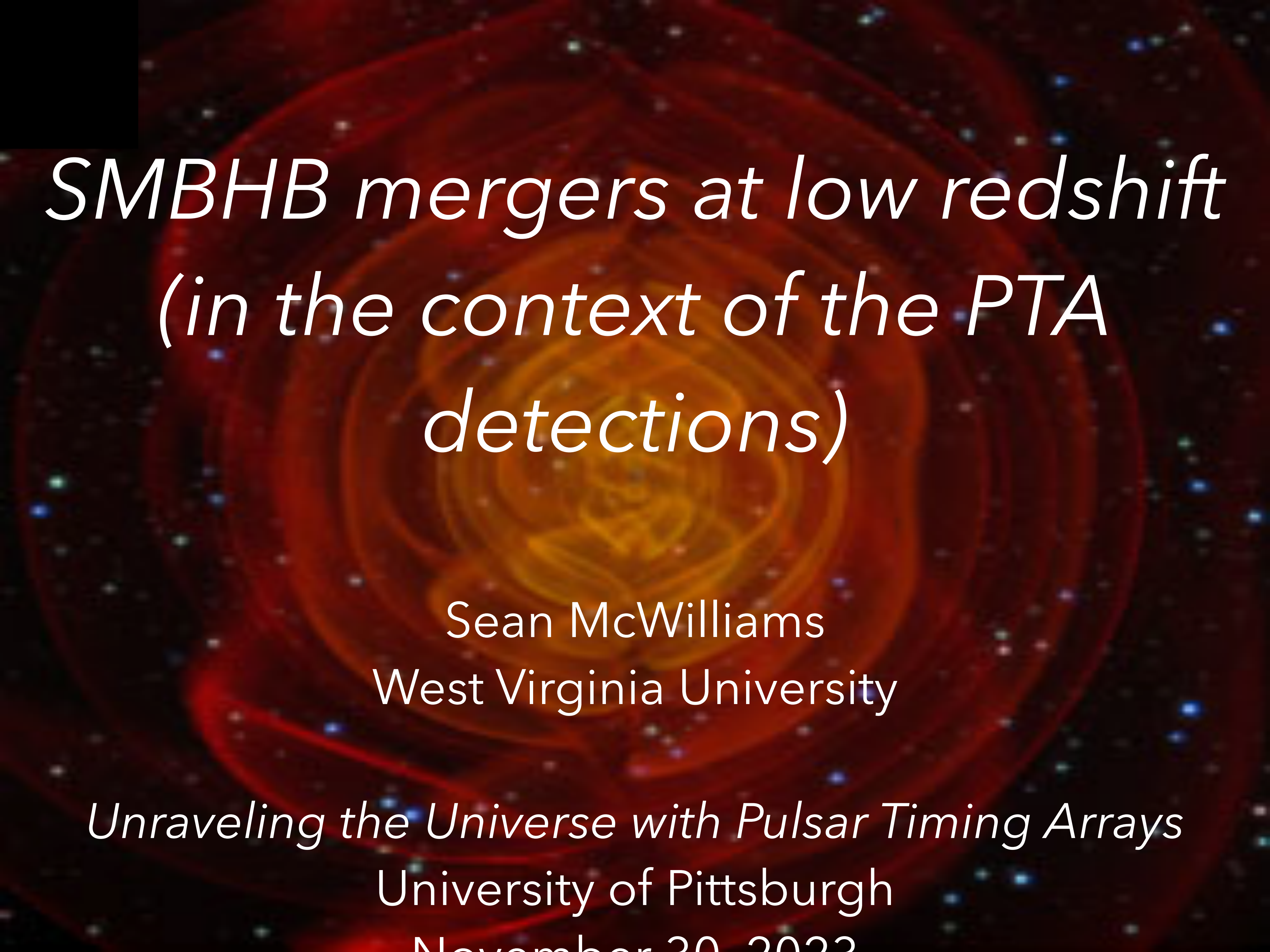

SMBHB mergers at low redshift (in the context of the PTA detections)

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Unraveling the Universe with Pulsar Timing Arrays
University of Pittsburgh
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NB: I’ll be assuming throughout that the signal PTAs observed is from SMBHB mergers! If it’s something else, ~everything I’m about to say will be wrong.

Galaxies and black holes

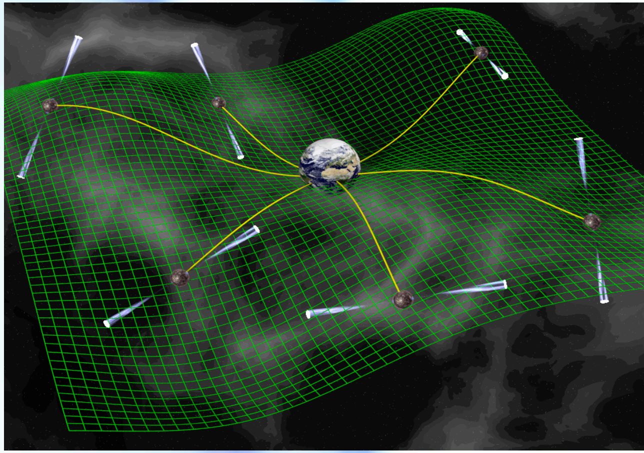
- At low redshift, all large elliptical galaxies contain a supermassive black hole
- At $z \sim 0$, various galactic properties obey scaling relations with the central black hole's mass
- Resolving the radius of influence is hard for everyone!
  - Can't be done observationally at $z > 0.2$ish
  - Can't be done by numericists trying to simulate galaxies (need subgrid models, see e.g. Ma *et al*. 2023 MNRAS 519 4 5543)
- We can use scaling relationships to infer black hole masses at larger redshifts
  - Probably wrong at high z, but hopefully ok at low

Galaxy and black hole mergers

- Within a common DM halo, two subhalos can merge due to dynamical friction.
- Eventually (Gyrs), the baryonic cores can merge due to… dynamical friction.
- Later (Gyrs), the central black holes can inspiral
  - By dynamical friction (again) until the binary hardens
  - Late stages are driven by scattering low L stars (“loss cone”), but eventually, you depopulate them by eating them faster than two-body relaxation timescale, so could stall (“final pc problem”)
  - Resolution: loss cone is refilled by gas accretion, Brownian BH motion, triaxial potential/tidal forces, other massive perturbers, a hard sneeze, etc
- Finally, GWs dominate the evolution, and the black holes can merge, but much more likely to be seen during the inspiral.
  - Increasingly convincing case for OJ 287 as a SMBHB ($M_\bullet \sim 10^8$-10^{10} $M_\odot$, $P \sim 12$ yr, $r_p \sim 0.085$ pc, $e \sim 0.65$, $z \sim 0.3$)

Stochastic GW signal from SMBHBs

- PTAs are sensitive to SMBHB mergers at $0 < z < \sim 1$, signal dominated by the most massive galaxies *that merge*
- Massive galaxies evolve due to mergers and star formation, were long thought to stop at low z – *"red and dead"*
- More recently, observations question this for Brightest Cluster Galaxies (BCGs) and other very massive ellipticals
  - Contain half the stellar mass of the Universe
- Lots of evidence, now including PTA observations, suggest that mergers drive the evolution of these galaxies, masses ~doubled since $z \sim 1$.



Evidence that dry (gas poor) major (mass ratio >~ 1/3) mergers dominate the growth of massive ETGs is compelling

- Observed evolution of the mass function (STM *et al*. 2014 ApJ 789 156 (MOP 2014))
- Observed “inside-out” growth (Bai *et al*. 2014 ApJ 789 134)
- Bautz-Morgan classification (Bautz and Morgan 1970 ApJ 162 L149)
- Statistical specialness of BCGs (Roohi *et al*. 2021 MNRAS 507 3 4016)
- Overmassive black holes in massive ETGs, relative to Faber-Jackson correlations of less massive galaxies (McConnell and Ma 2013 ApJ 764 184)
- Diminished scatter in Faber-Jackson correlations at the high-mass end (Montero-Dorta *et al*. 2016 MNRAS 456 3 3265)

But what about the Soltan argument??

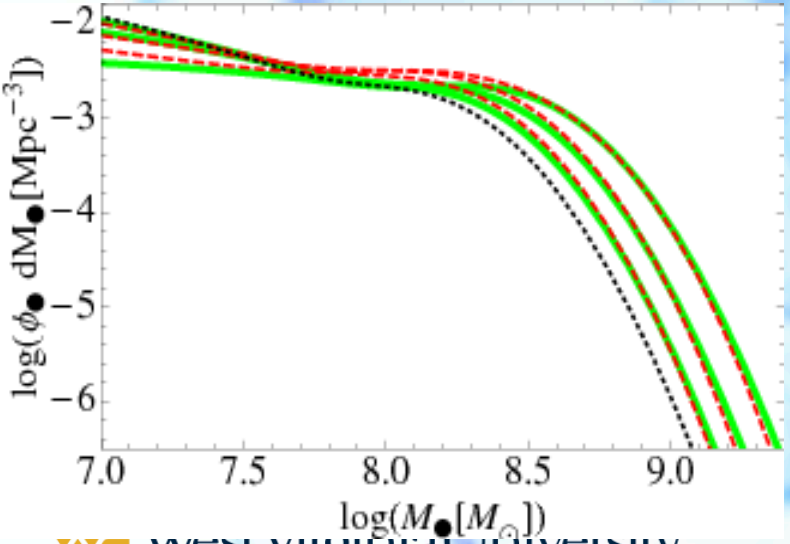
- You can estimate the mass density of SMBHs from the total luminosity coming from quasars, assuming they grow by accretion. Roughly matches locally observed result.
    - NB: NOT a law of Nature. Definitely not reliable beyond an order-of-magnitude level.
- Most quasars are at $z > 1$ (peak at $z \sim 2$).
- Back then, all SMBHs were probably growing through accretion.
- Most SMBHs aren't quasars.
- Mergers don't appreciably change the mass density of SMBHs.
- Given these points, the Soltan argument really doesn't constrain the growth mode of the most massive BHs at $z < \sim 1$.

Evolution of the Mass Function

- Number density of galaxies vs. mass is well-described by the Schechter function at $z > 1$, and for most galaxies at $z < 1$
- However, at $z < 1$, very massive galaxies deviate, appear to double their mass in $0 < z < 1$ despite being red and dead:

$$\phi(M)\,dM \equiv (\phi_{\rm low}+\phi_{\rm BCG})\,dM = \varphi\,M^{\alpha}\,\exp(-M)\,dM + \varphi\exp\left[-\frac{1}{2}\left(\frac{2.5\log M}{\sigma_M}\right)^2 - 1\right] dM$$

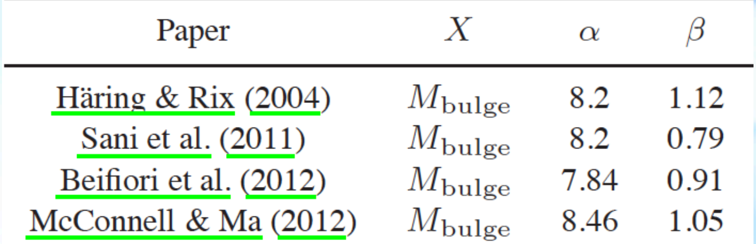
- BCGs appear to grow by comparable mass (1:1 - 4:1) mergers. Our simple merger-only model bears this out and matches observations.



$$\frac{\partial^3\phi_{\{\rm low,\,BCG\}}}{\partial M'\partial M''\partial z}\,dM'dM''dz = P(z)dz\,\phi_{\{\rm tot,\,BCG\}}(M')\,dM'\,\phi_{\{\rm tot,\,low\}}(M'')\,dM''$$

"… an expectation value for the characteristic strain $h_c(f = 1\ \mathrm{yr}^{-1}) = 4.1 \times 10^{-15}$ that may already be in tension with observational constraints." – MOP 2014

PTA GWs and scaling relationships



Paper	X	α	β
Häring & Rix (2004)	$M_{\rm bulge}$	8.2	1.12
Sani et al. (2011)	$M_{\rm bulge}$	8.2	0.79
Beifiori et al. (2012)	$M_{\rm bulge}$	7.84	0.91
McConnell & Ma (2012)	$M_{\rm bulge}$	8.46	1.05

$$\log_{10} M_\bullet = \alpha + \beta \log_{10} X,$$

– Sesana 2013

$$M_{\rm bulge}/10^{11} M_\odot$$

Useful numbers:

$10^{(8.46-8.2)} \approx 2$

$10^{(8.46-7.84)} \approx 4$

THIS WILL CHANGE THE LEVEL OF THE STOCHASTIC BACKGROUND BY THE SAME FACTOR

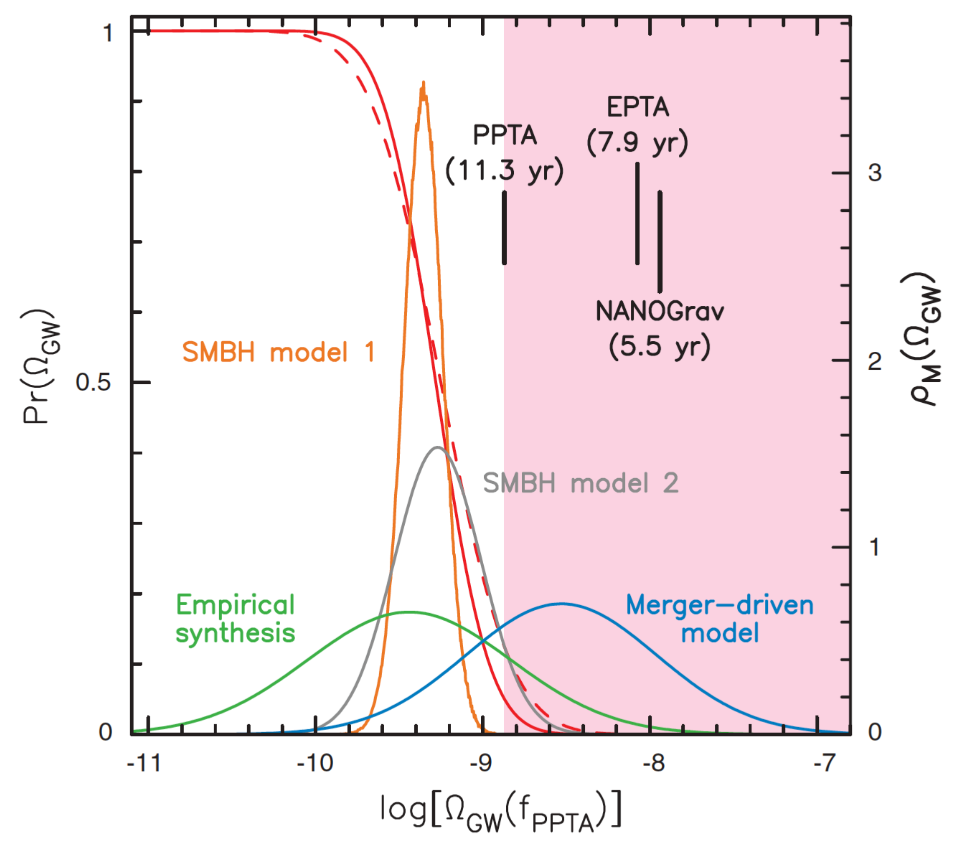
Why is McConnell and Ma's normalization "so" different?

- "This is likely due to differences in the galaxy samples: our core galaxies include 11 galaxies with $M_\bullet > 10^9 M_\odot$" – McConnell and Ma 2012
- If you limit your fit to more massive galaxies/black holes, you get a larger black hole mass normalization.
- Redshift dependence of relationships can also have a big impact, see Matt *et al.* 2023 MNRAS 524 3 4403, Simon 2023 ApJ 949 L24.

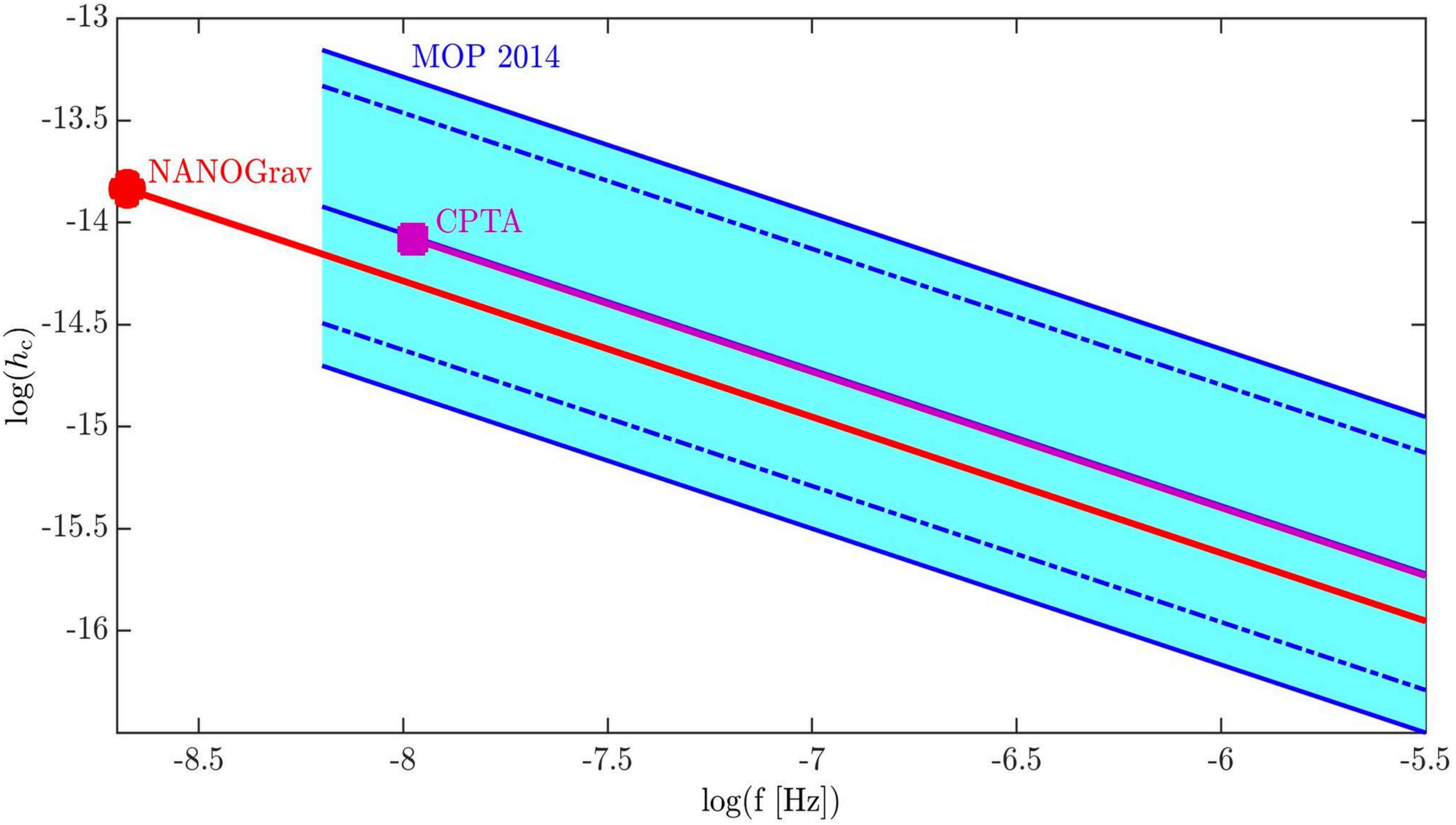
PPTA constrains theory(?)

“First, a model that assumes a scenario in which all evolution in the galaxy stellar mass function and in the SMBH mass function is merger-driven at redshifts $z < 1$ [MOP 2014] predicts a Gaussian GWB that is ruled out at the 91% confidence level.” – RS *et al* 2014

“PPTA observations exclude 46% of [Sesana 2013].” – RS *et al* 2014



Narrator: “No they didn’t.”



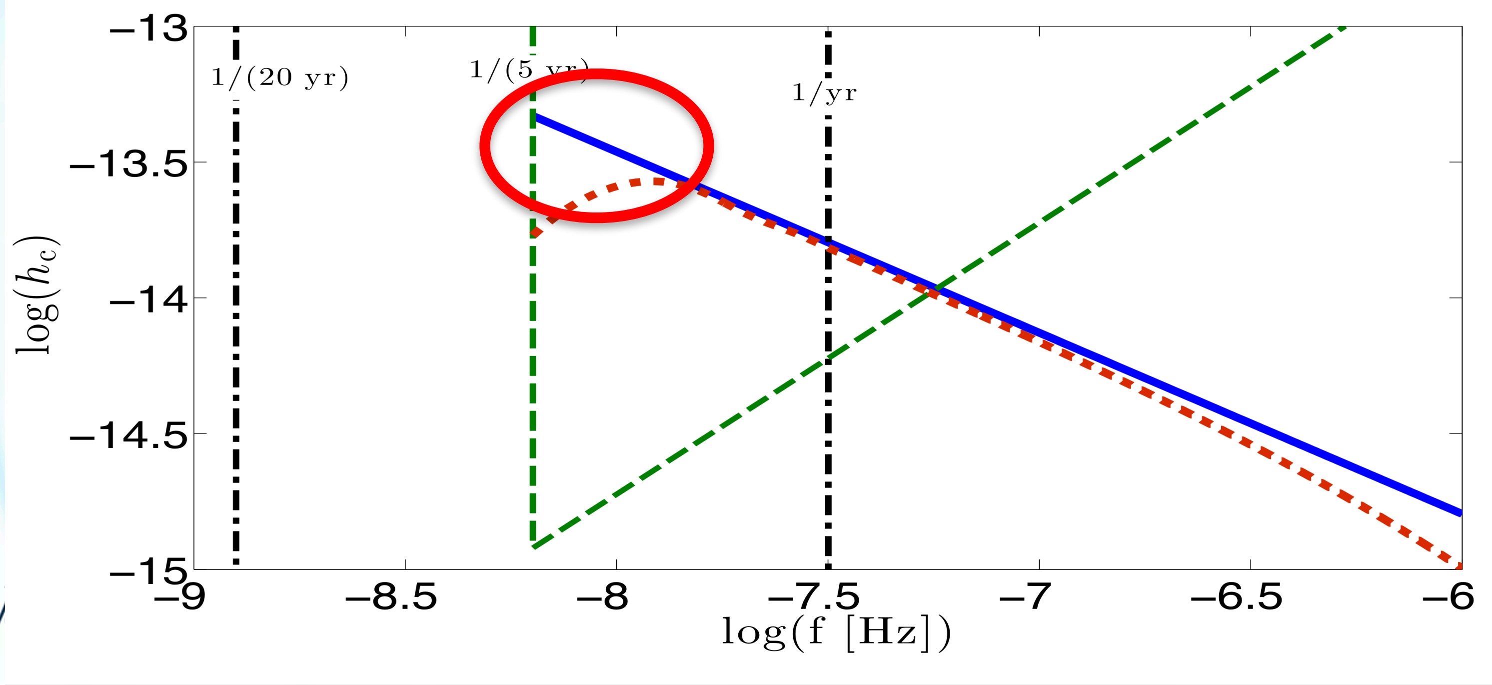
- The detected signal is very consistent with the merger-driven prediction.

Spectrum can differ at low frequencies

- Observational results quote $A_{1/\mathrm{yr}}$ assuming $h_c \propto f^{-2/3}$.
- Nontrivial behavior at low frequencies depends on solution to the “final parsec problem”
- We assumed stellar scattering, very efficient, yields

$$f_{\min} = 2.7\times10^{-9}\,\mathrm{Hz}\left(\frac{M_\bullet^h M_\bullet^s}{(10^8\,\mathrm{M}_\odot)^2}\right)^{-0.3}\left(\frac{M_\bullet^h + M_\bullet^s}{2\times10^8\,\mathrm{M}_\odot}\right)^{0.2}$$

- Some models assume either $f_{min} < 1/T_{obs}$, or include gas drag



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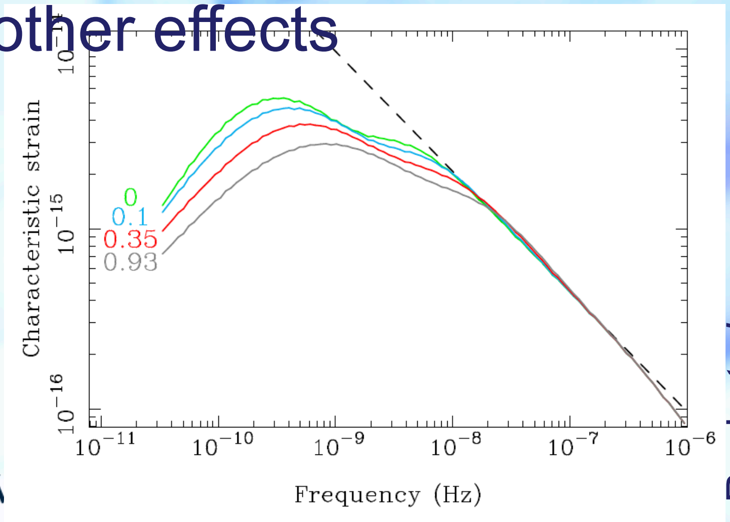
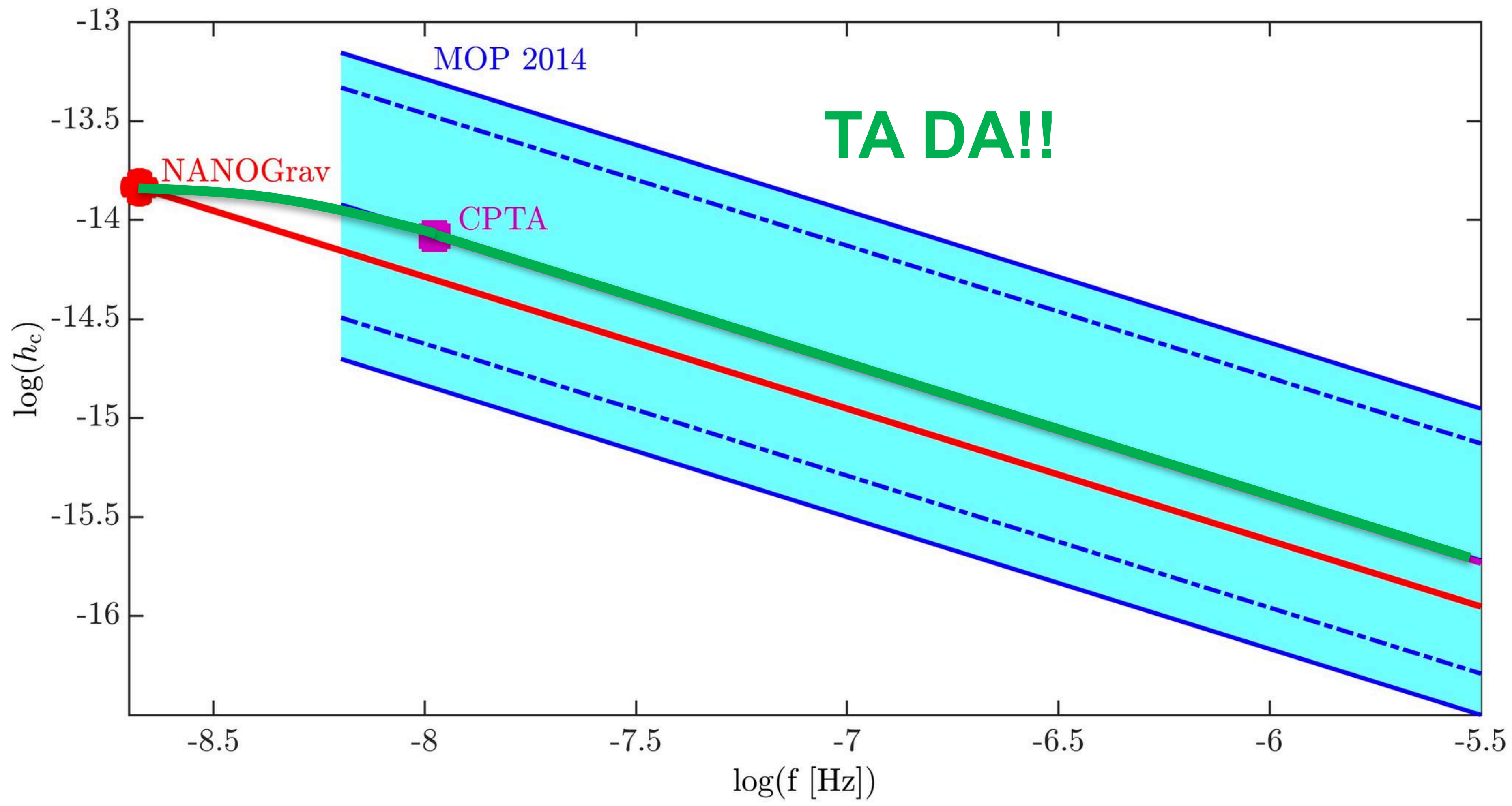
- Eccentricity also removes signal at low frequencies, but less significant than other effects



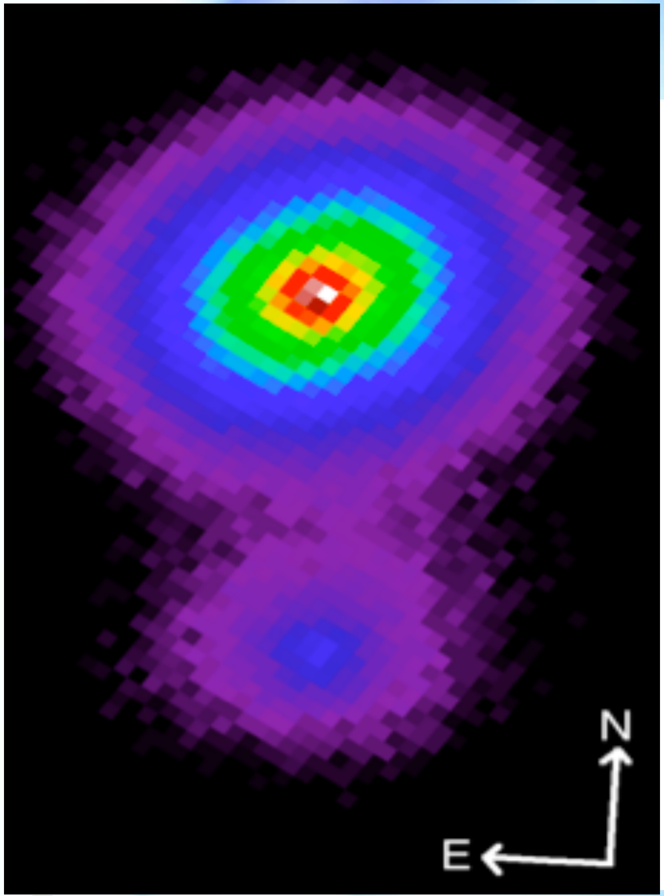
Ravi *et al*, http://arxiv.org/abs/1404.518


MOP 2014
TA DA!!
NANOGrav
CPTA
-13
-13.5
-14
-14.5
-15
-15.5
-16
$\log(h_c)$
-8.5
-8
-7.5
-7
-6.5
-6
-5.5
log(f [Hz])

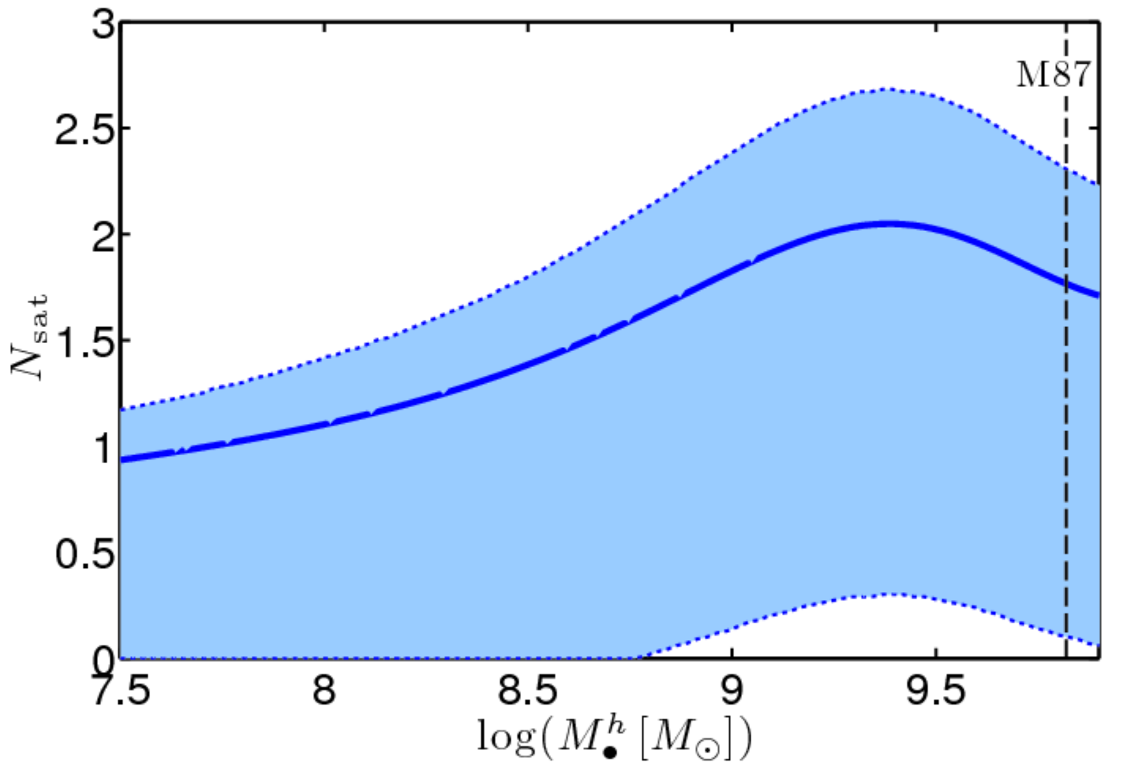
Stalled satellites

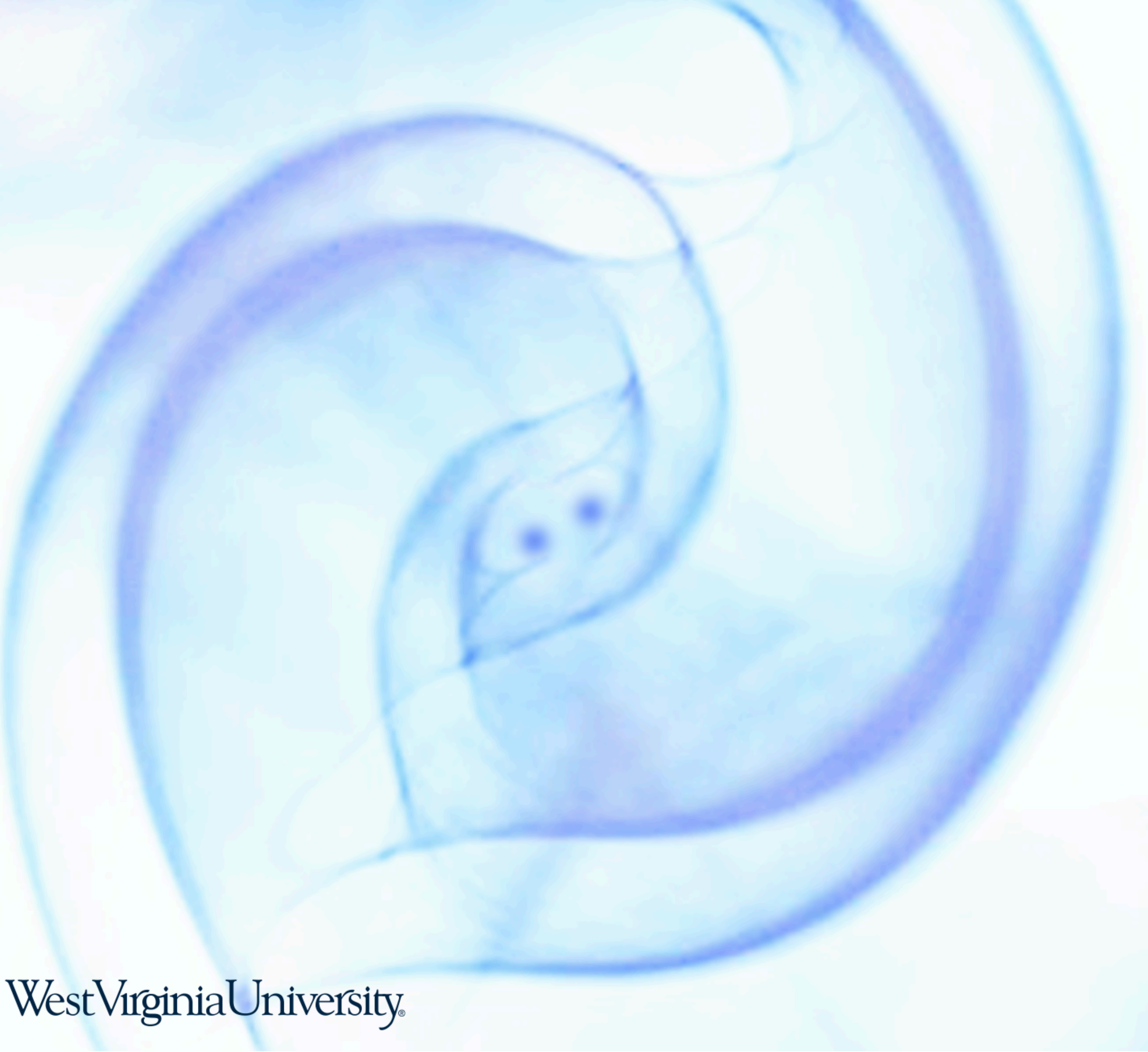
For cases where $t_{df} > t_H$, other observable signatures of galaxy mergers…

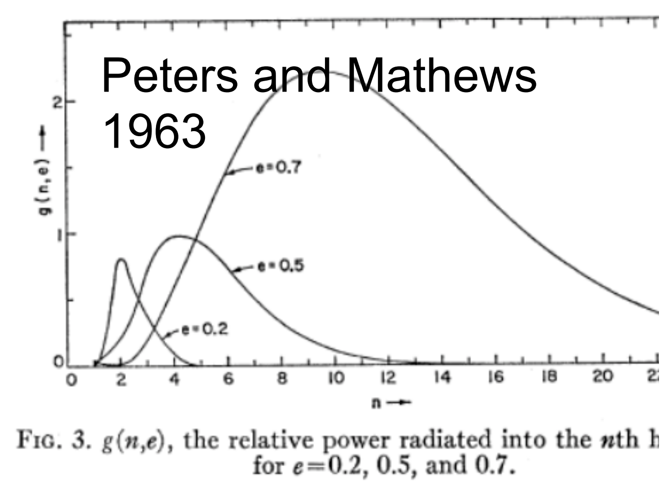
Massive satellites ➔ dual AGNs



Smaller satellites ➔ ULXs?

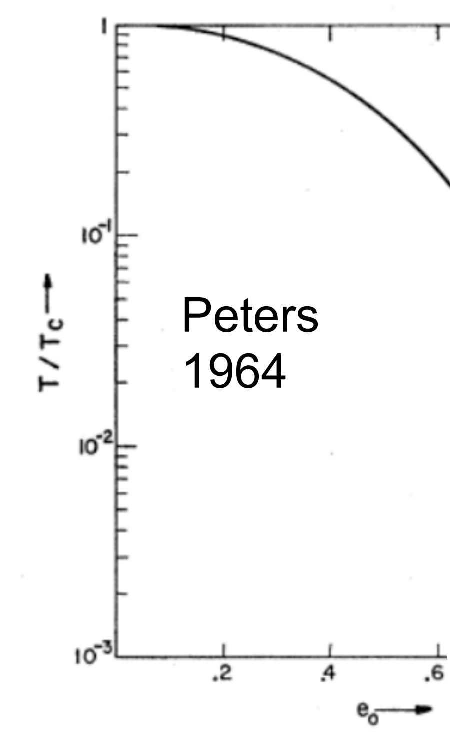






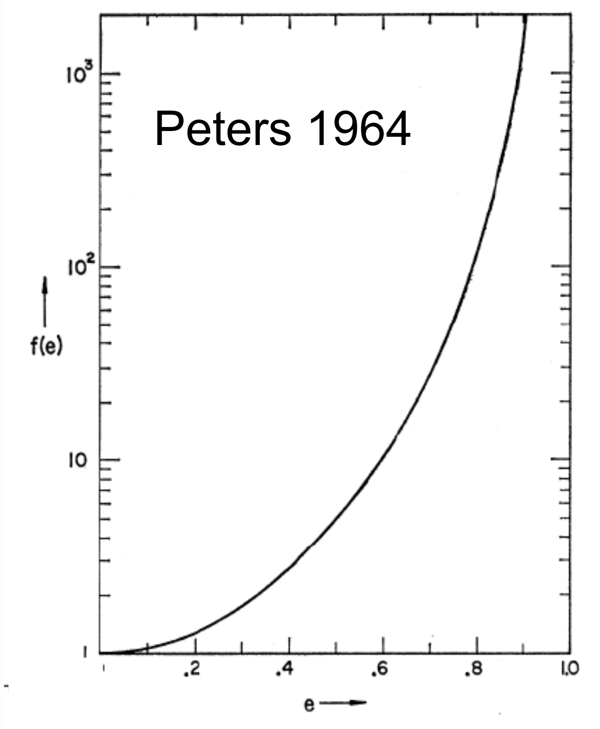
Peters and Mathews
1963

FIG. 3. $g(n,e)$, the relative power radiated into the nth h
for $e=0.2$, 0.5, and 0.7.



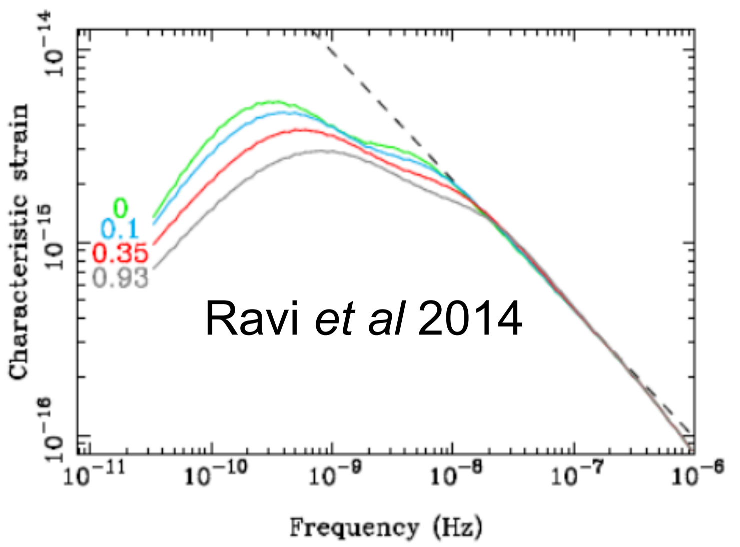
Peters
1964

FIG. 2. The ratio of the lifetime of an ecc
a circular one plotted against the initial ec
independent of the initial value of the sem



Peters 1964

. 2. "Enhancement factor" $f(e)$ plotted against e.



Ravi *et al* 2014

Figure 2. The solid lines depict characteristic strain spectra for $w_0 = 0$ (green), $w_0 = 0.1$ (blue), $w_0 = 0.35$ (red) and $w_0 = 0.93$ (grey); the w_0 values for each line are given at the left of the plot. All curves were calculated assuming a stellar density profile index of $\gamma = 1.5$. The black dashed line is the characteristic strain spectrum assuming circular orbits and purely GW-driven evolution for all SMBH binaries.