Slides to go along with

Cosmology with Gravitational Waves

Archisman Ghosh

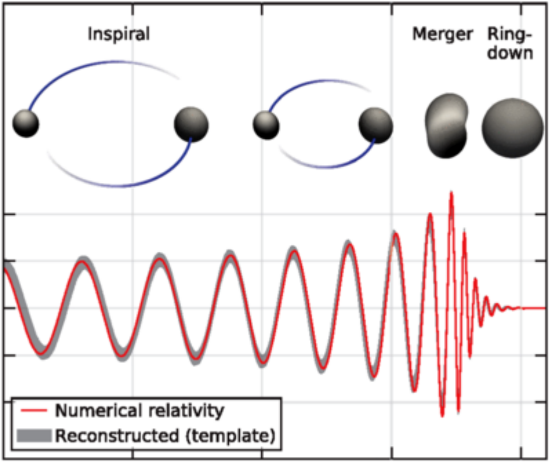
Nikhef, Amsterdam

2019 January 14

Cosmology – The next decade

ICTS Bangalore, 2019 January 03–25

GW Basics



Inspiral
Merger
Ring-down
Numerical relativity
Reconstructed (template)

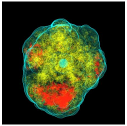
Gravitational and Electromagnetic Radiation: different probes for our universe

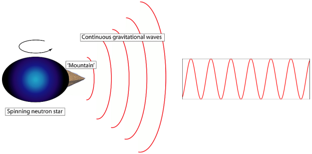
Oscillations of spacetime itself	Electric and magnetic fields propagating through spacetime
Coherent: dynamical state	Incoherent superposition of many emitters: thermodynamic state
Weakly interacting	Strongly interacting
$h \sim 1/r$	Energy flux $\sim 1/r^2$
wavelength ~/> size of source: analogous to sound	wavelength </<< size of emitting source: image
all sky sensitivity; poor angular resolution	deep imaging on small area; high angular resolution

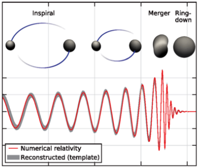
Slide from: **Samaya Nissanke**

Gravitational-wave sources

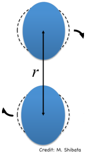
	Persistent	Transient
Unmodelled	Stochastic background Cosmological + BBH	Bursts Supernova explosions
Modelled	Continuous waves Spinning deformed NS	Compact binary coalescences NS-NS, NS-BH, BBH





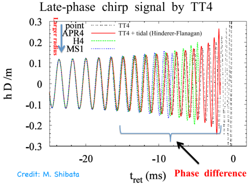


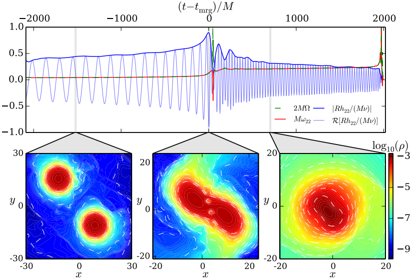
Tidal deformations in neutron stars



Neutron stars in binaries are tidally deformed.

Have a measurable effect on the orbital motion.





Bernuzzi *et al.* (2015)

Intrinsic parameters

- Component masses, $m_{1,2}$
- Component dimensionless spin angular momenta, $\vec{s}_{1,2}$ $\quad \vec{s} \equiv \frac{\vec{J}}{m^2}$
- Tidal parameters for neutron stars, $\lambda_{1,2}$
- Any residual eccentricity?

Two polarizations

Dominant (2, 2)-mode to leading order:

$$h_+(t) = \frac{2M\eta}{D}(\pi M f_{\rm GW})^2 (1 + \cos^2\iota)\cos 2\phi(t)$$
$$h_\times(t) = \frac{4M\eta}{D}(\pi M f_{\rm GW})^2 \cos\iota \sin 2\phi(t)$$

$$M \equiv m_1 + m_2 \qquad \eta \equiv \frac{m_1 m_2}{M^2}$$

- Distance, D
- Inclination angle, ι
- Phase at coalescence, ϕ_c
- Time of coalescence, t_c

Antenna beam pattern functions

- Polarization angle, ψ
- Two angles in the sky $(\theta, \phi) \longrightarrow (\alpha, \delta)$, right ascension and declination

$$F_{+}(\theta, \phi, \psi) = -\frac{1}{2}(1+\cos^2\theta)\cos 2\phi \cos 2\psi - \cos\theta \sin 2\phi \sin 2\psi \quad \text{(A.10)}$$

$$F_{\times}(\theta, \phi, \psi) = +\frac{1}{2}(1+\cos^2\theta)\cos 2\phi \sin 2\psi - \cos\theta \sin 2\phi \cos 2\psi \ . \quad \text{(A.11)}$$

These beam pattern functions are shown in Figure A.1.

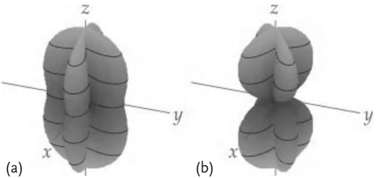


Figure A.1 The beam pattern functions $F_{+}^{2}(\theta, \phi, \psi = 0)$ (a) and $F_{\times}^{2}(\theta, \phi, \psi = 0)$ (b) for an interferometric gravitational-wave detector with orthogonal arms along the *x*- and *y*-axes.

CBC parameters

Intrinsic parameters: $\{m_1, m_2, \vec{s}_1, \vec{s}_2, \lambda_1, \lambda_2, \ldots\}$

Extrinsic parameters: $\{\alpha, \delta, d_L, \iota, \psi, \phi_c, t_c\}$

For BBHs masses are completely degenerate with the cosmological redshift and it is only possible to measure the "detector-frame" redshifted mass, $m^z \equiv m(1+z)$. For mergers involving a NS the degeneracy is approximate, but cannot be broken in practice by second-generation detectors.

15 parameters for BBHs

At least 17 parameters for BNS

phase $\Rightarrow$ redshifted chirp mass, $\mathcal{M}^z \equiv \frac{(m_1^z m_2^z)^{3/5}}{(m_1^z + m_2^z)^{1/5}}$, very accurately

$\Rightarrow$ mass ratio, $q \equiv \frac{m_2}{m_1}$, to a reasonable degree; **strongly correlated with spin & tidal**

amplitude $\Rightarrow$ combination of $\frac{\mathcal{M}^z(1+\cos^2\iota)}{d_L}$, $\frac{\mathcal{M}^z \cos\iota}{d_L}$ **(dominant 22-mode dependence)**

polarisation $\Rightarrow$ $\cos^2\iota$ poorly

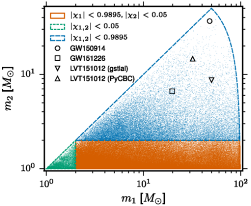
$\Rightarrow$ d_L to a reasonable degree

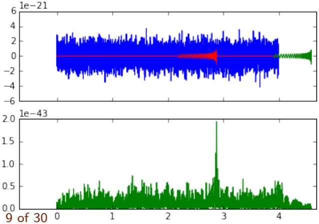
Data analysis of CBCs

Searches

Generate (real-time) triggers

Abbott *et al.*, PRX **6**, 041015 (2016)





Parameter estimation

Rigorous analysis of data around trigger

Low latency

quick

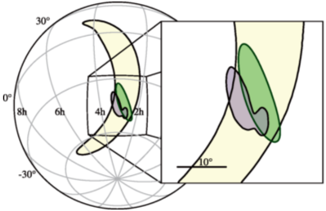
BayesSTAR

RapidPE

High latency

accurate

LALINFERENCE



Implications

Fundamental physics, astrophysics, cosmology

CBC parameter estimation

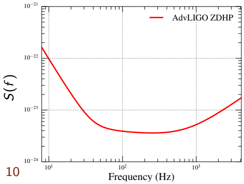
Bayesian parameter estimation: obtain the posterior probability distribution on the parameter space given the data and a prior probability distribution.

$$Posterior(\vec{\Omega}|\text{data}, I) = \frac{Prior(\vec{\Omega}|I)\,\mathcal{L}(\text{data}|\vec{\Omega}, I)}{Evidence(\text{data}, I)}$$

$$\vec{\Omega} = \{\mathcal{M}, q, \vec{s}_1, \vec{s}_2, \lambda_1, \lambda_2, \alpha, \sin\delta, d_L, \cos\iota, \psi, \phi_c, t_c\}$$

$$\begin{aligned}\mathcal{L}(\text{data}|\vec{\Omega}, I) &= P(\text{data}|\text{signal}(\vec{\Omega}), I)\\ &= \exp\left(-\frac{1}{2}\left\langle \text{data} - \text{signal}(\vec{\Omega})|\text{data} - \text{signal}(\vec{\Omega})\right\rangle\right)\end{aligned}$$

$\text{data} = \text{signal}(\vec{\Omega}) + \text{noise}, n$

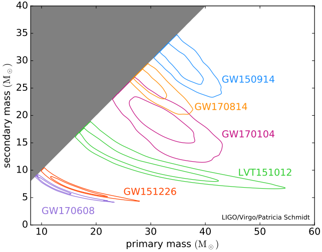


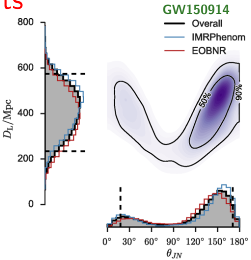
$$\langle n|n\rangle \equiv \int df \frac{||n(f)||^2}{S^2(f)}$$

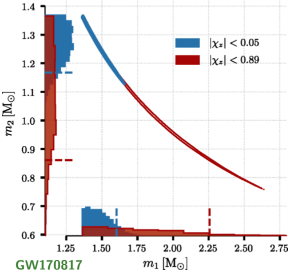
Gaussian noise

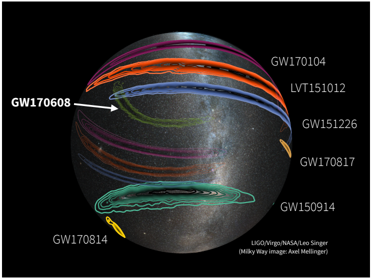
Parameter estimation results

Abbott *et al.*, PRL **116**, 061102 (2016)









Abbott *et al.*, PRL **119**, 161101 (2017)

GW Cosmology

Cosmography

H_0 : Hubble parameter
Ω_m : Matter fraction
Ω_Λ : Dark energy fraction

$\Omega_m + \Omega_\Lambda = 1$

Govern the expansion and acceleration of the universe.

Redshift-distance relation:

$$d_L = c(1+z)\int^z \frac{dz'}{H(z')} , \quad H(z) = H_0 \sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}$$

H_0 ↑ Hubble parameter
Ω_m ↑ Matter fraction
Ω_Λ ↑ Dark energy fraction

Cosmology: Hubble's law

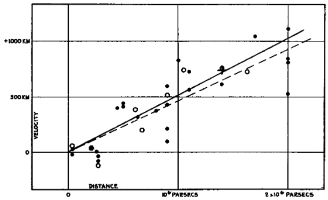
recession velocity of a galaxy in the local universe $\longrightarrow$ $v_H = H_0\ d$ $\longleftarrow$ distance to the galaxy

$\uparrow$

Hubble parameter

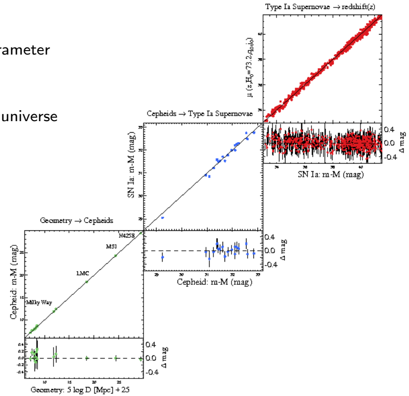
recession $\longrightarrow$ stretching of spacetime itself $\longrightarrow$ expansion of the universe

usually measured as a cosmological redshift $v_H = c\,z$



Edwin Hubble, *Proc. Nat. Acad. Sciences.* (1929)

Note: significant overestimate!

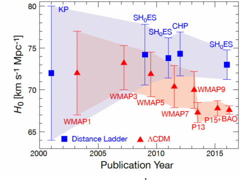


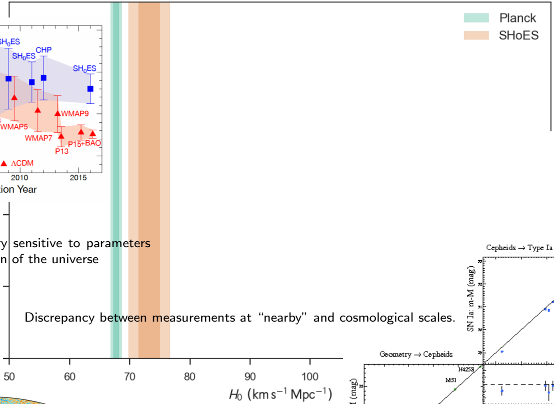
Cosmic distance ladder: Reiss *et al.* (2016)

State-of-the-art measurements of H_0

Two contrasting methods applied on nearby and very distant cosmological scales

Freedman (2017)



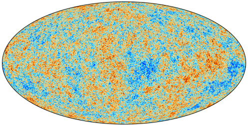


Standard candles

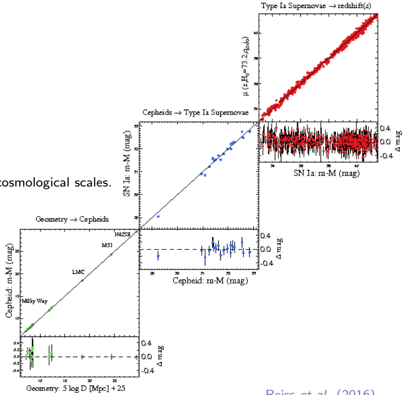
Cosmic distance ladder

CMB anisotropies: very sensitive to parameters that drive the expansion of the universe

Discrepancy between measurements at "nearby" and cosmological scales.



Planck collaboration (2015)



Reiss *et al.* (2016)

Three roads to GW cosmology

- Electromagnetic counterparts:

  Schutz (1986); MacLeod and Hogan (2008); Del Pozzo (2012); Chen *et al.* (2017); Nair *et al.* LIGO-P1700098

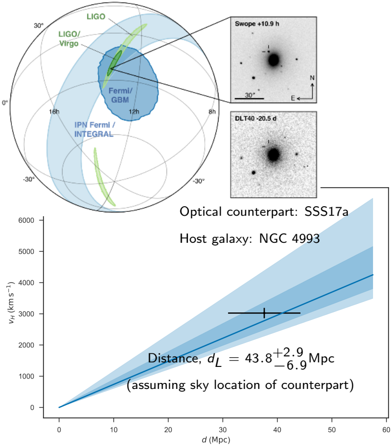
- Information from physics of NS:

  Mass-function. Taylor *et al.* (2012); Taylor & Gair (2012)

  Tidal deformations. Messenger & Read (2011); Del Pozzo *et al.* (2017)

- Angular correlations from GW localization. Oguri (2016)

Hubble parameter with GW170817



Optical counterpart: SSS17a

Host galaxy: NGC 4993

Distance, $d_L = 43.8^{+2.9}_{-6.9}$ Mpc

(assuming sky location of counterpart)

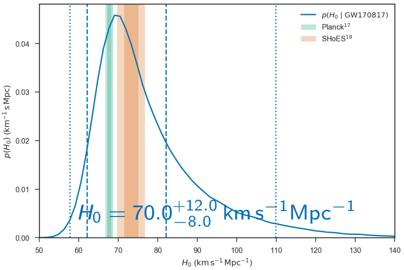
observed $v_{recession} = v_H + v_{peculiar}$

universe is not homogeneous at small scales:
galaxies attracted towards local matter overdensities

NGC 4993: $v_{recession} = 3327 \pm 72\ \mathrm{km\,s}^{-1}$

Correct for peculiar velocity of group of galaxies

$$v_H = 3017 \pm 166\ \mathrm{km\,s}^{-1}$$



$H_0 = 70.0^{+12.0}_{-8.0}\ \mathrm{km\,s}^{-1}\,\mathrm{Mpc}^{-1}$

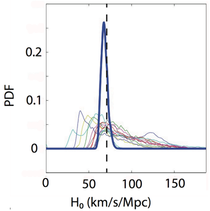
Independent of any distance ladder!

Abbott *et al.* Astrophys. J. **848** #2, L12 (2017); LSC-EPO

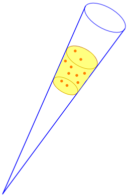
Abbott *et al.* Nature **551** #7678, 85-88 (2017)

What next?

Nissanke *et al.* (2013)



Multiple observations with transient counterparts.



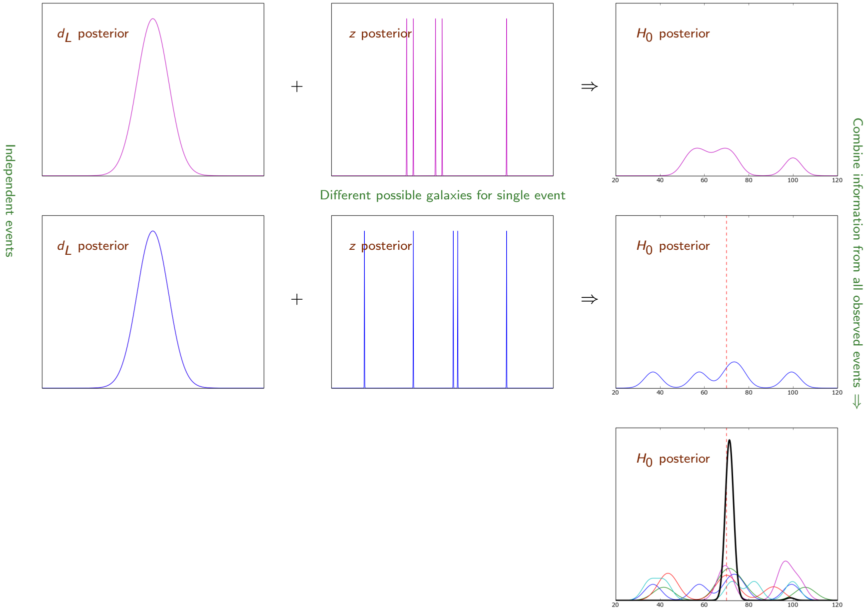
Narrow beam with potential host galaxies around optical counterpart if host galaxy not uniquely identified.

Schutz (1986)

A fully statistical analysis using cross-correlation with a galaxy catalog in absence of a transient optical counterpart.

applicable also for binary black holes

extension to other cosmological parameters?



Independent events
d_L posterior
+
z posterior
⇒
H_0 posterior
20 40 60 80 100 120
Different possible galaxies for single event
d_L posterior
+
z posterior
⇒
H_0 posterior
20 40 60 80 100 120
H_0 posterior
20 40 60 80 100 120
Combine information from all observed events ⇓

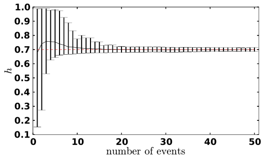
Statistical "cross-correlation" with galaxy catalogues

Idea in Schutz (1986).

MacLeod and Hogan (2008) in the context of LISA.

Del Pozzo (2012) in the context of Adv-LIGO.

aLIGO-Virgo; 30 CBCs to $z = 0.1$ + SDSS $\Rightarrow H_0$ to $\sim$ 5%



Selection effects!

Nair *et al.* LIGO-P1700098: EM and GW selection effects enter in a similar way.

H_0-statistical: selection effects

$$d_L H_0 \approx zc$$

GW selection effects

threshold SNR $\rightarrow$ interferometer horizon

only nearby signals detected

EM selection effects

depth of telescope

incomplete galaxy catalogues

Correct for / take into account possible contribution of galaxies missing from catalogue.

Detection efficiency:

$$\mathcal{N}_{\text{eff}}(\mathbf{\Omega}) = \int_{\mathcal{E}_{\text{det}}} d\mathcal{E} \int d\theta \; p(\mathcal{E}\,|\,\theta, \mathbf{\Omega}, \mathcal{H}, \mathcal{I})\, p(\theta\,|\,\mathbf{\Omega}, \mathcal{H}, \mathcal{I})$$

Integrated method of taking into account both effects.

Abbott *et al.* Nature **551** #7678, 85-88 (2017)

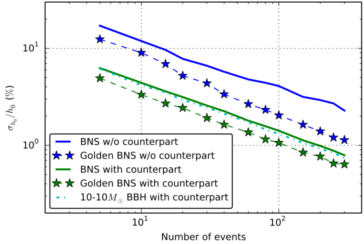
Mandel, Farr, Gair (2018); Chen *et al.* (2017)

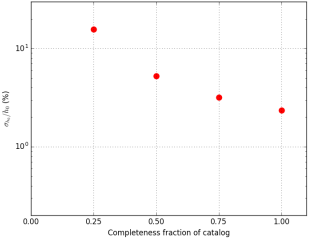
Messenger & Veitch (2013); Gray *et al.* (in prep.)

H_0-statistical: results on simulations

Chen *et al.* (2017)

Sur (2017, Masters thesis), Gray *et al.* (in prep.)





Incomplete galaxy catalogue

Ajith, Brady, Chen, Datrier, Del Pozzo, Fishbach, Gair, Ghosh, **Gray**, Hendry, Holz, **Magaña-Hernandez**, Messenger, **Qi**, Samajdar, **Sur**, Van Den Broeck, Veitch

Ongoing and future work

- Fold in probabilities of galaxies hosting the sources.

  Luminosity weighting.

  Astrophysically-motivated weighting of host galaxies?

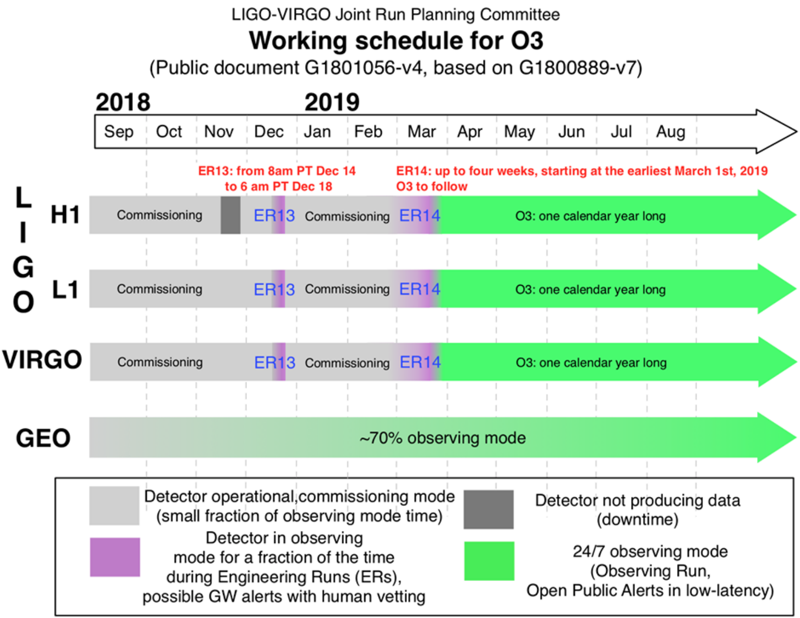
- Going beyond H_0?

  Caveat: incompleteness of galaxy catalogues.

  Sources correlated with visible matter distribution?

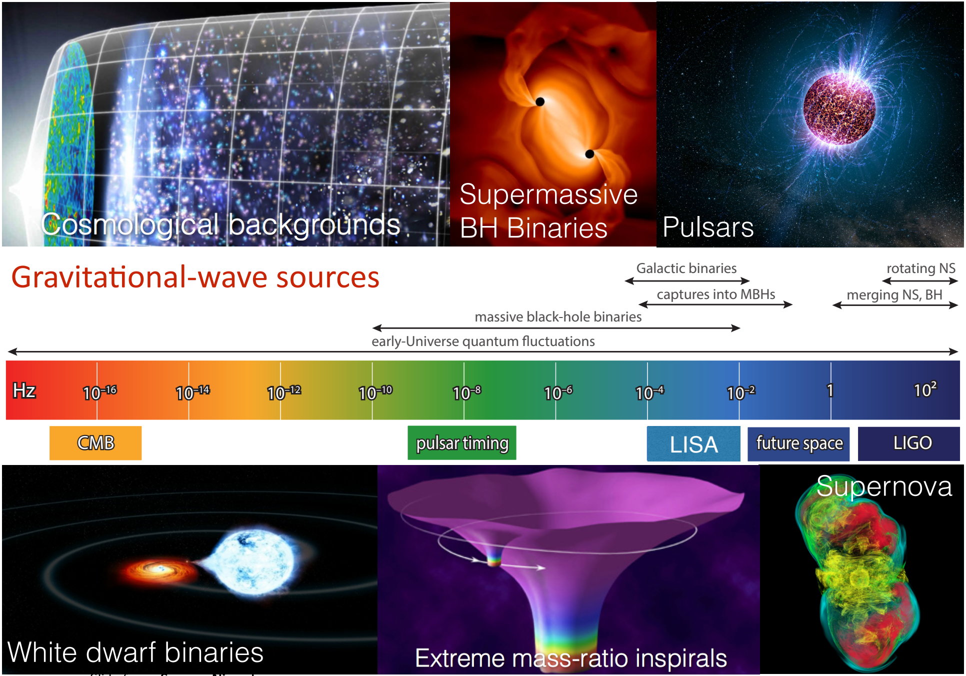
  Cluster catalogues $\Rightarrow$ probability density in redshift space?

- Cross-correlation with clustering more effective?



LIGO-VIRGO Joint Run Planning Committee
Working schedule for O3
(Public document G1801056-v4, based on G1800889-v7)
2018
2019
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
ER13: from 8am PT Dec 14 to 6 am PT Dec 18
ER14: up to four weeks, starting at the earliest March 1st, 2019 O3 to follow
LIGO
H1
Commissioning
ER13
Commissioning
ER14
O3: one calendar year long
L1
Commissioning
ER13
Commissioning
ER14
O3: one calendar year long
VIRGO
Commissioning
ER13
Commissioning
ER14
O3: one calendar year long
GEO
~70% observing mode
Detector operational,commissioning mode (small fraction of observing mode time)
Detector not producing data (downtime)
Detector in observing mode for a fraction of the time during Engineering Runs (ERs), possible GW alerts with human vetting
24/7 observing mode (Observing Run, Open Public Alerts in low-latency)

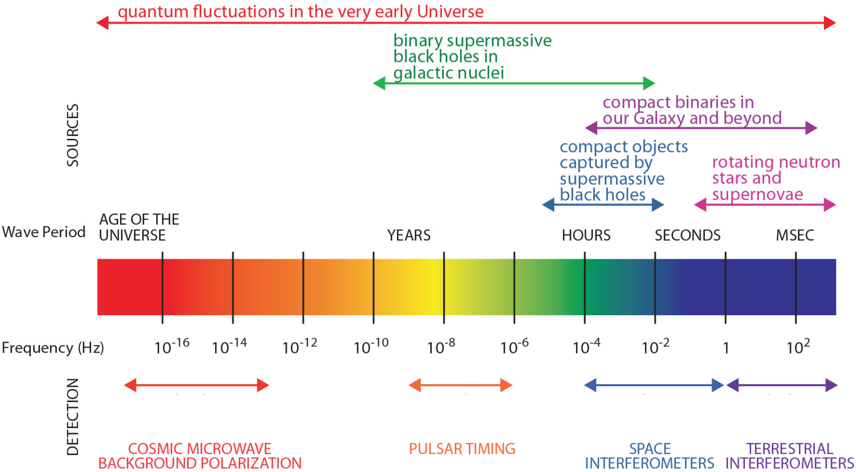
Future prospects



Slide from: **Samaya Nissanke**

First-order phase transitions, superstring kink & cusps, inflationary signature, new sources!

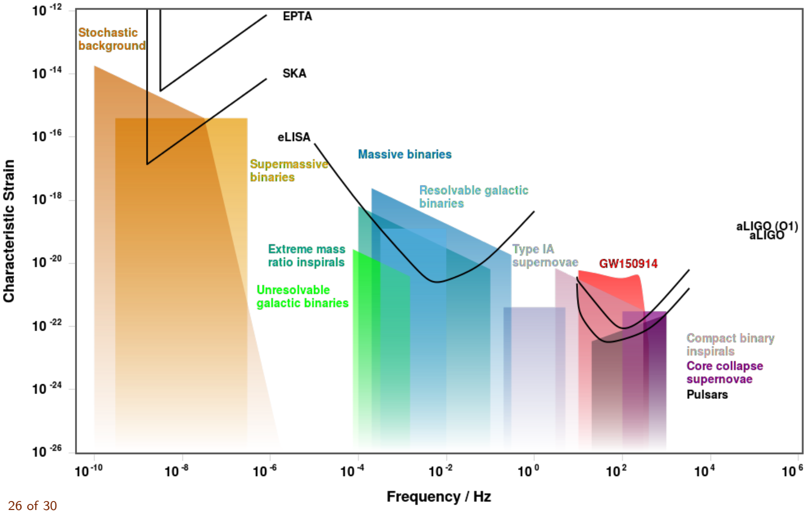
GW detectors



Slide from: **Samaya Nissanke**

Future detectors

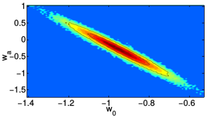
Moore, Cole, & Berry, http://rhcole.com/apps/GWplotter/



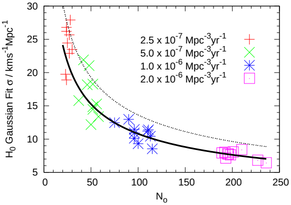
A host of methods

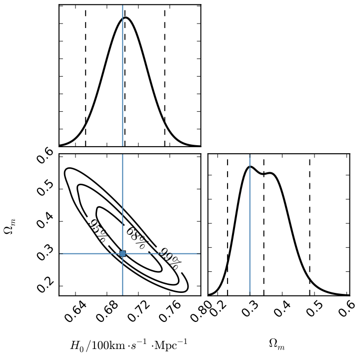
Paper	Detector	Source	Distance	Catalogue	Num.	Acc. H_0
MacLeod & Hogan (2008)	LISA	EMRI	$z \approx 0.5$	SDSS	20	1%
Del Pozzo (2012)	aLIGO-Virgo	CBC	$z = 0.1$	SDSS	30	5%
Taylor *et al.* (2012)	aLIGO-Virgo	BNS	$z \lesssim 0.15$		100	10%
Taylor & Gair (2012)	ET	BNS	$z \leqslant 4$			
Messenger & Read (2012)	ET	BNS	$z \approx 1$			
Del Pozzo *et al.* (2017)	ET	BNS	$z \leqslant 2$		1000	8%
Oguri (2016)	ET	BBH	$z \leqslant 1.5$			3%
Nishizawa (2012)	DECIGO/BBO	BNS			10^6	
Chen *et al.* (2012)	aLIGO-Virgo	CBC	$z \leqslant 0.1$	simulated	300	2%
	aLIGO-Virgo	CBC	$z \leqslant 0.1$	simulated	250	7%
	aLIGO-Virgo	CBC	$z \leqslant 0.1$	simulated	250	14%

Using information from physics / astrophysics of NS



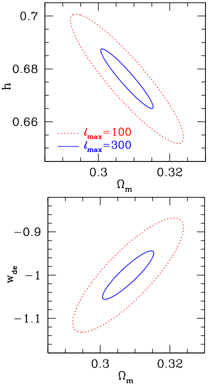
Mass-function: Taylor *et al.* (2012)





Tidal deformations: Del Pozzo *et al.* (2017)

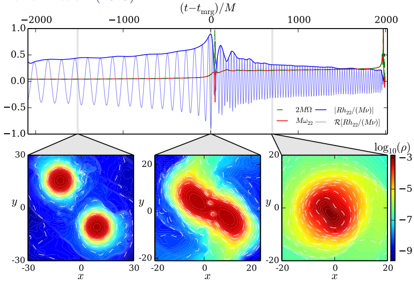
Clustering

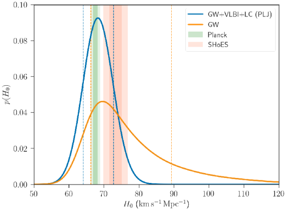


Oguri (2016)

Synergetic multimessenger science: road to the future

Bernuzzi *et al.* (2015)

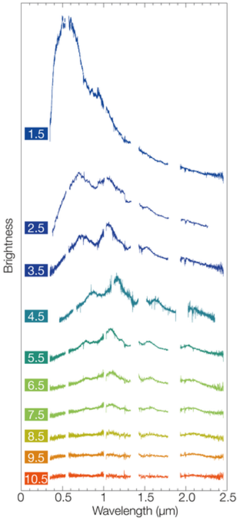




Hotokezaka *et al.* (2018): jet → inclination!

GW & EM!

Kilonova → NS-EoS?



Pian *et al.* (2017)