Gas, stars and gravitational waves

on the main driver of supermassive black hole binaries path to coalescence

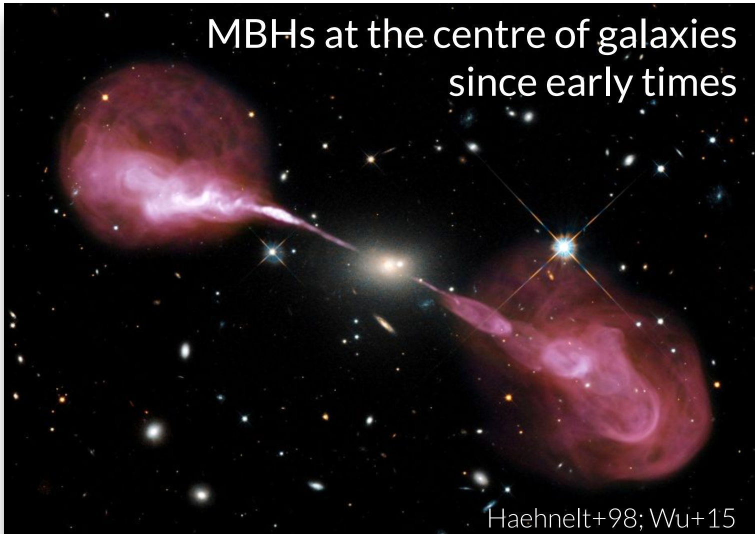
Elisa Bortolas

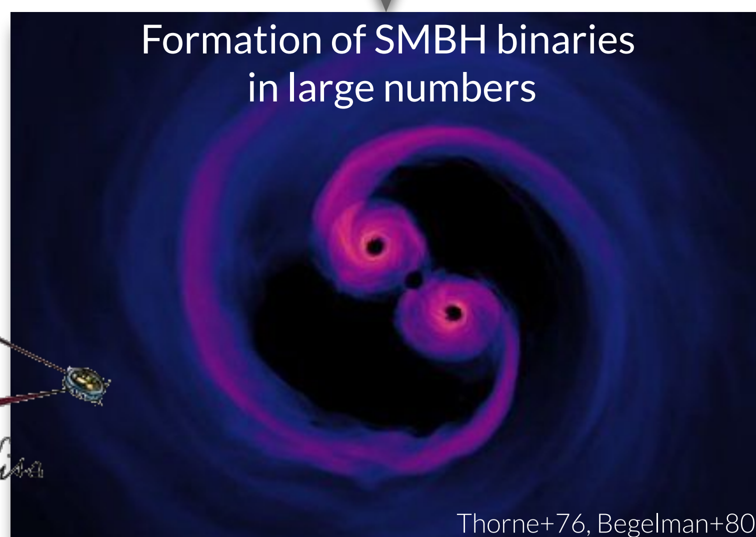
Main Collaborators:
A. Sesana, A. Franchini, M. Bonetti,
A. Gualandris, A. Lupi, M. Dotti,
L.Mayer, P.Capelo, …

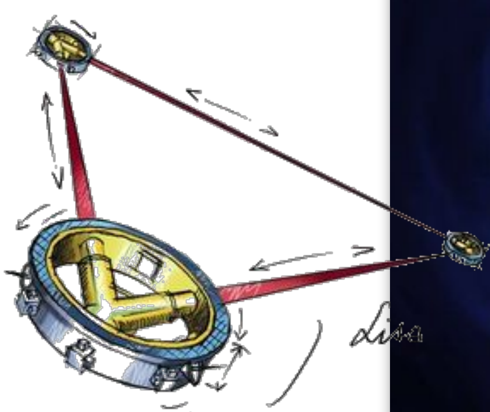
BINARY22 - Kavli Institute for Theoretical Physics

Santa Barbara, April 7th, 2022

Massive black hole binaries

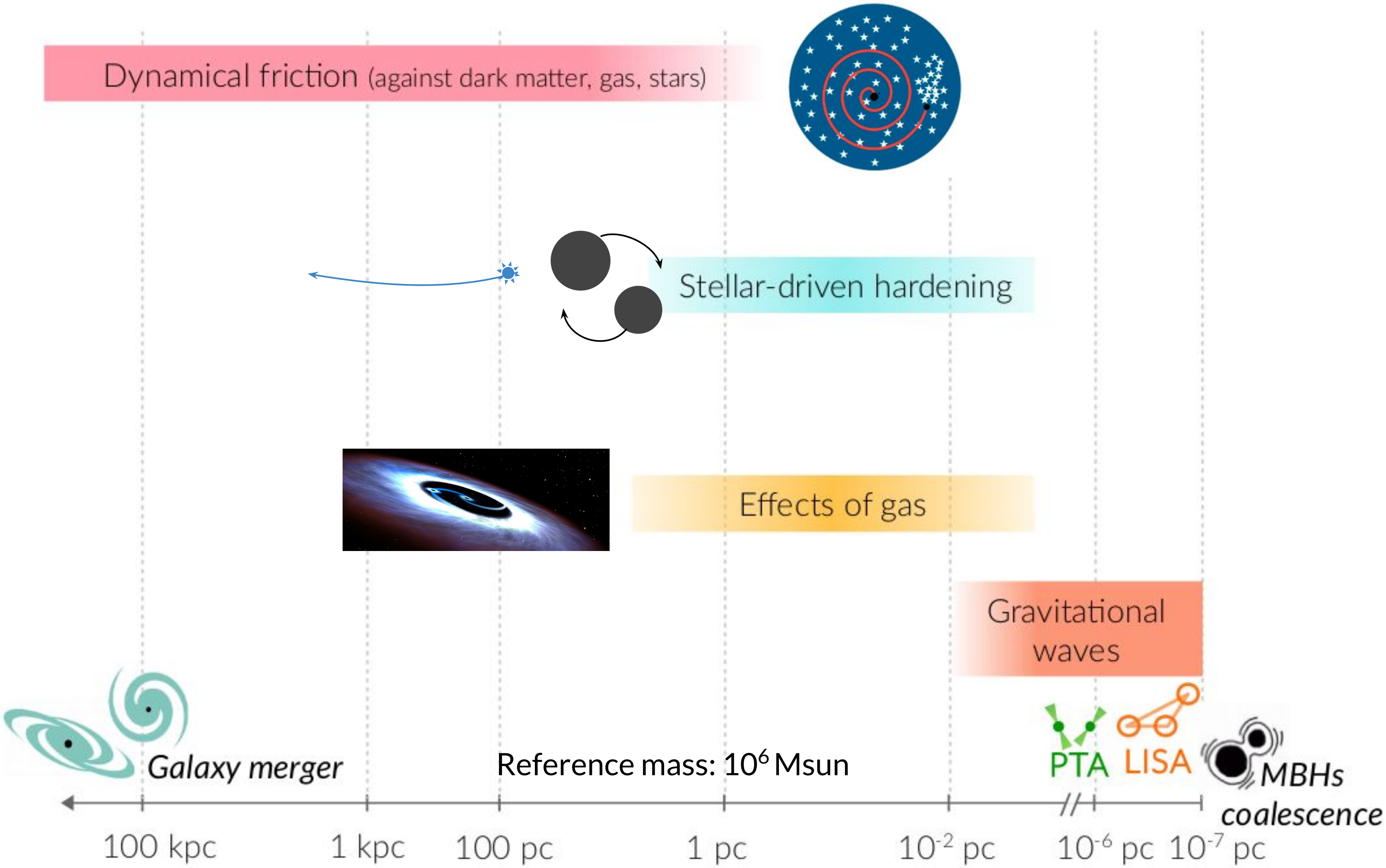






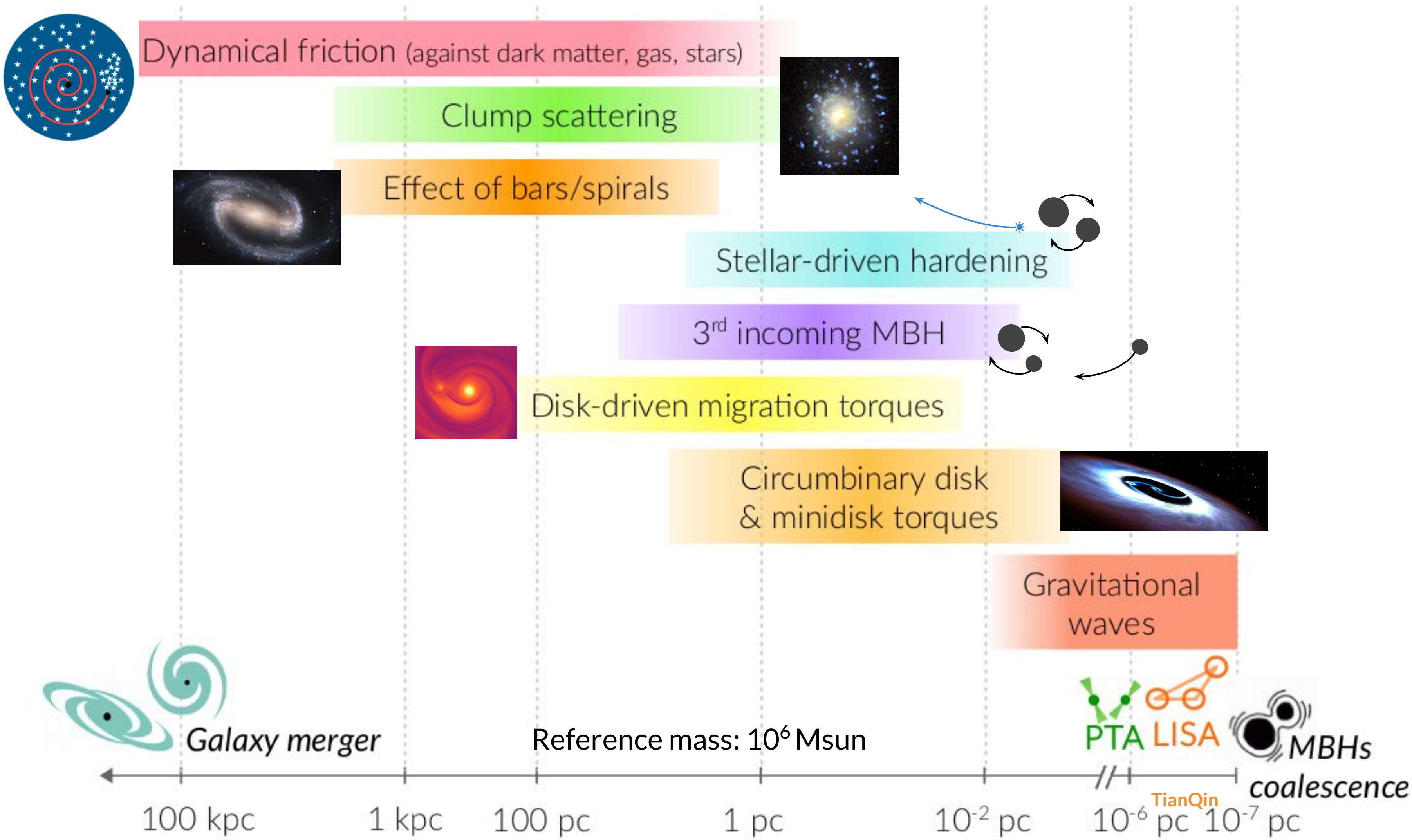
The path to coalescence ~40 years ago…

Begelman, Blandford and Rees 1980



Reference timescales:
A few 100 Myr to a few Gyr

…and the path to coalescence today



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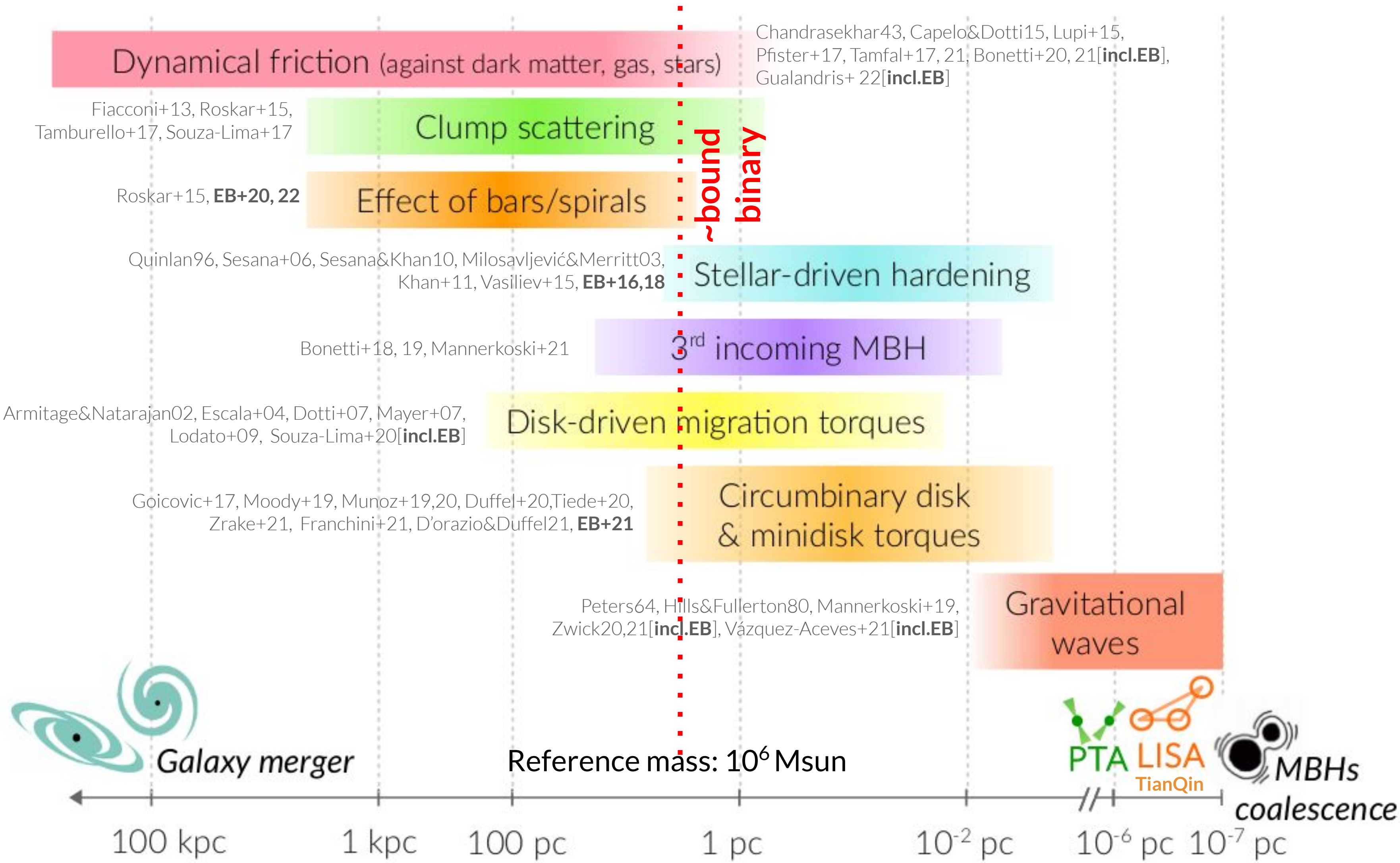

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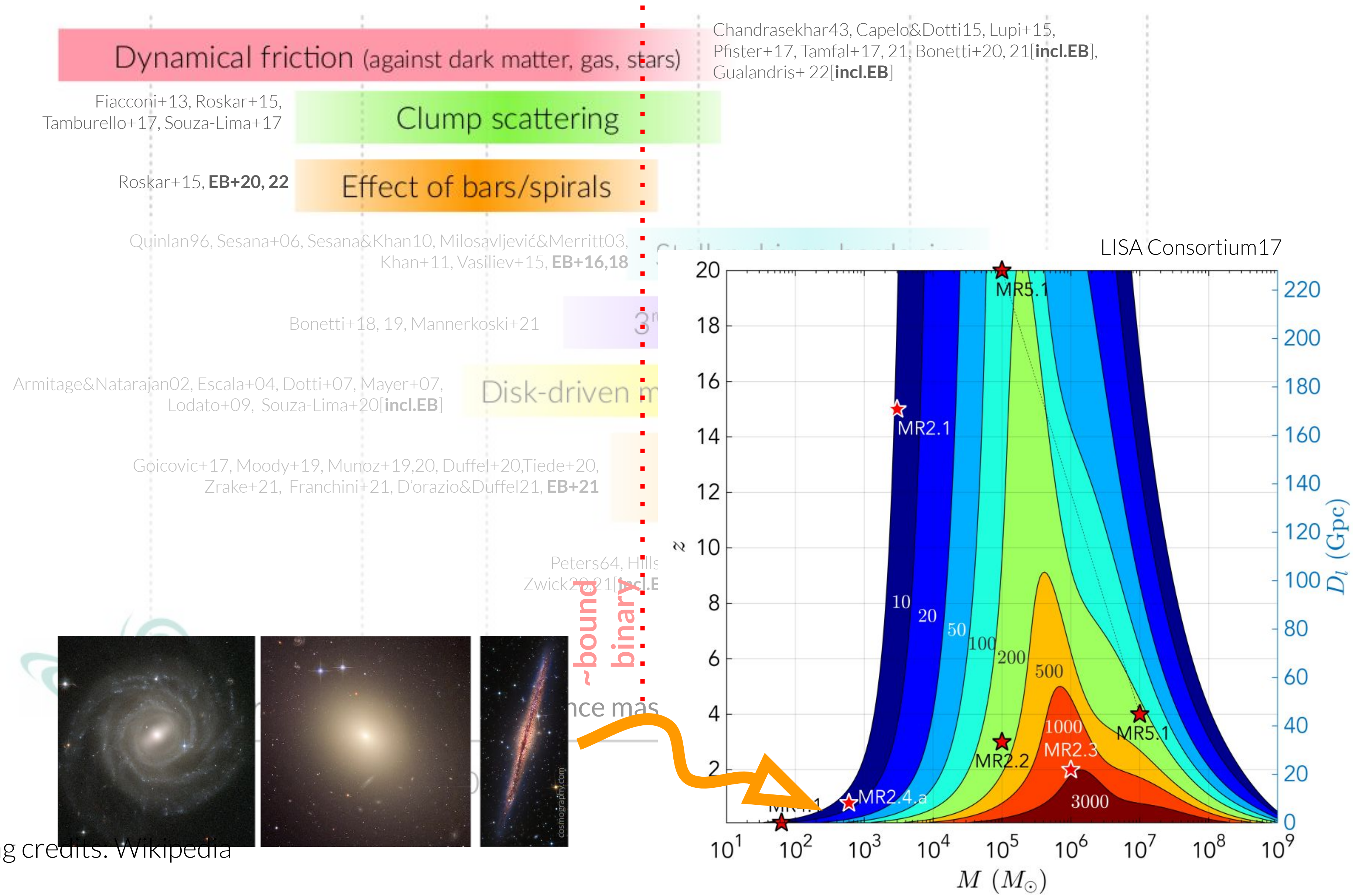
Real galaxies are complex environments



Img credits: Wikipedia

Real galaxies are complex environments

Dynamical friction (against dark matter, gas, stars)

Chandrasekhar43, Capelo&Dotti15, Lupi+15, Pfister+17, Tamfal+17, 21, Bonetti+20, 21[**incl.EB**], Gualandris+ 22[**incl.EB**]

Fiacconi+13, Roskar+15, Tamburello+17, Souza-Lima+17

Clump scattering

Roskar+15, **EB+20, 22**

Effect of bars/spirals

Quinlan96, Sesana+06, Sesana&Khan10, Milosavljević&Merritt03, Khan+11, Vasiliev+15, **EB+16,18**

Armit

-driven m

ede+20,
, EB+21

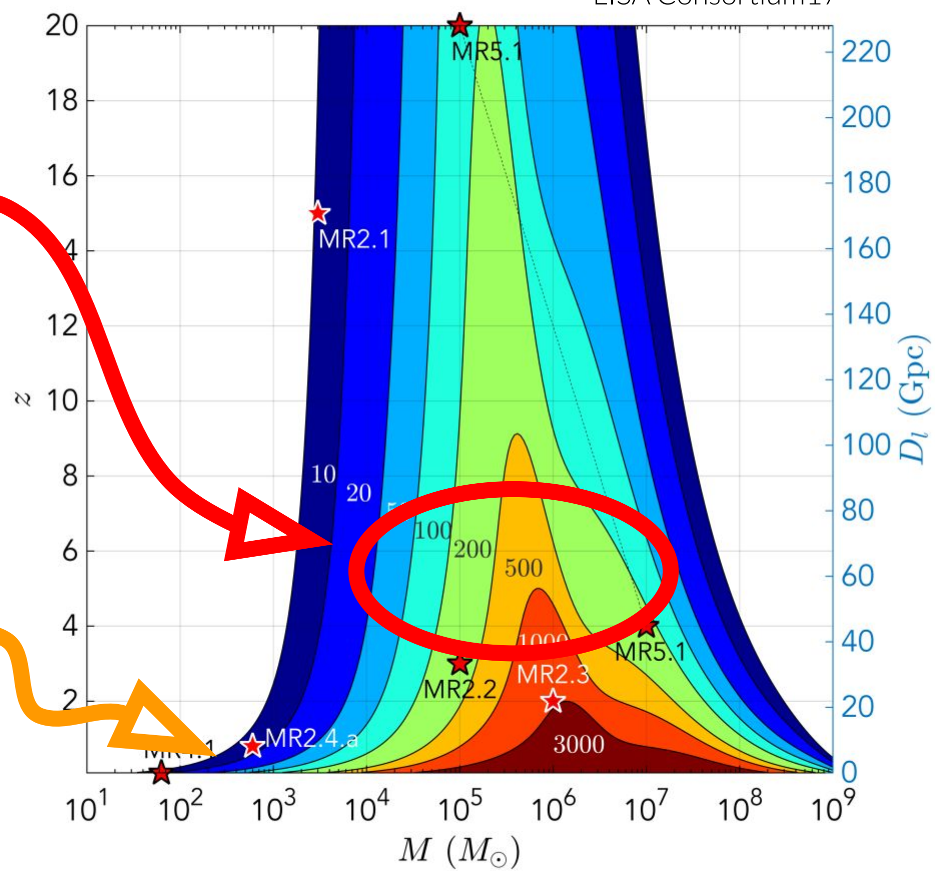
Peters64, Hills
vick20, 21[incl.E

~bound binary

nce mas

Img credits: Wikipedia

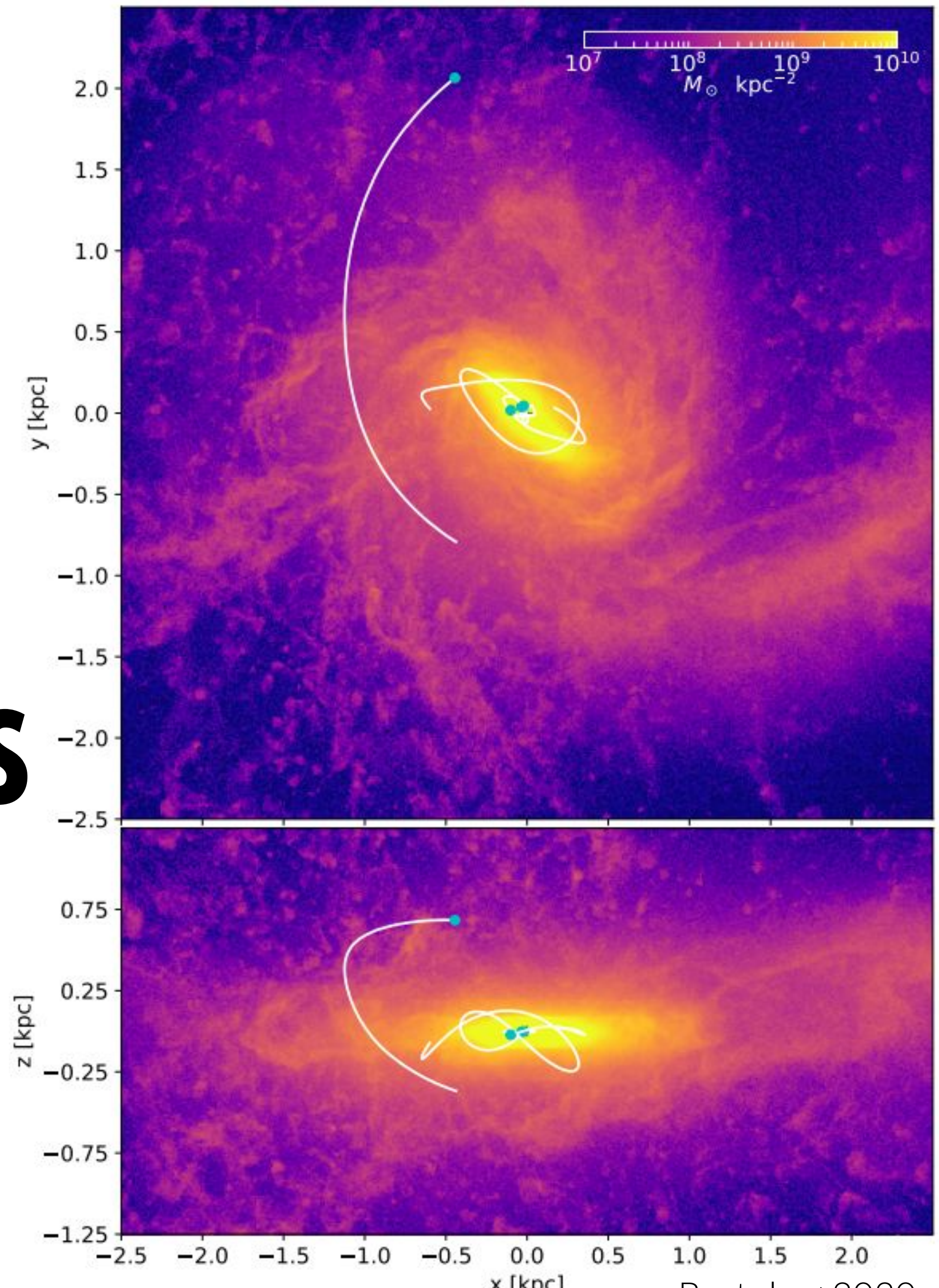
LISA Consortium17



The LARGE scale inspiral

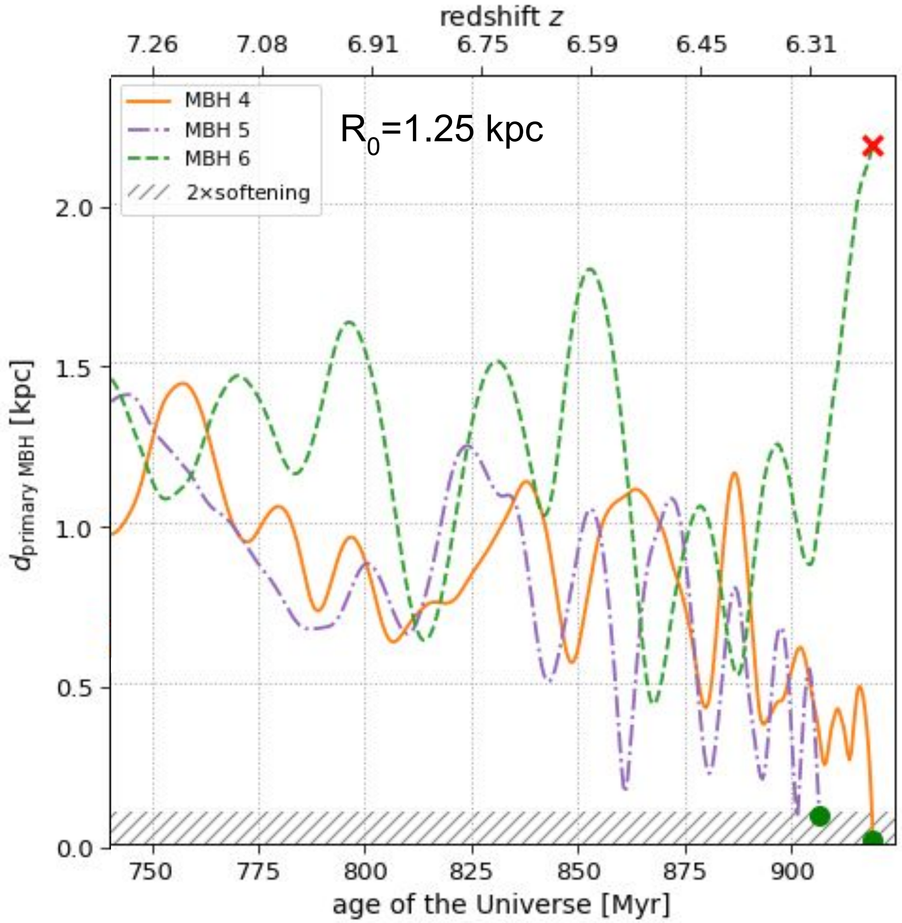
is the dynamical friction treatment good enough?

VS



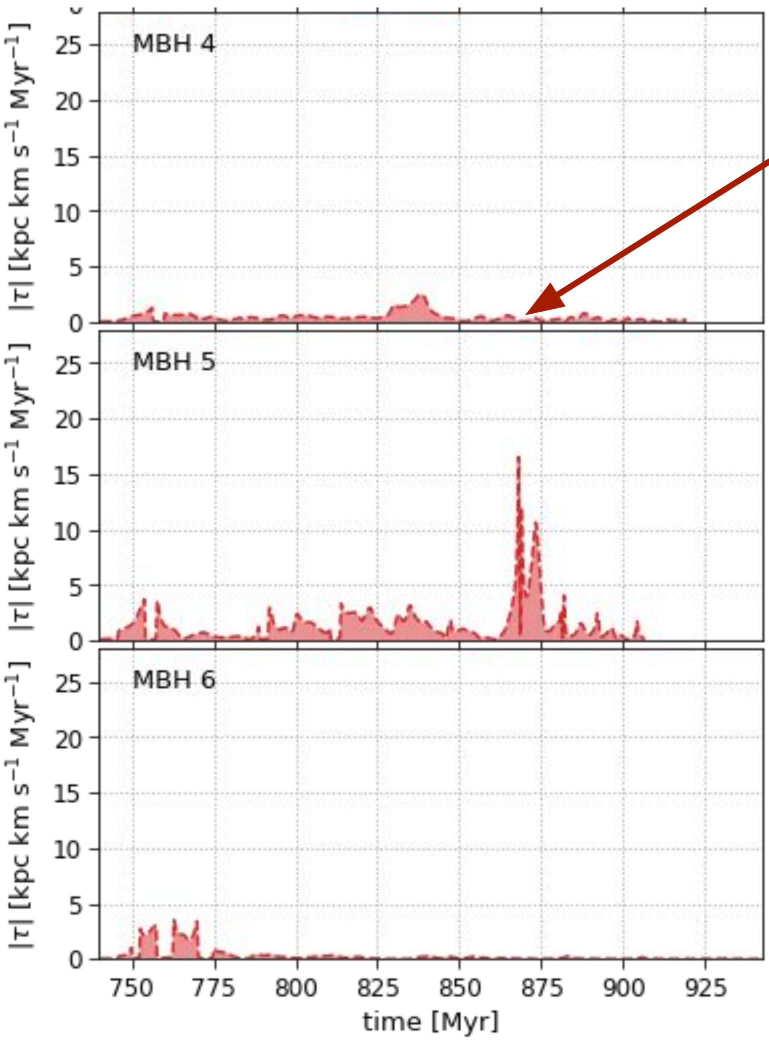
Bortolas+2020

BHs distance from the centre



Bortolas+2020

TORQUES MATTER!
Also at large scale



Dynamical friction torque modulus

From all components (dark matter, stars, gas)

Semi-analytical calculation in a sphere of 150 pc around each MBH

Gas Ostriker99

$$\mathbf{F}_{\rm DF}^{\rm gas} = -4\pi \ln\left[\frac{b_{\rm max}}{b_{\rm min}}\frac{(\mathcal{M}^2-1)^{1/2}}{\mathcal{M}}\right] G^2\, M_{\rm BH}^2 \rho_{\rm gas}\frac{\mathbf{V}}{V^3}$$

b_{min}=GM/v^2 ~0.1 pc (physical)

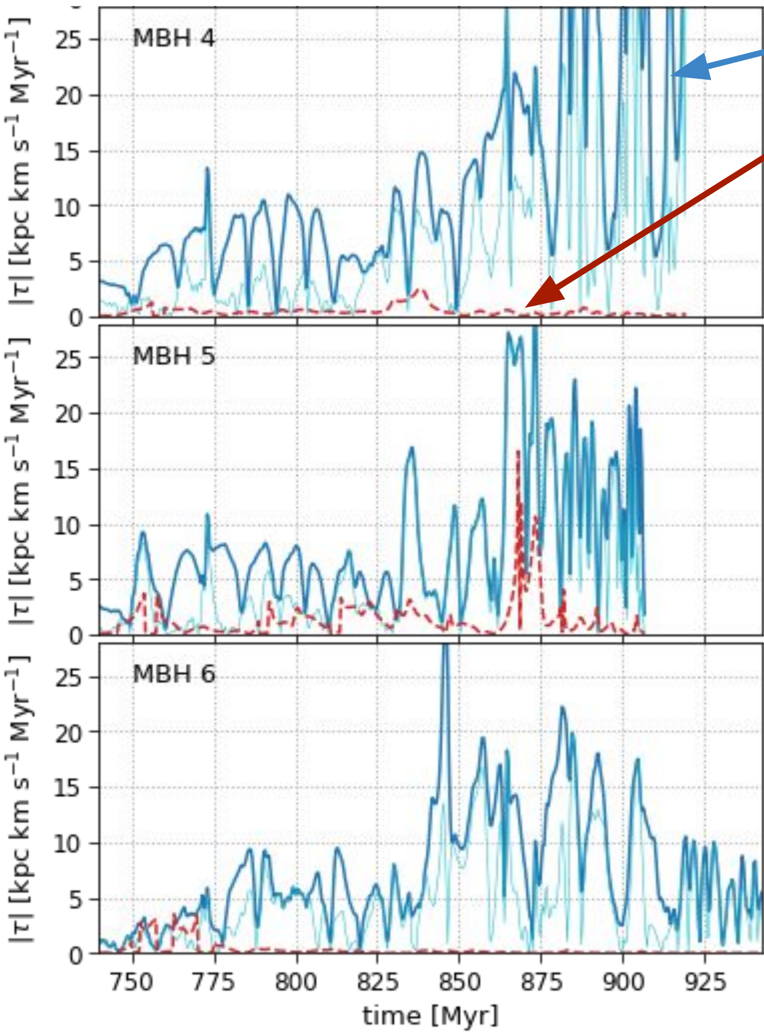
b_{max}=2 kpc (2 x disc scale radius)

Stars, DM Chandrasekhar43

$$\mathbf{F}_{\rm DF}^{\rm stars,\ DM} = -4\pi \ln \Lambda G^2 M_{\rm BH}^2 \rho_* \left[\mathrm{erf}\left(\frac{V}{\sqrt{2}\sigma}\right) - \left(\sqrt{\frac{2}{\pi}}\frac{V}{\sigma}\right)\exp\left(-\frac{V^2}{2\sigma^2}\right)\right]\frac{\mathbf{V}}{V^3}$$

Bortolas+2020

TORQUES MATTER!
Also at large scale



Global torque modulus

Dynamical friction torque modulus

From all components (dark matter, stars, gas)

Semi-analytical calculation in a sphere of 150 pc around each MBH

Gas — Ostriker99

$$\mathbf{F}_{\rm DF}^{\rm gas} = -4\pi \ln\left[\frac{b_{\rm max}}{b_{\rm min}}\frac{(\mathcal{M}^2-1)^{1/2}}{\mathcal{M}}\right] G^2\, M_{\rm BH}^2 \rho_{\rm gas}\frac{\mathbf{V}}{V^3}$$

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Bortolas+2020, see also Bortolas+22

Doggy bag #1

The simple dynamical friction treatment for massive black holes inspiral may be poor *in realistic galaxies especially:*

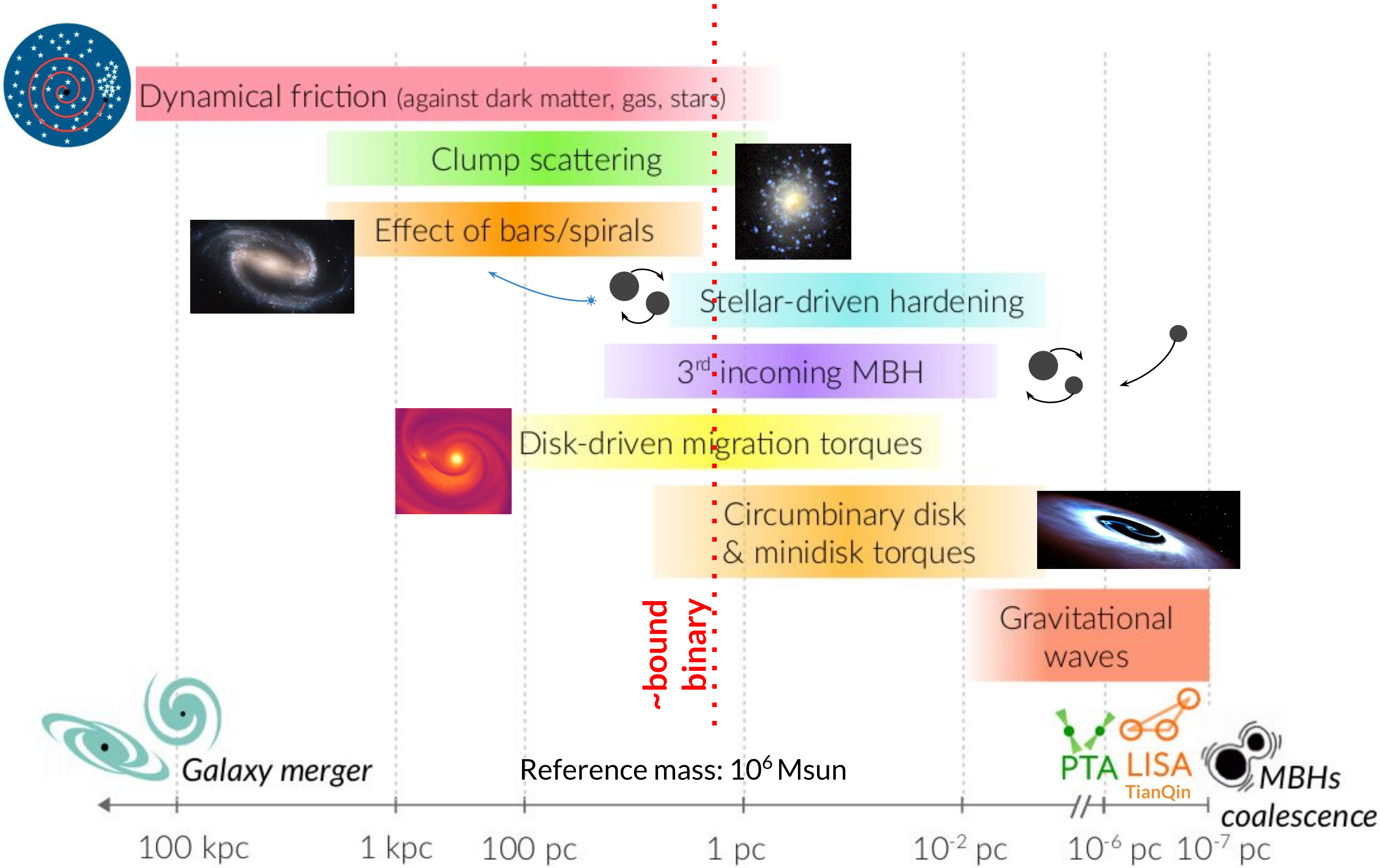
- *At high z*
- *In irregular/barred galaxies*

May I chip in…

5 cents for some discussion?

- *How to model this stochasticity in inexpensive semi-analytical models for studying the binary population and merger rates?*

Small scale (bound binary) evolution



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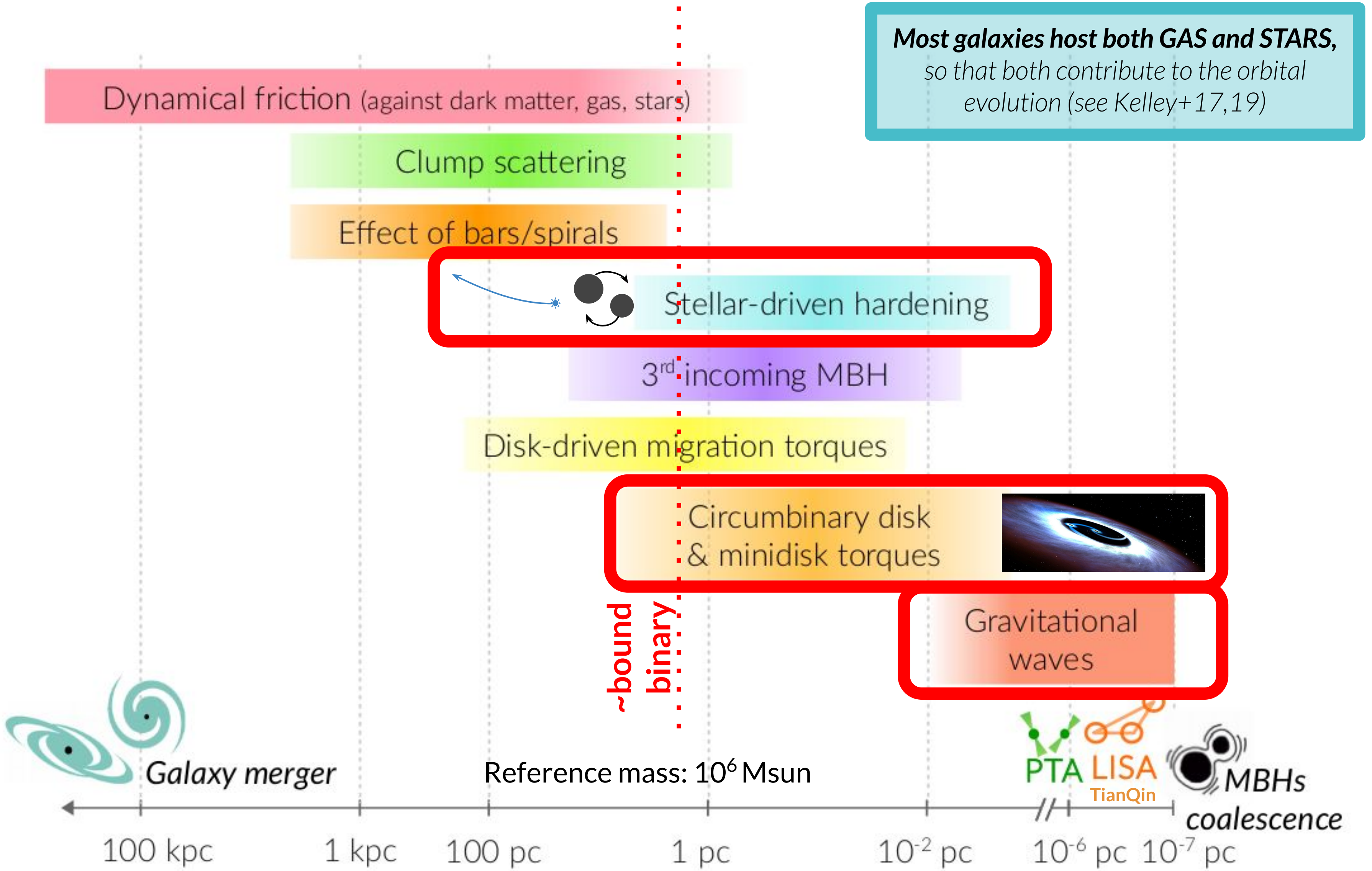
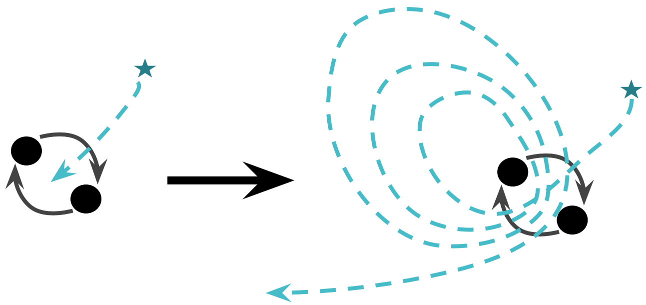
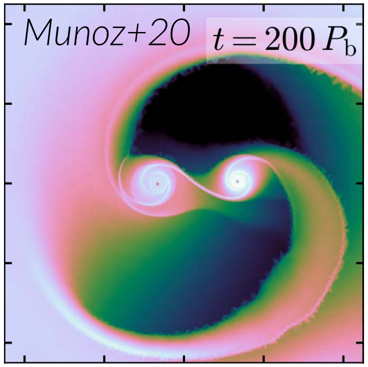


LET'S HAVE THE MOST PESSIMISTIC APPROACH

- **Stellar driven hardening** → Binary shrinking



- **Gas-driven evolution** → Shrinking or **expansion**?



Artymowicz&Lubow94, Moody+19, Munoz+19,20, Duffel+20, Tiede+20, Heath&Nixon20, Franchini+21, D'orazio&Duffel21+.... Almost everyone in the audience 😊

- **Gravitational wave emission** → Efficient small scale shrinking

• Stellar driven hardening

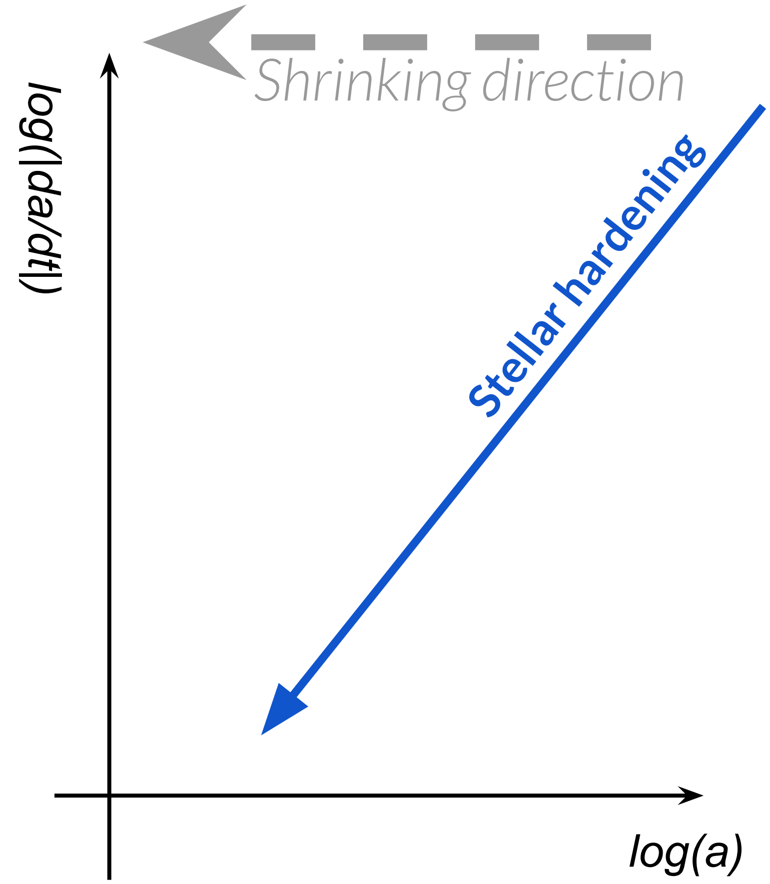
$$\frac{da_\star}{dt} \propto -a^2$$

No nuclear star cluster
M-sigma relation
(Kormendy&Ho13,Merrit+09)

Binary shrinking

$$\dot{a}_\star = -\frac{HG\rho}{\sigma}\,a^2$$

Quinlan96, Sesana+06, Sesana&Khan15



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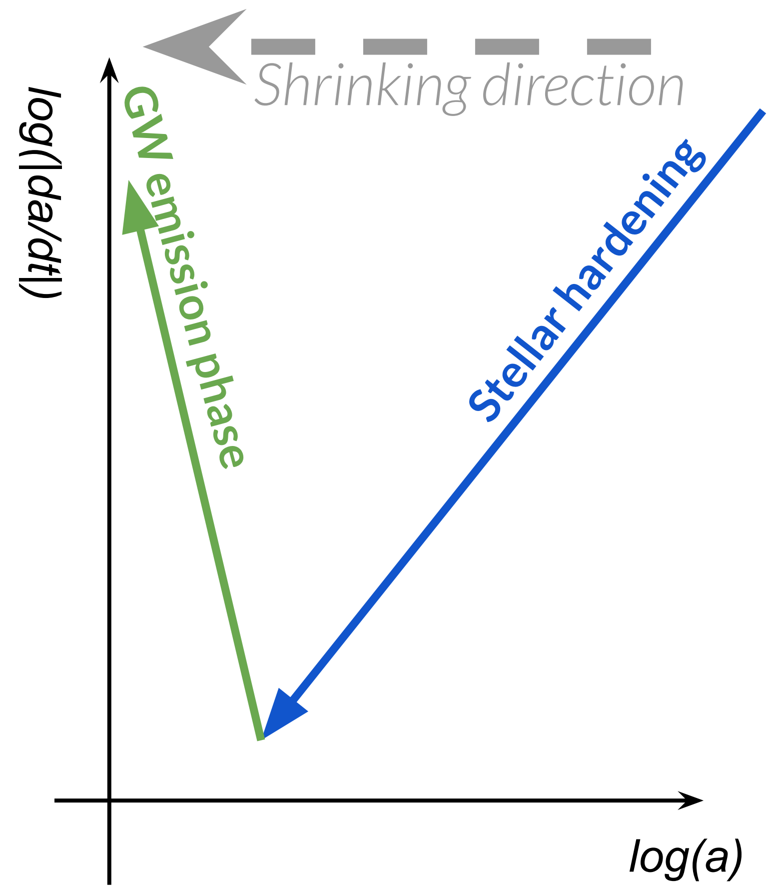


- **Gravitational wave emission**

$$\frac{da_{\rm GW}}{dt} \propto -a^{-3}$$

Efficient shrinking at small scale

$$\dot{a}_{\rm GW} = -\frac{64}{5}\frac{G^3}{c^5}\frac{q}{(1+q)^2}\frac{m^3}{a^3}$$

Peters64

- Stellar driven hardening

$$\frac{da_\star}{dt} \propto -a^2$$

Binary shrinking

- Gas-driven evolution

$$\dot{a}_{\rm gas} = 2.68 \frac{\dot{m}}{m} a$$

Munoz+20

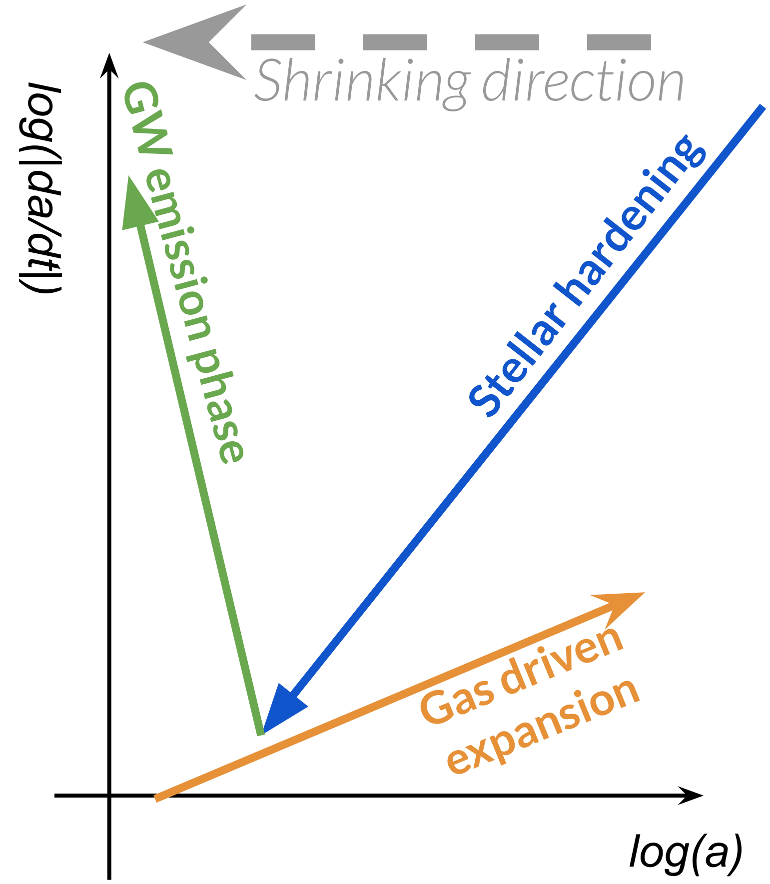
$$\frac{da_{\rm gas}}{dt} \propto +a$$

We assume binary **expansion**

- Gravitational wave emission

$$\frac{da_{\rm GW}}{dt} \propto -a^{-3}$$

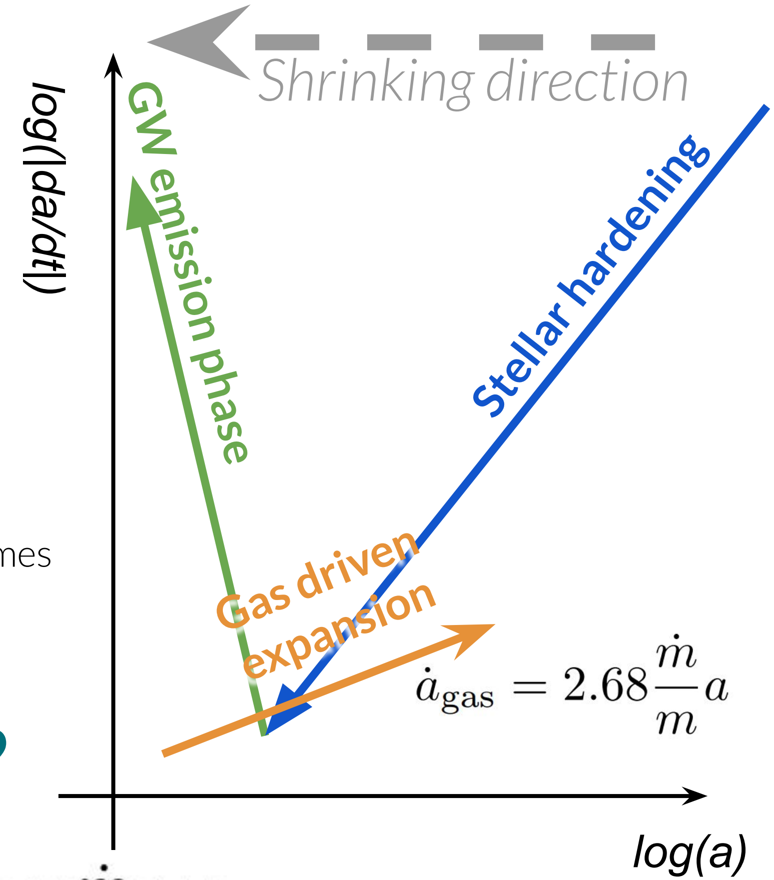
Efficient shrinking at small scale



When is the gas effective?

$$\begin{cases} \dot{a}_\star = -\dfrac{HG\rho}{\sigma}a^2 \\ \dot{a}_{\rm gas} = 2.68\dfrac{\dot{m}}{m}a \\ \dot{a}_{\rm GW} = -\dfrac{64}{5}\dfrac{G^3}{c^5}\dfrac{q}{(1+q)^2}\dfrac{m^3}{a^3} \end{cases}$$

Some more assumptions:
Equal mass binary;
Binary eccentricity = 0 at all times

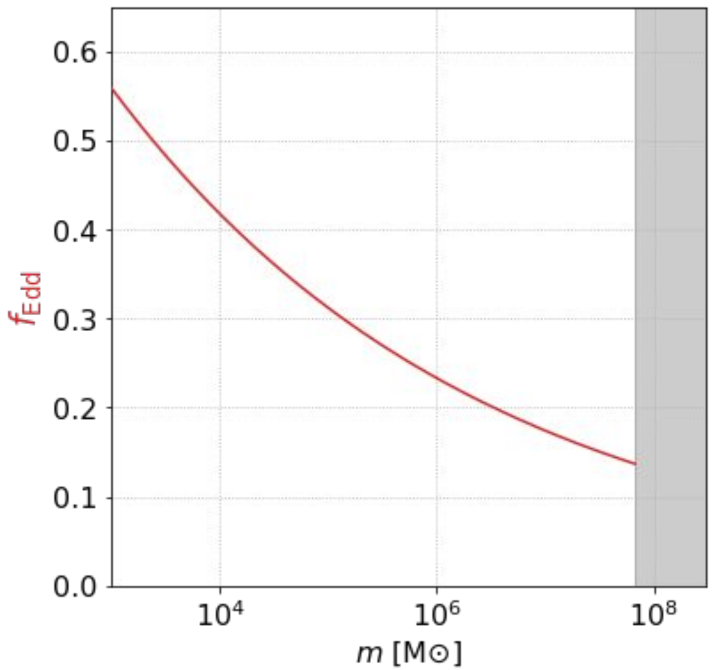


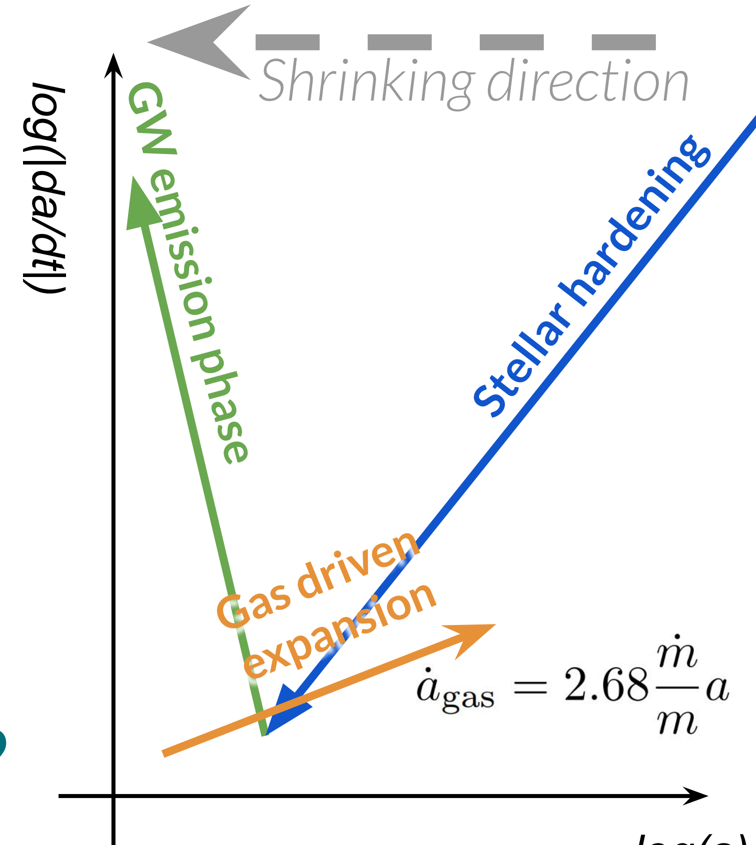
➡ How do we model accretion?

- **Fixed eddington ratio** $f_{\rm Edd}$ so that $\dot{m} = f_{\rm Edd}\dot{m}_{\rm Edd} \propto m$
  (the accretion rate grows linearly with the binary mass, and remains a fixed fraction of the Eddington accretion rate)

NOTE THAT DIFFERENT ASSUMPTIONS (FIXED MDOT) FOR THE MASS ACCRETION RATE RESULT IN AN EVEN LESS EFFICIENT GAS-DRIVEN EXPANSION

When is the gas effective?





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Bortolas+2021, ApjL, 918 L15

Can the binary expand indefinitely?

NO!

THE SELF GRAVITATING RADIUS

Franchini+21

Can the binary expand indefinitely?

NO!
THE SELF GRAVITATING RADIUS

Franchini+21

$$R_{sg} \propto f_{Edd}^{-22/45} \, m^{-7/45}$$

Perego+09

$R_{sg} \sim 10^{-2}$ pc for a 10^6 solar mass binary accreting at Eddington

Can the binary expand indefinitely?

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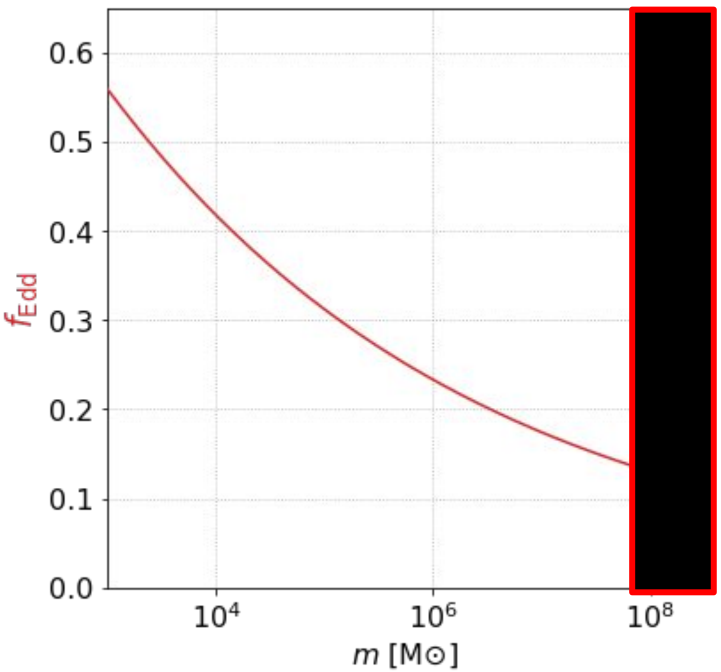
THE SELF GRAVITATING RADIUS



$$R_{sg} \propto f_{Edd}^{-22/45}\, m^{-7/45}$$

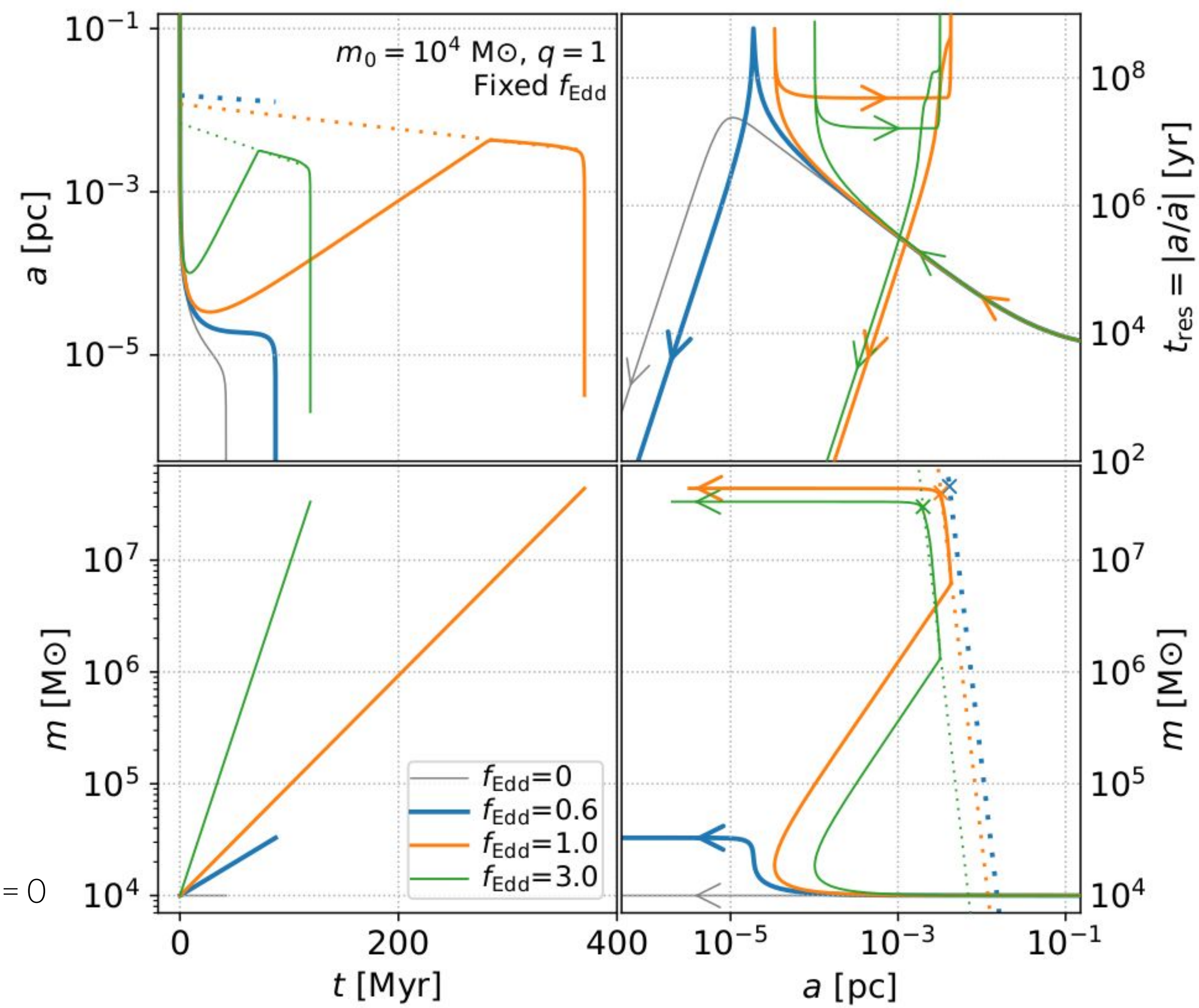
$R_{sg} \sim 10^{-2}$ pc for a 10^6 solar mass binary accreting at Eddington

Here the disk is self gravitating down to the scales at which GW always dominate

Elisa Bortolas, KITP, April 7 2022

Bortolas+2021, ApjL, 918 L15

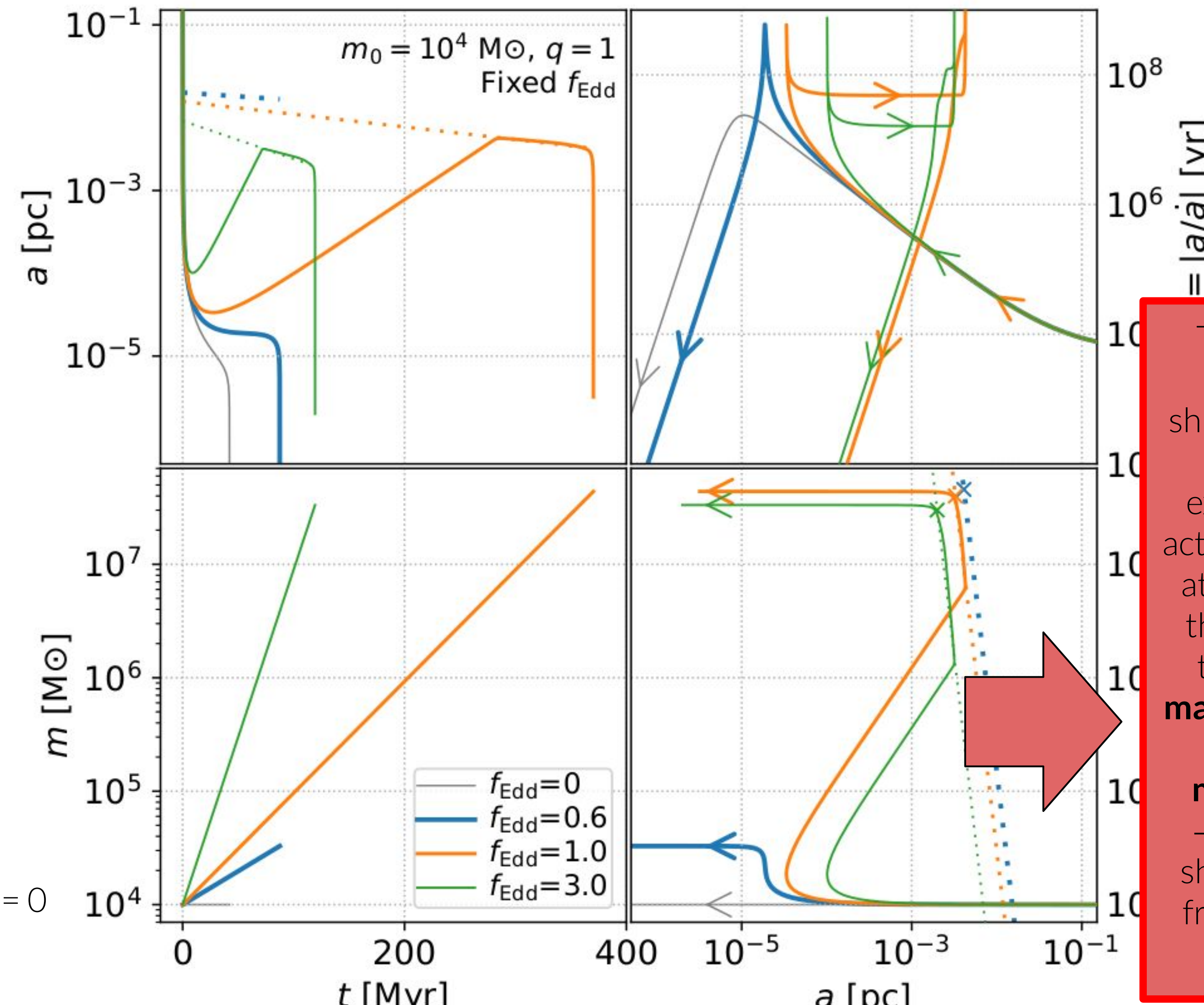
Evolution for fixed f_{Edd}



Equal mass binary;
Binary eccentricity = 0
at all times

Bortolas+2021, ApjL, 918 L15

Evolution for fixed f_{Edd}

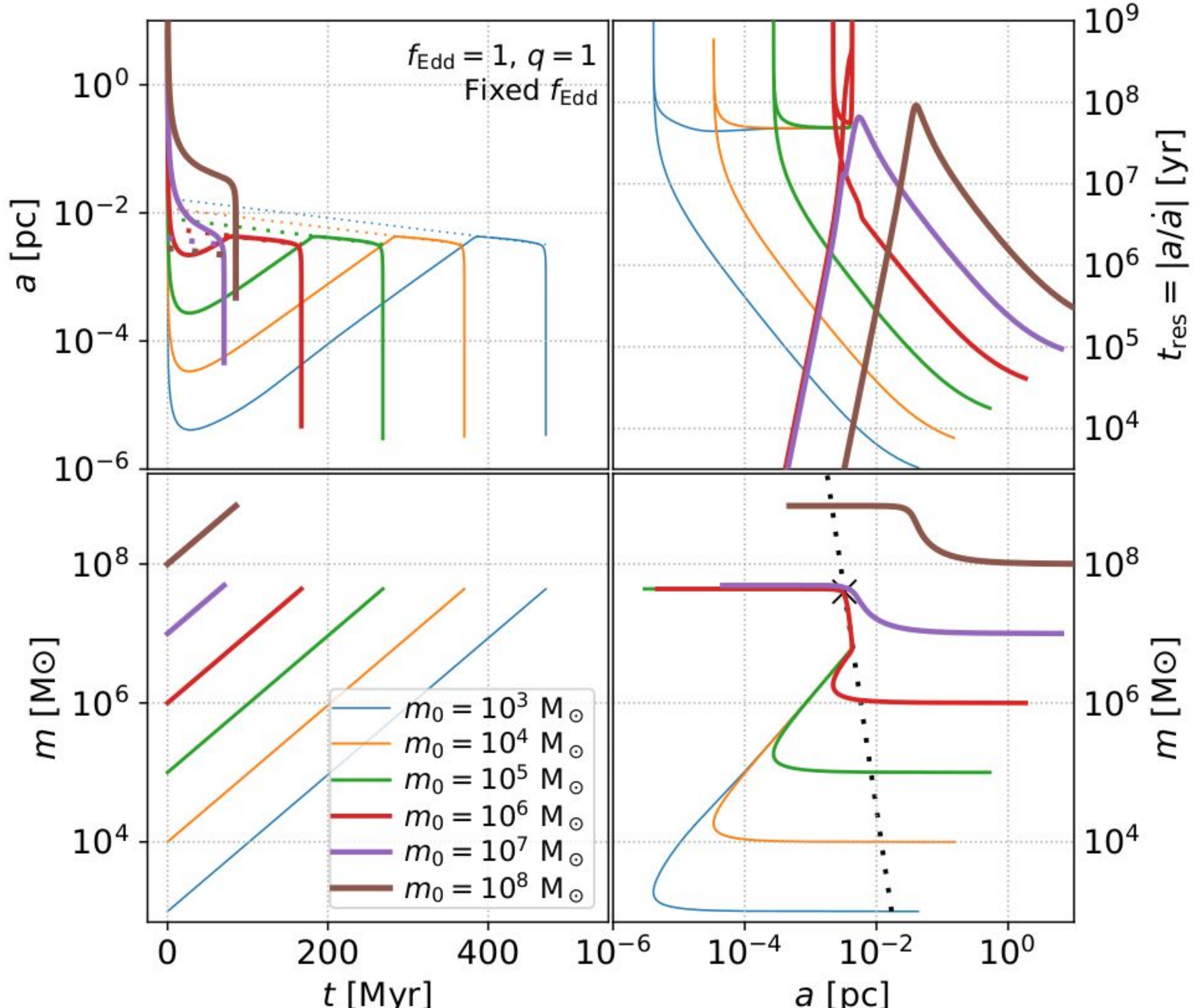


Equal mass binary;
Binary eccentricity = 0 at all times

The binary efficient shrinking even when gas expansion is active has to be attributed to the fact that the **binary mass grows by orders of magnitude** → this may shift binaries from LISA to PTA band

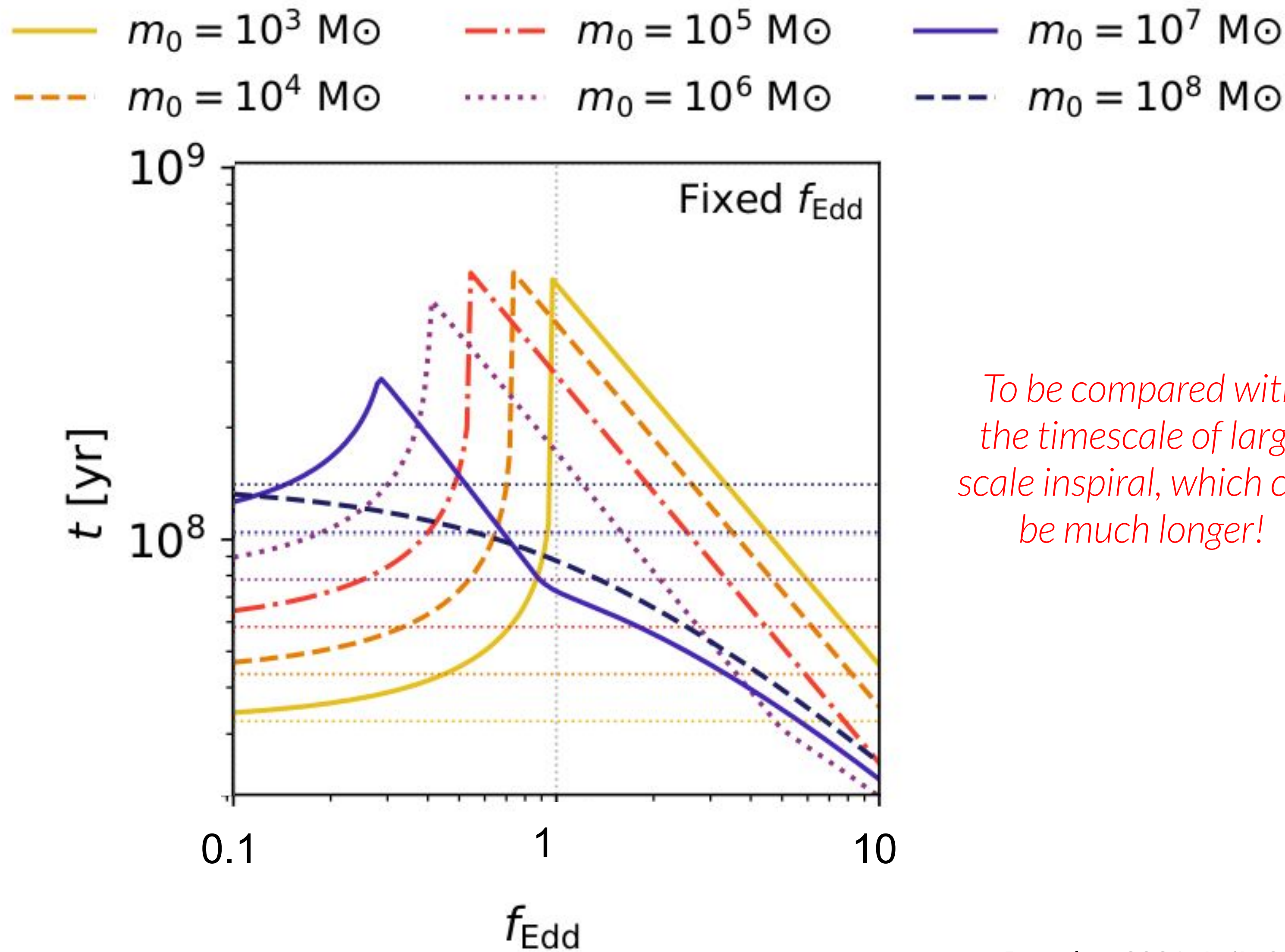
Bortolas+2021, ApjL, 918 L15

Different initial binary mass



Bortolas+2021, ApjL, 918 L15

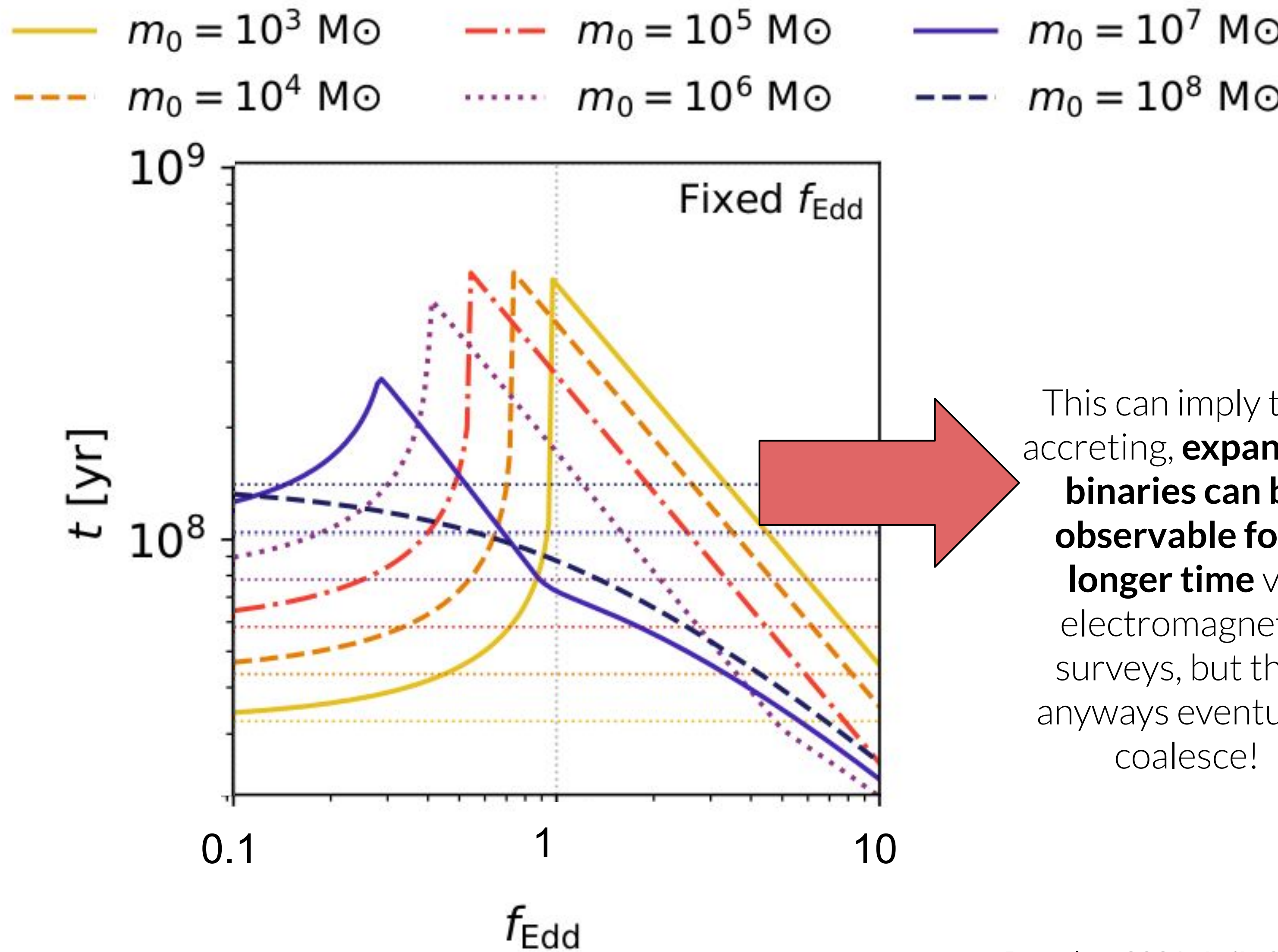
Inspiral timescale



To be compared with the timescale of large scale inspiral, which can be much longer!

Bortolas+2021, ApjL, 918 L15

Inspiral timescale



This can imply that accreting, **expanding binaries can be observable for a longer time** via eletromagnetic surveys, but they anyways eventually coalesce!

Bortolas+2021, ApjL, 918 L15

Doggy bag #2

- ***GAS AND STARS GENERALLY COEXIST!!***
- ***Gas driven expansion does not dramatically impact the coalescence time of massive binaries***

→ **Expansion necessarily reverts into shrinking** when the binary mass gets large enough owing to accretion: at that point, gravitational wave emission becomes dominant.

May I chip in…

another 5 cents for some discussions/ideas?

- *This would imply expanding binaries would be observed at lower frequencies (PTAs)*
- *We should think of better simulations/works accounting for concurrent effects of stars and gas*
- *Would it be possible to use a similar approach in the framework of stellar binaries? [e.g. tides instead of stellar hardening and so on…]*