



Neutron stars: gravitational-wave sources with matter

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Amaldi 2017





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

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- 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?

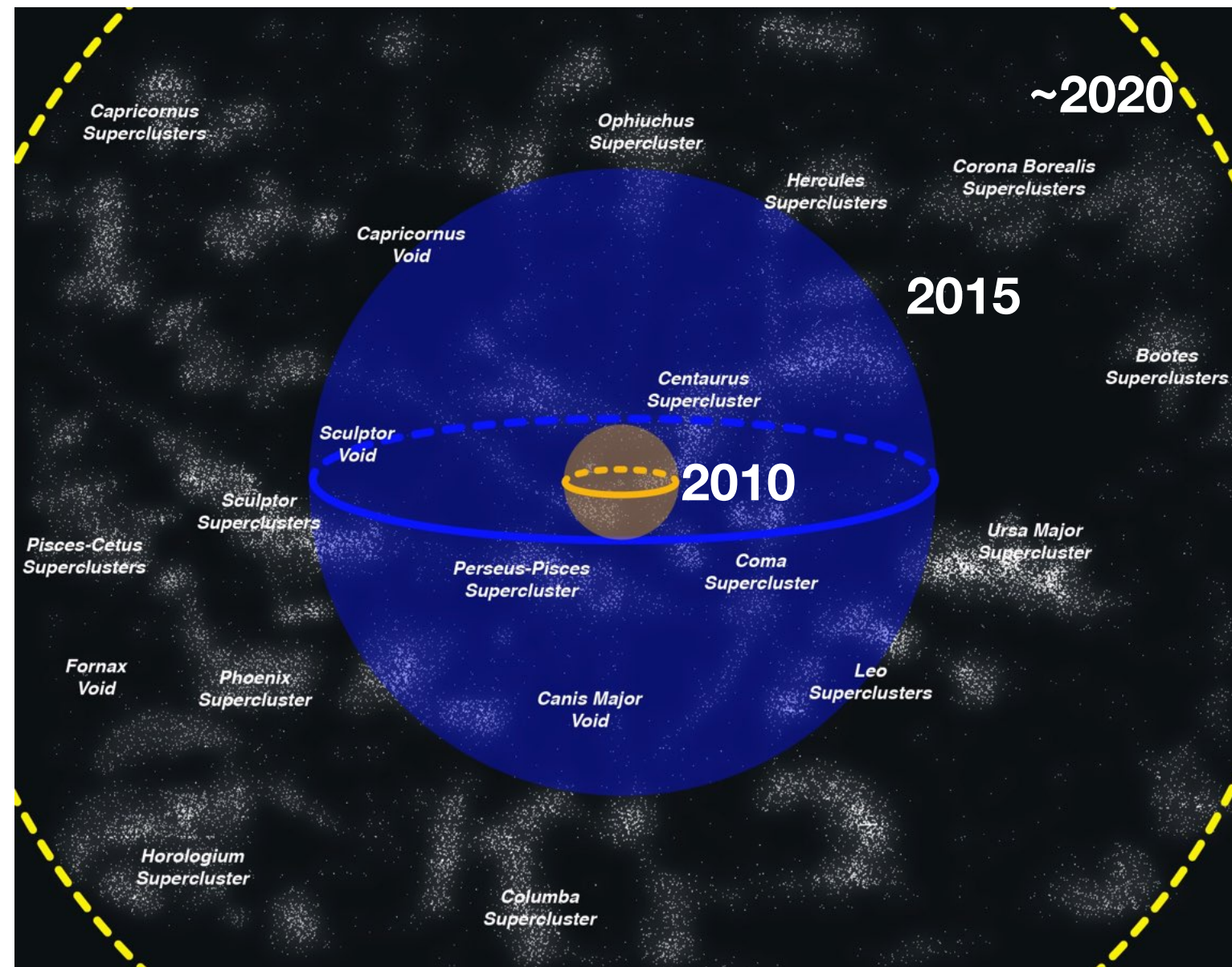
How well do we understand the matter has on other statements from LIGO CBC searches and parameter estimation?

Detection prospects of Advanced LIGO design

- binary neutron star mergers to ~ 200 Mpc
- neutron star–($10 M_{\text{sun}}$) black hole mergers to ~ 0.5 Gpc
- ($10-10 M_{\text{sun}}$) 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 $0.4 - 400 \text{ yr}^{-1}$

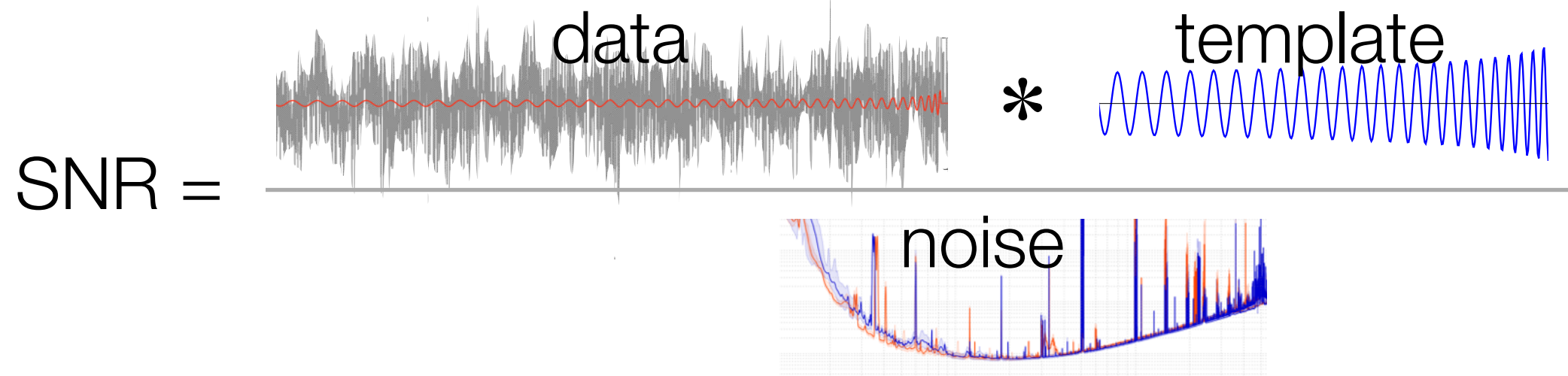
NSBH expected $0.2 - 300 \text{ yr}^{-1}$

LSC/Virgo 1003.2480

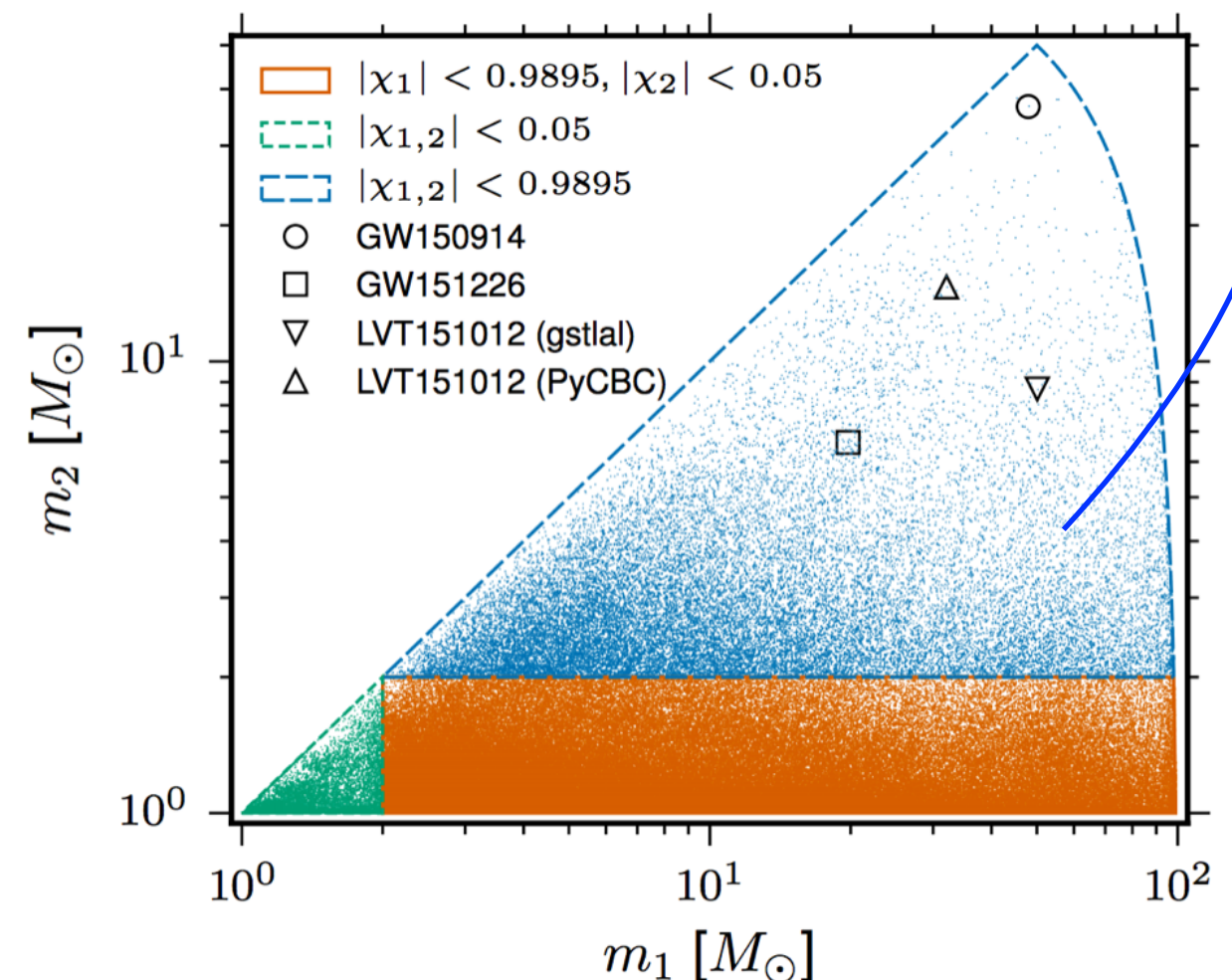
BBH expected $9 - 240 \text{ Gpc}^{-3} \text{ yr}^{-1}$

LSC/Virgo 1606.04856

Matched-filter search for compact binary mergers



- 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



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

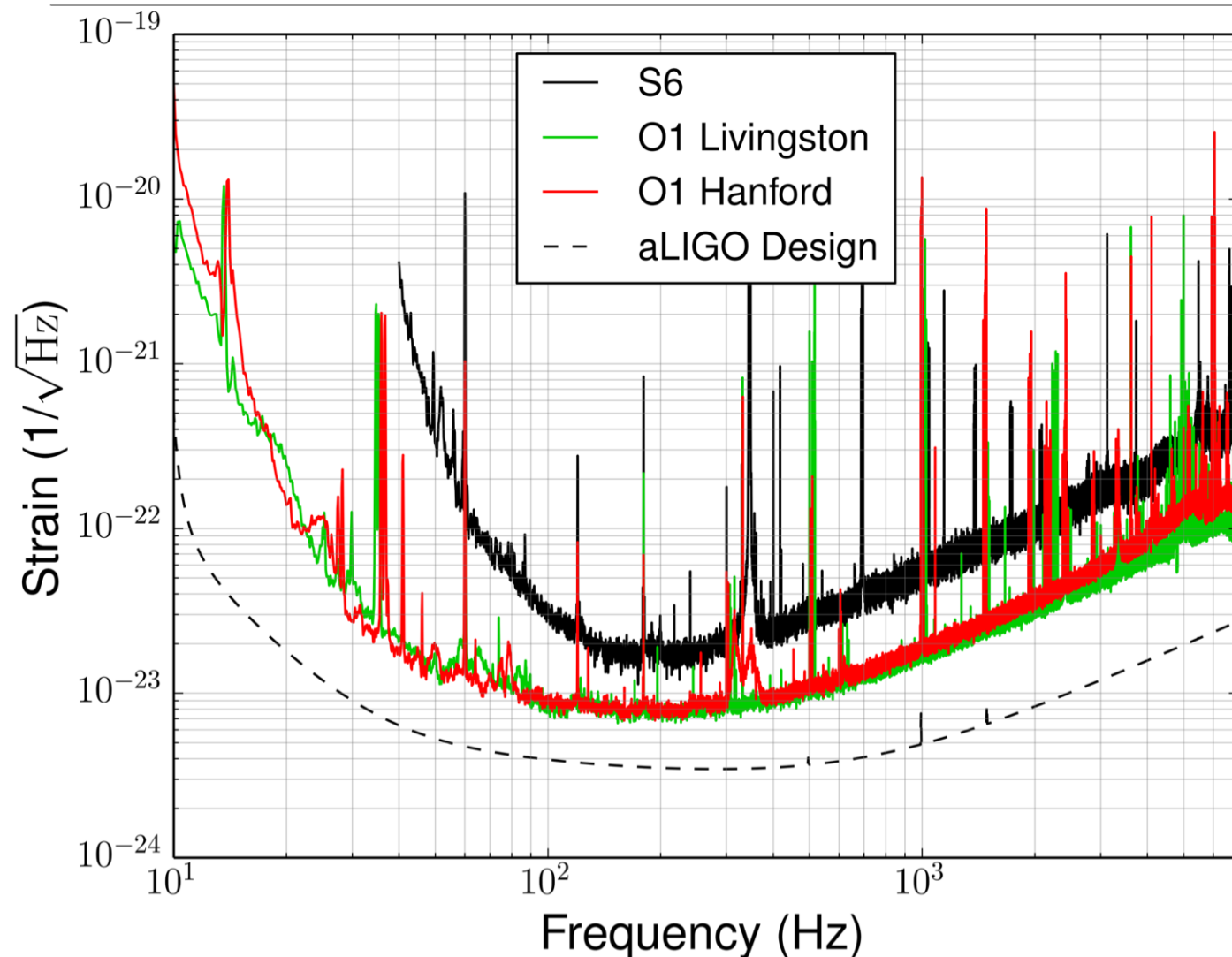


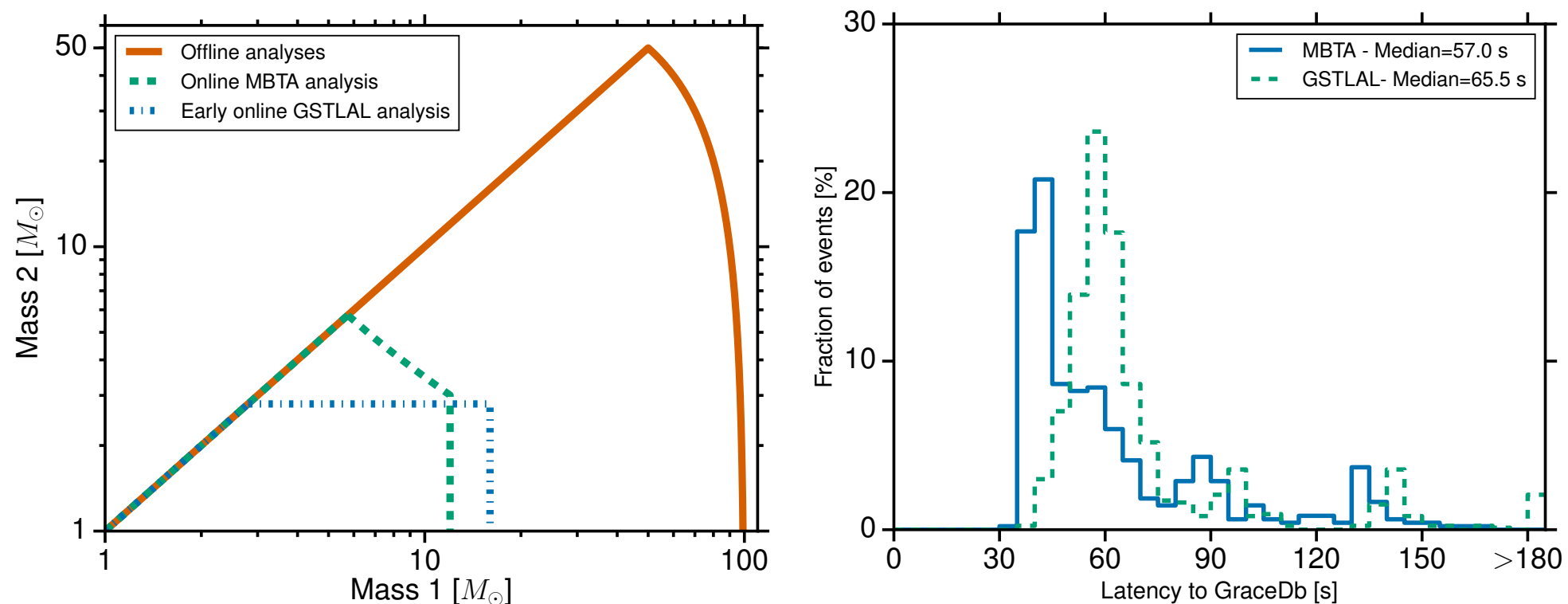
Figure by C. Messick

<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](https://arxiv.org/abs/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>)

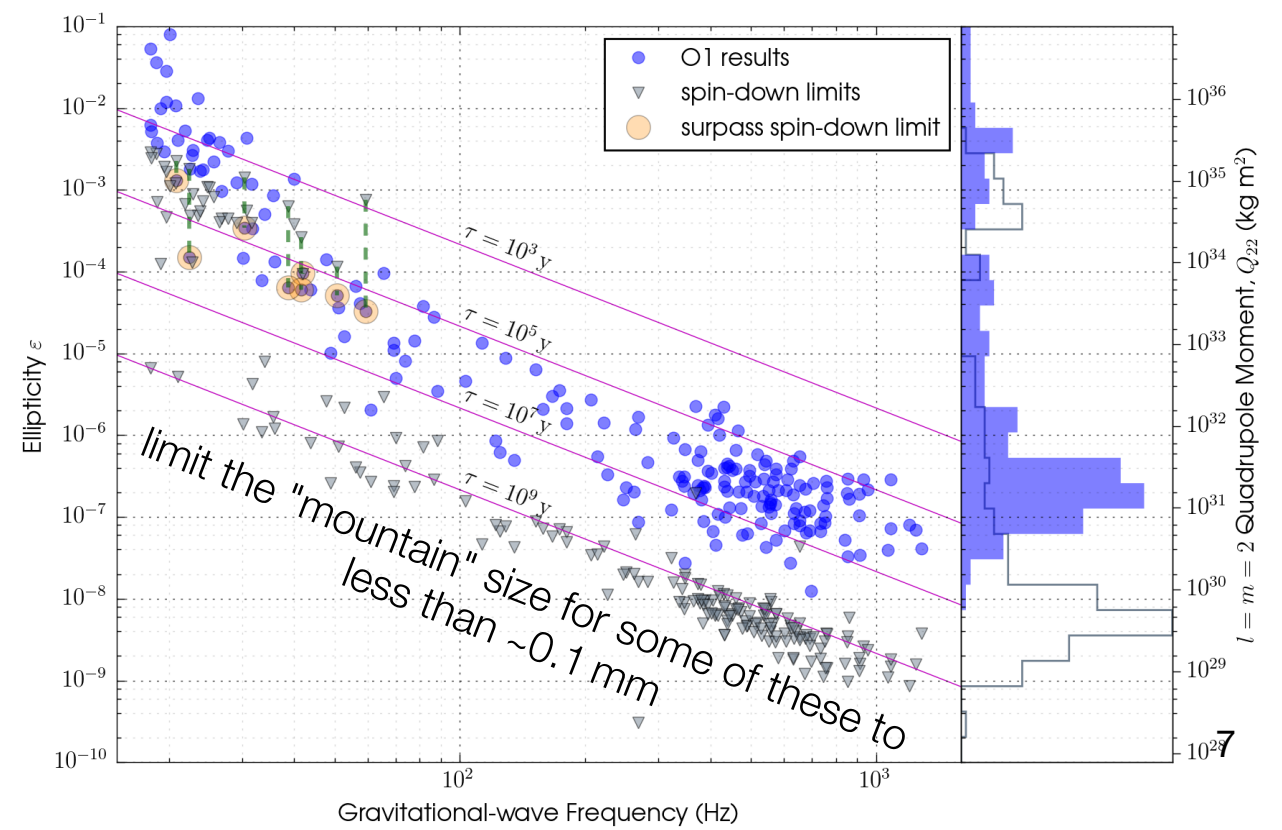
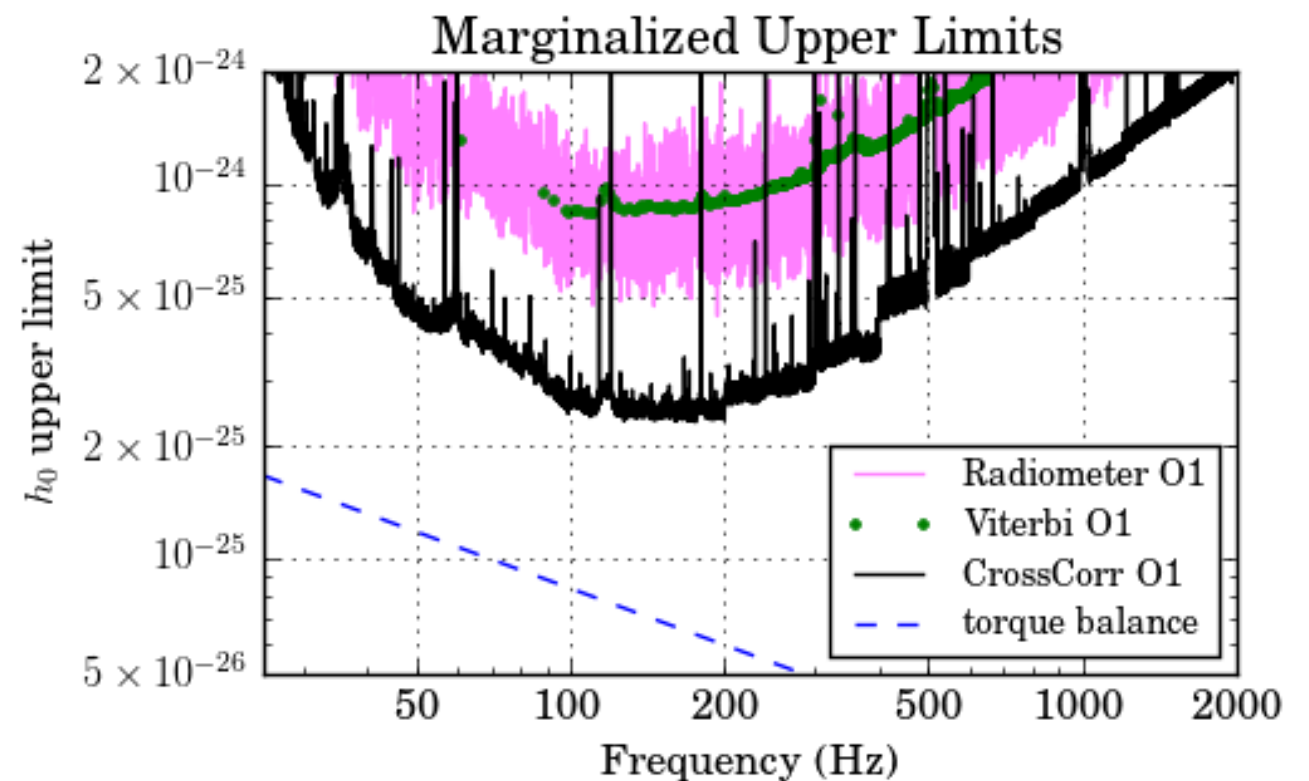
Neutron stars as continuous-wave sources: O1 upper limits

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



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

An unexpected lack of merging neutron stars?

Salpeter 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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Assume roughly the same
ratio of merger rates

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detection volume $\sim \text{SNR}^3$

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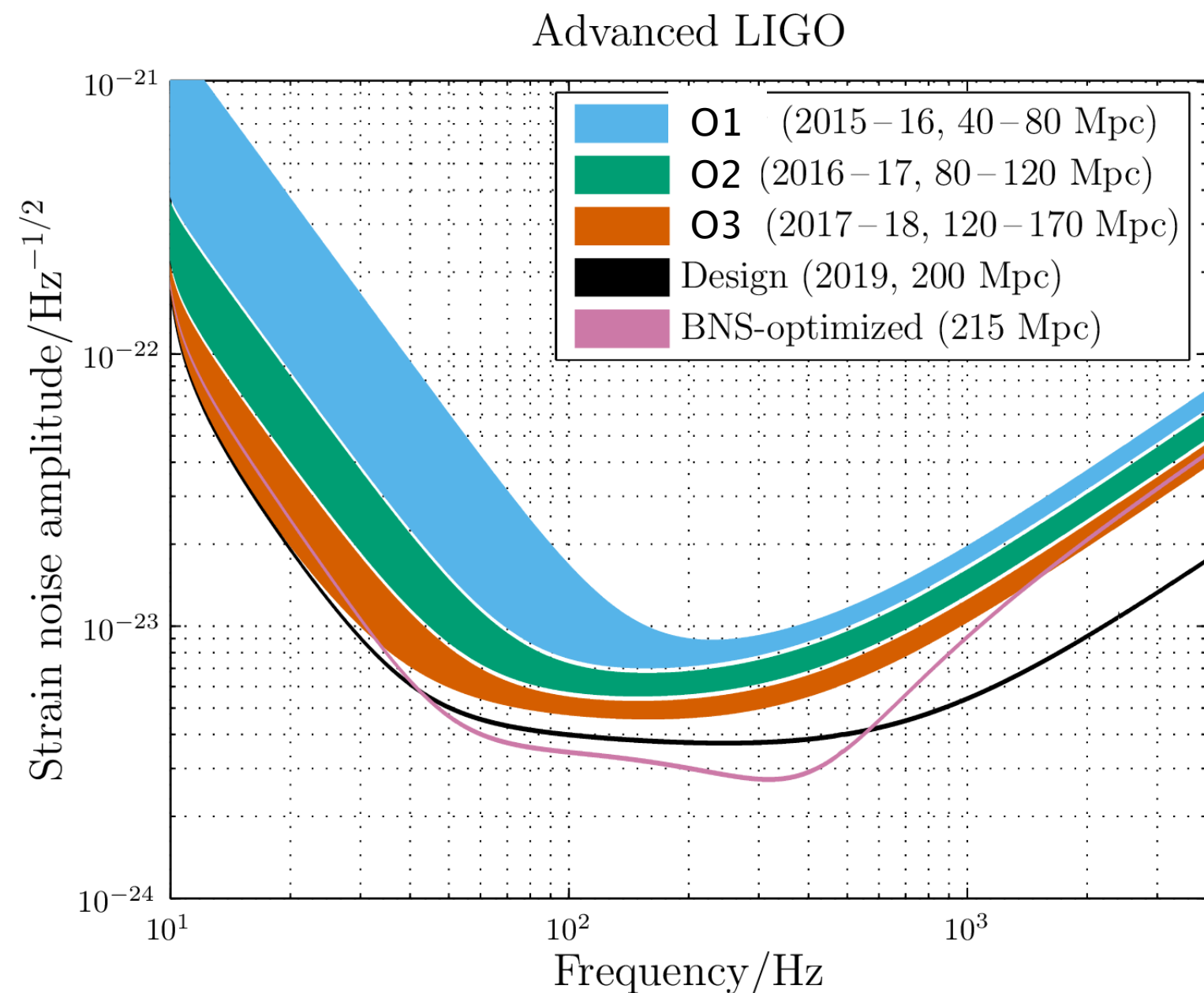
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“inspiraling binary black holes are likely to be detected first”

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

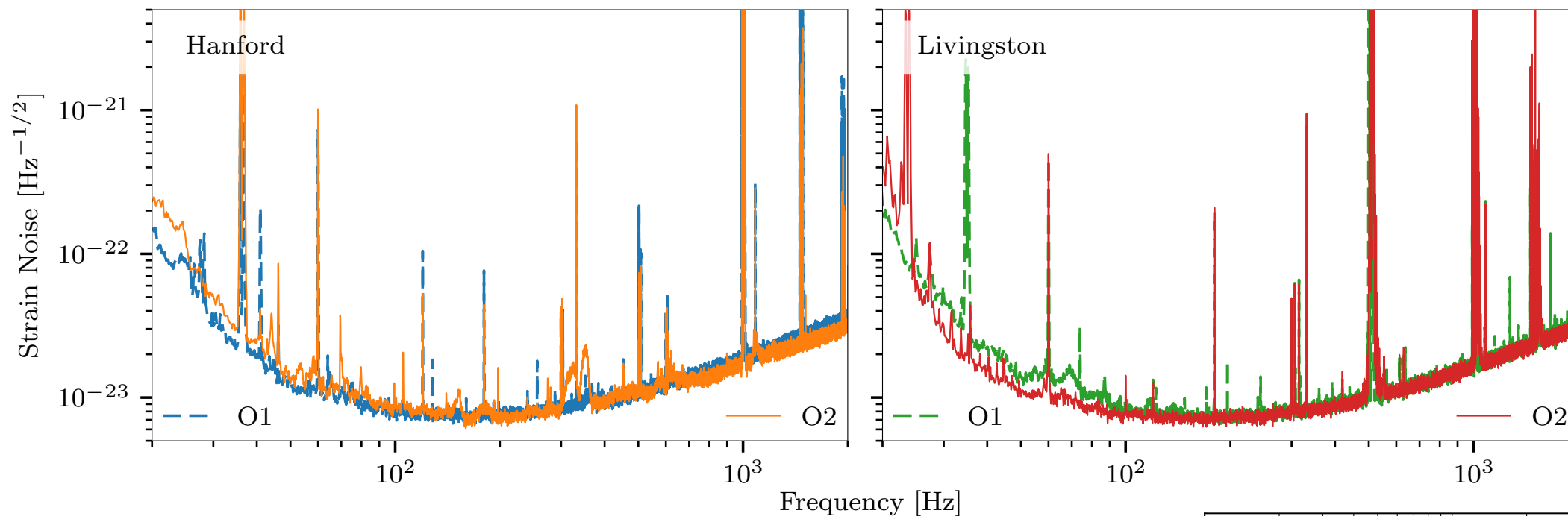
2016 Roadmap for observing neutron-star mergers



	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

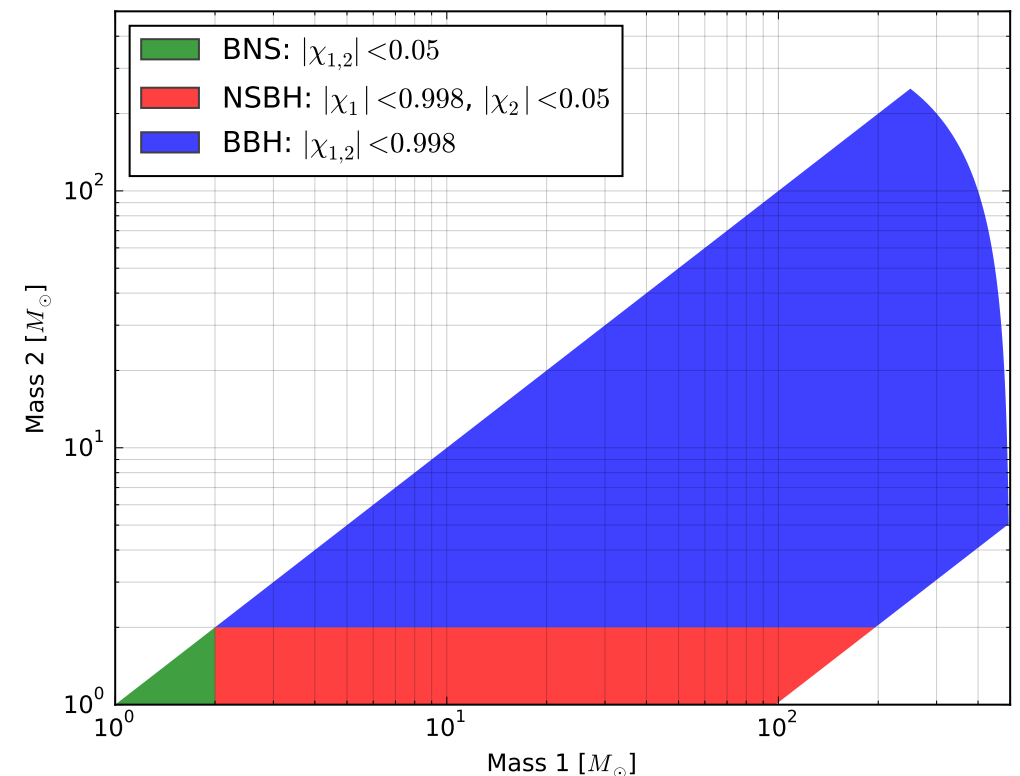
- LSC/Virgo Observing Scenarios <http://arxiv.org/abs/1304.0670>,
- Upper limits on the rates of binary neutron star and neutron-star-black-hole mergers from Advanced LIGO's first observing run <https://arxiv.org/abs/1607.07456>

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



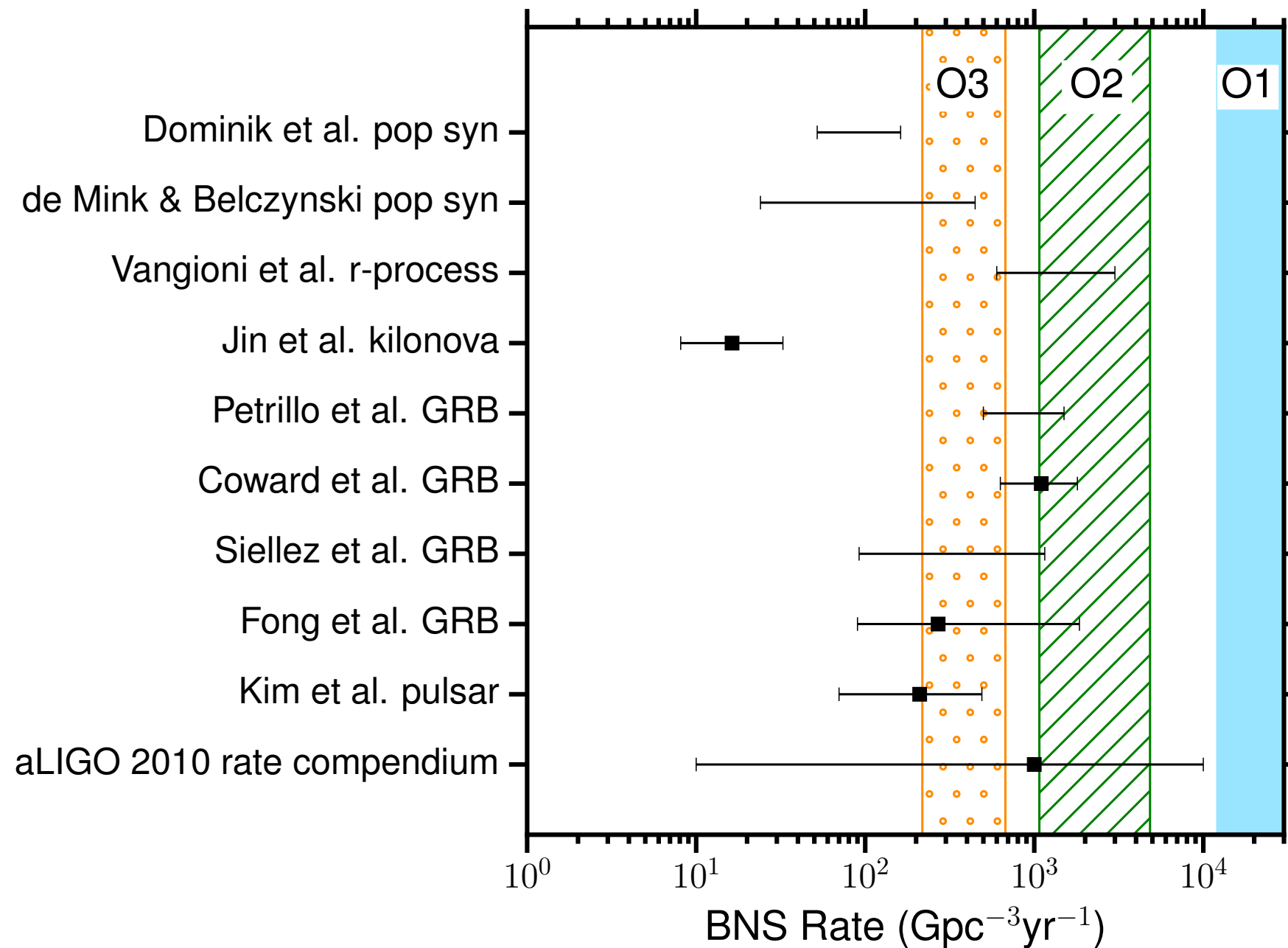
LSC/Virgo
“GW170104:
Observation of a
50-solar-mass
binary black hole
coalescence at
redshift 0.2”

- ~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.

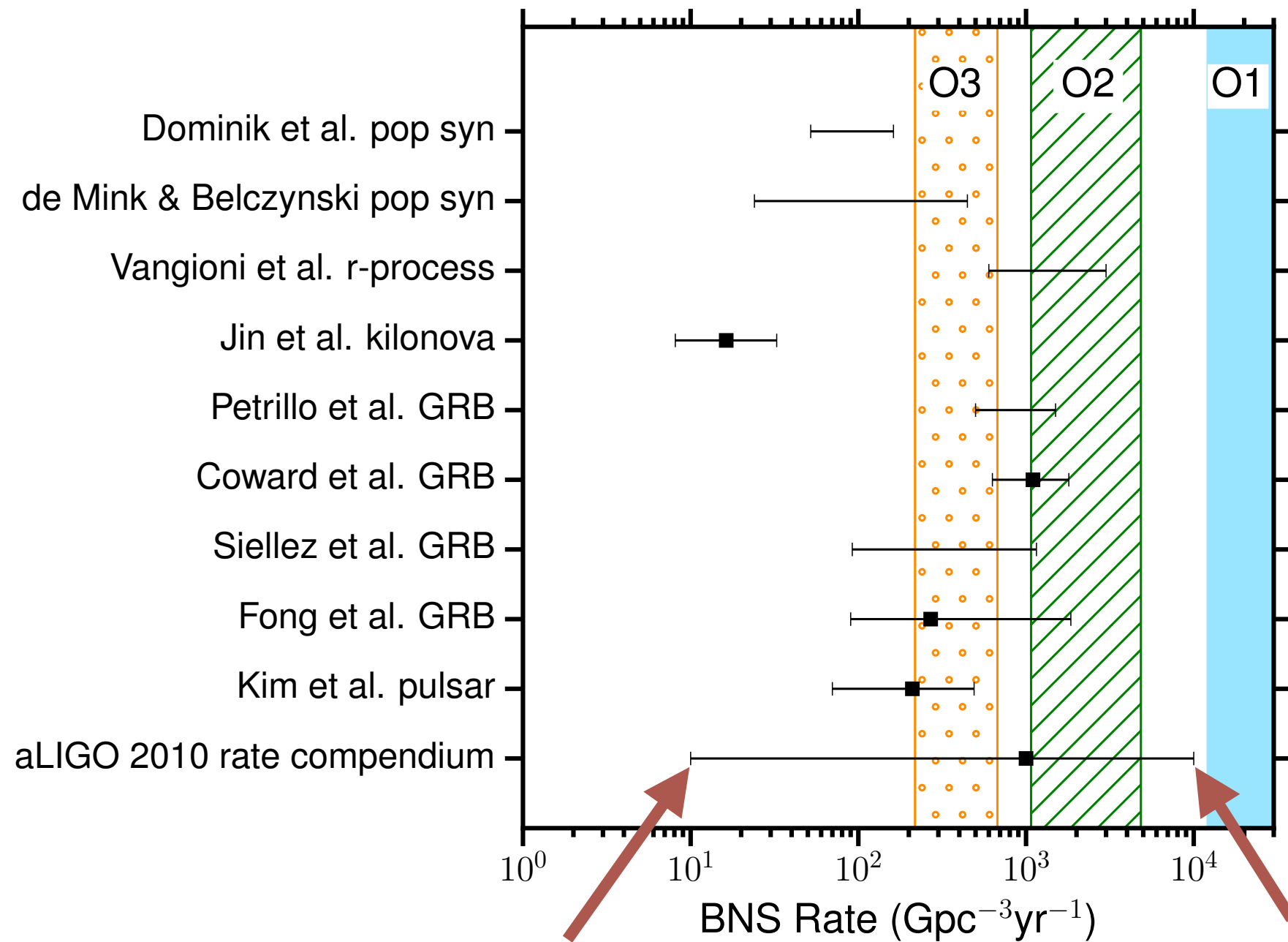


offline search template bank

O1 rate constraints and future expectations: binary neutron star mergers



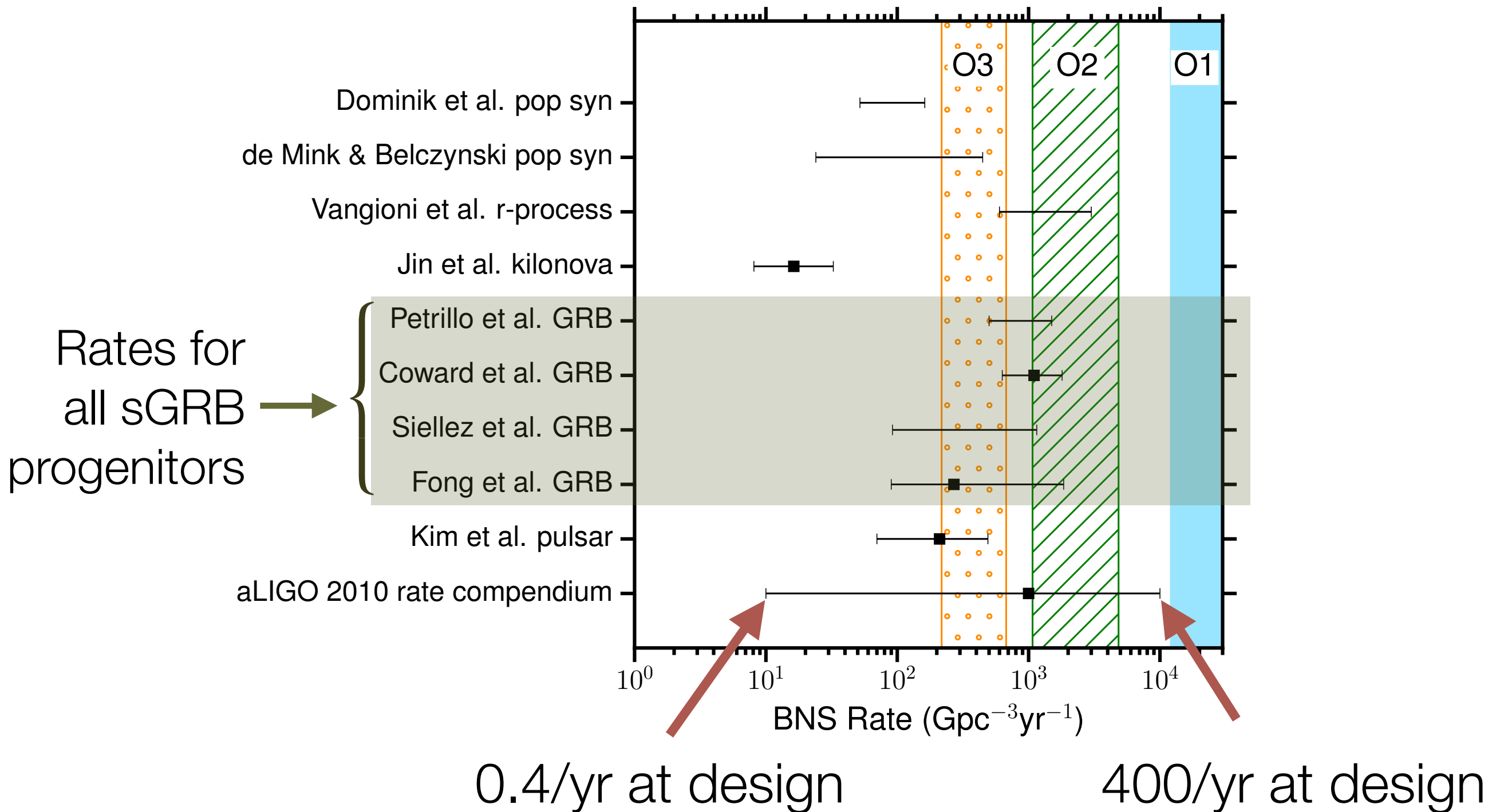
O1 rate constraints and future expectations: binary neutron star mergers



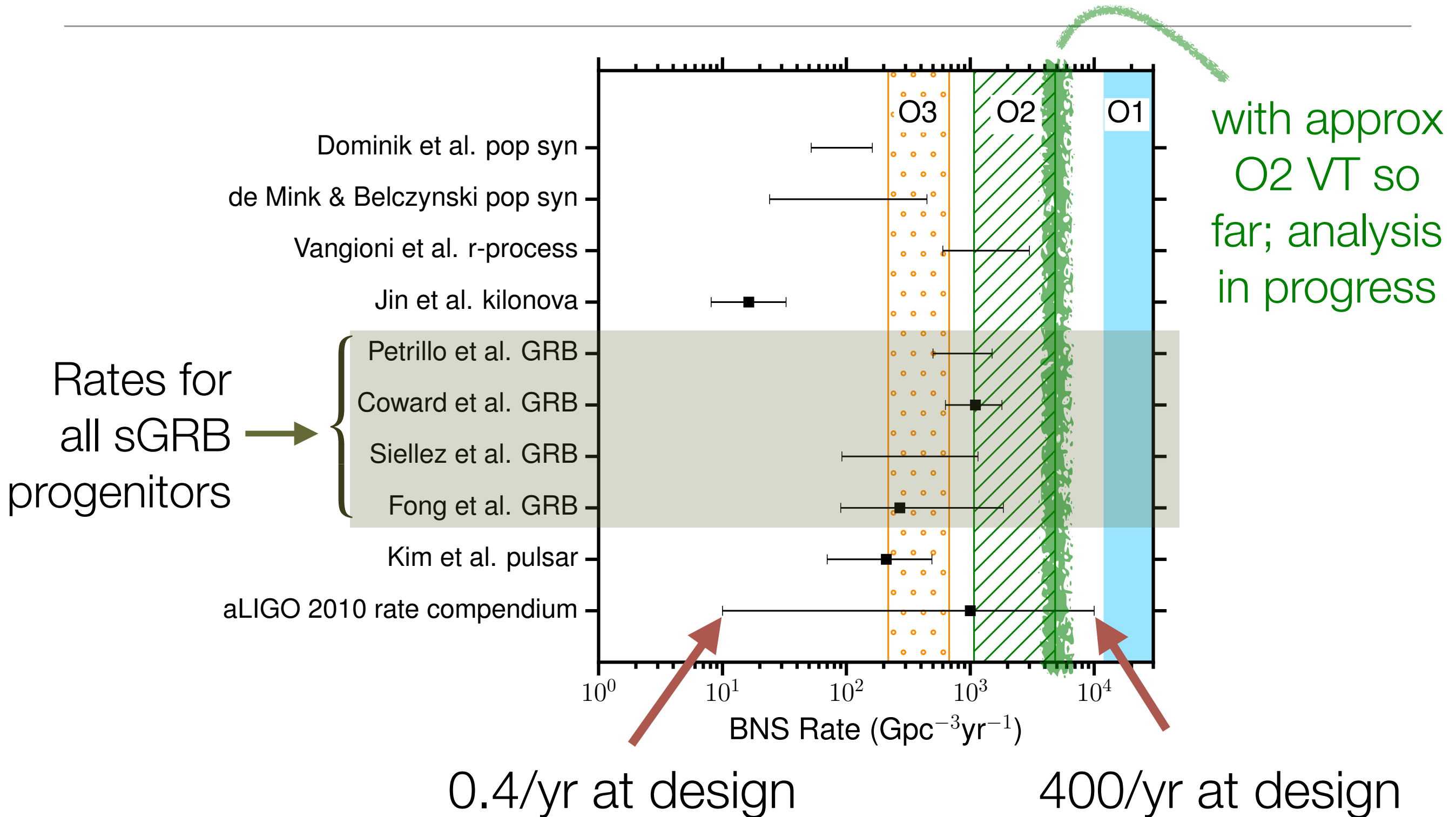
0.4/yr at design

400/yr at design

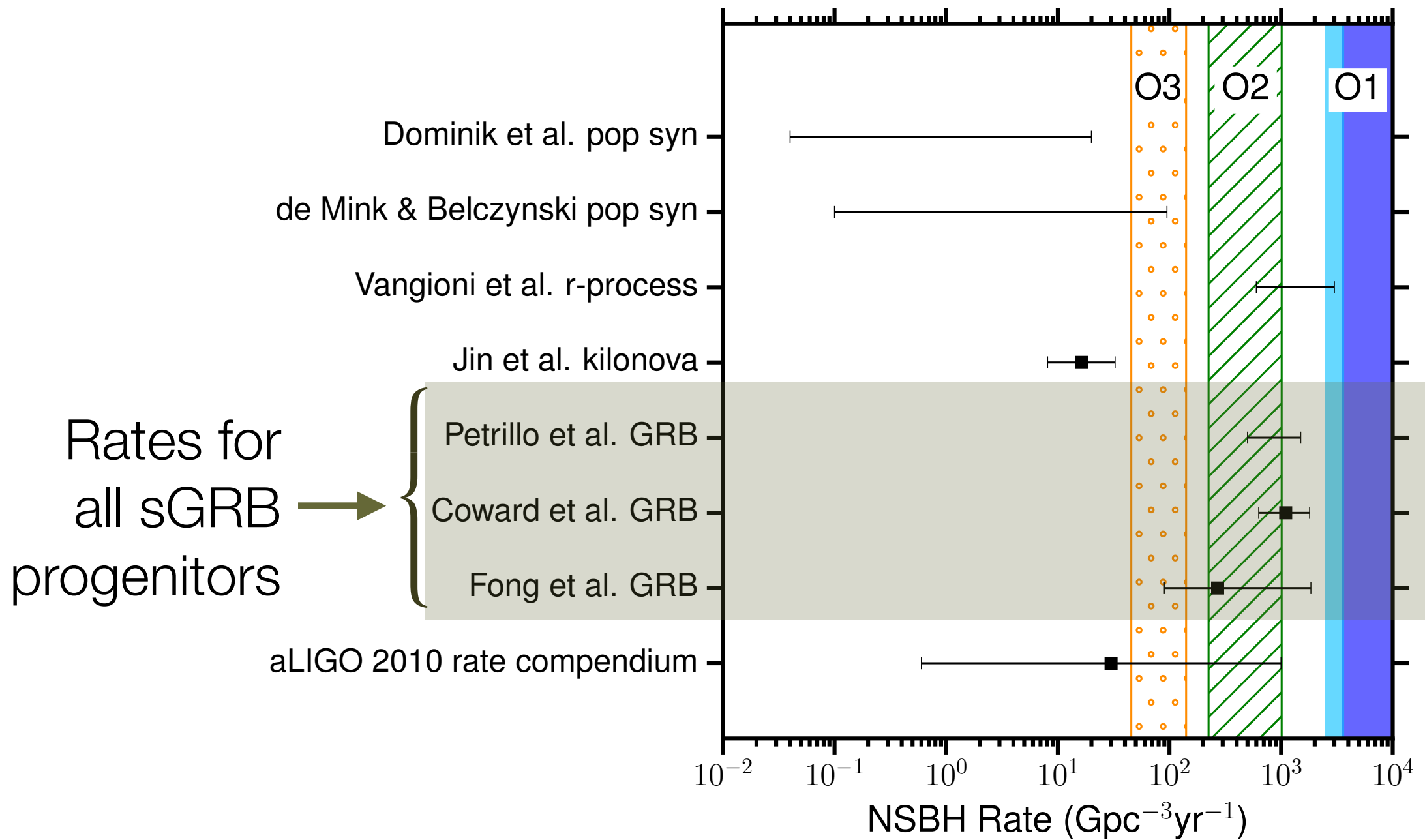
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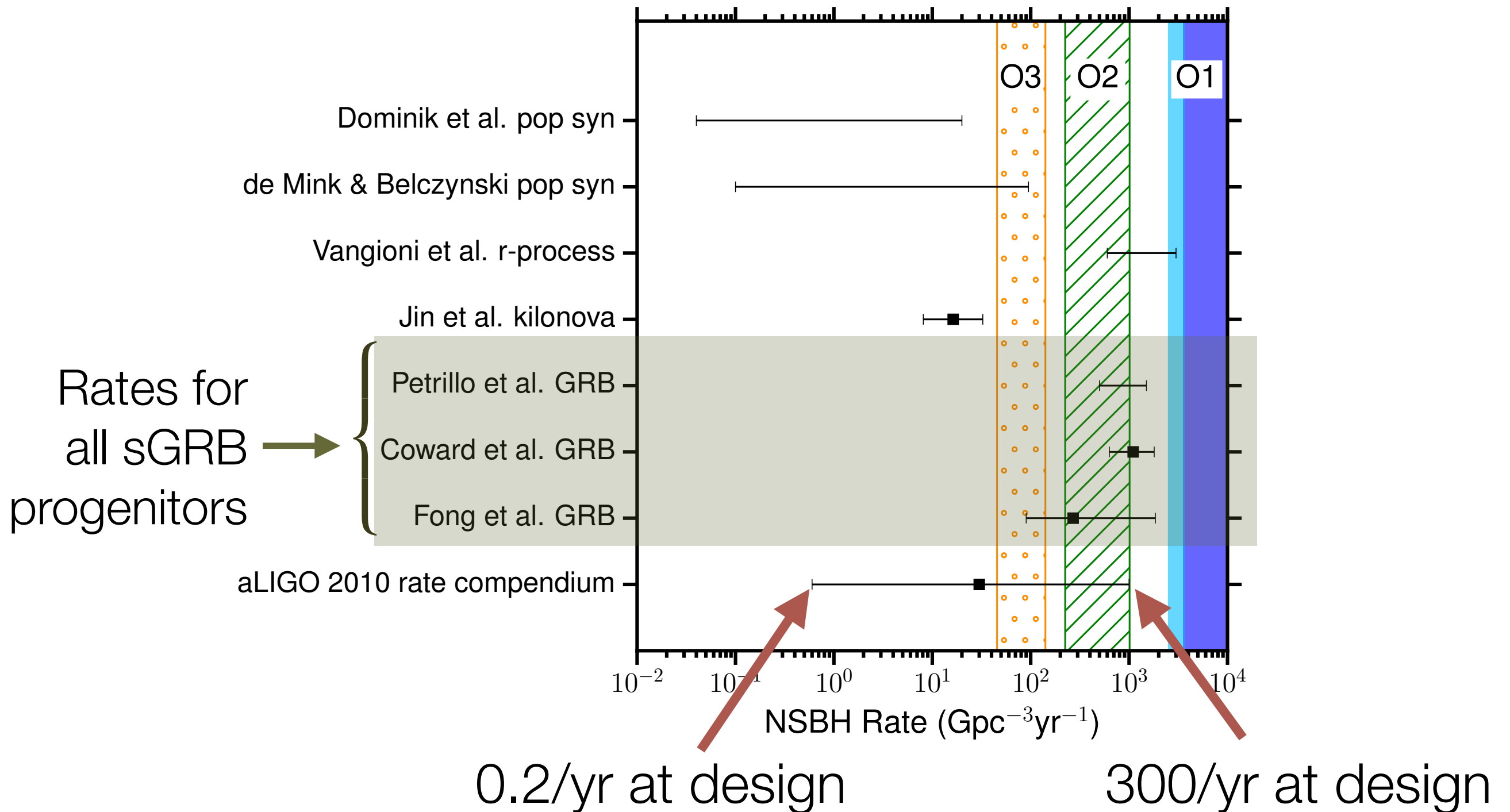
O1 rate constraints and future expectations: binary neutron star mergers



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

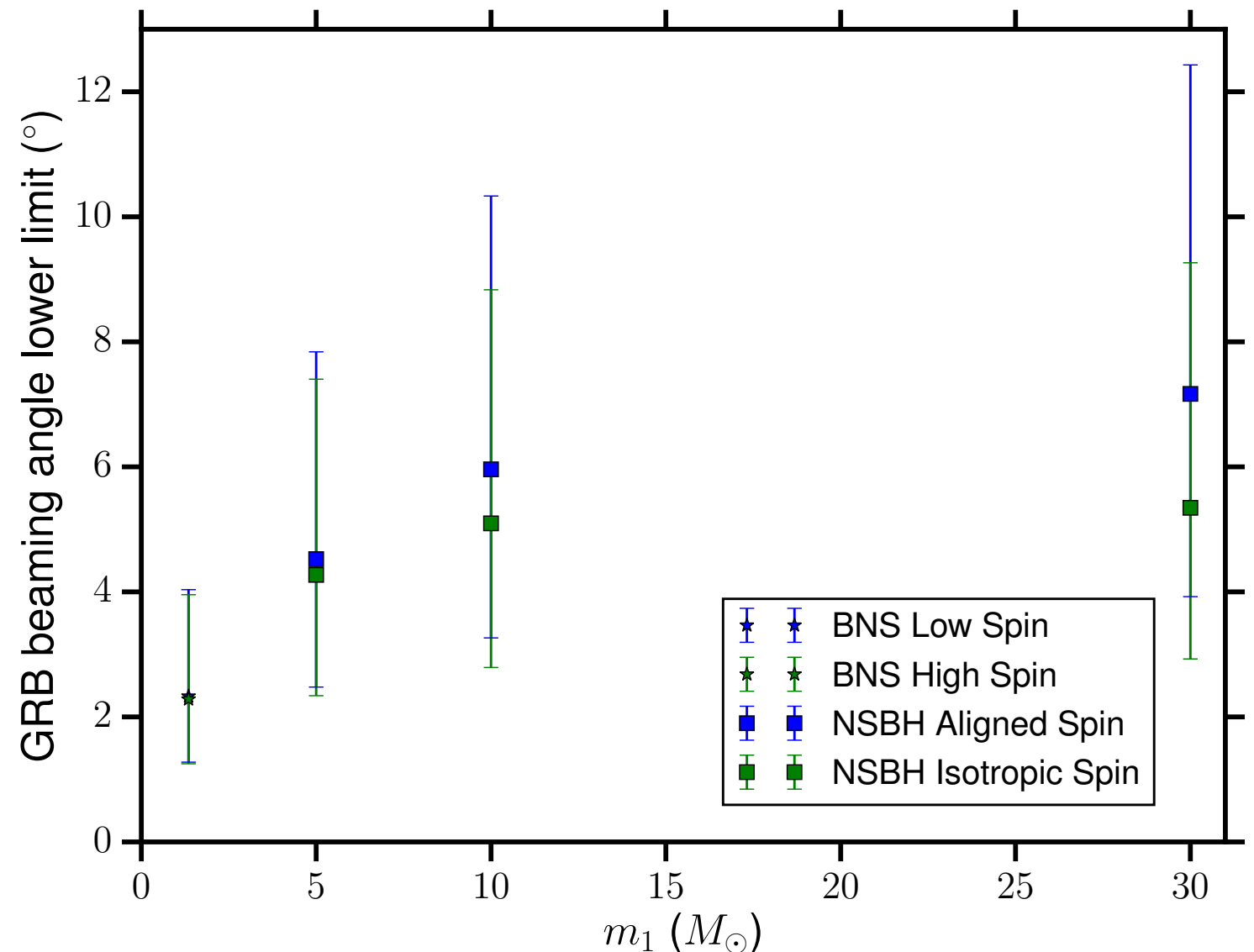


O1 rate constraints and future expectations: neutron-star/black-hole mergers

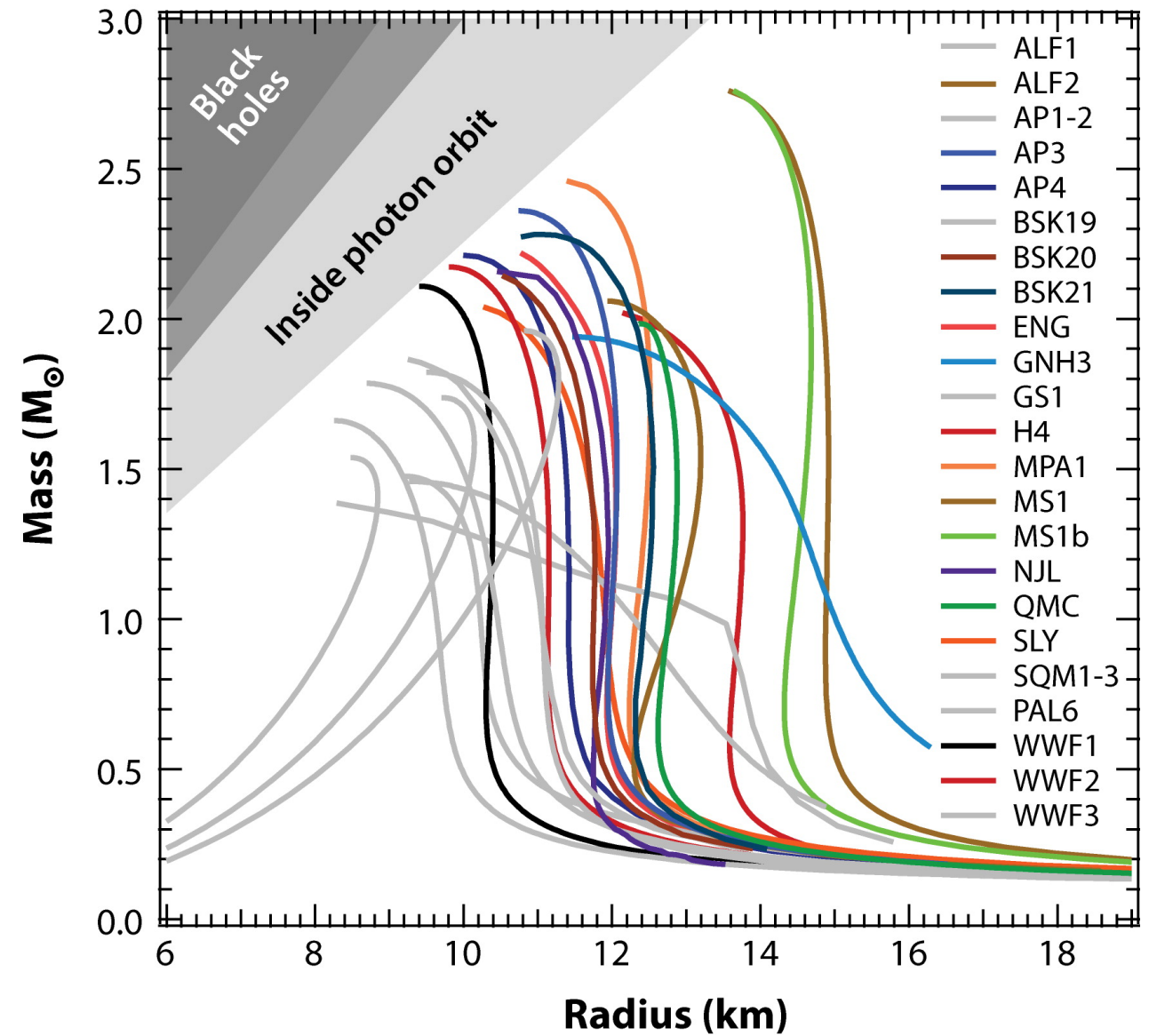
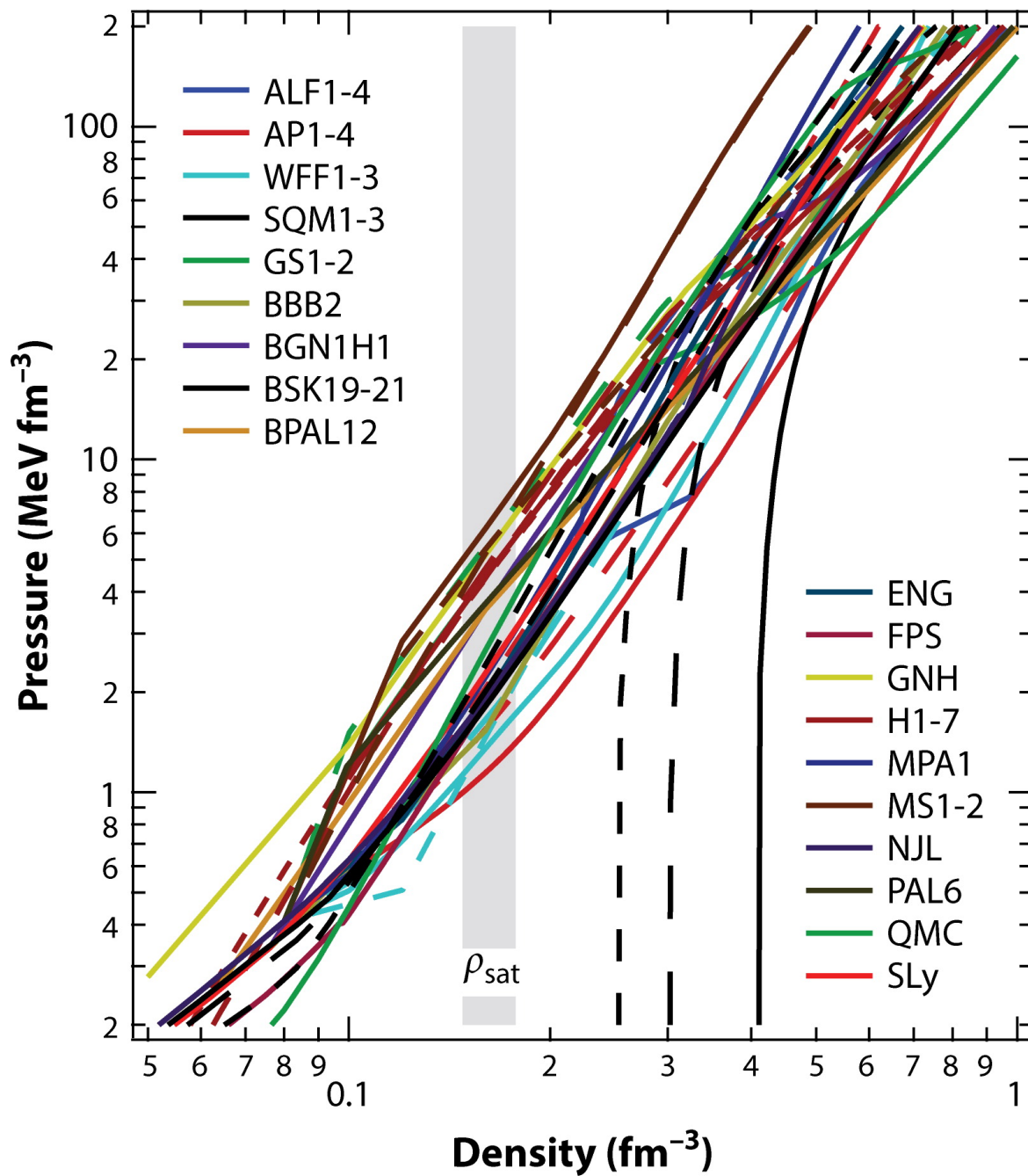


Advanced LIGO upper limits vs sGRB rates: gamma-ray burst beaming angle limit

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



Neutron-star matter



Özel F, Freire P. 2016.

Annu. Rev. Astron. Astrophys. 54:401–40

LIGO as an astrophysical-scale collider

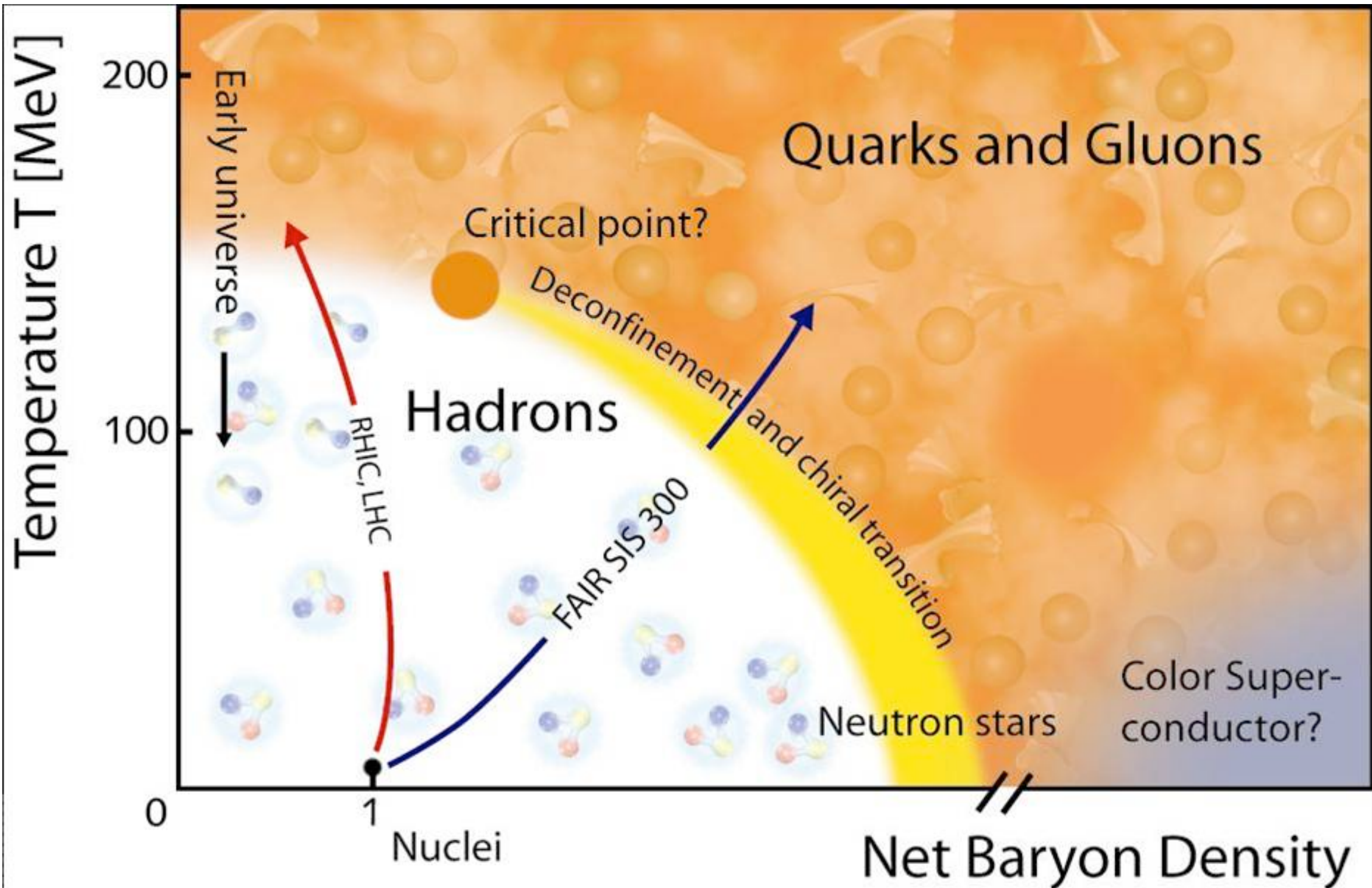


figure from FAIR CBM experiment

LIGO as an astrophysical-scale collider

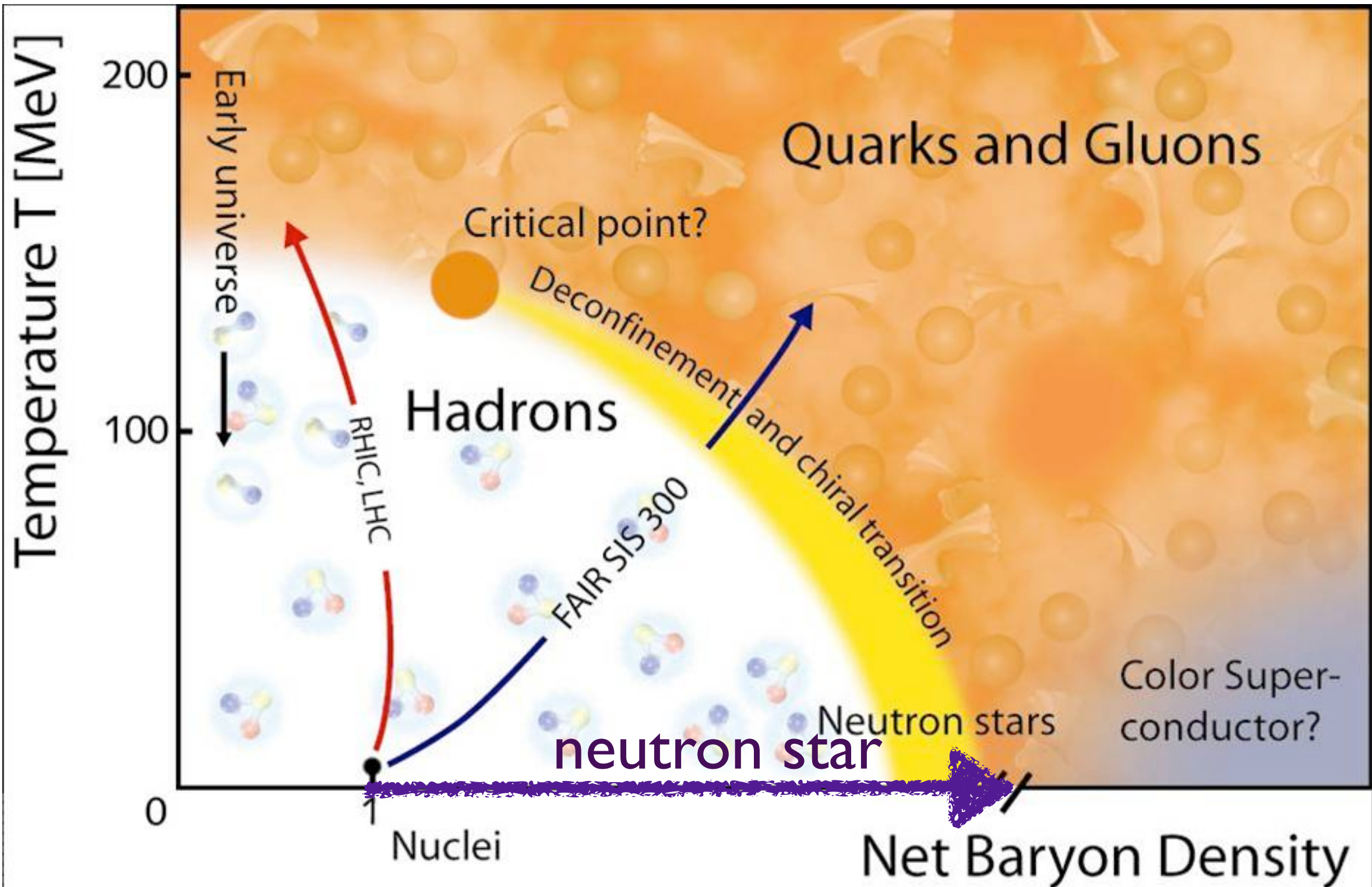


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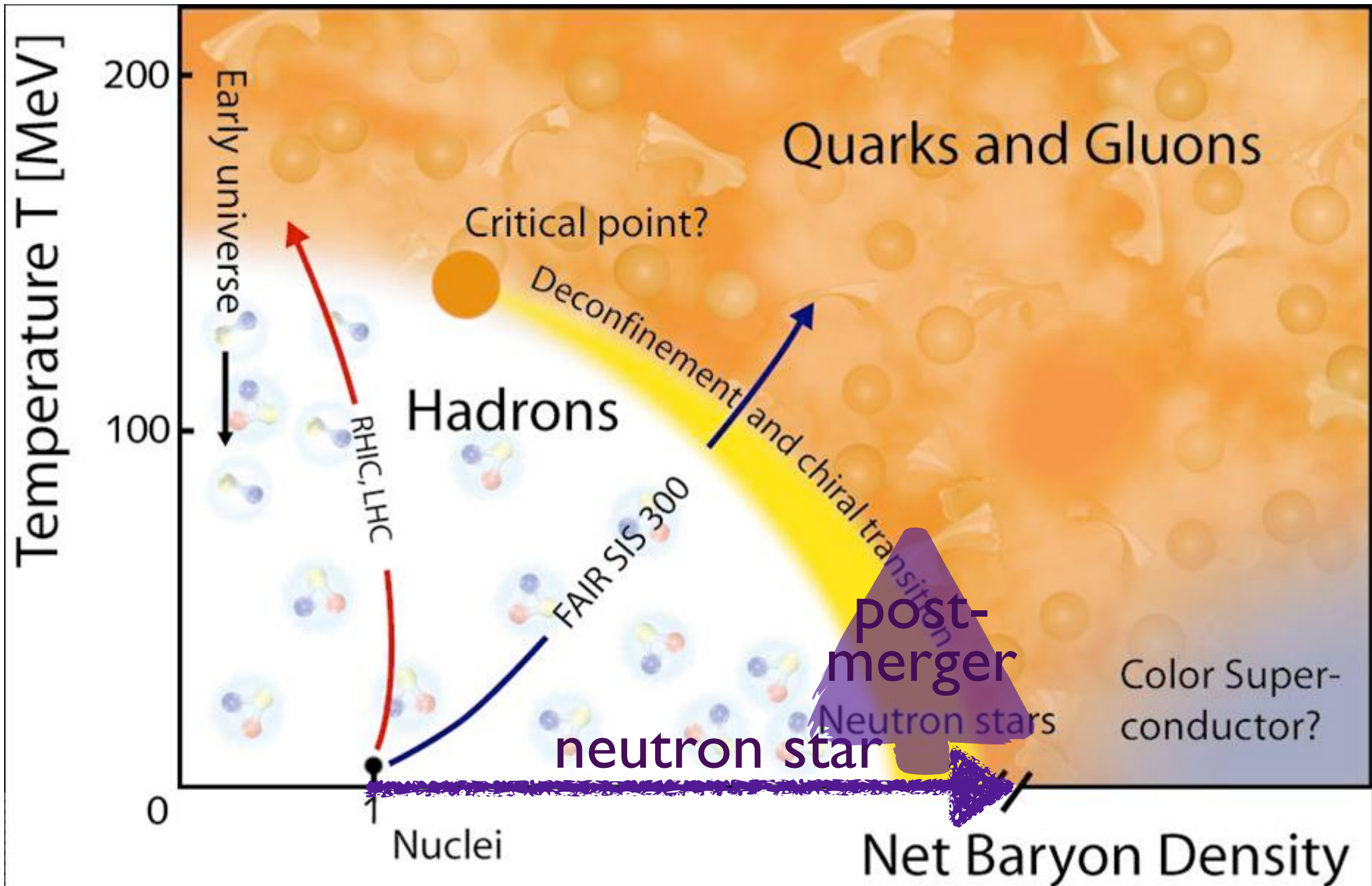
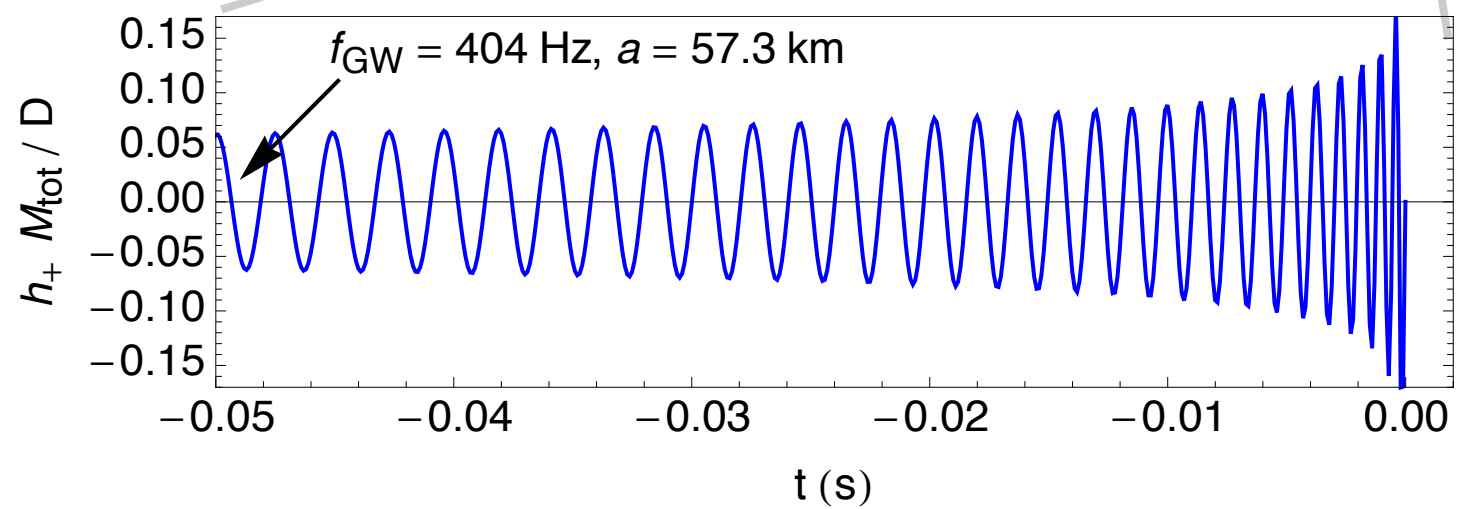
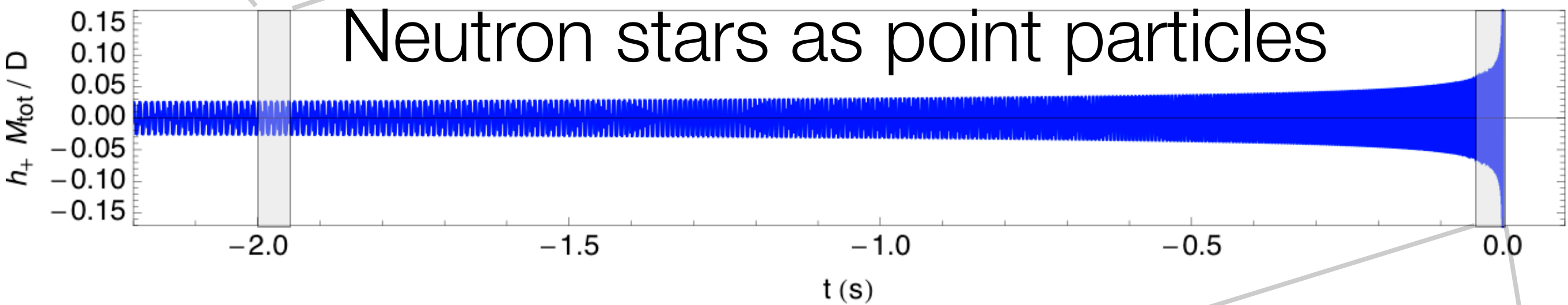
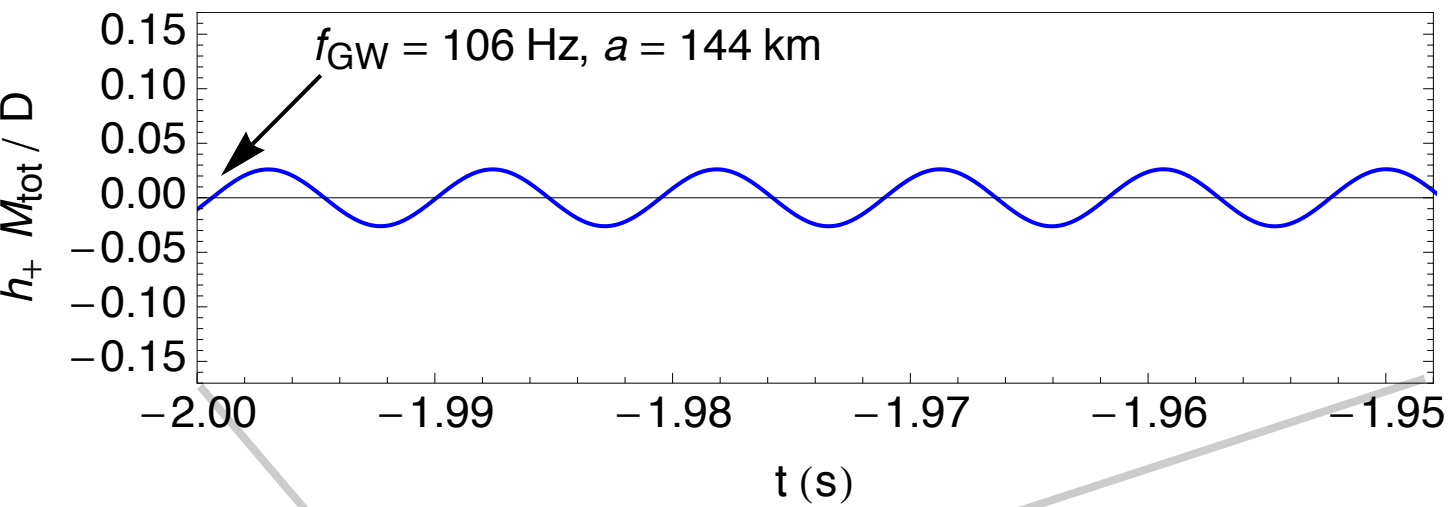
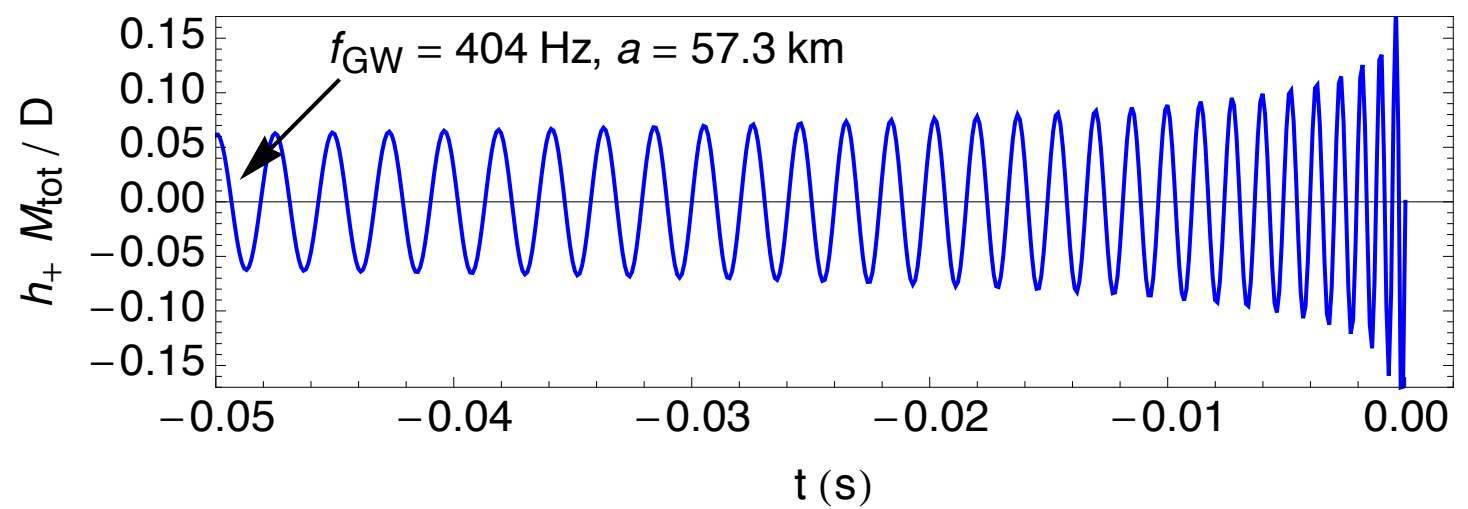
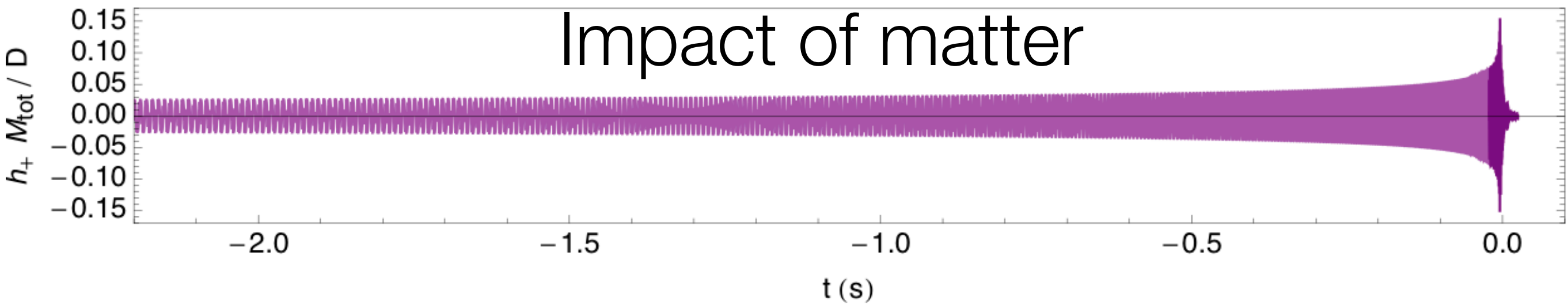
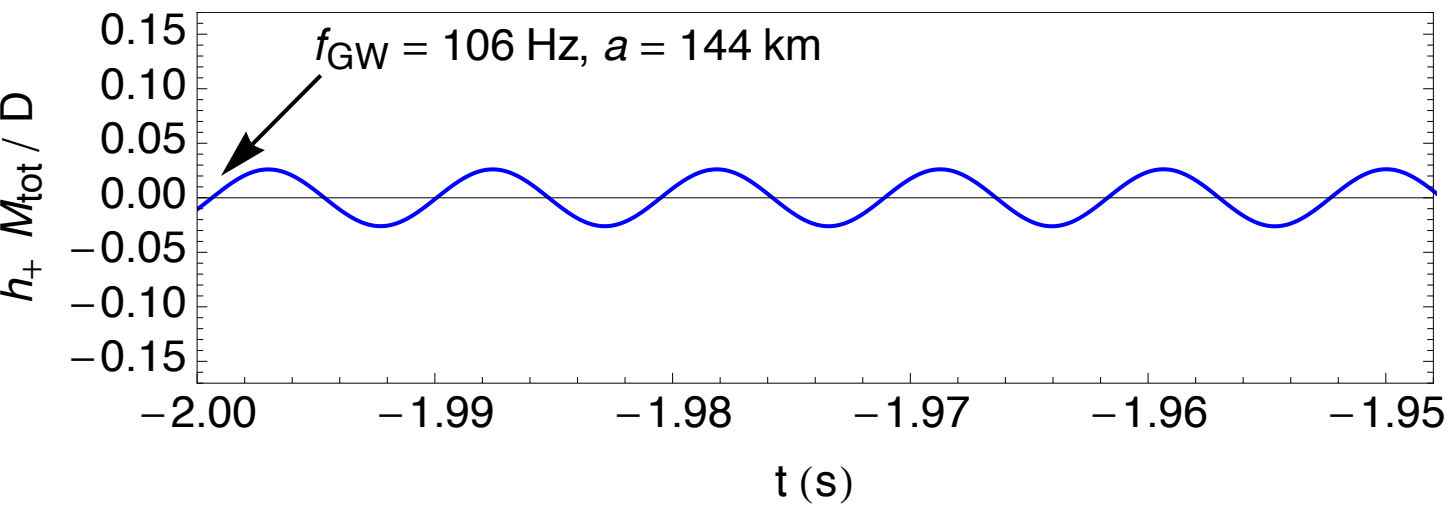
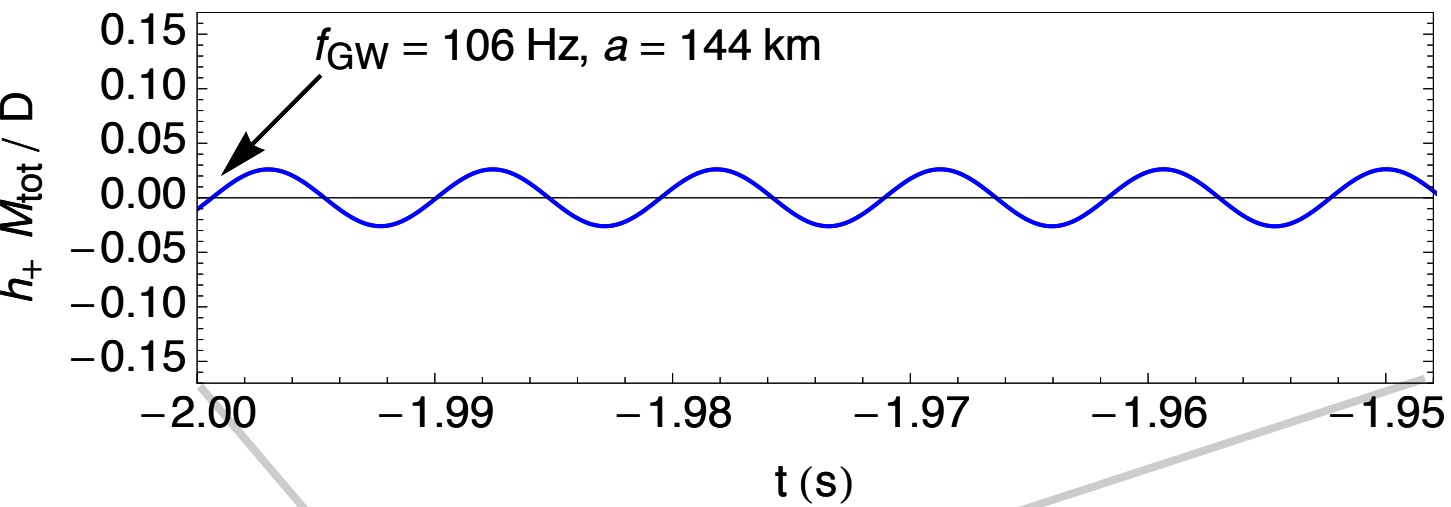


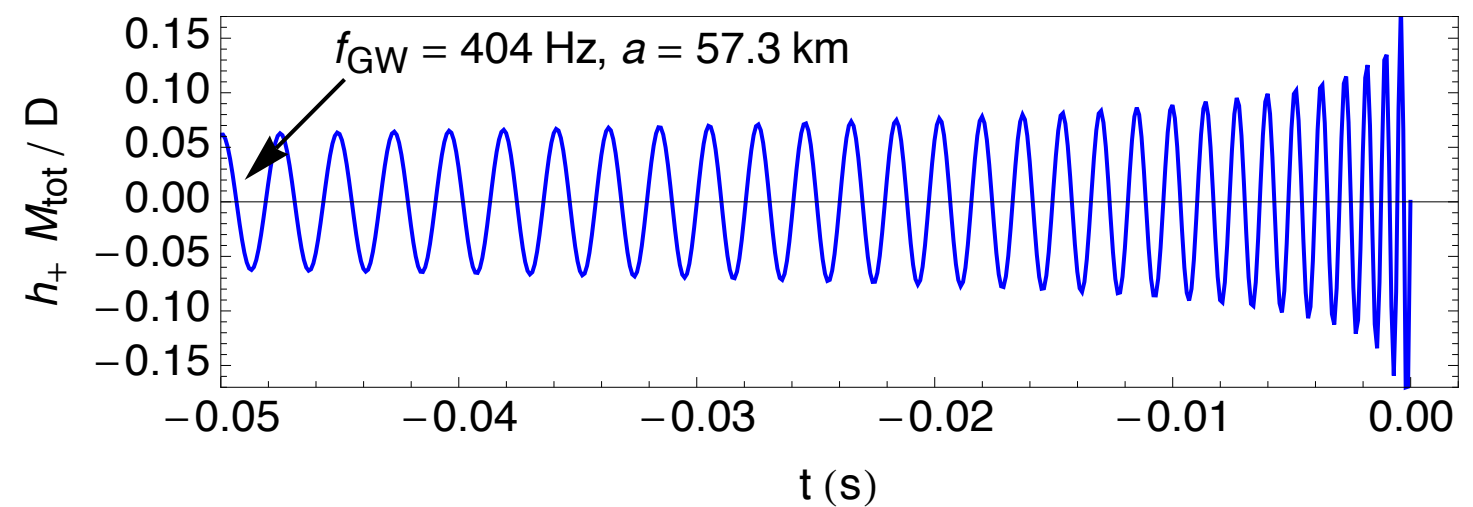
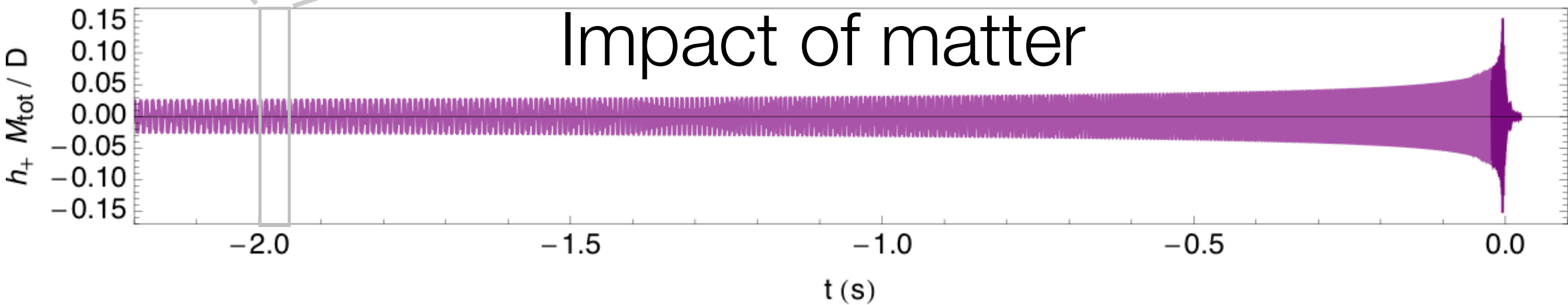
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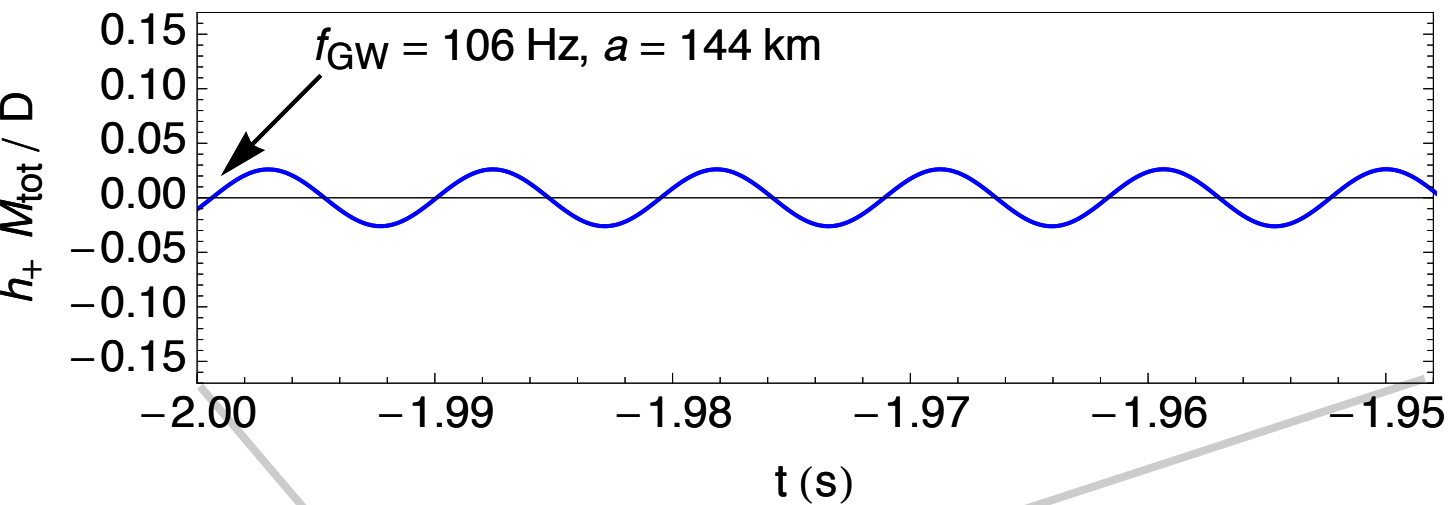




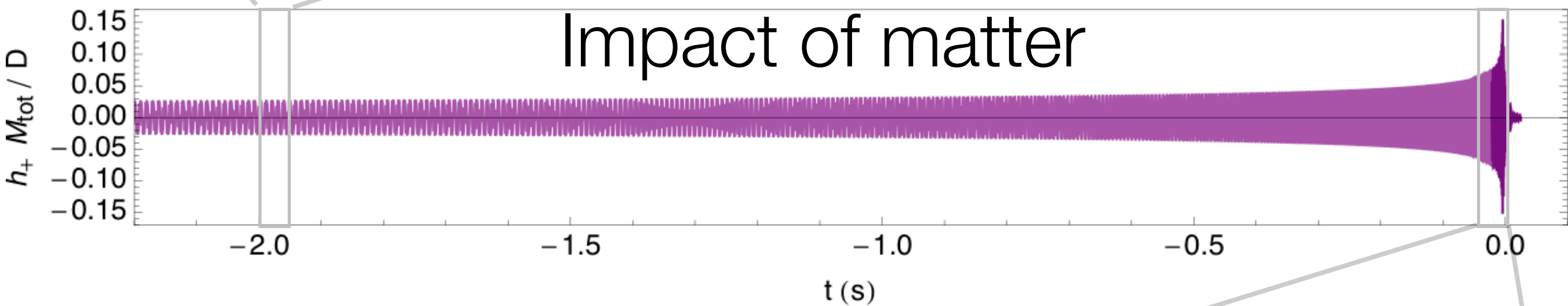


Hard to modify inspiral:
transfer of $\sim 10^{46}$ erg at
 ~ 100 Hz modifies phase
by 10^{-3} radians (Crust
shattering, Tsang et al
1110.0467)

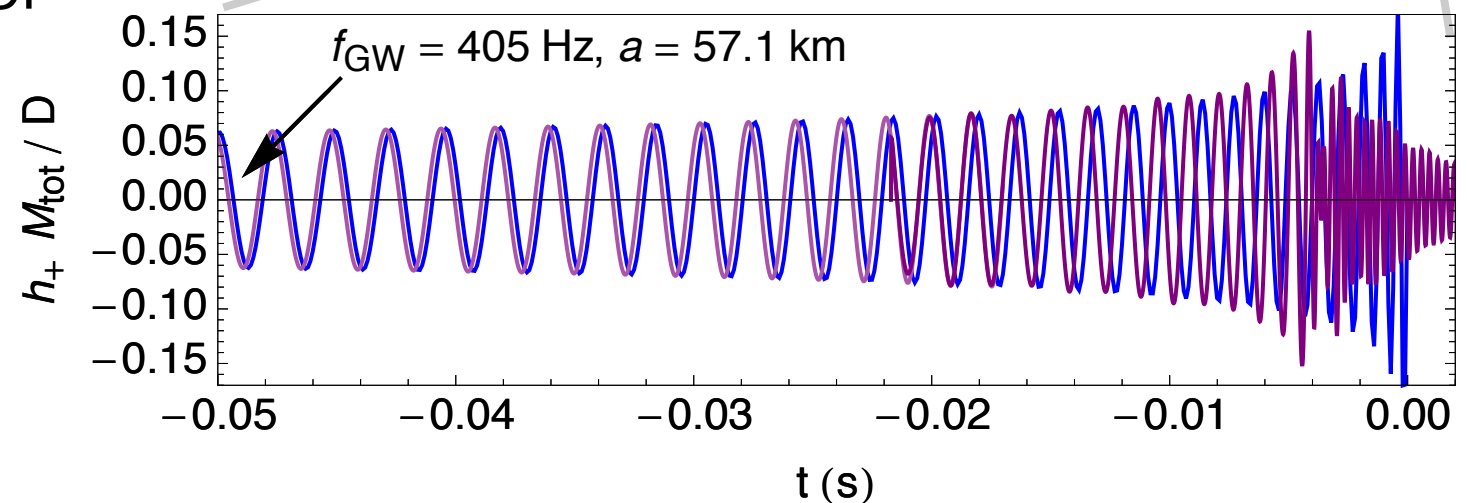


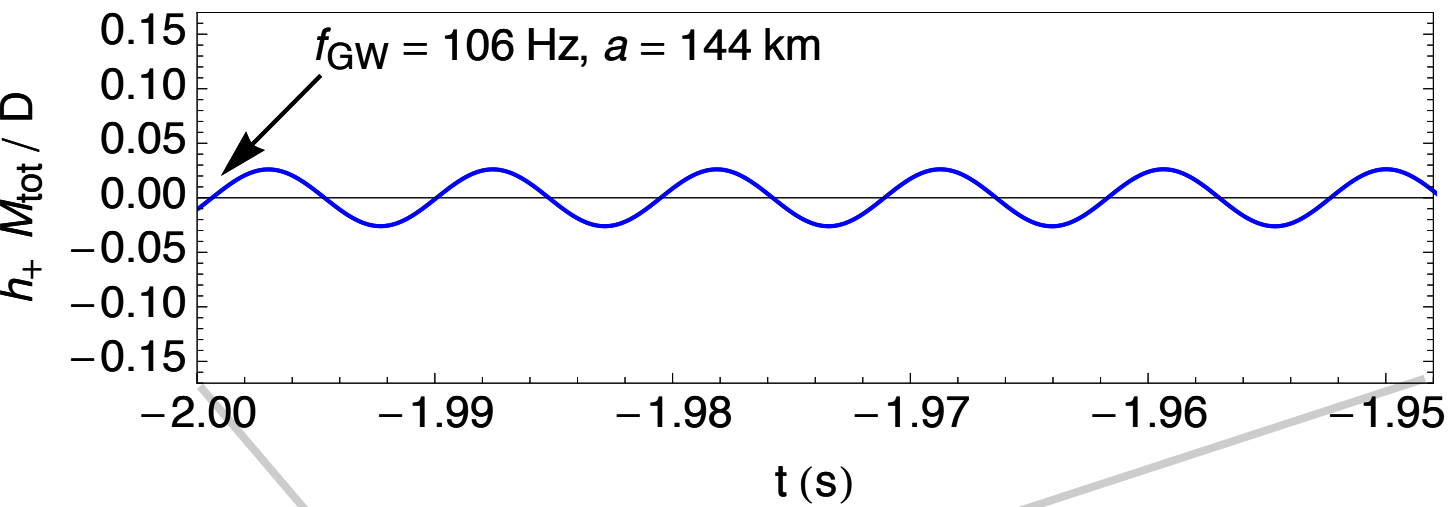


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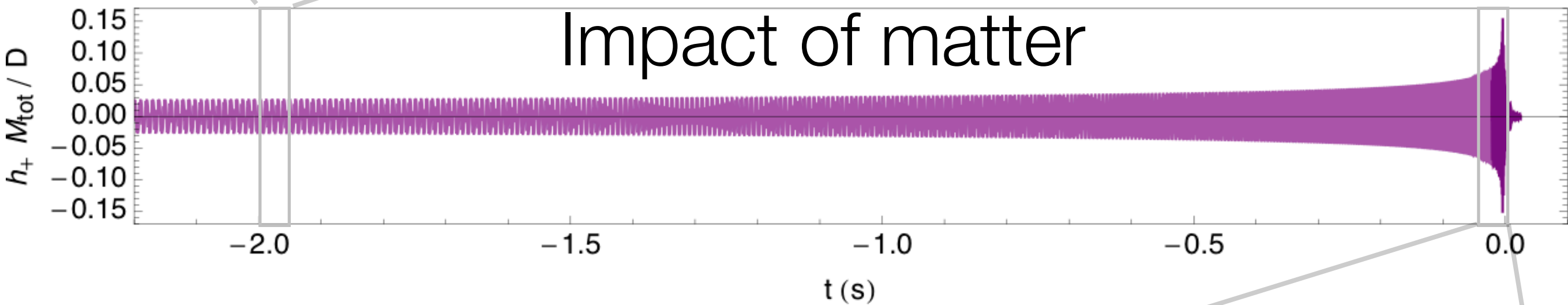


Tidal interactions lead to
 accumulated phase shift at higher
 frequencies.

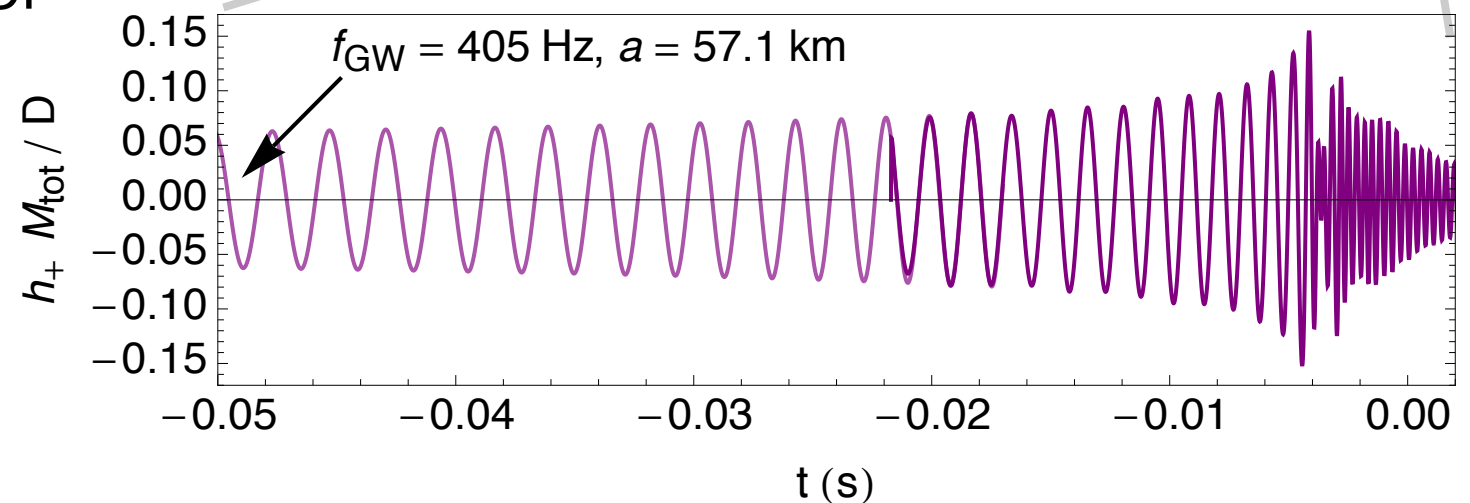


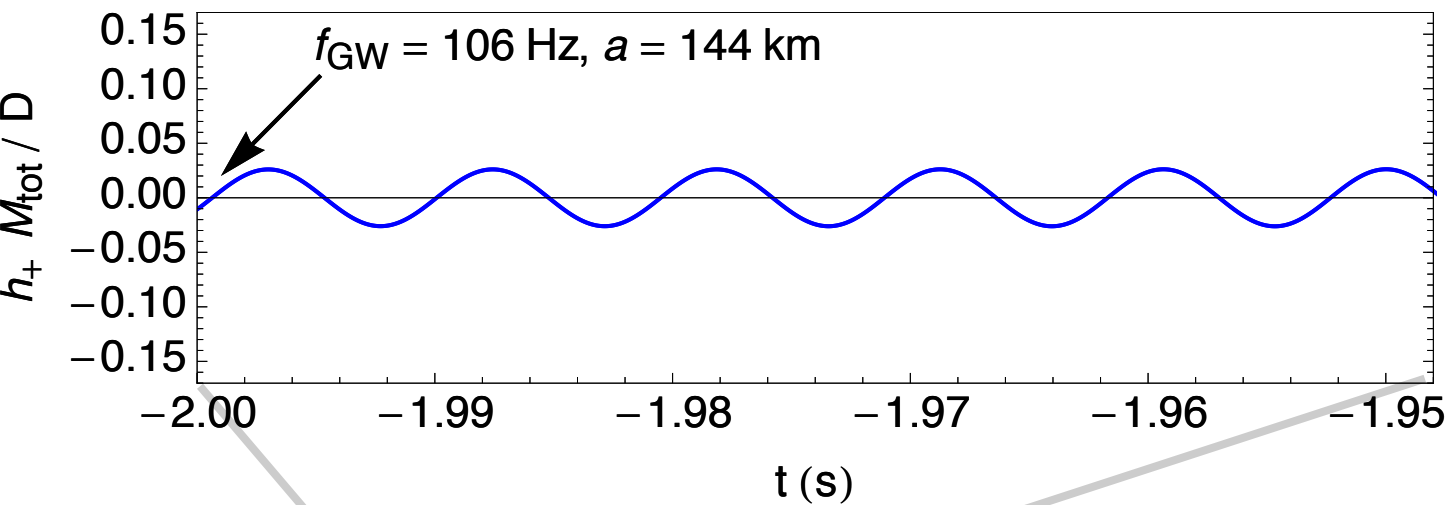


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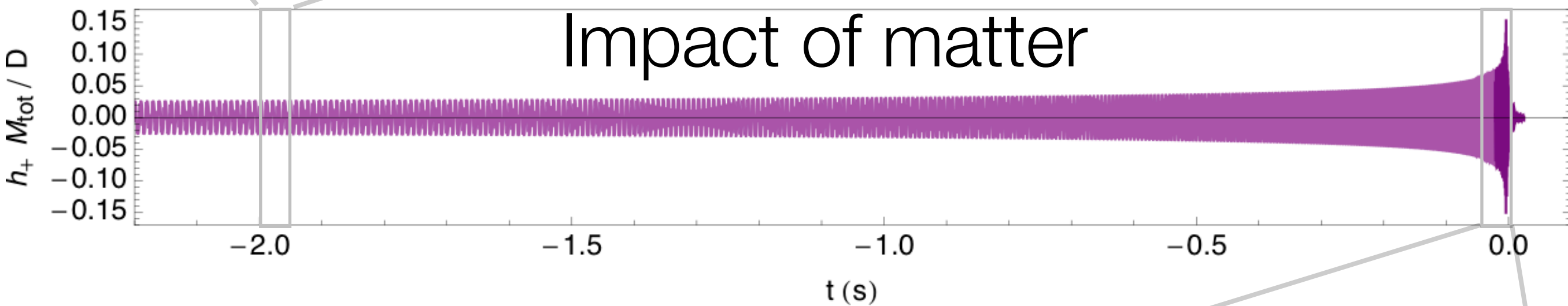


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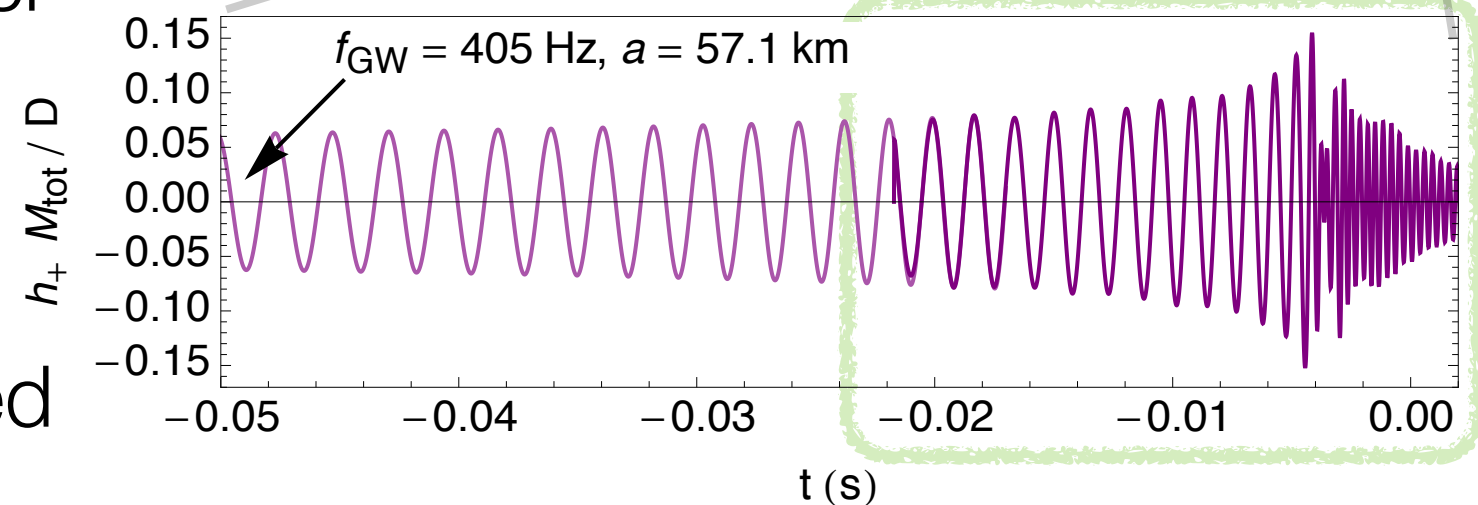
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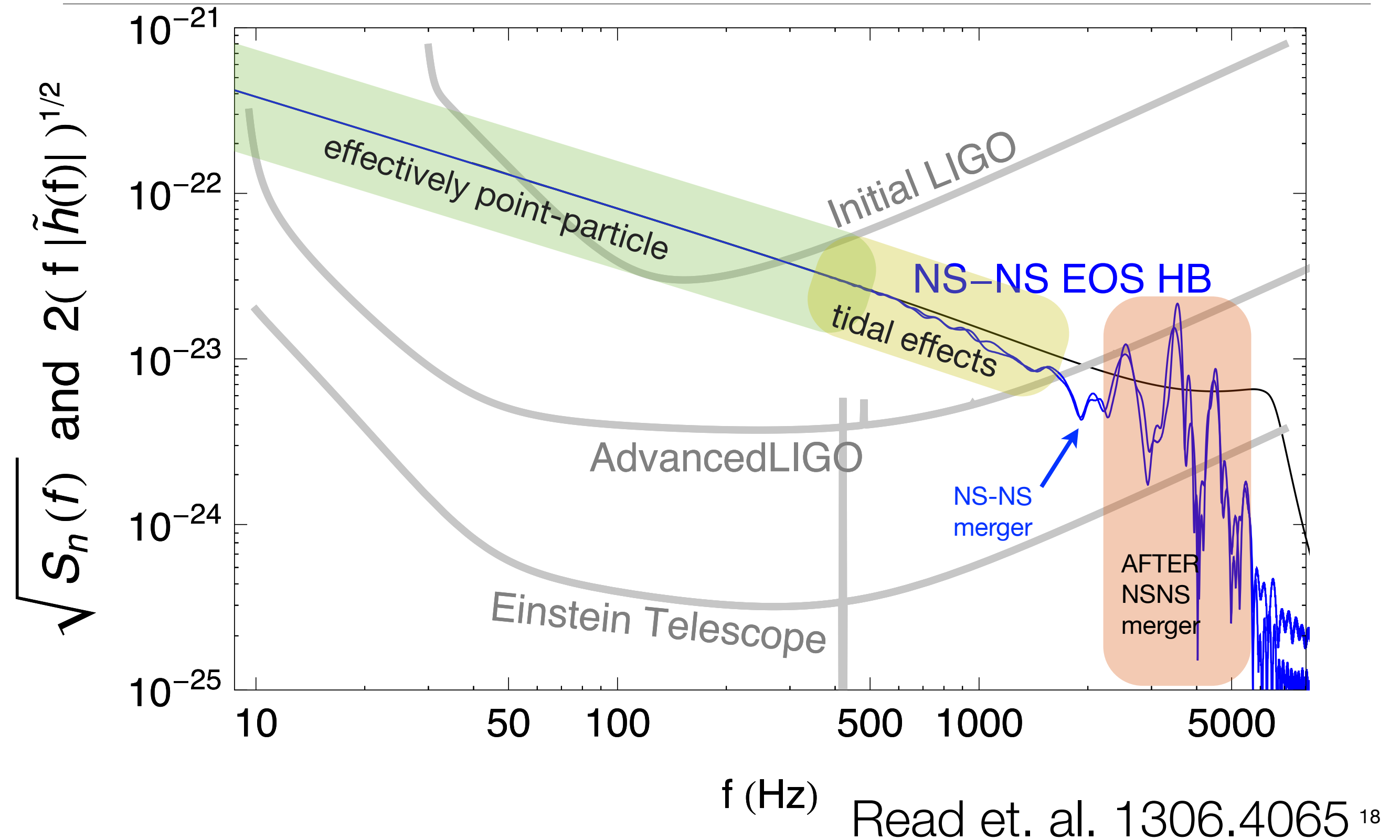
Impact of matter

Tidal interactions lead to
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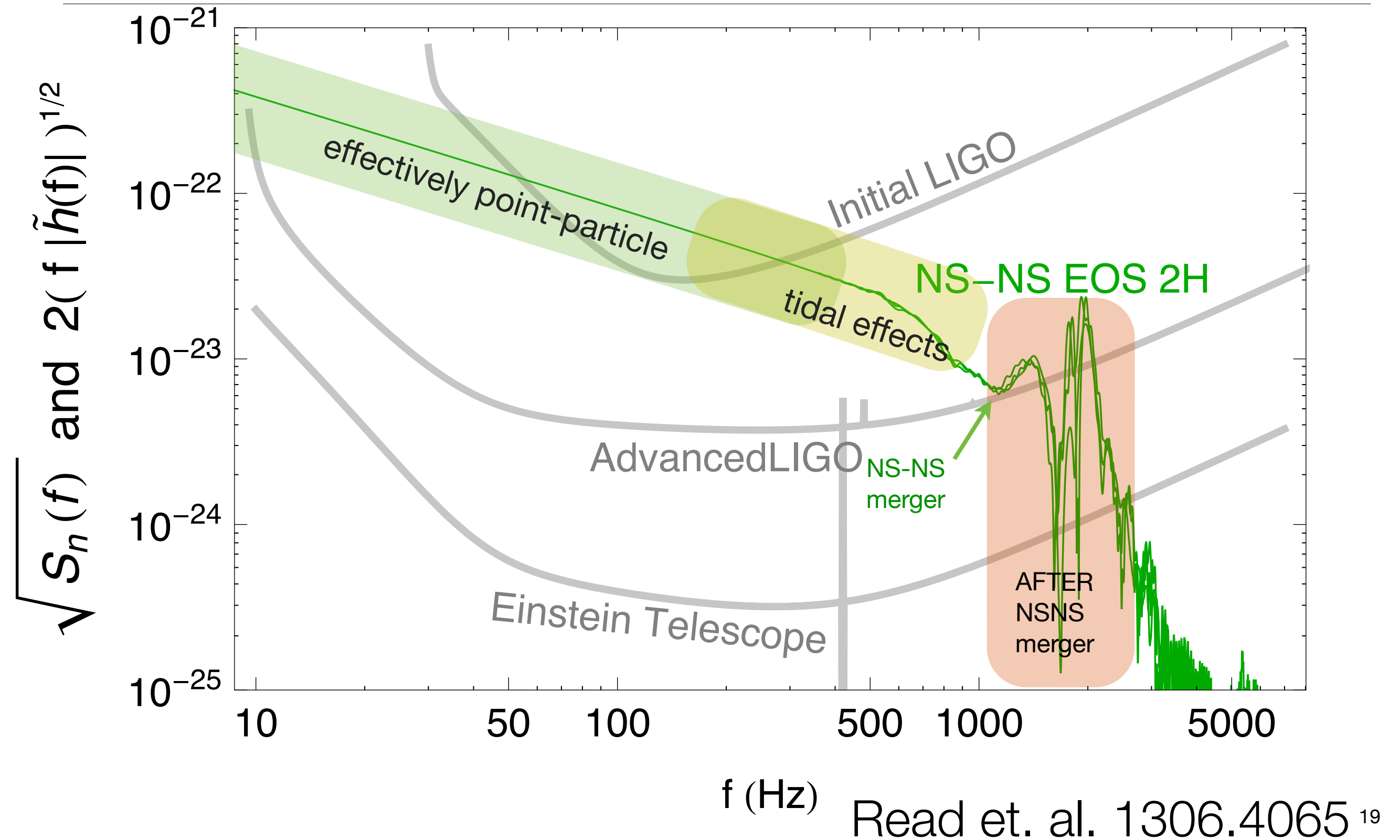
For the final coalescence,
 numerical simulations are required



Gravitational-wave spectrum of BNS

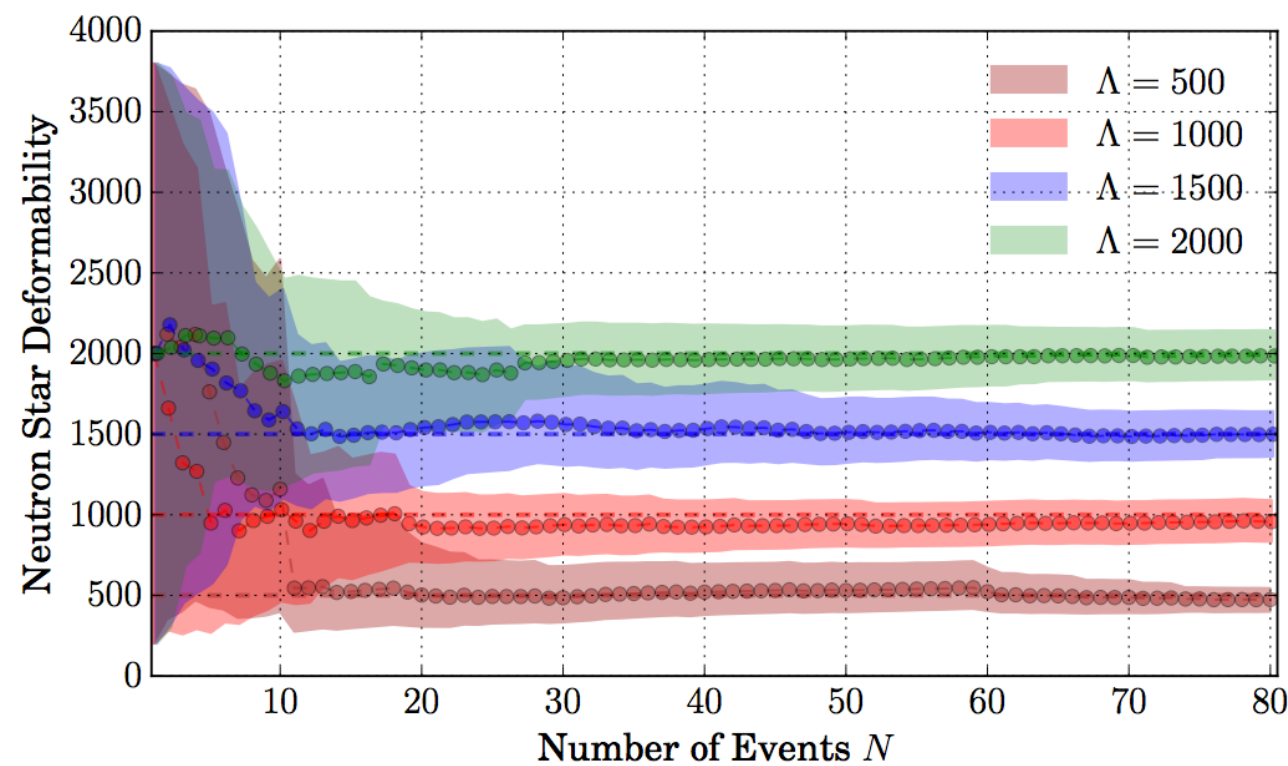
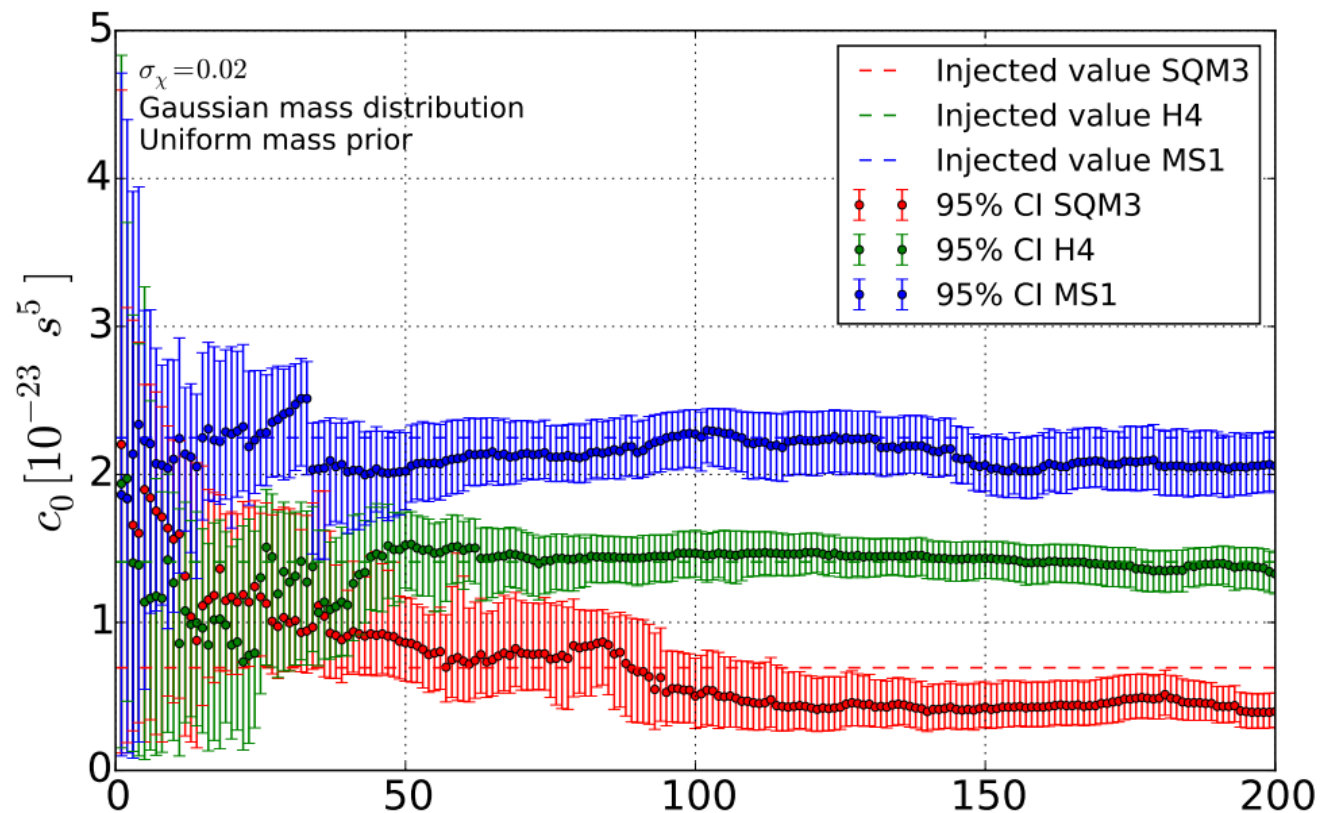


Gravitational-wave spectrum of BNS



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

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



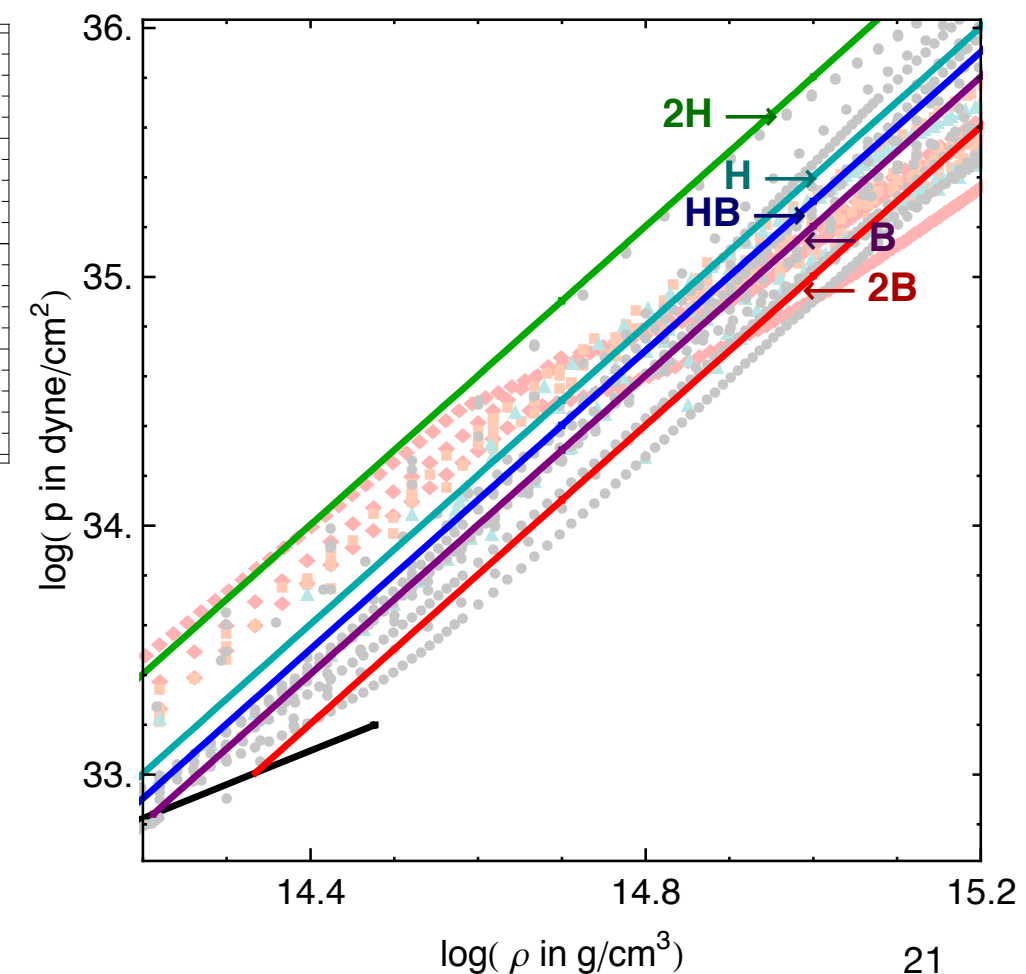
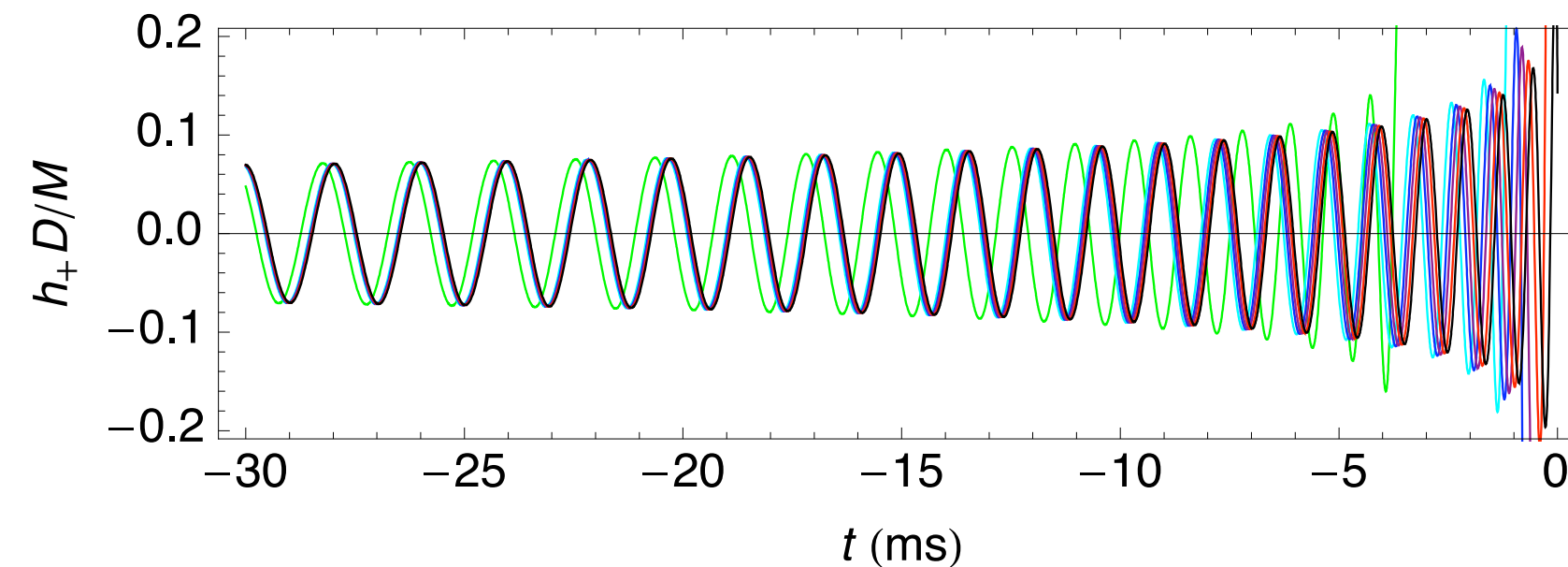
Kumar, Pürrer, Pfeiffer
arXiv:1610.06155

Tidal effects on inspiral



Haas et al arXiv:1604.00782

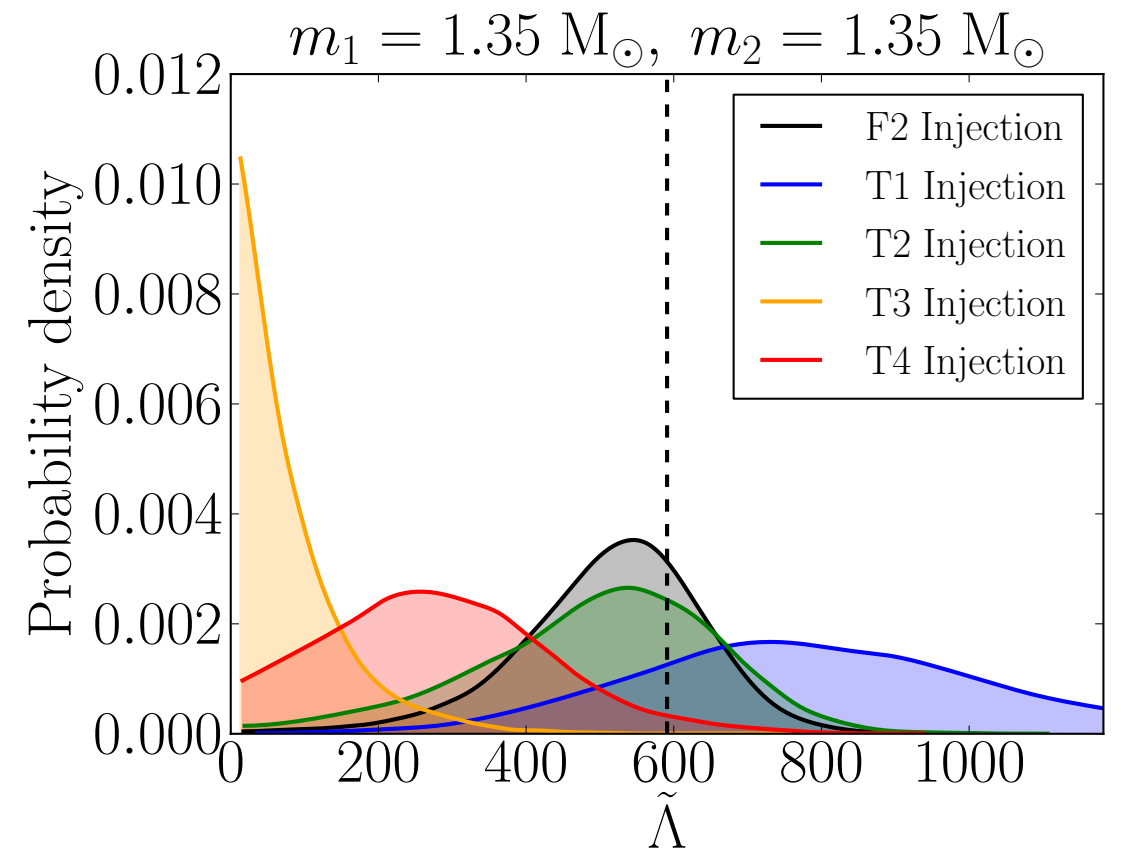
- Energy goes into deforming the neutron star(s), tidal bulges add a bit to the gravitational radiation.
- Modify GW at effectively high post-Newtonian order (Flanagan and Hinderer 0709.1915, Vines and Flanagan 1009.4919)



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?

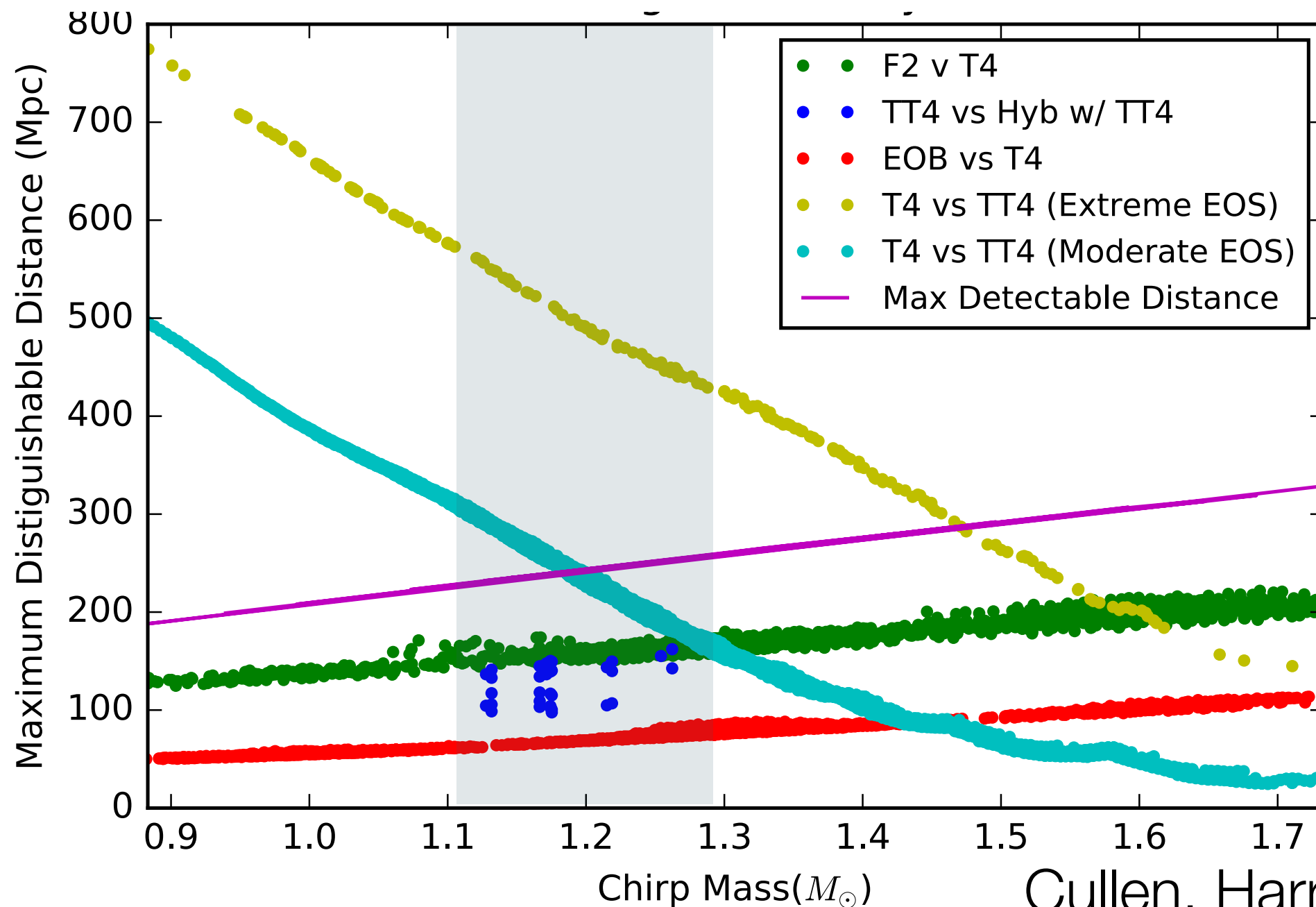
- Good estimates of the size and relevance of EOS-dependent (Damour et al 2012, Read et al 1306.4065)
- **Not** sufficient for best measuring EOS effects (Favata 1310.8288, Yagi/Yunes: 1310.8358, Wade et al.1402.5156)



Wade et al.1402.5156

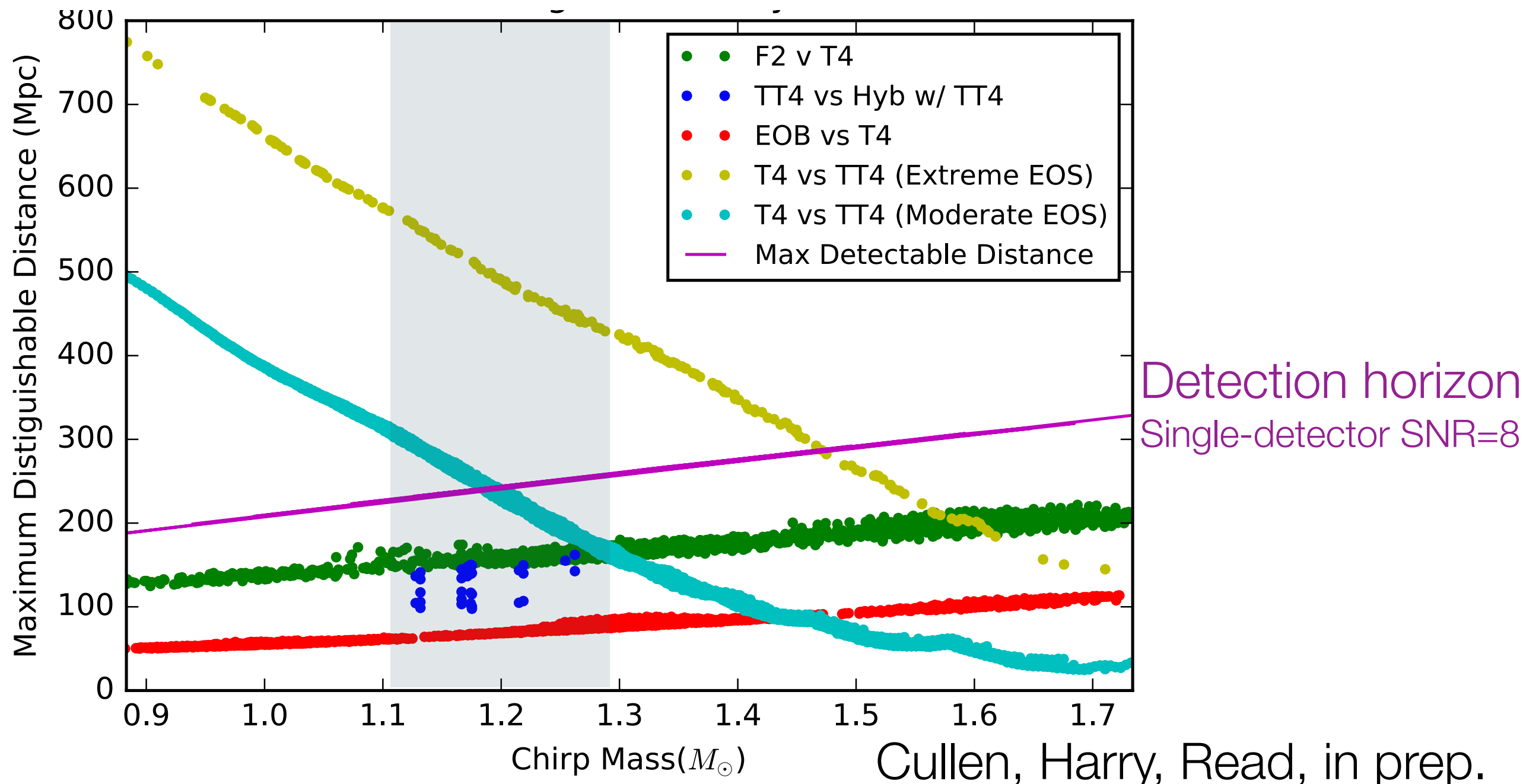
Relative importance of effects in BNS waveforms

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



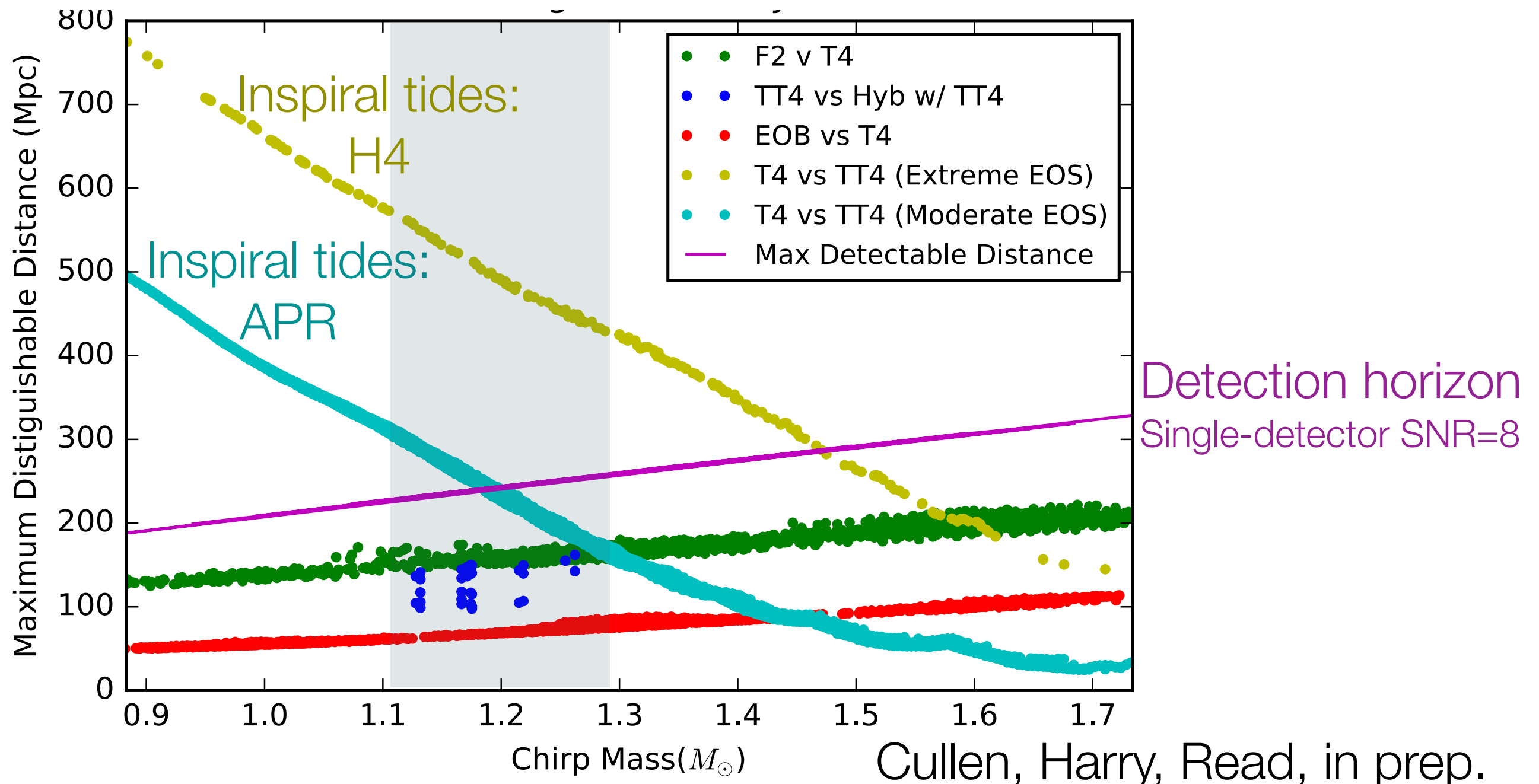
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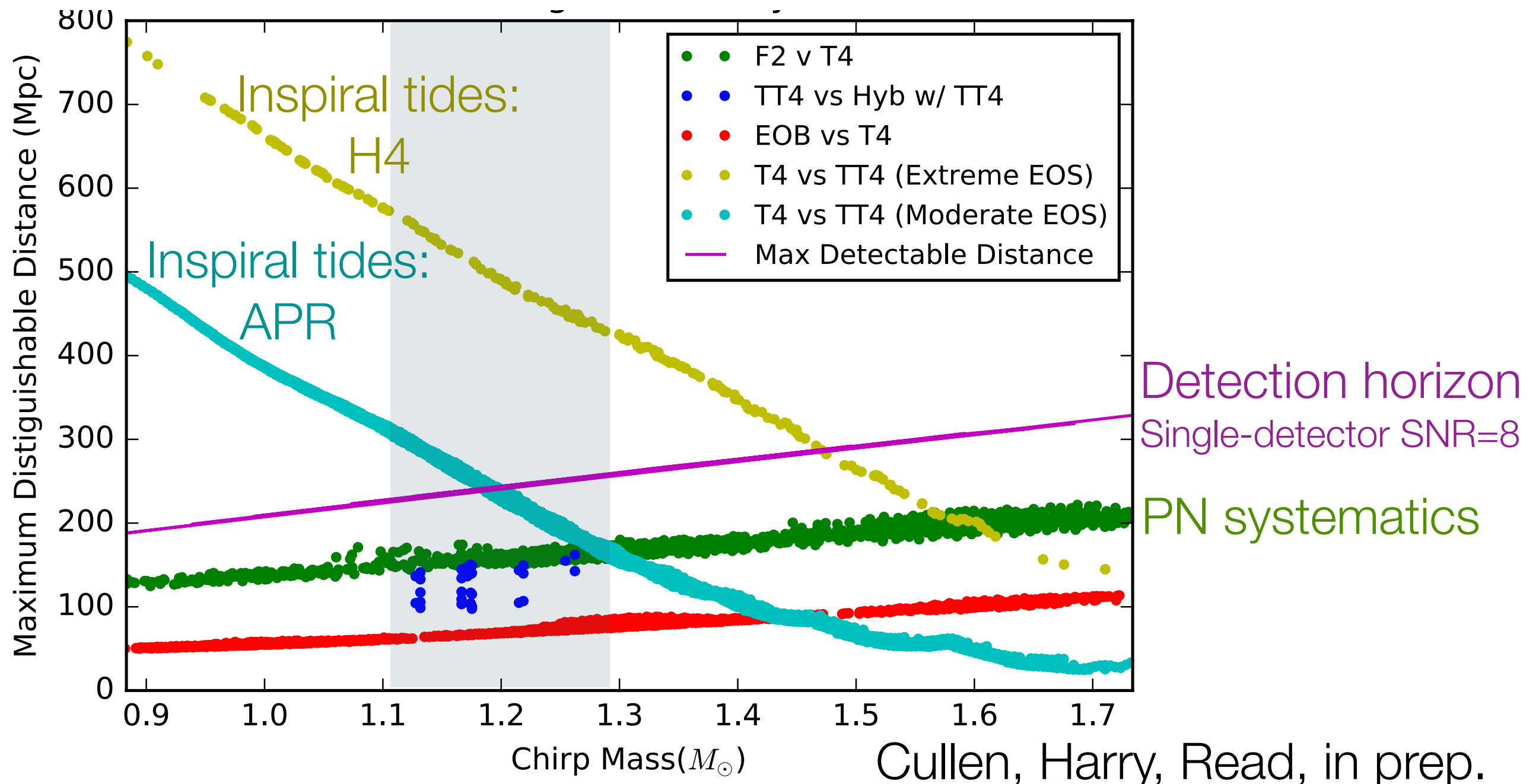
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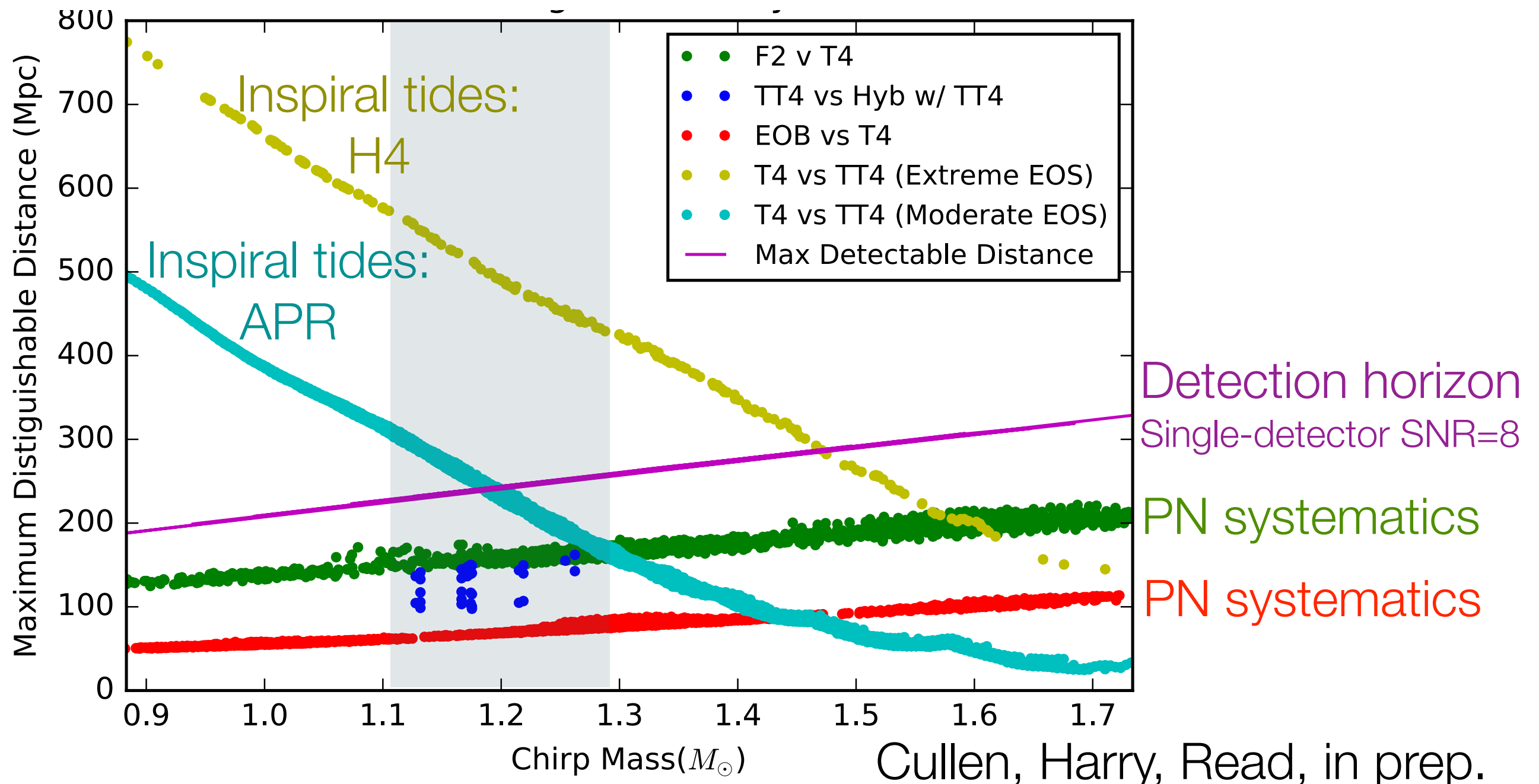
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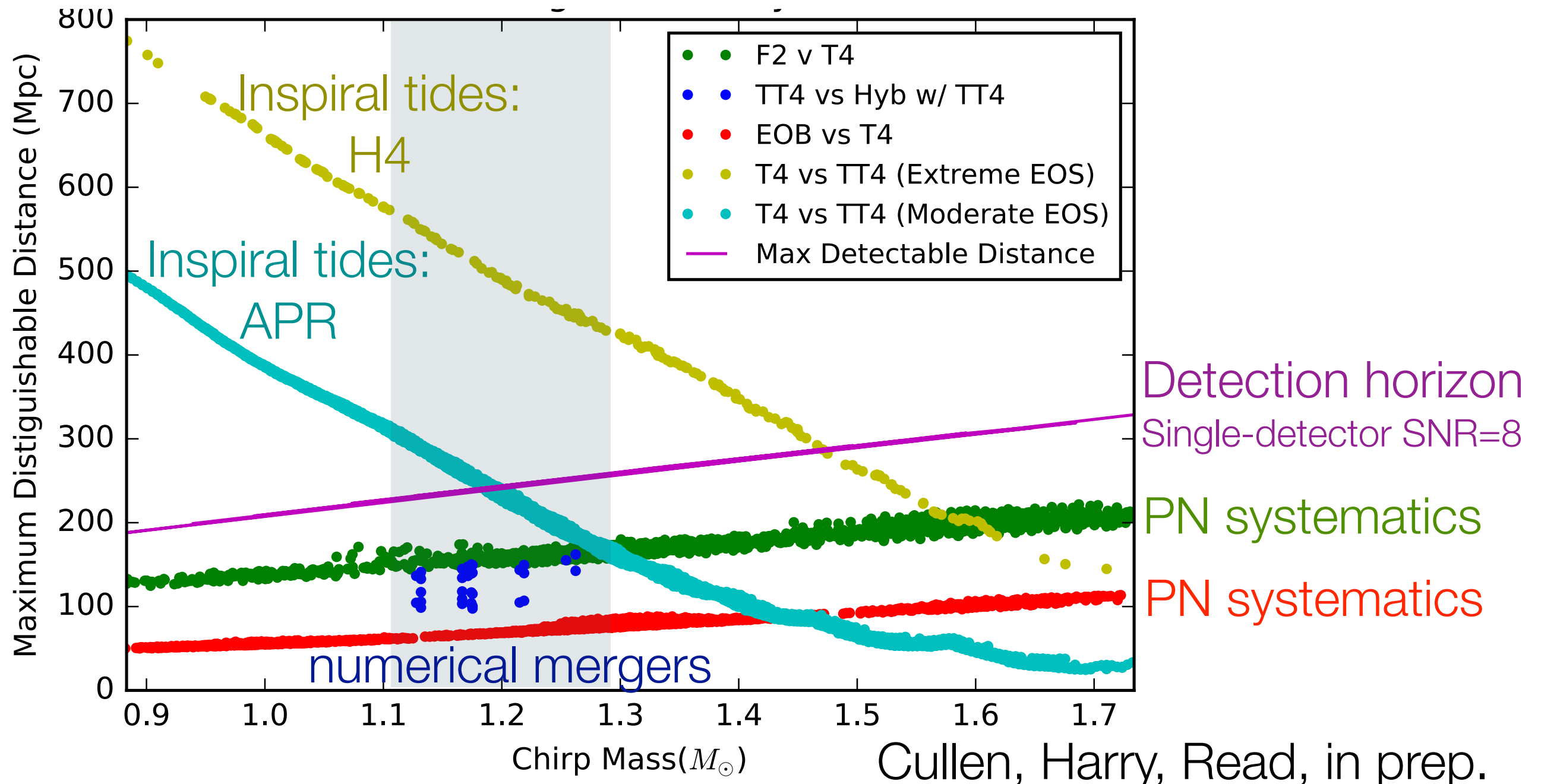
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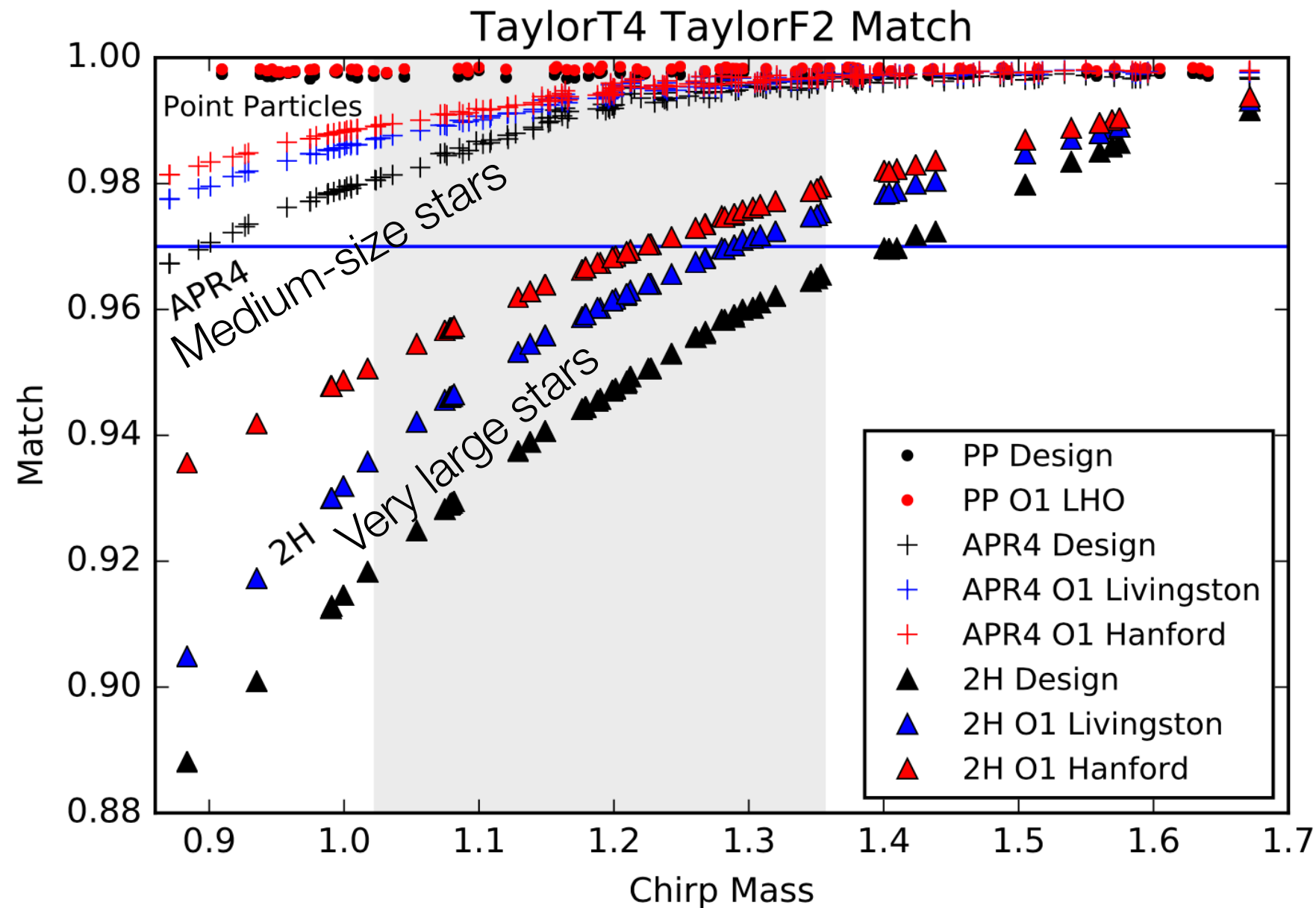
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Matter impacts on search: extreme tides!

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



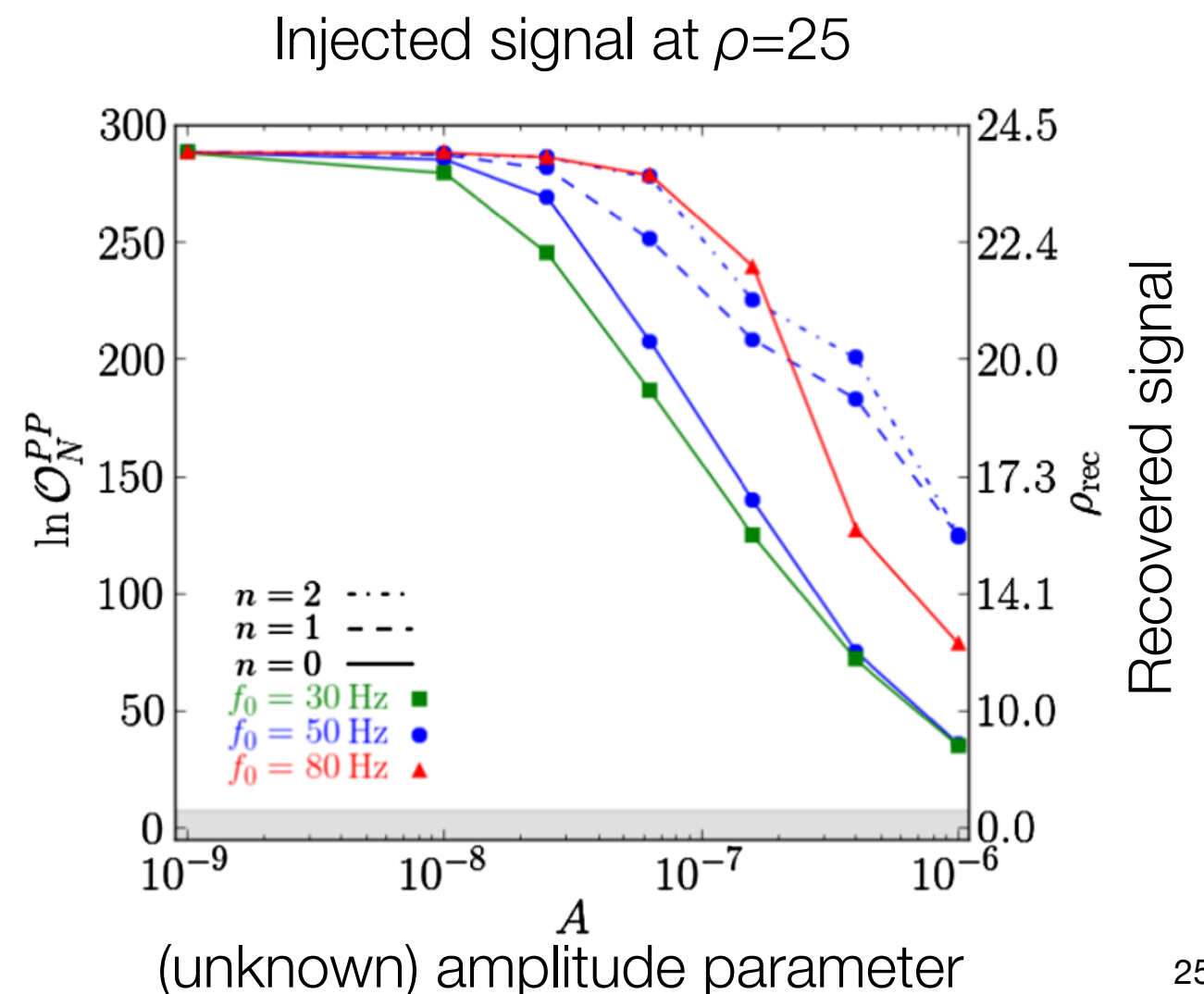
10% signal loss;
impact on template
bank fitting factors

Matter impacts on search: extreme tides!

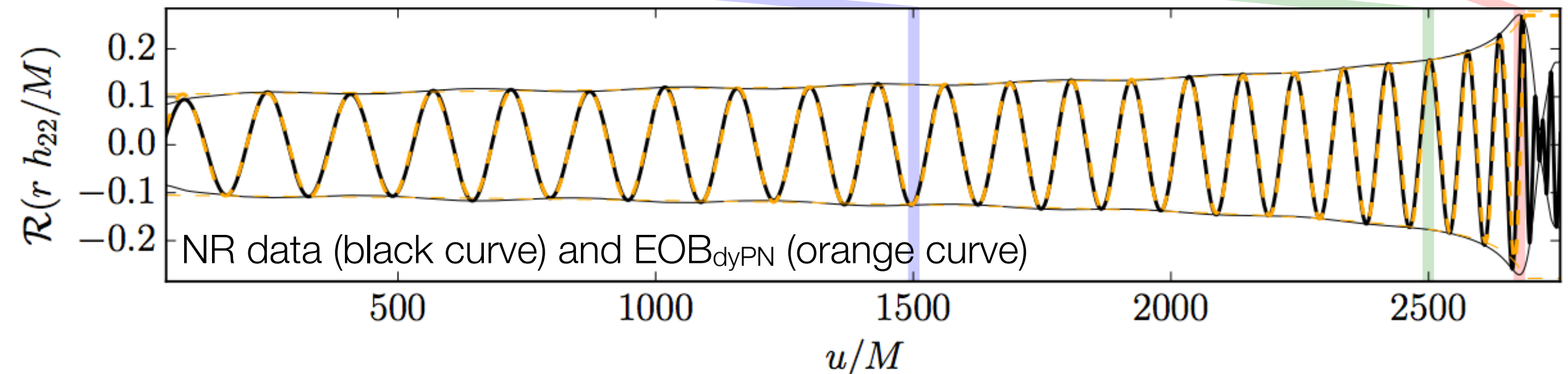
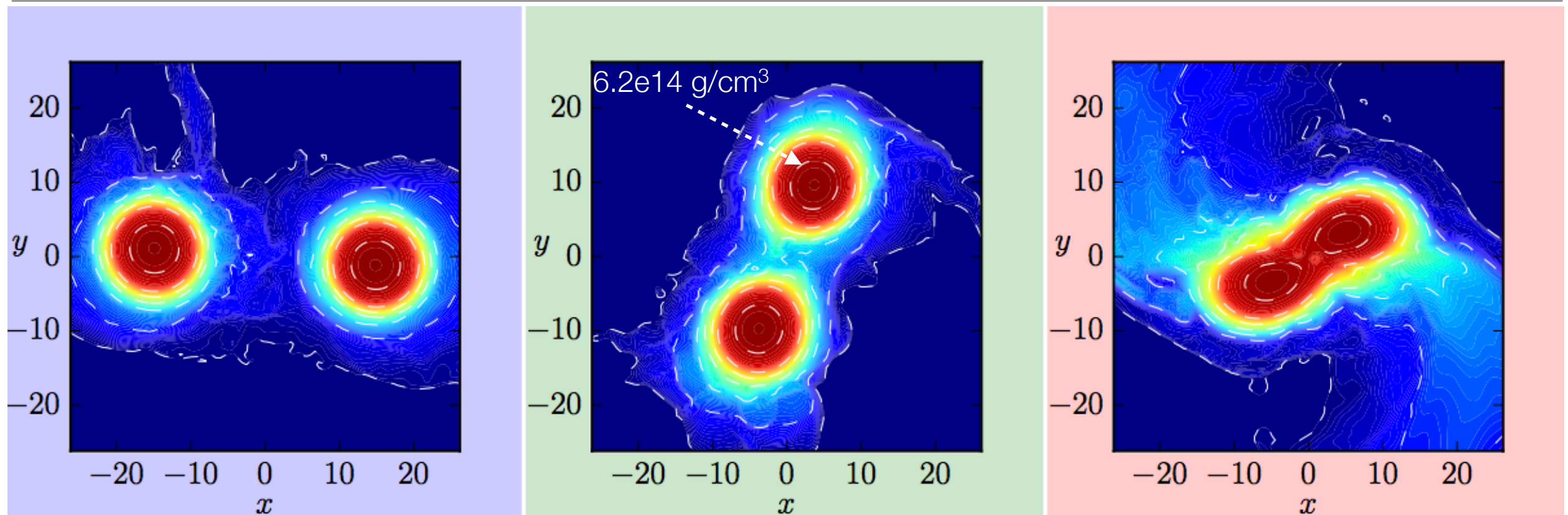
- Resonance with stellar modes transfers energy from orbit
- Unstable nonlinear mode couplings disrupt inspiral, impact search and parameter estimation (Essick, Vitale, Weinberg 1609.06362)



Resonant mode illustration, D. Tsang

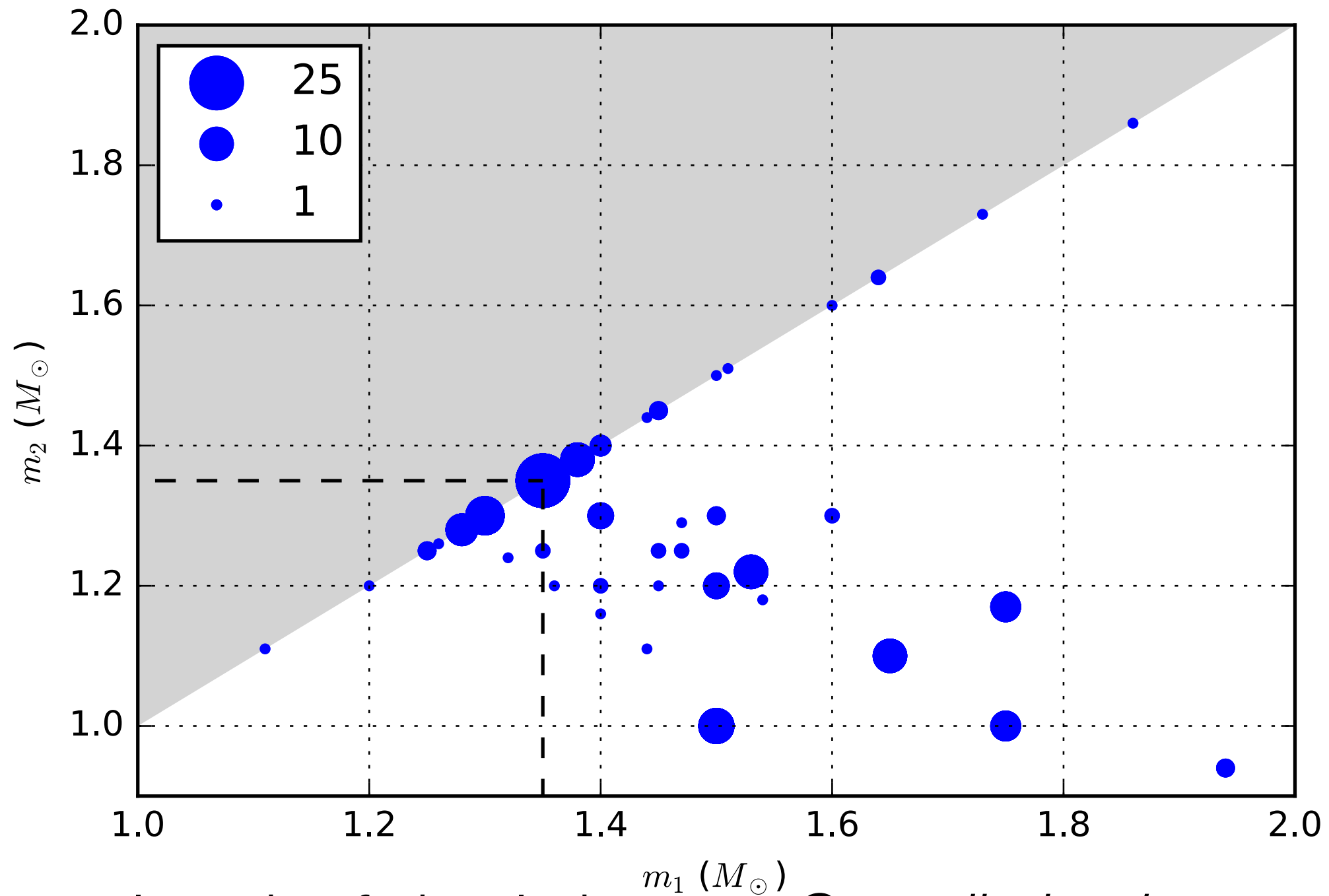


Inspiral-to-merger: accurate waveform models



Dietrich and Hinderer, arXiv:1702.02053

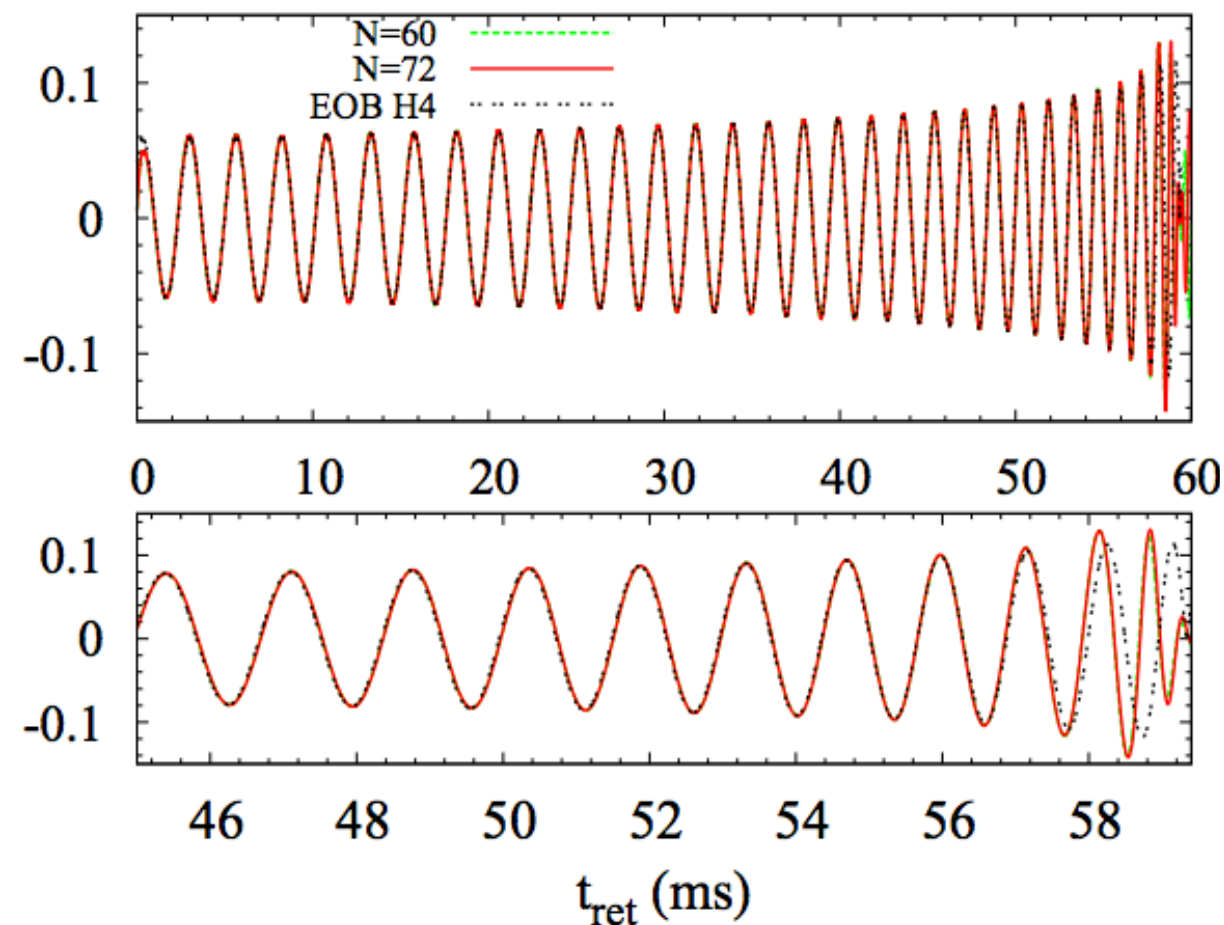
Status of BNS simulations: coverage of parameter space



not shown - length of simulations, resolution, EOS parameters... *Compilation in progress*
by T. Cullen

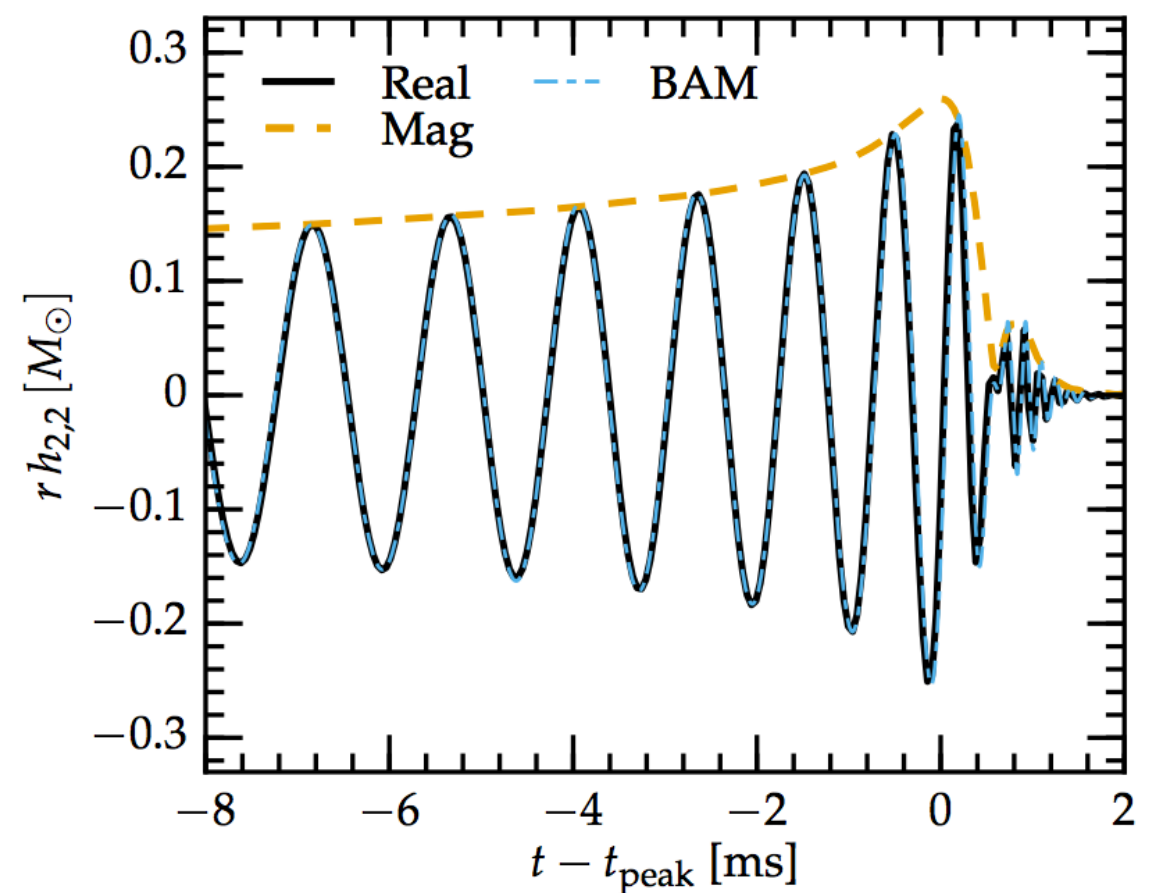
Long and accurate BNS simulations

Hotokezaka et al
1502.03457



estimated total phase error
<1 radian over ~ 200 radians

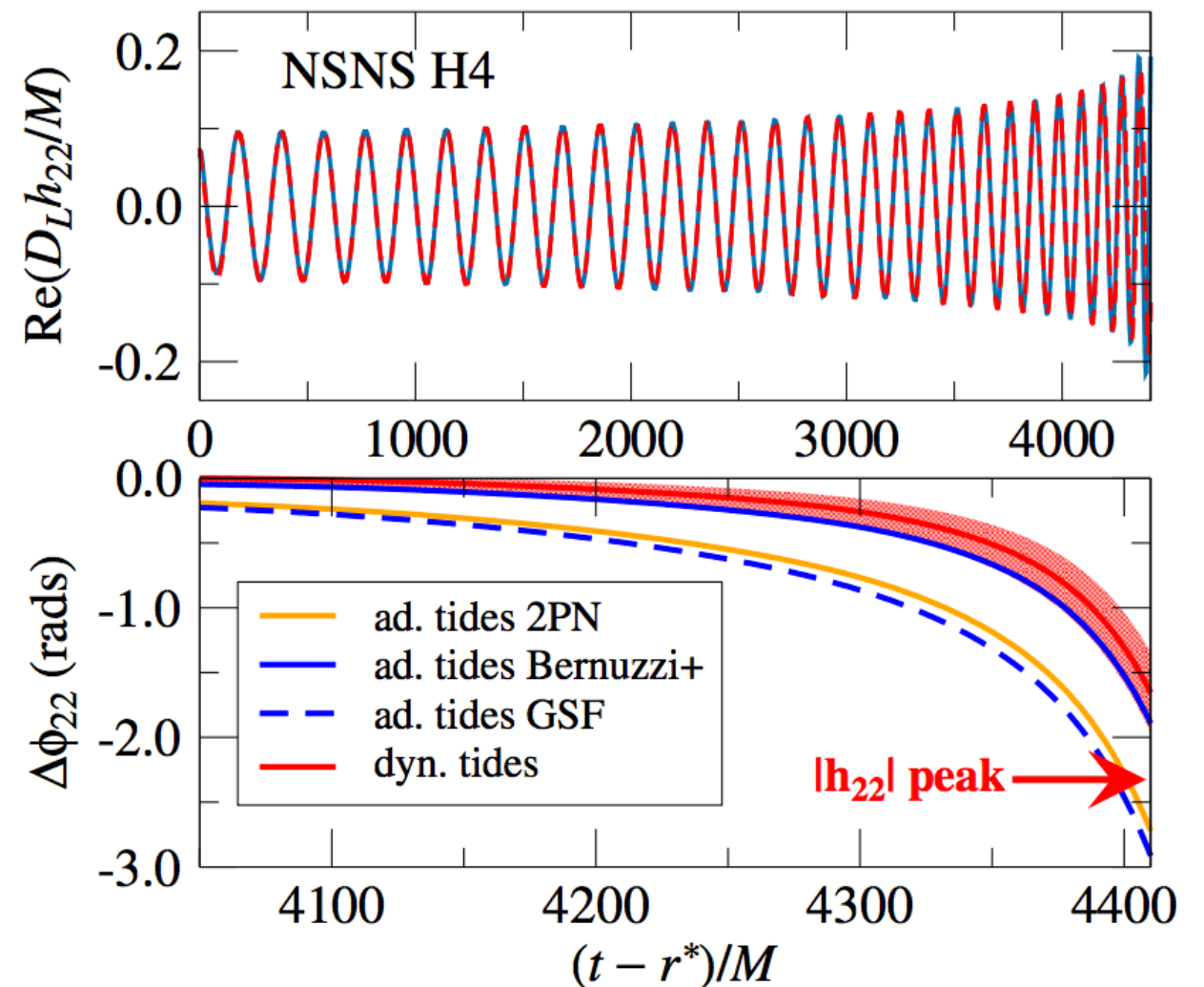
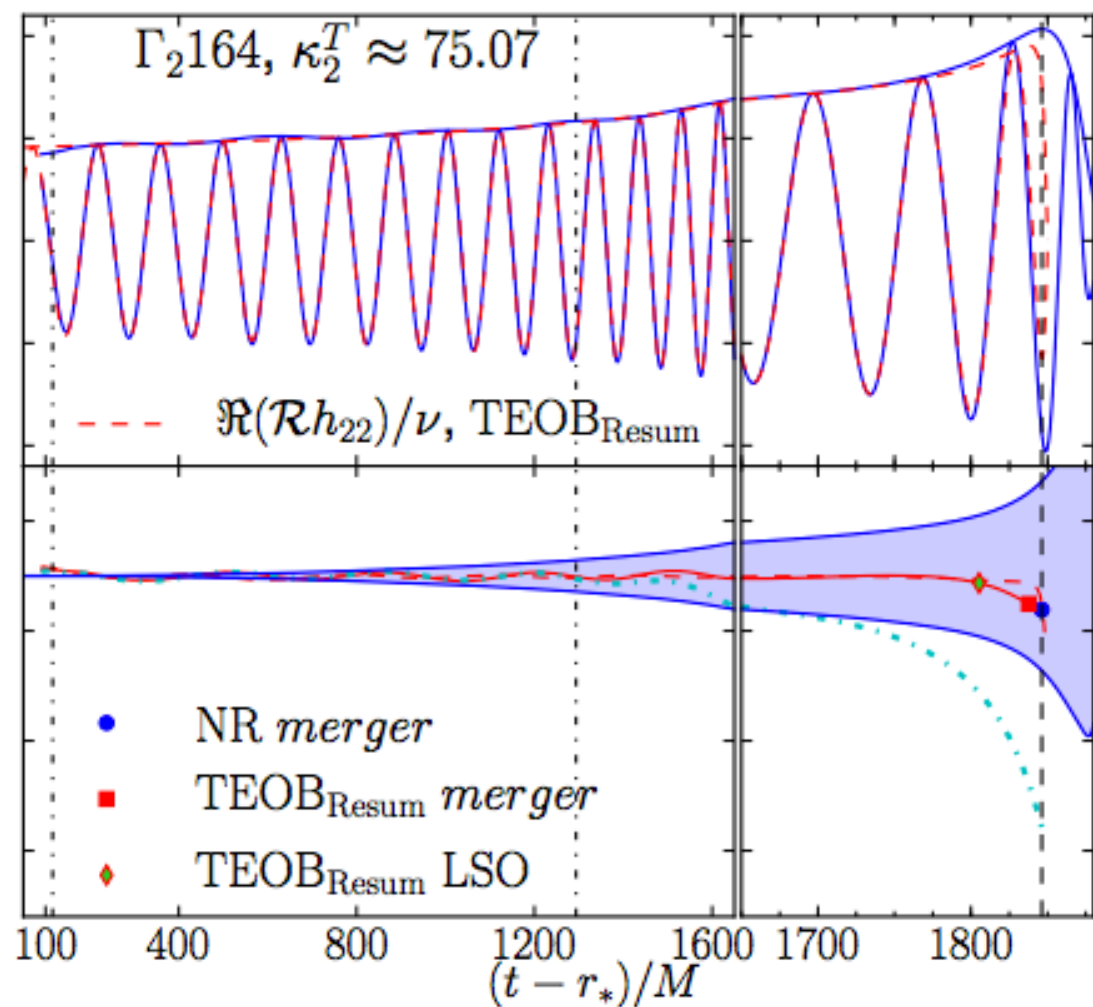
Haas et al 1604.00782
(22 orbits!) comparison to
Bernuzzi et al 1412.4553



Waveforms aligned
before -13.3 ms

Tidal effects in EOB models:

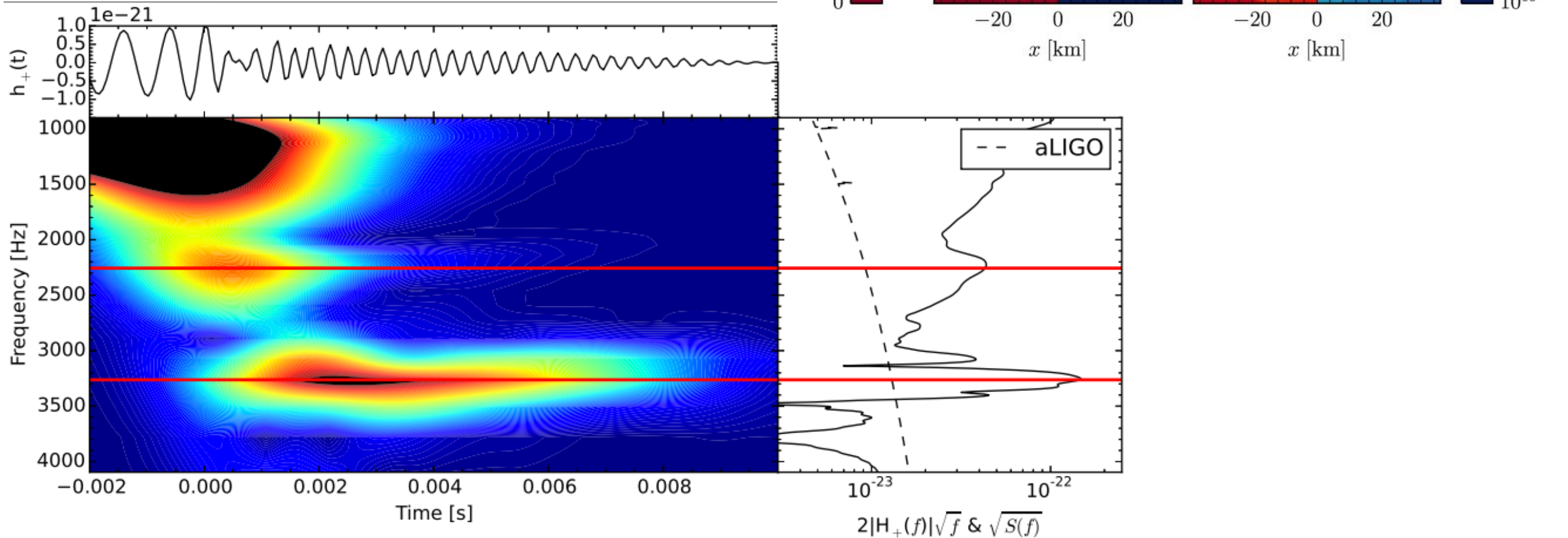
Bernuzzi et al 1412.4553, Hinderer et al 1602.00599



- 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) ²⁹

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

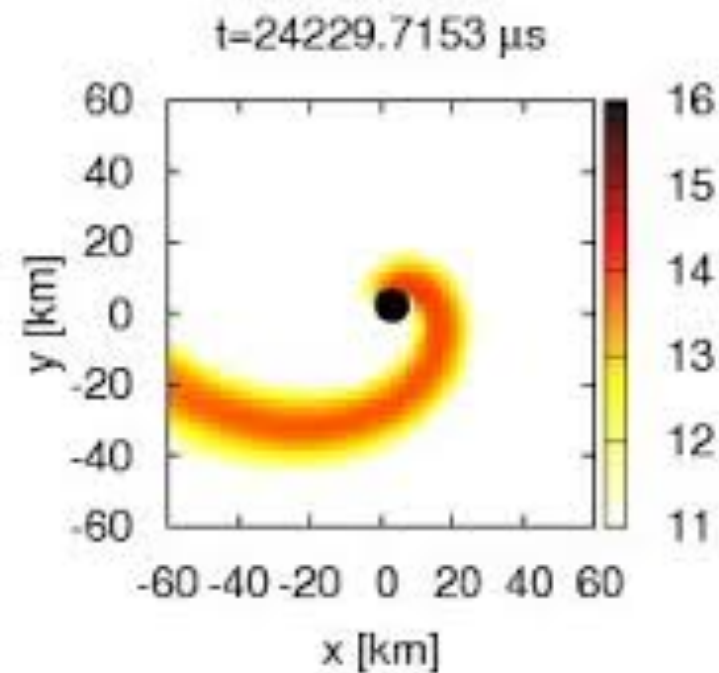
“disruptive” BHNS

Lackey et. al. 1303.6298

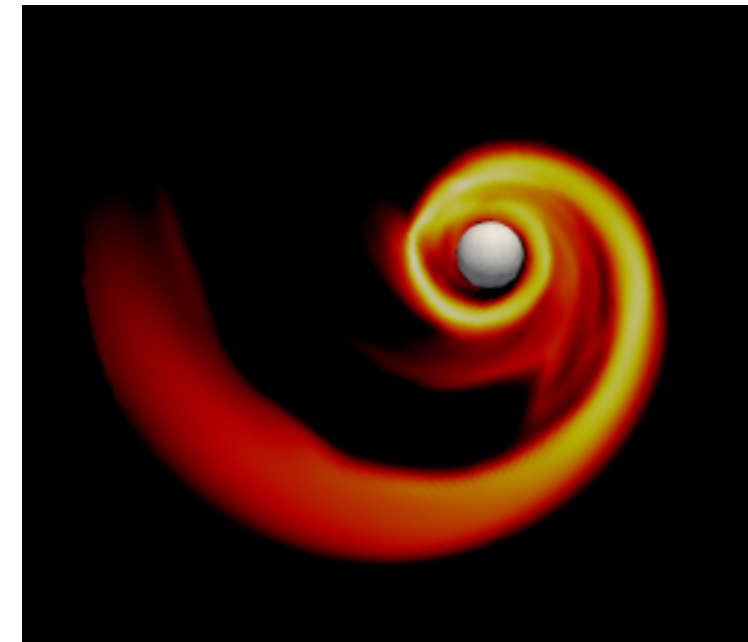
EOS effects on GW

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

SACRA, K Kyutoku



SXS, J Sanchez



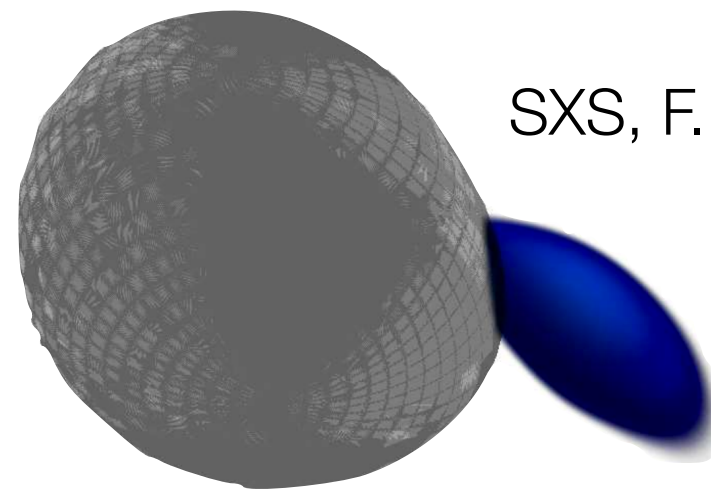
“nondisruptive” BHNS

Foucart et al 1307.7685

indistinguishable from BBH

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

SXS, F. Foucart



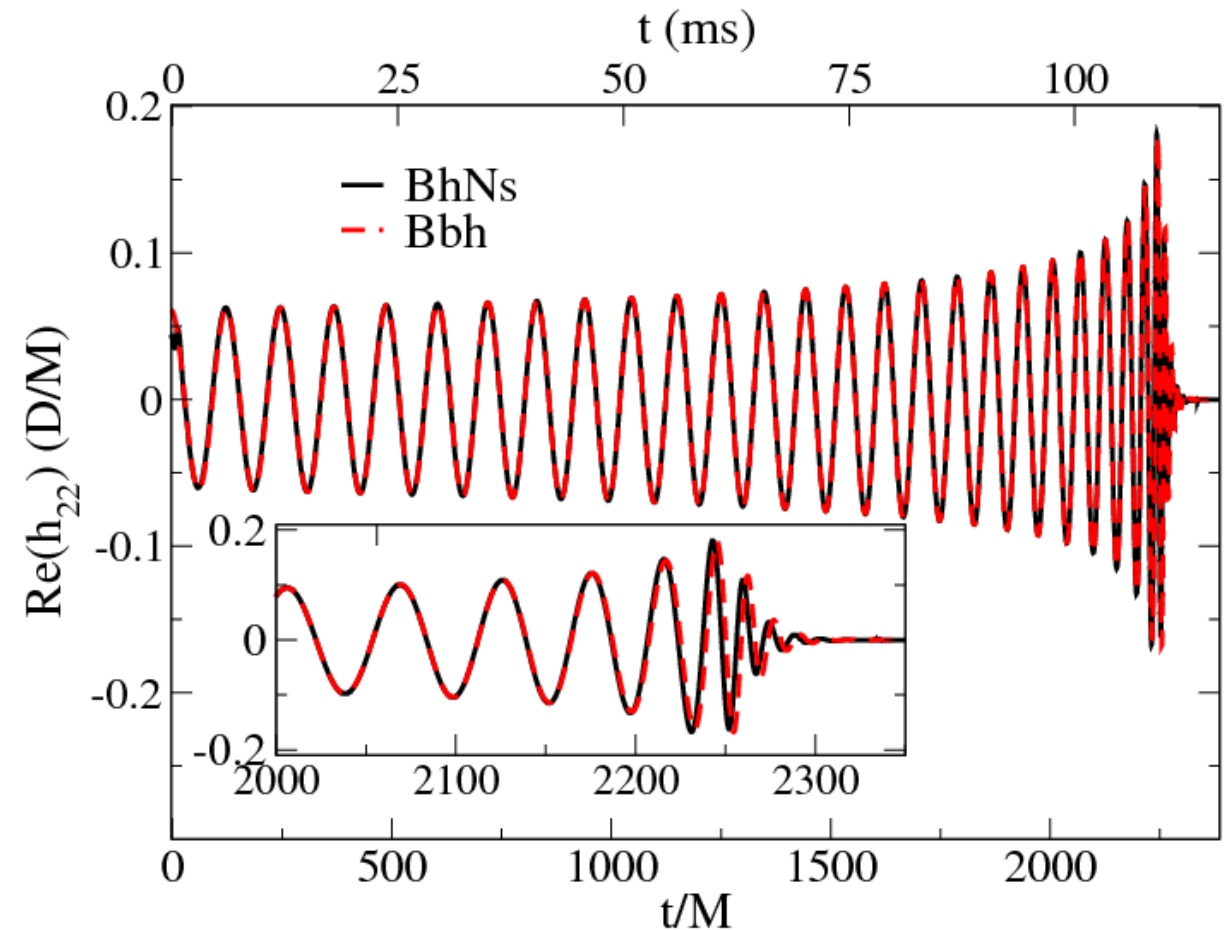
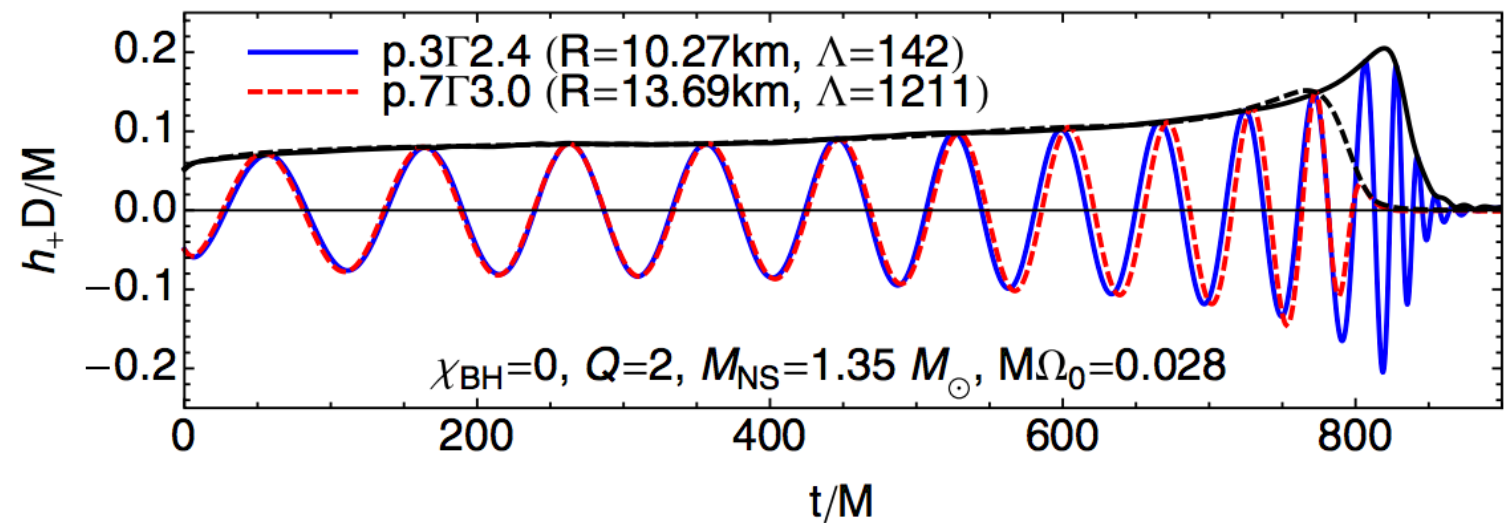
NSBH gravitational waves

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

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

“nondisruptive” BHNS
Foucart et al 1307.7685
indistinguishable from BBH

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



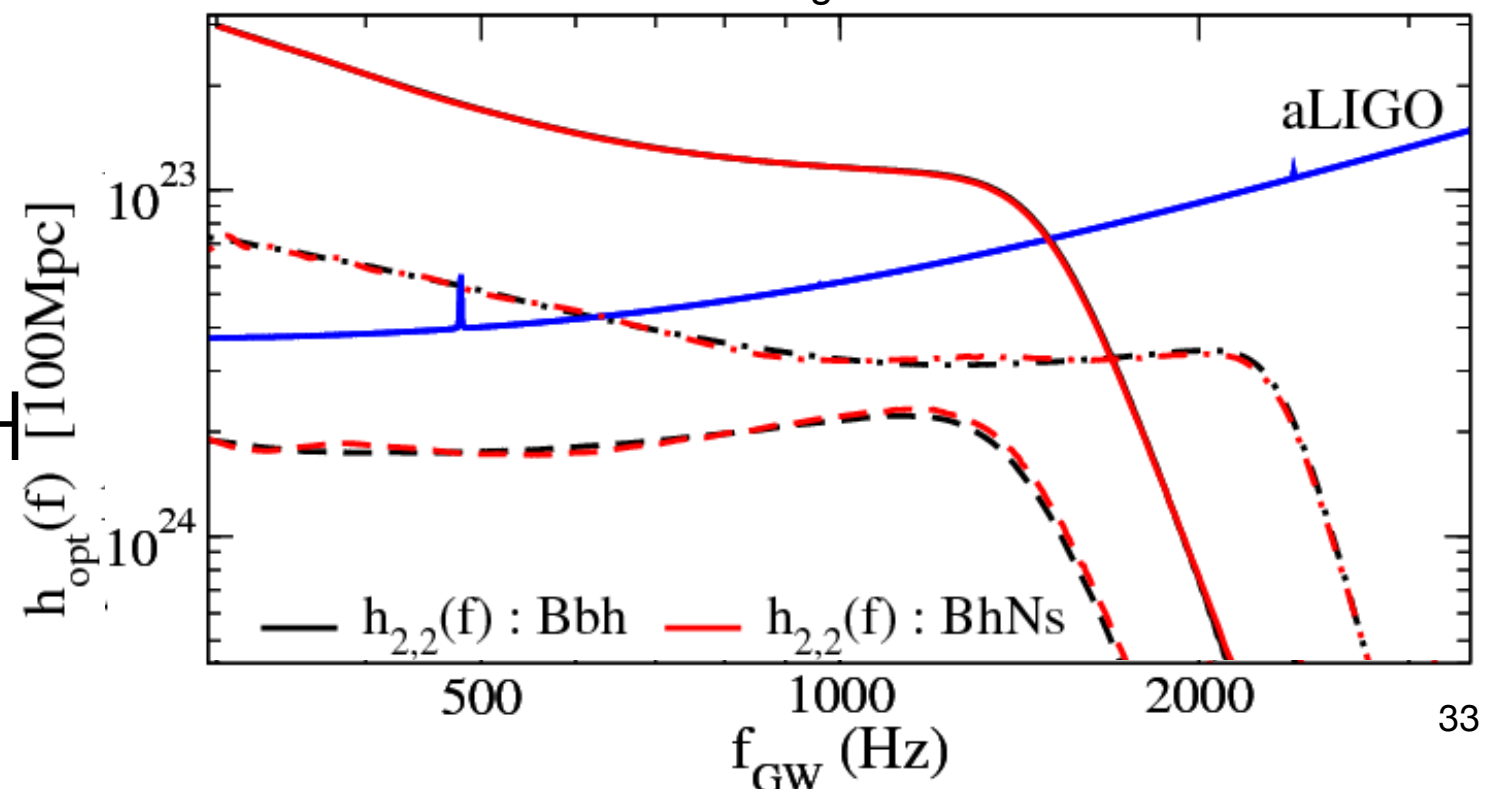
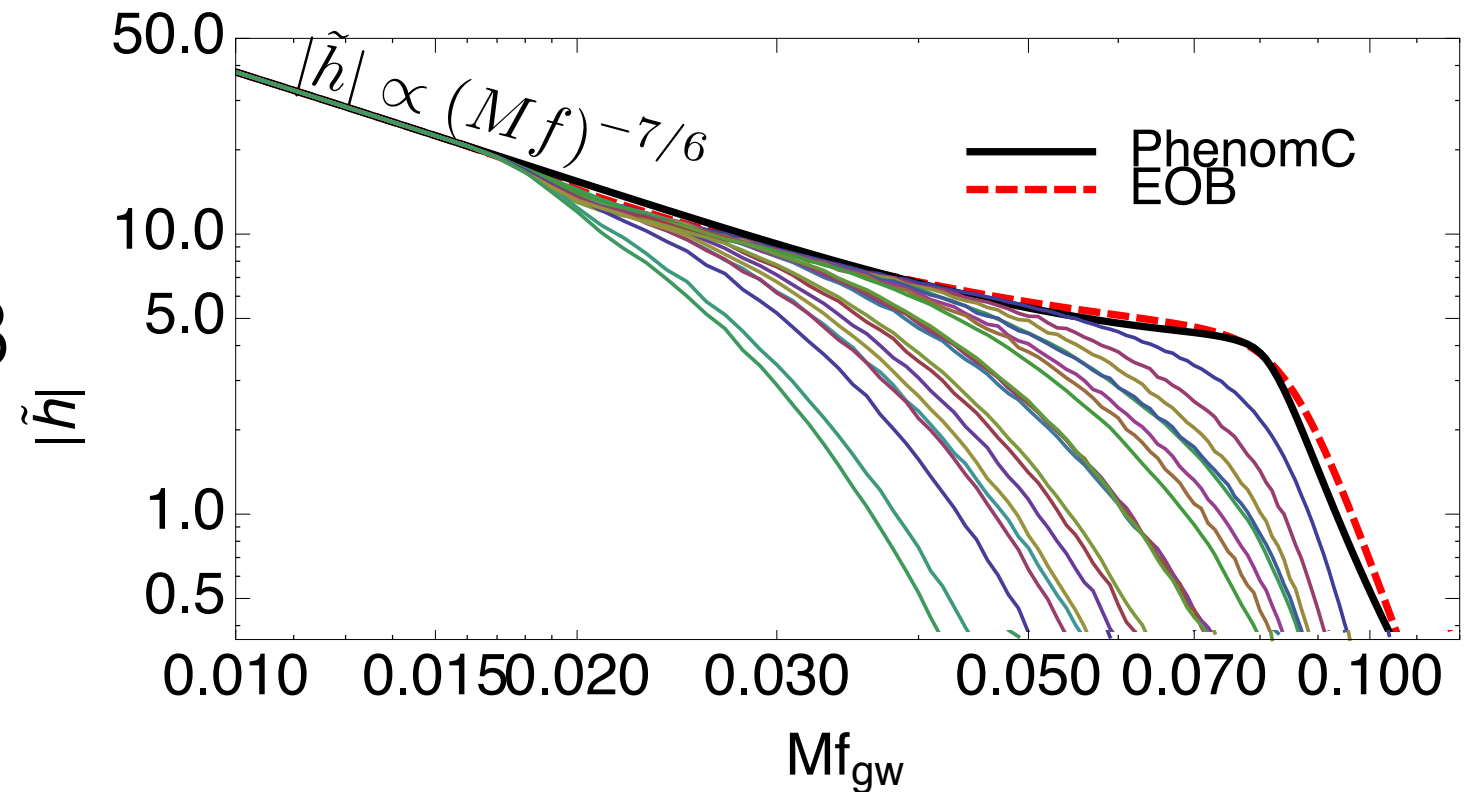
NSBH spectra

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

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

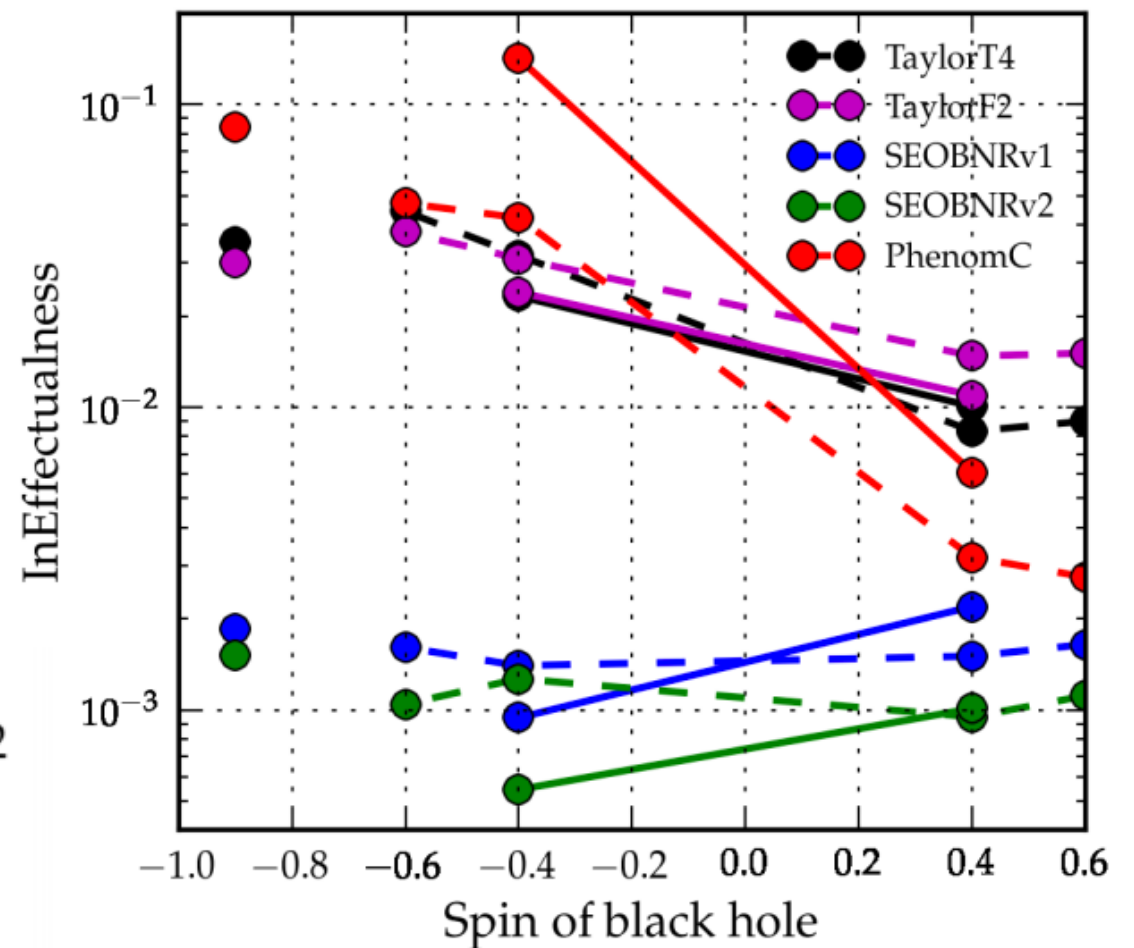
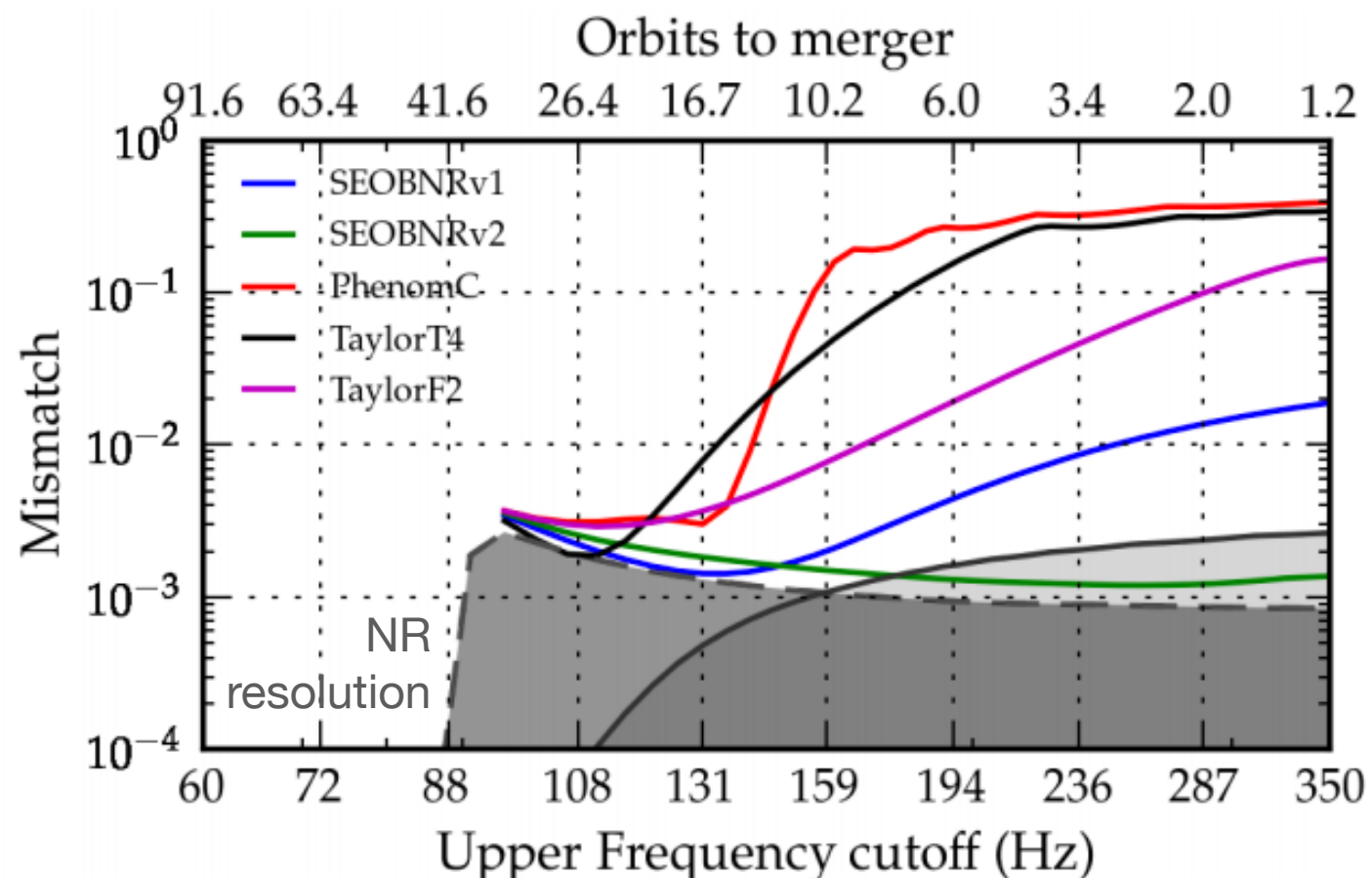
“nondisruptive” BHNS
 Foucart et al 1307.7685
 indistinguishable from BBH

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



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

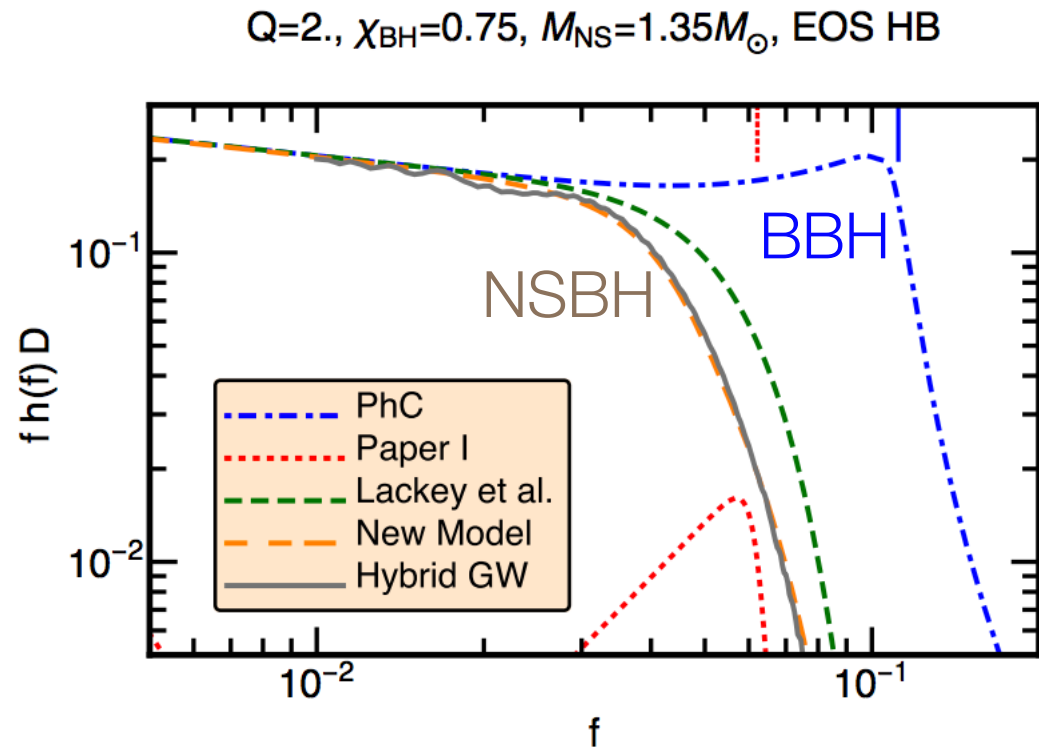
Kumar et al 1507.00103
Match and template-bank
effectualness of BBH
waveform models for high
mass-ratio NSBH



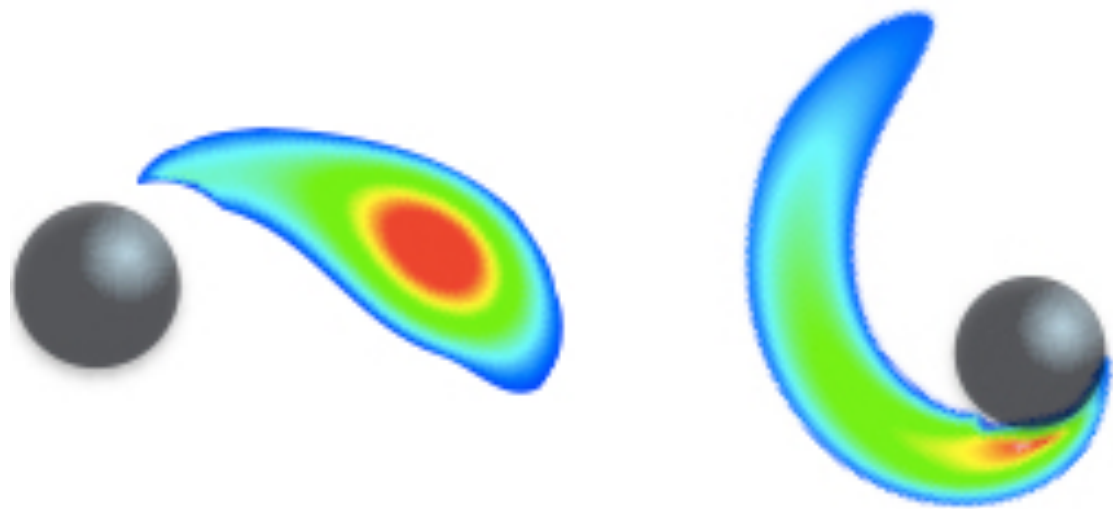
Parameter space
challenges:

- Possible high-spin BH
- High mass ratio

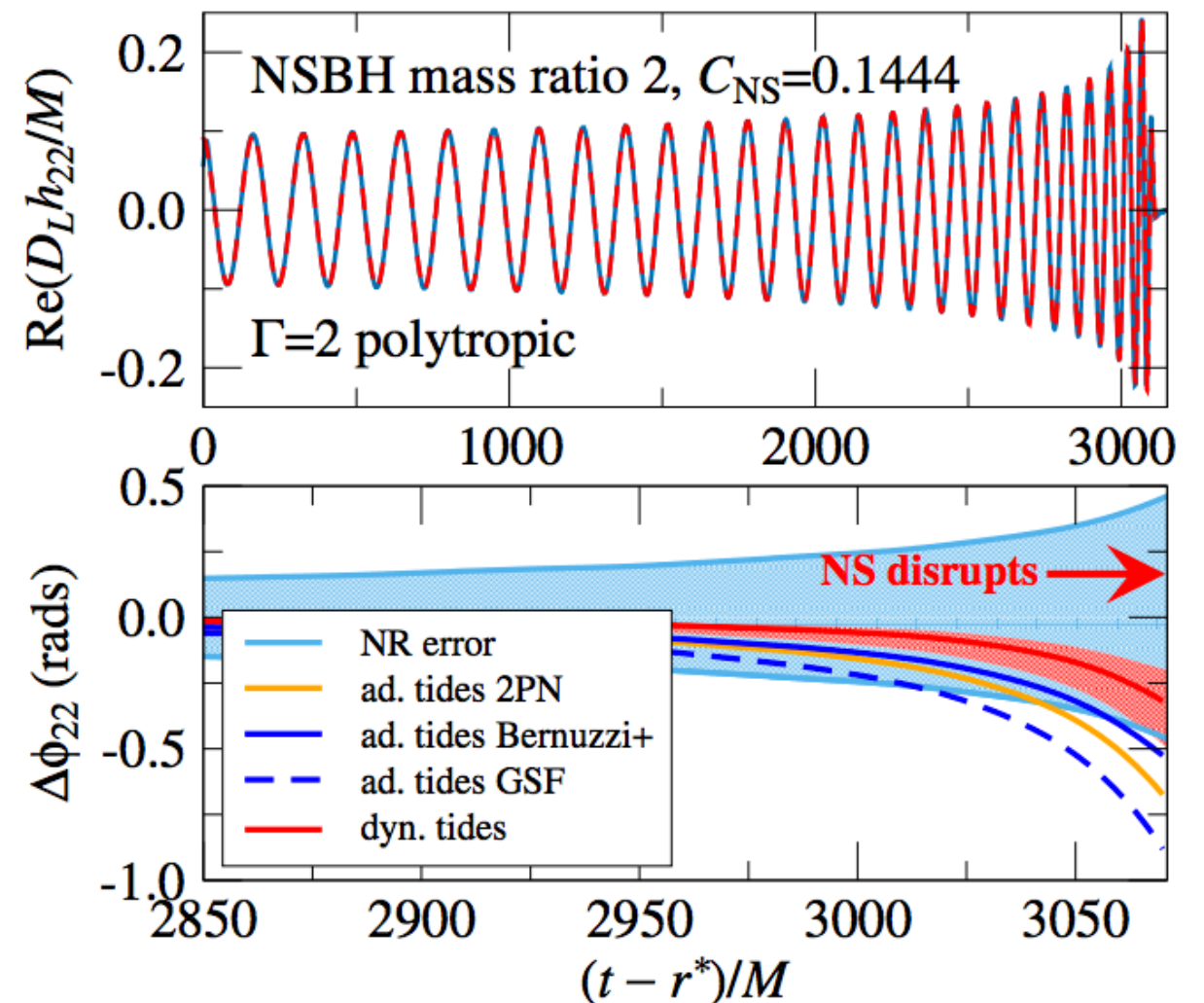
Disruptive NSBH: waveform models



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
- Burst 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

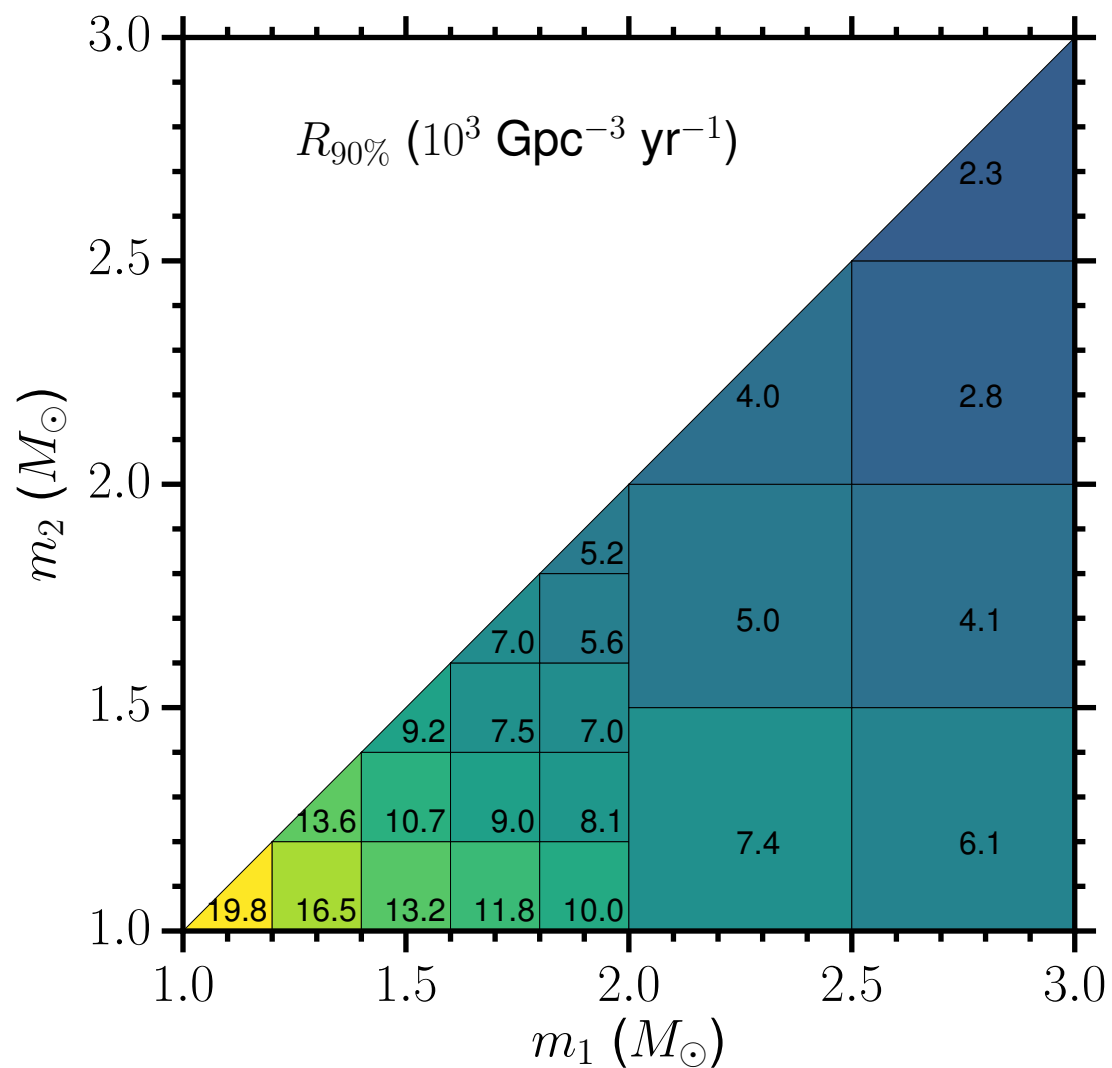
Implications of non-detection: rate constraint

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

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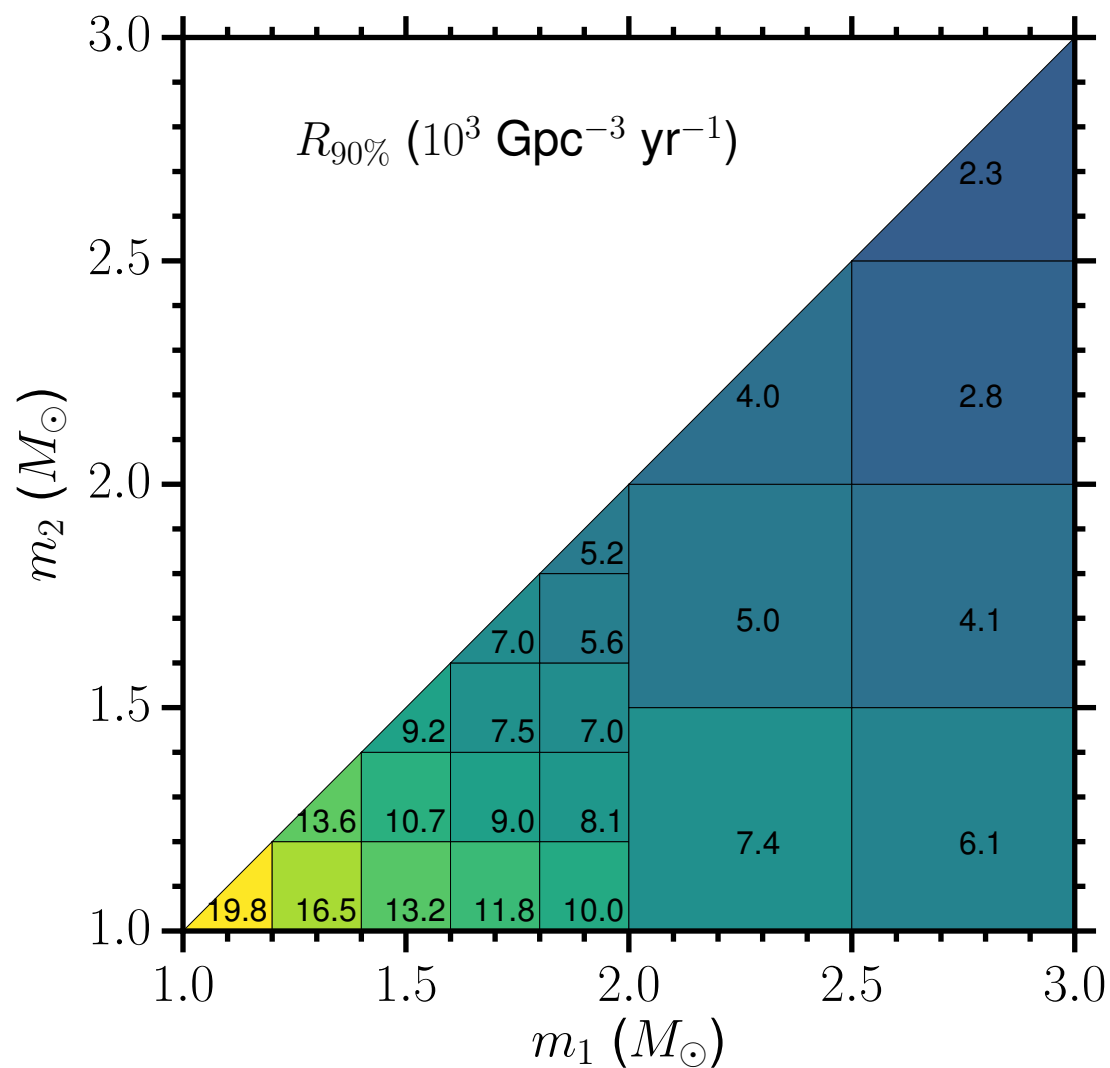
[1,3] M_{\odot} neutron stars



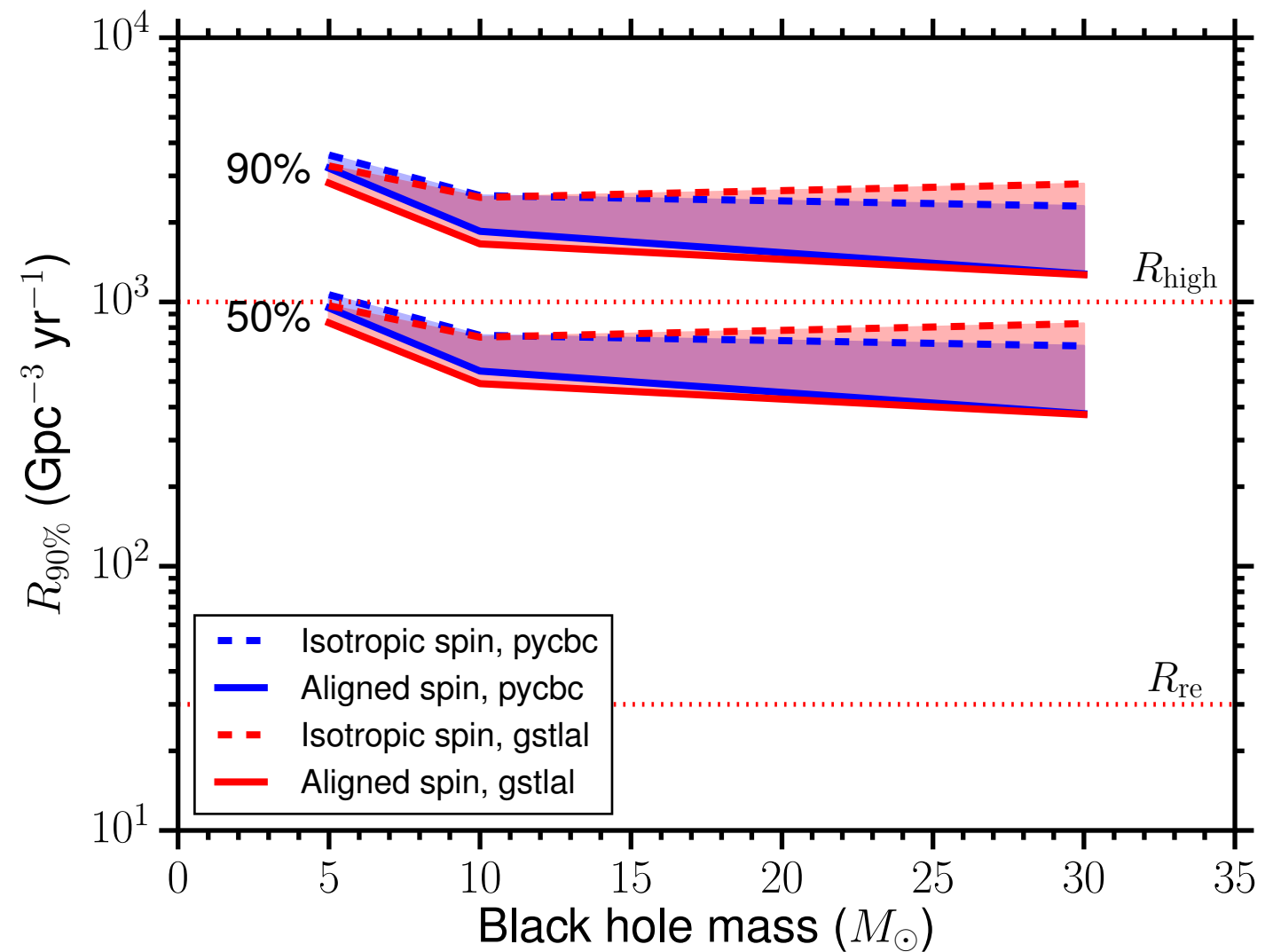
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[1,3] M_{\odot} neutron stars



Black holes and 1.4 M_{\odot} neutron stars



Lackey and Wade (40 signals)
<http://arxiv.org/abs/1410.8866>

