# Massive black hole binaries in the cosmic landscape

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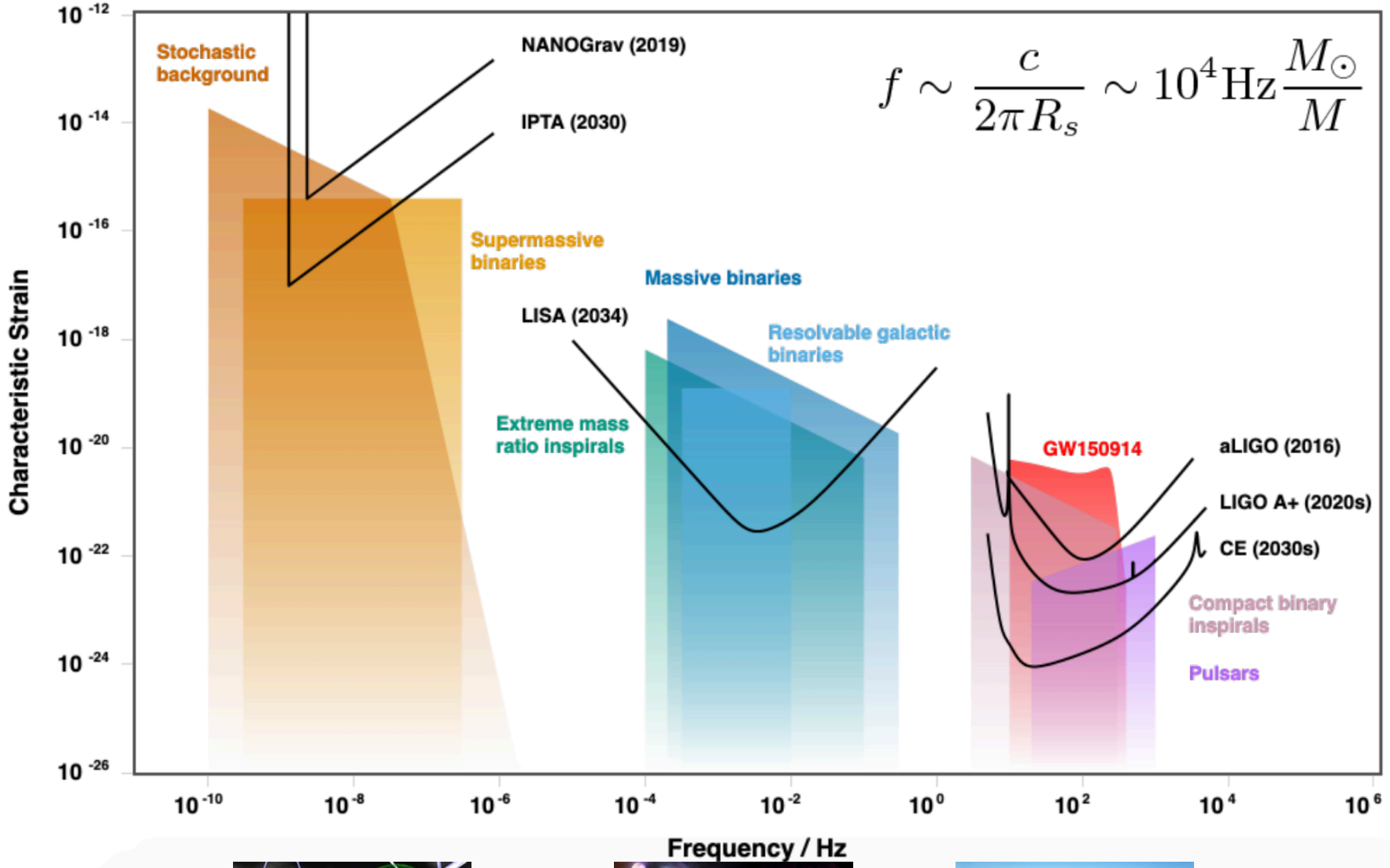
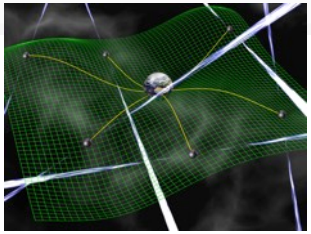
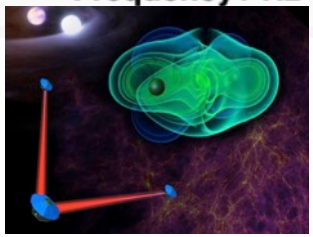

Characteristic Strain
Frequency / Hz
Stochastic background
NANOGrav (2019)
IPTA (2030)
Supermassive binaries
Massive binaries
LISA (2034)
Resolvable galactic binaries
Extreme mass ratio inspirals
GW150914
aLIGO (2016)
LIGO A+ (2020s)
CE (2030s)
Compact binary inspirals
Pulsars
$f \sim \frac{c}{2\pi R_s} \sim 10^4 \mathrm{Hz} \frac{M_\odot}{M}$

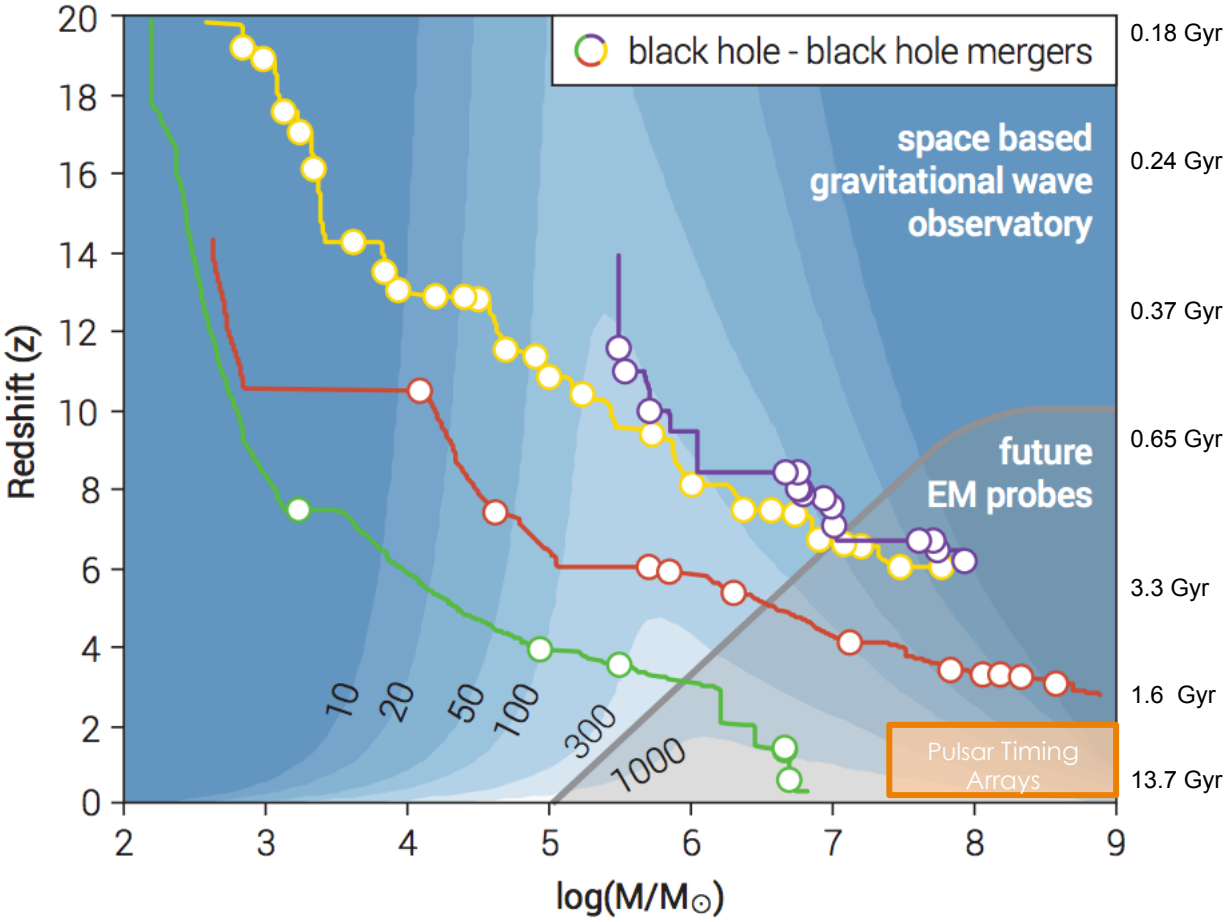




# Massive black holes and gravitational waves

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

Over time they sweep the LISA band, enter the EM domain and the most massive ones become emitters for Pulsar Timing Array experiments



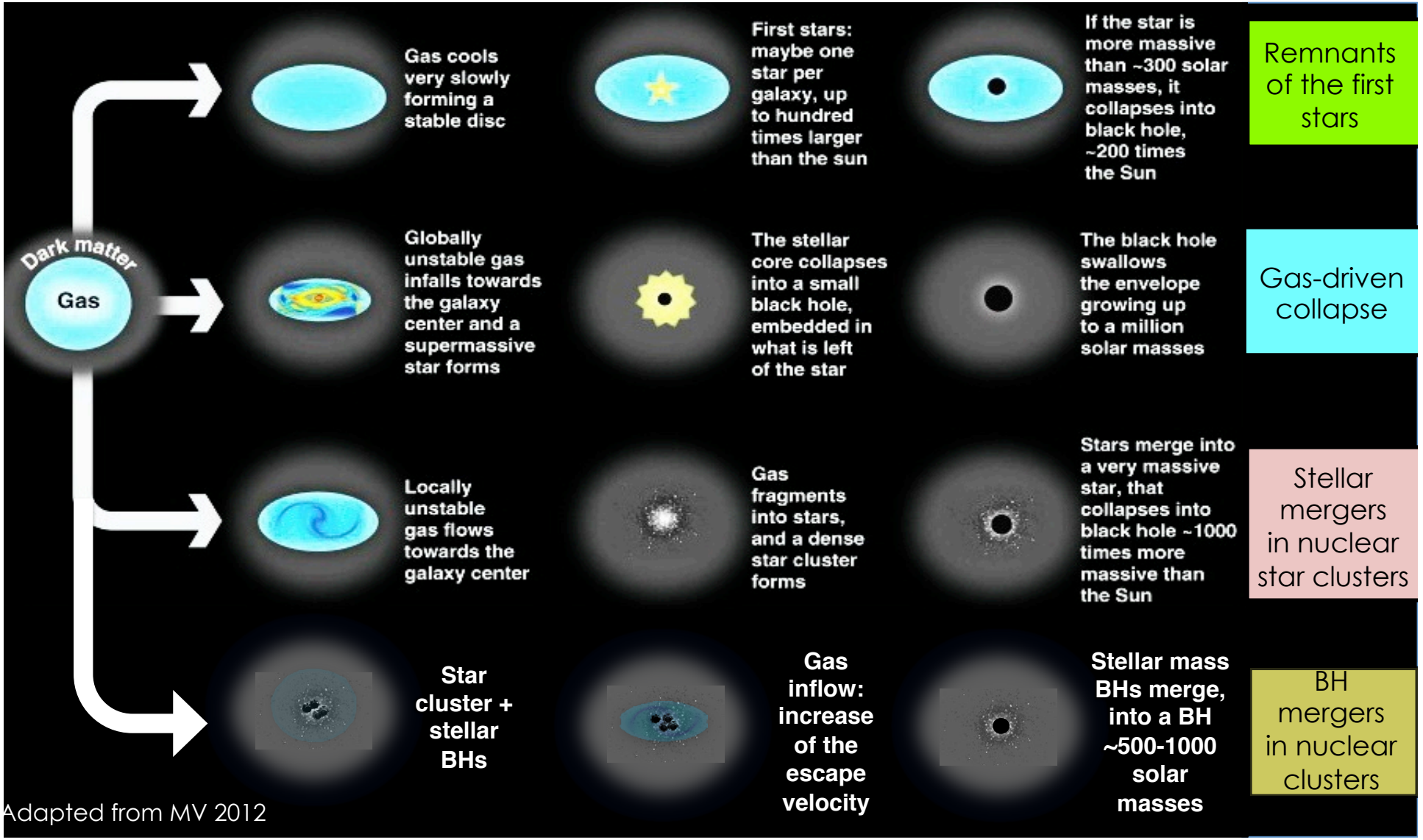
# What can gravitational waves do for massive black holes and galaxy evolution?

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

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

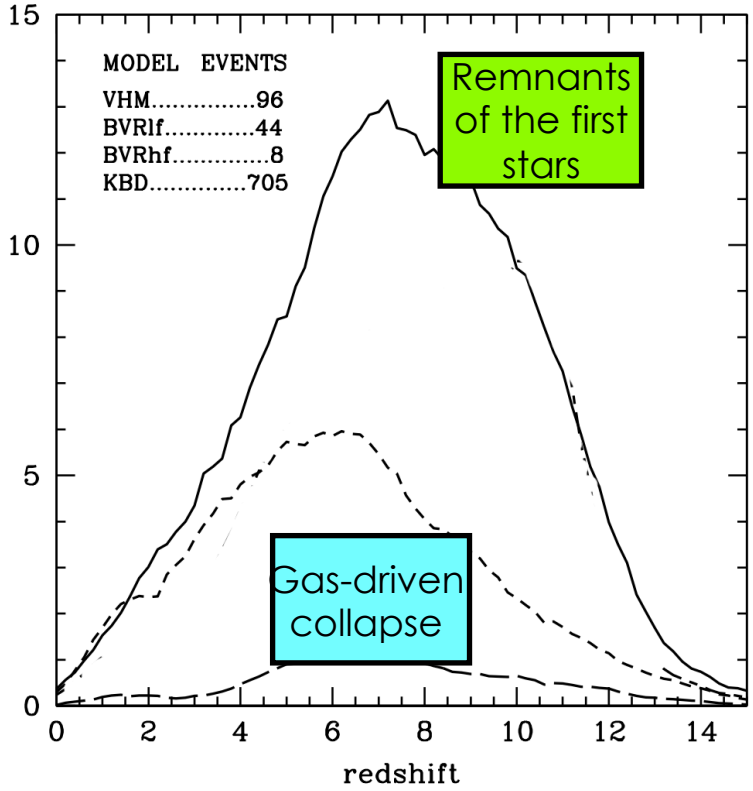
Arun+2008; Sesana, Gair, Berti, MV 2011; Sesana 2008,13;
Ravi+2012,15; Kulier+14; McWilliams+14; Kelley+17; Katz+19

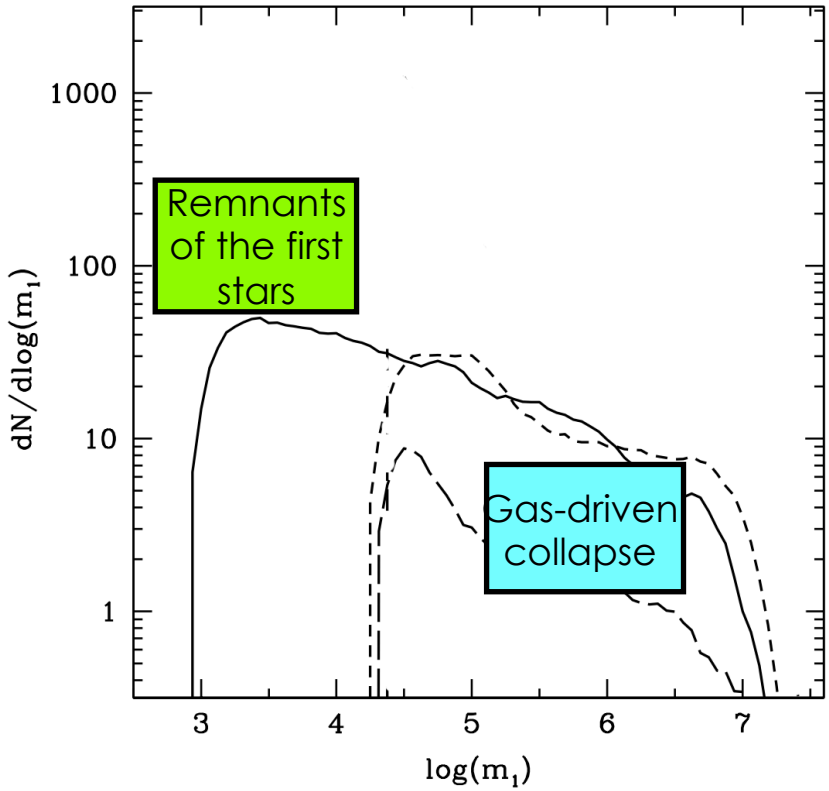
# The formation of massive black holes




Adapted from MV 2012

# Massive black hole formation and LISA




The mass and frequency in galaxies of MBH seeds is a key ingredient for understanding the shape of the redshift and mass distributions of the merger rate

Sesana,MV+08, Sesana+11, Ricarte+18, Dayal+18

# What can gravitational waves and massive black holes do for cosmology?

Gravitational wave sources can be standard sirens– the measured parameter is the *luminosity distance*

If we measure the *redshift* of an electromagnetic counterpart we obtain *cosmological parameters* and constrain several models of *modified gravity*

Schutz 86; Holz & Hughes 05; Cutler & Holz 09; Tamanini+16; Belgacem+19

# EM counterparts to MBH mergers

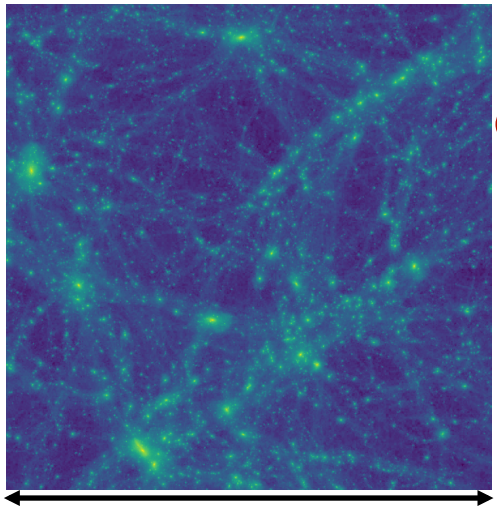
**Precursors**: use binary signatures to identify MBHs on the way to merger

**Afterglows**: use merger-induced features to identify where a MBH-MBH merger has taken place

- Starting today: to estimate the potential population and to develop strategies

- After LISA's launch and after a PTA detection: to actually measure the redshift and the MBH/galaxy properties

# Massive black hole mergers

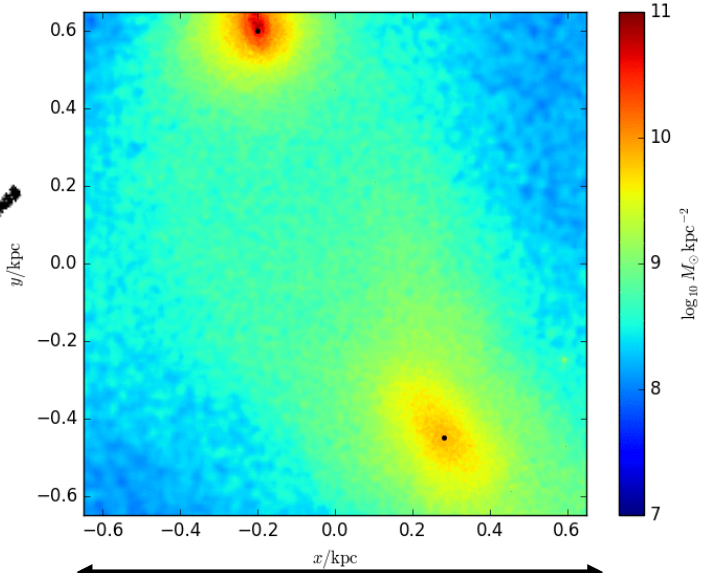


~100 Mpc (cosmology)

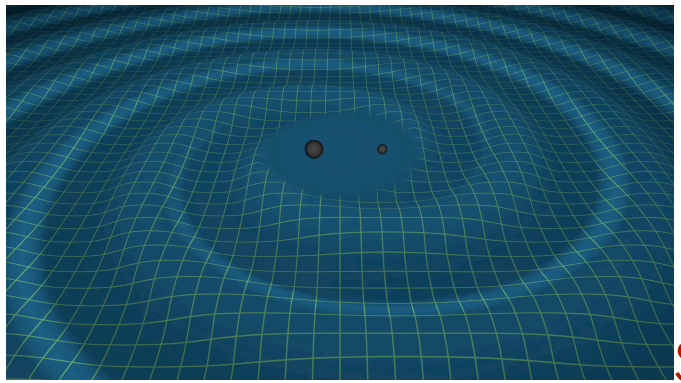
Gravity


~100 kpc -1 kpc (galaxy mergers)

Dynamical Friction




~1 kpc-1pc (binary formation)

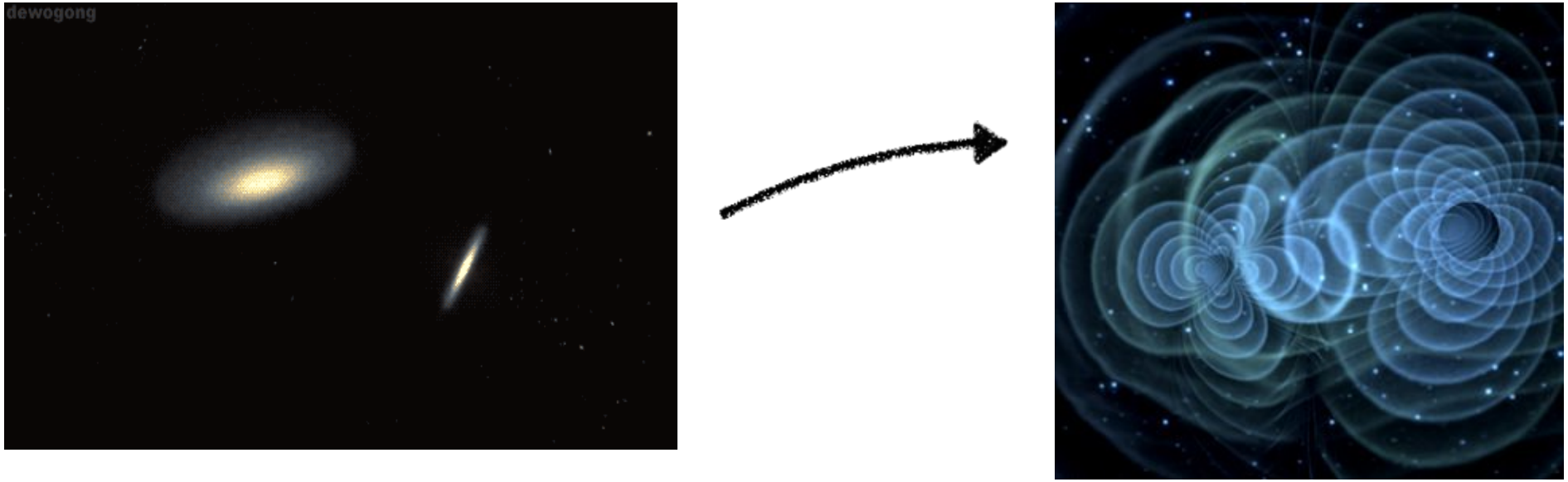


~1 millipc(BH merger)

Gas torques?
Stellar scattering?
Last pc problem

Courtesy of Hugo Pfister

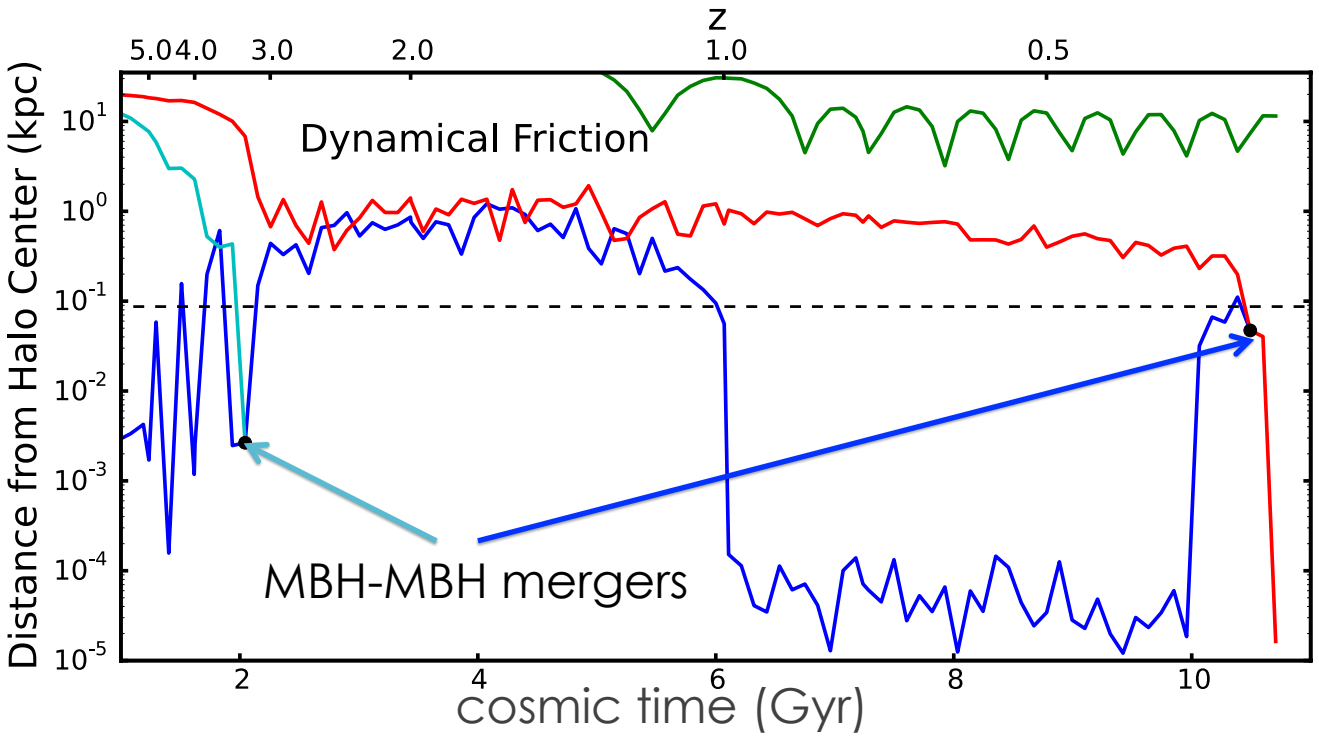
# EM counterparts to MBH mergers: *precursors*




Massive black hole mergers originate from galaxy mergers

Look for galaxies with morphological signatures of a recent merger?

# MBH dynamics – the first stage



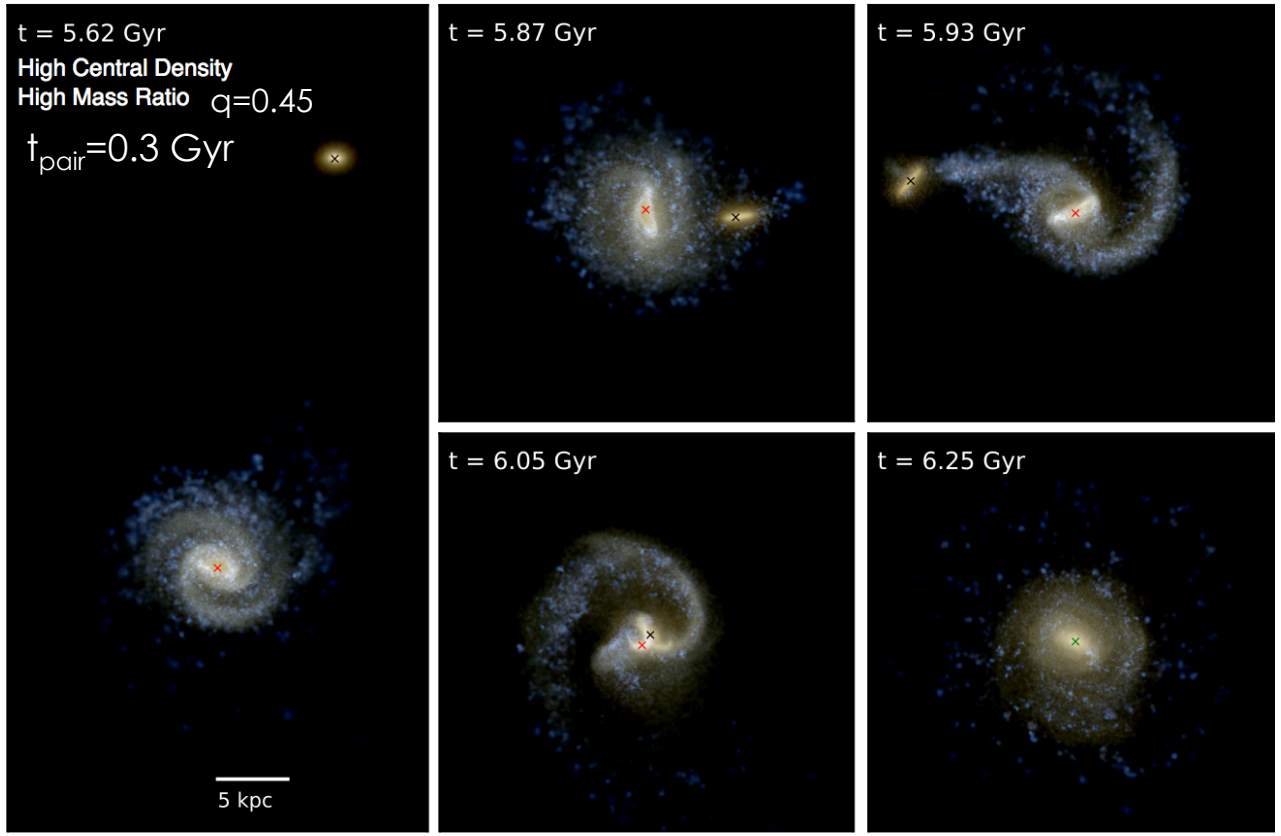

Cosmological 'zoomed-in' simulation of dwarf galaxy with mass ~ $10^{10}$ $M_\odot$ at z = 0.

MBH mass 5x$10^5$ $M_\odot$
dark matter particle mass 1.6 × $10^4$ $M_\odot$, gas particle mass 3.3 × $10^3$ $M_\odot$
gravitational softening 87 pc

Tremmel+15, Pfister+19

# Galaxy mergers vs MBH mergers

## Dependence on galaxy properties

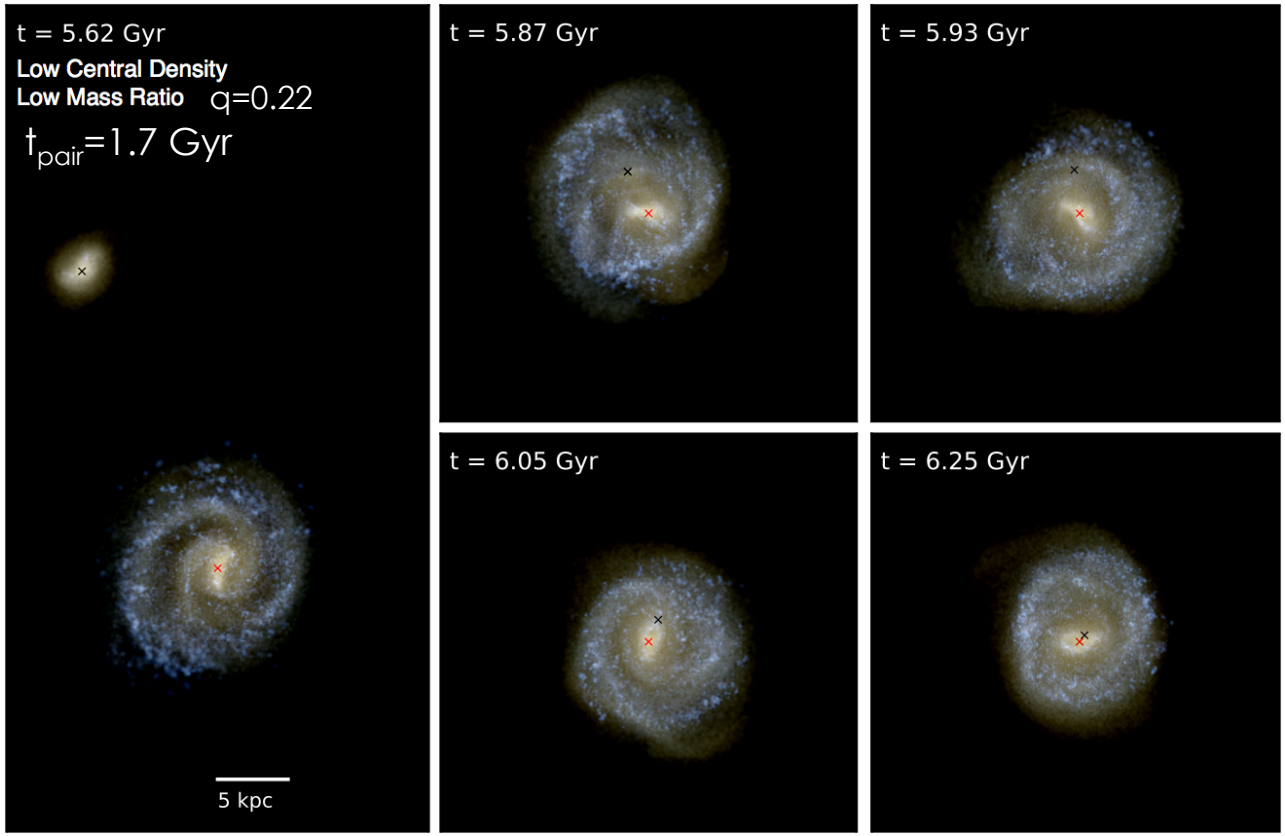



When the MBHs merge the host galaxies have a disturbed morphology

Tremmel+ 2017

# Galaxy mergers vs MBH mergers

## Dependence on galaxy properties




By the time the MBHs merge all merger signatures in the host galaxy have disappeared

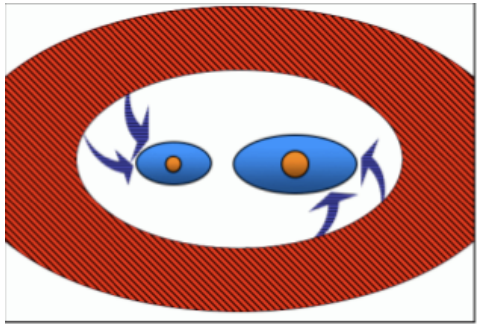
Tremmel+ 2017

# EM counterparts to MBH mergers: *precursors*

Focus on the final stages of the mergers – after the MBHs have formed a binary

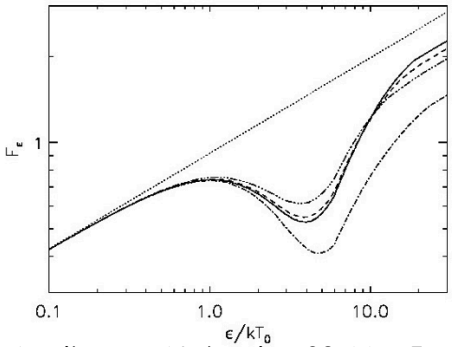
Sub-pc to milli-pc separations

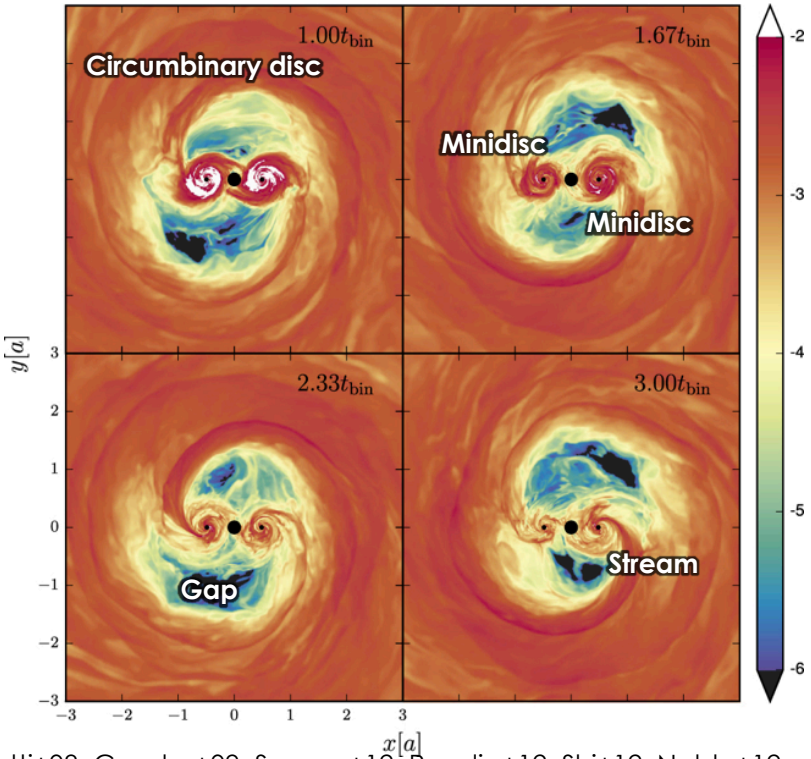
In a gas-rich environment: formation of a circumbinary disc



# EM counterparts to MBH mergers: *precursors*

- Possible periodicities in the light curve
- Double peaked emission line profiles (Doppler shift caused by binary motion)
- Gaps in the spectrum
- Shocks when streams hit the edges of mini-discs



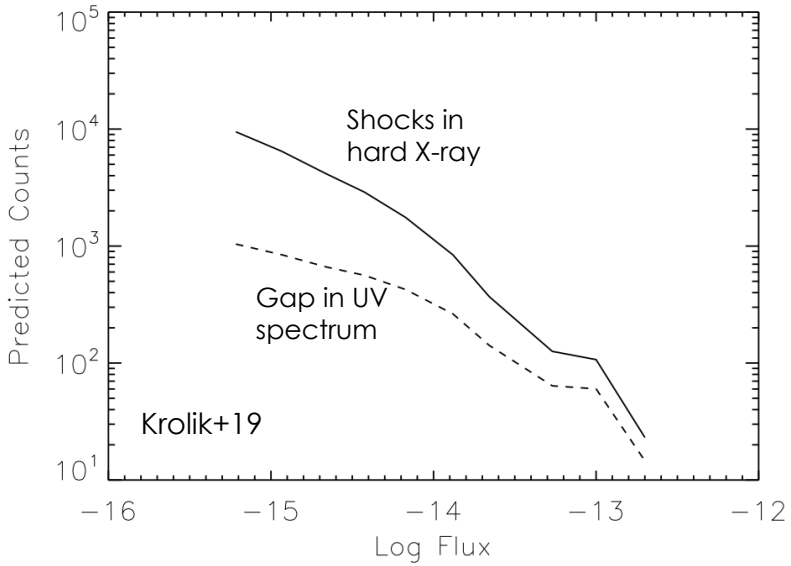




e.g.,Armitage & Natarajan 02; MacFadyen & Milosavljevic 08; Bogdanovic+08; Dotti+08, Cuadra+09; Sesana+12; Roedig+12; Shi+12; Noble+12; D'Orazio+13; D'Ascoli+19

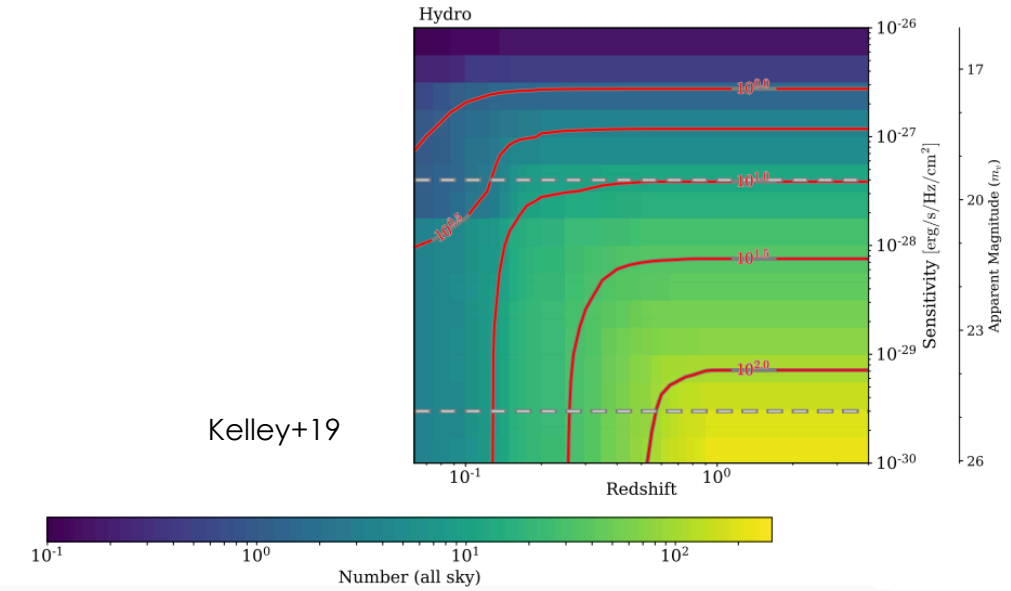
# EM counterparts to MBH mergers: *precursors*

Hydrodynamical cosmological simulations ~(100 Mpc)$^3$ box: masses, mass ratios, accretion rates of MBH binaries

- Gaps in the spectrum
- Shocks when streams hit the edges of mini-discs




- Possible periodicities in the light curve

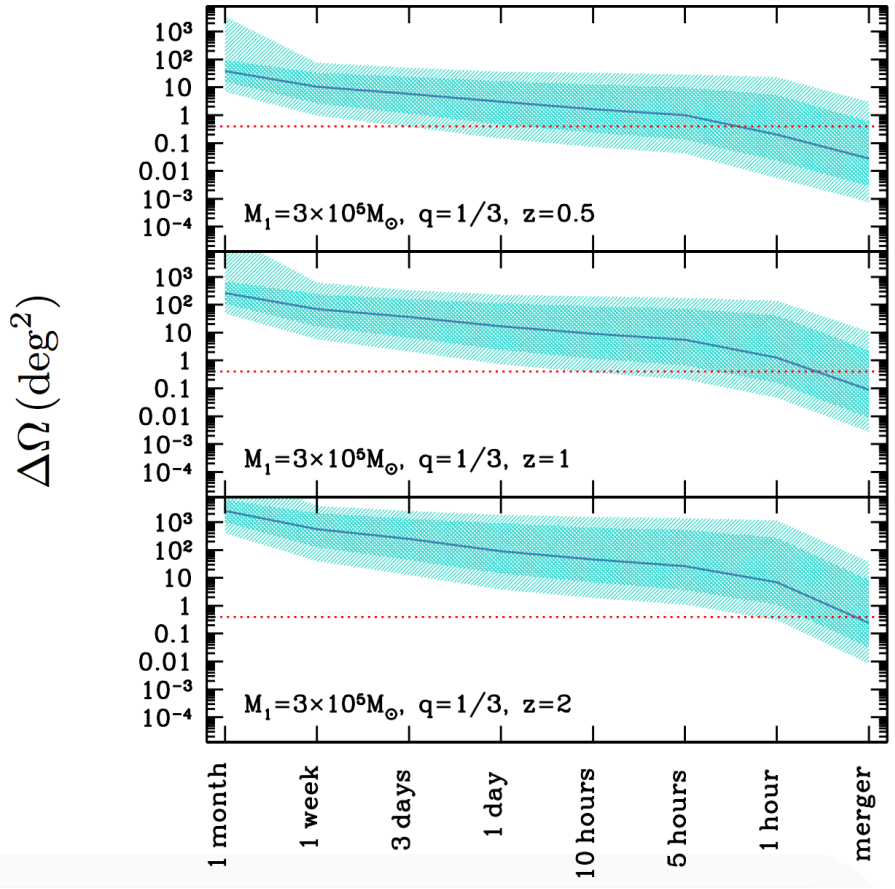


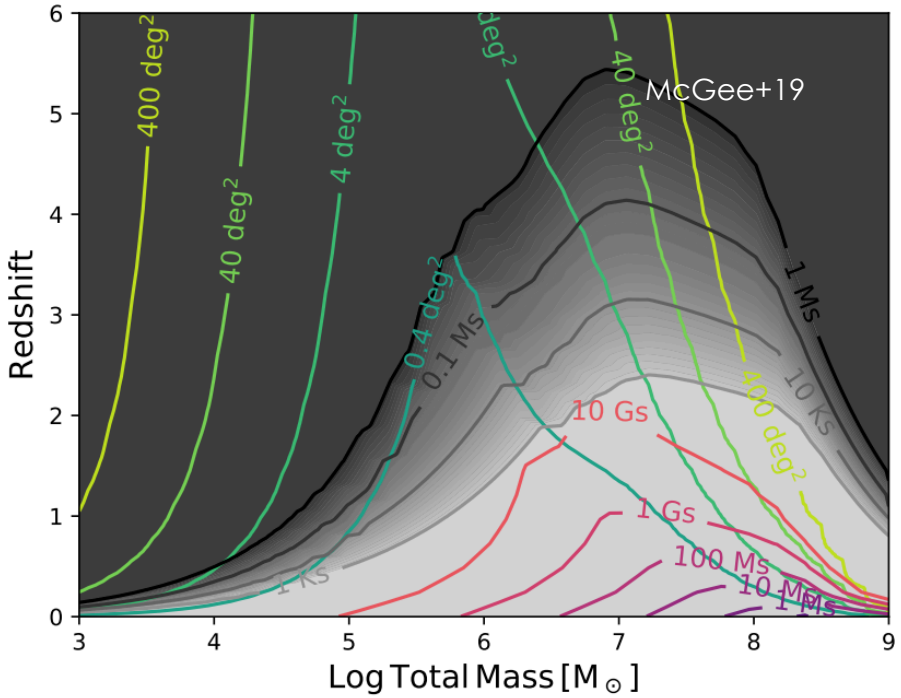

Kelley+19

See also Sesana+12

# EM counterparts to MBH mergers: *at merger*

- Sky localization improves with S/N => error box decreases as we get closer to the merger proper



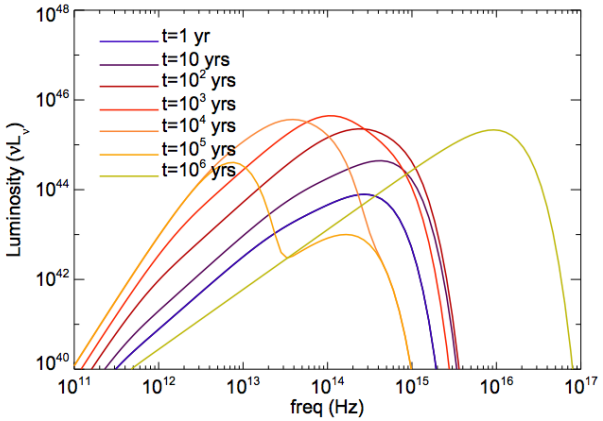



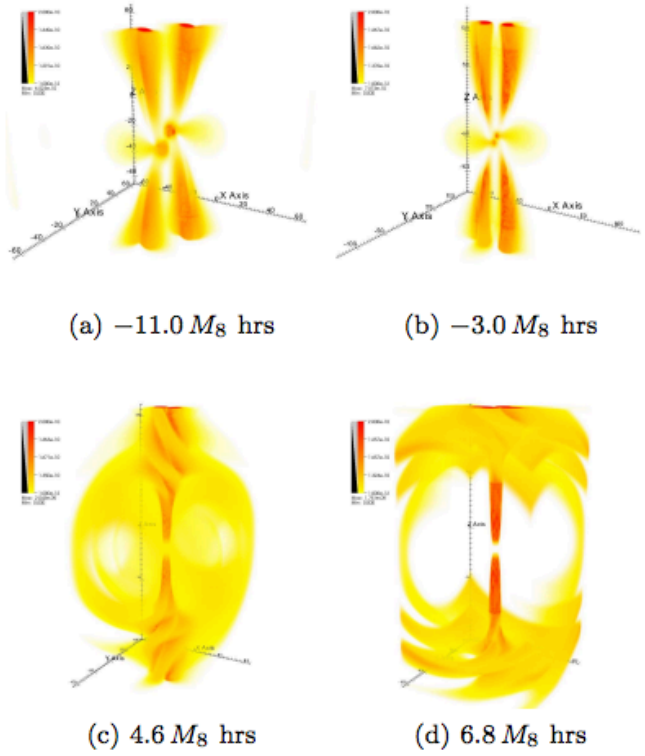

Courtesy of A. Mangiagli

LISA+ATHENA, McGee+18

# EM counterparts to MBH mergers: *afterglows*

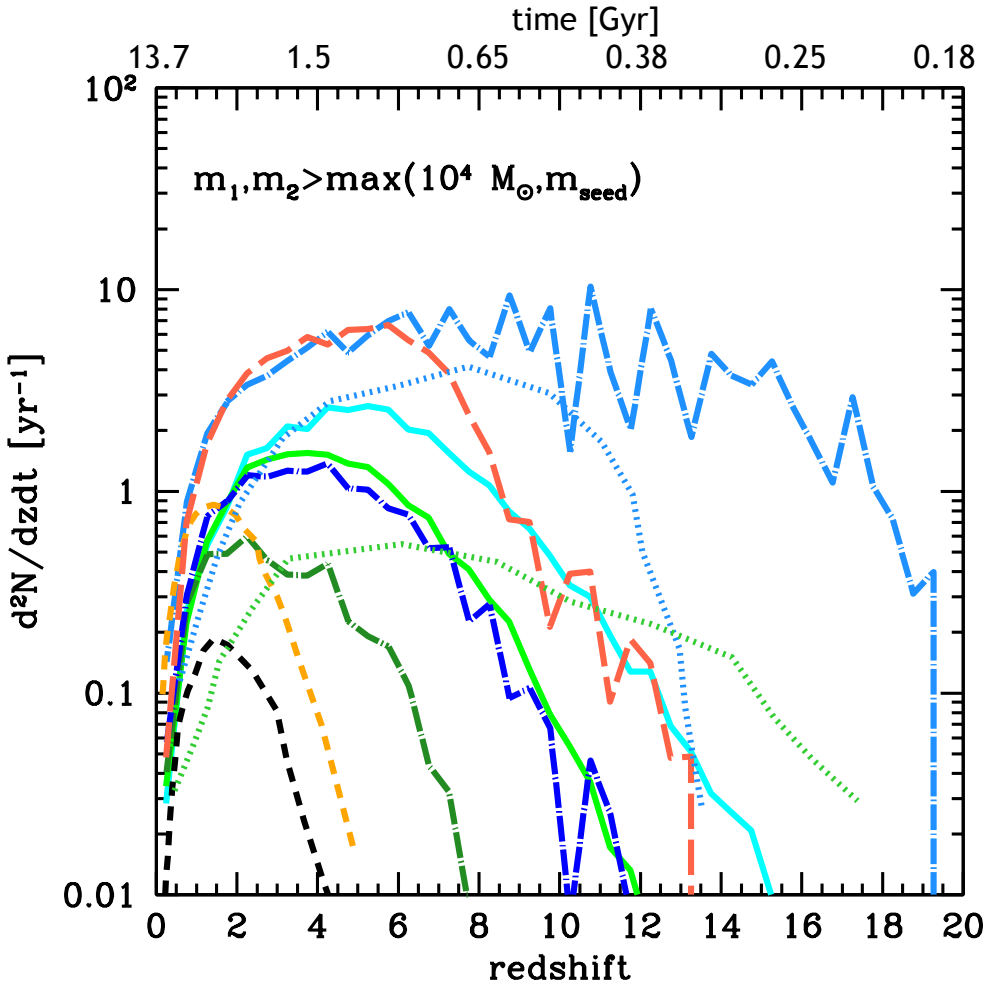
- Burst at merger as gas plows in from gap
- Perturbed discs
- Effect of recoils
- Dual/single jet




Armitage & Natarajan 02; Milosavljević & Phinney 05; Schnittman & Krolik 08; Palenzuela+10, etc etc

# LISA merger rate




SAMs:
Barausse+ ($M_{gal}>10^3$ Msun)
MV, Sesana+ ($M_{gal}>10^3$Msun)
Ricarte+ ($M_{gal}>10^4$ Msun)
cyan, light blue, blue: large BH seeds
light green, dark green: small BH seeds

SIMs:
Salcido+ (Eagle, $M_{gal}>10^8$ Msun)
Blecha+, Katz+ (Illustris, $M_{gal}>10^9$ Msun)
Tremmel+ (Romulus, $M_{gal}>10^7$ Msun)

Number of mergers per year: between 1 and 80

# Summary

GWs are a unique way of probing massive black hole evolution

LISA's GWs as standard sirens can give complementary constraints on cosmological parameters up to high-z

Strong constraints on modified gravity theories

EM counterparts to MBH mergers is a field still in its infancy