LIGO, NSF, Illustration: A. Simonnet (SSU)

Gravitational-Wave Astrophyiscs

RINGDOWN

INSPIRAL

MERGER

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Introduction

GW data analysis

GW waveform

GW parameter estimation

GW astrophysics

Pulsar astronomy and GW science

GW detection and multi-messenger astronomy

Publications on GW astronomy and astrophysics

Introduction

gravitational waves keep coming from cosmological distances

gravitational waves (GWs) vs electromagnetic waves (EMs)

1994 SLAC lectures by Kip Thorne

10^{-18} Hz (1/Hubble distance) - 10^4 Hz (1/light-travel time)

O(10) Hz *radio* - O(10^{26}) Hz *gamma-ray*

10 m wavelength
40 neV

300GeV (Fermi satellite LAT)

frequency band accessible on Earth: 10-2000 Hz (ex: advanced LIGO)

GW emission region != EM emission region

SCIENCE • VOL. 256 • 17 APRIL 1992

Authors in alphabetical order
total citation: 1397
(as of 2016.02.01; ADS)

LIGO: The Laser Interferometer Gravitational-Wave Observatory

Alex Abramovici, William E. Althouse, Ronald W. P. Drever, Yekta Gürsel, Seiji Kawamura, Frederick J. Raab, David Shoemaker, Lisa Sievers, Robert E. Spero, Kip S. Thorne, Rochus E. Vogt, Rainer Weiss, Stanley E. Whitcomb, Michael E. Zucker

The goal of the Laser Interferometer Gravitational-Wave Observatory (LIGO) Project is to detect and study astrophysical gravitational waves and use data from them for research in physics and astronomy. LIGO will support studies concerning the nature and nonlinear dynamics of gravity, the structures of black holes, and the equation of state of nuclear matter. It will also measure the masses, birth rates, collisions, and distributions of black holes and neutron stars in the universe and probe the cores of supernovae and the very early universe. The technology for LIGO has been developed during the past 20 years. Construction will begin in 1992, and under the present schedule, LIGO's gravitational-wave searches will begin in 1998.

Computational astrophysics and GW detection

GW sources are ALL astrophysical!

The data of this run (LIGO's 4th scientific run) were fully analyzed in search of gravitational waves from

1) binary inspirals,
2) narrow lines from known pulsars,
3) burst events as may be generated by supernovae and
4) a stochastic background.

quoted from LIGO-P050036-00-D

Developing accurate waveform models is crutial for GW detection AND implications

Bayesian inference is used for quantitative assessment of the quality of waveform models

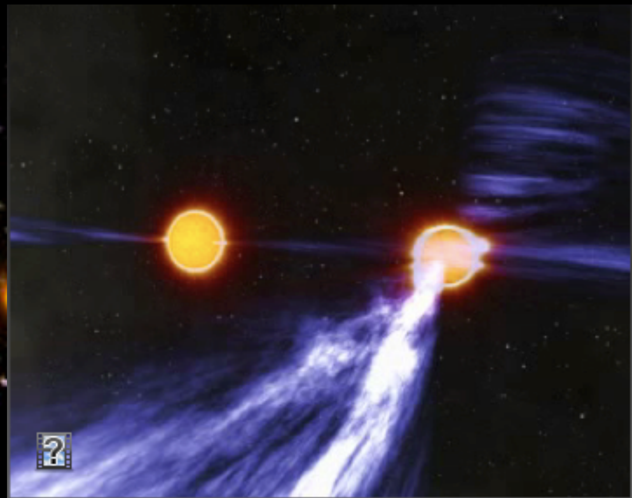
Systematic uncertainties can be reduced by improving astrophysical modeling of sources

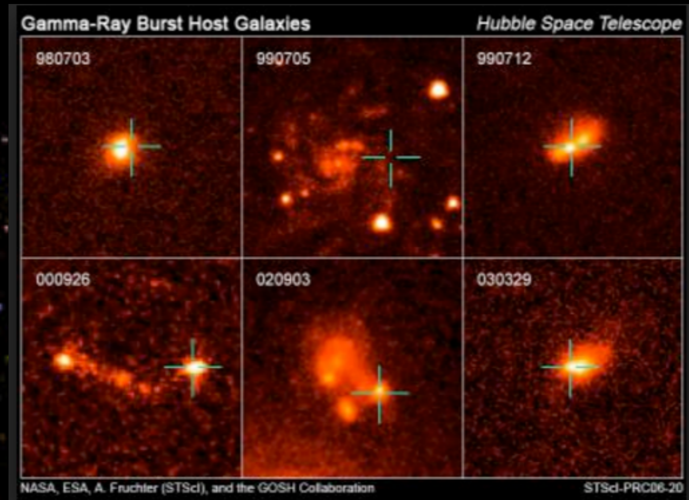
Astrophysical objects that can be detected, probed by GWs on Earth

Compact Binary Coalescences (NS, BH)

Gamma-Ray Bursts

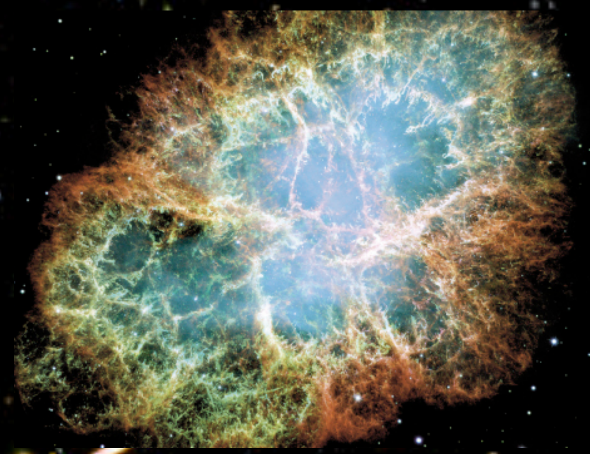
Galactic pulsar population and Supernovae





system mass: (1 - 300+) M_{sun}

detection frequency band: 10 - 300 Hz (BHs)
10 - 2000 Hz (NSs)

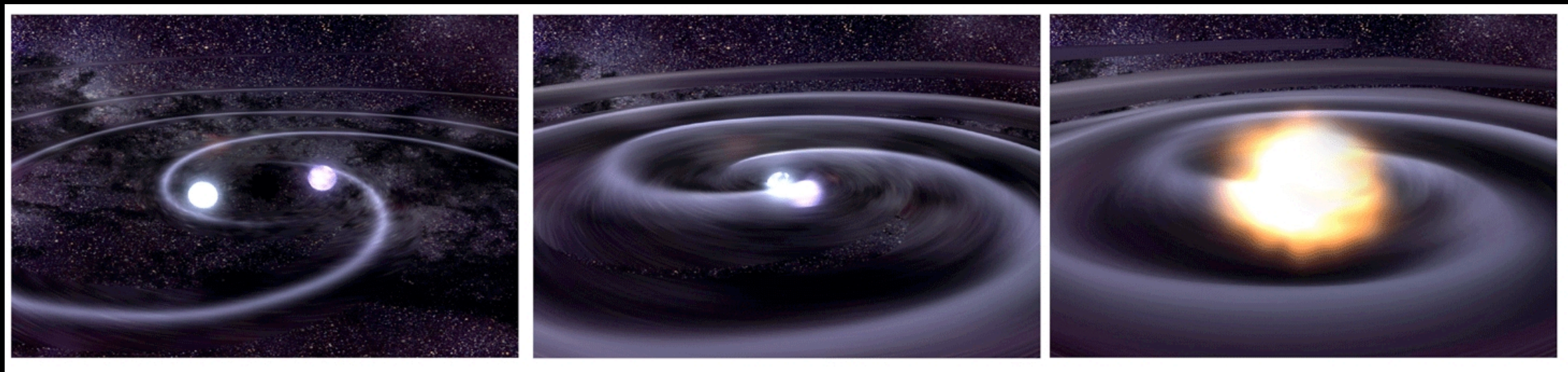


Crab nebular (supernova remnant)
NASA's Hubble image

compact binary coalescences (CBCs)
밀집 쌍성 병합

NS-NS, BH-NS, BH-BH

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



서로 떨어져 있는 두 천체가
중력으로 서로 끌어당기면서
중력파 방출.
나선형 궤도를 그리면서
점차 근접해감.

두 천체의 접촉발생

불안정하고 무거운 중성자별
---> 단일 블랙홀 생성

시공간의 왜곡이
점차 잦아듦

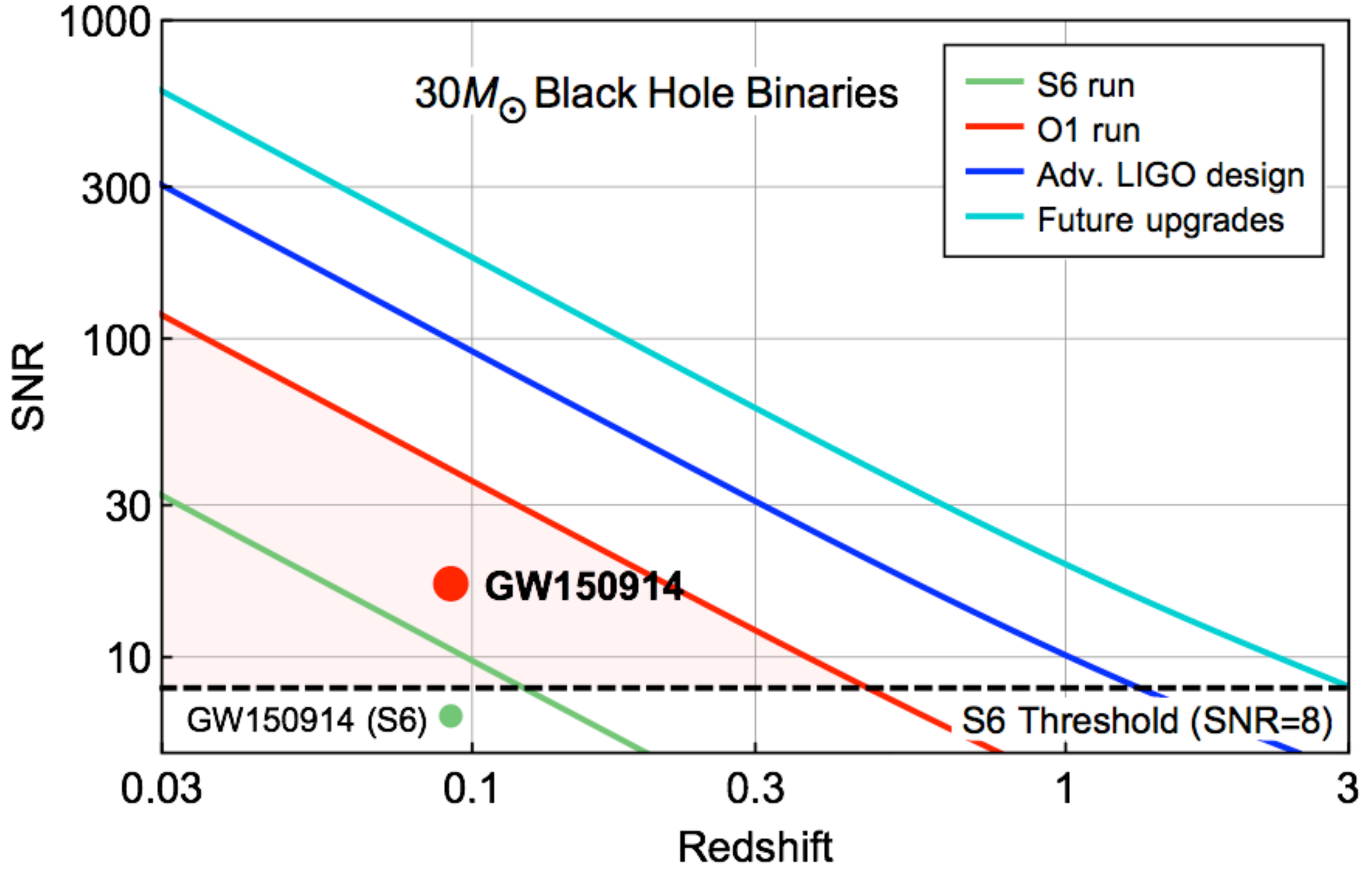
Advanced LIGO can detect BH-BH binaries up to z ~ a few

astrophysics

- formation rates
- formation environment
- evolution scenaria
- BH mass distribution
- standard sirens

cosmology

$$\text{SNR} = \frac{\text{GW strain from a source}}{\text{detector sensitivity}}$$



GW data analysis

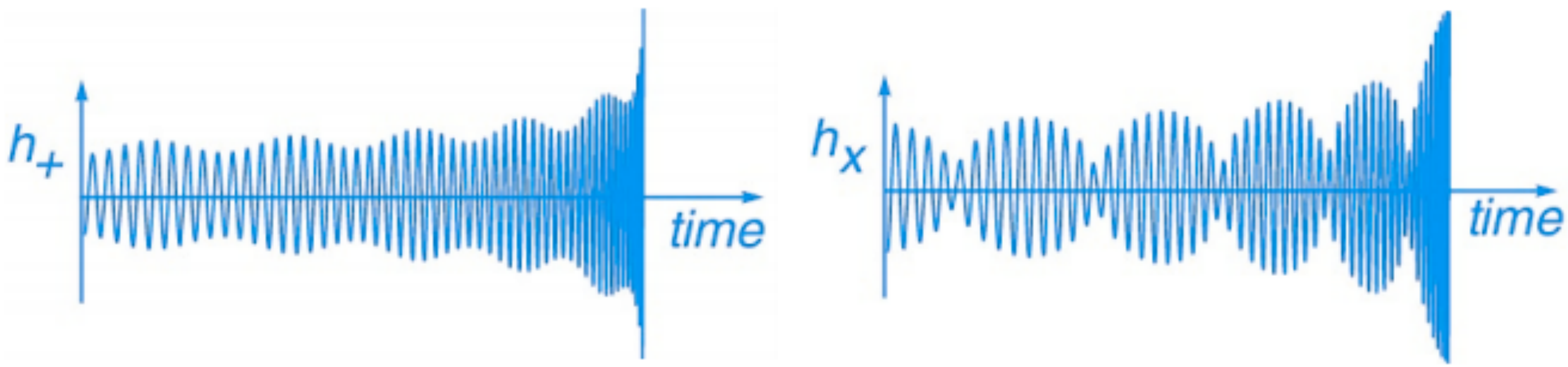
What is the signal received by the interferometer?

$h(t) = h_{+}(t)\,F_{+}(t) + h_{\times}(t)\,F_{\times}(t)$ "time series"

apparent strain amplitude = intrinsic h+,hx (mass, spin)
x
detector response F+, Fx (angle wrt the GW propagation)

$d(t) = h(t) + n(t)$

data = signal + noise ;
GW data analysis deals with extremely weak signals embedded in noise



GW waveform: underlying properties of a GW source are absorbed in $h_+(t)$ and $h_\times(t)$

$$\boxed{\frac{\delta L(t)}{L} = F_+(\theta,\, \phi,\, \psi) h_+(t) + F_\times(\theta,\, \phi,\, \psi) h_\times(t),}$$

advanced LIGO, advanced Virgo, KAGRA:
시간에 따른 중력파의 세기 변화를 레이저 간섭계로 검출

Required sensitivity of an interferometer for GW astrophysics:
displacement to measure must reach roughly a proton size (10^{-18} m)

GW data analysis flow

"LALsuite (LIGO Algorithm Library)"

GW data anlaysis

- astrophysical understanding

- GW waveform models of the sources

detector characterization
+
calibration

output: trigger candidates

search pipelines

output: confirmed GW signals

parameter estimation

output: observables of GW sources computed in probability density functions

Search and PE

initial, low-latency alerts
(for collaborators)

search
"matched filter"

- characteristic mass
- distance
- sky location

multiple pipelines
depending on source types
(sec - min)
requires many CPUs
due to a large number of
templates to search

memory optimization is also
important

paper publication
requires painstaking PE analyses

parameter estimation
"Bayesian inference"

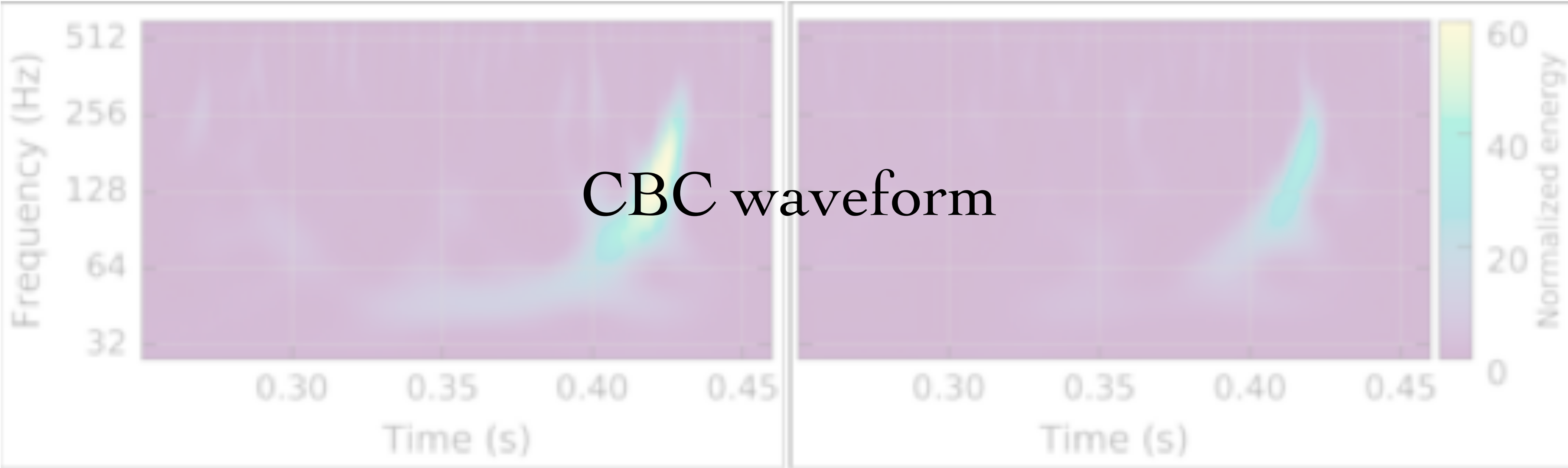
- masses, distance, sky location
- spin and total angular momentum
- orbital parameters (for binaries)

(minutes up to a few weeks)
requires 100% CPU time per one
serial job, multiple serial jobs on
many CPUs (OpenMPI)

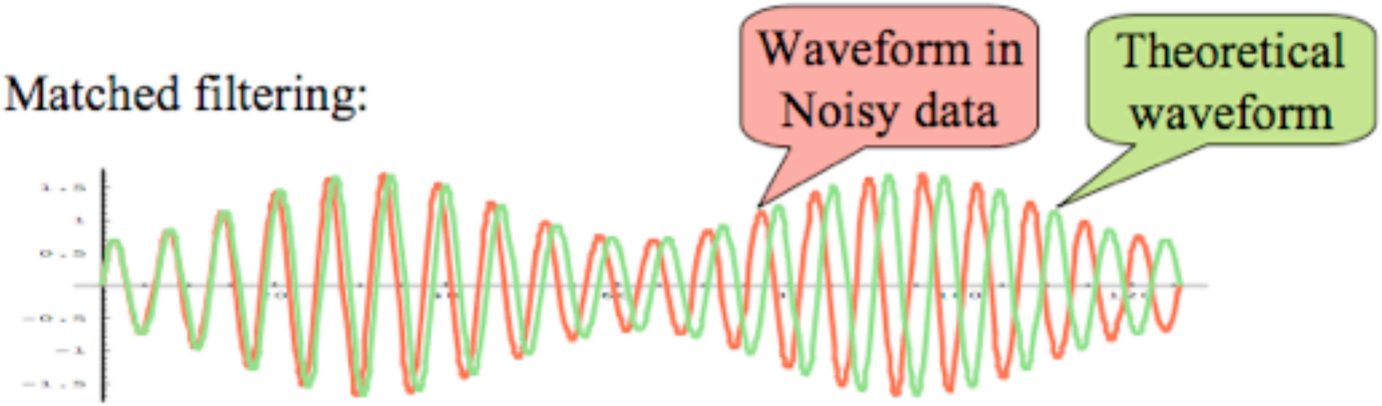
high-performance computing
resource is a MUST!

[KISTI GSDC]

CBC waveform



- Matched filtering:



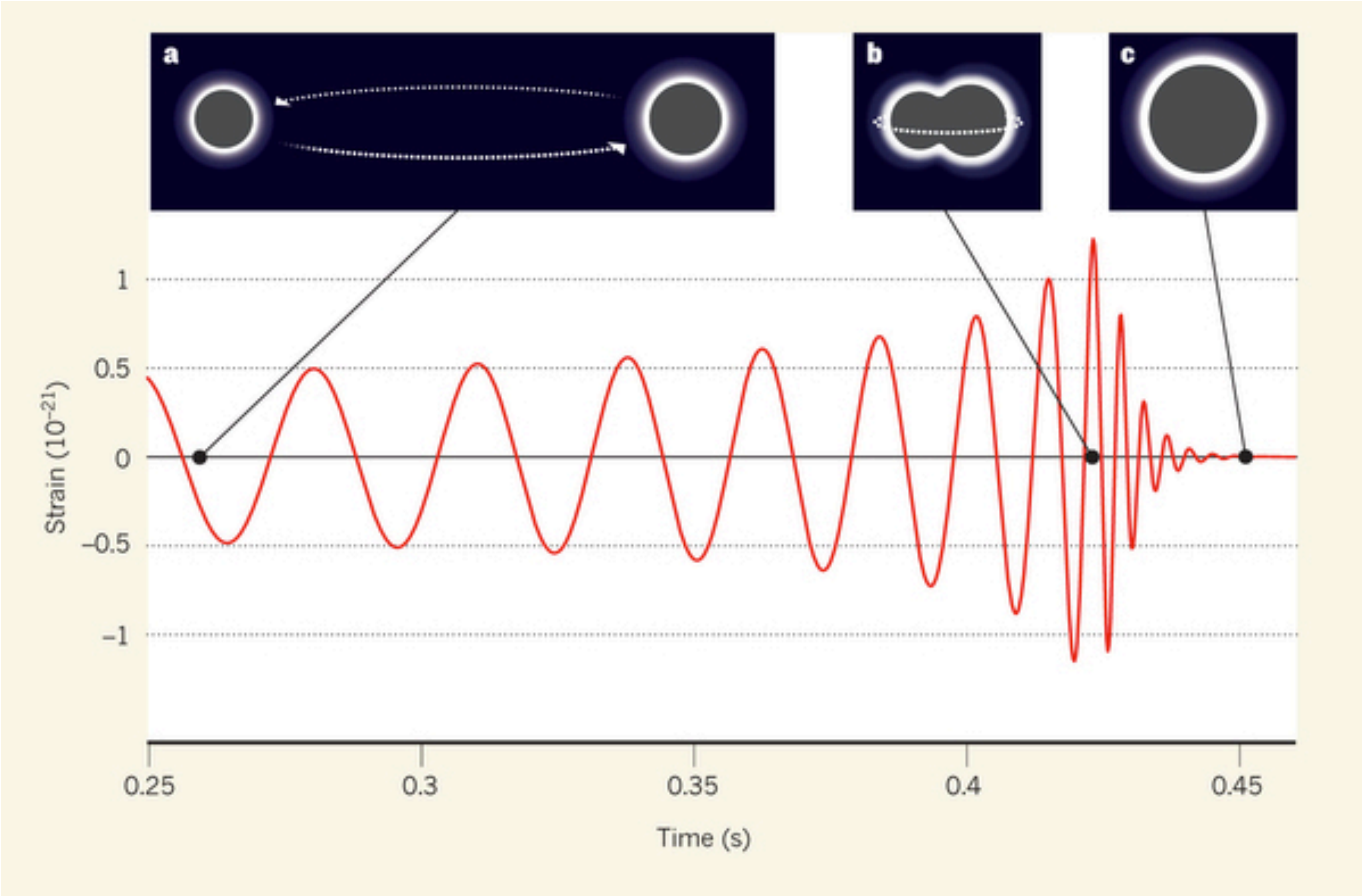
  - If waveforms slip by ~ 1 radian, it is obvious in cross correlation
  - LIGO: up to ~20,000 cycles (~100,000 radians)

“apparent” CBC waveform model h(t)

post-Newtonian+NR

numerical relativity
(NR)

NR
+
perturbation theory



Orbital evolution due to gravitational radiation

$$\frac{dE_{\rm orbit}}{dt} = -P \qquad E = -\frac{Gm_1m_2}{2a}$$

$$\left\langle\frac{dE}{dt}\right\rangle = -\frac{32}{5}\frac{G^4m_1^2m_2^2(m_1+m_2)}{c^5a^5(1-e^2)^{7/2}}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right). \quad (5.4)$$

$$a(e) = \frac{c_0 e^{12/19}}{(1-e^2)}\left[1+\frac{121}{304}e^2\right]^{870/2299}, \qquad (5.11)$$

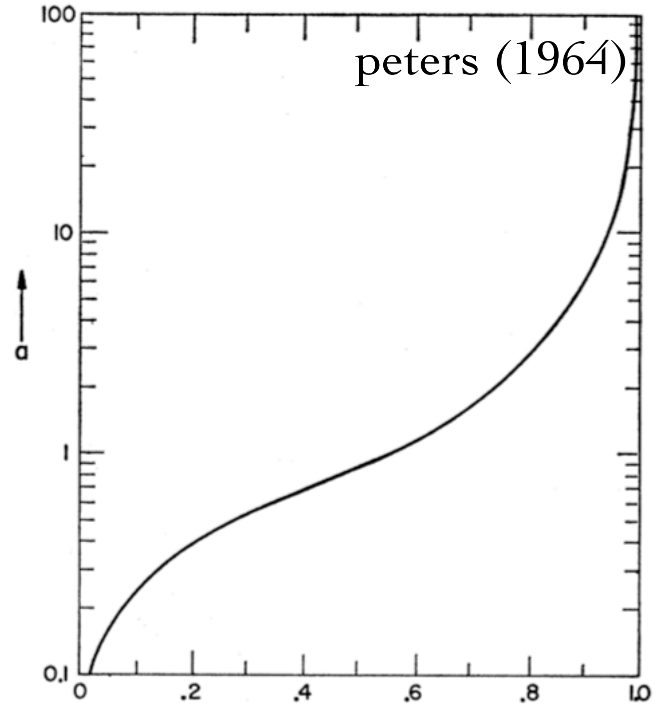
$$\left\langle\frac{de}{dt}\right\rangle = -\frac{19}{12}\frac{\beta}{c_0^4}\frac{e^{-29/19}(1-e^2)^{3/2}}{[1+(121/304)e^2]^{1181/2299}}. \quad (5.13)$$

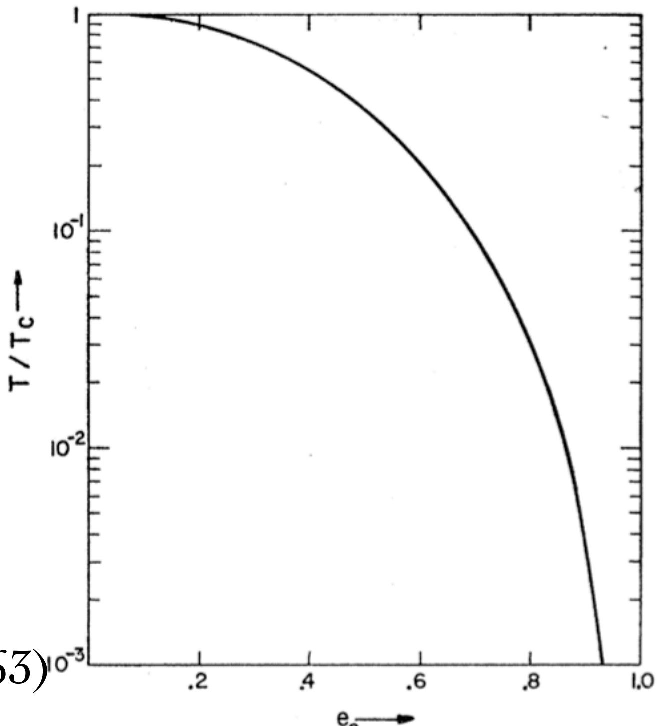
$$\beta = \frac{64}{5}\frac{G^3m_1m_2(m_1+m_2)}{c^5}$$

merger time t_{mrg}

$$\boxed{T(a_0,e_0) = \frac{12c_0^4}{19\beta}\int_0^{e_0}\frac{de\ e^{19/19}[\frac{121}{304}e^2]^{1181/2299}}{(1-e^2)^{3/2}}}$$

merging binaries: t_{mrg} < Hubble time

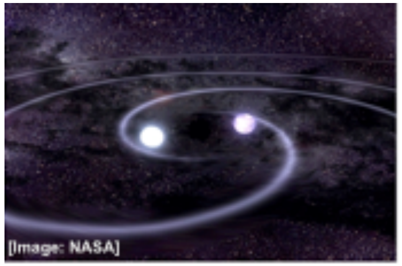




for derivations of these equations, see Peters and Mathews (1963)

Inspiral waveform and GW emission

Energy and angular momentum loss ---> GW emission



$$\left\langle \frac{da}{dt} \right\rangle = -\frac{64}{5} \frac{G^3 \mu M^2}{c^5 a^3 (1-e^2)^{7/2}} \left(1 + \frac{73}{24} e^2 + \frac{37}{96} e^4\right)$$

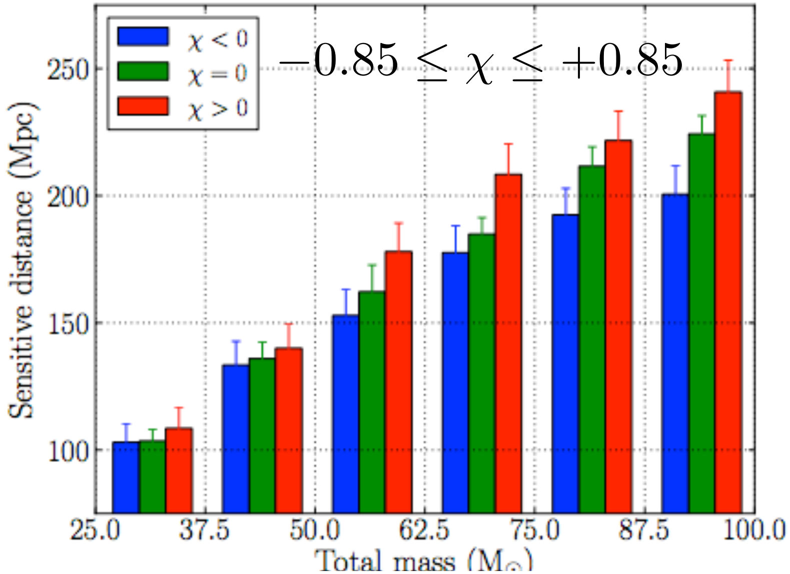
$$\left\langle \frac{de}{dt} \right\rangle = -\frac{304}{15} e \frac{G^3 \mu M^2}{c^5 a^4 (1-e^2)^{5/2}} \left(1 + \frac{121}{304} e^2\right)$$

(Peters and Mathews 1963)

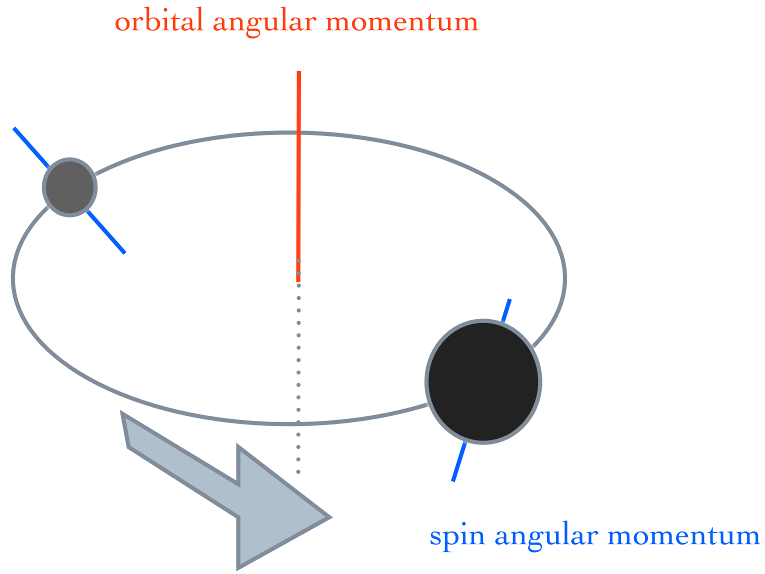
a (separation) and
e (eccentricity) decreases

the binary orbit shrinks and
circularized as it emits GWs

Effects of aligned spins on the detection distance



S6 + VSR2/3 (2009-2010) massive BH binary (25-100 M_{sun}) search
(inspiral+merger+ringdown) arXiv:1209.6533



simplest, quickest GW inspiral waveform model: **TaylorF2**

(in the frequency-domain, Newtonian amplitude)

For a binary consisting of masses m_1 and m_2, located at an "effective" distance $D_{\rm eff}$, we have

$$\tilde{h}(f; M, \eta, f_c) = \Theta(f_c - f) \left(\frac{1\,\mathrm{Mpc}}{D_{\rm eff}}\right) \mathcal{A}_{1\,\mathrm{Mpc}}(M, \eta)\, f^{-7/6}\, e^{i\varphi(f; M, \eta)}\,, \quad (10)$$

where

$$\mathcal{A}_{1\,\mathrm{Mpc}}(M, \eta) = \left(\frac{5\pi}{24}\right)^{1/2} \left(\frac{GM_\odot/c^2}{1\,\mathrm{Mpc}}\right) \times \times \left(\frac{\pi G M_\odot}{c^3}\right)^{-1/6} \left(\frac{\eta}{M_\odot}\right)^{1/2} \left(\frac{M}{M_\odot}\right)^{1/3}, \quad (11)$$

and the phasing φ of the frequency-domain waveform is given to 3.5pN accuracy by the formula [25, 26]

$$\begin{aligned}
\varphi(f; M, \eta) = {} & 2\pi f t_0 - 2\phi_0 - \pi/4 \\
& + \frac{3}{128\eta}\Bigg[v^{-5} + \left(\frac{3715}{756} + \frac{55}{9}\eta\right) v^{-3} - 16\pi v^{-2} \\
& + \left(\frac{15\,293\,365}{508\,032} + \frac{27\,145}{504}\eta + \frac{3085}{72}\eta^2\right) v^{-1} \\
& + \pi \left[\frac{38\,645}{756} - \frac{65}{9}\eta\right] \left[1 + 3\ln\left(\frac{v}{v_0}\right)\right] \\
& + \left[\frac{11\,583\,231\,236\,531}{4\,694\,215\,680} - \frac{640}{3}\pi^2 - \frac{6\,848}{21}\gamma\right] v \\
& + \left[\left(-\frac{15\,335\,597\,827}{3\,048\,192} + \frac{2\,255}{12}\pi^2 - \frac{47\,324.0}{63.0} - \frac{794\,8}{9}\right)\eta \right. \\
& \left. + \frac{76\,055}{1\,728}\eta^2 - \frac{127\,825}{1\,296}\eta^3\right] v \\
& + \pi \left[\frac{77\,096\,675}{254\,016} + \frac{378\,515}{1\,512}\eta - \frac{74\,045}{756}\eta^2\right] v^2 \Bigg]\,. \quad (12)
\end{aligned}$$

$$\boxed{v = \left(\frac{GM}{c^3}\pi f\right)^{1/3}}$$

post-Newtonian parameter

$$\boxed{M = m_1 + m_2}$$

total mass of a binary

$$\boxed{\eta = m_1 m_2/(m_1 + m_2)^2}$$

symmetric mass ratio
(dimensionless) $0 < \eta \le 1/4.$

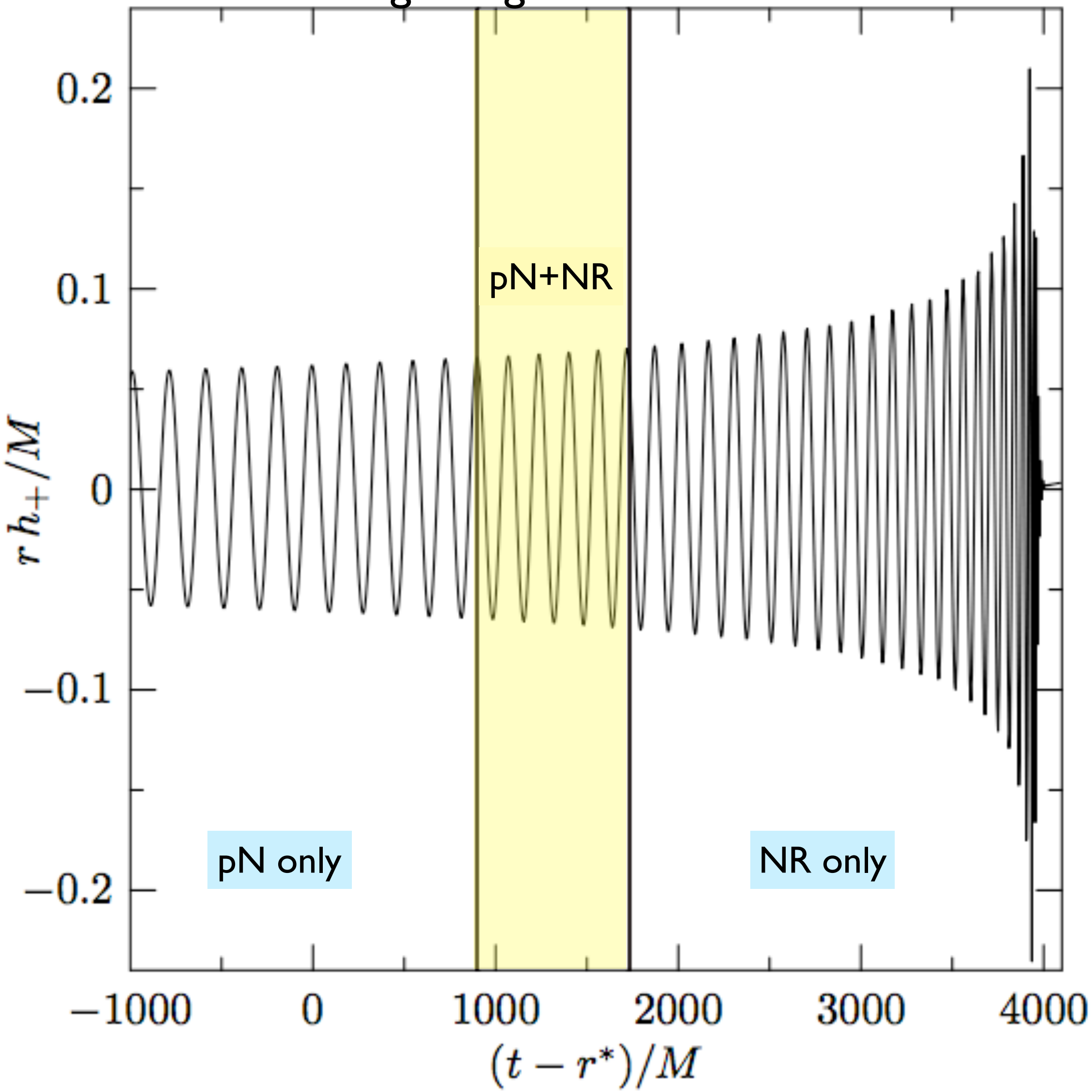
$$\boxed{\mathcal{M} \equiv \left(\frac{m_1^3 m_2^3}{m_1 + m_2}\right)^{1/5} = M\,\eta^{3/5}}$$

chirmass of a binary
(in solarM)

For a CBC more massive than several Msun,
a “hybrid” or “inspiral-merger-ringdown (IMR)” waveform is needed for analysis

(pN inspiral + NR merger-ringdown)

0: beginning of NR waveform

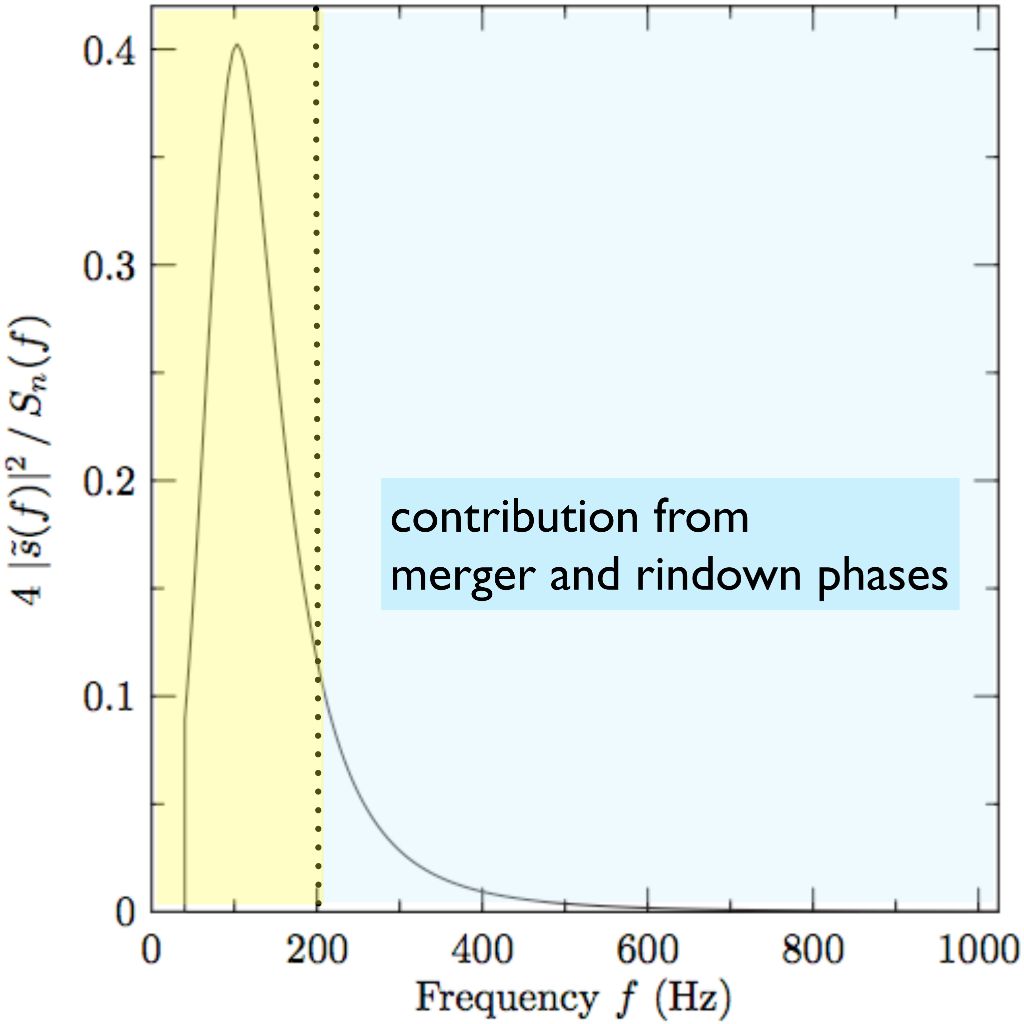


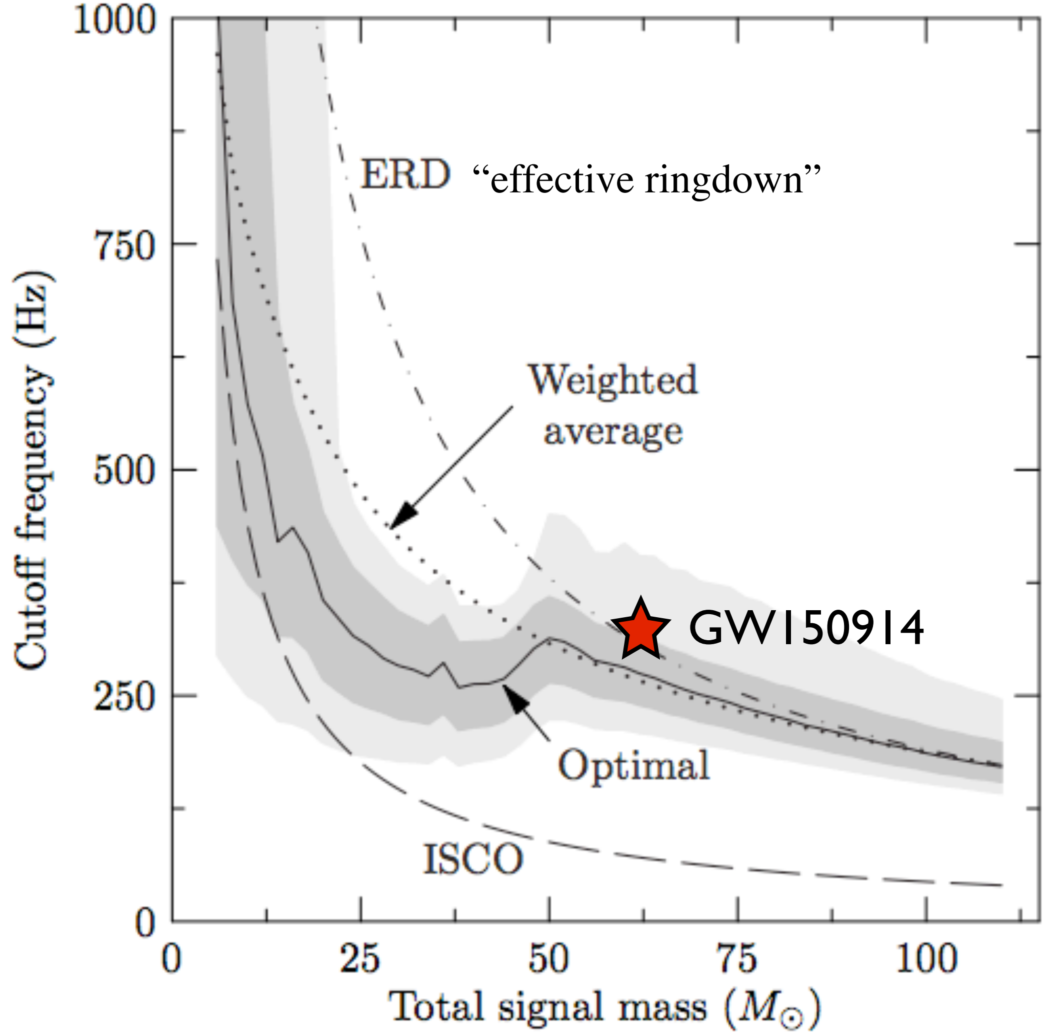
(10-10) M_{sun} BH-BH binary @100Mpc

inspiral-dominant region

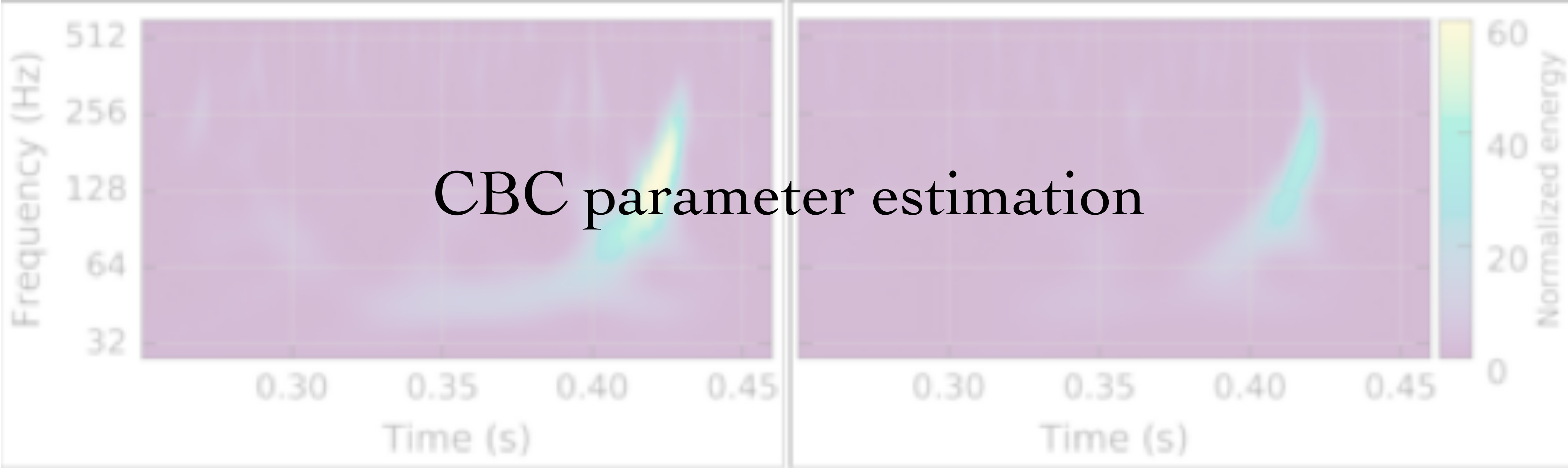
last stable orbit of BH-BH binaries
(max. frequency to apply pN)

200 Hz





CBC parameter estimation



detection ····································> **Bayesian PE**

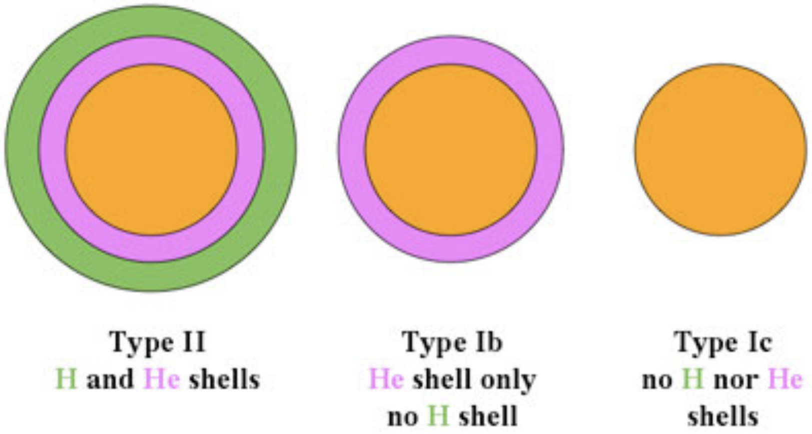
measuring observables
- source identification
- multi-messenger astronomy
- feedback to astrophysical modeling

High performance computing resource is a MUST

Number of CPUs:
1-2 waveform models (injection or template)
x 5 target CBCs x 3-5 multiple PE jobs = 15-150 CPUs

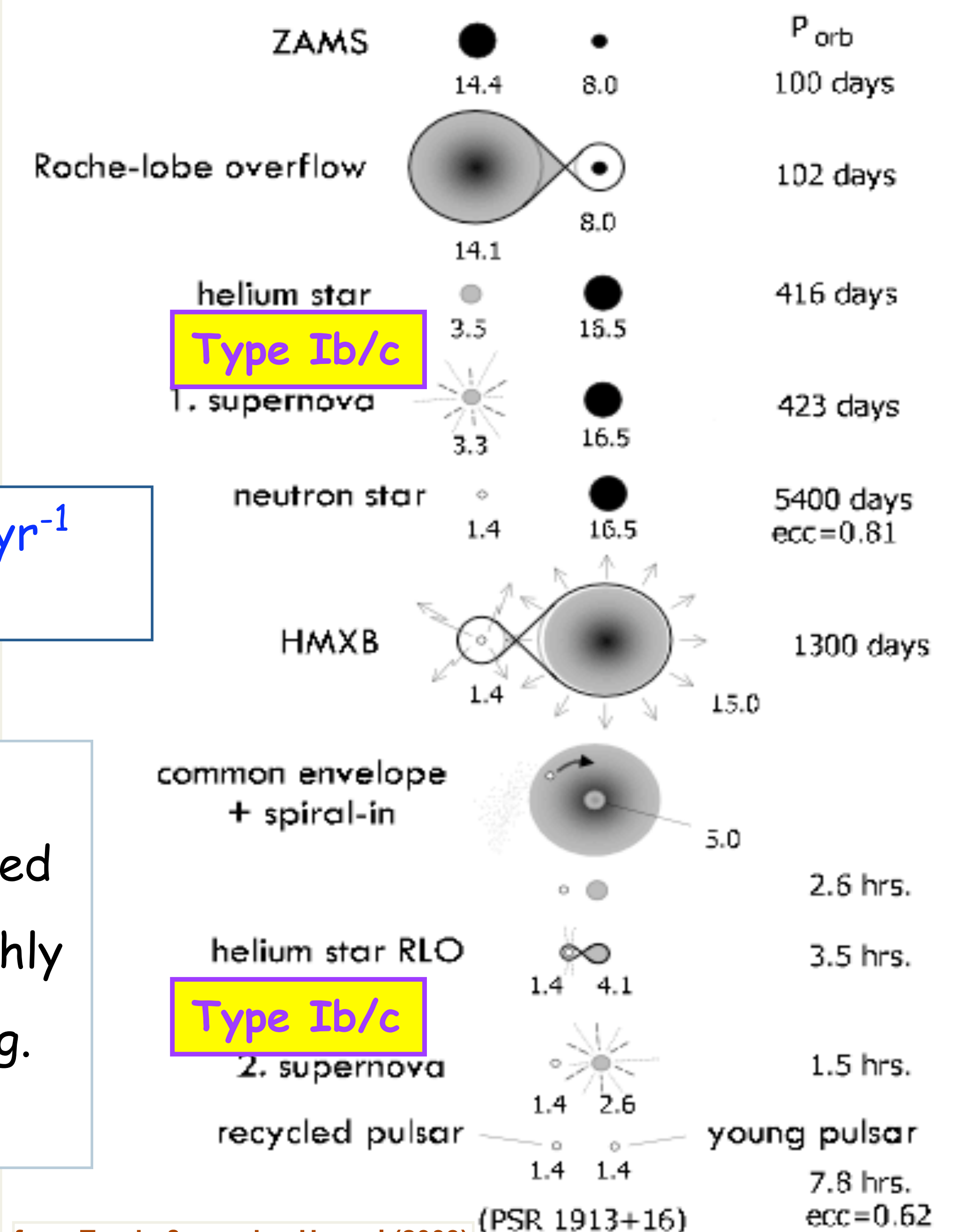
Computation time: a few days up to a few weeks

Astrophysical understanding on binary evolution is important to understand/interpret CBC data and to design future detectors



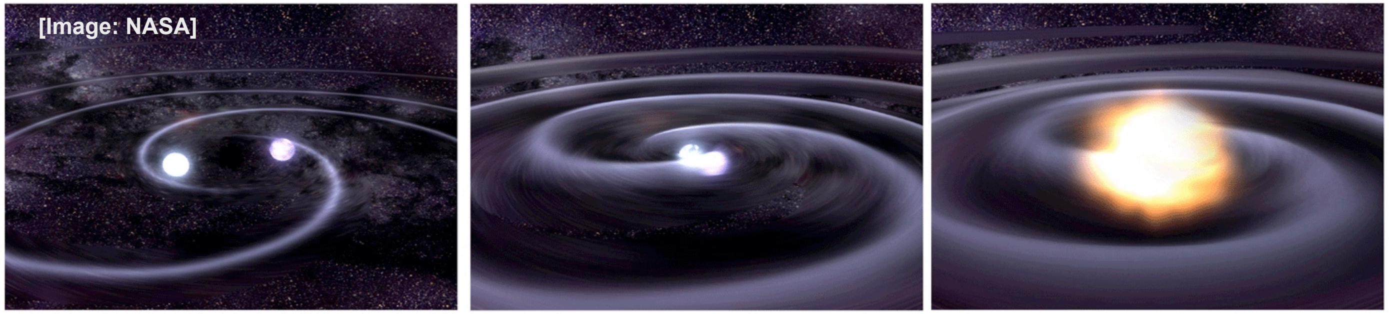
SN Ib/c rate (S0-Sb) = 600-1600 Myr^{-1}
(Cappellaro, Evans, Turatto 1999)

The fraction of SN Ib/c actually involved in the formation of DNS systems is highly uncertain, but it is likely to be small (e.g. 5% or less (population synthesis)



from Tauris & van den Heuvel (2003)

What can we learn from compact binaries?



inspiral	merge	ringdown
individual masses, distance, sky position, orientation BH spin	structure of a neutron star nuclear equation of state effects of magnetic fields	recoil kick (if unequal-masses) properties of the remnant (hypermassive NS, BH)
first detections multimessenger astronomy	tests of GR in the strong-field limit	

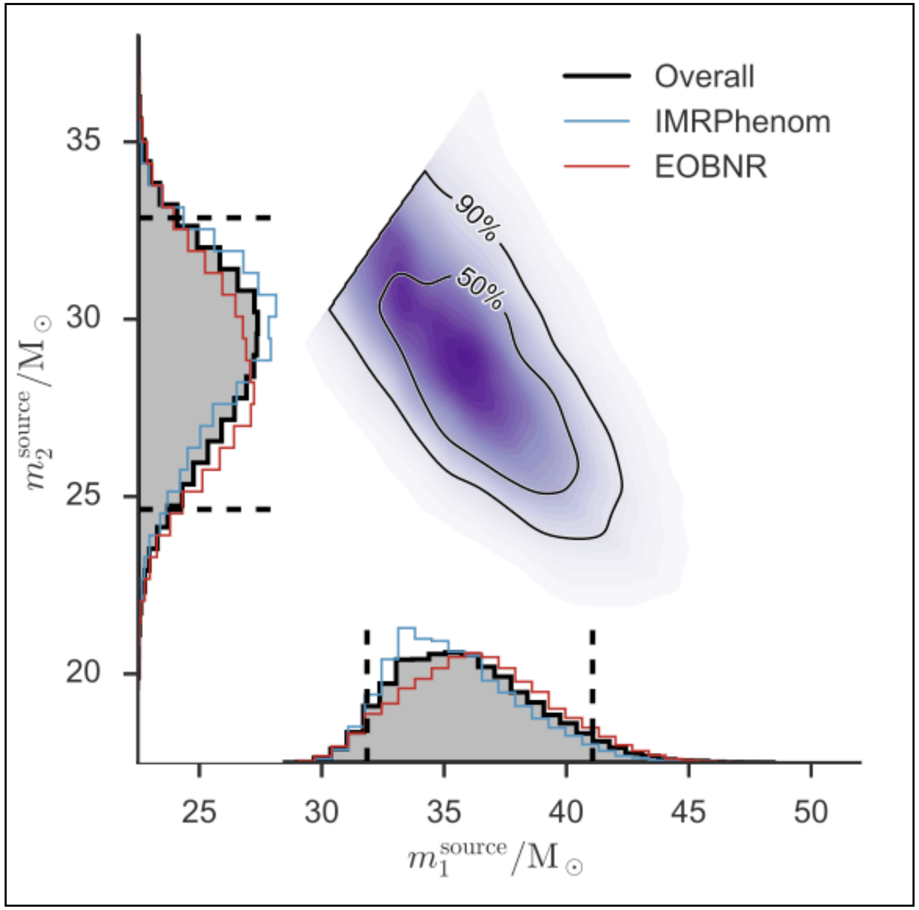
Monte Carlo population modeling
N-body simulation
(based on EM observations)

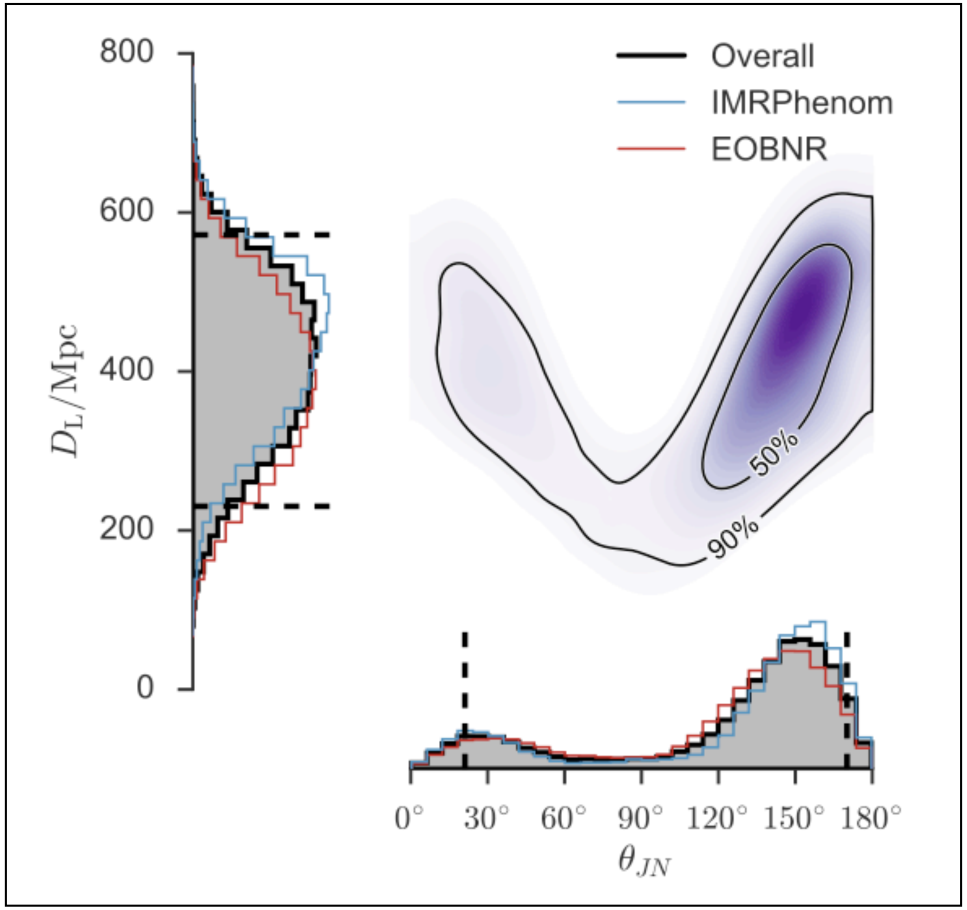
Bayesian
parameter estimation

(based on GW observations)

Example of GW parameter estimation: GW150914

"Properties of the binary black hole merger GW150914" LVC (2016)
http://arxiv.org/abs/1602.03840



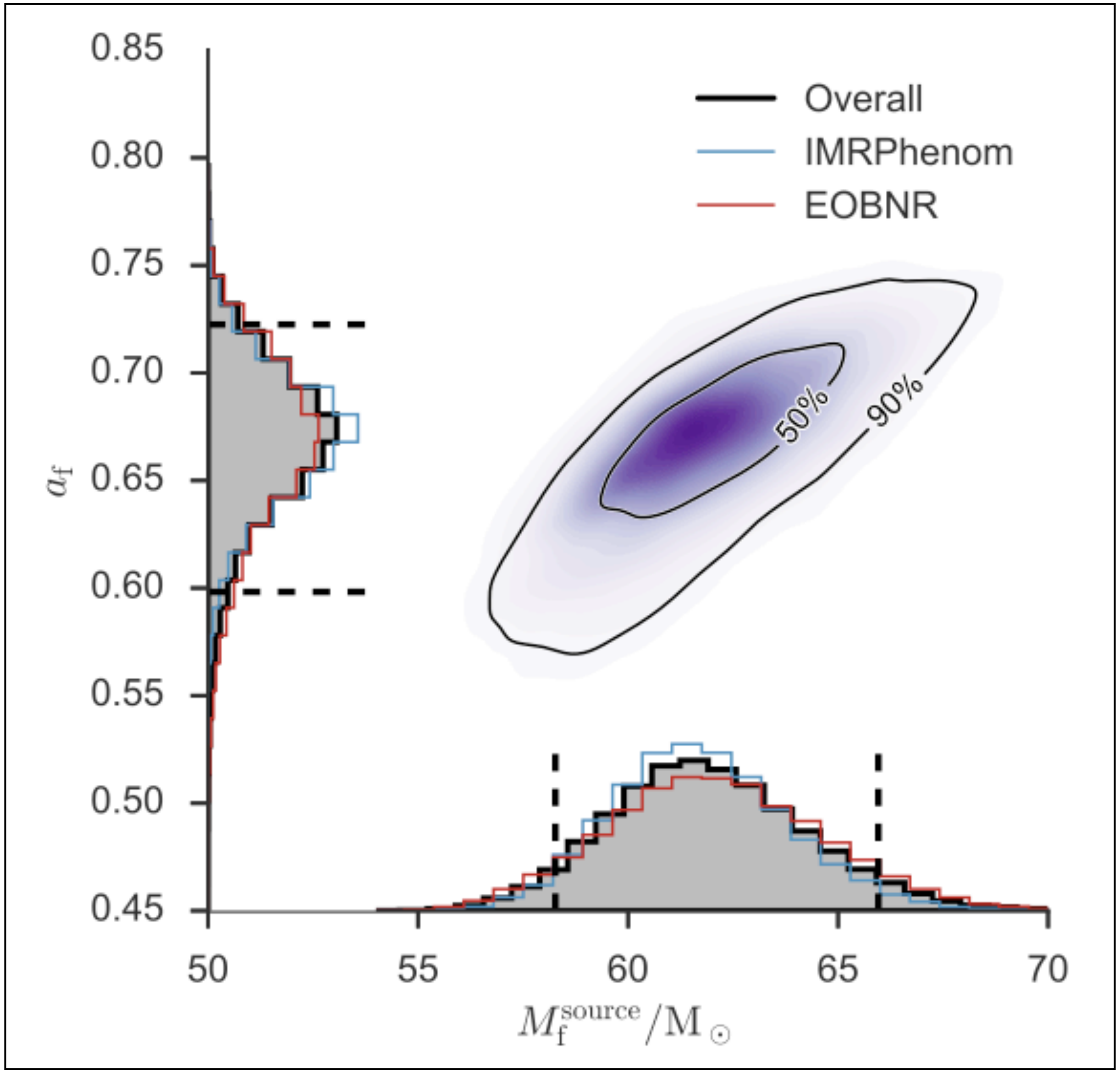


a BH-BH binary is the only astrophysical system that satisfies the following conditions:

individual masses of two stars are larger than **20+ M_{sun}**
the **min. separation** between two objects estimated from the max. GW frequency
(250 Hz = 2 x f_{orb}) ~ **a few hundreds km**

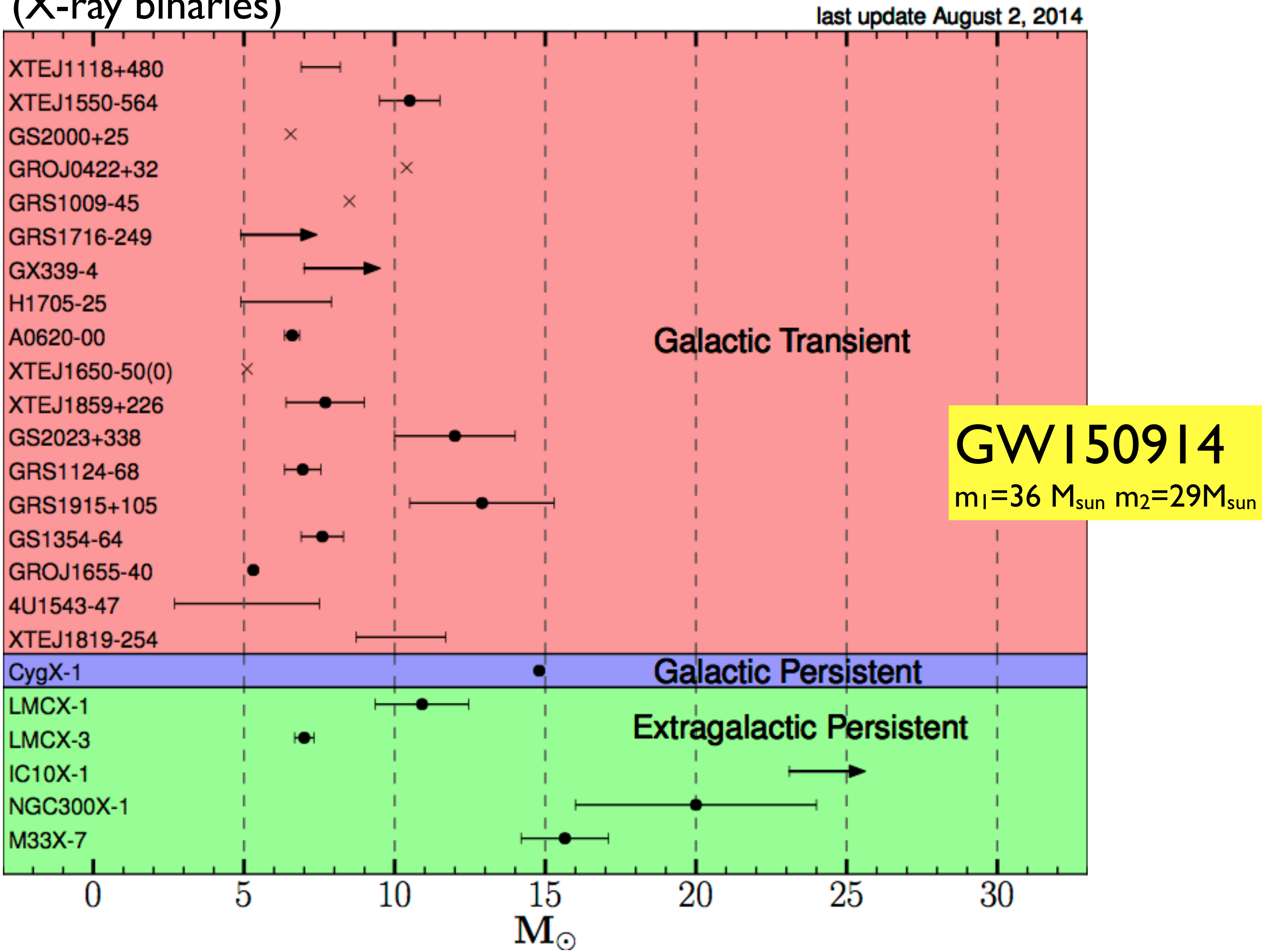
mass and spin of the firnal, single BH remnant

GW energy ~ three Suns ($E=mc^2$)



24 mass estimates of BH candidates (X-ray binaries)

credit: Grzegorz Wiktorowicz and Chris Belcynski



NS mass measurements from pulsar observations

Pulsar	Period (ms)	P_b (days)	Eccentricity	Pulsar Mass ($M_\odot$)	Companion Mass ($M_\odot$)	Companion Type
Young Pulsars in Relativistic Binaries						
J0737-3039B[1]	2773.5	0.102	0.08778	$1.2489^{+0.0007}_{-0.0007}$	$1.3381^{+0.0007}_{-0.0007}$	NS
J1141-6545[2]	393.9	0.198	0.17188	$1.27^{+0.01}_{-0.01}$	$1.02^{+0.01}_{0.01}$	WD
J1906+0746[3]	144.1	0.166	0.08530	$1.323^{+0.011}_{-0.011}$	$1.290^{+0.011}_{-0.011}$	WD or NS
B2303+46[4]	1066.4	12.340	0.65837	$1.34^{+0.10}_{-0.10}$	$1.3^{+0.10}_{-0.10}$	WD
Recycled Pulsars in Relativistic Double Neutron Star Binaries						
J0737-3039A[1]	22.7	0.102	0.08778	$1.3381^{+0.0007}_{-0.0007}$	$1.2489^{+0.0007}_{-0.0007}$	NS
B1534+12[5]	37.9	0.421	0.27368	$1.3332^{+0.0010}_{-0.0010}$	$1.3452^{+0.0010}_{-0.0010}$	NS
J1756-2251[6]	28.5	0.320	0.18057	$1.312^{+0.017}_{-0.017}$	$1.258^{+0.018}_{-0.017}$	NS
B1913+16[7]	59.0	0.323	0.61713	$1.439^{+0.0002}_{-0.0002}$	$1.3886^{+0.0002}_{-0.0002}$	NS
B2127+11C[8]	30.5	0.335	0.68139	$1.358^{+0.010}_{-0.010}$	$1.354^{0.010}_{0.010}$	NS

Kasian (2012) Ph.D. thesis

GW detection (parameter estimation) will provide independent estimates of NS/BH masses!

KGWG work on CBC data analysis: waveform development and parameter estimation

- Hyung Won Lee, Jeongcho Kim (Inje U.) master's degree thesis title (2015) "Data Analysis for Compact Binary Coalescence Inspiral Gravitational Wave" J Kim continues her PhD at Inje U.

- Chunglee Kim (SNU)

- Hee-Suk Cho (PNU->KISTI) PhD thesis title (2014) "GWs from CBC and parameter measurement error"

• Implmentation of **amplitude corrections** for time-domain inspiral waveform (TaylorT4) and frequency-domain inspiral waveform (TaylorF2) in LALSimulation (waveform library) in LALsuite and perform **Markov Chain Monter Carlo PE**

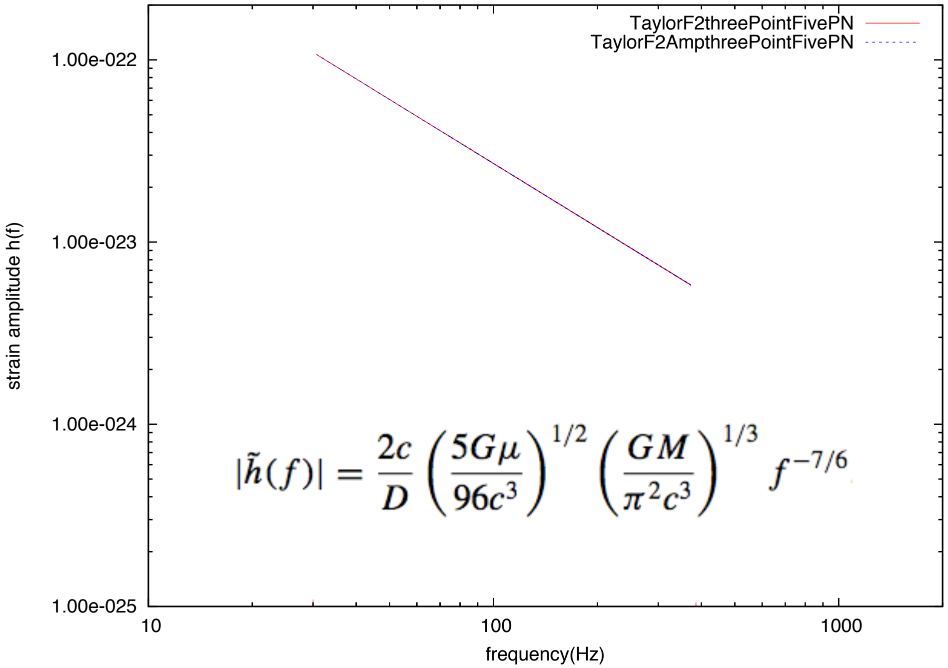
• finding an optimized parameter space (m1,m2) to search CBCs with non-spinning **inspiral-merger-ringdown waveforms** (Phnome series) by the **Fisher information matrix**

• Implmentation of **eccentric inspiral waveform** (TaylorF2) and perform **Markov Chain Monter Carlo PE**

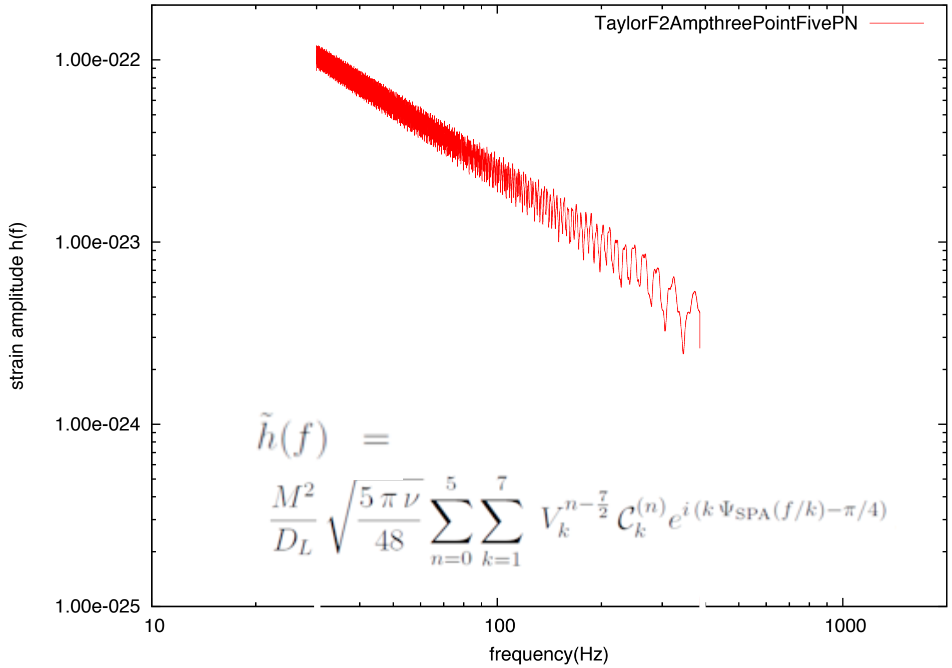
• developing **PE library for KAGRA**

Amplitude corrections and inspiral waveforms (TaylorF2)

inspiral GW waveform with
Newtonian amplitude
10-1.4 BH-NS



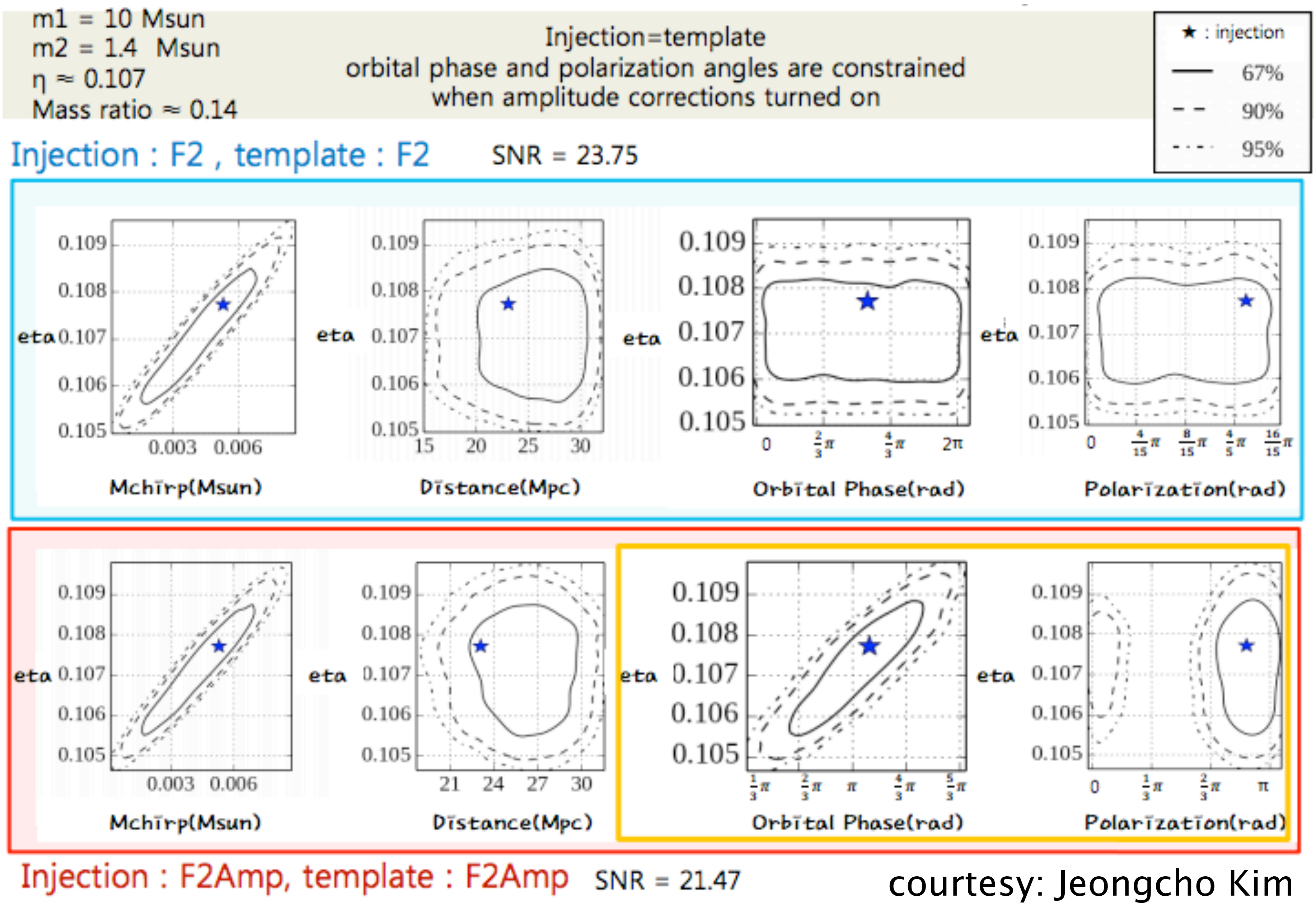
inspiral GW waveform with
up to 2.5pN **amplitude corrections**
10-1.4 BH-NS



- chirp (inspiral) signal length ~ 12 s

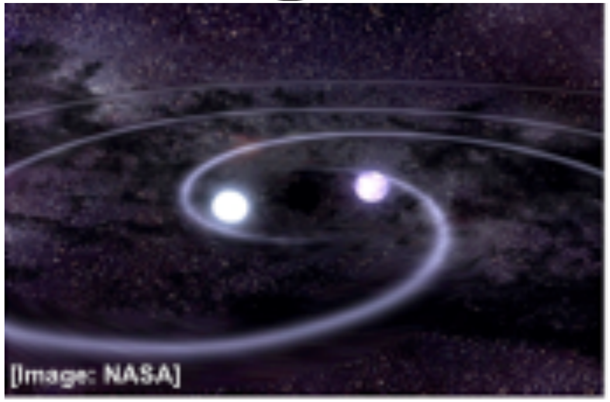
Results from MCMC PE:

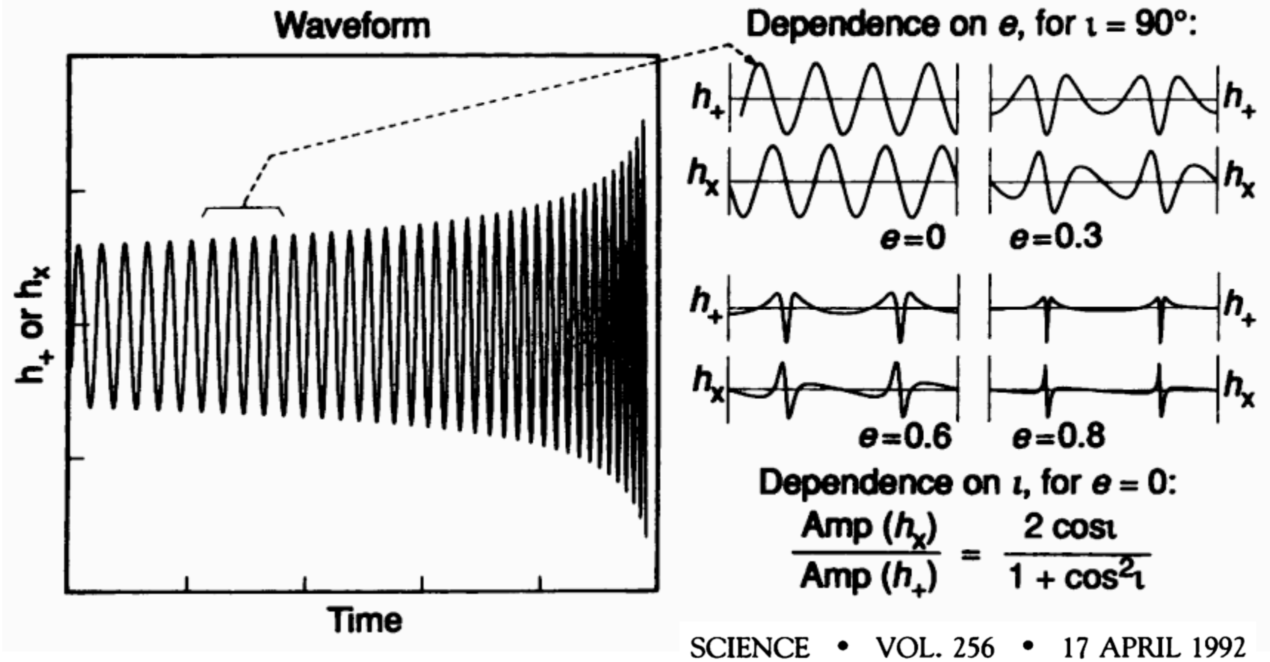
Amplitude corrections to post-Newtonian waveform are useful to measure **orbital phase** and **GW polarization angles**



courtesy: Jeongcho Kim

Eccentric waveform and PE accuracy (on-going)

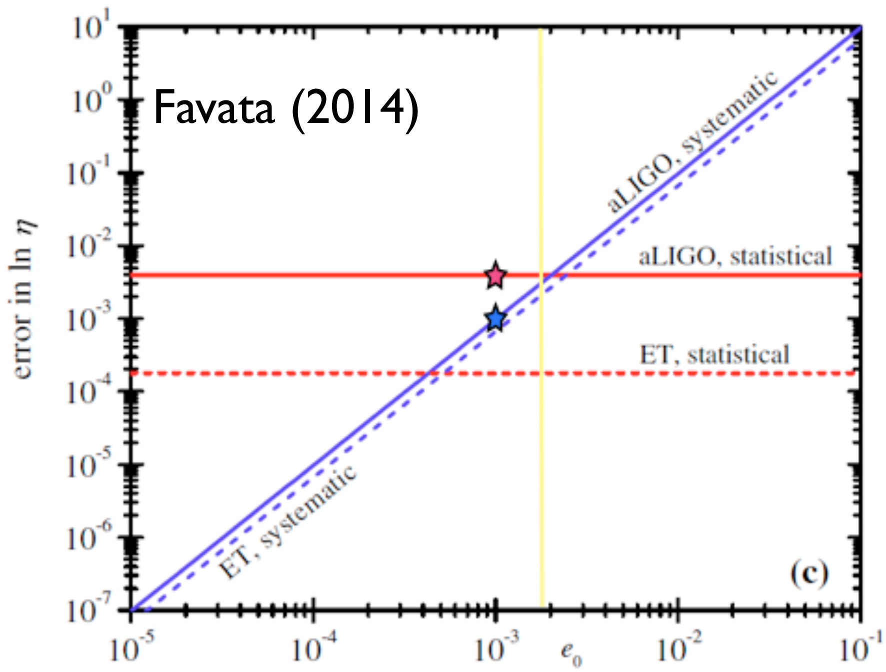




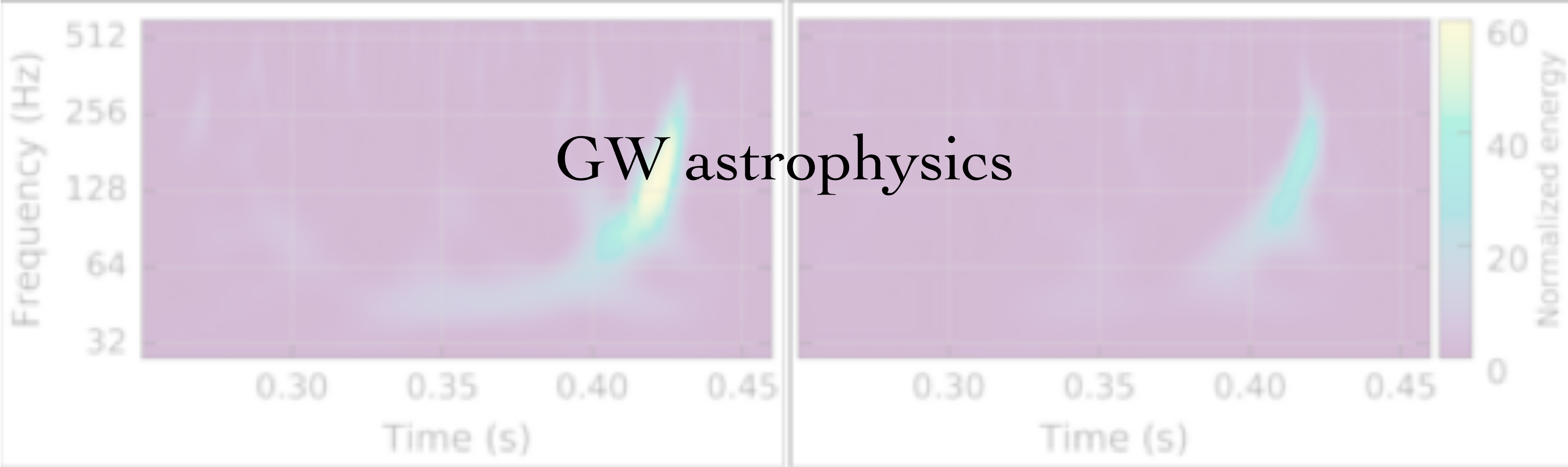
SCIENCE • VOL. 256 • 17 APRIL 1992

We measure error in the sysmetic mass ratio considering NS-NS binaries.

When e=0.001 (at f_{gw} =10Hz),
aLIGO statistical error (red star) is ~0.004,
aLIGO systematic error (blue star) is ~0.001



GW astrophysics



astrophysical implications of GW150914

rate calculations and feedback to astrophysical modeling

N-body simulation for globular cluster populations

"Astrophysical implications of the binary BH merger GW150914"

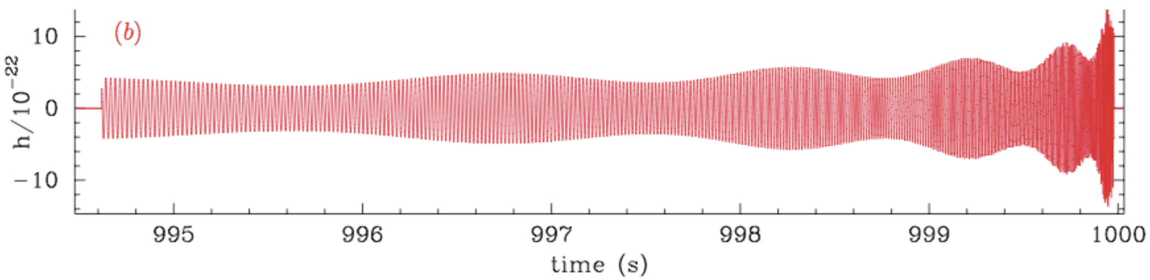
The LSC-Virgo collaboration: Abbott et al. (2016) ApJL

- Evidence of BHs more massive than 25 M_{sun} & a BH-BH binary merger

- **interpretation of GW150914 :**
"a heavy BH-BH merger formed in a low-metallicity environment in the local Universe"

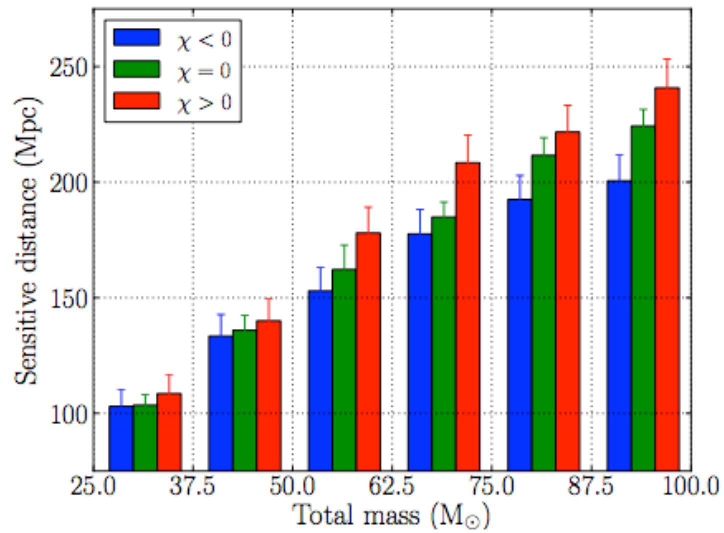
spin estimation is poor... formation site/scenario/BH kicks

longer "inspiral" signals are helpful to measure spin



effects of aligned and anti-agligned spins in the detection distance.

CBCs with aligned spins look "brighter"



GW detection rate expectations

The LIGO-Virgo collaboration; Abadie et al. (2010)

IOP Publishing — Classical and Quantum Gravity
Class. Quantum Grav. **27** (2010) 173001 (25pp) doi:10.1088/0264-9381/27/17/173001

TOPICAL REVIEW

Predictions for the rates of compact binary coalescences observable by ground-based gravitational-wave detectors

total citation: 590

Table 5. Detection rates for compact binary coalescence sources.

IFO	Source[a]	$\dot{N}_{\mathrm{low}}$ yr^{-1}	$\dot{N}_{\mathrm{re}}$ yr^{-1}	$\dot{N}_{\mathrm{high}}$ yr^{-1}	$\dot{N}_{\mathrm{max}}$ yr^{-1}
	NS–NS	>1	8	<80	based on Kim et al. 2015
	NS–BH	0.2	10	300	
Advanced	BH–BH	0.4	20	1000	
	IMRI into IMBH			10[b]	300[c]
	IMBH-IMBH			0.1[d]	1[e]

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

based on Galactic pulsar-NS populations
CK et al. (2015)

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

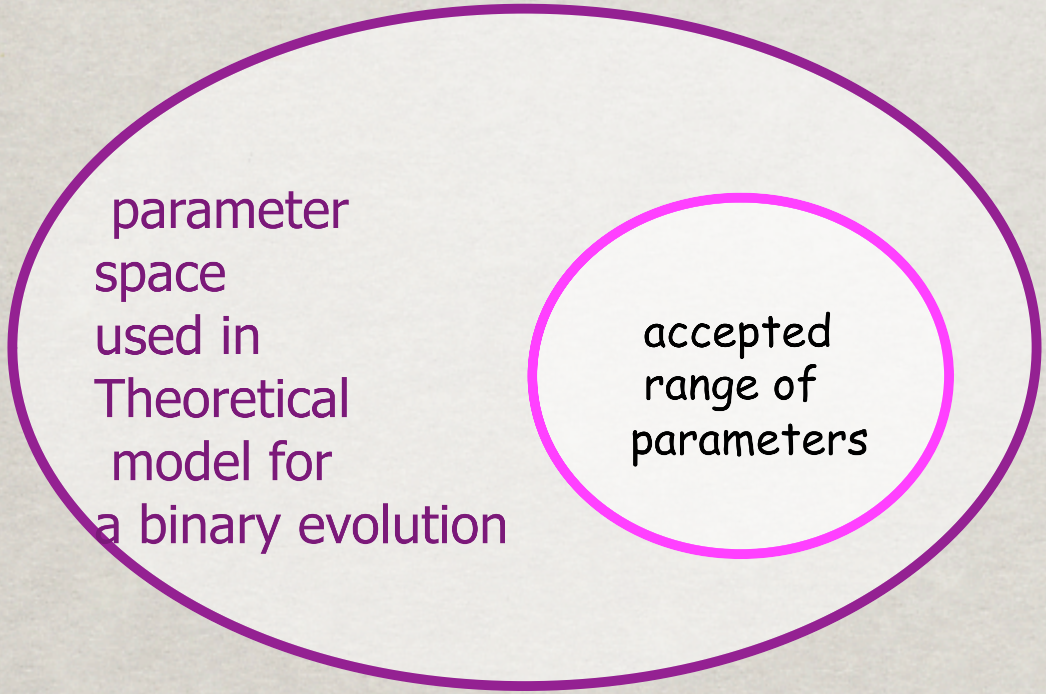
based on GW150914

Constraining theoretical models by GW detection

O'Shaughnessy, CK, et al. 2005, 2008

Establish a set of models (or parameters), which are consistent with empirical rate estimates.

Consider $R_{NS\text{-}NS\ (tight)}$ and $R_{NS\text{-}NS\ (wide)}$

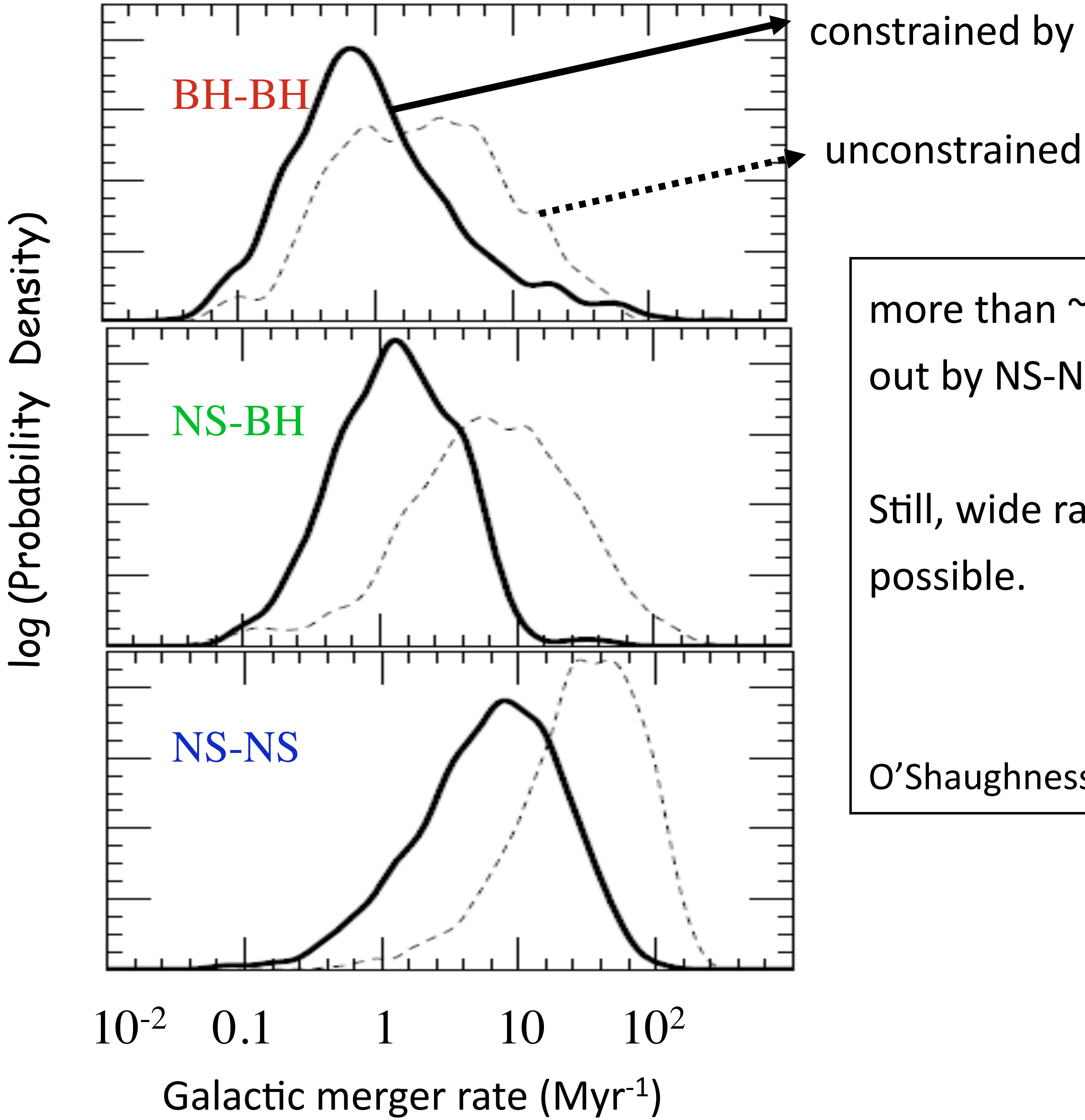


Empirical rates put strong constraints on population synthesis models

Calculate R_{gal} of BH binaries using only those models.

We vary 7 parameters relevant to mass ratio,
wind strength, SN kick dist. (3 parameters), CE energy transfer efficiency,
fraction of accreted mass during non-conservative MT

Constrained predictions with StarTrack



more than ~90% of models are ruled out by NS-NS rate constraints.

Still, wide range of parameters are possible.

O'Shaughnessy, CK et al. 2008, ApJ, 672, 479

CBCs and N-body simulations

Bae, CK, & Lee (2015), Dawoo Park, CK, Bae, & Lee (in prep)
N-body simulations of globular clusters in the Milky Way

Model: King model, no kick, no stellar evolution, typical velocity dispersion from known core-collapsed GC in MW, 1.4 M_{sun} NS, 0.7 M_{sun} normal stars in a cluster

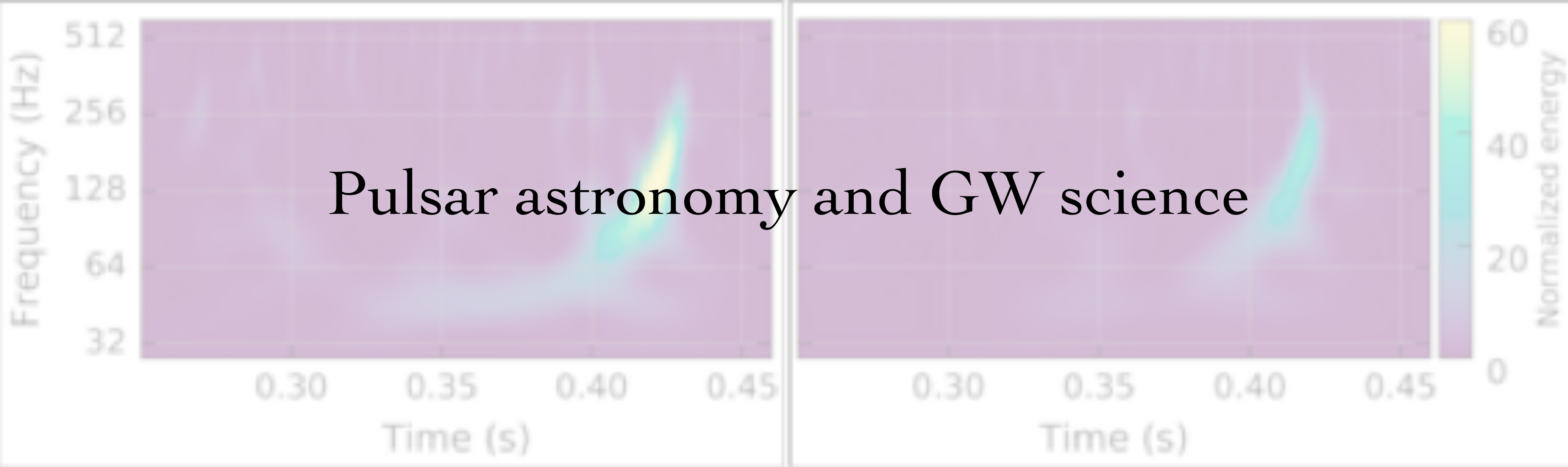
BH mass function: fixed (Bae et al.; 10 M_{sun}),
results from StarTrack (Park et al)

Results: "significant fraction of NS-NS and BH-BH binaries are ejected from a cluster. 30% of ejected binaries are to merge in a Hubble time"

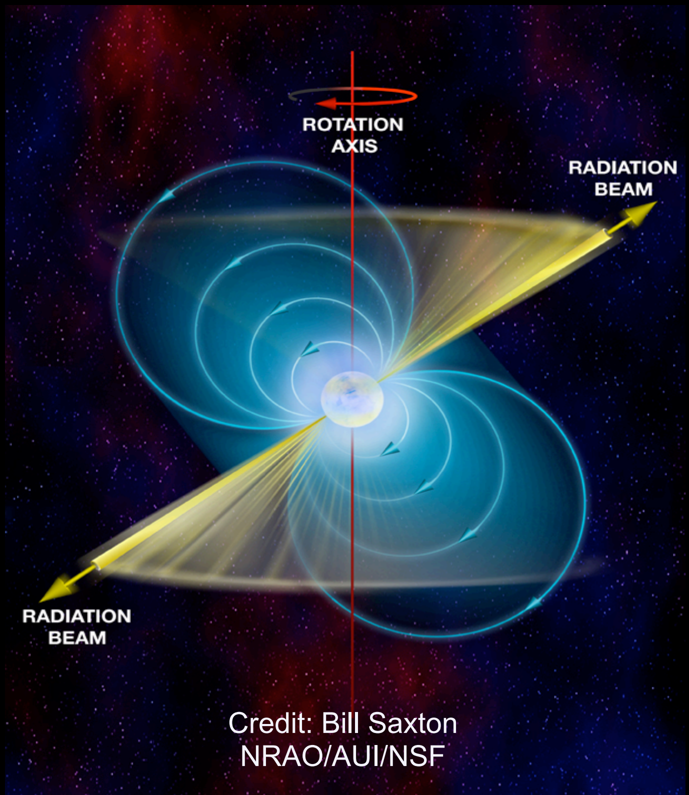
GW detection rates (Bae et al. 2013 vs Abadie et al. 2010):

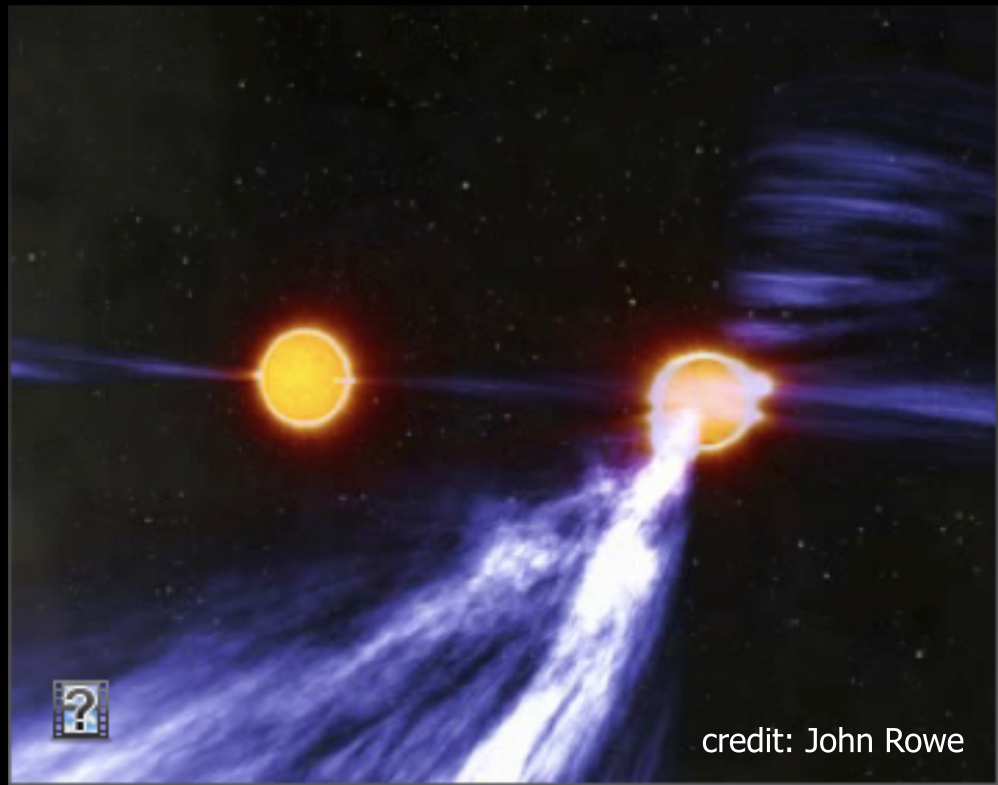
- NS-NS : **0.024 per yr** vs 40 per yr (cluster contribution is negligible)
- BH-BH : **15 per yr** vs 20 per yr (cluster/disk contribution is compatible)

Pulsar astronomy and GW science



Pulsars as gravitational-wave sources





all pulsars are neutron stars
(strongly magnetized, fast-spinning)

1.4 M_{sun} NS, 10 M_{sun} BH을 고려하면,

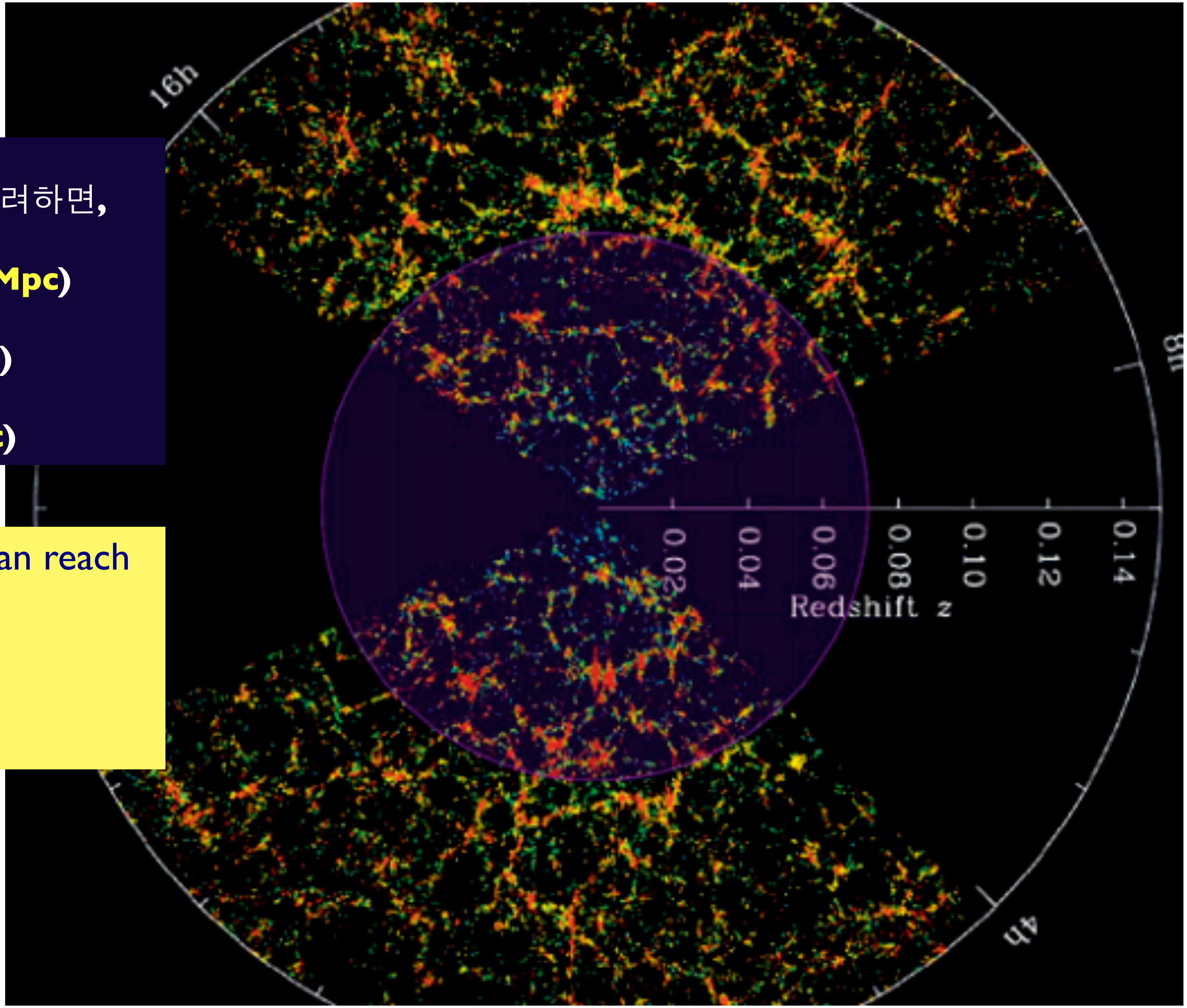
NS-NS : 1.3×10^9 광년 (~400 Mpc)

BH-NS : 3.3×10^9 광년 (1 Gpc)

BH-BH : 6.5×10^9 광년 (2 Gpc)

For NS-NS binaries, aLIGO can reach up to 400 Mpc or z ~ 0.1

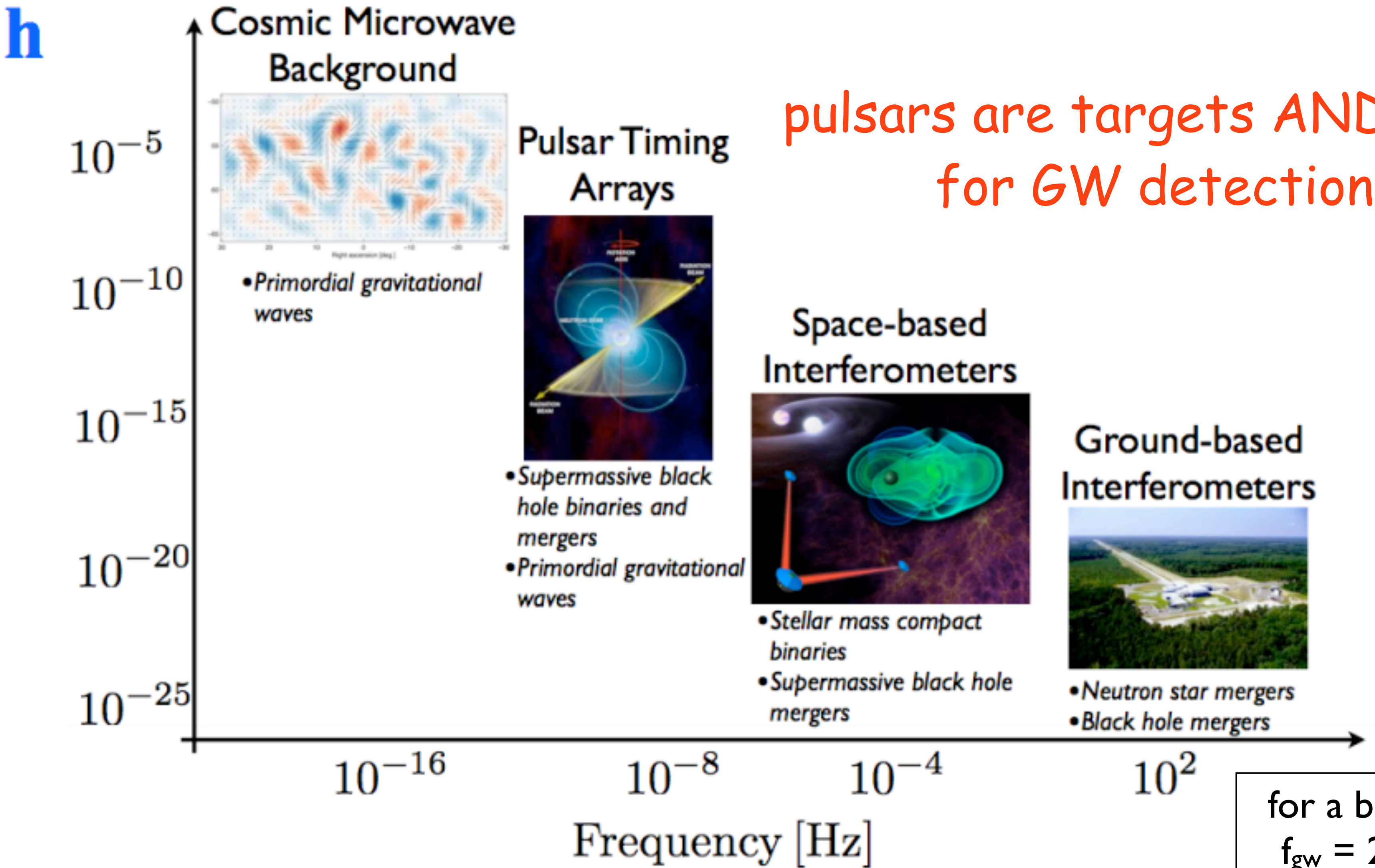
faintest 2MASS galaxies,
K = 14 mag @ 400 Mpc



“HF diagram” in GW science

(h: GW strain, f: GW frequency)

$$h_{\mu\nu} = \frac{2G}{Rc^4}\ddot{I}_{\mu\nu}$$

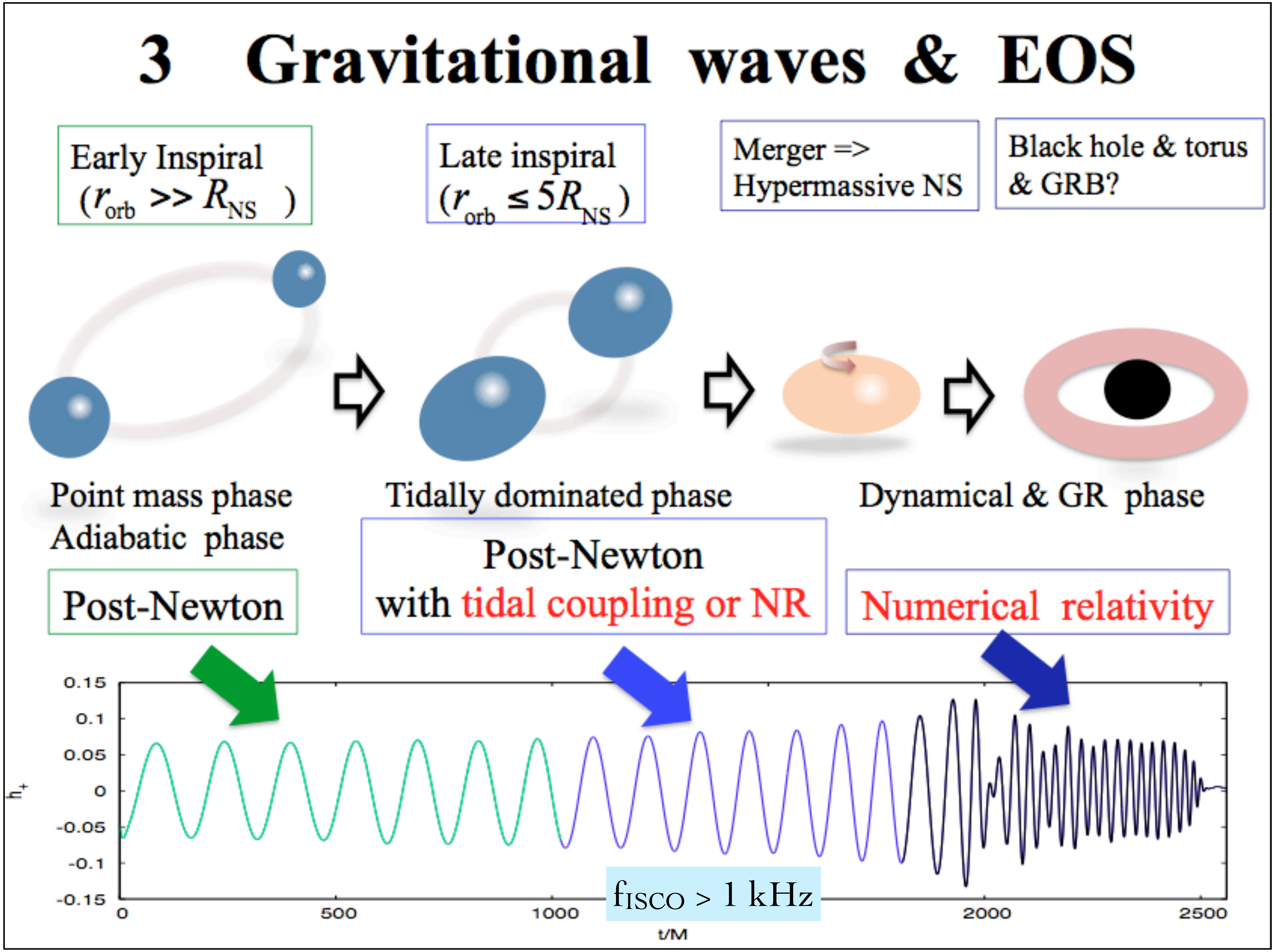


pulsars are targets AND tools for GW detection

for a binary, $f_{gw} = 2\ f_{orb}$

credit: X. Siemens and the NANOGrav Collaboration

NS-NS binary and GW astrophysics



M. Shibata's slide

Pulsar Science with the SKA

M. Kramer and B. Stappers

published on July 6, 2015 (http://arxiv.org/pdf/1507.04423.pdf)

quoted from ABSTRACT:

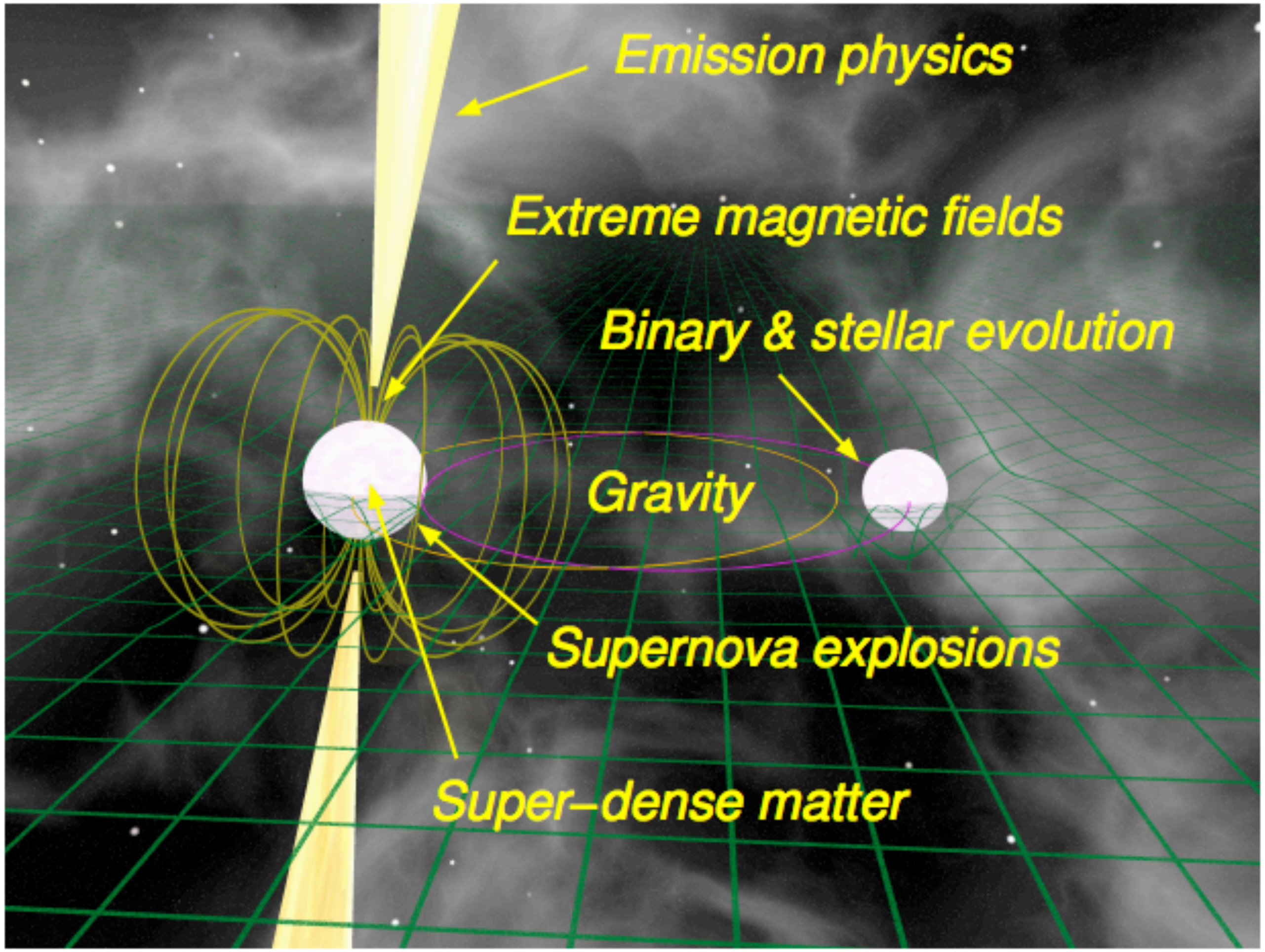
"The SKA will be transformational for many areas of science, but in particular for the study of neutron stars and their usage as tools for fundamental physics in the form of radio pulsars."

SKA-Japan Pulsar Science with the Square Kilometre Array

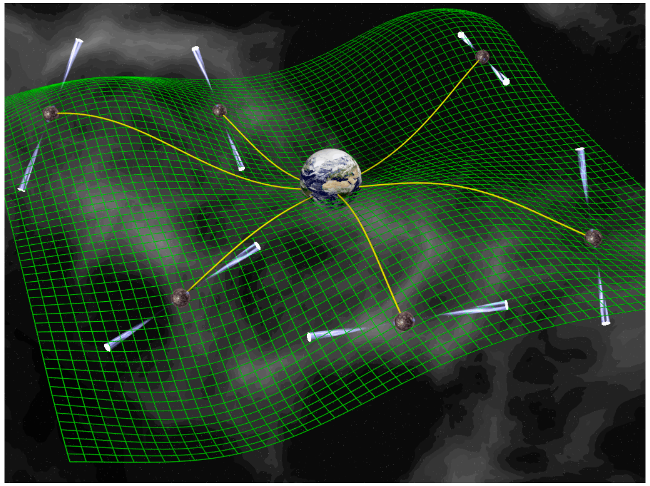
Keitaro TAKAHASHI[1], Takahiro AOKI[2], Kengo IWATA[3], Osamu KAMEYA[4], Hiroki KUMAMOTO[1], Sachiko KUROYANAGI[3], Ryo MIKAMI[5], Atsushi NARUKO[6], Hiroshi OHNO[7], Shinpei SHIBATA[8], Toshio TERASAWA[5], Naoy YONEMARU[1], Chulmoon YOO[3] (SKA-Japan Pulsar Science Working Group)

published on March 7, 2016

http://arxiv.org/pdf/1603.01951v1.pdf

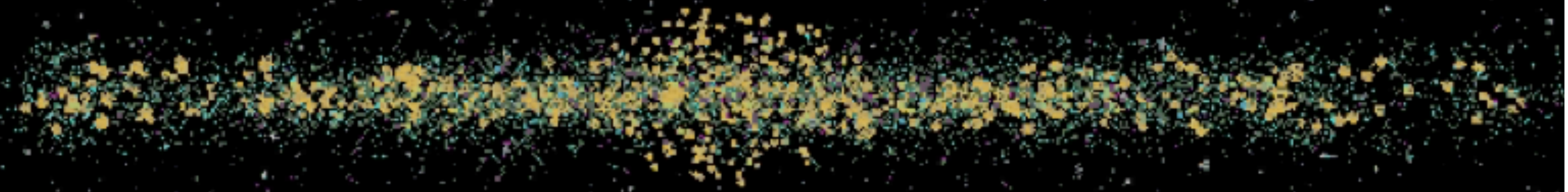


+ GW detection



pulsar timing

SKA will be able to provie an overview of Galactic neutron star population emitting radio waves toward Earth between 50 MHz up to 10 GHz (up to 1000+ DM)



Galactic Neutron Star Population

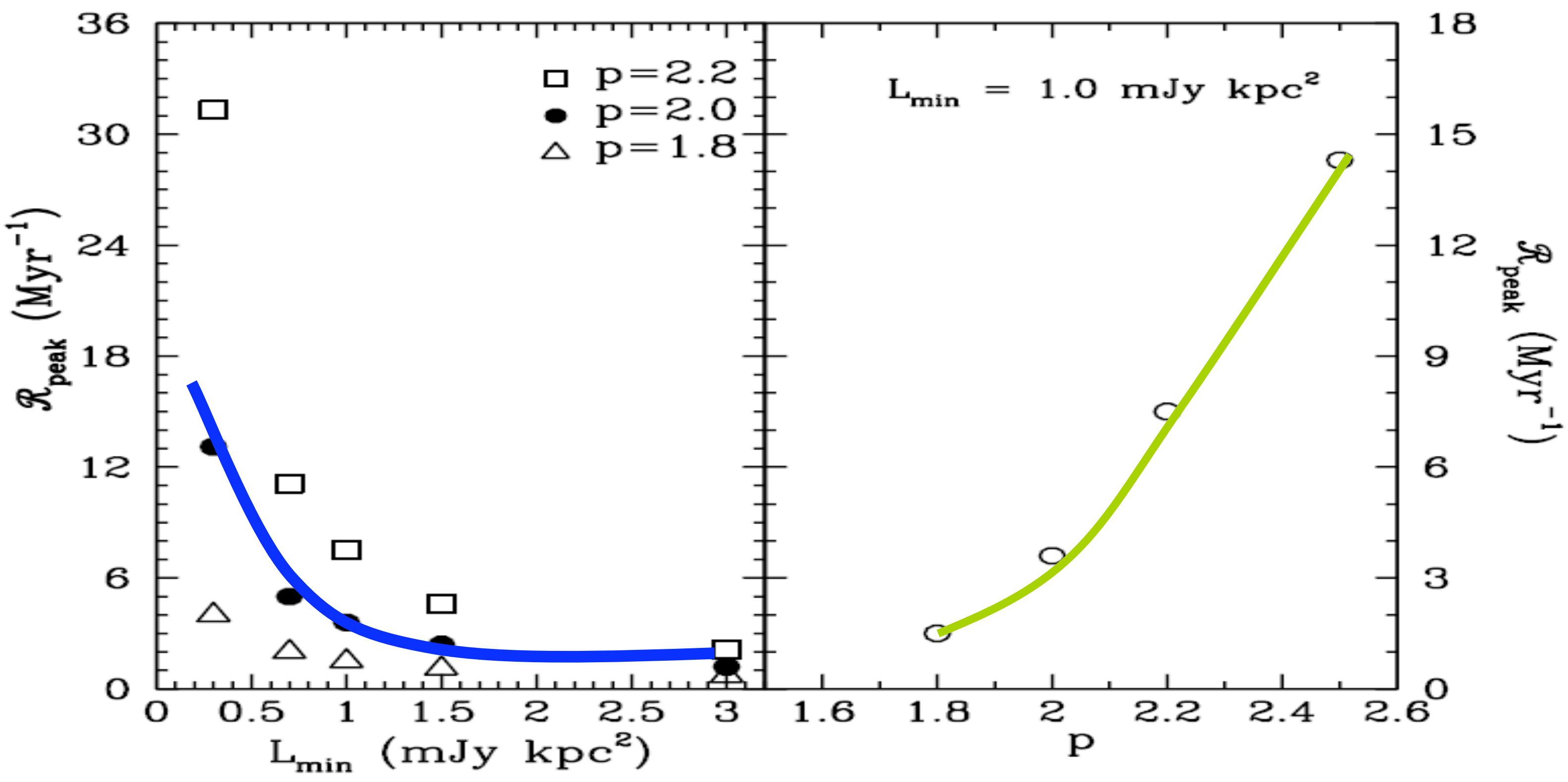
As of 2015,

Radio-active pulsars ~ 2300
Rotating radio transients (RRATs) ~100

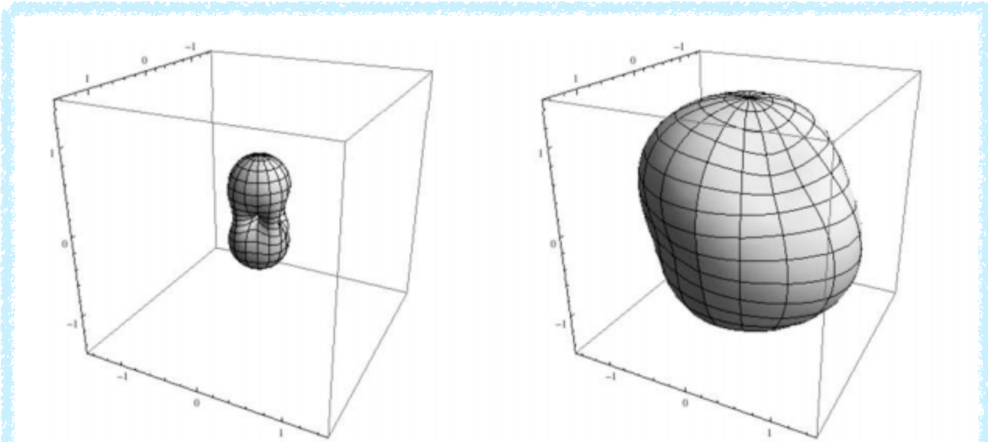
Magnetars ~ 29 (X-ray, gamma-ray, radio)

GW detection and SKA pulsar observations will be useful to constrain a pulsar luminosity function that is amain source of systematic uncertainty in NS-NS merger rate

$$\phi(L) = (p-1)L_{\min}^{p-1}L^{-p}$$



GW detection and multi-messenger astronomy



(a) single detector

(b) combined four detectors

average survey range (detection distance)
increases by ~2.8
for aLIGO+aVirgo+KAGRA

GW detection and multi-messenger astronomy

http://www.ligo.org/scientists/GWEMalerts.php

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LSC LIGO Scientific Collaboration VIRGO

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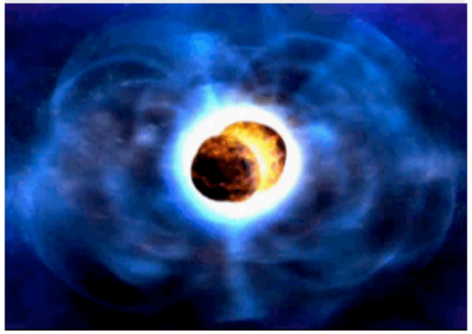
GW-EM alerts Data releases LSC Scientific publications

IDENTIFICATION AND FOLLOW UP OF ELECTROMAGNETIC COUNTERPARTS OF GRAVITATIONAL WAVE CANDIDATE EVENTS

The LIGO Scientific Collaboration (LSC) and the Virgo Collaboration have started taking data in 2015, and we expect the sensitivity of the network to improve over time. Gravitational-wave transient candidates will be identified promptly upon acquisition of the data; we aim for distributing information with an initial latency of a few tens of minutes initially, possibly improving later. The LSC and the Virgo Collaboration (LVC) wish to enable multi-messenger observations of astrophysical events by GW detectors along with a wide range of telescopes and instruments of mainstream astronomy.

In 2012, the LVC approved a statement (LSC, Virgo) that broadly outlines LVC policy on releasing GW triggers (partially-validated event candidates). Initially, triggers will be shared promptly only with astronomy partners who have signed a Memorandum of Understanding (MoU) with LVC involving an agreement on deliverables, publication policies, confidentiality, and reporting. After four GW events have been published, further event candidates with high confidence will be shared immediately with the entire astronomy community (and the public), while lower-significance candidates will continue to be shared promptly only with partners who have signed an MoU.



Devour thy Neighbor: An artist's illustration of two neutron stars close to merger look misshaped, becoming more oblong the closer they get to one another. A black hole is then formed and gamma rays shoot out as a GRB. (Credit: NASA/Swift)

GW triggers followed by EM observations

EM/neutrino triggers followed by GW archive searches

Best targets: gamma-ray bursts and afterglows (expected progenitor: NS-NS/NS-BH binaries)

GW detection and multi-messenger astronomy

다중신호 천문학

information obtained from GW triggers
with low-latency **Parameter Estimation (PE)**

time

detection significance

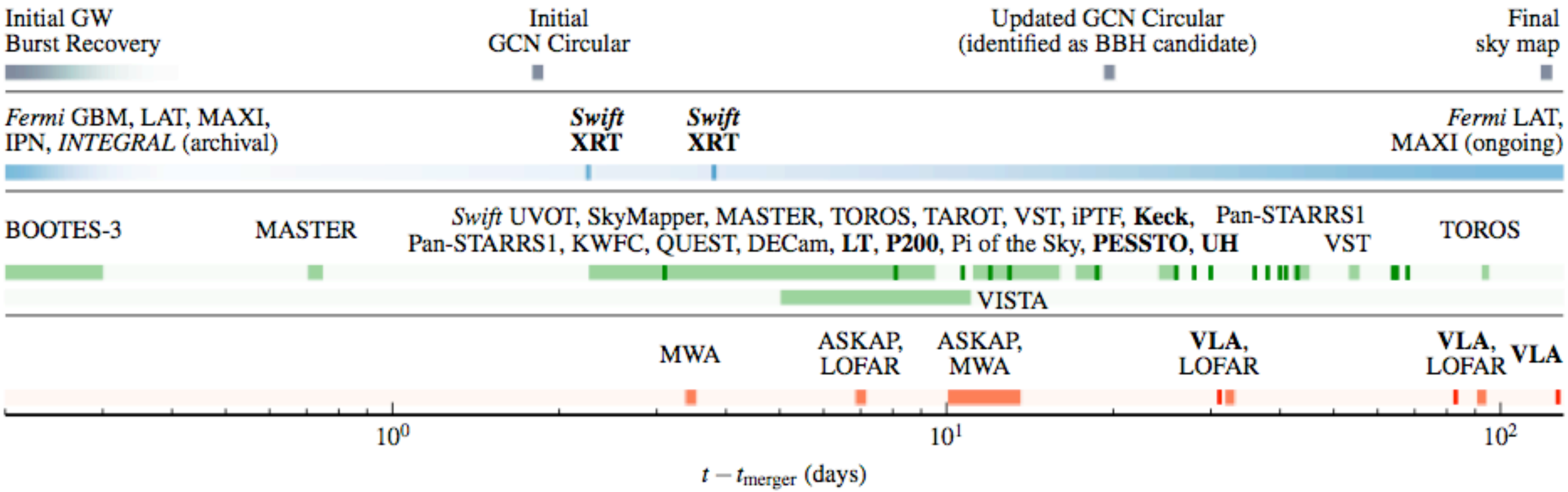
sky location

\+ **nature of the source**

better constrained chirp mass, spin, etc
by more extensive PE

LOCALIZATION AND BROADBAND FOLLOW-UP OF GW150914 15

(http://arxiv.org/abs/1602.08492, submitted to ApJL)

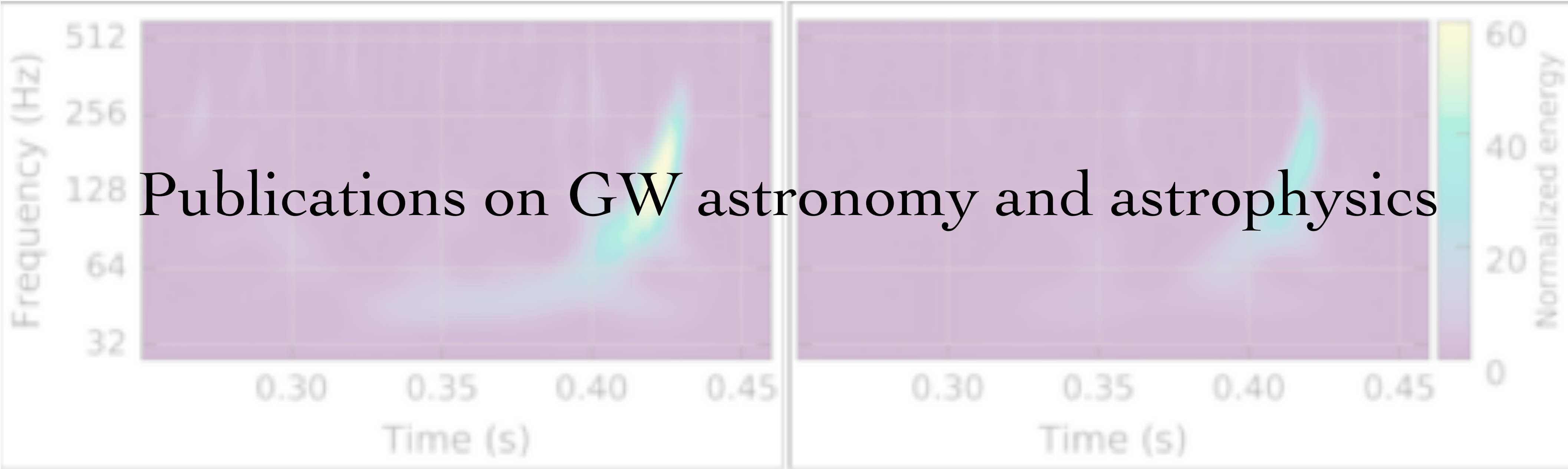


Computational astrophysics and Multi-messenger astronomy

On-going efforts within LIGO-Virgo collaboration

- GPU-based, parallelized search pipelines for detecting cosmic GW signals within seconds
- Bayesian approaches to obtain best localization of a GW trigger within minutes
- Alerting systems and protocols for follow-up observations are well-established (e.g. GCN)
- virtual observatory and/or GW source catalogue will be the next step

Publications on GW astronomy and astrophysics



examples of most cited GW papers (ADS, December 2015)

More work on **astrophysical implications** and **multimessenger astronomy** will come

1	2009RPPh...72g6901A Abbott, B. P.; Abbott, R.; Adhikari, R.; Ajith, P.; Allen, B.; Allen, G.; Amin, R. S.; Anderson, S. B.; Anderson, W. G.; Arain, M. A.; and 491 coauthors	609.000	07/2009	A E X R C S U	LIGO: the Laser Interferometer Gravitational-Wave Observatory	
2	2010CQGra..27q3001A Abadie, J.; Abbott, B. P.; Abbott, R.; Abernathy, M.; Accadia, T.; Acernese, F.; Adams, C.; Adhikari, R.; Ajith, P.; Allen, B.; and 702 coauthors	574.000	09/2010	A E X R C U	TOPICAL REVIEW: Predictions for the rates of compact binary coalescences observable by ground-based gravitational-wave detectors	**rates**
3	1993PhRvL..70.2984C Cutler, Curt; Apostolatos, Theocharis A.; Bildsten, Lars; Finn, Lee S.; Flanagan, Eanna E.; Kennefick, Daniel; Markovic, Dragoljub M.; Ori, Amos; Poisson, Eric; Sussman, Gerald J.	353.000	05/1993	A E X R C U H	The last three minutes - Issues in gravitational-wave measurements of coalescing compact binaries	**CBC data analysis**
4	1994PhRvD..49.6274A Apostolatos, Theocharis A.; Cutler, Curt; Sussman, Gerald J.; Thorne, Kip S.	255.000	06/1994	A E R C U H	Spin-induced orbital precession and its modulation of the gravitational waveforms from merging binaries	**waveform**
5	2002PhRvD..65b2002K Kimble, H. J.; Levin, Yuri; Matsko, Andrey B.; Thorne, Kip S.; Vyatchanin, Sergey P.	243.000	01/2002	A E X R C U H	Conversion of conventional gravitational-wave interferometers into quantum nondemolition interferometers by modifying their input and/or output optic	
6	2009Natur.460..990A Abbott, B. P.; Abbott, R.; Acernese, F.; Adhikari, R.; Ajith, P.; Allen, B.; Allen, G.; Alshourbagy, M.; Amin, R. S.; Anderson, S. B.; and 646 coauthors	213.000	08/2009	A E X R C U	An upper limit on the stochastic gravitational-wave background of cosmological origin	**stochastic**
7	2013arXiv1304.0670L LIGO Scientific Collaboration; Virgo Collaboration; Aasi, J.; Abadie, J.; Abbott, B. P.; Abbott, R.; Abbott, T. D.; Abernathy, M.; Accadia, T.; Acernese, F.; and 828 coauthors	204.000	04/2013	A X R C U	Prospects for Localization of Gravitational Wave Transients by the Advanced LIGO and Advanced Virgo Observatories	**multimessenger**

most cited papers with GW150914 in the title [ADS as of April 26, 2016]

2016ApJ...818L..22A Abbott, B. P.; Abbott, R.; Abbott, T. D.; Abernathy, M. R.; Acernese, F.; Ackley, K.; Adams, C.; Adams, T.; Addesso, P.; Adhikari, R. X.; and 955 coauthors	35.000	02/2016	A E F X R C S U Astrophysical Implications of the Binary Black-hole Merger GW150914
2016arXiv160203841T The LIGO Scientific Collaboration; the Virgo Collaboration	34.000	02/2016	A X R C U Tests of general relativity with GW150914
2016arXiv160203842A Abbott, B. P.; Abbott, R.; Abbott, T. D.; Abernathy, M. R.; Acernese, F.; Ackley, K.; Adams, C.; Adams, T.; Addesso, P.; Adhikari, R. X.; and 956 coauthors	30.000	02/2016	A X R C U The Rate of Binary Black Hole Mergers Inferred from Advanced LIGO Observations Surrounding GW150914
2016arXiv160203840T The LIGO Scientific Collaboration; the Virgo Collaboration	28.000	02/2016	A X R C U Properties of the binary black hole merger GW150914 [parameter estimation results]
2016arXiv160203839T The LIGO Scientific Collaboration; the Virgo Collaboration; Abbott, B. P.; Abbott, R.; Abbott, T. D.; Abernathy, M. R.; Acernese, F.; Ackley, K.; Adams, C.; Adams, T.; and 972 coauthors	16.000	02/2016	A X R C U GW150914: First results from the search for binary black hole coalescence with Advanced LIGO
2016arXiv160204460L Li, Xiang; Zhang, Fu-Wen; Yuan, Qiang; Jin, Zhi-Ping; Fan, Yi-Zhong; Liu, Si-Ming; Wei, Da-Ming	14.000	02/2016	A X R C U Implication of the association between GBM transient 150914 and LIGO Gravitational Wave event GW150914
2016arXiv160203847T The LIGO Scientific Collaboration; the Virgo Collaboration	14.000	02/2016	A X R C U GW150914: Implications for the stochastic gravitational wave background from binary black holes

references of the "astrophysical implications" paper of GW150914

2003ApJ...591..288H	964.000	07/2003	A E F X
Heger, A.; Fryer, C. L.; Woosley, S. E.; Langer, N.; Hartmann, D. H.	How Massive Single Stars End Their Life		
1975ApJ...195L..51H	823.000	01/1975	A F G
Hulse, R. A.; Taylor, J. H.	Discovery of a pulsar in a binary system		
1964PhRv..136.1224P	759.000	11/1964	A E R C U
Peters, P. C.	Gravitational Radiation and the Motion of Two Point Masses		
2006csxs.book..157M	701.000	04/2006	A X R C U
McClintock, Jeffrey E.; Remillard, Ronald A.	Black hole binaries		
1975MNRAS.173..729H	666.000	12/1975	A F G R C U
Heggie, D. C.	Binary evolution in stellar dynamics		
2010CQGra..27q3001A	629.000	09/2010	A E X R C U
Abadie, J.; Abbott, B. P.; Abbott, R.; Abernathy, M.; Accadia, T.; Acernese, F.; Adams, C.; Adhikari, R.; Ajith, P.; Allen, B.; and 702 coauthors	TOPICAL REVIEW: Predictions for the rates of compact binary coalescences observable by by ground-based gravitational-wave detectors		
1992A&A...264..105M	568.000	10/1992	A F G R C O U H
Maeder, Andre	Stellar yields as a function of initial metallicity and mass limit for black hole formation		

2003ApJ...584..985K	91.000	02/2003	A E F X R C S U H
Kim, C.; Kalogera, V.; Lorimer, D. R.	The Probability Distribution of Binary Pulsar Coalescence Rates. I. Double Neutron Star Systems in the Galactic Field		
2005ApJ...633.1076O	43.000	11/2005	A E F X R C S U
O'Shaughnessy, R.; Kim, C.; Fragos, T.; Kalogera, V.; Belczynski, K.	Constraining Population Synthesis Models via the Binary Neutron Star Population		
2007PhR...442...75K	72.000	04/2007	A E X R C S U
Kalogera, V.; Belczynski, K.; Kim, C.; O'Shaughnessy, R.; Willems, B.	Formation of double compact objects		
2014MNRAS.440.2714B	8.000	05/2014	A E F X R C S U
Bae, Yeong-Bok; Kim, Chunglee; Lee, Hyung Mok	Compact binaries ejected from globular clusters as gravitational wave sources		

CBCs and GW astrophysics

- **first detection and discoveries**

Are there BH binaries? YES!
What about BH-NS, NS-NS (em-quiet)?
CBC skymap, catalogue, virtual observatory

- **feedback to EM-based astronomy, astrophysics, numerical relativity, particle physics, cosmology**

Compact binary demography
Realistic astrophysical models for compact binaries and compact objects
Compact binary mergers as standard sirens
Associations with supernovae and/or gamma-ray bursts
Galaxy evolution, metallicity
Cosmic (massive) star formation history
GW waveform modeling