Recent Developments in the Physics of PBHs

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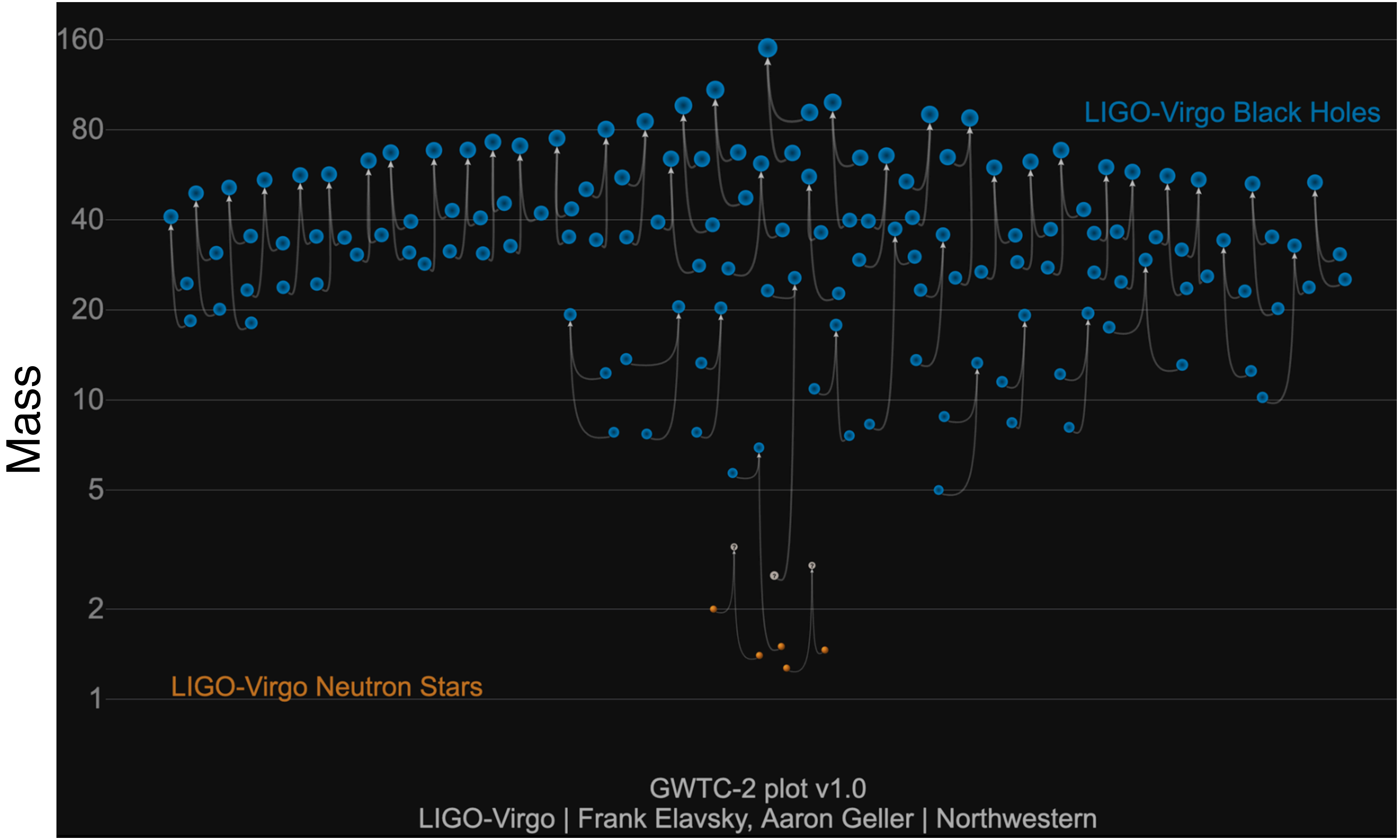
Plan of the talk

- PBHs and GWTC-2
- PBHs and NANOGrav 12.5 yr

In collaboration with V. Baibhav, E. Berti,V. De Luca,
V. Desjacques, G. Franciolini, P. Pani, K. Wong

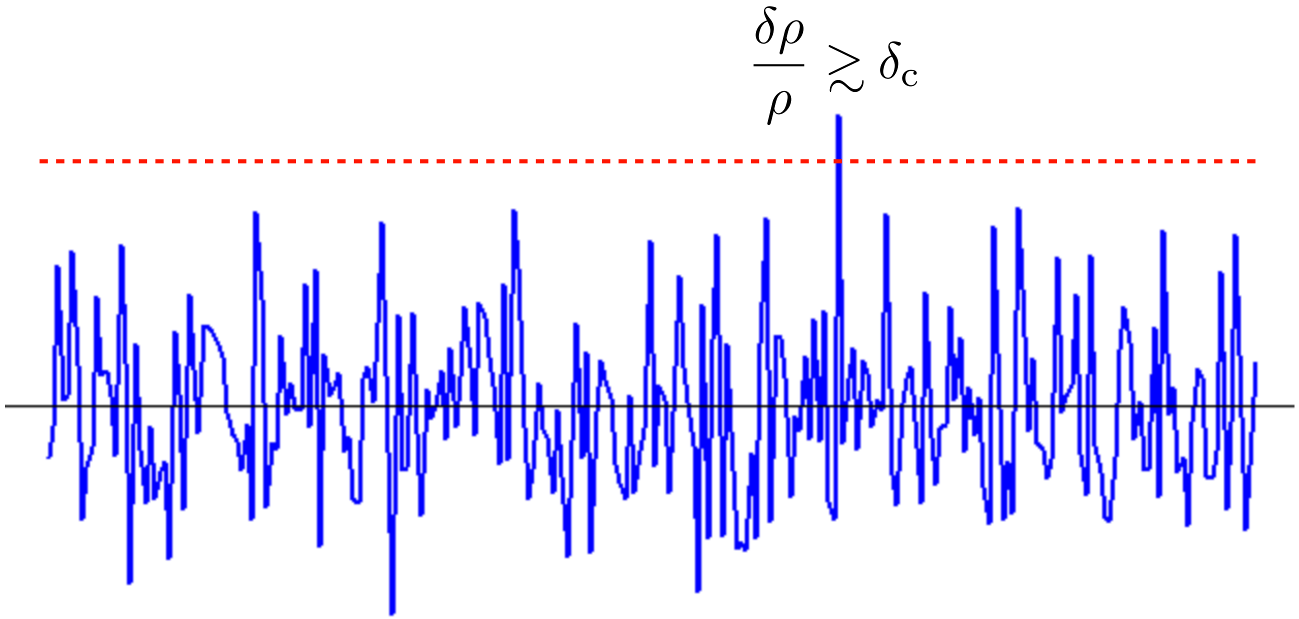
2009.04731 & 2011.01865

Motivation


Mass
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
LIGO-Virgo Neutron Stars
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

Assumption:

PBHs are originated from peaks of the density contrast



PBHs are rare events, tail of the distribution

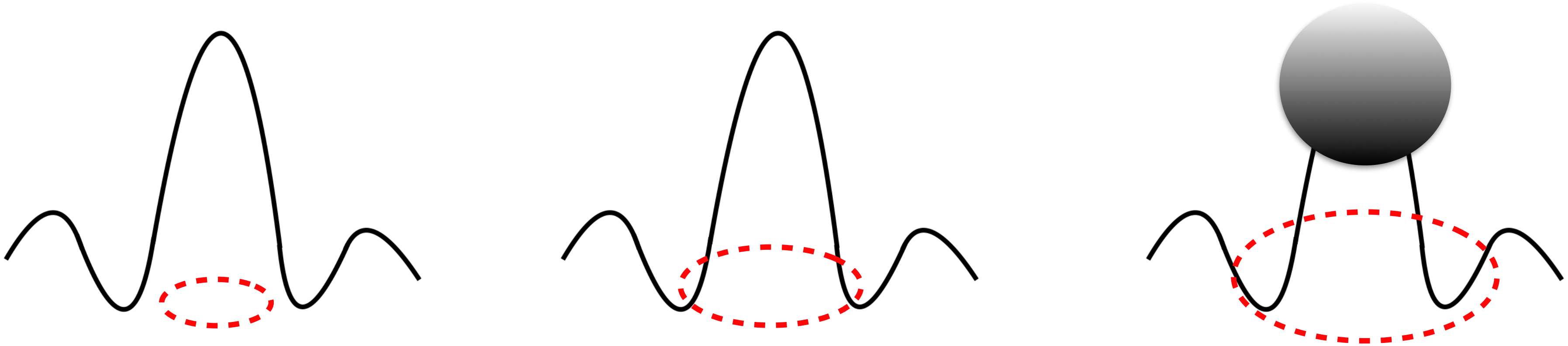
One possible mechanism: large fluctuations from inflation

Assumption:

PBHs are originated from peaks of the density contrast

$$\frac{\delta\rho}{\rho} \gtrsim \delta_{\rm c}$$

$$M_{\rm PBH} \sim M_{\rm H}$$



$$\beta(M) = \int_{\delta_{\rm c}}^{\infty} \frac{{\rm d}\delta}{\sqrt{2\pi}\sigma_\delta} e^{-\delta^2/2\sigma_\delta^2} \qquad \sigma_\delta^2 = \int_0^\infty {\rm d}\ln k W^2(k, R_H)\mathcal{P}_\delta(k)$$

Lot of work to go beyond the standard Gaussian lore

See I. Musco et al. (2020) for a simple prescription to calculate the threshold, including horizon crossing non-linear effects

Properties of PBHs at formation

The PBH mass function at formation

Mass distribution dependent on the curvature perturbation spectrum and statistical properties

Standard parametrisation

$$\psi(M_{\rm PBH}) = \frac{1}{\sqrt{2\pi} M_{\rm PBH}\sigma} \exp\left(-\frac{\ln^2(M_{\rm PBH}/M_c)}{2\sigma^2}\right)$$

May have different forms, e.g. if the curvature perturbation is broad, but still peaked at a given mass

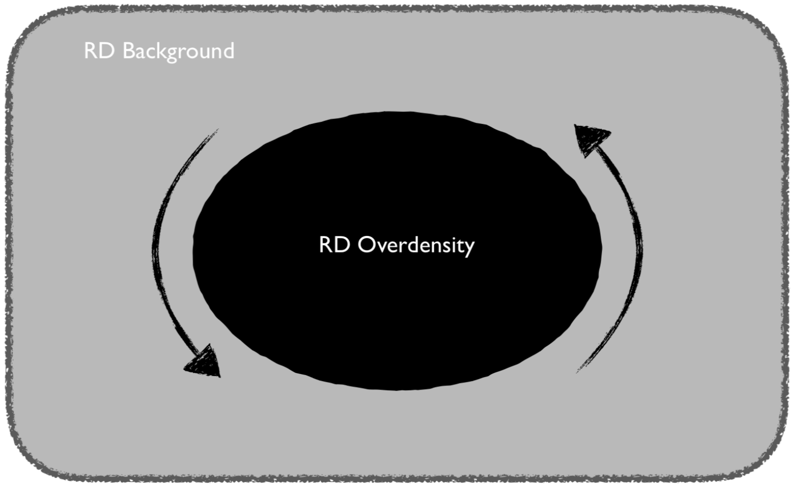
V. De Luca et al. (2020)

The spin of PBHs at formation is small

- PBHs originate from peaks, that is from *maxima* of the local density contrast. Need peak theory to obtain the probability distribution of the spin

- The spin results from the action of the torques generated by the gravitational tidal forces upon horizon crossing

- It is a *first-order* effect in perturbation theory when accounting for the fact that the collapse is not spherical



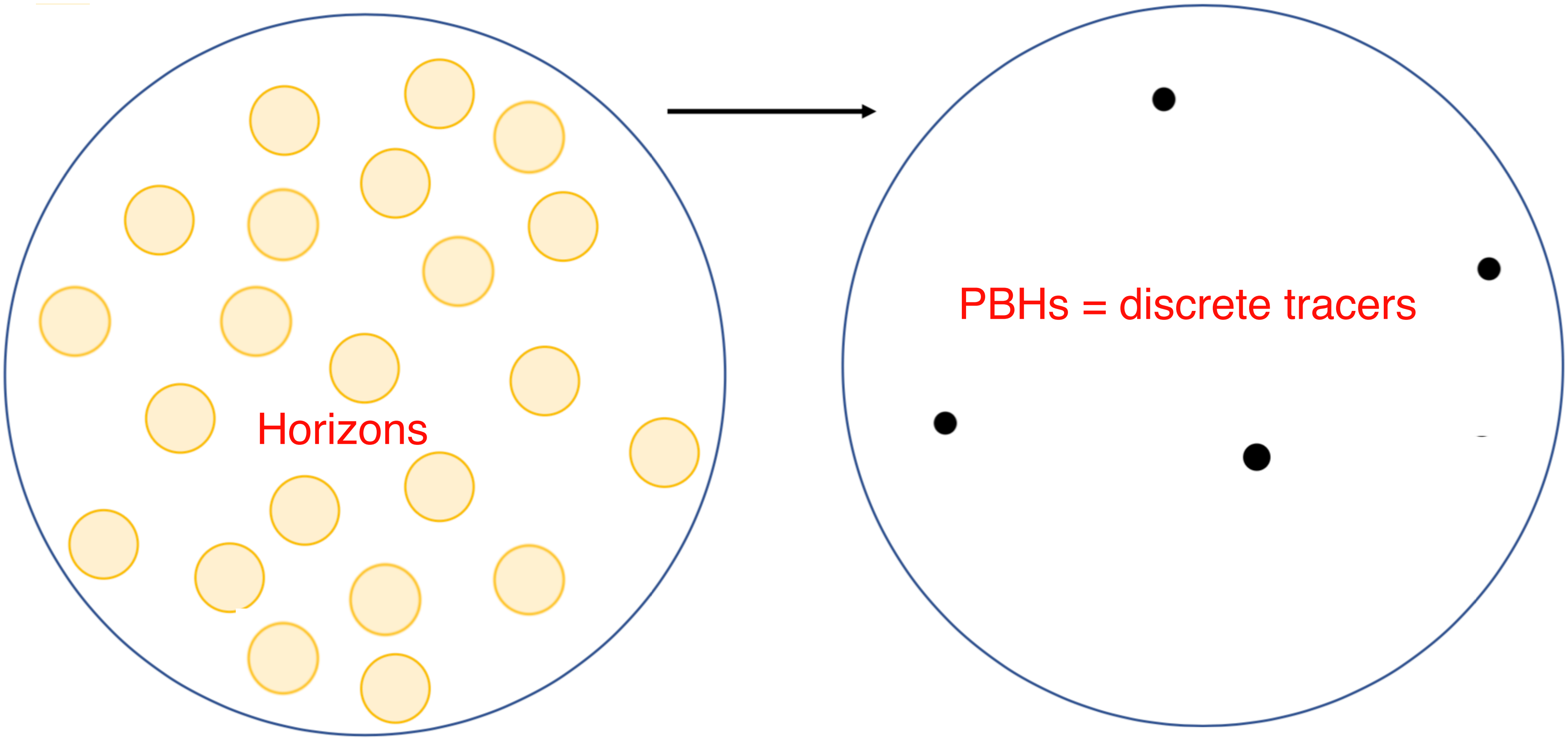
$$\vec{\chi} = \vec{S}/G_N M^2_{\rm PBH}$$

$$\chi_{\rm i} \sim 10^{-2}\sqrt{1-\gamma^2}$$

Shape of the density power spectrum

De Luca et al. (2018)

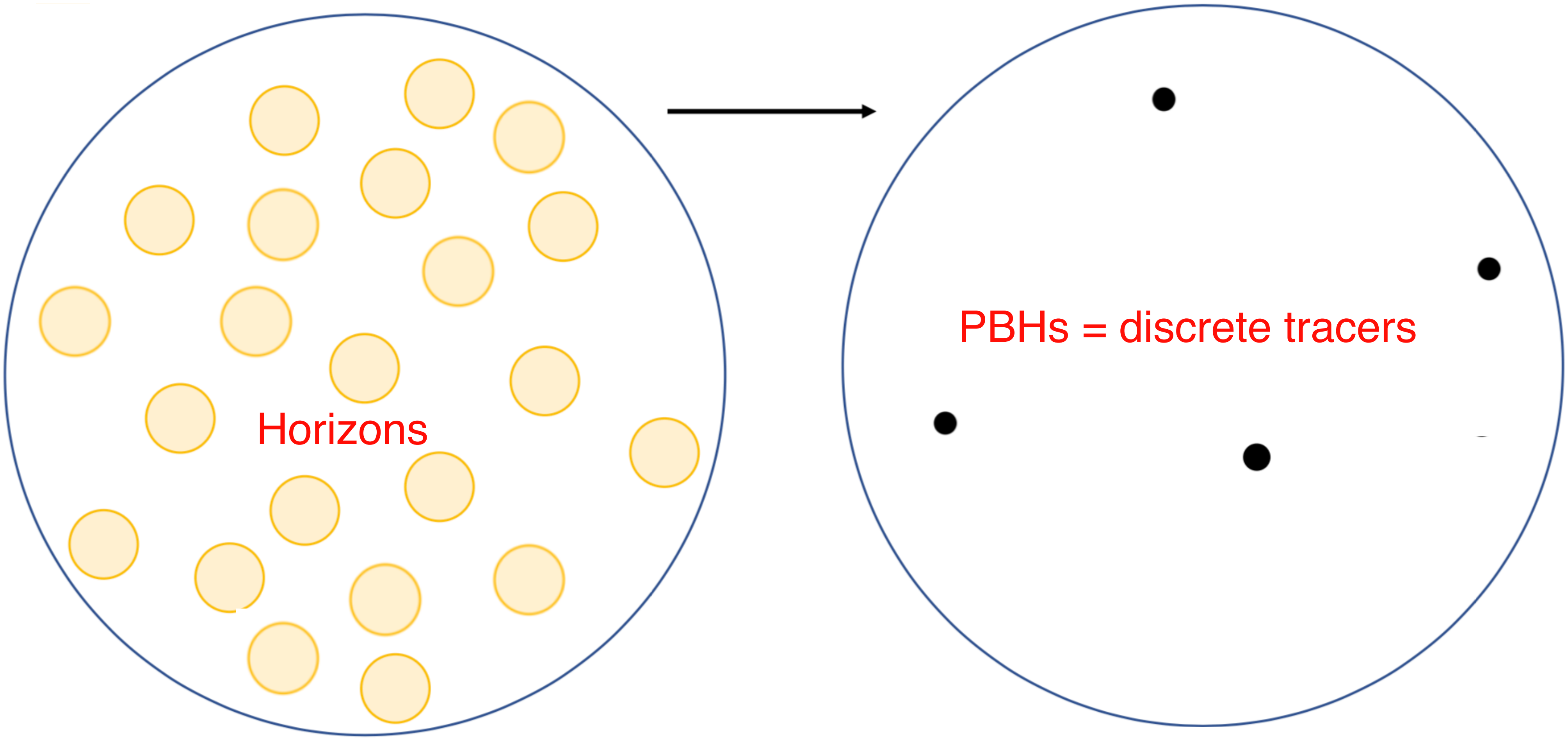
PBHs are not clustered at formation



$$\left\langle \frac{\delta\rho_{\rm PBH}(\vec{x},z)}{\bar{\rho}_{\rm DM}} \frac{\delta\rho_{\rm PBH}(0,z)}{\bar{\rho}_{\rm DM}} \right\rangle = \frac{f^2_{\rm PBH}}{n_{\rm PBH}} \delta_{\rm D}(\vec{x}) + \xi(x,z)$$

with V. Desjaques (2018)

PBHs are not clustered at formation

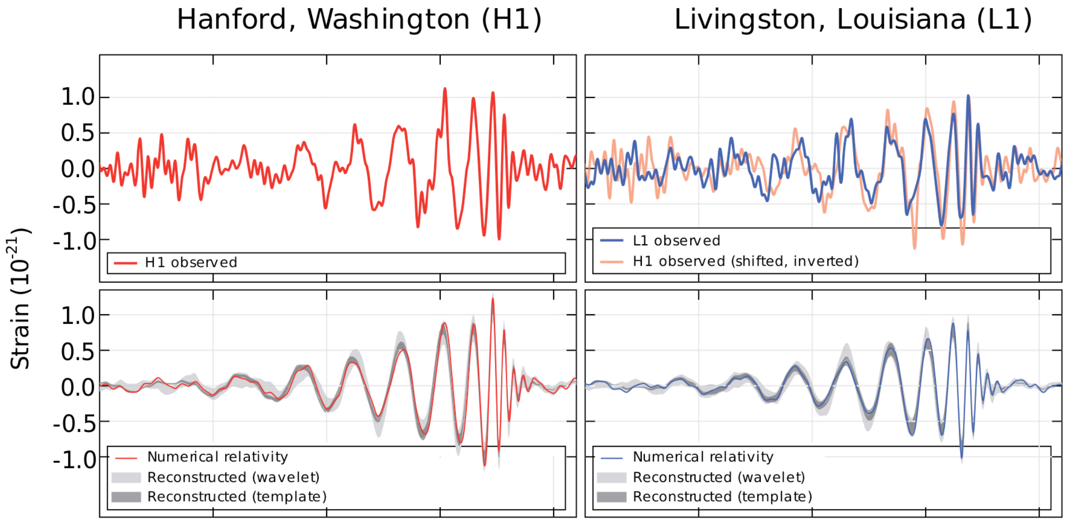


True also if the PBH mass function is broad
(understandable from the excursion set theory)

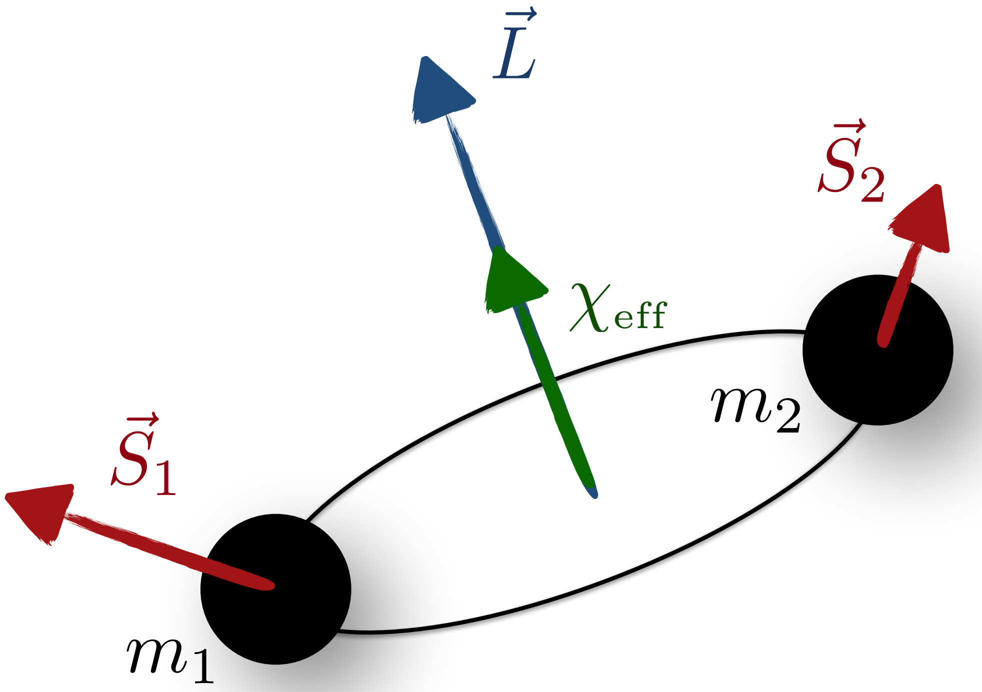
with Dizgah and Franciolini (2019)

GWTC-2 and PBHs

BH binary



GW150914, LIGO (2016)



Waveforms dependent on the binary event parameters

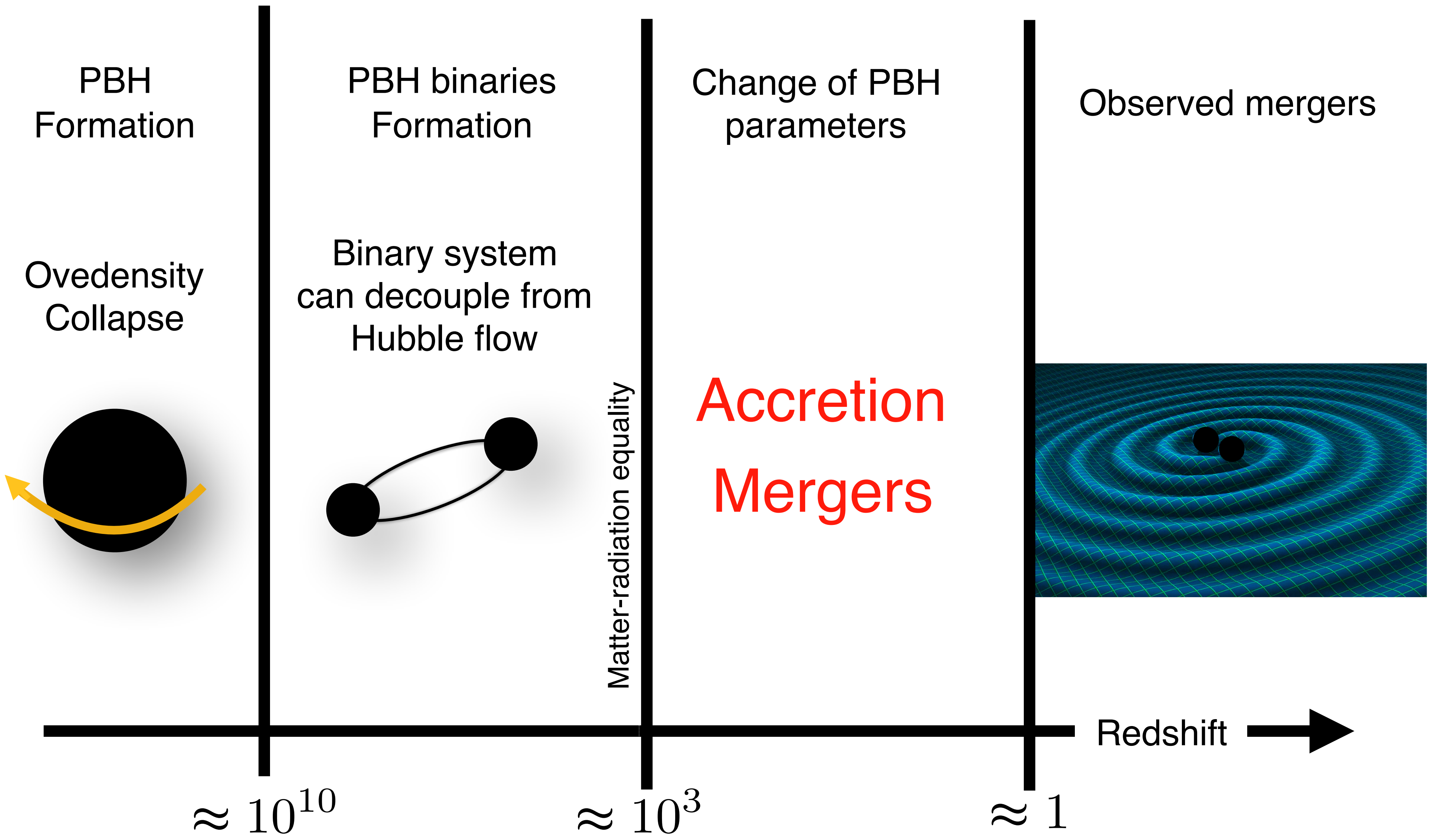
$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

$$q = m_2 / m_1$$

$$\chi_{\rm eff} = \frac{\vec{S}_1/m_1 + \vec{S}_2/m_2}{m_1 + m_2} \cdot \hat{L}$$

$$\ldots$$

PBH evolution



Accretion onto isolated PBHs

For $f_{\mathrm{PBH}} < 1$ PBHs coexist with another DM component in the universe

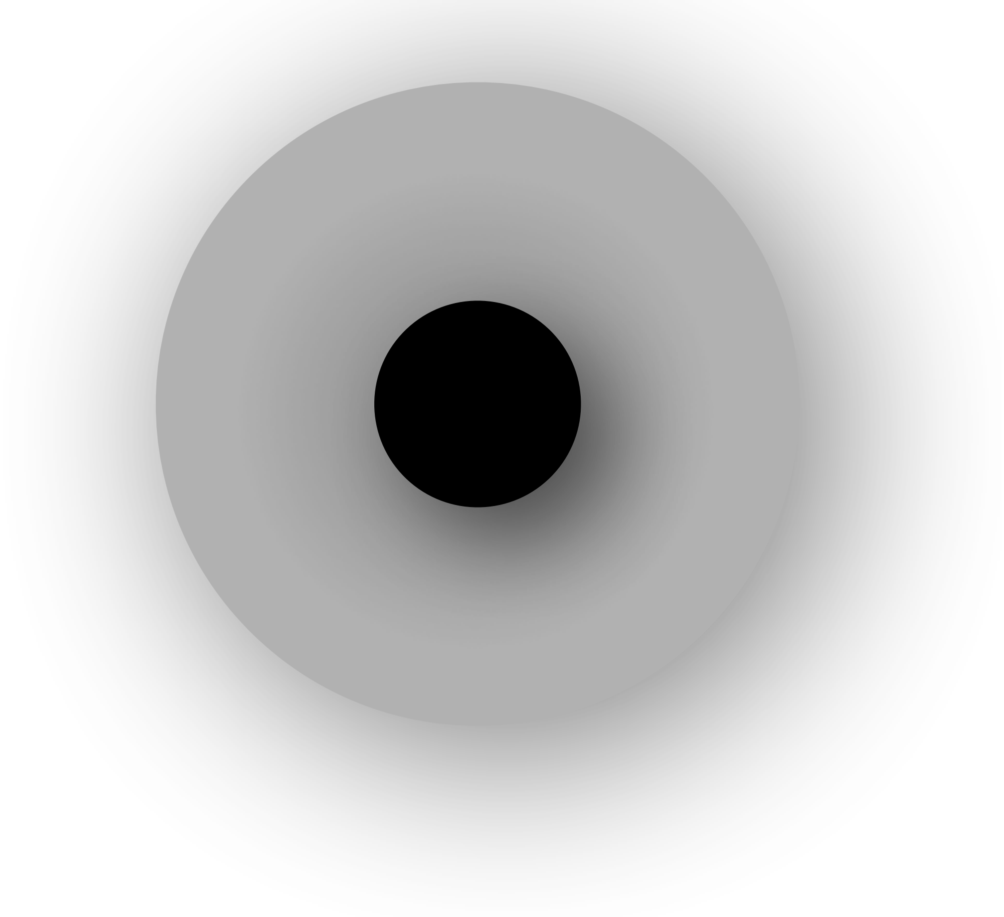
A DM halo builds up around the PBHs enhancing accretion

(larger gravitational potential well)

$$M_h(z) \approx 3 M_{\mathrm{PBH}} \left(\frac{1000}{1+z} \right)$$

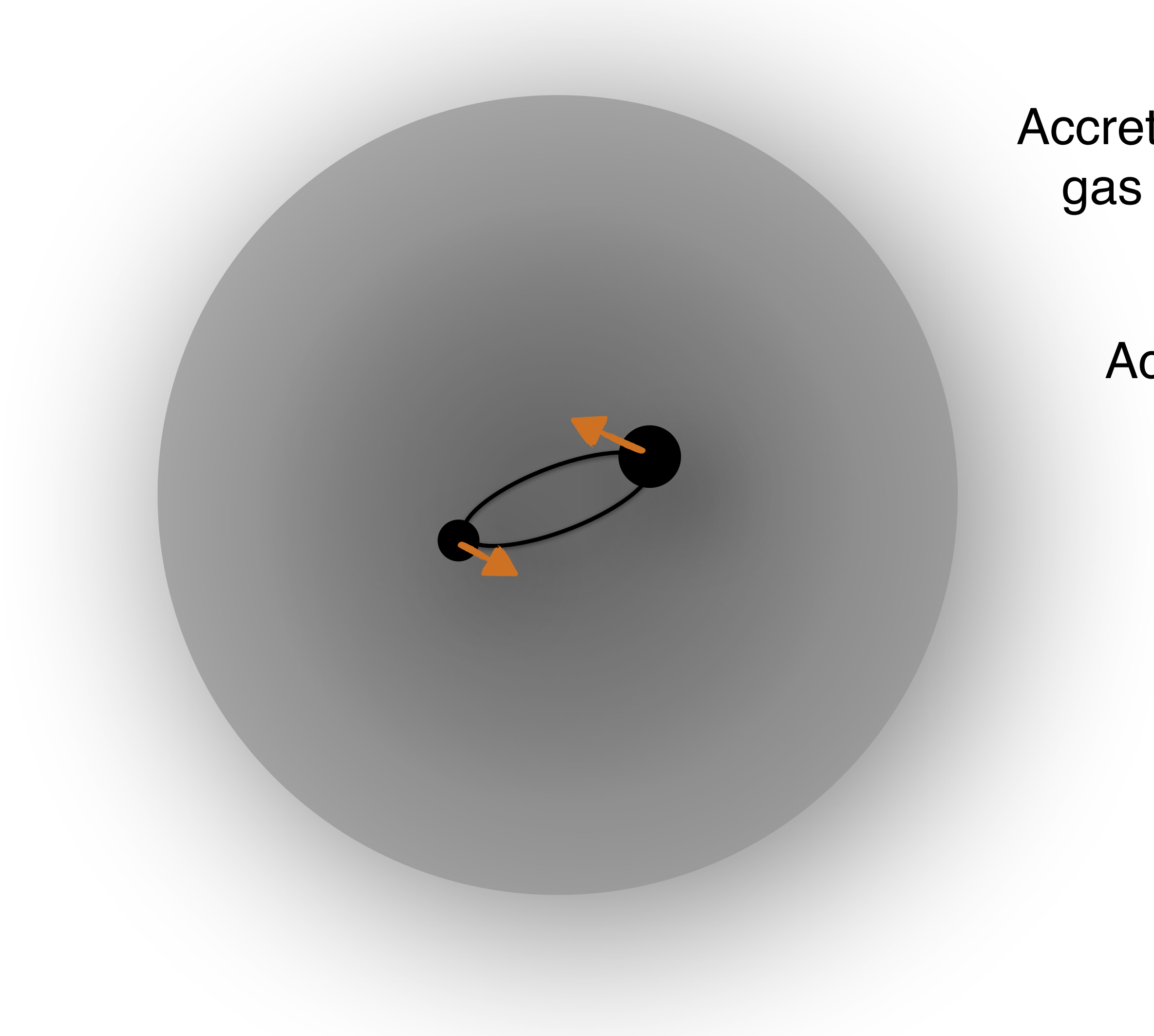
Bondy-Hoyle accretion from the surrounding baryonic fluid

$$\dot{M} = 4\pi \lambda m_H n_{\mathrm{gas}} v_{\mathrm{eff}}^{-3} M^2$$



M. Ricotti et al. (2005), …

Accretion onto PBH binaries



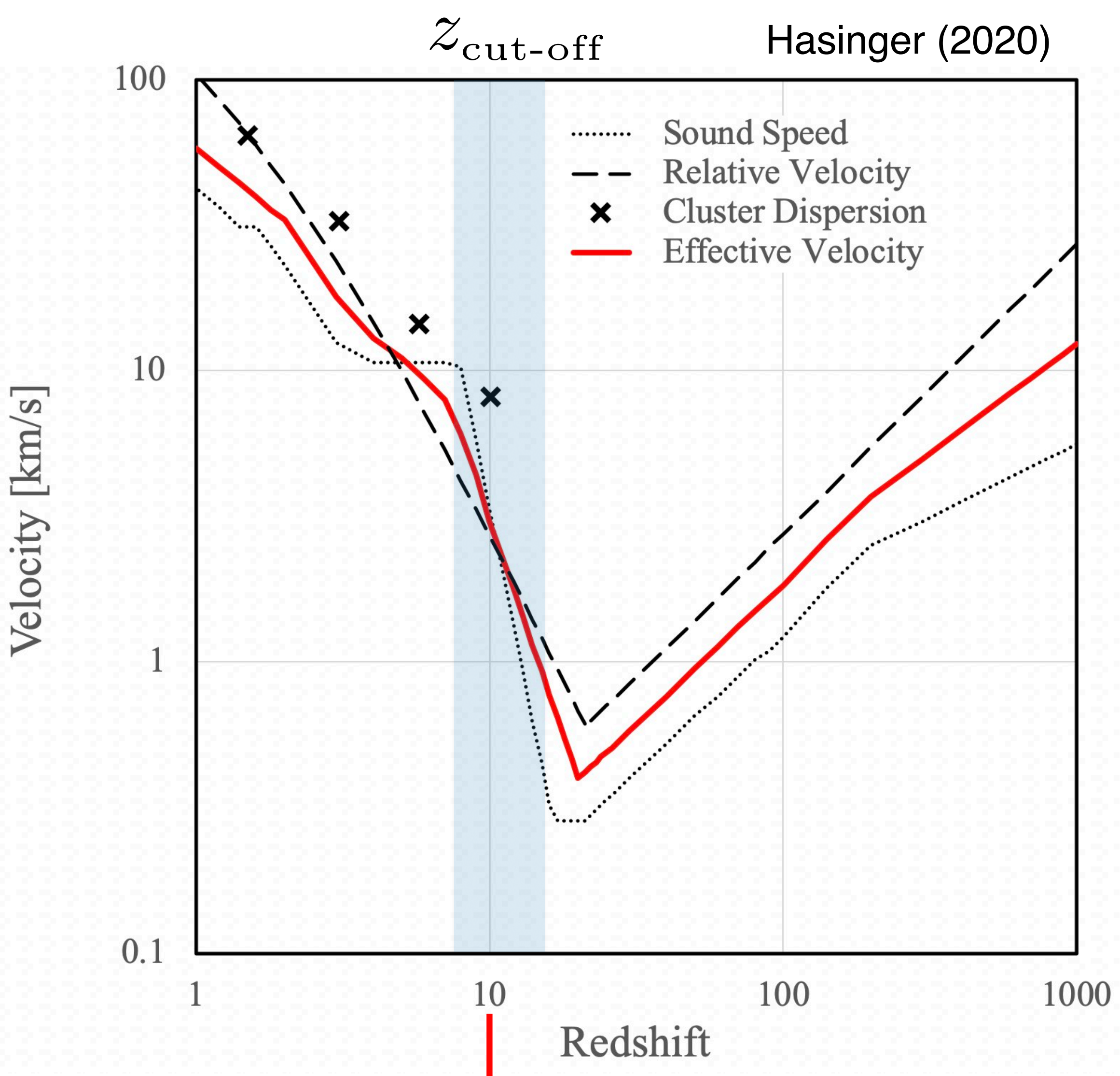
Accretion on the system enhances the gas density around the PBH binary

Accretion on the sigle PBH modulated by masses and orbital velocities

$$\dot{M}_1 = \dot{M} \frac{1}{\sqrt{2(1+q)}}$$

$$\dot{M}_2 = \dot{M} \sqrt{\frac{q}{2(1+q)}}$$

- The smaller PBH always experiences a larger relative accretion
- PBH can experience accretion for $M \gtrsim \mathcal{O}(10) M_\odot$



Structure formation
reionization epoch

- Virialised velocities
- Higher temperatures

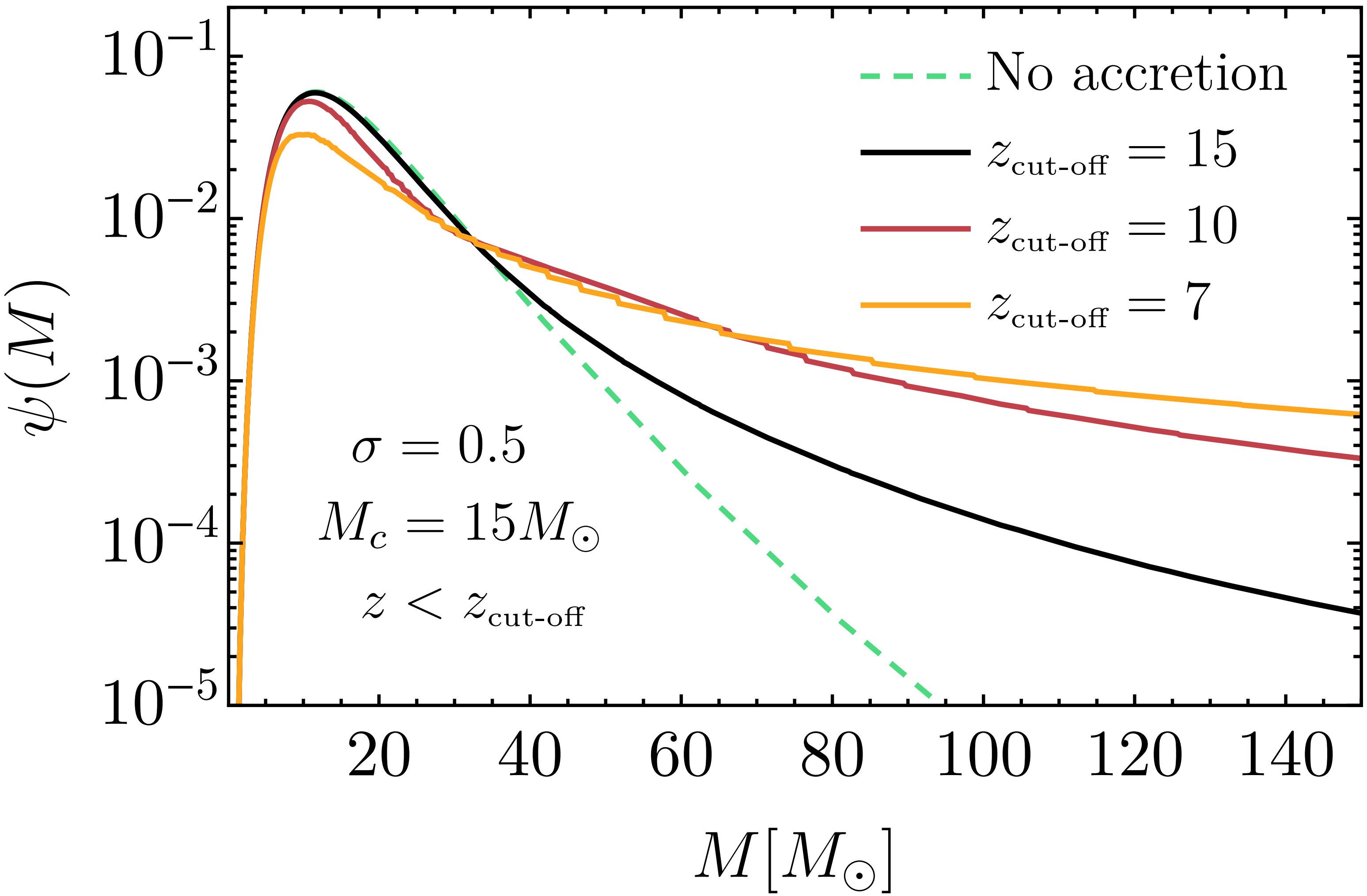
$$\dot{M} \approx \left(v_{\text{rel}}^2 + c_s^2\right)^{-3/2}$$

Strong suppression around

$z_{\text{cut-off}}$

Uncertainties
in the accretion model
accounted for by
varying the cut-off

PBH mass function evolution

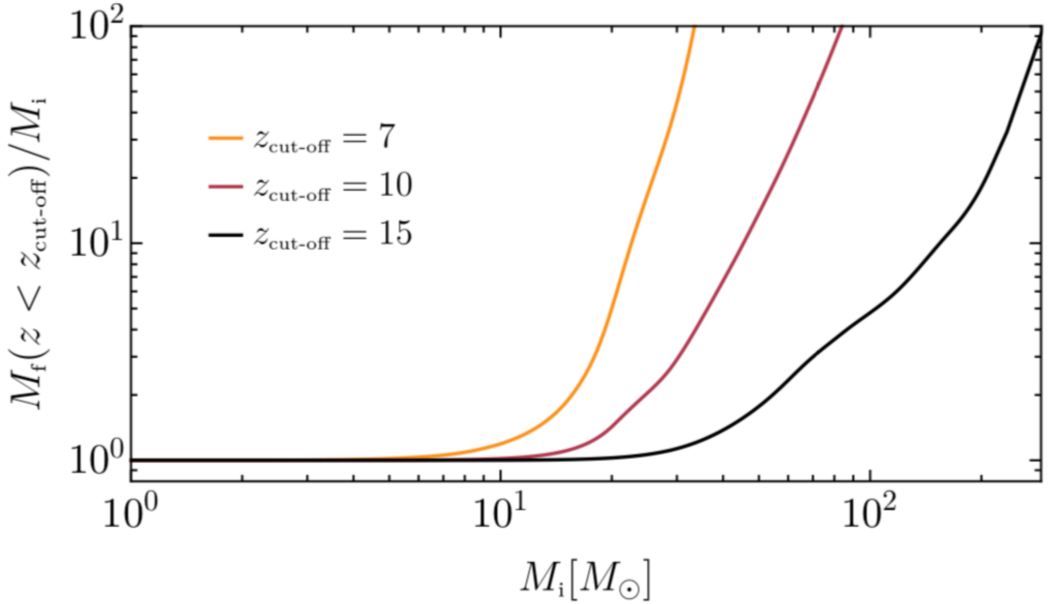


Non-linear mass evolution enhances large-mass tails

Fitting the GWTC-2 large mass tail

will push towards smaller central masses of the mass function

PBH mass evolution in binaries

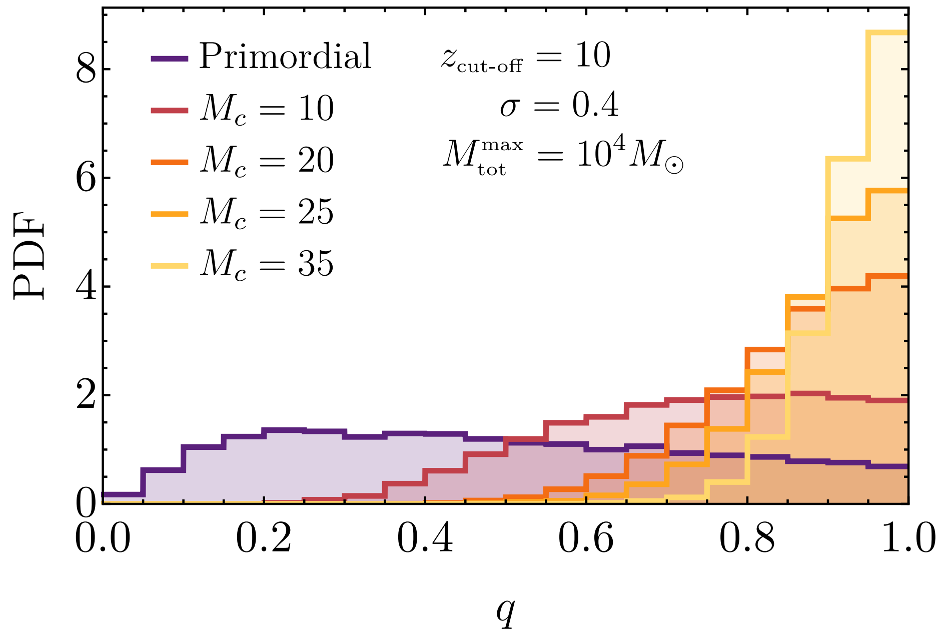


Large impact on masses, depending on the strength of accretion

$$\dot{q} = q \left(\frac{\dot{M}_2}{M_2} - \frac{\dot{M}_1}{M_1} \right)$$

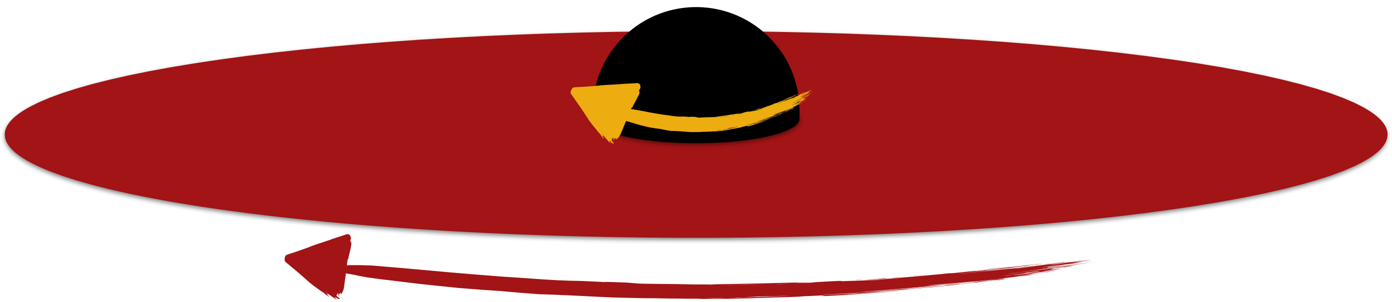
Evolution of the mass ratio distribution towards equal-masses

Same MF initial width, at larger masses



PBH spin evolution

If matter angular momentum is
large enough, an accreting disk forms,
leading to a spin growth



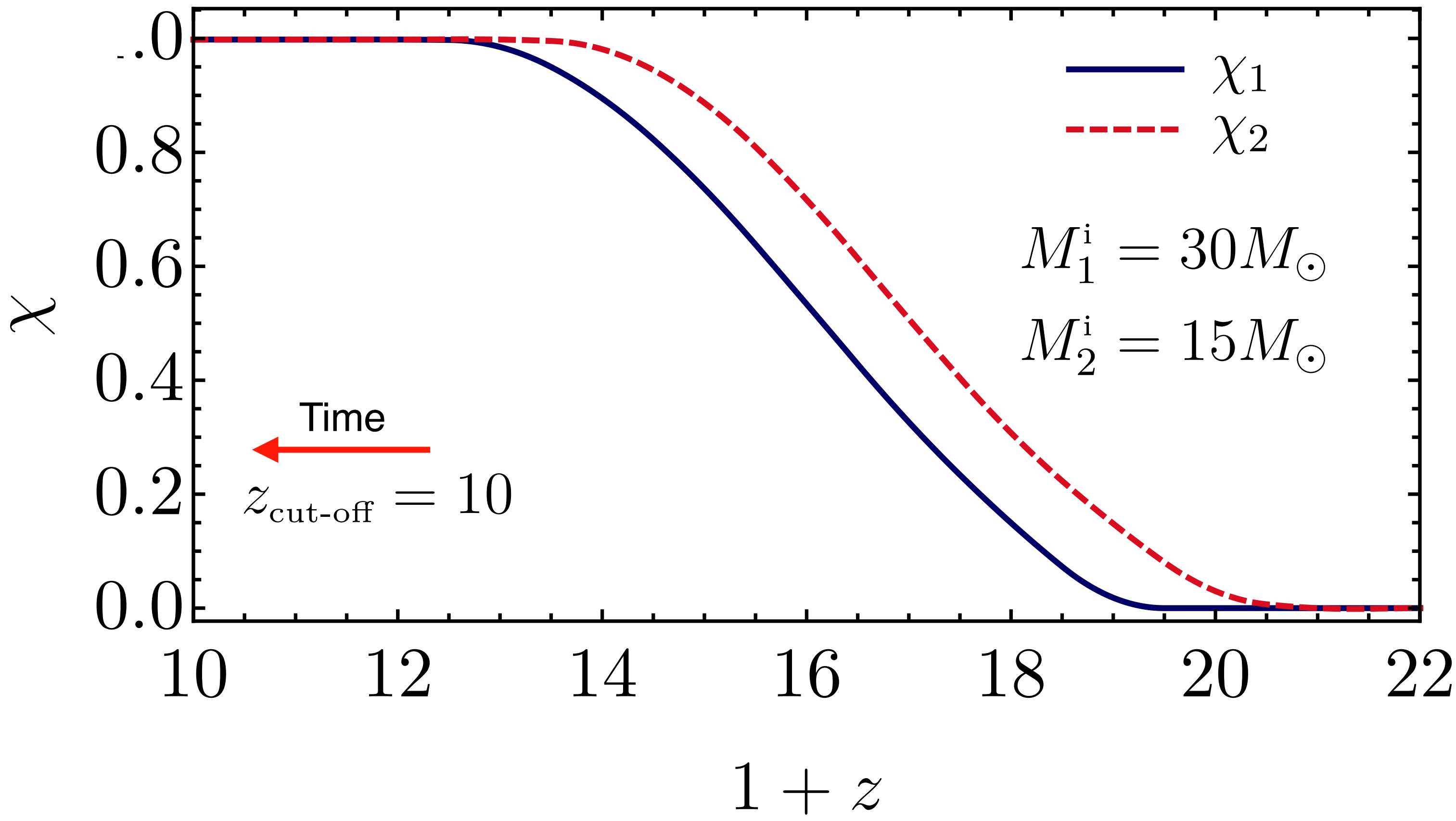
Angular momentum transfer
between gas and PBH

$$\dot{\chi} = g(\chi)\frac{\dot{M}}{M}$$

by solving the geodesic model of disk accretion

Bardeen et al. (1972)

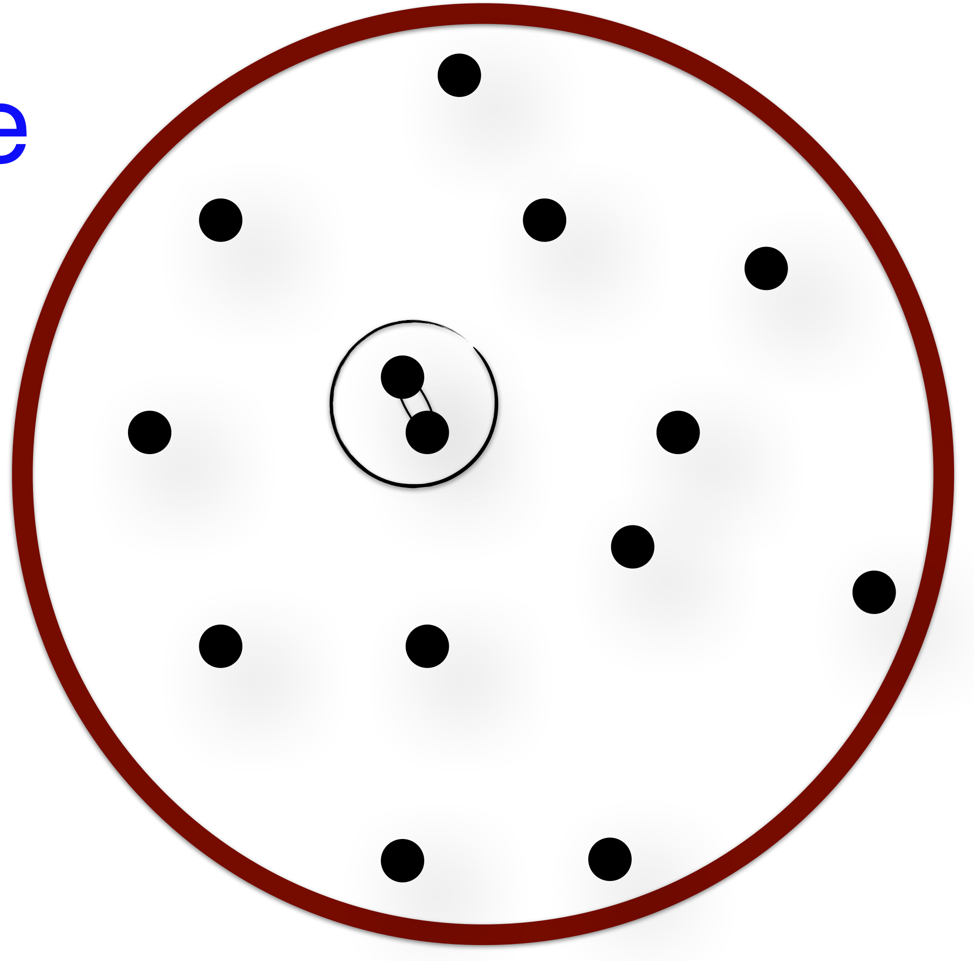
Spins pushed towards extremality



- Uncorrelated spin orientation
- Effective spin spreads around zero
- Accretion: low/large mass - low/large spin correlation

V. De Luca et al. (2020)

Merger rate



- Initial spatial Poisson distribution
- Random decoupling of binary systems

Compute probability of decoupling and the binary initial geometry

- Semi-major axis
- Eccentricity

M. Raidal et al (2018)

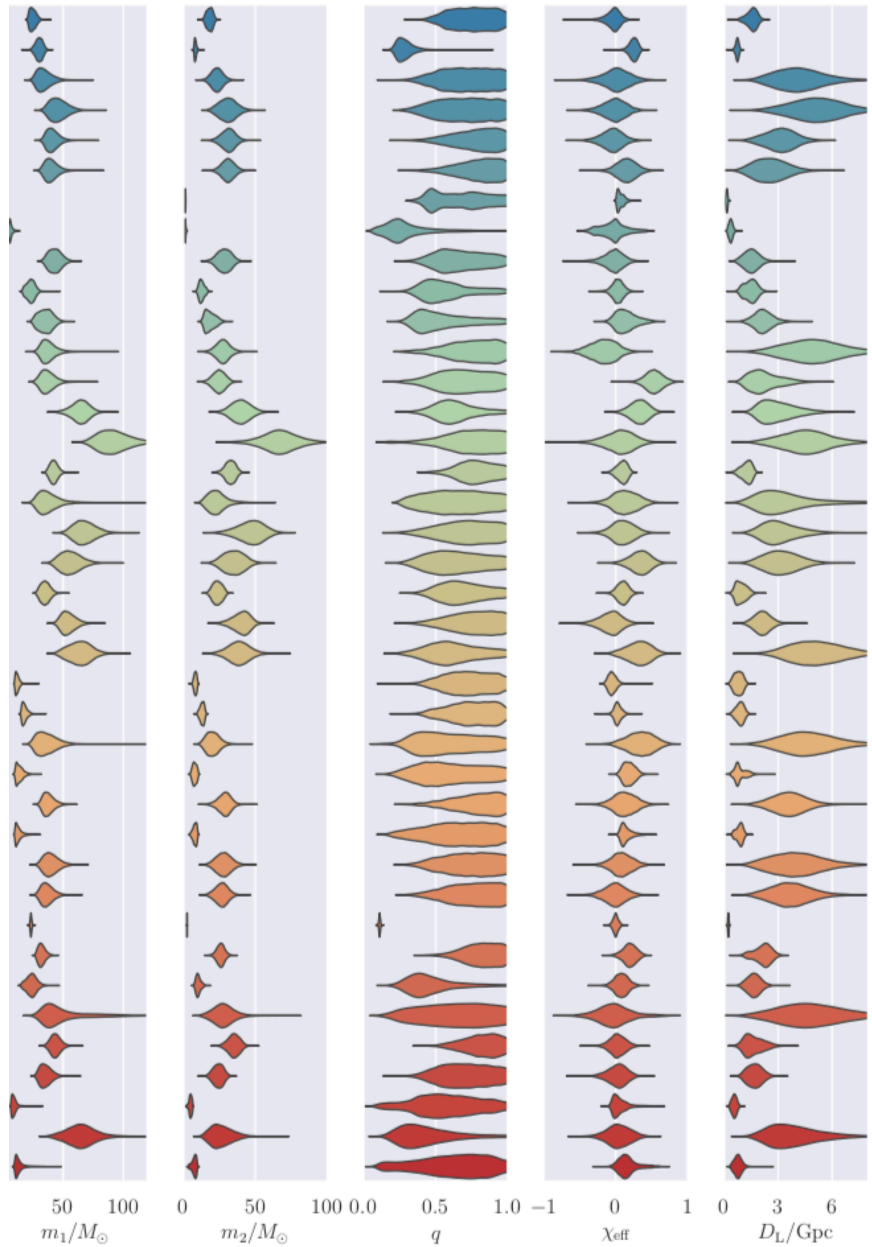
$$\frac{\mathrm{d}R}{\mathrm{d}m_1\mathrm{d}m_2} = \frac{1.6\times 10^6}{\mathrm{Gpc}^3\,\mathrm{yr}} f_{\rm PBH}^{\frac{53}{37}} \eta^{-\frac{34}{37}} \left(\frac{t}{t_0}\right)^{-\frac{34}{37}} \left(\frac{M_{\rm tot}}{M_\odot}\right)^{-\frac{32}{37}} S\left(M_{\rm tot}, f_{\rm PBH}\right) \mathcal{A}_{\rm acc}(m_j)\psi(m_1)\psi(m_2)$$

- Accretion hardens the binaries
- Larger masses leads to shorter mergers

V. De Luca et al. (2020)

GWTC-2=O1+O2+O3a

Event	M ($M_\odot$)	$\mathcal{M}$ ($M_\odot$)	m_1 ($M_\odot$)	m_2 ($M_\odot$)	$\chi_{\rm eff}$	D_L (Gpc)	z	M_f ($M_\odot$)	χ_f	$\Delta\Omega$ (deg^2)	SNR
GW190408_181802	$42.9^{+4.1}_{-2.9}$	$18.3^{+1.8}_{-1.2}$	$24.5^{+5.1}_{-3.4}$	$18.3^{+3.2}_{-3.5}$	$-0.03^{+0.13}_{-0.19}$	$1.58^{+0.40}_{-0.59}$	$0.30^{+0.06}_{-0.10}$	$41.0^{+3.8}_{-2.7}$	$0.67^{+0.06}_{-0.07}$	140	$15.3^{+0.2}_{-0.3}$
GW190412	$38.4^{+3.8}_{-3.7}$	$13.3^{+0.4}_{-0.3}$	$30.0^{+4.7}_{-5.1}$	$8.3^{+1.6}_{-0.9}$	$0.25^{+0.08}_{-0.11}$	$0.74^{+0.14}_{-0.17}$	$0.15^{+0.03}_{-0.03}$	$37.3^{+3.9}_{-3.9}$	$0.67^{+0.05}_{-0.06}$	21	$18.9^{+0.2}_{-0.3}$
GW190413_052954	$56.9^{+13.1}_{-8.9}$	$24.0^{+5.4}_{-3.7}$	$33.4^{+12.4}_{-7.4}$	$23.4^{+6.7}_{-6.3}$	$0.01^{+0.29}_{-0.33}$	$4.10^{+2.41}_{-1.89}$	$0.66^{+0.30}_{-0.27}$	$54.3^{+12.4}_{-8.4}$	$0.69^{+0.12}_{-0.13}$	1400	$8.9^{+0.4}_{-0.8}$
GW190413_134308	$76.1^{+15.9}_{-10.6}$	$31.9^{+7.3}_{-4.6}$	$45.4^{+13.6}_{-9.6}$	$30.9^{+10.2}_{-9.6}$	$-0.01^{+0.24}_{-0.28}$	$5.15^{+2.44}_{-2.34}$	$0.80^{+0.30}_{-0.31}$	$72.8^{+15.2}_{-10.3}$	$0.69^{+0.10}_{-0.12}$	520	$10.0^{+0.4}_{-0.5}$
GW190421_213856	$71.8^{+12.5}_{-8.6}$	$30.7^{+5.5}_{-3.9}$	$40.6^{+10.4}_{-6.6}$	$31.4^{+7.5}_{-8.2}$	$-0.05^{+0.23}_{-0.26}$	$3.15^{+1.37}_{-1.42}$	$0.53^{+0.18}_{-0.21}$	$68.6^{+11.7}_{-8.1}$	$0.68^{+0.10}_{-0.11}$	1000	$10.7^{+0.2}_{-0.4}$
GW190424_180648	$70.7^{+13.4}_{-9.8}$	$30.3^{+5.7}_{-4.2}$	$39.5^{+10.9}_{-6.9}$	$31.0^{+7.4}_{-7.3}$	$0.15^{+0.22}_{-0.22}$	$2.55^{+1.56}_{-1.33}$	$0.45^{+0.22}_{-0.21}$	$67.1^{+12.5}_{-9.2}$	$0.75^{+0.08}_{-0.09}$	26000	$10.4^{+0.2}_{-0.4}$
GW190425	$3.4^{+0.3}_{-0.1}$	$1.44^{+0.02}_{-0.02}$	$2.0^{+0.6}_{-0.3}$	$1.4^{+0.3}_{-0.3}$	$0.06^{+0.11}_{-0.05}$	$0.16^{+0.07}_{-0.07}$	$0.03^{+0.01}_{-0.02}$	–	–	9900	$12.4^{+0.3}_{-0.4}$
GW190426_152155	$7.2^{+3.5}_{-1.5}$	$2.41^{+0.08}_{-0.08}$	$5.7^{+4.0}_{-2.3}$	$1.5^{+0.8}_{-0.5}$	$-0.03^{+0.33}_{-0.30}$	$0.38^{+0.19}_{-0.16}$	$0.08^{+0.04}_{-0.03}$	–	–	1400	$8.7^{+0.5}_{-0.6}$
GW190503_185404	$71.3^{+9.3}_{-8.0}$	$30.1^{+4.2}_{-4.0}$	$42.9^{+9.2}_{-7.8}$	$28.5^{+7.5}_{-7.9}$	$-0.02^{+0.20}_{-0.26}$	$1.52^{+0.71}_{-0.66}$	$0.29^{+0.11}_{-0.11}$	$68.2^{+8.7}_{-7.5}$	$0.67^{+0.09}_{-0.12}$	94	$12.4^{+0.2}_{-0.3}$
GW190512_180714	$35.6^{+3.9}_{-3.4}$	$14.5^{+1.3}_{-1.0}$	$23.0^{+5.4}_{-5.7}$	$12.5^{+3.5}_{-2.5}$	$0.03^{+0.13}_{-0.13}$	$1.49^{+0.53}_{-0.59}$	$0.28^{+0.09}_{-0.10}$	$34.2^{+3.9}_{-3.4}$	$0.65^{+0.07}_{-0.07}$	230	$12.2^{+0.2}_{-0.4}$
GW190513_205428	$53.6^{+8.6}_{-5.9}$	$21.5^{+3.6}_{-1.9}$	$35.3^{+9.6}_{-9.0}$	$18.1^{+7.3}_{-4.2}$	$0.12^{+0.29}_{-0.18}$	$2.16^{+0.94}_{-0.80}$	$0.39^{+0.14}_{-0.13}$	$51.3^{+8.1}_{-5.8}$	$0.69^{+0.14}_{-0.12}$	490	$12.9^{+0.3}_{-0.4}$
GW190514_065416	$64.2^{+16.6}_{-9.6}$	$27.4^{+6.9}_{-4.3}$	$36.9^{+13.4}_{-7.3}$	$27.5^{+8.2}_{-7.7}$	$-0.16^{+0.28}_{-0.32}$	$4.93^{+2.76}_{-2.41}$	$0.77^{+0.34}_{-0.33}$	$61.6^{+16.0}_{-9.2}$	$0.64^{+0.11}_{-0.14}$	2400	$8.2^{+0.3}_{-0.6}$
GW190517_055101	$61.9^{+10.0}_{-9.6}$	$26.0^{+4.2}_{-4.0}$	$36.4^{+11.8}_{-7.8}$	$24.8^{+6.9}_{-7.1}$	$0.53^{+0.20}_{-0.19}$	$2.11^{+1.79}_{-1.00}$	$0.38^{+0.26}_{-0.16}$	$57.8^{+9.4}_{-9.1}$	$0.87^{+0.05}_{-0.07}$	460	$10.7^{+0.4}_{-0.6}$
GW190519_153544	$104.2^{+14.5}_{-14.9}$	$43.5^{+6.8}_{-6.8}$	$64.5^{+11.3}_{-13.2}$	$39.9^{+11.0}_{-10.6}$	$0.33^{+0.19}_{-0.22}$	$2.85^{+2.02}_{-1.14}$	$0.49^{+0.27}_{-0.17}$	$98.7^{+13.5}_{-14.2}$	$0.80^{+0.07}_{-0.12}$	770	$15.6^{+0.2}_{-0.3}$
GW190521	$157.9^{+37.4}_{-20.9}$	$66.9^{+15.5}_{-9.2}$	$91.4^{+29.3}_{-17.5}$	$66.8^{+20.7}_{-20.7}$	$0.06^{+0.31}_{-0.37}$	$4.53^{+2.30}_{-2.13}$	$0.72^{+0.29}_{-0.29}$	$150.3^{+35.8}_{-20.0}$	$0.73^{+0.11}_{-0.14}$	940	$14.2^{+0.3}_{-0.3}$
GW190521_074359	$74.4^{+6.8}_{-4.6}$	$31.9^{+3.1}_{-2.4}$	$42.1^{+5.9}_{-4.9}$	$32.7^{+5.4}_{-6.2}$	$0.09^{+0.10}_{-0.13}$	$1.28^{+0.38}_{-0.57}$	$0.25^{+0.06}_{-0.10}$	$70.7^{+6.4}_{-4.2}$	$0.72^{+0.05}_{-0.07}$	500	$25.8^{+0.1}_{-0.2}$
GW190527_092055	$58.5^{+27.9}_{-10.6}$	$24.2^{+11.9}_{-4.4}$	$36.2^{+19.1}_{-9.5}$	$22.8^{+12.7}_{-8.1}$	$0.13^{+0.29}_{-0.28}$	$3.10^{+4.85}_{-1.64}$	$0.53^{+0.61}_{-0.25}$	$55.9^{+26.4}_{-10.1}$	$0.73^{+0.12}_{-0.16}$	3800	$8.1^{+0.4}_{-1.0}$
GW190602_175927	$114.1^{+18.5}_{-15.7}$	$48.3^{+8.6}_{-8.0}$	$67.2^{+16.0}_{-12.6}$	$47.4^{+13.4}_{-16.6}$	$0.10^{+0.25}_{-0.25}$	$2.99^{+2.02}_{-1.26}$	$0.51^{+0.27}_{-0.19}$	$108.8^{+17.2}_{-14.8}$	$0.71^{+0.10}_{-0.13}$	720	$12.8^{+0.2}_{-0.3}$
GW190620_030421	$90.1^{+17.3}_{-12.1}$	$37.5^{+7.8}_{-5.7}$	$55.4^{+15.8}_{-12.0}$	$35.0^{+11.6}_{-11.4}$	$0.34^{+0.21}_{-0.25}$	$3.16^{+1.67}_{-1.43}$	$0.54^{+0.22}_{-0.21}$	$85.4^{+15.9}_{-11.4}$	$0.80^{+0.08}_{-0.14}$	6700	$12.1^{+0.3}_{-0.4}$
GW190630_185205	$58.8^{+4.7}_{-4.8}$	$24.8^{+2.1}_{-2.0}$	$35.0^{+6.9}_{-5.7}$	$23.6^{+5.2}_{-5.1}$	$0.10^{+0.12}_{-0.13}$	$0.93^{+0.56}_{-0.40}$	$0.19^{+0.10}_{-0.07}$	$56.1^{+4.5}_{-4.6}$	$0.70^{+0.06}_{-0.07}$	1300	$15.6^{+0.2}_{-0.3}$
GW190701_203306	$94.1^{+11.6}_{-9.3}$	$40.2^{+5.2}_{-4.7}$	$53.6^{+11.7}_{-7.8}$	$40.8^{+8.3}_{-11.5}$	$-0.06^{+0.23}_{-0.28}$	$2.14^{+0.79}_{-0.73}$	$0.38^{+0.12}_{-0.12}$	$90.0^{+10.8}_{-8.6}$	$0.67^{+0.09}_{-0.12}$	45	$11.3^{+0.2}_{-0.4}$
GW190706_222641	$101.6^{+17.9}_{-13.5}$	$42.0^{+8.4}_{-6.2}$	$64.0^{+15.2}_{-15.2}$	$38.5^{+12.5}_{-12.4}$	$0.32^{+0.25}_{-0.30}$	$5.07^{+2.57}_{-2.11}$	$0.79^{+0.31}_{-0.28}$	$96.3^{+16.7}_{-13.2}$	$0.80^{+0.08}_{-0.17}$	610	$12.6^{+0.2}_{-0.4}$
GW190707_093326	$20.0^{+1.9}_{-1.3}$	$8.5^{+0.6}_{-0.4}$	$11.5^{+3.3}_{-1.7}$	$8.4^{+1.4}_{-1.6}$	$-0.05^{+0.10}_{-0.08}$	$0.80^{+0.37}_{-0.38}$	$0.16^{+0.07}_{-0.07}$	$19.2^{+1.9}_{-1.3}$	$0.66^{+0.03}_{-0.04}$	1300	$13.3^{+0.2}_{-0.4}$
GW190708_232457	$30.8^{+2.5}_{-1.8}$	$13.1^{+0.9}_{-0.6}$	$17.5^{+4.7}_{-2.3}$	$13.1^{+2.0}_{-2.7}$	$0.02^{+0.10}_{-0.08}$	$0.90^{+0.33}_{-0.40}$	$0.18^{+0.06}_{-0.07}$	$29.4^{+2.5}_{-1.7}$	$0.69^{+0.04}_{-0.04}$	14000	$13.1^{+0.2}_{-0.3}$
GW190719_215514	$55.8^{+16.3}_{-10.0}$	$22.7^{+5.9}_{-3.7}$	$35.2^{+16.9}_{-9.9}$	$20.2^{+8.1}_{-6.5}$	$0.35^{+0.28}_{-0.32}$	$4.61^{+2.84}_{-2.17}$	$0.73^{+0.35}_{-0.30}$	$52.9^{+15.6}_{-9.5}$	$0.80^{+0.10}_{-0.16}$	2300	$8.3^{+0.3}_{-1.0}$
GW190720_000836	$21.3^{+4.3}_{-2.3}$	$8.9^{+0.5}_{-0.8}$	$13.3^{+6.6}_{-3.0}$	$7.8^{+2.2}_{-2.2}$	$0.18^{+0.14}_{-0.12}$	$0.81^{+0.71}_{-0.33}$	$0.16^{+0.12}_{-0.06}$	$20.3^{+4.5}_{-2.3}$	$0.72^{+0.06}_{-0.05}$	510	$11.0^{+0.3}_{-0.8}$
GW190727_060333	$65.8^{+10.9}_{-7.4}$	$28.1^{+4.9}_{-3.4}$	$37.2^{+9.4}_{-5.9}$	$28.8^{+6.6}_{-7.9}$	$0.12^{+0.26}_{-0.25}$	$3.60^{+1.56}_{-1.51}$	$0.60^{+0.20}_{-0.22}$	$62.6^{+10.2}_{-7.0}$	$0.73^{+0.10}_{-0.10}$	860	$11.9^{+0.3}_{-0.5}$
GW190728_064510	$20.5^{+4.5}_{-1.3}$	$8.6^{+0.5}_{-0.3}$	$12.2^{+7.1}_{-2.2}$	$8.1^{+1.7}_{-2.6}$	$0.12^{+0.19}_{-0.07}$	$0.89^{+0.25}_{-0.37}$	$0.18^{+0.05}_{-0.07}$	$19.5^{+4.6}_{-1.3}$	$0.71^{+0.04}_{-0.04}$	410	$13.0^{+0.2}_{-0.4}$
GW190731_140936	$67.1^{+15.3}_{-10.2}$	$28.4^{+6.8}_{-4.5}$	$39.3^{+11.8}_{-8.2}$	$28.0^{+8.9}_{-8.4}$	$0.08^{+0.24}_{-0.24}$	$3.97^{+2.56}_{-2.07}$	$0.65^{+0.32}_{-0.30}$	$63.9^{+14.4}_{-9.8}$	$0.71^{+0.10}_{-0.12}$	3000	$8.6^{+0.2}_{-0.5}$
GW190803_022701	$62.7^{+11.8}_{-8.4}$	$26.7^{+5.2}_{-3.8}$	$36.1^{+10.2}_{-6.7}$	$26.7^{+7.1}_{-7.6}$	$-0.01^{+0.25}_{-0.26}$	$3.69^{+2.04}_{-1.69}$	$0.61^{+0.26}_{-0.24}$	$59.9^{+11.2}_{-7.9}$	$0.69^{+0.10}_{-0.11}$	1500	$8.6^{+0.3}_{-0.5}$
GW190814	$25.8^{+1.0}_{-0.9}$	$6.09^{+0.06}_{-0.06}$	$23.2^{+1.1}_{-1.0}$	$2.59^{+0.08}_{-0.09}$	$0.00^{+0.06}_{-0.06}$	$0.24^{+0.04}_{-0.05}$	$0.05^{+0.009}_{-0.010}$	$25.6^{+1.0}_{-0.9}$	$0.28^{+0.02}_{-0.02}$	19	$24.9^{+0.1}_{-0.2}$
GW190828_063405	$57.5^{+7.5}_{-4.4}$	$24.8^{+3.3}_{-2.0}$	$31.8^{+5.8}_{-3.9}$	$25.9^{+4.4}_{-4.6}$	$0.19^{+0.15}_{-0.16}$	$2.22^{+0.63}_{-0.95}$	$0.40^{+0.09}_{-0.15}$	$54.5^{+6.9}_{-4.0}$	$0.76^{+0.06}_{-0.07}$	520	$16.2^{+0.2}_{-0.3}$
GW190828_065509	$34.1^{+5.5}_{-4.5}$	$13.3^{+1.2}_{-0.9}$	$23.8^{+7.2}_{-7.0}$	$10.2^{+3.5}_{-2.1}$	$0.08^{+0.16}_{-0.16}$	$1.66^{+0.63}_{-0.61}$	$0.31^{+0.10}_{-0.10}$	$32.9^{+5.7}_{-4.5}$	$0.65^{+0.09}_{-0.08}$	640	$10.0^{+0.3}_{-0.5}$
GW190909_114149	$71.2^{+54.3}_{-15.0}$	$29.5^{+17.5}_{-6.3}$	$43.2^{+50.7}_{-12.2}$	$27.6^{+13.0}_{-10.9}$	$-0.03^{+0.44}_{-0.36}$	$4.77^{+3.70}_{-2.66}$	$0.75^{+0.45}_{-0.37}$	$68.3^{+52.5}_{-14.5}$	$0.68^{+0.16}_{-0.18}$	4200	$8.1^{+0.4}_{-0.7}$
GW190910_112807	$78.7^{+9.5}_{-9.0}$	$33.9^{+4.3}_{-3.9}$	$43.5^{+7.6}_{-6.2}$	$35.1^{+6.3}_{-7.0}$	$0.02^{+0.19}_{-0.18}$	$1.57^{+1.07}_{-0.64}$	$0.29^{+0.17}_{-0.11}$	$75.0^{+8.7}_{-8.5}$	$0.70^{+0.08}_{-0.07}$	10000	$14.1^{+0.2}_{-0.3}$
GW190915_235702	$59.5^{+7.5}_{-6.2}$	$25.1^{+3.1}_{-2.6}$	$34.9^{+9.5}_{-6.2}$	$24.4^{+5.5}_{-6.0}$	$0.03^{+0.19}_{-0.24}$	$1.70^{+0.71}_{-0.64}$	$0.32^{+0.11}_{-0.11}$	$56.8^{+7.1}_{-5.8}$	$0.71^{+0.09}_{-0.11}$	380	$13.6^{+0.2}_{-0.3}$
GW190924_021846	$13.9^{+5.1}_{-0.9}$	$5.8^{+0.2}_{-0.2}$	$8.8^{+7.0}_{-2.0}$	$5.0^{+1.3}_{-1.9}$	$0.03^{+0.30}_{-0.09}$	$0.57^{+0.22}_{-0.22}$	$0.12^{+0.04}_{-0.04}$	$13.3^{+5.2}_{-1.0}$	$0.67^{+0.05}_{-0.05}$	380	$11.5^{+0.3}_{-0.4}$
GW190929_012149	$90.6^{+21.2}_{-14.1}$	$34.3^{+8.6}_{-6.5}$	$64.7^{+22.4}_{-18.9}$	$25.7^{+14.4}_{-9.7}$	$0.03^{+0.27}_{-0.27}$	$3.68^{+2.98}_{-1.68}$	$0.61^{+0.38}_{-0.24}$	$87.5^{+20.7}_{-14.1}$	$0.64^{+0.17}_{-0.23}$	1800	$9.8^{+0.8}_{-0.6}$
GW190930_133541	$20.3^{+9.0}_{-1.5}$	$8.5^{+0.5}_{-0.5}$	$12.3^{+12.5}_{-2.3}$	$7.8^{+1.7}_{-3.3}$	$0.14^{+0.31}_{-0.15}$	$0.78^{+0.37}_{-0.33}$	$0.16^{+0.07}_{-0.06}$	$19.3^{+9.3}_{-1.5}$	$0.72^{+0.07}_{-0.06}$	1800	$9.5^{+0.3}_{-0.5}$



Hierarchical Bayesian inference and ML

Event parameters $\vec{\theta}$

m_1 m_2 $\chi_{\rm eff}$ z

Population Hyperparameters $\vec{\lambda}$

M_c σ $f_{\rm PBH}$ $z_{\rm cut\text{-}off}$

$$p(\vec{\lambda}|\vec{d}) \propto p(\vec{\lambda}) \int \mathrm{d}\vec{\theta}\, p(\vec{d}|\vec{\theta}) p_{\rm pop}(\vec{\theta}|\vec{\lambda})$$

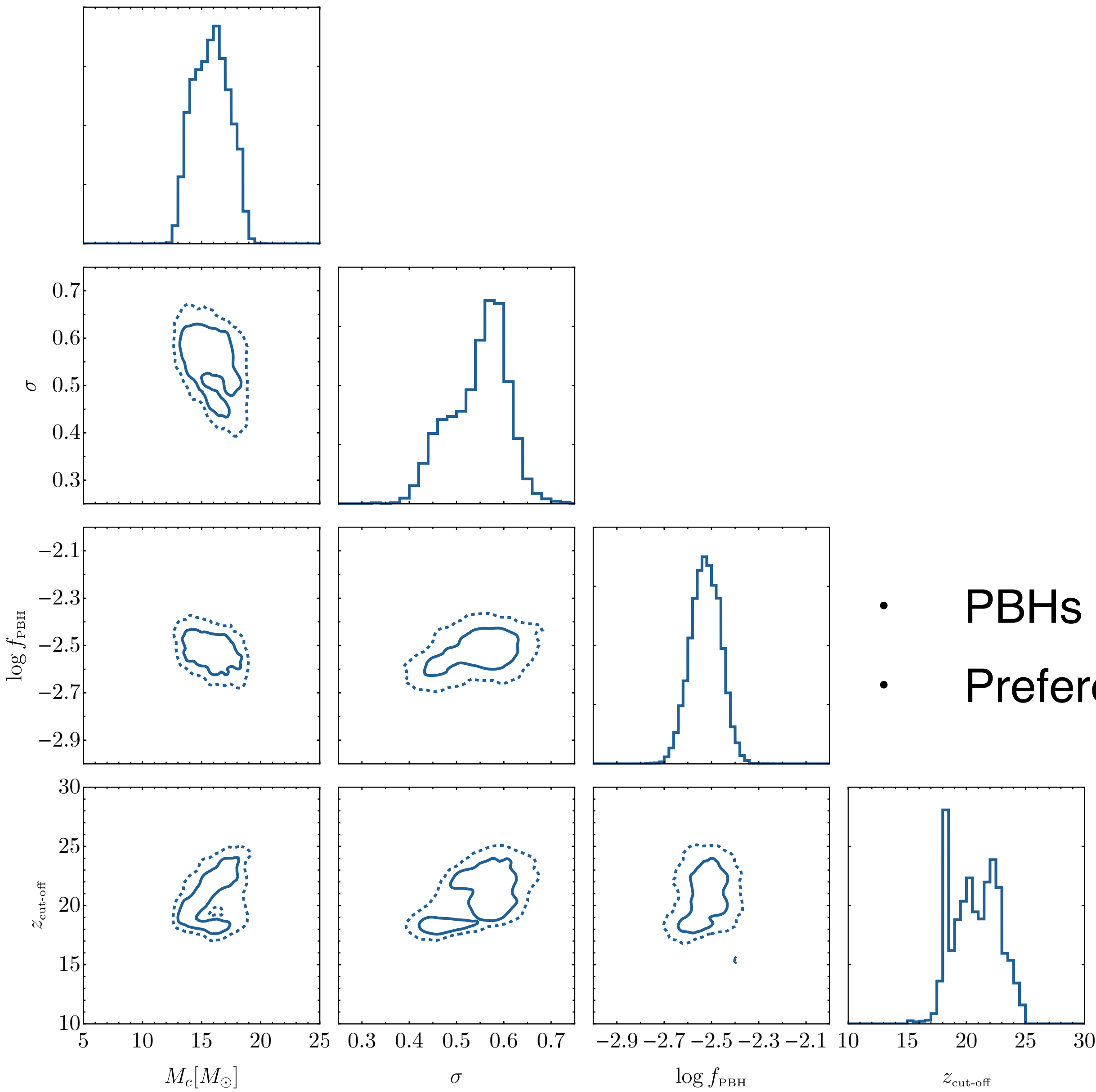
Posterior distribution

Hyperparameter prior

Single event likelihood

Population likelihood (ML)

Population posterior distribution



$$M_c \simeq 16 M_\odot$$

$$\sigma \simeq 0.56$$

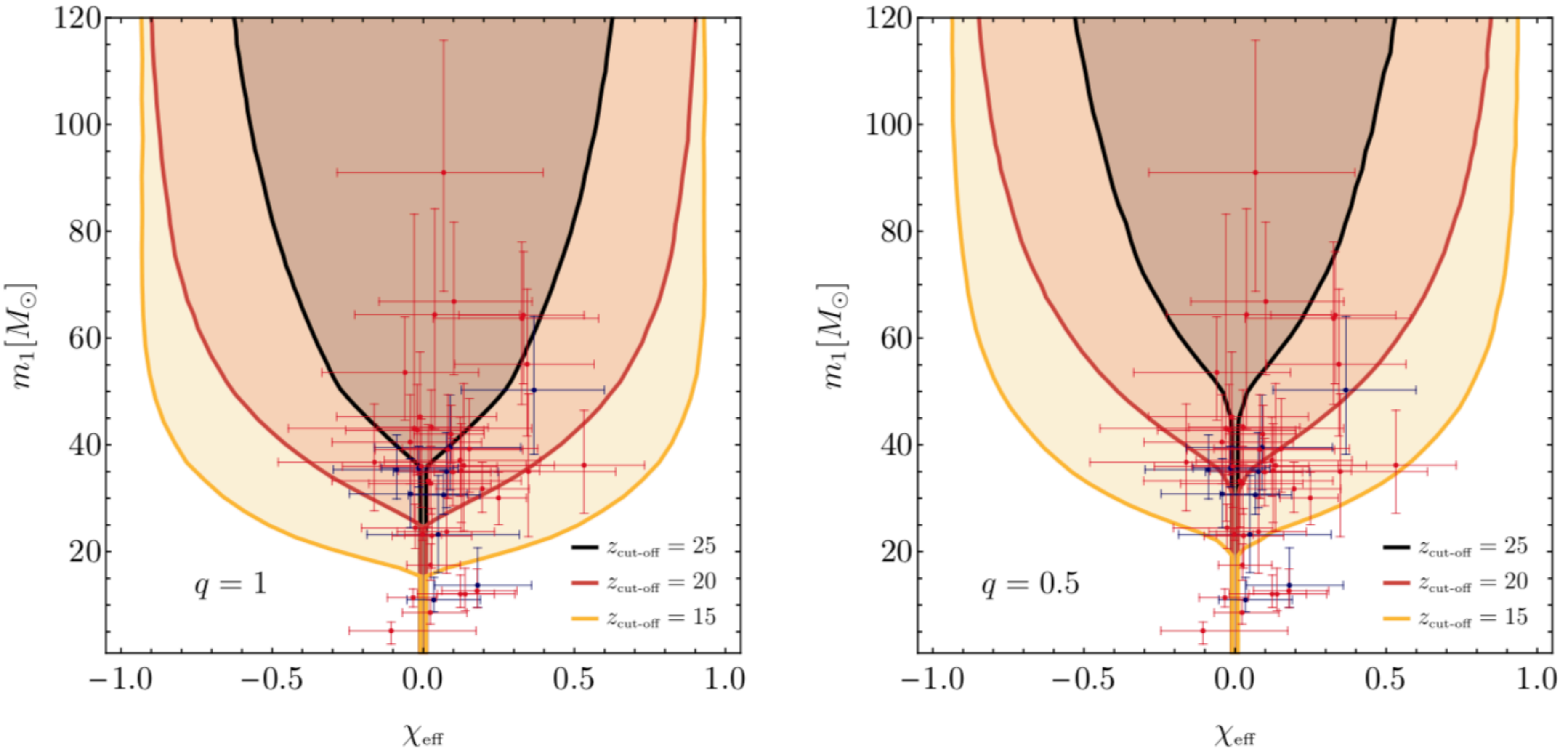
$$f_{\rm PBH} \simeq 3 \cdot 10^{-3}$$

$$z_{\text{cut-off}} \simeq 20$$

- PBHs are not the dark matter
- Preference for a mild accretion

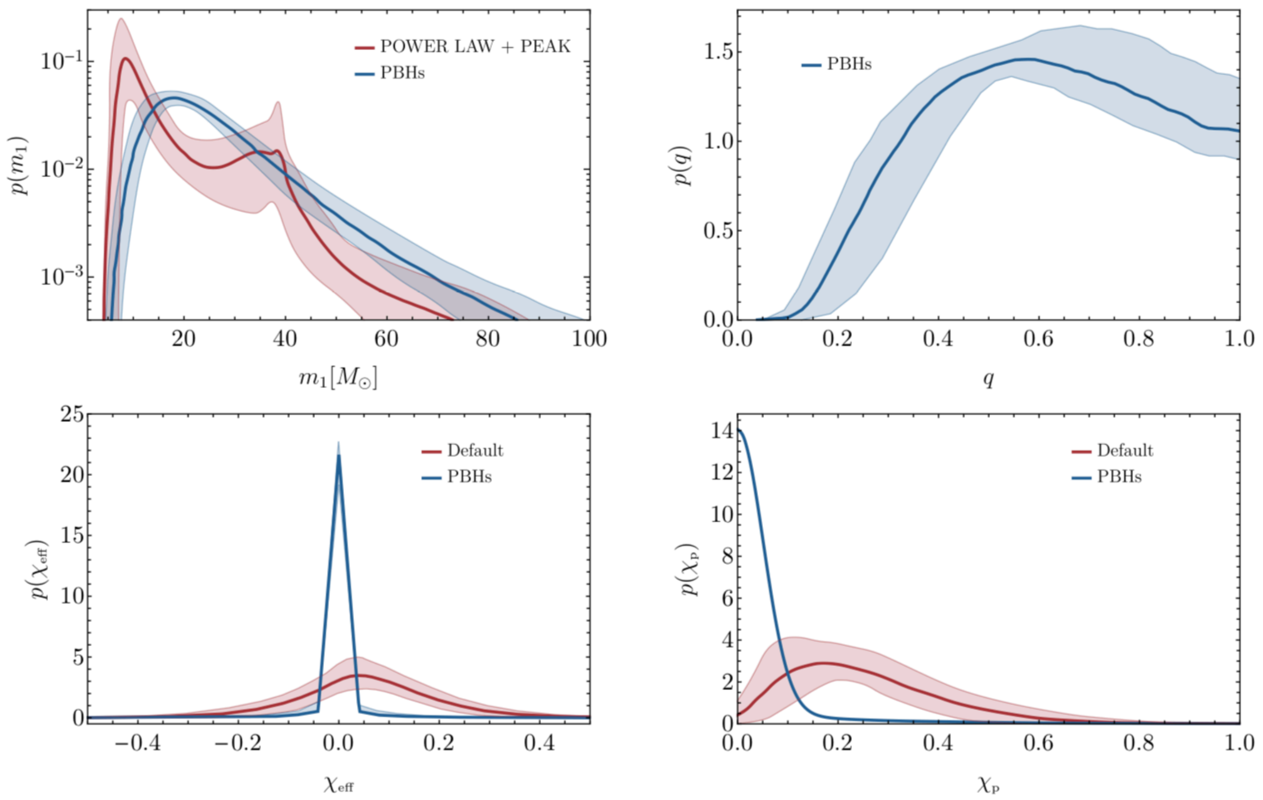
K. Wong et al. (2020)

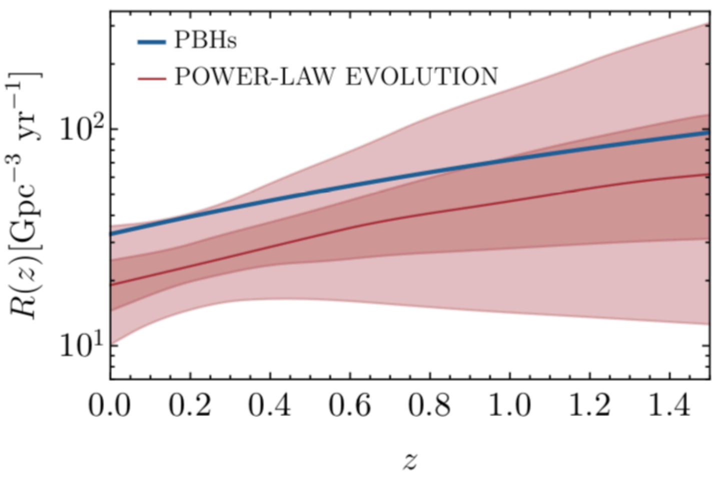
Prediction for the effective spin distribution



K. Wong et al. (2020)

PBH population properties





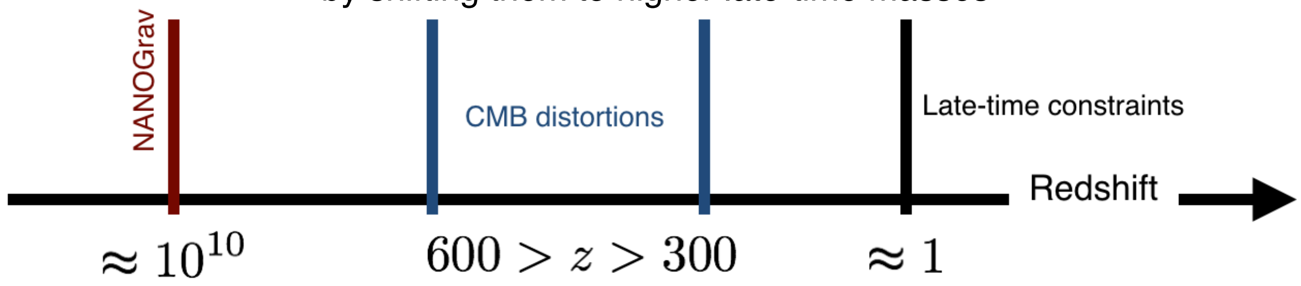
N.B.: LIGO/Virgo models are not *astrophysical,* which will introduce correlations among the event parameters, see 2011.03564, 2011.05332 for recent analysis

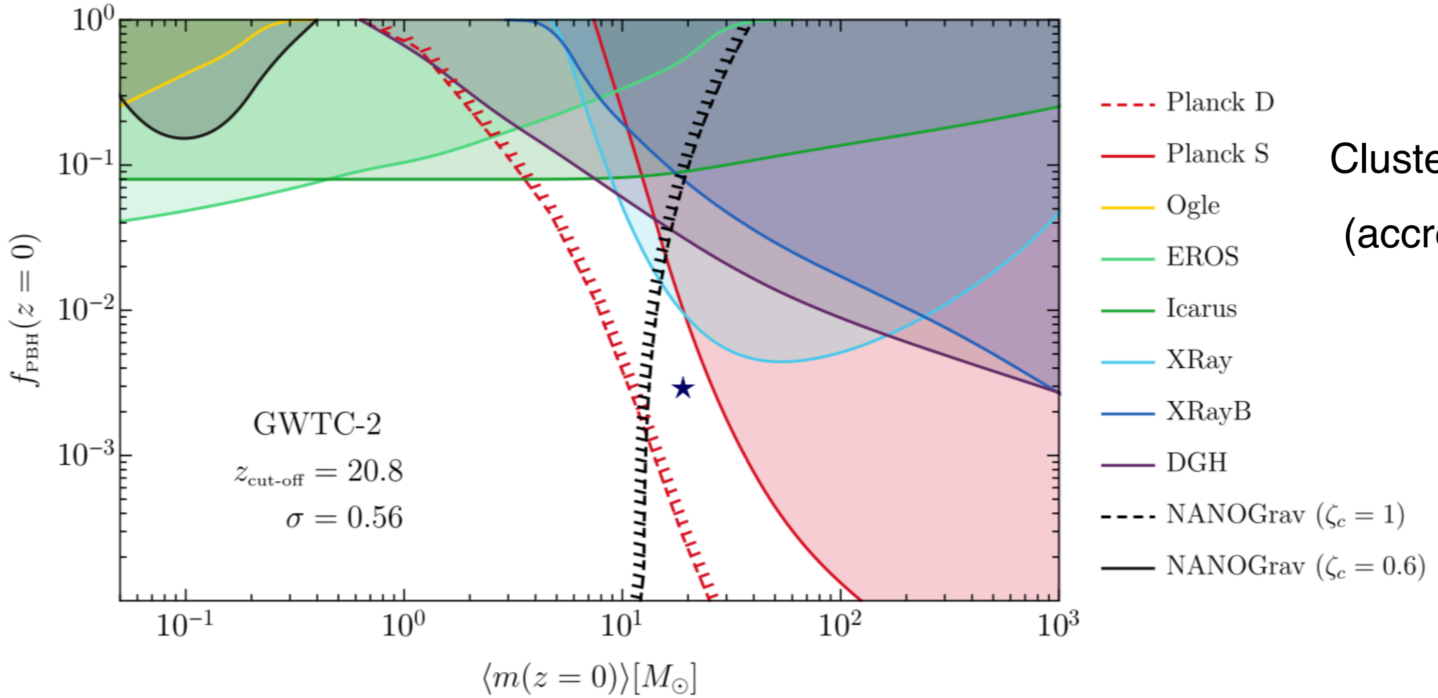
K. Wong et al. (2020)

The LIGO/Virgo events can be all PBHs not the dark matter in the universe

Accretion alleviates early-Universe bounds

by shifting them to higher late-time masses





Clustering may not change the result

(accretion bounds at high redshifts)

$$f_{\text{PBH}} \lesssim z \cdot 10^{-4}$$

K. Wong et al. (2020)

Conclusions

All GWTC-2 events may be PBHs, but PBHs are not the dark matter in the LIGO/Virgo mass band