

Title: Where do black hole binaries come from, and can we actually know that?

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Abstract:



animatthewcomics.com

CARL HASTER

WHERE DO BLACK HOLE BINARIES COME FROM
AND CAN WE ACTUALLY KNOW THAT?



CITA | ICAT

Canadian Institute for
Theoretical Astrophysics L'institut Canadien
d'astrophysique théorique

REMNANTS

OUR PRIMARY OBSERVABLE



Credit: paleoaerie.org

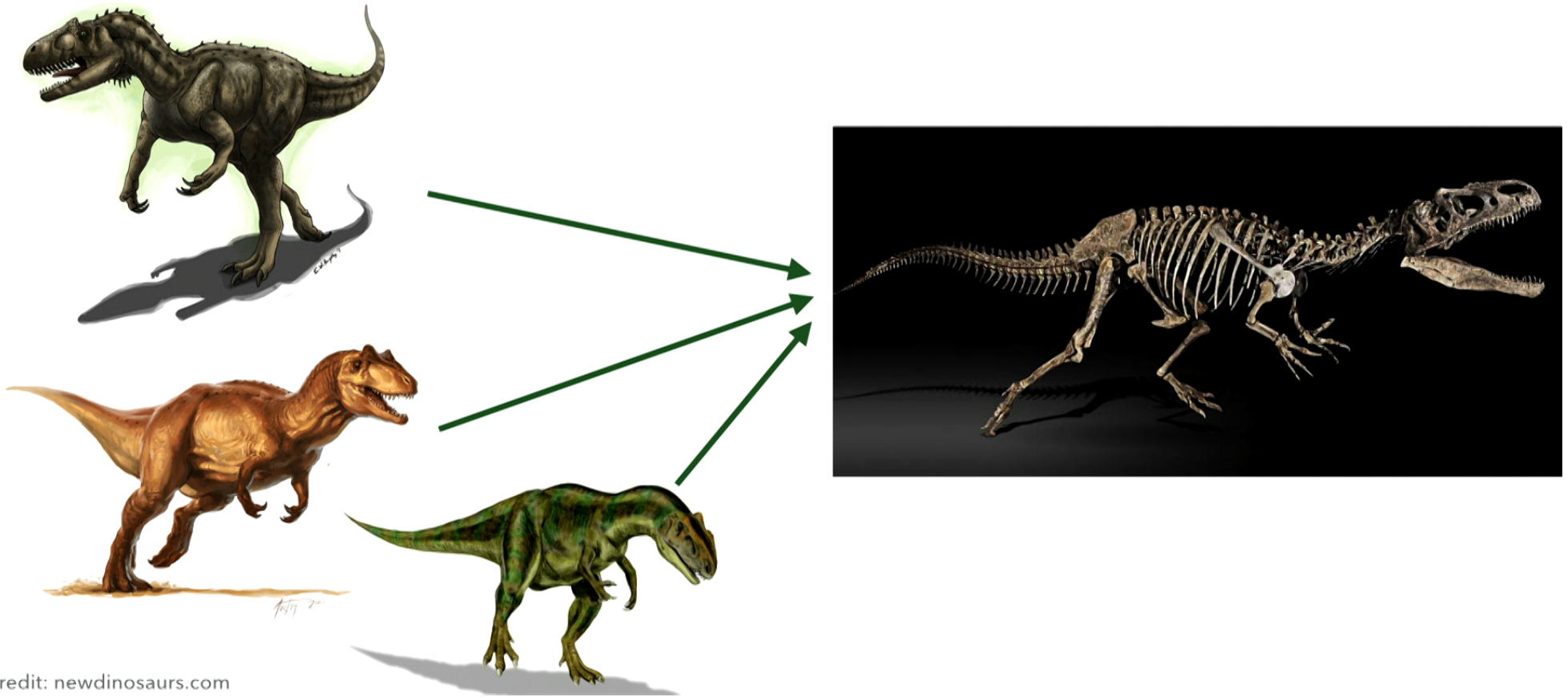
REMNANTS

OUR PRIMARY OBSERVABLE



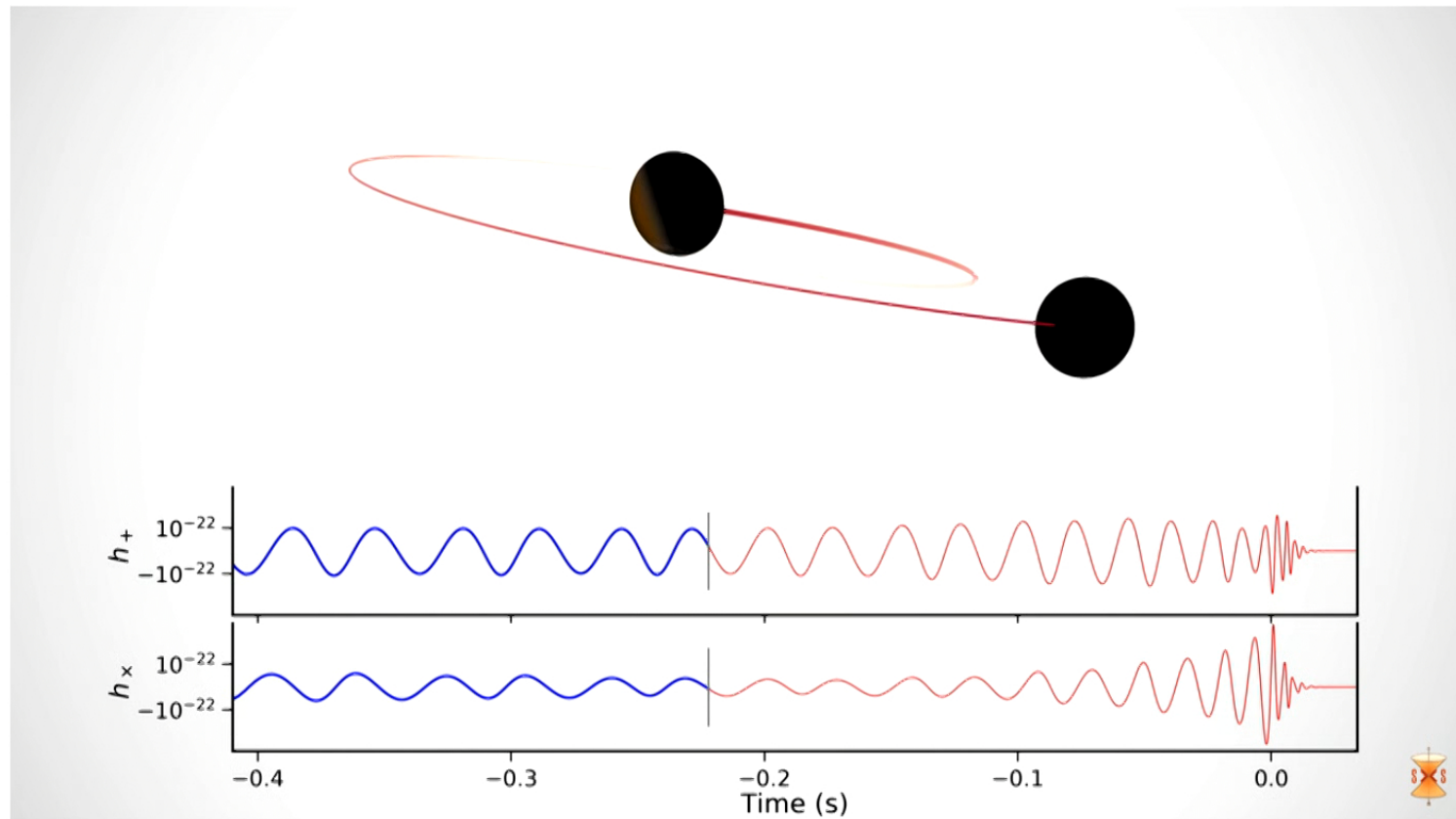
Credit: Sotheby's Via Bloomberg

INFER THE PAST THROUGH MODELLING



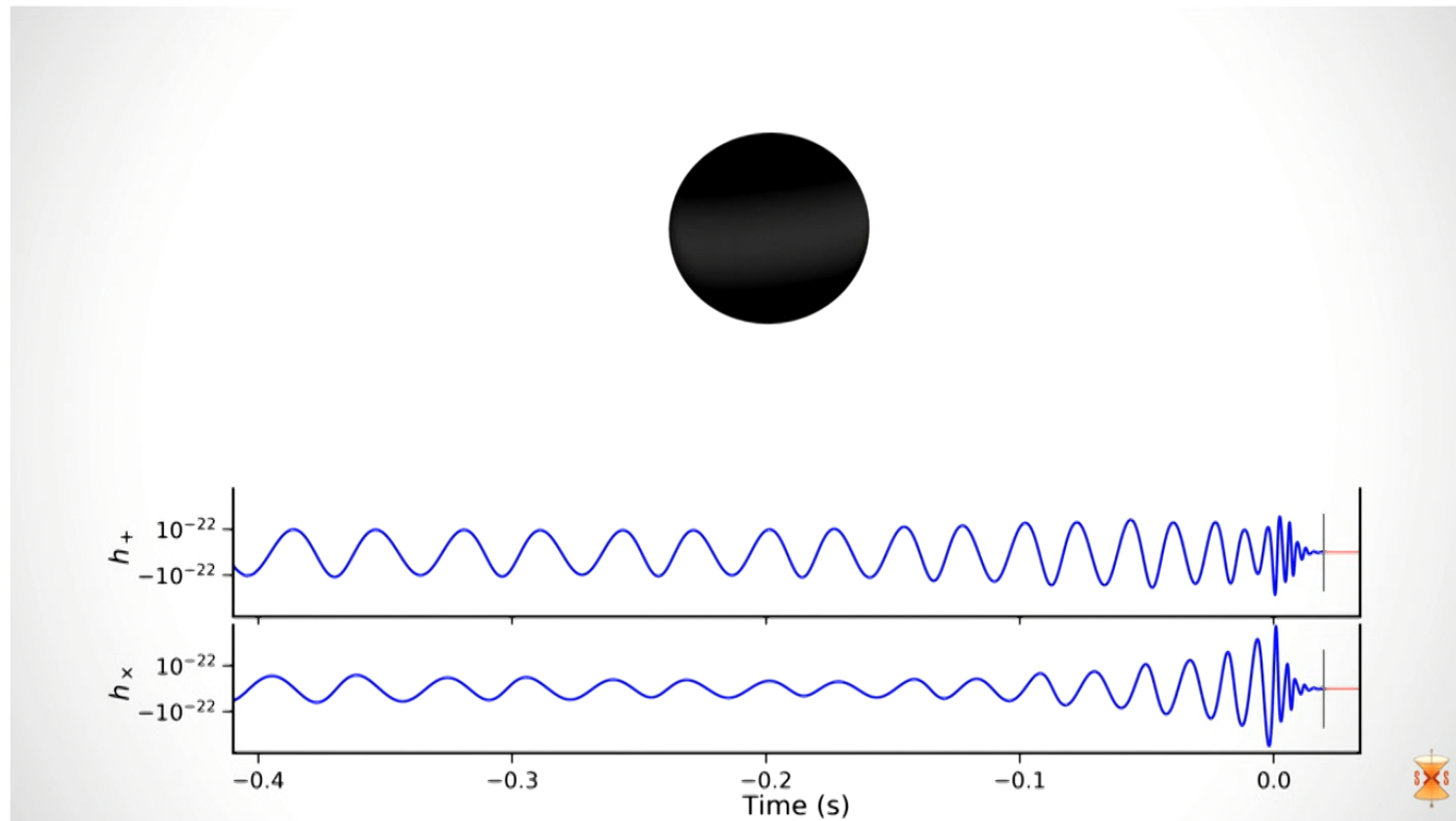
Credit: newdinosaurs.com

BINARY BLACK HOLE OBSERVATION



Credit: A. Babul/H. Pfeiffer/CITA/SXS

BINARY BLACK HOLE OBSERVATION



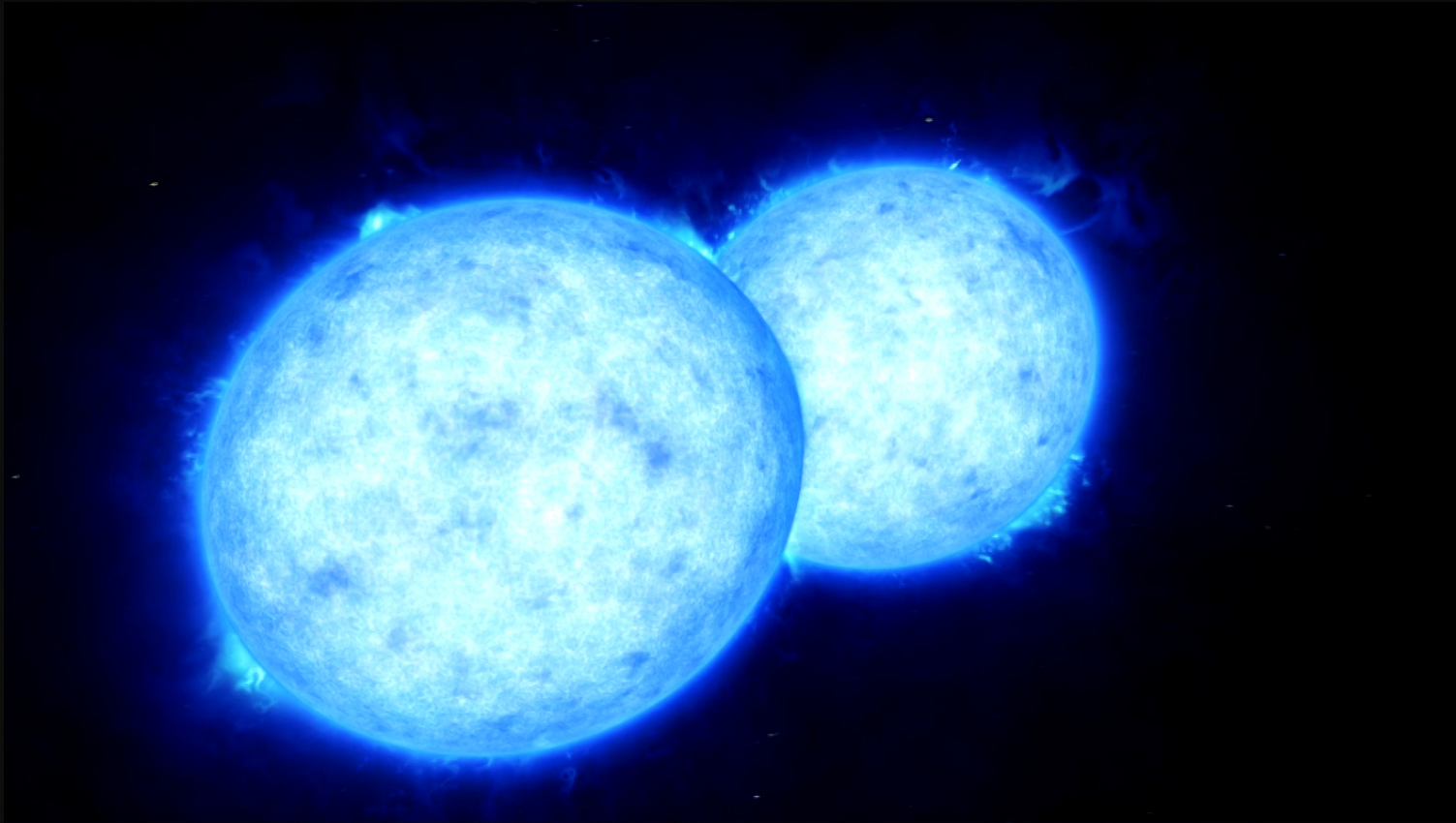
Credit: A. Babul/H. Pfeiffer/CITA/SXS

STELLAR PROGENITOR



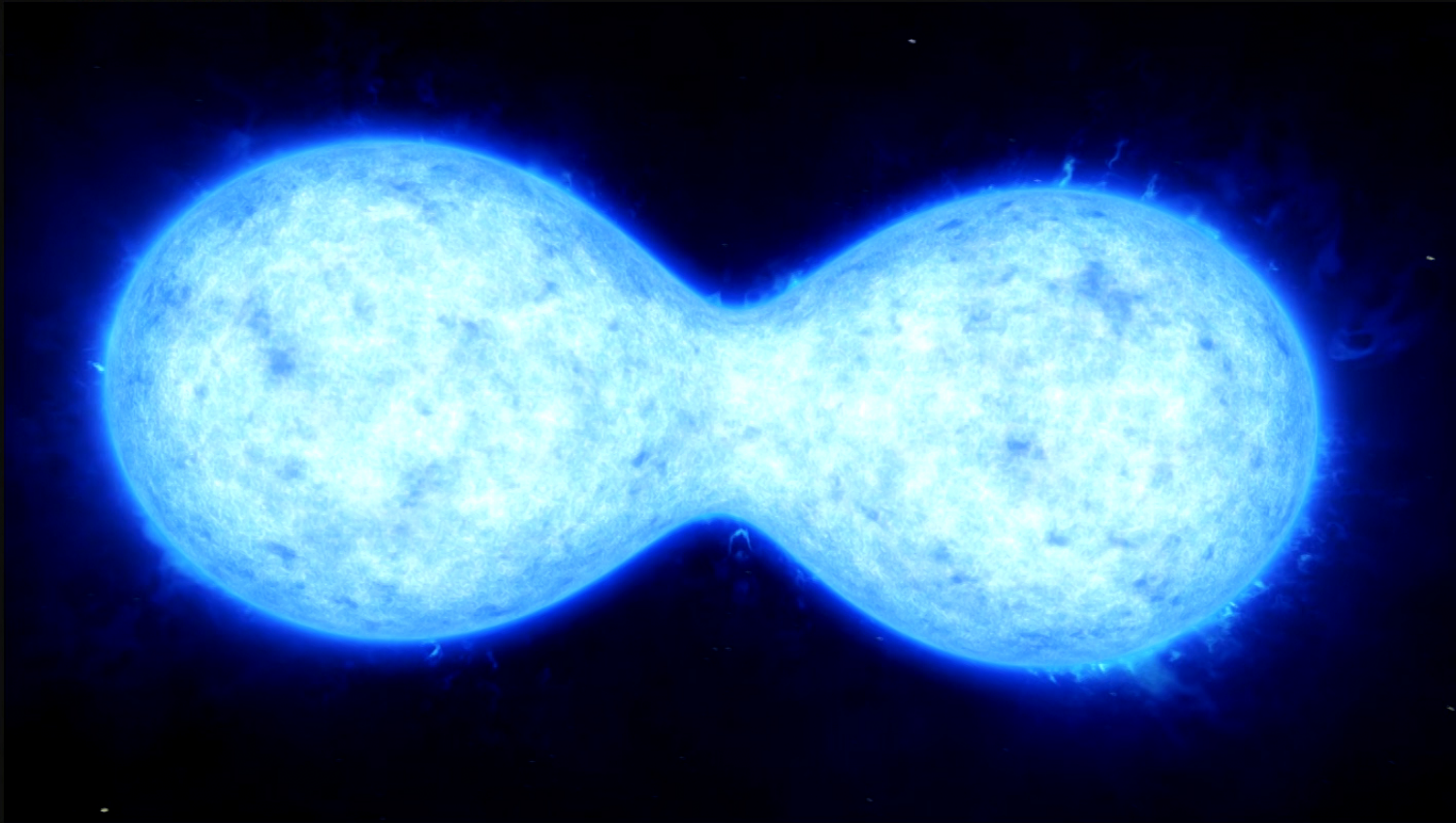
Credit: ESO/L. Calçada

STELLAR PROGENITOR



Credit: ESO/L. Calçada

STELLAR PROGENITOR



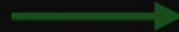
Credit: ESO/L. Calçada

CORRECT IDENTIFICATION OF EVOLUTION



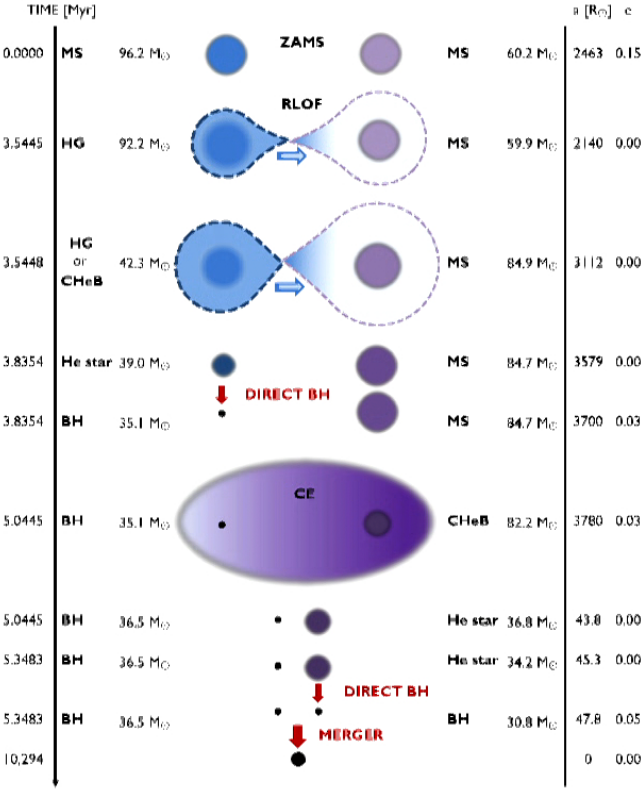
Credit: naturfoto.se

CORRECT IDENTIFICATION OF EVOLUTION

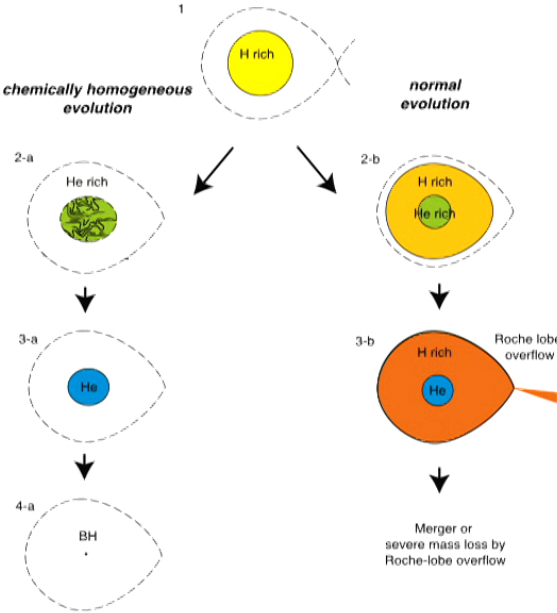


Credit: naturfoto.se

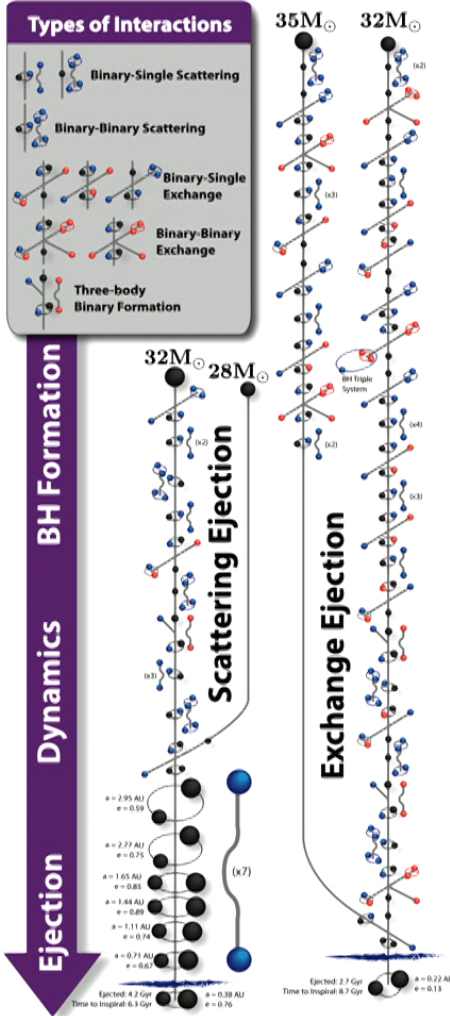
FORMATION CHANNELS



Belczynski et al., Nature (2016)



Mandel & de Mink, MNRAS (2016)



Rodriguez, CJH et al., ApJL (2016)

GRAVITATIONAL WAVE OBSERVABLES

▶ Mass

▶ Spin

▶ Orbit

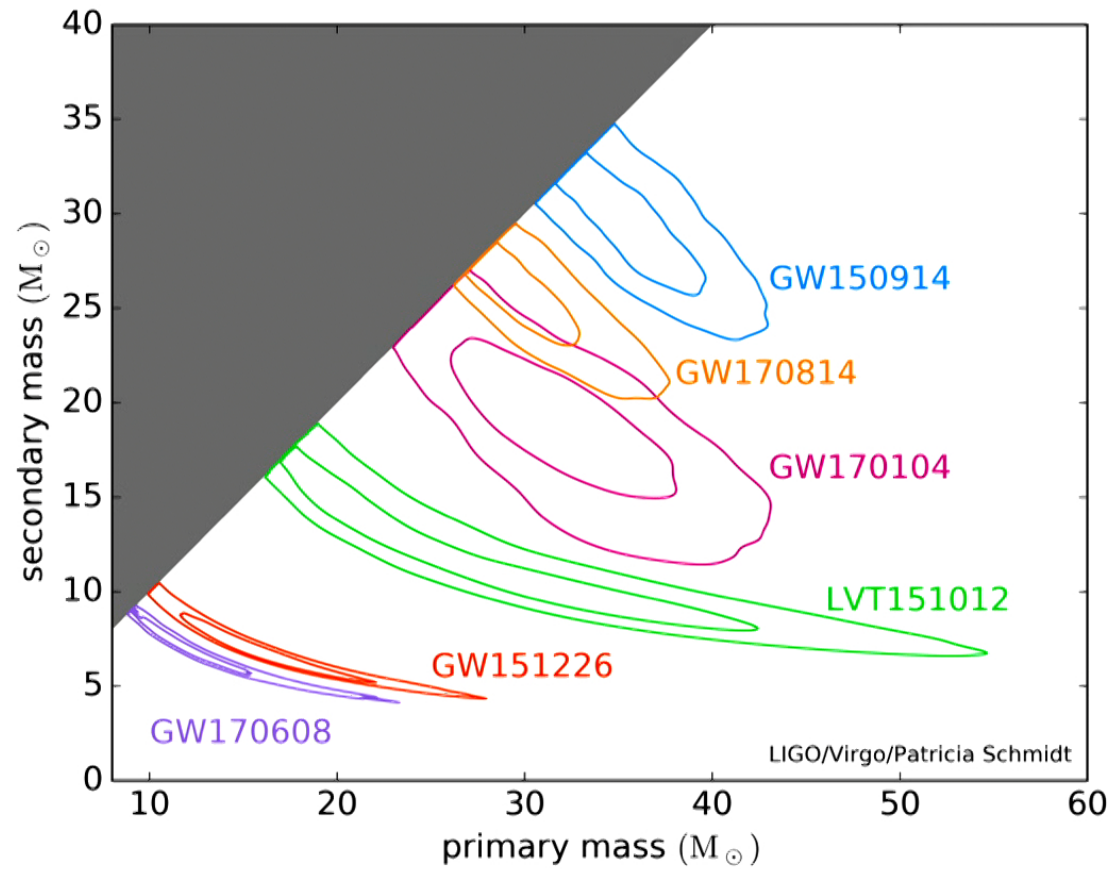
GRAVITATIONAL WAVE OBSERVABLES

- ▶ Mass
 - ▶ Mass ratio + mass magnitude
- ▶ Spin
- ▶ Orbit

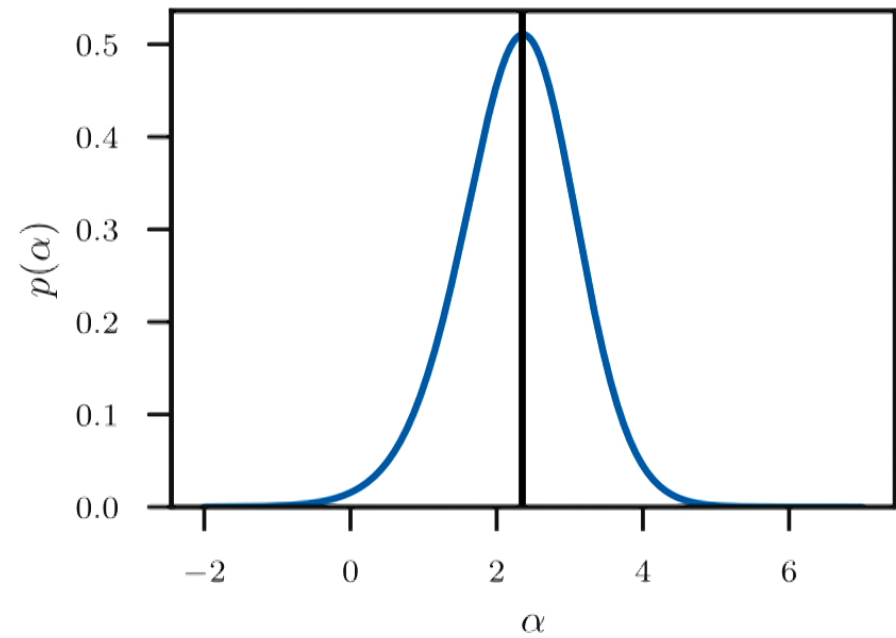
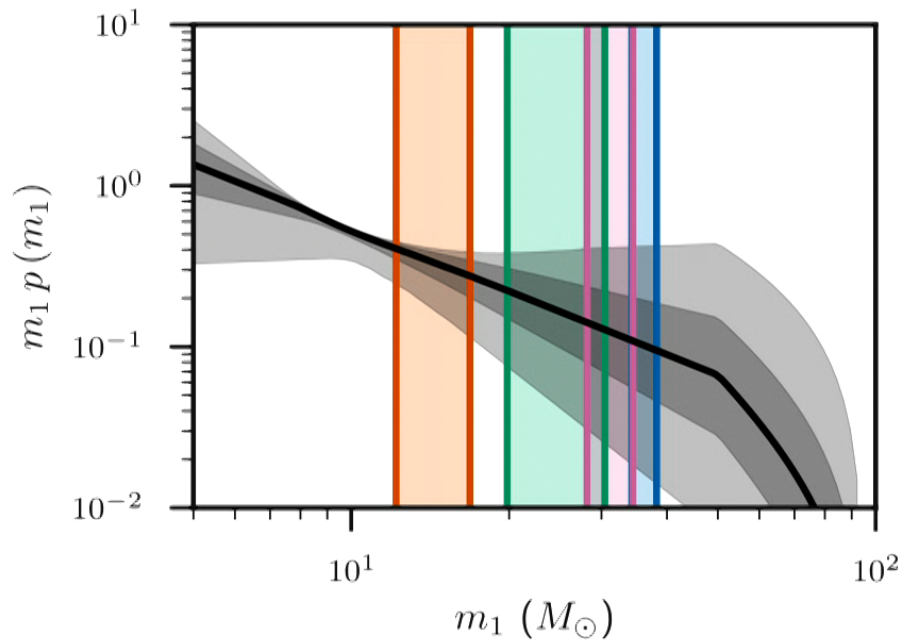
GRAVITATIONAL WAVE OBSERVABLES

- ▶ Mass
 - ▶ Mass ratio + mass magnitude
- ▶ Spin
 - ▶ Spin precession
- ▶ Orbit

BLACK HOLE MASSES



MASS DISTRIBUTION

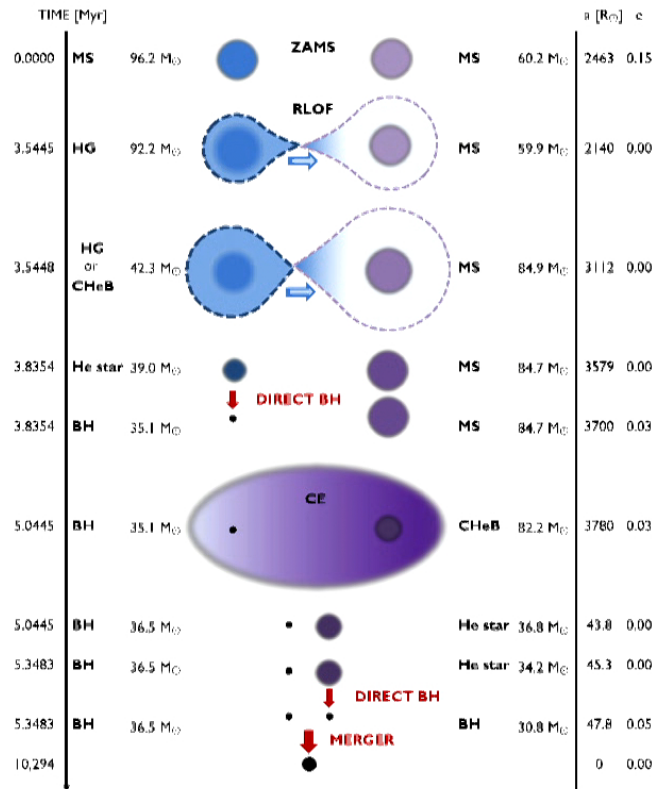


$$p(m_1) \propto m_1^{-\alpha} \frac{\min(m_1, 100M_\odot - m_1) - 5M_\odot}{m_1 - 5M_\odot}$$

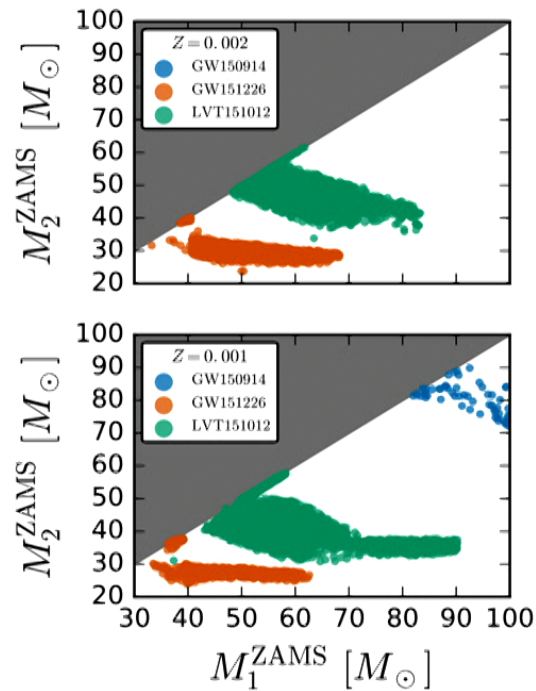
$$\alpha = 2.3^{+1.3}_{-1.4}$$

LVC, PRL (2017)

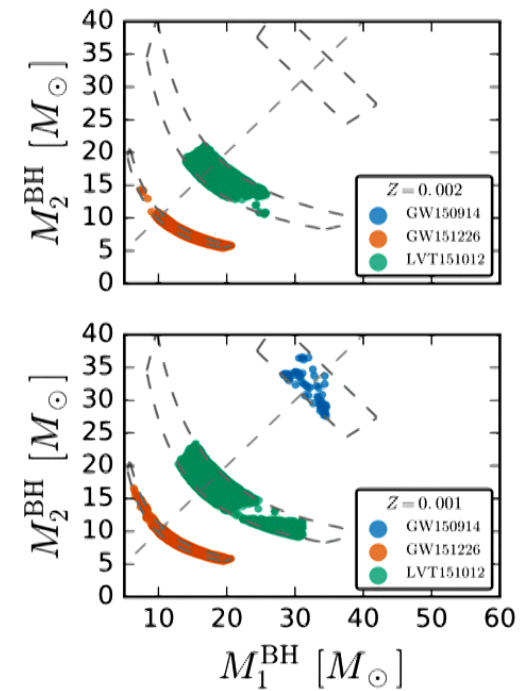
GALACTIC FIELD FORMATION



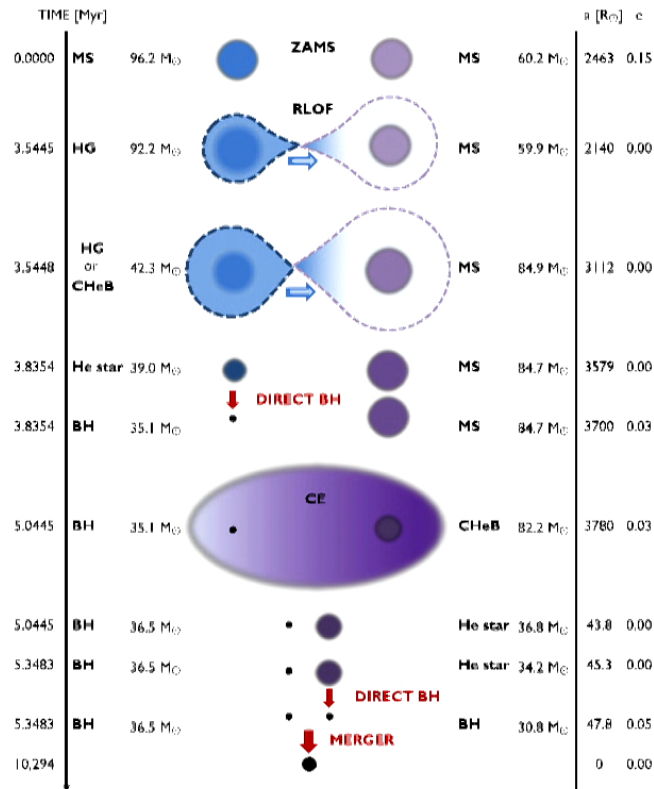
Belczynski et al., Nature (2016)



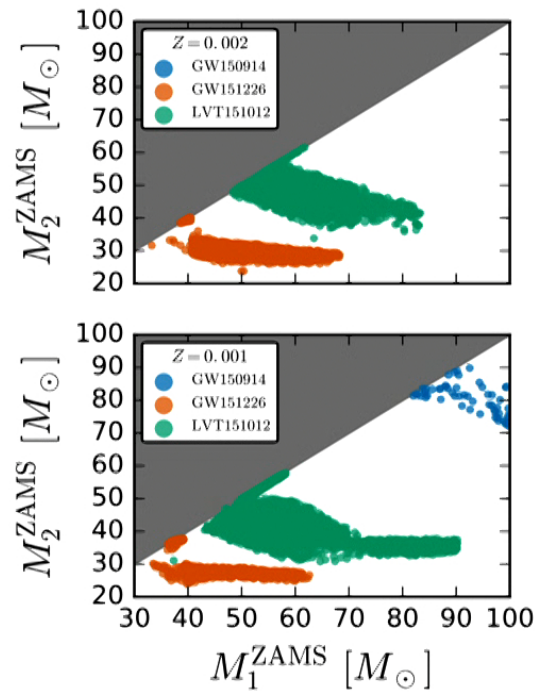
Stevenson et al., Nature Comm. (2017)



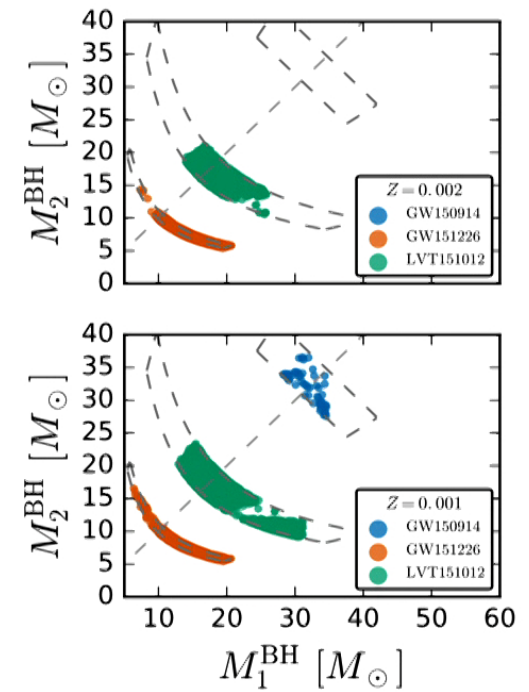
GALACTIC FIELD FORMATION



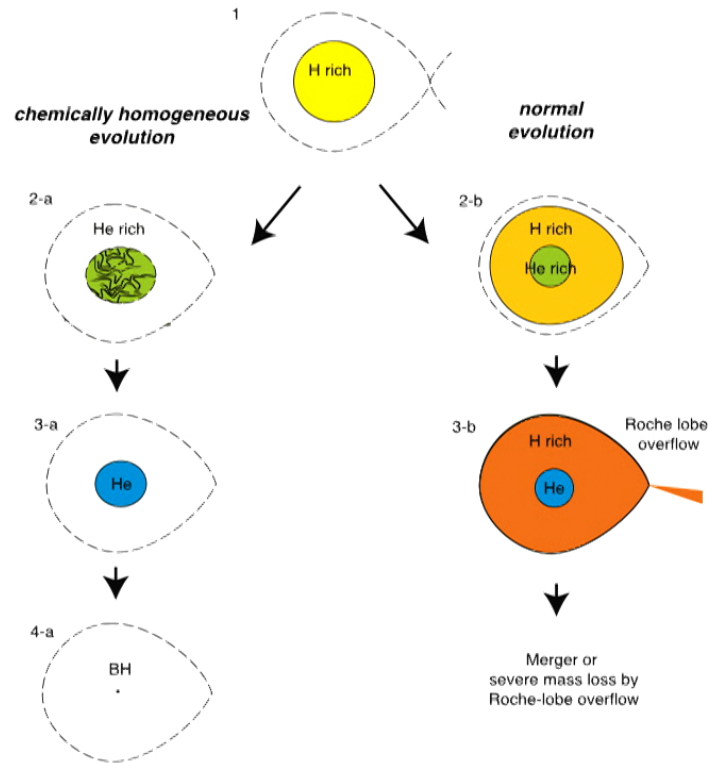
Belczynski et al., Nature (2016)



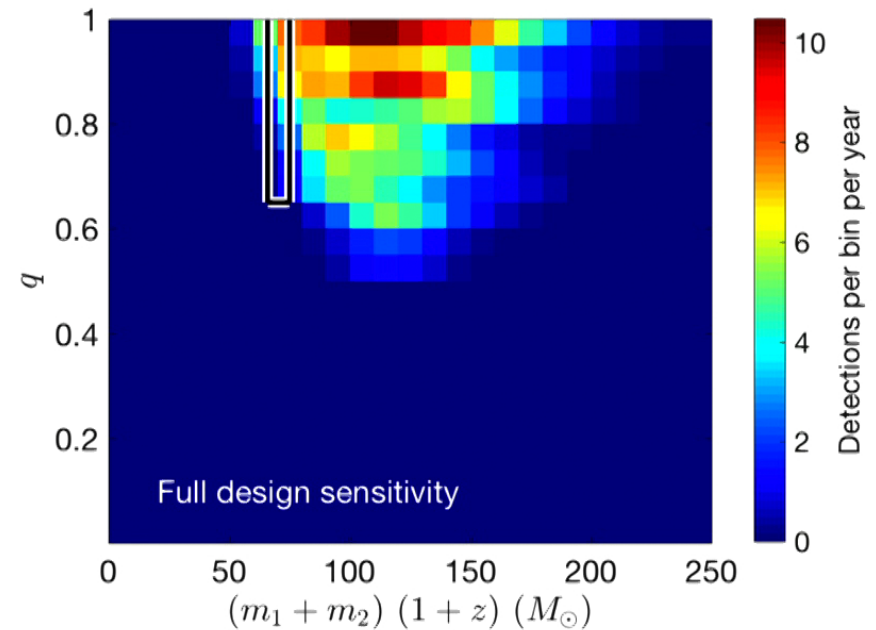
Stevenson et al., Nature Comm. (2017)



CHEMICALLY HOMOGENEOUS EVOLUTION

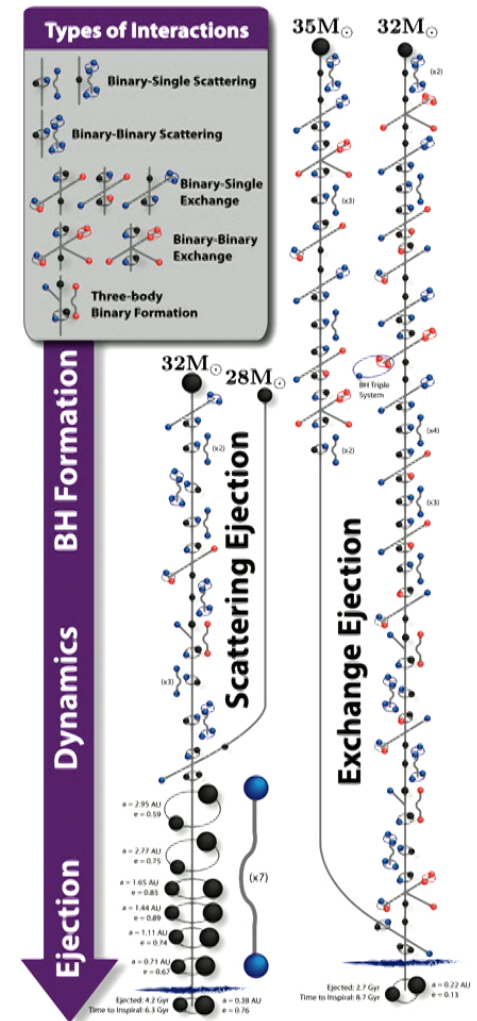
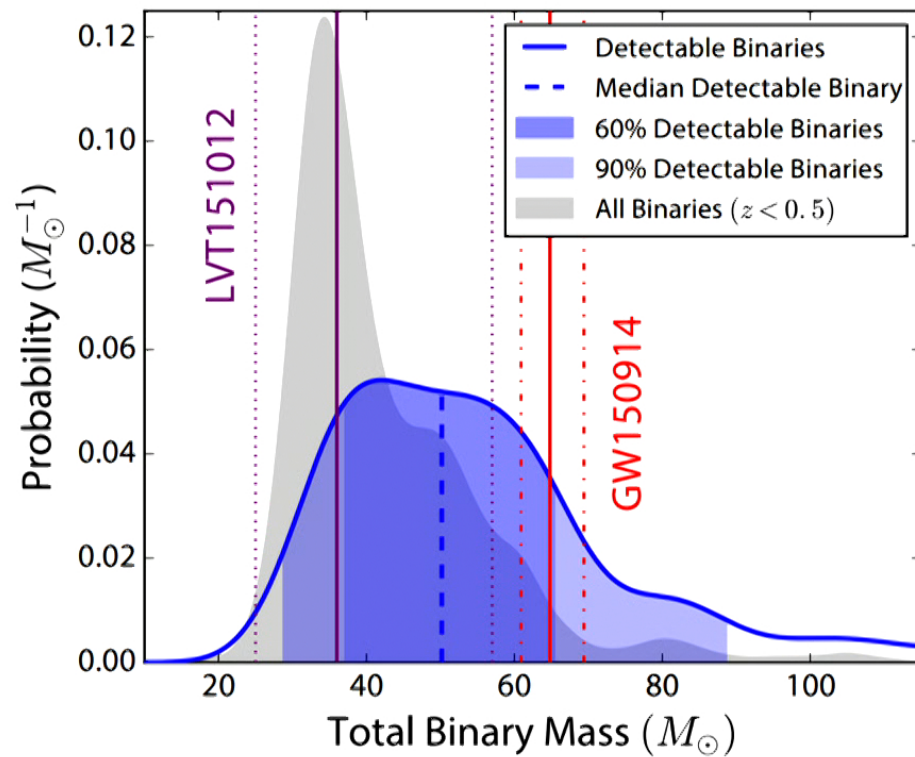


Mandel & de Mink, MNRAS (2016)

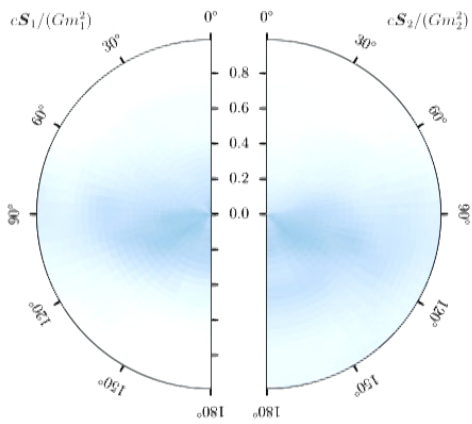


de Mink & Mandel, MNRAS (2016)

DYNAMICAL FORMATION

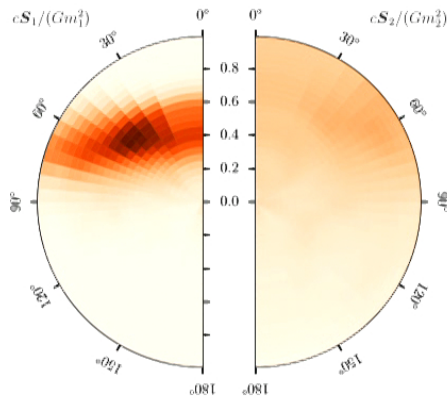


BLACK HOLE SPINS

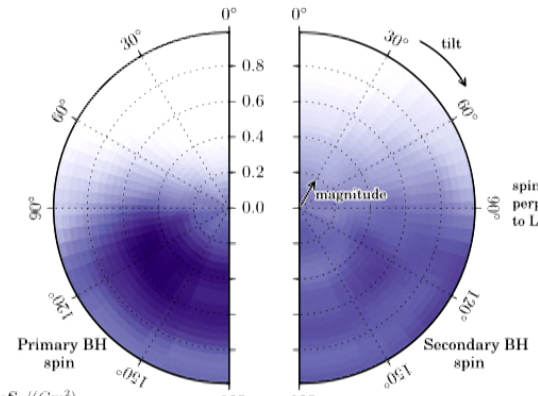


GW150914

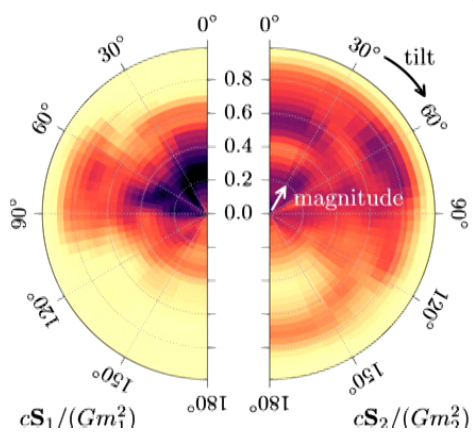
GW151226



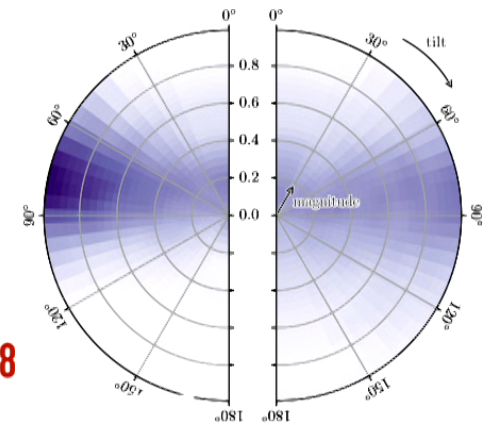
GW170104



GW170608

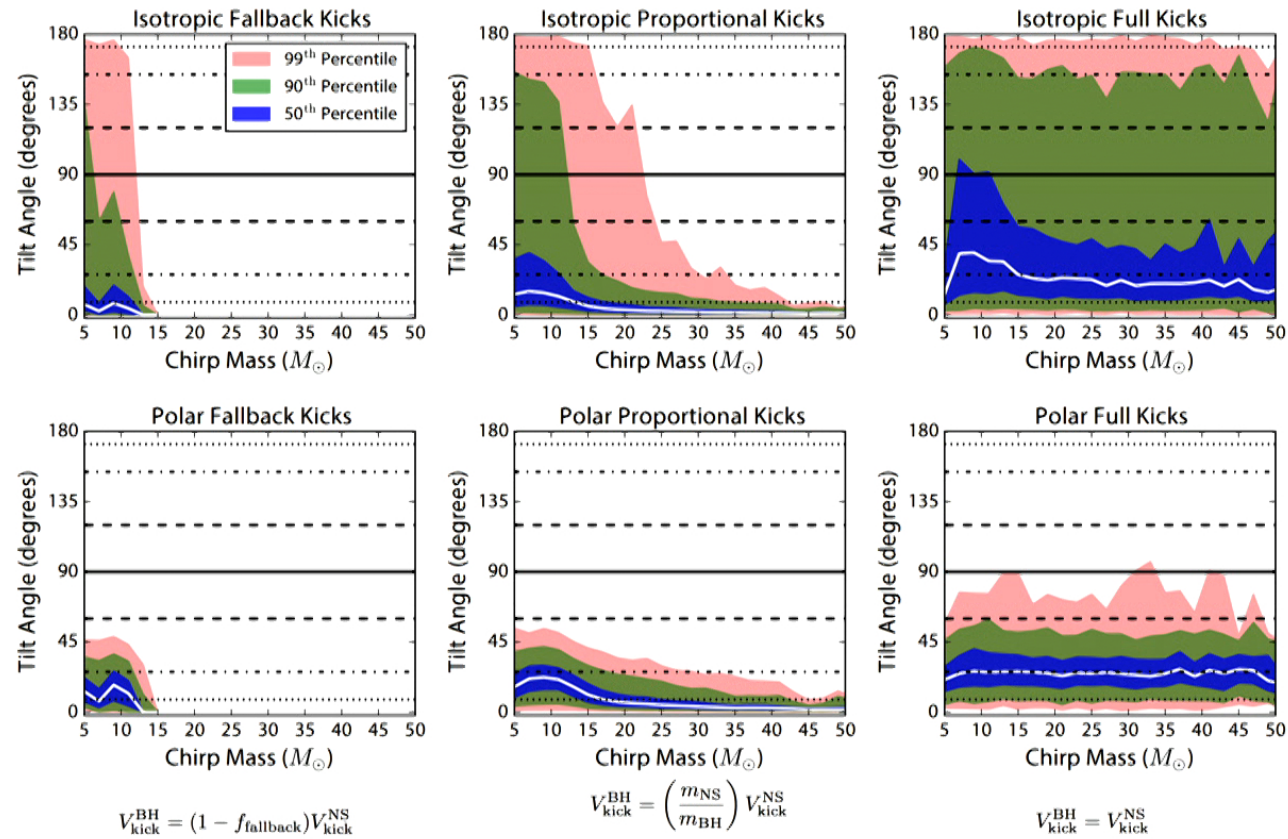


GW170814



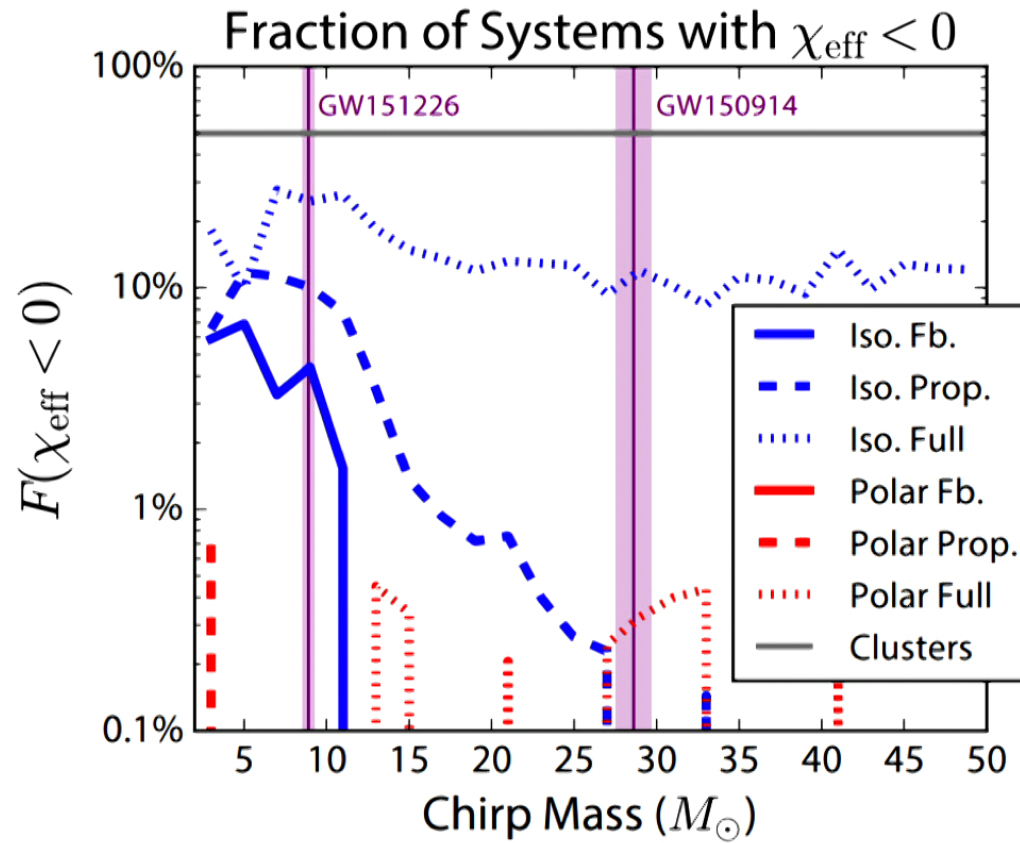
LVC, 2016-2017

SPIN – FIELD MISALIGNMENT



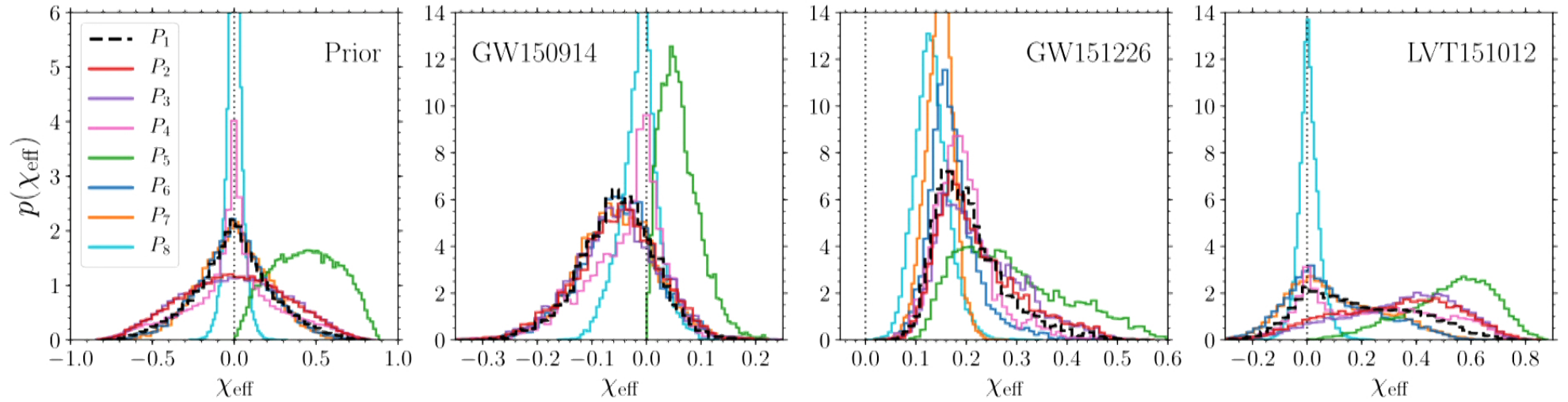
Rodriguez et al. ApJL (2016)

SPIN – FIELD MISALIGNMENT



Rodriguez et al. ApJL (2016)

SPIN

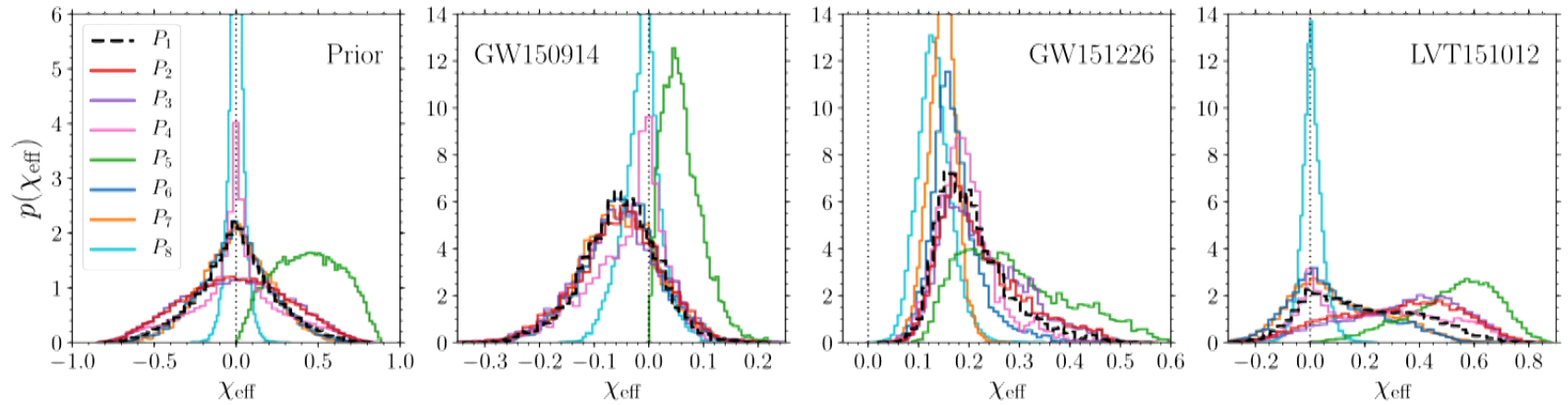


$$\chi_{\text{eff}} = \frac{m_1 a_1 \cos(\theta_1) + m_2 a_1 \cos(\theta_2)}{m_1 + m_2} \quad a_i = \left| \frac{c \vec{S}_i}{G m_i^2} \right| \quad \theta_i = \cos^{-1}(\hat{\mathbf{L}} \cdot \hat{\mathbf{S}}_i)$$

Vitale, Gerosa, CJH, Chatziioannou, Zimmerman, 1707.04637

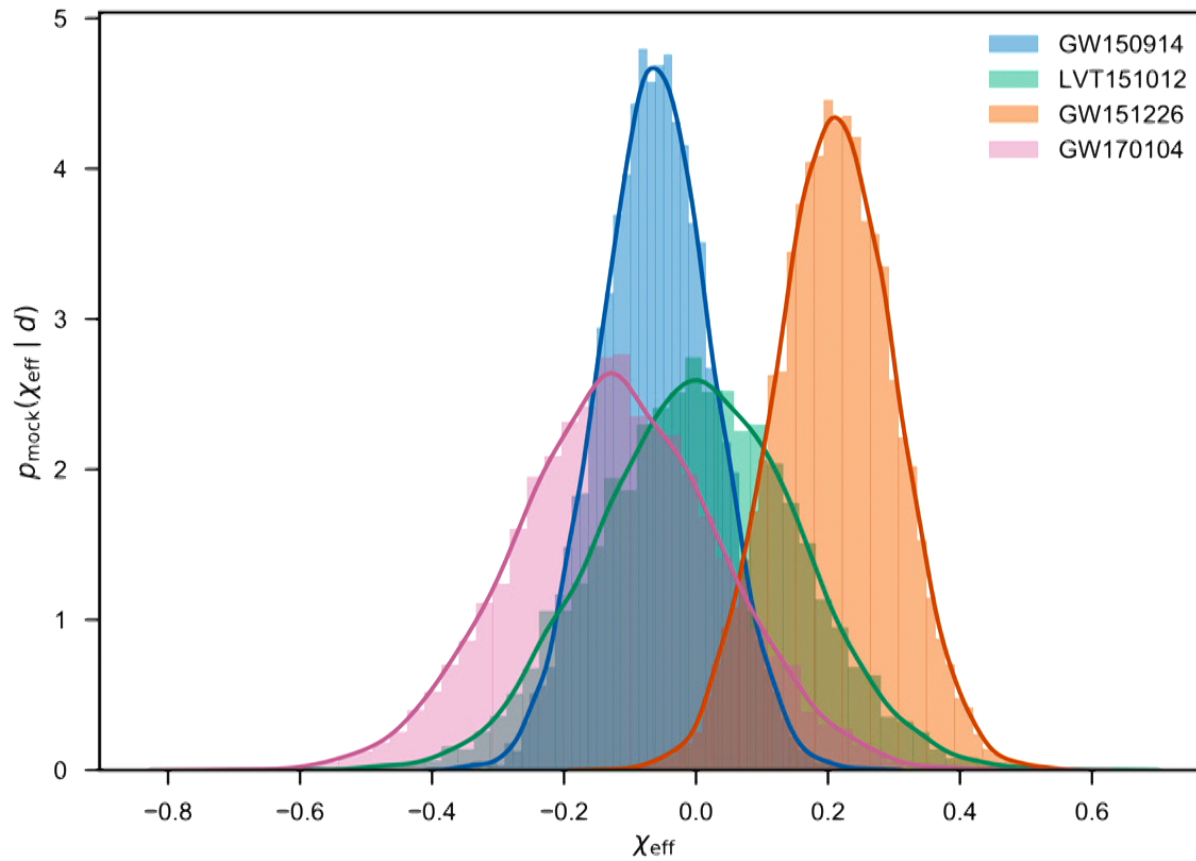
SPIN

	GW150914			GW151226			LVT151012		
	$D_{\text{KL}}^{\chi_{\text{eff}}}$	$D_{\text{KL}}^{\chi_{\text{p}}}$	$\log_{10} \mathcal{O}$	$D_{\text{KL}}^{\chi_{\text{eff}}}$	$D_{\text{KL}}^{\chi_{\text{p}}}$	$\log_{10} \mathcal{O}$	$D_{\text{KL}}^{\chi_{\text{eff}}}$	$D_{\text{KL}}^{\chi_{\text{p}}}$	$\log_{10} \mathcal{O}$
P_1	1.02	0.03	—	1.93	0.21	—	0.53	0.03	—
P_2	1.36	0.06	-0.3	1.78	0.04	0.0	0.89	0.05	-0.1
P_3	1.52	0.09	-0.4	1.76	0.02	0.0	0.95	0.04	0.0
P_4	0.88	0.12	0.0	2.56	0.70	-0.1	0.61	0.12	-0.1
P_5	4.21	1.75	-1.7	0.82	0.21	0.0	0.22	0.07	0.5
P_6	0.96	0.01	0.1	2.12	0.08	0.4	0.24	0.00	0.4
P_7	0.93	0.06	0.4	2.63	0.02	0.4	0.26	0.01	0.5
P_8	0.14	0.07	0.3	4.82	0.70	-1.7	0.03	0.02	-0.1



Vitale, Gerosa, CJH, Chatziioannou, Zimmerman, 1707.04637

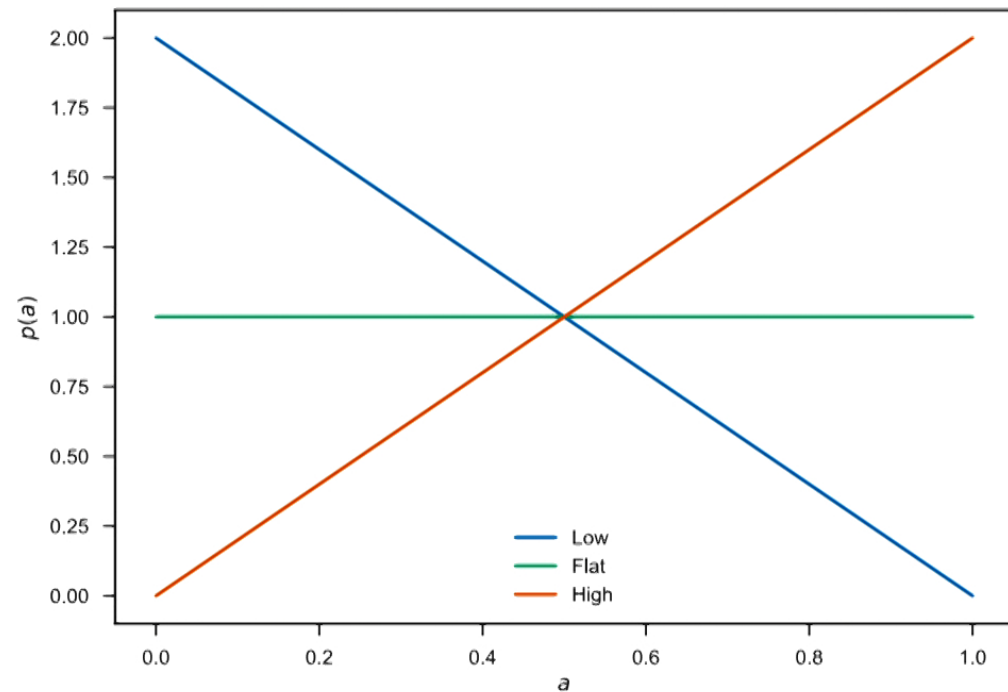
SPIN – POPULATION



Farr et al., Nature (2017)

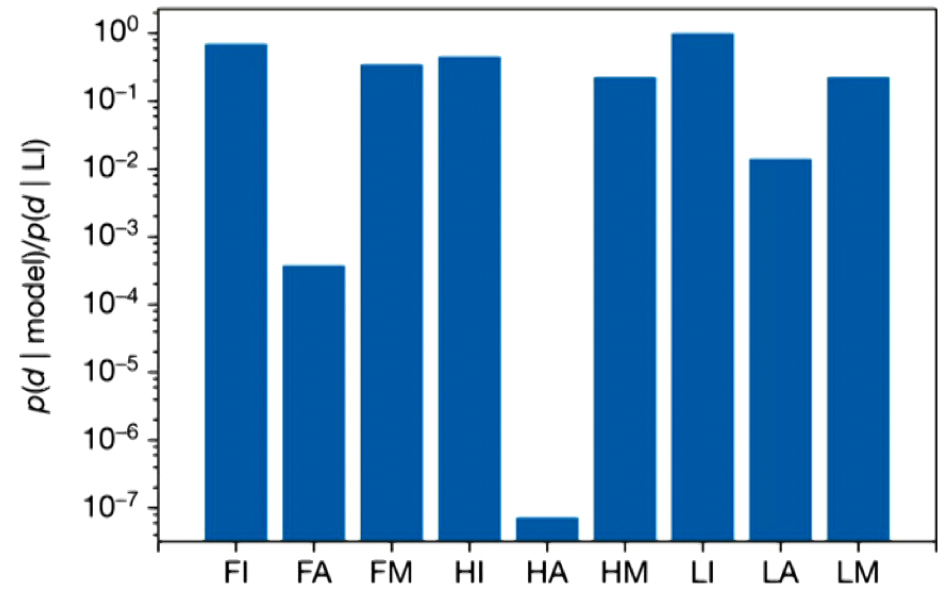
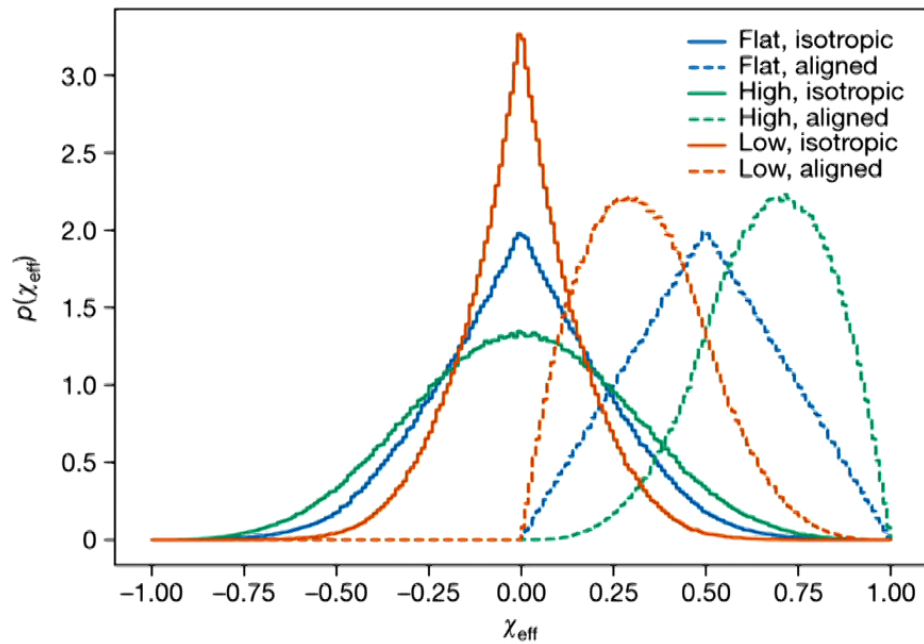
SPIN – POPULATION

- Isotropic
- VS
- Aligned



Farr et al., Nature (2017)

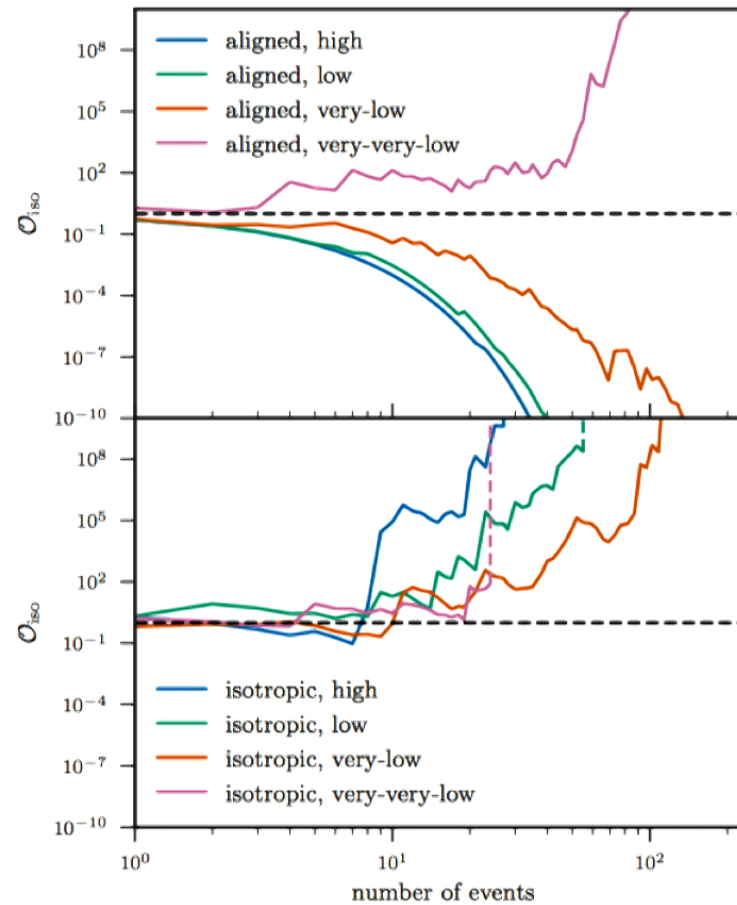
SPIN – POPULATION



Farr et al., Nature (2017)

SPIN – POPULATION

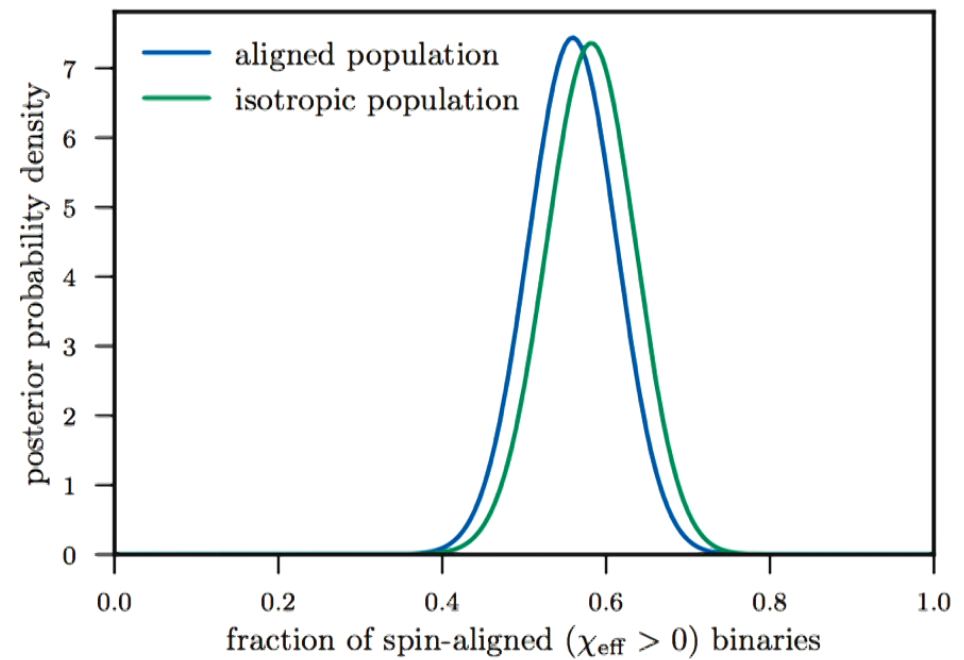
$$p(\chi_{\text{eff}}) = \begin{cases} 1 - \rho & -1 \leq \chi_{\text{eff}} < 0 \\ \rho & 0 \leq \chi_{\text{eff}} \leq 1 \end{cases}$$



Farr et al., 1709.07896

SPIN – POPULATION

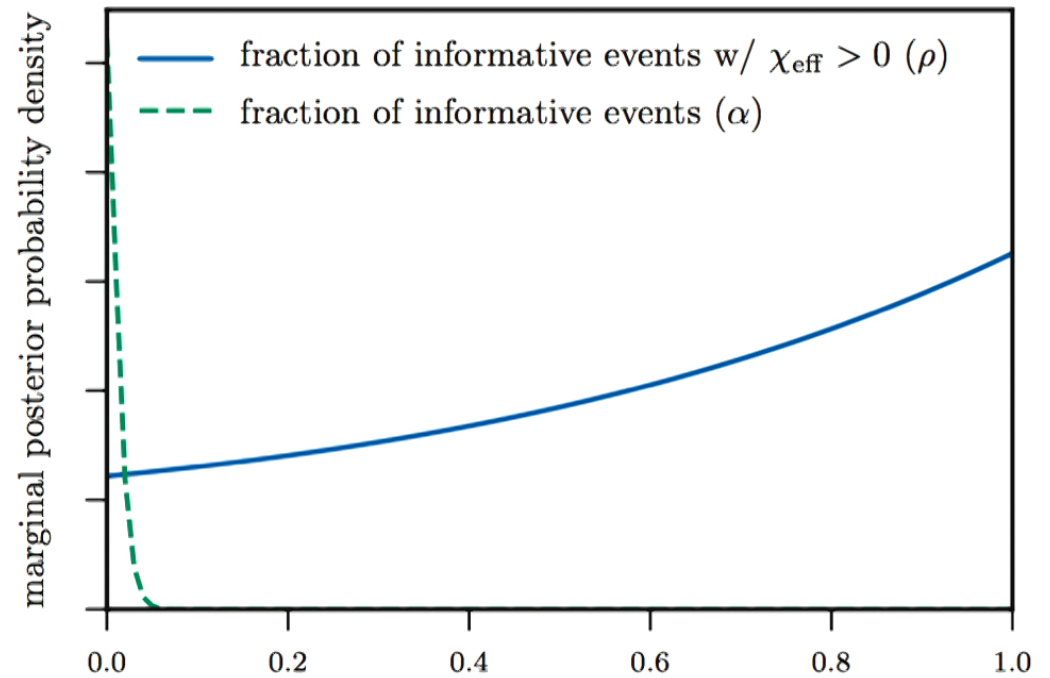
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Farr et al., 1709.07896

SPIN – POPULATION

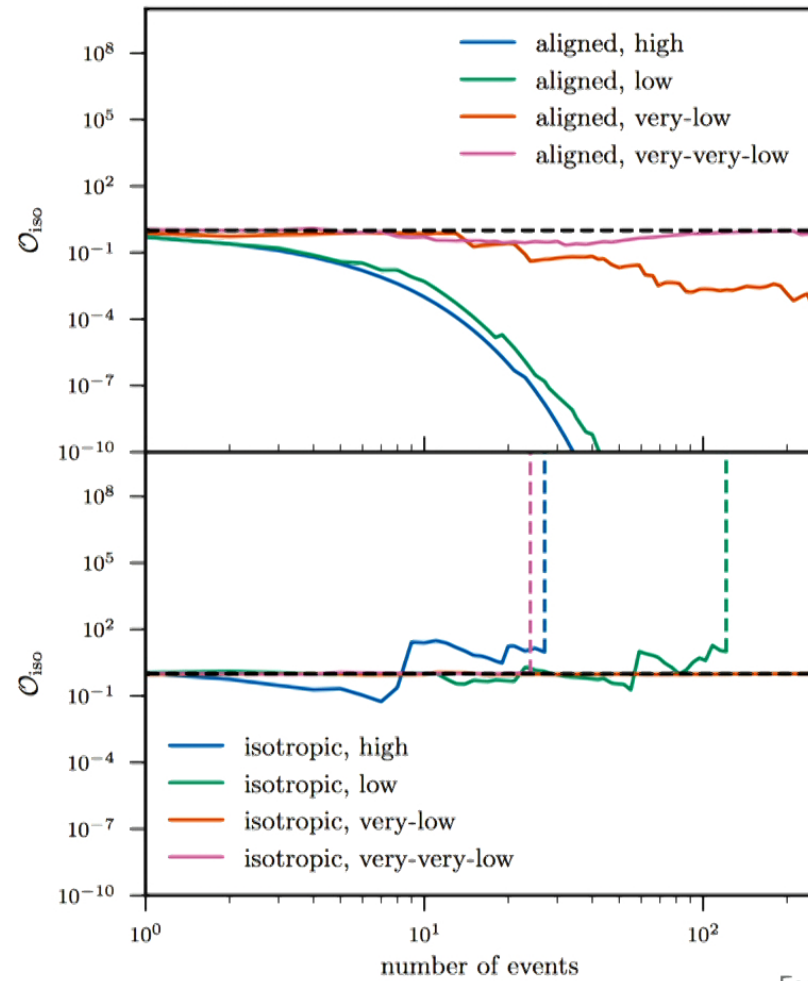
$$p(\chi_{\text{eff}}) = \begin{cases} 2\alpha(1-\rho)/(2-\Delta) & -1 \leq \chi_{\text{eff}} < -\frac{\Delta}{2} \\ (1-\alpha)/\Delta & -\frac{\Delta}{2} \leq \chi_{\text{eff}} < \frac{\Delta}{2} \\ 2\alpha\rho/(2-\Delta) & -1 \leq \chi_{\text{eff}} \leq -\frac{\Delta}{2} \end{cases}$$



Farr et al., 1709.07896

SPIN - POPULATION

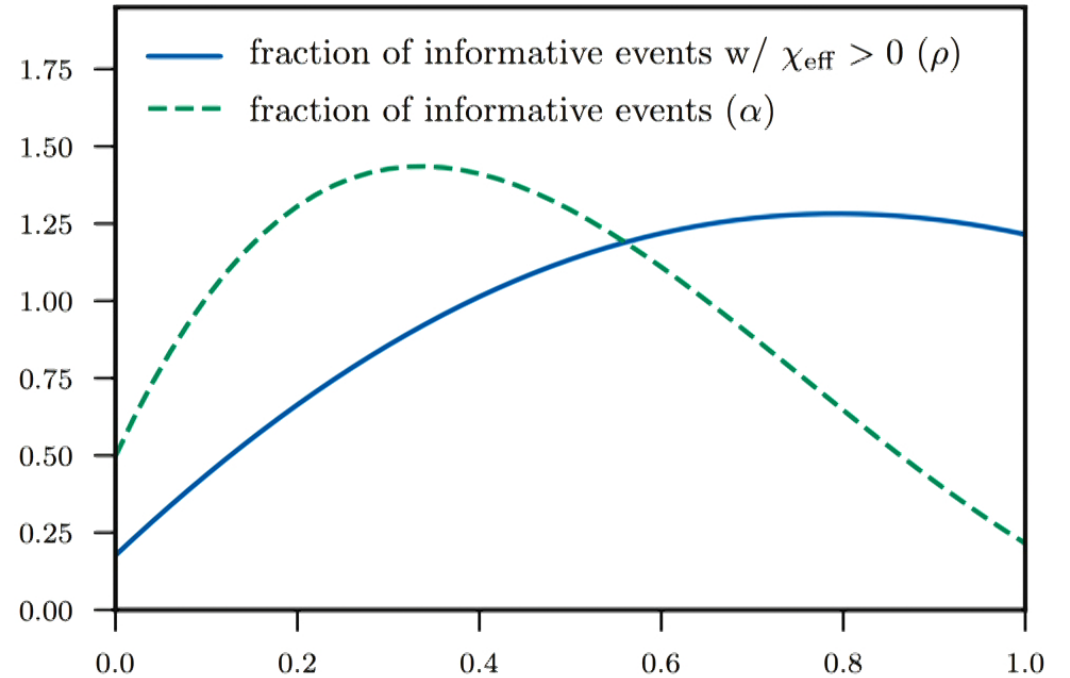
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Farr et al., 1709.07896

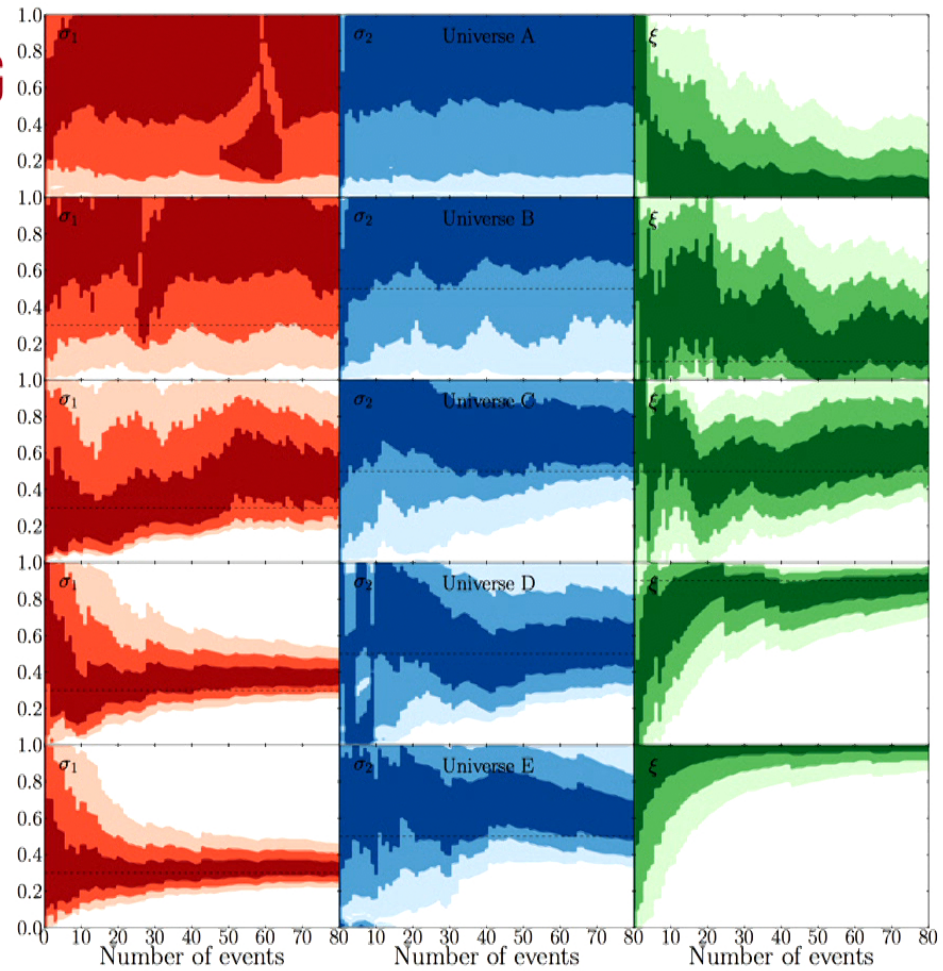
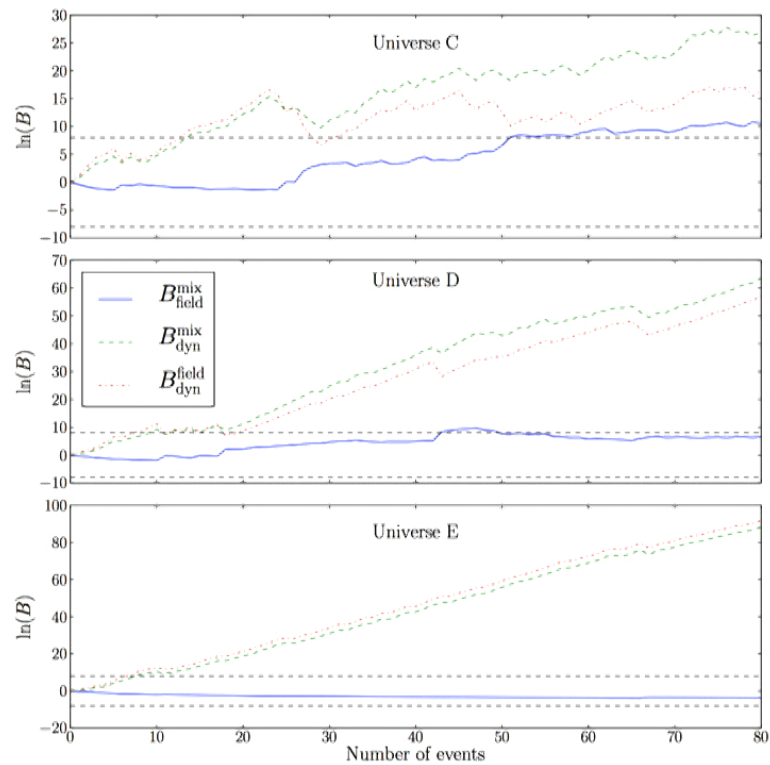
SPIN – POPULATION

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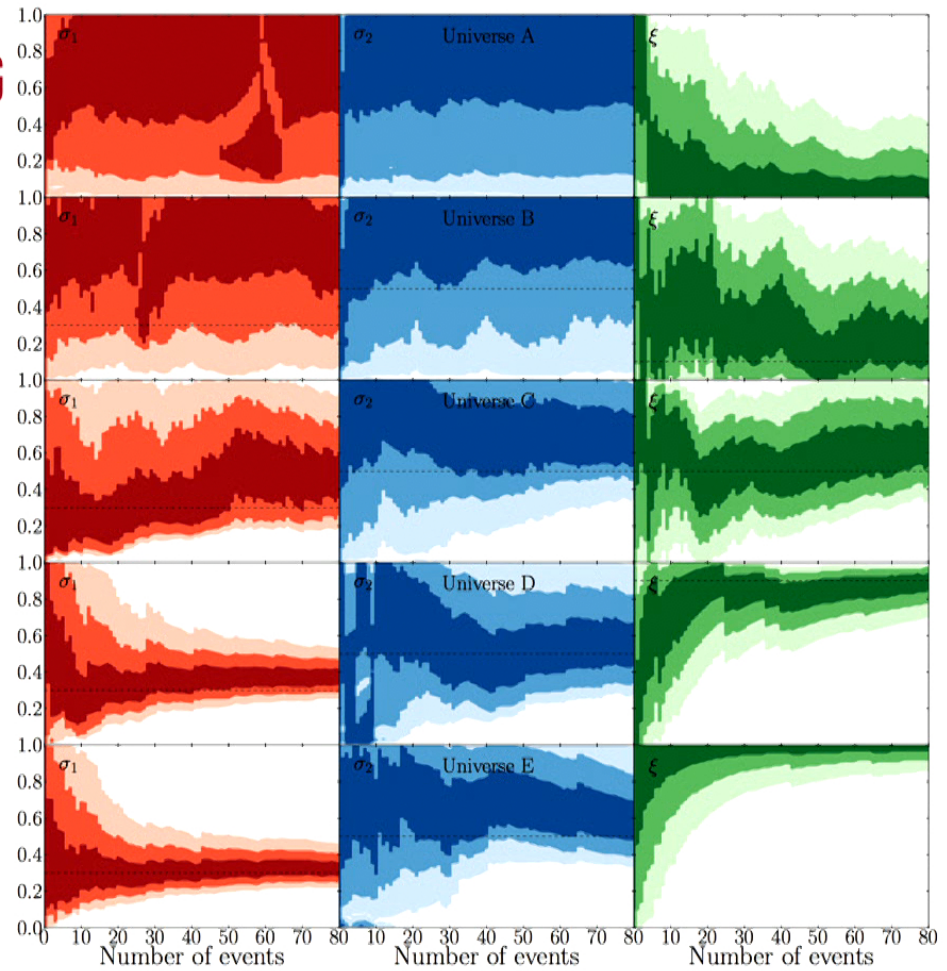
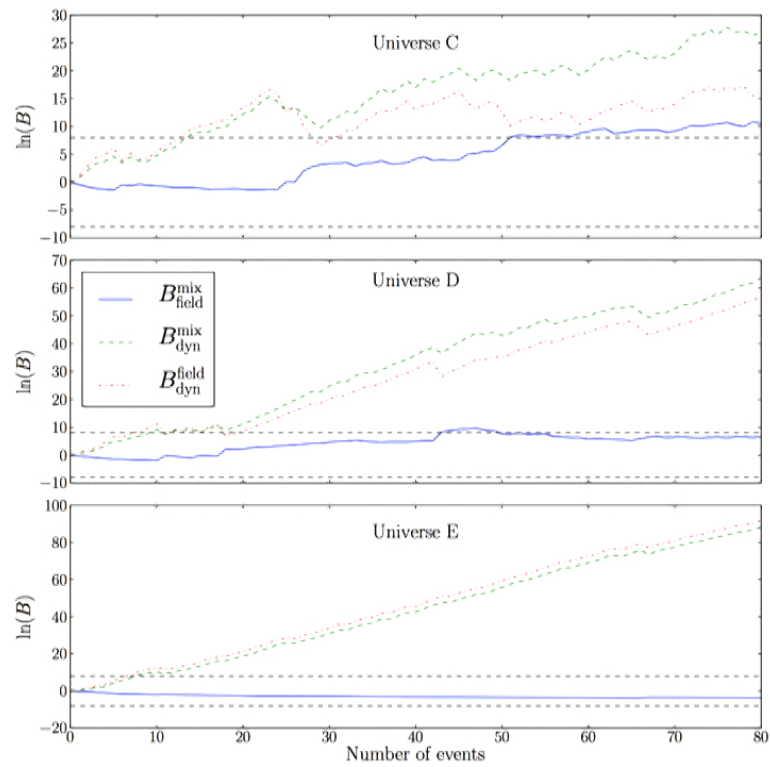
Farr et al., 1709.07896

SPIN – POPULATION MIXING



Talbot & Thrane, 1704.08370

SPIN – POPULATION MIXING



Talbot & Thrane, 1704.08370

SPIN – POPULATION MIXING

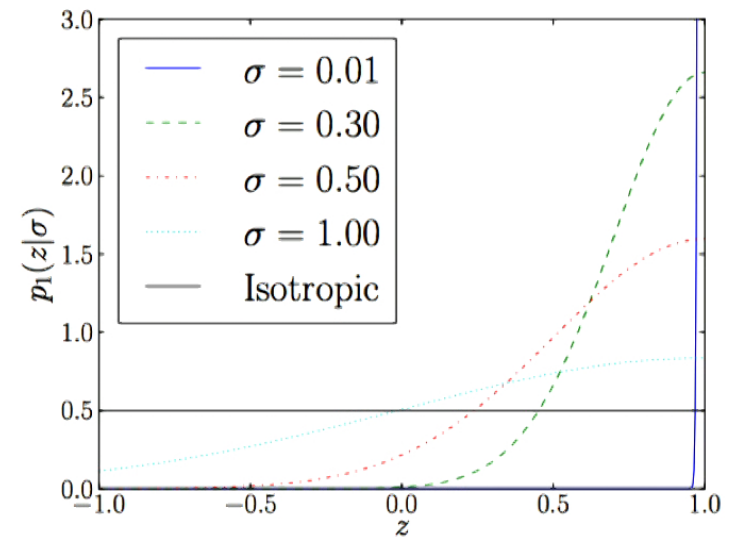
$$z_1 = \cos(\theta_1)$$

$$z_2 = \cos(\theta_2)$$

$$p_0(z_1, z_2) = \frac{1}{4}$$

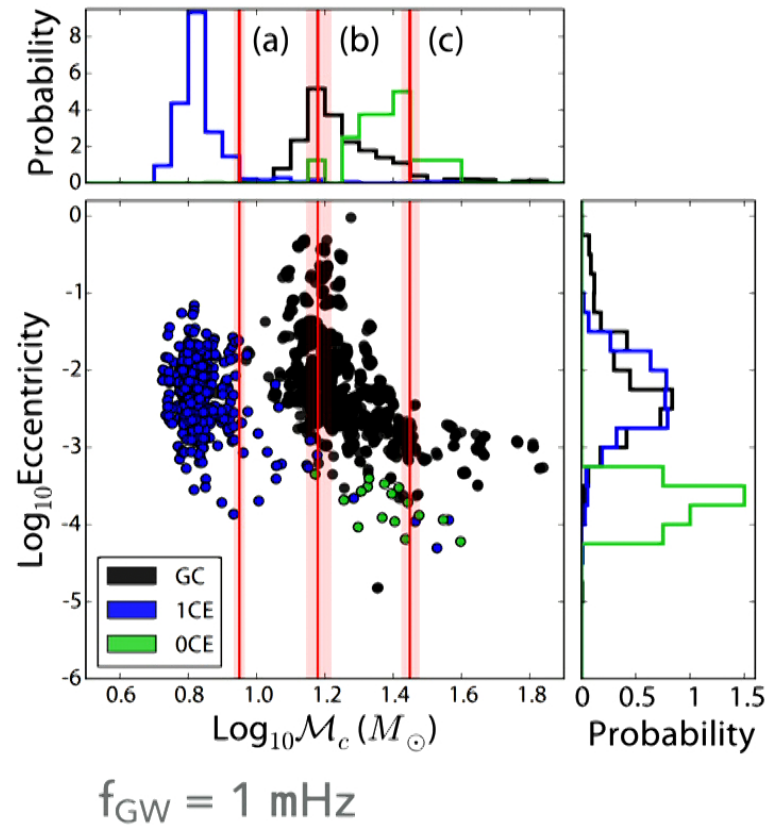
$$p_1(z_1, z_2) = \frac{2}{\pi} \frac{1}{\sigma_1} \frac{e^{-(z_1-1)^2/2\sigma_1^2}}{\text{erf}(\sqrt{2}/\sigma_1)} \frac{1}{\sigma_2} \frac{e^{-(z_2-1)^2/2\sigma_2^2}}{\text{erf}(\sqrt{2}/\sigma_2)}$$

$$p(z_1, z_2) = (1 - \xi)p_0 + \xi p_1$$

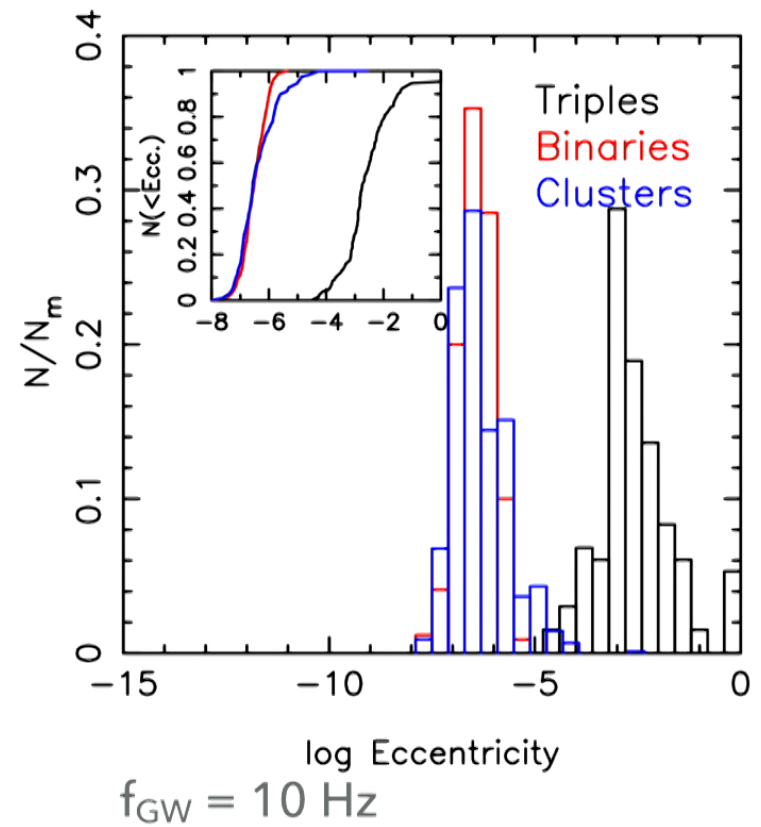


Talbot & Thrane, 1704.08370

ECCENTRICITY

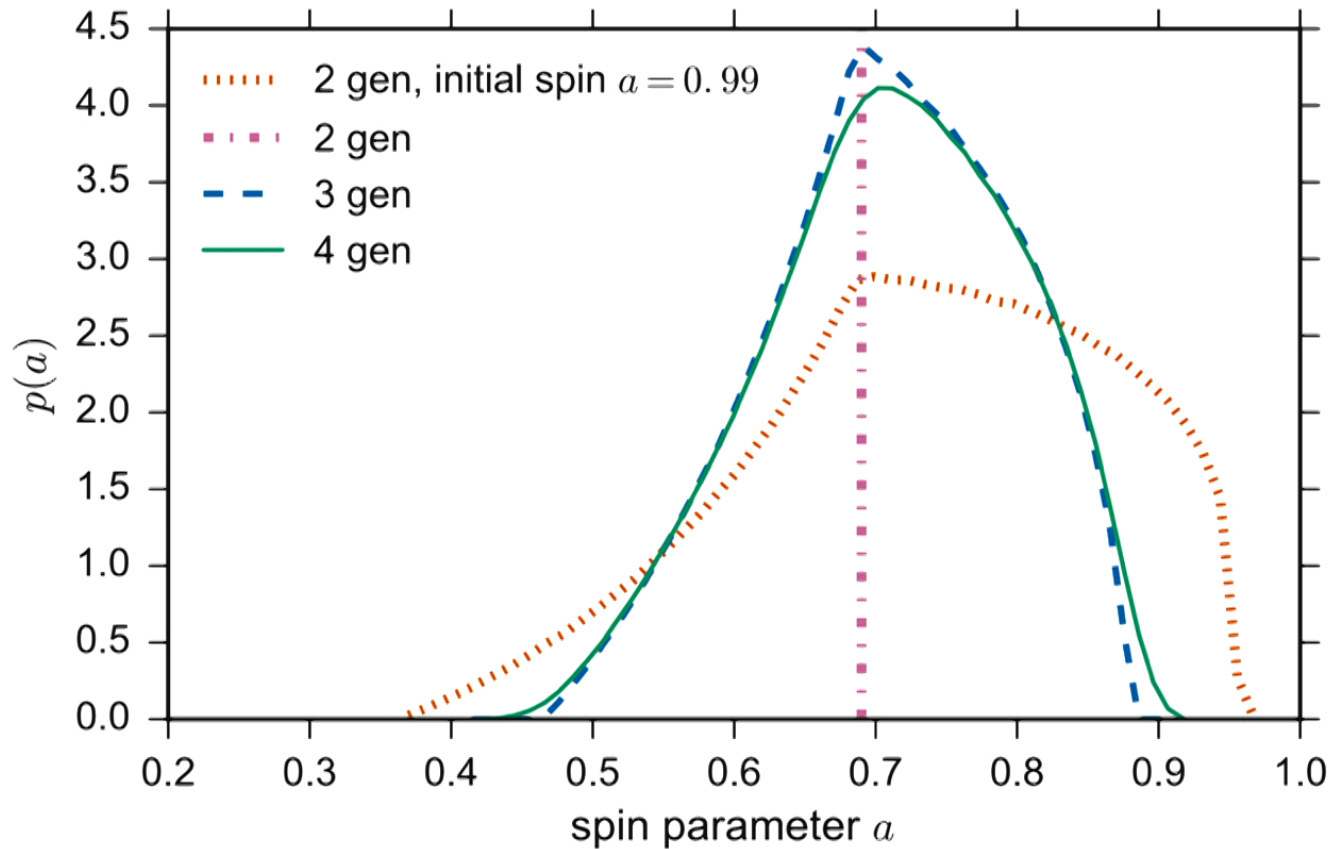


Breivik et al., ApJL (2016)



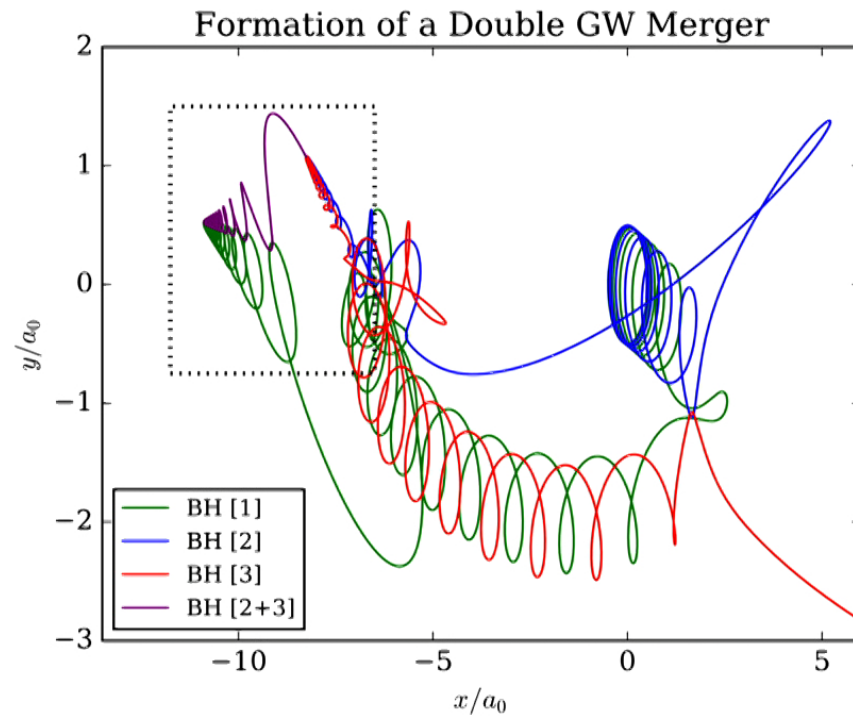
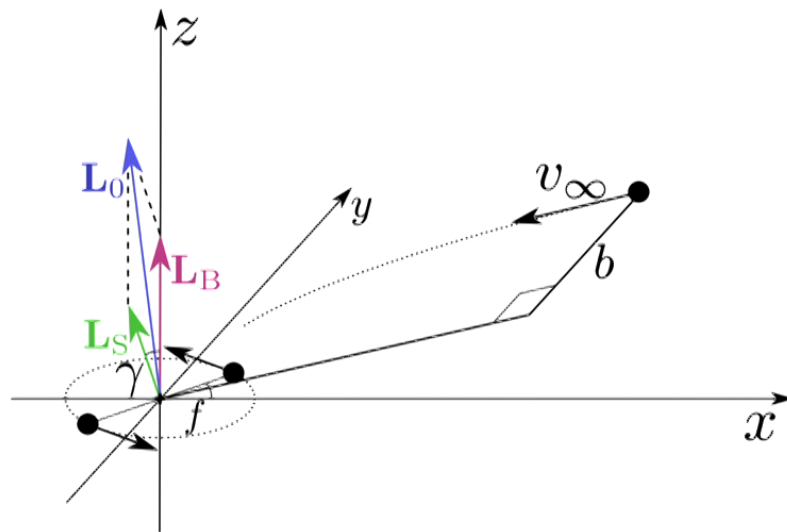
Antonini et al., ApJ (2017)

HIERARCHICAL BBH MERGERS



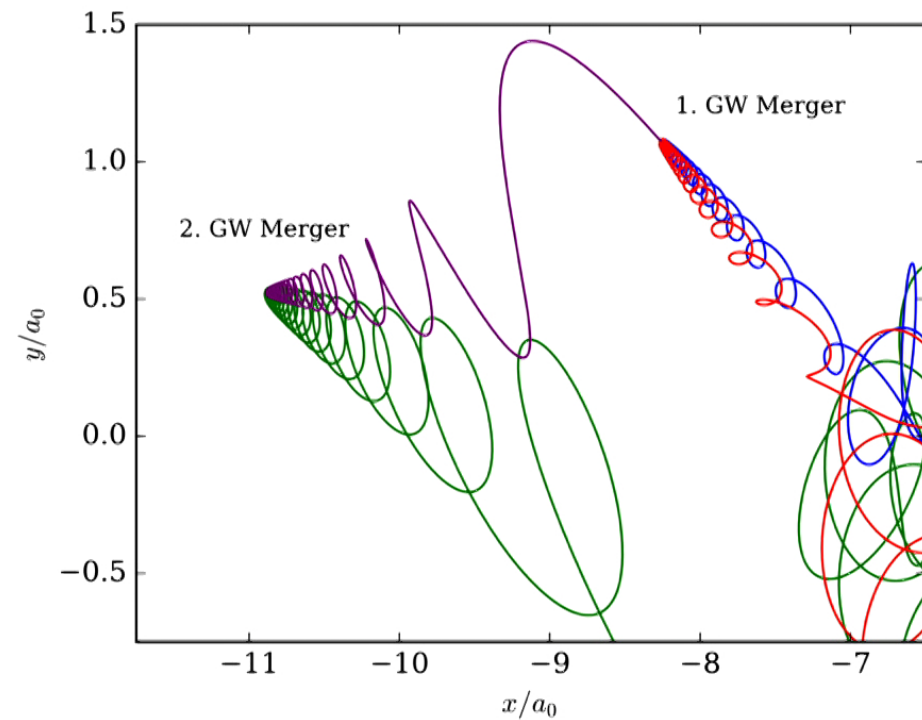
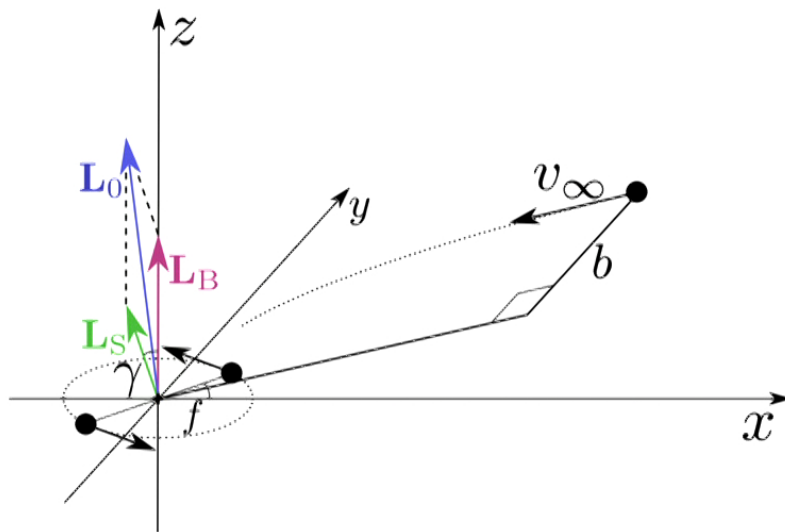
Fishbach, Holz, Farr, ApJ (2017)

HIERARCHICAL BBH MERGERS



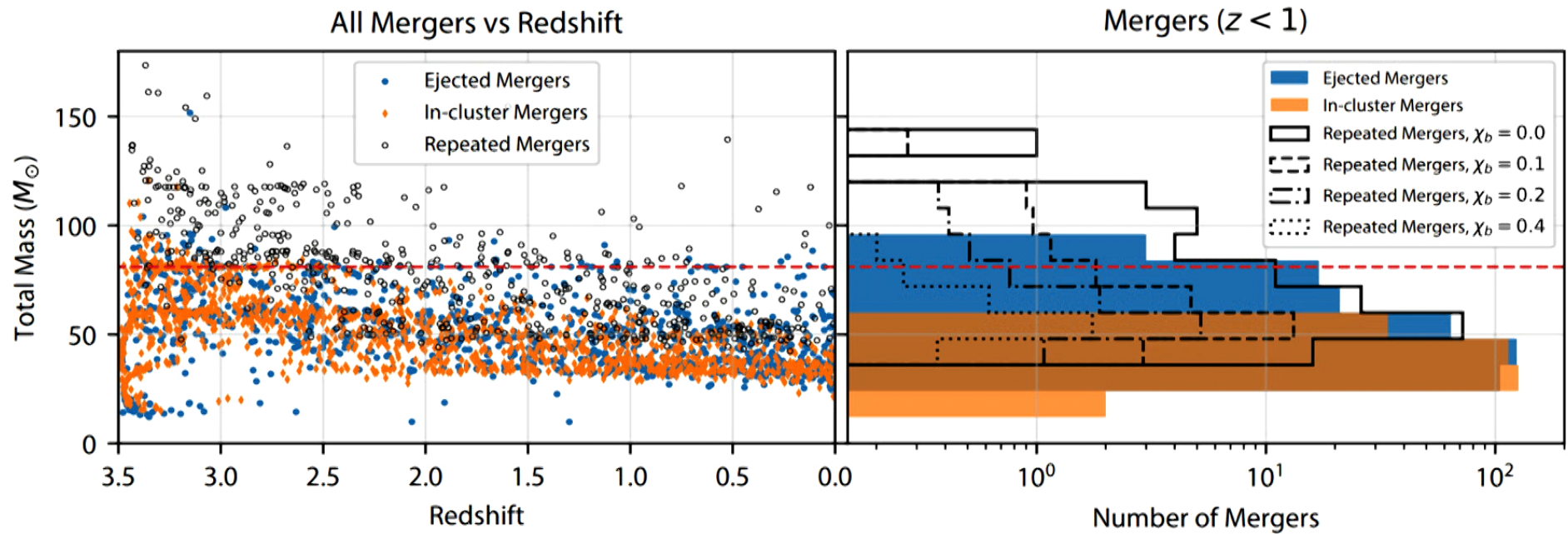
Samsing, Ilan, 1709.01660

HIERARCHICAL BBH MERGERS



Samsing, Ilan, 1709.01660

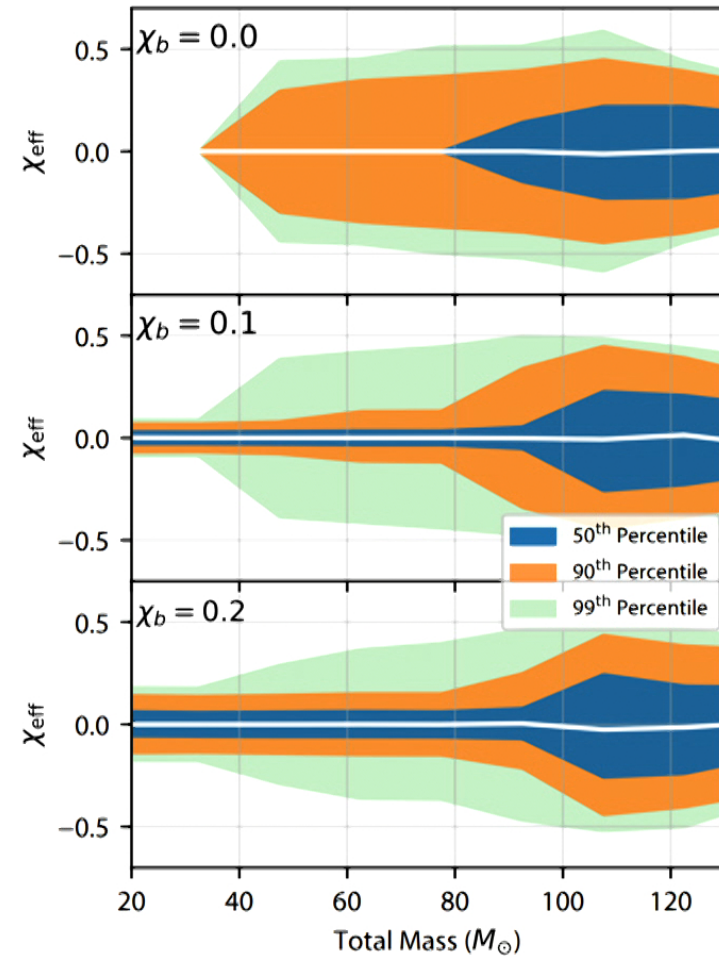
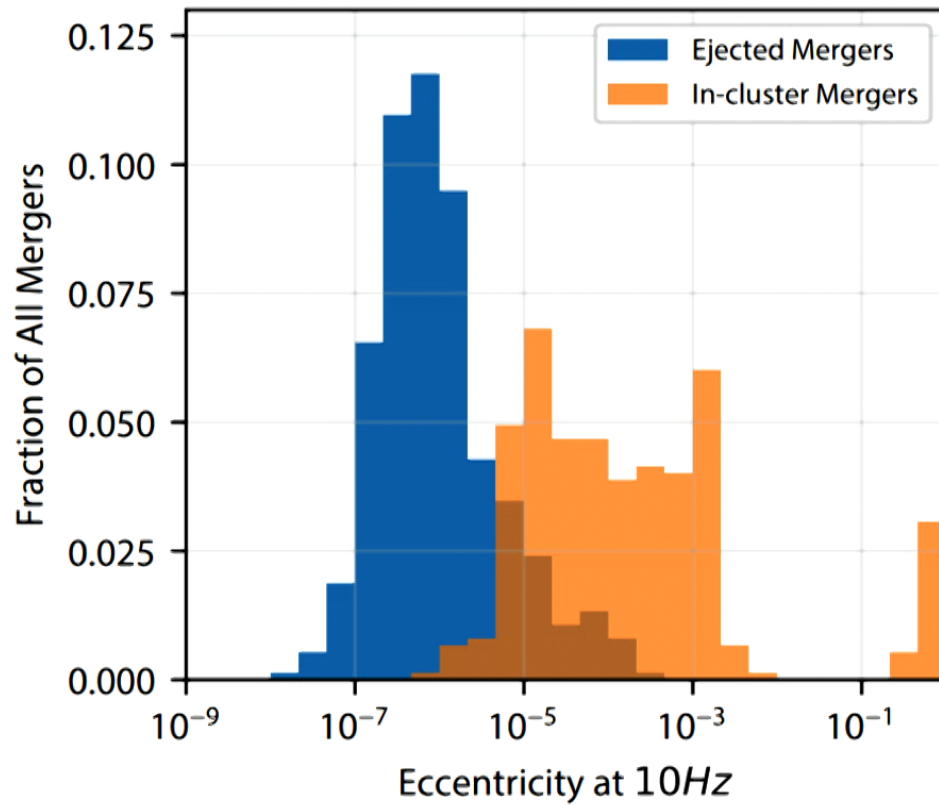
HIERARCHICAL BBH MERGERS



Rodriguez et al., PRL (2018)

HIERARCHICAL BBH MERGERS

Eccentricities ($z < 1$)



Rodriguez et al., PRL (2018)

NOT ALL IS LOST

