arXiv:1805.11579 and arXiv:1805.11581

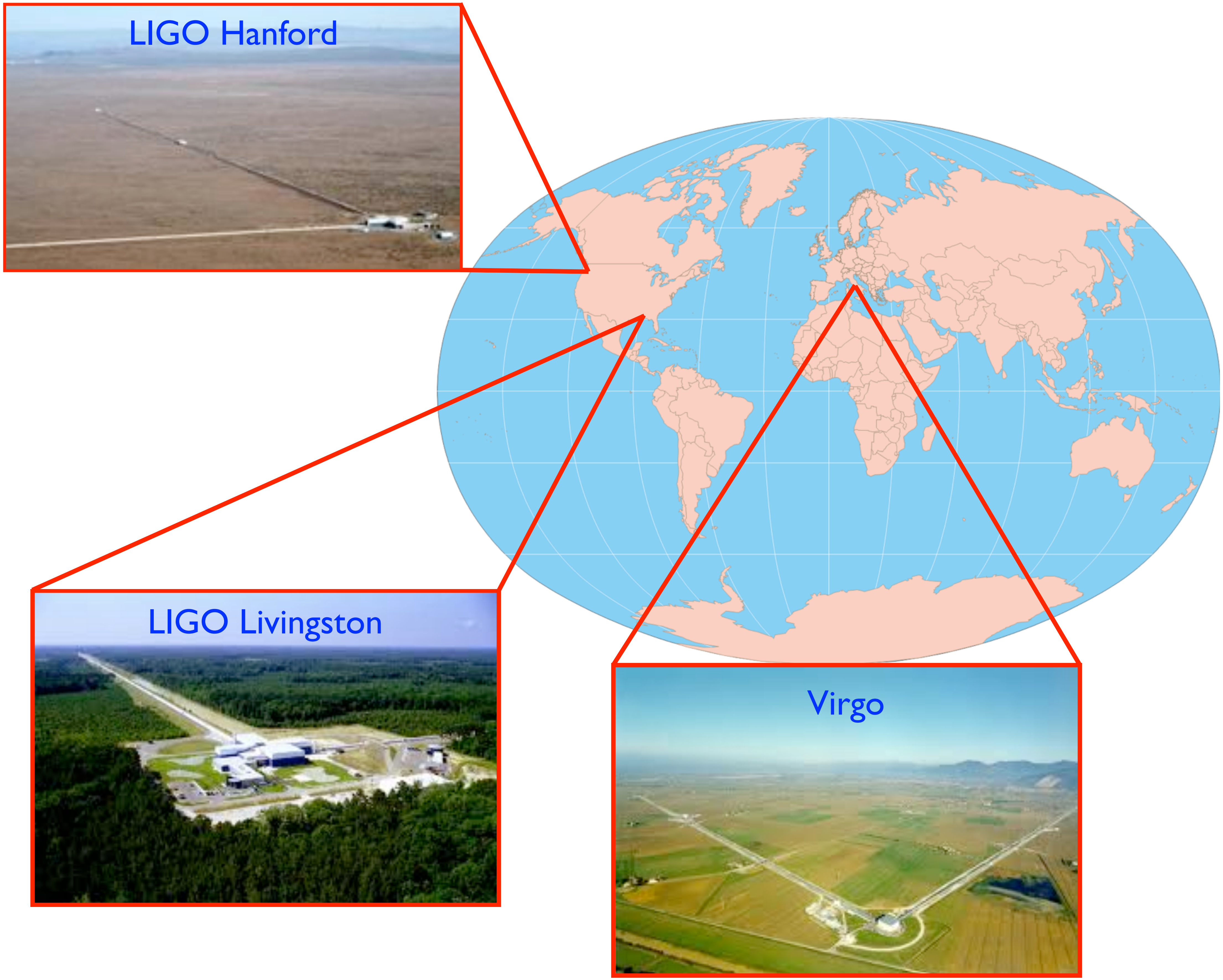
Properties of the binary neutron star merger GW170817

arXiv:1805.11579, arXiv:1805:11581

Ben Lackey on behalf of the LVC
Albert Einstein Institute-Potsdam, Germany

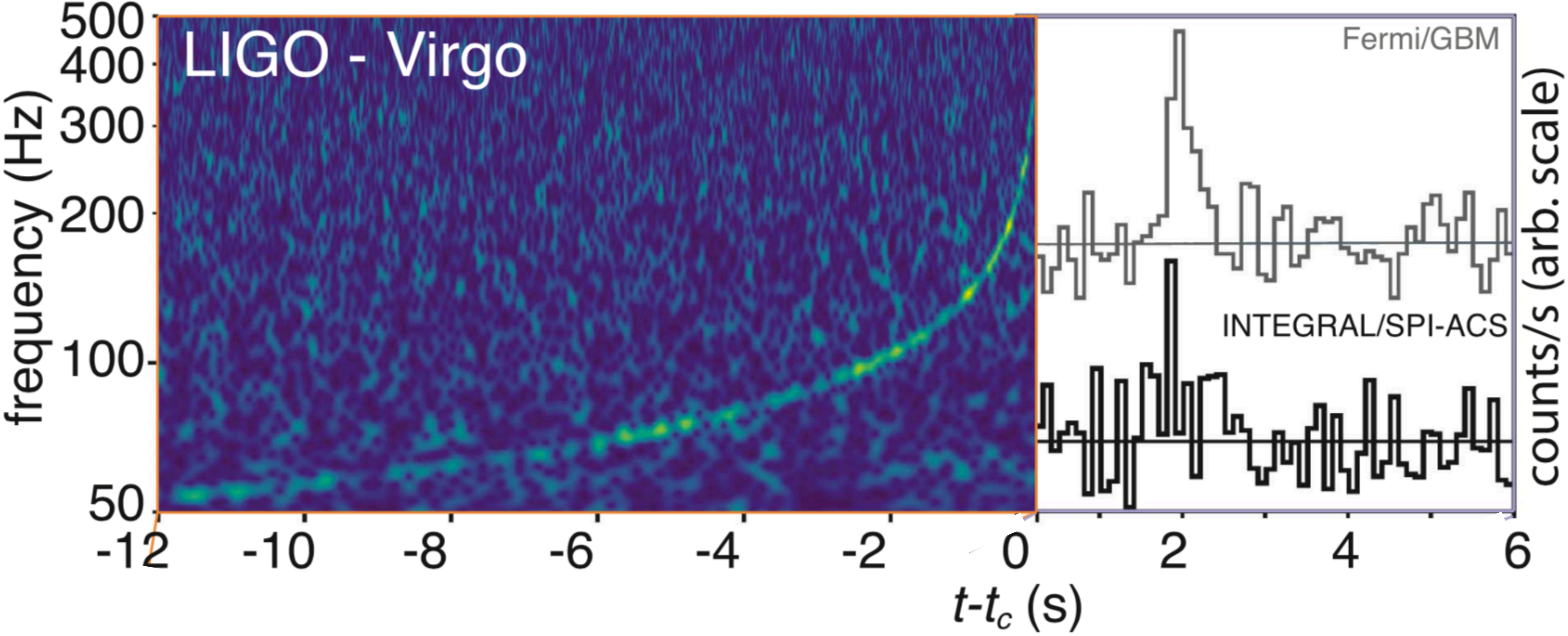
Conference on the Intersections of Particle and Nuclear Physics
Palm Springs, CA, 1 June 2018

Detection of GW170817



Detection of GW170817

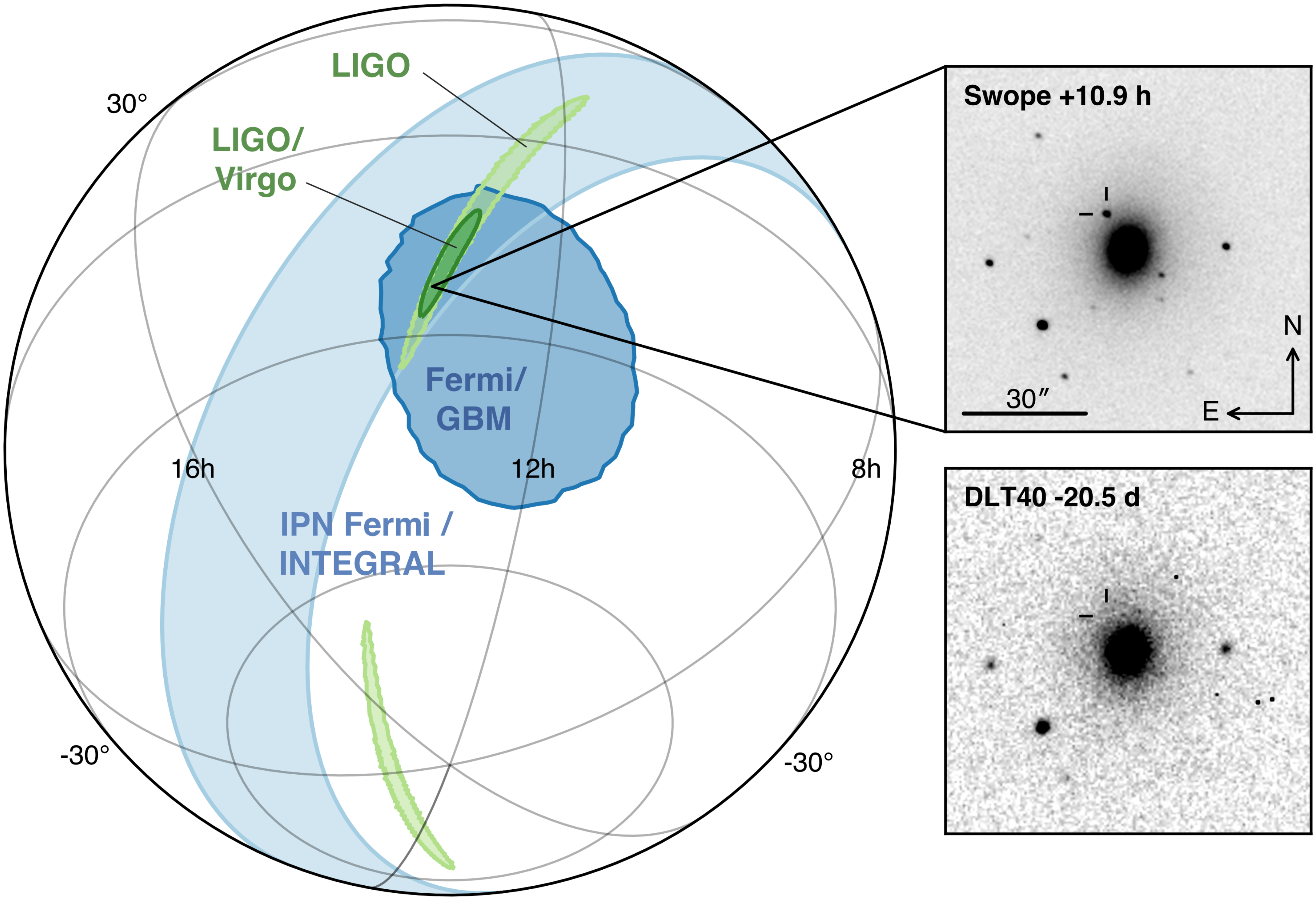
Full GW signal lasted ~100s in band



GRB 1.7s after merger

arXiv:1710.05833

Galaxy NGC4993 confirmed as source



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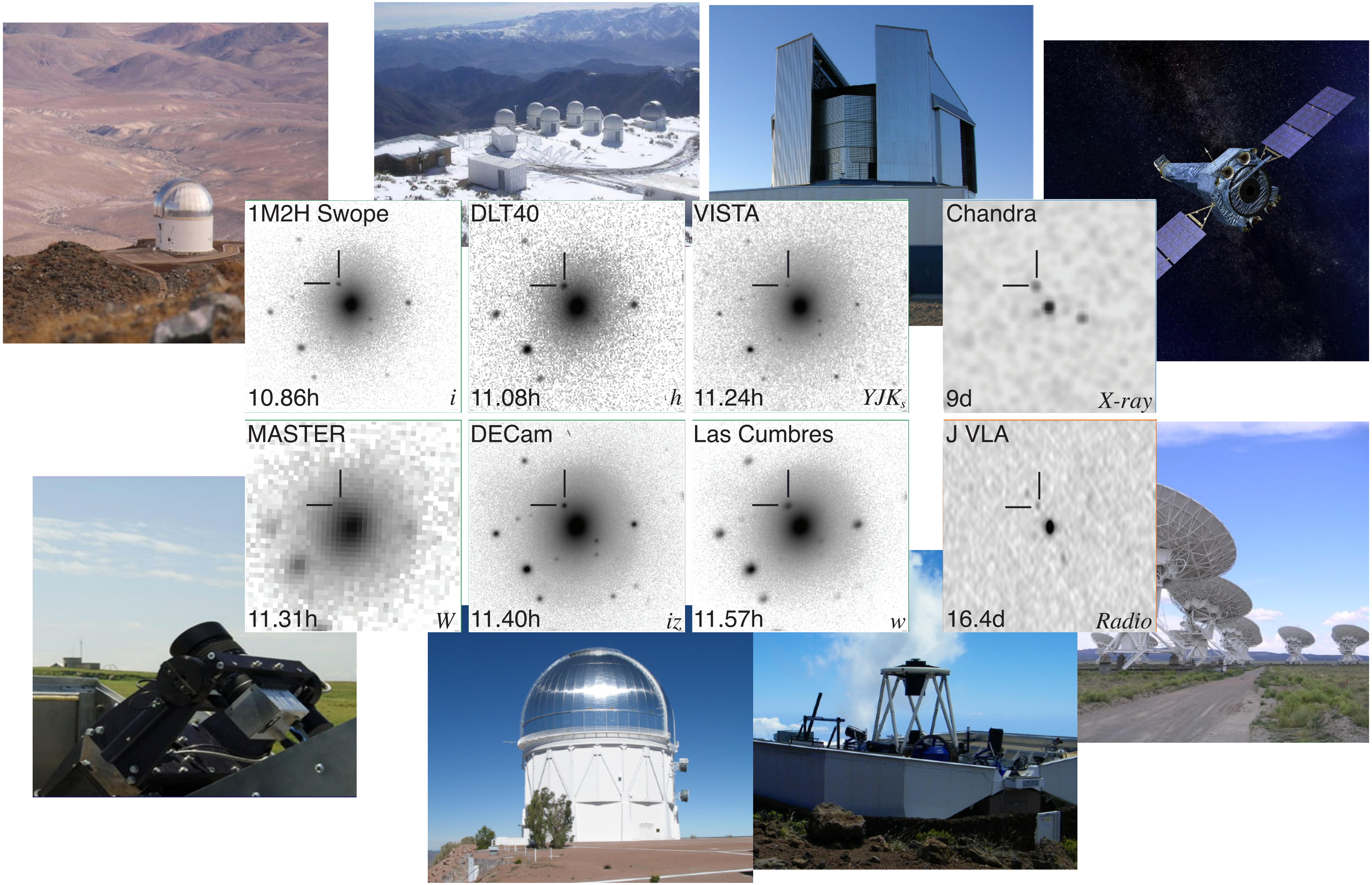


Parameter estimation

- Can estimate the parameters $\vec{\theta}$ of each inspiral from the data ***d*** with Bayes' theorem:

$$\overset{\text{Posterior}}{p(\vec{\theta}|d)} = \frac{\overset{\text{Prior}}{p(\vec{\theta})}\,\overset{\text{Likelihood}}{p(d|\vec{\theta})}}{\underset{\text{Evidence}}{p(d)}}$$

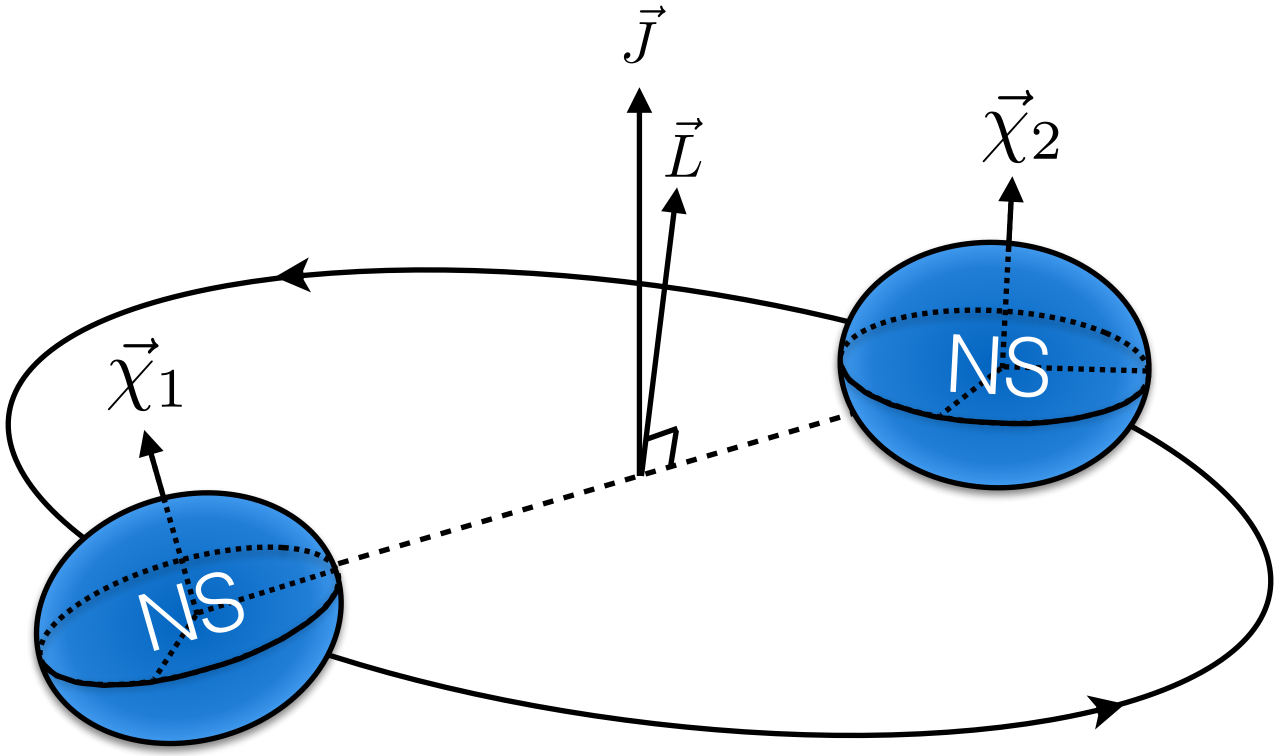
- Time series of stationary, Gaussian noise ***n*** has the distribution

$$p_n[n(t)] \propto e^{-(n,n)/2} \qquad (a,b) = 4\mathrm{Re}\int_0^\infty \frac{\tilde{a}(f)\tilde{b}(f)}{S_n(f)}\,df$$

- (data from detector ***d***) = (noise ***n***) + (model of GW signal $m(\vec{\theta})$)

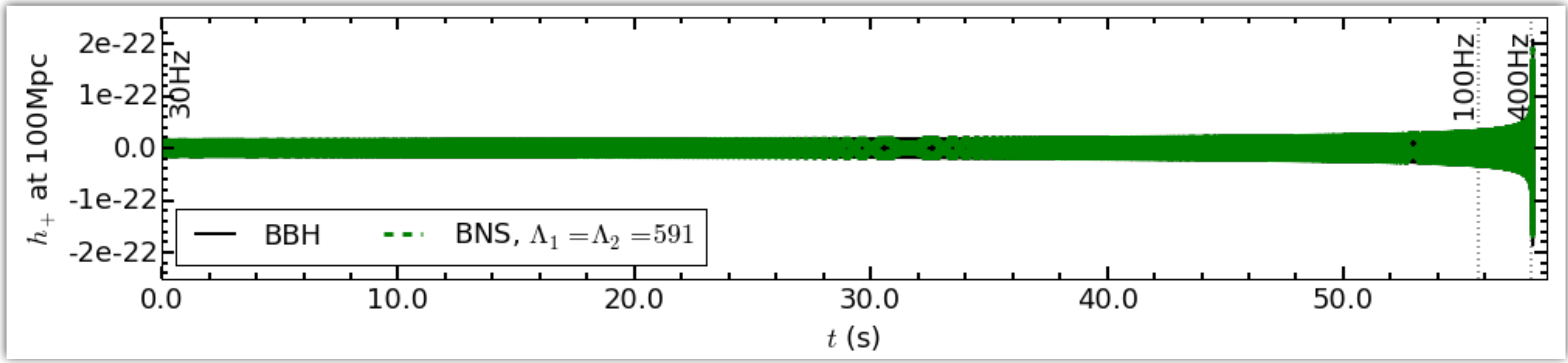
$$p(d|\vec{\theta}) \propto e^{-(d-m,d-m)/2}$$

Structure of waveforms



$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

$$\Phi(f) = 0\mathrm{PN}(f;\mathcal{M})\left[1 + 1\mathrm{PN}(f;q) + 1.5\mathrm{PN}(f;q,\vec{\chi}_1,\vec{\chi}_2) + 2\mathrm{PN}(f;q,\vec{\chi}_1,\vec{\chi}_2) + \cdots + 5\mathrm{PN}(f;q,\Lambda_1,\Lambda_2)\right]$$



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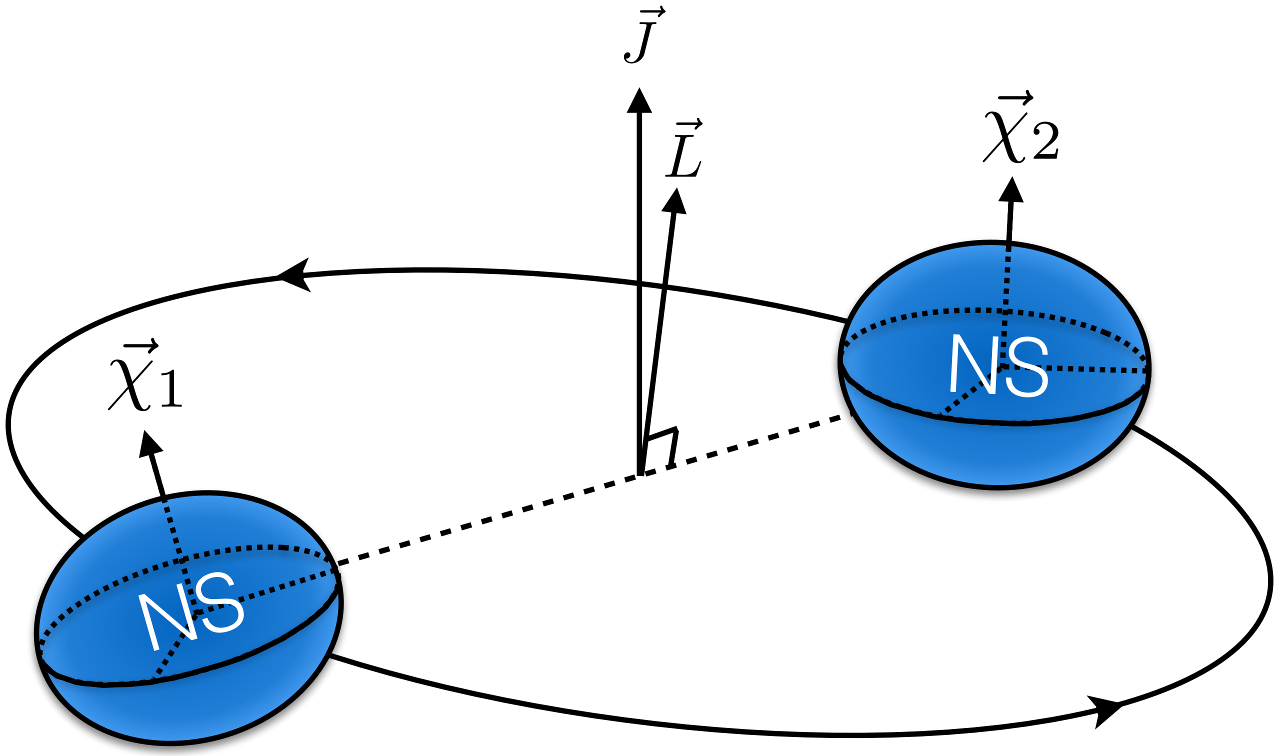
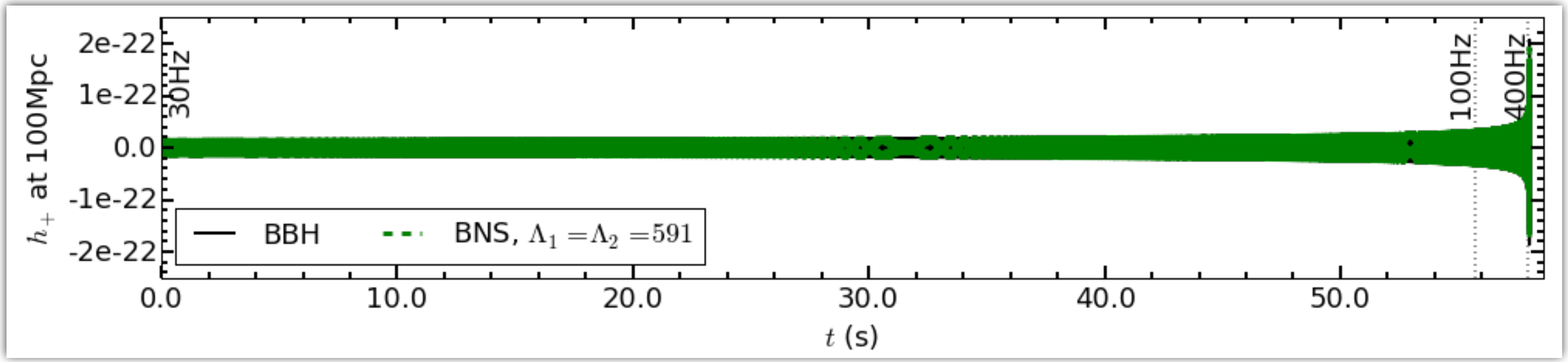


$$q = m_2/m_1$$

$(v/c)^2$

$$\Phi(f) = 0\mathrm{PN}(f;\mathcal{M})\,[1 + 1\mathrm{PN}(f;q) + 1.5\mathrm{PN}(f;q,\vec{\chi}_1,\vec{\chi}_2) + 2\mathrm{PN}(f;q,\vec{\chi}_1,\vec{\chi}_2) + \cdots + 5\mathrm{PN}(f;q,\Lambda_1,\Lambda_2)]$$



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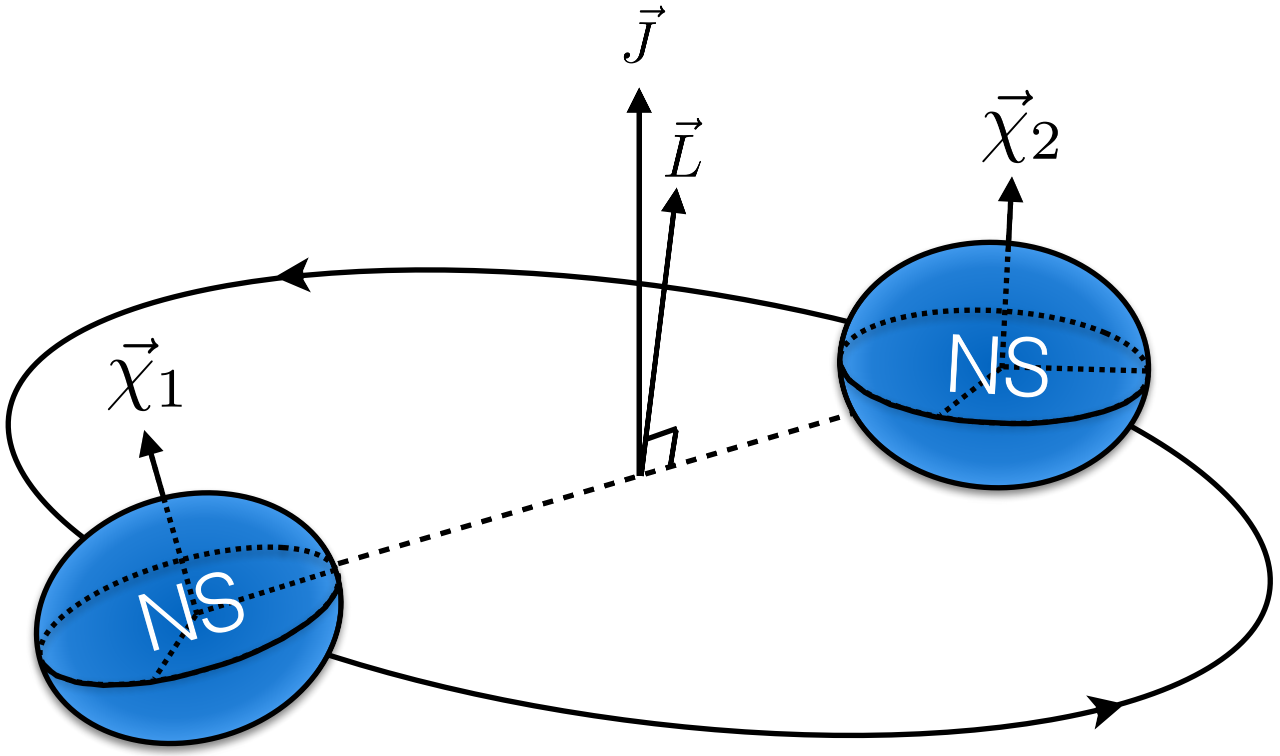

$$\chi_{\rm eff} = \frac{m_1\chi_{1z} + m_2\chi_{2z}}{m_1 + m_2}$$

$(v/c)^2$ $(v/c)^3$

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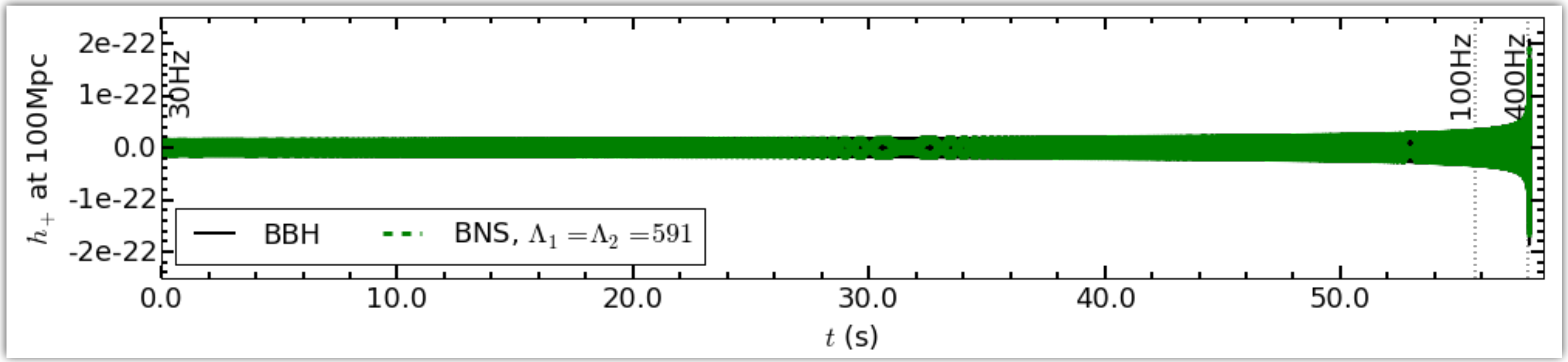

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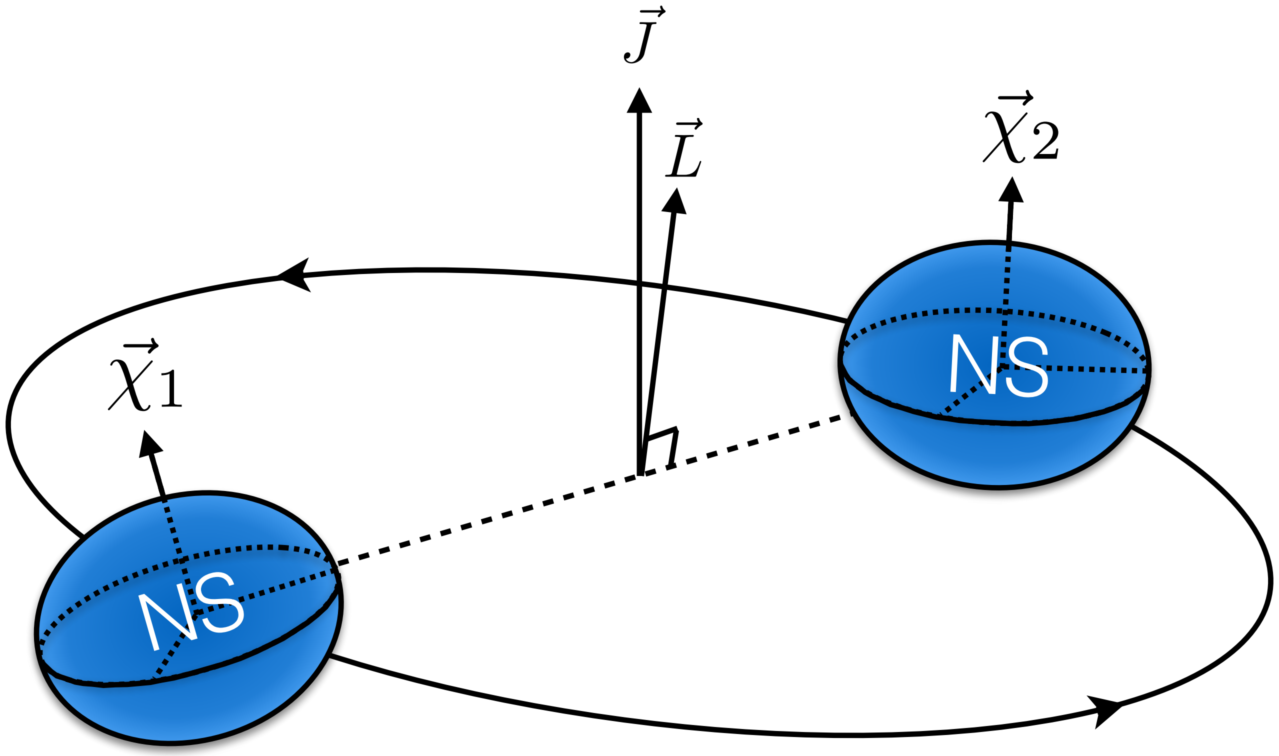

Spin-spin terms,
spin-induced
quadrupole moment

$(v/c)^2$ $(v/c)^3$ $(v/c)^4$

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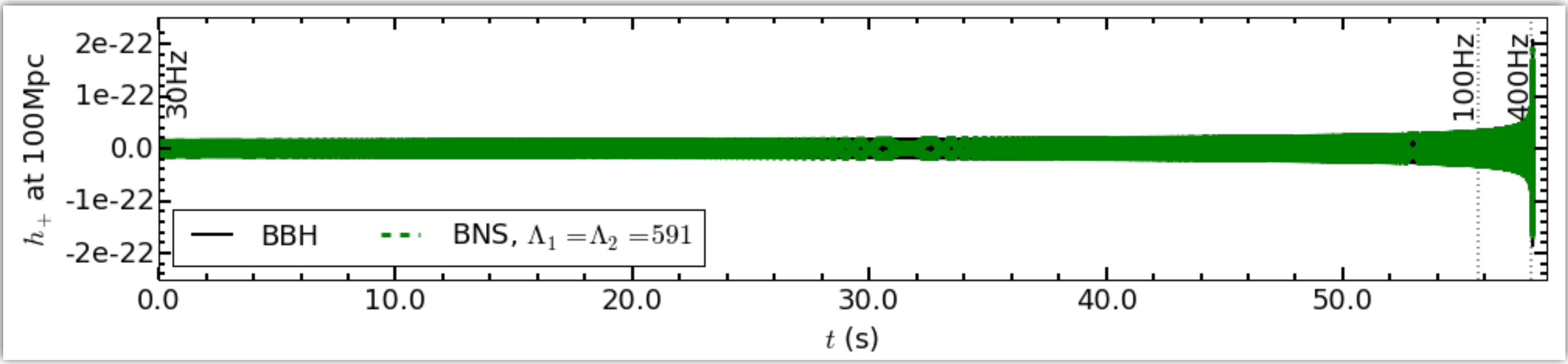

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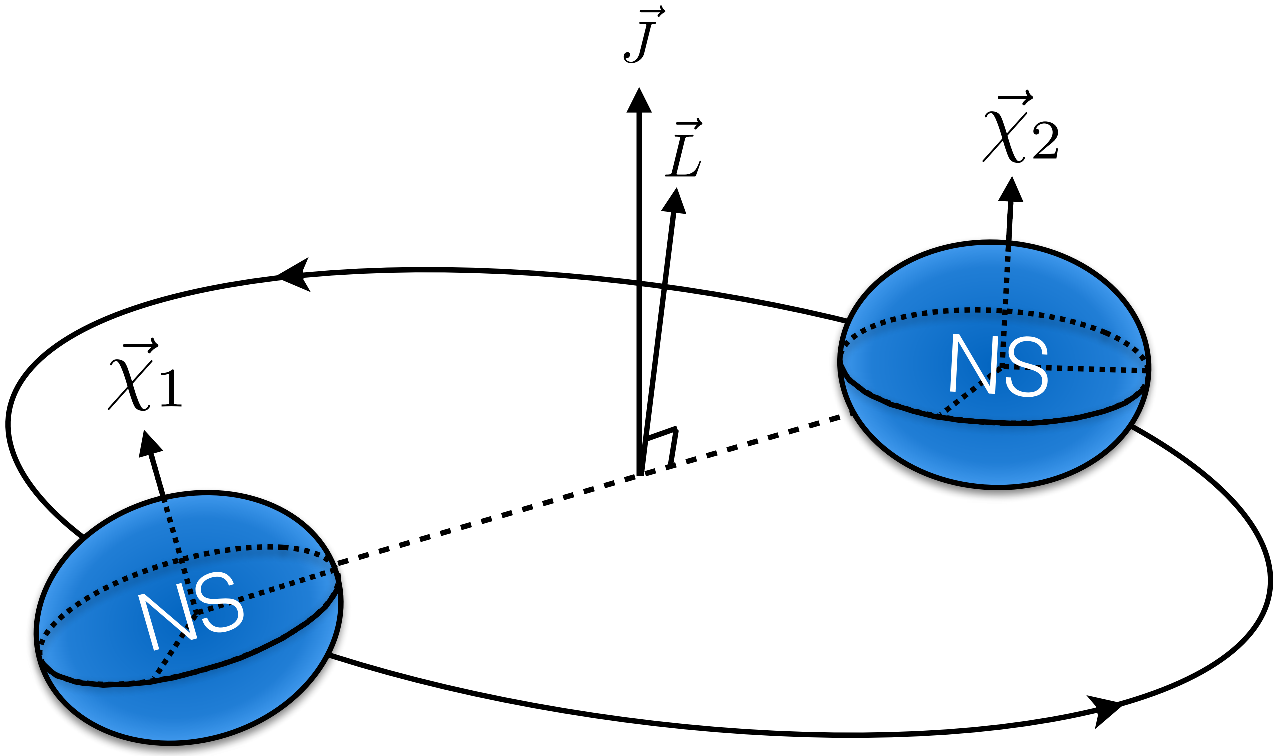
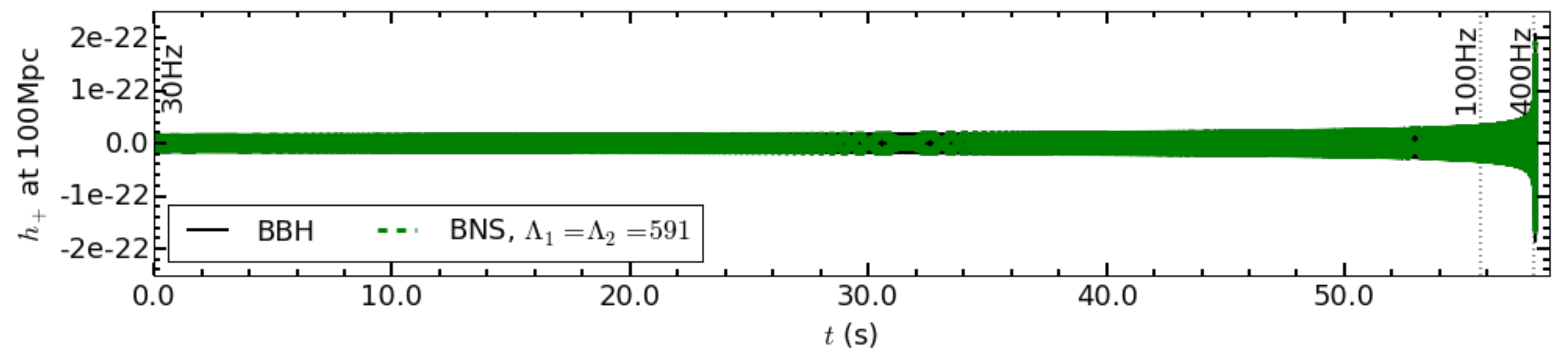


$$\tilde{\Lambda} = \frac{16}{13}\frac{(1+12q)\Lambda_1 + (12+q)q^4\Lambda_2}{(1+q)^5}$$

$(v/c)^2$ $(v/c)^3$ $(v/c)^4$ $(v/c)^{10}$

$$\Phi(f) = 0\mathrm{PN}(f;\mathcal{M})\left[1 + 1\mathrm{PN}(f;q) + 1.5\mathrm{PN}(f;q,\vec{\chi}_1,\vec{\chi}_2) + 2\mathrm{PN}(f;q,\vec{\chi}_1,\vec{\chi}_2) + \cdots + 5\mathrm{PN}(f;q,\Lambda_1,\Lambda_2)\right]$$



Structure of waveforms

- Tidal field $\mathcal{E}_{ij}$ from companion star induces a quadrupole moment Q_{ij} in the NS
- Amount of deformation depends on stiffness of EOS via the tidal deformability Λ:

$$Q_{ij} = -\Lambda(\mathrm{EOS}, m) m^5 \mathcal{E}_{ij}$$

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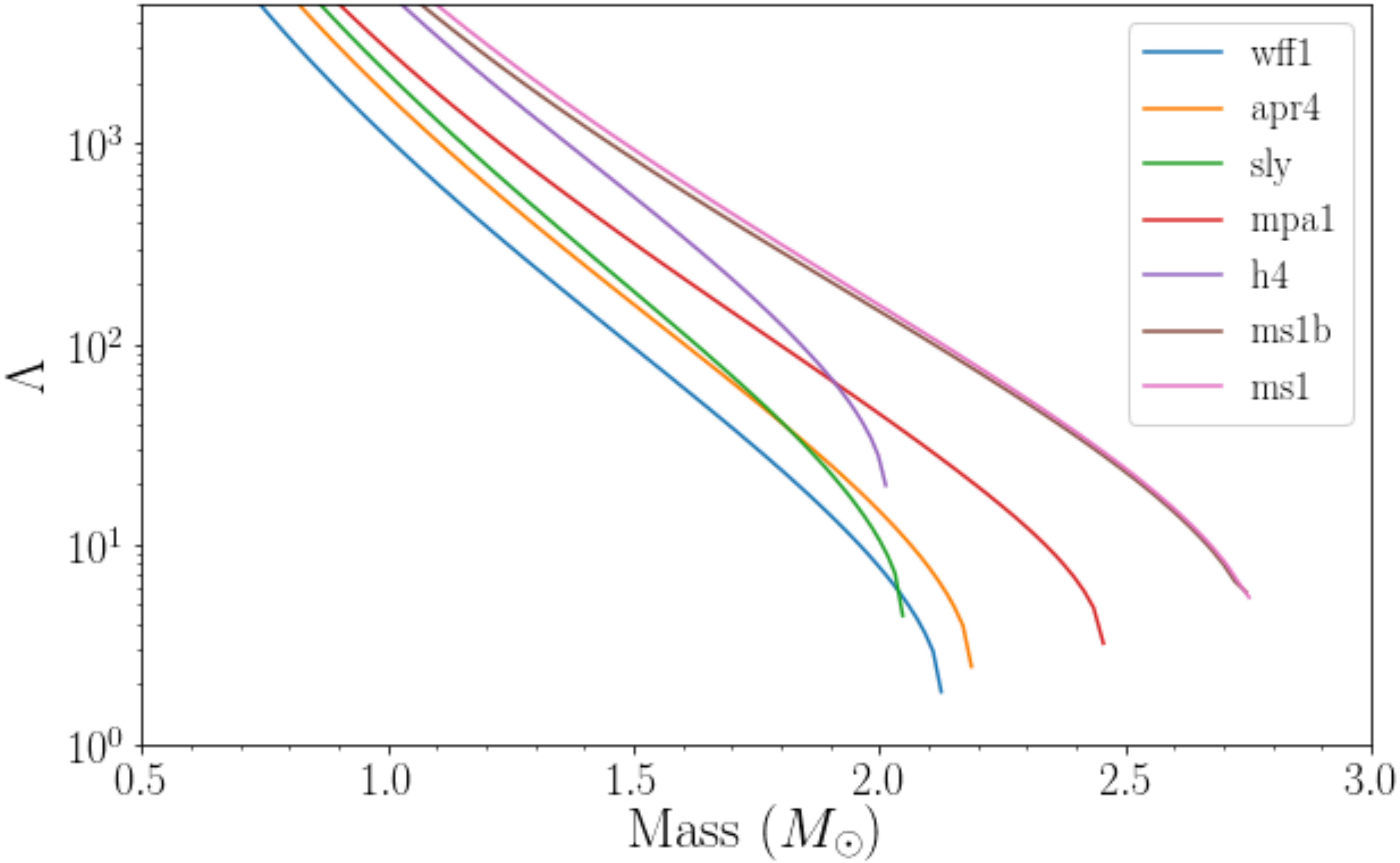
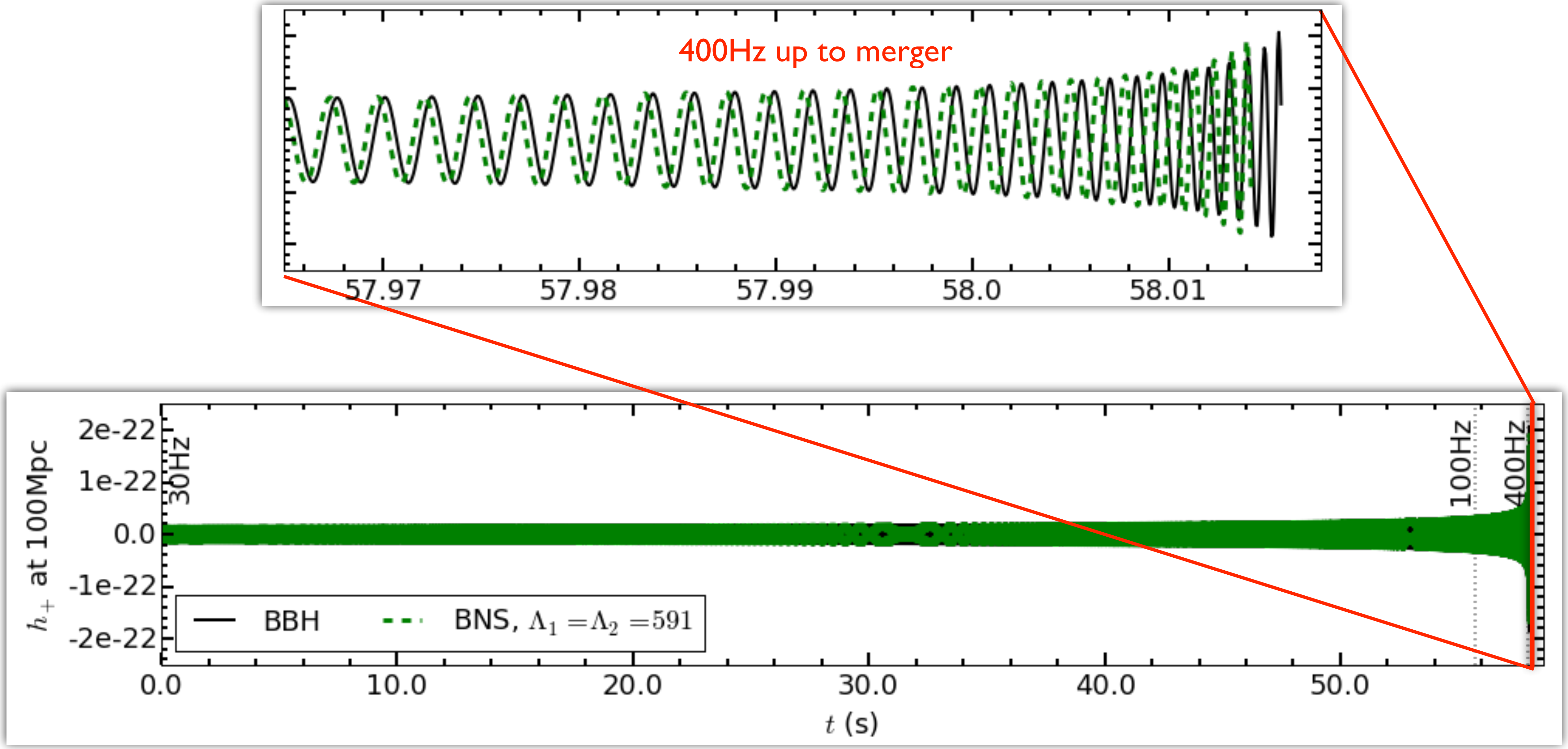


Structure of waveforms

Tidal effects $O(10)$ radians up to merger

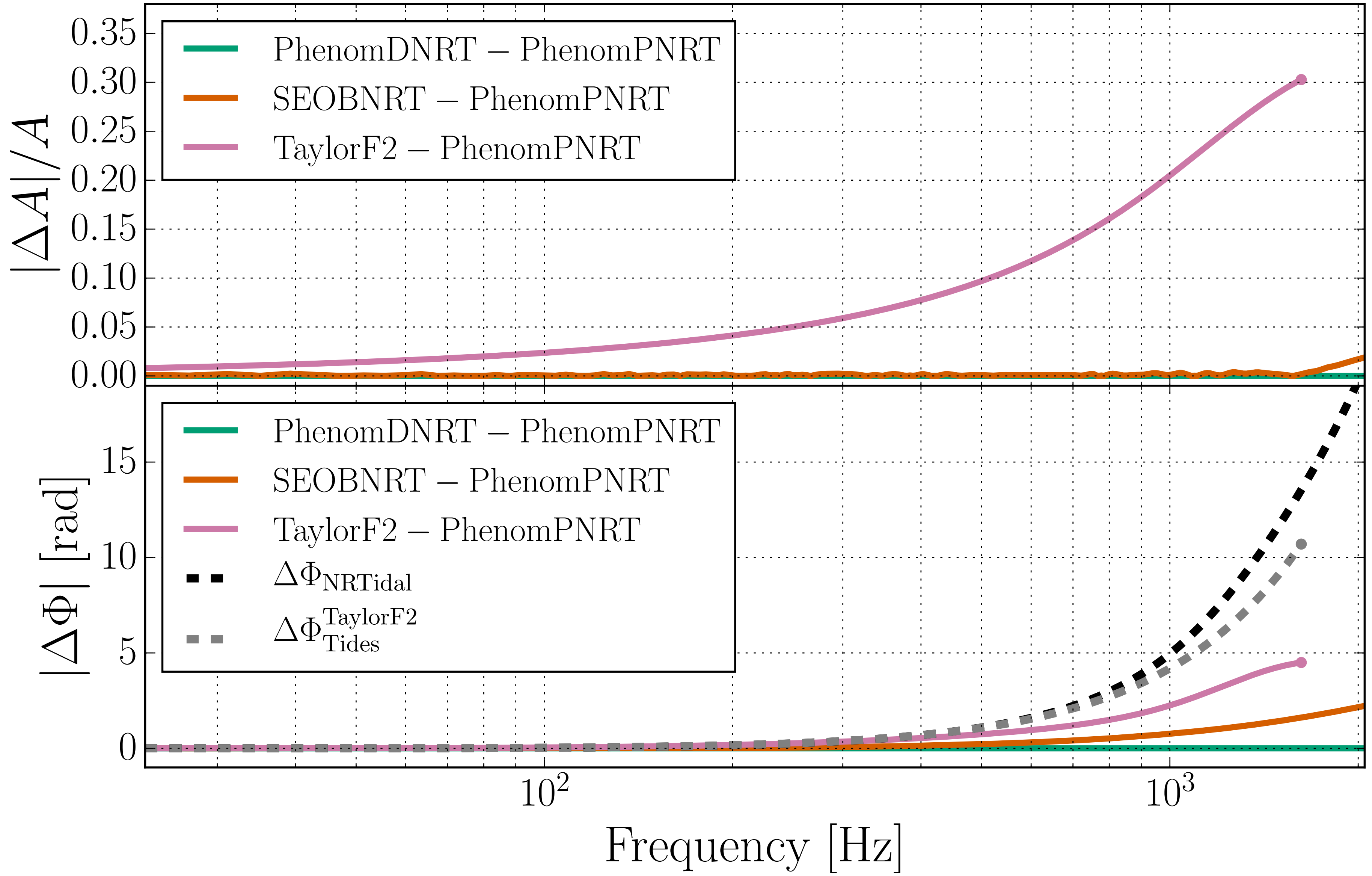


Waveform models

Model name	BBH- baseline	Tidal effects	Spin-Induced quadrupole effects	precession
TaylorF2	3.5PN (PP [56], SO [57] SS [58–61])	6PN [62]	None	✗
SEOBNRT	SEOBNRv4_ROM [63, 64]	NRTidal [65, 66]	None	✗
PhenomDNRT	IMRPhenomD [67, 68]	NRTidal [65, 66]	None	✗
PhenomPNRT	IMRPhenomPv2 [69]	NRTidal [65, 66]	3PN [58–61, 70]	✓

Discovery paper

Main results here



Priors

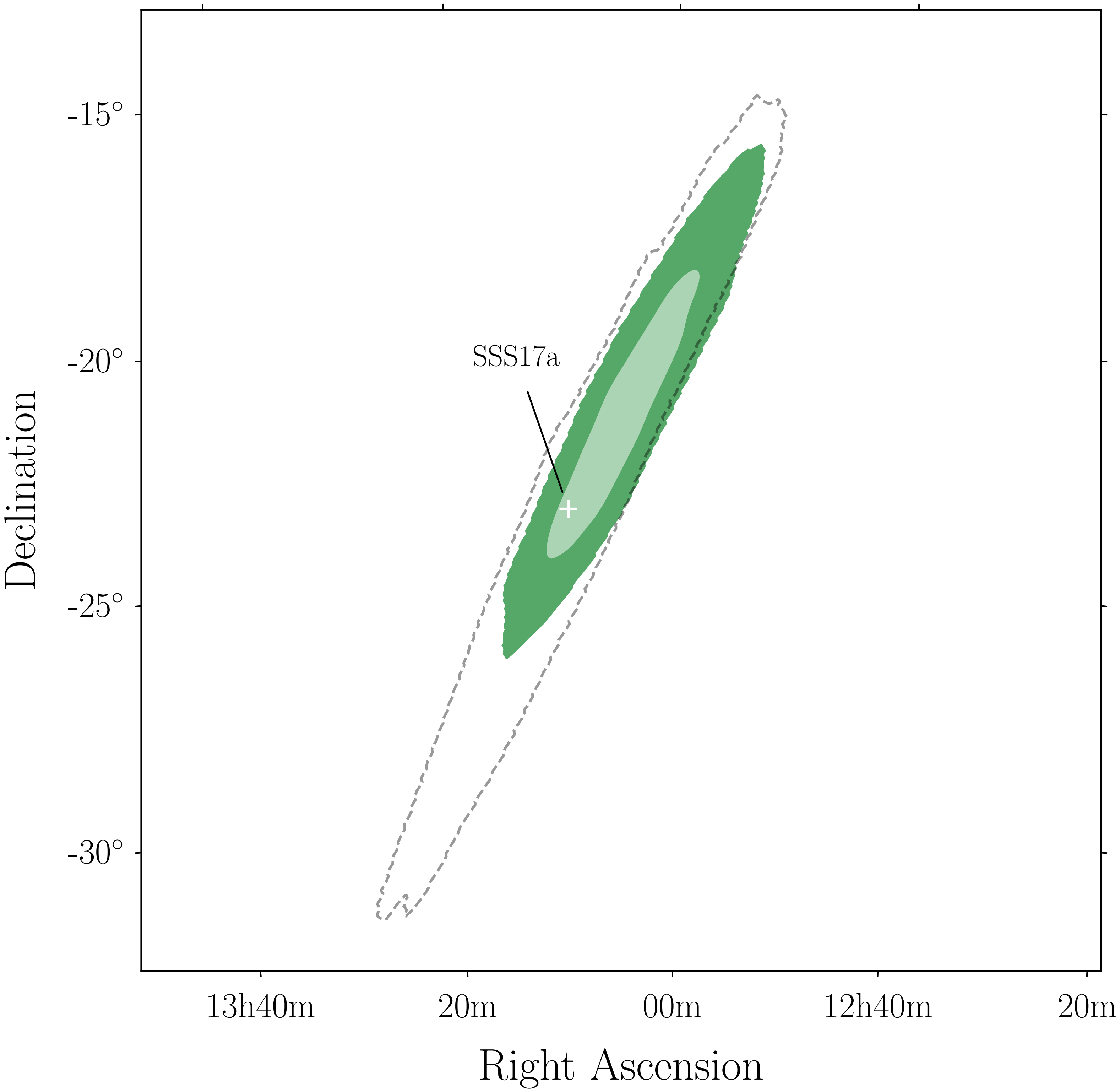
- Fixed sky location to that of NGC4993
- Bounds on masses wide enough to not affect posterior
- Spin priors:
    - Uniform on unit sphere
    - Two spin magnitude bounds: low-spin (<0.05), high-spin (<0.89)
- Tidal parameters Λ_1, Λ_2 uniform in range [0, 5000]

Updated analysis

- Additional waveform models (including precession, spin-induced quadrupole moment, tidal effects tuned to numerical simulations)
- Starting frequency of 23Hz (~3200 cycles) instead of 30Hz (~2700 cycles)
- Fixed sky location to that of NGC4993
- Improved Virgo calibration

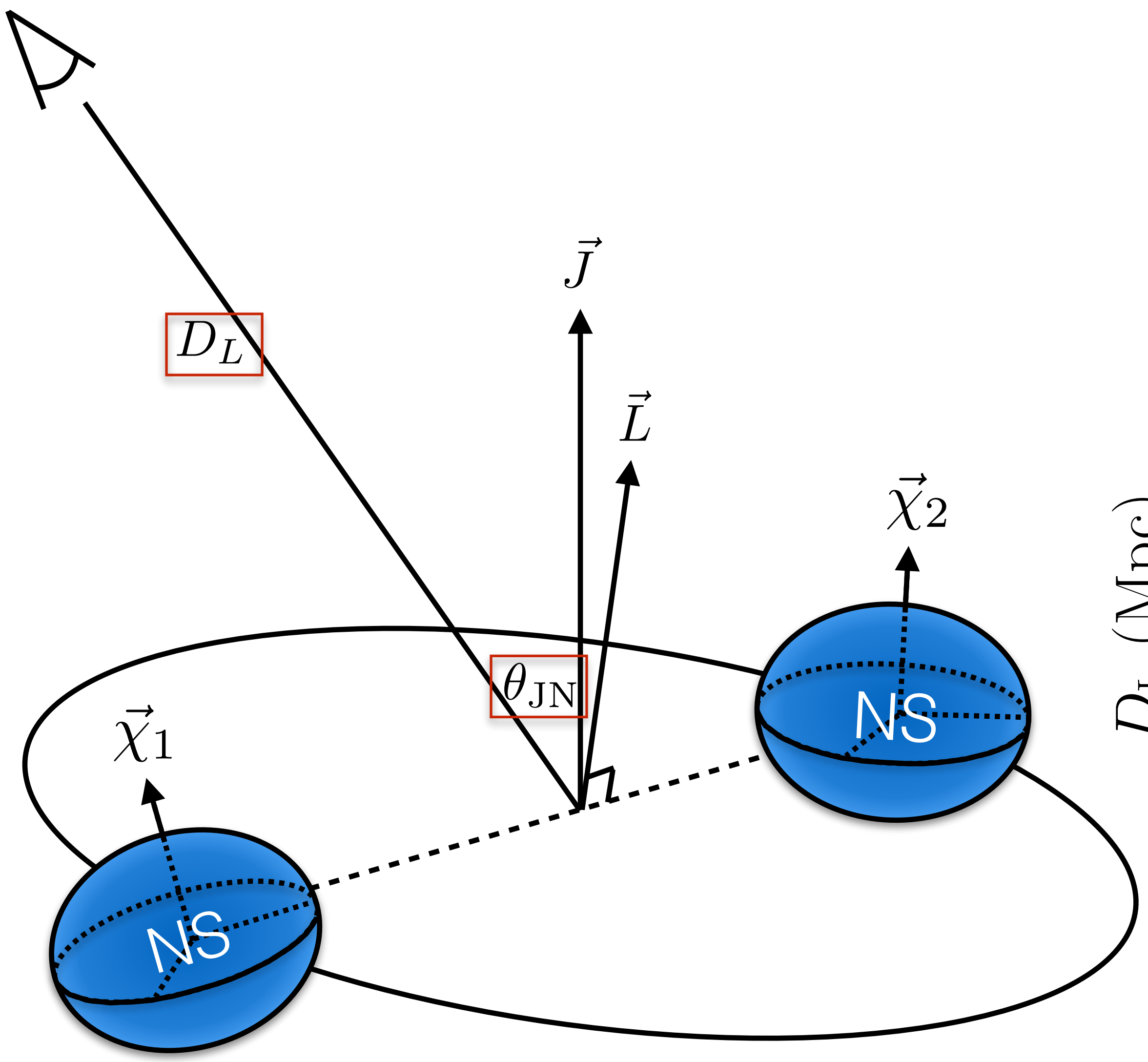
Sky position

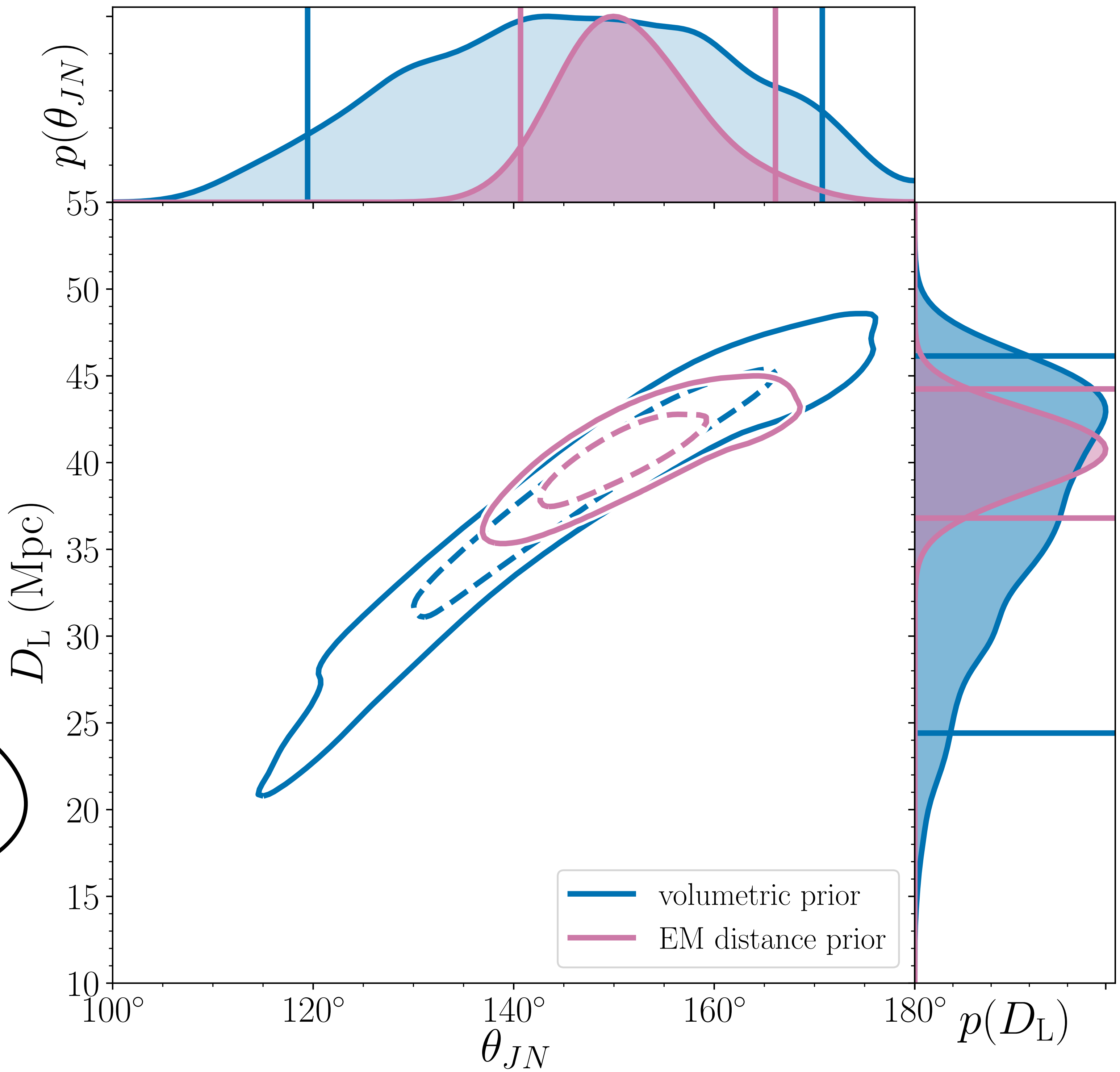
- 90% credible region has decreased from 28 deg² to 16 deg²



Distance-inclination

- Blue: Uniform in volume prior
- Pink: Distance to NGC4993 (arXiv:1801.06080) from EM observations
  - Angle between face-off and line of sight: $14°–40°$

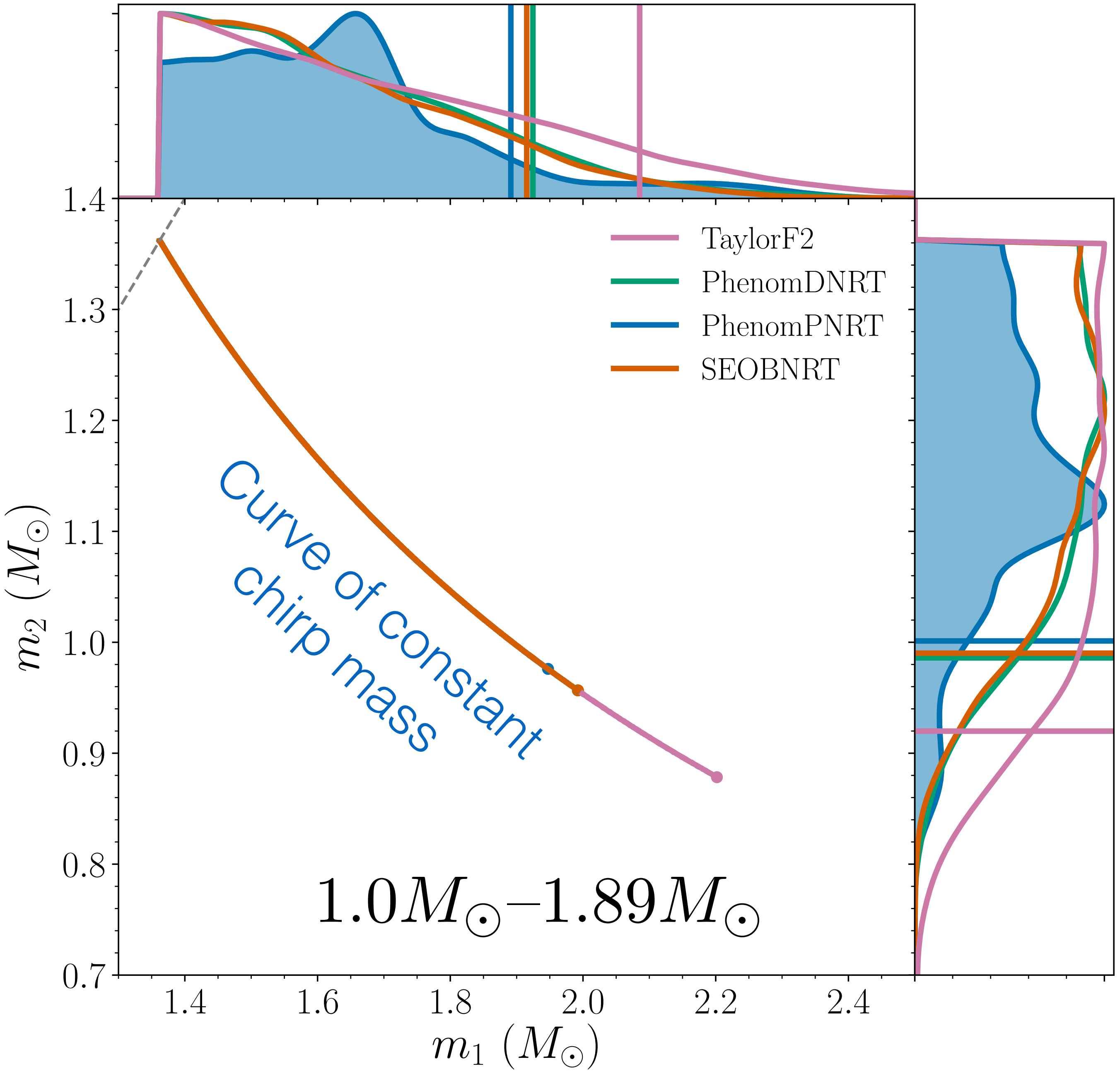




Masses

- 4 waveform models give consistent, but not identical, results
- Bounds ~10-20% tighter than discovery paper

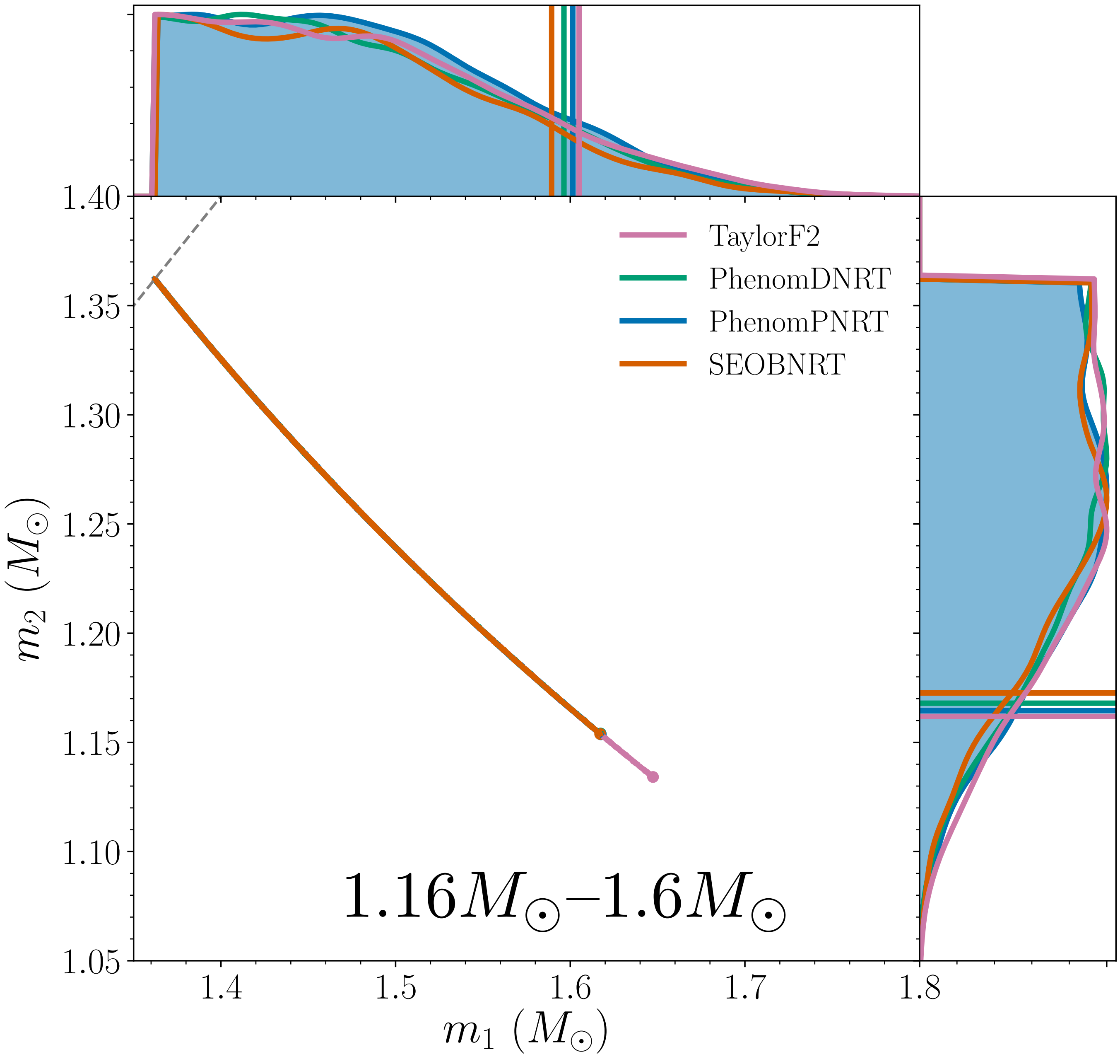
High-spin prior ($\chi < 0.89$)



Curve of constant chirp mass

$1.0 M_\odot$–$1.89 M_\odot$

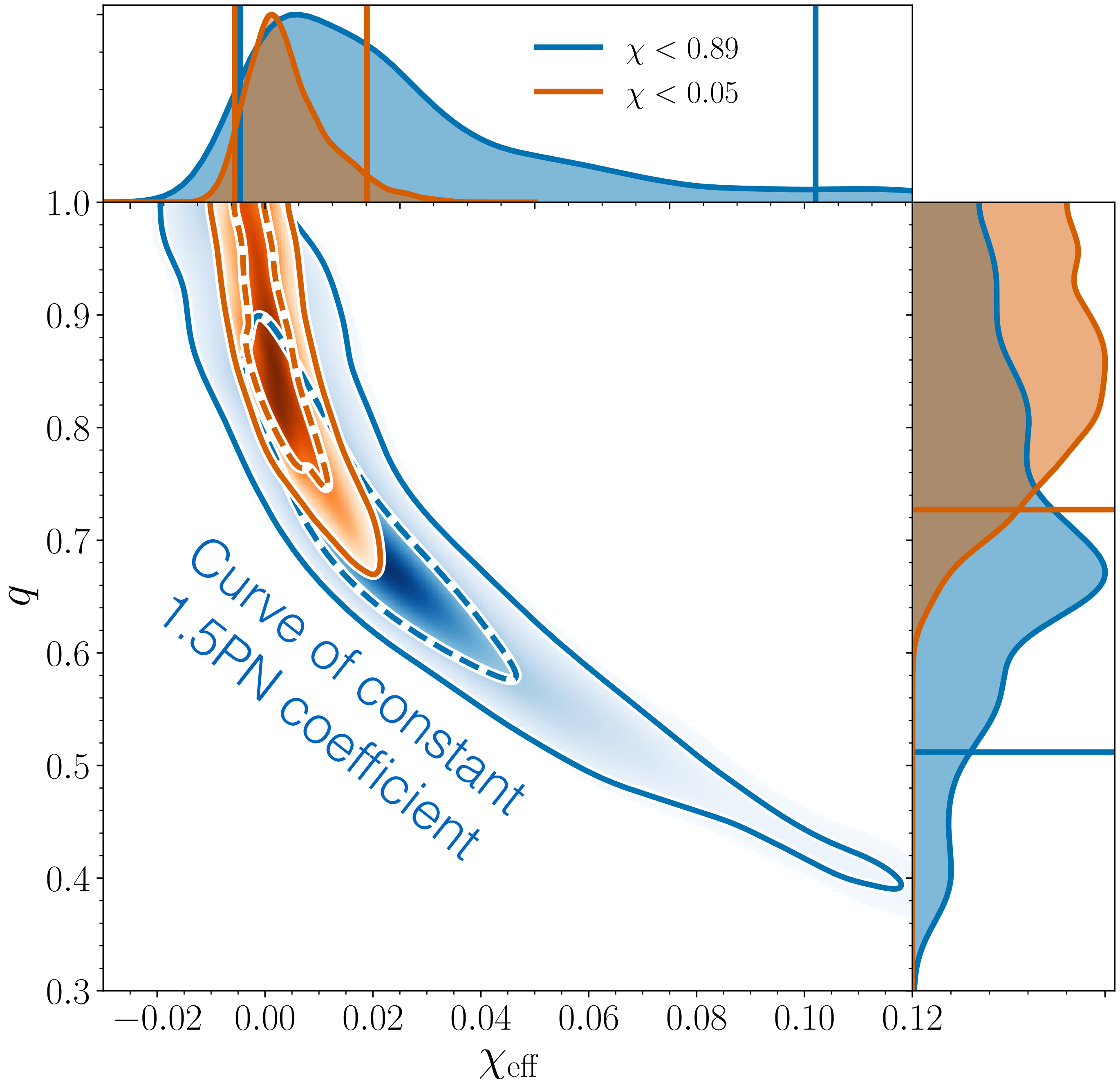
Low-spin prior ($\chi < 0.05$)



$1.16 M_\odot$–$1.6 M_\odot$

Spin aligned with angular momentum

- Posterior on χ_{eff} is asymmetric because negative spins are restricted by q=1 bound
- Consistent for all waveform models
- Low-spin result is highly affected by prior



$$\chi_{\text{eff}} = \frac{m_1\chi_{1z} + m_2\chi_{2z}}{m_1 + m_2}$$

Spin aligned with angular momentum

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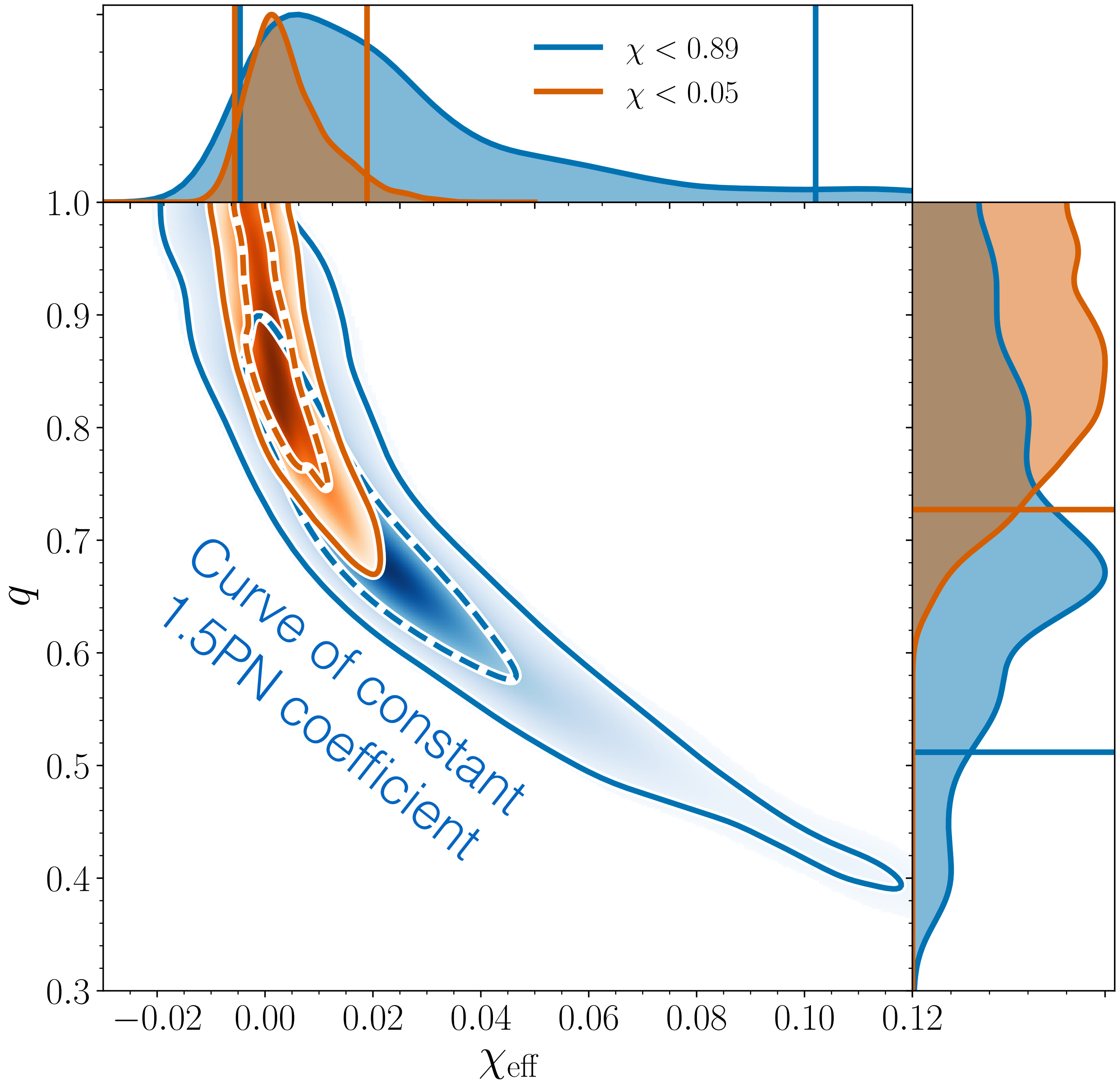

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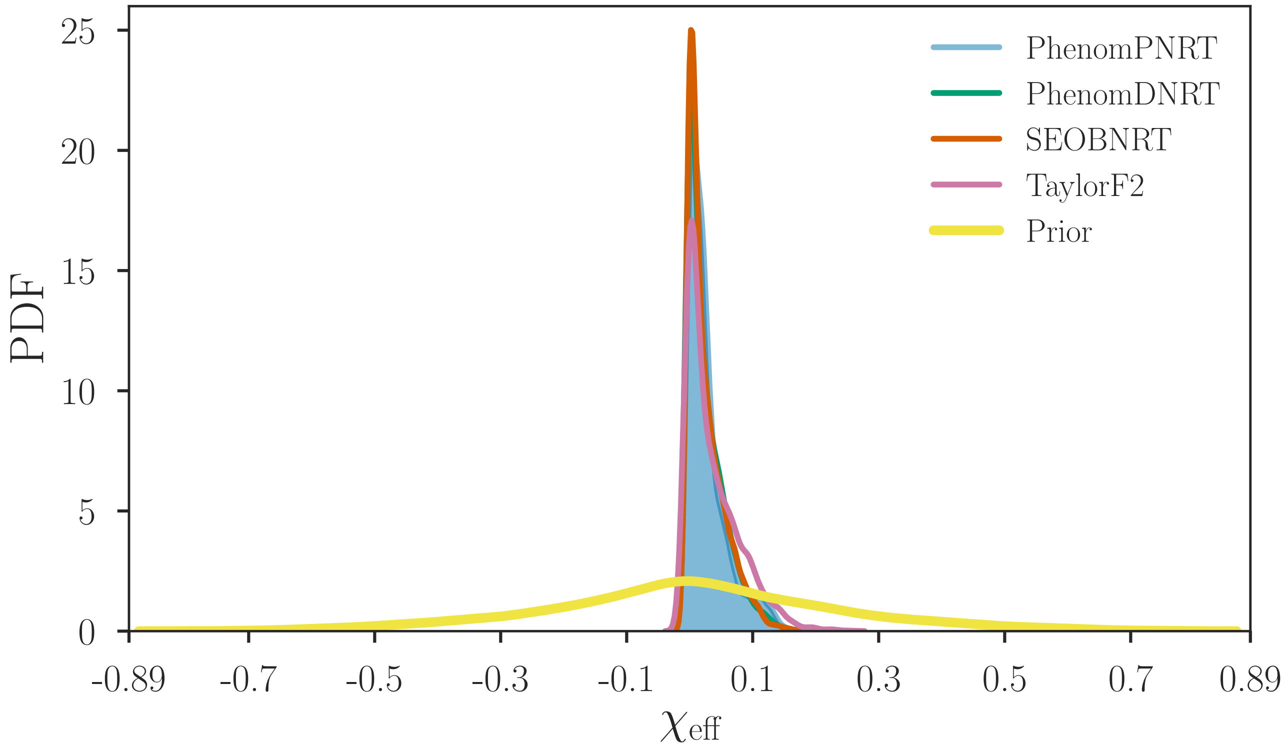

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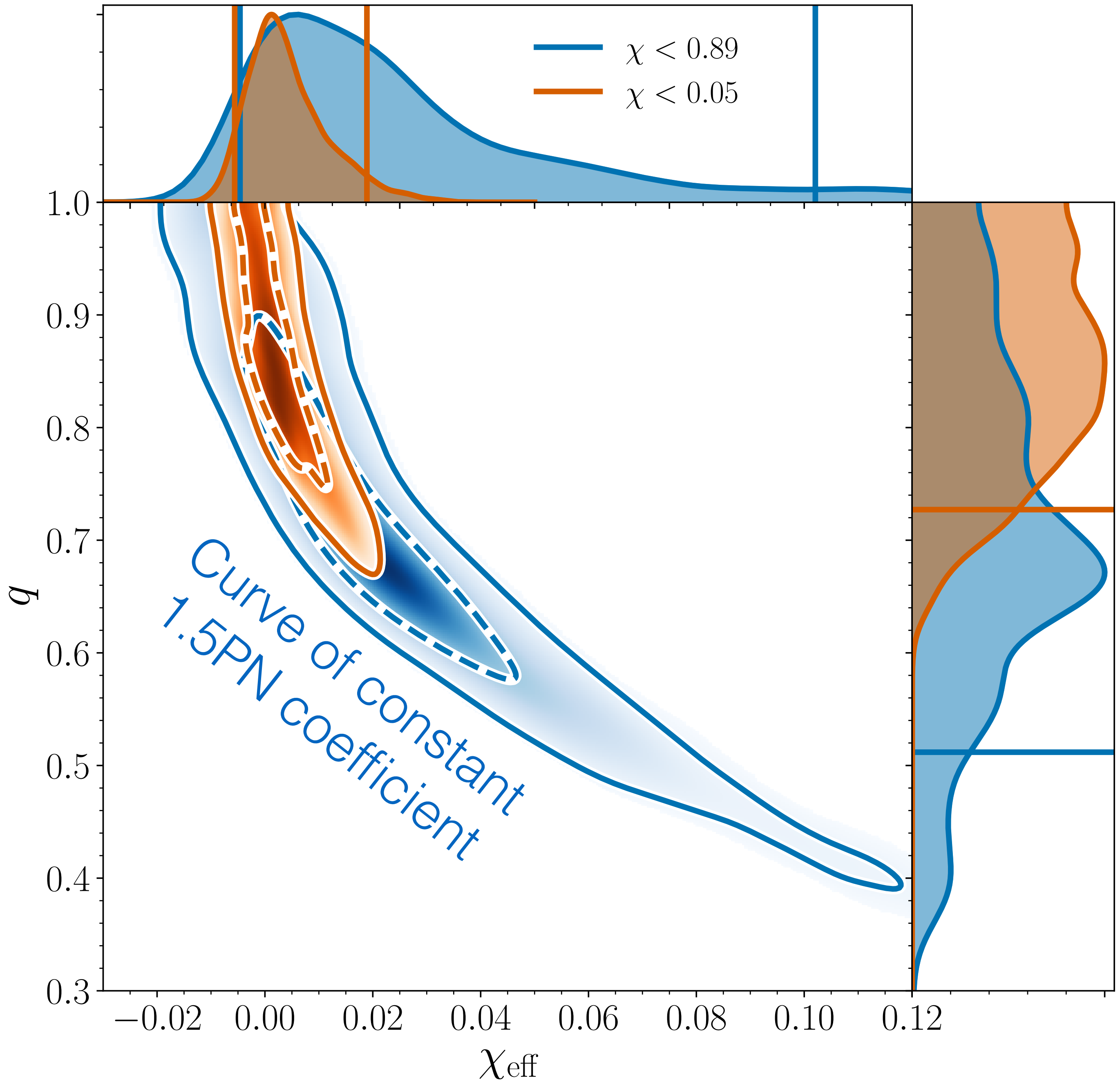
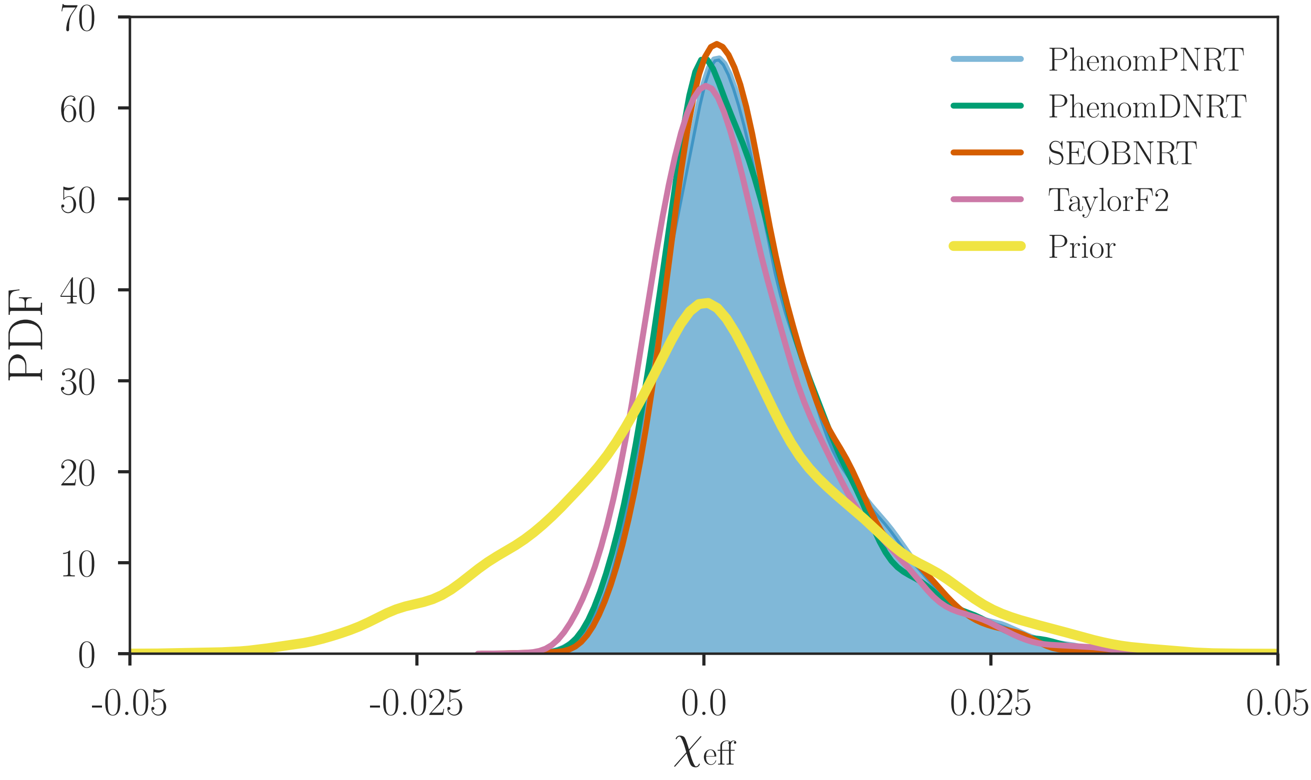


Curve of constant 1.5PN coefficient

$$\chi_{\mathrm{eff}} = \frac{m_1\chi_{1z} + m_2\chi_{2z}}{m_1 + m_2}$$

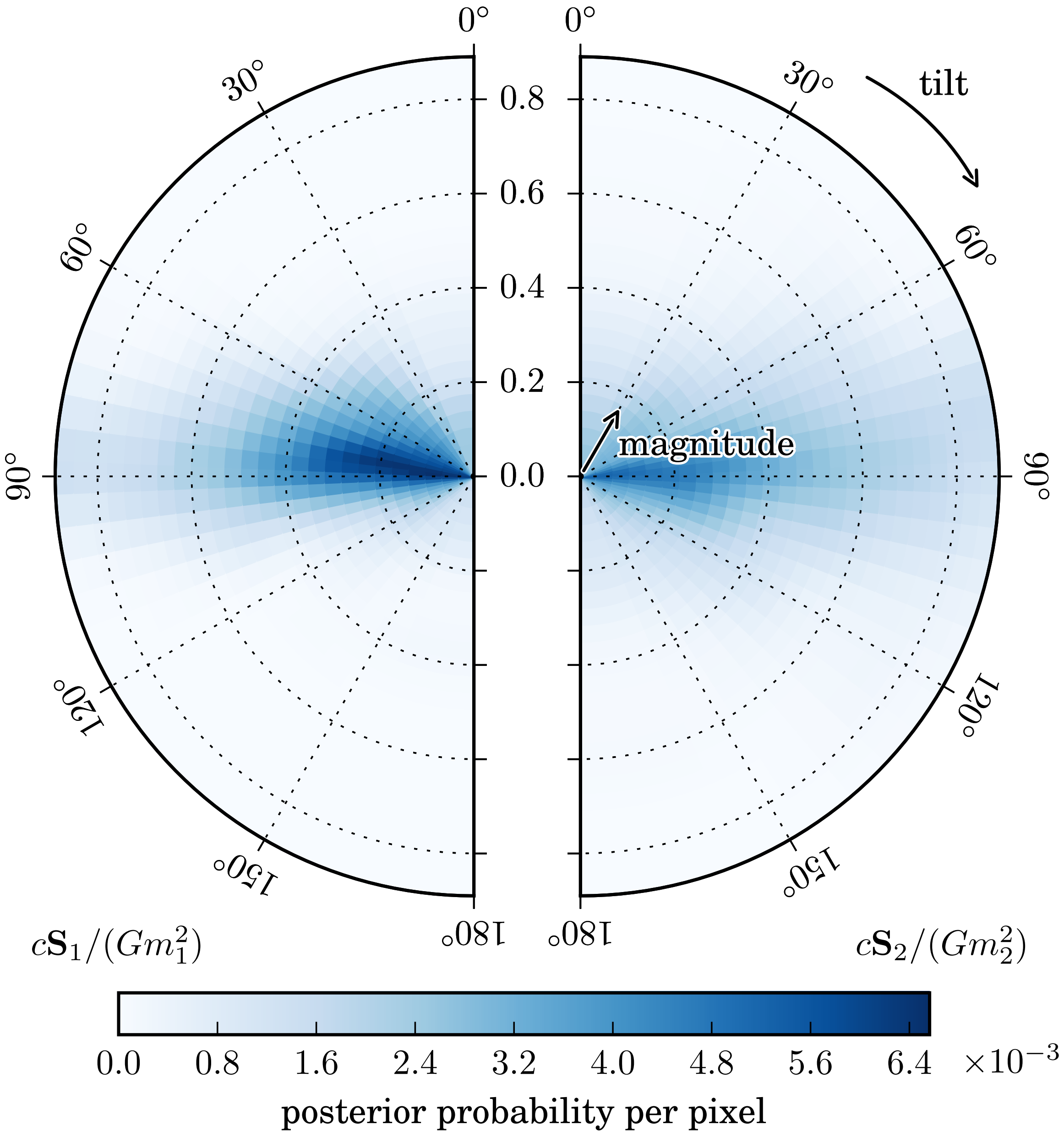
Low-spin prior ($\chi < 0.05$)



Precessing spin

- Very little evidence for individual spin magnitudes above 0.5
- If there is significant spin, the vectors must be perpendicular to total angular momentum

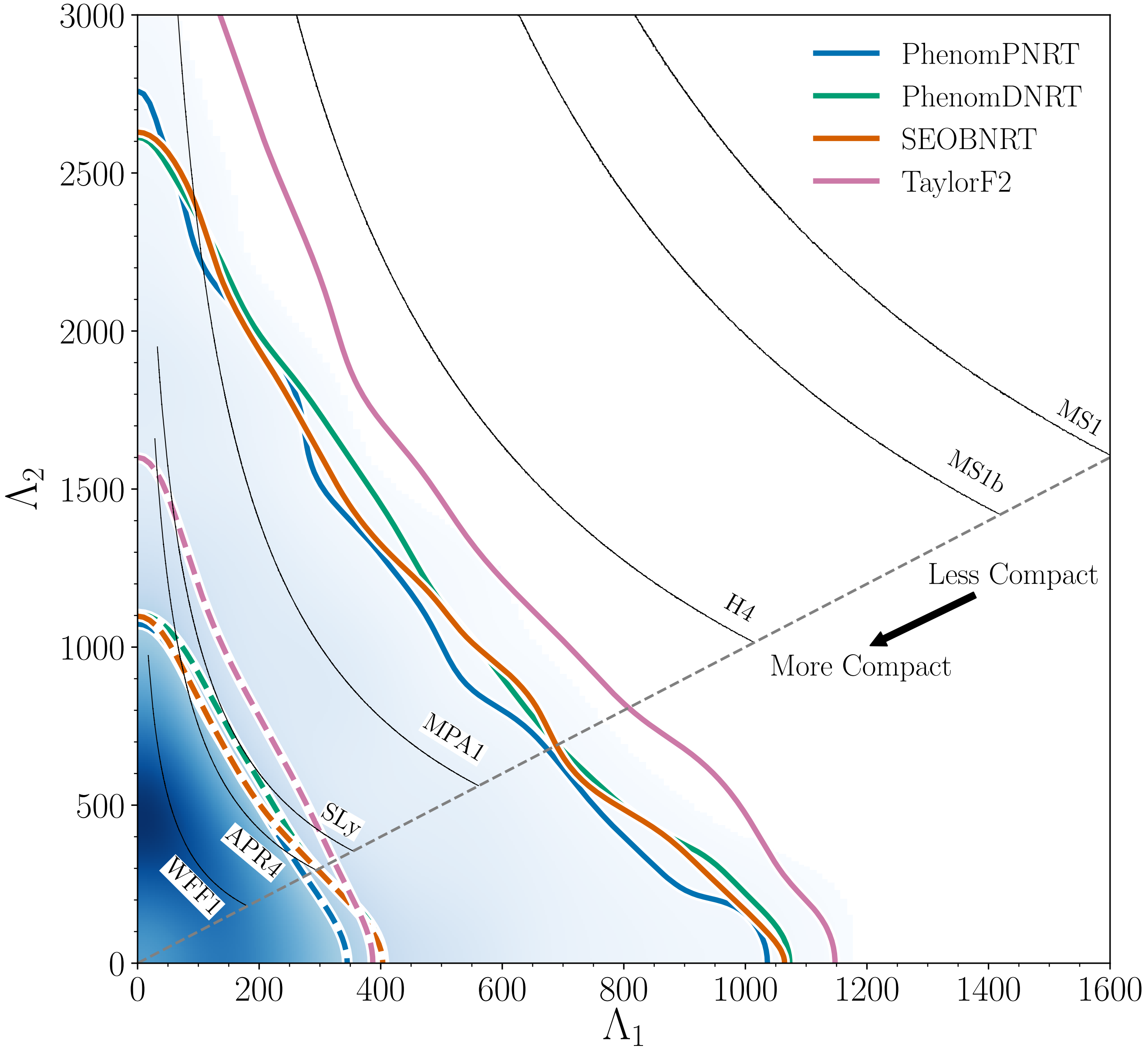
High-spin prior ($\chi < 0.89$)



Tidal parameters

- TaylorF2 result is ~10% more constraining than detection paper (lower f_low improves other parameters and decreases correlations)
- NRTidal models are another ~10% more constraining

High-spin prior ($\chi < 0.89$)



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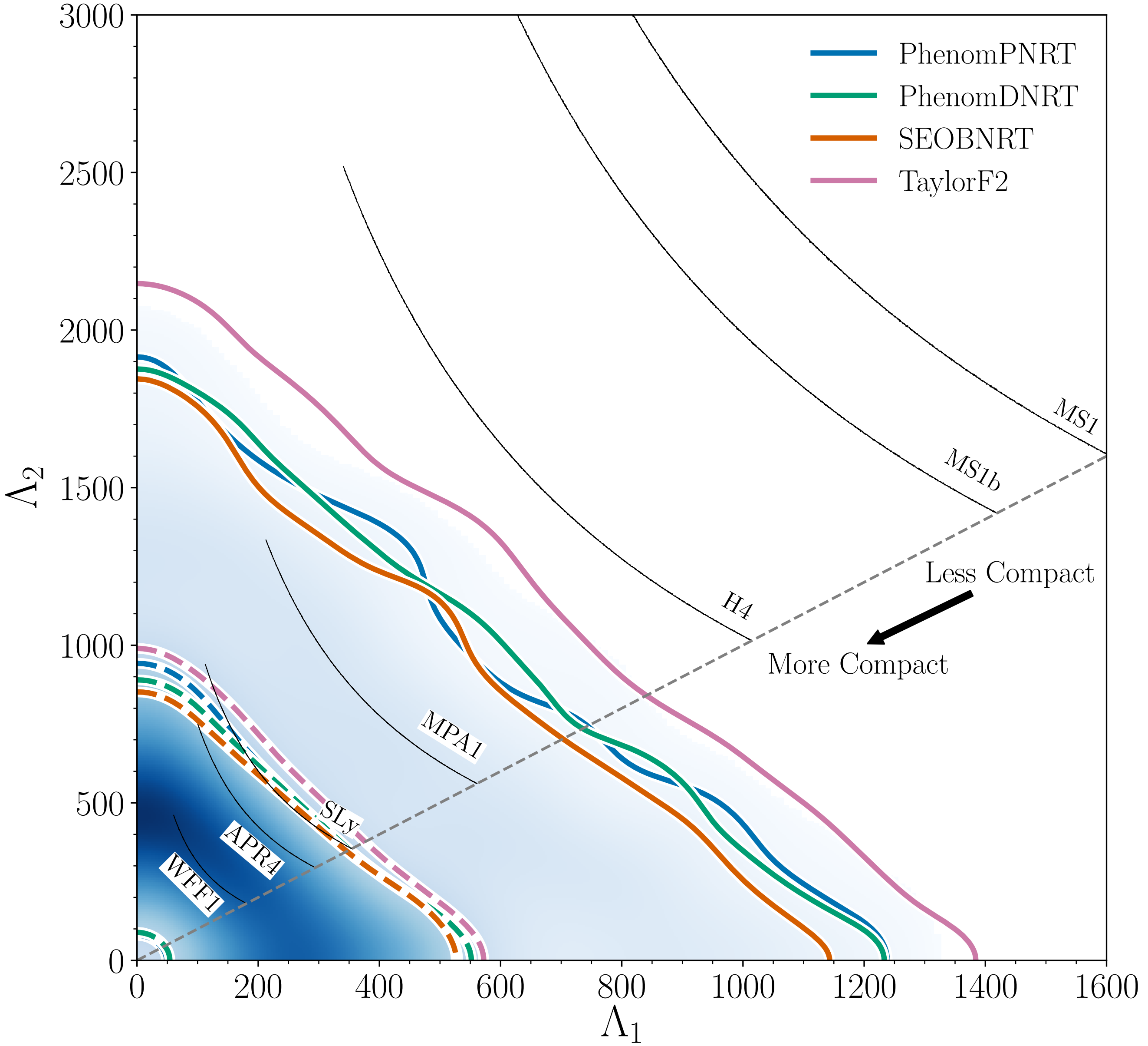

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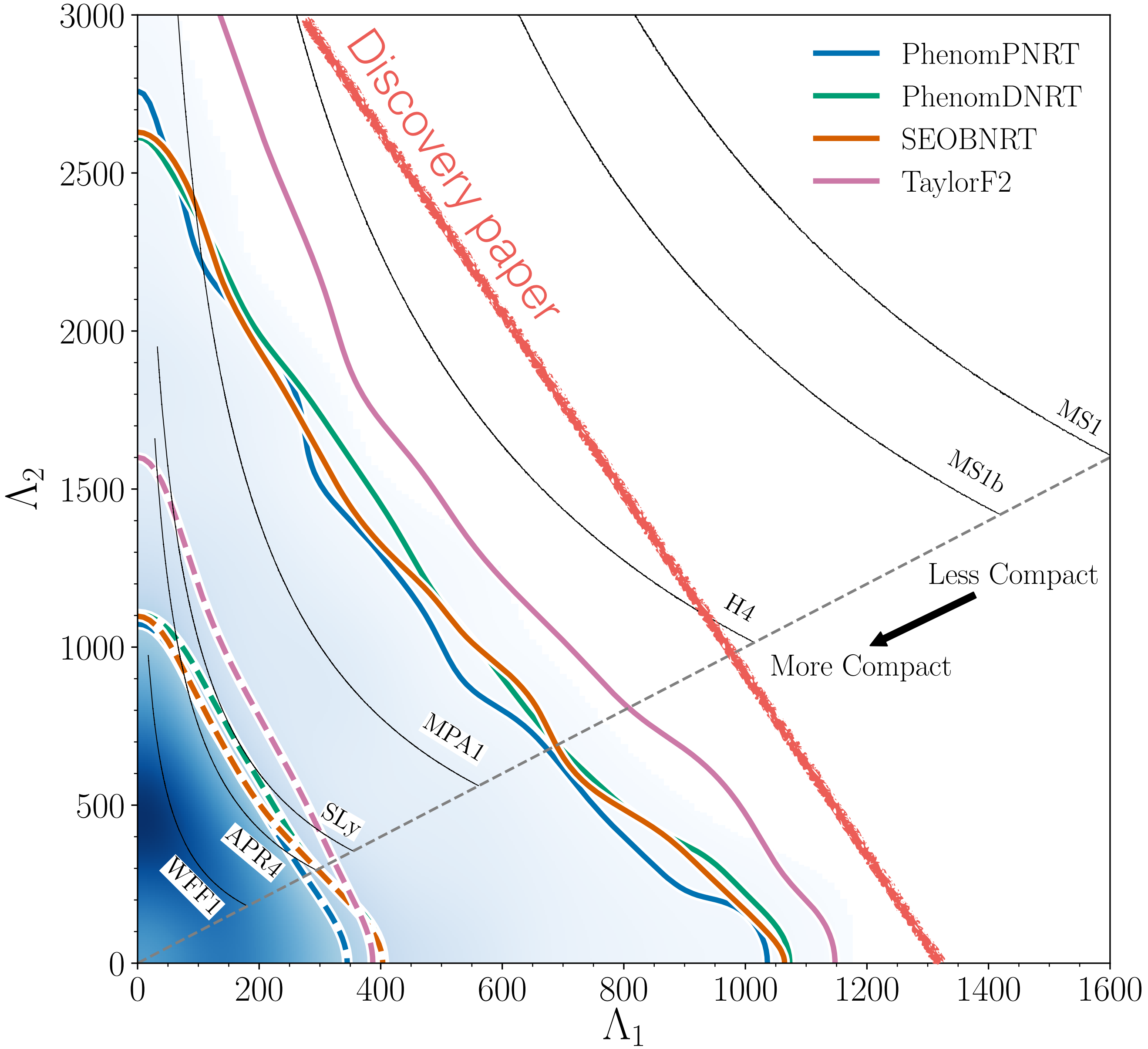

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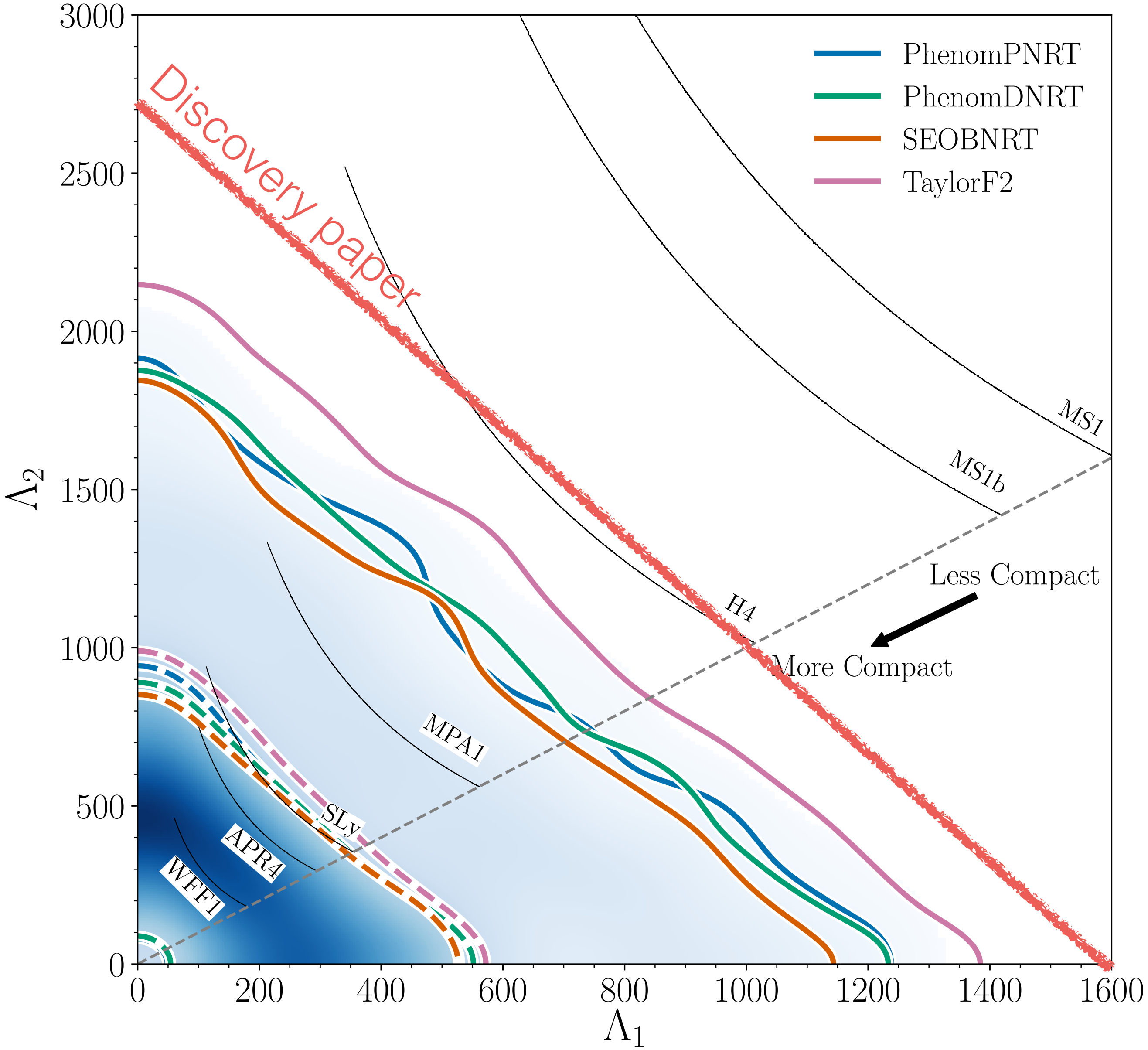
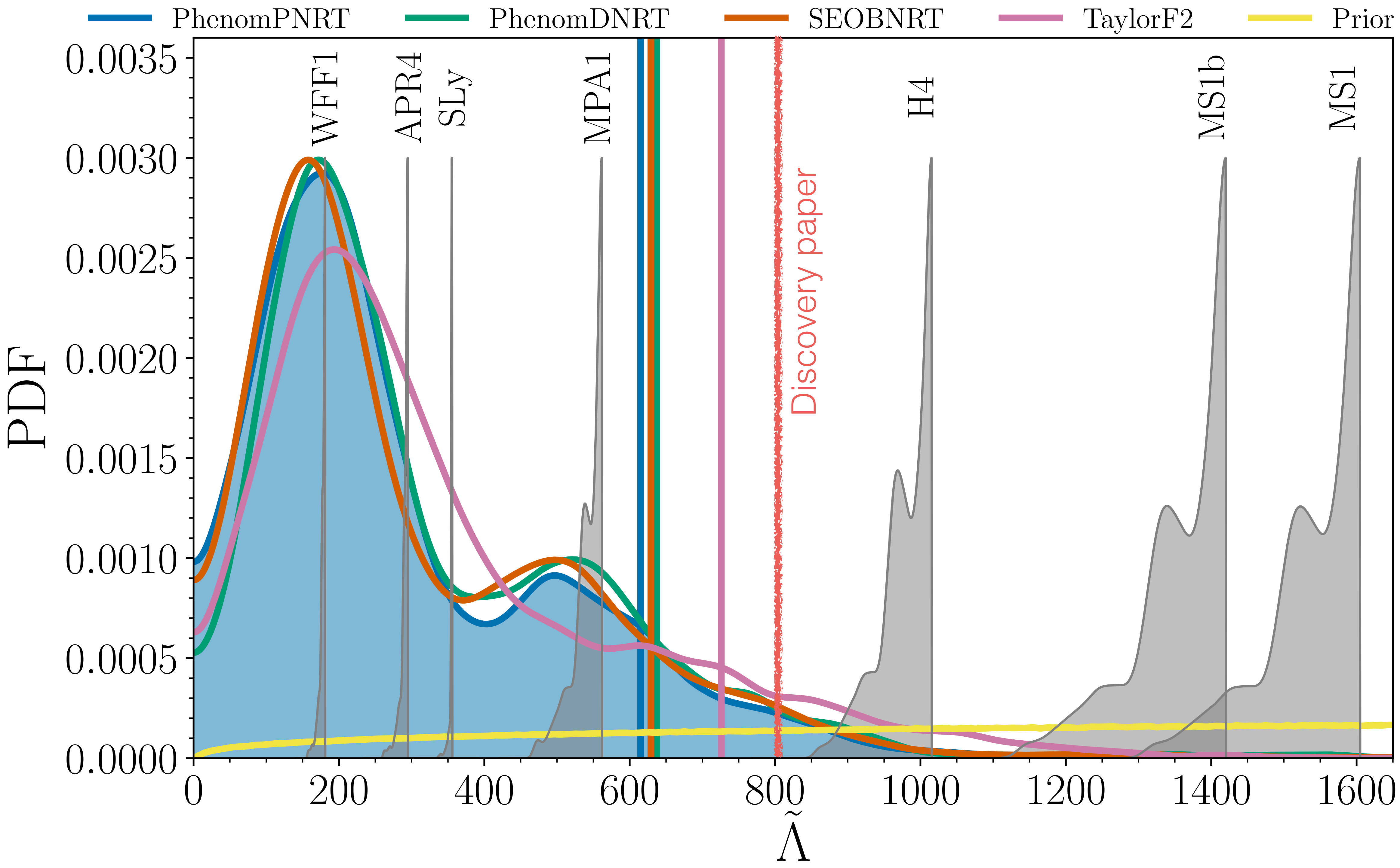


Low-spin prior ($\chi < 0.05$)

Leading order tidal parameter

- TaylorF2 90% upper limit is ~10% more constraining than detection paper

High-spin prior ($\chi < 0.89$)



Leading order tidal parameter

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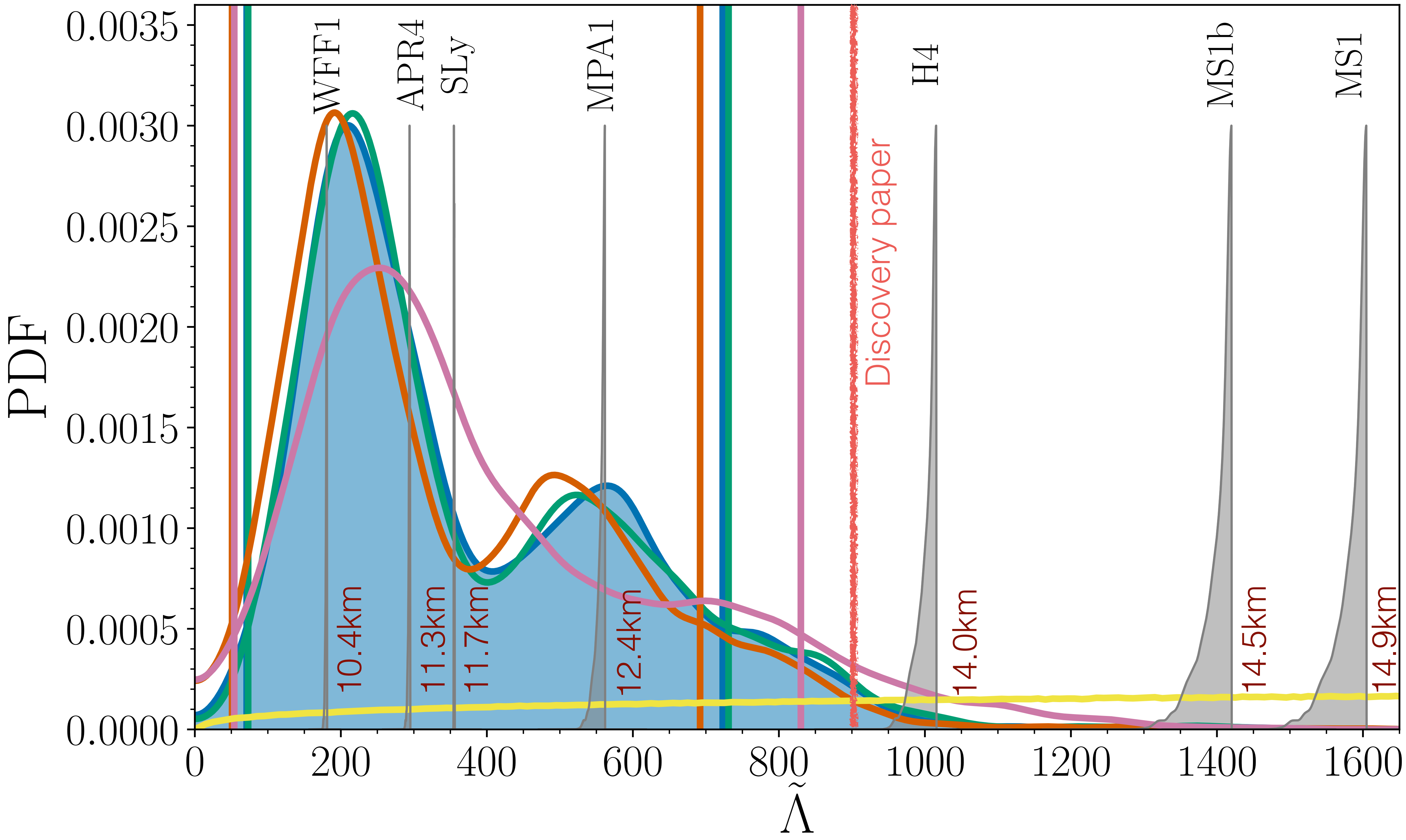
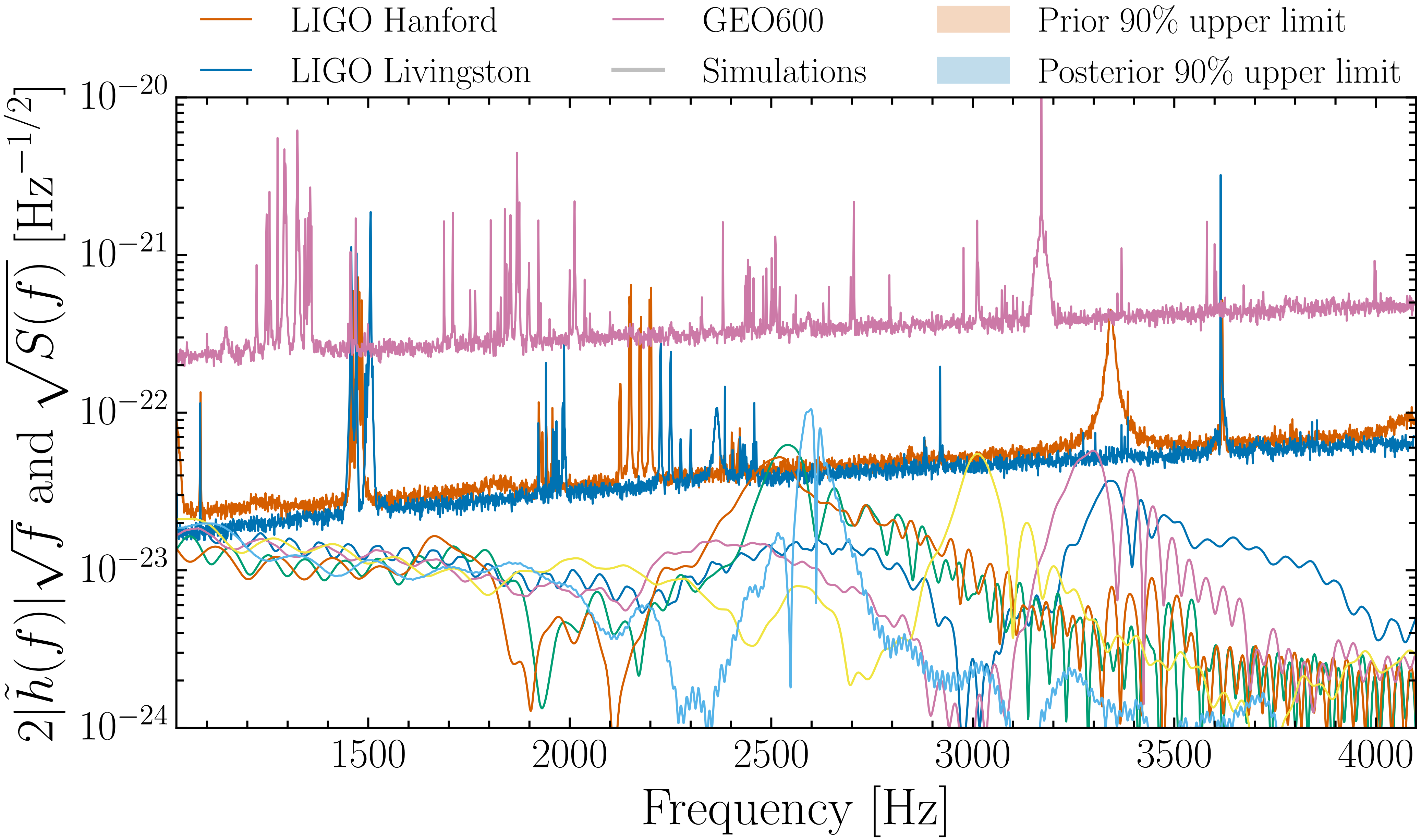


Upper limits on post-merger signal

- Post-merger data analyzed in frequency range 1-4kHz
- Unmodeled parameter estimation with sum of ≥ 2 sine-Gaussian wavelets
- SNR of post-merger constrained to be <6.7 (90% upper limit)
  - Numerical simulations suggest SNR of post-merger signal would be ~0.5



Summary

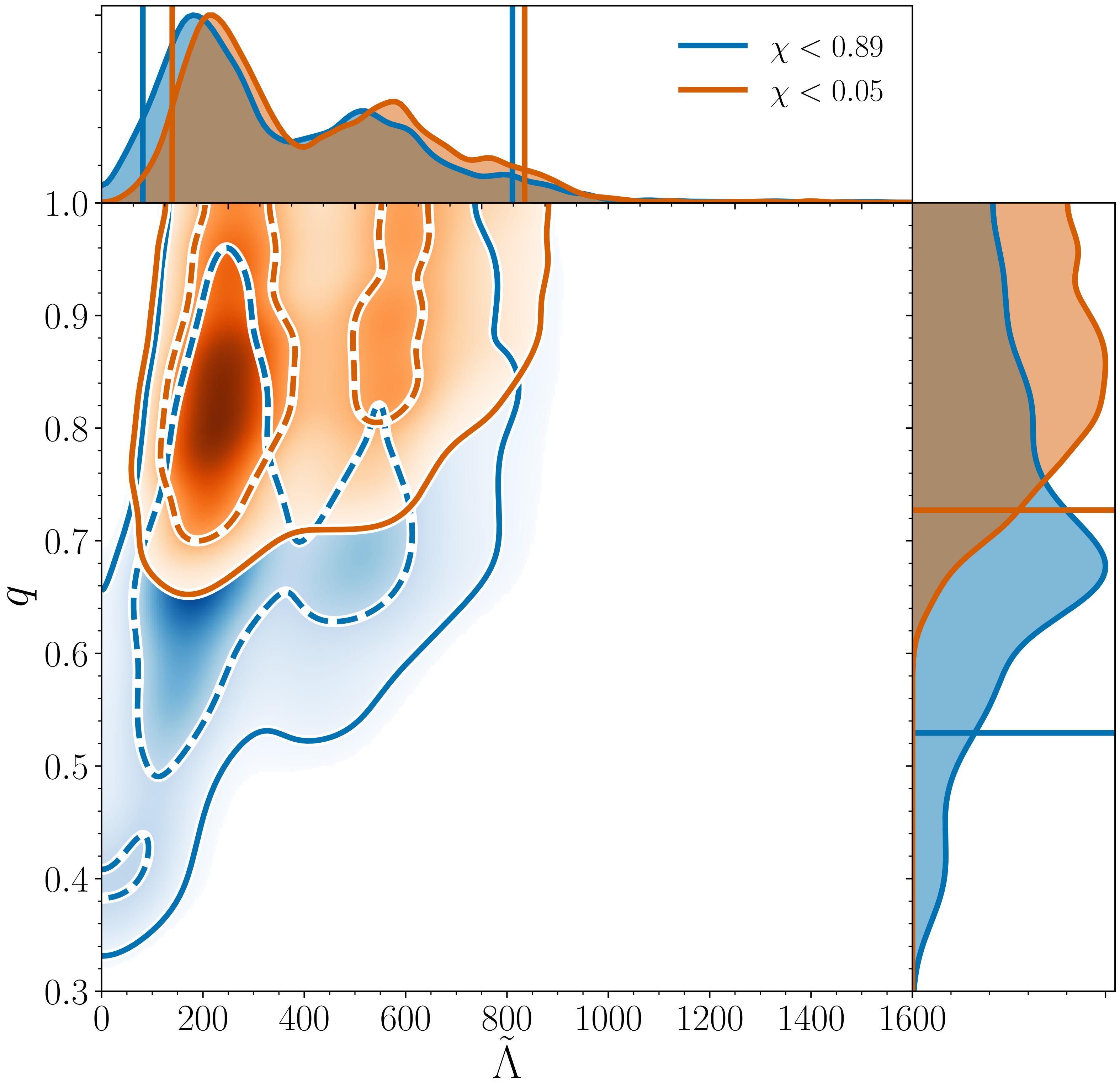
- Results consistent with discovery paper, but are more precise
- Evidence for non-zero tides under reasonable assumptions, but not definitive
- No evidence for or against post-merger signal, but upper limits can be placed on SNR and amplitude
- See Jocelyn Read's talk (Saturday, 2pm, Plenary 9) for details on NS radius

Initial posterior sample release:
https://dcc.ligo.org/LIGO-P1800061/public
https://dcc.ligo.org/LIGO-P1800115/public

Extra slides

Leading order tidal parameter

- $\tilde{\Lambda}$ has week correlation with mass ratio q

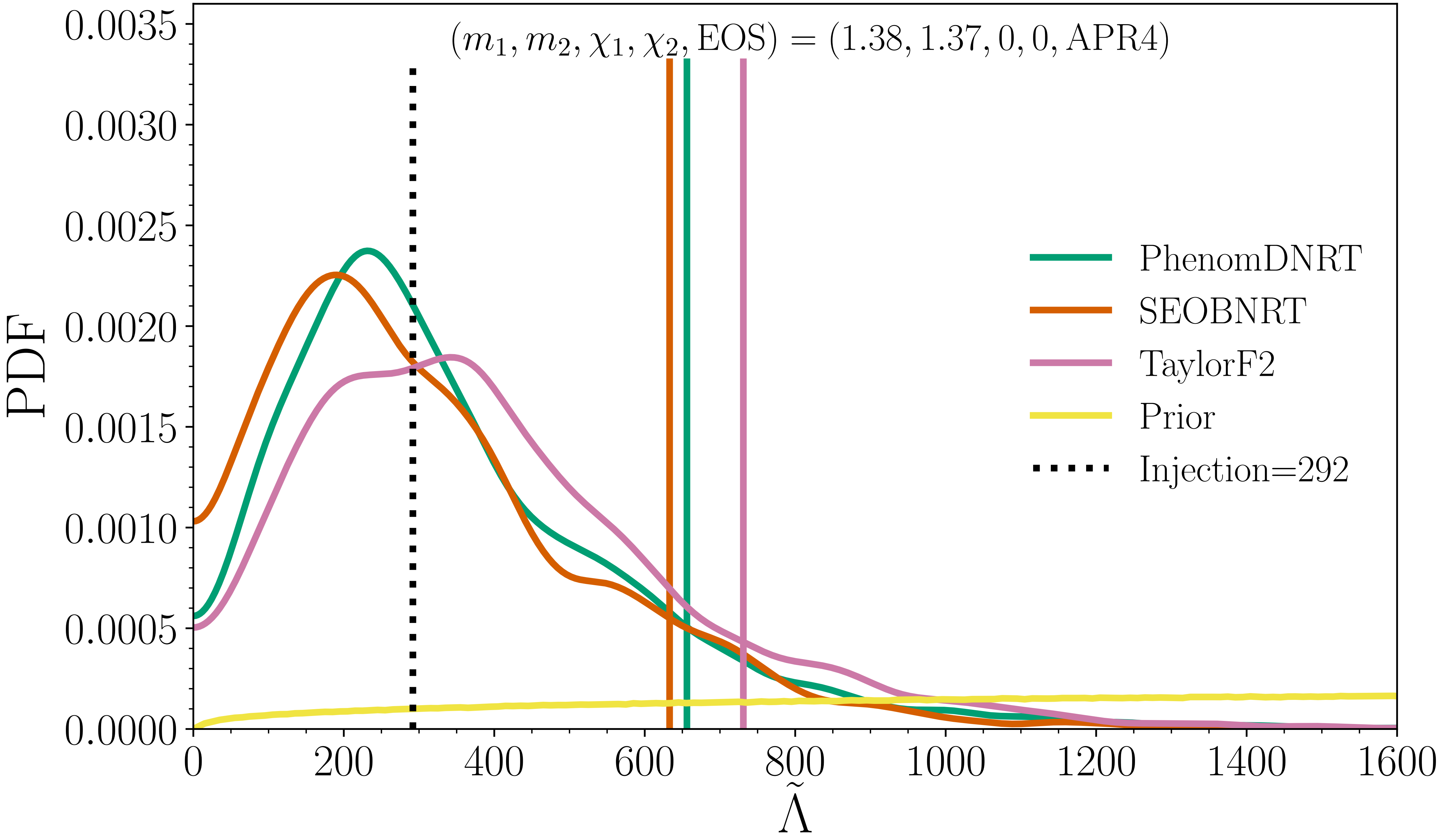


Improvements to parameter estimation

- Better waveform models being actively developed
    - Better analytic treatment with effective one body models
    - Faster evaluation with various numerical techniques
    - Improved treatment of precession
- Improved parameter estimation codes to use more expensive models
- Requiring that both NSs obey the same EOS
    - See Jocelyn Read's talk (Saturday, 2pm, Plenary 9)

Injections to verify tidal parameter recovery

- Injections used aligned-spin SEOBNRv4T time-domain waveform
- Injection parameters are consistent with GW170817 parameters



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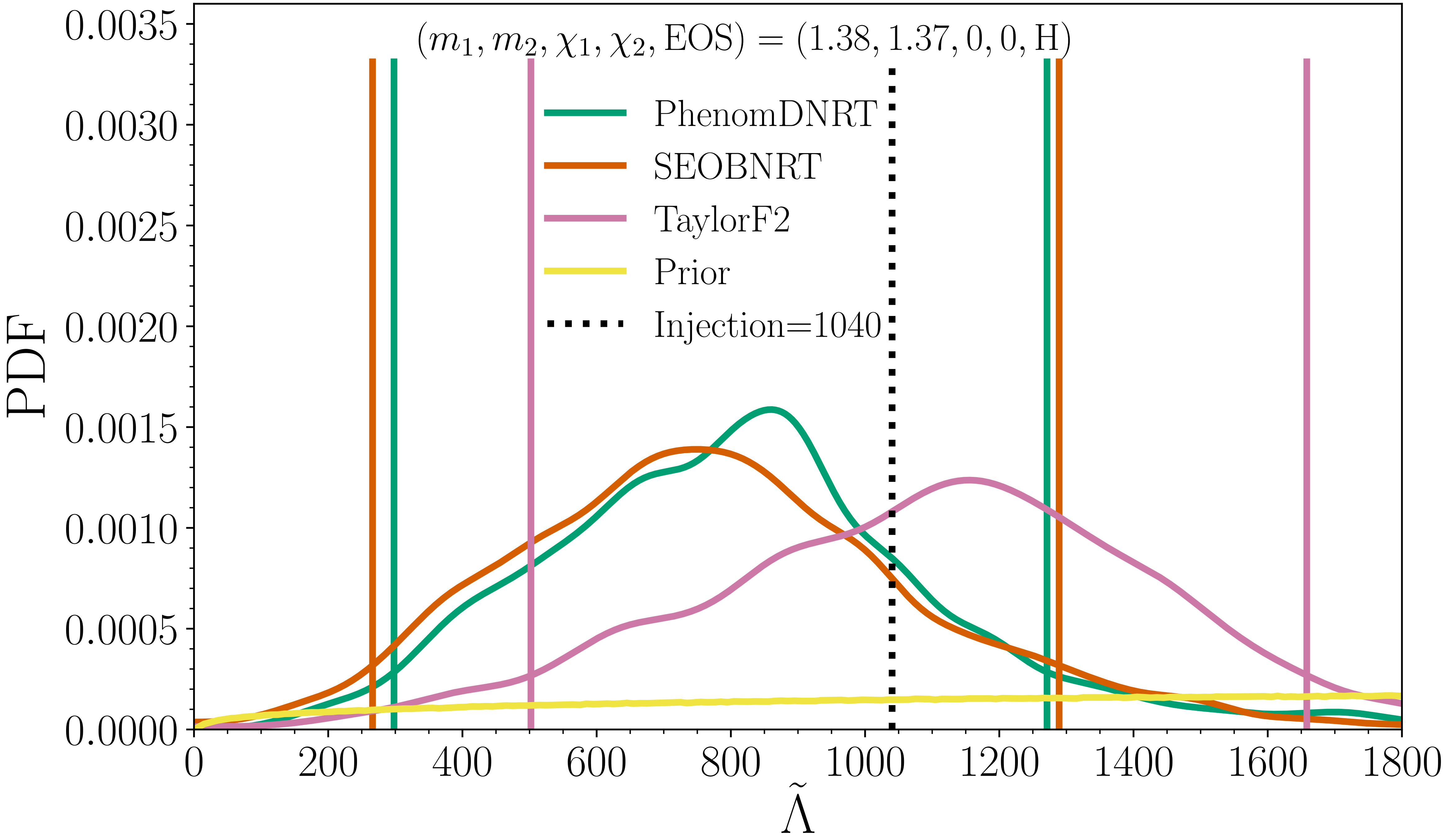

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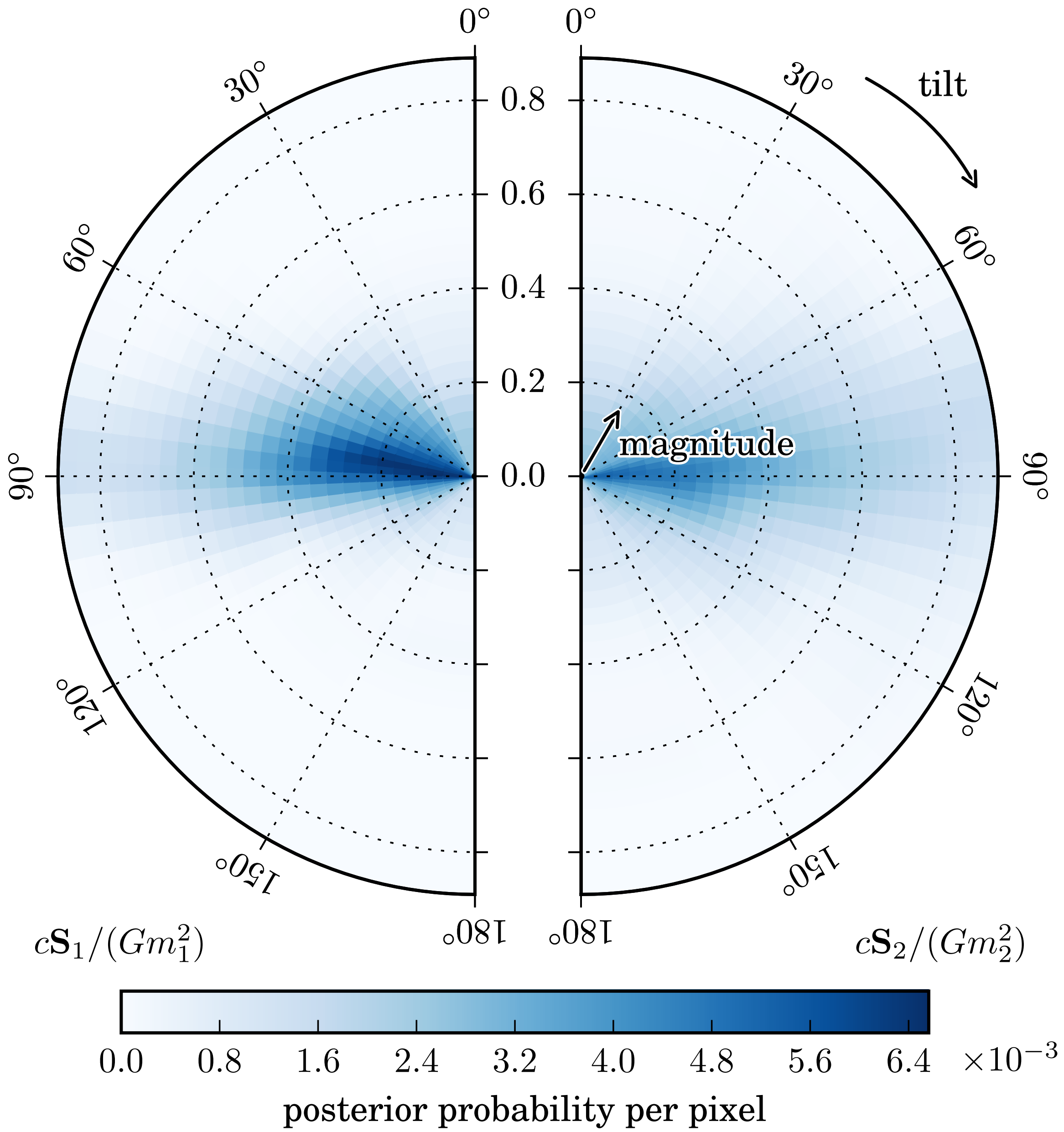

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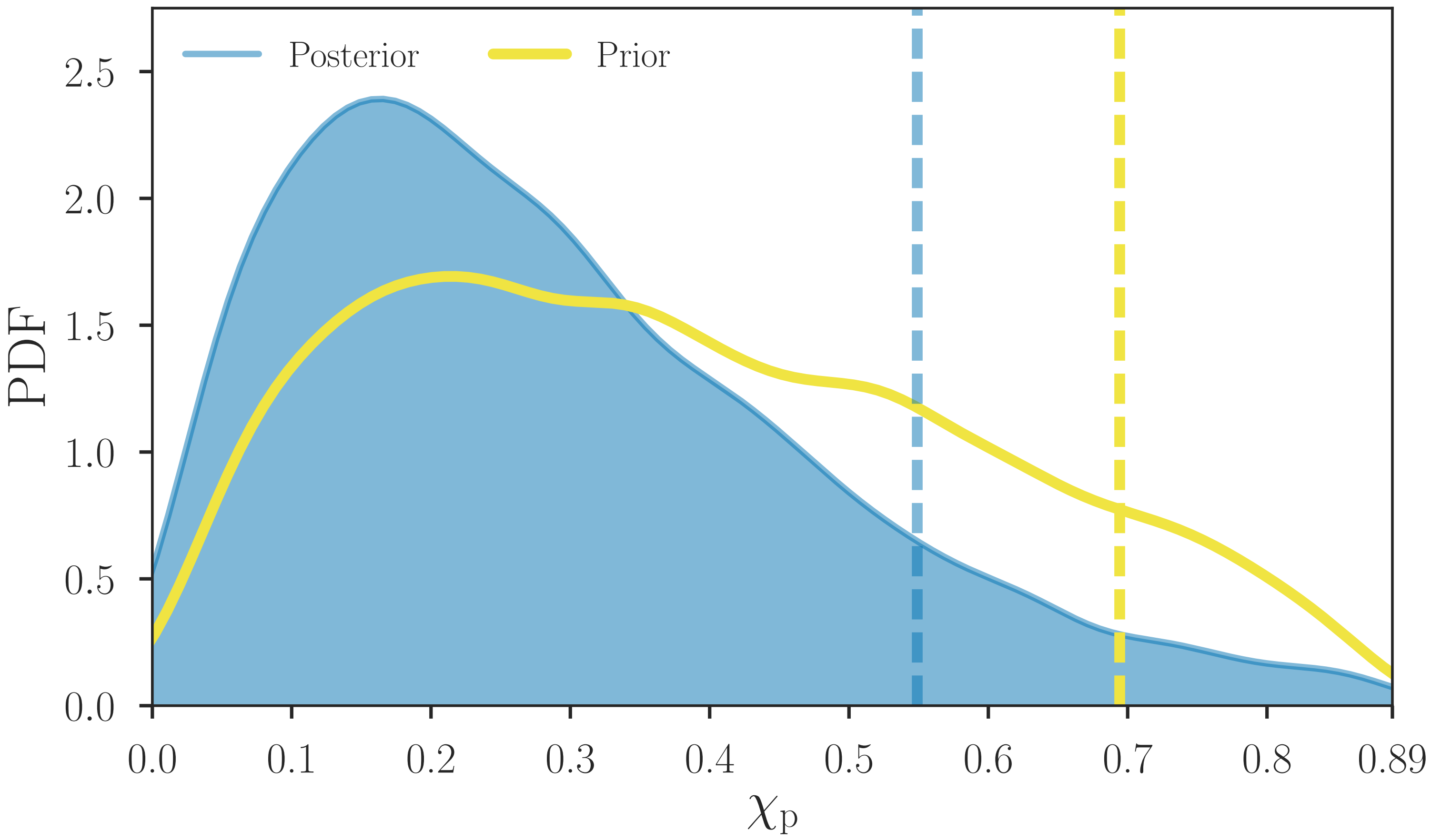

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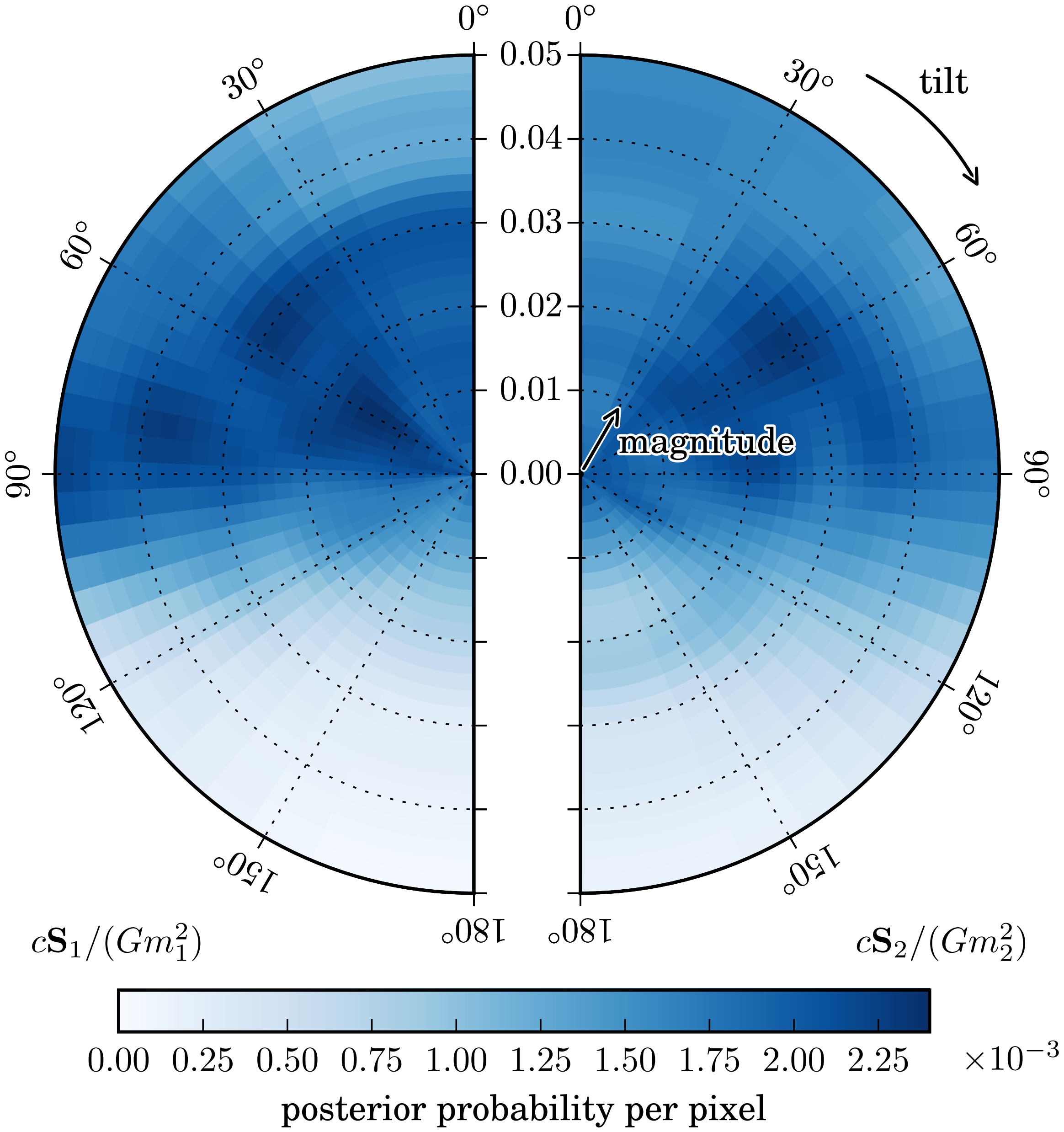

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