Connecting the physical properties of AGN and galaxies

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(University of Leicester)

The Art of measuring galaxy Physical Properties
Milan, 22nd Nov 2019

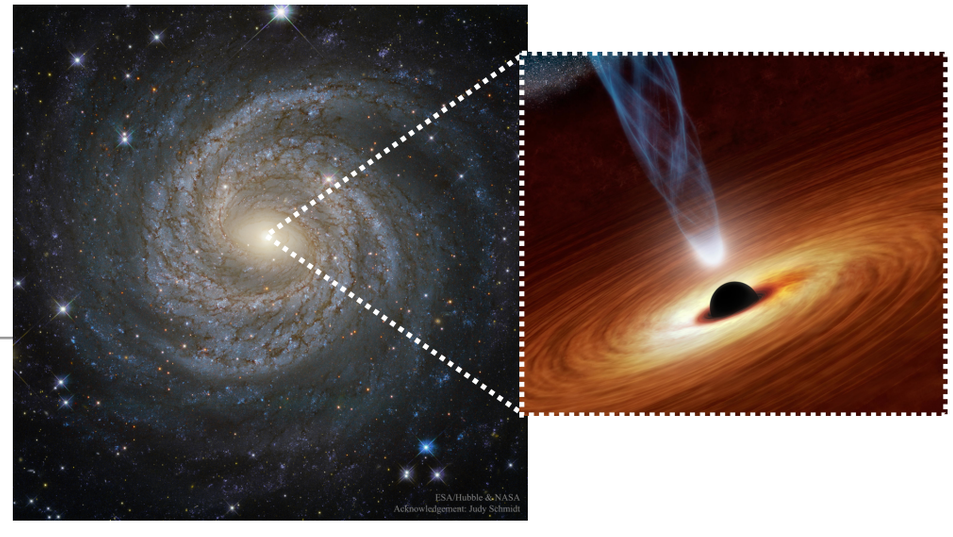
Take home points

- AGN samples identified at *any* wavelength are severely affected by **selection biases** and can give a biased view of which galaxies have AGN

- AGN exhibit a broad distribution of accretion rates, indicating **variability** on timescales ~0.1-1 Myr i.e. faster than changes in global galaxy properties

- Incidence of AGN in main-sequence star-forming galaxies correlates with SFR => both are related to **cold gas**? But… **not *just* cold gas** - additional mechanisms appear to trigger and fuel AGN in galaxies that are *not* on the main sequence.

Connecting the physical properties of AGN and galaxies



Key questions:

- When and where does **black hole growth** take place within the **evolving galaxy population**?
- What physical conditions in galaxies promote AGN activity?
  - Which physical mechanisms drive the growth of supermassive black holes?
- What is the **impact** of AGN on the evolution of galaxies?

Connecting the physical properties of AGN and galaxies

- Two approaches:

1. Select AGN:

    - What are the properties of their host galaxies? Are they different to non-AGN galaxies?
    - Do we see correlations between AGN properties (e.g. L_{AGN}) and the host properties (e.g. SFR)

Is there a direct connection between instantaneous BH growth and overall galaxy growth?

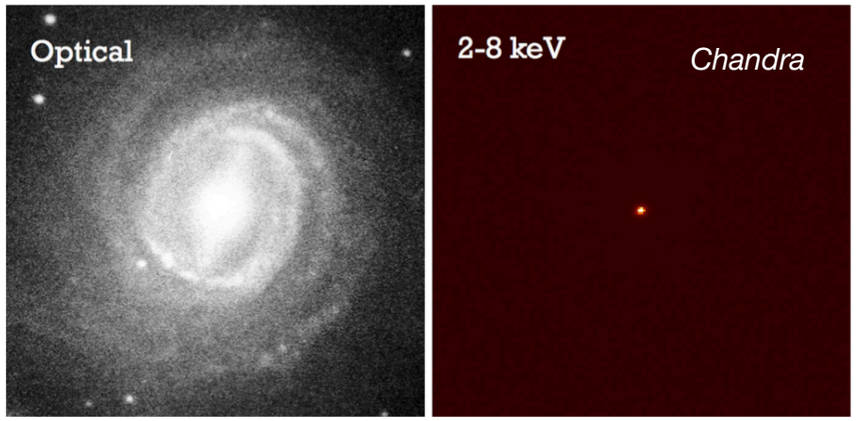
2. Select galaxies:

    - Where are AGN found within the galaxy population?
    - Do certain galaxies host *more* AGN or *more luminous* AGN?

What physical conditions promote AGN activity => what *fuels* or *triggers* an AGN?

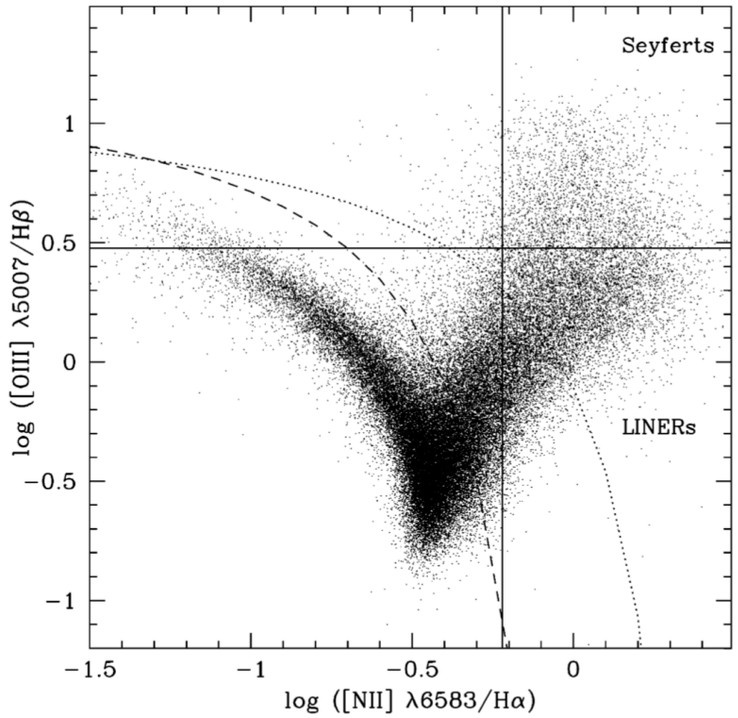
1) Select AGN - identification methods

X-ray

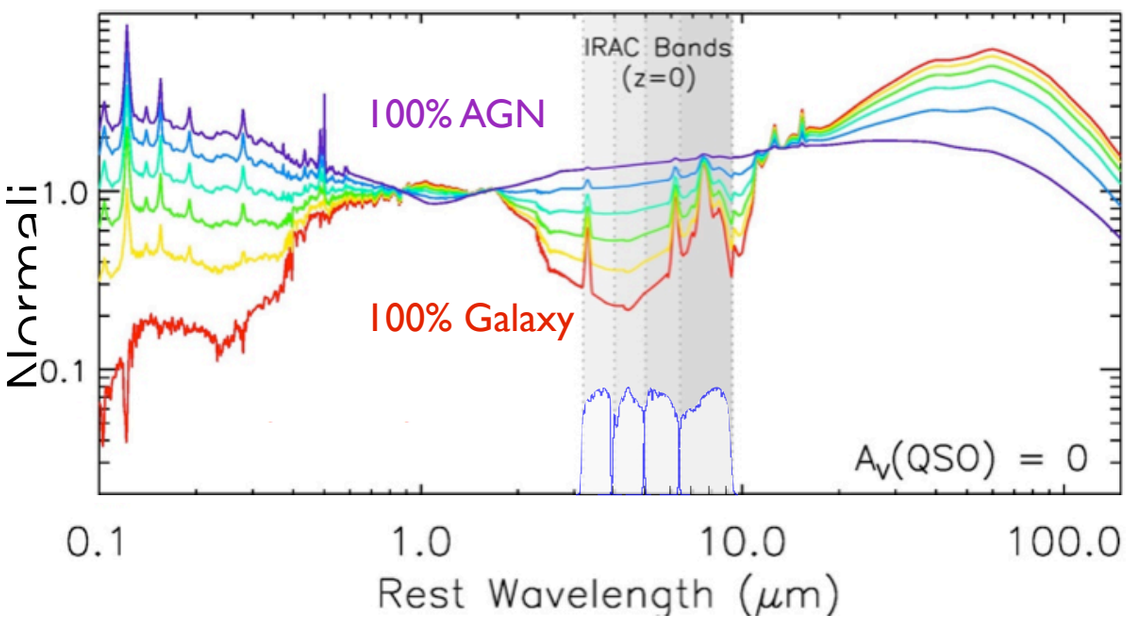


NGC 3783 - a local active galaxy
(see Brandt & Alexander 2015)

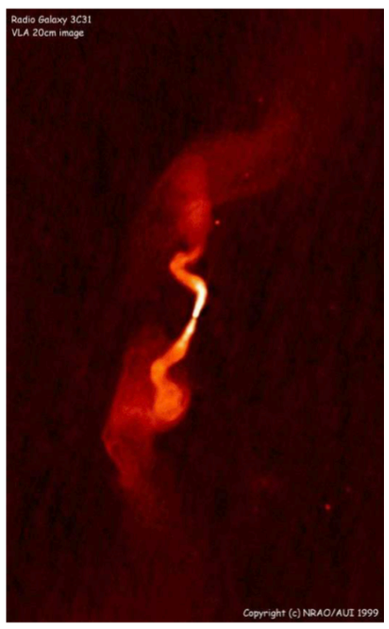
Optical (BPT)



Mid-IR



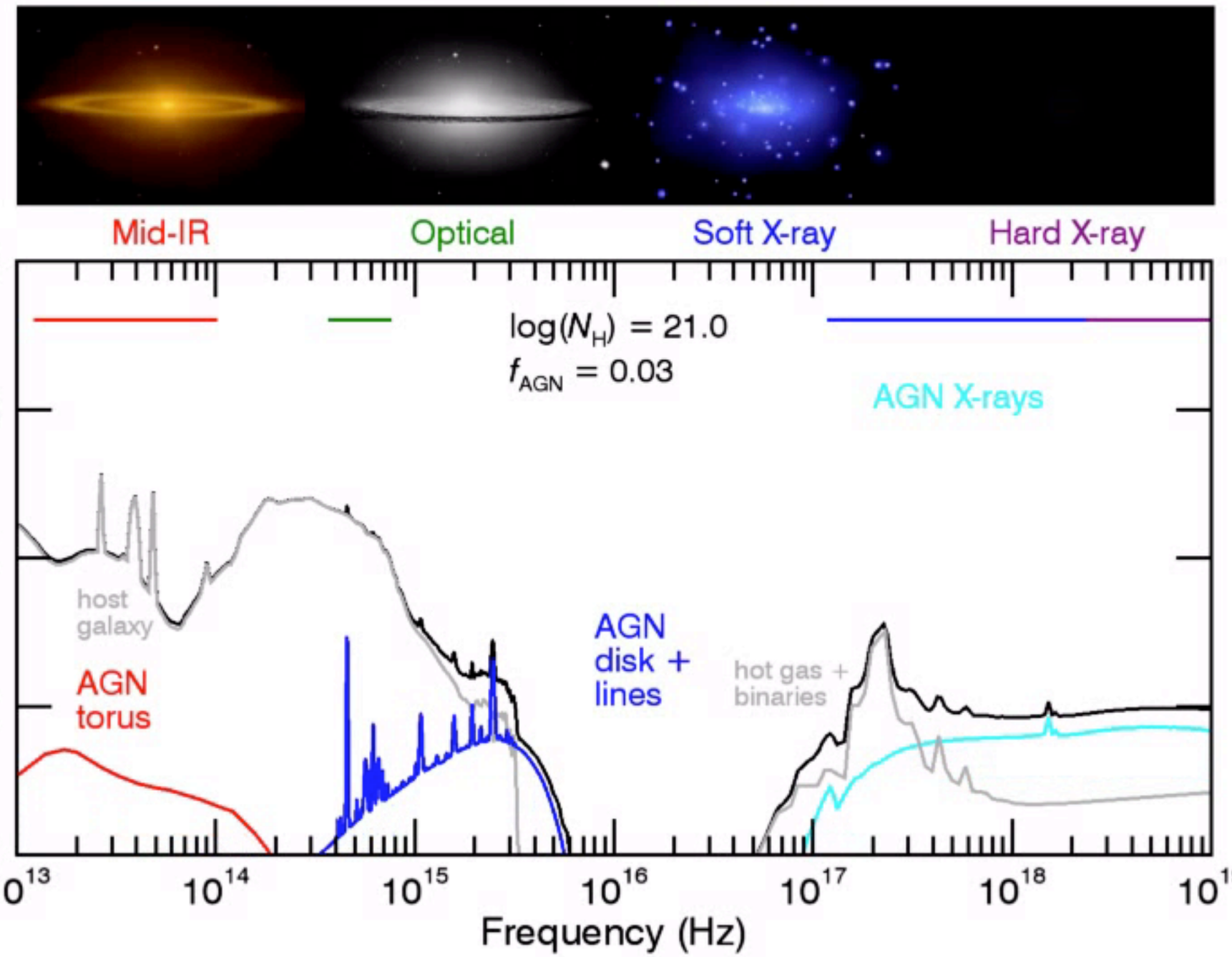
Radio



AGN vs. host galaxy light

Composite AGN and galaxy SEDs and images
for varying AGN dominance and obscuration

Hickox & Alexander (2018)
"Obscured Active Galactic Nuclei"
ARA&A, Volume 56



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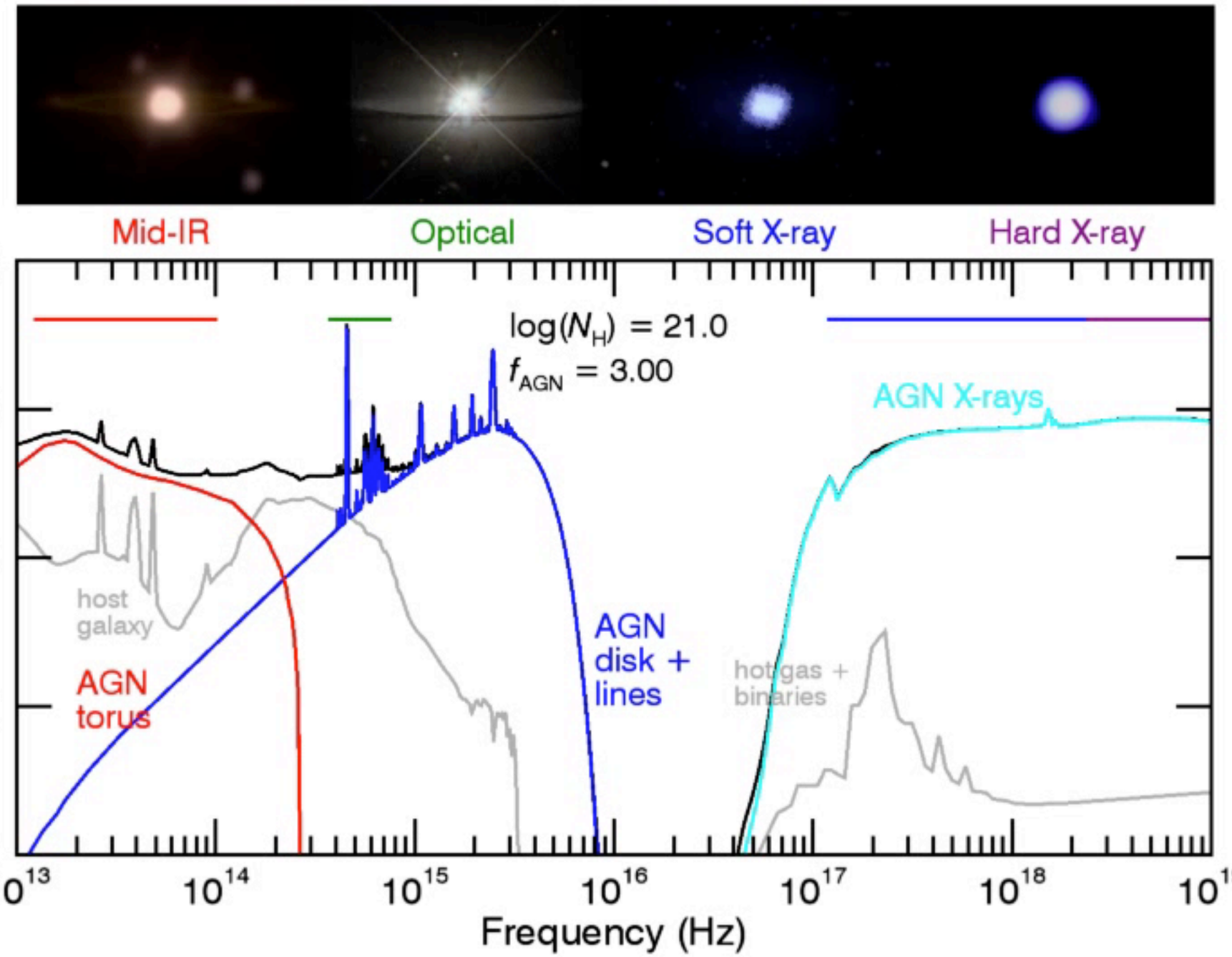

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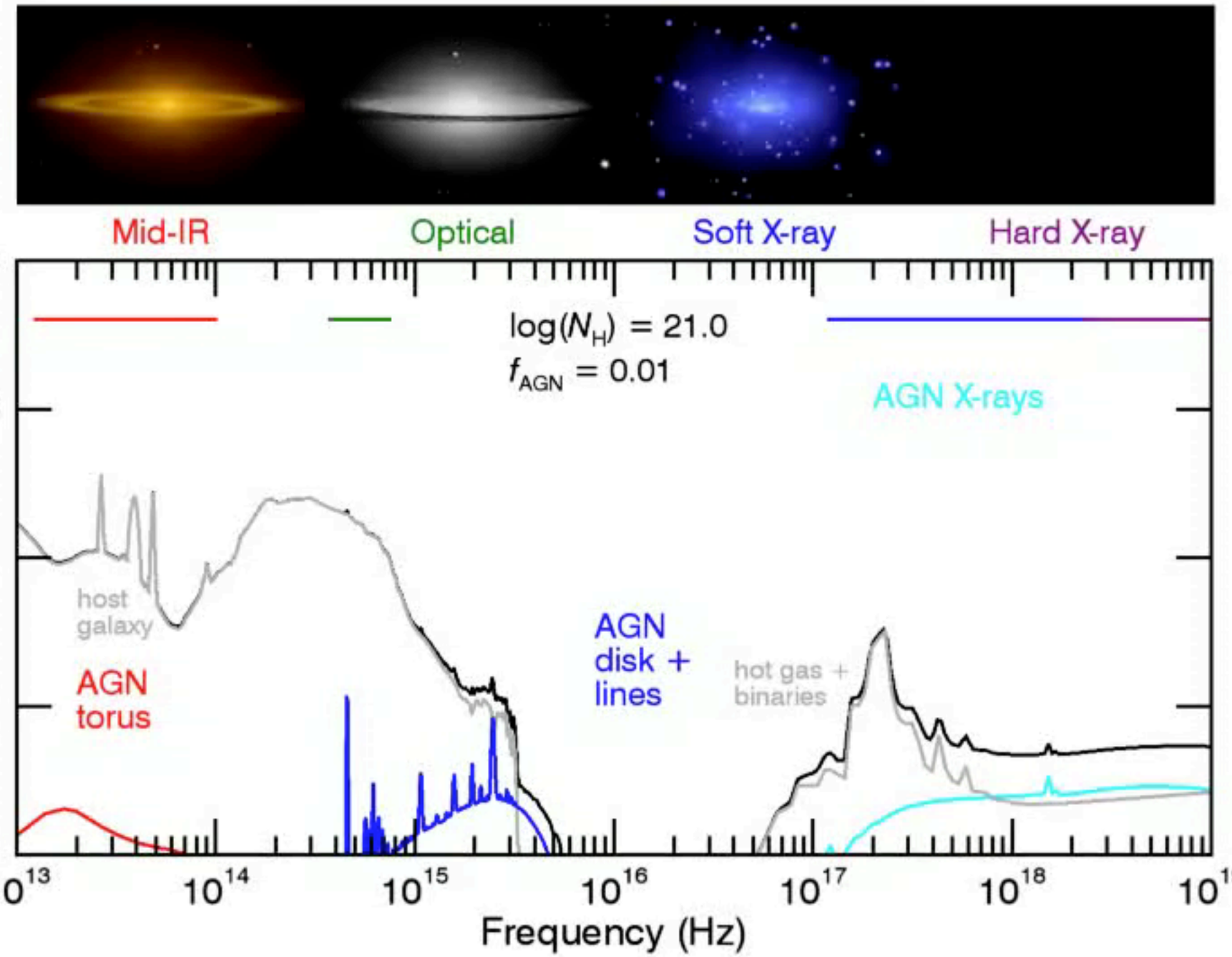
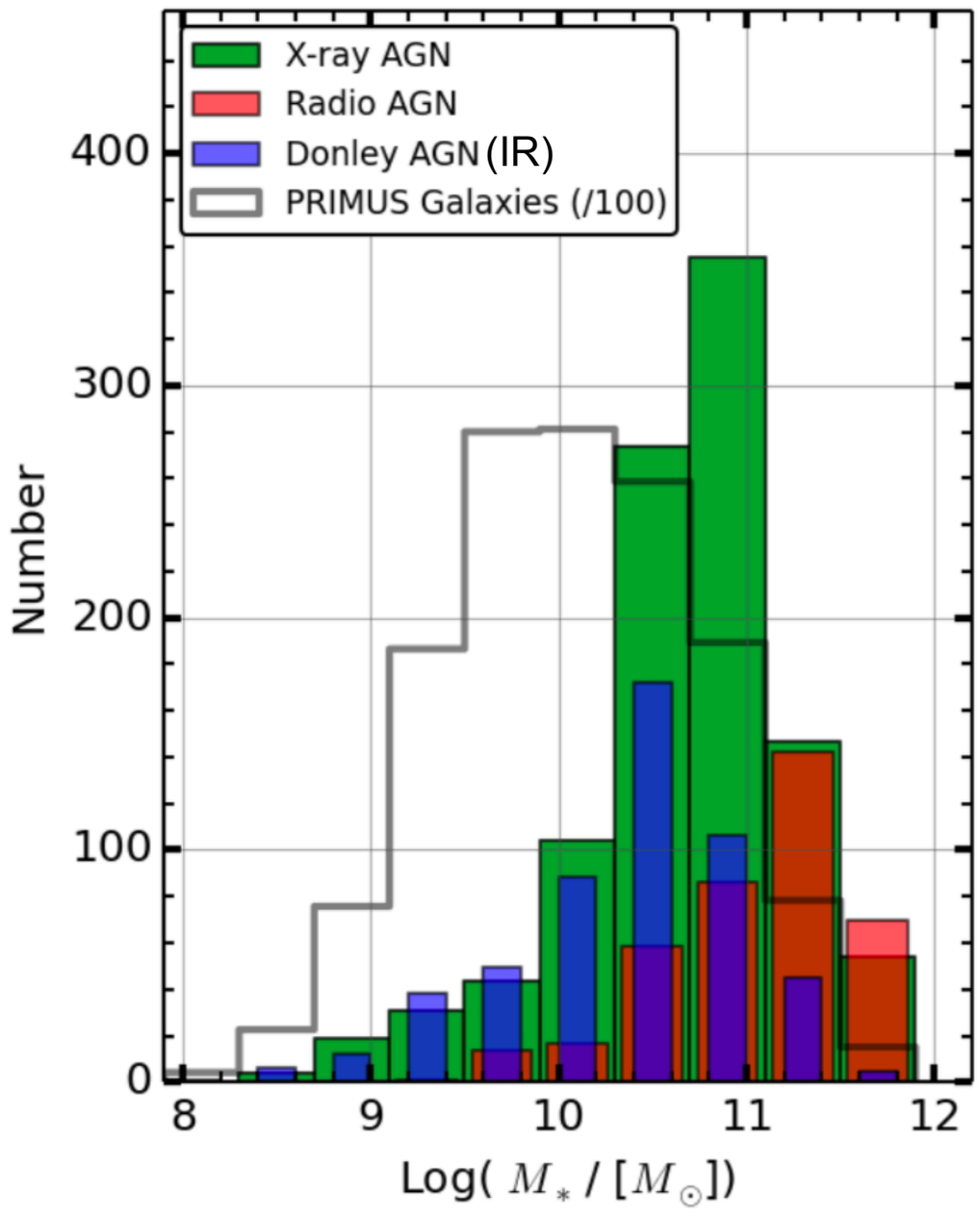


1) Select AGN => host stellar masses

- All AGN selection methods find that AGN are primarily in moderate to high stellar mass galaxies
  (mostly log $M_*/M_\odot$ ~ 10.5-11)

This is primarily a selection effect

- AGN with lower Eddington ratios are easier to detect in more massive galaxies
  see: Aird+12, Aird+13



Mendez, Coil, Aird et al. 2015
see also: Xue+10, Mendez+13

1) Select AGN => additional selection biases

Optical (BPT):

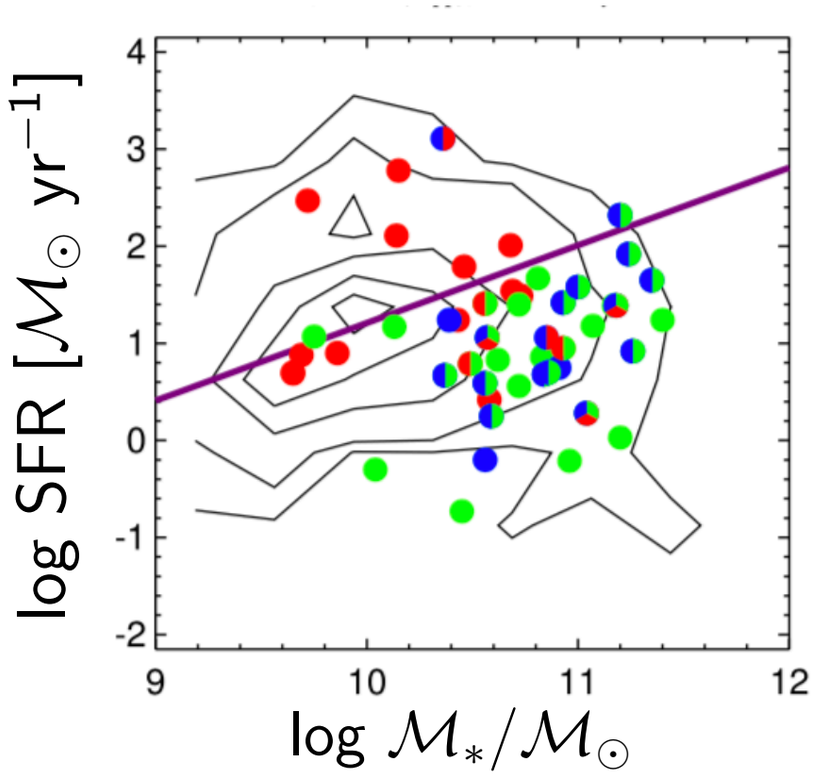
- biased against high SFRs

Mid-IR:

- biased against finding weakly accreting AGN
- slight bias *against* high stellar masses
- biased against high SFRs

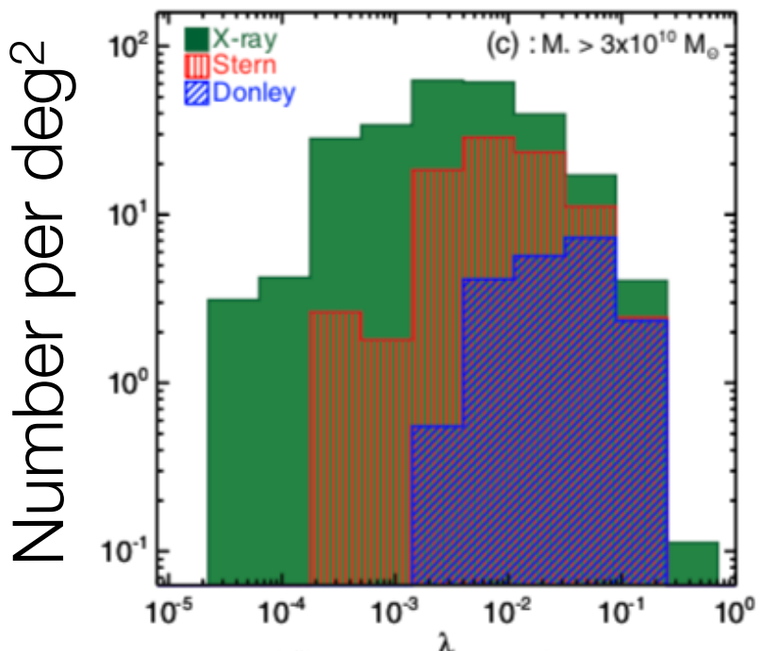
X-ray (2-10keV):

- Identifies broadest range of accretion rates
- Mostly unbiased against SFR
  (apart form very weak AGN in high-SFR hosts)
- Will miss most heavily obscured Compton-thick sources.
  (unclear if this will impact host properties)



Azadi+17
MOSDEF
survey
(z≈1.5-3.5)

Xray
Optical (BPT)
Mid-IR



Mendez+13
PRIMUS survey
(z=0.1-1)

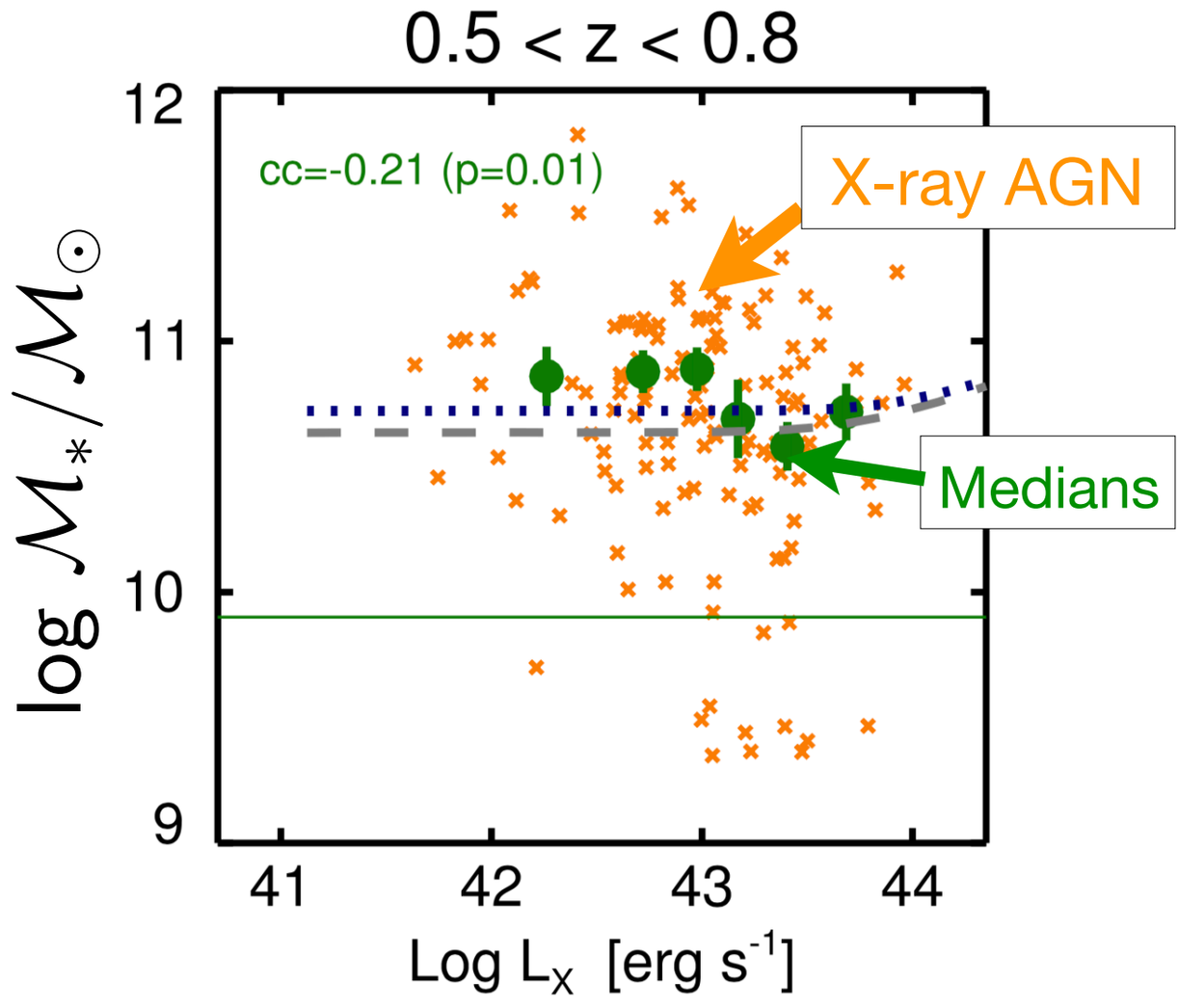
Xray
Stern (Mid-IR)
Donley (Mid-IR)

X-ray selected AGN samples: $M_{stellar}$ vs. L_X

- X-ray AGN are primarily in moderate to high stellar mass galaxies
  (mostly log $M_{stellar}/M_{sun}$ ~ 10.5-11)

- Broad distribution extending to low masses

- **No correlation with L_X**

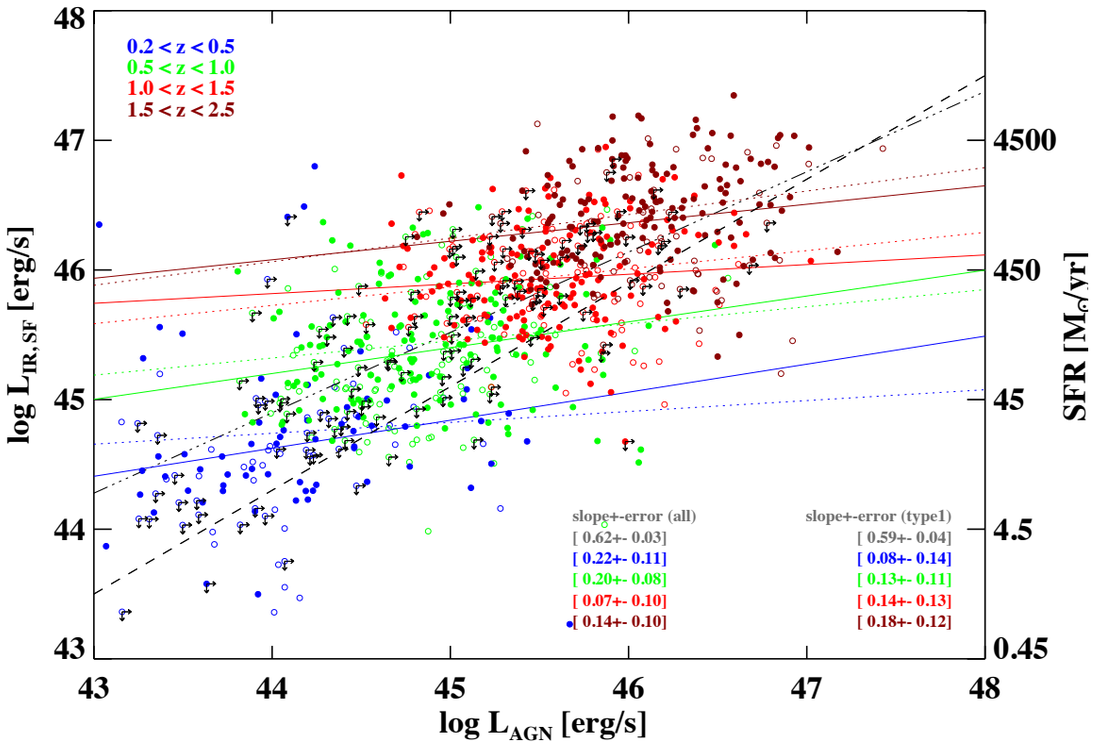


Azadi, Aird et al. 2015

X-ray selected AGN samples: SFR vs. L_X

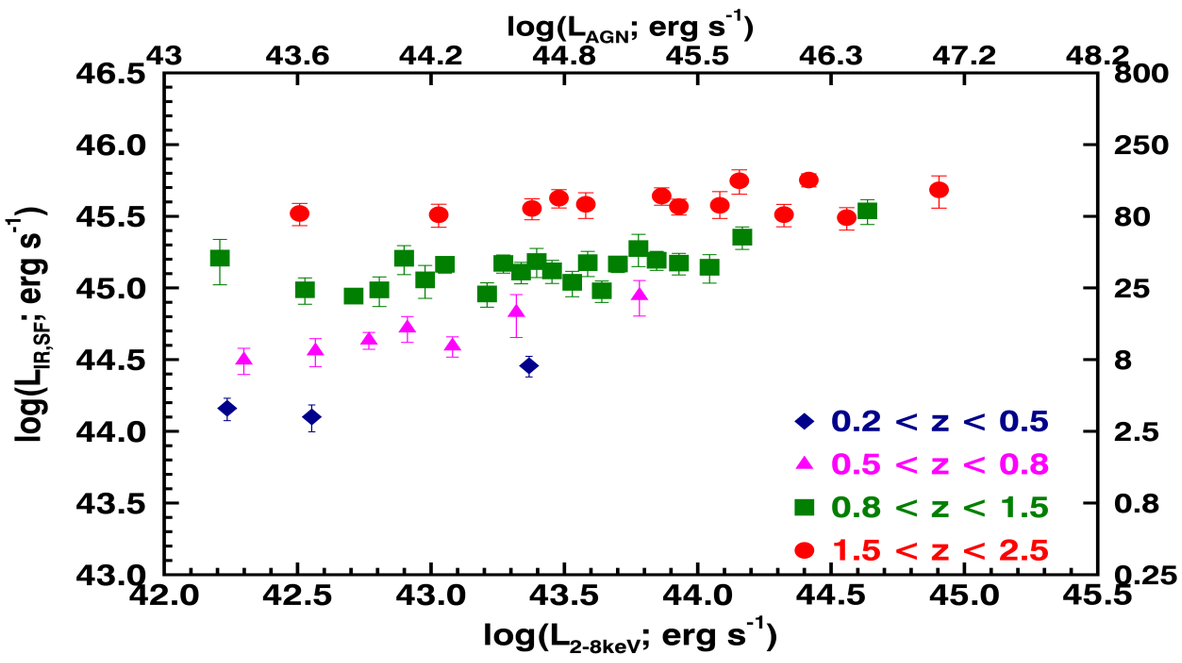
Dai+18

- bright X-ray sources and FIR detections only



Stanley+15

- fainter X-ray sources, stacking FIR data => average SFR



- Wide range of SFRs at a fixed L_X
- Relatively flat relationship between L_X and (average) SFR **at a fixed redshift**
- ***Average* SFRs are comparable to the main sequence of star formation for galaxies of the same stellar mass (log M_{stel}/M_{sun} ~10.5) and redshift**
- Overall shift to higher SFR at higher z (consistent with evolution of main sequence)

Conclusions: 1) Select AGN - measure host properties

- Primarily find AGN in moderate-to-high mass galaxies (selection bias)

- Average SFRs of AGN are roughly consistent with the main sequence of star formation (for equivalent $M_{stellar}$)

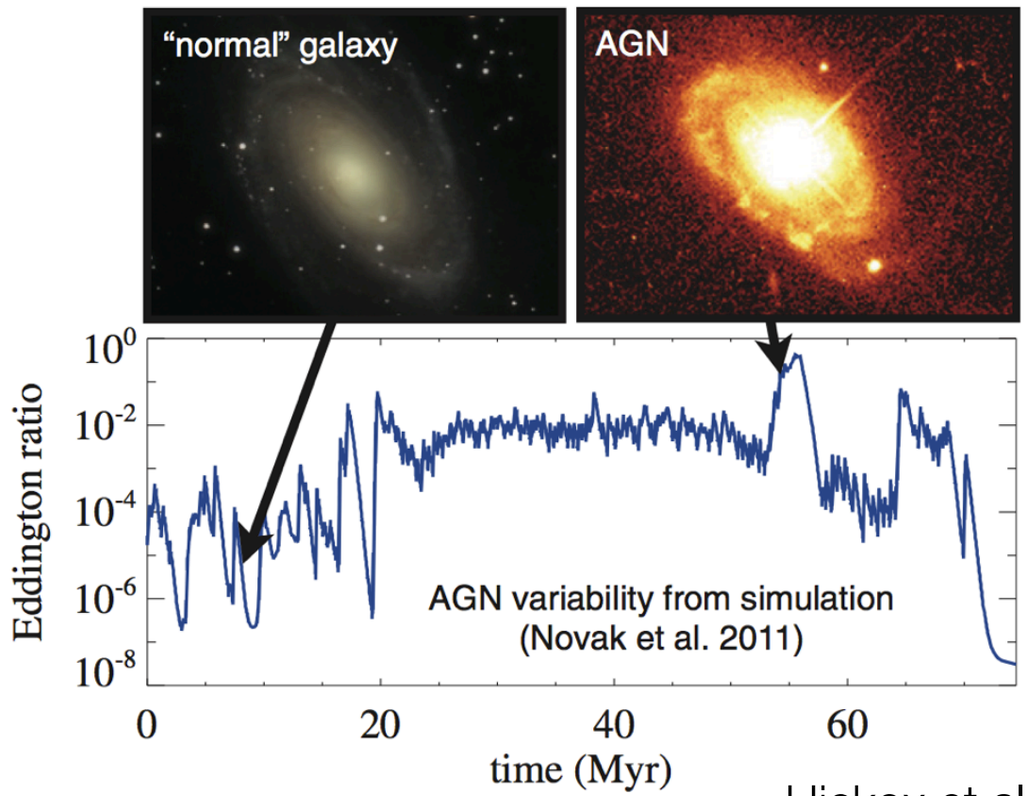
- Large **scatter** in $M_{stellar}$ and SFR at fixed L_X - no clear correlation between instantaneous level of black hole growth (traced by L_X) and the host galaxy properties

We observe the ***instantaneous*** level of AGN activity (e.g. traced by L_X)

But AGN activity ***varies*** on short timescales (≲Myr) *relative to the lifetime of the host galaxy* (~Myr-Gyr)

Variability on galactic timescales due to:

- Gas consumption
- Local feedback processes/self-regulation
- Overall changes in fuelling rate/ mechanism



Hickox et al. 2014

Will blur out any connection between the AGN luminosity and host galaxy properties

We observe the ***instantaneous*** level of AGN activity (e.g. traced by L_X)

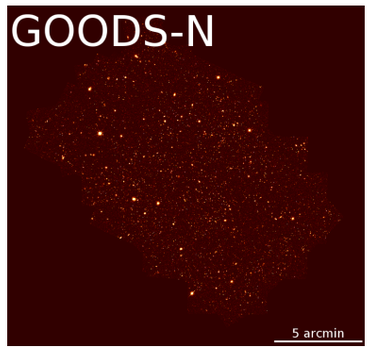
But AGN activity ***varies*** on short timescales (≲Myr) *relative to the lifetime of the host galaxy* (~Myr-Gyr)

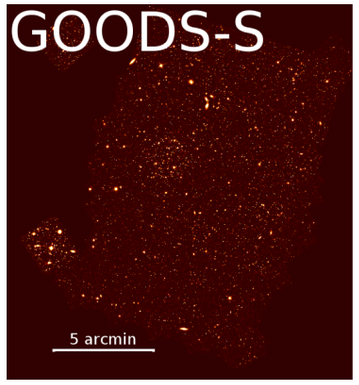
Take large samples of galaxies with *similar* properties and either:

a) Stack the X-ray emission => average over variability, recover average BH accretion
   e.g. Mullaney+12, Chen+13, Rodighierio+15, Yang+17

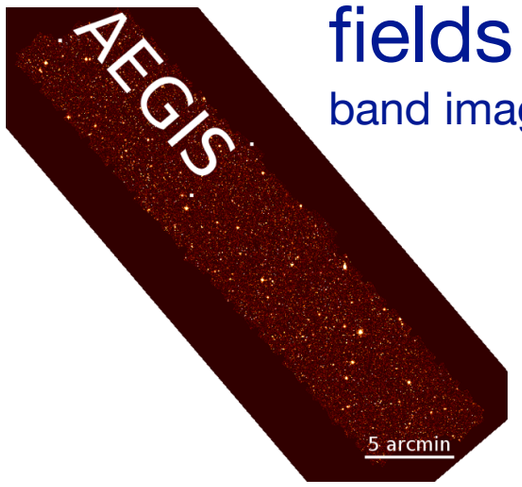
b) Directly measure the *distribution* of accretion rates
   e.g. Aird+12, Bongiorno+12, Yang+18, **Aird+18, Aird+19**

Starting point:
Select galaxies from deep **near-infrared** imaging



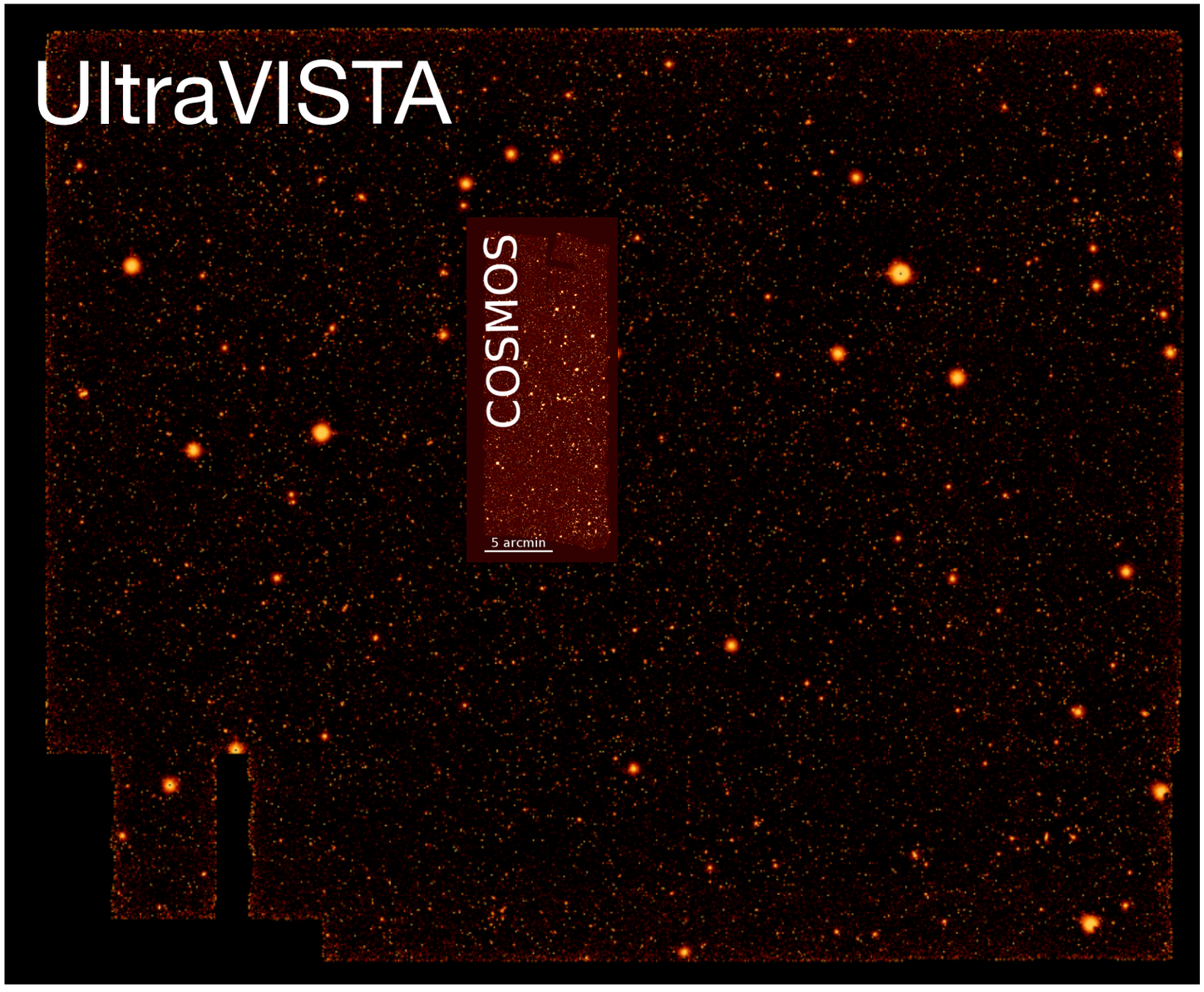


CANDELS/3DHST fields (ultradeep WFC3 *H*-band imaging)



Sample of
~120,000 galaxies
with $M_{*} \approx 10^{8.5\text{-}11.5}\ M_{\odot}$

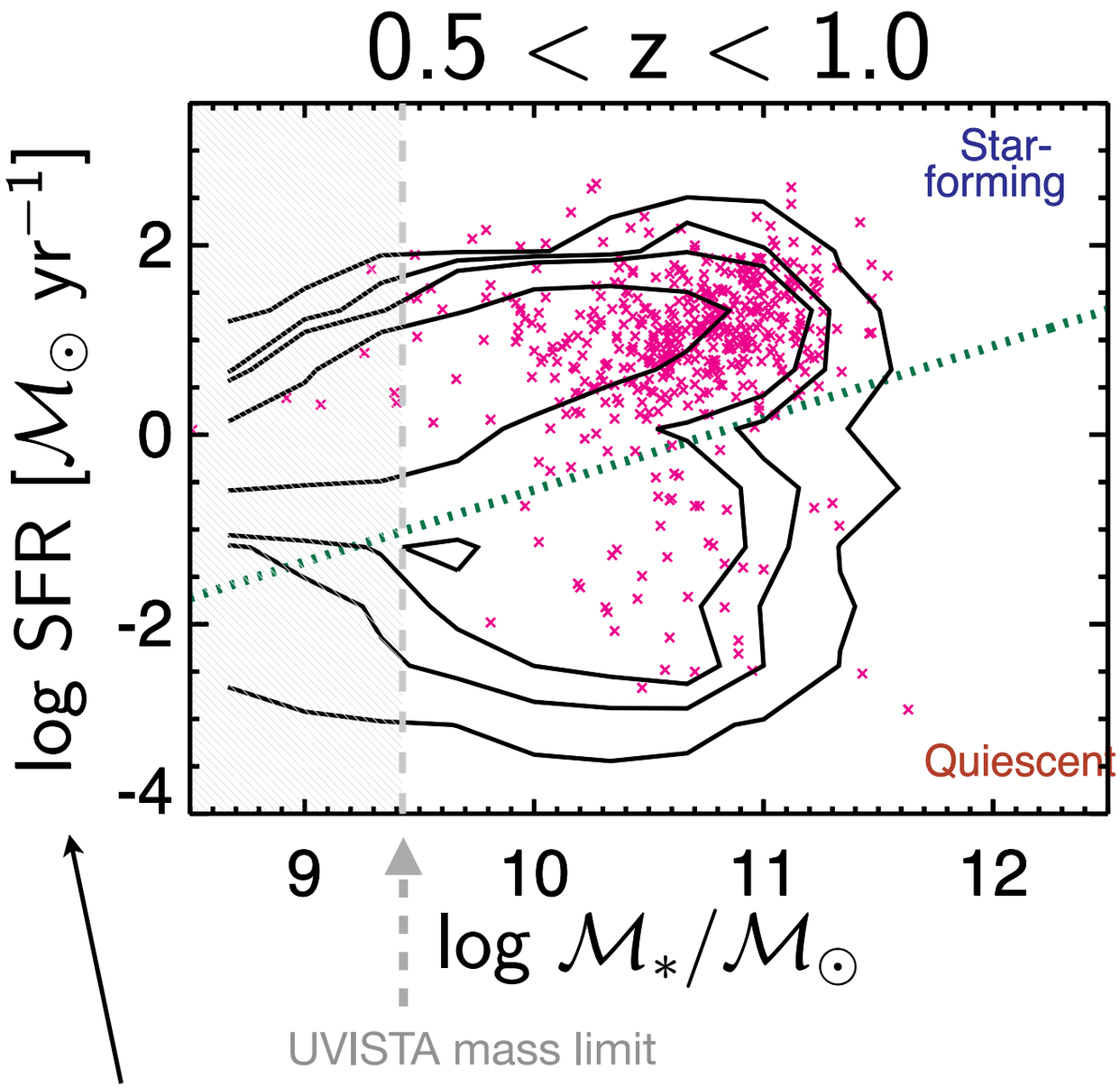
and z ≈ 0.1 - 4



\+ UltraVISTA

(deep K_S-band imaging over ~1.6 deg^2)

X-ray selected AGN across the galaxy population



From UV+IR or SED fits, corrected for AGN contamination for X-ray detections

- FAST: Kriek et al. 2009, see https://github.com/jamesaird/FAST

Galaxies

× X-ray detections

hard (2-7keV) detections from ~160ks-4Ms depth *Chandra* data across the CANDELS and UltraVISTA fields (Alexander+03, Xue+11, Nandra+15, Civano+16)

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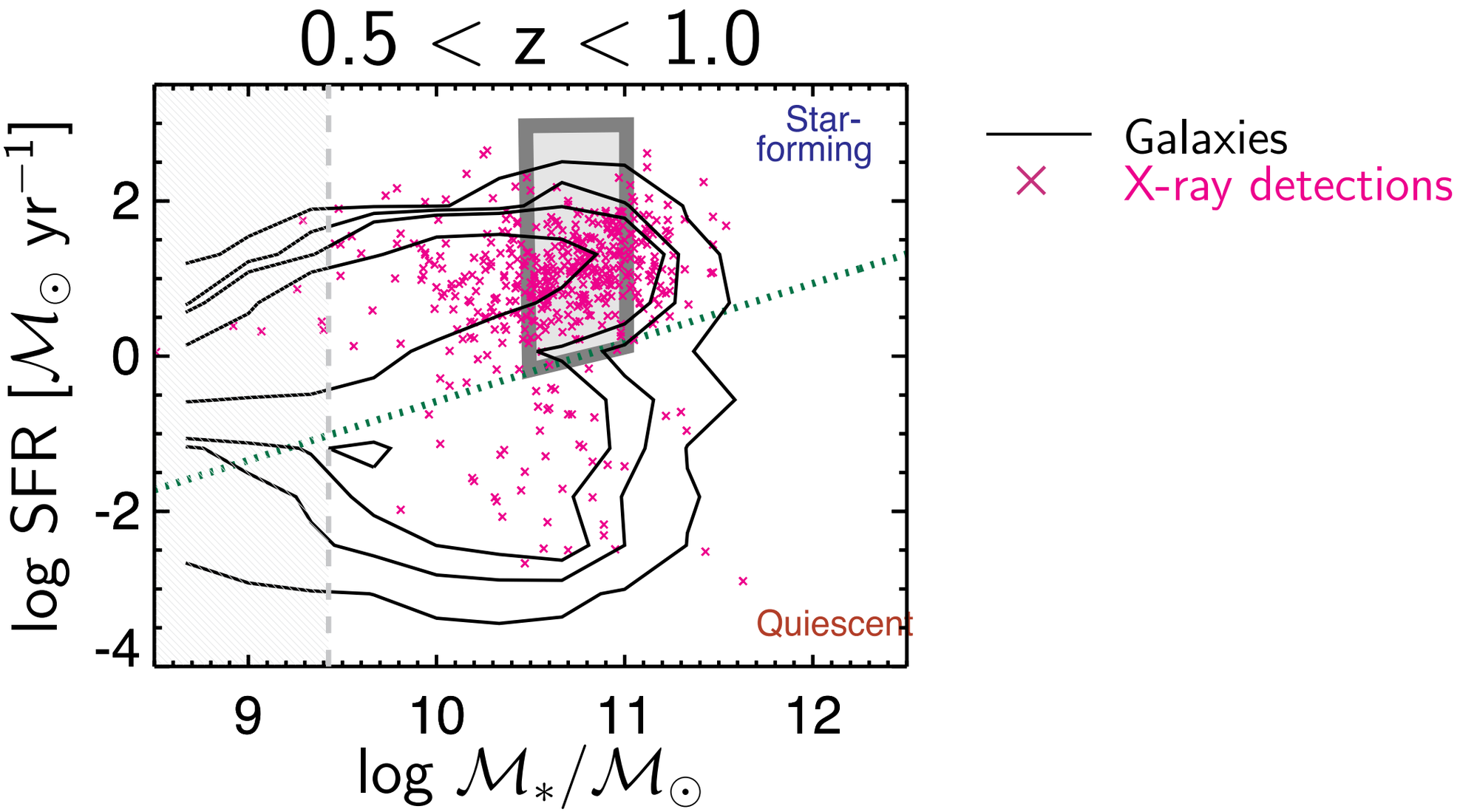

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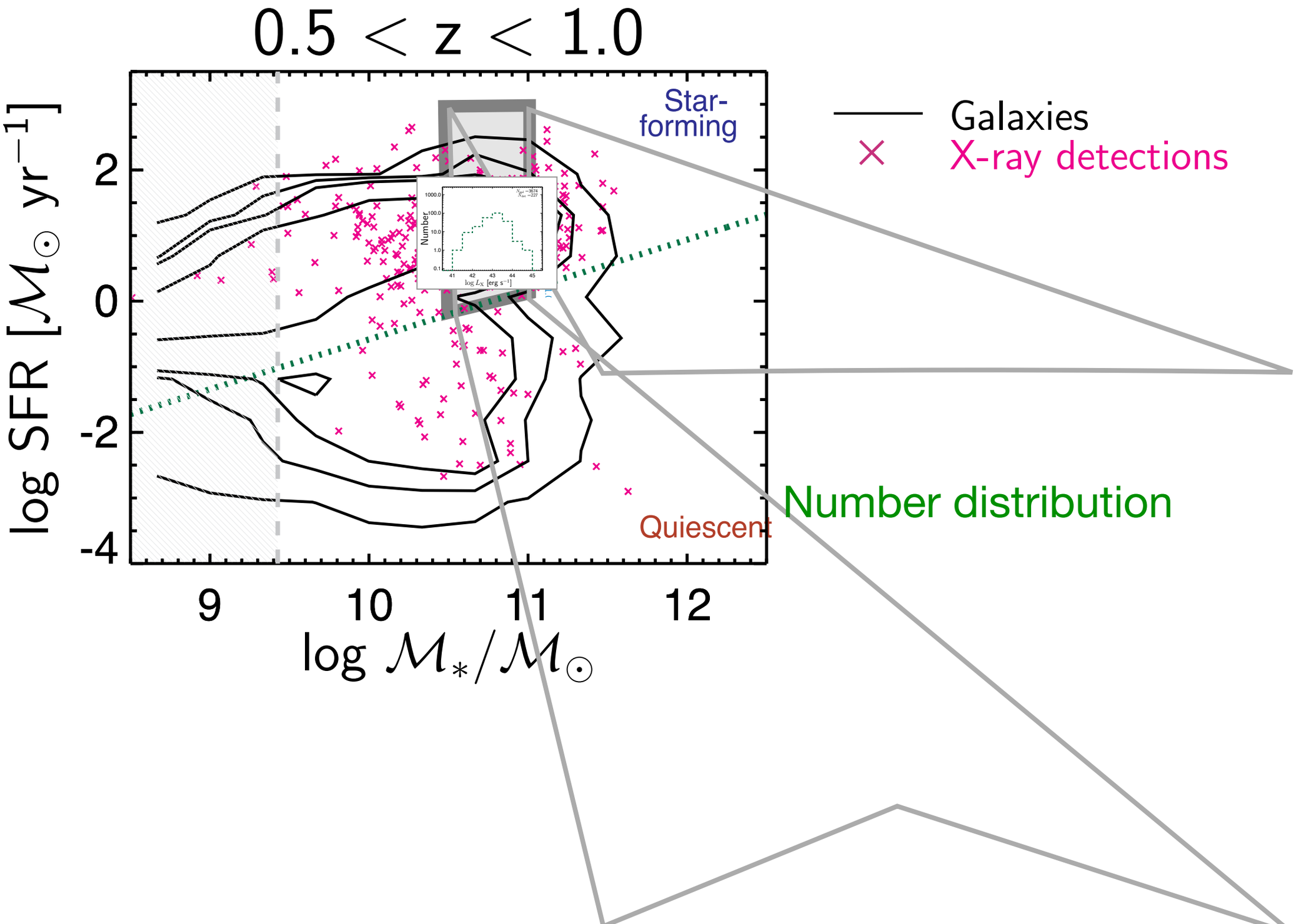

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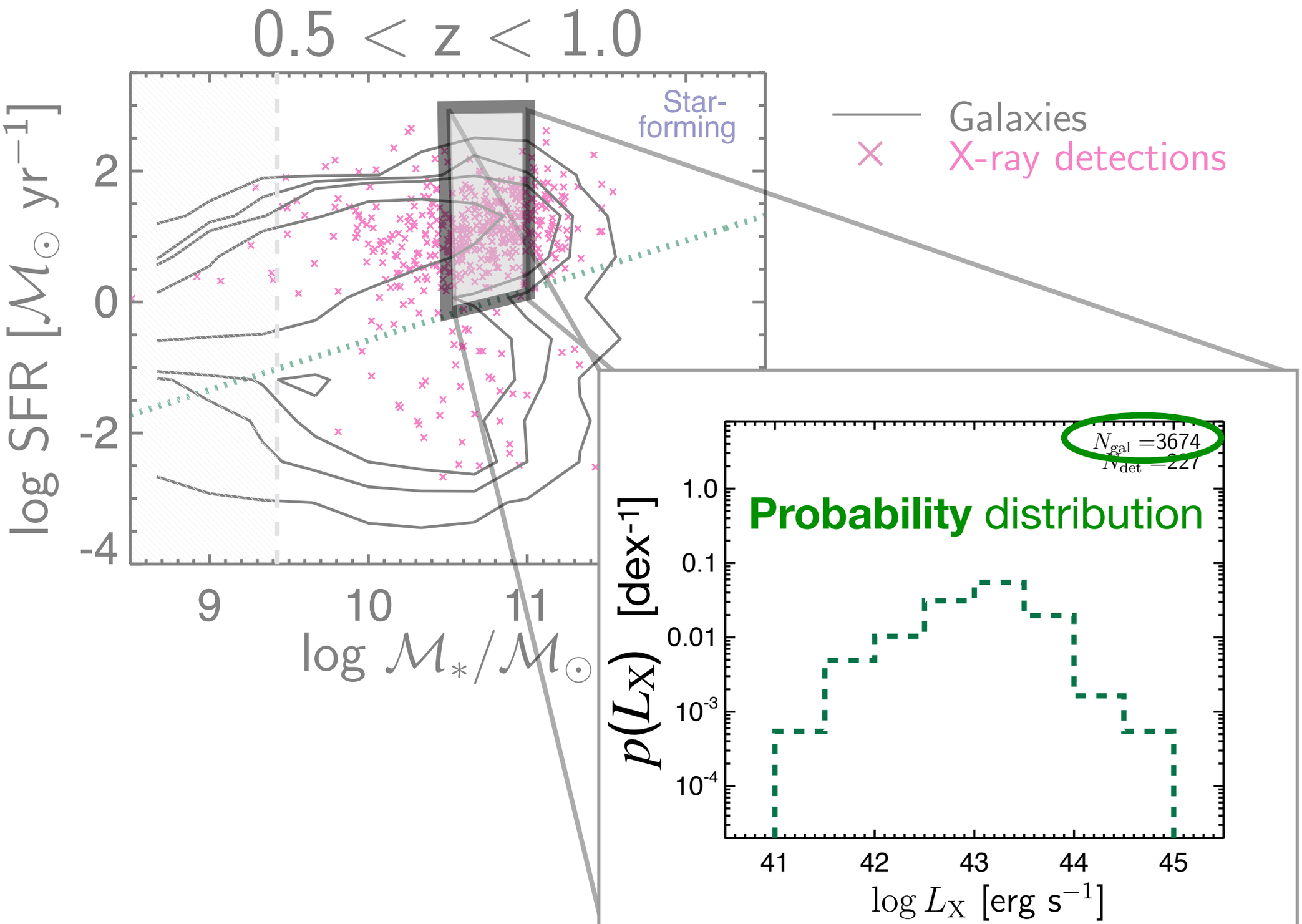
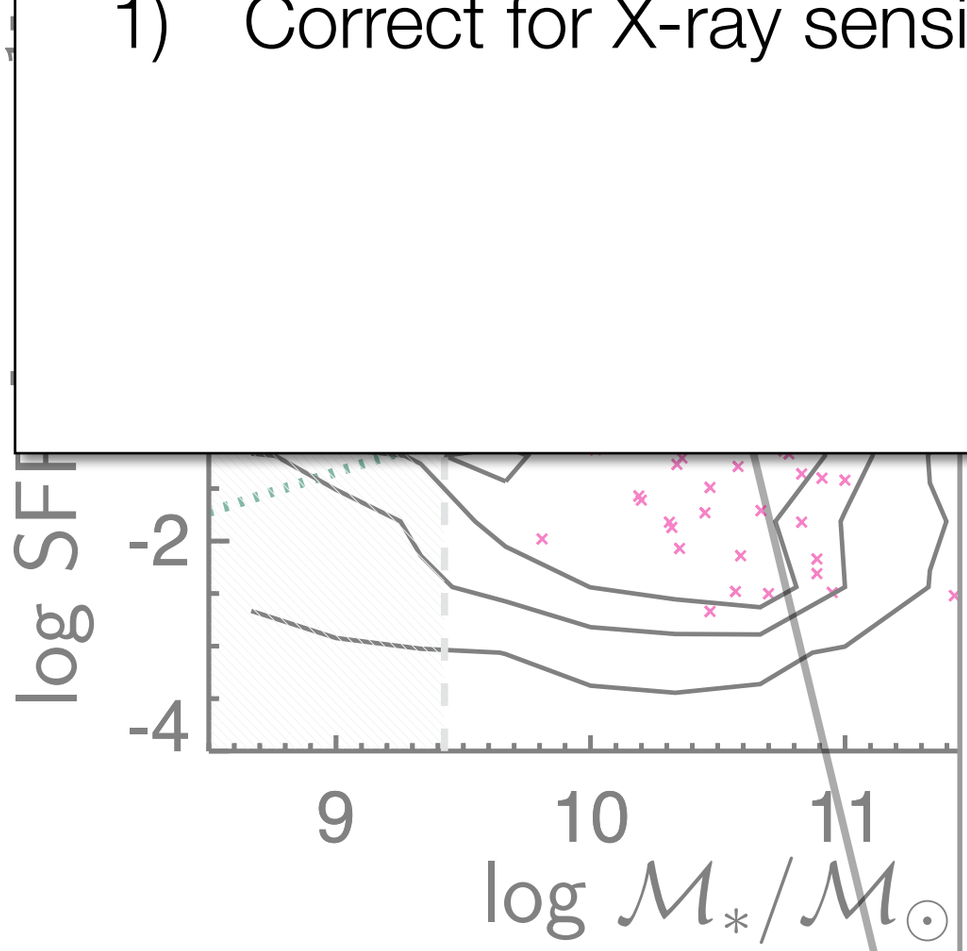
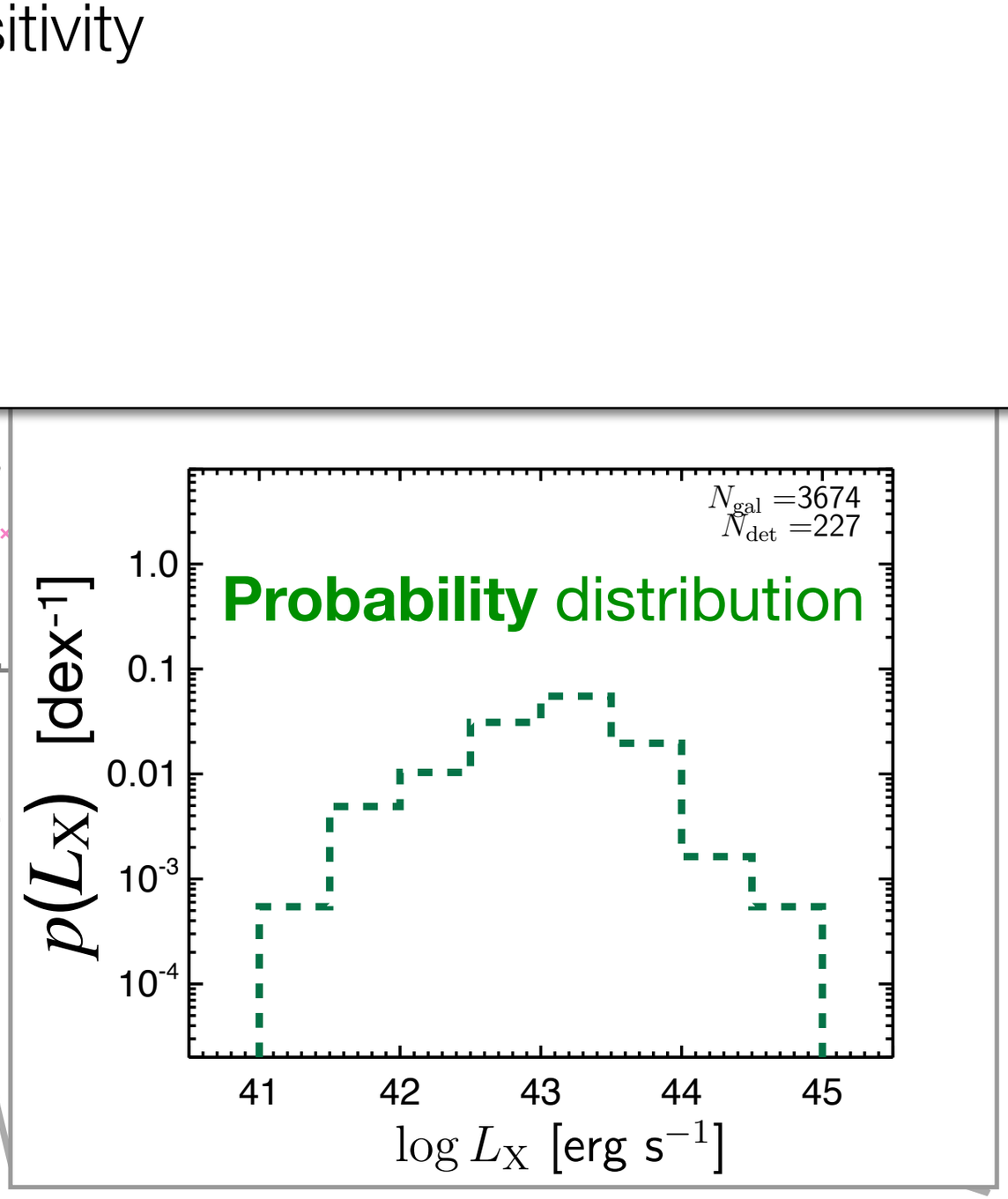


X-ray selected AGN across the galaxy population

Biased and incomplete picture - need to:

1) Correct for X-ray sensitivity





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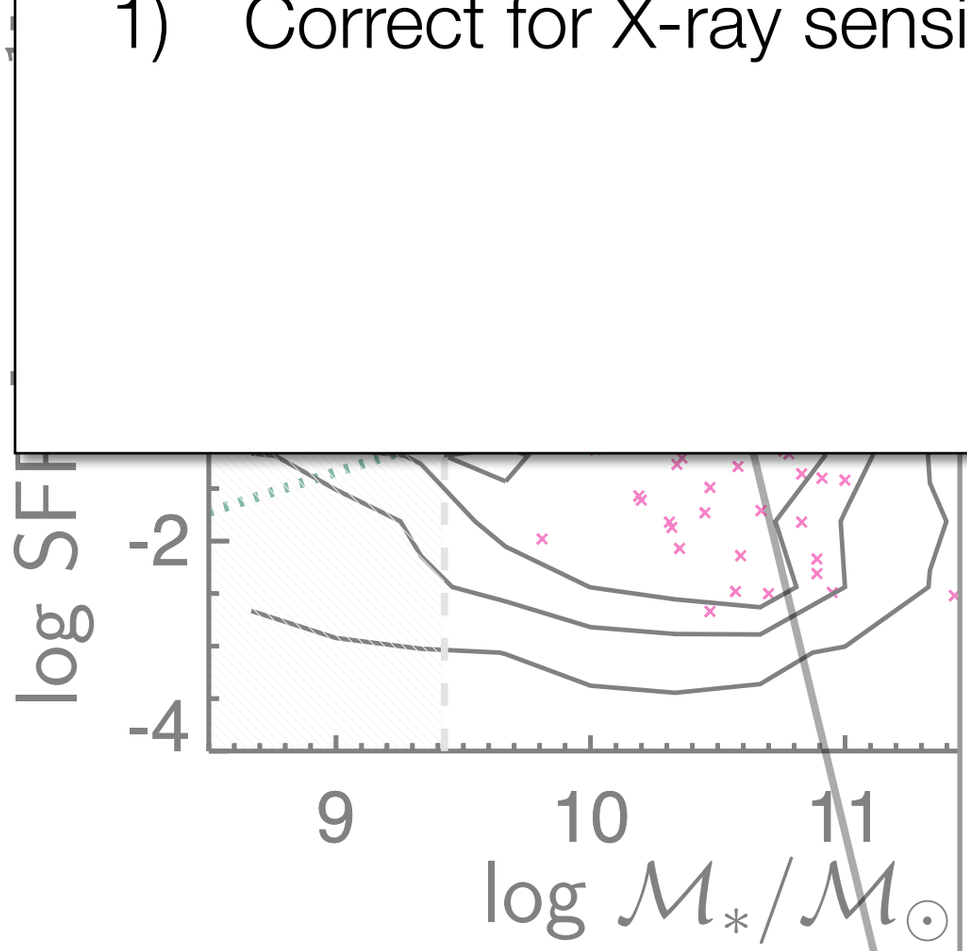
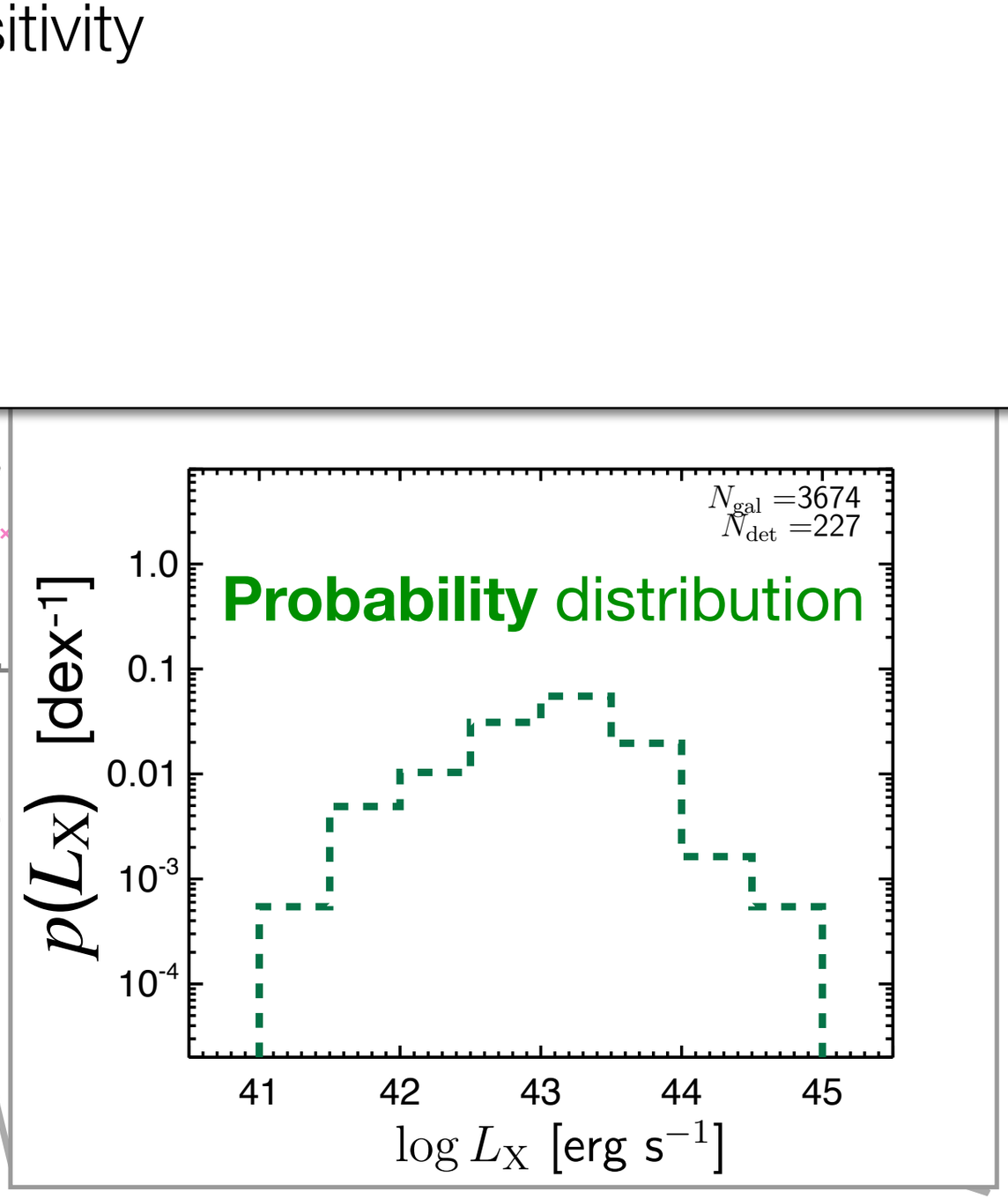
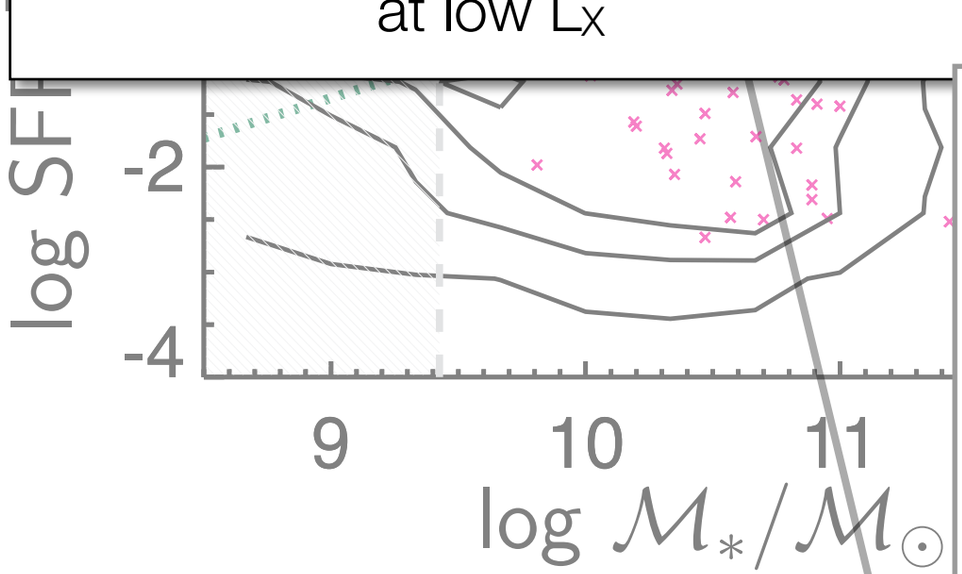


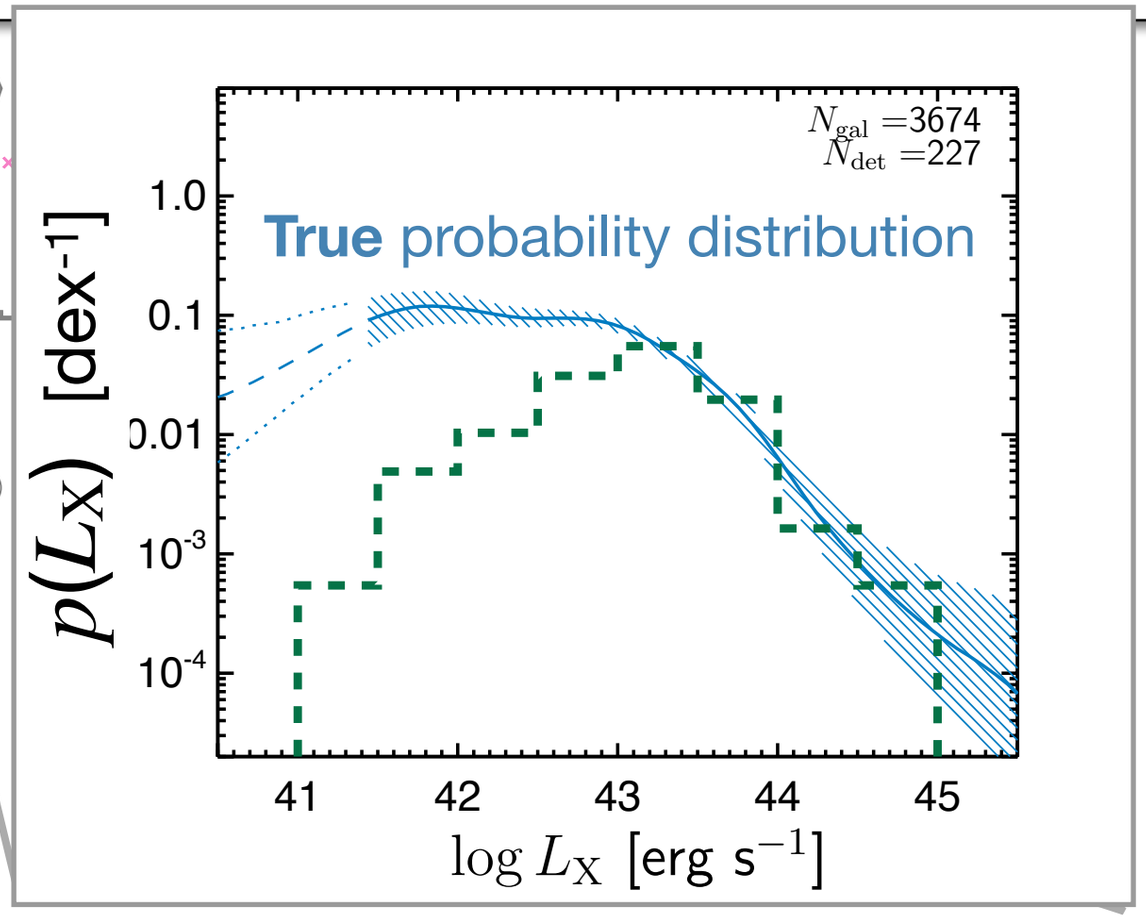


X-ray selected AGN across the galaxy population

Biased and incomplete picture - need to:

1) Correct for X-ray sensitivity
   - Use X-ray data at the position of every galaxy
   - Flexible Bayesian model to combine detections + non-detections
   - Correction for contamination from galactic processes (HMXBs, LMXBs) at low L_X

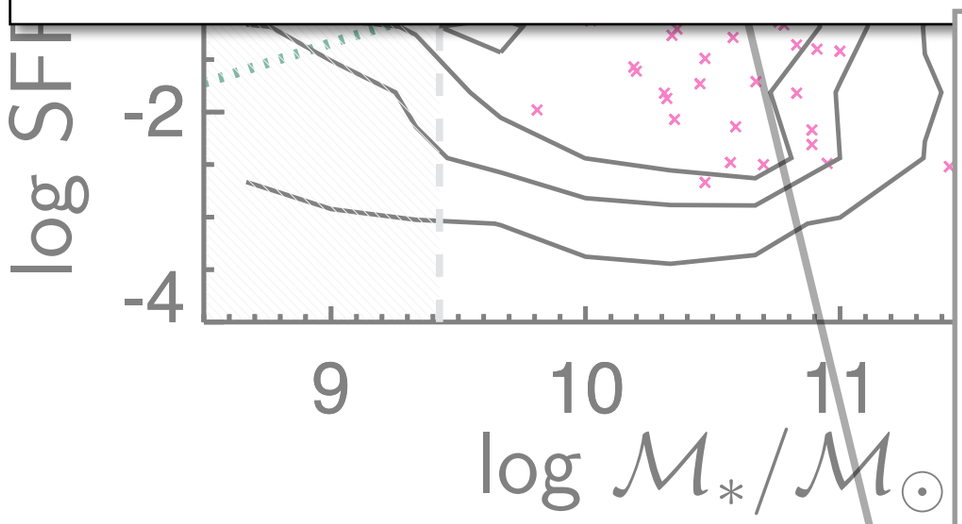


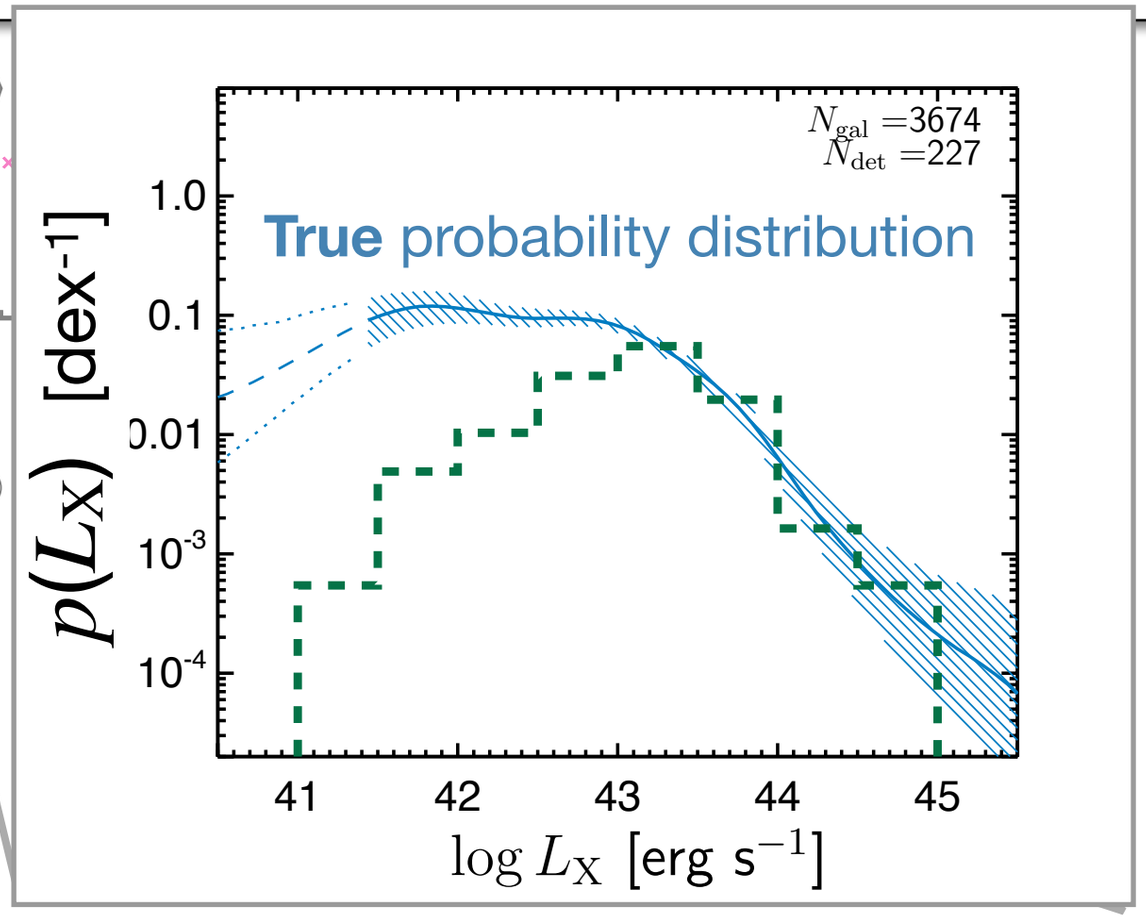


X-ray selected AGN across the galaxy population

Biased and incomplete picture - need to:

1) Correct for X-ray sensitivity
2) Correct for stellar-mass-dependent selection bias
   - Easier to detect an AGN with a *given accretion rate* in a high mass galaxy than a lower mass galaxy





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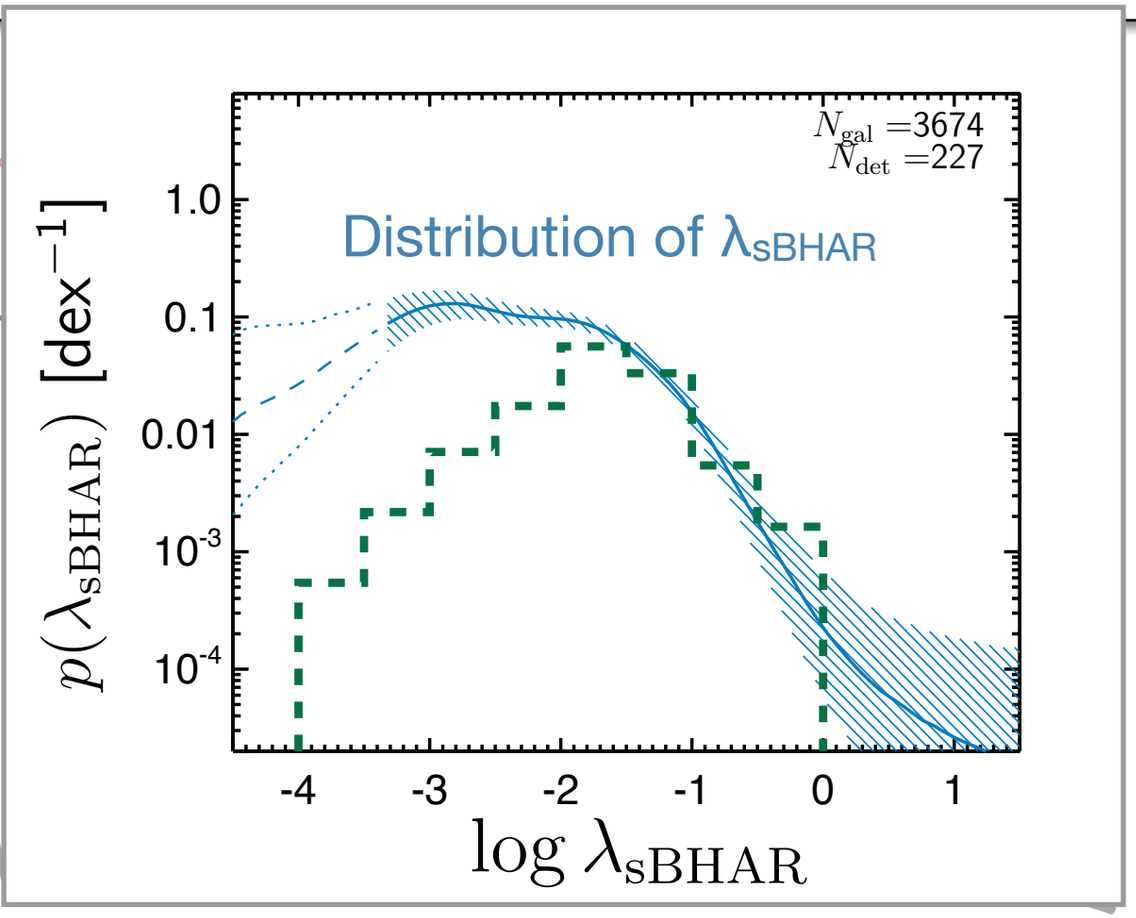
➡ measure distribution of ***specific*** **Black Hole Accretion Rate** (Aird et al. 2012)

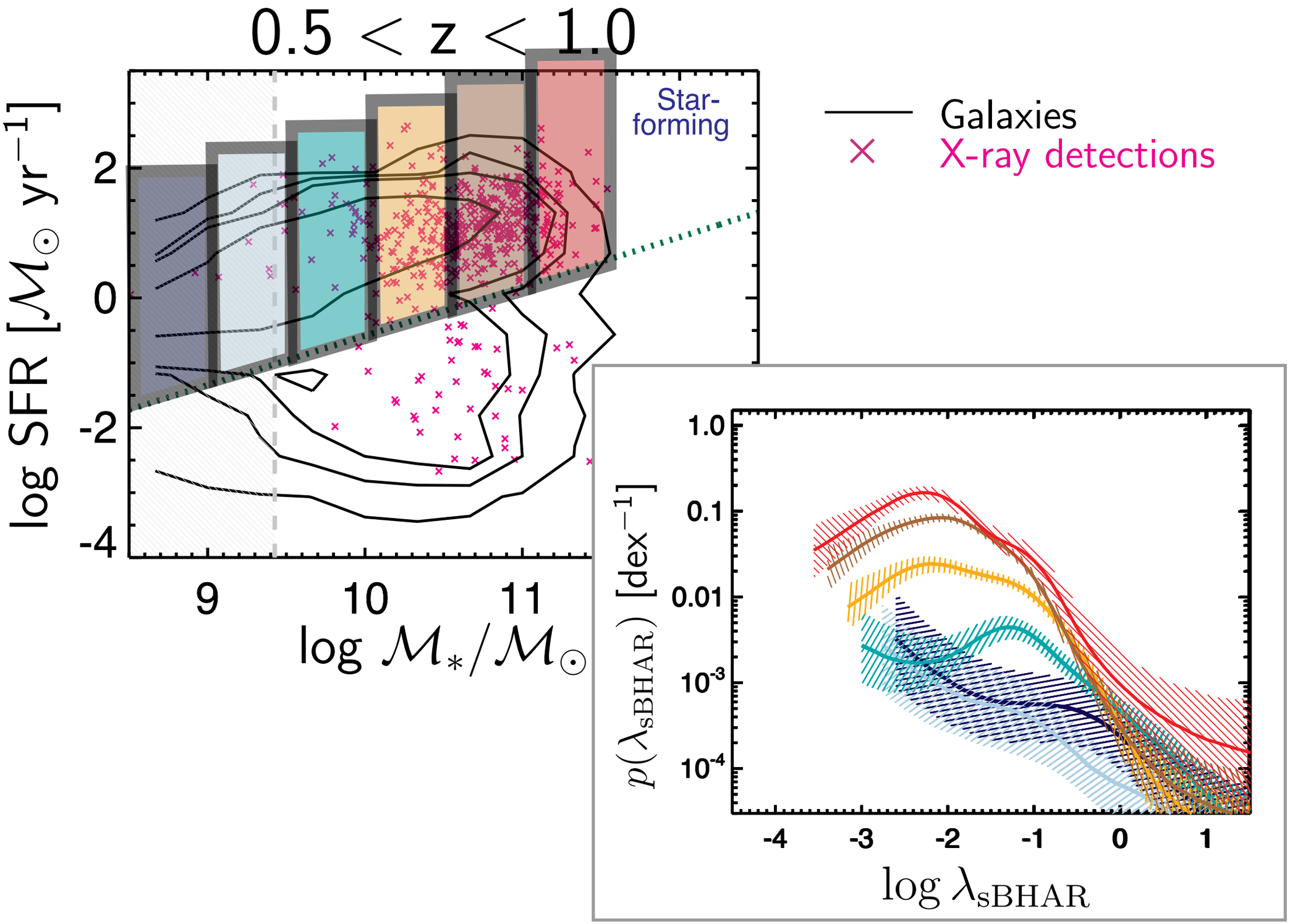
$$\lambda_{\rm sBHAR} \propto \frac{L_X}{M_*} \approx \lambda_{\rm Edd}$$

Eddington ratio



X-ray selected AGN in **star-forming** galaxies

***along* the main sequence**



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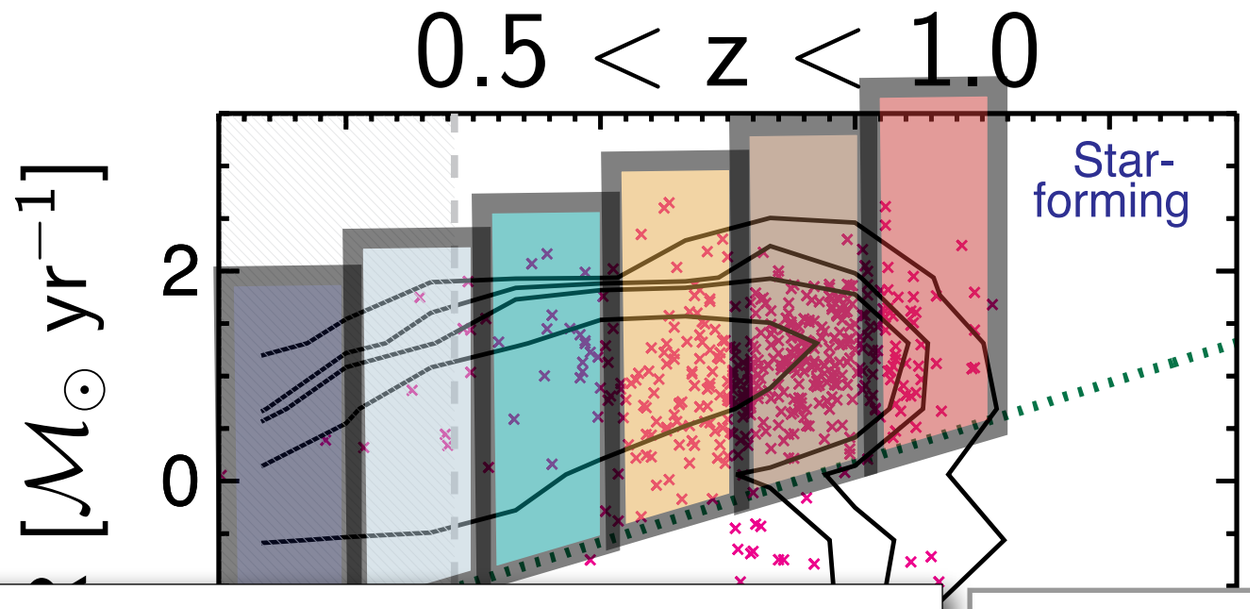
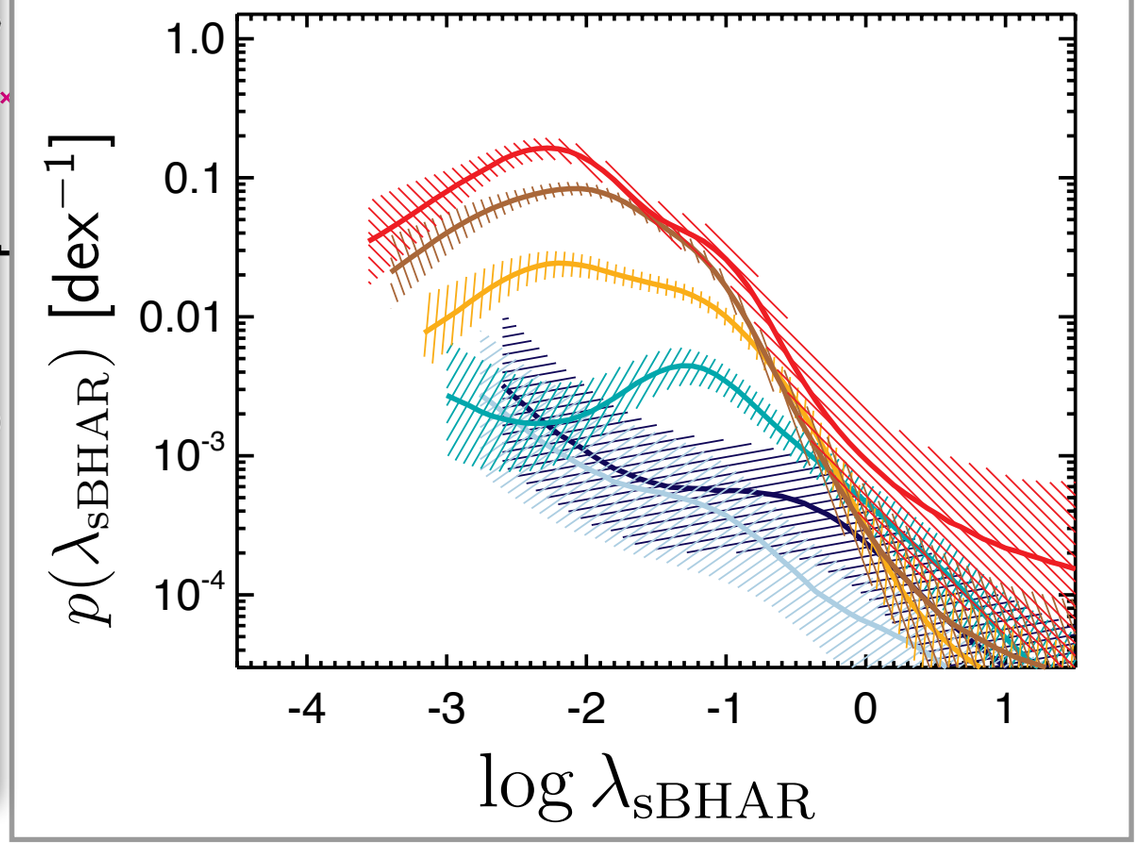


- Broad distribution of accretion rates at ***all*** M_*
  - Lower mass galaxies host AGN of *all* accretion rates, including rapidly accreting black holes
- Stellar mass dependence:
  - The fraction of galaxies with a moderate-accretion-rate AGN is lower for lower mass galaxies

(after accounting for selection bias i.e. that AGN *appear* less luminous for lower masses)



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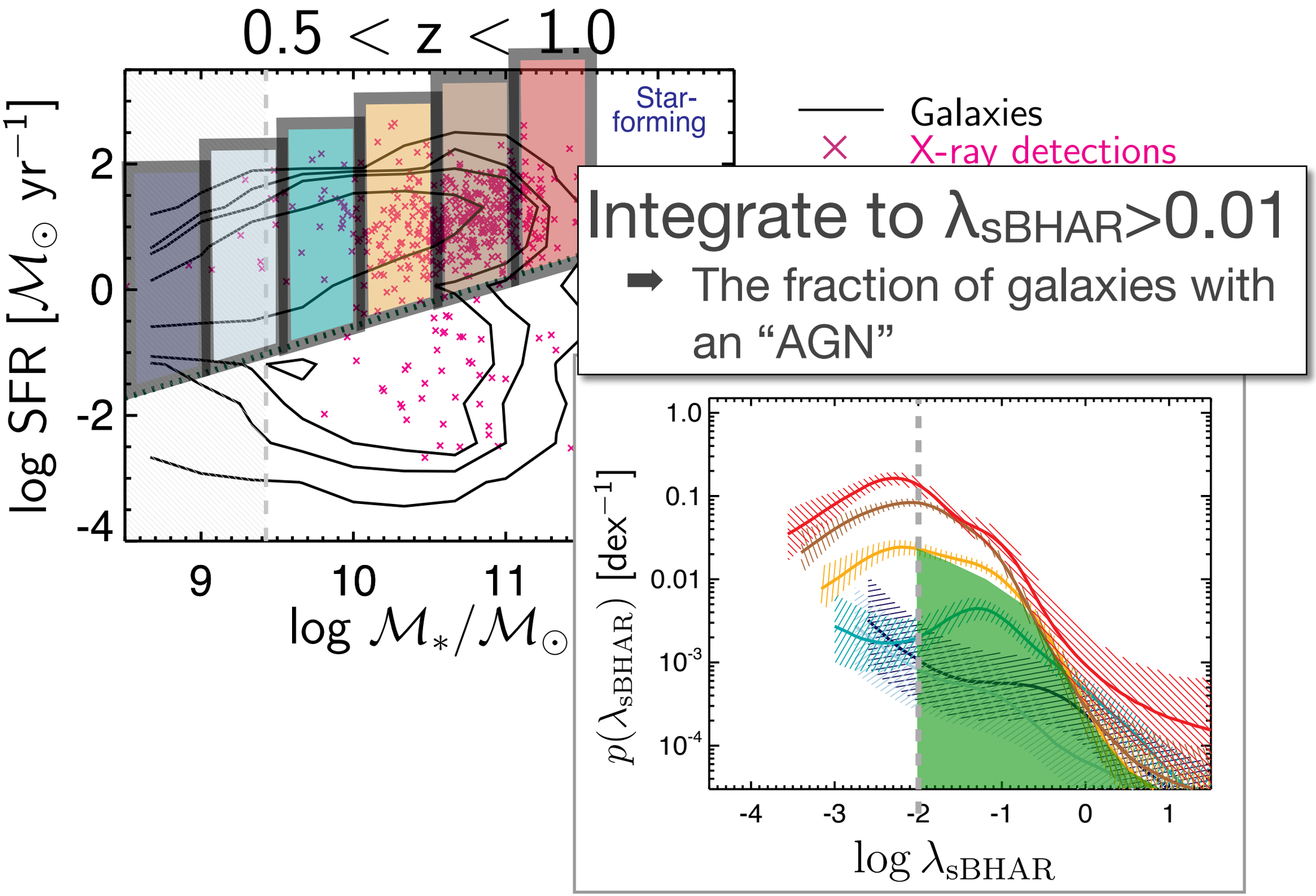
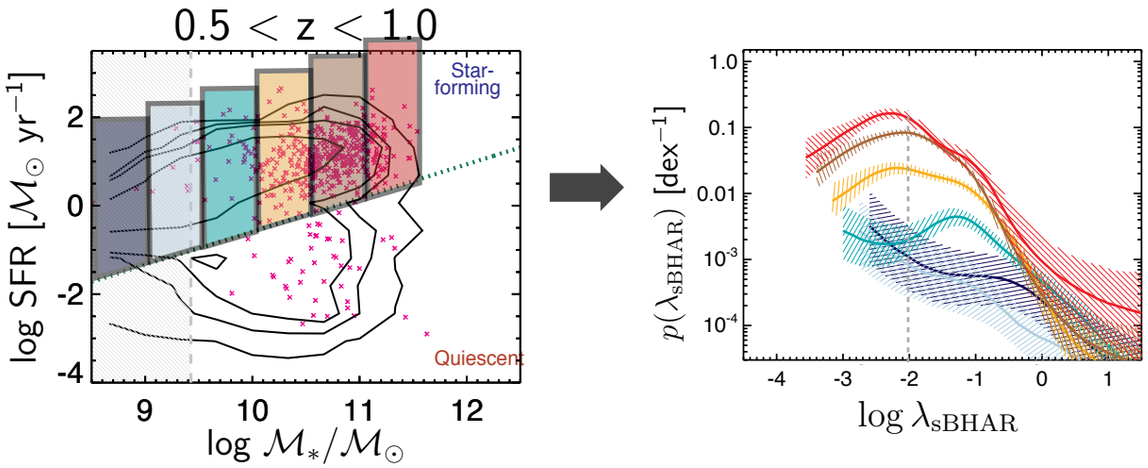


The incidence of AGN in **star-forming** galaxies

along **the main sequence**

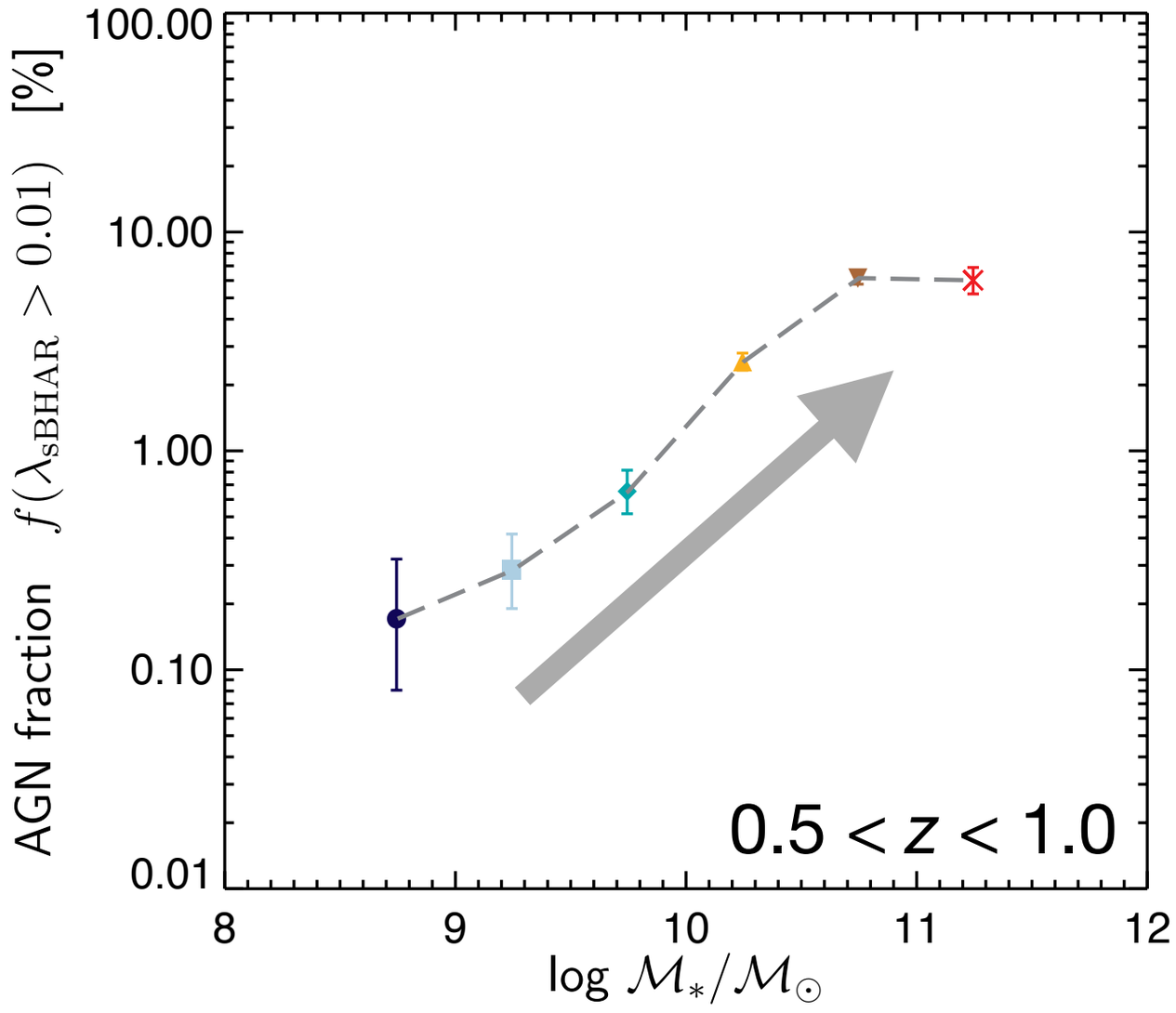
Aird, Coil & Georgakakis, 2019, MNRAS, 484, 4360



➡ AGN fraction

… as a function of M_*

- At fixed z, AGN fraction is higher for higher M_*



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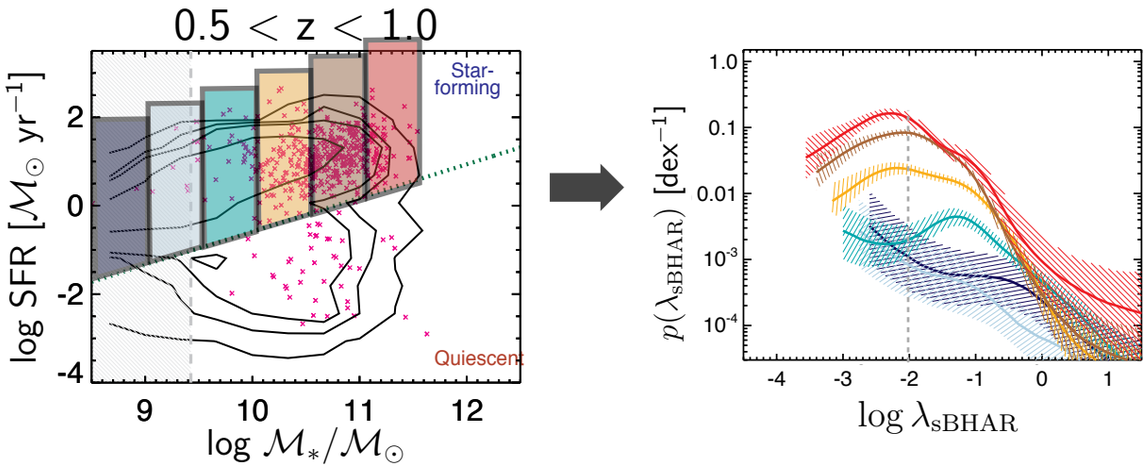

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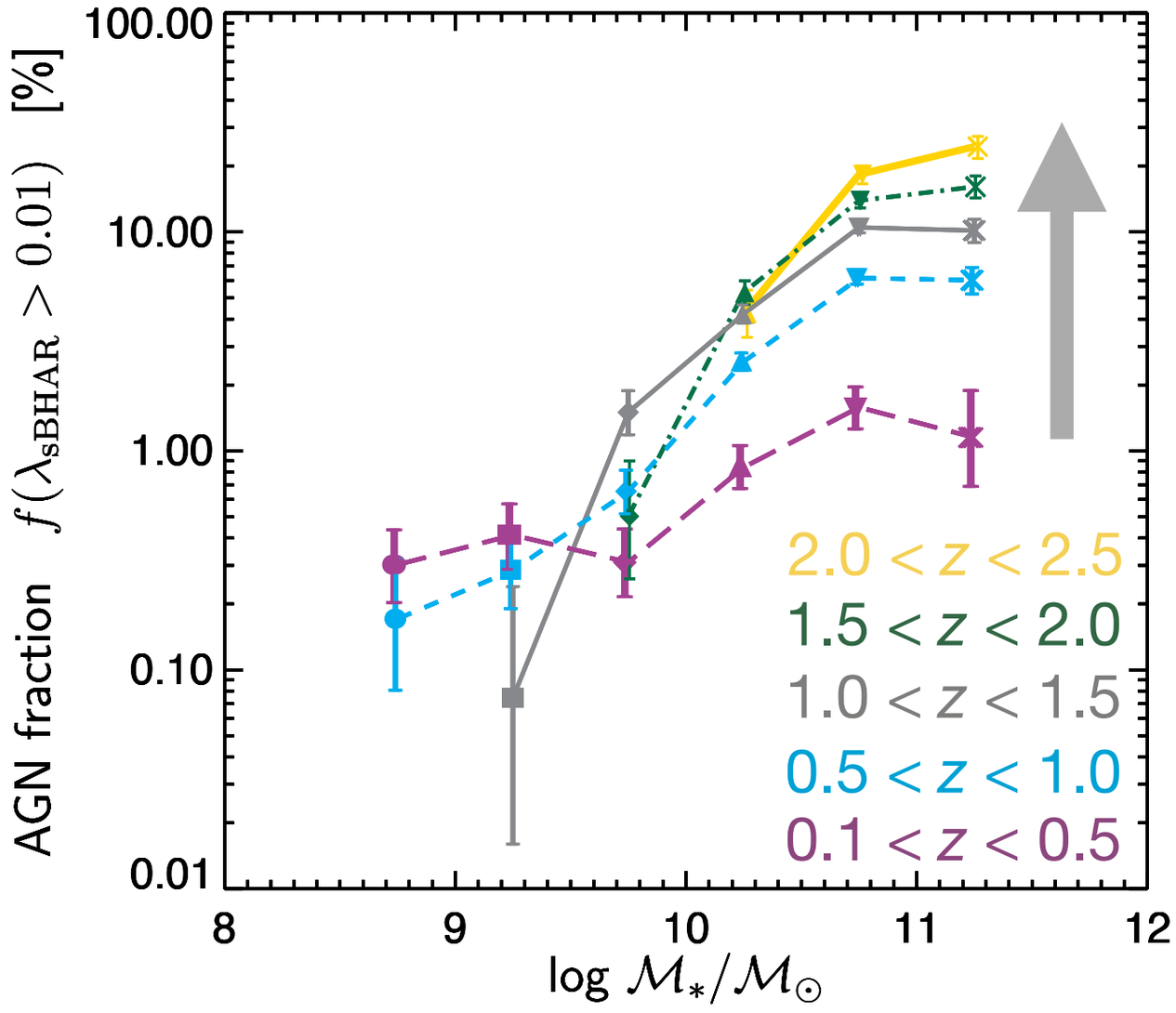
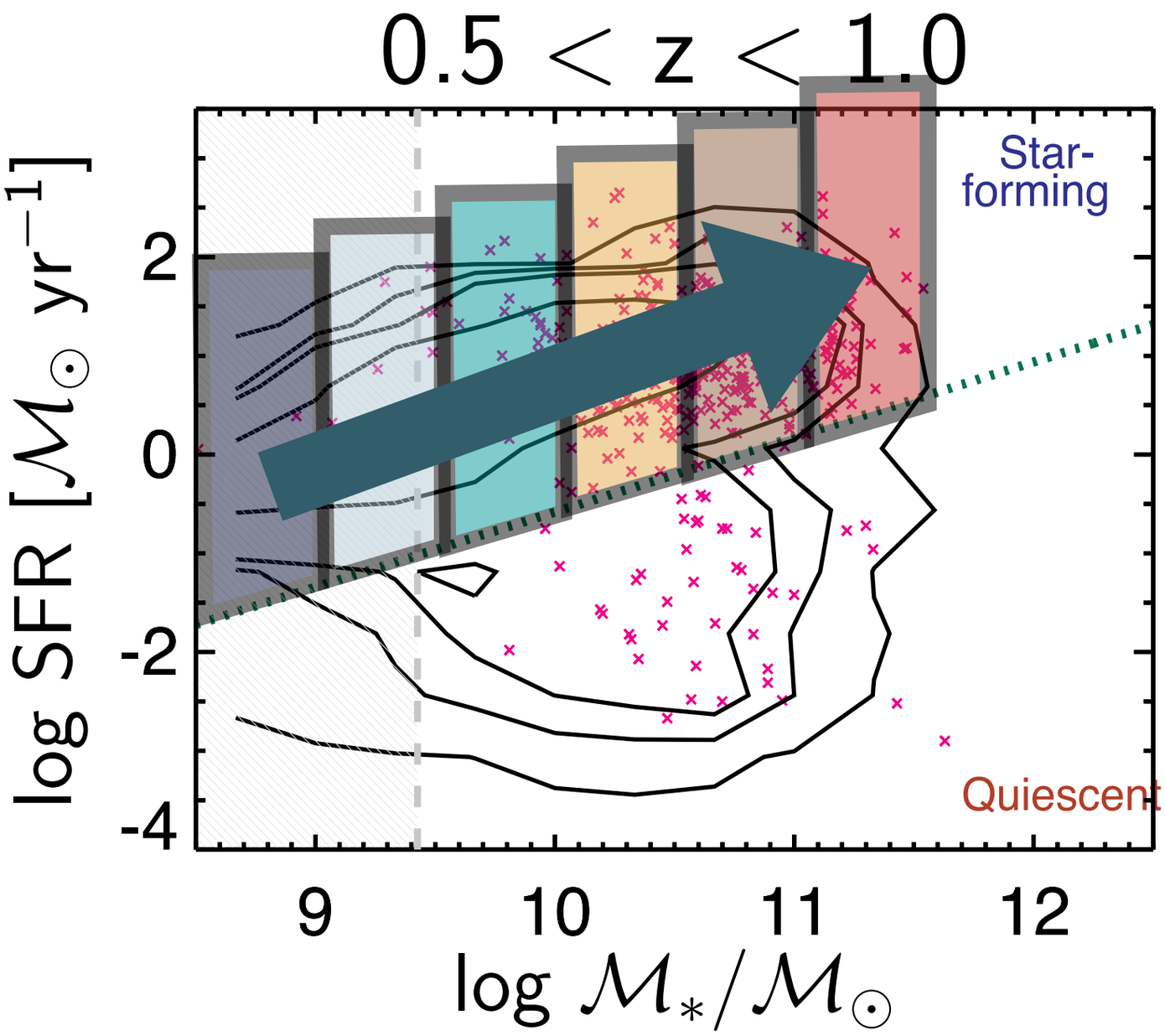


- At fixed z, AGN fraction is higher for higher M_*
- AGN fraction increases with z (for $M_* >\sim 10^{10}$ M_{sun})
- *Stellar-mass-dependent* redshift evolution (weaker at low M_*)

The incidence of AGN in **star-forming** galaxies

***along* the main sequence**



For star-forming galaxies, increasing mass ≡ increasing SFR (at a given *z*)

The incidence of AGN in **star-forming** galaxies

along **the main sequence**

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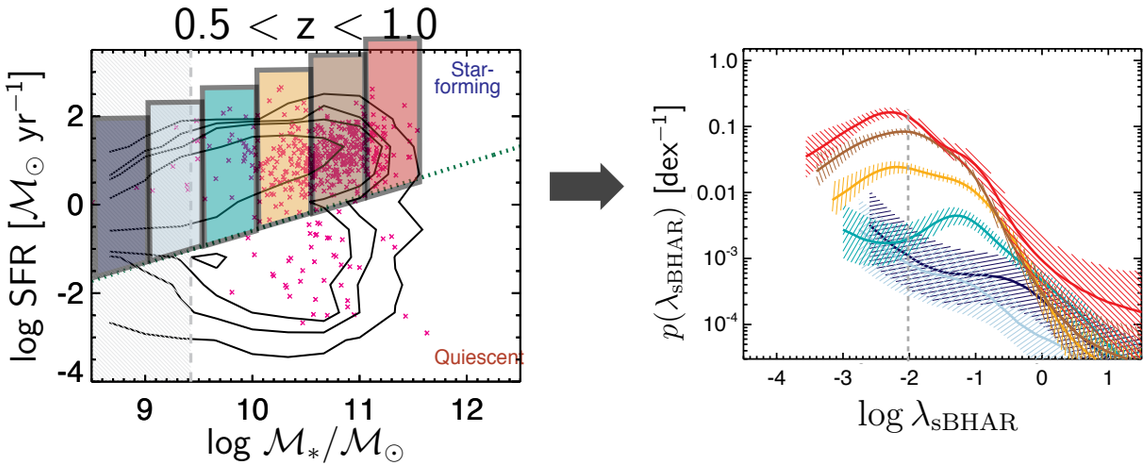
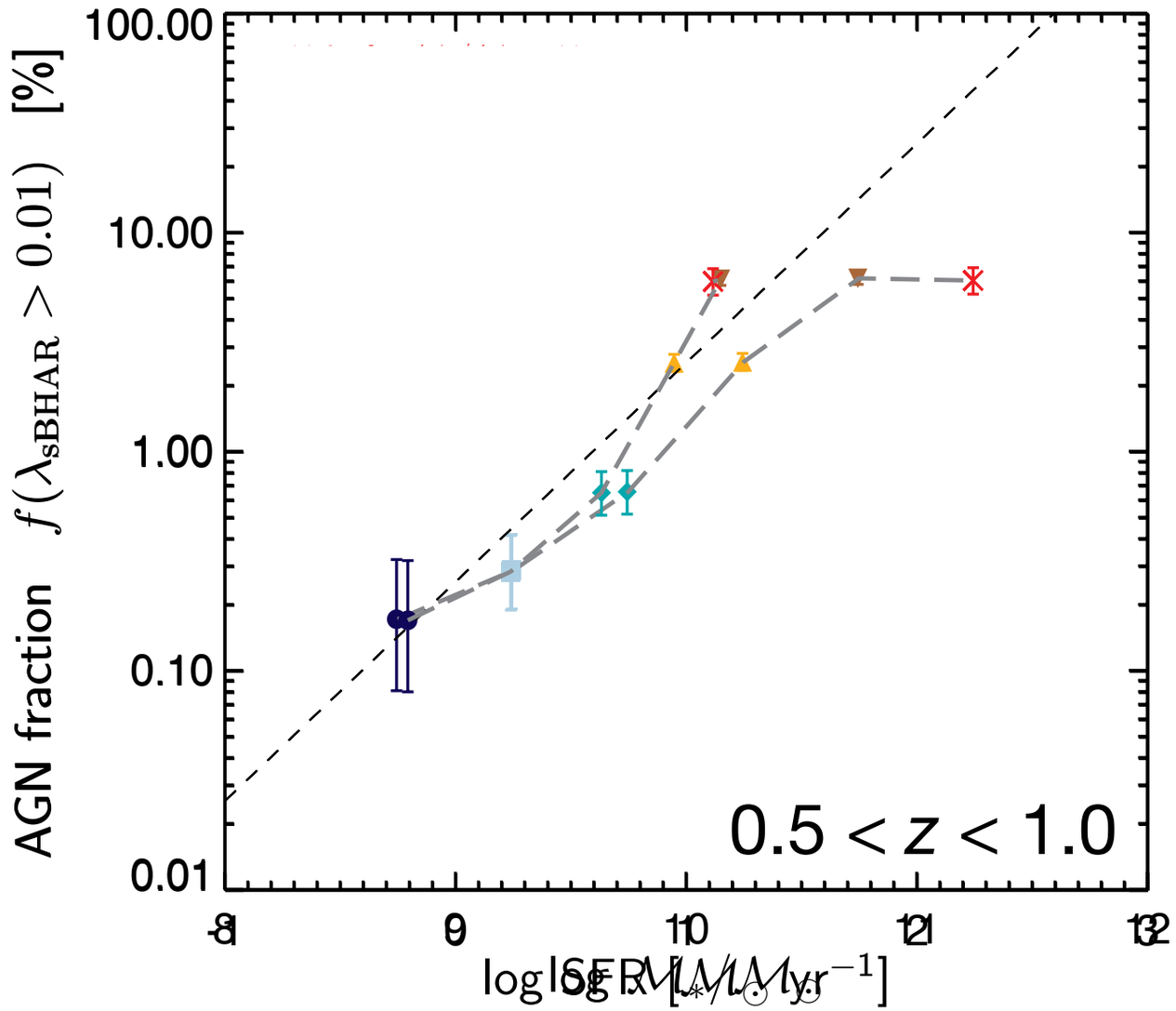


- ~ 1:1 correlation between AGN fraction and increasing average SFR
  (moving *along* the main sequence)

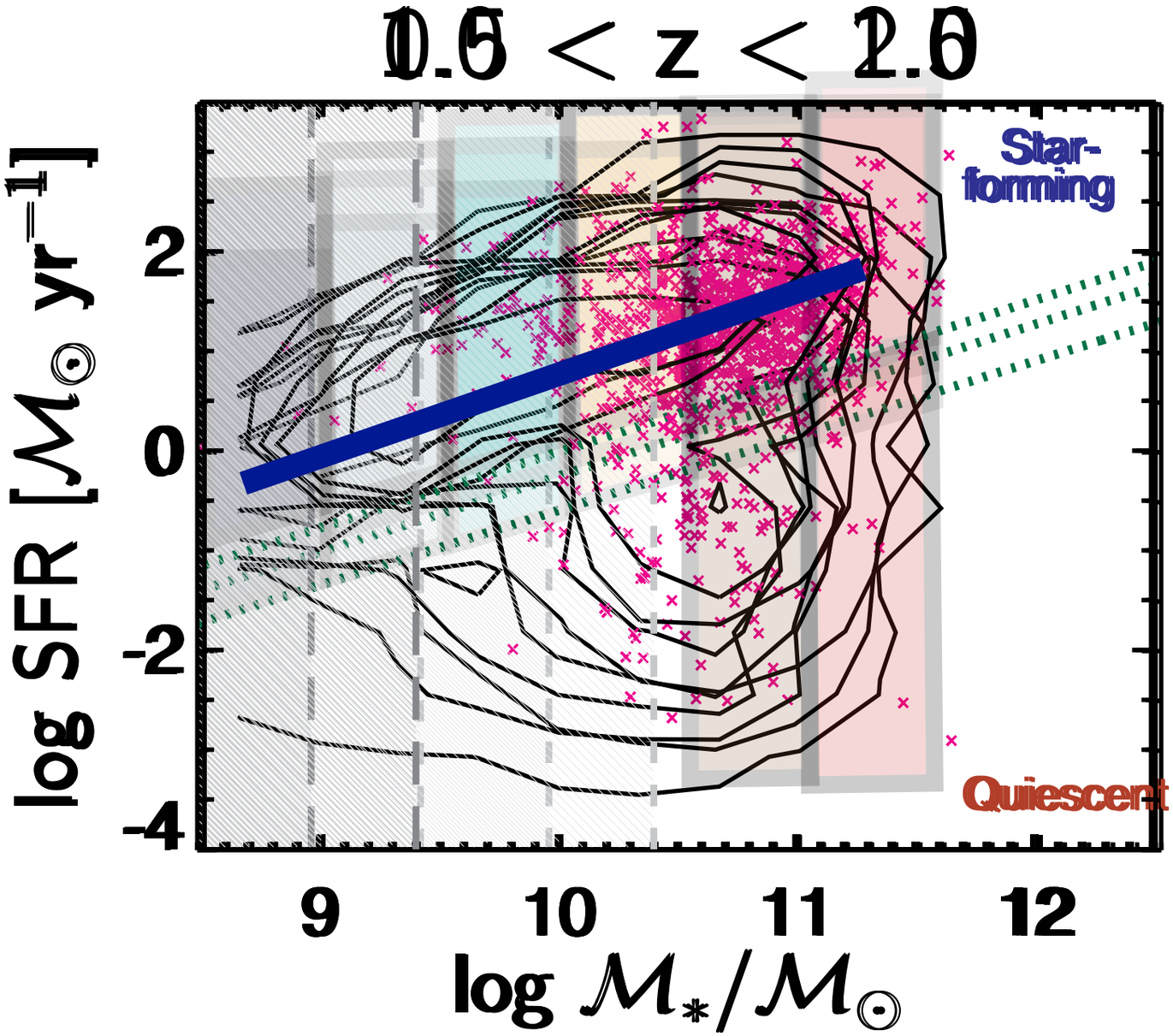
➡ AGN fraction

… as a function of ***SFR***



The incidence of AGN in **star-forming** galaxies

***along* the main sequence**



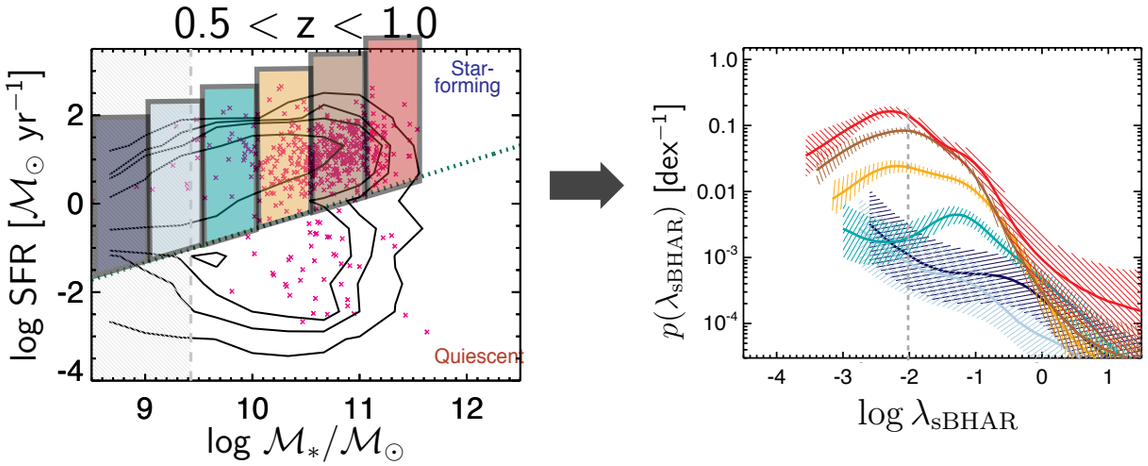
At higher z, main sequence evolves to higher SFR

- same mass bins probe higher SFR

The incidence of AGN in **star-forming** galaxies

along **the main sequence**

Aird, Coil & Georgakakis, 2019, MNRAS, 484, 4360



- ~ 1:1 correlation between AGN fraction and increasing average SFR
  (moving *along* the main sequence)
- Correlation *broadly* holds out to *z*~2.5
  (N.B. some redshift-dependent offsets)
- Incidence of AGN in star-forming galaxies *primarily* determined by SFR
  => common origin e.g. cold gas?

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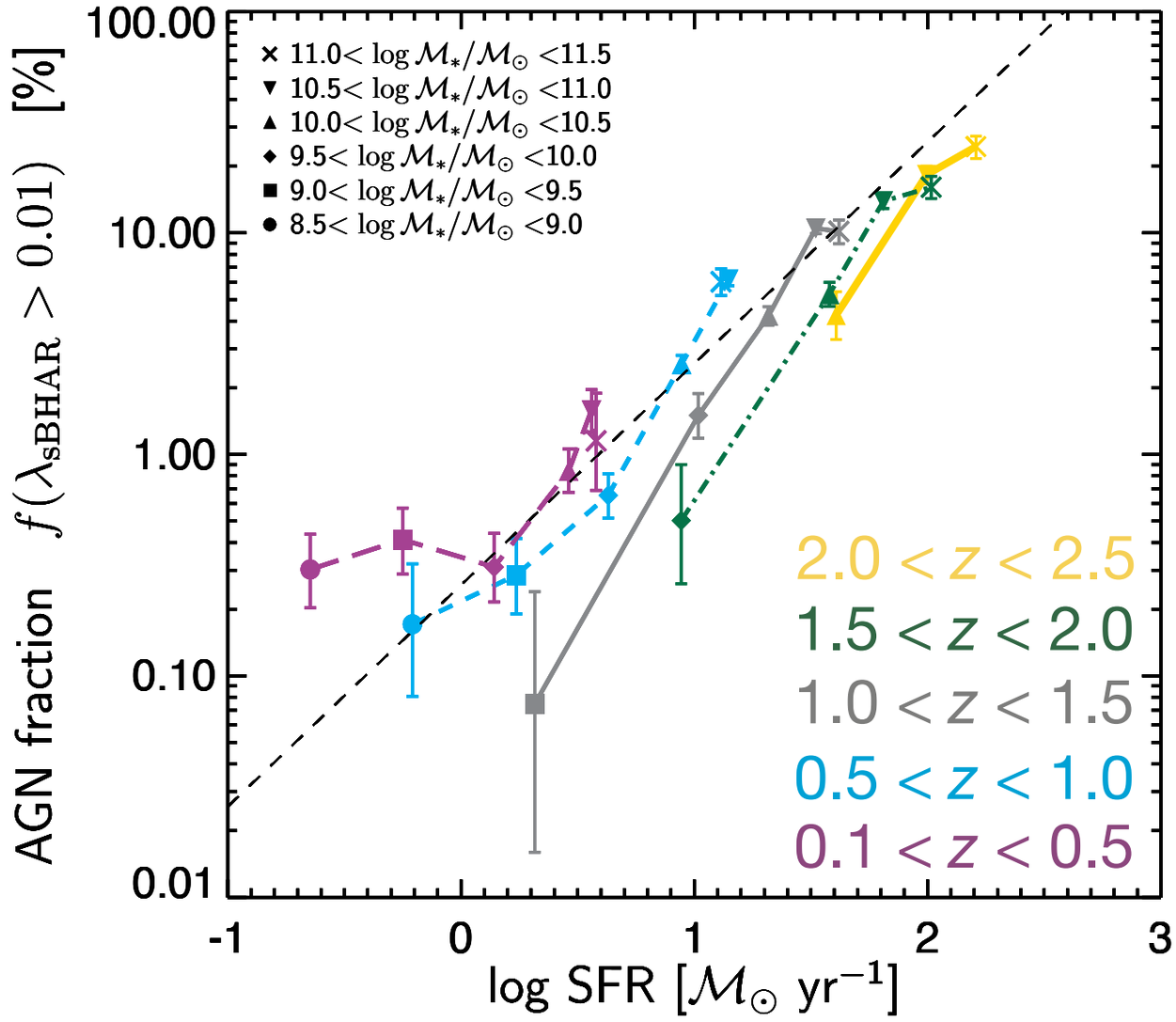
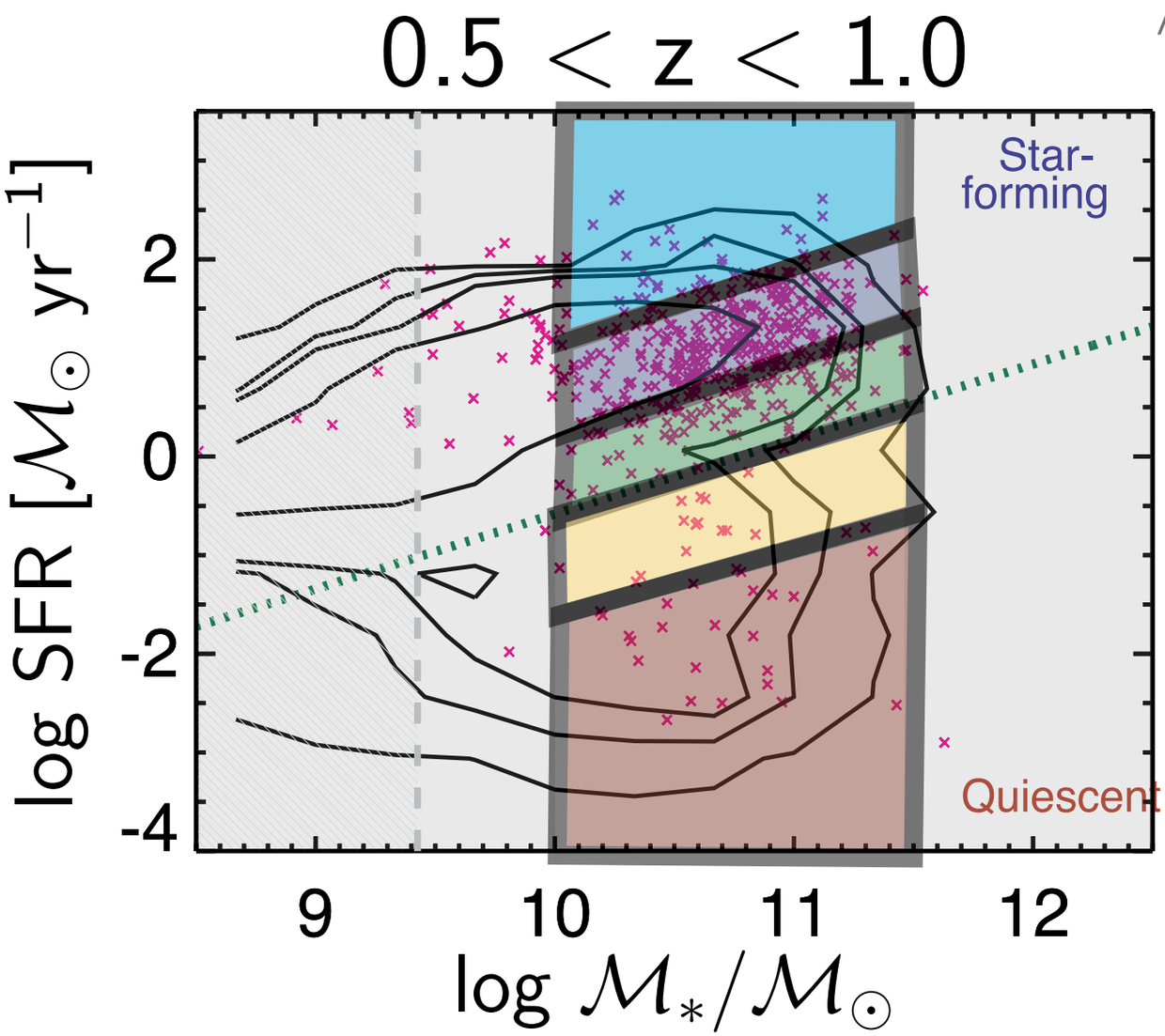
… as a function of ***SFR***



The incidence of AGN vs. $SFR/SFR_{MainSequence}$

Aird, Coil & Georgakakis, 2019, MNRAS, 484, 4360



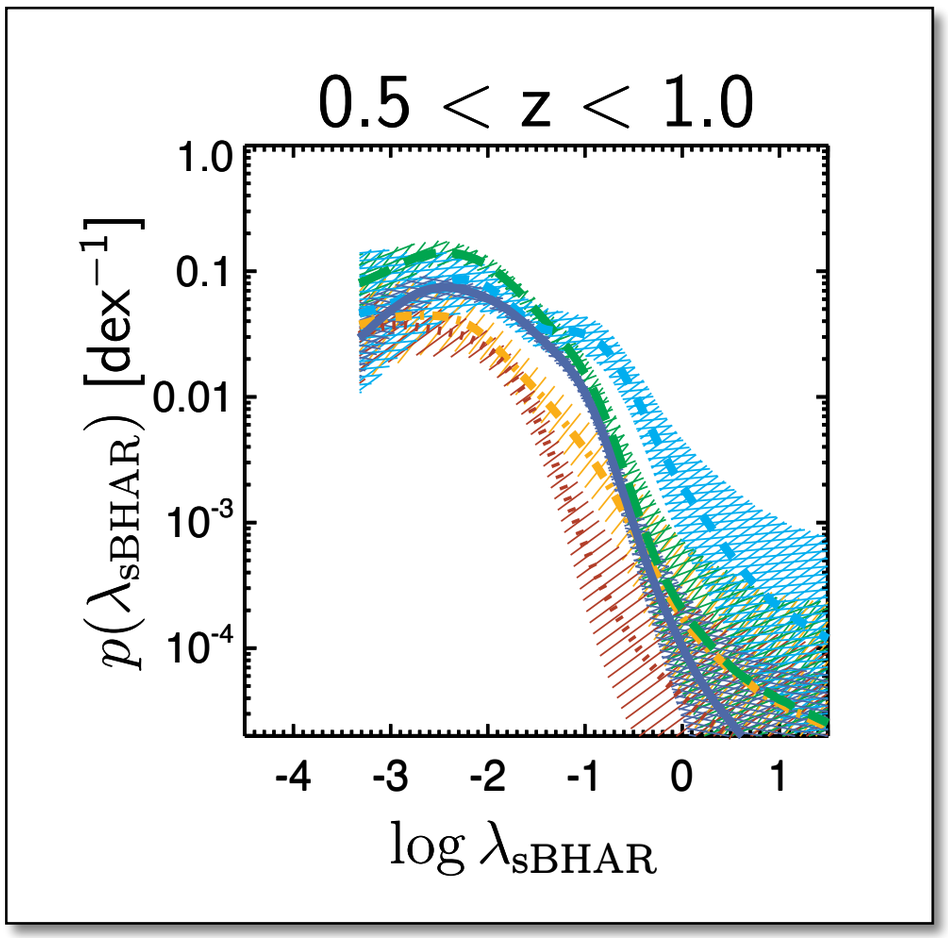
Starburst *(above* the MS)

On the Main Sequence

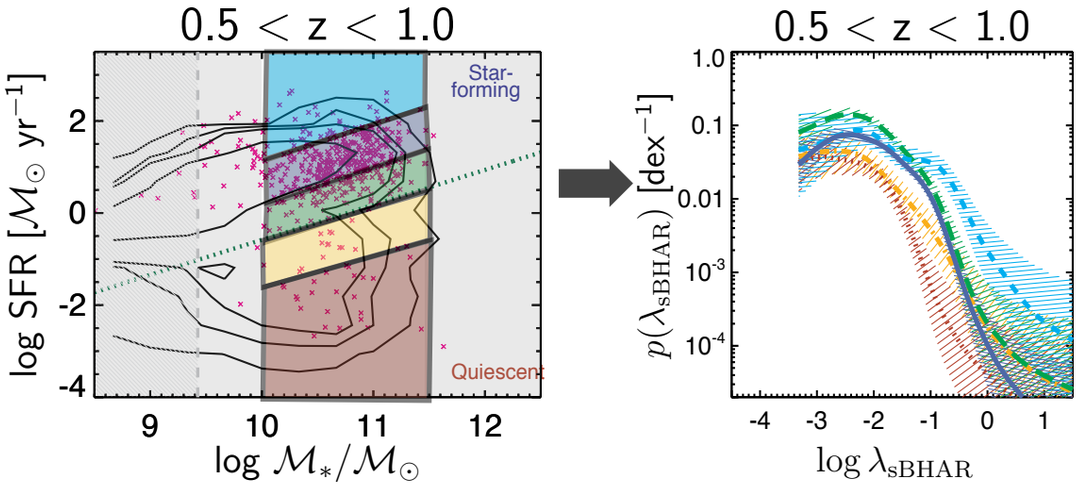
Sub-Main Sequence

Quiescent (high)

Quiescent (low)



The incidence of AGN ***across*** the main sequence



- Main sequence galaxies sit on correlation between AGN fraction and SFR

Aird, Coil & Georgakakis, 2019, MNRAS, 484, 4360

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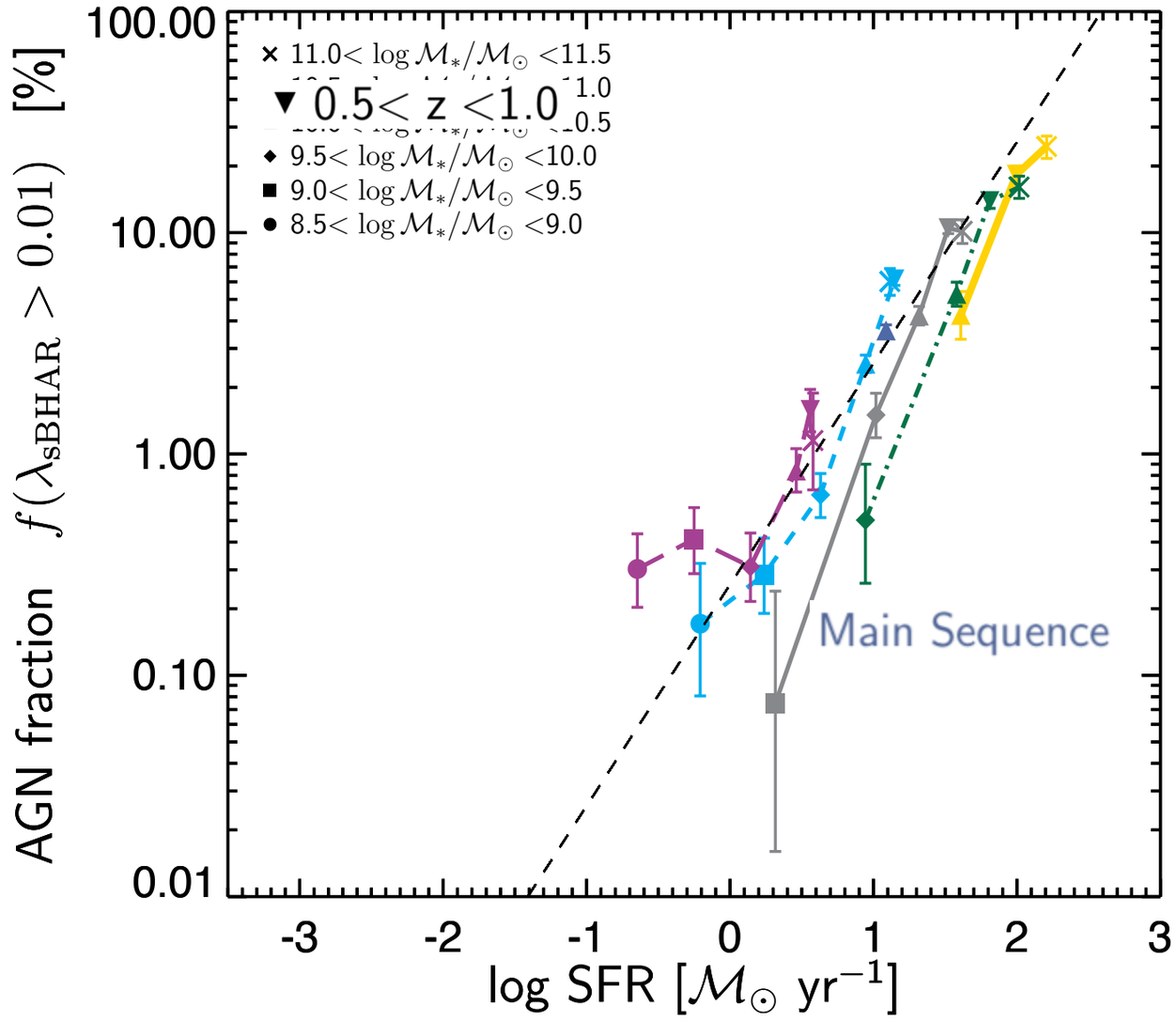

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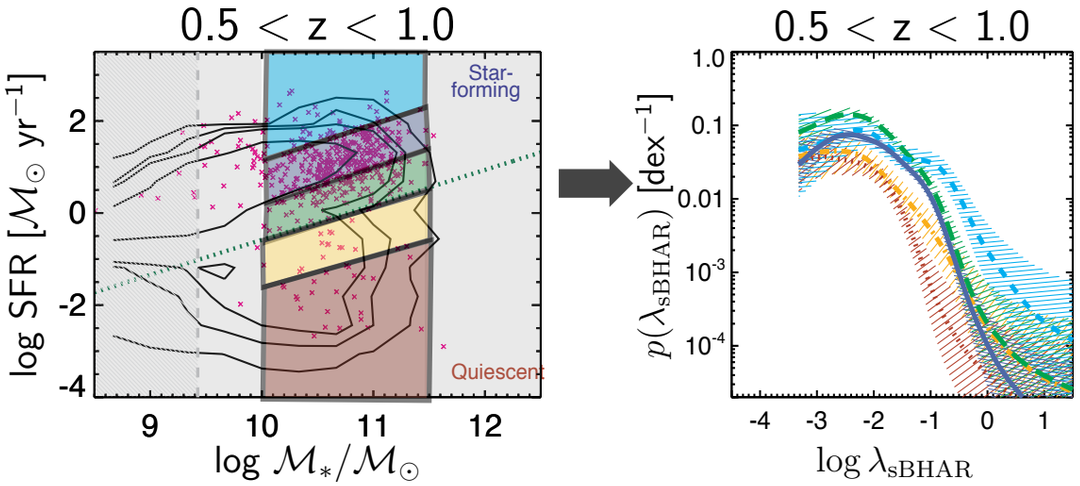

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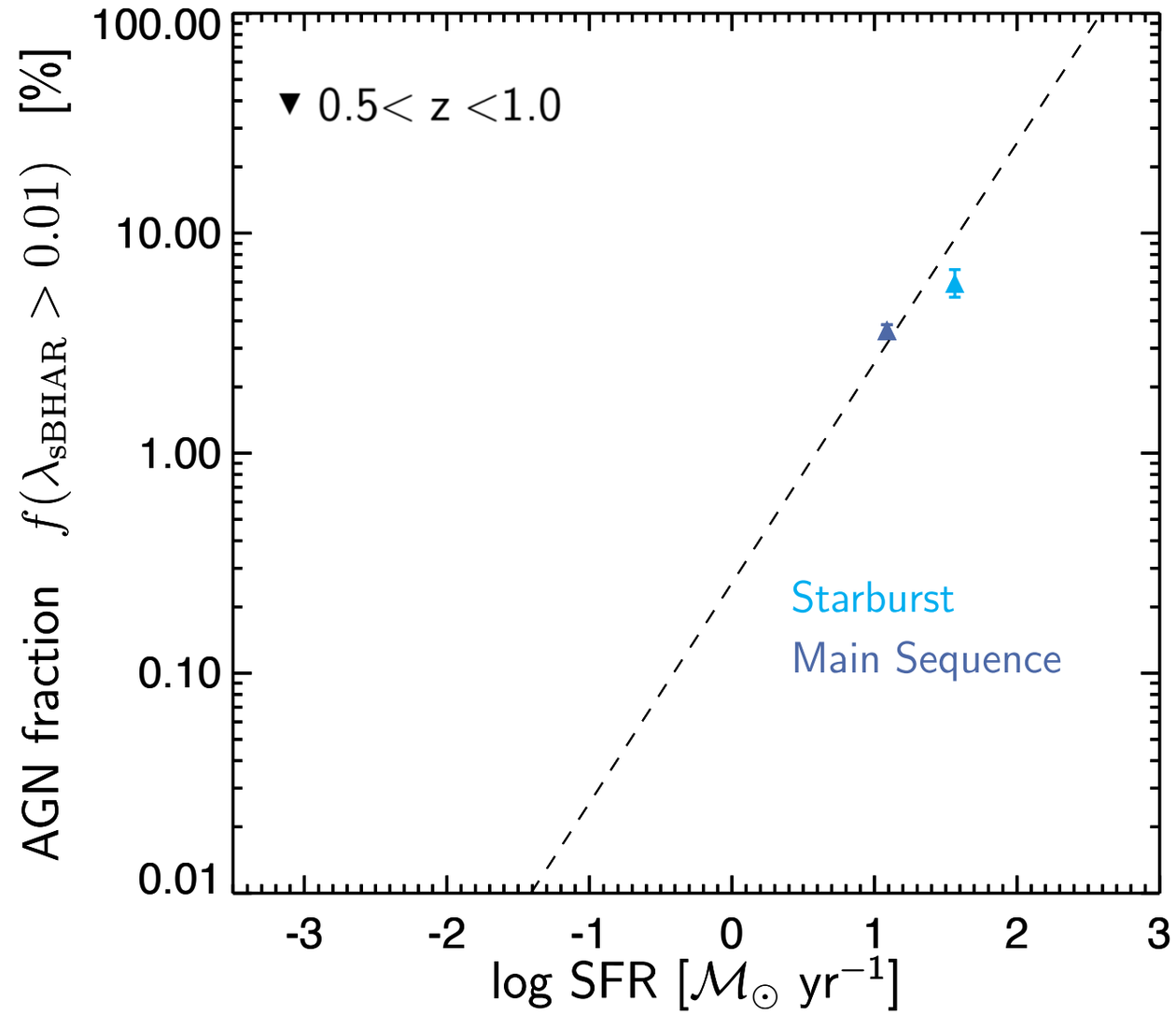
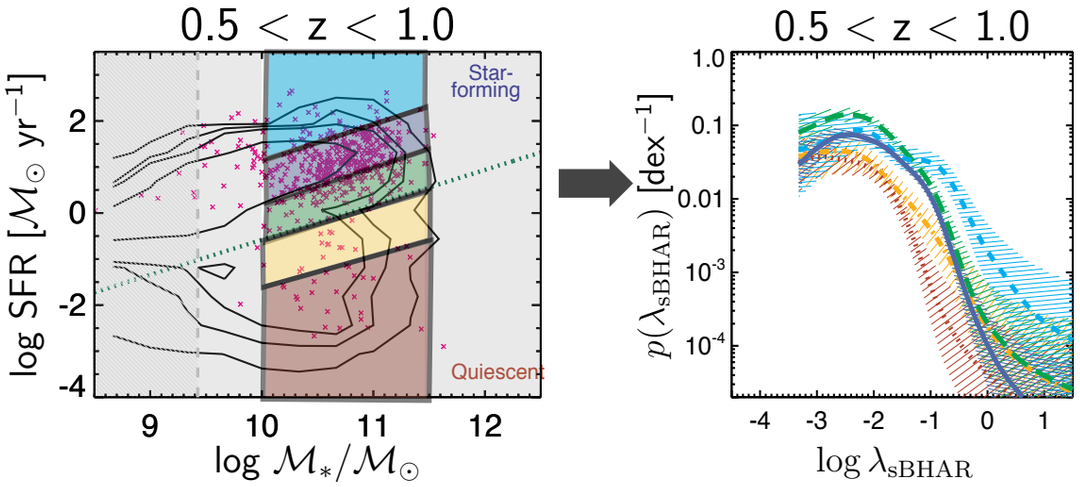


The incidence of AGN ***across*** the main sequence



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Aird, Coil & Georgakakis, 2019, MNRAS, 484, 4360

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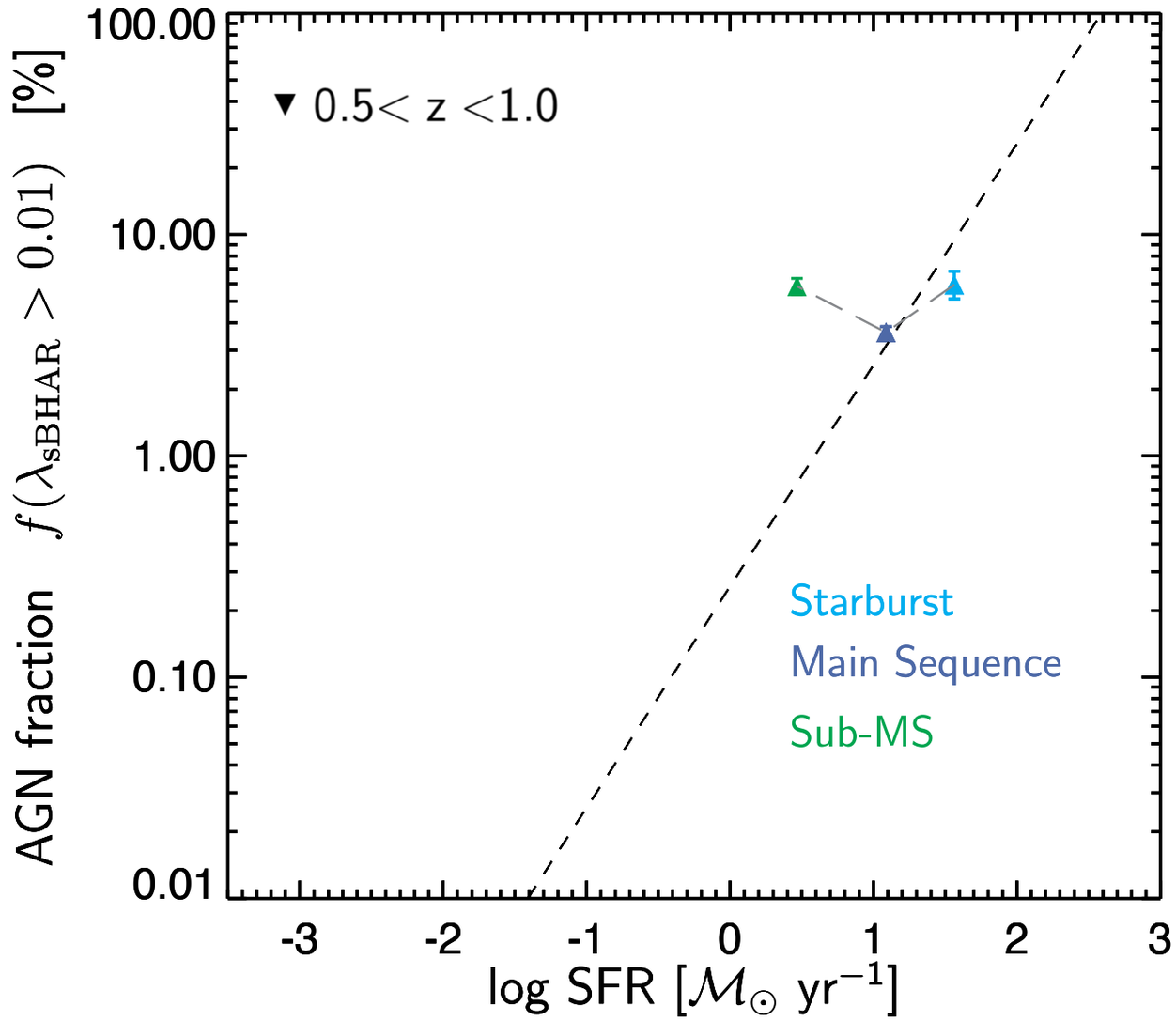

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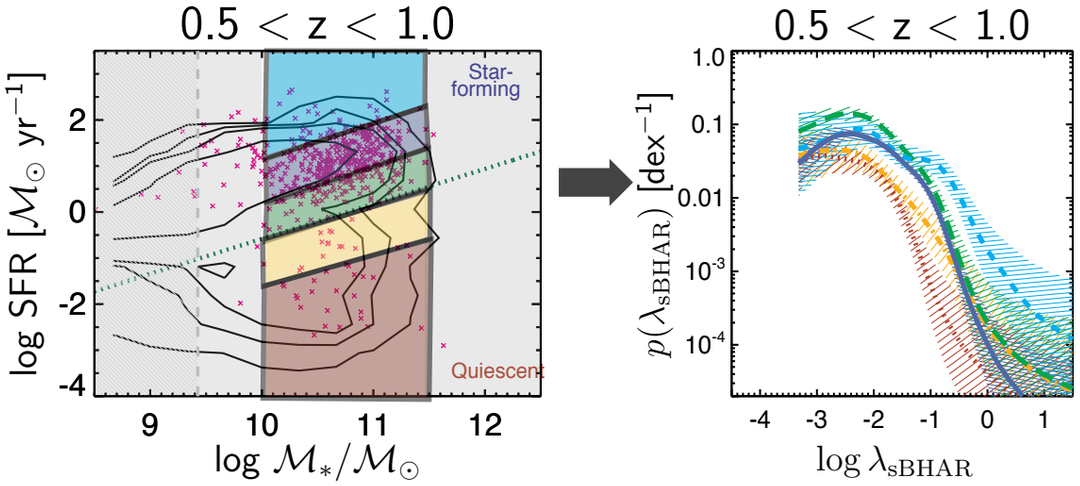

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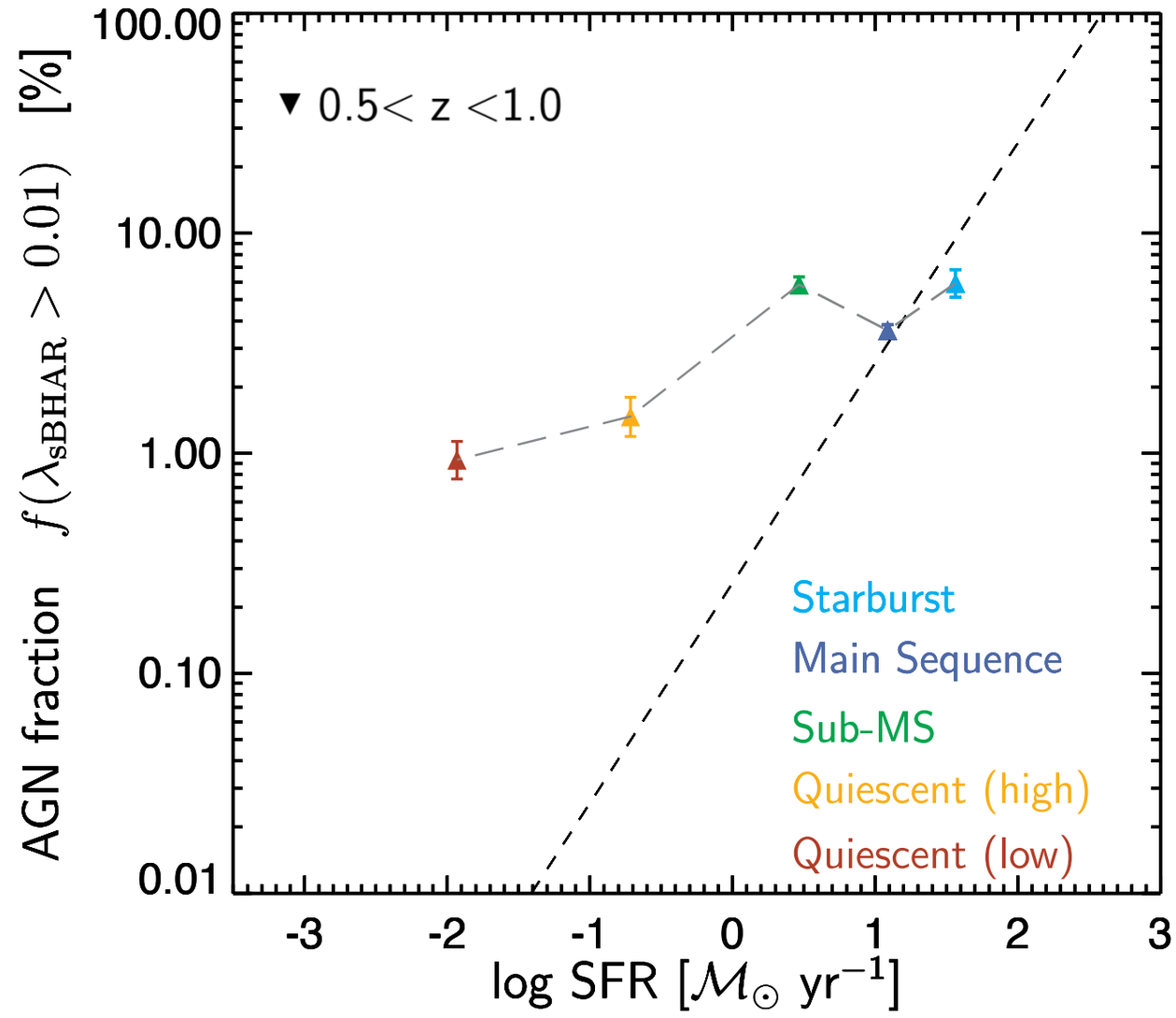

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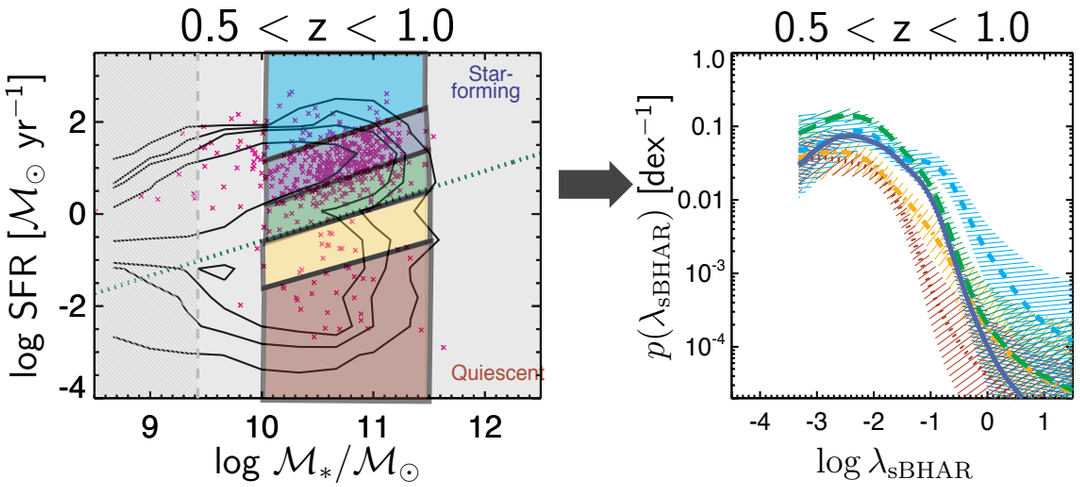

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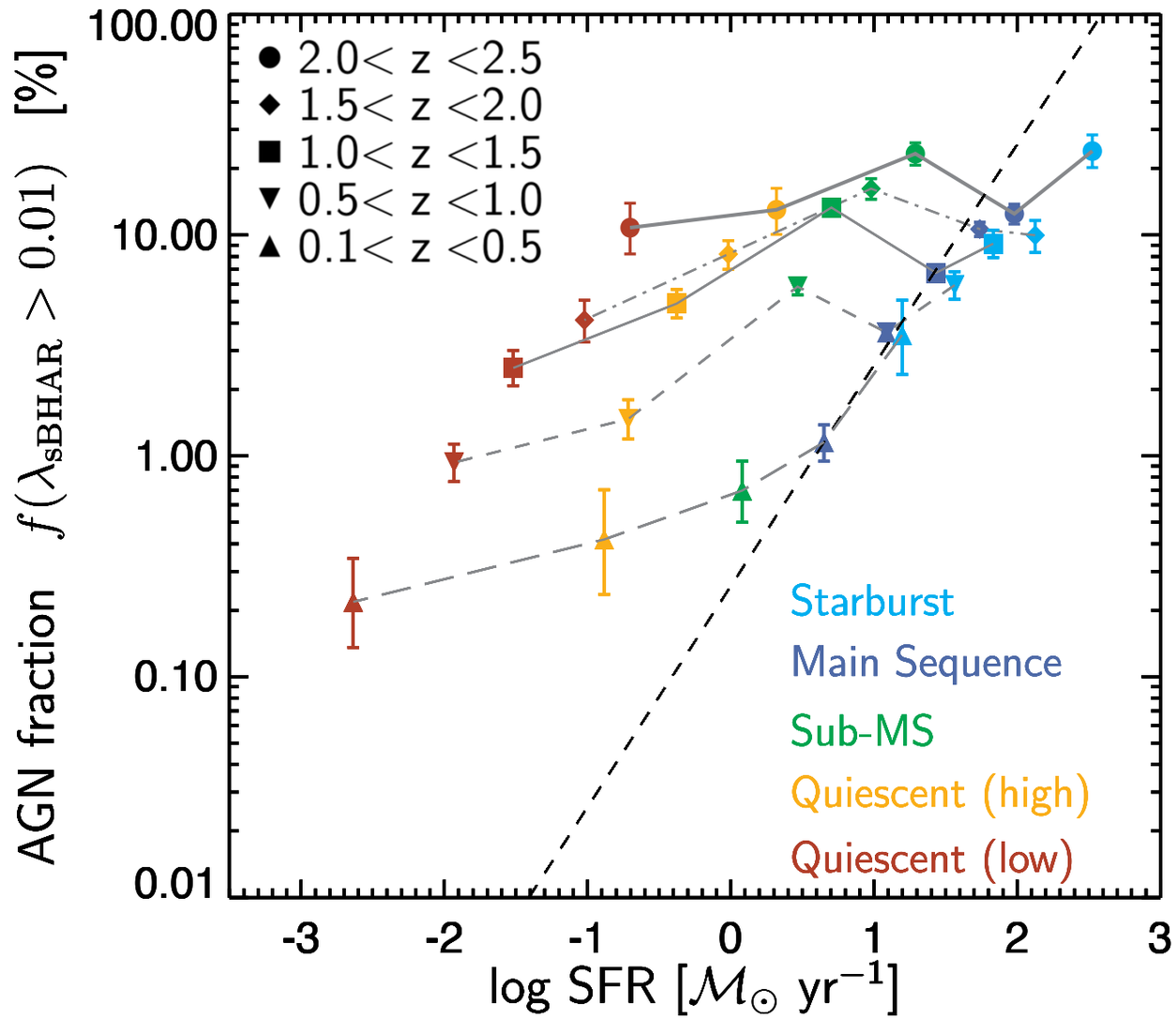

Conclusions: 2) Select galaxies - measure the incidence of AGN

- Use near-infrared (~stellar-mass) selected samples of galaxies combined with deep *Chandra* X-ray data to measure the **distribution** of *specific black hole accretion rates*

  Broad distribution of accretion rates reflecting ***variability*** of AGN (on ~galactic timescales)

- In **main-sequence star-forming** galaxies:

  Incidence of AGN correlates with the SFR
  => AGN fuelled by the *stochastic* accretion of cold gas?

- But for galaxies that are **below the main sequence**

  Enhanced AGN fraction
  => broader range of triggering/fuelling mechanisms
  i.e. not *just* cold gas that determines AGN activity

Take home points

- AGN samples identified at *any* wavelength are severely affected by **selection biases** and can give a biased view of which galaxies have AGN

- AGN exhibit a broad distribution of accretion rates, indicating **variability** on timescales ~0.1-1 Myr
  i.e. faster than changes in global galaxy properties

- Incidence of AGN in main-sequence star-forming galaxies correlates with SFR => both are related to **cold gas**?
  But… **not *just* cold gas** - additional mechanisms appear to trigger and fuel AGN in galaxies that are *not* on the main sequence.