Search for Proca-Star mergers through boson-mass coincidences and BBH mixture models

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Exotic Compact Objects (ECOs)

Eddington believed that nature would find a way to prevent the full collapse of a star into a black hole

BHs became the only acceptable solution to the collapse problem. Any observation otherwise would indicate beyond the standard physics

Hypothetical compact star composed of exotic matter (not made of electrons, protons, neutrons, or muons), and balanced against gravitational collapse by degeneracy pressure or other quantum properties

- nature of dark matter
- EoS of dense matter
- presence of horizons and singularities
- modified theories of gravity

Proca Stars

Boson stars: Bose Einstein condensates of ultralight bosons clumped together, one of the simples ECOs

Proca Stars: vector boson stars. Spinning Proca stars are dynamically robust – stable against non-axisymmetric perturbations

why do we care about them?

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why do we care about them?

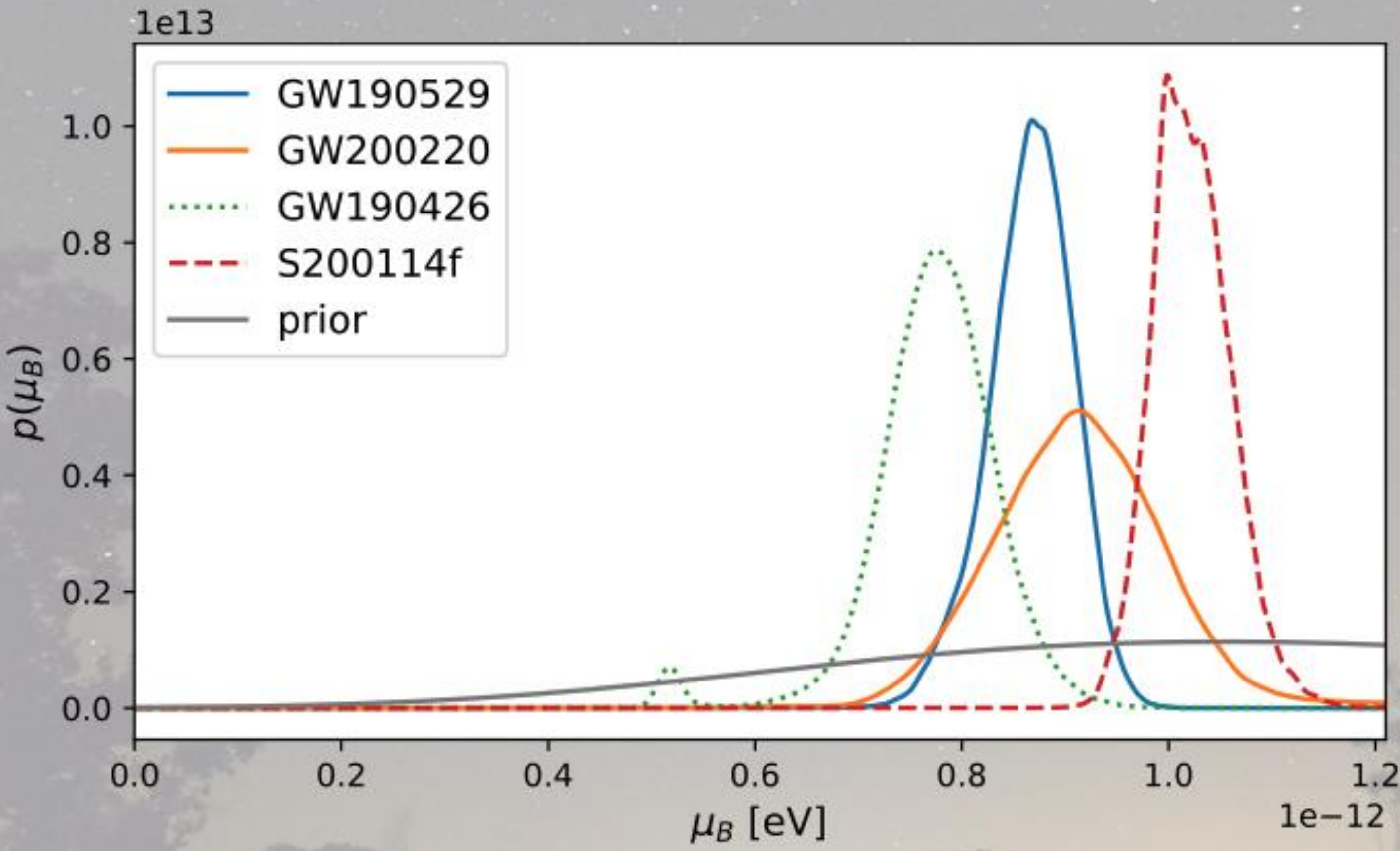
could mimic BH signals but evade stellar-collapse mass constraints

GW190521 consistent with a Proca-star merger (PSM)

⊕ GW190426 GW200220 same boson mass of $\mu_B \sim 8.7 \times 10^{13}$ eV

⊕ S200114 inconsistent mass! Proca preference

Proca Stars candidates



Proca Stars Mergers sub-populations

- we want to distinguish PSMs from BBHs
- problem: we may not have conclusive evidence from any individual event

Our approach: use consistent estimations of parameters (e.g. boson mass) across PSM candidates to identify PSMs sub-populations

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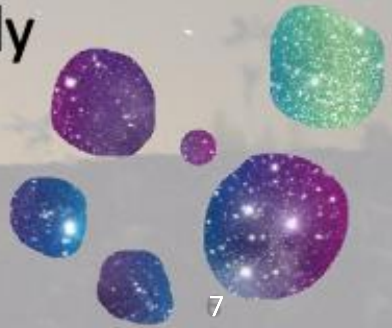
Mixture model:

mixed observation set of BBHs and *n* families of PSMs characterised by μ_B^i and a parameter ζ^i aka the fraction of observations of each family

common masses $\Rightarrow$ less number of PSM params!



Methodology: mixture model

➡ likelihood for the fraction of PSMs ζ

$$p(\{d_i\}|\zeta) = \prod_{i=1}^{i=N} \left[p(d_i|\mathrm{PSM})\zeta + p(d_i|\mathrm{BBH})(1-\zeta) \right] \propto \prod_{i=1}^{i=N} \left[\mathcal{B}^{\mathrm{PSM}}_{\mathrm{BBH}}\zeta + (1-\zeta) \right]$$

probability of data of the ith event given the PSM and BBH models against noise (Bayesian evidence)

Methodology: mixture model

- likelihood for the fraction of PSMs ζ

$$p(\{d_i\}|\zeta) = \prod_{i=1}^{i=N} \left[p(d_i|\mathrm{PSM})\zeta + p(d_i|\mathrm{BBH})(1-\zeta) \right] \propto \prod_{i=1}^{i=N} \left[\mathcal{B}_{\mathrm{BBH}}^{\mathrm{PSM}}\zeta + (1-\zeta) \right]$$

- likelihood for the fraction of PSMs ζ and the common boson mass μ_B

$$p(\{d_i\}|\zeta,\mu) = \prod_{i=1}^{i=N} \left[p(d_i|\mathrm{PSM}(\mu))\zeta + p(d_i|\mathrm{BBH})(1-\zeta) \right] \propto \prod_{i=1}^{i=N} \left[\mathcal{B}_{\mathrm{BBH}}^{\mathrm{PSM}(\mu)}\zeta + (1-\zeta) \right]$$

In the first one we were only considering evidence for each event.
Now we question whether there is only one boson sourcing the Proca-stars, i.e. only one PSM family

Methodology: mixture model

- likelihood for the fraction of PSMs ζ

$$p(\{d_i\}|\zeta) = \prod_{i=1}^{i=N} \left[p(d_i|\mathrm{PSM})\zeta + p(d_i|\mathrm{BBH})(1-\zeta) \right] \propto \prod_{i=1}^{i=N} \left[\mathcal{B}_{\mathrm{BBH}}^{\mathrm{PSM}} \zeta + (1-\zeta) \right]$$

- likelihood for the fraction of PSMs ζ and the common boson mass μ_B

$$p(\{d_i\}|\zeta,\mu) = \prod_{i=1}^{i=N} \left[p(d_i|\mathrm{PSM}(\mu))\zeta + p(d_i|\mathrm{BBH})(1-\zeta) \right] \propto \prod_{i=1}^{i=N} \left[\mathcal{B}_{\mathrm{BBH}}^{\mathrm{PSM}(\mu)} \zeta + (1-\zeta) \right]$$

Bayesian evidence for the PSM model with a boson mass prior consisting on a delta placed at $\mu_B = \mu$

$$p(d_i|\mathrm{PSM}(\mu)) = p(d_i|\mathrm{PSM}) \frac{p(\mu|d)}{p(\mu)}$$

Methodology: mixture model

- n Proca-star families with respective boson masses μ_B^i and fractions ζ^i

$$p(\{d_i\}|\{(\mu_B^j,\zeta_j)\}) = \prod_{i=1}^{i=N}\left[\sum_{j=1}^{N_{\text{bosons}}} p(d_i|\text{PSM}(\mu_B^j))\zeta_j + p(d_i|\text{BBH})\left(1-\sum_{j=1}^{N_{\text{bosons}}}\zeta_j\right)\right]$$

$$\propto \prod_{i=1}^{i=N}\left[\sum_{j=1}^{N_{\text{bosons}}} \mathcal{B}^{\text{PSM}}_{\text{BBH}}(\mu_B^j)\zeta_j + \left(1-\sum_{j=1}^{N_{\text{bosons}}}\zeta_j\right)\right]$$

Data used

4 GW events from [1]: GW190521, GW190426, GW200220 and S200114 with with PSM/BBH evidence

2 distance priors: a regular uniform prior in co-moving volume with H_0=67.74 km/s Mpc and a uniform prior in luminosity distance

uniform priors on the boson masses sampling over a discrete grid with

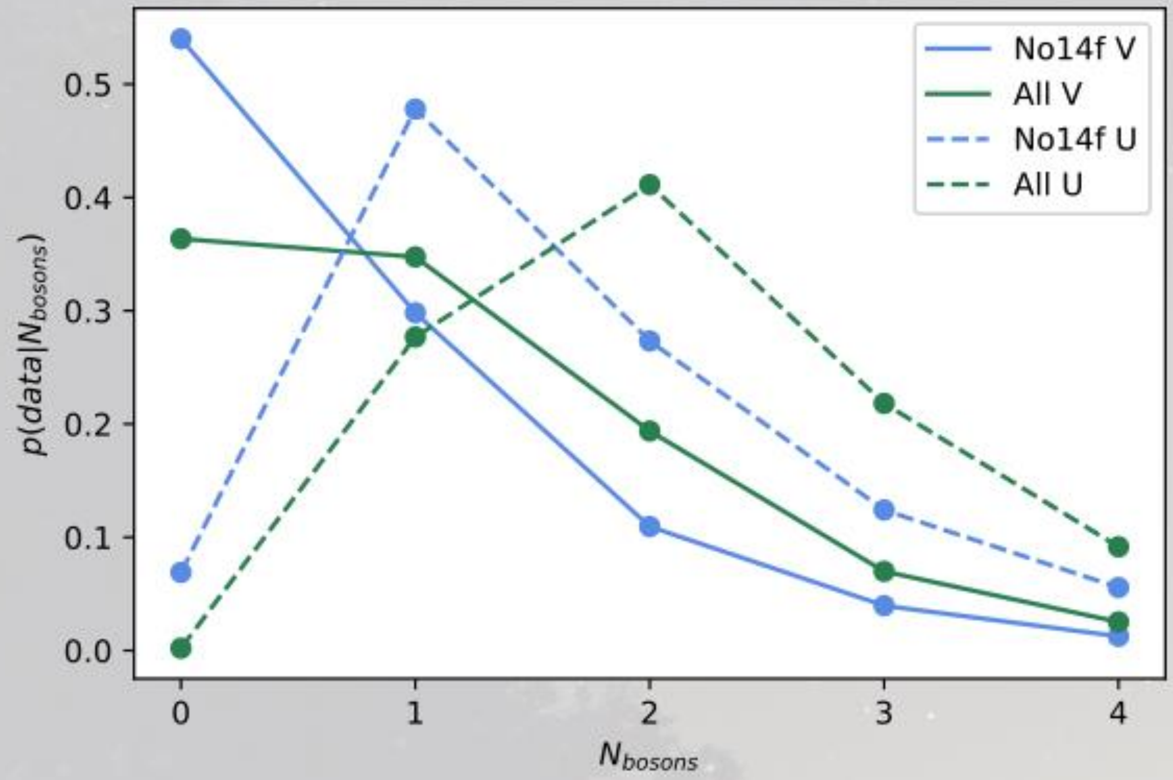
$$\delta\mu_B = 1 \times 10^{-15}\mathrm{eV}$$

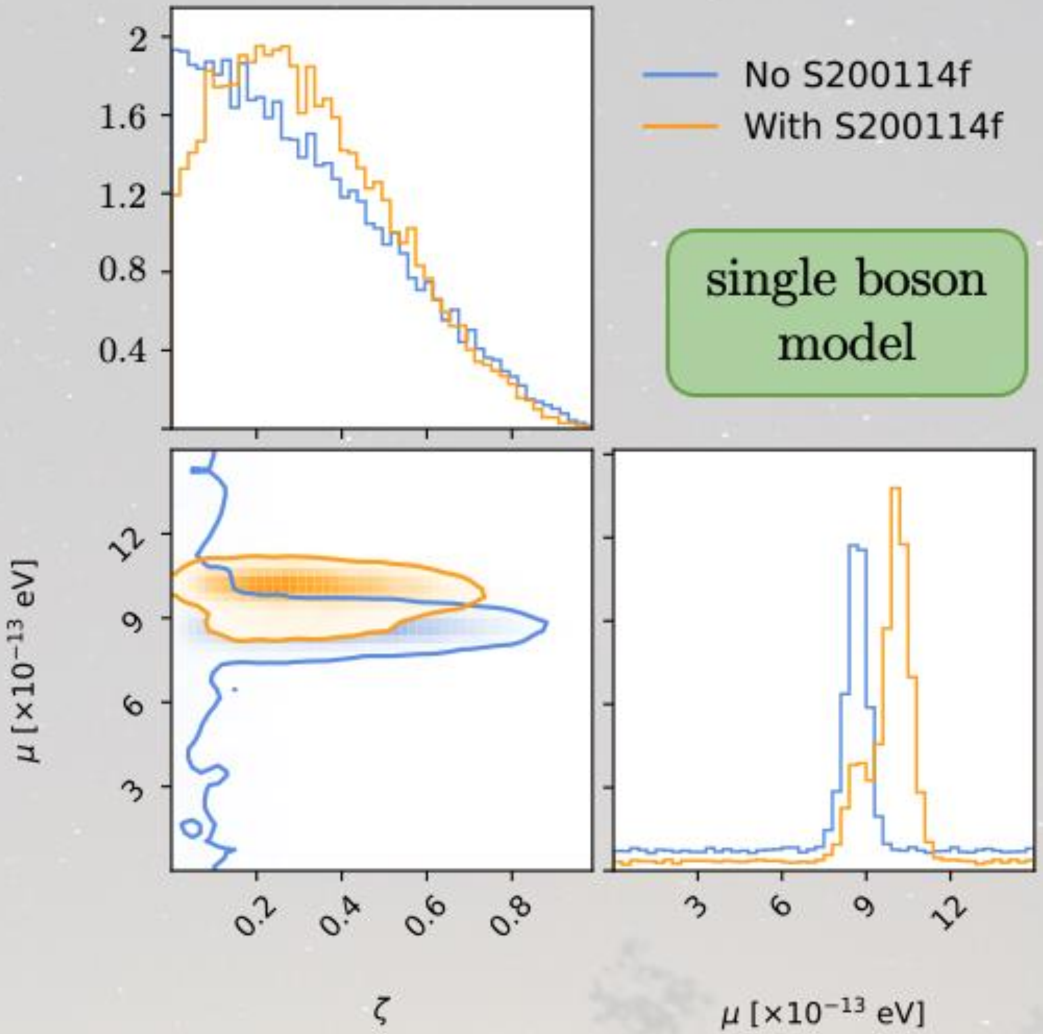
and uniform priors on the fractions of PSMs, all of them imposing

$$\mu_{i+1} \leq \mu_i \qquad \sum_i \zeta_i \leq 1$$

[1] J. Calderón Bustillo, N. Sanchis-Gual, S. H. Leong, K.Chandra, A. Torres-Forné, J. A. Font, C. Herdeiro, E. Radu, I. C. Wong, and T. G. Li, Physical Review D 108 (2023), 10.1103/physrevd.108.123020.

Results



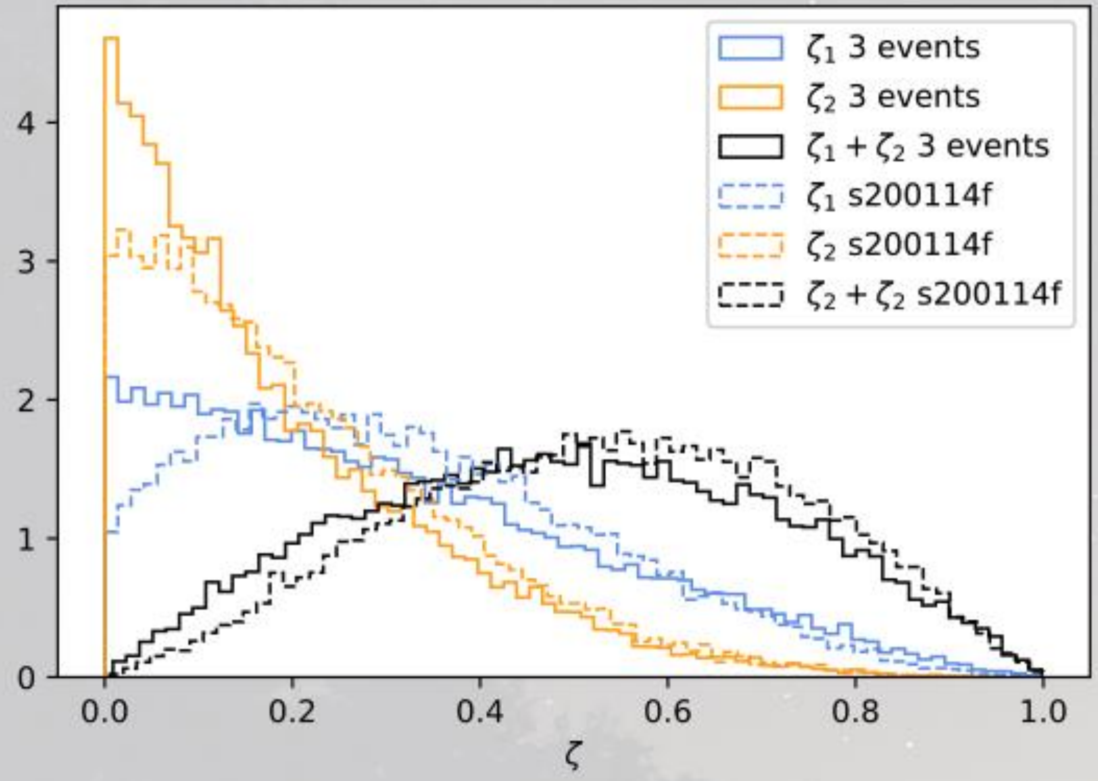


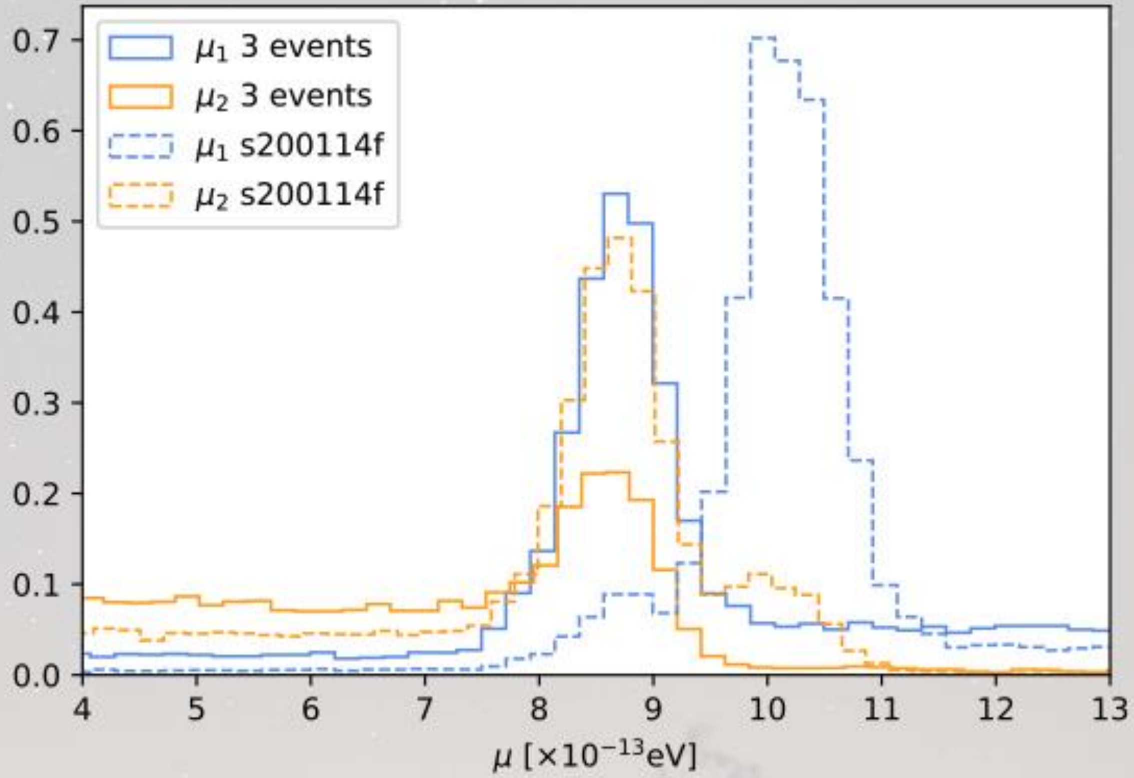
- current data weakly favours N_bosons = 0 (i.e. BBH)
- with S200114f N_bosons = 0 and 1 equally plausible (bc of inconsistent boson-mass estimates)

- without S200114f μ_B peaks near GW190521, but ζ is consistent with zero (no PSMs)
- with S200114f μ_B shifts to S200114f value

Results

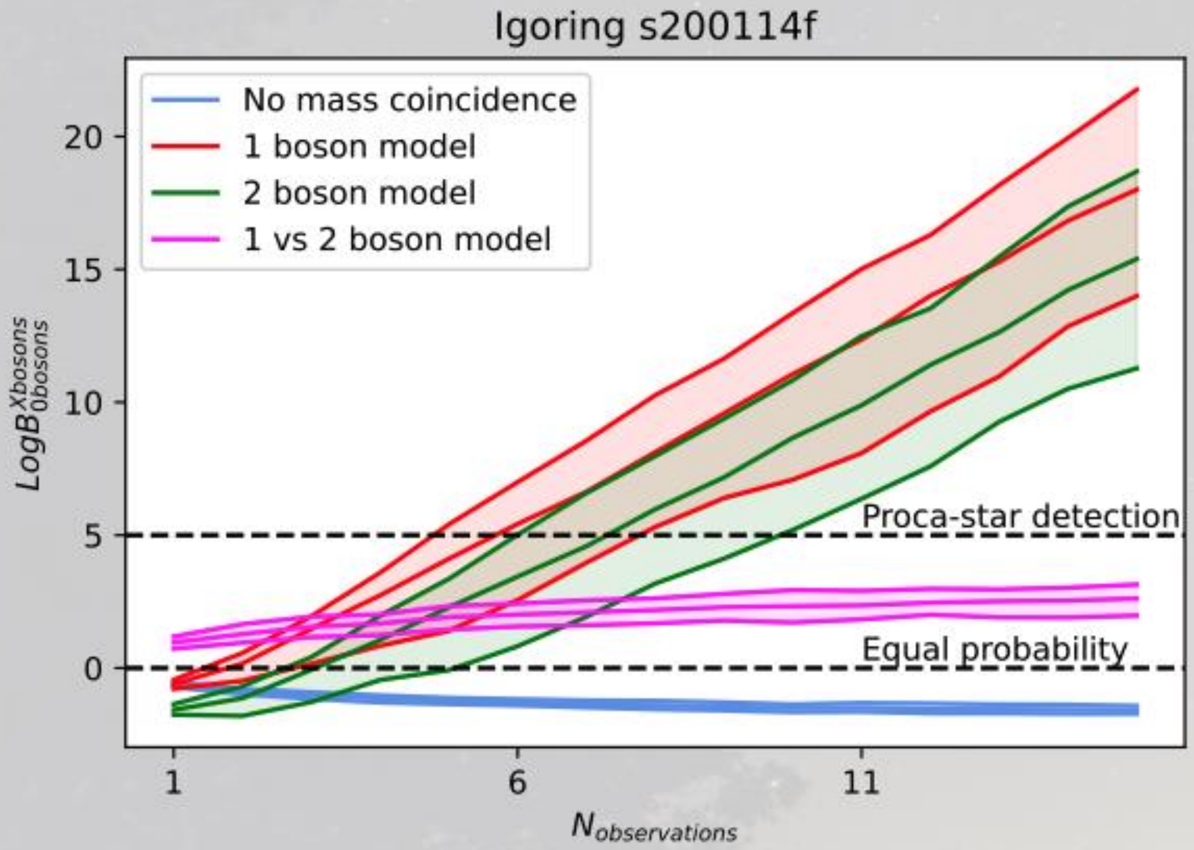
two boson model

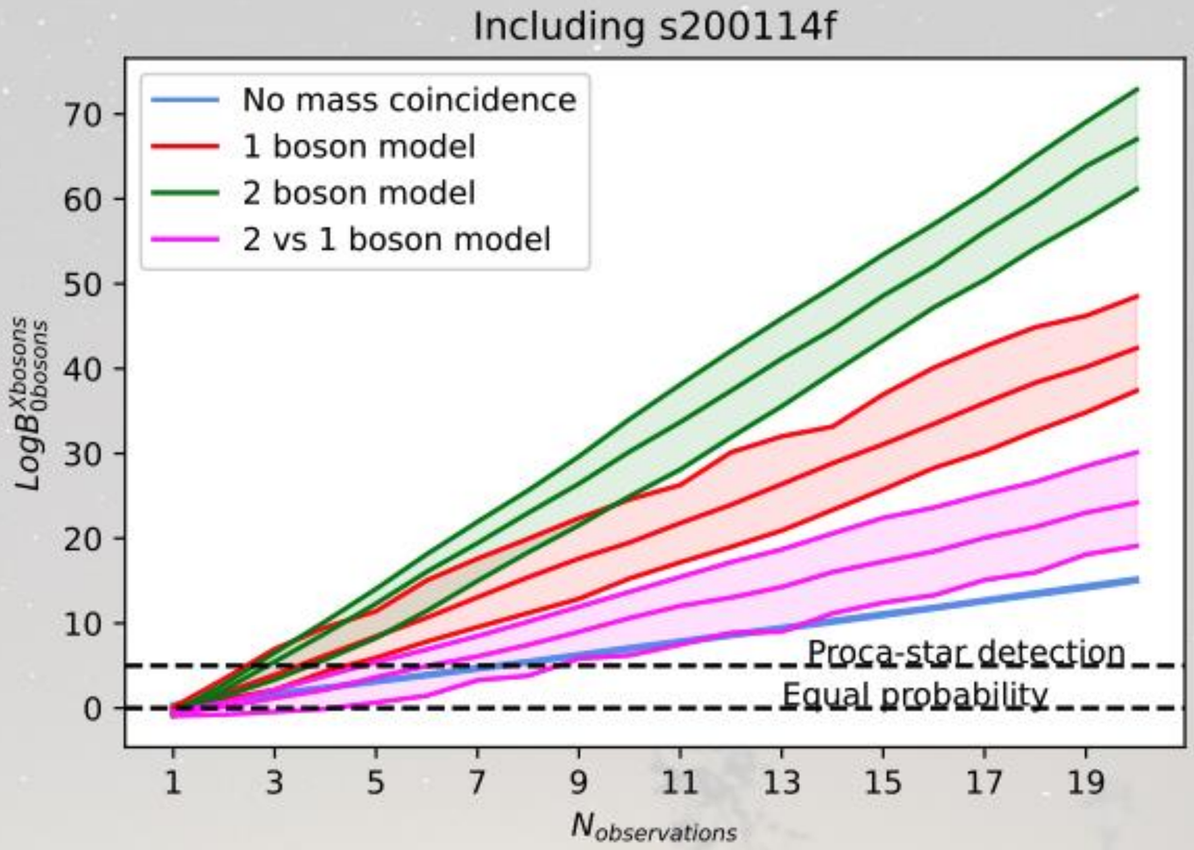




- masses split into two distinct peaks (GW190521 vs. S200114f values)
- Evidence for N_bosons = 2 case is slightly smaller than for N_bosons = 1 because of the Occam Penalty (two extra degrees of freedom)

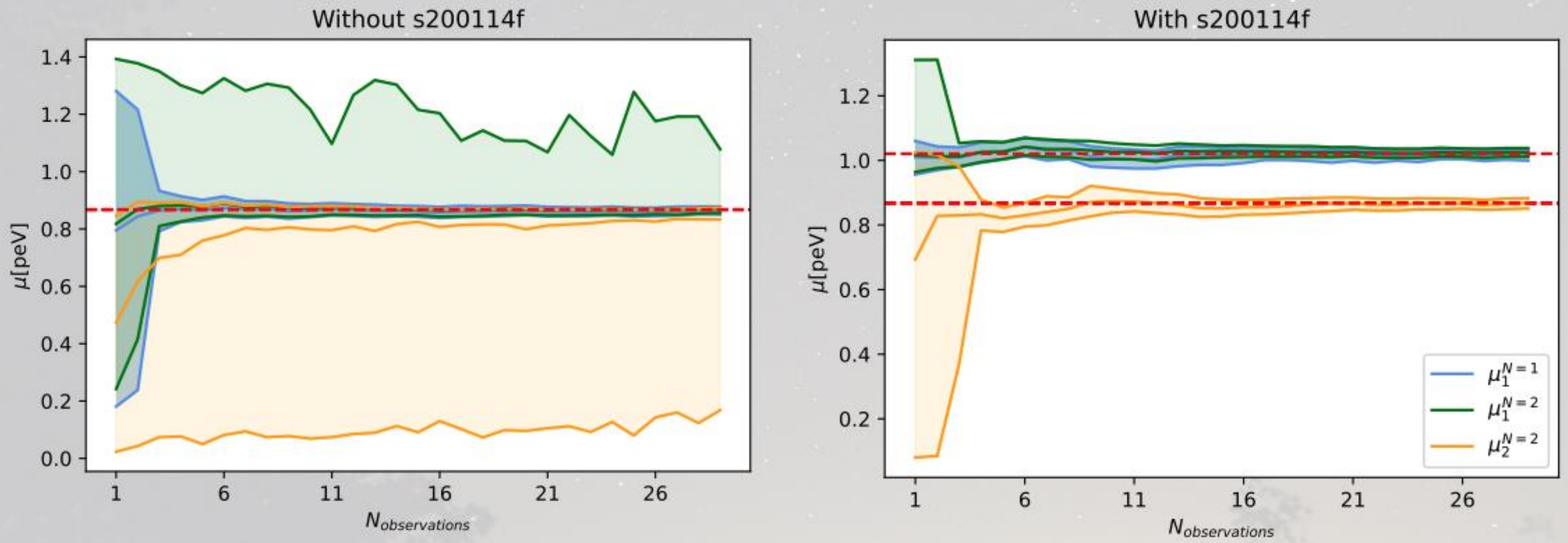
Mock data sets: how many detections we need





- evidence for N_bosons >= 1 grows with repeated observations of similar events
- without S200114f after ~8 obs, N_bosons = 1 is favoured if mass consistencies are enforced
- with S200114f N_bosons = 2 becomes conclusive after ~9 obs

Mock data sets: how many detections we need



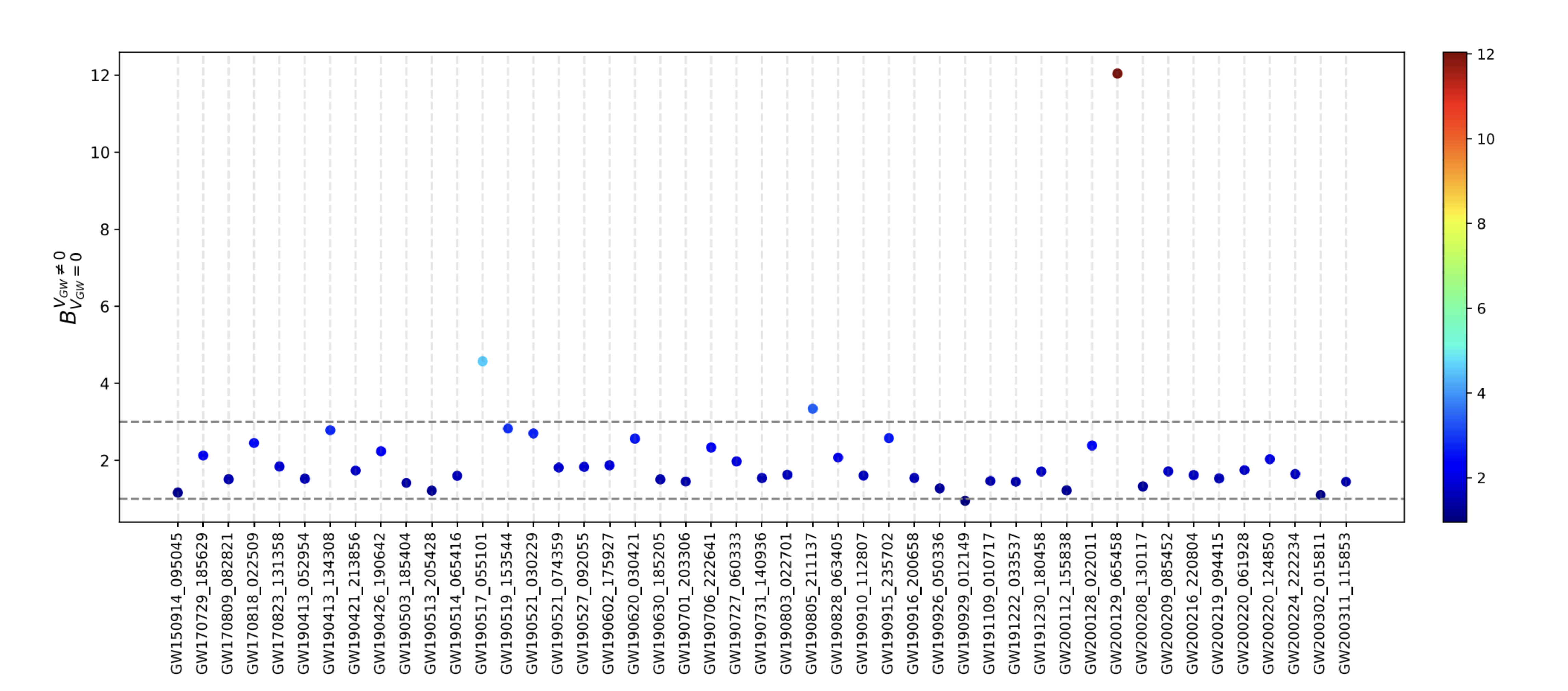
- without S200114f: progressive preference of N_bosons = 1 comes with tighter estimates of the boson mass
- with S200114f: clear separation into two masses, and the N_bosons = 1 model discards GW190521 and its copies as a PSMs

Implications

- Bayesian mixture models can uncover PSM sub-populations via boson-mass consistency
- Current data inconclusive but future observations (5–9 events) may reveal PSMs
- Framework generalizable to other ECOs
- Limitations: current PSM simulations are head-on mergers (weak and short signals; astrophysically unlikely)
- Future detectors could confirm PSMs by using mass consistency

Thanks!

Extra slides



Calderón Bustillo, Juan and del Rio, Adrian and Sanchis-Gual, Nicolas and Chandra, Koustav and Leong, Samson H. W., Physical Review D 134 (2025), 10.1103/PhysRevLett.134.031402.