From galaxy pairs counts to massive black hole mergers: predictions for LISA

Thierry Contini, **Rémi Delpech, Emmy Ventou**, Olivier Godet et al.

IRAP - Toulouse

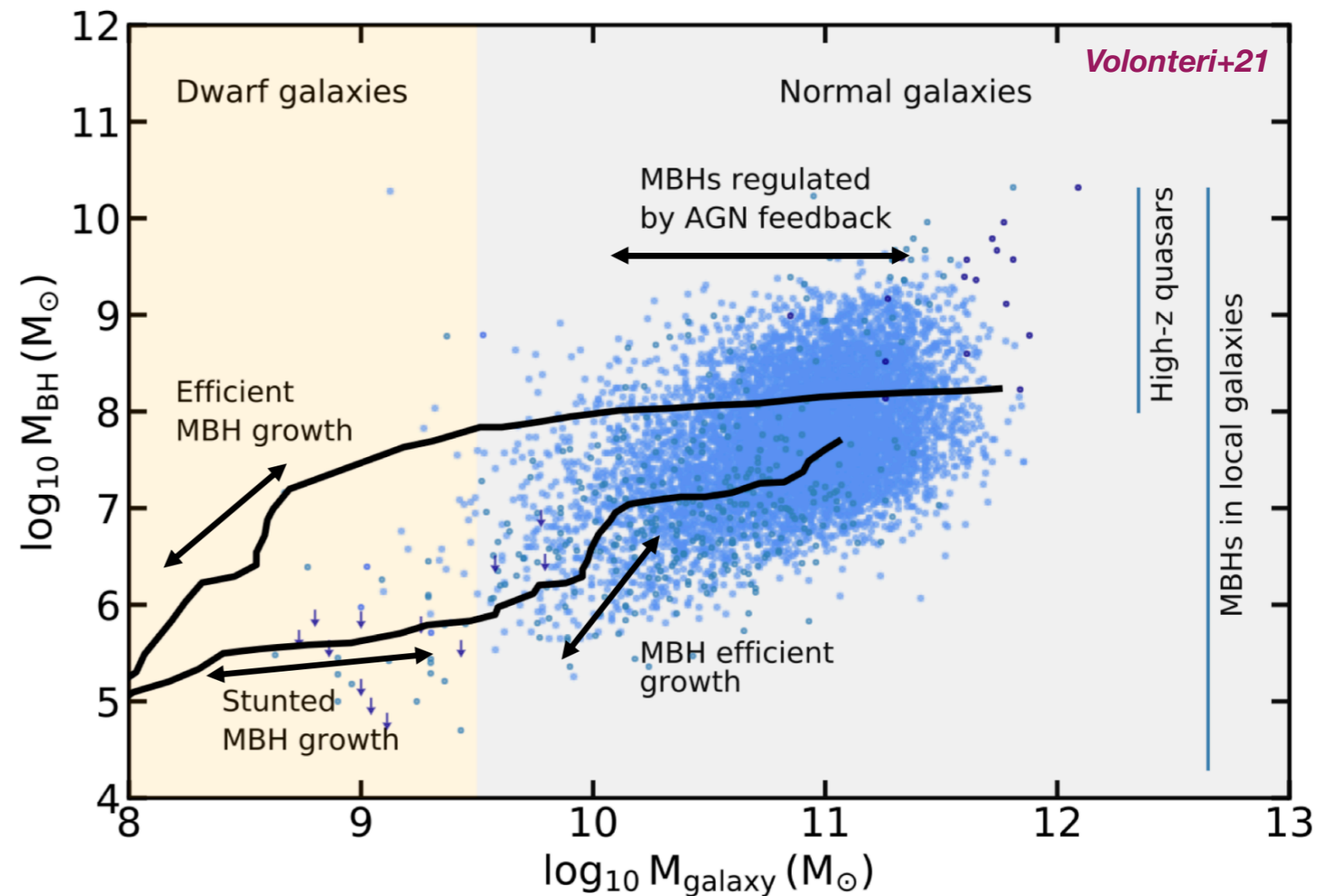# Massive black holes & their host galaxies

Co-evolution of galaxies and their MBH

How did the local MBH-galaxy scaling relations build up across cosmic time?

**MBH astrophysics with GWs**

- when do they **form**?

- how fast to they **grow** and **merge**?

- **spin, total mass** and **mass ratios** of merging MBH?

# Gravitational waves of merging black holes

GW frequency $\propto 1/M_{BH}$

- PTA (nHz) —> early **inspiral** phase of $M_{BH} \geq 10^8 \ M_{sun}$ binaries

- LISA (10^{-4}-10^{-1} Hz) —> **inspiral**, **merger** and **ringdown** phases of $M_{BH} \sim 10^4$-$10^7 \ M_{sun}$ binaries

Salcido+16

Laser Interferometer Space Antenna (credits: ESA)
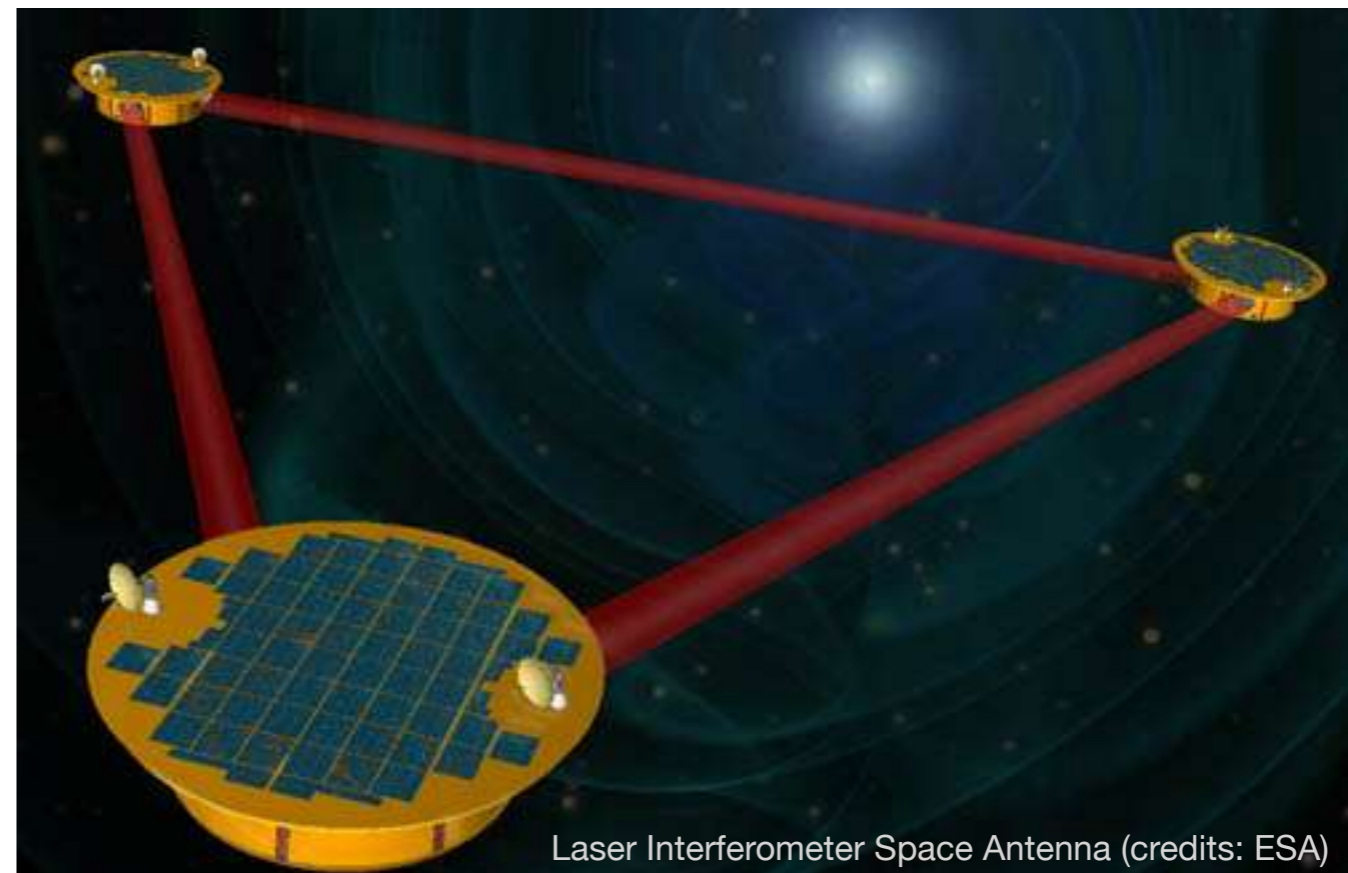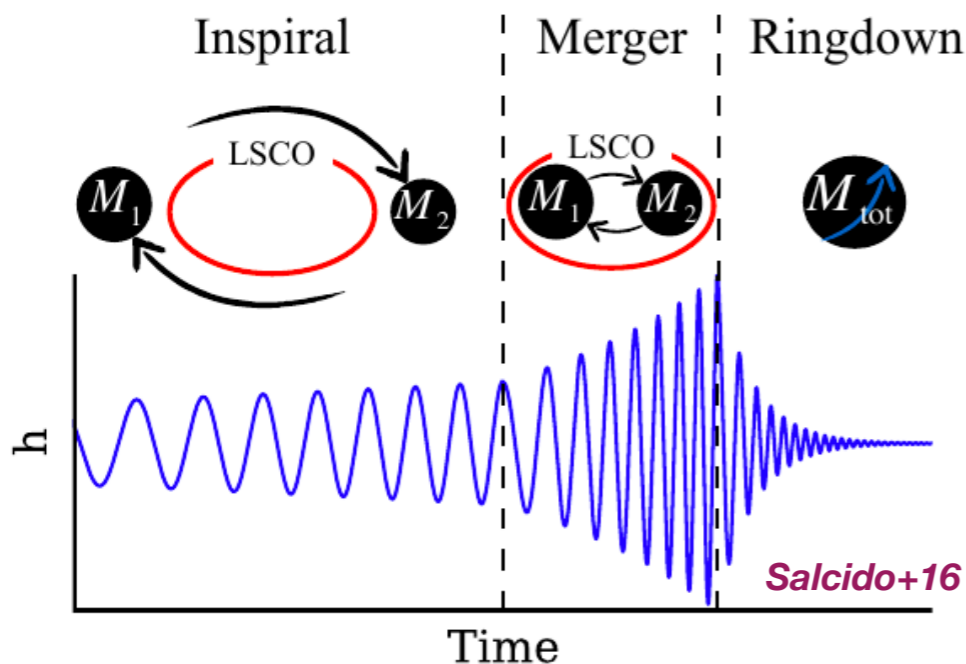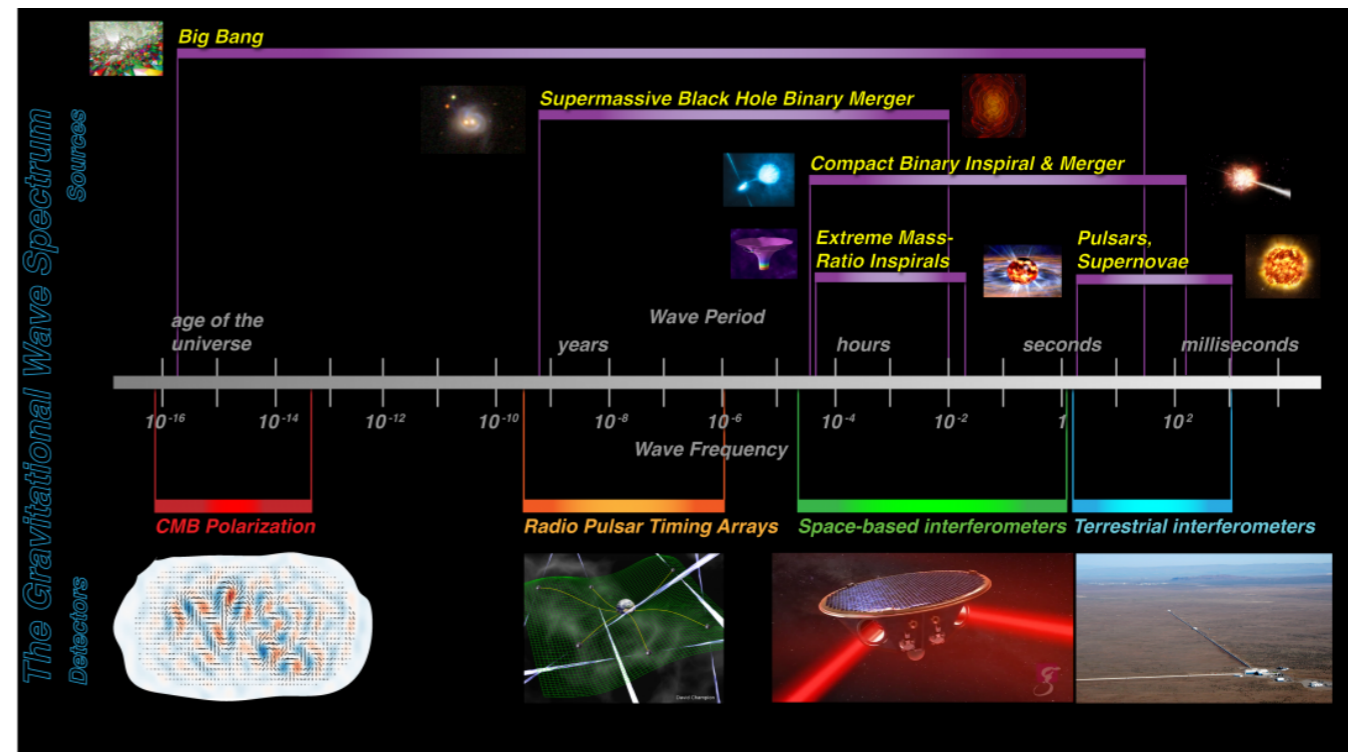
Prediction of merging MBH rate & detection by LISA

So far from **cosmological simulations** only

- EAGLE (Salcido+16)

- Illustris (Katz+20)

- Horizon-AGN (Volonteri+20)
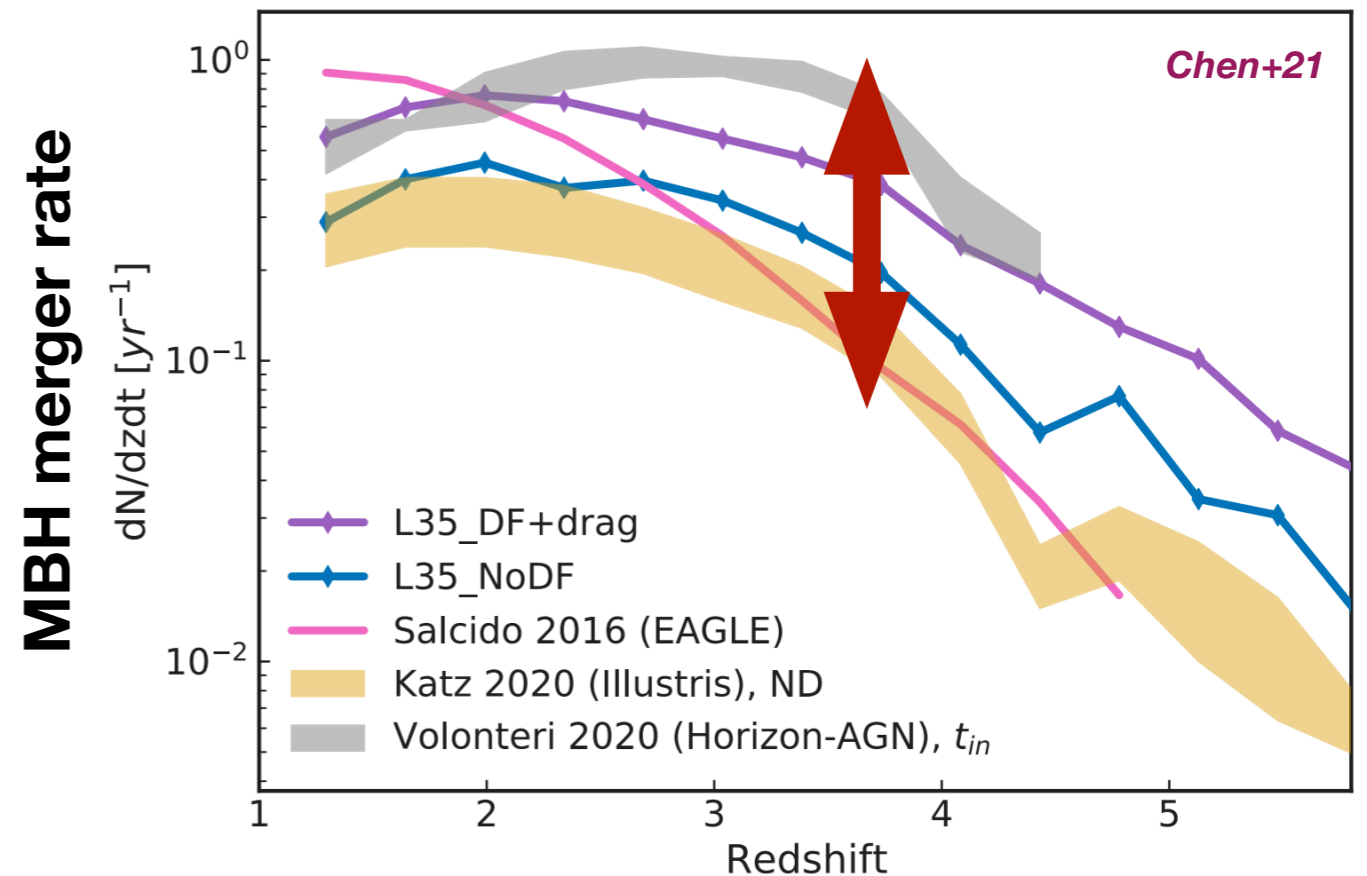
At least
an order of magnitude difference in the predictions

Chen+21

Reference	Base Population	MBHB Evolution Prescription	Merger Rate (yr^{-1})
Arun et al. (2009)	SAM	None	~ 22
Sesana et al. (2011)	SAM	None	~ 25
Klein et al. (2016)	SAM	DF,LC,VD,GW,Tri	~8
Berti et al. (2016)[1]	SAM	DF,LC,VD,GW,Tri	~8
Salcido et al. (2016)	Hydrodynamic	Constant[2]	~2
Bonetti et al. (2019)	SAM	DF,LC,VD,GW,Tri	~23
This Paper	Hydrodynamic	DF,LC,VD,GW	~ 0.5 − 1

Katz+19
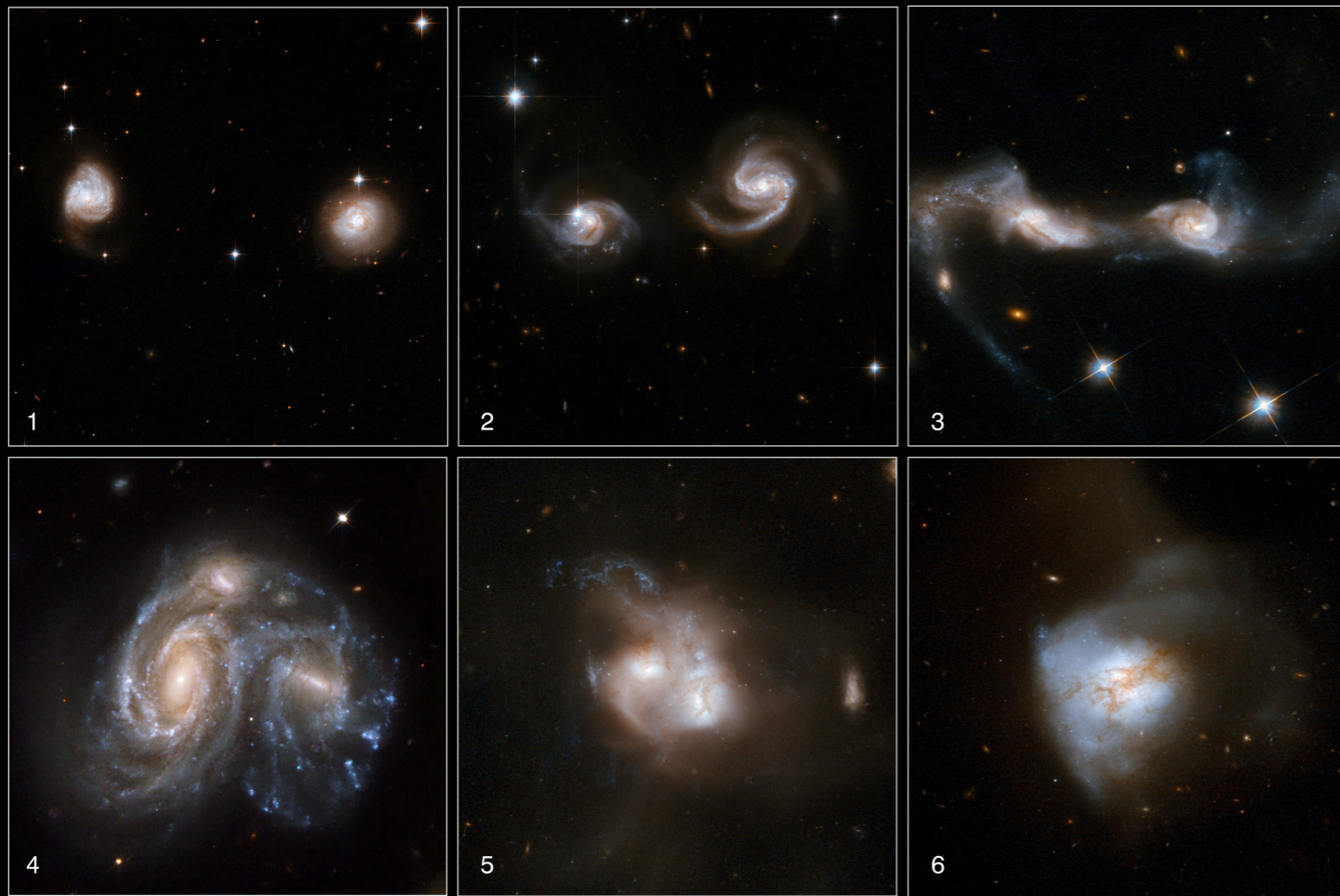
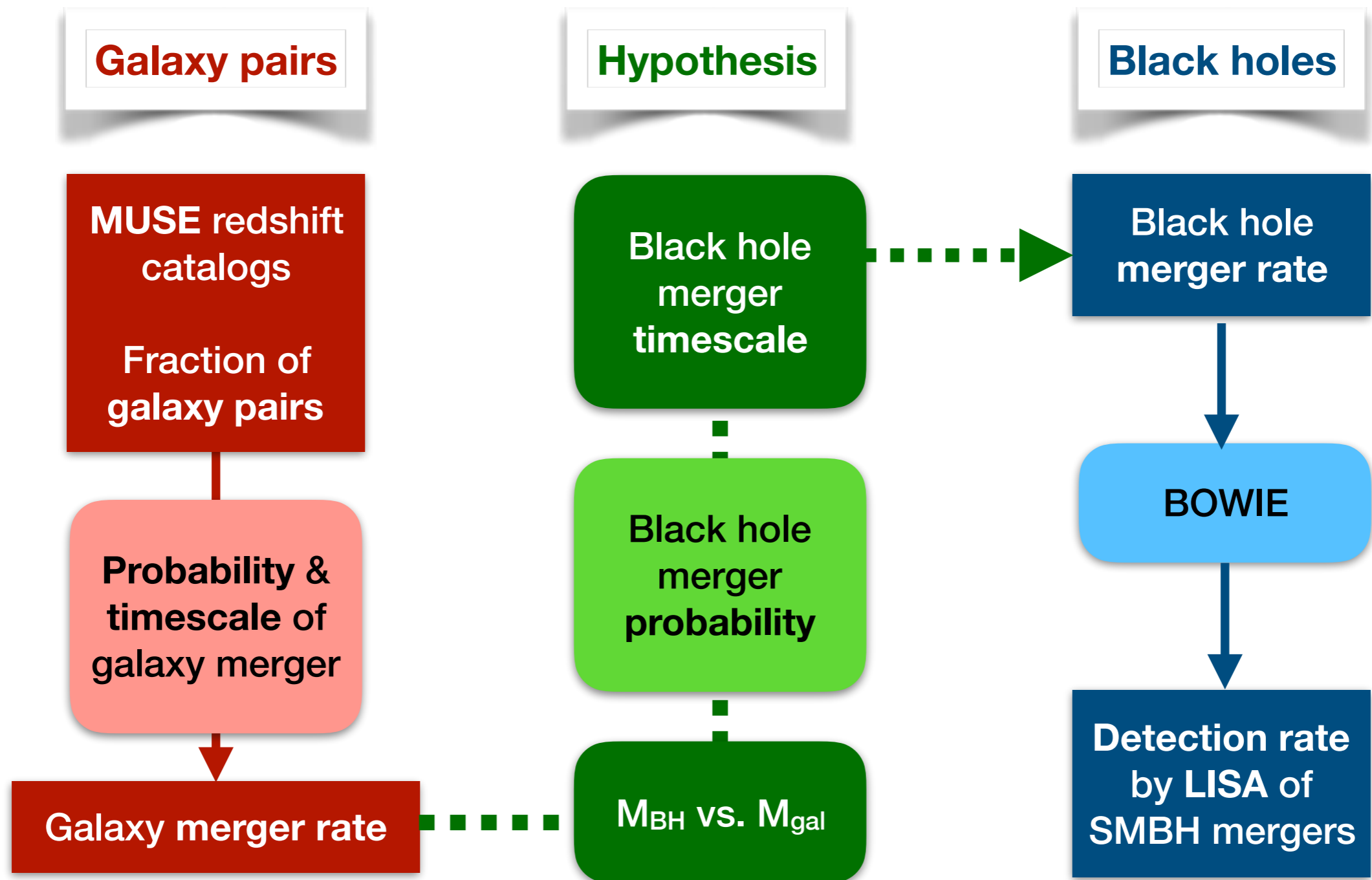Merger stages of interacting galaxies (credits: ESA)
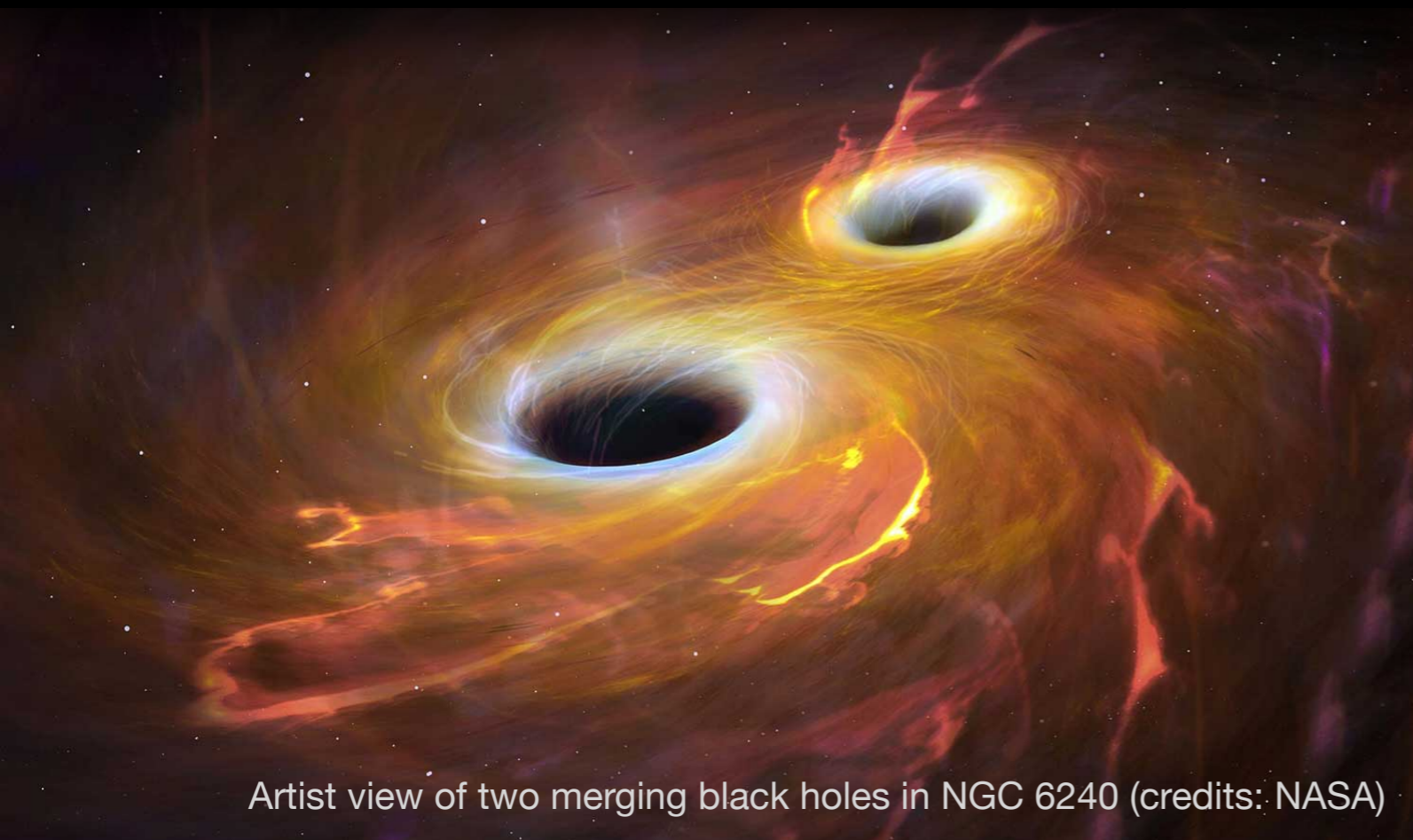
Artist view of two merging black holes in NGC 6240 (credits: NASA)
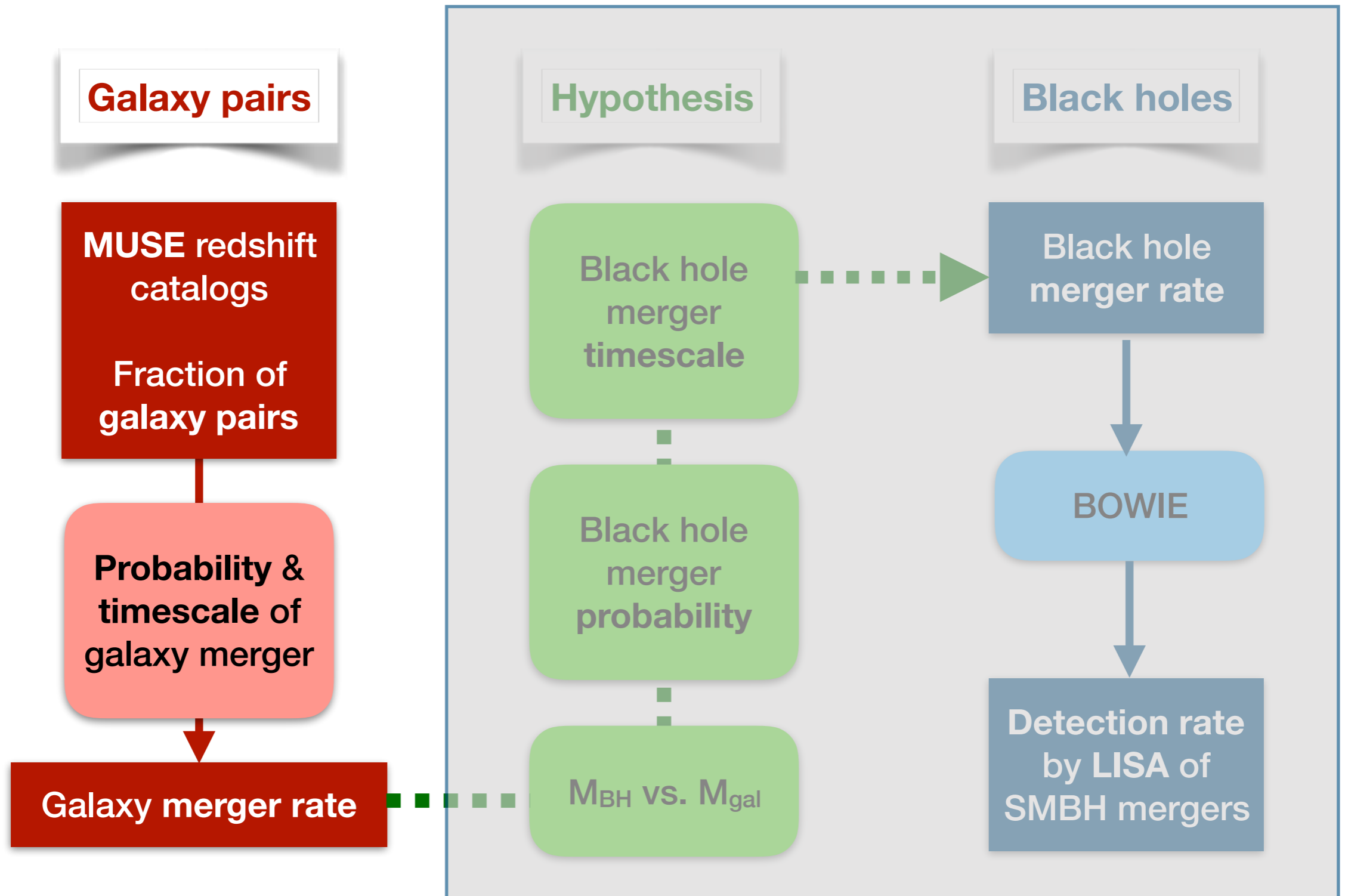
From <u>observed</u> galaxy pairs counts …

… to massive black holes mergers

Methodology

Galaxy pairs

Hypothesis

Black holes

MUSE redshift catalogs

Fraction of galaxy pairs

Probability & timescale of galaxy merger

Galaxy **merger rate**

Black hole merger **timescale**

Black hole merger **probability**

M_{BH} vs. M_{gal}

Black hole **merger rate**

BOWIE

Detection rate by **LISA** of SMBH mergers

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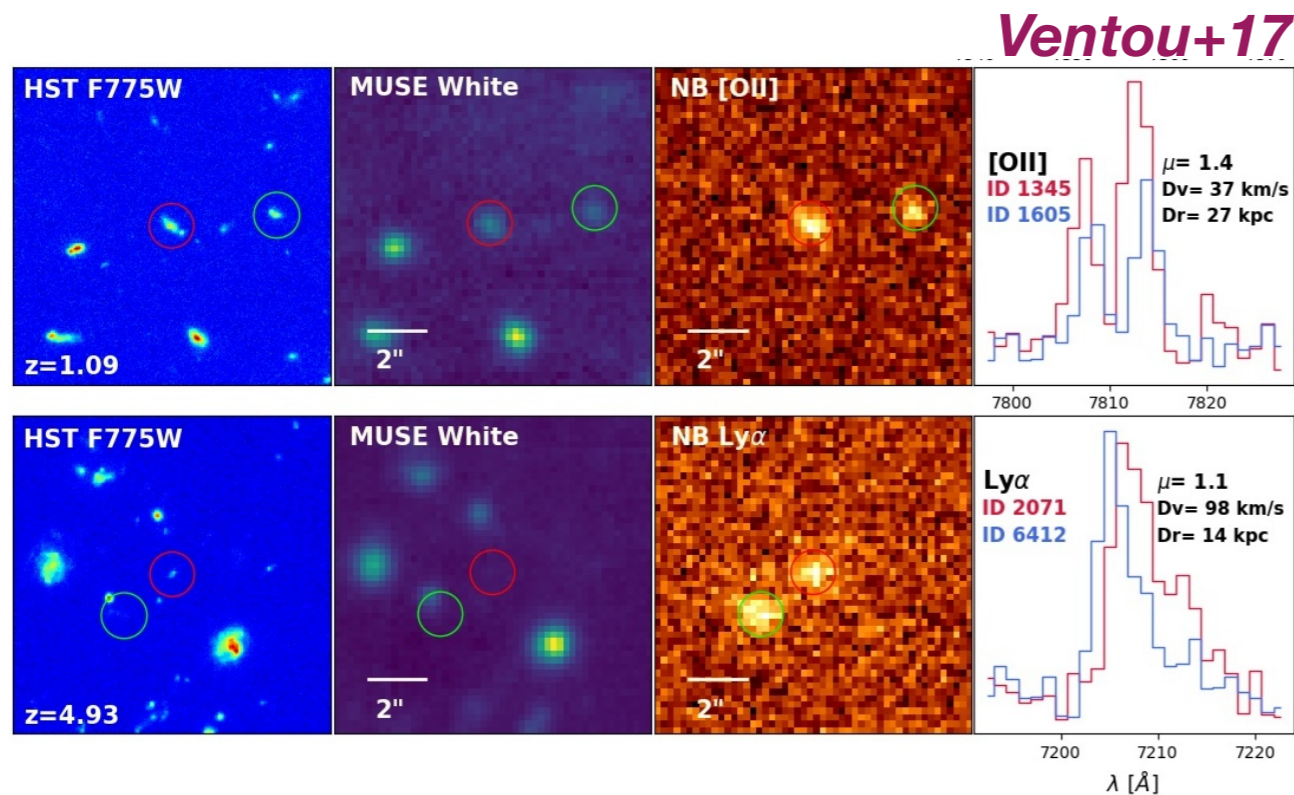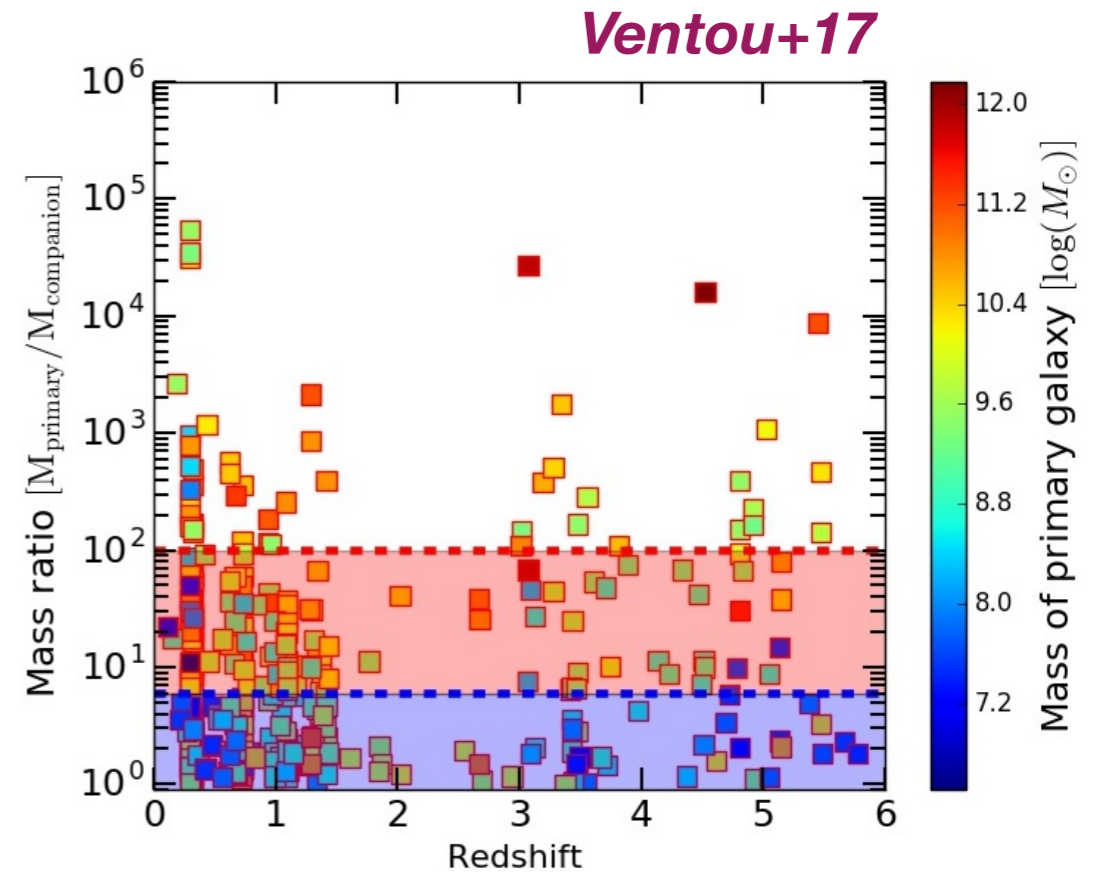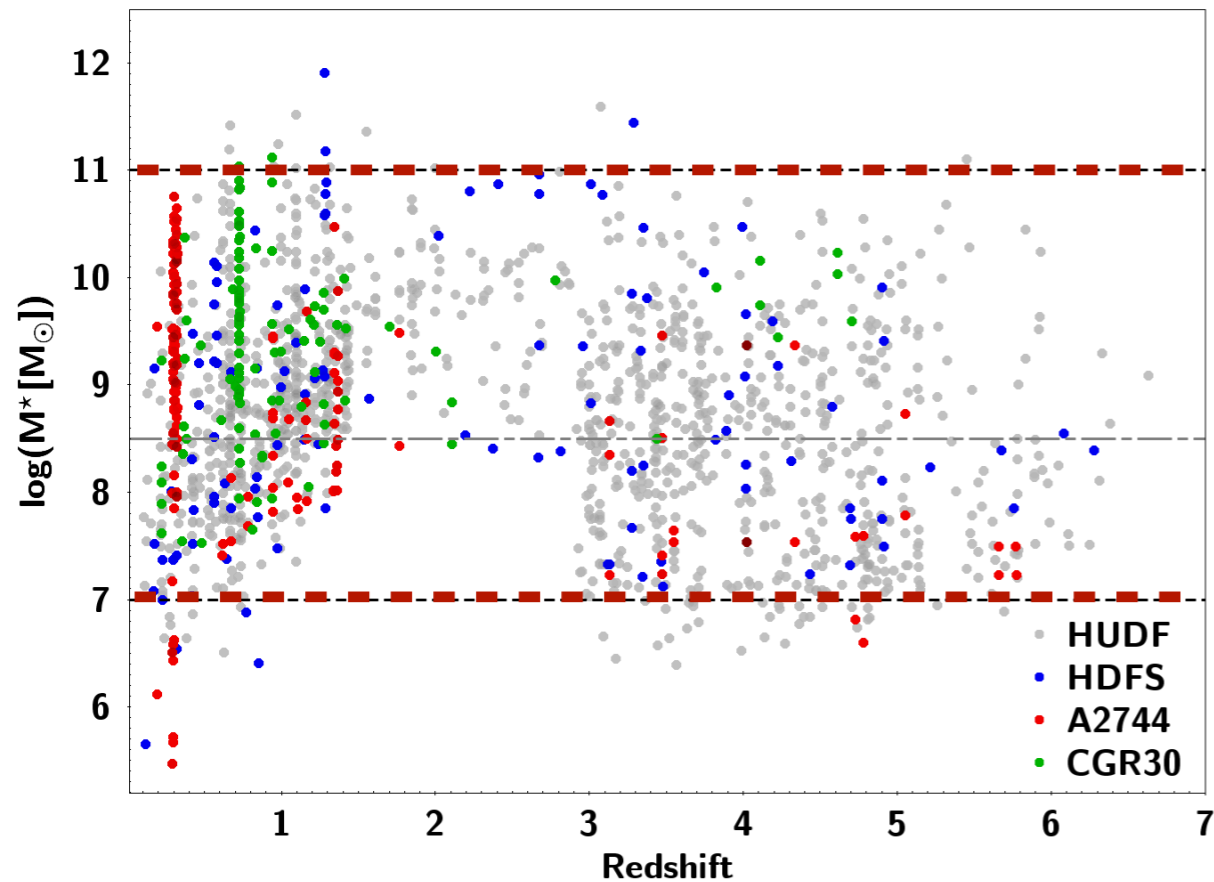
Galaxy pairs from MUSE redshift catalogs

- ~2100 galaxies up to z~7 from **MUSE deep fields**

- **261 close pairs** of galaxies

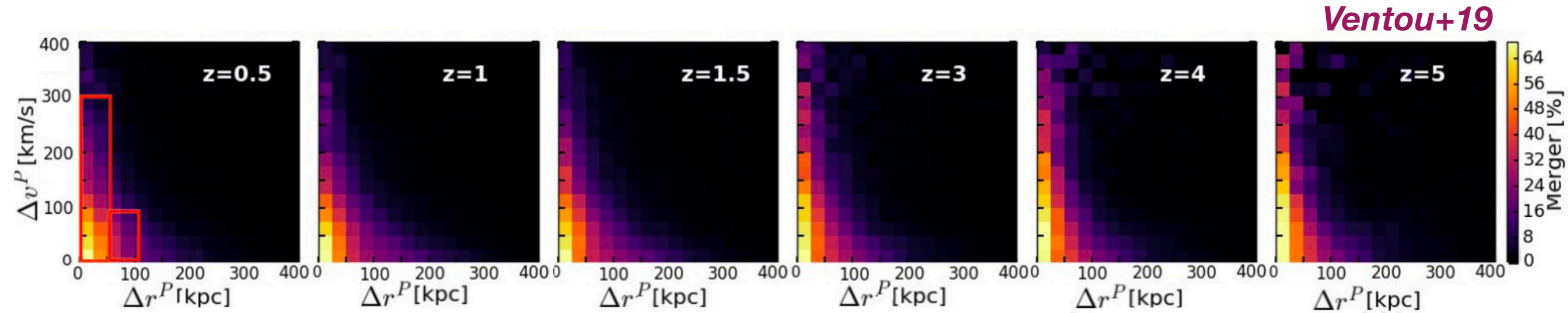- Accurate estimate of pairs **separation** (projected distance & velocity) and **galaxy masses**

Ventou+17

Ventou+17
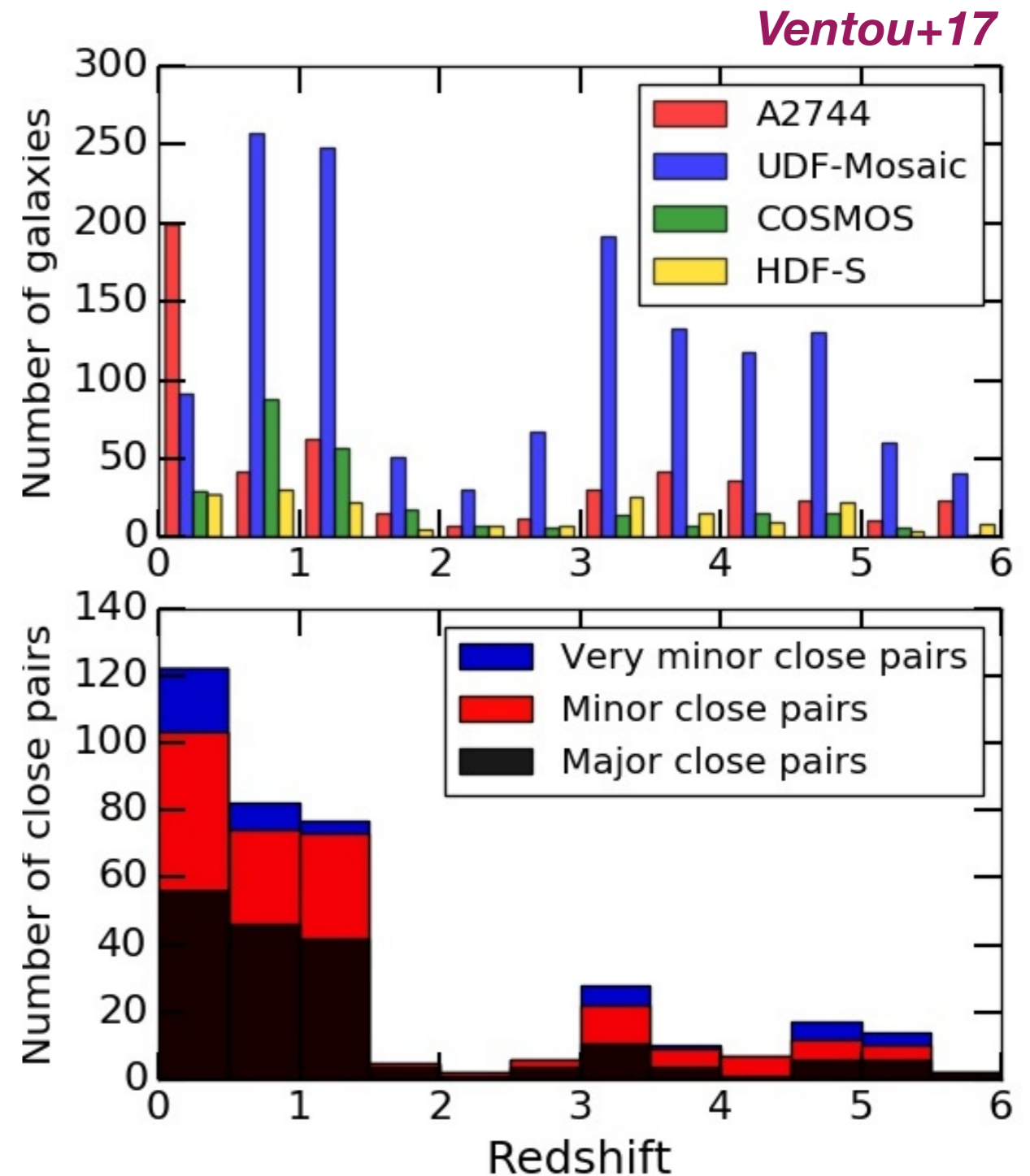
Galaxy pairs from MUSE redshift catalogs

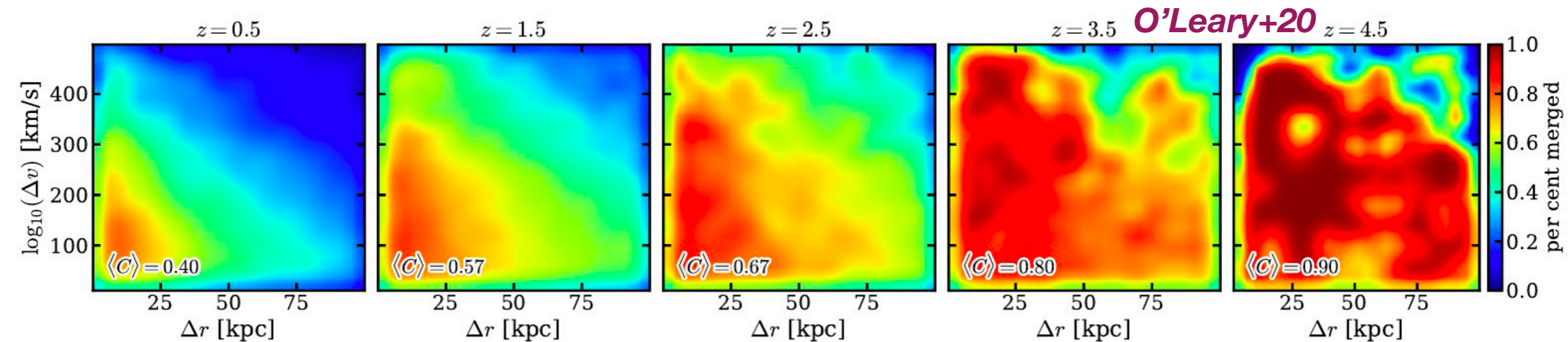

For completeness, selection of **galaxy pairs** based on:

- galaxy stellar masses: **$10^7 < M^* < 10^{11}$ M$_{sun}$**

- and mass ratios: **$1 < M_2/M_1 < 1/10$**

Probability of galaxy merging

Ventou+19

New criteria for pairs selection based on *Illustris* cosmological simulations

$$\begin{cases} 5 \leq \Delta r^P \leq 50 \, \text{kpc} \;\; \text{and} \;\; \Delta v^P \leq 300 \, \text{km s}^{-1} \\ \text{or} \; 50 \leq \Delta r^P \leq 100 \, \text{kpc} \;\; \text{and} \;\; \Delta v^P \leq 100 \, \text{km s}^{-1} \end{cases}$$

O'Leary+20

Redshift dependance
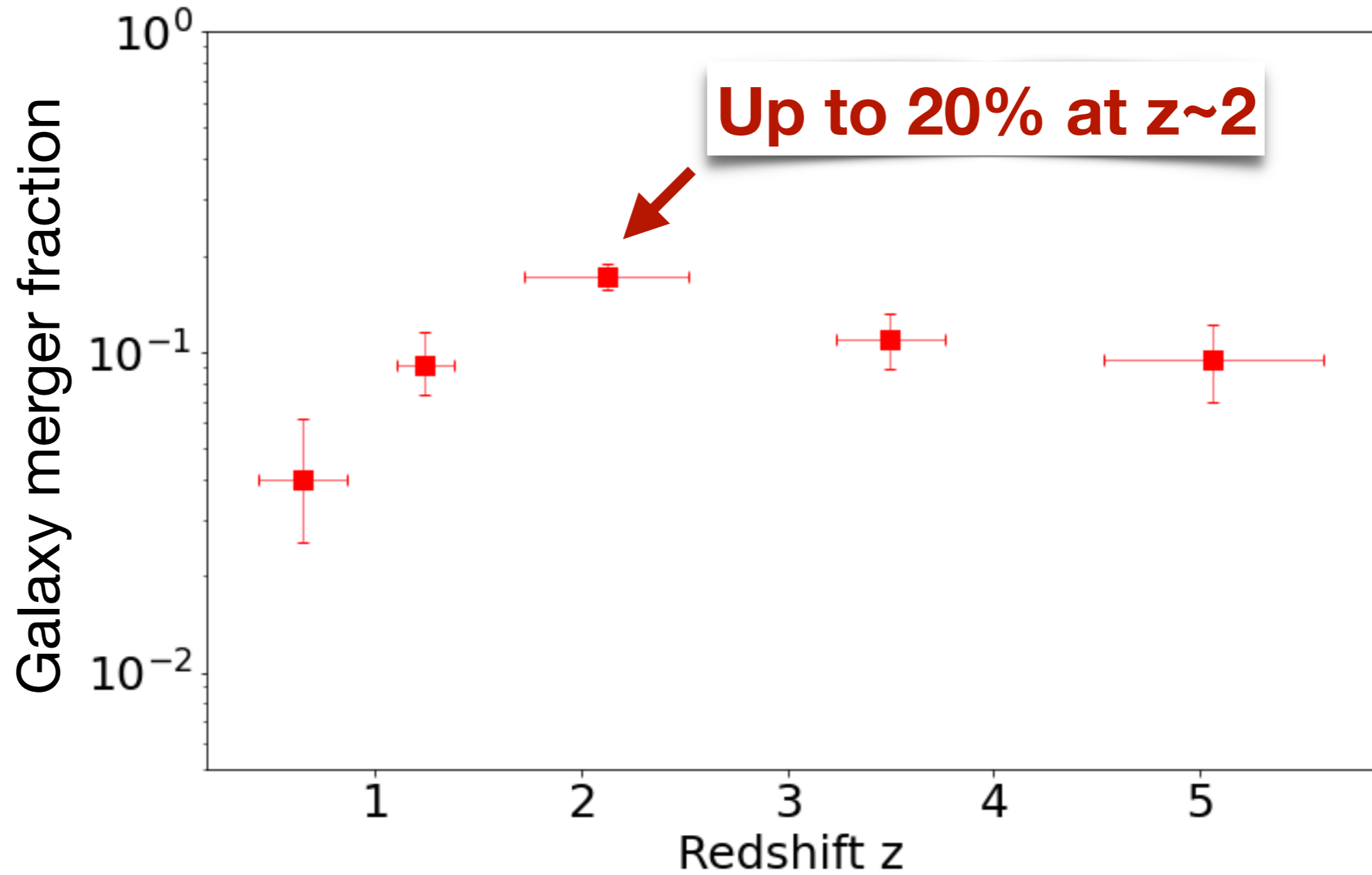
$$W(\Delta r_P, \Delta v_P, z)$$

Fraction of galaxy mergers

Redshift confidence
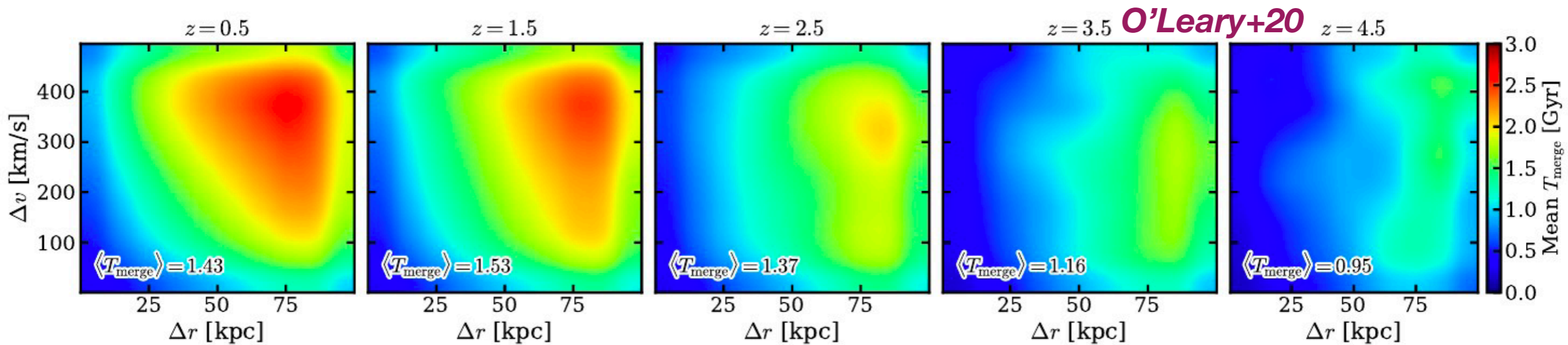
Redshift completeness

Merger probability

$$f_M(z_r) = C_1 \frac{\sum_{K=1}^{N_P} \frac{w_{z,K_1}}{C_2(z_{r,K_1})} \frac{w_{z,K_2}}{C_2(z_{r,K_2})} w_{A,K} W_K(\Delta r_{P,K}, \Delta v_{P,K}, z_{r,K})}{\sum_{i=1}^{N_g} \frac{w_z^i}{C_2(z_{r,i})}}$$

**Limited
spatial resolution**

**Limited
field-of-view**

Galaxy merger fraction
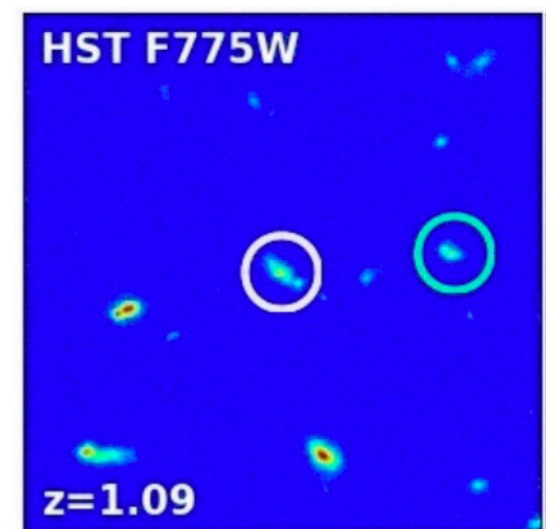

Up to 20% at z~2

Galaxy merger timescales

O'Leary+20
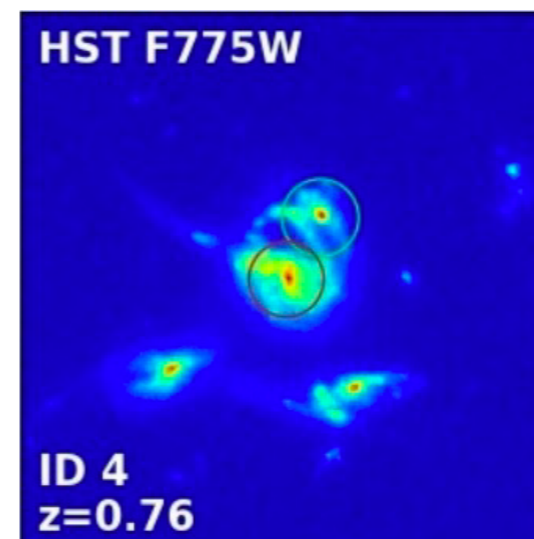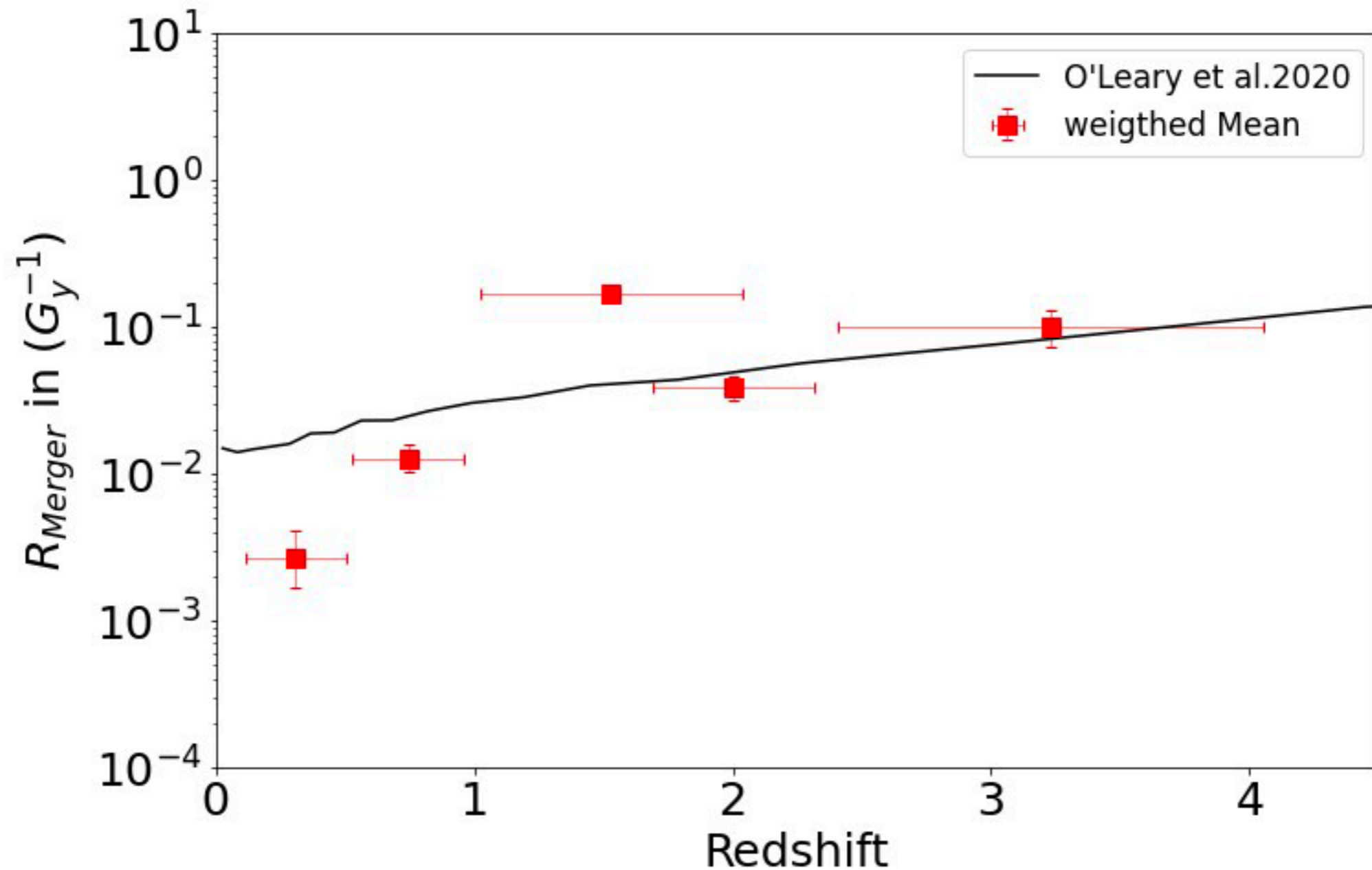
Merging timescale:

$$T_M(\Delta r_P, \Delta v_P, z)$$

Pair observation timescale:

$$T_{obs} = T_M \left[1 - \left(\frac{r_{p,min}}{\Delta r_P} \right)^2 \right]$$

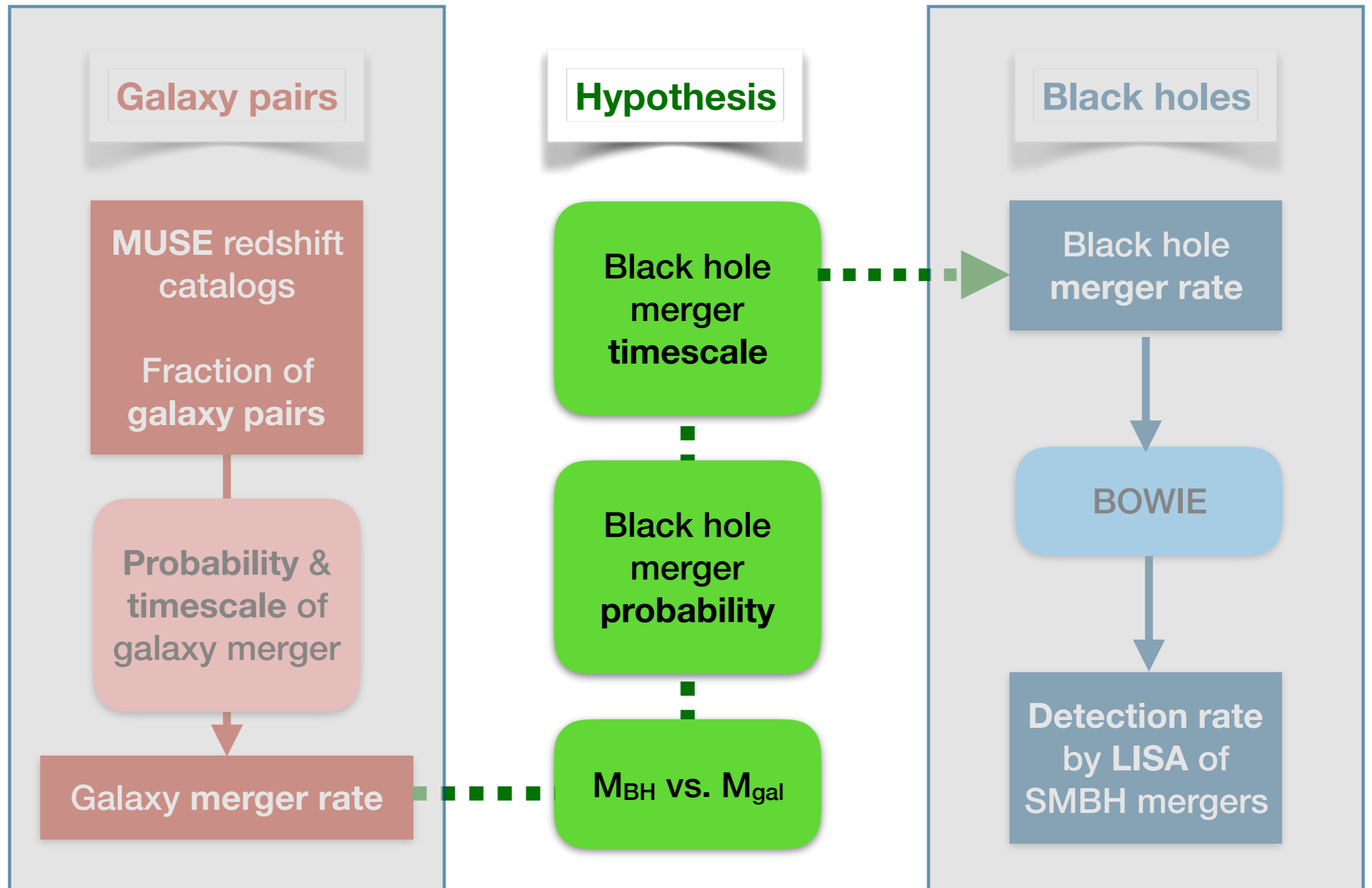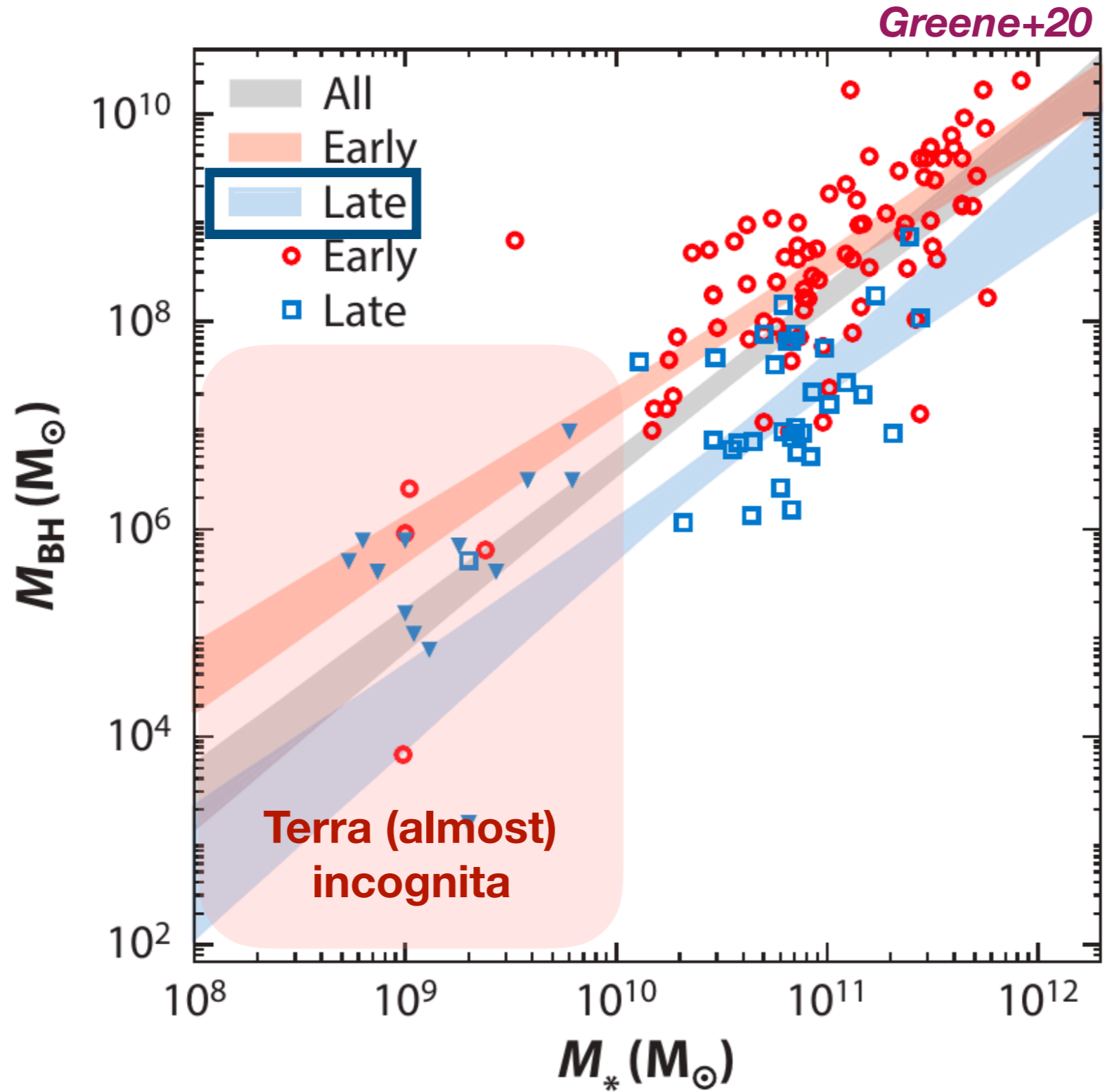# Galaxy merger rate

$$R_{Merger} = \frac{\text{Galaxy merger fraction}}{\text{Mean observation timescale}}$$

Methodology

Galaxy pairs

MUSE redshift catalogs

Fraction of galaxy pairs

Probability & timescale of galaxy merger

Galaxy **merger rate**

Hypothesis

Black hole merger **timescale**

Black hole merger **probability**

M_{BH} vs. M_{gal}

Black holes

Black hole merger rate

BOWIE

Detection rate by **LISA** of SMBH mergers

Black hole mass?

Greene+20

Probability of black hole merging

T<4 G_{yr}

Legend:
- ------ $q \in$ 0.75-1.00
- ------ $q \in$ 0.50-0.75
- ------ $q \in$ 0.25-0.50
- ------ $q \in$ 0.00-0.25

- Horizon-AGN
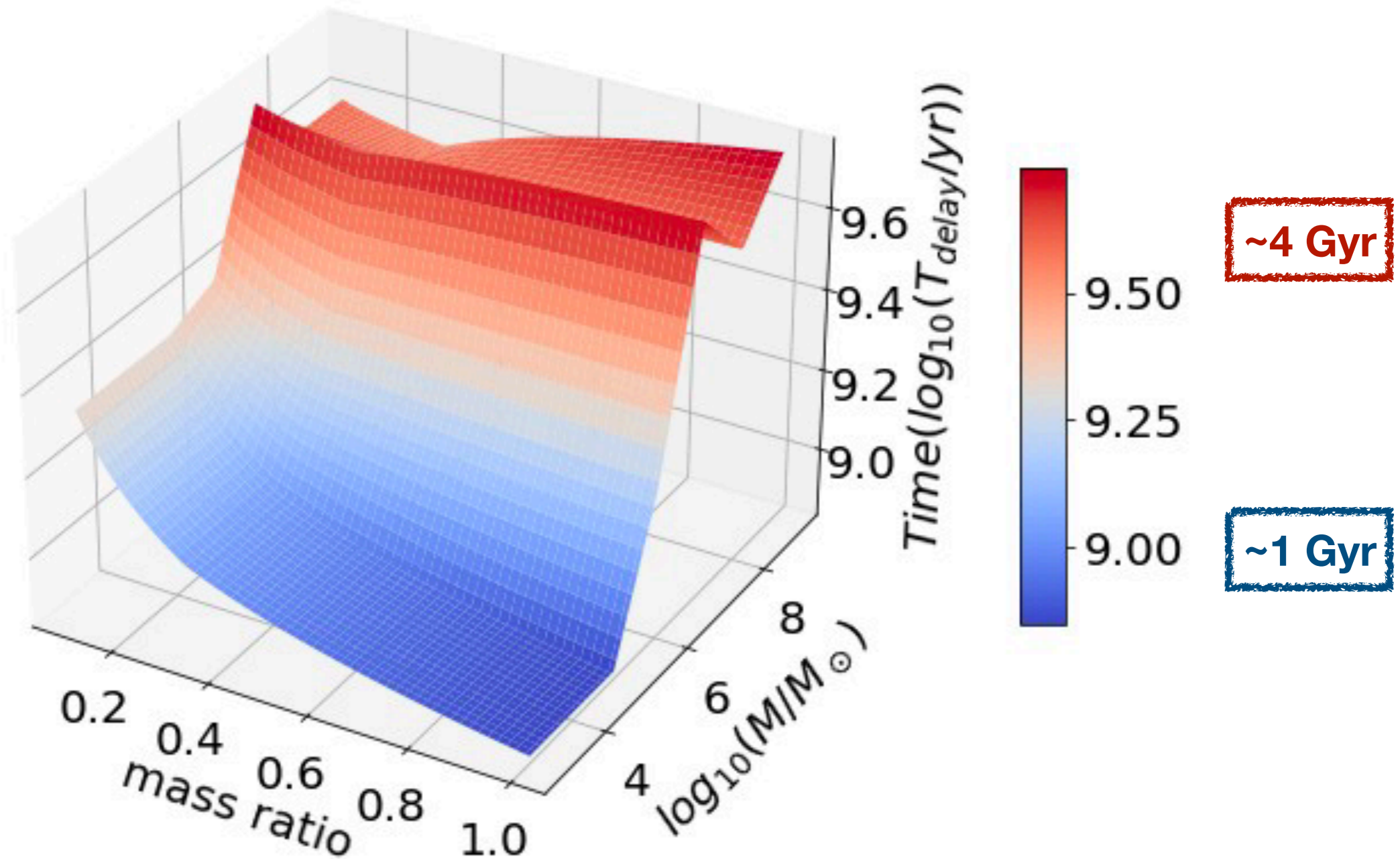- New-Horizon
- Adapted

Delpech+21, adapted from *Volonteri+20*
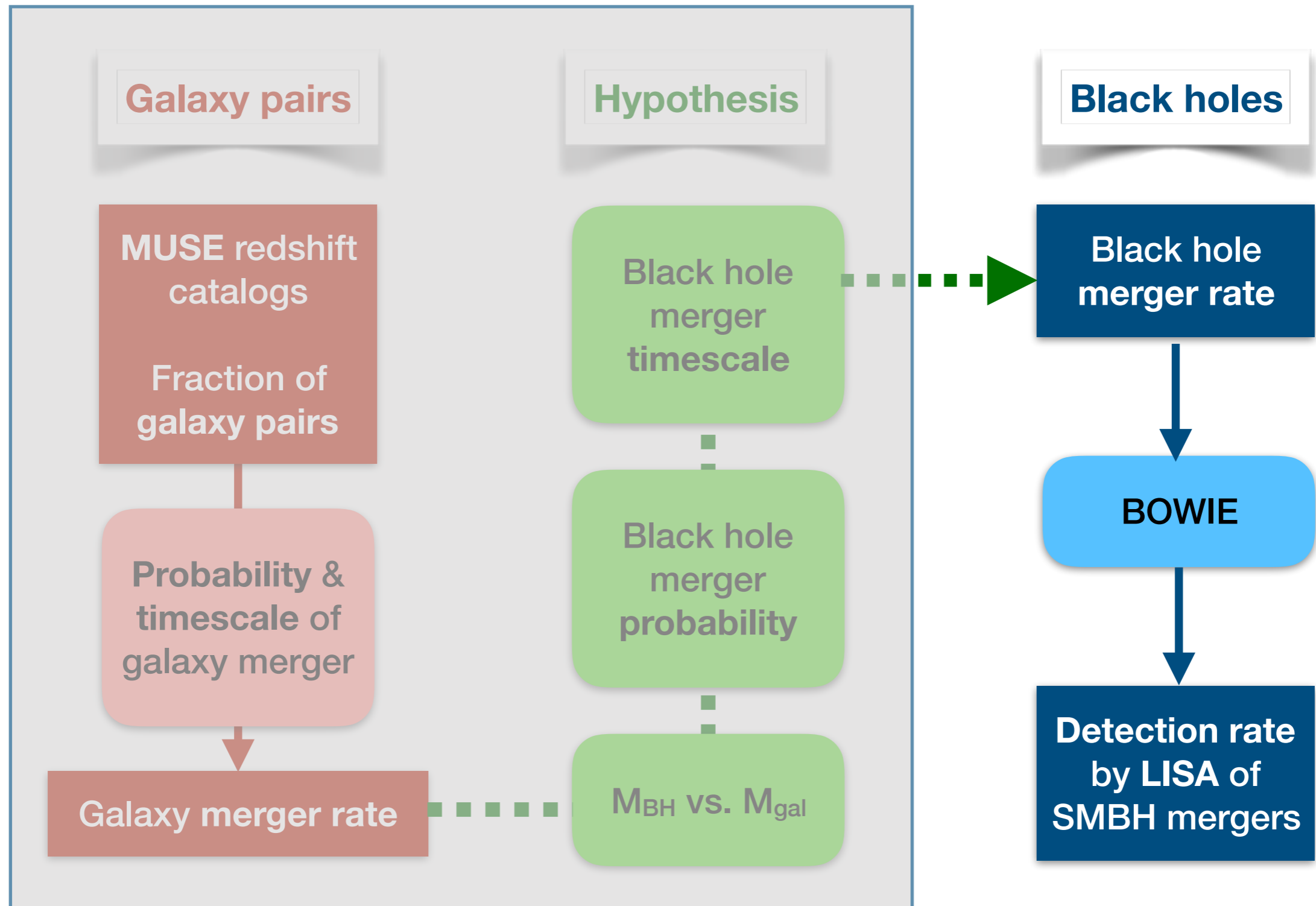
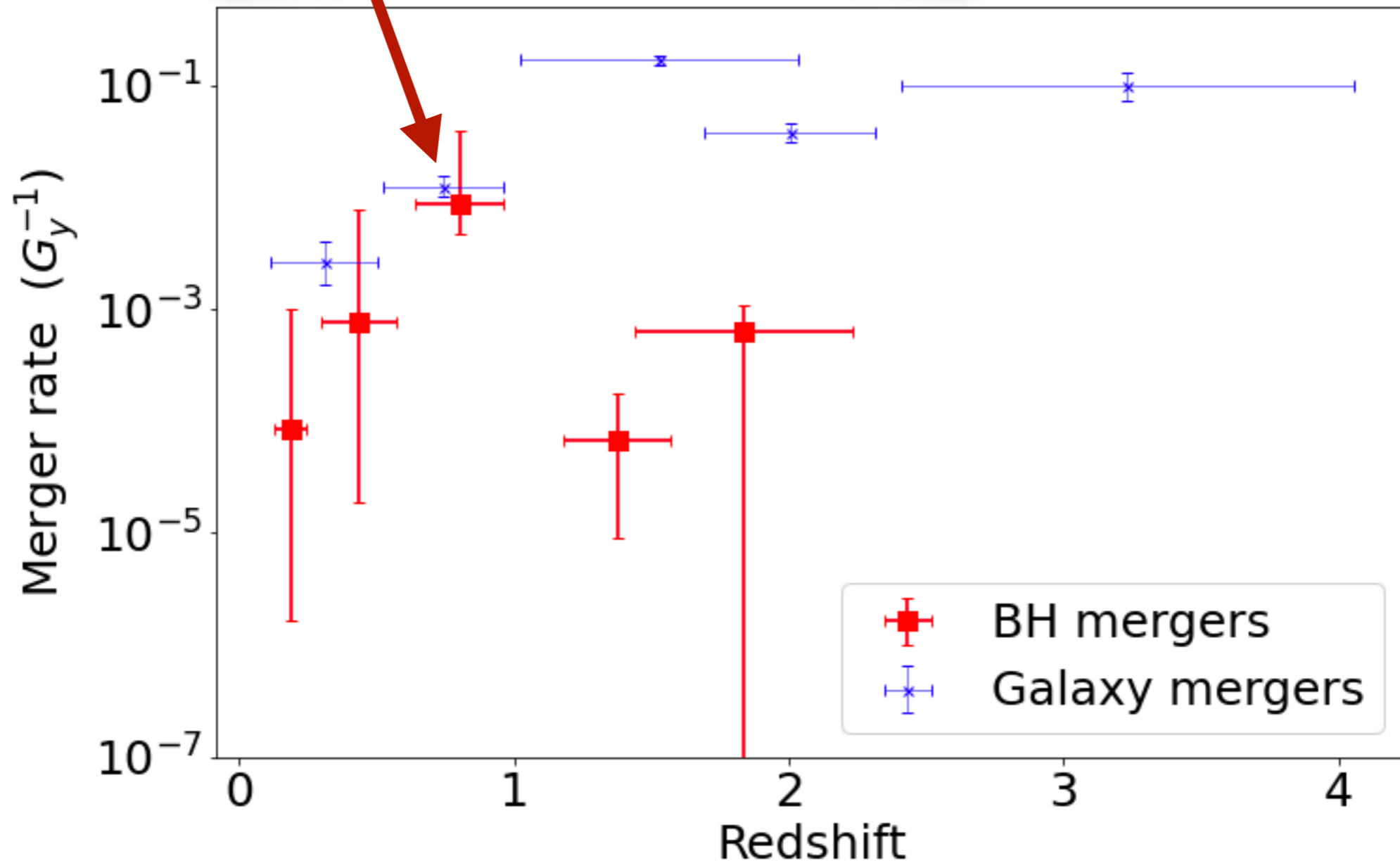Probability

$M_1(M_\odot)$
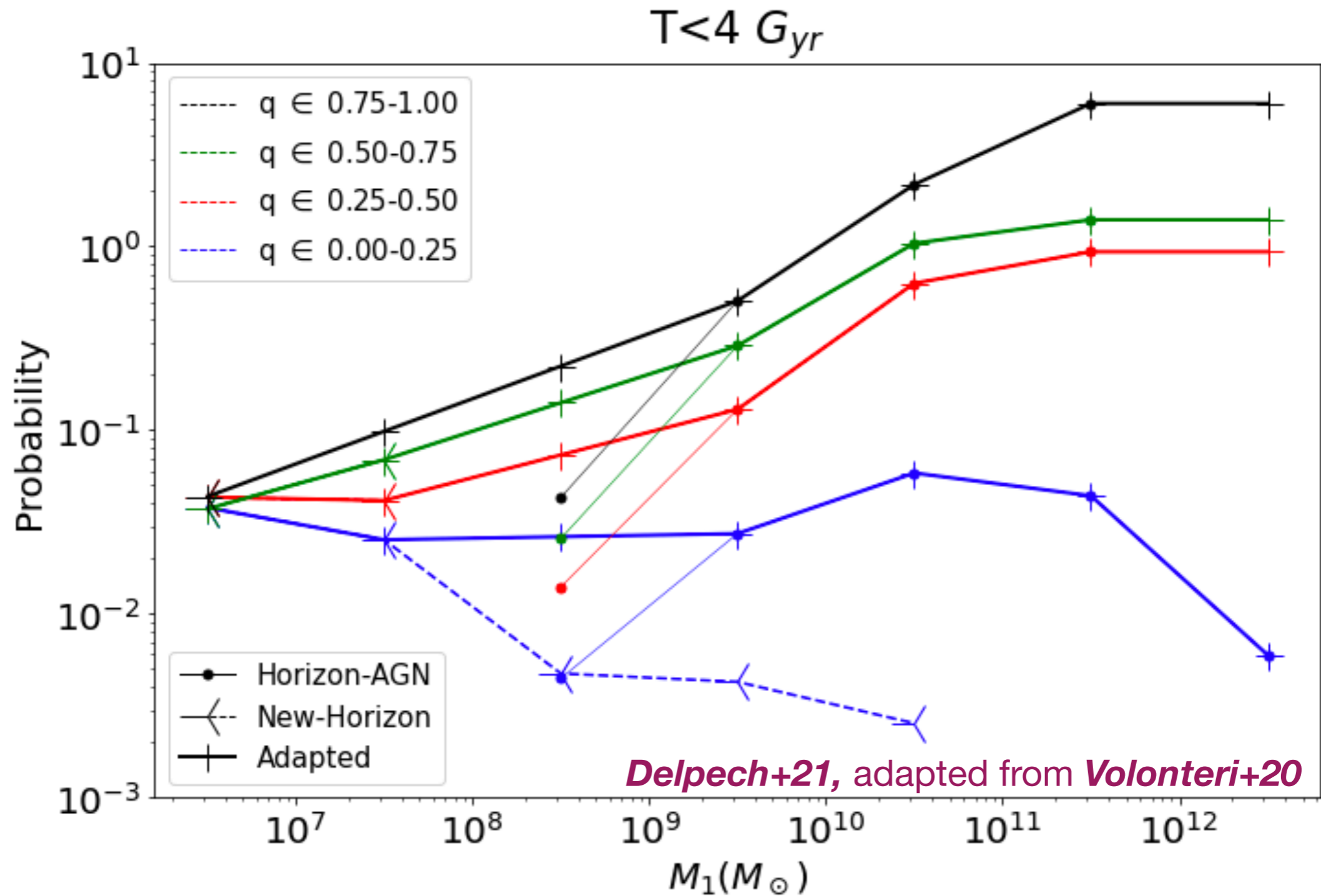
Black hole merger timescale

Delpech+21, estimated from merger timescale
probability distribution function of *Chen+20*

Methodology

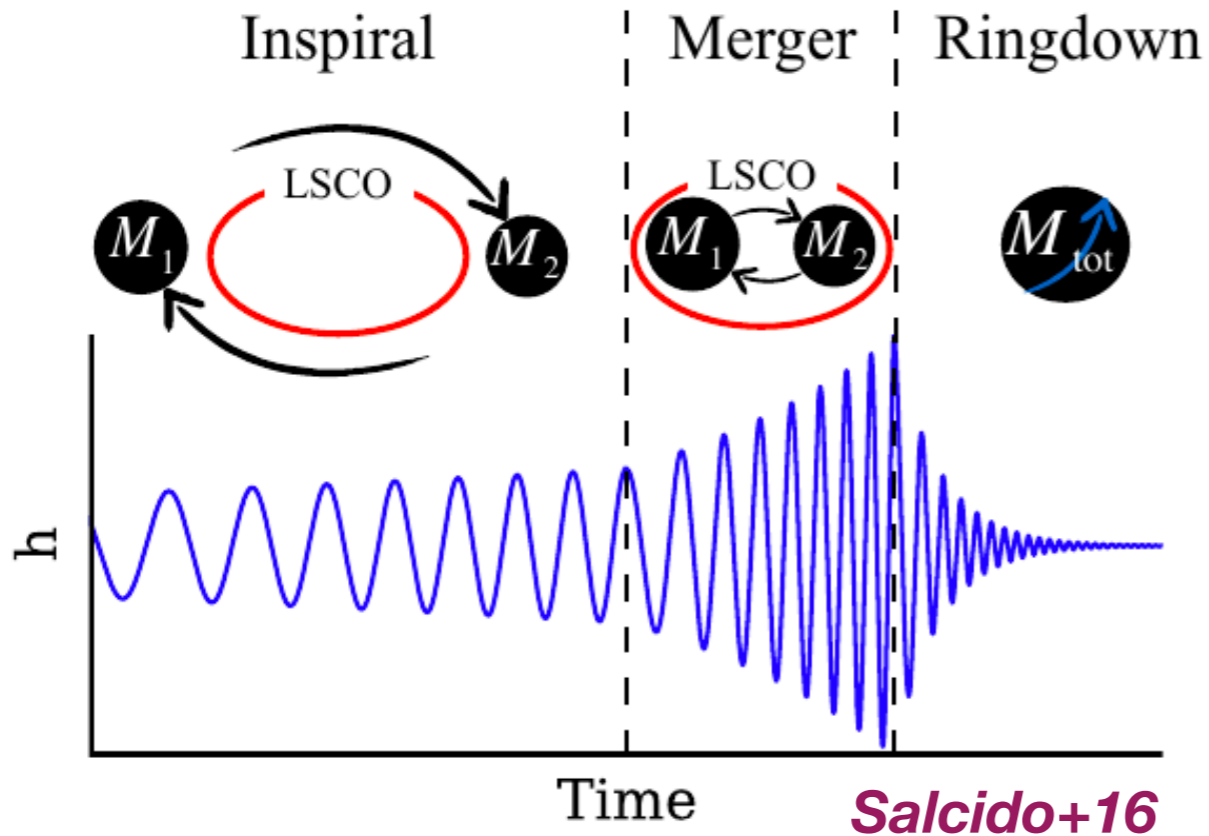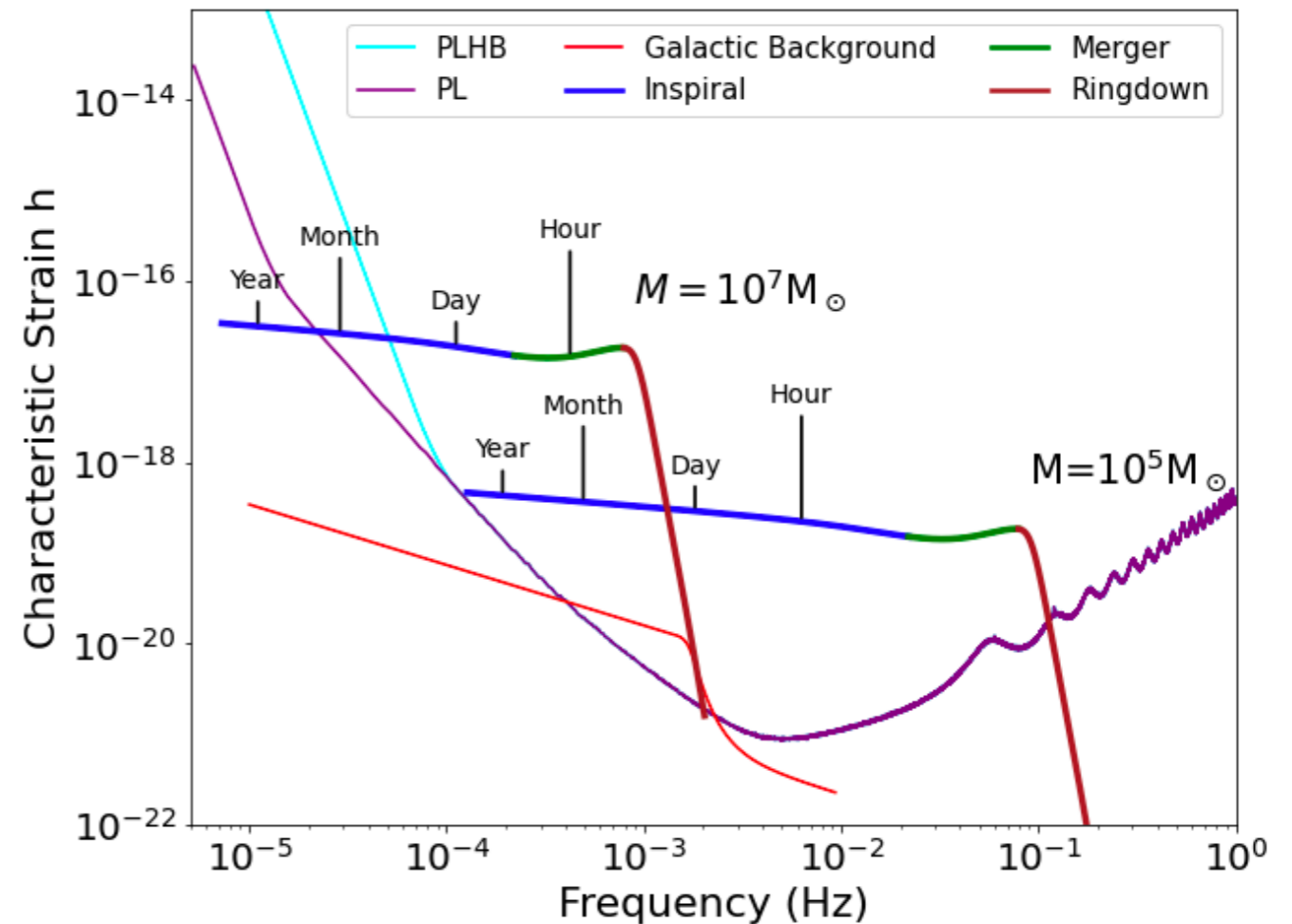# Black hole merger rate

up to 1% Gyr⁻¹ at z~0.8

Gravitational waves produced by BH merger

Inspiral Merger Ringdown

LSCO

LSCO

M_1 M_2

M_1 M_2

M_{tot}

h

Time

Salcido+16

**Different phases
of BH merger**

Redshift *z=1* - BH masses *$M_1=M_2$*

PLHB	Galactic Background	Merger
PL	Inspiral	Ringdown

$M = 10^7 M_\odot$

$M = 10^5 M_\odot$

Characteristic Strain h

Frequency (Hz)

Year Month Day Hour

Month Hour

Year Day

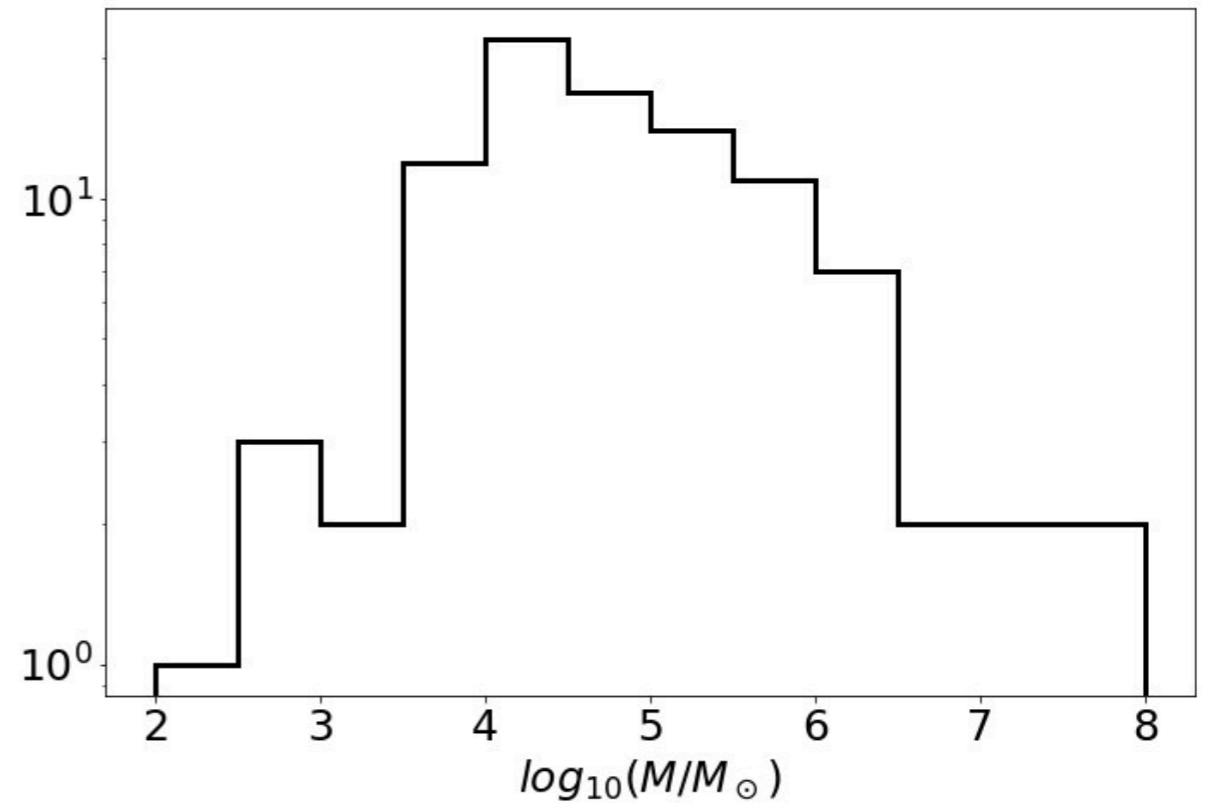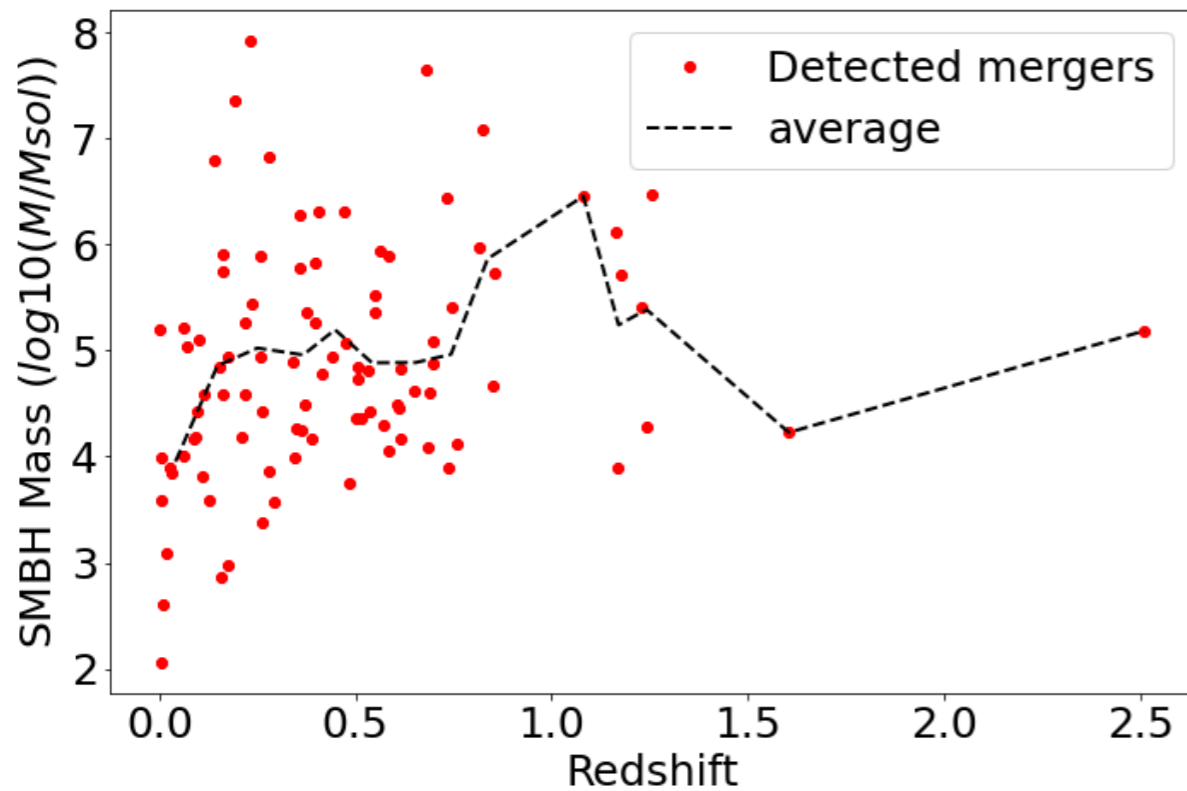using **BOWIE** analysis tool *(Katz & Larson 2018)*

LISA sensitivity

LISA detection rate of BH mergers

Most of the detections are at **redshift below ~1**

And for **~10^4-10^6 M$_{sun}$** BH masses

Perspectives

- **Increase samples of galaxy pairs** to reduce uncertainties, especially cosmic variance —> **x10 expected in the next 2 years** thanks to MUSE-GTO

- Improve our knowledge of **black hole in low-mass (dwarf) galaxies**

  - Demography —> scaling relations (M_{BH} vs. M^*)

  - BH merger timescale?

- Predict the **number of events detected by LISA over the mission lifetime**