# Did LIGO detect dark matter? An Update

**Simeon Bird (UCR)**

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

arXiv: 1603.00464
PRL 116 201301

# Primordial Black Hole Dark Matter

Black holes from
very early universe,
very high energies.

(LIGO collaboration)

**Don’t test this in an accelerator**

# Primordial Black Holes

- Form from small scales initial density perturbations
- If mass inside horizon > Schwarzchild mass:

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

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

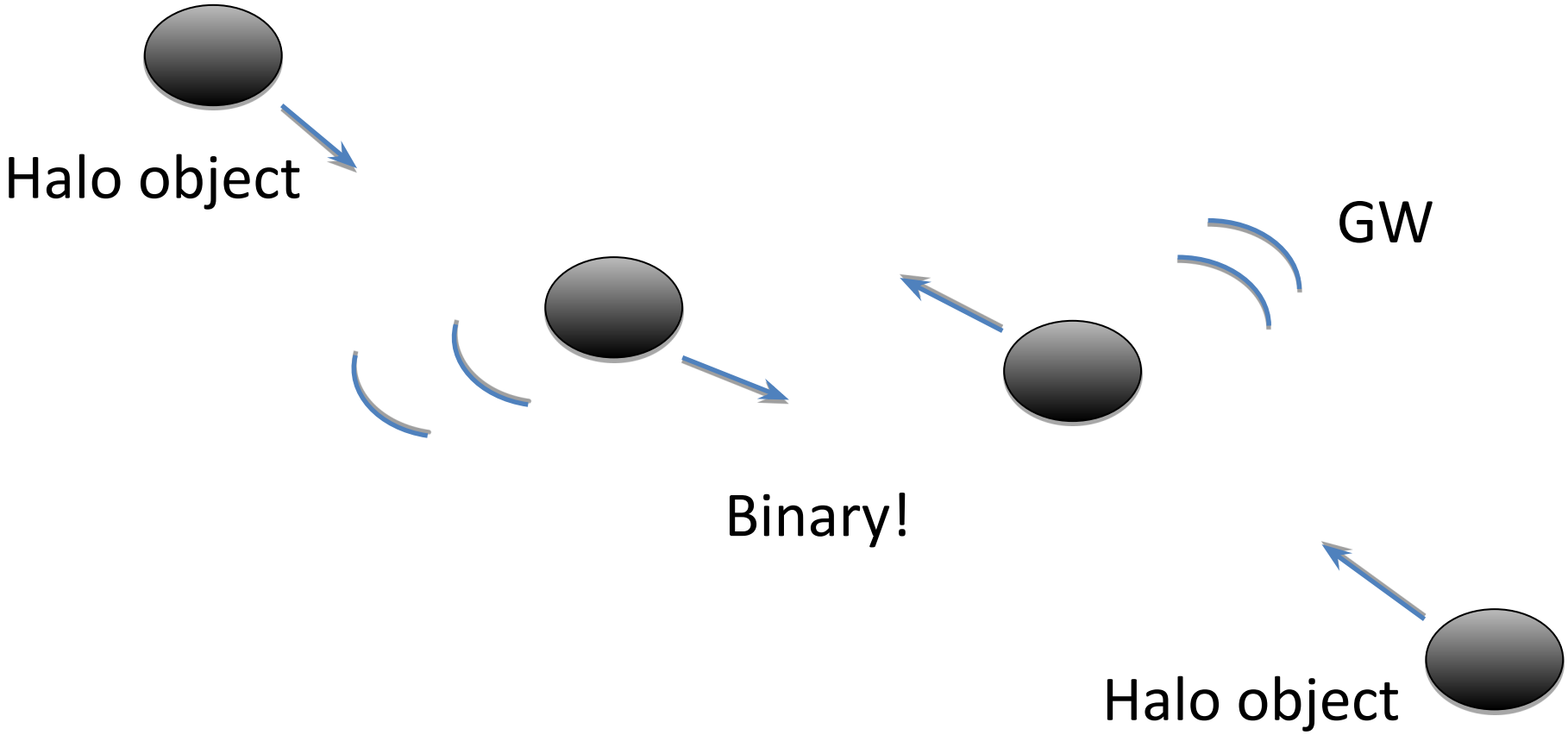
Mass, abundance inform about end of inflation

# Primordial Black Holes

Gravitating objects which do not interact with their surroundings

**Dark matter candidate.**

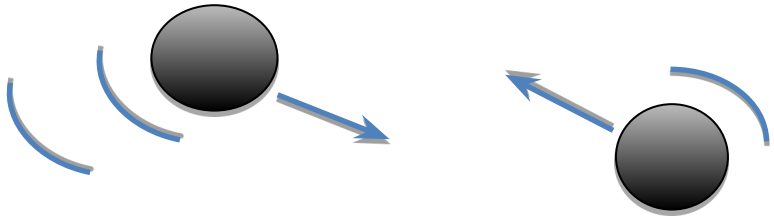
# PBH Gravitational Wave Emission



# PBH Gravitational Wave Emission

- PBHs comoving with DM
- Density/velocity distribution like N-body sims

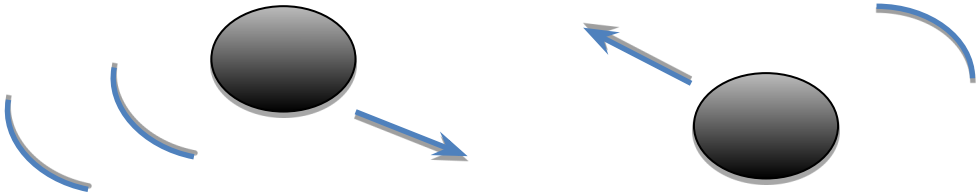
Gravitational wave emission from flybys in halos form binaries



# PBH Gravitational Wave Emission

These binaries form **LATE** and merge **FAST**

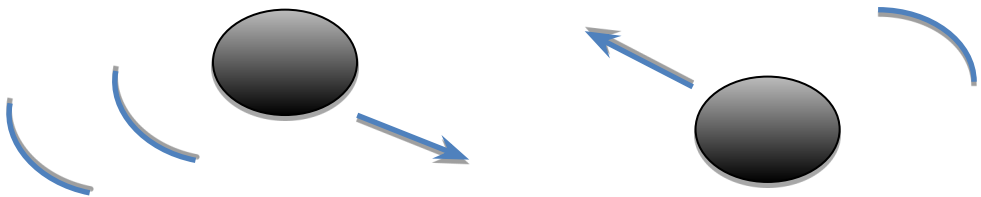
Sasaki+2016 model: early binary formation



# Did LIGO Detect Dark Matter?

Sasaki+ 2016:

- Early binary formation in a homogeneous fluid
- Slowly merging at z=0
- Leads to much higher merger rates ~$10^4$
- “Gravitational wave constraints on PBH fraction”



# Did LIGO Detect Dark Matter?

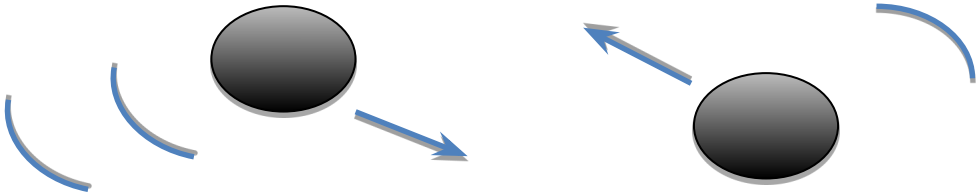
However:

- “Eliminating the LIGO bounds on primordial black hole dark matter” (Celine Bœhm): 2008.10743
- Binaries do not form as Hubble drag prevents them from being bound unless they are close
- Close binaries merge before z = 10

# Did LIGO Detect Dark Matter?

So:

- “Gravitational wave constraints on PBH fraction” are evaded.
- Flybys in late halos are dominant merger channel



# Strongest Constraints: Microlensing

- Non-detection of lensed supernovae (Zumalacarregui & Seljak): “No LIGO Macho”

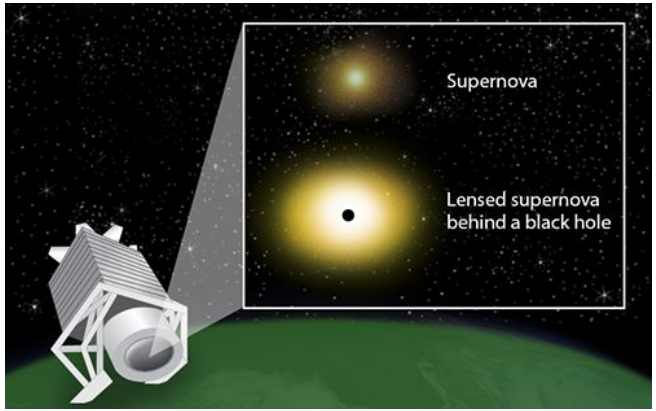



Image: APS magazine ‘Physics’

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

# Model Predictions:

- Small effective spin

$$\chi_{\mathrm{eff}} = \frac{(m_1 \boldsymbol{\chi_1} + m_2 \boldsymbol{\chi_2}) \cdot \hat{\boldsymbol{L}}}{m_1 + m_2}$$

# Model Predictions:

Effective inspiral spin aligned with orbital axis:

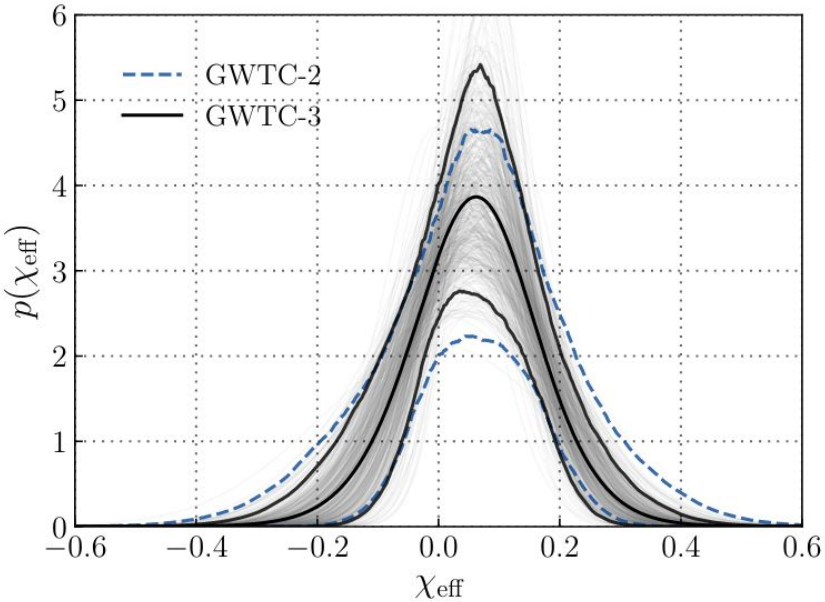
$$\chi_{\rm eff} = \frac{(m_1 \boldsymbol{\chi_1} + m_2 \boldsymbol{\chi_2}) \cdot \hat{\boldsymbol{L}}}{m_1 + m_2}$$

Very evolved binaries should have aligned or anti-aligned spins: +-1 (Lense-Thirring)

Recently formed binaries: each BH spin is uncorrelated

# Model Predictions:

Recently formed binaries: each BH spin is uncorrelated




$$\chi_{\rm eff} = \frac{(m_1 \boldsymbol{\chi_1} + m_2 \boldsymbol{\chi_2}) \cdot \hat{\boldsymbol{L}}}{m_1 + m_2}$$

LIGO O3: 2111.03634

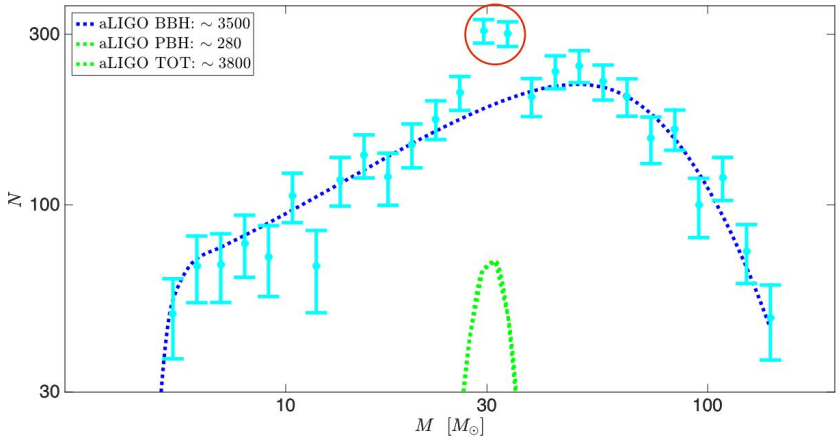
# Model Predictions:

- Small effective spin: dynamical origin
- Two populations:
  - Stellar remnants
  - Primordial

# Predictions:

- Two populations:
  - Power law stellar remnants
  - Primordial Gaussian

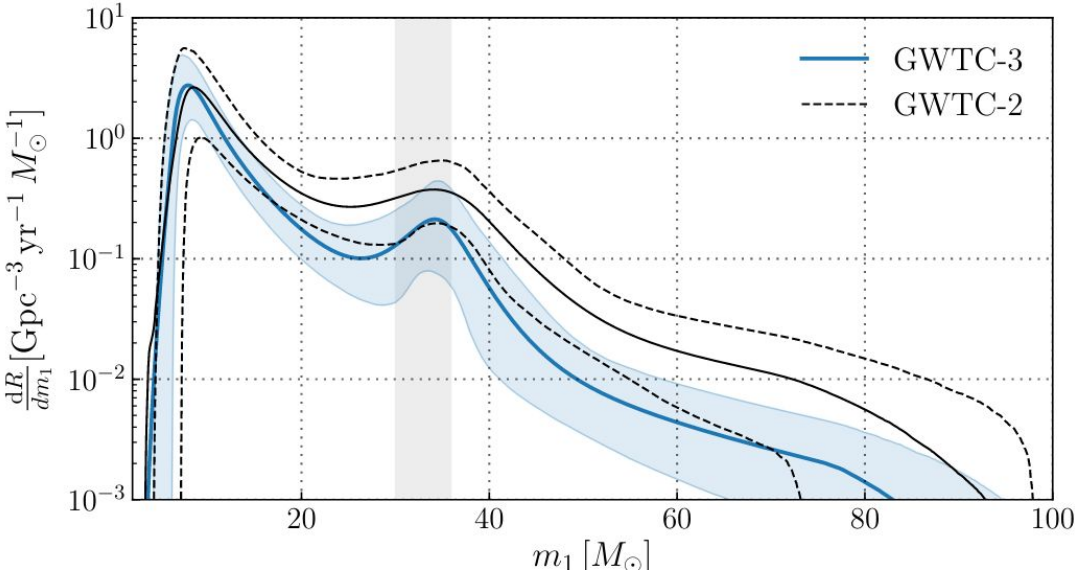
Predicted observed:




Kovetz+ 2017

# Predictions:

- Two populations:
  - Stellar remnants
  - Primordial




Primary BH mass:

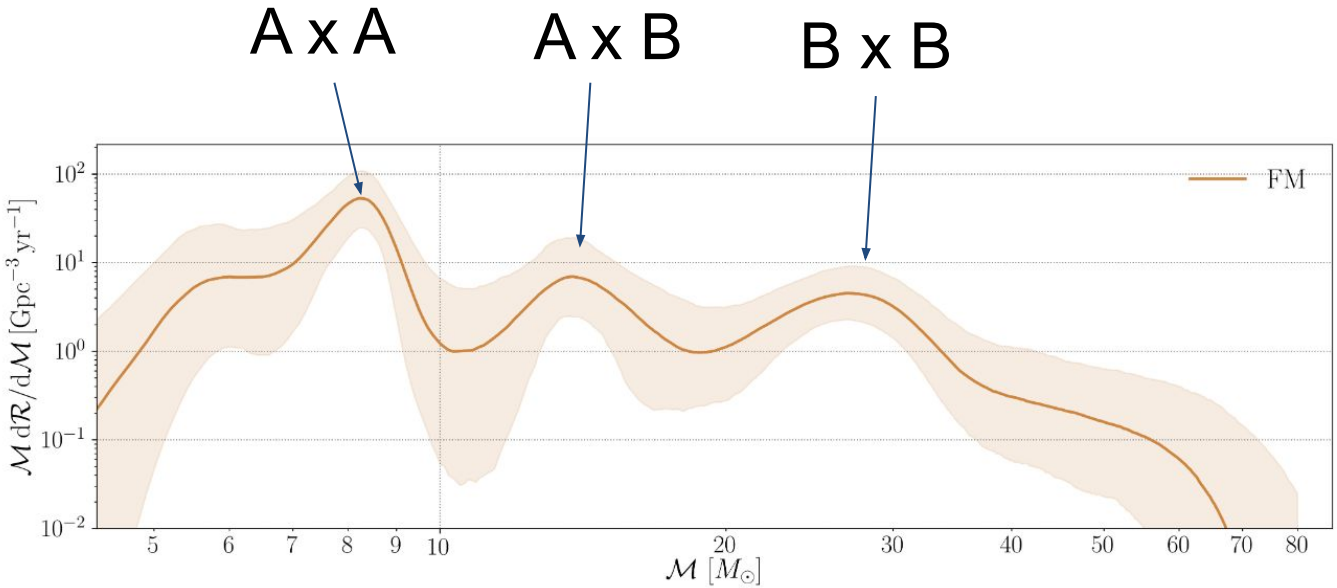
(after selection)

Model with Gaussian + power law

# Predictions:

## LIGO Mass function 2111.03634 : Pop A & B

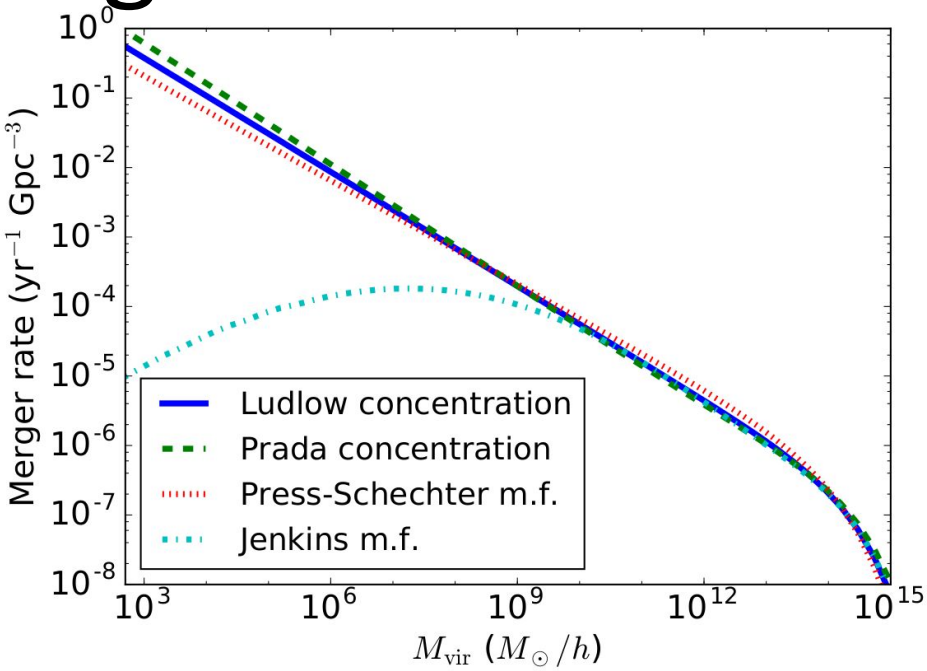
Chirp mass: $\mathcal{M} = (m_1 m_2)^{3/5}/(m_1 + m_2)^{1/5}$



# Predictions:

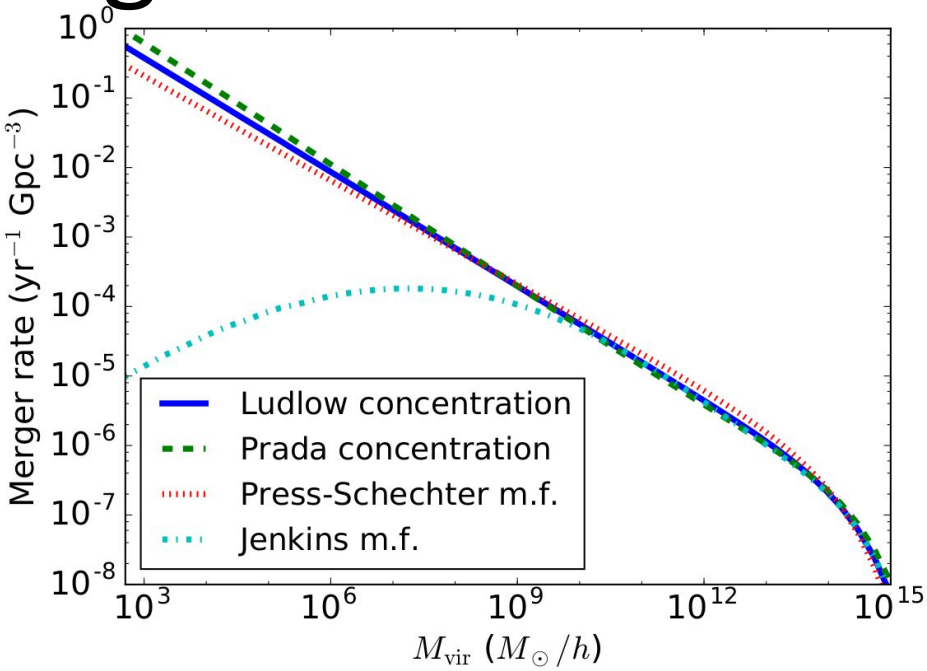
- Merger rate: $2 \pm 1\ \mathrm{yr}^{-1}\mathrm{Gpc}^{-3}$
- Merger rate for Gaussian component is poorly estimated but best-fit is: $2\ \mathrm{yr}^{-1}\mathrm{Gpc}^{-3}$

# Merger Rate Estimate Questions



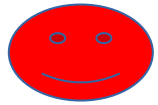
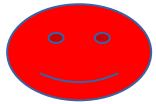
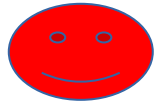

- Merger rate depends on profile of small halos
- Smaller than in N-body sims

# Merger Rate Estimate Questions




- Which are the smallest halos hosting PBH mergers?

# Predictions:

- Misaligned spins: dynamical origin 
- Two populations: 
- Merger rate: $2 \pm 1\ \mathrm{yr}^{-1}\mathrm{Gpc}^{-3}$ 

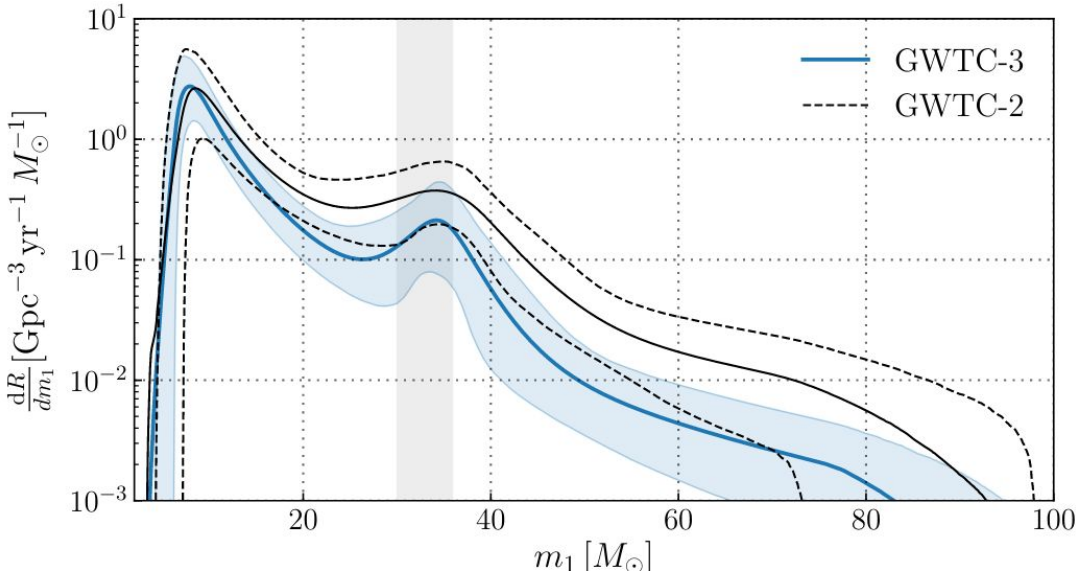
Need improved calculation with sims

# Binary Black Holes

How do binaries form?

- End points of stellar binary evolution
- Spins suggest not
- Dynamically from a globular cluster
- Rates suggest maybe not

**Primordial Black Holes?**

# Did LIGO detect dark matter?

Maybe?