Did LIGO detect dark matter?

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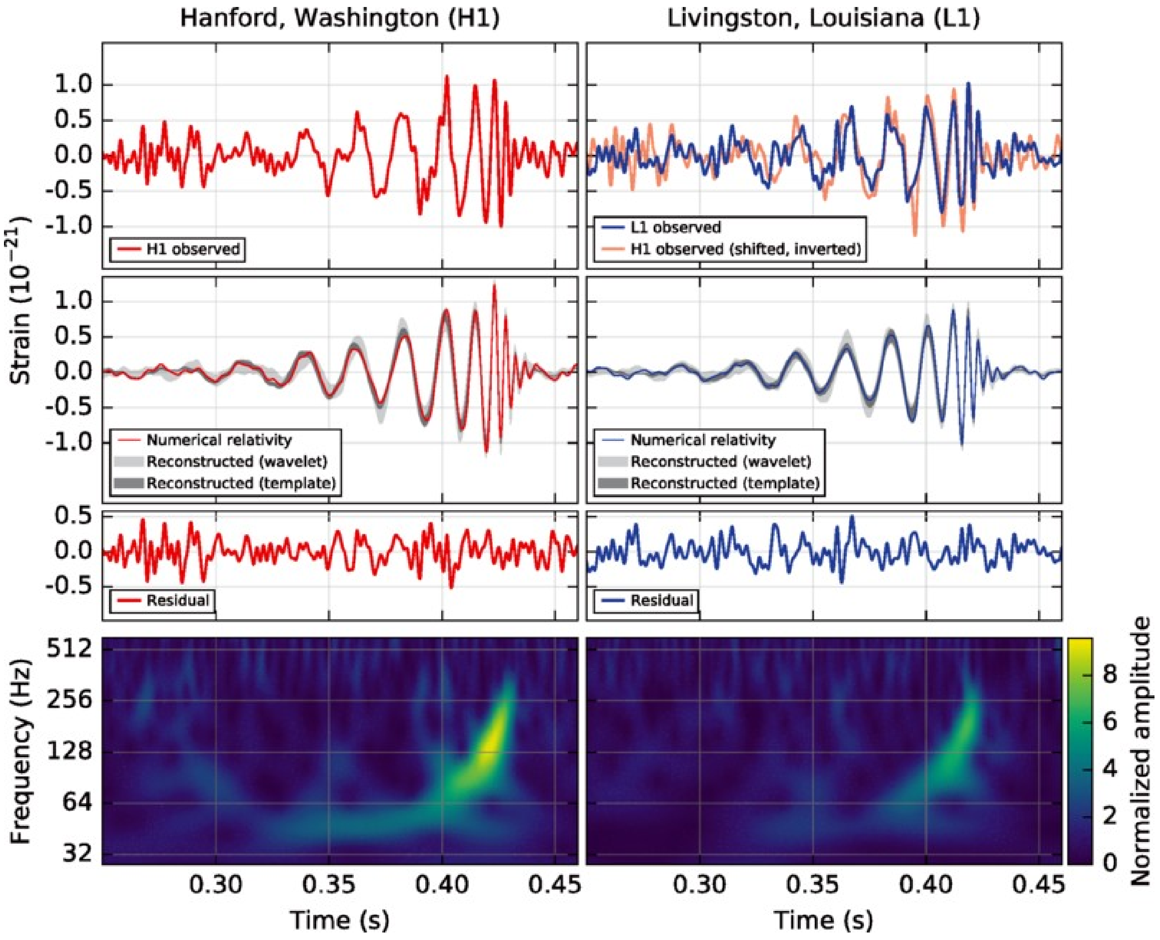
I. Cholis, J. Munoz, Y. Ali-Haimoud, M. Kamionkowski, E. Kovetz, A. Raccanelli, A. Riess

arXiv: 1603.00464
PRL 116 201301

LIGO detected Gravitational Waves

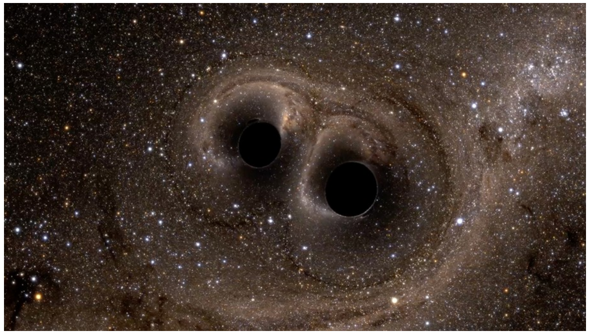


GW signal from two merging 30 solar mass BHs

How did the Black Holes form?

Are some of them

Primordial Black Hole Dark Matter



Don’t test this in an accelerator

Primordial Black Holes

Form from inflationary density perturbations

- If mass inside horizon > Schwarzchild mass:

$$\int_0^{\mathrm{hor}} P(k)W(k,R)dR > M_{\mathrm{Schwz}}$$

- Inflationary perturbations collapse to black hole
- Can be all dark matter: no constraints for 100 km

Mass, abundance free parameters

Forget about formation

Primordial Black Holes

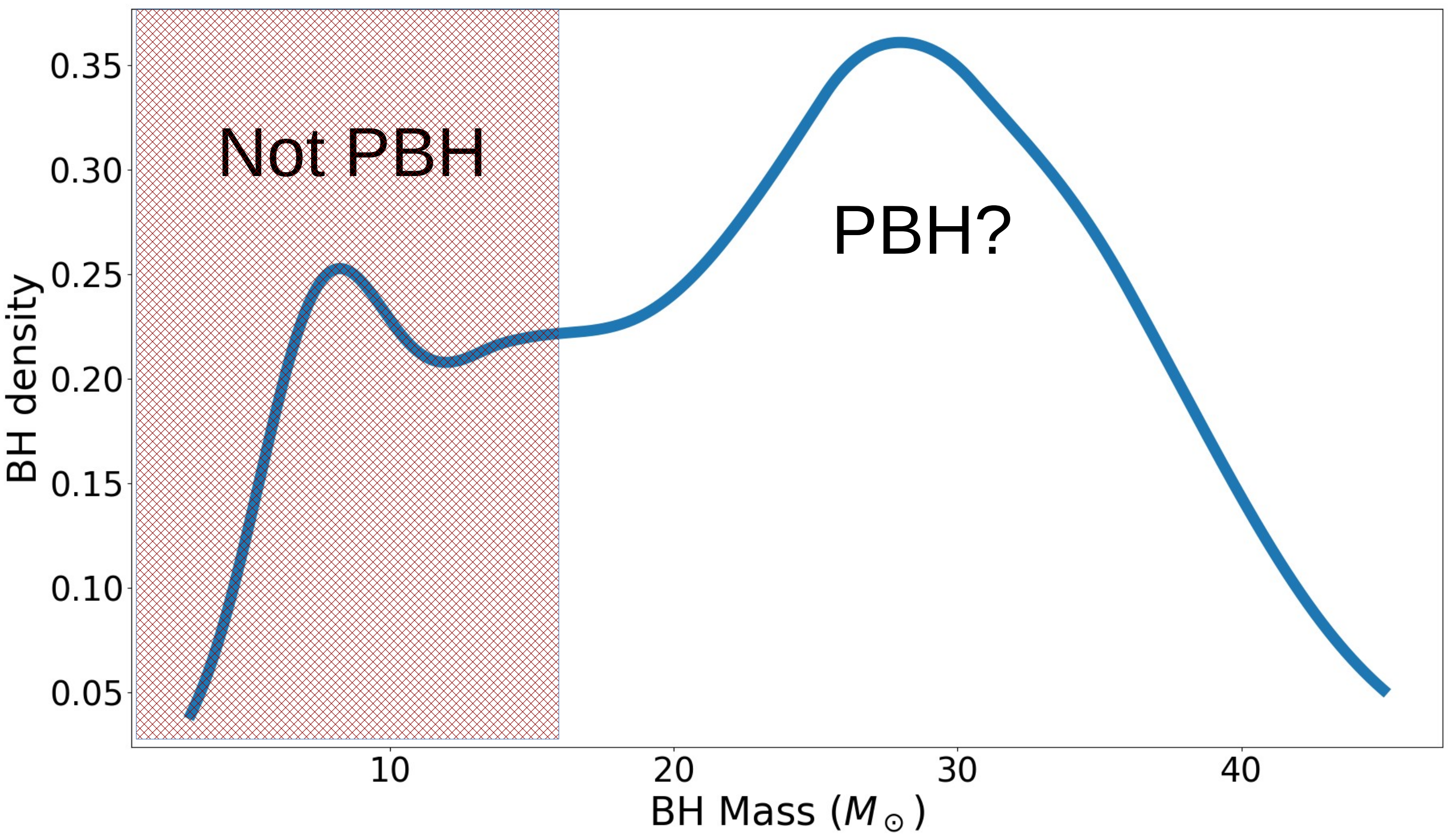
Form from inflationary density perturbations

- If mass inside horizon > Schwarzchild mass:

$$\int_0^{\mathrm{hor}} P(k)W(k,R)dR > M_{\mathrm{Schwz}}$$

- Not default: density peak from inflation end

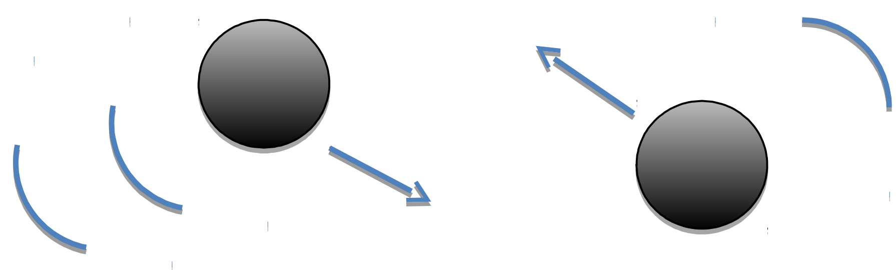
Two Populations from LIGO



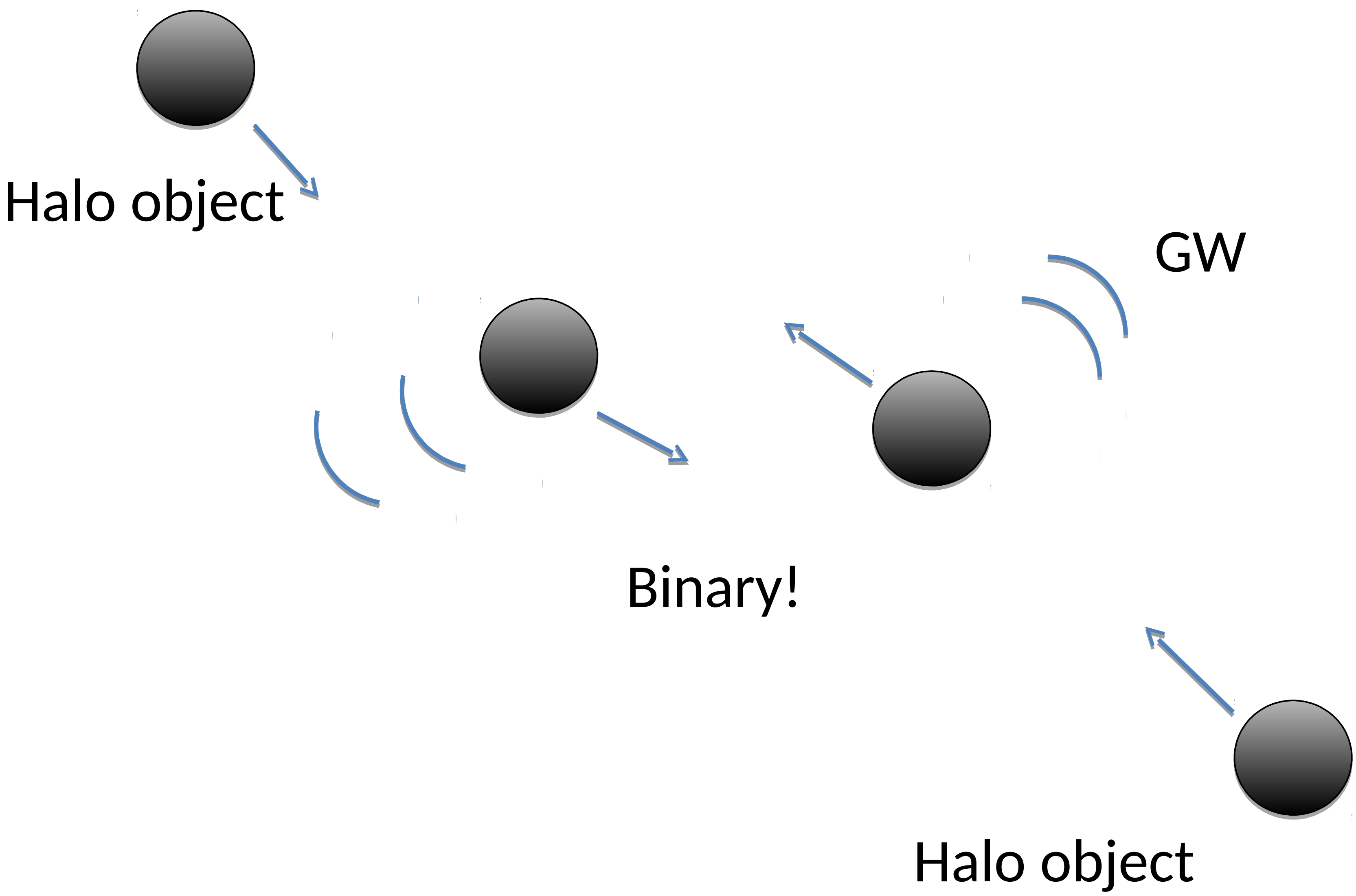
Does the Merger Rate Match LIGO?

PBH dark matter in halos like CDM

Binaries form at z=0 by GW emission



PBH Merger in Halos



Cross-Section

$$\sigma = \pi \left(\frac{85\pi}{3} \right)^{2/7} R_{\rm s}^2 \left(\frac{v_{\rm PBH}}{c} \right)^{-18/7}$$

(Quinlan & Shapiro 1989)

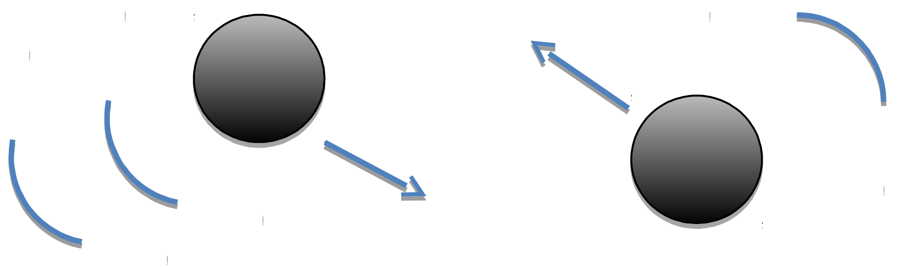
PBH velocity ~ halo velocity dispersion

Most mergers in smallest halos

Does the Merger Rate match LIGO?

Binary formation is slow, mergers are fast

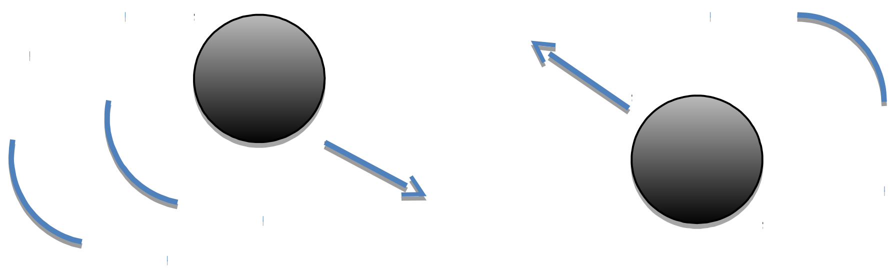
Black hole binaries form **today,** distributed as in dark matter halos



Does the Merger Rate match LIGO?

Sasaki 2016 has an alternative rate

Black holes binaries form **at early times,** distributed uniformly, merge slowly



May give higher rate, if little binary disruption

Merger Rate

Two-body encounter, so merger rate is:

$$\mathcal{R} = 4\pi \int_0^{R_{\rm vir}} r^2 \frac{1}{2} \left(\frac{\rho_{\rm nfw}(r)}{M_{\rm pbh}} \right)^2 \langle \sigma v_{\rm pbh} \rangle \; dr$$

Halo Profile

- NFW profile (Einasto profile similar):

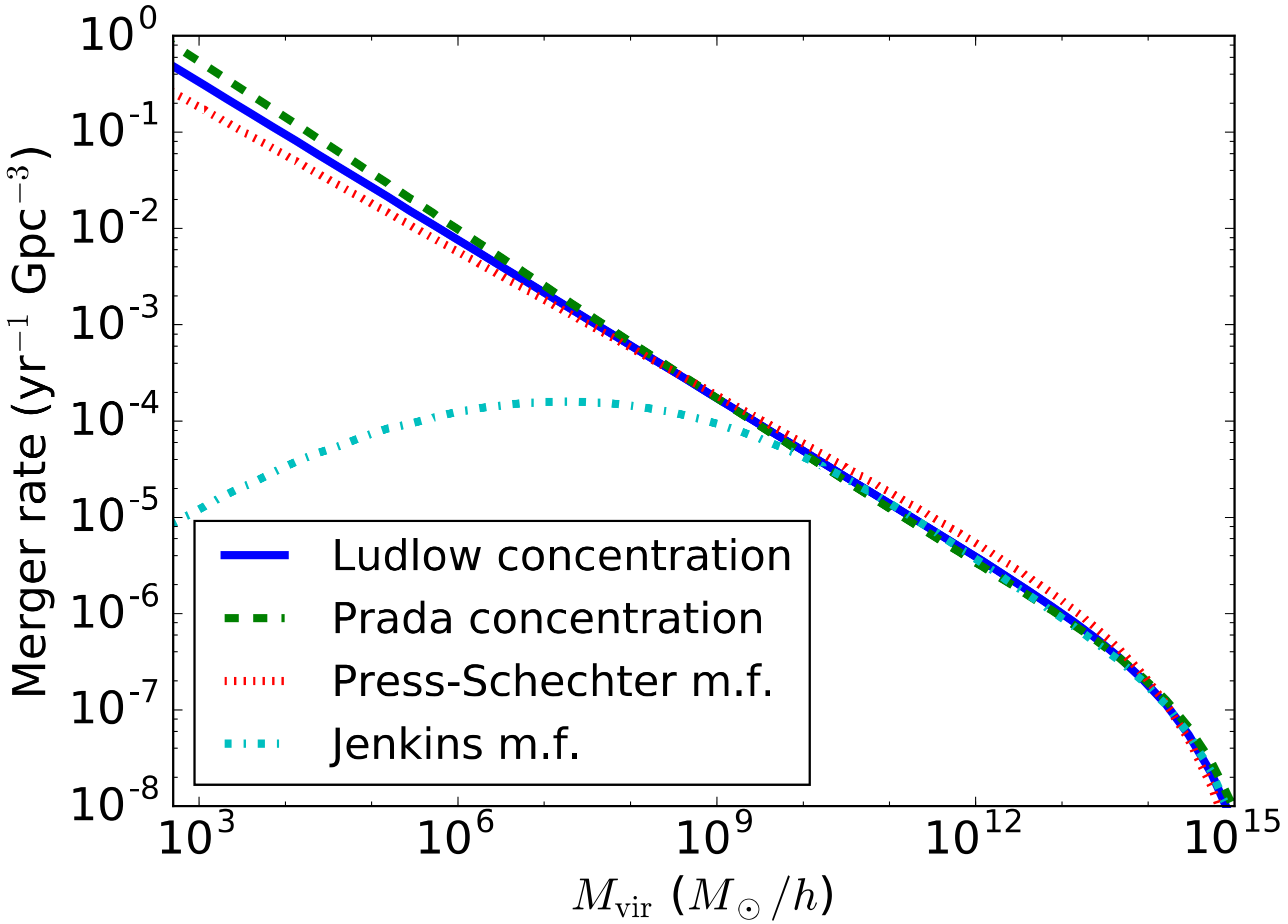
$$\rho_{\rm nfw}(r) = \rho_s \left[(r/R_s)(1+r/R_s)^2\right]^{-1}$$

- Concentration-mass relation:

$$C = R_{\rm vir}/R_{\rm s}$$

- Use simulations: Ludlow 2016, Prada 2015.

Total Merger Rate

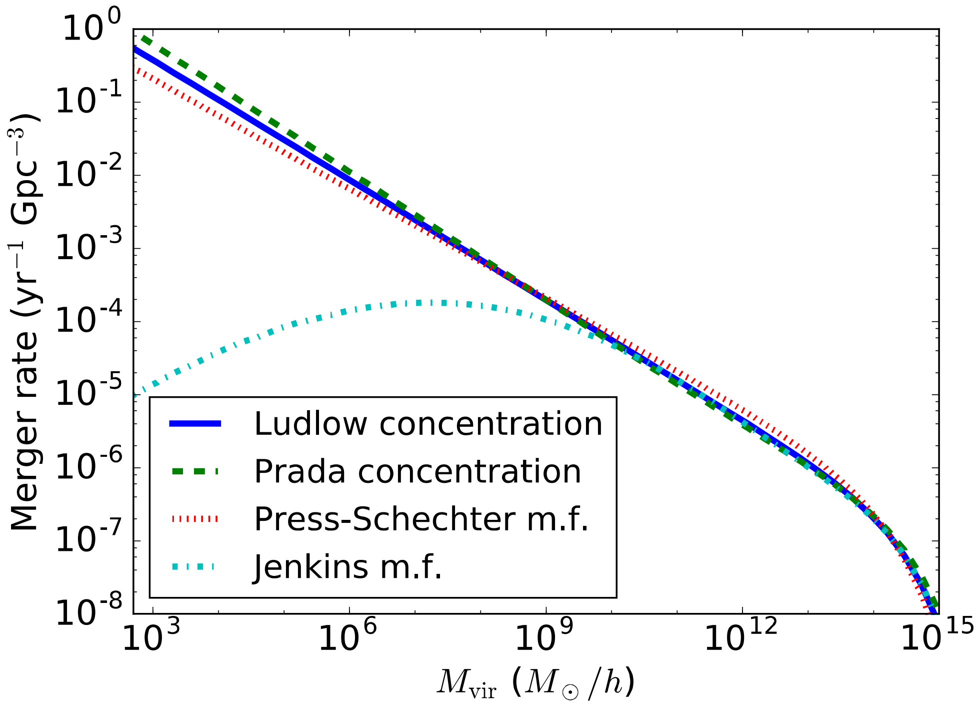


Lines show different dark matter models

Lower Limit

- At $M \sim 400 M_{\odot}$ assumptions break
- Mergers wide enough that timescale is Hubble time (so can be disrupted)
- Halos evaporate

Merger Rate



- Integrated: $2\ \mathrm{yr}^{-1}\mathrm{Gpc}^{-3}$
- LIGO: ~~$2 - 53\ \mathrm{yr}^{-1}\mathrm{Gpc}^{-3}$~~

  $0.5 - 12\ \mathrm{yr}^{-1}\mathrm{Gpc}^{-3}$

Merger Rate

- Total mergers: $2\,\mathrm{yr}^{-1}\mathrm{Gpc}^{-3}$

Very uncertain

This number could have been $10^{\pm 10}$

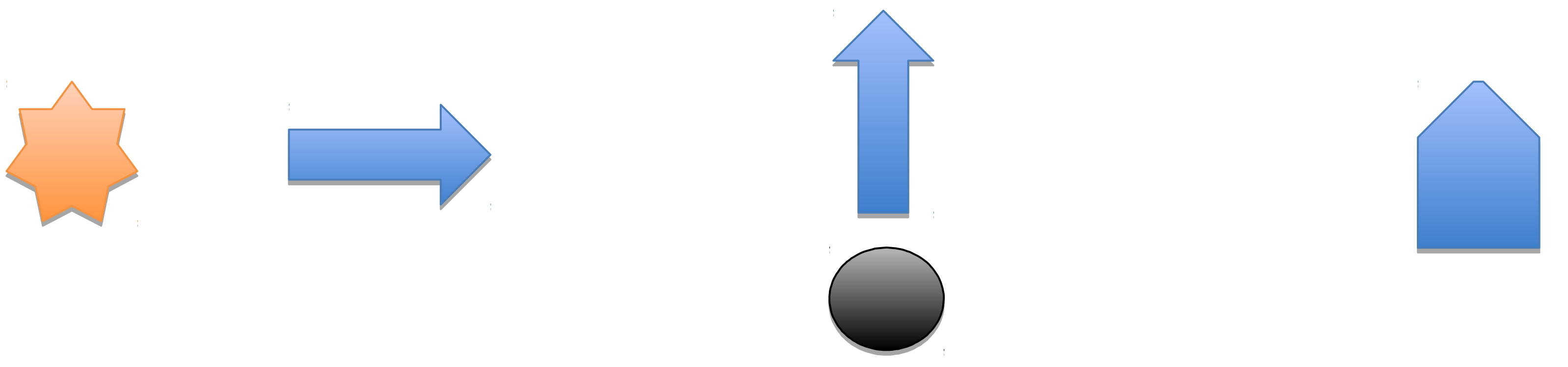
INTERESTING

Did LIGO Detect Dark Matter?

Possibly.

Are PBHs Ruled out?

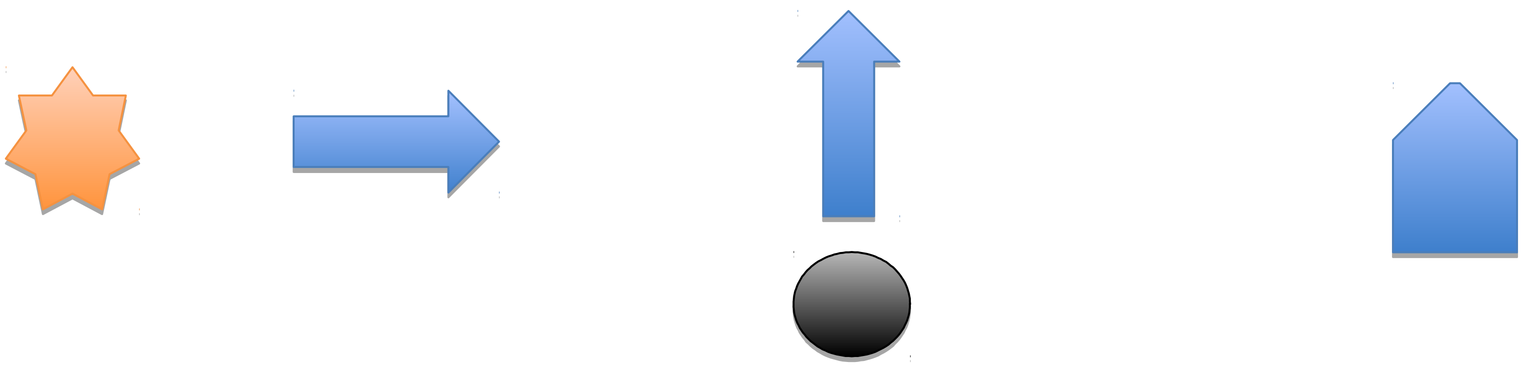
- Micro-lensing: Black hole in front of star



- Star brighter
- Strong constraints on PBH and other MACHO

More Microlensing

- No micro-lensing constraints if lens is too rare

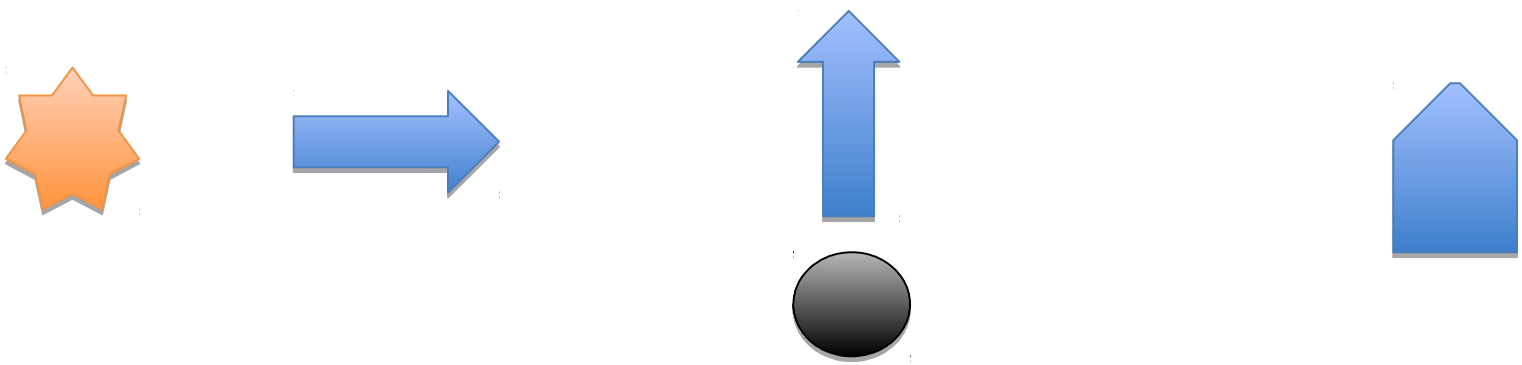


- Non-detection of lensing (OGLE, HSC):

$$M_{\rm PBH} > 20 M_\odot$$

Supernovae Microlensing

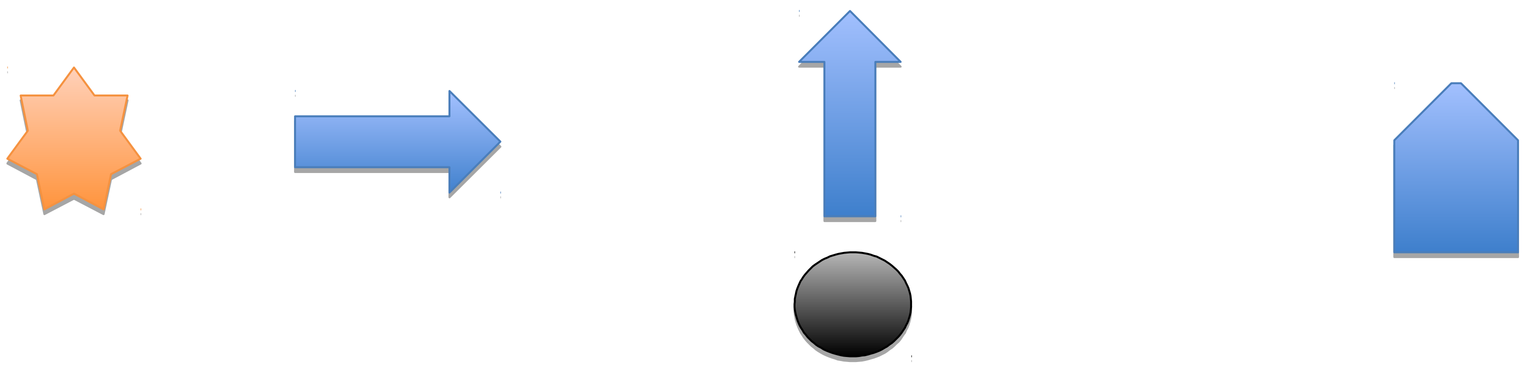
- Non-detection of lensed supernovae (Zumalacarregui & Seljak)



- PBH < 30 % of dark matter at 2-sigma

Future Microlensing

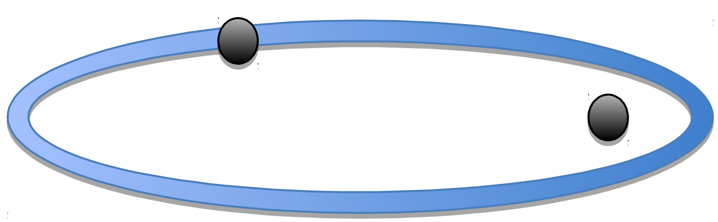
- Large Synoptic Survey Telescope
- 10 year survey images half the sky > 10^3 times



- Forecast PBH fraction < 10^{-4} for M_{PBH} > 10 M_{sun}

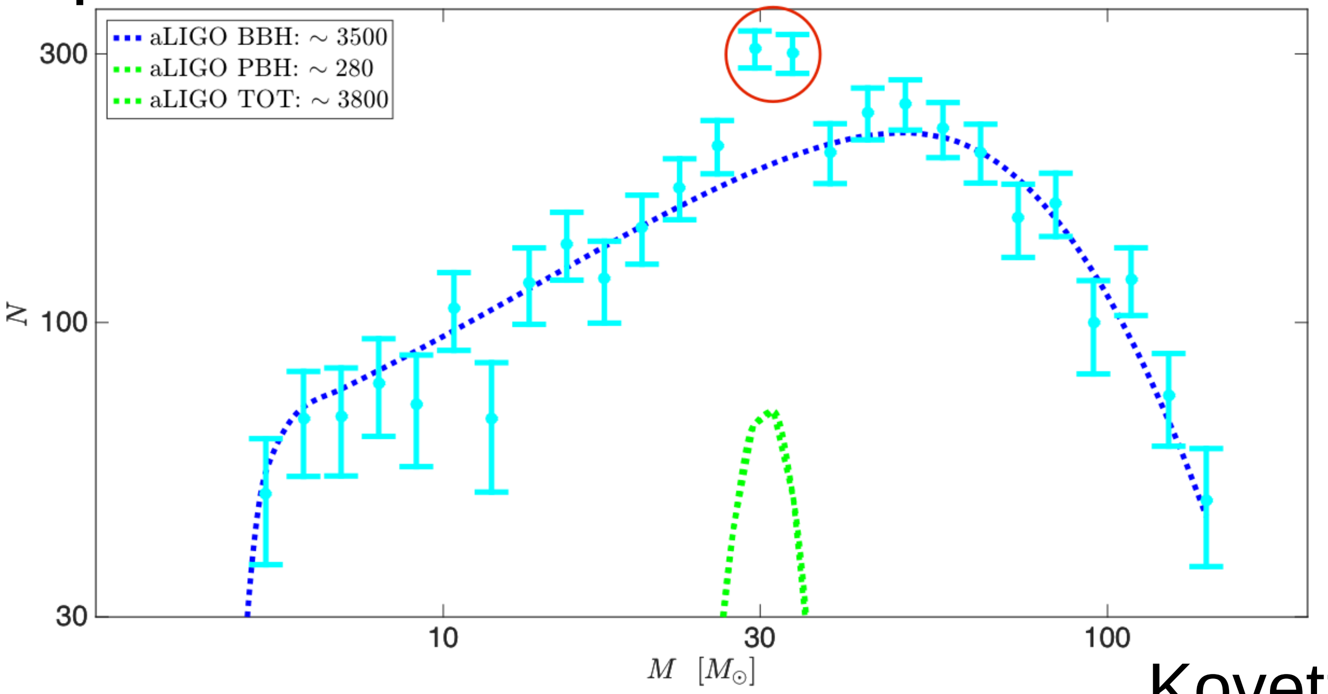
Initially Eccentric Binaries

- Stellar binary orbits are circular
- Dark matter orbits are elliptical
- PBH binaries are initially eccentric: O(1) aLIGO



LIGO Mass Function

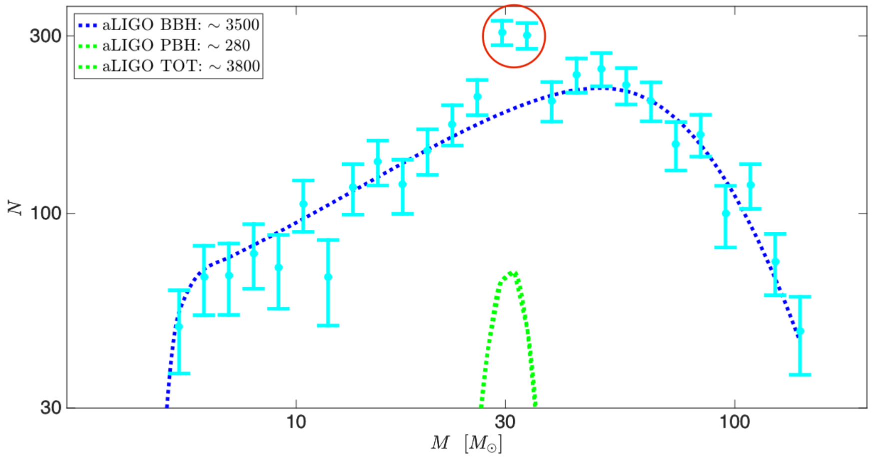
Two populations → non-smooth mass function



Kovetz 2017

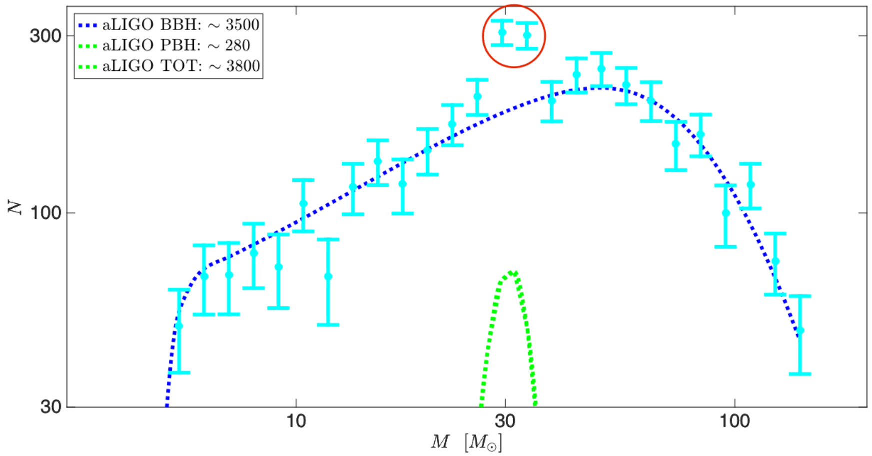
No hair theorem means no extra work

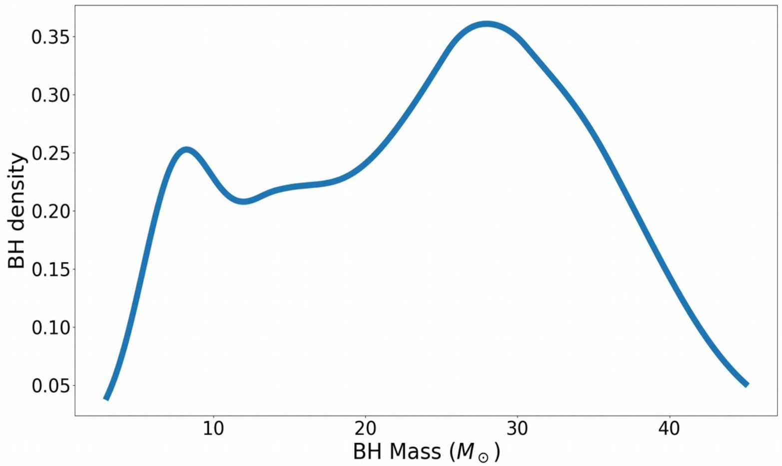
LIGO Mass Function



Simple mass function model:
- Power law IMF with ~ -2 index
- LIGO detection efficiency
- Peak numbers at ~ 50 solar: fewer events, but brighter, so LIGO probes larger volume

LIGO Mass Function





Current mass function has 12 objects:
not like simple model

Are PBH all the dark matter?

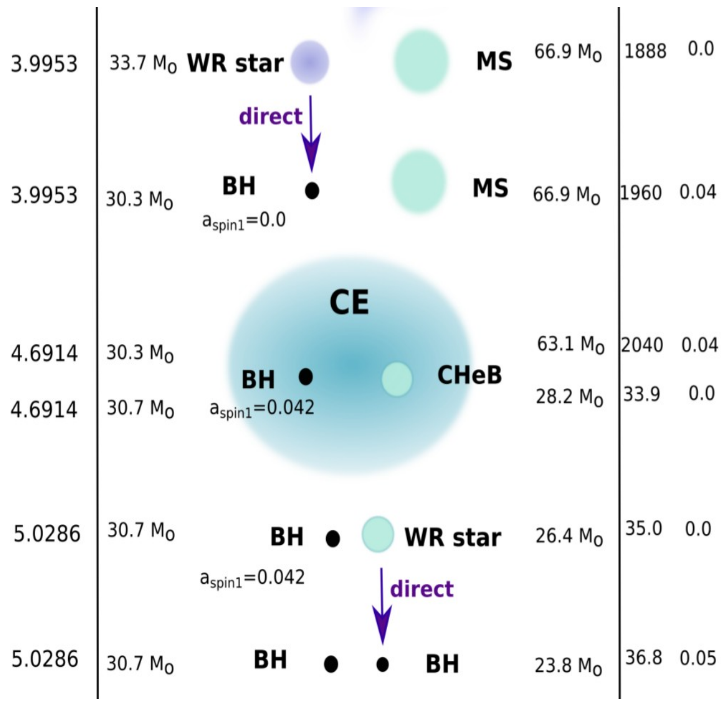
No

Are some LIGO mergers PBH?

We don’t know yet

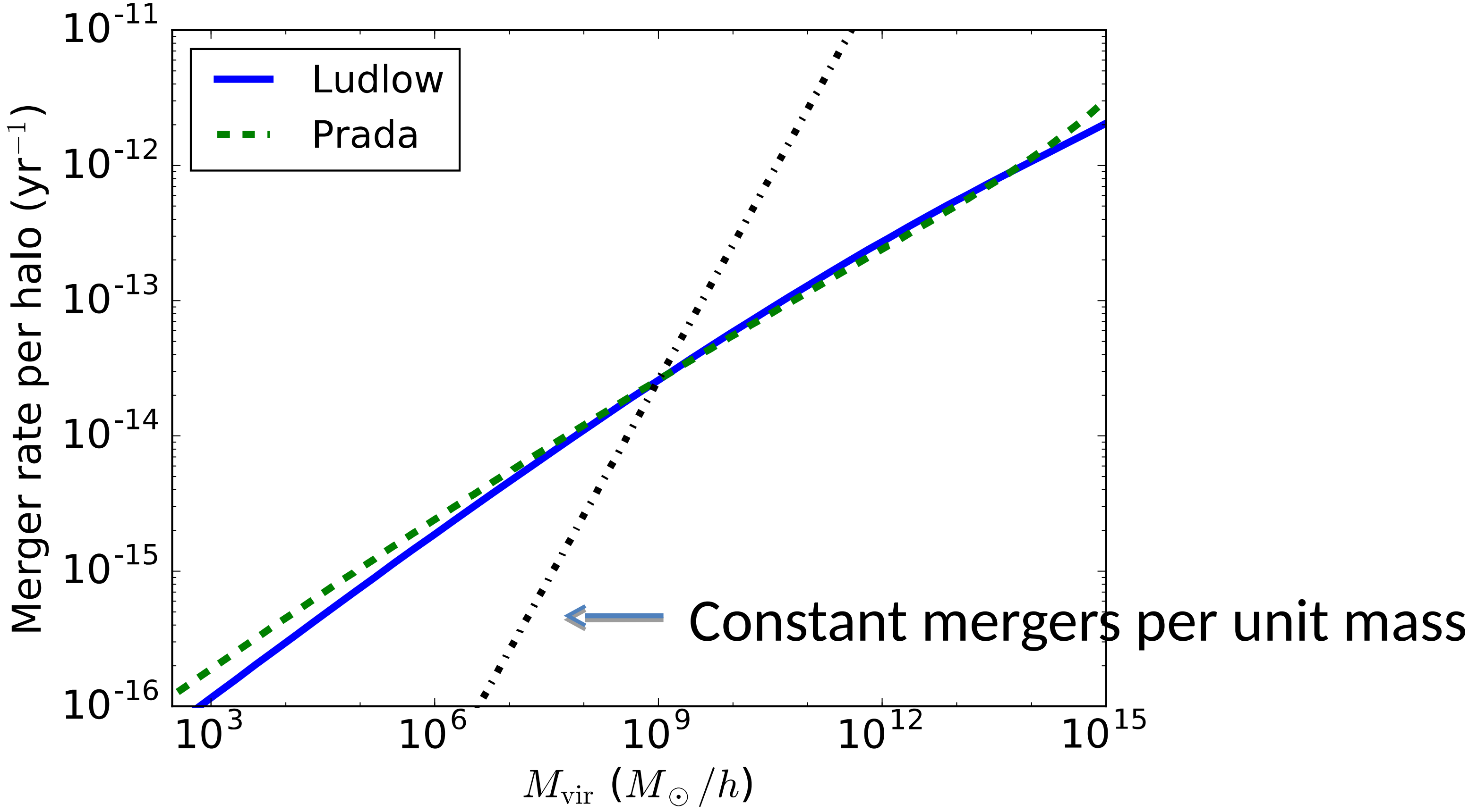
Other consequences

- **PBH binaries have randomly oriented spins**
- **Stellar evolution has aligned black hole spins**



Belczynski, K

Merger Rate Per Halo



Merger per unit mass larger in small halos

Can We Test This?

Mergers happen in small halos with no stars

- No EM counterparts
  - But we don't expect them anyway
- Localized away from galaxy
  - But LIGO's angular resolution isn't enough

Halo Evaporation

Evaporation timescale:

$$t_{\rm evap} \approx (14\mathcal{N}/\ln\mathcal{N})\,[R_{\rm vir}/(C\,v_{\rm dm})]\,,$$

(Binney & Tremaine)

- Accretion compensates in matter domination
- In DE domination, growth slows, halos evaporate: $z < 0.3 \implies t_{\rm evap} > 3{\rm Gyr}$

$$\implies M > 400 M_\odot$$