Massive black hole binaries in the cosmos

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BLACK

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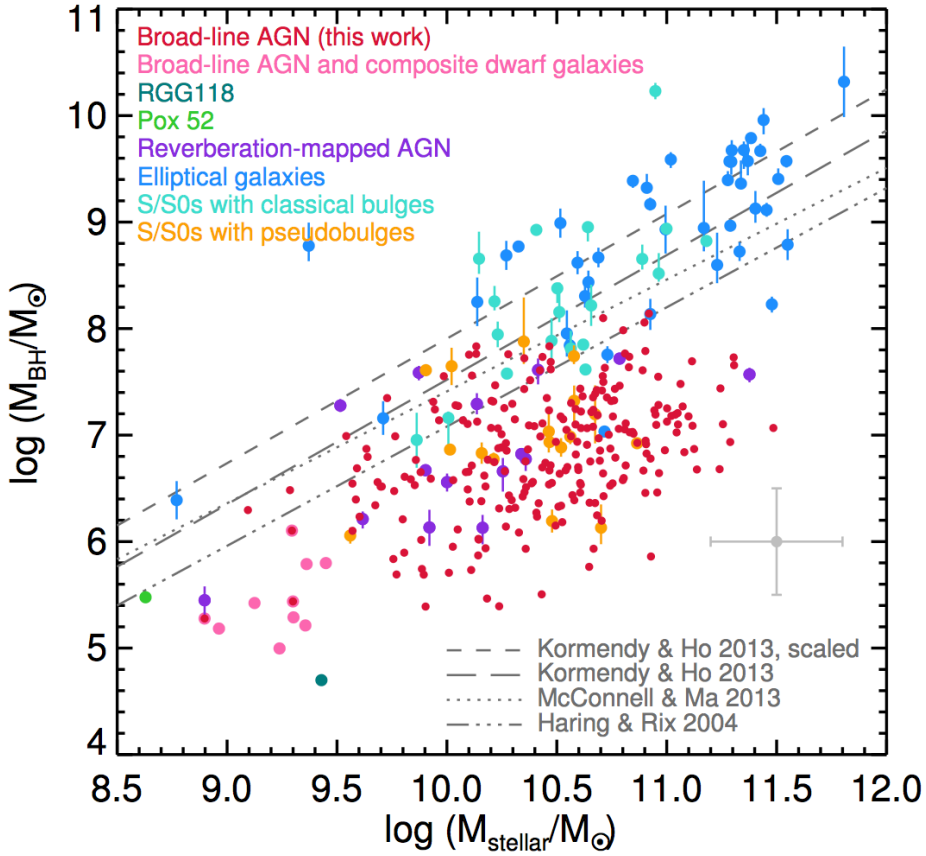
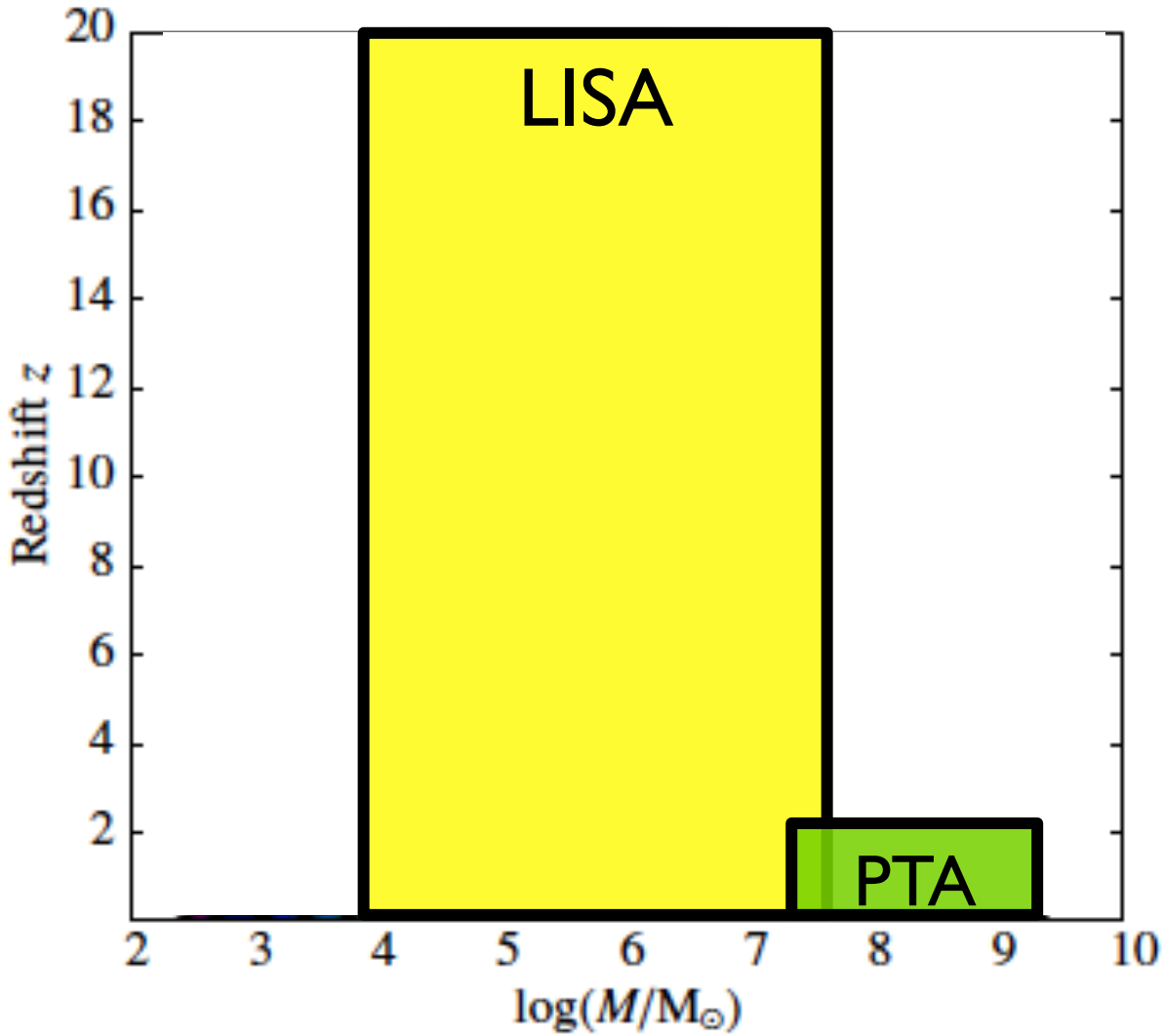
Massive black holes in galaxies

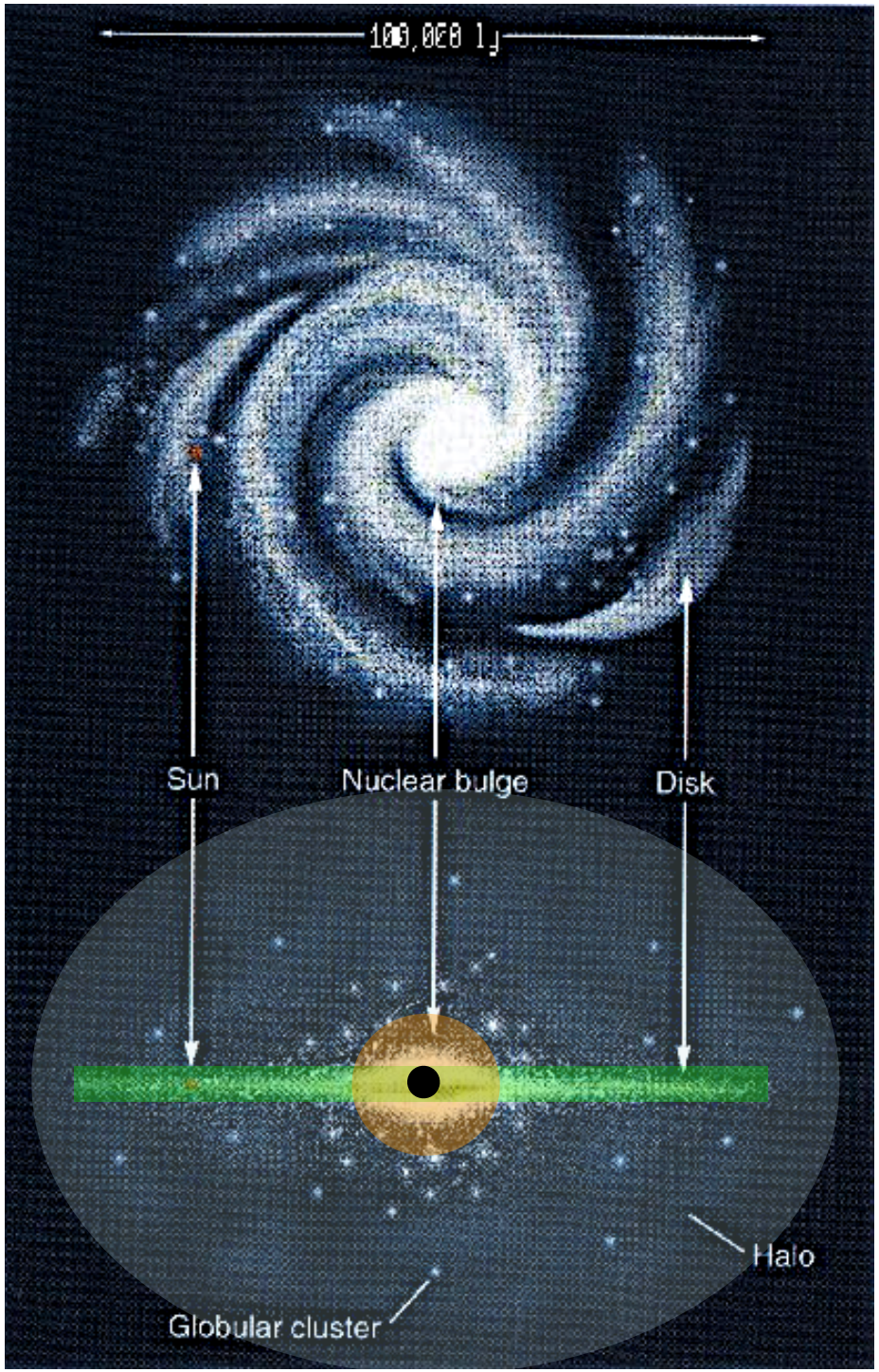


~100 MBHs detected in nearby galaxies to-date

Black hole masses scale with galaxy mass: ~10^{-3}-10^{-4} M_{gal}

MBHs mergers and gravitational waves





Galaxies

mass: 10^9-10^{12} M_{sun}

$R_{halo} \sim GM_{halo}/\sigma^2$ MEGAPARSEC

$R_{bulge} \sim GM_{bulge}/\sigma^2$ KILOPARSEC

1 parsec=3.26 light years=3×10^{18} cm
σ ~50-400 km/s for most galaxies

Massive Black Holes

mass: 10^5-10^9 M_{sun} ~ 10^{-3}-10^{-4} M_{gal}

$R_{bondi} \sim GM_{BH}/c_s^2$ PARSEC

$R_{inf} \sim GM_{BH}/\sigma^2$ PARSEC

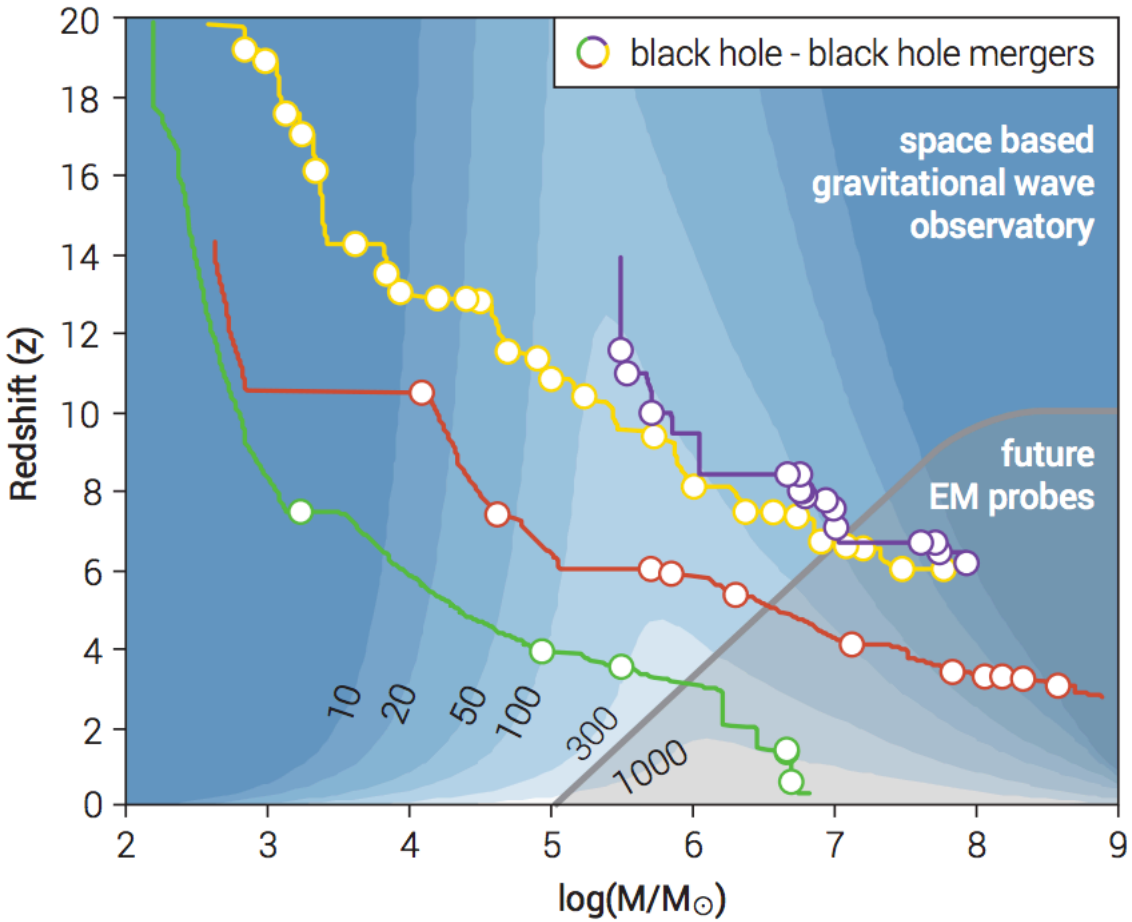
$R_{sch}=2GM_{BH}/c^2$ MICROPARSEC

c_s~10-100 km/s for most galaxies
$c=3\times10^5$ km/s

Massive black holes in galaxies

MBHs should grow along with galaxies through accretion and MBH-MBH mergers

Over time they sweep the LISA band, and if sufficiently massive, they become emitters for PTA experiments



What we need to predict a merger rate

How many galaxies host MBHs

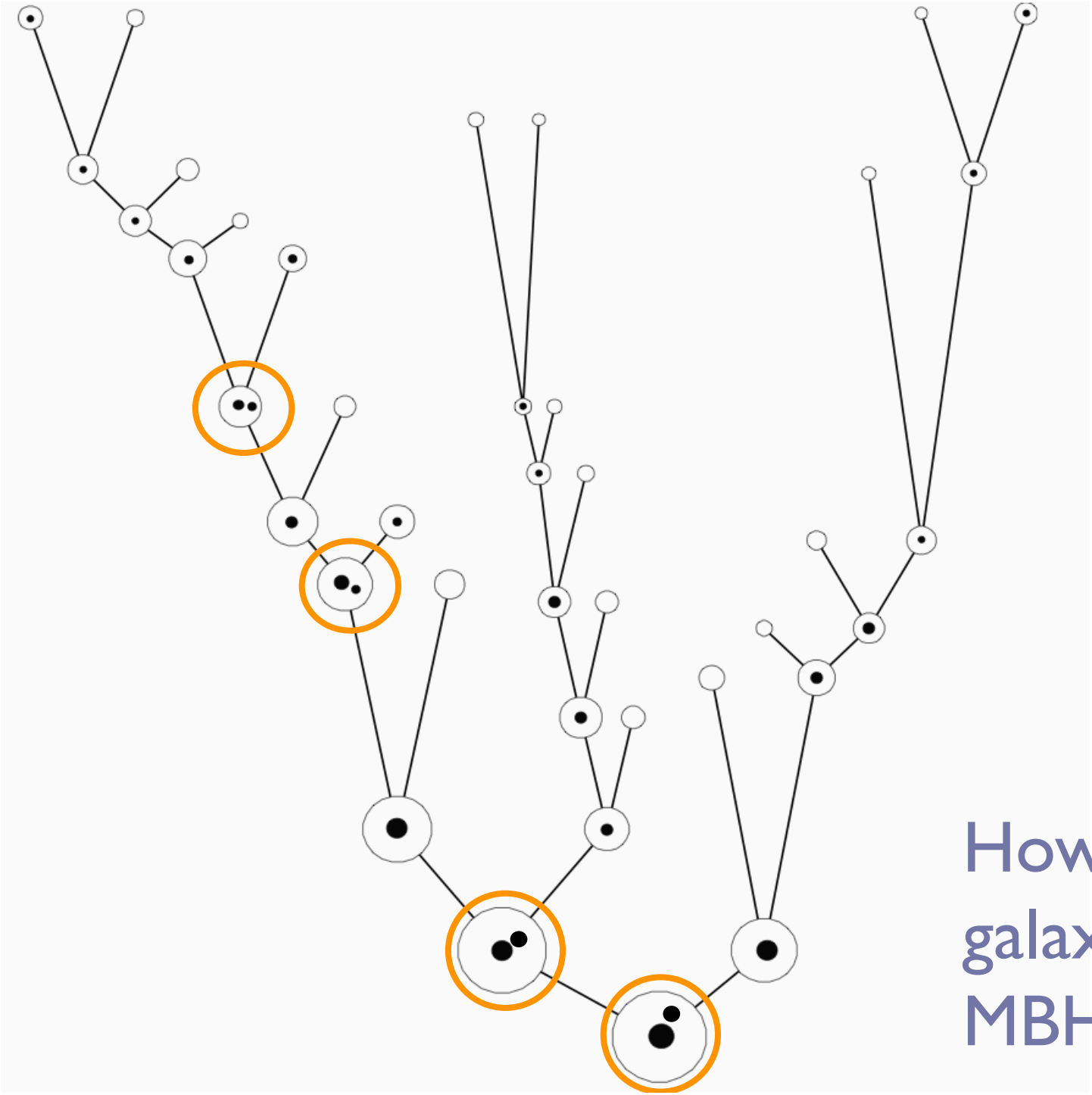
➔ when, where, how they form

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

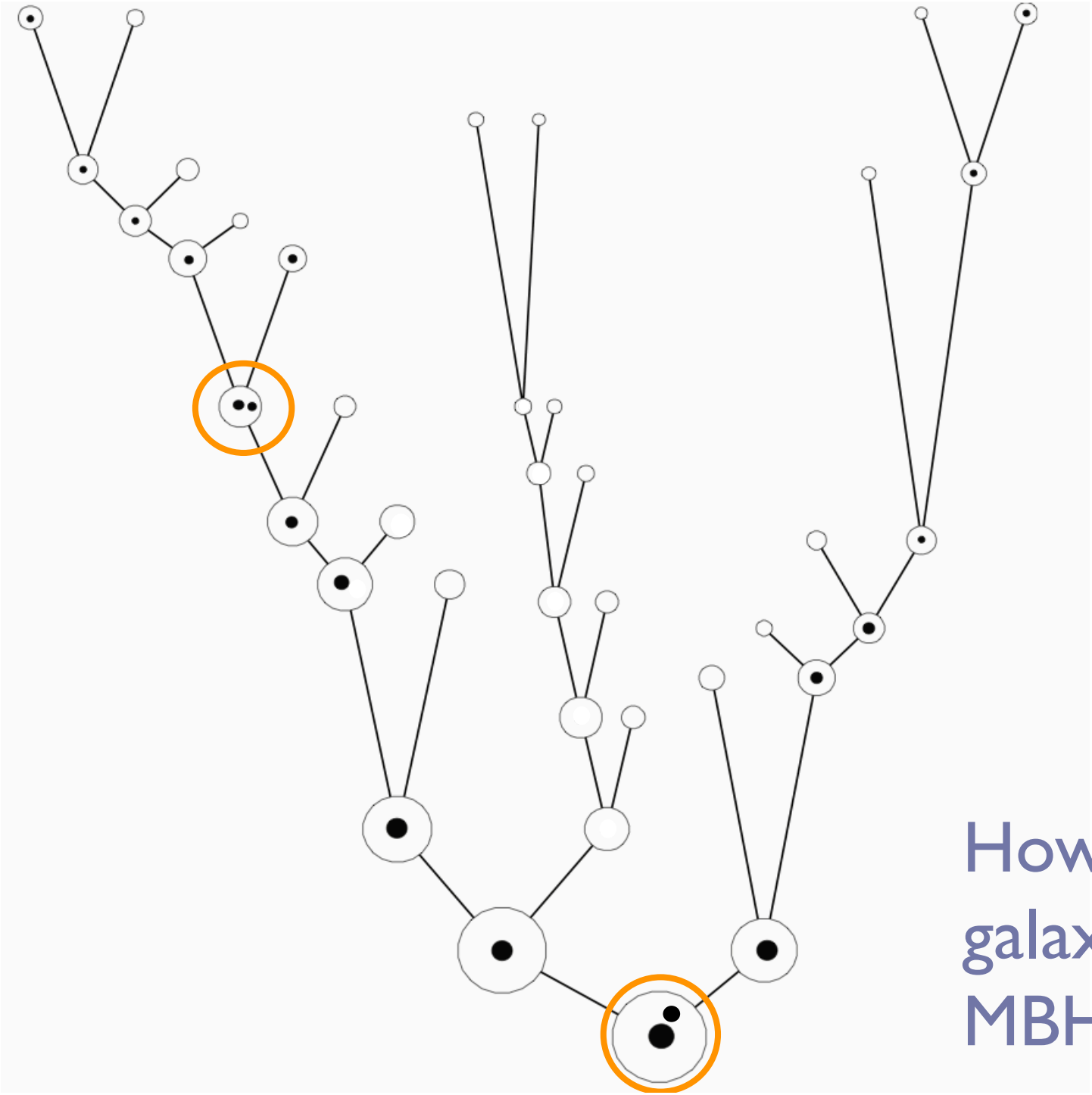
➔dynamics of MBHs in mergers

How MBHs grow in mass over time

➔accretion vs MBH-MBH mergers



How many galaxies host MBHs



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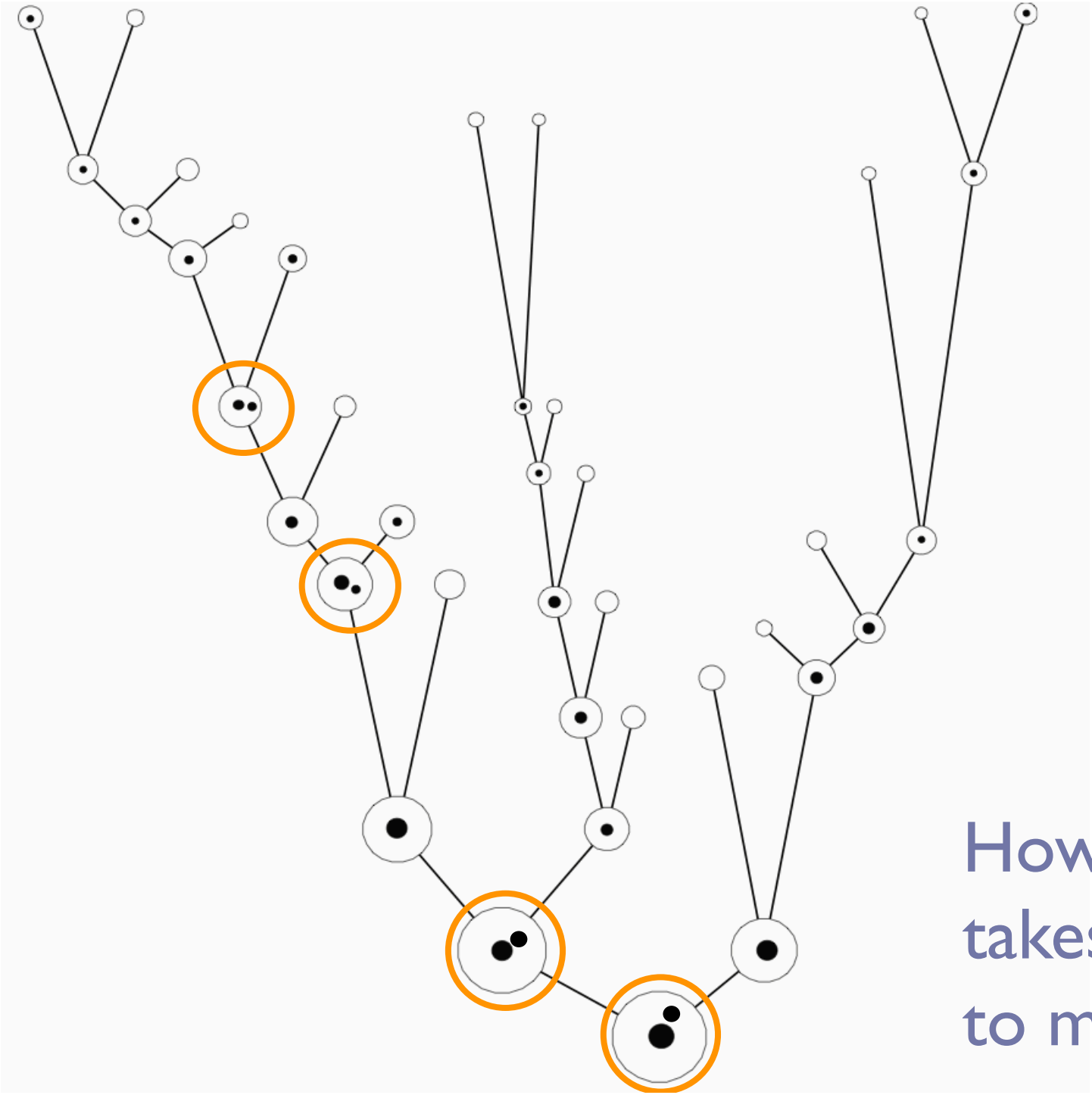
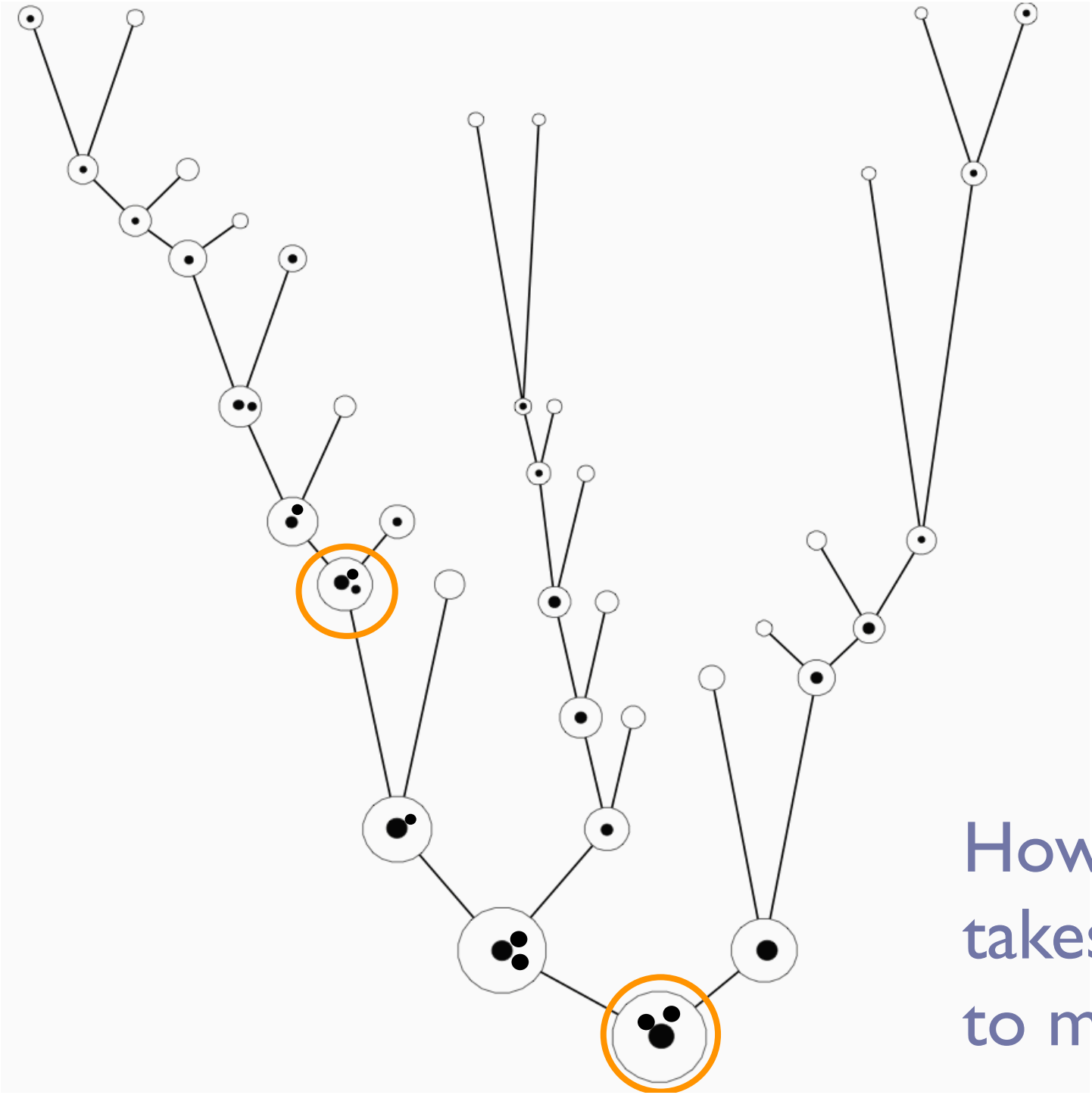


How long it takes for MBHs to merge



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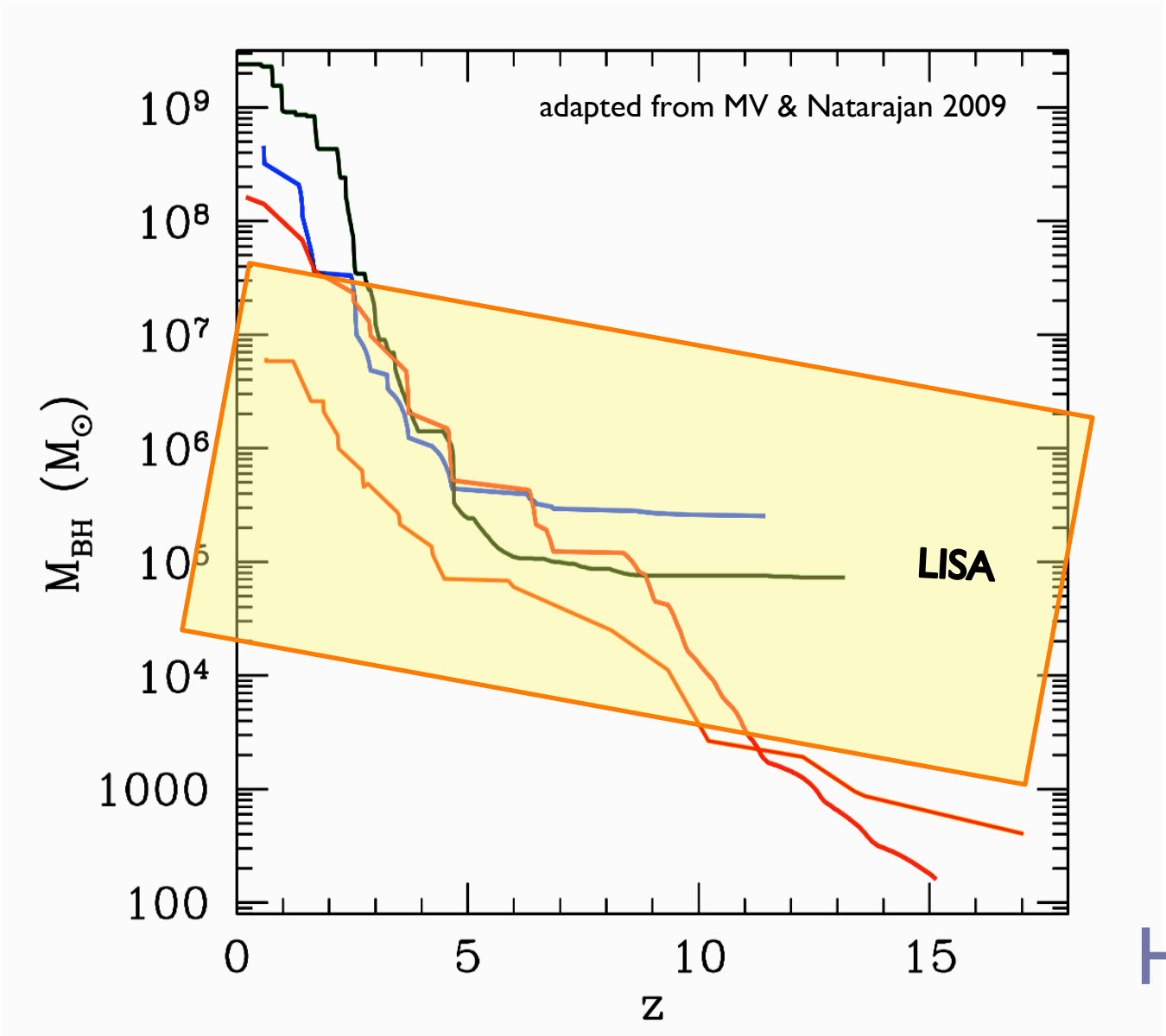
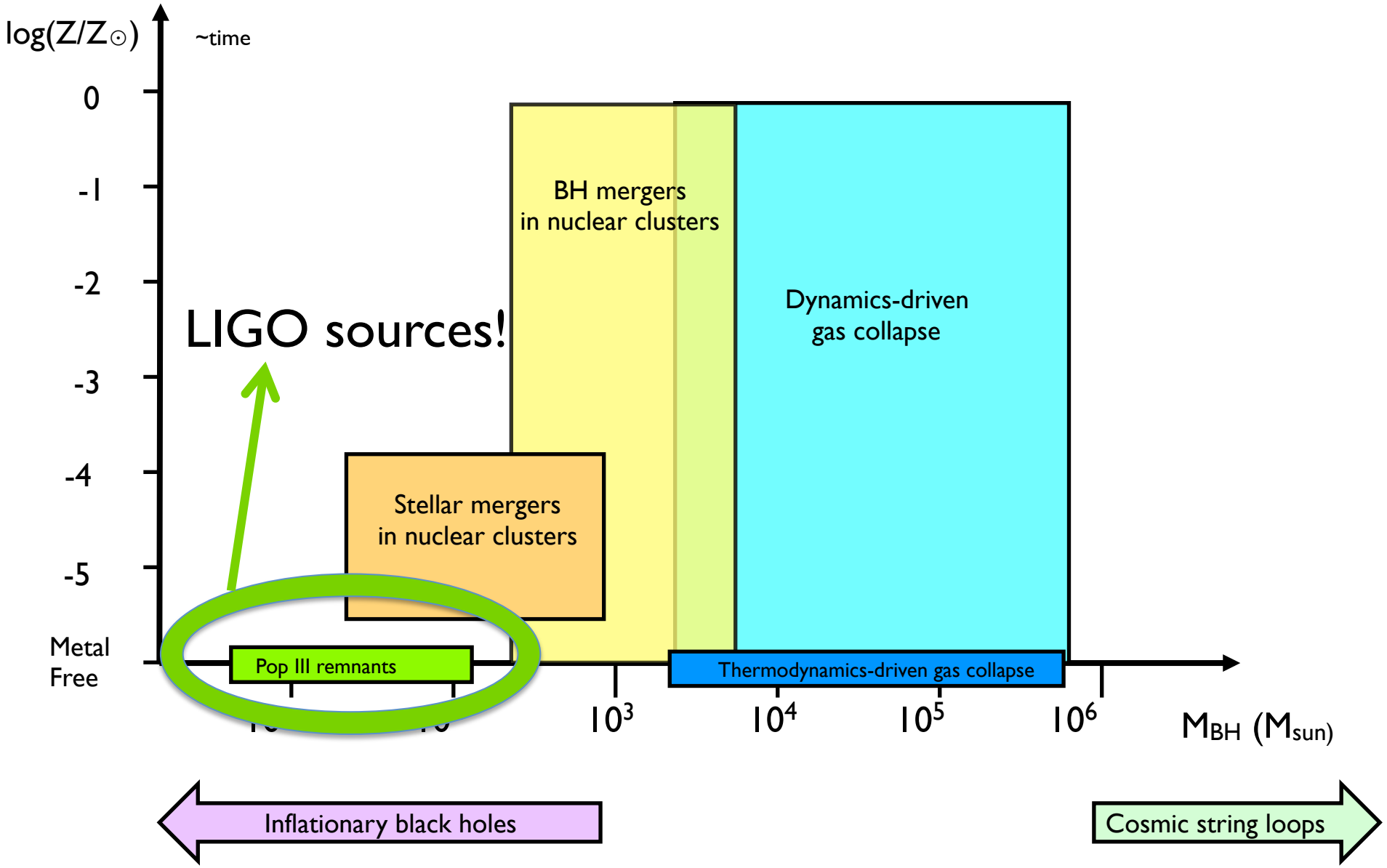


How MBHs grow in mass over time

Context: the cosmic merger rate

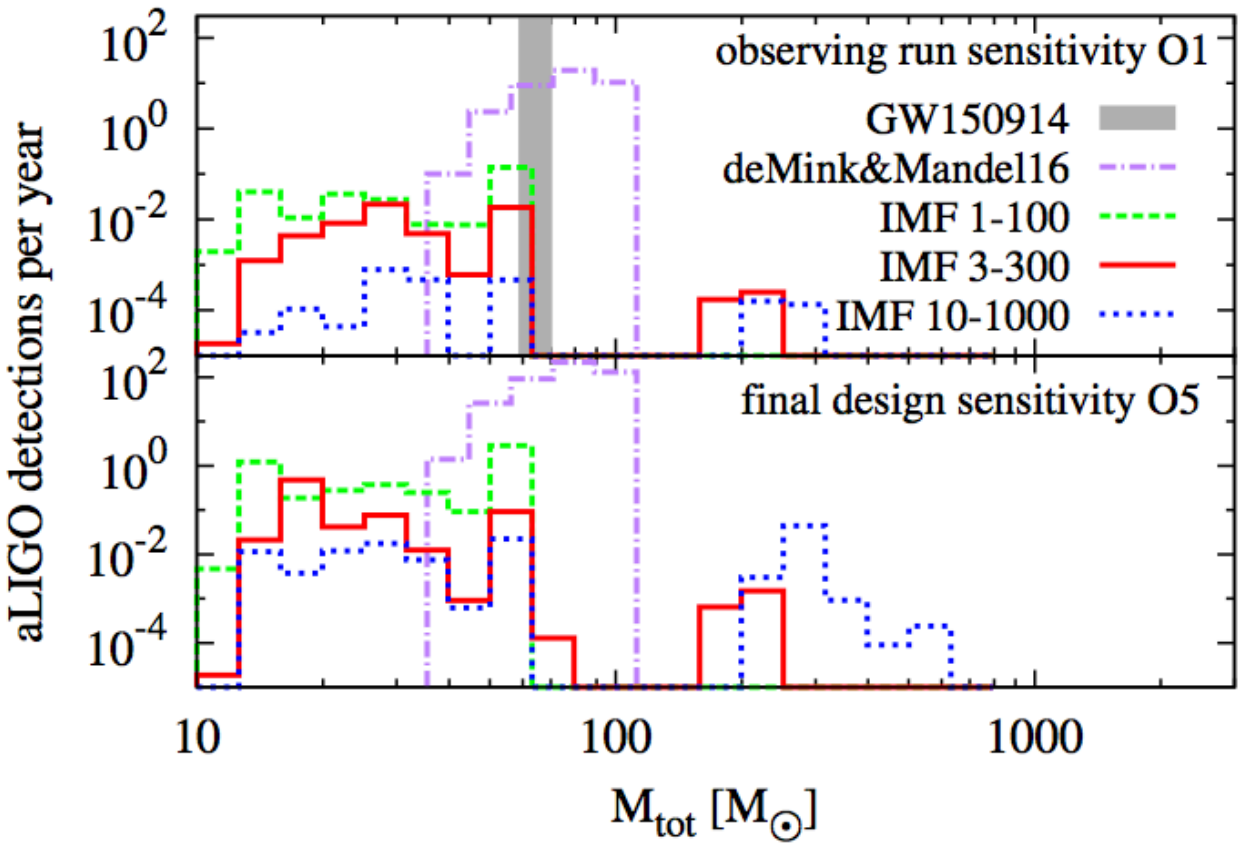
MBH formation



PopIII black holes: LIGO

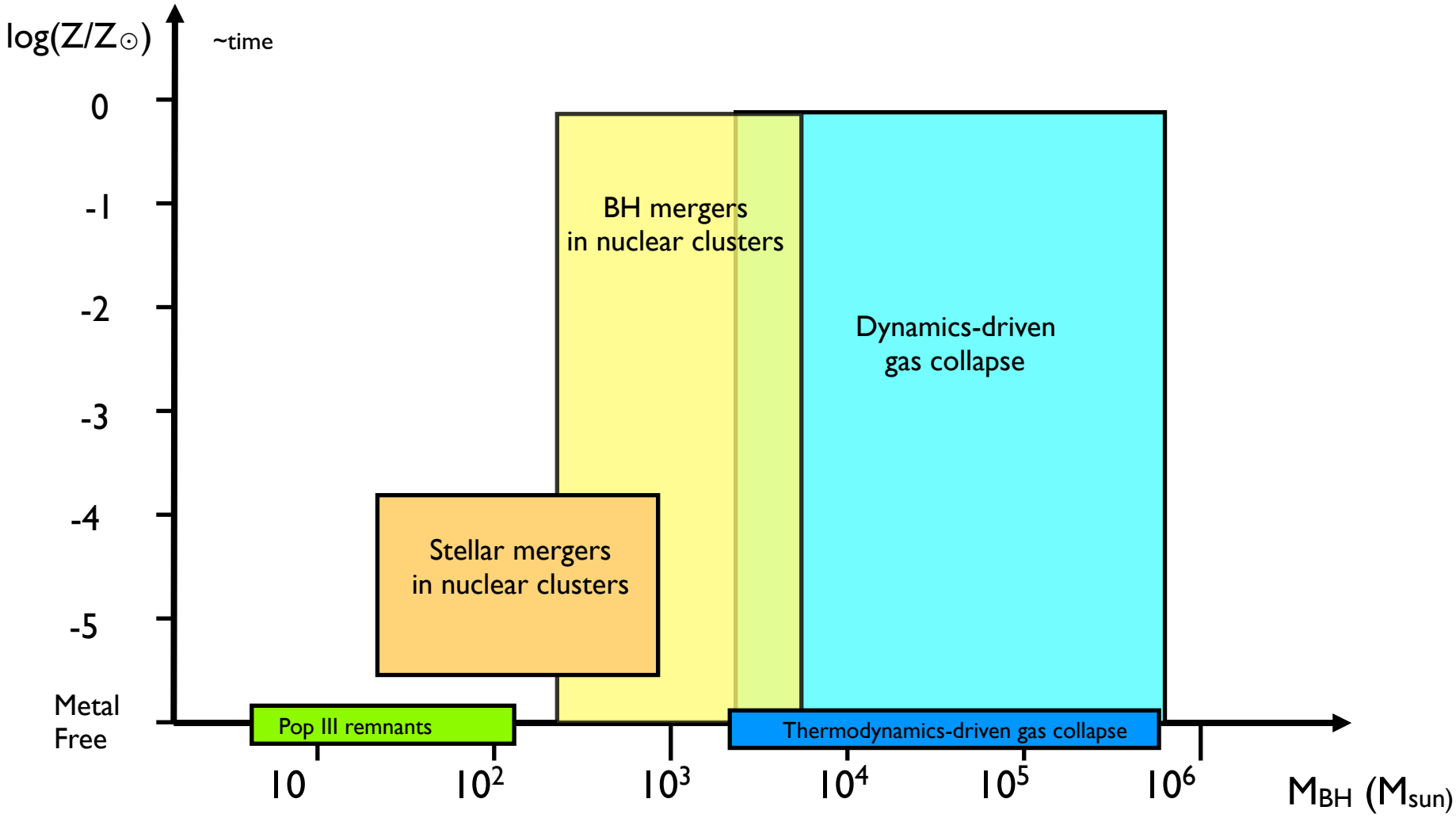
A fraction* of LIGO mergers are of primordial origin

(Kinugawa+14,16; Hartwig, MV+16; Inayoshi+16; Dvorkin+16)



* Yes, Chris, I agree with you

MBH formation



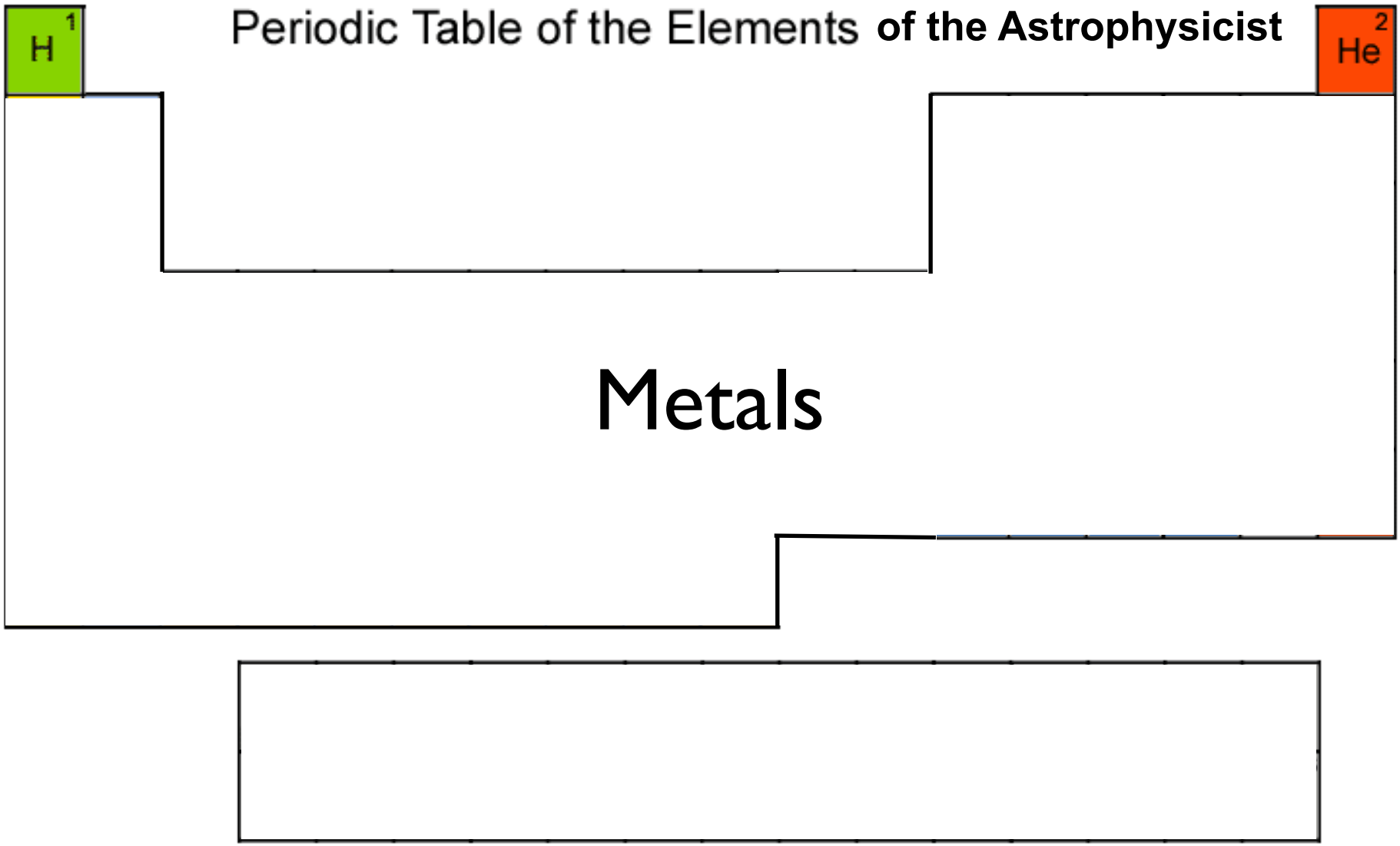
Common ⟶ Rare

Periodic Table of the Elements

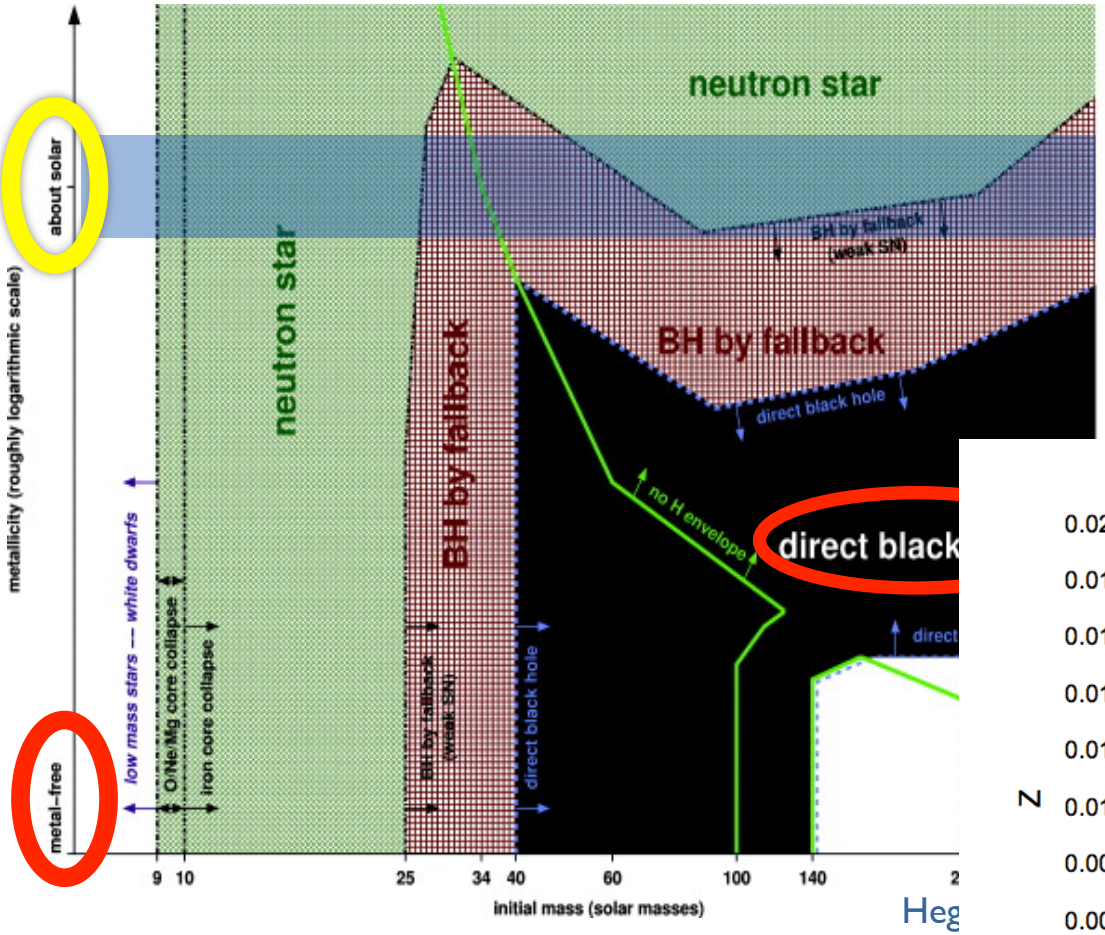
- hydrogen
- alkali metals
- alkali earth metals
- transition metals
- poor metals
- nonmetals
- noble gases
- rare earth metals

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Unq	105 Unp	106 Unh	107 Uns	108 Uno	109 Une	110 Unn								

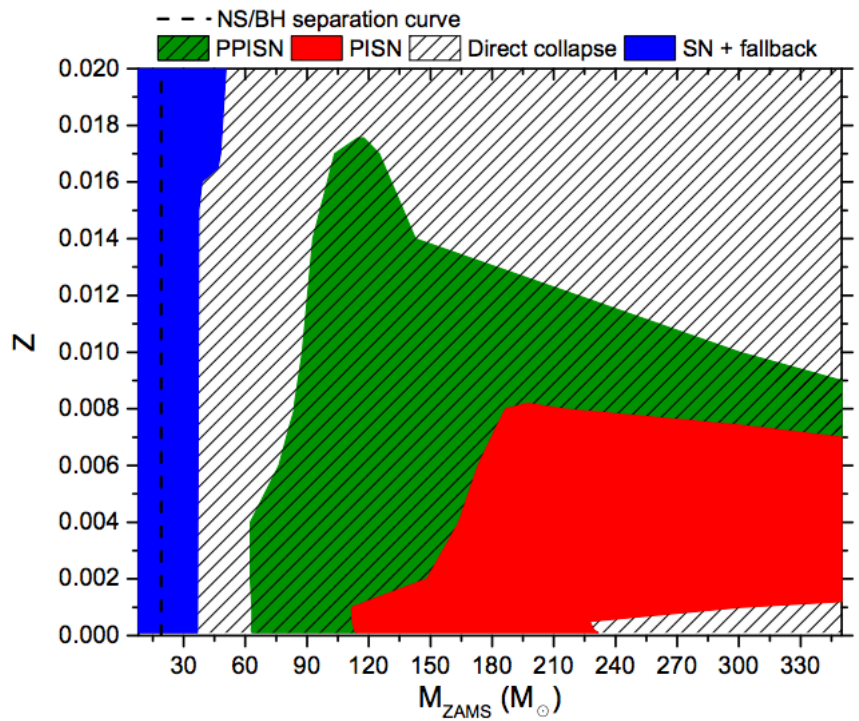
58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr


H 1
Periodic Table of the Elements of the Astrophysicist
He 2
Metals

Why low metallicity?



At low metallicity stars lose less mass through winds

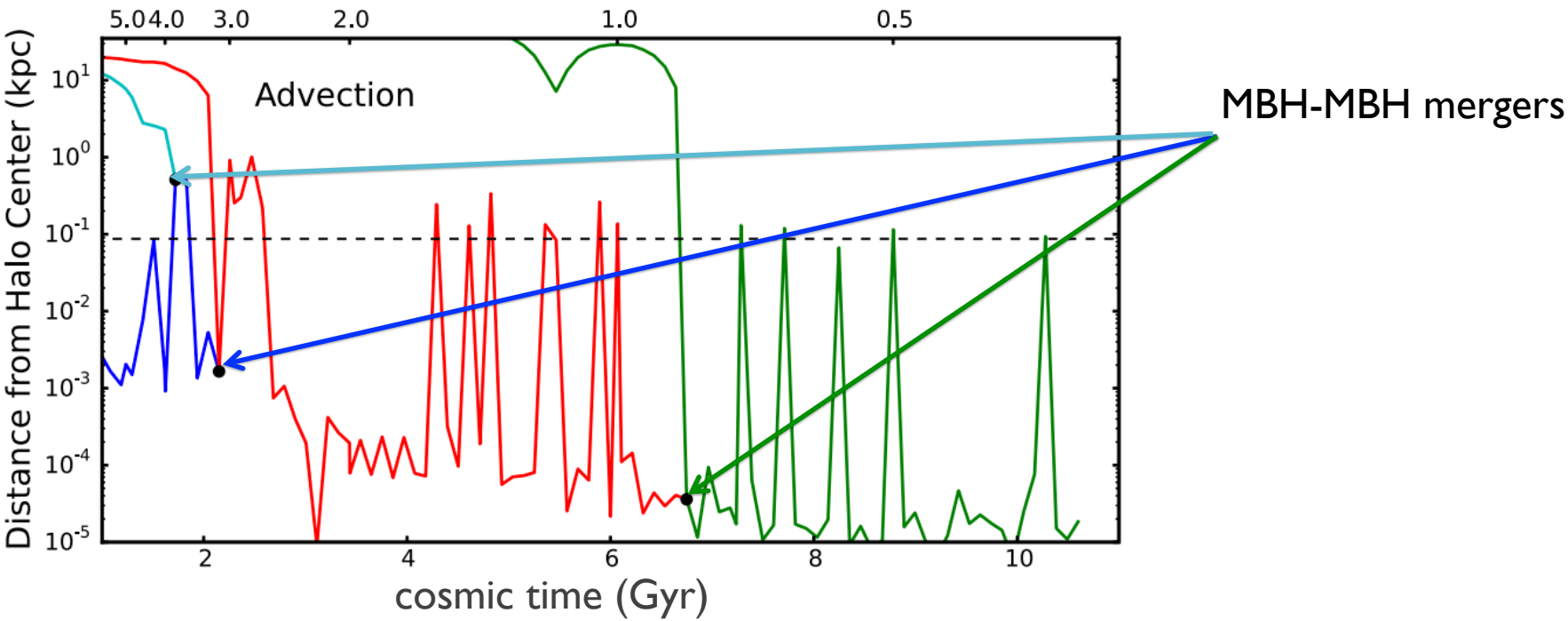


BH dynamics

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

How often mergers “fail”

MBH dynamics

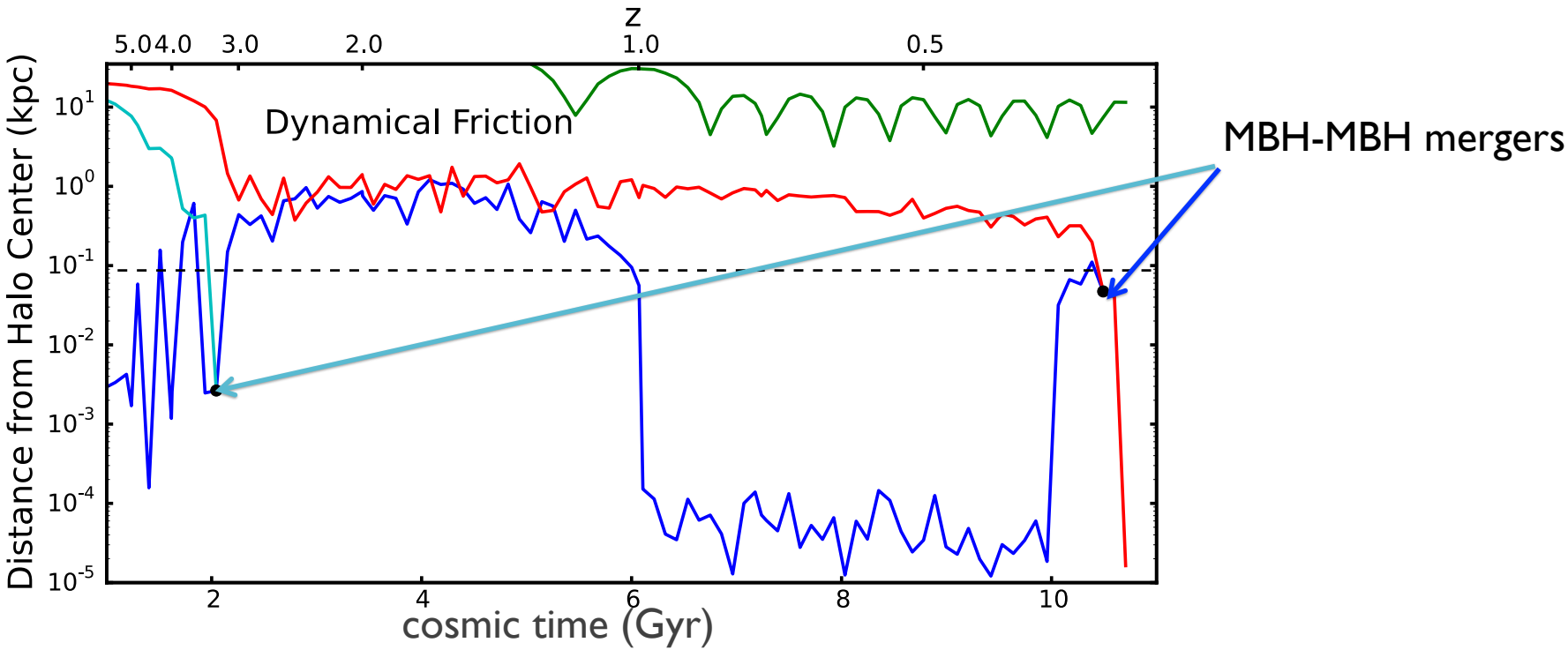


Cosmological 'zoomed-in' simulation of dwarf galaxy with mass ~ 10^{10} $M_\odot$ at z = 0.

dark matter particle mass 1.6×10^4 $M_\odot$
gas particle mass 3.3×10^3 $M_\odot$
gravitational softening 87 pc

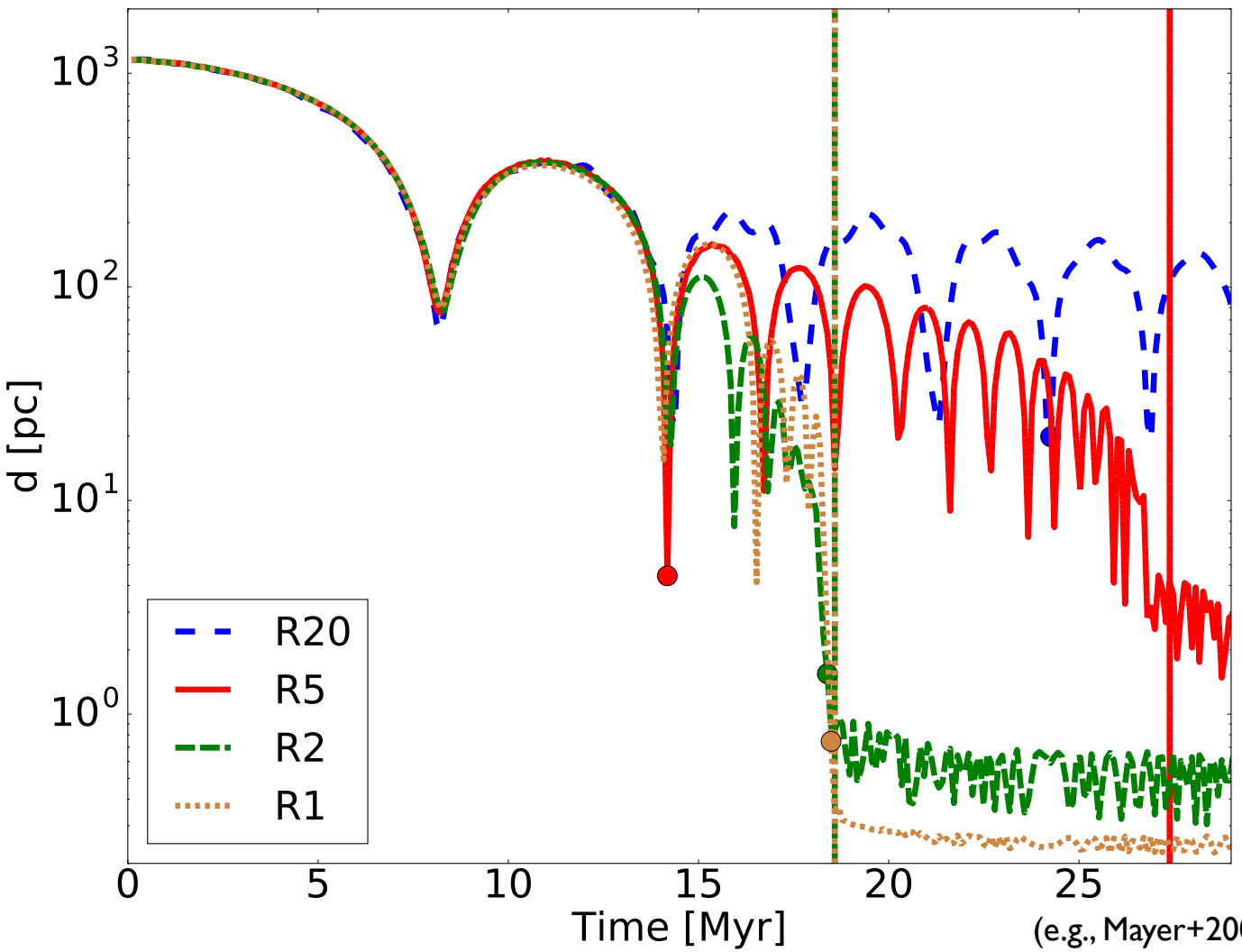
Tremmel+ 2015

MBH dynamics



It can take up to a few Gyr for two MBHs to reach ~10-100 pc separation from beginning of halo merger

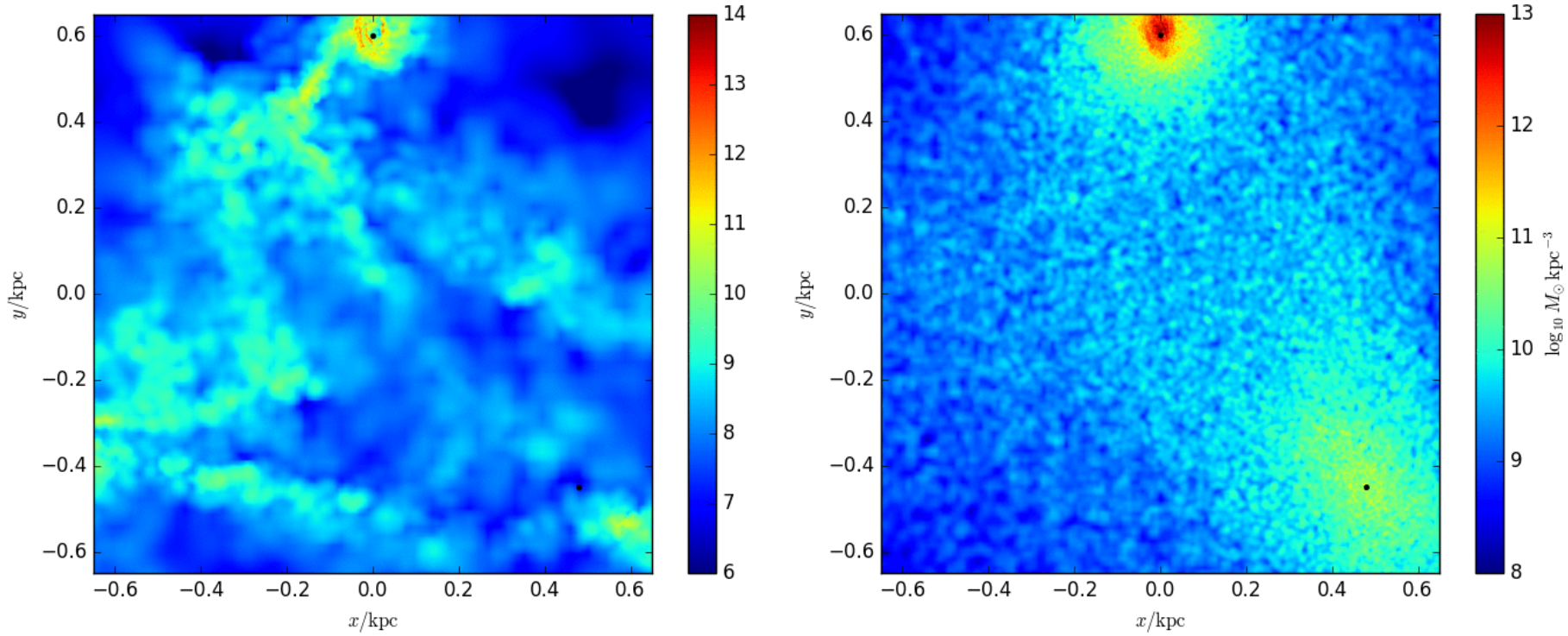
When the separation of the MBHs reach the minimum resolution of the simulation cannot follow dynamics anymore ➔ controlled re-simulations



R20=20 pc resolution
R5=5pc resolution
R2=2 pc resolution
R1=1 pc resolution

(e.g., Mayer+2007; Khan+12; Pfister+17)

Galaxy scales: 100 pc→1 pc

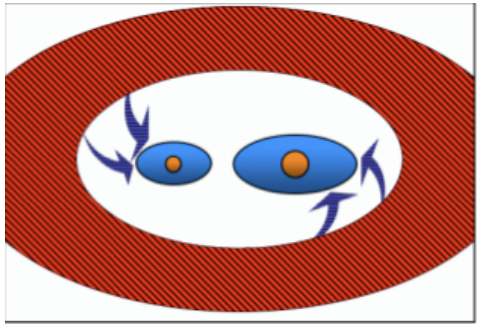


It takes ~few-100 Myr for two MBHs to reach ~1 pc separation from ~100 pc

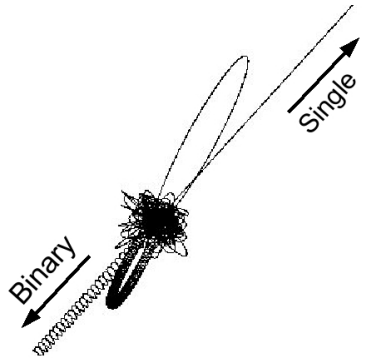
Pfister+ 2017

Final step: 1 → 0.01 pc

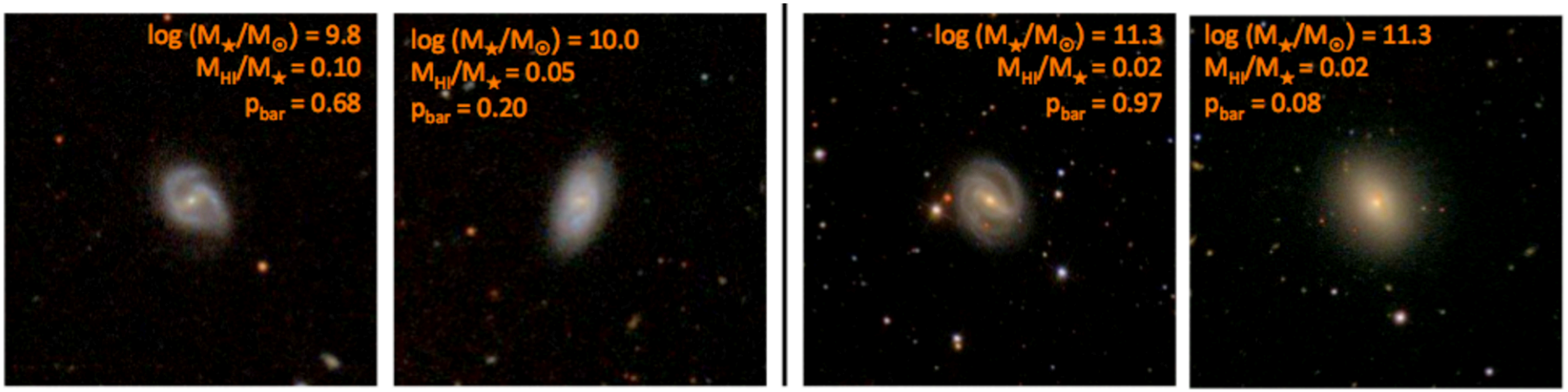
- Migration in a circumbinary disc to the GW-dominated regime should occur rapidly, ***~1-100 Myr***



- In a stellar-dominated environment: 3-body scattering, bringing the MBH to GW regime in ***~1 Gyr***



Massive black holes in galaxies



High-mass MBHs ⇔ High mass galaxies

High-mass galaxies ⇔ Gas poor galaxies

Credit: Hubble/GalaxyZoo

How long does this all take?

brief review: MV, Bogdanovic, Dotti, Colpi 2015

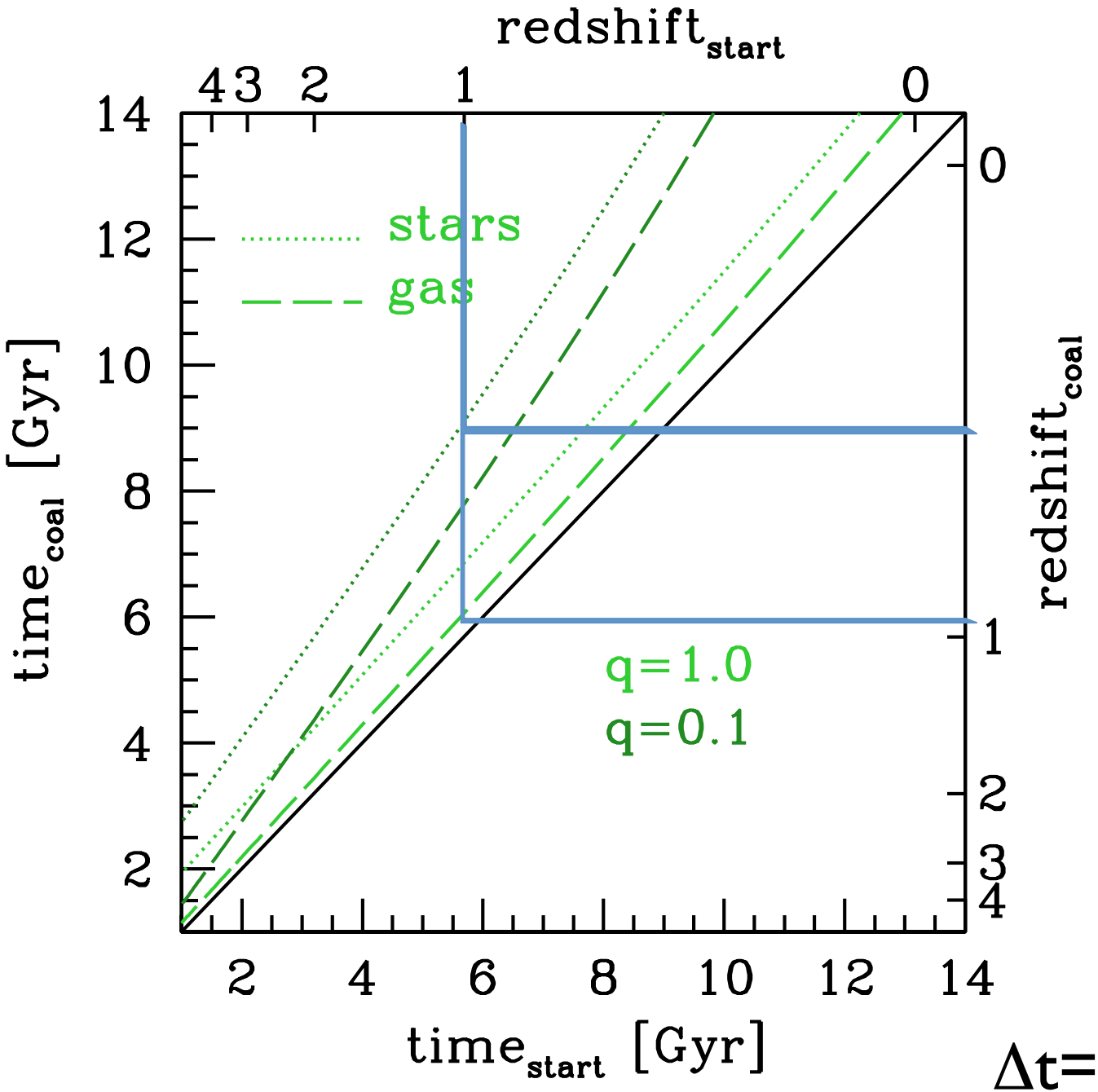
How long does this all take?

- For both gas and star-dominated mergers

An e=0, 10^8 M_{sun} binary with:

- q=1 will coalesce by z=0 if halo merger started by z~0.1-0.2 => **~1.5 Gyr**

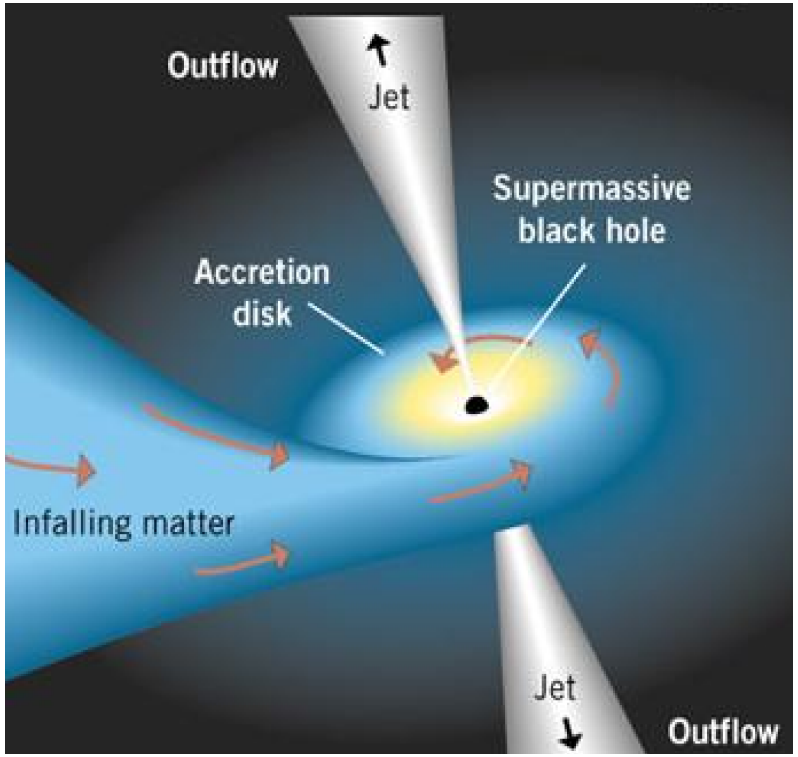
- q=0.1 will coalesce by z=0 if halo merger started by z~0.4-0.5 => **~5 Gyr**

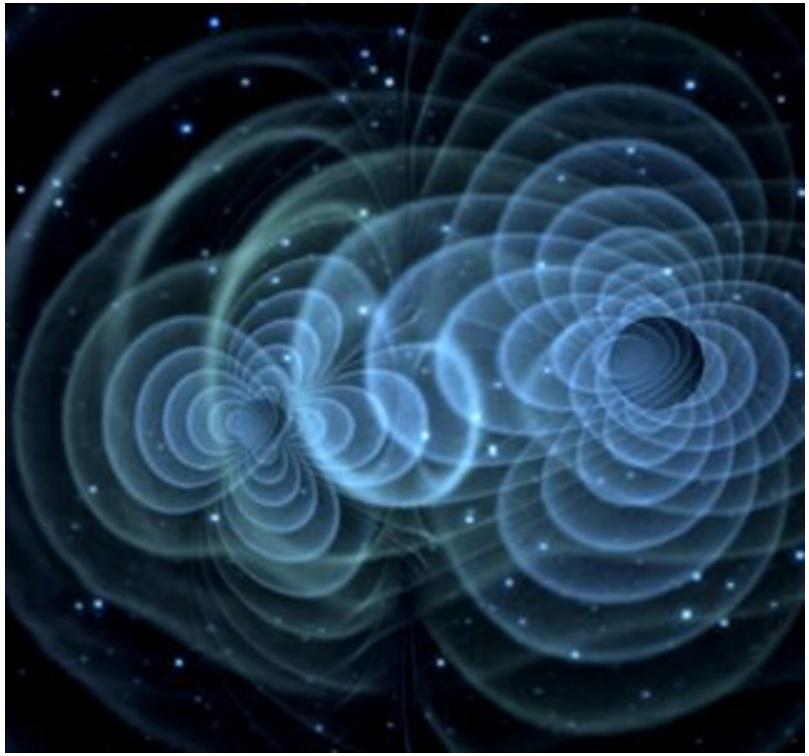


Δt=0.5-3.5 Gyr

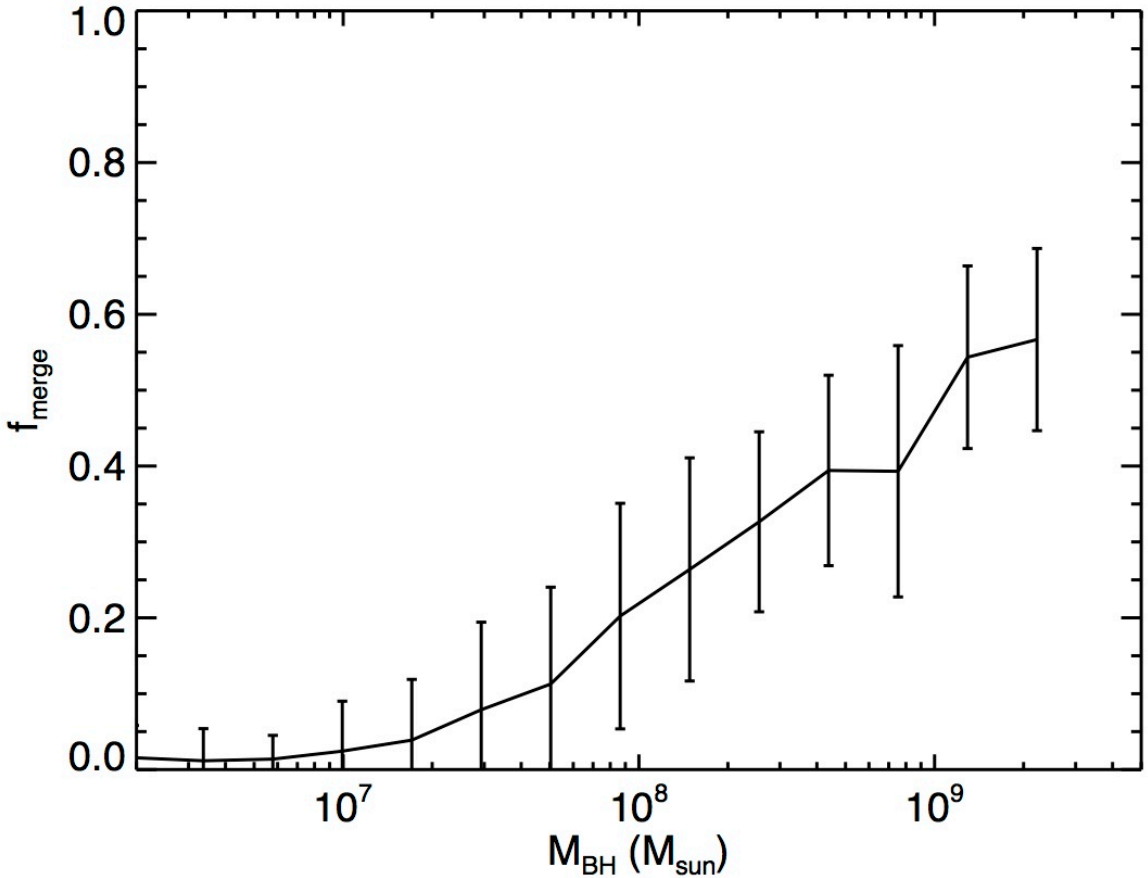
How do MBHs grow ?

Gas accretion vs MBH-MBH mergers





Are MBH-MBH mergers important?



High-mass MBHs!

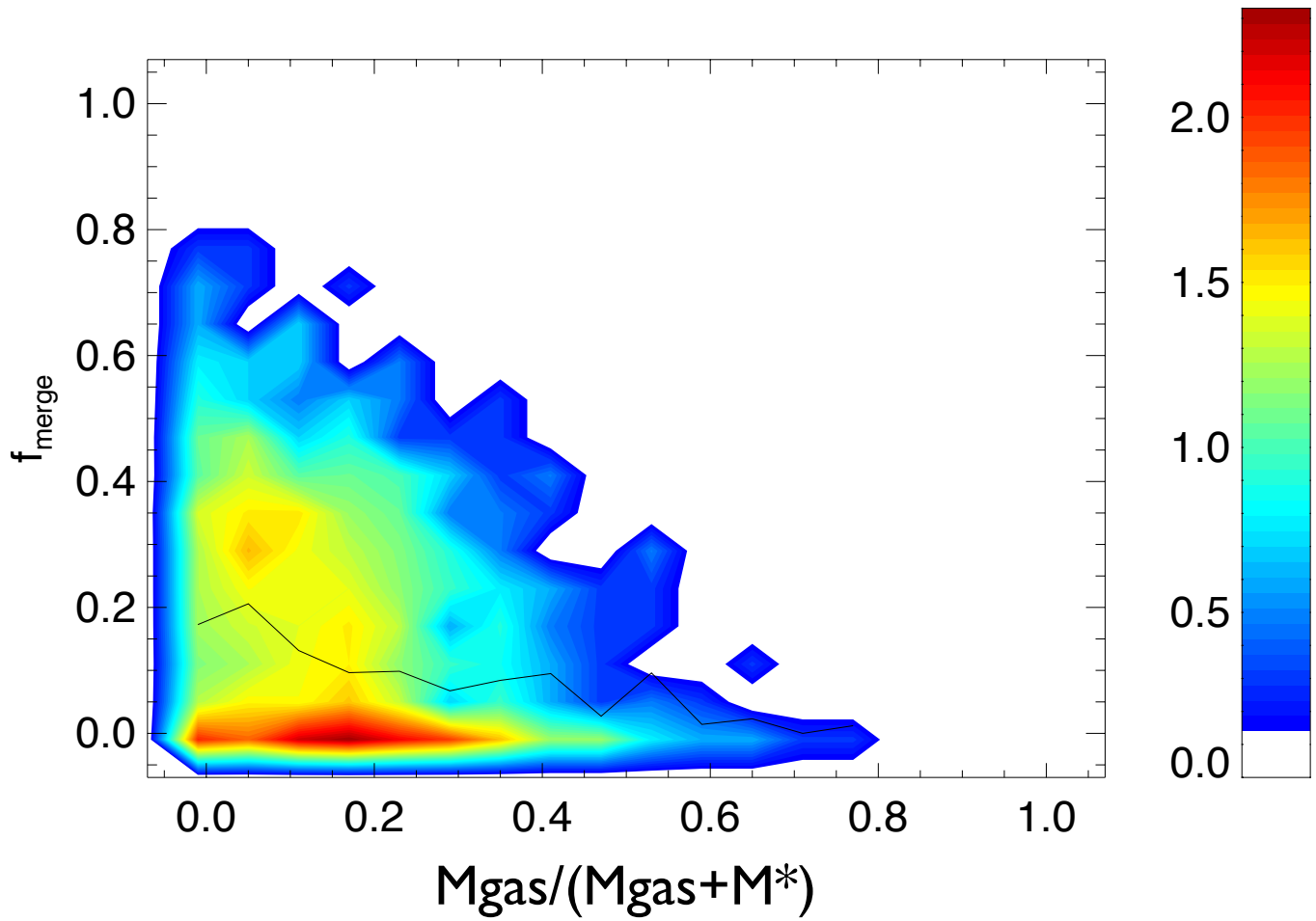
Fraction of mass gained through MBH-MBH mergers

$f_{merge}=\triangle M_{merge}/M_{BH}$

$\triangle$Mmerge is the sum of the masses of all merged MBHs and does not account for gas accretion on these MBHs

Dubois, Volonteri & Silk 2013

Are MBH-MBH mergers important?



Gas-poor galaxies!

Dubois, Volonteri & Silk 2013

All together now!

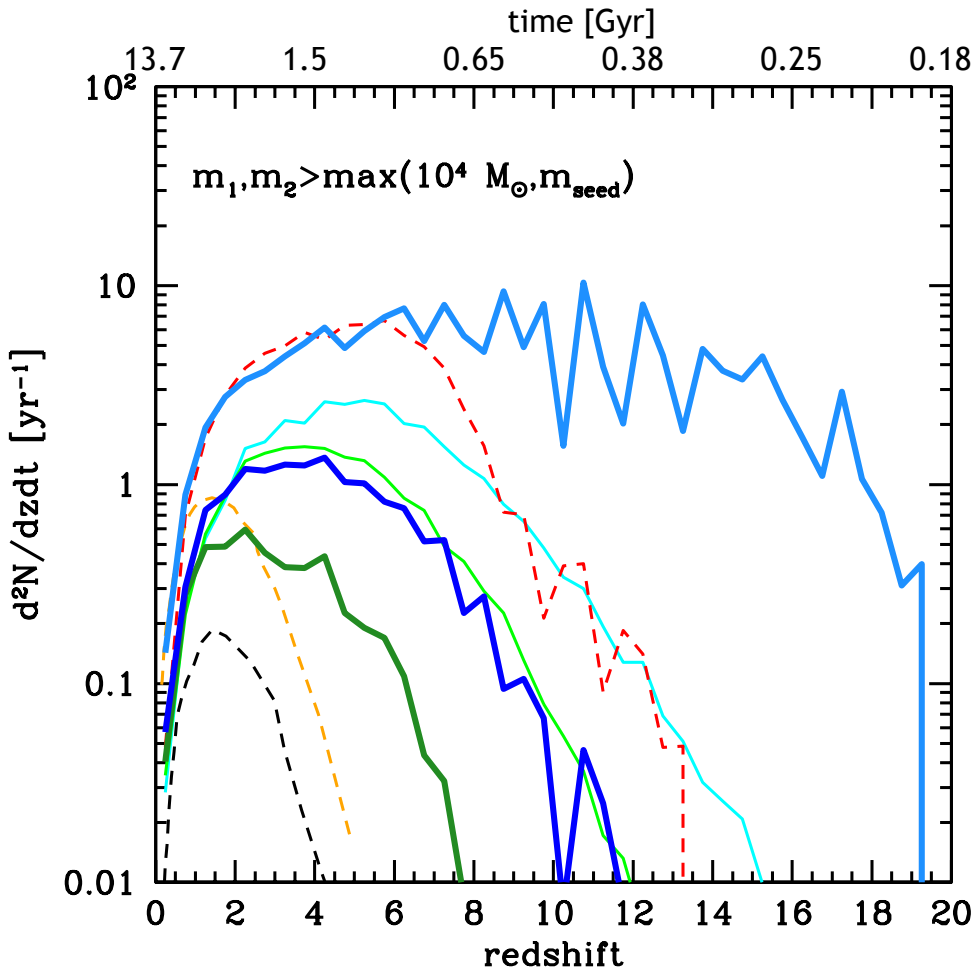
Cosmological simulations vs SAMs

- The advantage of an analytical approach is that in principle it has unlimited spatial and mass resolution

- The disadvantage is that one looses control on non-analytical processes (those that cannot be described by well behaved mathematical functions, e.g., galaxy mergers)

- In cosmological simulations the best possible resolution is ~100 pc, way way way far from when MBHs merge

LISA pseudo merger rate



SAMs:

Barausse+ (Mh>10^5-10^6 Msun)

MV, Sesana+ (Mh>10^5-10^6 Msun)

cyan, light blue, blue: large BH seeds

light green, dark green: small BH seeds

SIMs:

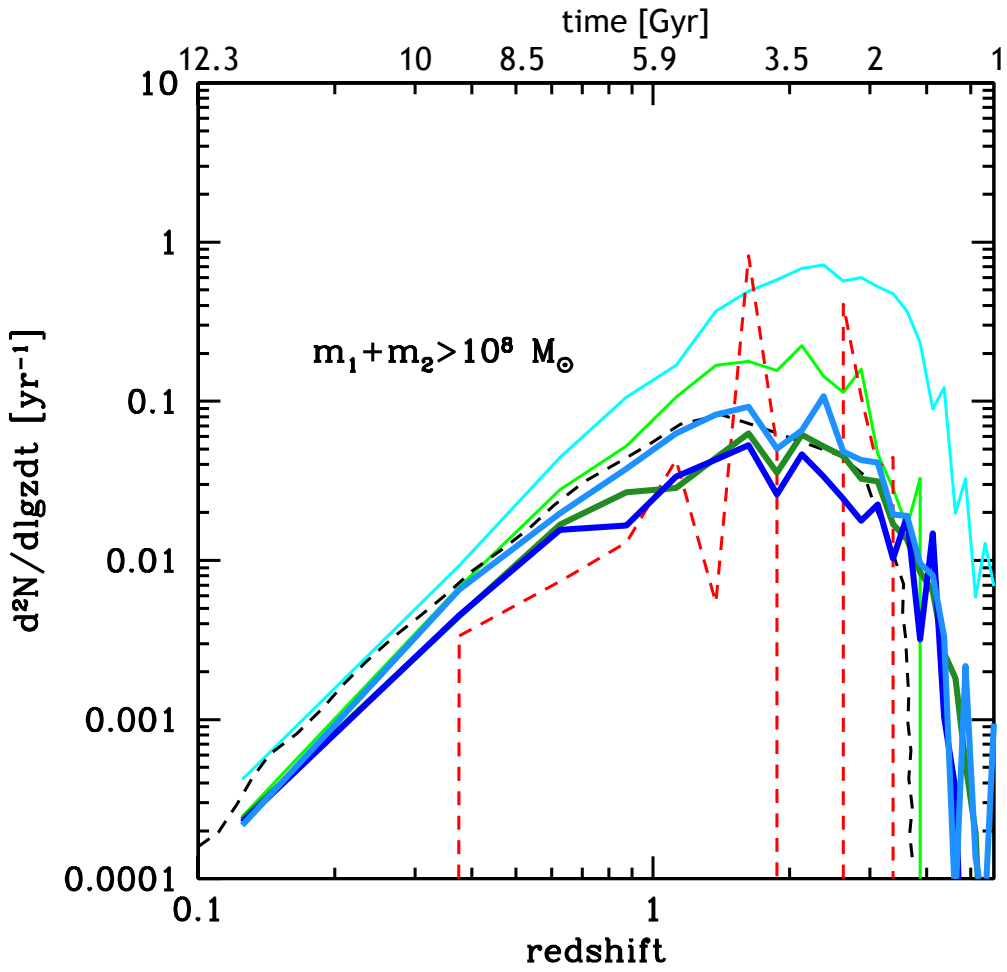
Salcido+ (Eagle, Mh>1.4e10 Msun)

Blecha+ (Illustris, Mh>1.4e11 Msun)

Tremmel+ (Romulus, Mh>3.5e8 Msun)

Number of mergers per year: between 1 and 80

PTA pseudo merger rate



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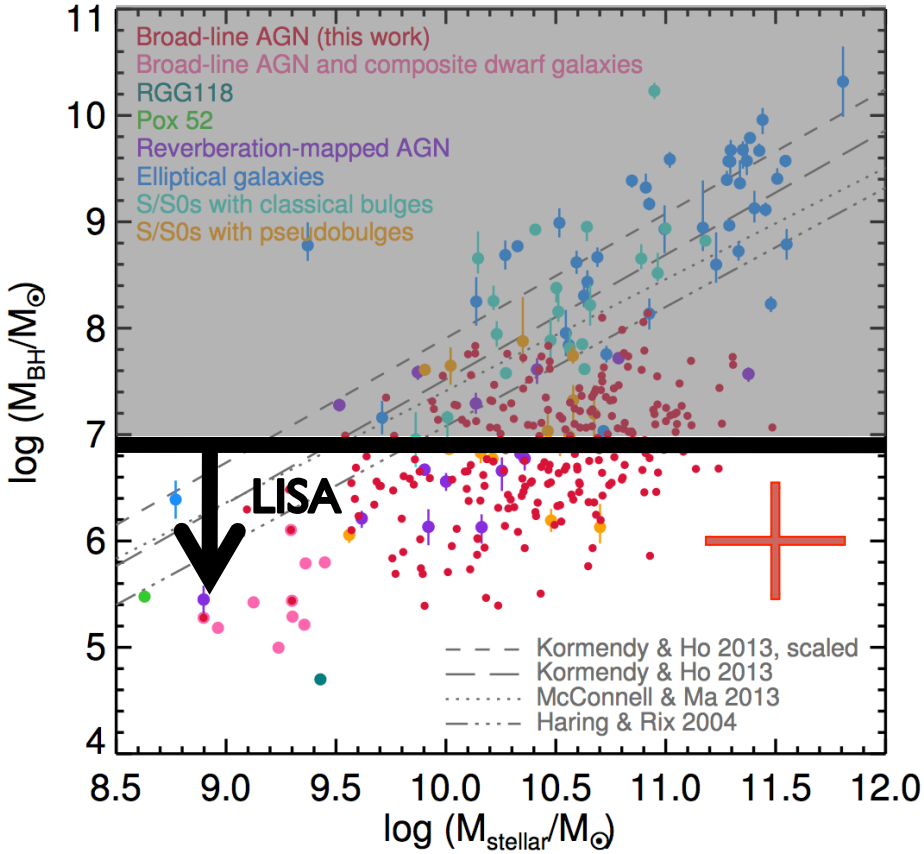
SIMs:

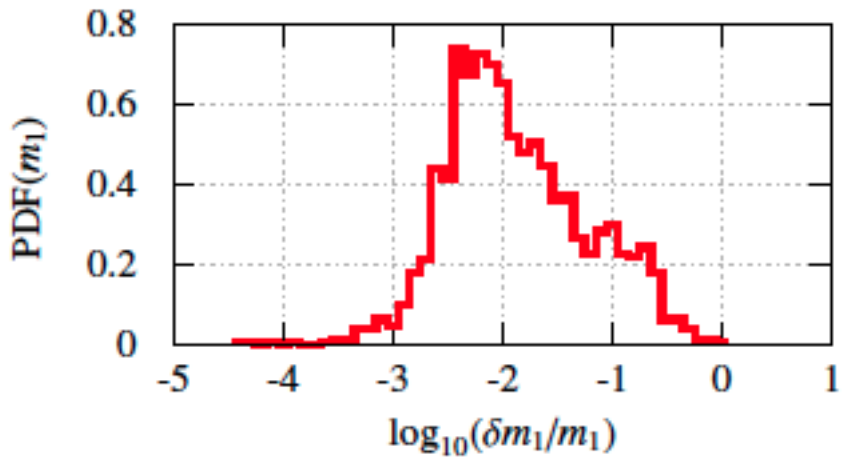
Blecha+ (Illustris, Mh>1.4e11 Msun)

Tremmel+ (Romulus, Mh>3.5e8 Msun)

Number of mergers per year: between 0.03 and 0.09

What can GWs do for MBHs?





What can GWs do for MBHs?

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

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

Model parameters describe the black hole population in the Universe: masses, mass ratios and redshifts of merging systems

Sesana, Gair, Berti, MV 2011

What can GWs do for MBHs?

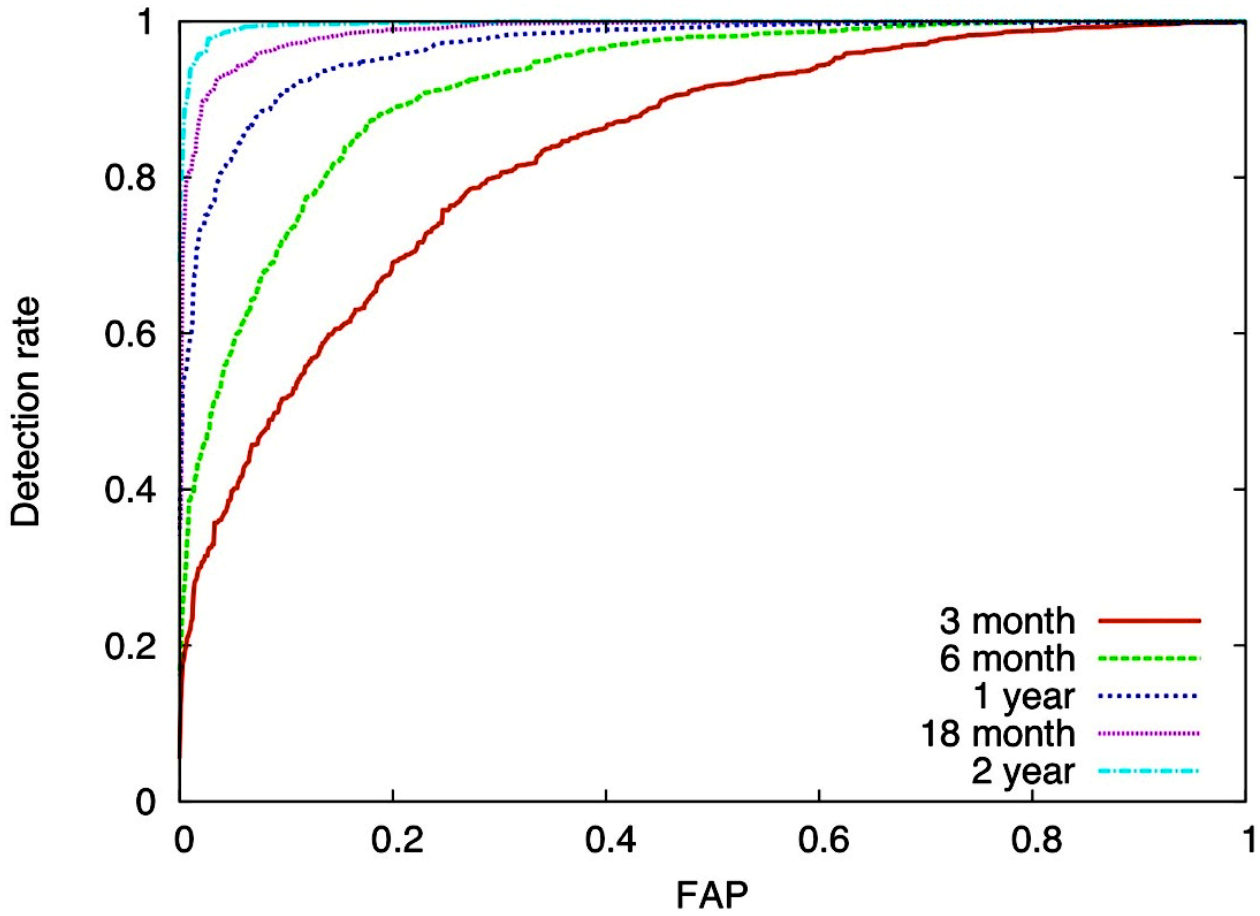
Models that differ by either BH seeds or accretion

E.g. many, but smaller, BH seeds vs fewer but more massive ones

E.g. slower or faster growth

How many detections do we need to identify a model?

LISAPE taskforce, Arun et al. 2008
Sesana, Gair, Berti, MV 2011



With a two-year observation we have more than a 90% probability that the parent model of an observed sample will be safely identified at >95% confidence level

Models vs reality

The true MBH population might not be perfectly described by our models, or come from a completely unexplored physical mechanism.

How can we analyze LISA's datastream to extract useful astrophysical information?

Create a new *artificial* model, independent of the 4 cases described above, but consistent with current constraints on the MBH population

Search the artificial model's datastream with pure models' distributions (masses, mass ratios and redshifts)

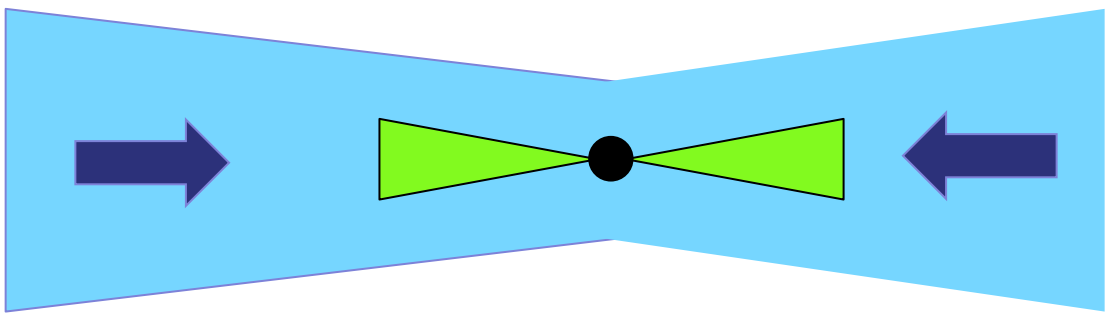
We can extract information about more complex MBH formation and growth histories by using models we understand well

A note on spins

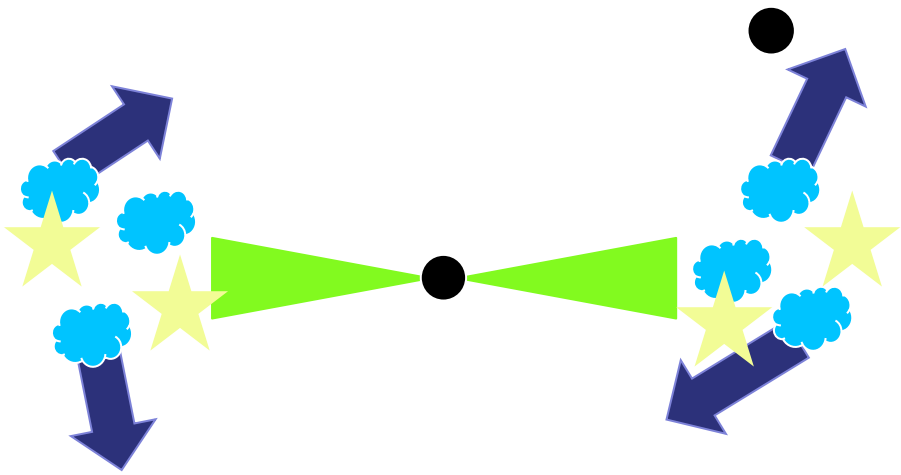
MBH mass evolution dominated by accretion (Yu & Tremaine 2002,Elvis et al 2002,Merloni et al 2004,etc)

Spin evolution is dominated by accretion too (Volonteri, Madau, Quataert & Rees 2005)

A note on spins



Coherent: accreted material has ~ constant direction of angular momentum vector



Chaotic: accretion of droplets of material with random direction of the angular momentum vector

(King & Pringle 2006)

A note on spins

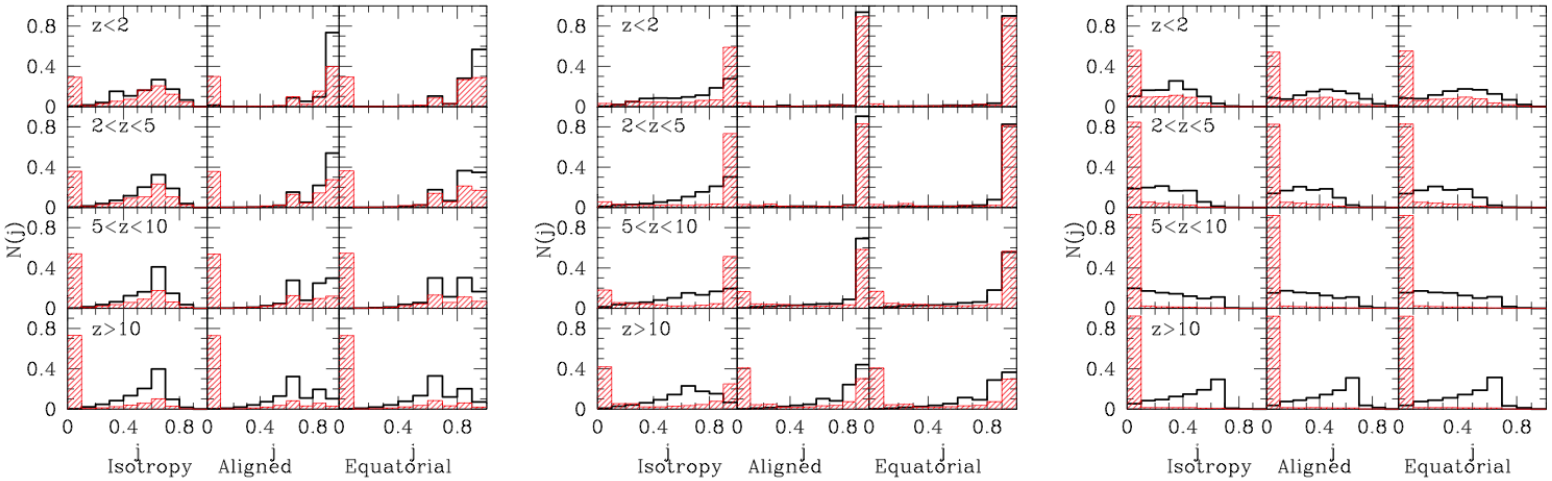


FIG. 4.— Spin evolution of merging BHs due to: mergers only (left); mergers and prolonged accretion (center); mergers and chaotic accretion (right). In each plot we consider three representative merger scenarios (see text) and we show histograms of the spin distribution for different ranges of variability of the redshift z. *Hatched (red) histogram:* spins of the binary members before merger. *Thick (black) histogram:* spins of BHs after merger.

Summary

MBHs in merging galaxies have along 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!