Title: Binary black hole spin distribution: The emerging picture from gravitational-wave astronomy

Speakers: Shanika Galaudage

Series: Strong Gravity

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Abstract: Population studies of gravitational-wave events allow us to probe stellar evolution and formation mechanisms of compact binaries. Recent work has painted a conflicting portrait of the distribution of black hole spins in merging binaries. In this talk, I describe the emerging picture of black hole spin using observations from LIGO-Virgo-KAGRA with a new spin model. We find evidence for two subpopulations of binary black holes: 1) merging binaries containing black holes with negligible spin, 2) binaries preferentially aligned with the orbital angular momentum and rapidly spinning. These results are consistent with predictions from studies of angular momentum transport in stars and suggest that the subpopulation of spinning black holes may be spun up via tidal interactions. I will also share insights of the binary black hole population using the latest catalogue of gravitational-wave events.

Zoom Link: https://pitp.zoom.us/j/93713298741?pwd=eFo2Q1lSTVBESWcyZXJlcFVKZ2hRQT09


Binary black hole spin distribution
The emerging picture from gravitational-wave astronomy
Shanika Galaudage
April 28, 2022 | Perimeter Institute - Strong Gravity seminar
LIGO VIRGO KAGRA
OzGrav
MONASH University
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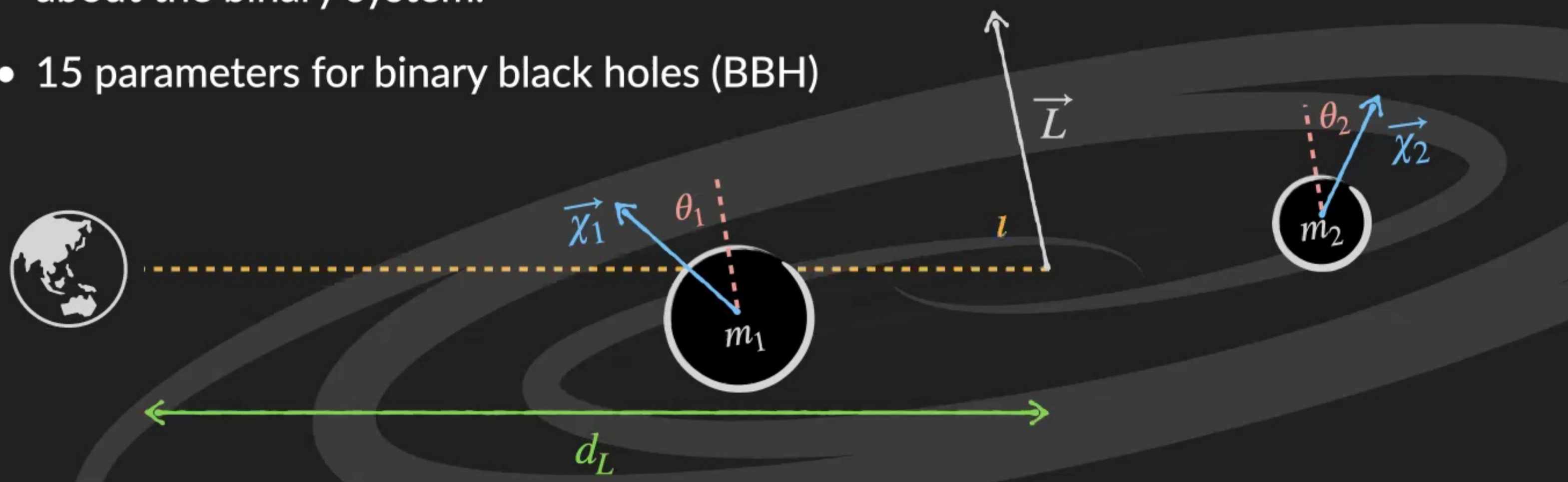
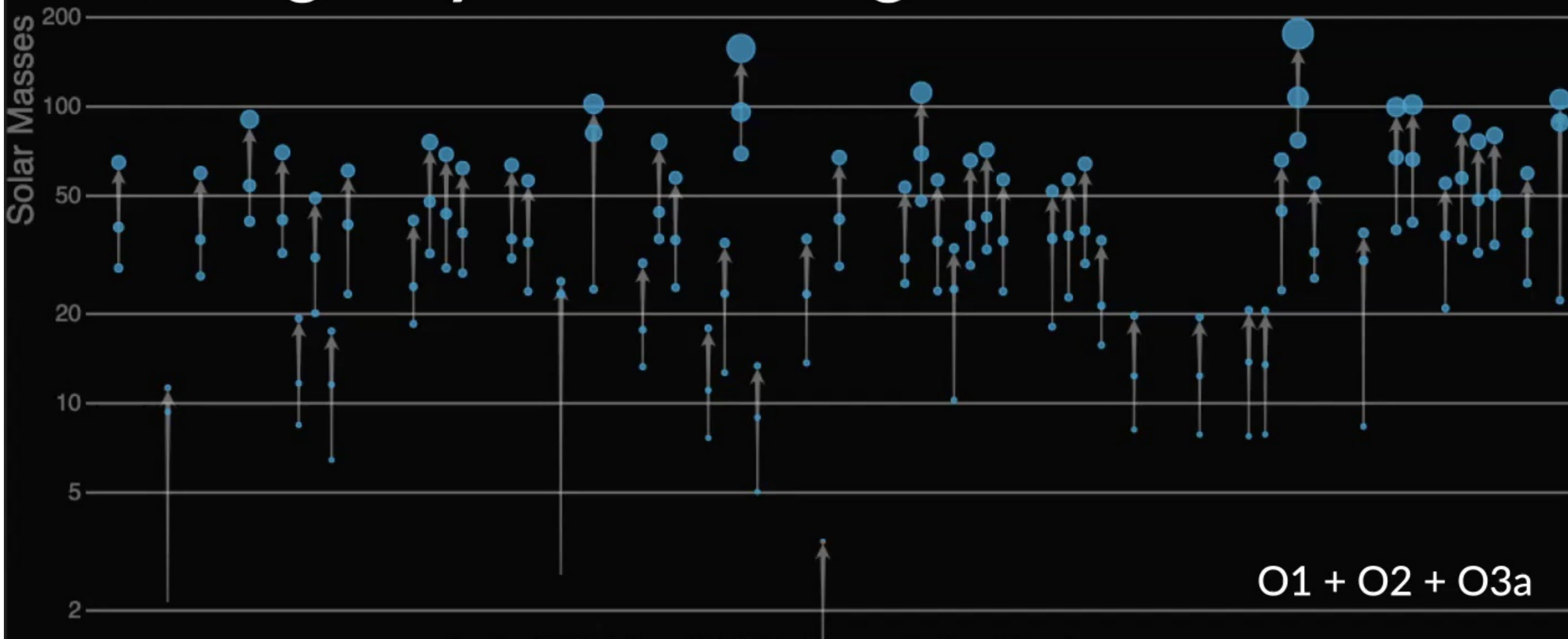
Gravitational waves

- Sources so far are mergers compact binary systems - signal carries information about the binary system.
- 15 parameters for binary black holes (BBH)



Stellar graveyard: LIGO-Virgo-KAGRA black holes



Credit: LIGO-Virgo-KAGRA / Aaron Geller / Northwestern

O1 + O2 + O3a =
GWTC-2

× 44

O1 + O2 + O3b =

O1 + O2 + O3a + O3b =
GWTC-3

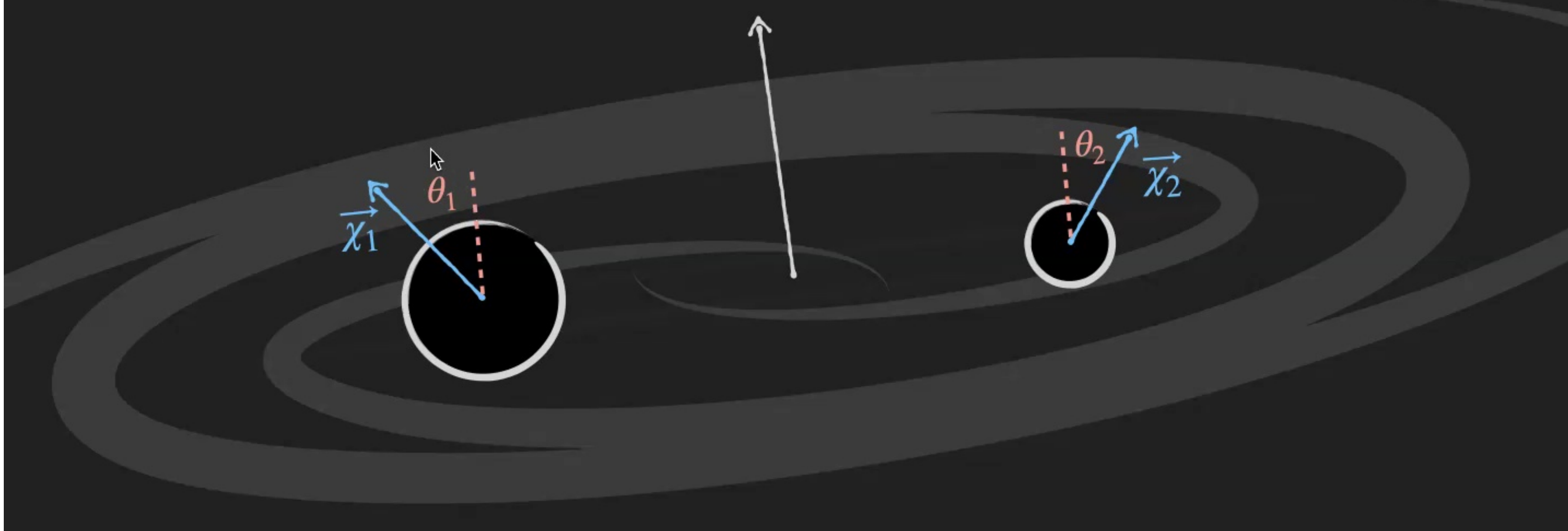
× 69

Population studies by LIGO-Virgo-KAGRA (LVK) collaboration used events FAR < 1/year; mass, spin and redshift distributions

Understanding the spin distribution

- Spin distributions inform us about formation and evolution of compact binaries.
- Two parameterisations generally used in gravitational-wave analyses: 1) physical spin quantities, 2) effective spin quantities.

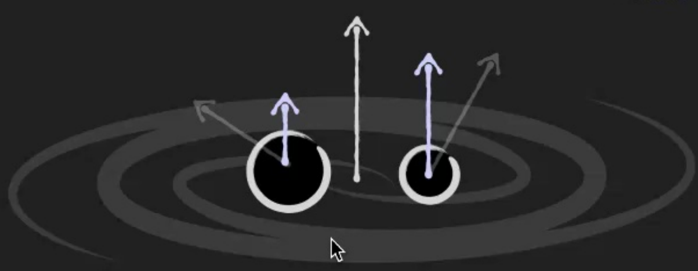
Spin parameters: physical quantities



Compact objects are sorted by mass; see Biscoveanu+ 2021 (arXiv:2007.09156) for work sorting by spin.

Spin parameters: effective spins

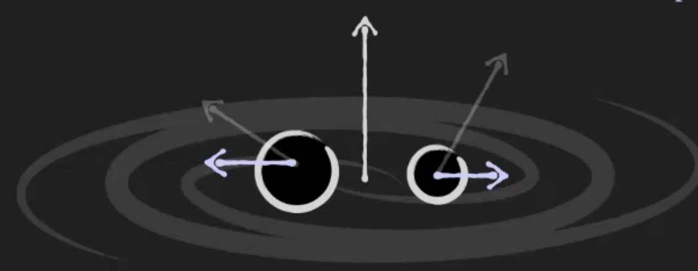
Effective inspiral spin parameter (χ_{eff})



$$\chi_{\text{eff}} = \frac{\chi_1 \cos(\theta_1) + q\chi_2 \cos(\theta_2)}{1+q}$$

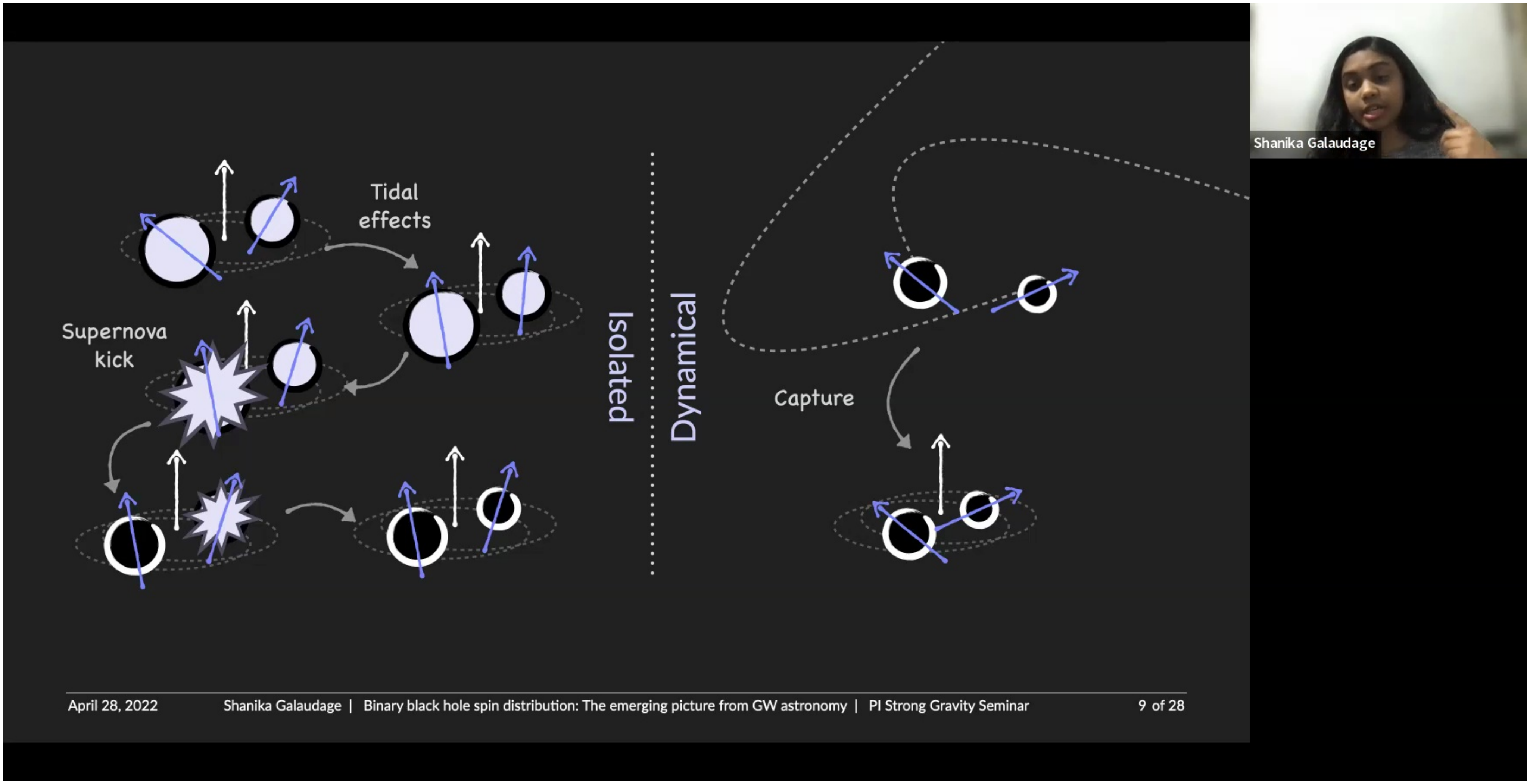
Mass weighted spin projected along orbital angular momentum vector; conserved over evolution

Effective precession spin parameter (χ_p)



$$\chi_p = \max\left[\chi_1 \sin(\theta_1),\ \frac{4q+3}{3q+4} q\chi_2 \sin(\theta_2)\right]$$

Mass weighted spin projected in the plane of the binaries orbit; measure of orbital precession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Tidal effects
Supernova kick
Isolated
Dynamical
Capture
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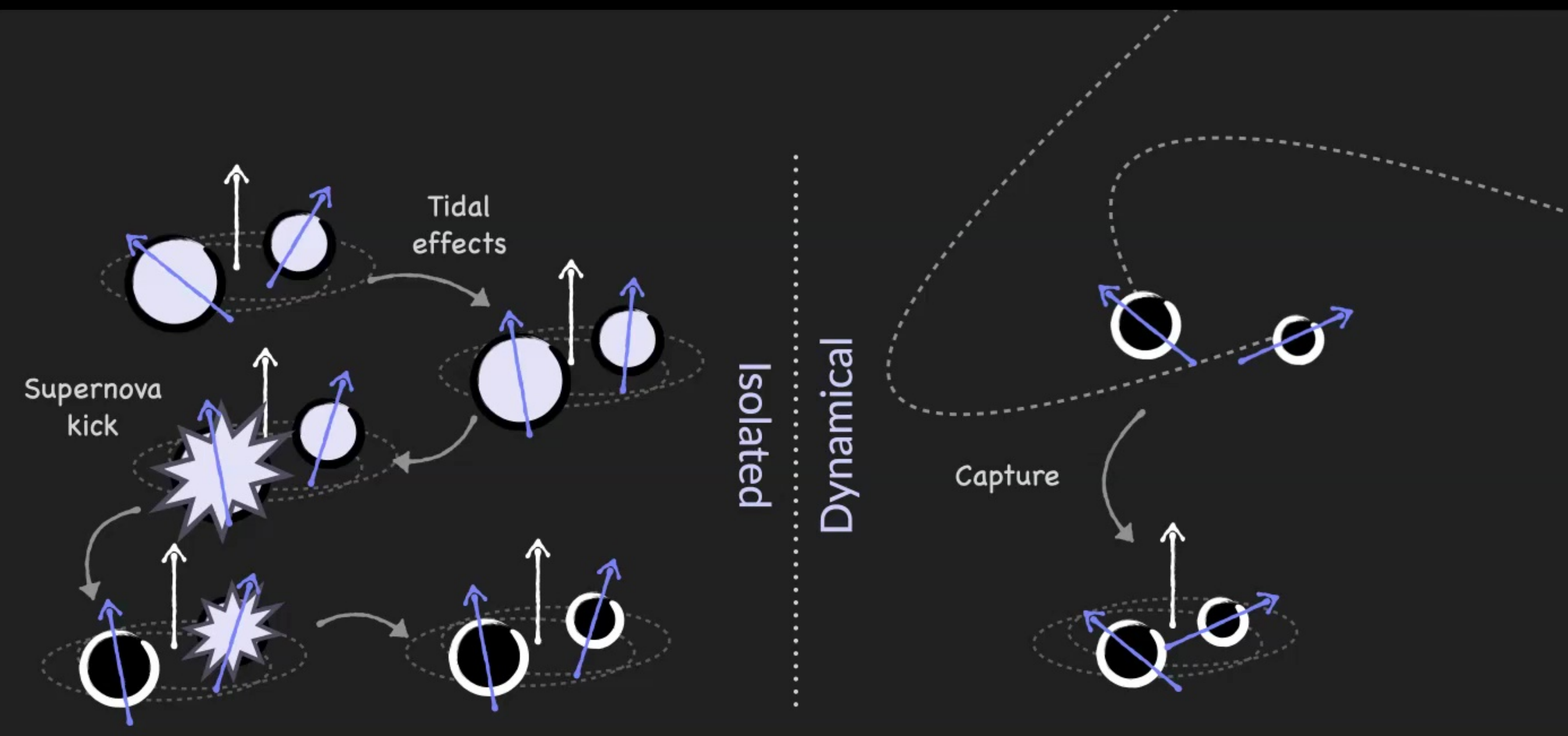
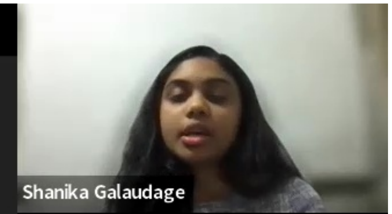
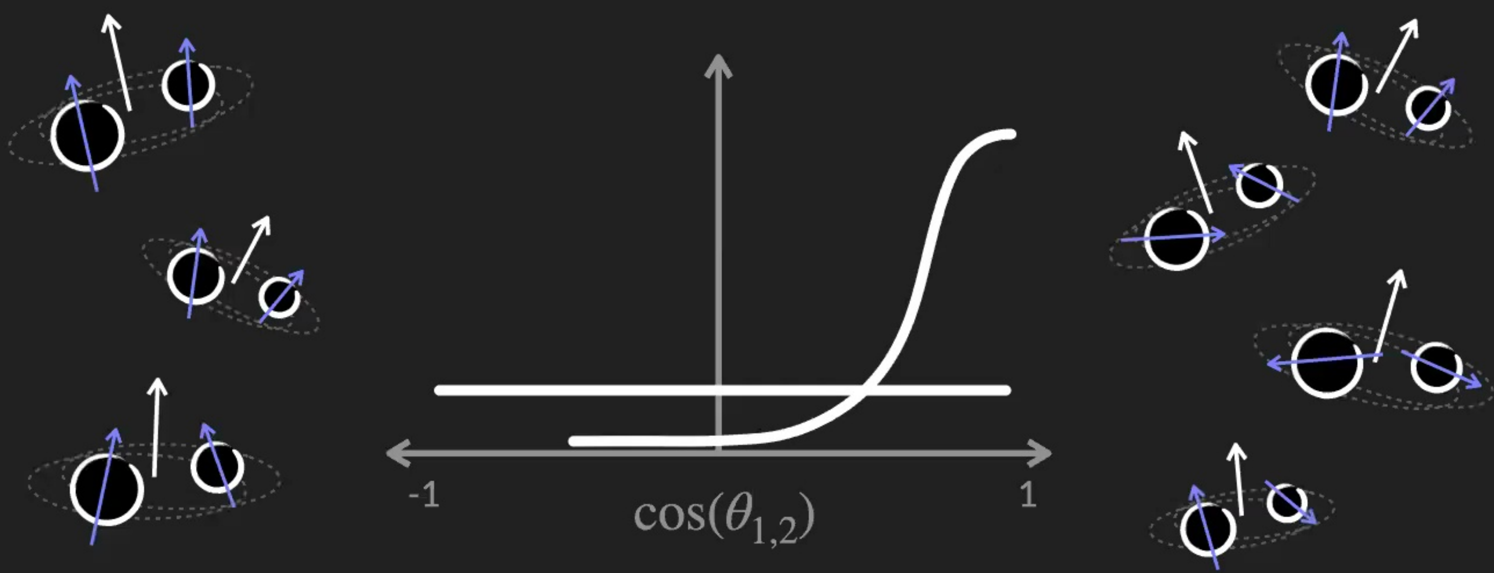


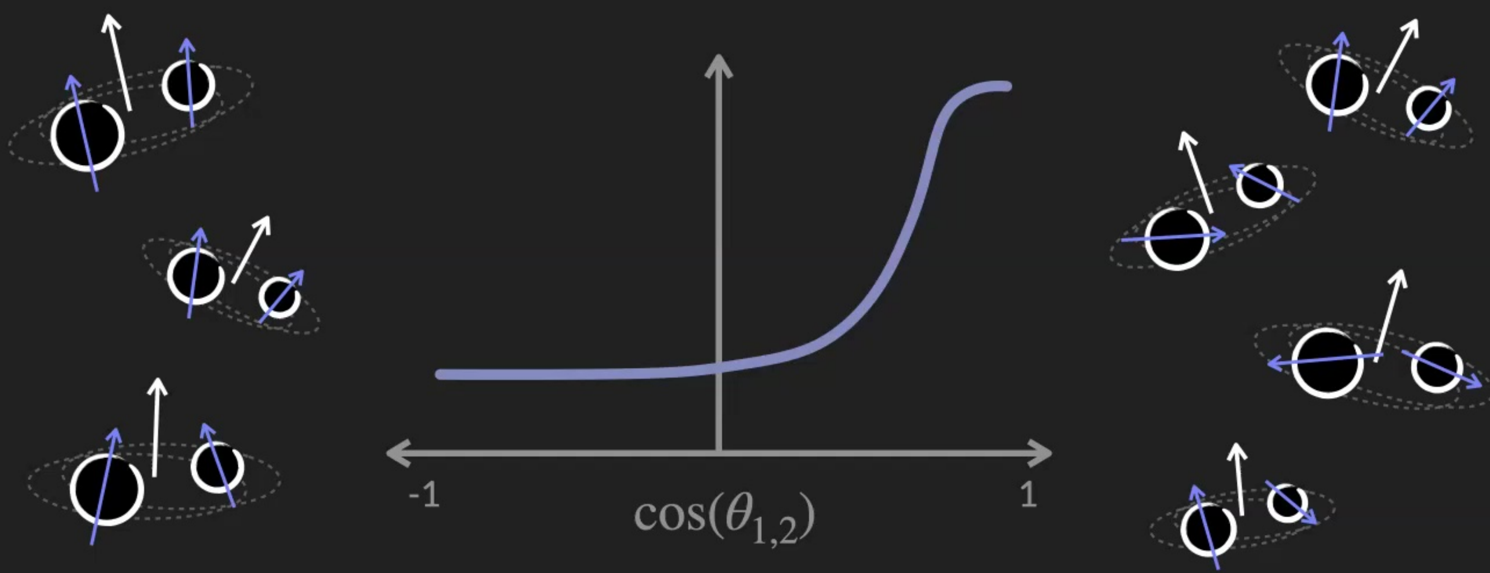


Hierarchical mergers would be strong evidence for dynamical assembly; see Kimball+ 2021 (arXiv:2011.05332)

Formation channels: what we expect in GWs

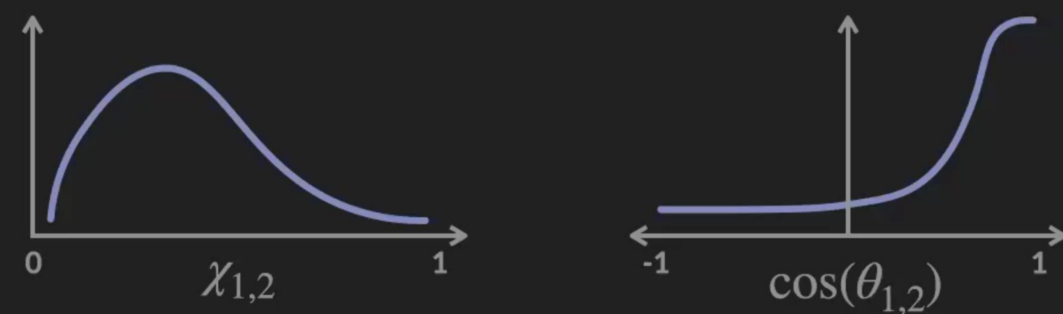


Formation channels: what we expect in GWs



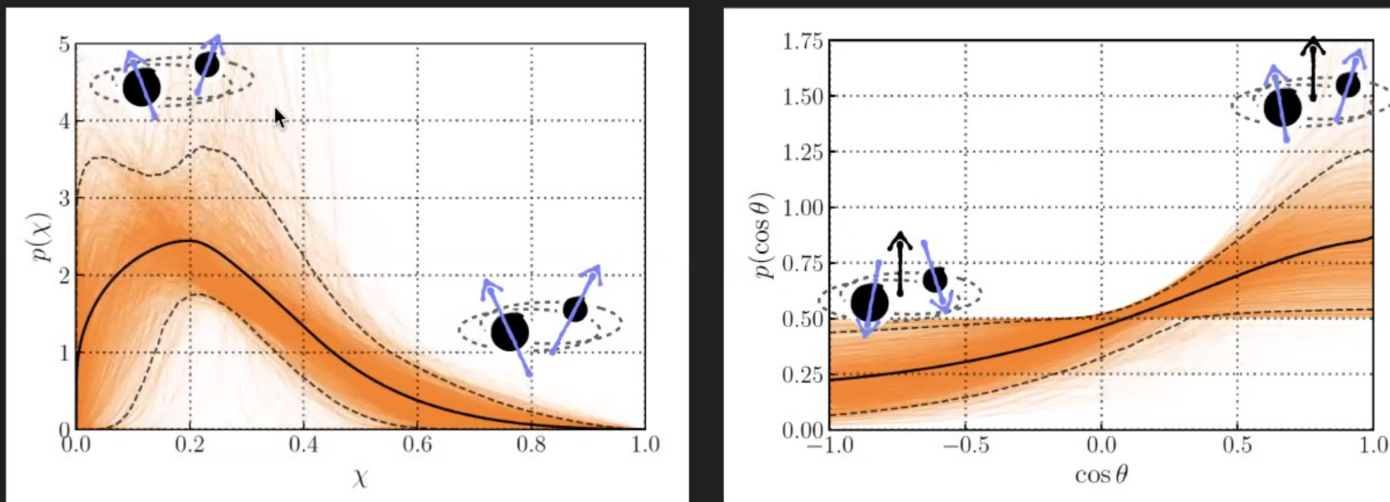
Population models used in LVK analysis

- Two spin models used for analysis: **Default** (physical spin quantities) and **Gaussian** (effective spin quantities).
- Both models gave qualitatively similar descriptions of the population.



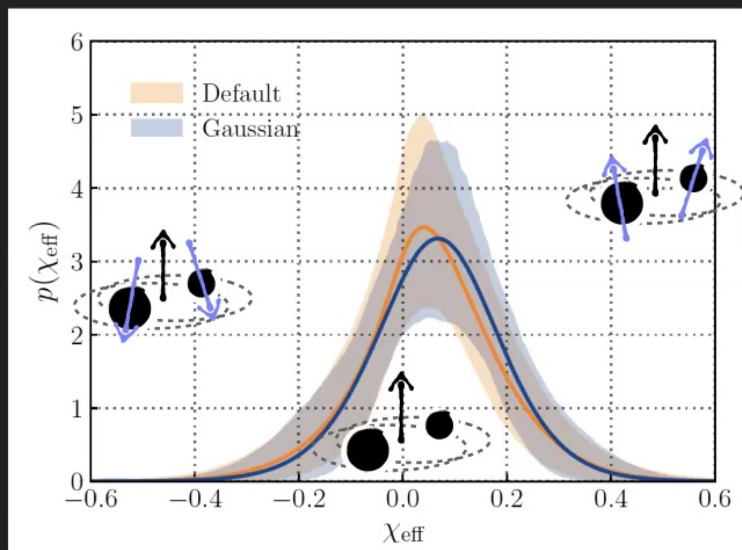
Default model for spin magnitude (left) and spin orientation (right).

What did we learn following GWTC-2



Spin magnitude (left) spin orientation (right) distributions: Solid curve - mean;
Dashed curve - 90% credible interval

What did we learn following GWTC-2



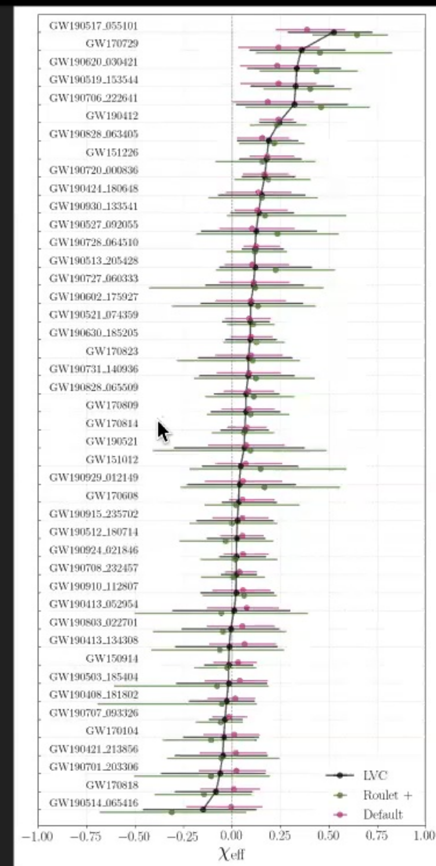
Effective inspiral spin distribution: Solid curve - mean; Shaded region - 90% credible interval

A conflicting picture

- From the LVK GWTC-2 populations paper, the spin models found support for a sub-population of binaries with $\chi_{\rm eff} < 0$ – Roulet+ 2021 (arXiv:2105.10580) dispute this finding.
- We attempt to resolve these disparate findings between LVK and Roulet+ by:
  - Re-analysing GWTC-2 with a more flexible model
  - Determine how sensitive the results may be to assumptions about the shape of the population models.

Event posteriors

- We find that looking at the posterior distributions of GWTC-2 events weighted by different priors gives the following distributions.
- Events are consistent with $\chi_{\mathrm{eff}} \geq 0$, therefore support for a sub-population of binaries with $\chi_{\mathrm{eff}} < 0$ in LVK analysis is likely a result of model misspecification.



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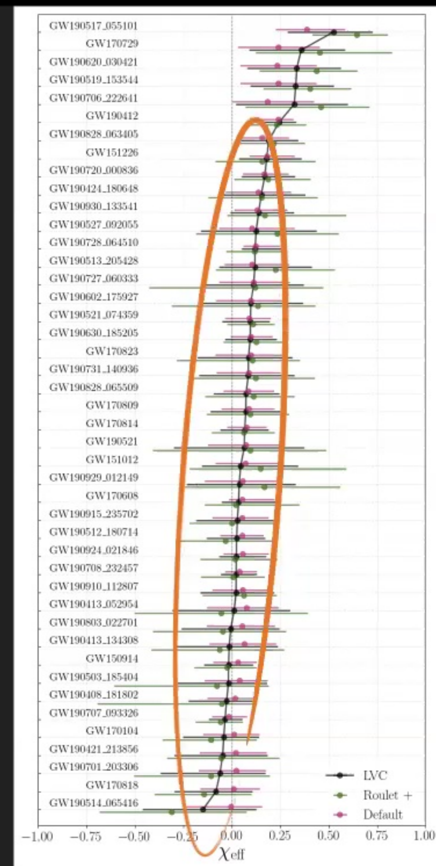
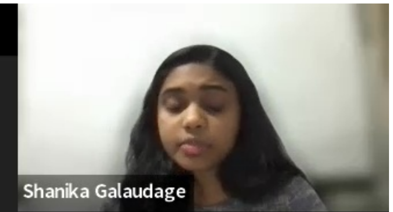
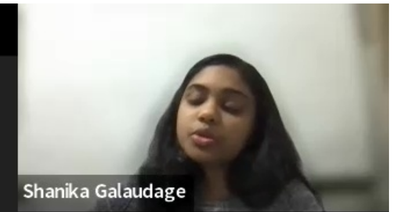




Accounting for negligible spin

- Theoretical studies of angular momentum transport show that black holes are born rotating slowly (Fuller & Ma 2019; Belczynski et al. 2020) indicate that some BBH should merge with negligible spin.
- The LVK analysis (Abbott et. al. 2021) did not use models that can account for a sub-population of binaries with black holes.
- We update our models to account for a subpopulation of black holes motivated by the expectation of BBH with $\chi \sim 0$



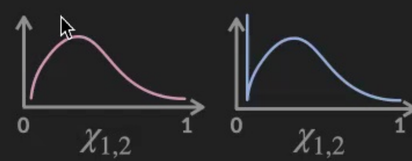
Population spin models: Default VS Extended

Spin magnitude model

$\mu = 0;\ \sigma = 0$

$$\pi(\chi_{1,2} \mid \alpha_\chi, \beta_\chi) = \mathrm{Beta}(\chi_{1,2} \mid \alpha_\chi, \beta_\chi)$$

$$\pi(\chi_{1,2} \mid \alpha_\chi, \beta_\chi, \lambda_0) = (1 - \lambda_0)\mathrm{Beta}(\chi_{1,2} \mid \alpha_\chi, \beta_\chi) + \lambda_0 G_t(\chi_{1,2})$$



Spin orientation model

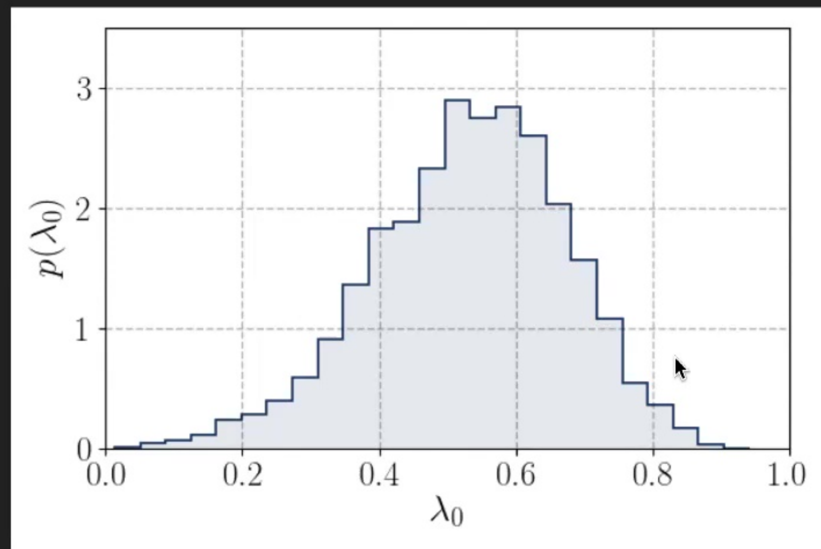
$z \equiv \cos(\theta)$

$$\pi(z_{1,2} \mid \zeta, \sigma_t) \propto \zeta G_t(z_{1,2} \mid \sigma_t) + (1 - \zeta)\mathfrak{I}(z_{1,2})$$

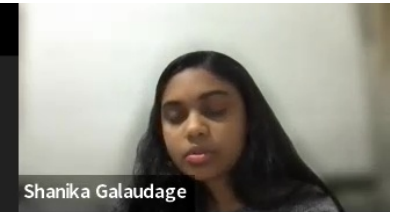
$$\pi(z_{1,2} \mid \zeta, \sigma_t, z_{\min}) \propto (\zeta G_t(z_{1,2} \mid \sigma_t) + (1 - \zeta)\mathfrak{I}(z_{1,2}))\Theta(z_{1,2} - z_{\min})$$

Fraction of BBH with negligible spin

- Figure shows the hyper-posterior for λ_0 fraction of binaries in $\chi_{1,2} \sim 0$ peak
- Support for a peak at $\chi_{1,2} \sim 0$, with $\sim 29 - 75\,\%$ of binaries characterised by negligible spin.

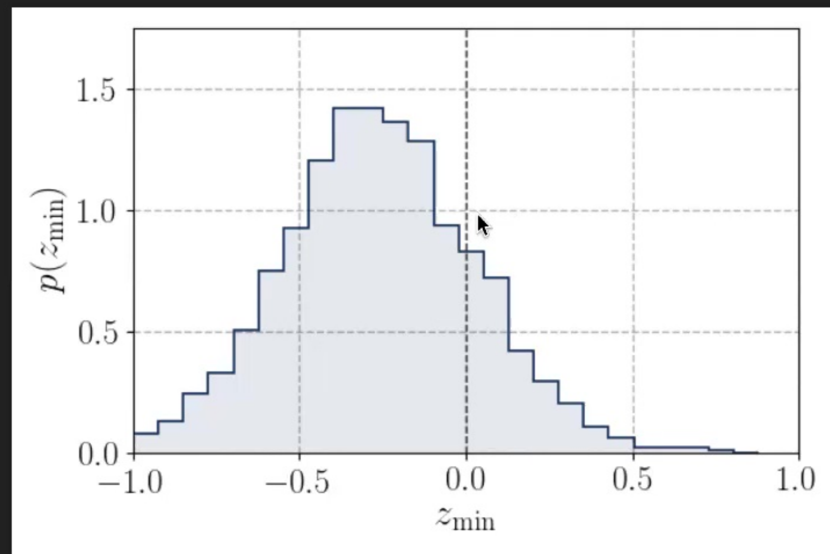


Hyper-posterior distribution for the fraction of binary black holes in zero spin peak



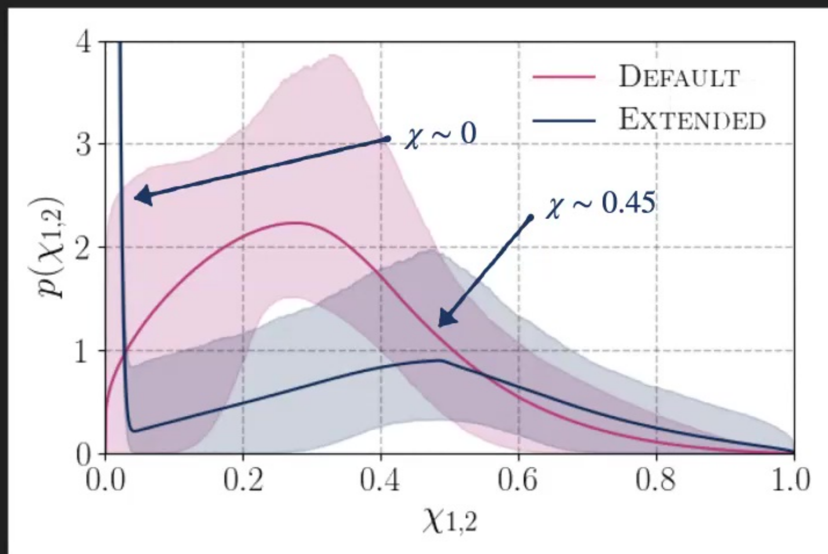
Minimum spin tilt

- Figure shows hyper posterior for z_{min} minimum cosine tilt angle
- Extended model consistent with $z_{\mathrm{min}} = 0$; no clear support for systems with misalignments $> 90\,\mathrm{deg}$ w.r.t the orbital angular momentum

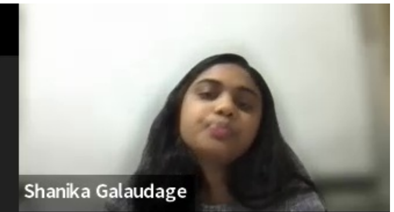


Hyper-posterior distribution for the minimum cosine of the spin tilt angle w.r.t. to the orbital angular momentum

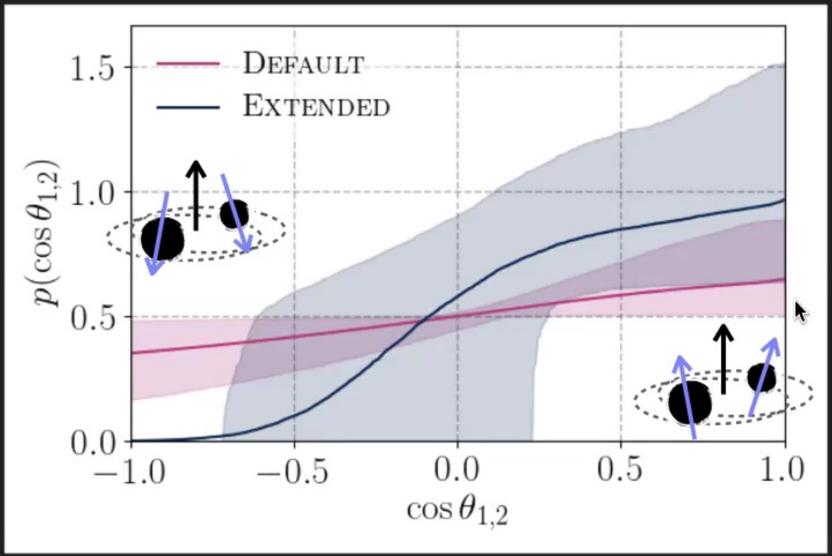
Spin magnitude



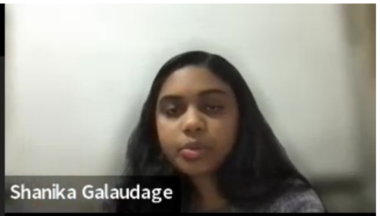
Spin magnitude distribution: Solid curve - mean; Shaded region - 90% credible interval

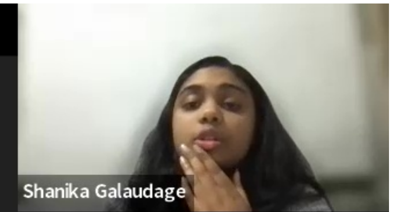


Spin orientation



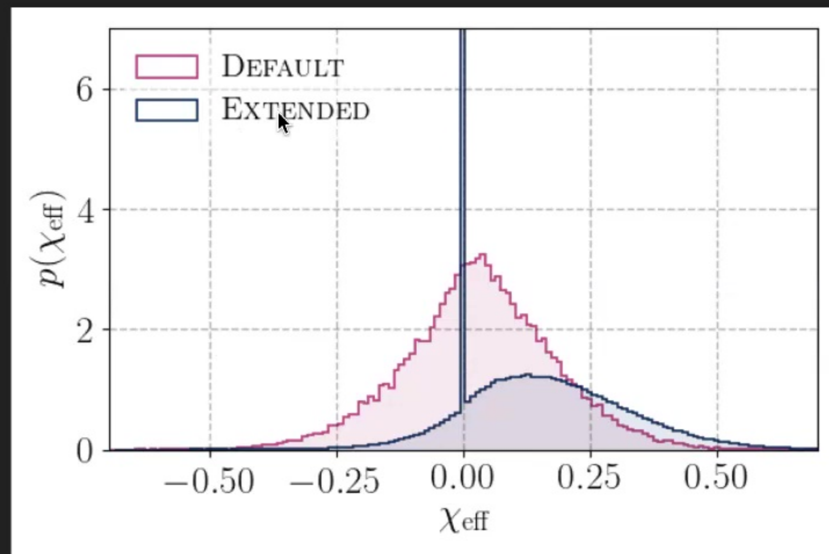
Spin orientation distribution: Solid curve - mean; Shaded region - 90% credible interval





Effective inspiral spin distribution

- The impact of allowing $\chi \sim 0$ in our updated model is evident in χ_{eff} distribution
- $\sim 54\,\%$ binaries in peak around $\chi_{\mathrm{eff}} \sim 0$, with fewer than $2\,\%$ of all binaries predicted to have $\chi_{\mathrm{eff}} < -0.1$



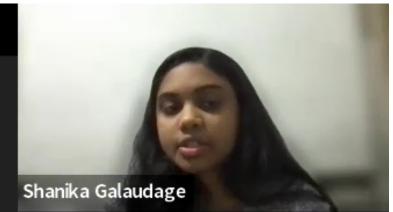
Population draws of the effective inspiral spin parameter.

Evidence for two subpopulations

- We find evidence for two subpopulations: 1) merging binaries with negligible spin; 2) merging binaries that are rapidly spinning and preferentially aligned.
- Extended model preferred over the Default by $\log_{10} B \approx 3.55$; $B \approx 3300$
- No clear support for negative effective inspiral spin; population consistent with isolated channel; if we only consider spin e.g. GW190521 is difficult to explain with isolated formation scenario; see Romero-Shaw+ (arXiv:2009.04771), Gayathri+ (arXiv:2009.05461).

Summary from GWTC-2

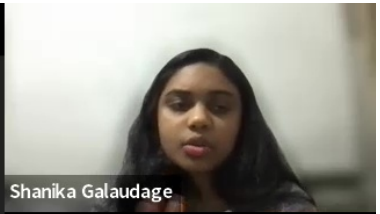
- Our results support the Roulet+ finding that the presence of a subpopulation with $\chi_{\rm eff} < 0$ is a model-dependent extrapolation.
- We do not rule out the presence of a subpopulation with $\chi_{\rm eff} < 0$ — we just do not find positive evidence for it (in GWTC-2)
- Majority of the population (54%) has negligible spin, remaining has $\chi \approx 0.45$
- More details available on arXiv:2109.02424 - supplementary materials are available at github.com/shanikagalaudage/bbh_spin



From GWTC-2 to GWTC-3: what changed?

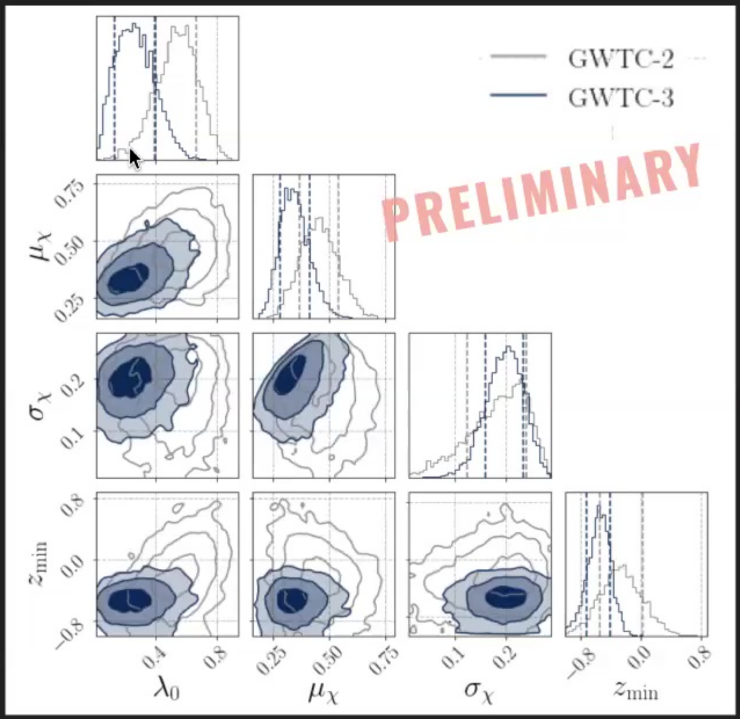
- Work led by Hui Tong (PhD student at Monash) looks at the population using the Extended model including O3b events + some additional investigations (publication in prep).
- Interesting events of note:
  - GW191109 — posterior support for $\chi_{\mathrm{eff}} < 0$
  - GW200129 — posterior support for large χ_p

  Note: There are some shifts in posteriors depending on the waveform used; see GWTC-3 catalogue for details (arXiv:2111.03606)

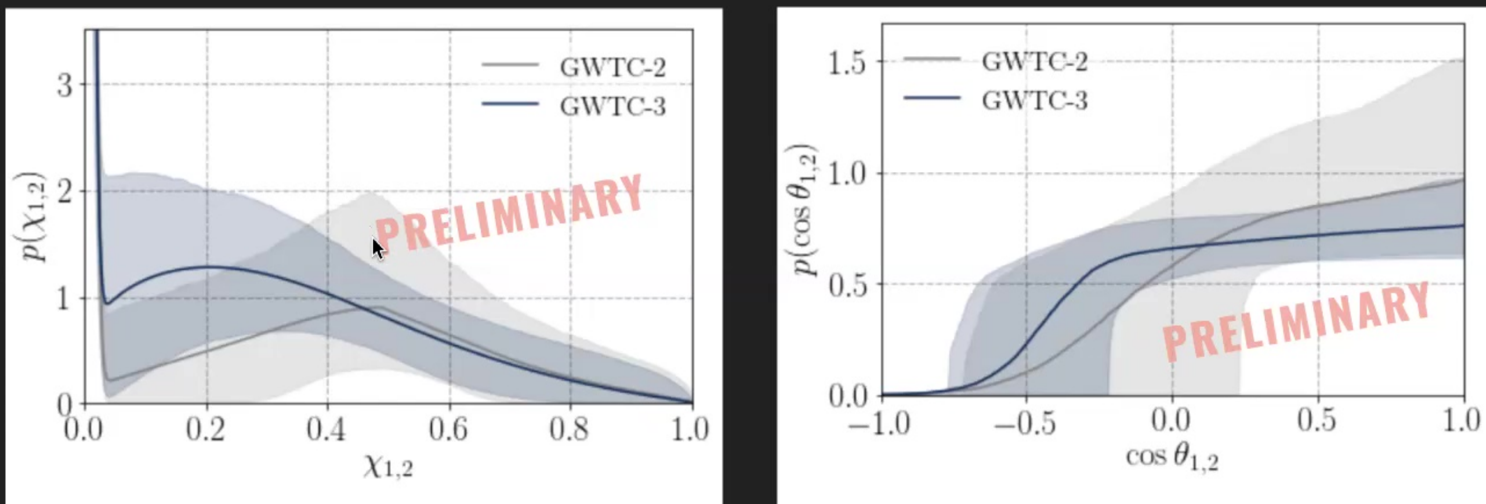


Hyper-posteriors

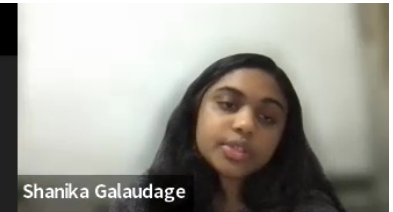
- From GWTC-3 analysis: less BBH in negligible spin subpopulation and spinning subpopulation is less rapidly spinning $\mu \approx 0.35$
- Posterior for $z_{\rm min}$ excludes zero.



Spin distribution

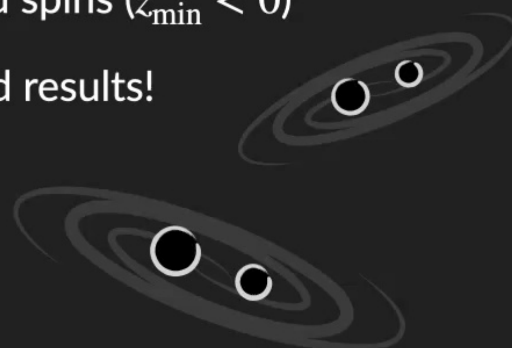


Spin magnitude (left) spin orientation (right) distributions: Solid curve - mean;
Shaded region - 90% credible interval



Summary

- Recent work painted a conflicting portrait of the merging BBH spin distribution. Our work adapts the spin model to account for binaries with negligible spin.
- We find support for merging BBH with negligible spin following GWTC-3.
- Results from GWTC-3 show evidence for misaligned spins ($z_{\rm min} < 0$)
- Stay tuned for complete GWTC-3 investigations and results!



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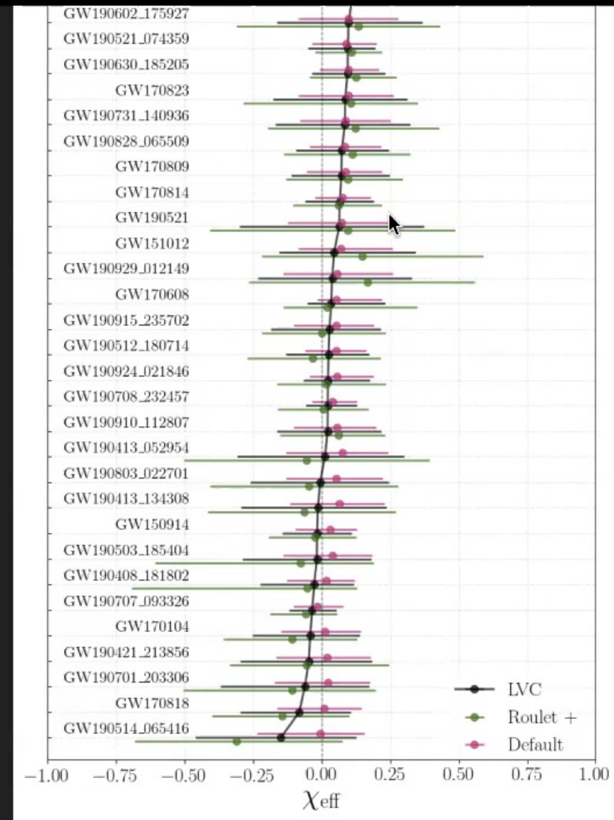
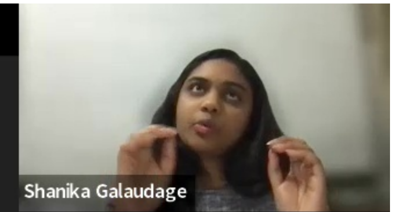
Population priors

- With a growing population we can better understand the true distribution.
- Currently we use uniform priors for physical spin parameters, but we can use the population spin distribution as the prior distribution instead!
- The **Default** data points (shown in pink) show the event posteriors weighted by the population model obtained from our hierarchical analysis.



Hyper-parameters and priors



Parameter	Description	Prior
λ_0	Mixing fraction of mergers with negligible spin, $\chi_{1,2} \lesssim \sigma_0$	U(0,1)
σ_0	Spread in $\chi_{1,2}$ for systems with negligible spin	$\sigma_0 = 0$
μ_χ	Mean of spin magnitude distribution	U(0,1)
σ_χ^2	The square of the width of the spin magnitude distribution	U(0,0.25)
ζ	Mixing fraction of mergers with preferentially aligned spin	U(0,1)
σ_t	Spread in projected misalignment for preferentially aligned black holes	U(0,4)
$z_{\min}$	Minimum value of the projected misalignment	U(-1,1)

Table 1. Summary of EXTENDED model hyper-parameters. The notation $U(a, b)$ indicates a uniform distribution on the interval ranging from a to b.