Title: Multi-Messenger Astronomy with Advanced LIGO-Virgo

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Abstract: <p>The first detections of gravitational waves by LIGO-Virgo initiated the era of Gravitation-Wave Astronomy. Gravitational-waves serve as a new and independent probe of the Universe. In addition, the combination of gravitational-waves with information from other messengers, such as electromagnetic emission from the same source, will lead to a more complete and accurate understanding of cosmology and astrophysics. In this talk, I will discuss some interesting learnings from the Advanced LIGO-Virgo first observing run and several scientific goals we expect to reach in the next few years.</p>


Image credit:SXS
Multi-Messenger Astronomy with Advanced LIGO-Virgo
Hsin-Yu Chen
THE UNIVERSITY OF CHICAGO
Perimeter Institute Strong Gravity Seminar, January 2017

Multi-Messenger Astronomy

Gravitational Wave

- mass
- spin
- sky location
- luminosity distance
- inclination

Electromagnetic Wave

- sky location
- spectrum
- light curve
- host galaxy
- redshift

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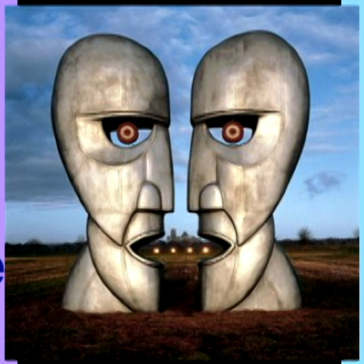

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"I am a binary black hole merger."

–GW150914

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"I am a binary black hole merger."

–GW150914

"Me too."

–LVT151012

"So am I."

–GW151226

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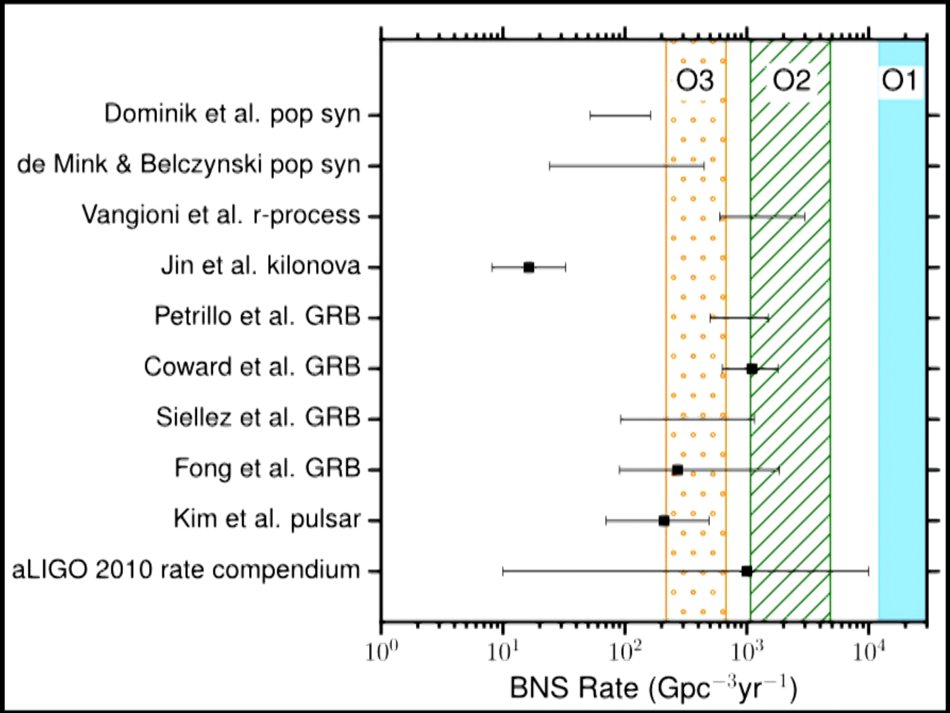
What LIGO hasn't detected (but likely will)

- Binary neutron star mergers



LIGO-Virgo Collaboration ApJL (2016)

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Short Gamma-Ray Burst

- Not associated with SN, found in early/late type galaxy, host galaxy offset →merging binary system
- Fermi GBM~45/yr, Swift BAT~10/yr
- Narrowly beamed: $\theta_j \leq 10°$

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- Fraction of sky covered by beamed gamma rays:

$$f_b = 1 - \cos\theta_j$$

- Observed v.s. progenitor rate of GRB:

$$\mathcal{R}_{\rm GRB} = \mathcal{R} f_b = \mathcal{R}(1 - \cos\theta_j)$$

Chen & Holz PRL (2013)

H.-Y. Chen, Jan. 2017

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Upper limit on merger rate [from LIGO O1 non detection]

Chen & Holz PRL (2013)

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Upper limit on merger rate [from LIGO O1 non detection] → **Lower limit on GRB beaming angle**

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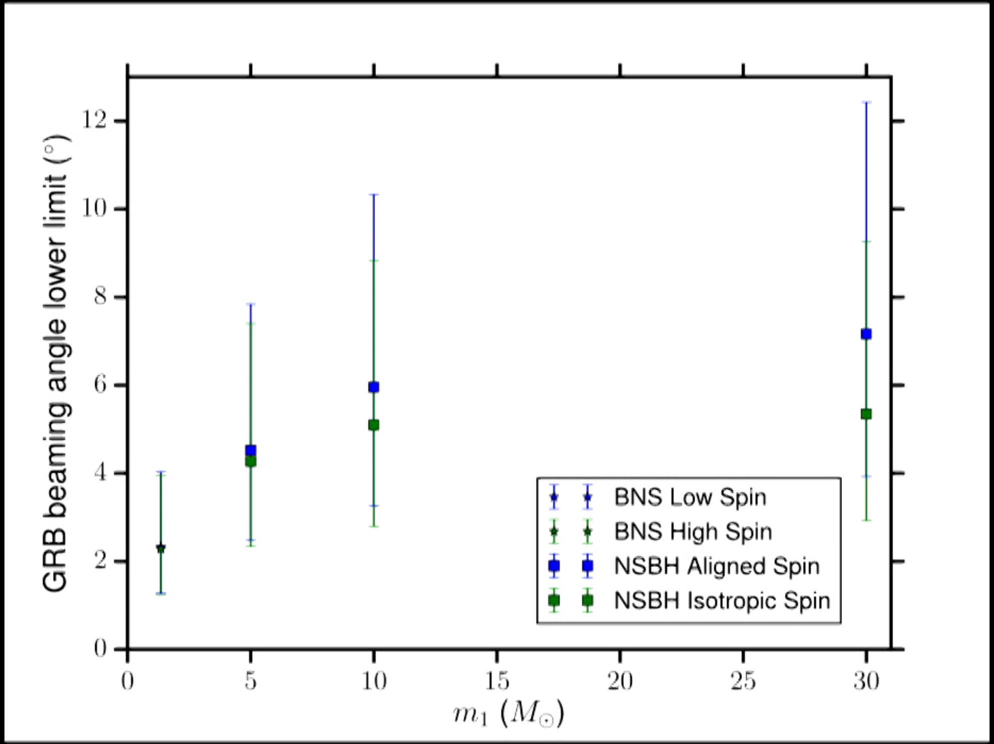
Astrophysical constraints from non-detection

- Short GRB beaming angle



LIGO-Virgo Collaboration ApJL (2016) H.-Y. Chen, Jan. 2017

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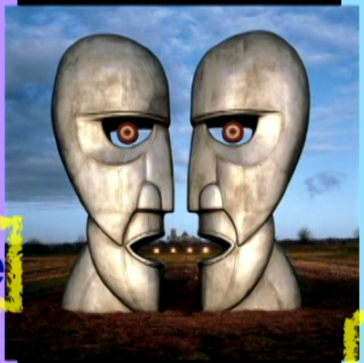

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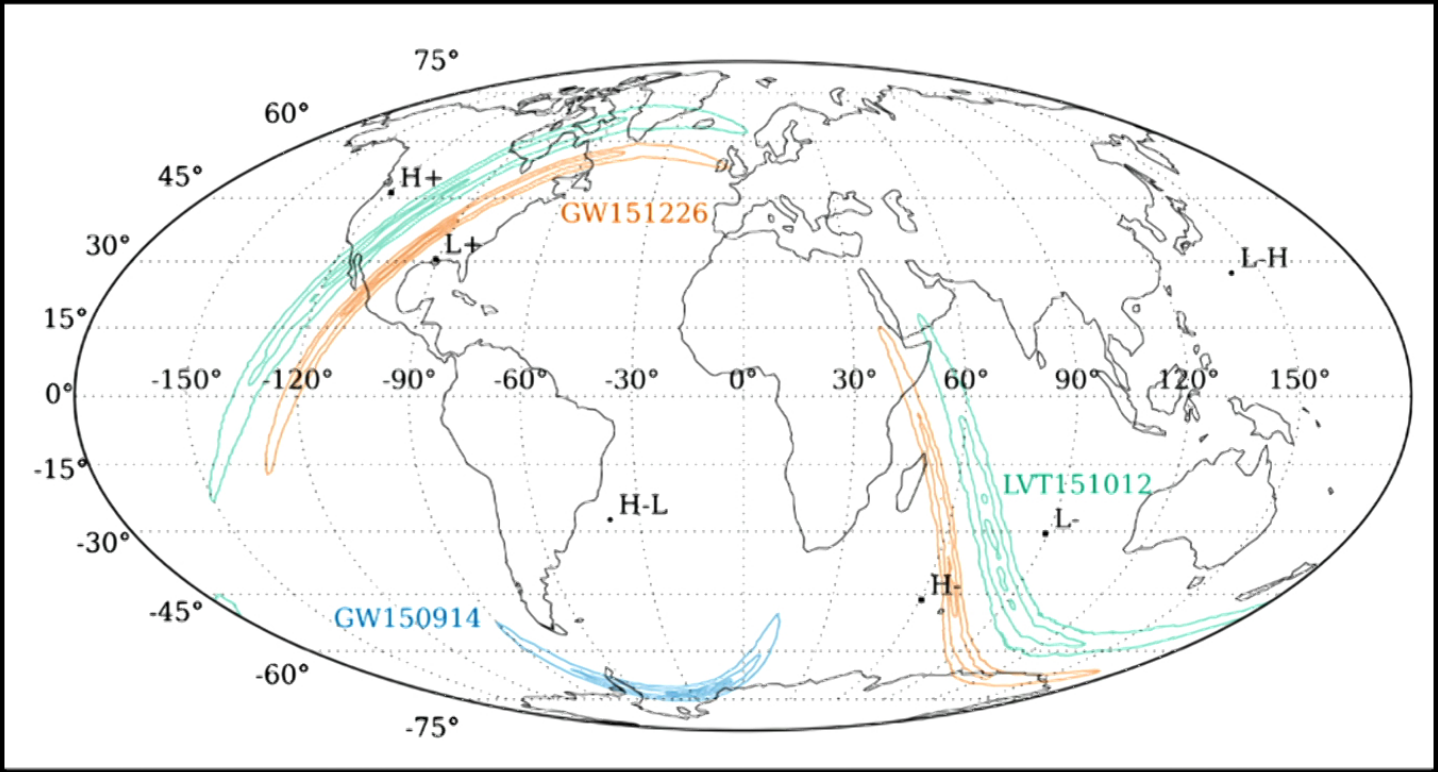
GW Localization Maps



LIGO-Virgo Collaboration PRX (2016)

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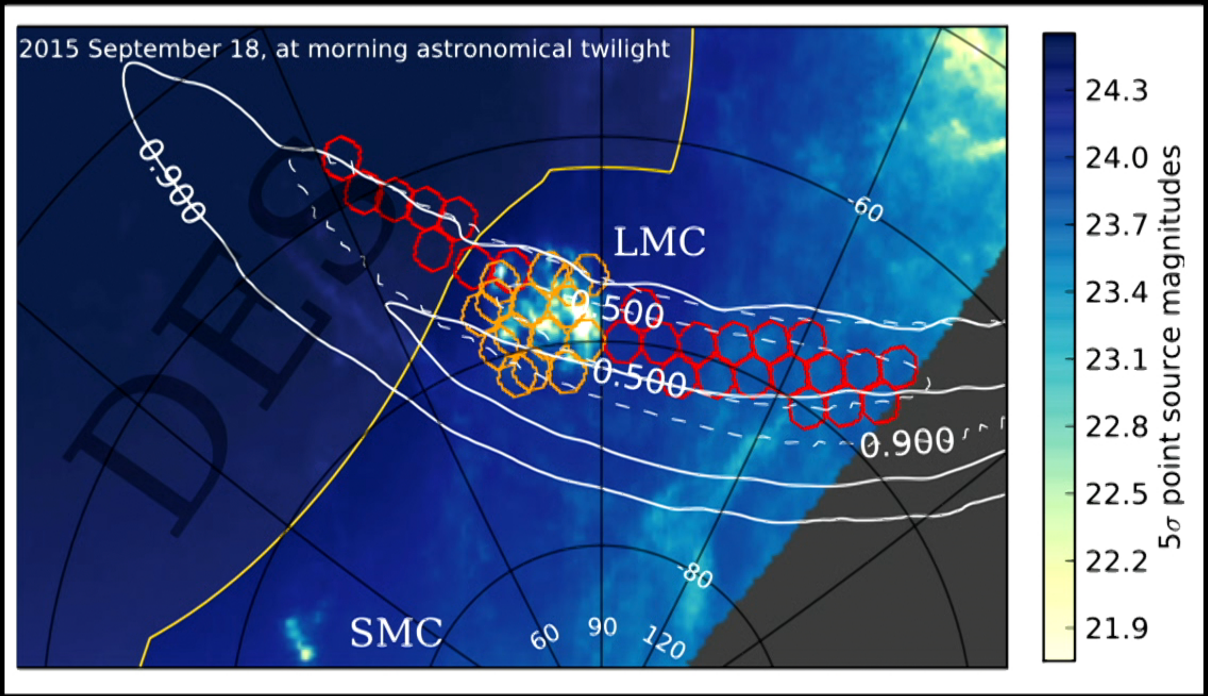
GW150914 DECam Follow-up



Soares-Santos et al. (2016), Annis et al. (2016)

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Dark Energy Camera (DECam)

Photo credit: Reidar Hahn, Fermilab

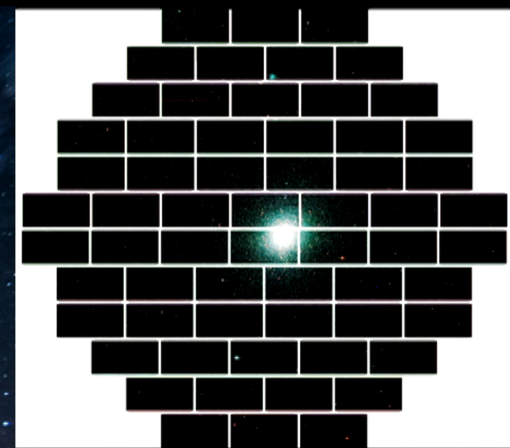

Photo credit: DES Collaboration

Cowperthwaite et al., ApJL (2016)
Soares-Santos et al., ApJL (2016)
Annis et al., ApJL (2016)

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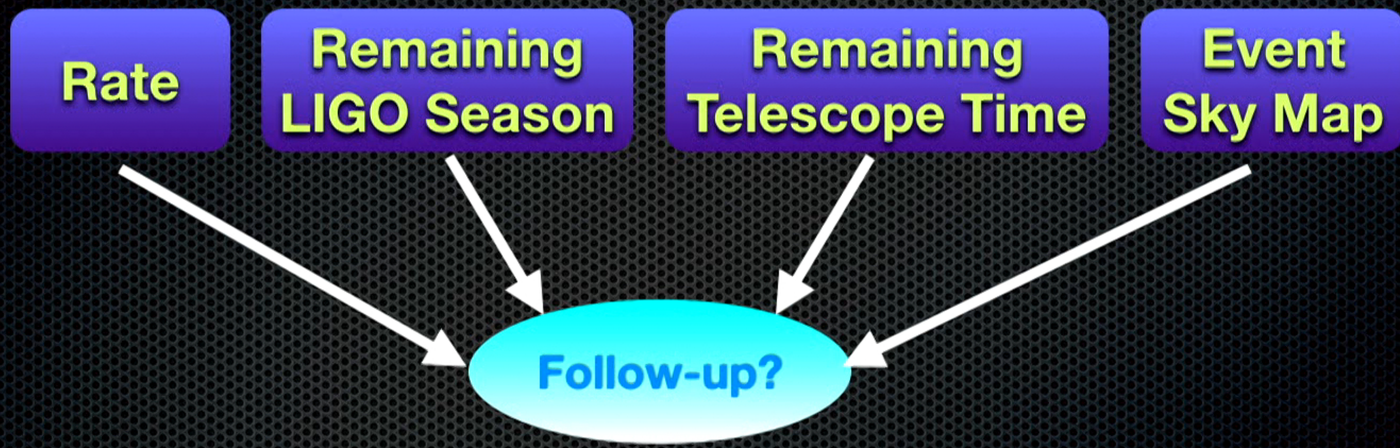
Follow-up Optimization Process

- Goal: Maximize successful followup



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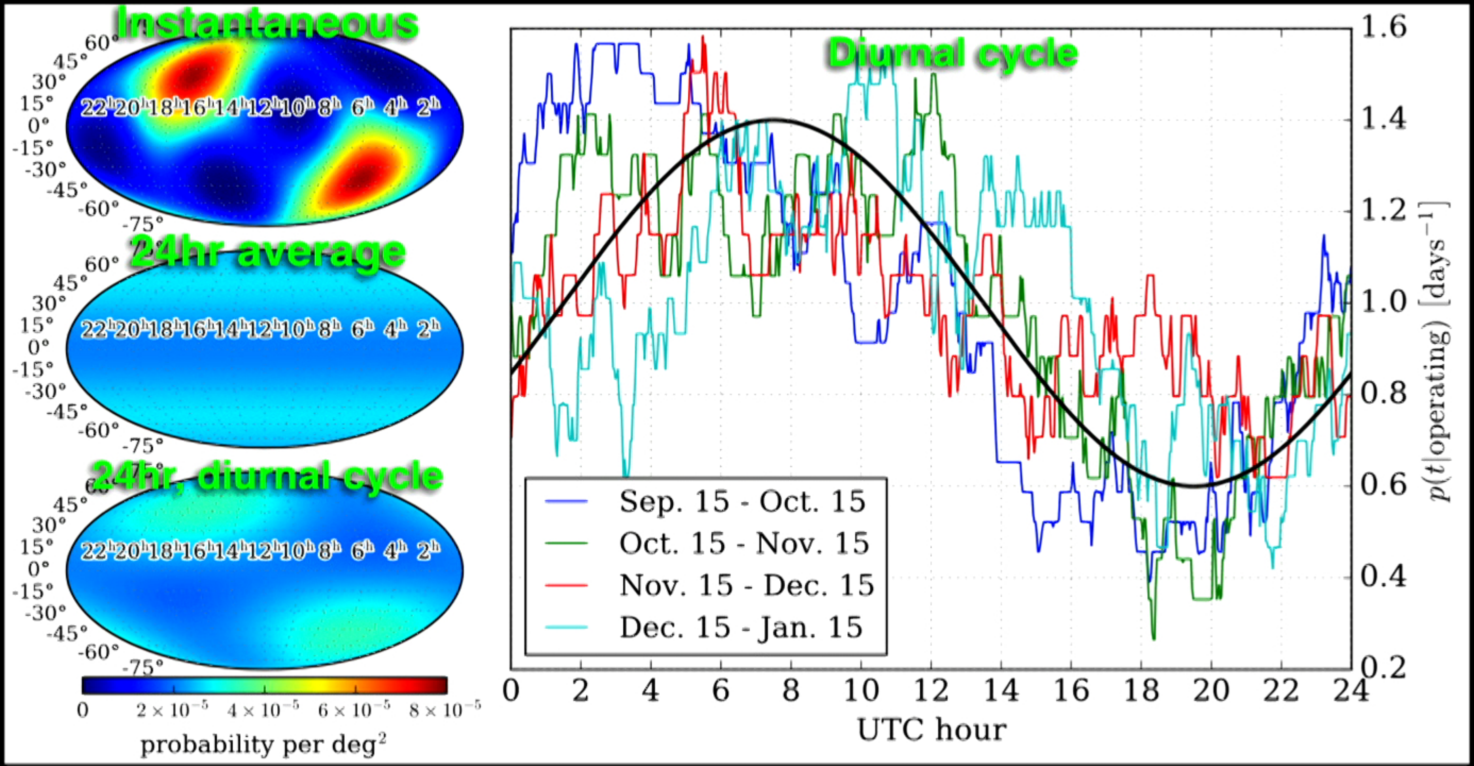
Selection Effects



Chen, Essick et al. ApJ (2017)

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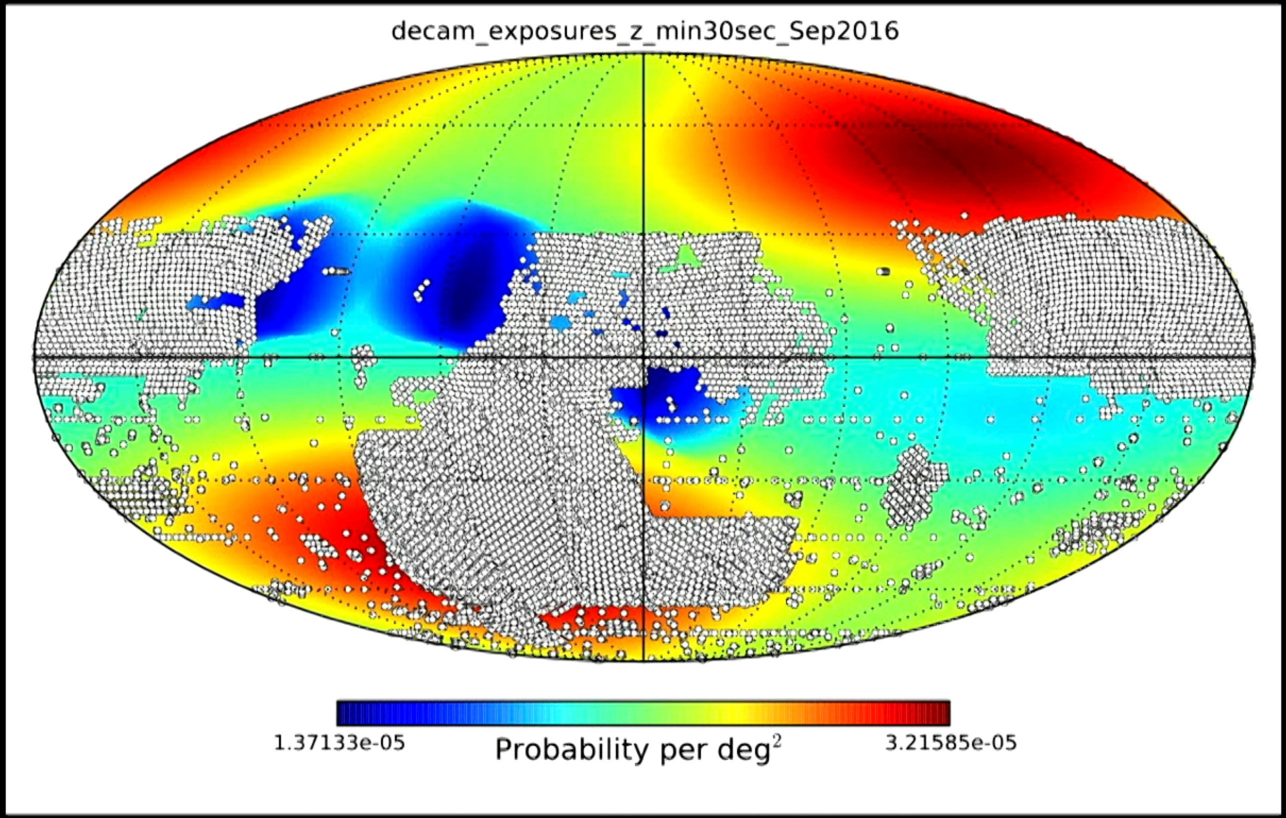
Selection Effects & EM Follow-up



Chen, Essick et al. ApJ (2017)

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Host Galaxy Identification

- Number of potential host galaxies
- Volume, volume, volume.
  - Binary neutron star: 10,000 Mpc^3
  - 10-10 $M_\odot$ binary black holes: 1-10 Million Mpc^3
  - 30-30 $M_\odot$ binary black holes: 10-100 Million Mpc^3

Chen & Holz (2016)

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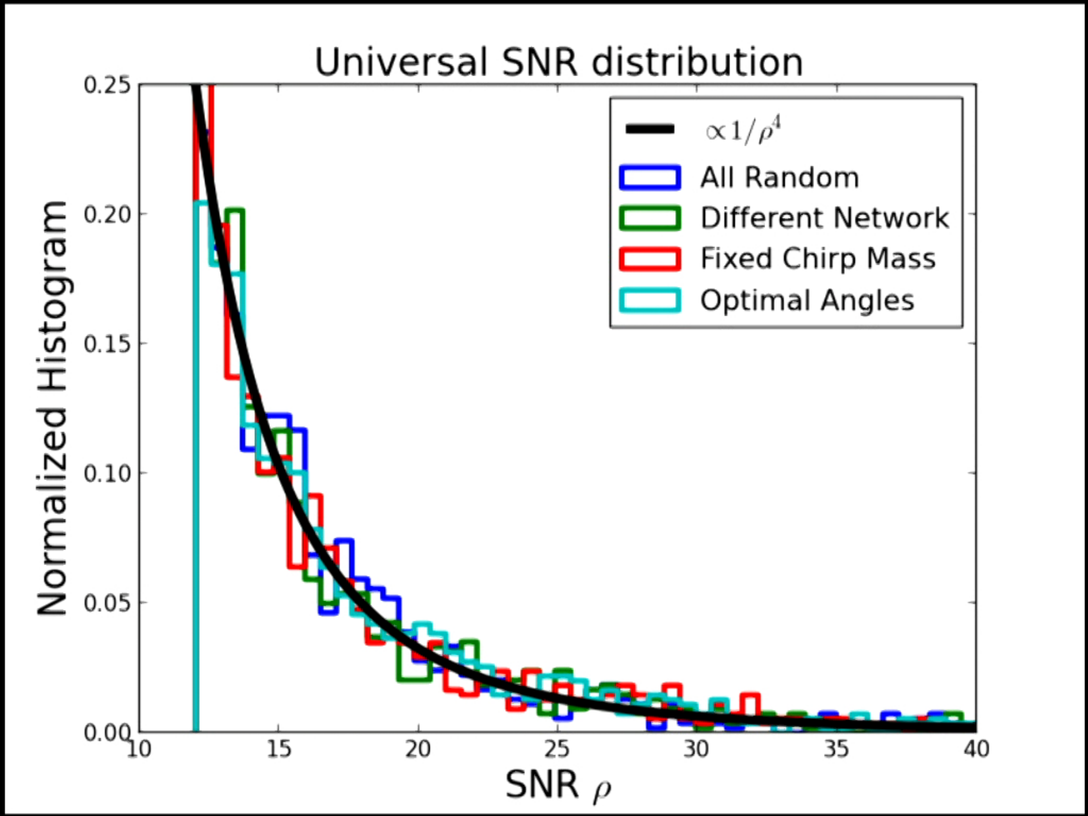
Finding the One



Chen & Holz (2014)

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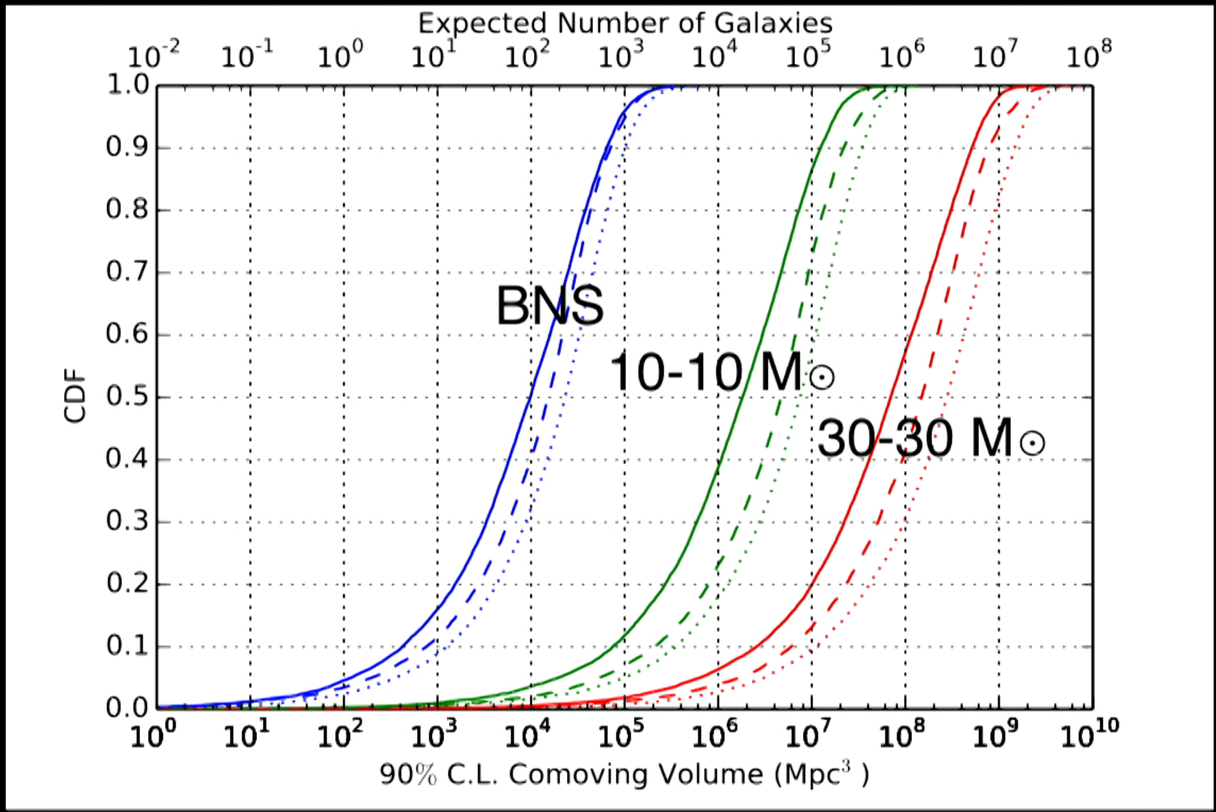
Finding the One



Chen & Holz (2016)

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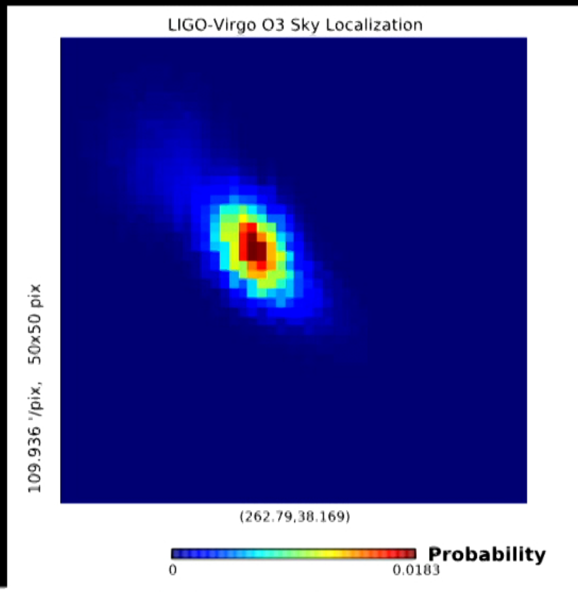
Finding the One



"Golden" BBH (10-10M☉)

O3 LIGO+Virgo.

2.5 deg^2 (90% C.L.)

800 Mpc^3 (90% C.L.)

Network	Mass($M_\odot$)	Median (Mpc^3)	< 100 Mpc^3 (%)	< 100 Mpc^3 ($\langle N_{\rm event}\rangle$)	< 1000 Mpc^3 (%)	< 1000 Mpc^3 ($\langle N_{\rm event}\rangle$)
HLV O3	(1.4, 1.4)	9.8×10^3	4.6	[0.0024, 0.24, 2.4]	16.1	[0.0083, 0.83, 8.3]
HLV O3	(10, 10)	1.8×10^6	0.3	[0.017, 0.085, 0.34]	1.0	[0.061, 0.34, 1.2]
HLV O3	(30, 30)	6.9×10^7	0.1	[0.021, 0.070, 0.21]	0.1	[0.055, 0.18, 0.55]
HLV design	(1.4, 1.4)	2.3×10^4	2.4	[0.0078, 0.78, 7.8]	8.9	[0.029, 2.9, 29]
HLV design	(10, 10)	7.4×10^6	0.2	[0.077, 0.38, 1.5]	0.6	[0.21, 1.0, 4.2]
HLV design	(30, 30)	2.8×10^8	0.0	[0.067, 0.22, 0.67]	0.1	[0.27, 0.89, 2.7]
HLVJI design	(1.4, 1.4)	1.5×10^4	3.5	[0.023, 2.3, 23]	11.5	[0.076, 7.6, 76]
HLVJI design	(10, 10)	4.6×10^6	0.2	[0.13, 0.66, 2.6]	0.7	[0.51, 2.5, 10]
HLVJI design	(30, 30)	1.5×10^8	0.0	[0.043, 0.14, 0.43]	0.1	[0.60, 2.0, 6.0]

Chen & Holz (2016)

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Summary

- The era of gravitational-wave astronomy and cosmology has begun
- GW-EM multi-messenger yields more accurate and complete measurements
- There are active EM follow-up programs
- Host galaxy identification is possible for golden events

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