UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

EPTA

LISA CONSORTIUM

# The massive black hole binary path to coalescence

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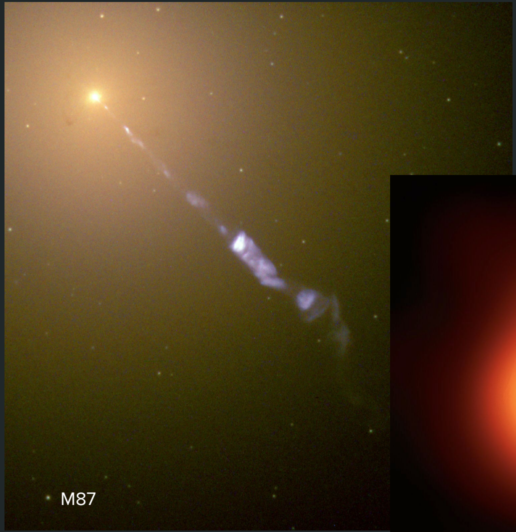
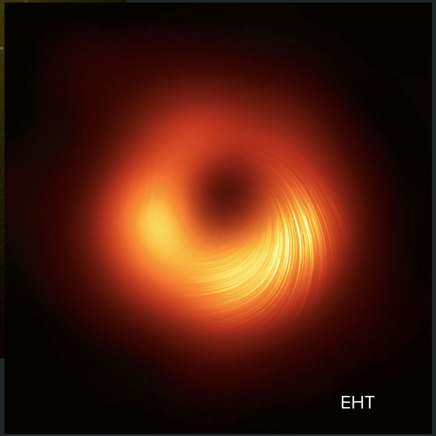
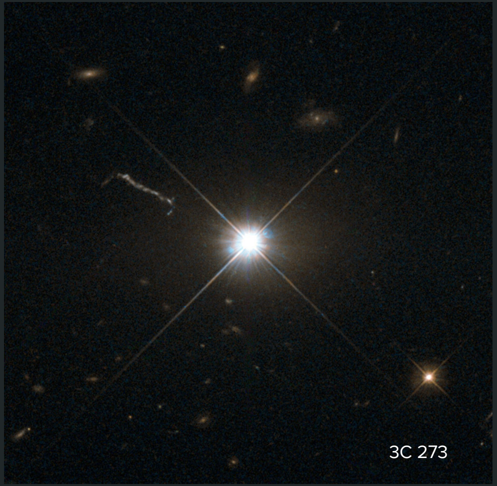
# Massive black holes

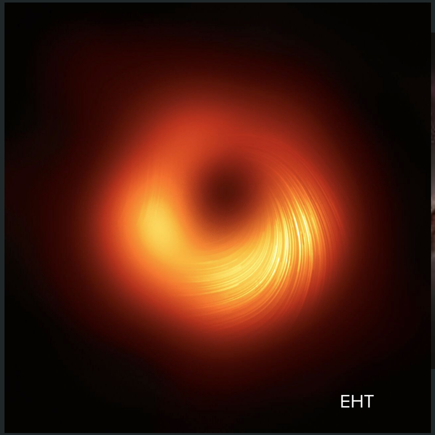
- Observed in the nuclei of several galaxies



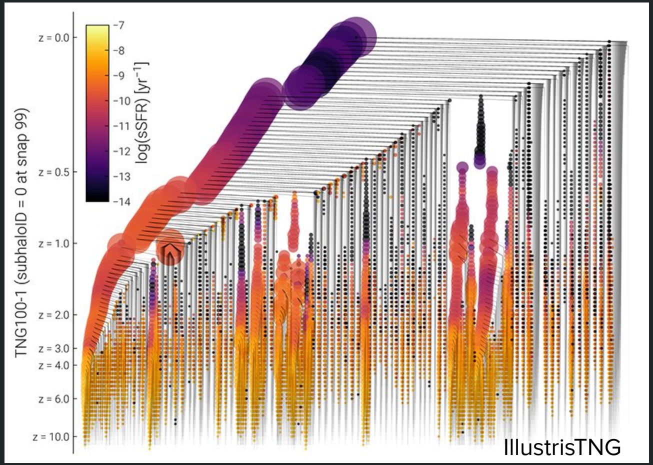



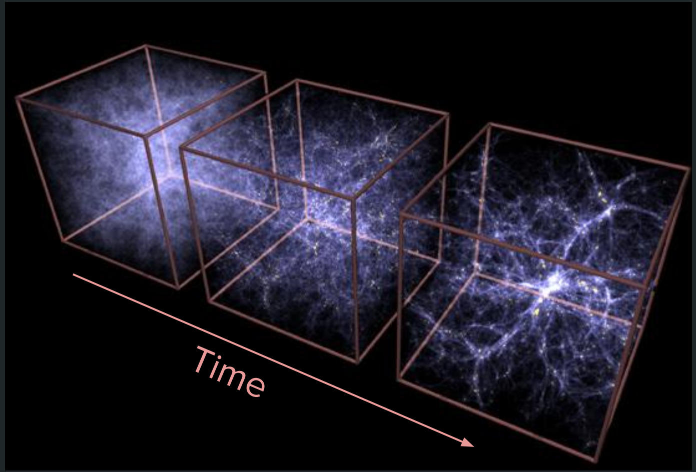
# Massive black holes




- Observed in the nuclei of several galaxies

- Following galaxy mergers, massive black hole binaries (MBHB) can form



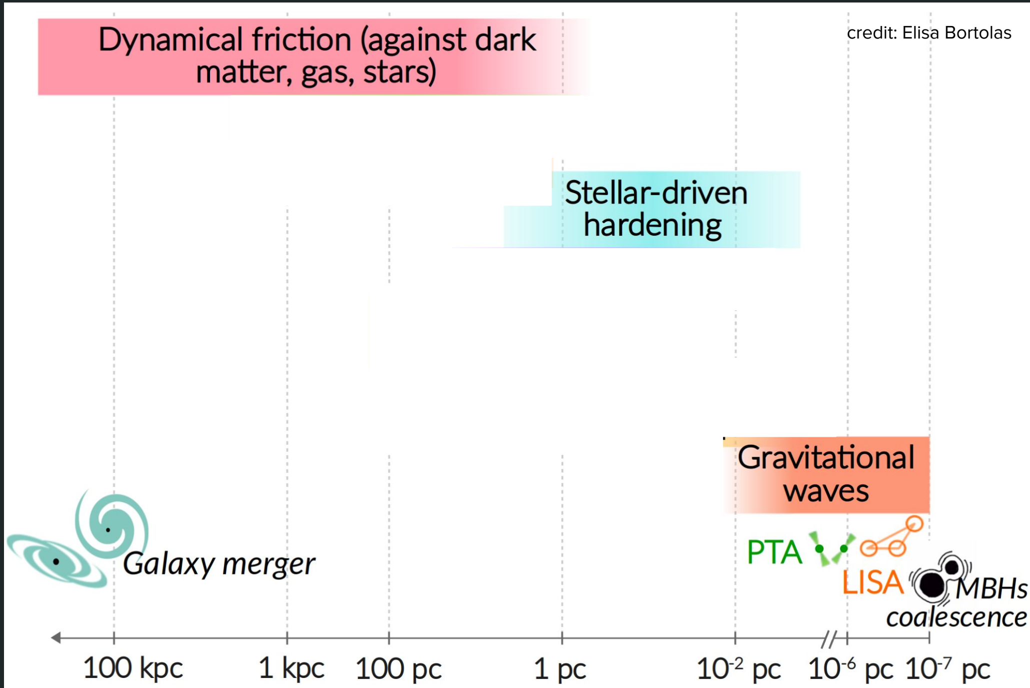
# MBHB path to coalescence - Multiscale studies

A journey covering almost 10 order of magnitude in separation!

↓

Historically, three main evolutionary phases were identified

(Begelman, Blandford & Rees 1980)



# MBHB path to coalescence - Multiscale studies

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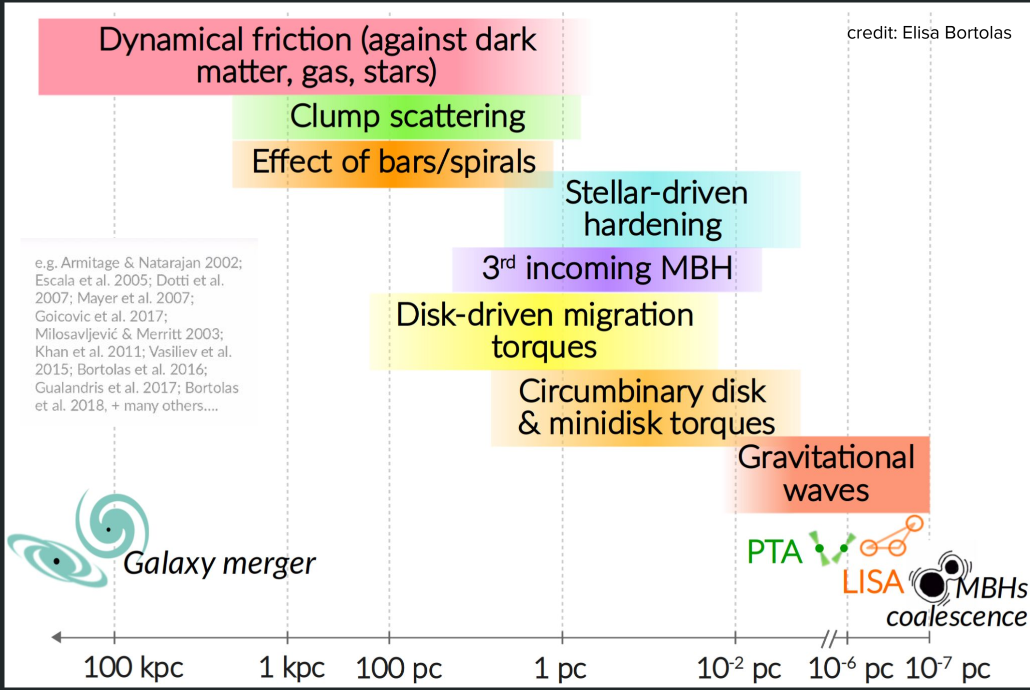
At each scale different approaches and techniques are needed



# MBHB path to coalescence - Multiscale studies

A journey covering almost 10 order of magnitude in separation!

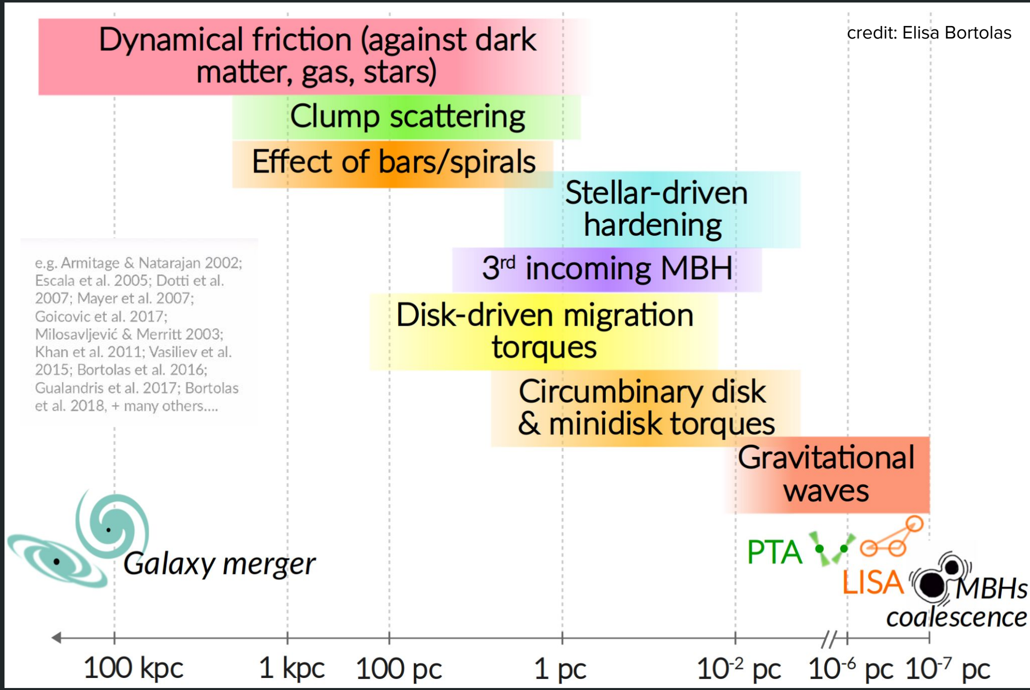
At each scale different approaches and techniques are needed

**Fully numerical**

More accurate, but expensive

**Semi-analytical**

Much faster, but make approximations




# MBHB path to coalescence - Large scale

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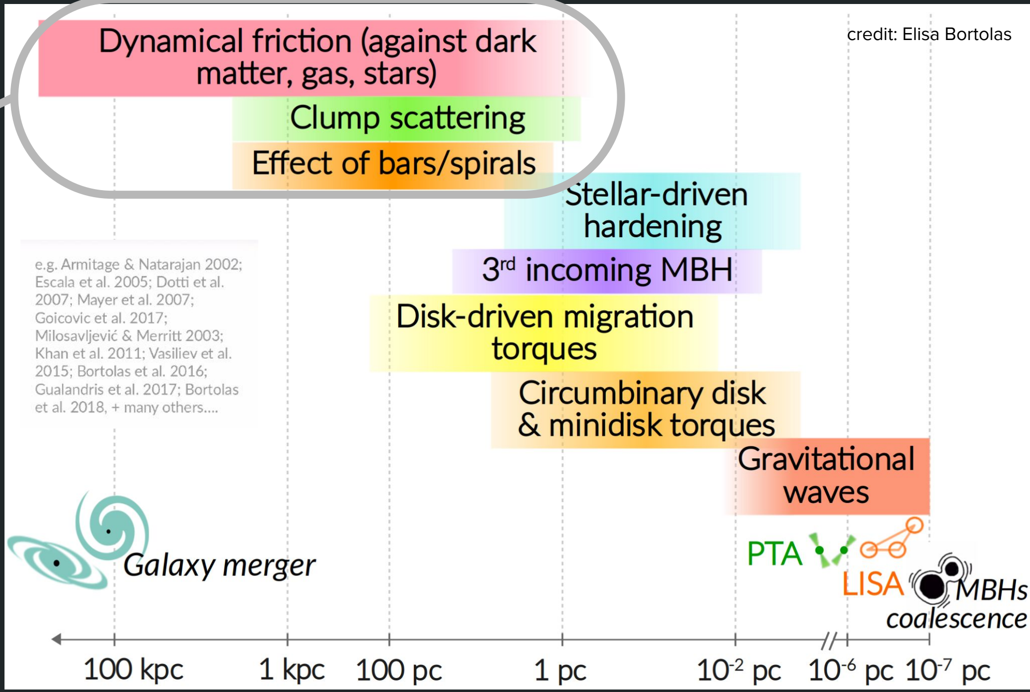
Dynamical friction:

Drag force arising from the cumulative effect of large number of hyperbolic encounters (Chandrasekhar 1943)




Generally considered the main driver of large scale evolution, but systematically analysed in idealised systems

Galaxies show a range of different morphologies, non-smoothness and a certain degree of rotation

Full N-body is the best you can do

A systematic study through N-body sims is not feasible

# MBHB path to coalescence - Large scale

Development of a **semi-analytical framework** to study the effect of **galactic morphology** on **MBH sinking timescale**

Ingredients:

- efficient evaluation of conservative acceleration from generic galactic profiles of any shape
- recipe for dynamical friction, also in rotationally supported structures
- Tidal stripping, if MBH surrounded by stars

Galaxy is considered a fixed background

$$\phi(\mathbf{x}) = \phi_{\rm halo} + \phi_{\rm disc} + \phi_{\rm bulge} + \dots$$

Dissipative force (though not really dissipative in nature)

$$\mathbf{a}_{\rm df} = -2\pi G^2 \ln(1+\Lambda^2) m_p \rho \left( \mathrm{erf}(X) - \frac{2X\mathrm{e}^{-X^2}}{\sqrt{\pi}} \right) \frac{\mathbf{v}_p}{|\mathbf{v}_p|^3},$$

Crucial test:

Validation against full N-body simulations

Bonetti+20, Bortolas+20, Varisco+23 in prep.

# MBHB path to coalescence - Large scale

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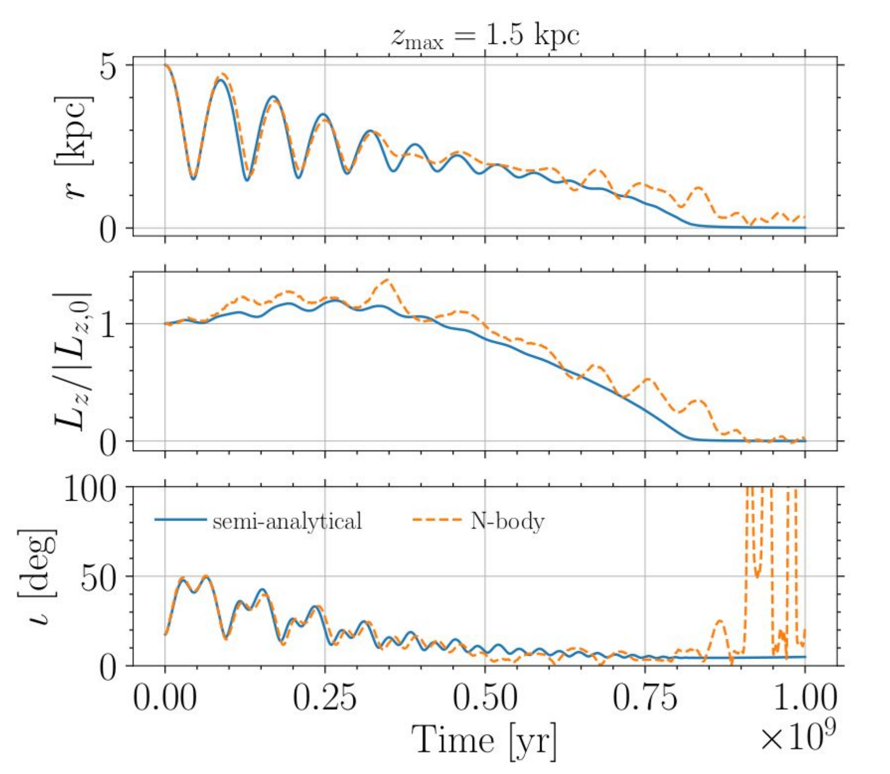
Disc galaxy




Bonetti+20, Bortolas+20, Varisco+23 in prep.

# MBHB path to coalescence - Large scale

**Evolution in barred galaxies**

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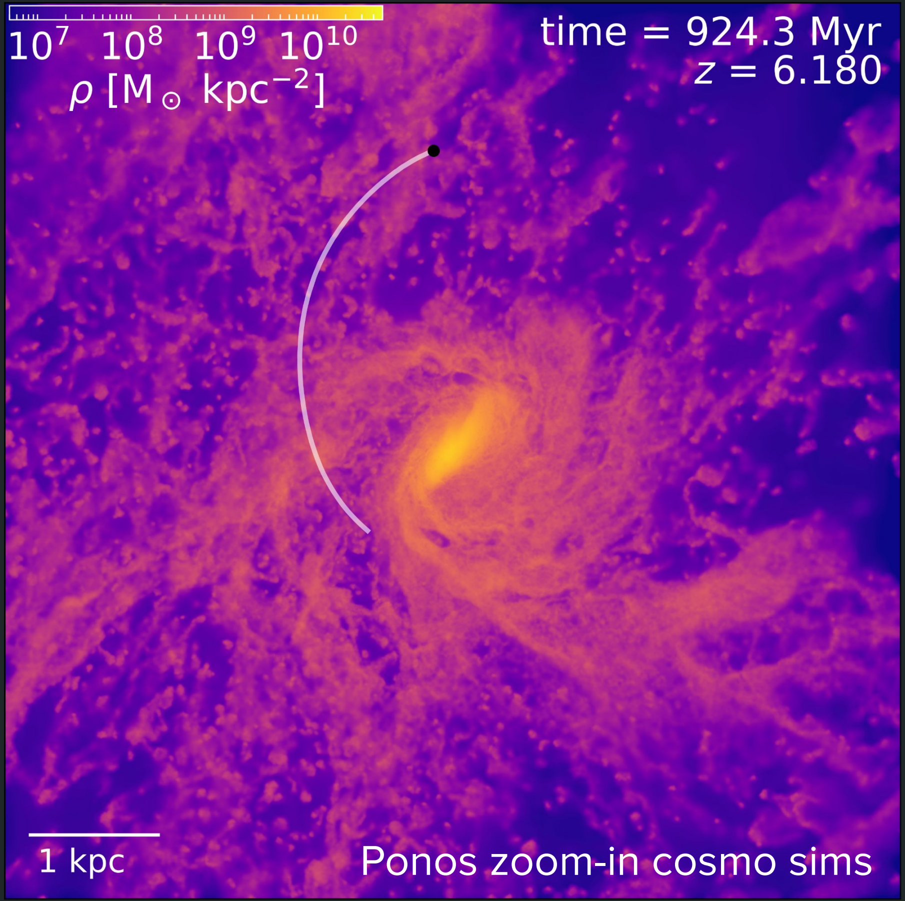
**Stochasticity becomes relevant**

an inspiralling MBH can undergo either a rapid sinking or erratic dynamics




Bortolas+21, Bonetti+21, Bonetti+20, Bortolas+20

# MBHB path to coalescence - Semi-analytical

## MBH evolution in semi-analytical barred galaxies

| Component | Model | Mass [$M_\odot$] | scale length [kpc] | others |
|---|---|---|---|---|
| Bulge* | Dehnen (1993) | $M_B = 5 \times 10^9$ | $r_B = 0.7$ | $\gamma = 1$ |
| Disc* | Exponential (Binney & Tremaine 2008) | $M_D = 3 \times 10^{10}$ | $(r_D, z_D) = (3, 0.3)$ | – |
| Halo | Navarro, Frenk & White (1996) | $M_H = 4.317 \times 10^{11}$, $M_V = 8 \times 10^{11}$ | $r_H = 16$, $r_V = 245$ | $c_H = 15.3$ |
| Bar | *Softened Needle* (Long & Murali 1992) | $M_{bar} = 1.8 \times 10^{10}$ | $(a, b, c)_{bar} = (5, 2, 0.3)$ | $\omega_{bar} = 40$ km s$^{-1}$ kpc$^{-1}$ |

Goal:

Take advantage of the computational efficiency to largely explore the parameter space of initial orbital configurations

Bortolas+22

# MBHB path to coalescence - Orbits in the rotating frame

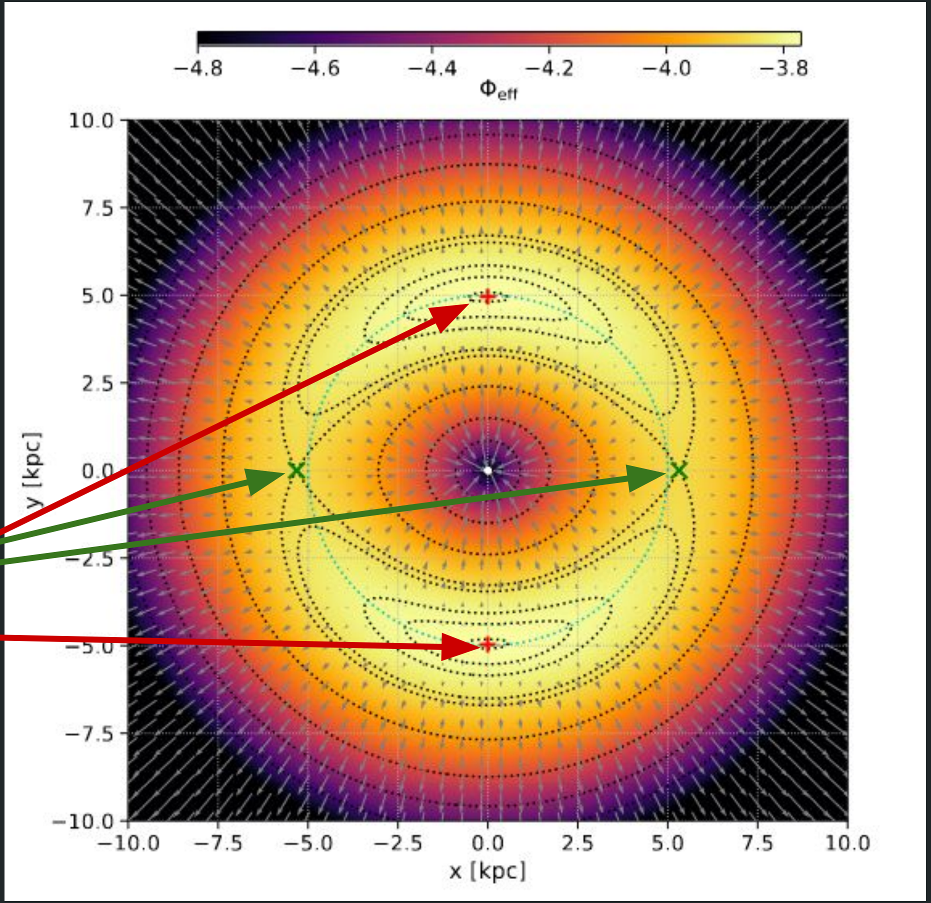
Effective potential:

$$\Phi_{\rm eff} = \Phi - \frac{1}{2}\omega_{\rm bar}^2 r^2$$

| Label | Value |
|---|---|
| Bar semi-major axis | 5.0000 kpc |
| Co-rotation radius | 5.0041 kpc |
| Inner Lindblad resonance | 0.5746 kpc |
| Outer Lindblad resonance | 8.8870 kpc |
| Saddle radius ($\Phi_{\rm eff}$) | 5.3165 kpc |
| Maxima radius ($\Phi_{\rm eff}$) | 4.9620 kpc |

Jacobi energy:

$$E_{\rm J} = v_p^2/2 + \Phi_{\rm eff}$$



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Effective potential:

$$\Phi_{\rm eff} = \Phi - \frac{1}{2}\omega_{\rm bar}^2 r^2$$

Jacobi energy:

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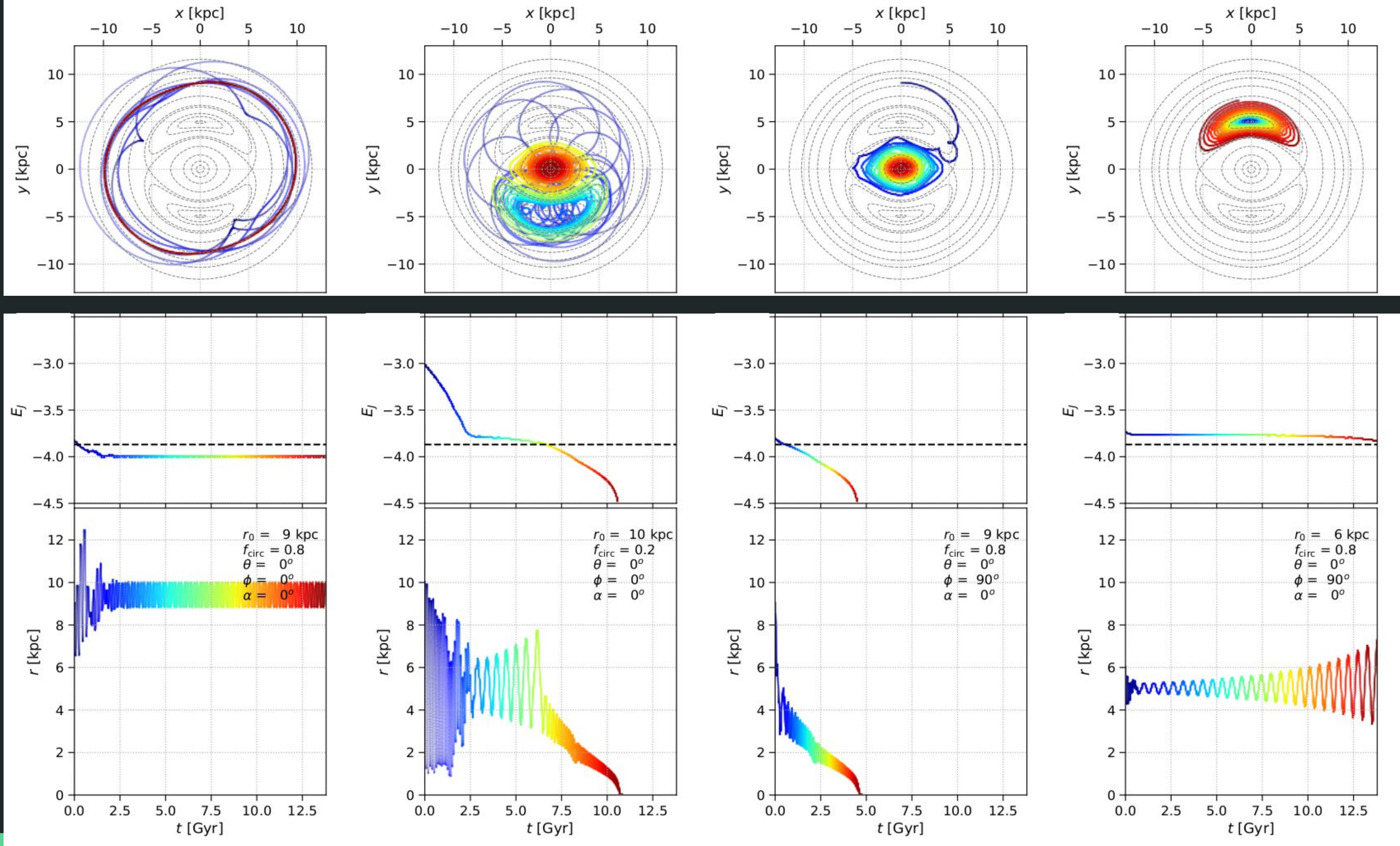
Radius from the galactic centre



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Goal:

Take advantage of the computational efficiency to largely explore the parameter space of initial orbital configurations

**Stochastic interaction between the bar and the infalling MBH can affect the evolution increasing the number of successful inspirals (<u>especially at low mass</u>), but in some cases hindering radial decay**

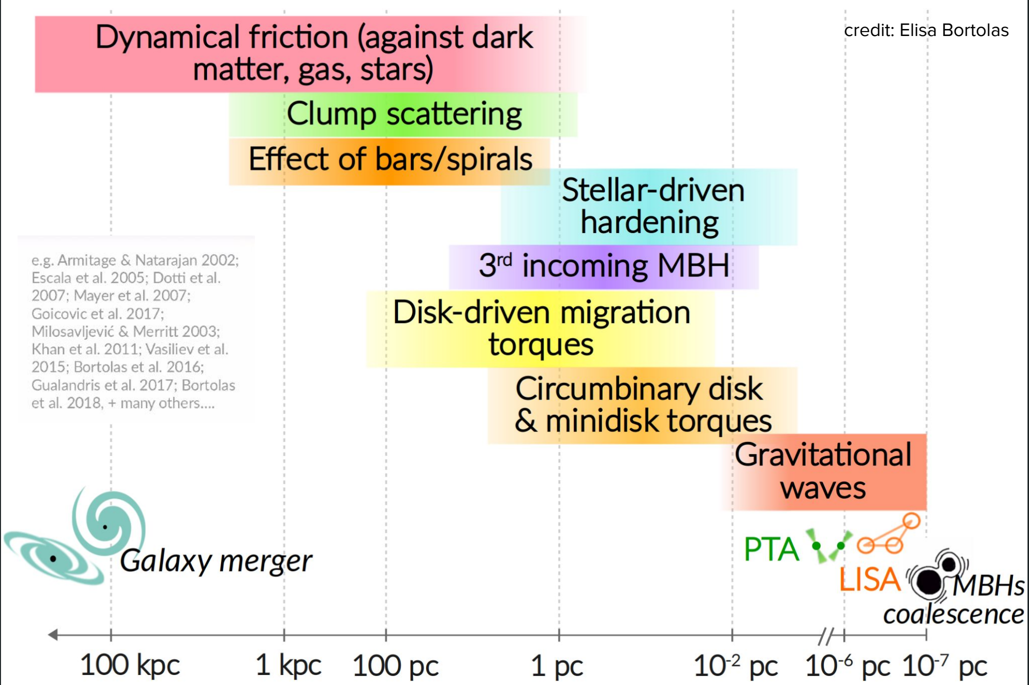
Bortolas+22

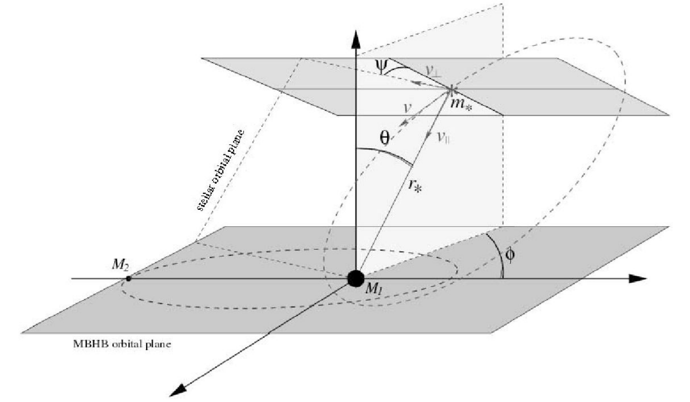
# MBHB path to coalescence - Large scale

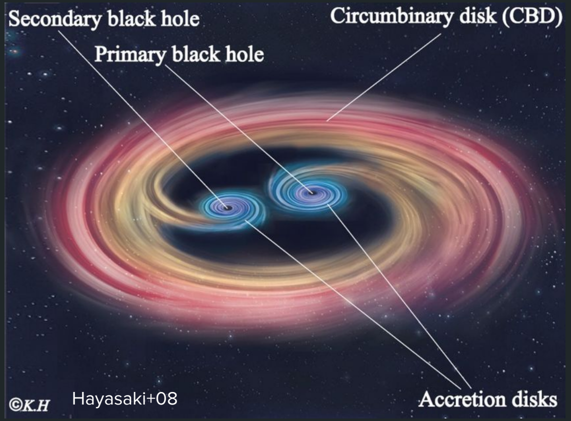
Bottom line: large scale inspiral of MBHs could be quite complex due to the complex nature of galaxies!

**Last kpc problem?**

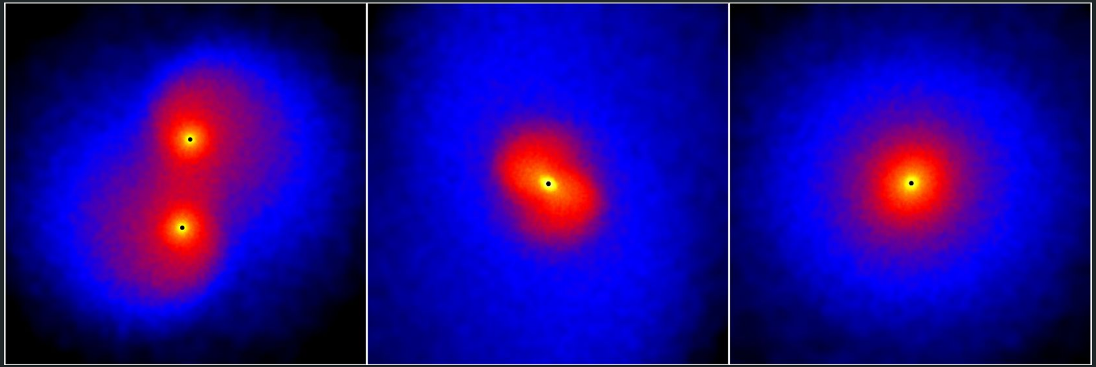
Particularly interesting for low mass MBH for which dynamical friction is less efficient and are much more influenced by a non-smooth background






# MBHB path to coalescence - Medium scale



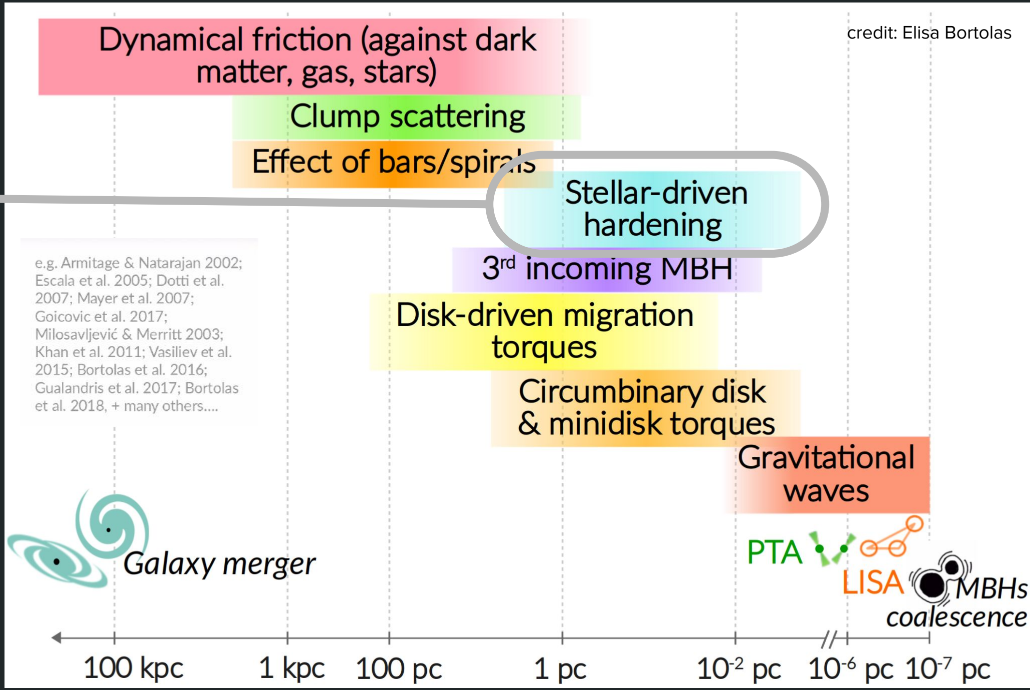
# MBHB path to coalescence - Medium scale: stars

Study of MBHB formation in gas-poor environments and associated evolutionary timescale

MBHBs eject stars in complex three-body interactions

Orbital elements evolve secularly

$$\dot{a} = -a^2 \frac{G\rho H}{\sigma}, \qquad \dot{e} = a \frac{G\rho H K}{\sigma}.$$




The loss-cone has to be refilled somehow!

Varisco+21, Bortolas+18, Khan+18, Vasiliev+15, Sesana+15, Sesana+06, Quinlan 96

# MBHB path to coalescence - Medium scale: stars

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$$\dot{e} = a \frac{G\rho H K}{\sigma}.$$

The loss-cone has to be refilled somehow!

Spherical systems: 2-body relaxation

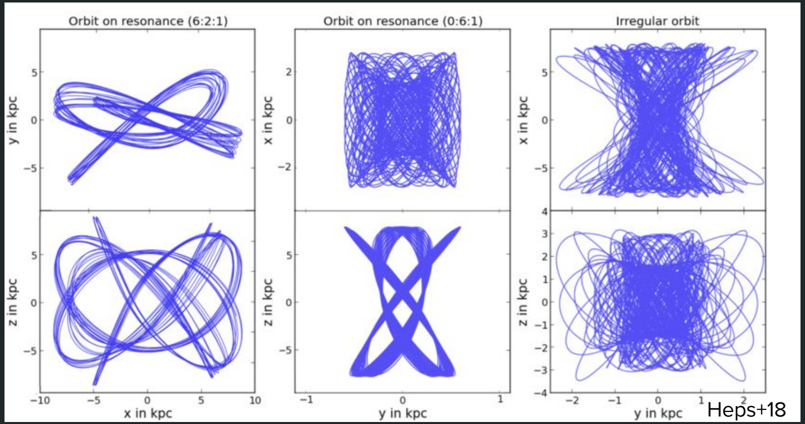
Non-spherical systems: Existence of centrophillic orbits

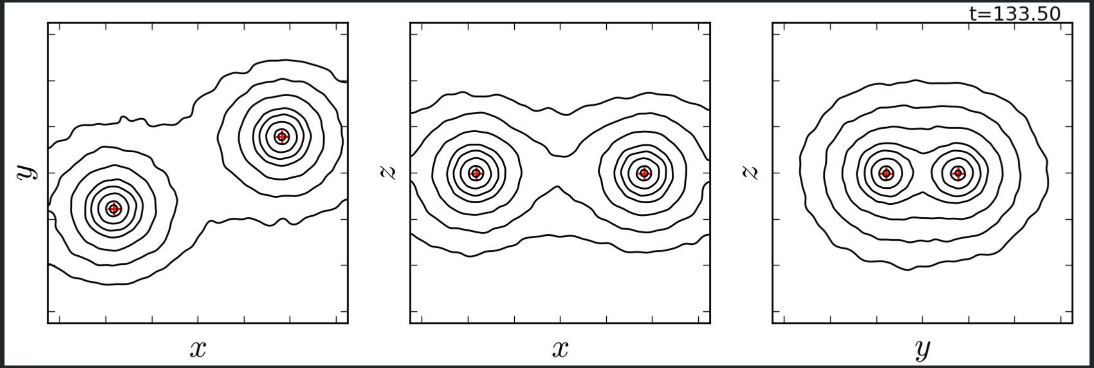
Varisco+21, Bortolas+18, Khan+18, Vasiliev+15, Sesana+15, Sesana+06, Quinlan 96

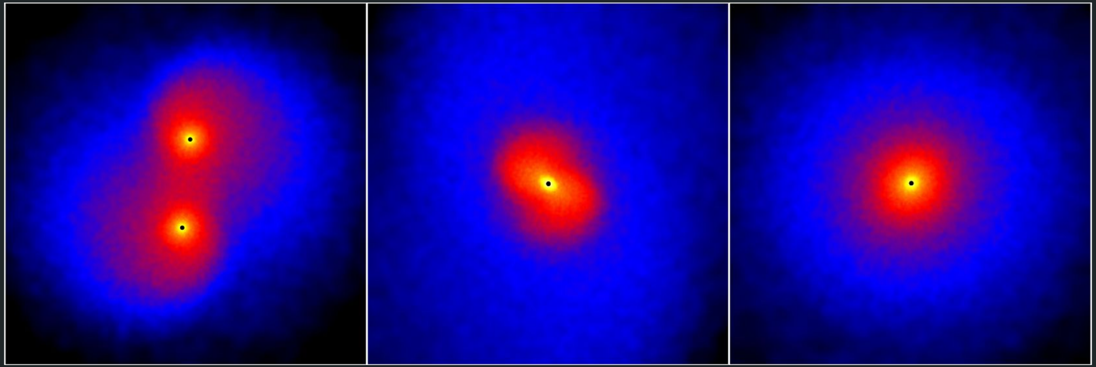
# MBHB path to coalescence - Medium scale: stars

$$\dot{a} = -a^2 \frac{G\rho H}{\sigma},$$
$$\dot{e} = a \frac{G\rho H K}{\sigma}.$$

## Deviations from spherical symmetry provide centrophillic orbits



# MBHB path to coalescence - Medium scale: stars

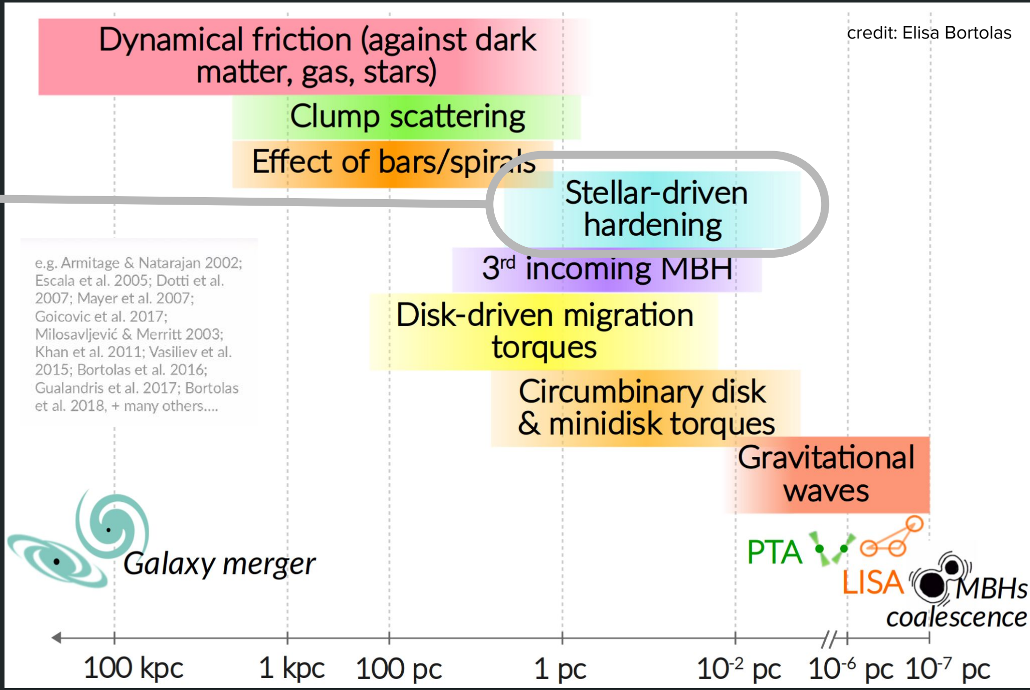
Study of MBHB formation in gas-poor environments and associated evolutionary timescale

What's missing:

- Assessment of eccentricity evolution (see Gualandris+22)
- MBHB CoM wandering
- effects due to galactic rotation

Techniques:

- Full N-body simulations
- scattering experiments

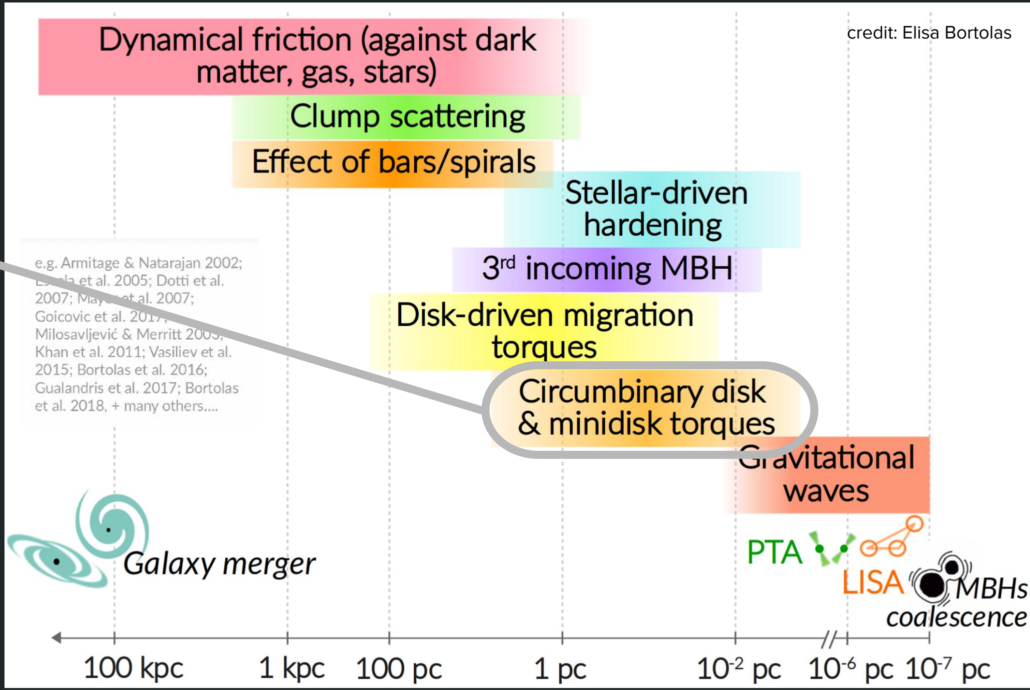



Varisco+21, Bortolas+18, Khan+18, Vasiliev+15, Sesana+15, Sesana+06, Quinlan 96

# MBHB path to coalescence - Medium scale: gas

Gas can plays an influential role in driving MBHB evolution

(and when accreted by a MBH allows us to observe it!)




Techniques:

- Full hydrodynamical simulations

Numerically solve Euler equations coupled with gravity

Franchini+21, Franchini+22, Tiede+20, Duffel+20, Munoz+19, Roedig+12, Dotti+07, Cuadra+06

# MBHB path to coalescence - Medium scale: gas

Gas can plays an influential role in driving MBHB evolution

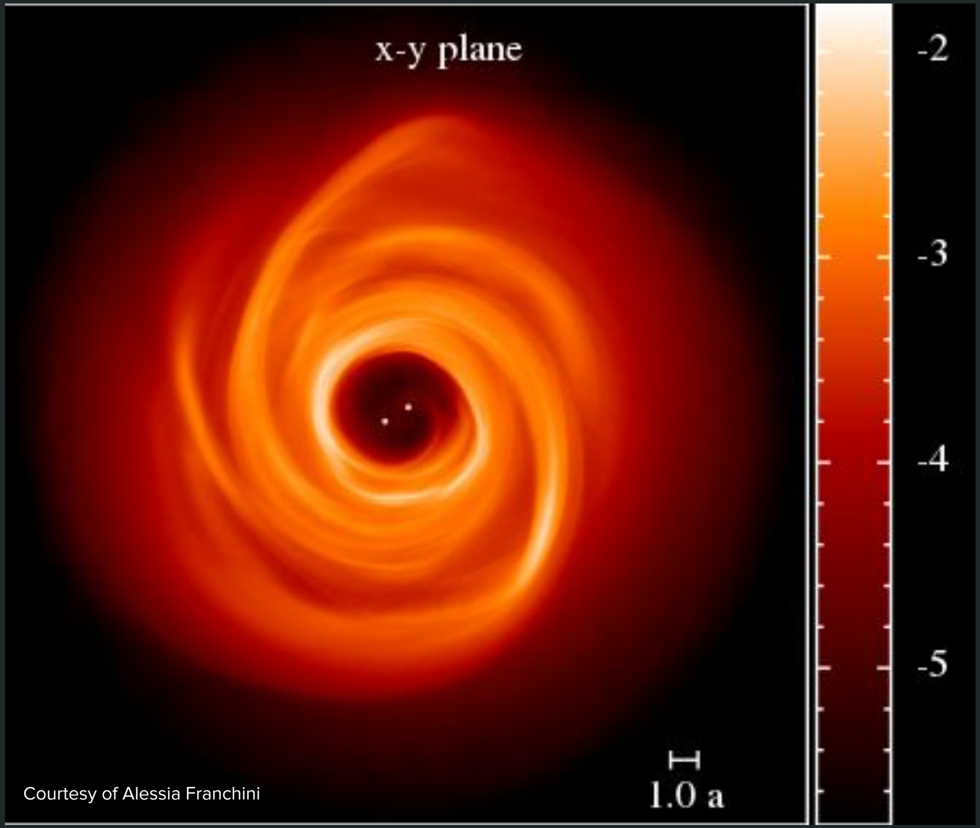
(and when accreted by a MBH allows us to observe it!)

<u>Yet no general consensus on the impact on binary properties</u>

Techniques:

- Full hydrodynamical simulations

Numerically solve Euler equations coupled with gravity (very expensive!)



# MBHB path to coalescence - Medium scale: gas

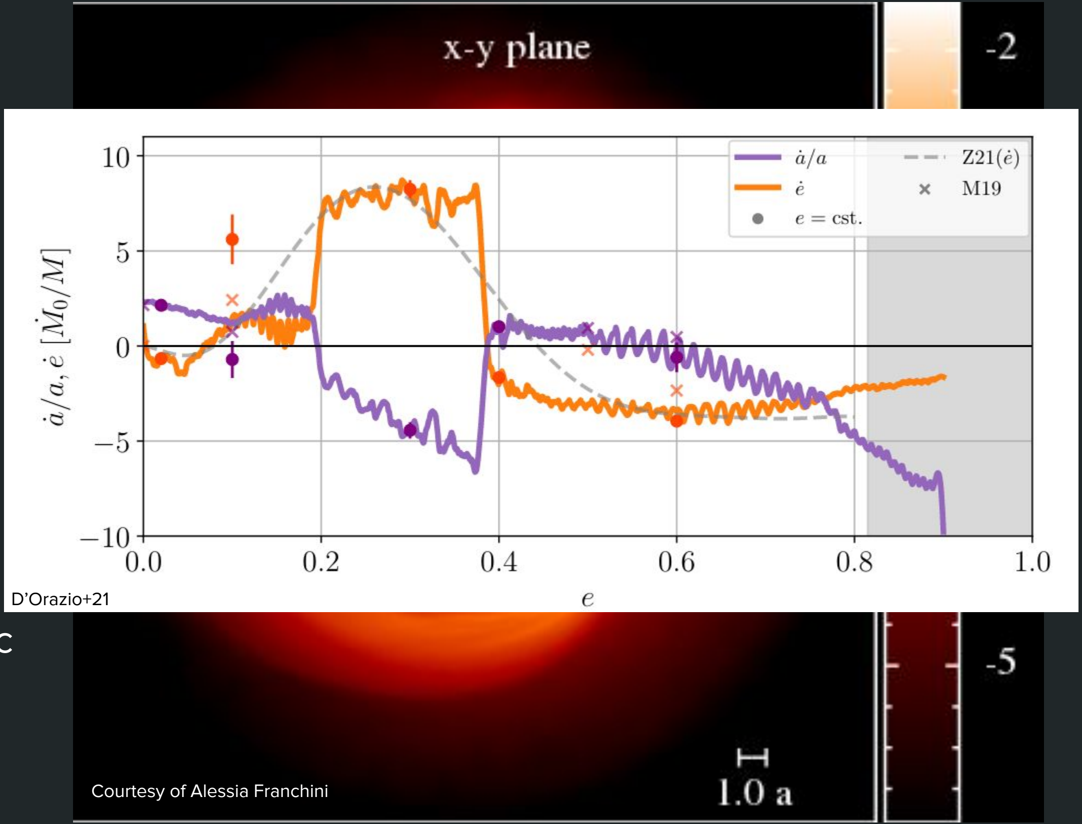
Gas can plays an influential role in driving MBHB evolution

<u>Yet no general consensus on the impact on binary properties</u>

Some claims point towards an expansion phase of MBHBs in gaseous media (e.g. Munoz+19, Duffell+20, D'Orazio+21)

Generally speaking, low-q and/or eccentric binaries seem to shrink

Different codes get different outcomes



D'Orazio+21

Courtesy of Alessia Franchini

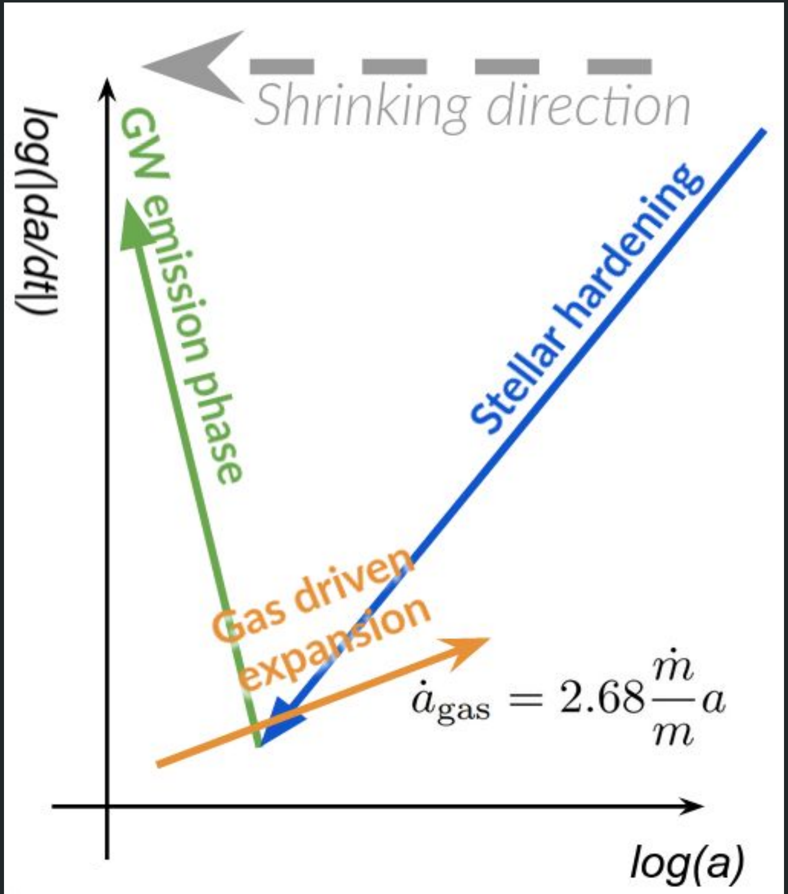
# MBHB path to coalescence - Medium scale: gas

**What should we expect if binaries actually expand?**

We study the competition with other evolutionary processes

We assume the worst case scenario

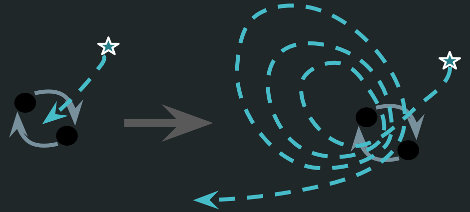
Gas always expands binaries up to self-gravitating radius




Bortolas+21

# MBHB path to coalescence - Medium scale: gas

- Stellar driven hardening



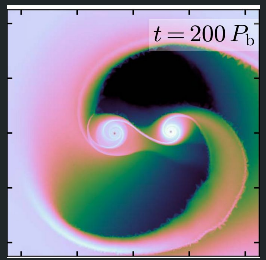
Binary shrinking

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

Quinlan 96, Sesana+06

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

- Gas-driven evolution




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

Munoz+20

Shrinking or **expansion**?

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

- Gravitational wave emission

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

Peters 64

Efficient small scale shrinking

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

Bortolas+21

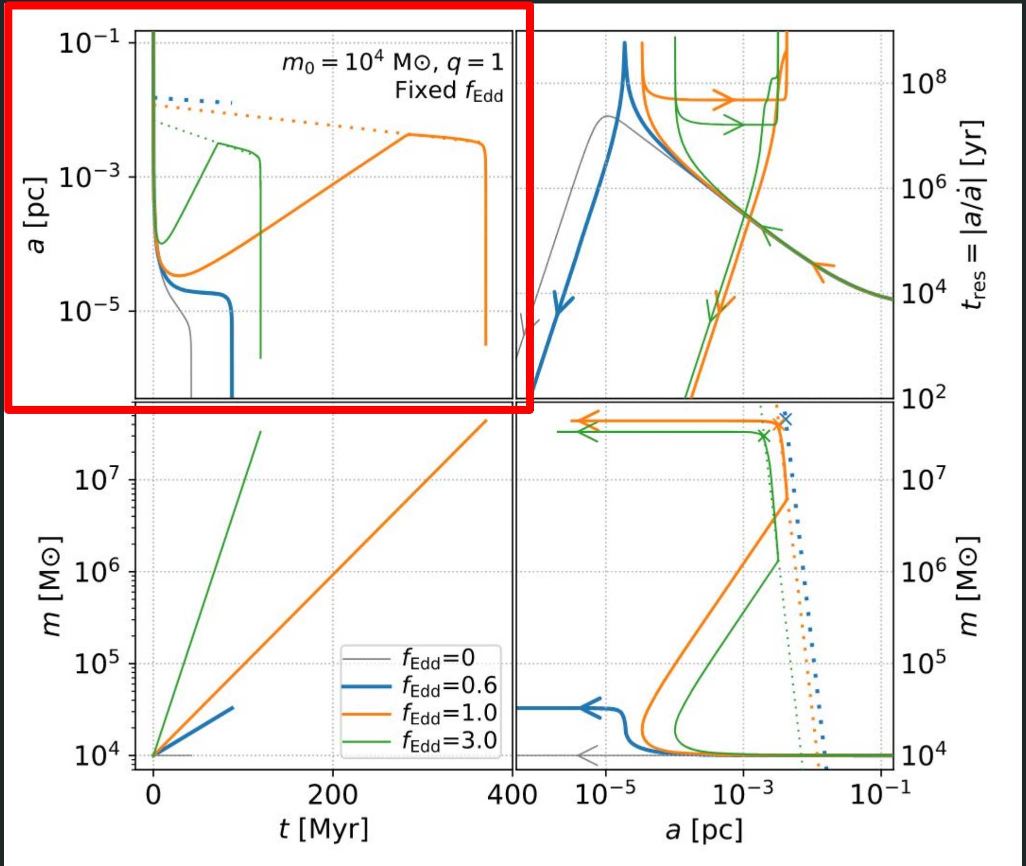
# MBHB path to coalescence - Medium scale: gas

**What should we expect if binaries actually expand?**

We assume that expansion cannot proceed above the self-gravitating radius

We found that highly accreting binaries can undergo expansion, BUT as the mass grows GW emission gets stronger!

Binaries always reach coalescence!




Bortolas+21

# MBHB path to coalescence - Medium scale: multiple MBHs

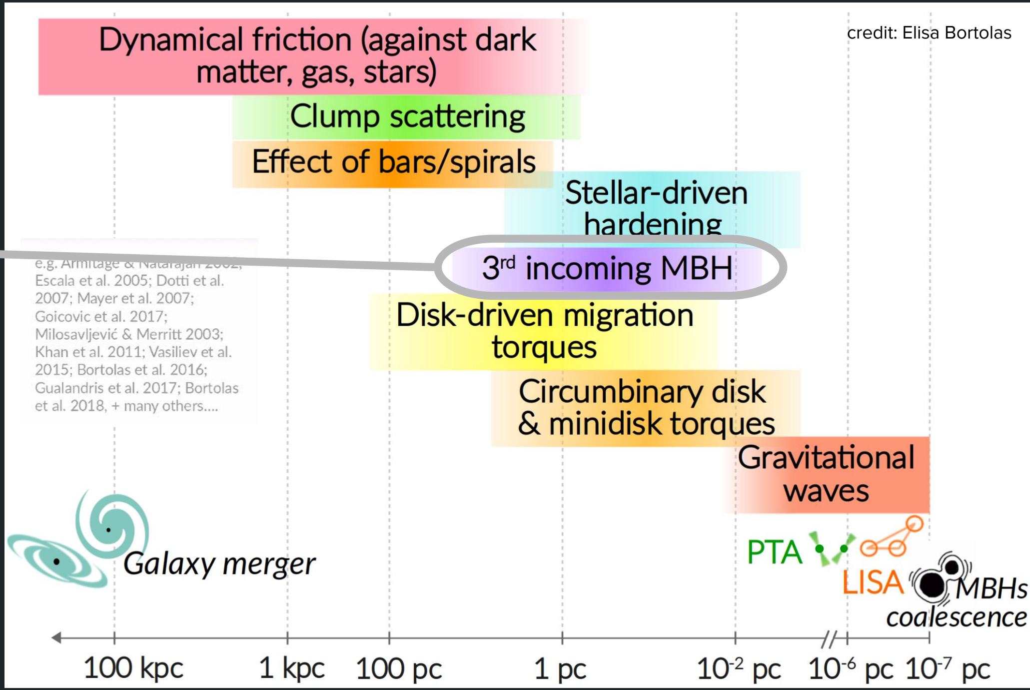
With long binary lifetimes, triplets/multiplets of MBH can form within the same galaxy

This triggers a complex and rich dynamics possibly leading to MBHB coalescence

Techniques:

- Post-Newtonian 3-body simulations embedded in galactic potential

  + effect of dynamical friction and stellar hardening




Bonetti+16, Bonetti+18, Bonetti+19

# MBHB path to coalescence - Medium scale: multiple MBHs

**Newtonian**

$$H_0 = \frac{1}{2}\sum_{\alpha}\frac{|\vec{p}_\alpha|^2}{m_\alpha} - \frac{G}{2}\sum_{\alpha}\sum_{\beta\neq\alpha}\frac{m_\alpha m_\beta}{r_{\alpha\beta}}$$

**1PN**

$$\begin{aligned}
H_1 = &-\frac{1}{8}\sum_{\alpha} m_\alpha\left(\frac{|\vec{p}_\alpha|^2}{m_\alpha^2}\right)^2 \\
&-\frac{G}{4}\sum_{\alpha}\sum_{\beta\neq\alpha}\frac{1}{r_{\alpha\beta}}\left[6\frac{m_\beta}{m_\alpha}|\vec{p}_\alpha|^2 - 7\vec{p}_\alpha\cdot\vec{p}_\beta - (\vec{n}_{\alpha\beta}\cdot\vec{p}_\alpha)(\vec{n}_{\alpha\beta}\cdot\vec{p}_\beta)\right] \\
&+\frac{G^2}{2}\sum_{\alpha}\sum_{\beta\neq\alpha}\sum_{\gamma\neq\alpha}\frac{m_\alpha m_\beta m_\gamma}{r_{\alpha\beta}r_{\alpha\gamma}}
\end{aligned}$$

**2.5PN**

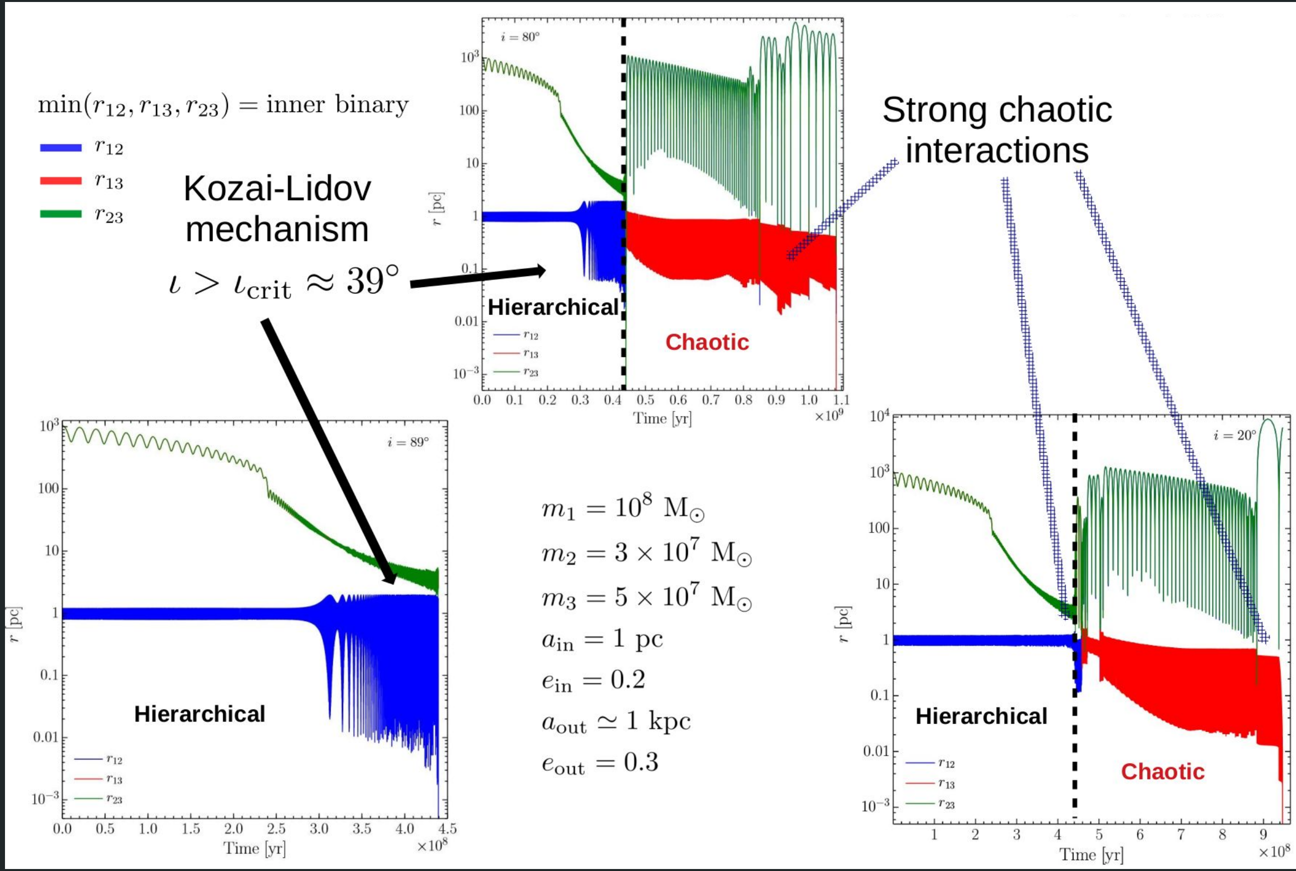
$$H_{2.5} = \frac{G}{45}\dot{\chi}_{(4)ij}(\vec{x}_{\alpha'},\vec{p}_{\alpha'};t)\chi_{(4)ij}(\vec{x}_\alpha,\vec{p}_\alpha)$$

$$\begin{aligned}
H_2 = &\frac{1}{16}\sum_{\alpha} m_\alpha\left(\frac{|\vec{p}_\alpha|^2}{m_\alpha^2}\right)^3 + \frac{G}{16}\sum_{\alpha}\sum_{\beta\neq\alpha}\frac{(m_\alpha m_\beta)^{-1}}{r_{\alpha\beta}}\left[10\left(\frac{m_\beta}{m_\alpha}|\vec{p}_\alpha|^2\right)^2 - 11|\vec{p}_\alpha|^2|\vec{p}_\beta|^2 - 2(\vec{p}_\alpha\cdot\vec{p}_\beta)^2\right. \\
&\left.+10|\vec{p}_\alpha|^2(\vec{n}_{\alpha\beta}\cdot\vec{p}_\beta)^2 - 12(\vec{p}_\alpha\cdot\vec{p}_\beta)(\vec{n}_{\alpha\beta}\cdot\vec{p}_\alpha)(\vec{n}_{\alpha\beta}\cdot\vec{p}_\beta) - 3(\vec{n}_{\alpha\beta}\cdot\vec{p}_\alpha)^2(\vec{n}_{\alpha\beta}\cdot\vec{p}_\beta)^2\right] \\
&+\frac{G^2}{8}\sum_{\alpha}\sum_{\beta\neq\alpha}\sum_{\gamma\neq\alpha}\frac{1}{r_{\alpha\beta}r_{\alpha\gamma}}\left[18\frac{m_\beta m_\gamma}{m_\alpha}|\vec{p}_\alpha|^2 + 14\frac{m_\alpha m_\gamma}{m_\beta}|\vec{p}_\beta|^2 - 2\frac{m_\alpha m_\gamma}{m_\beta}(\vec{n}_{\alpha\beta}\cdot\vec{p}_\beta)^2\right. \\
&-50m_\gamma(\vec{p}_\alpha\cdot\vec{p}_\beta) + 17m_\alpha(\vec{p}_\beta\cdot\vec{p}_\gamma) - 14m_\gamma(\vec{n}_{\alpha\beta}\cdot\vec{p}_\alpha)(\vec{n}_{\alpha\beta}\cdot\vec{p}_\beta) \\
&\left.+14m_\alpha(\vec{n}_{\alpha\beta}\cdot\vec{p}_\beta)(\vec{n}_{\alpha\beta}\cdot\vec{p}_\gamma) + m_\alpha(\vec{n}_{\alpha\beta}\cdot\vec{n}_{\alpha\gamma})(\vec{n}_{\alpha\beta}\cdot\vec{p}_\beta)(\vec{n}_{\alpha\gamma}\cdot\vec{p}_\gamma)\right] \\
&+\frac{G^2}{8}\sum_{\alpha}\sum_{\beta\neq\alpha}\sum_{\gamma\neq\alpha}\frac{1}{r_{\alpha\beta}^2}\left[2m_\beta(\vec{n}_{\alpha\beta}\cdot\vec{p}_\alpha)(\vec{n}_{\alpha\gamma}\cdot\vec{p}_\gamma) + 2m_\beta(\vec{n}_{\alpha\beta}\cdot\vec{p}_\beta)(\vec{n}_{\alpha\gamma}\cdot\vec{p}_\gamma)\right. \\
&\left.+\frac{m_\alpha m_\beta}{m_\gamma}\left(5(\vec{n}_{\alpha\beta}\cdot\vec{n}_{\alpha\gamma})|\vec{p}_\gamma|^2 - (\vec{n}_{\alpha\beta}\cdot\vec{n}_{\alpha\gamma})(\vec{n}_{\alpha\gamma}\cdot\vec{p}_\gamma)^2 - 14(\vec{n}_{\alpha\beta}\cdot\vec{p}_\gamma)(\vec{n}_{\alpha\gamma}\cdot\vec{p}_\gamma)\right)\right] \\
&+\frac{G^2}{4}\sum_{\alpha}\sum_{\beta\neq\alpha}\frac{m_\alpha}{r_{\alpha\beta}^2}\left[\frac{m_\beta}{m_\alpha}|\vec{p}_\alpha|^2 + \frac{m_\alpha}{m_\beta}|\vec{p}_\beta|^2 - 2(\vec{p}_\alpha\cdot\vec{p}_\beta)\right] \\
&+\frac{G^2}{2}\sum_{\alpha}\sum_{\beta\neq\alpha}\sum_{\gamma\neq\alpha,\beta}\frac{(n^i_{\alpha\beta}+n^i_{\alpha\gamma})(n^j_{\alpha\beta}+n^j_{\gamma\beta})}{(r_{\alpha\beta}+r_{\beta\gamma}+r_{\gamma\alpha})^2}\left[8m_\beta(p_{\alpha i}p_{\gamma j}) - 16m_\beta(p_{\alpha j}p_{\gamma i})\right. \\
&\left.+3m_\gamma(p_{\alpha i}p_{\beta j}) + 4\frac{m_\alpha m_\beta}{m_\gamma}(p_{\gamma i}p_{\gamma j}) + \frac{m_\beta m_\gamma}{m_\alpha}(p_{\alpha i}p_{\alpha j})\right] \\
&+\frac{G^2}{2}\sum_{\alpha}\sum_{\beta\neq\alpha}\sum_{\gamma\neq\alpha,\beta}\frac{m_\alpha m_\beta m_\gamma}{(r_{\alpha\beta}+r_{\beta\gamma}+r_{\gamma\alpha})r_{\alpha\beta}}\left[8\frac{\vec{p}_\alpha\cdot\vec{p}_\gamma - (\vec{n}_{\alpha\beta}\cdot\vec{p}_\alpha)(\vec{n}_{\alpha\beta}\cdot\vec{p}_\gamma)}{m_\alpha m_\gamma}\right. \\
&\left.-3\frac{\vec{p}_\alpha\cdot\vec{p}_\beta - (\vec{n}_{\alpha\beta}\cdot\vec{p}_\alpha)(\vec{n}_{\alpha\beta}\cdot\vec{p}_\beta)}{m_\alpha m_\beta} - 4\frac{|\vec{p}_\gamma|^2 - (\vec{n}_{\alpha\beta}\cdot\vec{p}_\gamma)^2}{m_\gamma^2} - \frac{|\vec{p}_\alpha|^2 - (\vec{n}_{\alpha\beta}\cdot\vec{p}_\alpha)^2}{m_\alpha^2}\right] \\
&-\frac{G^3}{2}\sum_{\alpha}\sum_{\beta\neq\alpha}\left(\sum_{\gamma\neq\alpha,\beta}\frac{m_\alpha^2 m_\beta m_\gamma}{r_{\alpha\beta}^2 r_{\beta\gamma}} + \frac{1}{2}\sum_{\gamma\neq\beta}\frac{m_\alpha^2 m_\beta m_\gamma}{r_{\alpha\beta}^2 r_{\beta\gamma}}\right) \\
&-\frac{3G^3}{8}\sum_{\alpha}\sum_{\beta\neq\alpha}\left(\sum_{\gamma\neq\alpha}\frac{m_\alpha^2 m_\beta m_\gamma}{r_{\alpha\beta}^2 r_{\alpha\gamma}} + \sum_{\gamma\neq\alpha,\beta}\frac{m_\alpha^2 m_\beta m_\gamma}{r_{\alpha\beta}^2 r_{\beta\gamma}}\right) \\
&-\frac{3G^3}{8}\sum_{\alpha}\sum_{\beta\neq\alpha}\sum_{\gamma\neq\alpha,\beta}\frac{m_\alpha^2 m_\beta m_\gamma}{r_{\alpha\beta}r_{\alpha\gamma}r_{\beta\gamma}} \\
&-\frac{G^3}{64}\sum_{\alpha}\sum_{\beta\neq\alpha}\sum_{\gamma\neq\alpha,\beta}\frac{m_\alpha^2 m_\beta m_\gamma}{r_{\alpha\beta}r_{\alpha\gamma}^3 r_{\beta\gamma}}\left[18r_{\alpha\gamma}^2 - 60r_{\beta\gamma}^2 - 24r_{\alpha\gamma}(r_{\alpha\beta}+r_{\beta\gamma})\right. \\
&\left.+60\frac{r_{\alpha\gamma}r_{\beta\gamma}^2}{r_{\alpha\beta}} + 56r_{\alpha\beta}r_{\beta\gamma} - 72\frac{r_{\beta\gamma}^3}{r_{\alpha\beta}} + 35\frac{r_{\beta\gamma}^4}{r_{\alpha\beta}^2} + 6r_{\alpha\beta}^2\right] - \frac{G^3}{4}\sum_{\alpha}\sum_{\beta\neq\alpha}\frac{m_\alpha^2 m_\beta^2}{r_{\alpha\beta}^3}.
\end{aligned}$$

**2PN**

# MBHB path to coalescence - Medium scale: multiple MBHs

Two-phase evolution: hierarchical and chaotic



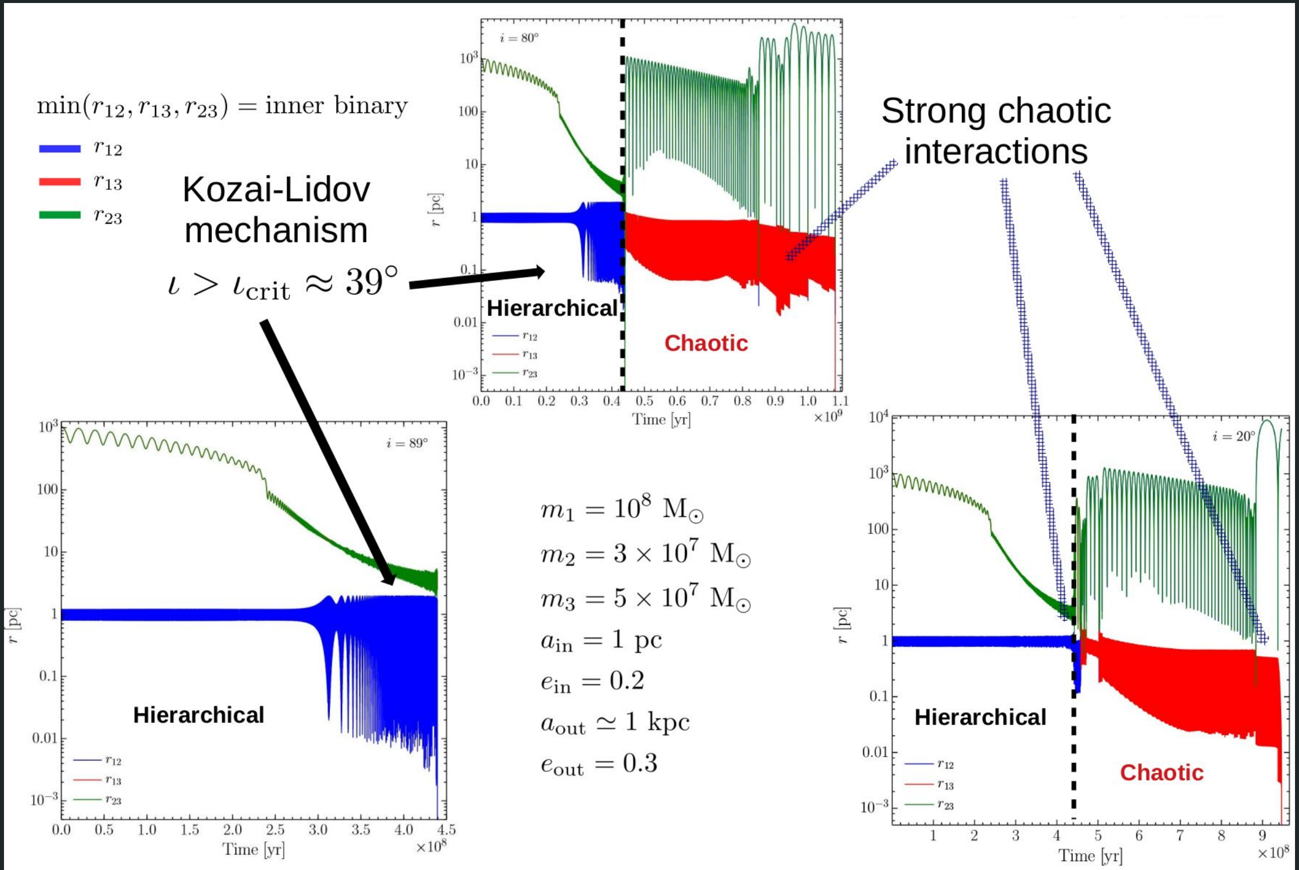

Bonetti+16, Bonetti+18, Bonetti+19

# MBHB path to coalescence - Medium scale

Two-phase evolution: hierarchical and chaotic

Secular processes

Strong encounters




Bonetti+16, Bonetti+18, Bonetti+19

# MBHB path to coalescence - Medium scale: multiple MBHs

$m_1 = 10^5 - 10^{10} \mathrm{M}_\odot$

$\log q_{\mathrm{in}} = -1.5, -1.0, -0.5, 0.0$

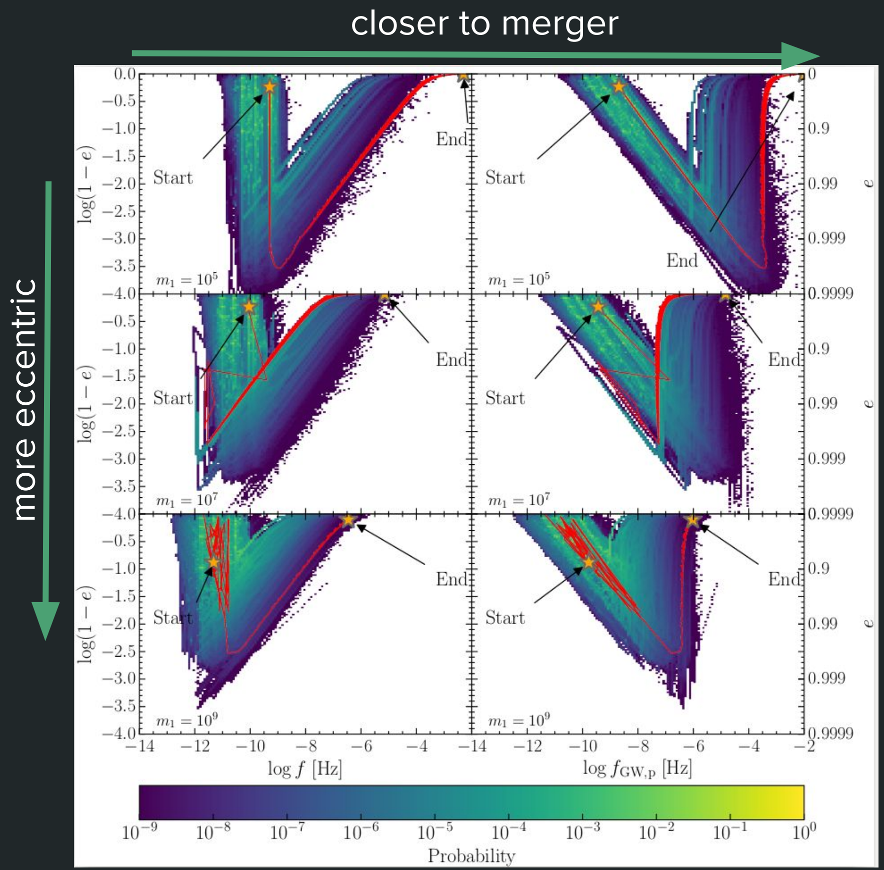
$\log q_{\mathrm{out}} = -1.5, -1.0, -0.5, 0.0$

$e_{\mathrm{in}} = 0.2, 0.4, 0.6, 0.8$

$e_{\mathrm{out}} = 0.3, 0.6, 0.9$

$\cos \iota =$ 13 values equally spaced in (-1,1)

**14976 simulations**




Bonetti+16, Bonetti+18

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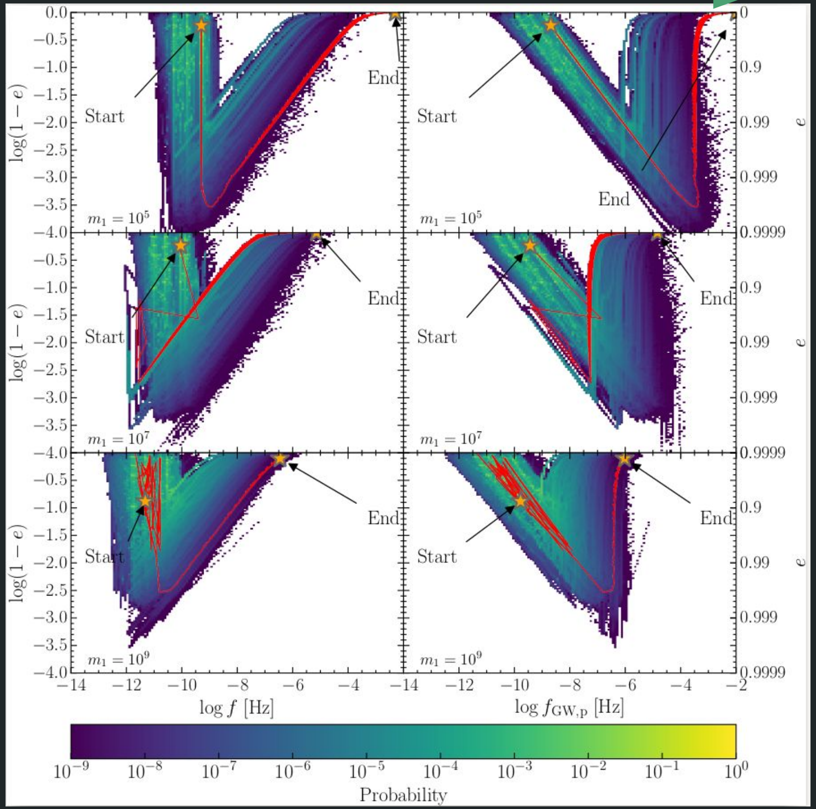
14976
simulations

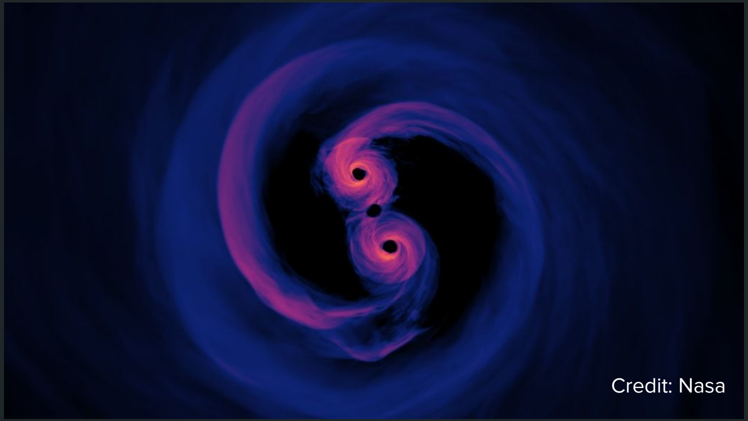
closer to merger

more eccentric




We found that around 20-30% of otherwise stalled binaries actually undergo a merger. Main driver is the high eccentricity.

Bonetti+16, Bonetti+18




# MBHB path to coalescence - Small scale

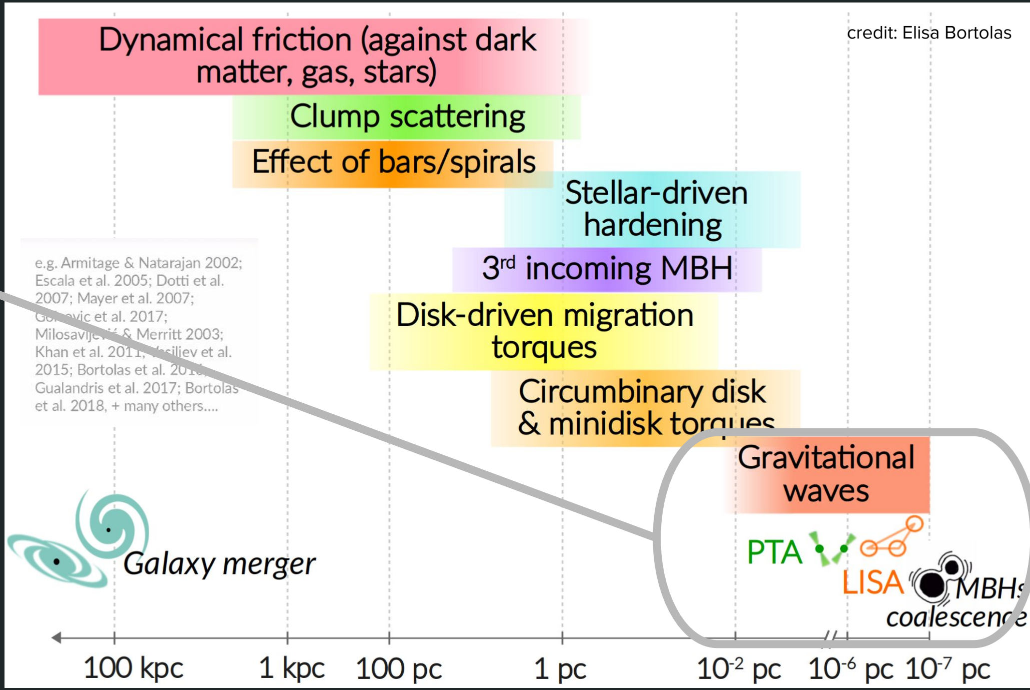
# MBHB path to coalescence - Small scale

PTA and LISA cover the relevant GW low frequency domain in which MBHBs are expected to shine

Theoretical modelling is instrumental to assess the merger rate and detection prospects

What GW experiments need:

- Generation of catalogues from cosmo simulations or SAMs
- GW signal data analysis and parameter estimation
- Envisage possible EM counterparts



# MBHB path to coalescence - Small scale

Built on top of dark matter cosmological merger tree

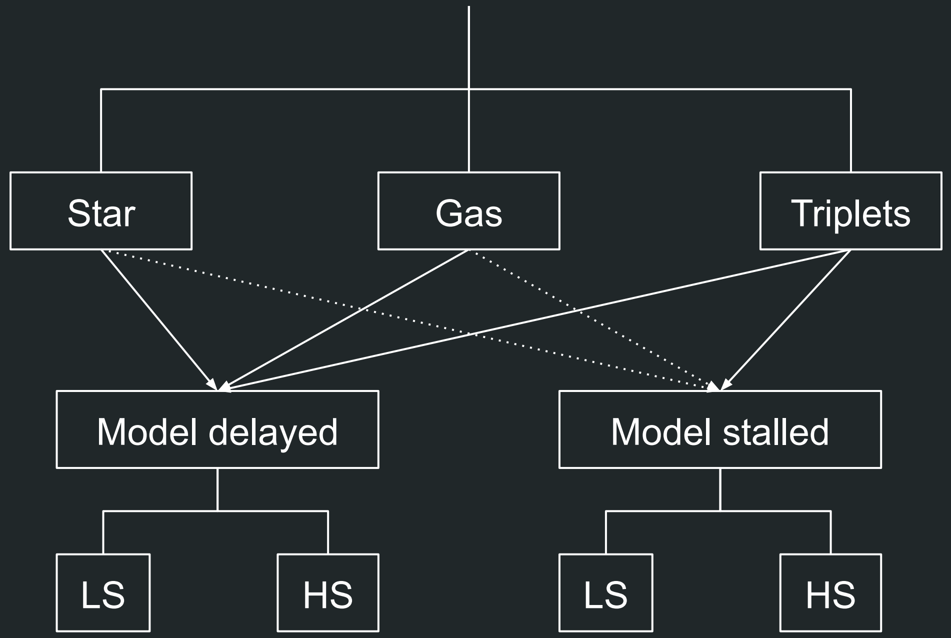
Simplified recipes to describe baryonic physics and BH formation

BH evolution implemented through the introduction of **time delays**

Pro: computationally efficient, large statistical sample of merging MBHBs

Con: make approximations

SAM of Barausse (2012) and later expansions

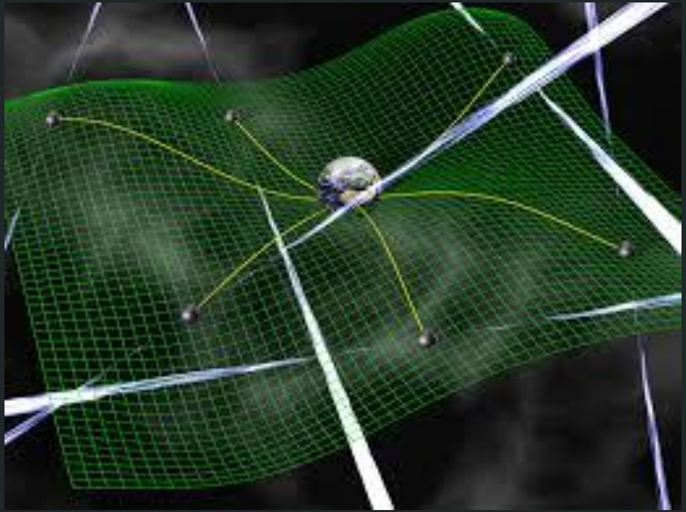



4 Universe realisation

Bonetti+18

# MBHB path to coalescence - **PTA**

PTA is a “galactic scale” GW detector



- GW background from BH of mass in range $10^7$-$10^{10}$ Msun
- Constant monitoring of several milliseconds pulsars
- Evidence of GW background found by PTA collaborations!!

# MBHB path to coalescence - **PTA**

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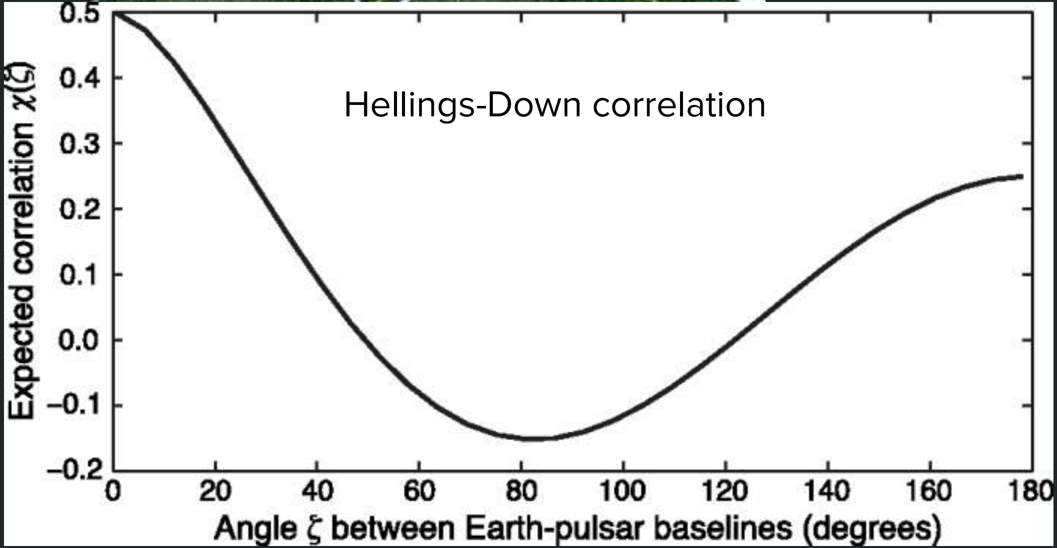


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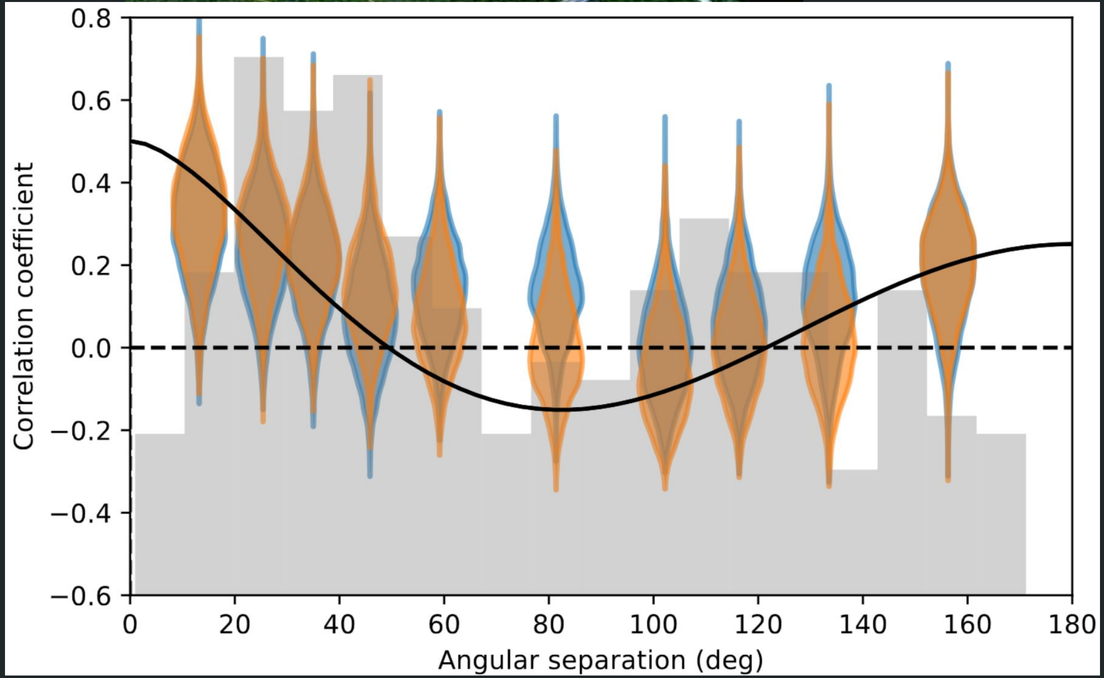


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Antoniadis+23

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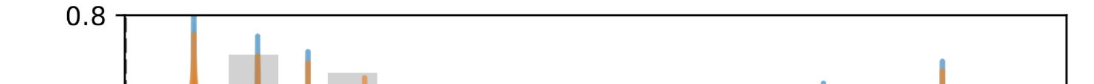
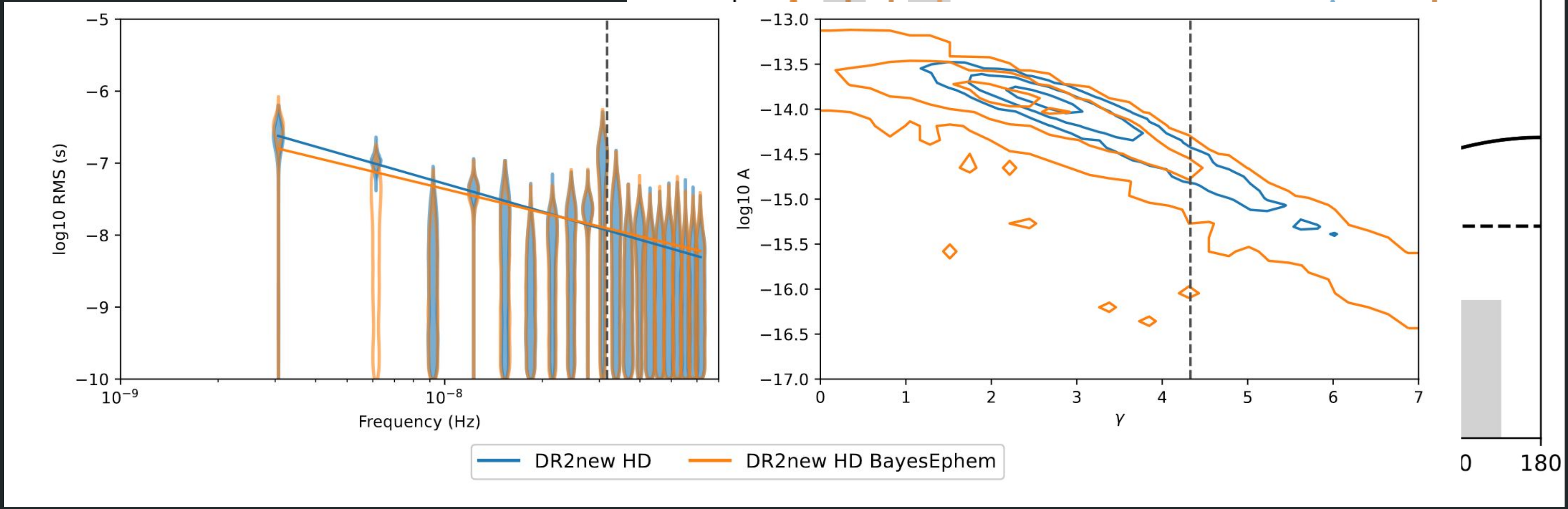
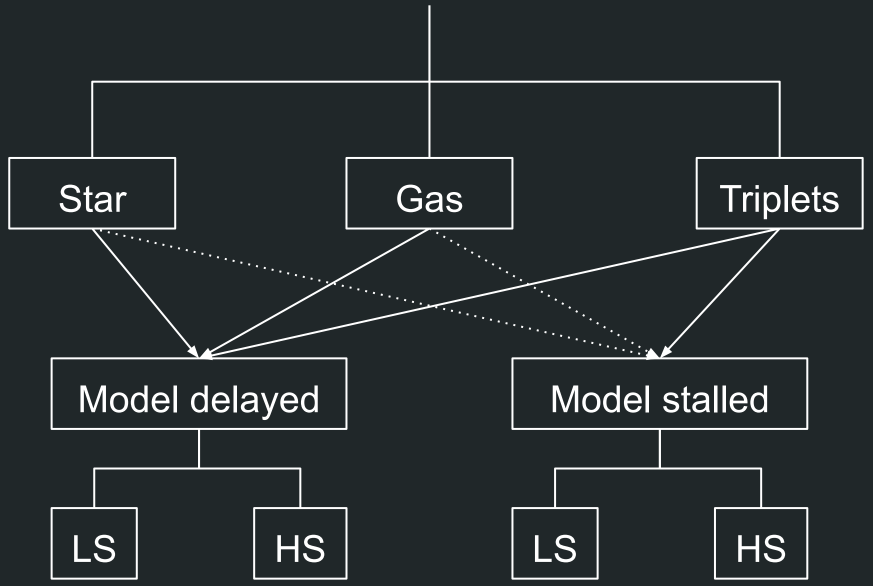


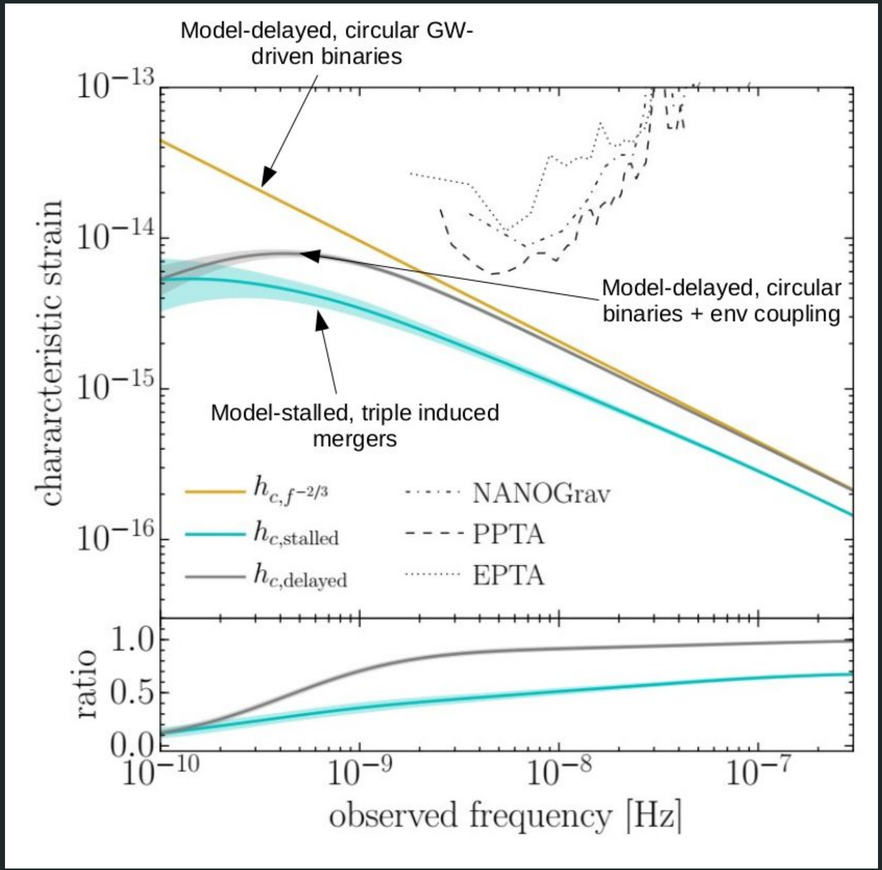




Antoniadis+23

# MBHB path to coalescence - **PTA**

SAM of Barausse (2012) and later expansions

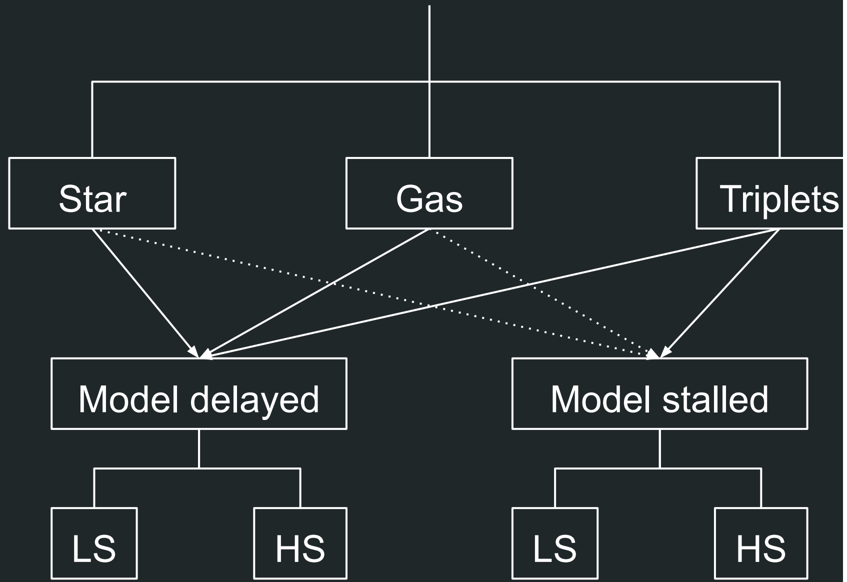


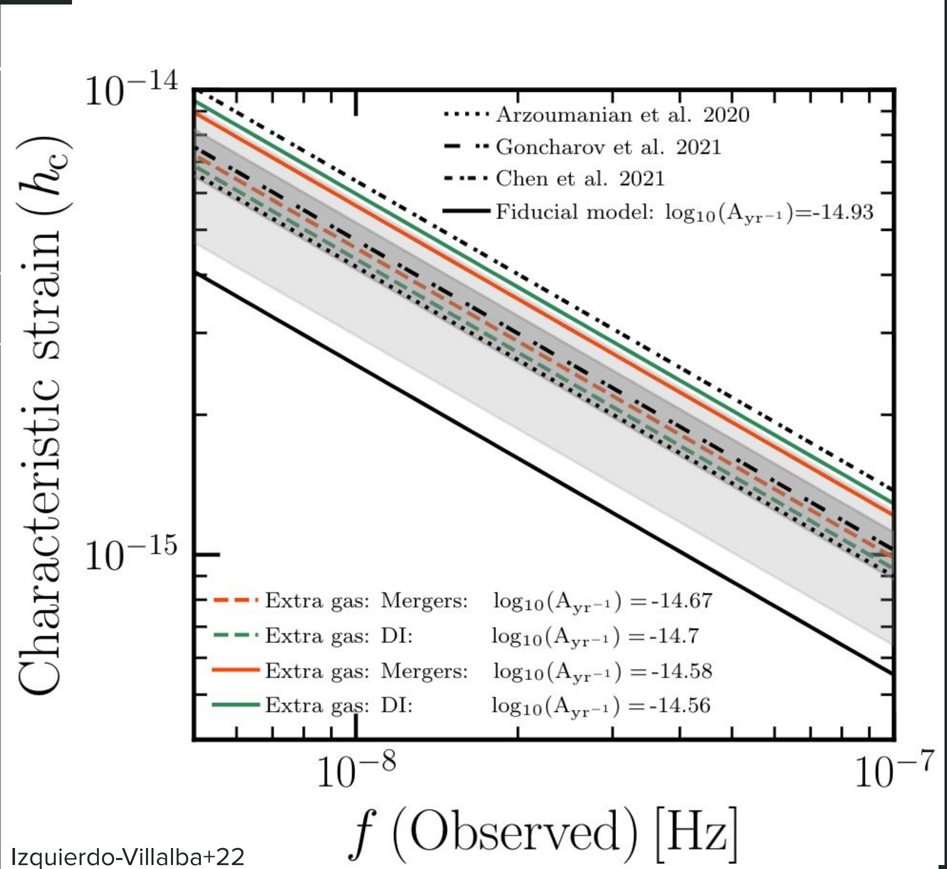

Bonetti+18

# MBHB path to coalescence - **PTA**

SAM of Barausse (2012) and later expansion

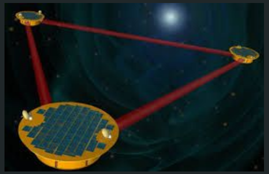



Bonetti+18

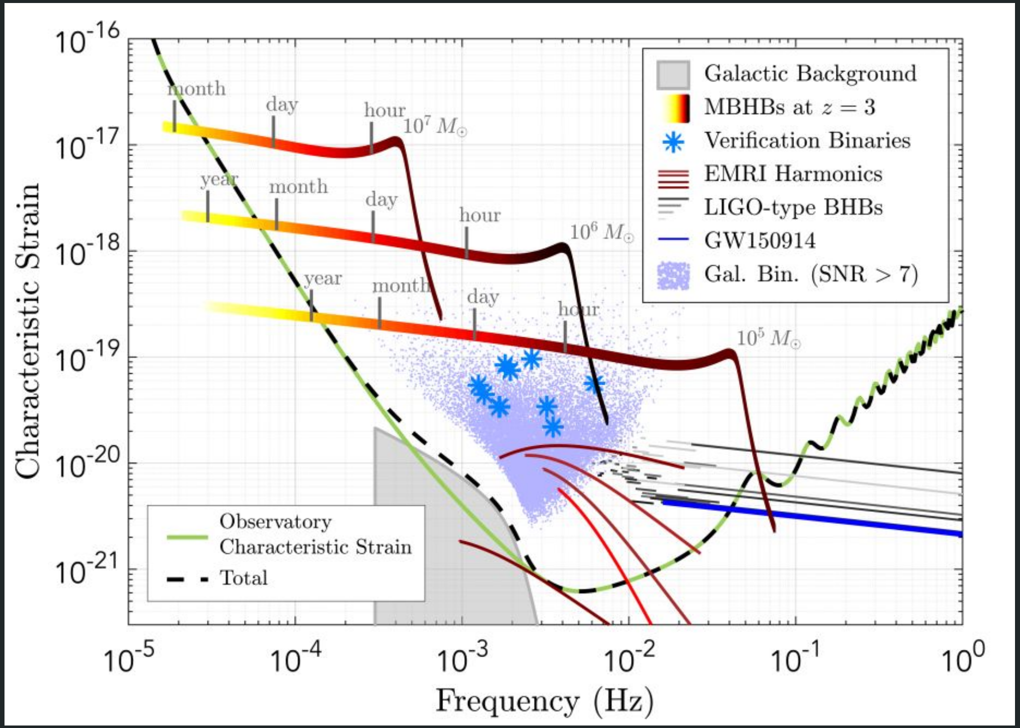



Izquierdo-Villalba+22

# MBHB path to coalescence - **LISA**



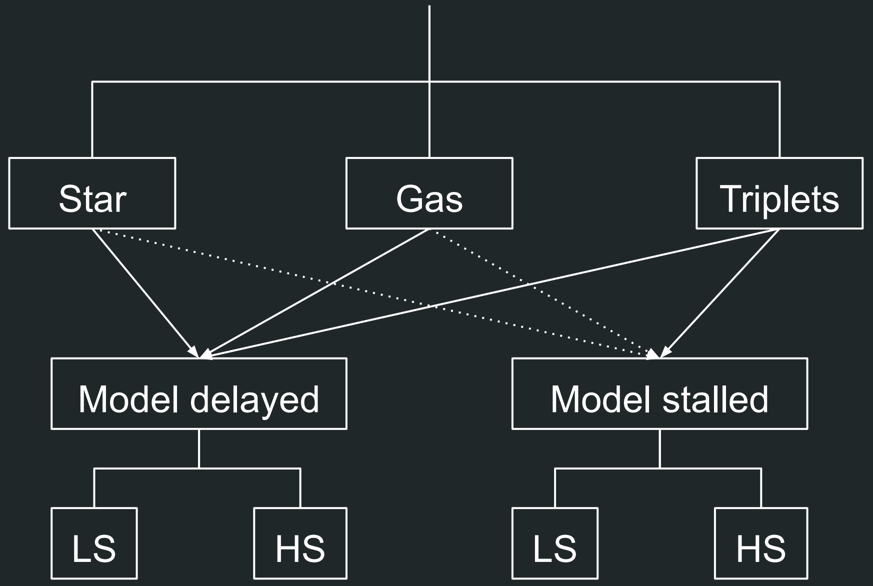
Interferometer in space made of a constellation of 3 satellites

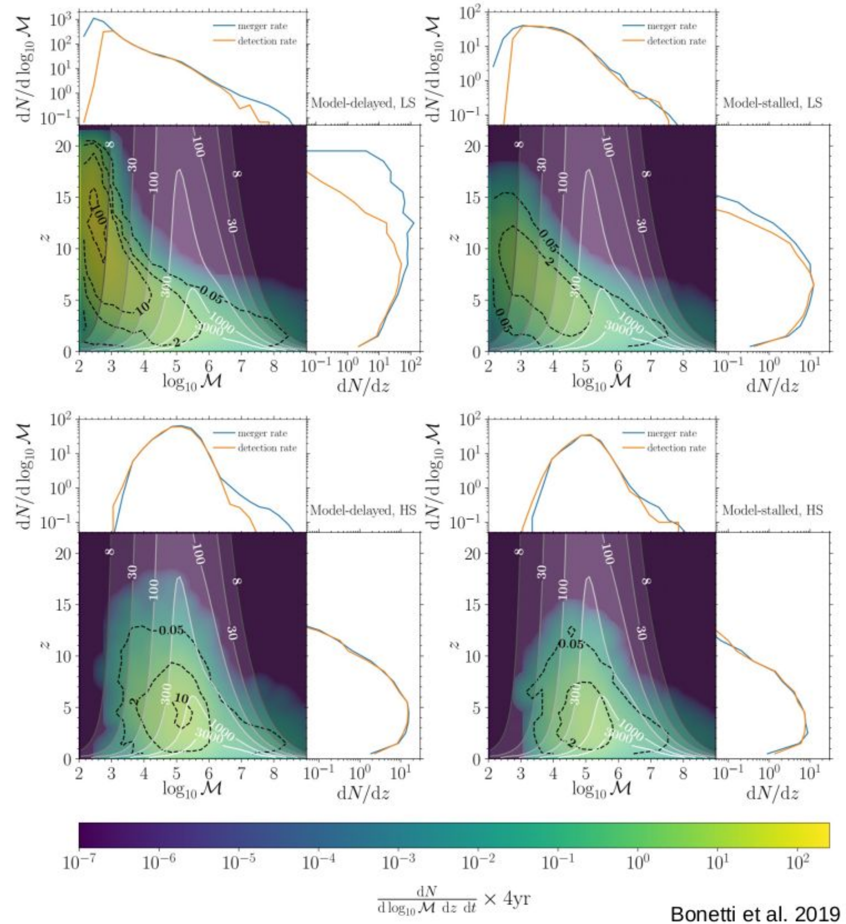



- Mass range $10^4$-$10^7$ Msun
- Detection of merging MBHB
- GW waveform is expected to encode precious astrophysical information
- Proper data analysis techniques are crucial
- Synergies with EM observatories (like LSST and Athena) and ground-based GW experiments (LIGO-Virgo, ET, CE)

# MBHB path to coalescence - **LISA**

SAM of Barausse (2012) and later expansions



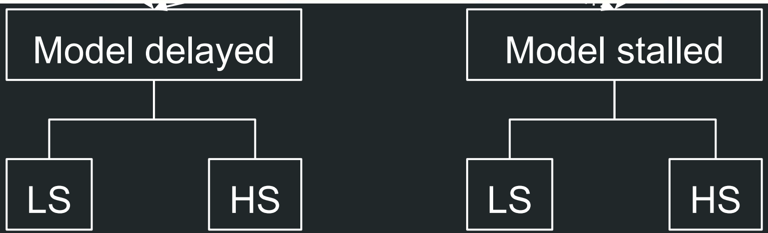



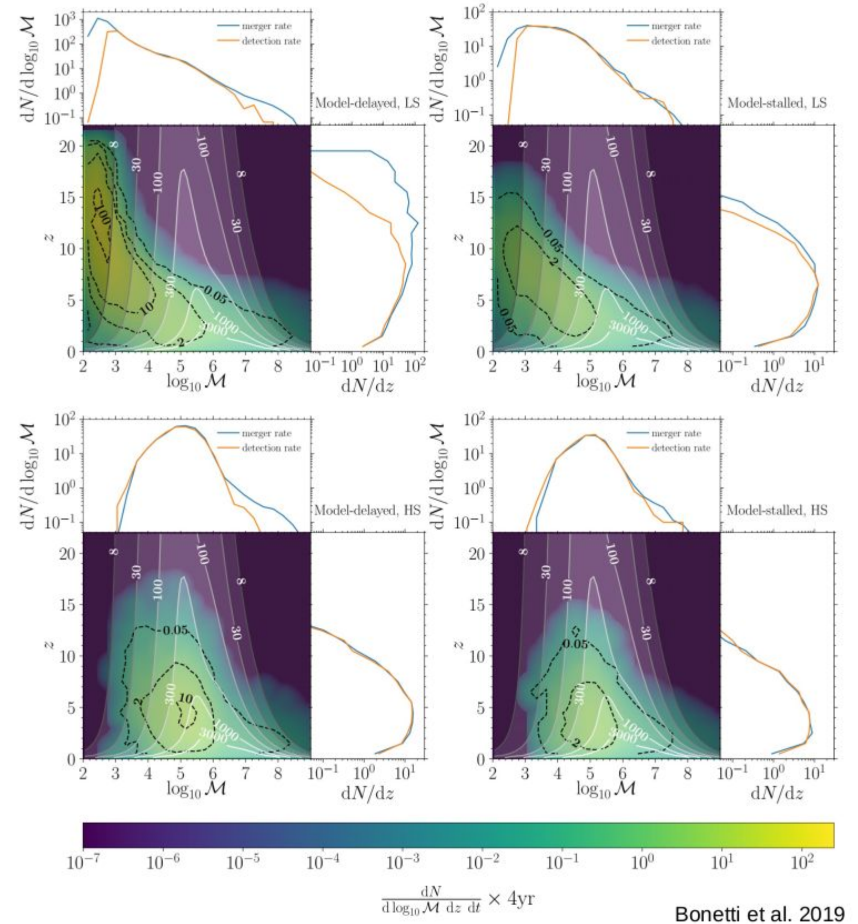

Bonetti et al. 2019

# MBHB path to coalescence - **LISA**

SAM of Barausse (2012) and later expansions

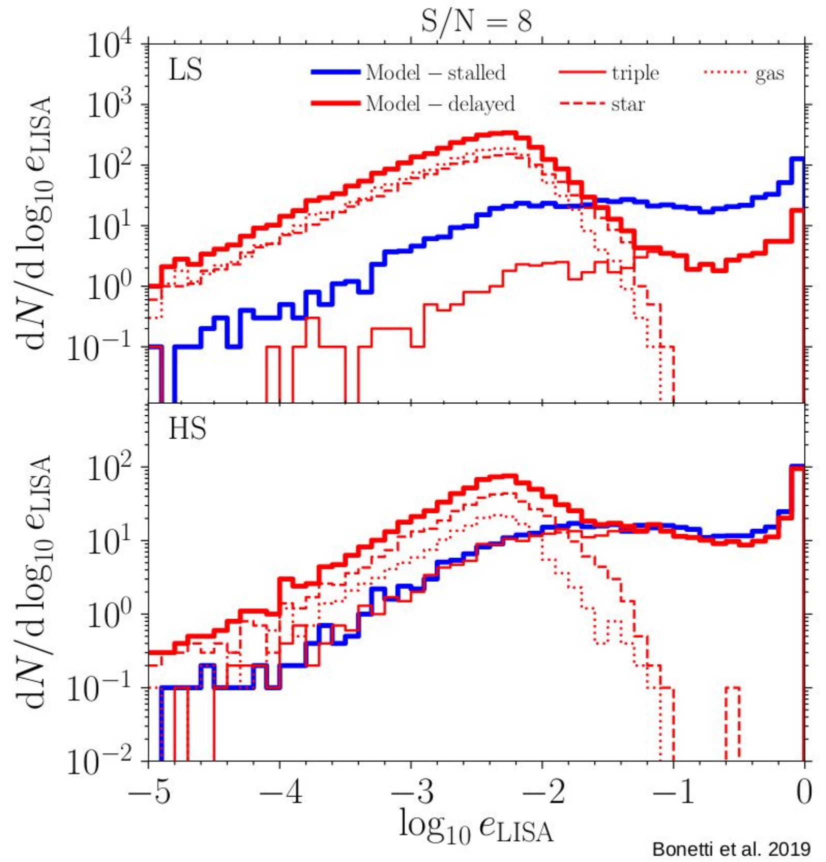
| Average number of mergers in 4 yr | | | | |
|---|---|---|---|---|
| | HS-stalled | LS-stalled | HS-delayed | LS-delayed |
| Triple | ~42 | ~86 | ~36 | ~15 |
| Total | ~42 | ~86 | ~90 | ~890 |




Bonetti et al. 2019

# MBHB path to coalescence - **LISA**




The eccentricity in the LISA band (i.e. when S/N = 8) can be quite high for MBHB within a triplet

| Average number of mergers in 4 yr | | | | |
|---|---|---|---|---|
| | HS-stalled | LS-stalled | HS-delayed | LS-delayed |
| Triple | ~42 | ~86 | ~36 | ~15 |
| Total | ~42 | ~86 | ~90 | ~890 |

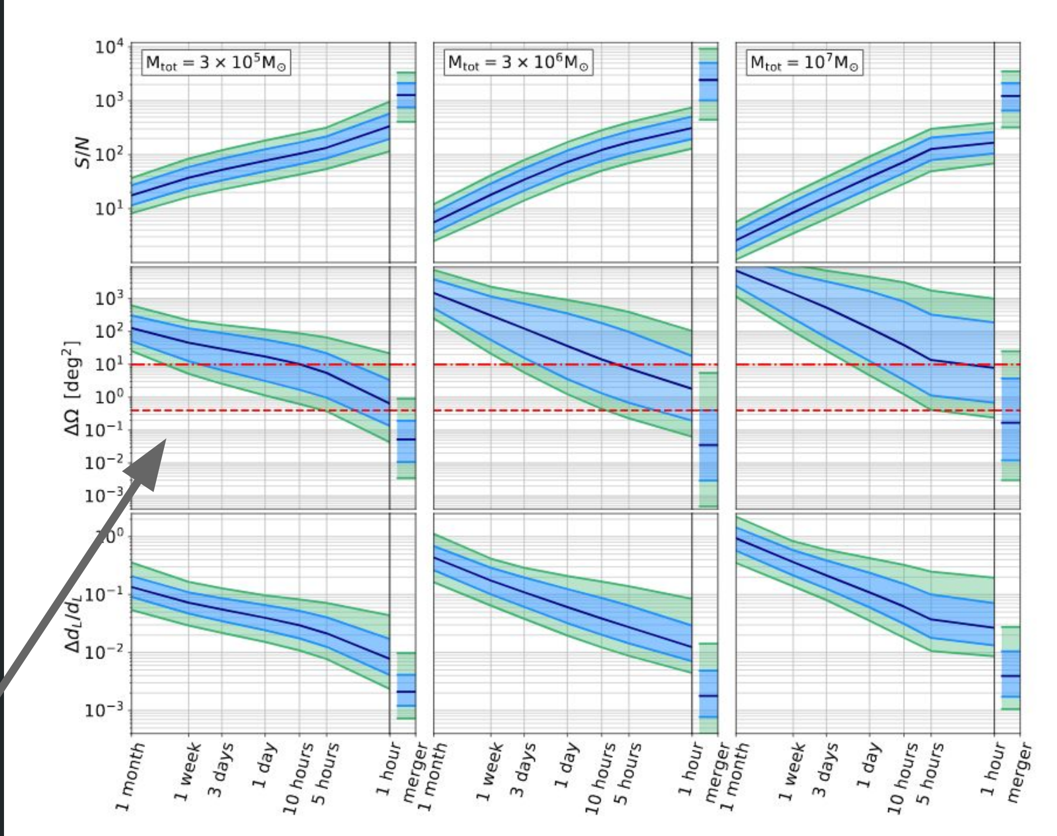
Possible “smoking gun” highlighting dynamically induced mergers

# MBHB path to coalescence - **LISA**

Interesting possibilities for multimessenger astrophysics (see many theoretical works about em signatures Bogdanovic+08, Dotti+12, Capelo+15, Volonteri+15, Capelo+17,...)

Synergies with EM observatories (e.g. LSST and Athena)

GW detection can (in some cases!) inform EM facilities about the sky position of the GW source




On the fly parameter estimation through Fisher matrix formalism

Mangiagli+20

# Conclusions

- MBHB path to coalescence is not always an obvious outcome of galaxy mergers. Several different processes drive MBHB evolution
- Meaningful assessment of MBH evolutionary timescale needs for an extensive parameter space exploration
- Hints of the followed path might be present in the GW signals. PTA evidence is finally opening the nano Hz sky
- Synergies between GW and EM observatories will be crucial to get the highest scientific reward achievable by upcoming missions

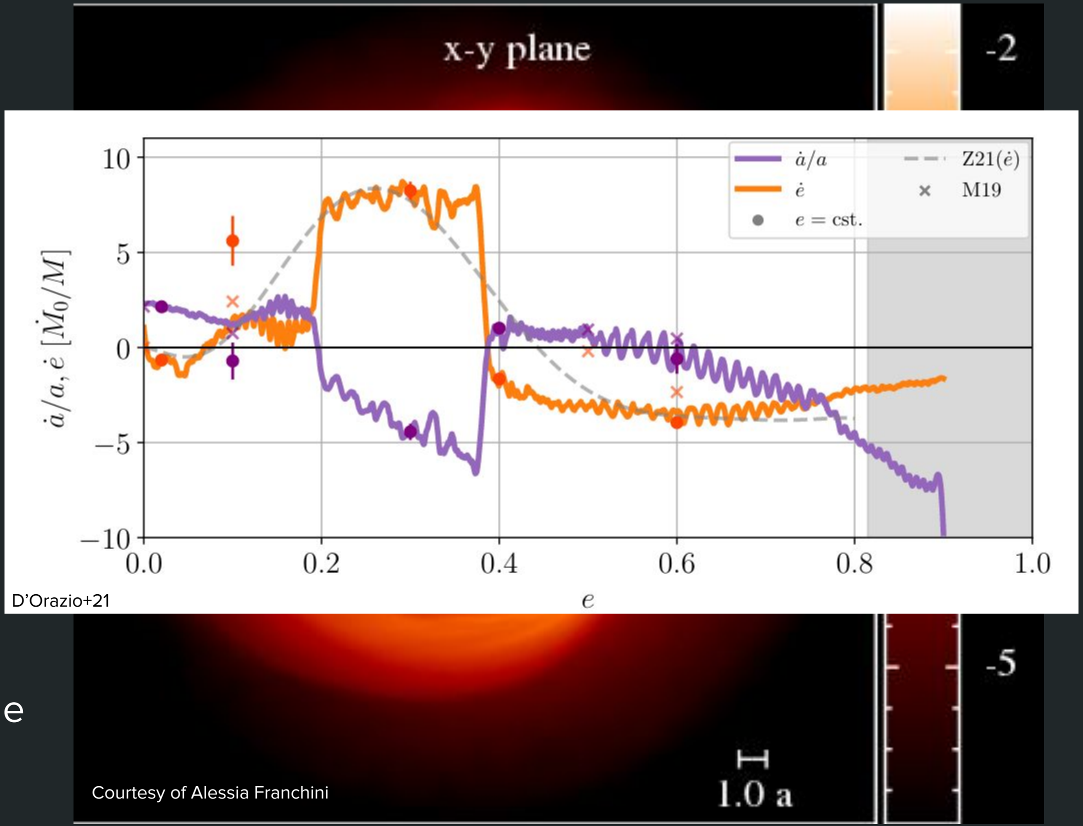
# MBHB path to coalescence - Medium scale: gas

Gas can plays an influential role in driving MBHB evolution

<u>Yet no general consensus on the impact on binary properties</u>

## NON SELF-GRAVITATING REGIME!

i.e. disk mass within MBH orbits is negligible




Courtesy of Alessia Franchini

D'Orazio+21

# MBHB path to coalescence - Medium scale: gas

**What should we expect if binaries actually expand?**

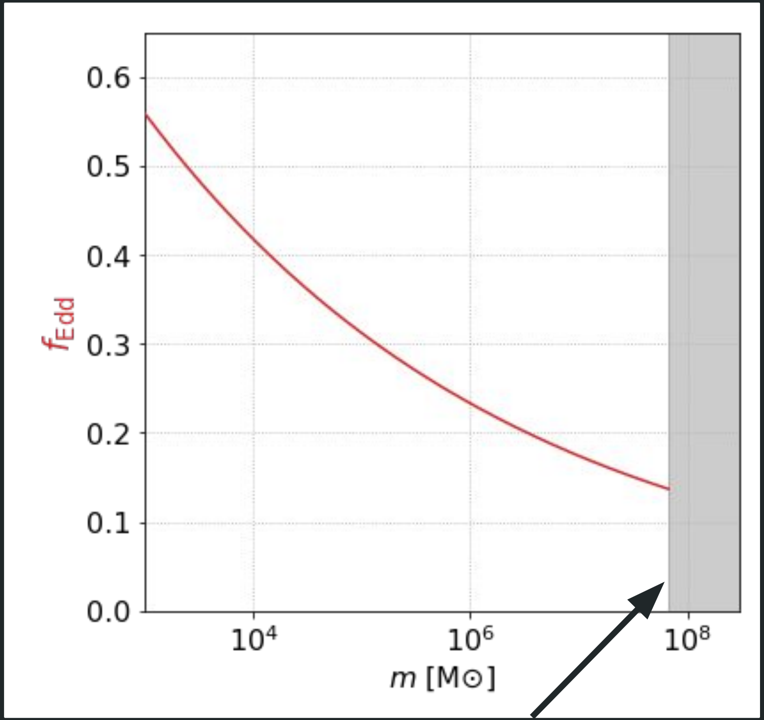
We study the competition with other evolutionary processes

We assume the worst case scenario

Gas always expands binaries up to self-gravitating radius

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

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

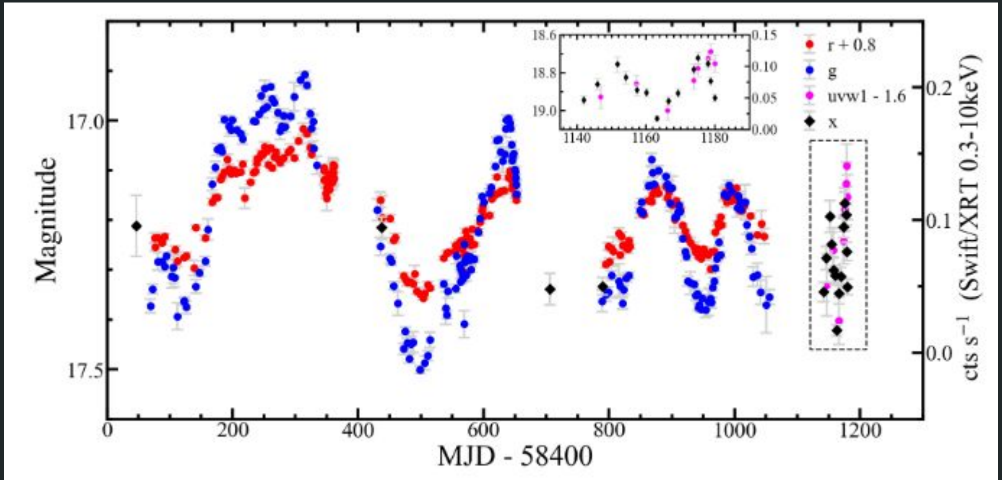



Here the disk is self gravitating down to the scales at which GW always dominate

Bortolas+21

# MBHB path to coalescence - **LISA**

## An extremely quick chirping MBHB




# Tick-Tock: The Imminent Merger of a Supermassive Black Hole Binary


Ning Jiang[1,2]‡, Huan Yang[3,4]‡, Tinggui Wang[1,2], Jiazheng Zhu[1,2], Zhenwei Lyu[3,4], Liming Dou[5], Yibo Wang[1,2], Jianguo Wang[6], Zhen Pan[3], Hui Liu[1,2], Xinwen Shu[7], Zhenya Zheng[8]

[1] *CAS Key Laboratory for Research in Galaxies and Cosmology, Department of Astronomy, University of Science and Technology of China, Hefei, Anhui 230026, China*
[2] *School of Astronomy and Space Science, University of Science and Technology of China, Hefei 230026, China*
[3] *Perimeter Institute for Theoretical Physics, Waterloo, ON N2L2Y5, Canada*
[4] *University of Guelph, Department of Physics, Guelph, ON N1G2W1, Canada*
[5] *Department of Astronomy, Guangzhou University, Guangzhou 510006, China*
[6] *Yunnan Observatories, Chinese Academy of Sciences, Kunming 650011, China*
[7] *Department of Physics, Anhui Normal University, Wuhu, Anhui, 241002, China*
[8] *Shanghai Astronomical Observatory, 80 Nandan Road, Shanghai 200030, China*



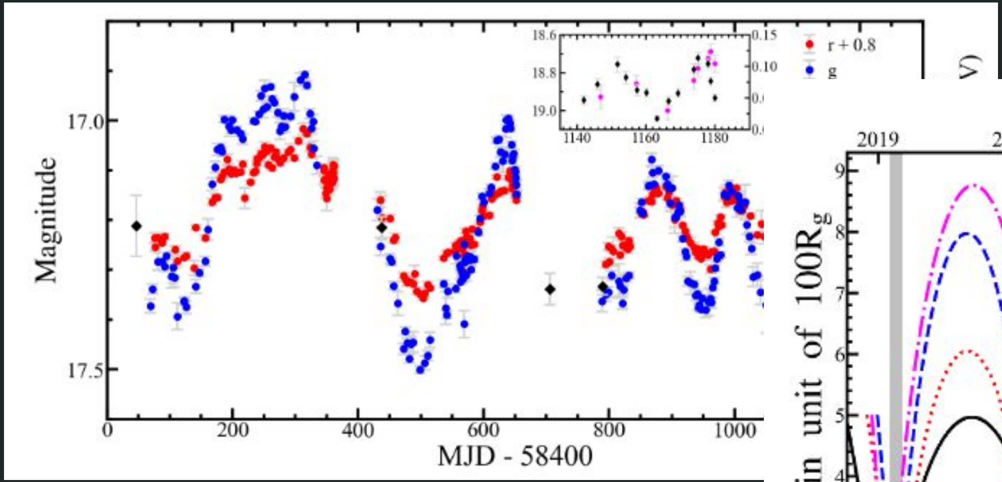
arXiv:2201.11633v1 [astro-ph.HE] 27 Jan 2022



**Supermassive black hole binaries (SMBHs) are a fascinating byproduct of galaxy mergers in the hierarchical universe[1]. In the last stage of their orbital evolution, gravitational wave radiation drives the binary inspiral and produces the loudest siren[2-4] awaiting to be detected by gravitational wave observatories. Periodically varying emission from active galactic nuclei has been proposed as a powerful approach to probe such systems[5-9], although none of the identified candidates are close to their final coalescence such that the observed periods stay constant in time. In this work, we report on the first system with rapid decaying periods revealed by its optical and X-ray light curves, which has decreased from about one year to one month in three years. Together with its optical hydrogen line spectroscopy, we propose that the system is an uneven mass-ratio, highly eccentric SMBH binary which will merge within three years, as predicted by the trajectory evolution model. If the interpretation is true, coordinated, multi-band electromagnetic campaign should be planned for this first binary SMBH merger event observed in human history, together with possible neutrino measurements. Gravitational wave memory from this event may also be detectable by Pulsar Timing Array with additional five-to-ten year observation.**

# MBHB path to coalescence - **LISA**

An extremely quick chirping MBHB

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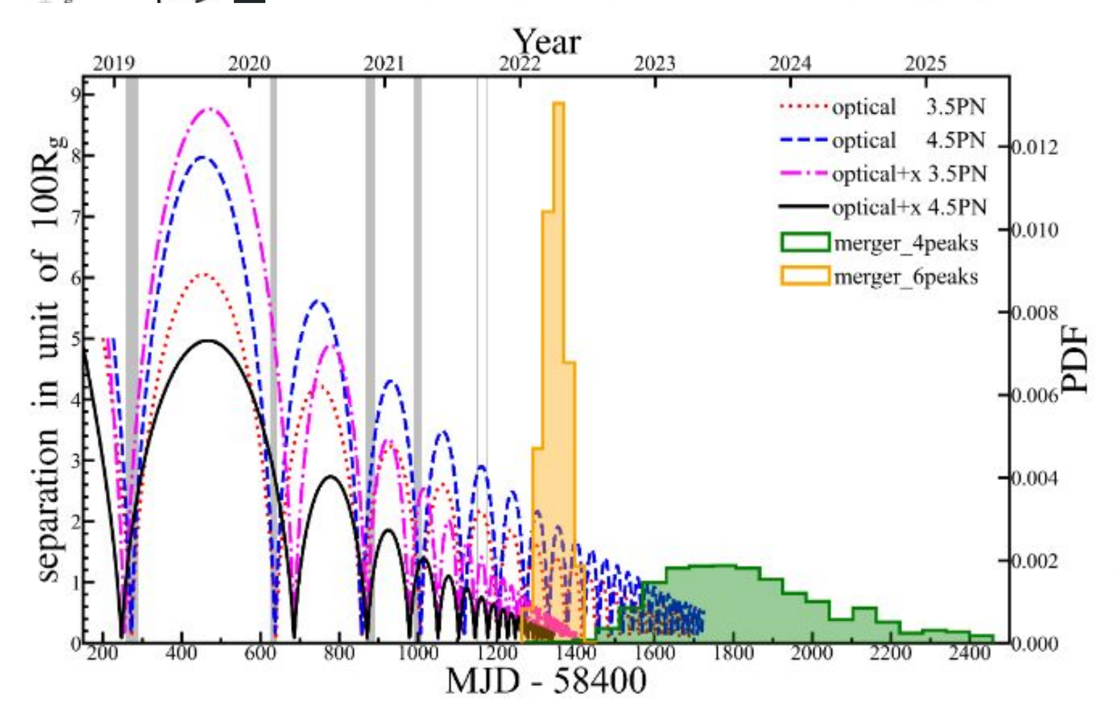


If a confirmed MBHB, it must be extremely eccentric!

Only very few mechanisms could produce such kind of MBHB