HSC

HSC-SSP view of Dust Obscured Galaxies

Toba et al. 2015, PASJ, 67, 86

Toba et al. 2016b, in prep.

Yoshiki TOBA (鳥羽 儀樹)

(Ehime Univ. => ASIAA)

Tohru Nagao, Michael A. Strauss, Masaru Kajisawa, Tomo Goto, Masa Imanishi, and the HSC-DOGs team

HSC-SSP view of Dust Obscured Galaxies

🍊 **IR Luminosity Function**

Toba et al. 2015, PASJ, 67, 86

🍊 **IR Luminosity Density**

2016b, in prep.

Toba+15
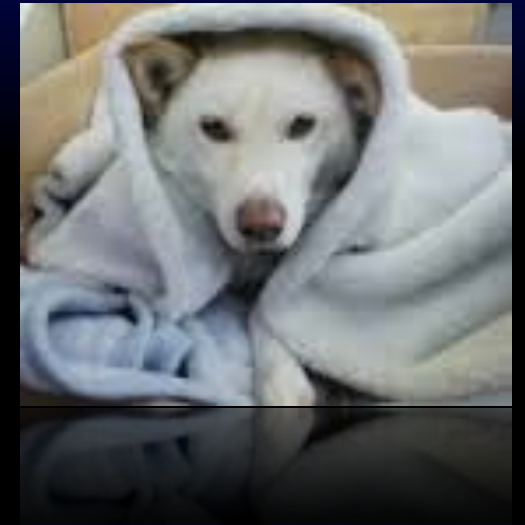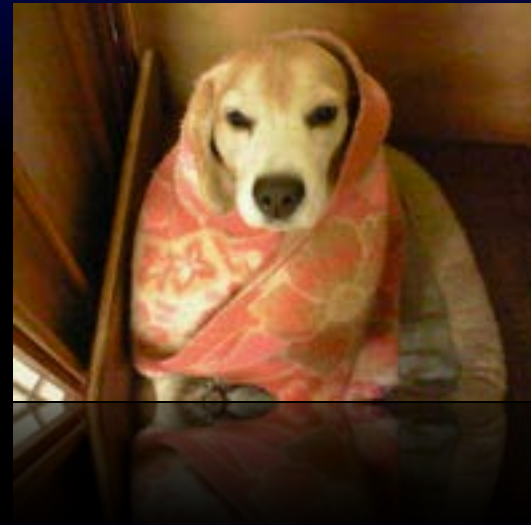
Yoshiki TOBA (鳥羽 儀樹)

🥟 **Auto Correlation Function**

Toba+16b in prep.

Tohru Nagao, Michael A. Strauss, Masaru Kajisawa
Tomo Goto, Masa Imanishi, and the HSC-DOGs team

Dogs are obscured by blanket..

Introduction

What are Dust Obscured Galaxies (DOGs)?

Dust Obscured Galaxies

R - [24] ≥ 7.5 (AB mag)
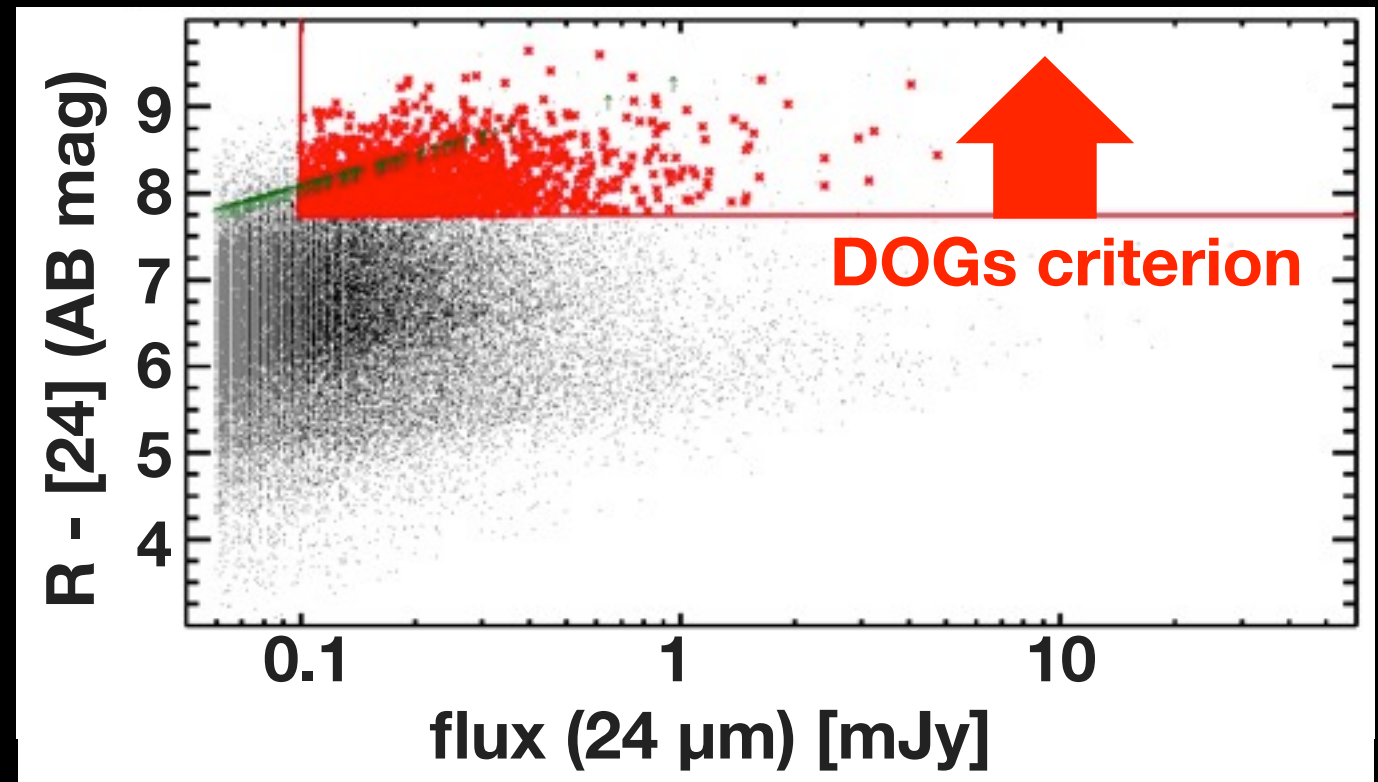
- An optically faint but IR bright objects.

~ ULIRGs
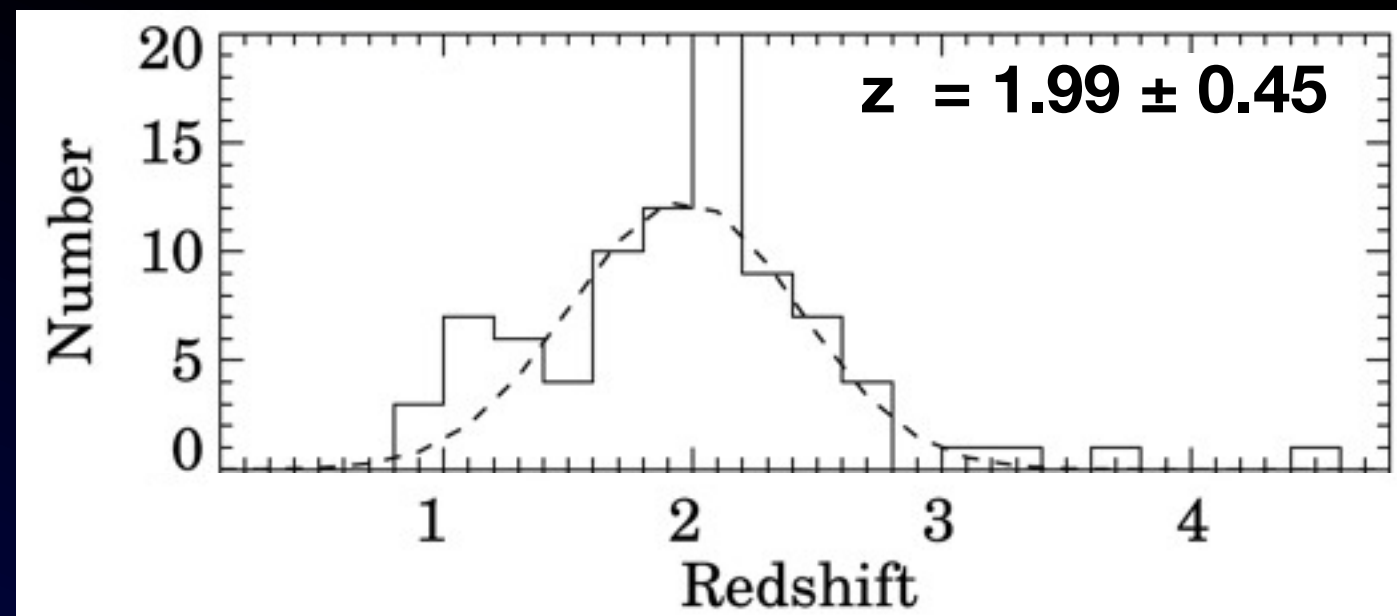
- Most DOGs are ultra-luminous infrared galaxies (ULIRGs: $L_{IR} \geq 10^{12} L_{sun}$).

z ~ 2

- Confirmed from follow-up observations (NIR and MIR spectroscopy).

DOGs criterion

Calanog+13

z = 1.99 ± 0.45

Dey+08

Two types of DOGs

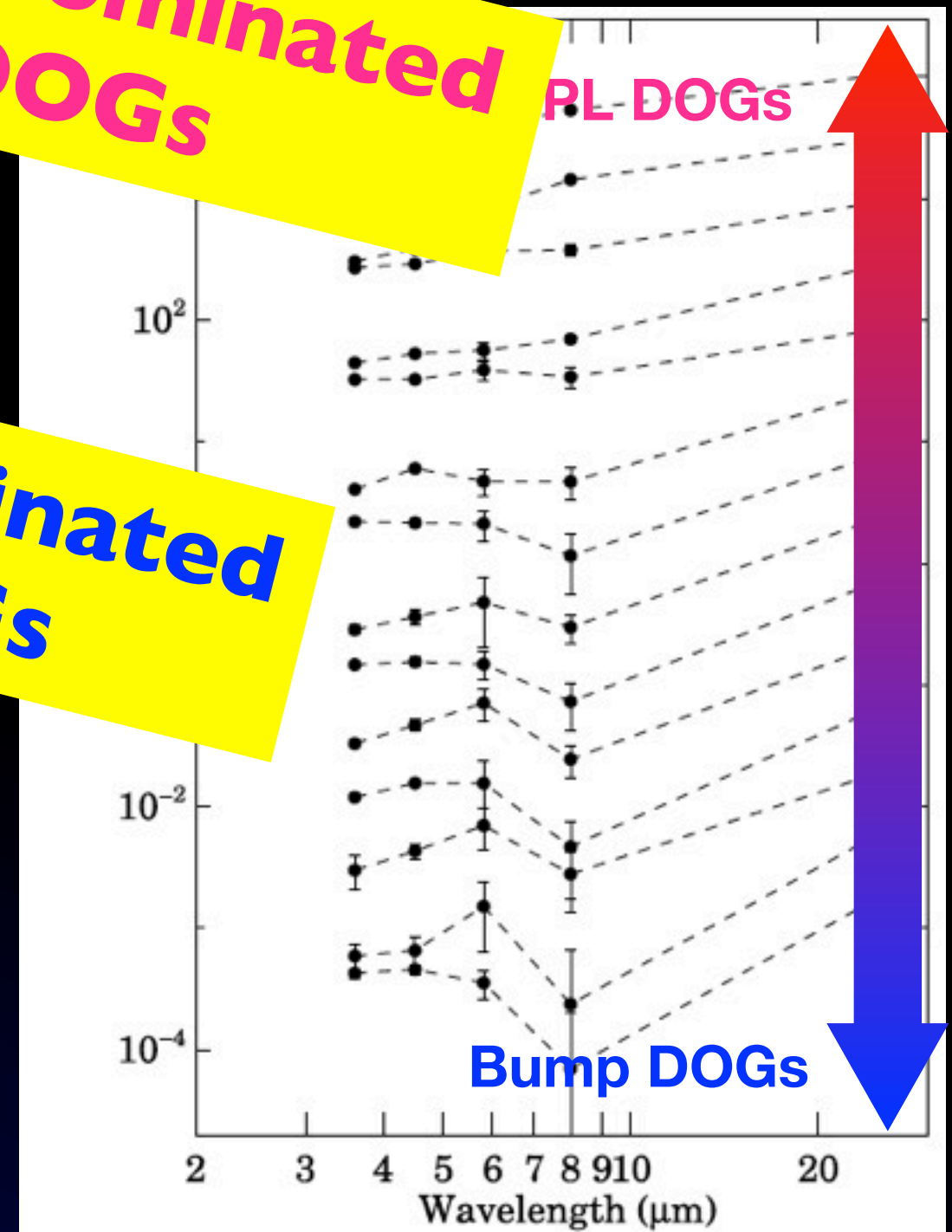**AGN-dominated DOGs**

SF-dominated DOGs

Power-Law (PL) DOGs

- They show a rising power-law SED, which indicates an AGN activity.

Bump DOGs

- They show a rest-frame 1.6 μm "bump" in their SEDs.
- They also show strong PAH emission.,which indicates a SF activity.

PL DOGs

Bump DOGs

Dey+08

IR bright DOGs ≃ PL DOGs

- The fraction of PL DOGs (i.e., AGN-dominated DOGs) increases with increasing MIR flux.

- IR-bright DOGs are expected to be AGN dominated DOGs.

- The number densities of DOGs decreases with increasing MIR flux., which means IR-bright DOGs are very low.

- It requires a large area survey.

Dey+08
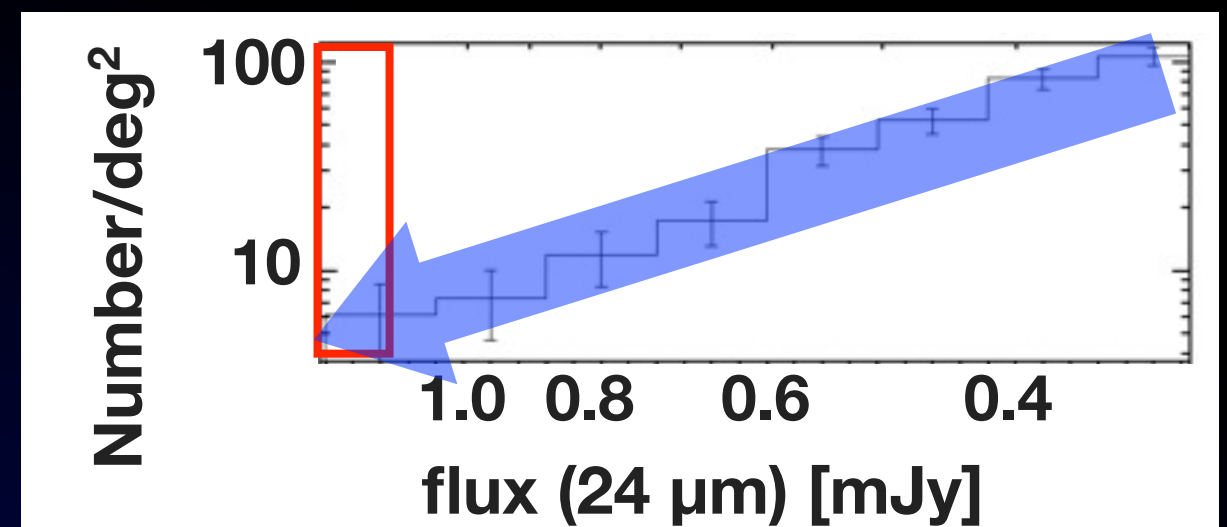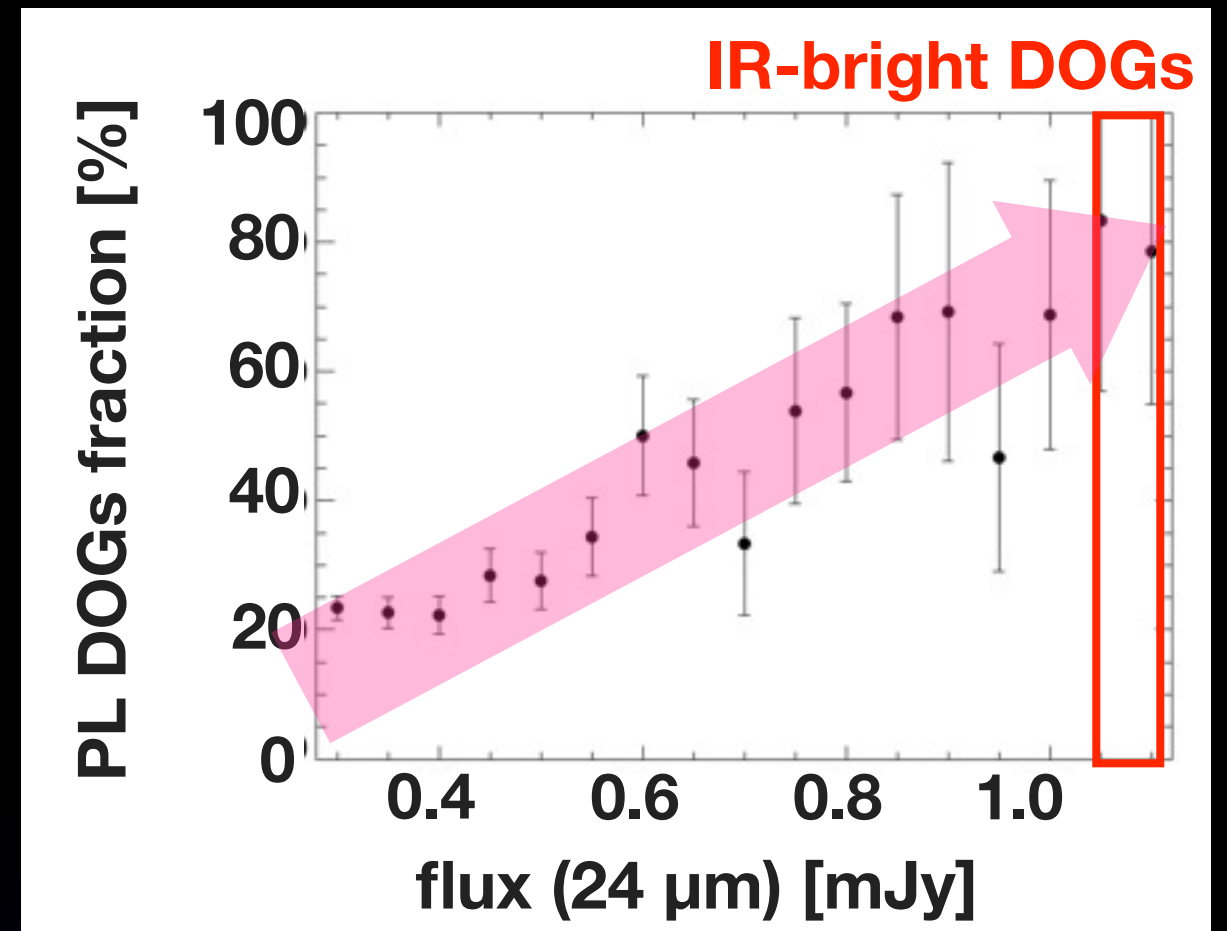
What are the DOGs?

IR-bright, optically faint obj. z~2

Bump DOGs ・ PL DOGs

IR bright DOGs ≃ PL DOGs
≃ AGN-dominated DOGs

Importance of DOGs

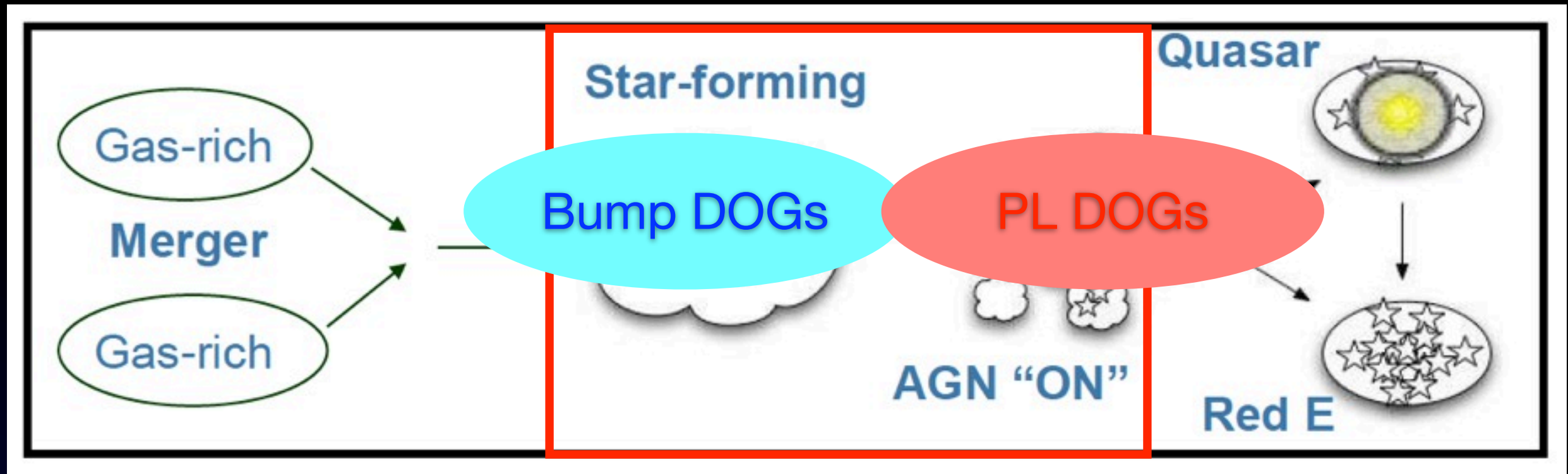# Importance of DOGs

Importance of DOGs

←Peak BH accretion

←PLDOGs phase

① F₂₄ = 231. μJy　24/R = 260
② F₂₄ = 109. μJy　24/R = 177
③ F₂₄ = 768. μJy　24/R = 845
④ F₂₄ = 858. μJy　24/R = 1016
⑤ F₂₄ = 75.0 μJy　24/R = 115

Growing-up phase!?

Narayanan+10

9

Importance of DOGs

Quasar
Star-forming
Gas-rich
Merger
Gas-rich
AGN "ON"   Red E

1200
1000
800
io at z=2

★ ● ←**Peak BH accretion**

←**PLDOGs phase**

Time [Gyr]
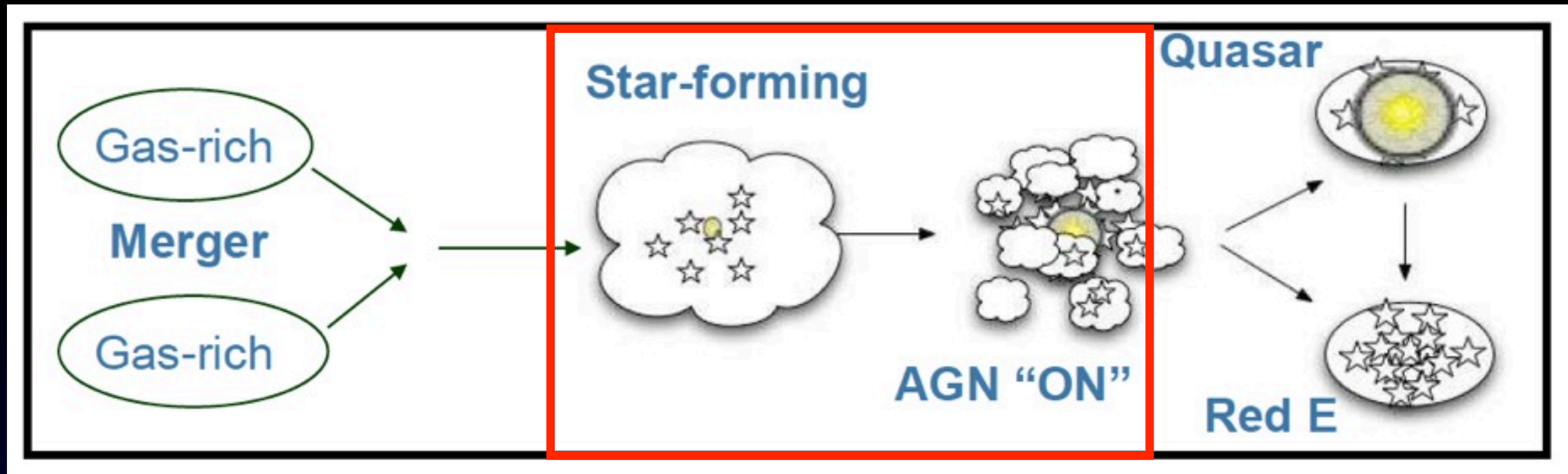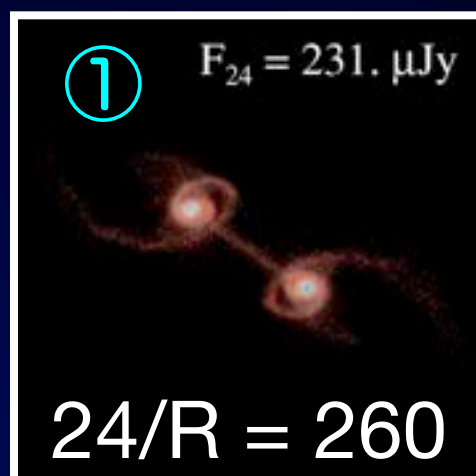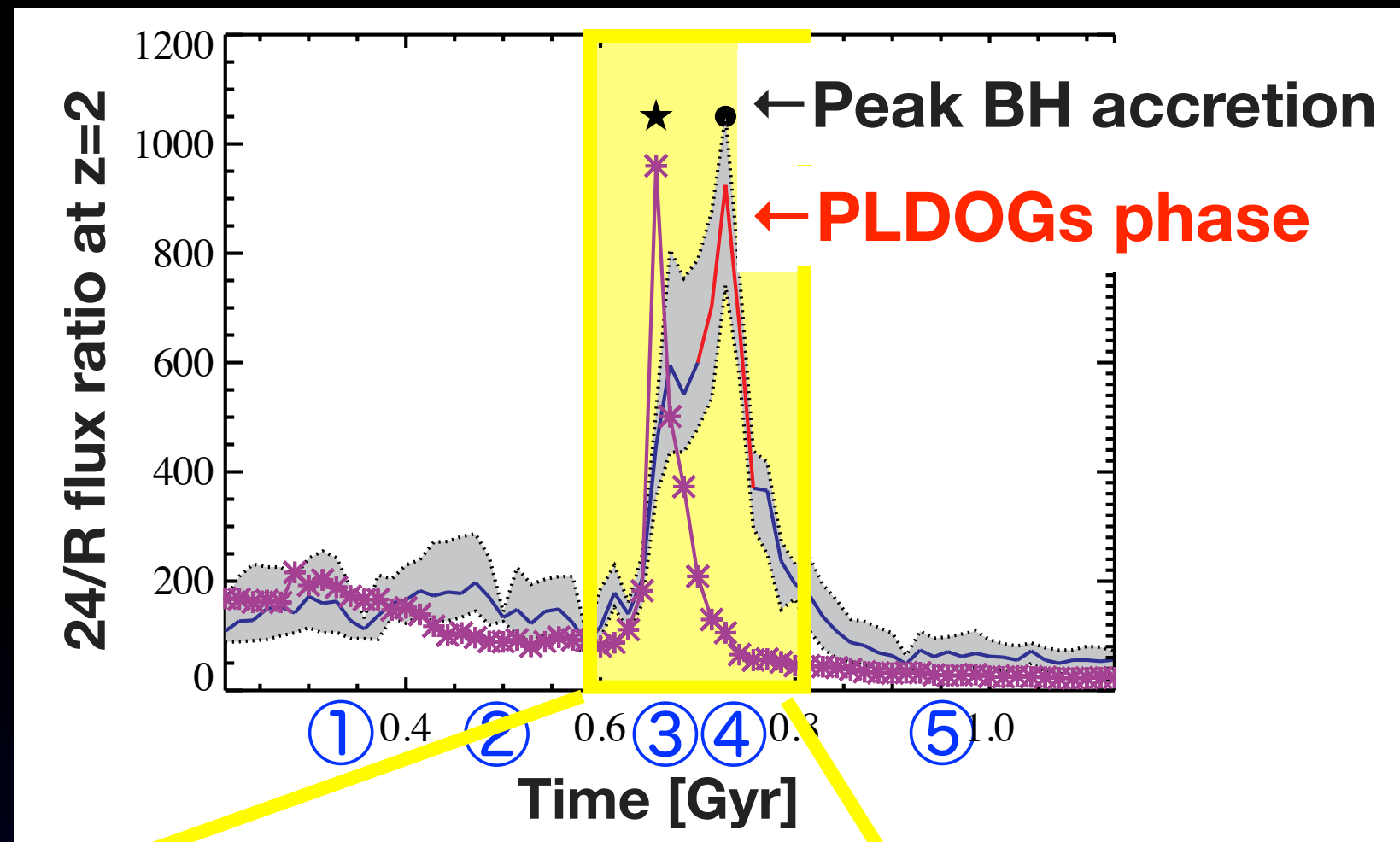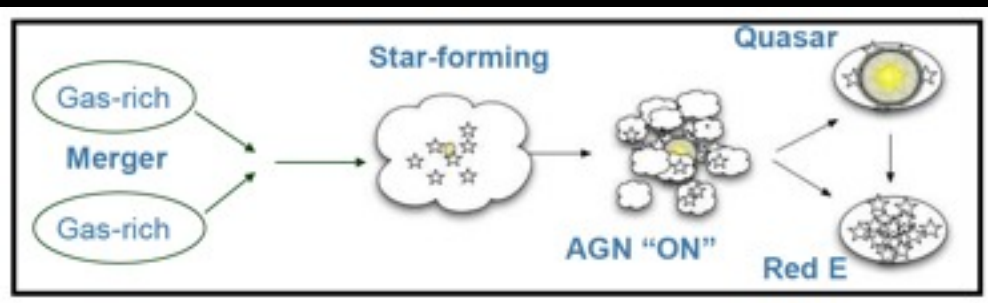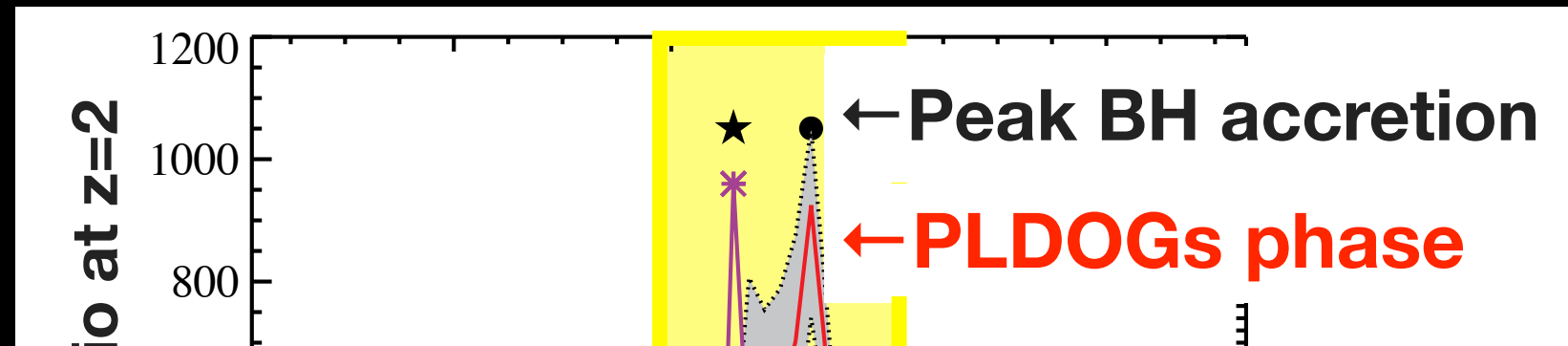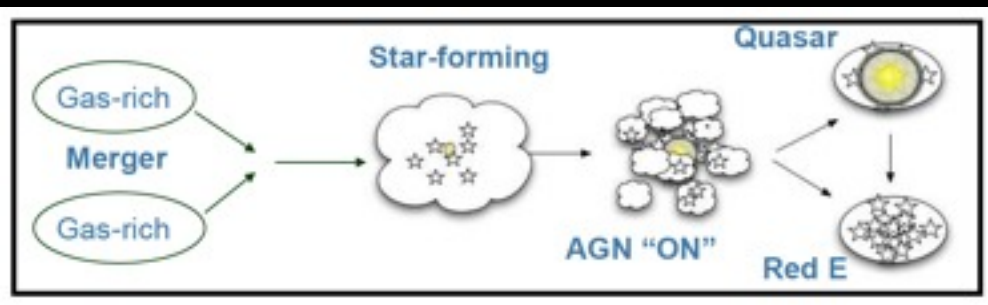
IR-bright DOGs could constitute a key population for understanding the co-evolution of galaxies and SMBHs.

① $F_{24} = 231. \mu Jy$ ② $F_{24} = 109. \mu Jy$ ③ $F_{24} = 768. \mu Jy$ ④ $F_{24} = 858. \mu Jy$ ⑤ $F_{24} = 75.0 \mu Jy$

Growing-up phase!?

24/R = 260   24/R = 177   24/R = 845   24/R = 1016   24/R = 115

Narayanan+10   9
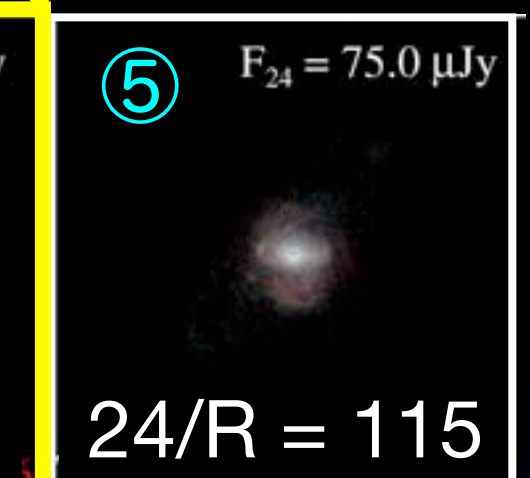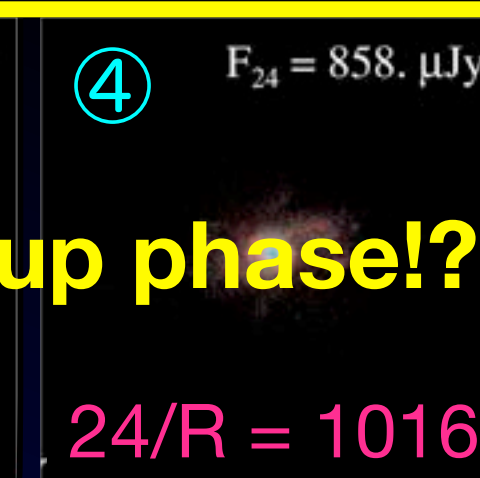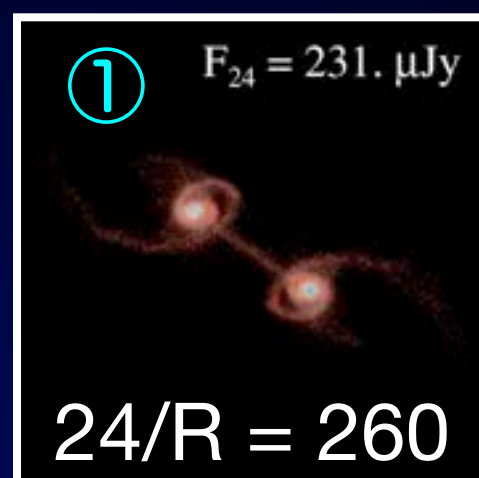
Purpose of this study

(1) Search for IR-bright DOGs based on the HSC with VIKING and WISE

(2) Investigating their photometric and statistical properties

Purpose of this study
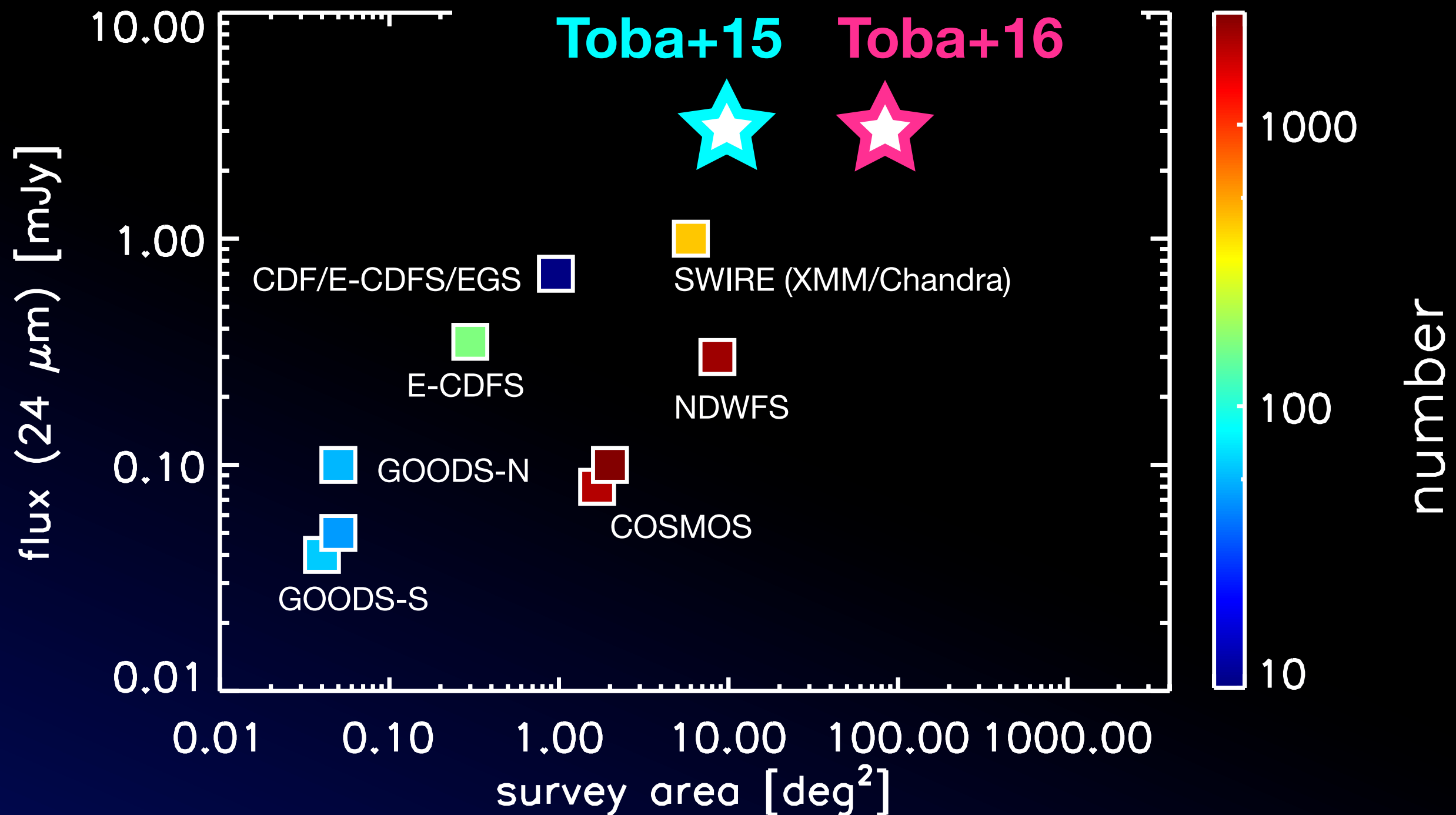
Data and Analysis

How do we discover IR bright DOGs?

HSC, VIKING, and WISE

	band	limiting mag (5σ、2″)	Total number of objects
HSC S14A_0	i	~26	16,392,815
	y	~24	
VIKING DR1	Z	23.1	14,773,385
	Y	22.3	
	J	22.1	
	H	21.5	
	Ks	21.2	
ALLWISE	3.4	19.6	747,634,026
	4.6	19.3	
	12	16.4	
	22	14.5	

※ AB mag

GAMA 14hr field (~10 deg^2)
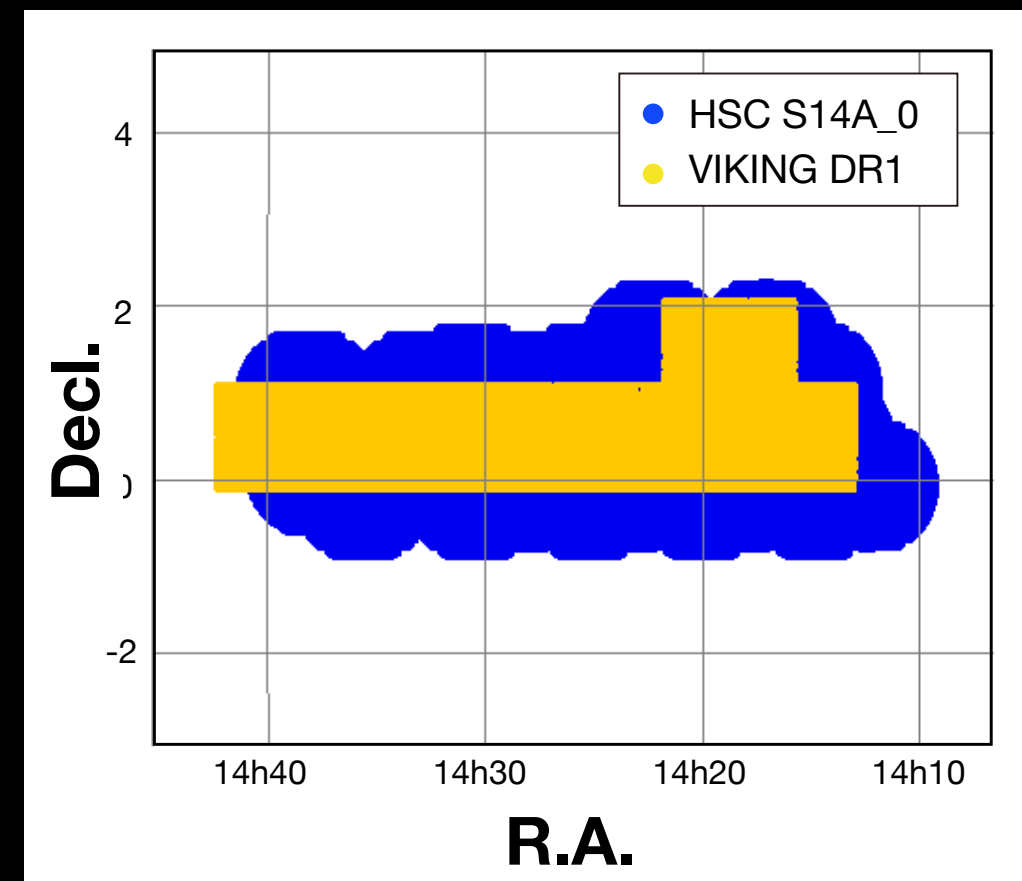
We used those bands to search for IR-bright DOGs

Sample Selection

16,392,815 **mosaic_sourcelist__deepcoadd**   14,773,385 **VIKING DR 1**   747,634,026 **ALLWISE**

filter01 = 'HSC-I'
deblend_nchild = 0 AND
flag_detect_is_tract_inner is True
flag_detect_is_patch_inner is True
AND
flag_flags_pixel_edge is False
flag_flags_pixel_saturated_center is False
flag_flags_pixel_cr_center is False
flag_flags_pixel_bad is False
flag_cmodel_flux_flags is False
flag_centroid_sdss_flags is False

In the GAMA 14 region ?

672,843   YES

priOrSec = 0
OR
priOrSec= FrameSetID
AND
ksppErrBits = 0
SN (Ks mag) ≥ 5

w4_sat= 0
w4_cc_map= 0
ext_flg = 0
SN (22 μm) ≥ 3

YES

6,024,570 **HSC sample**   234,286 **VIKING sample**   9,439,990 **WISE sample**

YES   YES

In the overlap region with VIKING?   In the overlap region with VIKING?

3,414,154   YES   1,339   YES   13

Sample Selection

16,392,815   mosaic_sourcelist__deepcoadd   14,773,385   VIKING DR 1   747,634,026   ALLWISE

A search radius

30''

30''

HSC

multiple counterpart

WISE

Sample Selection

16,392,815   mosaic_sourcelist__deepcoadd   14,773,385   VIKING DR 1   747,634,026   ALLWISE

In the GAMA 14 region ?

filter01 = 'HSC-I'
deblend_nchild = 0 AND
flag_detect_is_tract_inner is True
flag_detect_is_patch_inner is True
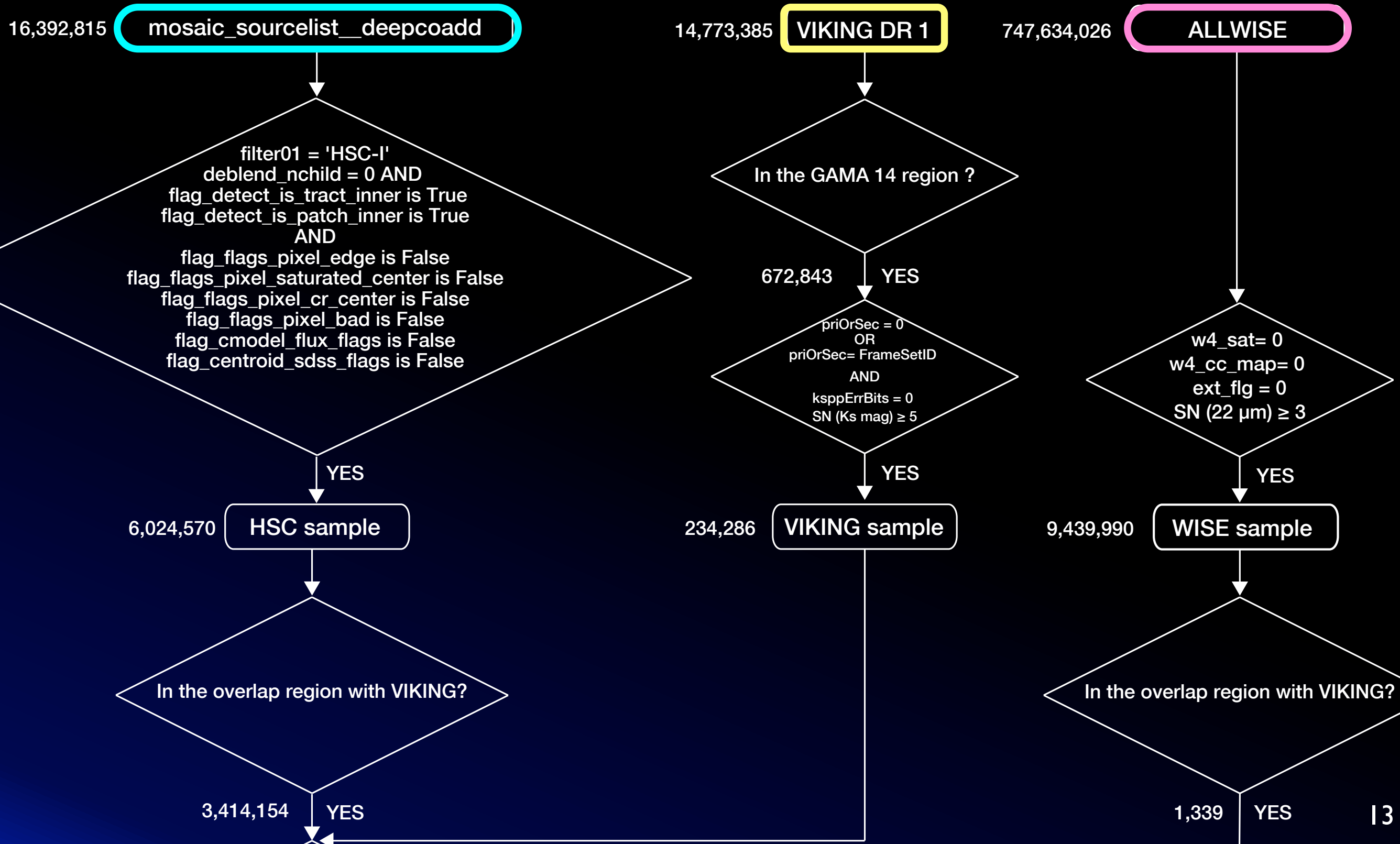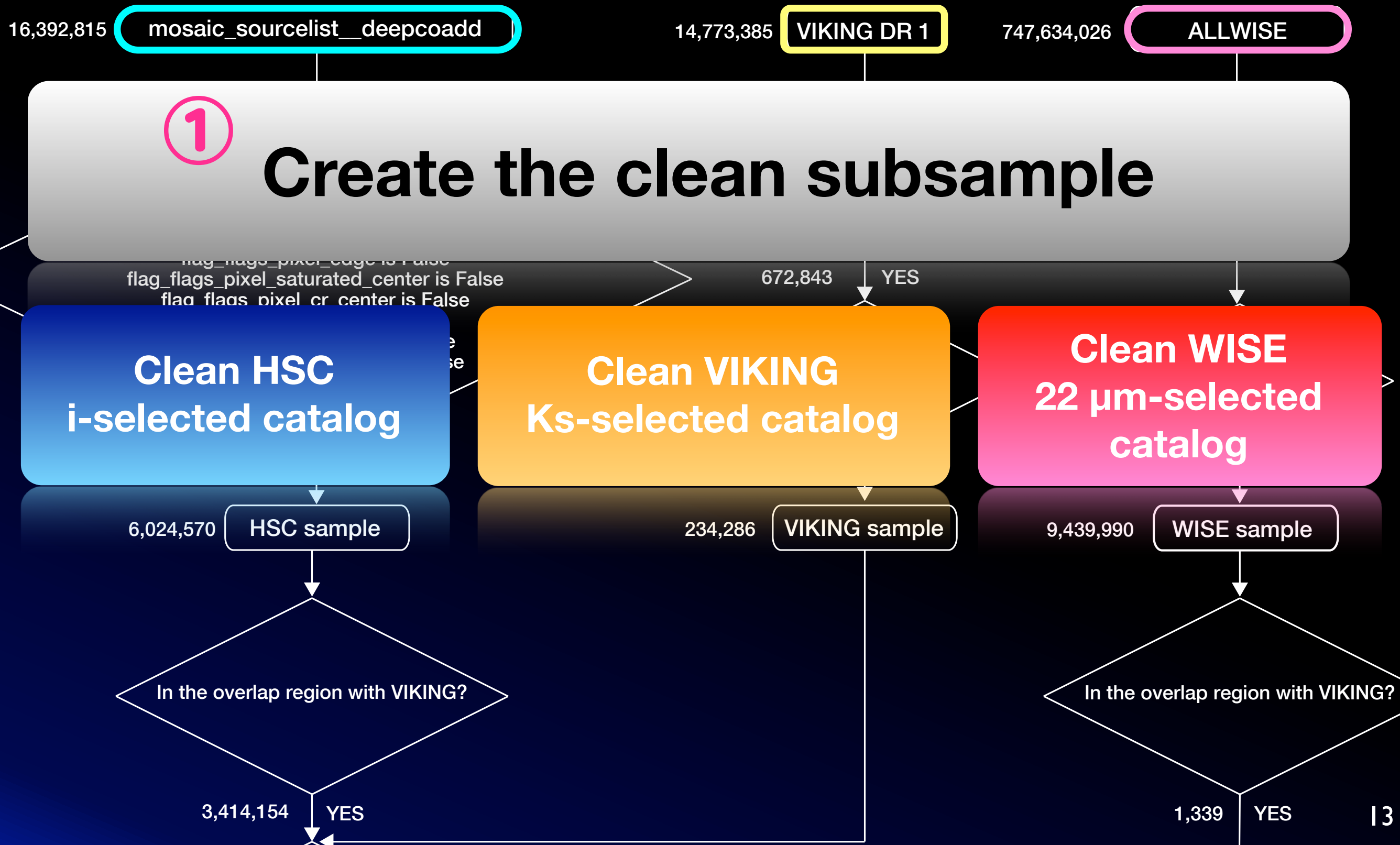AND
flag_flags_pixel_edge is False
flag_flags_pixel_saturated_center is False
flag_flags_pixel_cr_center is False
flag_flags_pixel_bad is False
flag_cmodel_flux_flags is False
flag_centroid_sdss_flags is False

672,843   YES

priOrSec = 0
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AND
ksppErrBits = 0
SN (Ks mag) ≥ 5

w4_sat= 0
w4_cc_map= 0
ext_flg = 0
SN (22 μm) ≥ 3

YES

YES   YES   YES

6,024,570   HSC sample   234,286   VIKING sample   9,439,990   WISE sample

In the overlap region with VIKING?   In the overlap region with VIKING?

3,414,154   YES   1,339   YES   13

Sample Selection

16,392,815 | mosaic_sourcelist__deepcoadd

14,773,385 | VIKING DR 1

747,634,026 | ALLWISE

① **Create the clean subsample**

flag_flags_pixel_edge is False
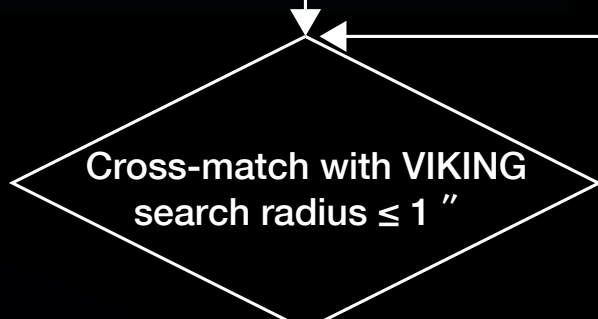flag_flags_pixel_saturated_center is False
flag_flags_pixel_cr_center is False

672,843 | YES

**Clean HSC
i-selected catalog**

**Clean VIKING
Ks-selected catalog**

**Clean WISE
22 µm-selected
catalog**

6,024,570 | HSC sample

234,286 | VIKING sample

9,439,990 | WISE sample

In the overlap region with VIKING?

In the overlap region with VIKING?

3,414,154 | YES

1,339 | YES

13

**Clean HSC
i-selected catalog**

**Clean VIKING
Ks-selected catalog**

**Clean WISE
22 μm-selected
catalog**

g?

?

3,414,154 | YES

1,339 | YES

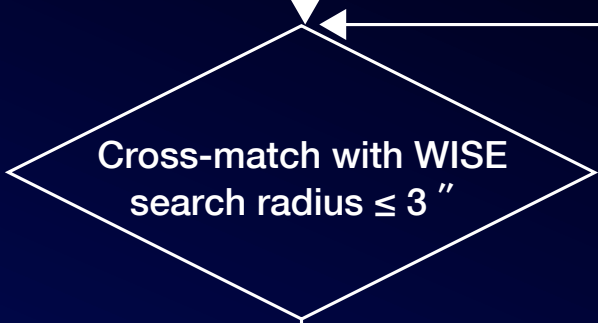Cross-match with VIKING
search radius ≤ 1 ″

178,062 | YES

i mag - ks mag ≥ 1.2

YES

83,910 | HSC-VIKING sample

Cross-match with WISE
search radius ≤ 3 ″

207 | YES

3,414,154 | YES

1,339 | YES

**Clean WISE
22 μm-selected
catalog**

Cross-match with VIKING
search radius ≤ 1 ″   ②

178,062 | YES

i mag - ks mag ≥ 1.2   ③

YES

83,910   HSC-VIKING sample

Cross-match with WISE
search radius ≤ 3 ″   ④

207 | YES

i mag - [22] ≥ 7.0   ⑤

YES

48   HSC-WISE DOGs

HSC-WISE DOGs (48)
HSC-WISE non-DOGs (159)

i − [22] [AB mag]

i − Ks [AB mag]

3,414,154 | YES

Cross-match with VIKING
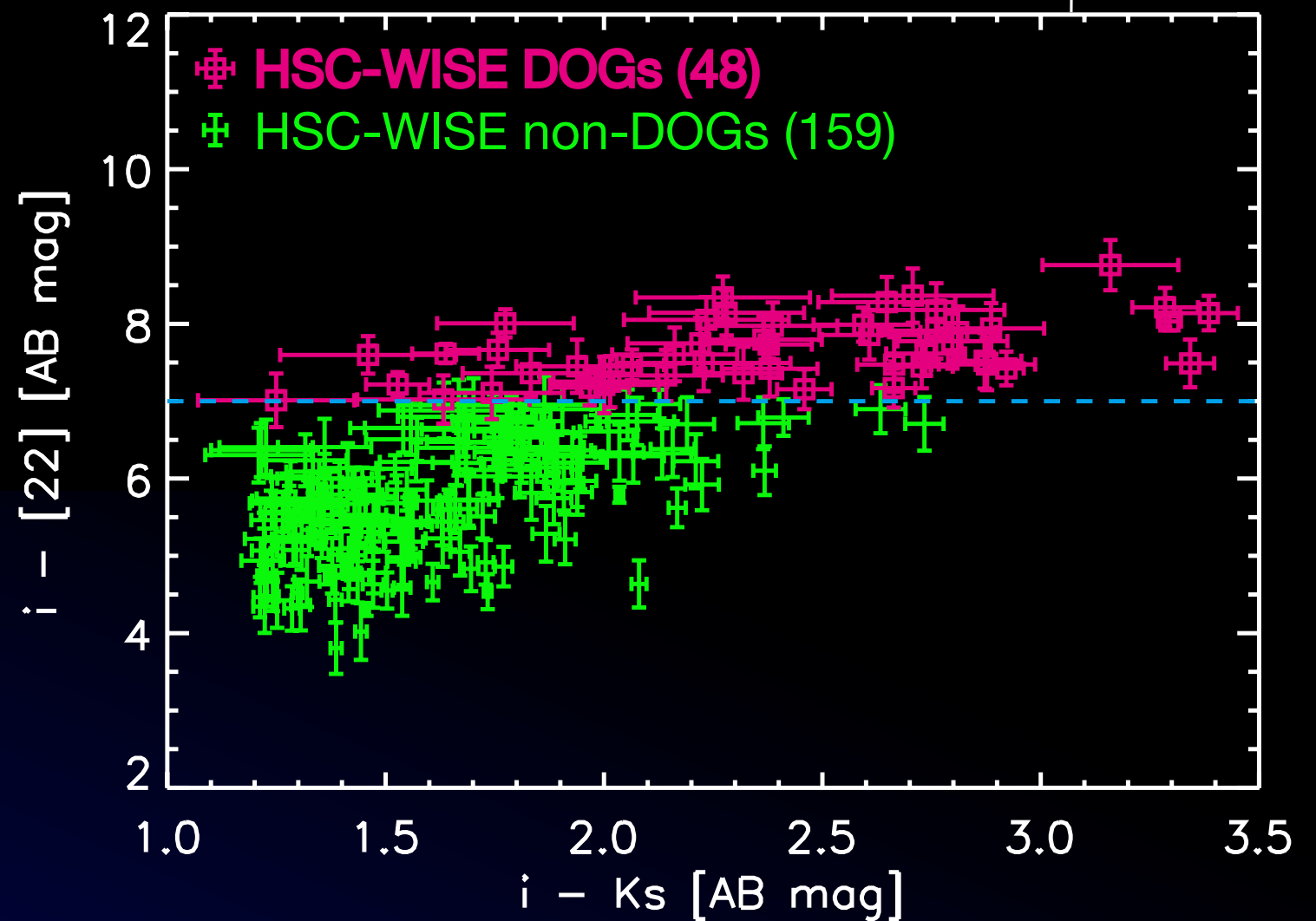search radius ≤ 1 ″   ②

178,062 | YES

i mag - ks mag ≥ 1.2   ③

YES

1,339 | YES

**Clean WISE
22 μm-selected
catalog**

48 IR-bright DOGs were selected

Cross-match with WISE
search radius ≤ 3 ″   ④

207 | YES

i mag - [22] ≥ 7.0   ⑤

YES

48   HSC-WISE DOGs

HSC-WISE DOGs (48)

$i - [22]$ [AB]

$i - Ks$ [AB mag]
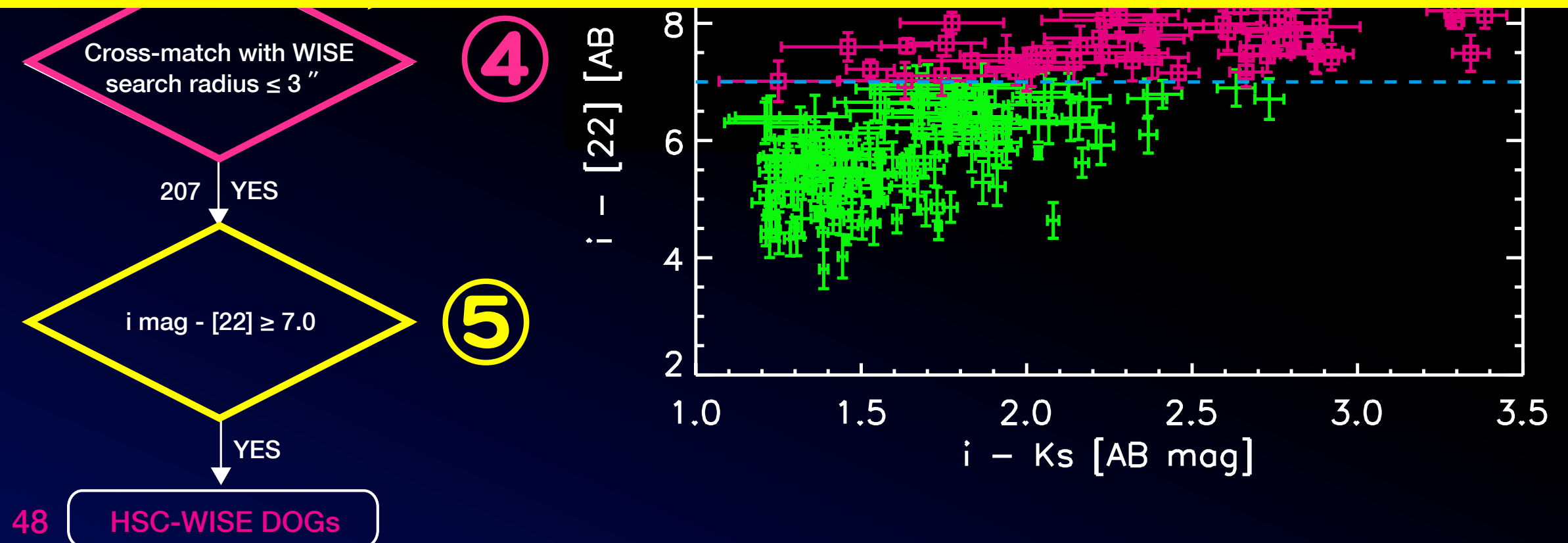
Type Classification (PL /Bump)

K_s-band excess

$$E_{Ks} = \frac{f_\nu(Ks)}{f_\nu^{\mathrm{fit}}(4, 6, 12, 22\ \mu\mathrm{m})}$$

f$_\nu$ [Jy]

K-band excess E$_{Ks}$

observed wavelength [μm]

$E_{Ks} < 3$: PL DOGs
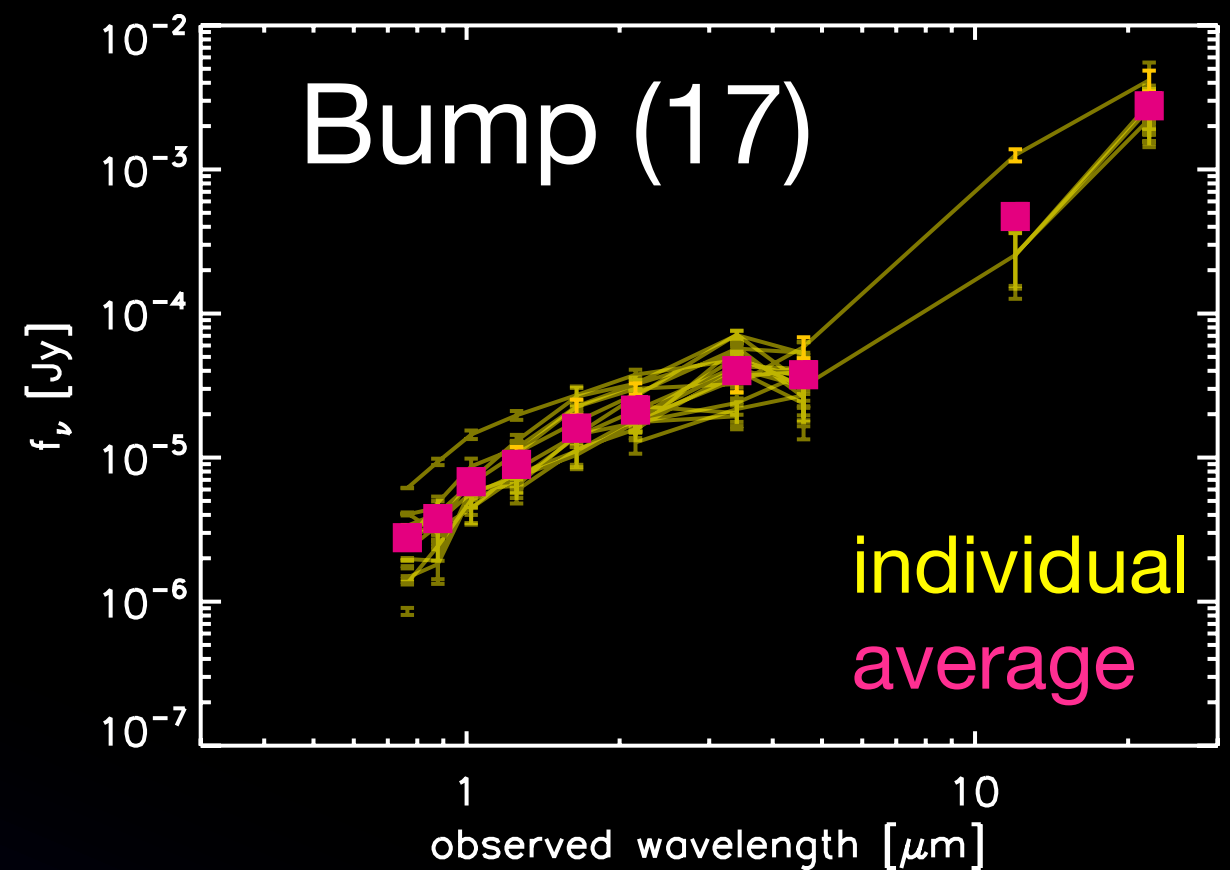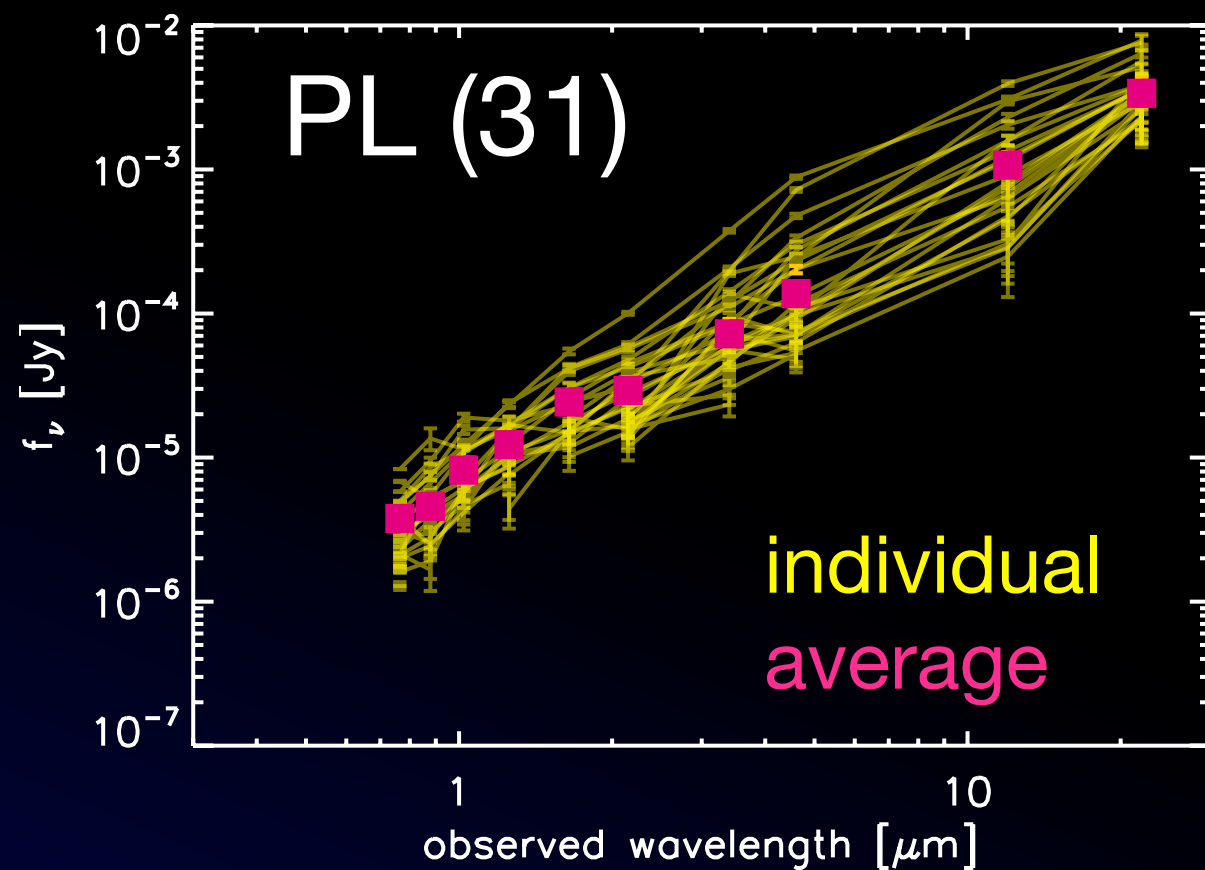
$E_{Ks} > 3$: Bump DOGs

16
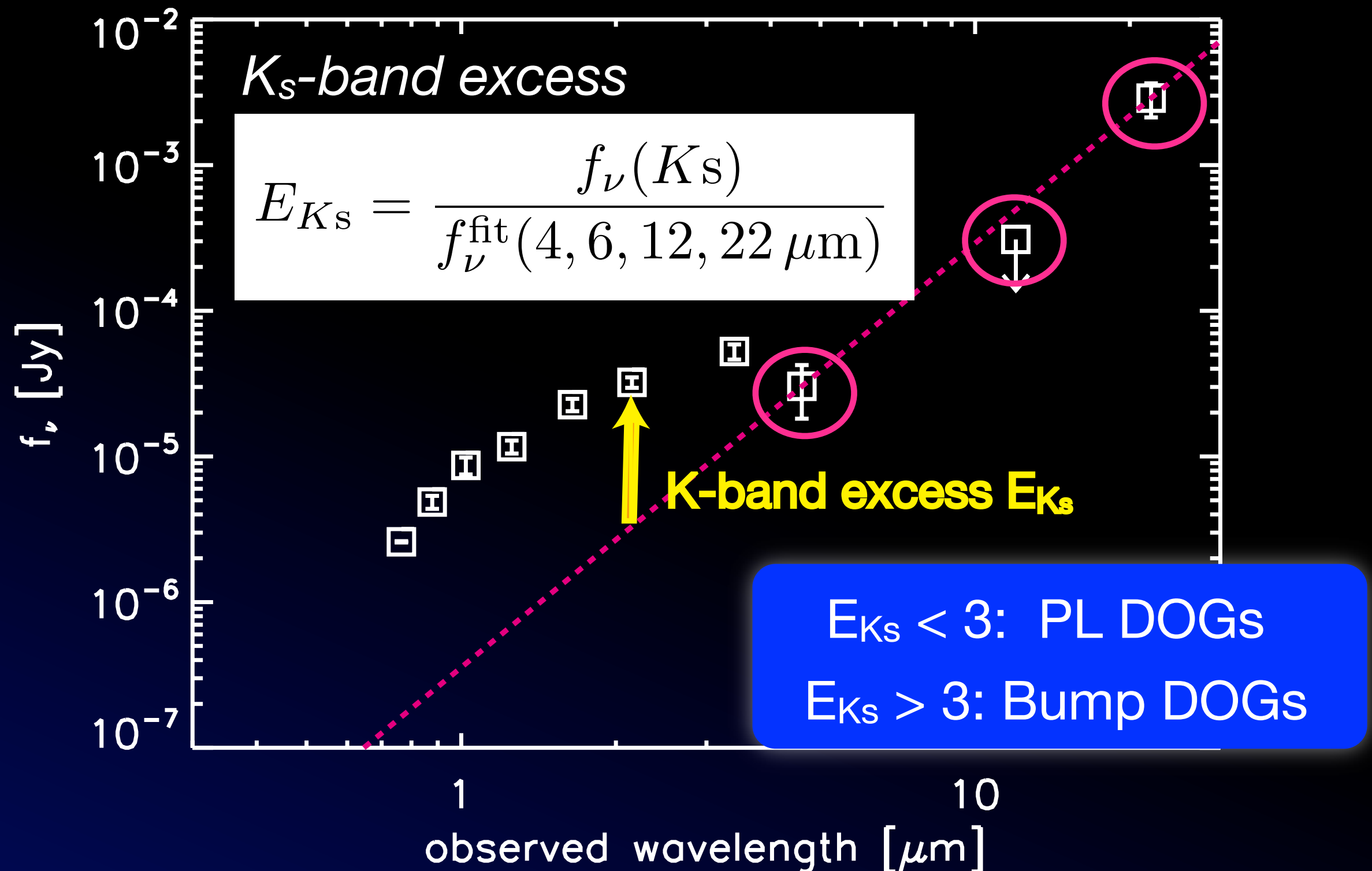
Results and Discussions

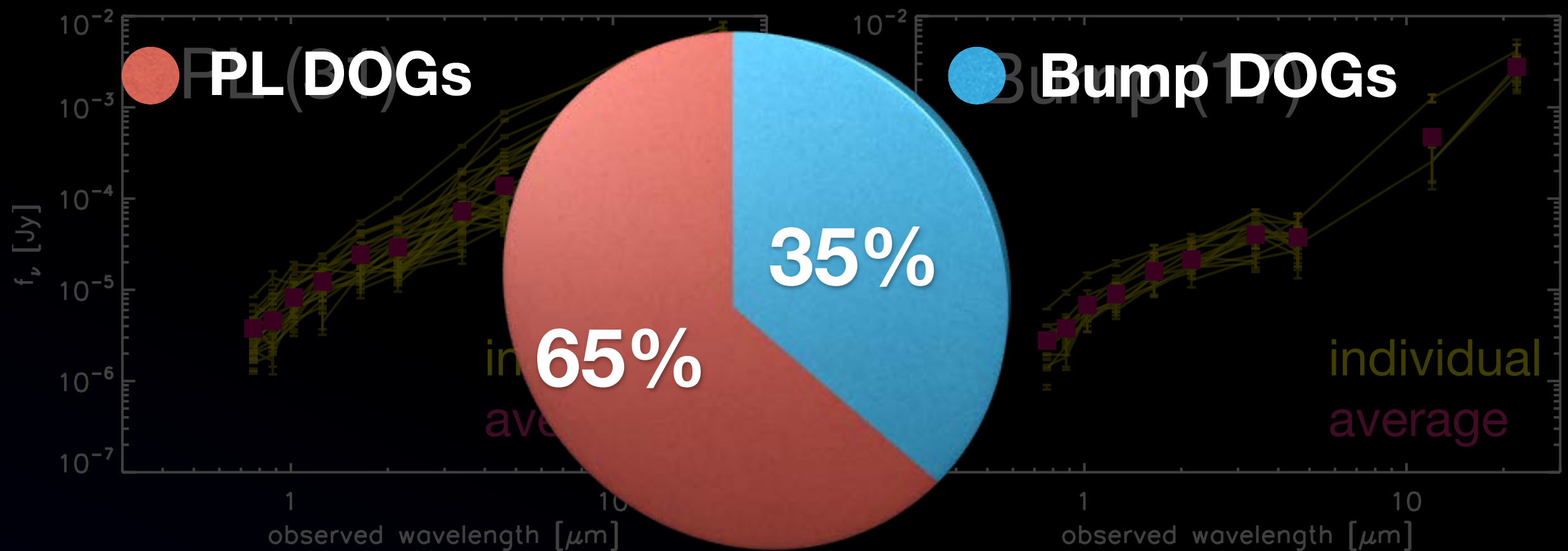## Photometric and Statistical properties of IR-bright DOGs

- Spectral Energy Distributions
- IR Luminosity Function
- IR Luminosity Density

SEDs for PL and Bump DOGs

SEDs for PL and Bump DOGs

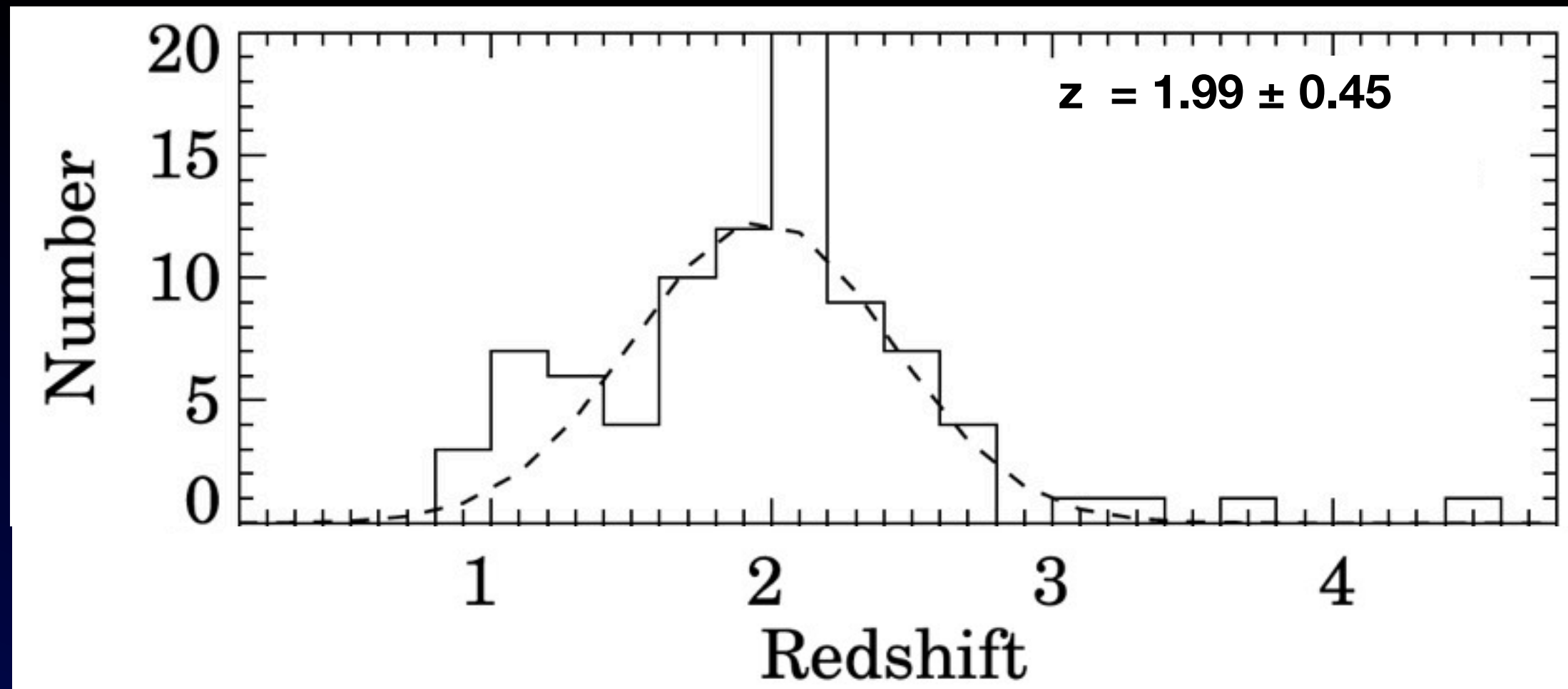**About 65% of our DOGs sample
were classified as PL DOGs**

Total IR luminosity function

Assuming that the redshift distribution for our DOG sample is Gaussian (z= 1.99 ± 0.45; Dey et al. 2008)

Dey+08

Total IR luminosity function

Assuming that the redshift distribution for our DOG sample is Gaussian (z= 1.99 ± 0.45; Dey et al. 2008)

$L_{IR}/\nu L_\nu$ (24μm) = 6.5 ± 1.4

Melbourne+12

Total IR luminosity function

Assuming that the redshift distribution for our DOG sample is Gaussian (z= 1.99 ± 0.45; Dey et al. 2008)

$$\phi(L)dL = \sum_i^N \frac{1}{V_{max}(i)}$$

log ϕ [Mpc^{-3}dex^{-1}]

log L$_{IR}$ [L$_\odot$]

☐ Calanog et al. 2013

★ This work (18 IR luminous DOGs)

Newly constrained by our study

Total IR luminosity function

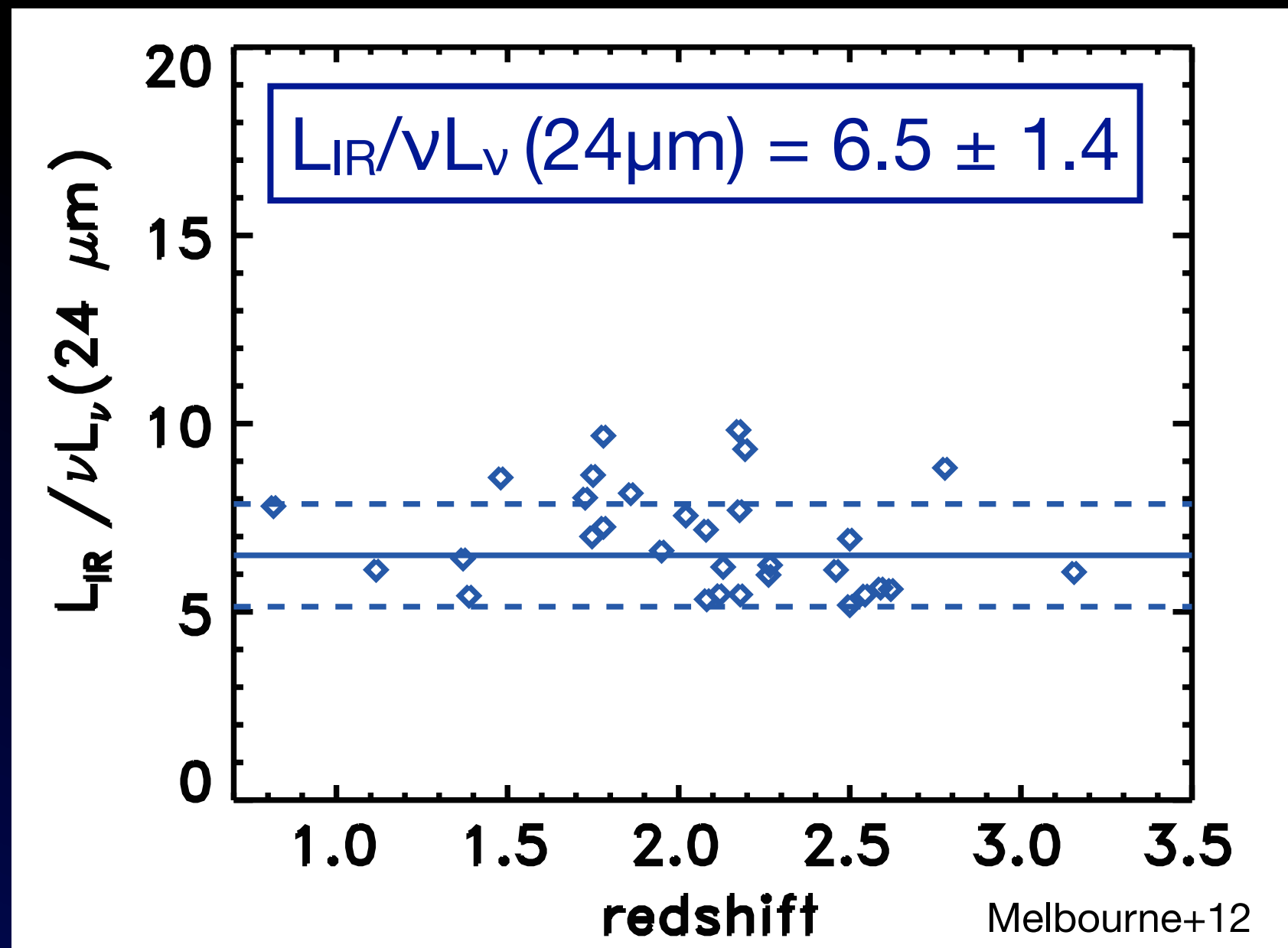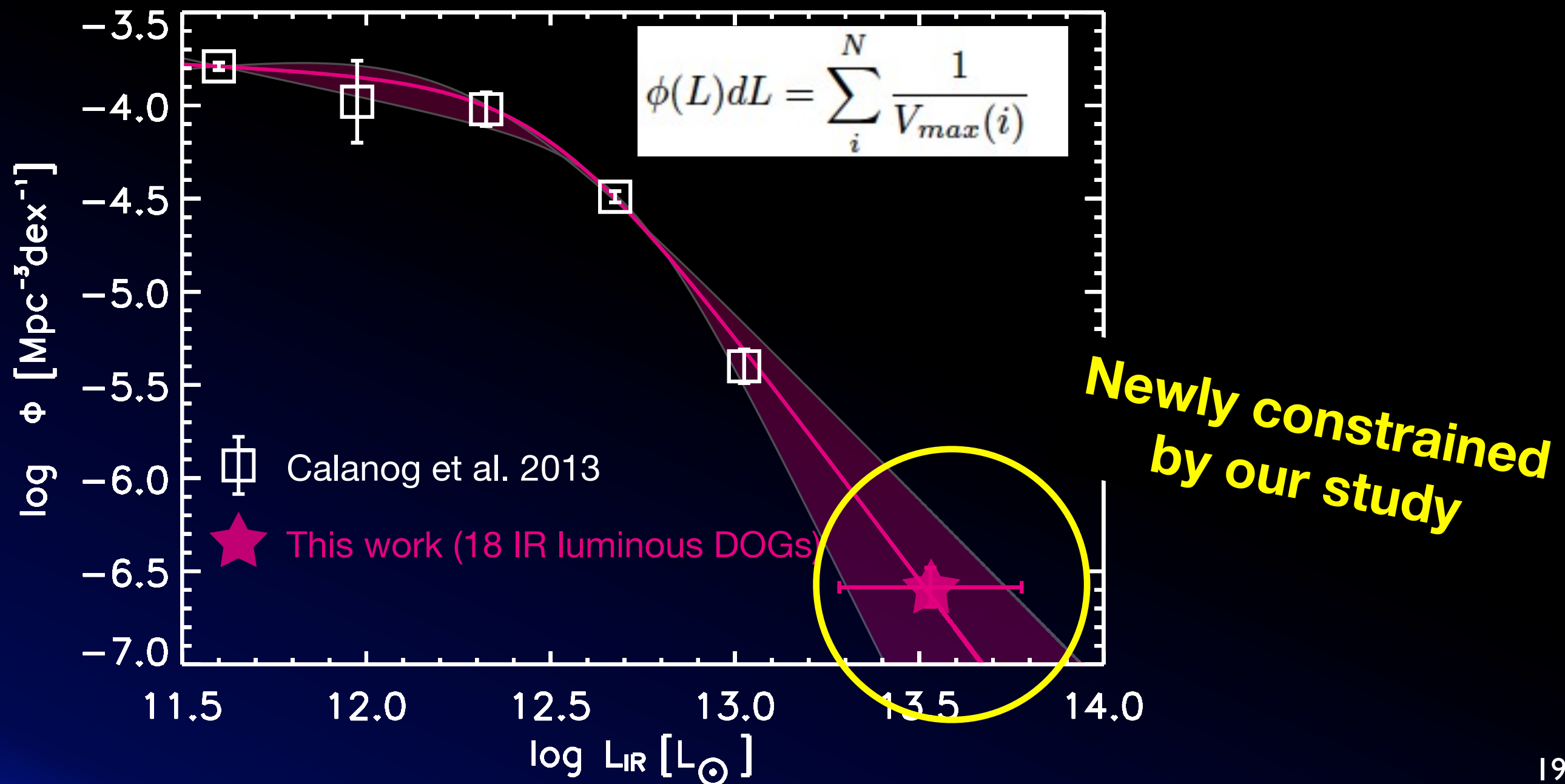Assuming that the redshift distribution for our DOG sample is Gaussian (z= 1.99 ± 0.45; Dey et al. 2008)

$$\phi(L)dL = \sum_{i}^{N} \frac{1}{V_{max}(i)}$$

The shape of LF can be fitted well by double-power law.

wly constrained by our study

$\log \phi$

−6.0   ☐ Calanog et al. 2013

−6.5   ★ This work (18 IR luminous DOGs)

−7.0

11.5   12.0   12.5   13.0   13.5   14.0

$\log L_{IR} [L_{\odot}]$

Total IR luminosity density ρ_{IR}

$$\rho_{IR} = \int L_{IR}\phi(L)\mathrm{d}L$$

Legend:
- ✳ Murphy et al. 2011 (M11)
- ☐ Dey et al. 2008
- ☐ This work (DOGs)
- ★ This work (IR-bright DOGs)
- ULIRGs (M11)
- AGNs (M11)

Newly constrained by our study

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Total IR luminosity density ρ_{IR}

✳ Murphy et al. 2011 (M11)   ⊡ Dey et al. 2008

☐ This work (DOGs)

★ This work (IR-bright DOGs)
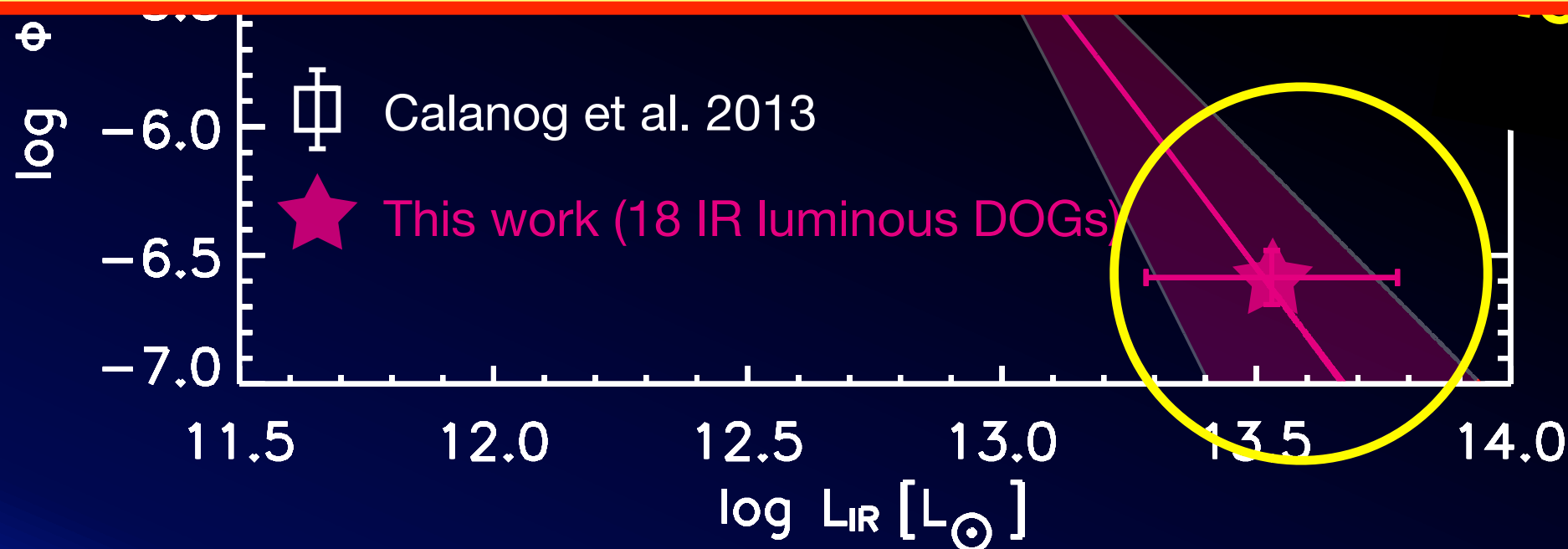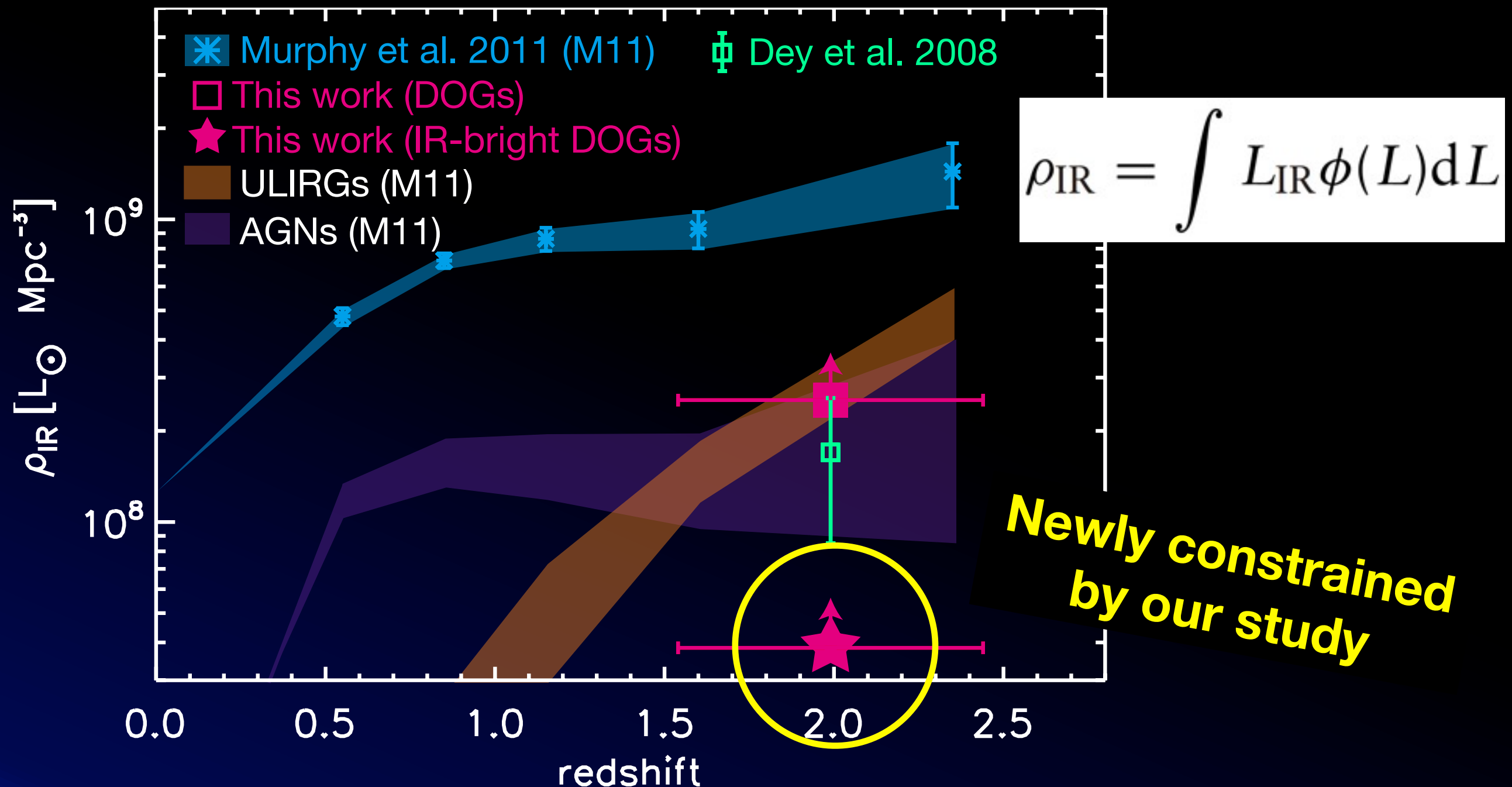
The contribution of ρ_{IR} (IR-bright DOGs) to that of other populations;

ρ_{IR} (ULIRGs @z~2): > 9%

ρ_{IR} (All DOGs @ z~2): > 15%

by our study

redshift

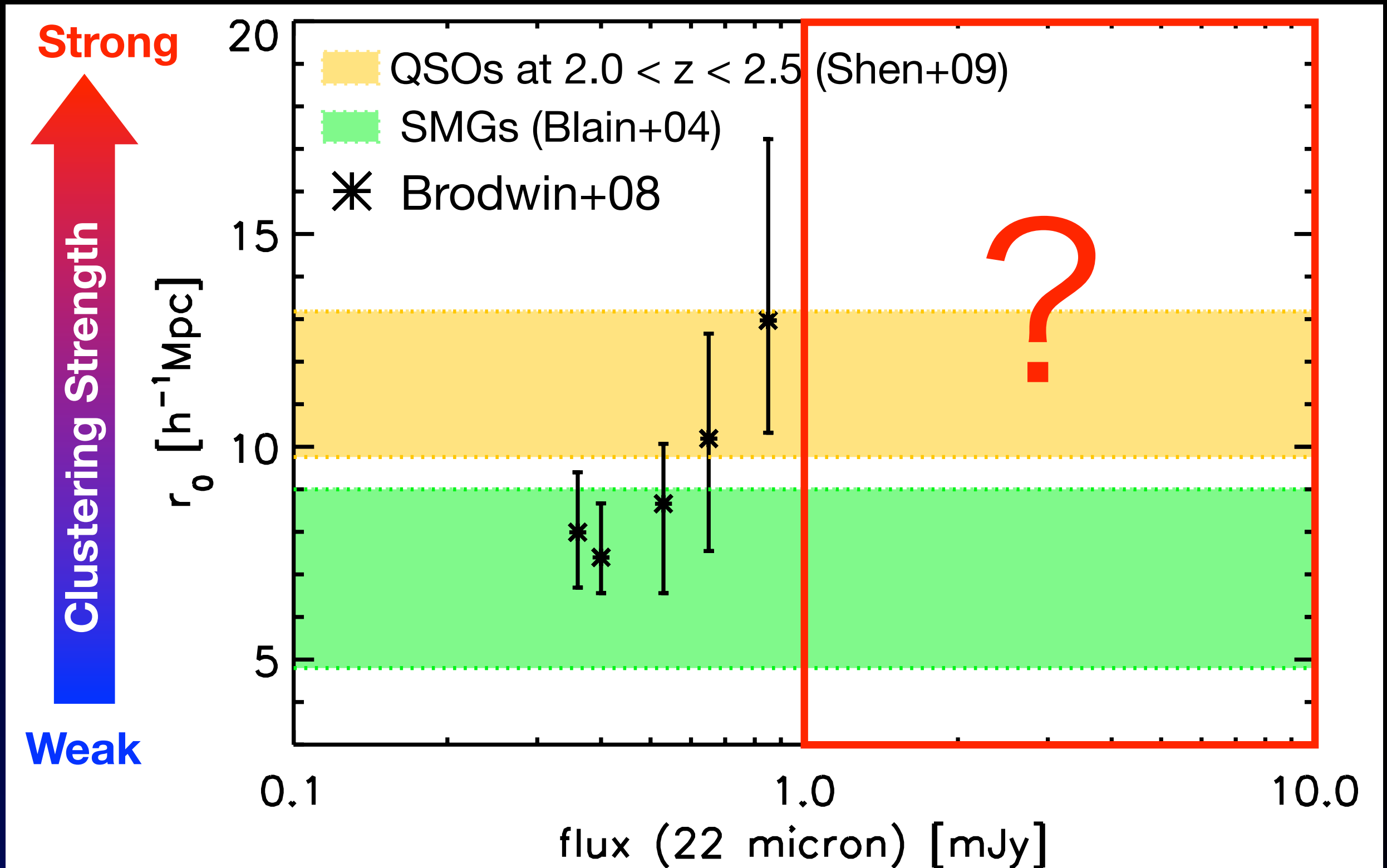# Current Status of DOGs search

Search for IR-bright DOGs based on latest dataset

Clustering properties of IR-bright DOGs discovered by HSC S15B and ALLWISE

Toba, Nagao, Kajisawa et al. in prep.

Field Selection -5/7 fields~

Random points

1411 IR-bright DOGs were selected

Spatial Distribution of DOGs

23

Auto Correlation Function of DOGs

ACF: $\omega(\theta) = A_\omega\ \theta^{-\beta}$

$\beta = 0.9$ (Brodwin+08)

$A_\omega = 11.3 \pm 3.72$

Spatial Distribution of DOGs
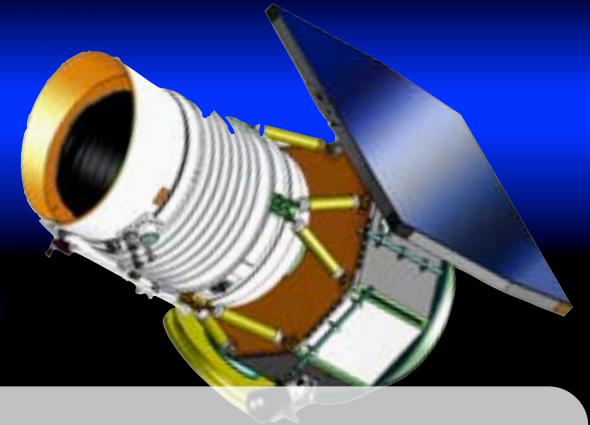
Spatial Distribution of DOGs

Summary

- We **newly discovered 48 DOGs based on the HSC, VIKING, and WISE** data.

- Assuming that the redshift distribution for our DOGs sample (z = 1.99 ± 0.45), we derived the space density of them. The IR LF including data obtained from the literature is fitted well by a double-power law.

- We also derived lower limit of IR LD for our sample, and its contributions to the ρ_{IR} (ULURGs) and ρ_{IR} (All DOGs) are >9%, and >15%, respectively

- The clustering analysis of 1,411 DOGs discovered by latest dataset could indicates that **they are strongly clustered.**

I ♥ DOGs