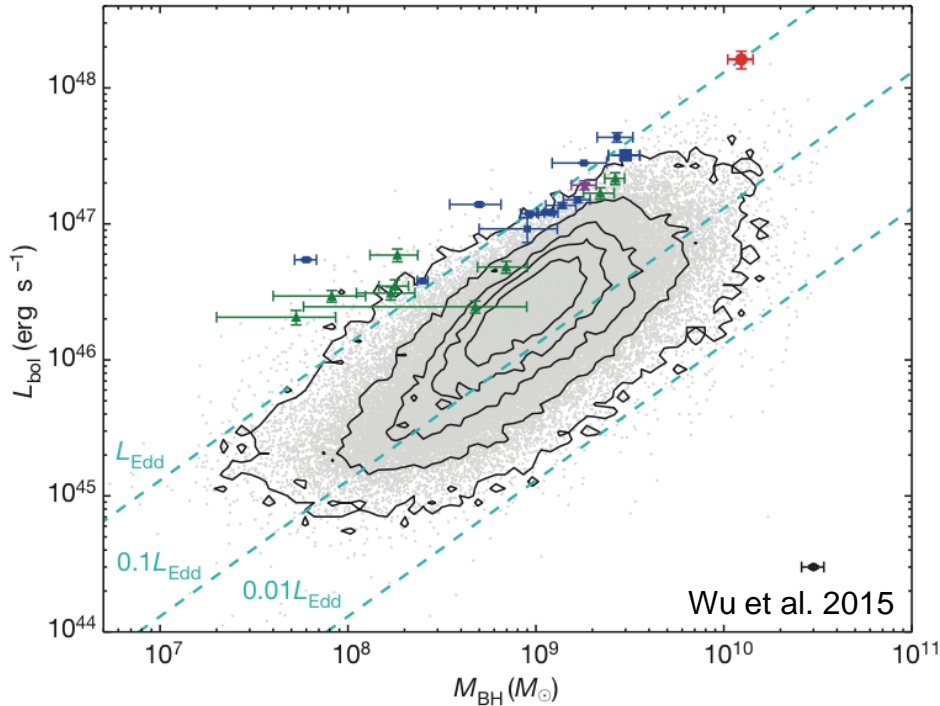


Gravitational waves as probes of massive black hole evolution

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Massive black holes in the Universe



Powering quasars as
luminous as $L \sim 10^{11} - 10^{13}$
 L_{sun}

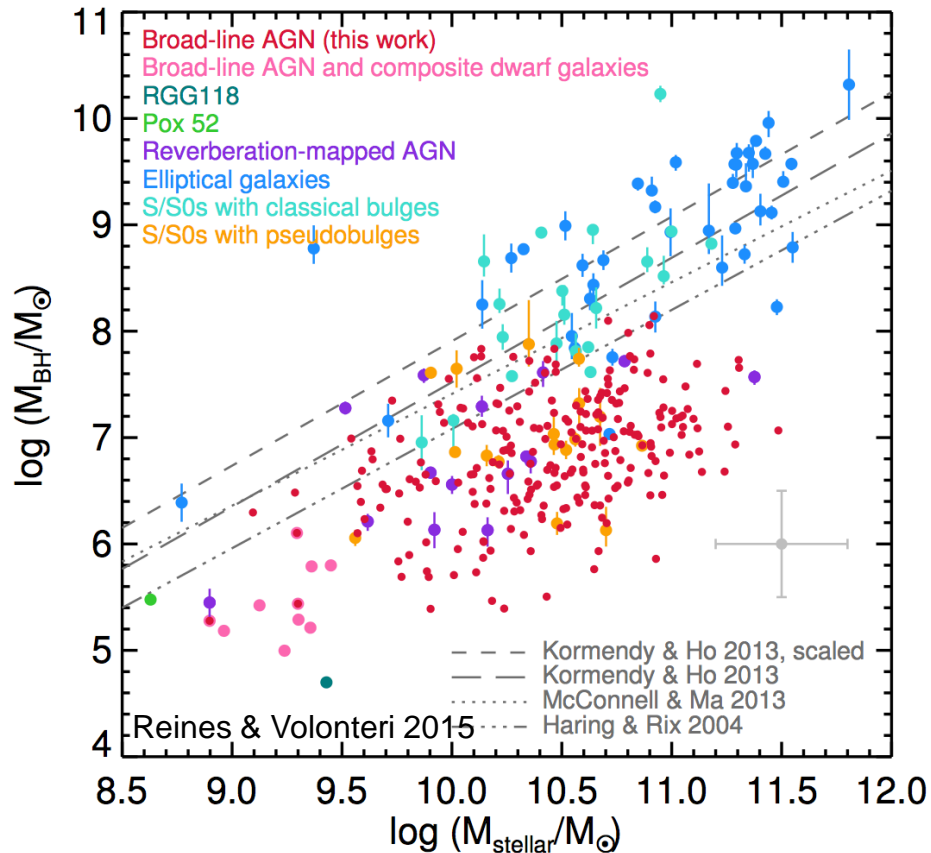
The engines are accreting
black holes with masses up
to several billions of M_{sun}

... and down to $< 10^6 M_{\text{sun}}$
in faint AGN



POX 52, Kunth+87, Barth+04, Thornton+08

Massive black holes in the Universe



~100 massive black holes detected in nearby galaxies to-date

Black hole mass scales with galaxy mass: $\sim 10^{-3}-10^{-4} M_{\text{gal}}$

Massive black holes as GW emitters

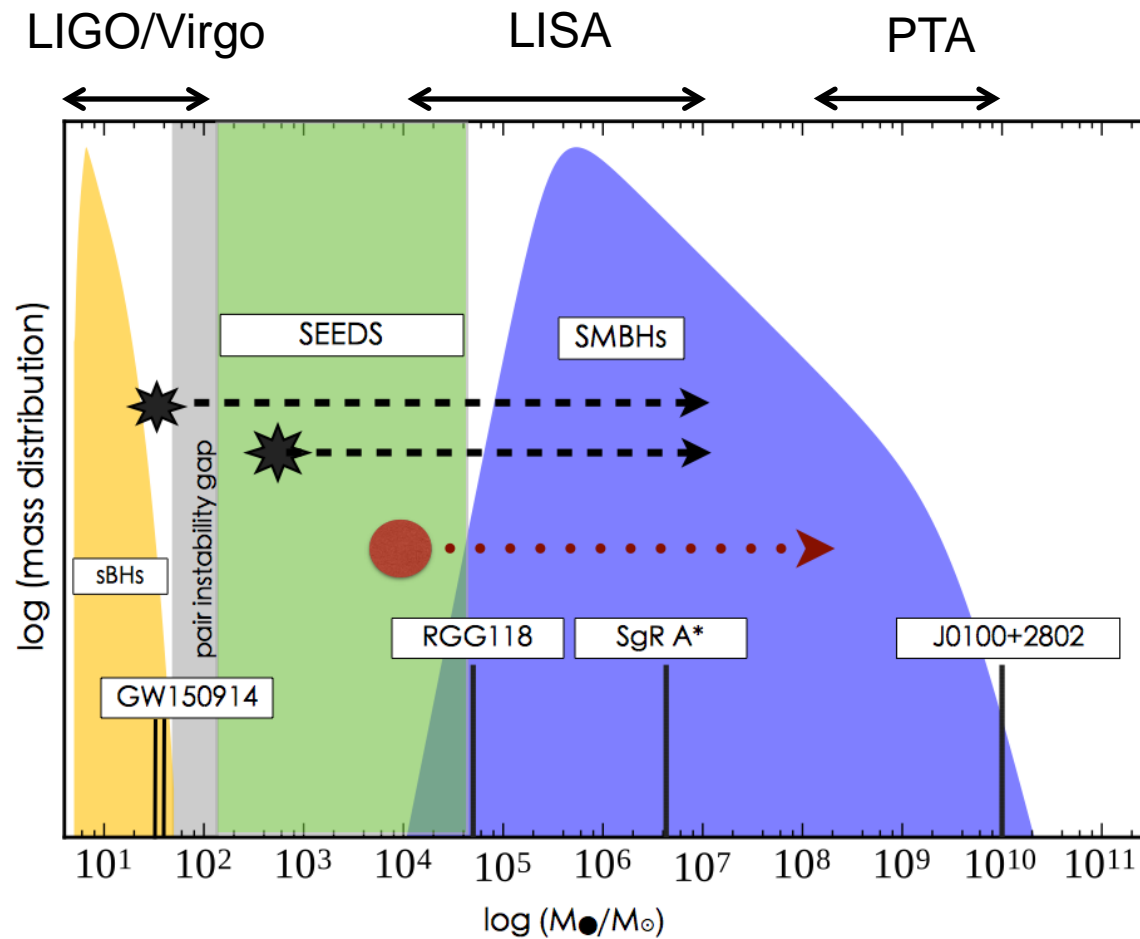
$$f \sim \frac{c}{2\pi R_s} \sim 10^4 \text{ Hz} \frac{M_\odot}{M}$$

10 M_{sun} binary: $f < 10^3$ Hz LIGO/Virgo inspiral/merger

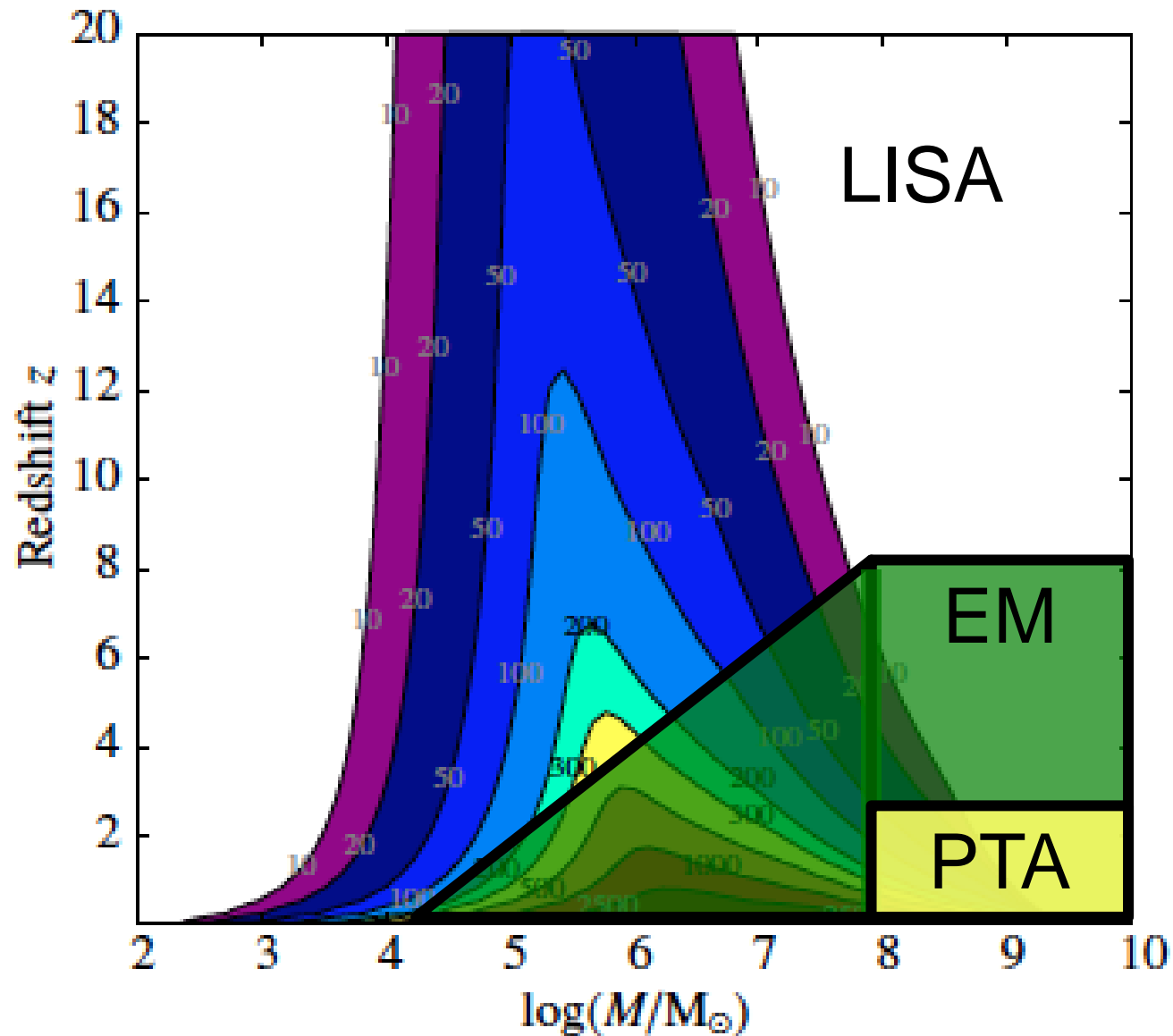
$10^6 M_{\text{sun}}$ binary: $f < 10^{-2}$ Hz LISA
inspiral/merger

$10^9 M_{\text{sun}}$ binary: $f < 10^{-6}$ Hz PTA
inspiral+bkg

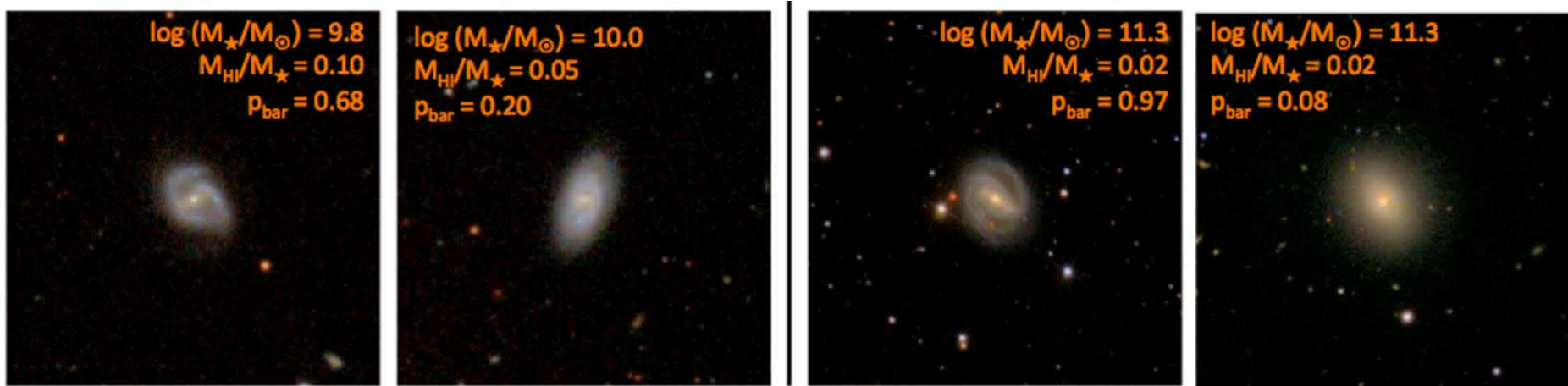
Massive black holes as GW emitters



Massive black holes as GW emitters



Massive black holes in galaxy mergers



High-mass galaxies \leftrightarrow Gas poor galaxies

High mass galaxies \leftrightarrow High-mass MBHs

Massive black holes in galaxy mergers

- High-z and small galaxies: gas is important
- Low-z and large galaxies: star-dominated
- Different dynamical evolution (see Monica's talk)
- Different gravitational-wave probes (LISA, PTA)

LISA and the cosmic evolution of massive black holes

Detect massive black holes up to the highest redshifts

Probe a mass range inaccessible through EM observations

PTA probes the cosmic evolution of massive black holes in a way complementary to LISA

Whether the most massive black holes build-up by mergers

Constrain merger timescales

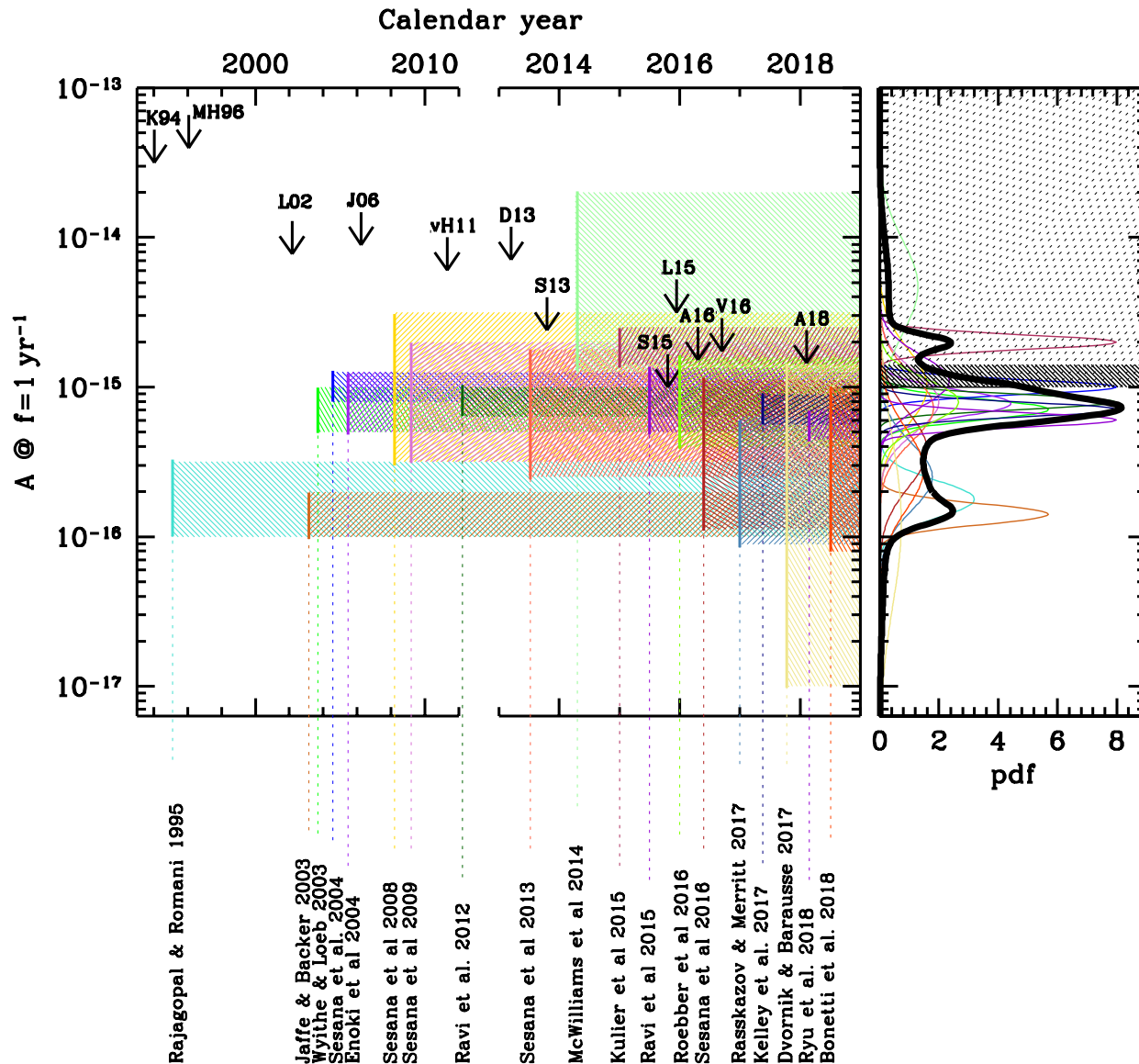
What can GWs do for MBHs?

What can we infer about the black hole population from the full set of events observed by LISA or the PTA background?

Use observed distribution of source parameters to compare with models. Which model provides the better explanation of the data?



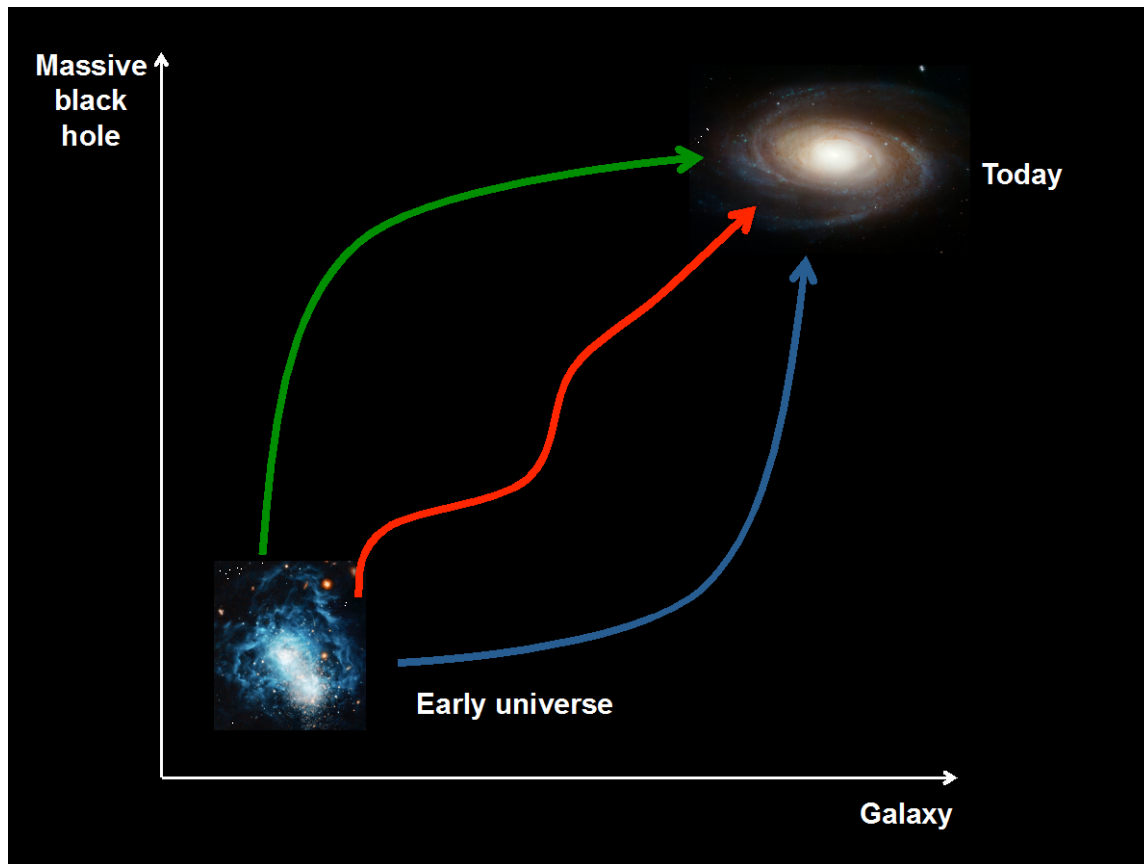
What can GWs do for MBHs?



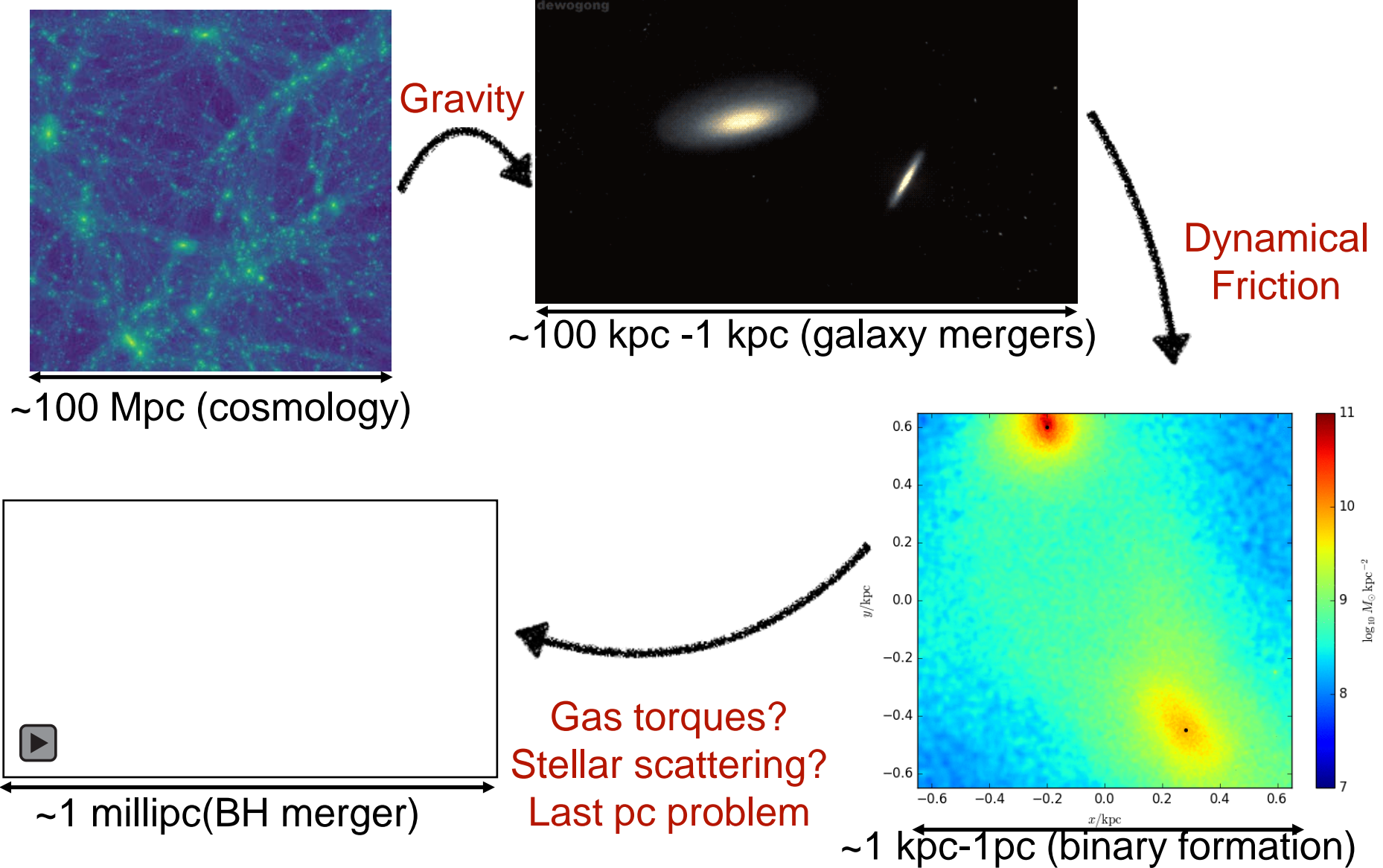
Courtesy of A. Sesana

Massive black holes in galaxies

Massive black holes should naturally grow along with galaxies through accretion and MBH-MBH mergers and influence the galaxy through feedback



The journey of two black holes



Massive black hole mergers and GWs

How many galaxies host MBHs

→ when, where, how they form

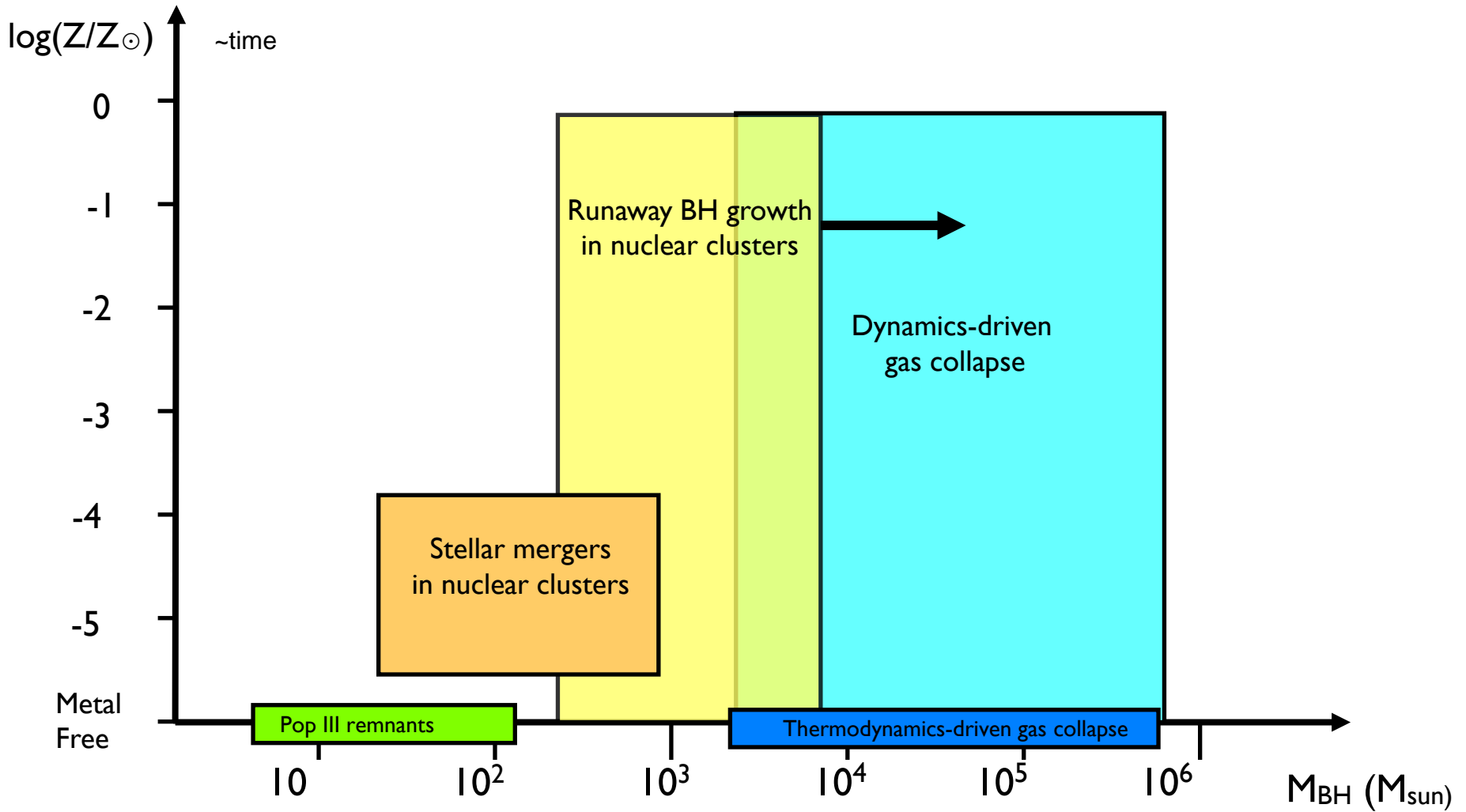
How long it takes for MBHs to merge in halo/galaxy merger

→ dynamics of MBHs in mergers

How MBHs grow in mass over time

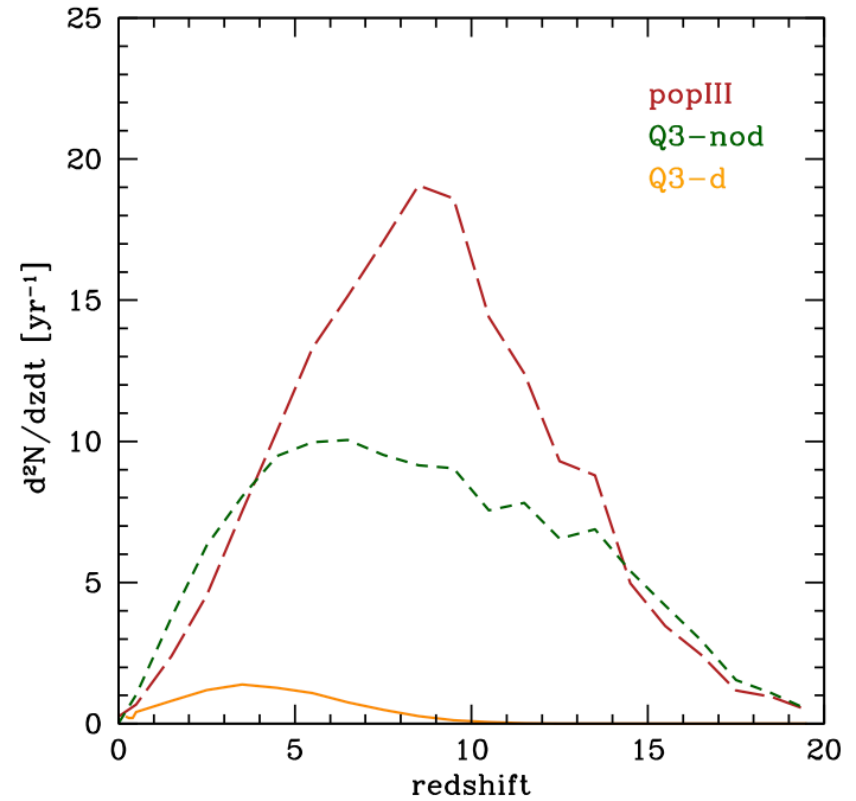
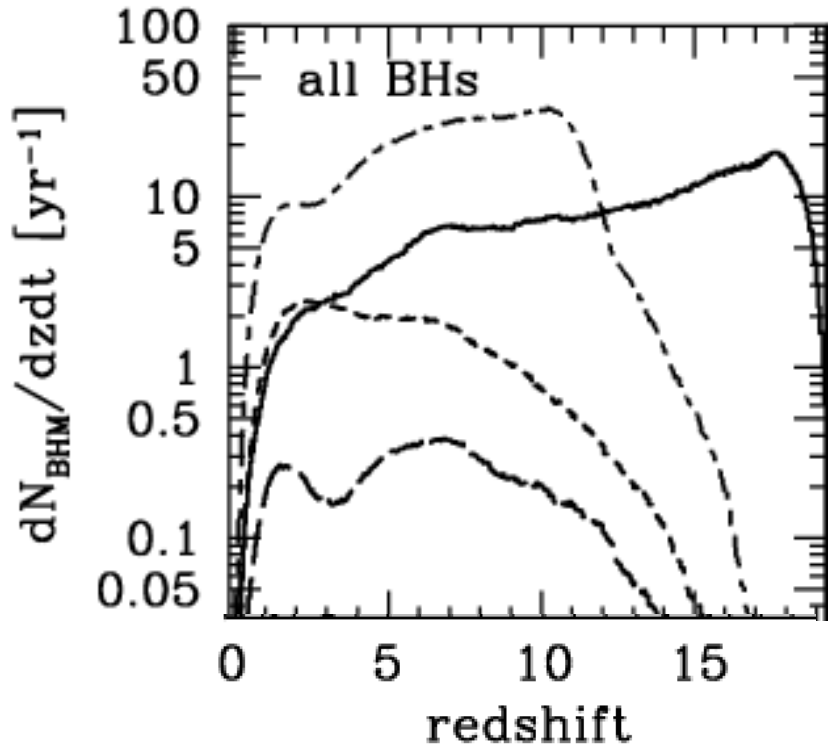
→ accretion vs MBH-MBH mergers

Massive black hole formation



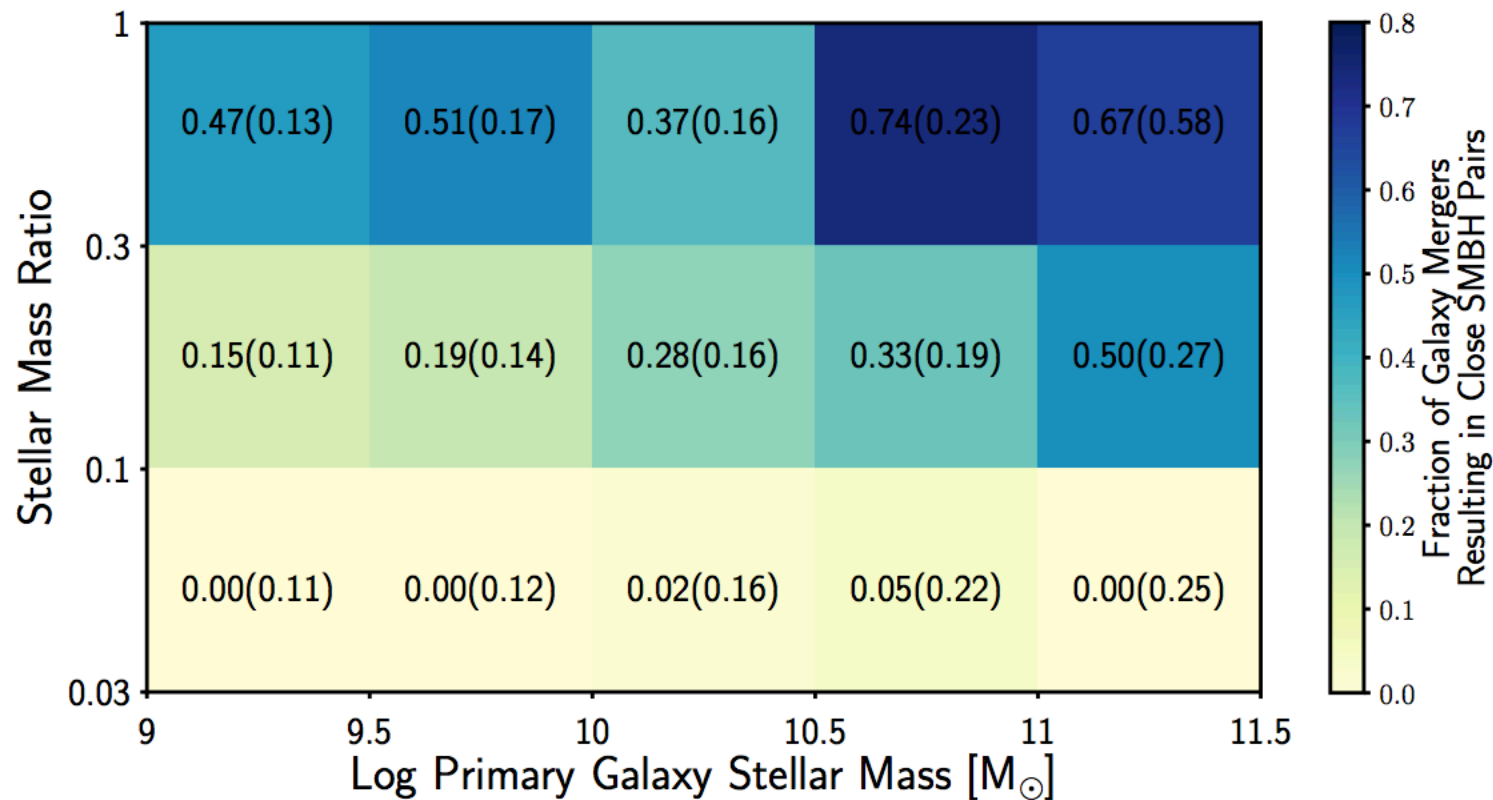
Common \longrightarrow Rare

Massive black hole formation

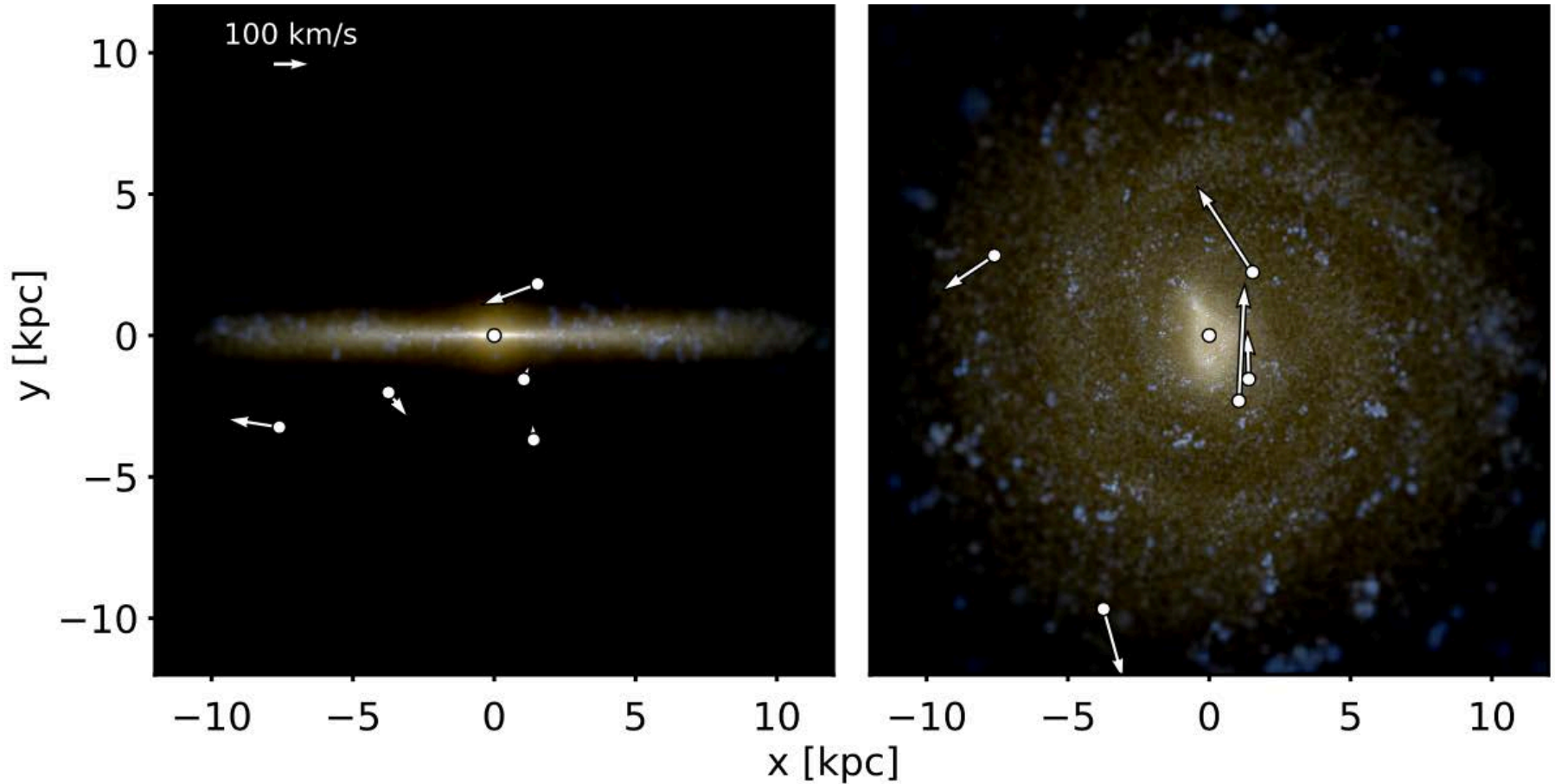


Can stellar mass BHs
become massive?!?!

Massive black hole dynamics – galaxy scale

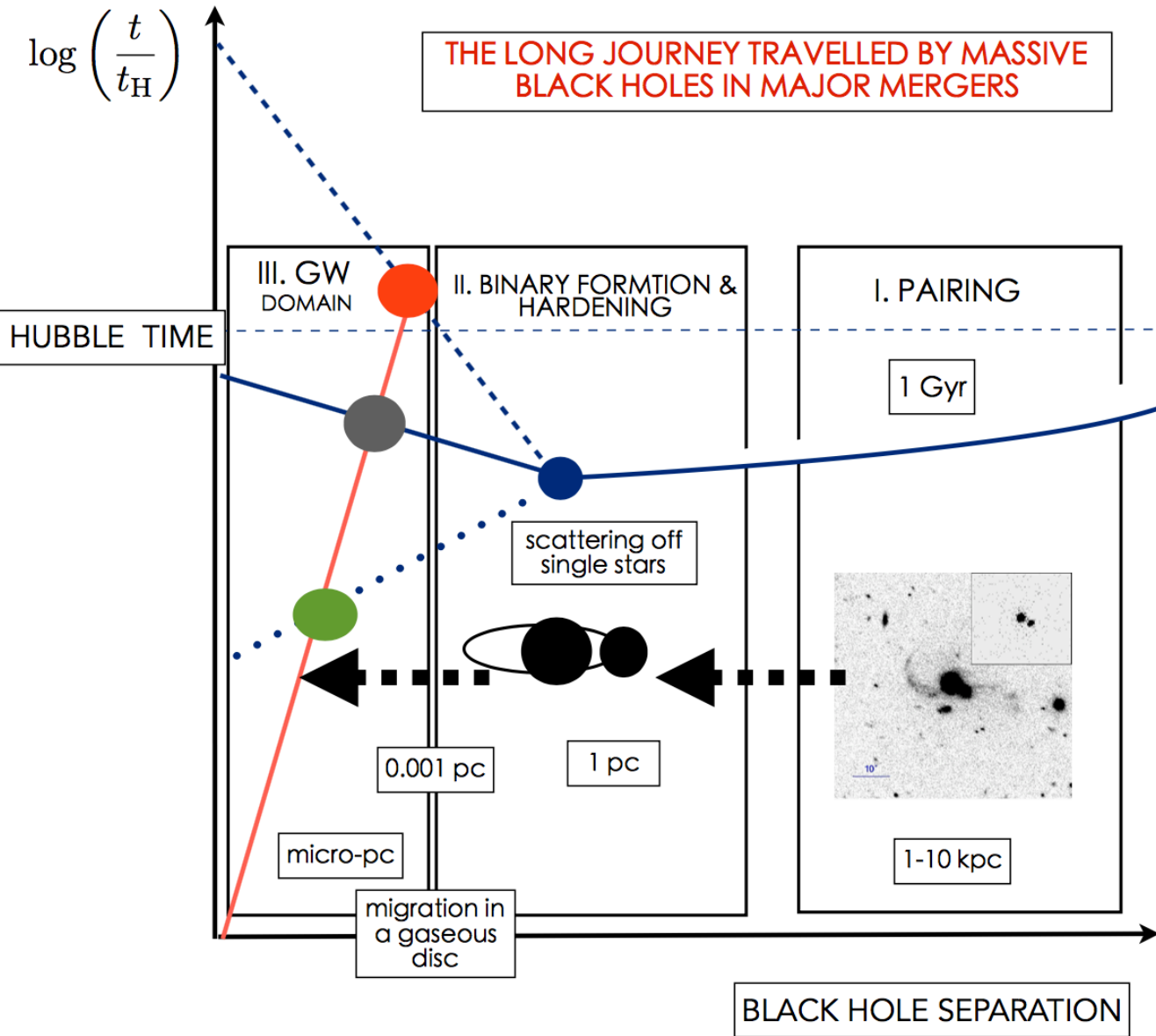


Wandering black holes



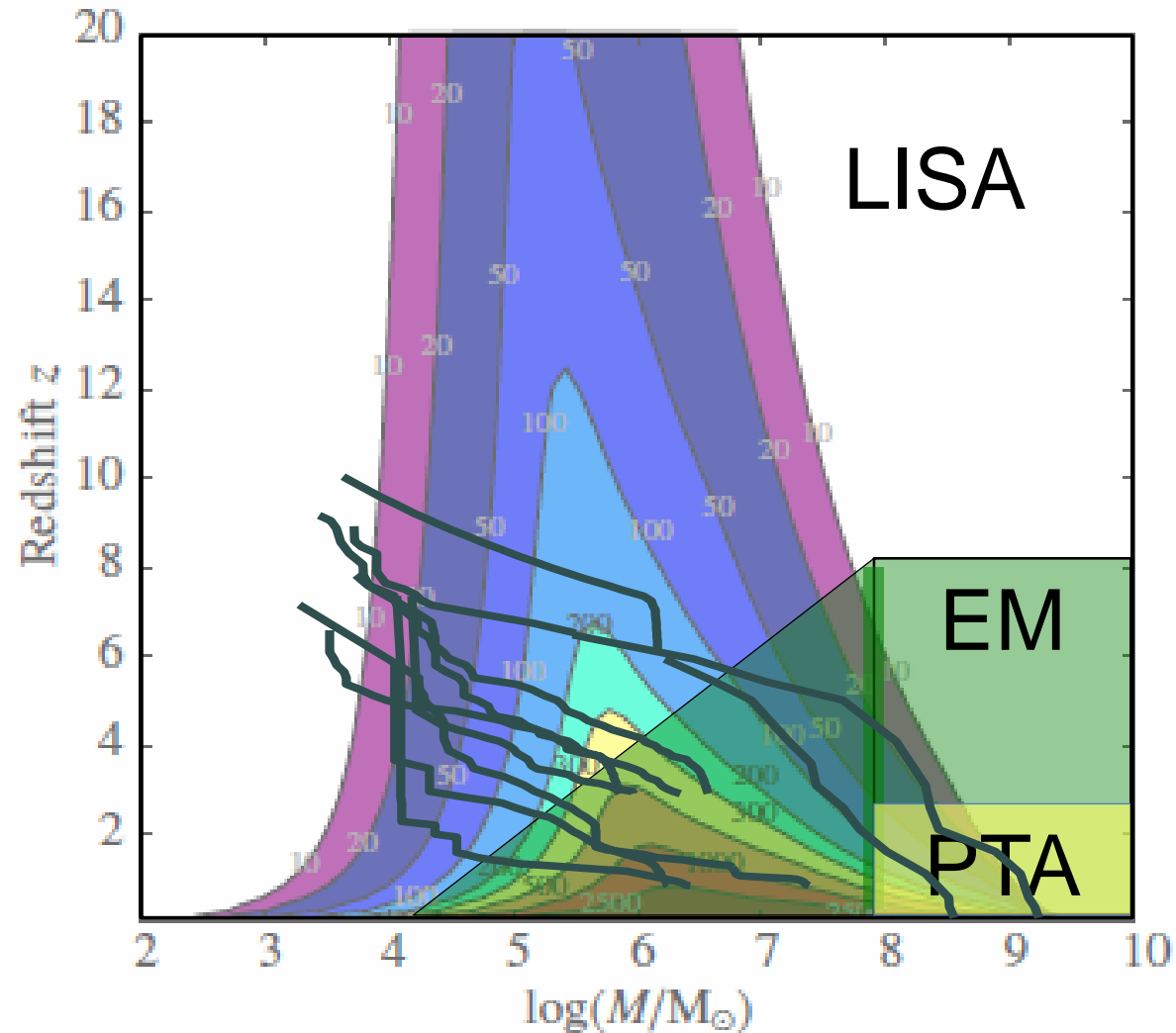
Tremmel+ 2018
Governato+94; Schneider+02;
Volonteri+03, 05; Bellovary+10

Massive black hole dynamics – further

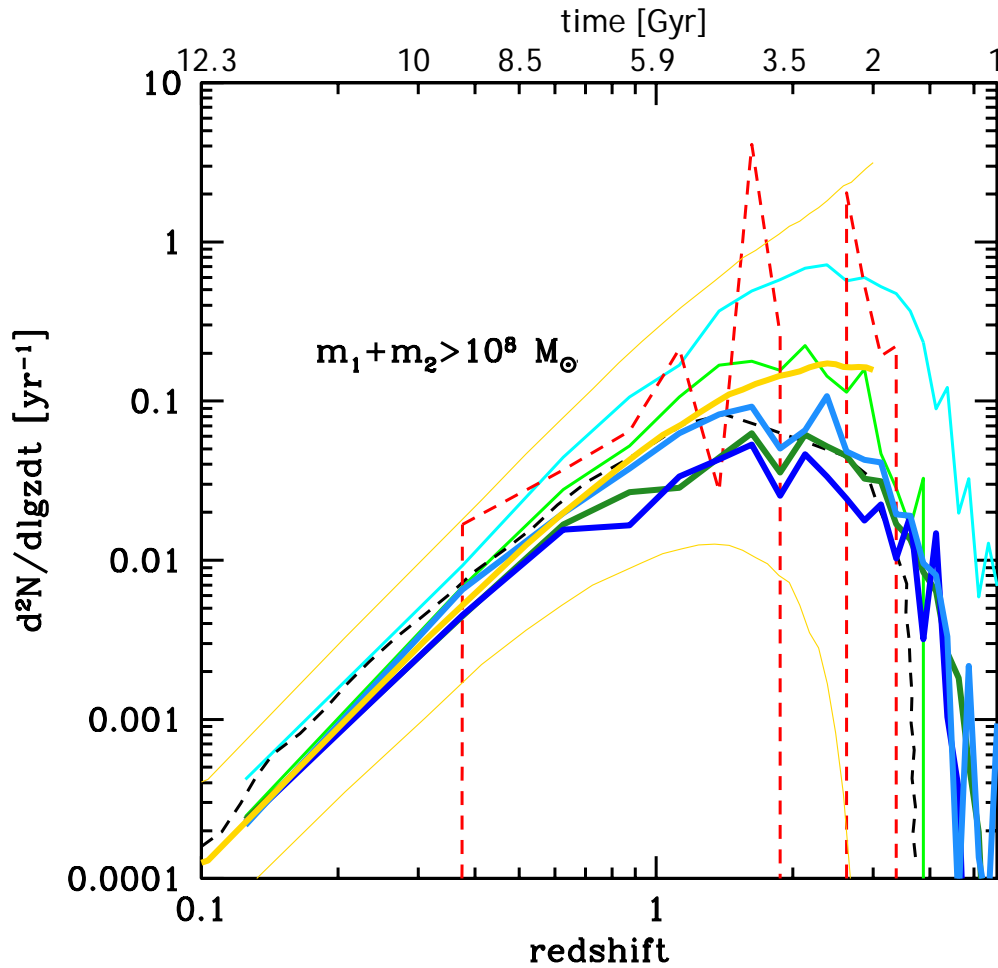


see Monica's talk

Tracking massive black hole growth



PTA pseudo merger rate



SAMs:

Barausse+ ($M_h > 10^5 - 10^6 M_{\text{sun}}$)

MV, Sesana+ ($M_h > 10^5 - 10^6 M_{\text{sun}}$)

cyan, light blue, blue: large BH seeds

light green, dark green: small BH seeds

SIMs:

Blecha+ (Illustris, $M_h > 1.4e11 M_{\text{sun}}$)

Tremmel+ (Romulus, $M_h > 3.5e8 M_{\text{sun}}$)

Empirical:

Sesana+13

Number of mergers per year: between 0.03 and 0.09

Summary

MBHs in merging galaxies have a long journey: beginning to end, it takes between 1 and 10 Gyr with large uncertainties

Full “merger rate” predictions still have large uncertainties – be careful when you pick a merger rate!

Turning this around, GWs are a unique way of probing MBH evolution

Best and cleanest way to find the first MBHs!

Will know about MBH dynamics!

