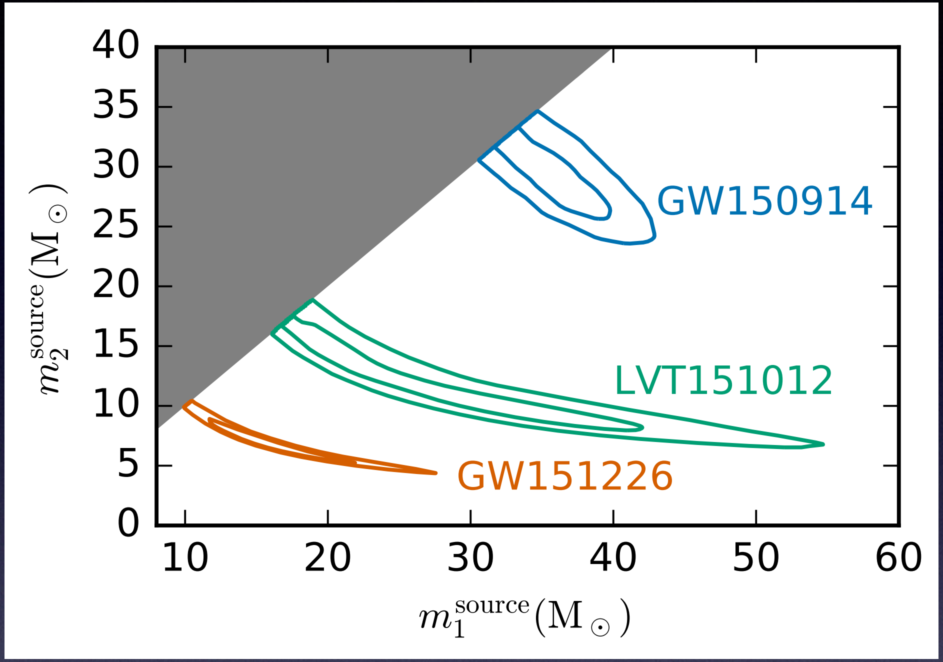
The Dawn of Gravitational-Wave Astrophysics



Vicky Kalogera

Dept of Physics & Astronomy

Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA)

in part for the LIGO-Virgo Collaborations

NORTHWESTERN UNIVERSITY

LSC VIRGO

CIERA

LIGO

LSC

LIGO Scientific Collaboration

Trinity University

University of Maryland

Andrews University

Washington State University

California State University Fullerton

The University of Alabama in Huntsville

Whitman College

American University, Washington, DC

Sonoma State University

indigo

Montclair State University

University of Glasgow

Australian National University

University of the West of Scotland UWS

Texas Tech University

Tsinghua University

R·I·T

Max Planck Institute for Gravitational Physics
Albert Einstein Institute

University of Strathclyde

Michigan

CITA ICAT
Canadian Institute for Theoretical Astrophysics
L'institut Canadien d'astrophysique théorique

Università degli Studi del Sannio

NASA Goddard Space Flight Center

ICTP SAIFR

The University of Western Australia

ACU

University of Cambridge

Southern University Agricultural & Mechanical College

Columbia University in the City of New York

The University of Chicago

Montana State University

The University of Mississippi

The University of Adelaide Australia

Caltech

University of Minnesota

University of Birmingham

The University of Melbourne

Universitat de les Illes Balears

University of Washington

GEO 600

UTRGV

Carleton College

University of Wisconsin Milwaukee

Syracuse University

Cardiff University
Prifysgol Caerdydd

Northwestern

Universität Hamburg

Monash University

INPE

UF University of Florida

Georgia Institute of Technology

Korean Gravitational-Wave Group

LSU Louisiana State University

ACIGA

University of Southampton

Charles Sturt University

Embry-Riddle Aeronautical University

Leibniz Universität Hannover

Penn State

Hobart and William Smith Colleges

Science & Technology Facilities Council
Rutherford Appleton Laboratory

Northwestern | CIERA CENTER FOR INTERDISCIPLINARY EXPLORATION AND RESEARCH IN ASTROPHYSICS

LIGO Team

- **Astrophysics of LIGO sources**
  - computational modeling of compact object binaries
  - predictions for LIGO observations
  - interpretation of observed systems

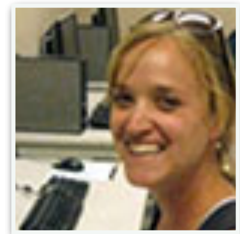
- **LIGO data analysis**
  - advanced method development
  - data characterization
  - source parameter estimation

Northwestern | CIERA

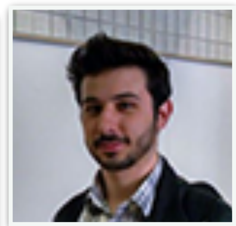
CENTER FOR INTERDISCIPLINARY EXPLORATION AND RESEARCH IN ASTROPHYSICS

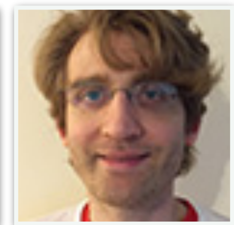
LIGO Team

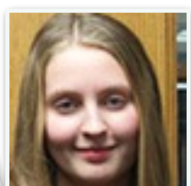








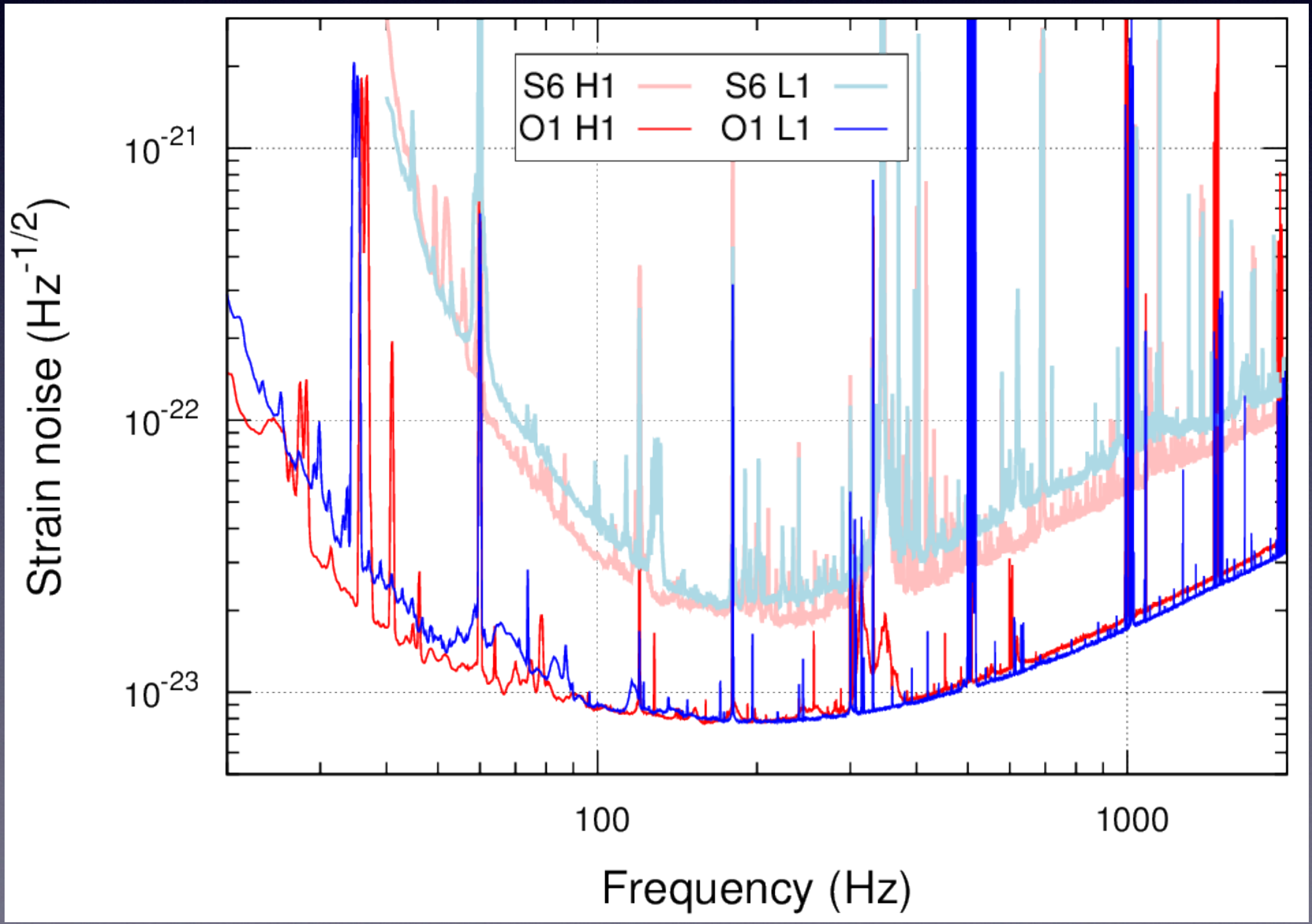




Advanced LIGO

Key Detector Upgrades

- Increased Laser Power
- Bigger Mirror Masses
- Better Mirror Coatings
- Improved Seismic Isolation



The LVC, PRL, published,
arXiv/1602.03837

Advanced Detectors: Plan for Observing Runs

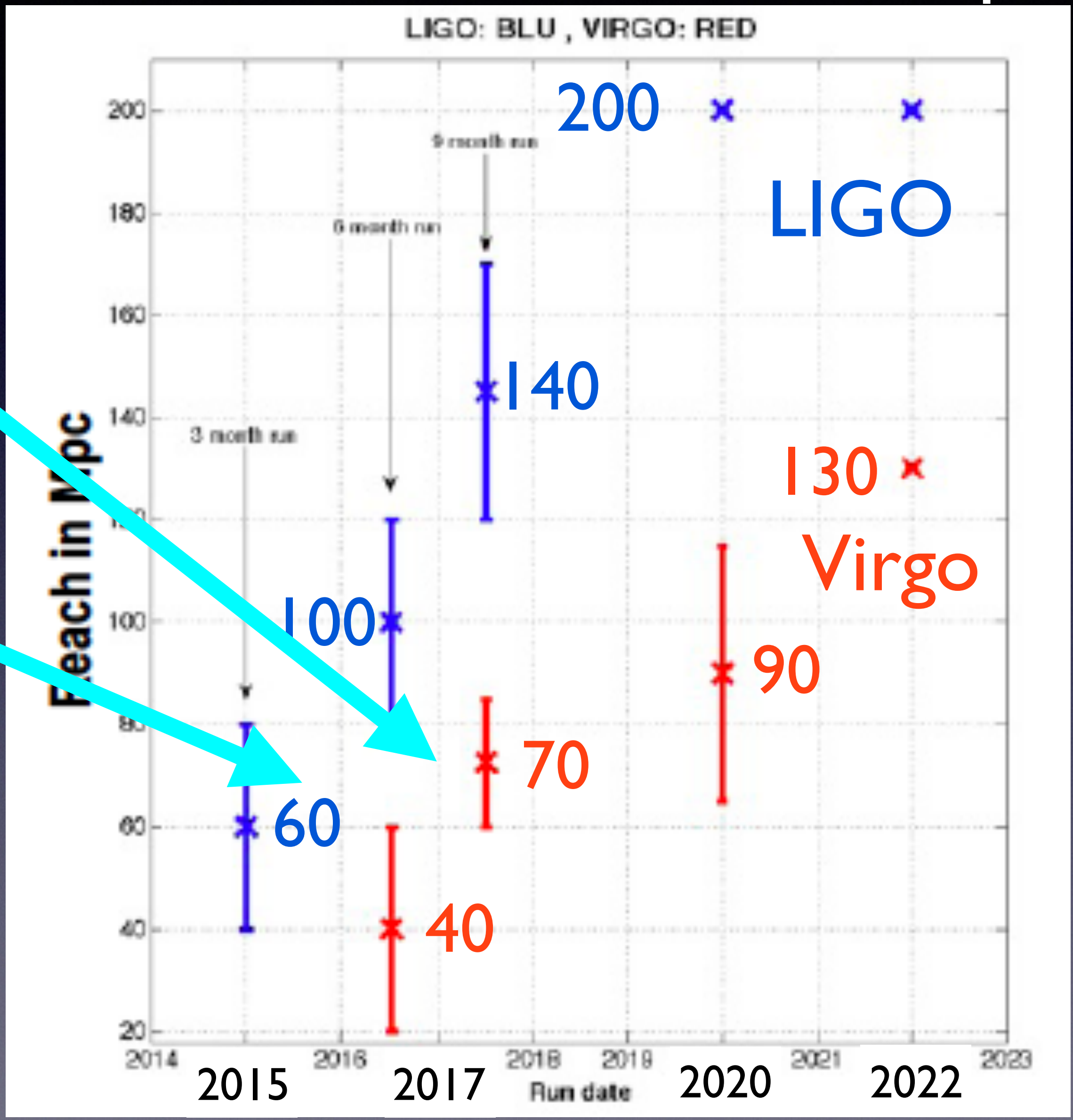
O2

Dec 2016 -

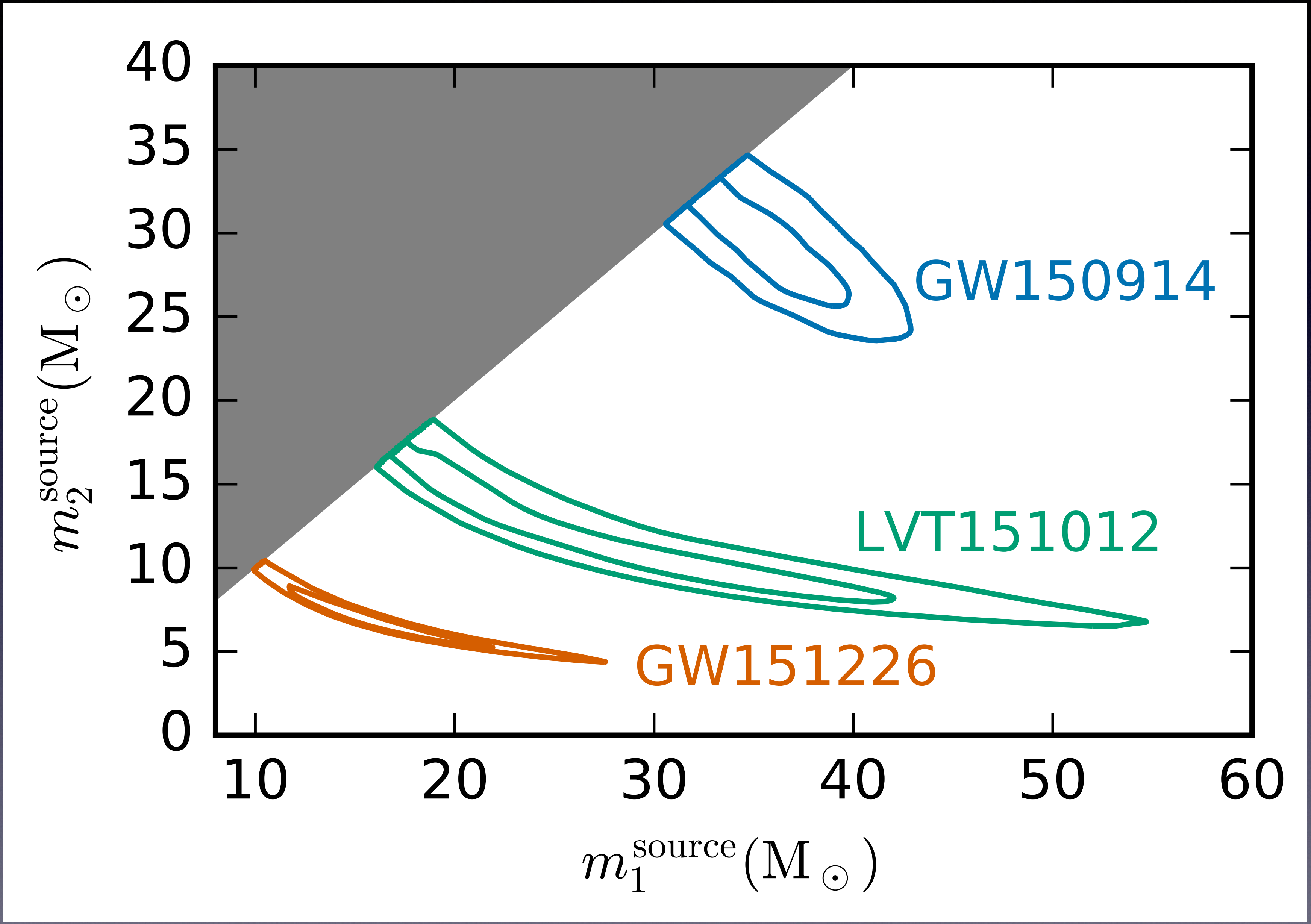
O1

Sep 2015 - Jan 2016

NS-NS Reach in Mpc



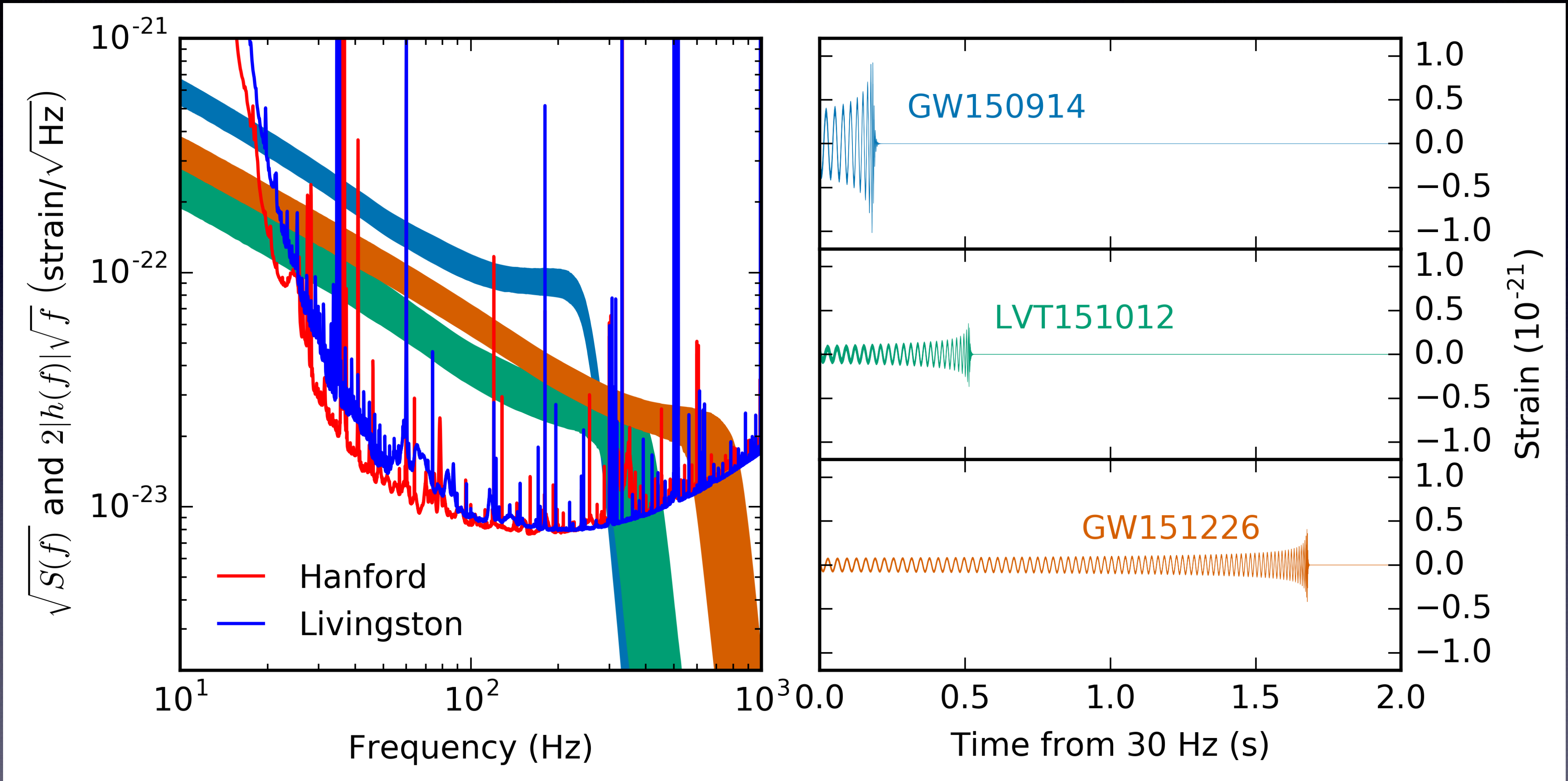
LIGO Detections



LSC VIRGO

The LVC, PRX, published, arXiv/1606.04856

LIGO Detections



The LVC, PRX, published, arXiv/1606.04856

Event Search Significance

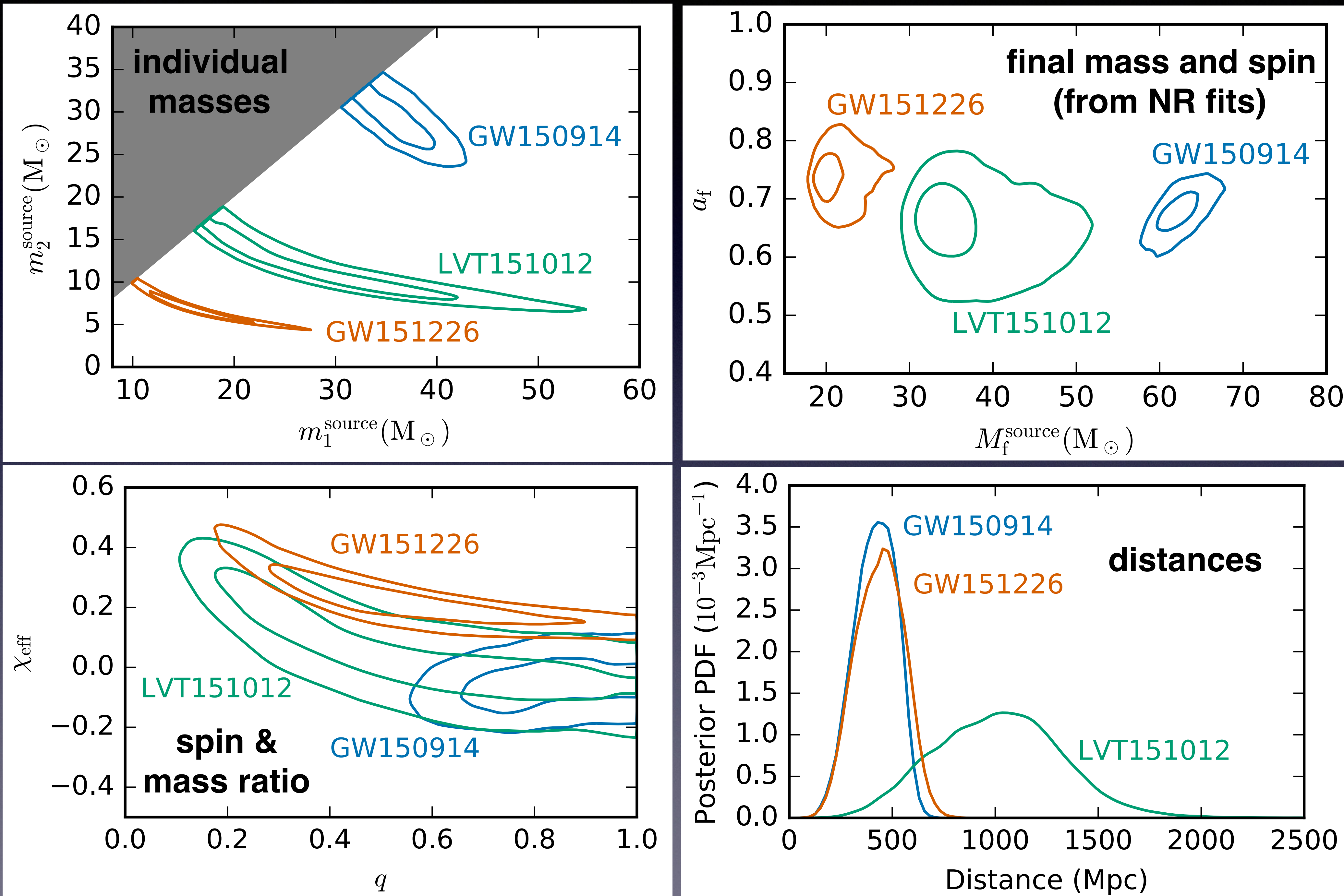
Physical Parameter Estimation

Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate $\mathrm{FAR}/\mathrm{yr}^{-1}$	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\,\sigma$	$> 5.3\,\sigma$	1.7σ
Primary mass $m_1^{\mathrm{source}}/\mathrm{M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\mathrm{source}}/\mathrm{M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass $\mathscr{M}^{\mathrm{source}}/\mathrm{M}_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$15.1^{+1.4}_{-1.1}$
Total mass $M^{\mathrm{source}}/\mathrm{M}_\odot$	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$	37^{+13}_{-4}
Effective inspiral spin χ_{eff}	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
Final mass $M_{\mathrm{f}}^{\mathrm{source}}/\mathrm{M}_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	35^{+14}_{-4}
Final spin a_{f}	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.66^{+0.09}_{-0.10}$
Radiated energy $E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\mathrm{peak}}/(\mathrm{erg\,s}^{-1})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$
Luminosity distance $D_{\mathrm{L}}/\mathrm{Mpc}$	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}
Source redshift z	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$	$0.20^{+0.09}_{-0.09}$
Sky localization $\Delta\Omega/\mathrm{deg}^2$	230	850	1600

The LVC, PRX, published, arXiv/1606.04856

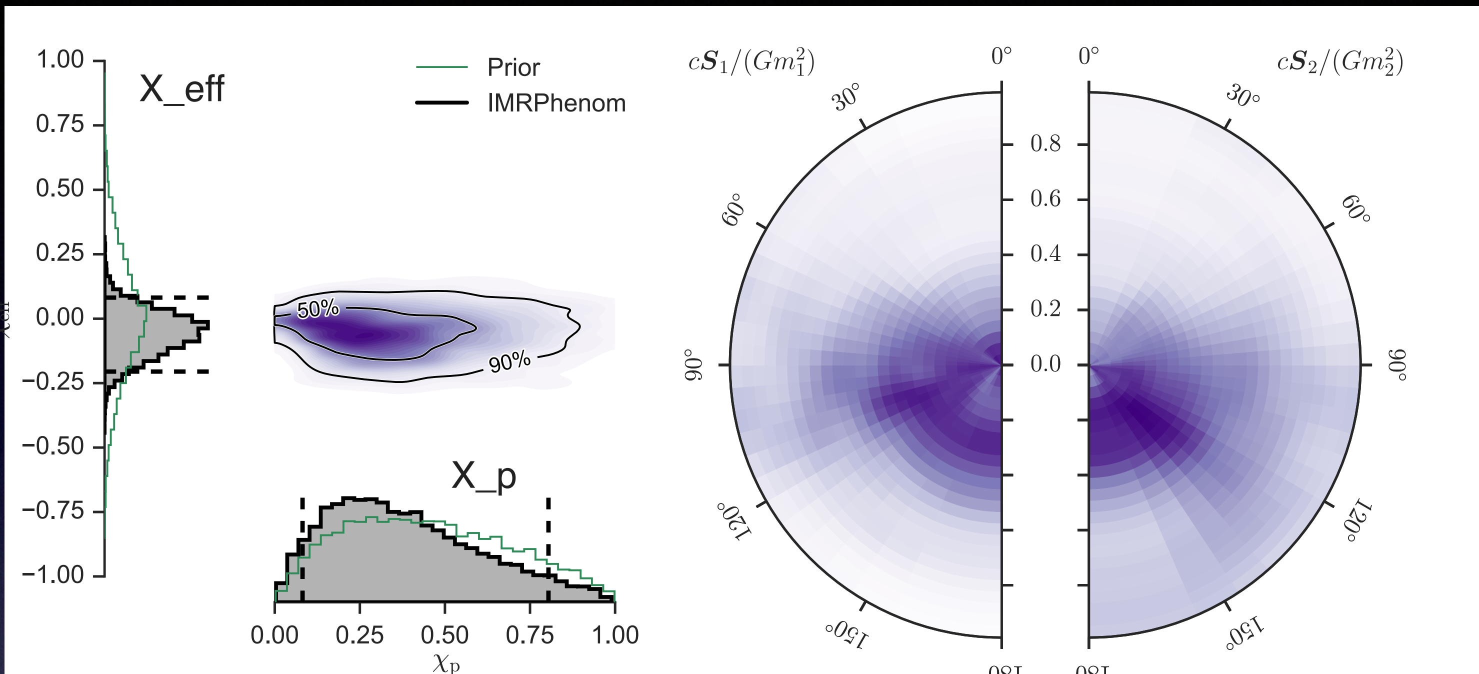
Black-Hole Masses & Spins

The LVC, PRX, published, arXiv/1606.04856

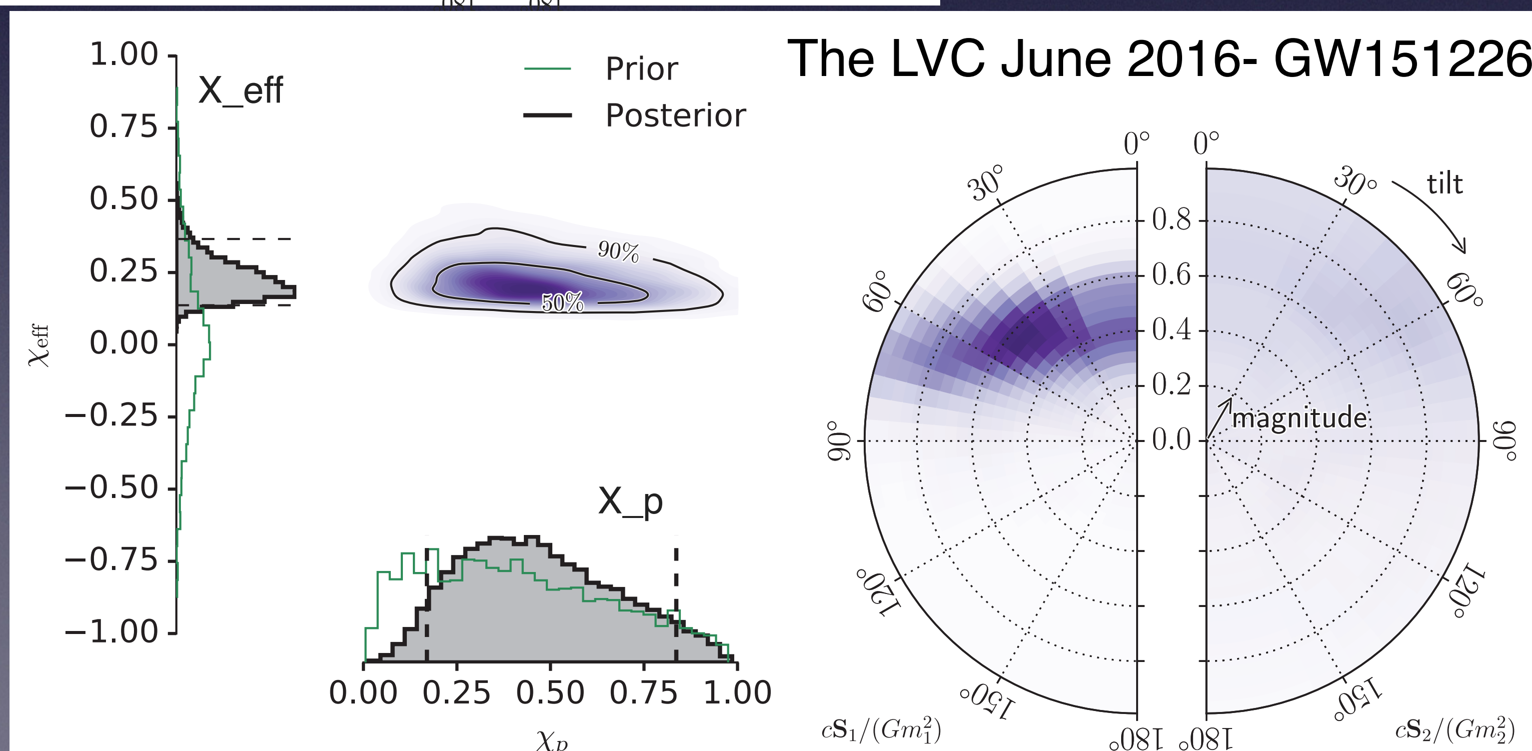


spin tilt measurements

The LVC Feb 2016- GW150914

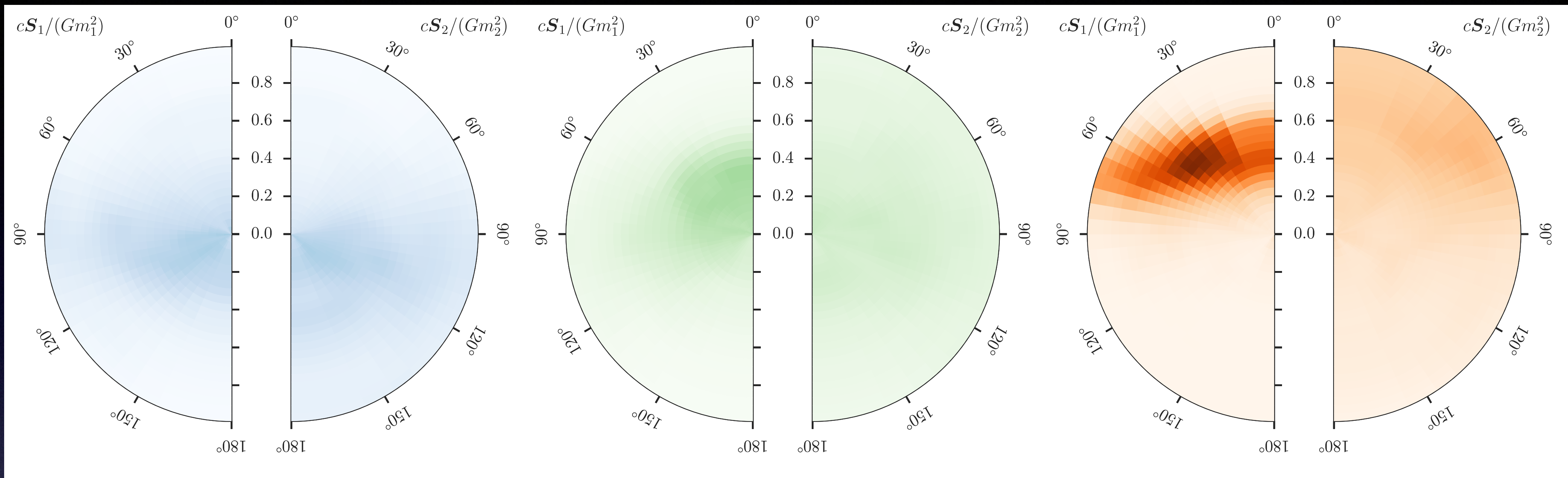


The LVC June 2016- GW151226



Black-Hole Spins from LIGO

The LVC, PRX, published, arXiv/1606.04856



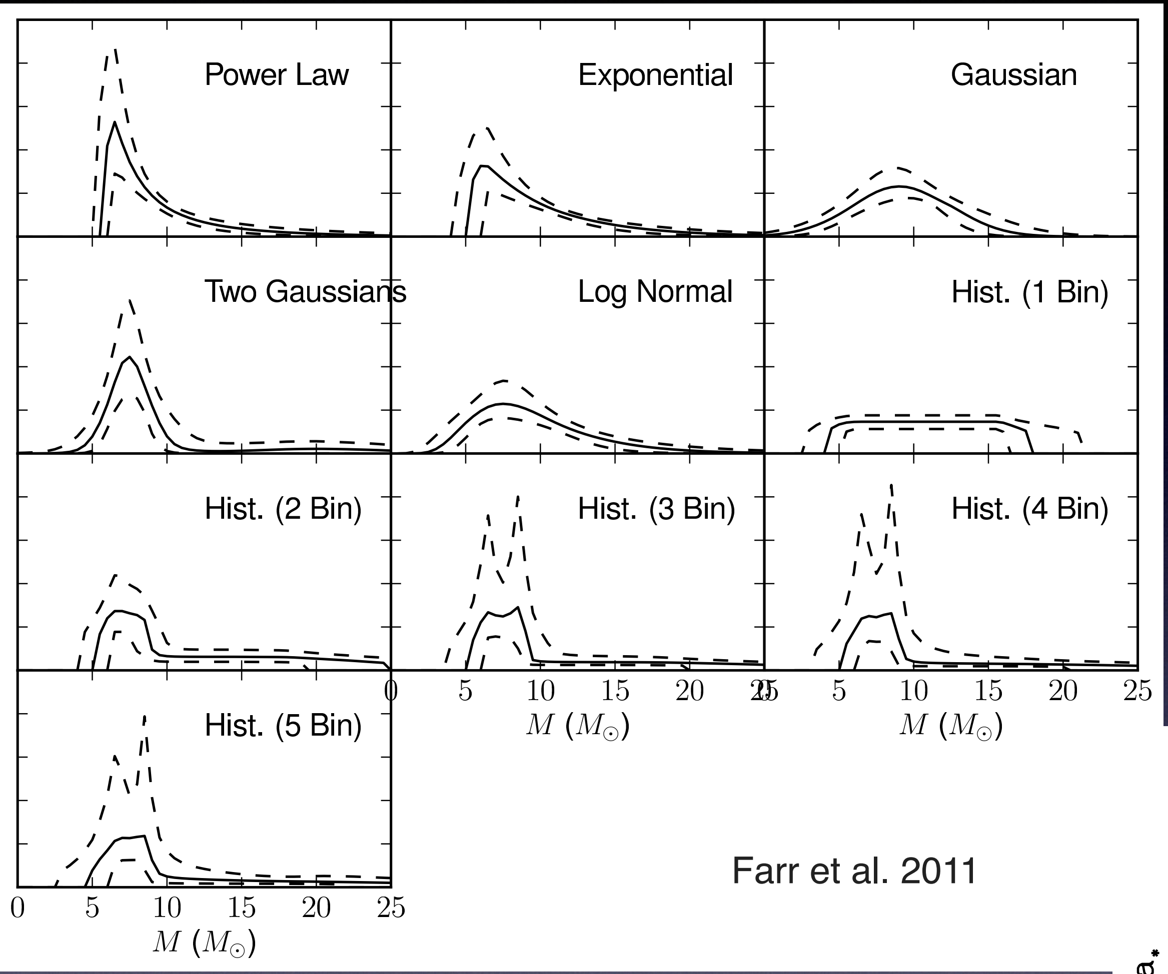
X_eff	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$

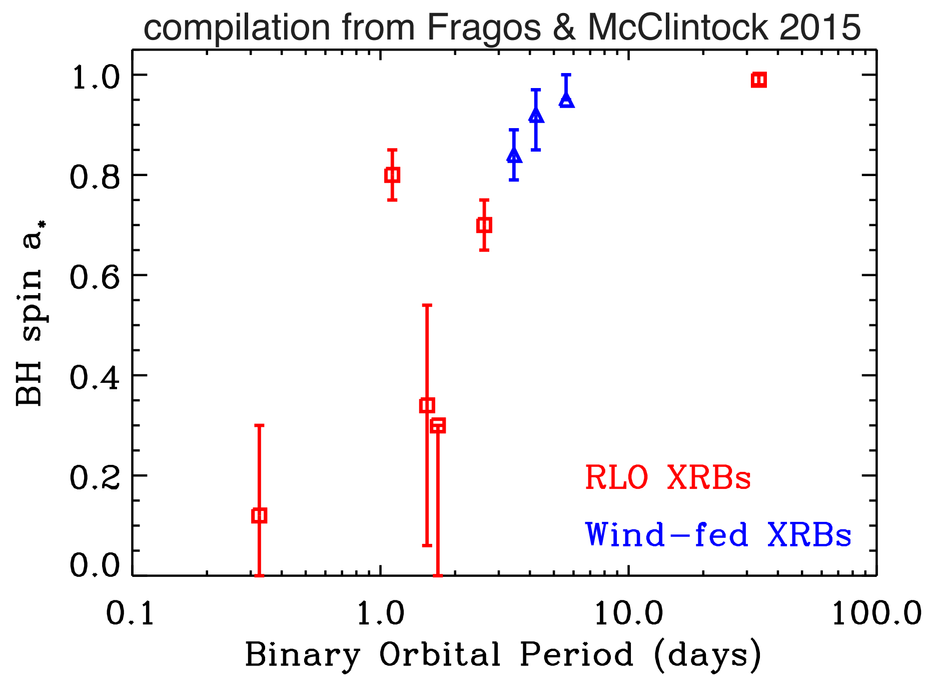
Aligned Spin components:
either small or high and directly anti-aligned

Perpendicular Spin components:
not constrained so far …

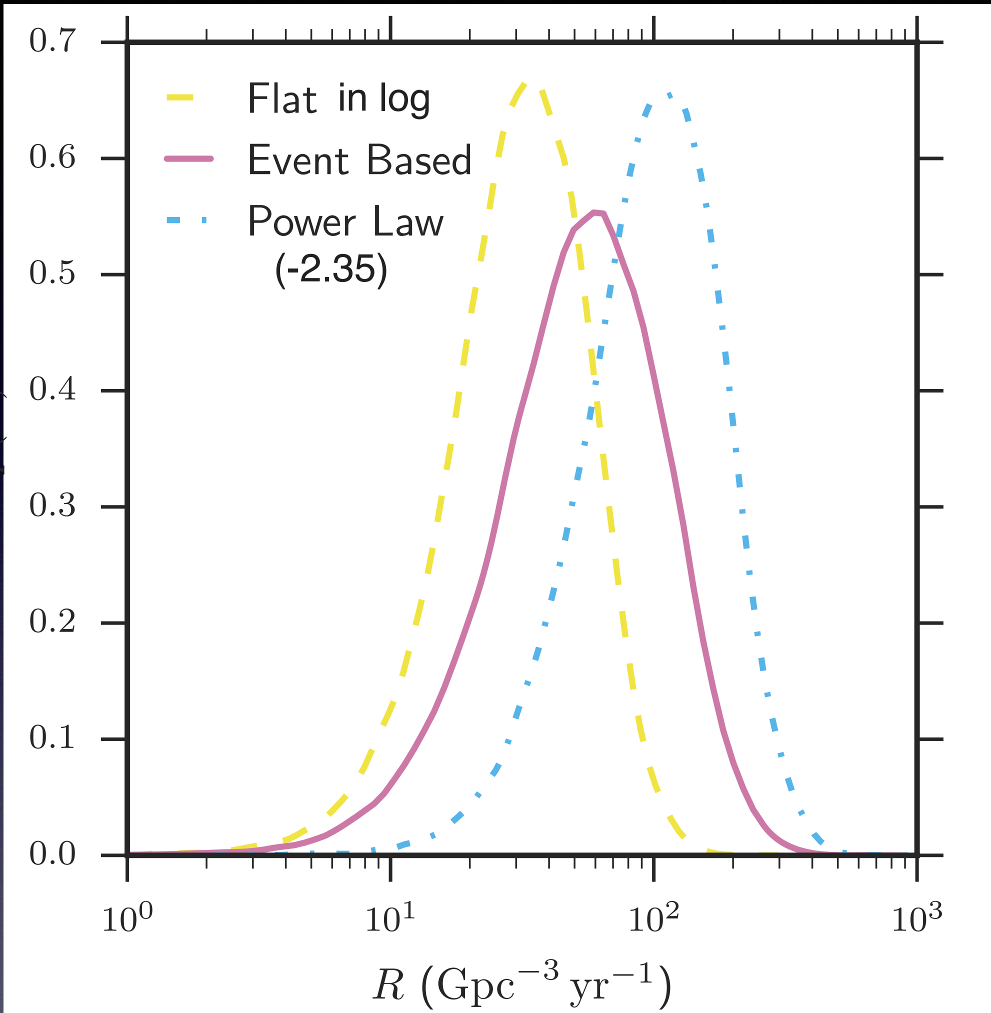
BH Spins have NOT been shown to be small

Black-Hole Masses & Spins from XRBs





BH-BH merger rate

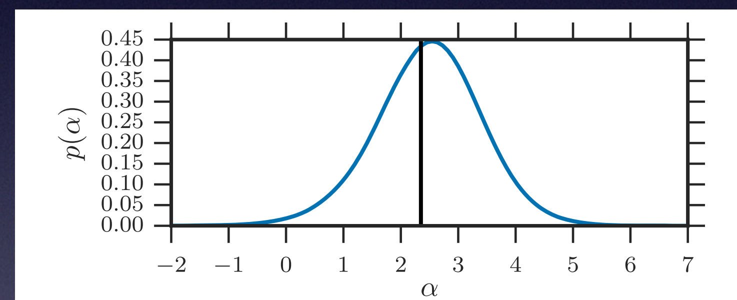


mass-distribution dependent

$$p(m_1) \propto m_1^{-\alpha}$$

$$\alpha = 2.5^{+1.5}_{-1.6}$$

BH mass function



current 90% constraint: 9 - 240 per Gpc^3 per yr

model predictions: 0 - 1,000 per Gpc^3 per yr

rates below ~10 per Gpc^3 per yr are excluded

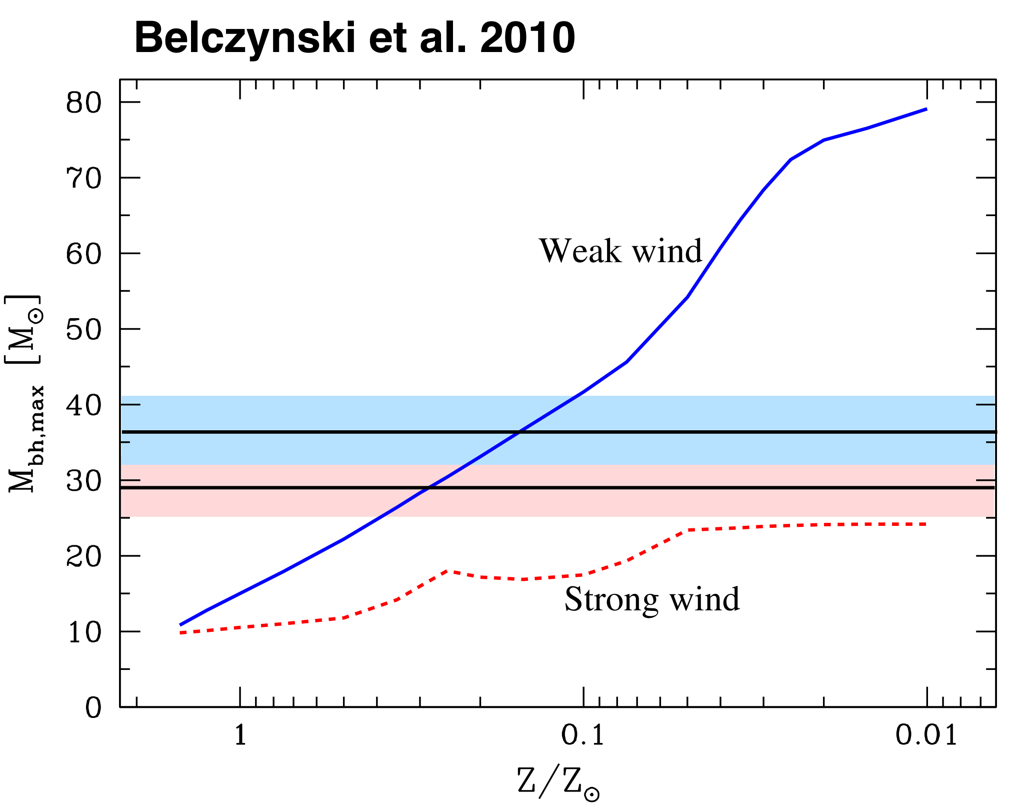
The LVC, PRX, published, arXiv/1606.04856

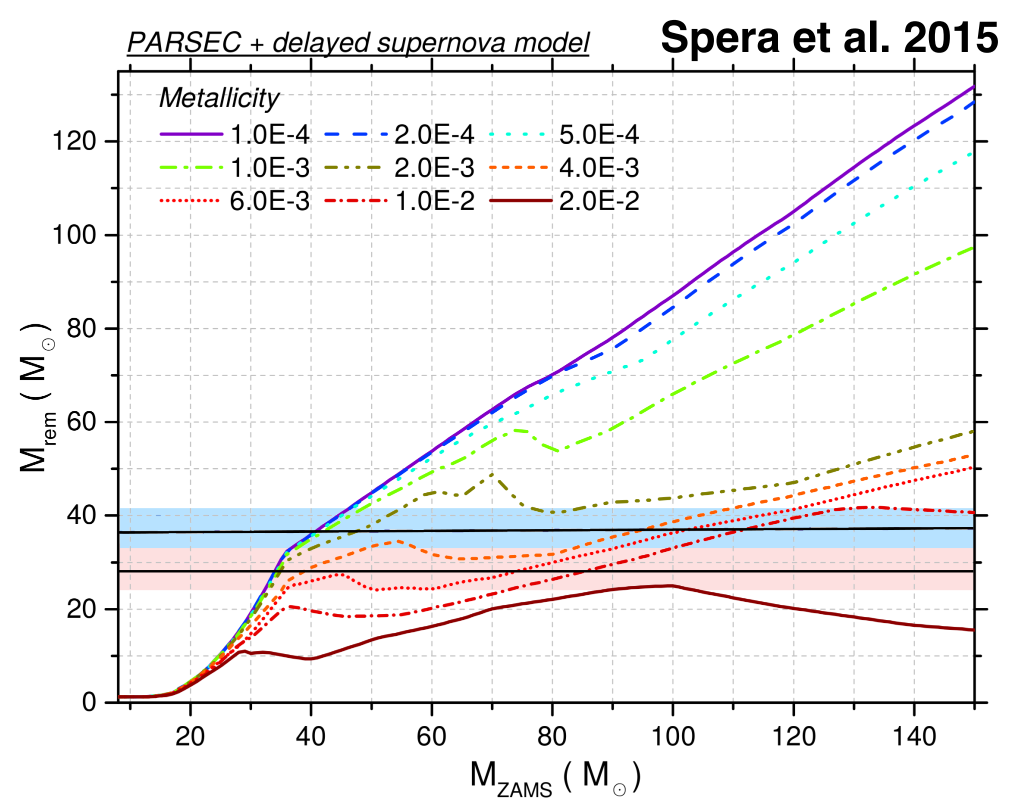
LIGO Detections:

What can we learn about BH progenitors?

GW150914: Binary BH Astrophysics

- First Binary BH system
- Heaviest stellar-mass Black Holes (>~ 25 Msun)



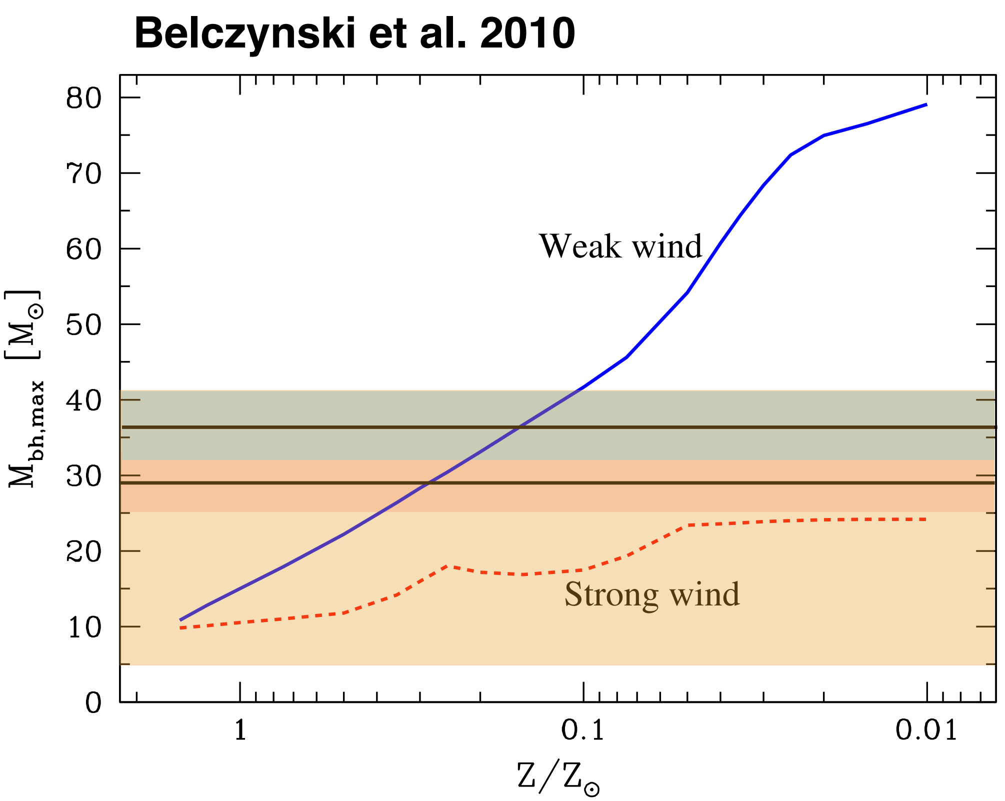


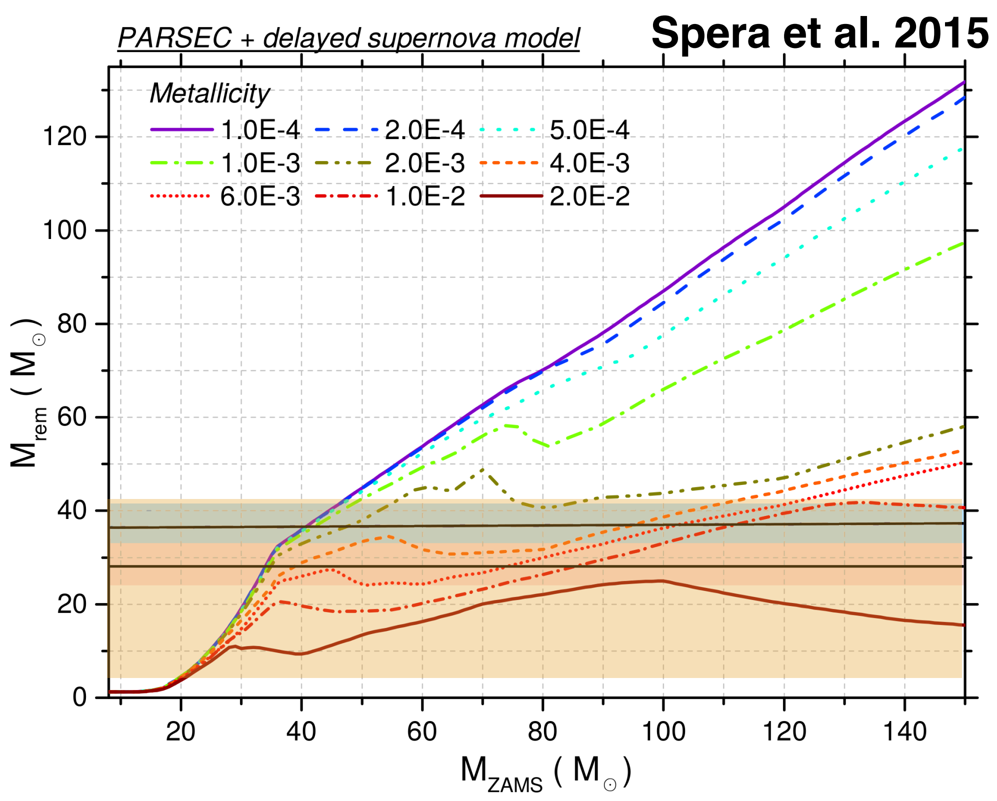
Z < 1/2 solar

LSC VIRGO The LVC, ApJL, published, arxiv/1602.03846

LIGO Binary BH Astrophysics

wide range of metallicities





BBH Formation

Isolated Binaries

solar - Z to PopIII

rapid rotation

Dense Clusters

globular clusters

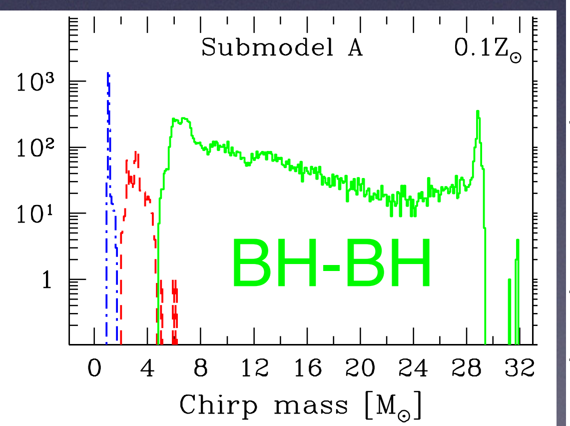
young clusters

galactic centers

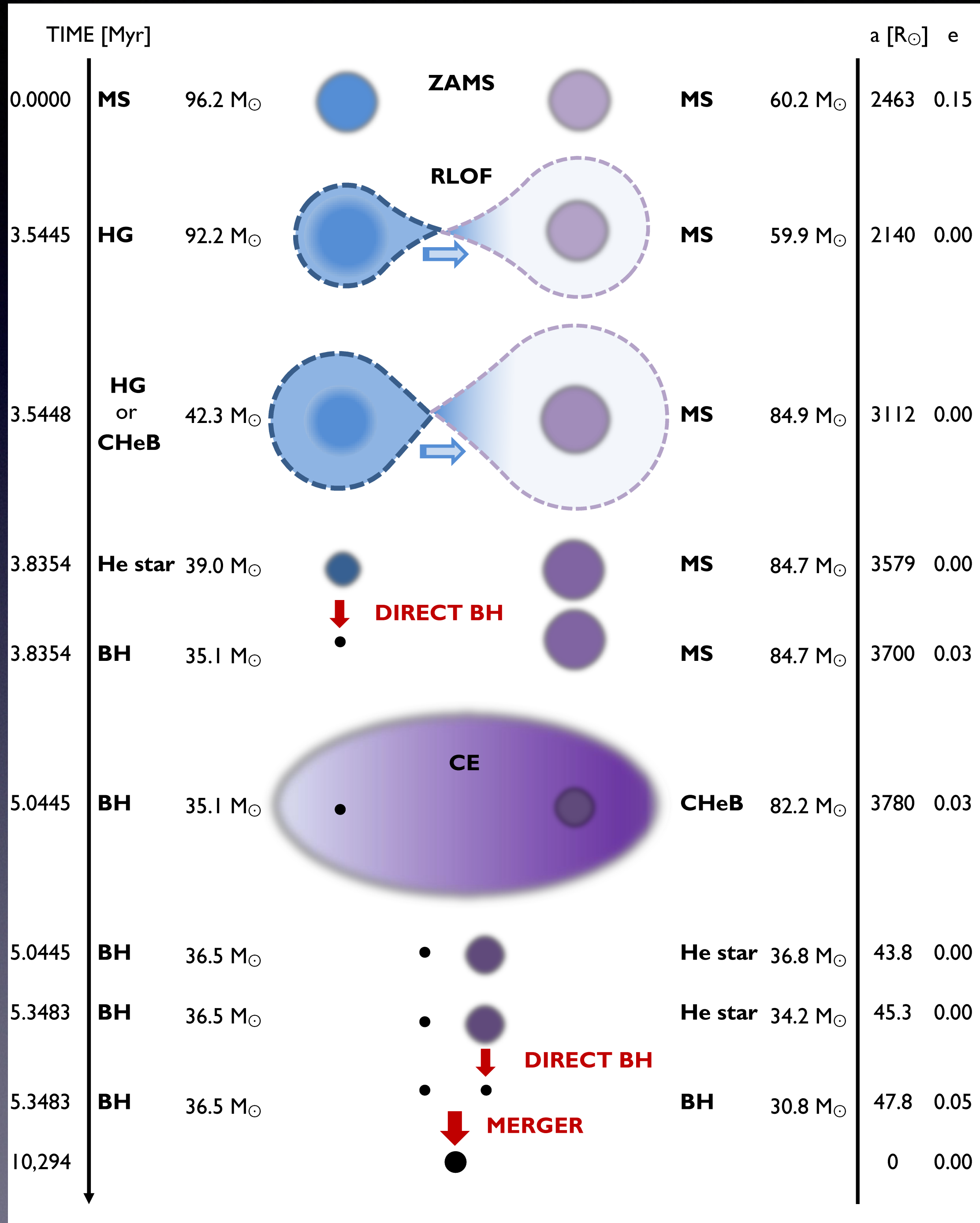
BBH Formation from Isolated Binaries

"regular" stars

BH masses & BBH rates: consistent



Dominik et al. 2012
Belczynski et al. 2016a,b



stable mass transfer

common envelope

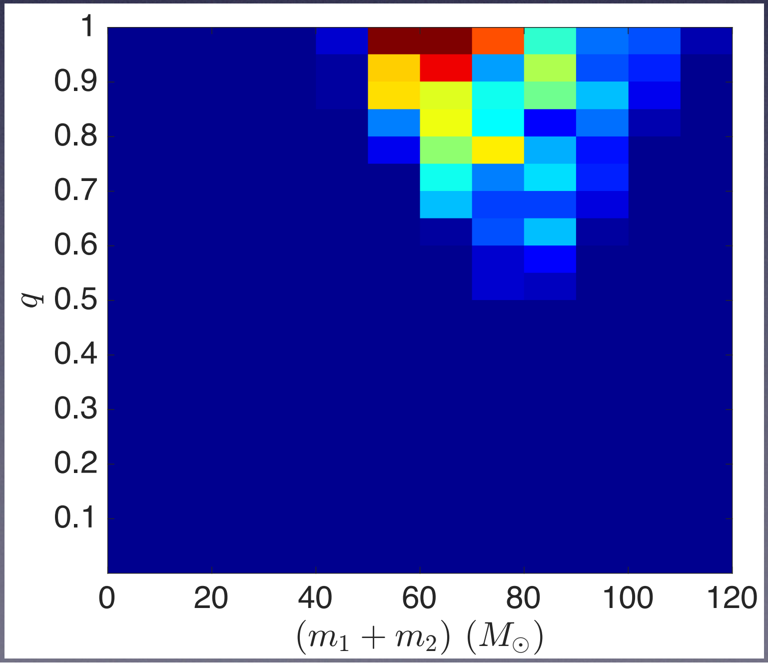
low BH kicks

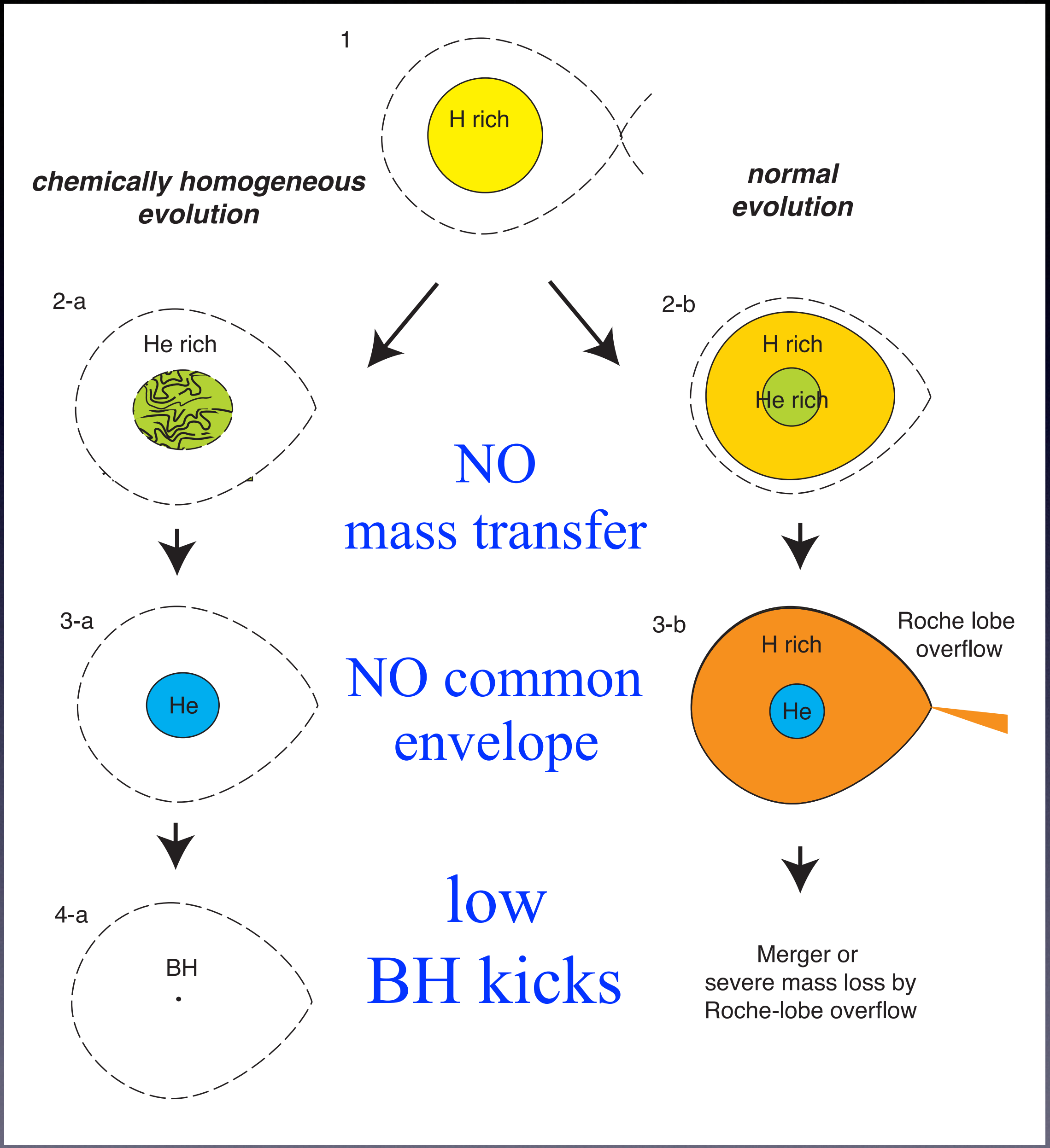
BBH Formation from Isolated Binaries

rapidly rotating, homogeneous stars

BBH rates: consistent

Low BH masses: not consistent





Mandel & de Mink 2016

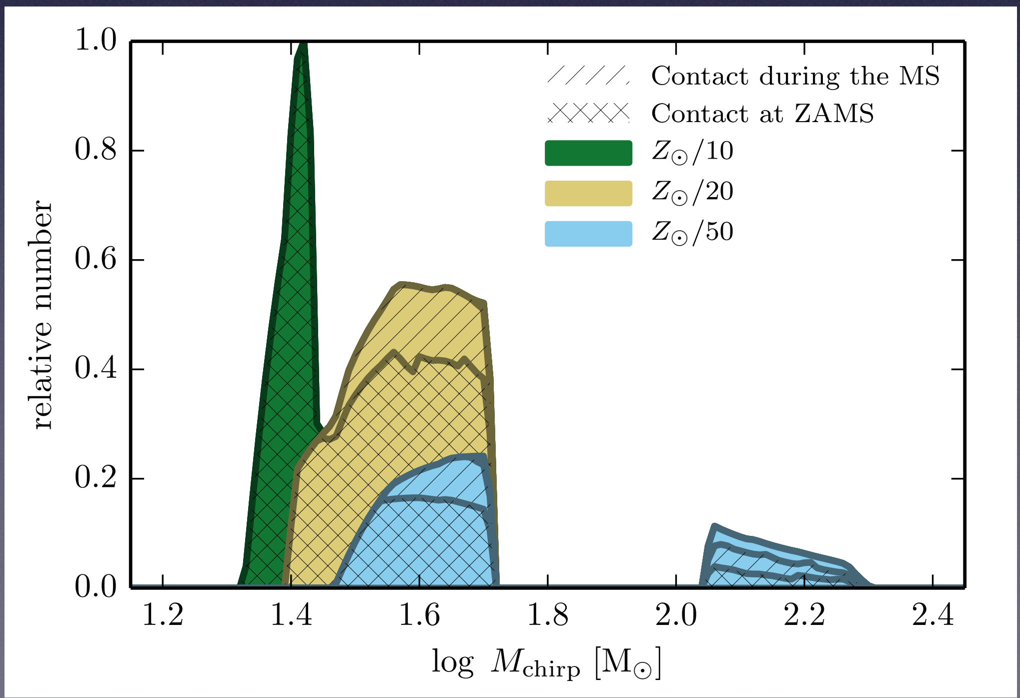
de Mink & Mandel 2016

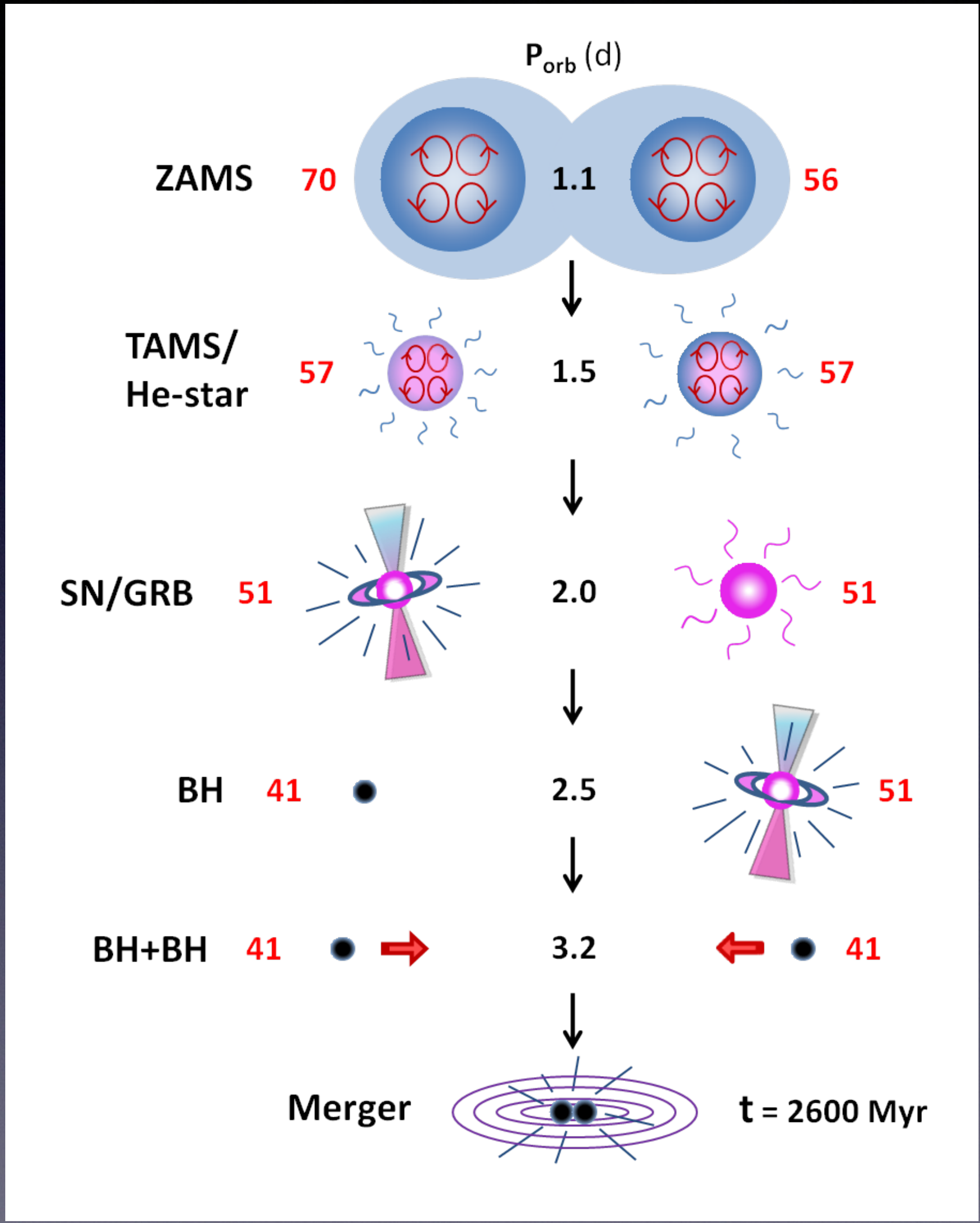
BBH Formation from Isolated Binaries

rapidly rotating, homogeneous stars in contact binaries

BBH rates: consistent

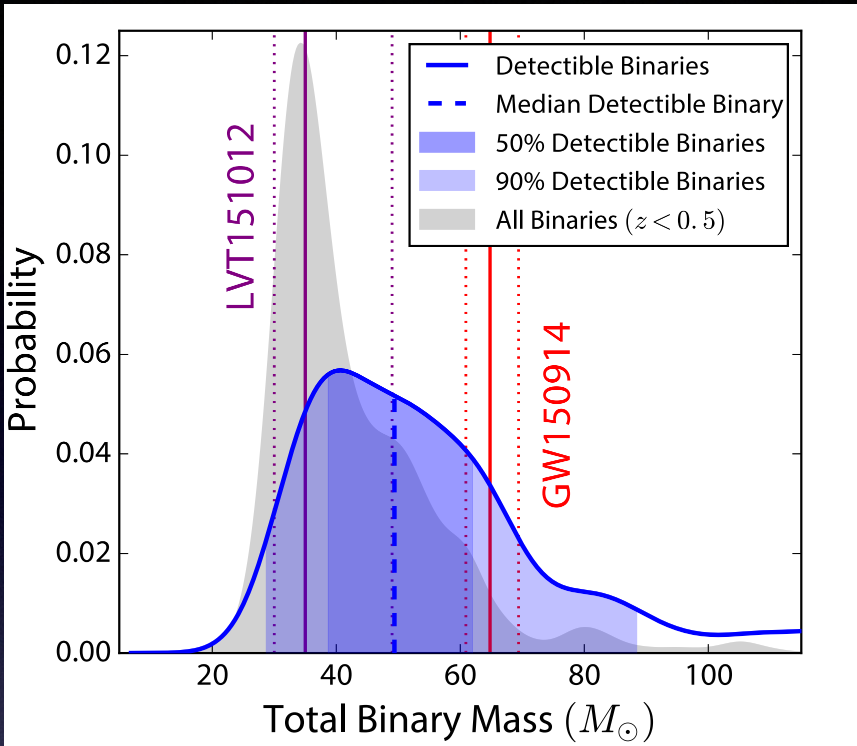
Low BH masses: not consistent

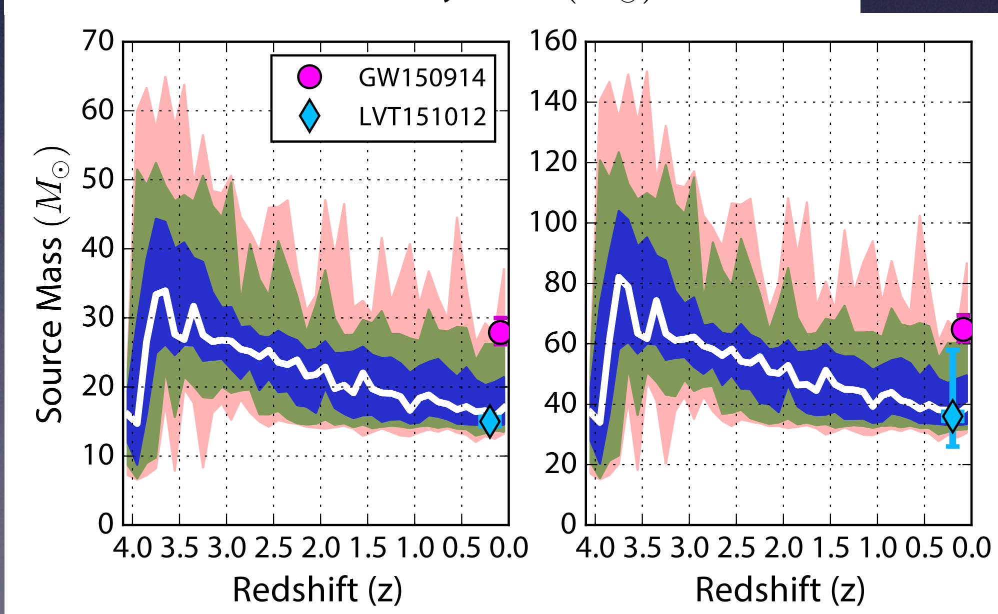




Marchant et al 2016

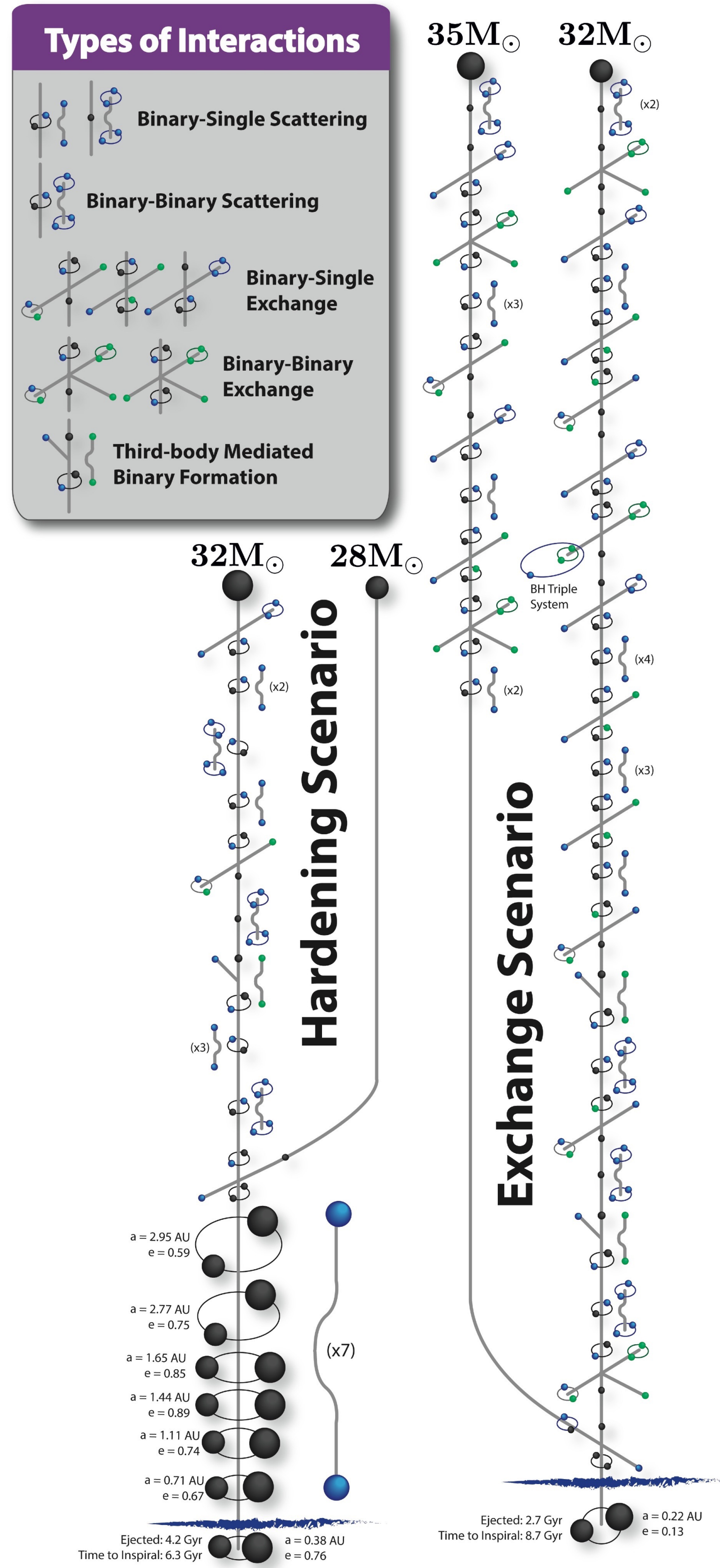
BBH Formation in Globular Clusters





BBH rates: consistent

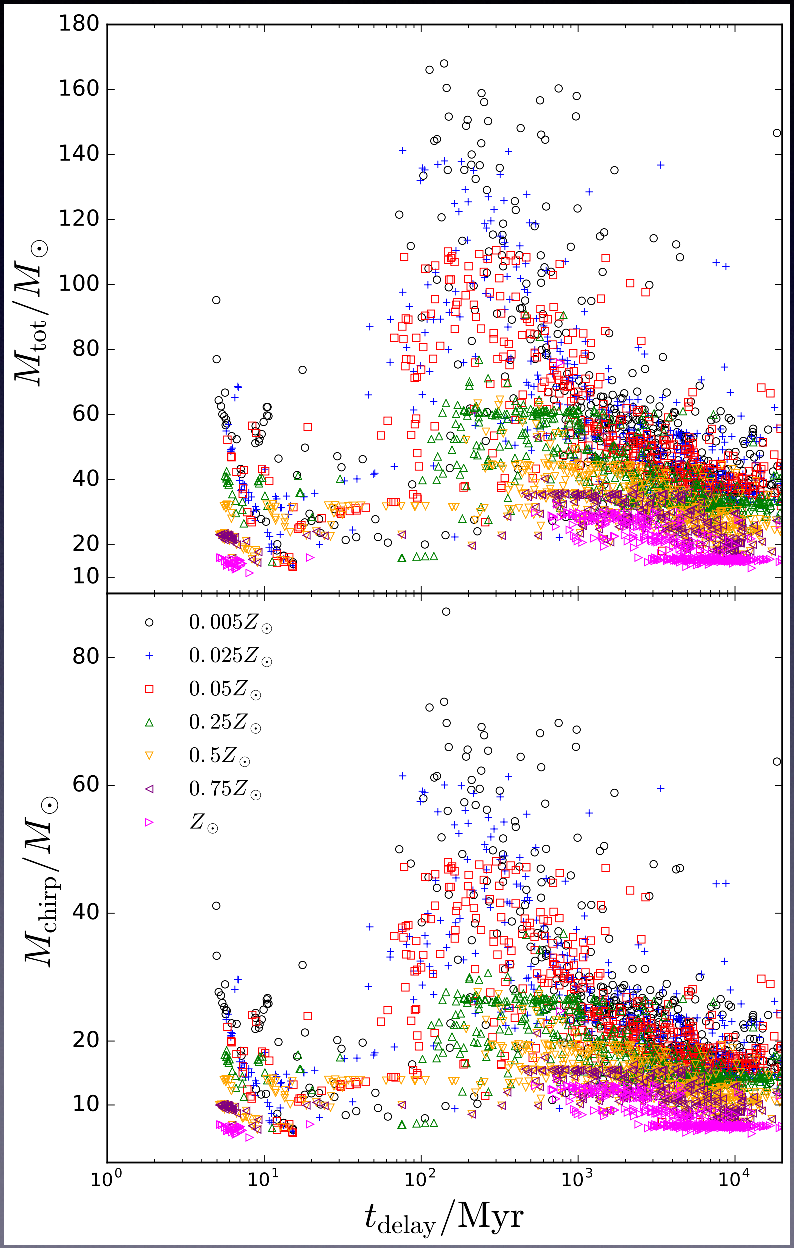
Low BH masses: not consistent



Rodriguez et al. 2016a, 2016b
also Breivik et al. 2016

BBH Formation in Young High-Z Clusters

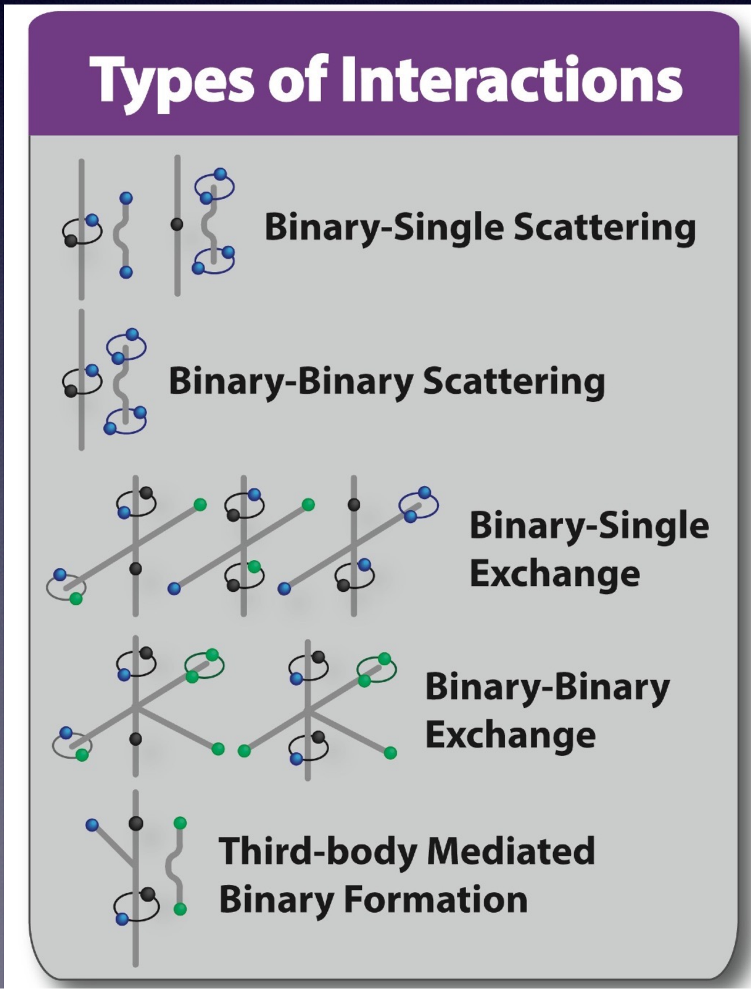
Chatterjee et al. 2017



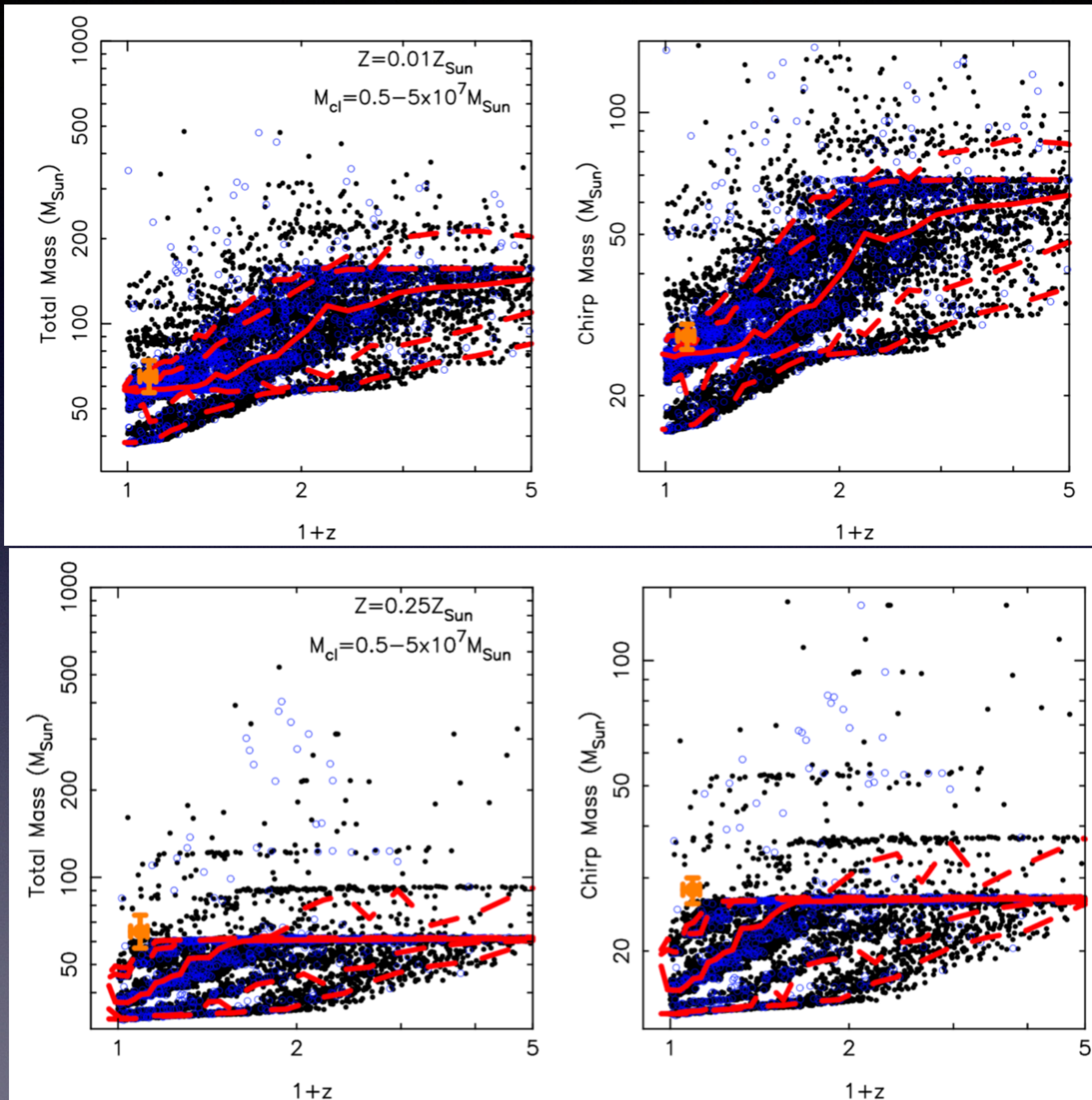
BBH rates: consistent

High BH masses: not consistent

Rodriguez et al. 2017



BBH Formation in Galactic Nuclei



Antonini & Rasio 2017

BBH rates:
too low by ~0.1

BH masses:
consistent

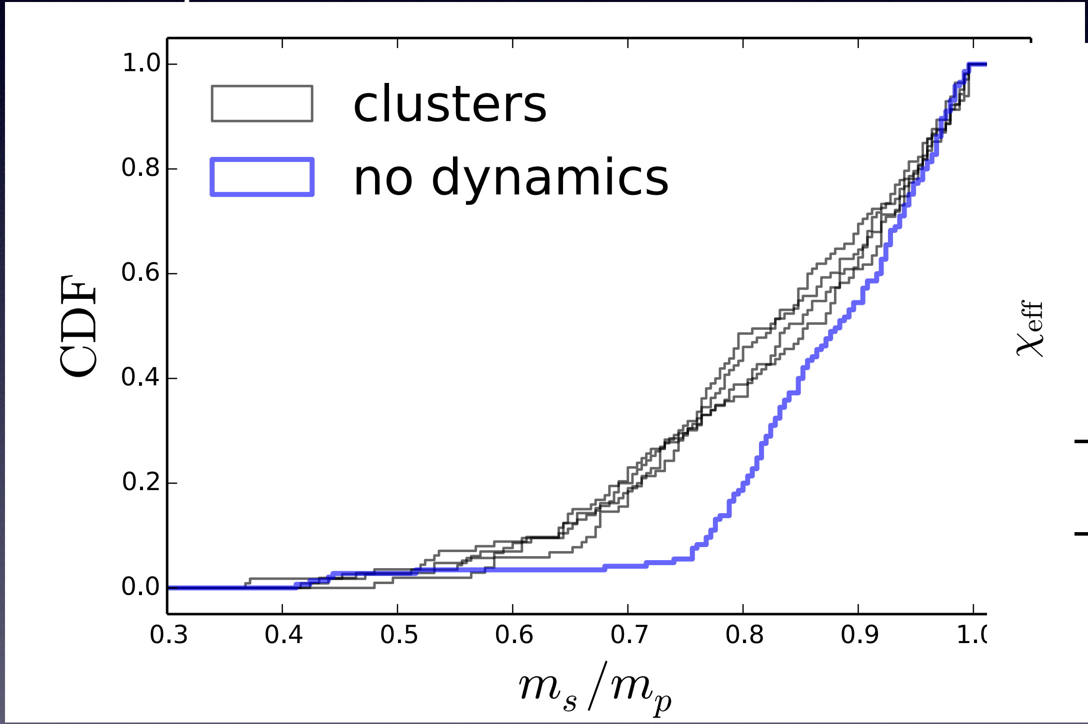
Binary BH Formation: can we distinguish among paths?

- chirp masses: below 10 or 20 solar masses?
- mass ratios: ~1 or unequal?
- spin orientations: mostly aligned or random?
- rate evolution with redshift: peaked or broad?
- orbital eccentricity: measured in the LISA band?

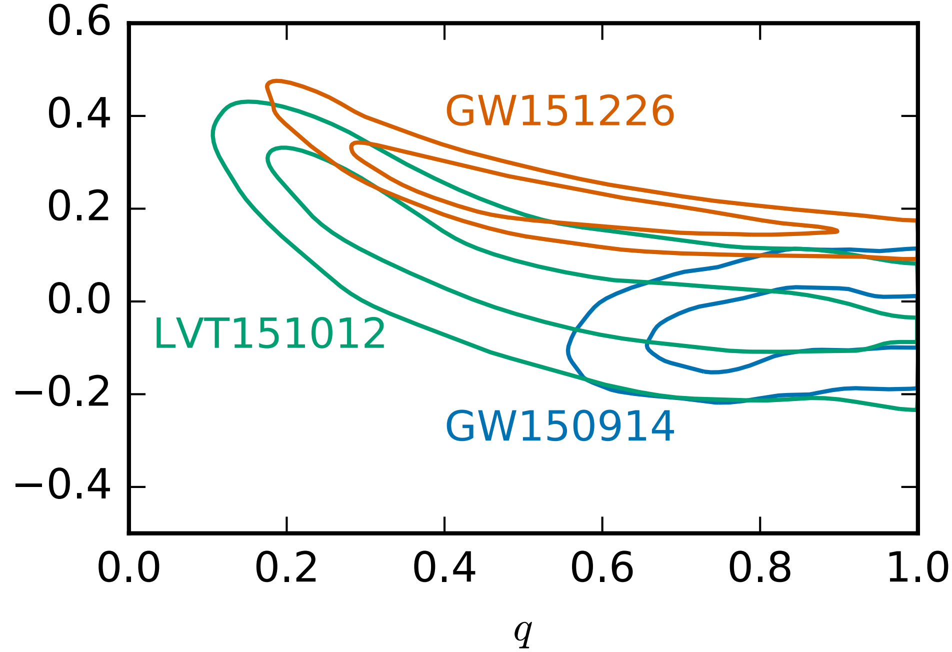
Binary BH Formation: can we distinguish among paths?

- **mass ratios:** ~1 or unequal?

Chatterjee et al. 2016



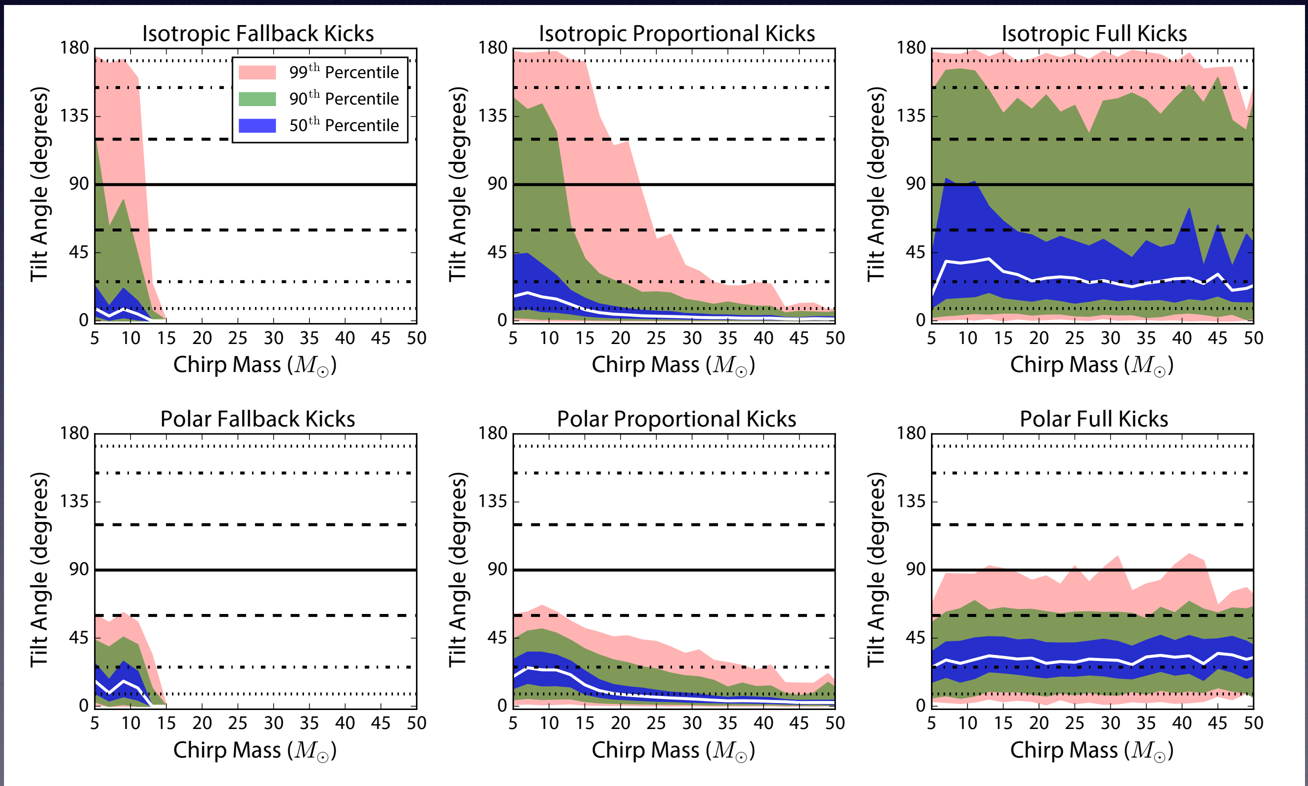
The LVC 2016



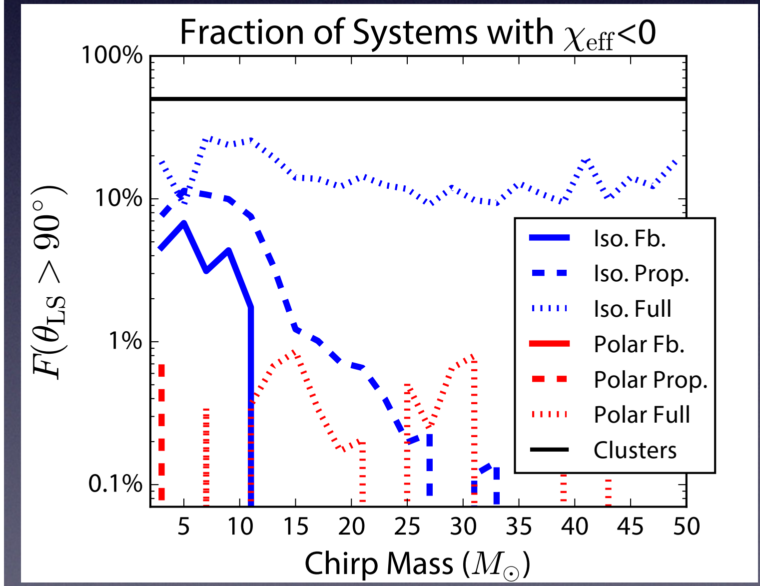
- **spin orientations:** mostly aligned or random?
- **rate evolution with redshift:** peaked or broad?

Binary BH Formation: can we distinguish among paths?

- **spin orientations:** mostly aligned or random?



Rodriguez et al. 2016



also
Vitale et al. 2016
Stevenson et al. 2017

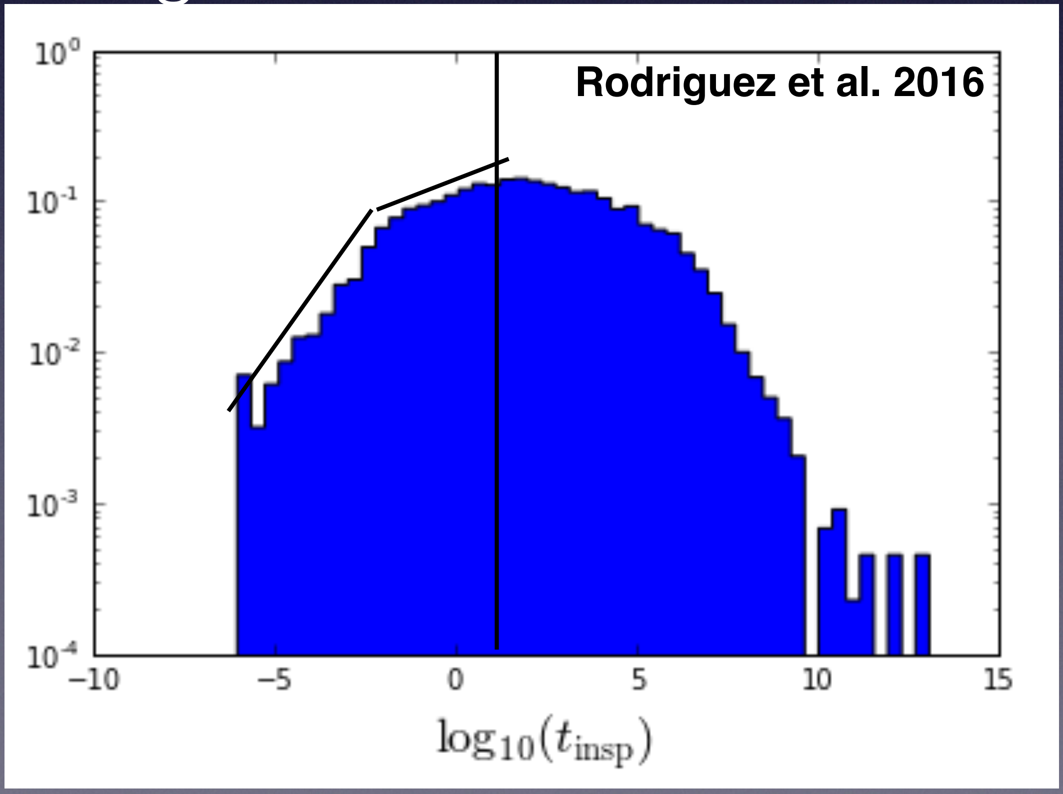
Binary BH Formation: can we distinguish among paths?

- **rate evolution with redshift: peaked or broad?**

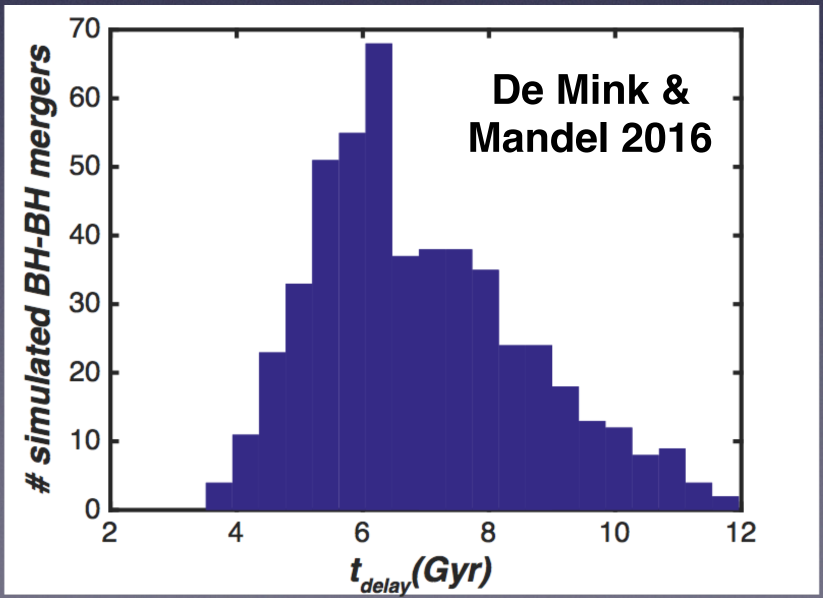
time-delays:

field binaries: 1/tau

globular clusters

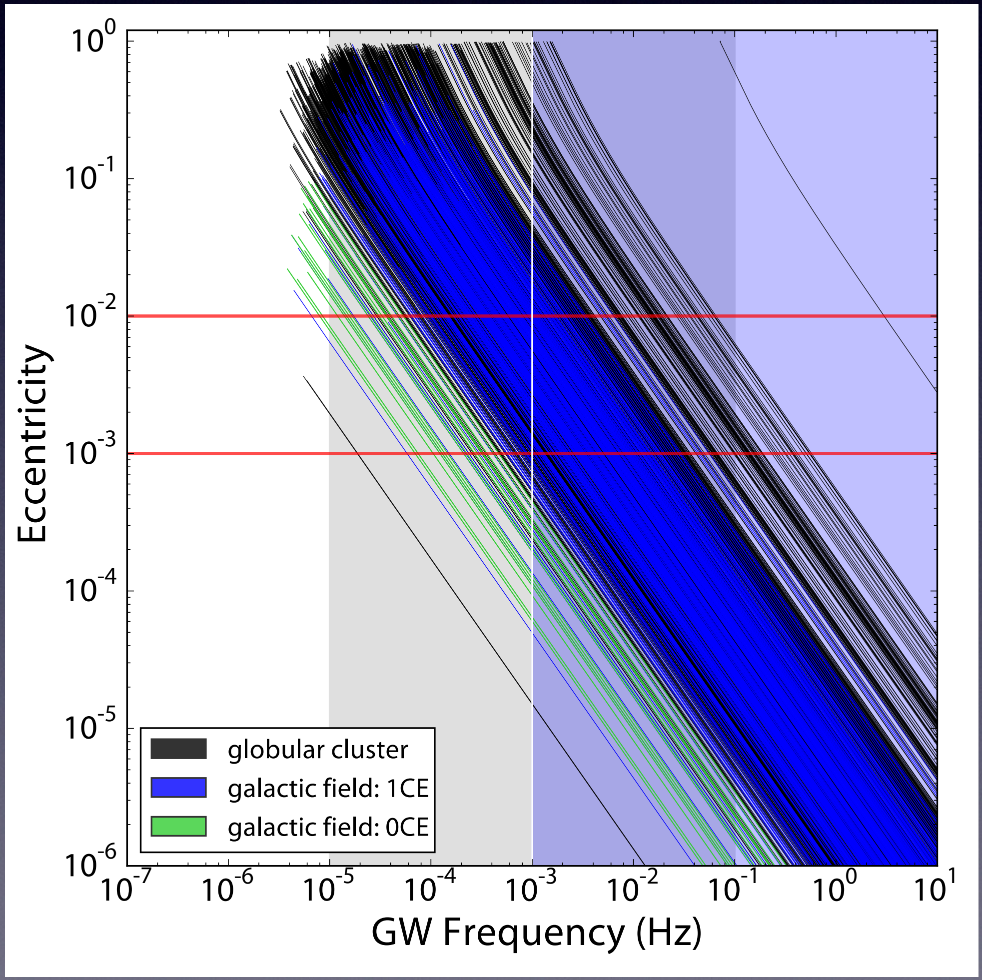


Case M binaries



Binary BH Formation: can we distinguish among paths?

- **orbital eccentricity:** measured in the LISA band?



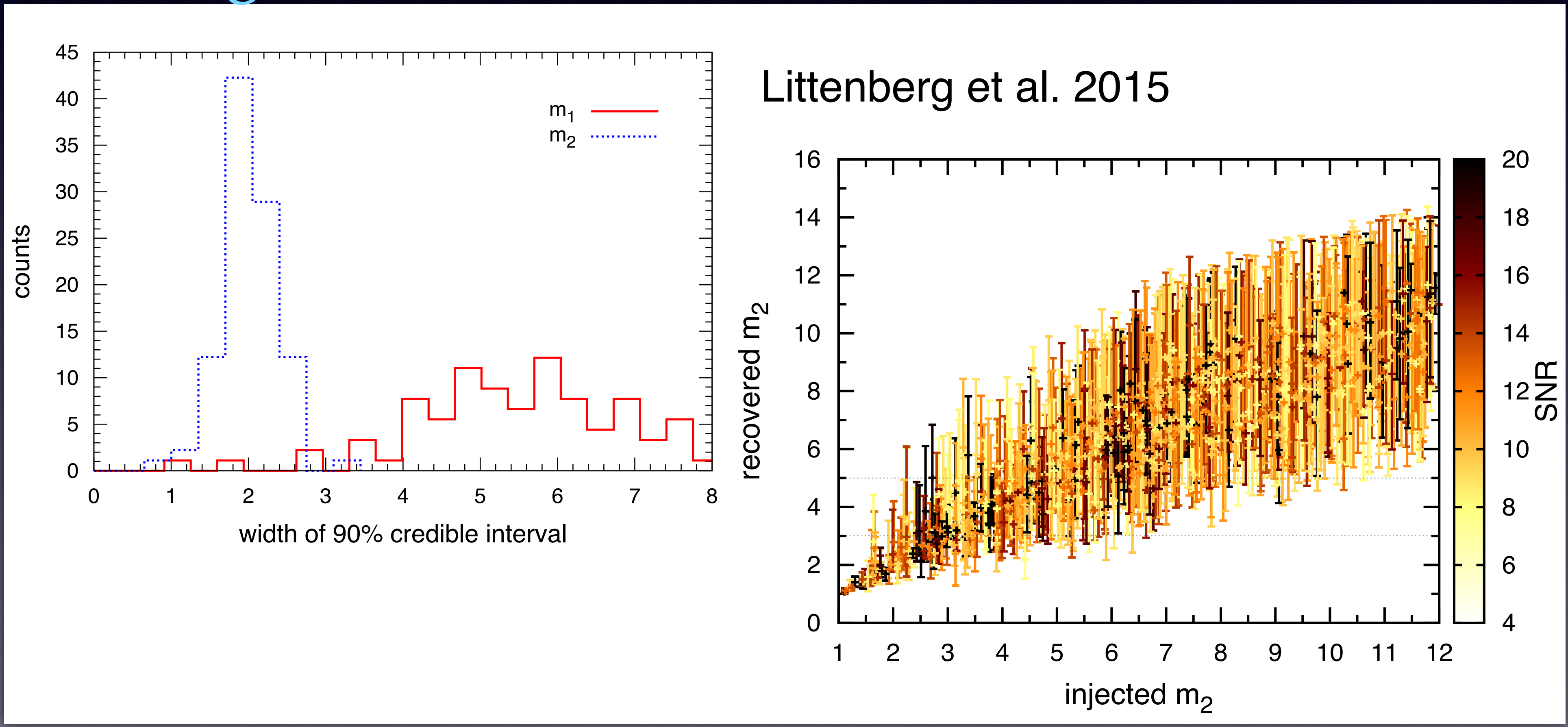
Breivik et al. 2016

What else could GW detections reveal about BHs?

- BHs in the low-end mass gap? (3-5 solar masses)

Ozel et al. 2010; Farr et al. 2011

although…

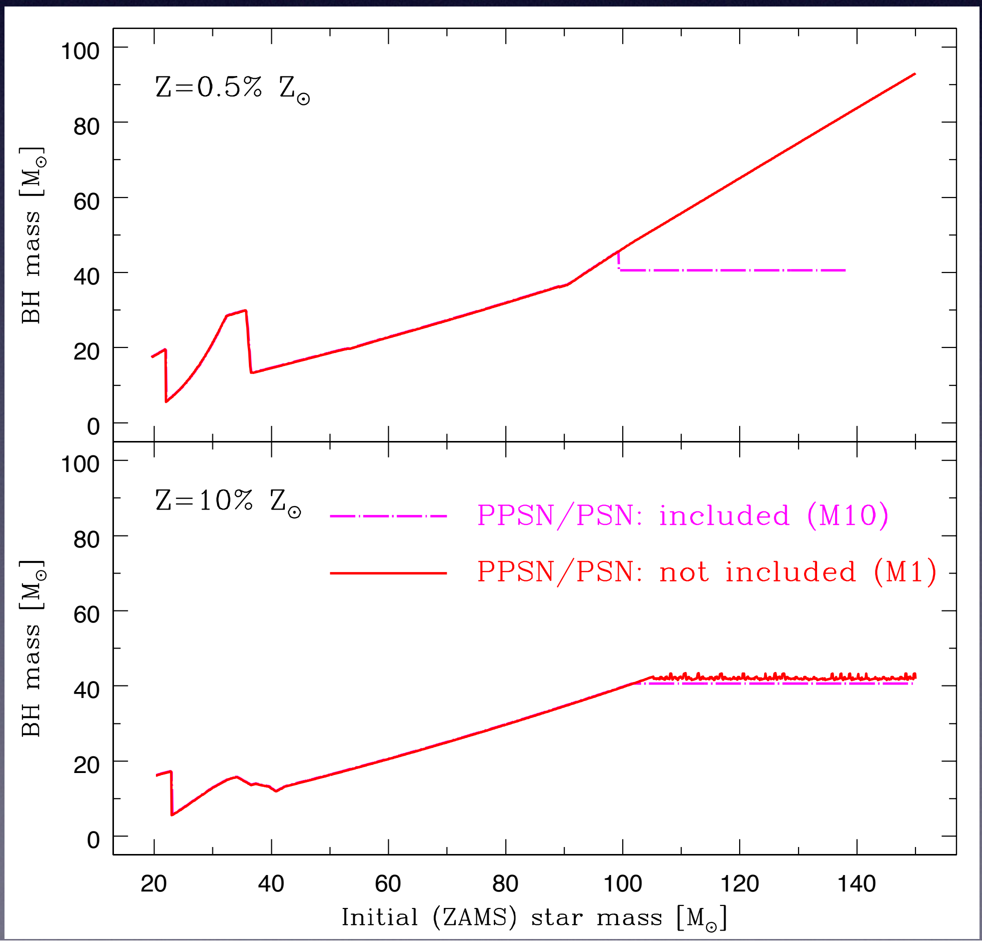


What else could GW detections reveal about BHs?

- BHs in the low-end mass gap? (3-5 solar masses)

Ozel et al. 2010; Farr et al. 2011

- Reveal a high-mass gap? (40 - 130 solar masses)



Woosley 2017; Belczynski et al. 2016

What else could GW detections reveal about BHs?

- BHs in the low-end mass gap? (3-5 solar masses)

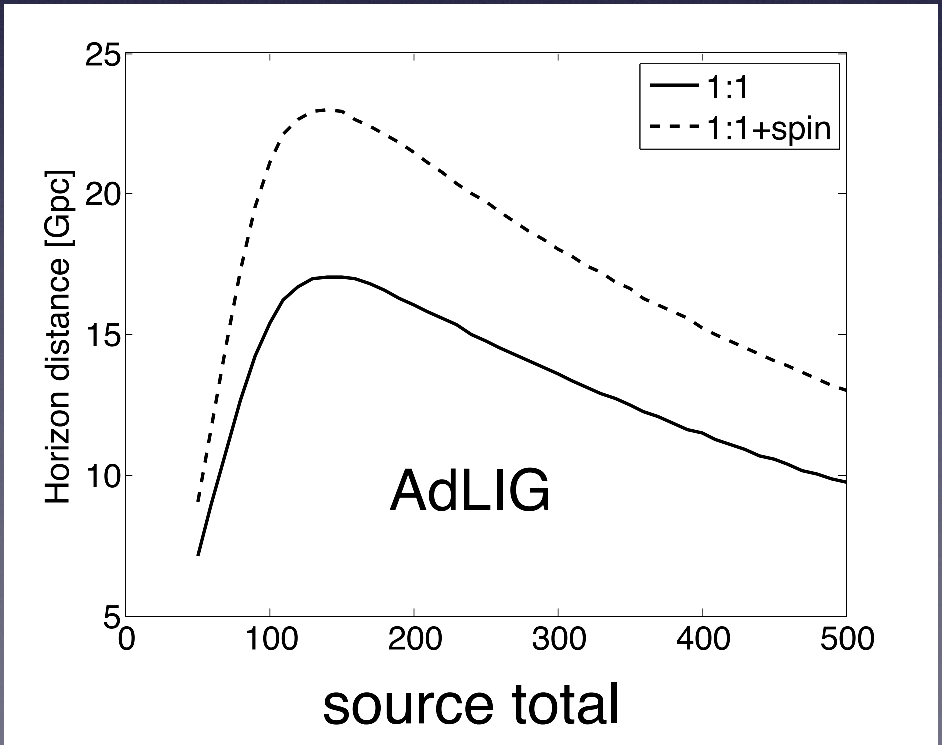
Ozel et al. 2010; Farr et al. 2011

- Reveal a high-mass gap? (40 - 130 solar masses)

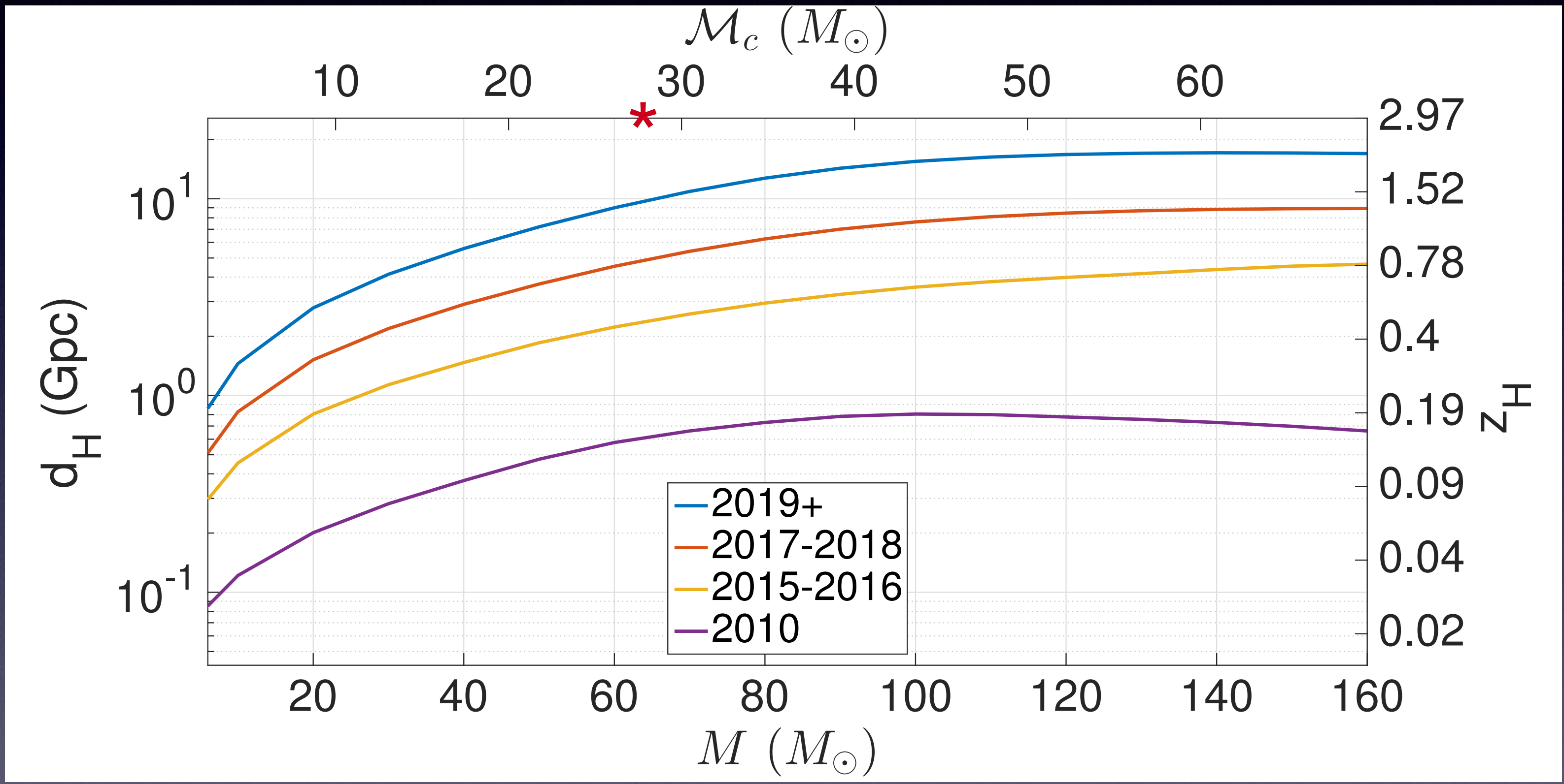
Woosley 2017; Belczynski et al. 2016

- Firm detection of IMBHs ?

Mandel



In the Era of Gravitational-Wave Astrophysics



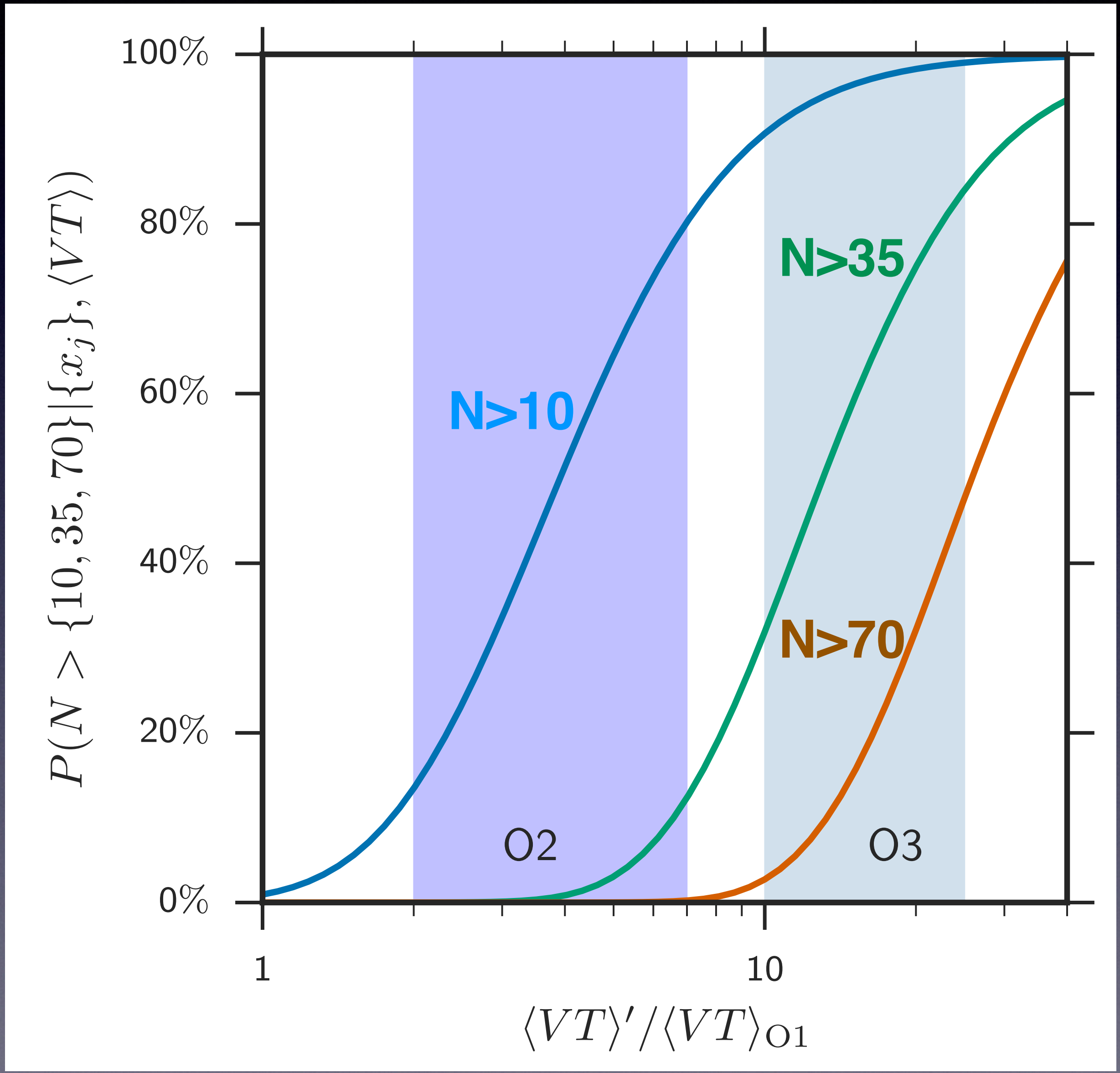
The LVC, ApJL, published, arXiv/1602.03846

In the Era of Gravitational-Wave Astrophysics

More BBH detections to come …

Reveal underlying BBH mass distribution

Quantitative model constraints



The LVC, PRX, published, arXiv/1602.03842

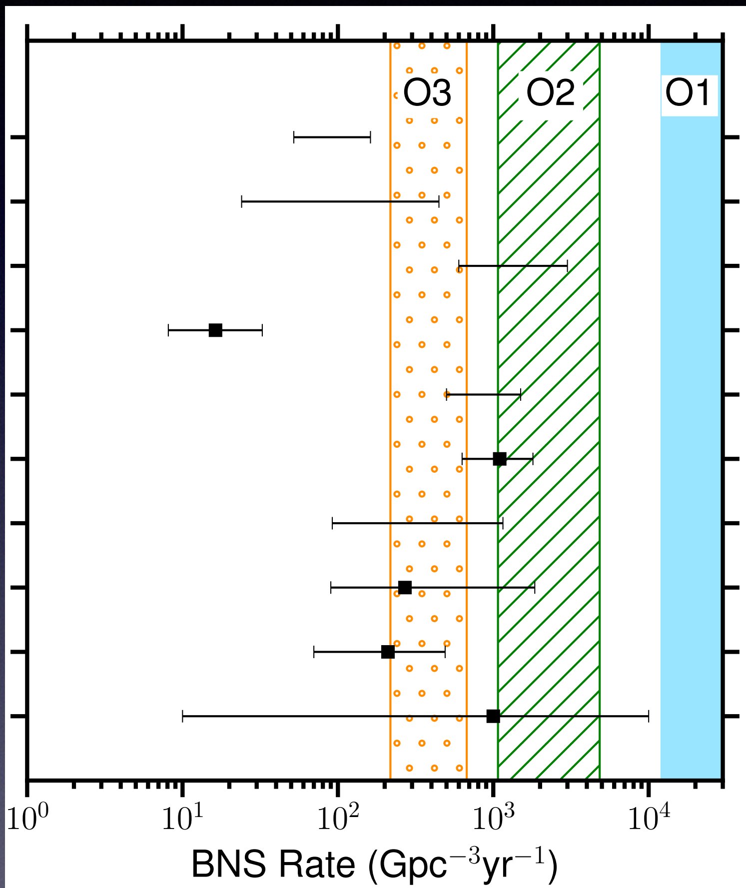
Neutron Star Mergers

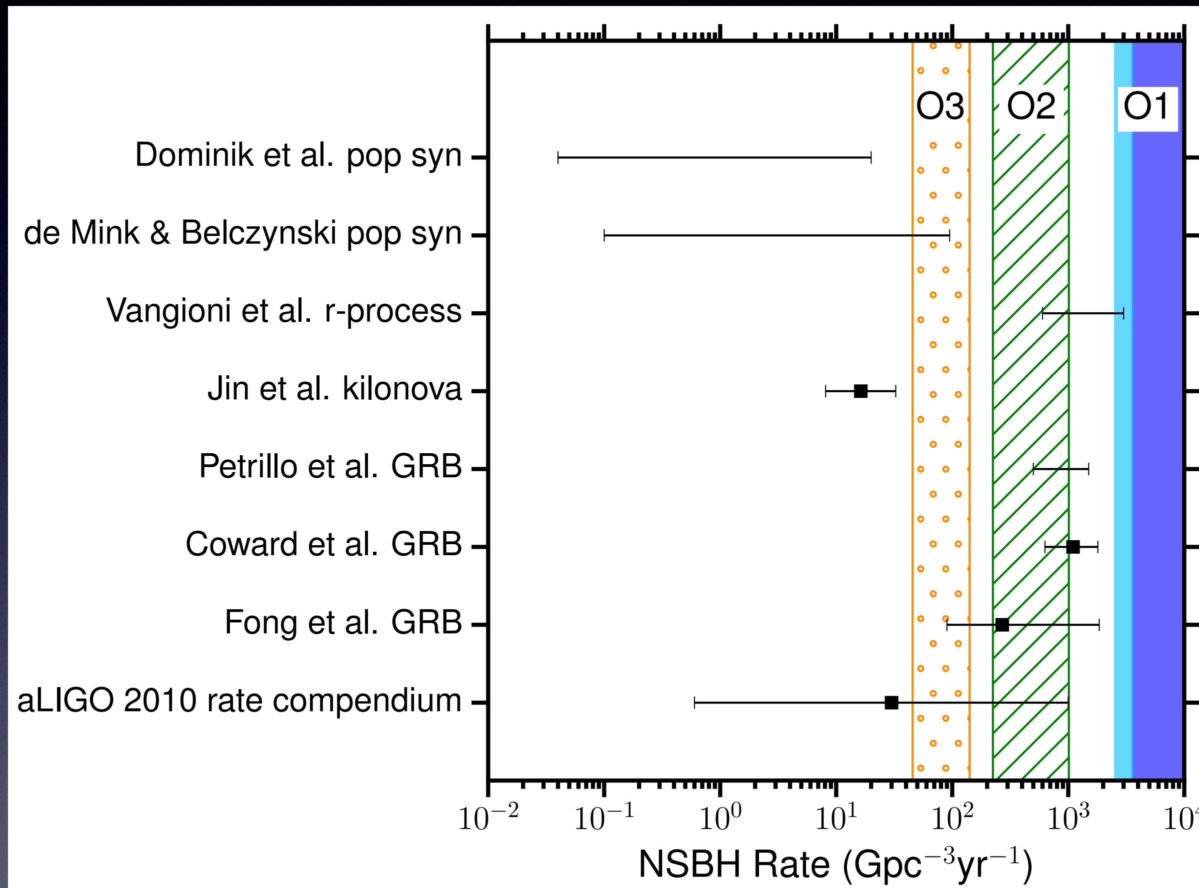
- NS-NS or NS-BH coalescence events?
- tight upper limits and firm rate measurements?

- BH/NS mass and spin distributions?
- EM counterparts?
  - GRBs / X-ray afterglows / kilonovae / radio afterglows?
- host galaxies?

- new way to measure Ho?
- NS EOS constraints?

Neutron Star Mergers





LSC VIRGO

The LVC, ApJL, in press, arXiv/1607.07456