Looking into the Universe via GWs

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Outline

- GW150914: the original GW signal, a BBH
- Compact objects as GW sources
- Prospects of GW astronomy
- Summary

1915 general relativity (A.Einsten)

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1960s resonance detector (J. Webber)

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1970s GW existence is proved (Hulse-Taylor)

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1980s laser interferometer (Weiss, Drever, et al.)

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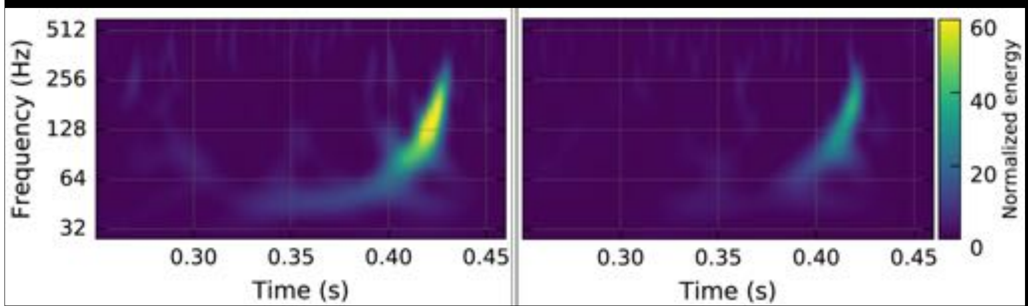
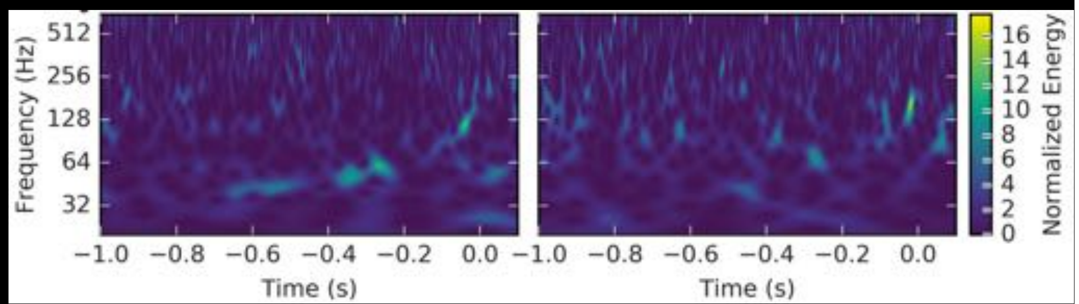
2015 GWs from BH-BH detected!

GW150914



GW151226



GW150914 Binary BH-BH (BBH) merger

"Observation of Gravitational Waves from a Binary Black Hole Merger"
(12 Feb, 2016)
1300+ citations (as of today)

with advanced LIGO (H1+L1)

Observation run 1 (O1)
Sep. 12, 2015 ~ Jan. 12, 2016

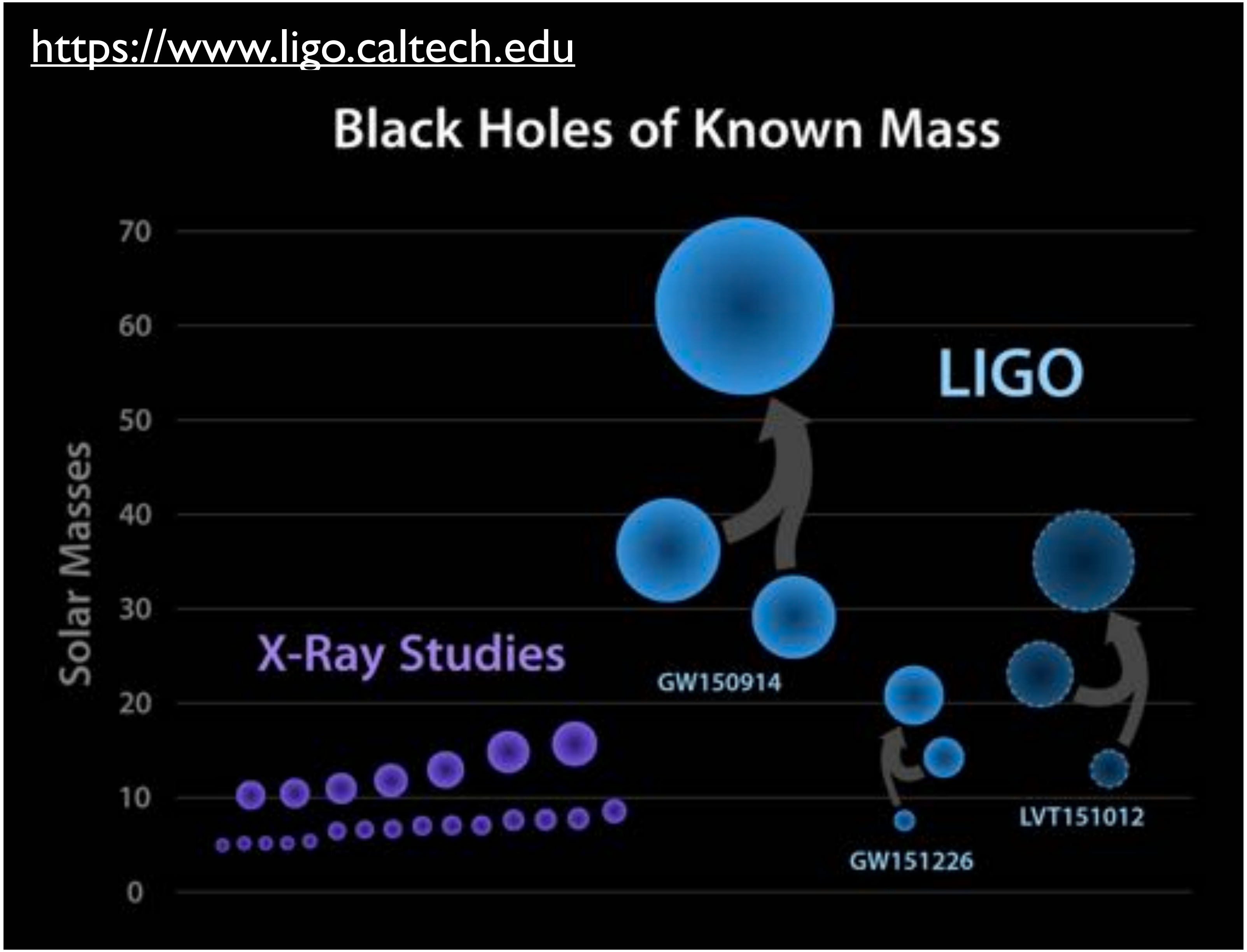
2 confirmed BBHs
1 BBH candidate

Observation run 2 (O2)
since November, 2016 till now

Global network of GW detectors

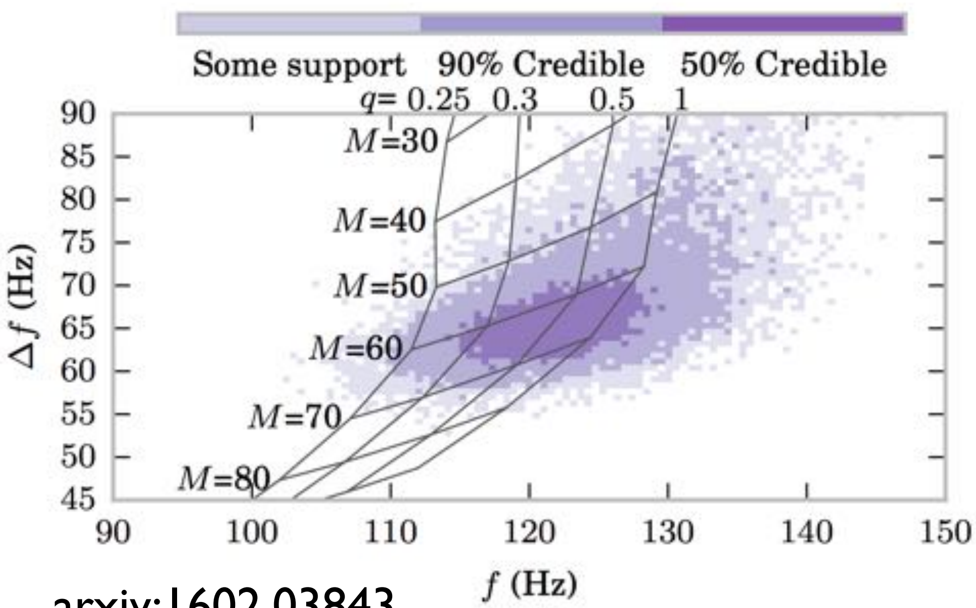
frequency range: ~20-2000 Hz

BH astronomy is now available with GWs!

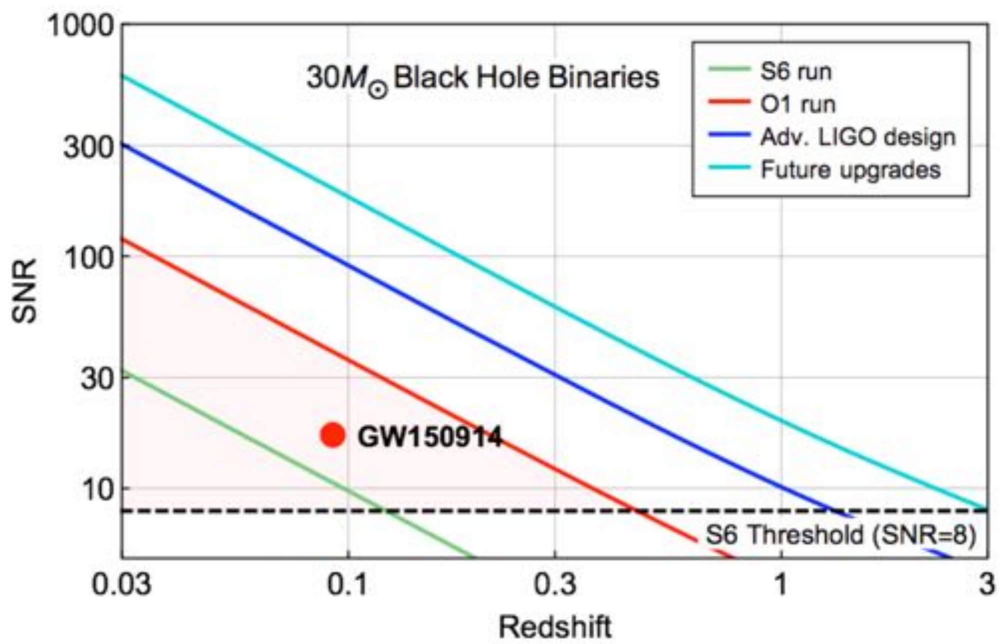


What can we do with an “audio-band” detector on Earth?

- **sources**: BBH, NS-NS, BH-NS
- **masses**: O(1) ~ O(100) M_{sun}
- **signal duration**: seconds for BBHs ~ minutes for NS-NSs
- **localization**: O(1)~ O(1000+) sq.deg
- **distance**: Mpc up to Gpc



arxiv:1602.03843



Estimation of physical parameters

GW detection

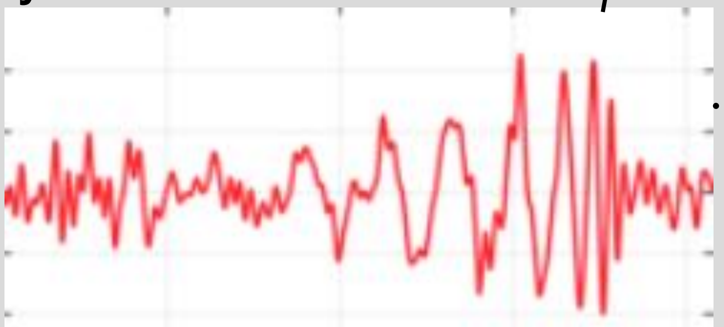
Measuring observables

- m_1, m_2, spin(s)
- distance
- sky location

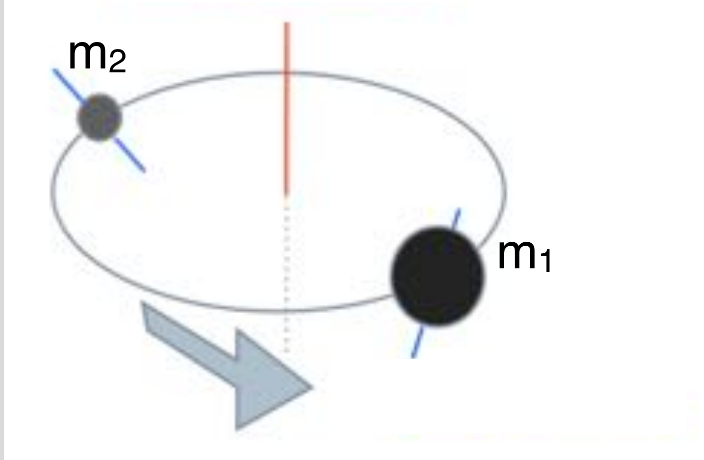
Followup observations

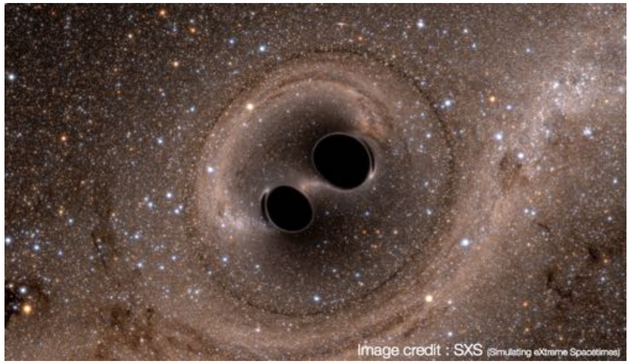
Astrophysics

two sites of LIGO
on Earth detect GWs
by 7ms time difference



"parameter estimation"

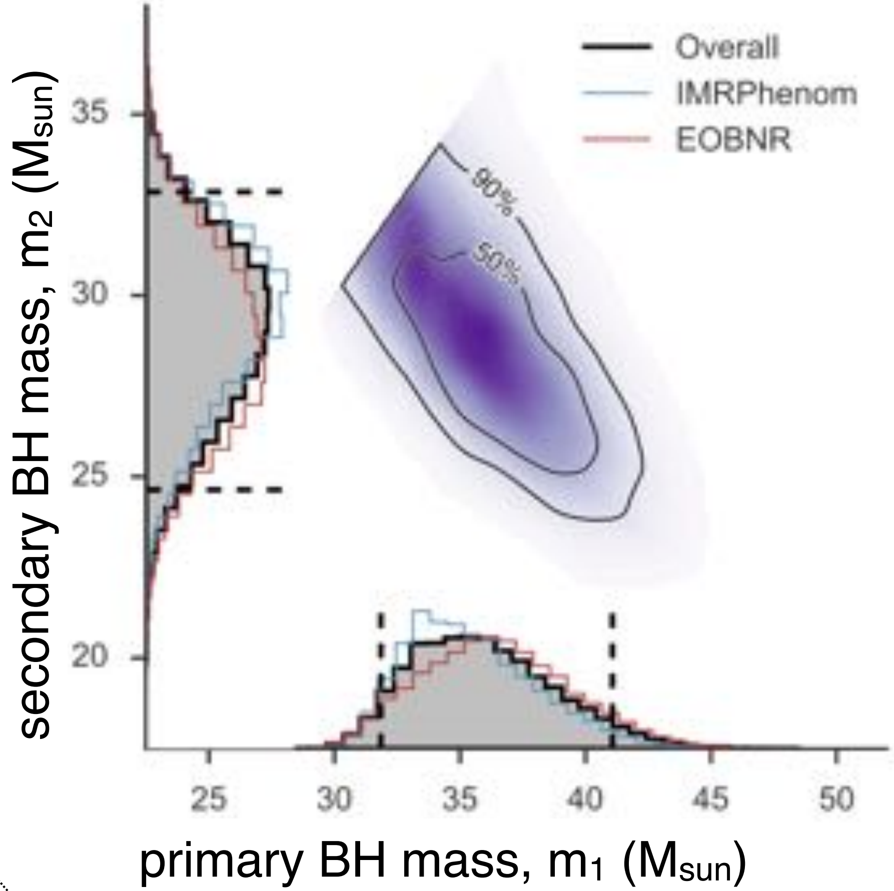




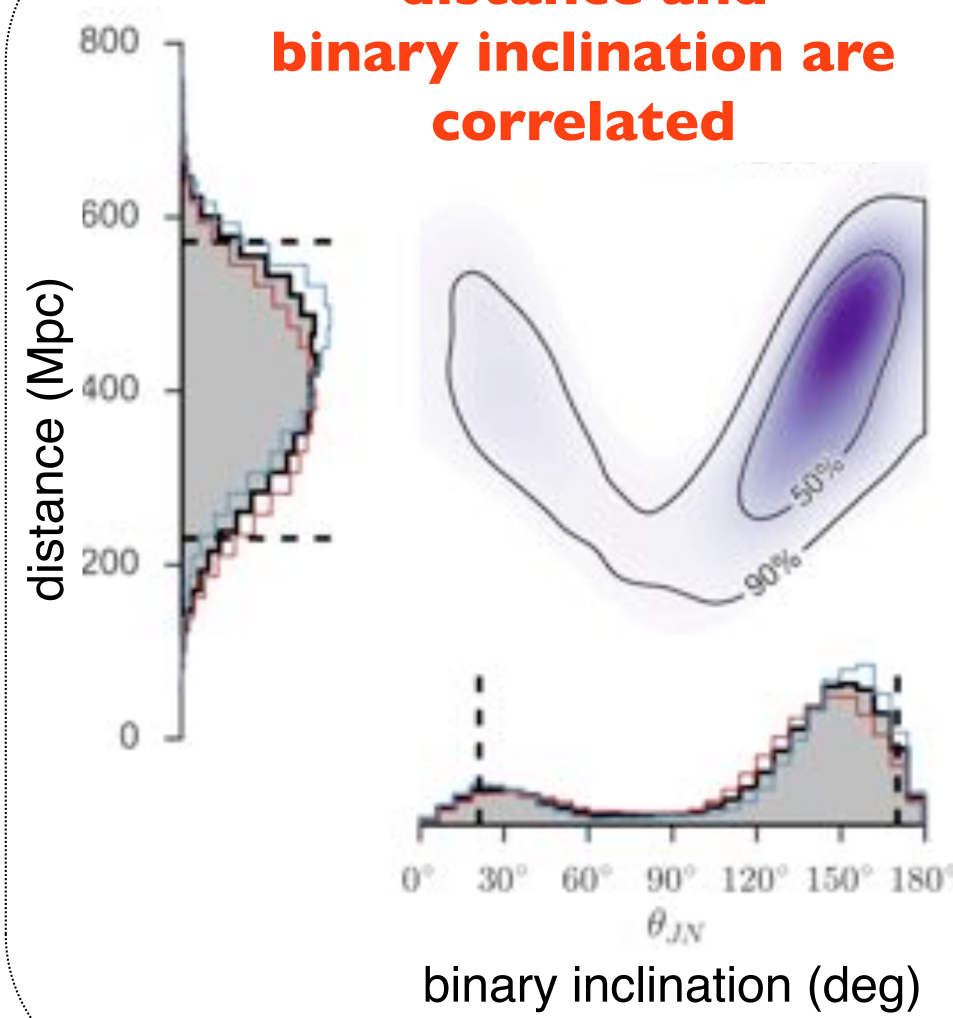
example of parameter estimation: GW150914

two GW waveform models for BH-BH binaries (IMRPhenom and EOBNR)

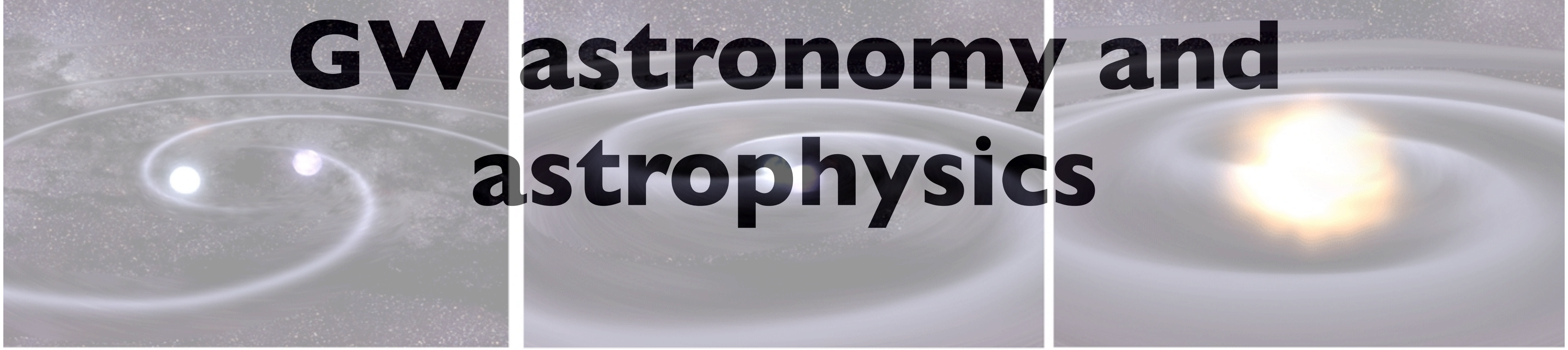
massive BHs in binaries



distance and binary inclination are correlated



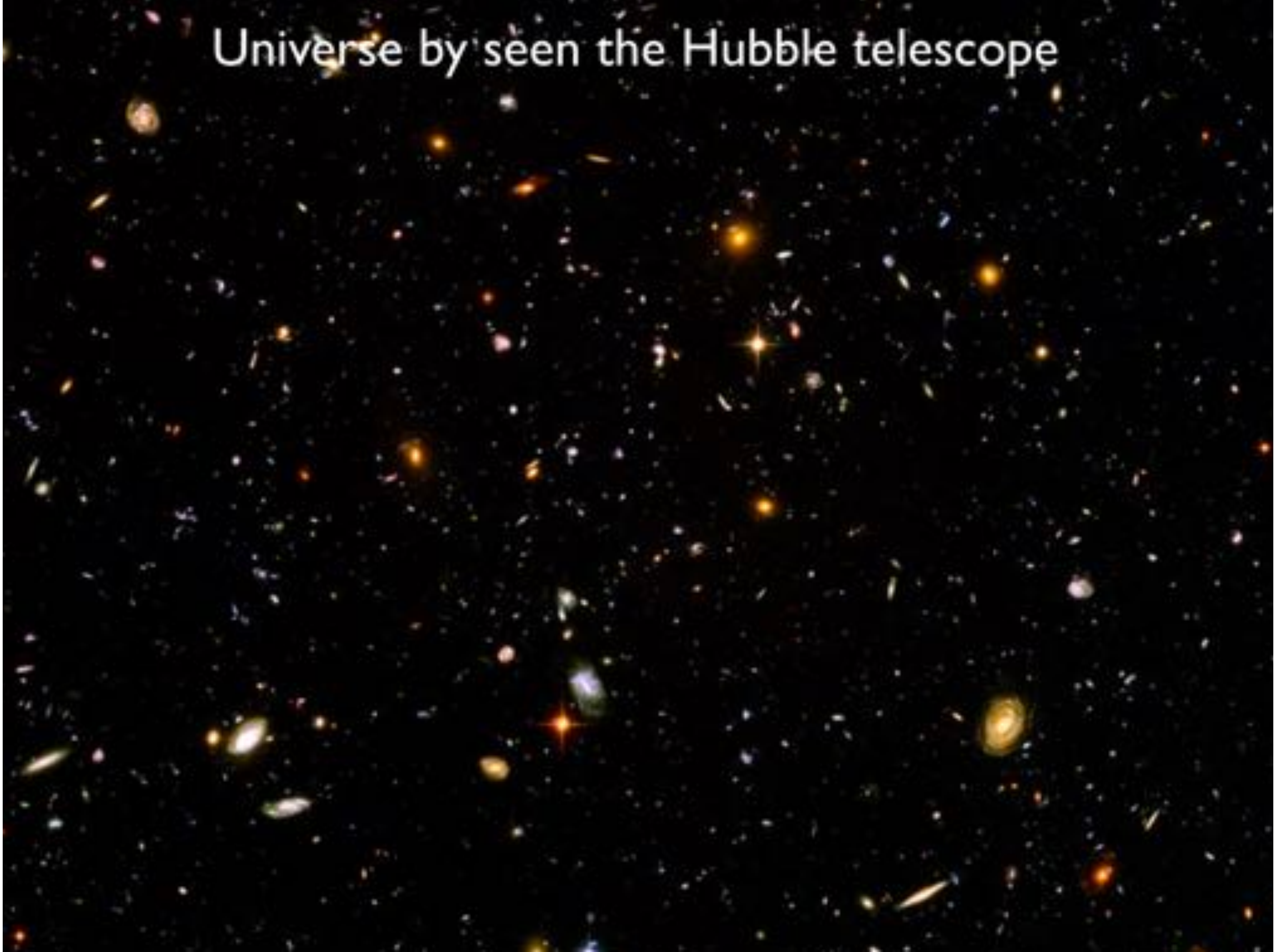
GW astronomy and astrophysics



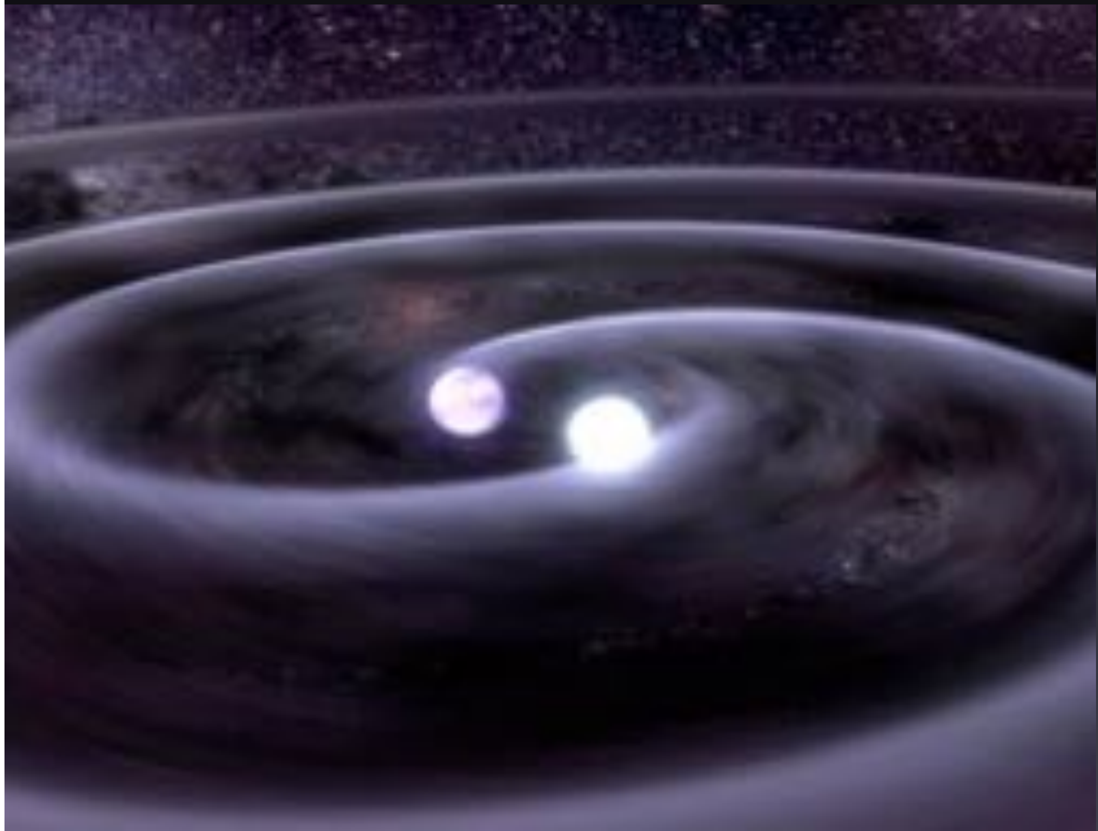
General relativity
Theoretical astrophysics
Cosmology

GW data analysis

+ follow-up observations


Universe by seen the Hubble telescope

Compact binaries



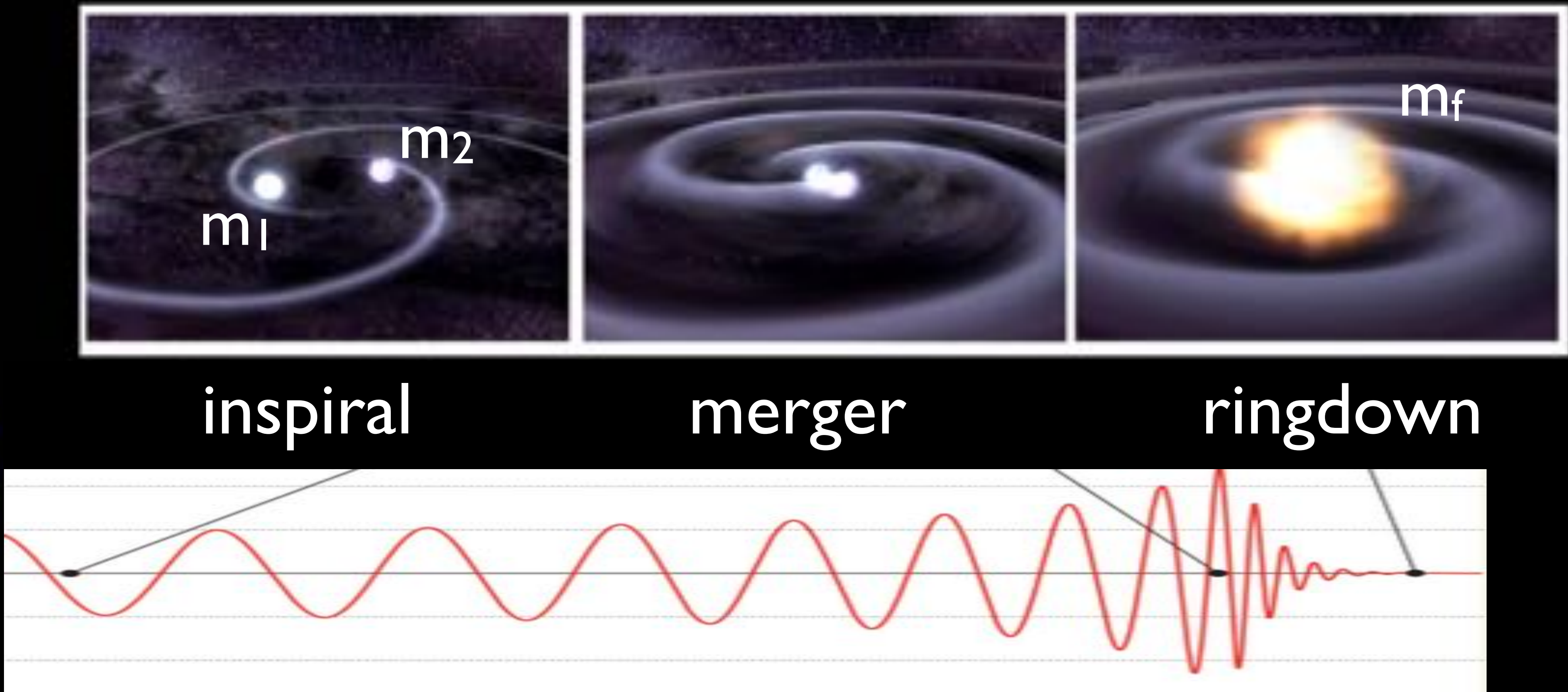
binary BH-BH (BBHs)
BH-NS
NS-NS

Solar system

Main GW sources:
Compact Binary Coalescences (CBCs)

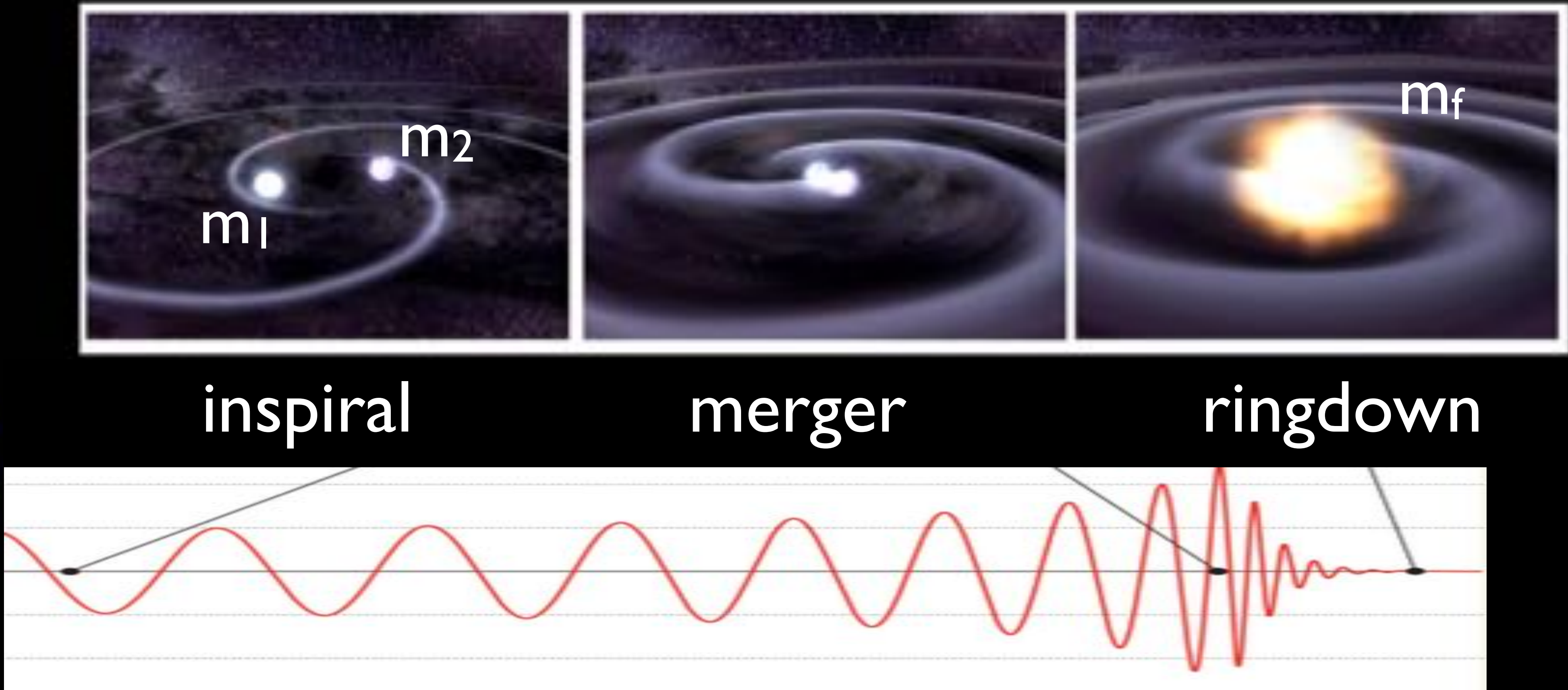
NS-NS, BH-NS, BH-BH

$2\ M_{sun} < m_1 + m_2 < 300+\ M_{sun}$



Main GW sources:
Compact Binary Coalescences (CBCs)

$m_1+m_2 \sim m_f$ + GWs



compact objects as GW sources

Q: How/where do they form and evolve?

Q: How would their GW waveform look like? (frequency, amplitude)
How their orbit evolves as emitting GWs?

Q: Are they detectable ? (detector type and location)

Q: How often they merge (and emit GWs?) in the Universe? Where?
source event rate density $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$

Q: How many of such events can be detectable by GW detectors?
detection rate (per time)

CBC rate estimates are one of the key observables in GW astronomy

Having detection rates at hand, we can

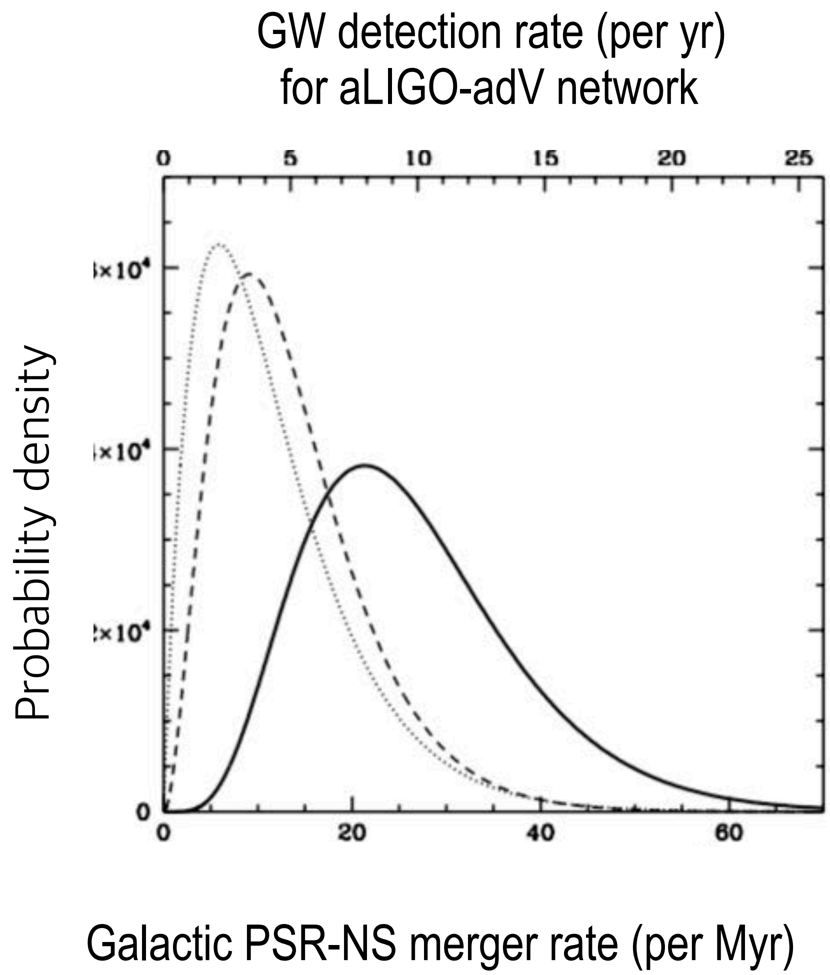
1) **assess a detector design and performance**

2) **constrain astrophysical models** (e.g. BH mass function)

The LSC-Virgo "rates" review paper, CQG (2010)

Bayesian inference from observed sample is a framework to compute GW detection rates for CBCs

CK, Kalogera, Lorimer, ApJ (2003)

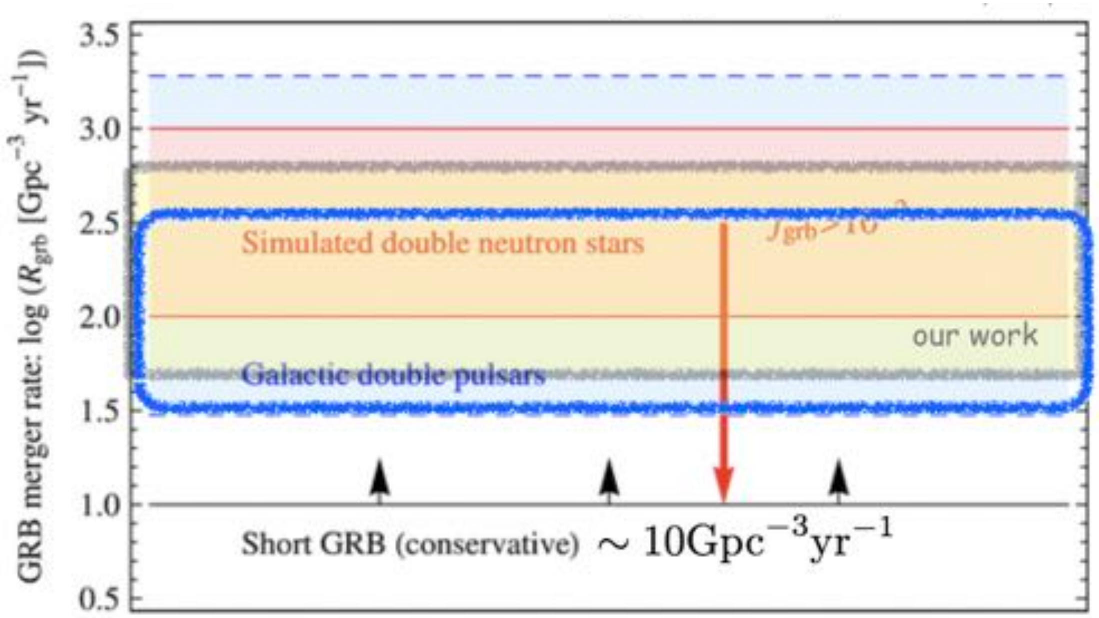


CK, Perera, McLaughlin, MNRAS (2015)

Astrophysical implications of GW observations

rate comparison between populations

SNe vs NS/BH vs GRBs



$$\mathcal{R}_{\mathrm{gal,NS-NS}} \sim 50 - 700\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$

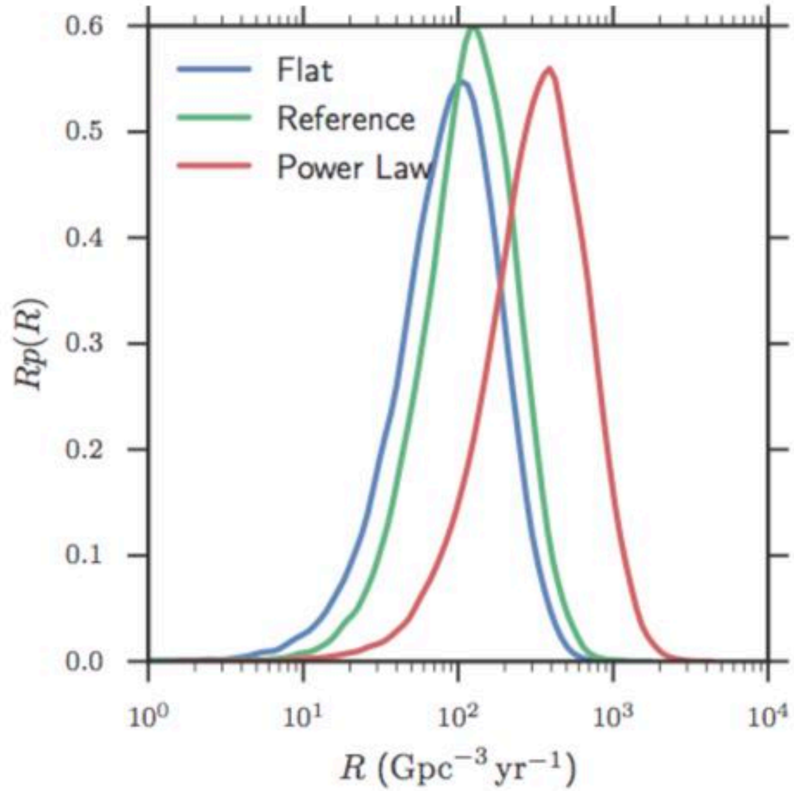
CK, Perera, McLaughlin (2015)

$$\mathcal{R}_{\mathrm{gal,BH-BH}} \sim 33 - 332\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$

GW150914 (2015)

rates can constrain underlying properties

stellar-mass BH population

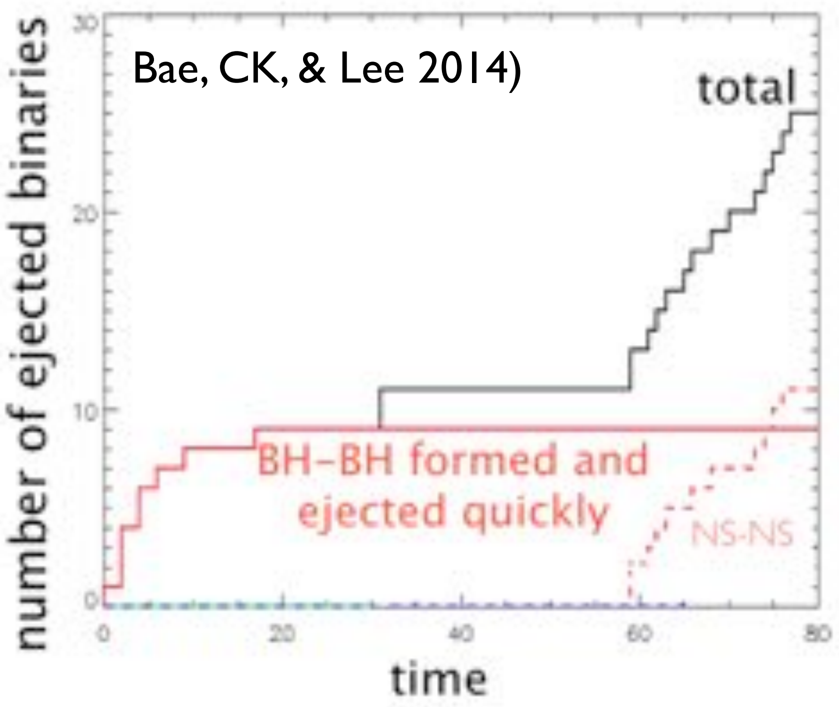


Formation and evolution of BBHs
I astrophysical approach

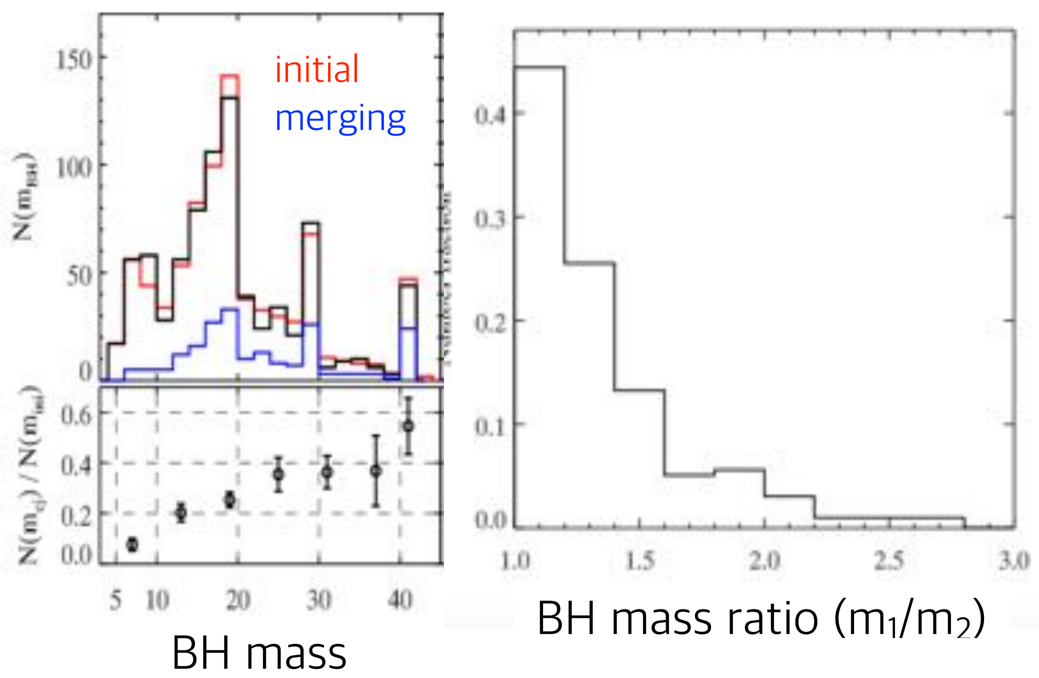
- **field population :** population synthesis (massive star evolution
- **cluster population:** N-body, Monte Carlo, etc

- BH-BH binaries are predicted to be dominant GW sources (GW150914, GW151226)

- "observed" BH mass function can be biased toward heavier ones



Park, CK et al. arxiv:1703.01568



Formation and evolution of BBHs
II GW data analysis (parameter estimation)

Two ingredients for parameter estimation

- waveform model (template to match with GW signals)
- theoretical understanding (priors)

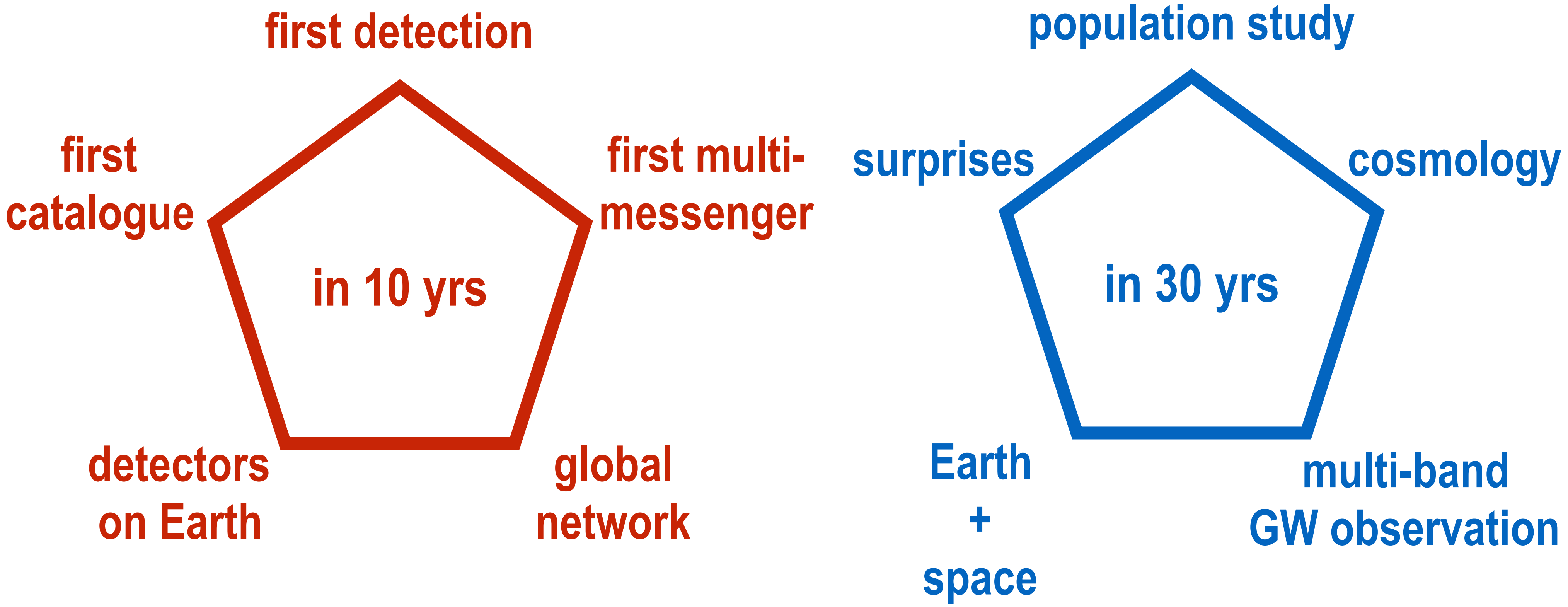
Parameter estimation allows us

- to identify nature of GW sources (BBH? NS-NS?)

- to establish empirical distribution of source properties
  (e.g. mass function, distances)

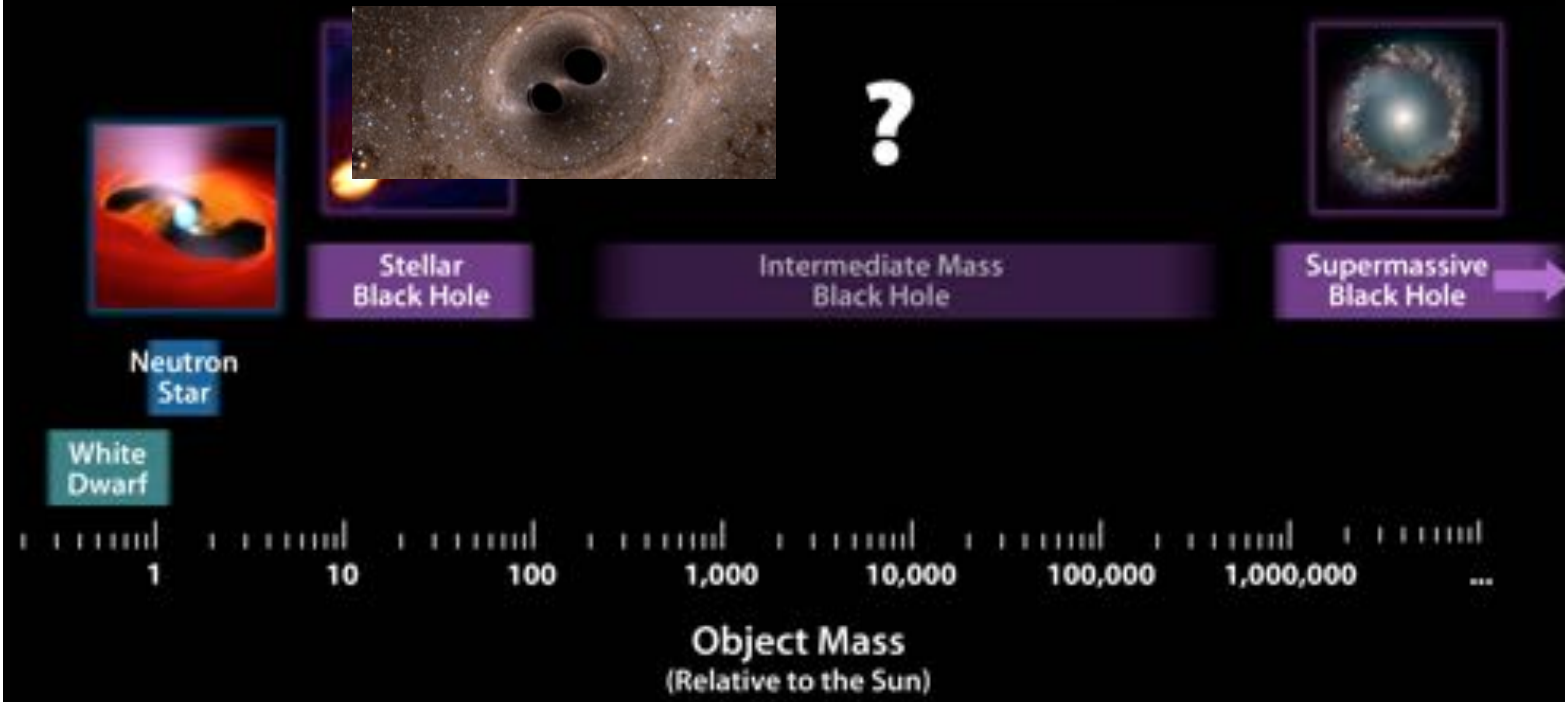
- to understand CBC formation and evolution by constraining
  theoretical models

Prospects of GW astronomy

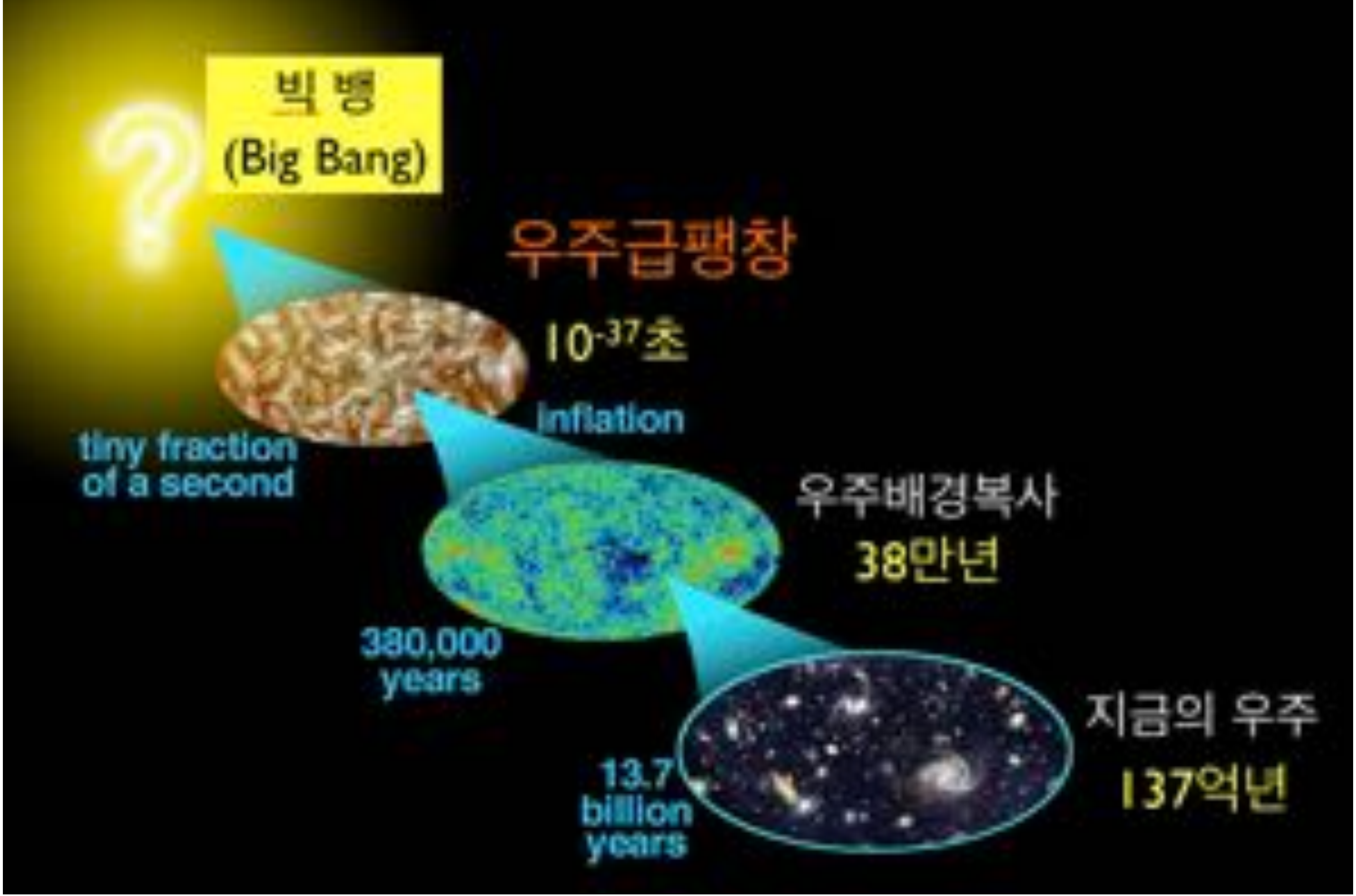


astrophysics on compact objects
—> stellar and galactic astronomy + cosmology

GWs as tools to understand the formation and evolution of compact binaries



GWs as probes for Early Universe



LIGO-Virgo collaborations, Nature (2009)

Multi-band observation is important for GW astronomy!

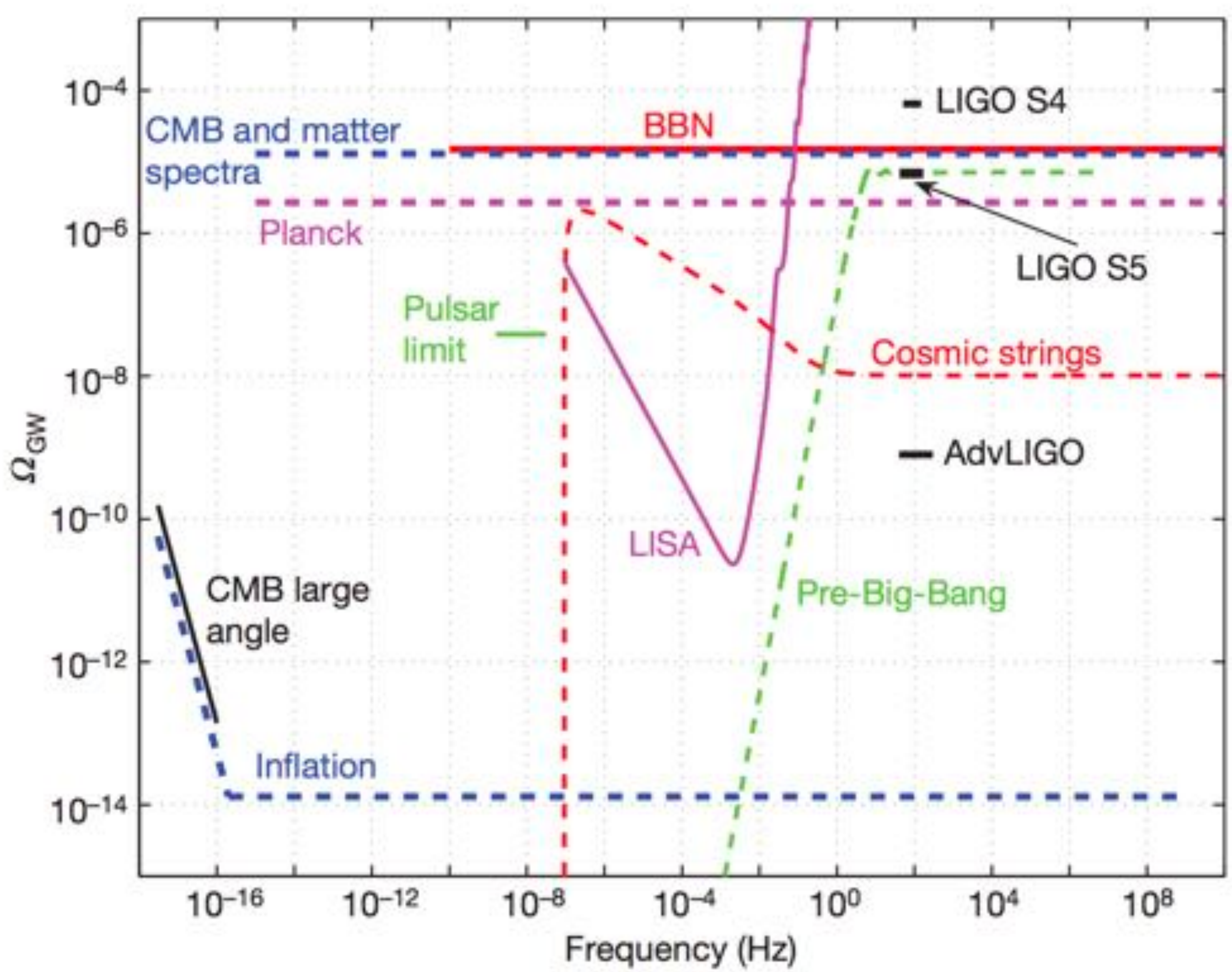


Fig 2. Abbott et al. (2009)

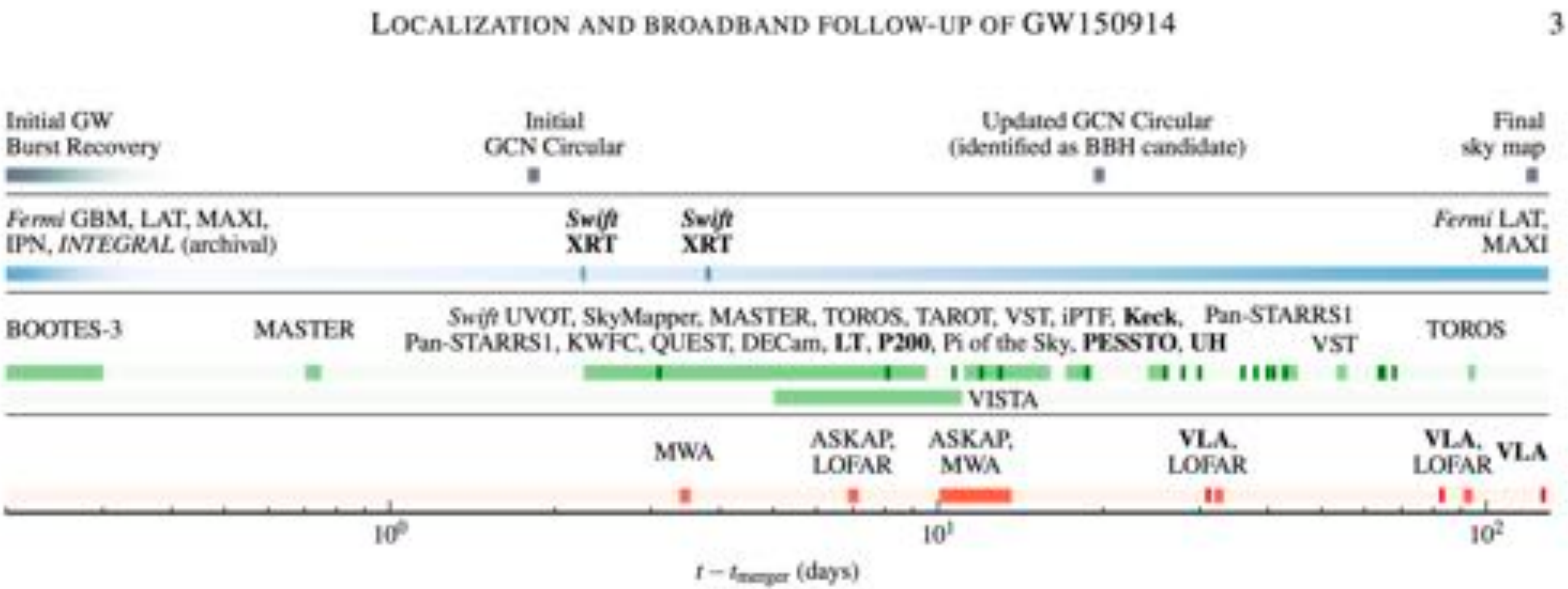
$$\Omega_{\rm GW}(f) = \frac{f}{\rho_c}\frac{d\rho_{\rm GW}}{df},$$

where $d\rho_{\rm GW}$ is the energy density in the frequency interval f to $f + df$, $\rho_c = 3H_0^2c^2/8\pi G$ is the critical energy density required to close the Universe, and $H_0 = 67.8 \pm 0.9$ km/s/Mpc [16].

Multi-messenger Astronomy

Detection of EM afterglows of GW triggers (and vice versa)

* Low-f GW observation is useful to provide more time for alerts by days up to months



Night Sky from Antarctica

How the Universe would look like in GWs?

Summary

• GW astronomy began with the detection of GW150914
"international collaboration" plays a key role in the big science

• In the next decades, GW astronomy will provide useful information to understand compact object populations (BH, NS) and massive star phenomena (SNe, GRBs)

NOTE: strong constraints on theoretical (astrophysical) models would be available with $O(10^3 \sim 10^4)$ observations.

• Low-frequency GW observation below 10 Hz is important for precision GW astronomy (e.g. test of equivalent principle in strong-field regime) and multi-messenger astronomy (longer obs time than LIGO-type detectors)

• More detections will come soon!