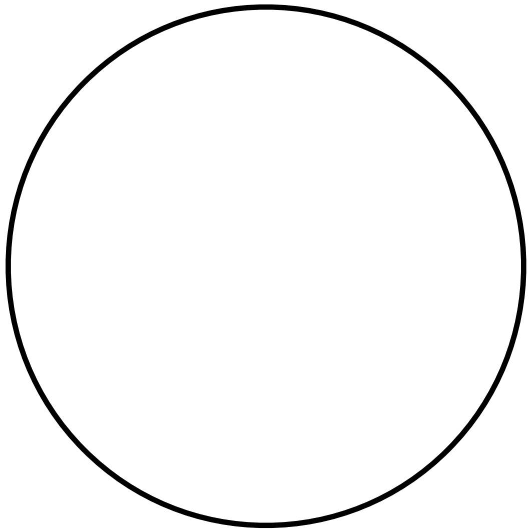
Dynamical environments are interesting III: Can we find them, & making very exotic sources

Richard O'Shaughnessy

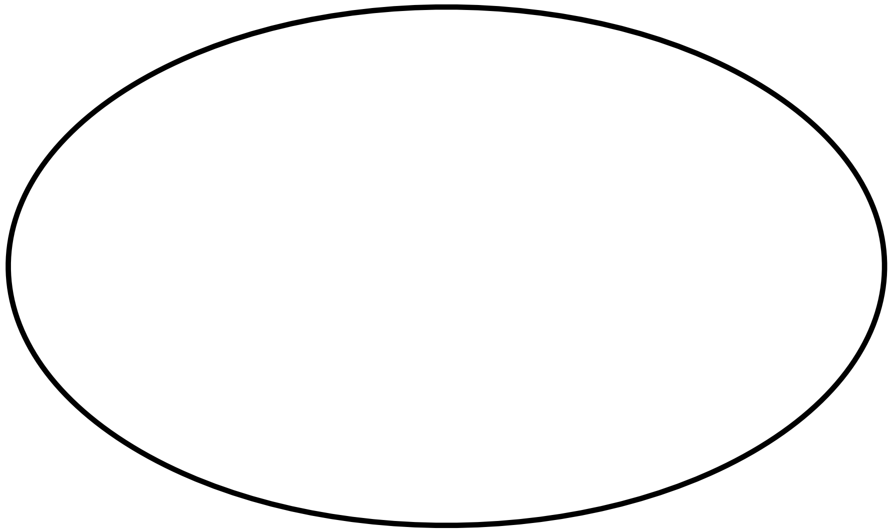
2019-07-~~16~~ 17 Gravast19

Part 1: Identifying eccentric sources [skip me]

Eccentricity for GW: A review (ground-based IFOs)



More from Alessandra Thursday



- Circular
  - Locally constant separation
  - Monotonic orbital phase

$$\Phi_{orb} \simeq \omega_{orb} t$$

- Eccentric
  - Time-varying separation
    - **Strong field stronger**
  - Phase more complex
    - **Multiple harmonics**, impacts detection & PE for band-limited IFOs
    - Technical: tools from dynamics

$$\begin{aligned} t\omega_{\rm orb} &= \psi - e\sin\psi \\ \psi &= t\omega_{\rm orb} + \sum_{n=1}^{\infty} \frac{2}{n} \sum J_n(ne) \sin nt\omega_{\rm orb} \\ r/a &= 1 + e^2/2 - \sum_{n=1}^{\infty} \frac{2e}{n} J'_n(ne) \cos nt\omega_{\rm orb} \end{aligned}$$

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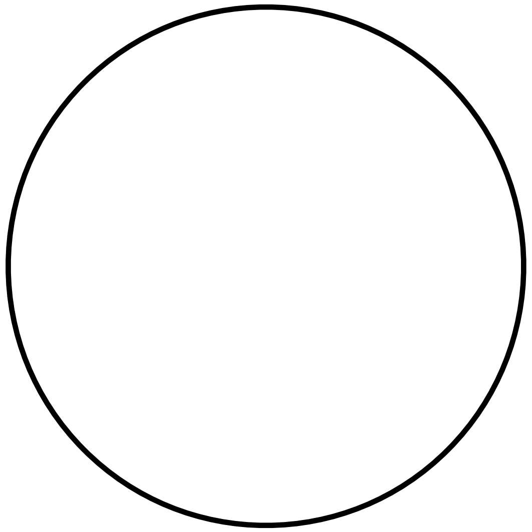
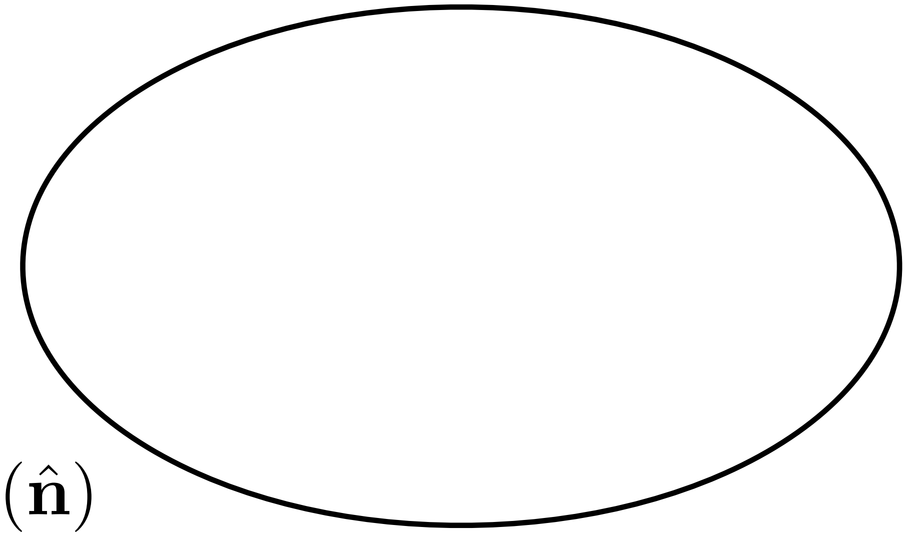




More from Alessandra Thursday

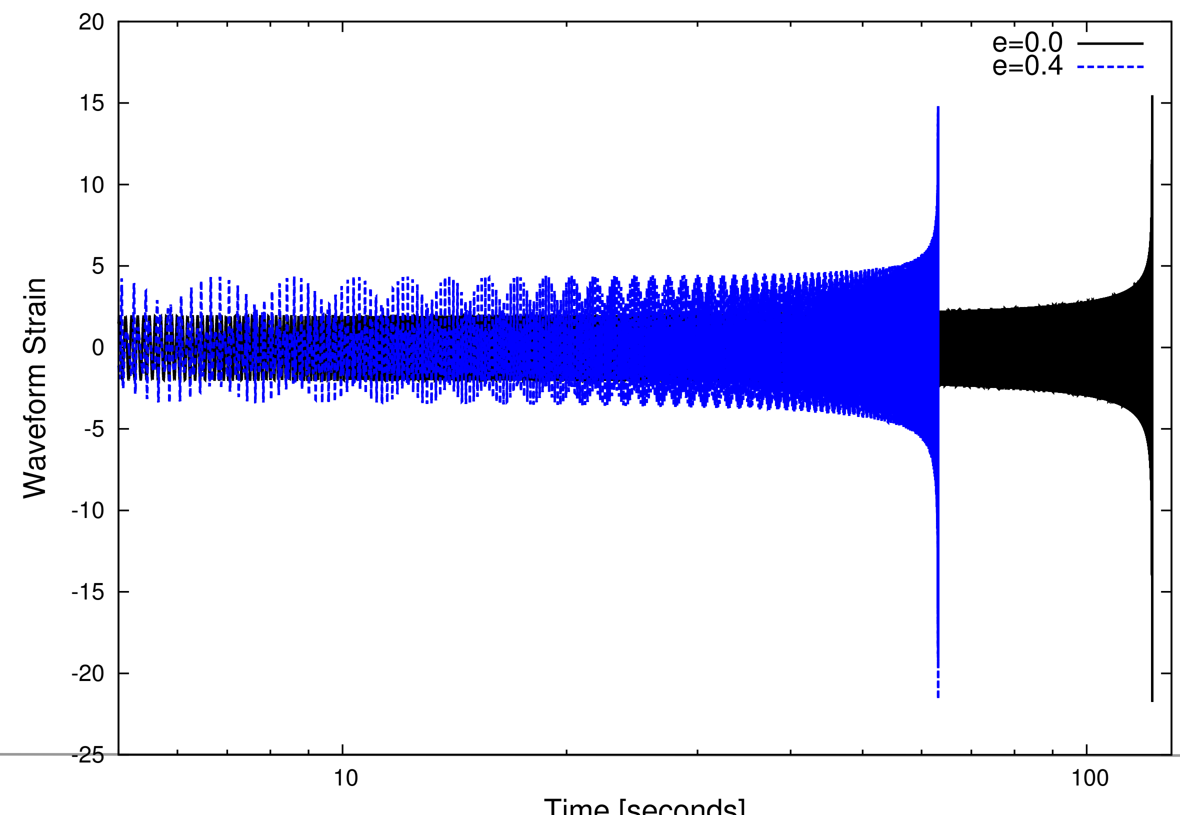
$$h = \sum_{lm} h_{lm} {}^{(-2)}Y_{lm}(\hat{\mathbf{n}})$$

- Circular
  - Without precession, simple

$$h_{lm} = A_{lm} e^{-im\Phi_{orb}}$$

- Eccentric
  - Strongly modulated, e ~ 1/f late

$$h_{lm} = \sum_k A_{lmk} e^{-ik\Phi_{orb}}$$



Huerta et al 1408.3406

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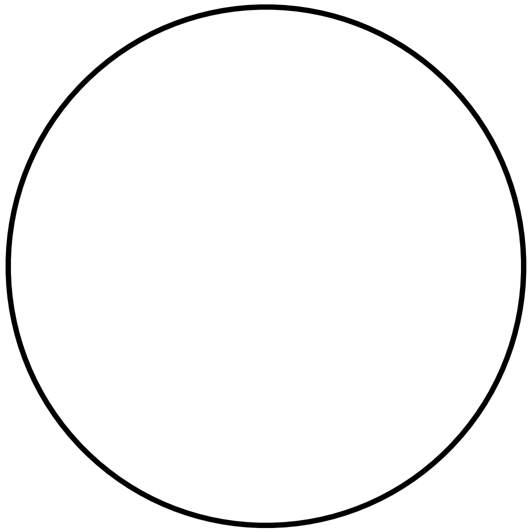

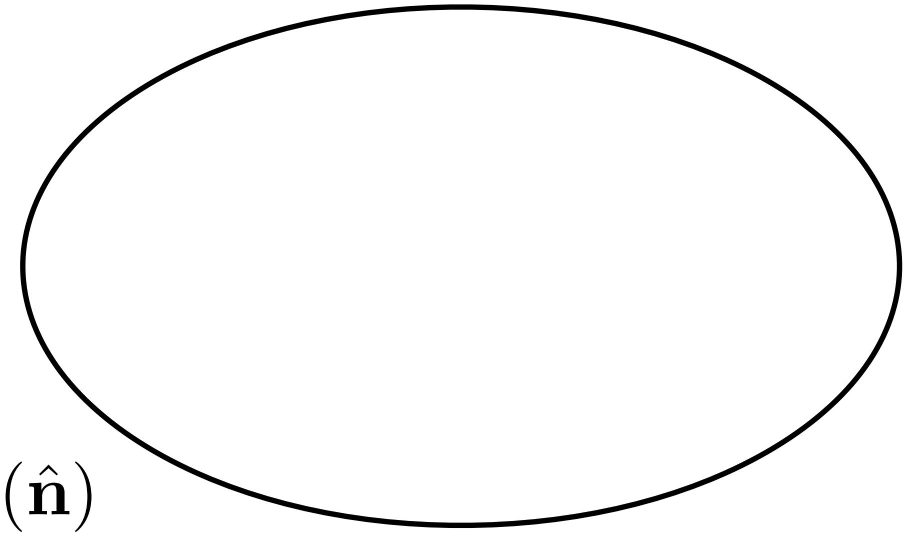

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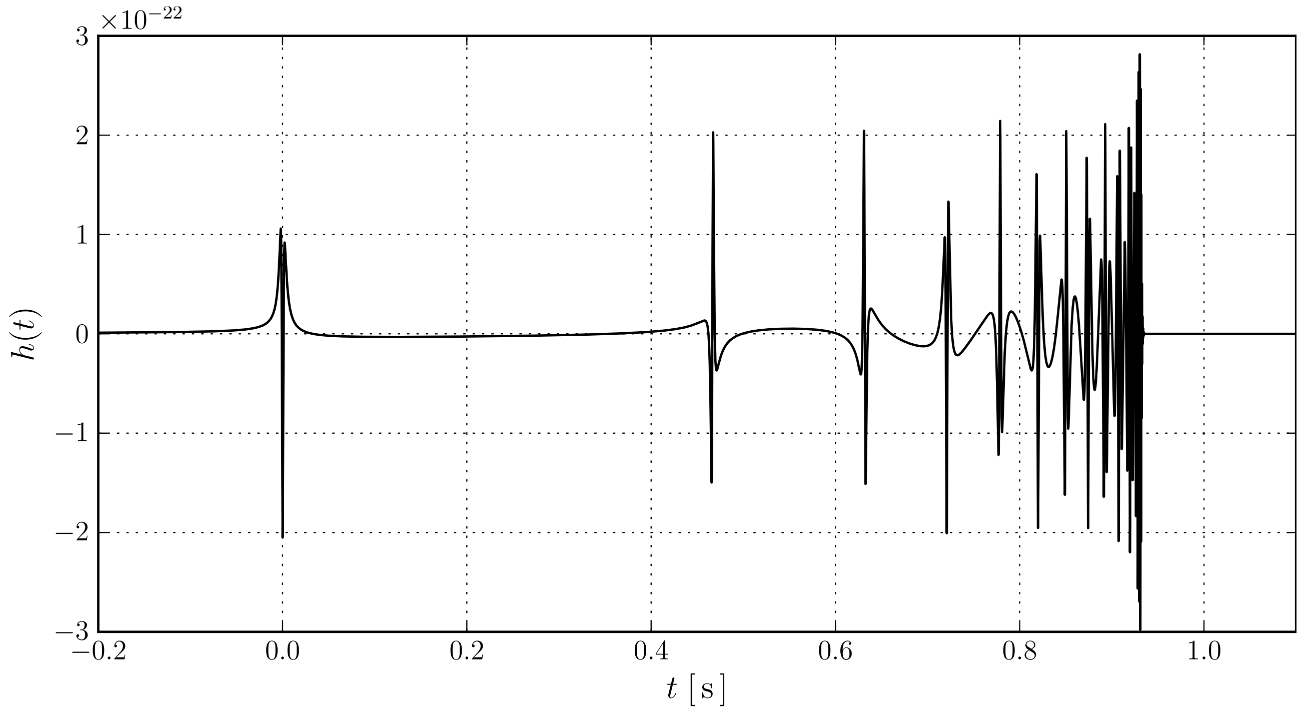
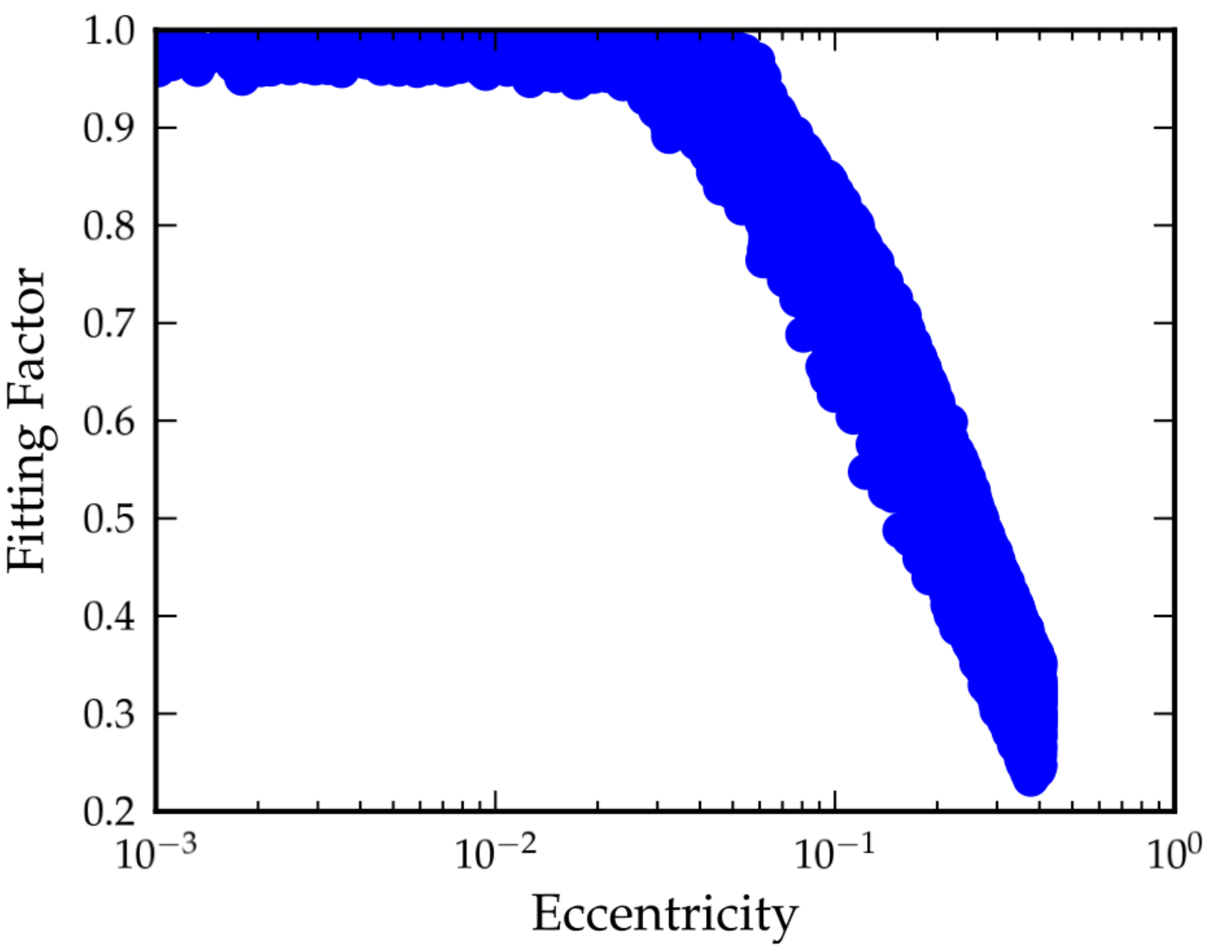


Tai et al 2014

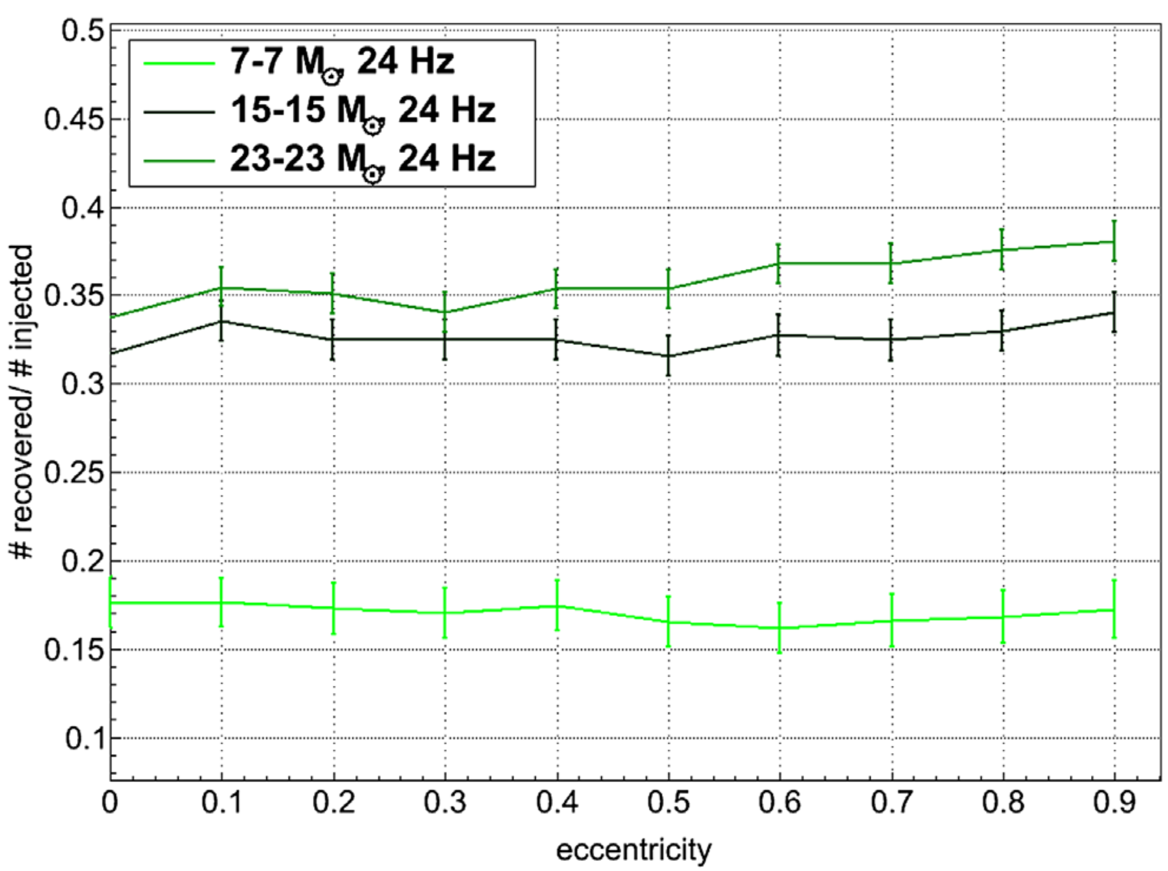
Impact of eccentricity on searches

- Rules of thumb:
  - Binary highly circular, unless large eccentricity at fmin
  - Small phase deviations can be captured by search templates
  - Large eccentricity … work in progress [Tai et al 1403.7754, Tiwari et al 2016 PRD, Thrane & Coughlin; Abbott et al 2019; …]

Huerta and Brown (1301.1895) templates
[neutron stars, e0 at 15 Hz in aLIGO]



Tiwari et al PRD 2016 burst search
[O2, e0 at 24 Hz]



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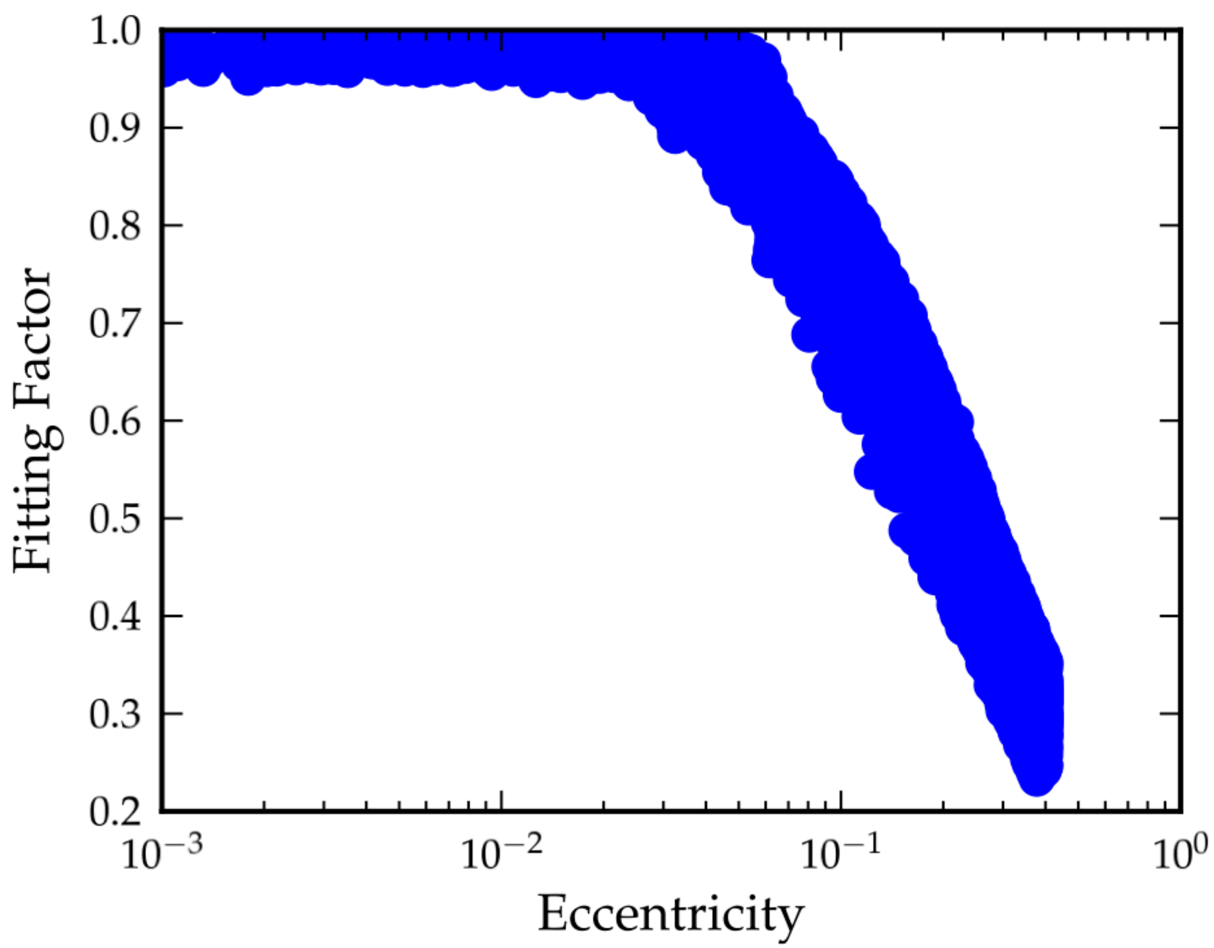
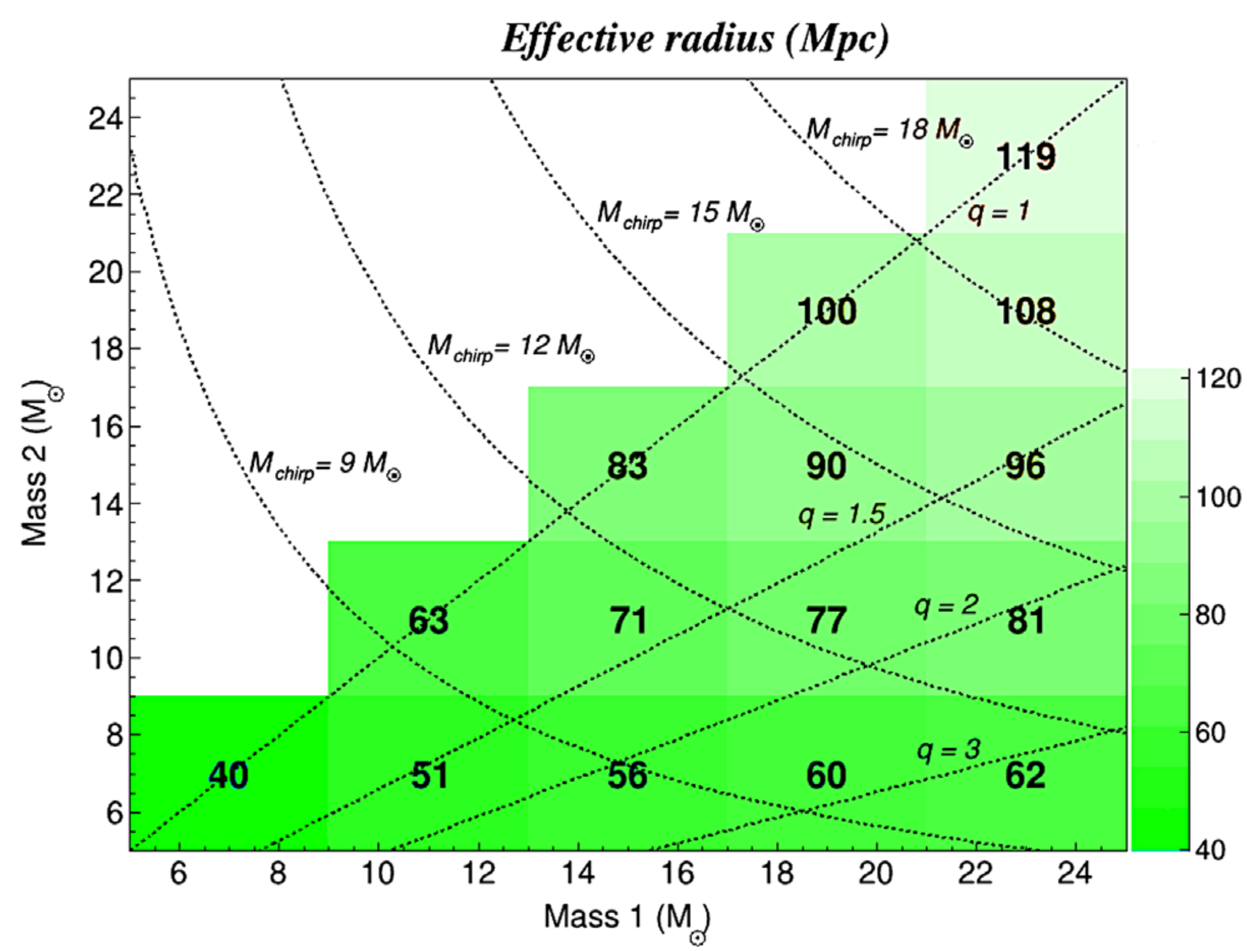
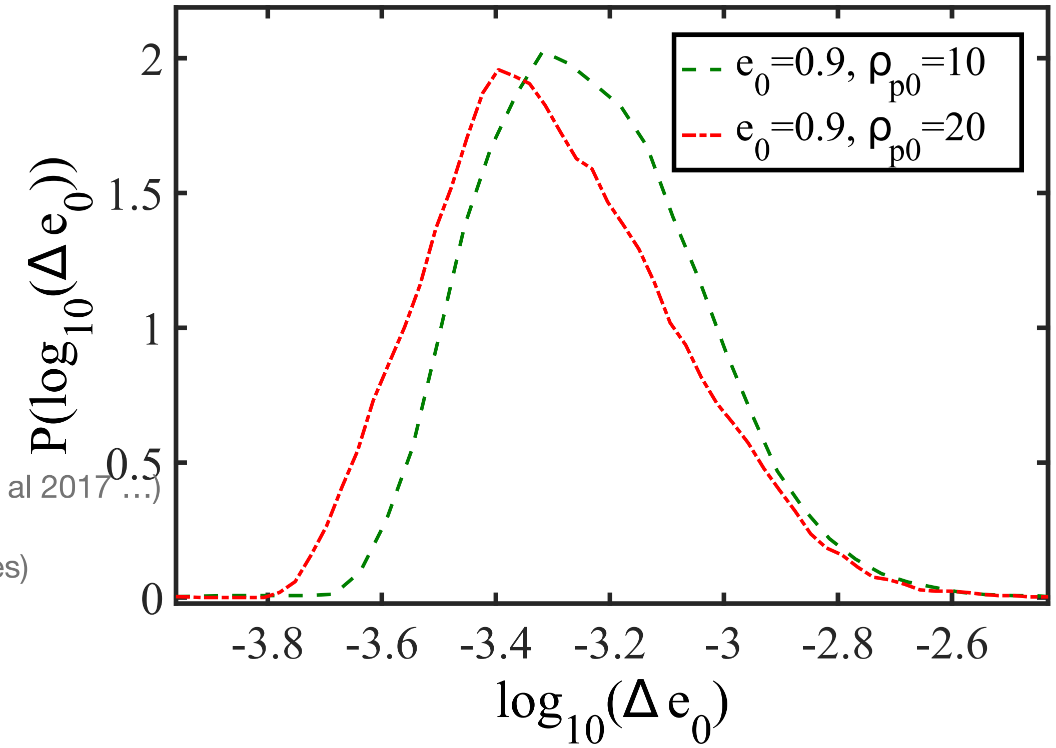


Tiwari et al PRD 2016 burst search [O2]



Accessing eccentricity?

- **Eccentricity decreases rapidly, but we can form ~ in band**
  - Eccentricity and precession usually expected simultaneously (ouch!)
- Modest eccentricity: **Very accessible observationally (LIGO)**
  - Example (Lower et al 2018): GW150914-like event, full eccentric PE .. e>0.05 fine!
  - Example (George/Huerta, PhysLett B 2018): Machine learning for point estimates
  - Example (Gondan et al ApJ 2018): Fisher estimate (below), for high-SNR systems
    - This case: d=100 Mpc , 30+30 Msun,
    - Using inspiral-only model
      - similar to “phase-connected bursts”



- See also previous mismatch and PE studies (e.g., J. Henry 2014; Sun et al 2015; Ma et al 2017 …)
- Measurement accuracy explored thoroughly in LISA context (e.g., Cornish/Lang/Hughes)

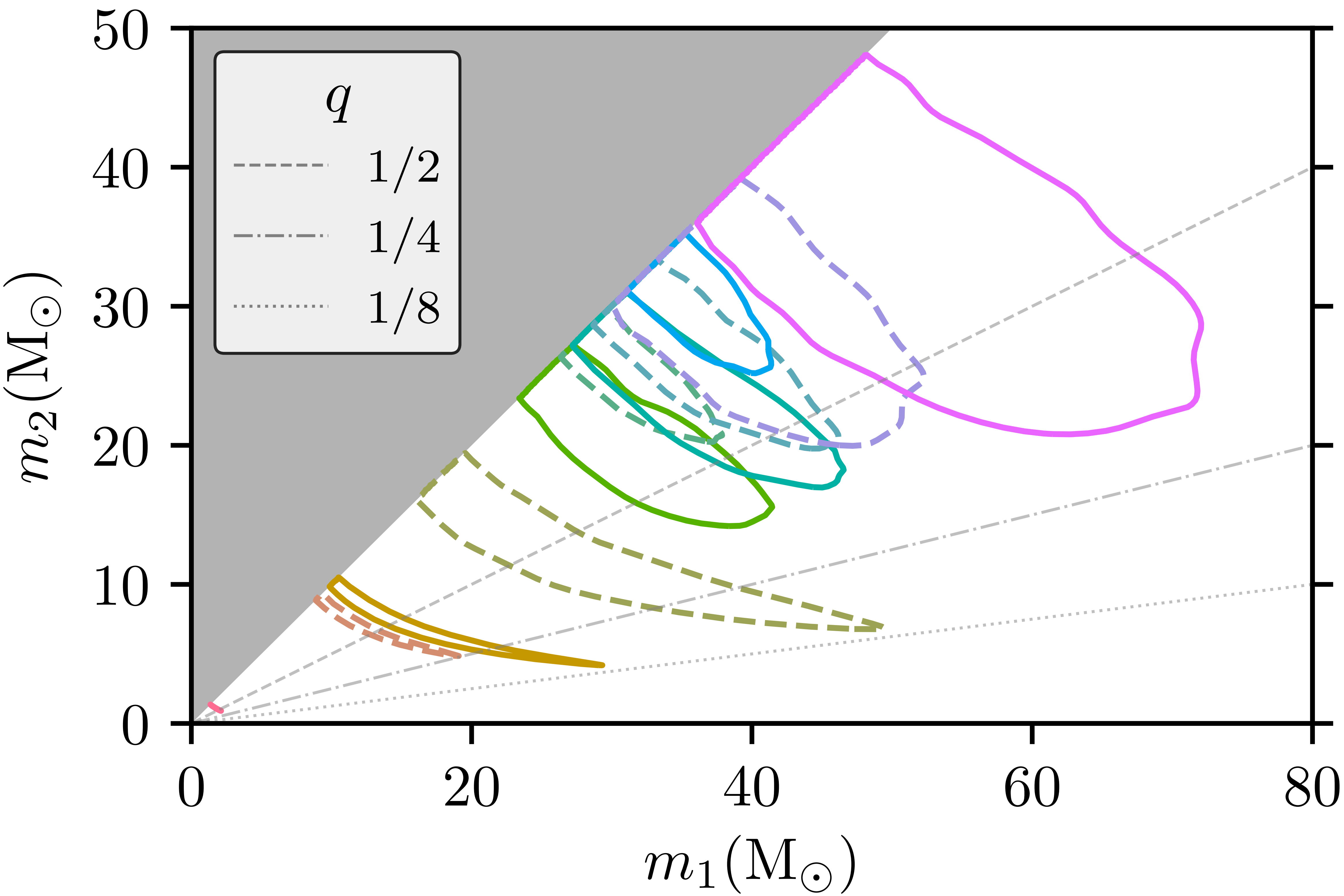
- Main limitation: Reliable models (for search or training) for **massive BBH**
  - **…in progress** (e.g., NCSA group and others)

Part 2: Contribution from AGN disks

McKernan, Ford, ROS, Wysocki 2019 (1907.04356)

Yang, Bartos et al (1906.09281)

Mass & event rate: where we are now



Abbott et al 1811.12907

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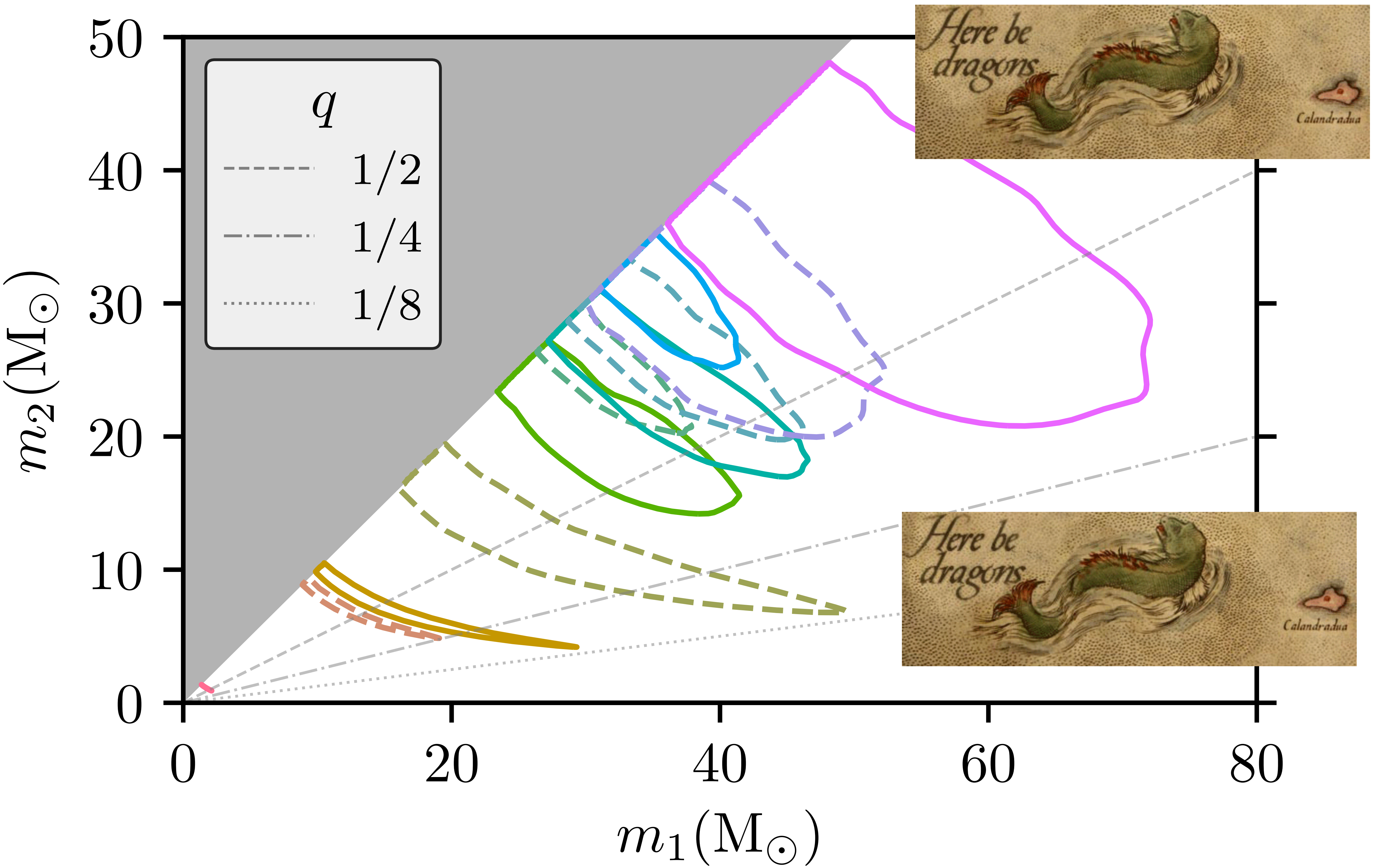


Abbott et al 1811.12907

…but where did they come from?

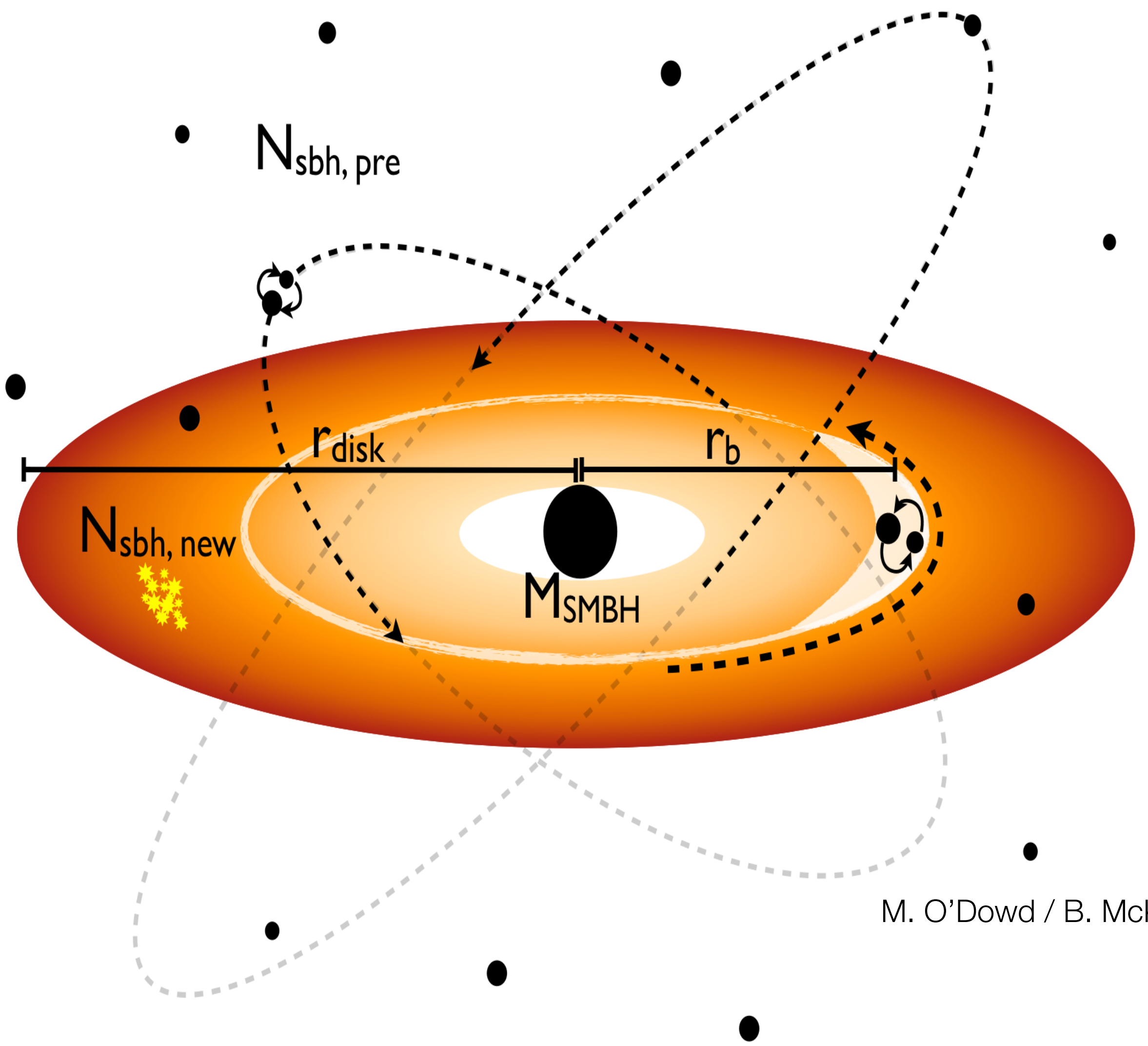
- Conventional [cluster,field], or
- Primordial?
- **Near supermassive BHs?**

brief but **efficient** mechanism

McKernan 2012,2014; Bartos 2017,McKernan 2018, Secunda 2018 …

See also **McKernan, Ford, ROS, Wysocki 2019 (1907.04356)**

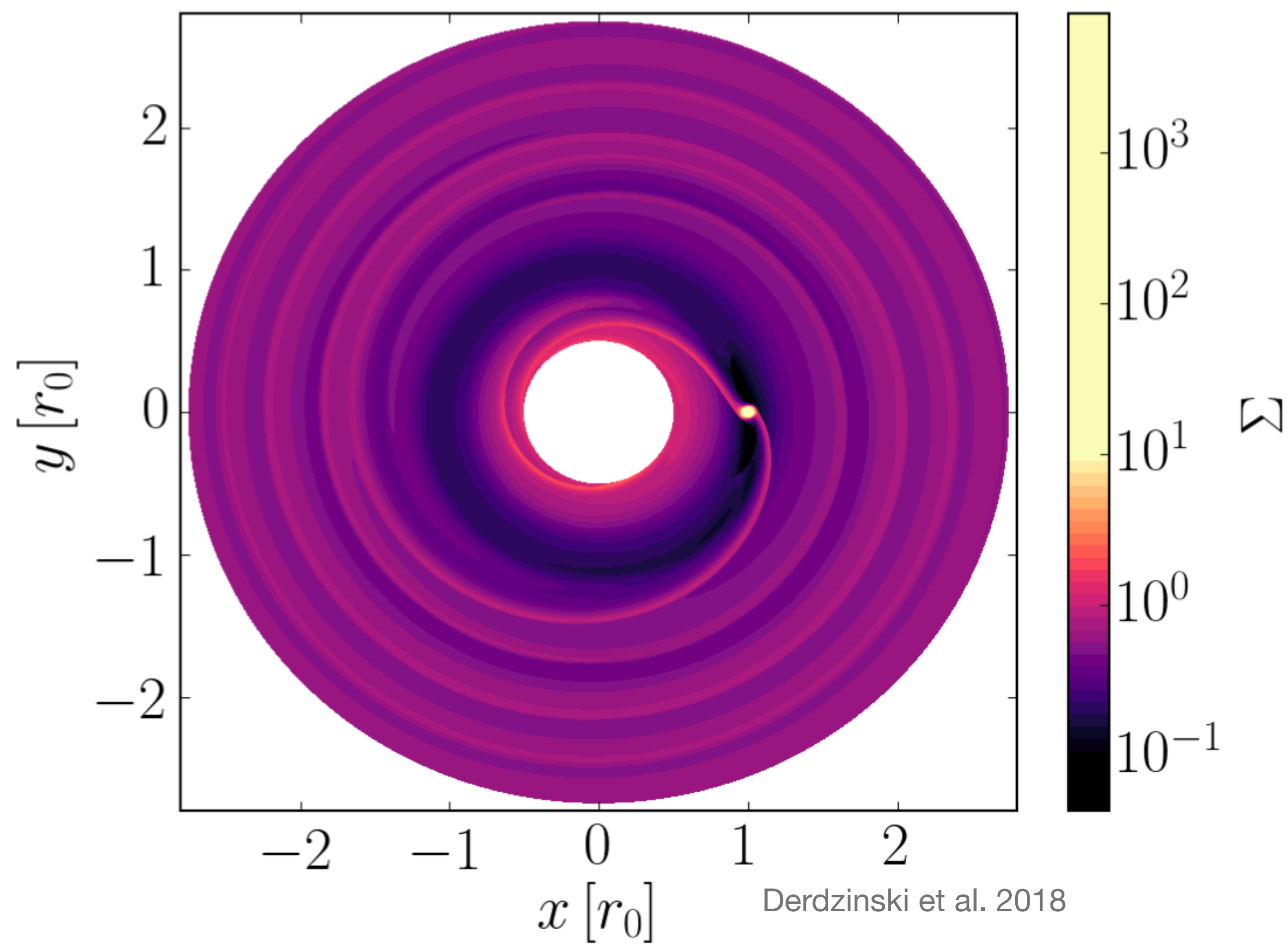
- …outliers and exotic products as signatures?



M. O'Dowd / B. McKiernan

AGN disks: making high mass & high-q binaries

- Many BHs near galactic nucleus
- During active phase, disk can capture them … brief but **efficient**
- BHs migrate through the disk
  - Bigger go faster
  - “Migration trap” ~ 100 M: balanced torques Bellovary et al 2016

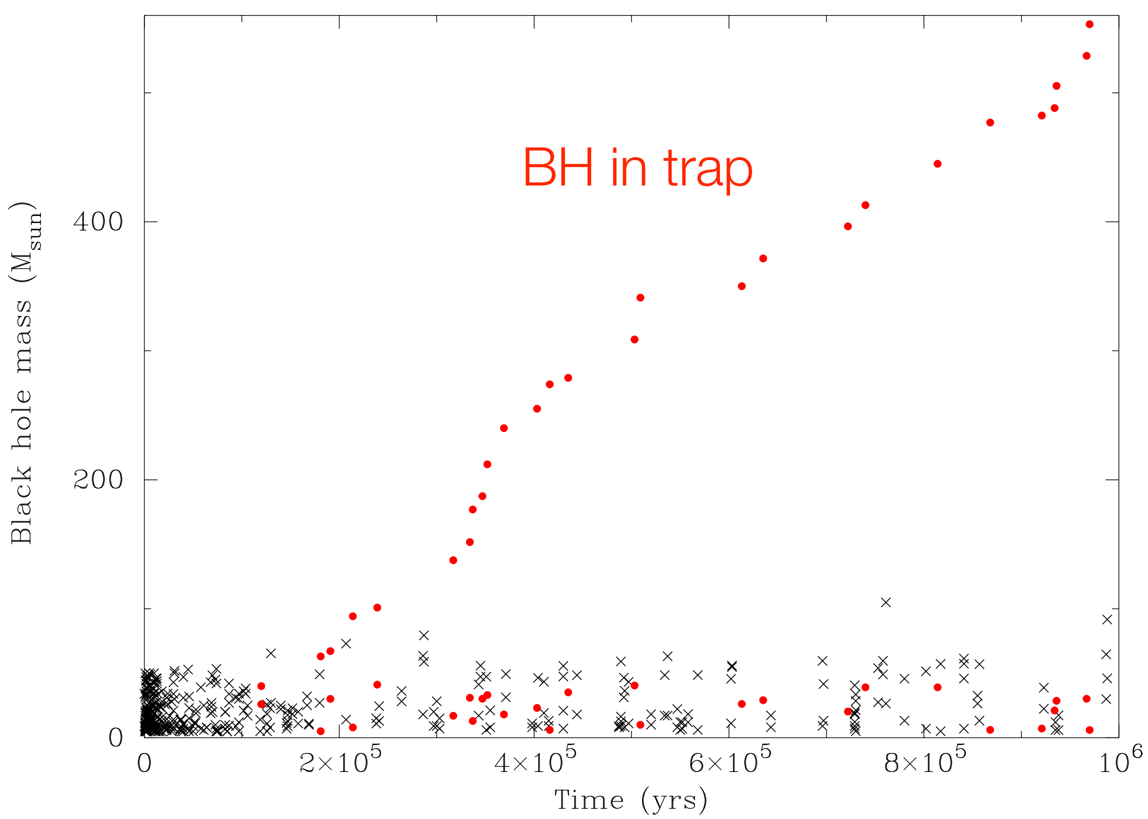


Derdzinski et al. 2018

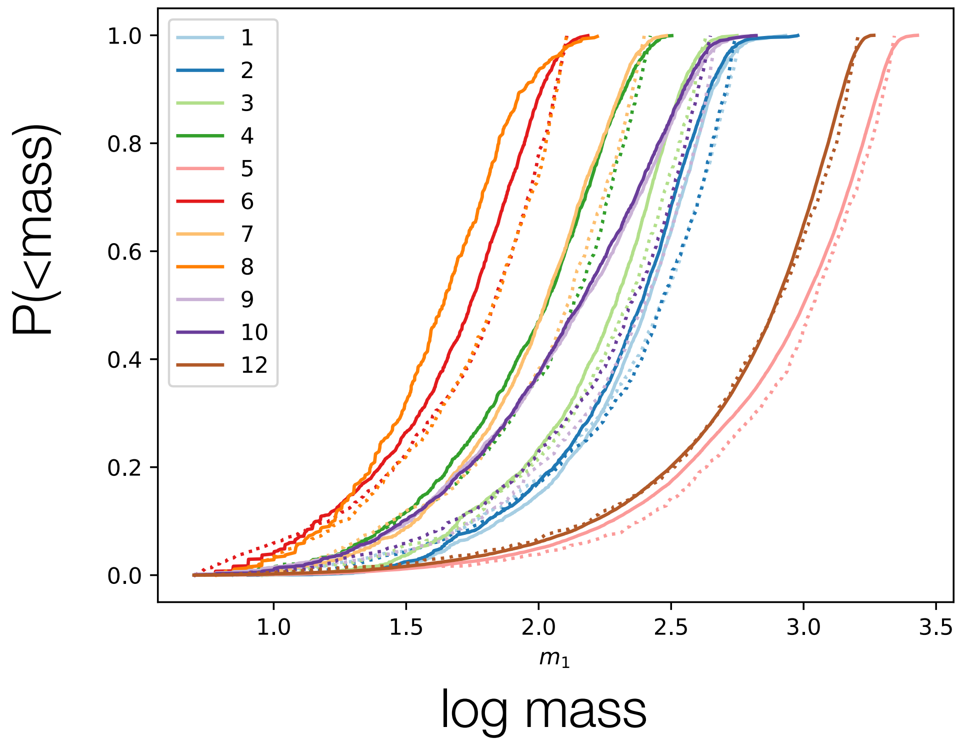
With migration and “grind-in” : high-q, high-M

- Simulate this a lot, see what masses/spins of BBHs form, how often, & why
  - Two-component phenomenology (time-averaged): “trap” and bulk
    - Trap: Builds up ~ **O(1)** IMBH at a time, linearly

BHs in mergers

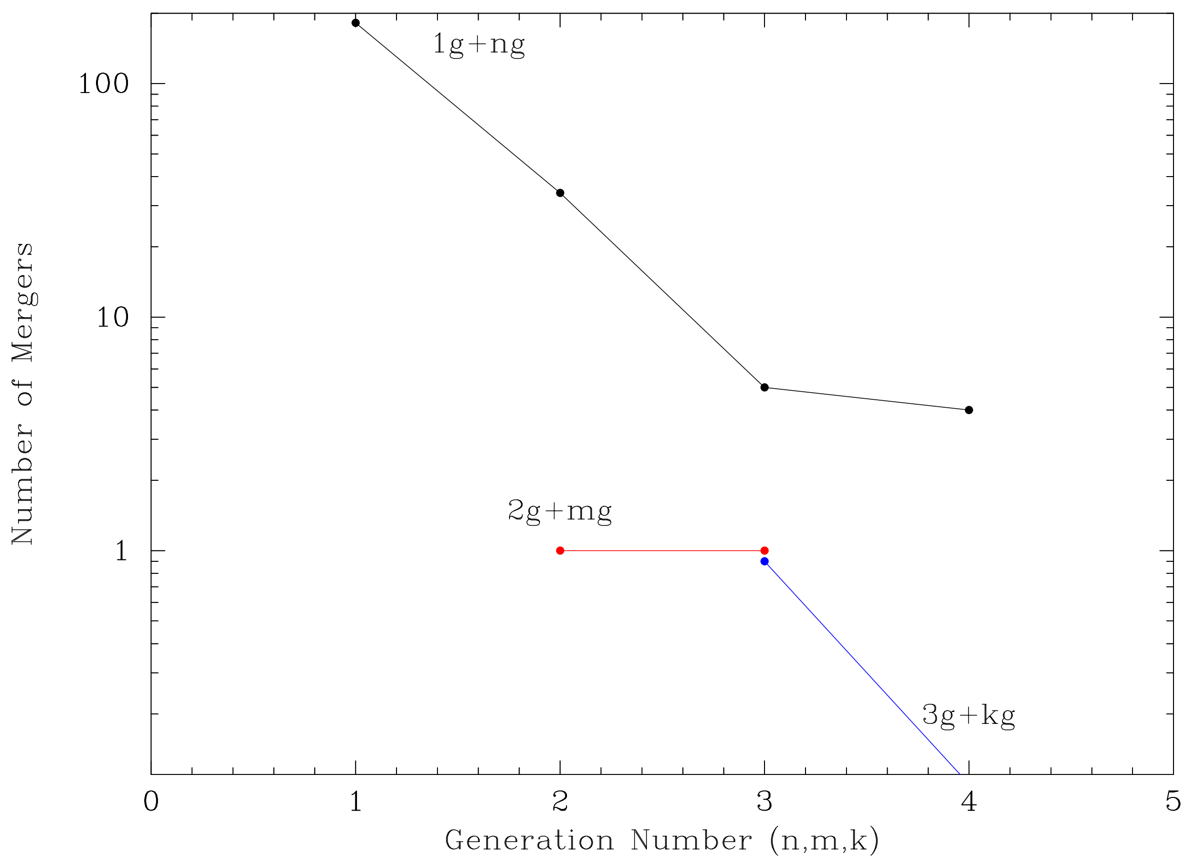


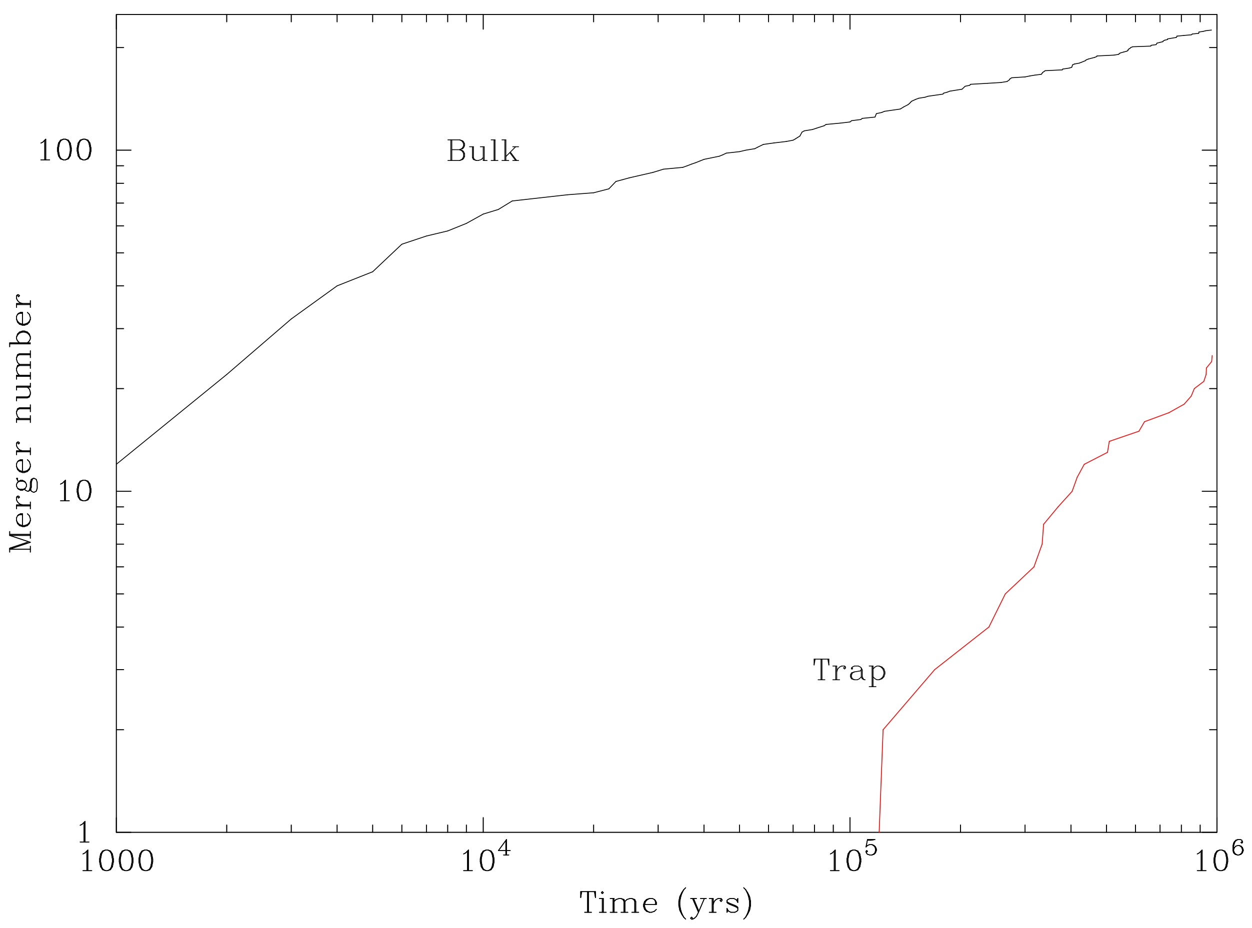
Largest BH in mergers, in trap



AGN disk growth of BHs

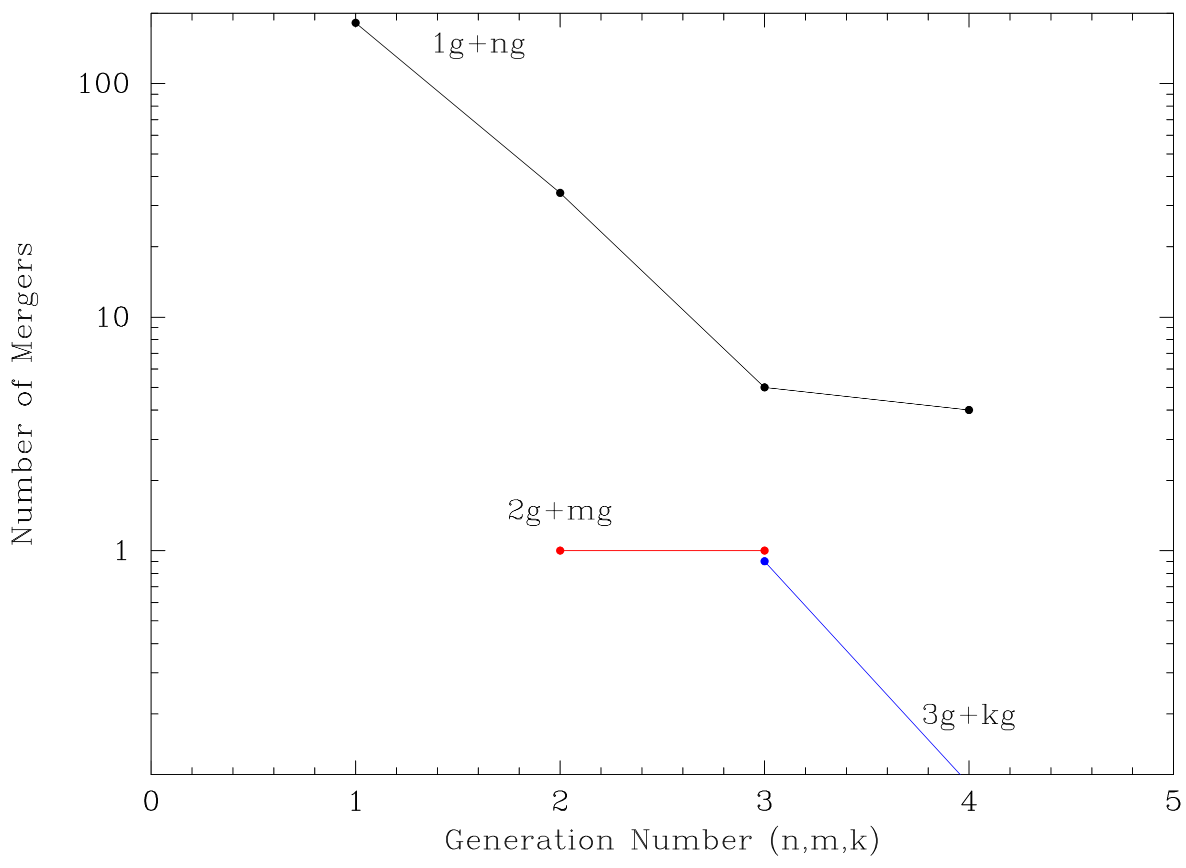
- Most mergers in “bulk”, similar to input population
  - Build up (hierarchical) IMBHs

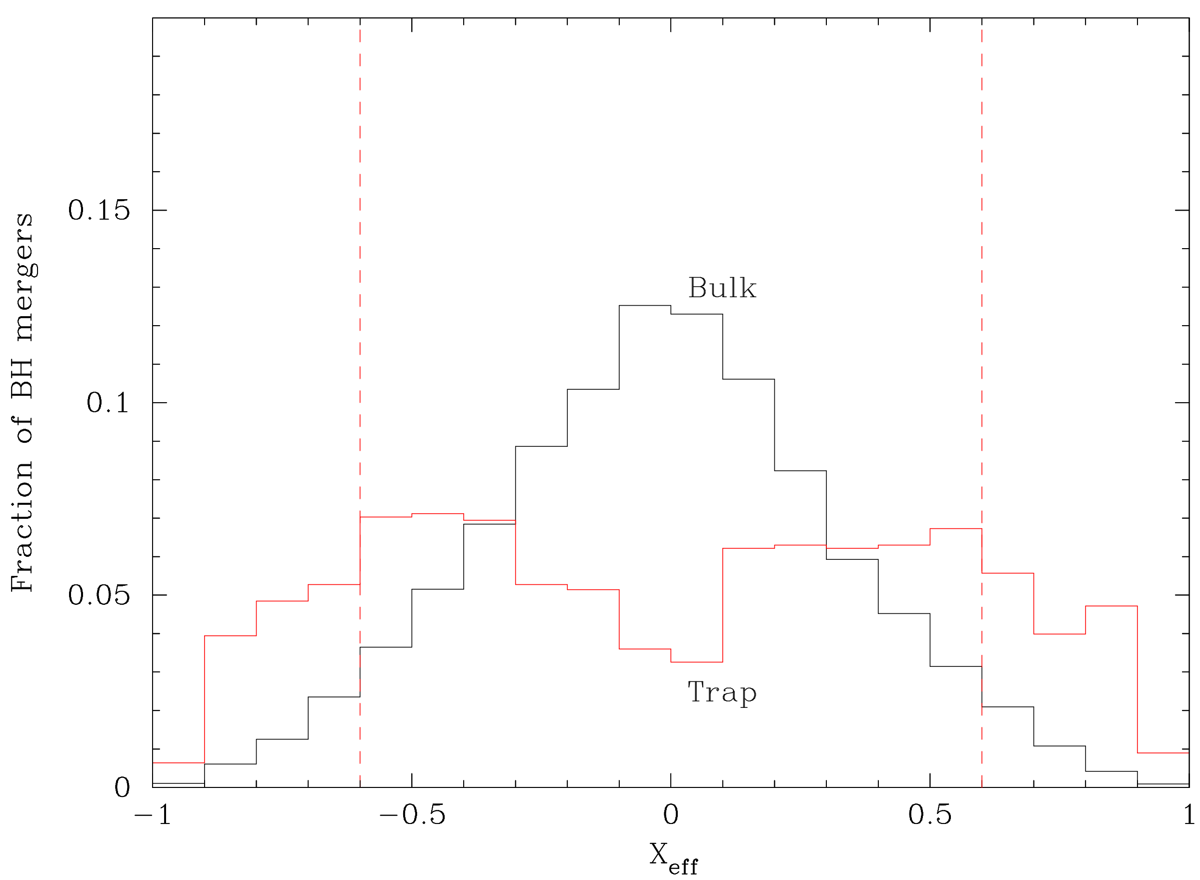




AGN disk growth of BHs

- Most mergers in “bulk”, similar to input population
- Hierarchical spins (χ_{eff}) are bimodal





Some context: Rates?

- Examples of recent estimates: McKernan ApJ 2018; Stone et al 2017 MNRAS; Ford & McKernan 2019
- "AGN" volume density: $10^{-3}\mathrm{Mpc}^{-3}$
  - Best estimate: Current galaxy/SMBH density $2\times 10^{-5} M_\odot/\,\mathrm{Mpc}^3$ mod lifetime/duty cycle: ~
    [X-ray bg (Cowie et al 2003, …); X-ray selected AGN surveys; cosmo sims matching AGN LF (e.g., Hirschmann 2013)]. Rate vs redshift similar to SFR (/1000)
- Integrated disk masses: Very large — lazy estimate

$$\dot{M}_{\rm edd}\tau_{AGN} \simeq 2\times 10^6 M_\odot \frac{\tau}{10\mathrm{Myr}}\frac{M}{10^8 M_\odot}$$

  - Expect many BHs formed in flow [e.g., Stone et al 2017] …implies **lower limit** on BH merger rate
  - Disk strongly impacts BH binary formation, evolution [migration, binaries]

- Many BHs near SMBH due to mass segregation / cusp [e.g., our GC ~ 10^4 , review Amaro-Seoane et al 2007]
  - Accretion flow & stellar dynamics advect/segregate BHs into AGN disk
    - Must also get "ground" into disk plane [e.g., McKernan et al 2014 and refs therein]
  - Assume O(1000) BH initially, O(100/Myr) advected

Some context: Rates?

- Examples of recent estimates: **McKernan ApJ 2018;** Stone et al 2017 MNRAS; Ford & McKernan 2019

$$\mathcal{R} \simeq n_{gn} \frac{(N_{bh} f_d) f_{\rm AGN} f_b}{\tau_{\rm AGN}}$$

$$\simeq 10^3 \frac{N_{bh} f_d}{10^4} \frac{10 Myr}{\tau_{\rm AGN}} f_{\rm AGN} f_b$$

simplified version of McKernan 2018

$f_{\rm AGN}$ fraction of GN that are merger sites

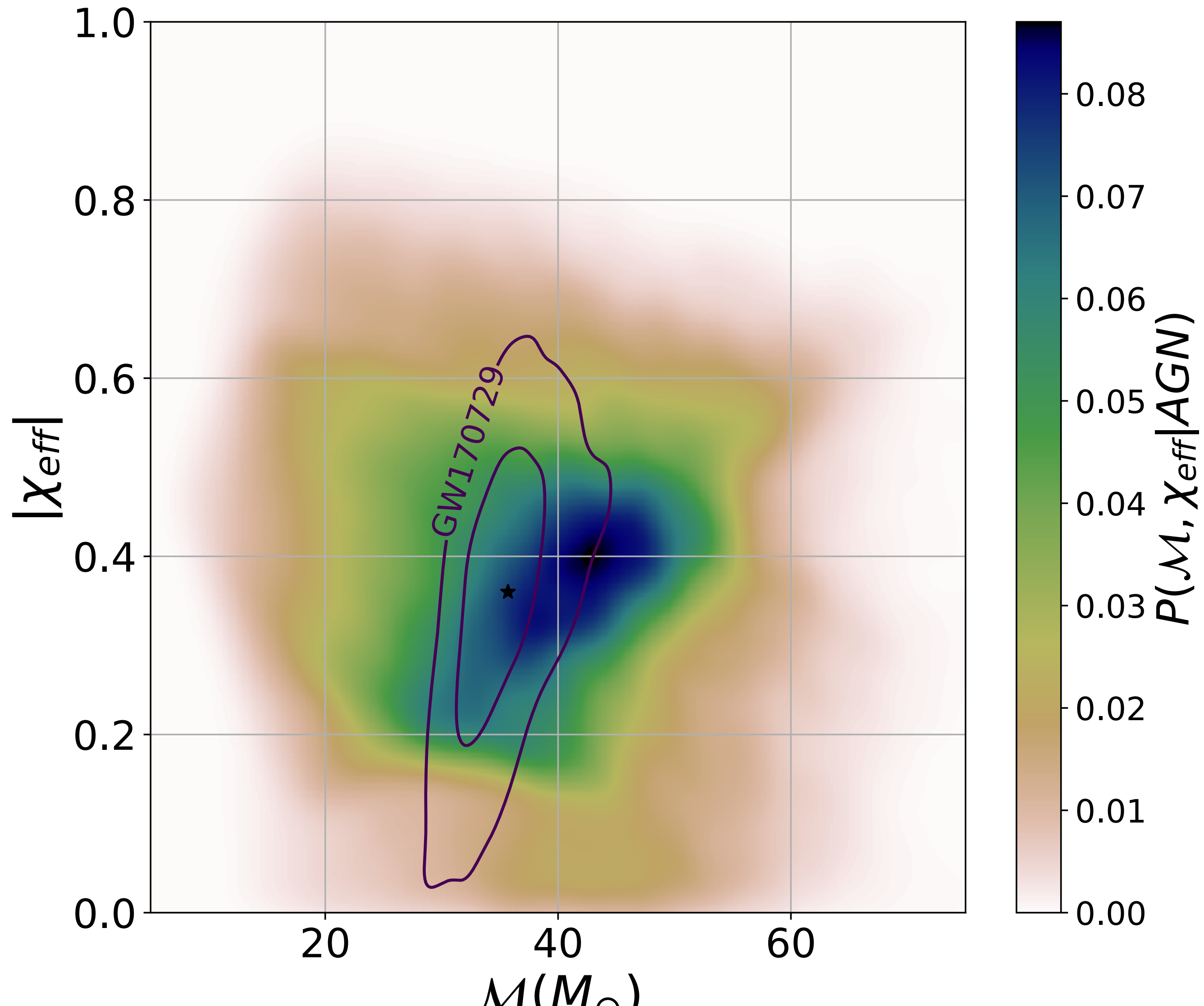
f_b fraction of BHs that form binaries (some left behind,…)

$N_{bh} f_b$ number of BH that enter disk

Comparing with observations?

- Consistent with spin, q for 170729,   given a plausible seed population (BF ~ 1)
- Similarly: No compelling evidence favoring a hierarchical scenario in some earlier work
  (without, with HM : Kimball et al arxiv:1903.07813 Chatziouannou et al 1903.06742)

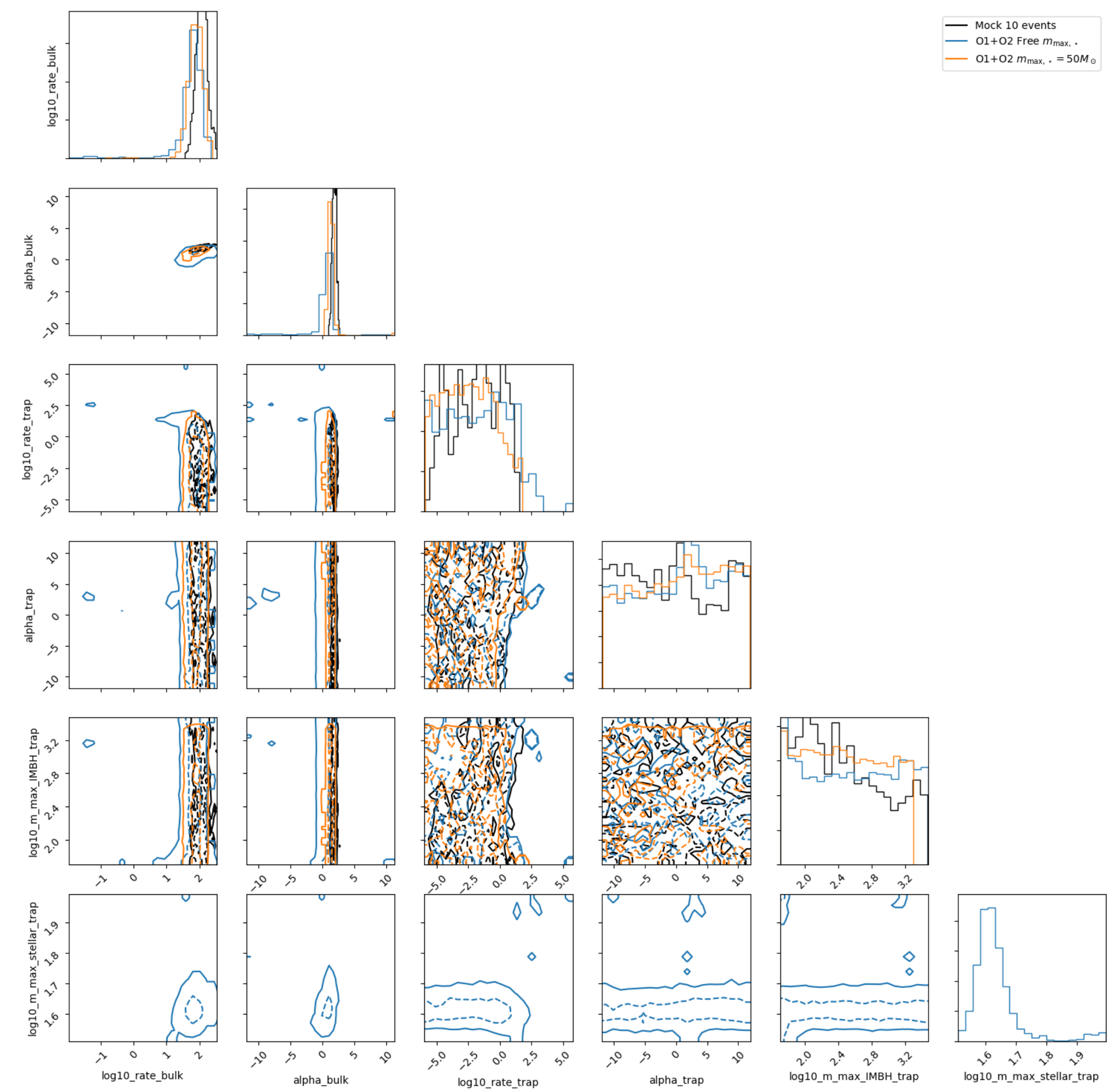
Yang et al 2019
(color scale shows hierarchical contribution *only*)



Comparing with observations?

- AGN constraints are **already interesting**
  - Limits parameter space of possible AGN e.g., Ford & McKernan 2019
- Example: Merger rate limits from AGN disk model (real data & simulated O3, assuming no “trap” signatures)

Model	R_{trap}		α_{trap}		R_{bulk}		α_{bulk}	
Fixed	0.00	10.82	-10.56	10.92	32.19	167.09	0.59	1.85
Free	0.00	161.14	-10.72	10.84	7.50	143.26	-3.37	1.60



Bonus slides

- Run parameter table

Run	N_{BH}	N_{gr} (/Myr)	γ	M_{Lower} ($M_\odot$)	M_{Upper} ($M_\odot$)	τ_{AGN} (Myr)	a	trap (r_g)	disk	t_-/t_+
R1	869	10^2	1	5	50	1	u	$700r_g$	SG	5
R2	869	10^2	1	5	50	1	u	$700r_g$	SG	1
R3	100	10^2	1	5	50	1	u	$700r_g$	SG	5
R4	851	10^2	2	5	50	1	u	$700r_g$	SG	5
R5	851	10^2	2	5	50	5	u	$700r_g$	SG	5
R6	851	10^2	2	5	15	1	u	$700r_g$	SG	5
R7	851	10^2	2	5	50	1	(1-a)	$700r_g$	SG	5
R8	851	0	2	5	50	1	u	$700r_g$	SG	5
R9	851	0	2	5	50	5	u	$700r_g$	SG	5
R10	851	0	2	5	50	5	u	$700r_g$	SG	1
R11	851	10^2	2	5	50	1	u	none	SG	5
R12	851	10^2	2	5	50	1	u	$500r_g$	TQM	5