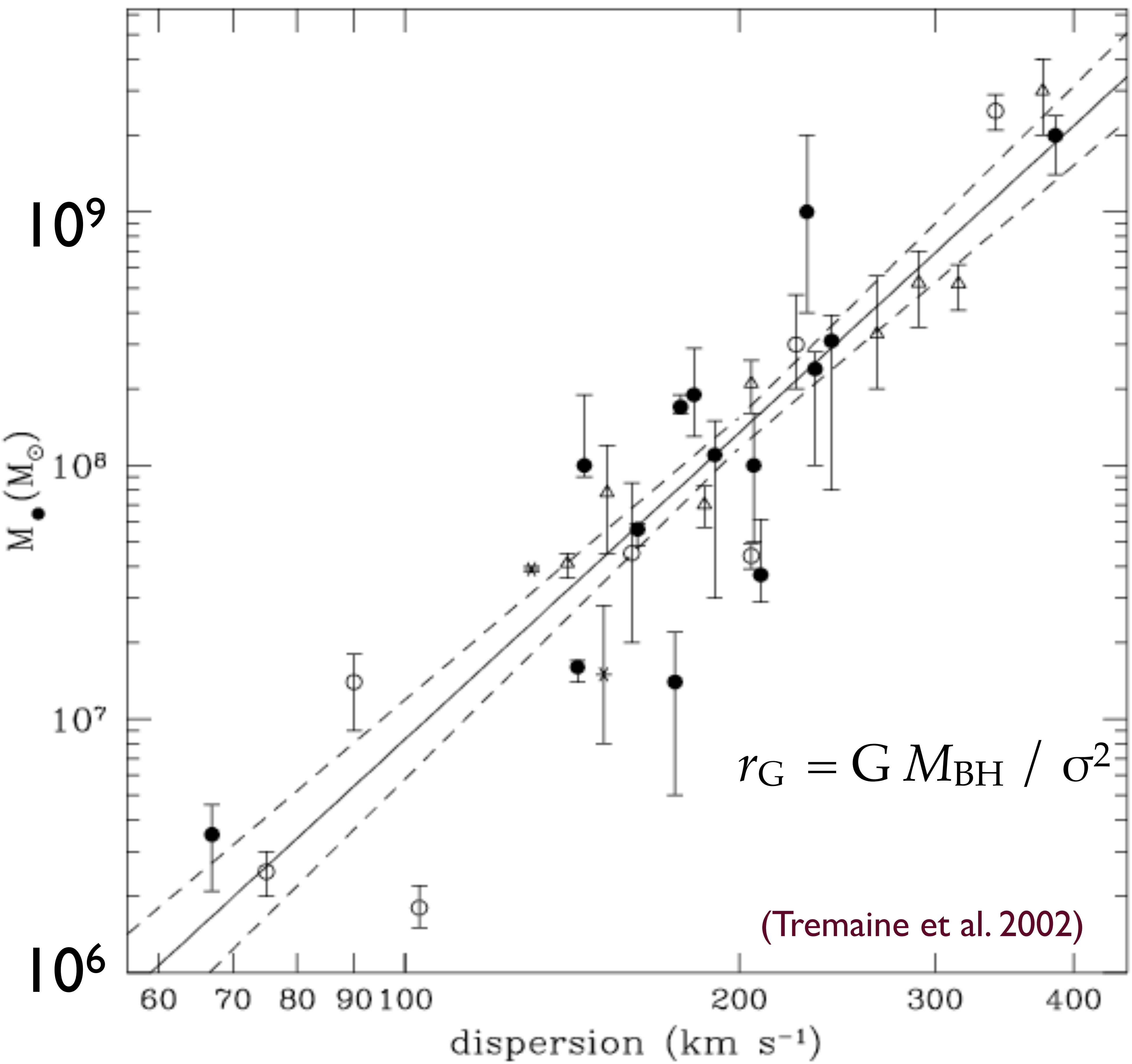
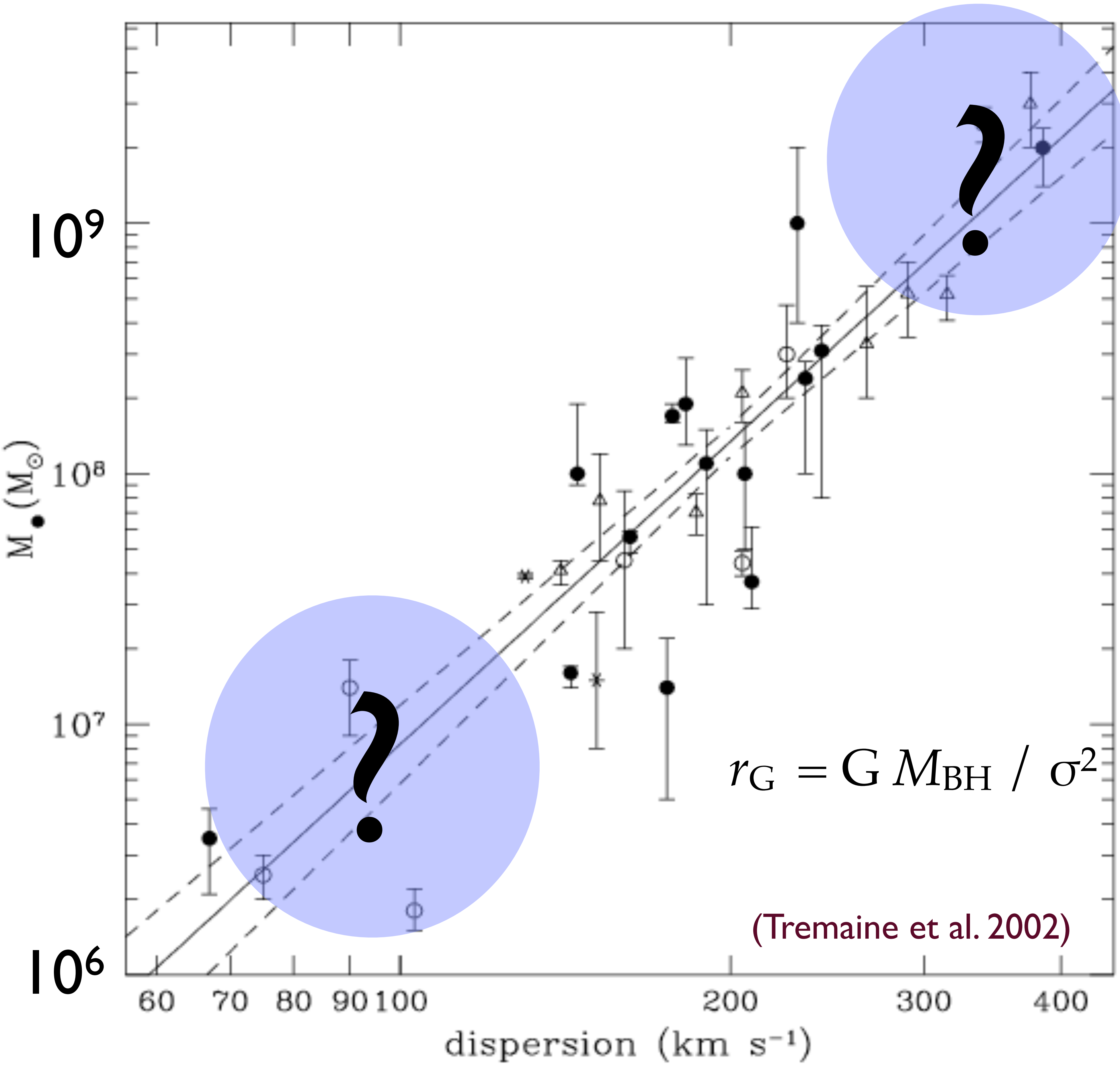
# Black Hole Demographics and The Future

Jenny Greene (Princeton)

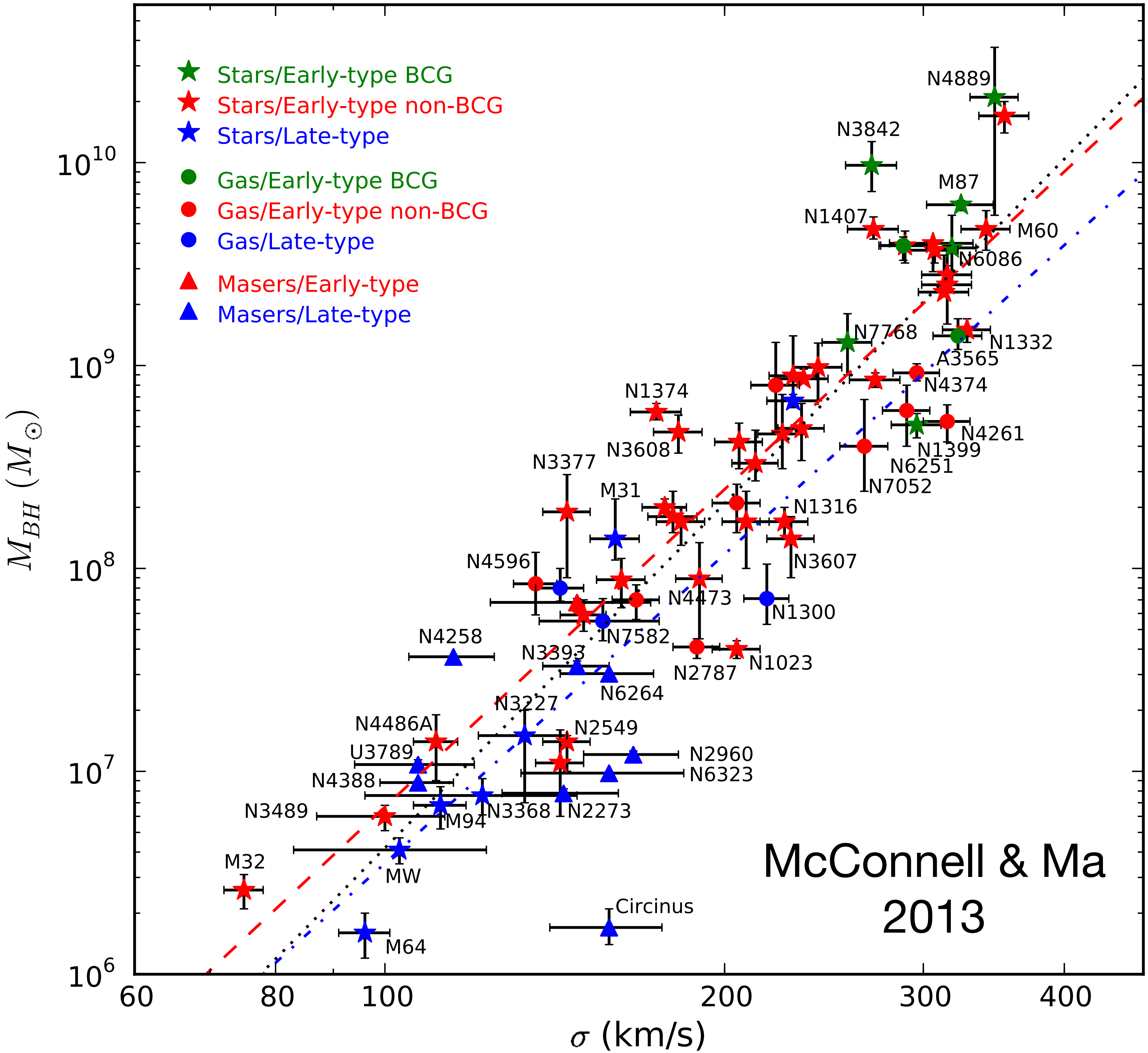



$$r_G = G\, M_{BH} \,/\, \sigma^2$$

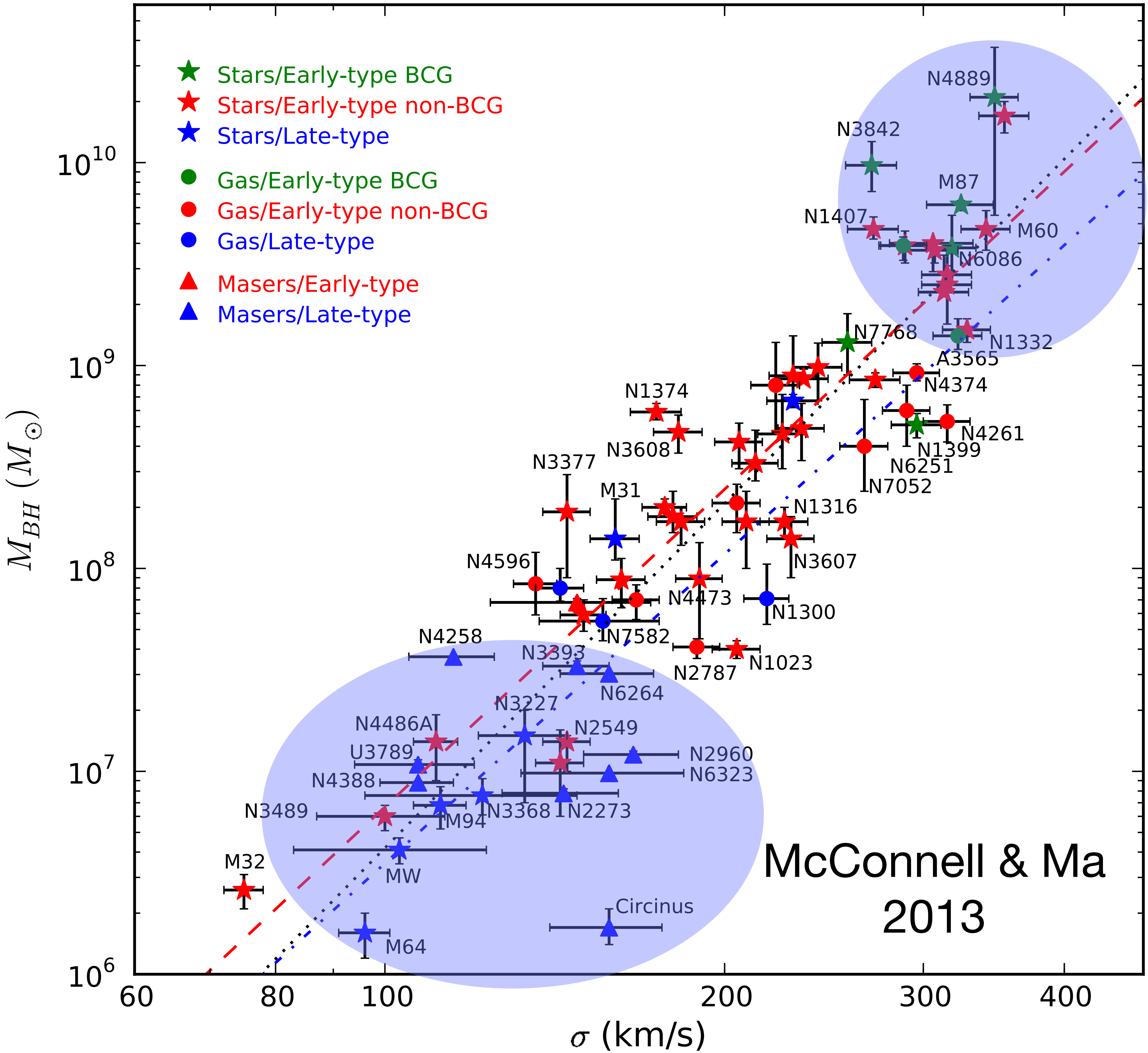
(Tremaine et al. 2002)



10^9
10^6
10^8
10^7
M• (M☉)
60
70
80
90
100
200
300
400
dispersion (km s⁻¹)
?
?
$r_G = G\, M_{BH} / \sigma^2$
(Tremaine et al. 2002)



Stars/Early-type BCG
Stars/Early-type non-BCG
Stars/Late-type
Gas/Early-type BCG
Gas/Early-type non-BCG
Gas/Late-type
Masers/Early-type
Masers/Late-type
N4889
N3842
M87
N1407
M60
N6086
N7768
N1332
A3565
N4374
N1374
N3608
N4261
N1399
N6251
N7052
N3377
M31
N1316
N3607
N4596
N4473
N1300
N7582
N4258
N3393
N2787
N1023
N6264
N3227
N4486A
N2549
U3789
N2960
N6323
N4388
N3489
M94
N3368
N2273
M32
MW
M64
Circinus
McConnell & Ma
2013
$10^{10}$
$10^9$
$10^8$
$10^7$
$10^6$
60
80
100
200
300
400
$M_{BH}$ ($M_\odot$)
$\sigma$ (km/s)



Stars/Early-type BCG
Stars/Early-type non-BCG
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Gas/Early-type BCG
Gas/Early-type non-BCG
Gas/Late-type
Masers/Early-type
Masers/Late-type
$M_{BH}$ ($M_\odot$)
σ (km/s)
$10^{6}$
$10^{7}$
$10^{8}$
$10^{9}$
$10^{10}$
60
80
100
200
300
400
N4889
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M94
N3368
N2273
M32
MW
M64
Circinus
McConnell & Ma
2013

# Megamaser Disk Galaxies

Ai-Lei Sun (Princeton graduate student), Anil Seth (Utah), Ronald Laesker (MPIA)

Feng Gao (NRAO), Cheng-Yu Kuo (ASIAA), James Braatz, Fred Lo, James Condon (NRAO)

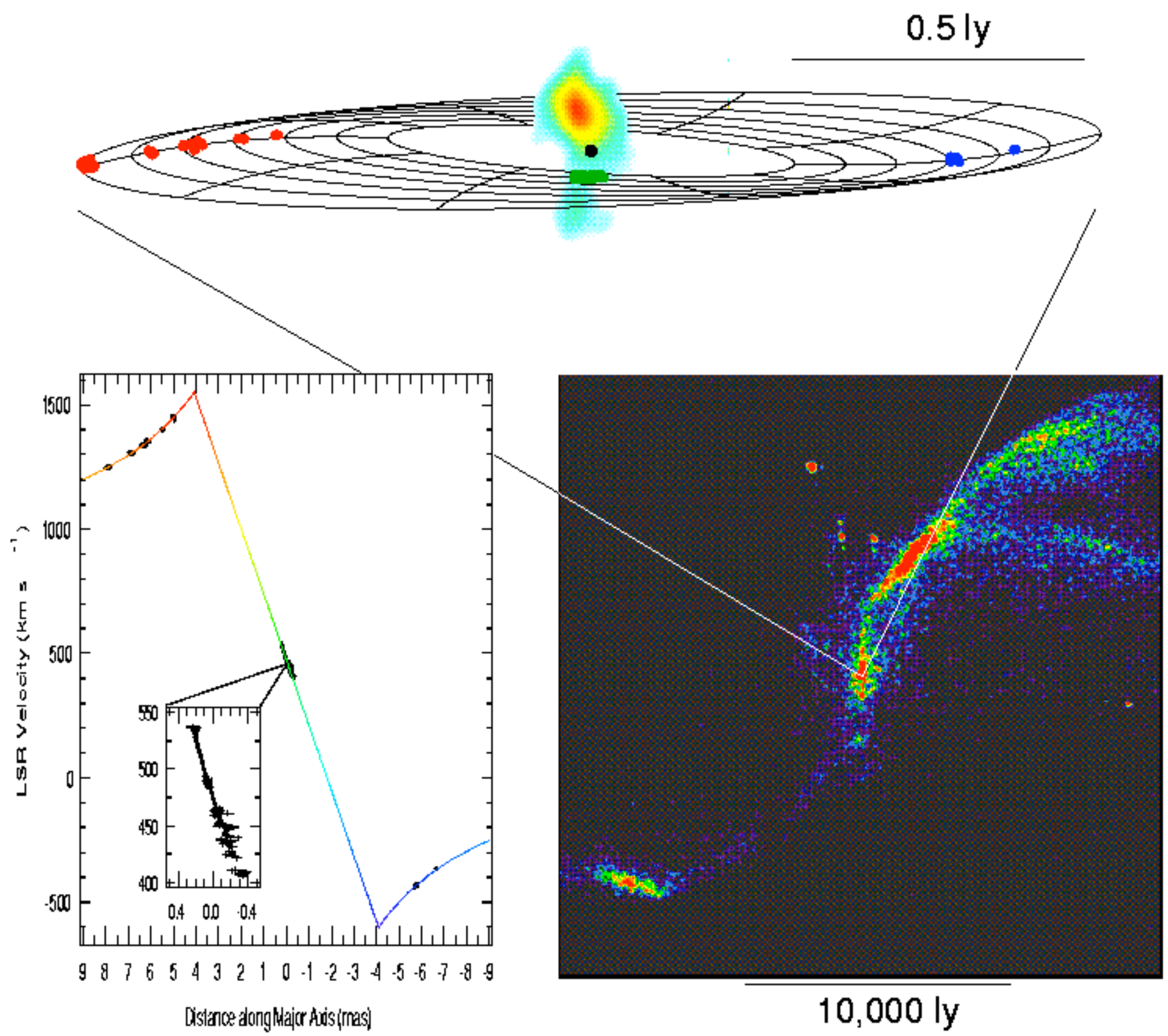
# NGC 4258

$H_2O$ megamasers (microwave amplification by stimulated emission; $10^2$-$10^4$ $L_\odot$) as dynamical tracers

Very precise BH mass (3.9±0.1 x $10^7$ $M_\odot$), relatively free of systematic bias

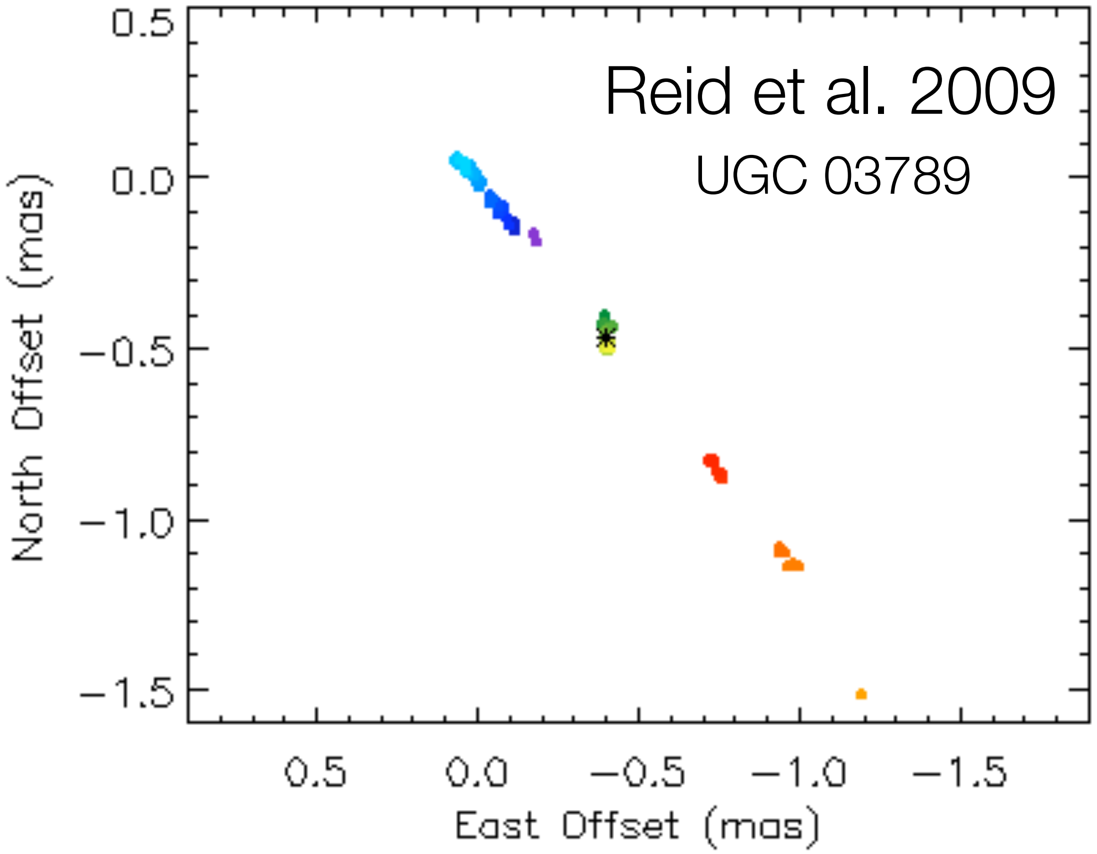
With accelerations, also measure an independent distance

Along with MW, best case to rule out astrophysical alternatives to SMBH (e.g., Maoz et al. 1995, 1998)



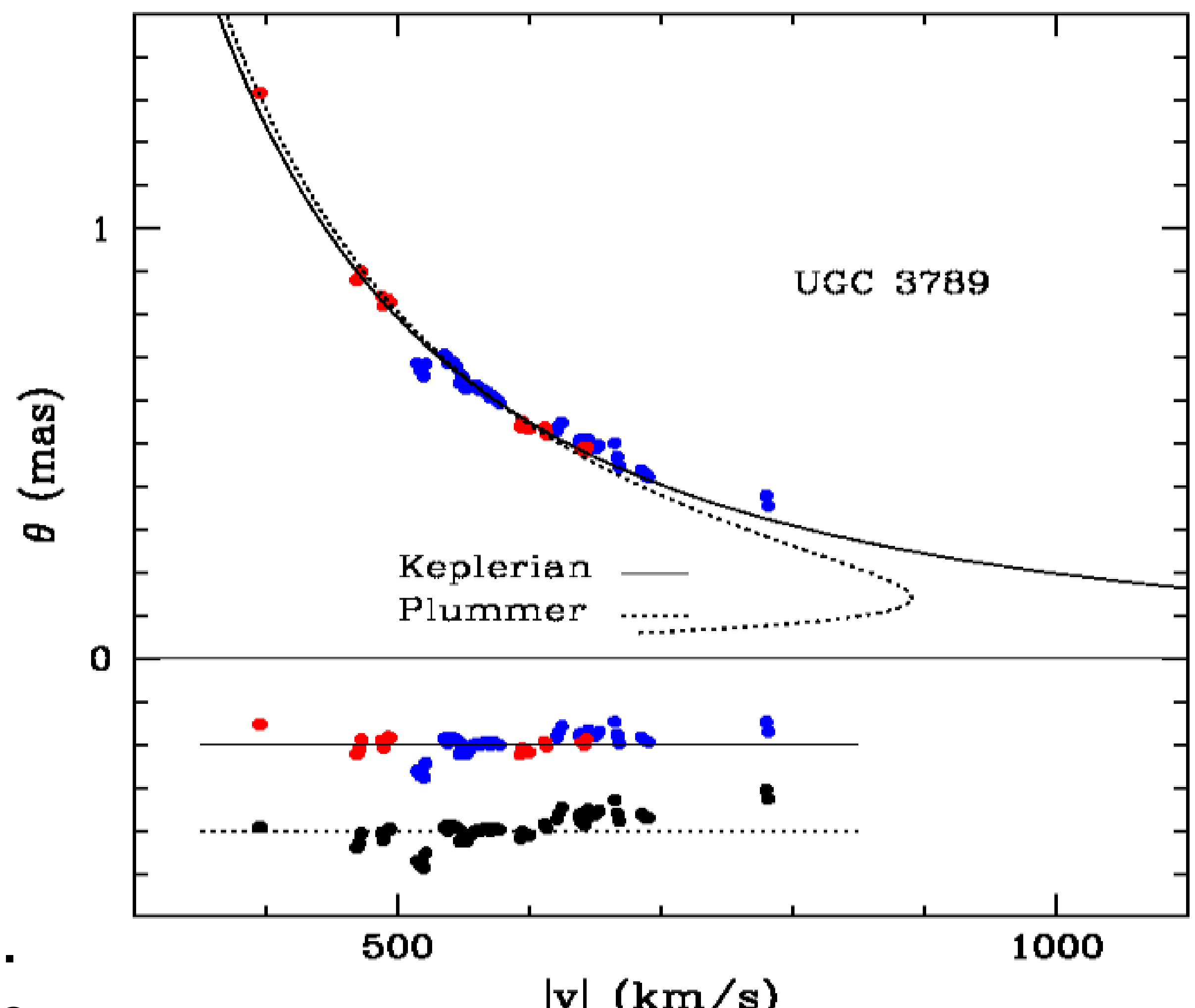

Miyoshi et al., Herrnstein et al., Greenhill, Humphreys, Moran
galaxy is ~7 Mpc away

# VLBI

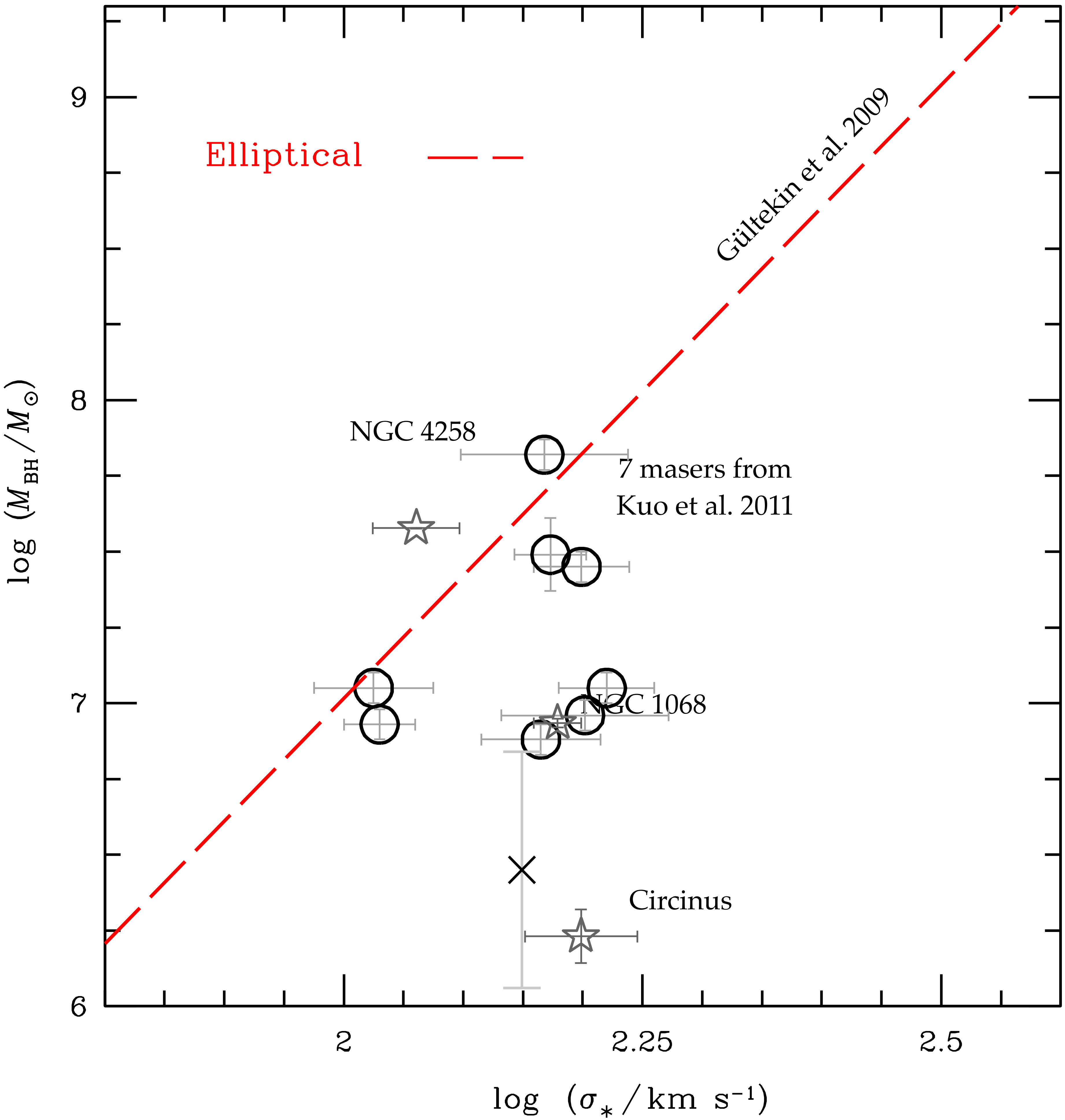



Spatial distribution on the sky reveals an edge-on disk

Rotation curves reveal Keplerian rotation around a (very) compact object

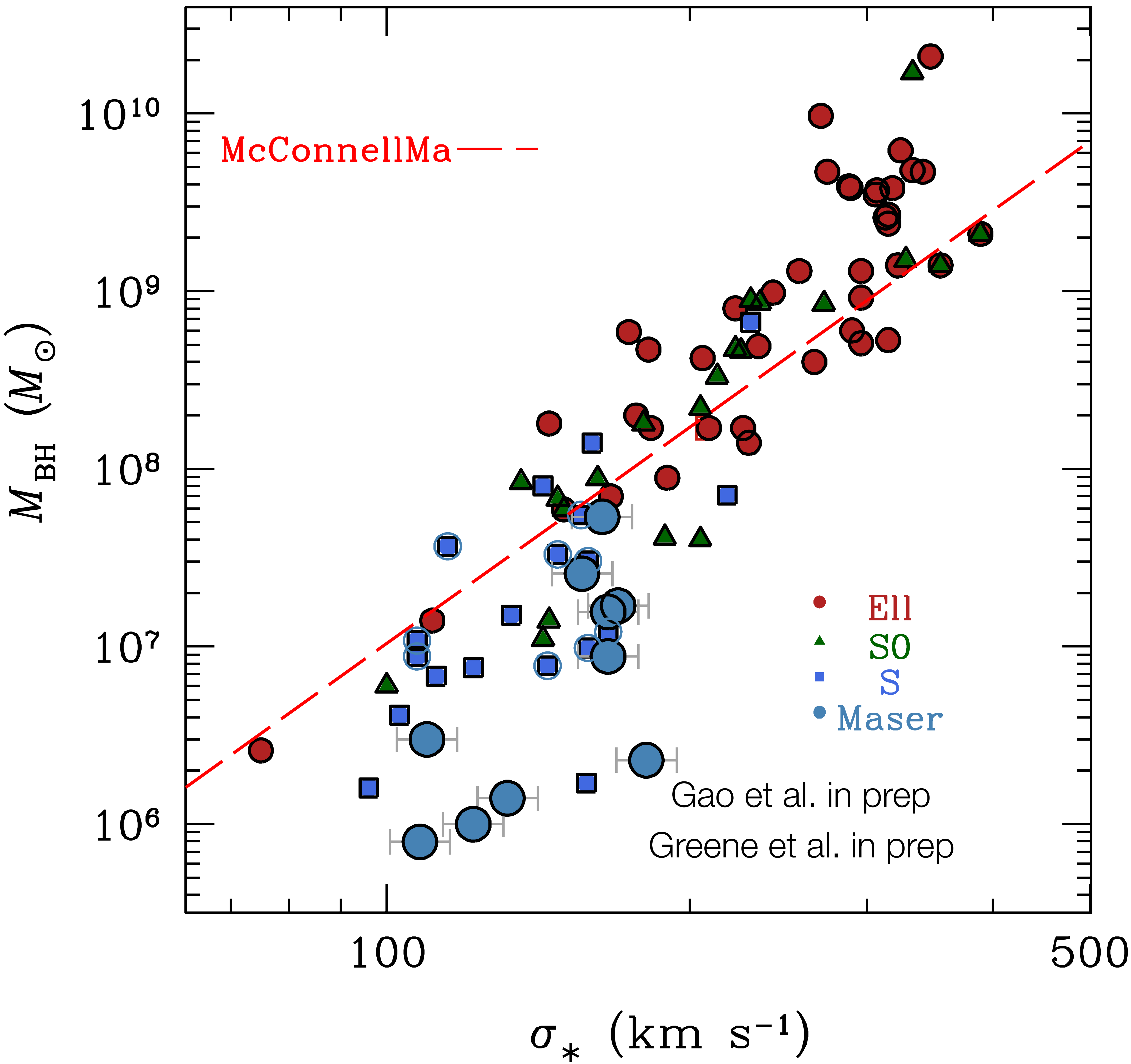



Kuo et al. 2011 presents 7 new BH masses.
Gao, Braatz, et al. in prep will present 5 more.

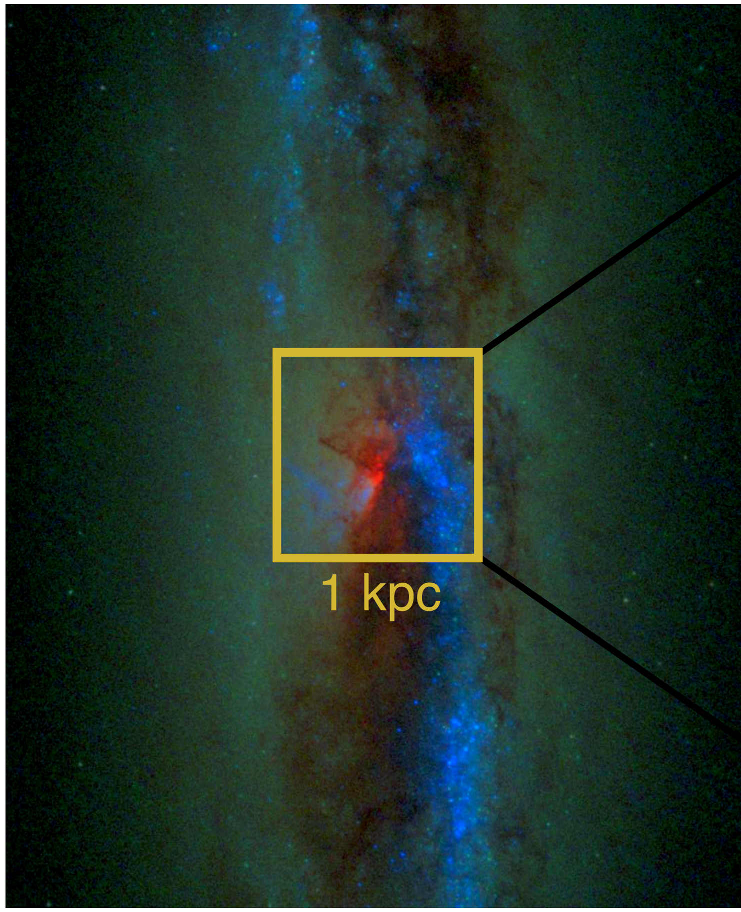



See also Hu 2008,
Gadotti & Kauffman 2008,
Kormendy et al. 2011

Greene et al. 2010

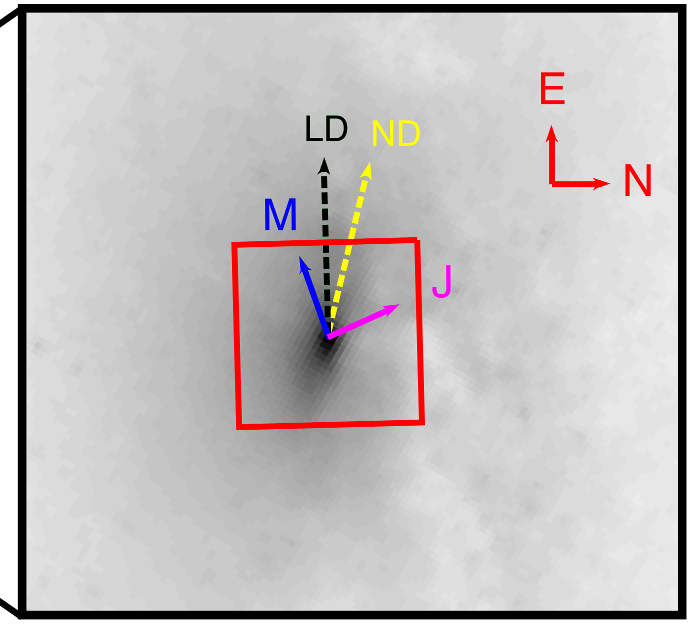


$10^{10}$
$10^{9}$
$10^{8}$
$10^{7}$
$10^{6}$
$M_{BH}$ $(M_\odot)$
McConnellMa
Ell
S0
S
Maser
Gao et al. in prep
Greene et al. in prep
100
500
$\sigma_*$ (km $s^{-1}$)

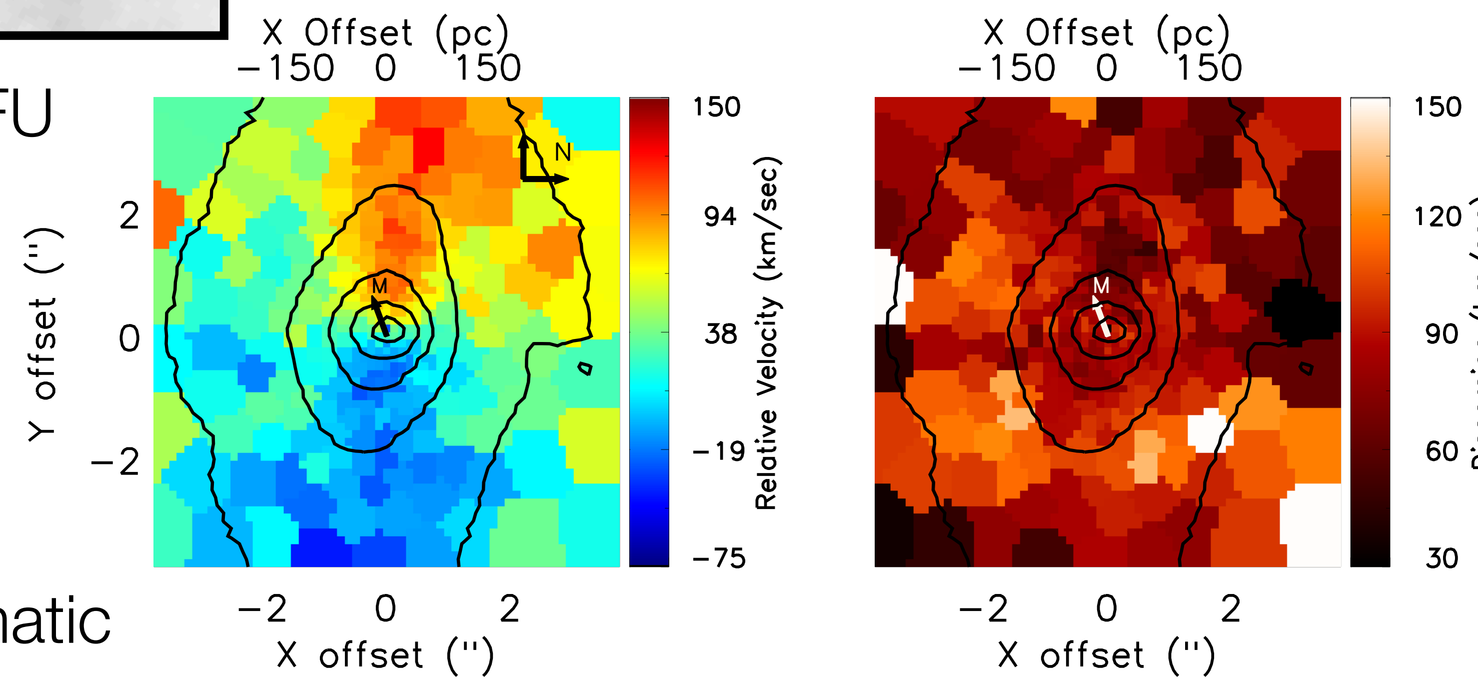



NGC 4388
(Virgo)

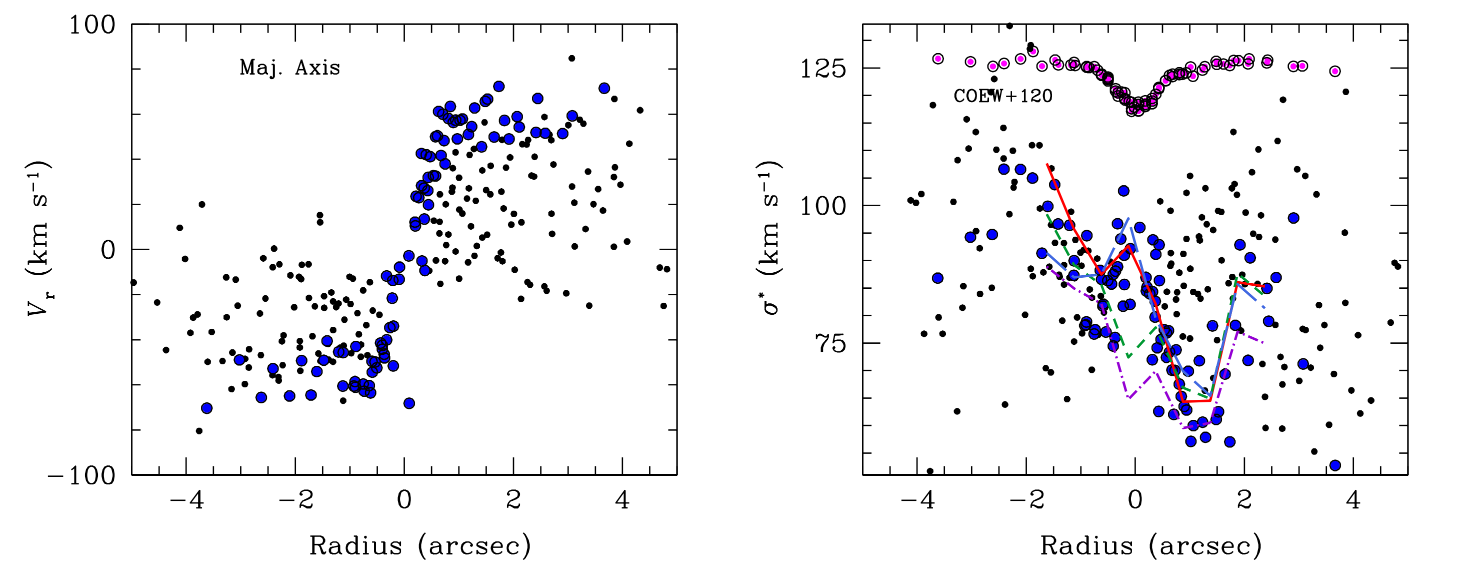
Greene et al. 2014

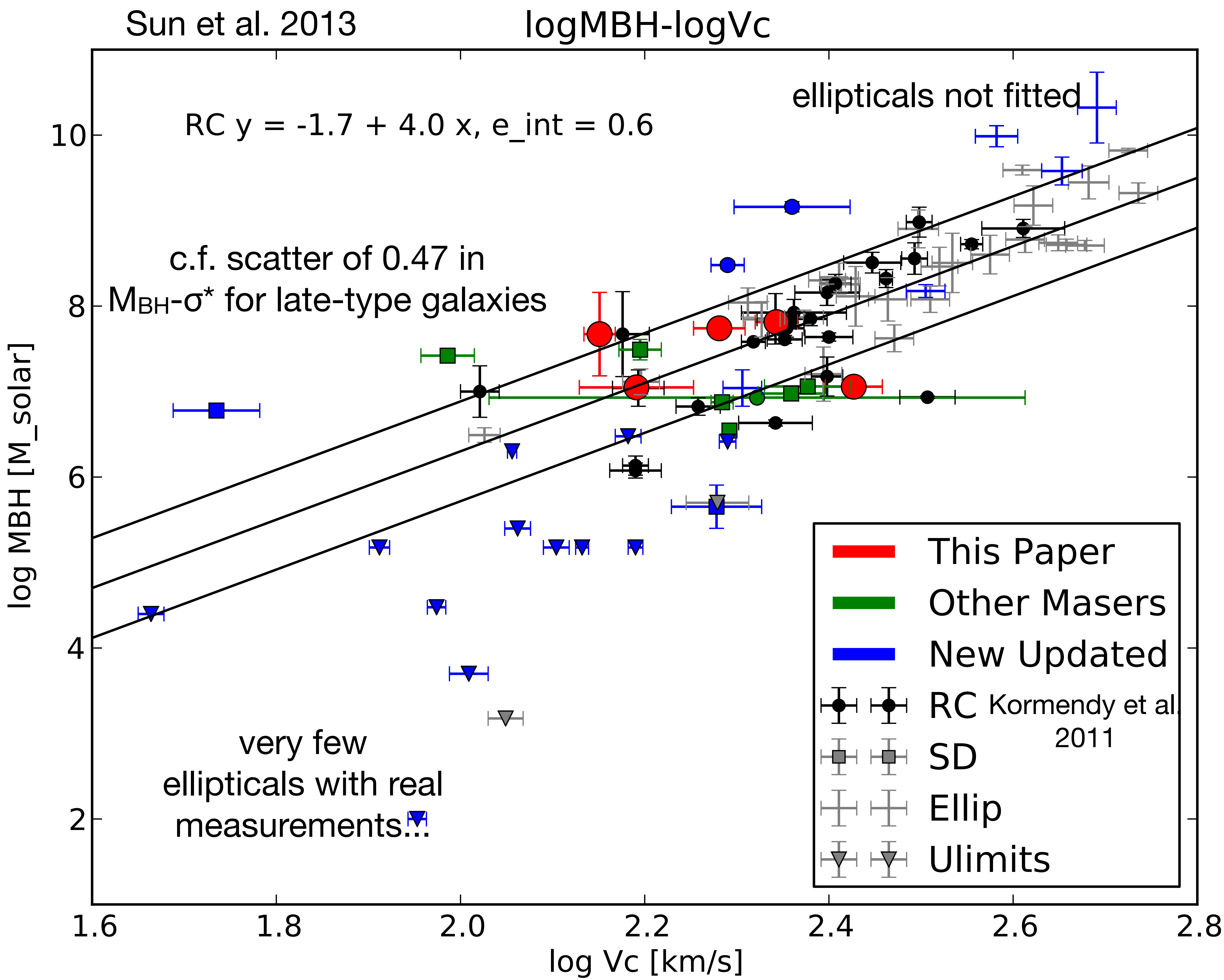



SINFONI IFU

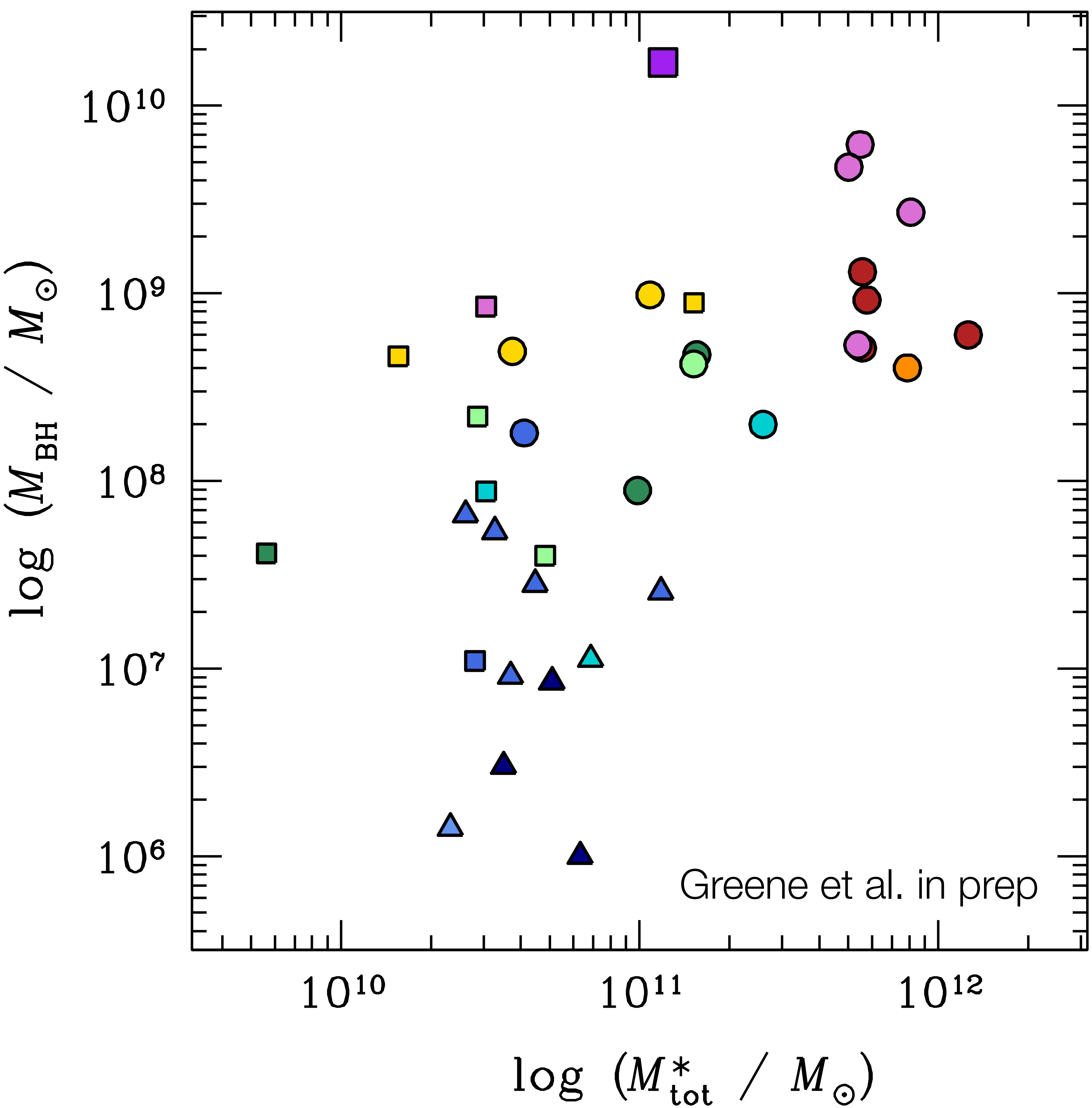



Stellar Kinematic
Fields





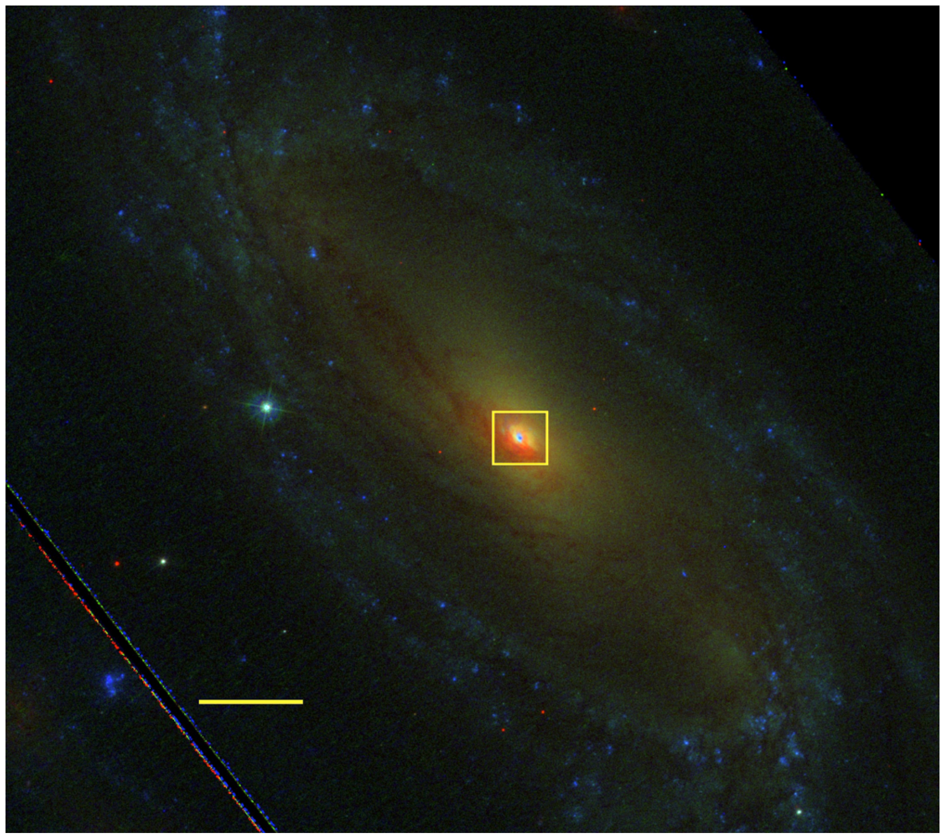
Sun et al. 2013
logMBH-logVc
RC y = -1.7 + 4.0 x, e_int = 0.6
ellipticals not fitted
c.f. scatter of 0.47 in
MBH-σ* for late-type galaxies
very few
ellipticals with real
measurements...
This Paper
Other Masers
New Updated
RC
Kormendy et al.
2011
SD
Ellip
Ulimits
log MBH [M_solar]
log Vc [km/s]
1.6
1.8
2.0
2.2
2.4
2.6
2.8
2
4
6
8
10

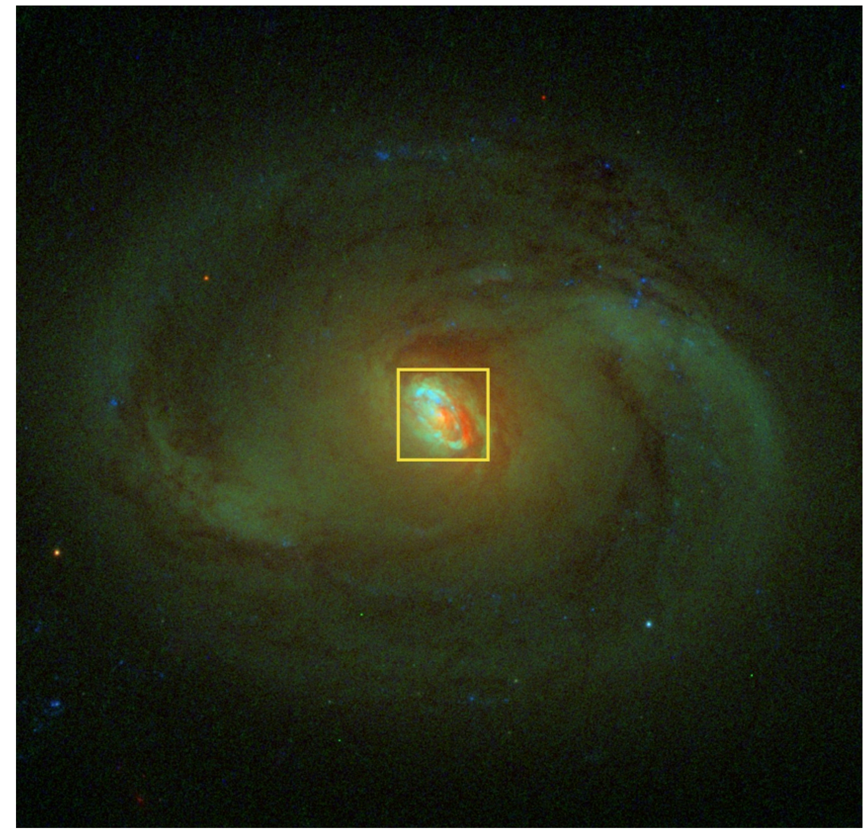


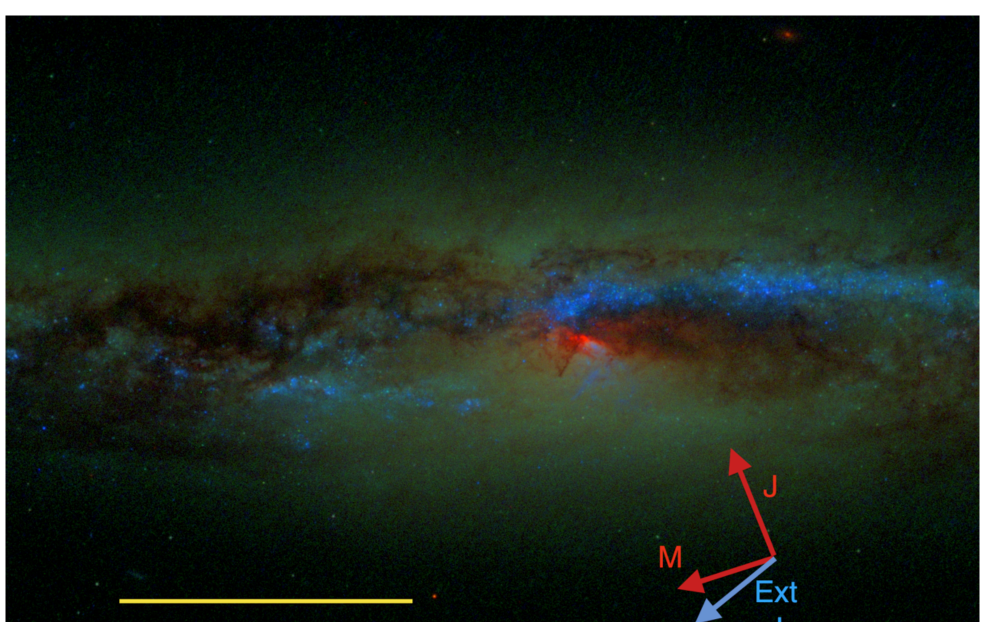
$10^{10}$
$10^{9}$
$10^{8}$
$10^{7}$
$10^{6}$
$\log\ (M_{\rm BH}\ /\ M_\odot)$
Greene et al. in prep
$10^{10}$
$10^{11}$
$10^{12}$
$\log\ (M^*_{\rm tot}\ /\ M_\odot)$

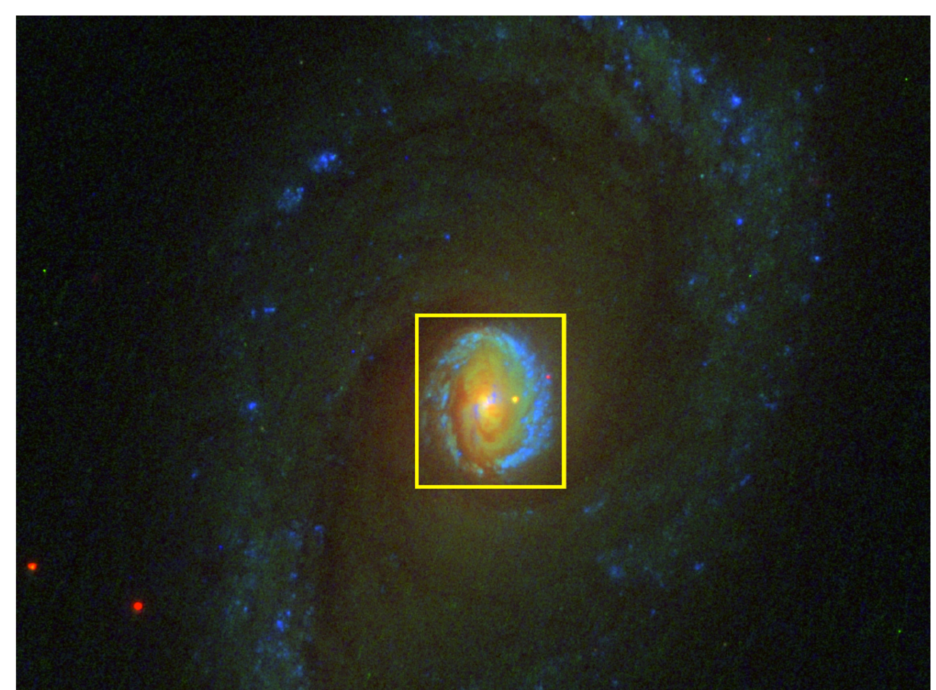
# Also $M_{BH}$-$M_{bulge}$...

Laesker, Greene, Seth, et al. in prep

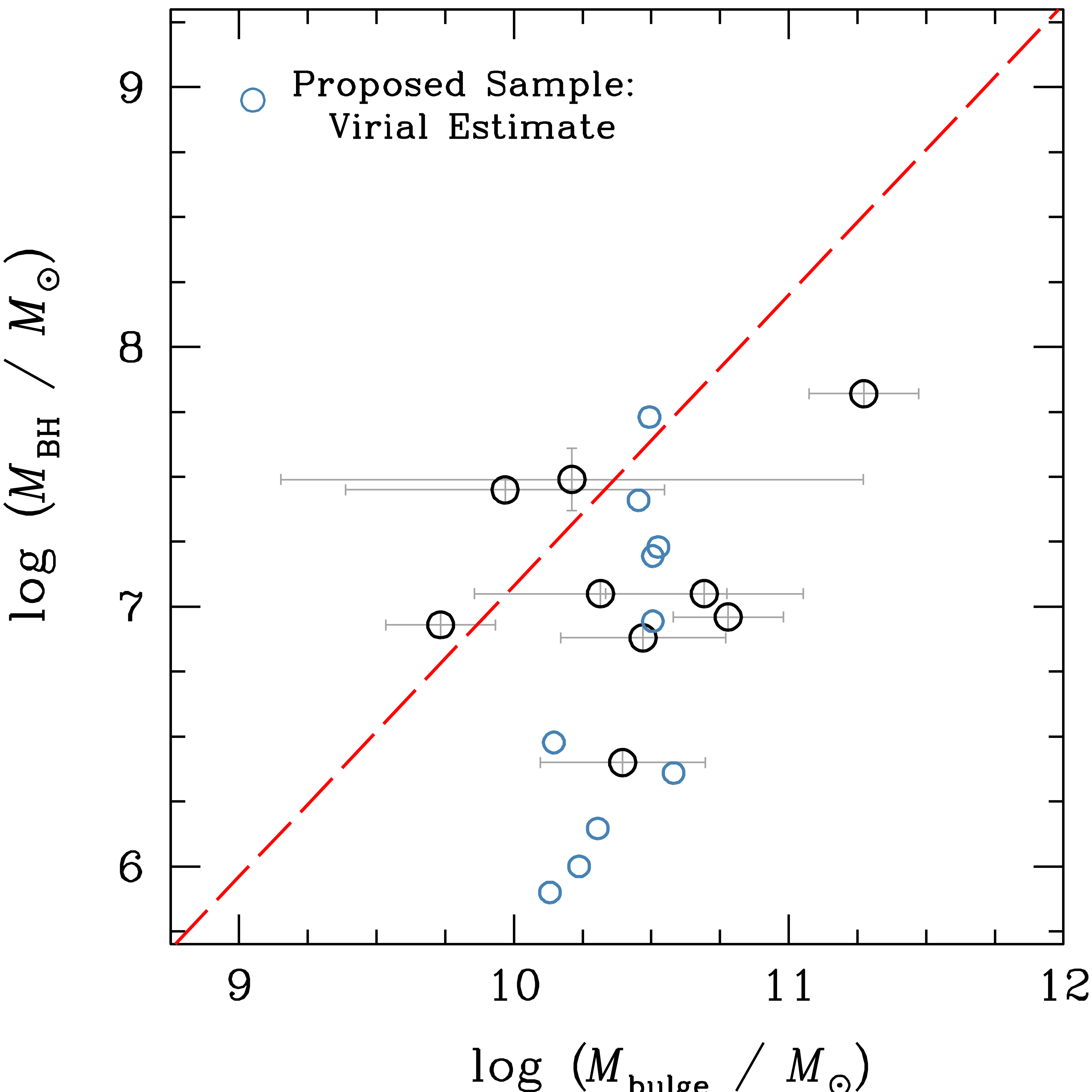


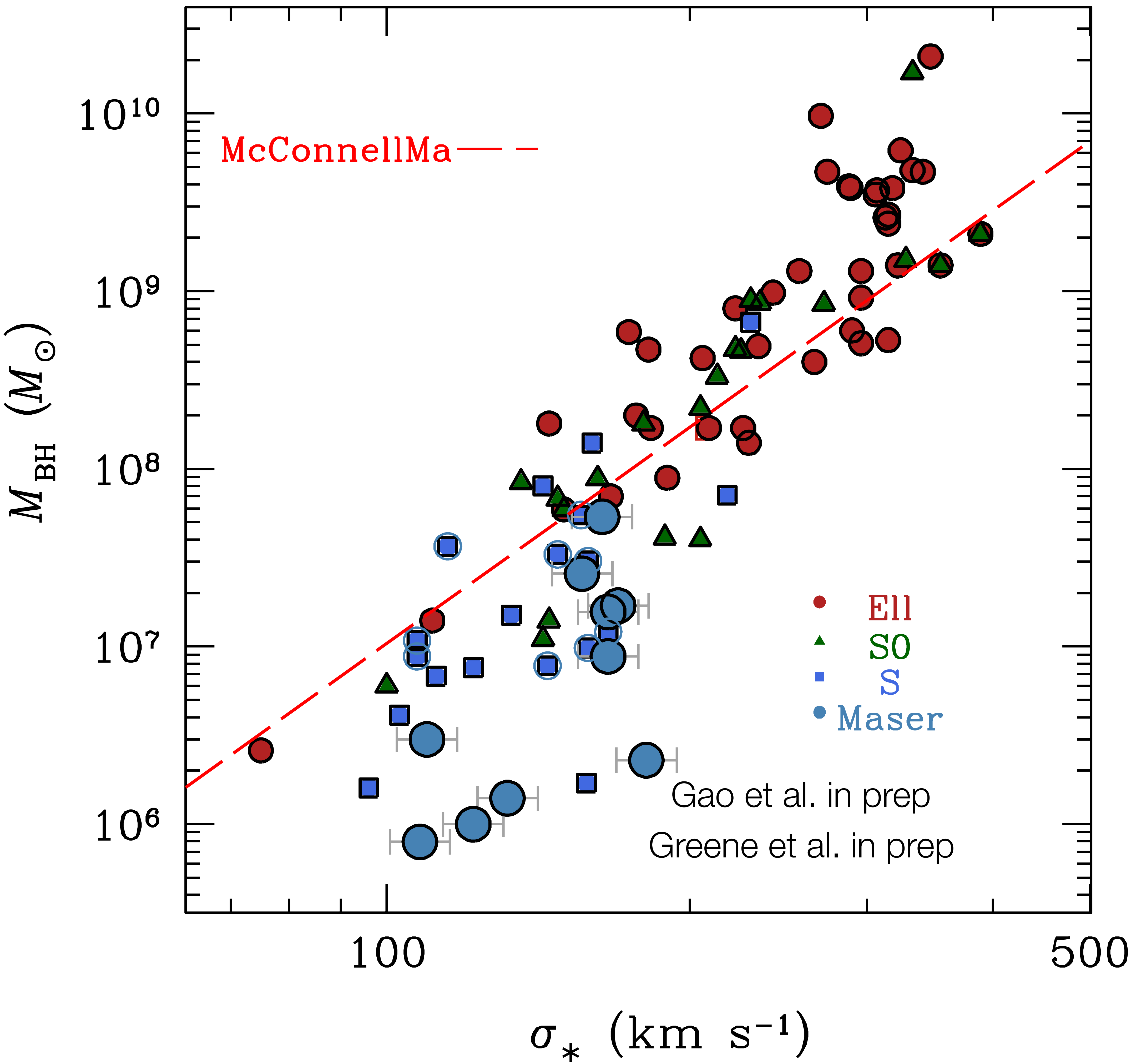




Laesker et al. in prep





McConnellMa
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$M_{BH}$ $(M_\odot)$
100
500
$\sigma_*$ (km s$^{-1}$)
Ell
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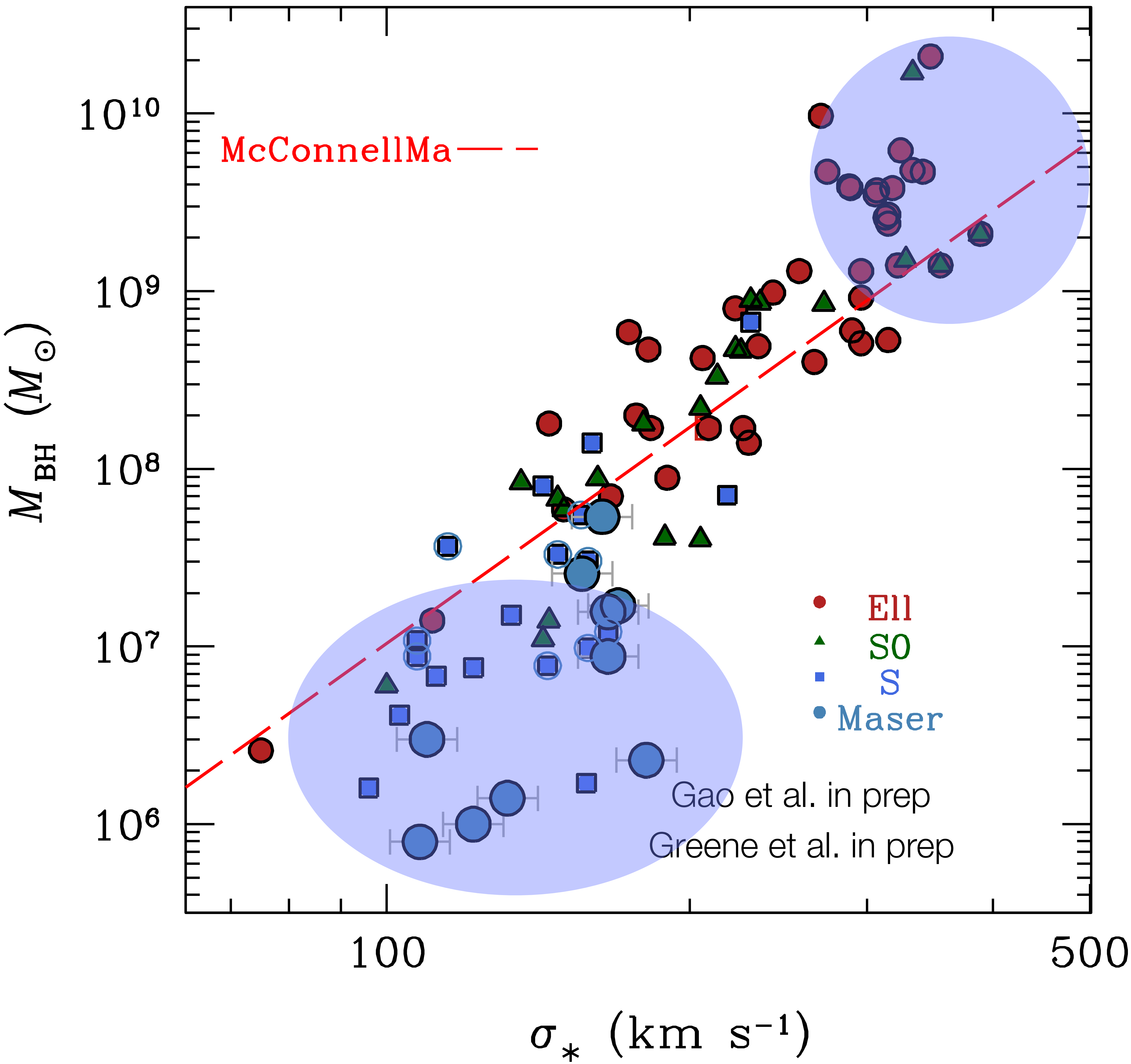
Maser
Gao et al. in prep
Greene et al. in prep



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100
500
$\sigma_*$ (km s$^{-1}$)

# MASSIVE

**~100 most MASSIVE galaxies within ~100 Mpc (2MASS selected)**

**Uniform IFU spectroscopy on 2’ scales with VIRUSP (McDonald Obs.) and AO-assisted with OSIRIS and NIFS**

**Uniform, deep K-band imaging, eventually also X-ray, radio, HST, etc...**

CP Ma, Greene, McConnell et al. submitted
(arXiv: 1407.1054)

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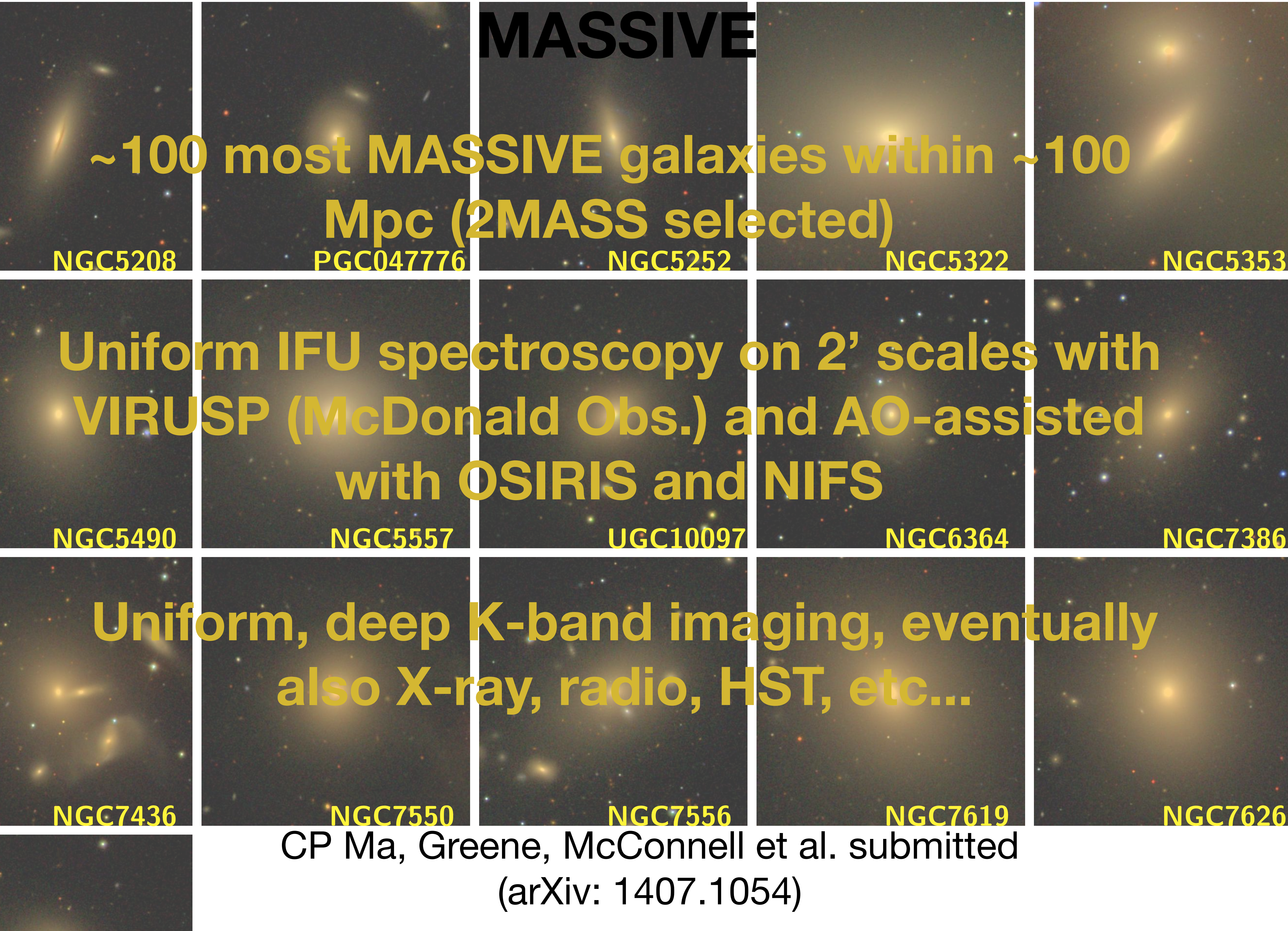


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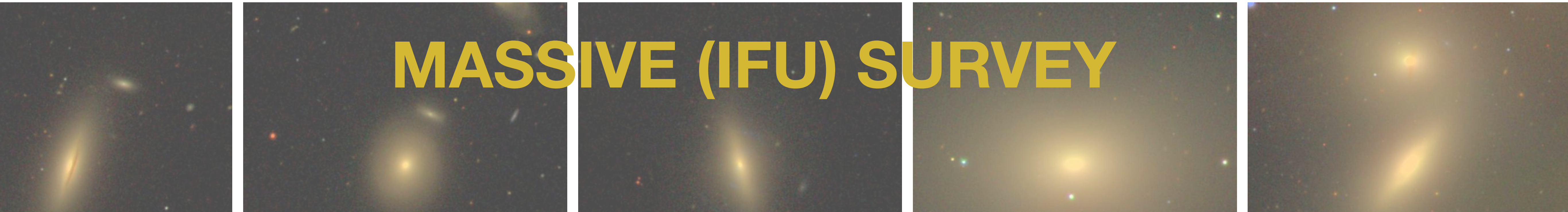
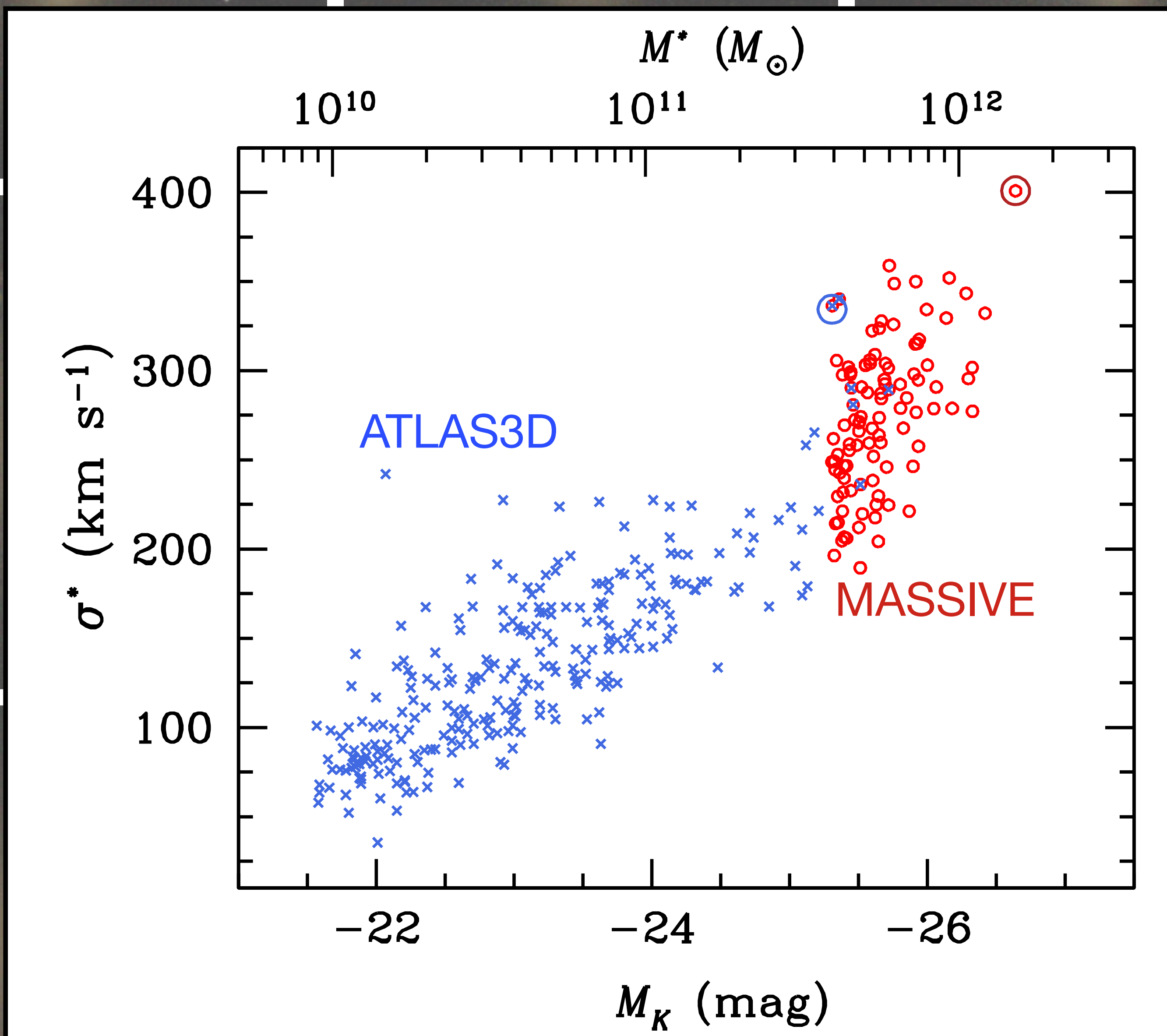
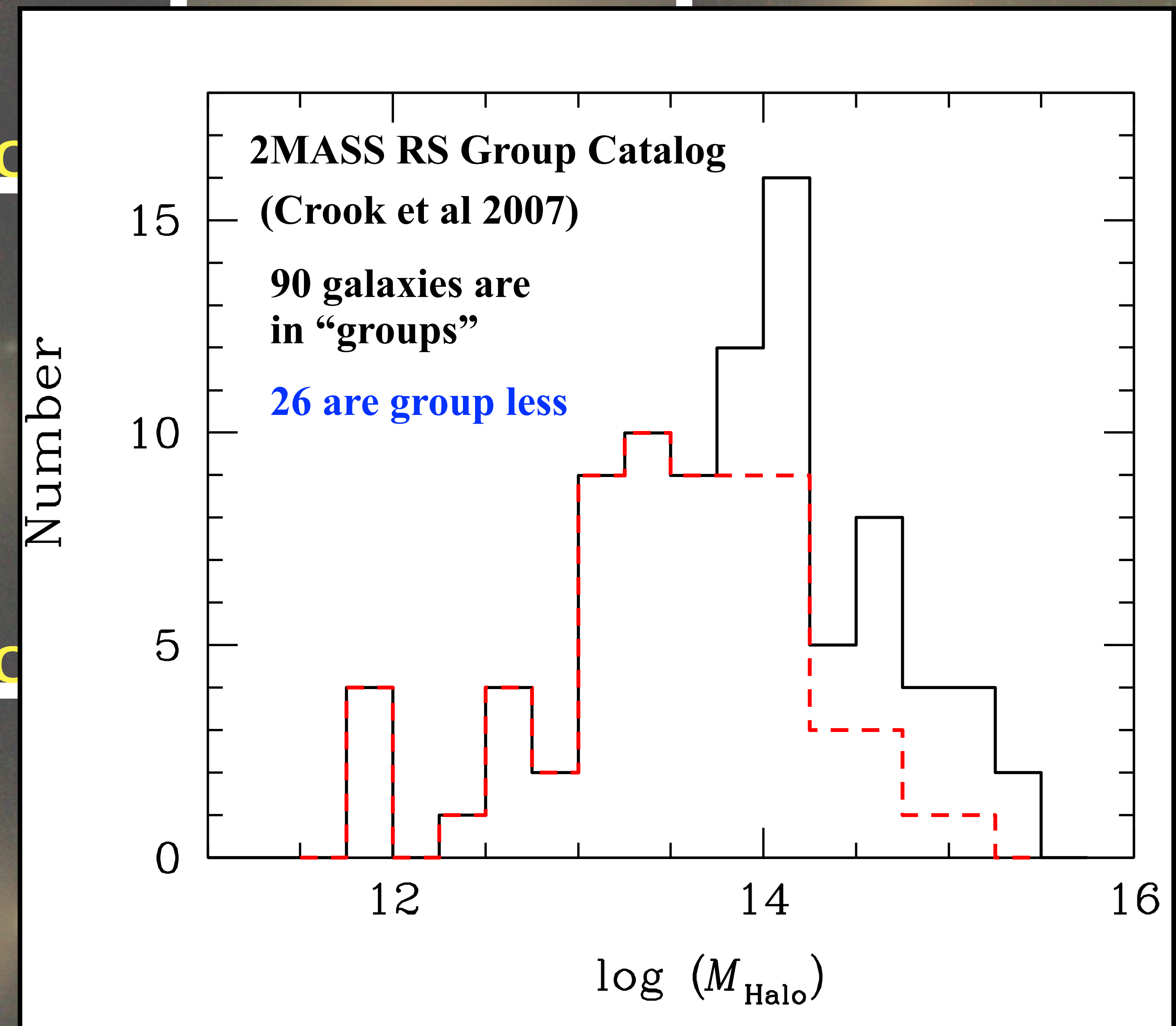
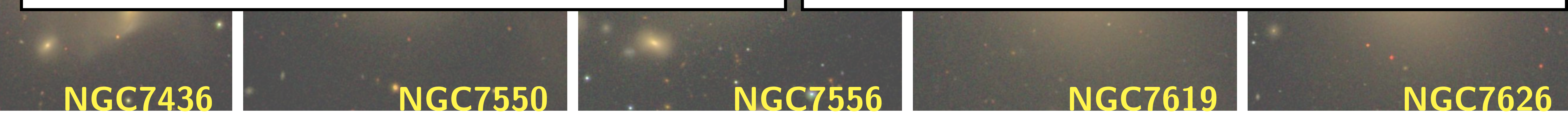
# MASSIVE (IFU) SURVEY



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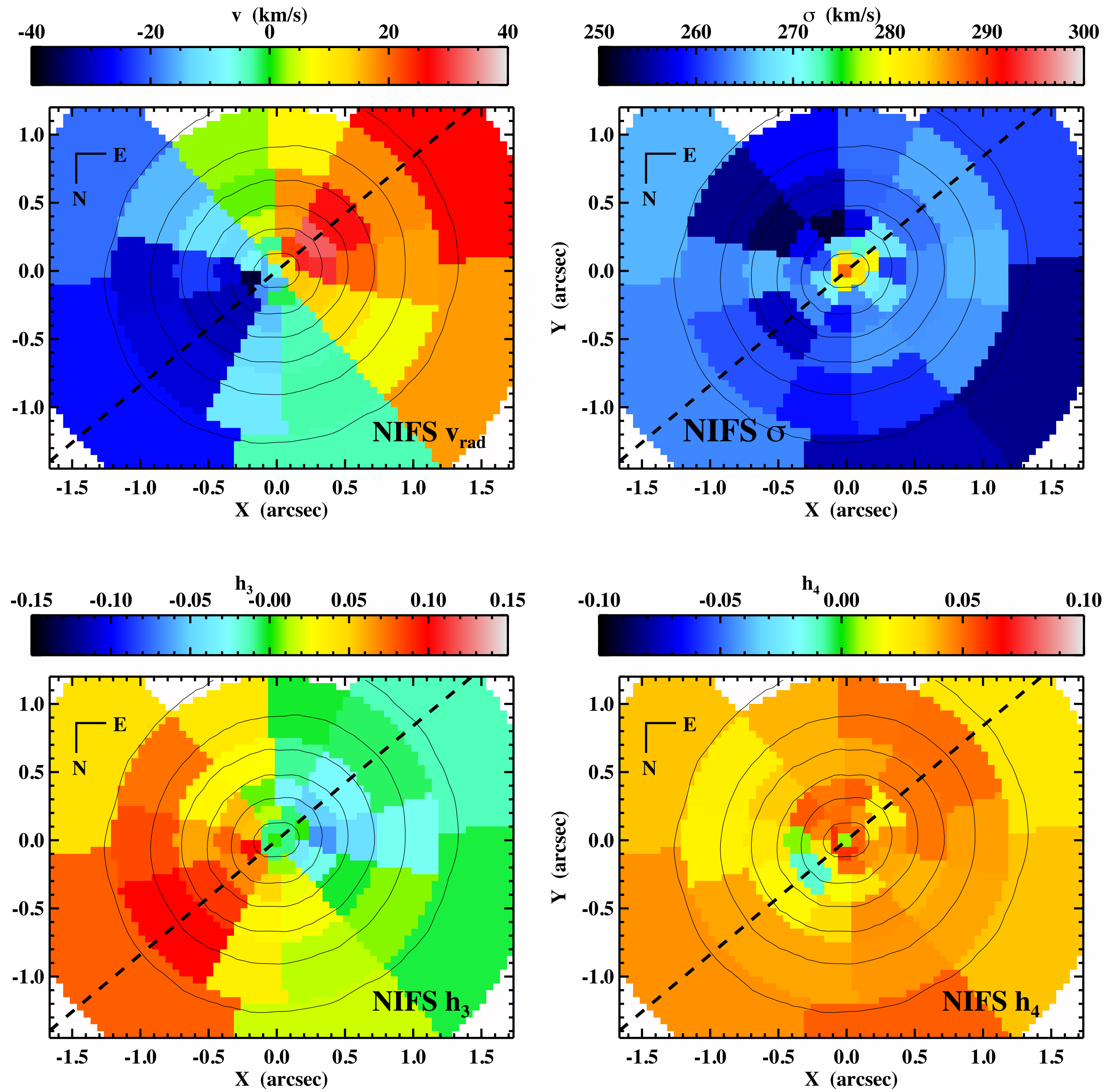
# Gemini NIFS

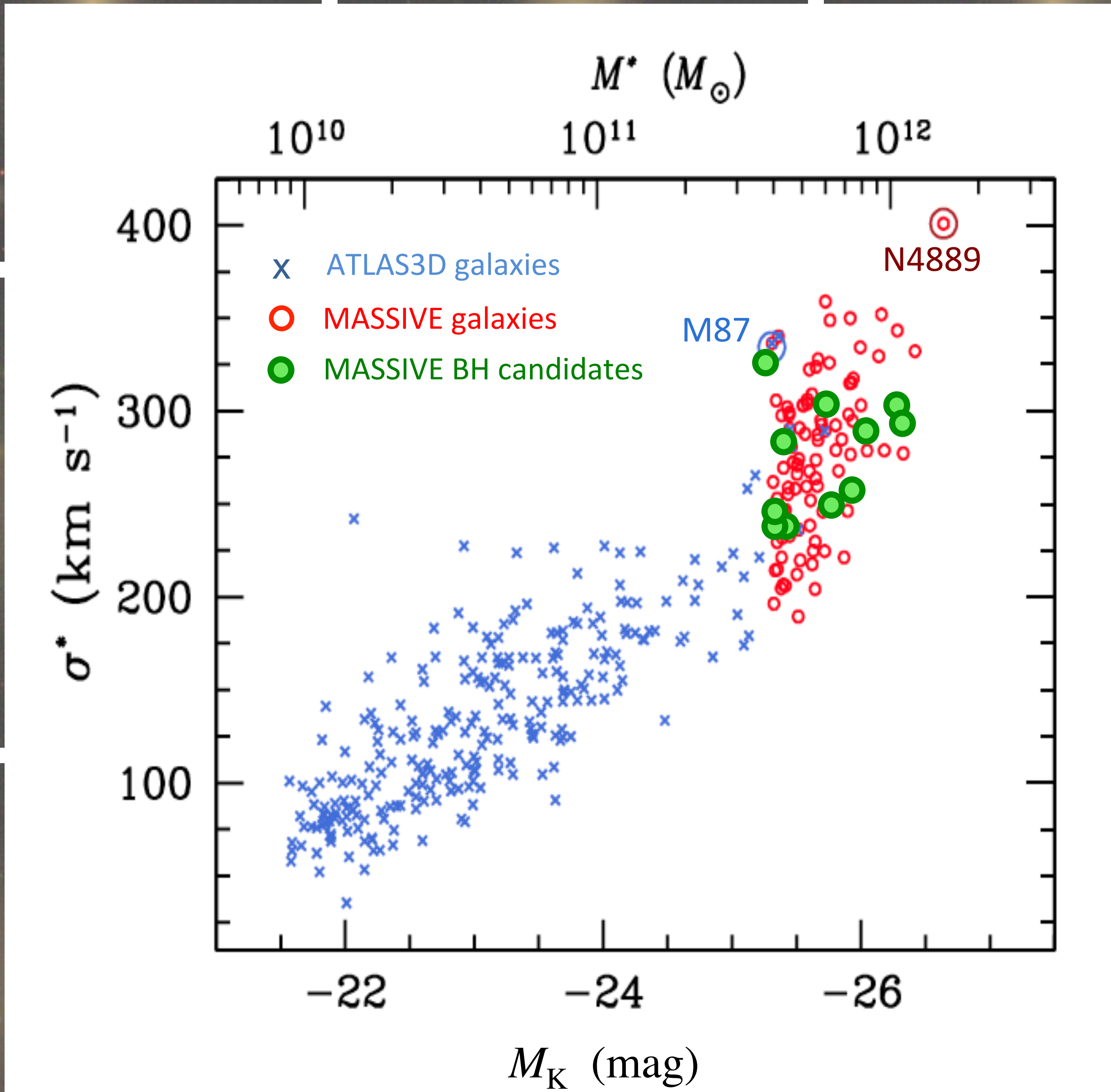
McConnell et al (in prep)

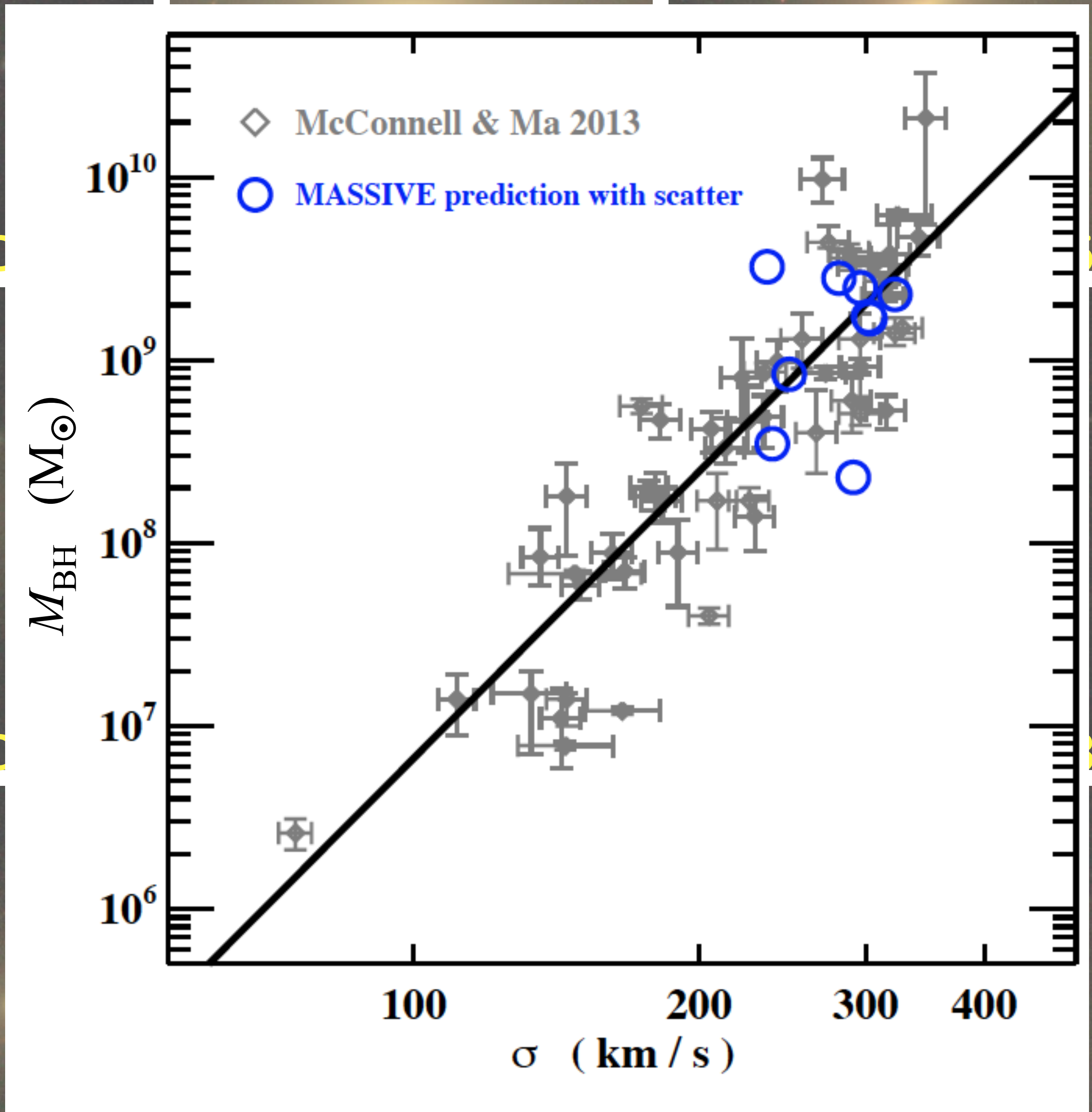
NGC 4552




Black hole mass

# MASSIVE (IFU) SURVEY




NGC7436 NGC7550 NGC7556 NGC7619 NGC7626

CP Ma, Greene, McConnell et al. submitted
(arXiv: 1407.1054)

# The Future

WIll we measure BH masses dynamically at cosmological redshifts?

Will we do a Sloan-like galaxy survey at z~2?

Will we spatially separate star formation/bulge formation from QSO light in z~2 QSOs?

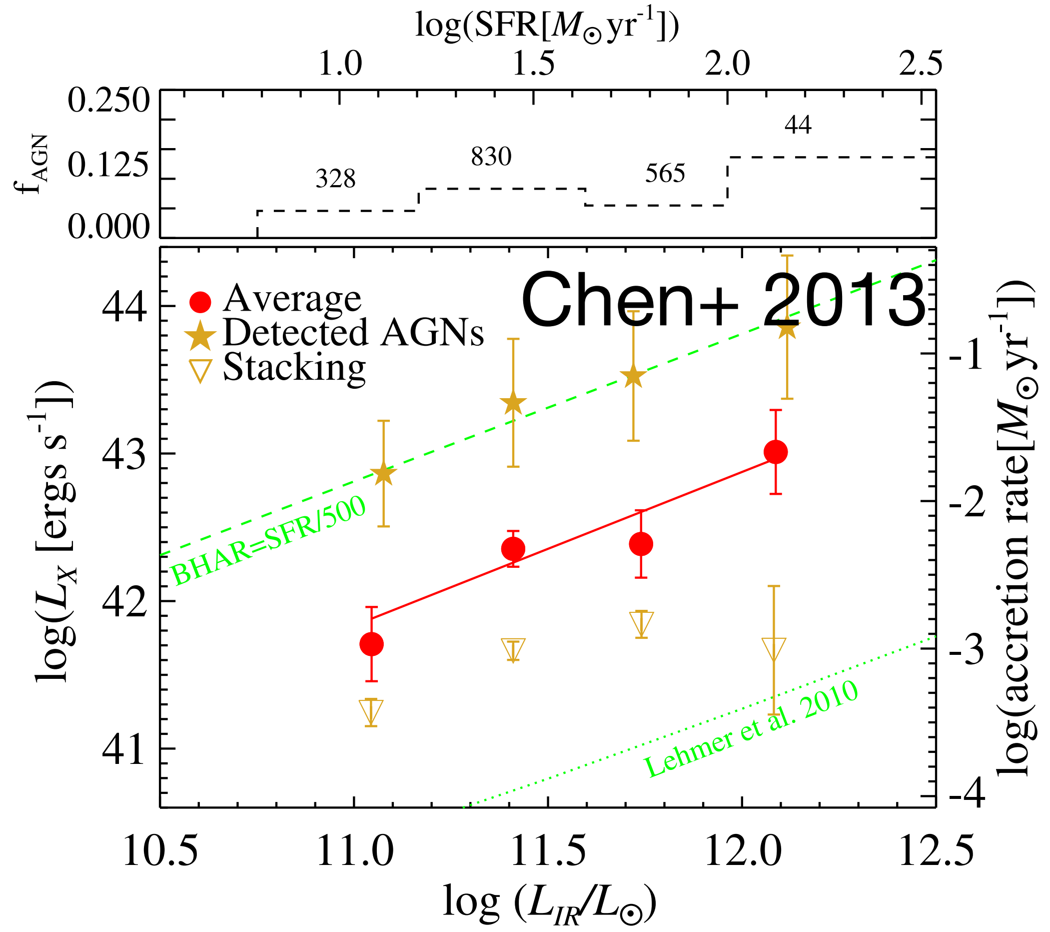
Will we measure gas content directly in the AGN we find?

Will we find all the Compton thick AGN?

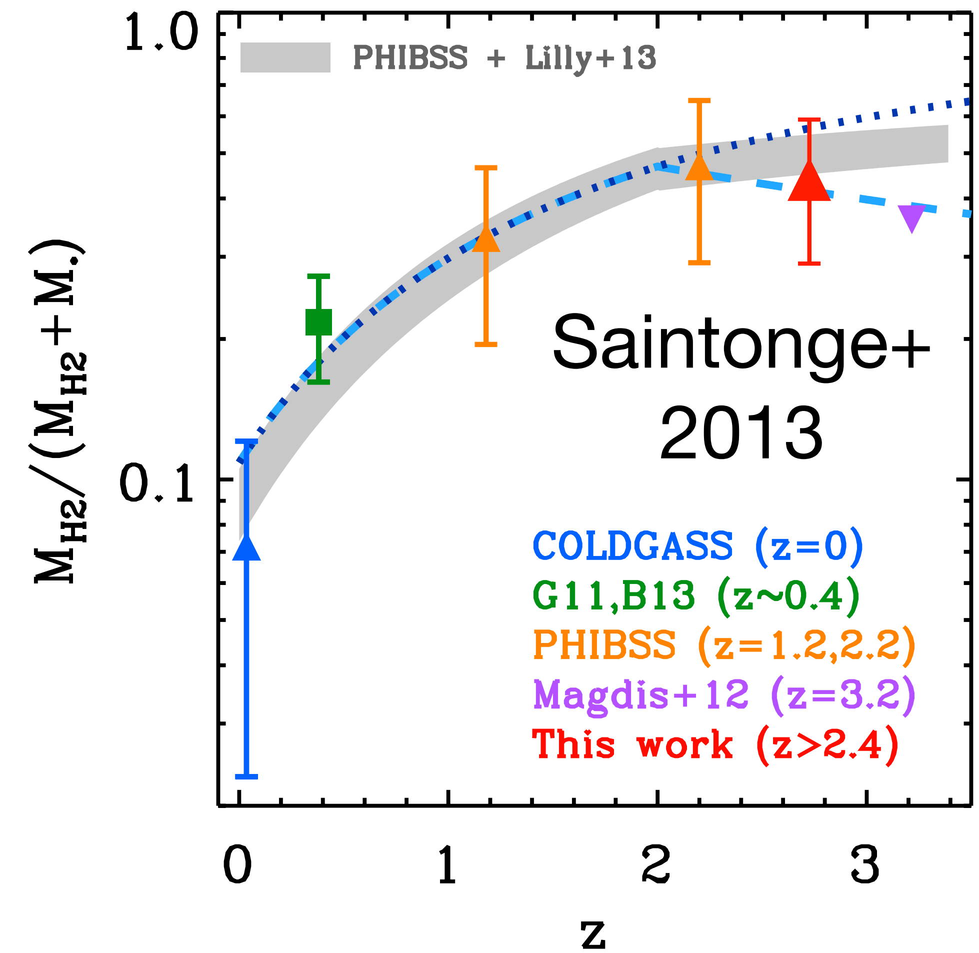
# After 40 years...

# After 40 years...

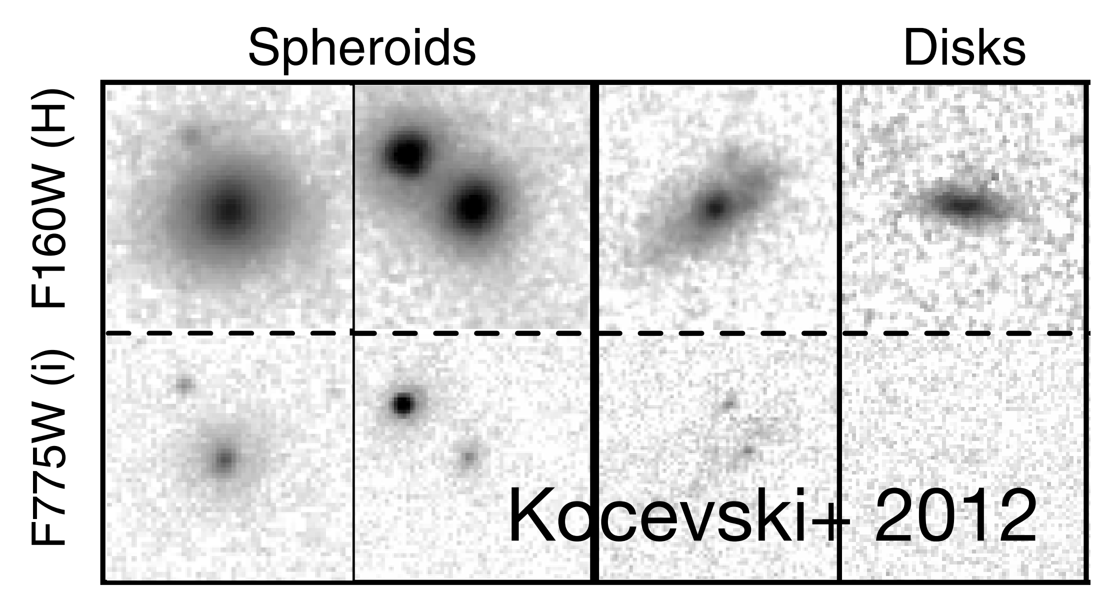
What is the future of the AGN-star formation connection?



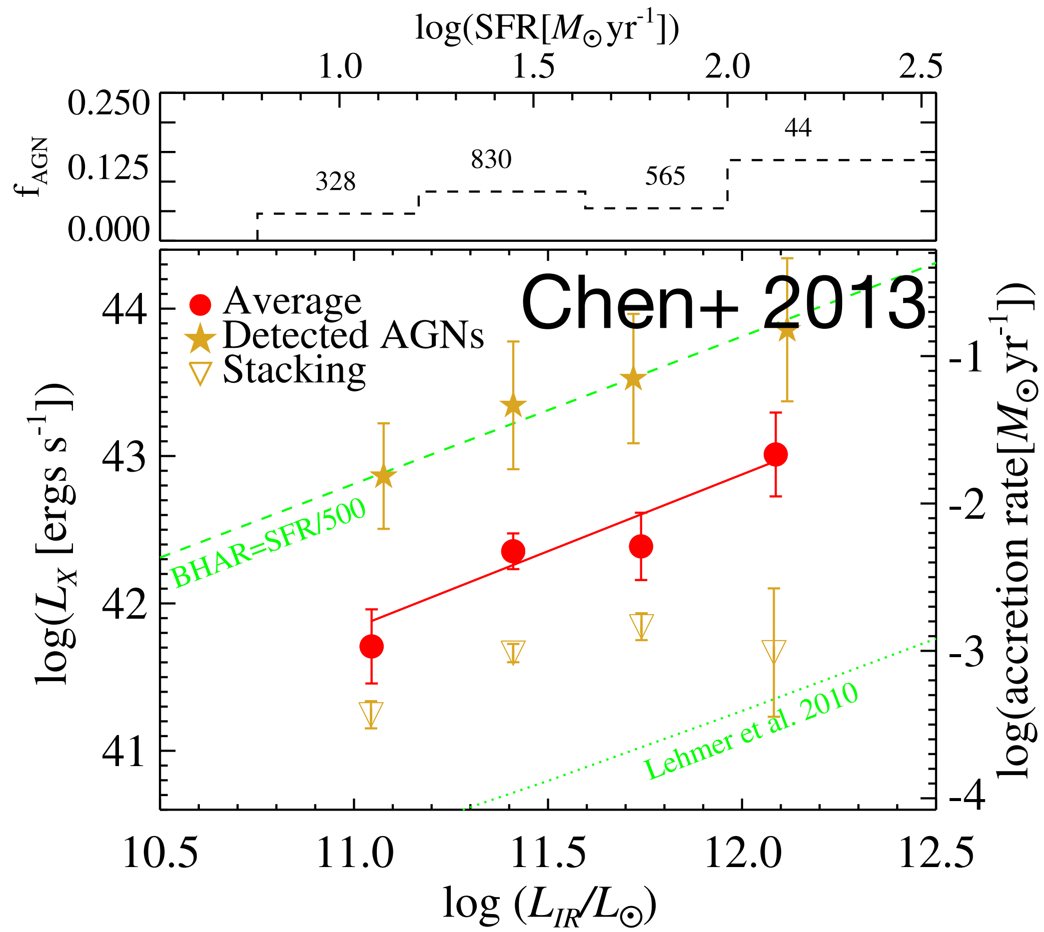

--> Large, well-defined galaxy AND AGN samples; SFRs (FIR), Lbol

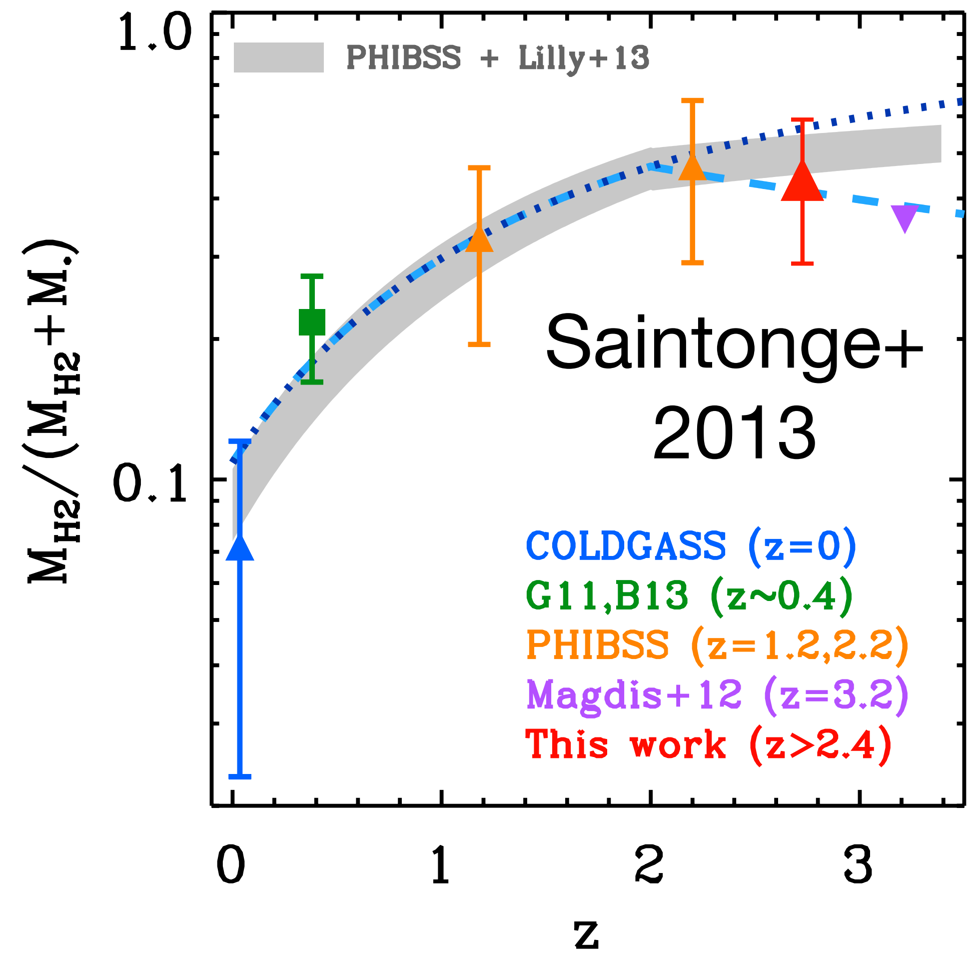



--> Gas fractions, SFRs required




--> Morphology matters

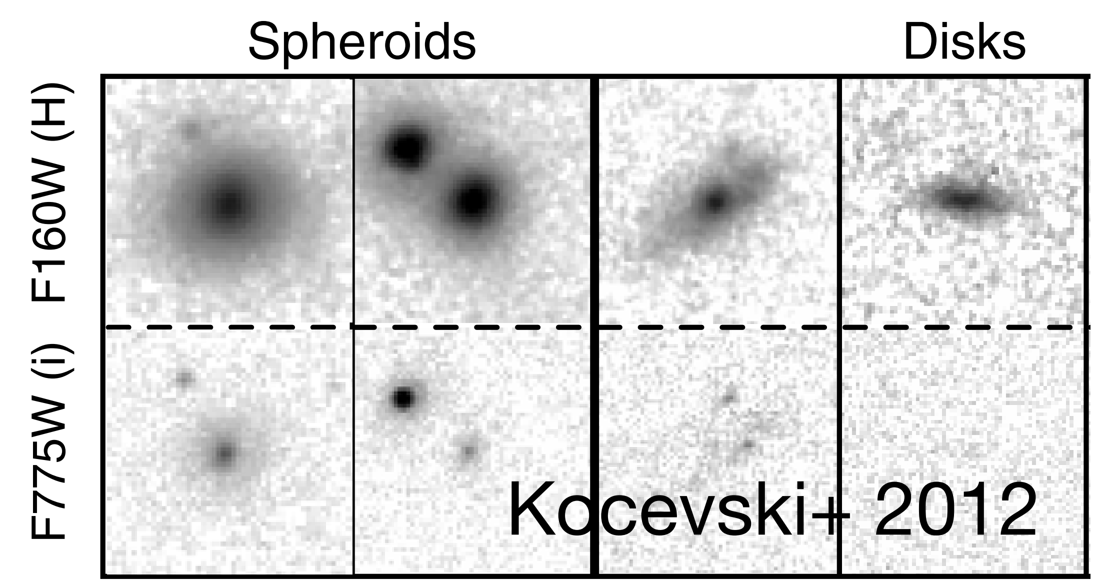


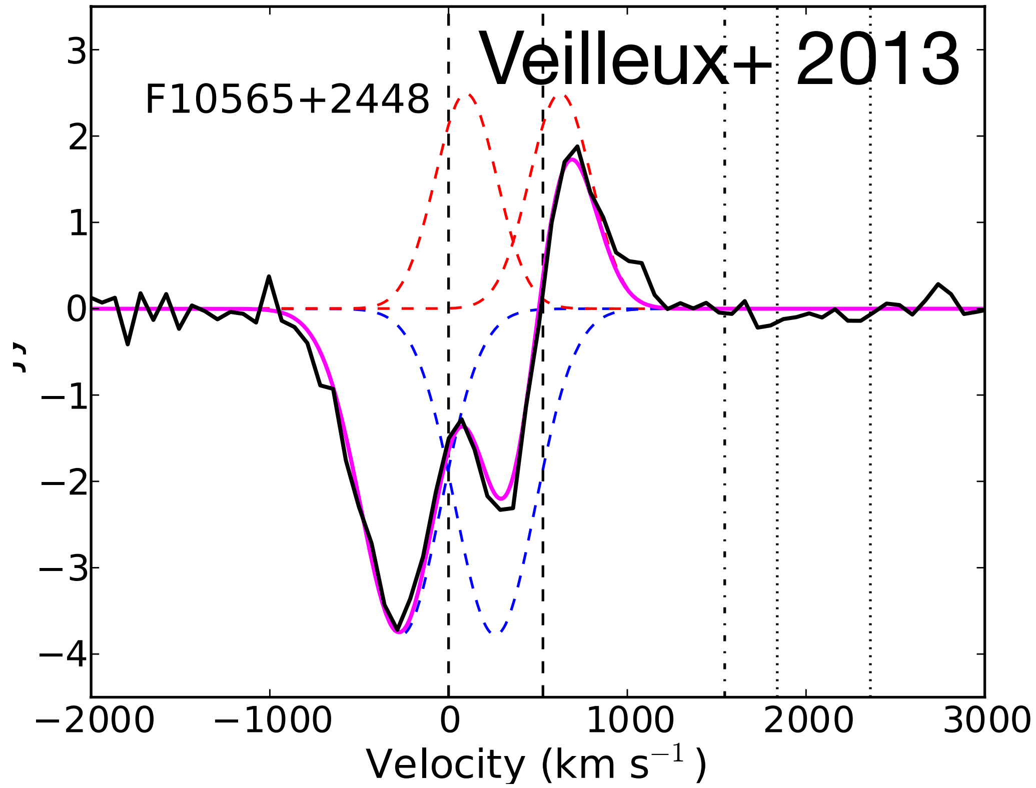

--> Large, well-defined galaxy AND AGN samples; SFRs (FIR), Lbol

--> Gas fractions, SFRs required

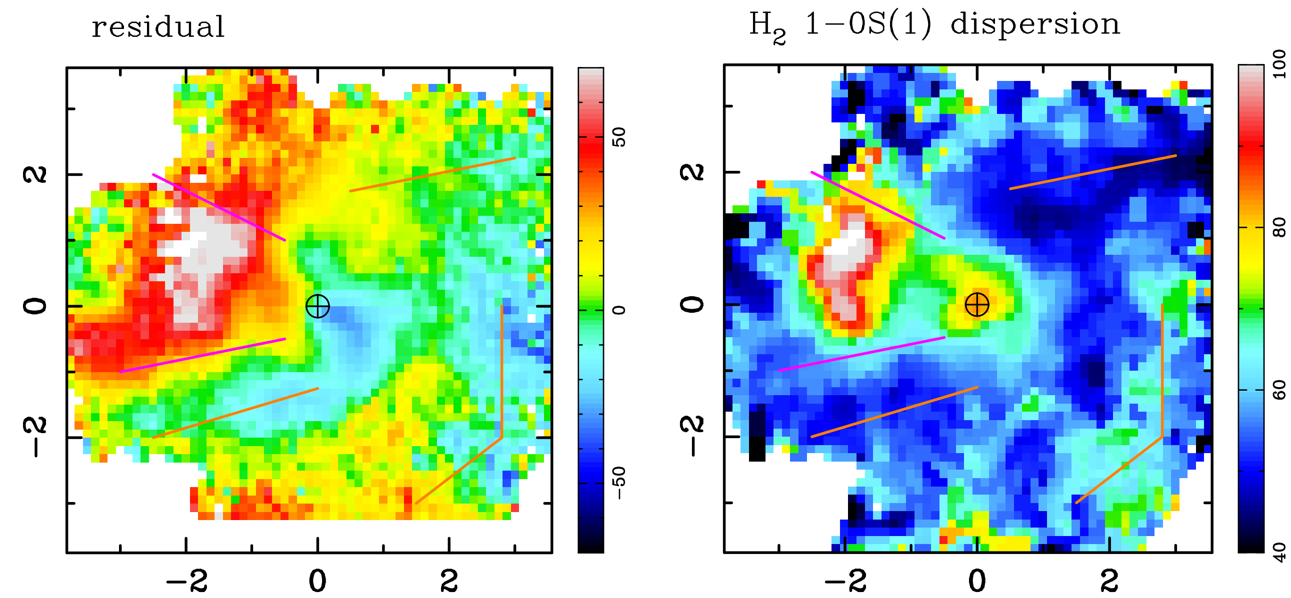
Scale matters




--> Morphology matters

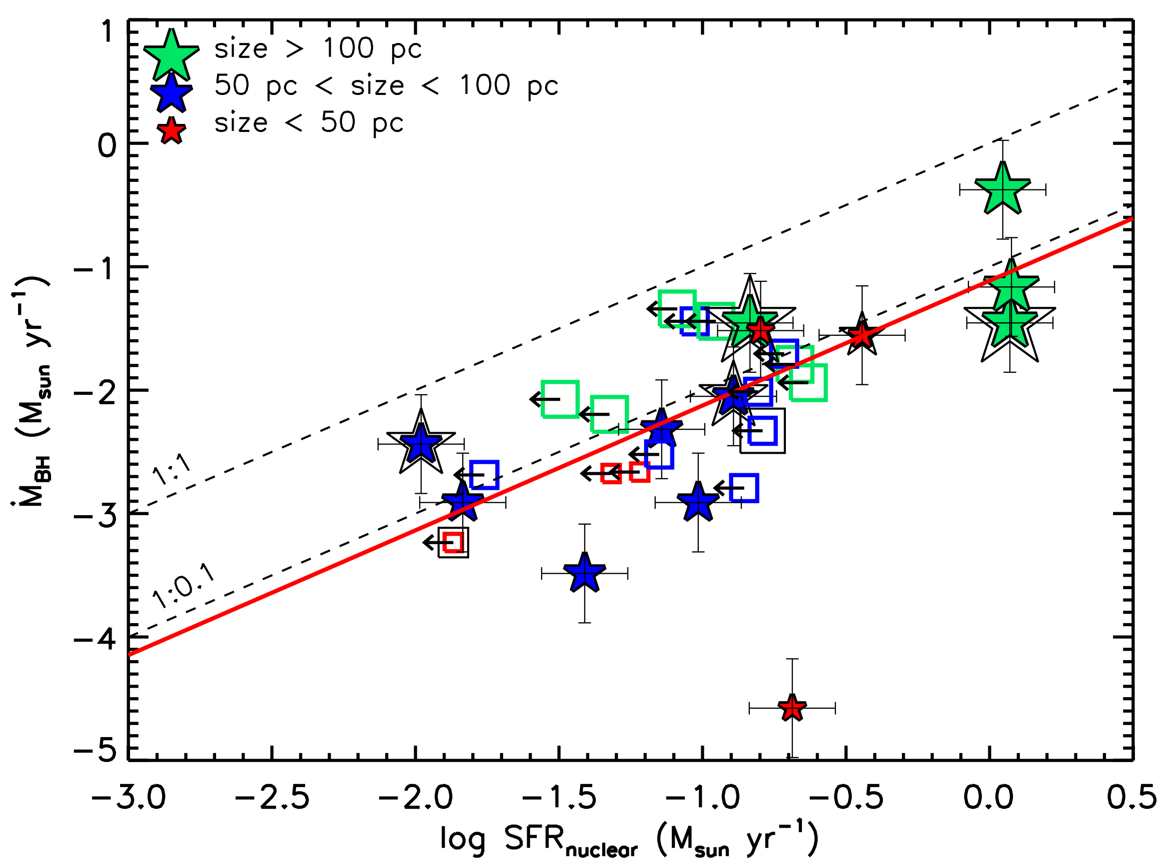



--> outflows on large scales



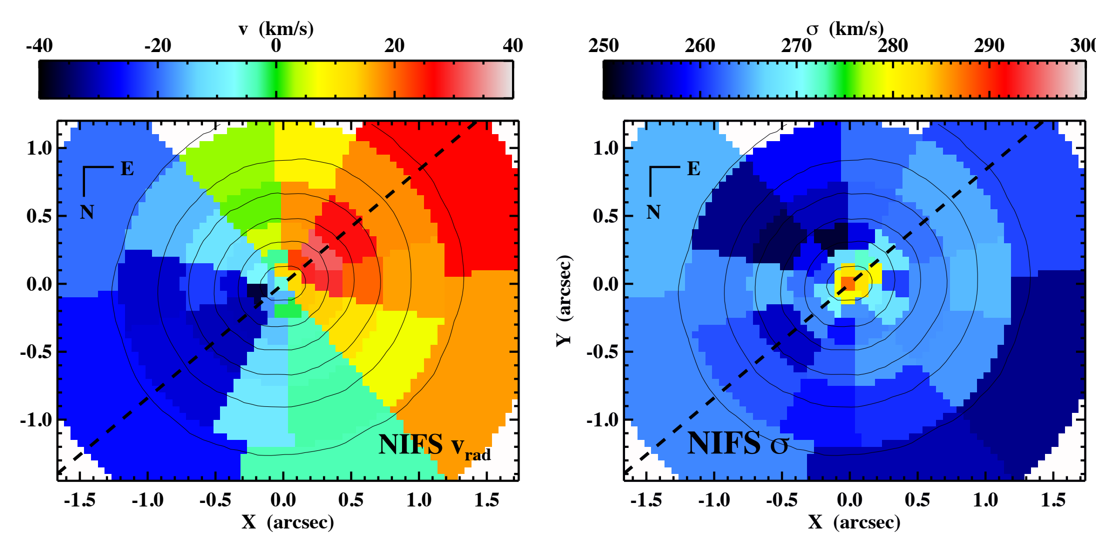

Davies+ 2014

--> inflows and outflows on smaller scales




Esquej+ 2014

--> star formation on smaller scales



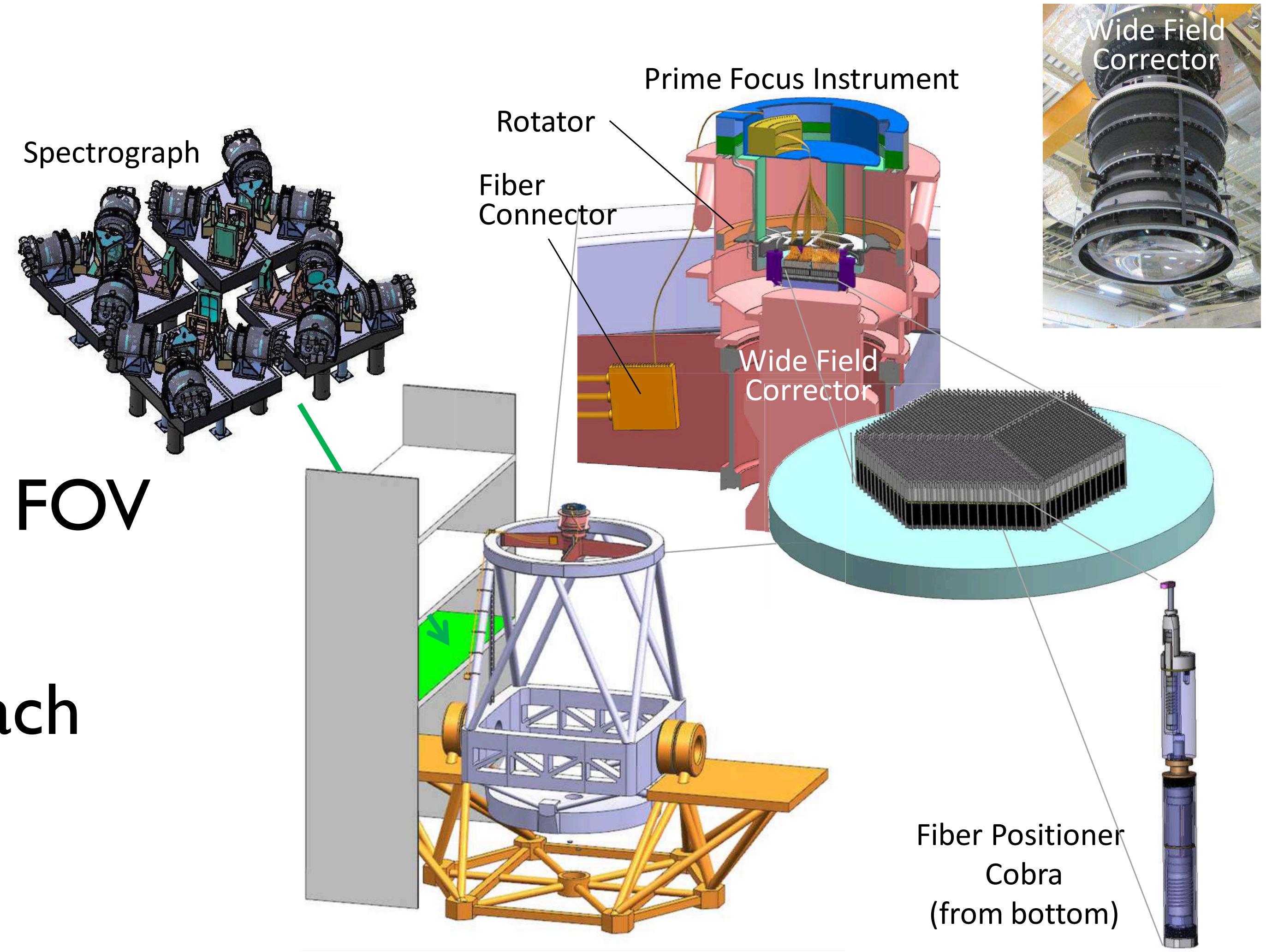

McConnell et al.

--> BH sphere of influence

# Next Generation Surveys

# New Redshift Surveys: Prime Focus Spectrograph

# The Spectrographs




2400 fibers at prime focus, 1.3 deg$^2$ FOV

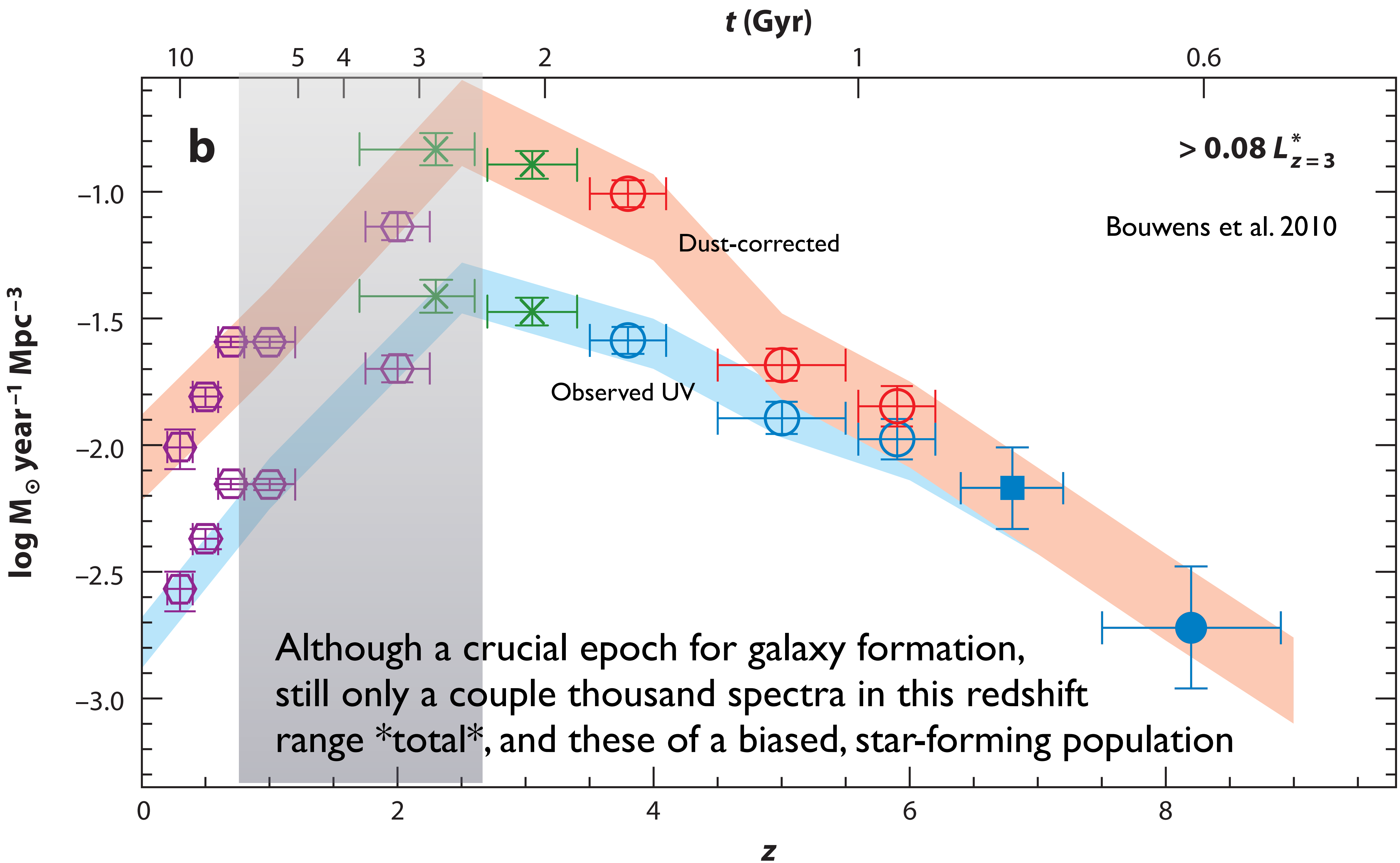
4 spectrographs; 600 1.13” fibers each

3 channels:

3800-6500A, R~2000

6500-10000A, R~3500

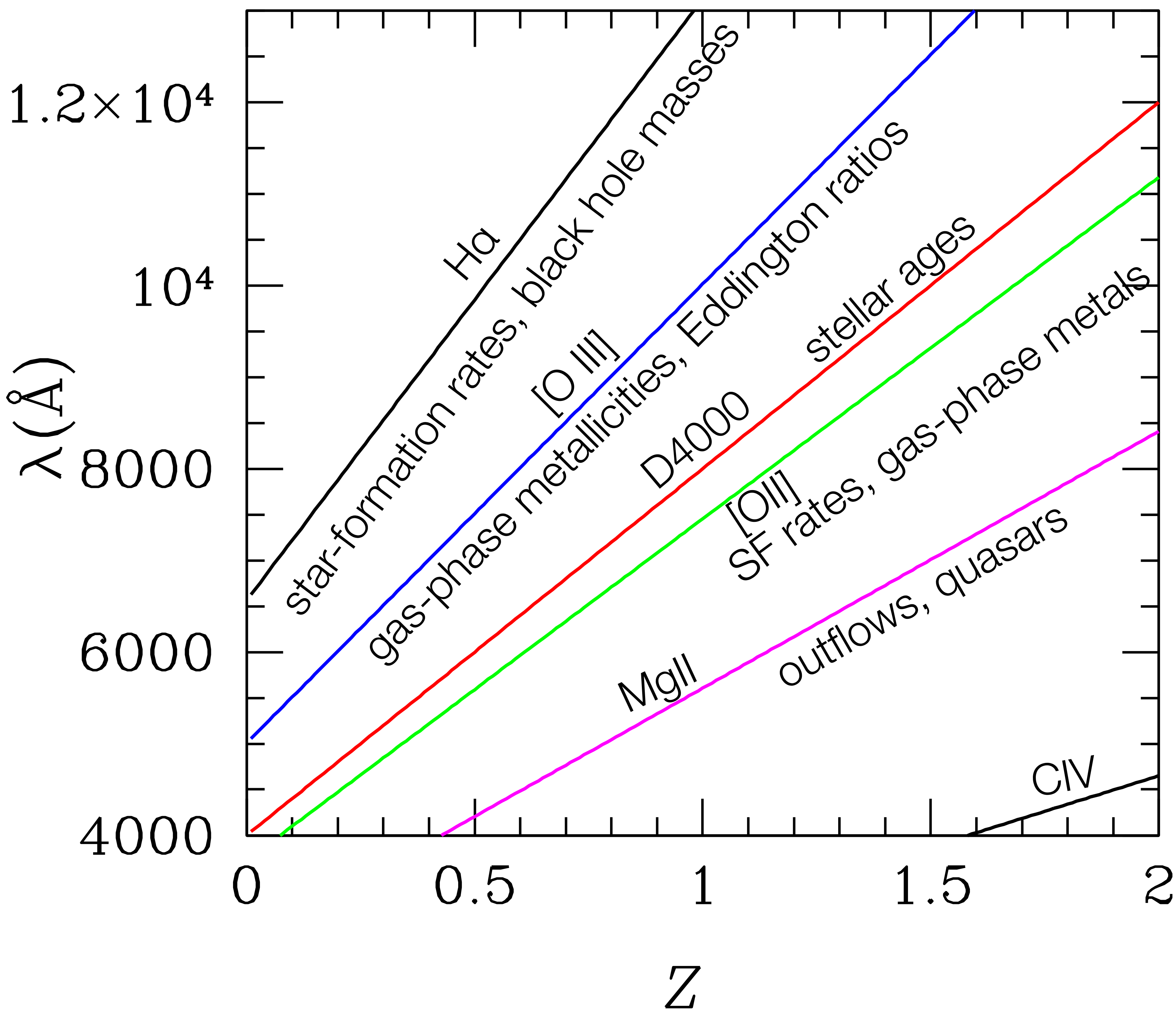
10000-12600, R~4500 (high resolution needed to work between night sky lines)




Survey: ~10 deg$^2$ to $J_{AB}$~23.5 mag

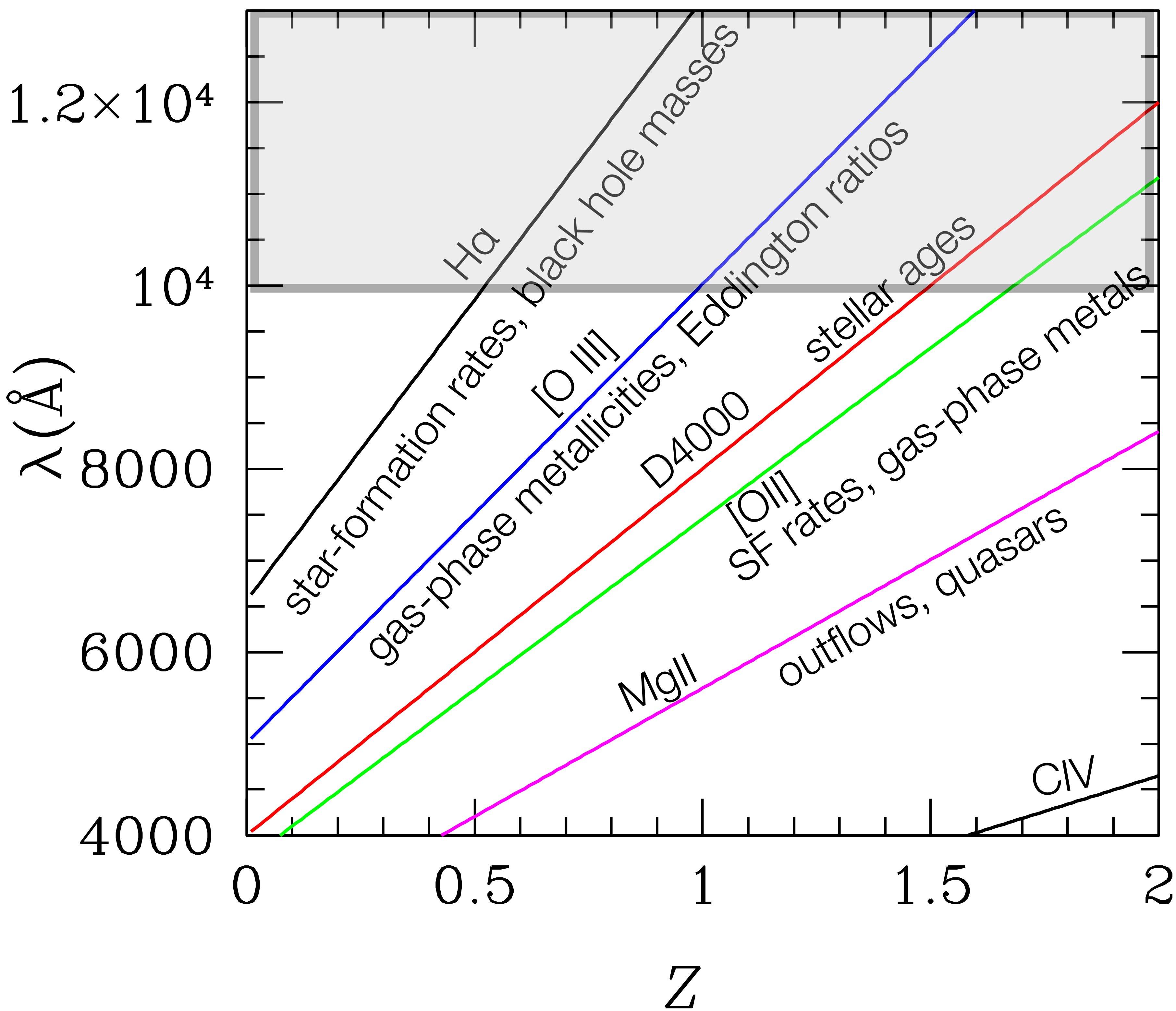
~few x $10^{10}$ M*, z~1.5

# Like SDSS at z~1-2




Ly α at z~3.5 where [OII] is lost, so no z gaps at all!

# Like SDSS at z~1-2



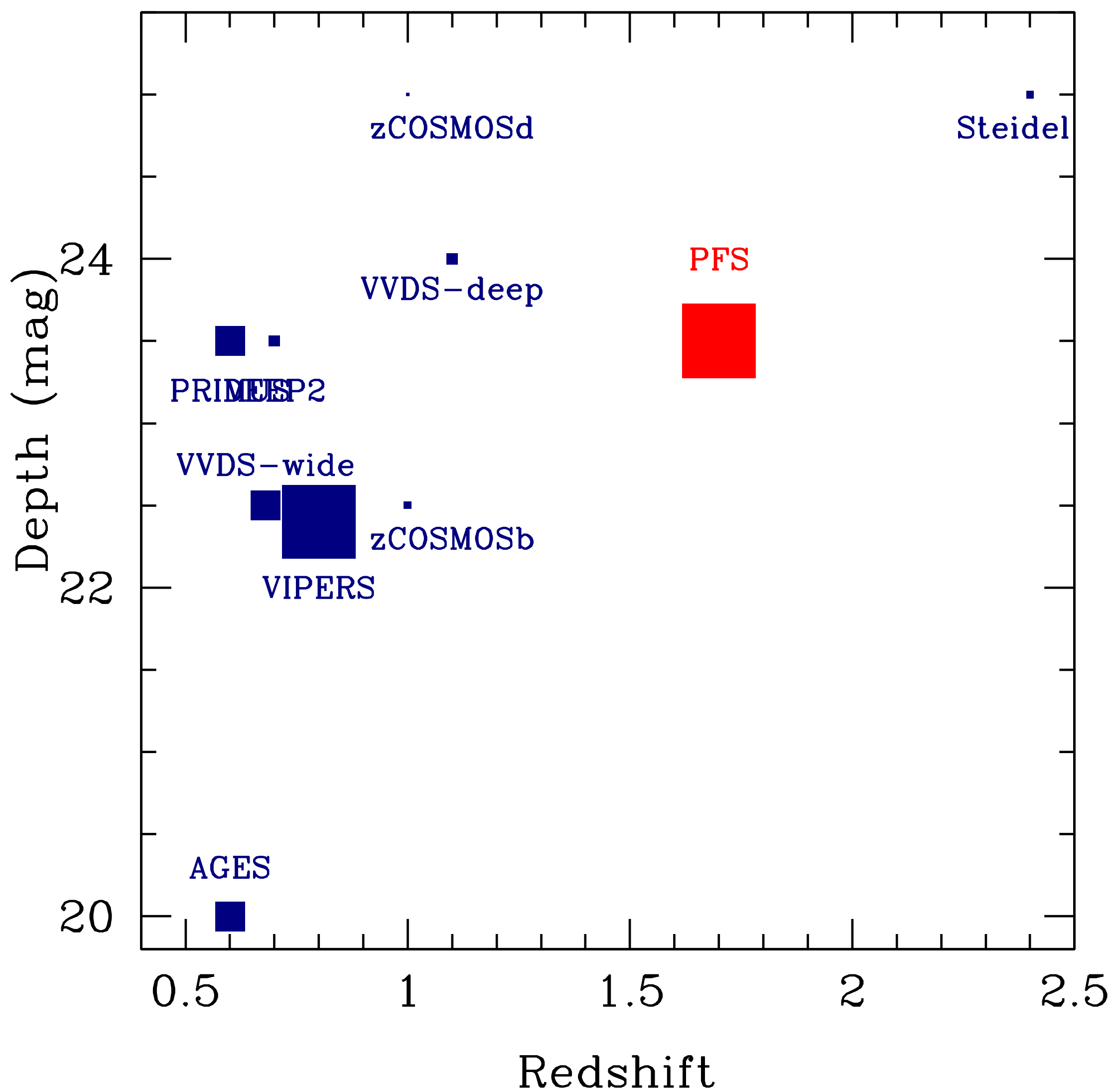

Need the NIR!

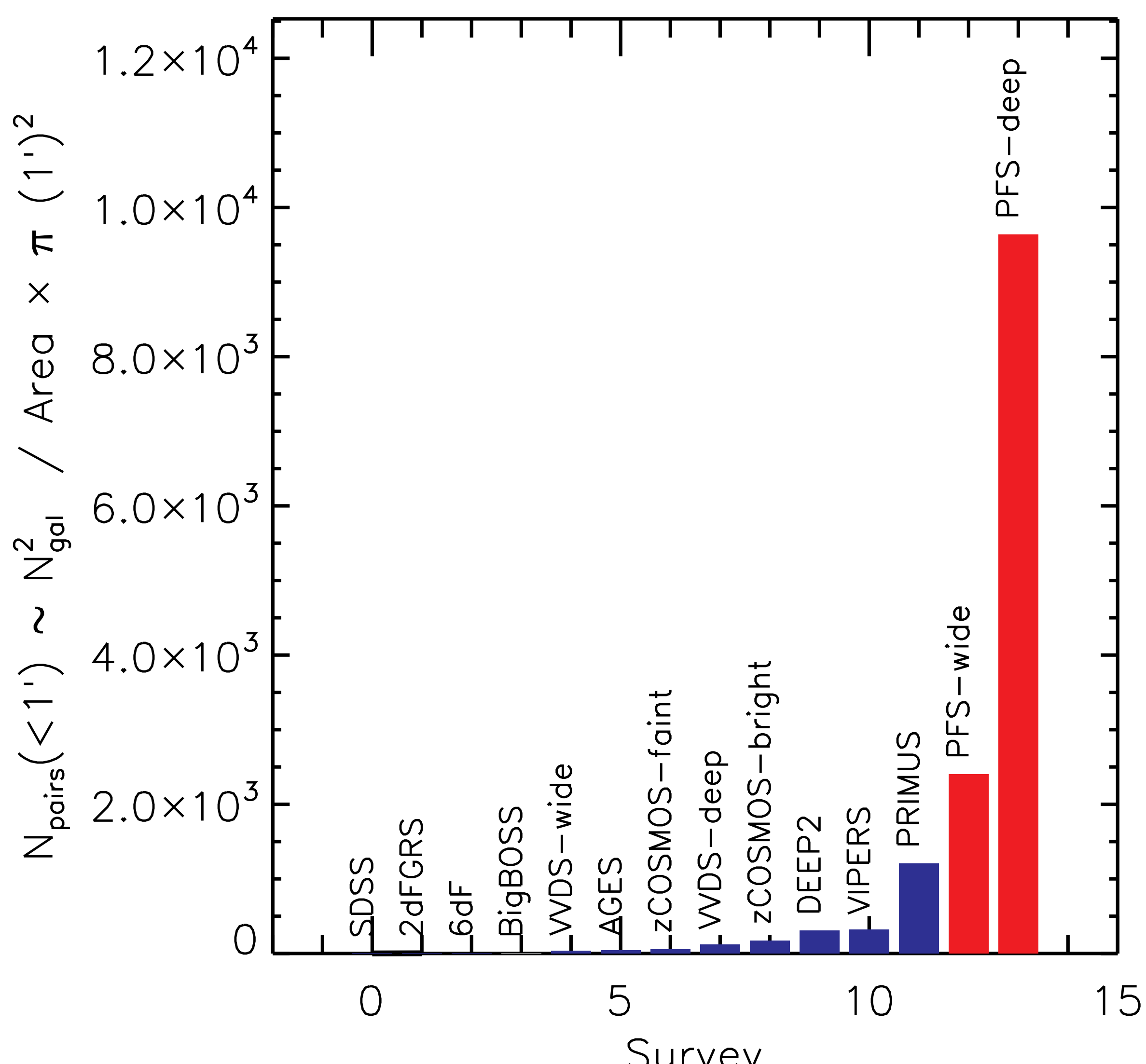
Ly α at z~3.5 where [OII] is lost, so no z gaps at all!

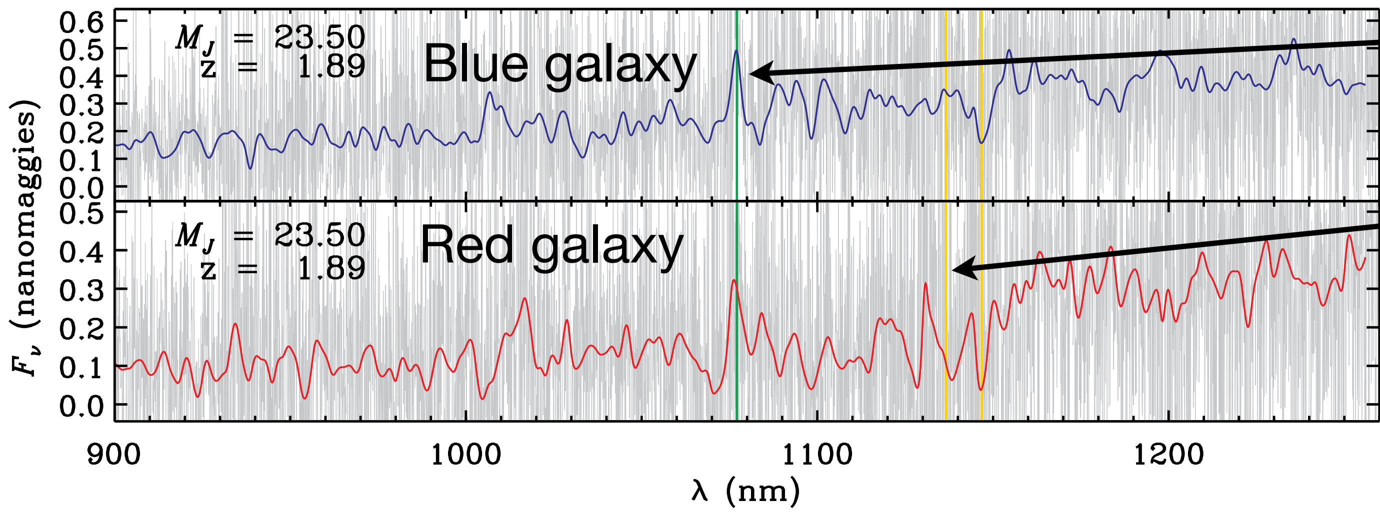
# J-band selected sample to ~23.5 AB mag
# mass ~ few x $10^{10}$ $M_\odot$,
# ~30,000 gals/deg$^2$ over 10 deg$^2$

# Color-selected QSOs to z~7

# And bright drop-outs and LAEs to z~7



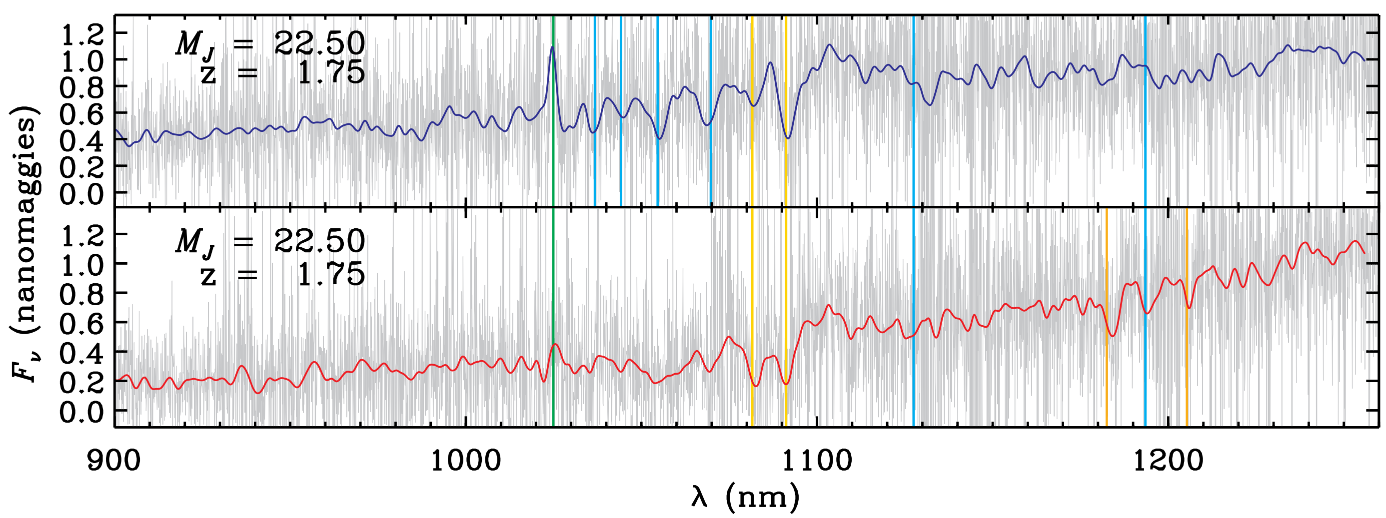





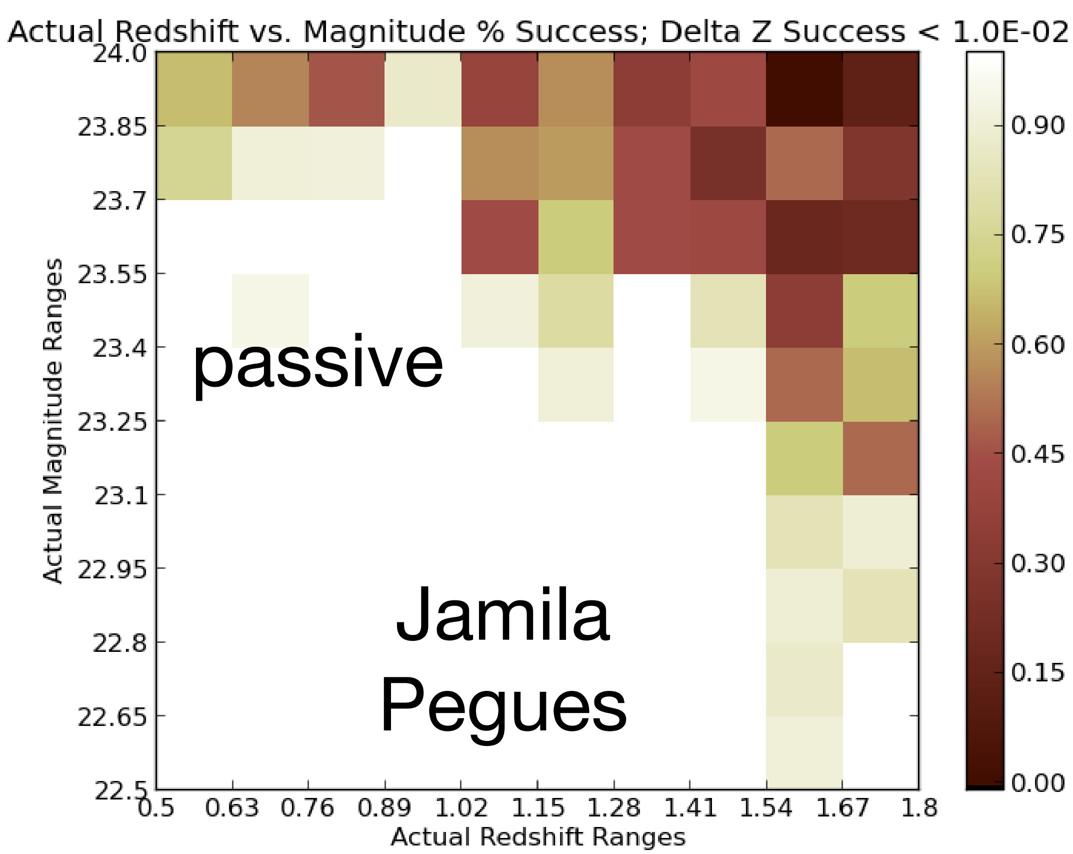

Star-formation rates

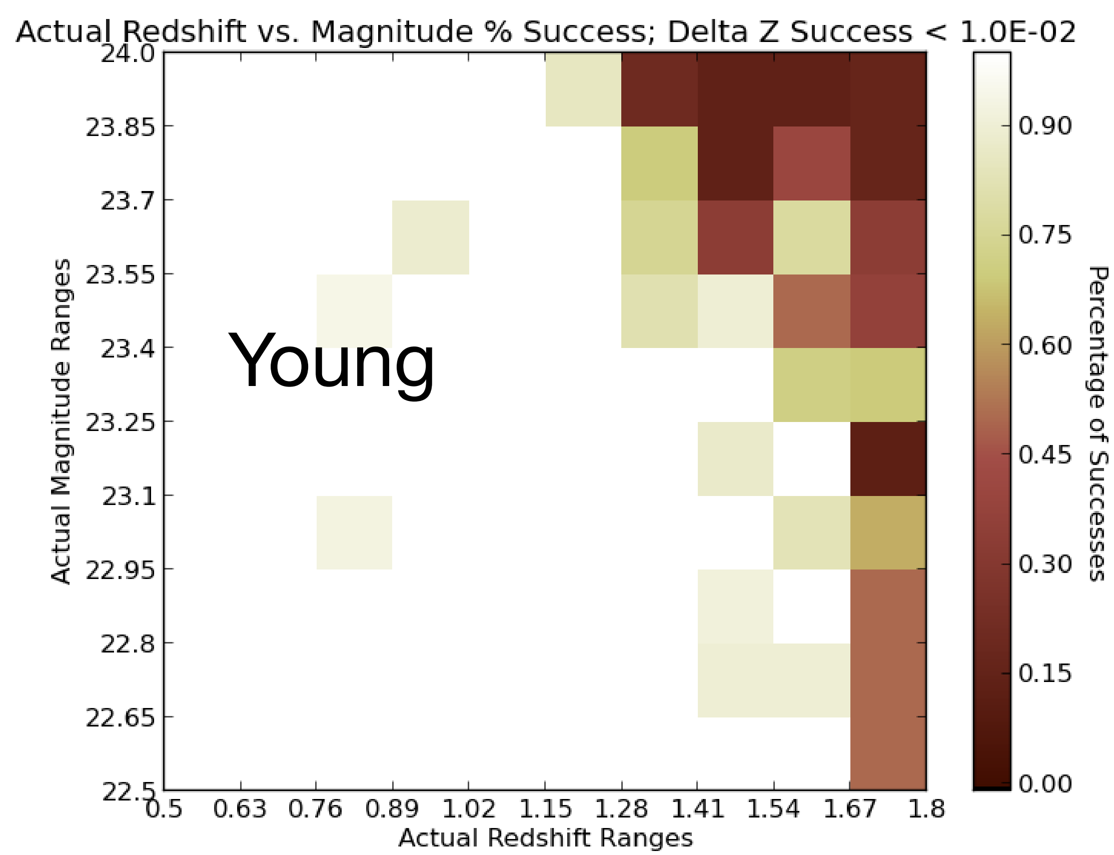
Stellar ages

(Note: Spectra are inverse-variance weighted and smoothed to R~300)

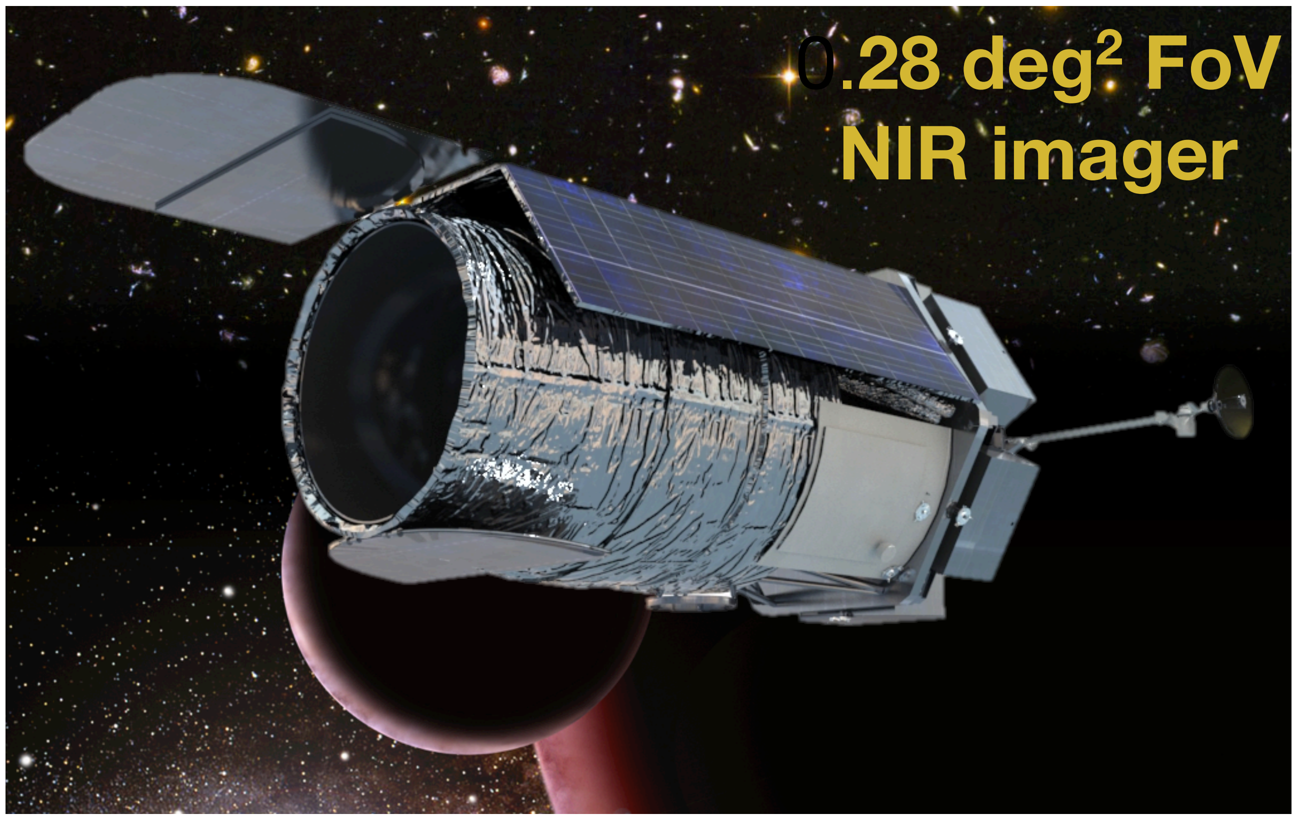


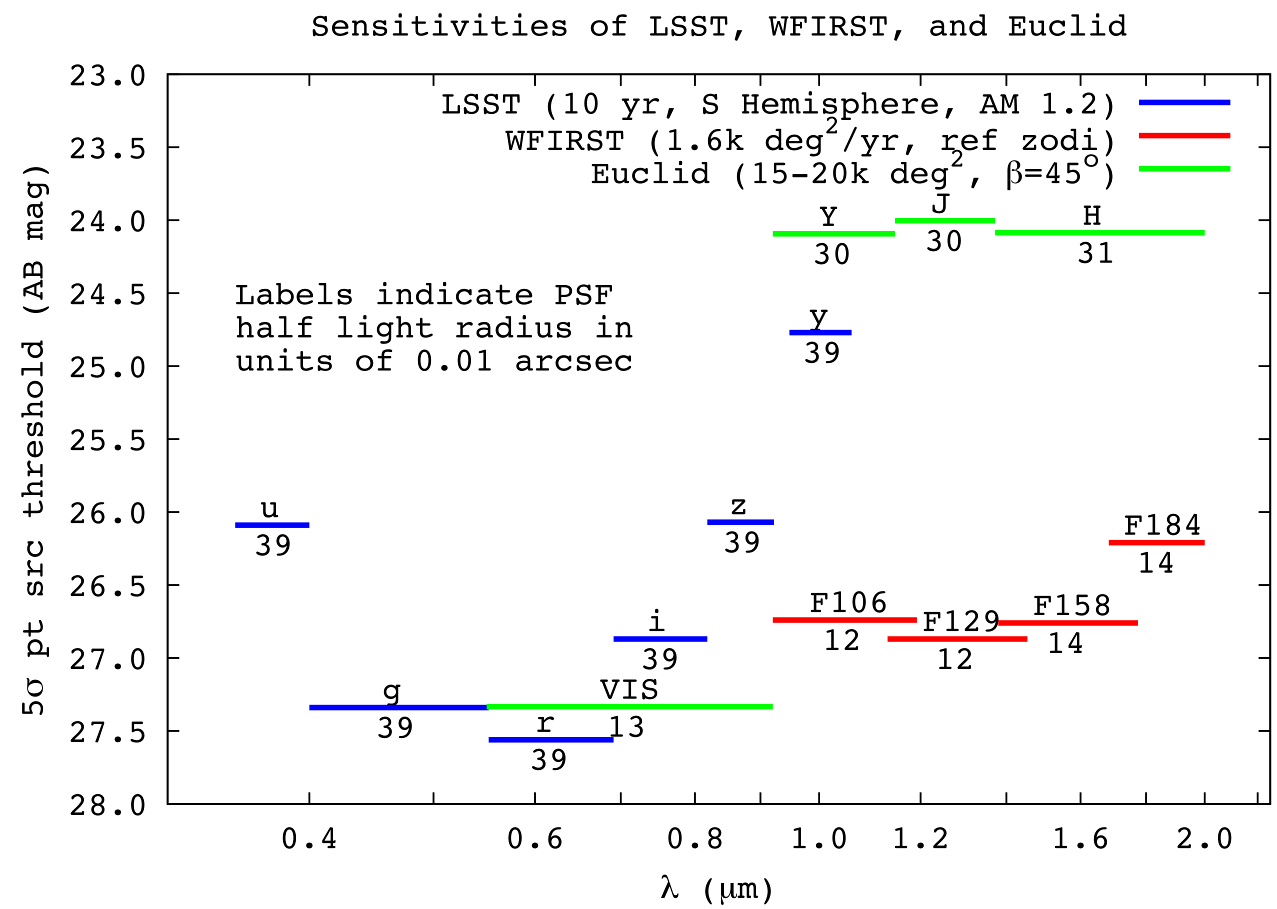

SF history, chemistry velocity dispersion



# Morphologies: WFIRST, Euclid, LSST




| | Band (μm) | Exp Time (sec) | Time Required (Days/1000 deg²) | Point Source Depth | Extended Source Depth | PSF EE50 (arcsec) |
|---|---|---|---|---|---|---|
| Y | 0.927-1.192 | 5 x 184 | 50 | 26.8 | 25.6 | 0.12 |
| J | 1.131-1.454 | 6 x 184 | 59 | 26.9 | 25.7 | 0.12 |
| H | 1.380-1.774 | 5 x 184 | 50 | 26.8 | 25.7 | 0.14 |
| F184 | 1.683-2.000 | 5 x 184 | 50 | 26.2 | 25.2 | 0.14 |
| Grism | 1.350-1.950 | 6 x 362 | 118 | $4.6\times10^{-17}$ | $1.0\times10^{-16}$ | 0.18 |

IFU: 3x3” FoV

0.6-2 micron

R~100

# Jets and SFRs: Radio Continuum

VLA Sky Survey:
A+B config, S-band
Not Yet Determined

All-Sky : 100 microJy, 1800 hrs (all 1 sigma)

WIDE : 10,000 $deg^2$, 50 microJy, 3000 hrs

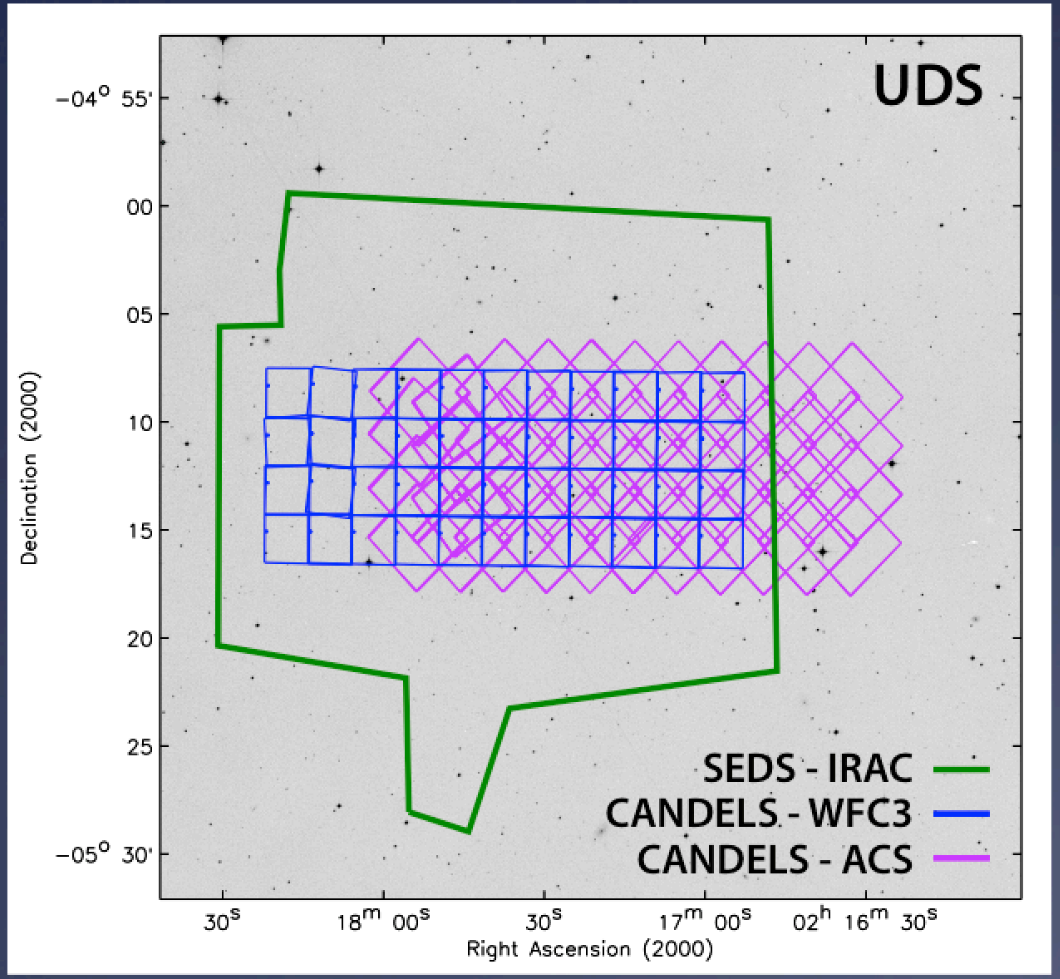
*LIRGs to z~0.15, QSOs to z > 5*

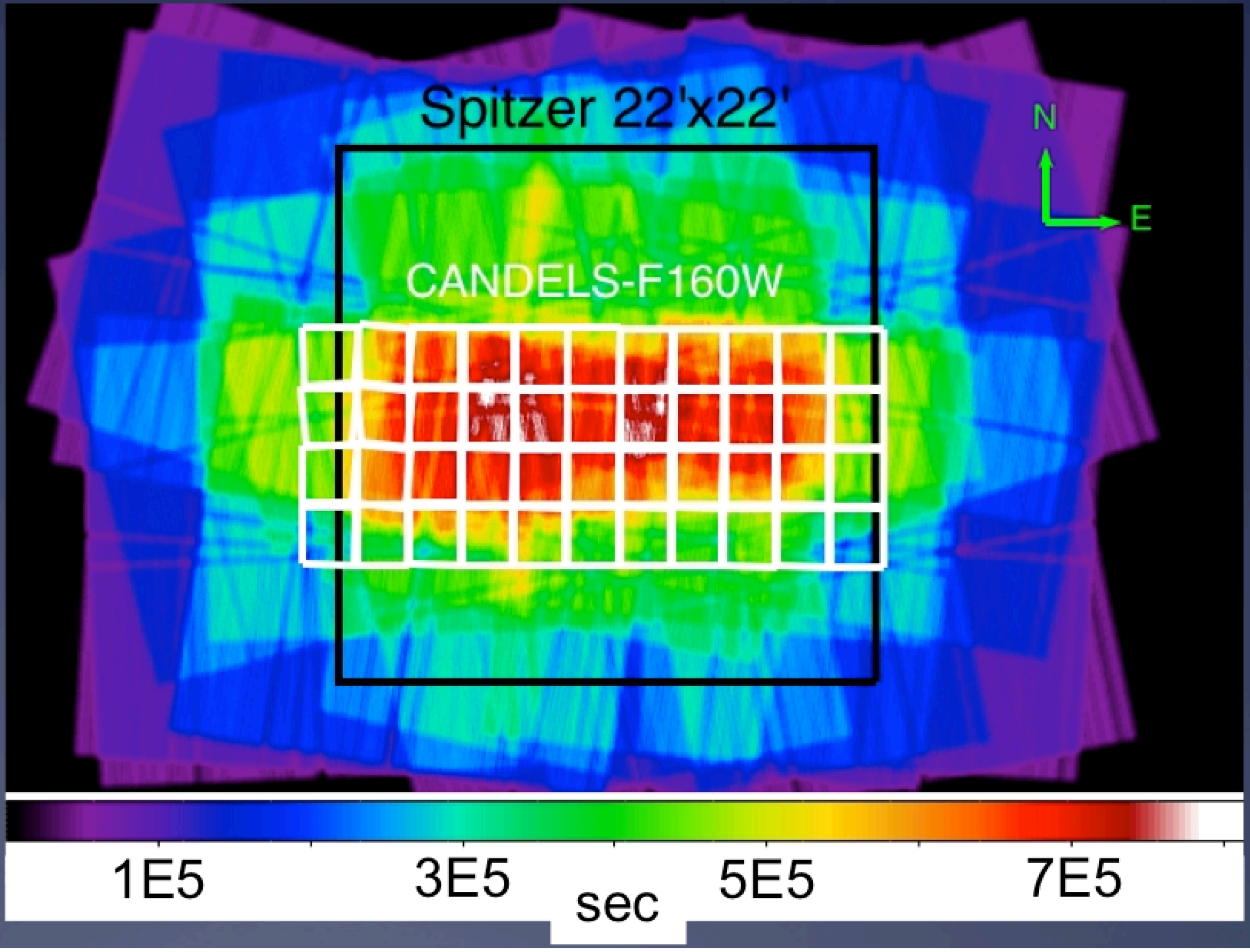
DEEP : 10 $deg^2$, 1.5 microJy, 3000 hrs

*~50 solar mass/yr at z~1.5*

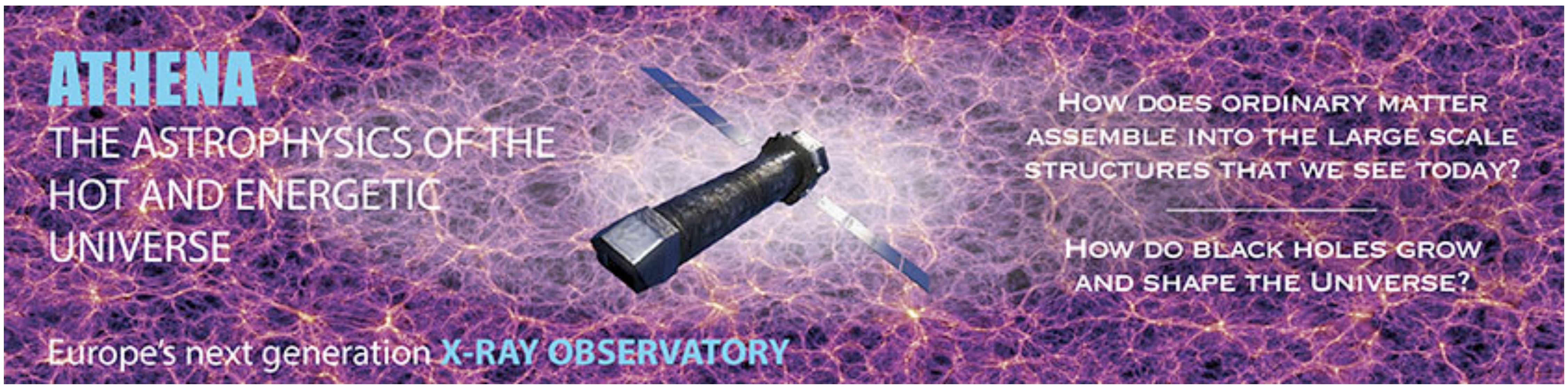
# UDS XVP Survey

- Cycle 16 Chandra X-ray Visionary Project. PIs: G. Hasinger, D. Kocevski
- Covering 22'x22' SEDS area in UKIDSS/UDS with 1.25 Msec.
- Average exposure of 700 ksec in CANDELS region.
- Science Goals:
  - Nature of BH seeds at z~6-10 via cross-correlating X-ray and IR backgrounds.
  - Host properties of Compton-thick AGN selected via spectral modeling.



# Lbol/SFR: X-ray and Far-IR

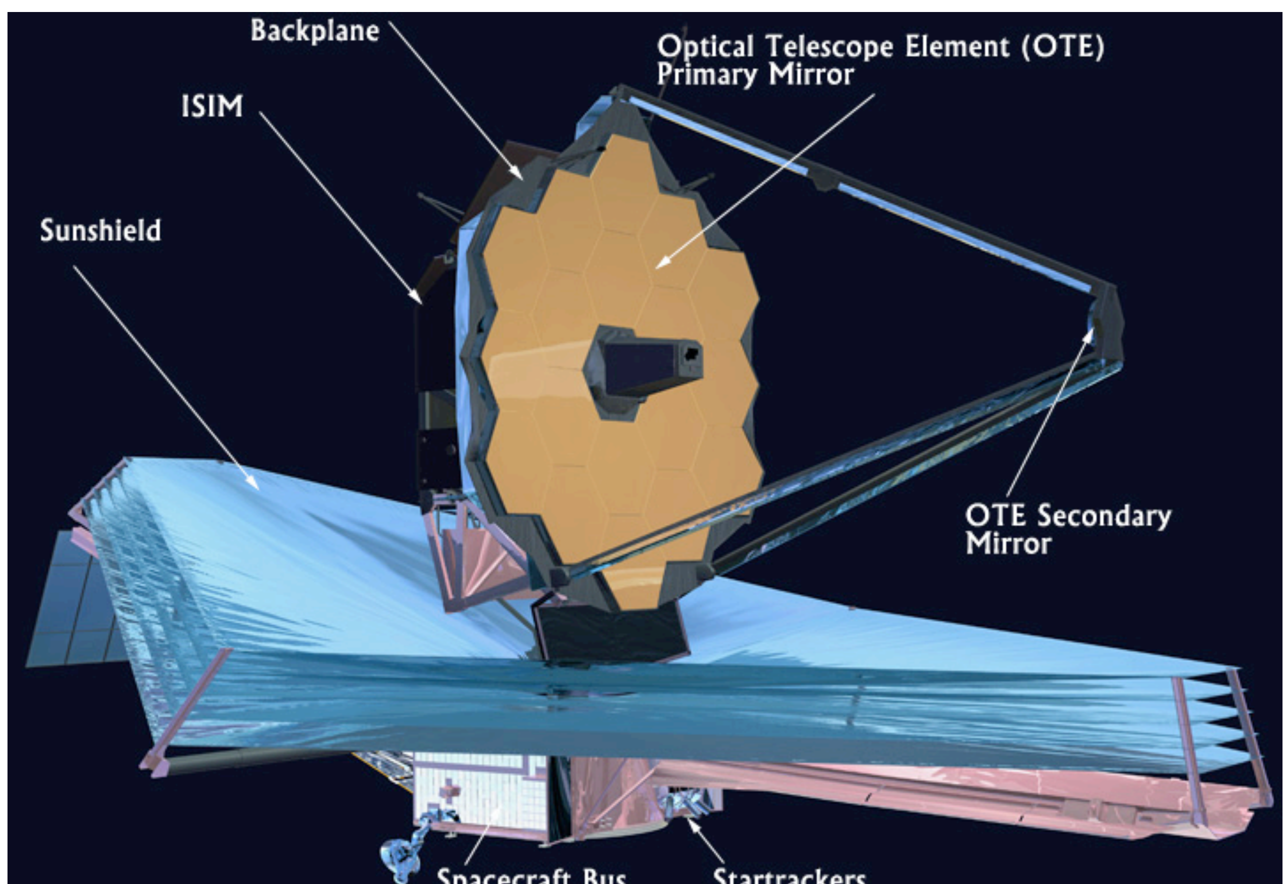



FIR?

# SFRs, Morphologies: JWST

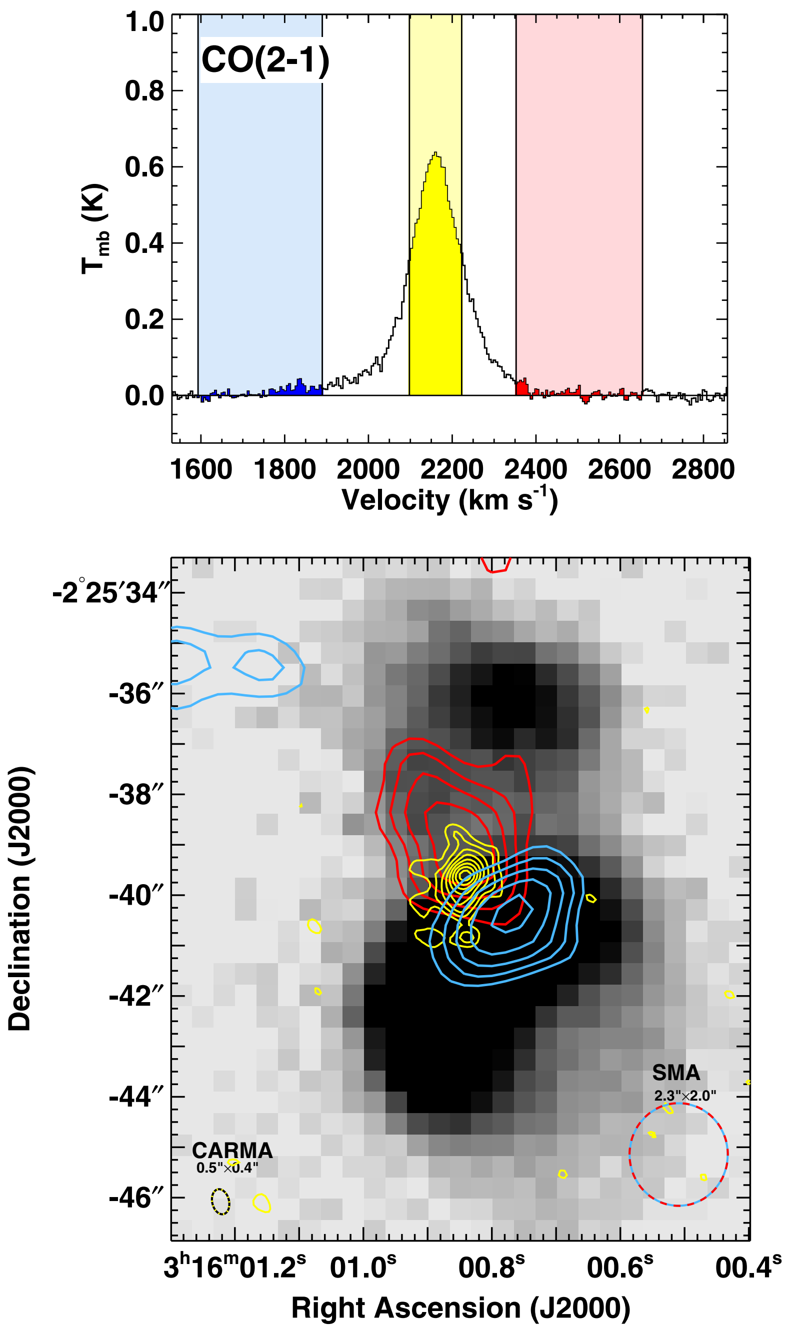
Imaging: 2x4’ FOV 0.6 - 28 micron

Spectroscopy: 0.6 - 30 micron
some IFU, some multi-object

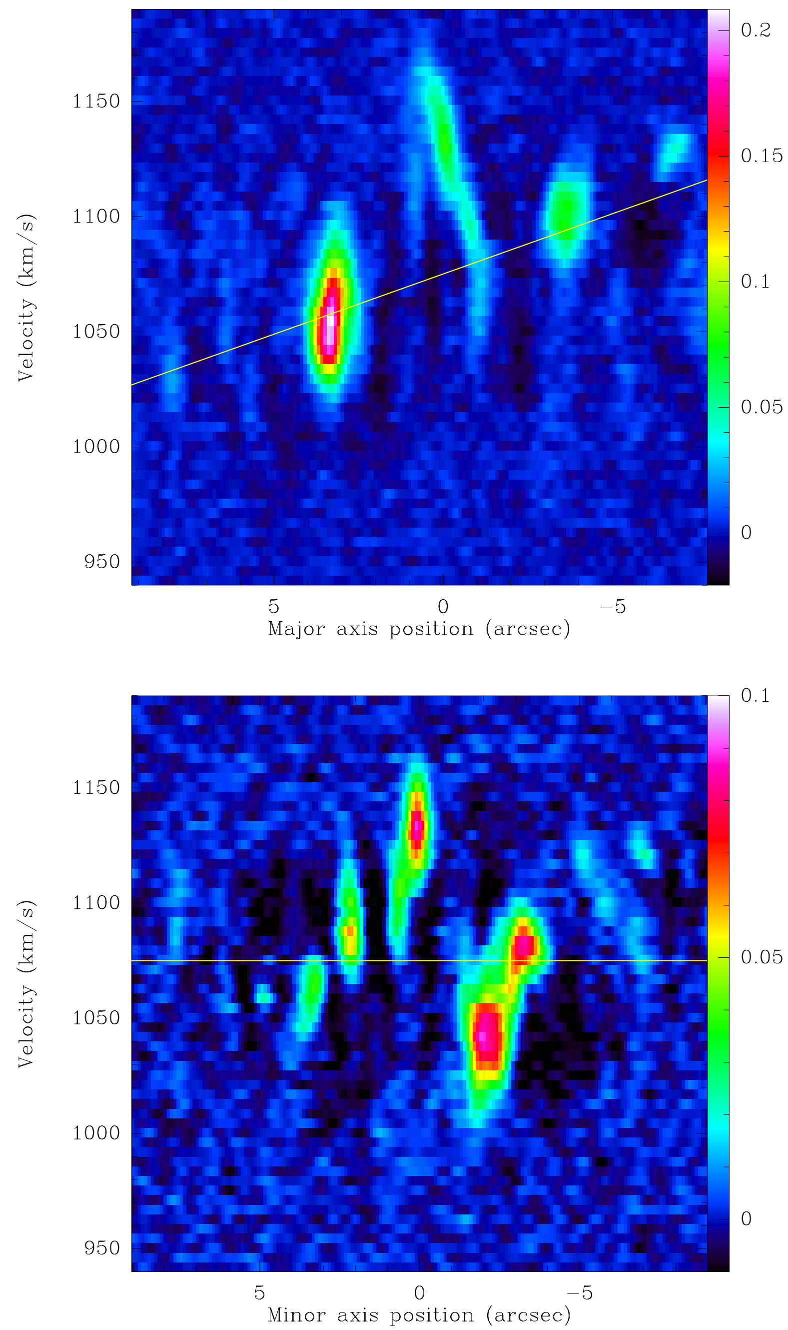


# Gas Content and Outflow: ALMA

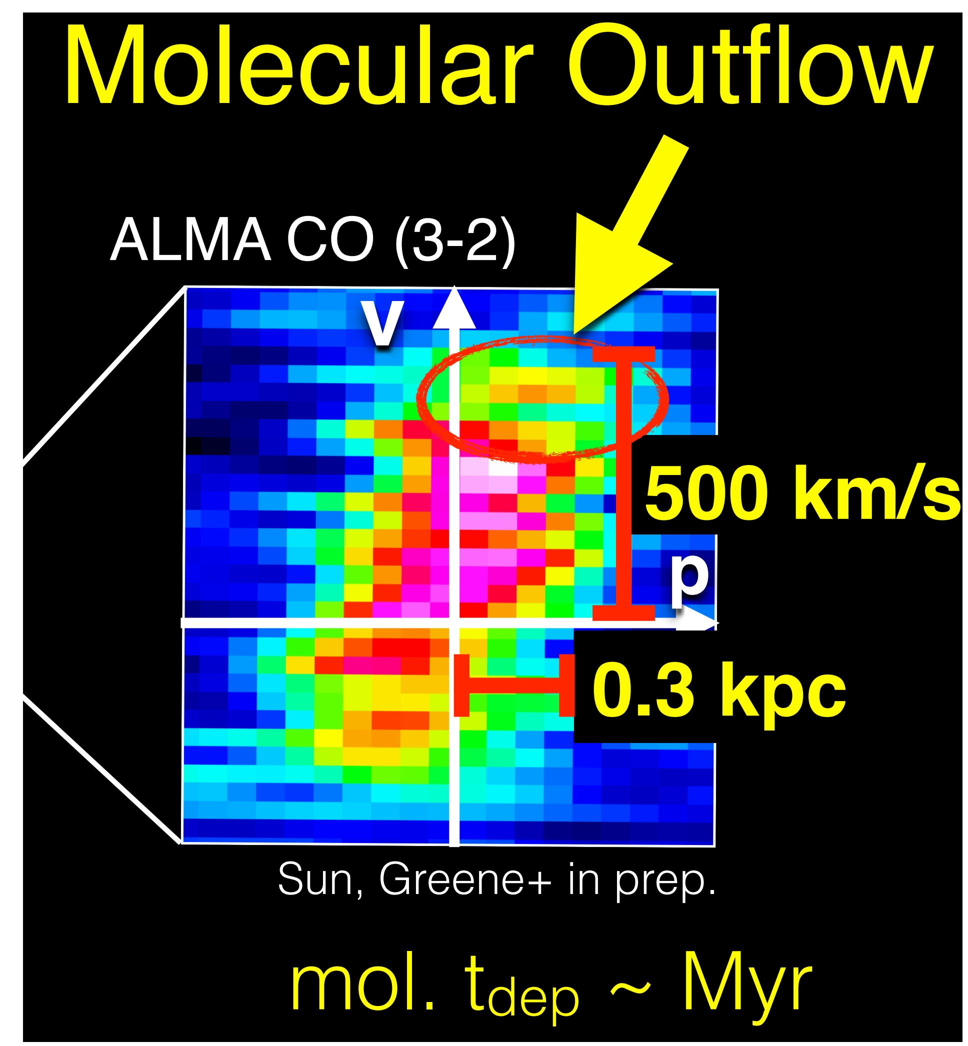
Alatalo et al. 2011




Combes et al. 2013

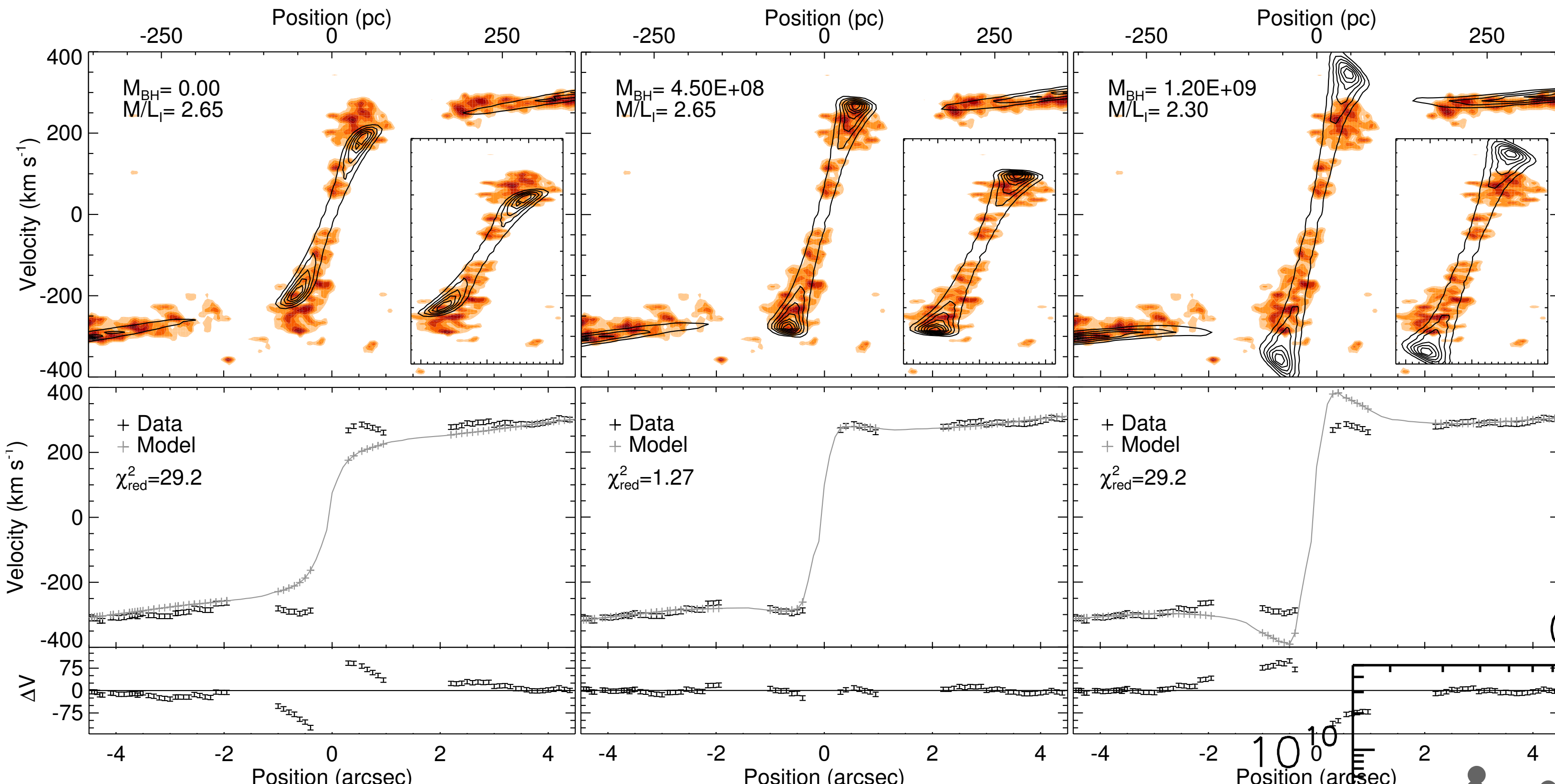



Sun, Greene et al. 2014



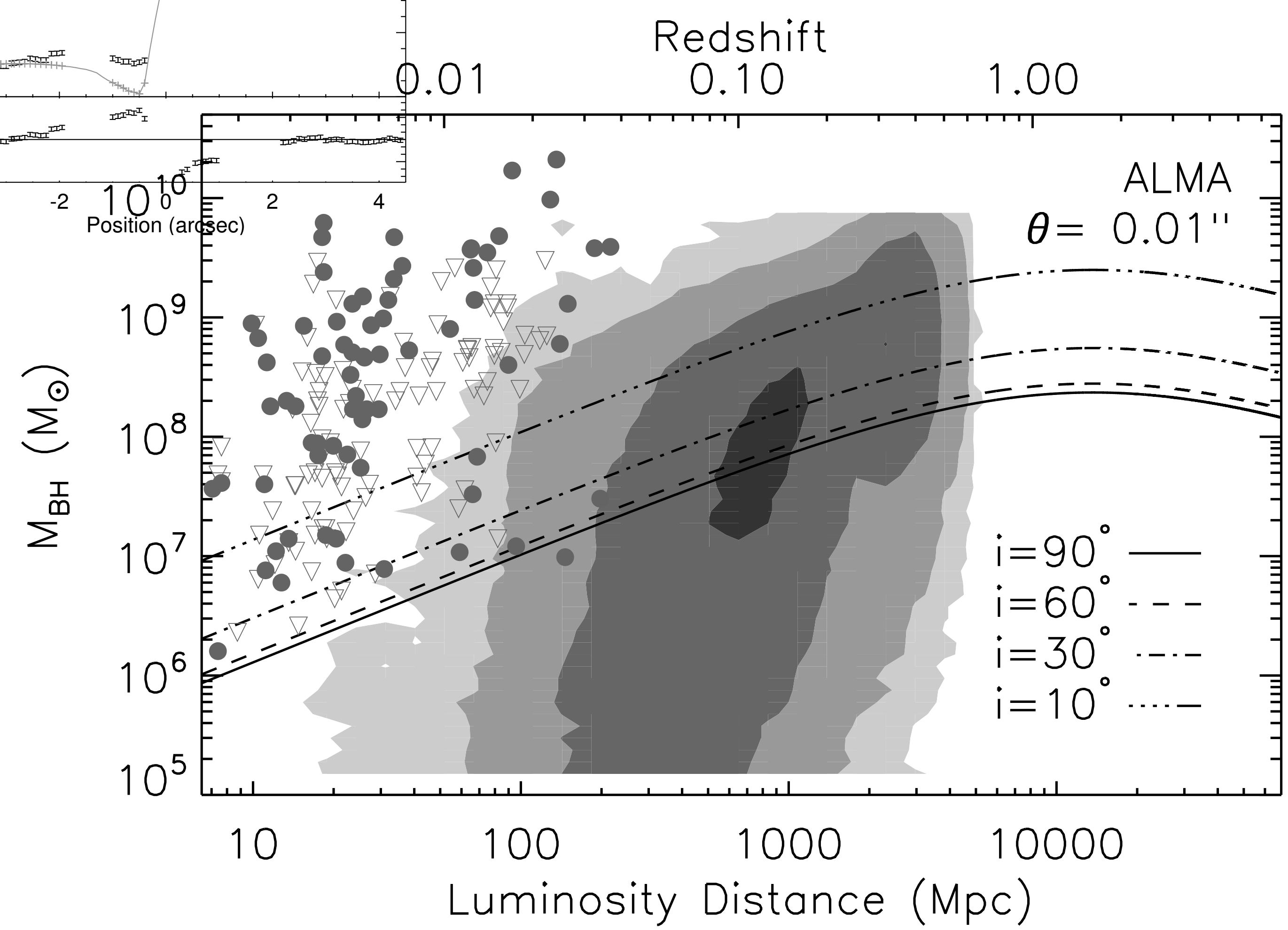
# ALMA: Black Hole Masses

NGC4256

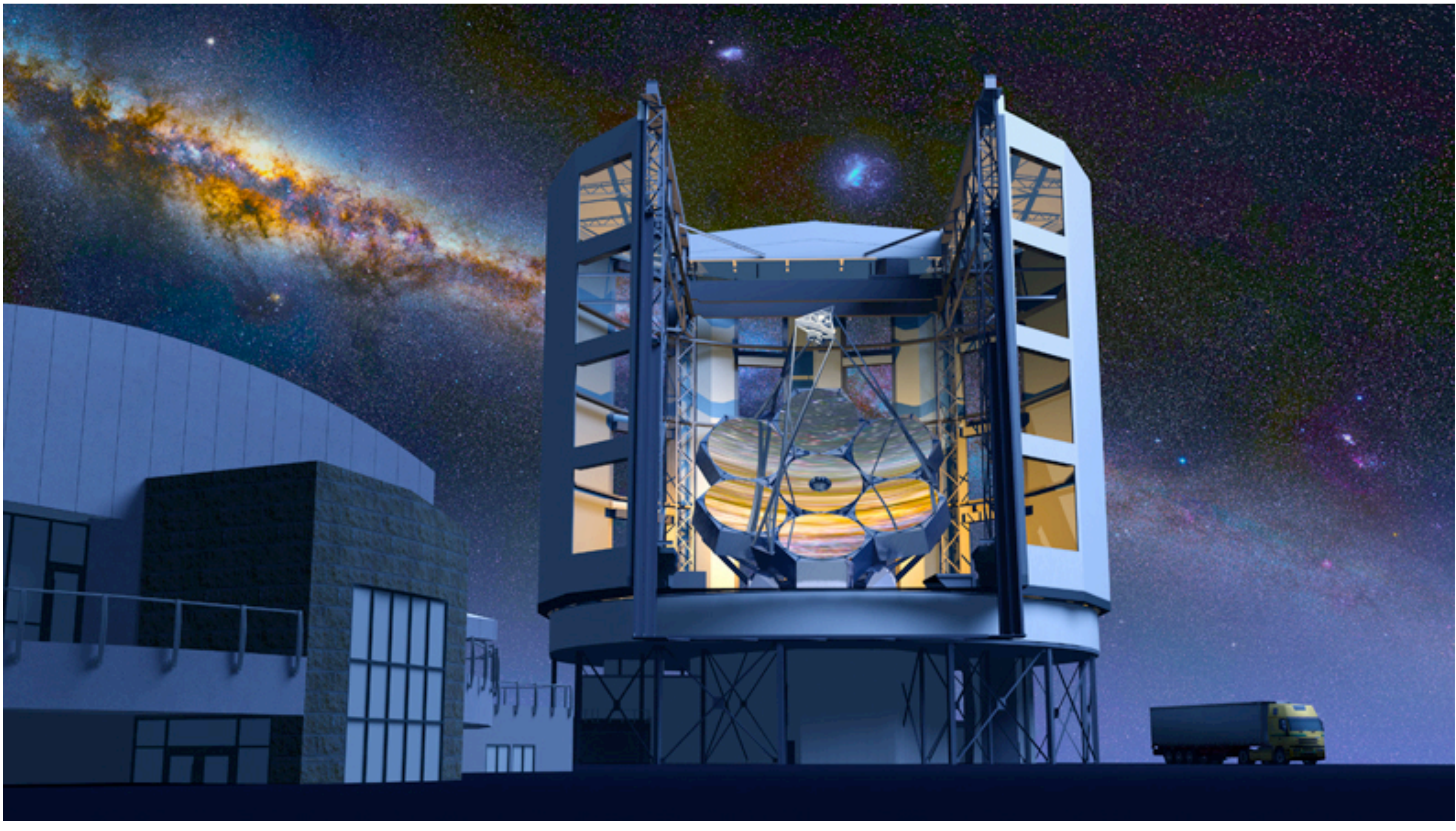



T. Davis et al. 2013

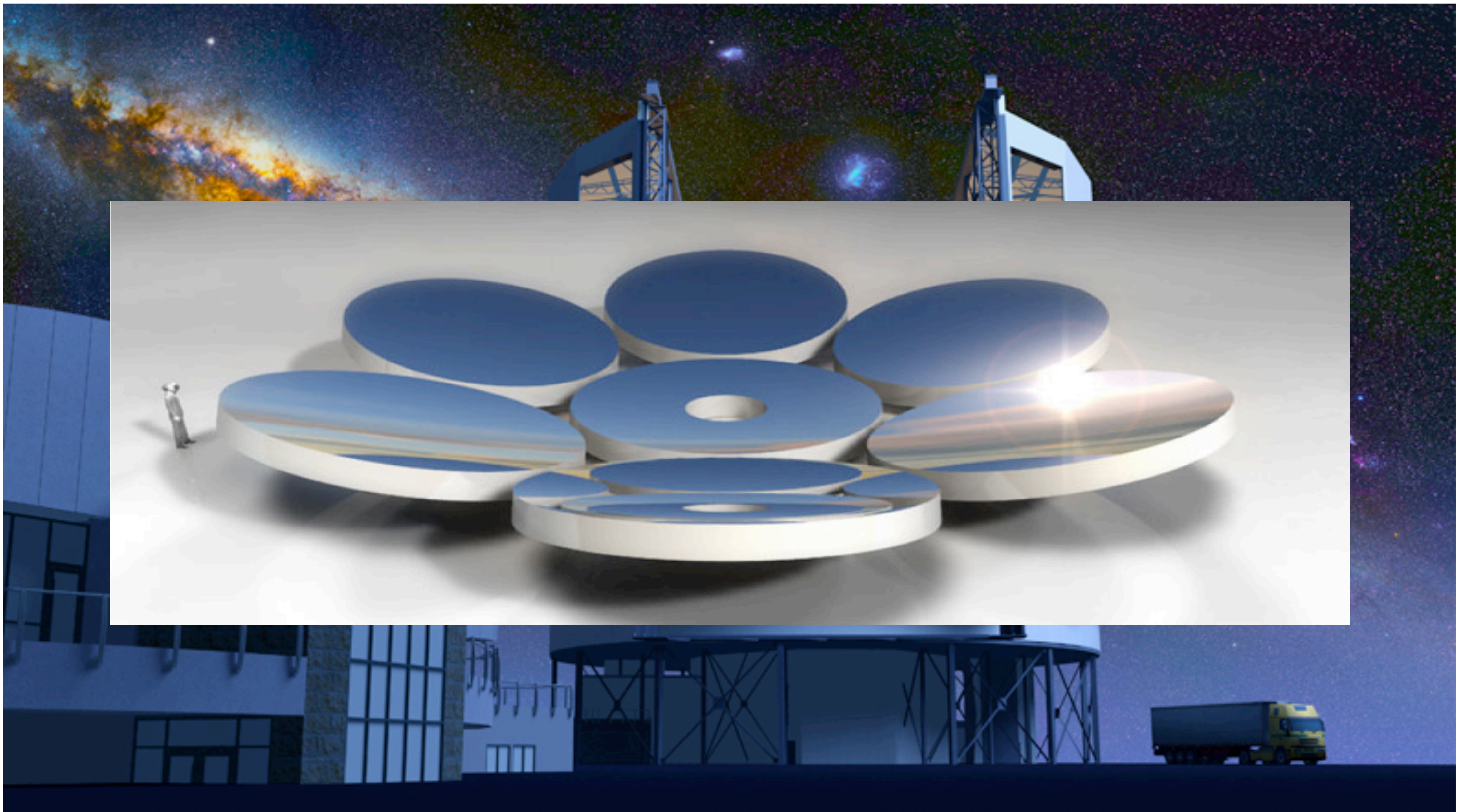
T. Davis 2014



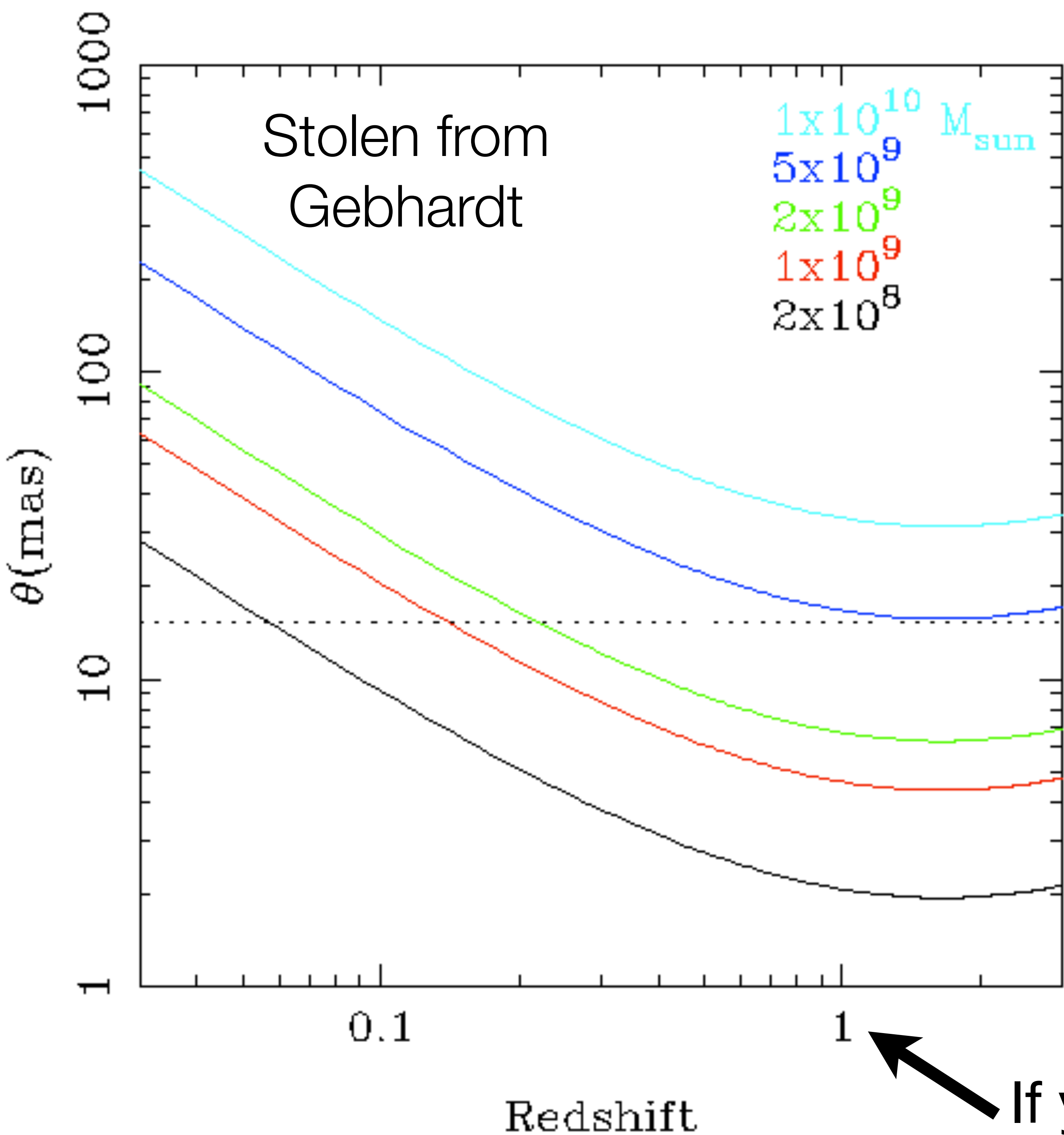
# Next Generation Telescopes: GMT-IFU



# Next Generation Telescopes: GMT-IFU



# Black Hole Masses at High Redshift




Sphere of influence for black holes of various masses versus redshift

If you can make it there you'll make it anywhere

# Theory

Stuff we can do right now! (Schaye et al 2014; Furlong et al 2014)Simulations are now good enough to use them to understand the Universe. EAGLE papers VI-XI. Use the simulations to understand the *biases* in the observational data… mock catalogues for galaxies *and* AGN

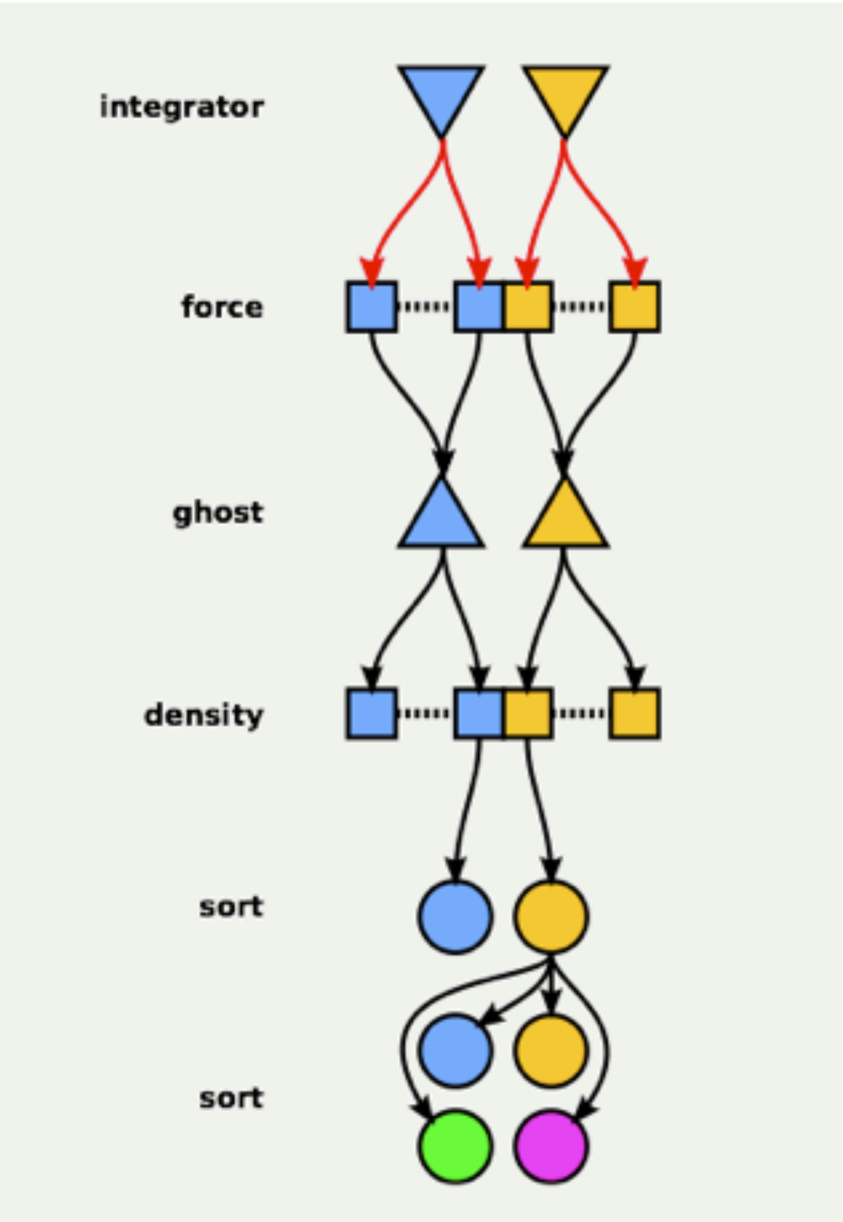
Stuff we can do next!

Linking large scale simulations and small scale simulations; Exploit the Mori-Zwanzig formula; Understand the ISM! … lots of "extra physics

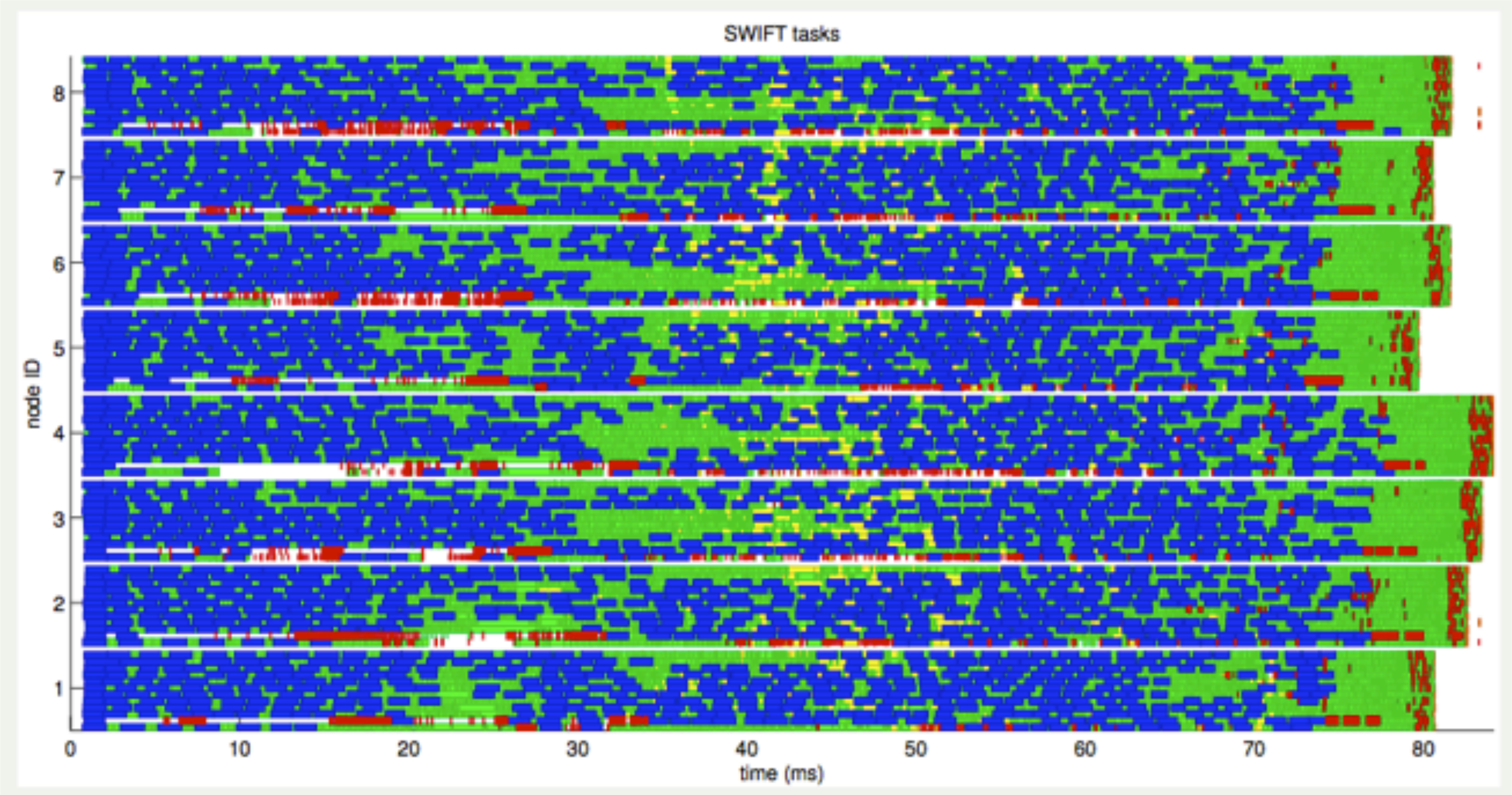
Repeat a lot of times…

# Preparing for the next generation

- SWIFT is a new open source SPH code that will use task based parallelism (Pedro Gonnet 2013)




The work is split into tasks, their dependencies and their conflicts. The task scheduler optimises the order of task execution so that no processor is idle…




Example run: colours indicate different tasks

# Conclusions

- Next generation surveys like PFS will give us large samples of galaxies AND AGN out to z~2

- We will have the capabilities to measure morphologies, gas fractions, star formation rates, and bolometric luminosities

- We will get nature to reveal her closely guarded secret of whether SFR or AGN activity rules

- See you again in 20 years to discuss how we don’t know anything about BHs or SFR.