Neutron stars:
gravitational-wave sources with matter

Jocelyn Read
Gravitational Wave Physics and Astronomy Center
California State University Fullerton
for the LIGO Scientific Collaboration and Virgo Scientific Collaboration
Amaldi 2017

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Neutron stars:
gravitational-wave sources **that** matter

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Neutron stars:
gravitational-wave sources that still matter

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GW PAC GRAVITATIONAL WAVE Physics and Astronomy Center @ CALIFORNIA STATE UNIVERSITY FULLERTON

- Advanced LIGO results so far
  - Astrophysical implications
- Impact of matter on compact binaries
  - Measurement prospects and status
  - Waveform models

How ready are we to learn about the properties of neutron-star matter from LIGO detections?

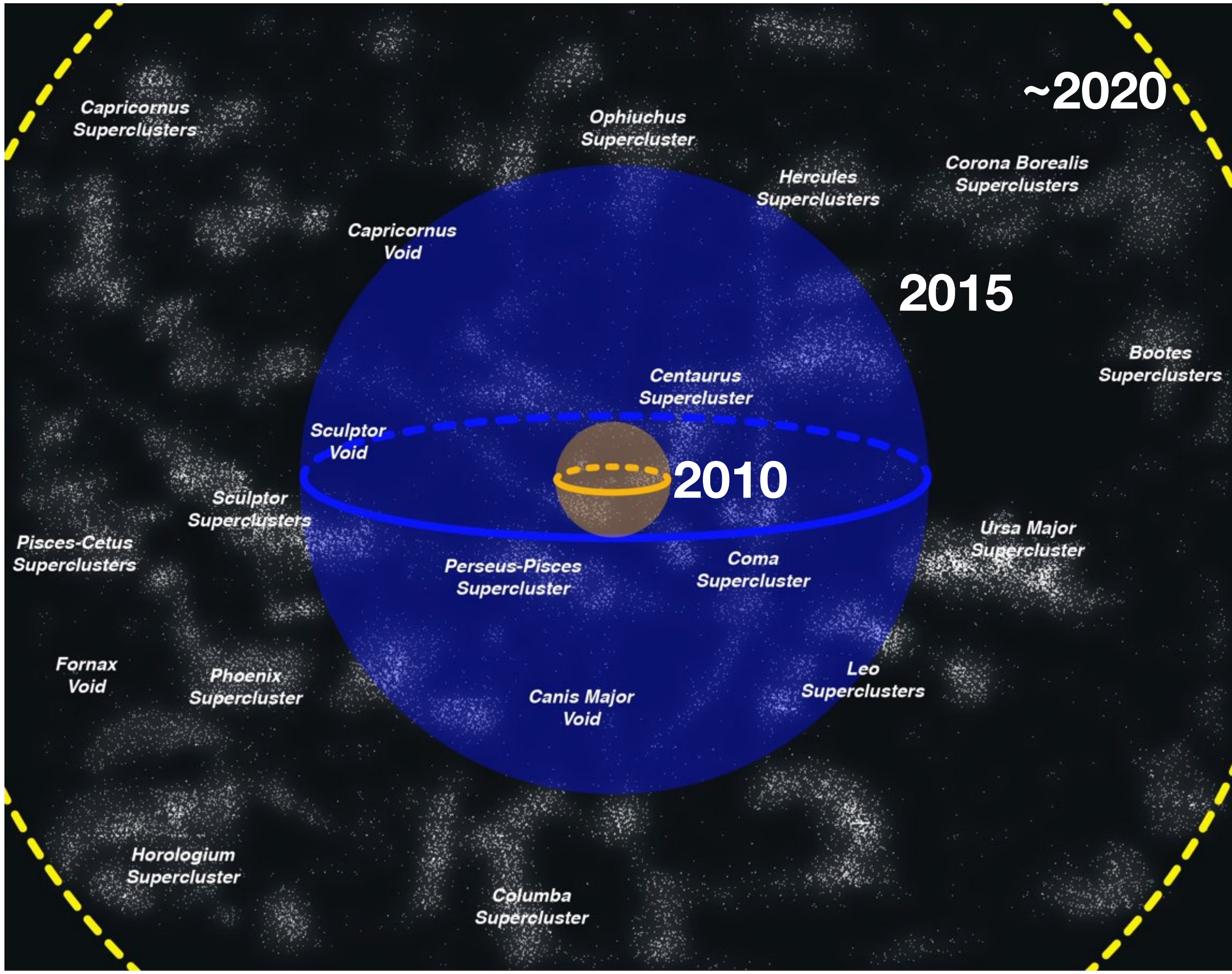
How well do we understand the matter has on other statements from LIGO CBC searches and parameter estimation?

Detection prospects of Advanced LIGO design

- binary neutron star mergers to ~200 Mpc
- neutron star–(10 M_{sun}) black hole mergers to ~0.5 Gpc
- (10-10 M_{sun}) binary black hole mergers to ~1 Gpc

(LIGO White Paper: https://dcc.ligo.org/LIGO-T1400054/public, rates above sky-averaged)

initial LIGO BNS range: up to 20 Mpc
image: Shane Larson, Northwestern University

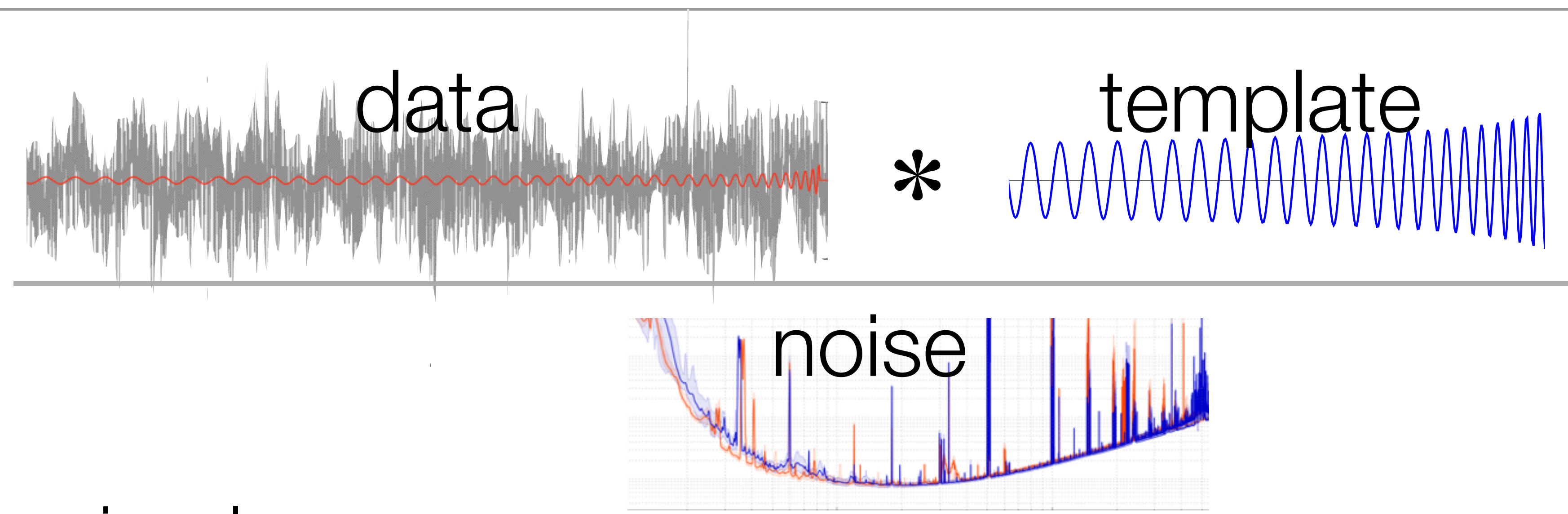


BNS expected 0.4 - 400 yr^{-1}
NSBH expected 0.2 - 300 yr^{-1}
LSC/Virgo 1003.2480

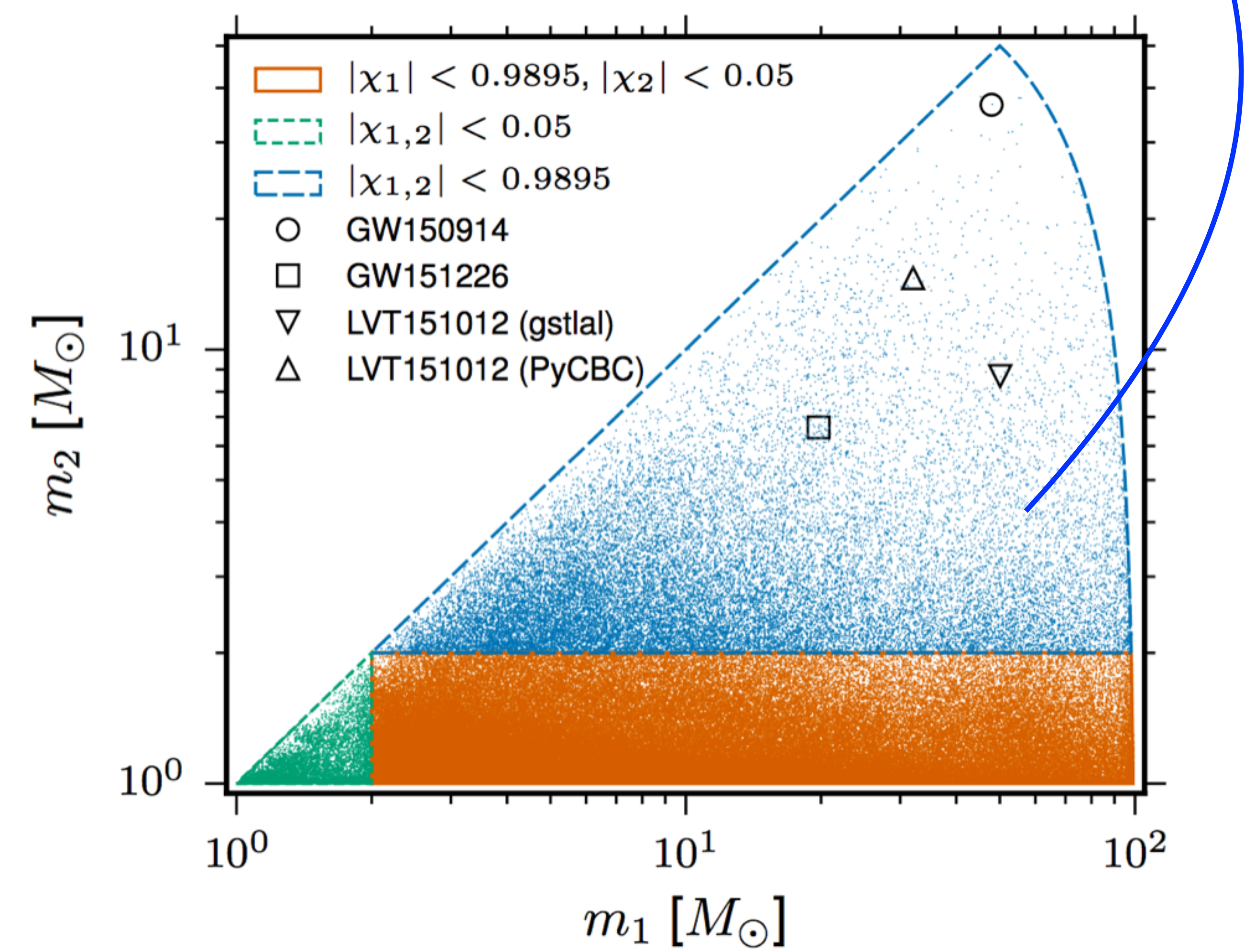
BBH expected 9 – 240 Gpc^{-3} yr^{-1}
LSC/Virgo 1606.04856

Matched-filter search for compact binary mergers

SNR =



- Integrate known signal predictions against data over many cycles, for coincident time and parameters
  - χ^2-weighted SNR, time slide background estimate
  - Relative likelihood of noise model and signal, single detector background estimate



"Binary Black Hole Mergers in the first Advanced LIGO Observing Run" https://arxiv.org/abs/1606.04856

First observing run (O1) from Sept 18 2015 to Jan 12 2016

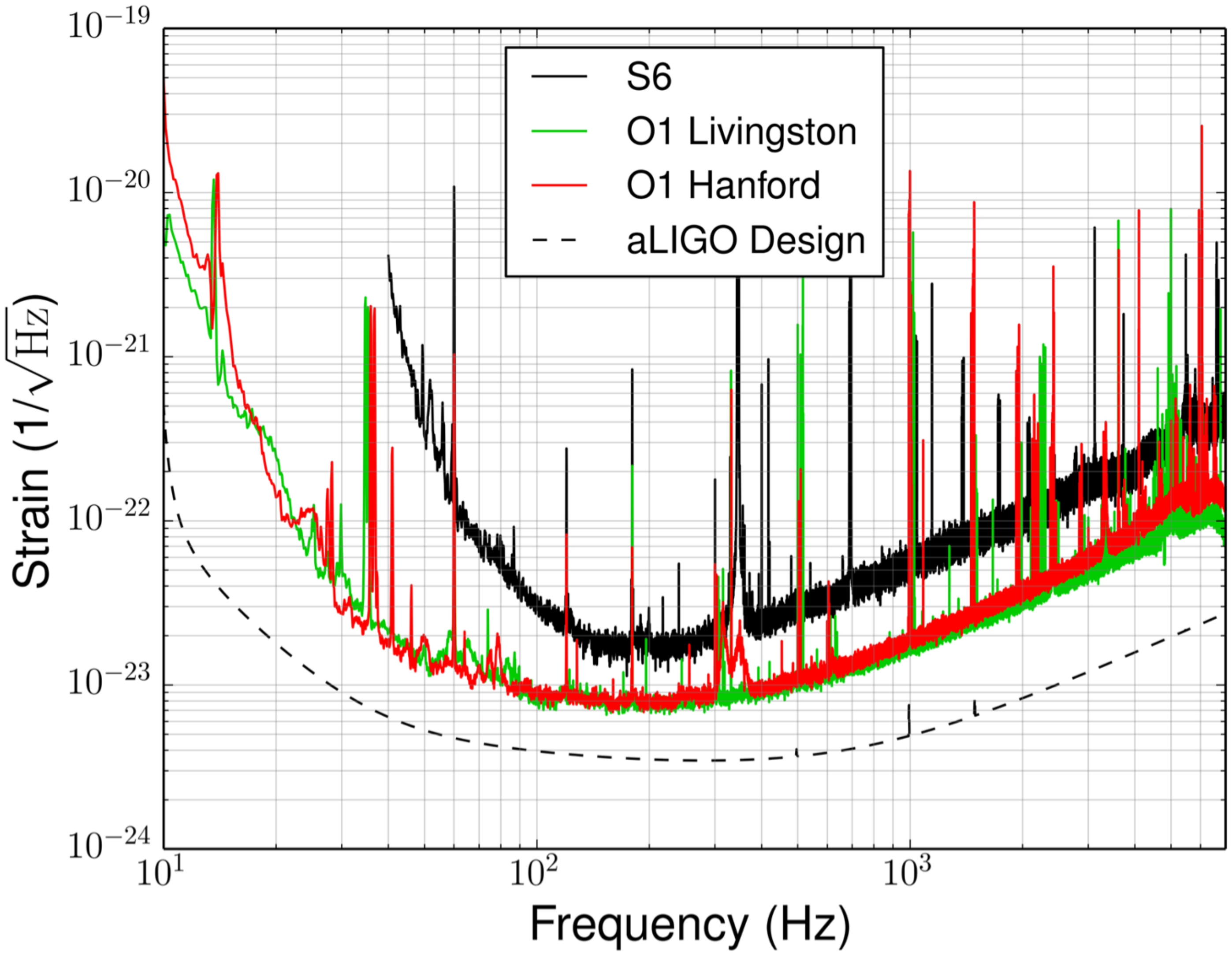


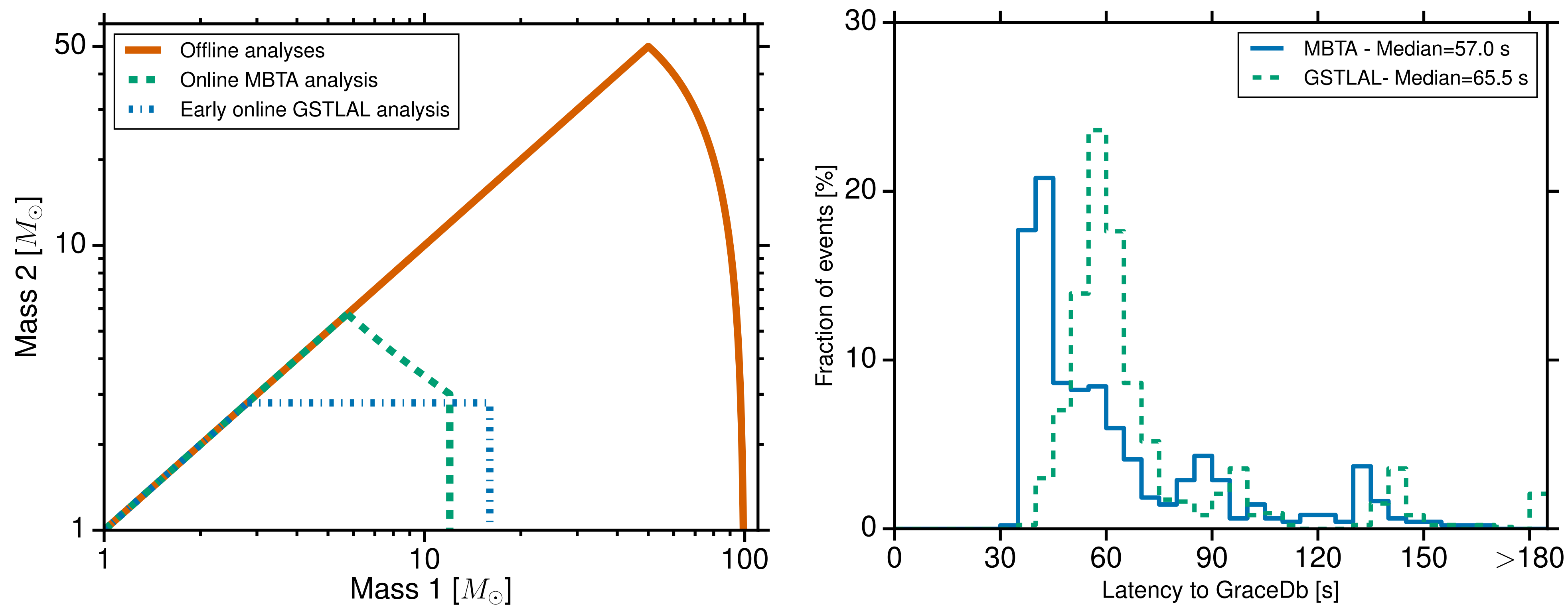
Figure by C. Messick

https://dcc.ligo.org/LIGO-G1500623/public , https://dcc.ligo.org/LIGO-T1100338/public

- 49 days coincident data
- ~70 Mpc reach for BNS
- No detections (or detection candidate triggers) have low-mass components
- Upper limits on the rates of BNS and NSBH mergers
- https://arxiv.org/abs/1607.07456

Rapid followup

- O1 low-latency search targeted potentially EM-bright parameters of particular interest for electromagnetic followup. (arxiv:1607.07456)

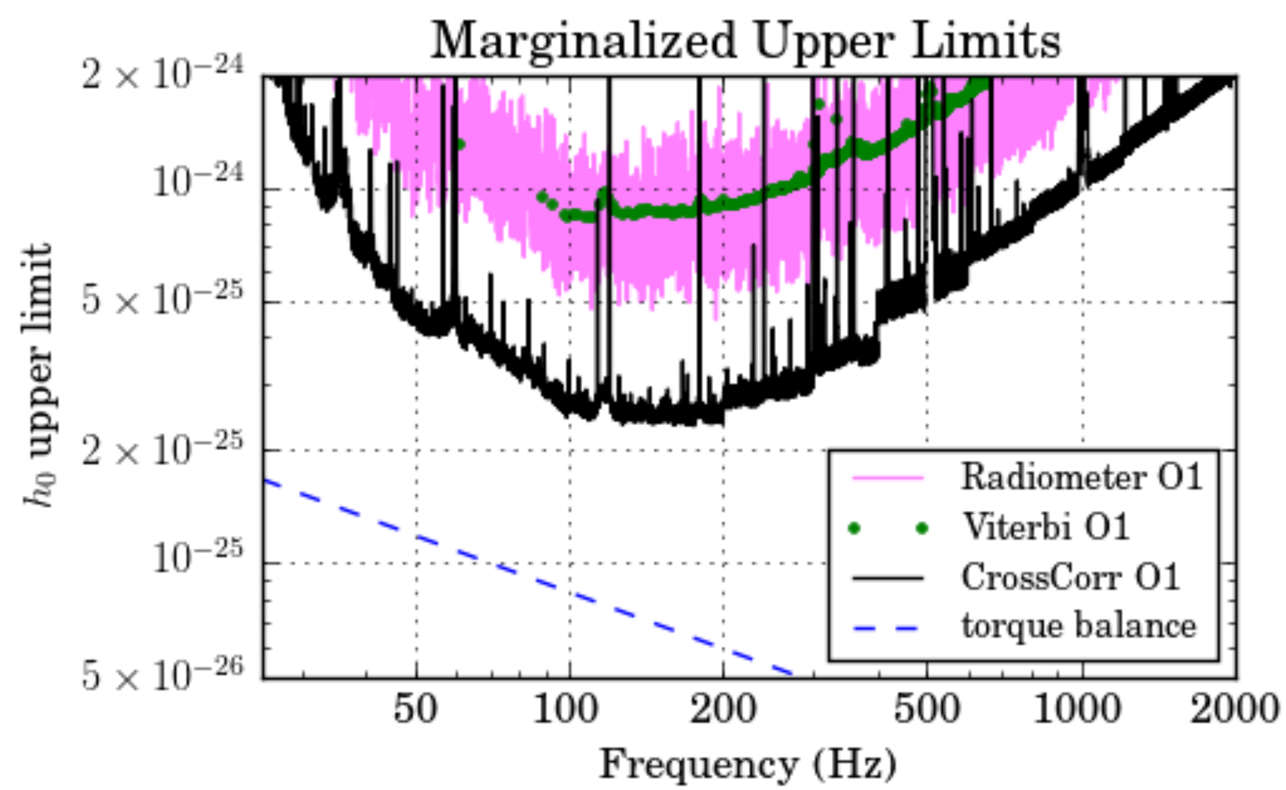


- O2 low-latency alerts include probability estimates for a neutron-star component and for a post-merger accretion disk
  - Notes on the EM-bright classification (https://dcc.ligo.org/LIGO-T1600571/public)

Neutron stars as continuous-wave sources: O1 upper limits

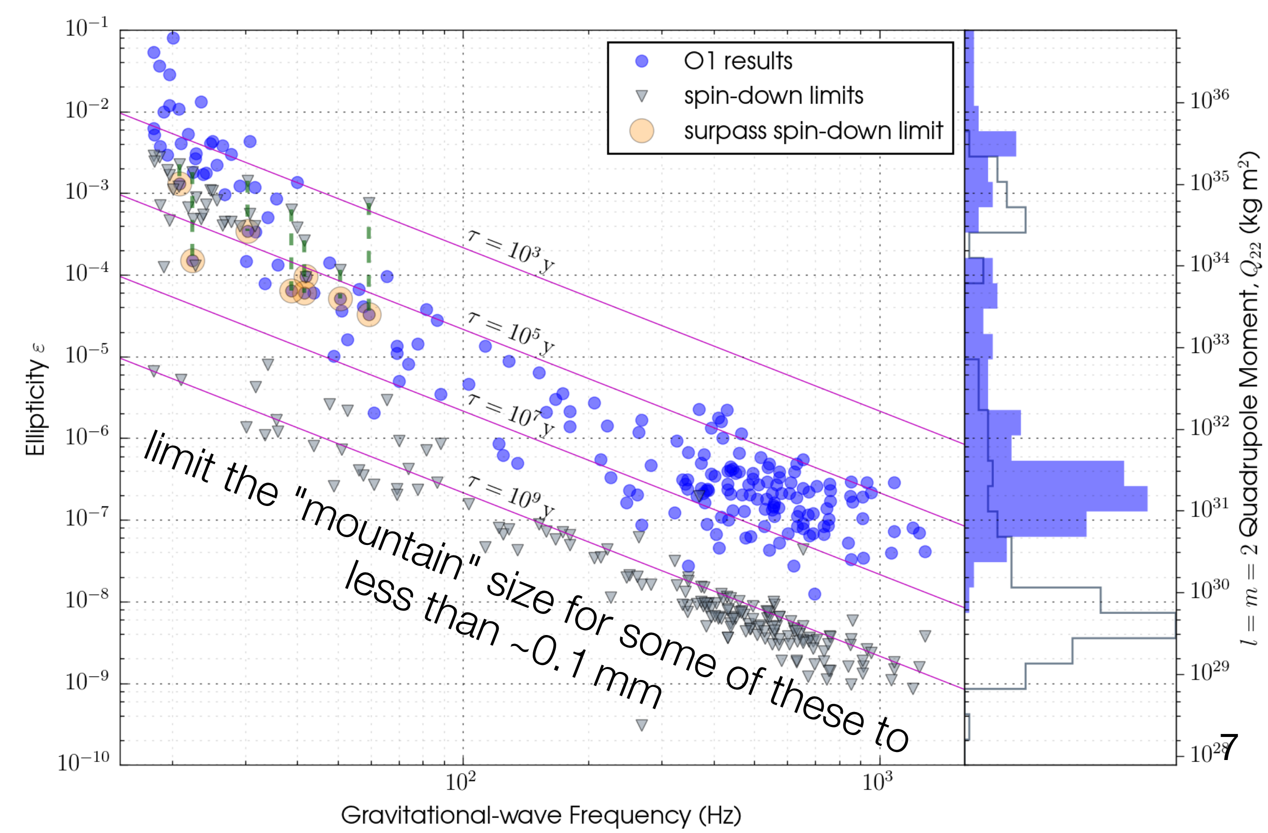
Upper Limits on Gravitational Waves from Scorpius X-1[…] in Advanced LIGO Data

LSC/Virgo arXiv:1706.03119



First search for gravitational waves from known pulsars with Advanced LIGO

LSC/Virgo arXiv:1701.07709



thanks to E. Berti for pointer!

An unexpected lack of merging neutron stars?

L.P.Grishchuk, V.M.Lipunov, K.A.Postnov, M.E.Prokhorov, B.S.Sathyaprakash, astro-ph/0008481

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An unexpected lack of merging neutron stars?

Saltpeter initial mass function for BH vs NS progenitor star

$$\frac{N(M > 80M_\odot)}{N(M > 10M_\odot)} = \left(\frac{80M_\odot}{10M_\odot}\right)^{-1.35} \simeq 0.06.$$

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SNR scales with $\mathscr{M}^{5/6}$; detection volume ~ SNR^3

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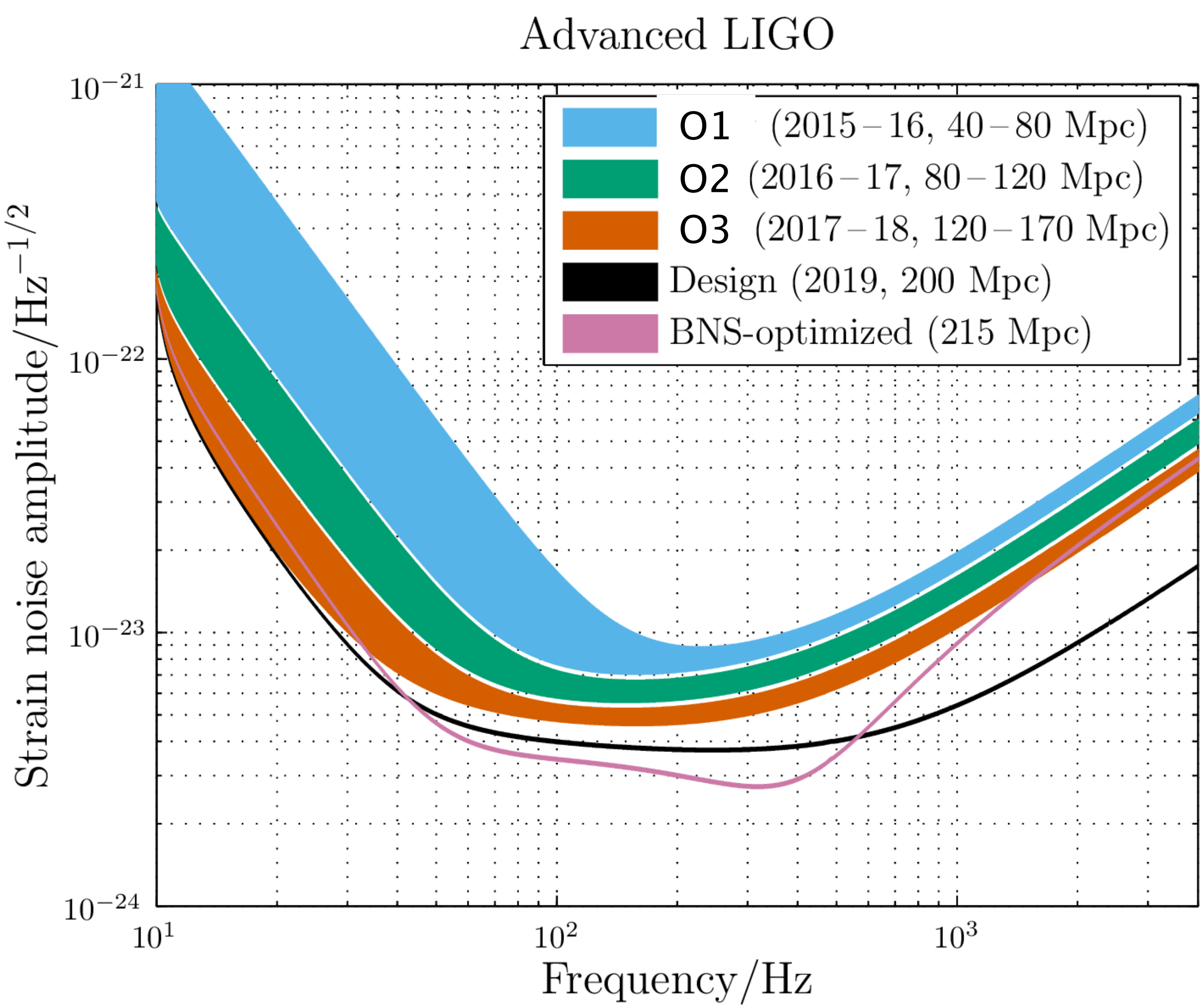
"inspiraling binary black holes are likely to be detected first"

L.P.Grishchuk, V.M.Lipunov, K.A.Postnov, M.E.Prokhorov, B.S.Sathyaprakash, astro-ph/0008481

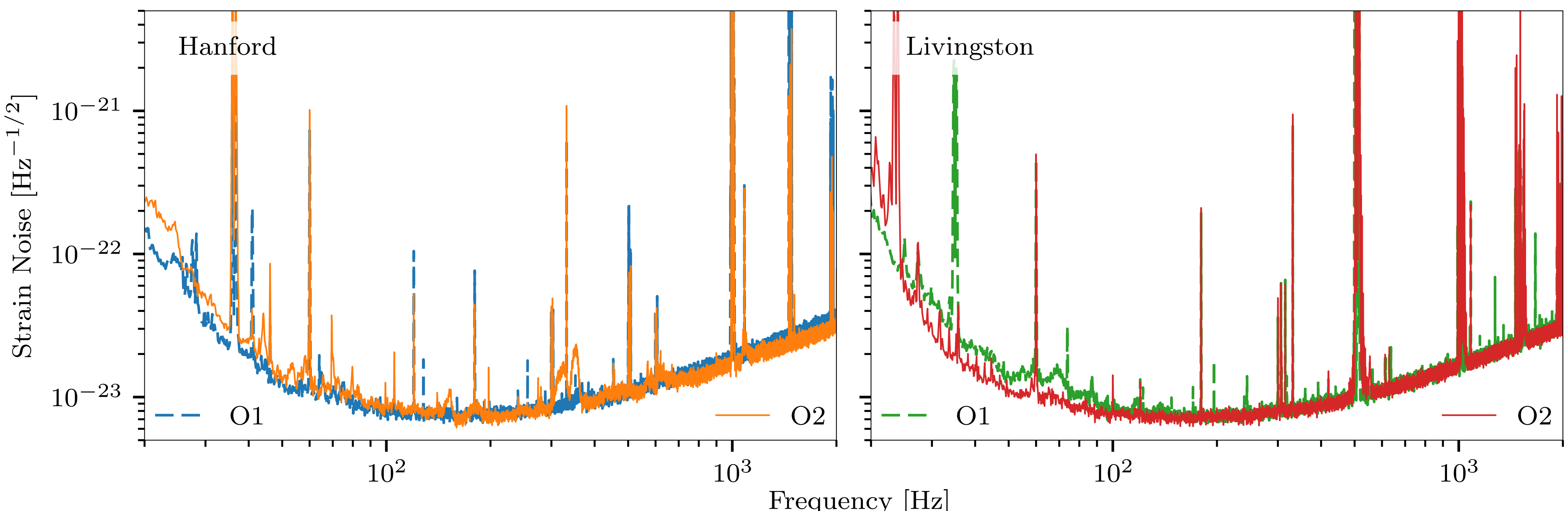
2016 Roadmap for observing neutron-star mergers



	BNS range/ Mpc	BNS detections expected (similar BHNS)
O1 4 mo	**70**	0.0005-4 (none detected)
O2 6 mo	80-120	0.006-20 (underway)
O3 9 mo	120-170	0.04-100
Design 1 year	200	0.2-200

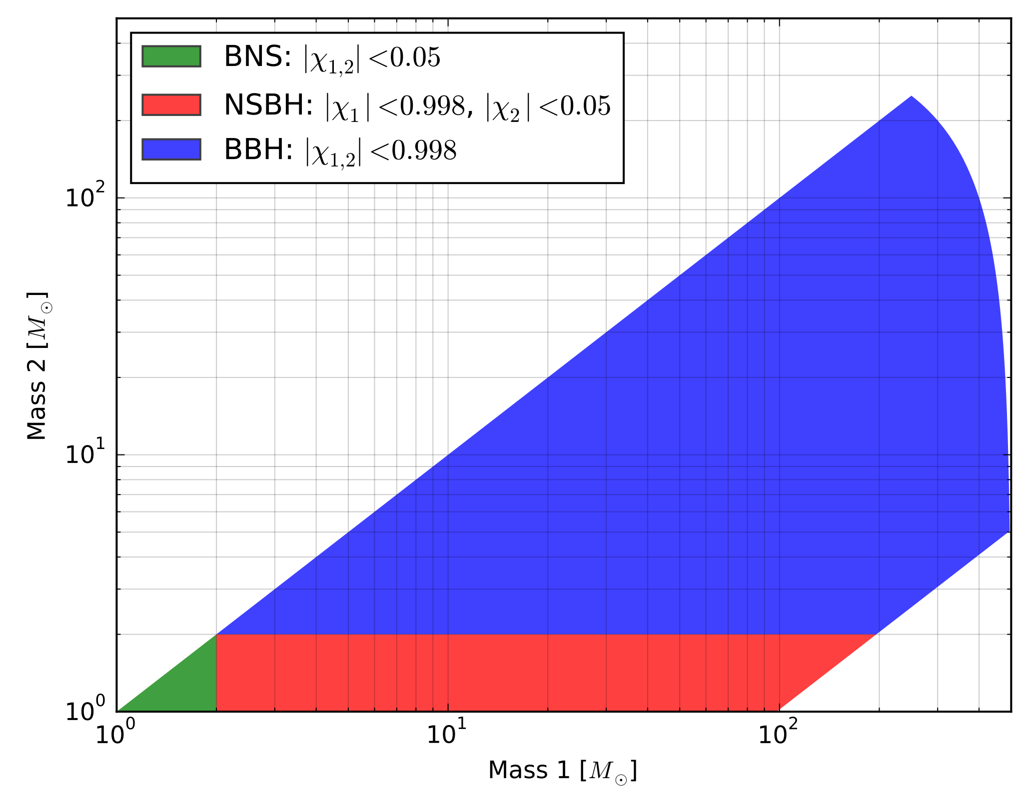
- LSC/Virgo Observing Scenarios http://arxiv.org/abs/1304.0670,
- Upper limits on the rates of binary neutron star and neutron-star--black-hole mergers from Advanced LIGO's first observing run https://arxiv.org/abs/1607.07456

Second observing run (30 Nov 2016–25 Aug 2017)



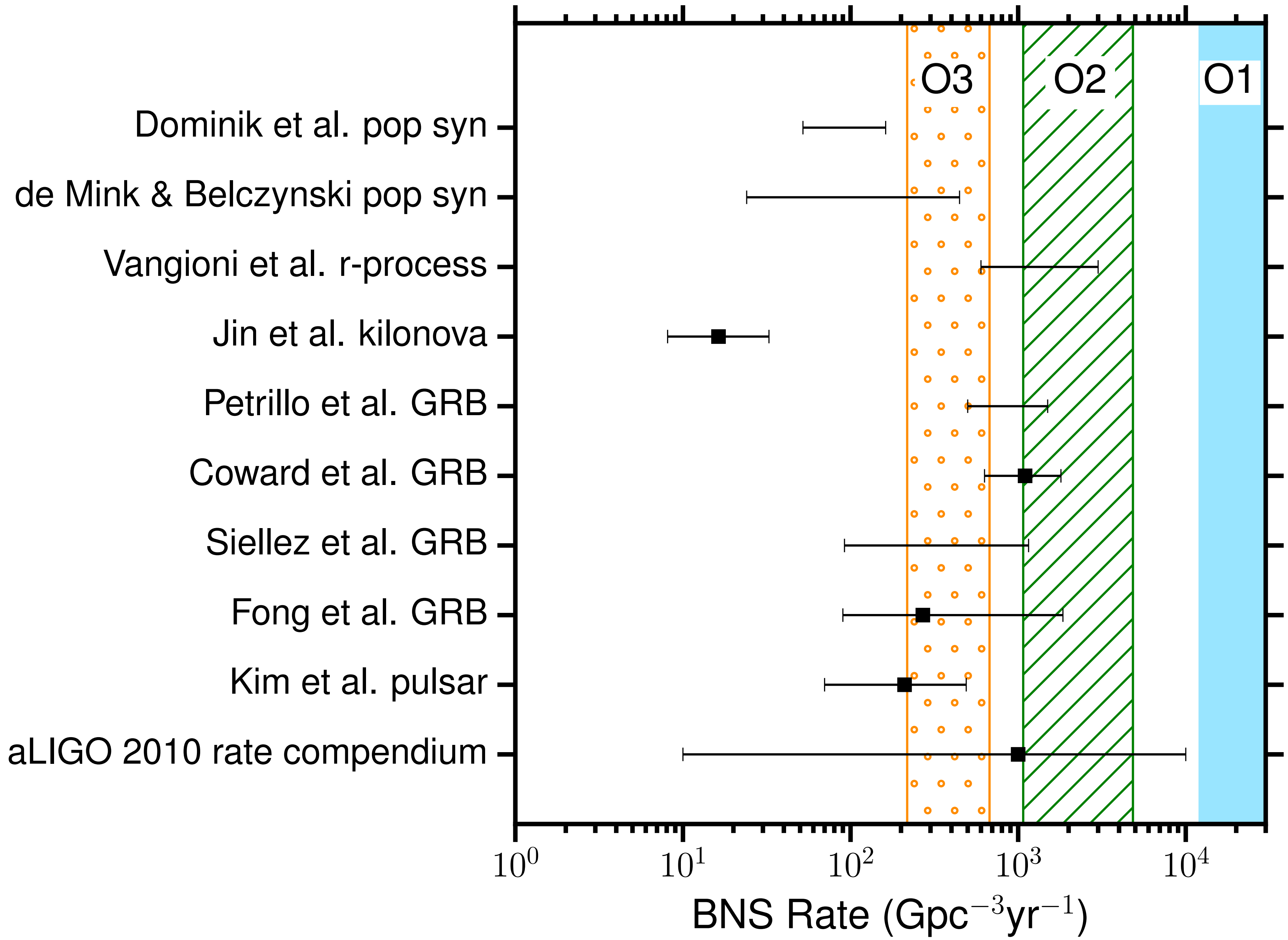
LSC/Virgo "GW170104: Observation of a 50-solar-mass binary black hole coalescence at redshift 0.2"

- ~81 days of coincident data as of June 23
- ~70 Mpc reach for BNS
- 8 online analysis triggers sent for EM followup; one confirmed as BBH GW170104, remaining analysis in progress.



offline search template bank
Dal Canton and Harry, arXiv:1705.01845

O1 rate constraints and future expectations: binary neutron star mergers



Upper limits on BNS and NSBH mergers https://arxiv.org/abs/1607.07456

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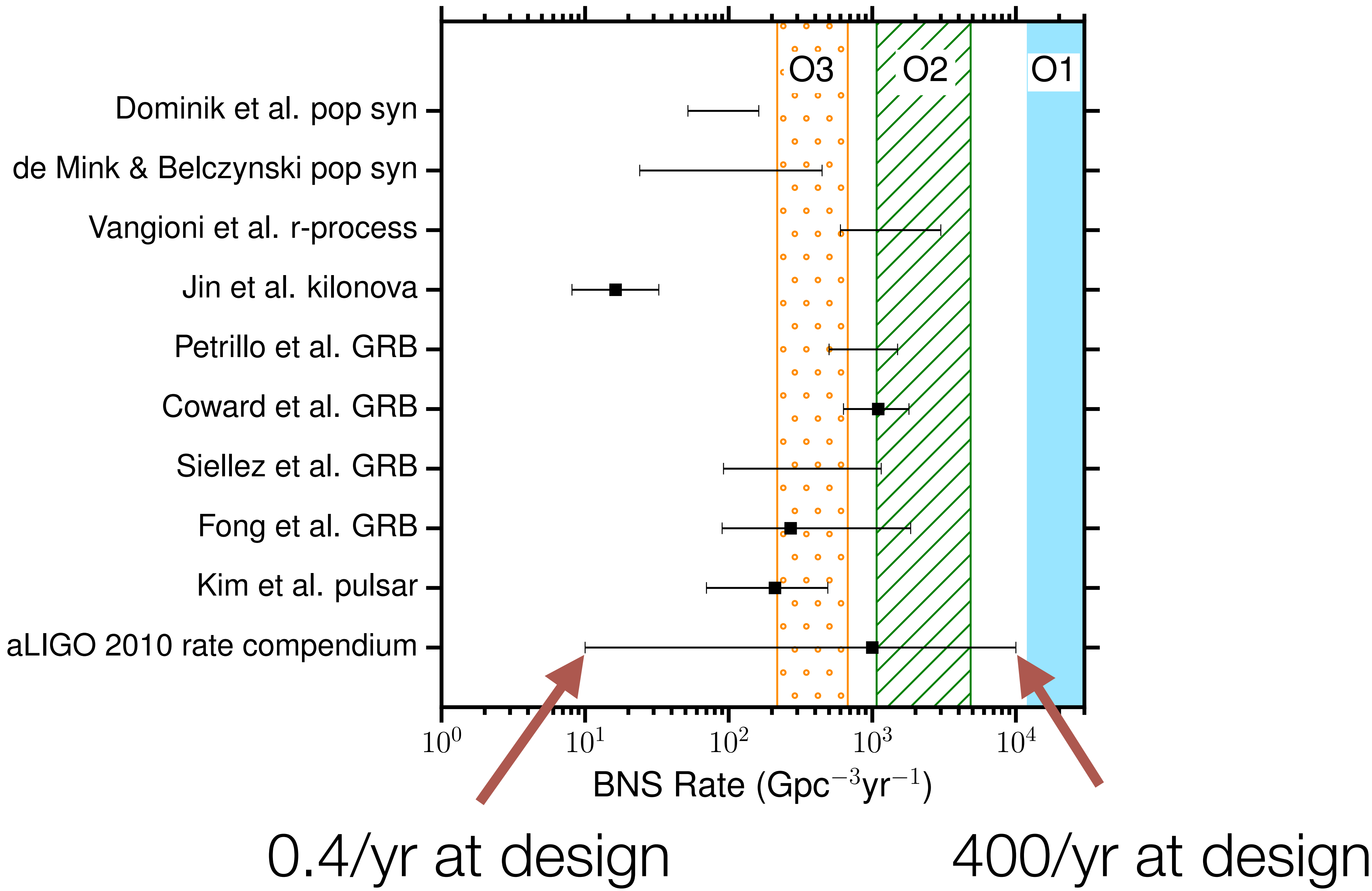

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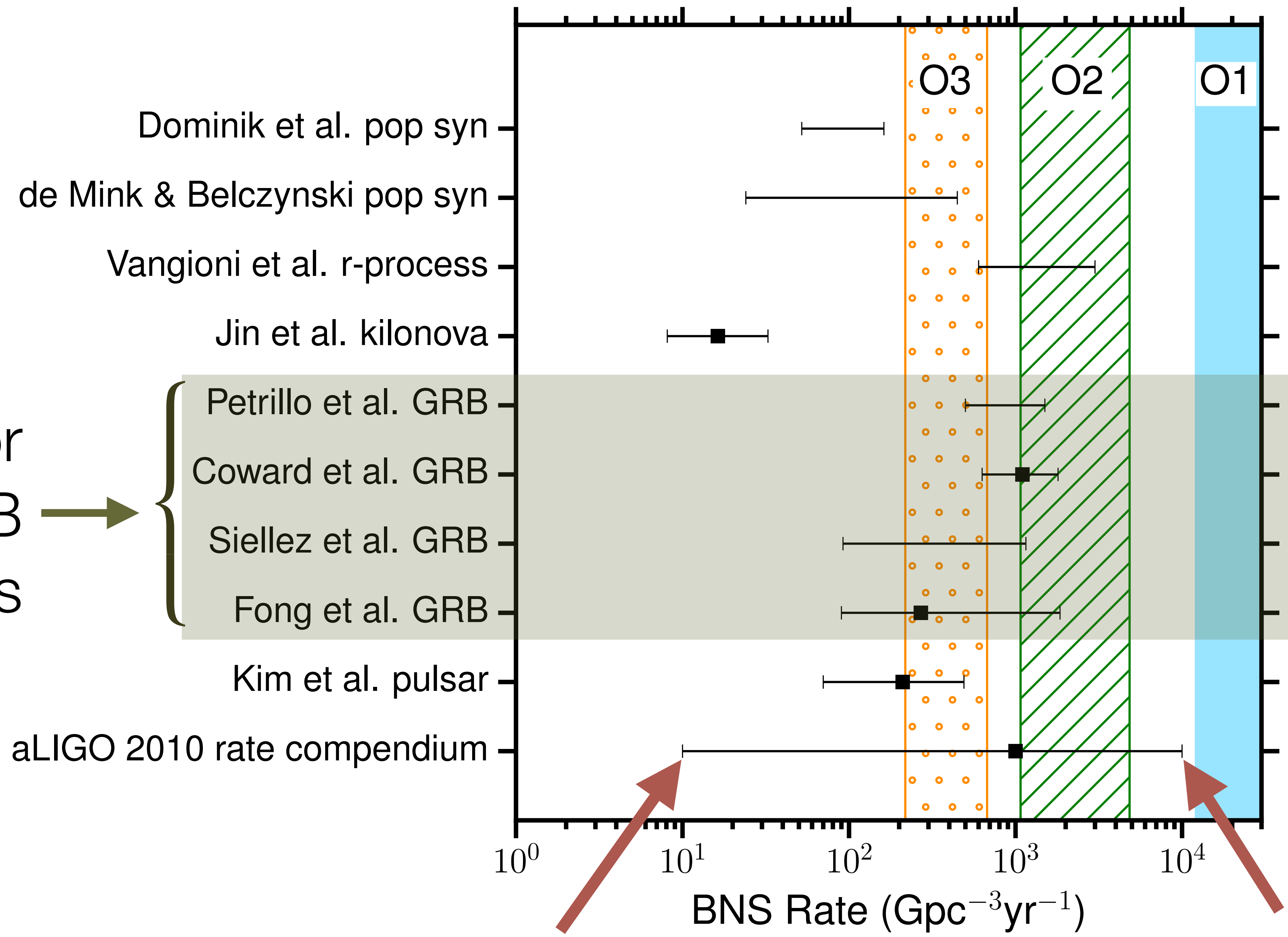
O1 rate constraints and future expectations: binary neutron star mergers

Rates for all sGRB progenitors



0.4/yr at design

400/yr at design

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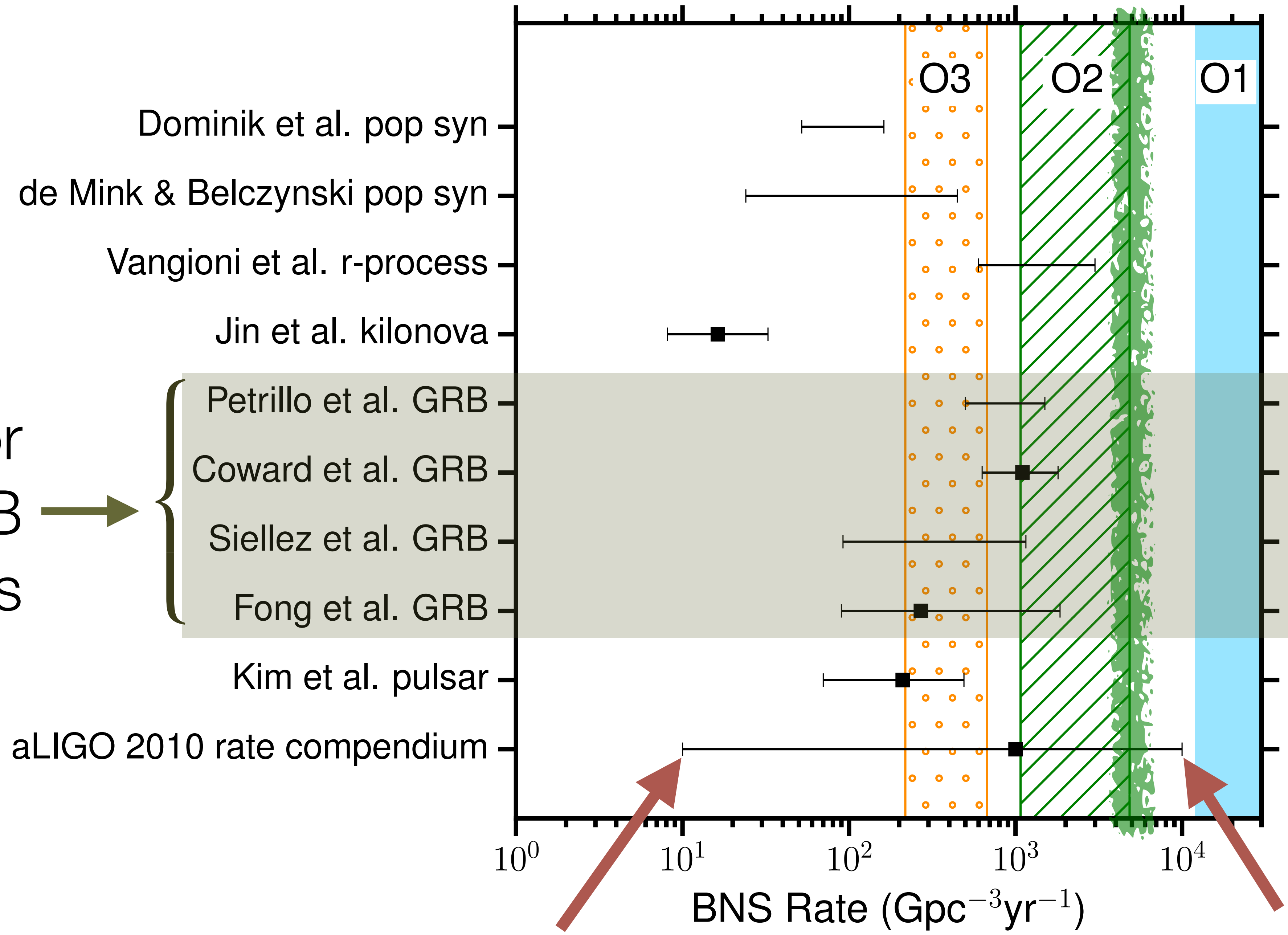


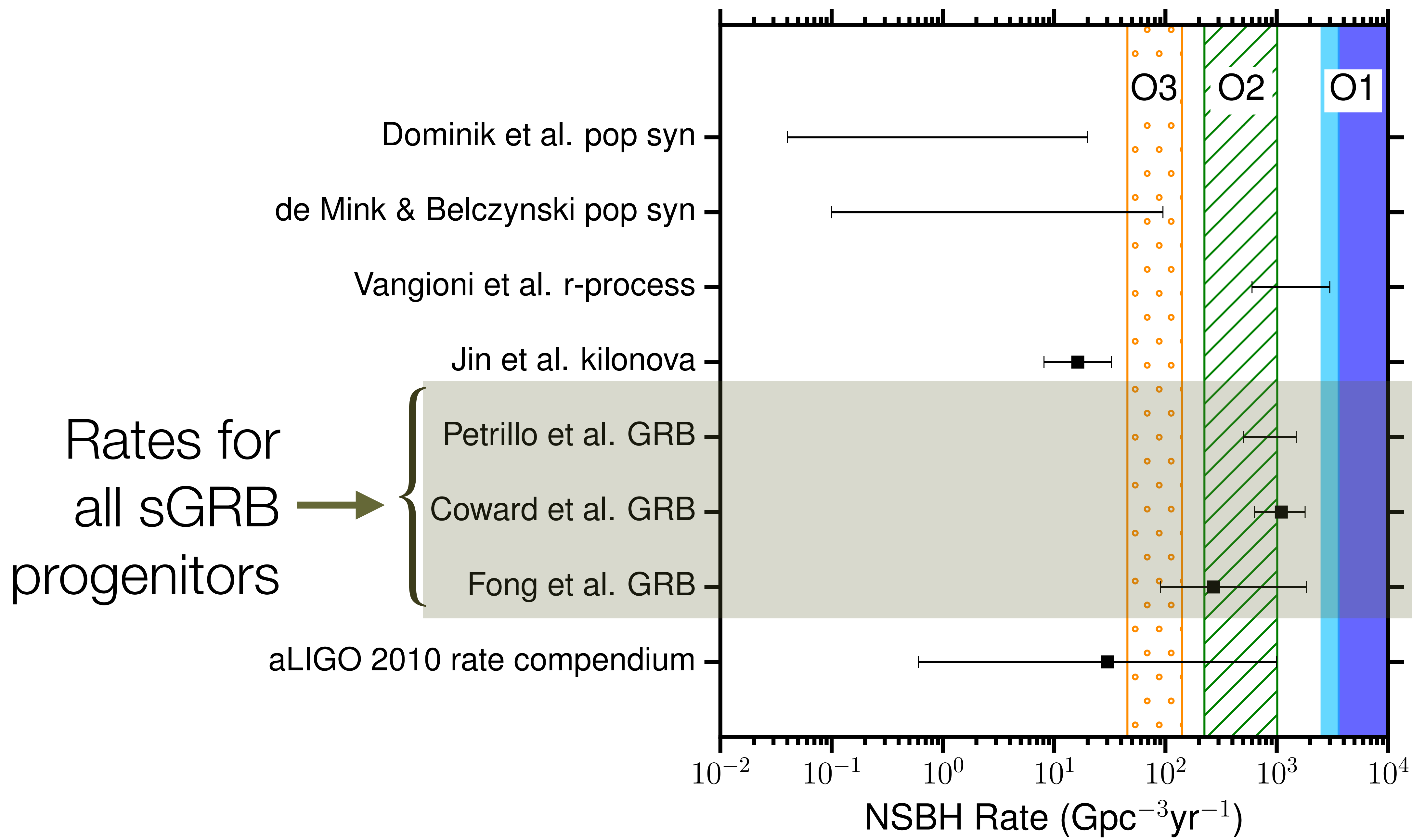
with approx O2 VT so far; analysis in progress

0.4/yr at design

400/yr at design

Upper limits on BNS and NSBH mergers https://arxiv.org/abs/1607.07456

O1 rate constraints and future expectations: neutron-star/black-hole mergers



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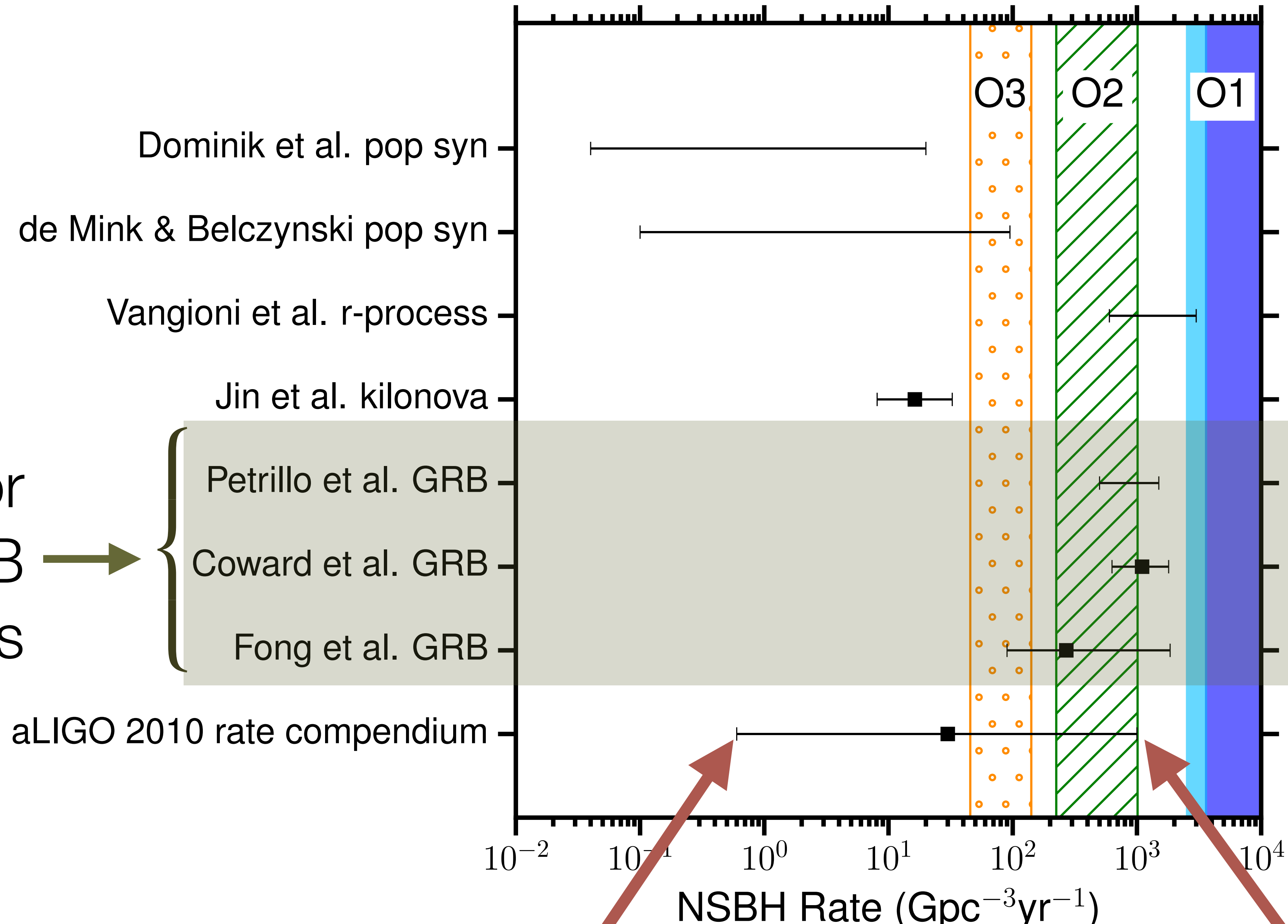


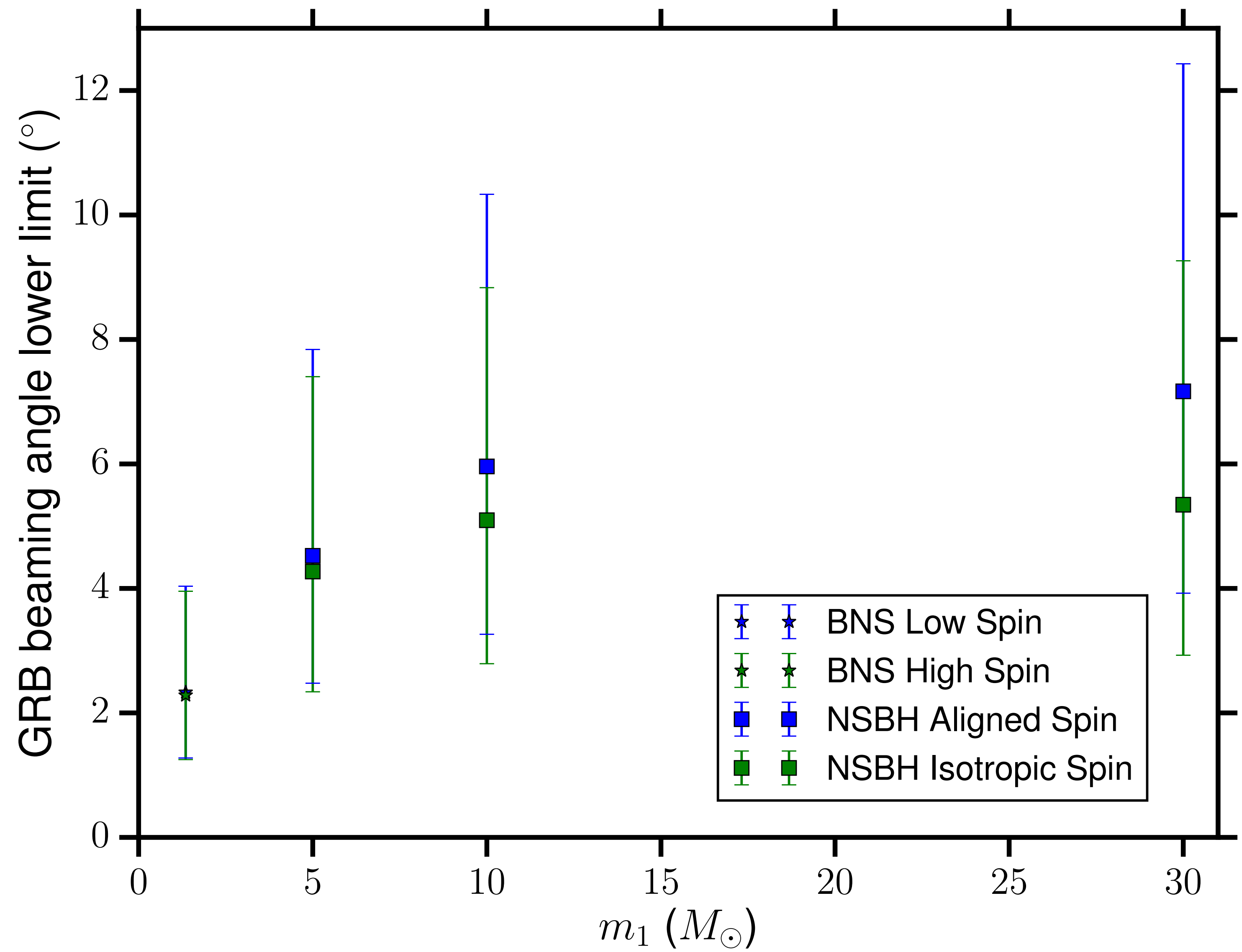
0.2/yr at design

300/yr at design

Upper limits on BNS and NSBH mergers https://arxiv.org/abs/1607.07456

Advanced LIGO upper limits vs sGRB rates: gamma-ray burst beaming angle limit

- Short GRB observed rate is 10^{+20}_{-7} Gpc^{-3} yr^{-1}
- Derive lower limit on beaming angles for a fixed class of progenitors using LIGO's 90% upper rate limits
- Beaming angle observations ~3–25°



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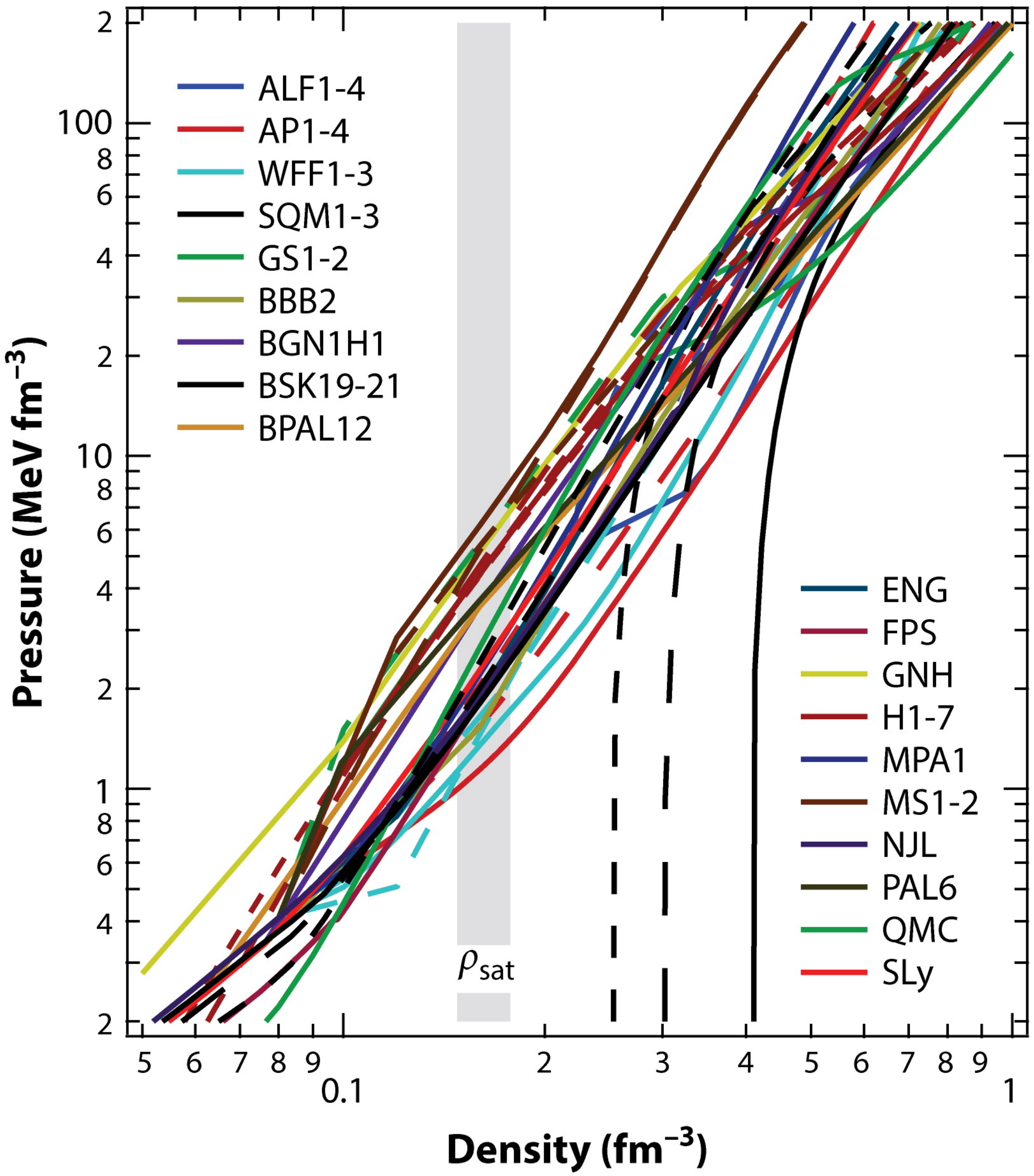
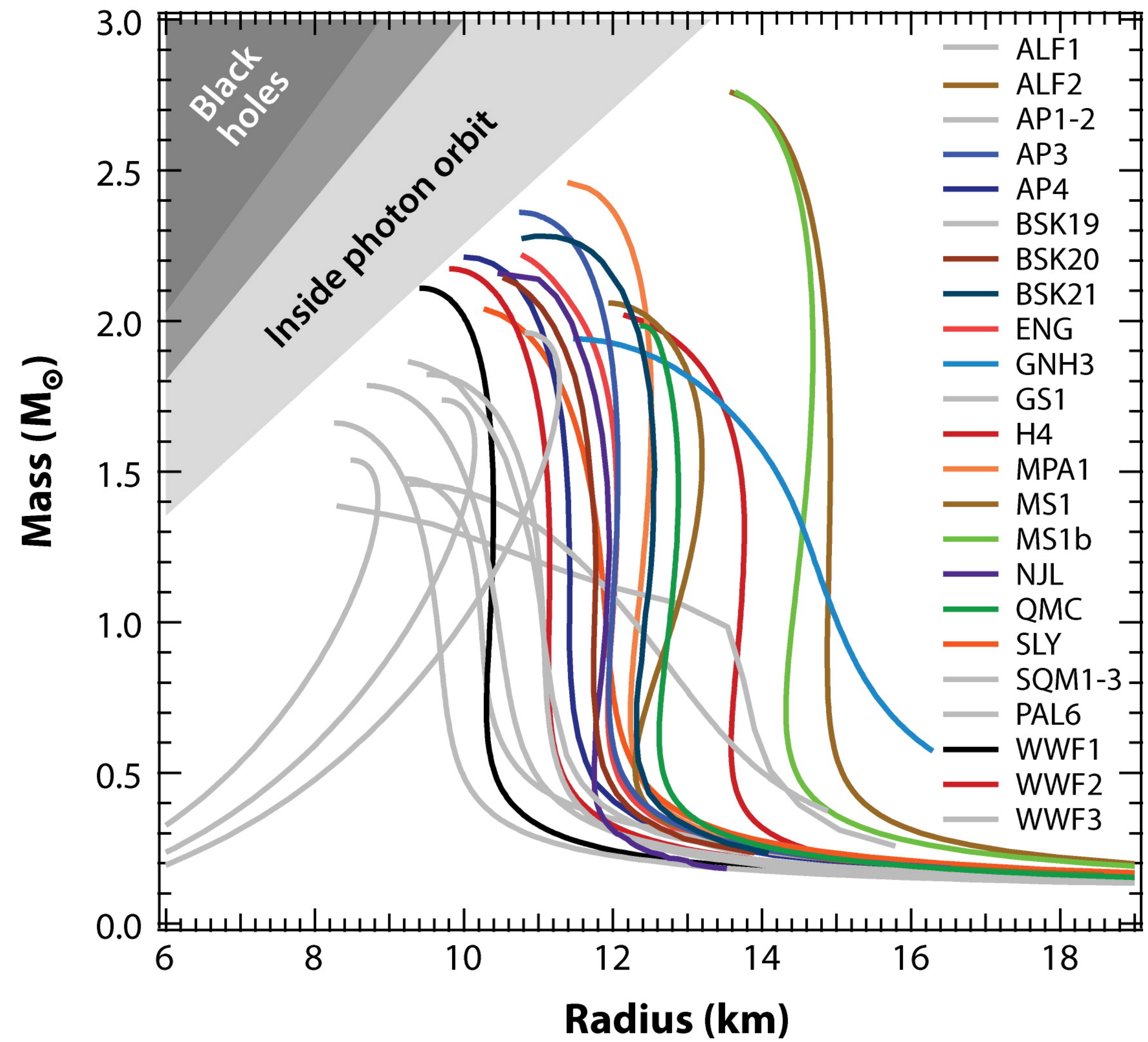
Neutron-star matter





Özel F, Freire P. 2016.
Annu. Rev. Astron. Astrophys. 54:401–40

LIGO as an astrophysical-scale collider

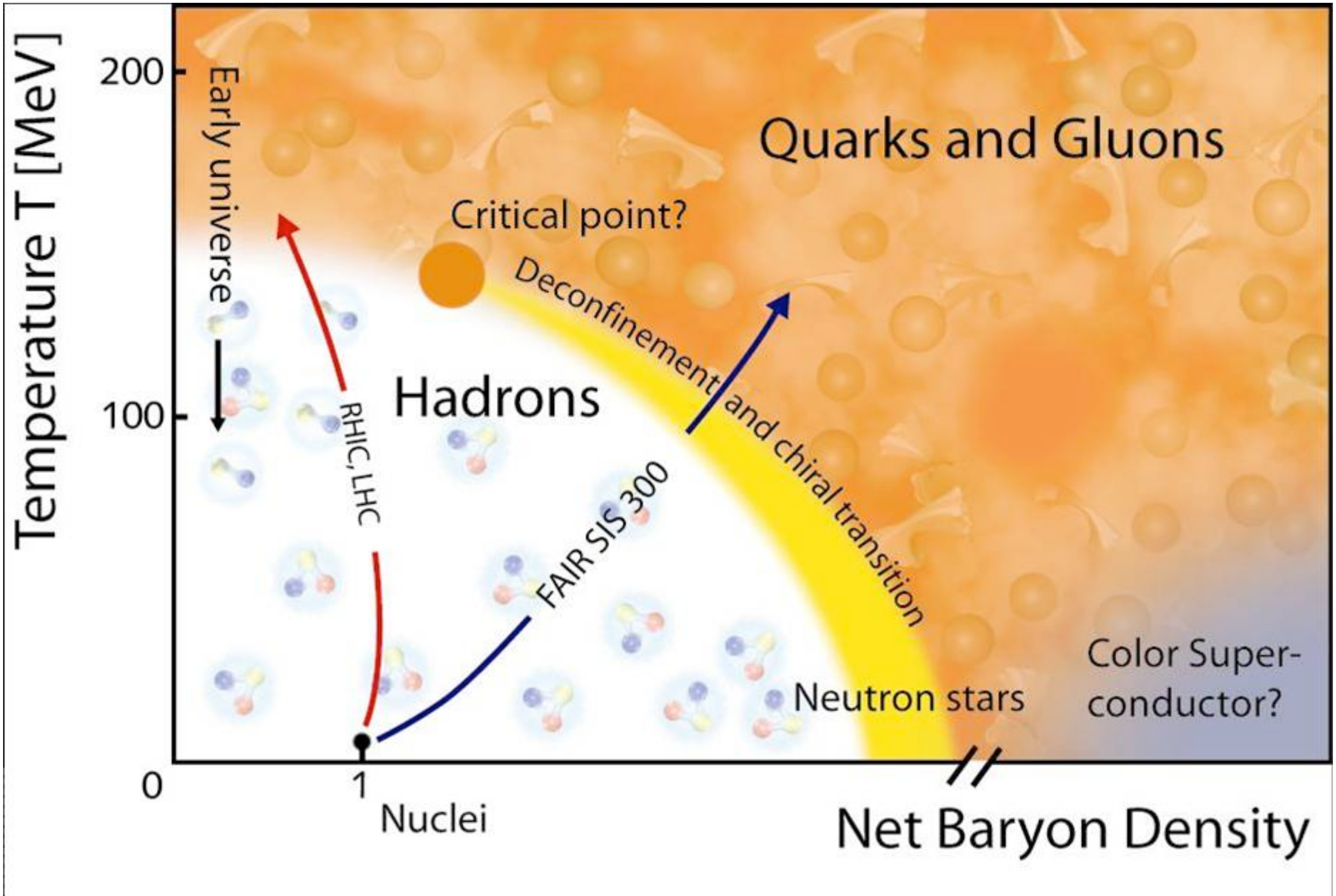


figure from FAIR CBM experiment

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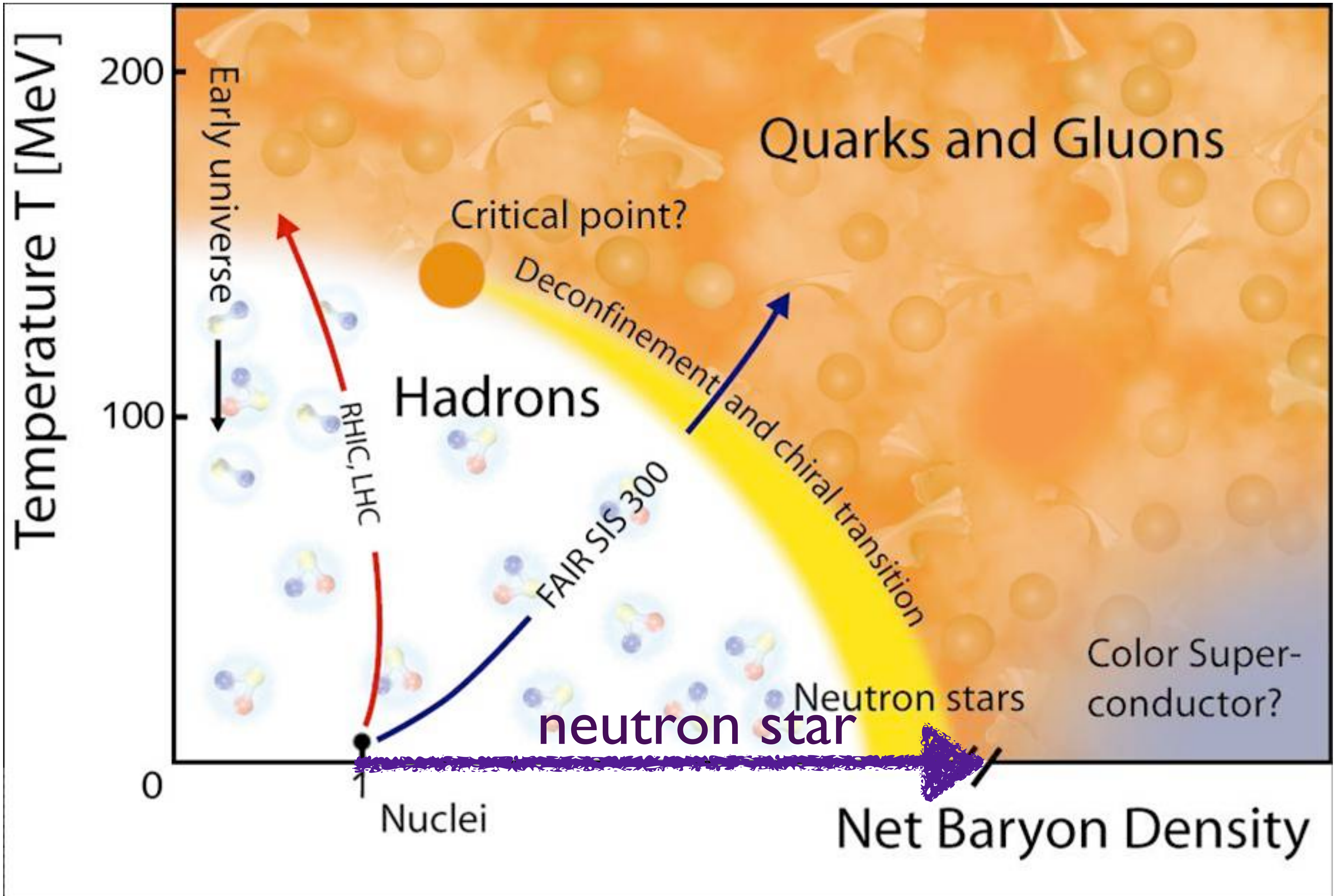

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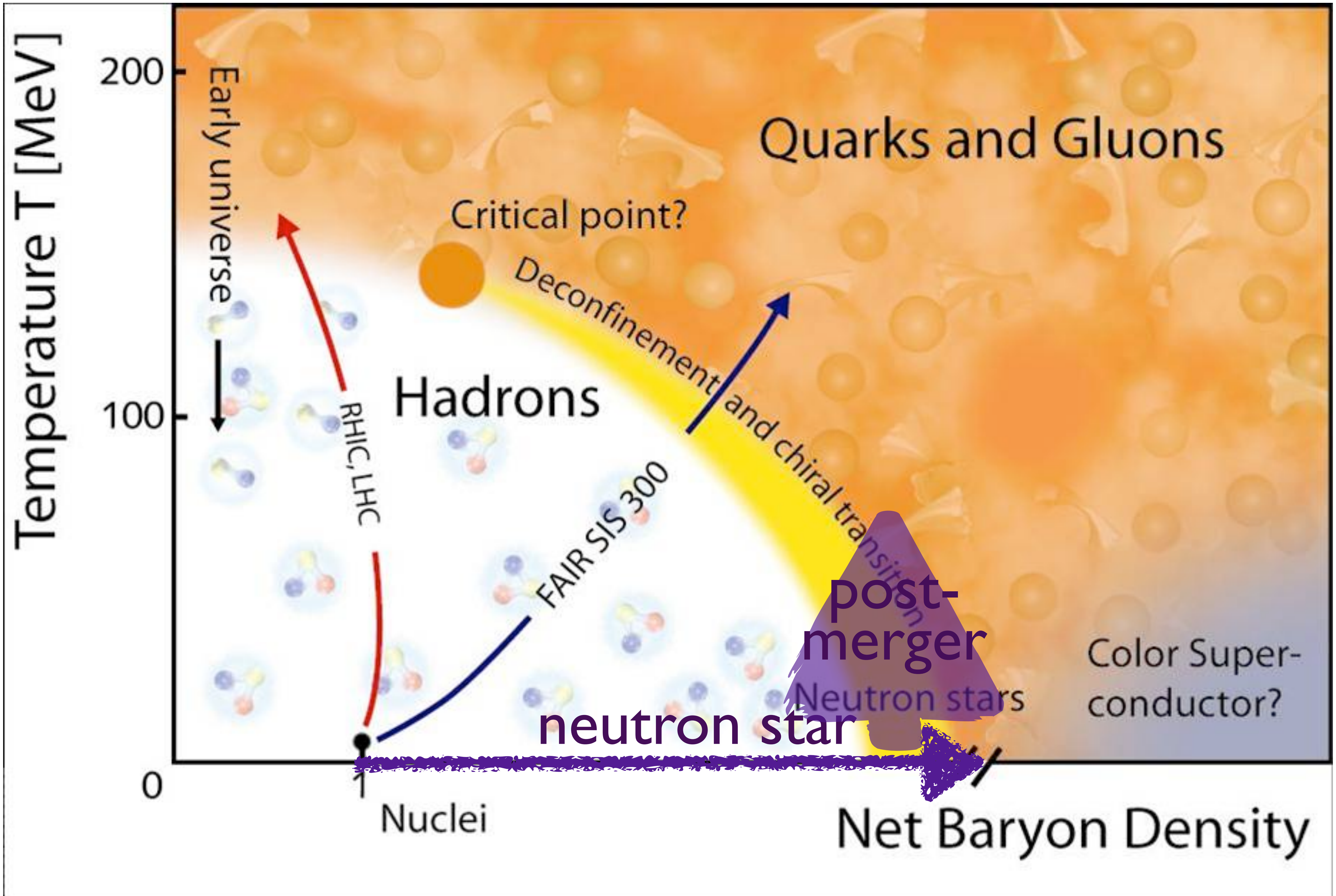

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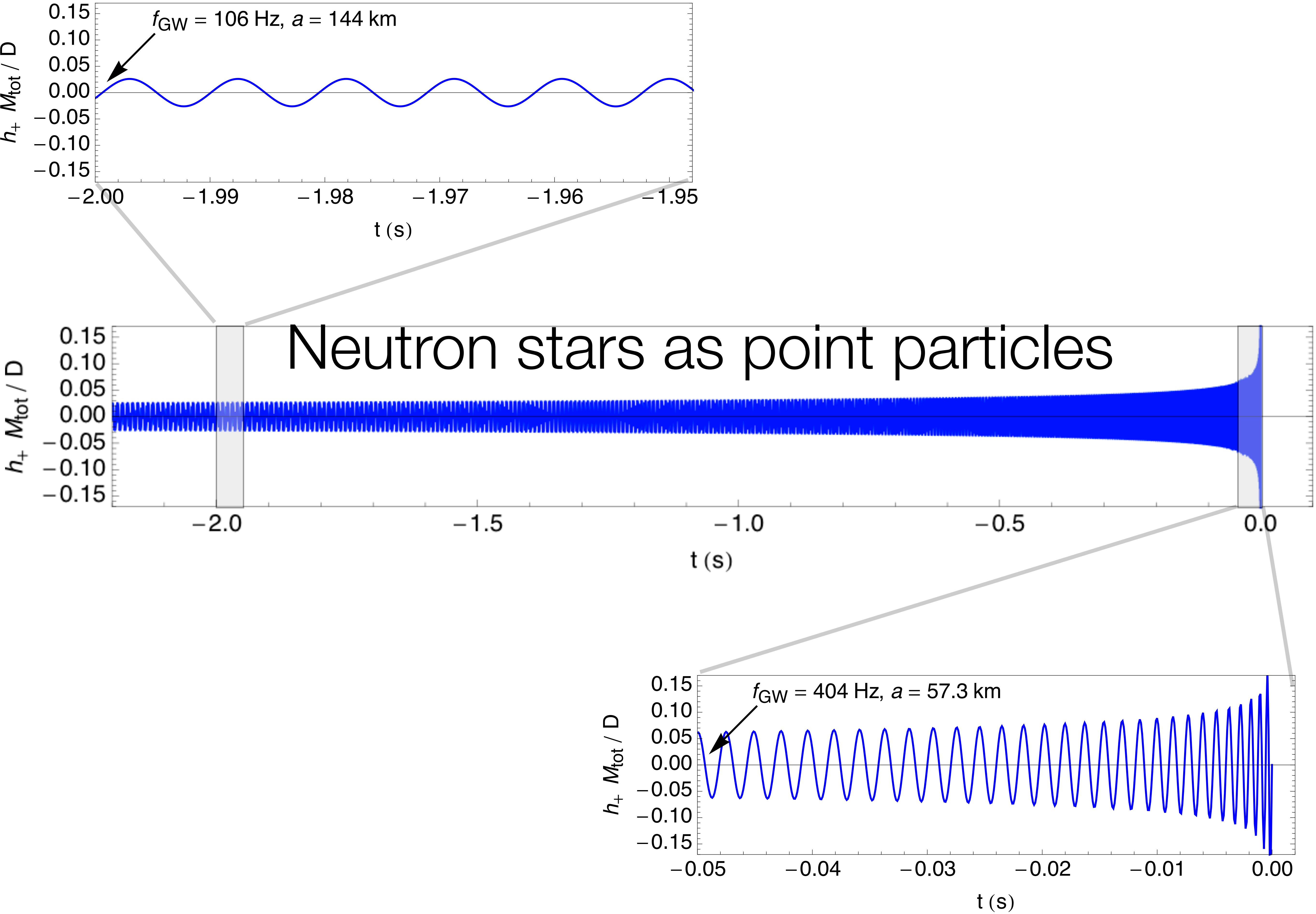
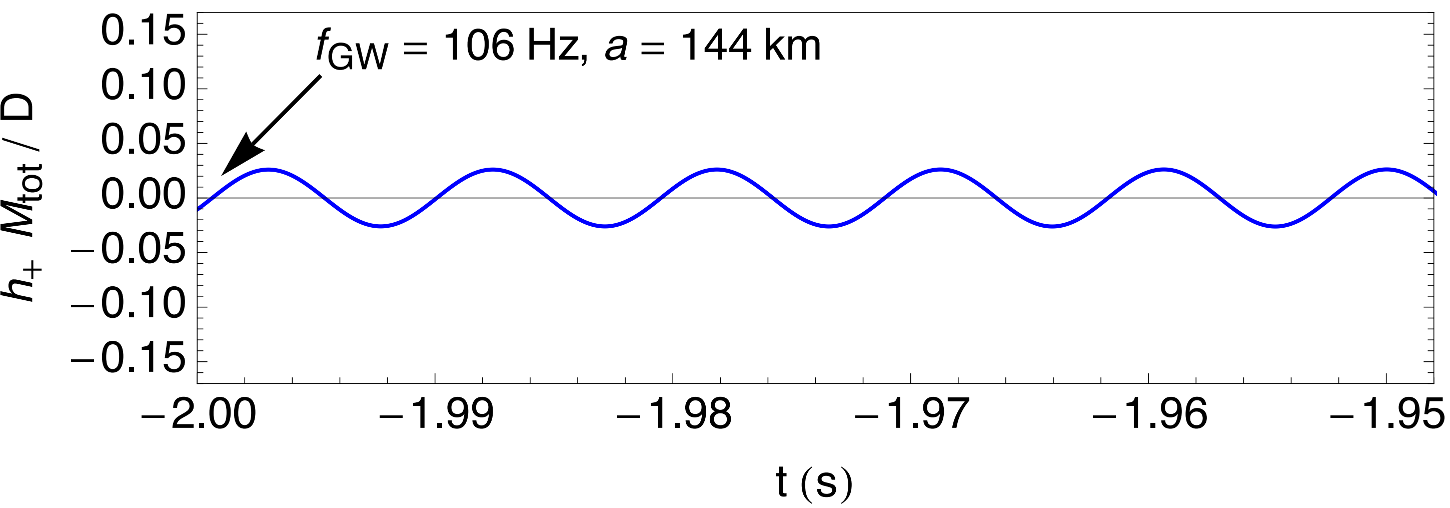
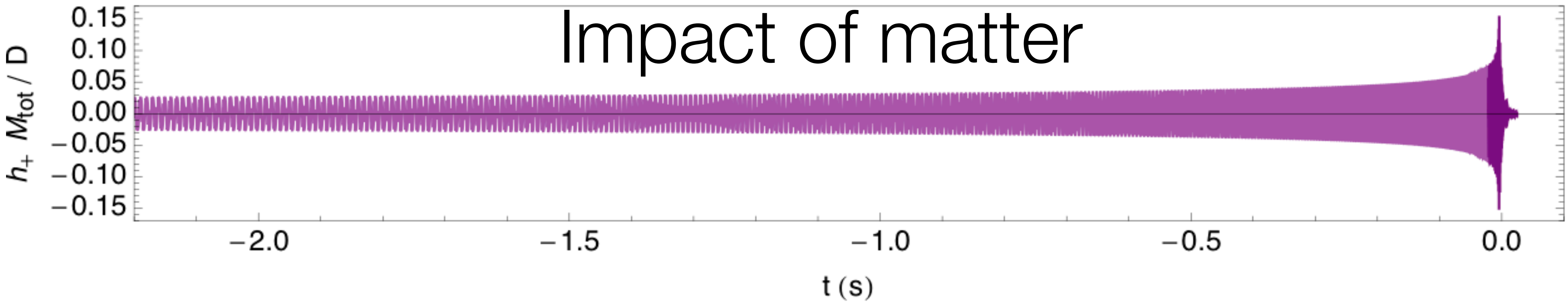
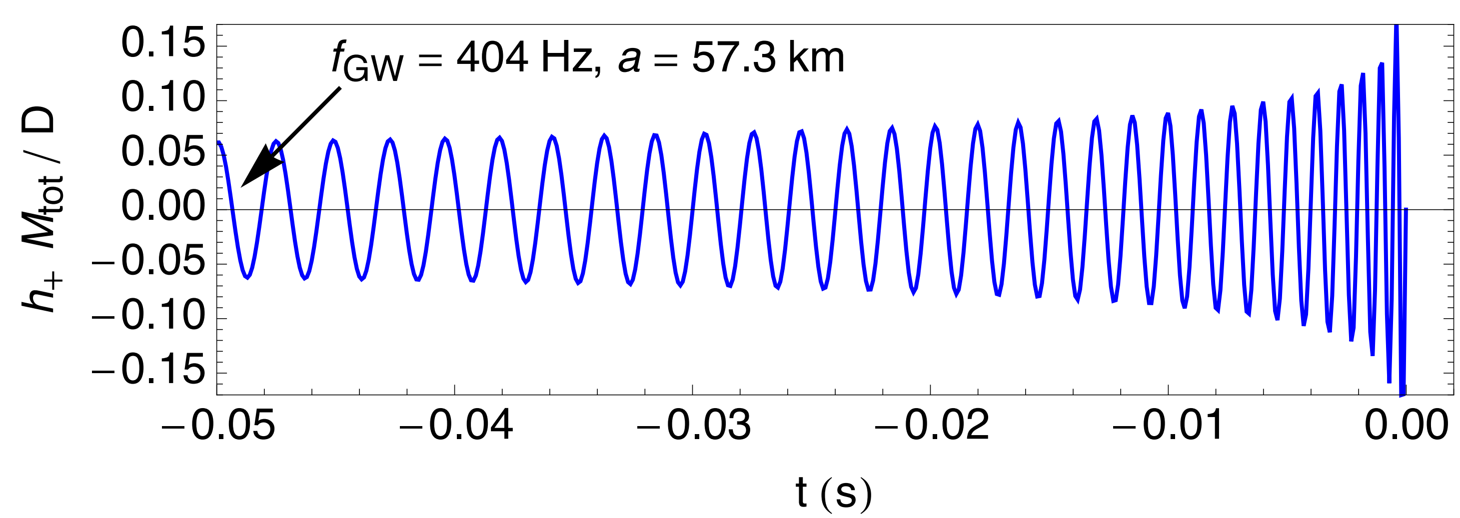
Neutron stars as point particles



Impact of matter

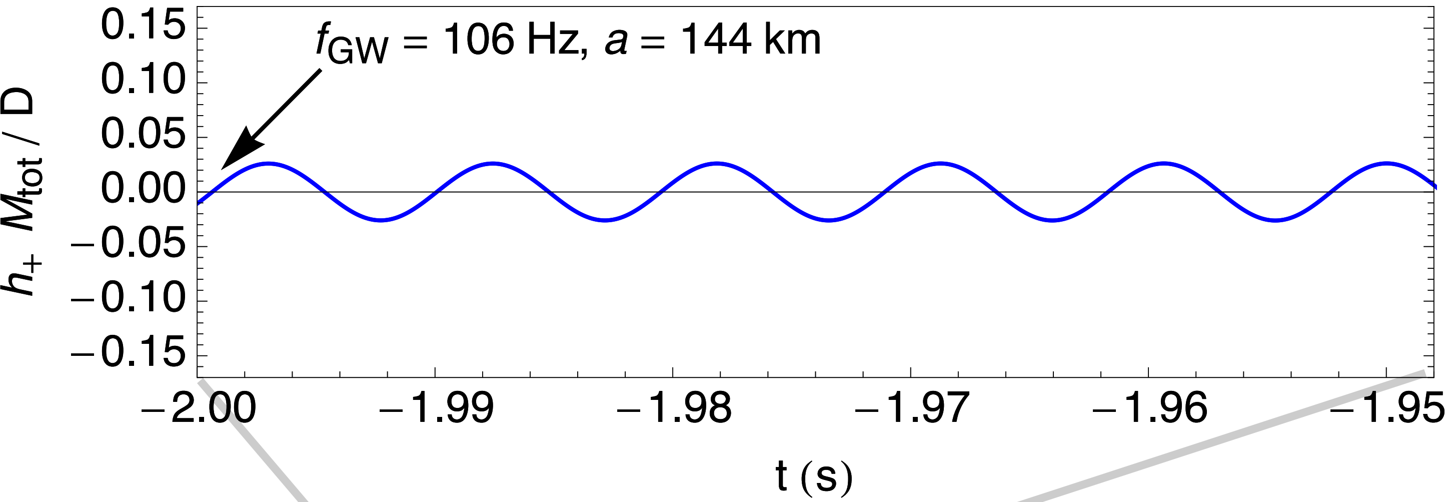


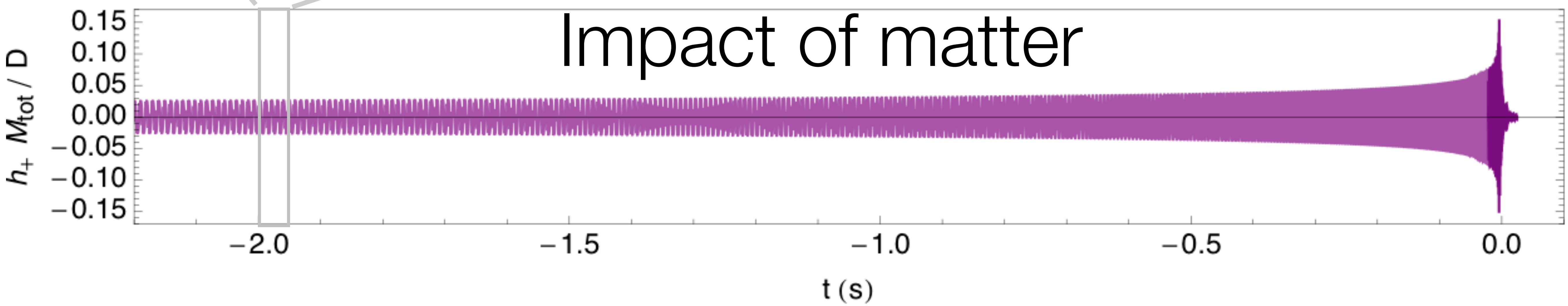


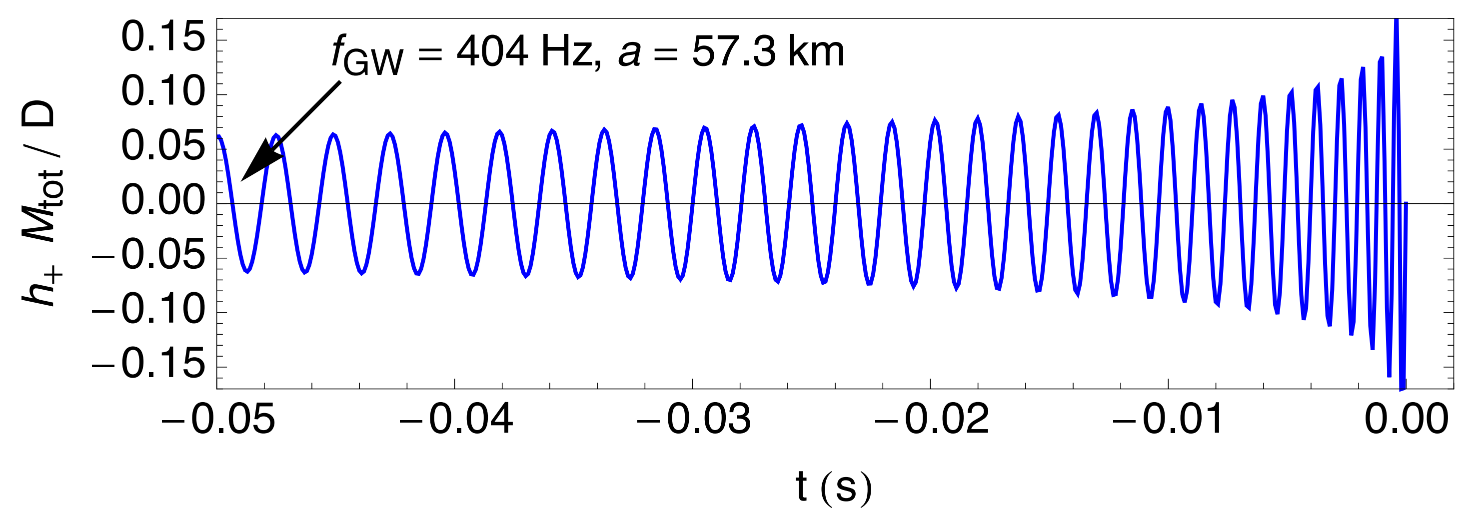


Impact of matter

Hard to modify inspiral: transfer of ~10^{46} erg at ~100 Hz modifies phase by 10^{-3} radians (Crust shattering, Tsang et al 1110.0467)







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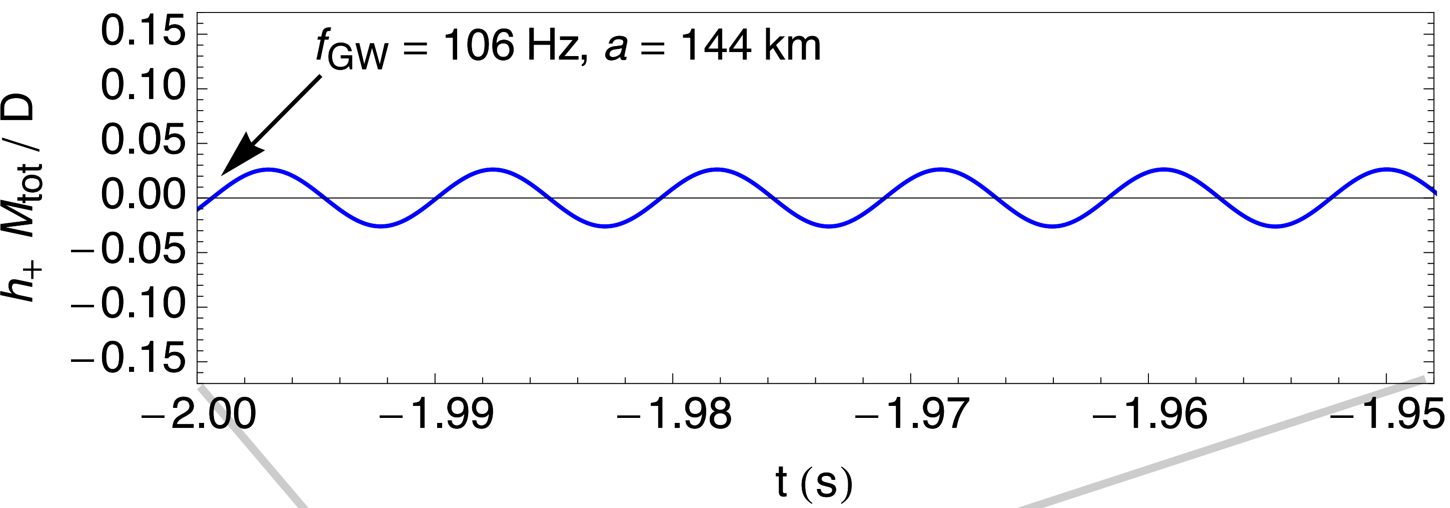
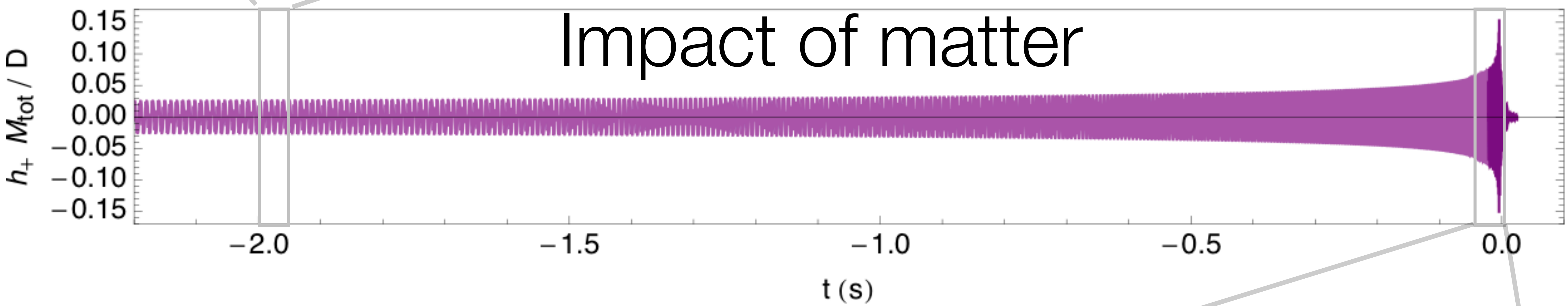
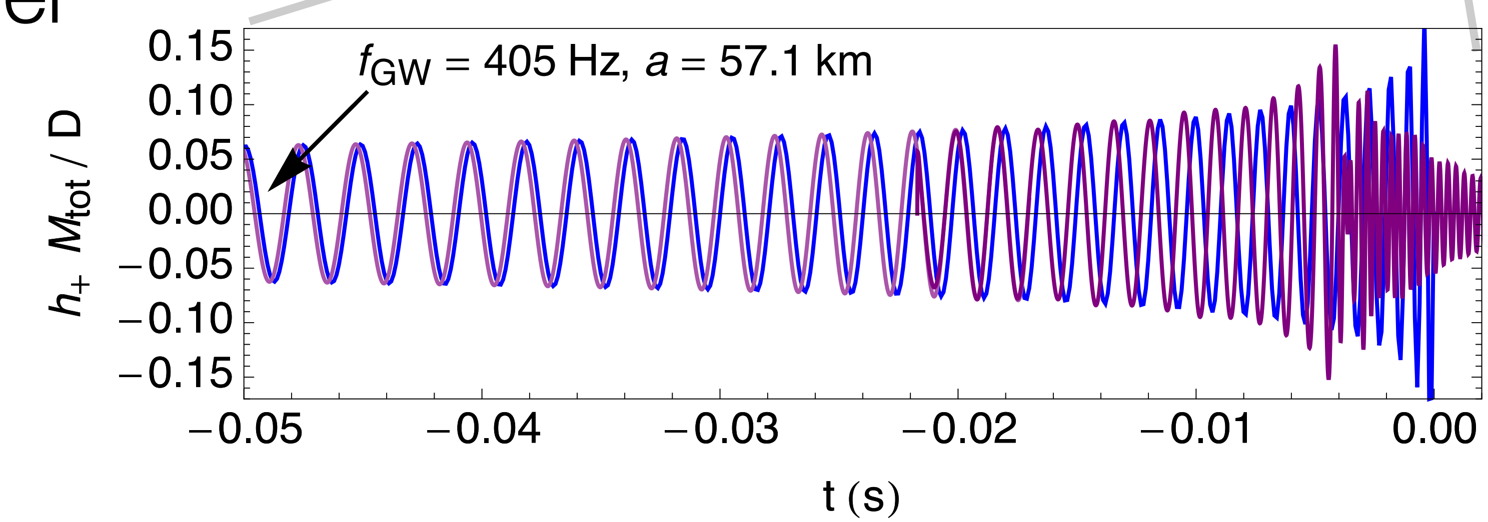




Tidal interactions lead to accumulated phase shift at higher frequencies.



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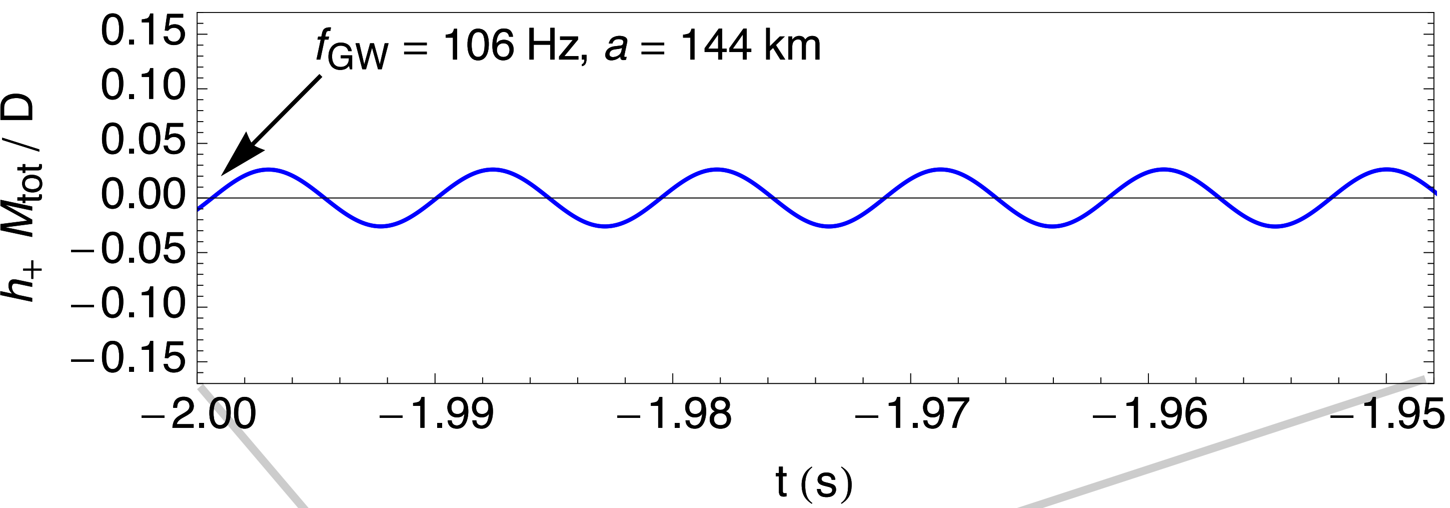

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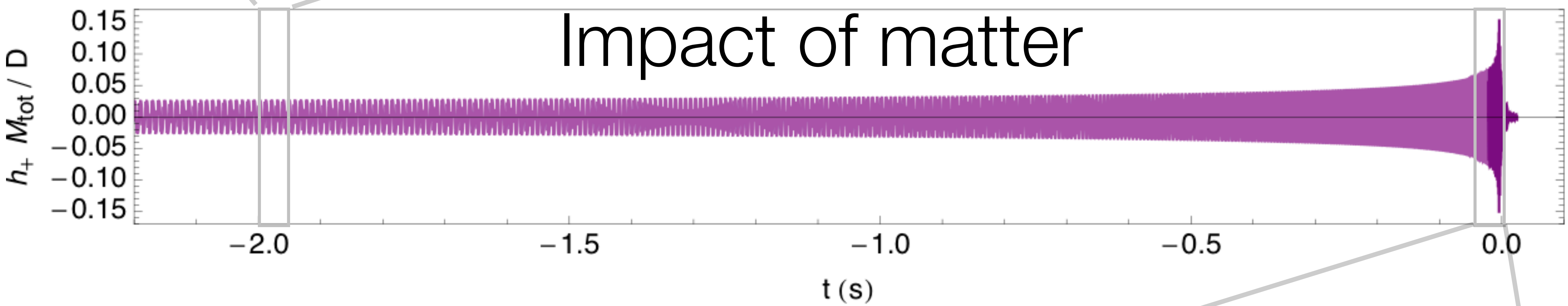

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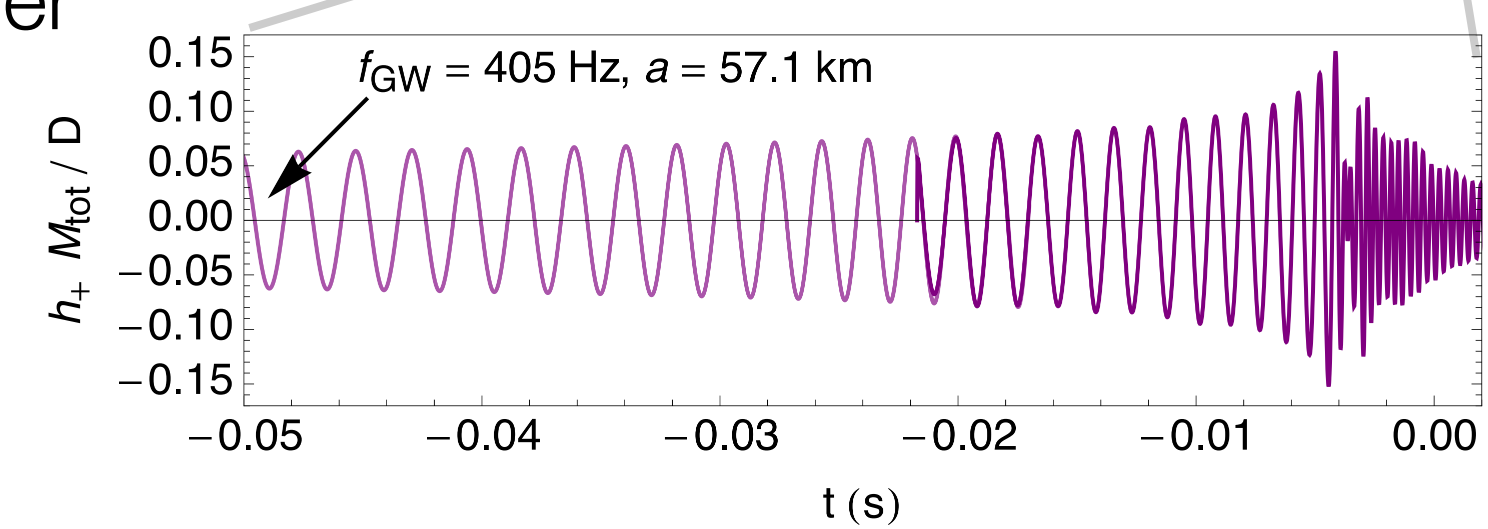

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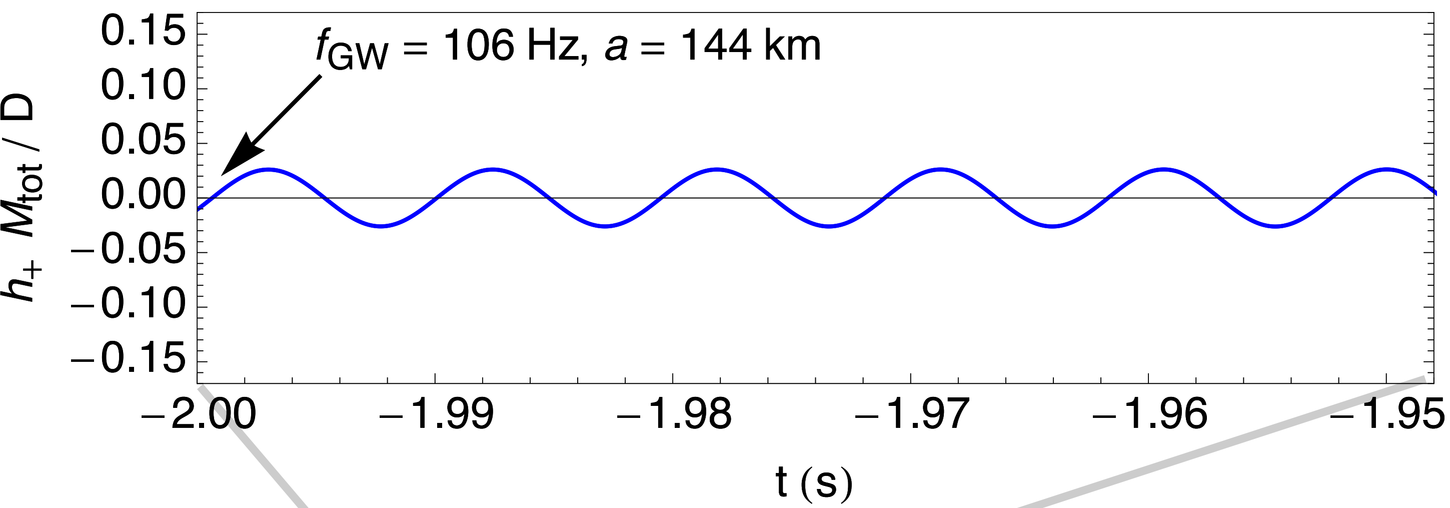

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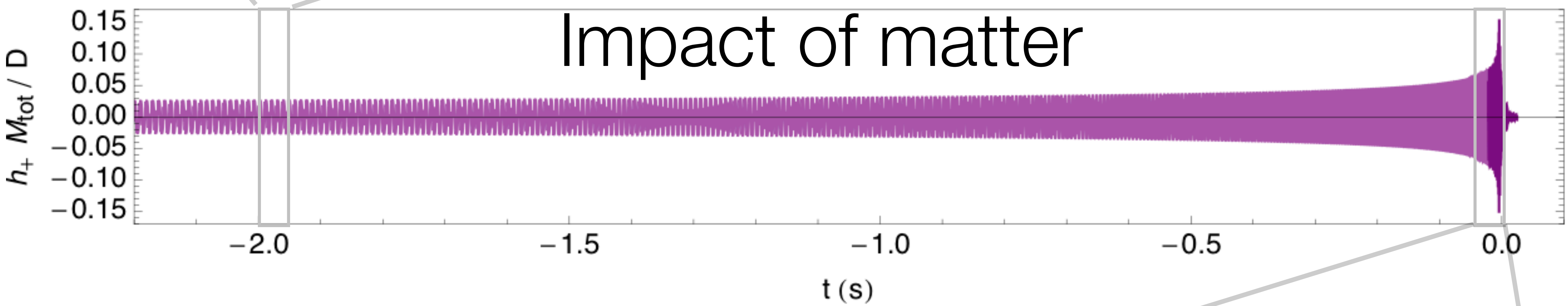

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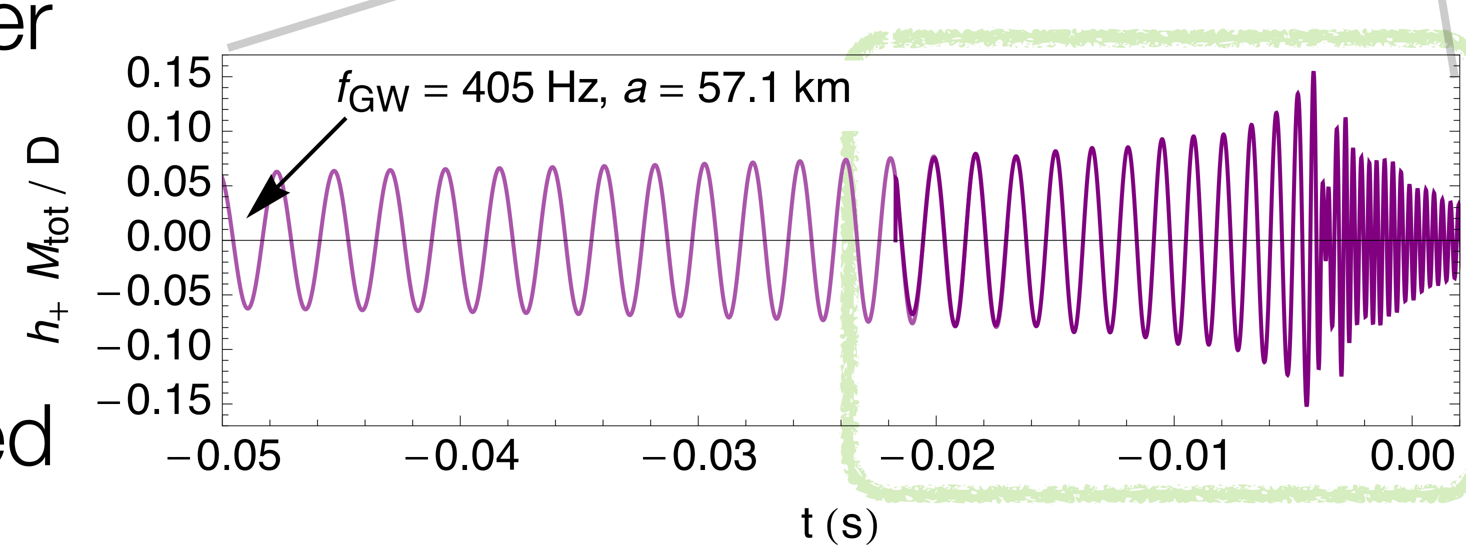
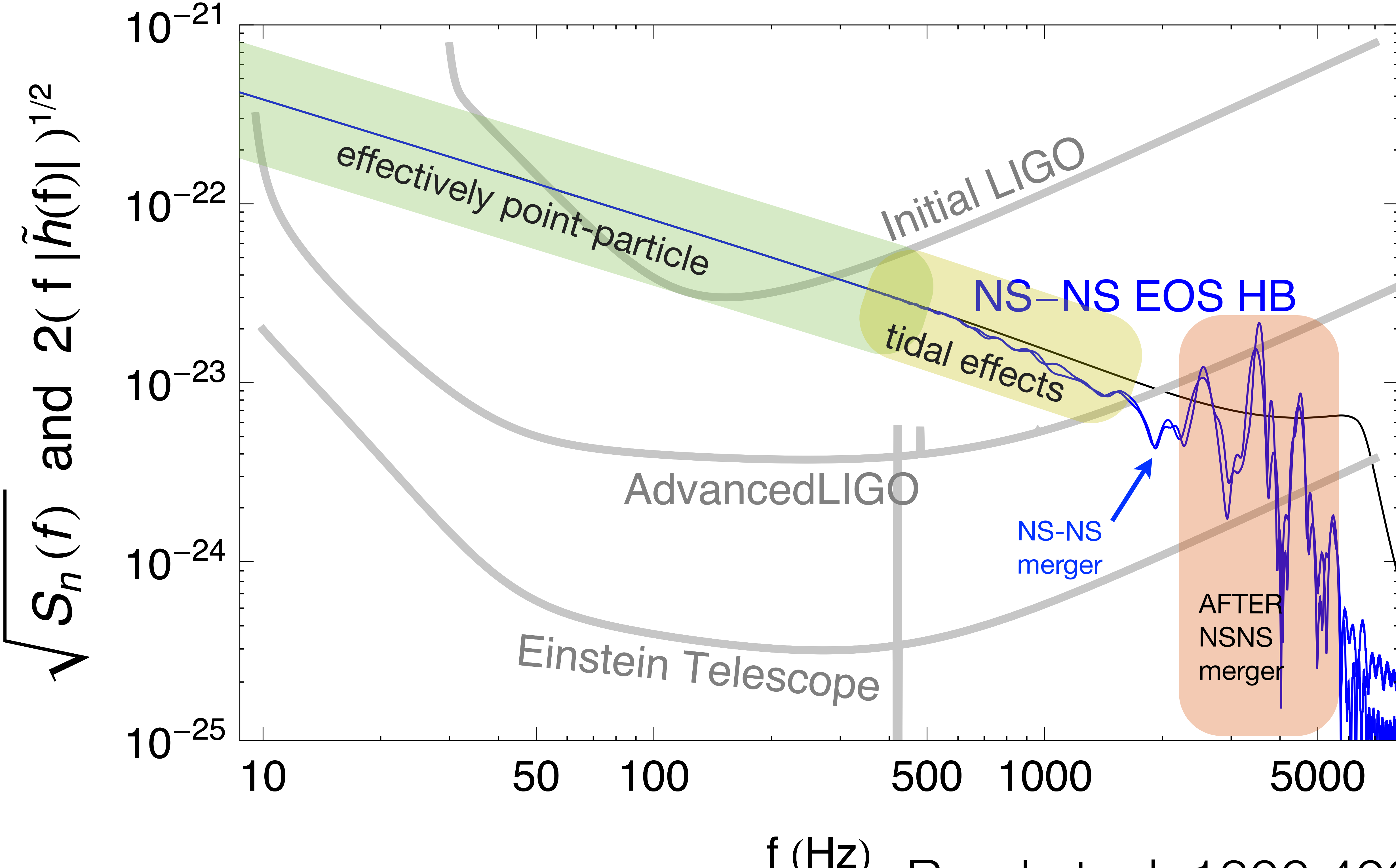
For the final coalescence, numerical simulations are required



Gravitational-wave spectrum of BNS



Read et. al. 1306.4065

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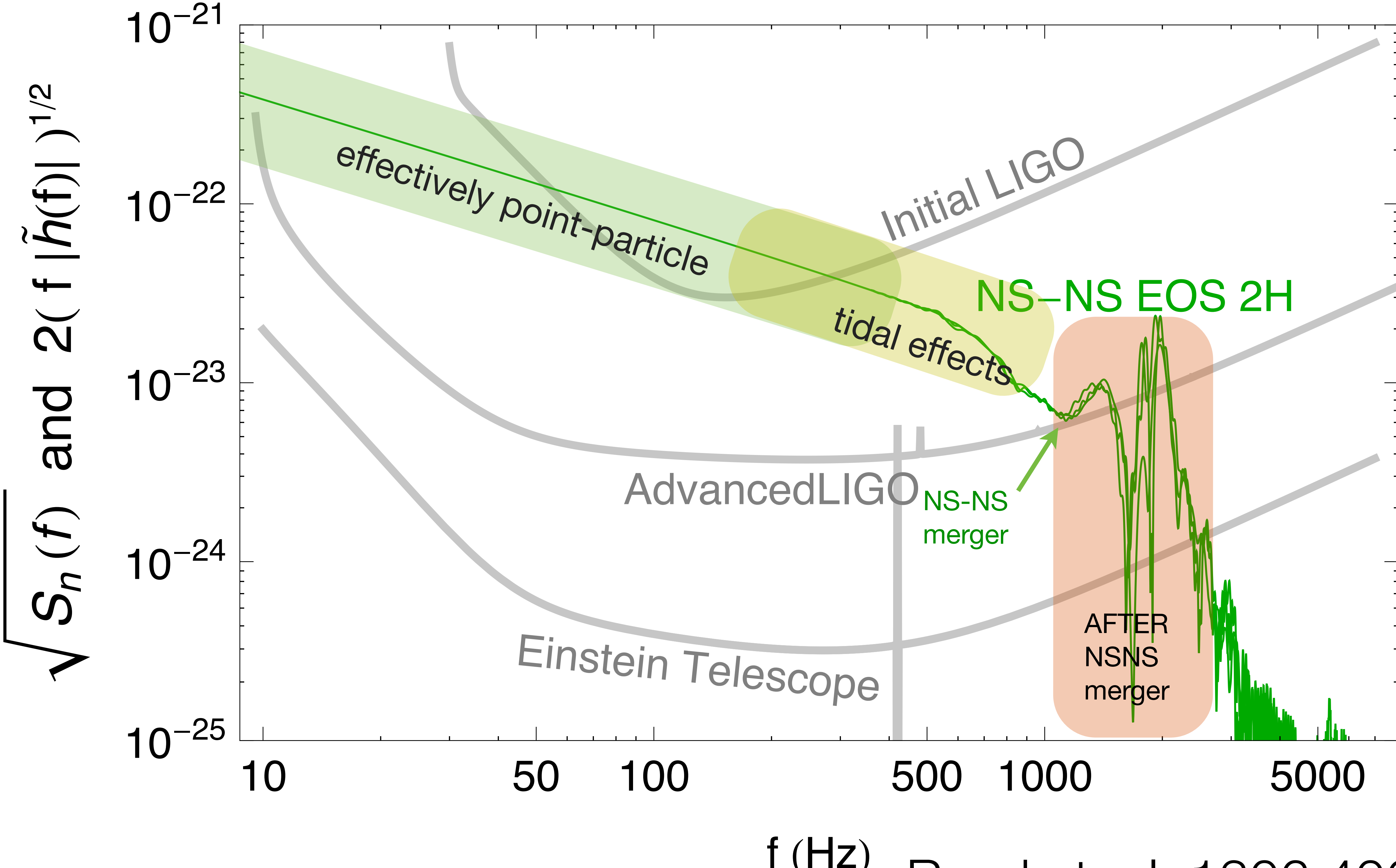
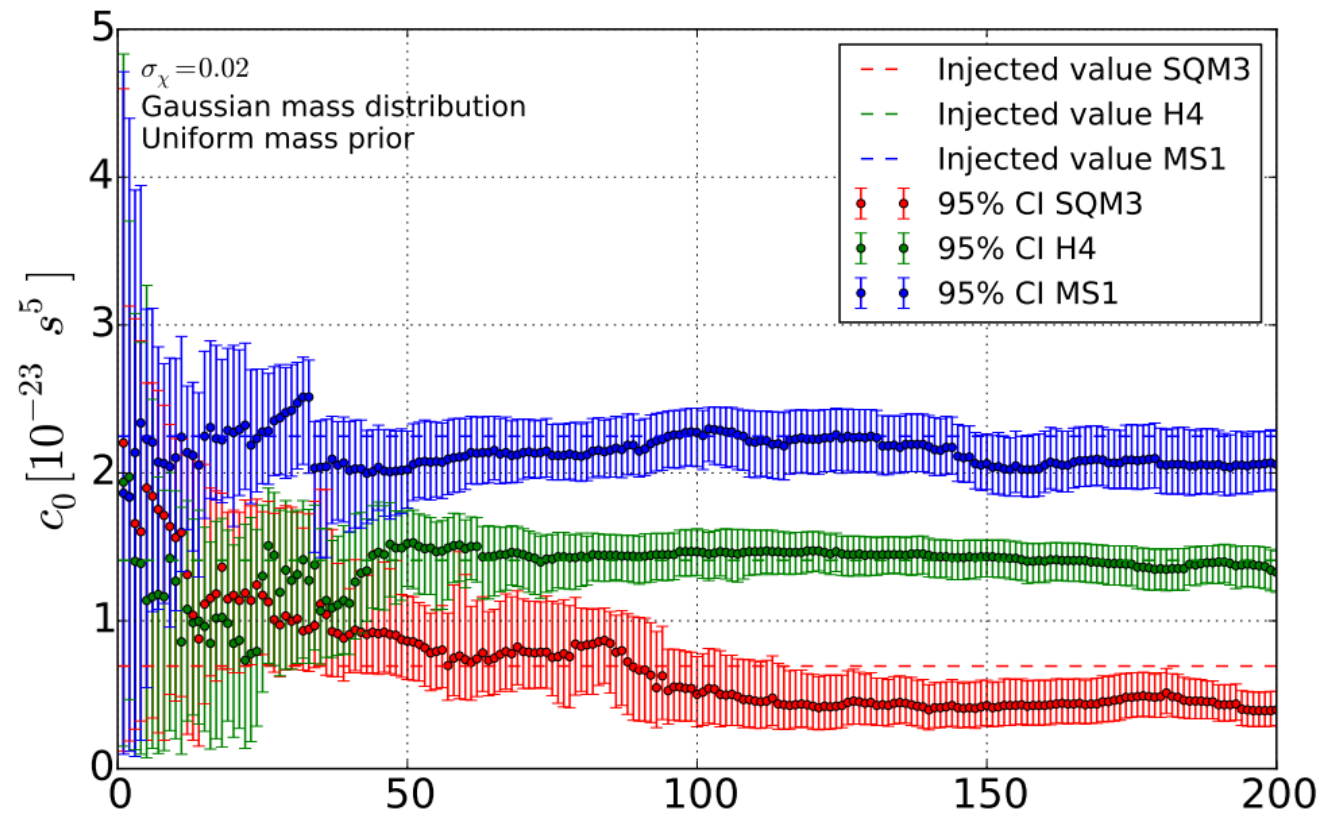


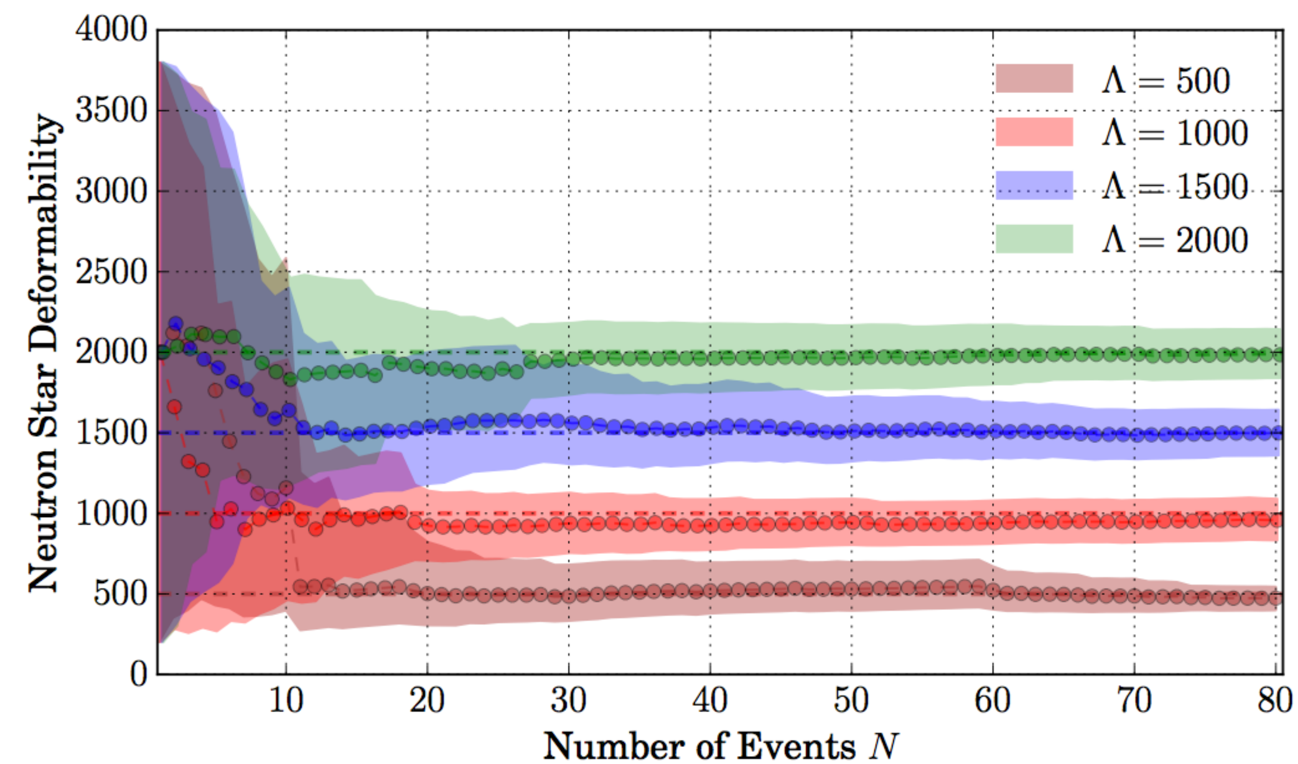
Read et. al. 1306.4065

Learning about neutron-star matter from a population of GW signals

- Neutron-star mergers, or *disruptive* black-hole/neutron-star mergers: “Interesting” with ~tens of detections
- Subject to priors and systematics
- Relies on accurate waveform modeling!



Agathos et al arXiv:1503.05405

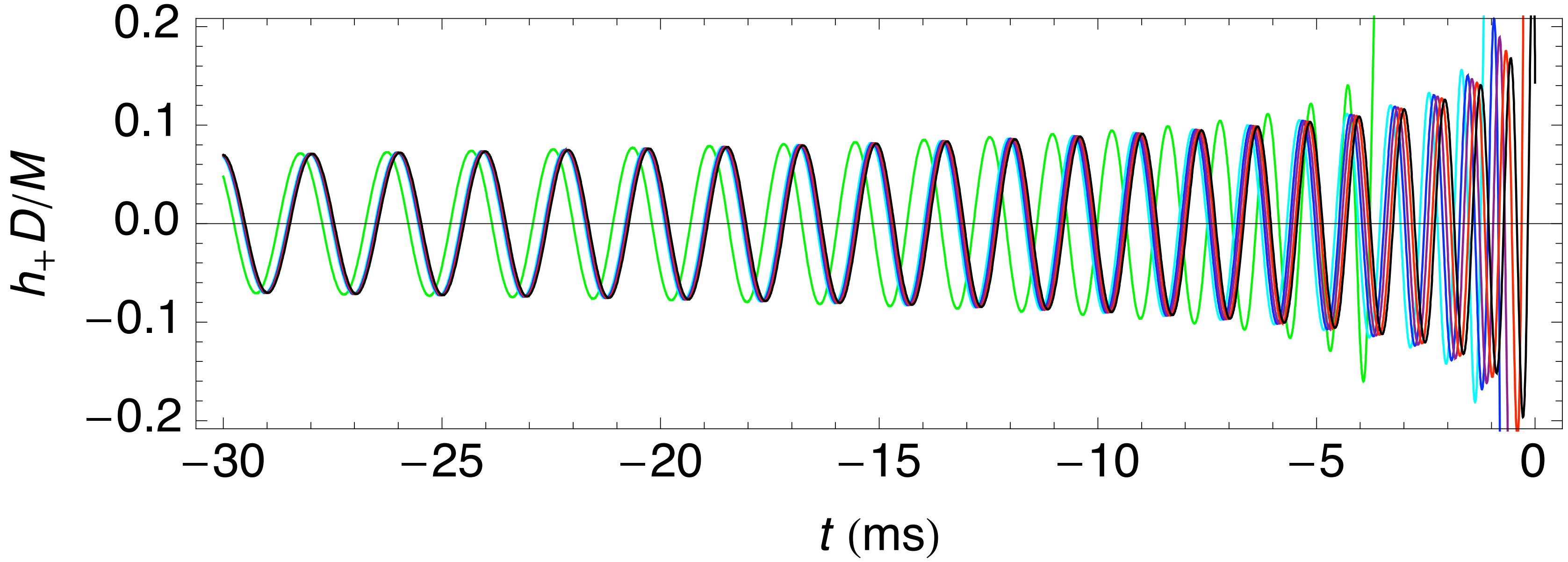


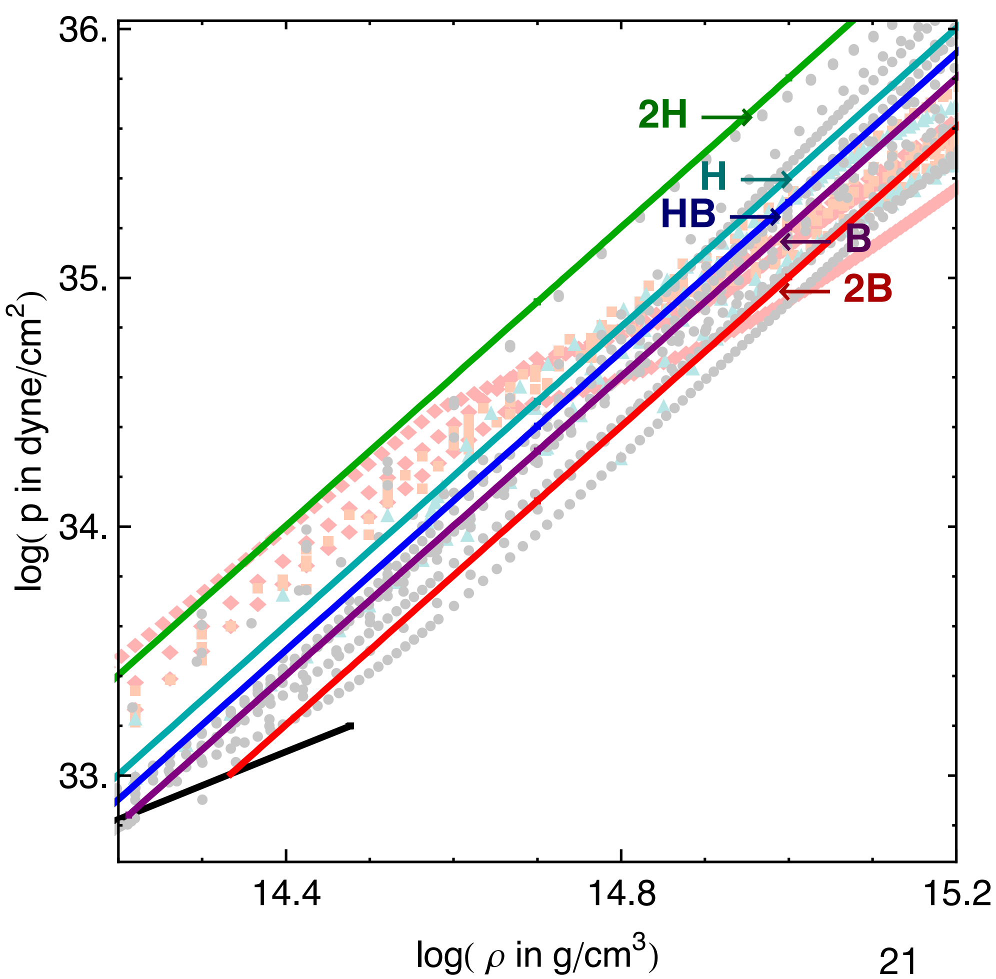
Kumar, Pürrer, Pfeiffer arXiv:1610.06155

Tidal effects on inspiral

Haas et al arXiv:1604.00782

- Energy goes into deforming the neutron star(s), tidal bulges add a bit to the gravitational radiation.
- Modify GW at effectively high post-Newtonian order (Flanagan and Hinderer 0709.1915, Vines and Flanagan 1009.4919)



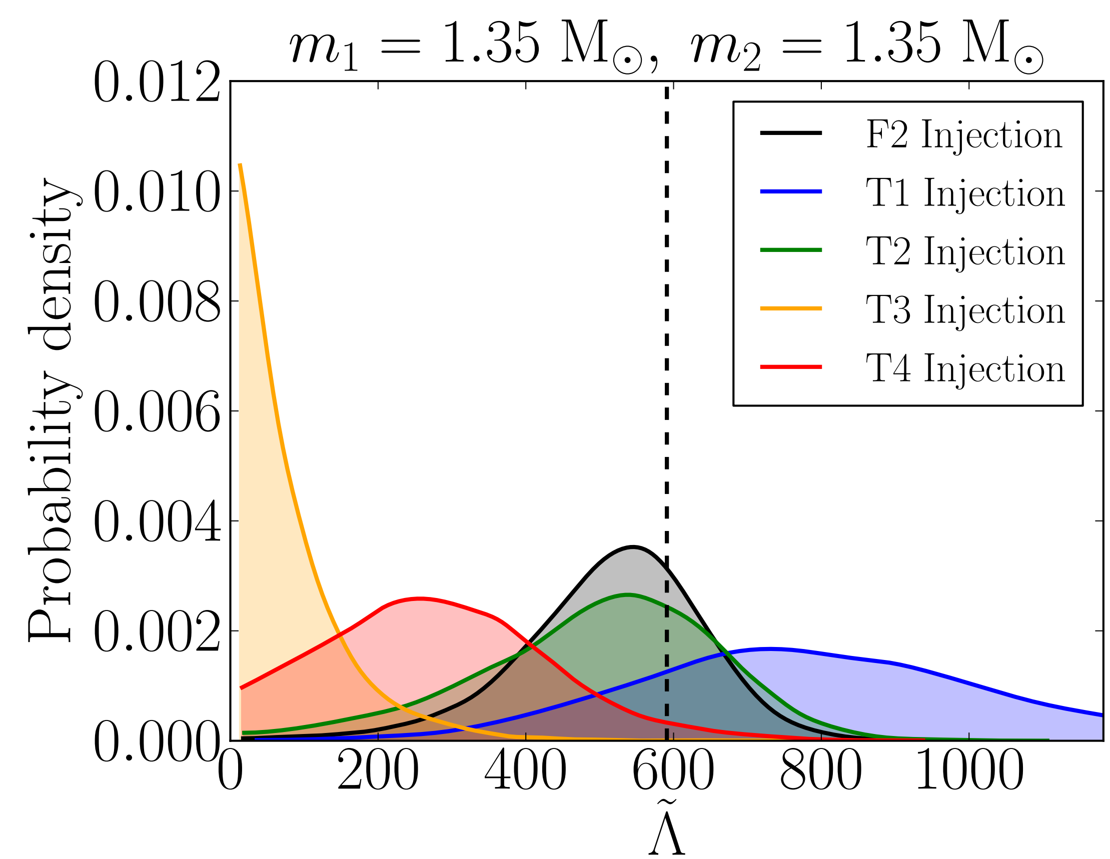


Size of effect on waveform goes as $\Lambda = \frac{2}{3} k_2 \left(\frac{R}{M} \right)^5$

Waveform models for parameter estimation: post-Newtonian tides for inspiral?

- Good estimates of the size and relevance of EOS-dependent (Damour et al 2012, Read et al 1306.4065)

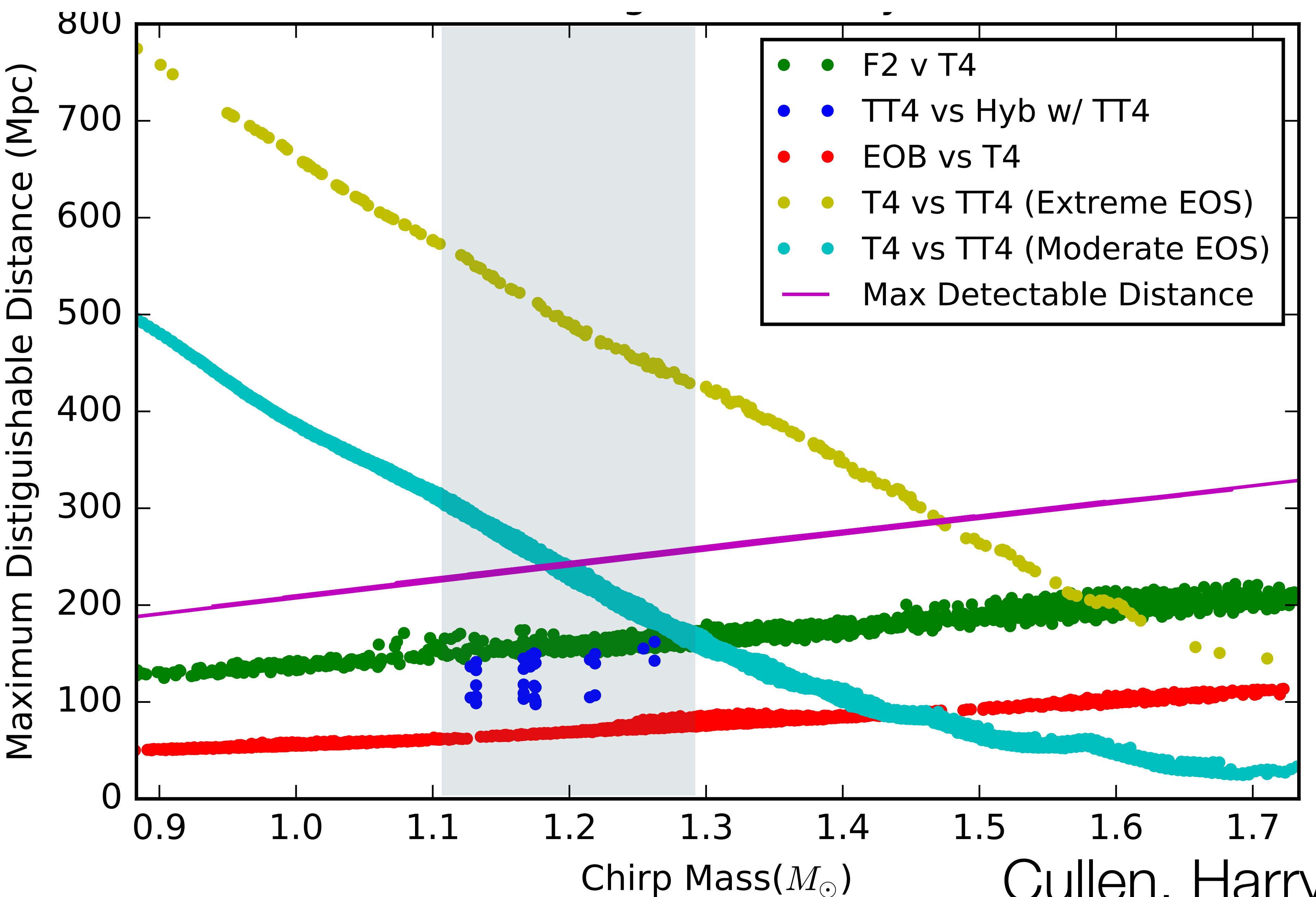
- **Not** sufficient for best measuring EOS effects (Favata 1310.8288, Yagi/Yunes: 1310.8358, Wade et al.1402.5156



Wade et al.1402.5156

Relative importance of effects in BNS waveforms

Maximum distinguishable distance: distance at which difference between waveforms has SNR 1; proportional to size of difference



Cullen, Harry, Read, in prep.

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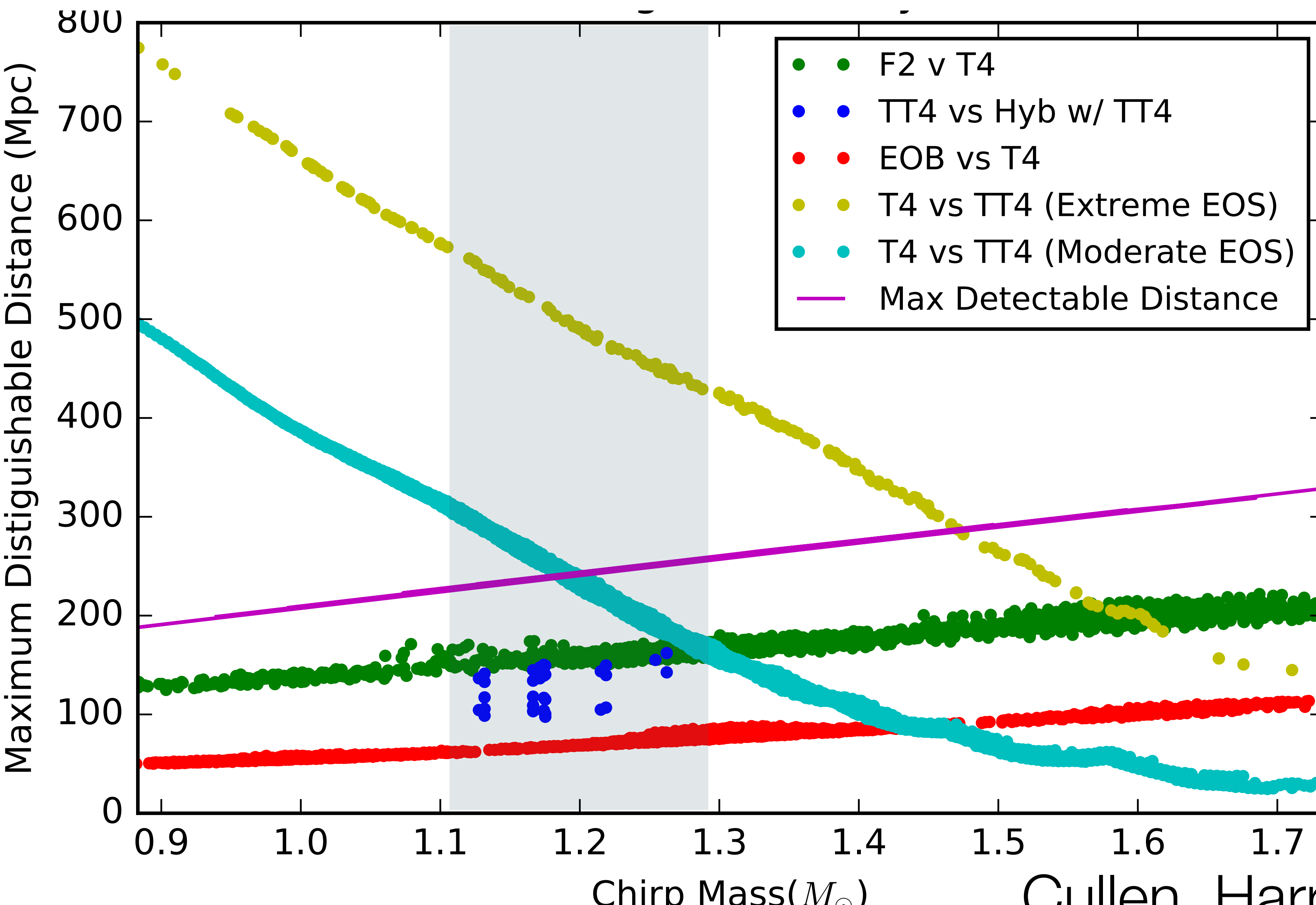

Detection horizon

Single-detector SNR=8

Cullen, Harry, Read, in prep.

Relative importance of effects in BNS waveforms

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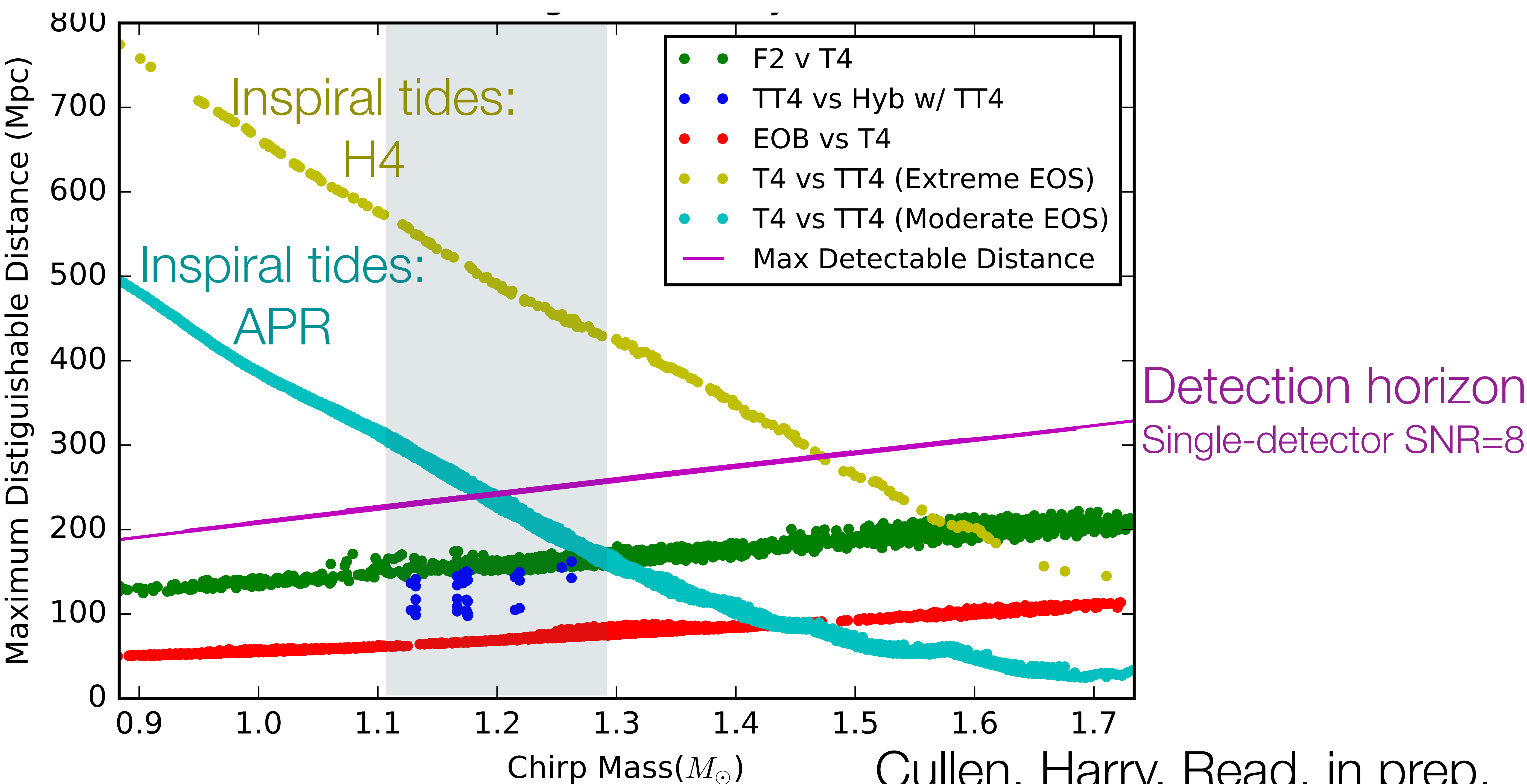

Cullen, Harry, Read, in prep.

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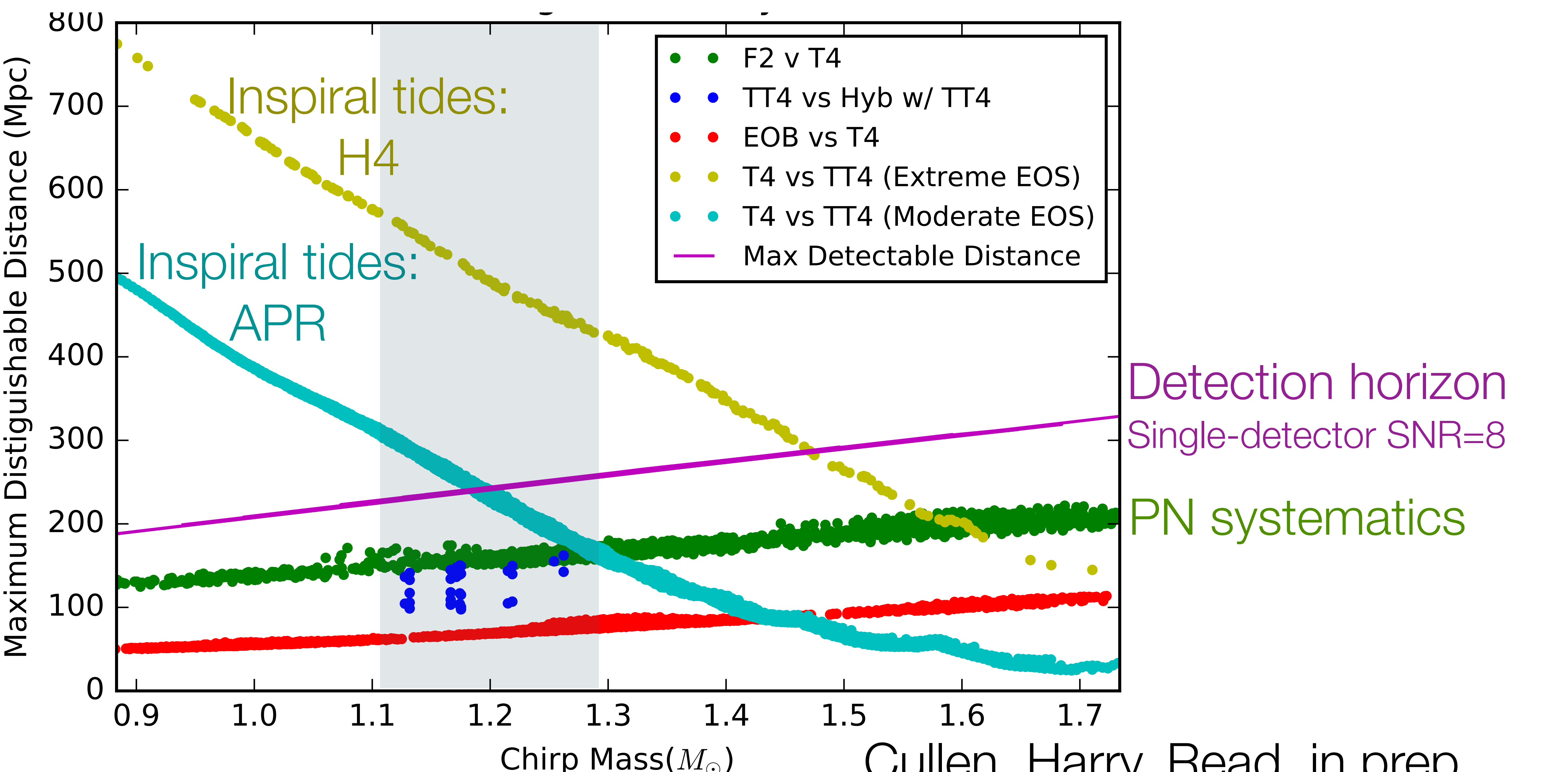

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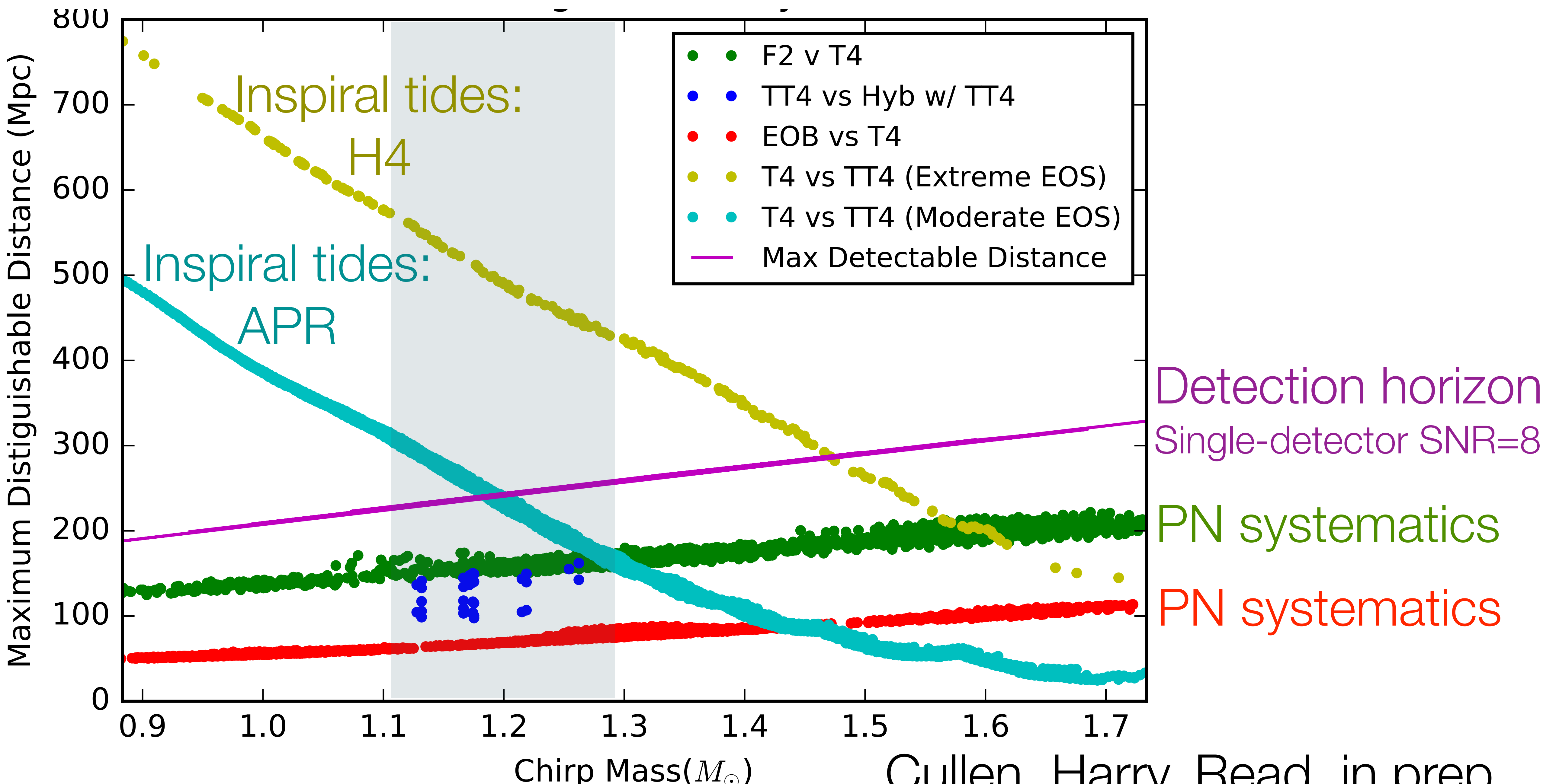

Cullen, Harry, Read, in prep.

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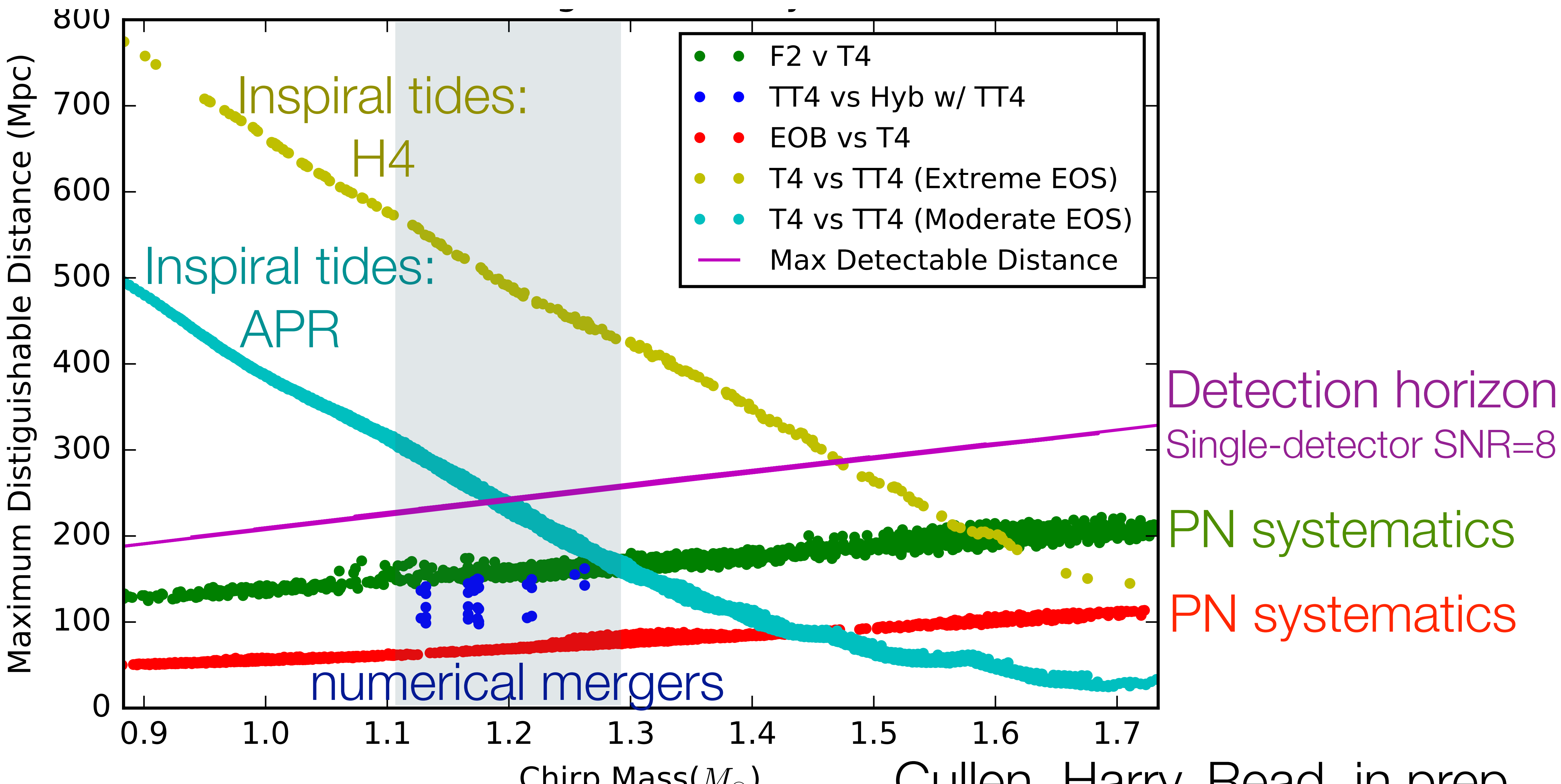
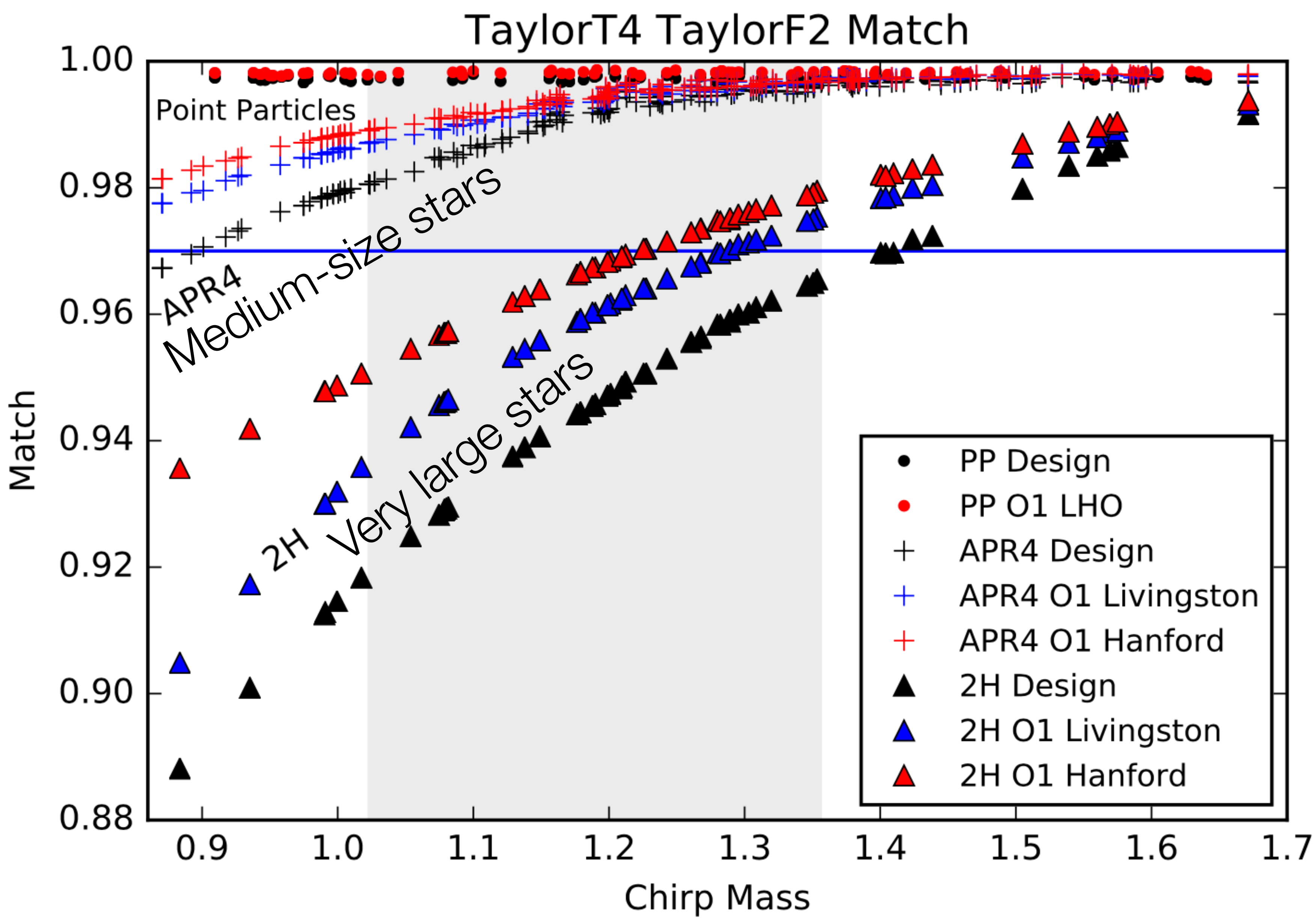


Cullen, Harry, Read, in prep.

Matter impacts on search: extreme tides!

- If neutron stars are large, tidal effects induce waveform mismatch & reduce effective search volume



10% signal loss;
impact on template bank fitting factors

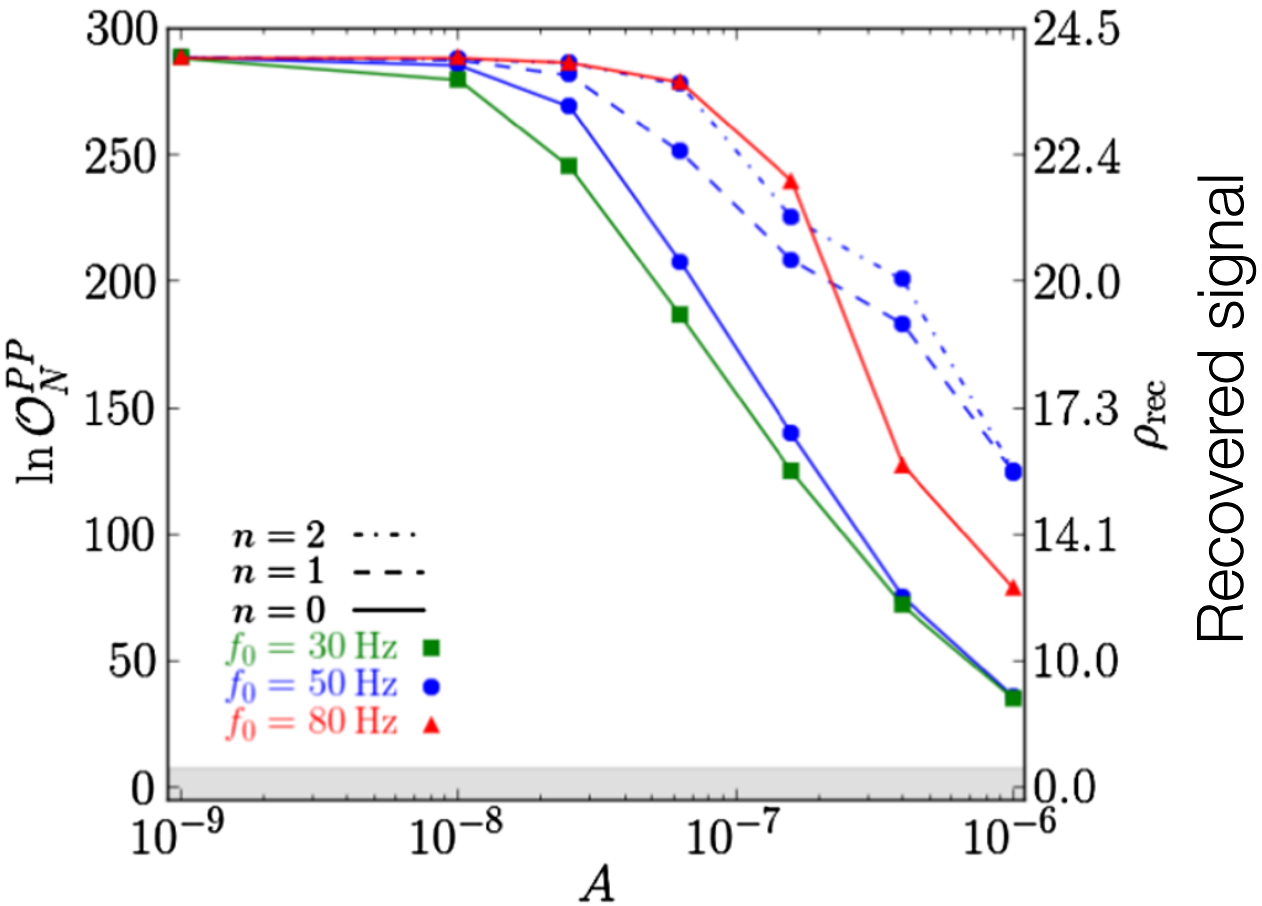
Cullen, Harry, Read, in prep.

Matter impacts on search: extreme tides!

- Resonance with stellar modes transfers energy from orbit
- Unstable nonlinear mode couplings disrupt inspiral, impact search and parameter estimation (Essick, Vitale, Weinberg 1609.06362)

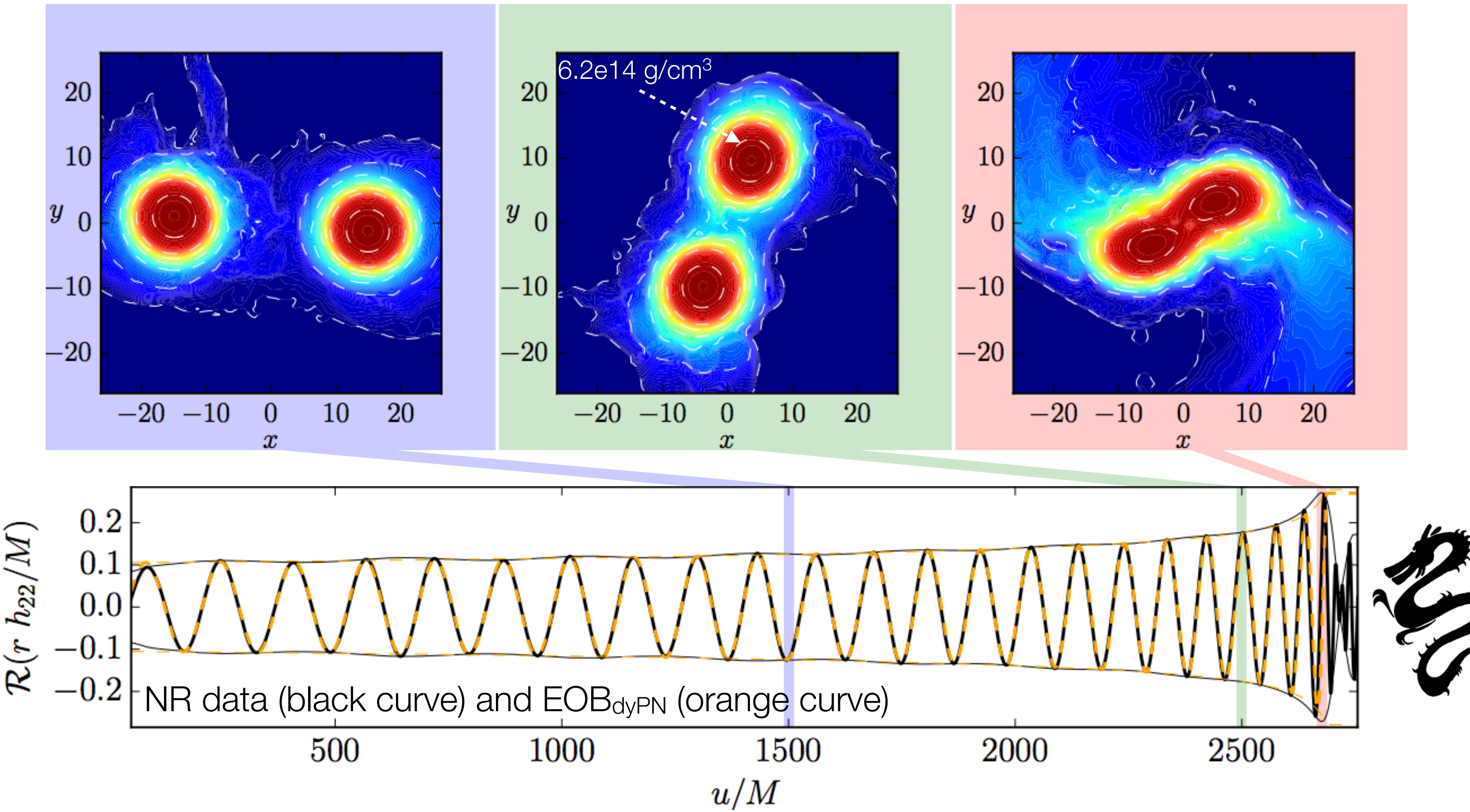
Resonant mode illustration, D. Tsang

Injected signal at ρ=25



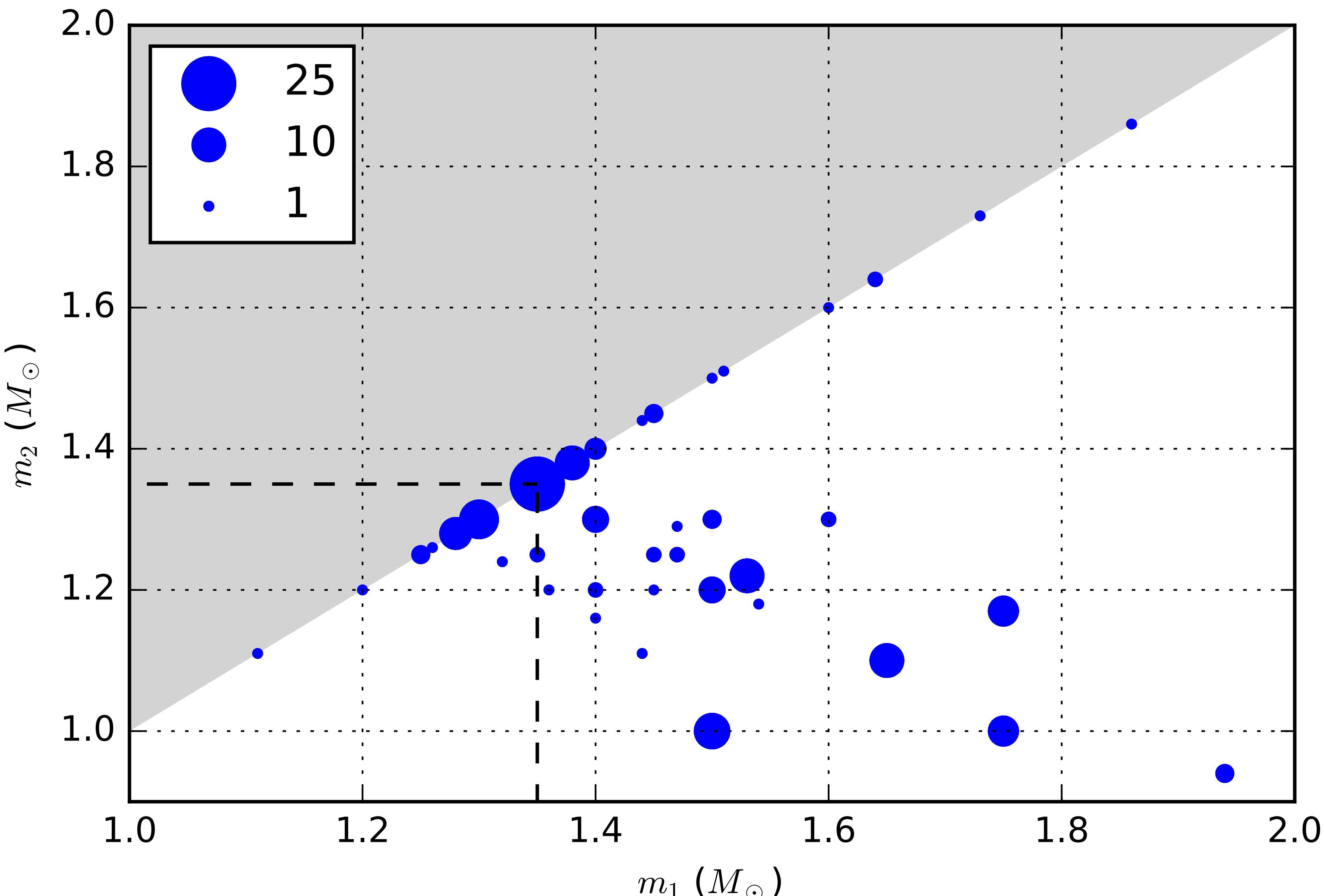
(unknown) amplitude parameter

Inspiral-to-merger: accurate waveform models



Dietrich and Hinderer, arXiv:1702.02053

Status of BNS simulations: coverage of parameter space

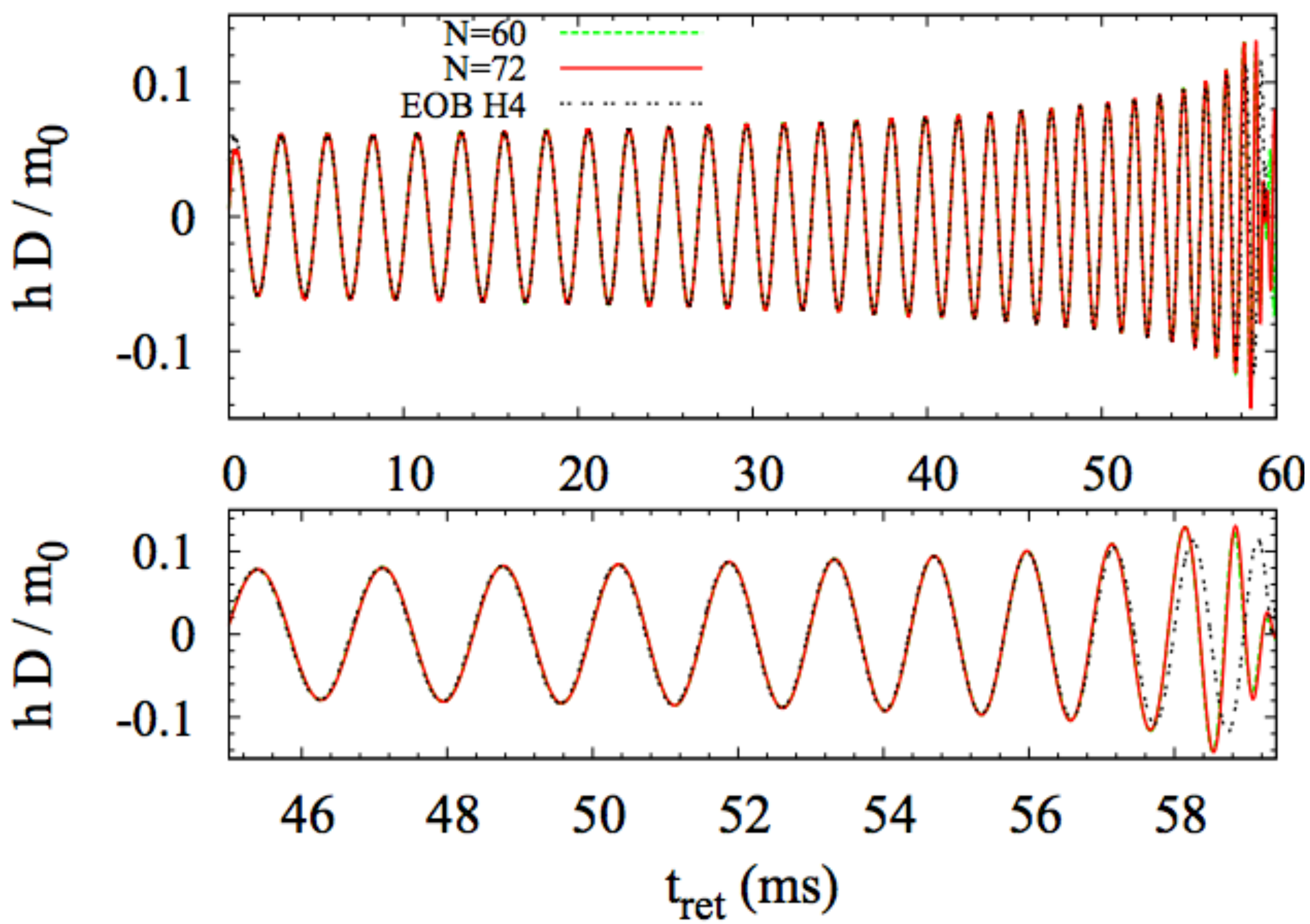


not shown - length of simulations, resolution, EOS parameters…

Compilation in progress by T. Cullen

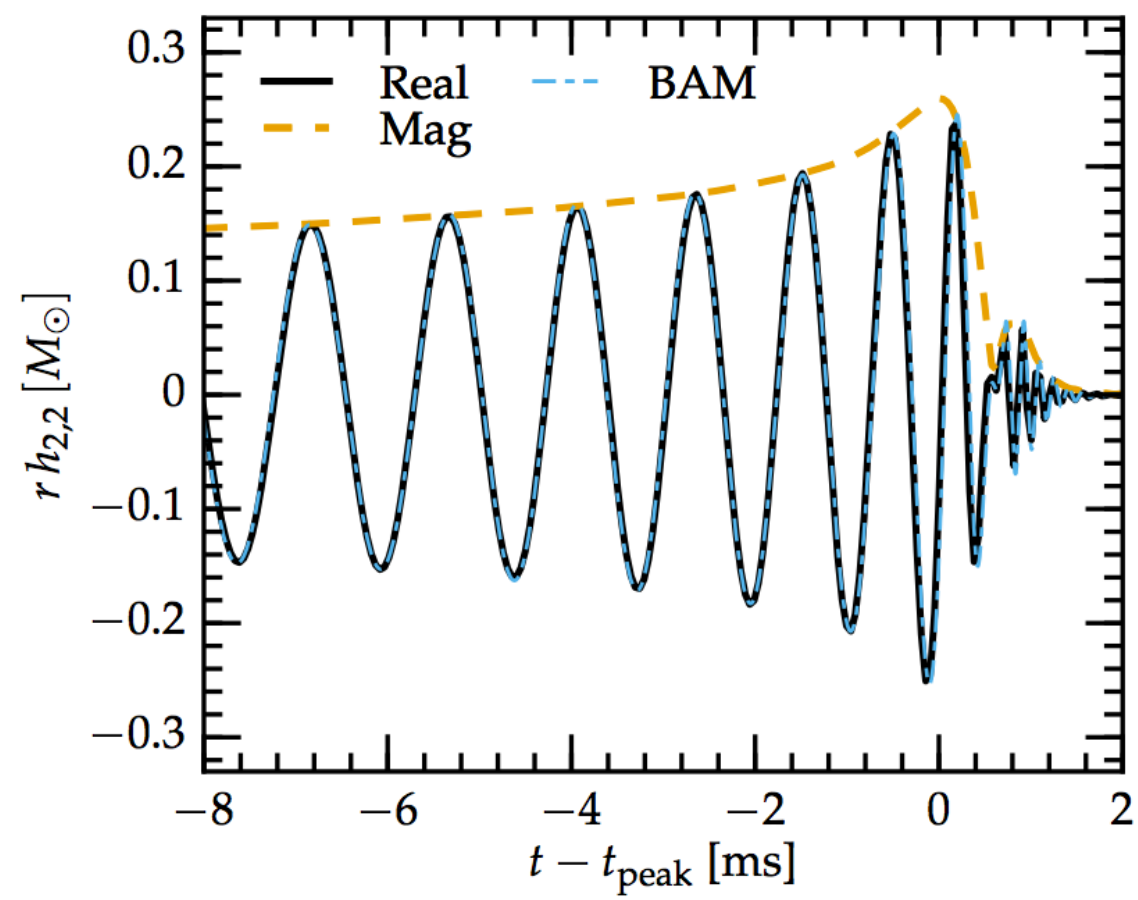
Long and accurate BNS simulations

Hotokezaka et al 1502.03457



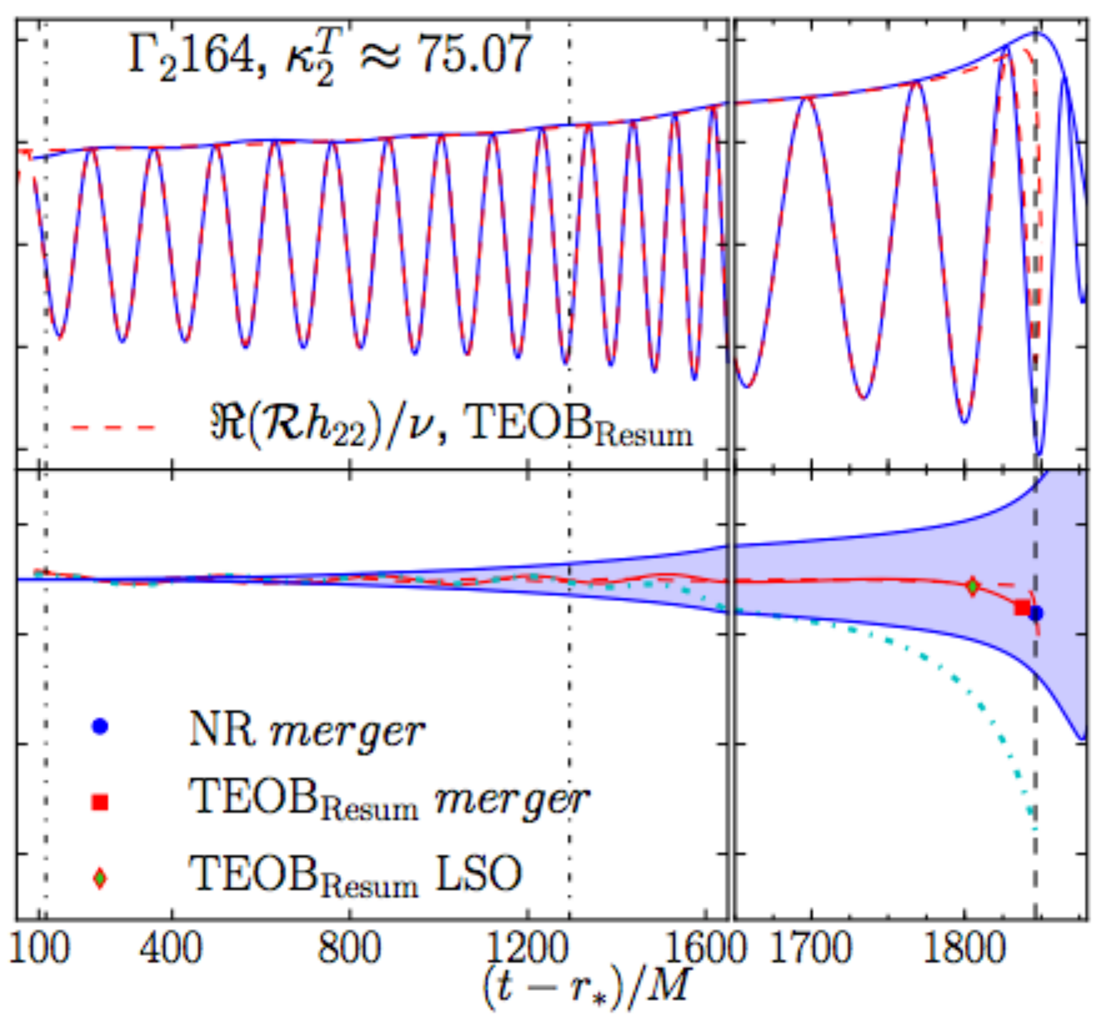
estimated total phase error <1 radian over ~200 radians

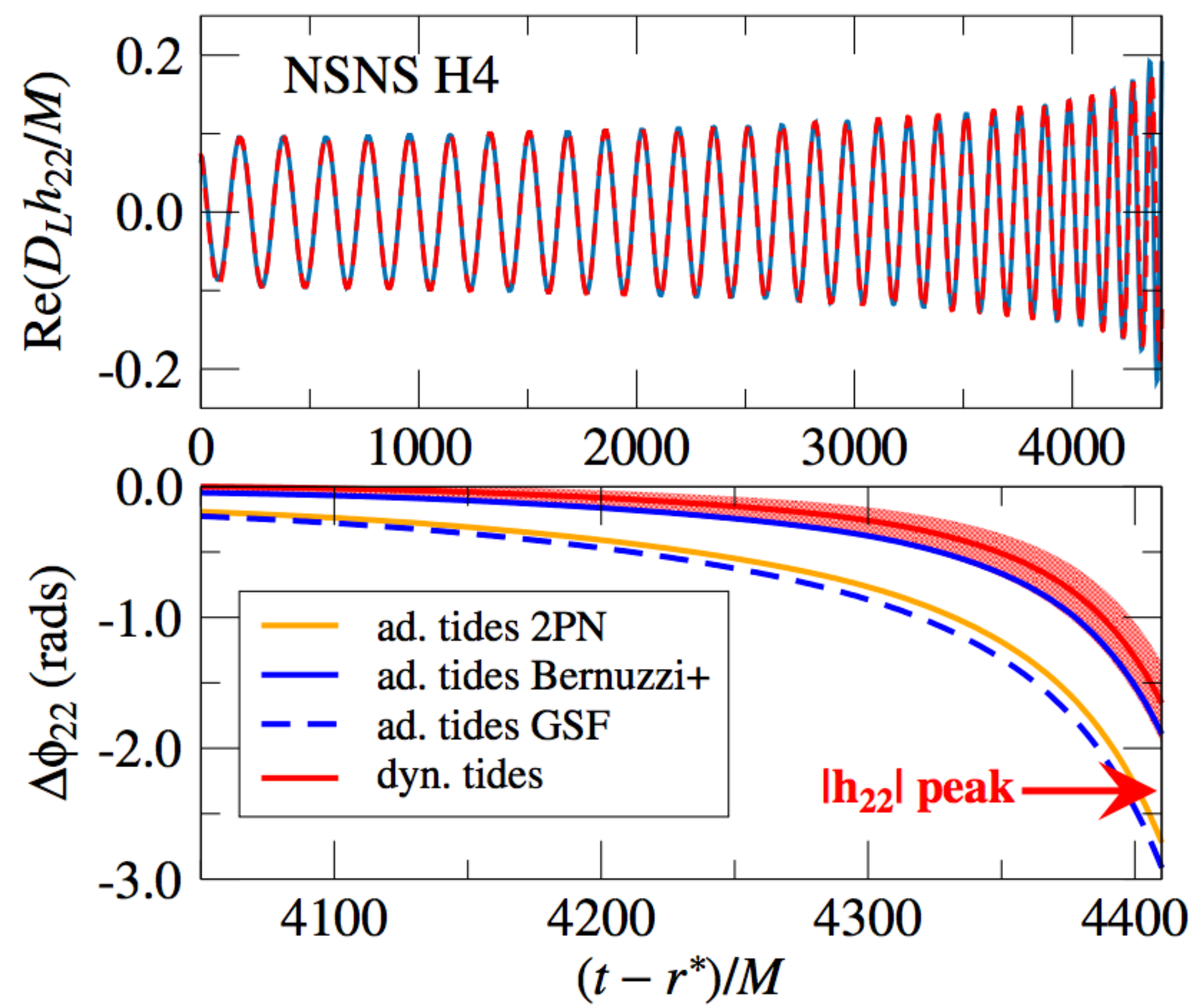
Haas et al 1604.00782 (22 orbits!) comparison to Bernuzzi et al 1412.4553



Waveforms aligned before -13.3 ms

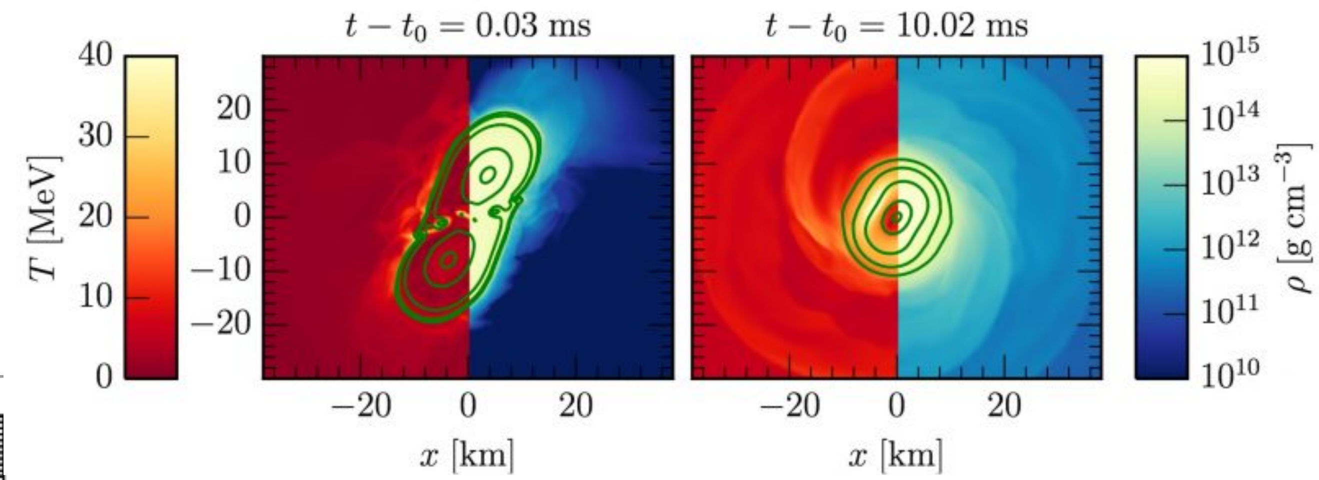
Tidal effects in EOB models: Bernuzzi et al 1412.4553, Hinderer et al 1602.00599



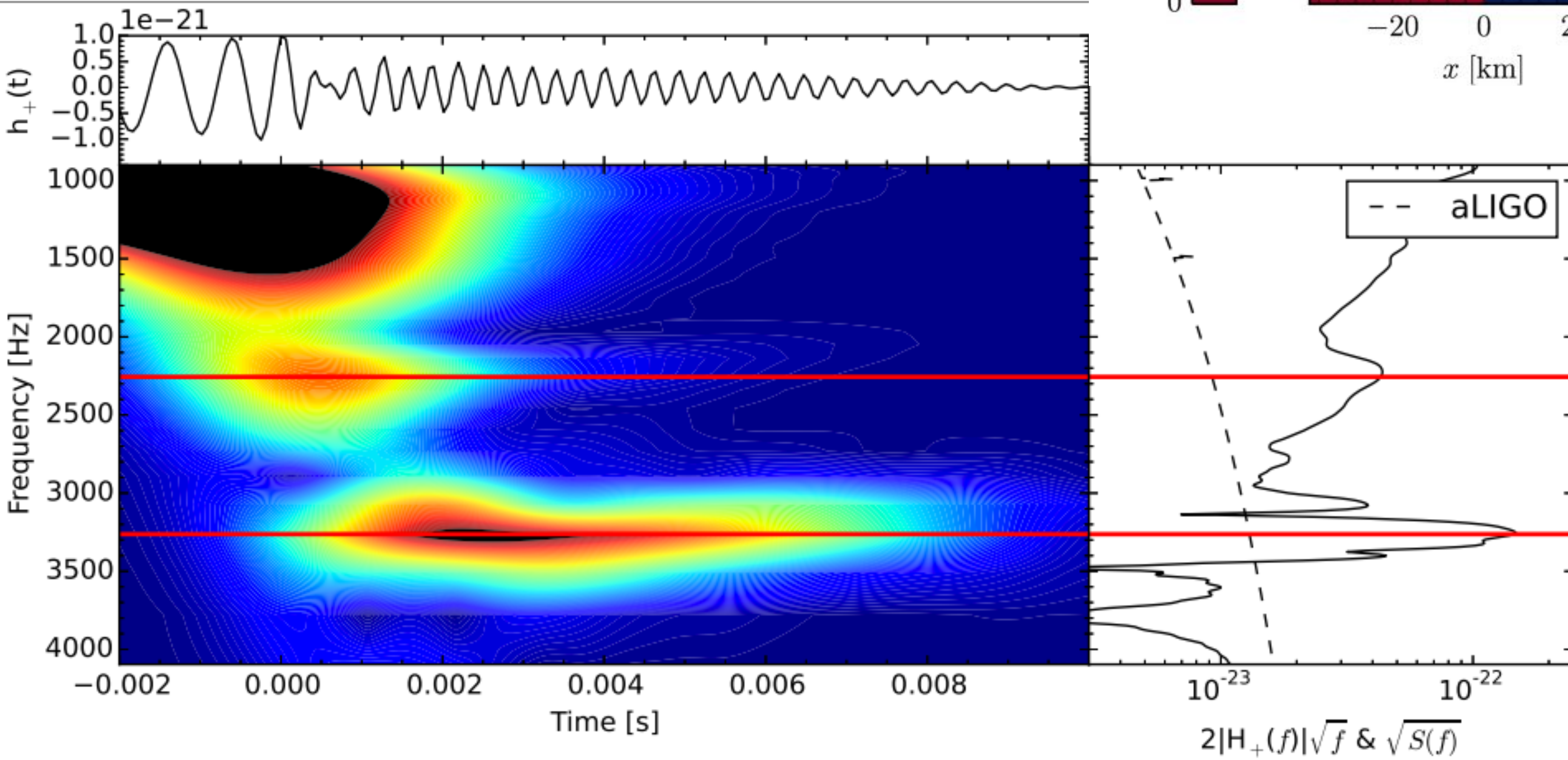


- EOB plus tidal corrections plus higher-order effects: semi-analytic models capture inspiral-to-merger phase
- Phenomenological extensions to improve agreement with NR (Bernuzzi, Dietrich, & Tichy; PN-based Lockett-Ruiz, Park & Read)

Bernuzzi et al 1512.06397



BNS post-merger



Clark et al 1509.08522:

- burst follow-up to measure post-merger signals
- frequency measurement only for nearby (~ 30 Mpc) sources

Combine multiple sources - independent EOS information

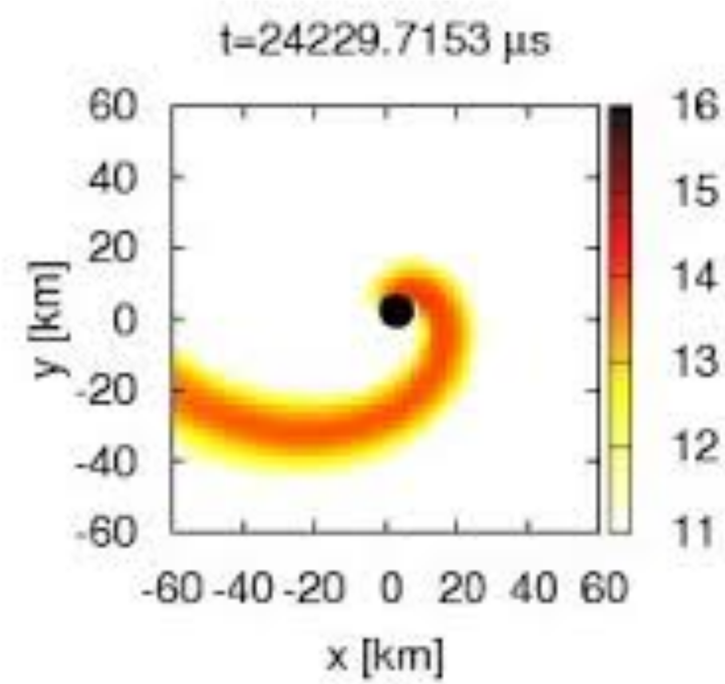
- Bose et al 1705.10850, Yang et al 1707.00207

Black-hole/neutron-star mergers

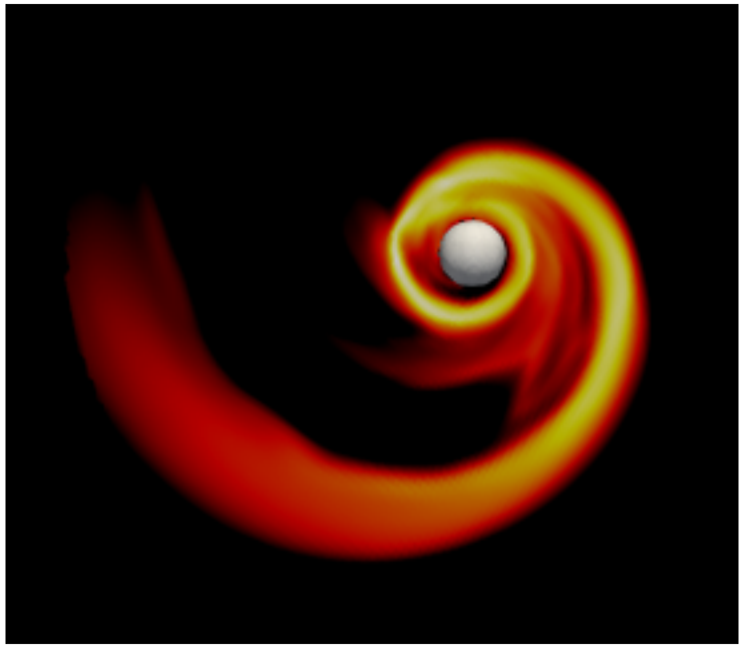
“disruptive” BHNS
Lackey et. al.1303.6298
EOS effects on GW

$q = M_{BH}/M_{NS} = 2-5$

SACRA, K Kyutoku

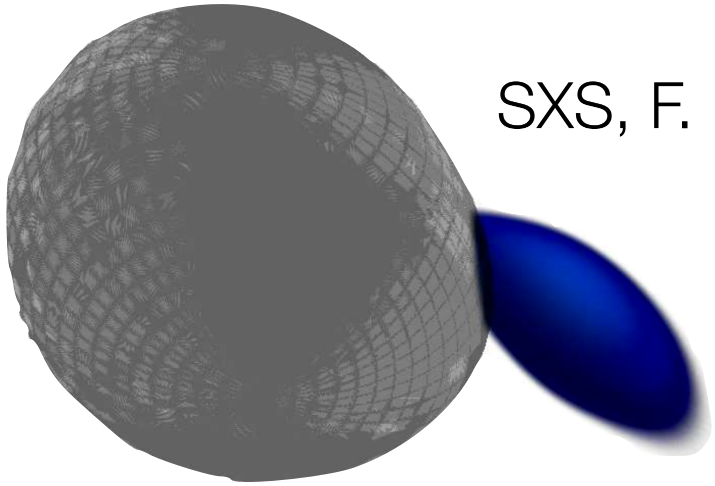


SXS, J Sanchez



“nondisruptive” BHNS
Foucart et al 1307.7685
indistinguishable from BBH

$q = M_{BH}/M_{NS} \gtrsim 6$

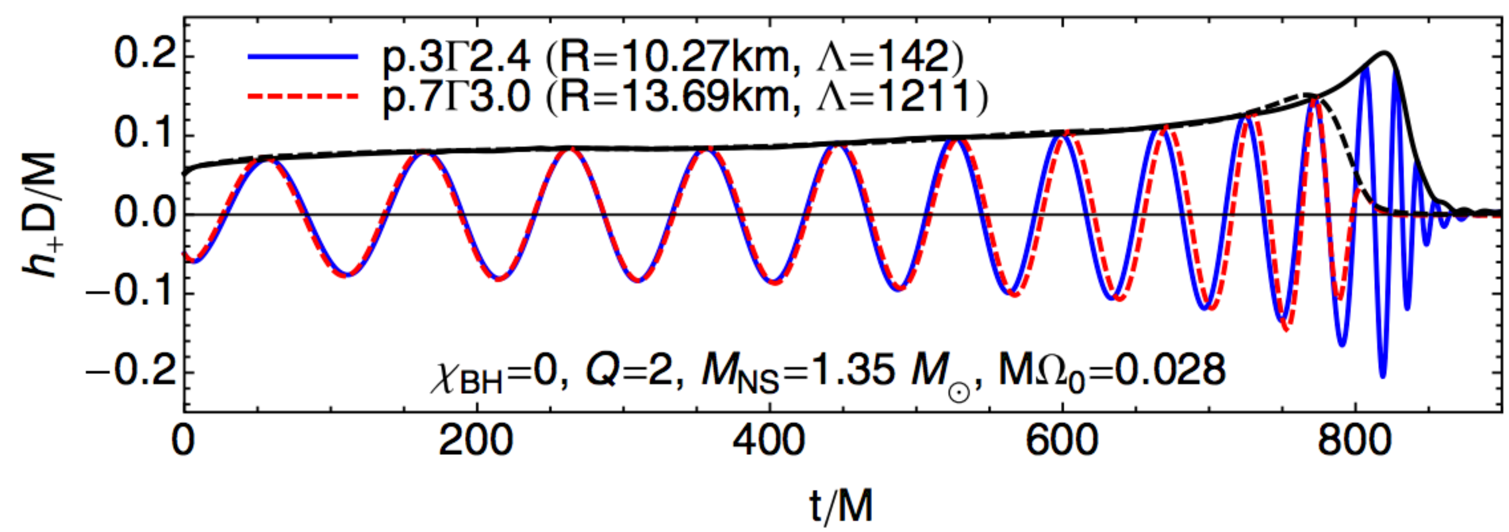


SXS, F. Foucart

NSBH gravitational waves

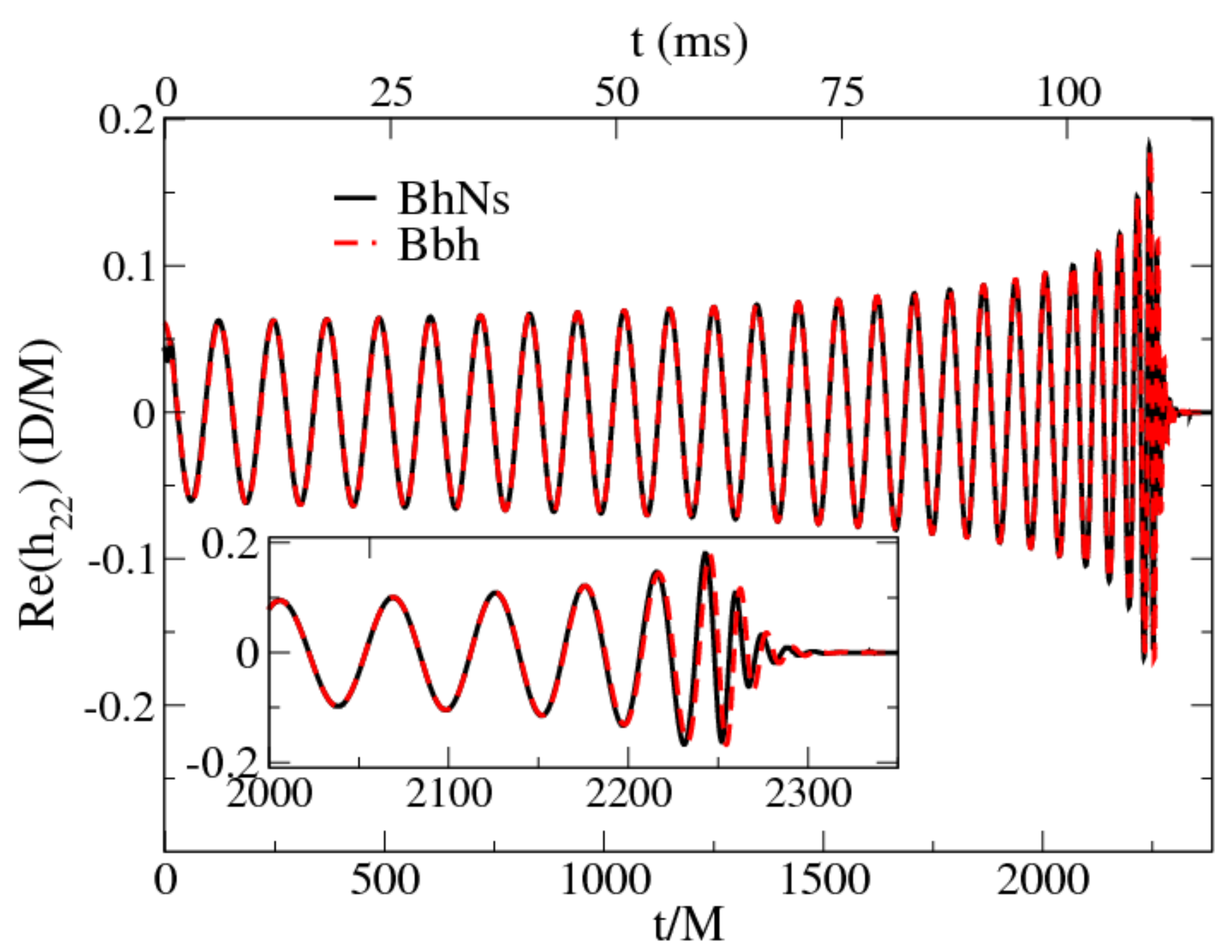
“disruptive” BHNS
Lackey et. al.1303.6298
EOS effects on GW

q = MBH/MNS = 2—5



“nondisruptive” BHNS
Foucart et al 1307.7685
indistinguishable from BBH

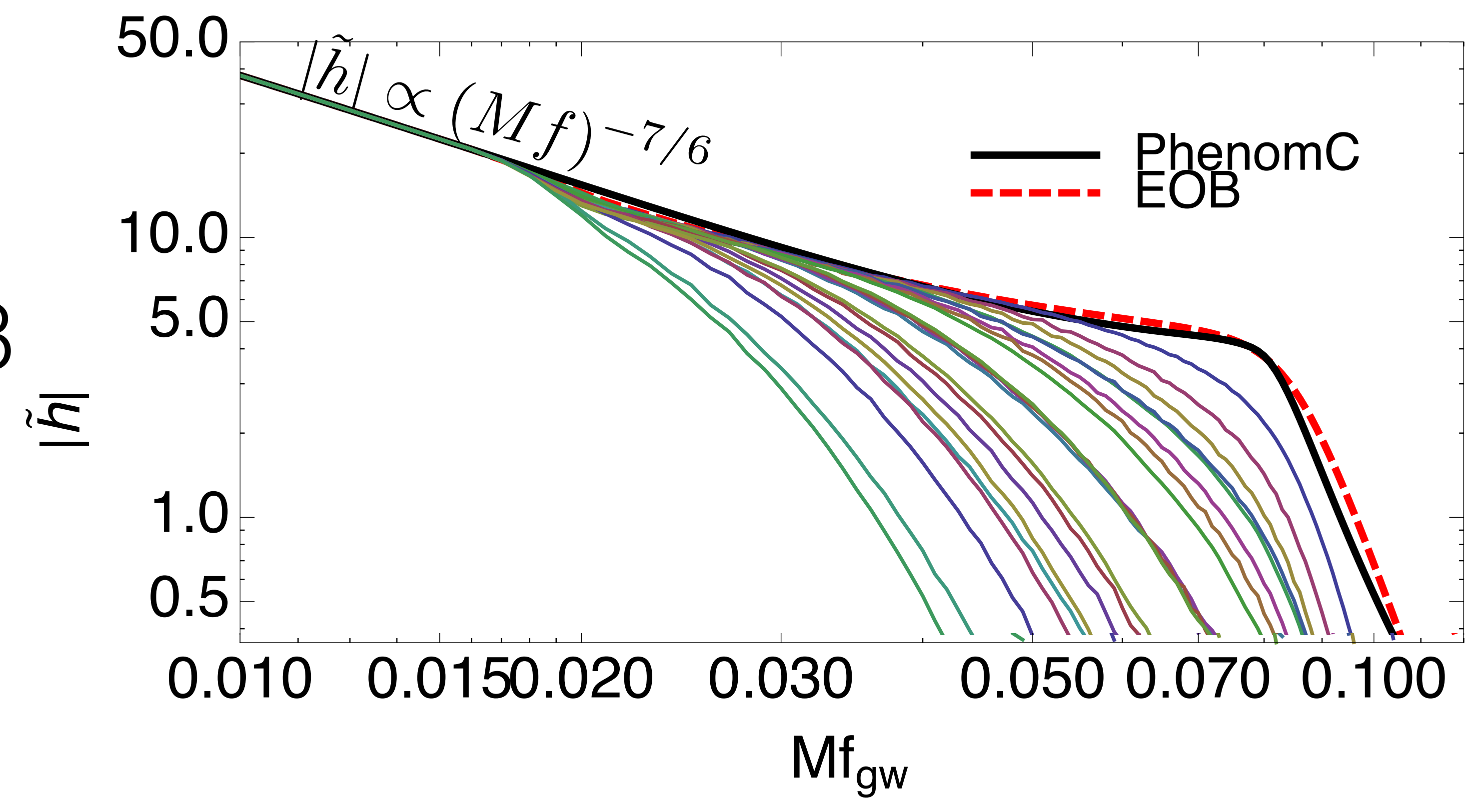
q = MBH/MNS = 6



NSBH spectra

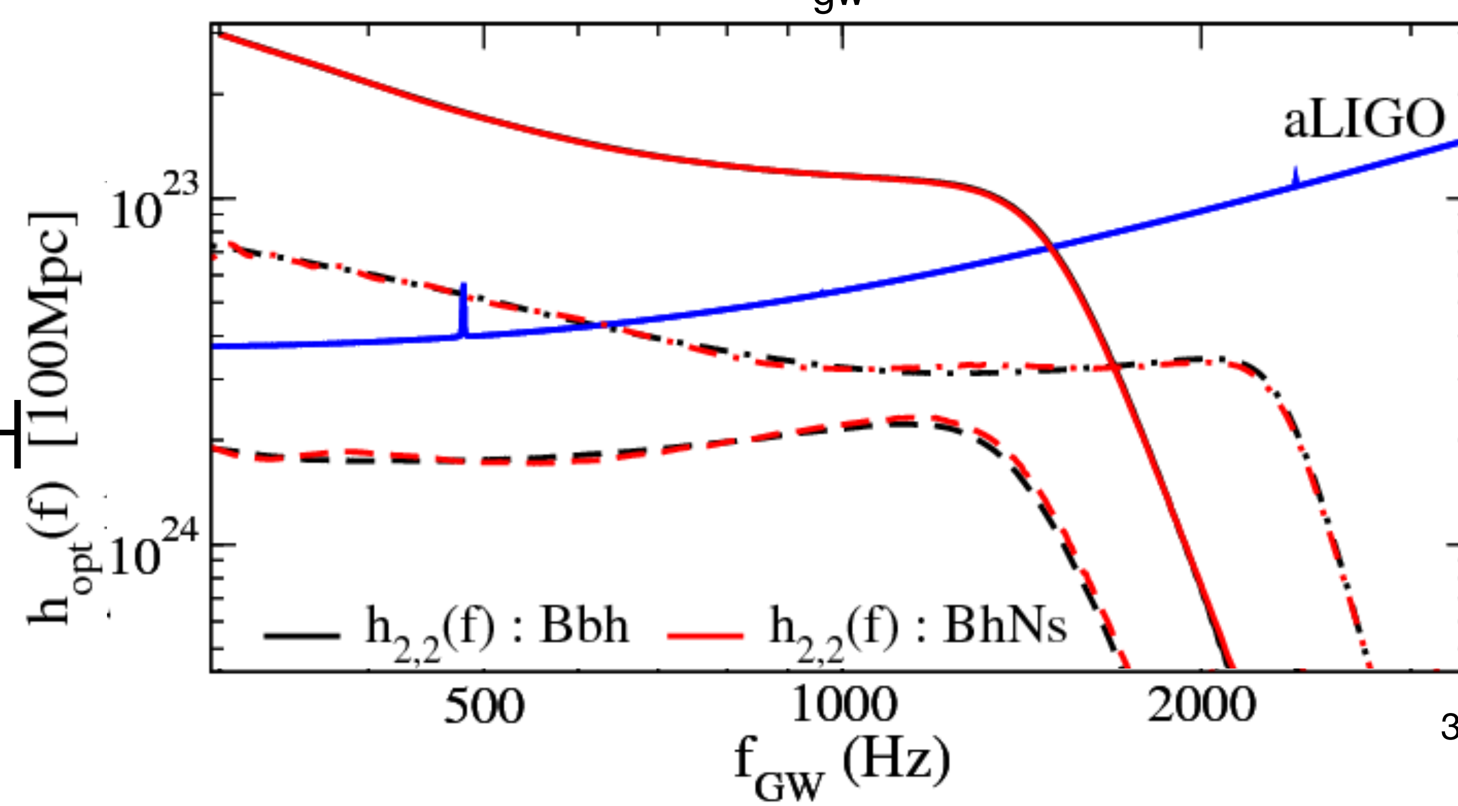
"disruptive" BHNS
Lackey et. al.1303.6298
EOS effects on GW

q = MBH/MNS = 2—5



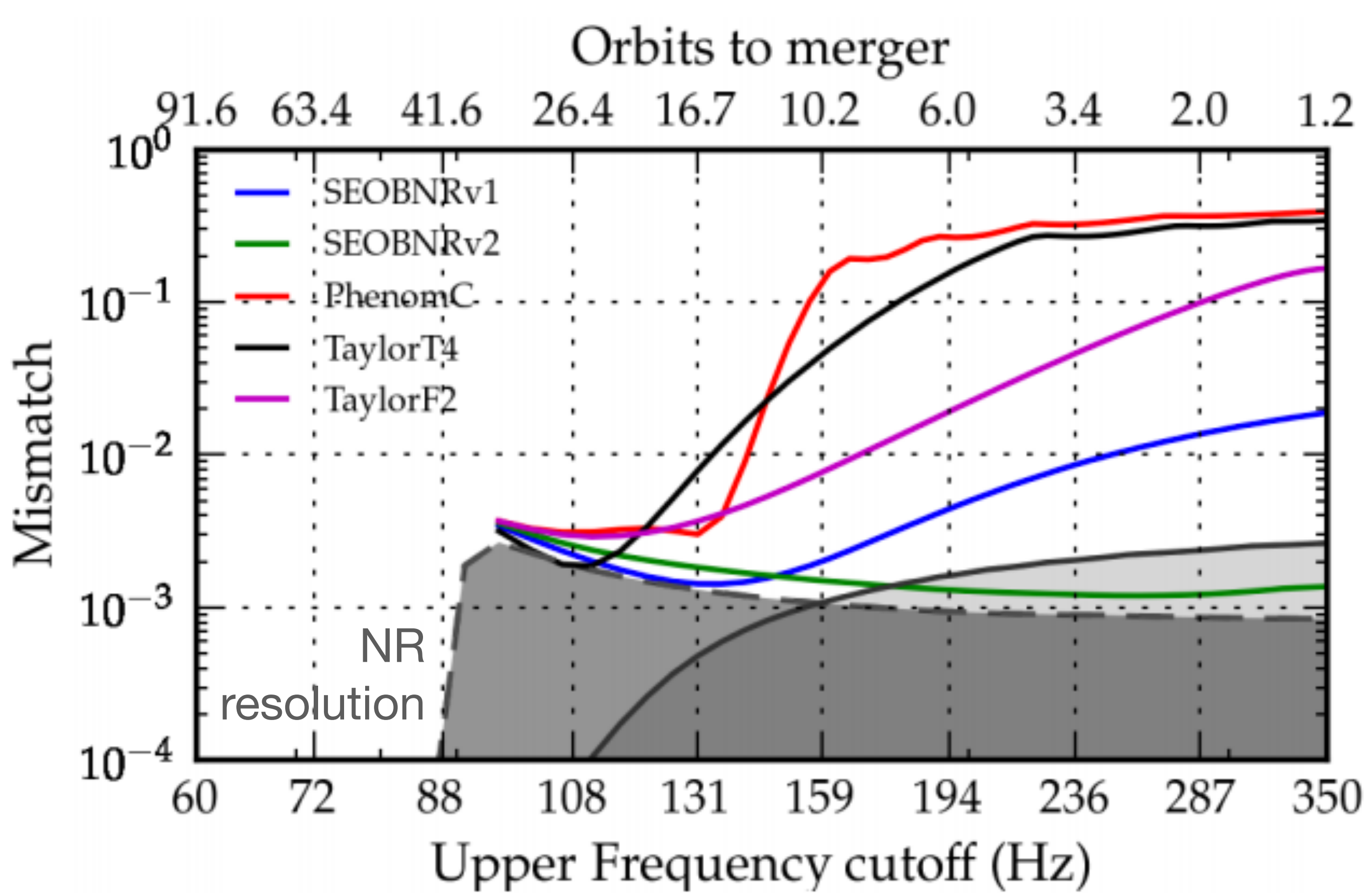
"nondisruptive" BHNS
Foucart et al 1307.7685
indistinguishable from BBH

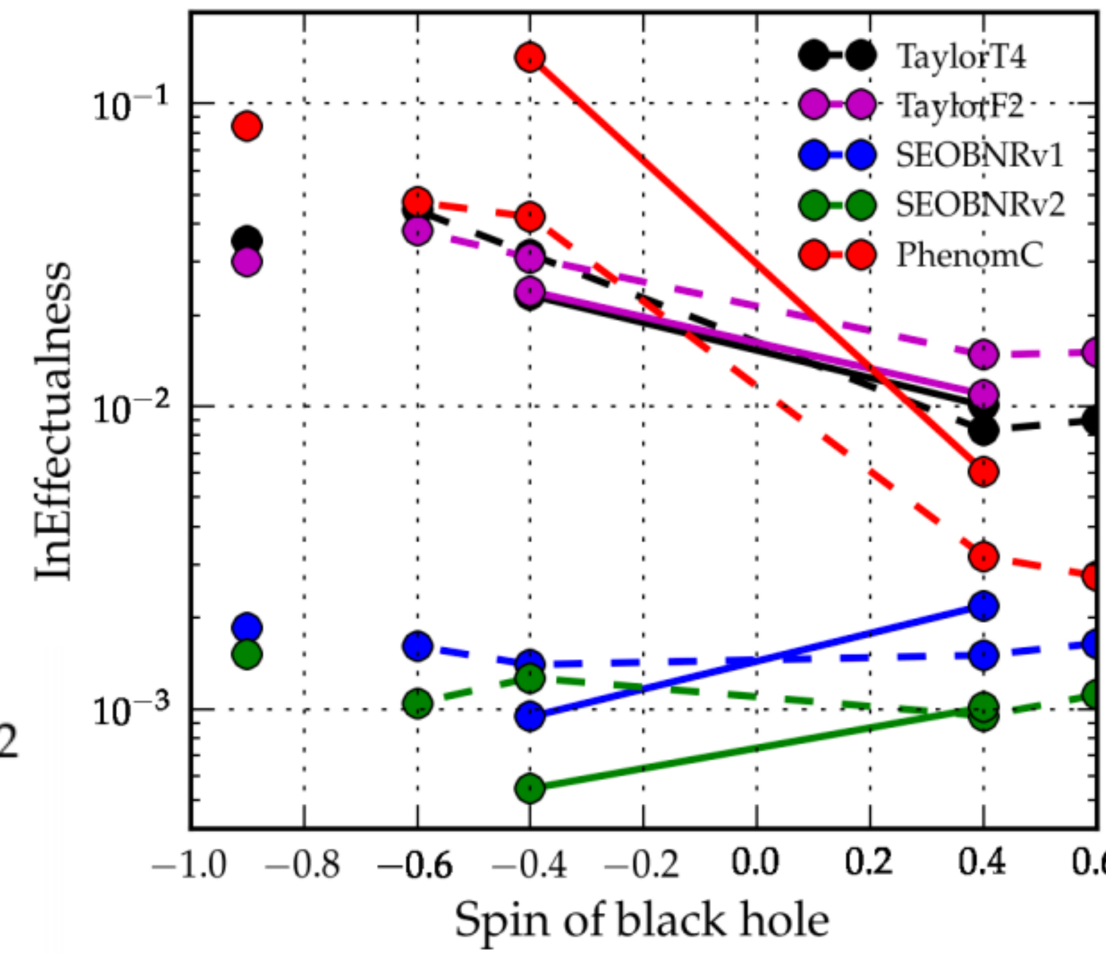
q = MBH/MNS = 6



Nondisruptive BHNS require accurate BBH inspiral-merger-ringdown waveform models

Kumar et al 1507.00103
Match and template-bank effectualness of BBH waveform models for high mass-ratio NSBH

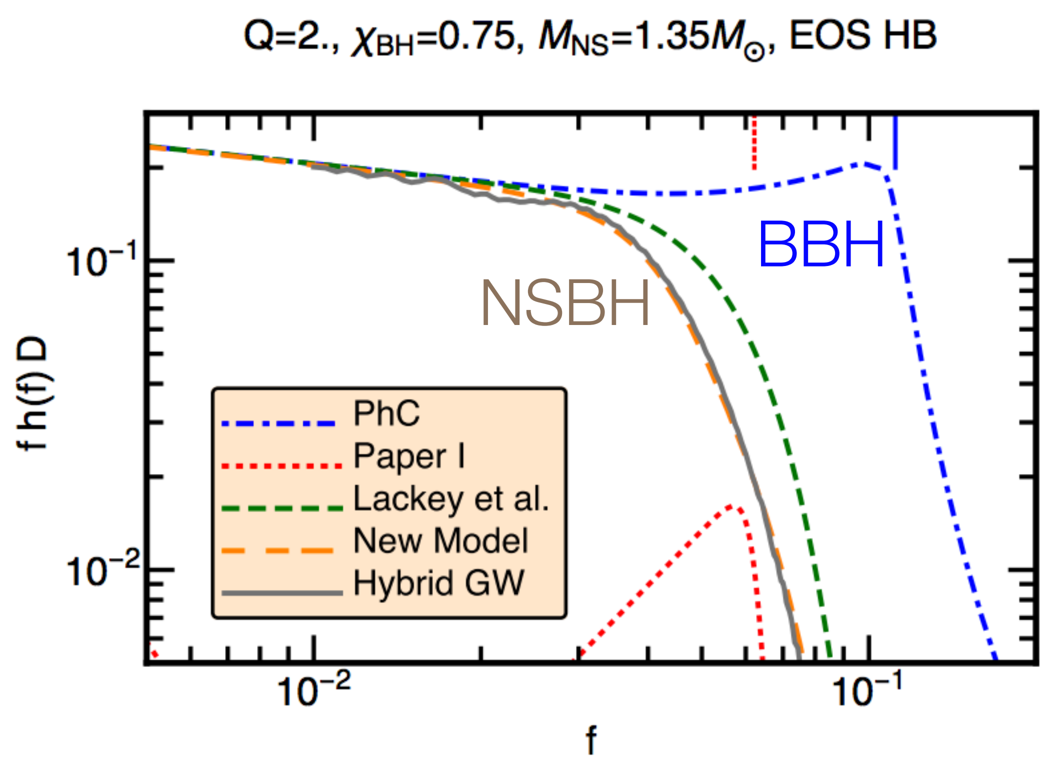




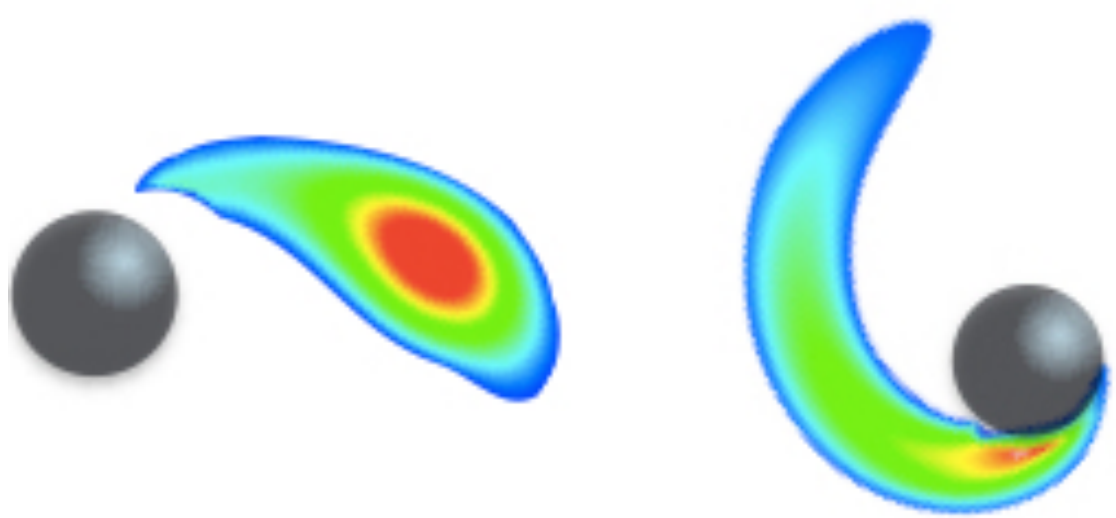
Parameter space challenges:

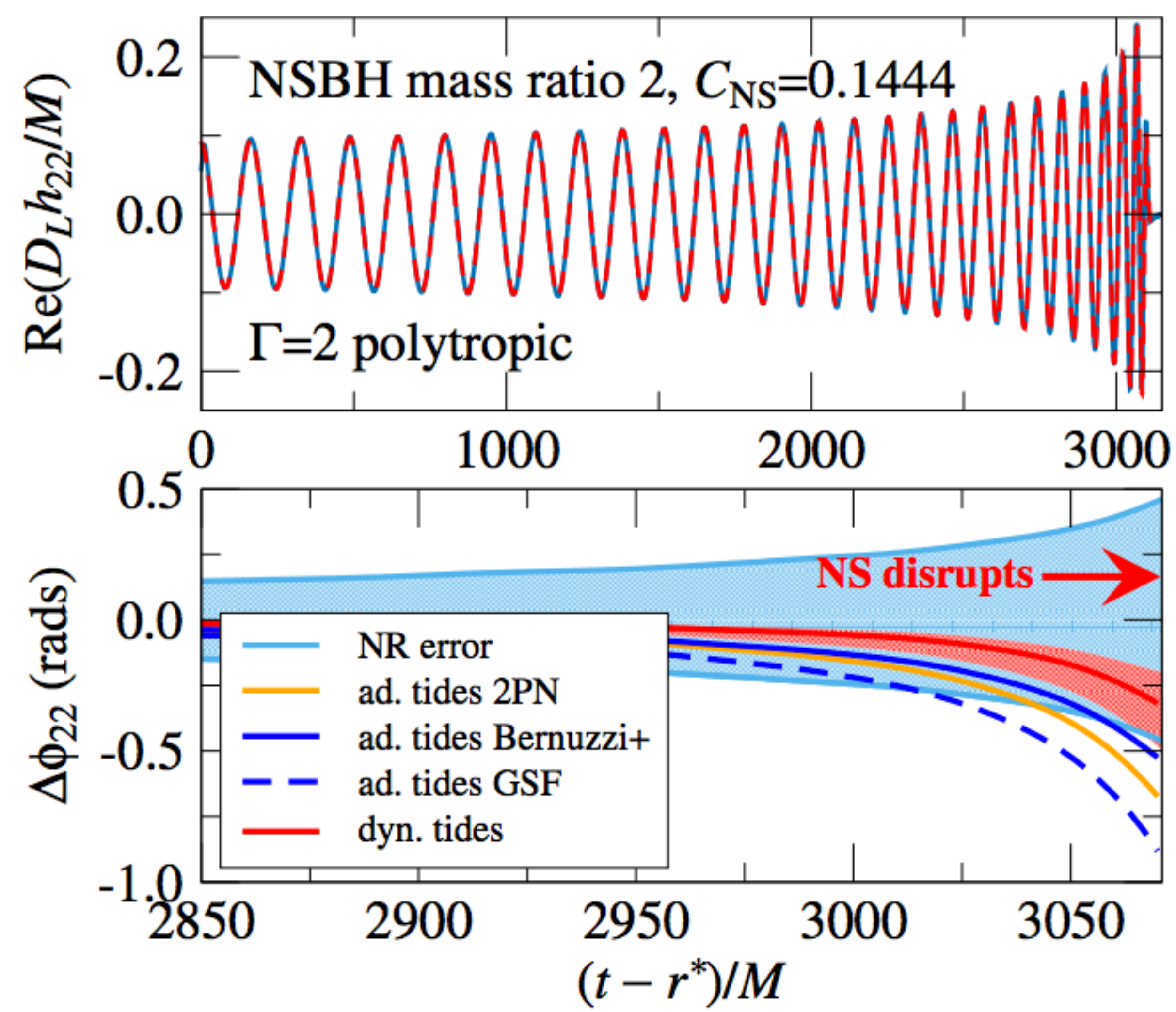
- Possible high-spin BH
- High mass ratio

Disruptive NSBH: waveform models



Phenomenological NSBH waveform from hybrid fits Pannarale et al 1509.00512





EOB+ higher order NSBH Hinderer et al 1602.00599

Are we ready for matter?

- Sophisticated waveform models incorporating matter are becoming available and steadily being improved:
  - Rely on closed-form (early) inspiral and numerical merger
  - Variant EOB models, phenomenological models for binary neutron star mergers
  - Tidal resonant EOB and phenomenological models for disruptive NSBH mergers
- Bust follow-up can constrain NS EOS from post-merger
  - How to optimally combine pre/post merger information?
- Careful assessment of systematic error is ongoing!

Extra slides

Implications of non-detection: rate constraint

- No candidates have low-mass components (Upper limits on BNS and NSBH mergers https://arxiv.org/abs/1607.07456)

Implications of non-detection: rate constraint

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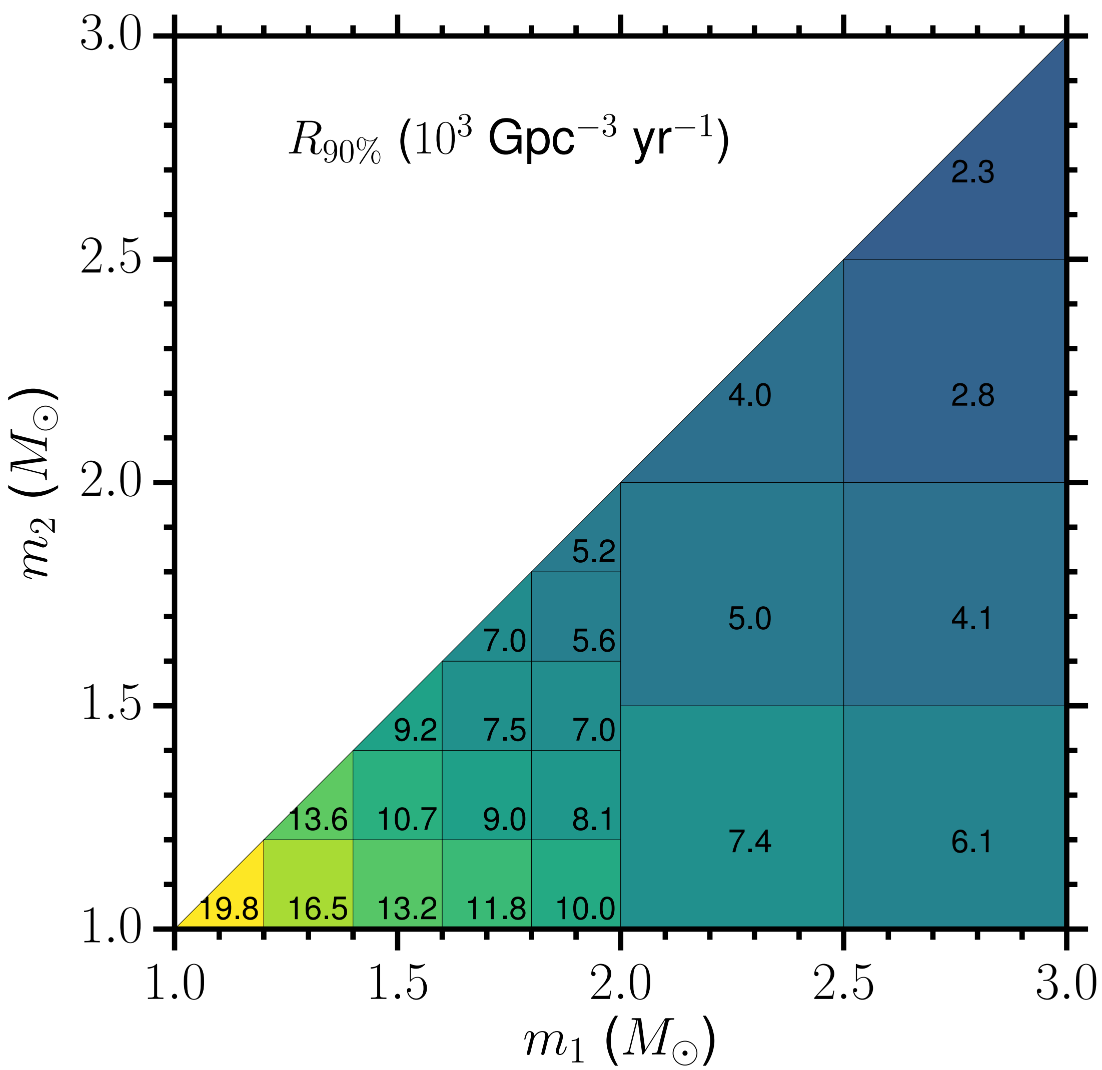
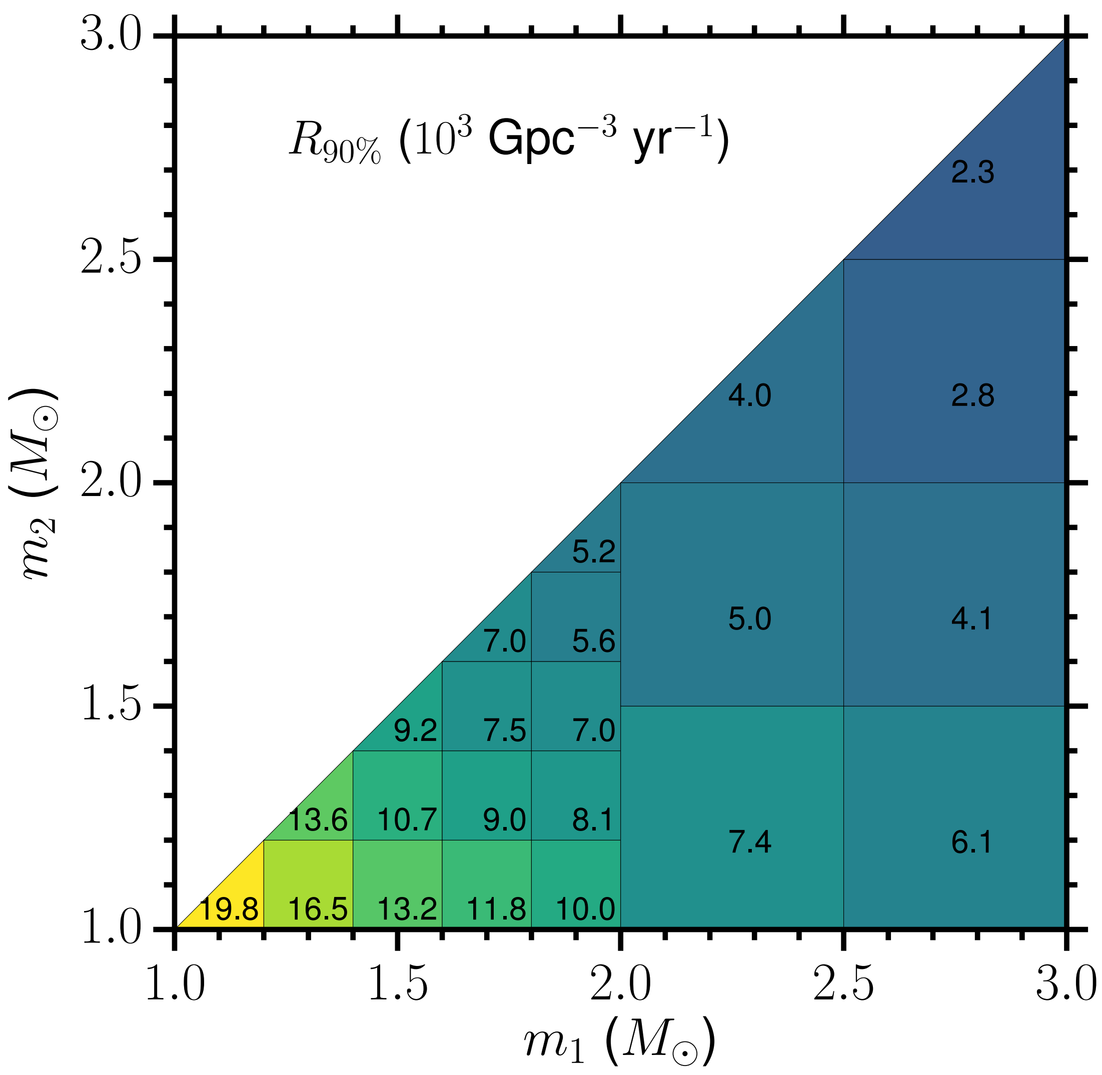
[1,3] $M_\odot$ neutron stars



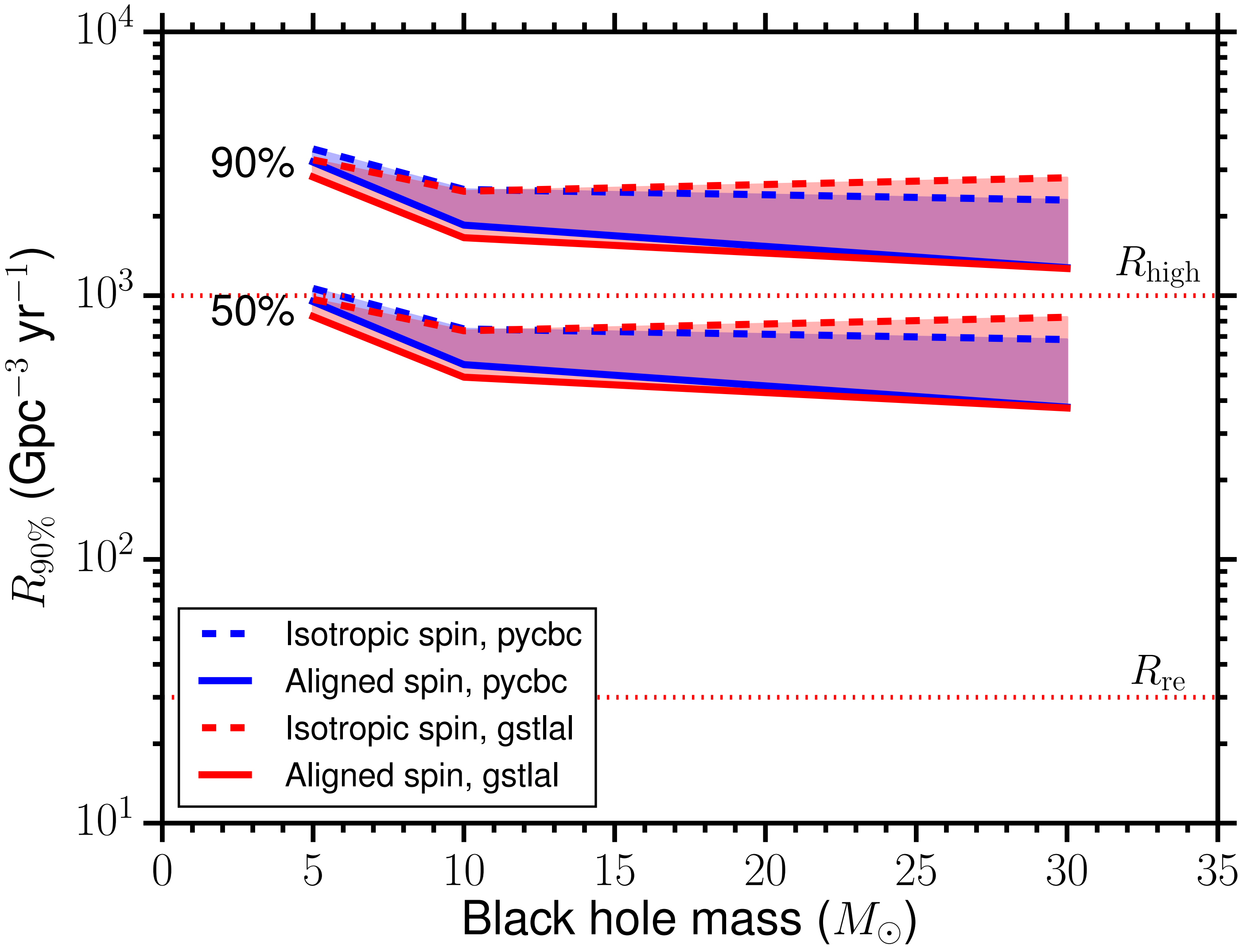
Implications of non-detection: rate constraint

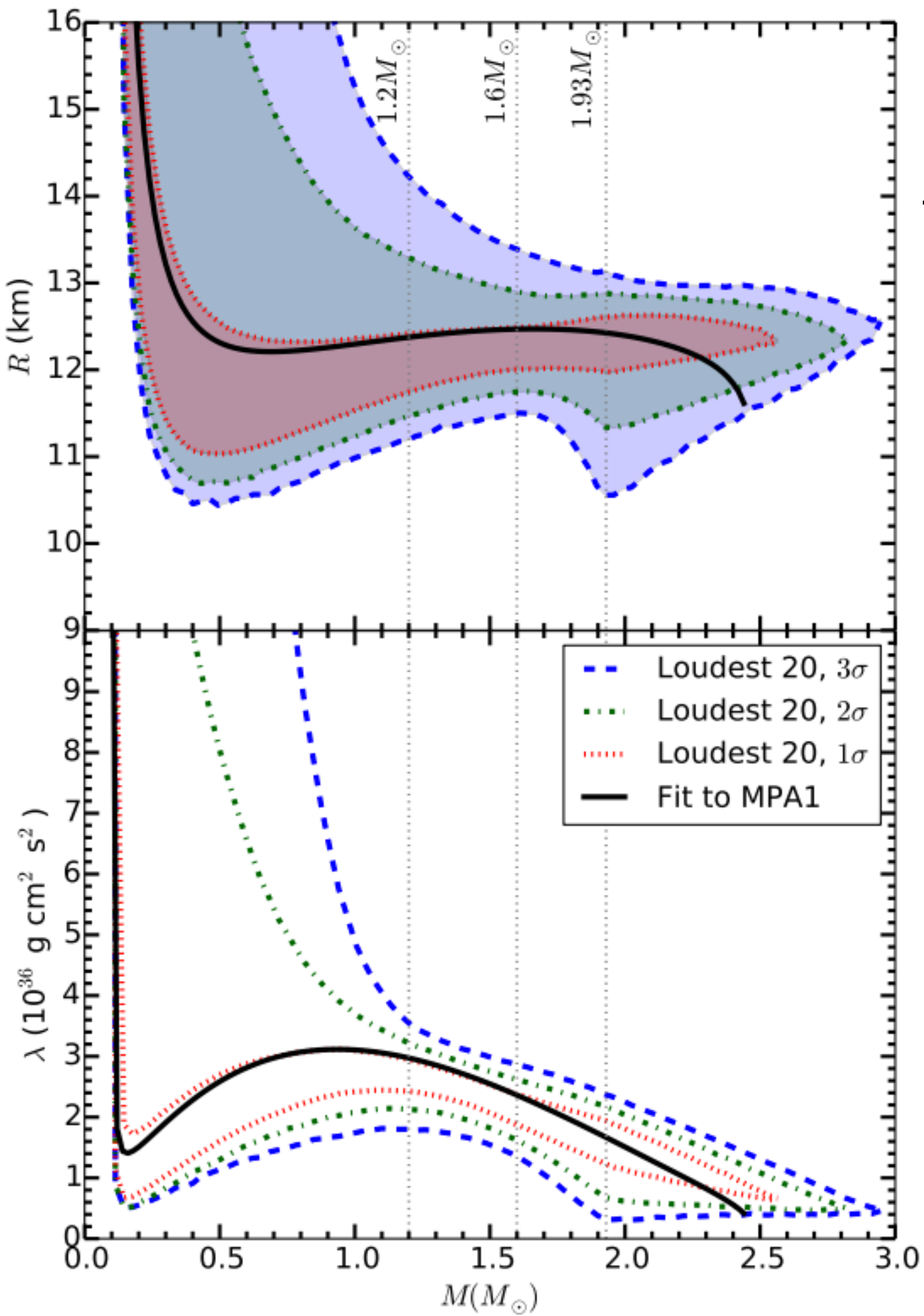
- No candidates have low-mass components (Upper limits on BNS and NSBH mergers https://arxiv.org/abs/1607.07456)

[1,3] M⊙ neutron stars



Black holes and 1.4 M⊙ neutron stars





Lackey and Wade (40 signals)

http://arxiv.org/abs/1410.8866