Neutron star binaries:
Information obtained with only GW

Richard O'Shaughnessy

TCAN workshop, RIT 2020-07-06

See:
- Wysocki et al arxiv:2001.01747
- Nepal et al CQG 2020

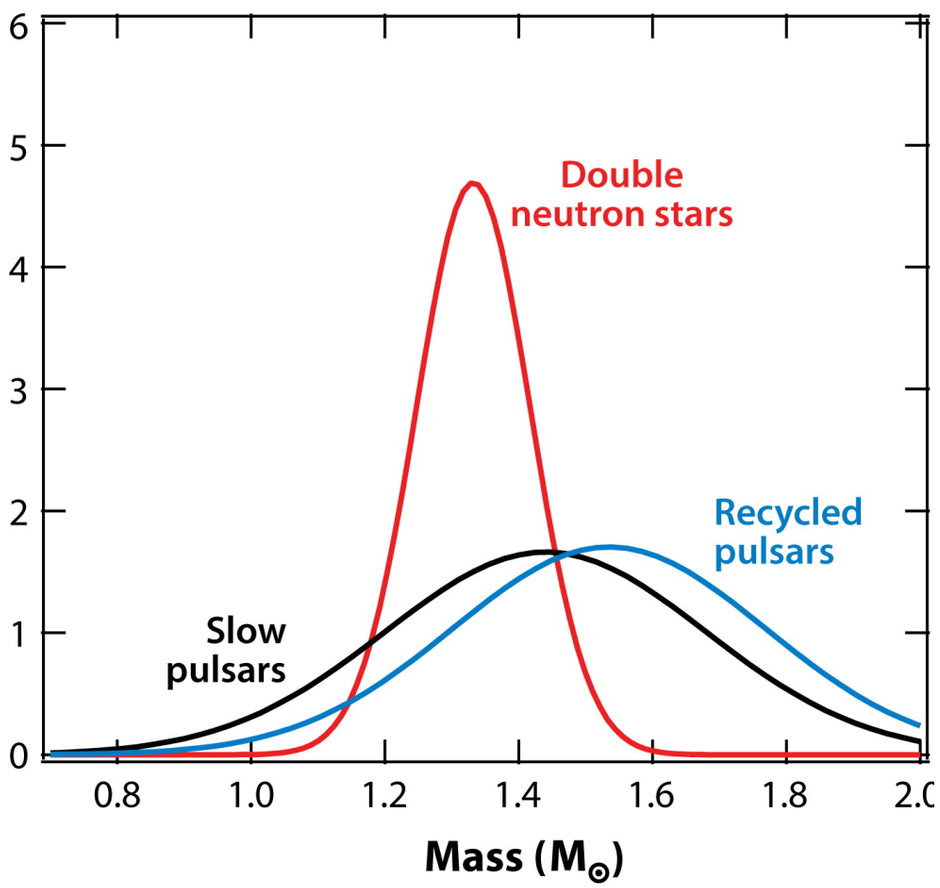
Outline

- Binary neutron stars
  - Combining many events
  - EOS constraints

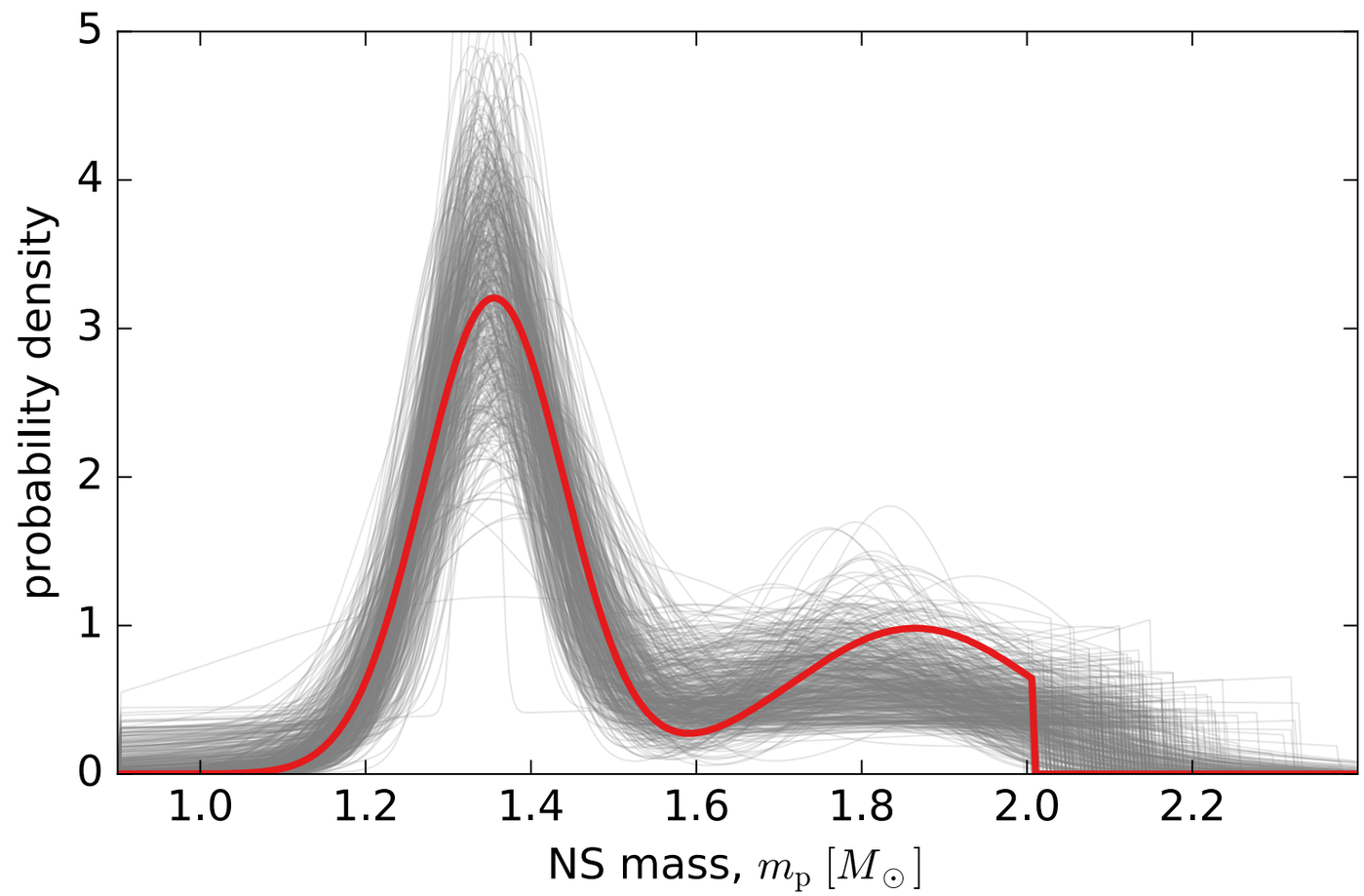
- Asymmetric binaries (“BH-NS”)
  - Single exceptional events by example: Learning from 0814
  - How well can we constrain parameters of a precessing binary?

Context: Probing NS populations

- Many multi messenger probes of NS / BNS properties, like masses, spins, …
  - Pulsar observations most numerous -> mass distribution



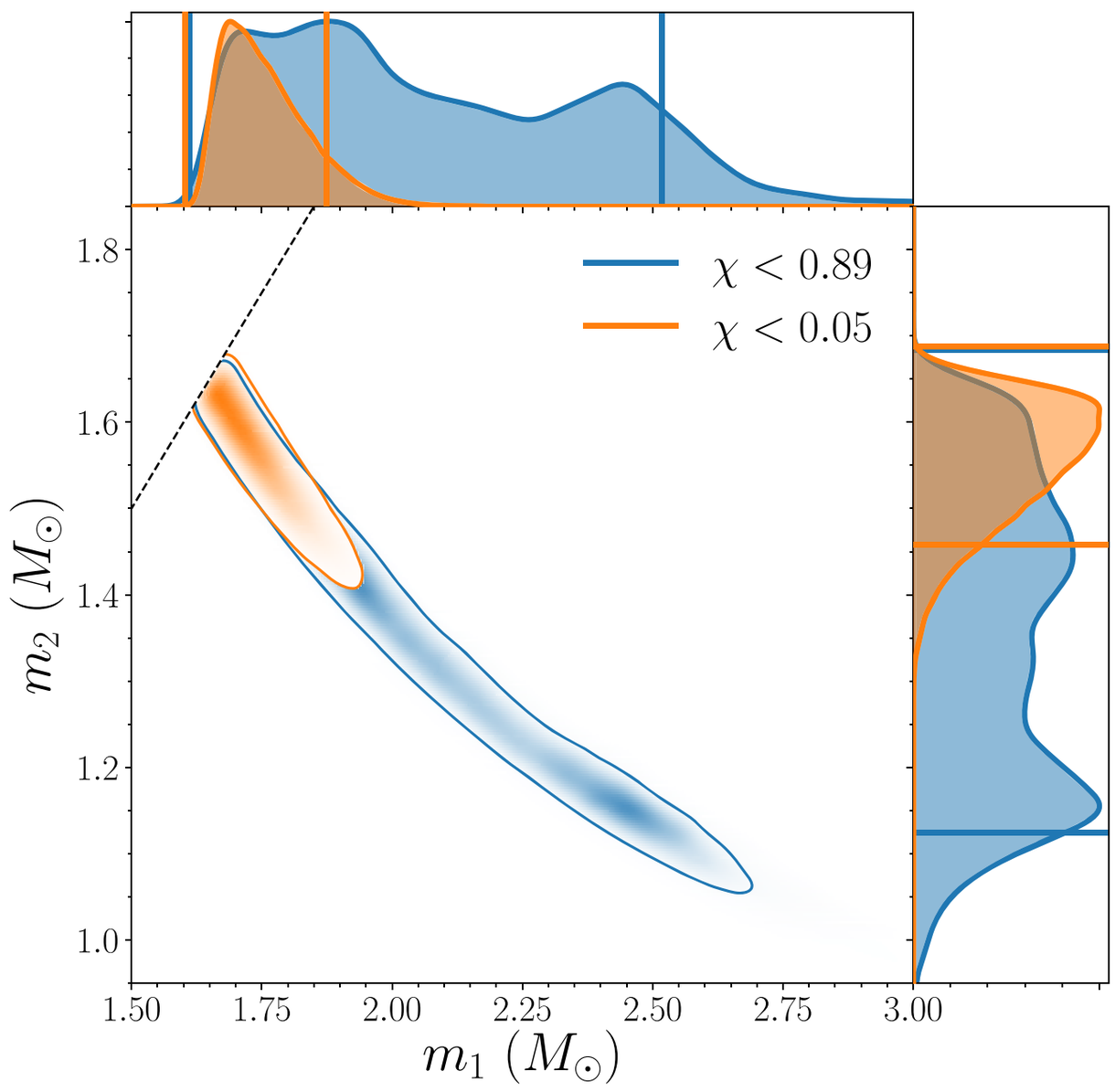
Ozel and Freire 1603.02698



Alsing et al 2018

How our measurements correlate mass/spin/tides

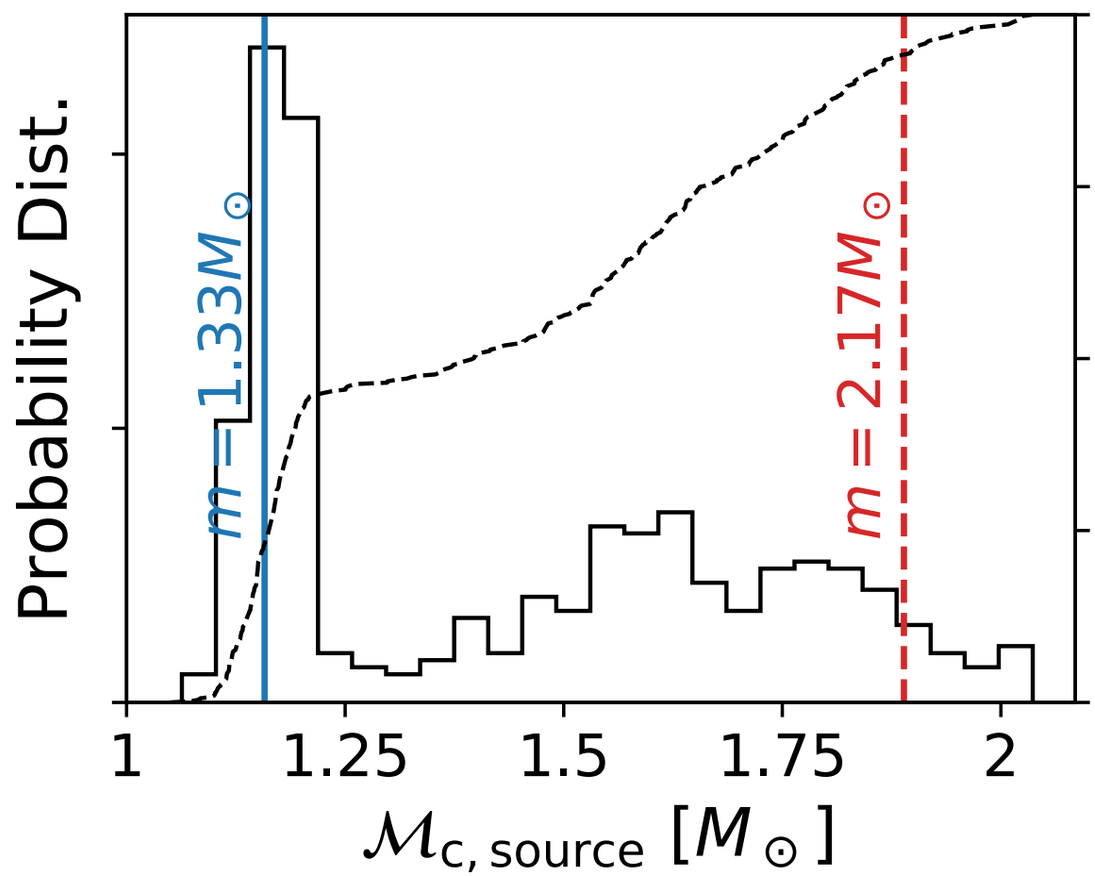
- Prior knowledge about NS spins strongly impacts interpretation of NS masses (and thereby tidal constraints)



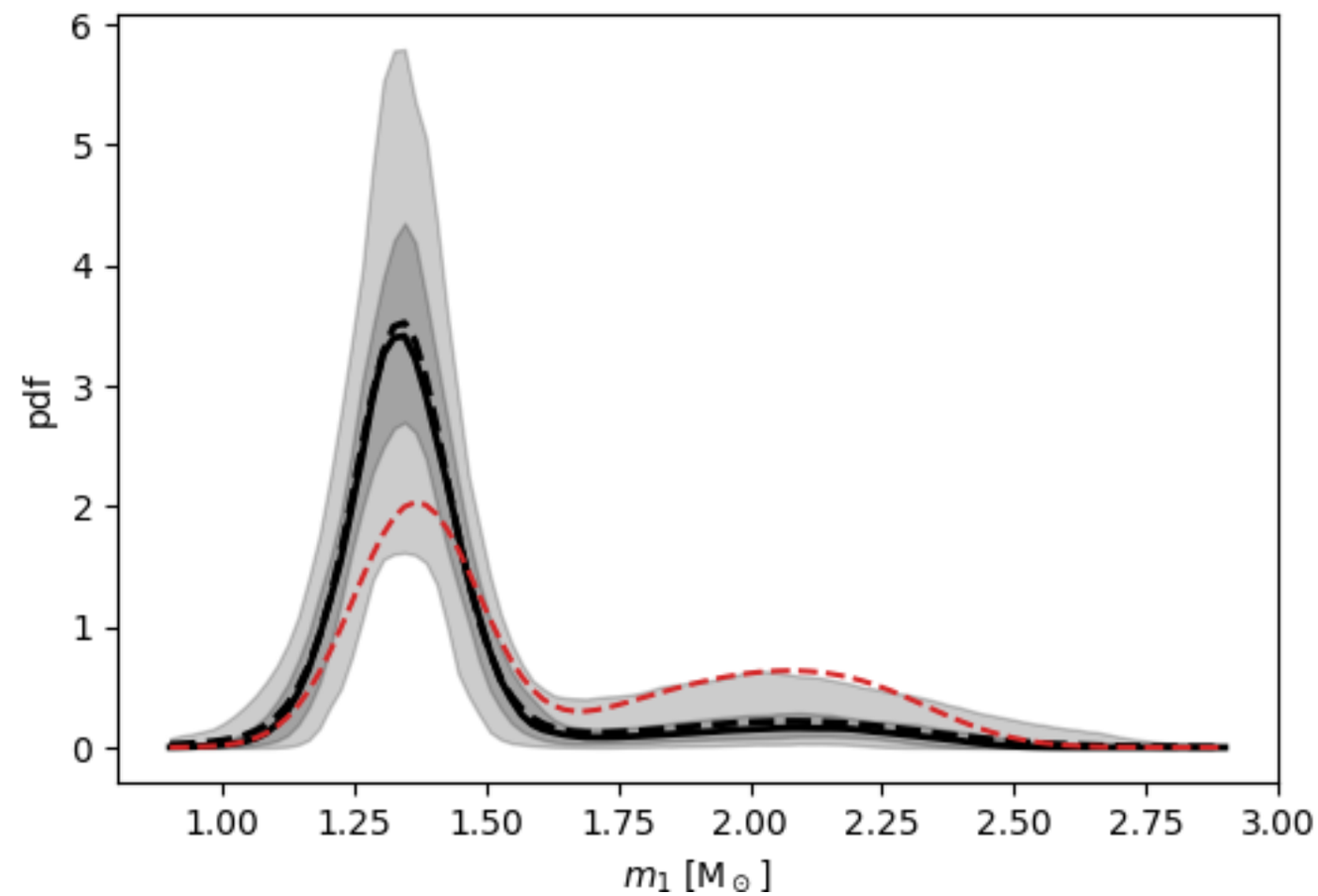
Abbott et al 2020 (190425z)

Synthetic GW survey of NS-NS mergers

- What happens if we combine all information, mass/spin/tides?
  - We correctly recover the mass distribution



Synthetic observed systems

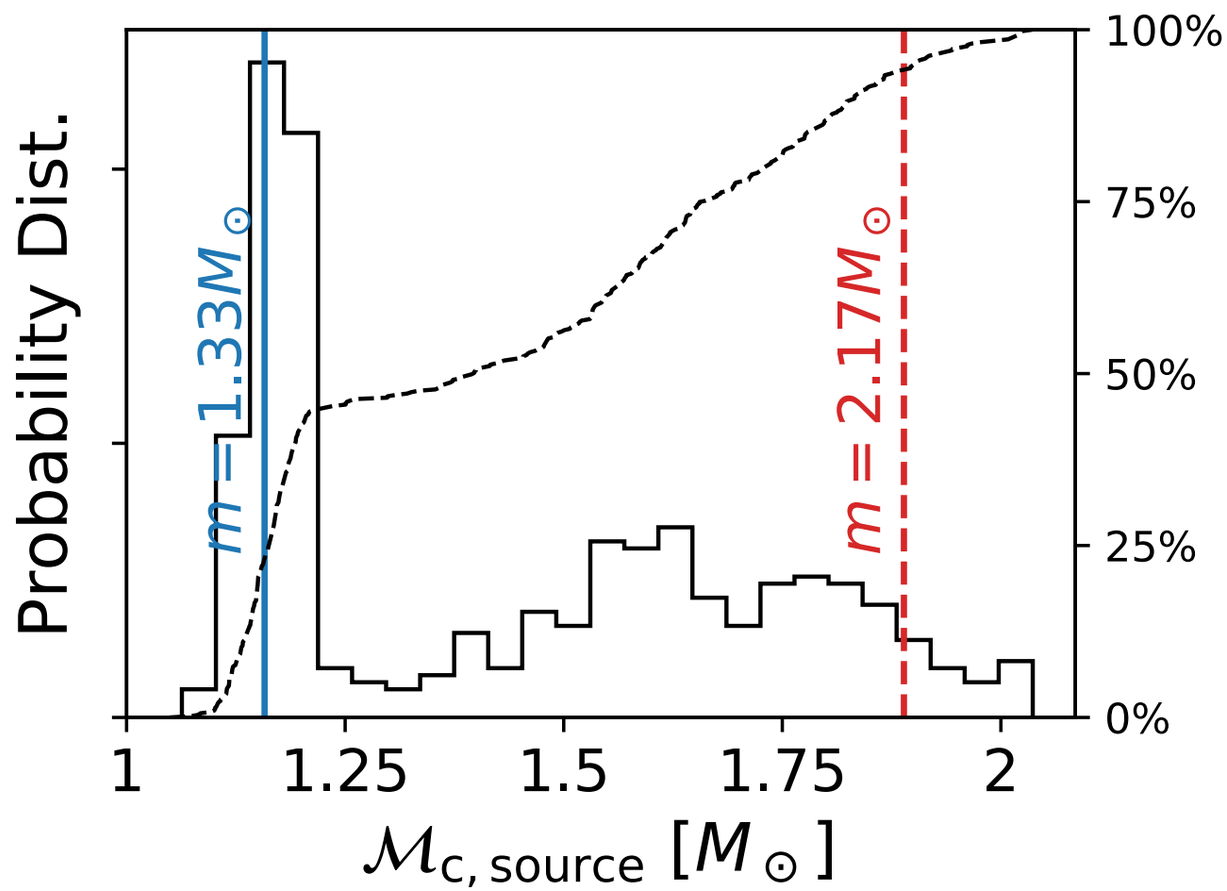


Recovery of injected population

Wysocki et al, arxiv:2001.01747

Synthetic GW survey of NS-NS mergers

- What happens if we combine all information, mass and spin?
  - & spin, and identify multiple populations



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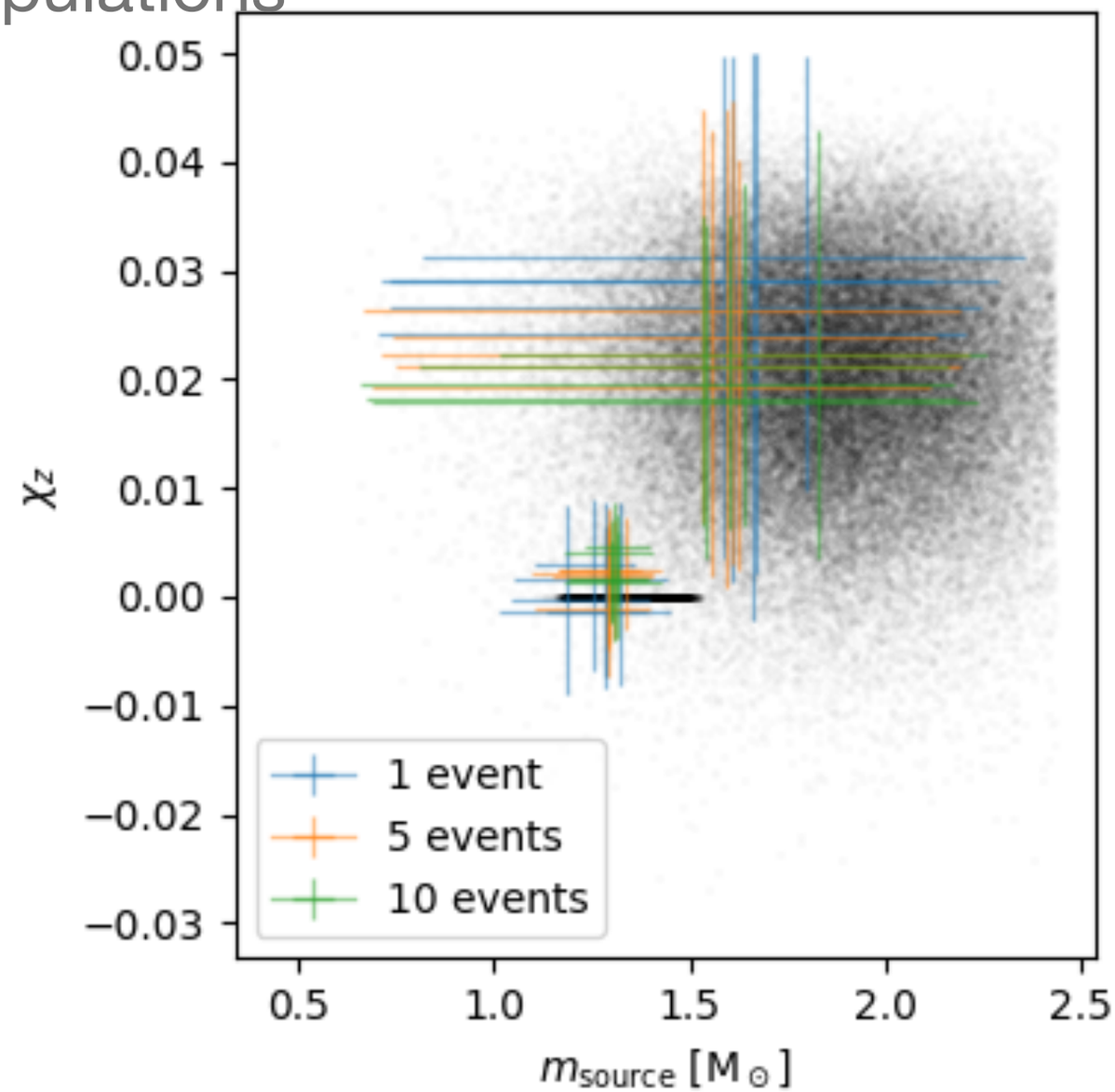

Recovery of injected population

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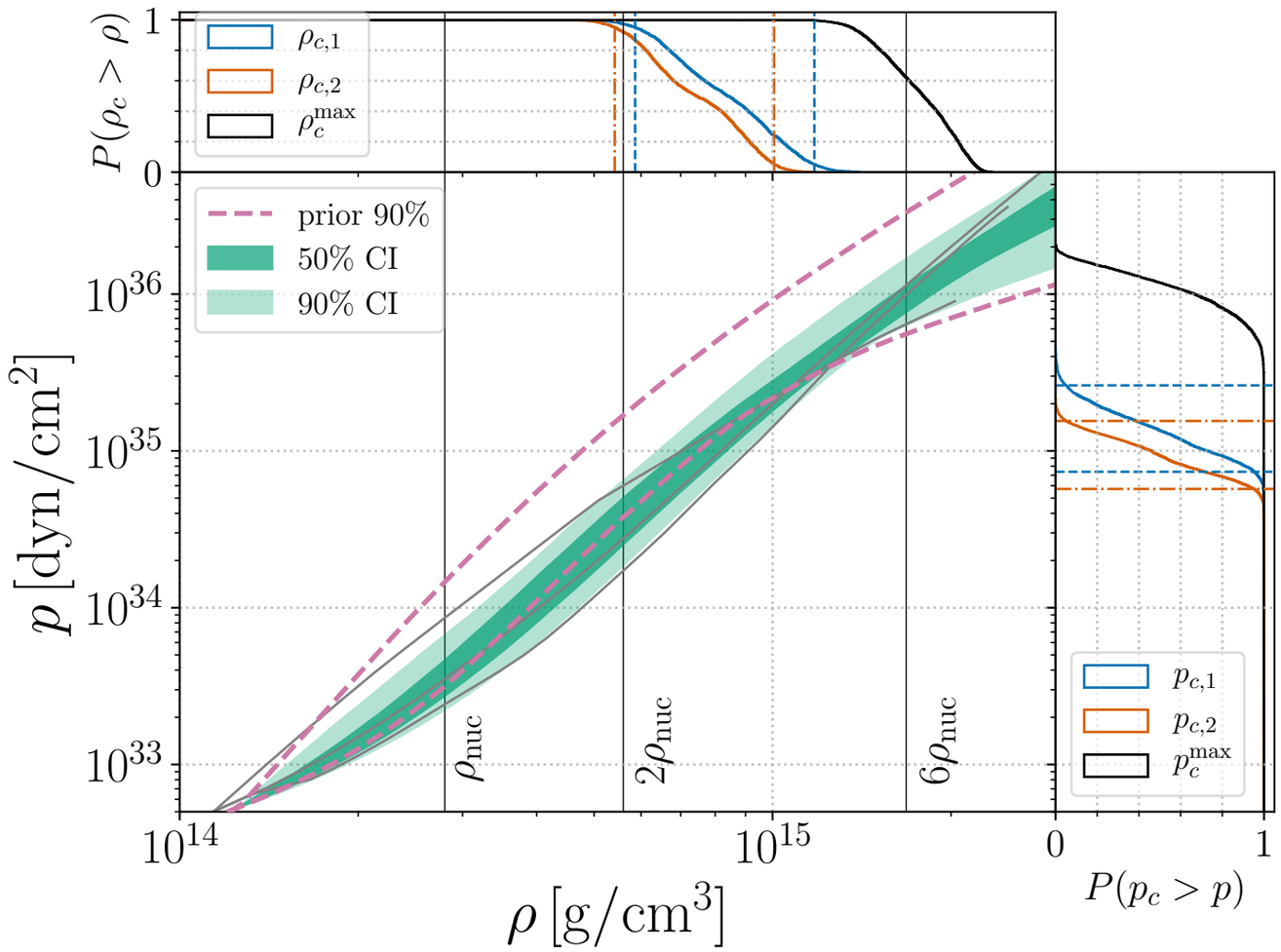
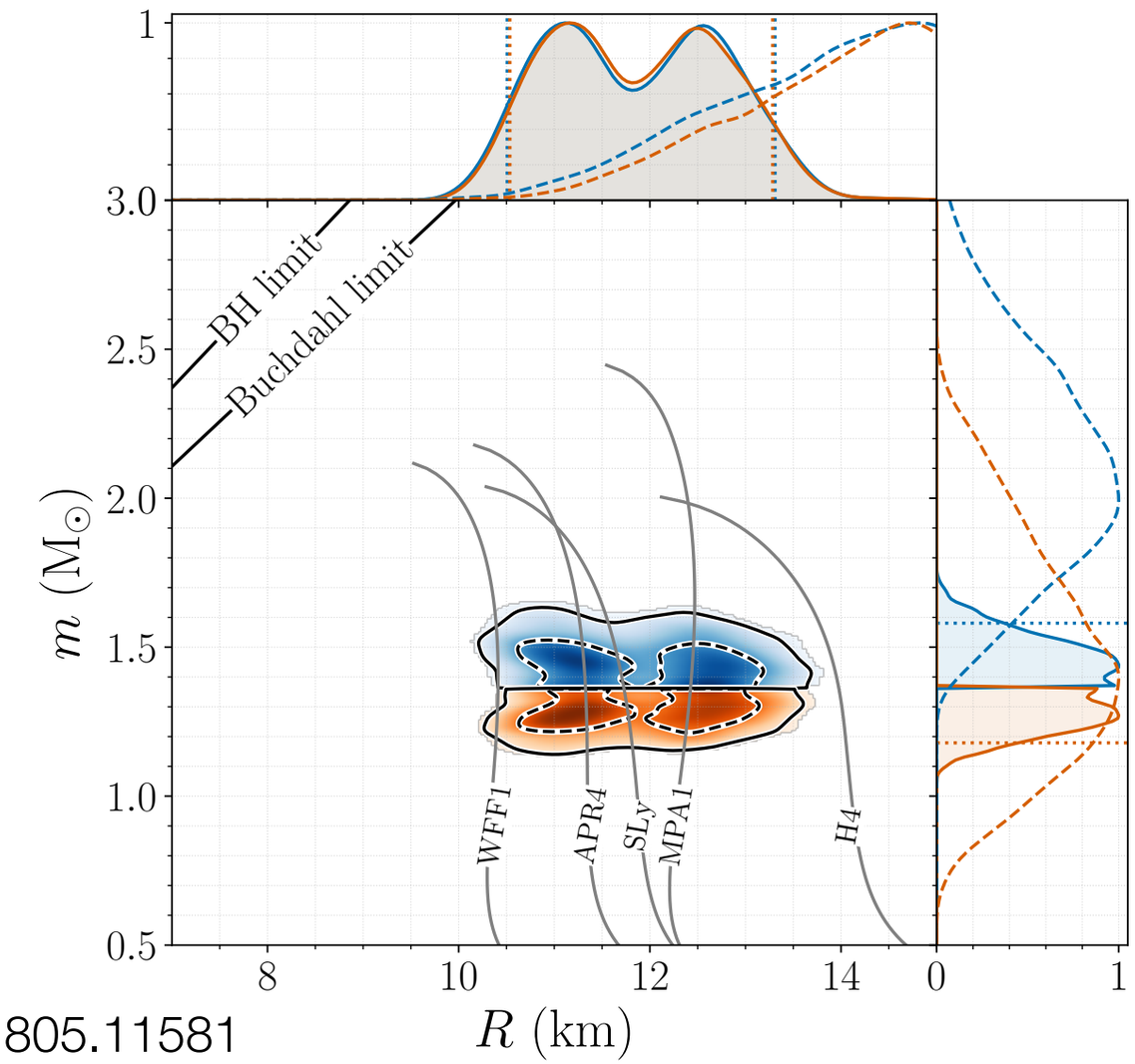
Nuclear equation of state

- (Chirp) mass (one data point = consistent with galactic)
- (Aligned part of) spin small, consistent with galactic
- Tides and the nuclear EOS

require $\Lambda = \Lambda(m)$





Abbott et al 1805.11581

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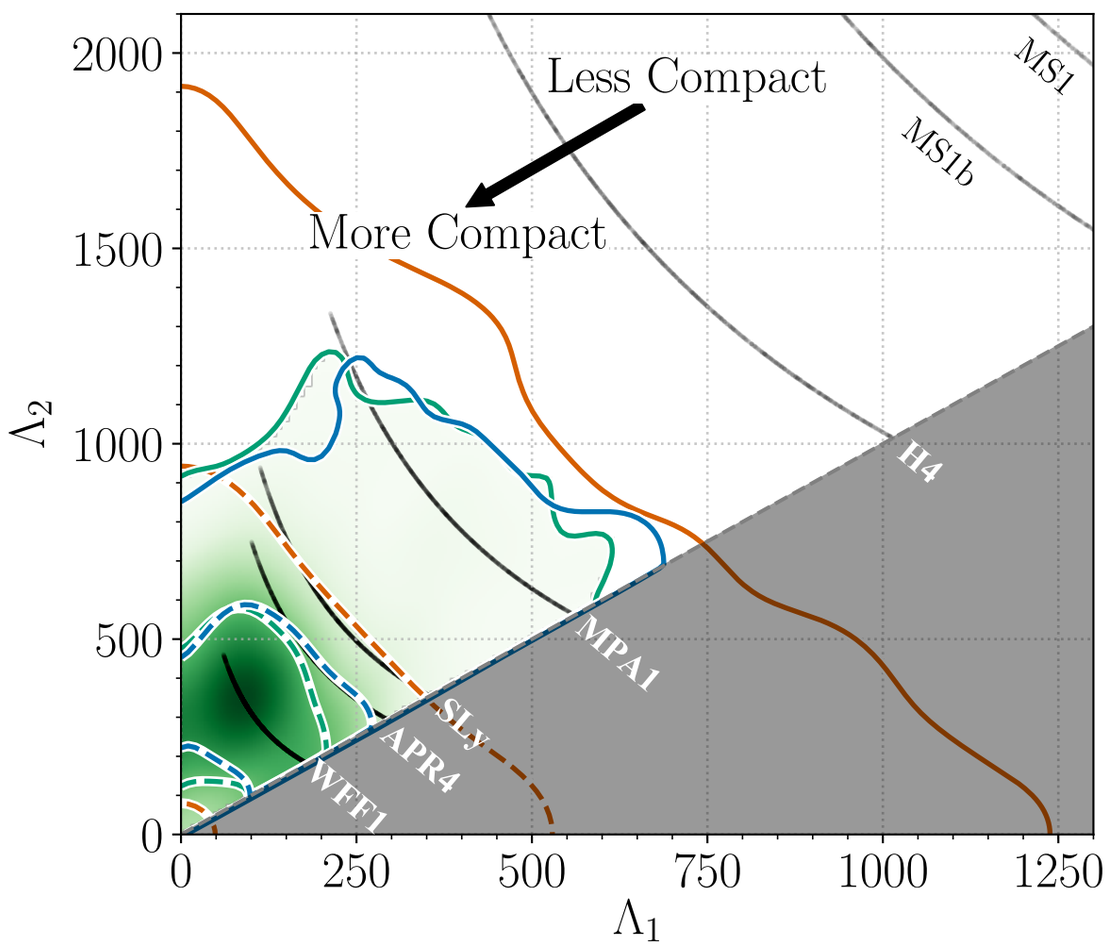
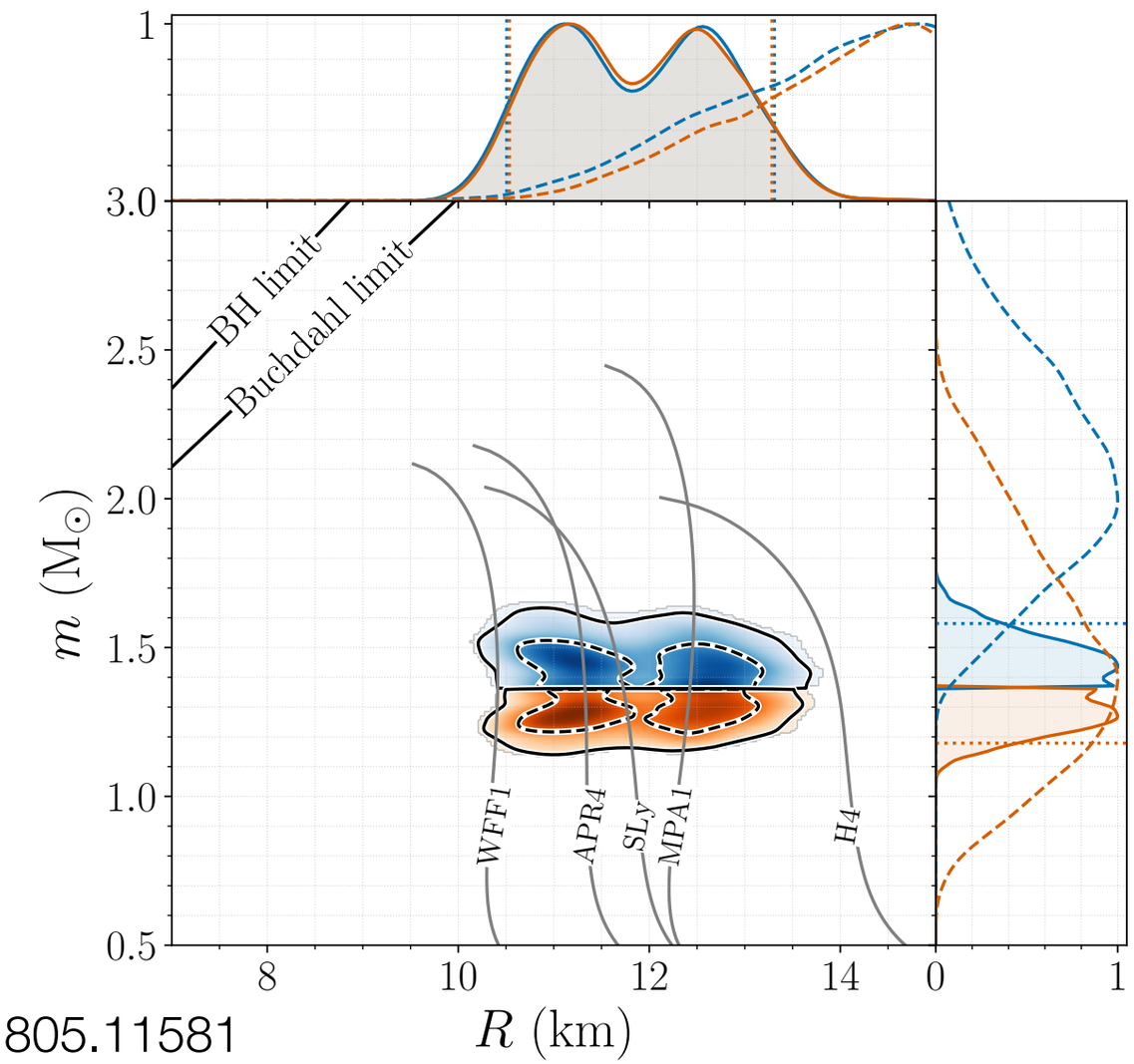


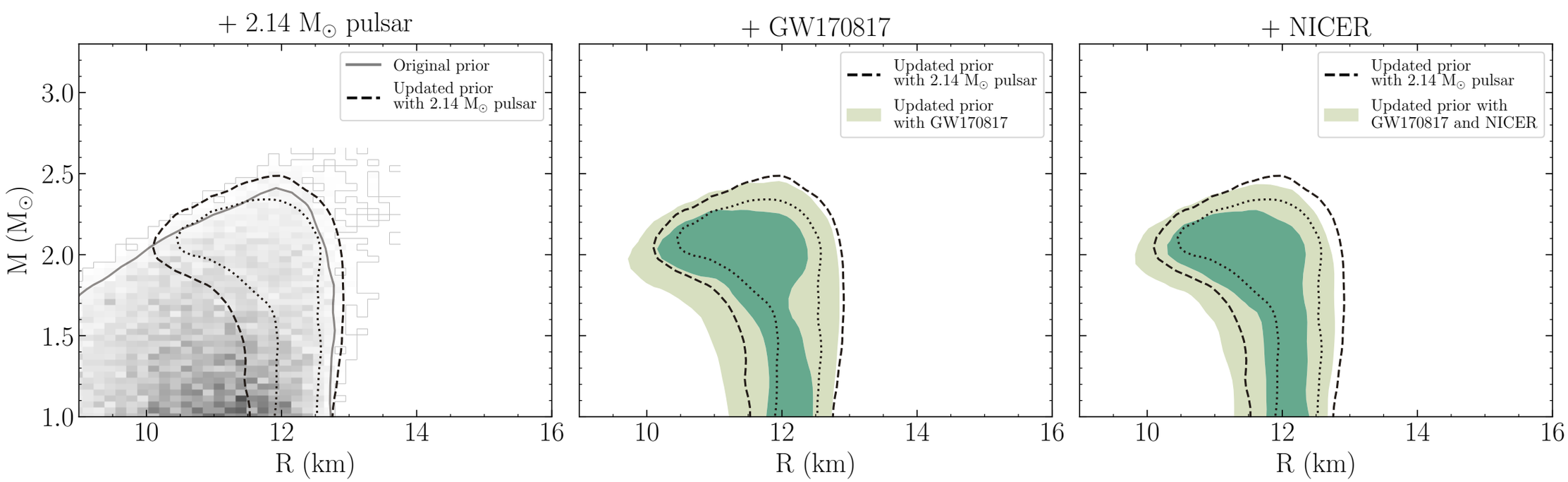


Abbott et al 1805.11581

Context: Probing NS matter properties

- NS size & maximum mass set by the nuclear EOS

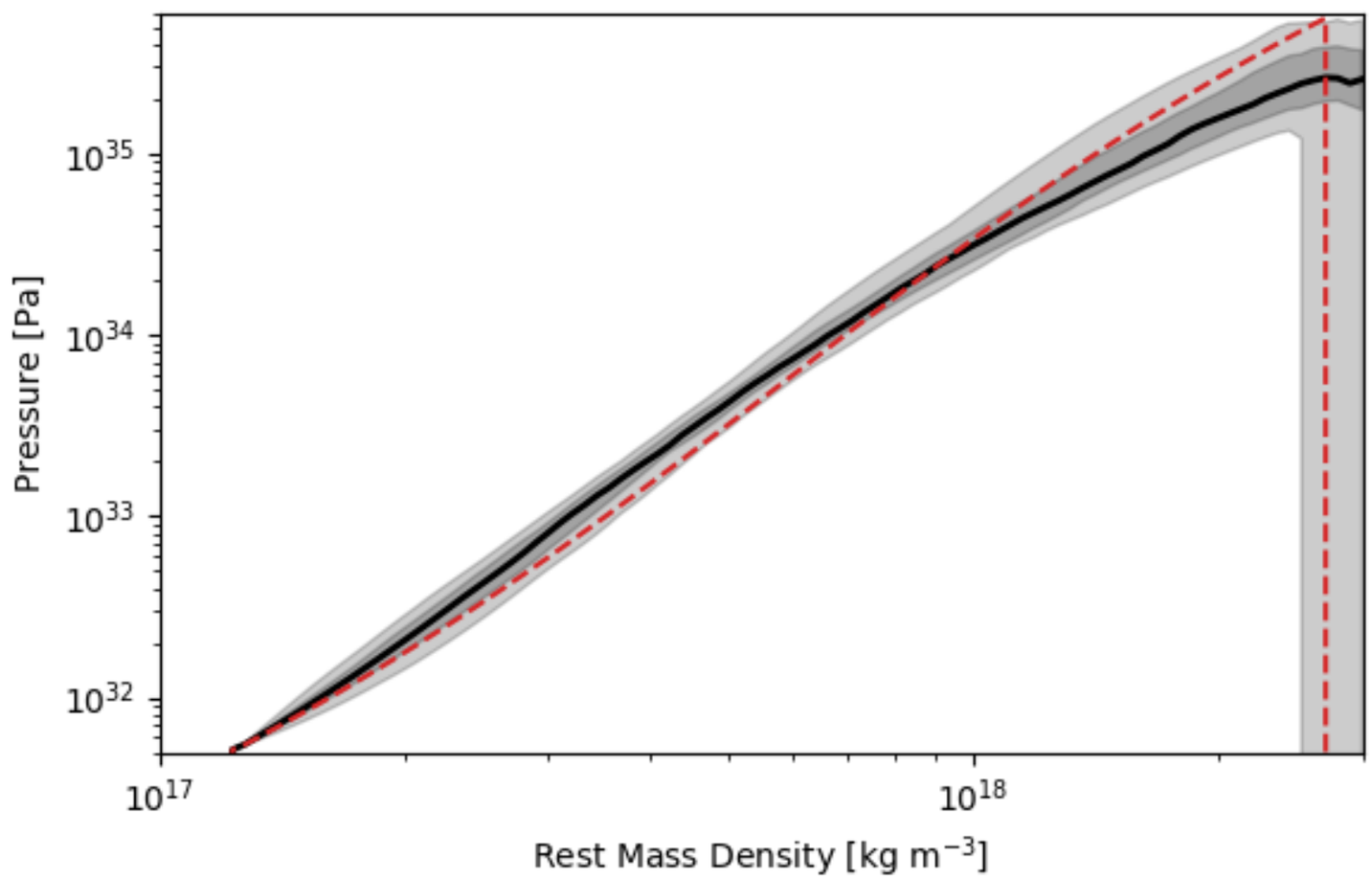
- Other observations probe nature of NS matter (e.g., size/tides)



Raaijmakers et al 2019 [see also Riley et al 2019,Miller et al 2019, …]
[talks earlier in this session, and Steiner et al in session J]

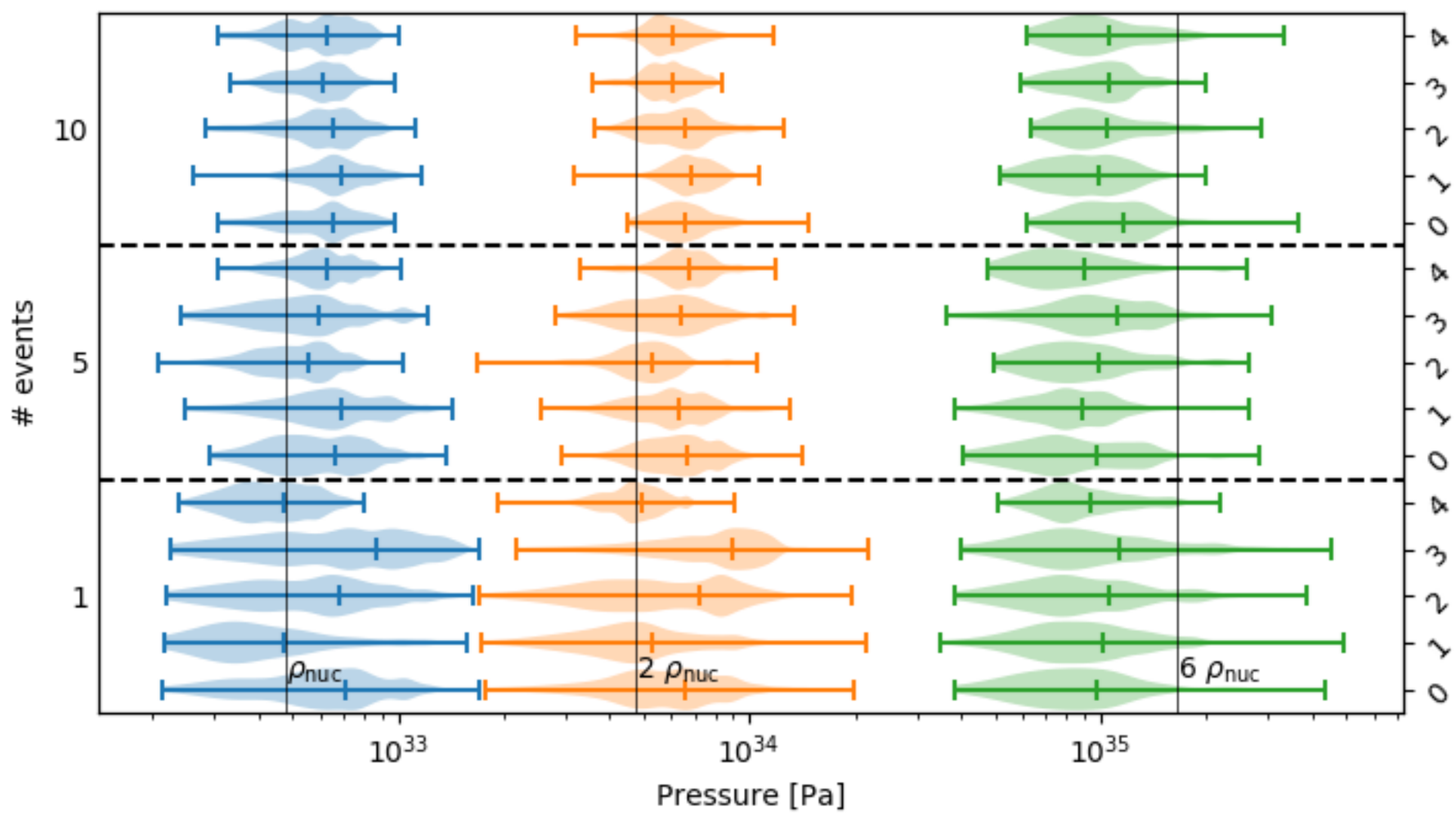
Synthetic GW survey of NS-NS mergers

- What happens if we combine all information, mass and spin?
  - and the nuclear EOS



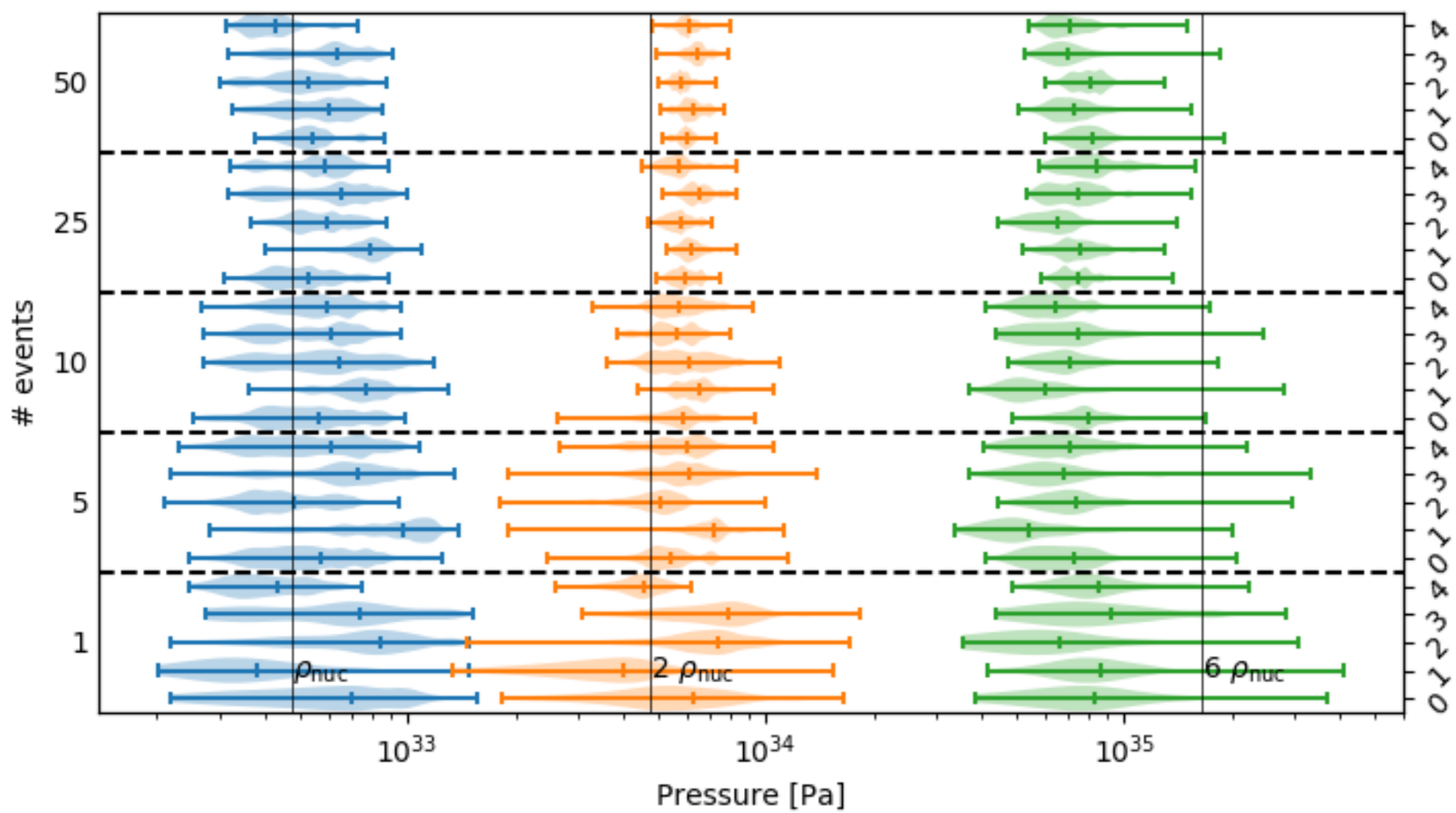
How important is joint mass/spin/EOS inference?

- Consider several small surveys of 1, 5, 10, … BNS mergers
  - Using a mass/spin model that is compatible with the data, recover EOS



How important is joint mass/spin/EOS inference?

- Consider several small surveys of 1, 5, 10, … BNS mergers
  - Using a mass/spin model that is **oversimplified**, we **introduce biases in the recovered EOS**



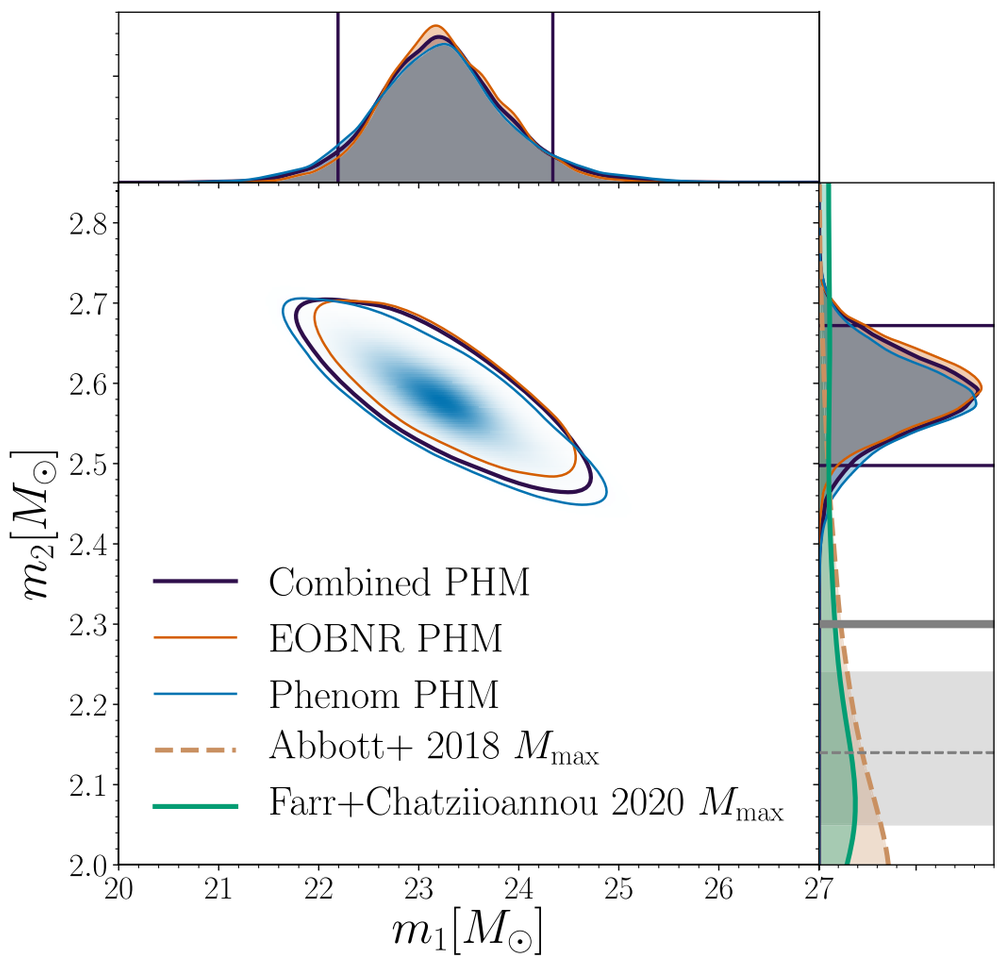
Neutron stars: Conclusions

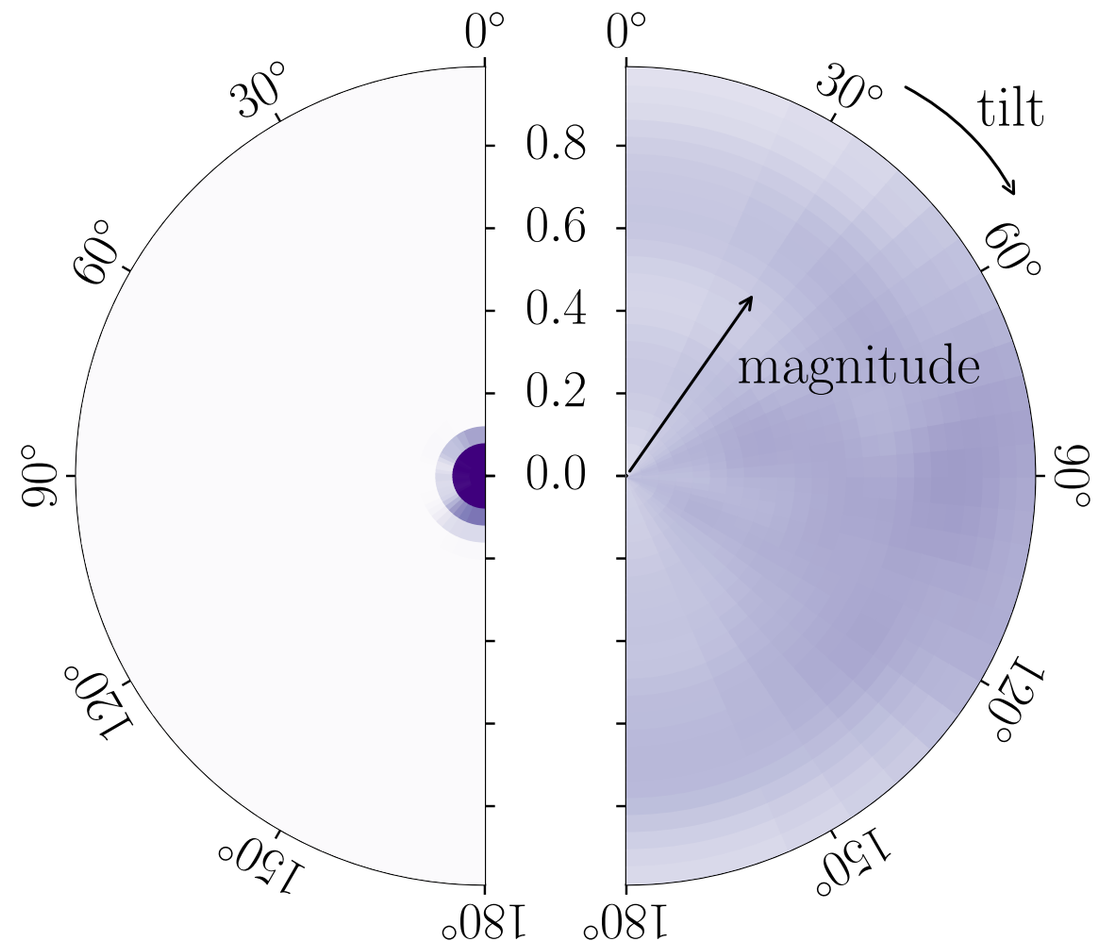
- Joint inference critical
  - Nature & our measurements correlate interesting questions [e.g., mass/spin/tide degeneracy]
  - Do better at every challenge using maximal information … and **can misinterpret if you don't fit all properties together**
  - Going forward: helps with ambiguous events (GW190425z)

- Joint inference practical
  - Likelihood-based helps overcome computational hurdles, without reinventing GW inference or using high-d KDEs
  - Public codes and data products (e.g. RIFT GW likelihood)

Asymmetric binaries: Exceptional event as example

- Asymmetric binaries: **much** tighter constraints

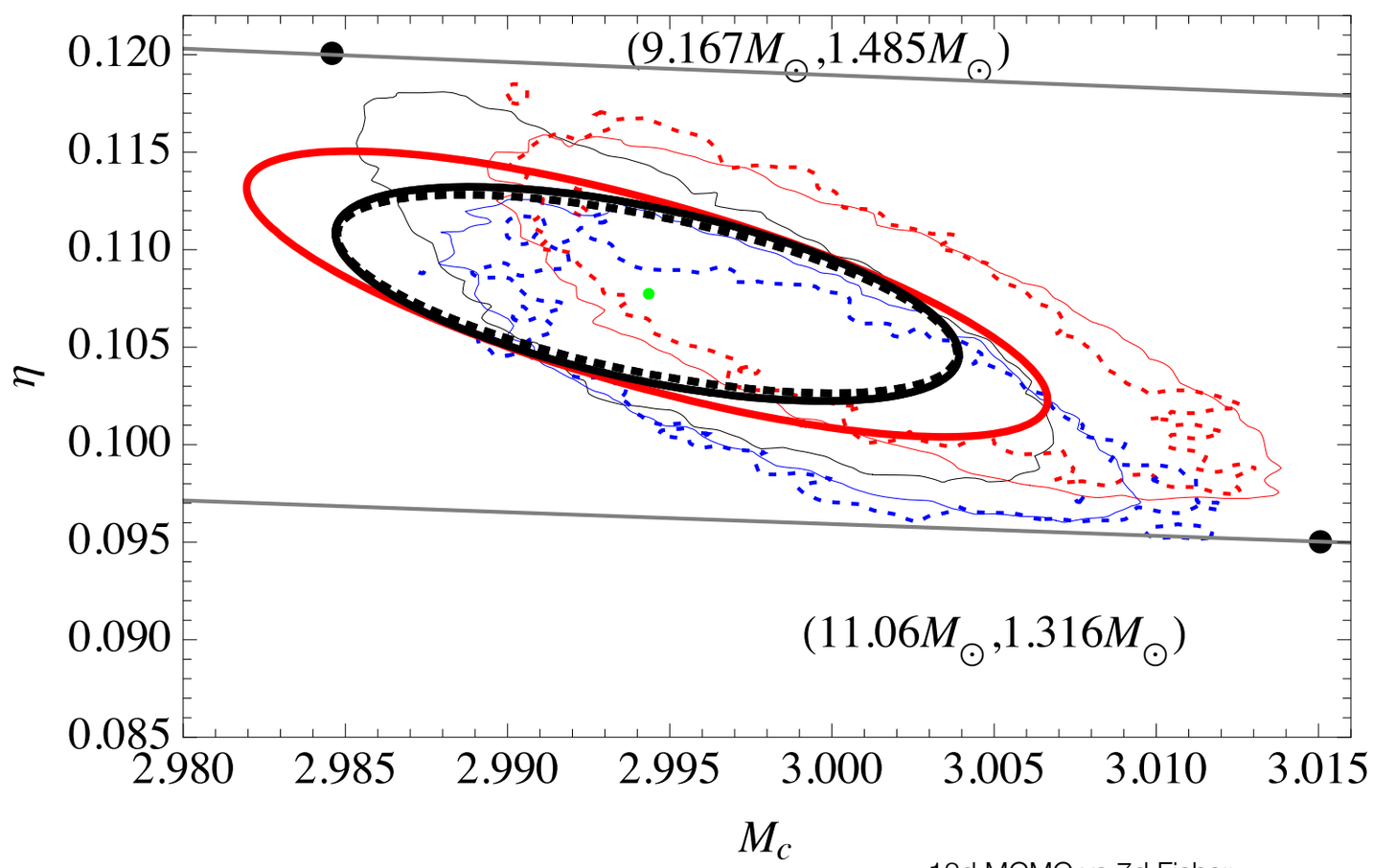




GW190814 (Abbott et al 2020)

Why can we learn so much?

- NS in asymmetric binaries: **much** tighter constraints
  - Precession (and higher modes) can break degeneracies



12d MCMC vs 7d Fisher
ROS et al 2014 (PRD 89 102005)

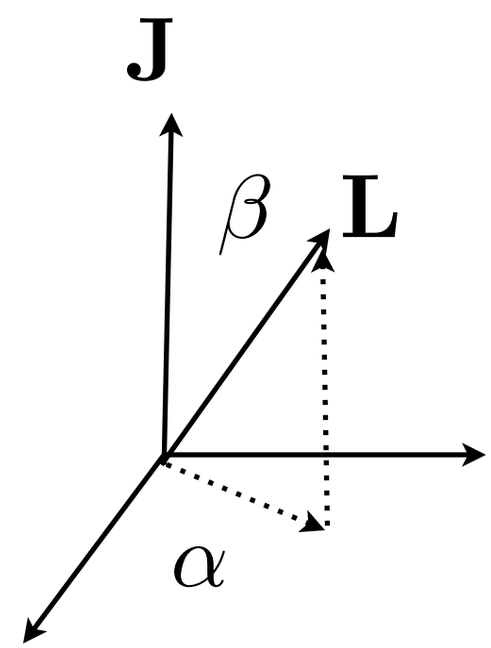
Approximate precessing kinematics

$$\partial_t \mathbf{X} = \mathbf{\Omega}_X \times \mathbf{X}, \quad \mathbf{X} = \mathbf{L}, \mathbf{S}_1, \mathbf{S}_2$$

- Example: one spin

$$\frac{d\hat{\mathbf{L}}}{dt} \simeq \frac{\mathbf{J}}{r^3}\left(2 + \frac{3m_2}{2m_1}\right) \times \hat{\mathbf{L}}$$

$$|\mathbf{J}| = |\mathbf{L} + \mathbf{S}|$$



[Apostolatos et al 1994]

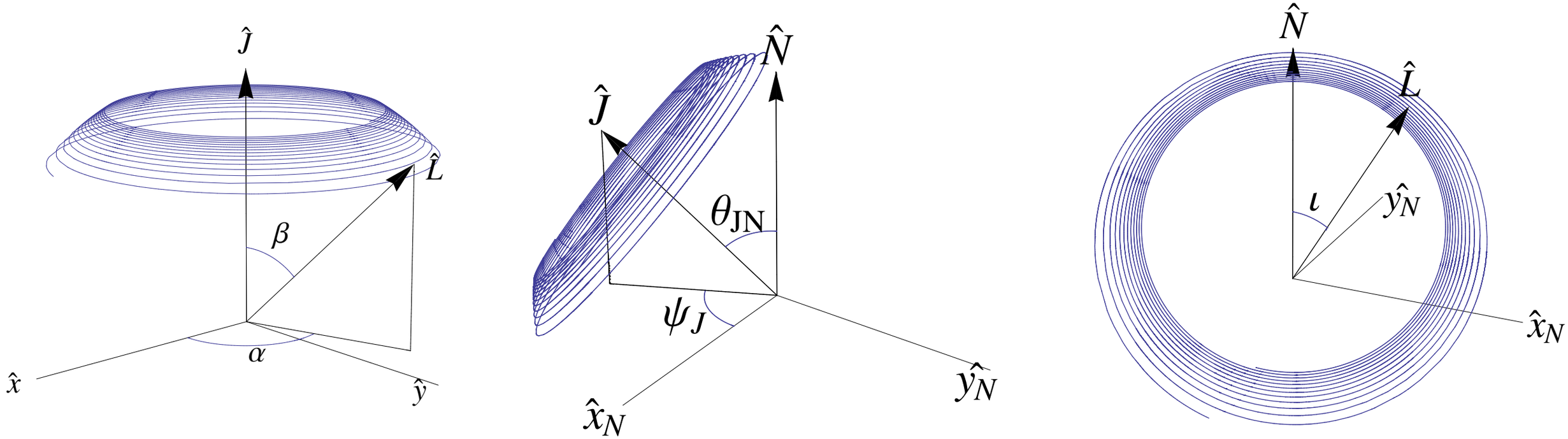
- Extend known single-spin precession solutions
  - $\beta(v)$: set by |L| and (conserved) L.S
  - α : precession phase

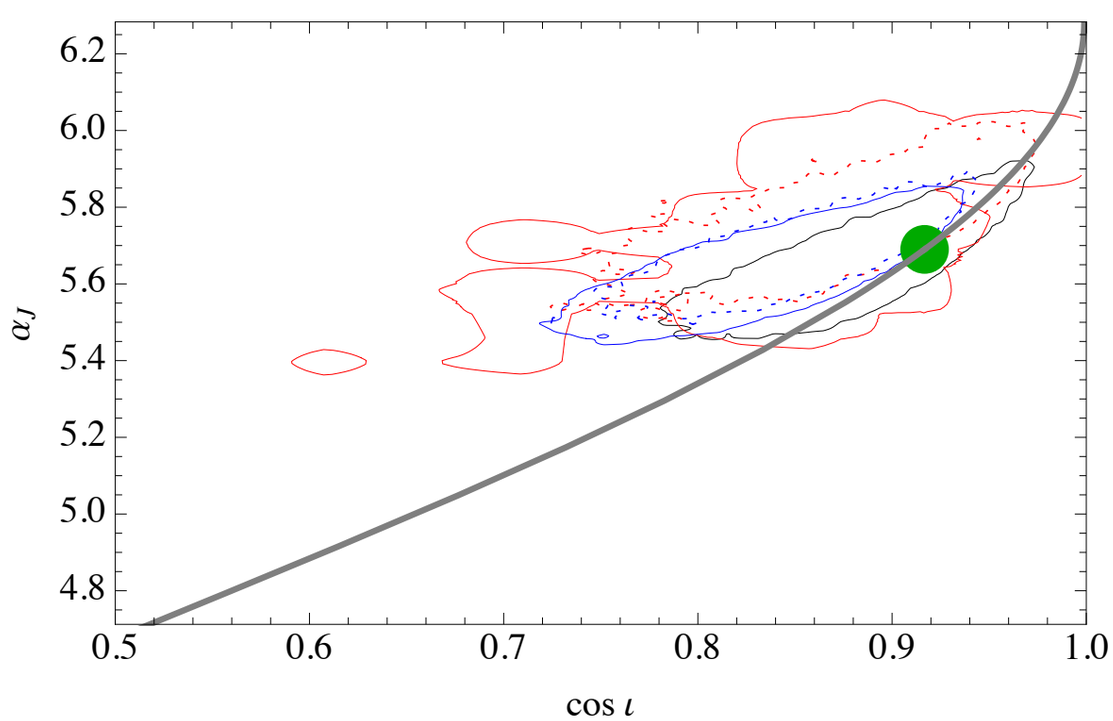
$$= \int \Omega_p \frac{dt}{dv} dv$$

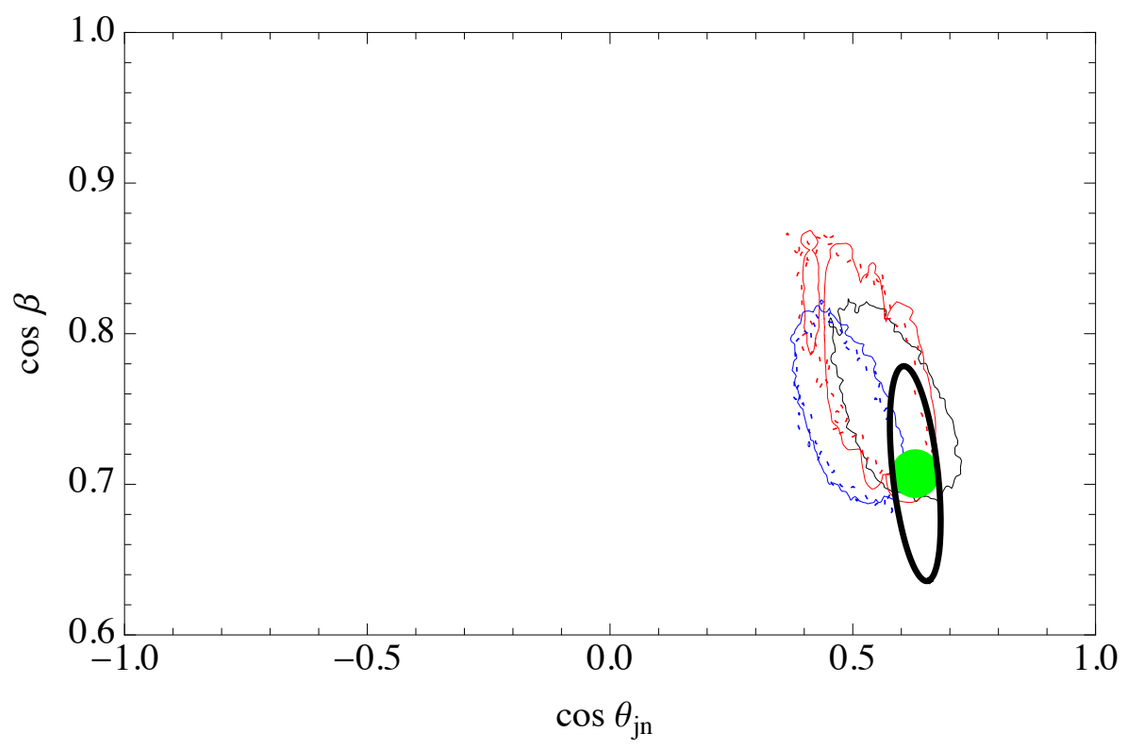
: analytic approximations exist

Apostolatos et al 1994; Lundgren and ROS 2013

Sample precessing geometry: BH-NS







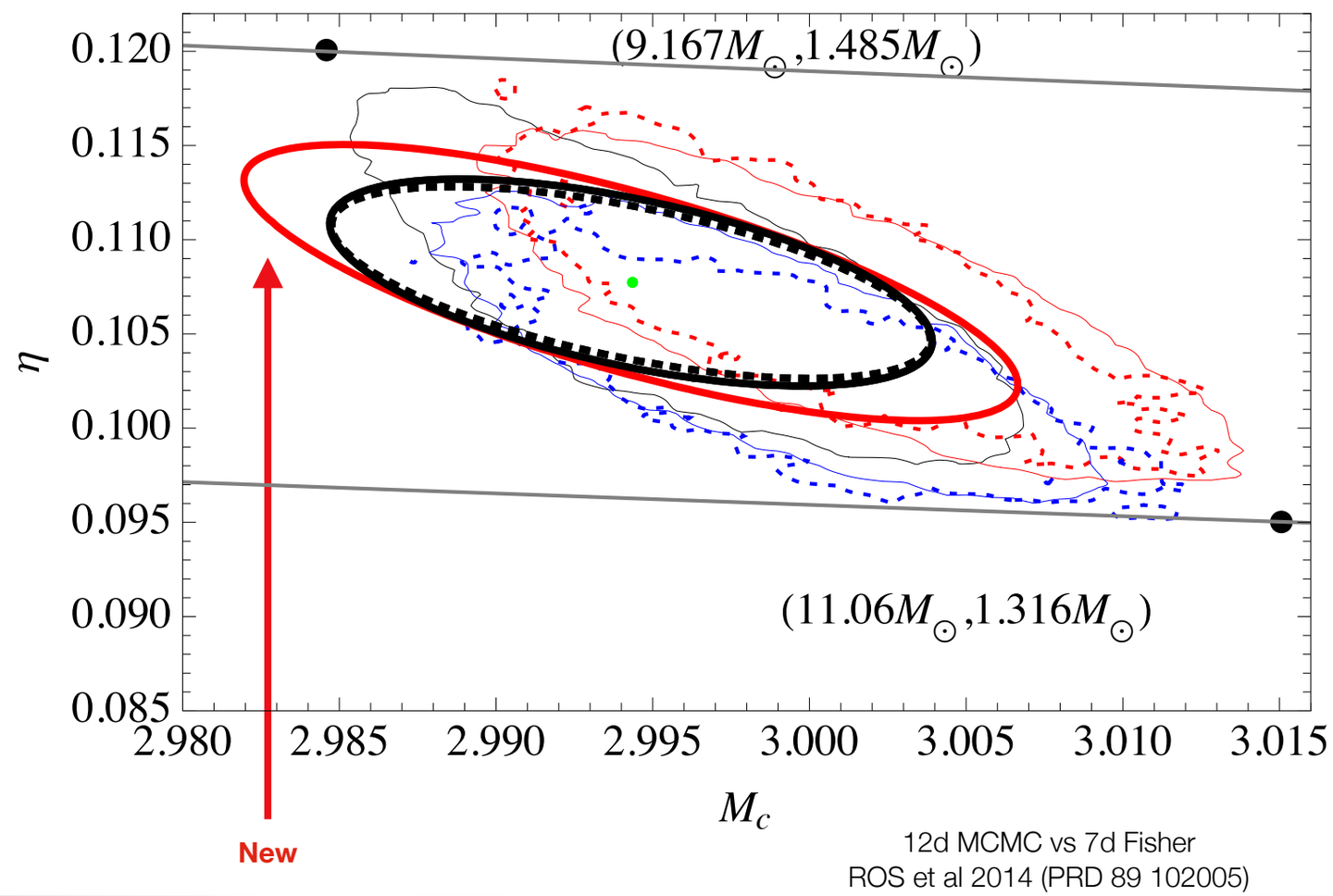
Simple approximate (intrinsic) Fisher matrix

$$\rho^2_{2ms} \equiv |{}_{-2}Y_{2m}(\theta_{JN}) d^2_{m,2s}(\beta)|^2 \int_0^\infty \frac{df}{S_h(f)} \frac{4(\pi \mathcal{M}_c{}^2)^2}{3d_L^2} (\pi \mathcal{M}_c f)^{-7/3}$$

- Amplitude
- Angular dependence
- Phase

$$\hat{\Gamma}^{(ms)}_{ab} = \frac{\int_0^\infty \frac{df}{S_h(f)} (\pi \mathcal{M}_c f)^{-7/3} \partial_a(\Psi_2 - 2\zeta - ms\alpha)\partial_b(\Psi_2 - 2\zeta - ms\alpha)}{\int_0^\infty \frac{df}{S_h(f)} (\pi \mathcal{M}_c f)^{-7/3}}$$

- Good:
  - Easy to calculate
  - Similar to nonprecessing (weighted average)
  - Intuition about separating parameters
- "Bad"
  - Ansatz / approximation
  - At best, retains all degeneracies of full problem (phases, …)



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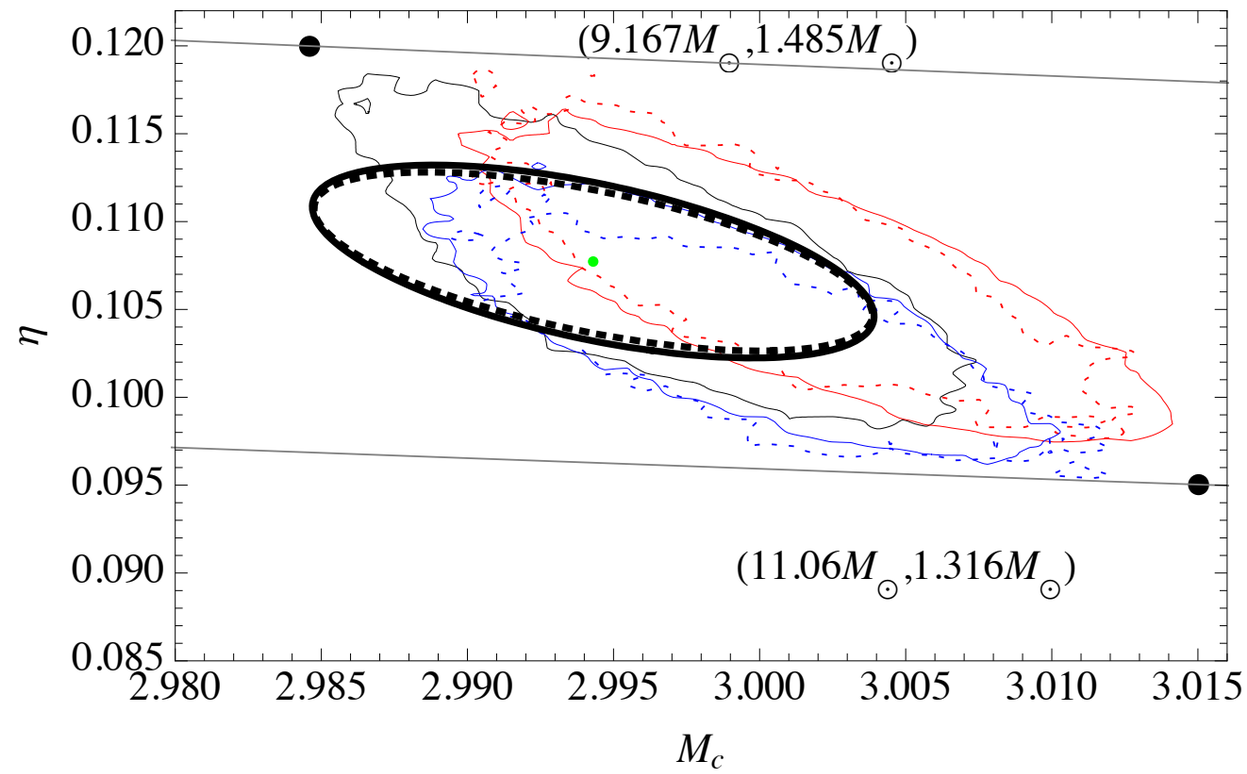
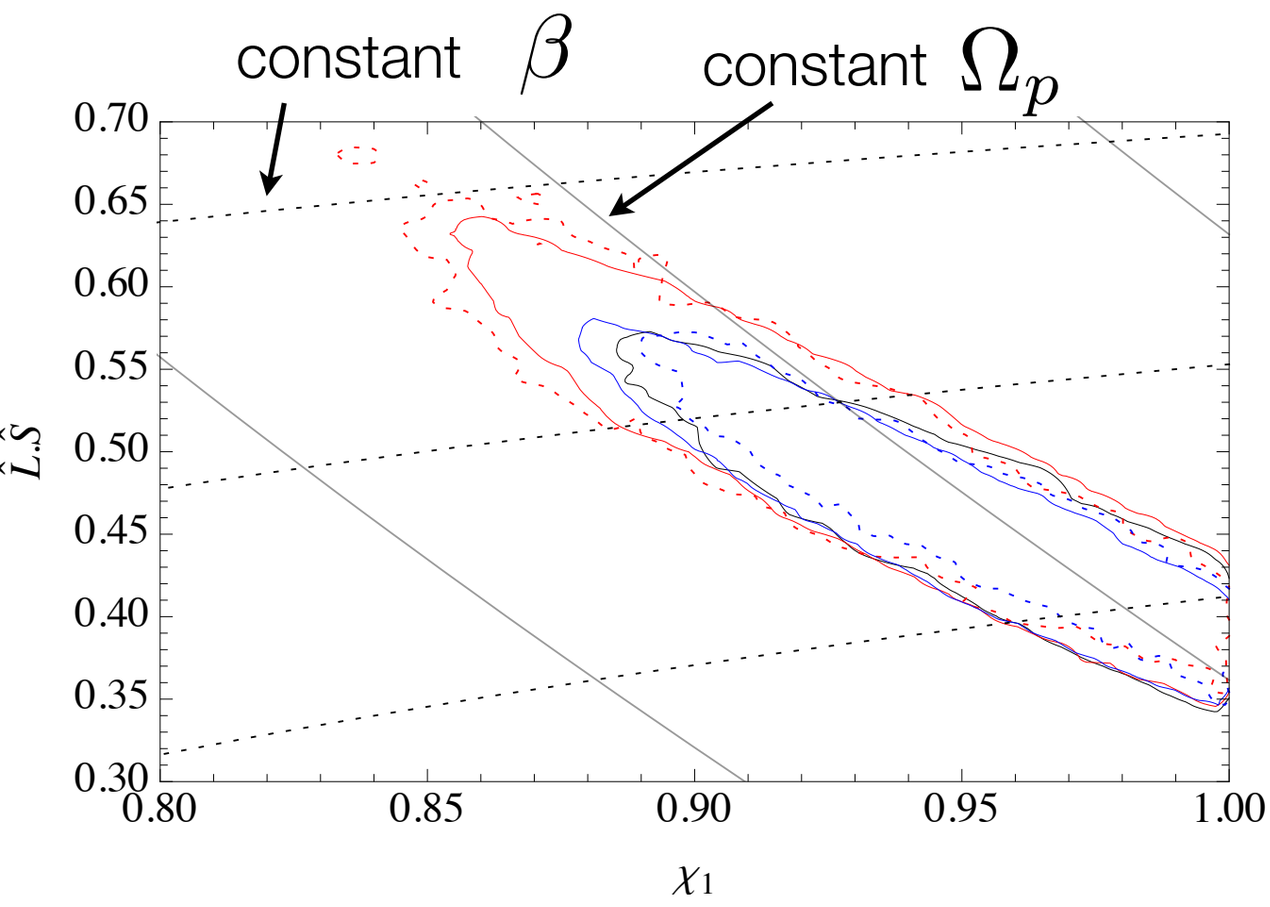
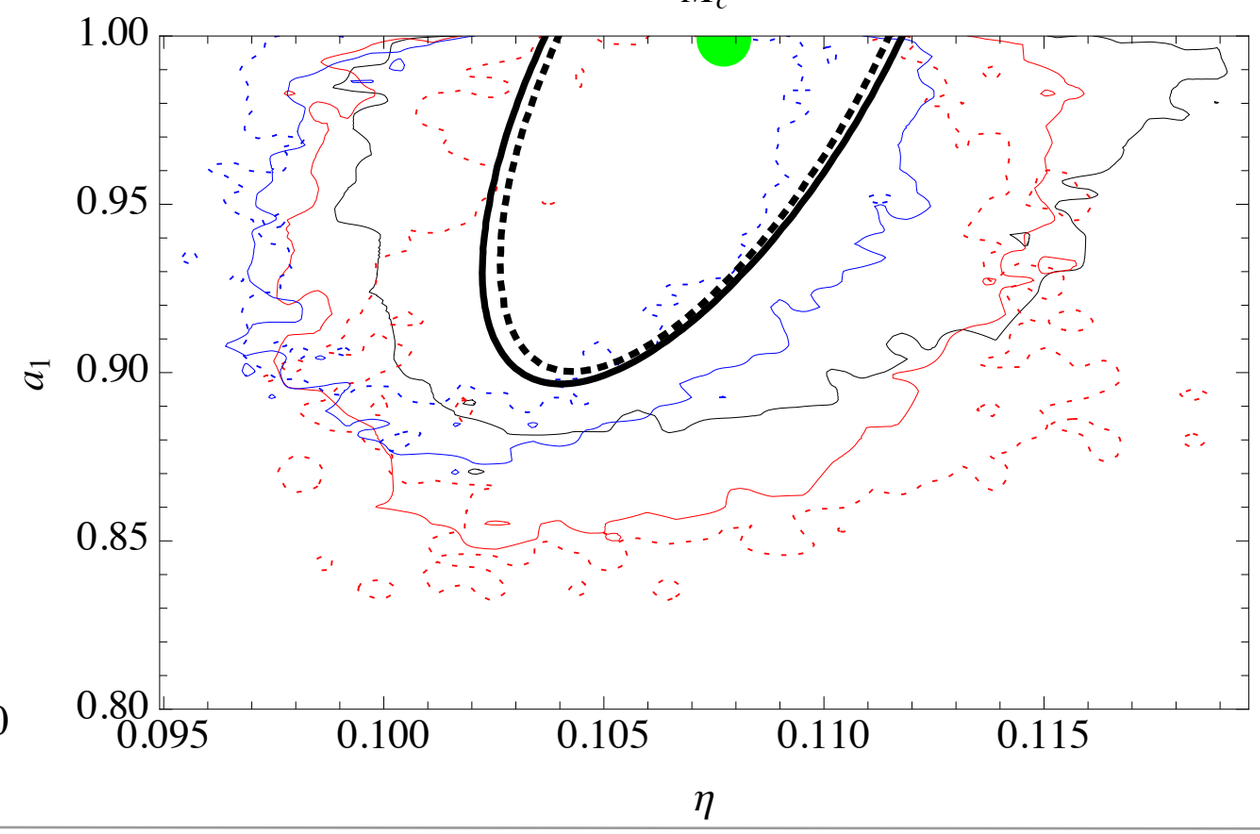
Precession-induced modulation

- Chirp rate, precession rate set limits
  - More cycles -> more accuracy
- Precession enables measurements
  - Spin-orbit misalignment
  - Mass ratio $\times 3$ better







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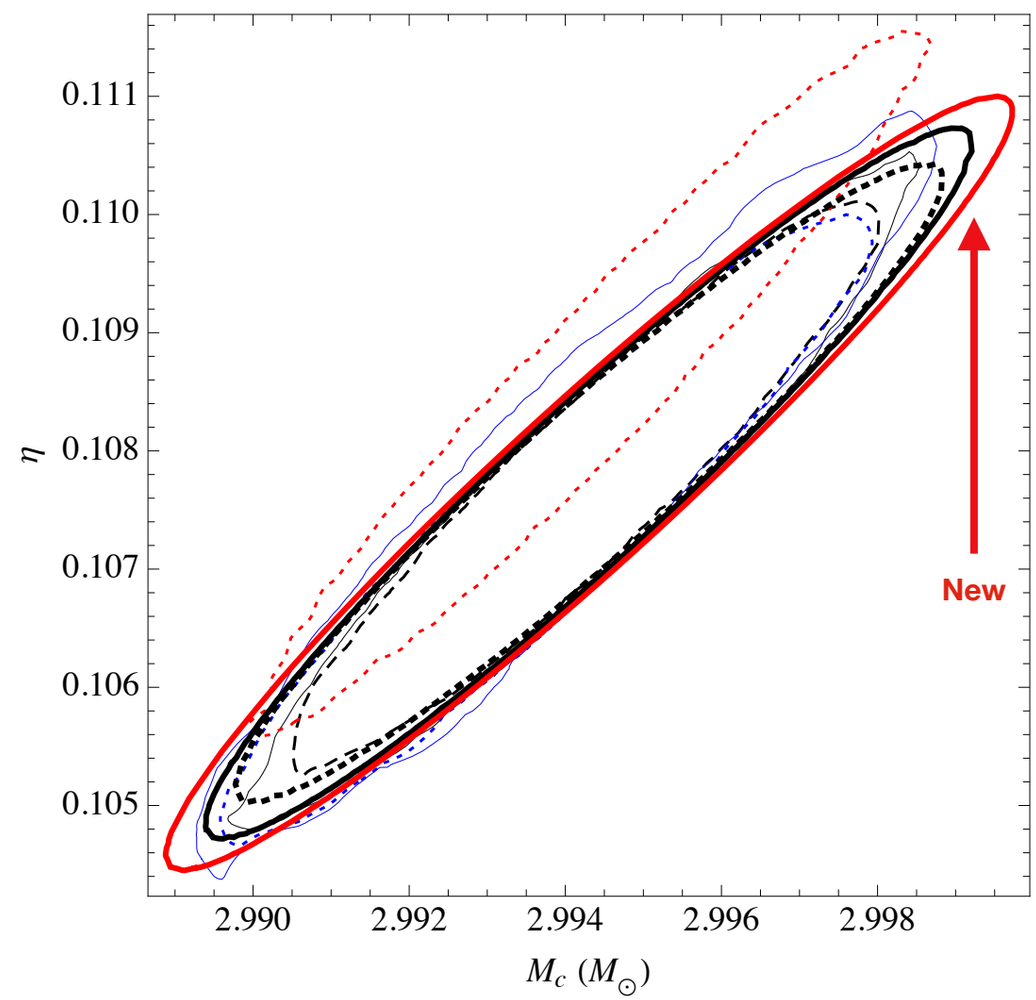


9d MCMC vs 4d Fisher
ROS et al 2014 (PRD 89 064048)

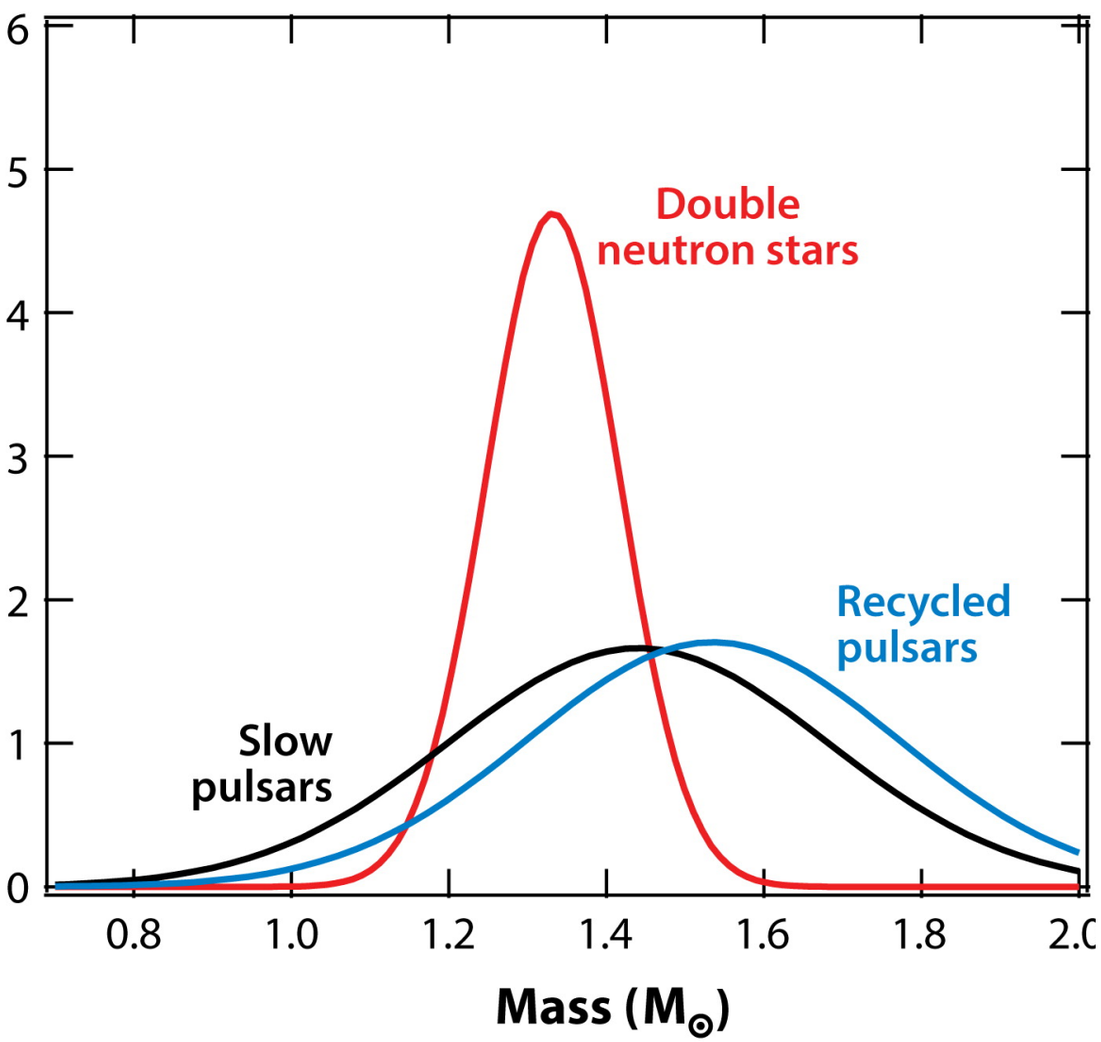
Advertisement: inference code for multiple events

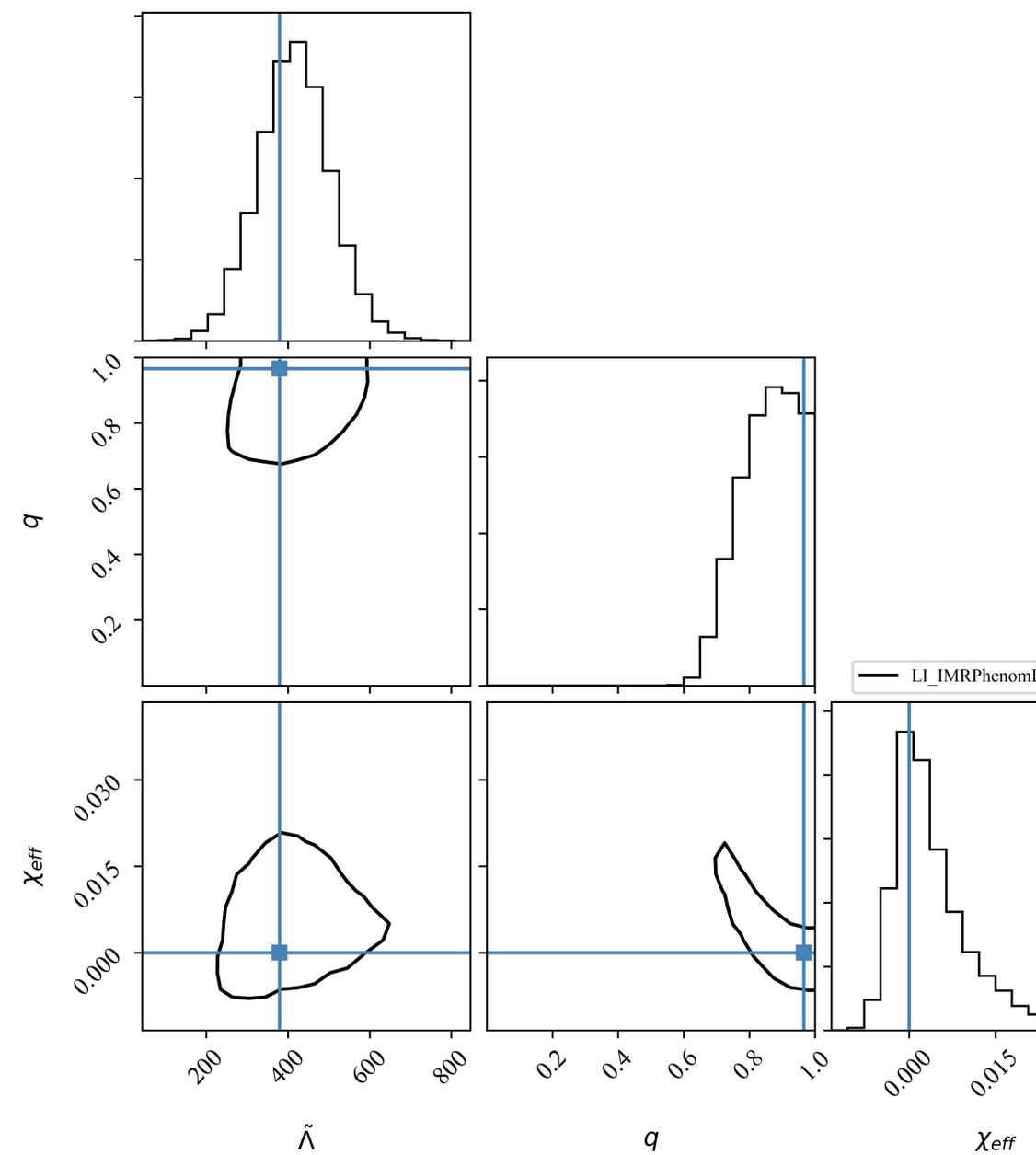
- Do you want to use GW observations for EOS constraints and/or population inference? But…
  - Don't want to reinvent GW inference or keep up with the latest GW waveform models yourself?
  - Worried about introducing approximations (KDEs, fixed chirp masses, …) to make your calculation tractable?
  - Don't want to invent your own population inference code to combine many events?
- PopModels & RIFT do this all for you!
  - Extensively used in prior work (e.g., O1/O2 BBH by LVC)
  - This project: proof of concept for fast, easy multi-population work
- Code associated with this project ported to main repo soon!

https://git.ligo.org/daniel.wysocki/bayesian-parametric-population-models

Combine everything

- Joint distribution: **mass, mass ratio, spin, tides**
  - Needed/valuable due to correlated measurement uncertainties





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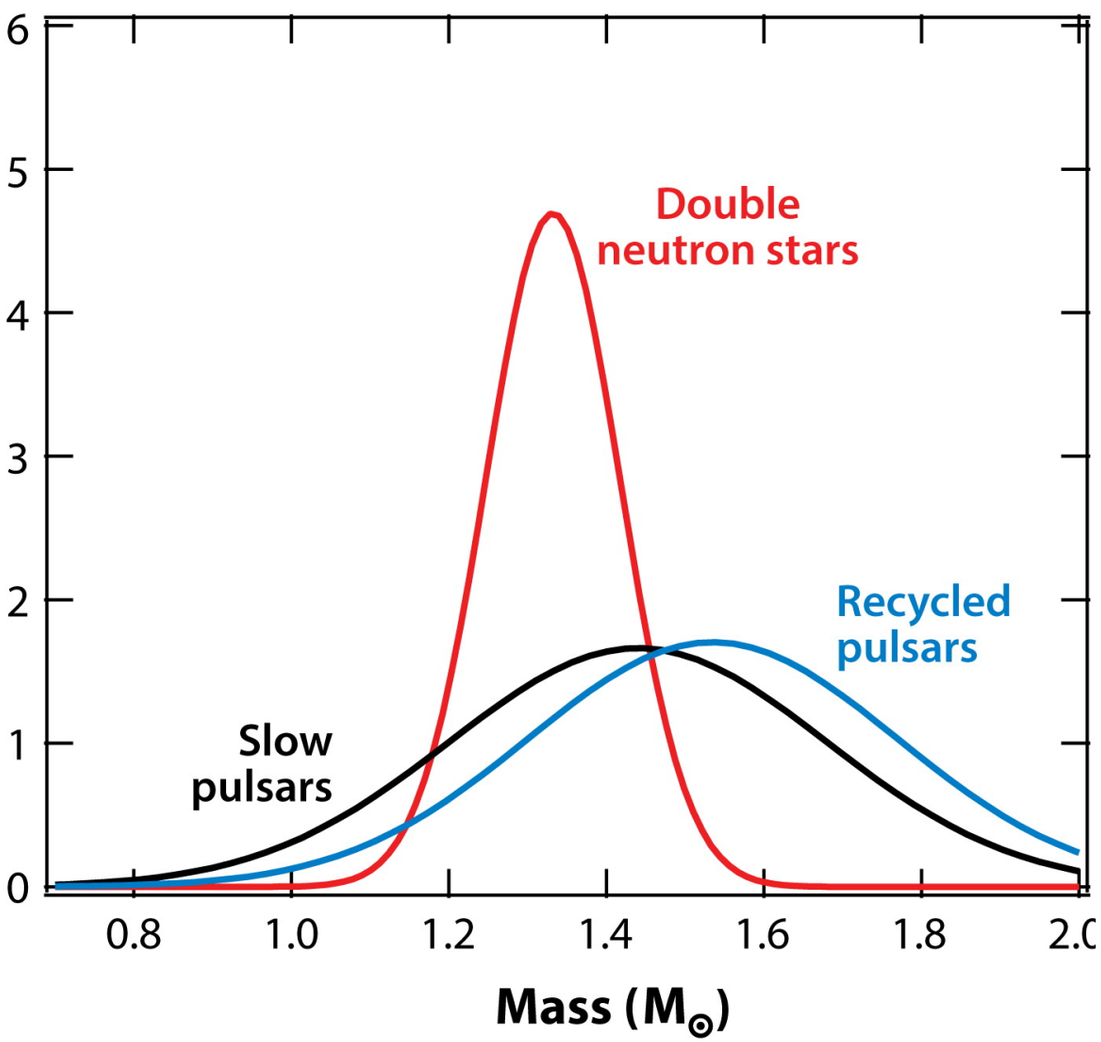
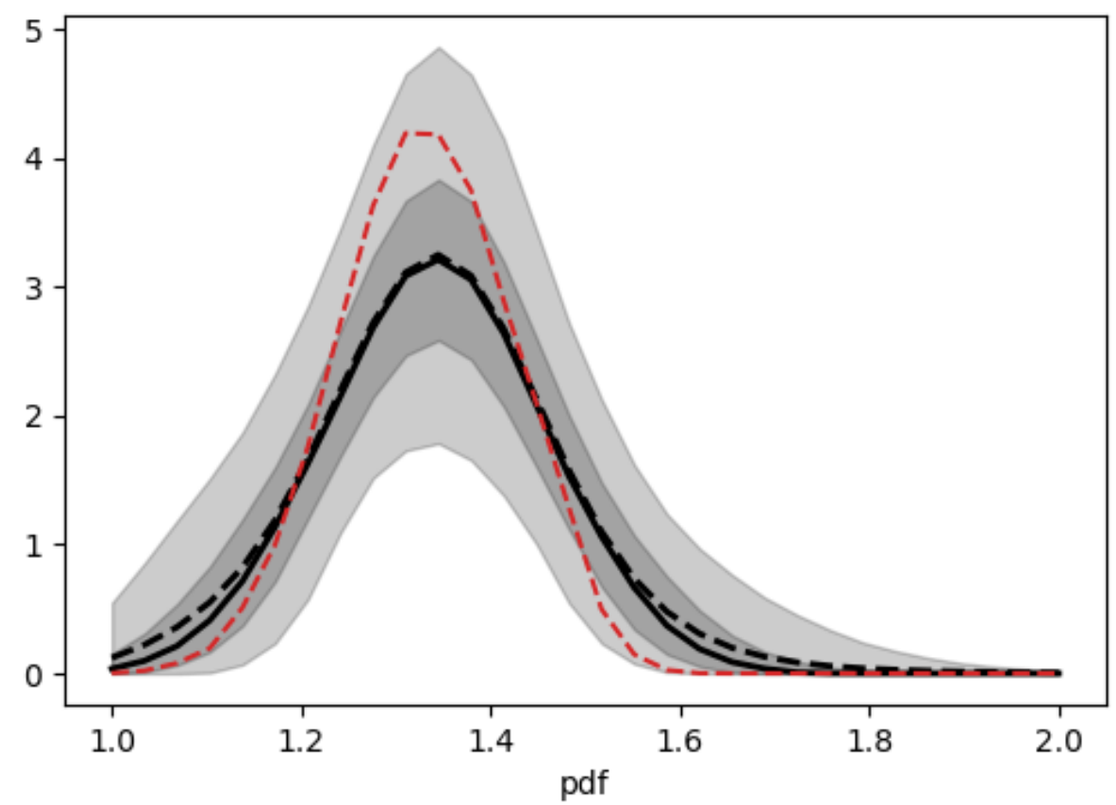




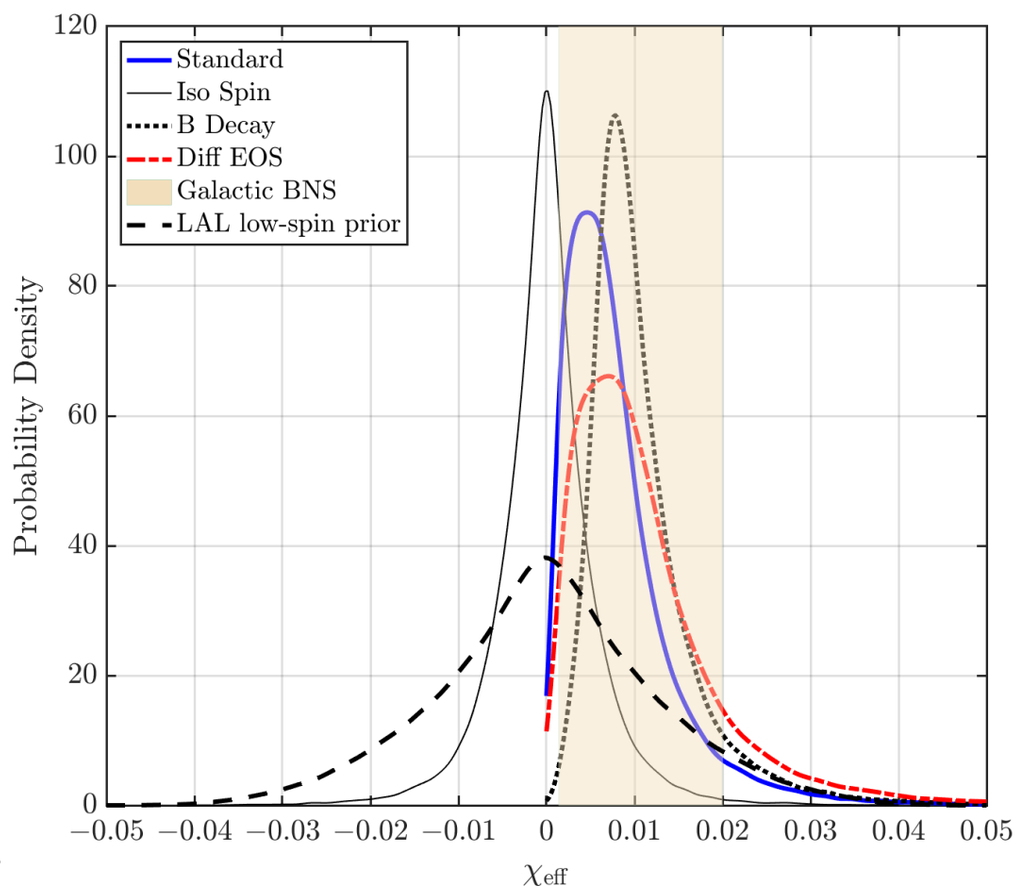
Wysocki, ROS et al 2018
Wysocki, ROS et al in prep

…and some BNS astrophysics too

- O3: Expect O(1) event has measurable/nonzero spin
  - Some galactic merging binary NS have roughly $\chi_{\rm eff} \simeq 0.01$

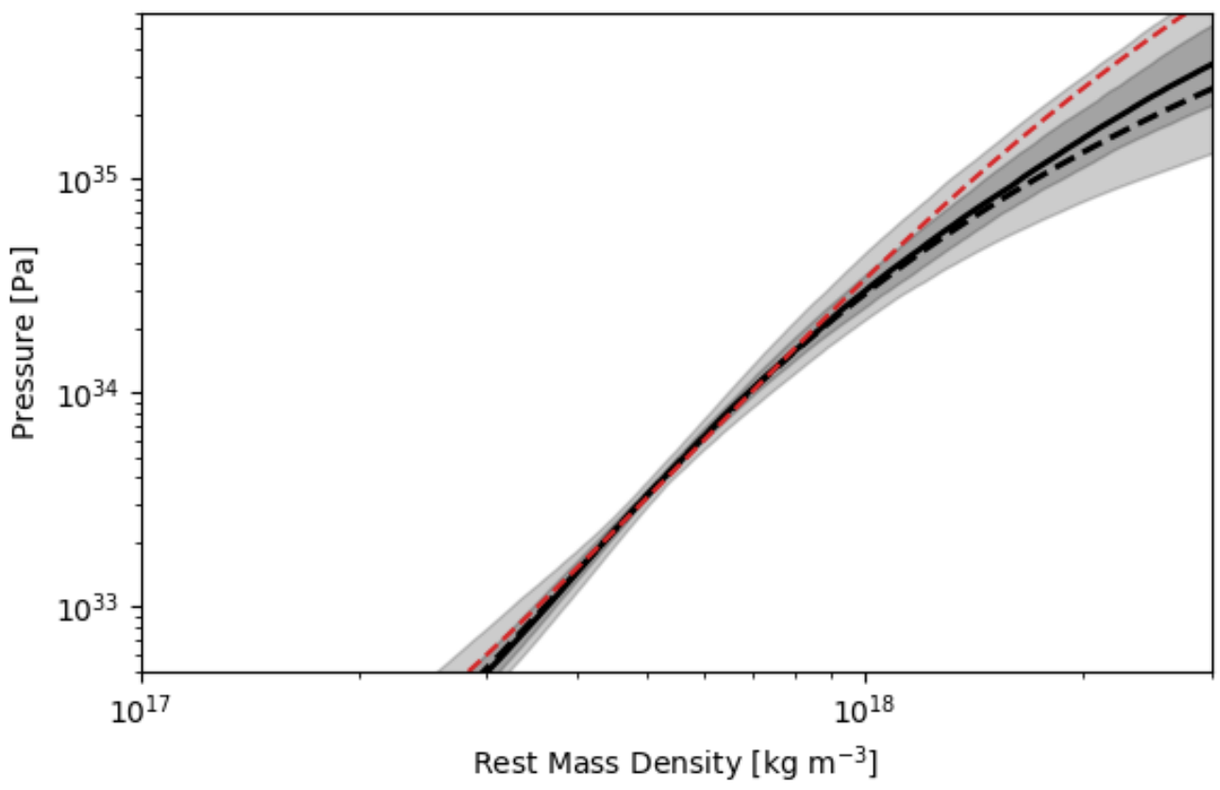
    $\chi = S/M^2 \simeq 0.5(f\,{\rm ms})$
- BNS mass/spin distribution has lots of value itself!
  - constrain NS spin down models [Zhu et al 1711.09226]
  - SN physics (natal spins/masses) … and **impacts ejecta for BNS mergers**

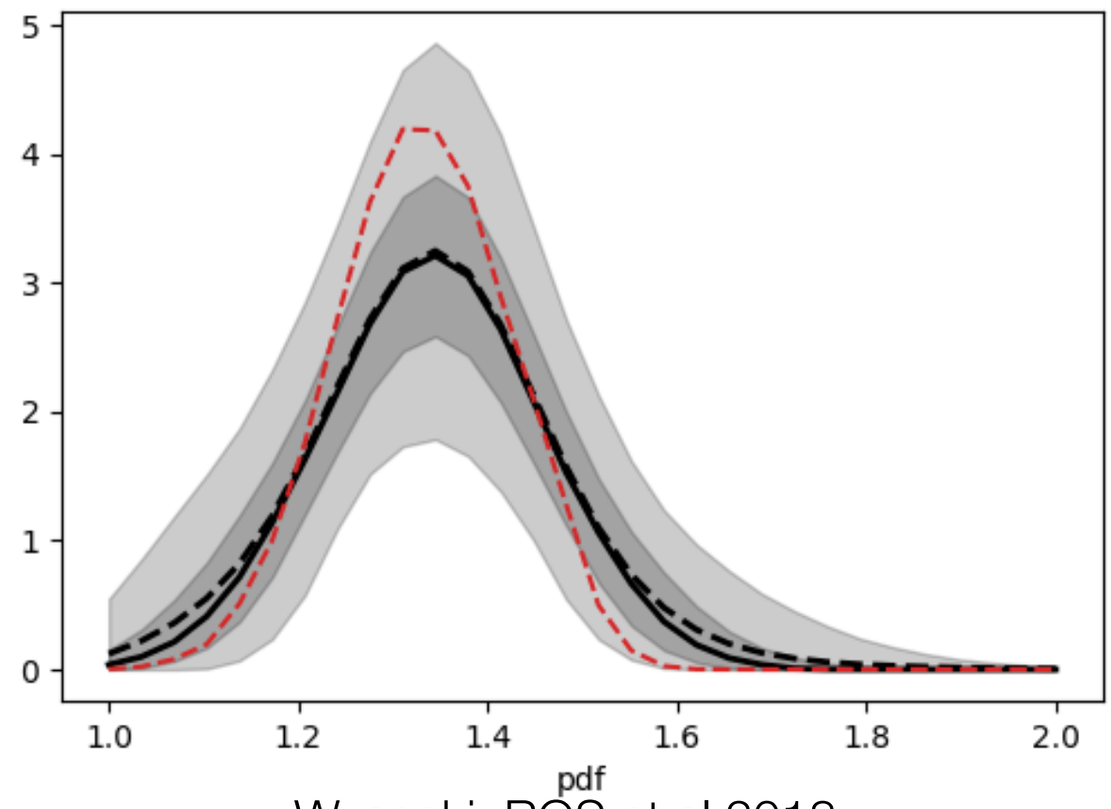
Most et al 2019
East et al 2019



Nuclear equation of state: Many observations

- Joint distribution: **mass, mass ratio, spin, tides**
  - Needed/valuable due to correlated measurement uncertainties
- Synthetic data example (APR4, narrow BNS masses,7 **loud** events)
  - Same code can immediately exploit new constraints (EM BNS mergers, X-ray,…)





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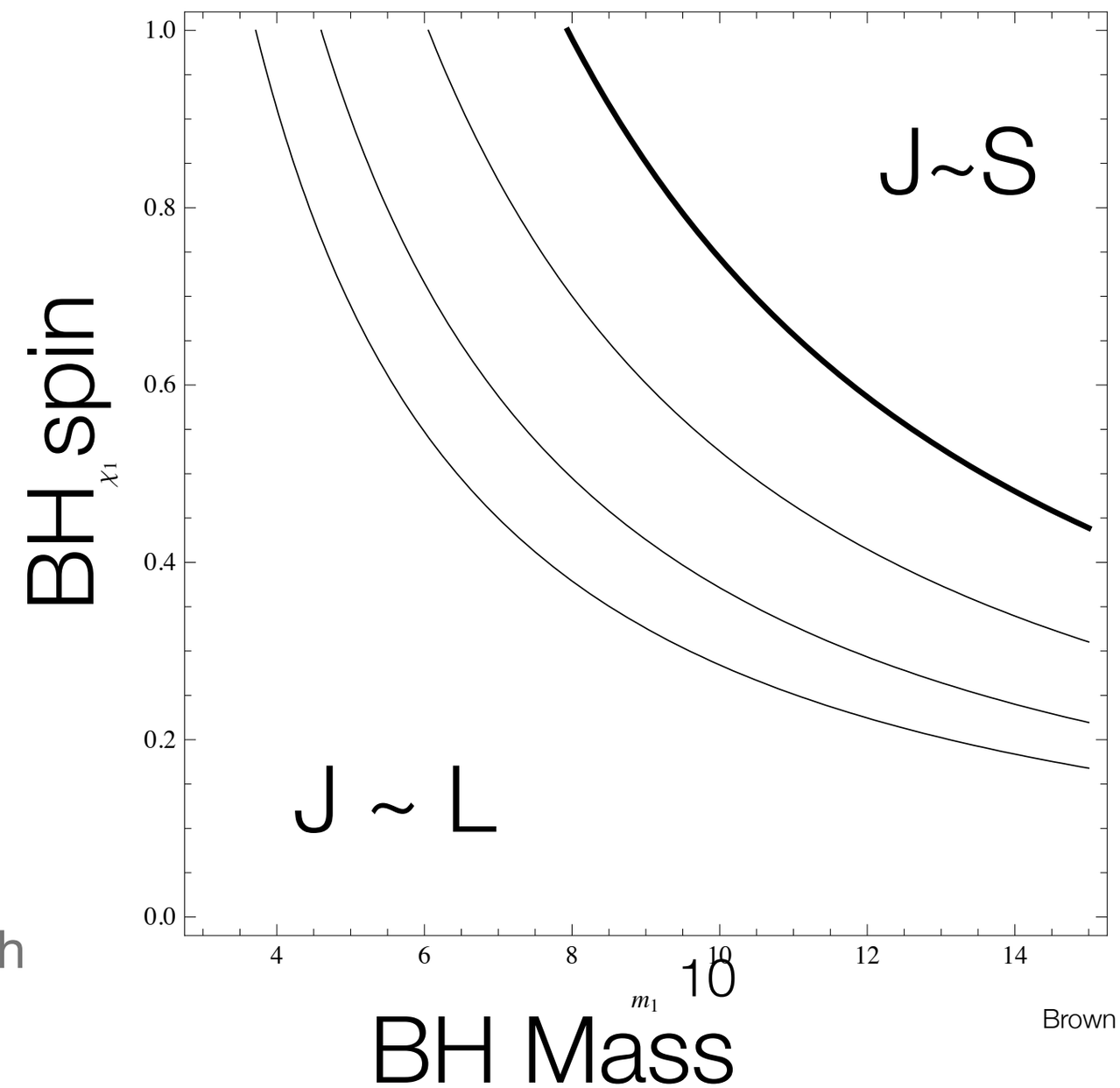
Nuclear equation of state

- Other news:
  - Models: Improved parameterizations/nonparametric, nuclear theory inputs, etc
    - e.g., Essick 2018 (1811.12529), Reddy 2019, …
  - Complementary data:
    - NICER (radius measurements from X-ray bursts) soon
    - New NS with high mass (2.17$\pm$ 0.1) (PSR J0740+6620, Cromartie et al 2019)
  - Modeling work:
    - Debate on lower bound on tides set by large ejecta (Radice 2018-> Kiuchi et al 2019)
  - Comparisons of EOS to GW observations:
    - Updated analysis from LIGO pending, comparing different EOS

Beyond the mass distribution: Power of spin

- Misalignments trace key kinematic effects (kicks or dynamics)
- "Single spin" (e.g., unequal mass or BH-NS binary):
  - Key misalignment is ~ *conserved* since past infinity.
    - Easy to interpret for astrophysics
    - Very many GW and precession cycles *possible*
    - Strong precession requires high mass ratio and BH spin
- "Two spin" (e.g., comparable mass):
  - both spins accessible



Brown et al 201