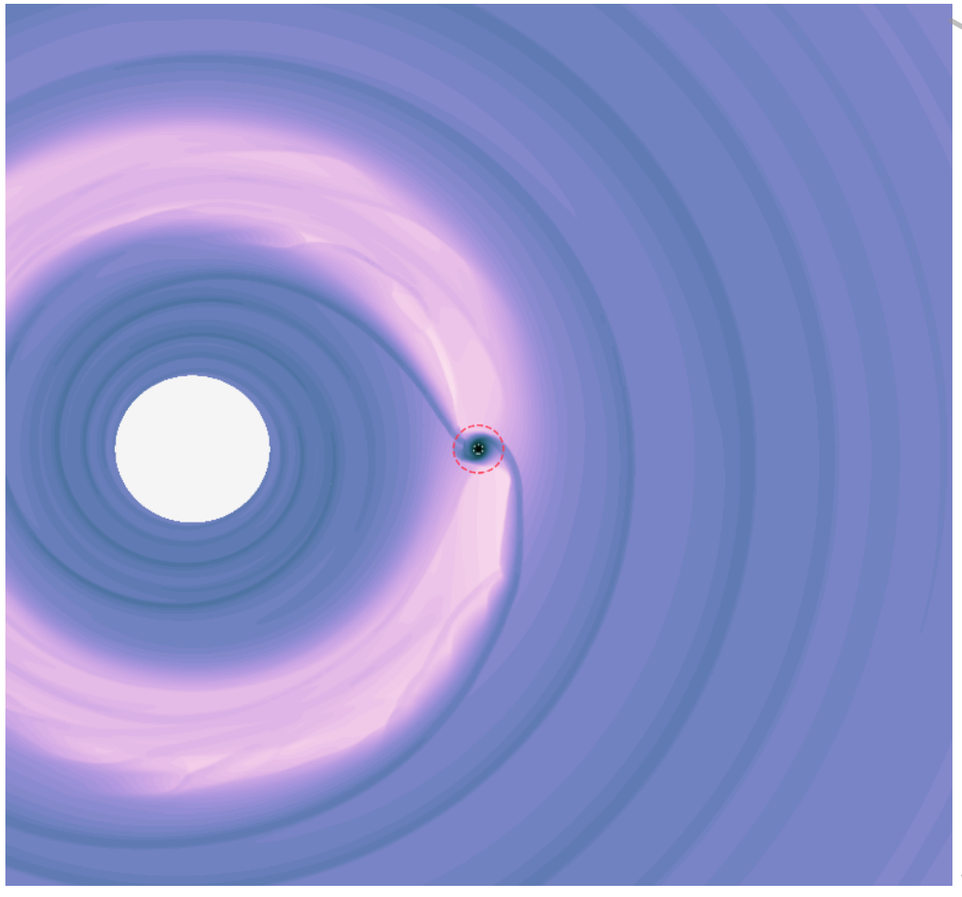
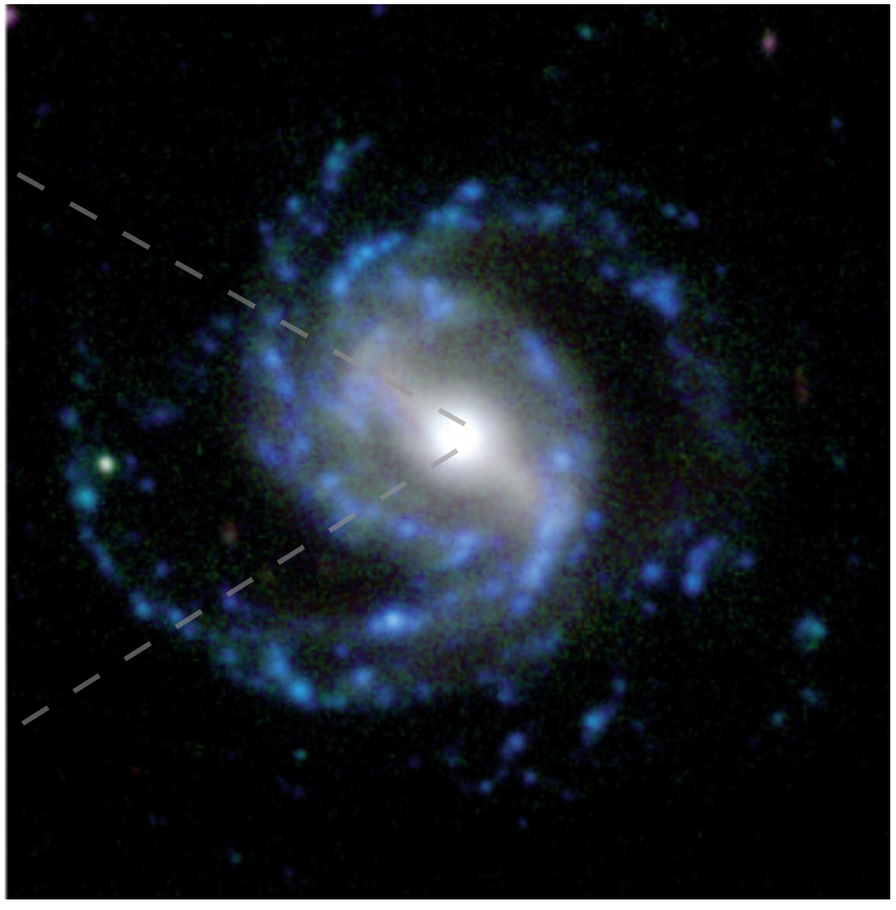
milliHz GW sources in AGN accretion disks





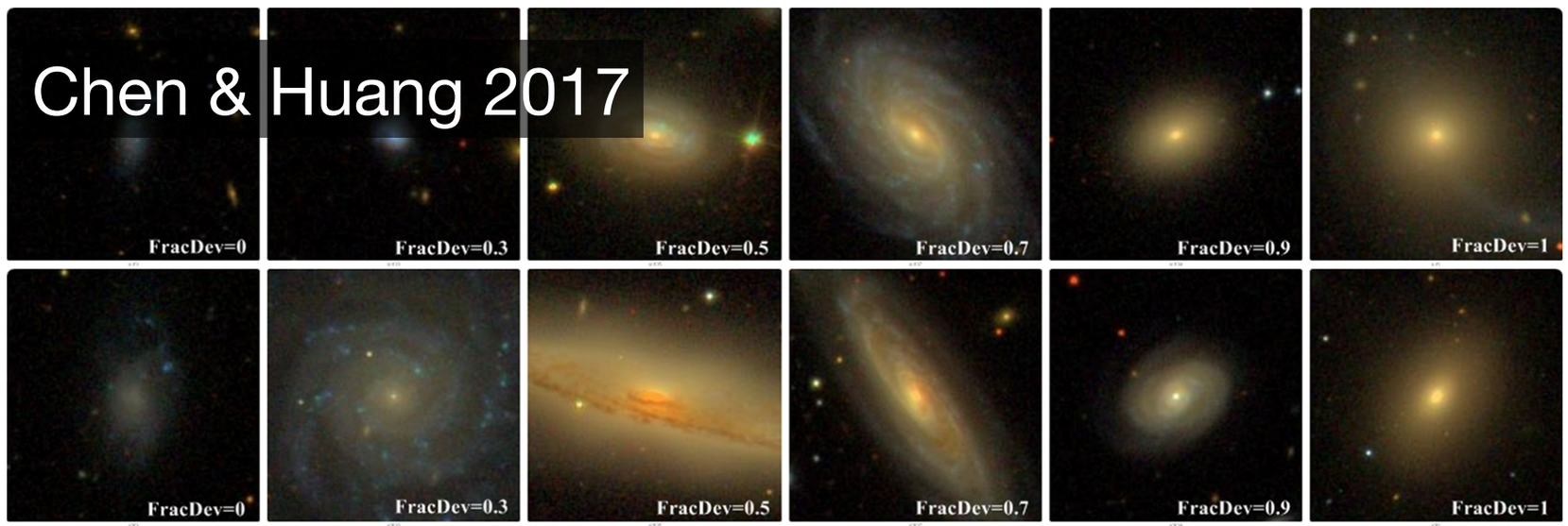
Andrea Derdzinski
Institute for Computational Science
University of Zurich
TianQin Astro Workshop Aug 2022

Universität Zürich[UZH]

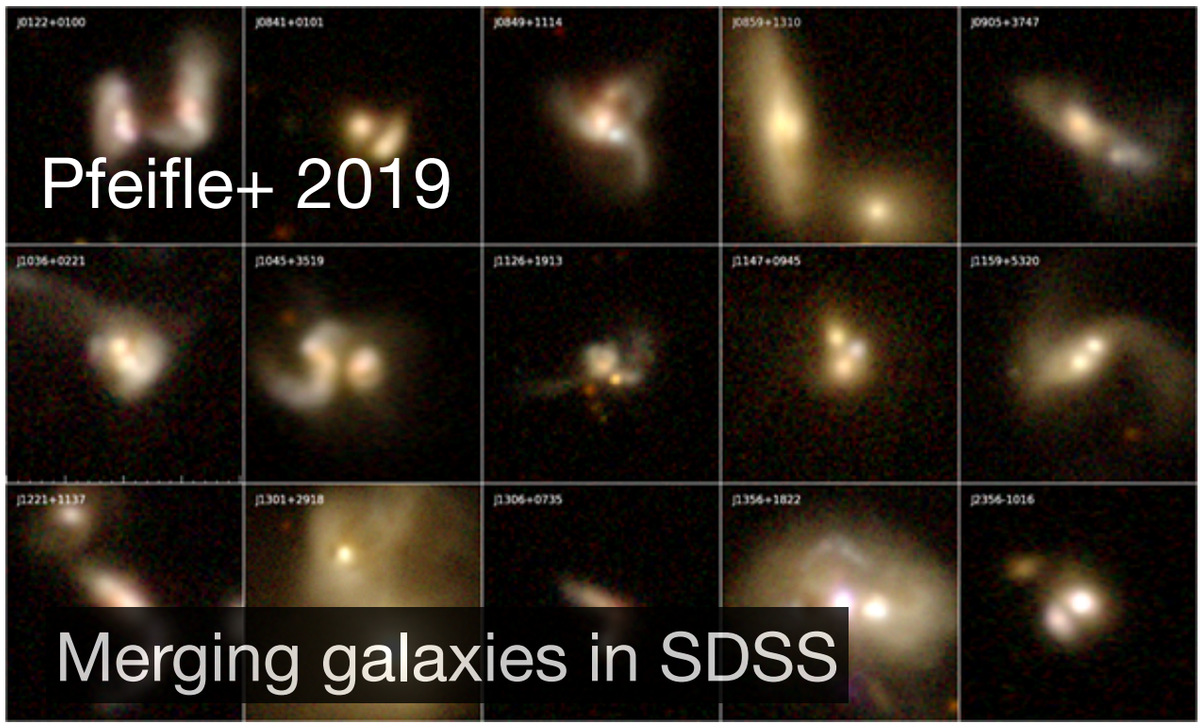
1-10% of galaxies have Active Galactic Nuclei*

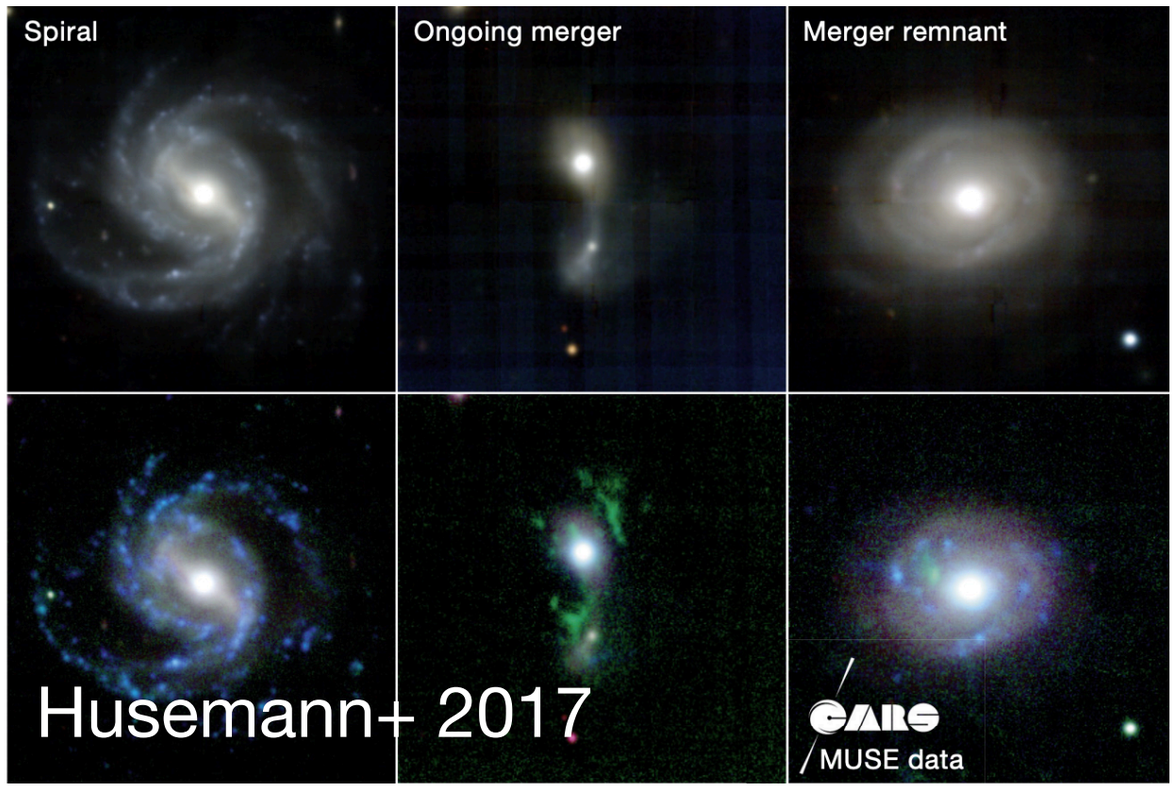
***depends on redshift, AGN type, etc.**

Shankar+ 2013, Jones+ 2016



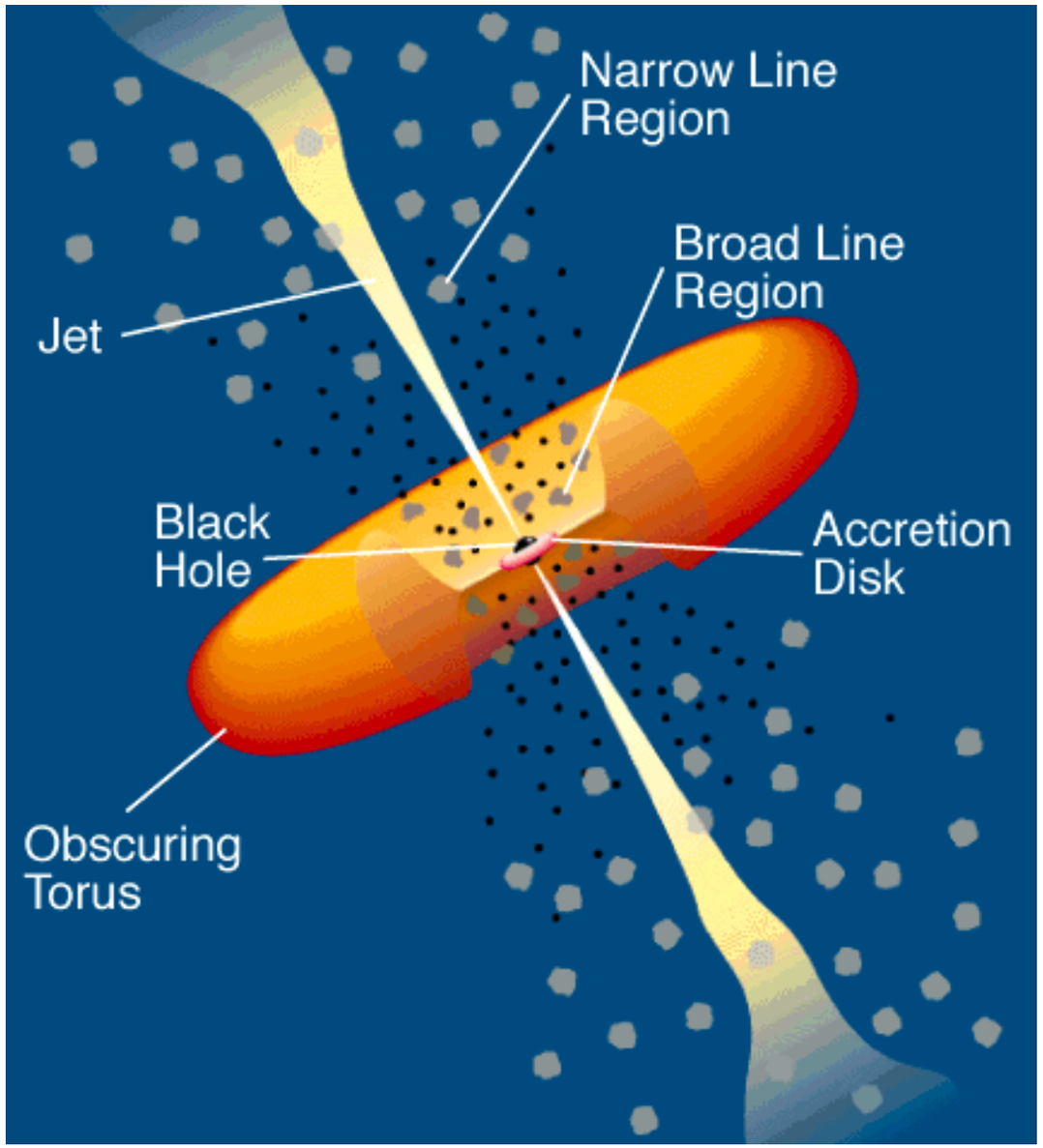
Gas inflow triggered by galaxy mergers:





Andrea Derdzinski andrea@ics.uzh.ch University of Zurich

How well do we understand AGN accretion disks?



Standard model for radiatively efficient flows (small scales): steady-state, geometrically thin, relatively dense

(Shakura & Sunyaev 1973, Novikov & Thorne 1974)

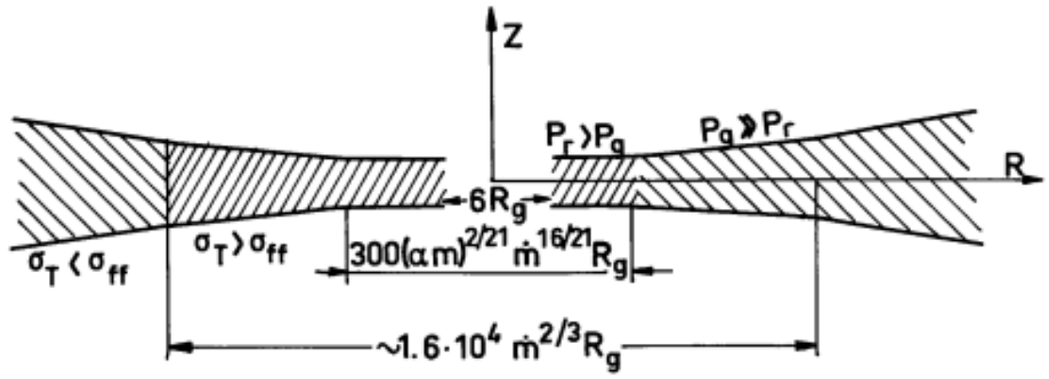
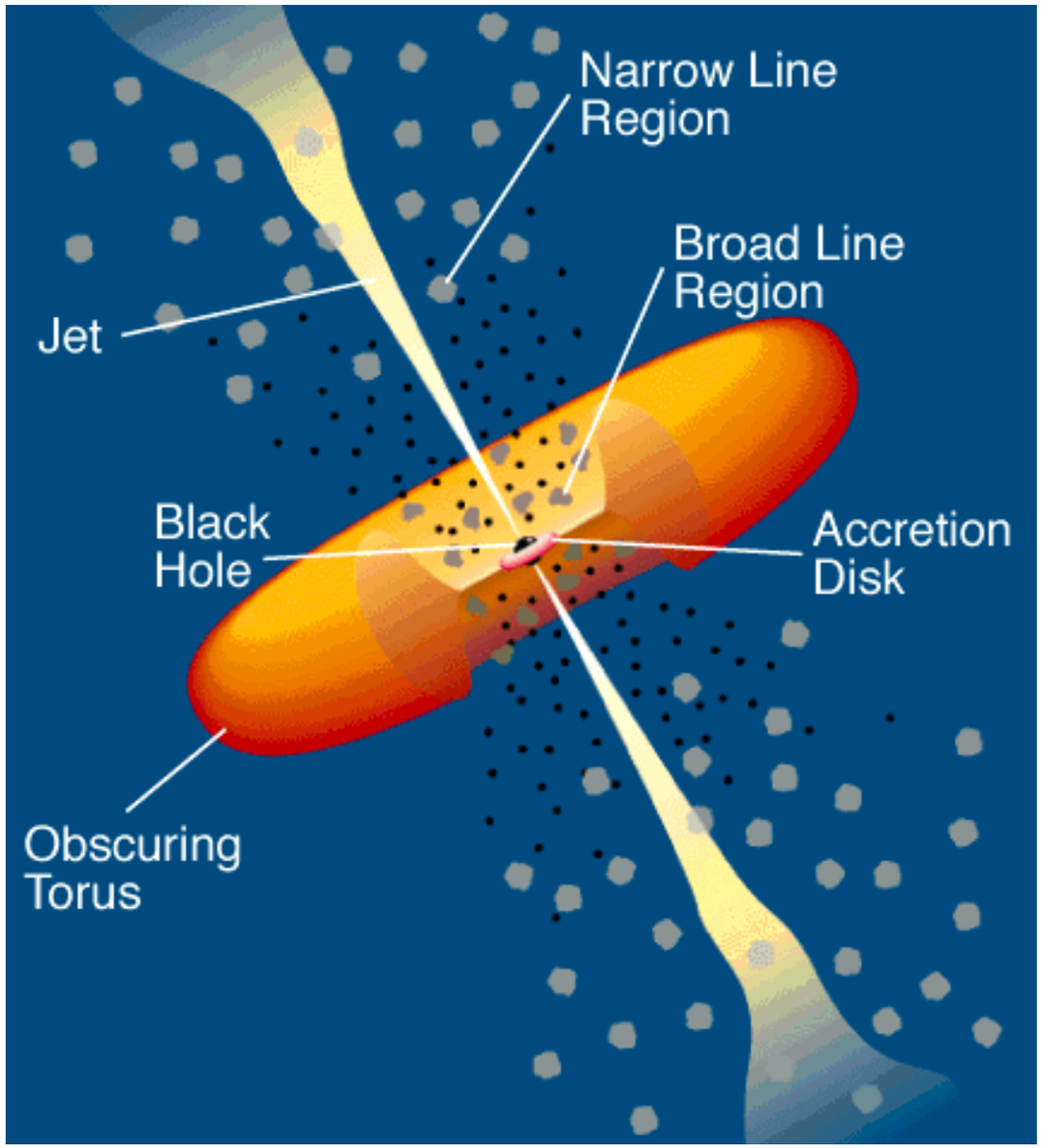


Fig. 10. The regions of disk having different physical conditions

- Uncertainties in precise structure, emission features, efficiency of angular momentum transport / AGN lifetime…

  see Padovani 2017

How well do we understand AGN accretion disks?



Standard model for radiatively efficient flow
geo
(Shak 1974)

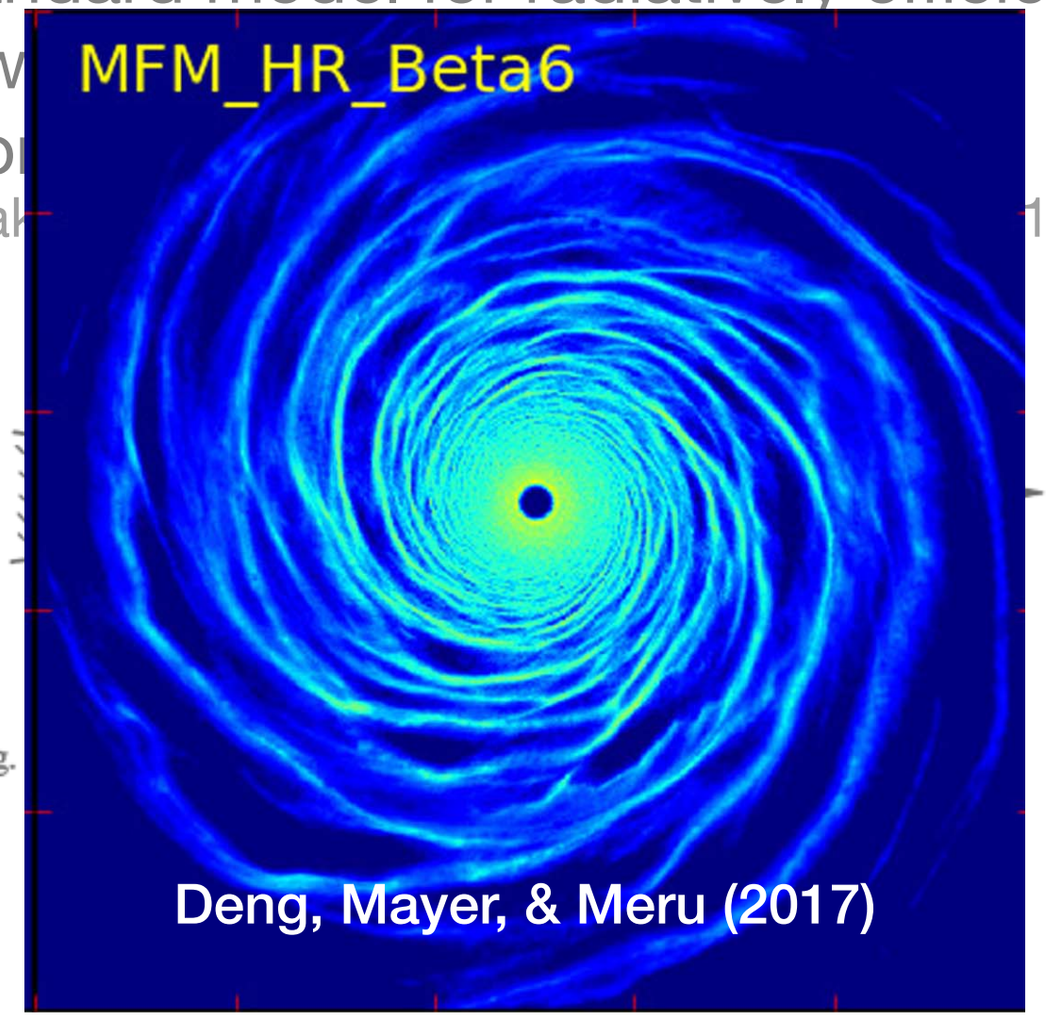
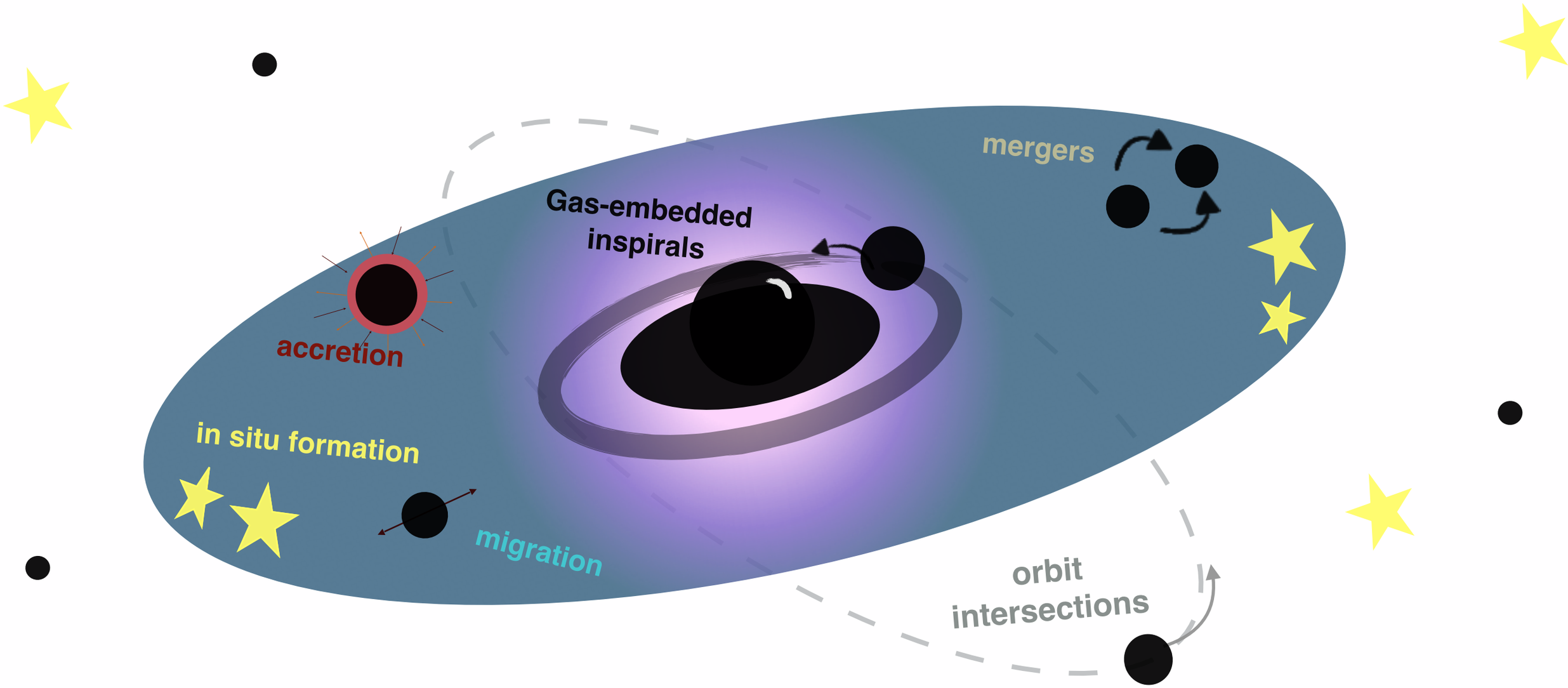


Fig.

Gravitational instability beyond ~0.01 pc
(Toomre 1964)

- Uncertainties in precise structure, emission features, efficiency of angular momentum transport / AGN lifetime…
  see Padovani 2017

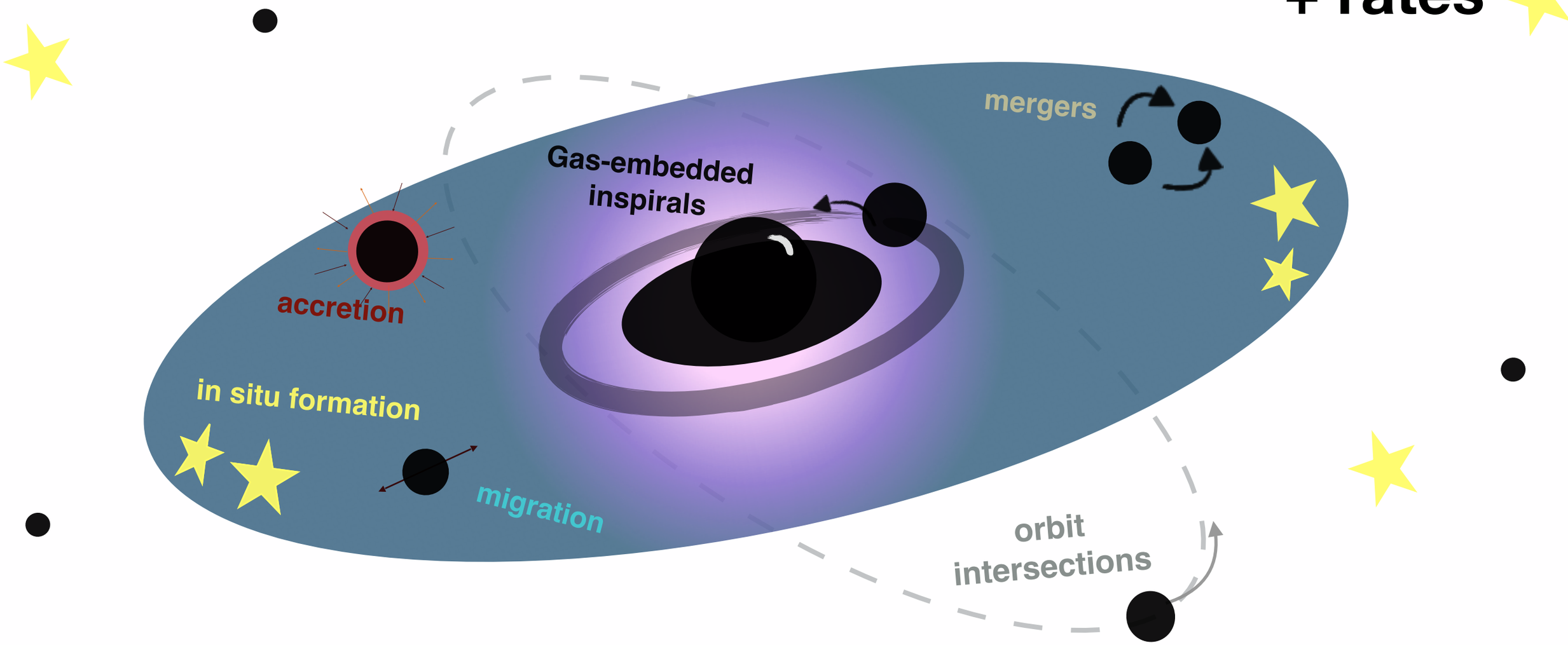
The presence of a gas disk influences BH interaction



- **Orbit capture of stars and BHs**
  Syer, Clarke & Rees 1991, Kennedy+ 2016, Macleod & Lin 2020, Fabj+2020, Nasim+2022

- **In-situ star formation in gravitationally unstable regions**
  Toomre 1964, Shlosman & Begelman 1987, Goodman & Tan 2004, Levin 2007

The presence of a gas disk influences BH interaction + rates



- **pre-LIGO/VIRGO/KAGRA sBH binaries / formation of IMBHs**

  McKernan+2012, Bellovary+2016, Stone+2017, Bartos+2017, Yang+2019, Secunda+ 2019, McKernan+2020, Tagawa+2020

- **Extreme and intermediate mass ratio inspirals**

  Pan & Yang 2021, Pan, Lyu, & Yang 2021, Derdzinski & Mayer 2022

Rates

- sBHs like GW190521: < 1 - 10 events during LISA mission
  Sberna+ 2022,

  Will be higher for TianQin!

  see also Gröbner+ 2020, Tagawa+2020, Ford & McKernan 2021

Gas-embedded EMRIs vs. other channels:

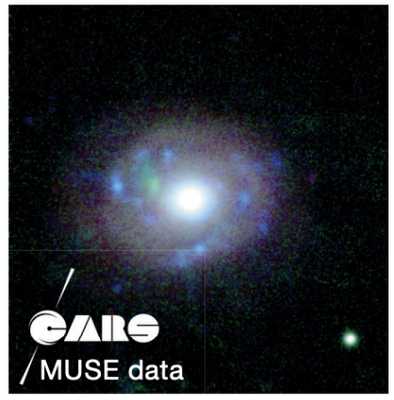
- Disk-capture EMRIs:
  ~0.1 - 0.6 yr^{-1} Gpc^{-3} (Tagawa+ 2020, see also Pan & Yang 2021)

- In-situ EMRIs in unstable AGN disks:
  ~0.5 - 10 yr^{-1} Gpc^{-3} (Derdzinski & Mayer 2022)

- ‘dry’ dynamical EMRIs:
  ~0.02 - 2 yr^{-1} Gpc^{-3}
  (Bar-Or & Alexander 2016, Babak+ 2017, Pan & Yang 2021, Broggi+ 2022)

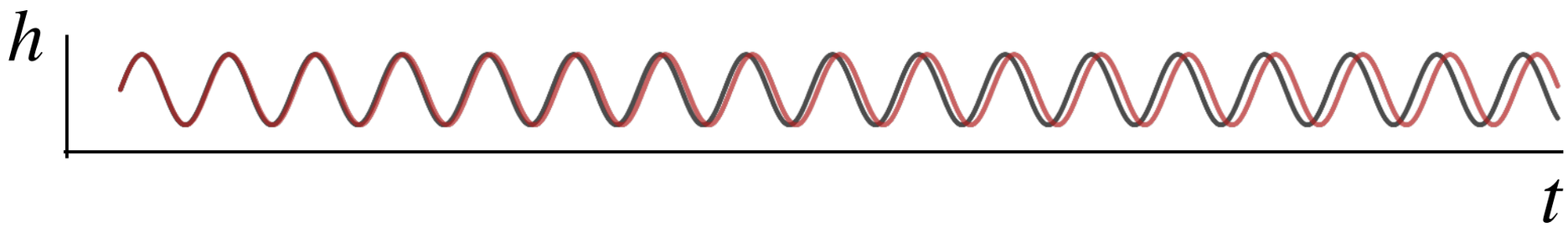
Gas signatures in mHz GWs

from sBHs, EMRIs, IMRIs, IMBH binaries



- Interaction with the environment affects the amplitude and phase evolution of the source

- Induce bias in parameter estimation OR possibly measure environmental properties



Gas signatures in mHz GWs

from sBHs, EMRIs, IMRIs, IMBH binaries

- sBH binaries in AGN experience gas drag, accretion, Doppler modulation, etc.
  Chen+2020, Caputo+2020, Toubiana+2021, Sberna+ 2022
  - Can measure central SMBH mass, binary distance and inclination Sberna+ 2022:

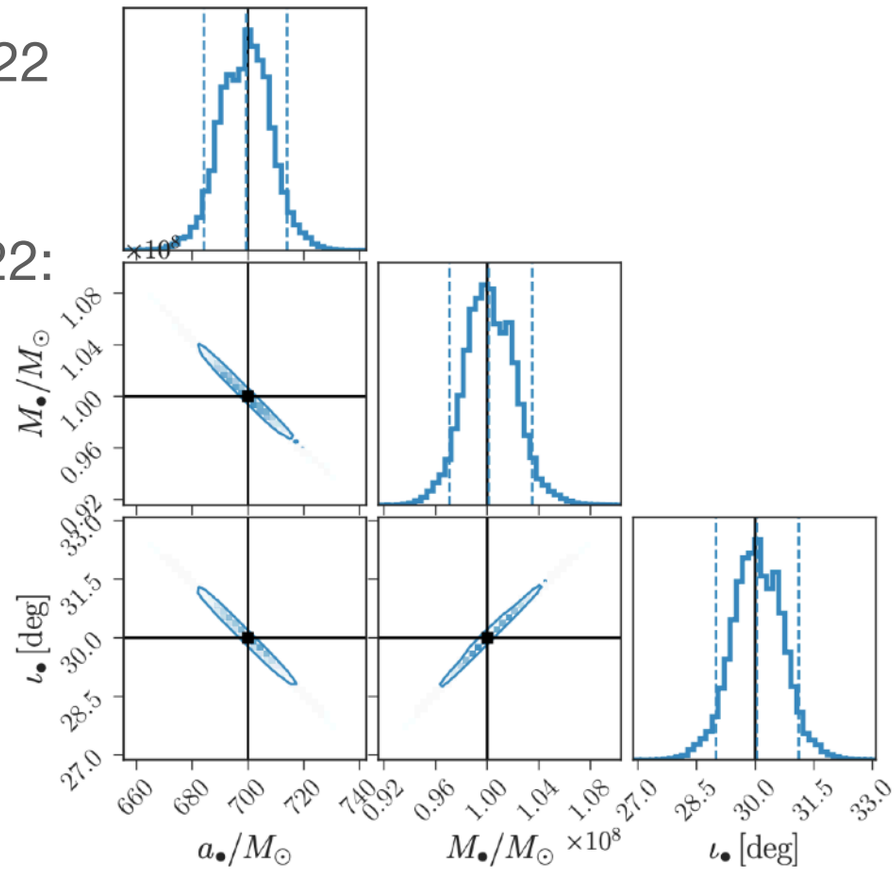
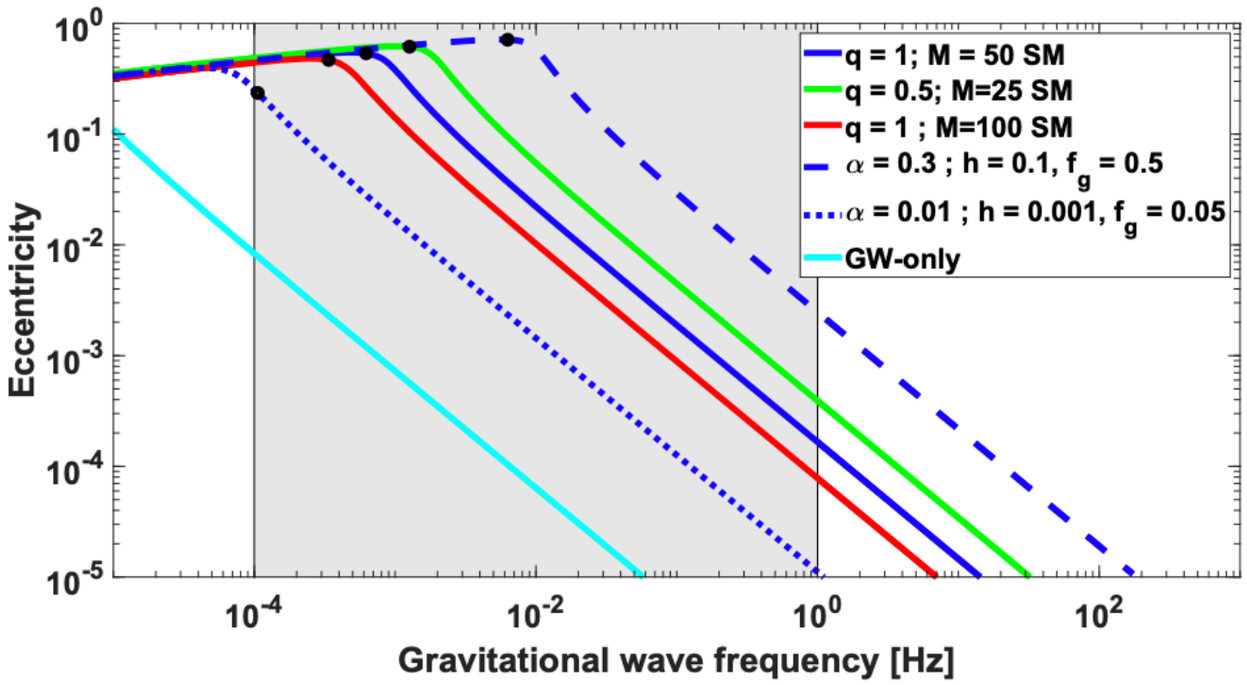


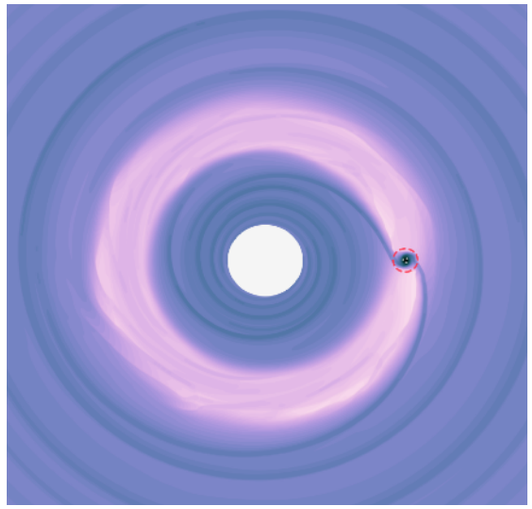
FIG. 5. Inference of the SMBH mass ($M_\bullet$) and the parameters of the outer orbit: inclination $\iota_\bullet$ and orbital radius $a_\bullet$. The true (cosmologically redshifted) parameters are marked by black lines, while the dashed vertical lines indicate 90% CLs.

- Disk interaction affects eccentricity:
  Ishibashi and Gröbner 2020:



Gas signatures in mHz GWs

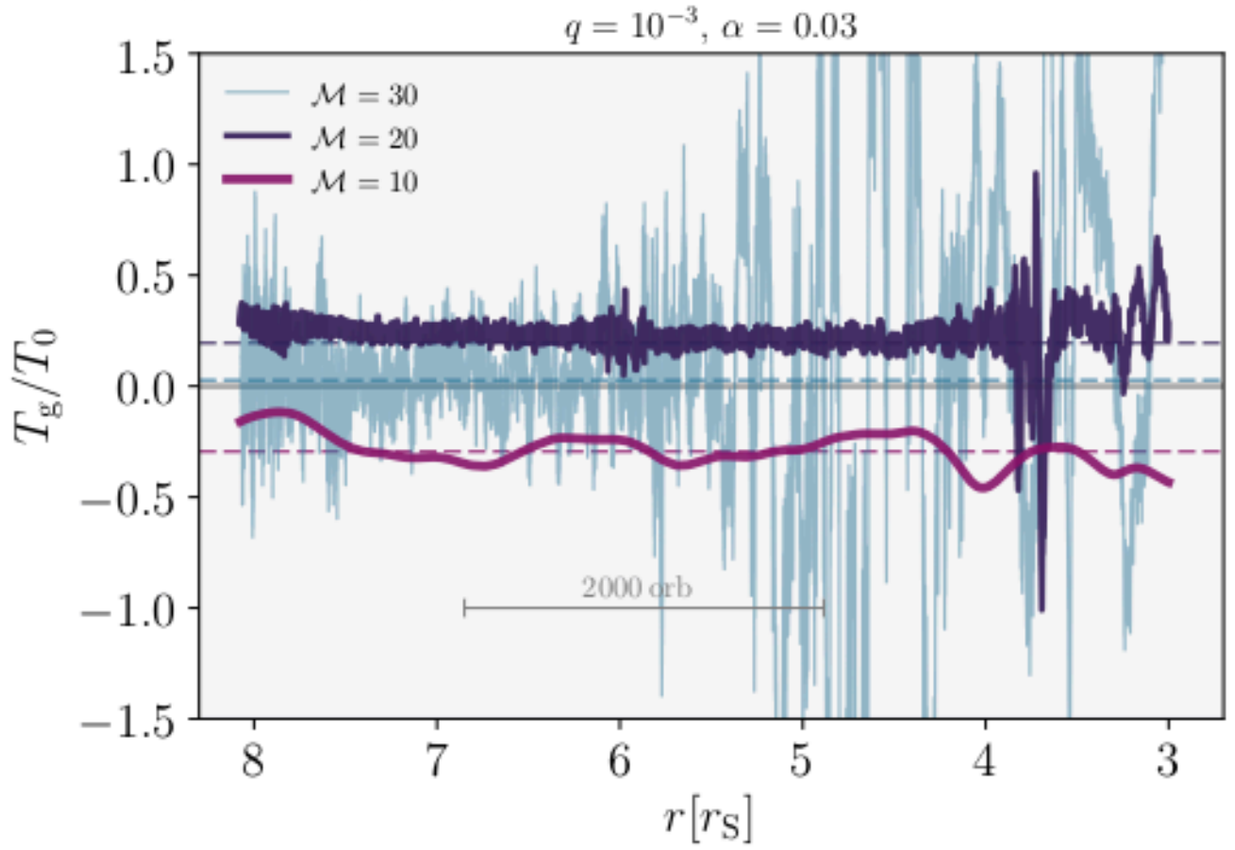
from sBHs, **EMRIs, IMRIs**, IMBH binaries



2D Hydro simulation of an IMRI

- Gas torques on EMRIs: detectable in dense disks
  Chakrabarti 1996, Yunes+2011, Kocsis+ 2011, Barausse+2015, Speri+2022

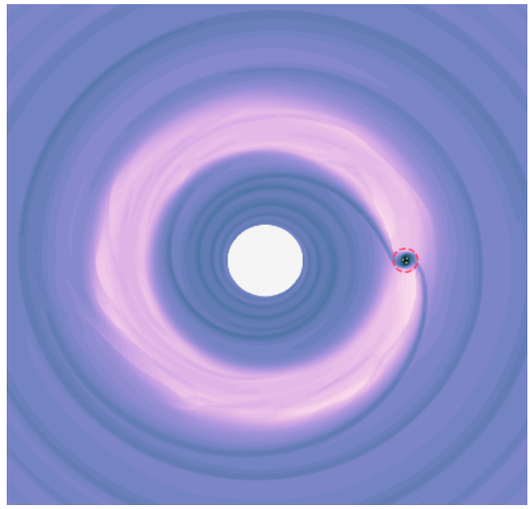
- Torques sensitive to gas parameters: inward/outward, variable —> characteristic waveform deviations
  Derdzinski+2019, 2021



Andrea Derdzinski andrea@ics.uzh.ch University of Zurich

Gas signatures in mHz GWs

from sBHs, EMRIs, IMRIs, IMBH binaries



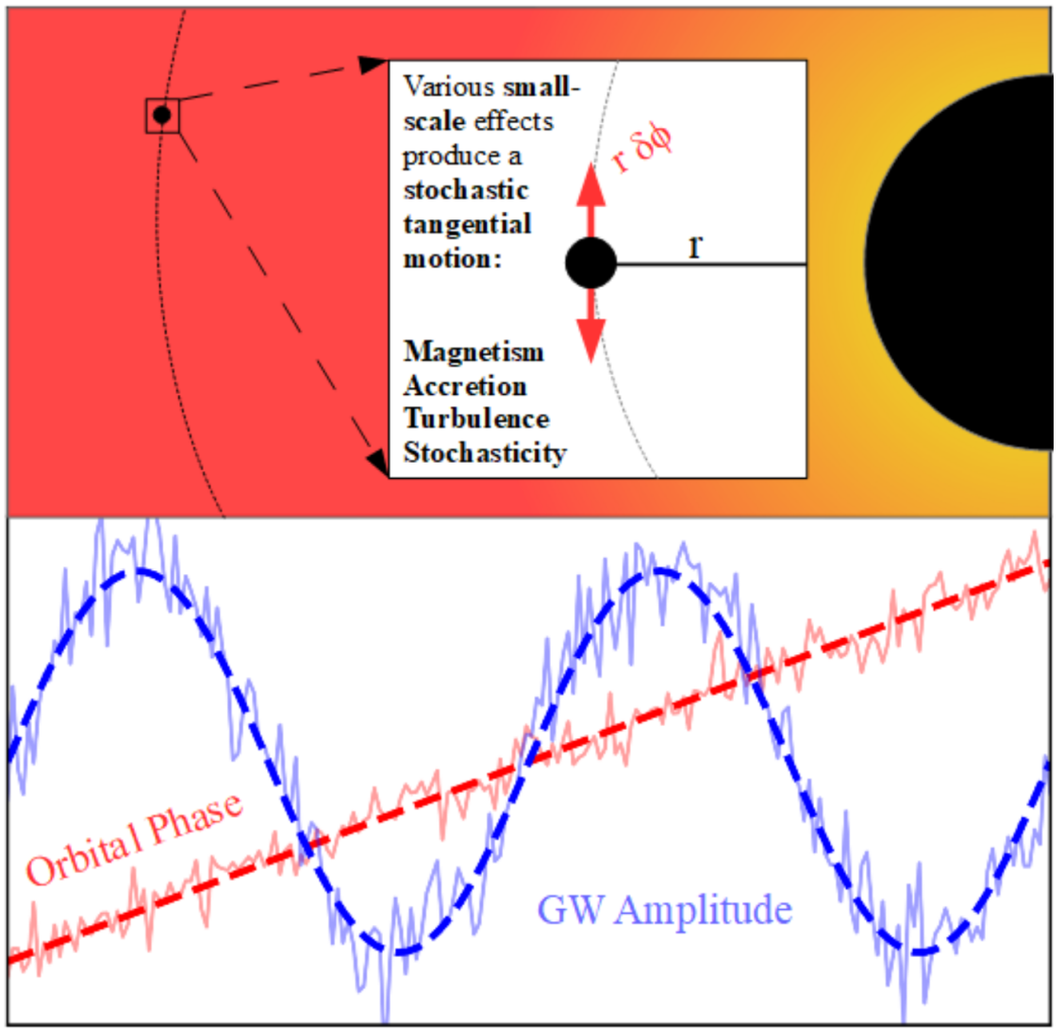
2D Hydro simulation of an IMRI

- Gas torques on EMRIs: detectable in dense disks
  Chakrabarti 1996, Yunes+2011, Kocsis+ 2011, Barausse+2015, Speri+2022

- Torques sensitive to gas parameters: variable —> characteristic waveform
  Derdzinski+2019, 2021

- Torque variability, turbulence imparts additional dephasing:
  Zwick et al 2022

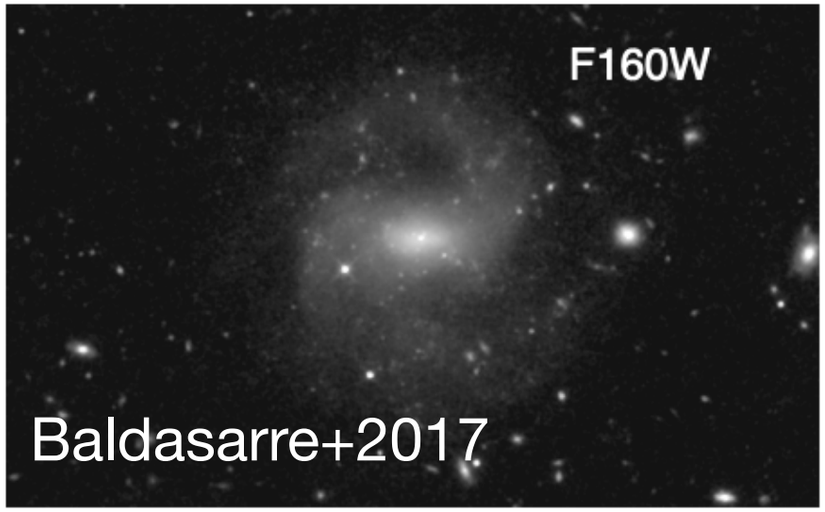
- More work to do…



Gas signatures in mHz GWs

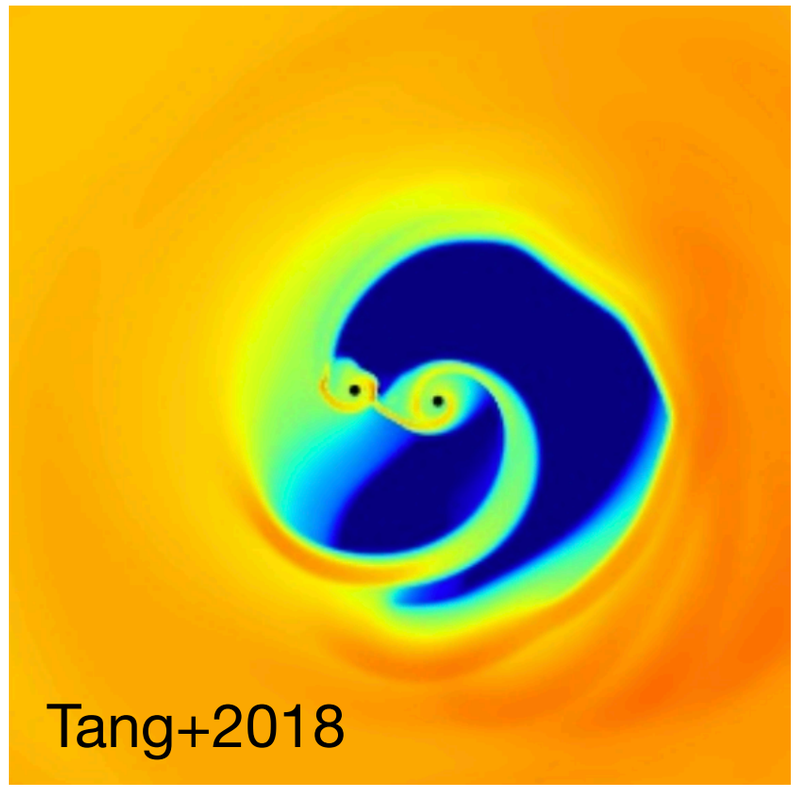
from sBHs, EMRIs, IMRIs, IMBH binaries

- e.g. Active dwarf galaxy with 50000 M_{sun} BH:
  or merging, accreting BH seeds
  Sassano et al 2021

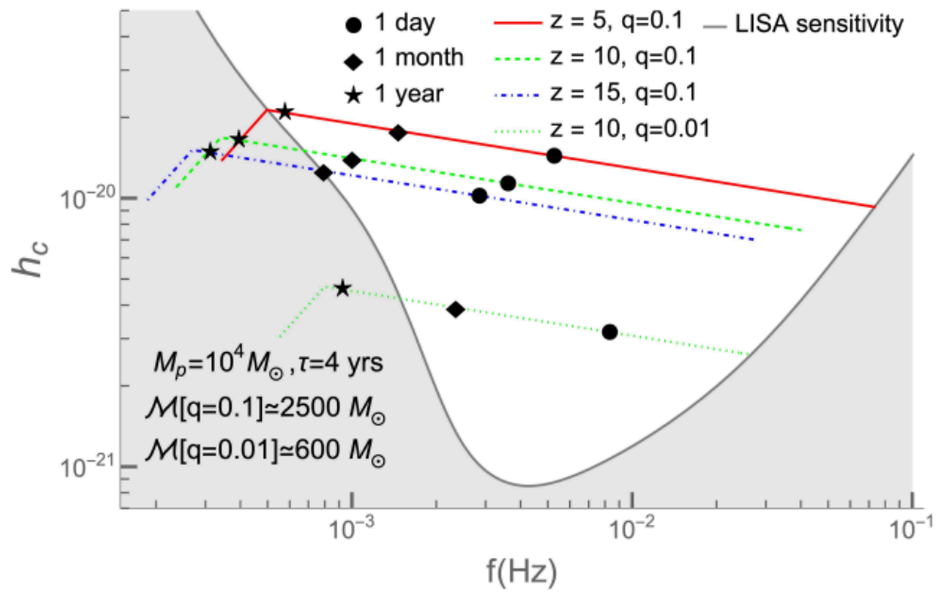


If there is a secondary BH and a steady state accretion disk…

- Gas accretes onto BHs all the way to merger
  Farris+2015, Tang+ 2018



Garg et al. 2022

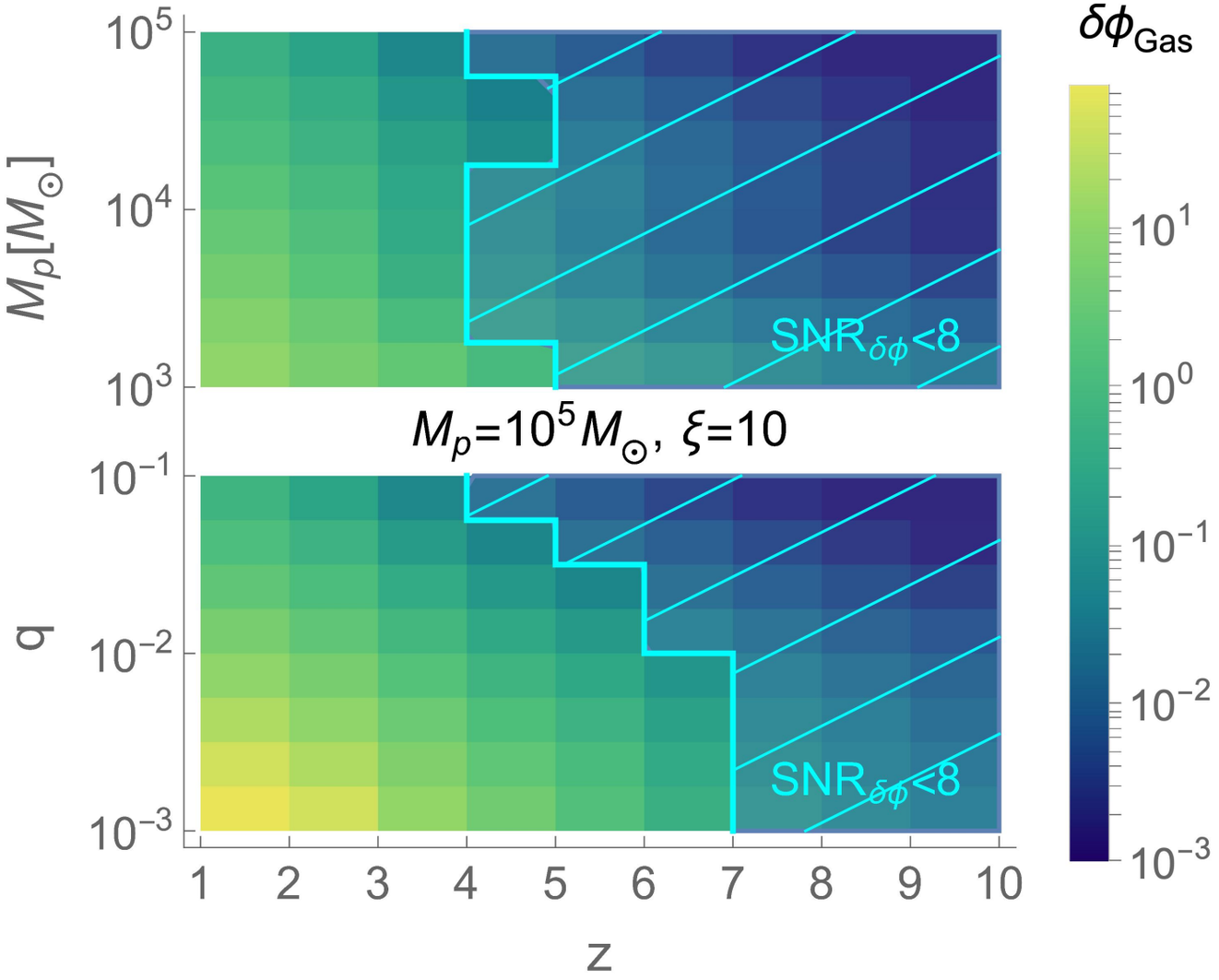


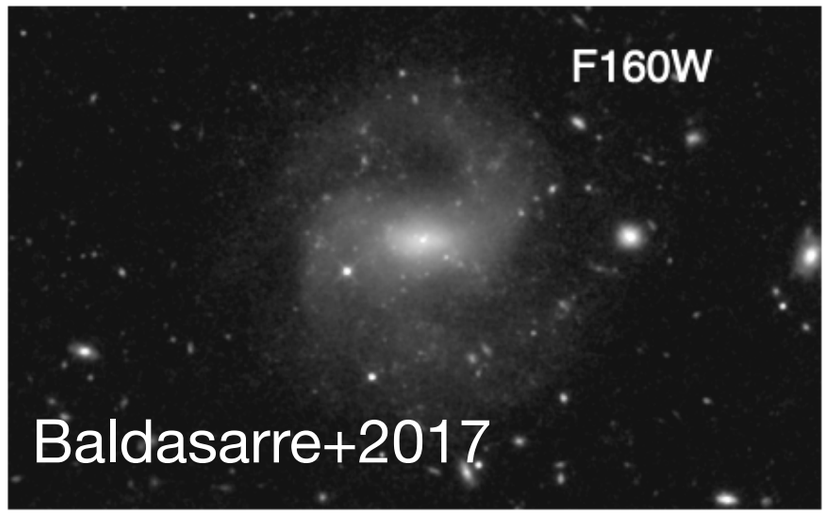
Gas signatures in mHz GWs

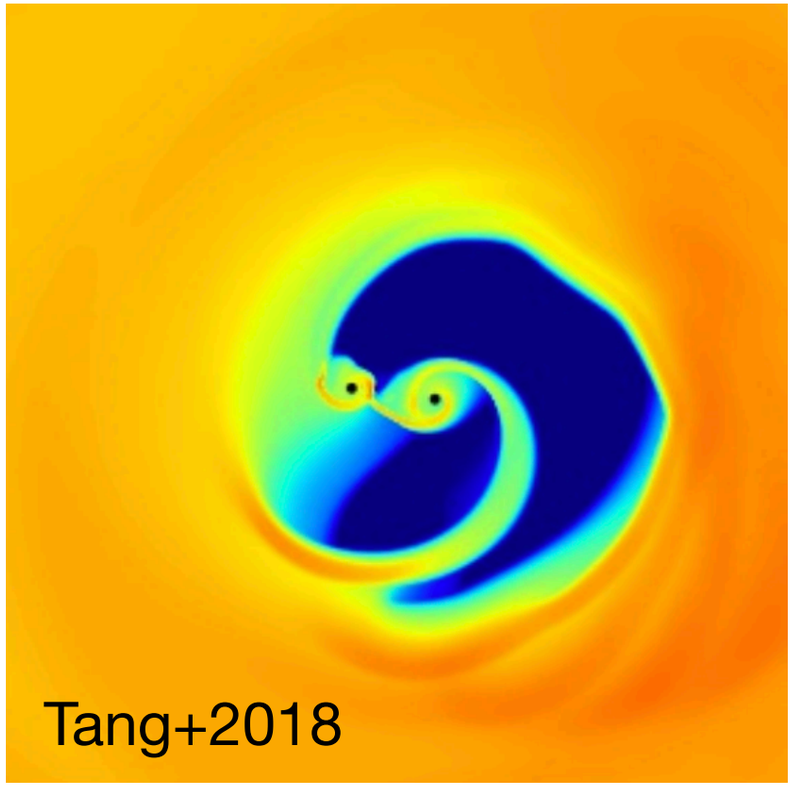
from sBHs, EMRIs, IMRIs, IMBH binaries

Phase shifts during a LISA observation

Garg et al. 2022







Andrea Derdzinski andrea@ics.uzh.ch University of Zurich

Summary

- Many GW sources form and evolve in gaseous environments: SMBHs, sBHs, EMRIs and IMRIs

- Interaction with gas affects orbital evolution prior to and *during* GW evolution

- Need improved models to predict gas interplay and detectability

- TianQin sensitive to higher freq. range: need to quantify rates
  + required sensitivity of waveforms

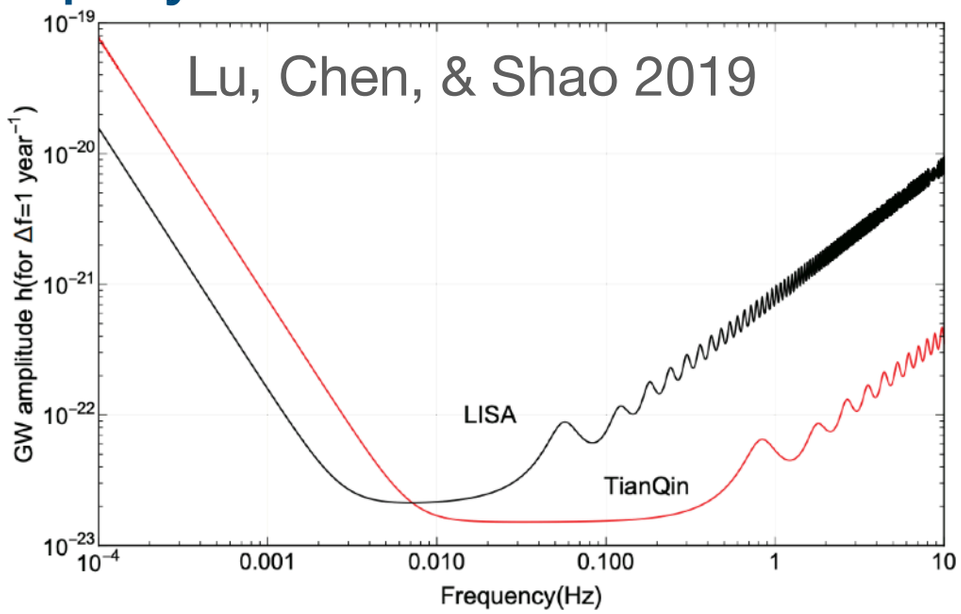


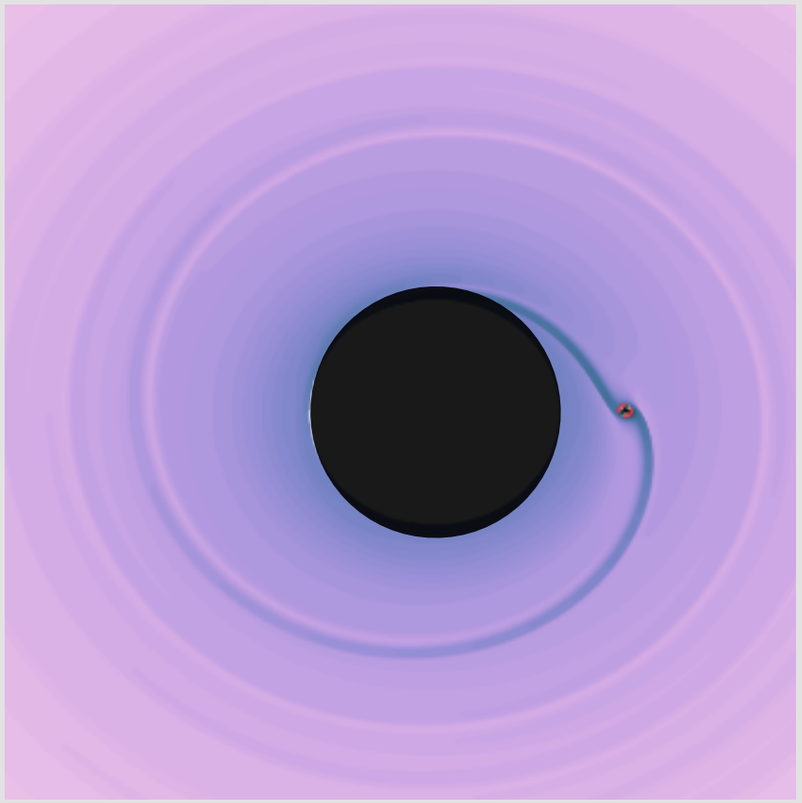
FIG. 5: Sensitivity curves for the GW detectors (LISA and TianQin) averaging all-sky sources in the four-link configurations.

Gas torques on “BHs”

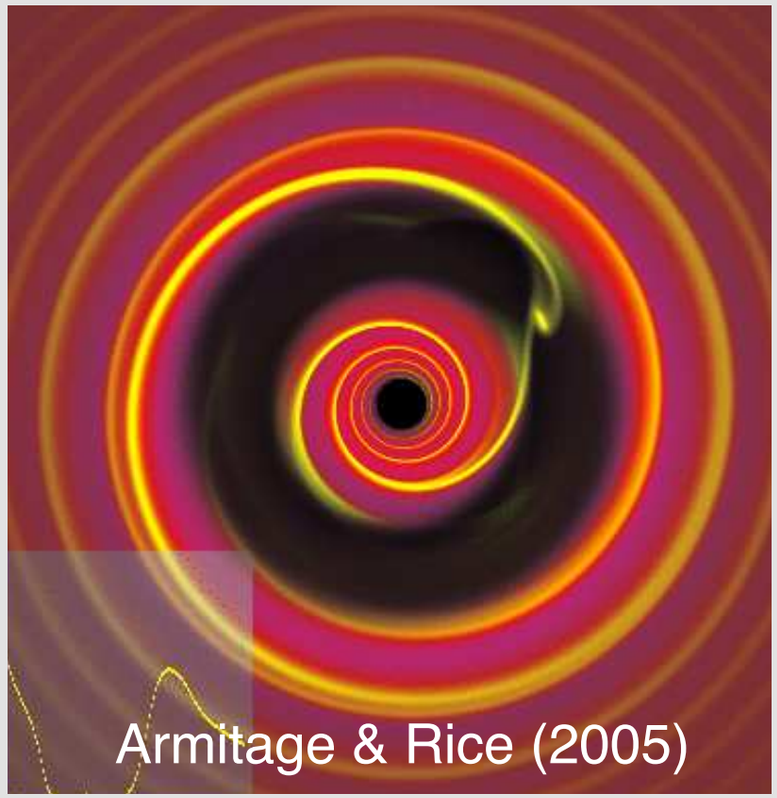
$$q \equiv \frac{M_2}{M_1}$$

co-rotating, ~circular, isothermal EOS

low q

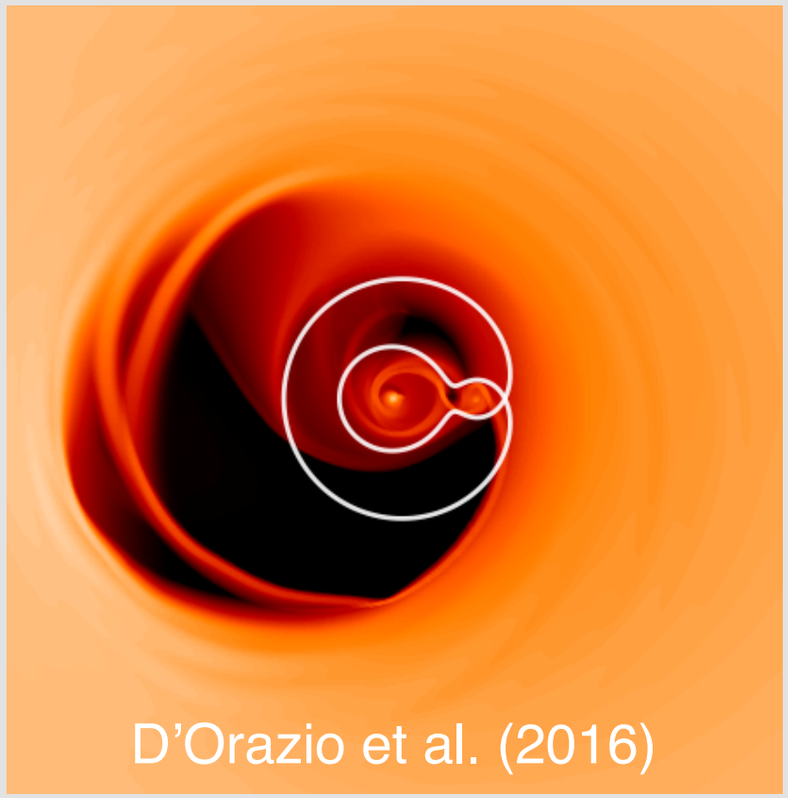


intermediate q



Armitage & Rice (2005)

near-equal q



D’Orazio et al. (2016)

2D hydro simulations
(surface density)

10^{-4} 10^{-3} 10^{-1}

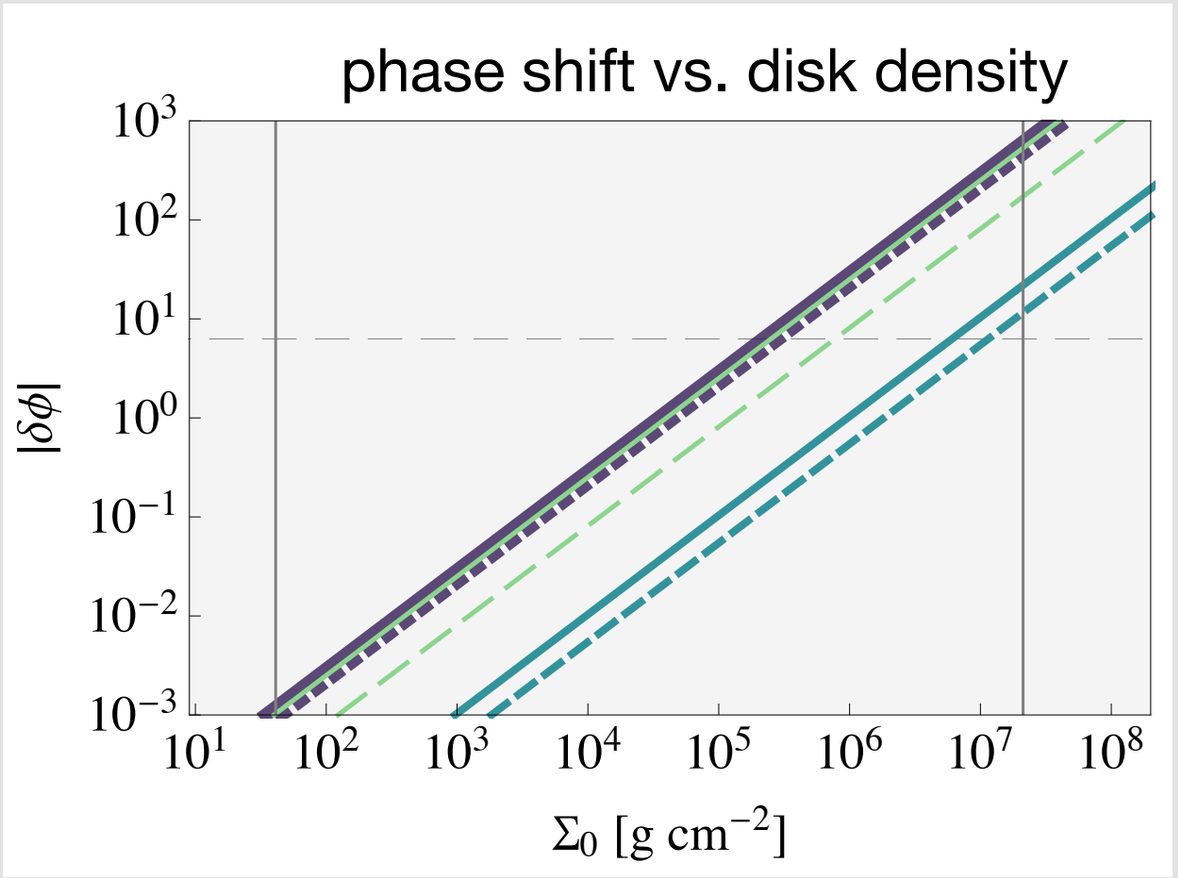
q

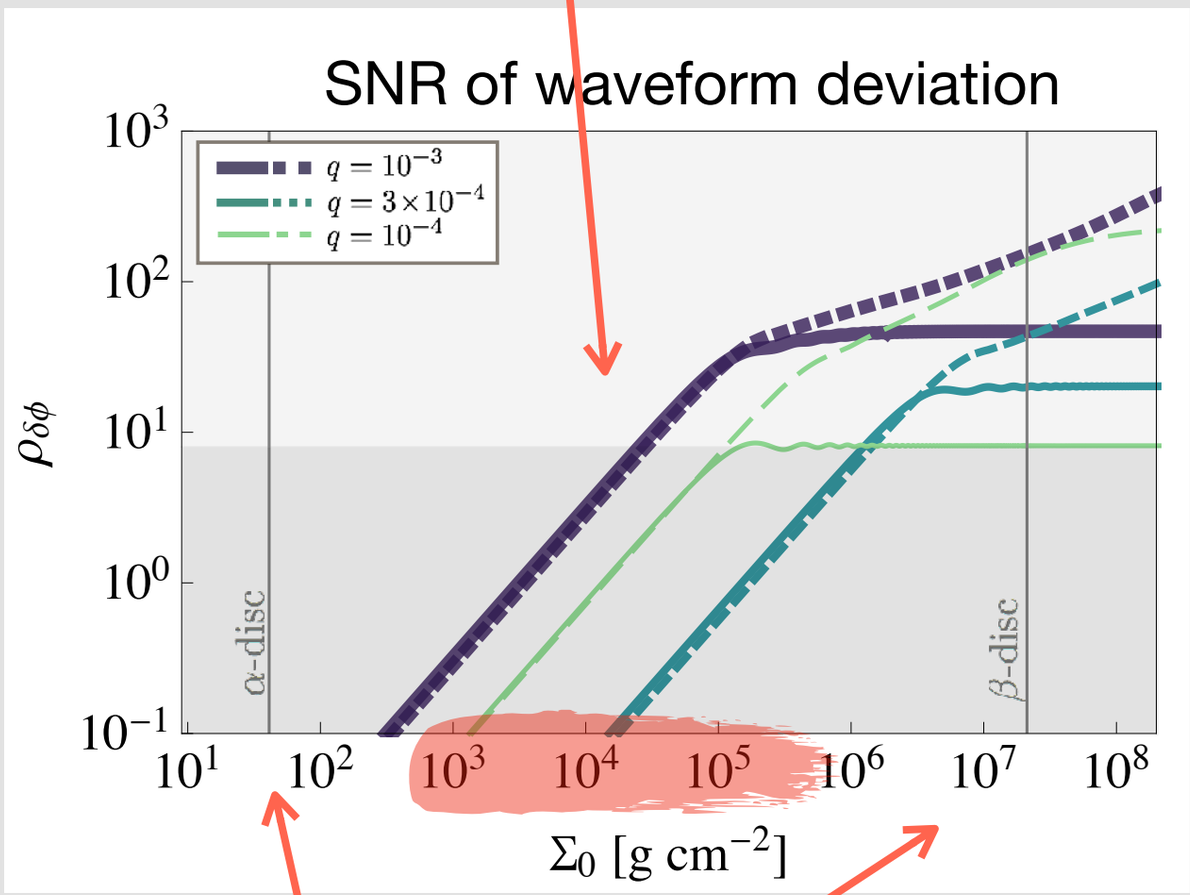
Detectability of gas interaction in GWs

Accumulation of phase shift depends on disk profile

$$\delta\phi \propto \Sigma(r)$$

Disk densities inferred from Seyfert spectra (Jiang et al. 2019)

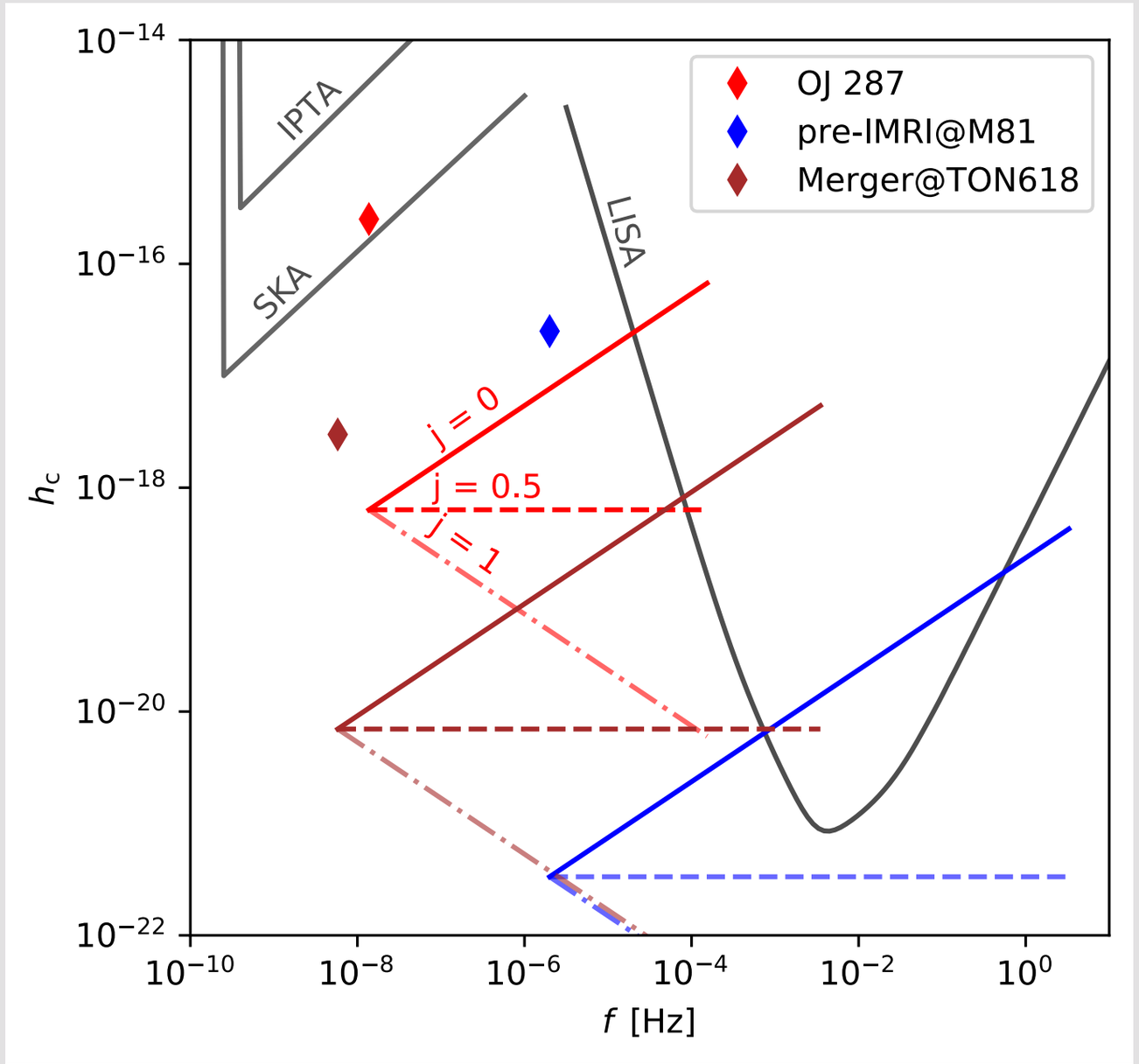




How dense are inner AGN accretion disks?

AD, D'Orazio, Duffell, Haiman, MacFadyen (2021)

DWs of loud, low-frequency SMBHBs



Zwick et al. 2022