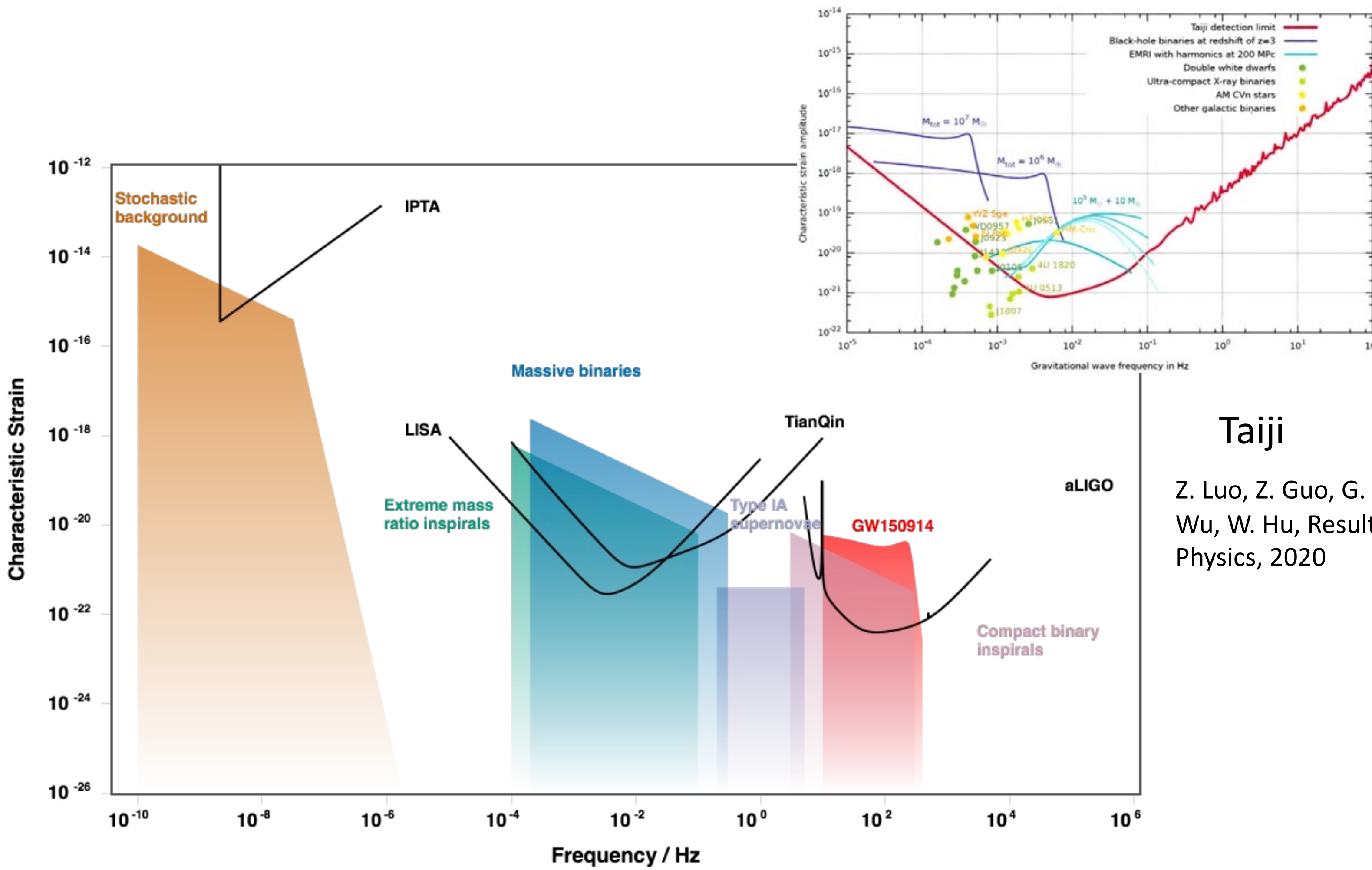
Probing Astrophysical Environments of Massive Black Holes with Extreme Mass-Ratio Inspirals

Huan Yang
Astronomy Department, Tsinghua University

Collaborators: Ya-ping Li, Zhen Pan, Zhenwei Lyu, Jun Zhang, Beatrice Bonga, Scott Hughes

Transient Phenomena and Physical Processes Around Supermassive Black Holes, T. D. Lee Institute, Oct. 17, 2024,

Space-based Gravitational Wave Detection (LISA/Taiji/Tianqin)



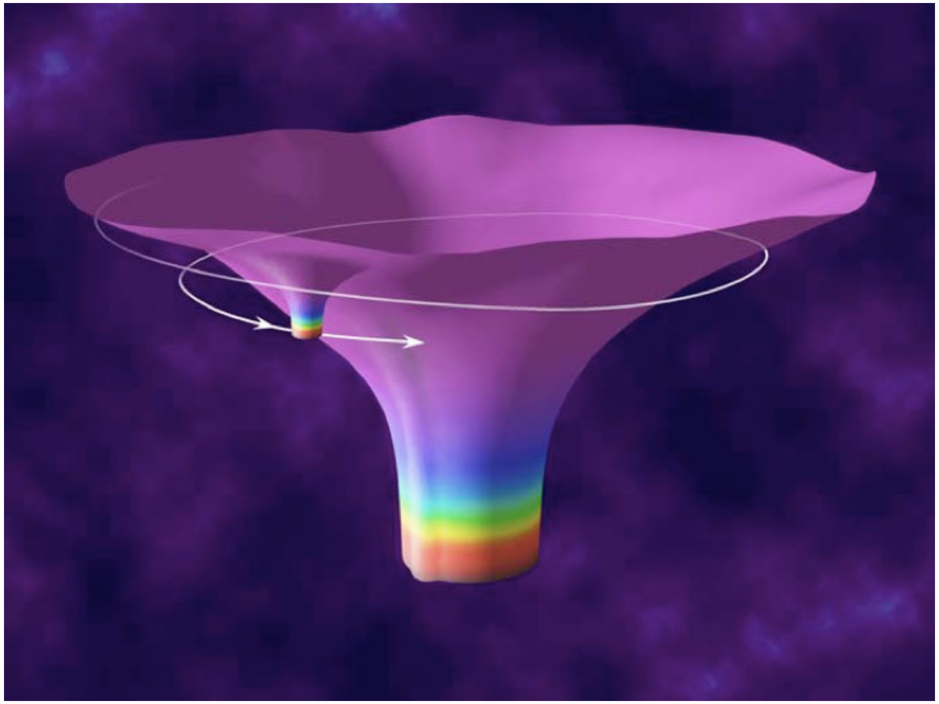
Taiji

Z. Luo, Z. Guo, G. Jin, Y. Wu, W. Hu, Results in Physics, 2020

Figure adapted from gwplotter.com

Extreme Mass Ratio Inspirals (EMRIs)

- Extreme mass-ratio inspirals: stellar-mass object (black holes, neutron stars, compact stars) orbiting around the massive black hole (10^5-10^7 solar mass).

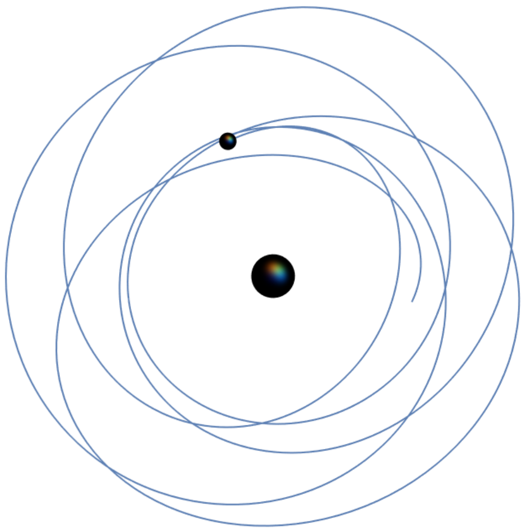


EMRI Dynamics

- A point particle moves along a geodesic of a rotating black hole spacetime: the motion is "separable" and periodic in (r, θ, φ) directions, with different orbital frequencies $(\omega_r, \omega_\theta, \omega_\varphi)$.

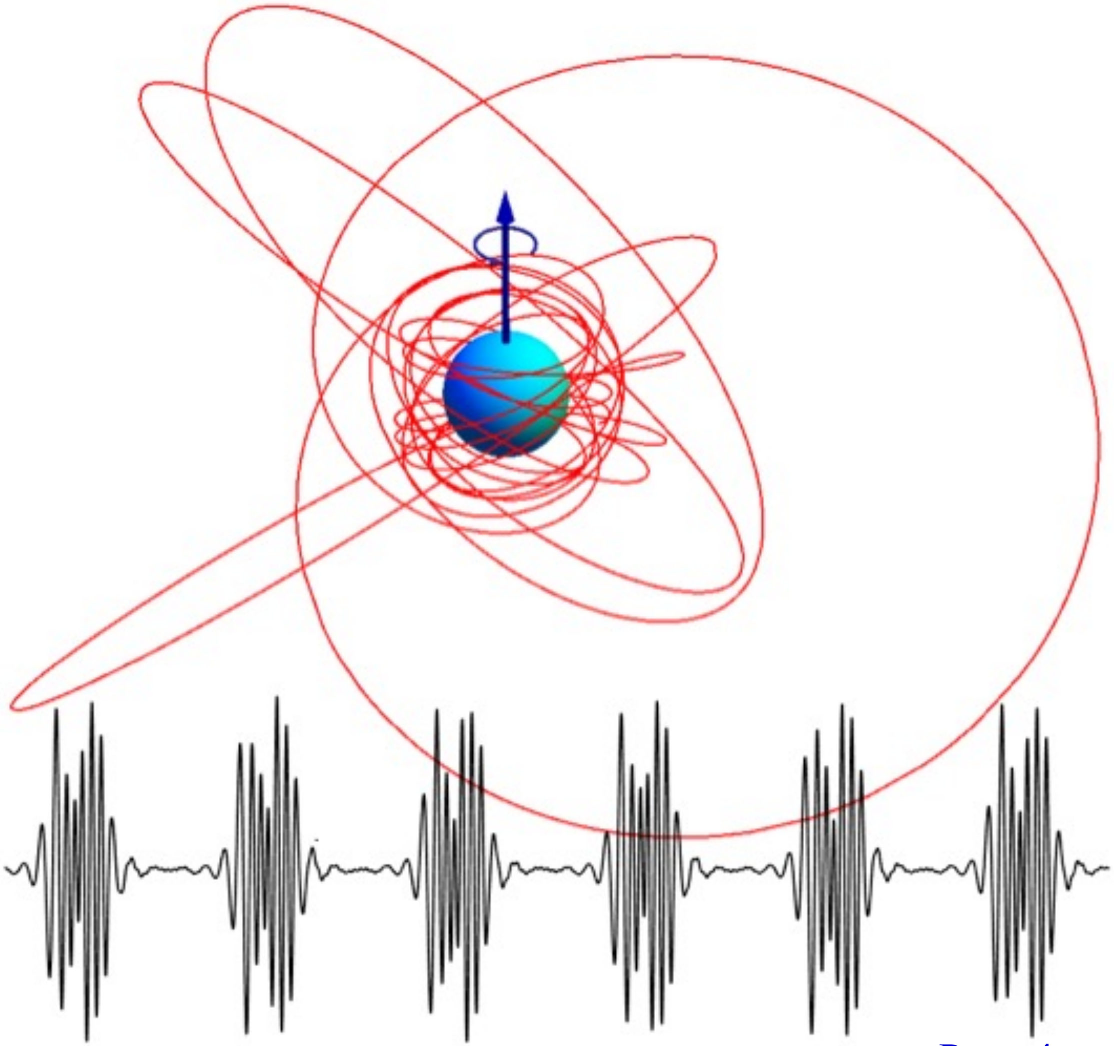
- Gravitational waves carry away energy and angular momentum, so that the orbit slowly shrinks in time.

- A typical EMRI is in-band for 10^4-10^5 cycles.



EMRI Waveform

- 10^4-10^5 cycles in band means ~ 10^5-10^6 rad in the waveform phase.
- A "perturbation" of 10^{-6} in size may accumulate and generate ~ 1 rad phase change
- EMRI → ideal tool for measuring small perturbations: opportunities for studying astrophysics and fundamental physics
- Measurement uncertainty of eccentricity, spin, mass ~ 10^{-4} - 10^{-6}



Overview

- EMRIs with axion clouds around supermassive black holes
- EMRIs with close stellar objects
- Wet EMRIs: formation and motion within AGN disks

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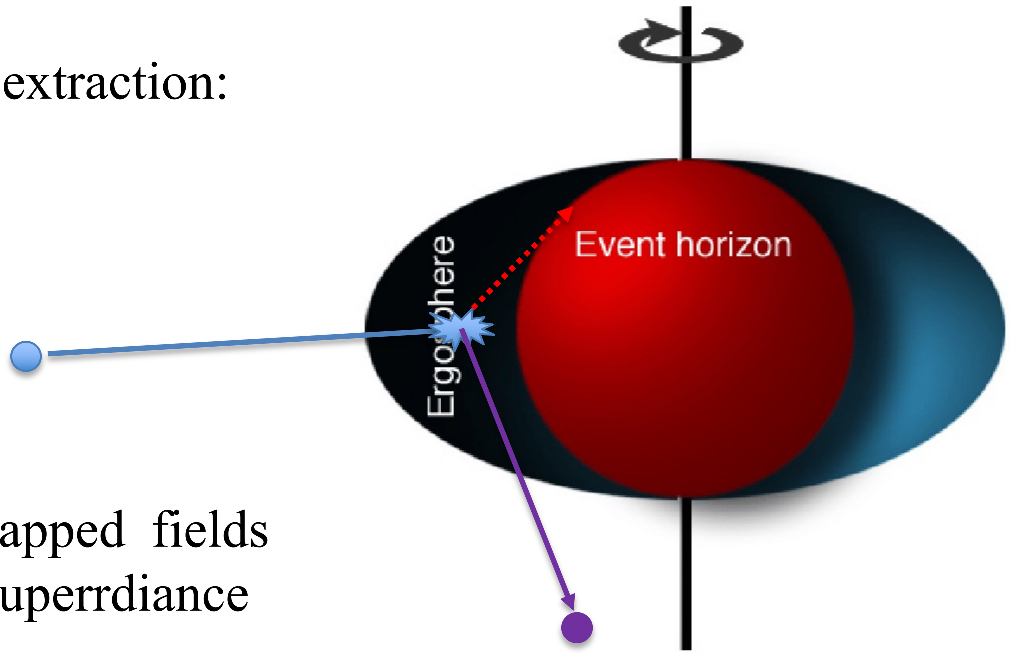
Black hole superradiance

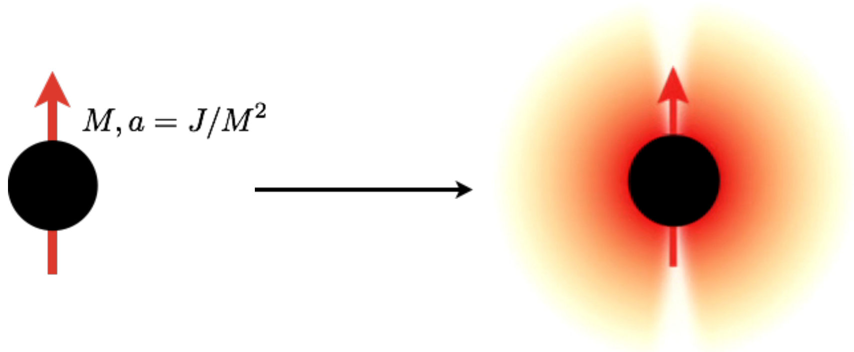
- Penrose process with energy extraction:

$E_1 = E_2 + E_3$, E_2<0

$\rightarrow E_1 > E_3$



- Switch particle to fields: trapped fields with continuous extraction: superrdiance



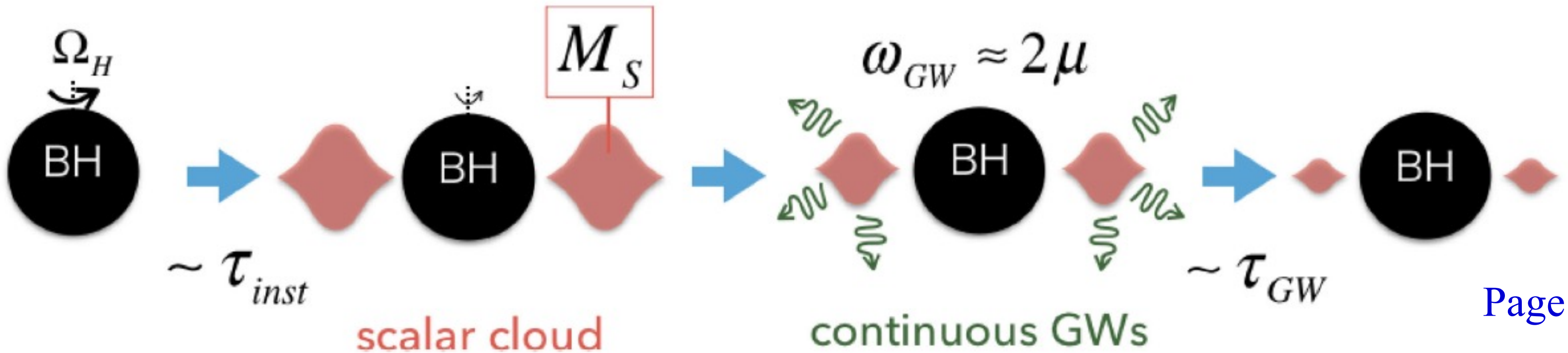
Penrose 1969
Press & Teukolsky 1972
Zouros & Eardley 1979
Detweiler 1980

Superradiant Cloud

- Superradiant process transfers black hole angular momentum to the axion cloud (Dark Matter Candidates), until $\omega = m\,\Omega_H$
- Defining a dimensionless quantity α ~ BH size/axion wavelength

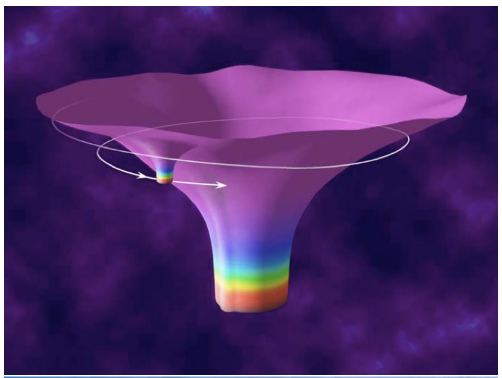
$$\alpha \equiv \mu M \simeq 0.1 \left(\frac{M}{10 M_\odot}\right)\left(\frac{\mu}{10^{-12}\mathrm{eV}}\right)$$

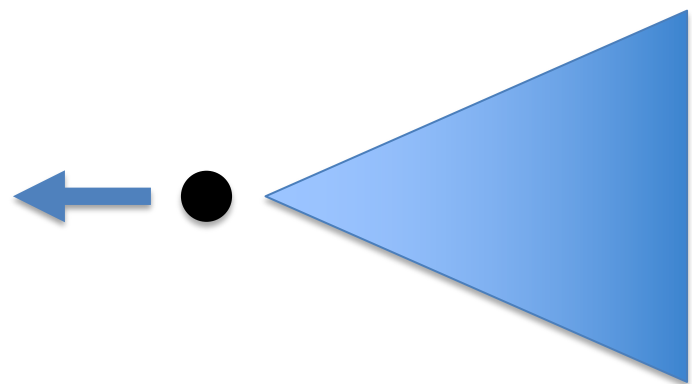
- Two relevant timescales:
  - Growth timescale ~ 12 days $(0.1/\alpha)^9 (M/10\ M_\odot)$
  - GW radiation decay timescale ~ 10^9 years $(0.1/\alpha)^{15} (M/10\ M_\odot)$
- Cloud mass ~ α M



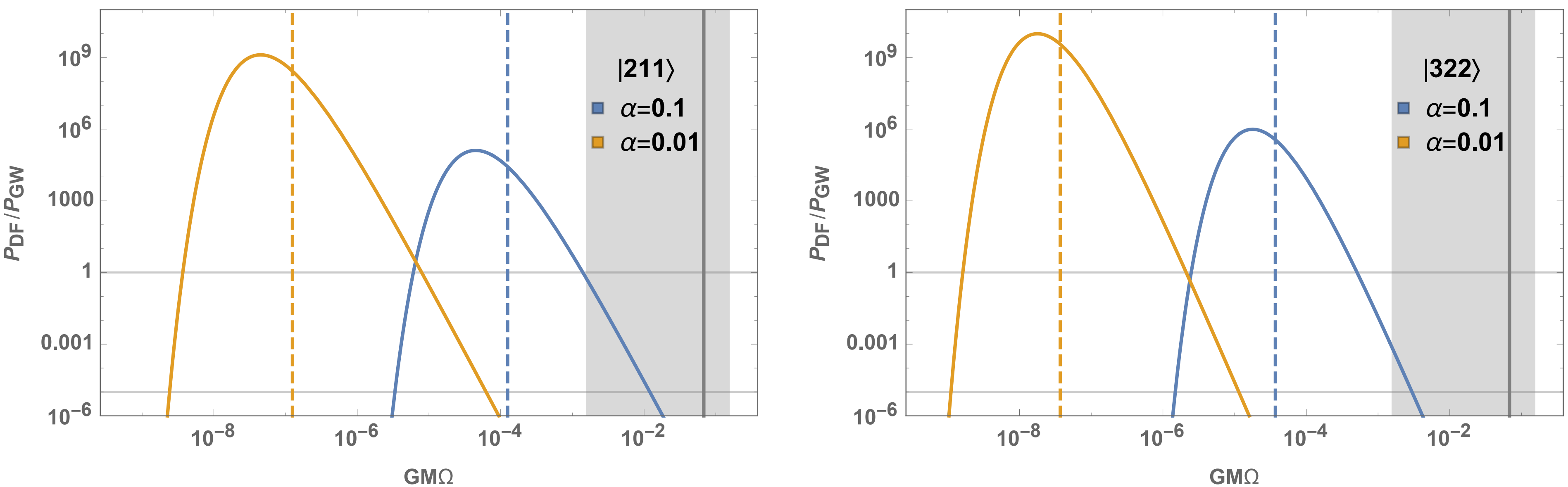
Cloud interaction: extreme mass-ratio inspirals

- Cloud exists for EMRIs (extreme mass-ratio inspirals, one of main sources of LISA). Main interaction: dynamical friction [Zhang, HY, PRD 2020], modified gravitational potential, modified gravitational wave flux.





Detectable parameter range

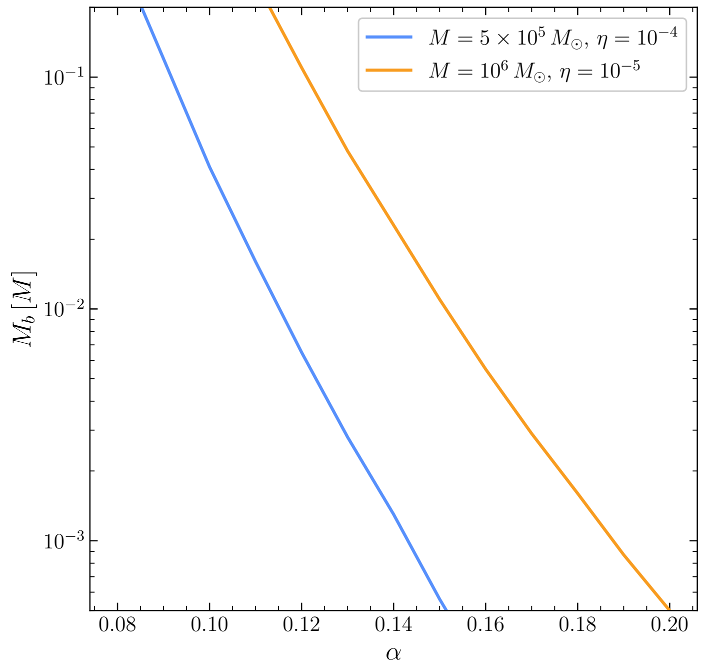


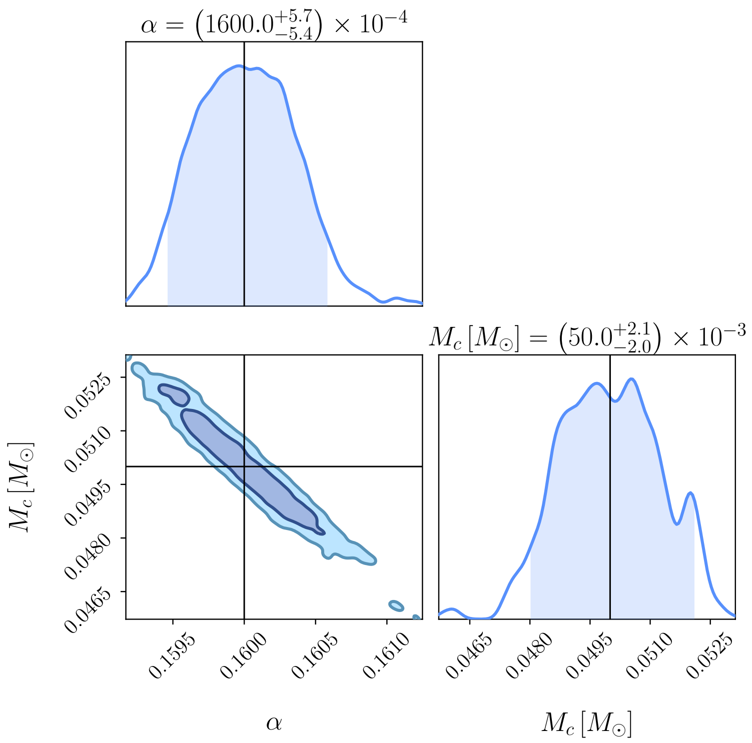
Zhang, HY, PRD 2020

Implementation to the FEW for Parameter Estimation

- FastEMRIWaveform (FEW) is the most accurate EMRI waveform analysis code, which will likely be used for space-borne detectors (as developed by the LISA Consortium).

- We have developed the "environmental effect" model for FEW, including axions.





Khalvati et al. HY, in preparation

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- EMRIs with close stellar objects
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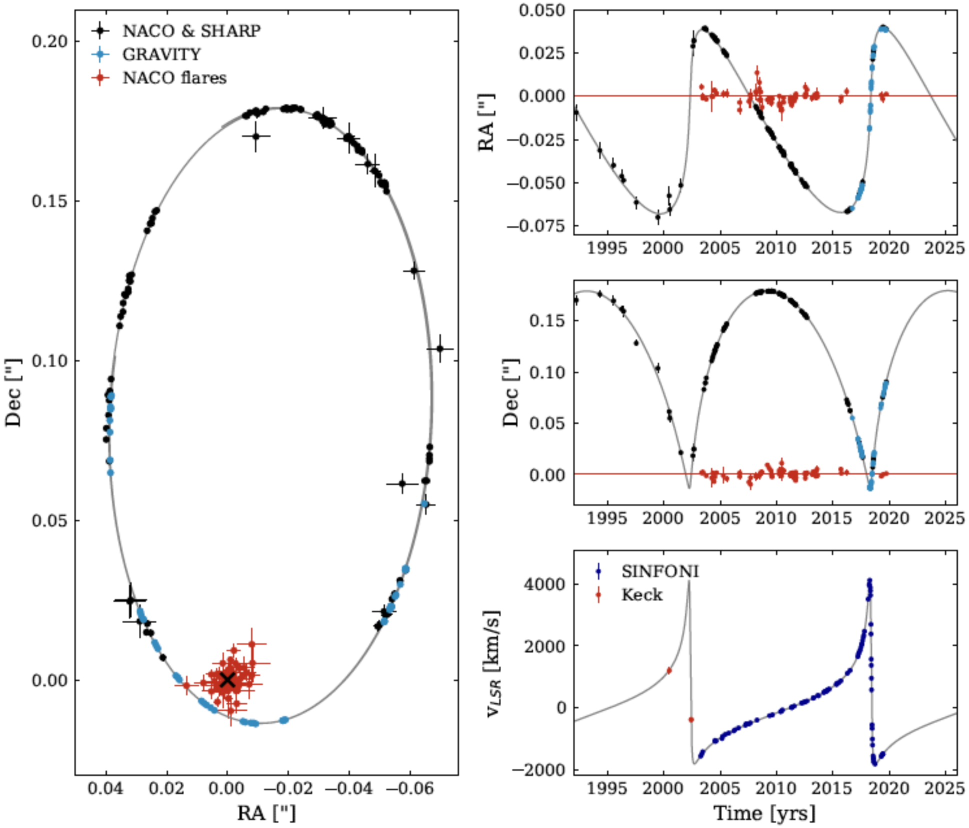
Close stars to Sgr A*

- The observation of the S2 star in our galactic center has led to the identification of compact object (~4 million solar mass) in galactic center – a strong evidence for SMBH [Nobel Prize 2020, Ghez & Genzel]!

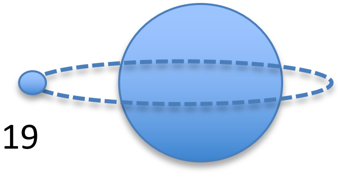


Measuring the GR precession by the GRAVITY Collaboration, 2020

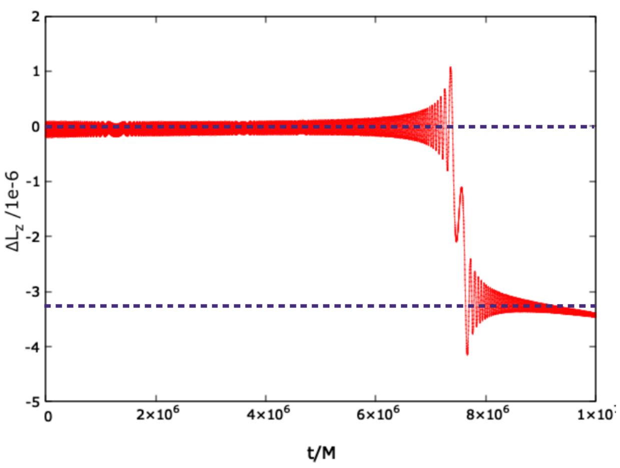
Directly probing the companion

- The presence of a stellar-mass companion generally adds an oscillatory force on the EMRI object – no long-term effect.

HY and M. Casals, PRD 2017
B. Bonga, HY and S. Hughes, PRL 2019



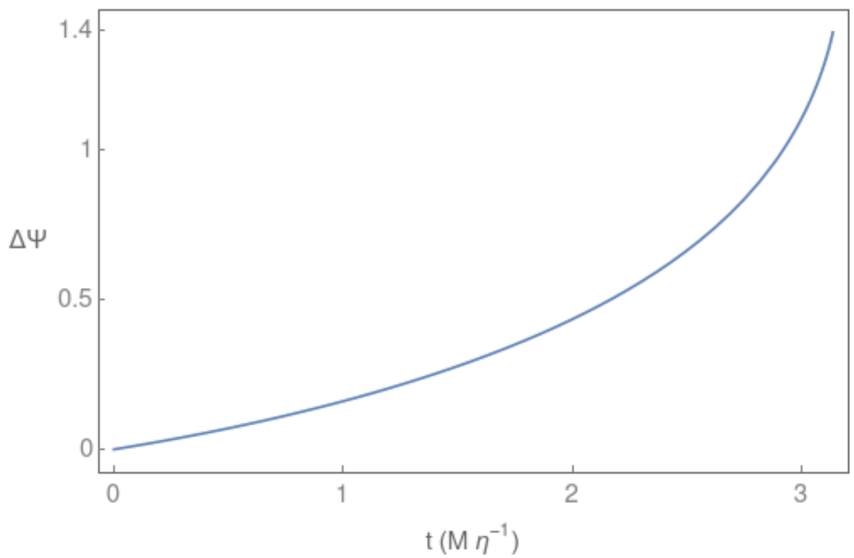
- Except at resonances the "extra" conservative forces can change the conserved quantities (i.e., modified Kerr metric). Sometimes there are chaotic behavior.



$$k\omega_\theta + n\omega_r + m\omega_\phi \approx 0$$

Tidal Resonance

- The “jump” of conserved quantities across a resonance will cause long-term shift of the gravitational wave phase. This can be used to detect the companion.



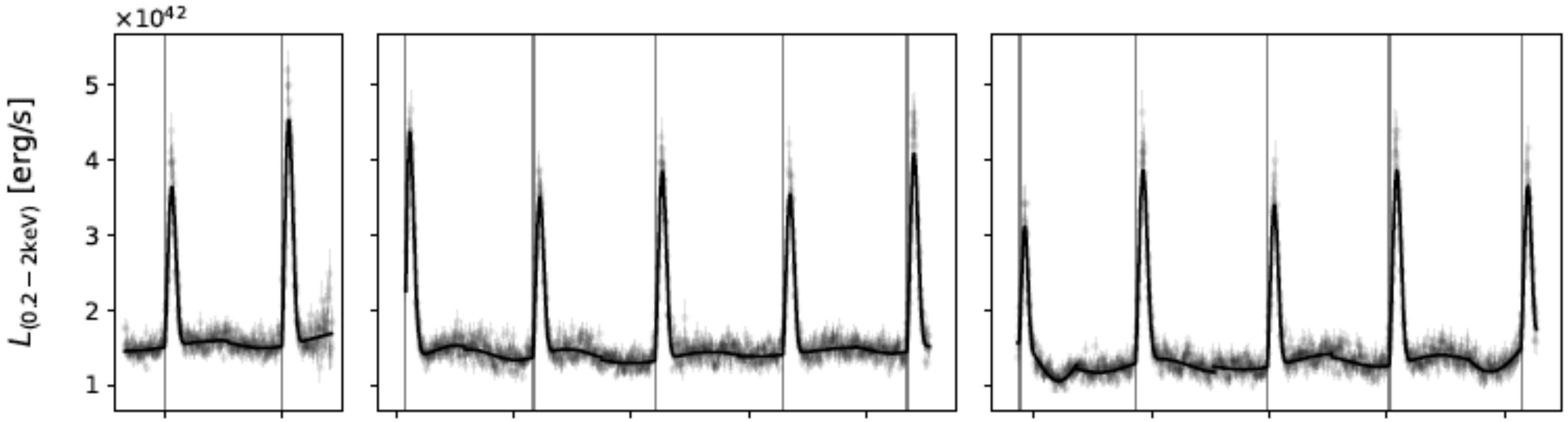
$$\Delta\Psi := \int_0^{T_{\rm plunge}} 2\Delta\omega_\phi dt$$

$$= 1.4\left(\frac{\mu}{10M_\odot}\right)^{-\frac{1}{2}}\left(\frac{M}{M_{\rm SgrA^*}}\right)^{\frac{7}{2}}\left(\frac{M_*}{10\,M_\odot}\right)\left(\frac{R}{4.3\,{\rm AU}}\right)^{-3}$$

O(100) gravitational radii !

QPE and stellar-mass objects close to SMBH

- One of the leading models for QPEs is the "TDE disk+EMRI" scenario [Linial & Metzger 2023]. The timing of X-ray flares can be used to infer the orbital radius of these EMRIs: O(100) gravitational radii ! [Cong Zhou et al. 2024 ab]



- Arcodia et al 2024 predicts comparable QPE abundance v.s. LISA massive BHs.

Where do they come from?

Overview

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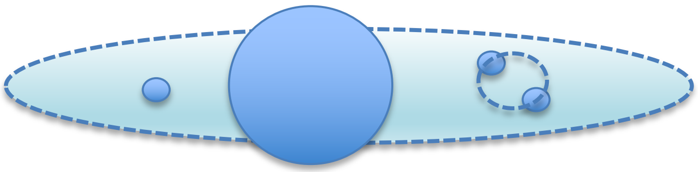
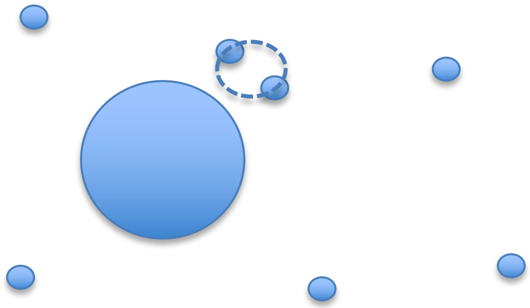
- Wet EMRIs: formation and motion within AGN disks

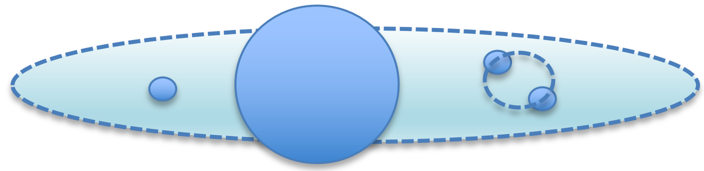
Formation of EMRI systems

- Formation channels:
  - "Dry formation", which is mainly driven by multi-body scattering in the nuclear star cluster.
  - "Wet formation", which is assisted by the accretion flow around the massive black hole;





Wet Formation Channel



- The wet formation channel relies on the interaction between the accretion disk and the nuclear cluster around the supermassive black holes. The rate calculation requires consistent modelling for disk+cluster.

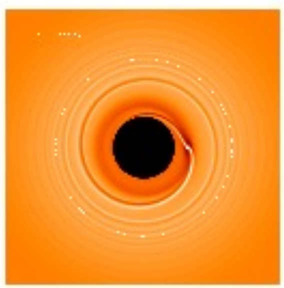
- Roughly 1% of local galaxies and 10% of high-redshift galaxies have AGNs. However, we will show that AGNs will dramatically accelerate EMRI formations.

- The sBHs trapped in accretion disk may form sBHBs – a promising source for ground-based gravitational wave detection.

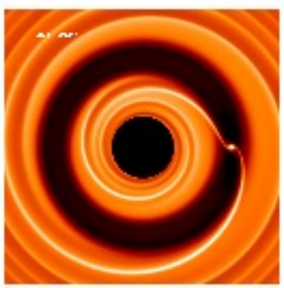
Disk forces

- The main sBH-disk interaction include density wave generation, head wind effect (BH absorption), feedback.

- The migration force/torque (density wave & corotation torques) is extensively studied in planetary systems. Likely similar things happen in AGN disks.



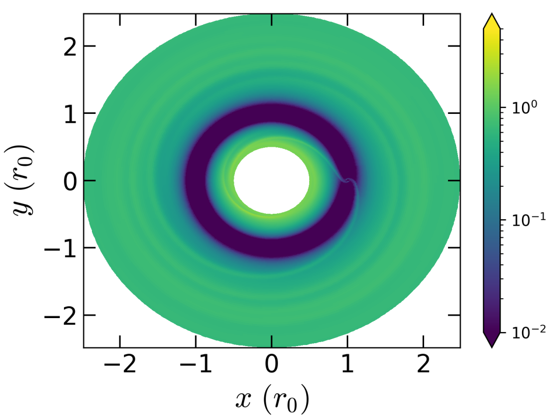
Type I

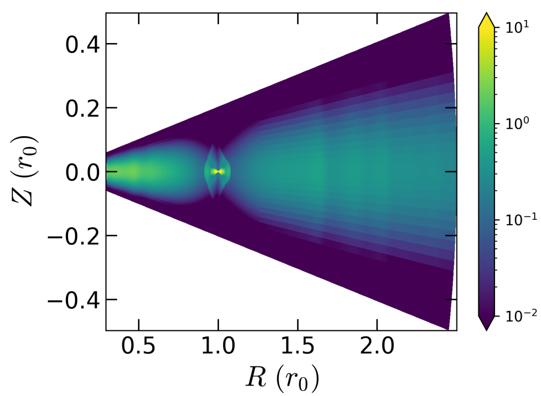


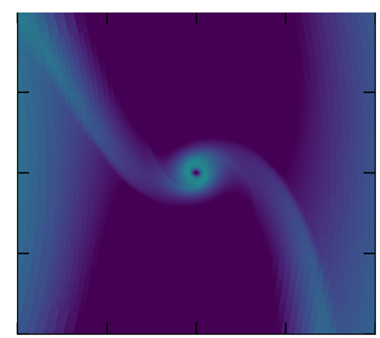
Type II

Type III

- Gravitationally capture of disk material (Bondi accretion). Material infall & circularize and form circum-single disk, eventually join the outflow or accrete onto the sBH.





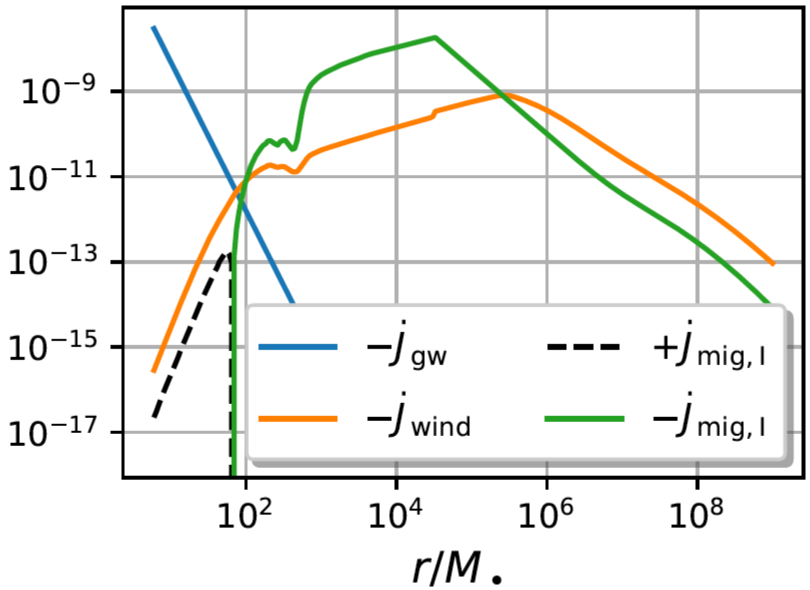


Courtesy of 李亚平

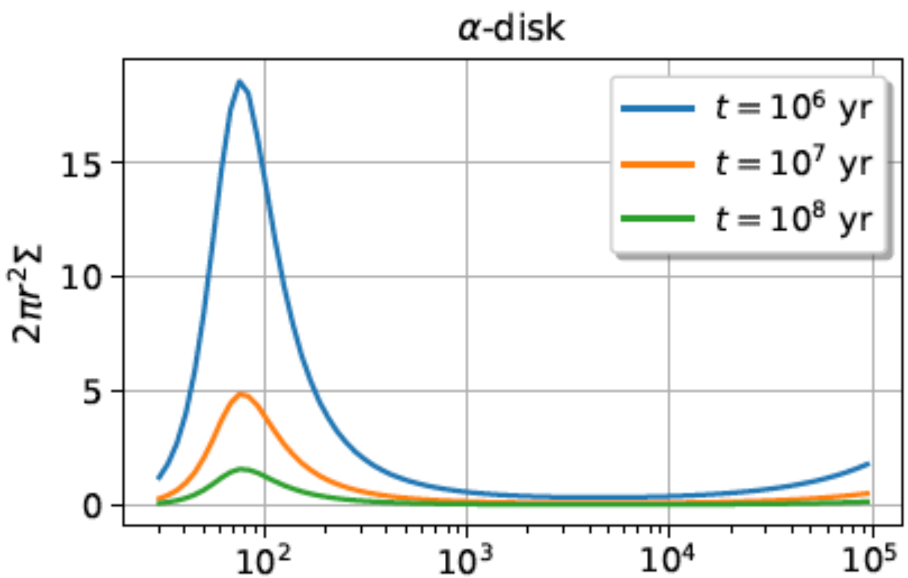
Disk forces and stalling of sBHs

- The migration torque and the head-wind effect dominates for r > O(10^2) M, and at smaller radii the gravitational wave torque dominates.

- The migration is slow at the intersection – accumulation of sBHs at O(10^2) M!



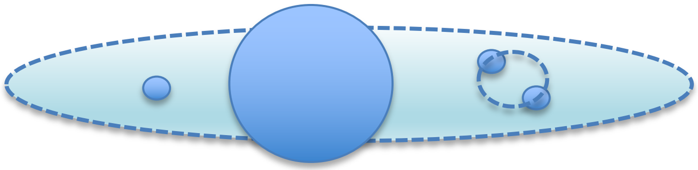
Z. Pan, HY, PRD 2021

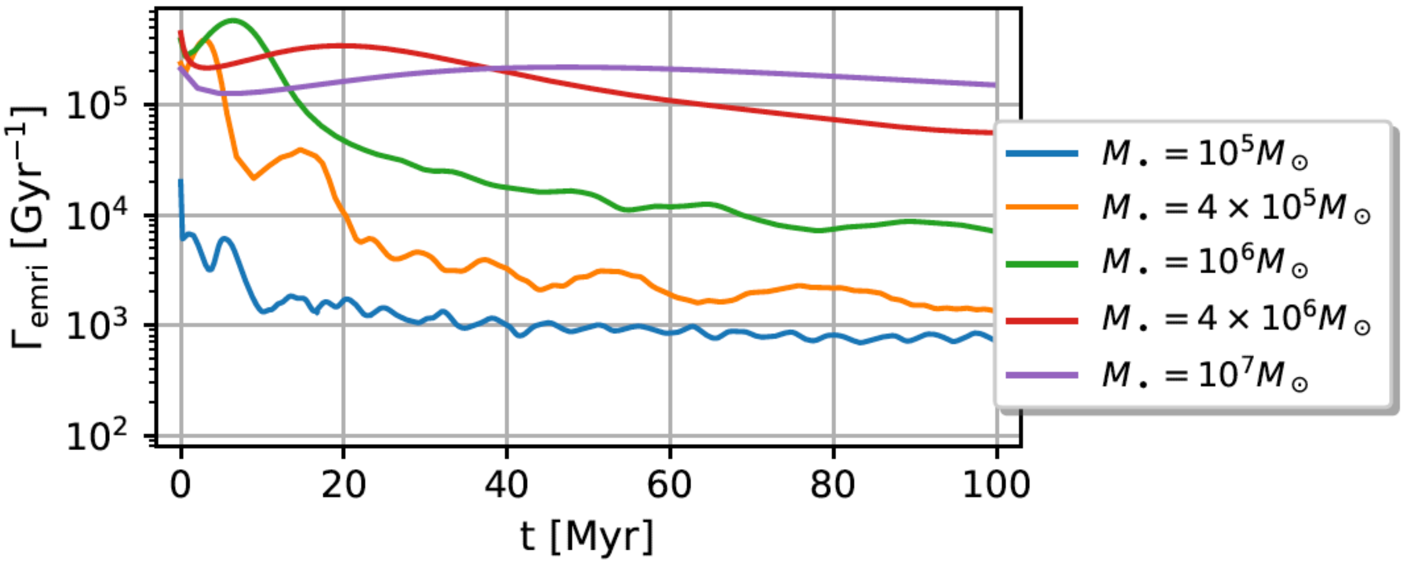


Z. Pan, Z. Lyu, HY, PRD 2022

α-disk model for 4 million solar mass black holes

Wet Formation Rate





$$M_\bullet = 4 \times 10^6 M_\odot,\quad \frac{\langle \Gamma_{\rm disk} \rangle}{\langle \Gamma_{\rm loss-cone} \rangle} = \mathcal{O}(10^2 - 10^3)$$

$$M_\bullet = 1 \times 10^5 M_\odot,\quad \frac{\langle \Gamma_{\rm disk} \rangle}{\langle \Gamma_{\rm loss-cone} \rangle} = \mathcal{O}(10^1 - 10^2)$$

AGN fraction:

$$f_{\rm AGN}(z \lesssim 1) \sim 1\%$$

$$f_{\rm AGN}(z \gtrsim 1) \sim 1\% - 10\%$$

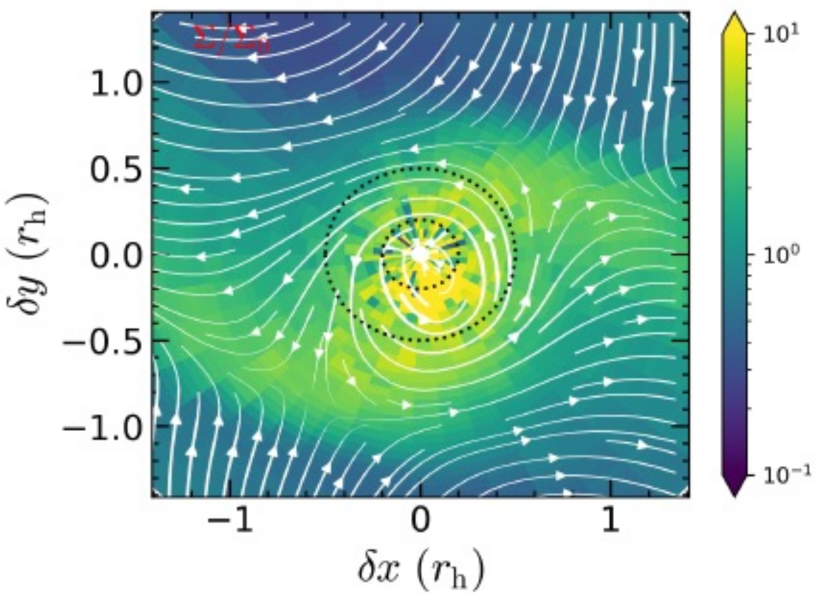
Comparison between Dry/Wet Formations

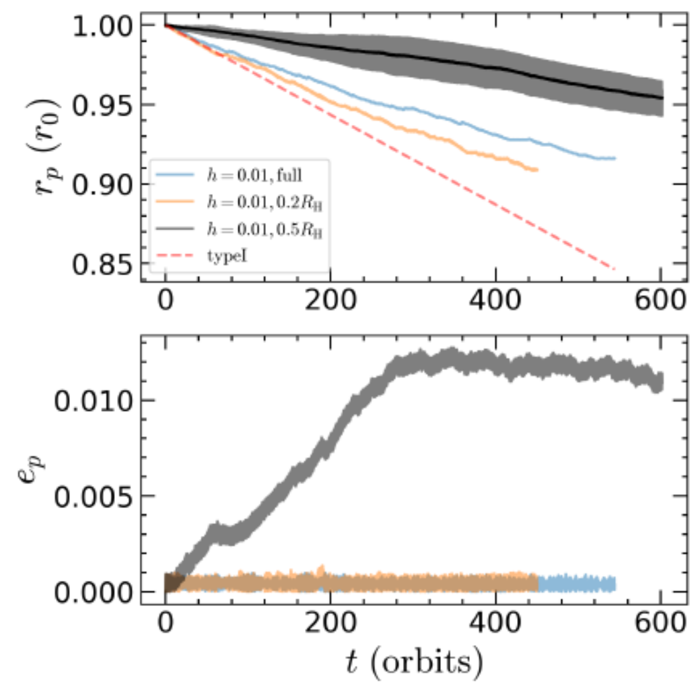
Dry EMRIs	$f_\bullet$	N_p					Total rate [yr^{-1}]	LISA detectable rate [yr^{-1}]
	$f_{\bullet,-0.3}$	0					3500	150
		10					1300	120
		10^2					150	14
	$f_{\bullet,+0.3}$	0					160	10
		10					130	10
		10^2					15	1
Wet EMRIs	$f_\bullet$	$\mathbb{M}$:	(γ, δ)	μ_{cap}	(T_{disk} [yr], f_{AGN})	AGN Disk	Total rate [yr^{-1}]	LISA detectable rate [yr^{-1}]
	$f_{\bullet,-0.3}$	M_1 :	(1.5, 0.001)	1	(10^8, 1%)	α-disk	11000	600
		M_2 :	(1.5, 0.001)	0.1			11000	760
		M_3 :	(1.5, 0.002)	1			24000	1500
		M_4 :	(1.8, 0.001)	1			8100	240
		M_5 :	(1.5, 0.001)	1	(10^8, 1%)	TQM disk	23000	1900
		M_6 :	(1.5, 0.001)	1	(10^7, 1%)	α-disk	39000	4200
		M_7 :	(1.5, 0.001)	0.1			21000	3000
		M_8 :	(1.5, 0.002)	1			80000	9800
		M_9 :	(1.8, 0.001)	1			22000	1400
	$f_{\bullet,+0.3}$	M_1 :	(1.5, 0.001)	1	(10^8, 1%)	α-disk	2100	49
		M_2 :	(1.5, 0.001)	0.1			2000	57
		M_3 :	(1.5, 0.002)	1			4300	100
		M_4 :	(1.8, 0.001)	1			1900	18

- Wet EMRIs may be at least as frequent as dry EMRIs.
- Wet EMRIs have e ~0, many dry EMRIs have e <=0.3 in the detection band
- LISA detection sensitivity on e ~ O(10^{-5})

Indirect probe using eccentricity

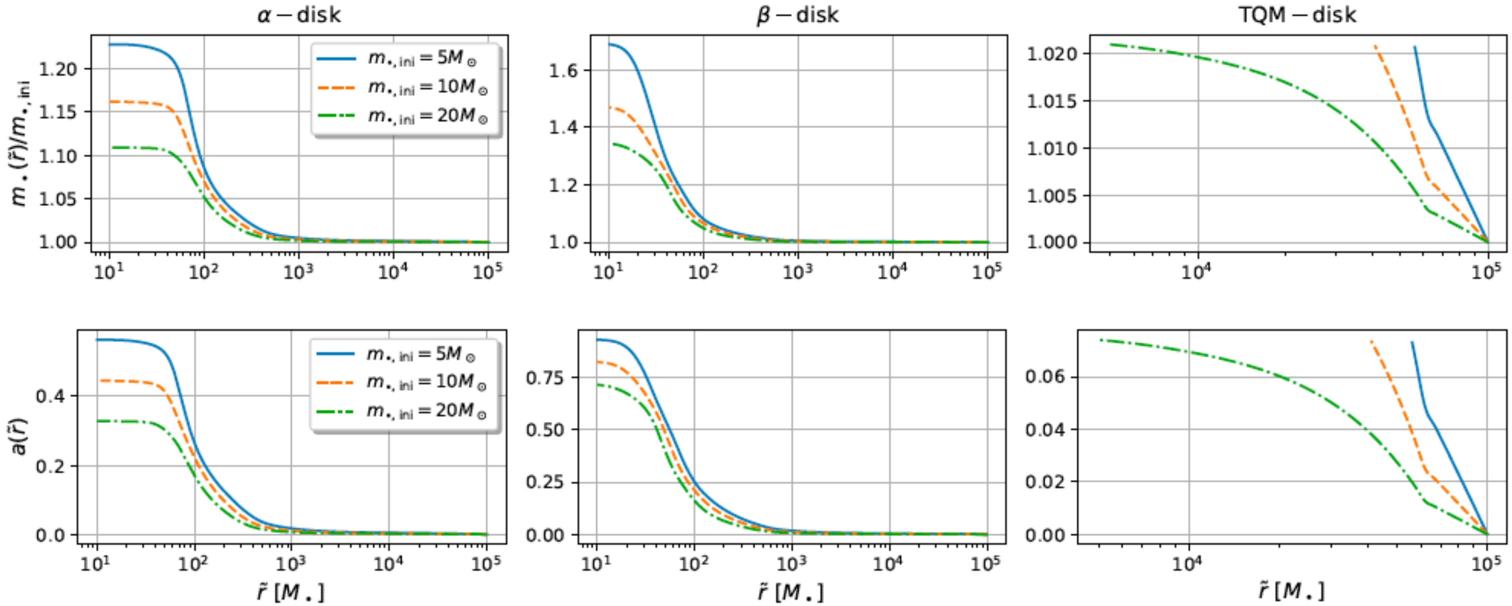
- Dry EMRIs tend to have O(0.1) eccentricity in band.
- Wet EMRIs should have negligible eccentricity, but how small should it be?
- Novel eccentricity excitation scheme (associated with density wave emission) when Hill radius is larger than the disk thickness, while the circum-single disks try to damp out the eccentricity [Y. Li, HY, Z. Pan, in preparation].





Indirect probe using mass and spin

- sBHs embedded in AGNs will accrete: mass and spin change.
- Semi-analytical circum-single disk treatment: inflow-outflow model for supercritical accretion flows [Yuan et al. 2012].
- Mass and spin evolution [Pan, Yang, 2021]:



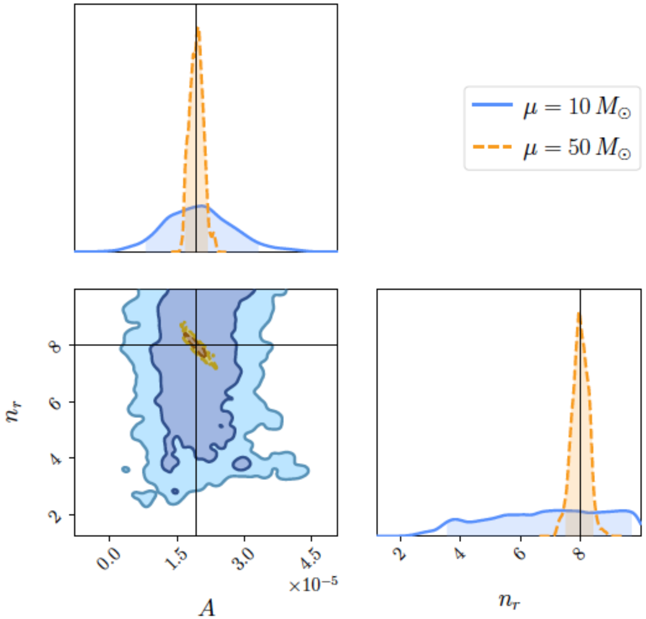
Direct probe with GW observations

- In the LISA(Tianqin, Taiji) band, the disk migration torque is small compared with the GW torque. It also depends on the disk profile and the sBH mass.

- The GW phase due to disk interaction may be parametrized:

$$\dot{L}_{\rm mig} = A\left(\frac{p}{10M}\right)^{n_r} \dot{L}^{(0)}_{PN} \qquad A \sim 7\times 10^{-10}\left(\frac{0.1}{\alpha}\right)\left(\frac{f_{\rm Edd}}{0.1}\frac{0.1}{\epsilon}\right)^{-3}\left(\frac{M}{10^6 M_\odot}\right)$$

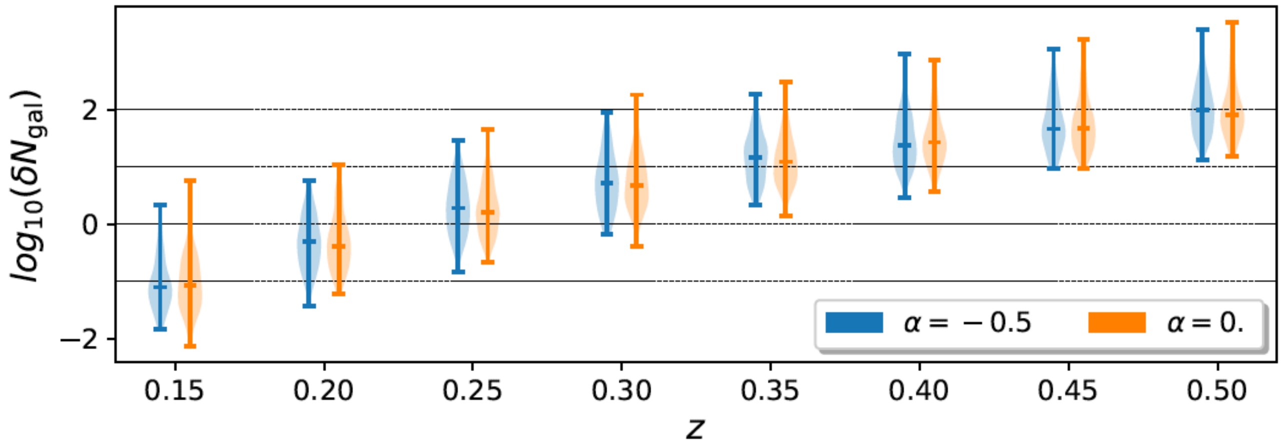
- Parameter Estimation of GW observation may be used to infer disk properties.



Khalvati et al. HY, in preparation

Multi-messenger Opportunities

- Wet EMRIs may be observed both by GWs and EM (radio, optical, etc.) signal.
    - Localization (galaxy identification) is possible for low-redshift EMRIs (z<0.5):



Pan & Yang, 2020

- Order of magnitude improvement with a network (LISA/Tianqin/Taiji)
- Science opportunities: testing disk/jet model, transient EM signal， Hubble constant measurement, etc

Conclusion

- EMRIs are likely a major component of LISA sources.
- They will be used to probe axion clouds around SMBHs, nearby stellar companion at the center of nuclear cluster.
- Wet EMRIs may form naturally in AGN disks. They may be a major formation channel for EMRIs for spaceborne detections.
- Indirect and Direct probes of wet EMRIs.