Astronomy and Astrophysics with Gravitational Waves: BBH Population Properties Inferred from LIGO/Virgo's O1 & O2

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Midwest Supernova and Transients Workshop, Feb 25-26, 2019

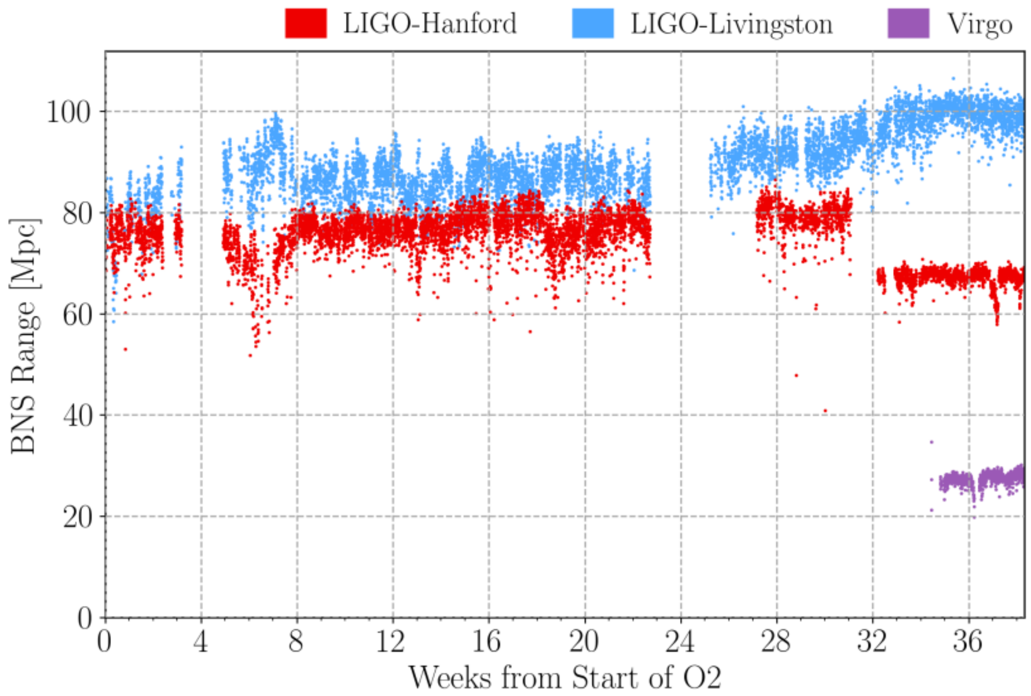
Public paper and data release

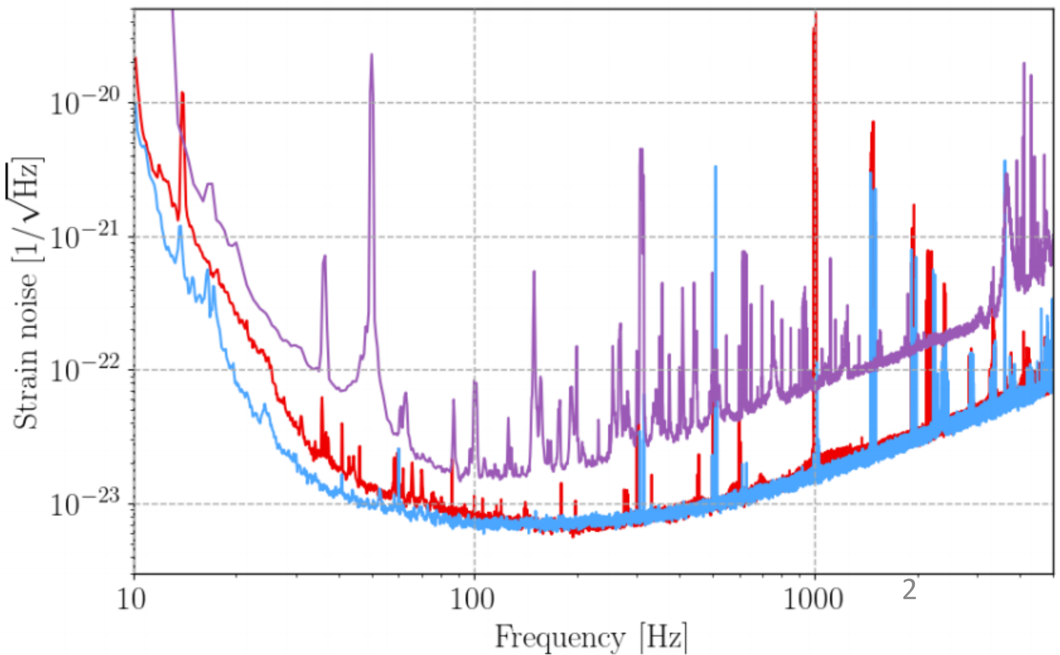
GWTC-1: https://dcc.ligo.org/LIGO-P1800307/public

BBH Pops: https://dcc.ligo.org/LIGO-P1800324/public

LIGO and Virgo During O1 and O2

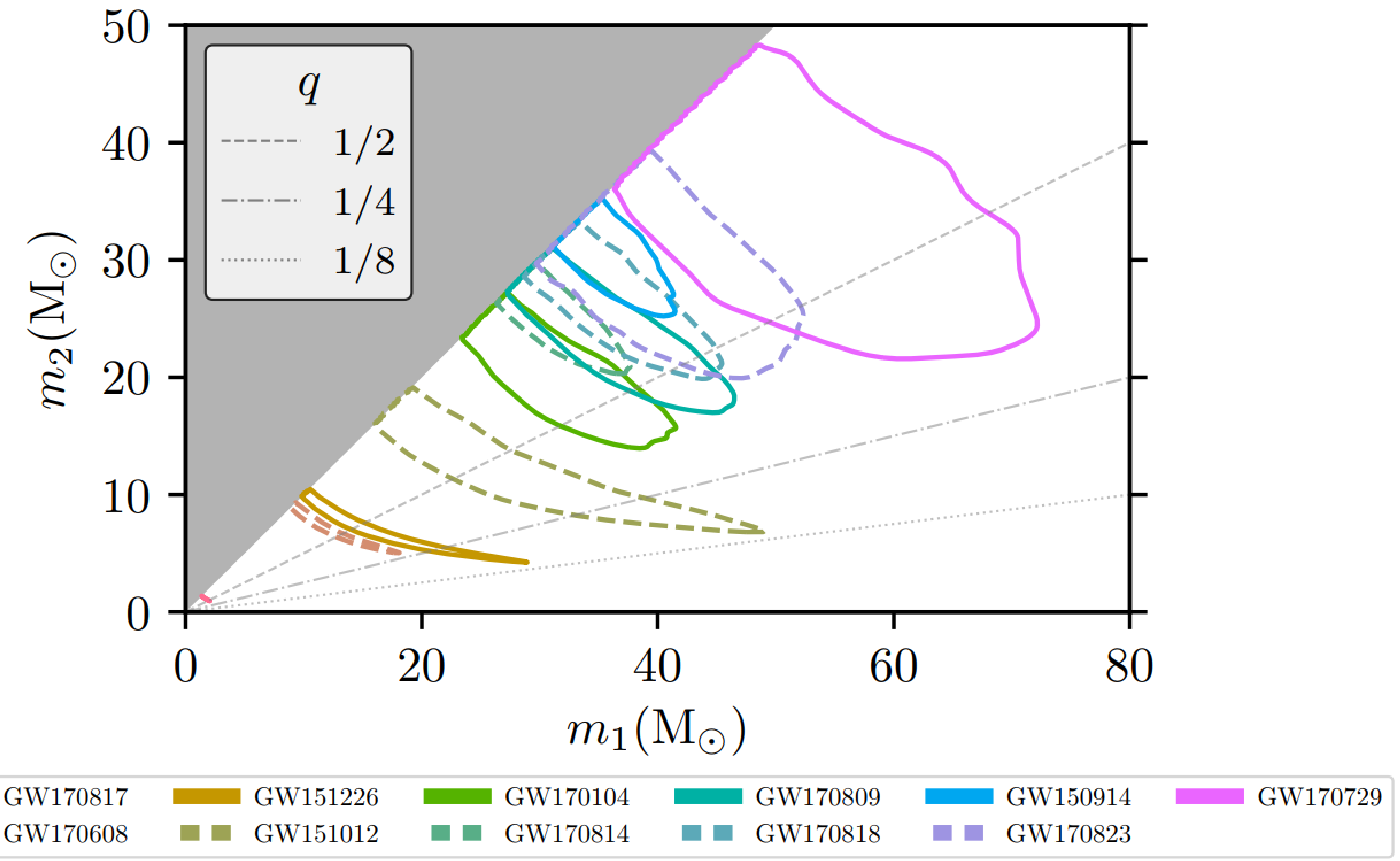
- Observing runs
  - **O1 aLIGO:** Sept. 12th, 2015 - Jan. 19th, 2016
  - **O2 aLIGO:** Nov. 30th, 2016 - Aug. 25th, 2017
  - **O2 Adv. Virgo:** joined Aug 1st, 2017
- Top: BNS range for each instrument during O2
- Bottom: representative amplitude spectral density of the total strain noise
- Coincident analysis time: 166.6 days (O1: 48.6 days, O2: 118 days)
- O2 data were recalibrated and cleaned leading to increased sensitivity





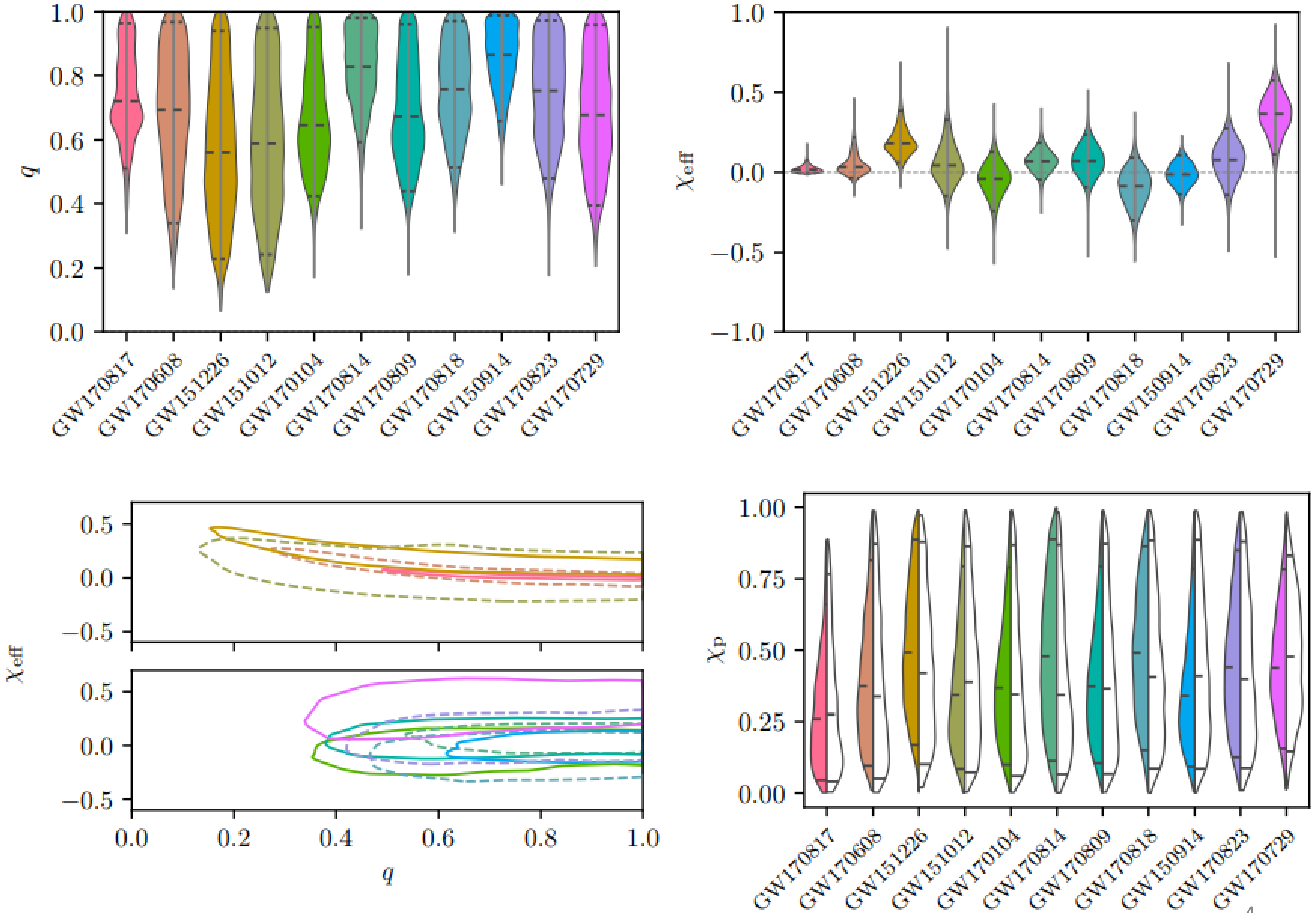
Courtesy: Michael Purrer

Event Parameters: Component Masses

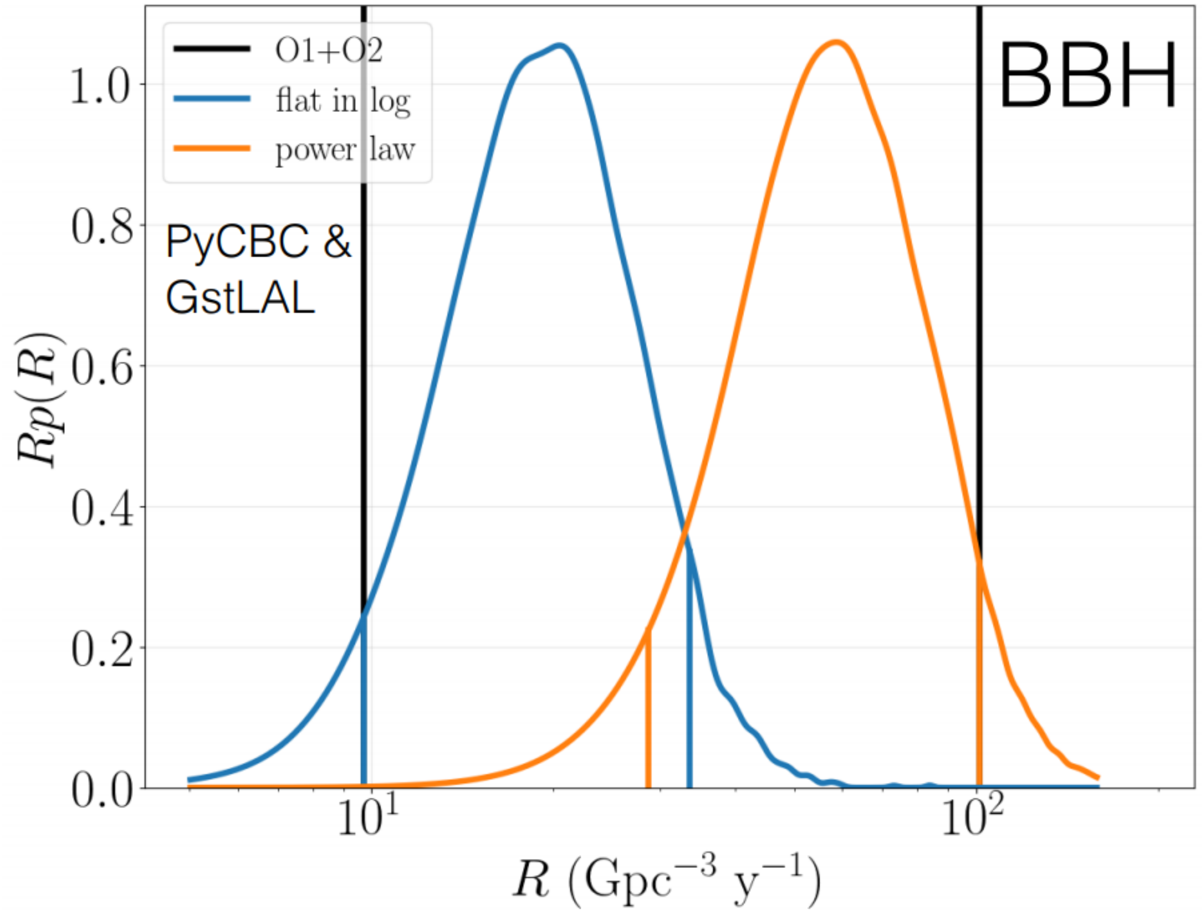


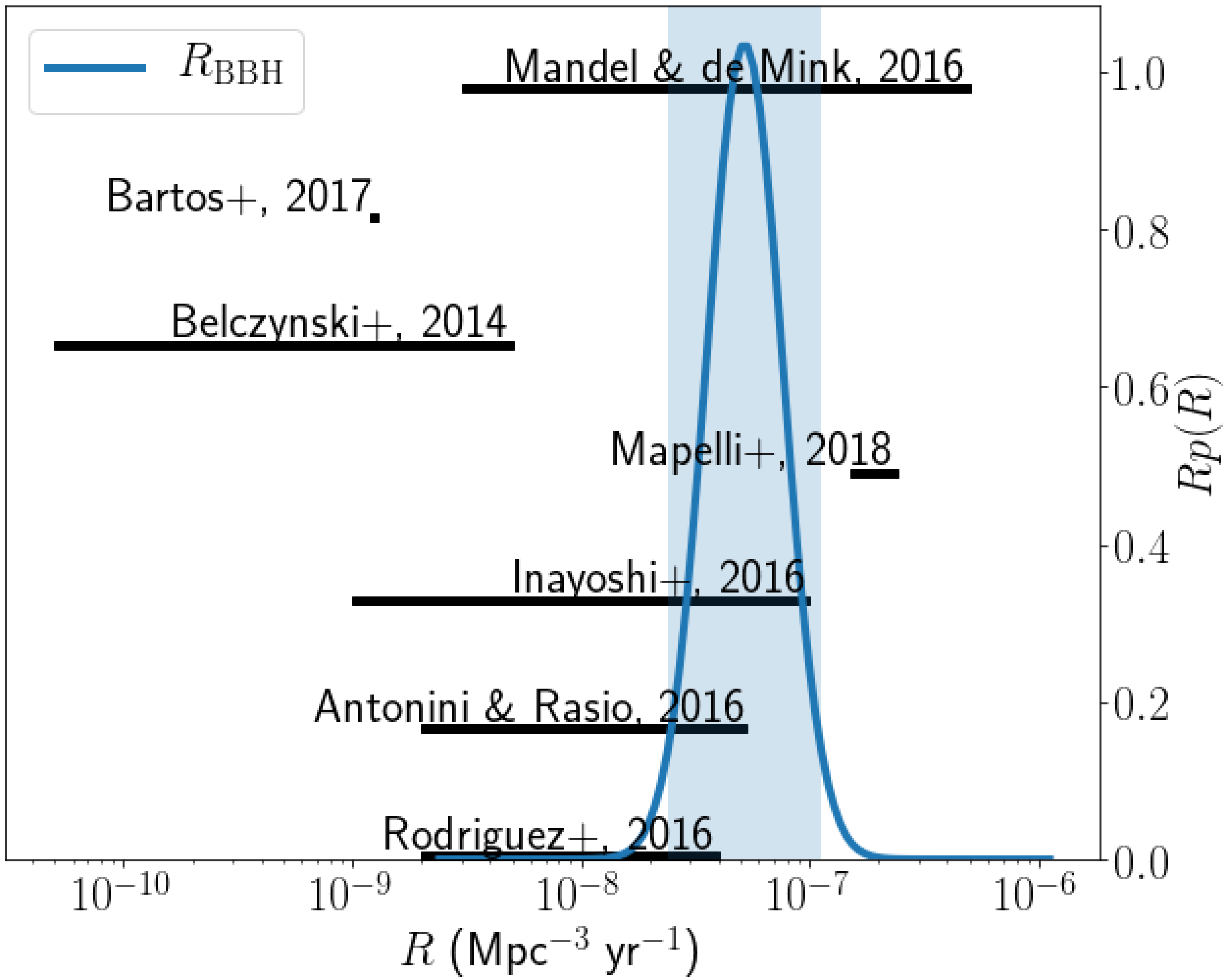
Event Parameters: Mass Ratio and Eff. Spin

- No convincingly asymmetric mass ratio events
- Only two events with non-zero χ_{eff}
- New events are all at higher masses (e.g. > 20 $M_{\odot}$)
- Precession mostly follows expectation from prior



BBH Event Rates: Observation vs. Prediction





Population Modelling and Selection

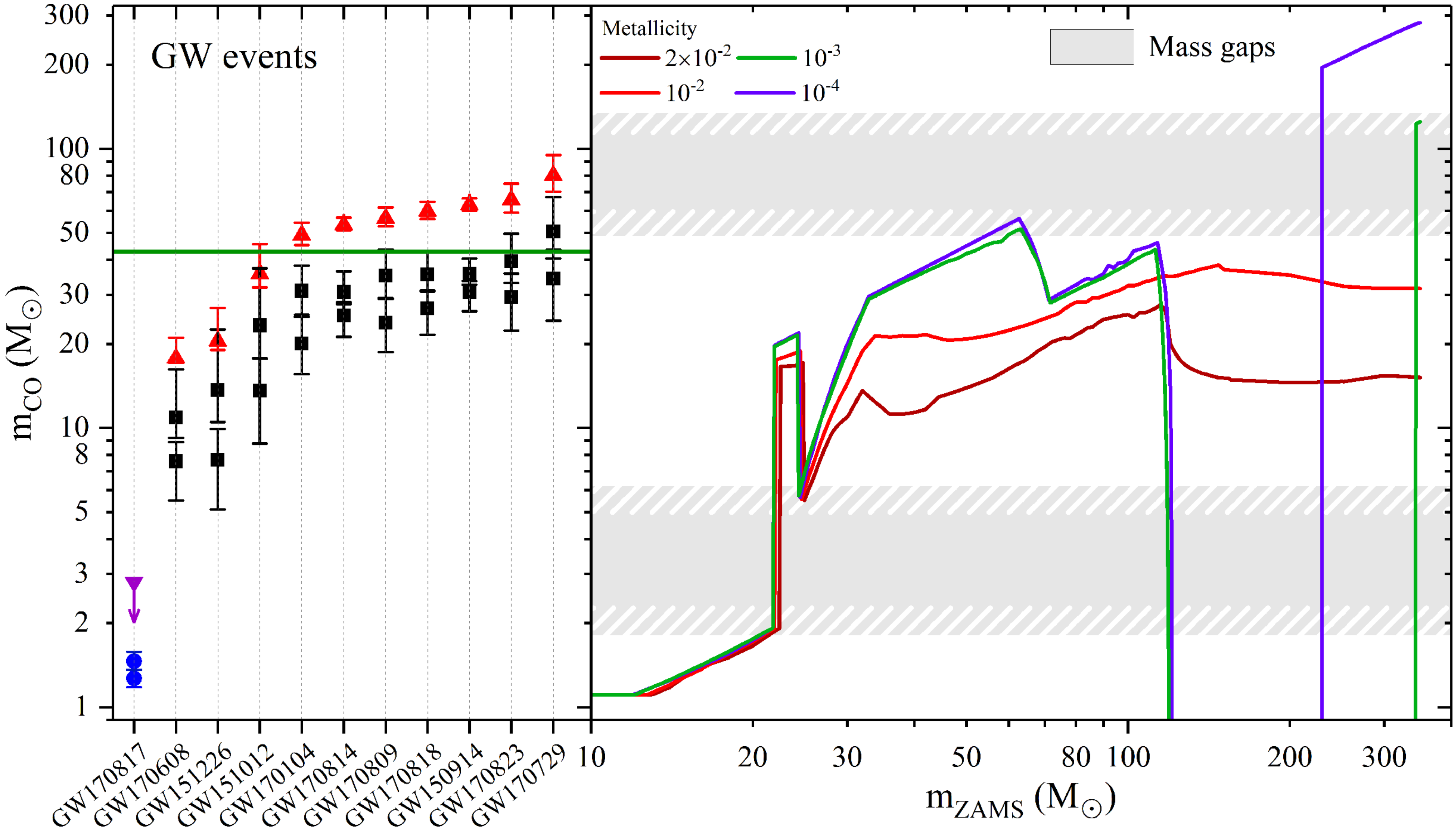
- Perform Bayesian model inference on the product of a set of ***mass***, ***spin***, and ***redshift*** models using our **ten** BBH event posteriors from **O1 and O2**, specifically:

  - Probe the GW merger rate distribution over mass and mass ratio

  - Probe the shape of the spin distribution of BH in GW binaries

  - Examine models of rate evolution with redshift

Some Astrophysical Context



Mass Distributions

After four events (GW170104): power law (primary mass)

α : power law slope

Fixed mass bounds at 5 and 100 $M_\odot$

O2 – Model A/B/C: power law (primary mass)

α : power law slope

$\mathbf{m_{min}}$: minimum power law cutoff

$\mathbf{m_{max}}$: maximum power law cutoff

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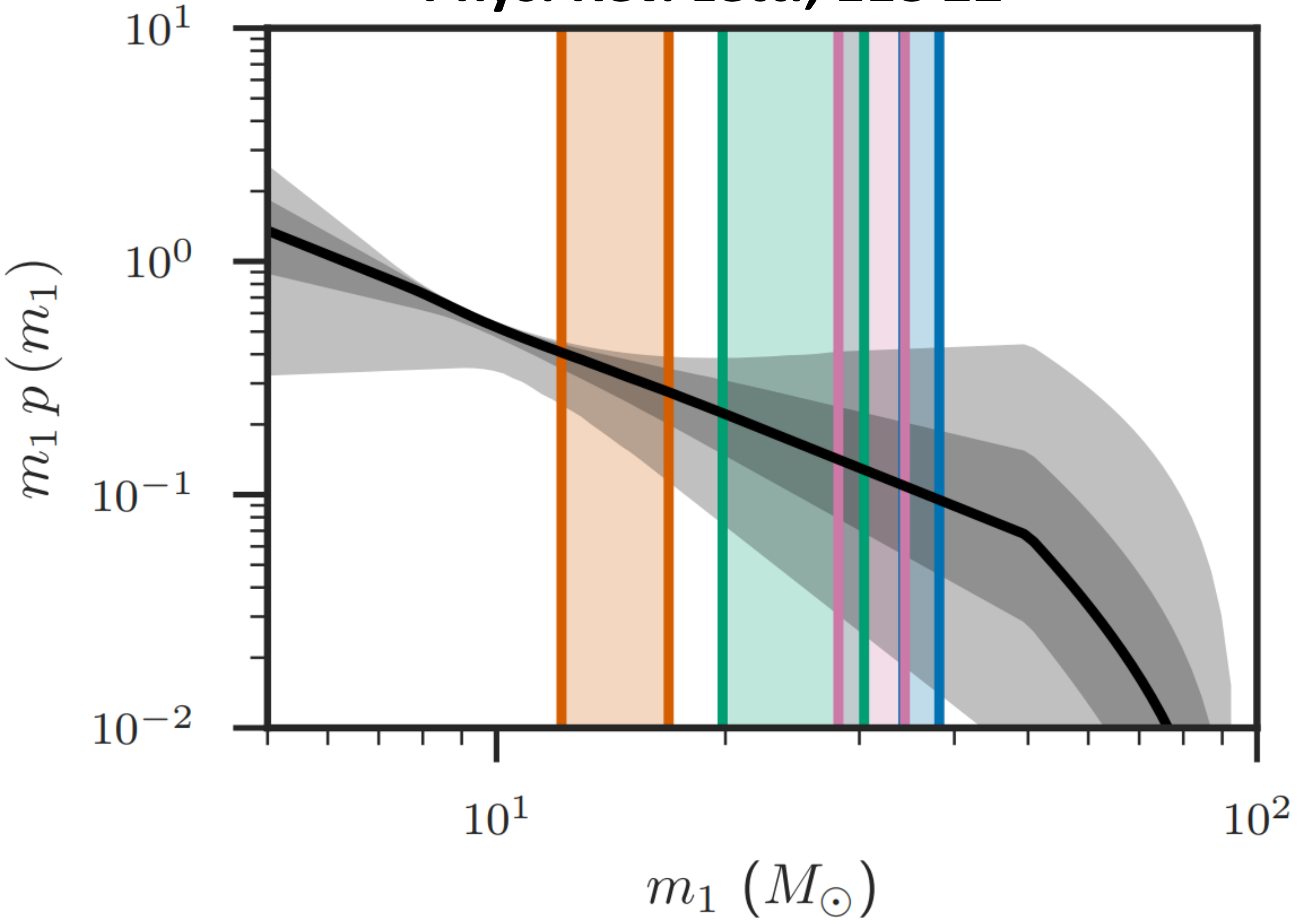
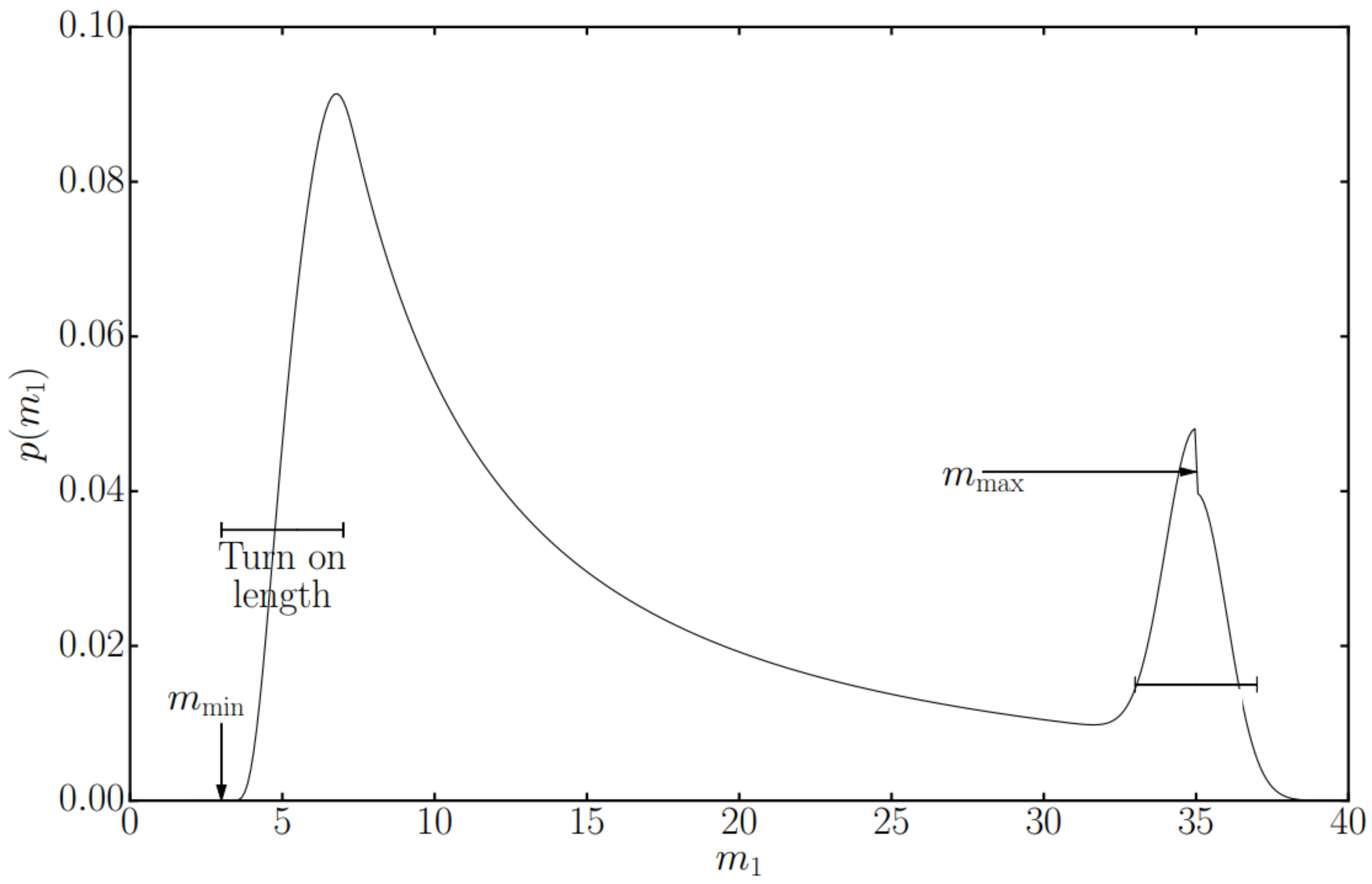


$$p(m_1, m_2 | m_{\min}, m_{\max}, \alpha, \beta_q) = \begin{cases} C(m_1) m_1^{-\alpha} q^{\beta_q} & \text{if } m_{\min} \leq m_2 \leq m_1 \leq m_{\max} \\ 0 & \text{otherwise.} \end{cases}$$

Mass Distributions

Ap. J., 856 2



O2 – C: PL + Gaussian component (primary mass)

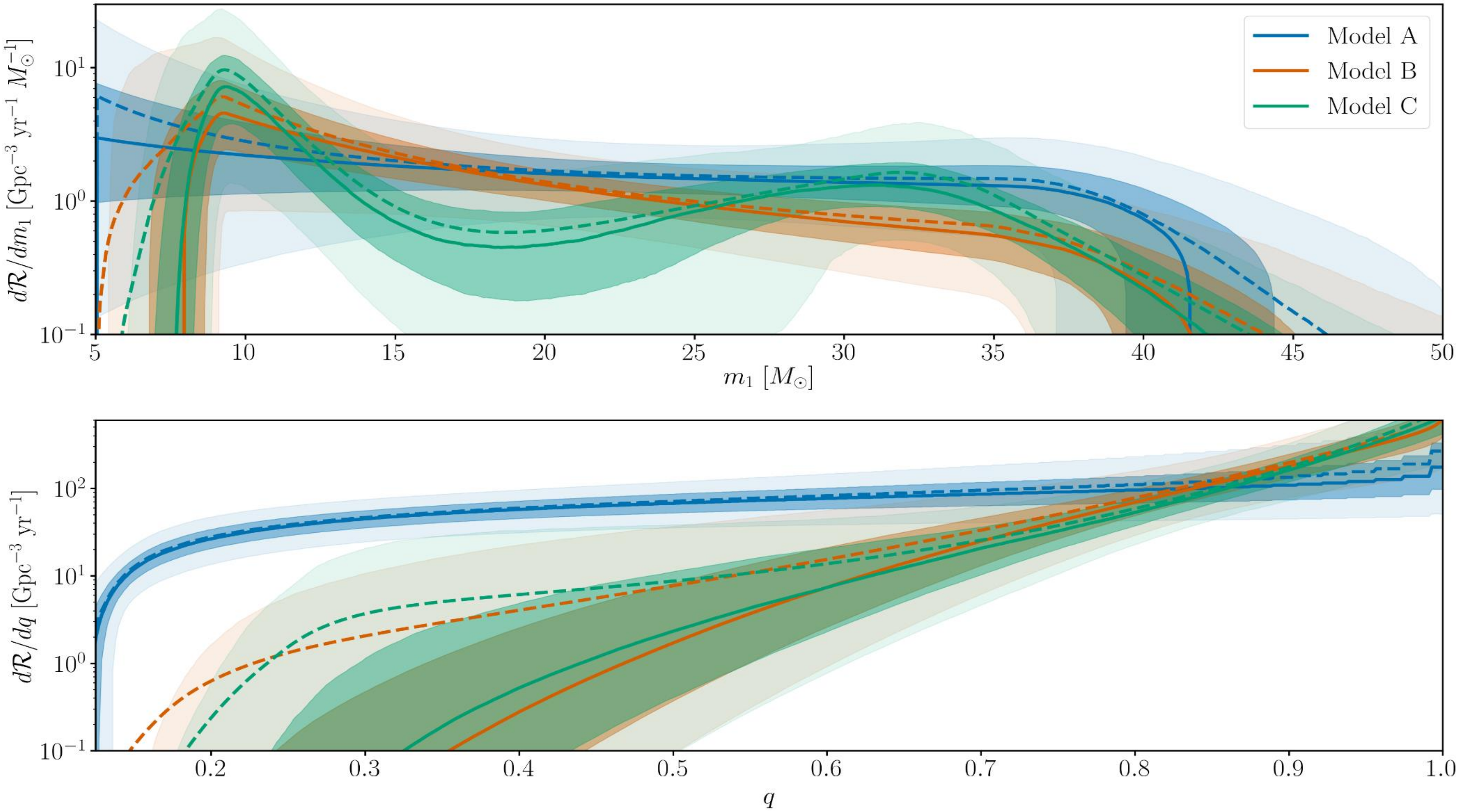
λ_m : mixture parameter
μ_m σ_m : Gaussian parameters
δm: low mass tapered turn on

$$p(m_1|\theta) = \left[(1-\lambda_m)A(\theta)m_1^{-\alpha}\Theta(m_{\max}-m_1) + \lambda_m B(\theta)\exp\left(-\frac{(m_1-\mu_m)^2}{2\sigma_m^2}\right)\right] S(m_1, m_{\min}, \delta m),$$

$$p(q|m_1,\theta) = C(m_1,\theta)q^{\beta_q}S(m_2, m_{\min}, \delta m).$$

Mass-Dependent Event Rate Distributions

- Merger rate with mass dependence
  - Model A/B: Light more frequent than heavier
  - Model C: **lnBF ~ 2** for build up (Gaussian) at high masses
- Mass ratios
  - near flat or declining
  - most asymmetric mergers disfavored



99% mass limits on top panel:

Model A: 43.8 $M_\odot$ Model B: 42.8 $M_\odot$ Model C: 41.8 $M_\odot$

New Model Parameter Constraints

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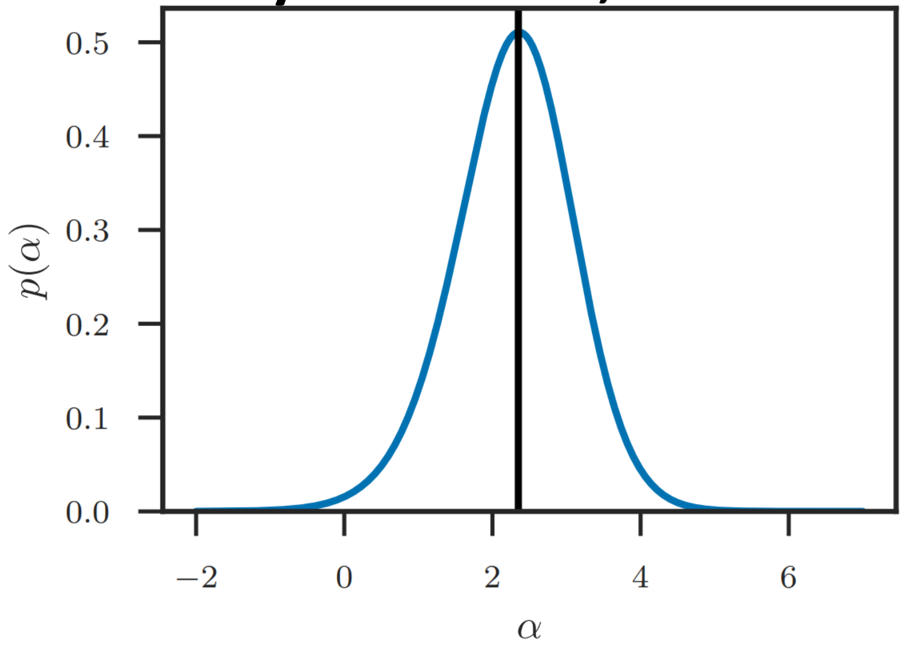
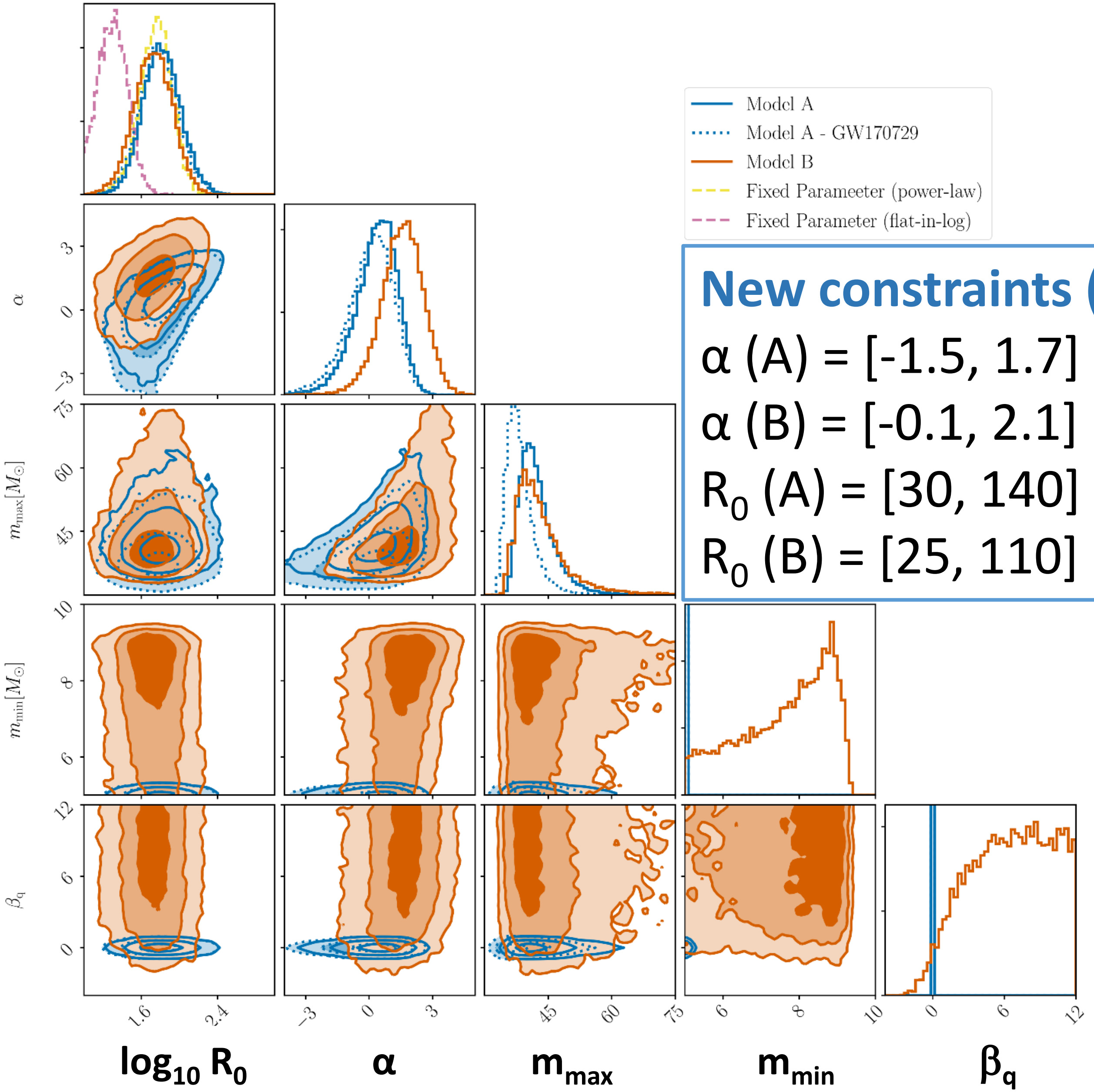


Above: Power law index with four events: m_{min} = 5, m_{max} = 100



New constraints (10 events):

α (A) = [-1.5, 1.7]

α (B) = [-0.1, 2.1]

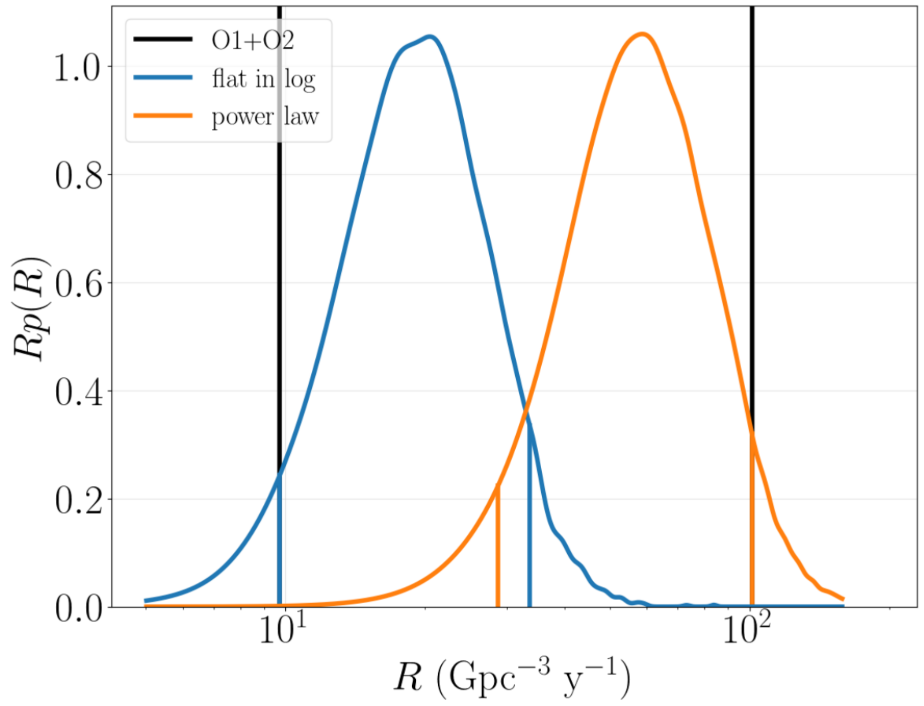
R_0 (A) = [30, 140] $Gpc^{-3}yr^{-1}$

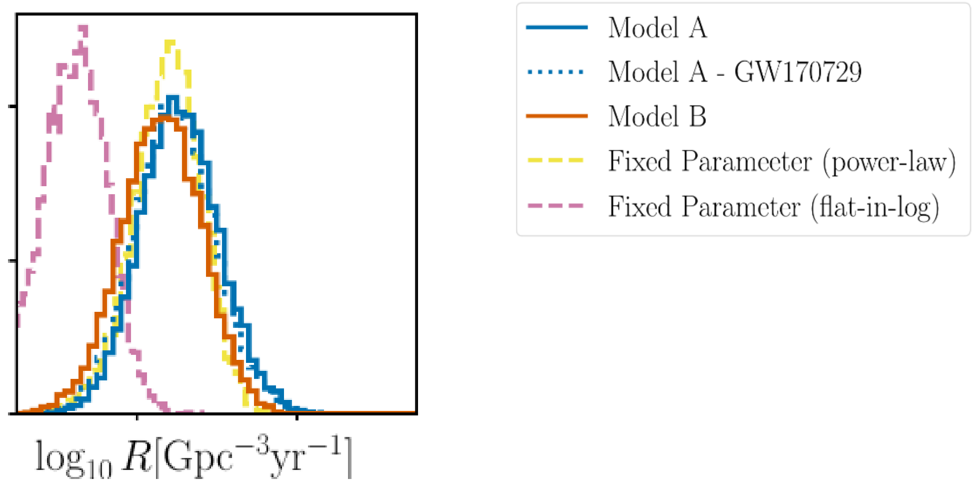
R_0 (B) = [25, 110] $Gpc^{-3}yr^{-1}$

Rate Distributions

- Current observational rates assume uniform in comoving volume
- Flexible models compare well with fixed param. choices in catalog

O2 Catalog



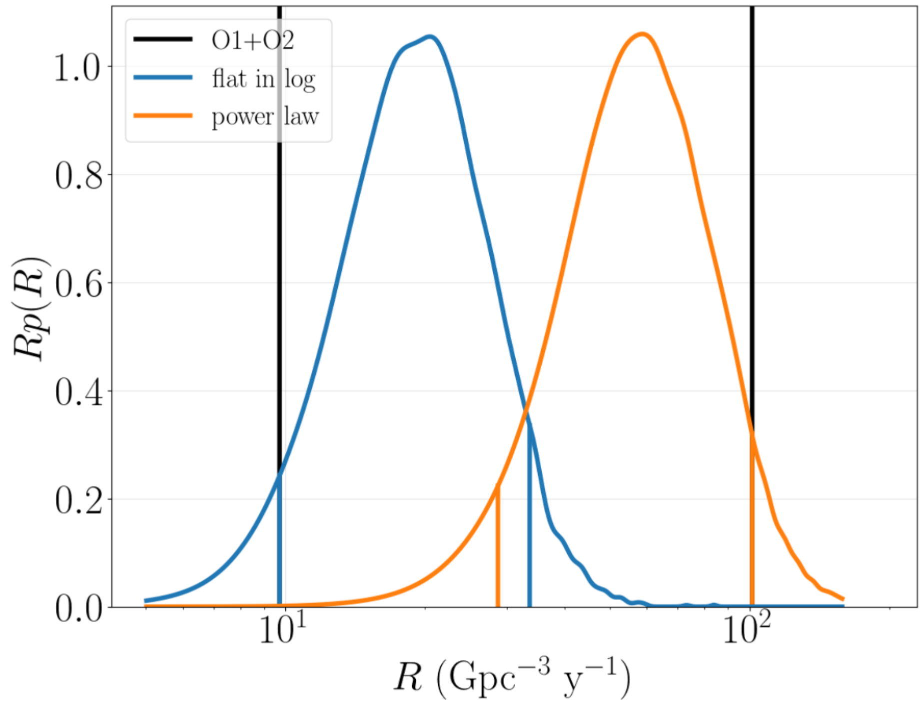


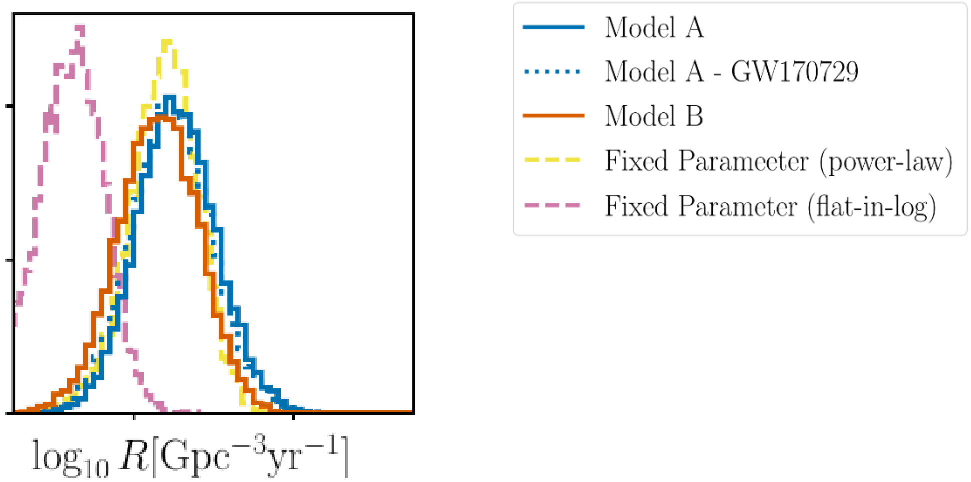
O2 Populations

Rate Distributions

- Current observational rates assume uniform in comoving volume
- Flexible models compare well with fixed param. choices in catalog
- Rate evolution with redshift is possible
    - Model rate evolution with redshift with power law
    - Also allow mass Model A to vary given strong covariance between mass and redshift distribution

O2 Catalog

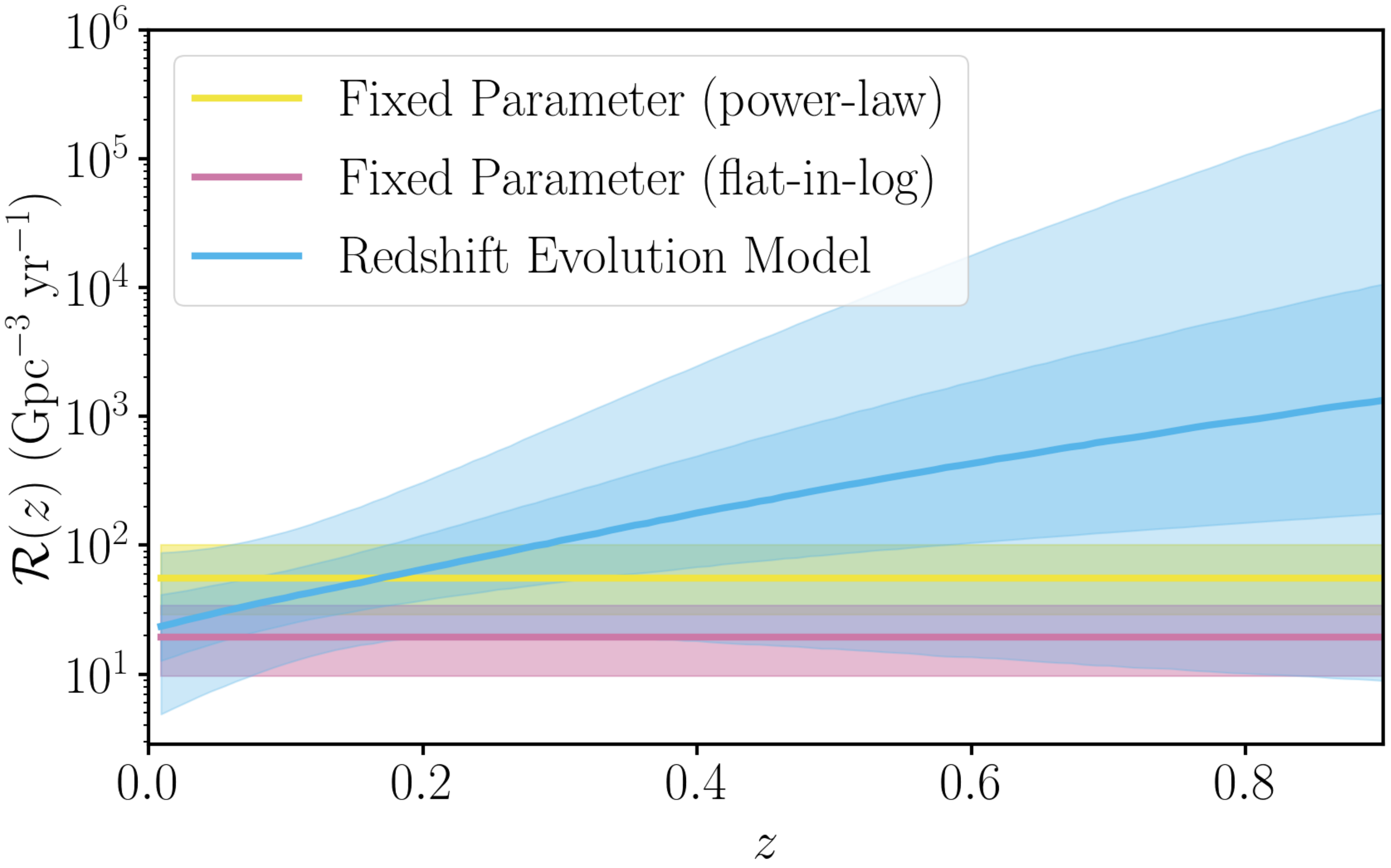


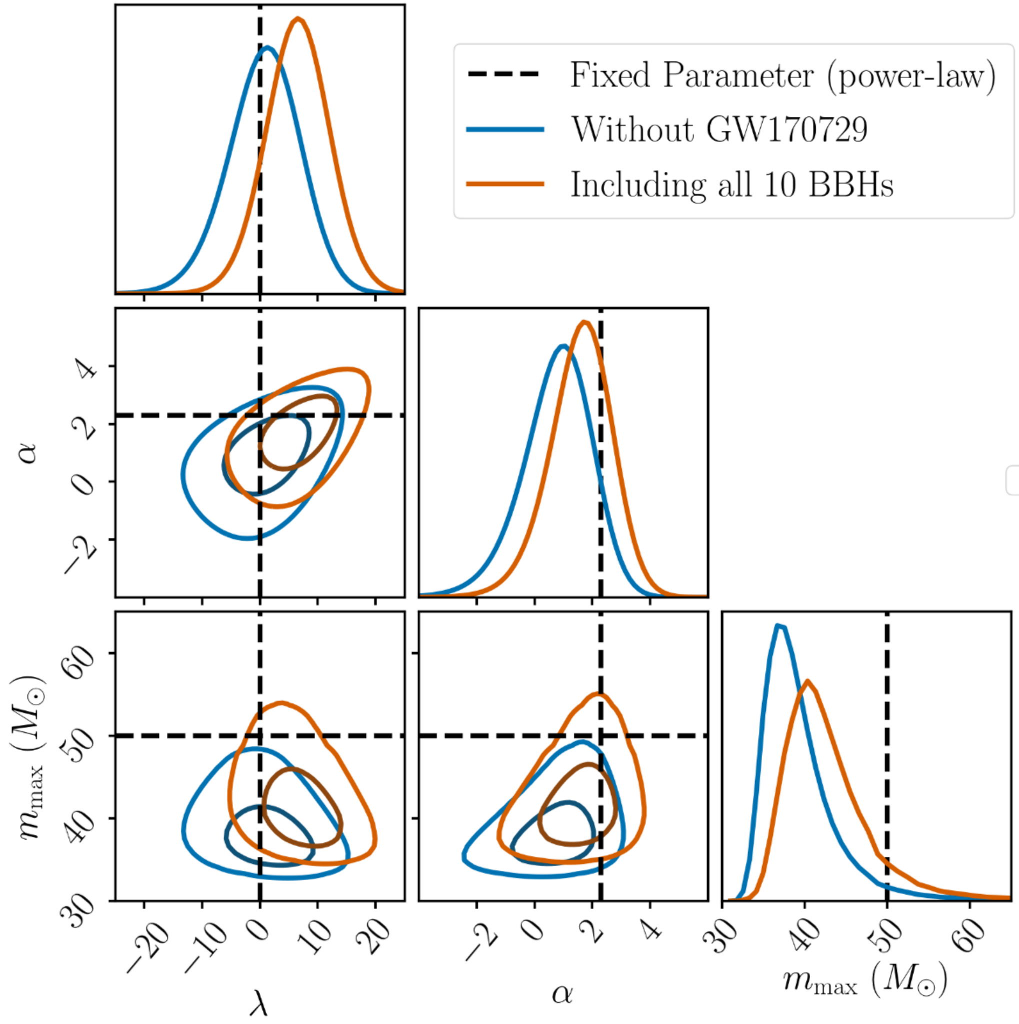


O2 Populations

Rate Evolution

Probability rate increases with z: 0.88





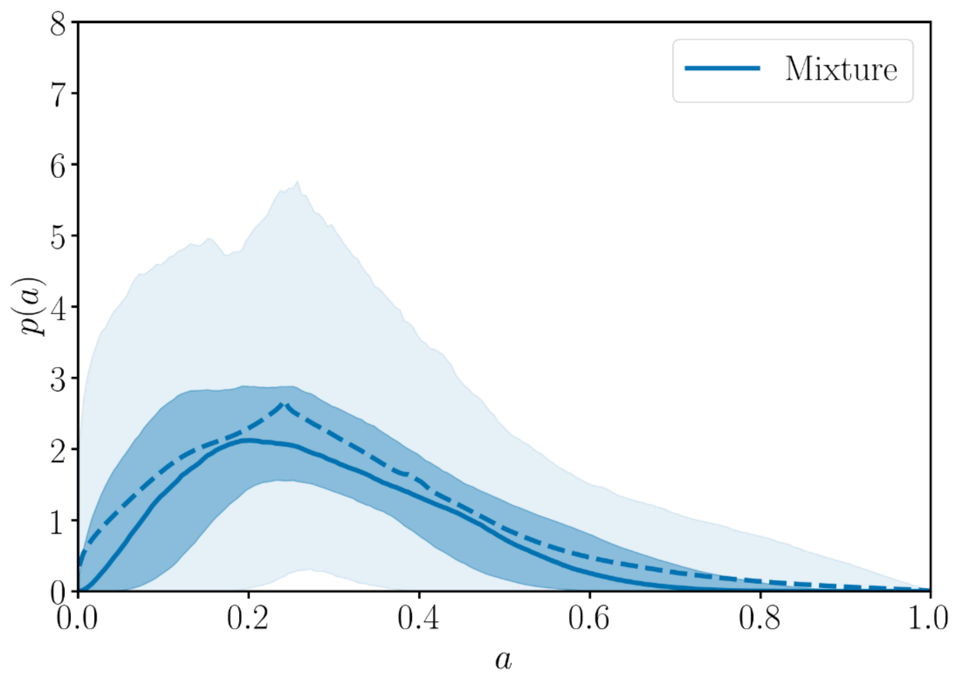
$$\frac{d\mathcal{R}}{dm_1 dm_2}(z) = \mathcal{R}_0 p(m_1, m_2 \mid \alpha, m_{\max})(1+z)^{\lambda}$$

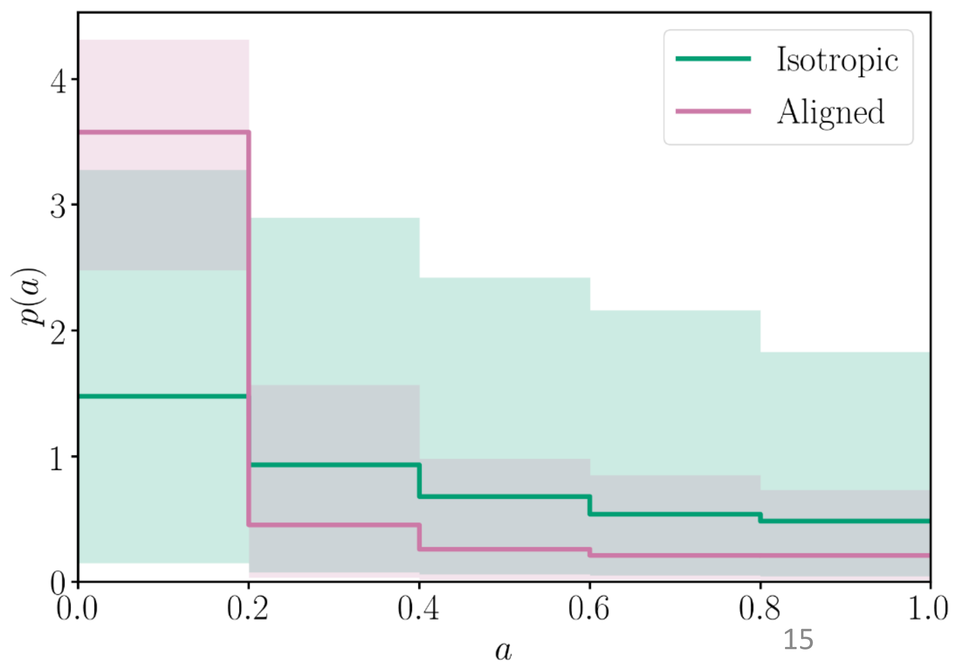
Spin Magnitude / Tilt

- Parametric (top) distribution, marginalizing over all mass and spin tilt / mixture parameters
  - Some preference for spins which decline away from zero

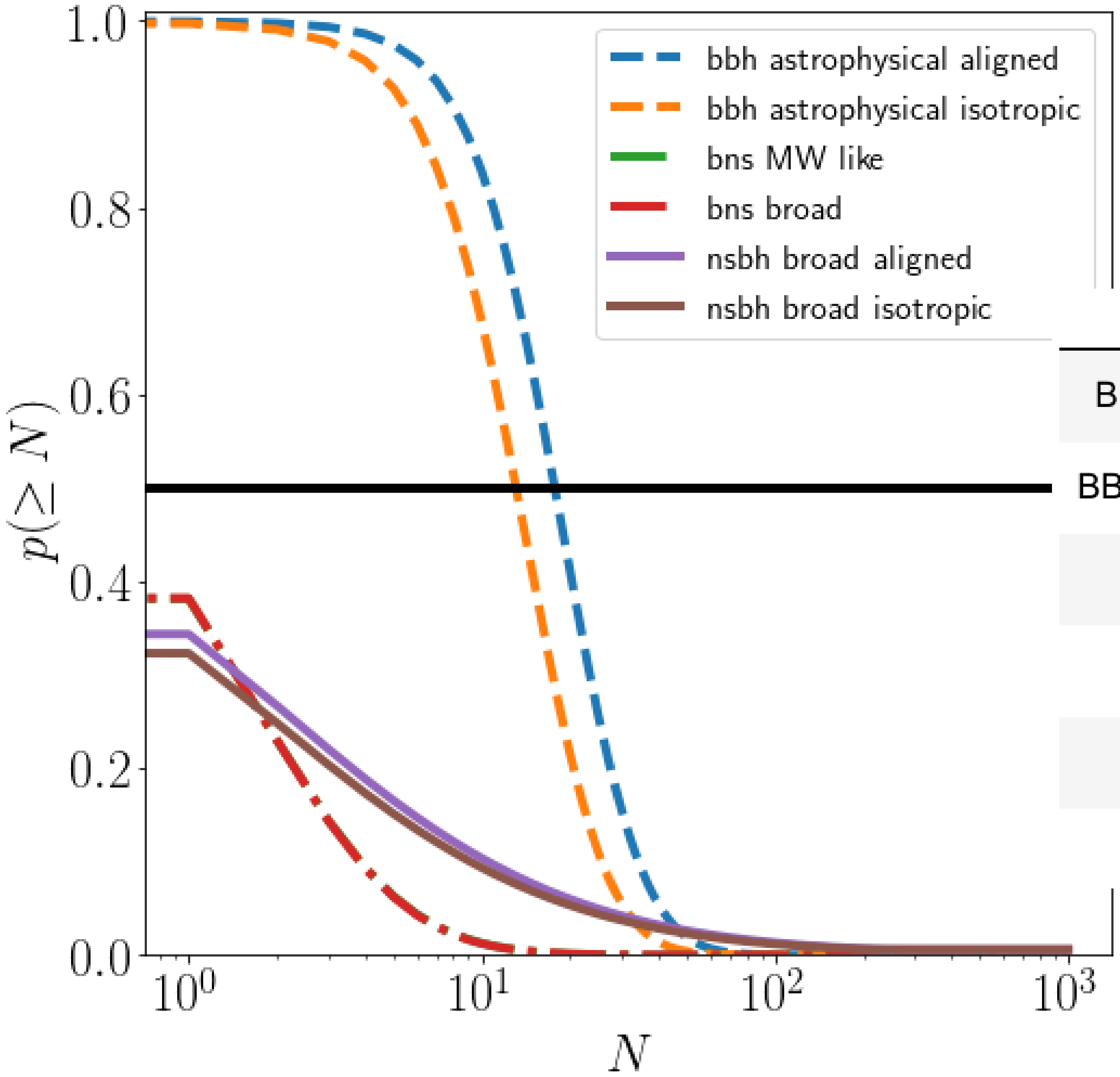
$$p(a_i|\alpha_a, \beta_a) = \frac{a_i^{\alpha_a - 1}(1 - a_i)^{\beta_a - 1}}{\mathrm{B}(\alpha_a, \beta_a)}$$

- Non-parametric (bottom), 5 bin analysis, fix tilts to isotropic or *exactly* aligned
  - Aligned distribution favors lower spins
  - Isotropic spins mostly flat





O3 Predictions



source category	VT (1 yr, 0.5 DC)	N_d
BBH / bbh_astrophysical_aligned	3.5×10^{-1} Mpc^3 yr	18^{+23}_{-11}
BBH / bbh_astrophysical_isotropic	2.6×10^{-1} Mpc^3 yr	14^{+17}_{-9}
BNS / bns_mw_like	1.7×10^{-3} Mpc^3 yr	1^{+5}_{-1}
BNS / bns_broad	2.3×10^{-3} Mpc^3 yr	1^{+5}_{-1}
NSBH / nsbh_broad_aligned	2.4×10^{-2} Mpc^3 yr	0^{+25}_{-0}
NSBH / nsbh_broad_isotropic	2.1×10^{-2} Mpc^3 yr	0^{+22}_{-0}

Conclusions

- **4 new BBH:** No new significant NSBH or BNS
- **More detections**: 10s more in O3 will tighten rate and model constraints as time goes on

- Power law slopes: **shallower** than O1, low mass binaries **more frequent** than high mass
  - **Lower mass gap**: not enough sensitivity below 5 $M_\odot$
  - **Heavy BH constraints**: most BH < 45 $M_\odot$
  - **Mass ratio**: power index on q bounded above 0 at 90%: B [0.8, 11.5] / C [0.1, 11.4]
  - **Mild evidence** for second population component (λ_m: [0.1, 0.7], lnBF ~ 2)

Conclusions (cont.)

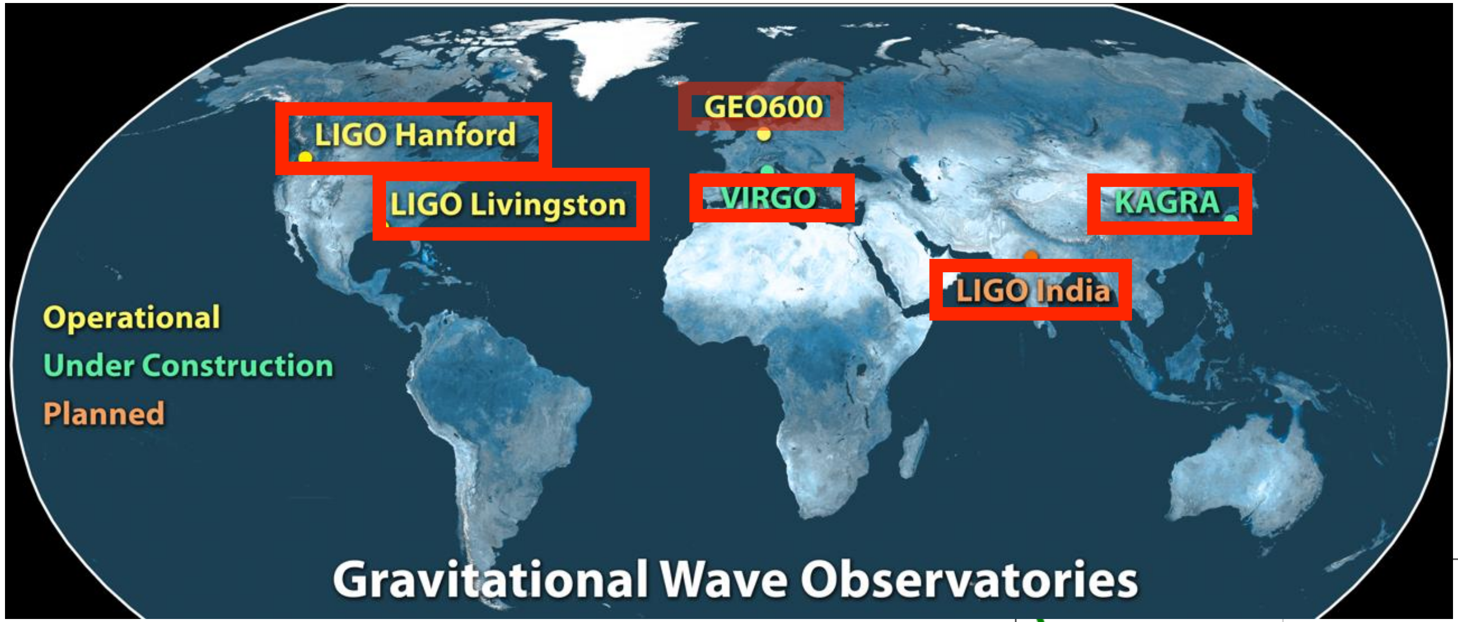
- Spin distribution **disfavors extremely high spins** under **aligned** scenario, **isotropic** spins **less constrained**
  - **Spin magnitude**: most extreme spins excluded
  - **Spin tilt / mixtures**: no conclusive statements
  - **Specific magnitude models** explored and **consistent** with above

- **Rate evolution with redshift**: upward sloping and uniform in comoving are favored
  - **Local rate distribution is consistent** even when varying over mass model parameters

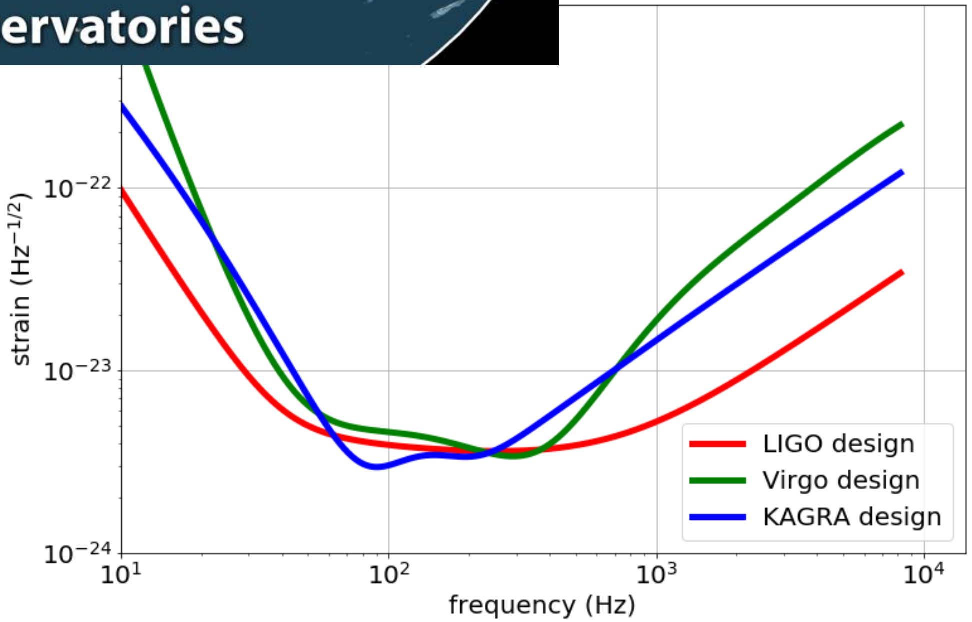
- Models allowing for **self-consistent integration** with detection significance also being developed
- Public paper and data release: https://dcc.ligo.org/LIGO-P1800324/public

Bonus Slides

The Next ~5 Years

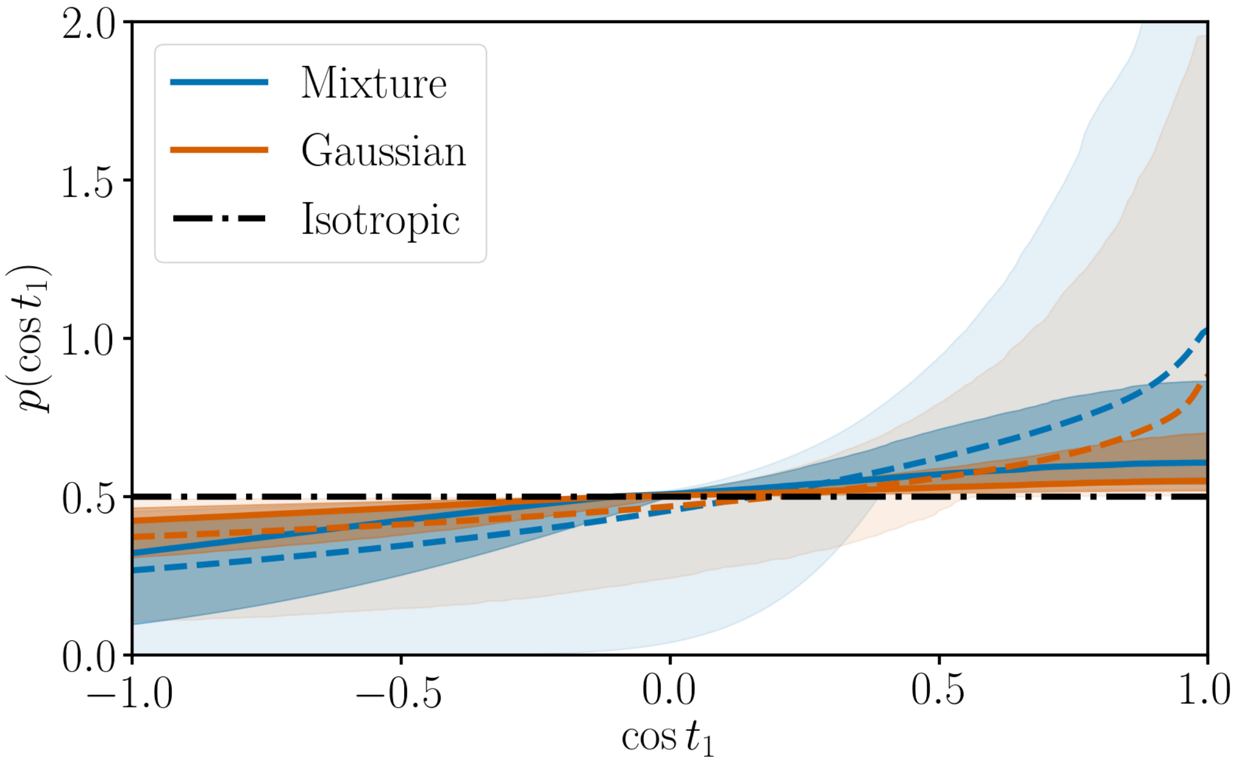


→ Kagra likely to join O3
→ 202X LIGO to meet design sensitivity (blue curve)
→ 4 and 5 detector networks by mid 2020s
→ LIGO India tentatively for 2024



Spin Magnitude / Tilt

- **Gaussian** model (ζ = 1) and **Mixture** model (0 < ζ < 1)
- **Mixture** fraction (ζ) uninformative
  - both model constraints return similar distributions
- **Gaussian** model: large *allowed* misalignment
  - wide tilt distributions which resemble isotropy



$$p(\cos t_1, \cos t_2 | \sigma_1, \sigma_2, \zeta) = \frac{(1-\zeta)}{4} + \frac{2\zeta}{\pi} \prod_{i \in \{1,2\}} \frac{\exp\left(-(1-\cos t_i)^2/(2\sigma_i^2)\right)}{\sigma_i \mathrm{erf}(\sqrt{2}/\sigma_i)}.$$

Isotropic (uniform in cos t_1)

Gaussian

New in O2

- Found four new binary black hole merger events: **GW170729**, **GW170809**, **GW170818**, **GW170823**
- **151012** designated as a GW event
  - higher significance because of improved detection pipelines and better determined rate estimates (…and personal intervention by Chase Kimball)
- Not all events found with all searches
  - All "GW" monikered events have $p_{noise} < 0.05$

Courtesy: Michael Purrer

Event	UTC Time	FAR [y^{-1}] PyCBC	FAR [y^{-1}] GstLAL	FAR [y^{-1}] cWB	Network SNR PyCBC	Network SNR GstLAL	Network SNR cWB
GW150914	09:50:45.4	$< 1.53 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	$< 1.63 \times 10^{-4}$	23.6	24.4	25.2
GW151012	09:54:43.4	0.17	7.92×10^{-3}	–	9.5	10.0	–
GW151226	03:38:53.6	$< 1.69 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	0.02	13.1	13.1	11.9
GW170104	10:11:58.6	$< 1.37 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	2.91×10^{-4}	13.0	13.0	13.0
GW170608	02:01:16.5	$< 3.09 \times 10^{-4}$	$< 1.00 \times 10^{-7}$	1.44×10^{-4}	15.4	14.9	14.1
GW170729	18:56:29.3	1.36	0.18	0.02	9.8	10.8	10.2
GW170809	08:28:21.8	1.45×10^{-4}	$< 1.00 \times 10^{-7}$	–	12.2	12.4	–
GW170814	10:30:43.5	$< 1.25 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	$< 2.08 \times 10^{-4}$	16.3	15.9	17.2
GW170817	12:41:04.4	$< 1.25 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	–	30.9	33.0	–
GW170818	02:25:09.1	–	4.20×10^{-5}	–	–	11.3	–
GW170823	13:13:58.5	$< 3.29 \times 10^{-5}$	$< 1.00 \times 10^{-7}$	2.14×10^{-3}	11.1	11.5	10.8

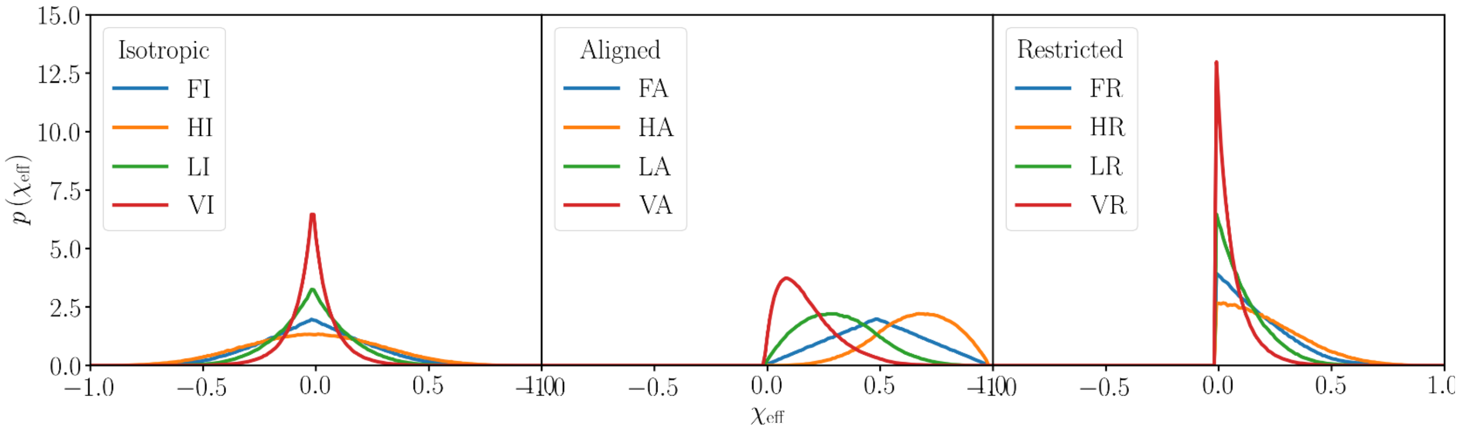
Fixed Mag. Distr. Model Selection

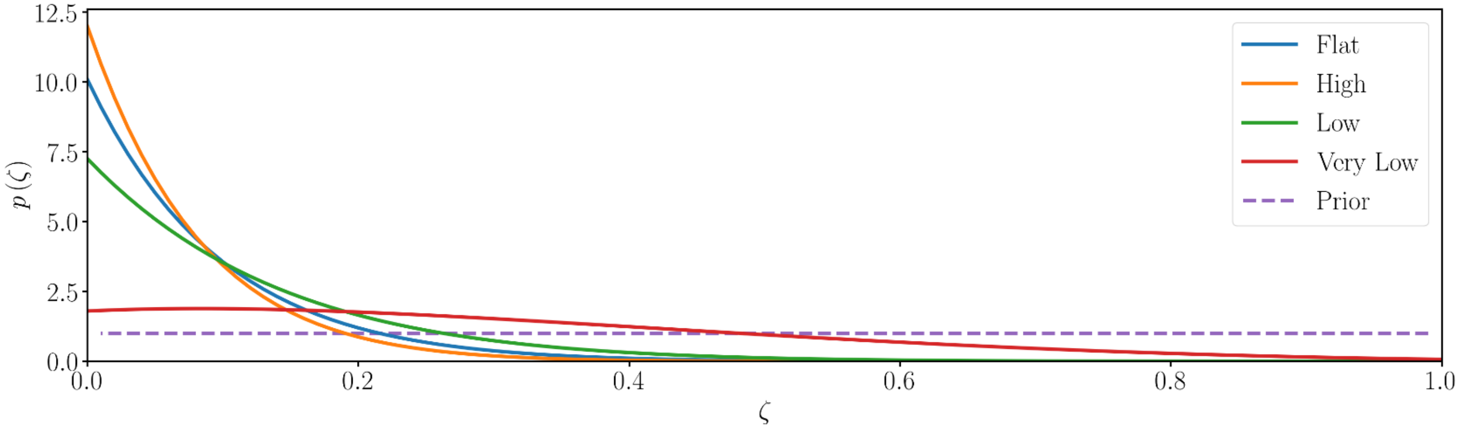
Bottom : Magnitude models, mixture posterior
Right: log Bayes Factors for variety of fixed magnitude / tilt distributions

$q=1$	Very low	Low	Flat	High
Isotropic	1.10	0.0	-0.93	-2.07
Restricted	3.39	3.26	1.31	0.11
Aligned	1.58	-4.12	-12.92	-32.37

$q=0.5$	Very low	Low	Flat	High
Isotropic	1.14	0.0	-1.03	-2.41
Restricted	3.45	3.26	1.23	-0.25
Aligned	1.69	-3.71	-12.22	-30.73

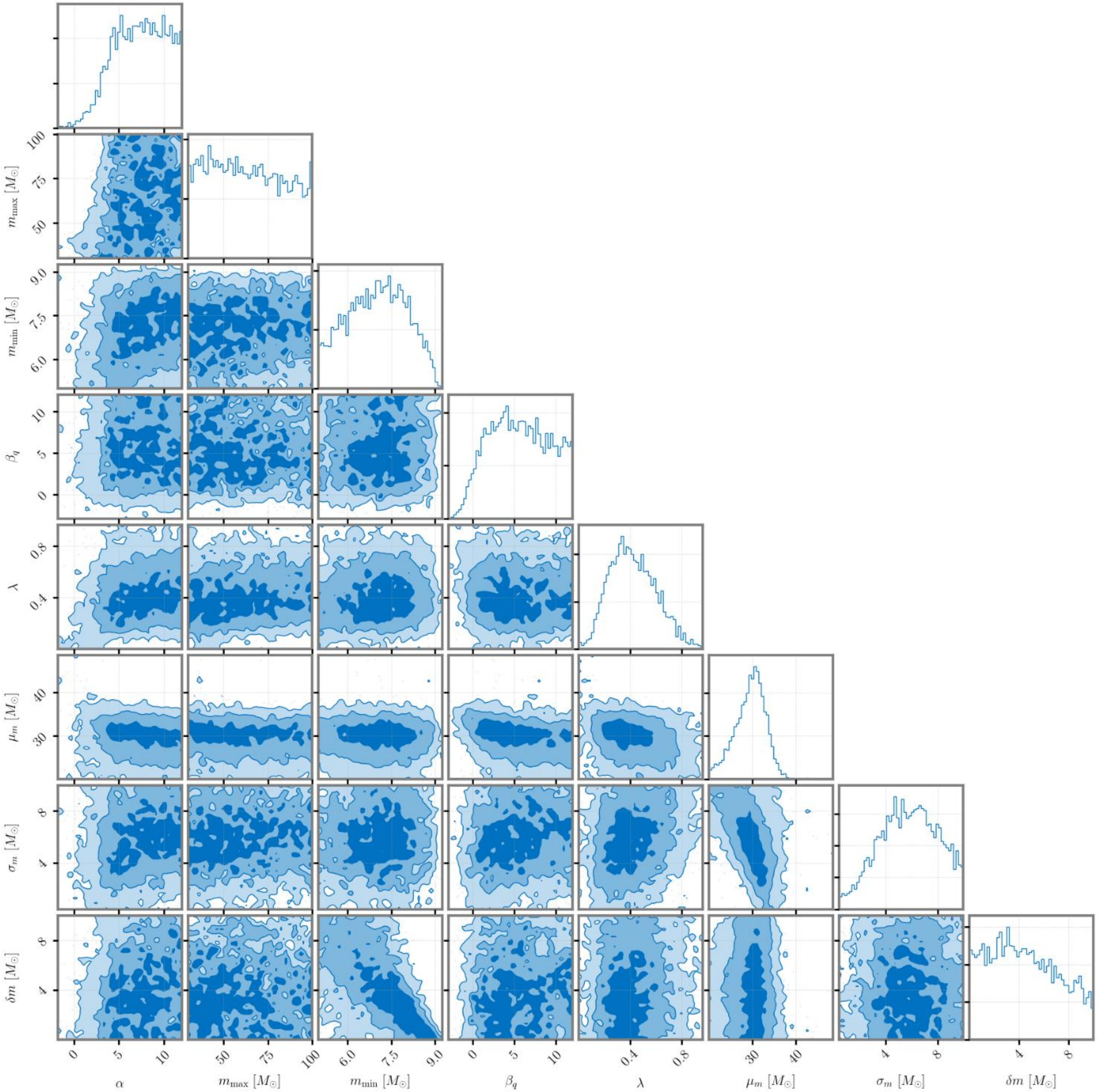
fixed param.	Very low	Low	Flat	High
Isotropic	1.40	0.0	-2.63	-4.61
Restricted	1.76	0.11	-2.78	-4.88
Aligned	-3.78	-14.45	-24.28	-48.00





$$\chi_{\rm eff} = \frac{(\boldsymbol{\chi}_1 + q\boldsymbol{\chi}_2)\cdot \hat{\boldsymbol{L}}}{1+q}$$

Model C (PL + Gaussian)



Population Modelling Basics

- **The goal**: determine the particulars of binary evolution physics through a parameterized (λ) model

- **How?**: Determine the imprint of those processes on the GW binary physical parameter distribution (θ)

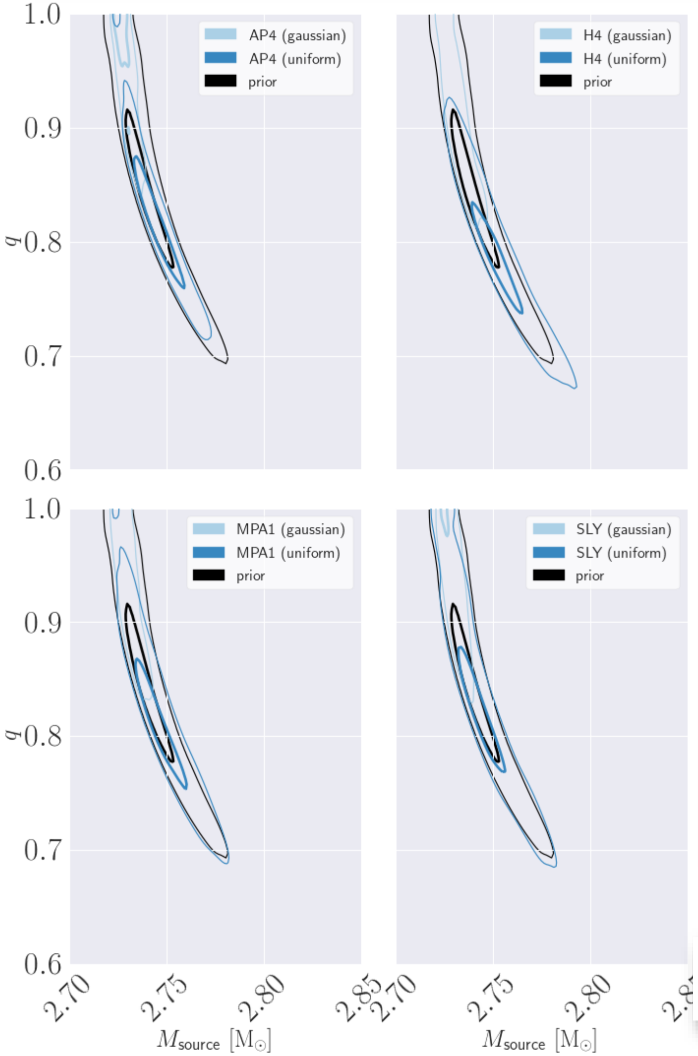
$$p(\{x_i\}|\vec{\lambda}) = \prod_{i=1}^{N} p(x_i|\vec{\lambda}) = \prod_{i=1}^{N} \int d\vec{\theta} p(x_i|\vec{\theta}) p(\vec{\theta}|\vec{\lambda})$$

- Fold GW posterior measurements ($\{x_i\}$) together with modelling to determine most favored model parameters, from the observations and thus the physical prescriptions

$$p(\{x_i\}|\vec{\lambda}) = \prod_{i=1}^{N} \frac{1}{S} \sum_{k=1}^{S} \frac{p(\vec{\theta}_k|\vec{\lambda})}{p(\vec{\theta}_k)}$$

GW170817 + Galactic DNS

Joint total mass / mass ratio posteriors with constrains from kN ejecta mass applied --- mass asymmetry has moderate tension with Galactic DNS distribution

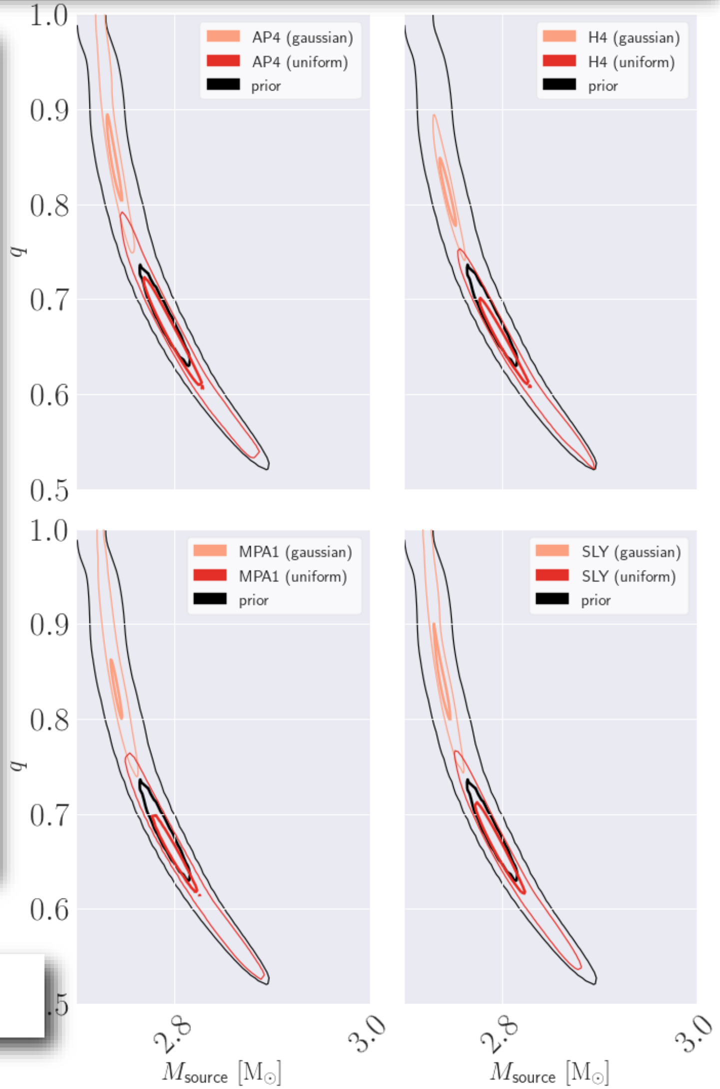


Left: blue component, low spin priors

Right: red component, high spin priors

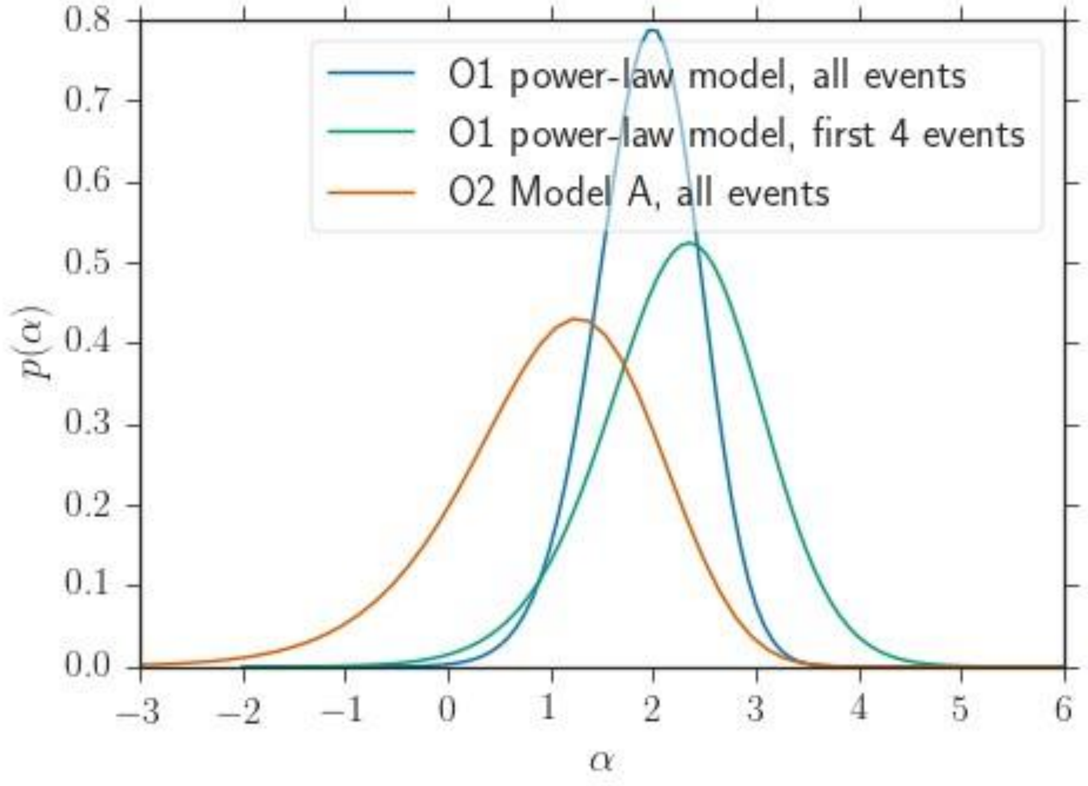
Mostly EoS indep.

Pankow (2018)



What if?

- …we had carried over the O1 model to new events?



Courtesy: Maya Fishbach

Green: Power law index with **four** events

m_{min} = 5, m_{max} = 100

Blue: Power law index with **ten** events

m_{min} = 5, m_{max} = 100

Orange: Power law index with ten events

Model A

Mass Distributions

Model A/B/C: power law (primary mass)
α : power law slope
m_{min} : minimum power law cutoff
m_{max} : maximum power law cutoff

Model B/C: power law (mass ratio)
β_q : Power law slope

$$p(m_1, m_2 | m_{\min}, m_{\max}, \alpha, \beta_q) = \begin{cases} C(m_1) m_1^{-\alpha} q^{\beta_q} & \text{if } m_{\min} \leq m_2 \leq m_1 \leq m_{\max} \\ 0 & \text{otherwise.} \end{cases}$$

Power Law

α, m_{min}, m_{max}

Gaussian

λ_m, μ_m, σ_m

Low Mass Tapering

$$p(m_1|\theta) = \left[(1-\lambda_m)A(\theta)m_1^{-\alpha}\Theta(m_{\max}-m_1) + \lambda_m B(\theta)\exp\left(-\frac{(m_1-\mu_m)^2}{2\sigma_m^2}\right)\right] S(m_1, m_{\min}, \delta m),$$

$$p(q|m_1,\theta) = C(m_1,\theta) q^{\beta_q} S(m_2, m_{\min}, \delta m).$$

Spin Distributions

O2 -- Model A/B/C: Beta distribution (spin magnitudes)

α_a β_a : Beta parameters

$\alpha > \beta$ -> inclining

$\alpha < \beta$ -> declining

$$p(a_i|\alpha_a, \beta_a) = \frac{a_i^{\alpha_a - 1}(1 - a_i)^{\beta_a - 1}}{\mathrm{B}(\alpha_a, \beta_a)}$$

O2 -- Model A/B/C: mixture distribution (spin tilts)

ζ : Mixture parameter

σ_i : degree of spin alignment allowed

$$p(t_1, t_2|\sigma_1, \sigma_2, \zeta) = \frac{(1 - \zeta)}{4}$$

Isotropic (uniform in cos t_1)

$$+ \frac{\zeta}{2\pi} \prod_{i \in \{1,2\}} \frac{e^{-(1-\cos t_i)^2/(2\sigma_i^2)}}{\sigma_i \mathrm{erf}(\sqrt{2}/\sigma_i)}.$$

Gaussian