Primordial Black Hole Dark Matter and the LIGO/Virgo observations

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Black Hole Formation in the early radiation dominated Universe: How and When

Cosmic Horizon Length: $r_H \simeq ct$

Schwarzschild radius: $r_s = \frac{2GM}{c^2}$

Critical Universe: $H_c^2 = \frac{1}{4t^2} = \frac{8\pi}{3} G\rho_c \to \rho_c = \frac{3}{32\pi G t^2}$

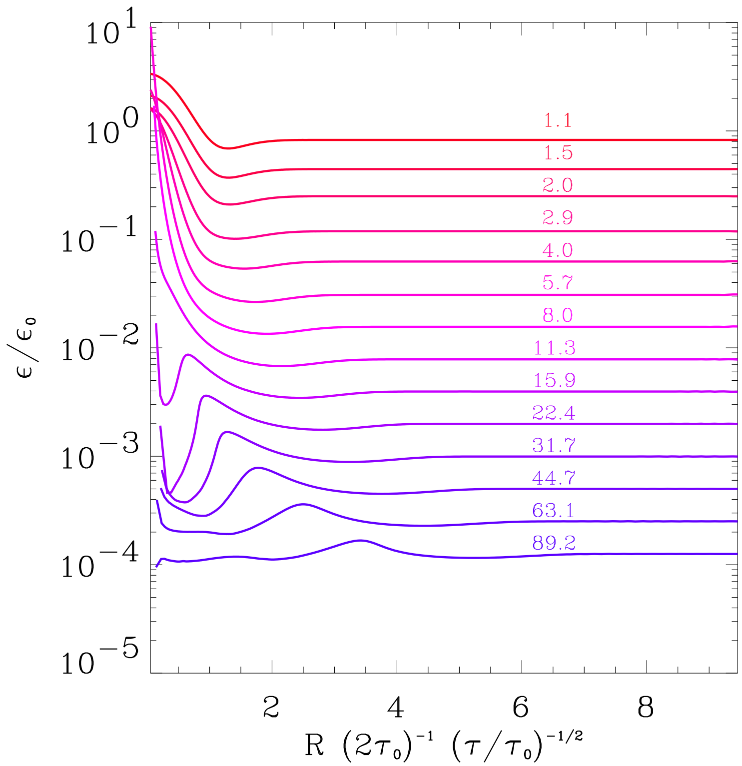
"Schwarzschild radius" in critical Universe: $r_S \simeq \frac{1}{16} ct$

Jeans length: $r_J \simeq c_S t$ with $c_S = \frac{1}{\sqrt{3}} c$

$\to$ an order unity energy fluctuation may form a black hole when entering into the horizon but collapse has to occur against pressure forces

Zel'dovich,Novikov,Hawking,Carr 67-75

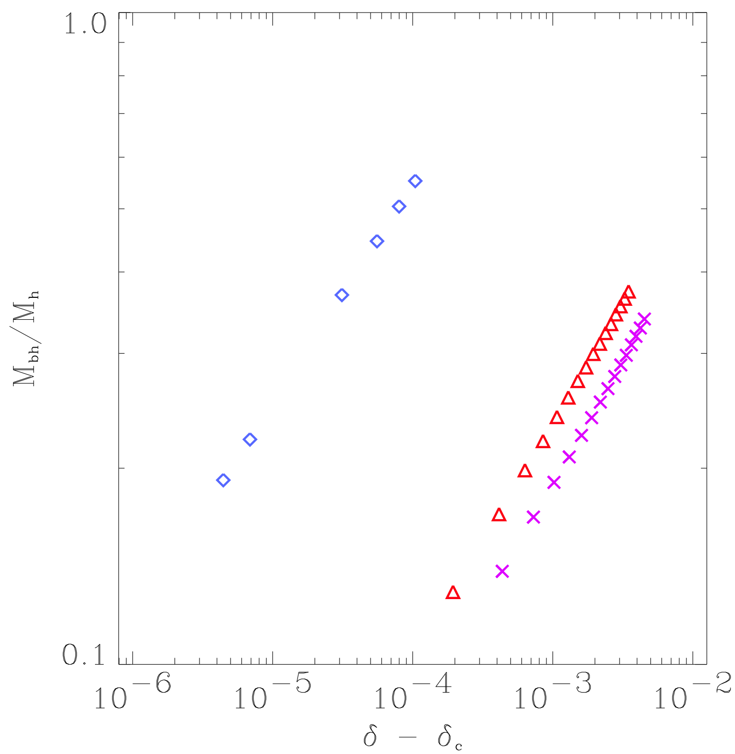
First Fully General Relativistic Simulations of Primordial Black Hole Formation



critical phenomena in GR:

$$M_{\rm pbh} = \kappa M_H (\delta - \delta_c)^{\gamma}$$

$\gamma \approx 0.36$ and $\delta_c \simeq 0.4 - 0.7$



Niemeyer & K.J 98,99

Production of PBHs during the QCD epoch → preferred mass scale

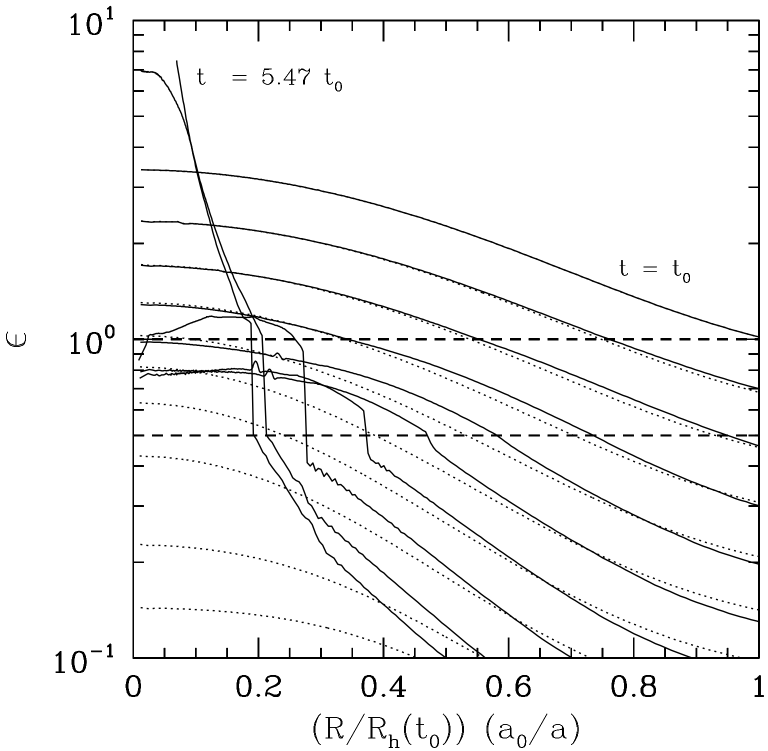
first order phase transition

$$c_S^2 = \frac{\partial p}{\partial \langle \rho \rangle} \simeq 0$$

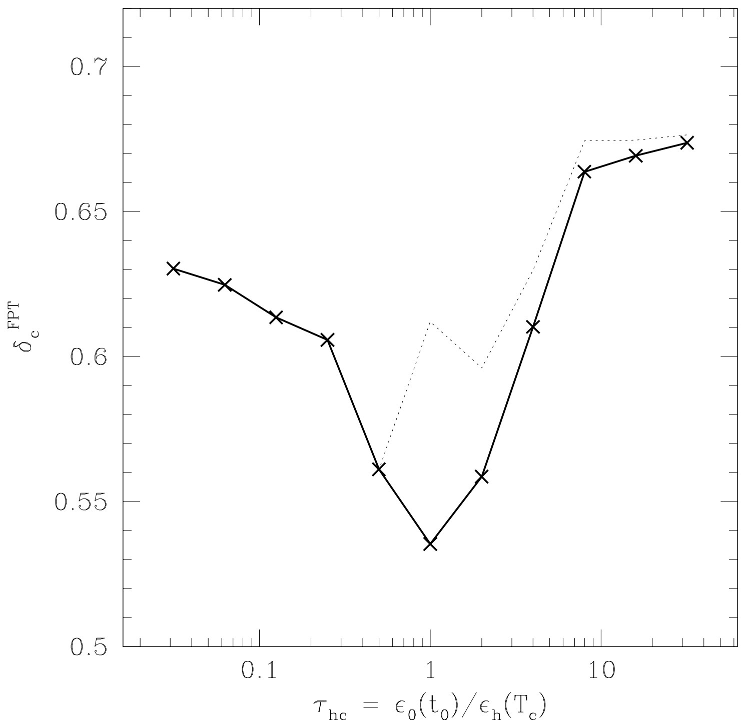
but similar temporary pressure drop during

→ higher order transitions

→ annihilation periods



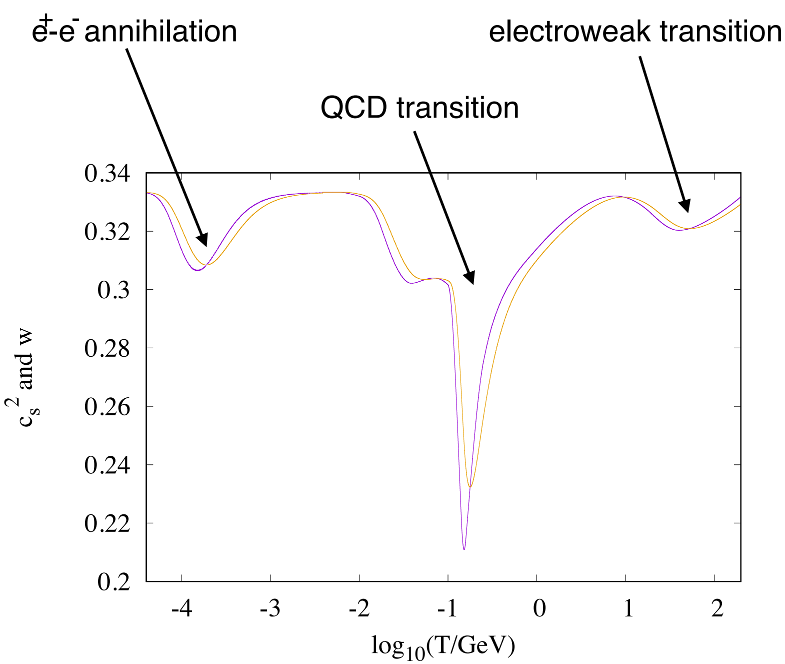
critical threshold for PBH formation



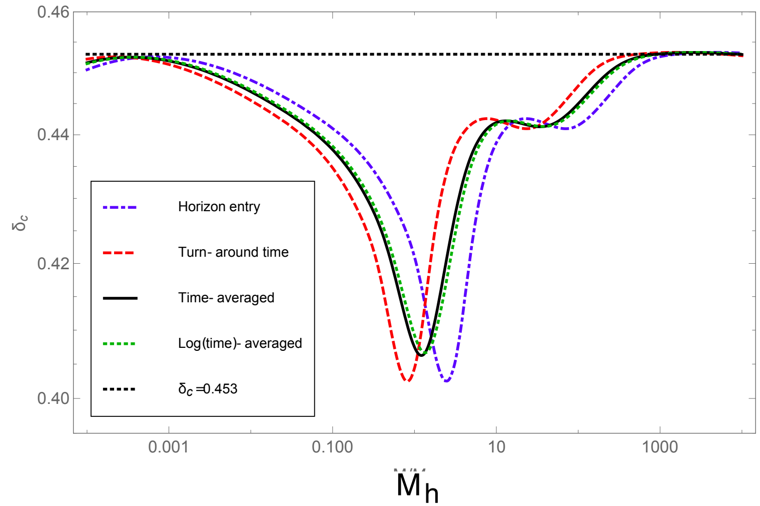
K.J. 97, K.J. & Niemeyer 99

The early Universe equation of state is by now known precisely below T< a few 100's GeV

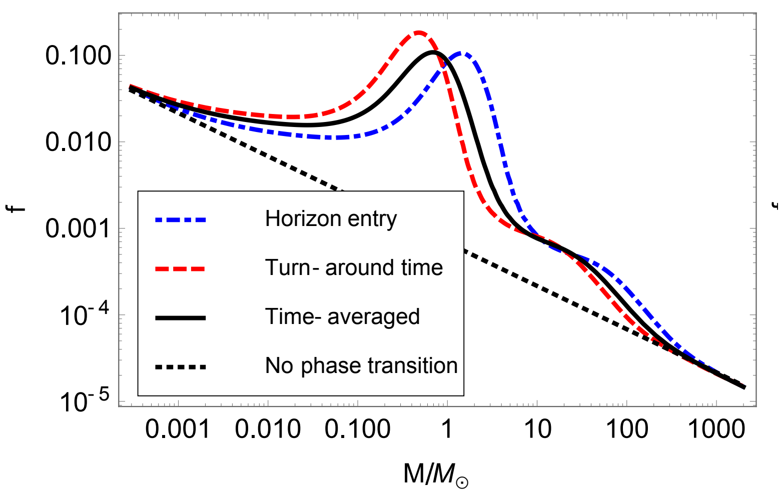
Borsanyi et al 16



critical threshold for PBH formation



PBH mass spectrum



Byrnes et al 18

PBHs are a perfect cold dark matter candidate

However, there are two subtle differences compared to particle dark matter

→ PBHs start there lifes at essentially zero peculiar velocity

→ the individual dark matter “particle” mass is large

Zero Pecuilar Velocities ⟶ Formation of very eccentric binaries

Nakamura et al 97

Sasaki et al 16

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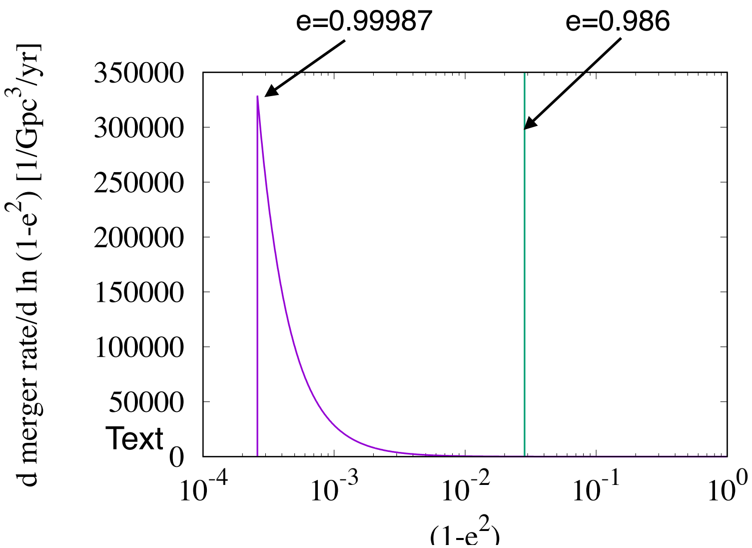
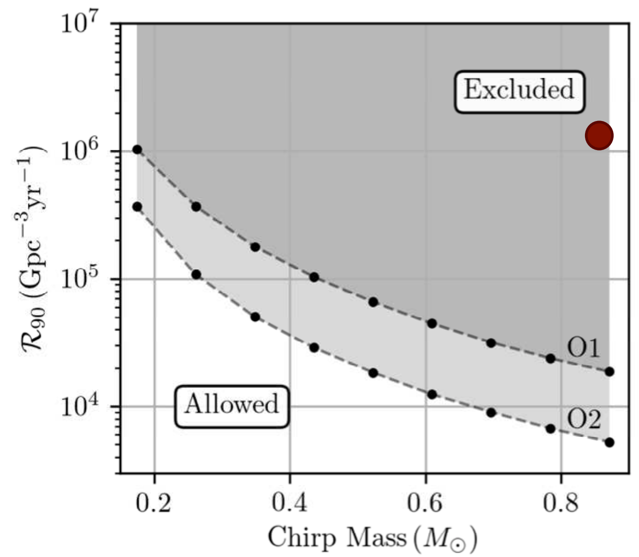


very "non-equilibrium" distribution

$$\frac{\mathrm{d}P_b}{\mathrm{d}a\mathrm{d}e} = \frac{3}{4}\frac{1}{\langle x\rangle^{3/2}}a^{1/2}\frac{e}{(1-e^2)^{3/2}}$$

$$t_{\rm coal} = \frac{3}{170}\frac{1}{GM_{\rm BH}^3}a^4(1-e^2)^{7/2}$$



$$t\frac{\mathrm{d}P_{\rm coal}}{\mathrm{d}t}(10\,{\rm Gyr}) \simeq$$

$$10^{-9}\int_0^{e_{\rm max}}\mathrm{d}e\frac{e}{\left(1-e^2\right)^{45/16}}$$

$e_{\rm max} \simeq 0.99987$ for $M_{BH} = 30\,M_\odot$

~30 solar mass PBH dark matter have a merger rate factor ~100 than LIGO/Virgo observes

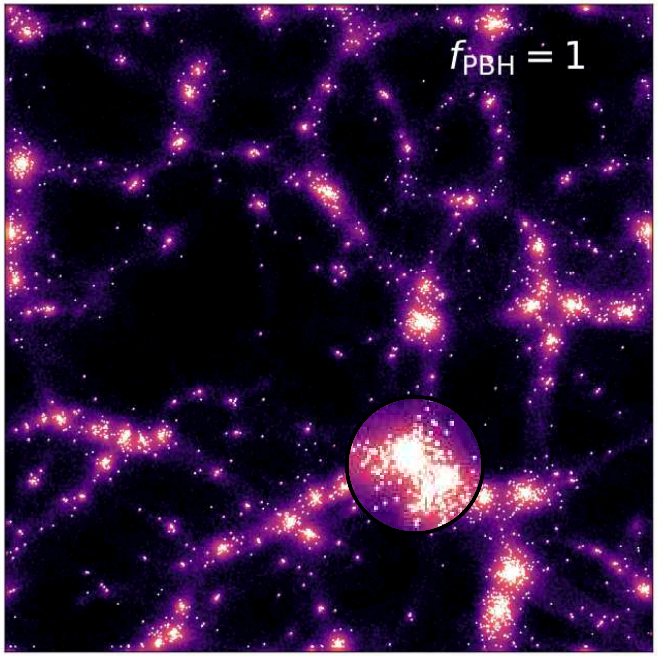
~1 or ~30 solar mass dark matter ruled out by LIGO/Virgo ?

Poisson fluctuations in the number of PBHs in a particular volume

→ Additional isocurvature density fluctuations

→ Formation of PBH clusters at very high redshifts

Inman & Ali-Hamoud 19



$$\delta(N) = \Delta N/N = 1/\sqrt{N}$$

$$D(a) \approx \left(1 + \frac{3}{2}\frac{a}{a_{eq}}\right)$$

$$D(a)\delta(N) \approx 1.68$$

$$n_{cl} \approx 1.6 \times 10^5 \frac{1}{\rm pc^3}\left(\frac{M_{pbh}}{M_\odot}\right)^{-1} N_{cl}^{-3/2}$$

However, PBH clusters evaporate later again

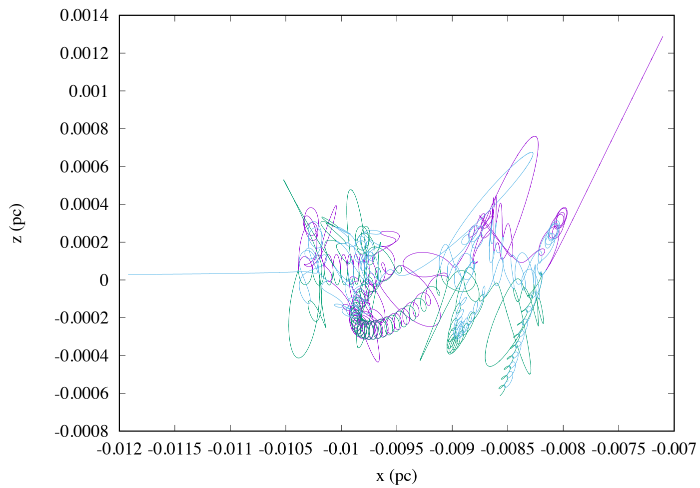
$$t_{evap} \approx 140 t_{relax} \approx 14 \frac{N_{cl}}{\ln N_{cl}} \frac{R_{cl}}{v_{cl}}$$

	z_{form}	z_{evap}	n_{cl} $(1/{\rm pc}^3)$	v_{cl} (km/s)	R_{cl} (pc)
$N_{cl} = 10$	1200	165	9500	0.76	0.063
$N_{cl} = 100$	320	15	190	0.93	0.50
$N_{cl} = 1300$	85	0	3.6	1.1	4.4

Detailed numerical simulations of PBH binaries with singles in clusters

Can three-body interactions make a little step towards a more equilibrated eccentricity distribution ?

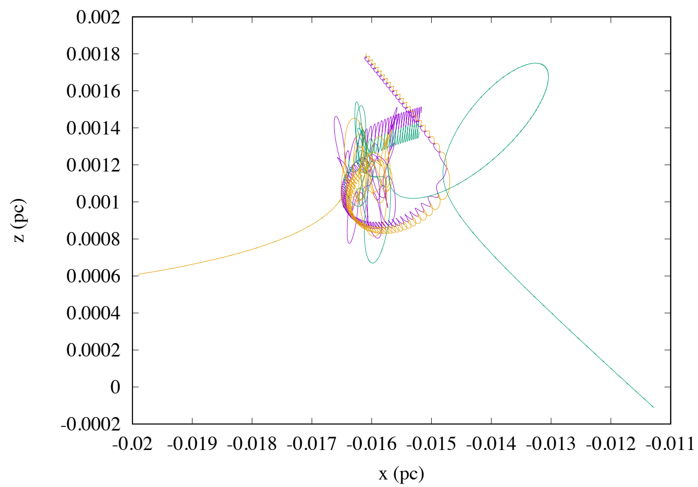
parameters: two binary massses M_{b1}, M_{b2}, perturber mass M_p, two inclination angles of orbital plane θ, ϕ, parameter describing where on the orbit the binary is Ψ, and six velocities



only the few closest approach interactions are important

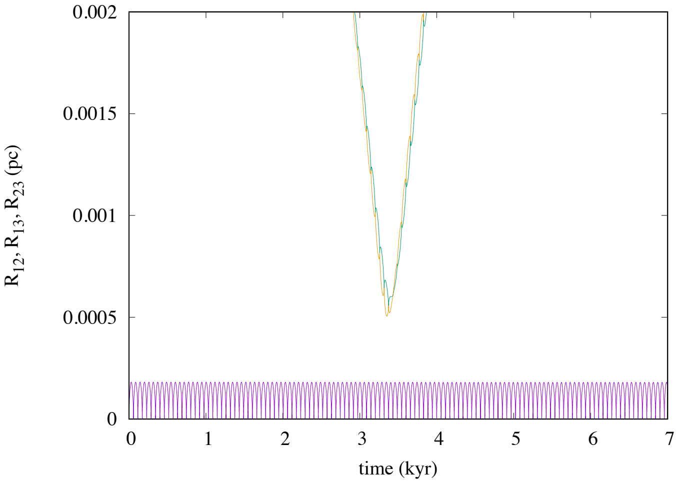
$$\Delta N_{sc} = \pi b^2 v_{cl} n_{cl} \Delta t \sim 10 - 100$$

$$\Delta t(N_{cl}) = t_{evap} - t_{form}$$

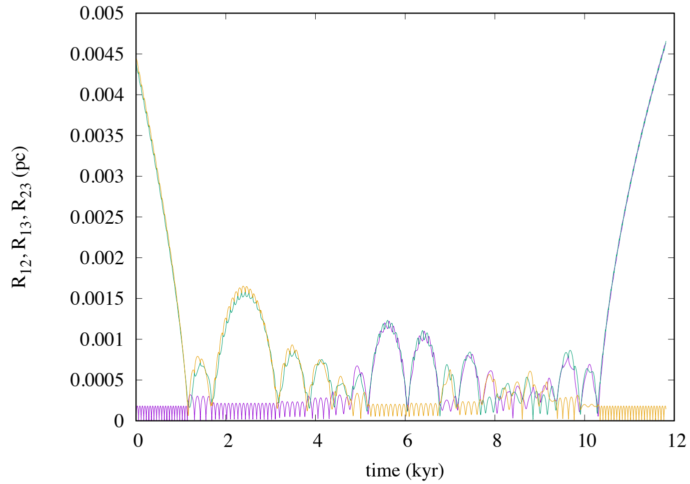


Examples of PBH binary - single encounters - all 30 solar mass binaries have initial merger times of 10 Gyrs

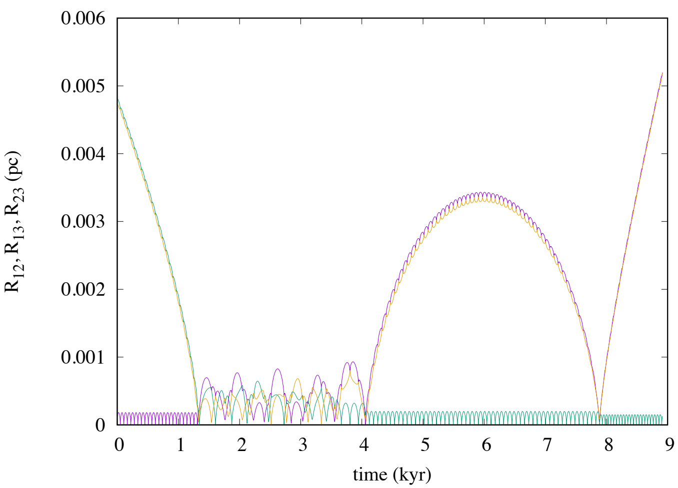
Relative distances over time



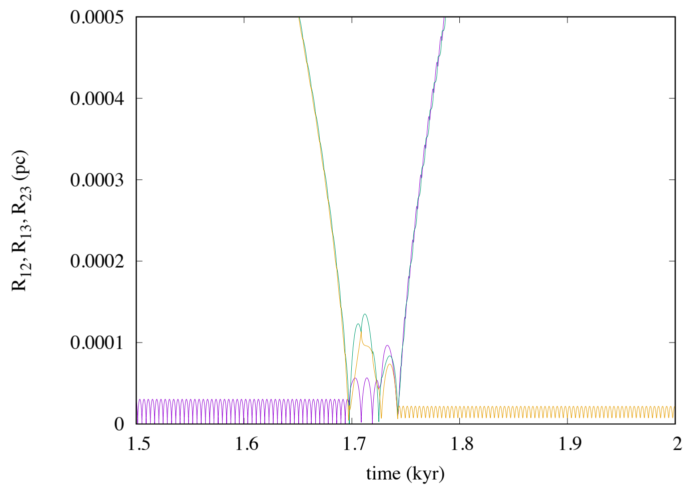
e_ini = 0.99987 -> e_fin 0.99919   tau_fin = 6000 Gyrs



e_ini = 0.999 -> e_fin = 0.902   tau_fin = 1x10^11 Gyrs



e_ini = 0.99987 -> e_fin = 0.915   tau_fin = 3x10^10 Gyrs



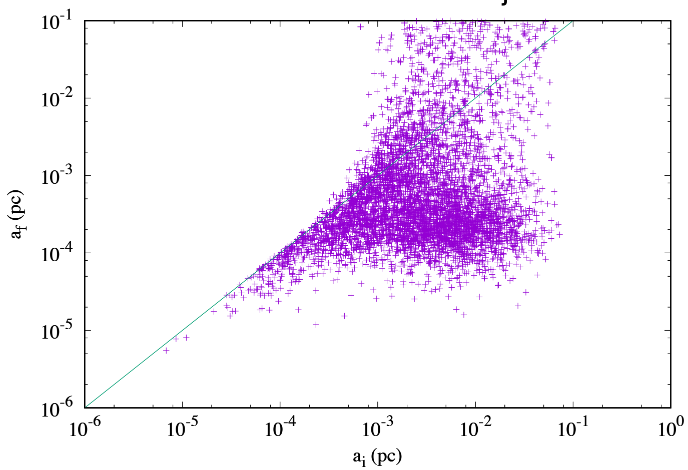
e_ini = 0.999 -> e_fin = 0.47   tau_fin = 1x10^10 Gyrs

Monte-Carlo simulation of binary properties after multiple scatterings over the life time of N=100 cluster

The initial very eccentric distribution is assumed

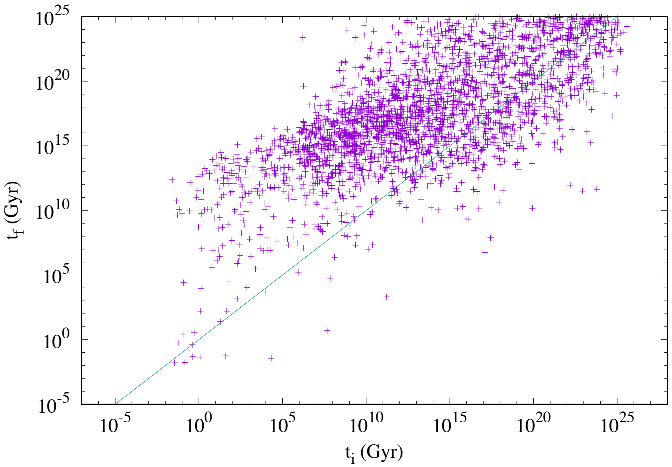
$$t_{\rm coal} = \frac{3}{170}\frac{1}{GM_{\rm BH}^3}a^4(1-e^2)^{7/2}$$

Final versus initial semi major axis

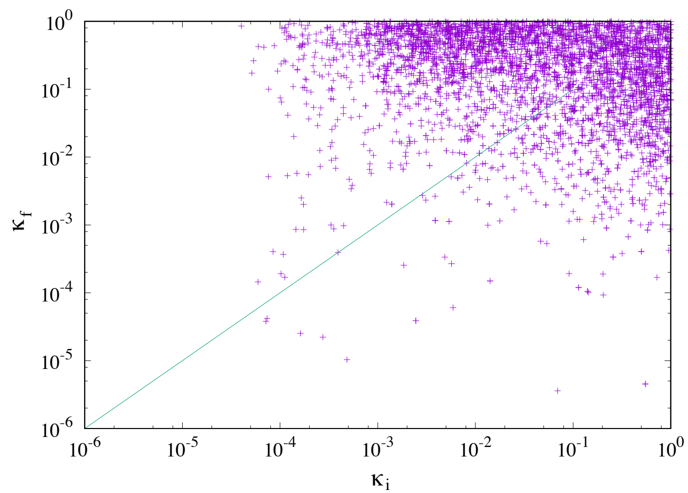


Heggie, Hills 75

Final versus initial coalescence time

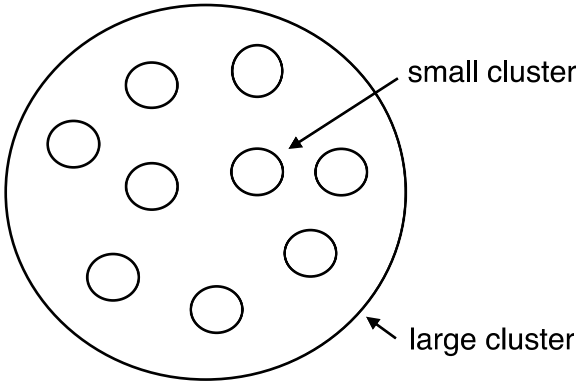


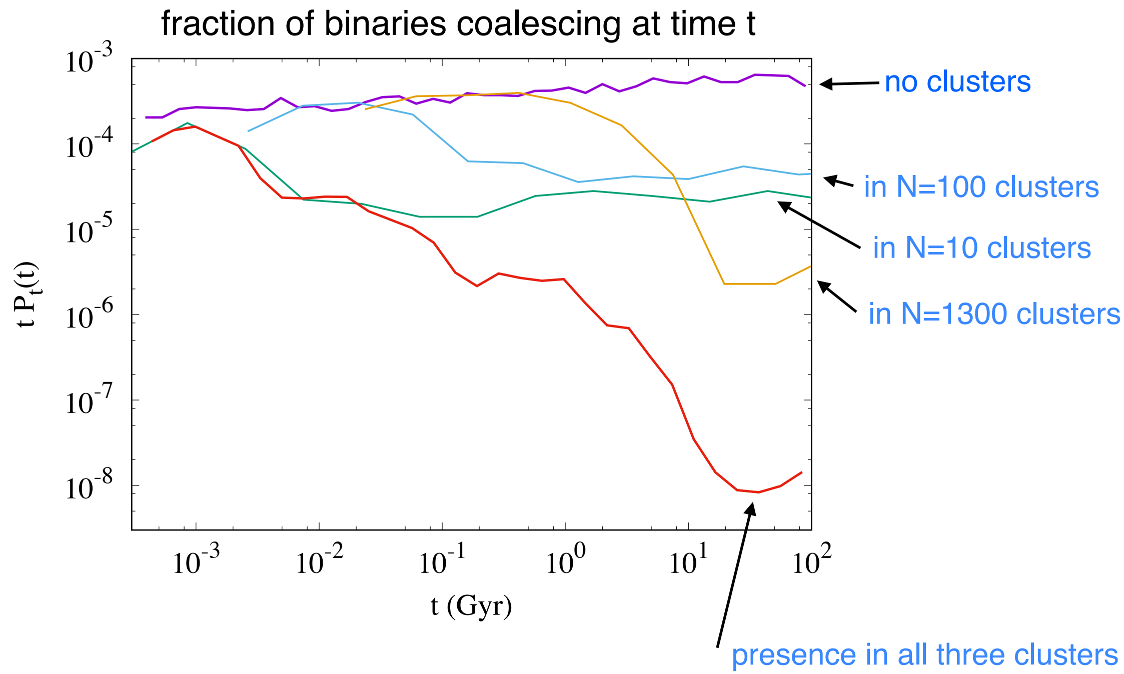
Final versus initial (1-e^2)



Combined effect by presence of binaries in different size clusters

Hierarchical structure formation





"Typical" impact parameter

$$b_{typical}(N_{cl}) \propto \frac{\ln^{1/2} N_{cl}}{N_{cl}^{1/6}}$$

Total suppression of merger rate at t = 10 Gyrs by a factor 3×10^4

LIGO/Virgo observations most likely do not rule out ~1 or ~30 solar mass PBH dark matter

however, loophole, if too many binaries never make it into a cluster the merger rate is too high

LIGO/Virgo signal explained by direct encounters of two single PBHs in present-day clusters ?

The typical PBH resides in a N~1300 cluster at present

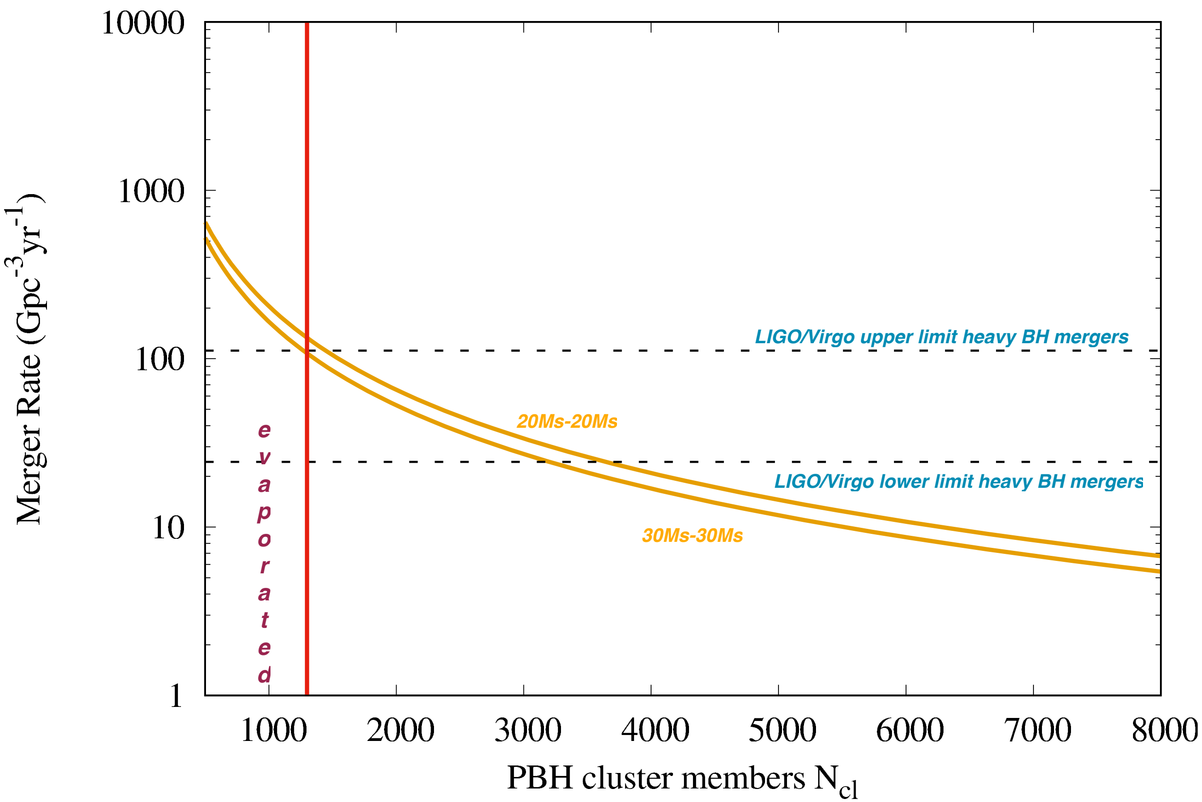
$$f_{direct} = \frac{\Delta n_{pbh}}{n_{pbh}} = \frac{1}{2}\sigma_{capt} v_{cl} n_{cl} \Delta t$$

$$\sigma_{capt} = 2\pi \left(\frac{85\pi}{6\sqrt{2}}\right)^{2/7} \left(\frac{G}{c}\right)^{2} (M_1 + M_2)^{10/7} (M_1 M_2)^{2/7} \left(\frac{v}{c}\right)^{-18/7}$$

$$\mathcal{M} = \left(\frac{f_{direct}}{\Delta t}\right) \left(\frac{f_M(M_{pbh})\rho_{pbh}^{avg}}{M_{pbh}}\right)$$

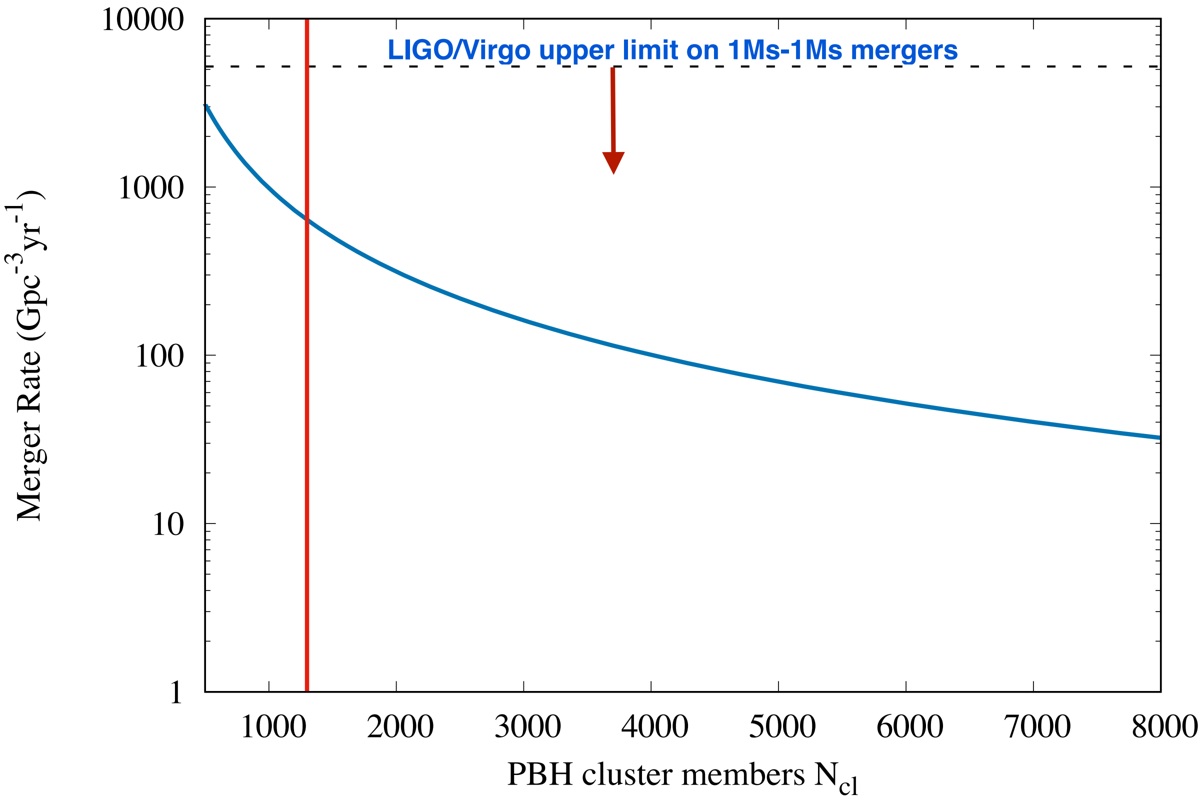
PBH mass function dominated at 20-30 solar mass, inflationary peak

$$\mathcal{M}^{d}_{M_b - M_b} \approx 108 \, \frac{1}{\mathrm{Gpc^3 yr}} \left(\frac{M_b}{30 M_\odot} \right)^{-11/21} \left(\frac{N_{cl}}{1300} \right)^{-137/84}$$



PBH mass function dominated by 1 solar mass from QCD equation of state

Why have no solar mass- solar mass PBH mergers have been found ?



Because the LIGO/Virgo efficiency not high enough to find them currently !

What about the observed heavy BH-BH mergers ?

The QCD mass spectrum shows a shoulder at M ~ 30 solar mass

$$M_b \simeq 30 M_\odot \gg M_s \simeq 1 M_\odot$$

$$f_M(M_b) \simeq 10^{-2} \ll f_M(M_s) \simeq 1$$

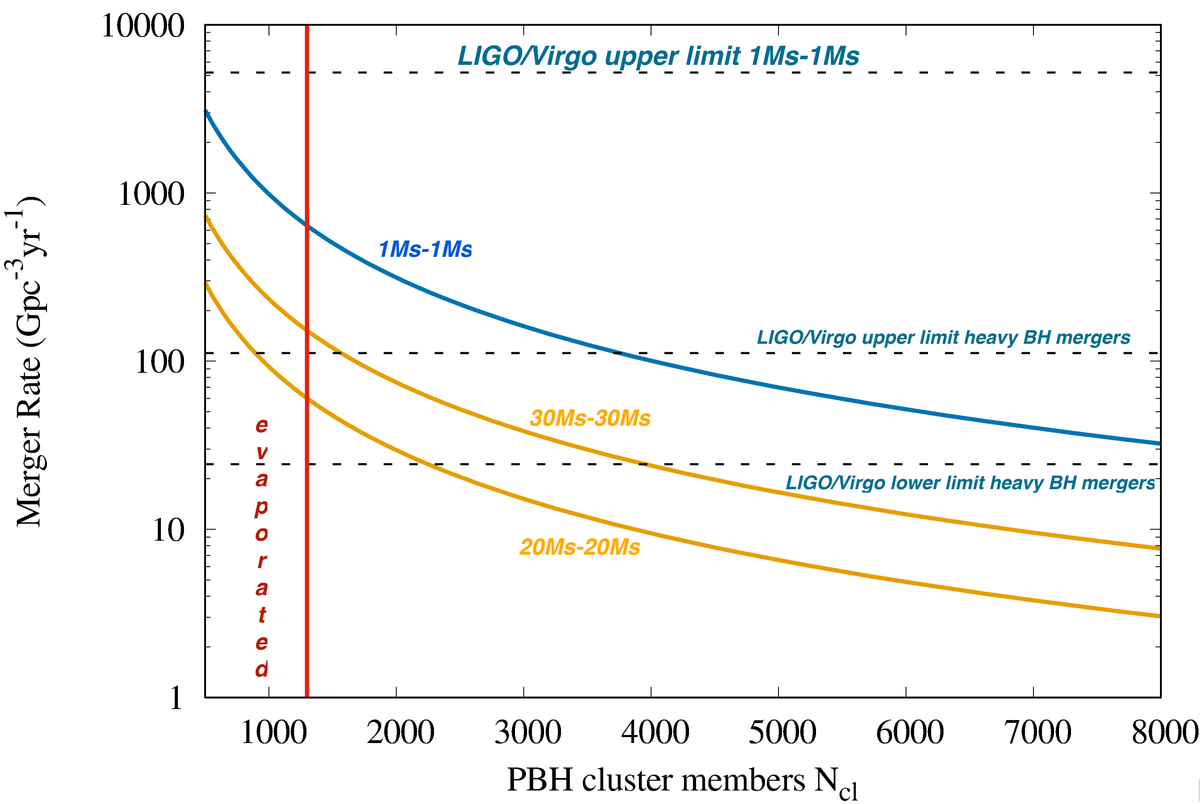
sinking of heavier PBHs to the center of the cluster

$$v(M_b) \simeq v_{cl} \sqrt{M_s/M_b} \ll v_{cl}$$

$$r^{vir}_{M_b} \simeq r_{cl} \sqrt{M_s/M_b}$$

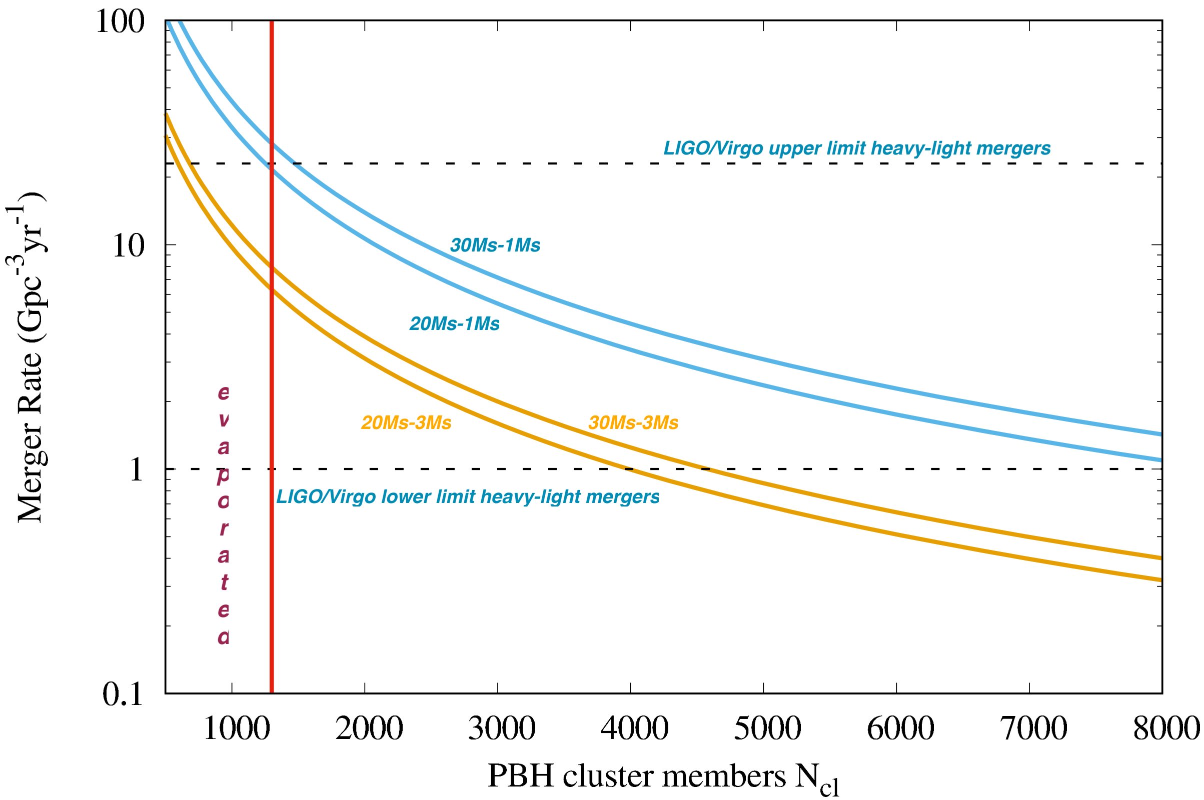
Again the merger rate fits the observations !

$$\mathcal{M}^{d}_{M_b-M_b} \approx 152\,\frac{1}{\mathrm{Gpc}^3\mathrm{yr}}\left(\frac{f_M(M_b)}{10^{-2}}\right)^2\left(\frac{M_b}{30M_\odot}\right)^{16/7} \times\left(\frac{M_s}{1M_\odot}\right)^{-59/21}\left(\frac{N_{cl}}{1300}\right)^{-137/84}$$



What about GW190814 the unequal mass merger rate ? Again it works !

$$\mathcal{M}^{d}_{M_b-M_s} \approx 28.2 \, \frac{1}{\mathrm{Gpc}^3\mathrm{yr}} \left(\frac{f_M(M_b)}{10^{-2}}\right) \left(\frac{M_b}{30M_\odot}\right)^{5/7} \times \left(\frac{M_s}{1M_\odot}\right)^{-26/21} \left(\frac{N_{cl}}{1300}\right)^{-137/84}$$



This is highly non-trivial ! When the only parameter is fixed to have all dark matter in PBHs, all the merger rates are approximately matching the LIGO/Virgo rates !!!

-> the mass scale of ~30 solar mass

-> the merger rate of ~30-30 solar mass binaries

-> why ~1-1 solar mass have not been observed yet

-> the merger rate of asymmetric mass mergers

Conclusions:

-> LIGO/Virgo have by now detected a larger number of BH-BH mergers, some of them with surprising properties

-> the possibility that these BHs could be mostly primordial AND that ~1-30 solar mass could make up ALL of the dark matter had been widely rejected due to too large predicted merger rates from an initial binary population

-> by numerical simulation I have shown that three-body interactions in PBH clusters inevitably lead to a very significant reduction of the merger rate of this initial population making it likely unimportant

-> I have shown that QCD equation of state inspired mass functions can match all currently observed merger rates, whereas inflationary peak scenarios can match the "30-30" solar mass rate

-> recent observations by Nanograph seem to lend credibility to such a scenario

-> new microlensing observations on the dark matter solar mass scale should be performed (after all MACHO had found > 10 events)

We have so far restricted our attention to the QCD transition and furthermore implicitly assumed that color-confinement in the early universe proceeds via a first order transition. Lattice gauge simulations are still not conclusive as to the order of the QCD transition, mainly due to finite resolution effects and the difficulties associated with simulating bare quark masses [20, 27, 28]. We wish to stress that a possible reduction of the effective speed of sound may be a generic feature of cosmic phase transitions and may not necessarily be tied to the character of a transition. In fact, a reduction in the speed of sound of order 10-20% for a few Hubble times does occur during the cosmic e^+e^--annihilation [29] (the nature of the e^+e^--annihilation is very different from that of a first-order QCD color-confinement transition). This effect of pressure reduction during phases of e^+e^--creation and -annihilation is also well known in stellar evolution calculations, commonly referred to as the pair-instability, and relates to the conversion of relativistic energy density (photons) to e^+e^-- rest mass energy density. We note that there is the possibility of an enhancement in PBH formation on the e^+e^--annihilation horizon mass scale of approximately, $M \sim 10^5 M_\odot$.