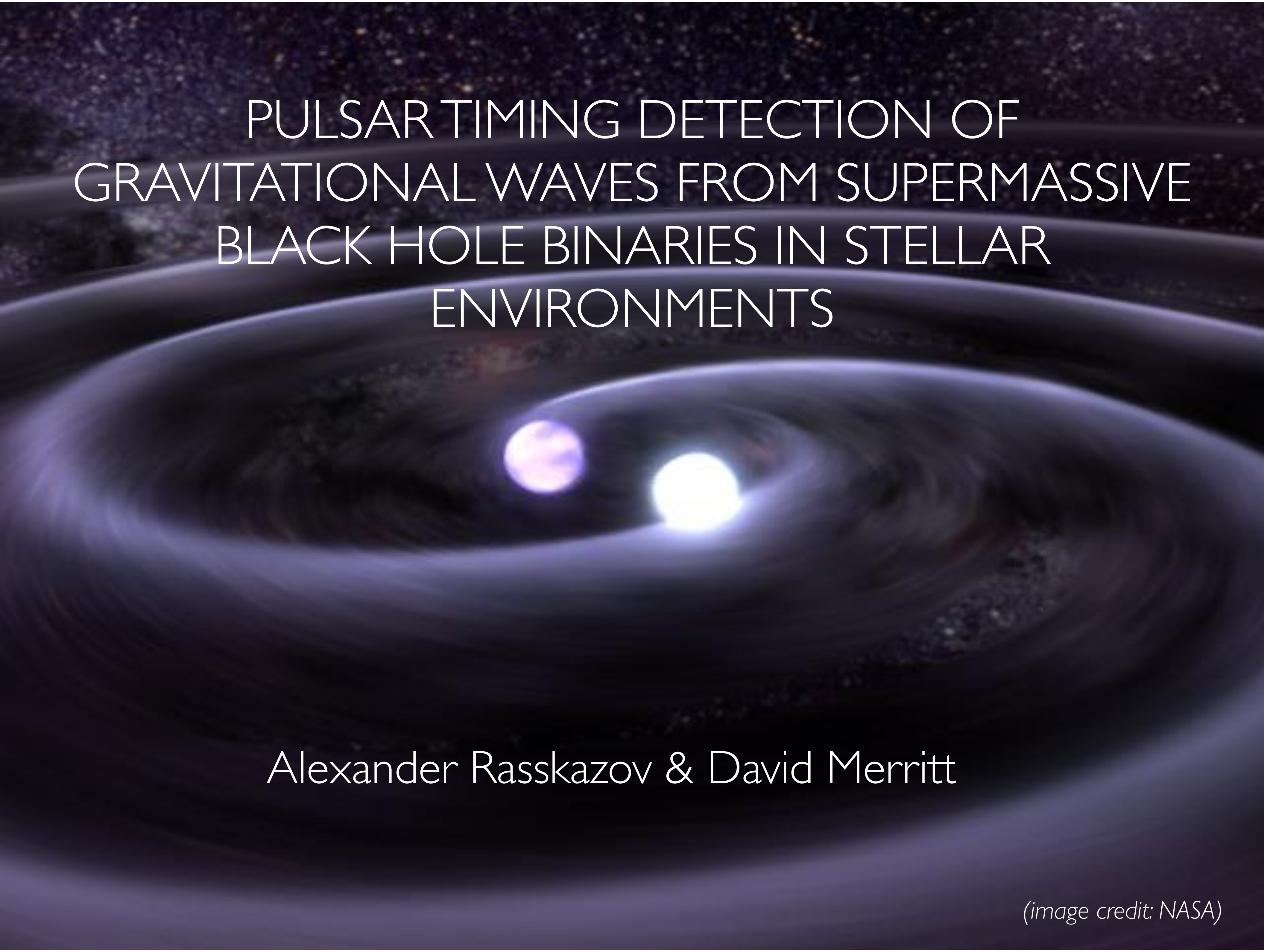
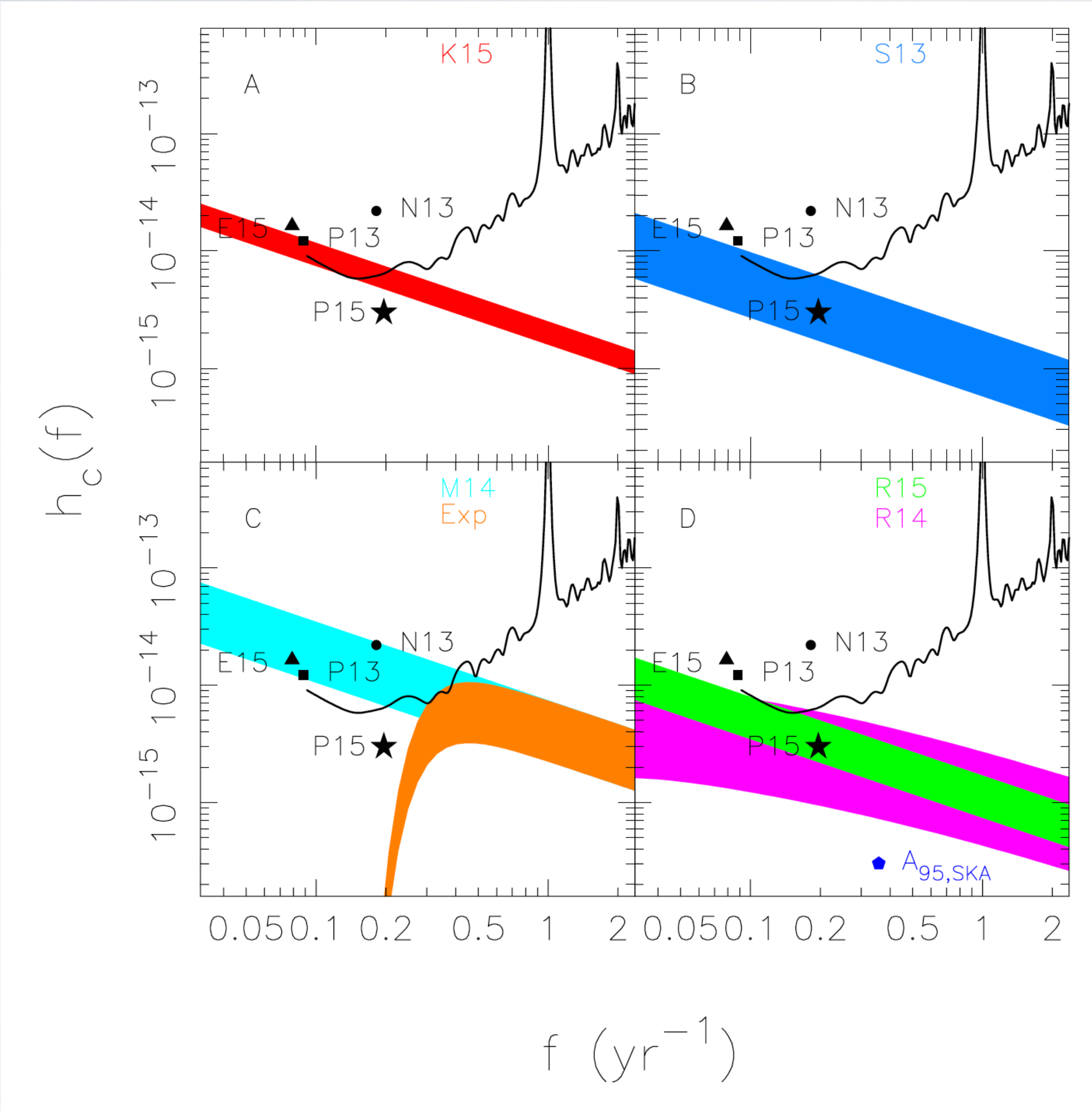
PULSAR TIMING DETECTION OF GRAVITATIONAL WAVES FROM SUPERMASSIVE BLACK HOLE BINARIES IN STELLAR ENVIRONMENTS



Alexander Rasskazov & David Merritt

(image credit: NASA)

CURRENT PTA CONSTRAINTS



Shannon et al. (2015)

- Current PTA limits are in tension with galaxy merger models

- Possible explanation: the effects of stellar environment

DYNAMICAL EVOLUTION OF BINARY SUPERMASSIVE BLACK HOLES

1. Unbound SMBHs, energy loss due to dynamical friction
2. Bound SMBHs, energy loss due to interactions with stars/gas
3. Tightly bound SMBHs, energy loss due to GW emission
4. Coalescence
5. Recoil

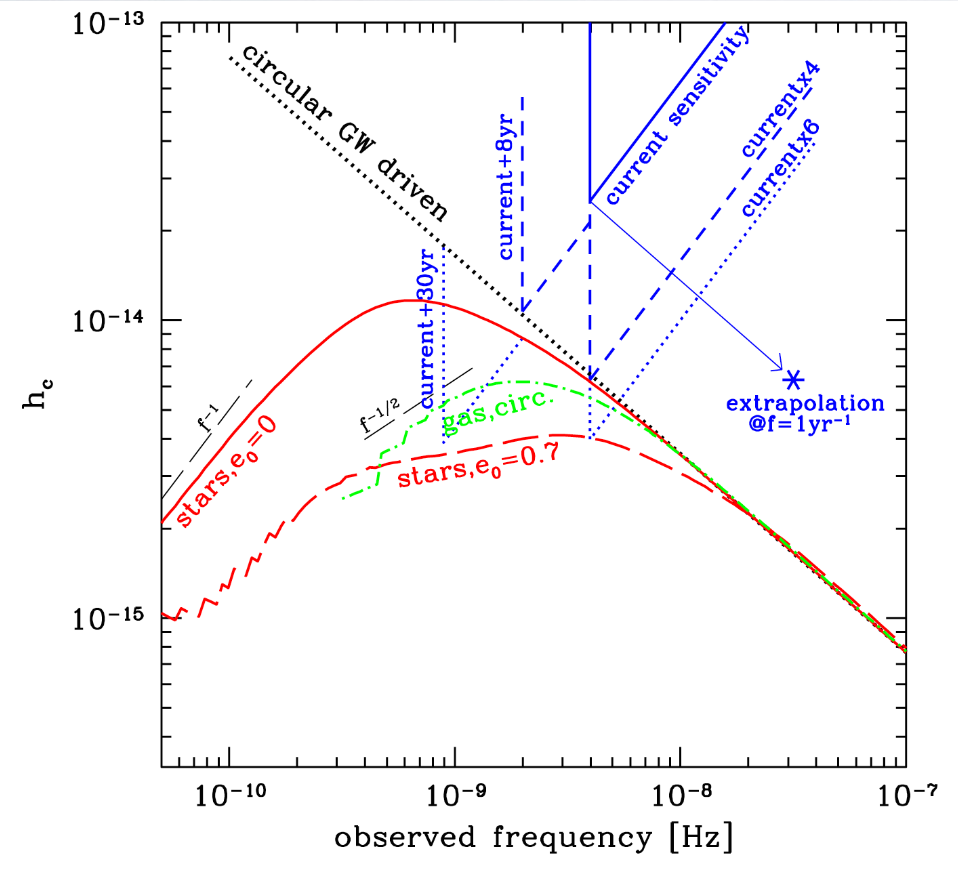
SUPERMASSIVE BINARY'S DYNAMICAL EVOLUTION

1. Unbound SMBHs, energy loss due to dynamical friction
2. Bound SMBHs, energy loss due to interactions with stars/gas
3. Very close SMBHs, energy loss due to GW emission
4. Coalescence
5. Recoil

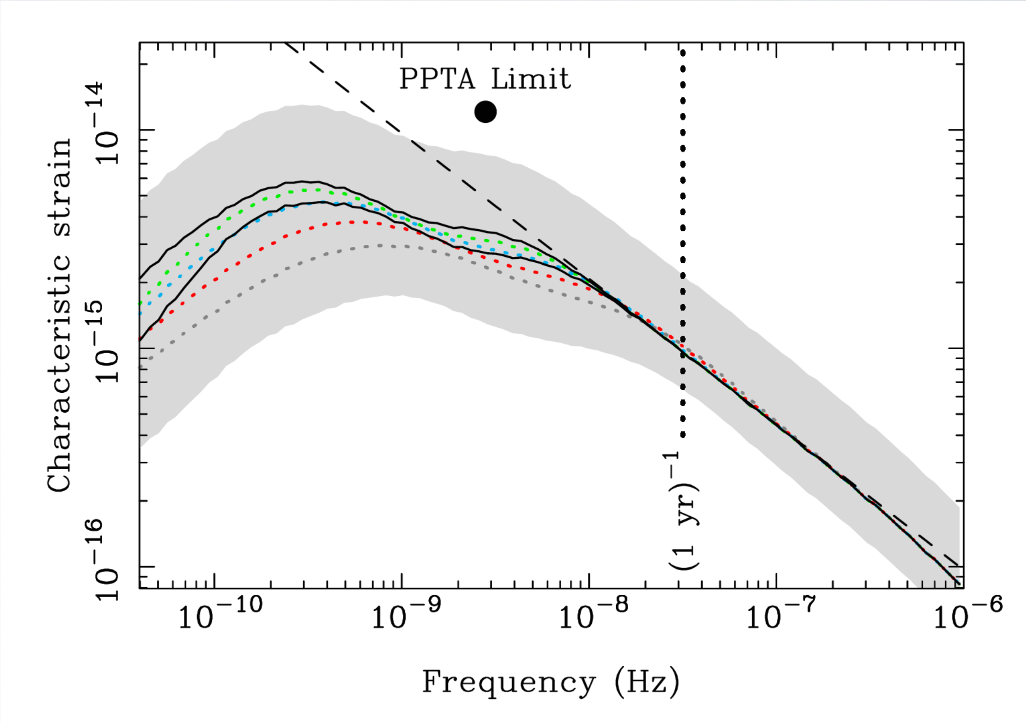
detectable GW emission

PREVIOUS RESULTS

Sesana (2013)



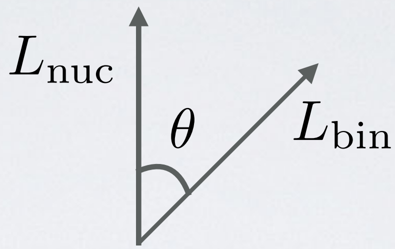
Ravi et al. (2014)



NUCLEAR ROTATION MATTERS

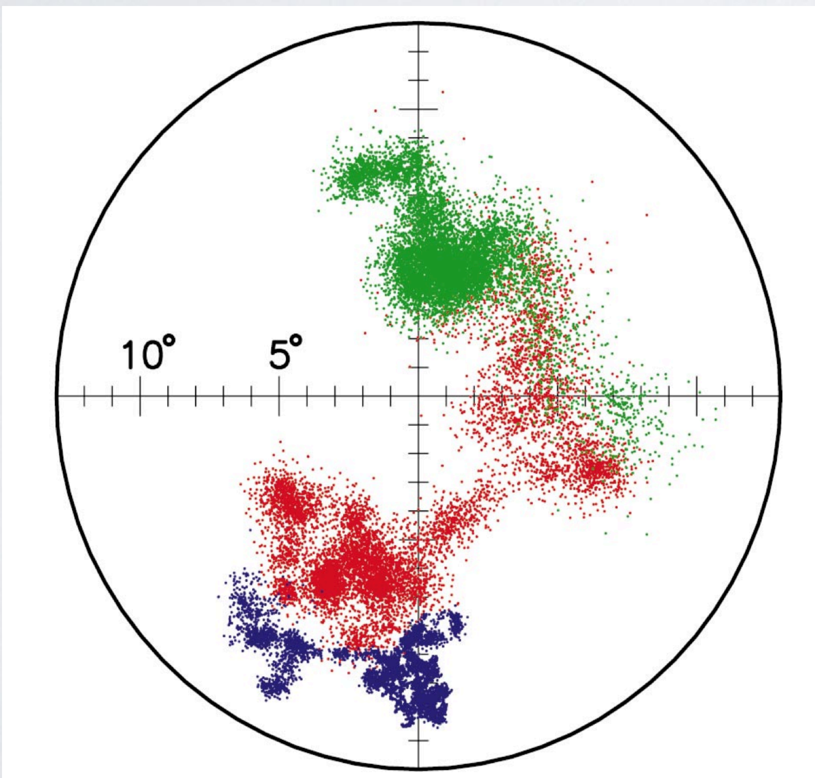
NON-ROTATING NUCLEUS

$$\frac{d\theta}{dt} \approx 0$$

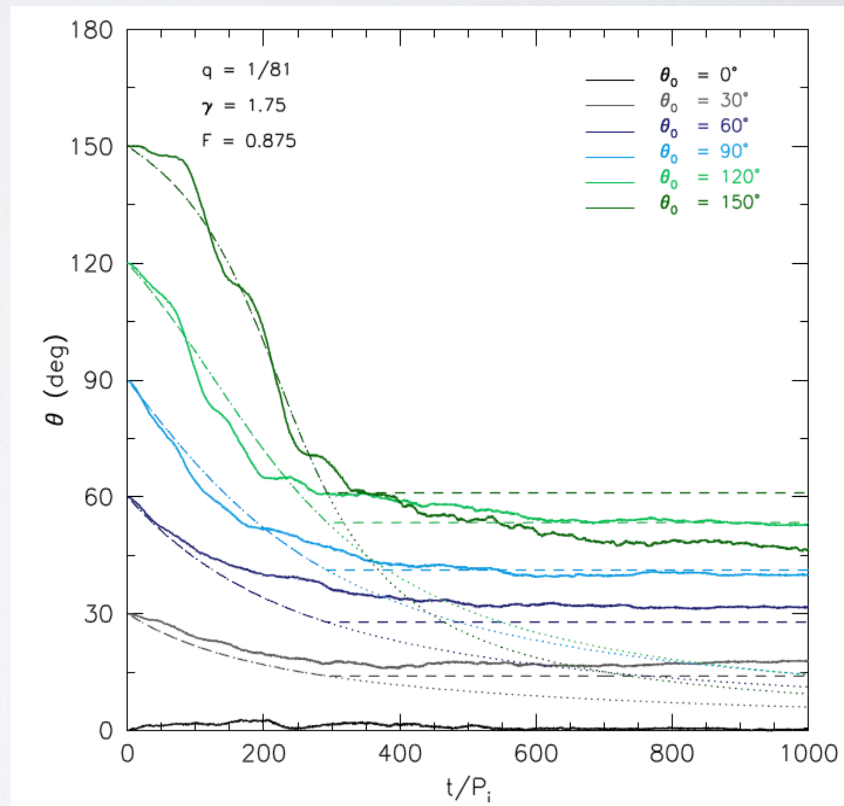


ROTATING NUCLEUS

$$\frac{d\theta}{dt} < 0$$



Milosavljevic & Merritt (2001)

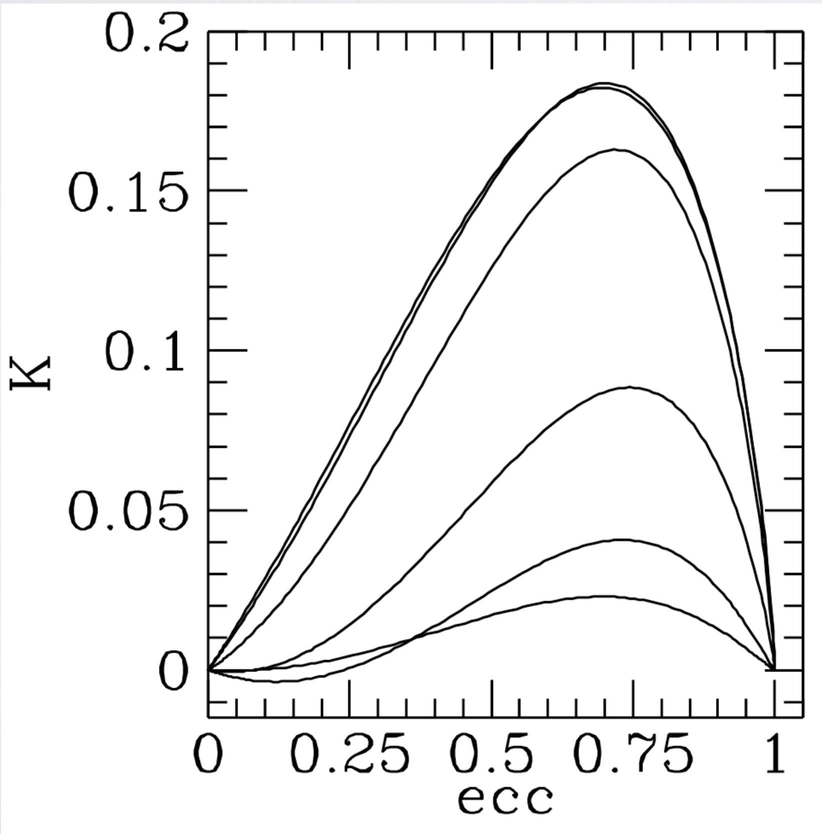


Gualandris et al. (2012)

NUCLEAR ROTATION MATTERS

NON-ROTATING NUCLEUS

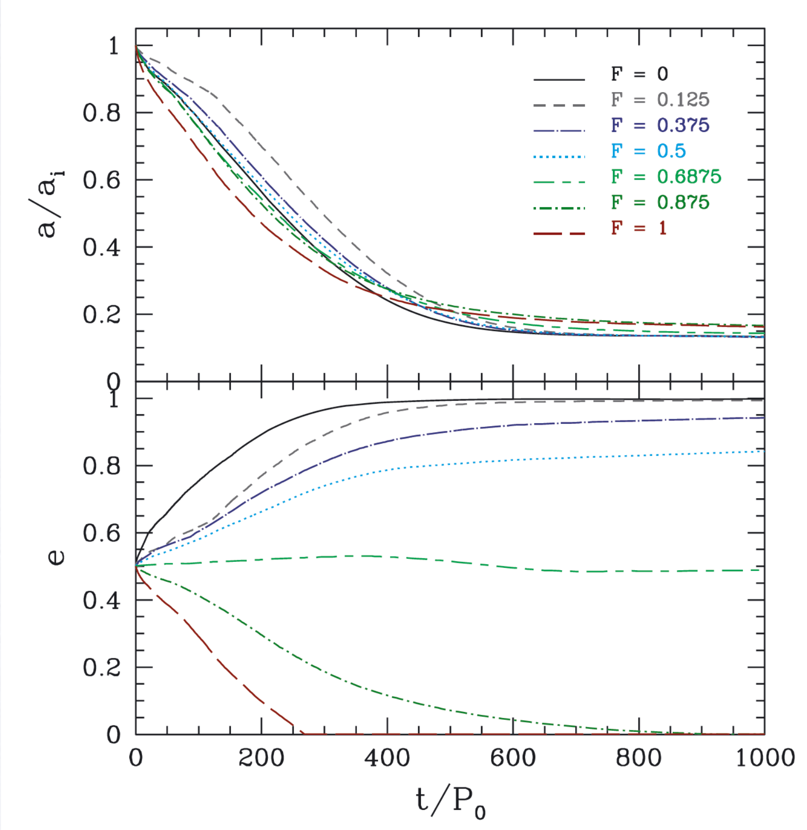
$$\frac{de}{dt} > 0$$



Quinlan (1996)

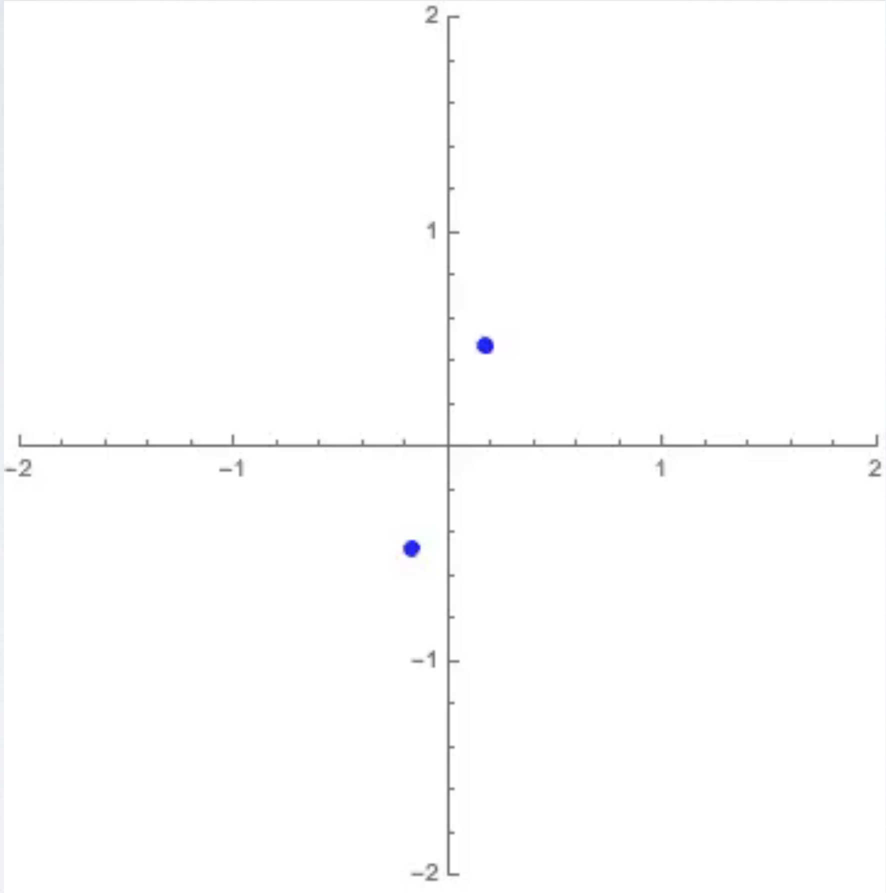
ROTATING NUCLEUS

$$\frac{de}{dt} < 0, \ \theta \approx 0$$
$$\frac{de}{dt} > 0, \ \theta \approx \pi$$



Sesana et al. (2011)

SCATTERING EXPERIMENTS



$$\frac{da}{dt}, \frac{de}{dt}, \frac{d\theta}{dt} = \text{average of } \delta a,\ \delta e,\ \delta\theta \text{ over all interactions}$$

NEW FEATURES COMPARED TO THE PREVIOUS STUDIES*

- Allowing the binary to evolve out of a fixed plane, which can strongly impact the eccentricity evolution:

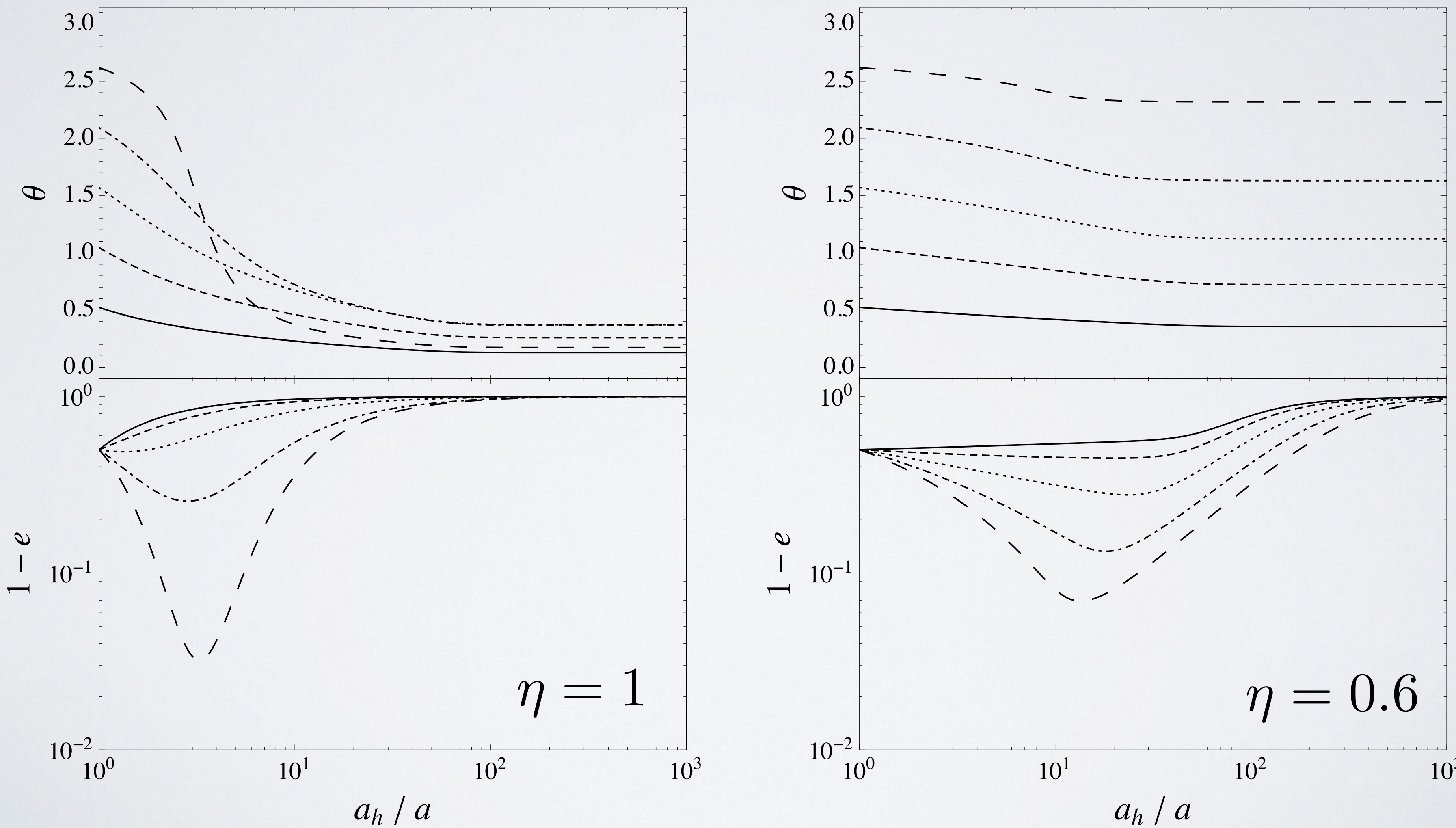
$$\frac{d\theta}{dt} \sim (2\eta - 1)\sqrt{\frac{1+e}{1-e}}\sin\theta$$

$$\frac{de}{d\ln a} = 1.5\,e\,(1-e^2)^{0.7}\,[0.15 - (2\eta - 1)\cos\theta]$$

**Sesana (2013), Ravi et al. (2014), McWilliams et al. (2014) etc.*

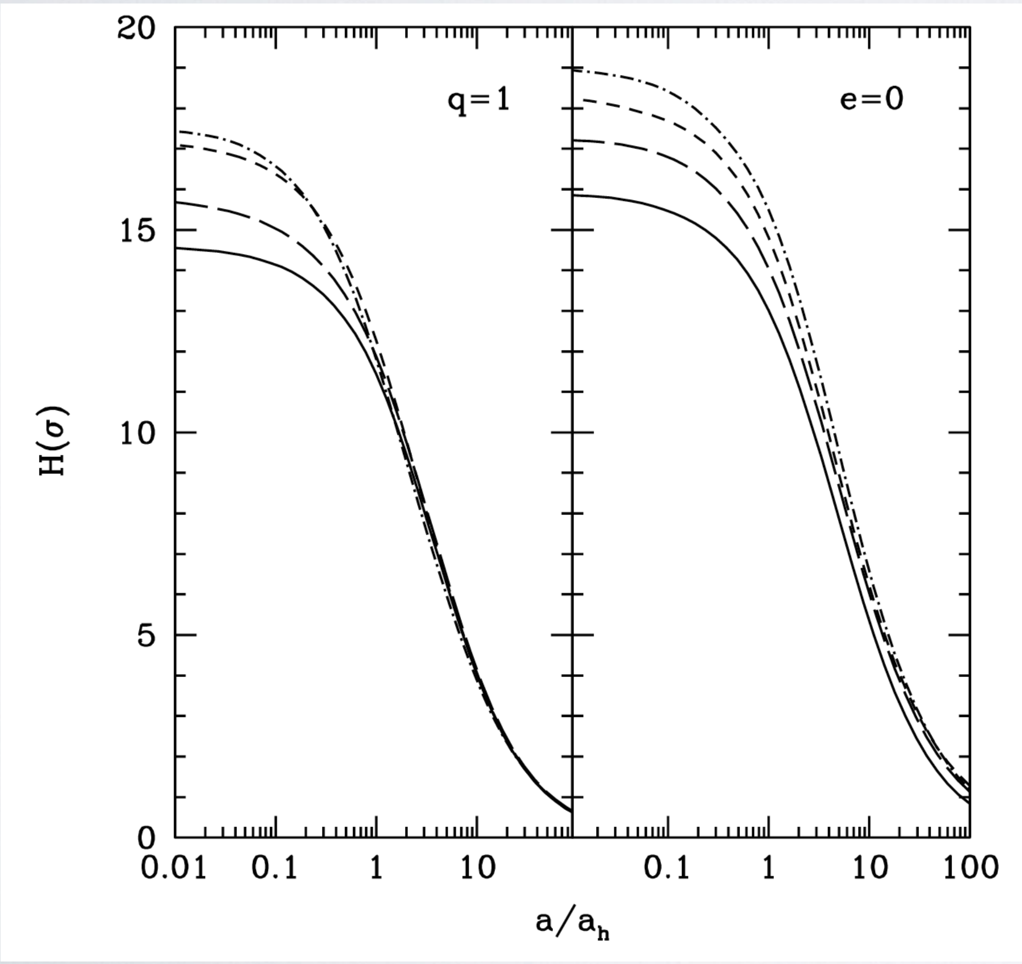
NEW FEATURES COMPARED TO THE PREVIOUS STUDIES

- GW emission doesn't depend on θ, but eccentricity evolution does



NEW FEATURES COMPARED TO THE PREVIOUS STUDIES

- Previous papers assumed infinite and homogenous stellar medium



$$H = \frac{\sigma}{G\rho}\frac{d(1/a)}{dt} \approx \mathrm{const}$$

Sesana et al. (2006)

NEW FEATURES COMPARED TO THE PREVIOUS STUDIES

- Incorporating the Vasiliev, Antonini & Merritt (2015) solution to the "final-parsec problem"

$$S \equiv \frac{d(1/a)}{dt} = \mu S_{\rm infl} \left(\frac{a}{a_h}\right)^{\nu},$$

$$S_{\rm infl} \equiv 4\sqrt{\frac{GM}{r_{\rm infl}^5}}$$

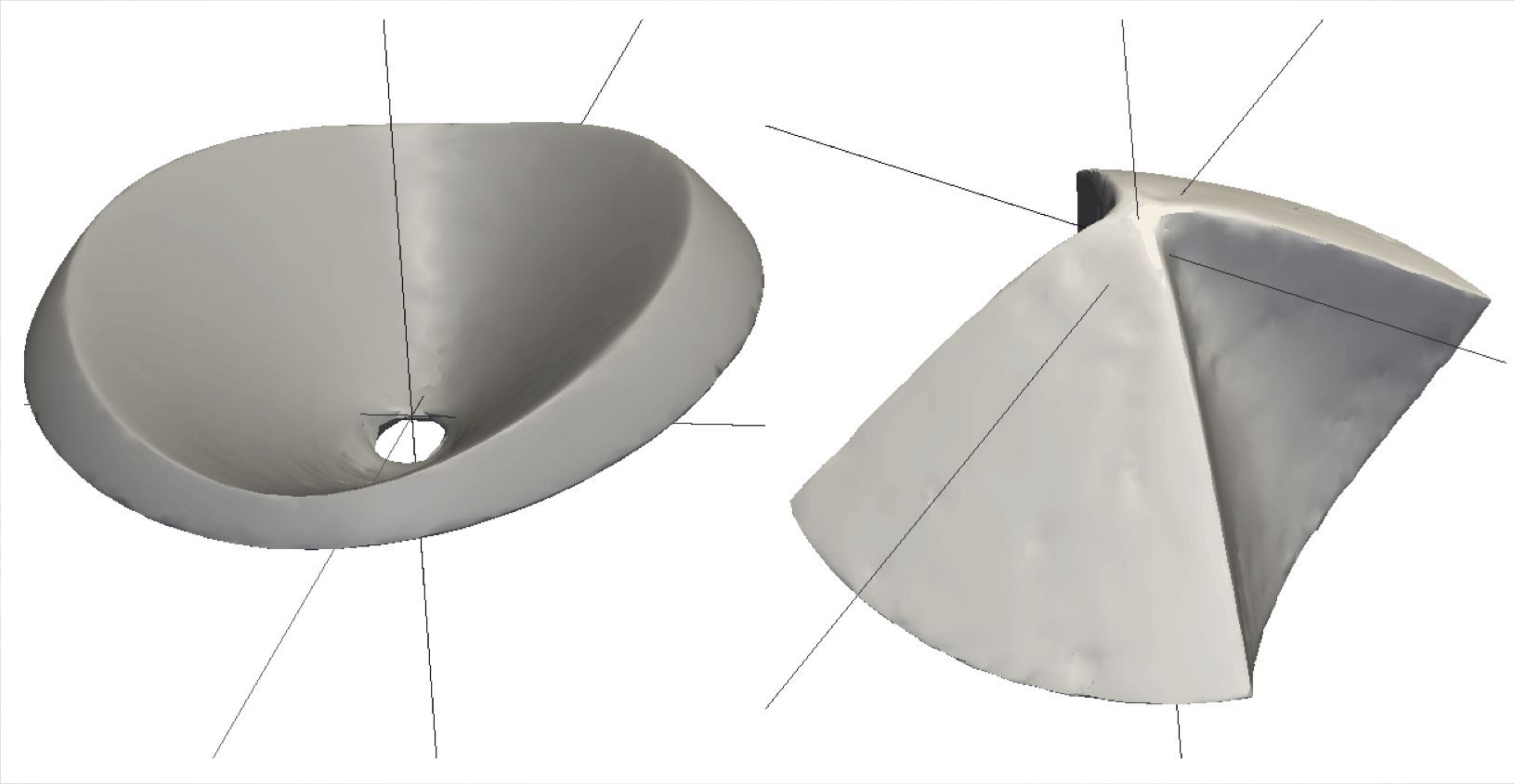
$$\text{Spherical} : \nu \simeq 0,\ \mu \simeq (N_\star/10^5)^{-1}$$

$$\text{Axisymmetric} : \nu \simeq 0,\ \mu \simeq (N_\star/10^5)^{-1/2}$$

$$\text{Triaxial} : \nu \simeq 0.3 \ldots 0.6,\ \mu \sim 1$$

NEW FEATURES COMPARED TO THE PREVIOUS STUDIES

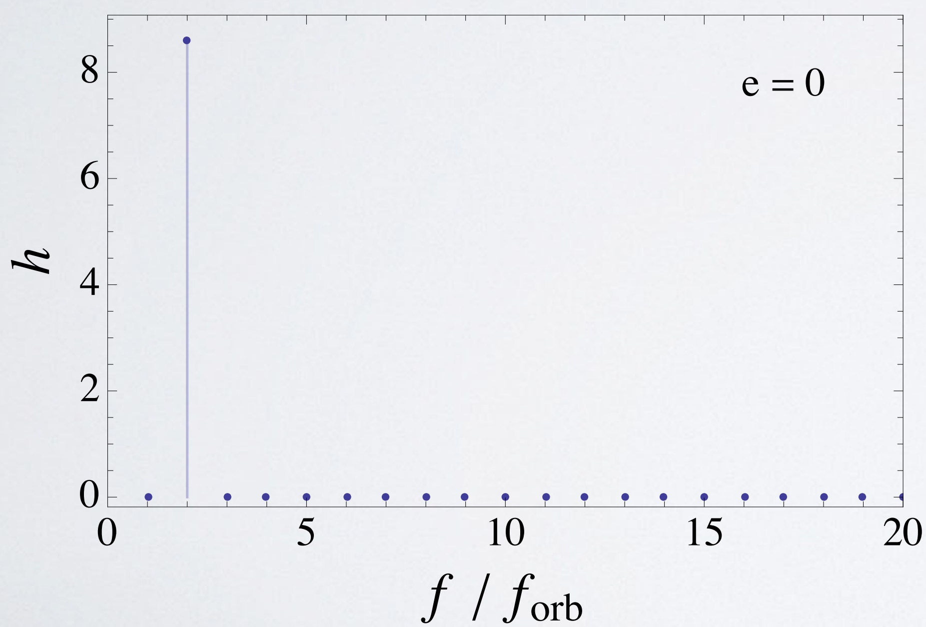
Orbits around SBHs in non-spherical galaxies



GW SPECTRUM OF A BINARY BLACK HOLE

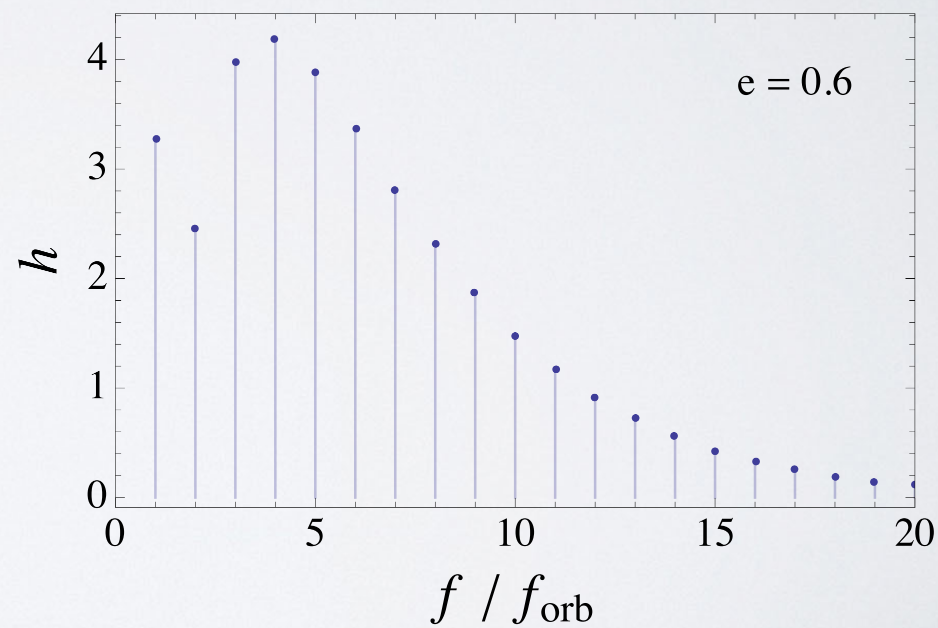
Circular

$$h(f) \sim \delta(f - 2f_{\mathrm{orb}})$$



Eccentric

$$h(f) \sim \sum_{n=1}^{\infty} g(n,\, e)\, \delta(f - n f_{\mathrm{orb}})$$



TOTAL GW BACKGROUND

$$N(a,t)da = \text{number of binaries per comoving volume}$$
$$\text{with semimajor axes } a \ldots a + da$$

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial a}(N\dot{a}) = 0$$

$$N(a,t) = \frac{\dot{\mathcal{N}}_m(t_f)}{|\dot{a}(a)|}, \ \dot{\mathcal{N}}_m \sim (1+z)^2$$

Galaxy merger rate at the moment when BSBH was formed

(Xu et al. 2012)

Generalizing Phinney (2001):

$$\Omega_{\rm GW}\rho_c c^2 = \frac{32}{5}\frac{G^{7/3}}{c^5}\mathcal{M}^{10/3} f \int_{t(\infty)}^{0} dt \cdot$$
$$\cdot \sum_{a_c<a_n<a_h} \left(n\left|\frac{df_{\rm orb}}{da}(a_n)\right|\right)^{-1}\left(\frac{2\pi f_r}{n}\right)^{10/3} g(n,e(a_n))\frac{\dot{\mathcal{N}}_m(t_f(a_n,t))}{|\dot{a}(a_n)|}$$

TOTAL GW BACKGROUND

$$N(a,t)da = \text{number of binaries per comoving volume}$$
$$\text{with semimajor axes } a \ldots a + da$$

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial a}\left(N\dot{a}\right) = 0$$

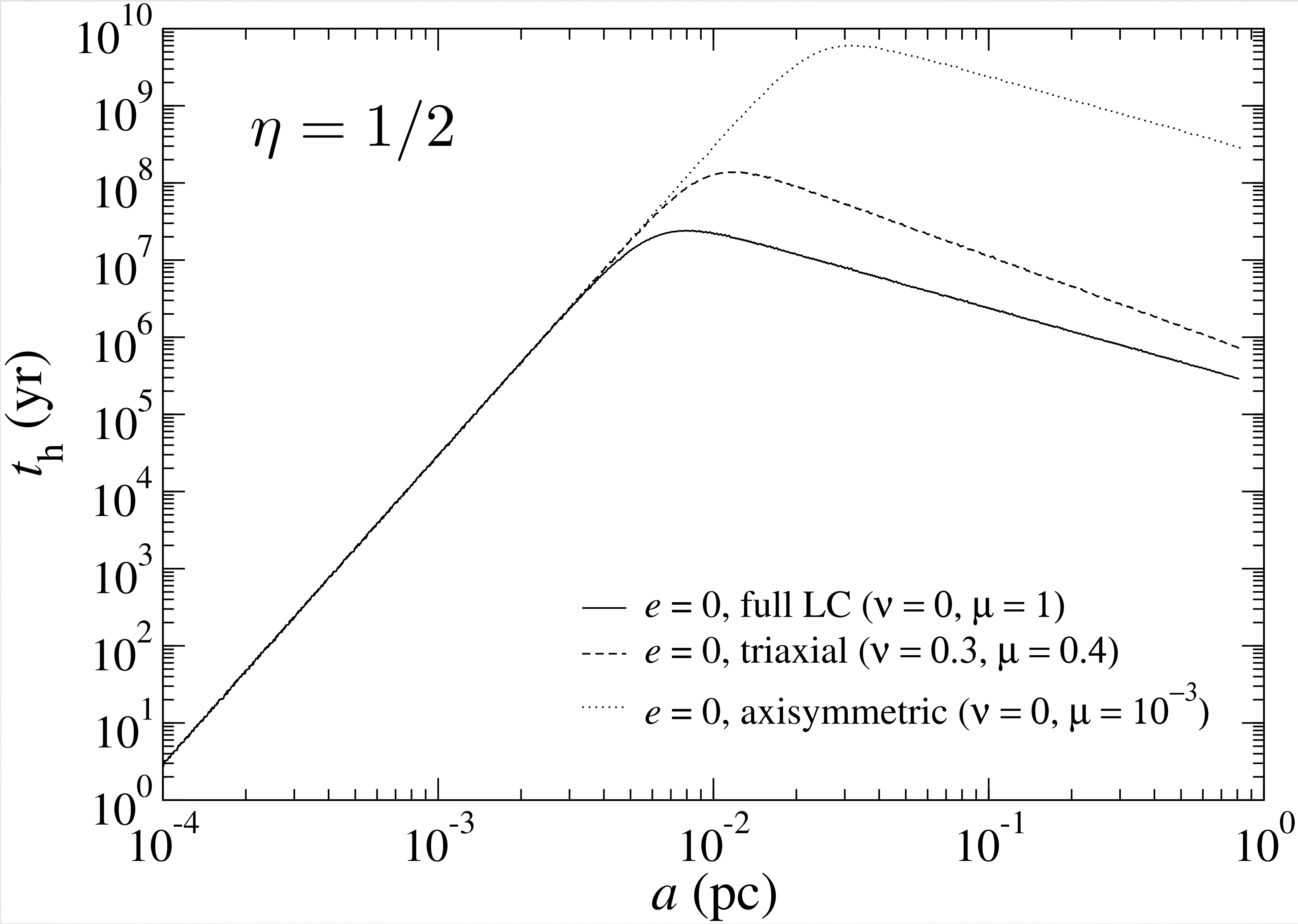
$$N(a,t) = \frac{\dot{\mathcal{N}}_m(t_f)}{|\dot{a}(a)|},\ \dot{\mathcal{N}}_m \sim (1+z)^2$$

Following Phinney (2001):

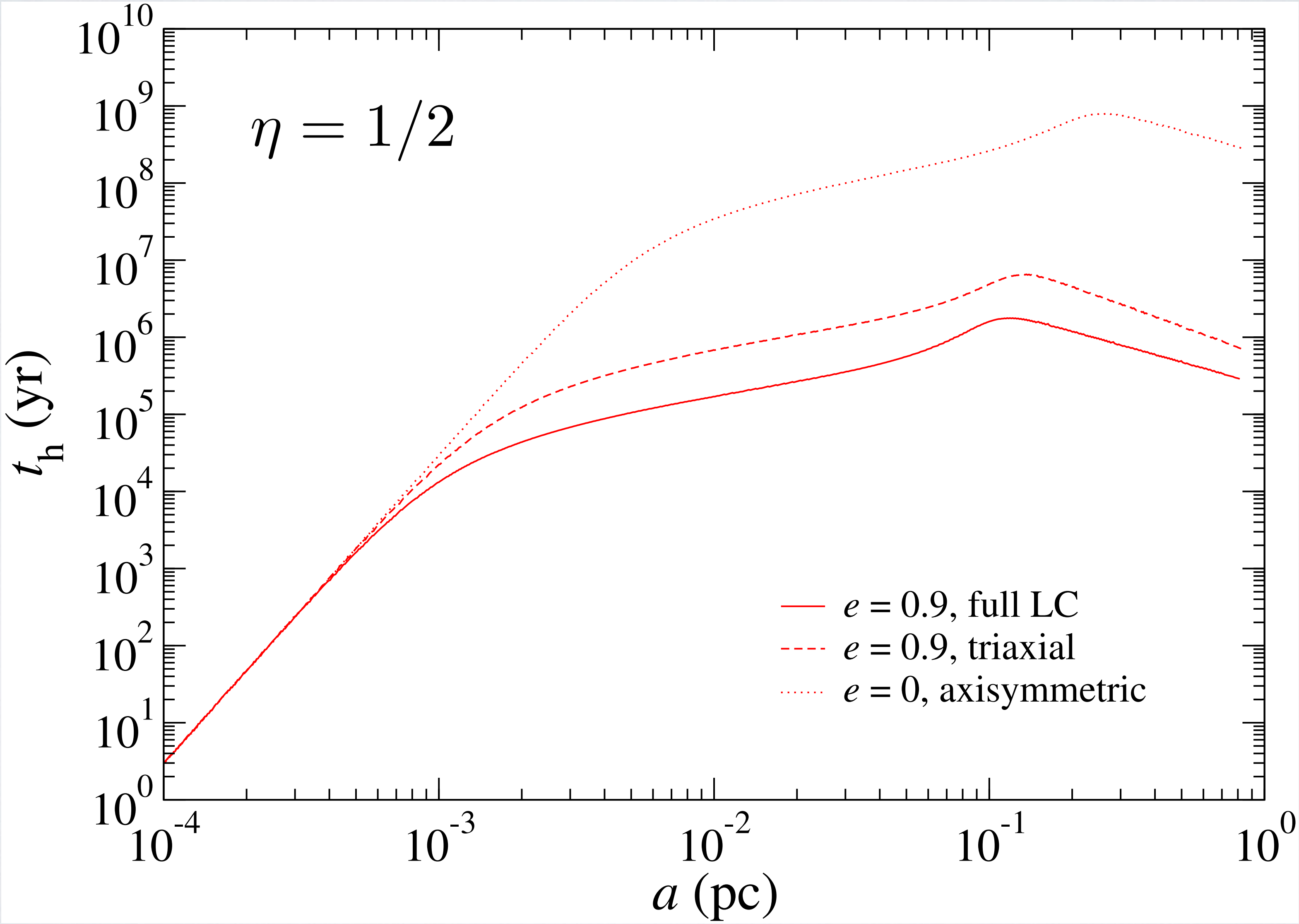
Lifetime of the binary (t_f - t) can be long

$$\Omega_{\rm GW}\rho_c c^2 = \frac{32}{5}\frac{G^{7/3}}{c^5}\mathcal{M}^{10/3} f \int_{t(\infty)}^{0} dt \cdot$$
$$\cdot \sum_{a_c<a_n<a_h} \left(n\left|\frac{df_{\rm orb}}{da}(a_n)\right|\right)^{-1}\left(\frac{2\pi f_r}{n}\right)^{10/3} g(n,e(a_n))\frac{\dot{\mathcal{N}}_m(t_f(a_n,t))}{|\dot{a}(a_n)|}$$

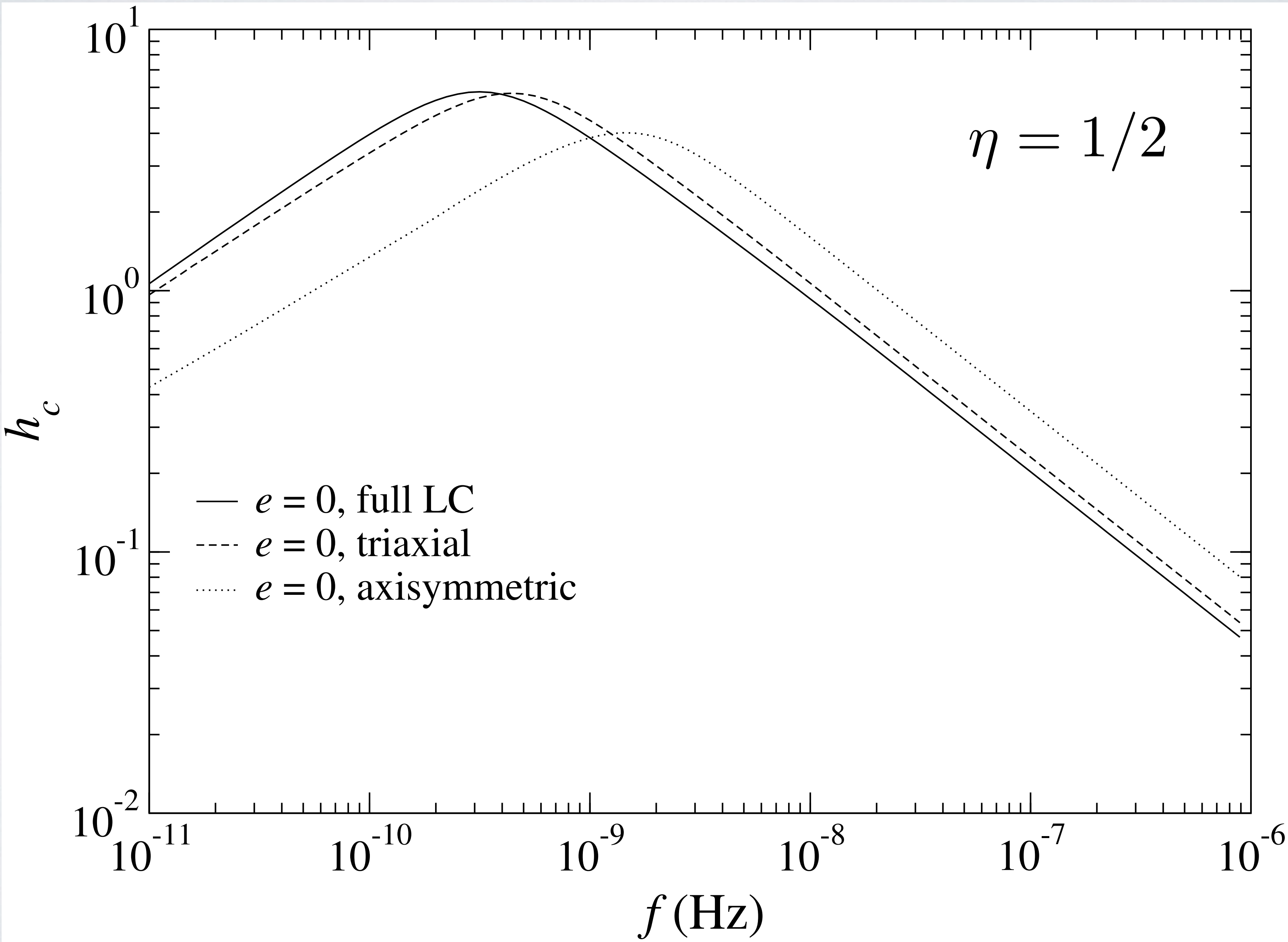
HARDENING TIMESCALES



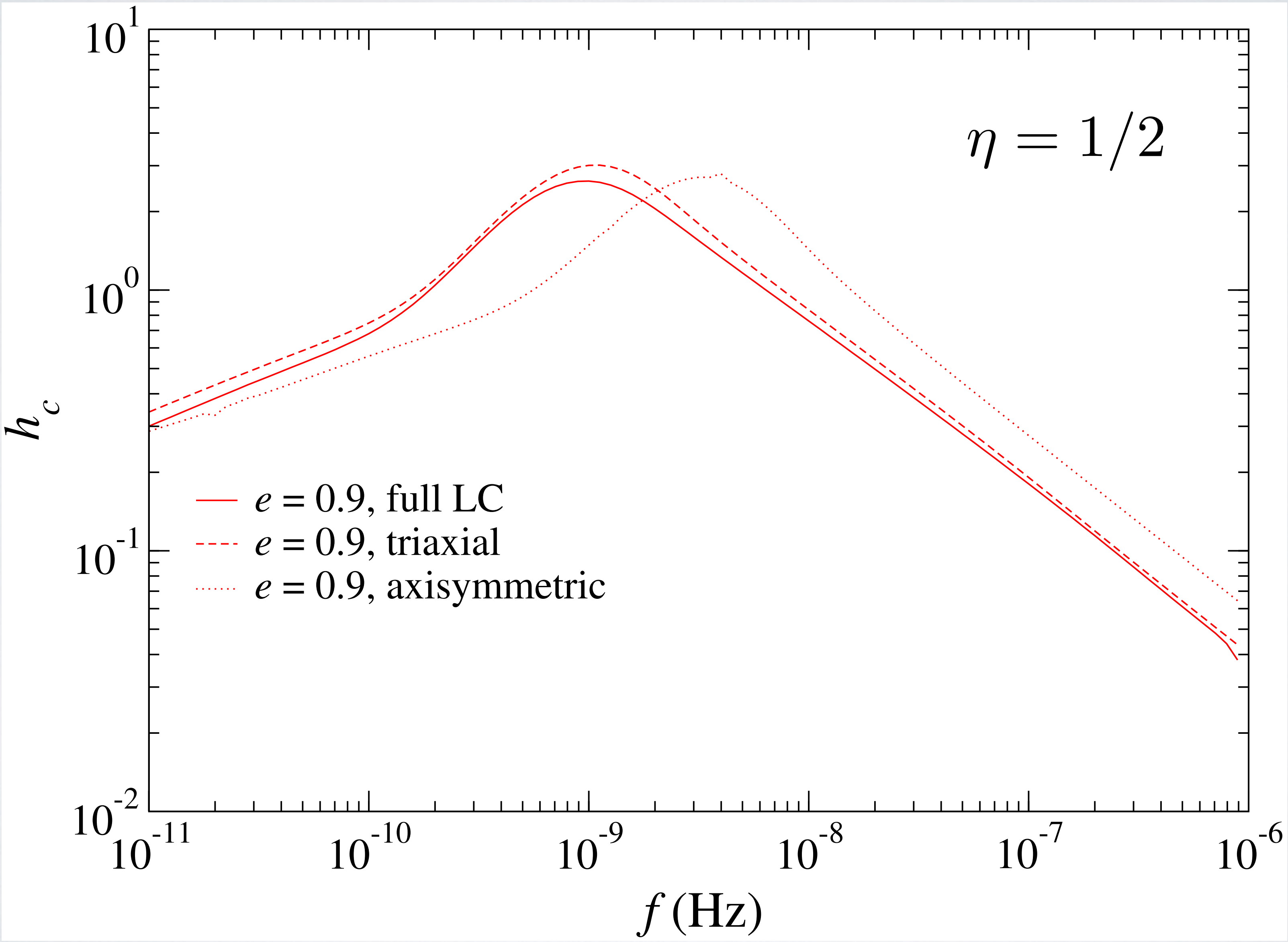
HARDENING TIMESCALES



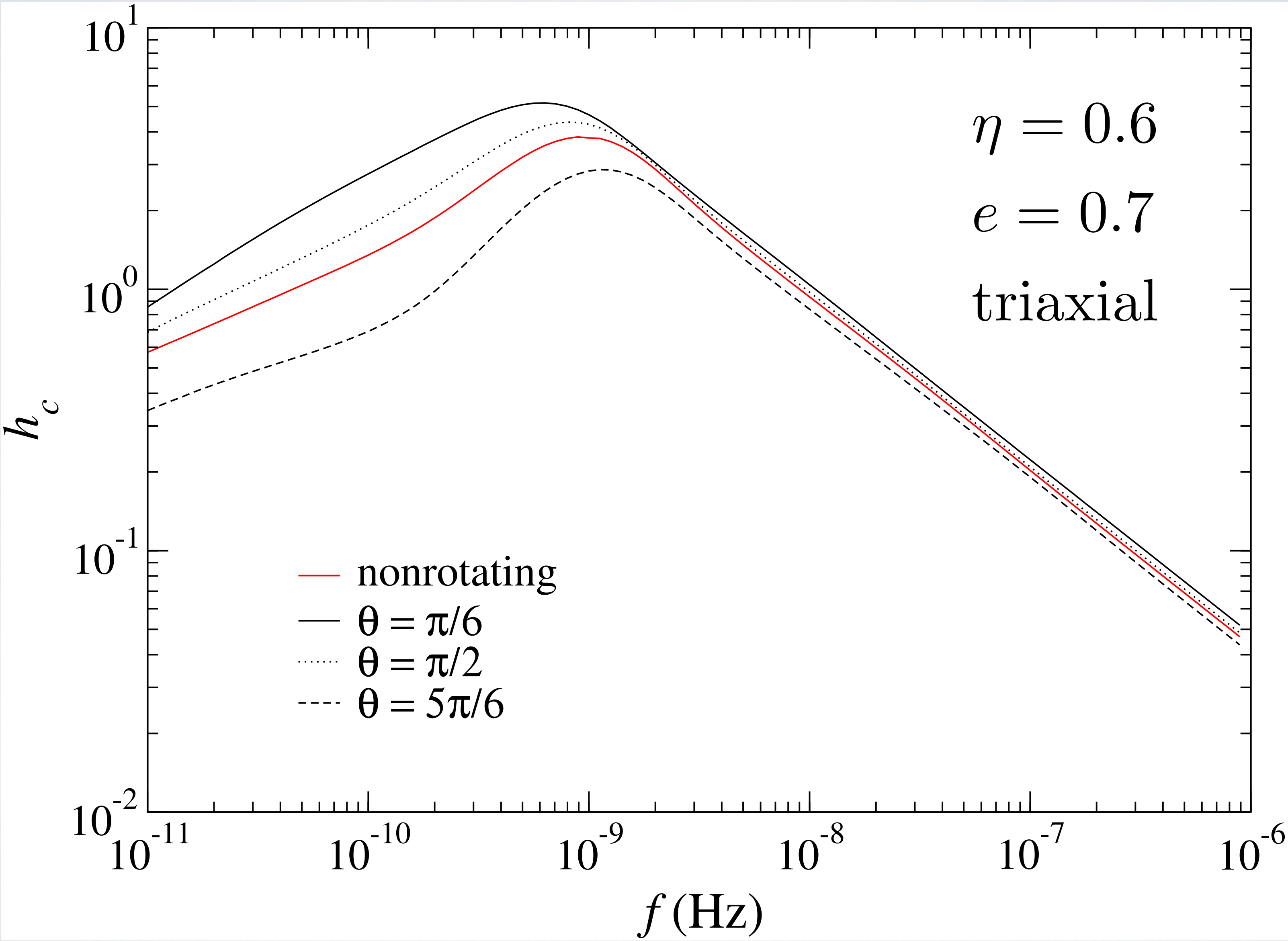
STOCHASTIC GW BACKGROUND



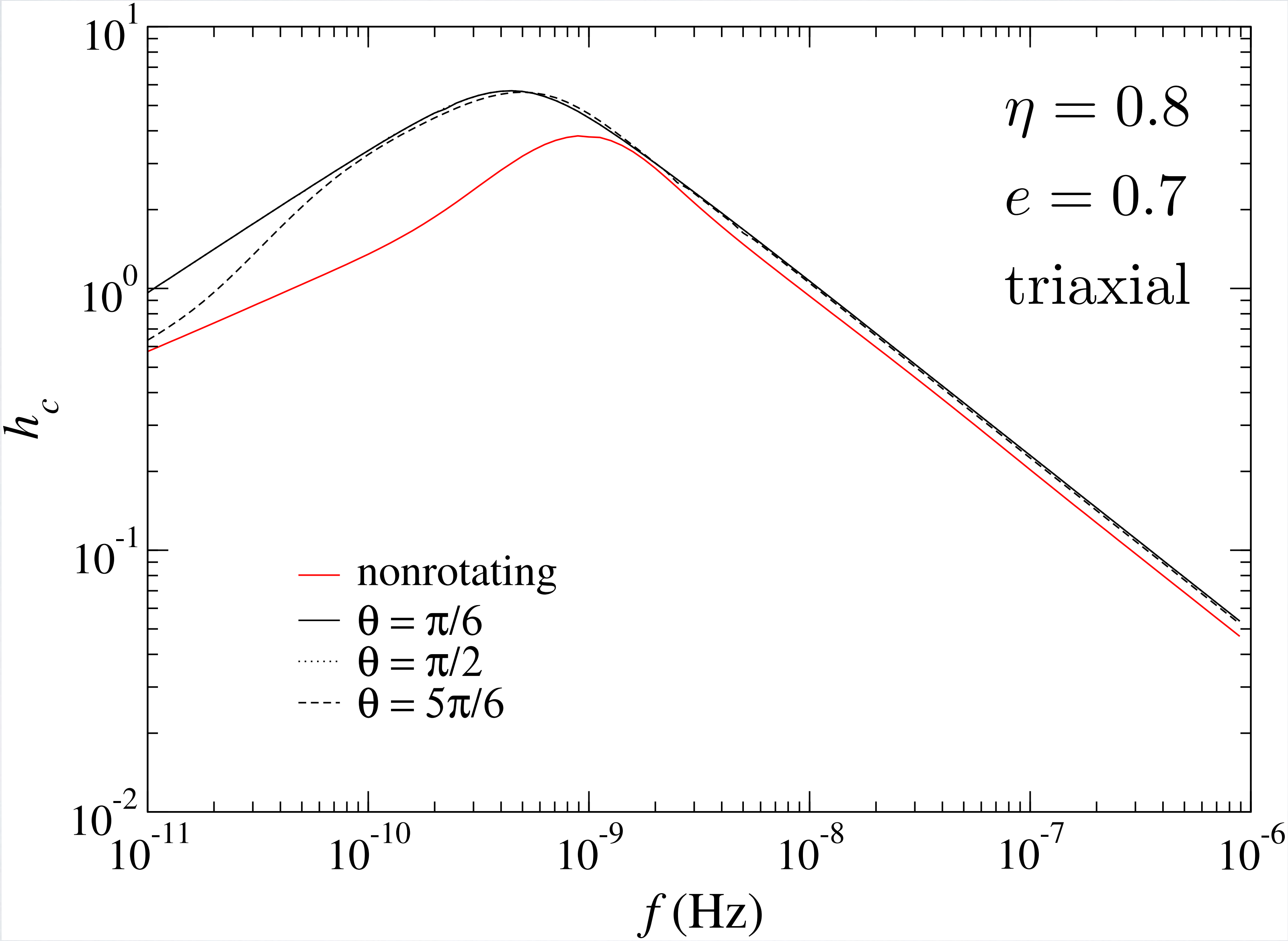
STOCHASTIC GW BACKGROUND



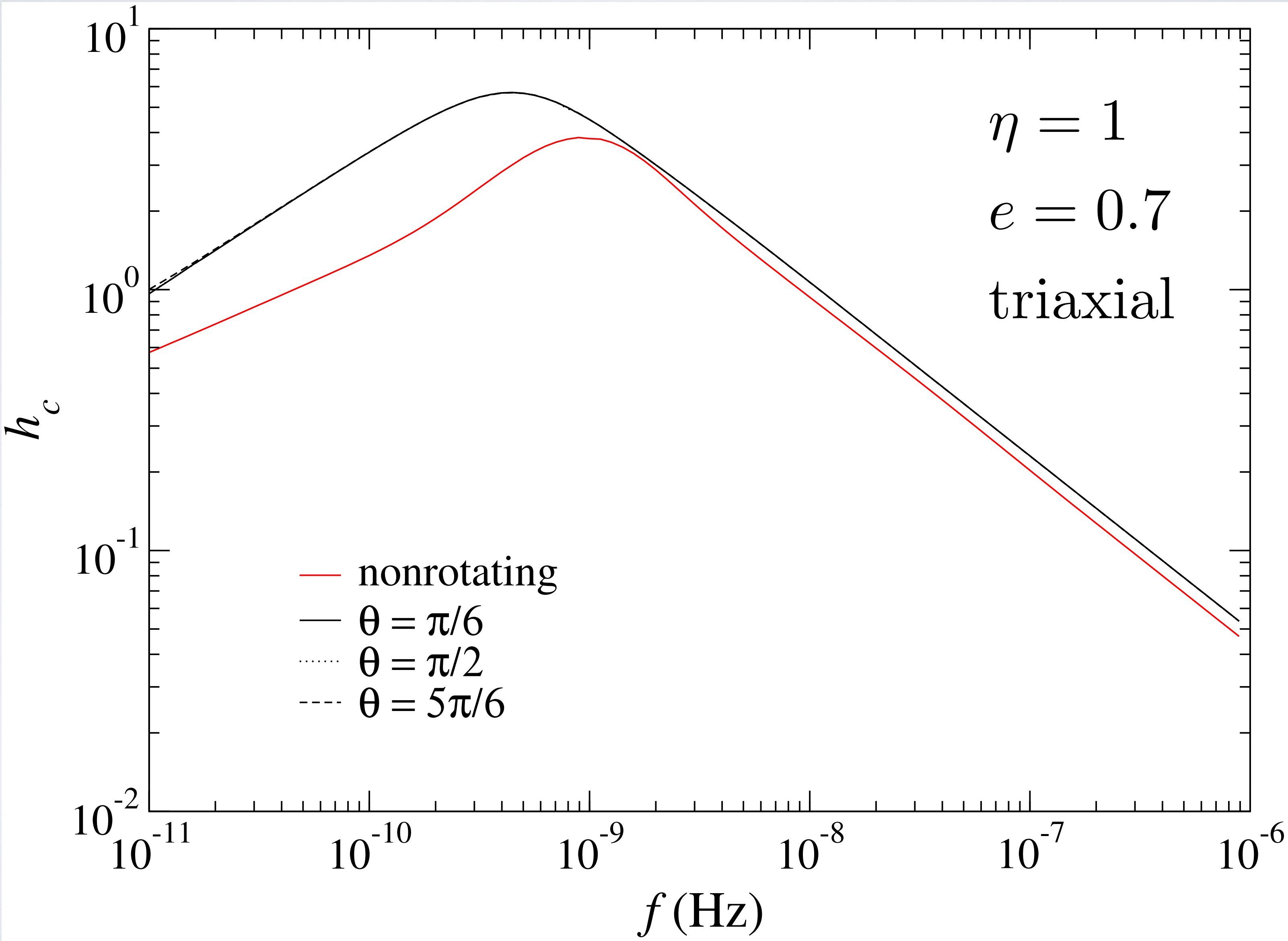
STOCHASTIC GW BACKGROUND



STOCHASTIC GW BACKGROUND



STOCHASTIC GW BACKGROUND



SUMMARY

- Previous calculations of stochastic GW background are generalized to include:
  - Evolution of stellar nucleus
  - Rotation of stellar nucleus
- Effects of nuclear evolution:
  - Triaxial or axisymmetric - the spectrum is shifted towards higher frequencies (especially for axisymmetric)
  - Spherical - BSBH fail to produce GW emission due to "final parsec problem"

SUMMARY

- Effects of nuclear rotation:
  - Corotating - initial eccentricity quickly falls to zero and has no impact on GW spectrum
  - Counterrotating - eccentricity can grow significantly (especially in case of slow rotation) and reduce GW emission at low frequencies
- Plans for future work: calculate total GW background for the distribution of binary masses, initial conditions etc.


THANK YOU!
(image credit: NASA)