Astrophysical Rates of Gravitational-Wave Compact Binary Sources in O3

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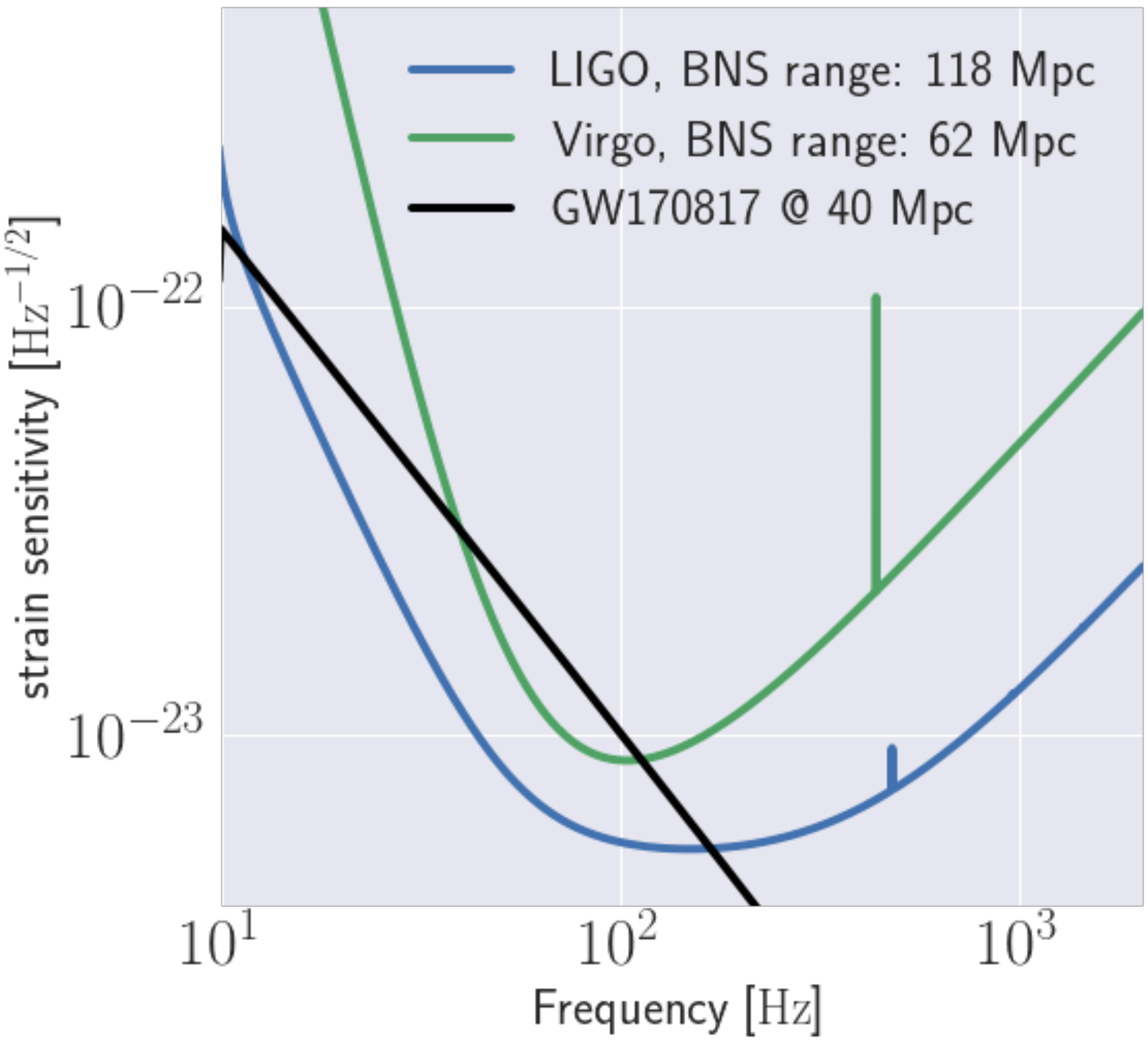
for the LIGO and Virgo Collaborations

DCC: LIGO-G1800370

Strain sensitivity for LIGO and Virgo
Values are projected and representative, **but not official**
Actual strain sensitivity **may be different** in O3



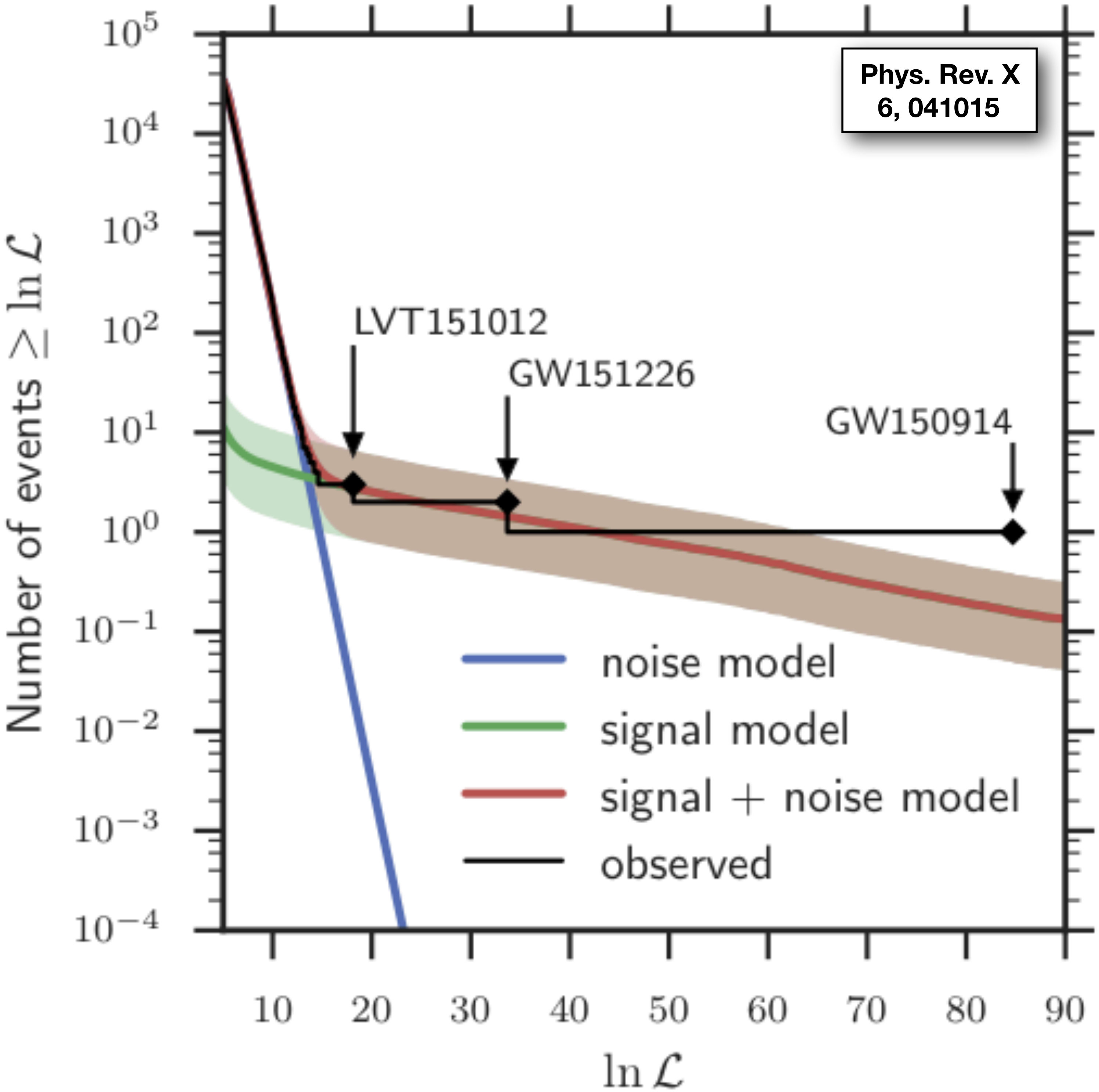
BNS **ranges** quoted for a **1.4+1.4** M⊙ face-on system at **SNR 8** in a single instrument, averaged over binary orientations and sky location

for O3…
Expected LIGO BNS range: **120 Mpc**
Expected Virgo BNS range: **65 Mpc**

GW170817 is at **1/3** (LIGO) of the sky/orientation averaged range for O3

Calculating event rates and significance

Model comparison of noise background and signal distributions of ranking statistic



Expected number of counts calibrated to surveyed space-time volume <VT>

$$V = \int f(z, \mathcal{M}_c, \cdots) \frac{1}{1+z} \frac{dV}{dz} dz$$

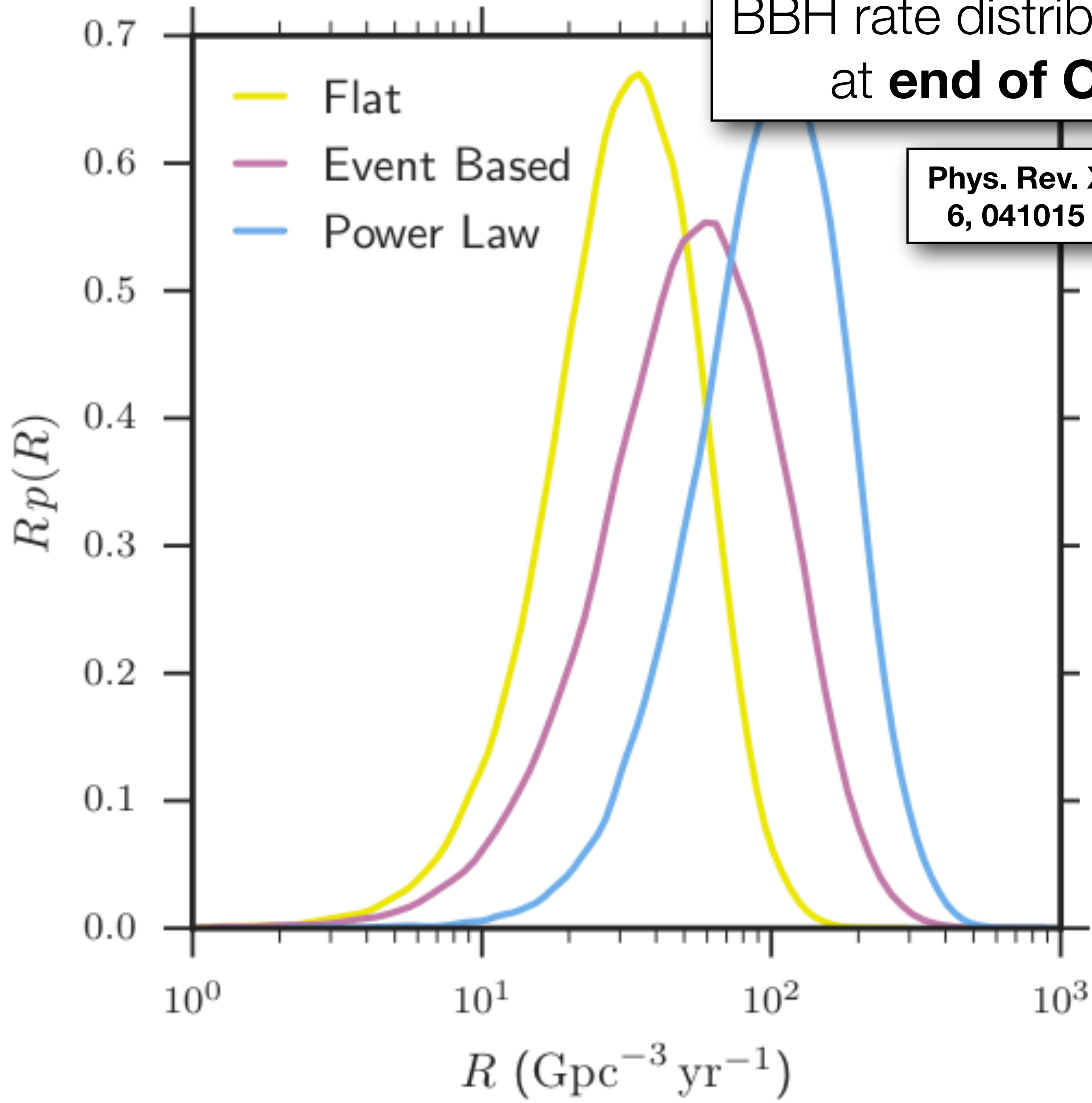
→ R ~ N/<VT>

Moving pieces

VT is dependent on instrument duty cycle and SNR threshold

alerts could have smaller SNRs than “gold plated” events

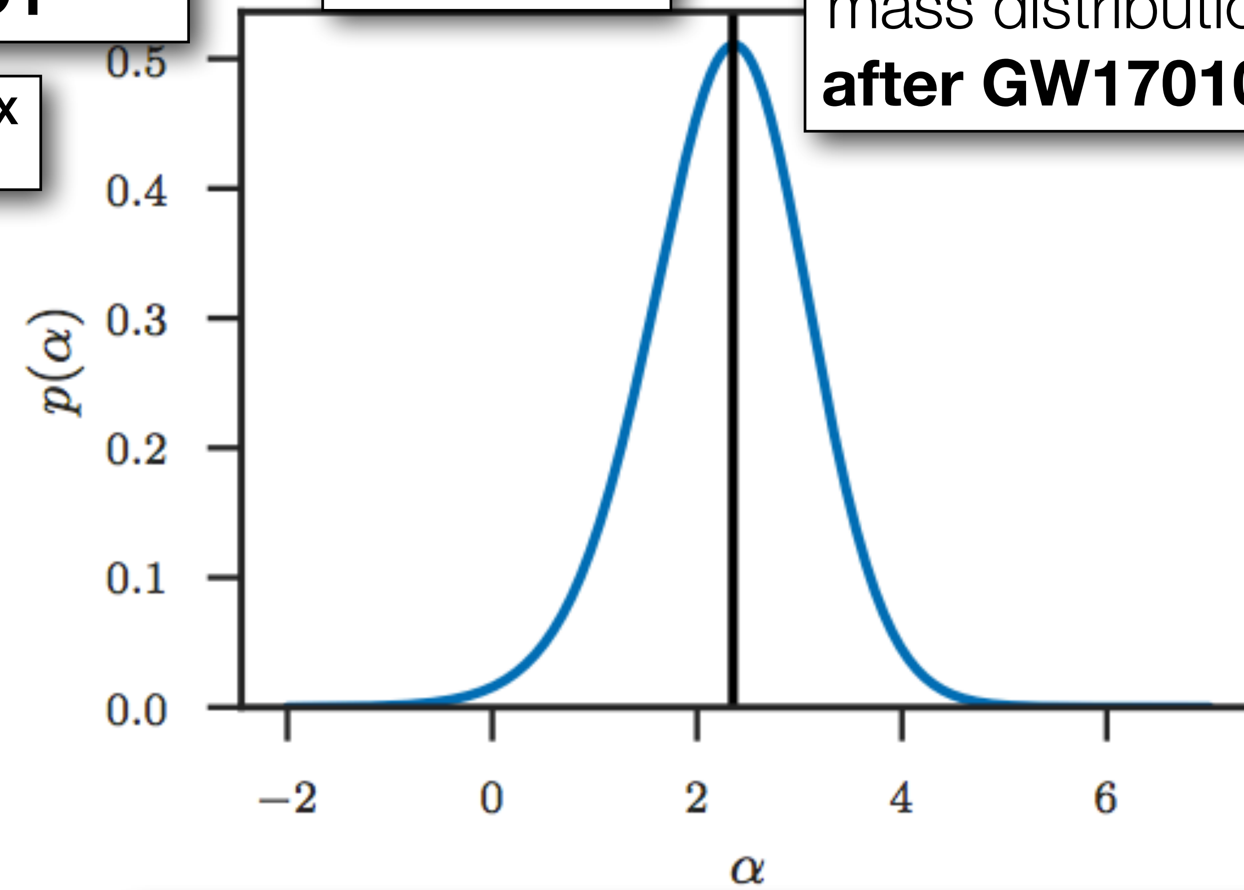
all binary physics is not encoded in searches: *assumed SNR loss is small*



BBH rate distributions at **end of O1**

Phys. Rev. X 6, 041015

Phys. Rev. Lett. 118, 221101



primary BH mass distribution **after GW170104**

Basic Pop. Modeling: Assume **$p(m_1) \propto m_1^{-\alpha}$** and fit observations to model

After GW170104 (N_{BBH}=3.9)
Uniform in log mass: **12 - 65 Gpc^{-3}yr^{-1}**
Power law (α=-2.35) *only*: **40 - 213 Gpc^{-3}yr^{-1}**
Unified interval: **12 - 213 Gpc^{-3}yr^{-1}**

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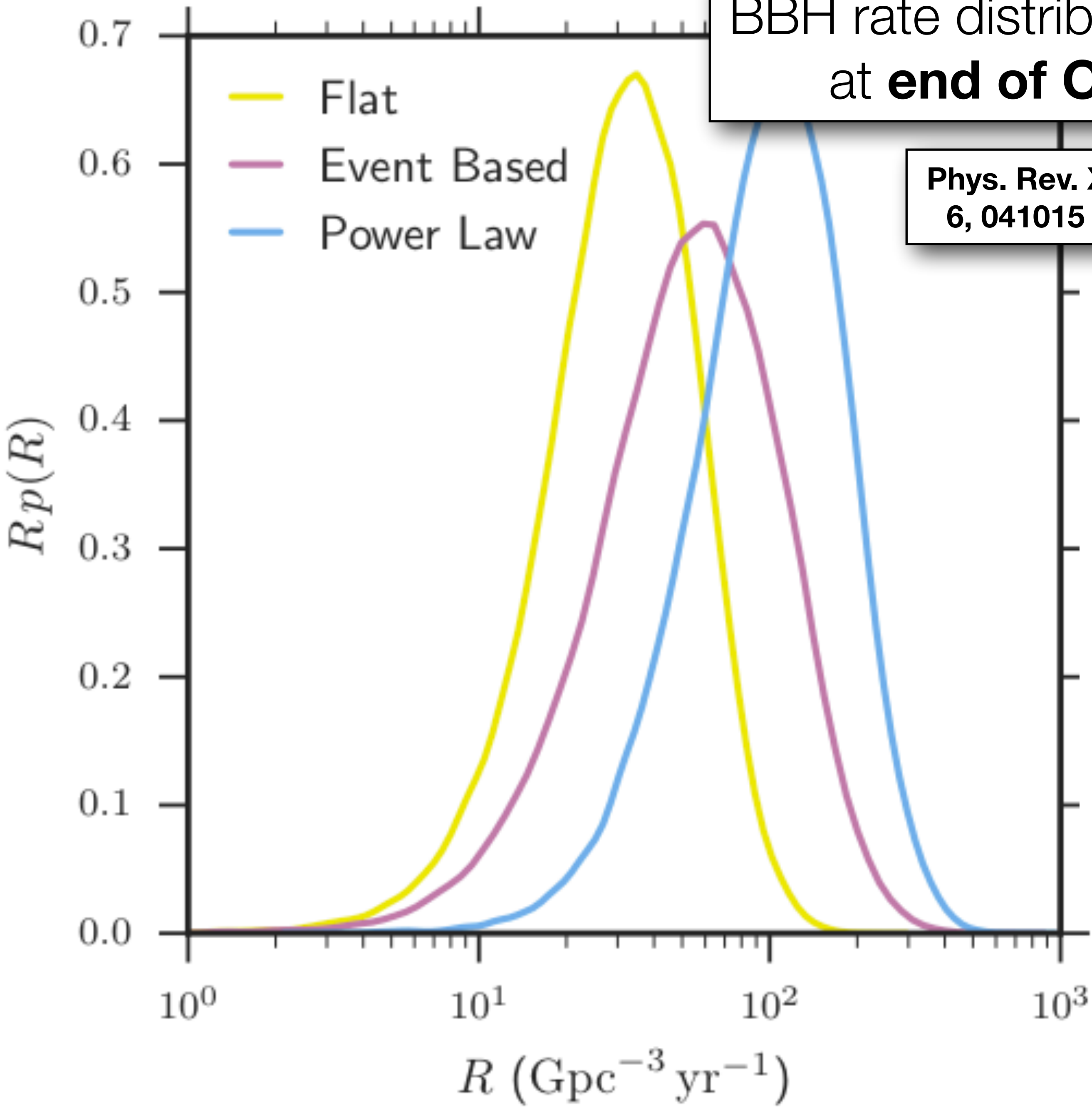

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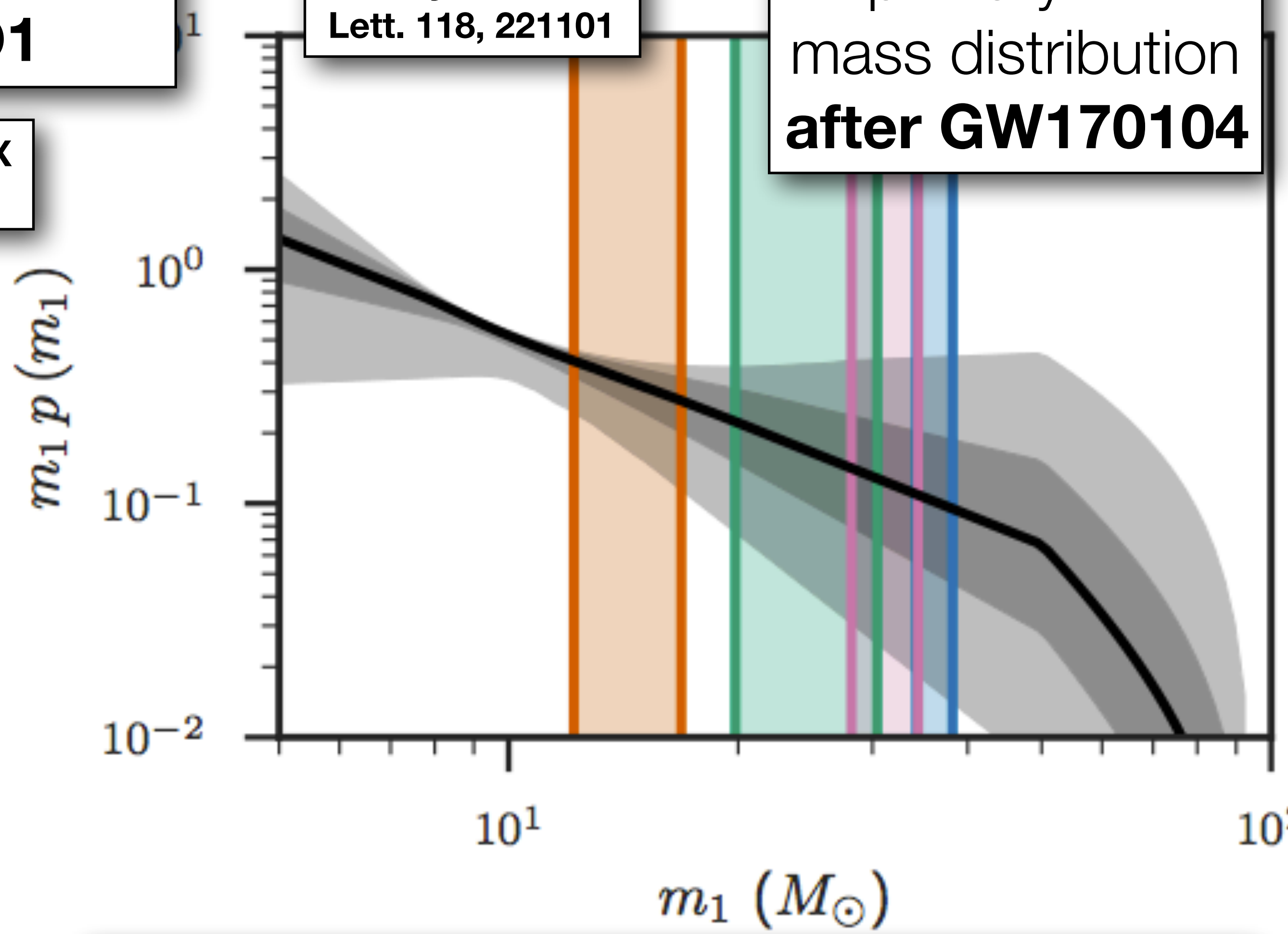

Towards Pop. Distributions:
Constraints on the primary mass distribution from current observations (assumes power law from previous slide)

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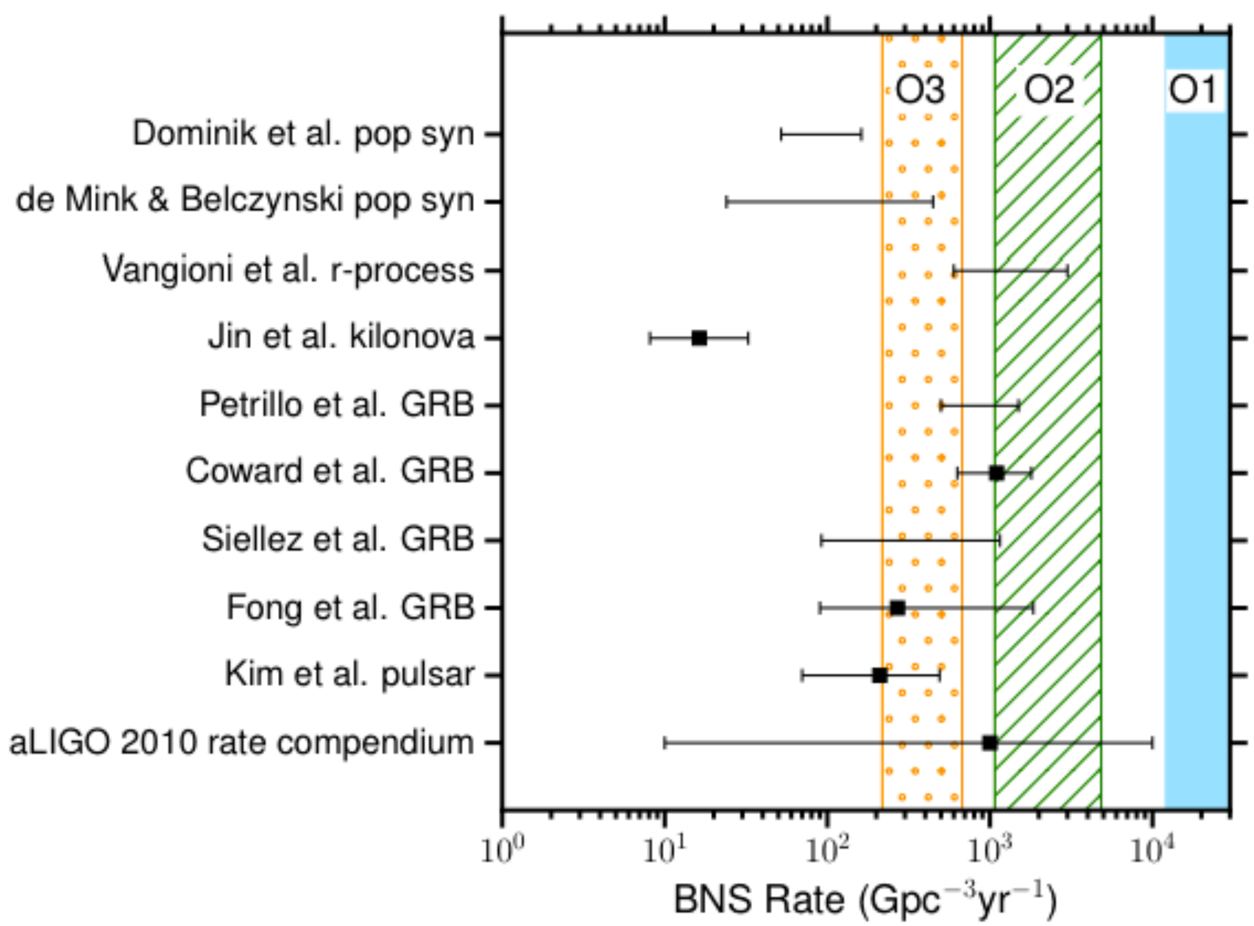
BNS/NSBH rate distributions at **end of O1**

ApJ Letters, 832, 2



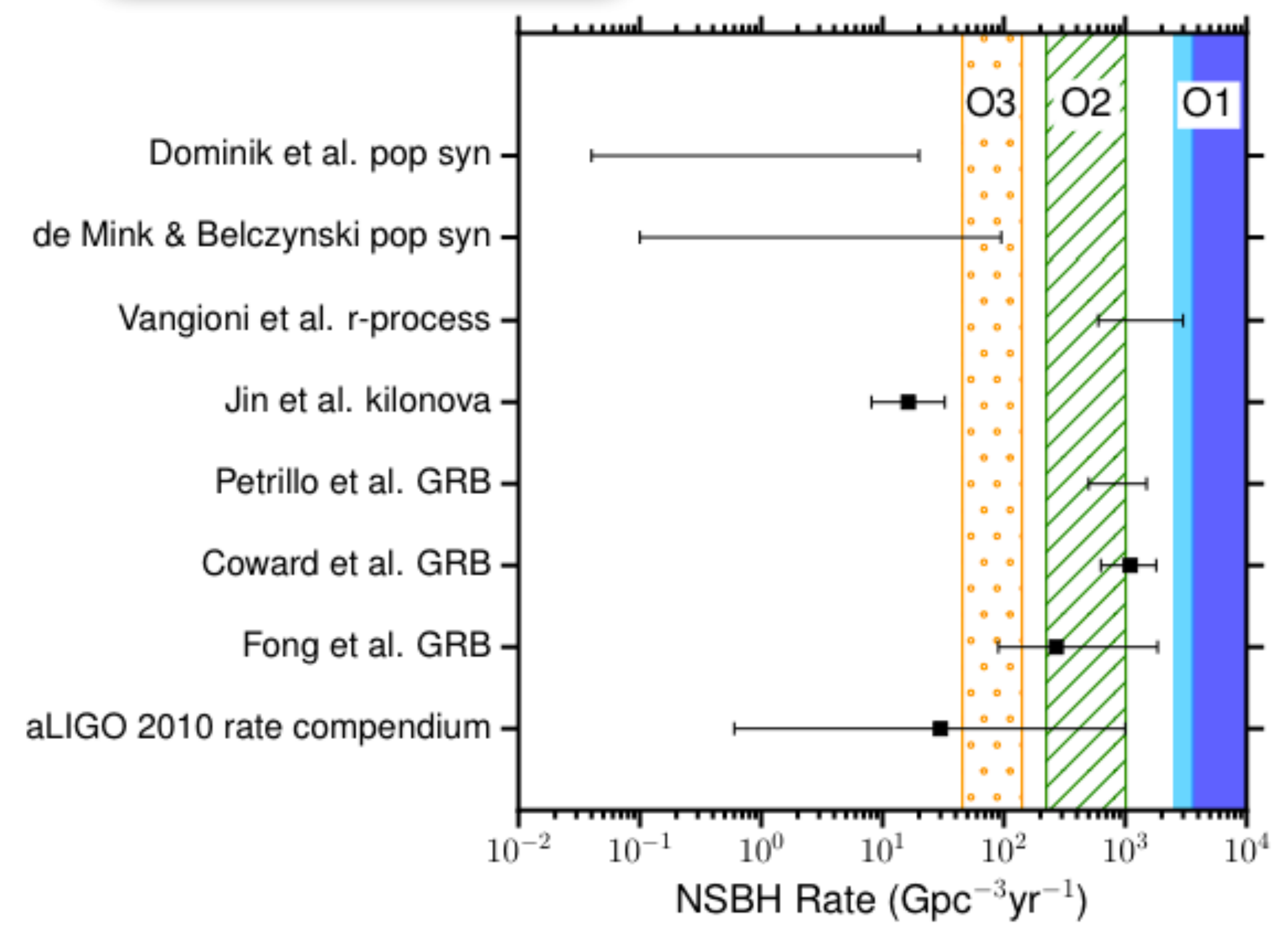


TABLE IV: Compact binary coalescence rates per Mpc^3 per Myr.[a]

Source	R_{low}	R_{re}	R_{high}	R_{max}
NS-NS (Mpc^{-3} Myr^{-1})	0.01 [1]	1 [1]	10 [1]	50 [16]
NS-BH (Mpc^{-3} Myr^{-1})	6×10^{-4} [18]	0.03 [18]	1 [18]	
BH-BH (Mpc^{-3} Myr^{-1})	1×10^{-4} [14]	0.005 [14]	0.3 [14]	

Class. Quantum Grav. 27 (2010) 173001

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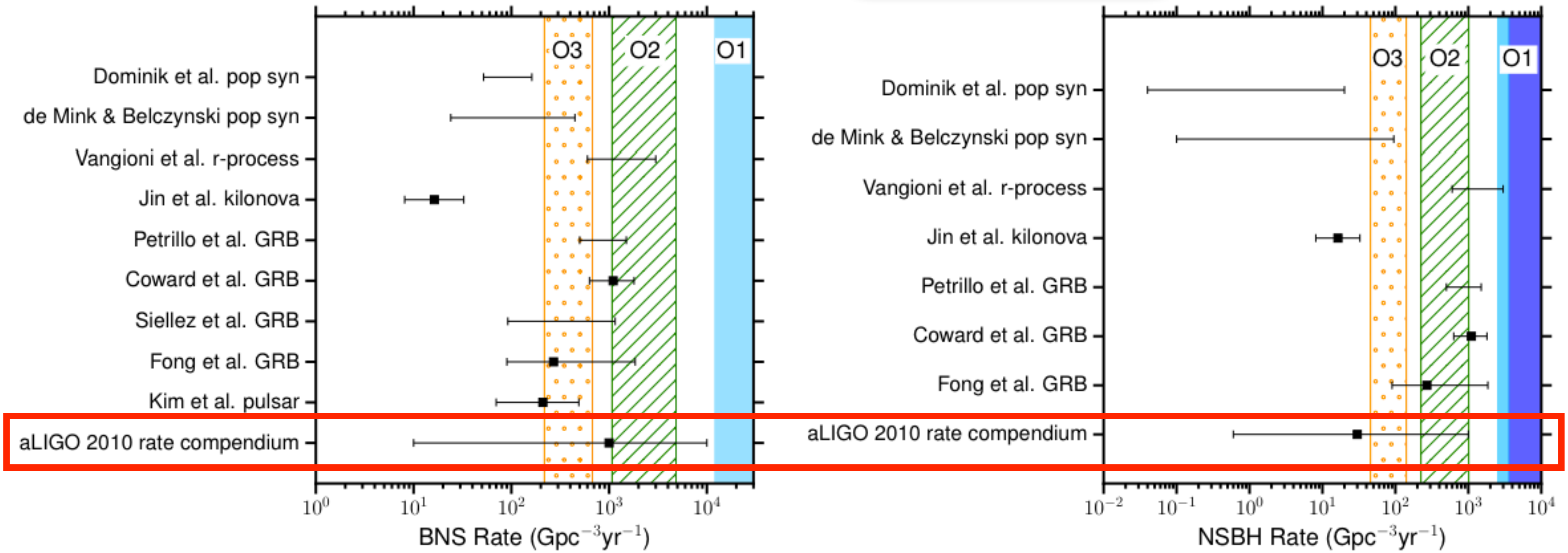

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Living Reviews in Relativity (in press)

Epoch			2015 – 2016	2016 – 2017	2018 – 2019	2020+	2024+
Planned run duration			4 months	9 months	12 months	(per year)	(per year)
Expected burst range/Mpc		LIGO	40 – 60	60 – 75	75 – 90	105	105
		Virgo	—	20 – 40	40 – 50	40 – 70	80
		KAGRA	—	—	—	—	100
Expected BNS range/Mpc		LIGO	40 – 80	80 – 120	120 – 170	190	190
		Virgo	—	20 – 65	65 – 85	65 – 115	125
		KAGRA	—	—	—	—	140
Achieved BNS range/Mpc		LIGO	60 – 80	60 – 100	—	—	—
		Virgo	—	25 – 30	—	—	—
		KAGRA	—	—	—	—	—
Estimated BNS detections			0.05 – 1	0.2 – 4.5	1 – 50	4 – 80	11 – 180
Actual BNS detections			0	1	—	—	—
90% CR	% within	5 deg^2	< 1	1 – 5	1 – 4	3 – 7	23 – 30
		20 deg^2	< 1	7 – 14	12 – 21	14 – 22	65 – 73
	median/deg^2		460 – 530	230 – 320	120 – 180	110 – 180	9 – 12
Searched area	% within	5 deg^2	4 – 6	15 – 21	20 – 26	23 – 29	62 – 67
		20 deg^2	14 – 17	33 – 41	42 – 50	44 – 52	87 – 90

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post-GW170817:
$R_{BNS} \sim 3.2 \times 10^{-7} - 4 \times 10^{-6}\ Mpc^{-3} yr^{-1}$

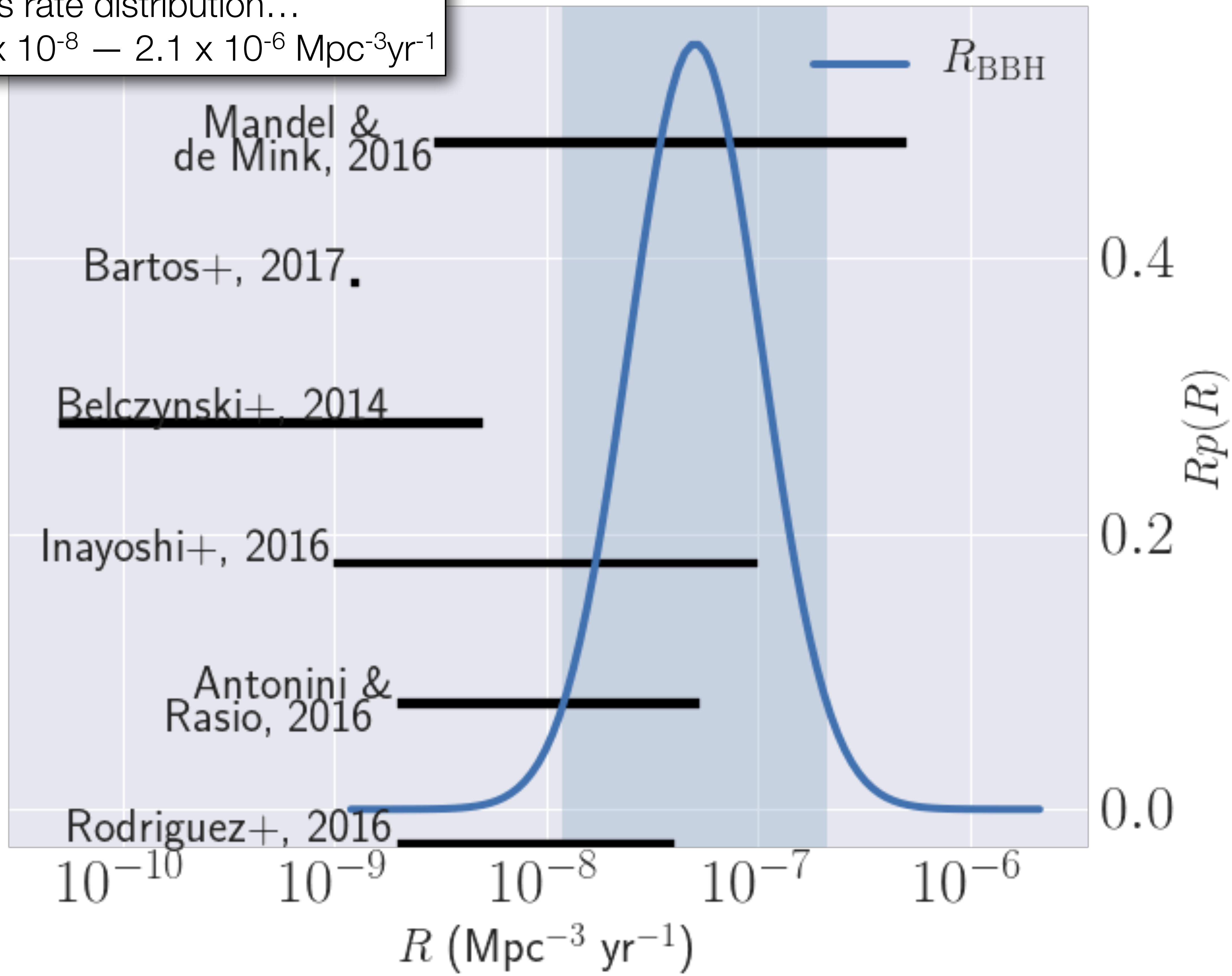
Phys. Rev. Lett. 119, 16110

Binary Black Hole Rates (post-GW170104)

Phys. Rev. Lett. 118, 221101

This rate distribution…

$R_{BBH} \sim 1.2 \times 10^{-8} - 2.1 \times 10^{-6}\ \mathrm{Mpc^{-3} yr^{-1}}$



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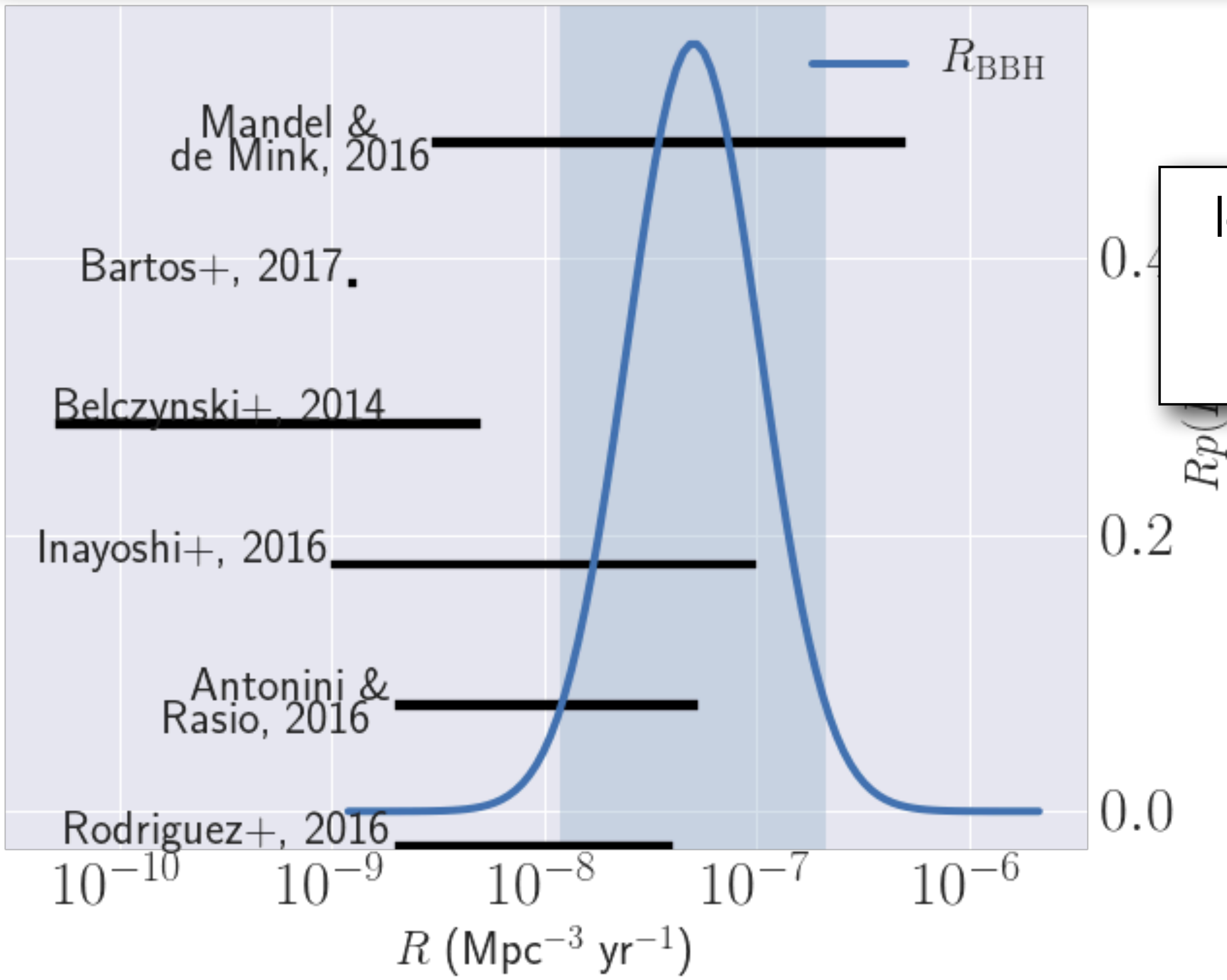

Assumptions:
$\rho_{net} > 12$
T_{obs}: 1 yr with 50% duty cycle

log-uniform: $p(m_1) \sim m^{-1}$ ($5 < m_1 < 100\ M_\odot$)
…with O3 surveyed space-time volume:
$VT_{BBH} \sim 7 \times 10^8$ Mpc^3 yr

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$R_{BBH} \sim 1.2 \times 10^{-8} — 2.1 \times 10^{-6}$ Mpc^{-3}yr^{-1}

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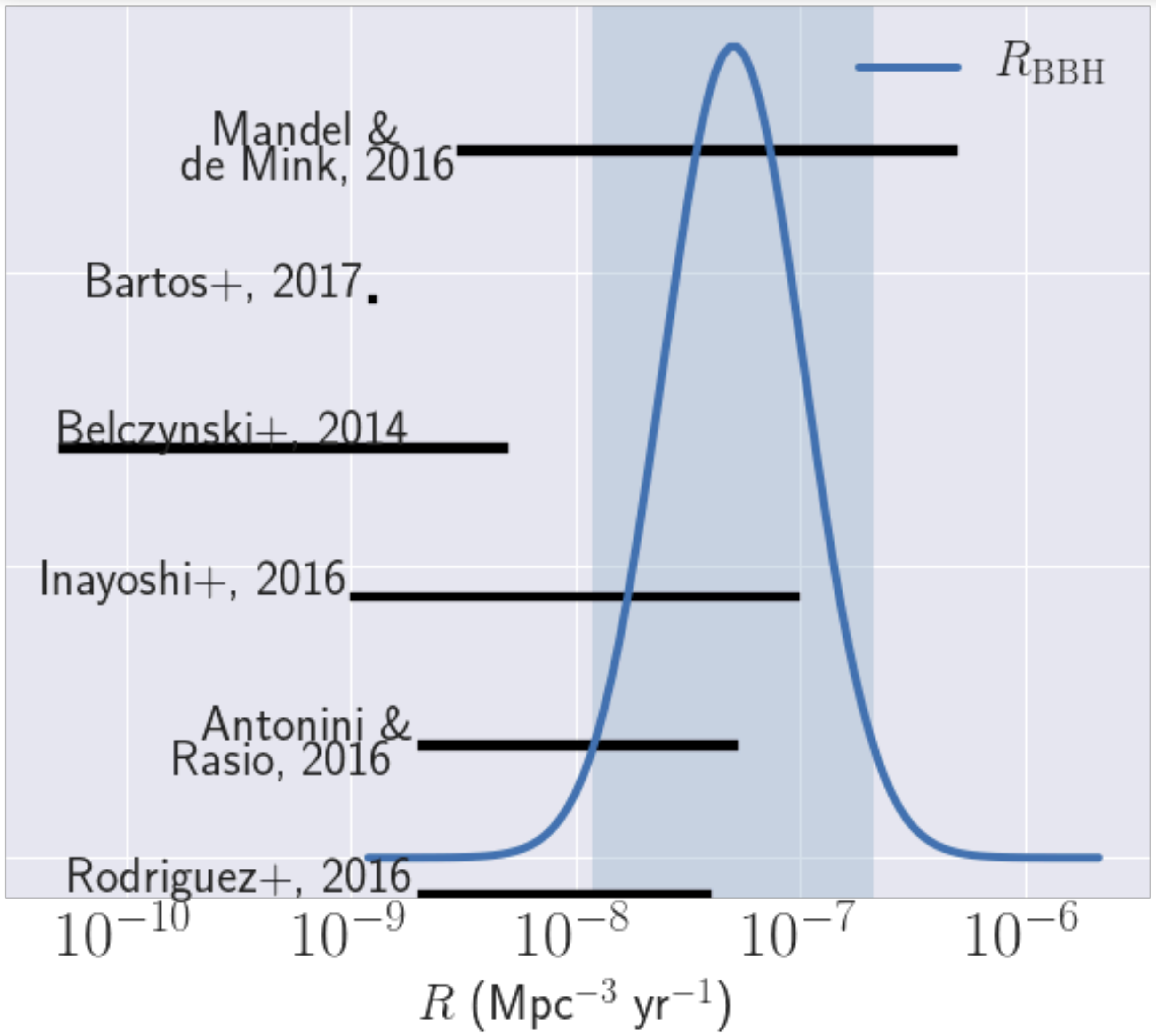

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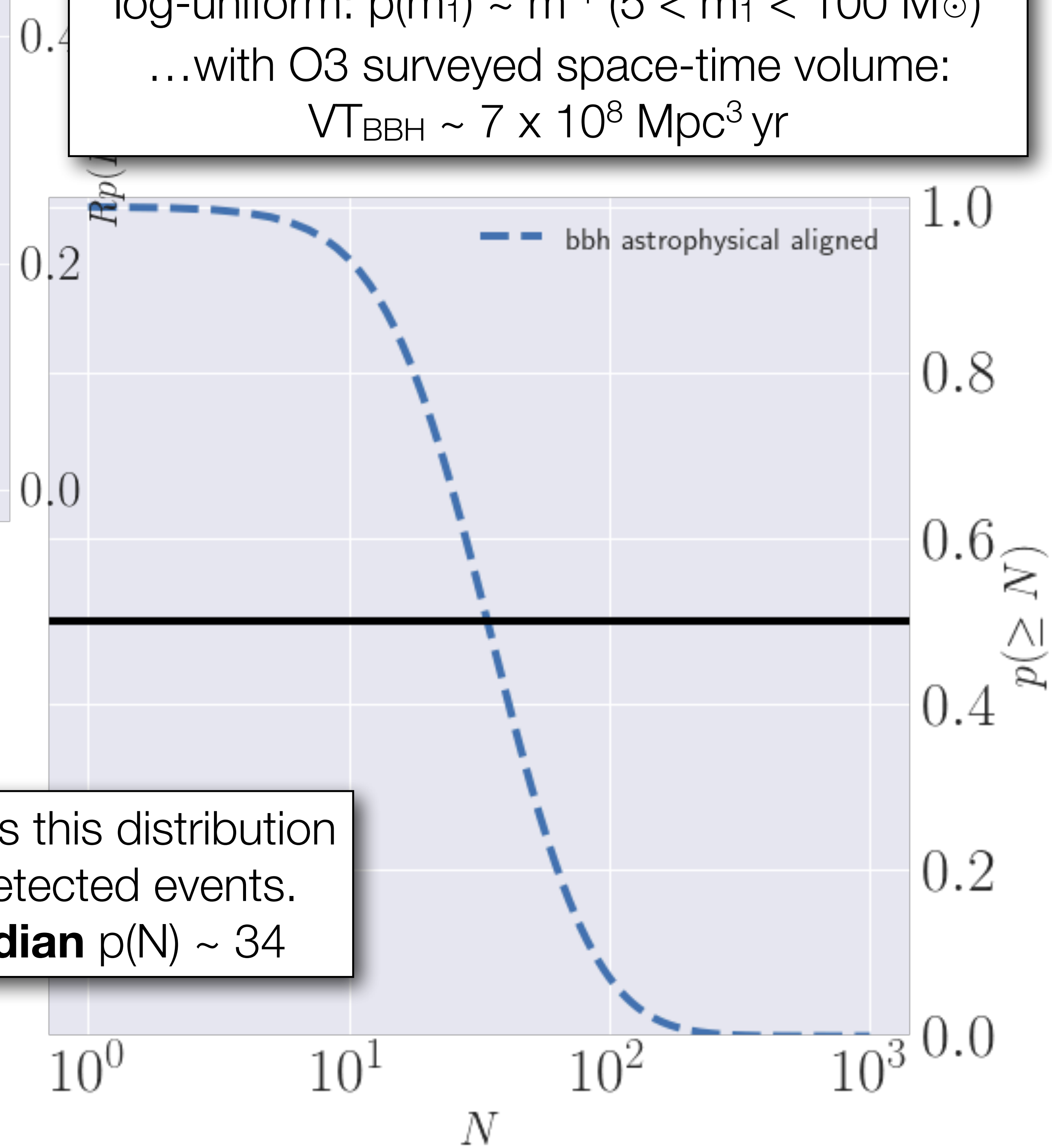

…gives this distribution of detected events.
median p(N) ~ 34

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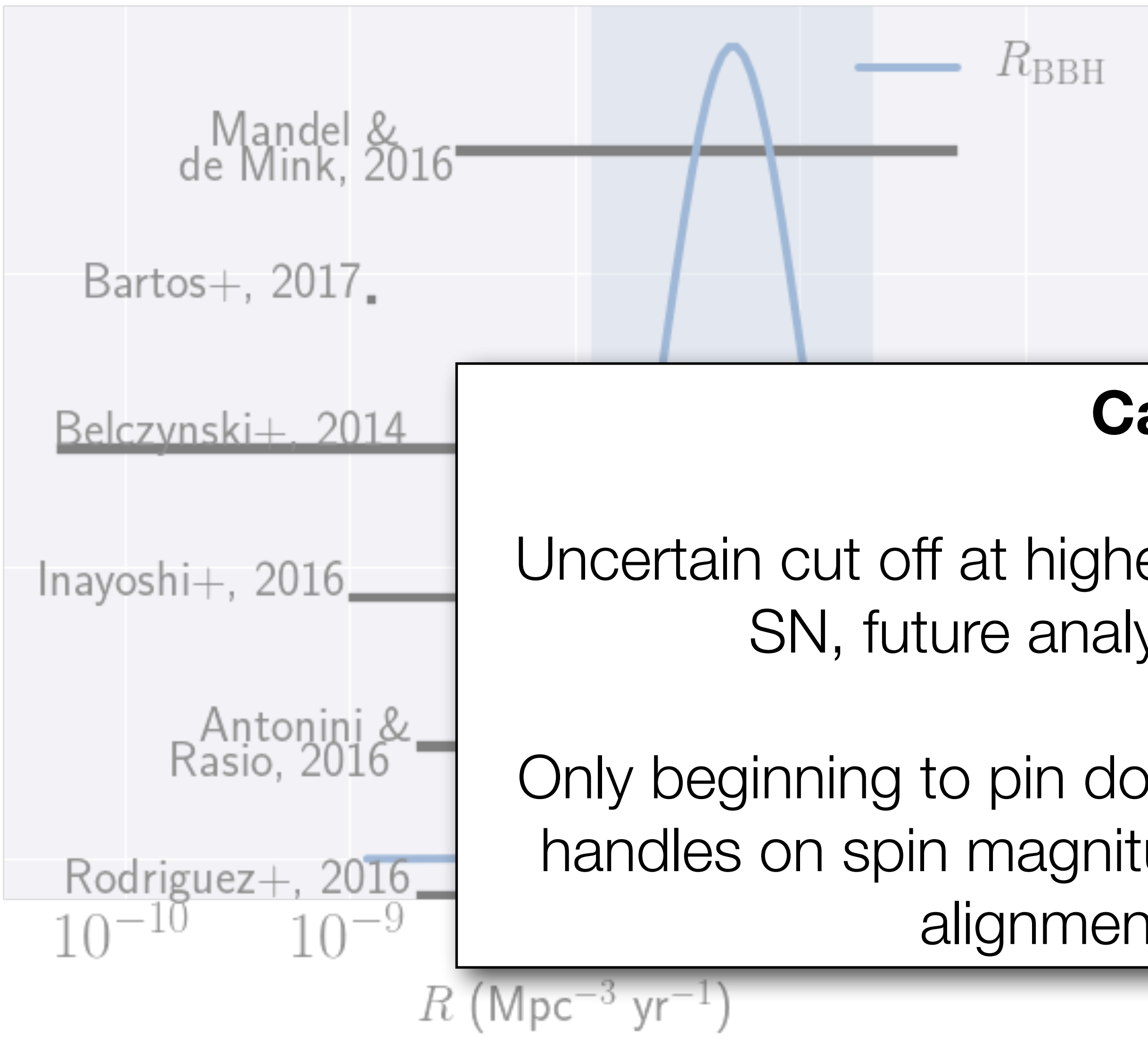

Caveats

Uncertain cut off at higher masses from pair-instability SN, future analyses to measure this

Only beginning to pin down crude mass distributions, handles on spin magnitude distribution and putative alignment in nascence

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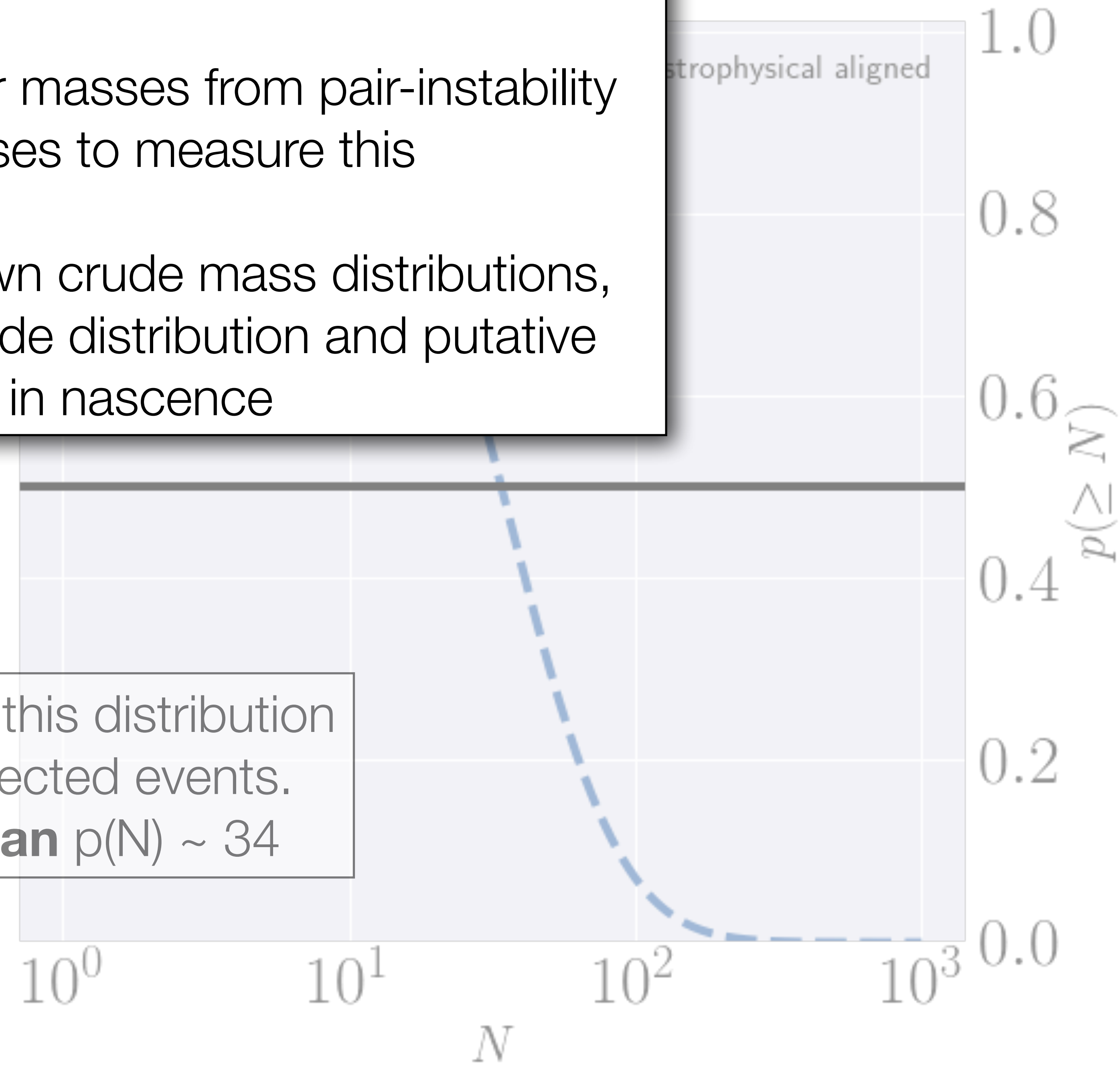

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Binary Neutron Star Rates (post-GW170817)

ApJ Letters, 832, 2
Phys. Rev. Lett. 119, 16110

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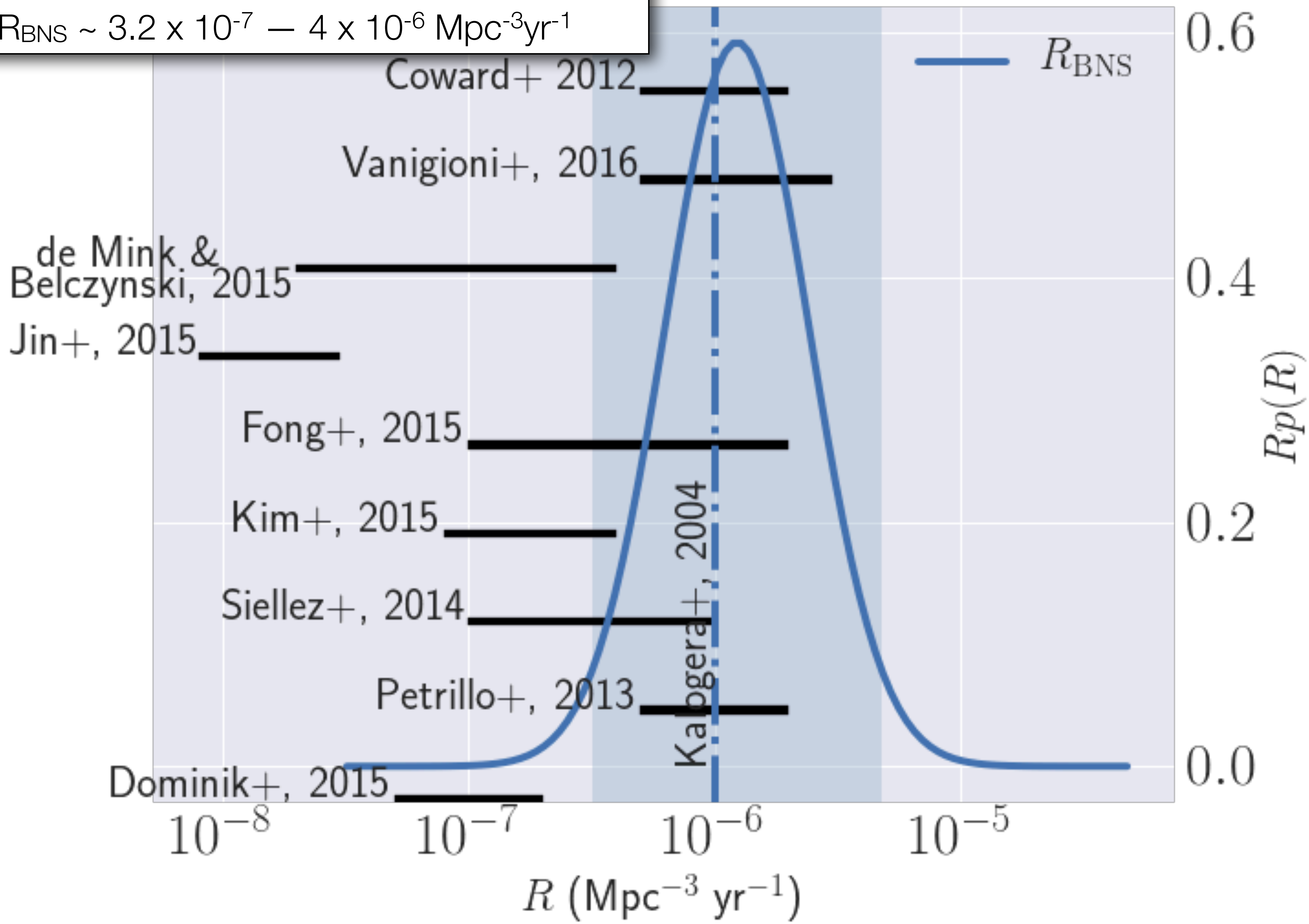
R_{BNS} ~ 3.2×10^{-7} — 4×10^{-6} $Mpc^{-3}yr^{-1}$



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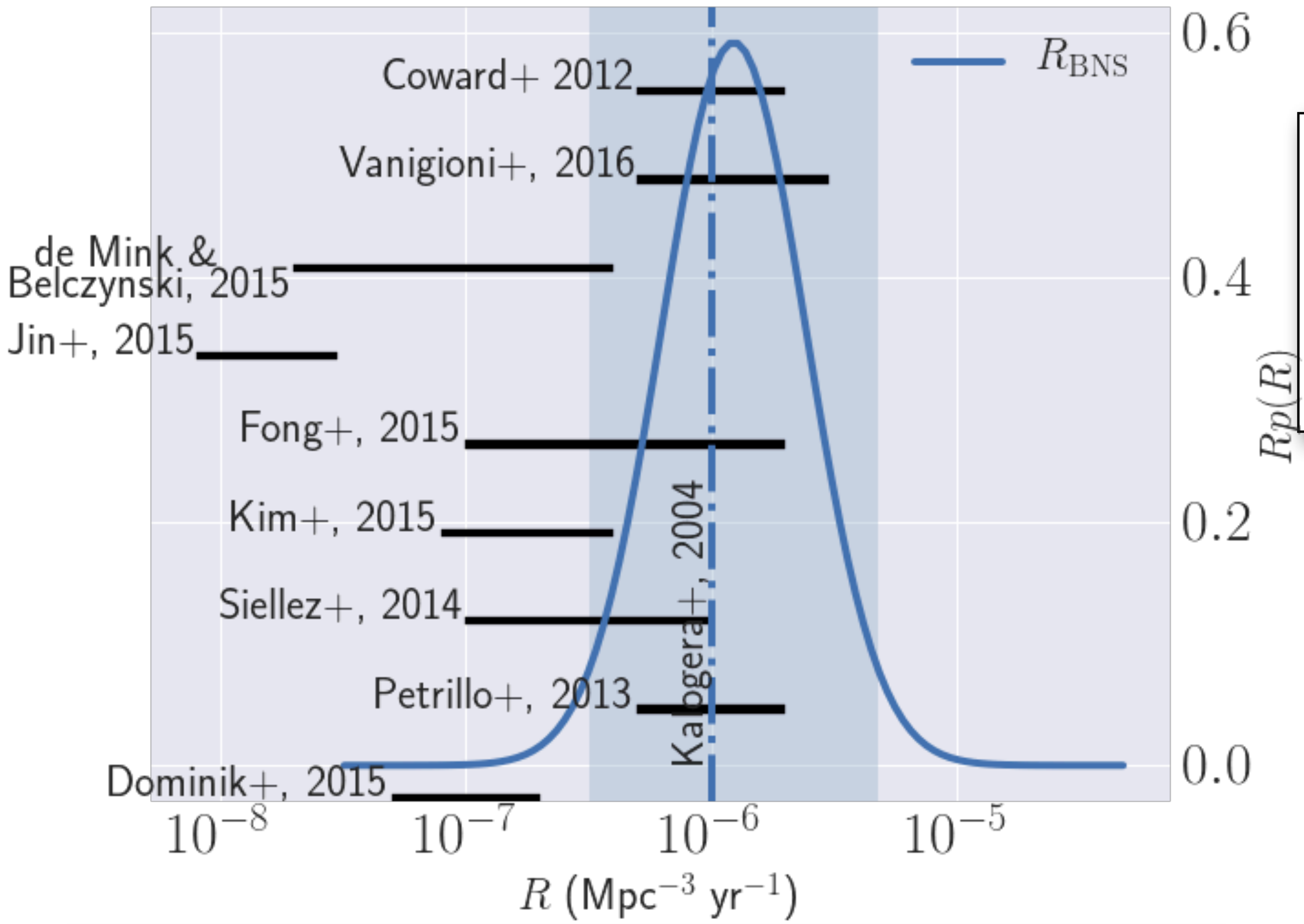

Broad (uniform): 1-3 M☉
'Milky Way-like': 1.33 ± 0.09 M☉
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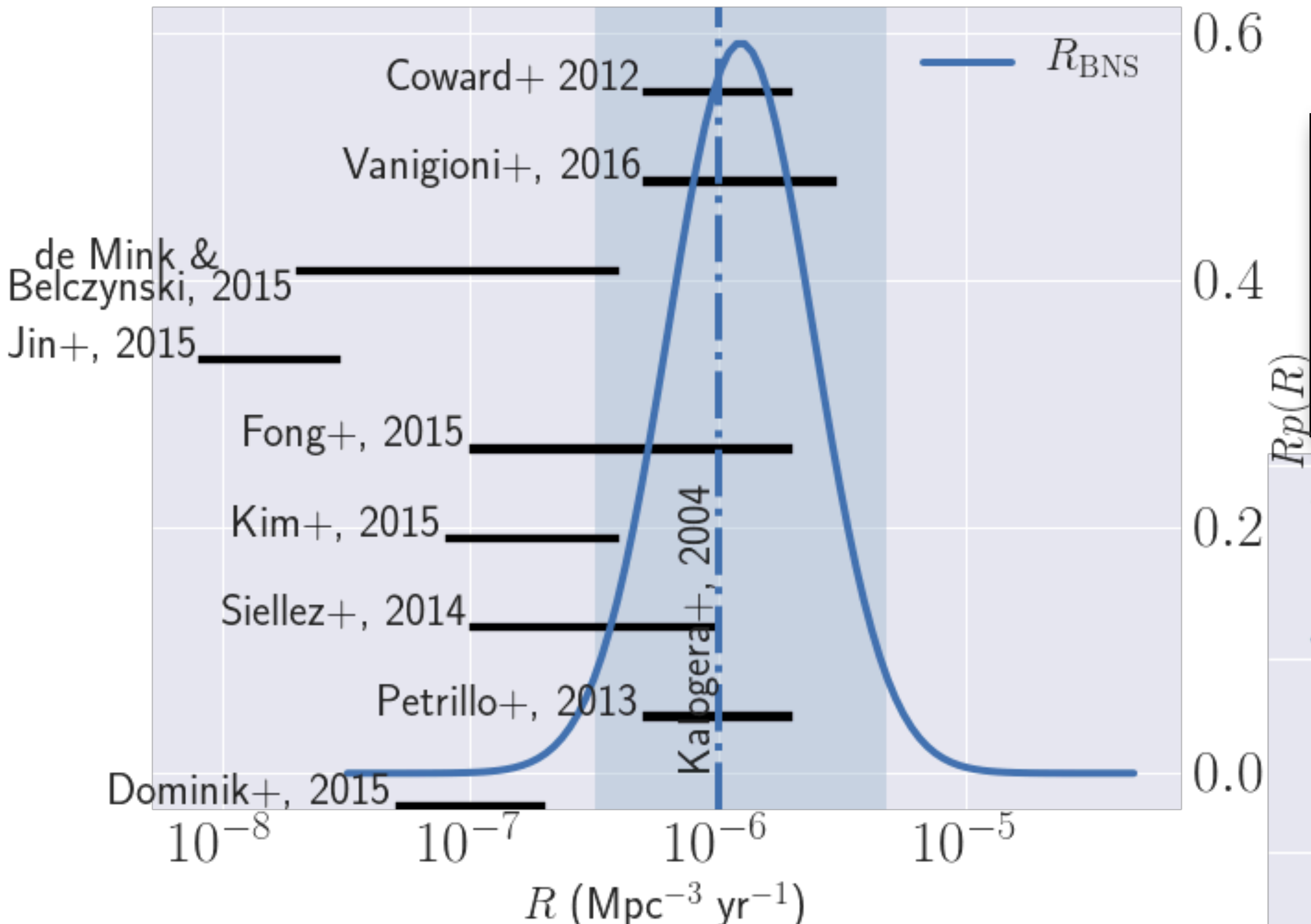

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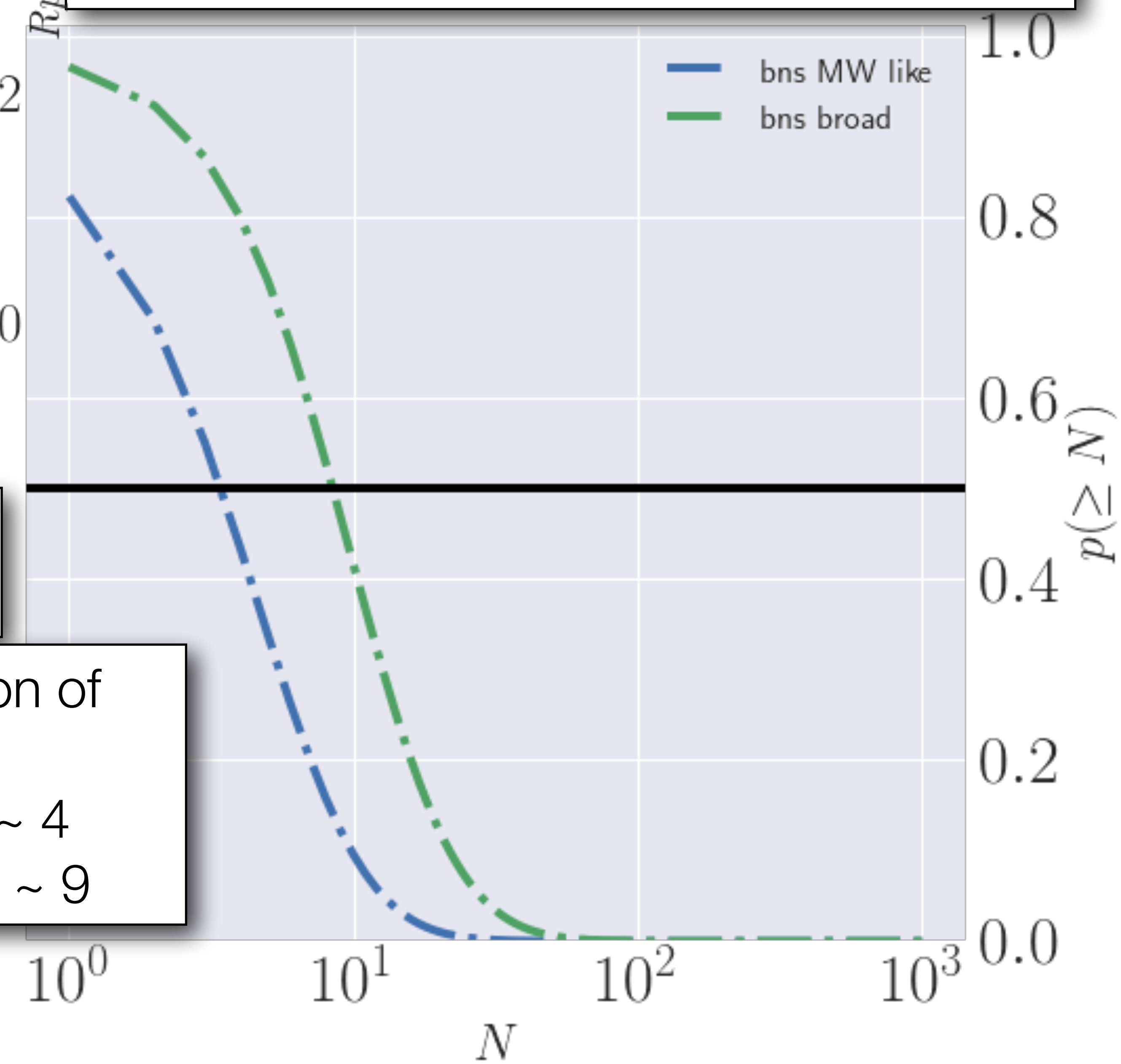

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median p(N) / MW ~ 4
median p(N) / broad ~ 9

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…pace-time volume:
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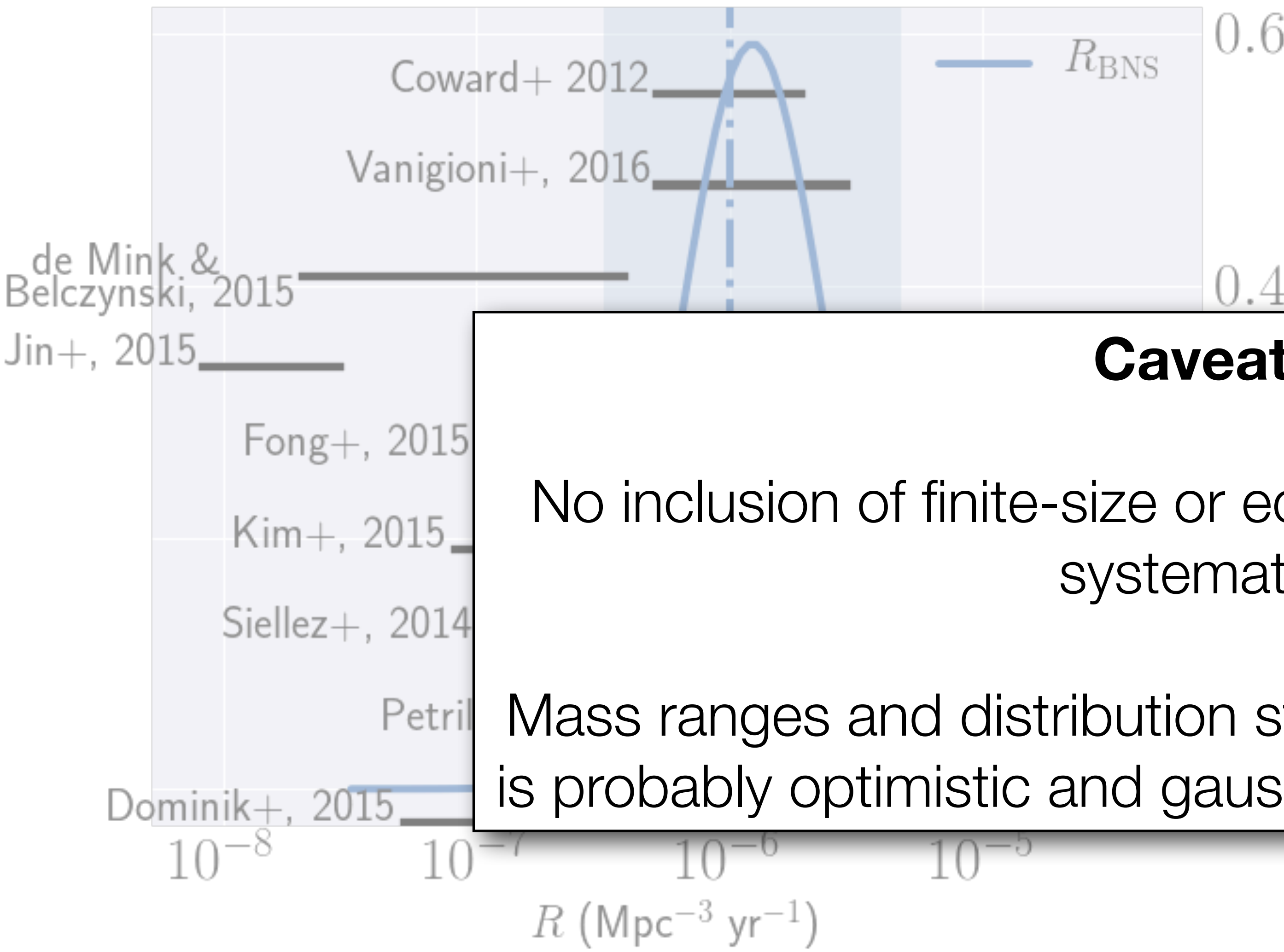

Caveats

No inclusion of finite-size or equation of state induced systematics

Mass ranges and distribution still uncertain, 1-3 uniform is probably optimistic and gaussian may be conservative

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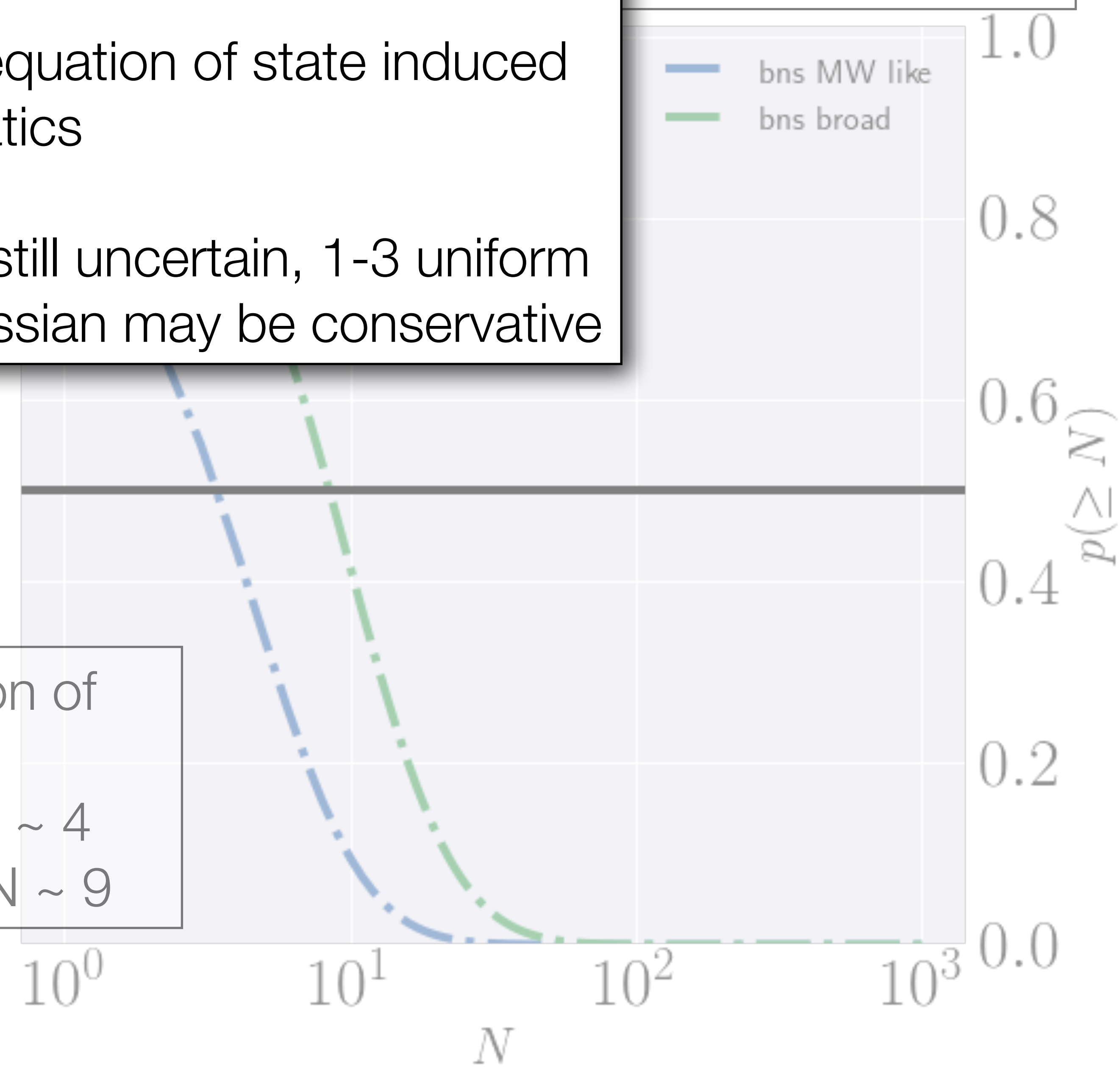
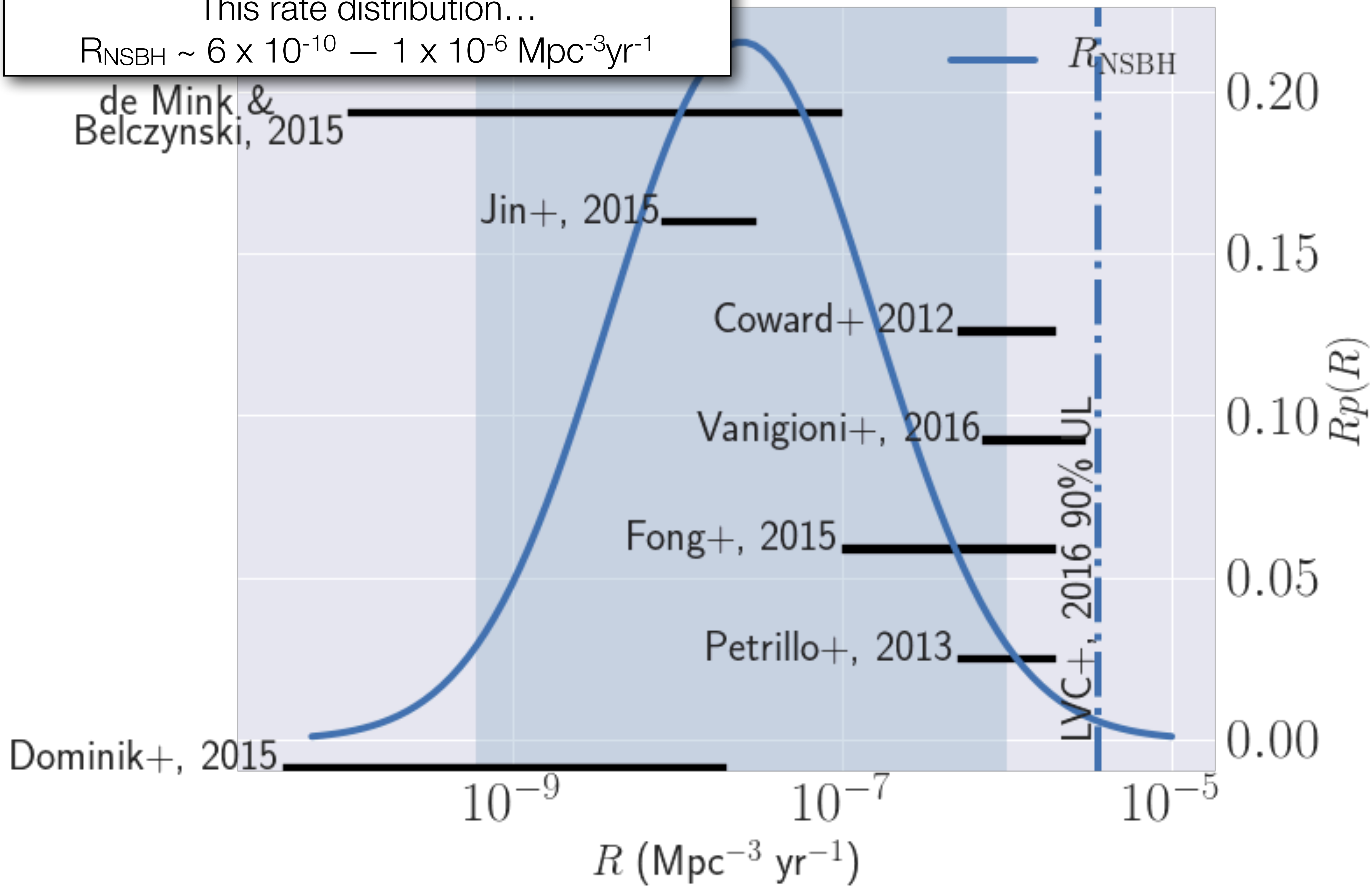


NSBH Rates (much uncertainty)
p(R) limits taken from Abbott+, 2010, assumes log-normal peaked away from zero

ApJ Letters, 832, 2

This rate distribution…
$R_{NSBH} \sim 6 \times 10^{-10} — 1 \times 10^{-6}$ $Mpc^{-3}yr^{-1}$



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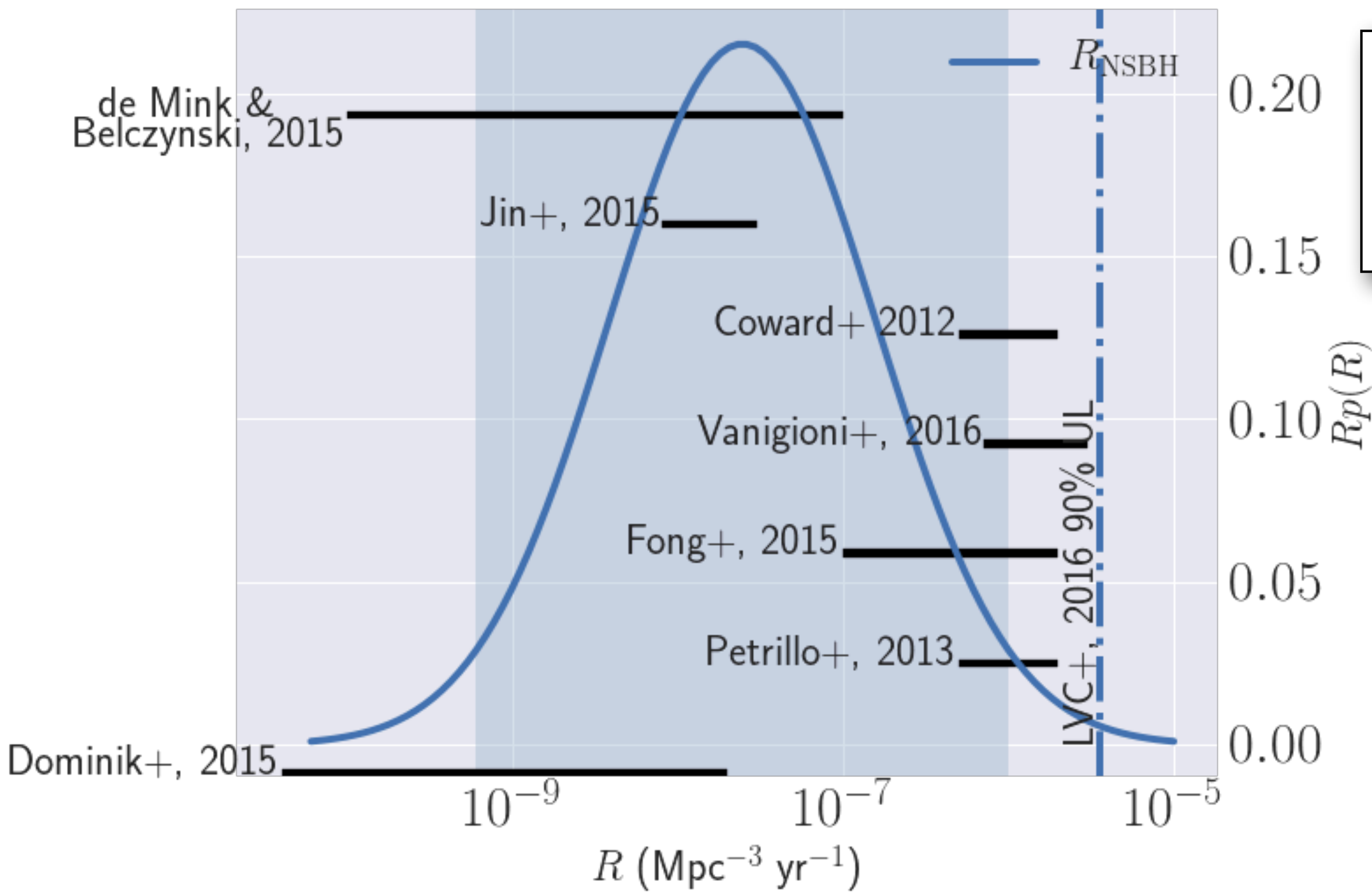

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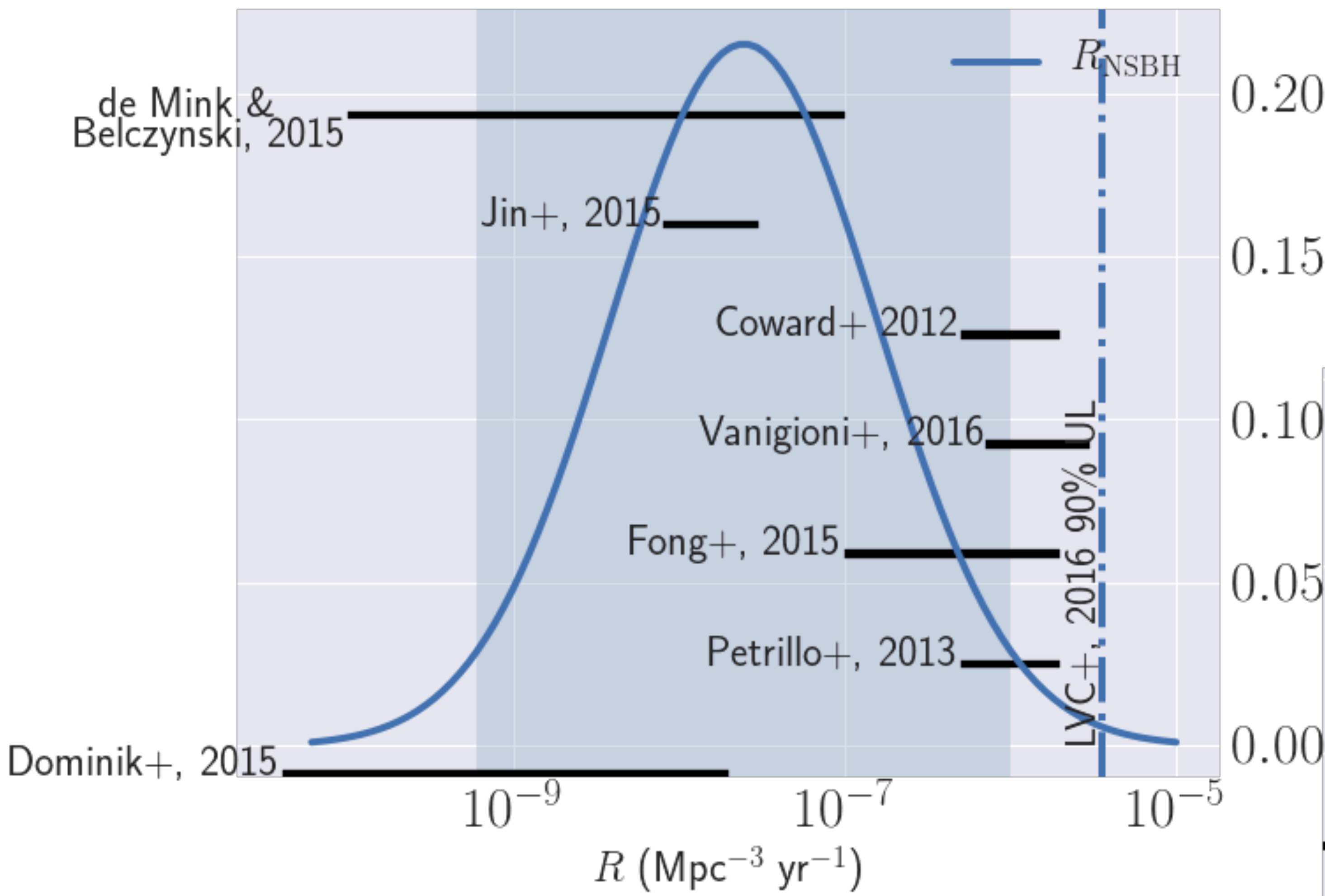

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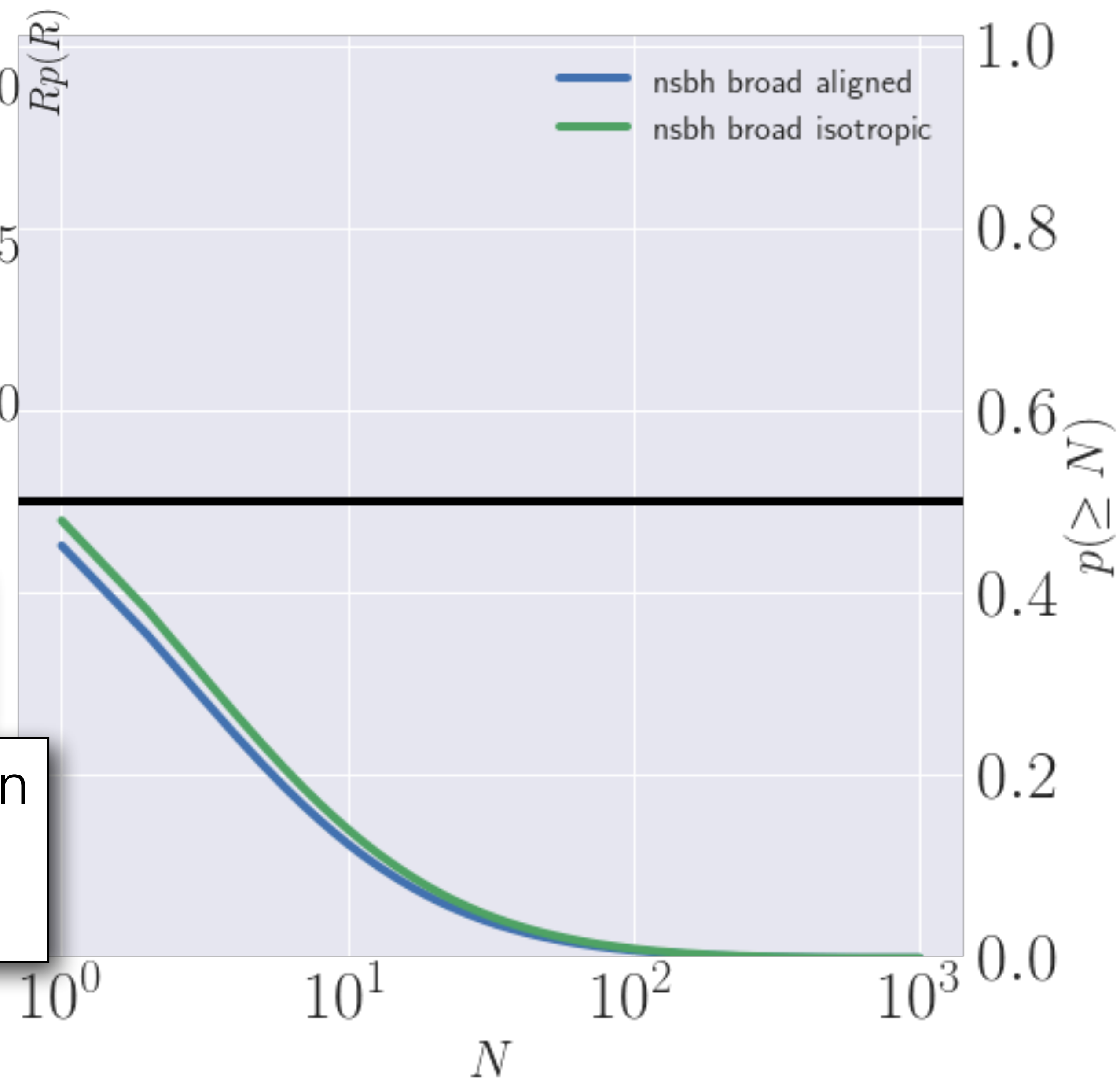

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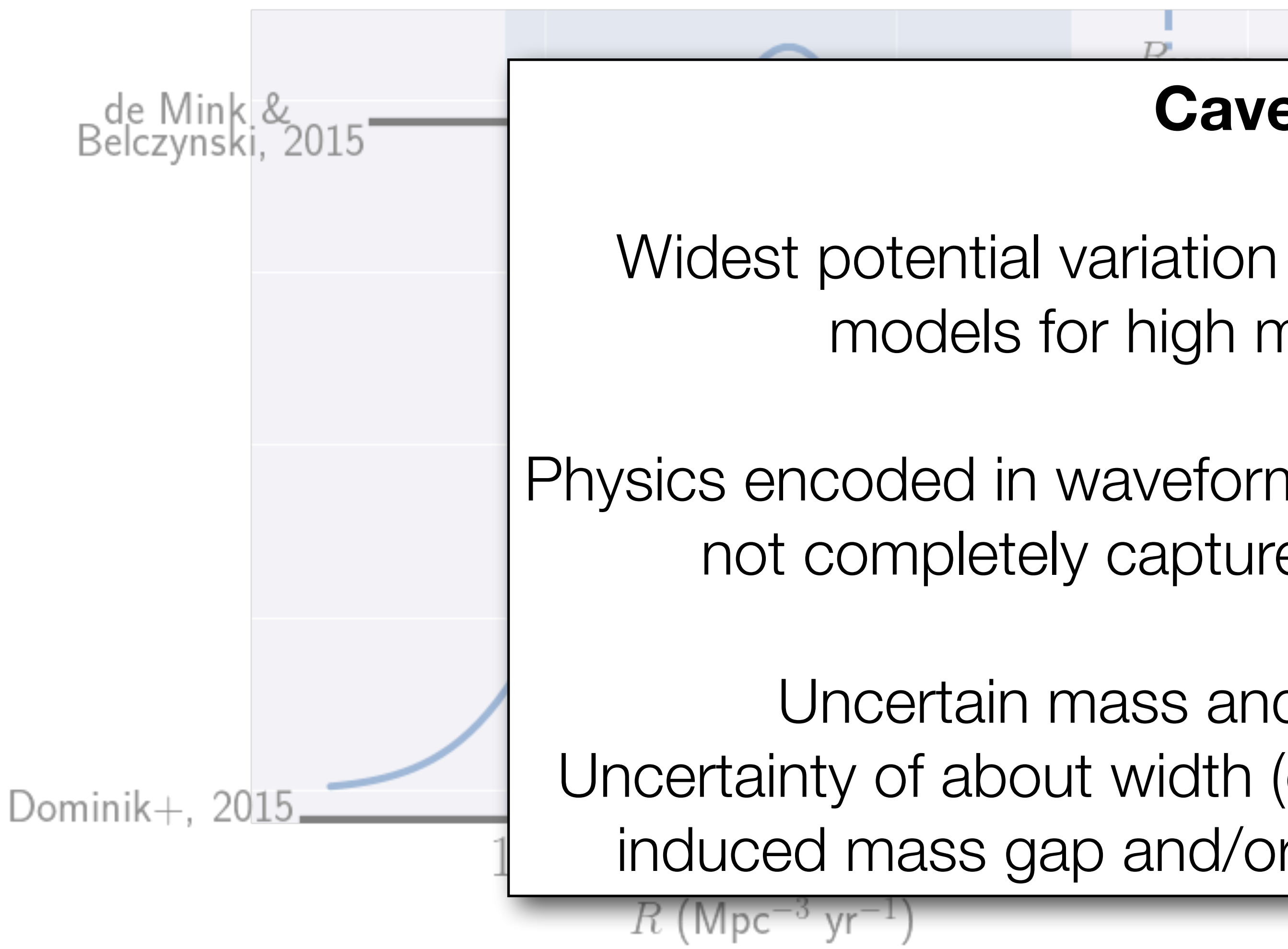

...$^{-1}$ ($5 < m_1 < 100\ M_\odot$)
...space-time volume
... x 10^8 Mpc^3 yr

Caveats

Widest potential variation in mass ratio, no reliable models for high mass ratio events

Physics encoded in waveforms (e.g. precession) which is not completely captured by online searches

Uncertain mass and spin distributions
Uncertainty of about width (or even existence) of ccSN induced mass gap and/or upper limit on NS mass

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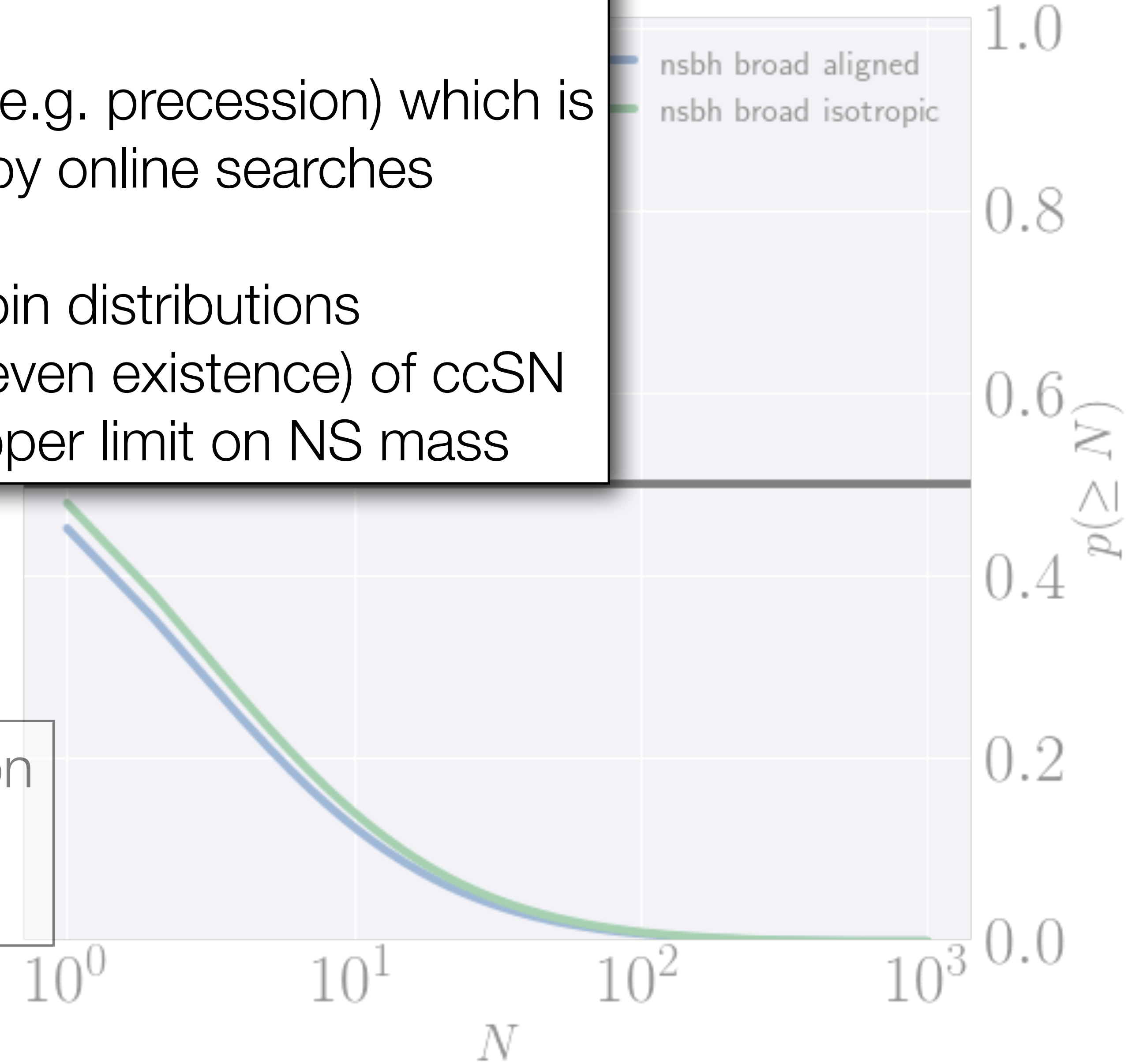
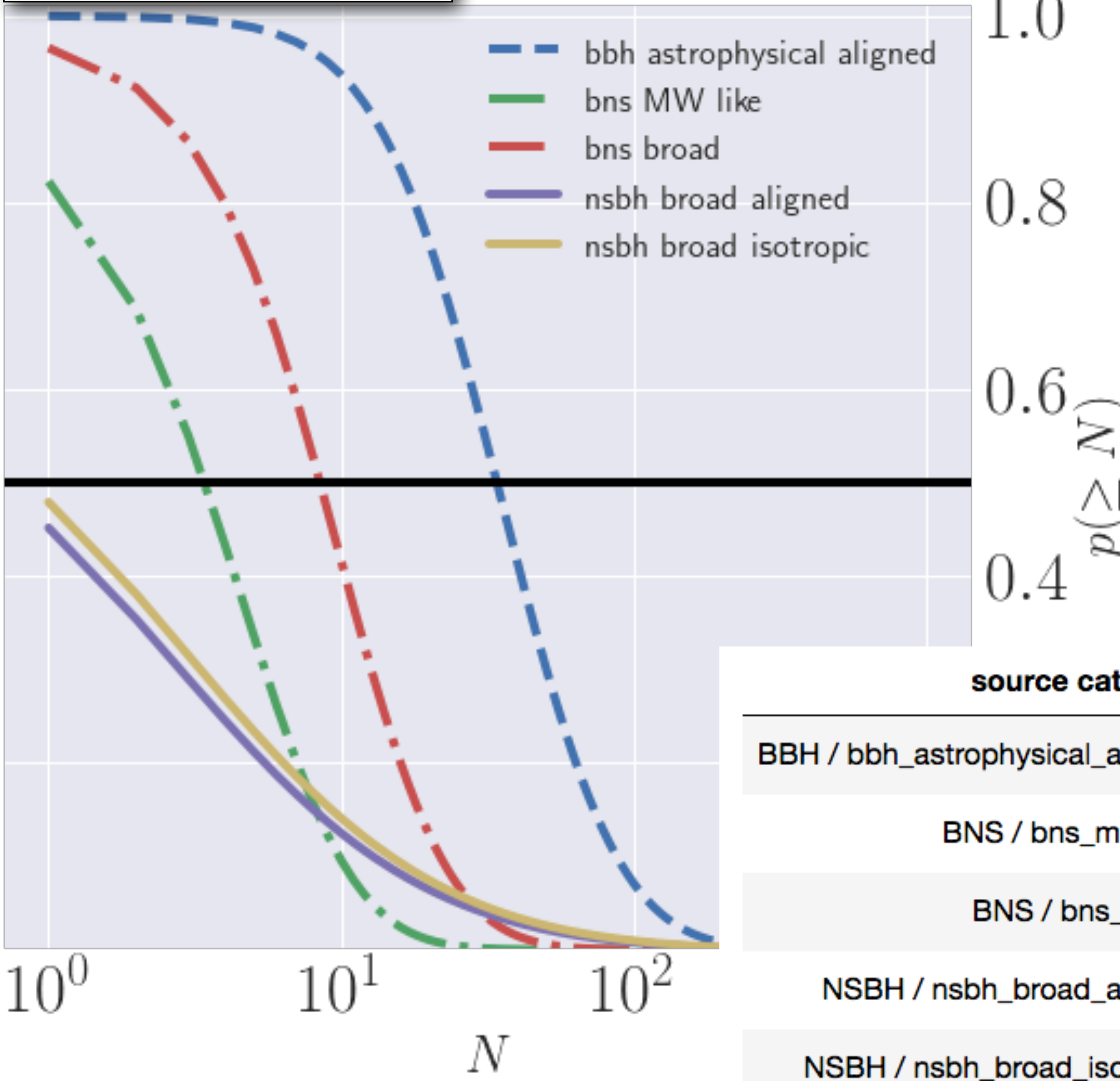


Source Summary



source category	full year VT	N_d
BBH / bbh_astrophysical_aligned	6.8×10^8 Mpc^3 yr	35^{+78}_{-26}
BNS / bns_mw_like	3.2×10^6 Mpc^3 yr	4^{+9}_{-4}
BNS / bns_broad	7.3×10^6 Mpc^3 yr	9^{+19}_{-7}
NSBH / nsbh_broad_aligned	4.9×10^7 Mpc^3 yr	1^{+24}_{-1}
NSBH / nsbh_broad_isotropic	5.7×10^7 Mpc^3 yr	1^{+28}_{-1}

Source Summary

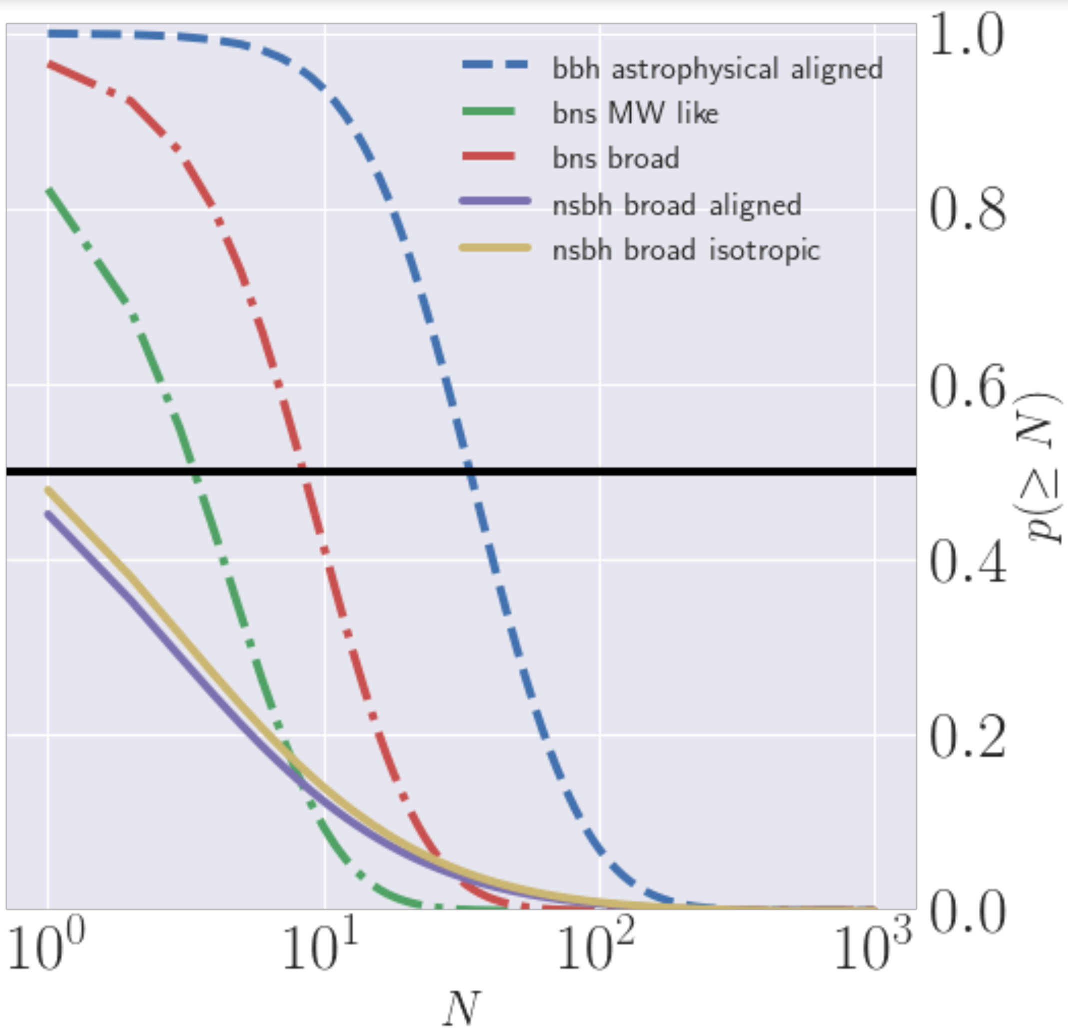
Take Aways

BBH rate will **dominate**, possibly by more than an order of magnitude, up to **~few/wk., at least ~few/mo.**

1-10 BNS, possibly up to **~1/mo.**

VT has **strong mass dependence** but **very mild dependence** on assumed spin distribution

NSBH: N=0 not ruled out in any scenario, most give **~50% N>0**



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