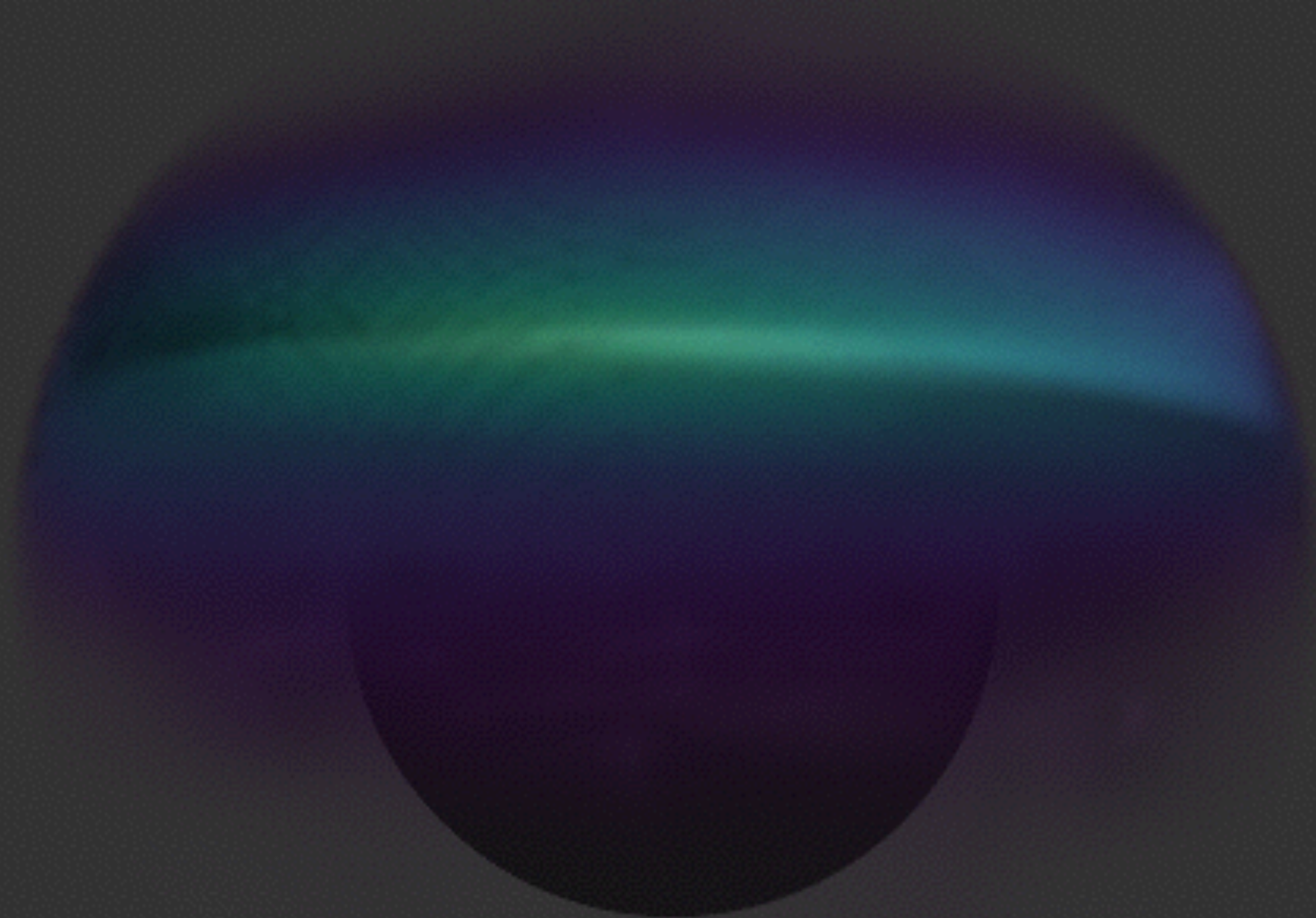
Measuring Spin with LIGO



Ben Farr

KITP: Massive Stars Workshop

THE UNIVERSITY OF CHICAGO

15 Model Parameters

Intrinsic	Extrinsic
Masses (2) Spins (6)	Location (2) Distance (1) Inclination (1) Orientation (2) Merger Time (1)

Bayesian Inference

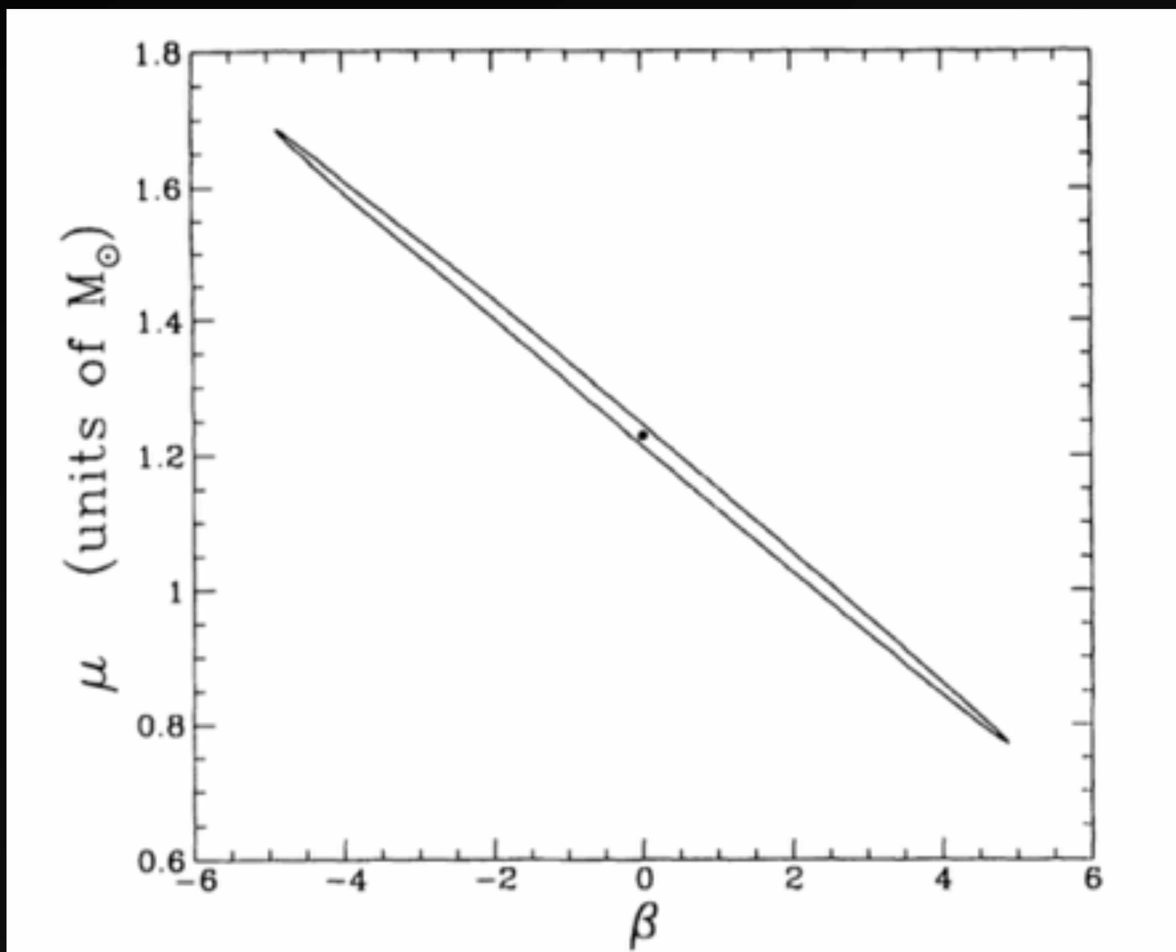
$$p(\vec{\theta}|d) \propto p(\vec{\theta})p(d|\vec{\theta})$$

Posterior

Prior

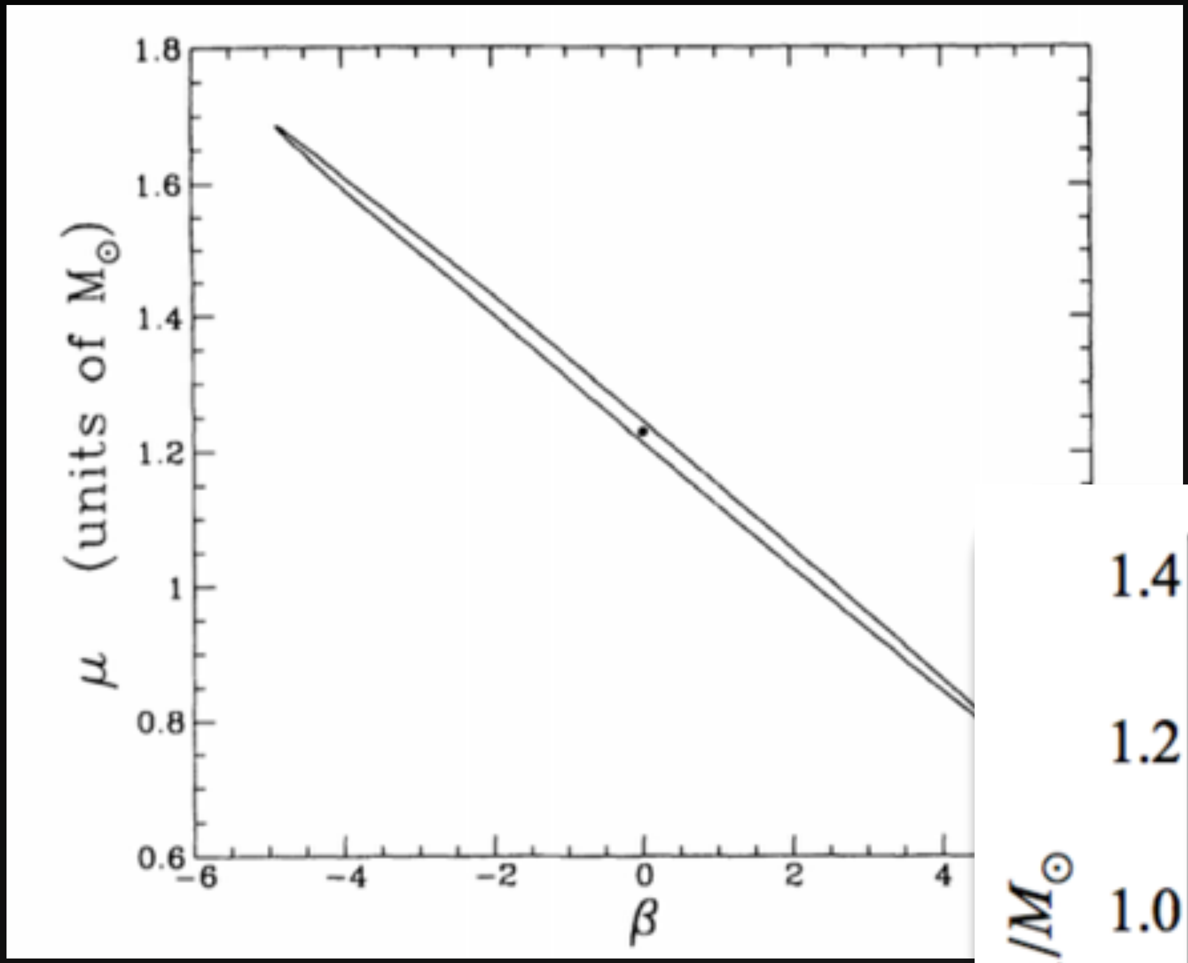
Likelihood

Mass-Spin Degeneracy

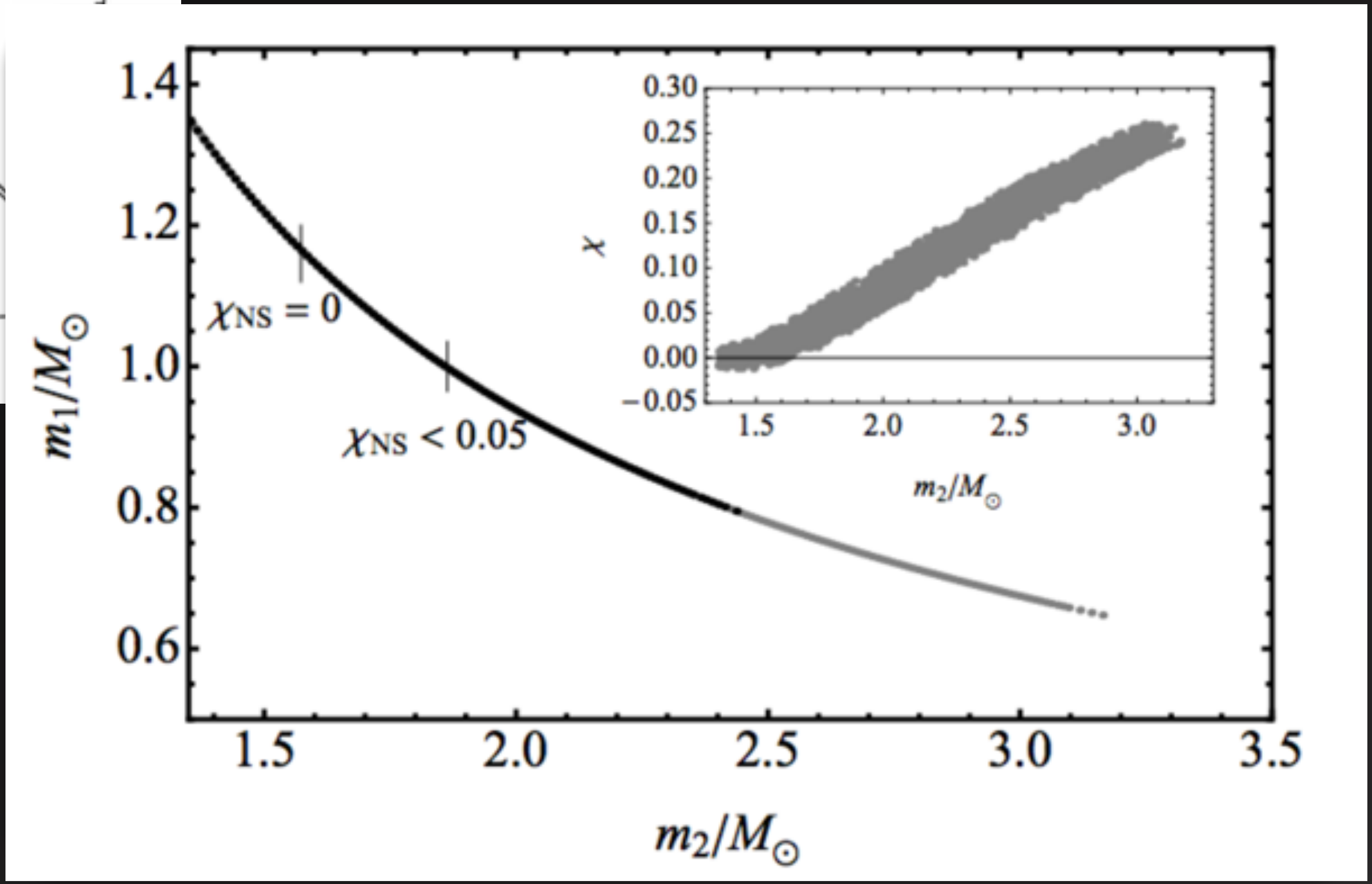


Cutler & Flanagan (1994)

Mass-Spin Degeneracy

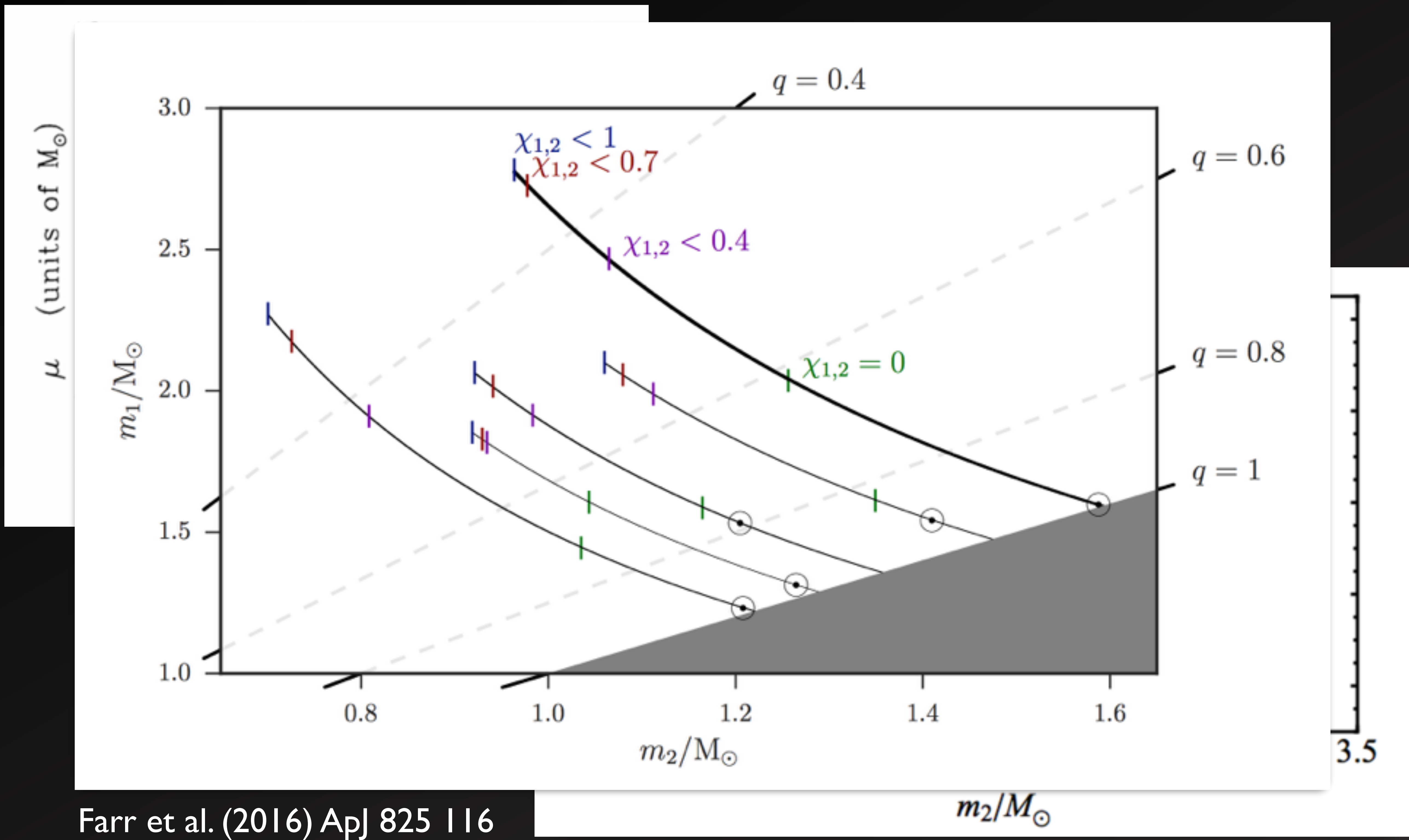


Cutler & Flanagan



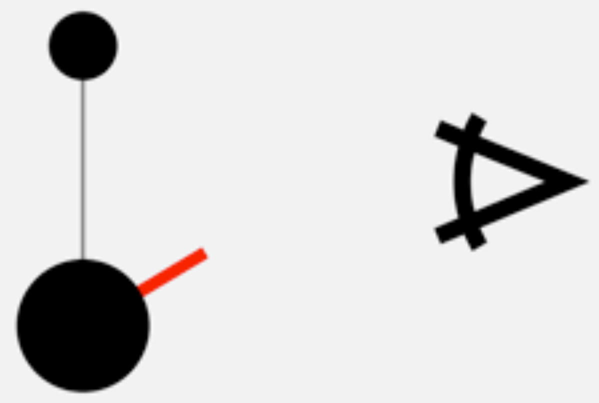
Hannam et al. (2013)

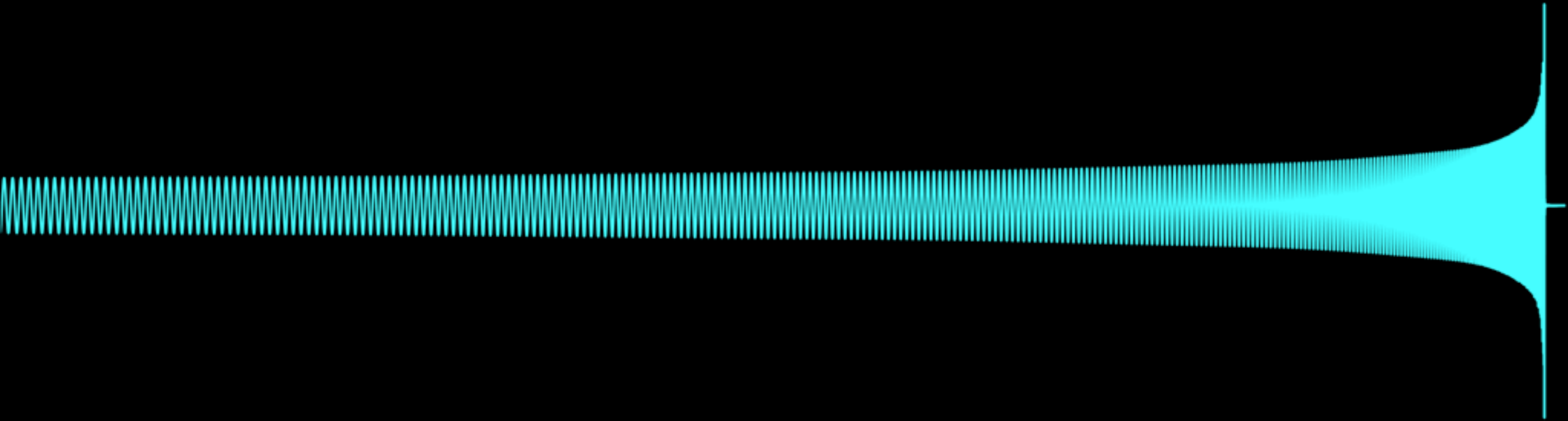
Mass-Spin Degeneracy



Farr et al. (2016) ApJ 825 116

Hannam et al. (2013)





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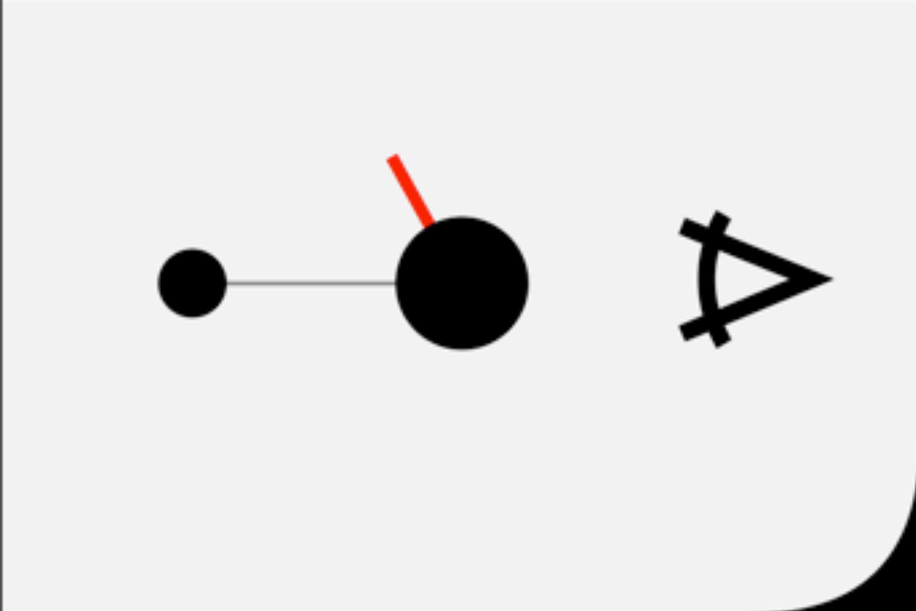

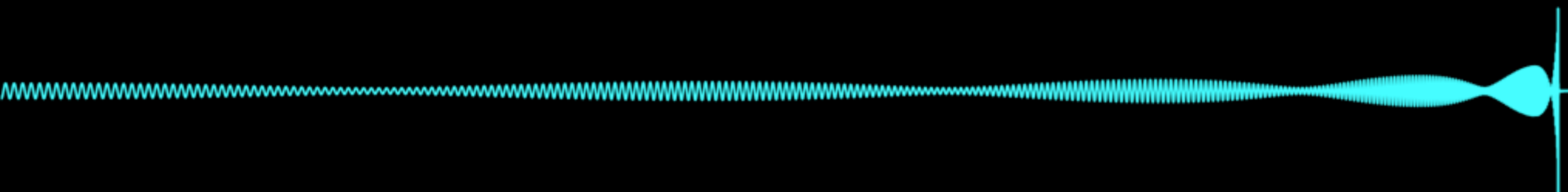

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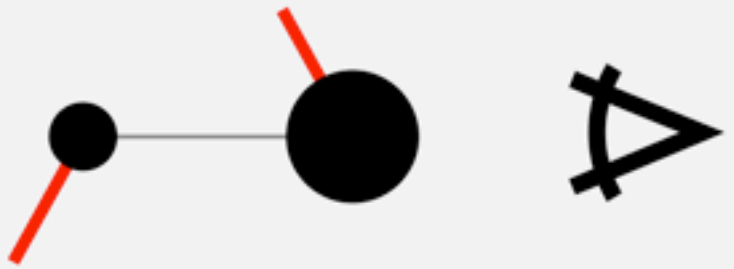

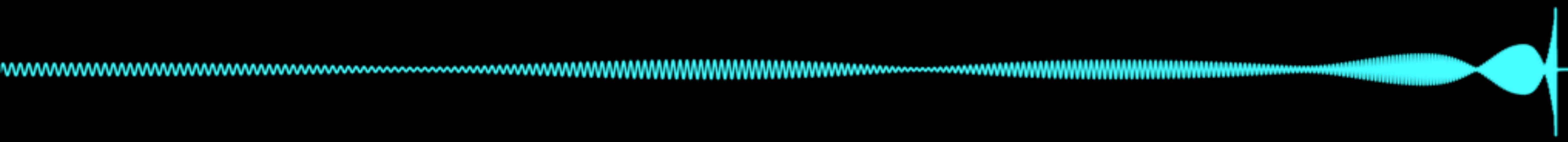

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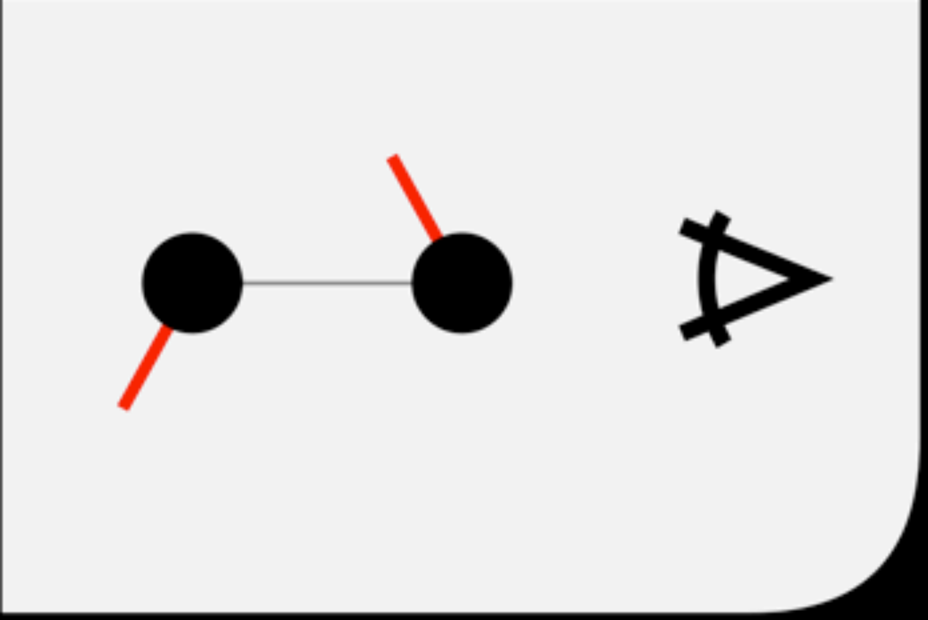

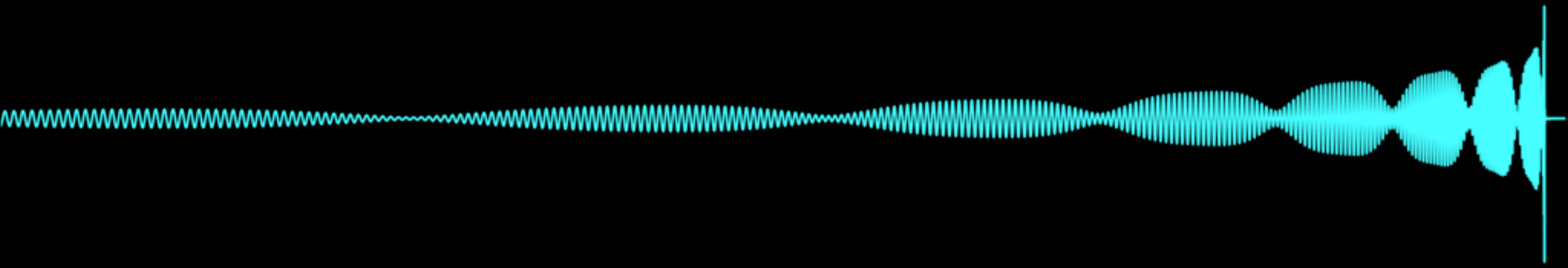

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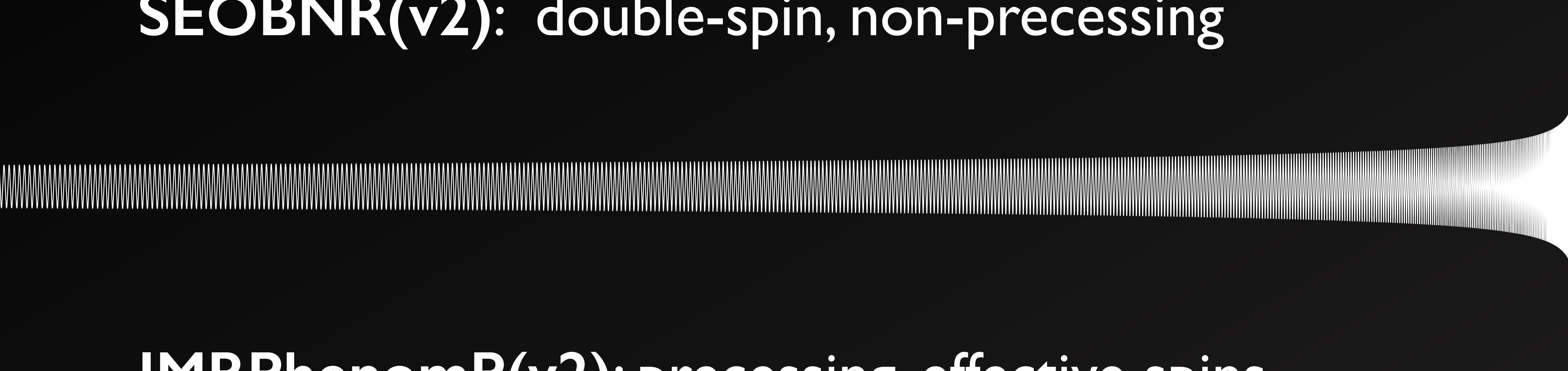
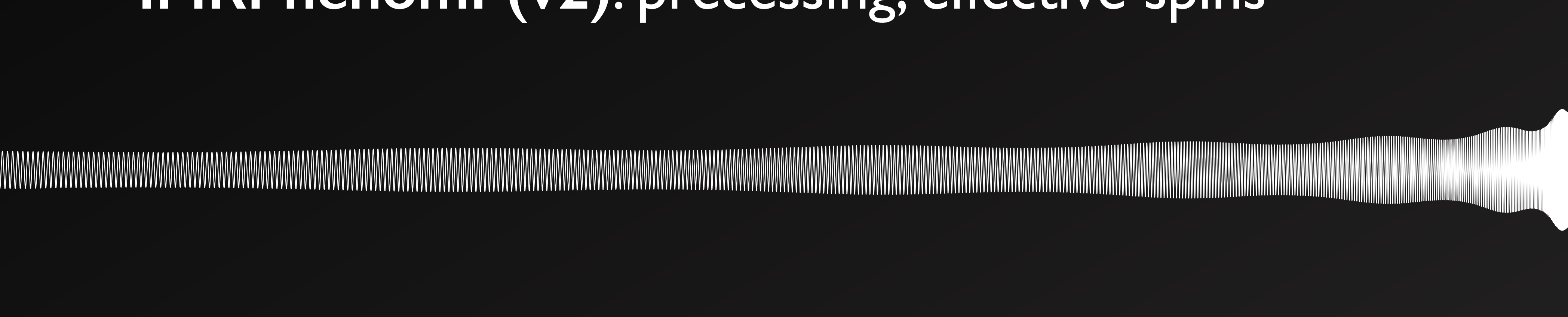
O1 Models

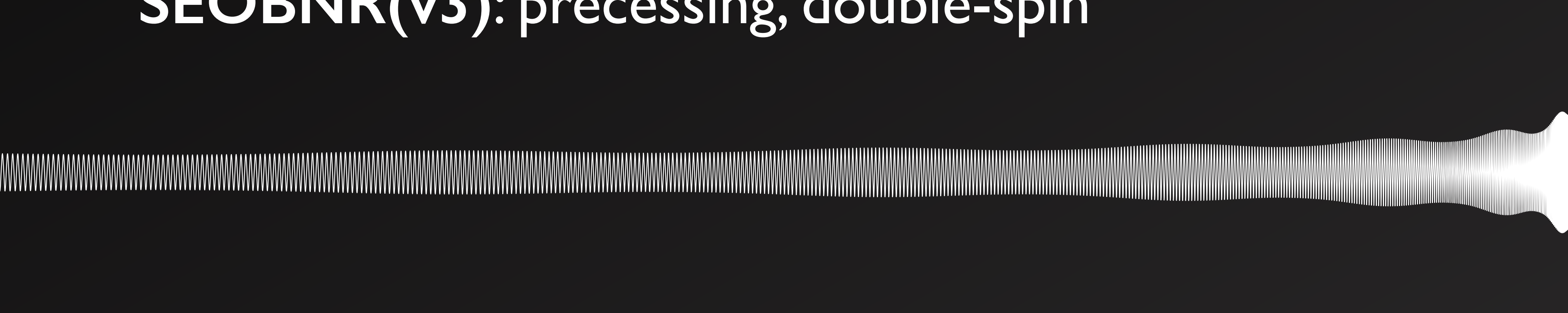
SEOBNR(v2): double-spin, non-precessing



IMRPhenomP(v2): precessing, effective spins

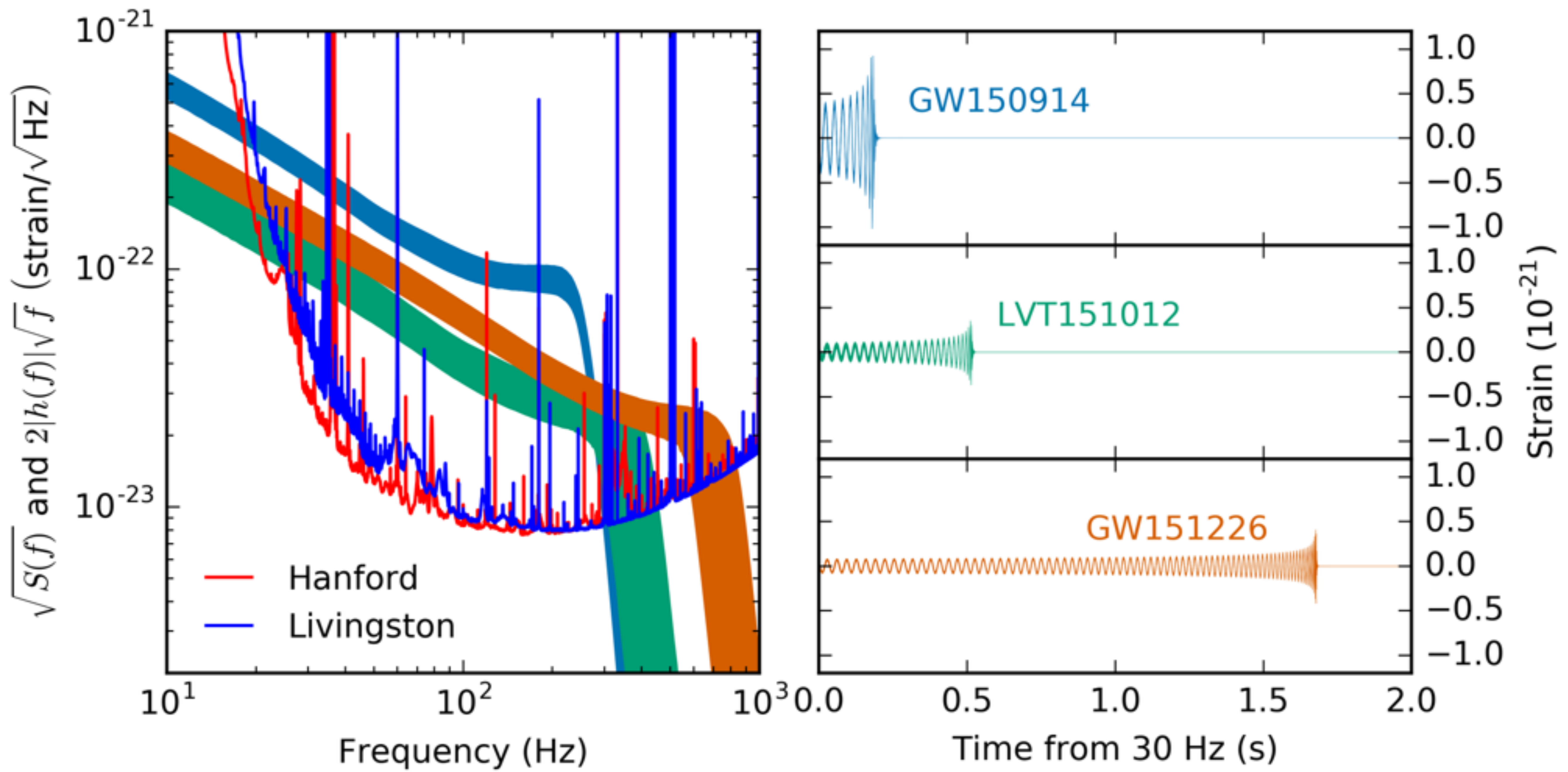


SEOBNR(v3): precessing, double-spin



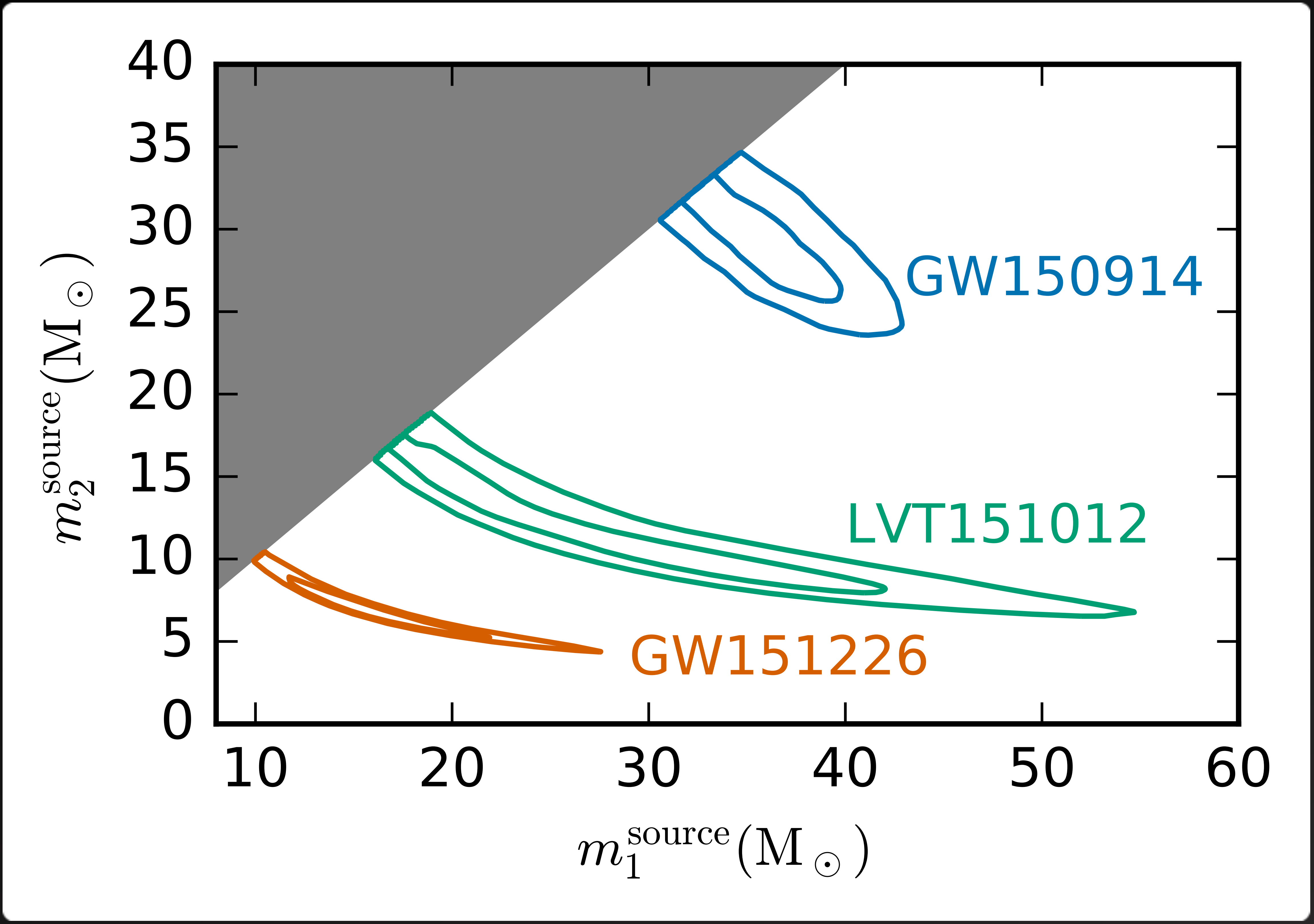
BBHs in O1

non-precessing



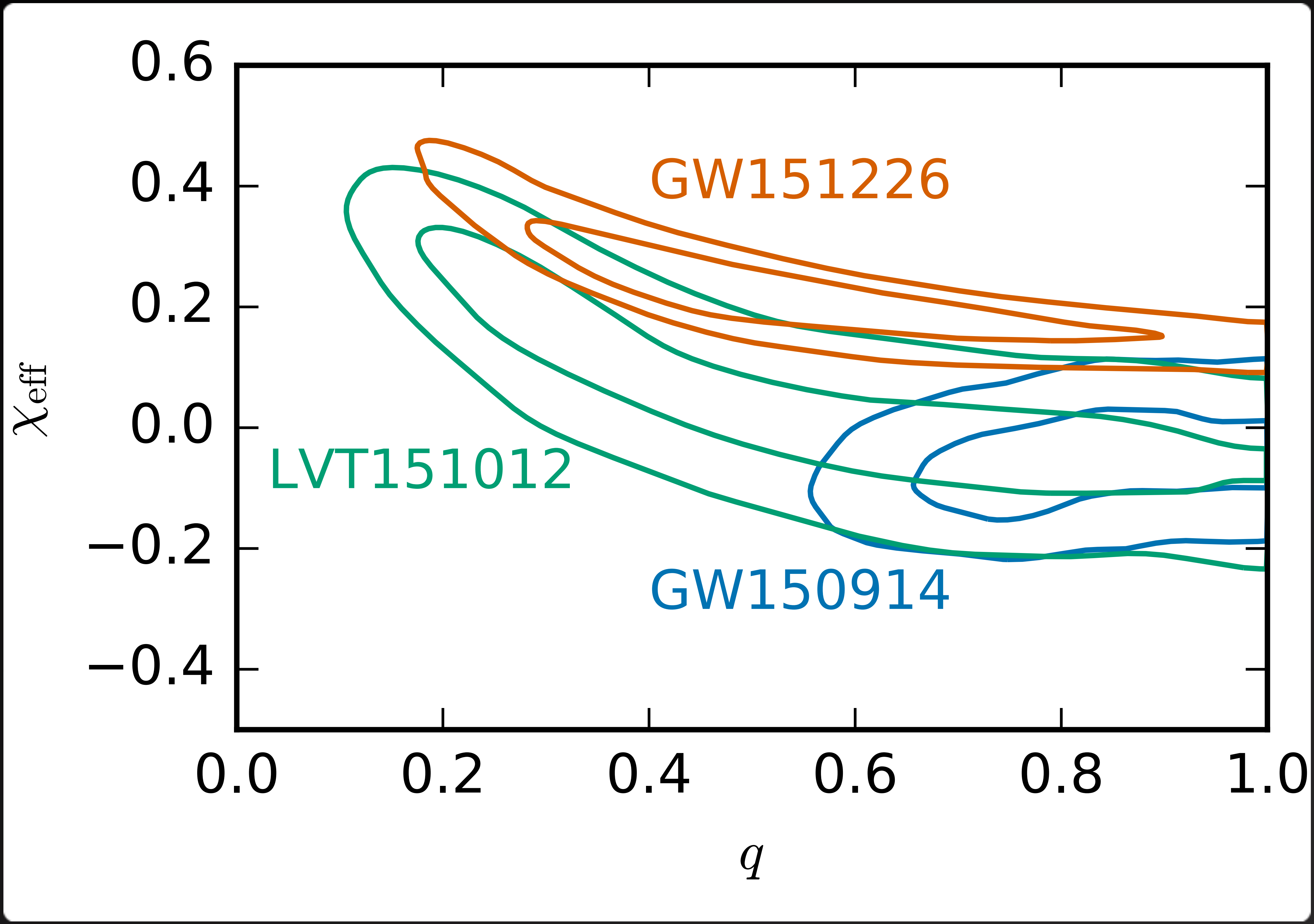
Abbott et al. (2016)

Black Hole Masses



Abbott et al. (2016):
PRX 6, 041015

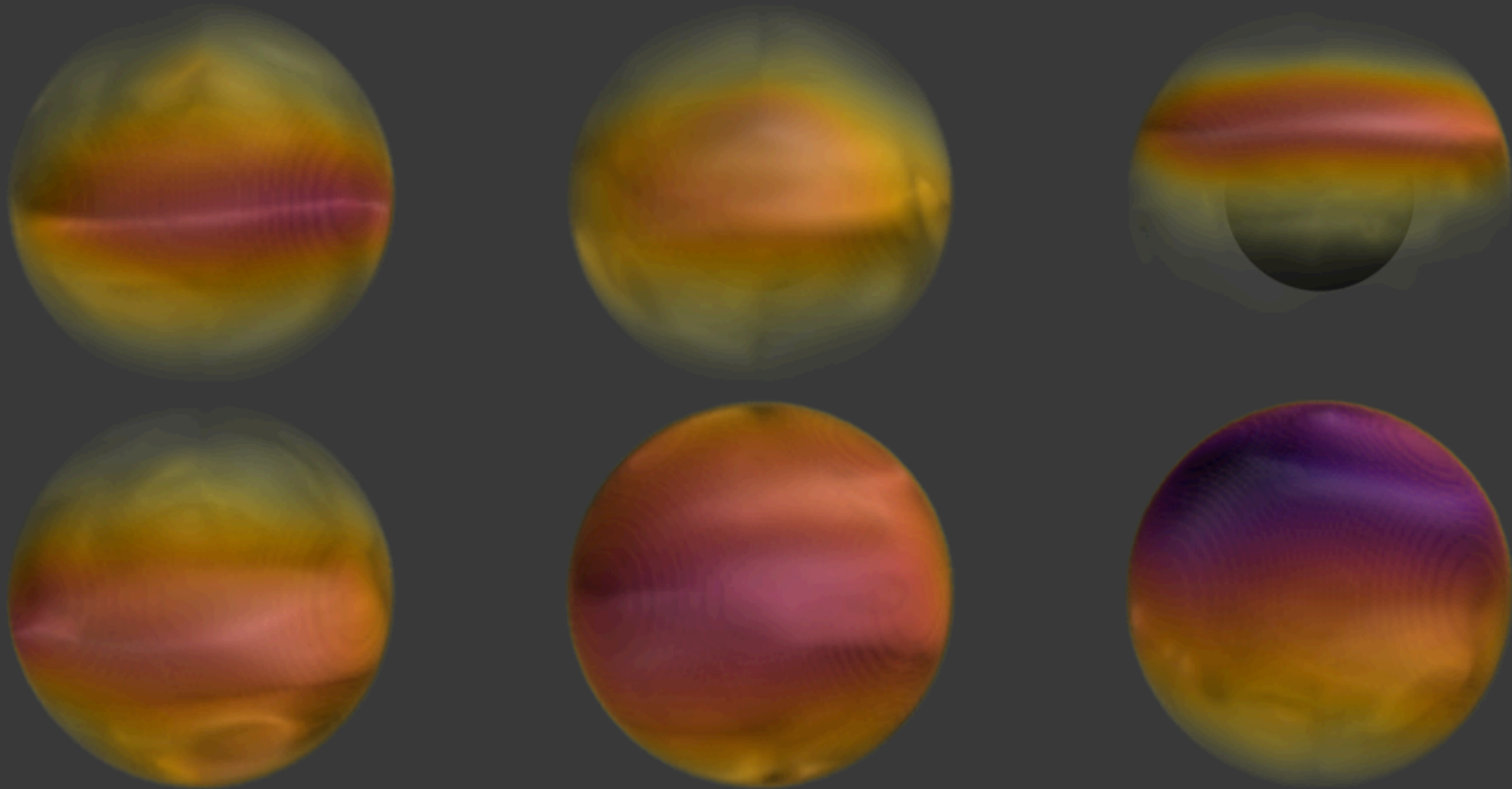
Mass-Spin Degeneracy



Abbott et al. (2016): PRX 6, 041015

O1 Spin Constraints

GW150914 LVT151012 GW151226

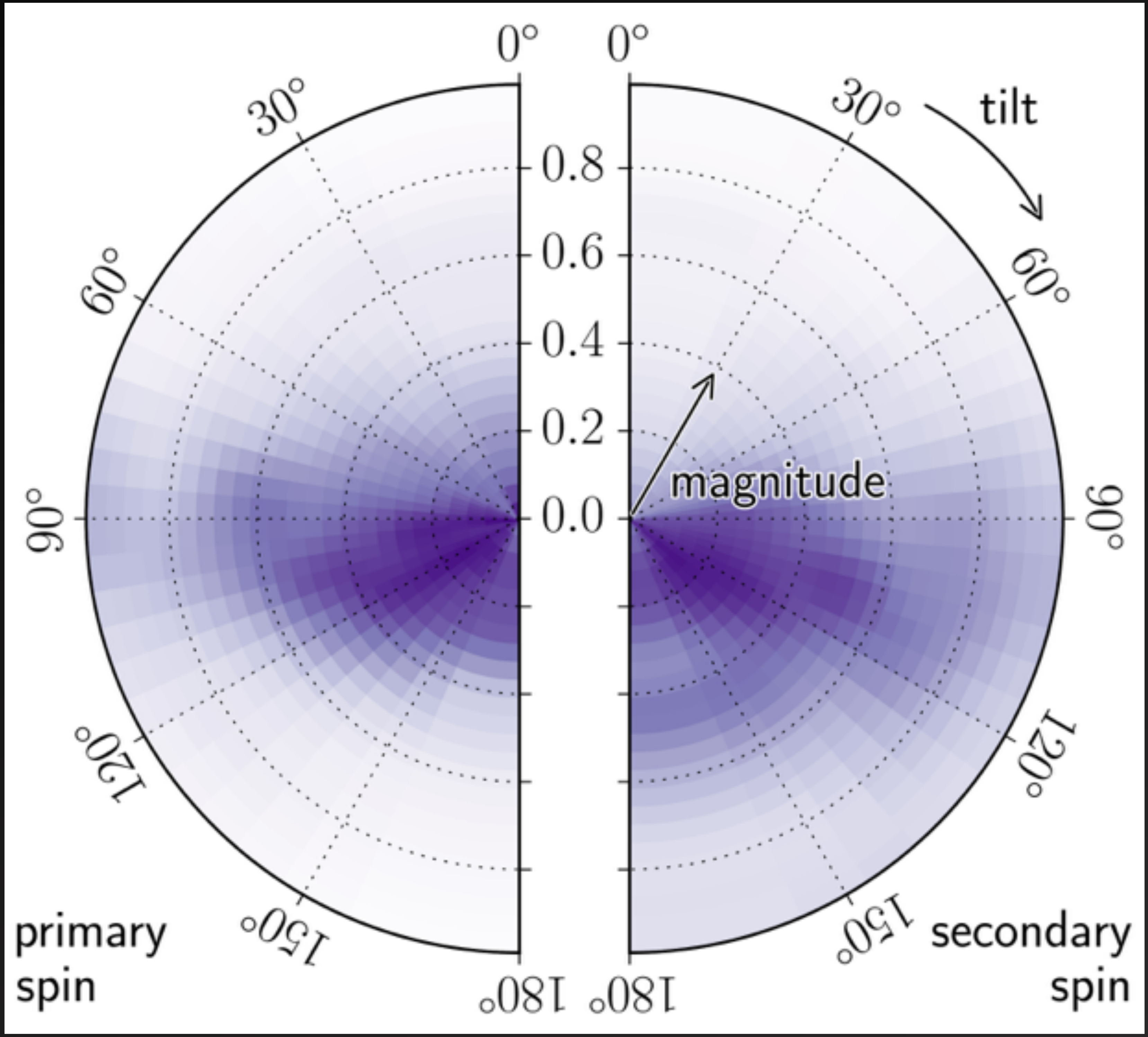


Black Hole Spins

Abbott et al. (2016): PRX 6, 041015

GW150914

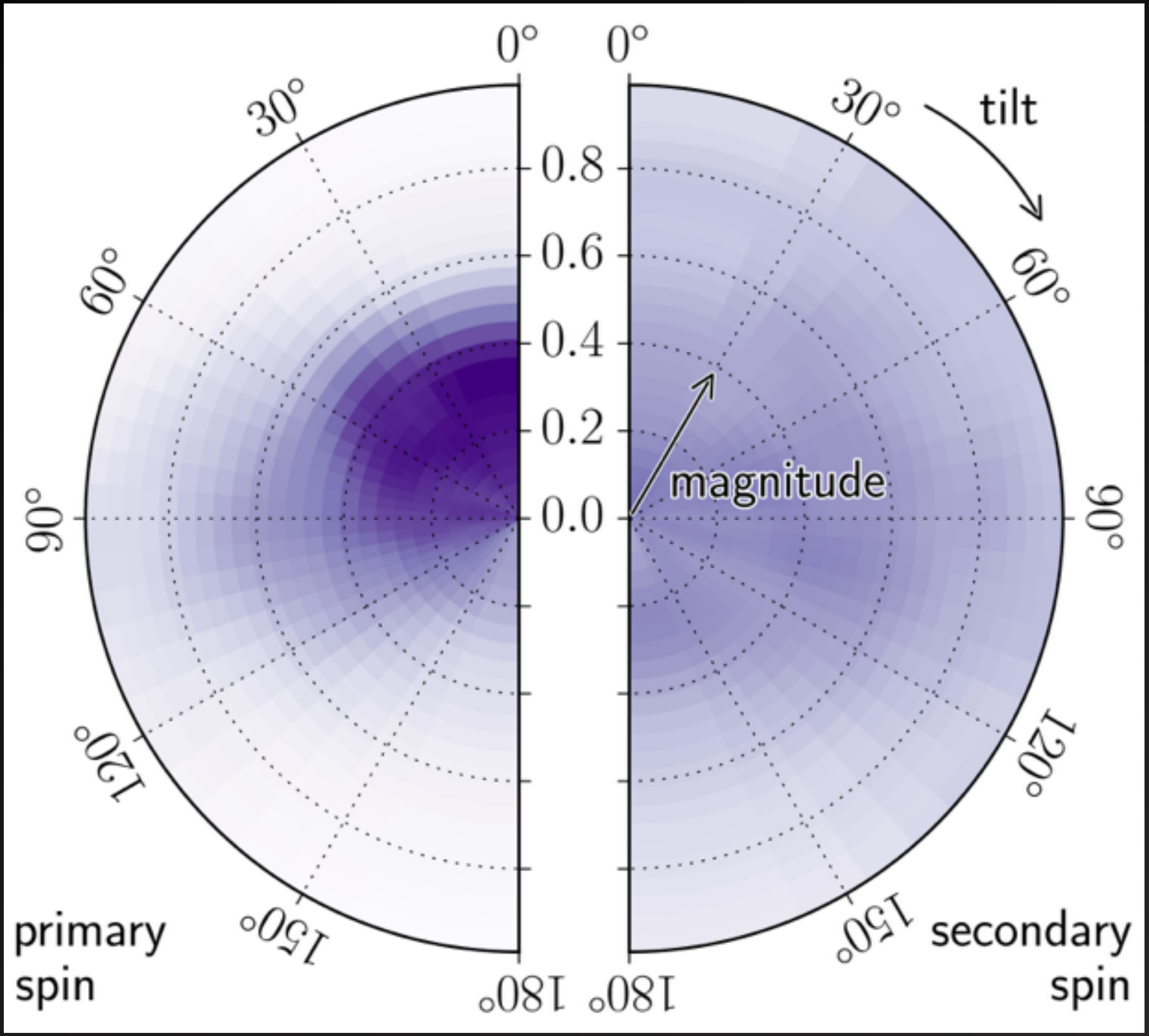
BH spin
not extremal



Black Hole Spins

Abbott et al. (2016):
PRX 6, 041015

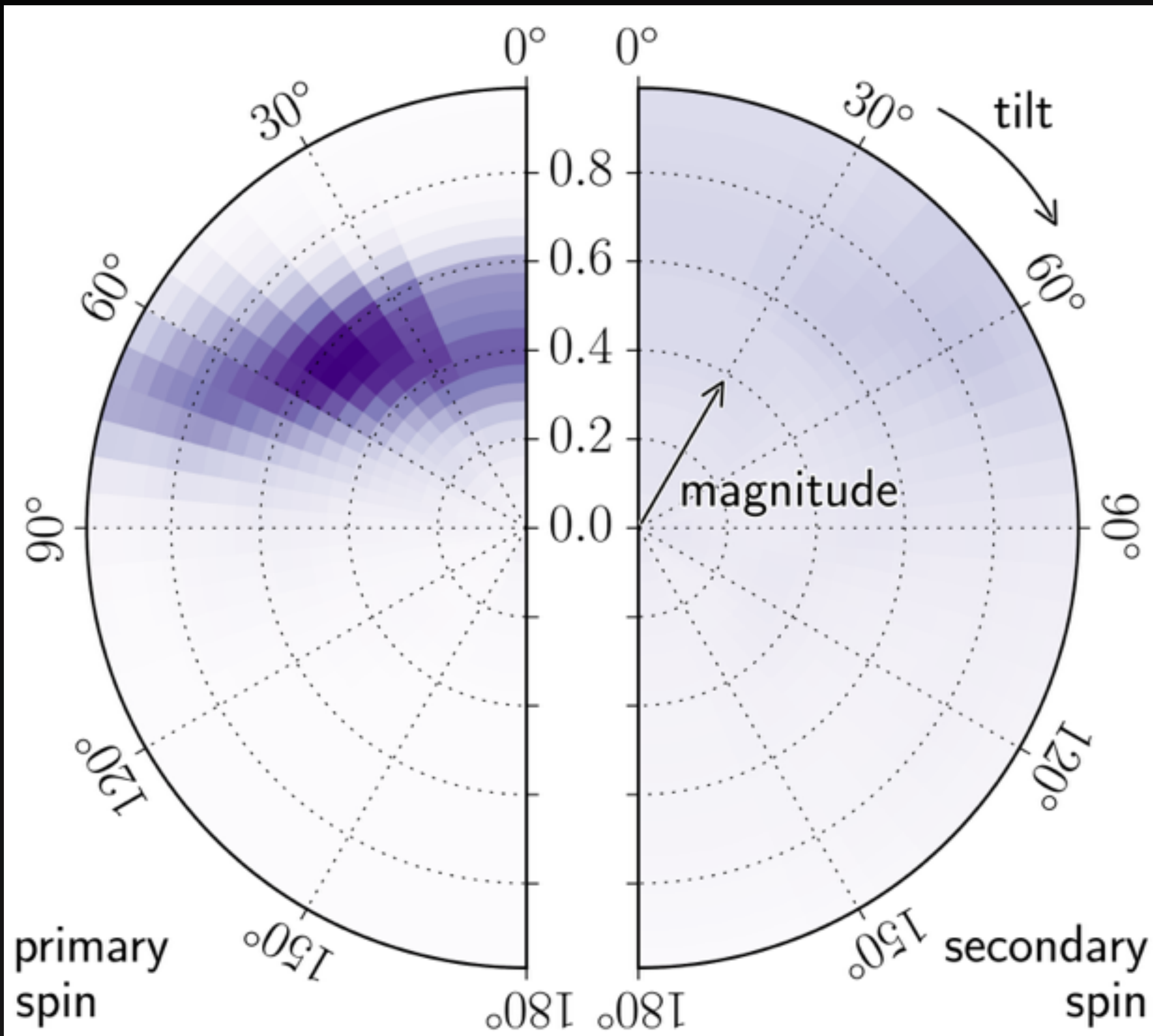
LVT151012



Black Hole Spins

Abbott et al. (2016): PRX 6, 041015

GW151226



At least one spinning BH

Next Step: Population Inference

Goal: Use multiple detections to infer population characteristics

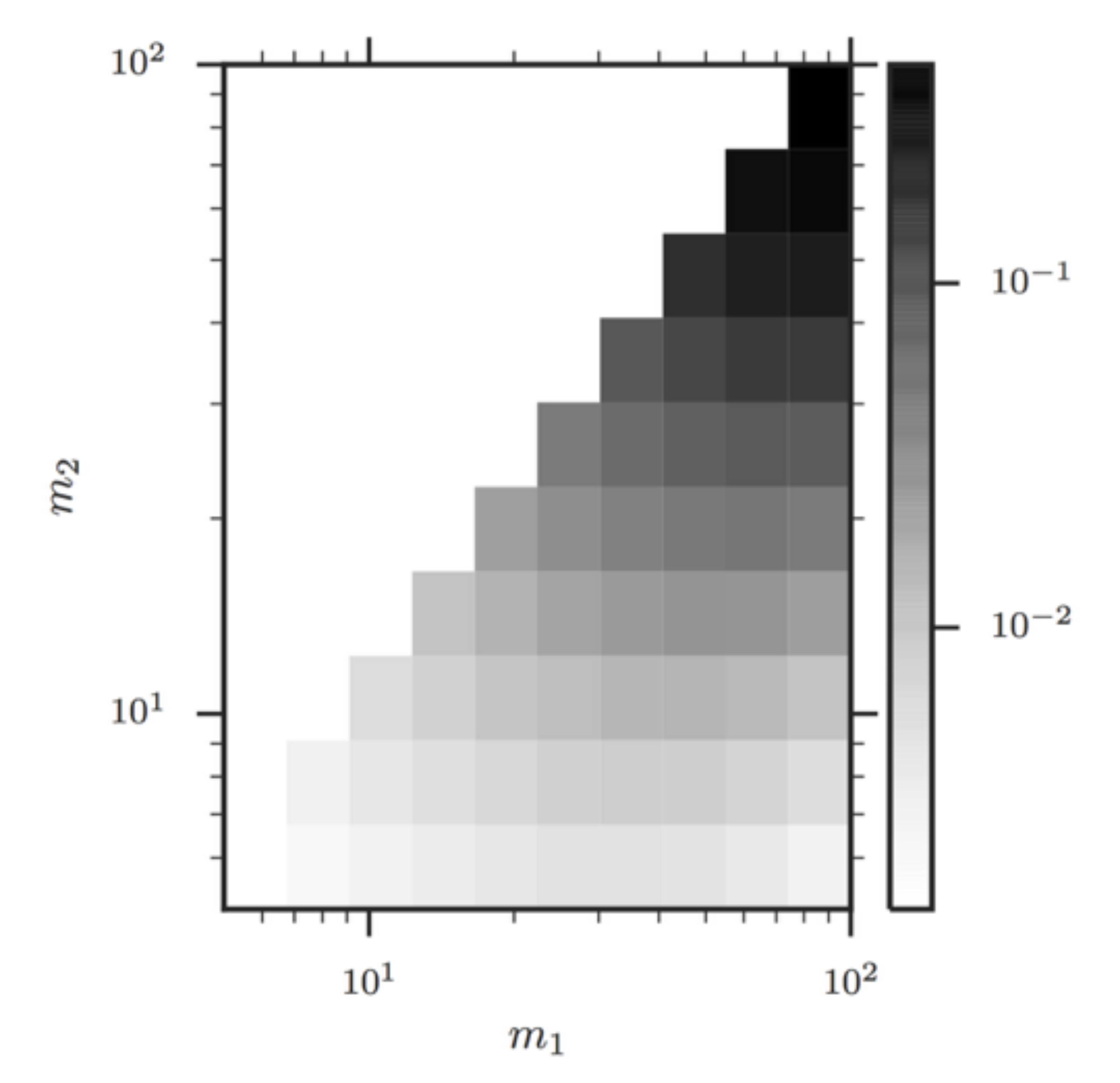
Challenges:

- We never precisely characterize sources
- Detections may sparsely cover parameters space

Population Inference

Parameterized Model:

$$\Gamma_{\boldsymbol{\alpha}}(\boldsymbol{\theta}) \begin{cases} \exp(\alpha_1) & \boldsymbol{\theta} \in \Delta_1 \\ \exp(\alpha_2) & \boldsymbol{\theta} \in \Delta_2 \\ \ldots & \\ \exp(\alpha_K) & \boldsymbol{\theta} \in \Delta_K \\ 0 & \text{otherwise} \end{cases}$$



Gaussian Process Prior

Gaussian process to regularize the histogram

$$
\begin{aligned}
p(\boldsymbol{\alpha}) &= p(\boldsymbol{\alpha}|\mu, \lambda) \\
&= \mathcal{N}[\boldsymbol{\alpha}; \boldsymbol{\mu}, K(\{\Delta_j\}, \boldsymbol{\lambda})]
\end{aligned}
$$

$\boldsymbol{\mu}, \boldsymbol{\lambda}:$ hyperparameters for the mean and length scales of the GP,

Hierarchical Bayesian Inference

Population posterior density:

$$p(\vec{\alpha}|\{d_i\}) \propto p(\vec{\alpha}) \int p(\{d_i\}|\{\theta_i\}) p(\{\theta_i\}|\vec{\alpha}) d\{\theta_i\}$$

Gaussian process prior

Single-event likelihood

Single-event (population-based) prior

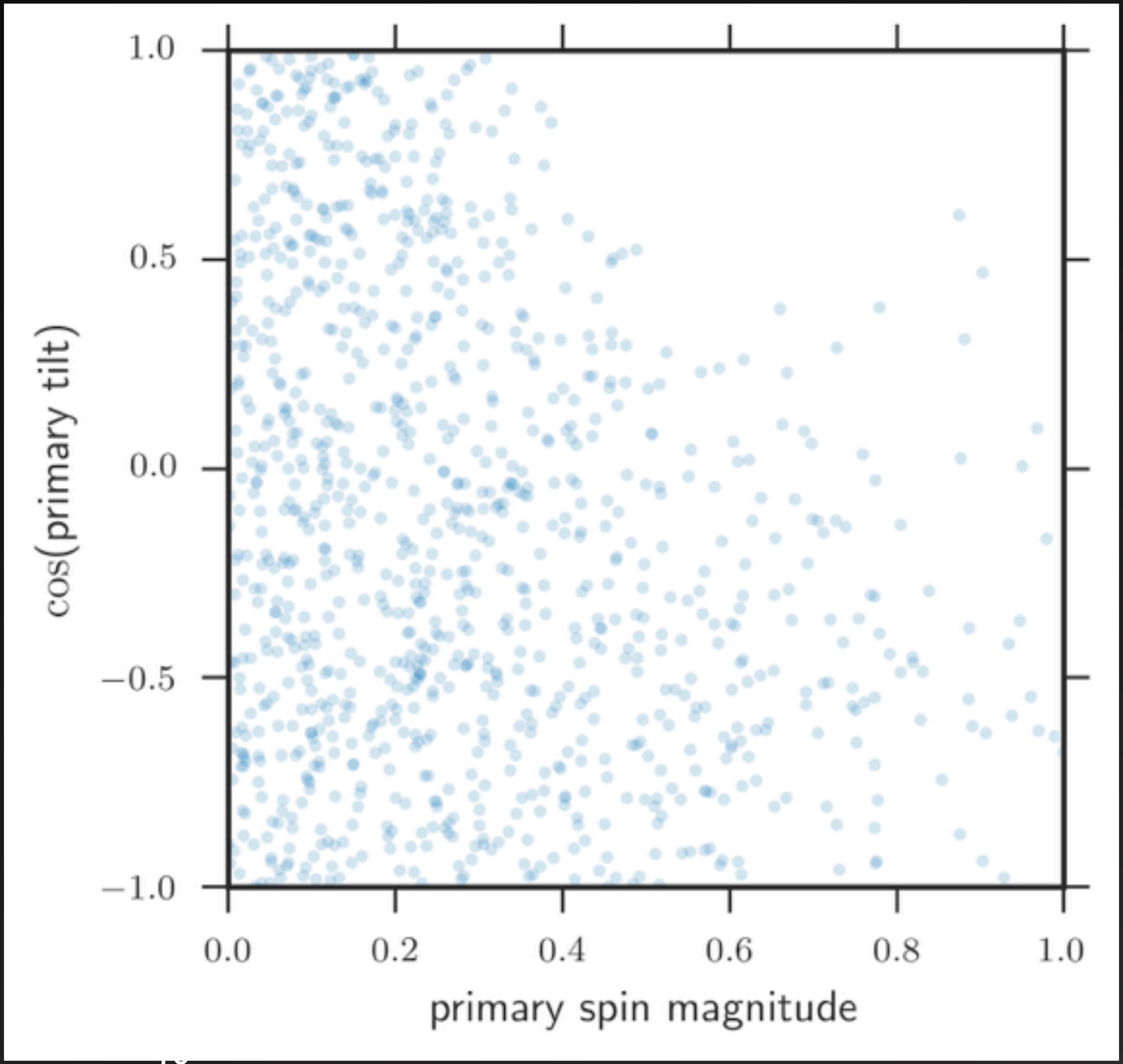
$$p(\{\boldsymbol{\theta_i}\}|\boldsymbol{\alpha}) = \exp\left(-\int \hat{\Gamma}_{\boldsymbol{\alpha}}(\boldsymbol{\theta}) d\boldsymbol{\theta}\right) \prod_i \hat{\Gamma}_{\boldsymbol{\alpha}}(\boldsymbol{\theta_i})$$

Hogg et al. (2010)
Mandel, Farr, Colonna et al. (2016)

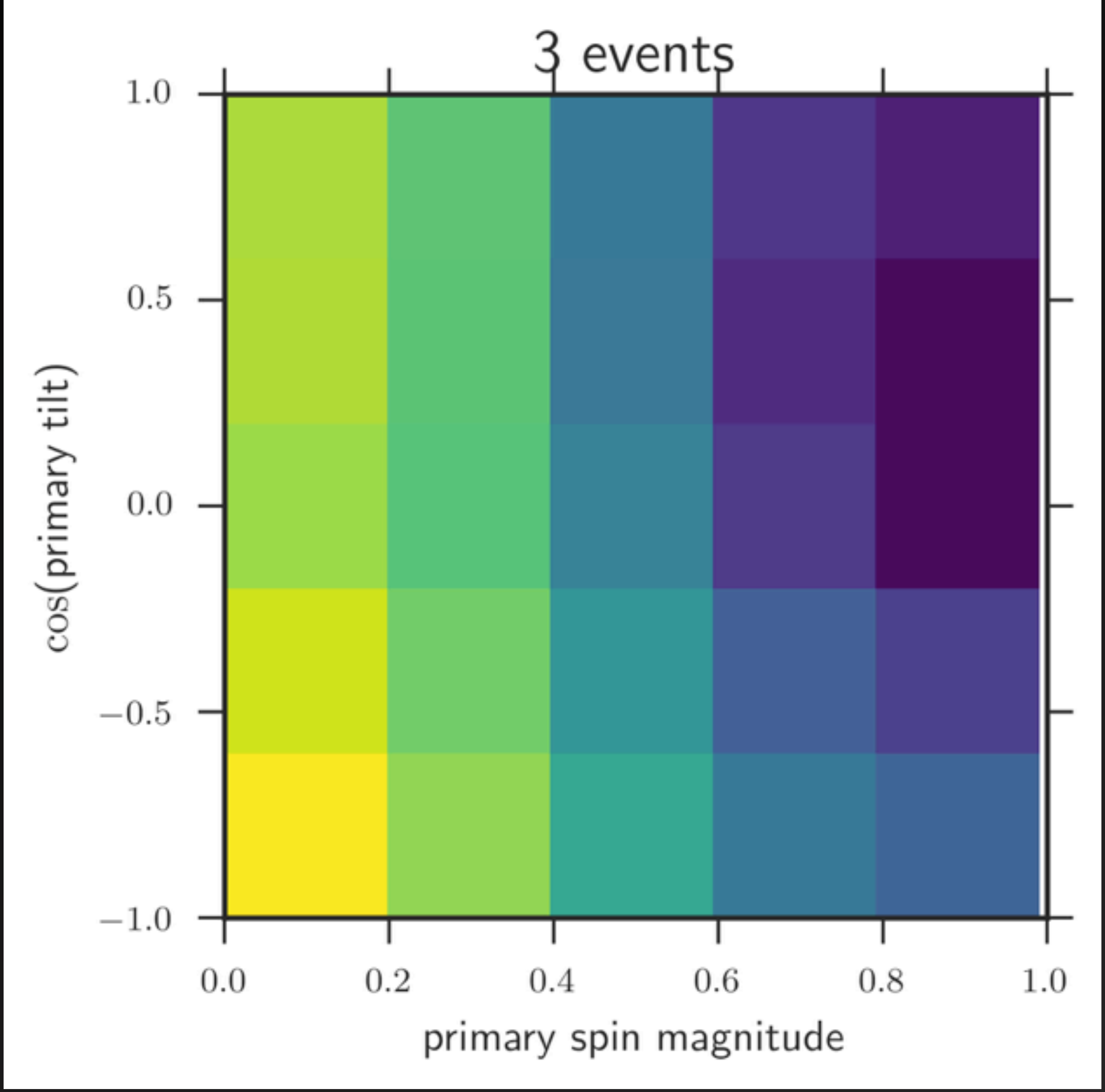
Spin Distribution

Simulated distribution:
primary spin < 0.5
primary tilt < 45°

Individual Event Posteriors:

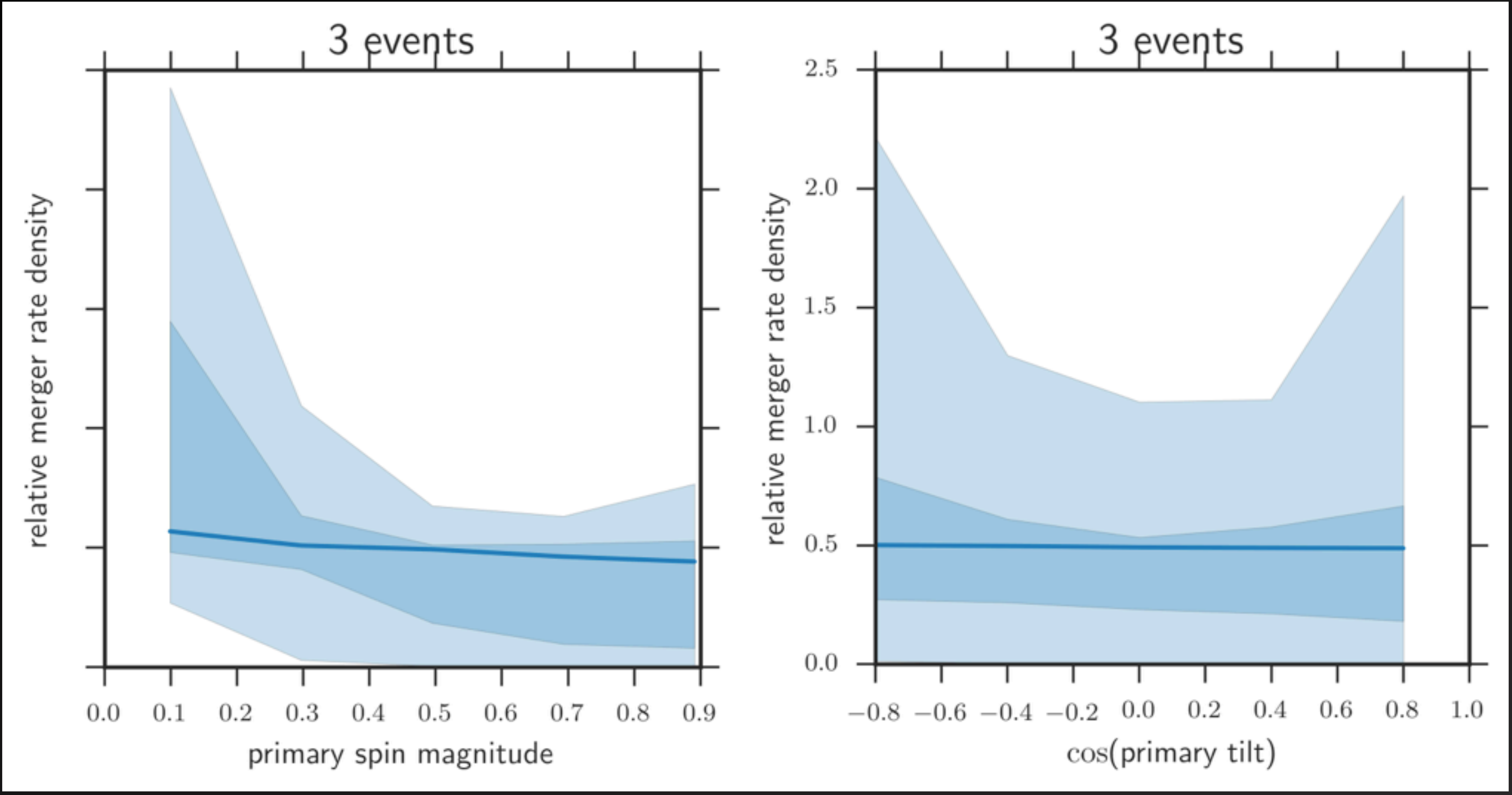


Spin Distribution



Farr et al. (in prep)

Spin Distribution



 Farr et al. (in prep)

Spin Distribution

Support for non-uniform distribution of spin magnitudes after ~10 events.

Rule out isotropic spin distribution after ~20 events.

Conclusions

Interesting population characteristics may be found after only ~10 events.

After 10's of events, strong features in the population begin to be constrained.

Possibly by the end of O2, likely by the end of O3, things should get interesting.

Questions?