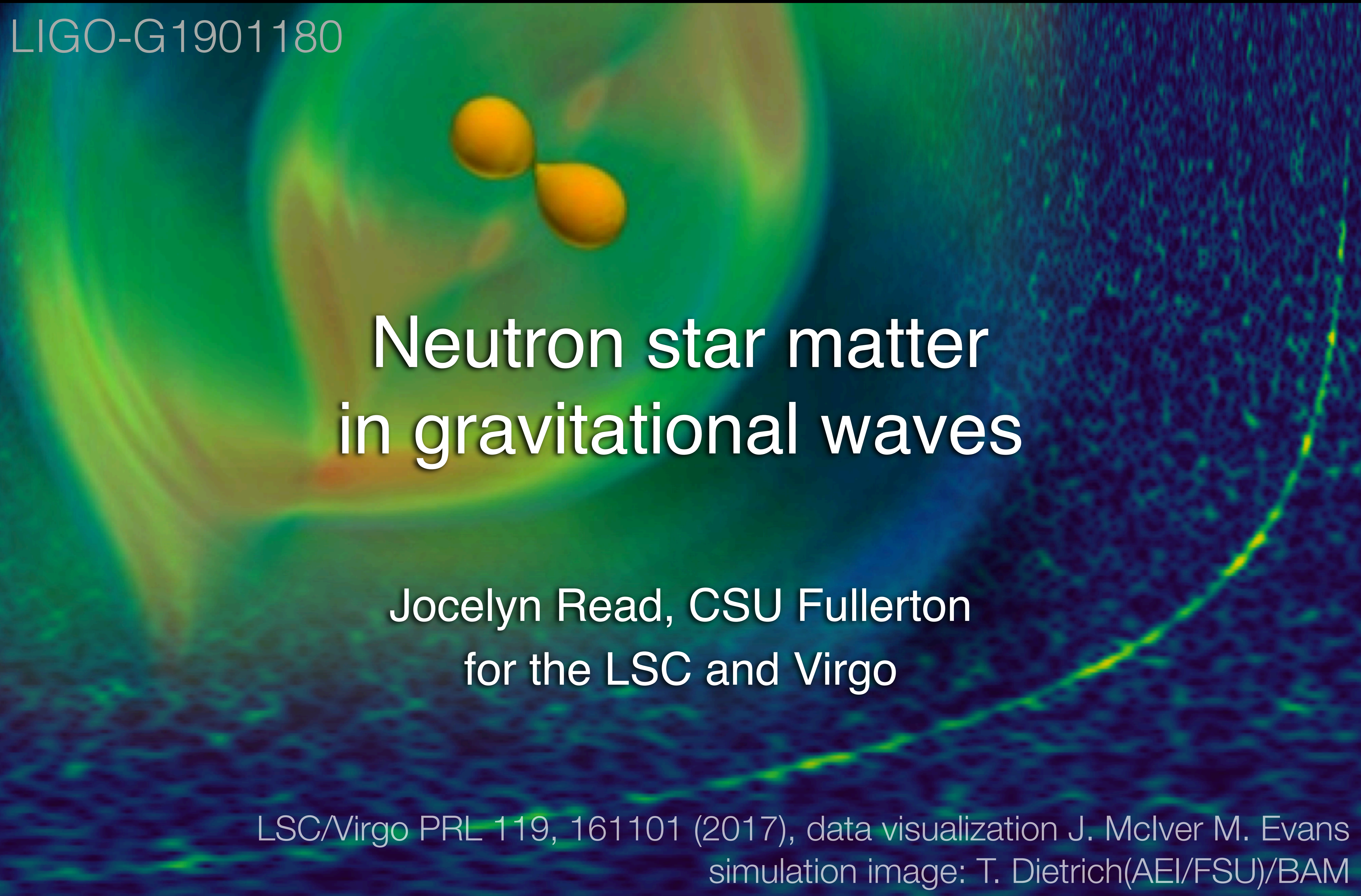
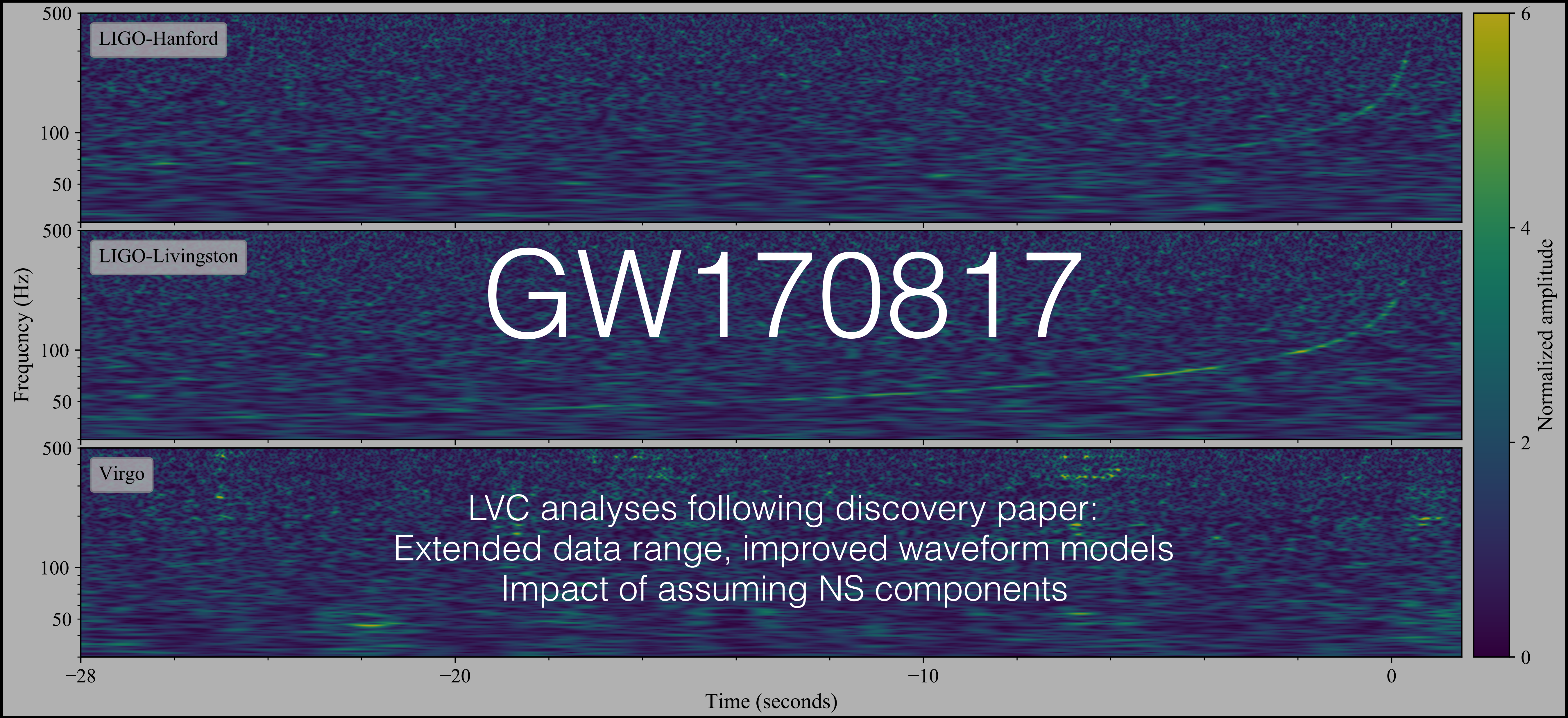
LIGO-G1901180



Neutron star matter in gravitational waves

Jocelyn Read, CSU Fullerton
for the LSC and Virgo

LSC/Virgo PRL 119, 161101 (2017), data visualization J. McIver M. Evans
simulation image: T. Dietrich(AEI/FSU)/BAM



GW170817

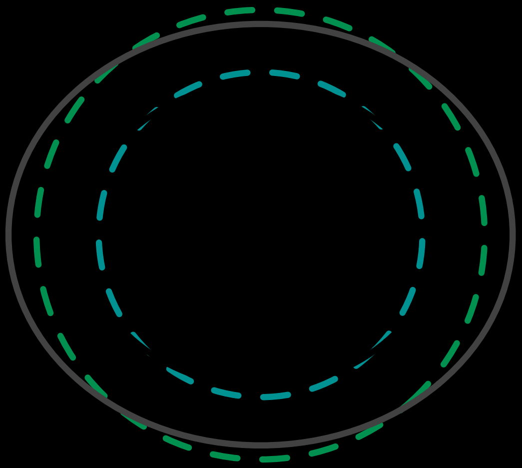
LVC analyses following discovery paper:
Extended data range, improved waveform models
Impact of assuming NS components

LSC/Virgo Discovery PRL 119, 161101 (2017)
LSC/Virgo Source Properties Phys. Rev. X 9, 011001 (2019)
LSC/Virgo Radius & EOS Phys. Rev. Lett. 121, 161101 (2018)
LSC/Virgo GWTC-1 1811.12907, accepted PRX

Tidal deformability

- Defined here by linear perturbation of isolated star

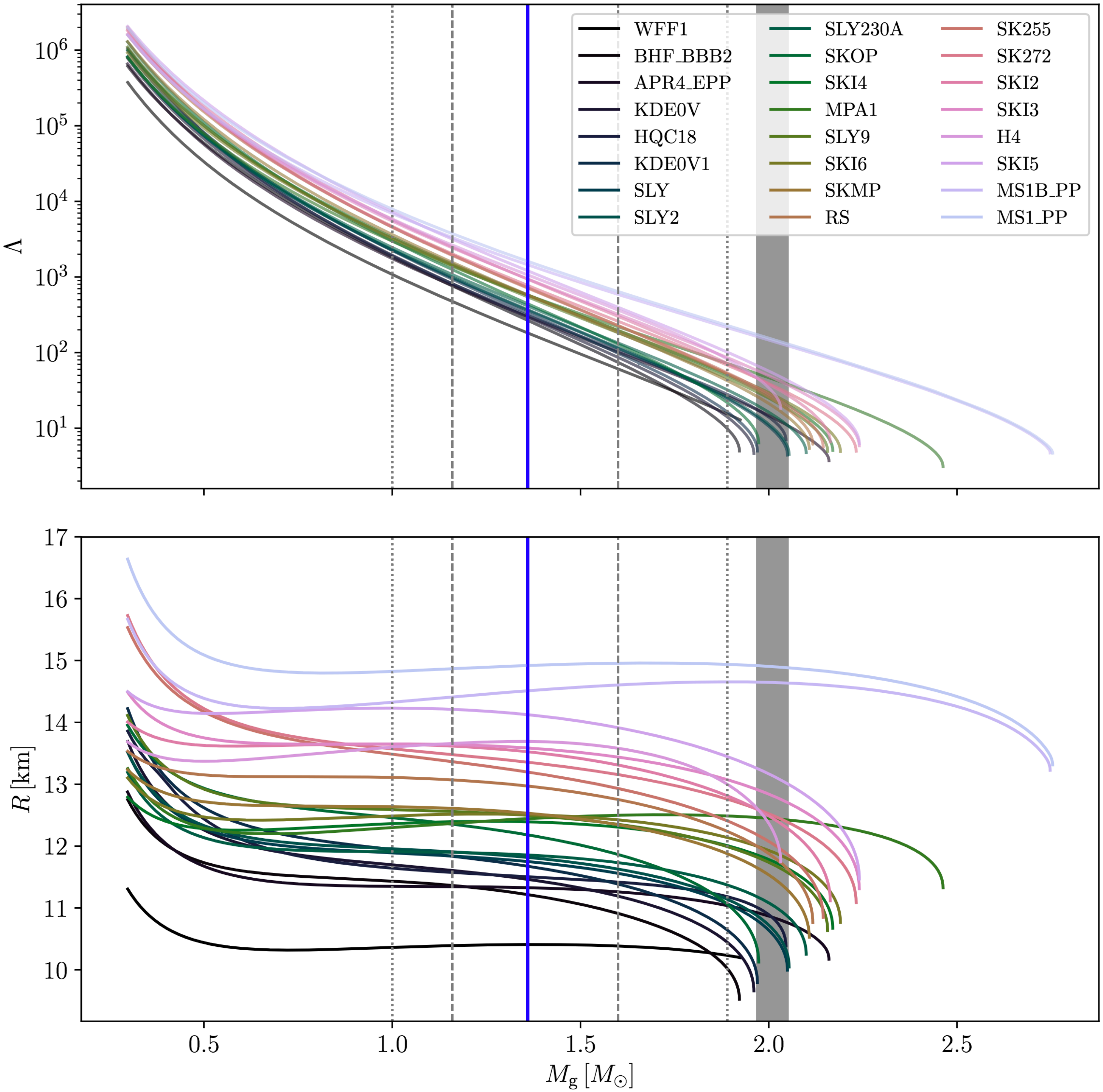
$$\lambda_i = \frac{\text{quadrupole deformation of star } i}{\text{strength of external tidal field}}$$



Dimensionless form:

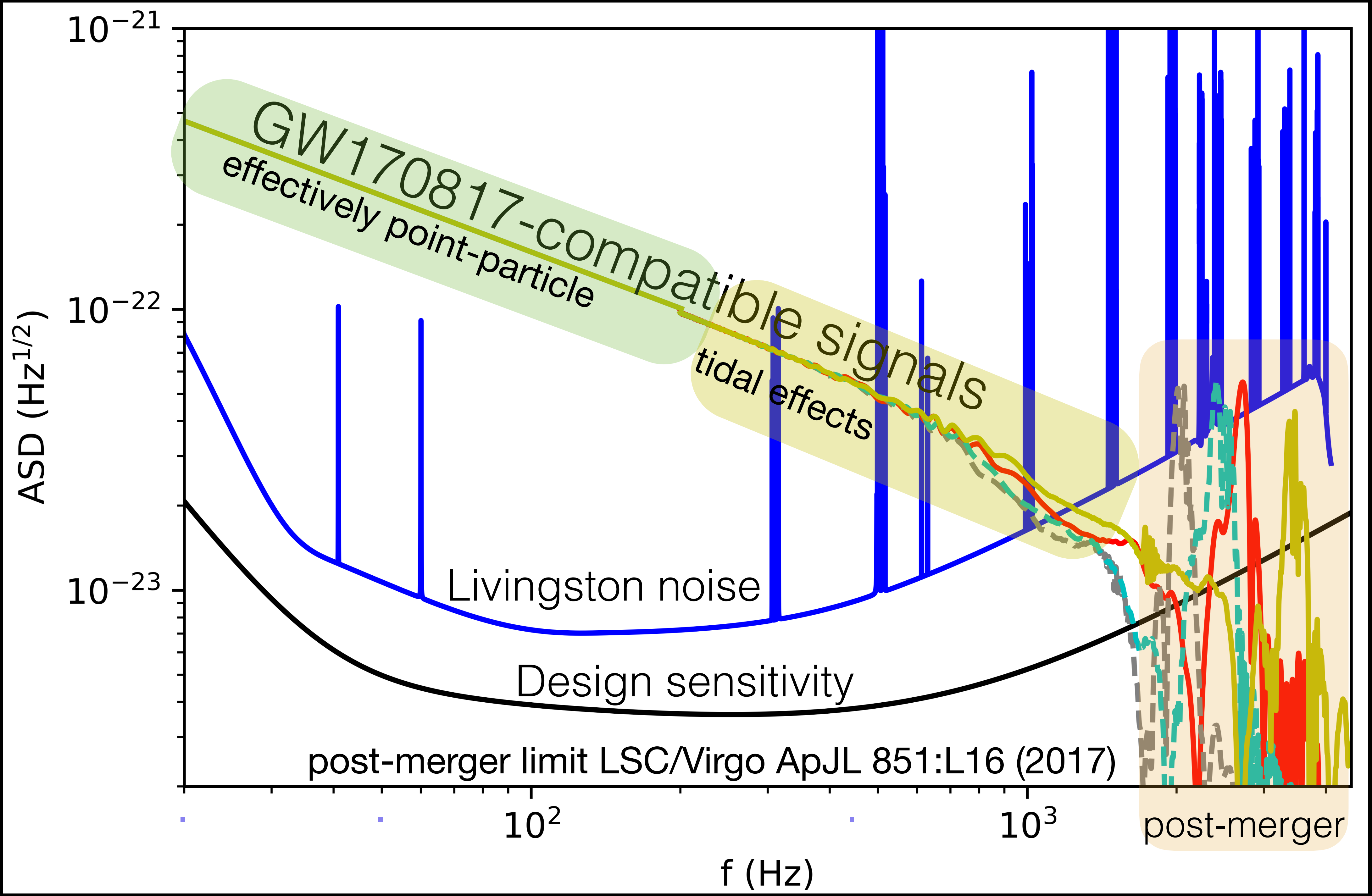
$$\Lambda_i = \frac{\lambda_i}{m_i^5} = \frac{2}{3} k_2 \left(\frac{R_i}{m_i} \right)^5$$

- R radius, m mass of star ⬅ *most EOS impact on tides*
- k_2 relativistic love number (Damour 1983) ≃ 0.05–0.15
  - Mass distribution inside the star, not surface deformation



LVC Model comparison paper, in prep

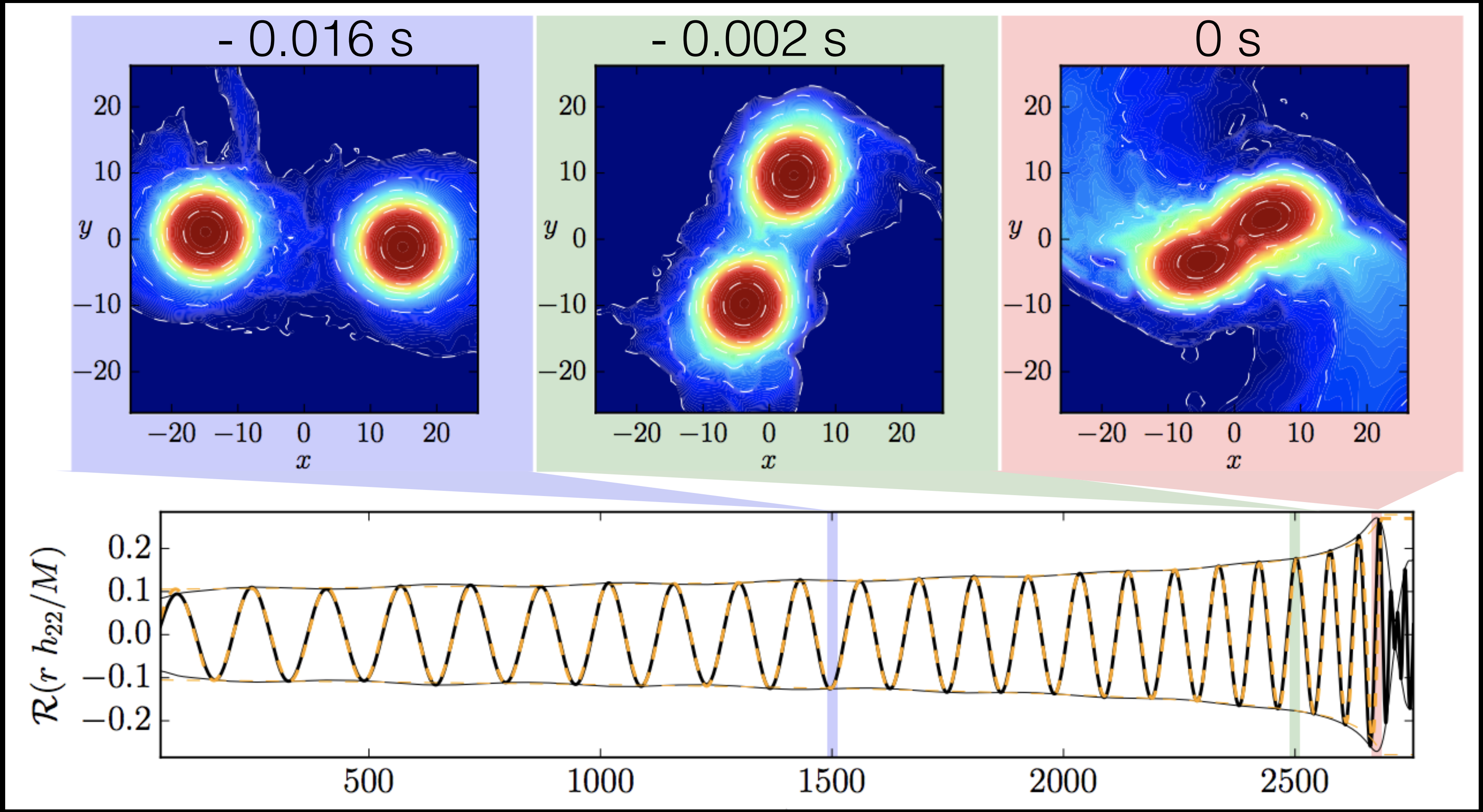
Matter Imprint on GW170817



EOS:
SLy
ALF2
H4
MS1

E. Leon/LIGO/Virgo. Noise curves from LIGO-P1800061-v11
Numerical simulation data (above ~500 Hz) courtesy Tim Dietrich (AEI/FSU/BAM Collaboration)
Simulations published in Phys. Rev. D95(12):124006 and Phys. Rev. D95(2):024029

Gravitational waves

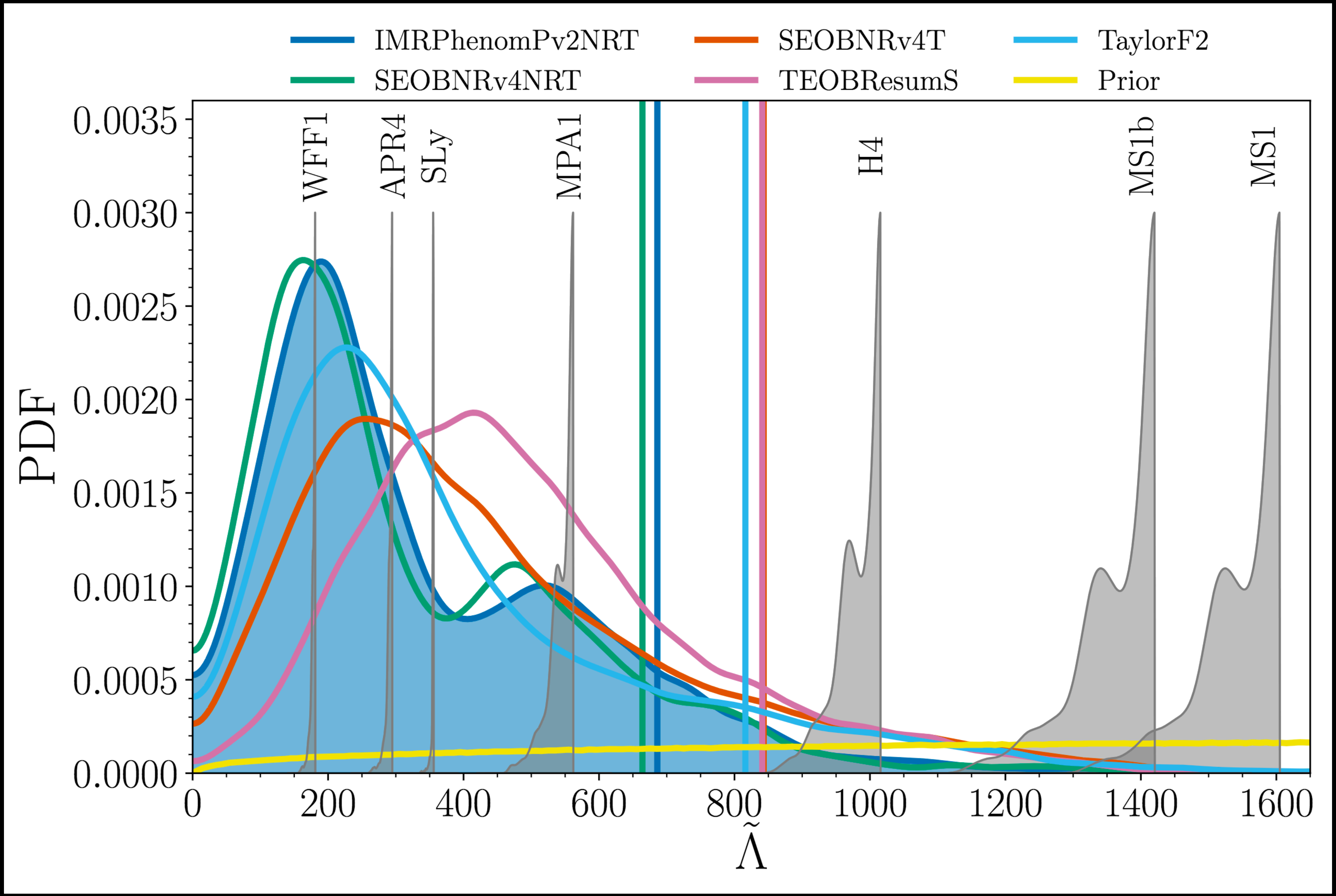


Dietrich and Hinderer
1702.02053

- Parameterize waveforms *up to merger* as function of mass, spin, and Λ_1, Λ_2 (Read et al 1306.4065, Bernuzzi et al 1402.6244, …)
  - **Modification to BBH:** Phasing correction from leading order tides + phenomenological higher order fit from numerical relativity (Dietrich et al 1706.02969 & 1905.06011)
  - **Semi-analytic BNS/NSBH models**: Integrated effective-one-body potentials w/ tides and higher-order terms, resummation, dynamical tides (Nagar et al 1806.01772, Hinderer et al 1602.00599)

Tides:

$$\tilde{\Lambda} = \frac{16}{13}\frac{(m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{(m_1 + m_2)^5}$$



Fiducial WF:

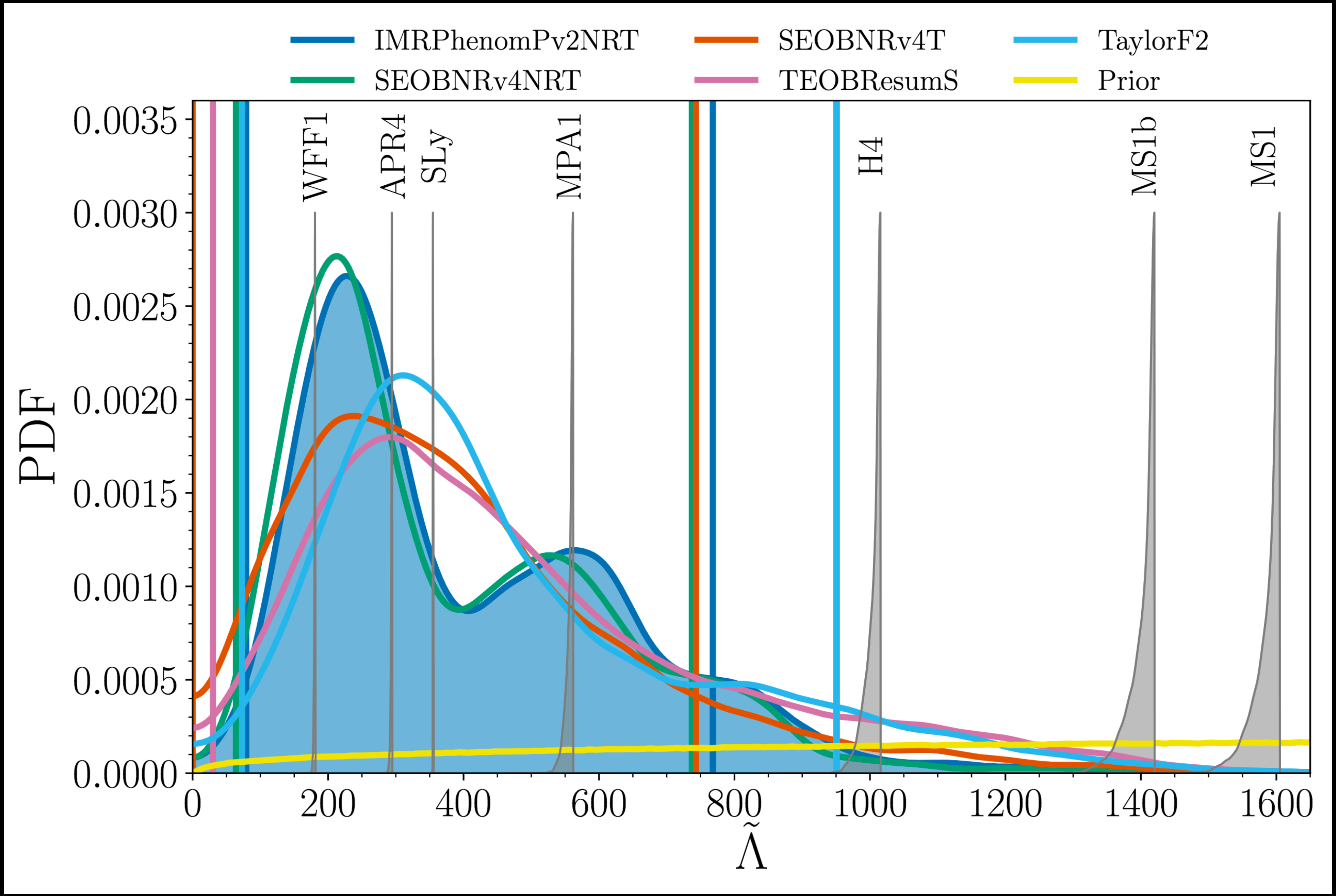
$\tilde{\Lambda} < 686$

Component samples reweighted for effective prior flat in $\tilde{\Lambda}$

Bars denote 90% highest probability density credible interval

LSC/Virgo GWTC-1 1811.12907, accepted PRX

Tides: $\tilde{\Lambda} = \frac{16}{13}\frac{(m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{(m_1 + m_2)^5}$



Assume
$\chi < 0.05$

Fiducial WF:

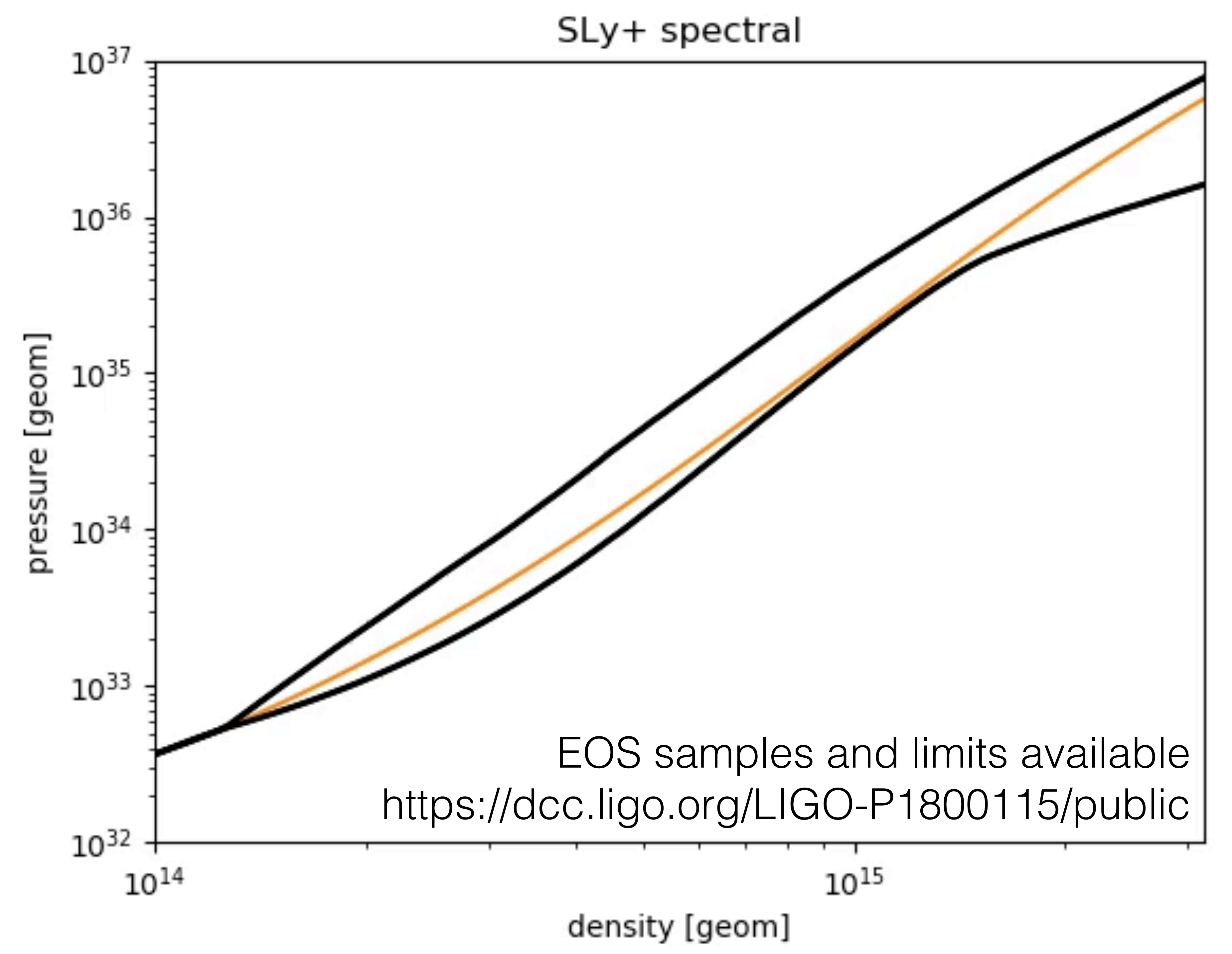
$\tilde{\Lambda} = 330^{+438}_{-251}$

Component samples reweighted for effective prior flat in $\tilde{\Lambda}$
Bars denote 90% highest probability density credible interval

LSC/Virgo GWTC-1 1811.12907, accepted PRX

See also C. Miller talk earlier today

Sampling the equation of state

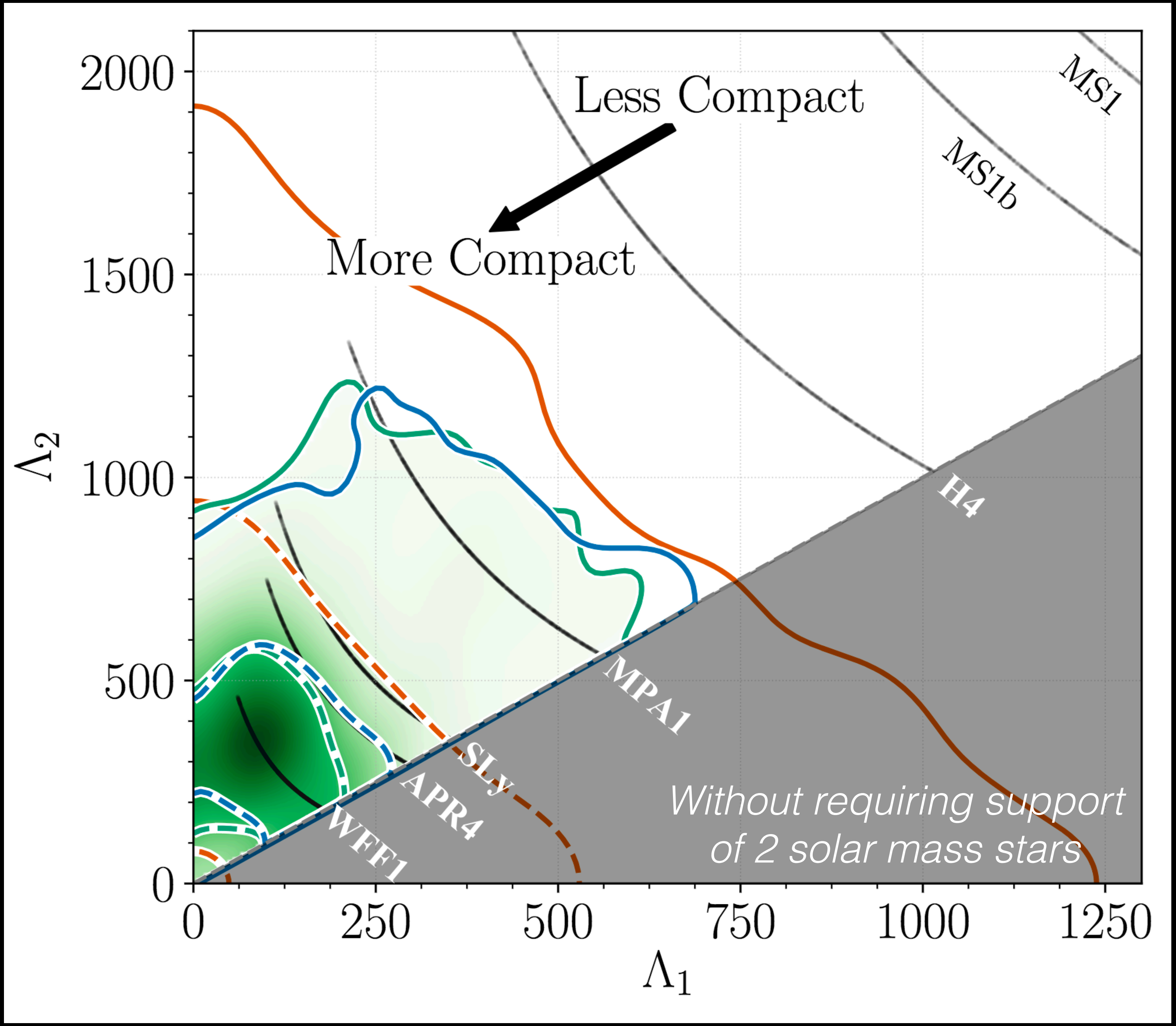


EOS samples and limits available
https://dcc.ligo.org/LIGO-P1800115/public

Animation: Rossella Gamba, LSC/Virgo
Based on LSC/Virgo EOS 1805.11581

Parameter estimation with common EOS

$\chi < 0.05$



Source properties

LVC 1805.11579

Independent Λ

Common EOS

LVC 1805.11581

Common spectral-parameterized eos

Carney et al 1805.11217

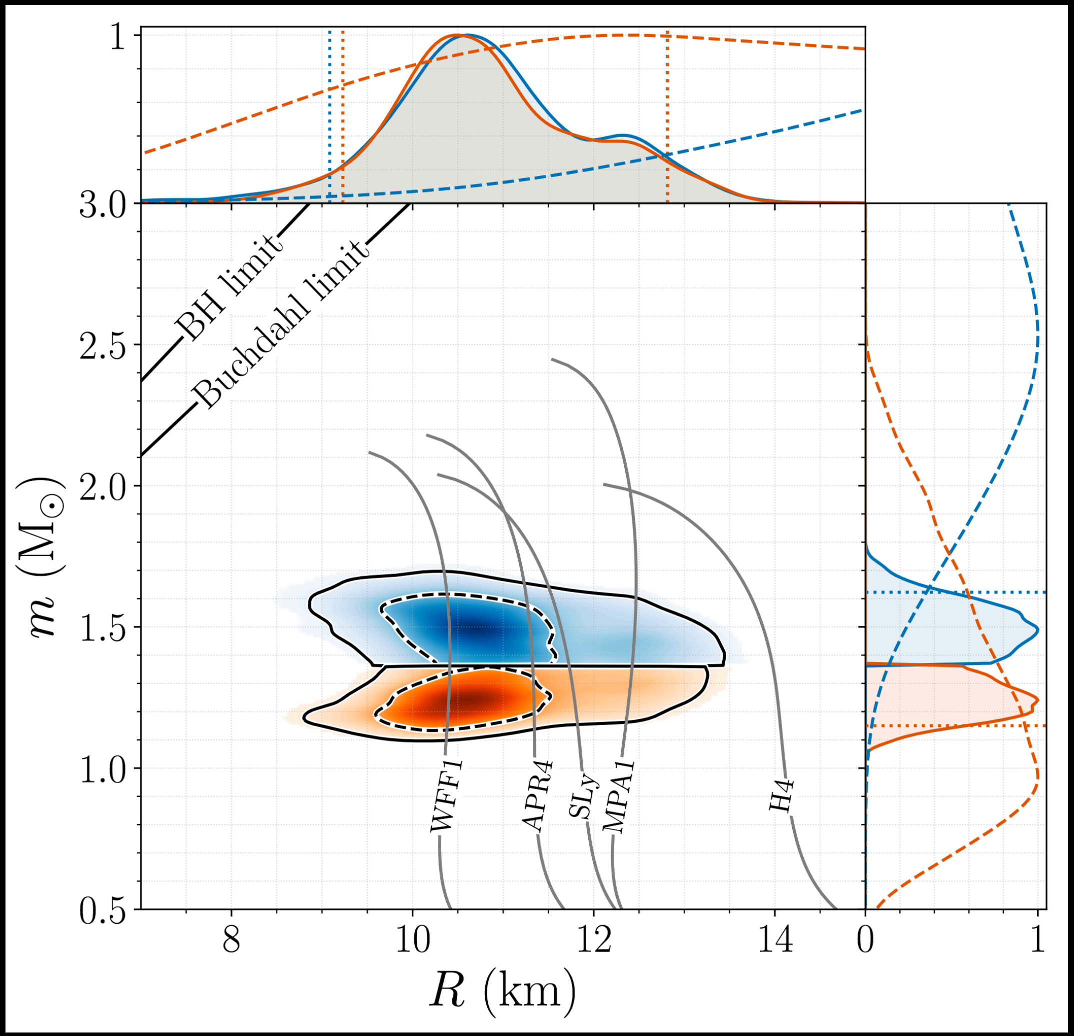
Quasi-universal (EOS-insensitive) relations between components

Chatziioannou et al 1804.03221

Common-EOS Radius constraints

GW data

$R_1=10.8^{+2.0}_{-1.7}$, $R_2=10.7^{+2.1}_{-1.5}$



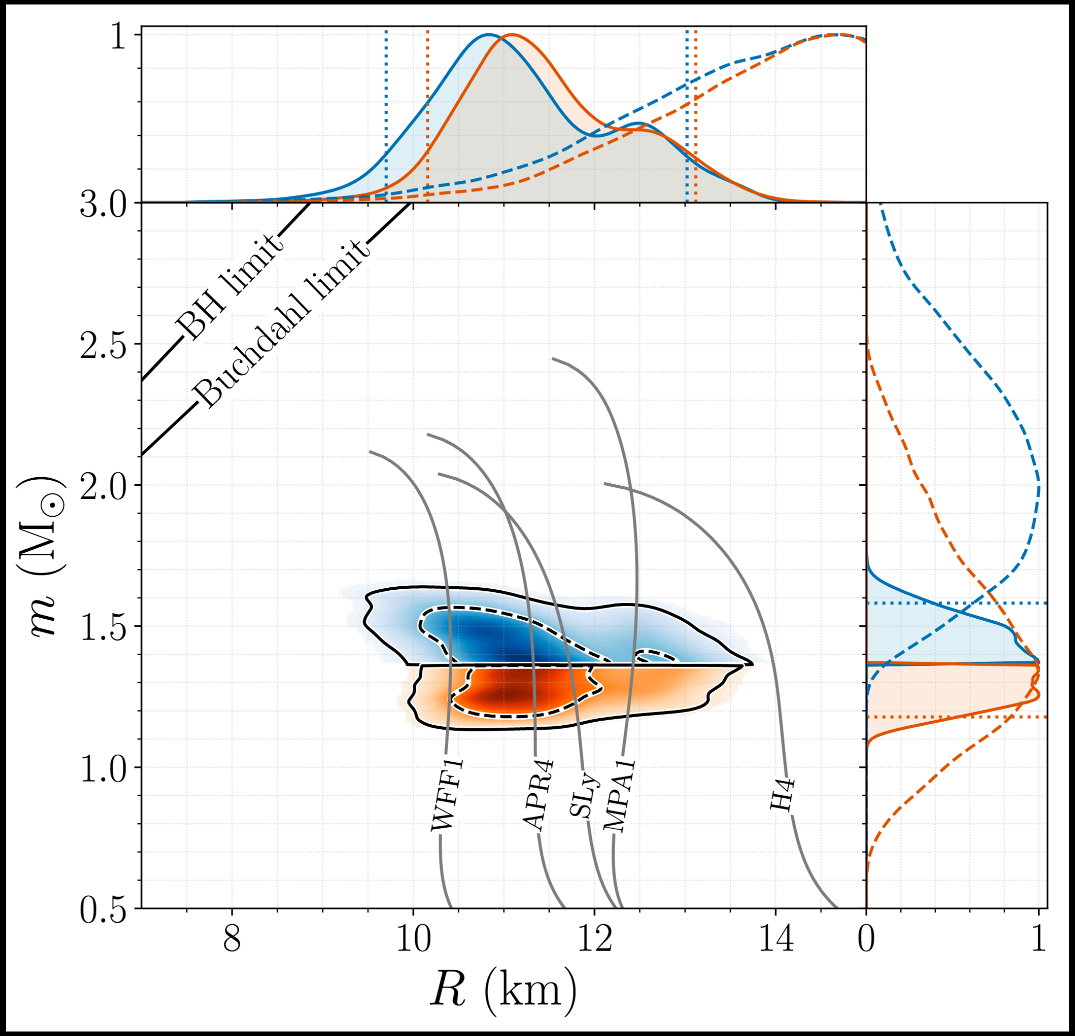
Quasi-universal Λ_1-Λ_2 & Λ-R

Quasi-universal method

Chatziioannou et al 1804.03221

GW data

smooth, causal EOS



Spectral parameterized EOS

Parameterized EOS Method:

Carney et al 1805.11217

LSC-Virgo EOS 1805.11581

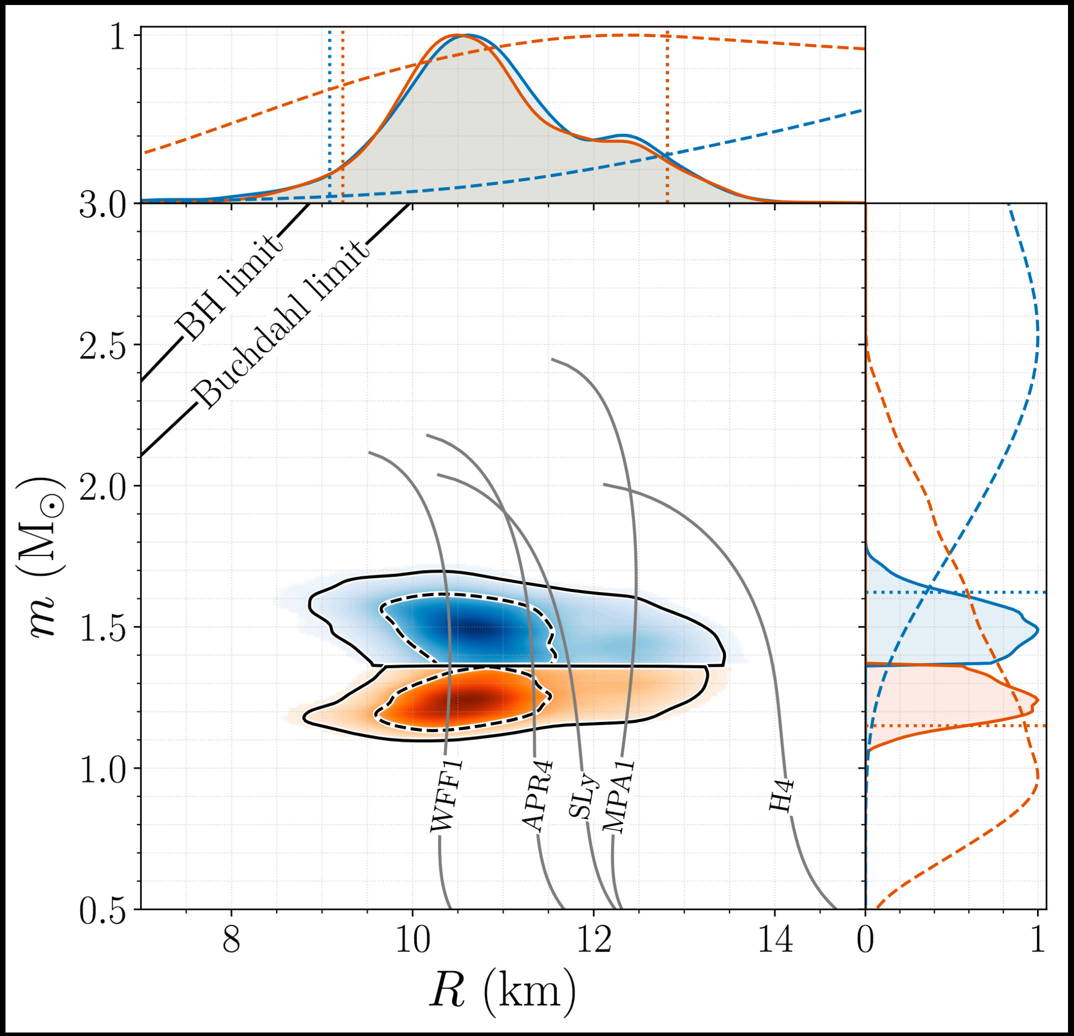
Common-EOS Radius constraints

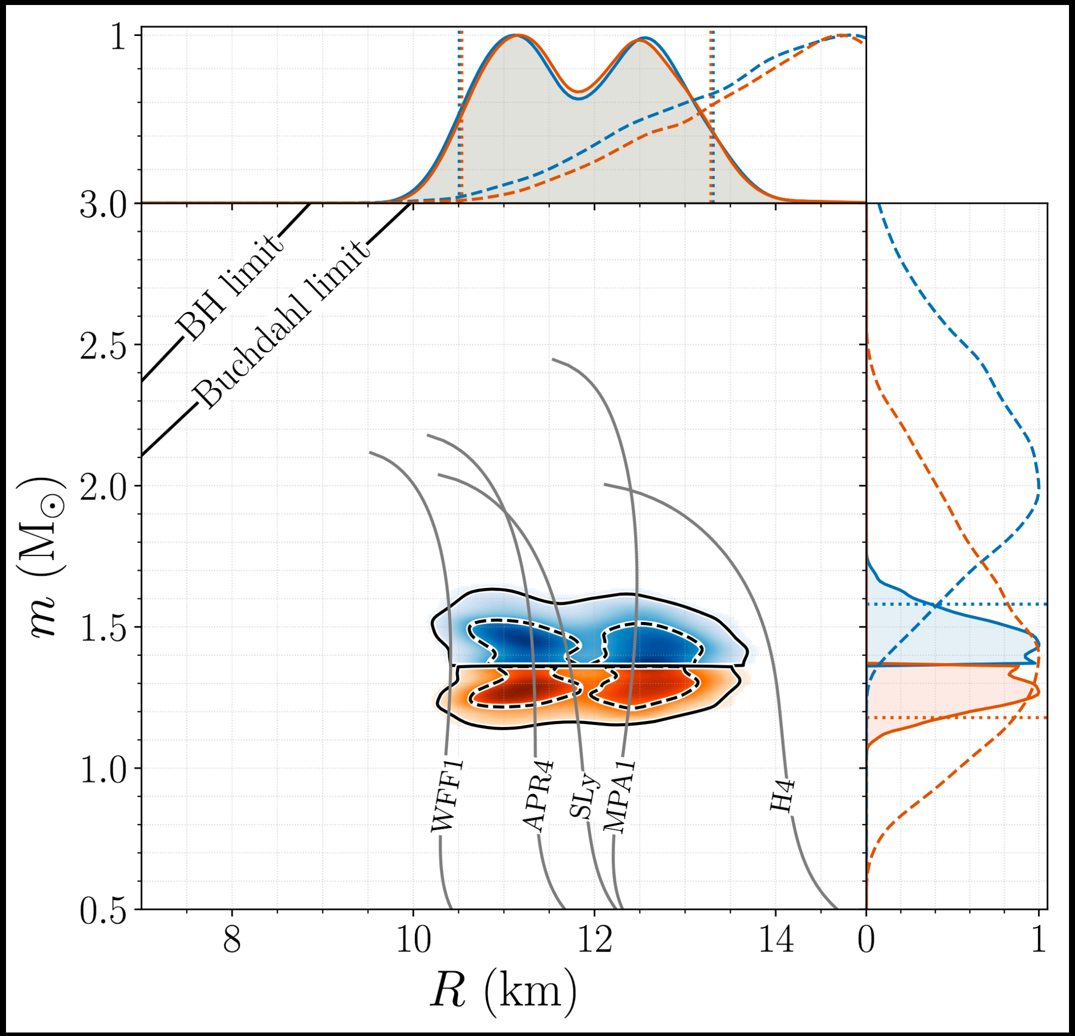
GW data

$R_1=10.8^{+2.0}_{-1.7}$, $R_2=10.7^{+2.1}_{-1.5}$

GW data + 1.97 M_{sun} star

$R_1=11.9^{+1.4}_{-1.4}$, $R_2=11.9^{+1.4}_{-1.4}$





Quasi-universal Λ_1-Λ_2 & Λ-R

Quasi-universal method
Chatziioannou et al 1804.03221

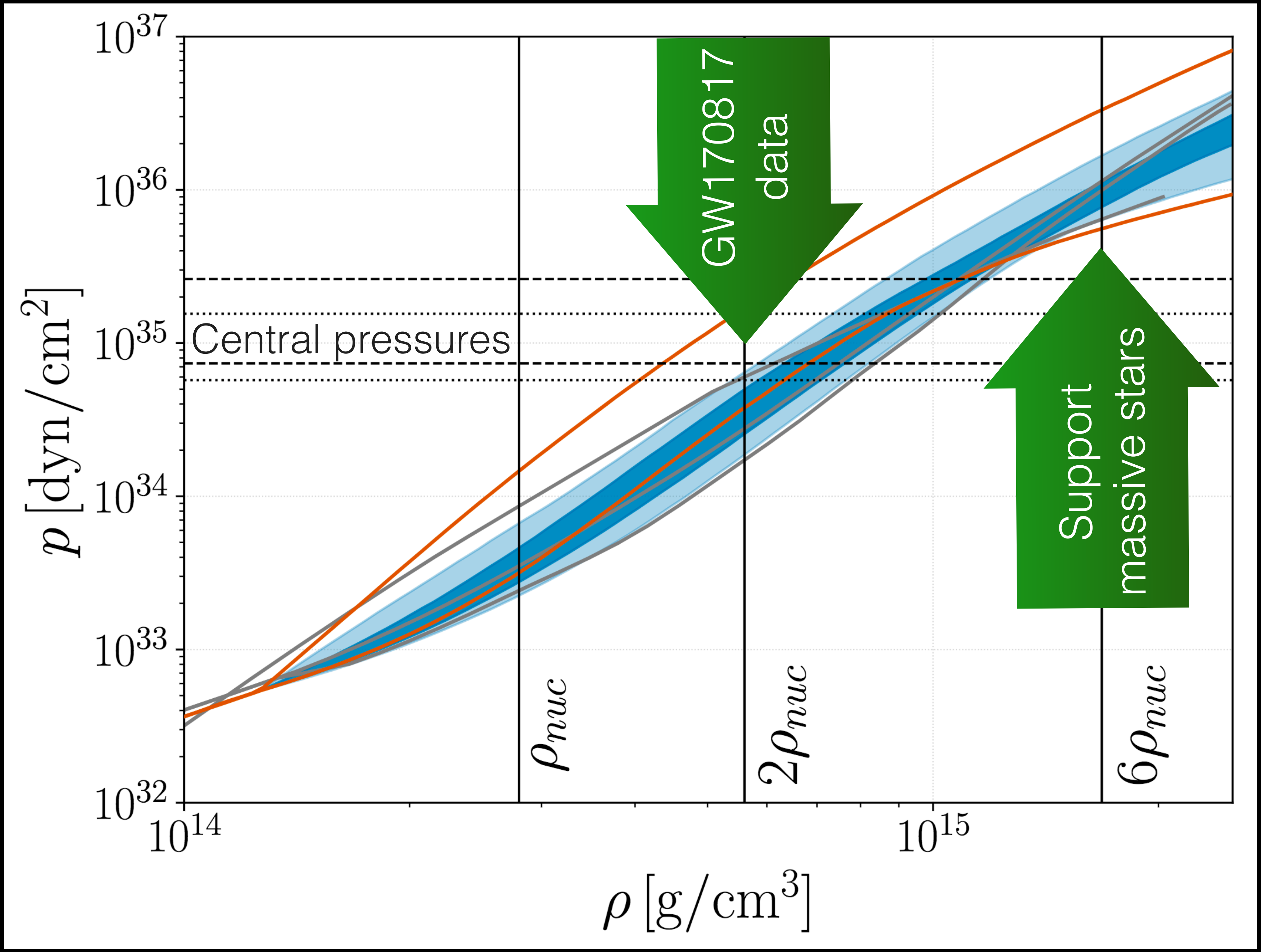
Spectral parameterized EOS

Parameterized EOS Method:
Carney et al 1805.11217

LSC-Virgo EOS 1805.11581

GW170817 + $M_{max} > 1.97\ M_\odot$

Twice saturation: 22^{+11}_{-17} MeV fm^{-3} (GW only: 18^{+7}_{-15} MeV fm^{-3})



Prior 90% range

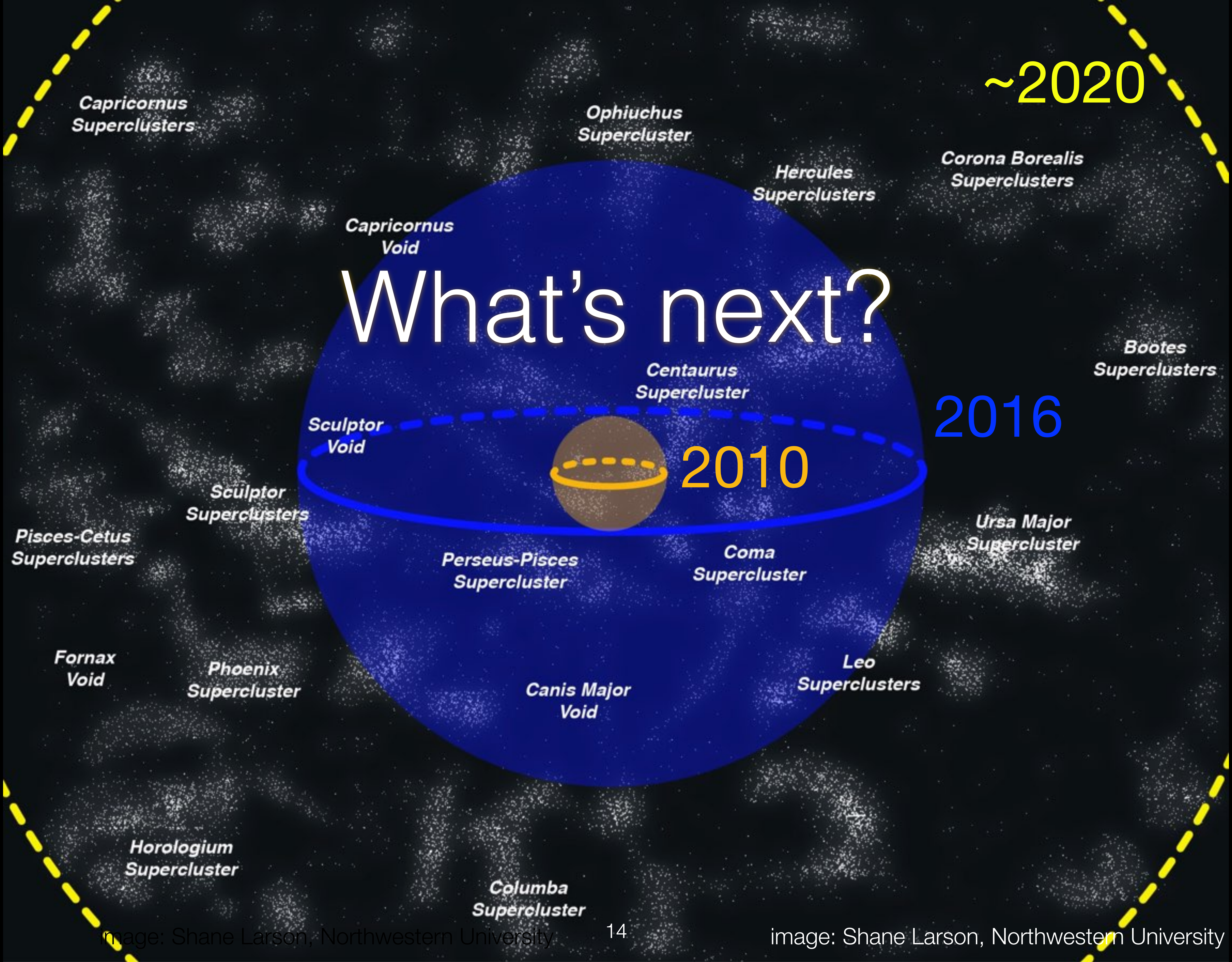
Posterior 90% (50%) range

For comparison:
H4 (top)
APR4
WFF1 (bottom)

Overlaps x-ray constraints (e.g. Steiner, Lattimer, Brown 2010)

LSC-Virgo EOS 1805.11581

What’s next?



~2020

2016

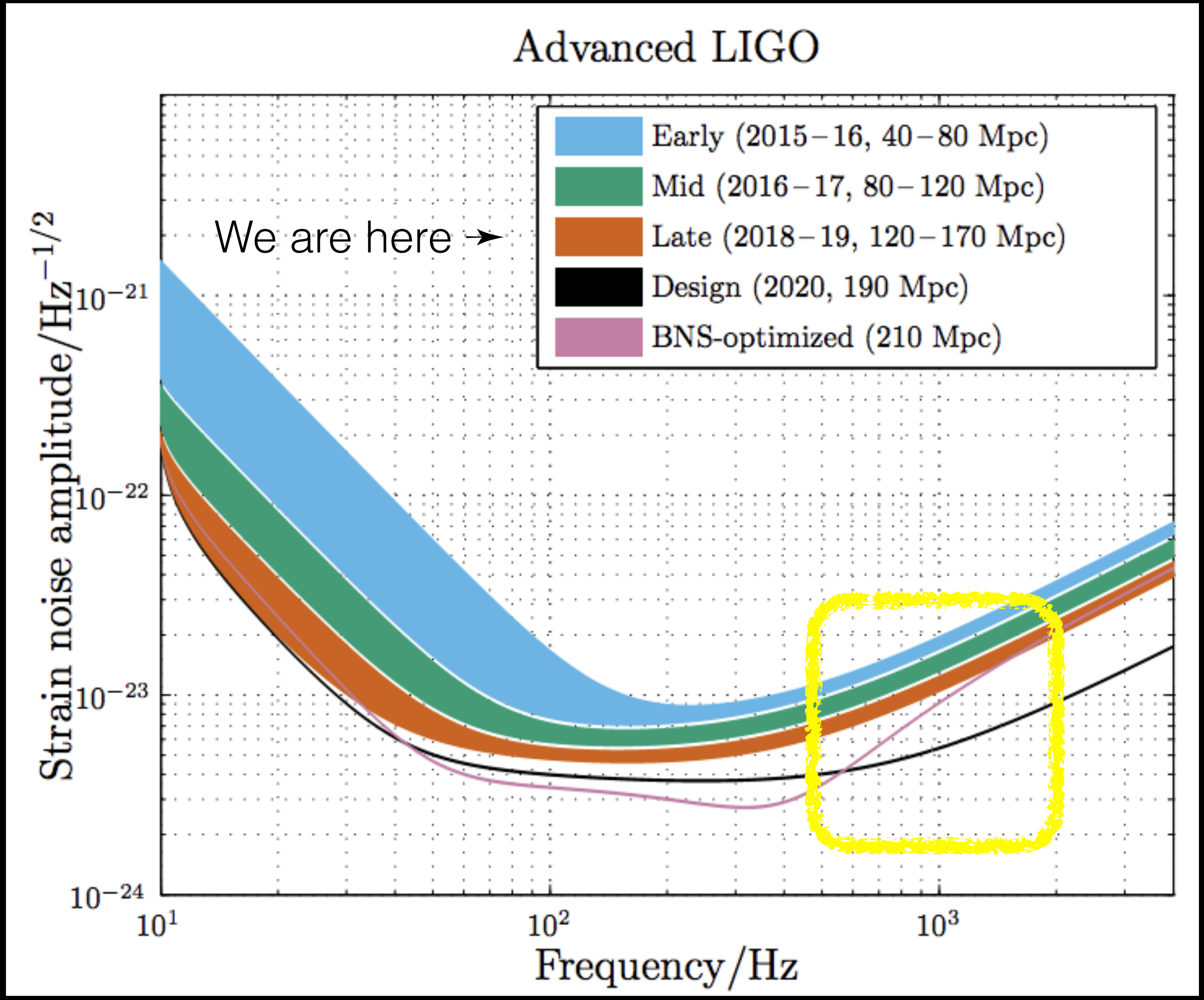
2010

image: Shane Larson, Northwestern University

image: Shane Larson, Northwestern University

Observing Plan (under development)

Advanced LIGO/Virgo goal:
improve BNS range by factor ~2 from O2 (rate x 8)
high-frequency sensitivity by factor ~4

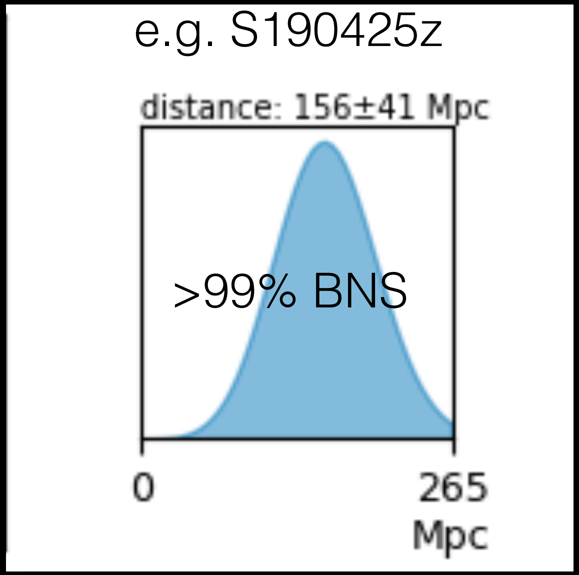


O1+O2 based rate
110–3840 Gpc^{-3} yr^{-1}
LSC/Virgo arXiv:1811.12907, accepted PRX

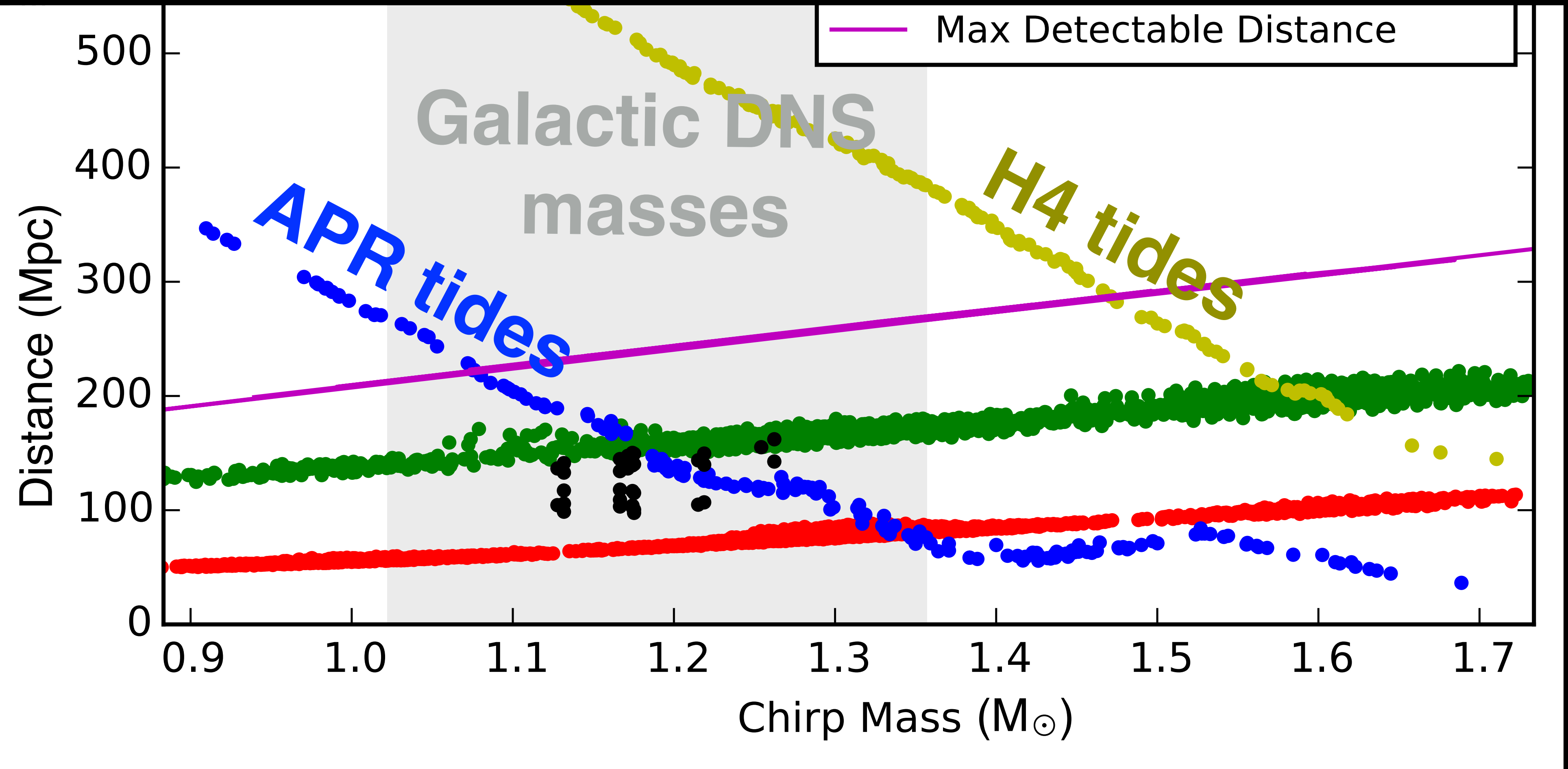
1000 Gpc^{-3} yr^{-1}
⬇
~40 yr^{-1} detected w/
Advanced LIGO Design
LSC/Virgo Class.Quant.Grav.27:173001
(2010)

KAGRA/LIGO/Virgo Observing scenarios, Living Reviews in Relativity; 21:3; 2018

Tidal signatures in Advanced LIGO signals



Maximum distinguishable distance (Mpc)
with Advanced LIGO design sensitivity



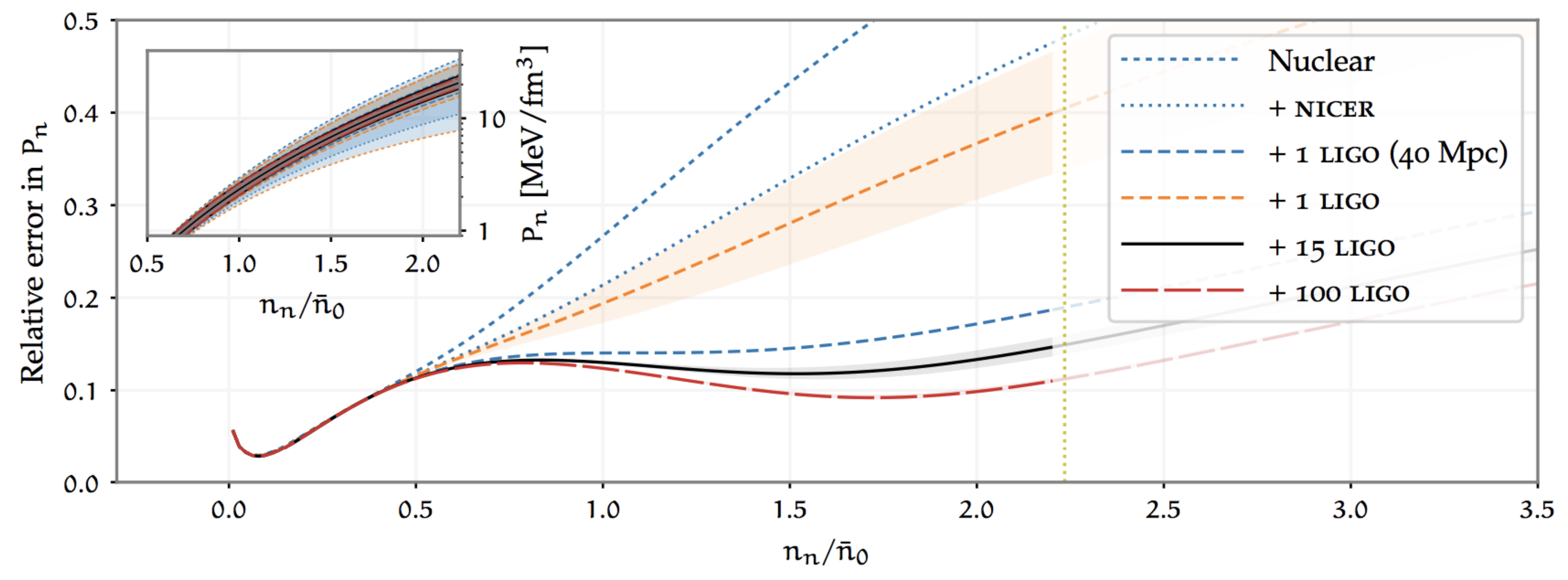
Component masses randomly drawn from (1.0,2.0) M⊙

“distinguishable” effect size compared to BBH is ~ 1σ

Measurement error depends on correlations, ∝ D

Cullen, Harry, Read and Flynn
CQG, arXiv:1708.04359

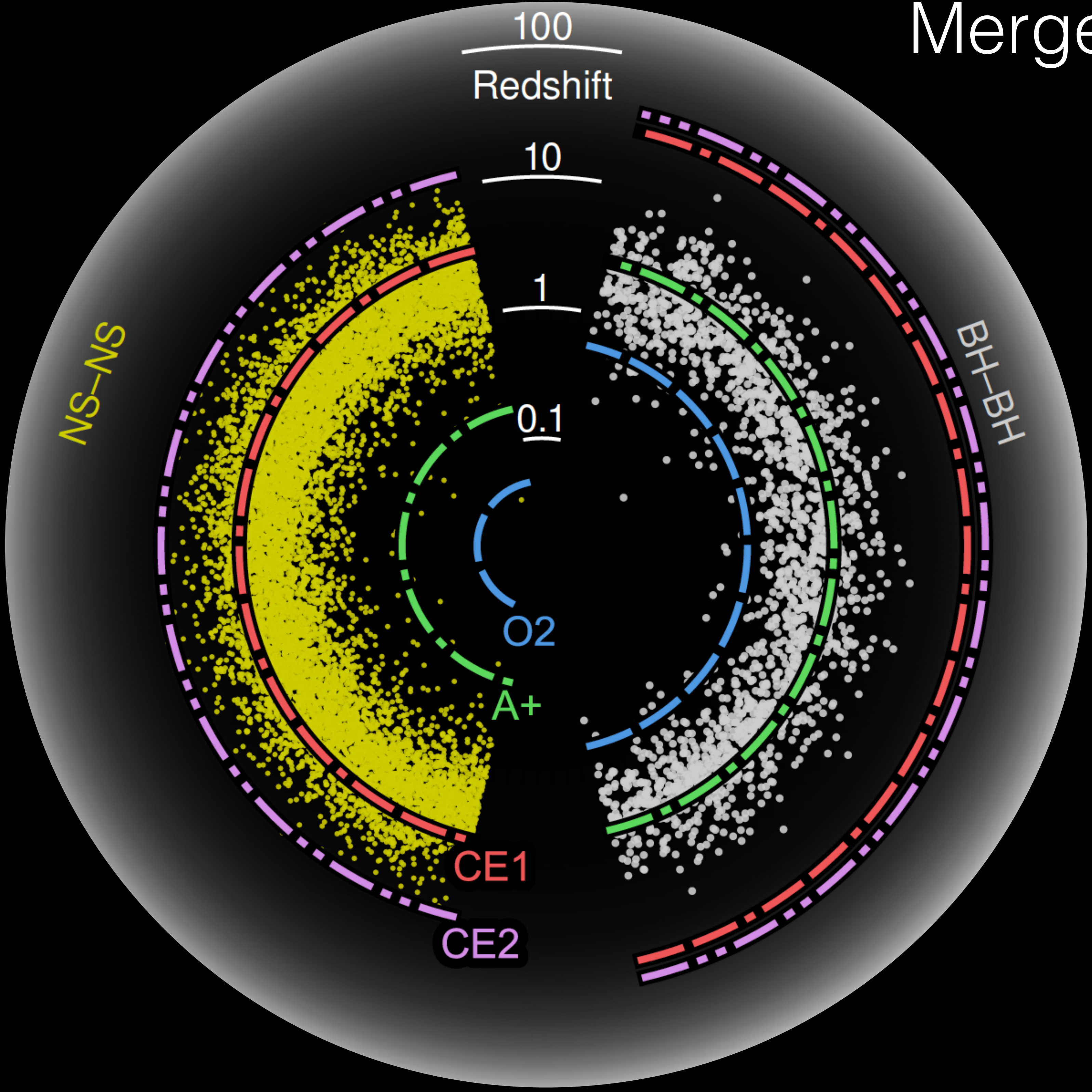
Advanced Era EOS constraint potential



Forbes et al 1904.04233

Beyond LIGO/Virgo:

Mergers across the Universe



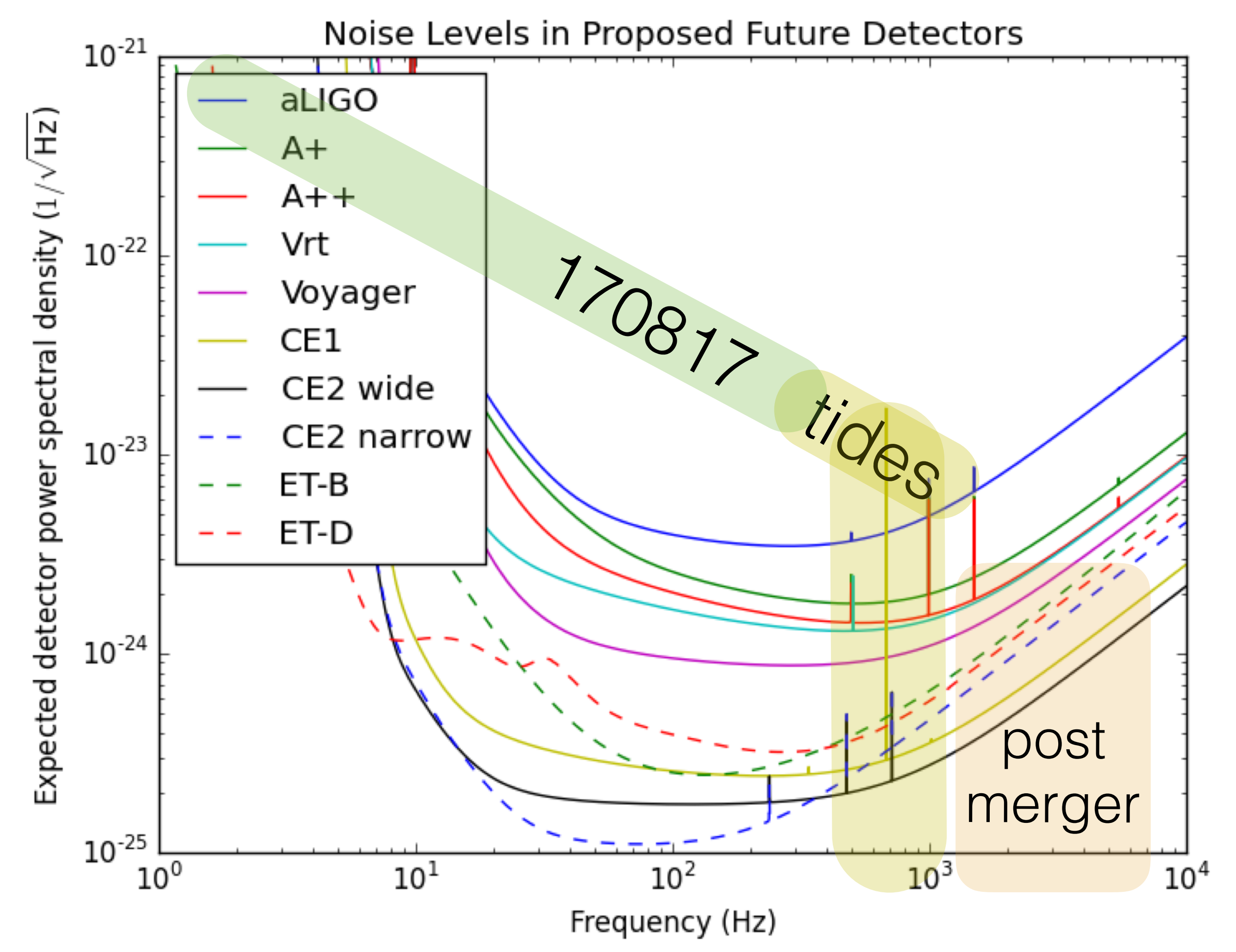
A+: LIGO facility upgrade for ~2025

CE1/CE2: 2030s era facilities, Einstein Telescope/Cosmic Explorer

The US Program in Ground-Based Gravitational Wave Science

arXiv:1903.04615

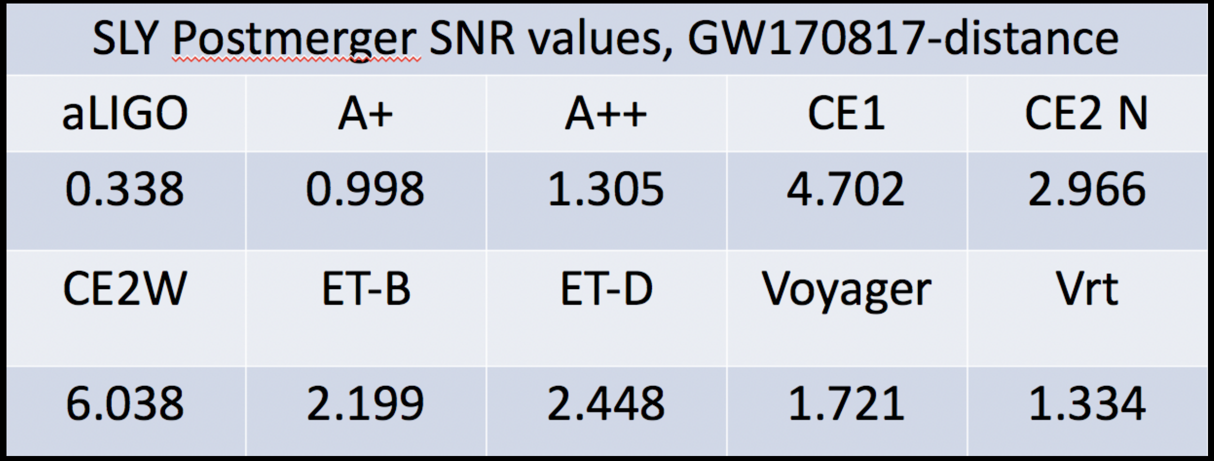
Precision neutron-star measurements with future observatories



Inspiral Λ measurement error scales inversely as noise level ~ 500-1000 Hz

Factor of ~10 improvement with 3G

Post-merger:


SLY Postmerger SNR values, GW170817-distance

aLIGO	A+	A++	CE1	CE2 N
0.338	0.998	1.305	4.702	2.966
CE2W	ET-B	ET-D	Voyager	Vrt
6.038	2.199	2.448	1.721	1.334

Measurement and
SNR estimates:
Isabella Molina, CSUF

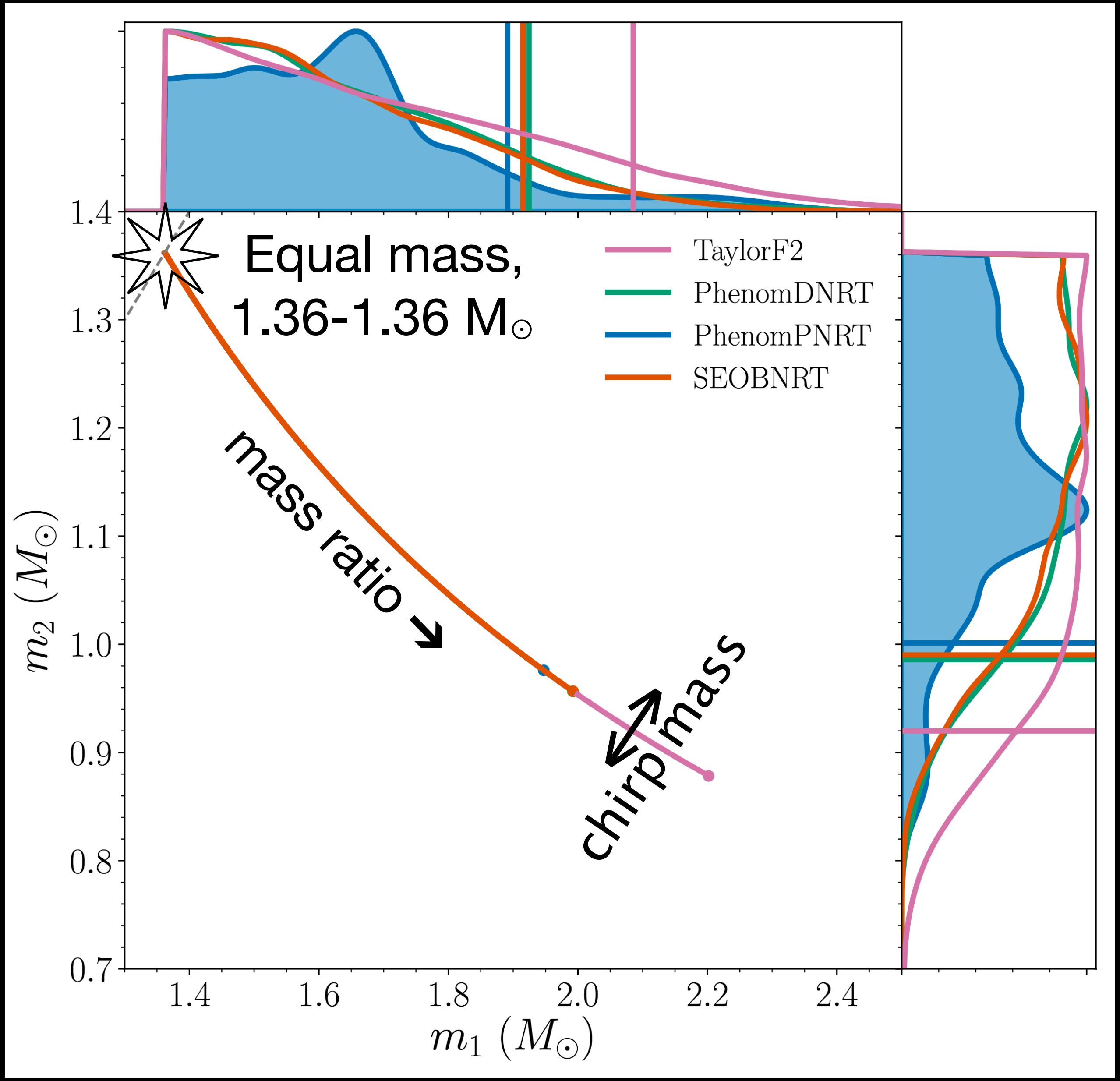
See also
Adhikari et al arXiv:1905.02842

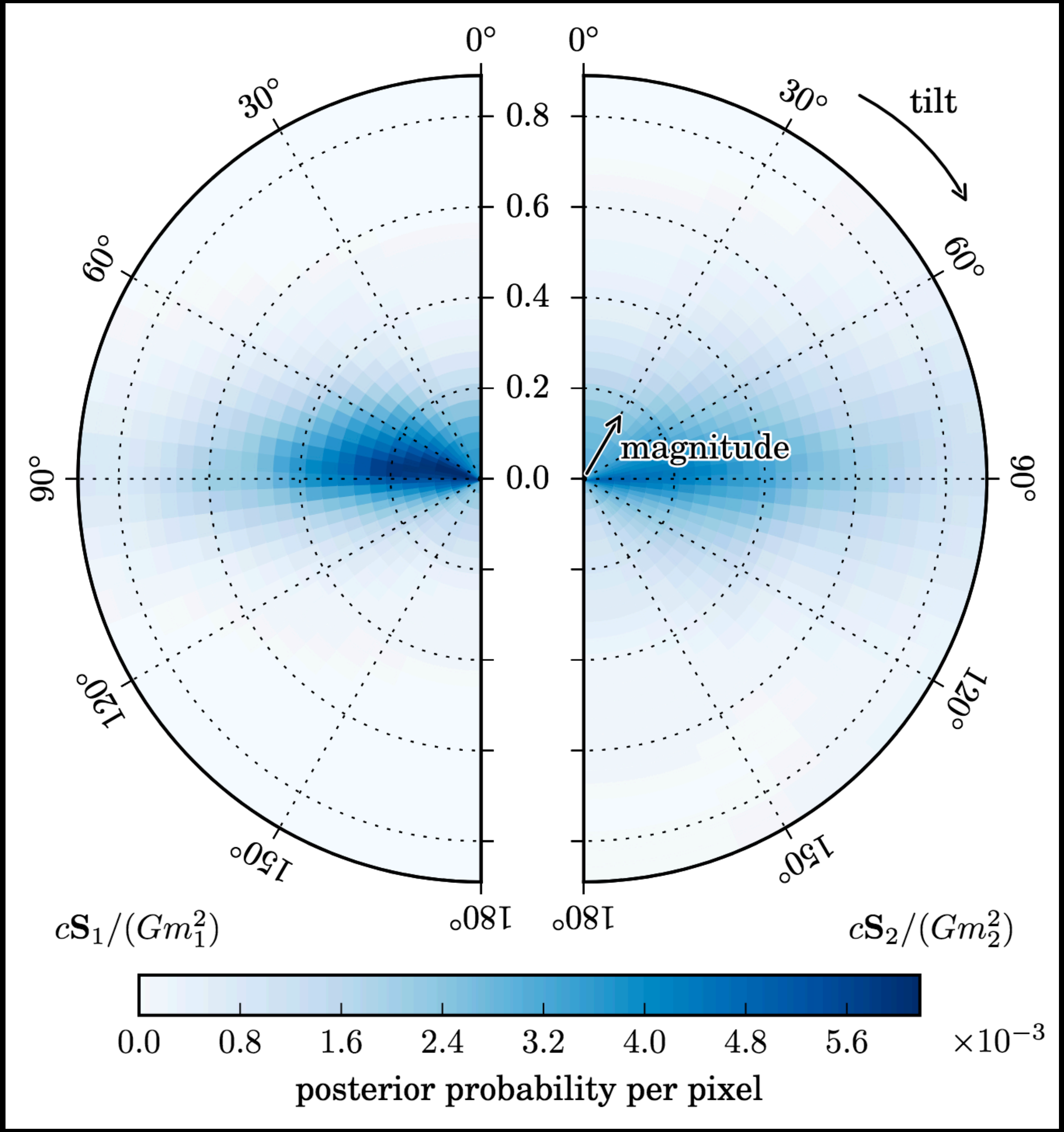
Thank you!

Extra slides

Measurement: Masses and Spin

Gravitational-wave strain data
Minimal assumptions about source properties

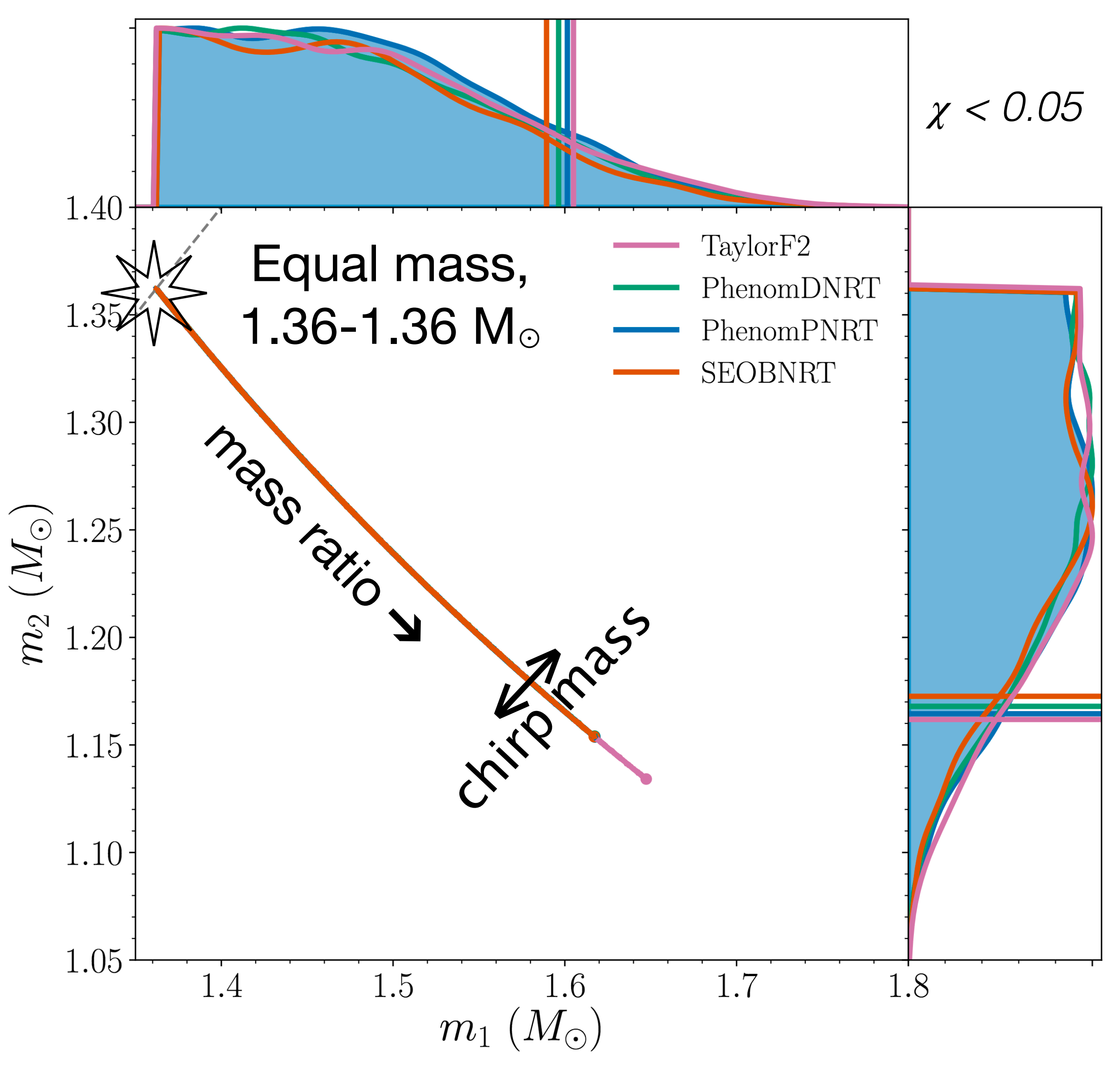


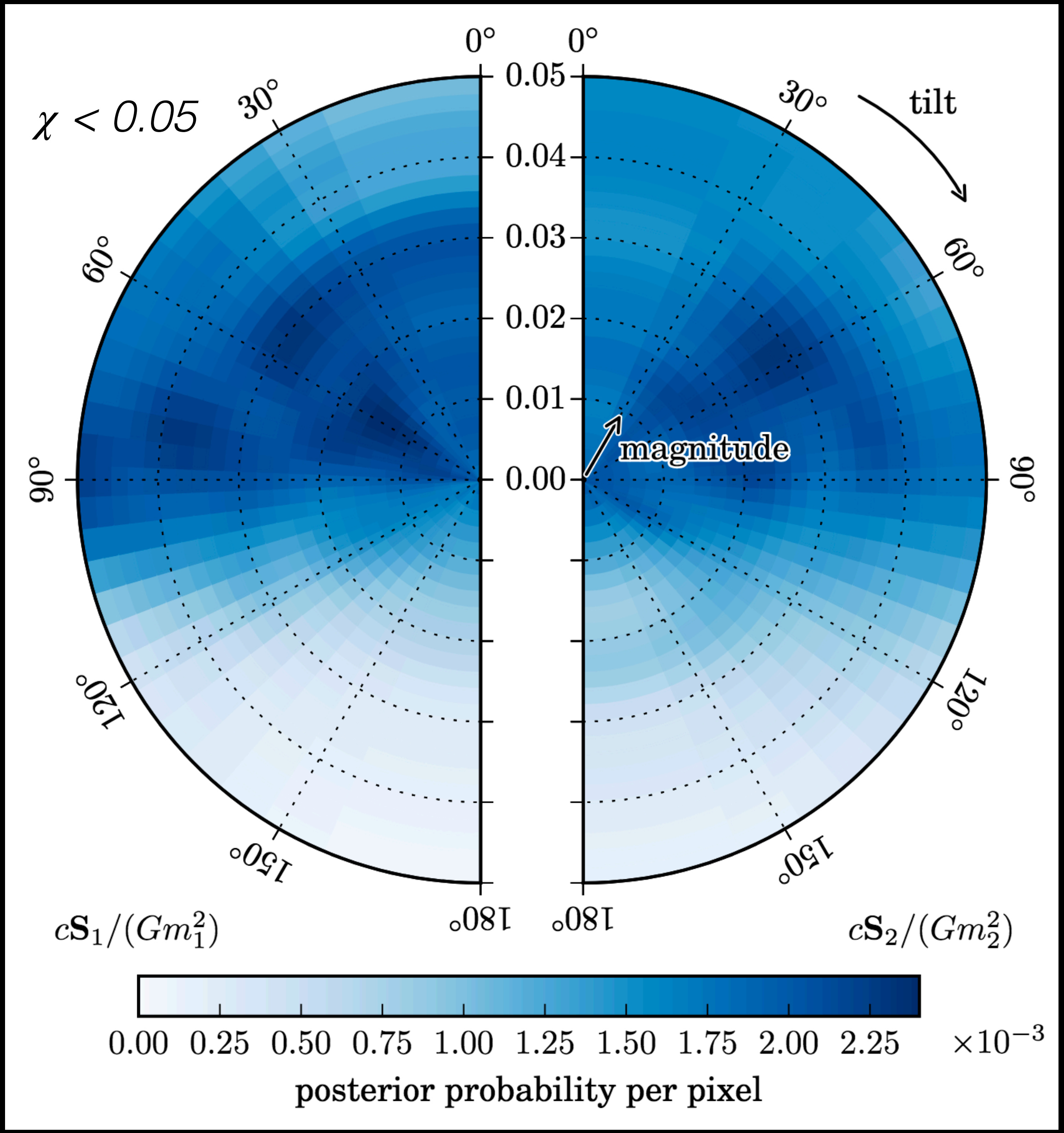


LVC Source Properties 1805.11579

Measurement: Masses and Spin

Assume low spins, motivated by galactic DNS
Limits mass/spin degeneracy, shift toward equal mass

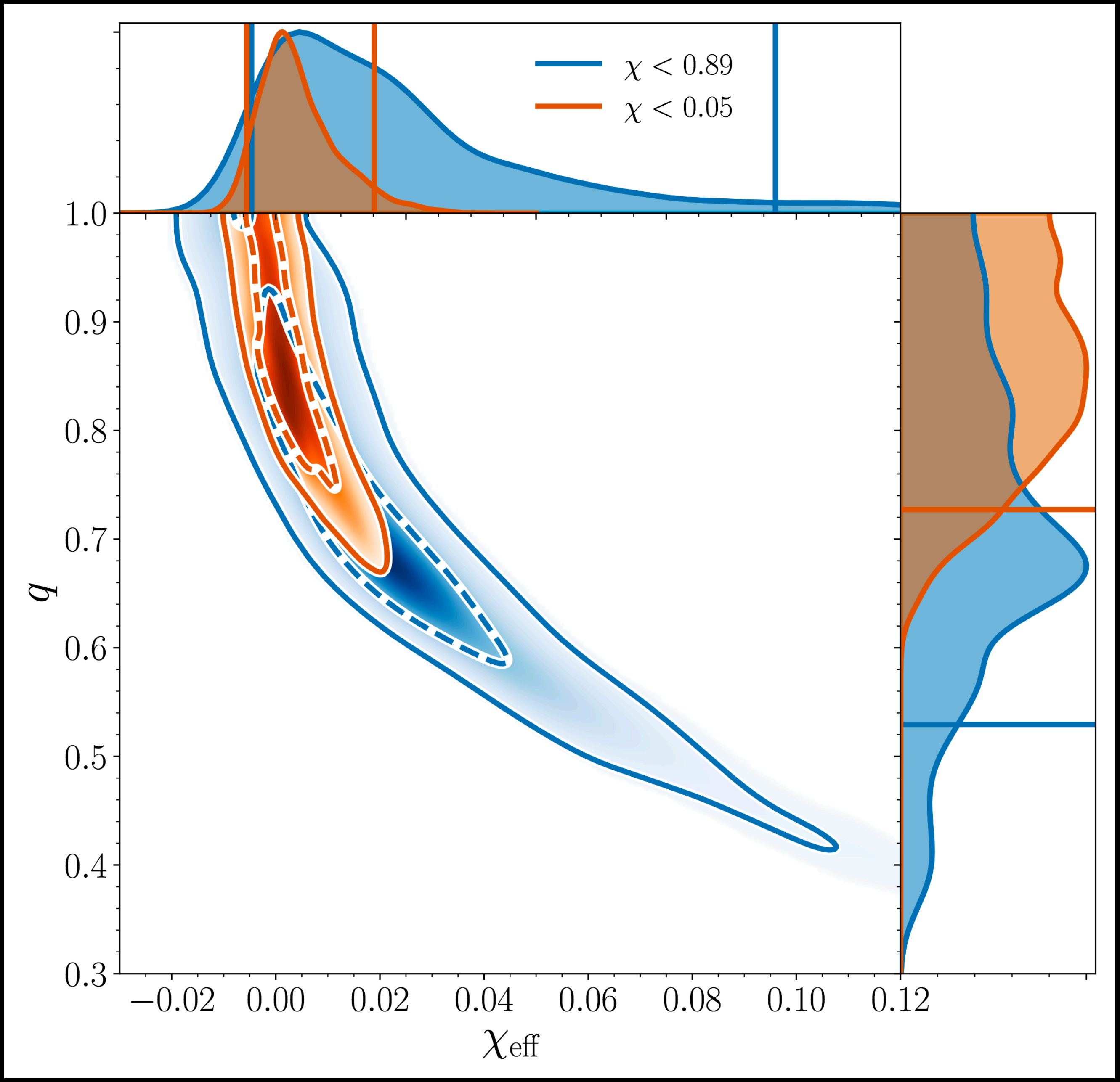


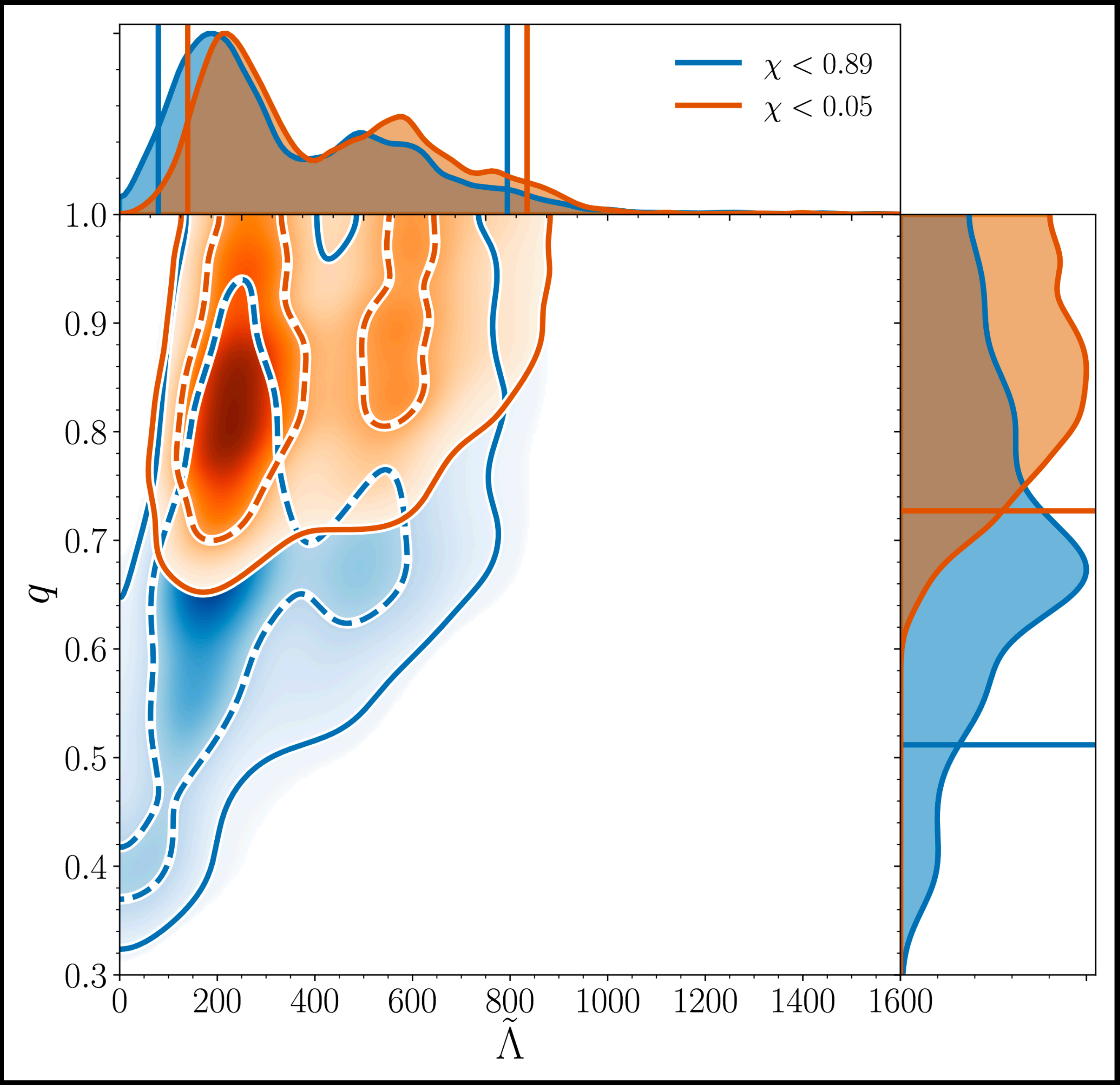


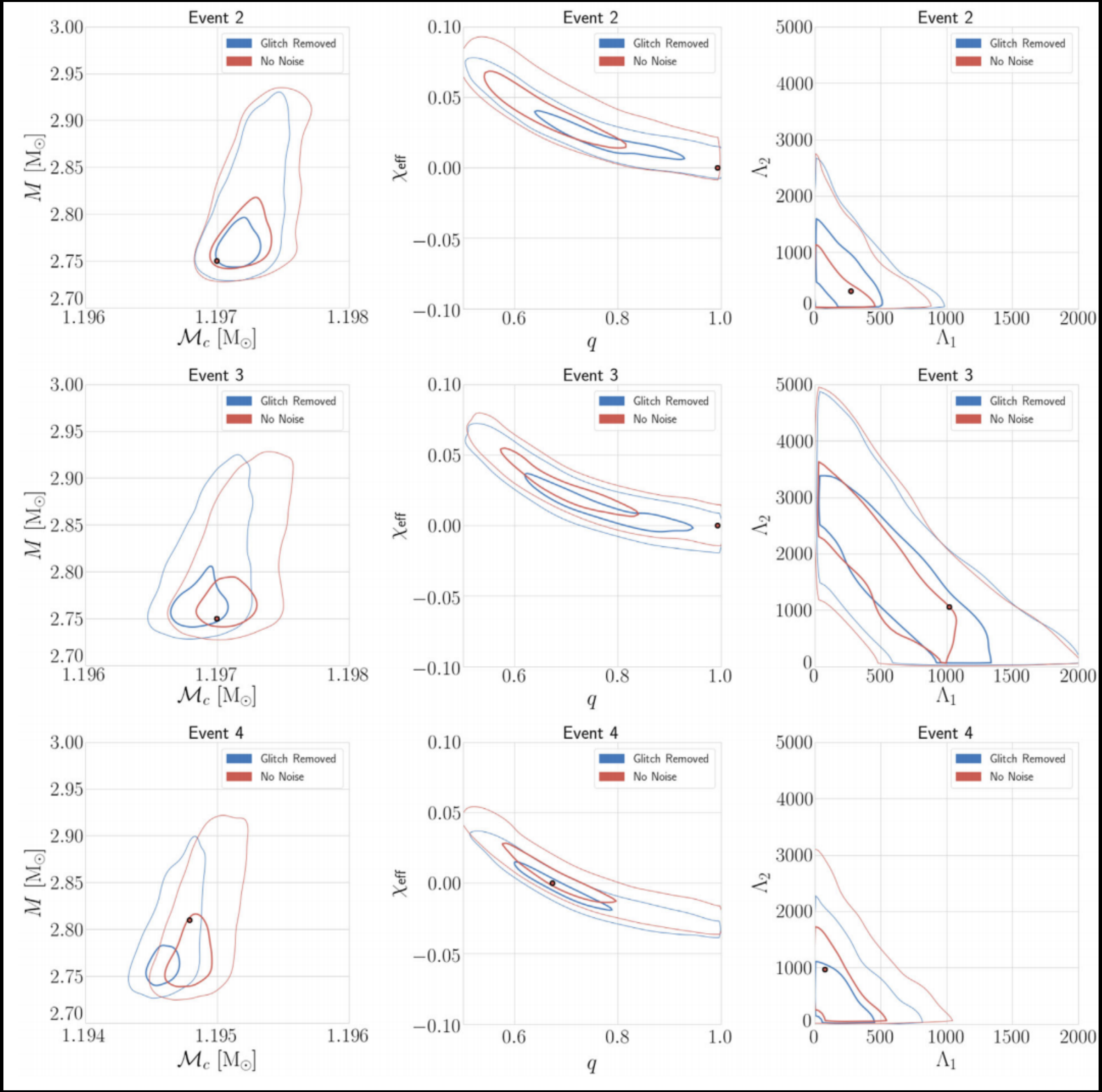
LVC Source Properties 1805.11579

Correlations with mass and spin

LVC Source Properties *1805.11579*







Validation of glitch removal

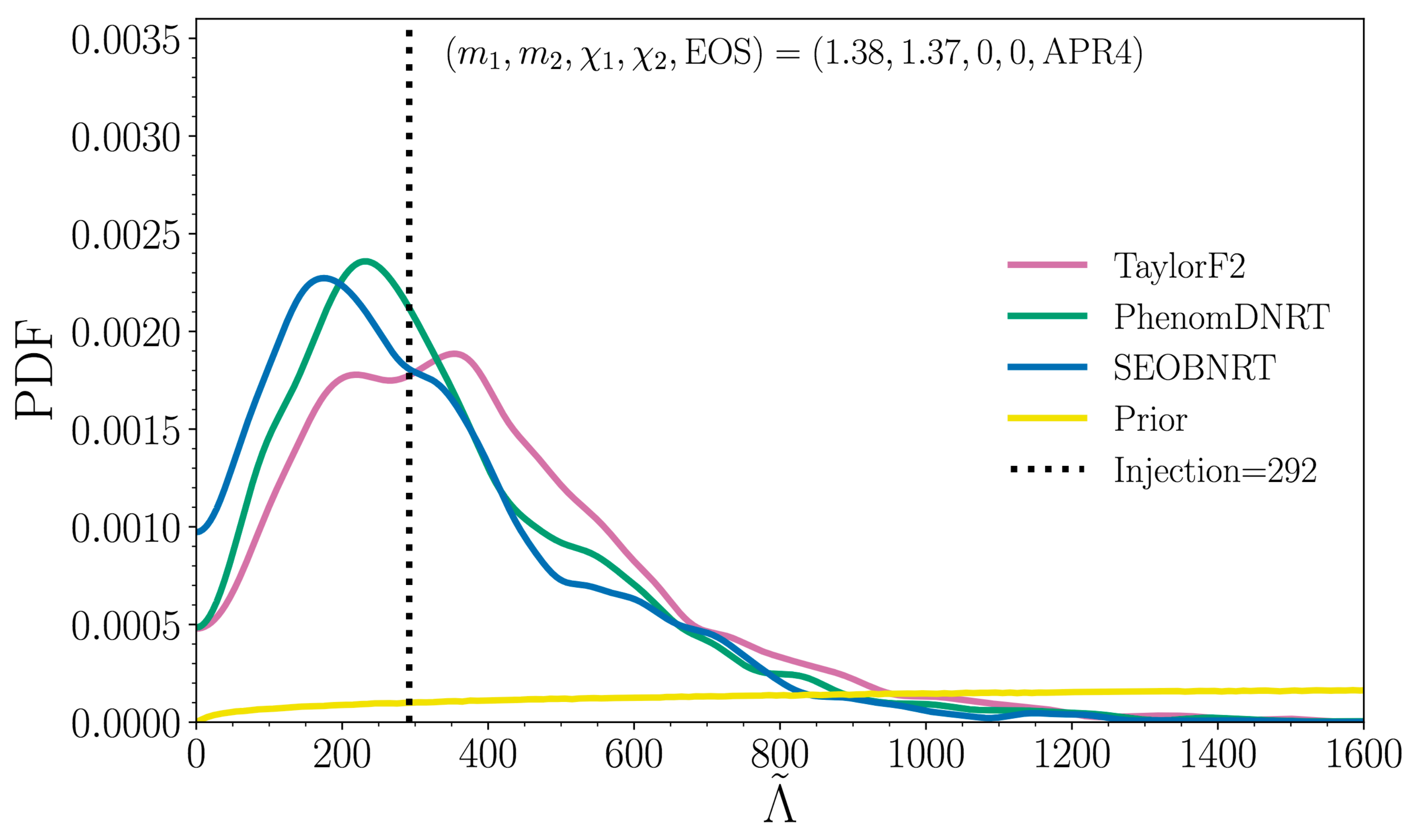
Pankow et al
1808.03619

LVC Source Properties 1805.11579

Waveform Systematics on $\tilde{\Lambda}$

- Synthetic waveforms (here, Tidal sEOB) injected similar to GW170817 (SNR, masses, sky location) with APR4 EOS

- Dashed: injection
- Recovery with variant waveform models
- Equal mass, non-spinning NS



Similar injection/recovery tests with Nagar et al's TEOBResum motivated discovery paper usage of TaylorF2 for upper limit

LVC Source Properties 1805.11579

Waveform Systematics on $\tilde{\Lambda}$

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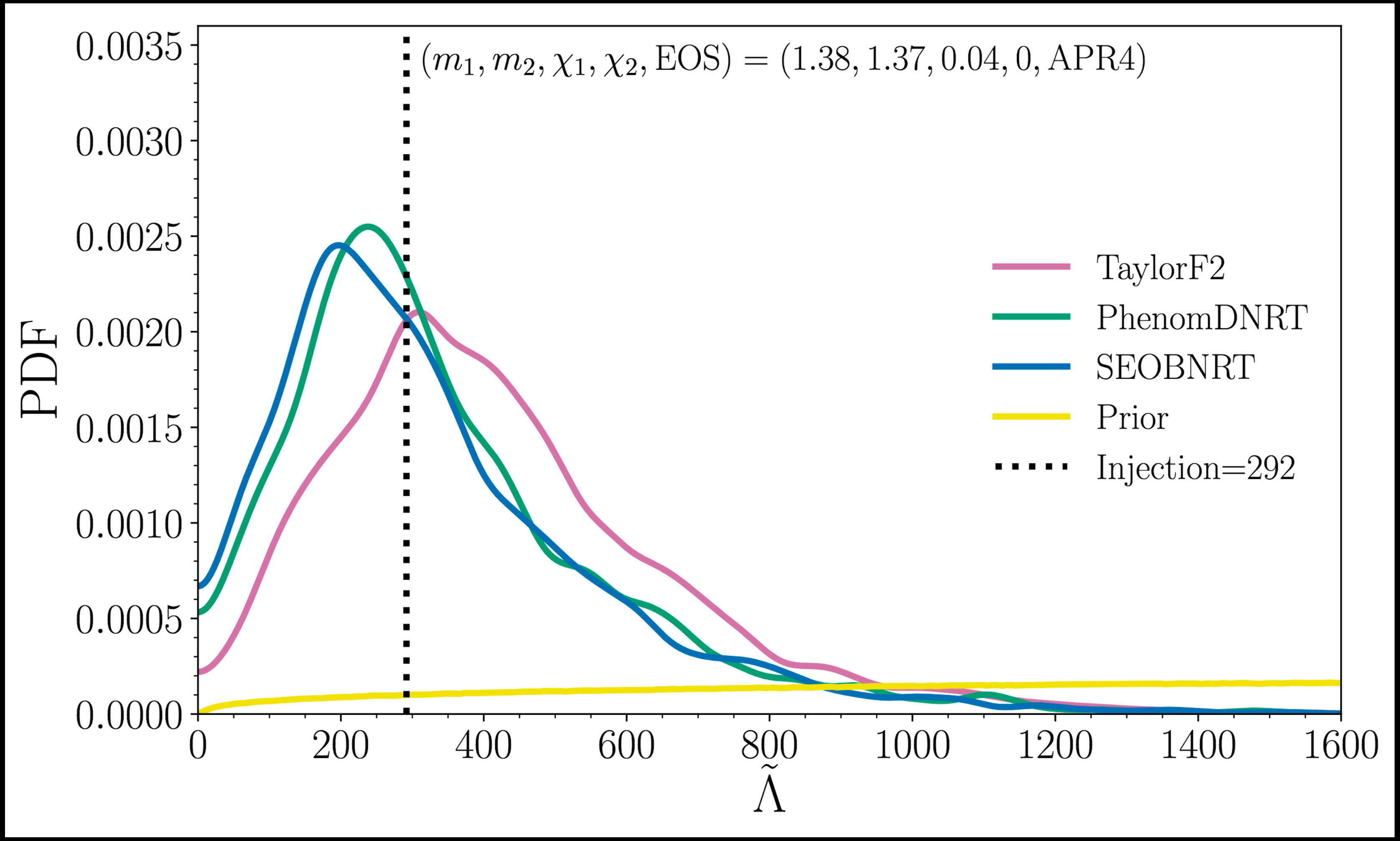

LVC Source Properties 1805.11579

Waveform Systematics on $\tilde{\Lambda}$

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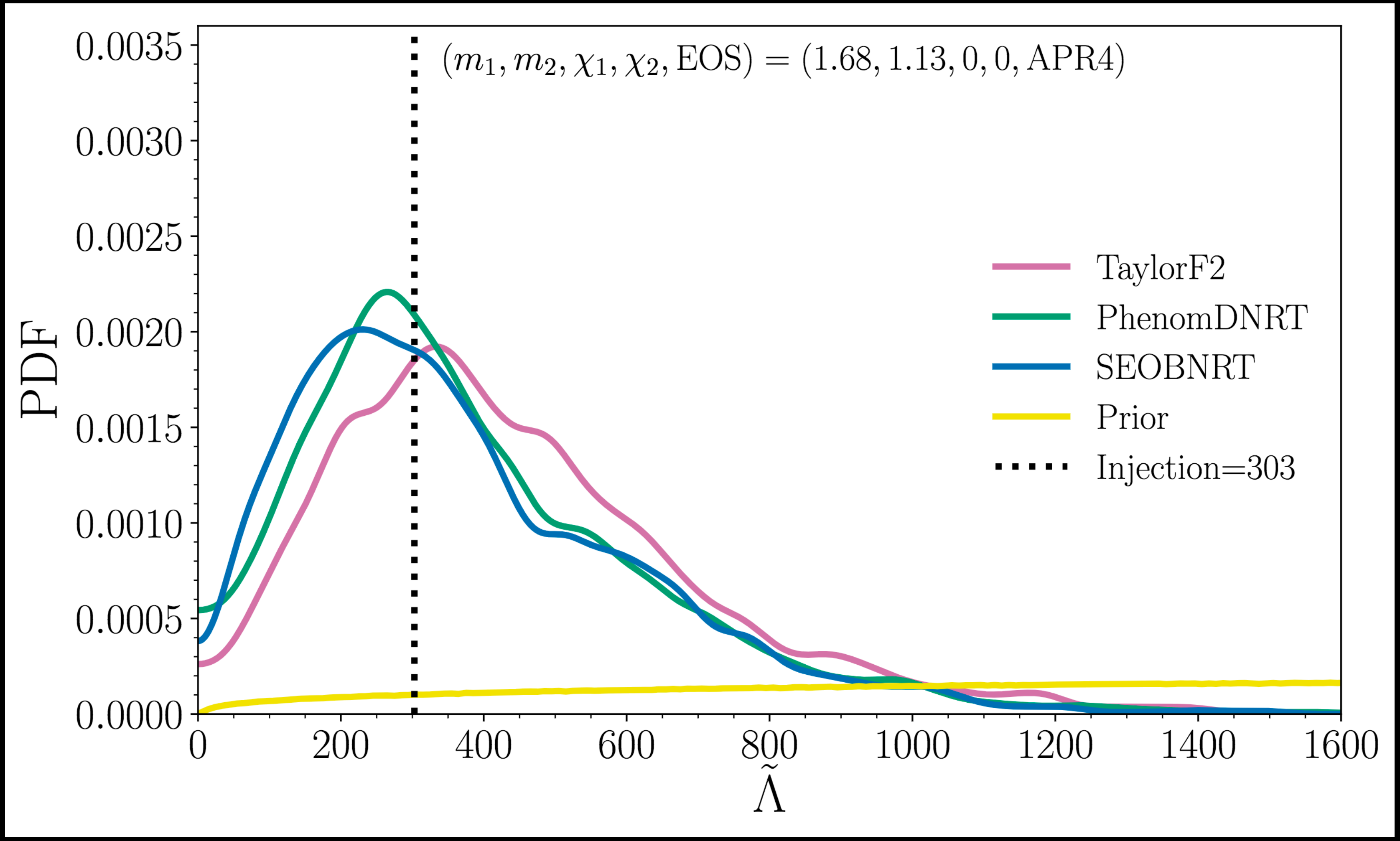
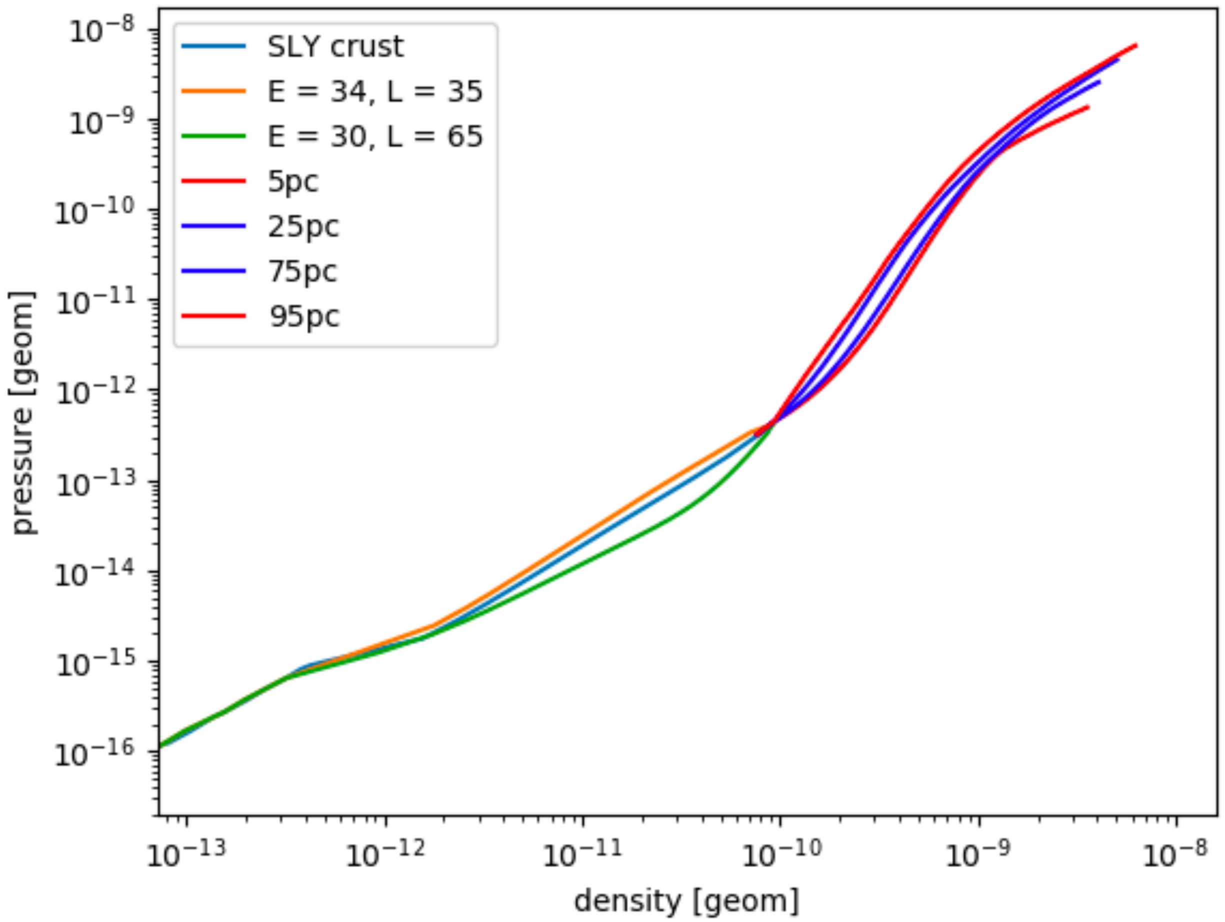
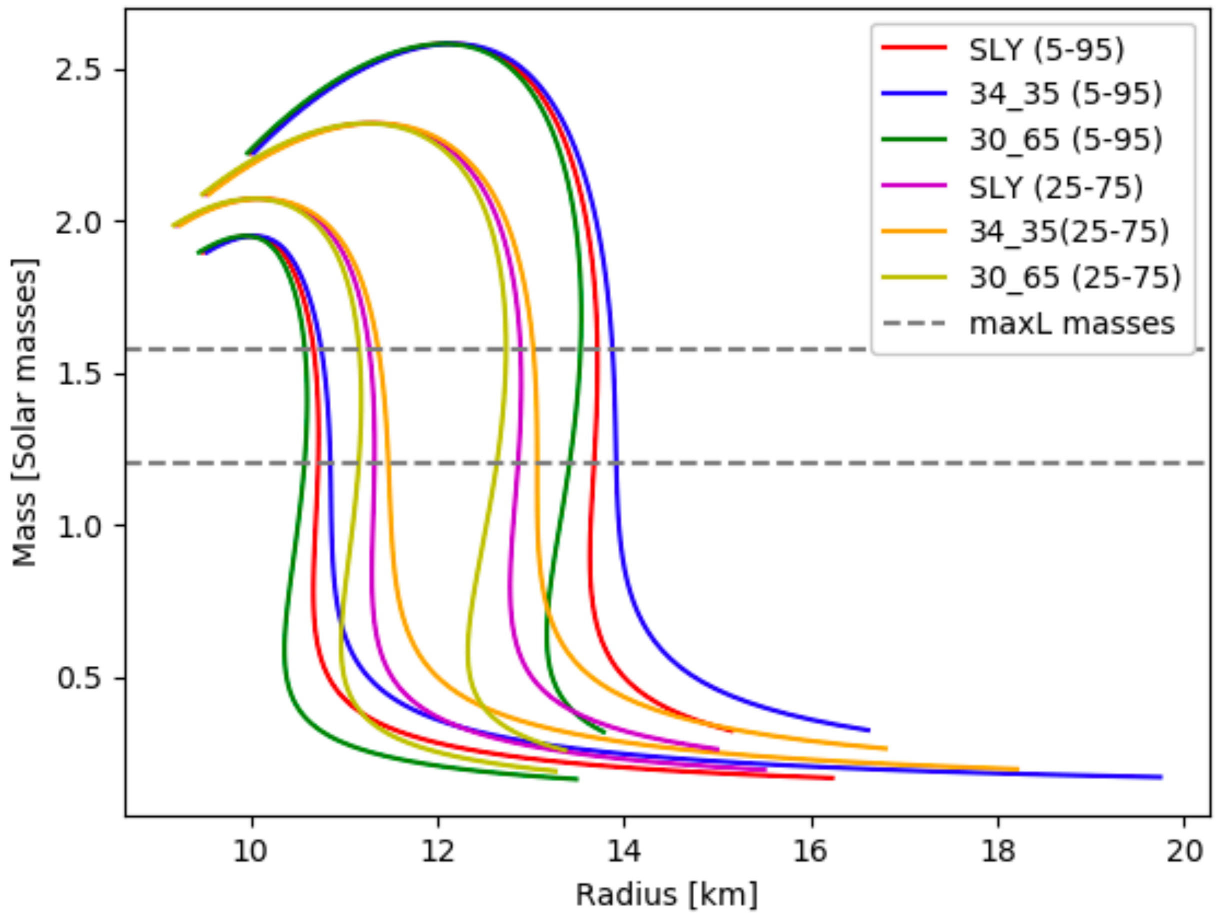


Impact of crust variation

Rossella Gamba, Les Wade, Jocelyn Read, arXiv:1902.04616

Gravitational-waves depend only on above-nuclear density



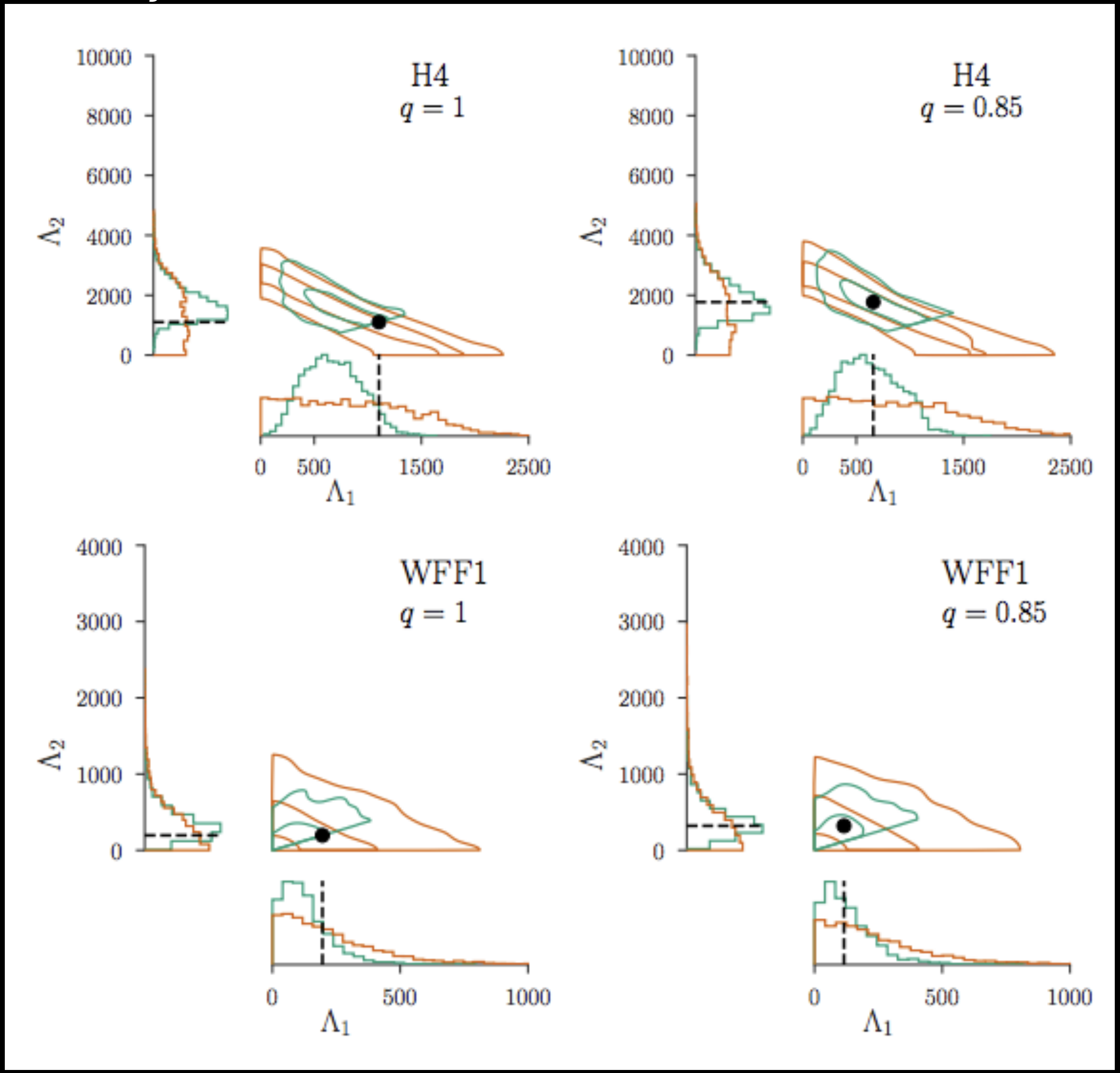


Systematic uncertainty on radius implications ~0.3km

Common-EOS analysis:

Quasi-universal relations

Injected waveform tests



Independent Λ quasi-universal

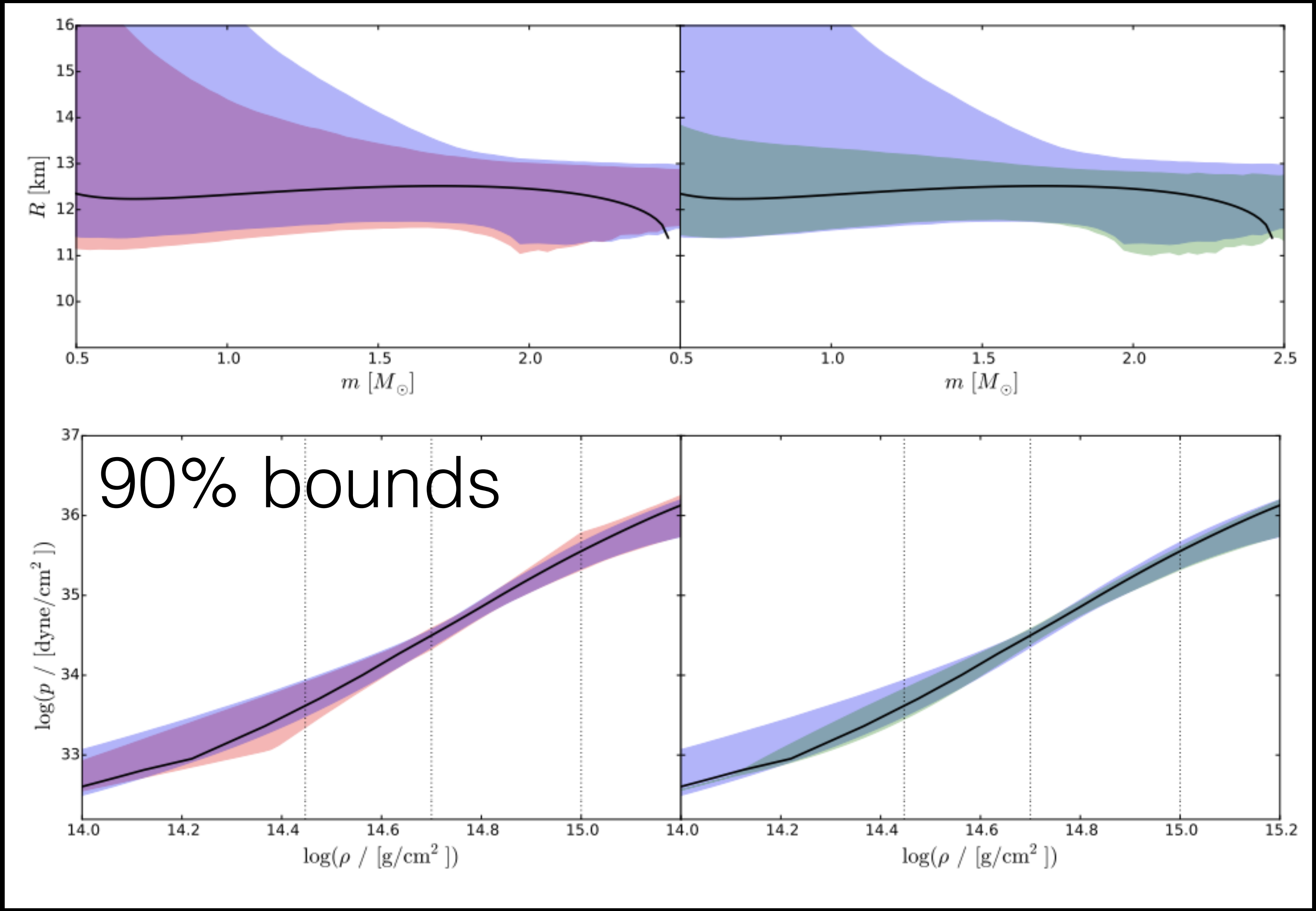
Chatziioannou et al
1804.03221

- Apply quasi-universal relations determined from candidate EOS
  - Yagi and Yunes, Class. Quant. Grav. 33, 13LT01 (2016)
- Link Λ_1 and Λ_2 in sampling, depending on mass ratio
- Marginalize over relation error; tighter constraints for compact NS injections

Common-EOS analysis:

Parameterized EOS

Injected waveform tests



Piecewise Polytropes

Spectral Decomposition

Carney et al
1805.11217

- Parameterize underlying EOS
- Sample in EOS parameters, derive $\Lambda(m_1)$ and $\Lambda(m_2)$ for samples, waveforms
- Enforce causality and support of maximum observed mass
- Direct implications for $p(\rho)$, $R(M)$