(Ground-based) Gravitational wave astronomy and compact objects in clusters

(an attempt to provoke discussion, by)

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KITP globular cluster program

2009-03-19

Plan

- Birthrates of massive clusters?
- Merger mechanisms, rates?
  - IMBH-IMBH
  - BH-BH (clusters)
  - BH-BH (field “contamination”)

- GW as cluster constraints?
  - Rates?
  - Mass distributions?
  - Spin, eccentricity?
  - Sky positions?

Birthrates of massive clusters?

Observed GC

$$M \simeq 10^{5.5}$$
$$n_{cl} \simeq 3/Mpc^3$$

PZ and McMillan

Total SFR

$$\dot\rho(t_{now}) \simeq 0.01 M_\odot/Mpc^3$$
$$\rho_o \equiv \int \dot\rho dt$$
$$\simeq \frac{1}{0.55}\Omega_* \rho_c \simeq 5\times 10^8 M_\odot/Mpc^3$$
$$\simeq 10^3 \times \rho_{GC}$$

Nagamine et al

SFR in clusters?

Are all stars formed in clusters? 20% 10% ….. ?

SFR in massive clusters?

- MF evolves [e.g.,Gieles talk]
- p(M)~ M^{-2} --> equal mass per logarithmic bin
  --> significant SFR into rare, massive clusters

Fractions

- g_{cl}: fraction of SFR-> cluster
- g : clusters that form IMBH
- g_{evap}: clusters that segregate fast

IMBH-IMBH mergers

Mechanism

- IMBHs via runaway
  - Mass $M_{IMBH} = M_{cl}/500$
  - Binary?

Talks:PZ, Umbreit

Gurkan 2004; Umbreit talk

- Segregate, bind

- Harden; binary decays fast

Effectively instantaneously

Fregeau et al astro-ph/0605732
Freitag et al astro-ph/0610478v1

IMBH-IMBH mergers

Rates (aLIGO)

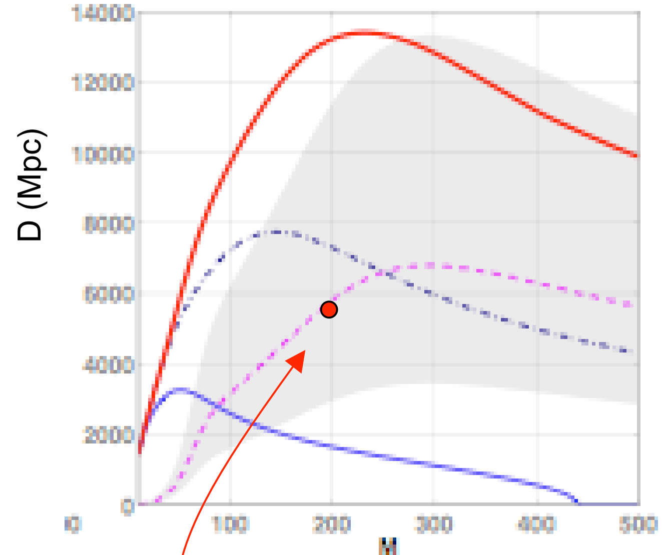
<u>Simple</u>:

- g_{cl}: fraction of SFR-> clusters
- g : clusters that form IMBH
- $\dot M_{D<D_c}$: star formation rate on past light cone inside D

$$R_D \simeq g_{cl} g \frac{\dot M_{D<D(200 M_\odot)}}{10^5 M_\odot}$$

ringdown: $R_D \simeq 10\mathrm{yr}^{-1}(g_{cl}/0.1)(g/0.1)$

full NR: ....



aLIGO horizon range
Ajith, 0710.2335

Fregeau et al
only ringdown

<u>Details</u>:

Cluster MF ~ M^{-2} (included in Fregeau et al; increases result)

Beampattern, network (not included; slight increase)

Mass ratio distribution (not included; decreases: R ~ q^3 : less E_{rad}. But)

(others: higher harmonics, realistic search issues, …)

BH-BH (clusters)

Mechanism (simple)

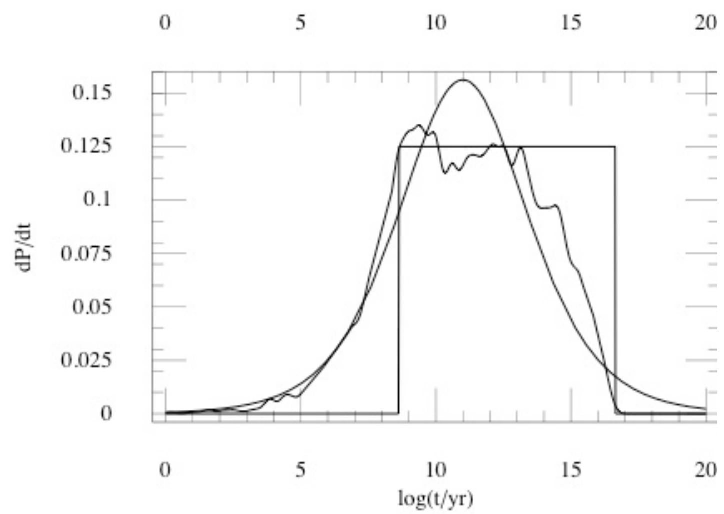
- Massive clusters $M>3x10^4$
  - Significant fraction of all cluster mass
  - Numerous massive BH per cluster
  - BHs segregate, decouple
    - assume ~instantly, efficiently after SN
  - BH-BH binaries ejected

$$N_{bh} \simeq 3 \times 10^{-3} M_{cl}/M_{\odot}$$

$$M_{bh} \simeq 10 - 25 M_{\odot}$$

$$N_{\rm bin} \approx 0.07 N_{\rm bh}$$

- Ejected binaries
  - Hot, broad spread of energies ($10^{3.5\text{-}4.5}$kT)
  - Broad spread of merger delays
    (~1/t decay of rate/cluster)
  - Significant fraction merges (O(50%), mod v_{cl})
  - Old, young SFR contribute!
    - Ok if restricted to early or recent universe



O'Leary et al astro-ph/0508224

PZ and McMillan ApJ 528 L17

BH-BH (clusters)

Rate (simple)

– Integrate over past star formation

$$R_{\rm evap} \simeq 0.8 g_{cl} g_{evap} {\rm Mpc}^{-3}{\rm Myr}^{-1}$$

– Network rate (aLIGO, 2 ifo)

$$R_D \simeq 1{\rm yr}^{-1}\left(\frac{D_{bns,1IFO}}{190{\rm Mpc}}\right)^3\left(\frac{m_{bh}}{20M_\odot}\right)^{15/6}\frac{g_{cl}}{0.1}\frac{g_{evap}}{10^{-3}}$$

minimum consistent with present density

Related (nuclear star clusters: Cole)

$$R \simeq 10^{-3}{\rm Mpc}^{-3}{\rm Myr}^{-1}$$

– Higher ‘v’ (30-60 km/s); faster mergers ?

Miller and Lauberg

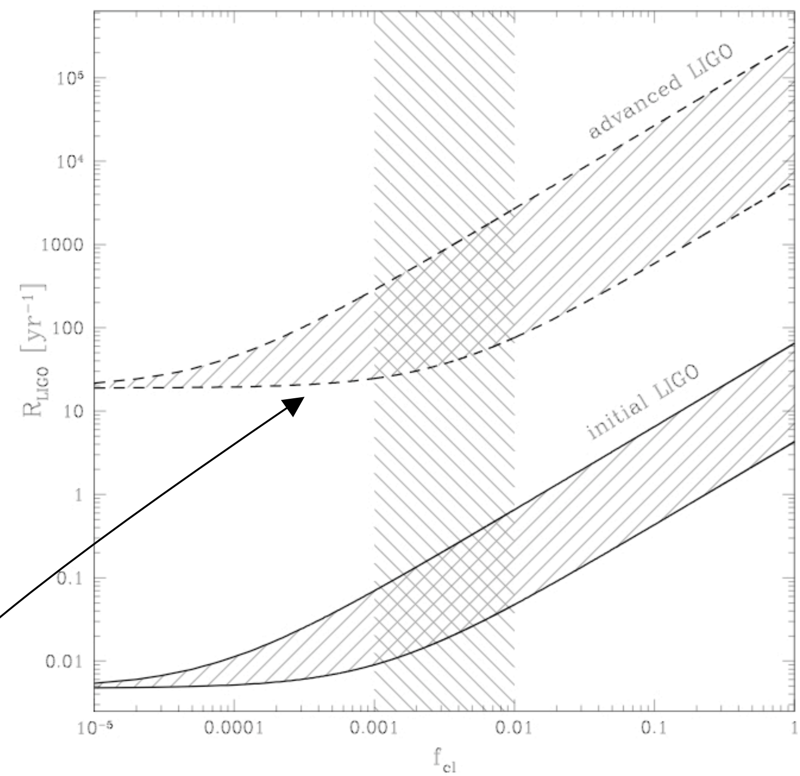
BH-BH (clusters)

Mechanism : clusters+ single,binary evolution

- Assume BHs mixed
- Many interactions before merger
- Steady rate (~ 3/Gyr/5x10^5 M$_\odot$, or)

$$\frac{dN}{dtdM} \simeq 6 \times 10^{-9}/\mathrm{Myr}\,M_\odot$$

- Small rapid component



$$R_D \simeq \frac{\mathrm{dN}}{\mathrm{dtdM}} \times (10\mathrm{Gyr}) \times (0.01\mathrm{M}_\odot/\mathrm{Mpc}^3\mathrm{Myr}) \times \mathrm{V_{detect}}$$

$$\simeq 20\mathrm{yr}^{-1}\frac{g_{cl}}{10^{-3}}(m_{bh}/20M_\odot)^{15/6}$$

Ivanova et al 0706.4096, 0501131
Sadowski et al 0710.0878
+ talks in this workshop….

BH-BH (clusters)

Mechanism : Galactic nuclei (w/ SMBH)

- As GC
  - Bigger (10^7) but one per galaxy
- Larger velocity
  - Shorter merger time ($t \sim a^4 \sim v^{-8}$; v~60-70 km/s vs 10 km/s)
- Capture into very eccentric orbits
  - More eccentricity preserved in LIGO band
- Scaling ~ independent of SMBH mass (M-v conspiracy?)

Rates

- Optimistic interpretation (Cole - assumes unlikely density effect; x30 too high)

$$R \simeq 8 \times 10^{-10} \mathrm{yr}^{-1}/\mathrm{Mpc}^3$$

$$R_D \simeq 17 \mathrm{yr}^{-1} \left(\frac{D_{bns}}{190 Mpc}\right)^3 \left(\frac{m_{bh}}{20 M_\odot}\right)^{15/6}$$

<u>Extras</u>:

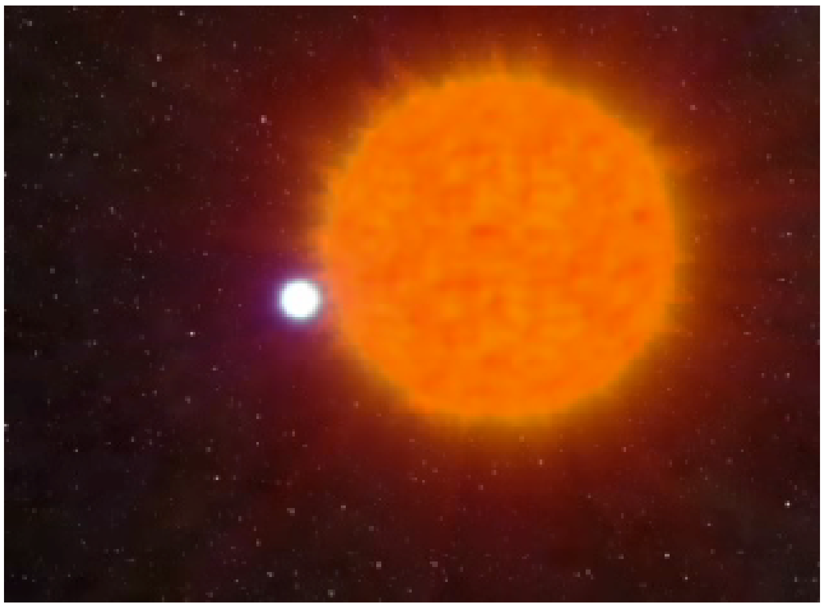
- MF near nucleus could be biased

O'Leary et al 0807.2638

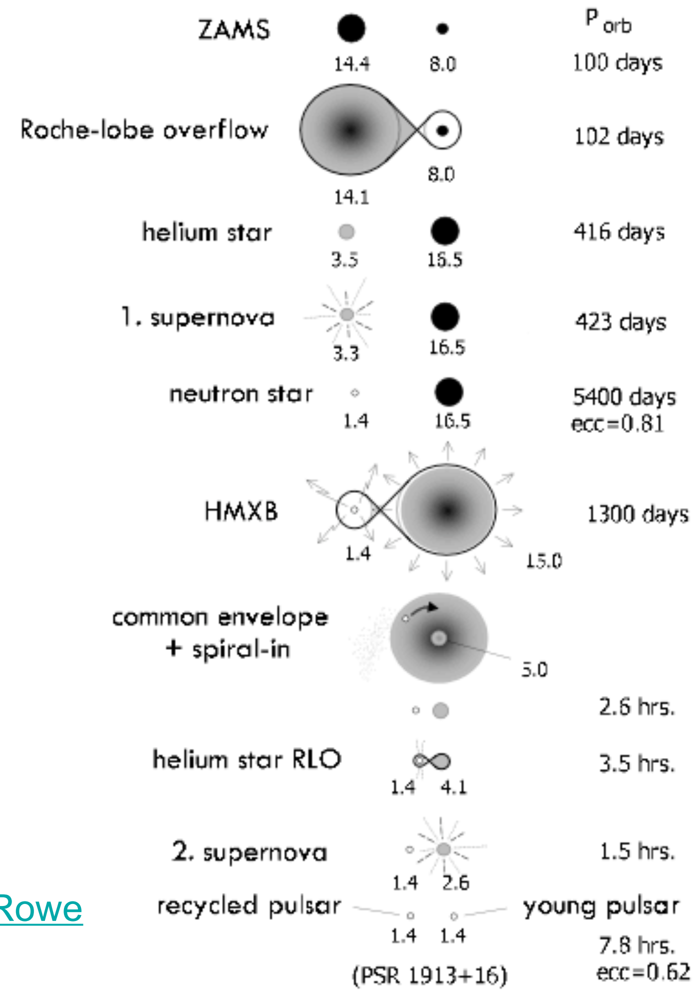
BH-BH (field "contamination")

Mechanism

- Isolated binary evolution
  [many talks here: EvdH]



Movie: John Rowe

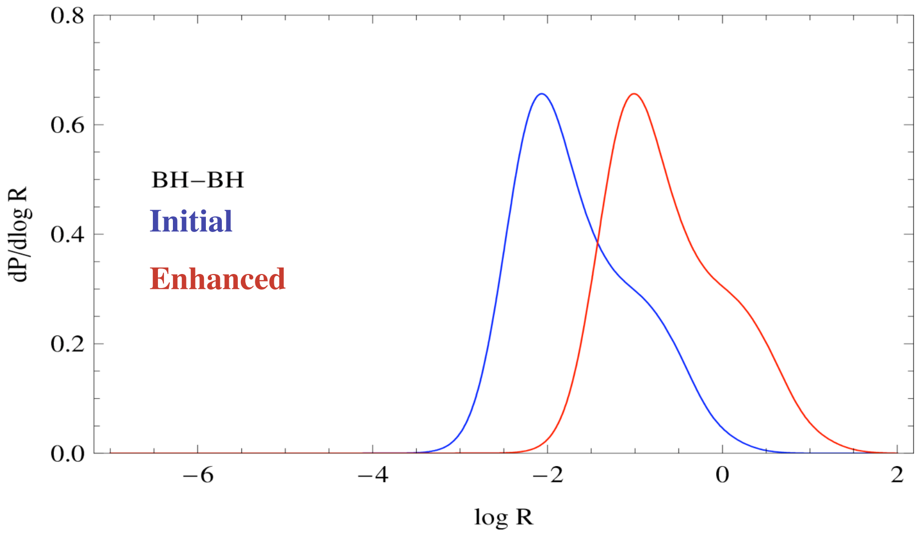


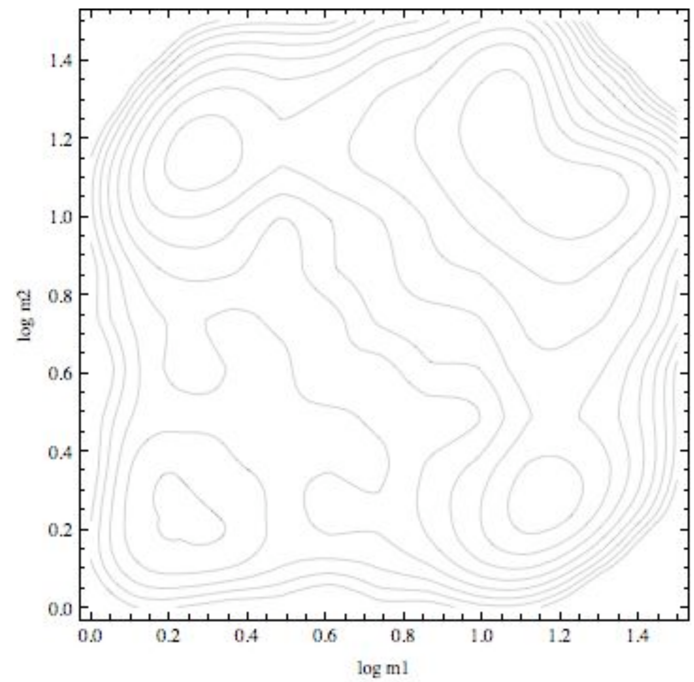
Voss and Tauris 2003

BH-BH (field "contamination")

Rates

- Few-O(1000)/yr





…may be higher, w/ more high-mass BH

(low metallicity over-represented)

O'Shaughnessy et al in prep

Scorecard

IMBH-IMBH

Cluster: z~ few source; SFR on light cone

GW: Circular; random(?) spins

Merger, ringdown waves

BH-BH from GC

Cluster: z<1 source; SFR on, off light cone

GW: ~circular, random spins

Inspiral, merger waves

BH-BH from nuclear clusters

Cluster: z<1 source; SFR off light cone

GW: Highly eccentric, random spins (GW dectection: ouch!)

Cluster observations with GW?

Rule of thumb:

$$\delta X/X \simeq O(1)/\rho$$

Real calculation:
Van der Sluys et al 0710.1897

$a=0.5, \Theta=20^{o}$

Table (SNR 17, 2-detector)

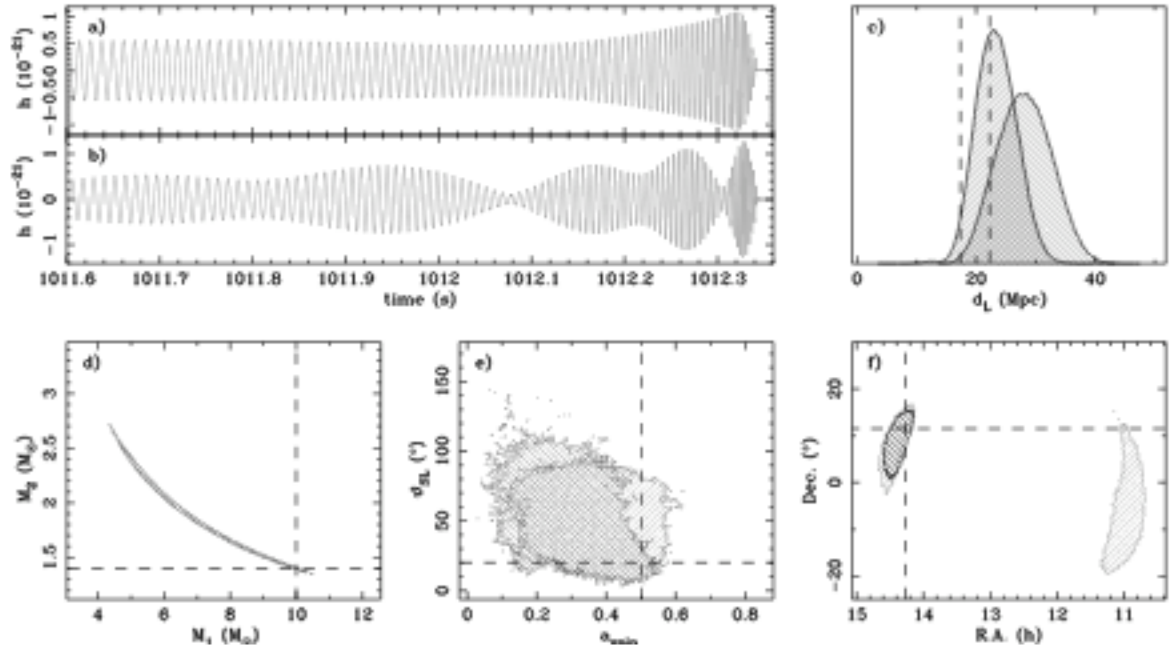


TABLE I
INJECTION DETAILS AND WIDTHS OF THE 90%-PROBABILITY INTERVALS OF THE MCMC RUNS DESCRIBED IN THE TEXT

n_{det}	a_{spin}	θ_{SL} (°)	d_L (Mpc)	M_1 (%)	M_2 (%)	$\mathcal{M}$ (%)	η (%)	t_c (ms)	d_L (%)	a_{spin}	θ_{SL} (°)	ϕ_c (°)	α_c (°)	Pos. ($°^2$)	Ori. ($°^2$)
2	0.0	0	16.0	95	83	2.6	138	18	86	0.63	—	323	—	537	19095
2	0.1	20	16.4	102	85	1.2	90	10	91	0.91	169	324	326[a]	406	16653
2	0.1	55	16.7	51	38	0.88	59	7.9	58	0.32	115	322	326	212	3749
2	0.5	20	17.4	53[b]	42[a]	0.90	50[b]	5.4	46[a]	0.26	56	330	301[b]	111[a]	3467[a]
2	0.5	55	17.3	31	24	0.62	41	4.9	21	0.12	24	323	269[a]	19.8	178[a]
2	0.8	20	17.9	54[a]	42[a]	0.86[a]	54[a]	6.0	56	0.16	25[a]	325	319	104[a]	1540
2	0.8	55	17.9	21	16	0.66	29	4.7	22	0.15	15	320	323	22.8	182[a]

Roever et al gr-qc/0609131
Cutler and Flanagan
Van den Broeck and Sengupta
Bose and Ajith 0901.4936

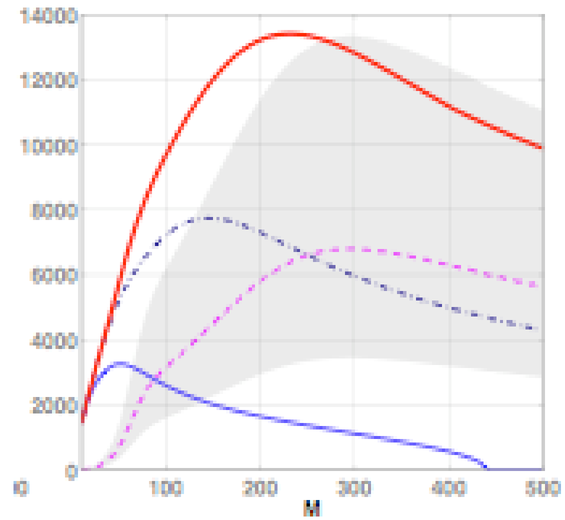
Cluster observations with GW?

Rates

- Probably degenerate

Mass distribution?

- Measurables:
  - Chirp mass accurate
  - Mass ratio: harder (few cycles)

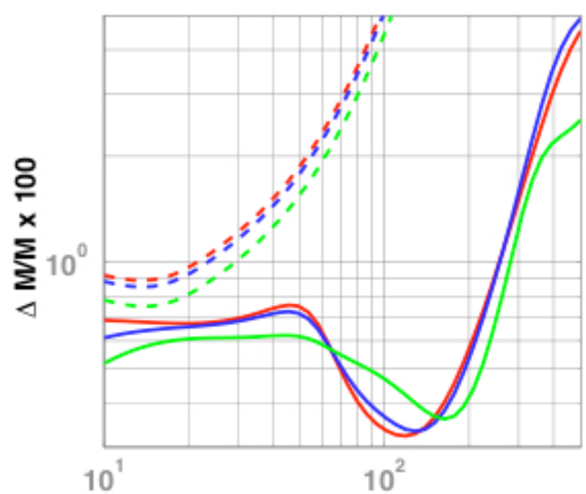


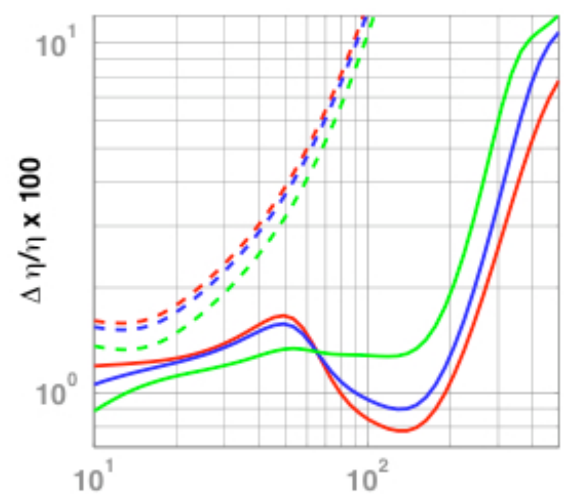
Example:

- Binary at 1Gpc

- SNR increases w/ mass
  until ~ 200 Msun

Bose and Ajith 0901.4936





Application 1: Ideal IMBH

M~200; D~ 12Gpc

dM/M ~ few*1%

deta/eta ~ few*10%

[cosmology not included]

Cluster observations with LIGO?

Spin?

- Tricky for M>15+15
  - short waveform (few cycles)
- Strong degeneracies; change with mass
- Alignment/nonalignment test:
  - Inutition: yes
  - Possible: ? NR simulations…

Sky positions

- Galaxy cluster-scale identification?
  - …marginal…

Cluster observations with LIGO?

Eccentricity?

- Noticable effect expected
  - “dissimilar” to circular search templates

- Problem: Templates lacking
  - eccentricity + random spin?
  - High-ish mass??

Tessmer and Gopakumar
Cokelear et al

Conclusions

- GW : unique probe of cluster evolution
- Plausible timeline
  - Upper-limit phase: (< 2015?)
    - Rates: rule out extreme models
  - Detection phase: (>2015?)
    - Low mass: distinguish cluster, field fractions (mass, spins)
    - High mass: IMBH existence, alignment (?)
  - Third-generation detector phase: (>2020?)
    - Low mass:
      - Mass distribution vs redshift
      - High SNR: clear separation of spin, aligned + random population
    - High mass: test GR