Title: : From black holes to the Big Bang: astrophysics and cosmology with gravitational waves and their electromagnetic counterparts

Speakers: Andrea Biscoveanu

Series: Strong Gravity

Date: October 27, 2022 - 1:00 PM

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Abstract: The growing catalog of gravitational-wave signals from compact object mergers has allowed us to study the properties of black holes and neutron stars more precisely than ever before and has opened a new window through which to probe the earliest moments in our universe's history. In this talk, I will demonstrate how current and future gravitational-wave observations can be uniquely leveraged to learn about astrophysics and cosmology. With the current catalog of events detected by the LIGO and Virgo gravitational-wave detectors, I will present evidence for a correlation between the redshift and spin distributions of binary black holes and discuss its astrophysical implications. With joint observations of short gamma-ray bursts and binary neutron star mergers accessible in the next few years, I will describe how to constrain the jet geometry and shed light on the central engine powering these explosions. Finally, with the sensitivities expected for the next generation of gravitational-wave detectors, I will present the statistically optimal method for the simultaneous detection of a foreground of compact binary mergers and a stochastic gravitational-wave background from early-universe processes.

Zoom Link: https://pitp.zoom.us/j/95280675686?pwd=RThMeStWeWl1VlBuV1cvYW8zTXgydz09

LIGO

From black holes to the Big Bang: astrophysics and cosmology with gravitational waves and their electromagnetic counterparts

Sylvia Biscoveanu

10/27/2022

Perimeter Strong Gravity Seminar

Collaborators: Thomas Callister, Carl-Johan Haster, Salvatore Vitale, Ken Ng, Will Farr, Colm Talbot, Rory Smith, Eric Thrane

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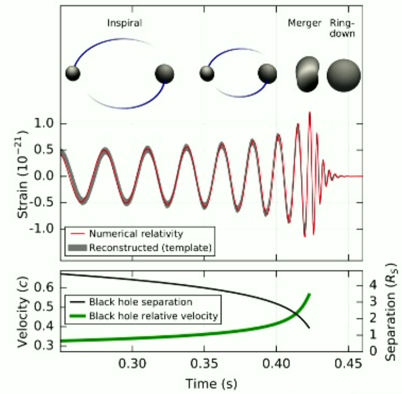
What we've learned

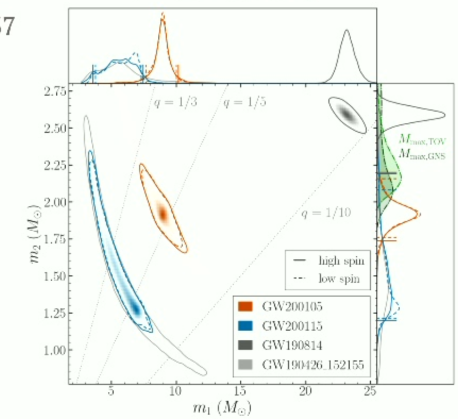
The gravitational-wave data obtained by the LIGO-Virgo-Kagra collaboration since 2015 has taught us that:

1. **Compact object binaries** that merge within a Hubble time exist in the Universe
2. Neutron stars and black holes in binaries have masses spanning the range $\sim 1 - 100\ M_{\odot}$
3. The spins (angular momenta) of the component compact objects in these binaries are small
4. Binary neutron star mergers are the progenitors of some short gamma-ray bursts and the astrophysical sites of most heavy-element nucleosynthesis
5. The fraction of the total energy density of the universe contributed by gravitational waves is $\Omega_{GW} \leq 5.8\times10^{-9}$



arxiv:1602.03837

arxiv:2106.15163



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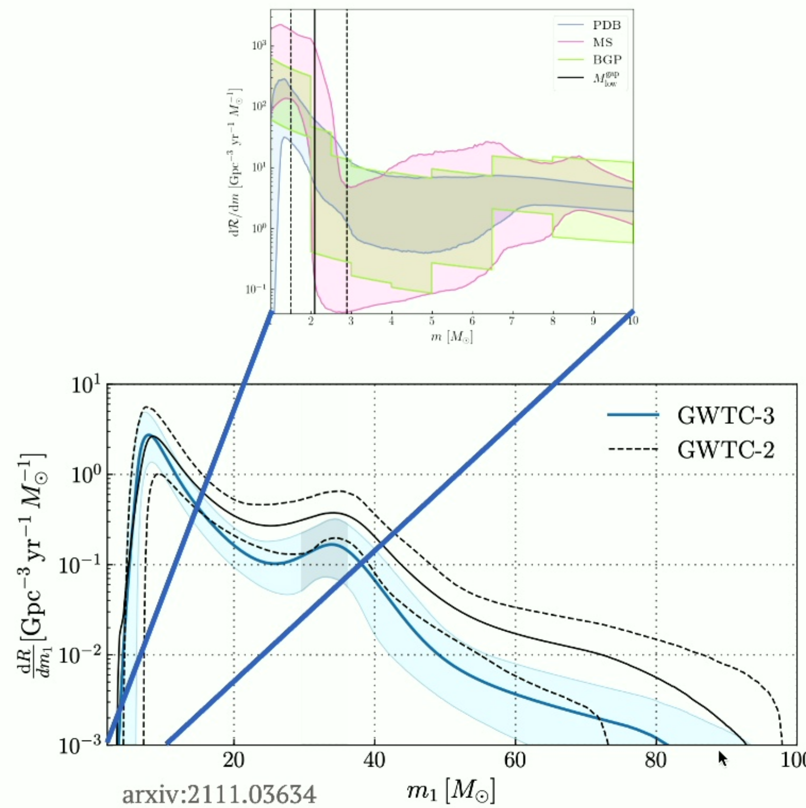

arxiv:2111.03634

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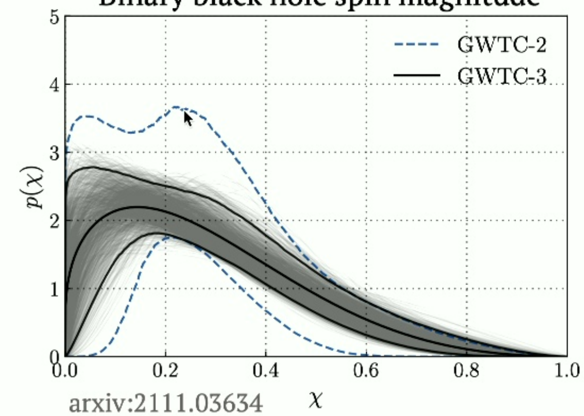
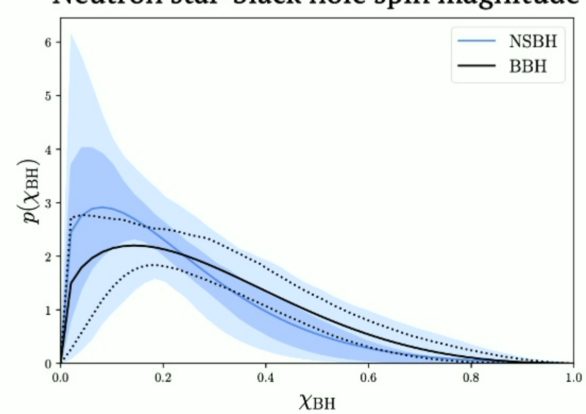
Binary black hole spin magnitude



arxiv:2111.03634

Neutron star-black hole spin magnitude



SB, Landry, Vitale, arxiv:2207.01568

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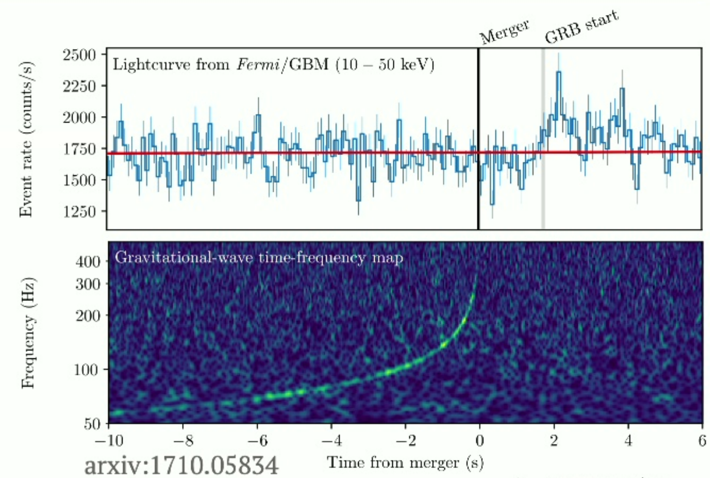
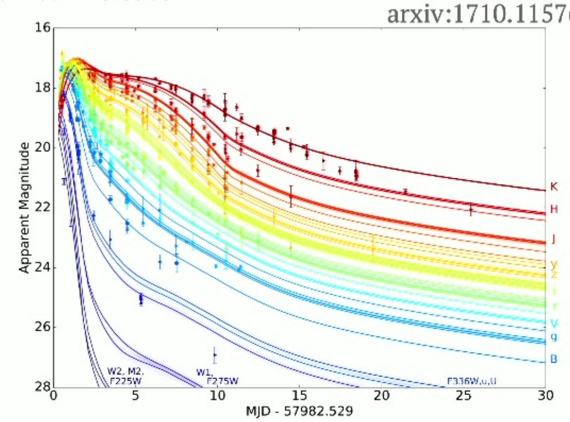


arxiv:1710.05834

arxiv:1710.11576



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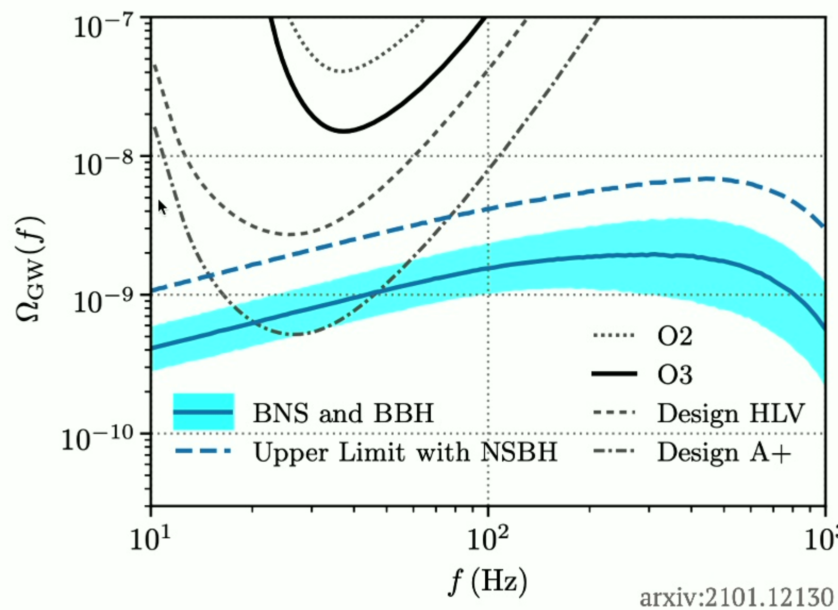
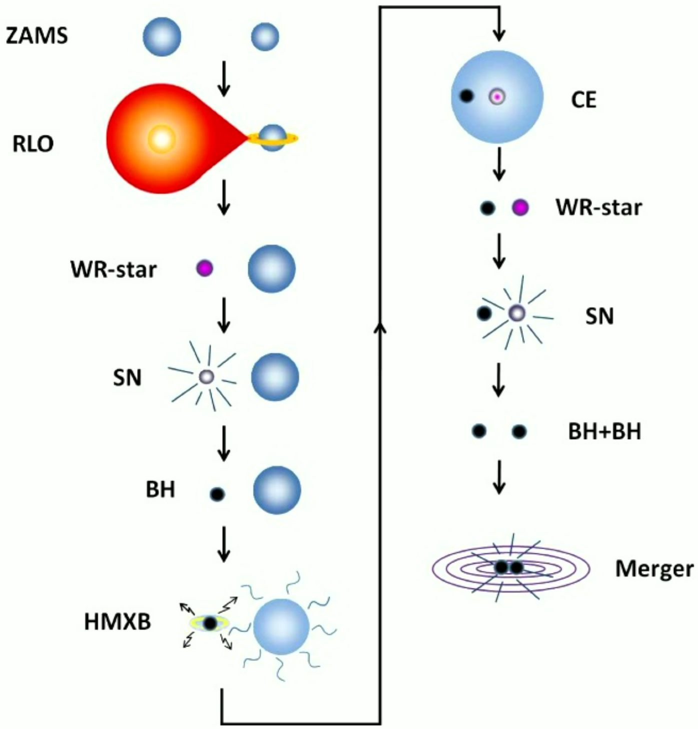


arxiv:2101.12130

Outline – why we care

- ➢Learn about binary black hole formation channels
  - Correlation between the redshift and effective spin for systems observed by the LIGO and Virgo gravitational-wave (GW) detectors
- ➢Learn about the central engine powering short gamma-ray burst (sGRB) jets
  - Multimessenger method to constrain the jet geometry using a population of coincident sGRB and GW observations obtained in the next few years
- ➢Learn about early-universe processes like preheating and phase transitions
  - Statistically optimal method for the simultaneous detection of a foreground of compact object mergers and a cosmological stochastic gravitational-wave background

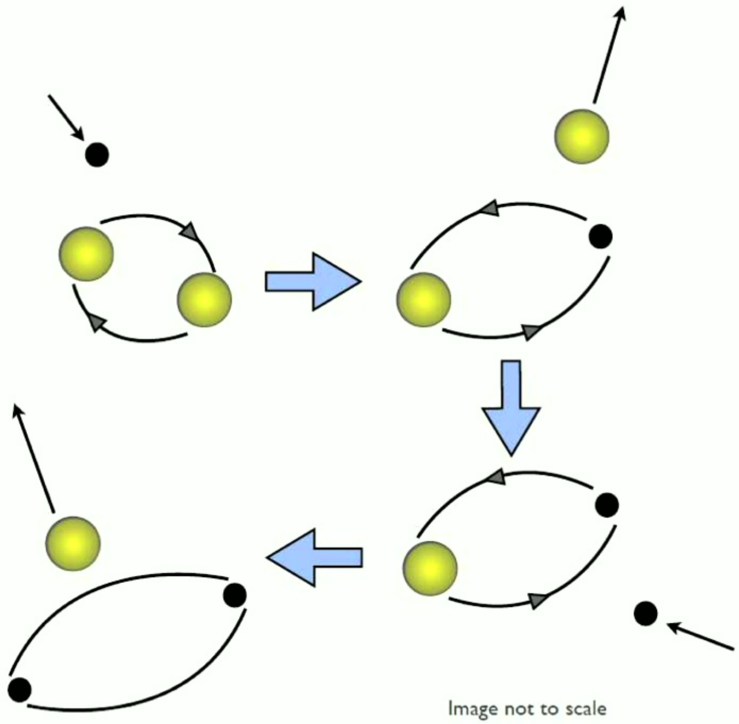
Formation of black hole binaries



http://www-astro.physics.ox.ac.uk/~podsi/grav_waves.pdf

- Gravitational-wave observations of binary black holes can tell us how these systems form and evolve
- Two main formation channels:
  - Field formation
    - Preferentially aligned spins
    - Low spin magnitude for first-born BH
    - Second-born BH can be spun up
    - Upper and lower mass gaps
    - Preference for equal mass ratios

Formation of black hole binaries

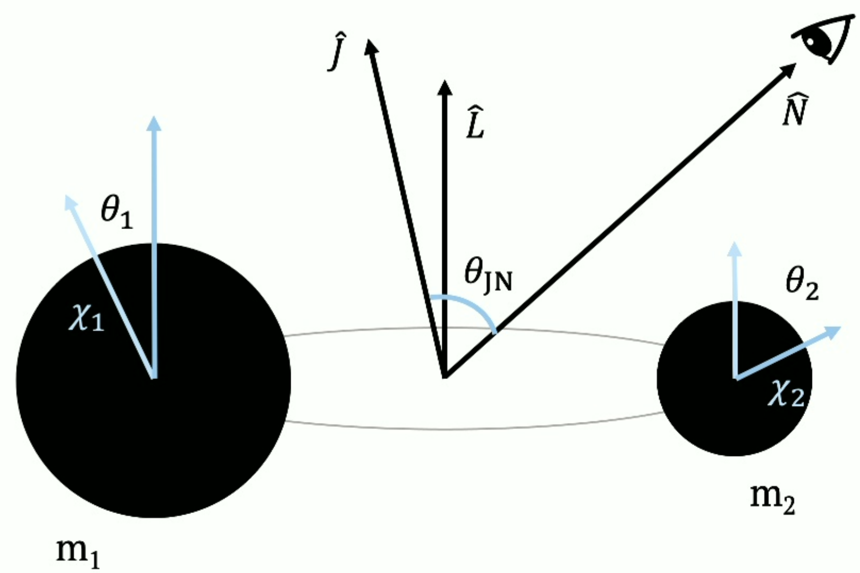


http://www-astro.physics.ox.ac.uk/~podsi/grav_waves.pdf

- Gravitational-wave observations of binary black holes can tell us how these systems form and evolve
- Two main formation channels:
  - Dynamical formation
    - Isotropic spin tilt distribution
    - Low spin magnitudes except for hierarchical mergers
    - Can populate mass gaps
    - Sub-population with unequal mass ratios

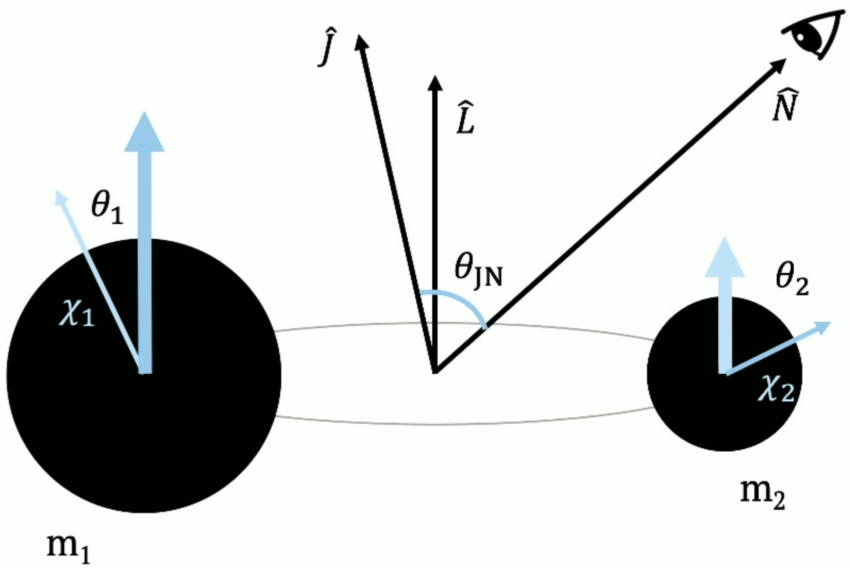
Binary black hole parameters

- Quasicircular binary black hole systems detected by LIGO in gravitational-waves are characterized by 15 parameters
  - Intrinsic – masses and spins
  - Extrinsic – distance (redshift), inclination, sky position, etc.



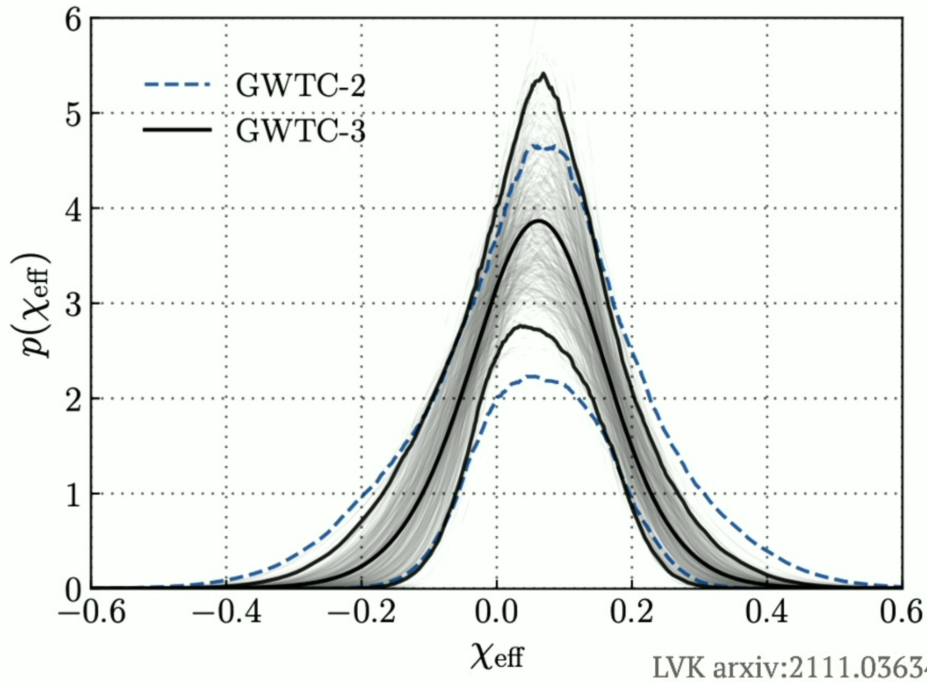
Binary black hole parameters

- Quasicircular binary black hole systems detected by LIGO in gravitational-waves are characterized by 15 parameters
  - Intrinsic – masses and spins
  - Extrinsic – distance (redshift), inclination, sky position, etc.
- χ_{eff} - best measured spin parameter with gravitational waves, mass-weighted spin aligned with the orbital angular momentum



Population analysis

- Determine the distribution of effective spin across a population of detections instead of looking just at individual events
- BBHs detected during LIGO-Virgo's third observing run with false alarm rate < 1/yr, 69 BBH
- Account for detector selection effects to measure the properties of the astrophysical rather than the observed population
- Model χ_{eff} as a Gaussian distribution with unknown mean and width (based on Roulet et al., arxiv:1806.10610, Miller et al., arxiv:2001.06051)



LVK arxiv:2111.03634

Correlations with effective spin

- Callister et al. arXiv:2106.00521 find an anti-correlation between the mean of the $\chi_{\rm eff}$ distribution and the mass ratio
- Extend this model to look for correlations between spin and primary mass and spin and redshift (or both!)

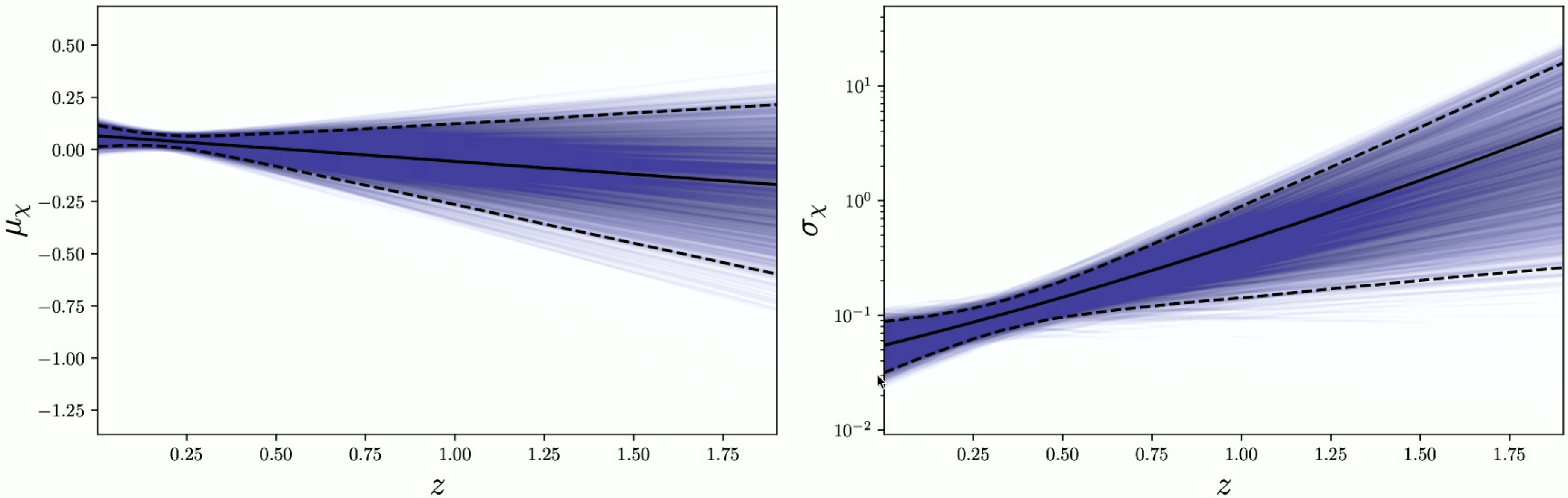
$$\pi_{\rm pop}(\chi_{\rm eff}|\Lambda_{\chi_{\rm eff}}, m_1, z) = \mathcal{N}(\chi_{\rm eff}; \mu_\chi, \sigma_\chi),$$

$$\mu_\chi(z, m_1) = \mu_0 + \delta\mu_z(z - 0.5) + \delta\mu_{m_1}\left(\frac{m_1}{10\ \mathrm{M}_\odot} - 1\right)$$

$$\log\sigma_\chi(z, m_1) = \log\sigma_0 + \delta\log\sigma_z(z - 0.5) + \delta\log\sigma_{m_1}\left(\frac{m_1}{10\ \mathrm{M}_\odot} - 1\right)$$

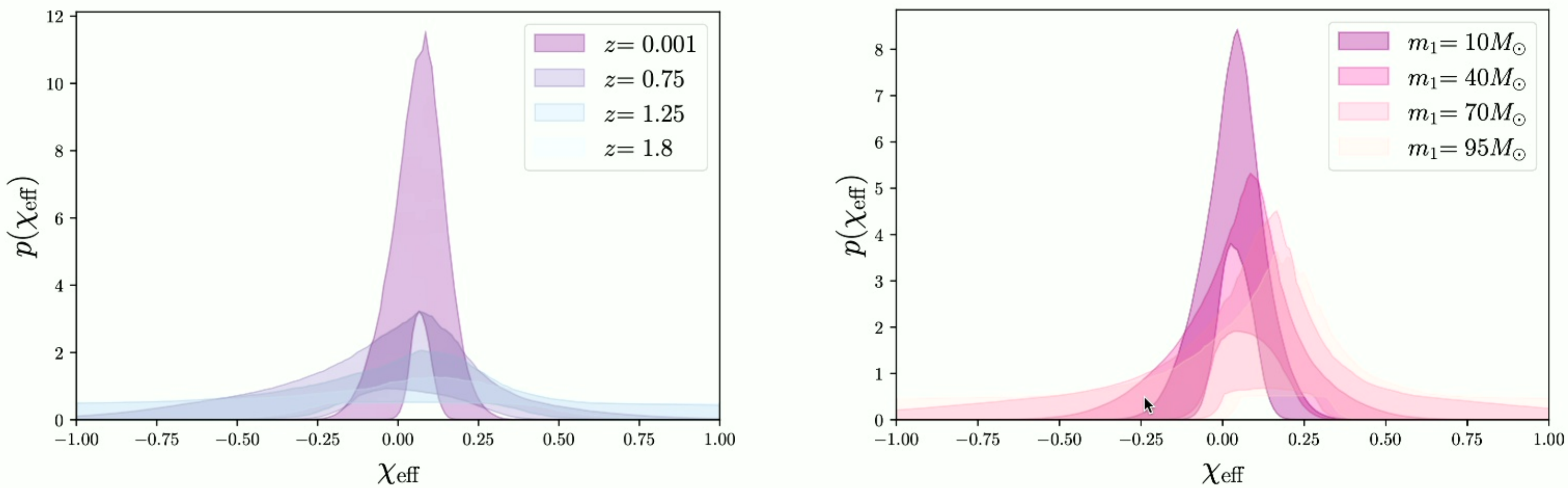
S.B., Callister, Haster, Ng, Vitale, Farr, arxiv:2204.01578

Correlations with effective spin



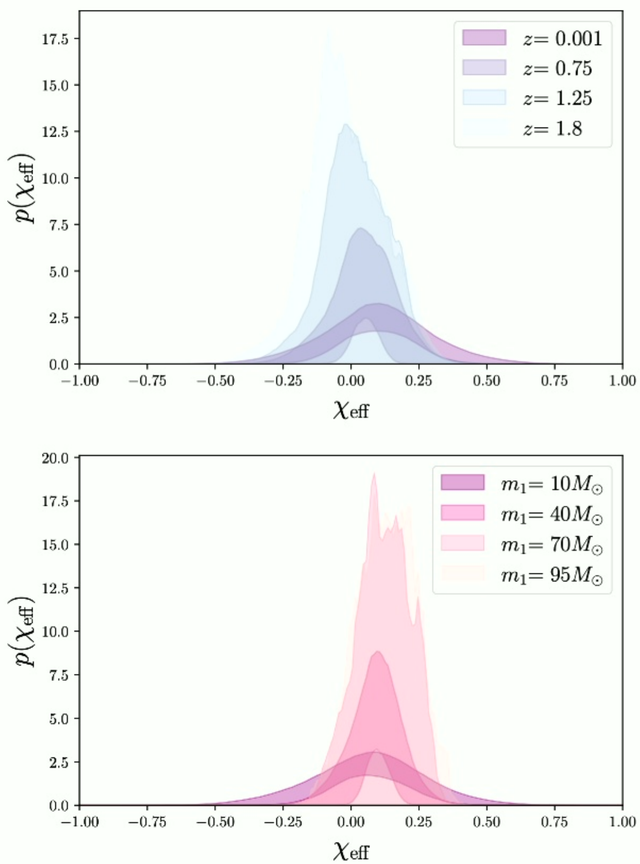
- χ_{eff} distribution broadens with redshift at 98.6% credibility when allowing only for redshift correlations

Correlations with effective spin

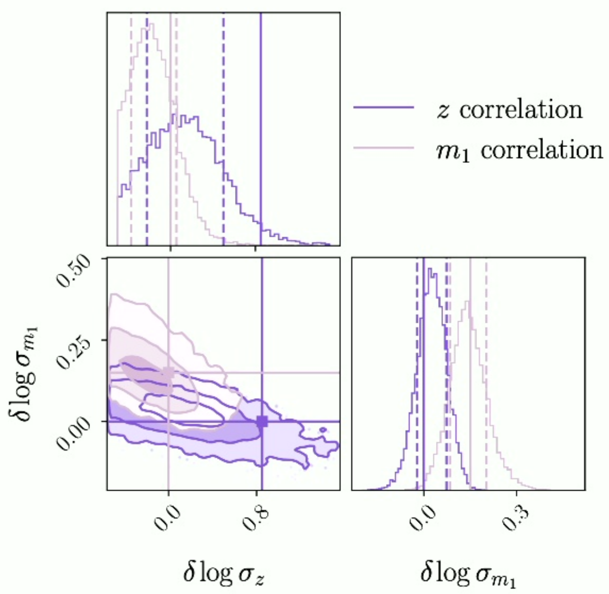


- $\chi_{\rm eff}$ distribution broadens with primary mass at 93.5% credibility when allowing only for primary mass correlations
- When allowing for correlations with both parameters, no correlation with either is disfavored at 96.2% credibility

Verifying the correlation



- Unlikely to be a spurious correlation due to individual spin, redshift measurements
- Mass-spin correlation easier to unambiguously distinguish in simulations



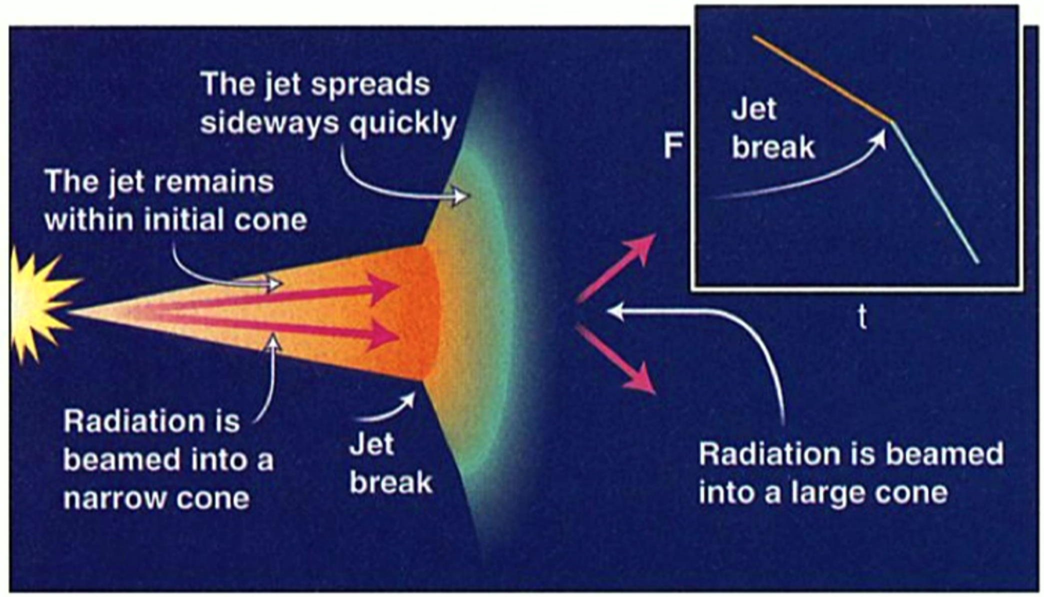
Astrophysical implications of correlation

- Mixtures between populations formed via different channels would more easily explain a correlation between the mean of the effective spin distribution and the redshift
  - Ex: Binaries formed in the field with preferentially positive spins dominating at higher redshifts
- Broadening of the distribution might be explained in terms of change in natal spin distribution with redshift
  - Tidal spin-up correlated with delay time, redshift
  - Relationship between metallicity, efficiency of angular momentum transport, and stellar mass

➢ 2.45σ significance of correlation is comparable to other putative correlations (i.e., mass ratio and effective spin)

Short gamma-ray bursts

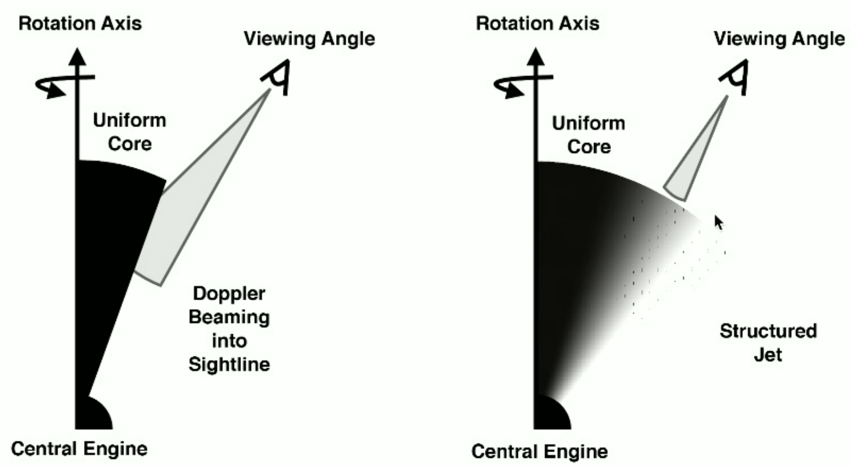
- GRBs are the most energetic EM explosions observed in the universe, but their launch mechanism remains unknown.
- Understanding the geometry of the GRB jet can shed light on the central engine driving the emission
- Traditional calculation of jet opening angle relies on observing a steepening in the afterglow light curve across all wavelengths



Piran DOI: 10.1126/science.1068157

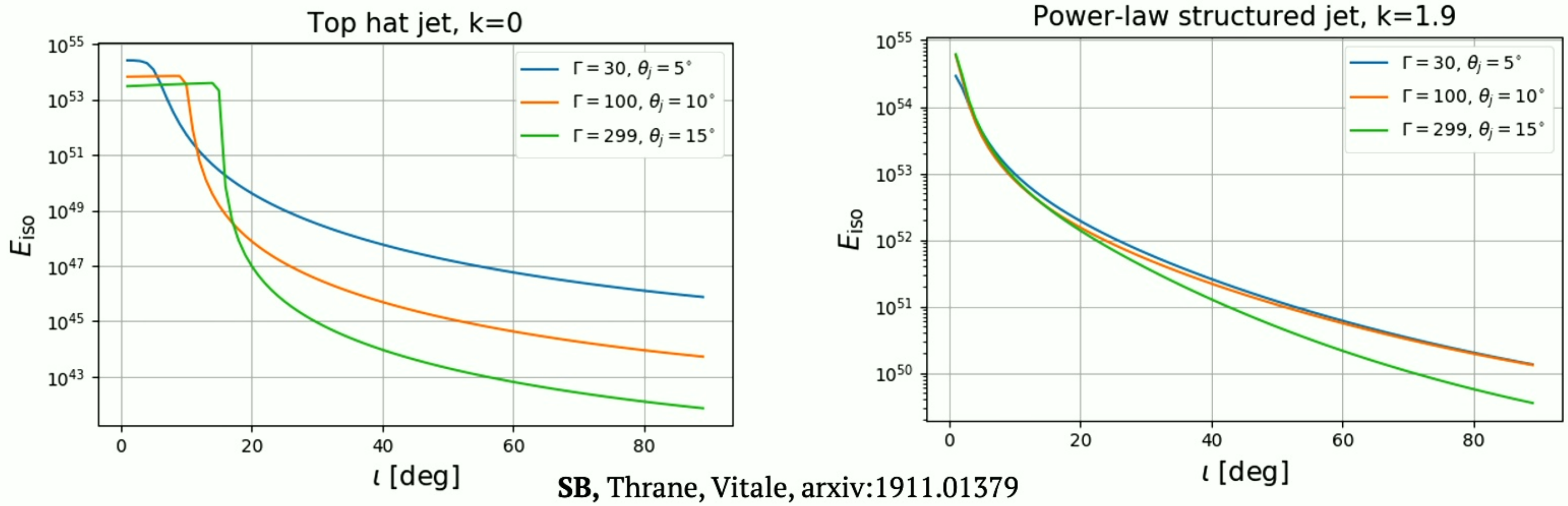
Emission profile models

- Coincident GW and EM observations of a GRB provide an independent measurement of the inclination angle and distance.
- Devise a Bayesian method using coincident observations to constrain the opening angle, emission profile, and other properties without a jet break observation.



LVC, Fermi, INTEGRAL arxiv:1710.05834

Isotropic equivalent energy



SB, Thrane, Vitale, arxiv:1911.01379

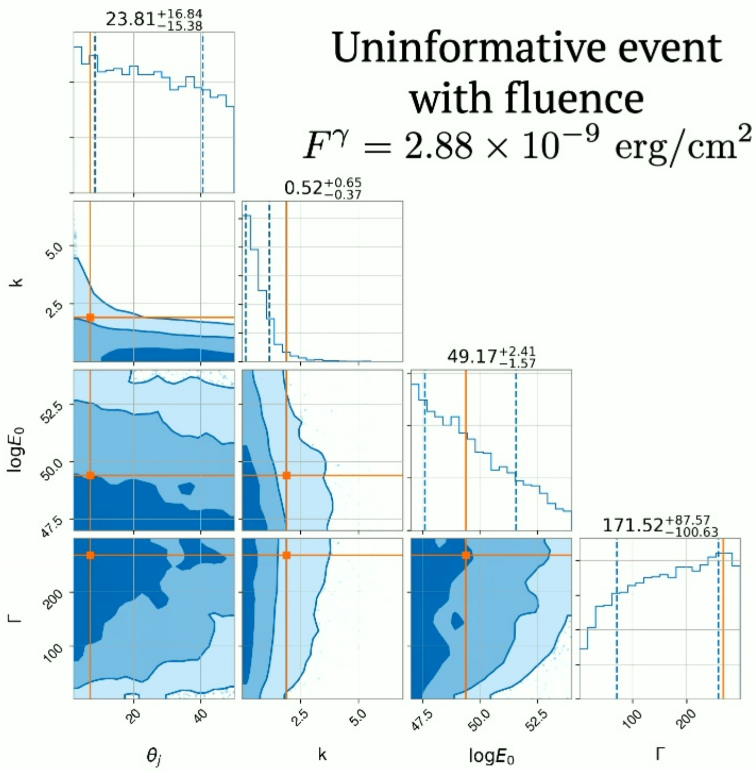
- Measure fluence (energy/area) but want to model isotropic equivalent energy:

$$F^{\gamma} = \frac{E^{\rm iso}(1+z)}{4\pi d_L^2}$$

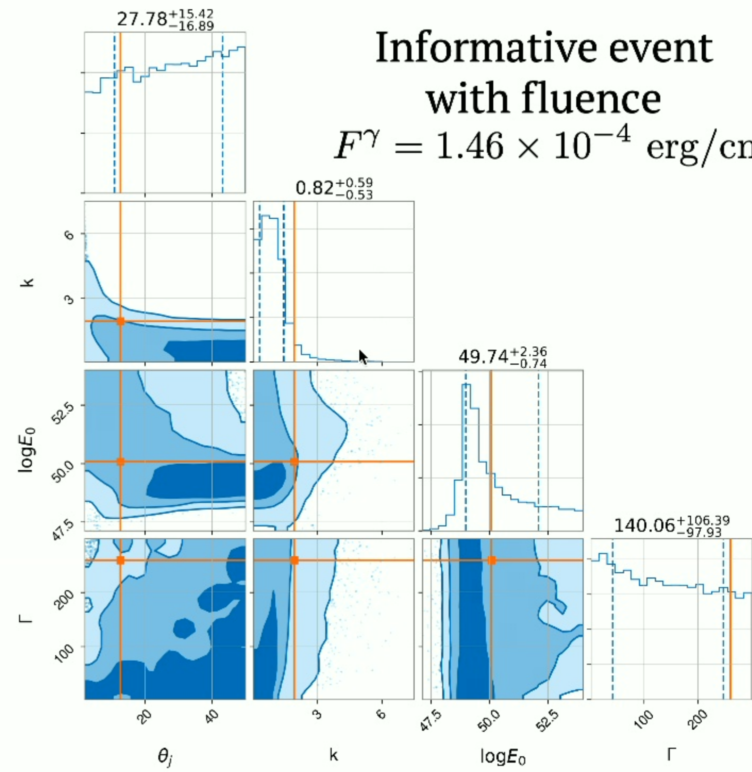
- Parameterize $E^{\rm iso}$ in terms of total energy, opening angle, Lorentz factor, and power-law index $(E_{\rm tot}, \theta_j, \Gamma, k)$

Individual-event analysis

Uninformative event with fluence $F^{\gamma} = 2.88 \times 10^{-9}$ erg/cm^2



Informative event with fluence $F^{\gamma} = 1.46 \times 10^{-4}$ erg/cm^2

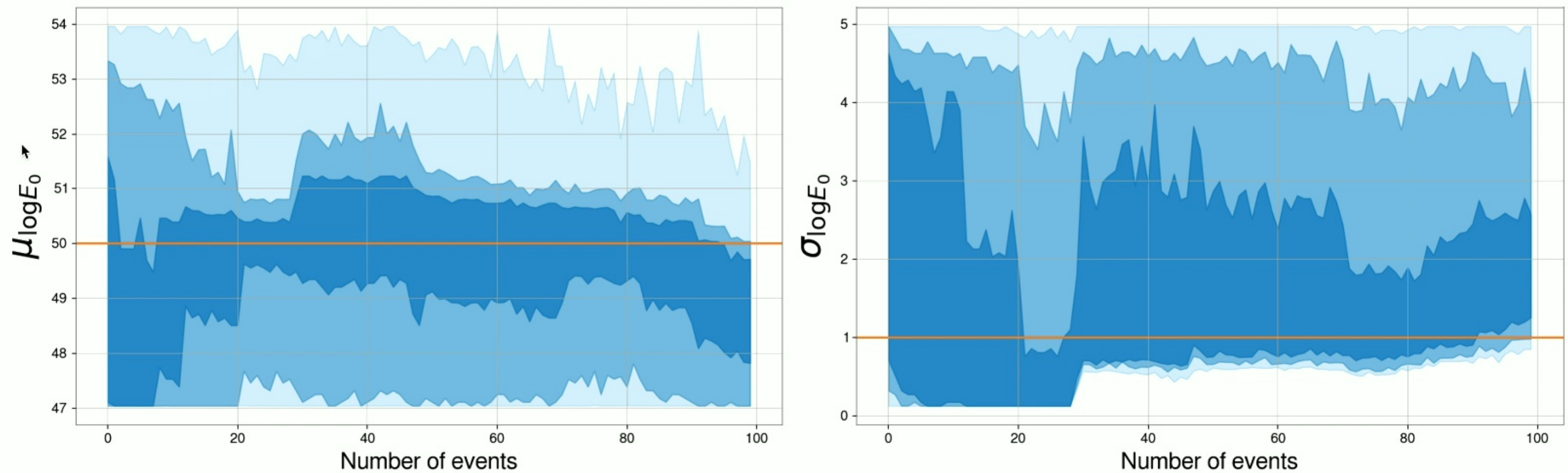


Measuring GRB population parameters

- Not all GRBs will have the same opening angle, Lorentz factor, and energy budget.
- Measure the distributions from which these parameters are drawn for a population of coincident GW-GRB detections.
- Assume that these parameters are Gaussian-distributed with unknown means and widths.
- Simulate 100 BNS events detectable with gravitational waves, assume a corresponding fluence measurement or upper limit is available for each (no GRB selection effects)

Population results – energy

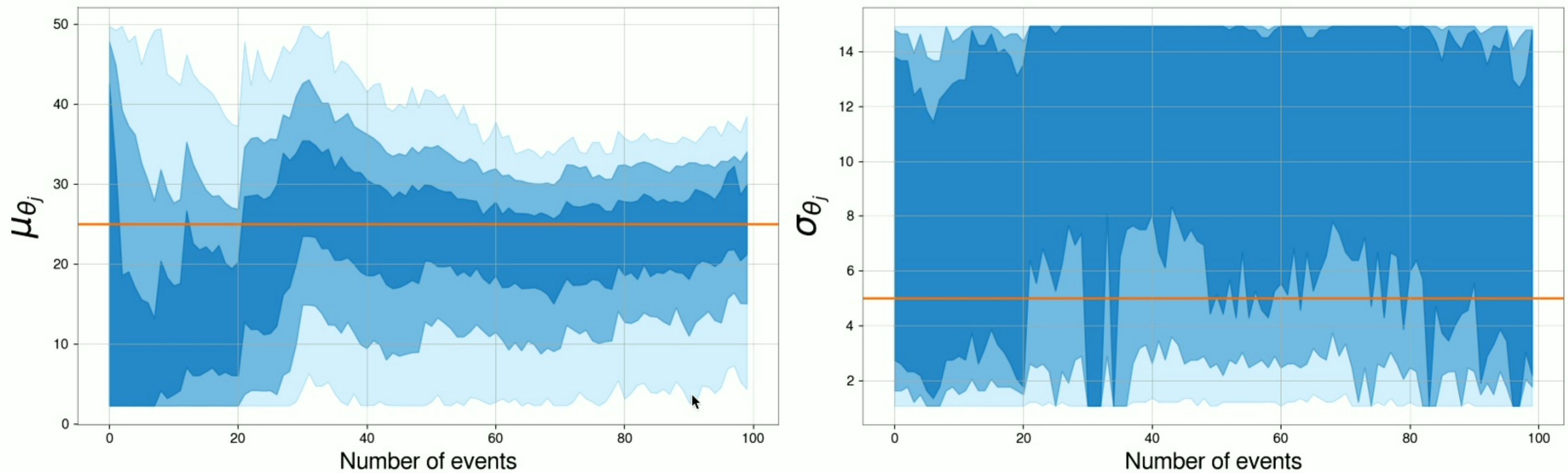
Top-hat jet: $\mu_{\log E} = 50, \sigma_{\log E} = 1$



- Total energy easier to measure for top-hat jet population due to bigger effect on normalization of E^{iso}
- With 100 detections, measure mean and width to ~2 dex at 1σ credibility

Population results – opening angle

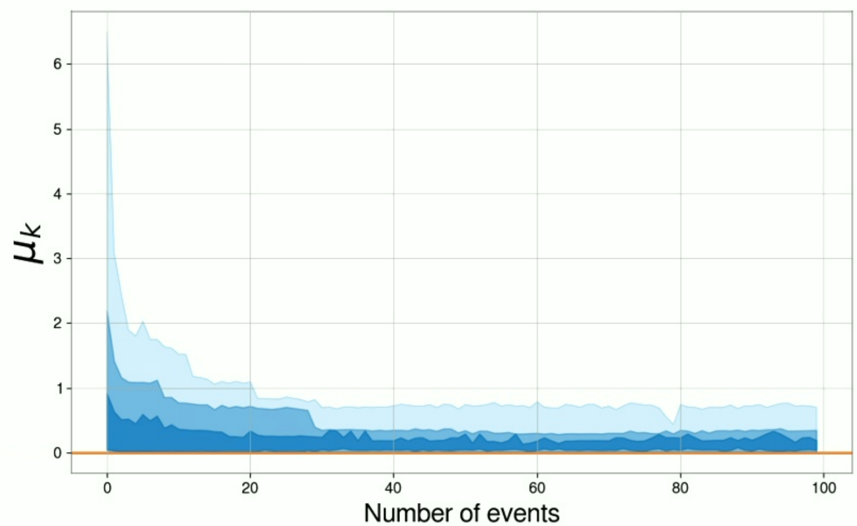
Top-hat jet: $\mu_\theta = 25, \sigma_\theta = 5$



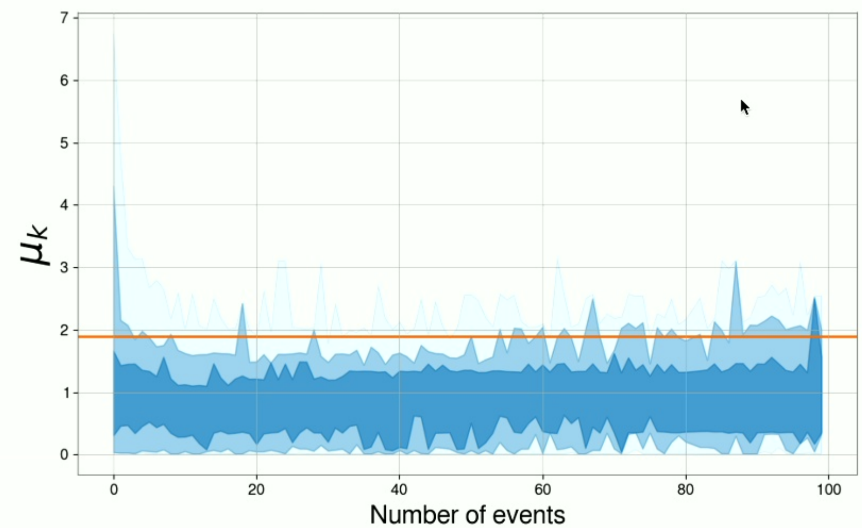
- Similar constraints on both parameters for both emission profiles, mean measured to within $\sim 10°$ at 1σ credibility

Population results – structure

Top hat, k=0



Structured jet, k=1.9



- Posterior on the power-law index for the structed jet population immediately peaks away from 0 – can distinguish structure

Conclusions - GRB jet structure

- Developed a new method for measuring the GRB jet geometry that does not require an observation of the multi-wavelength afterglow
- For a single high-SNR event, we can constrain the log-energy but the other parameters are degenerate
- With a population of 100 coincident events:
  - Measure the mean of the opening angle distribution to within $\sim 10°$
  - Find clear evidence in favor of the jet angular profile structure when present
  - Use these constraints to learn about the jet central engine
- We could accumulate 100 GW BNS events with a simultaneous GRB fluence measurement or upper limit with one year of observing at O5 sensitivity

Outline

- Learn about binary black hole formation channels
  - Correlation between the redshift and effective spin for systems observed by the LIGO and Virgo gravitational-wave (GW) detectors
- Learn about the central engine powering short gamma-ray burst (sGRB) jets
  - Multimessenger method to constrain the jet geometry using a population of coincident sGRB and GW observations obtained in the next few years
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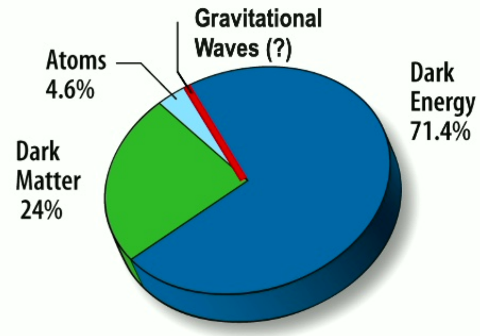
The stochastic background

- A random gravitational wave signal produced by many overlapping, individually indistinguishable sources
  - Astrophysical
  - Cosmological
- Persistent and unmodeled, in contrast to GWs from compact binary mergers which are transient and modeled

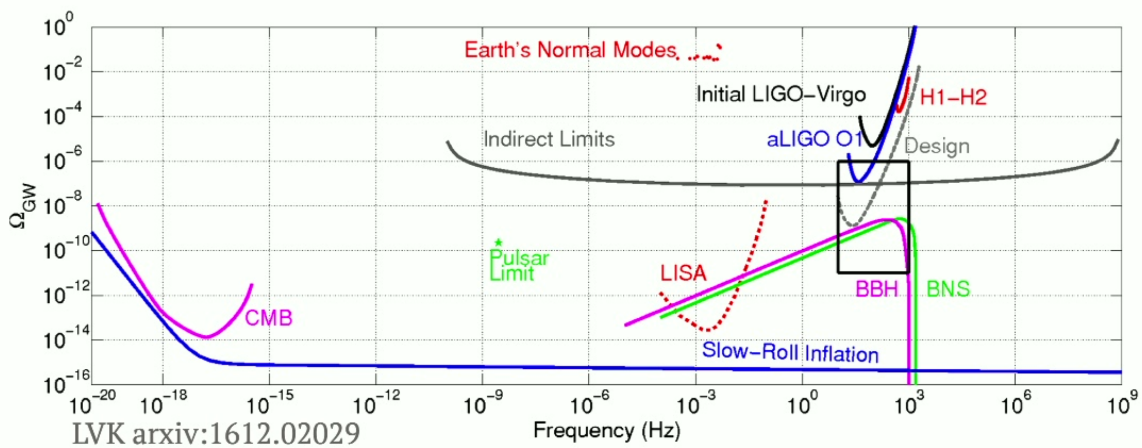
$$\Omega_{\rm gw}(f) = \frac{1}{\rho_{\rm critical}} \frac{d\rho_{\rm gw}}{d\ln f}$$

$$\Omega_{\rm gw} = \Omega_\alpha (f/f_0)^\alpha$$



Motivation

- The background of unresolvable compact binary coalescences (CBCs) is highly non-Gaussian with estimated amplitude $\Omega_{\rm gw}(f = 25\ \text{Hz}) \approx 10^{-9}$
- Primordial backgrounds from cosmological sources are Gaussian but much weaker, $10^{-17} \lesssim \Omega_{\rm gw}(f) \lesssim 10^{-10}$
- Subtraction of the CBC waveform from the data to reveal the primordial background only works for resolvable signals



LVK arxiv:1612.02029

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Cross-correlated stochastic search

- Assume the stochastic background is isotropic, unpolarized, stationary, and Gaussian
- The strain in each detector is the sum of a signal and noise component
  - Noise is uncorrelated in spatially separated detectors but same signal is present in both
- Correlate the strain signal from two detectors sufficiently far apart to minimize common noise sources
- Stochastic background manifests itself as excess power in two detectors

$$\tilde{s}(f) = \tilde{h}(f) + \tilde{n}(f)$$

signal noise

$$Y \propto \langle \tilde{s}_I^*(f) \tilde{s}_J(f) \rangle$$

$$\langle Y \rangle = \Omega_{gw}$$

Allen + Romano, arxiv:gr-qc/9710117

The optimal search for a non-Gaussian background

- Instead of assuming signal is persistent and unmodeled:
  - Split data into short segments
  - Use deterministic waveform models for merging binaries
  - Calculate the "evidence" for two hypotheses in each segment
    - CBC signal vs noise
- Combine segments to measure the total fraction of segments that contain a merger → proxy for the merger rate and Ω_{GW}
- Can reduce the time to detection from the order of years to the order of hours because it models the non-Gaussianity of the signal

Smith + Thrane, arxiv:1712.00688

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Smith + Thrane, arxiv:1712.00688

Adding a Gaussian background

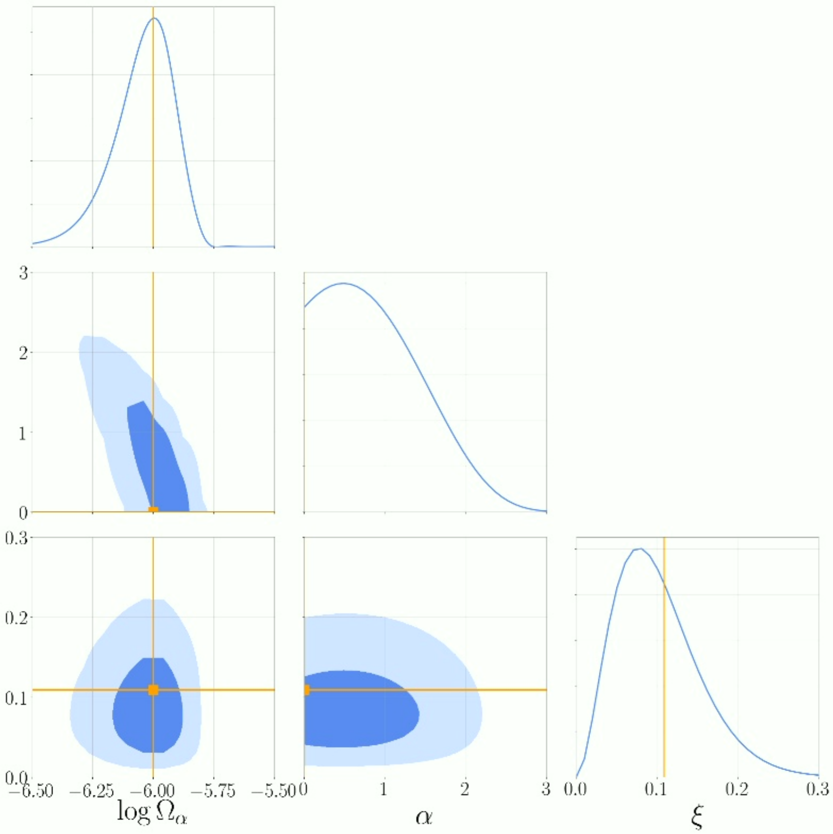
- Same framework, but in each segment allow for the presence of both compact binary merger and a Gaussian stochastic background
- Avoids contamination of the Gaussian background because both signals are accounted for simultaneously including uncertainties
- Take a weighted sum of the probability distributions inferred for the stochastic parameters inferred under the "signal" and "noise" models independently
  - "Signal" model – merger + stochastic background + detector noise
  - "Noise" model – stochastic background + detector noise

SB, Talbot, Thrane, Smith, arxiv:2009.04418

Demonstration

- Use Hanford-Livingston detector network assuming LIGO design sensitivity
- Simulate 4s segments of data, each with a Gaussian cosmological background signal with ($\log\Omega_\alpha = -6, \alpha = 0$)
  - SNR=5.4 for 101 segments
- In 11/101 segments, add a binary black hole signal
  - Signal-to-noise ratios ranging from 2.06-12.17, median 3.54
- Break calculation down into two steps to facilitate combining posteriors on the stochastic background parameters across all segments

Results



$$\log \Omega_\alpha = -5.96^{+0.08}_{-0.16}$$

$$\alpha = 0.49^{+1.14}_{-0.49}$$

$$\xi = 0.08^{+0.09}_{-0.05}$$

Signal-to-noise Bayes factor for the Gaussian background:

$$\ln \mathrm{BF}^S_N = 11.16$$

Recovery is unbiased with no sensitivity loss!

Conclusions – cosmological background

- We have demonstrated the statistically optimal method for the simultaneous detection of a Gaussian background and an astrophysical foreground
- In the absence of the astrophysical foreground, there is no statistical advantage to using the fully Bayesian method over the standard cross-correlation based on the recovered lnBF
- Can extend this method to include the uncertainty in the BBH mass, spin, and redshift distributions and to include the BNS foreground
- Method is also applicable to multiple Gaussian backgrounds with different spectral shapes

What's next?

- Conclusions about the binary black hole population are still model-driven
  - Consider alternative approaches to phenomenological models like "non-parametric" models or direct parameterization in terms of theoretical models
- The BNS observations expected in the next few years carry great multimessenger potential
  - Constrain the neutron star equation of state and kilonova properties like composition and geometry
- Data analysis challenges facing XG detectors will affect the detectability of the cosmological background
  - Work out a fully Bayesian method to deal with issues like overlapping signals, noise model uncertainties, and waveform systematics