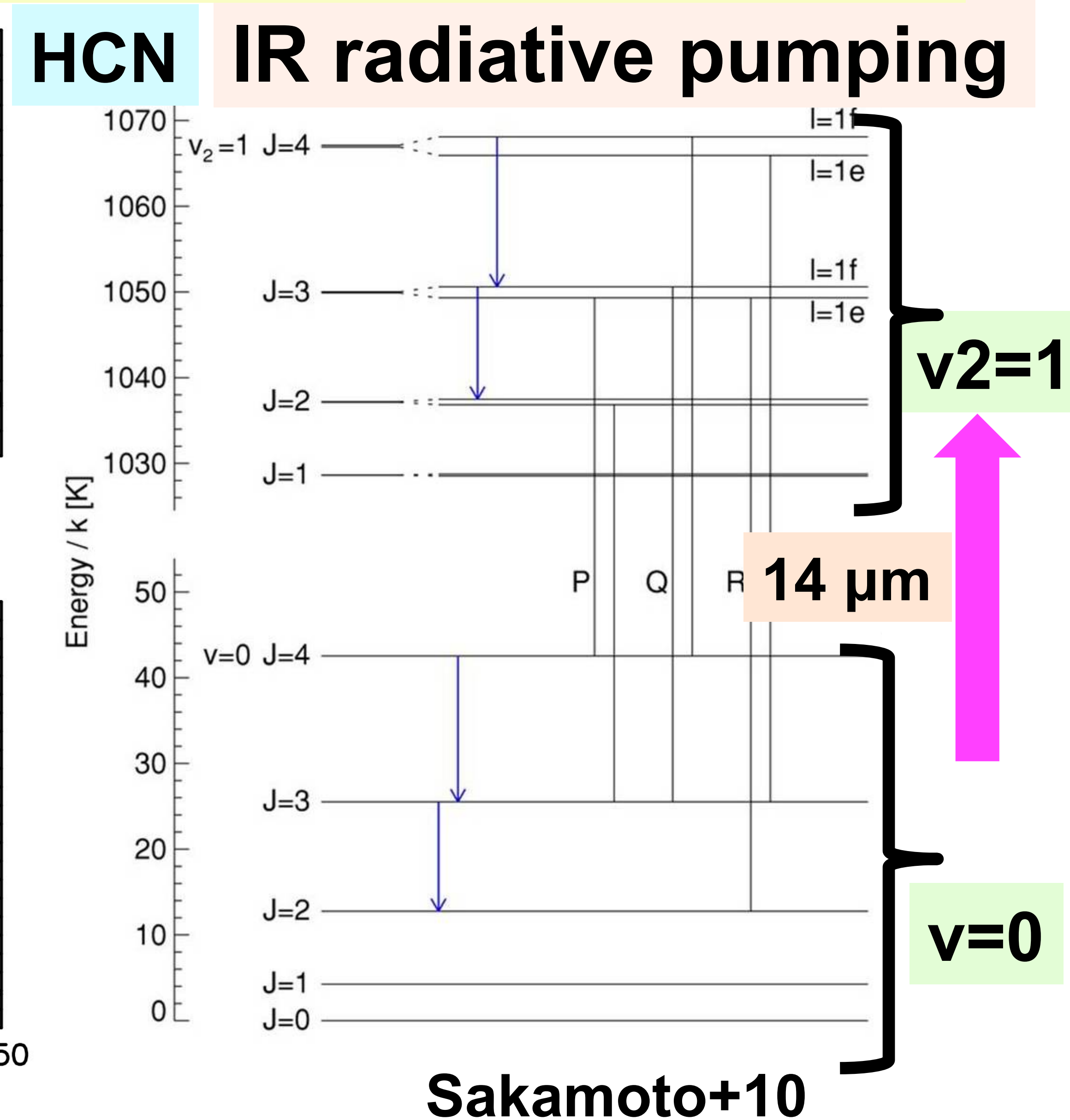
A, B, K: SB

E, F: ULIRG (IR no-AGN)

Imanishi+17b (in prep)

IR-elusive, (sub)mm-detectable buried AGNs?

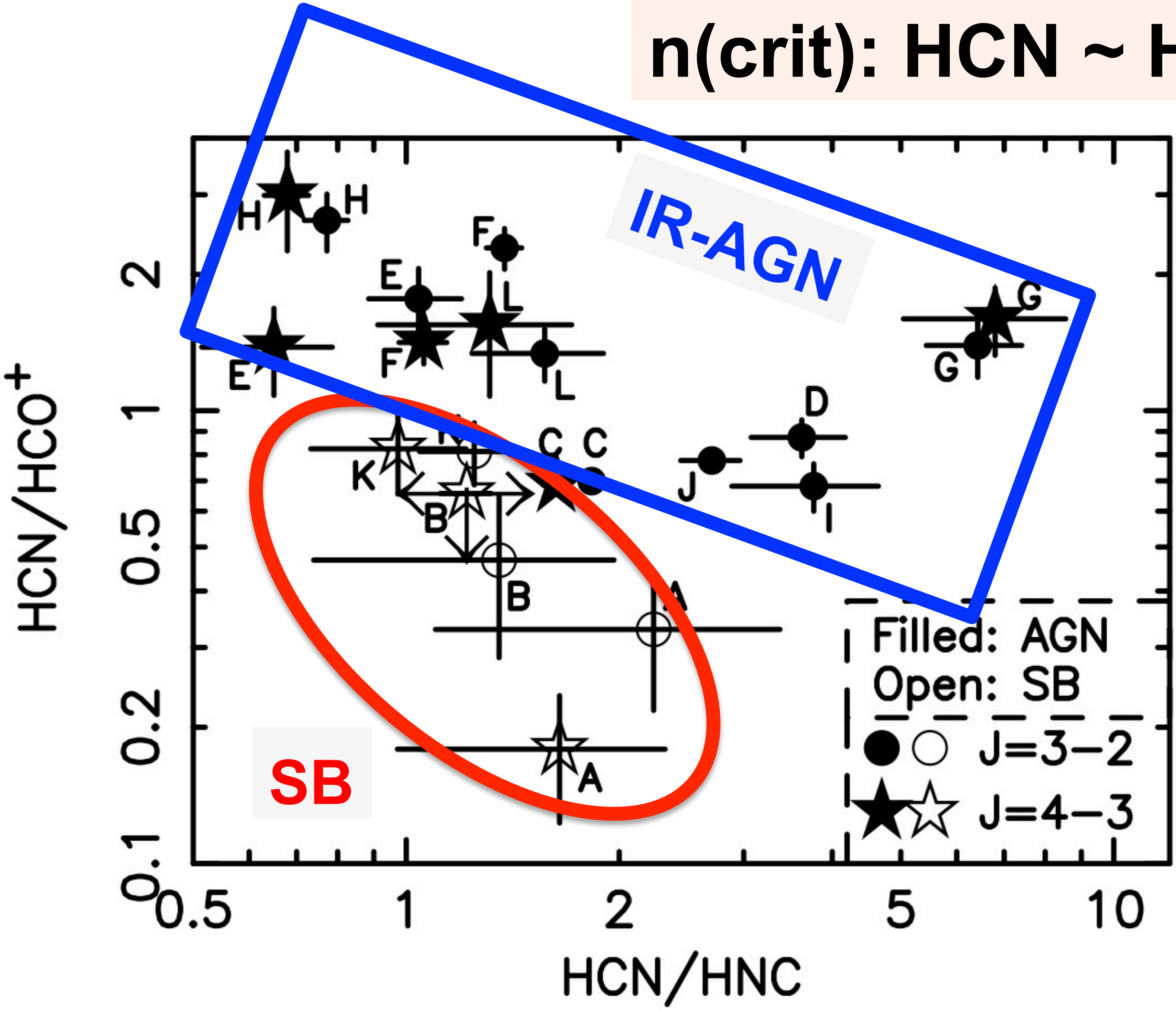




Interpretation

1. High HCN excitation

n(crit): HCN ~ HNC > HCO^+

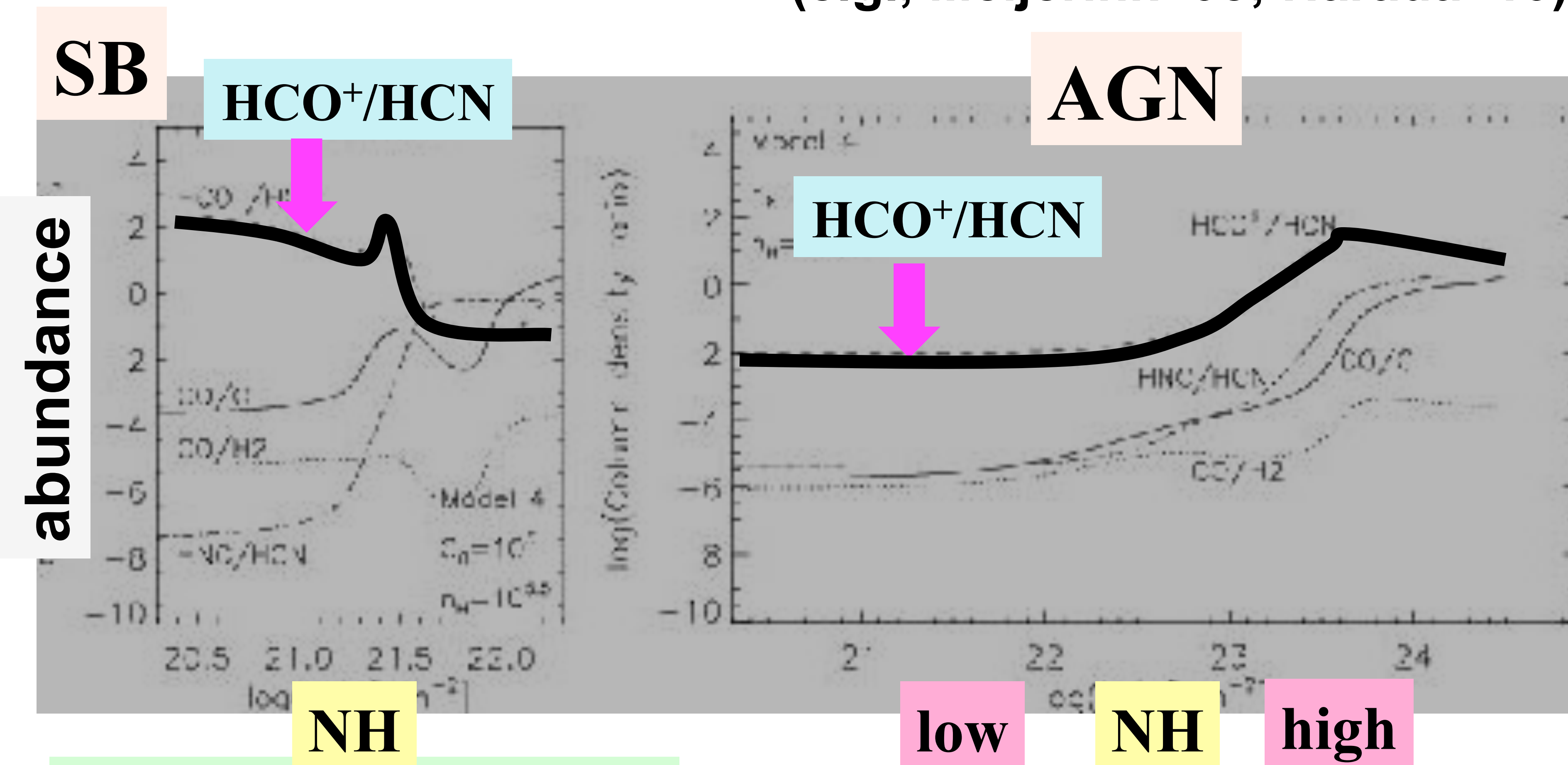


Imanishi+17b (in prep)

2. High HCN abundance in AGN

X-ray and/or hot dust/gas chemistry

(e.g., Meijerink+05; Harada+10)



density=10^5.5 cm^-3

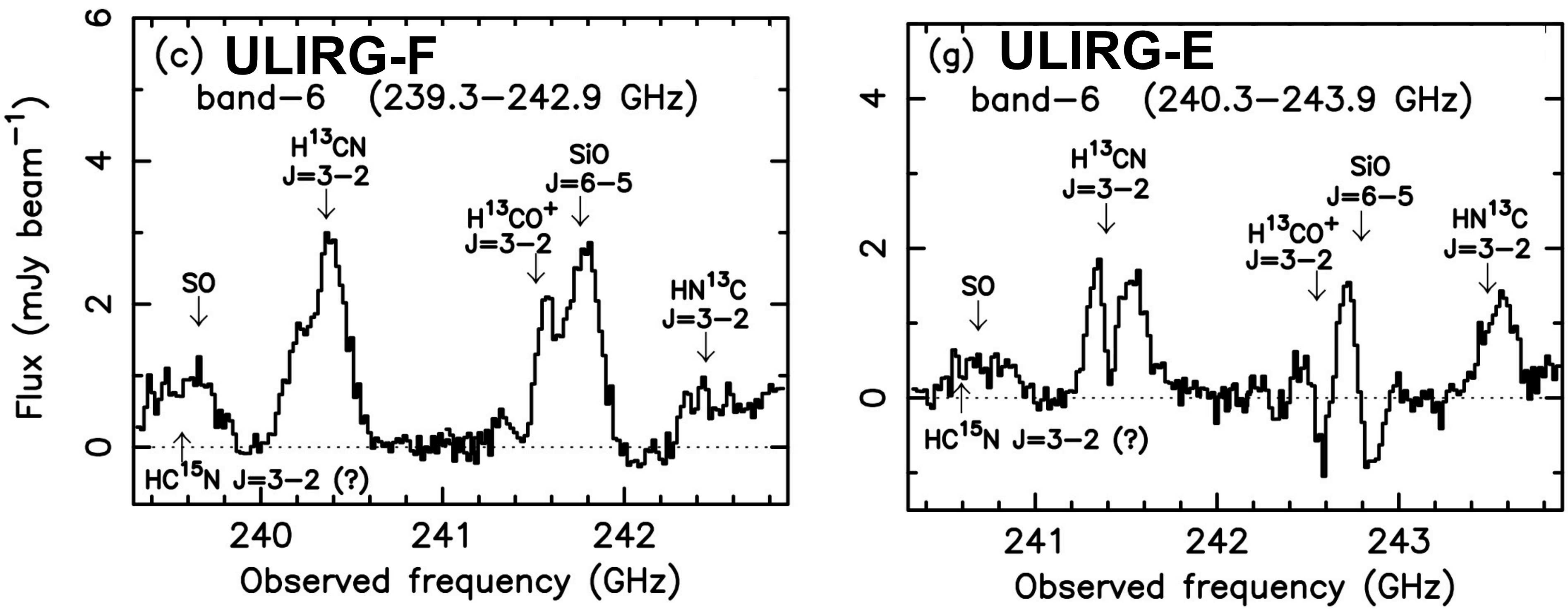
Meijerink+05

Isotopologue line observations

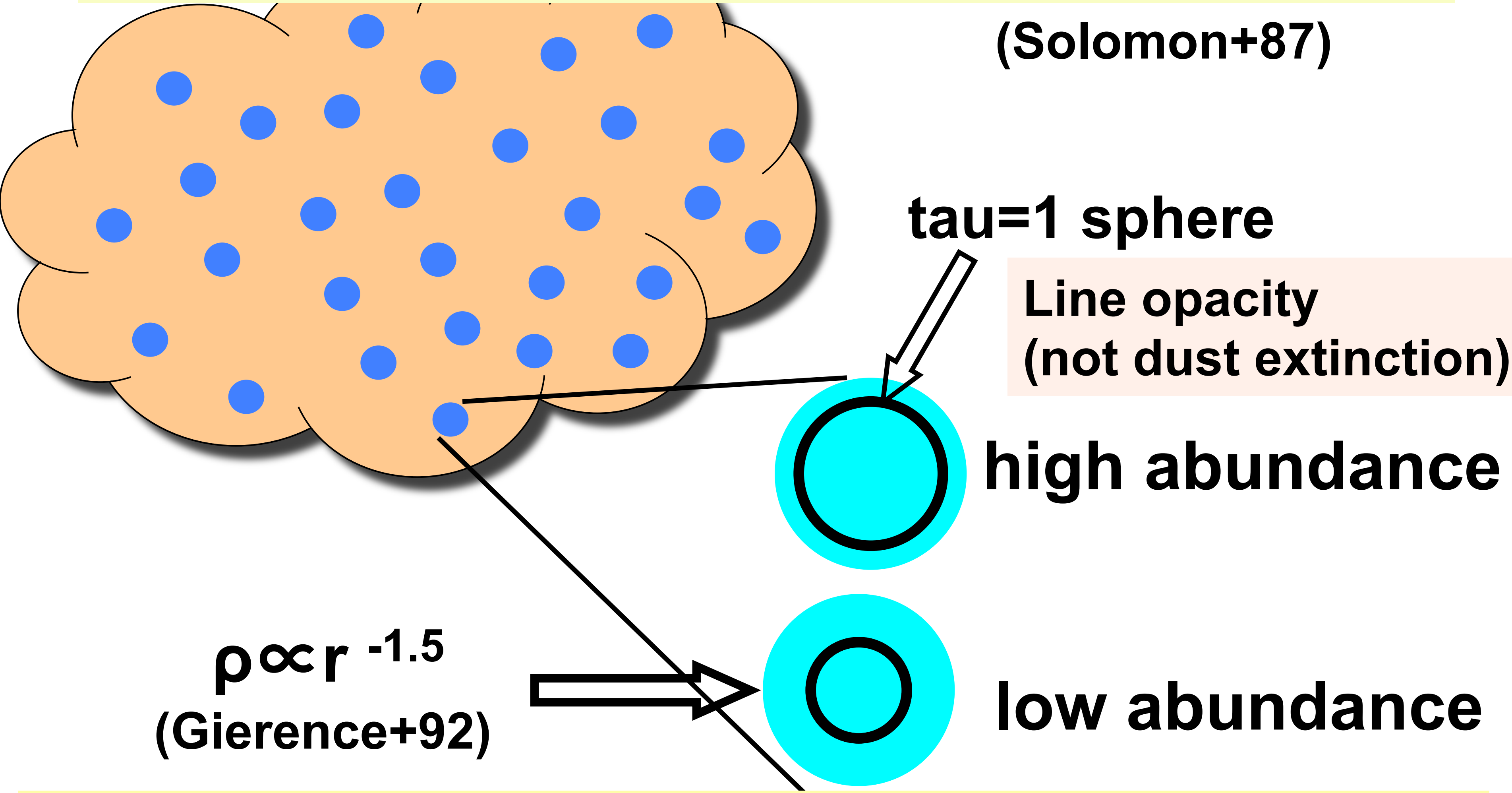
$\frac{HCN}{H^{13}CN} < \frac{HCO^+}{H^{13}CO^+}, \frac{HNC}{HN^{13}C}$ (J=3-2)

→ HCN J=3-2 higher line opacity

HCN higher abundance ?



Molecular gas (clumpy structure)

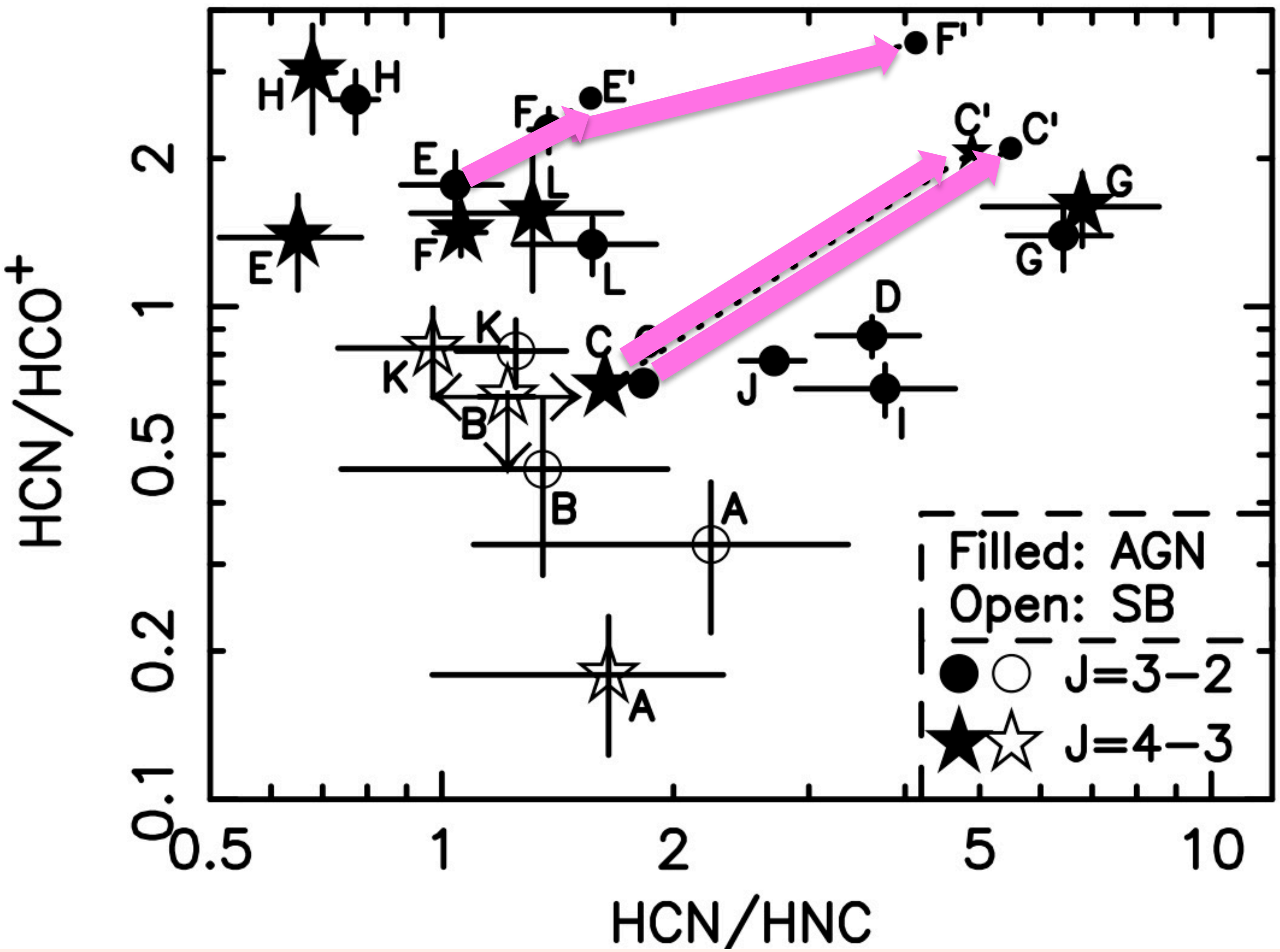


abundance ↑ → surface area ↑ → flux ↑

Imanishi+07 AJ 134 2366

HCN/HCO+ flux ratio (revised)

$^{12}C/^{13}C$~50 in ULIRGs assumed (Henkel+14)



Imanishi+17b in prep

Line-opacity-corrected, intrinsic flux ratios

Sumamry of our ALMA study

<u>(Sub)millimeter molecular line flux ratios</u> are a powerful tool to study elusive buried AGNs in ULIRGs.

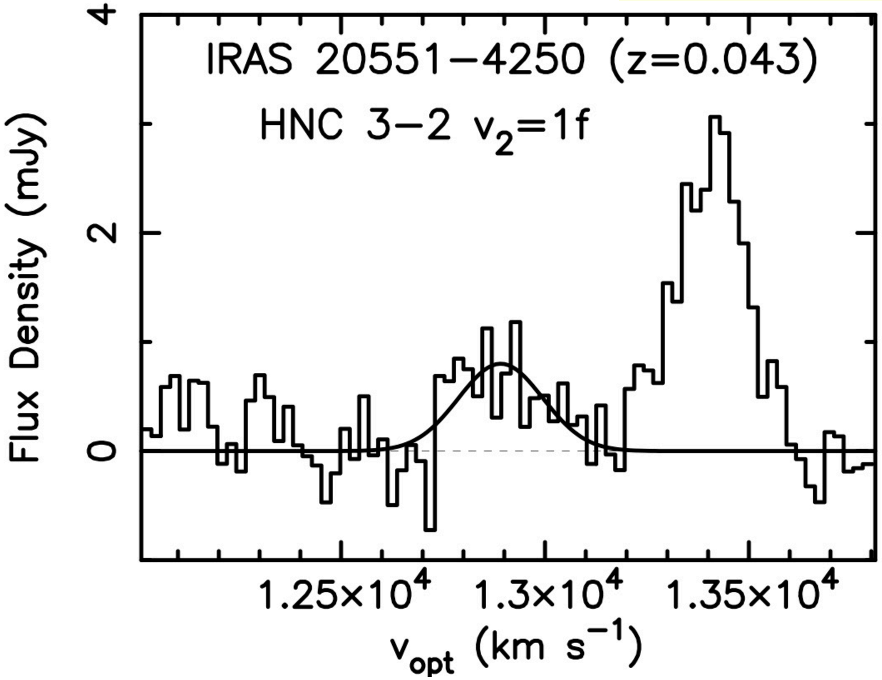
→ Sensitive to <u>IR-elusive</u> deeply buried AGN?

<u>Line opacity (not dust extinction)</u> correction will make our method even more convincing.

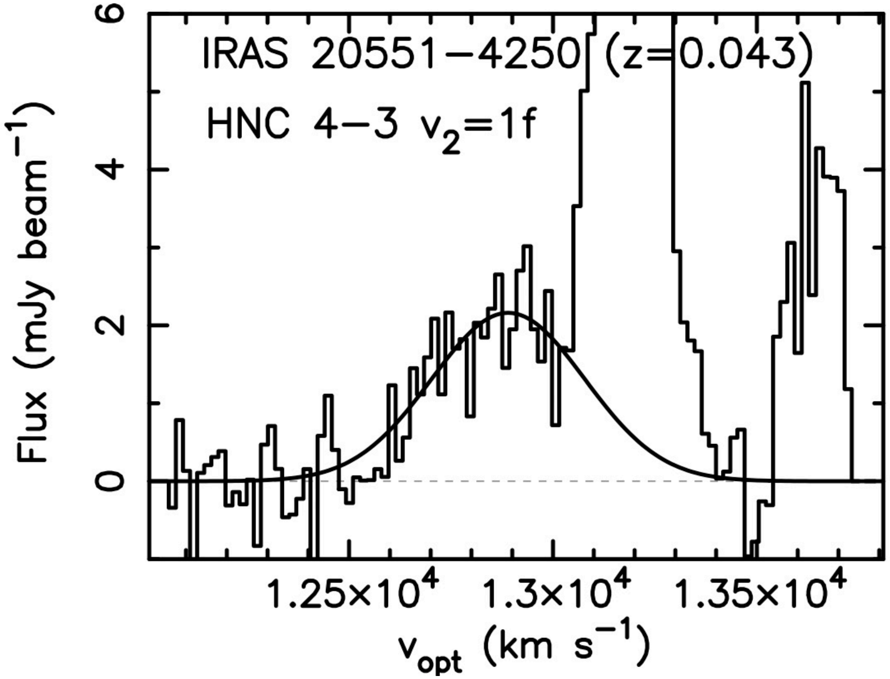
Imanishi+13 AJ 146 91; +14 AJ 148 9
Imanishi+16a ApJ 825 44, +16b AJ 152 218
Imanishi+17a (submitted), 17b (in prep)

End

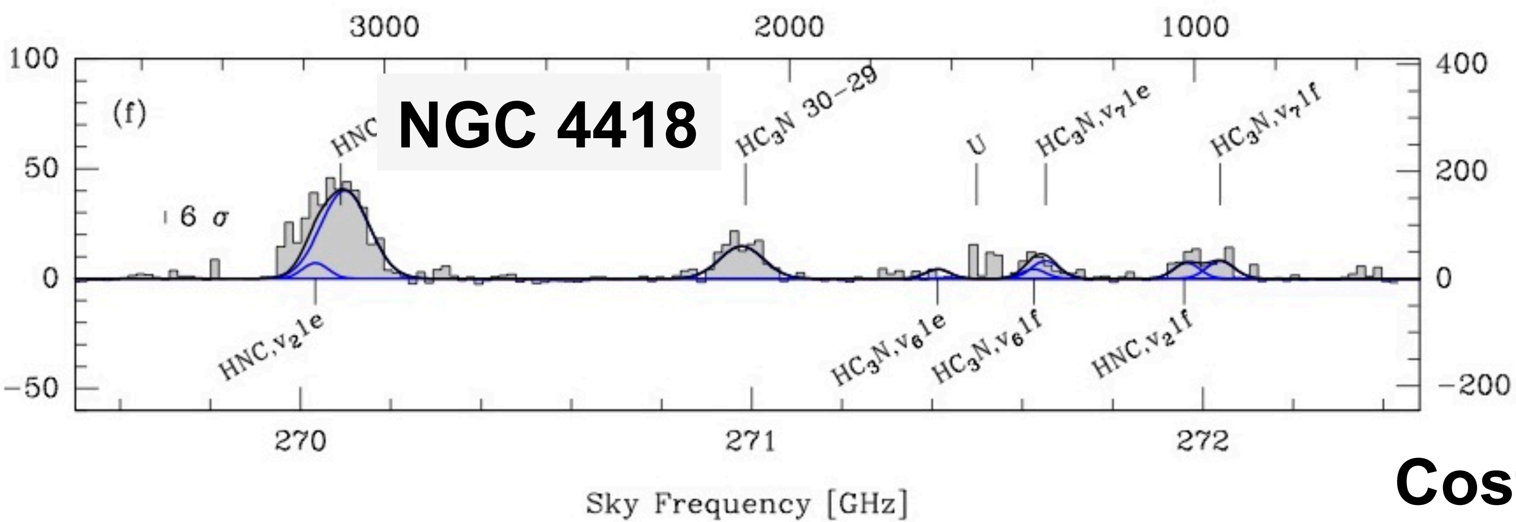
HNC-VIB (>690 K)



Imanishi+13b AJ 146 91

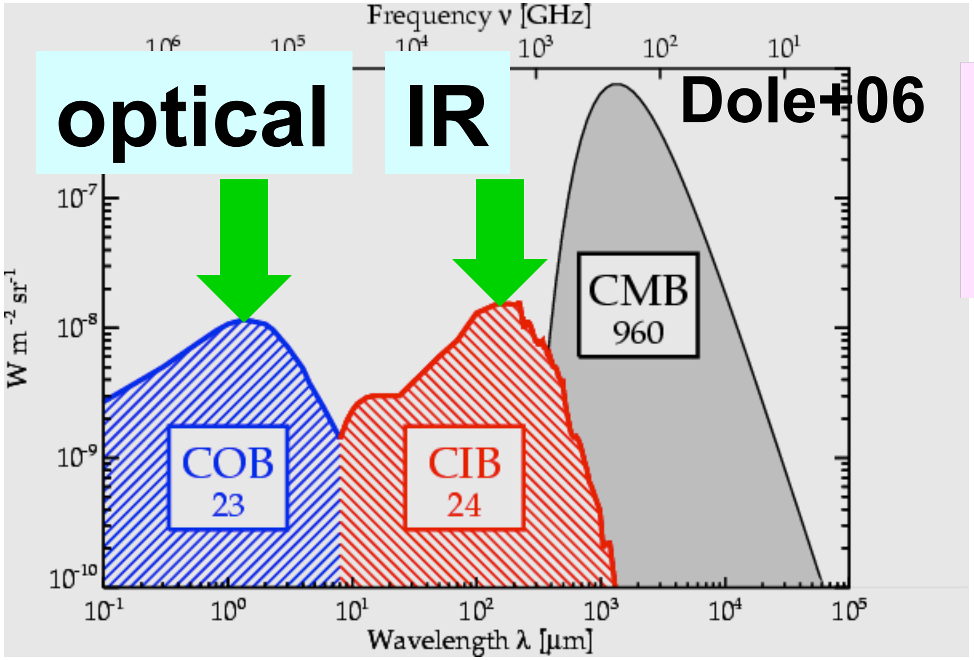


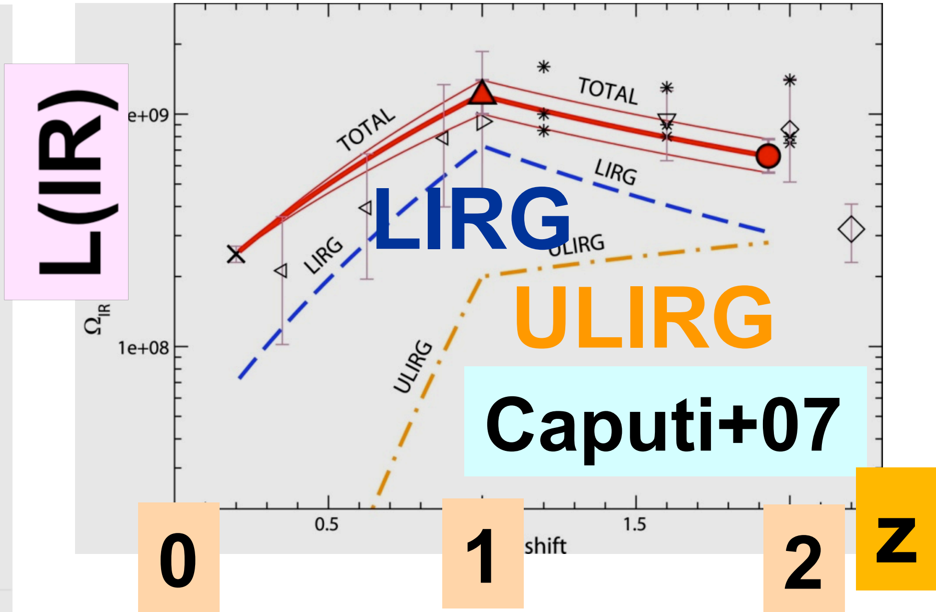
Imanishi+16b ApJ 825 44

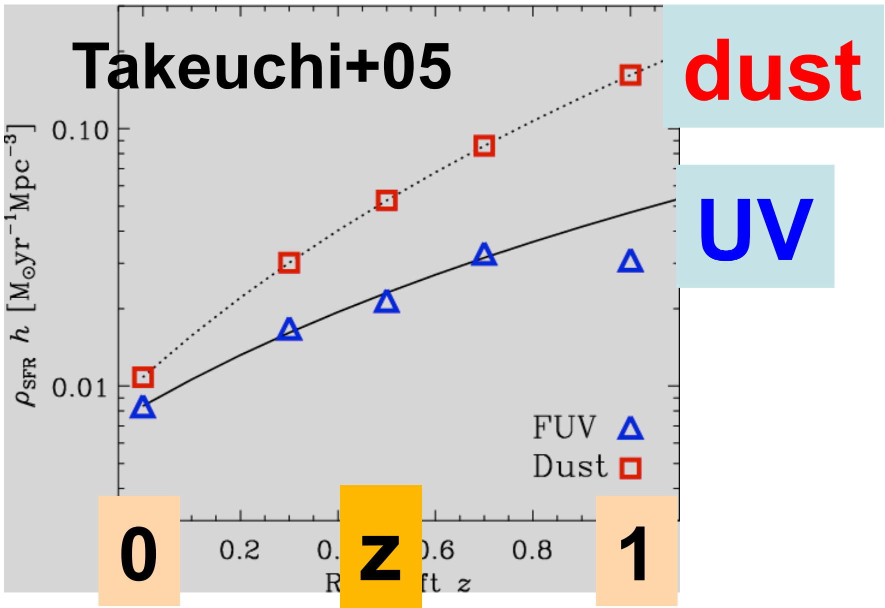


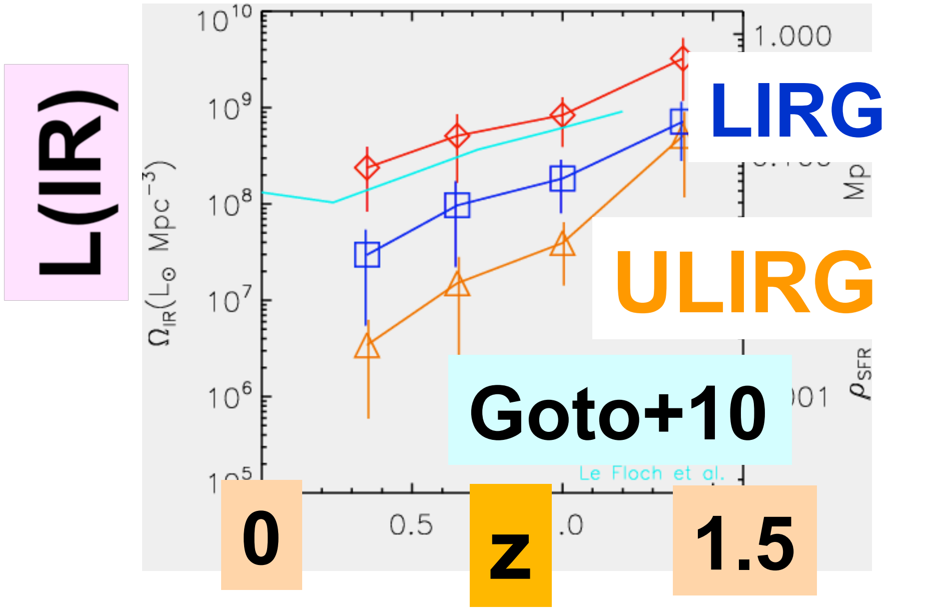
Costagliola+13

More than half of cosmic activity is obscured



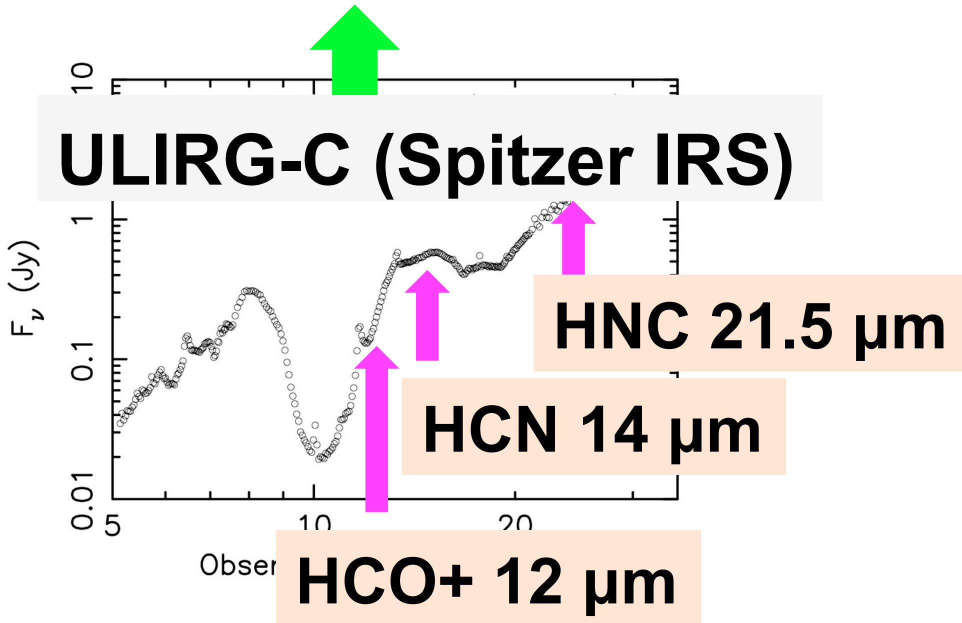






IR radiative pumping

∝ Einstein B coefficient (v=0→1) x Fv (IR) x N (v=0)



v2=1 / v=0 column density ratio (J=3)

model HCN : HCO+ : HNC = 1 : 0.5 : 9

v2=1column ratio (J=3) (column ∝ flux/Aul)

Obs. HCN : HCO+ : HNC = 1 : <0.20 : 0.69

abundance HCN : HCO+ = >2.5 : 1 HCN : HNC = 13 : 1

2. High HCN line opacity?

ULIRG-C v2=1f