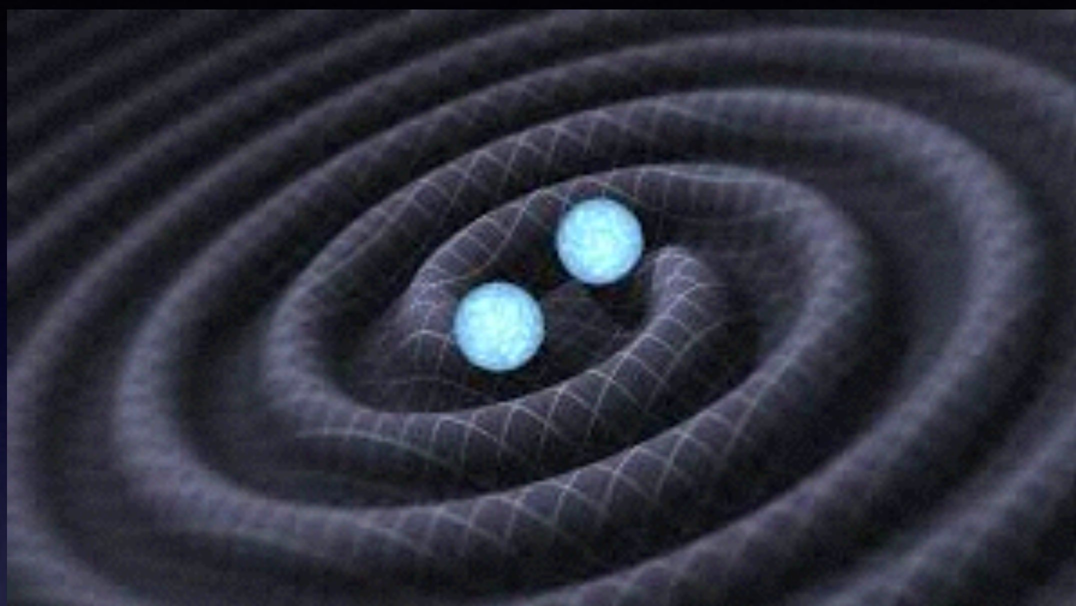
Searching for Dark Matter in Gravitational Waves



S. Bird, I.C, J. Munoz, Y. Ali-Haimoud, M. Kamionkowski, E. Kovetz, A. Raccanelli and A. Riess (JHU) PRL 116.201031, (arXiv:1603.00464)

I.C., E. Kovetz, Y. Ali-Haimoud, S. Bird, M. Kamionkowski, J. Munoz, A. Raccanelli PRD 94 084013 (arXiv:1606.07437)

A. Raccanelli, E. Kovetz, S.Bird, I.C. J Munoz PRD 94 023516 (arXiv: 1605:01405)

V. Mandic, S. Bird, I.C. PRL 117.201102 (arXiv:1608.06699)

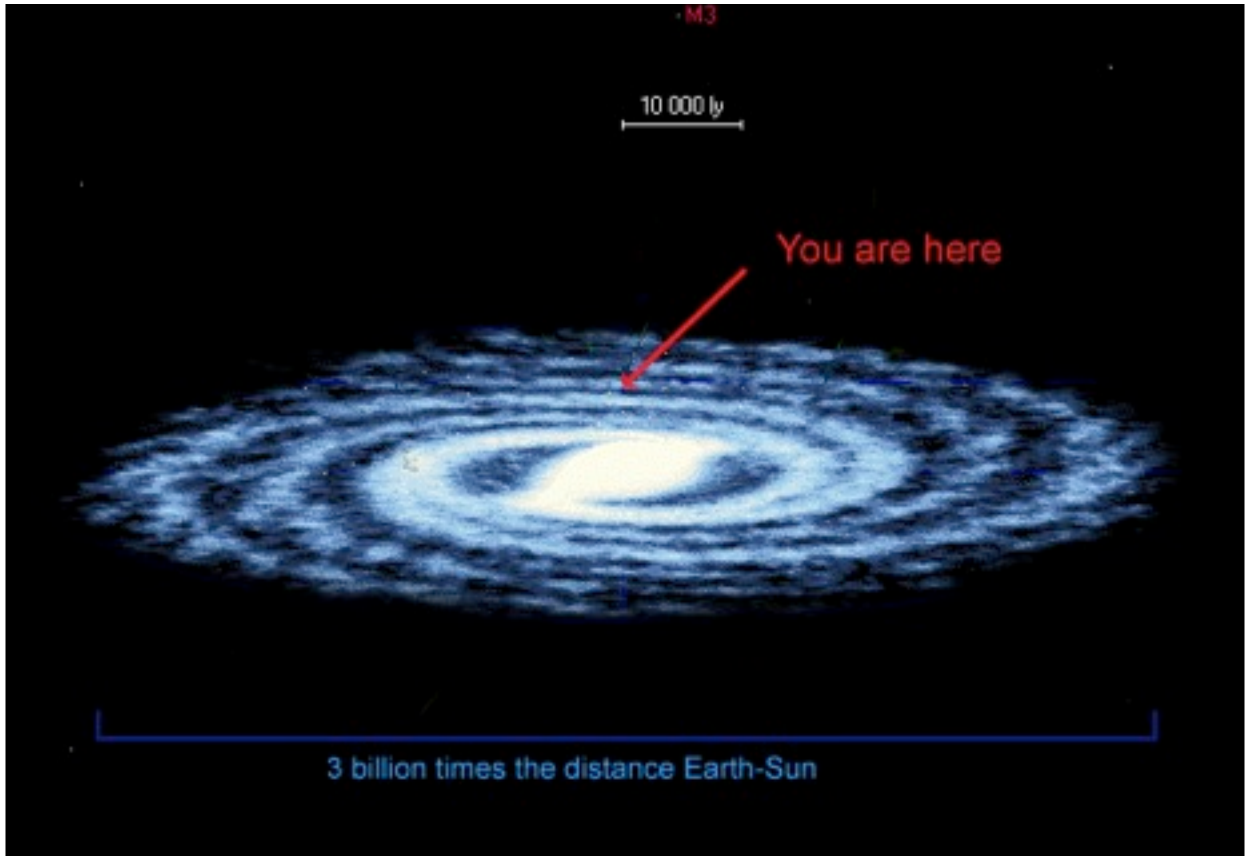
I.C. arXiv:1609.03565

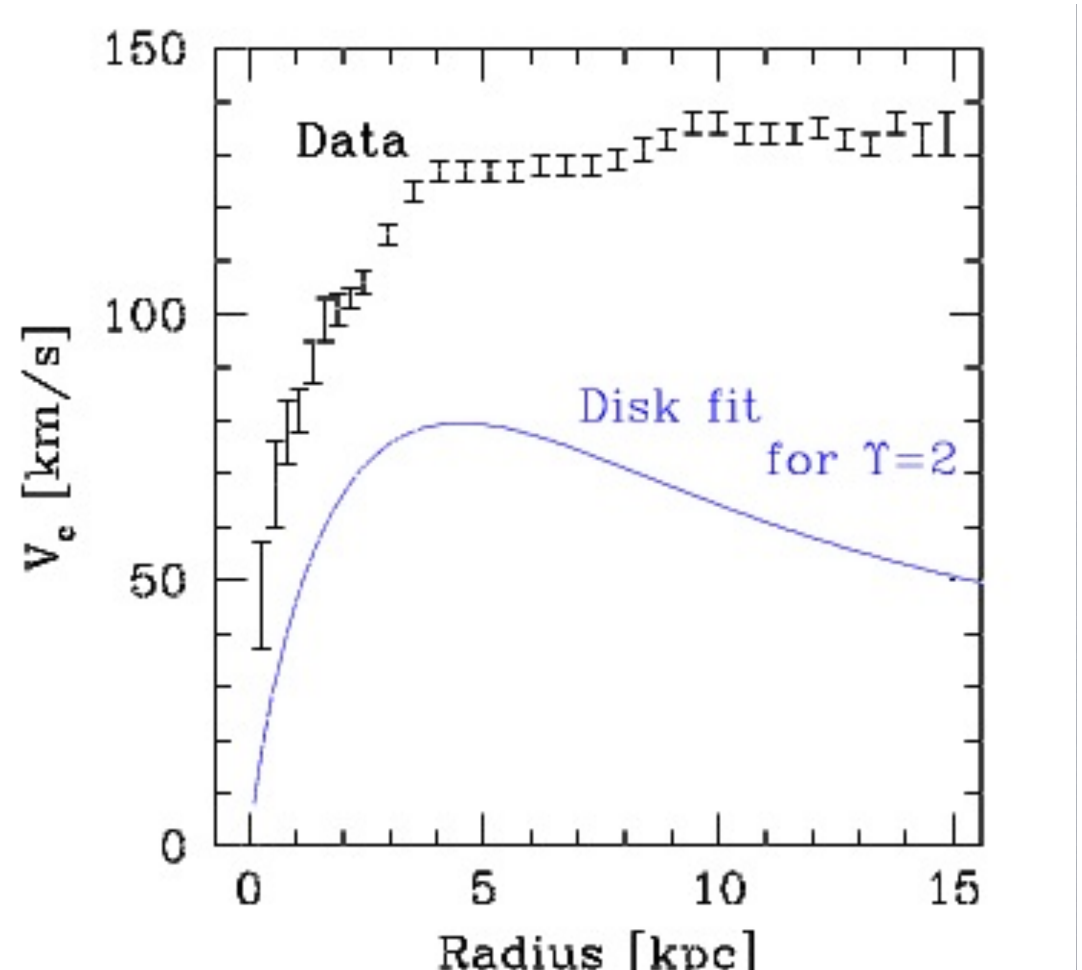
E. Kovetz, I.C., P. Breysse, M. Kamionkowski arXiv:1611:01157

Ilias Cholis 1/18/2017

Evidence for Dark Matter

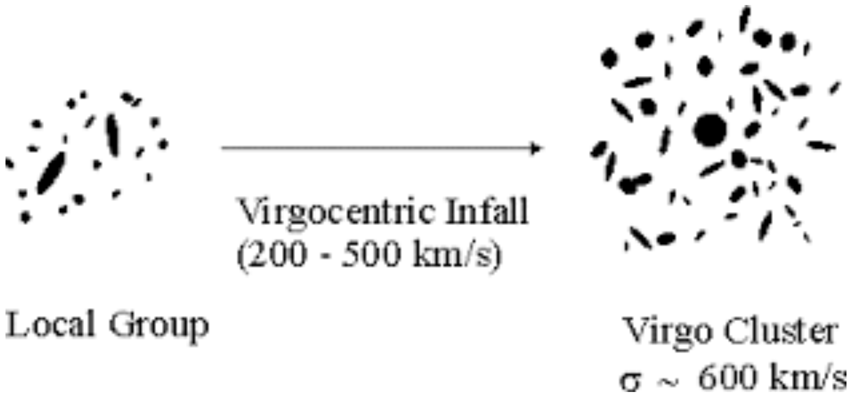
- galactic rotation curves

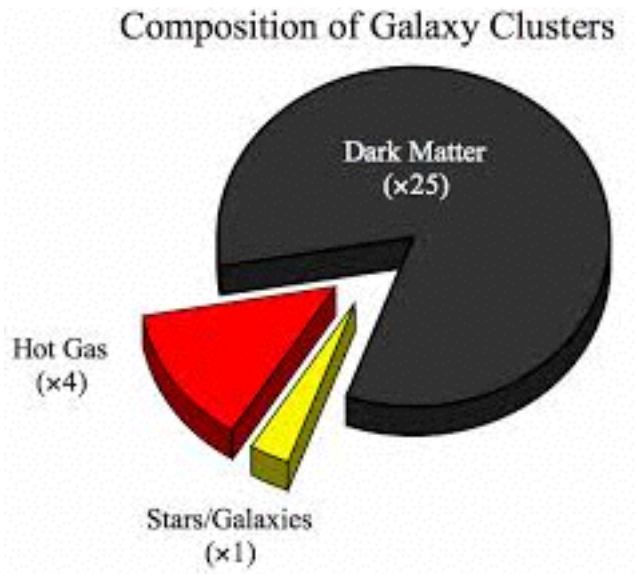




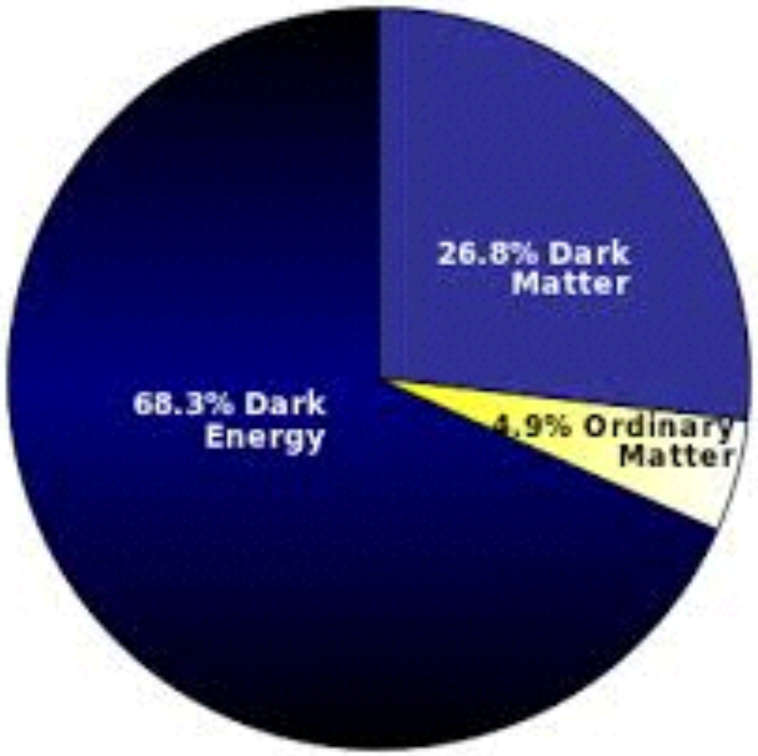
NGC 2403 rotation curve and model

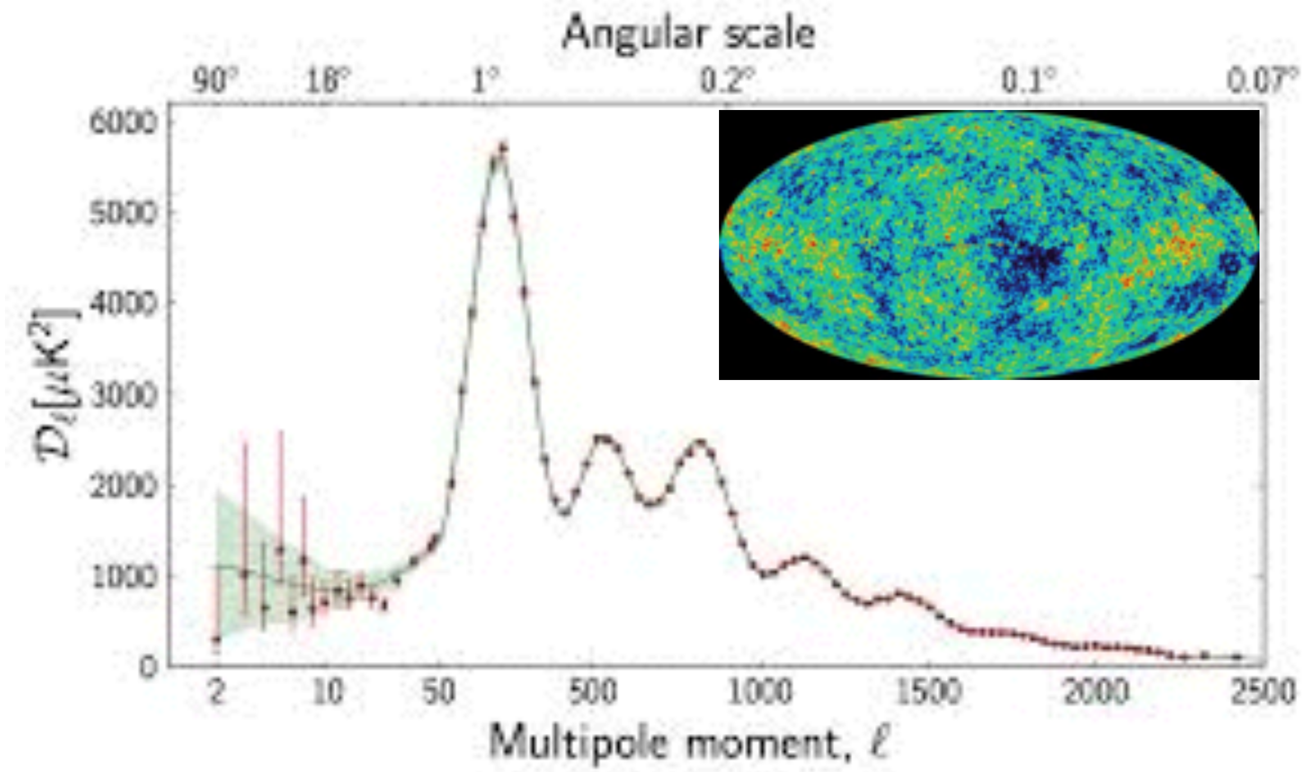
- velocity dispersion of galaxies in clusters



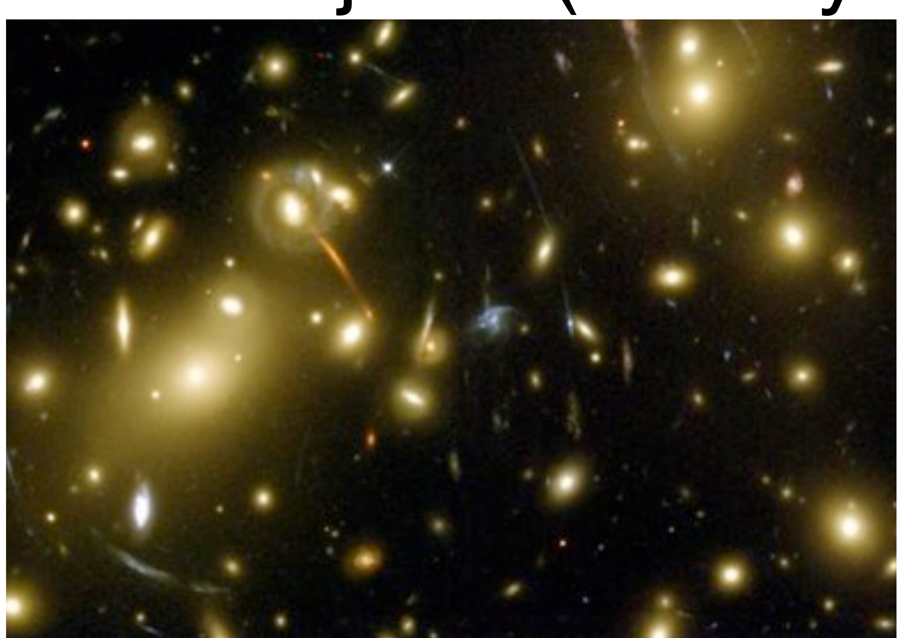


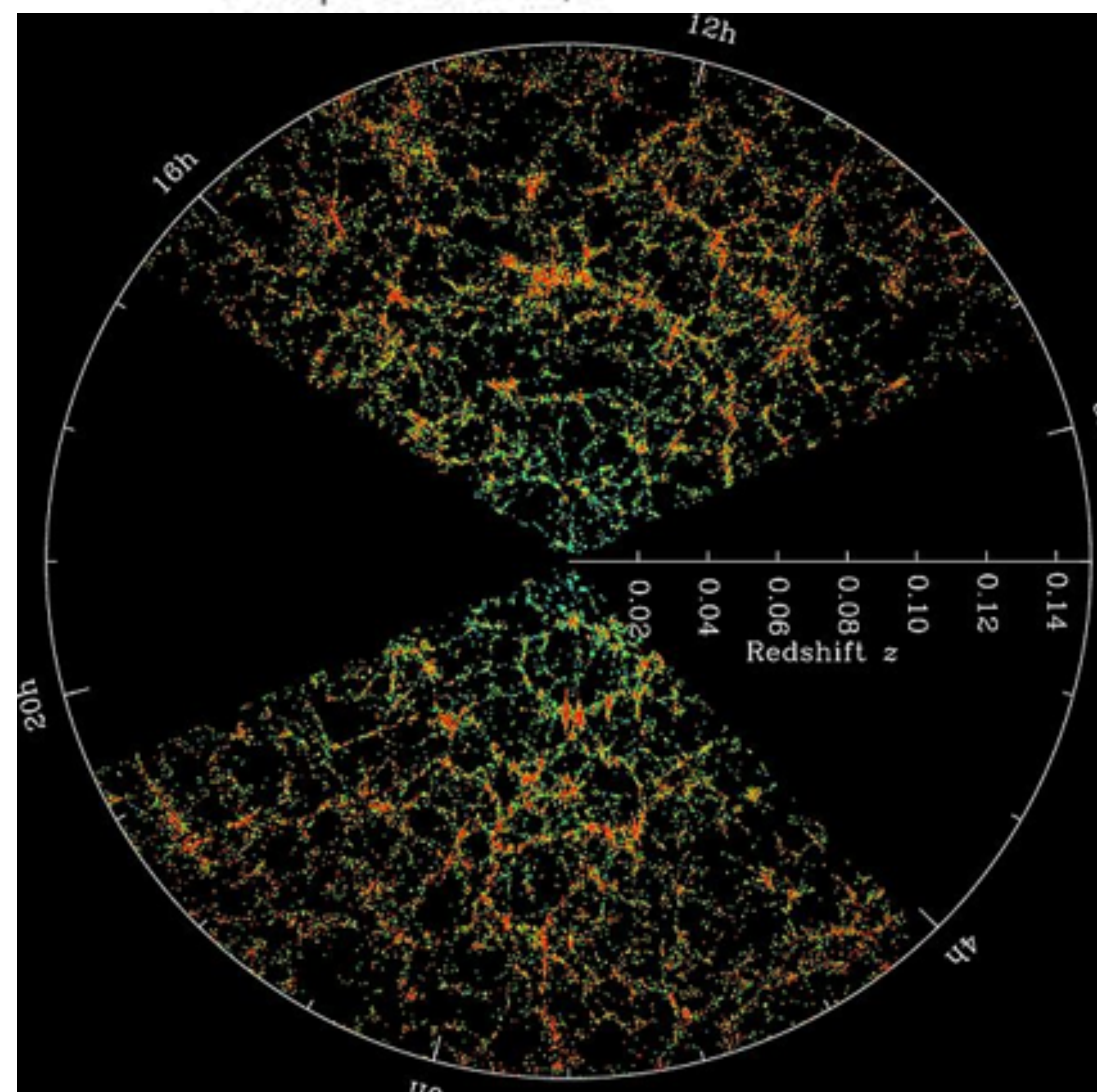
- CMB data and SN Ia data



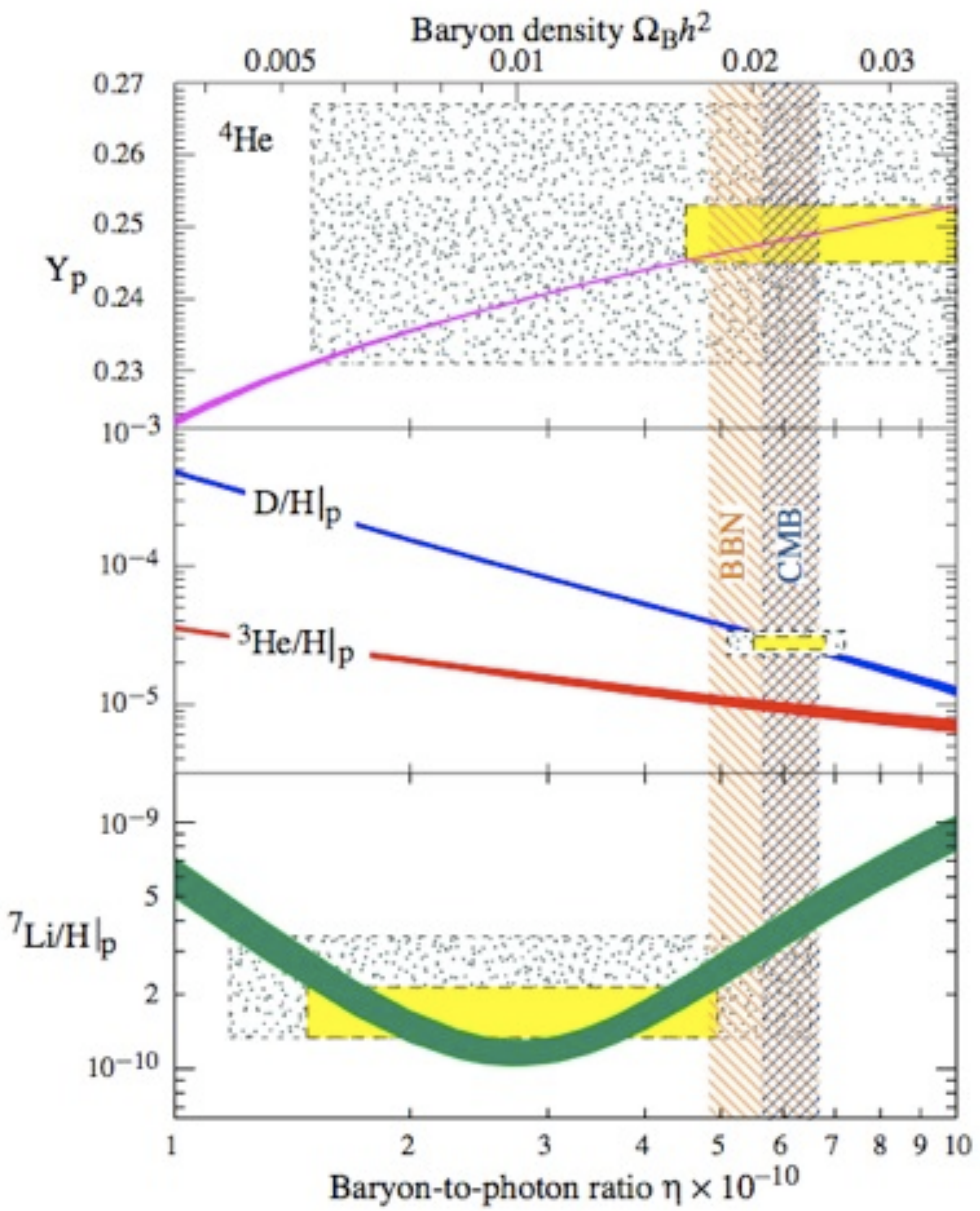


- Observed distribution of galaxies:
- strong lensing measurements of background objects (usually galaxies)

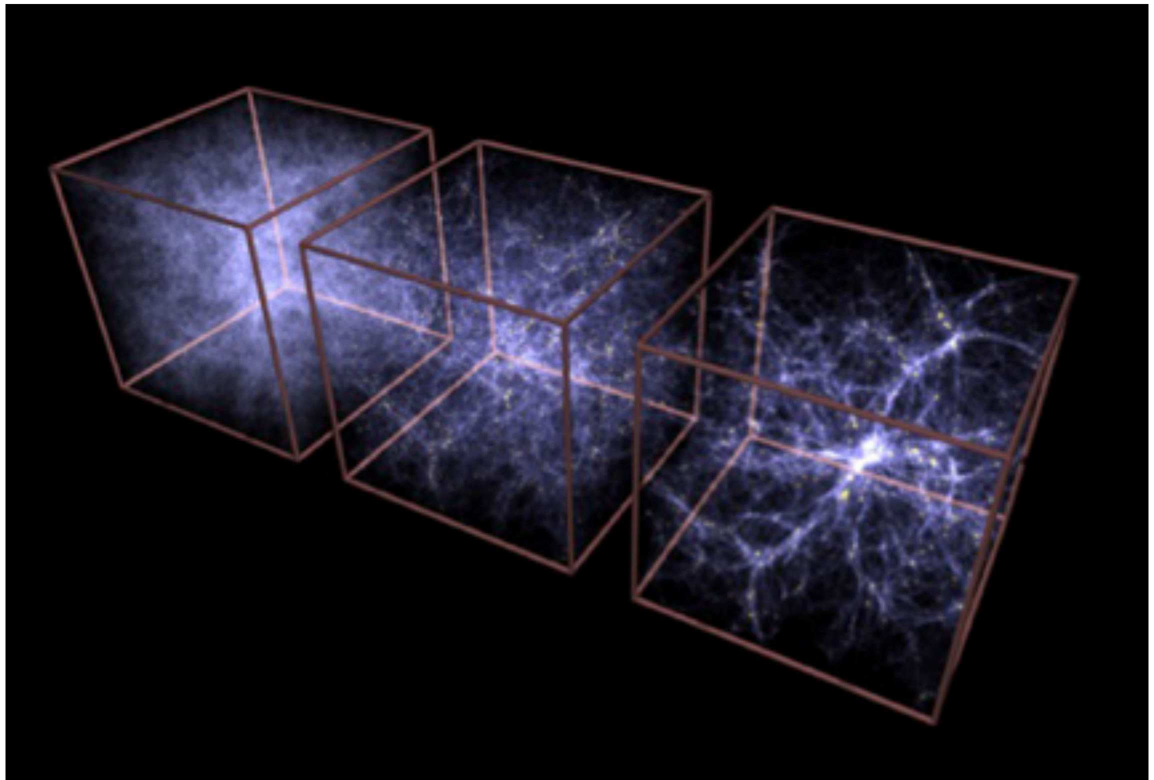




- collisions of galaxy clusters (e.g. bullet cluster)

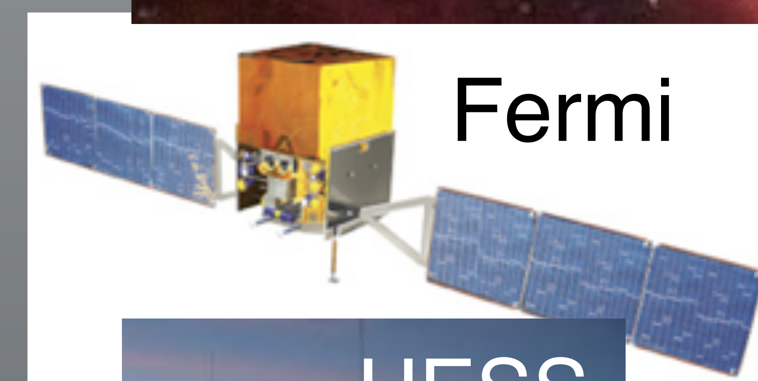


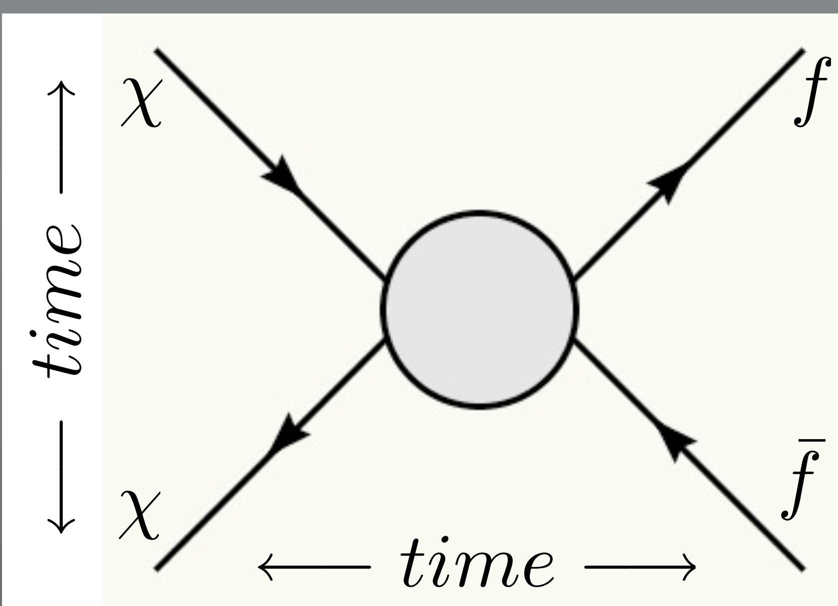
- success of BBN (DM is non-baryonic)
- growth of structure (cold DM)

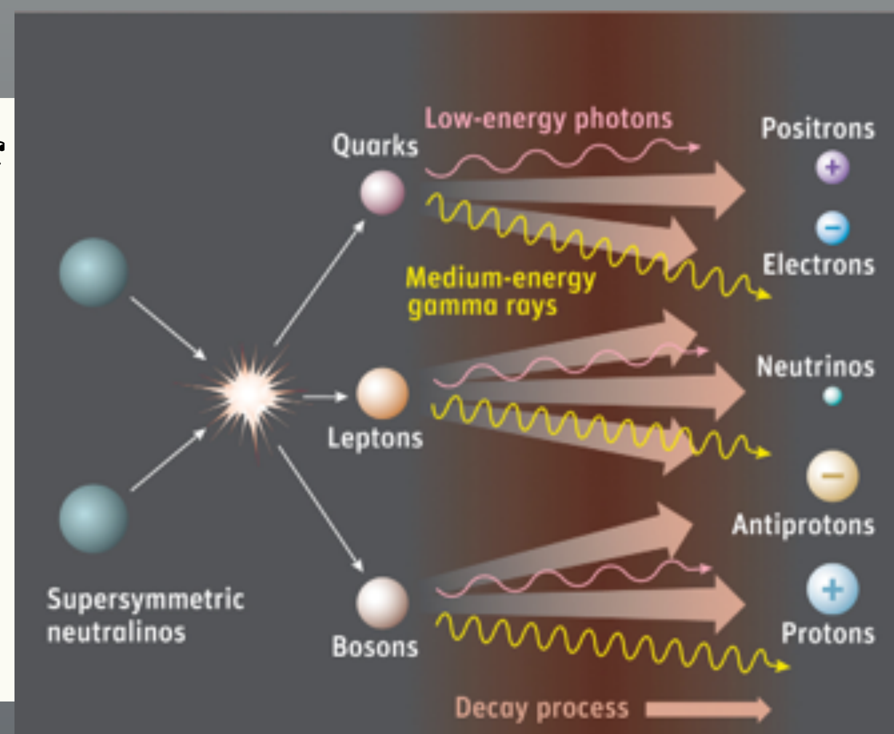


Searches for Particle Dark Matter

Direct Detection scattering off normal matter, Xe, Ar, Ge, Si:



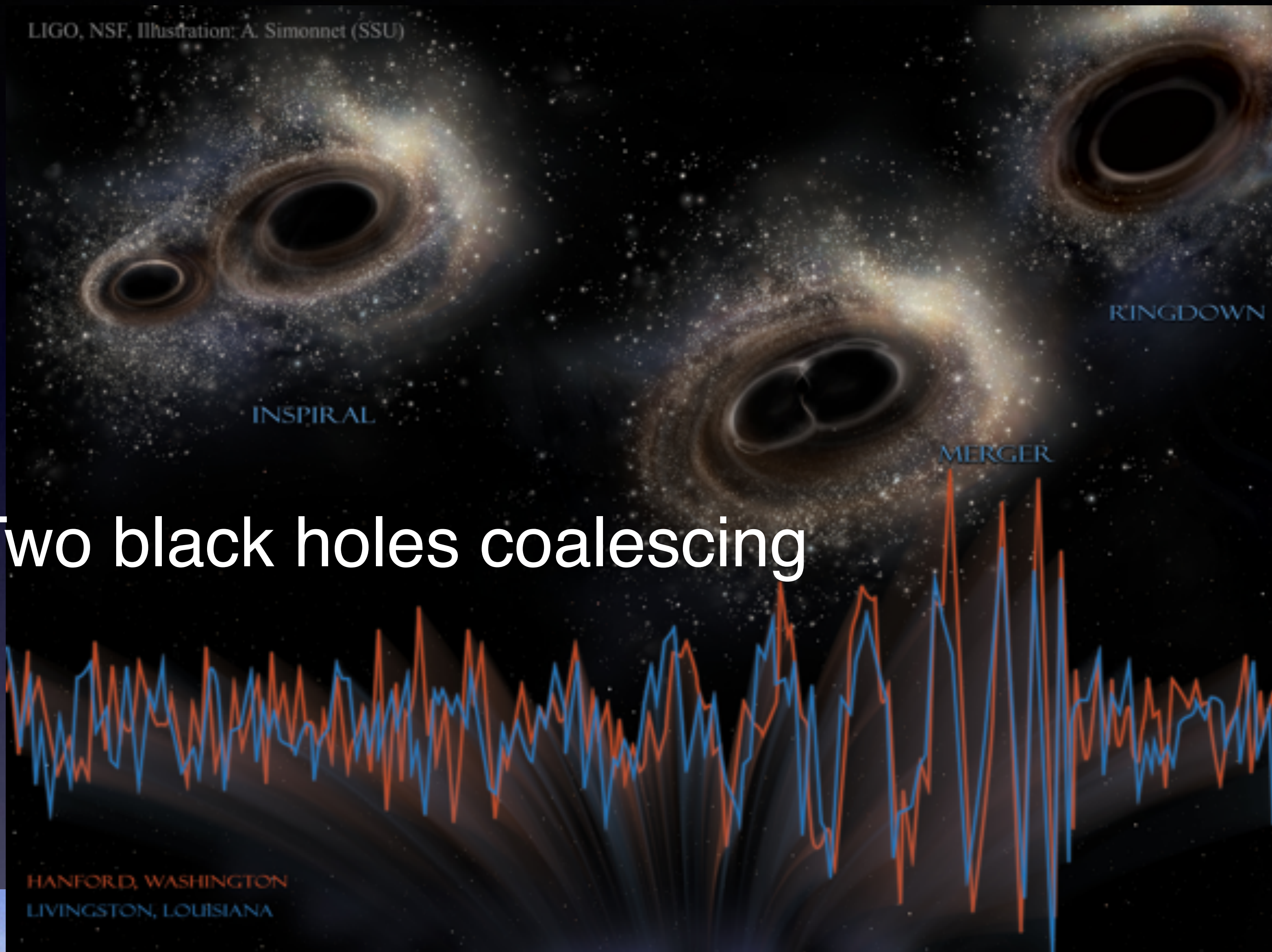




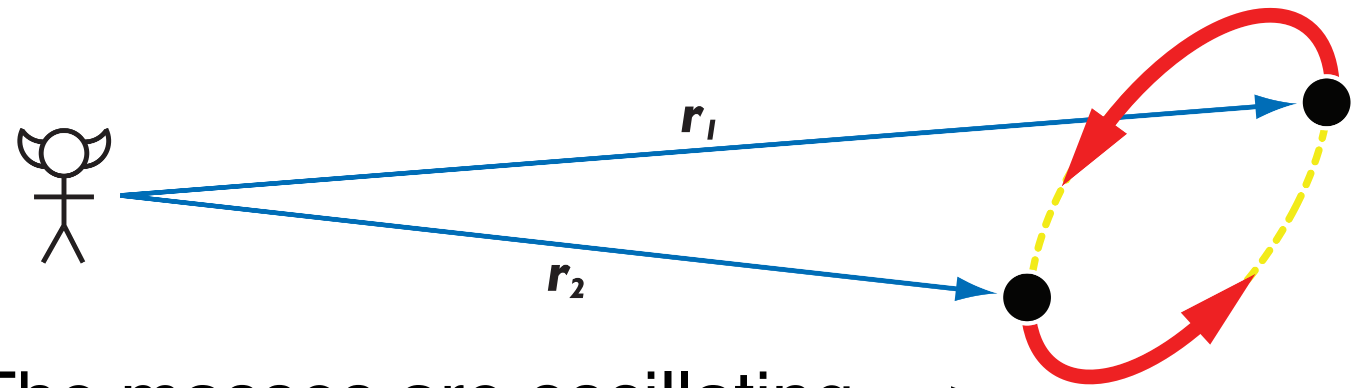
Indirect detection: annihilation into gamma-rays, cosmic rays, neutrinos

Dark matter production at colliders

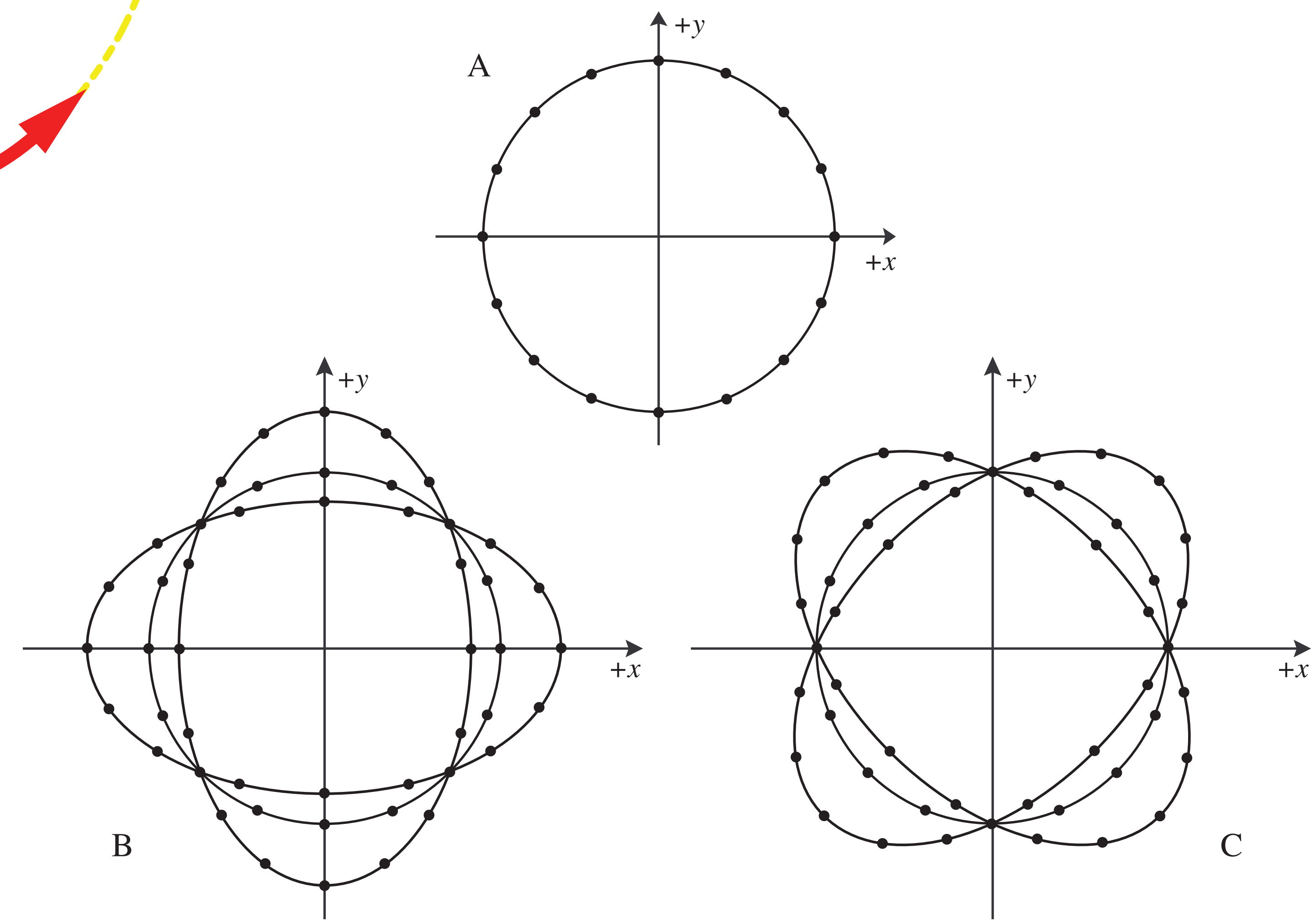
What about Gravitational Waves?



Hand-wavy Pictures

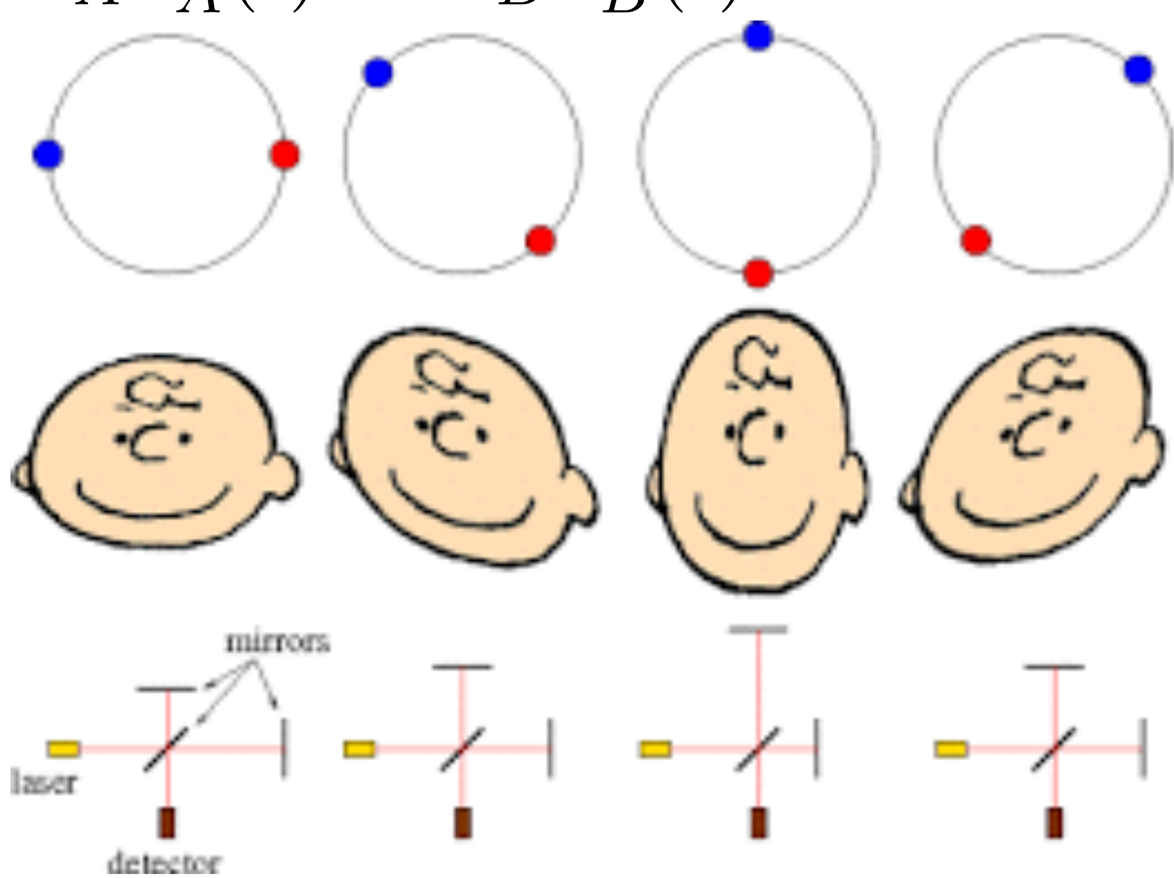


GWs travel at speed of light



The masses are oscillating —> frequency. Energy is damped into Gravitational Waves with the quadrulopar radiation being the dominant.

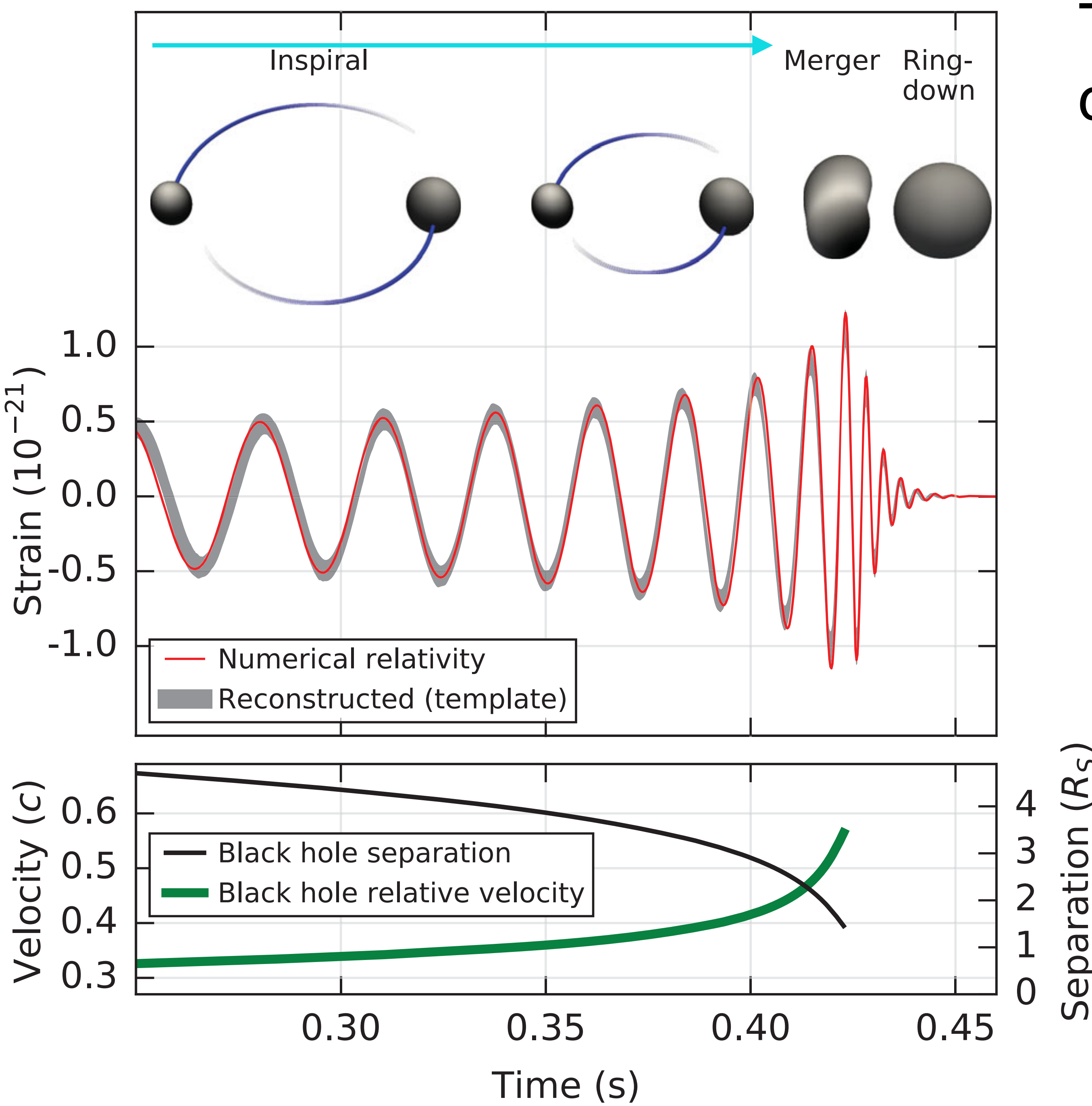
$$m_A x_A^2(t) + m_B x_B^2(t)$$



: effect at interferometers

What we expect to observe when two Black Holes coalesce (merge)

Energy is damped into GWs —> The system gets closer and masses rotate faster. Frequency Increases with time (“chirp”). So does the amplitude (this is not a system that will return to equilibrium)



There is a gravitational radius associated with an object of mass M:

$$R_{Sch} = \frac{2GM}{c^2}$$

$$R_{Sch}(1M_{\odot}) = 2.95km$$

$$R_{Sch}(36M_{\odot}) = 106km$$

Last Stable (~Keplerian) Orbit at

$$R = \left(\frac{GM_{tot}}{\omega_{max}^2}\right)^{1/3}$$

~3 times the Schwarzchild radius

Basic Estimates

GWs travel at the speed of light: $\lambda = c/f$

Take a binary of two compact objects (Kepler's third law):

$$f = \sqrt{\frac{G}{4\pi}\frac{M_{tot}}{a^3}}$$

take $M_{tot} = 20M_\odot$ and $a = 500km$ thus $2f \sim 80Hz$

or $\lambda \sim 5 \times 10^3 km$ Earth Size (ground-based Observatories)

take $M_{tot} = 10^6 M_\odot$ and $a = 5 \times 10^6 km$ thus $2f \sim 10^{-2} Hz$

or $\lambda \sim 3 \times 10^7 km$ (space-based Observatories)

Basic Scalings

Chirp mass:

Ignoring redshift.

$$M_c = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

Amplitude of signal *during* Inspiral:

$$h_c \sim \frac{G}{c^3}\frac{M_c}{d_L}(\frac{G}{c^3}\pi\, f\, M_c)^{2/3}$$ —> (for a given freq.): $h_c \sim M_c^{5/3}/d_L$

(observations are at a certain freq. range) $\sim 10^{-21}$

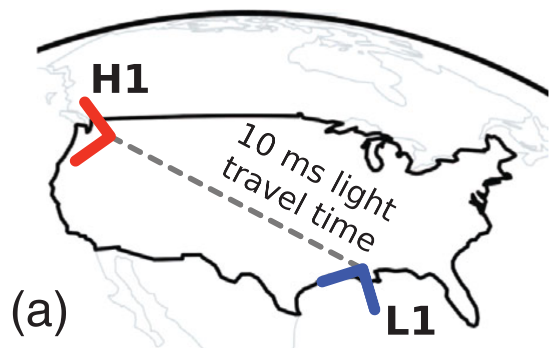
How to measure those:

$$M_c = \frac{c^3}{G}(\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f})^{3/5}$$ <— measuring f and $\dot{f}$ we get M_c

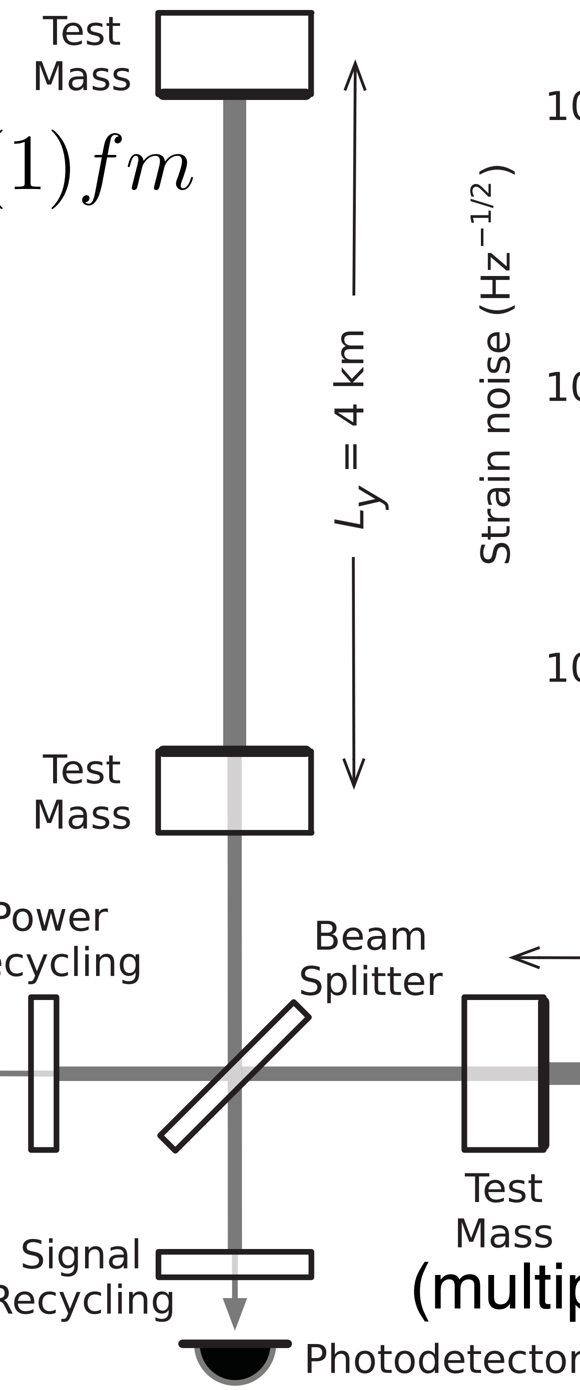
$$\Delta L(t) = \delta L_x - \delta L_y = h(t) \cdot L$$

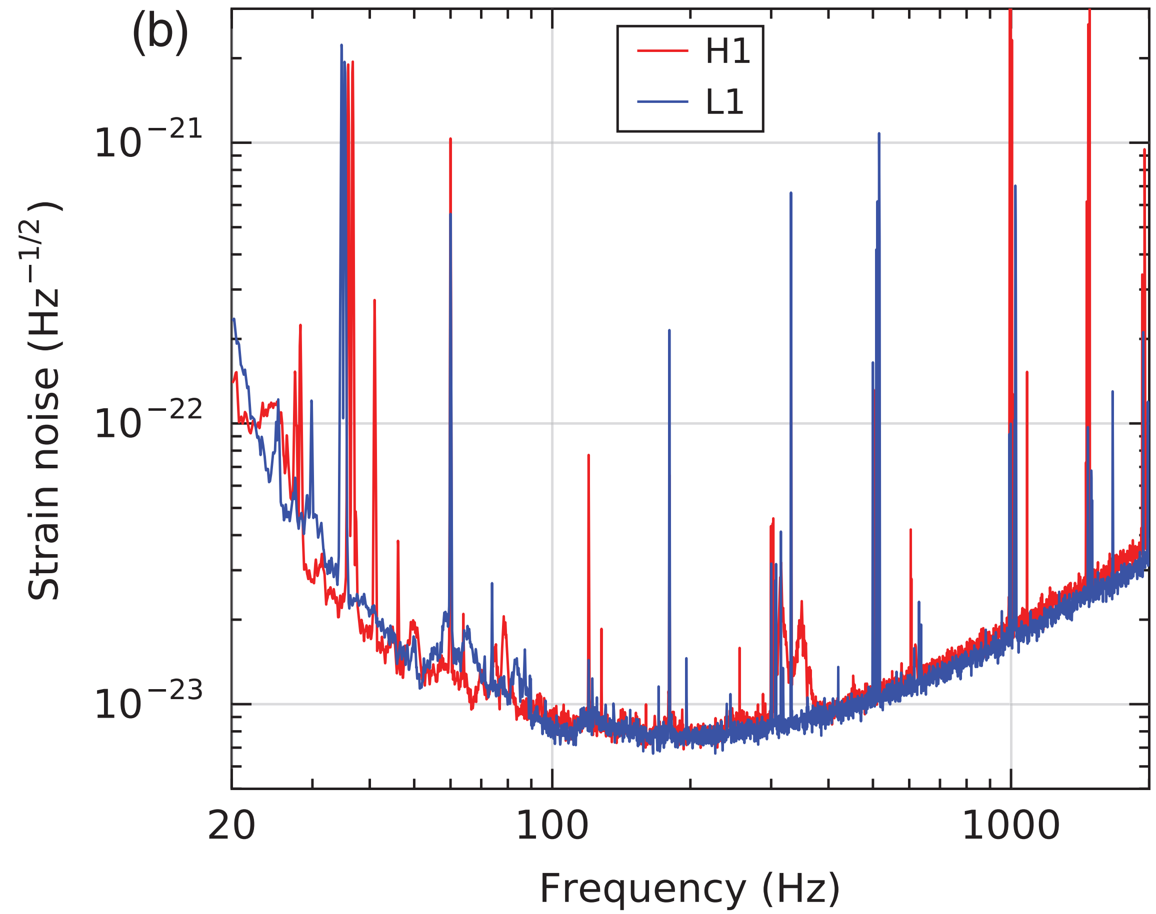
LIGO Detectors

$$\Delta L(t) \sim 10^{-21} \times 10^{3} km \sim O(1) fm$$



$$L_x = L_y = L = 4\ km$$





resonant cavity
(multiplies the effect of GWs by a factor of 300)

$$h_+(t) = A_{GW}(t)(1 + cos^2 i) cos\phi_{GW}(t)$$

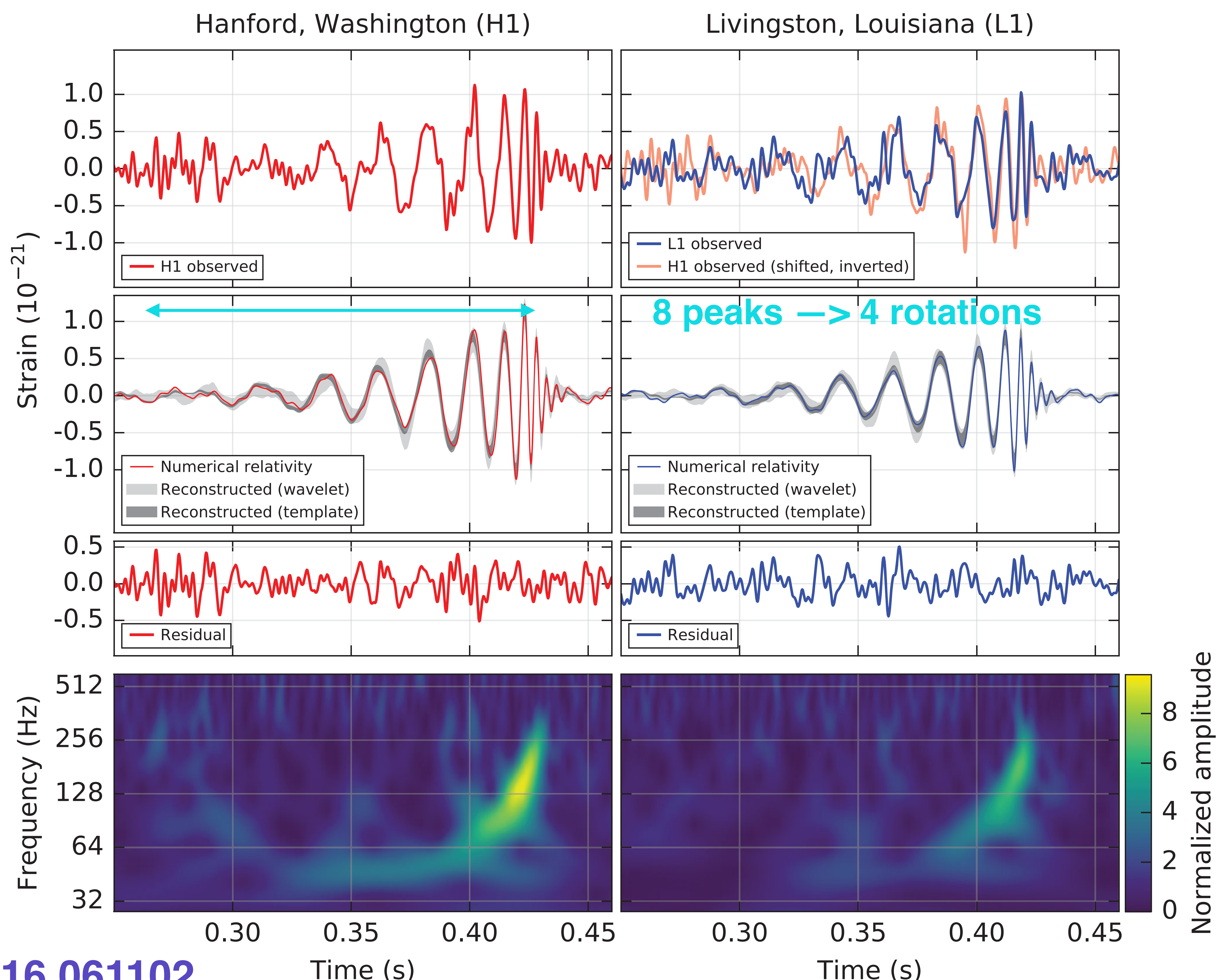
$$h_\times(t) = -2A_{GW}(t) cos(i)\ sin\phi_{GW}(t)$$

instrument

$$h_k(t) = F_k^+ h_+(t) + F_k^\times h_\times(t)$$

the two grav. wave polarizations

The GW150914 event



PRL 116.061102

The first ever Gravitational Waves signal detection

On Sept. 14th at 9:50:45 UTC (Coordinated Universal Time), the two detectors of aLIGO observed a gravitational wave signal from the coalescence of two Black Holes. It was observed between 35 and 250 Hz.

The observed Properties are (90 % credible intervals):

$$m_1 = 36^{+5}_{-4} M_\odot$$

$$m_2 = 29^{+4}_{-4} M_\odot$$

$$\rightarrow \quad m_{loss} = 3.0^{+0.5}_{-0.5} M_\odot \quad \rightarrow \quad \dot{E}_{max} = 3.6 \times 10^{56} erg/s$$

(instantaneous)

$$m_{final} = 62^{+4}_{-4} M_\odot$$

$$\alpha = 0.67^{+0.05}_{-0.04}$$

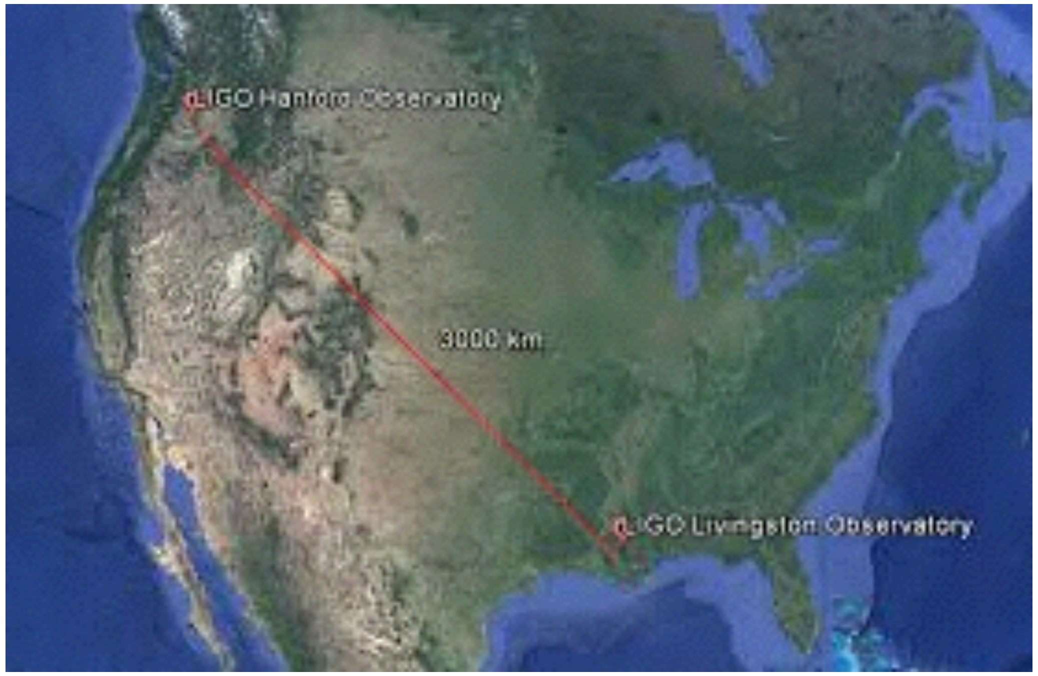
final spin: $\alpha = \frac{c \mid \vec{S} \mid}{GM^2}$

$$d_L = 410^{+160}_{-180} Mpc$$

$z_s = 0.09^{+0.03}_{-0.04}$ (Planck Cosm. Param.)

The event was observed with a time delay of $t_d = 6.9^{+0.5}_{-0.4} ms$ between Livingston LA and Hanford WA.

Detection Significance: 5.1σ



Remaining properties

The luminosity distance is correlated to the inclination of the orbital plane to the line of sight θ_{JN} . Total angular momentum $\vec{J}$.

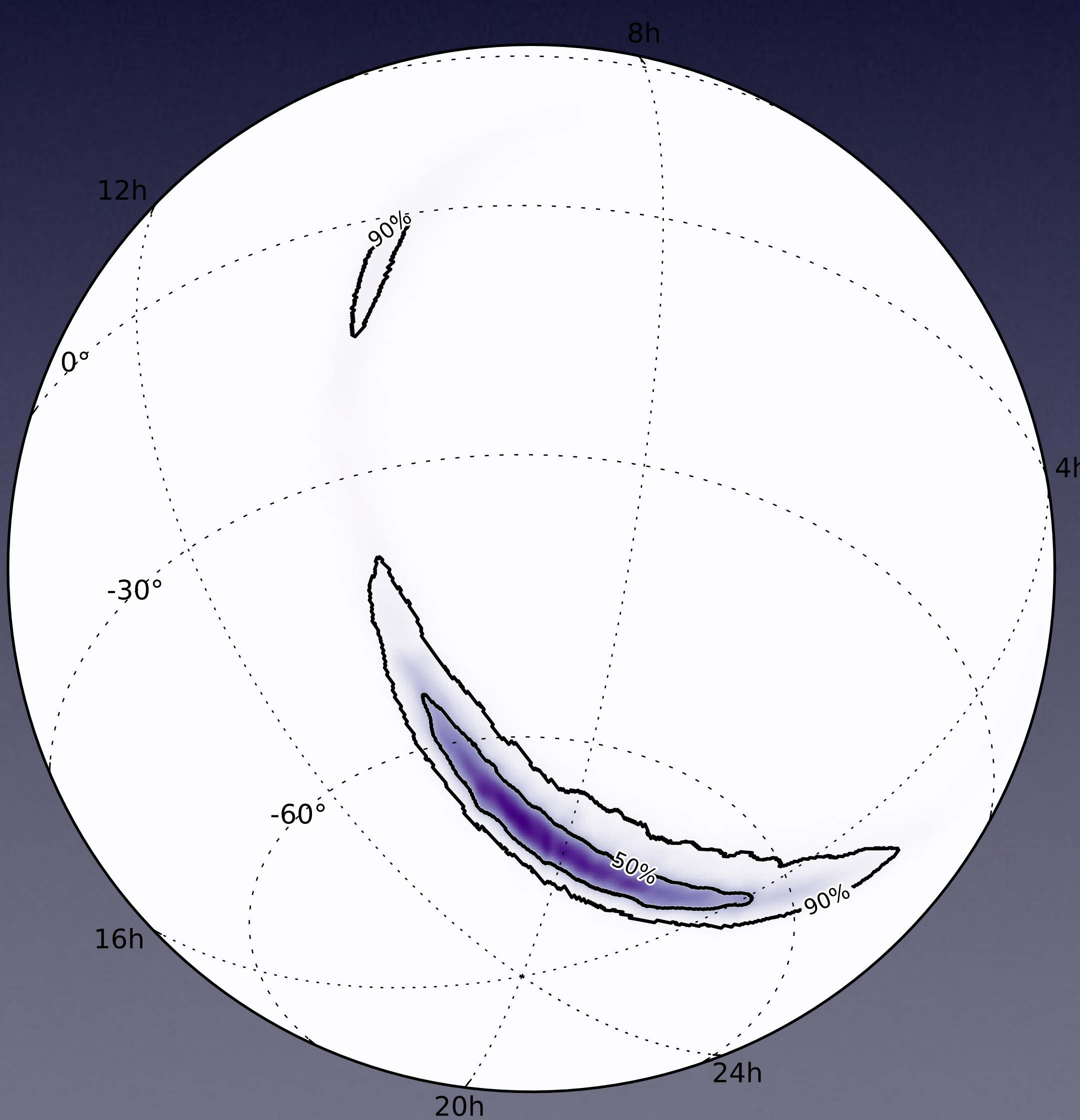
$\vec{J}$ is almost constant during the inspiral.

$45^\circ < \theta_{JN} < 135^\circ$ with a probability of 0.35

50% probability within 140 deg^2

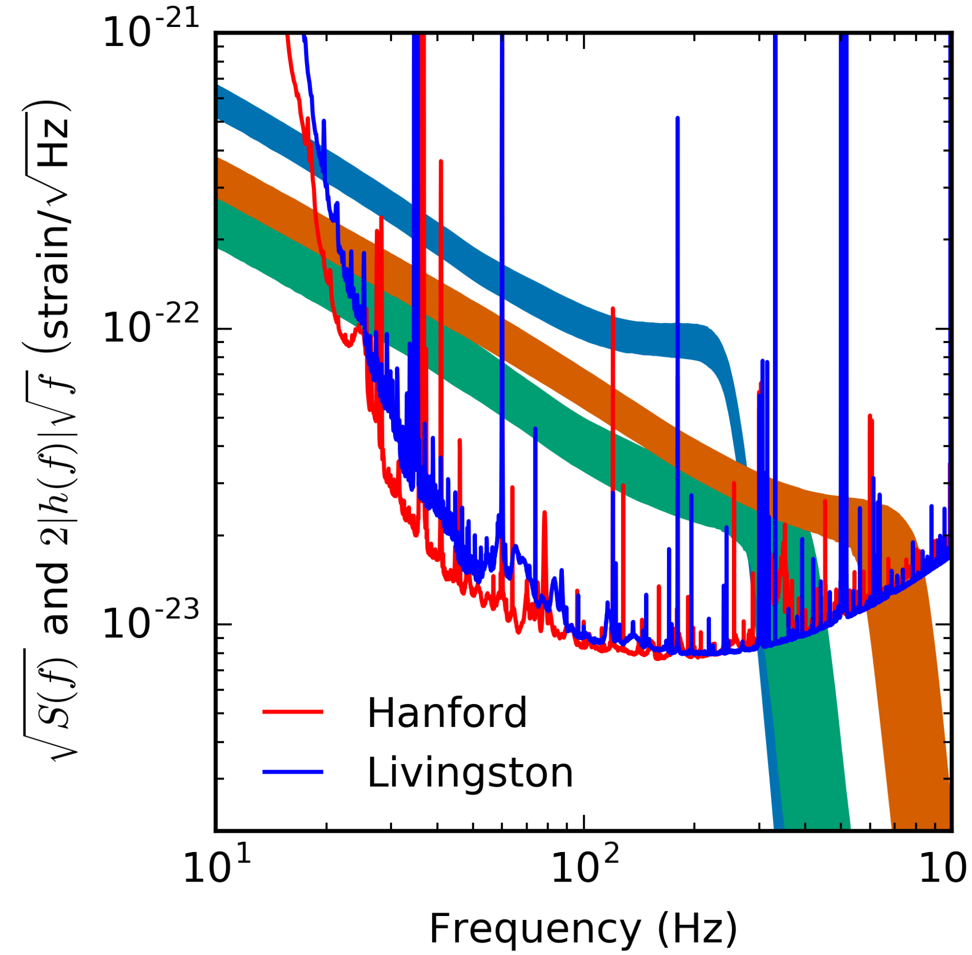
90% probability within 590 deg^2

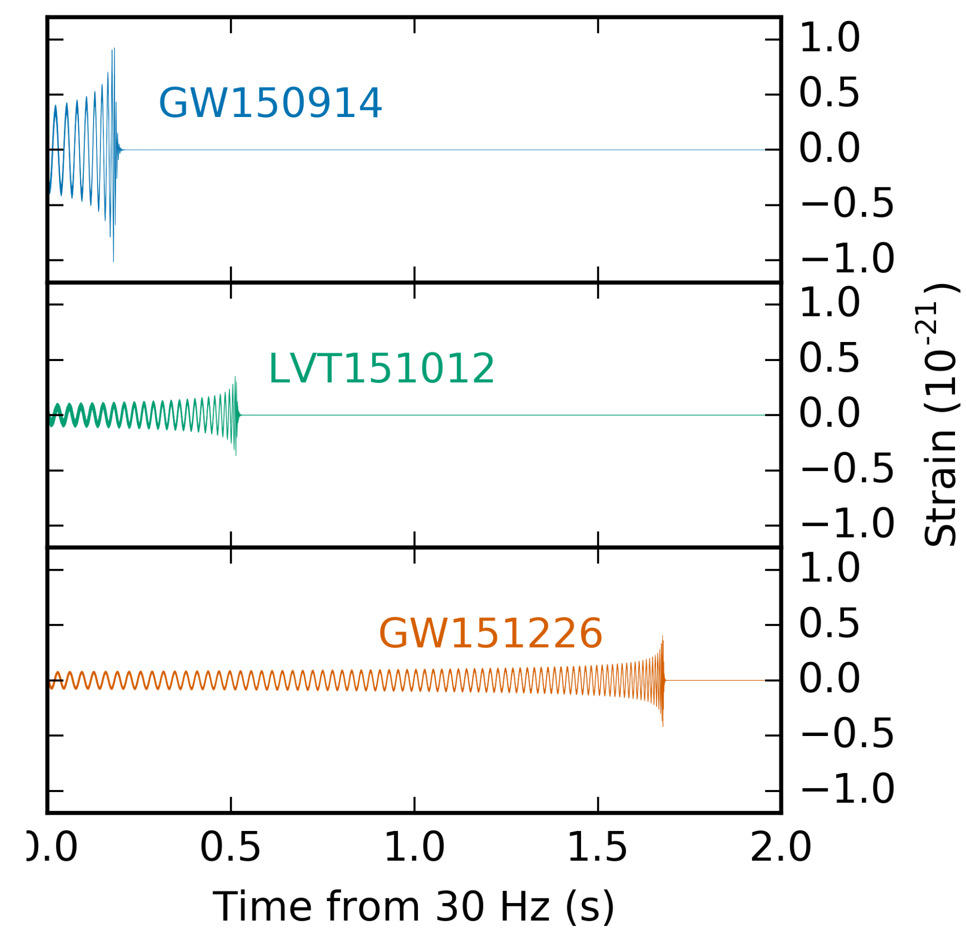
Searches by EM and neutrino detectors. No evident counterpart as would be likely in any case.



All (~3) events

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





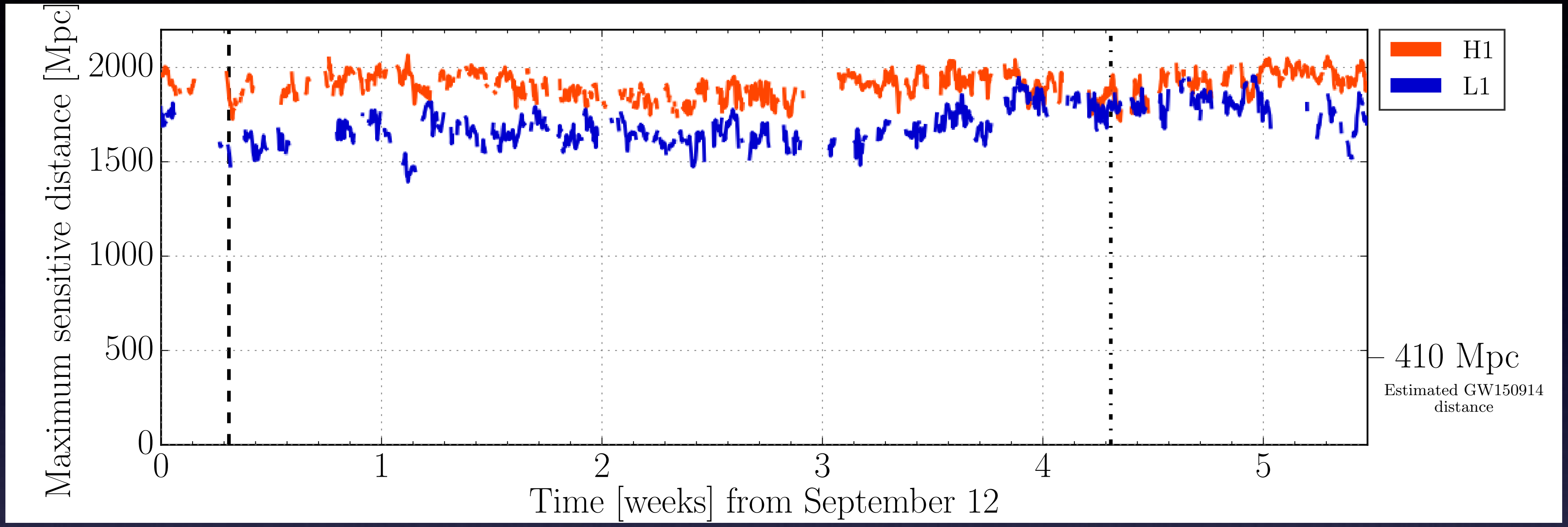
Rate of gravitational waves from BH-BH

Very simple one:

1 event in 16 live days. —> 25 per yr.

sensitivity redshift, z of 0.3, 1.6 Gpc —> Vol~7 Gpc^3

$$3.5 Gpc^{-3} yr^{-1}$$



The GW was observed at high S/N, there are going to be other events (as the LVT151012). Also if BHs are from Pop III stars or are at globular clusters or at regions of low metallicity and high grav. potential they will have some mass distribution and also will have some redshift distribution.

Going over astrophysical uncertainties in the above assumptions:

Using only GW150914 (fixing the masses, spins): $2 - 53\, Gpc^{-3} yr^{-1}$

Using both GW150914 and LVT151012: $6 - 400\, Gpc^{-3} yr^{-1}$

LIGO's combined range: $2 - 400\, Gpc^{-3} yr^{-1}$

LIGO's upgraded O1 (2015-16) run:

Mass distribution	$R/(\mathrm{Gpc}^{-3}\mathrm{yr}^{-1})$		
	PyCBC	GstLAL	Combined
Event based			
GW150914	$3.2^{+8.3}_{-2.7}$	$3.6^{+9.1}_{-3.0}$	$3.4^{+8.6}_{-2.8}$
LVT151012	$9.2^{+30.3}_{-8.5}$	$9.2^{+31.4}_{-8.5}$	$9.4^{+30.4}_{-8.7}$
GW151226	35^{+92}_{-29}	37^{+94}_{-31}	37^{+92}_{-31}
All	53^{+100}_{-40}	56^{+105}_{-42}	55^{+99}_{-41}
Astrophysical			
Flat in log mass	31^{+43}_{-21}	30^{+43}_{-21}	30^{+43}_{-21}
Power Law (−2.35)	100^{+136}_{-69}	95^{+138}_{-67}	99^{+138}_{-70}

PBH?

TABLE II. Rates of BBH mergers based on populations with masses matching the observed events, and astrophysically motivated mass distributions. Rates inferred from the PyCBC and GstLAL analyses independently as well as combined rates are shown. The table shows median values with 90% credible intervals.

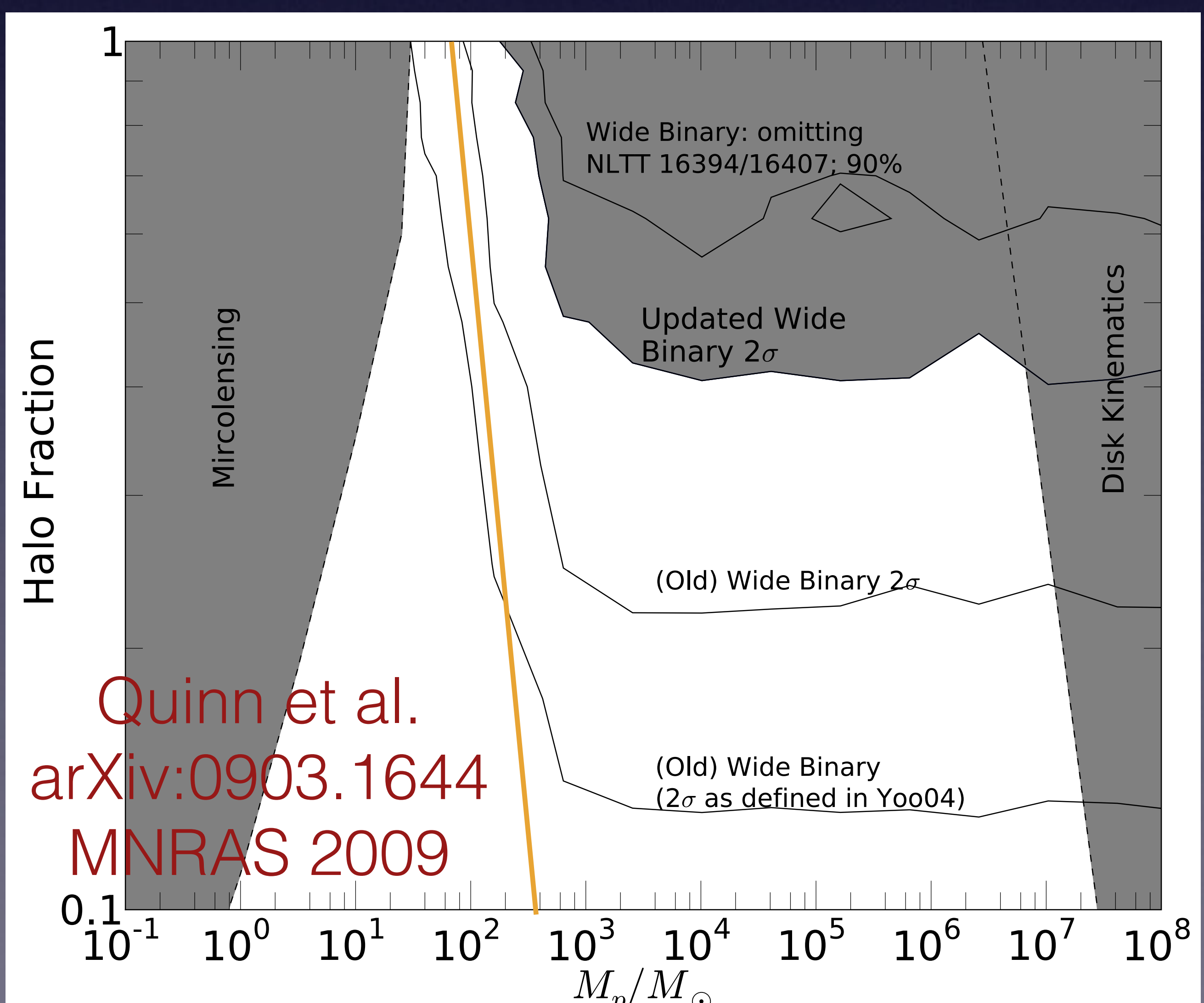
Different estimates on the coalescence rates come from different astrophysical assumptions

Making a connection with DM

Work with Simeon Bird, Julian B Munoz,Yacine Ali-Haimoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli and Adam Riess (JHU)
PRL 116.201031 (arXiv:1603.00464)

Assuming Dark Matter is composed by Primordial BHs.

There is some allowed parameter space around ~20-70 $M_\odot$



For the remainder I will assume that all DM is composed of PBHs and set their mass to 30 $M_\odot$

Limits on spectral distortions of the CMB are efficient above 100 $M_\odot$
Ali-Haimoud & Kamionkowski (1612.05644)

Limits from GC in dwSphs (e.g. Eridanus II) (Tim Brandt arXiv:1605.03662) are robust below 15$M_\odot$.

Limits from micro-lensing of macro-lensed quasars depend on the DM profile and vel. dips. prof.

How fast do two BHs form a binary?

$$\sigma = 2^{3/7}\,\pi \left(\frac{85\,\pi}{6\sqrt{2}}\right)^{2/7} R_s^2 \left(\frac{v}{c}\right)^{-18/7}$$

In easy units:

$$\sigma = 1.37 \times 10^{-14}\, M_{30}^2\, v_{199}^{-18/7}\, \mathrm{pc}^2$$

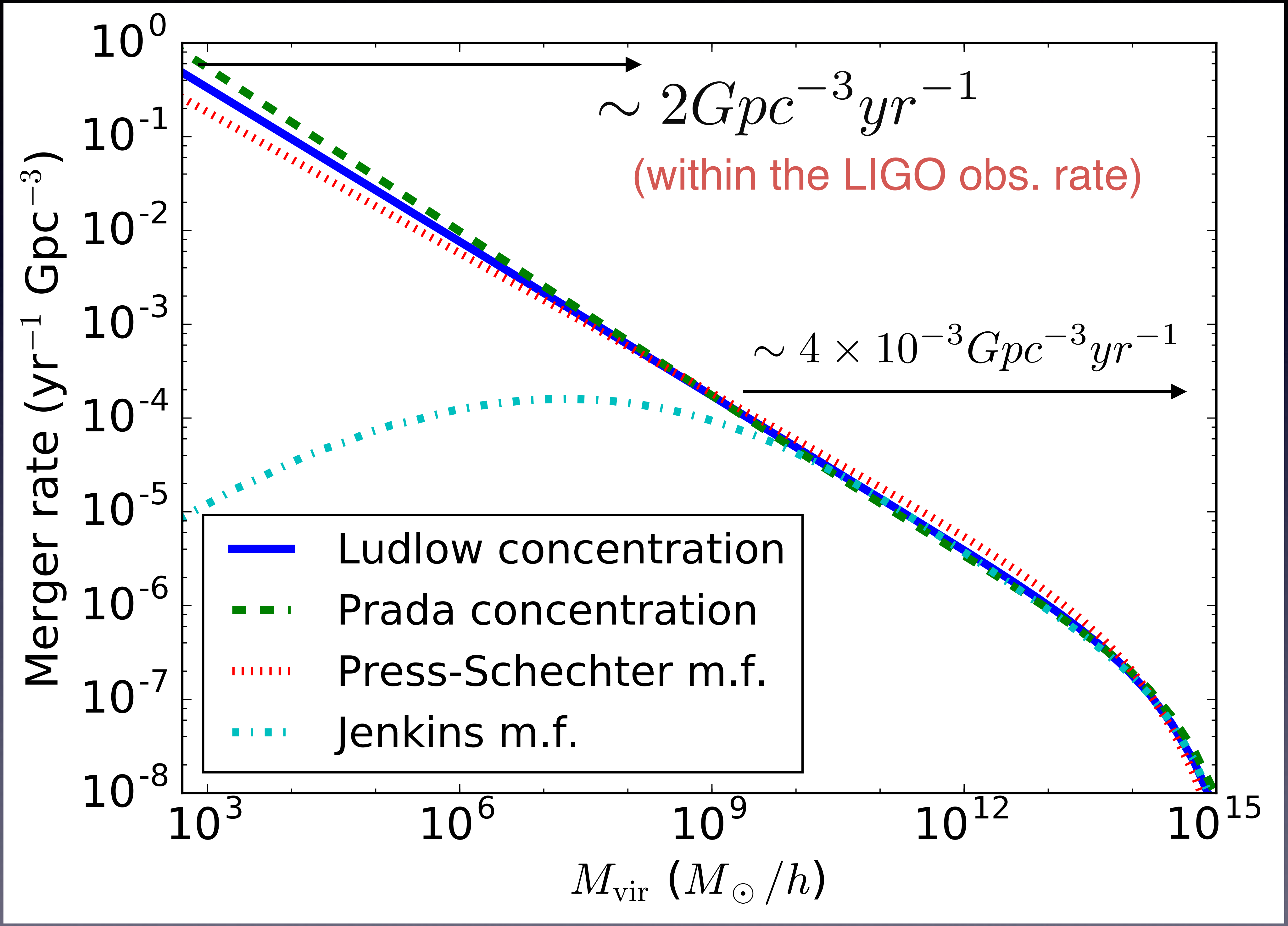
Assuming an NFW profile for the PBHs:

$$\rho_{NFW}(r) = \frac{\rho_0}{(r/R_s)\cdot(1+r/R_s)^2}$$

One gets a Rate of PBHs mergers:

$$\mathcal{R} = 4\pi \int_0^{R_{\rm vir}} r^2 \frac{1}{2}\left(\frac{\rho_{\rm nfw}(r)}{M_{\rm pbh}}\right)^2 \langle \sigma v_{\rm pbh}\rangle\; dr$$

After including information regarding the difference DM halos properties (concentration, and velocity dispersions) and effects on the smallest DM halos:



S. Bird, IC, J. Munoz et al. (2016)

By 2019 the sensitivity will have increased to z<0.75

We expect $O(10^2)$ events from PBHs (if they compose 100% of DM) by 2025.

All may be in a narrow mass range around 30 solar masses.

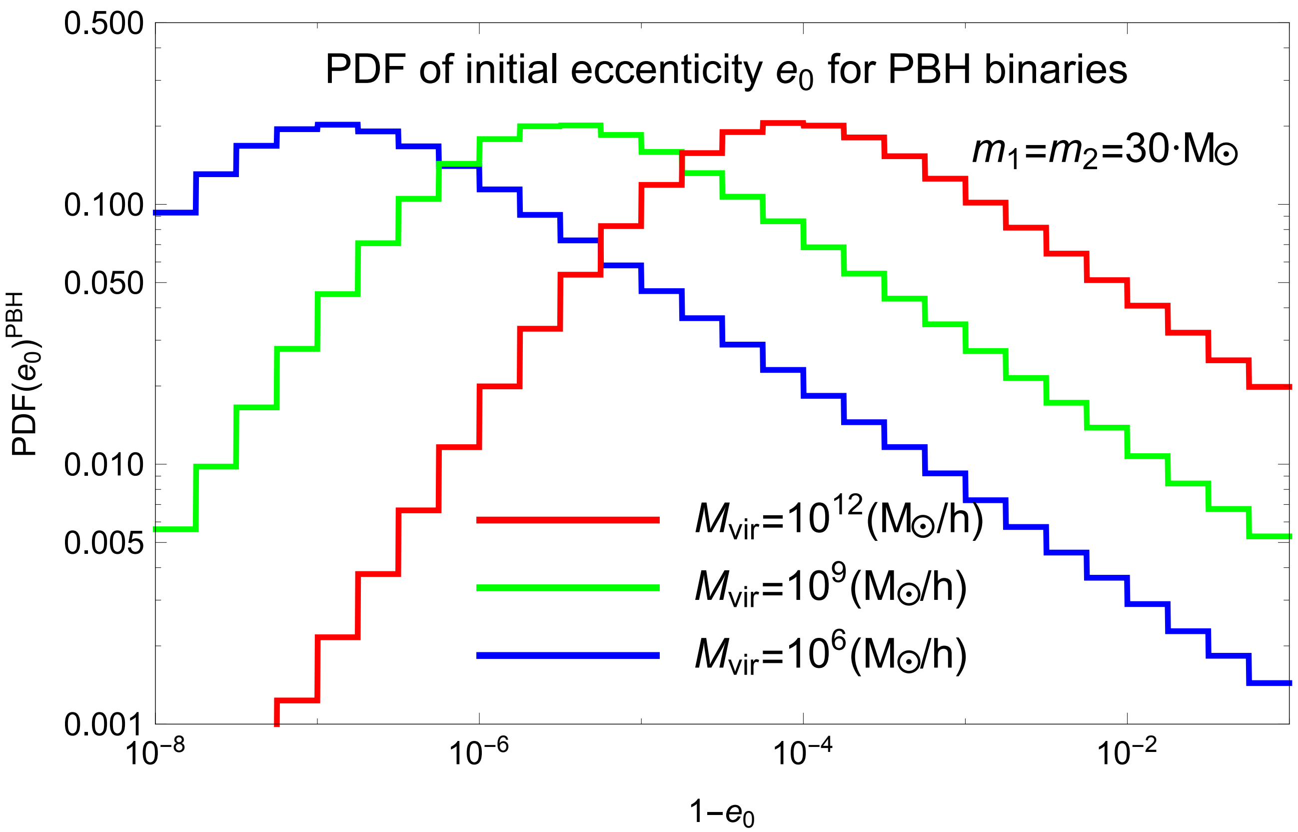
No other EM or neutrino signals. (typical though given that BH-BH give GW only)

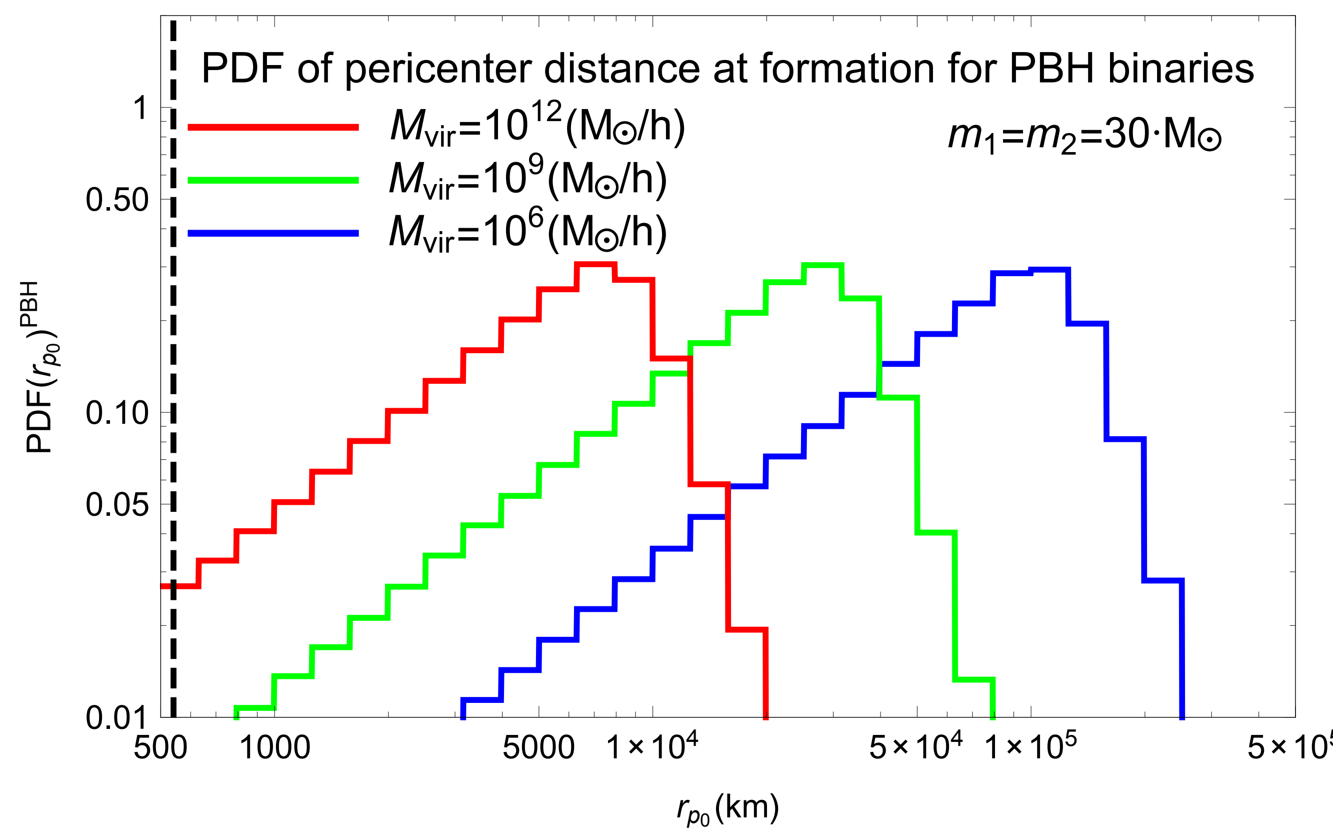
Following the DM distribution (need better angular resolution though).

Basic Uncertainties in the rate calculation:
DM profile (factor of ~3)
Mass-Concentration relationship (factor of ~3)
Sub-halo contribution (previous slide) and discreteness of smallest halos.

Future directions for DM by PBHs

When these binaries form they have high initial eccentricities and small peri-center distances:





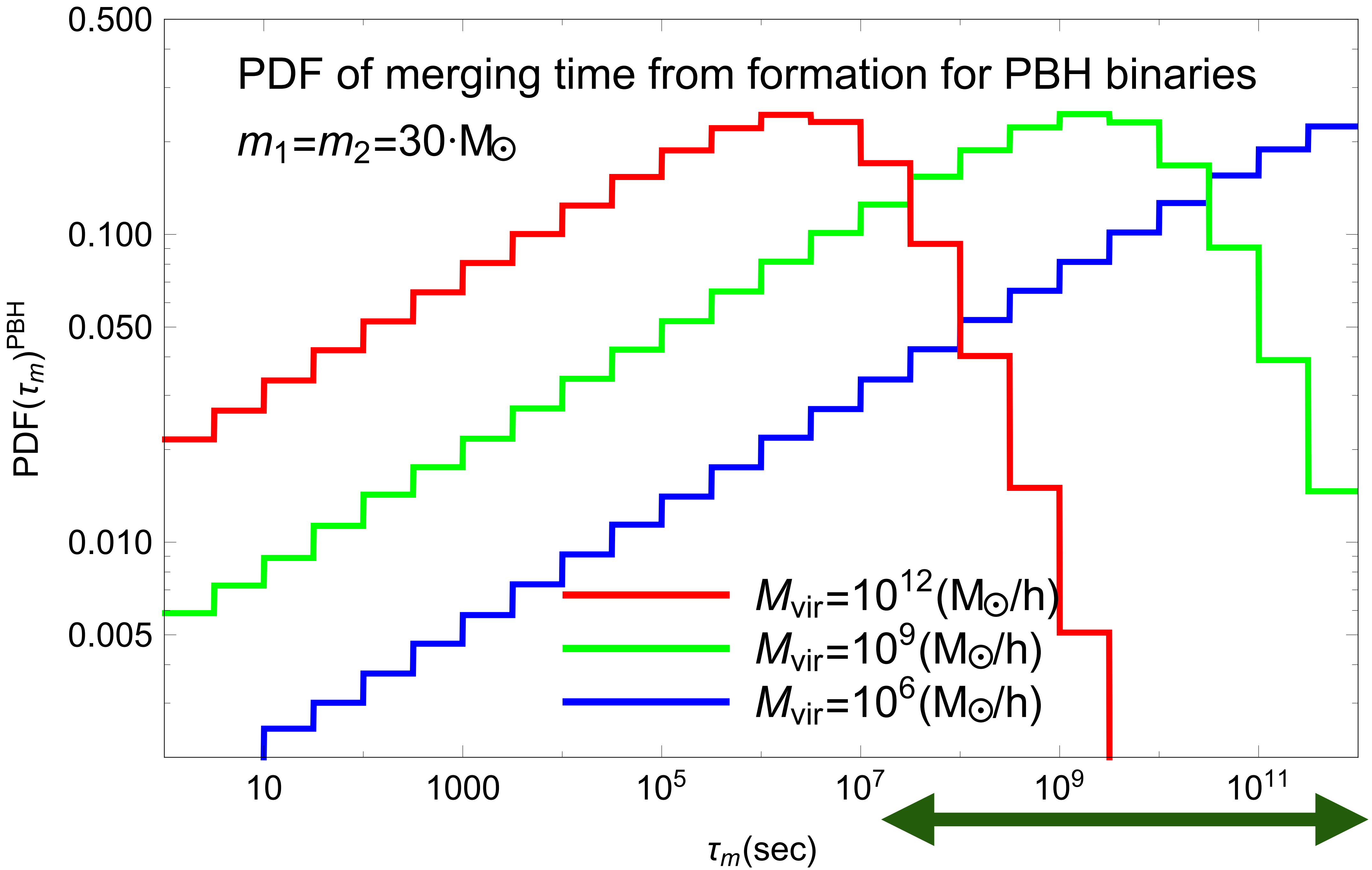
PDFs of the PBH formed binaries

$$(1-e_0)^{\rm peak} \simeq 2.6\xi\eta^{2/7}(w/c)^{10/7} \quad \xi \simeq 1, \eta = 1/4$$ for equal BH masses

$$r_{p_0} \simeq 2\times10^4 km (v_{DM}/20km/s)^{-4/7} \qquad w \simeq 2/20/200\ km/s$$

I.C., E. Kovetz, Ali-Haimoud, S. Bird, M. Kamionkowski, J. Munoz and A. Raccanelli (JHU) PRD 94 084013 (arXiv:1606.07437)

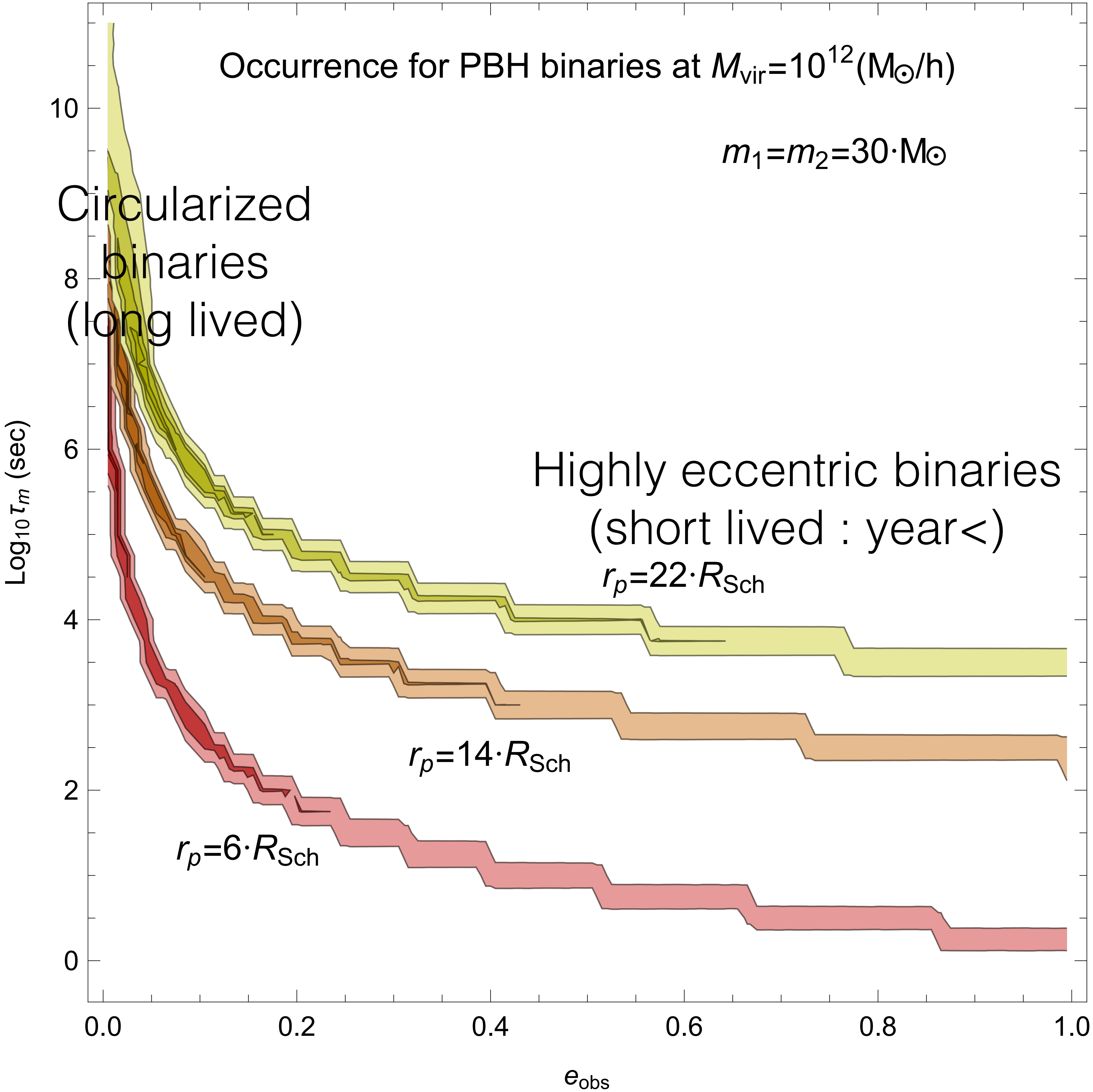
Which in turn result in dramatically different timescales until merger:



By the time of LIGO observation fully circularized.

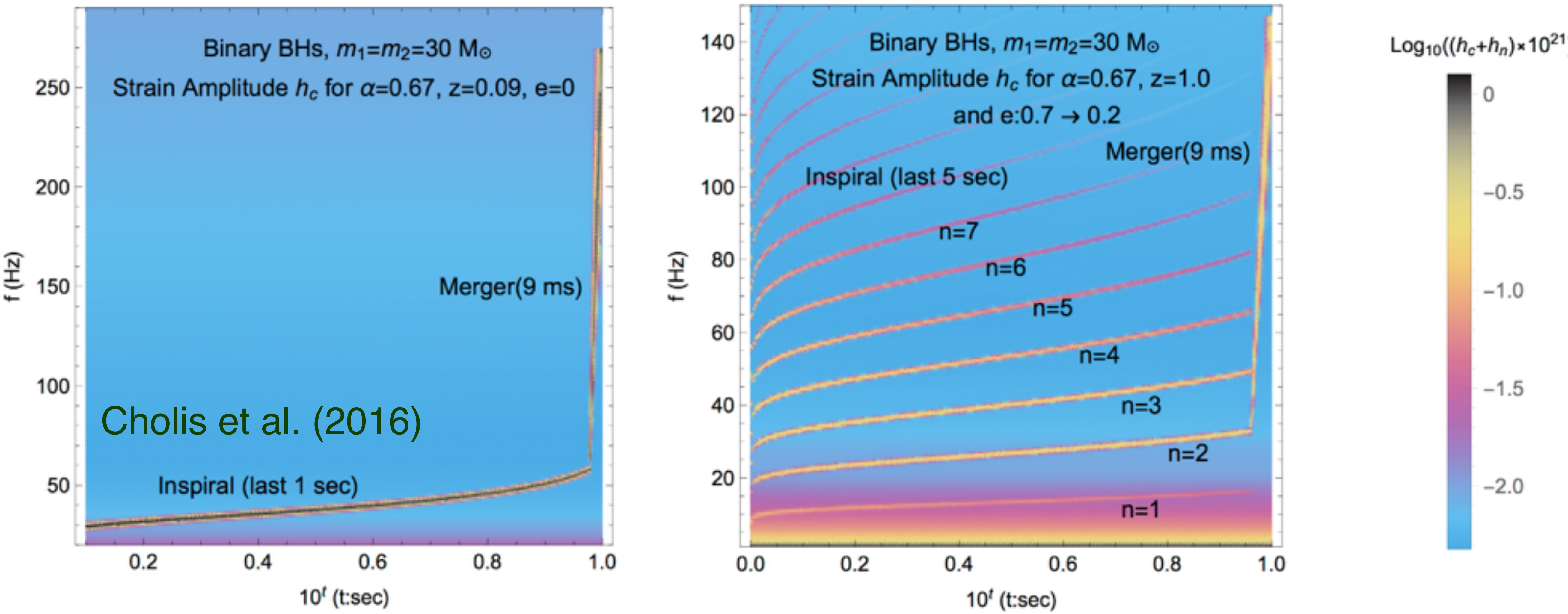
Cholis et al. (2016)

Time from formation to merger



final eccentricity
(observable at pericenter dist. of 6/14/22 Rsch)

A rare case? (see many more modes of grav. waves)



simplified noise (LIGO final design)

With LIGO we expect O(1) events while with the Einstein Telescope we expect O(10) events with multiple modes detected from PBH binaries. Other astrophysical mechanisms for Binary BHs have typical time-scales of evolution that is ~Myrs-Gyrs. With Future eLISA we will also be able to trace back some PBH systems to earlier stages (days-years before the merger event) and thus observe the binaries at even higher eccentricities.

Future Direction:
The stochastic GW background

For every event like the GW150914 there are many more too distant or not powerful enough to be resolved above the threshold.
These create a “stochastic” grav. wave background.

The energy density of GWs can be described by:

$$\Omega_{GW} = \frac{f}{\rho_c}\frac{d\rho_{GW}}{df}$$

<— energy density between f and f+df

$$\Omega_{GW} = \frac{f}{\rho_c H_0}\int_0^{z_{max}} dz \frac{R_m(z,\theta_k)}{(1+z)\sqrt{\Omega_\Lambda + \Omega_M(1+z)^3}} \frac{dE_{GW}(f_s,\theta_k)}{df_s}$$

f_s :frequency at source

θ_k :astrophysics assumptions, (mass distr. of BHs and z-distr.)

$\frac{dE_{GW}(f_s,\theta_k)}{df_s}$: energy density spectrum, for inspiral typically

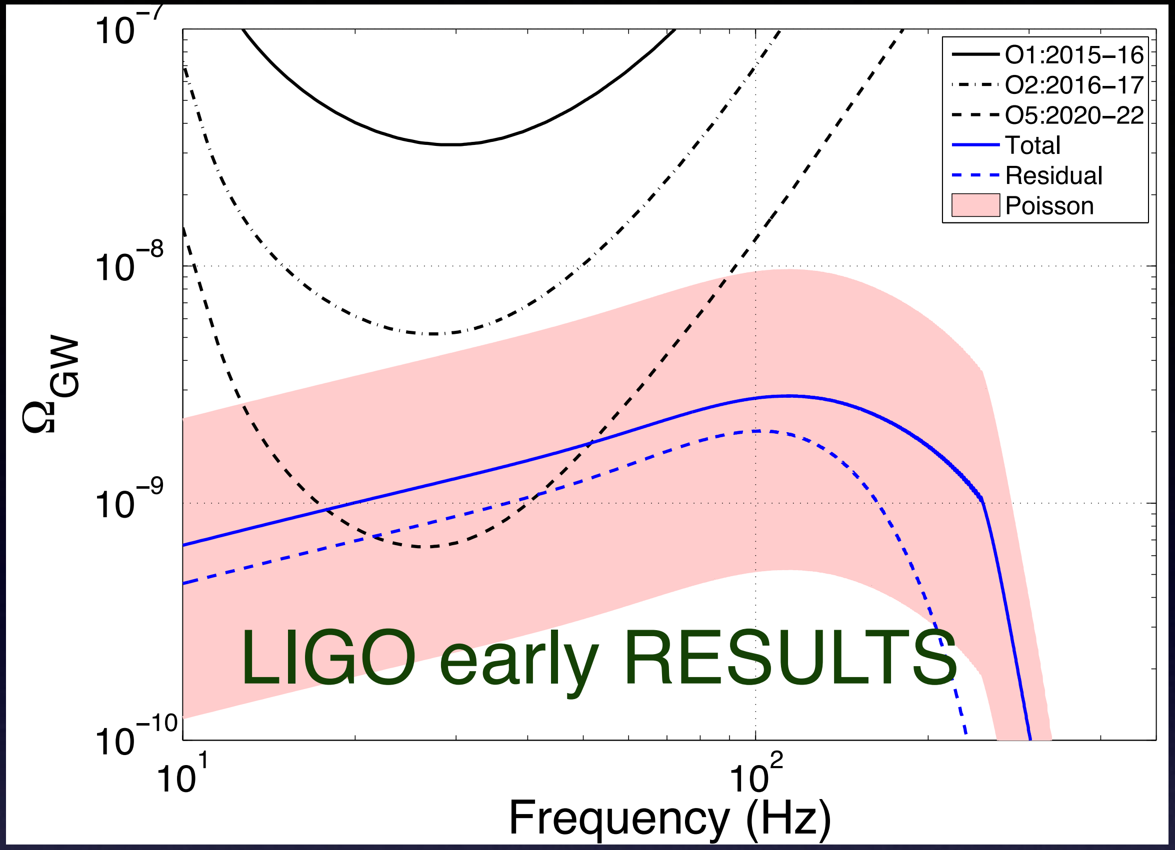
$$R_m(z,\theta_k) = \int_{t_{min}}^{t_{max}} R_f(z_f,\theta_k) P(t_d,\theta_k) dt_d$$

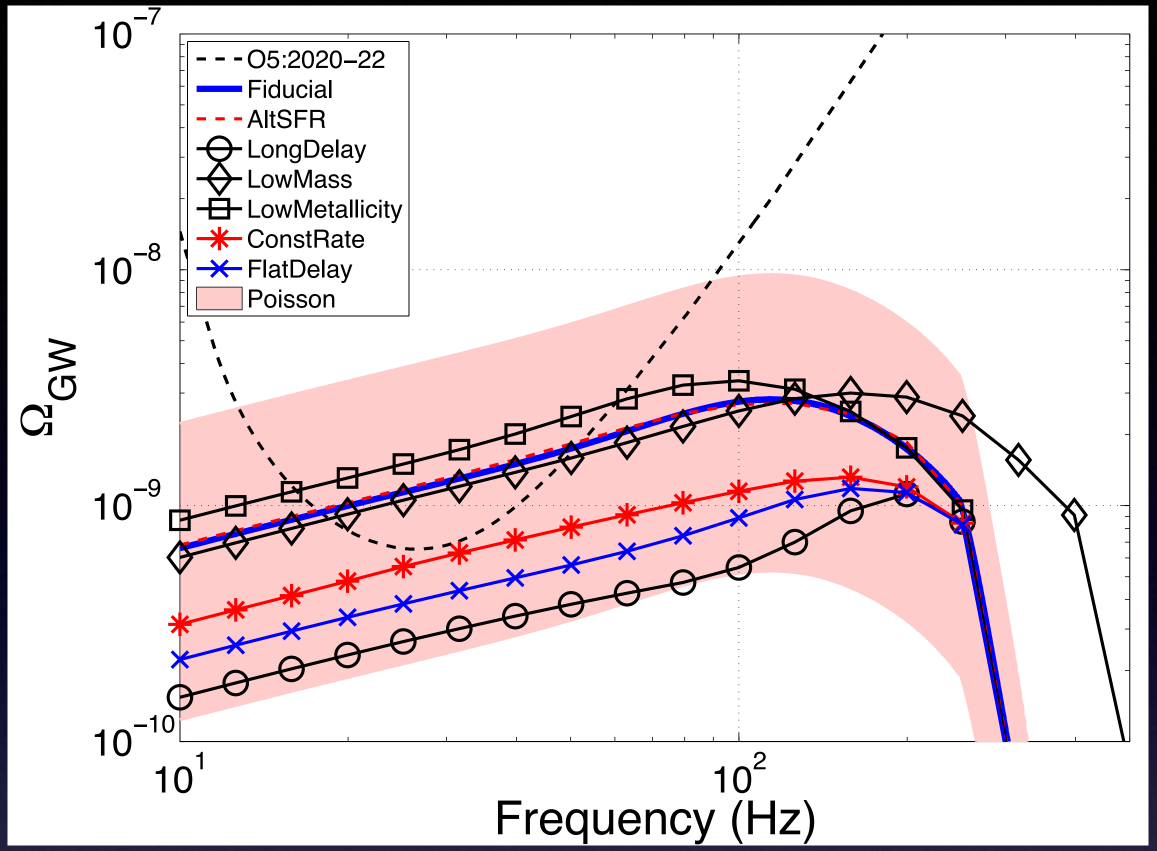
:rate of BH-BH merger

$R_f(z_f,\theta_k)$: binary formation rate

$P(t_d,\theta_k)$: distr. of time delay

Measuring the stock. back will probe the GW sources





Based on the rate of $2 - 53\, Gpc^{-3} yr^{-1}$ and assuming a conventional

Star Formation Rate (SFR) “Fiducial”

Star Formation Rate doesn’t affect much such a calculation (“AltSFR”)

“Long Delay”: it takes at least 5 Gyrs for a merger to occur (largely separated objects with slow rel. velocity before binary creation). “Flat delay” : 1 Gyr.

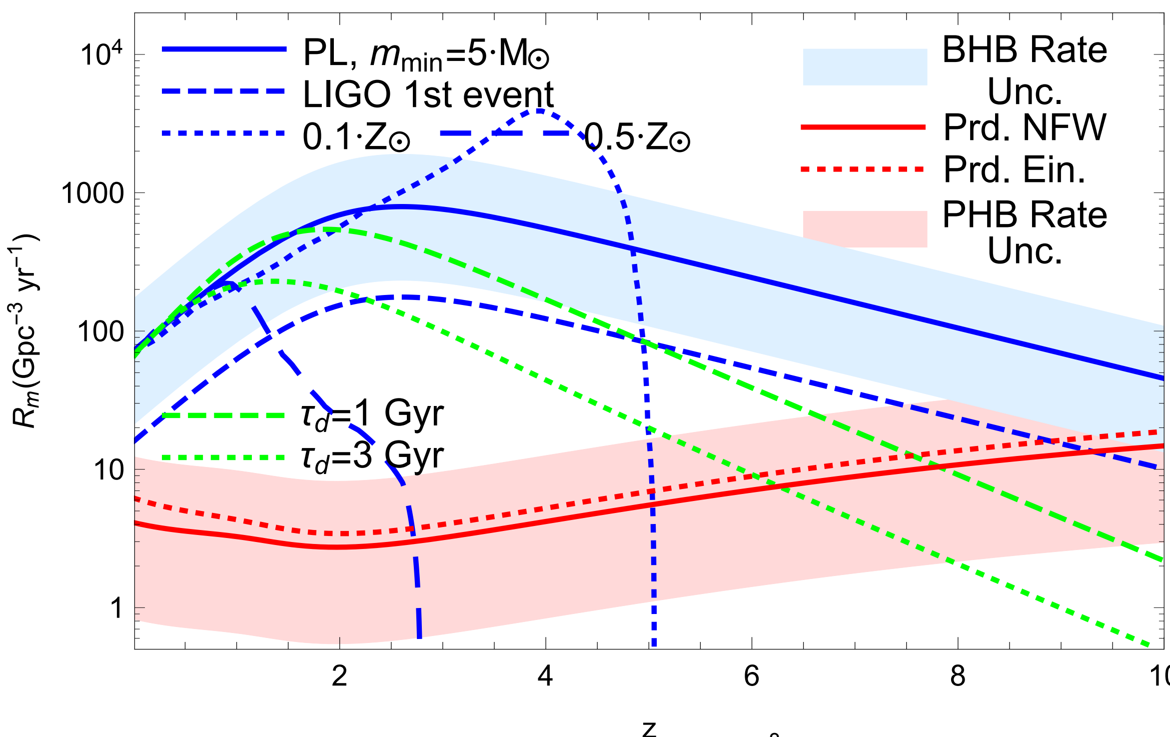
“Low mass”: assuming 15 $M_{\odot}$ BHs. More power at higher frequencies.

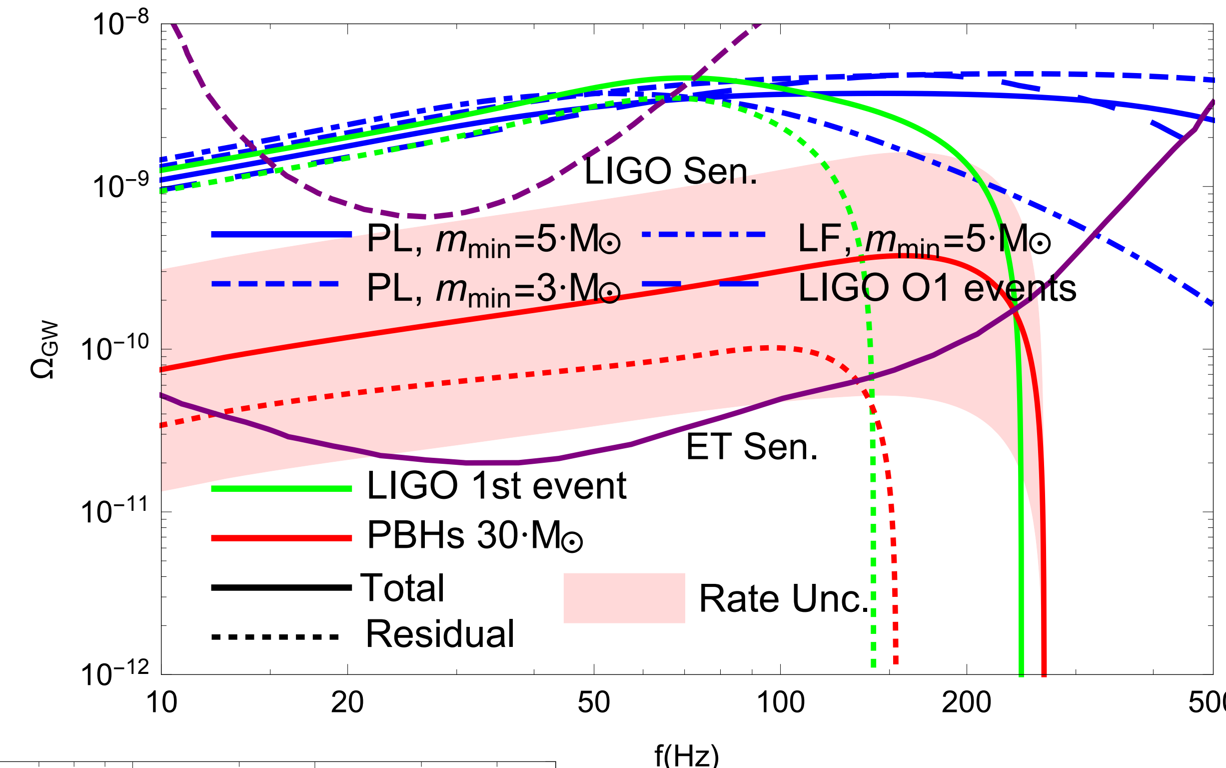
Lower metallicity increases the number density of BHs

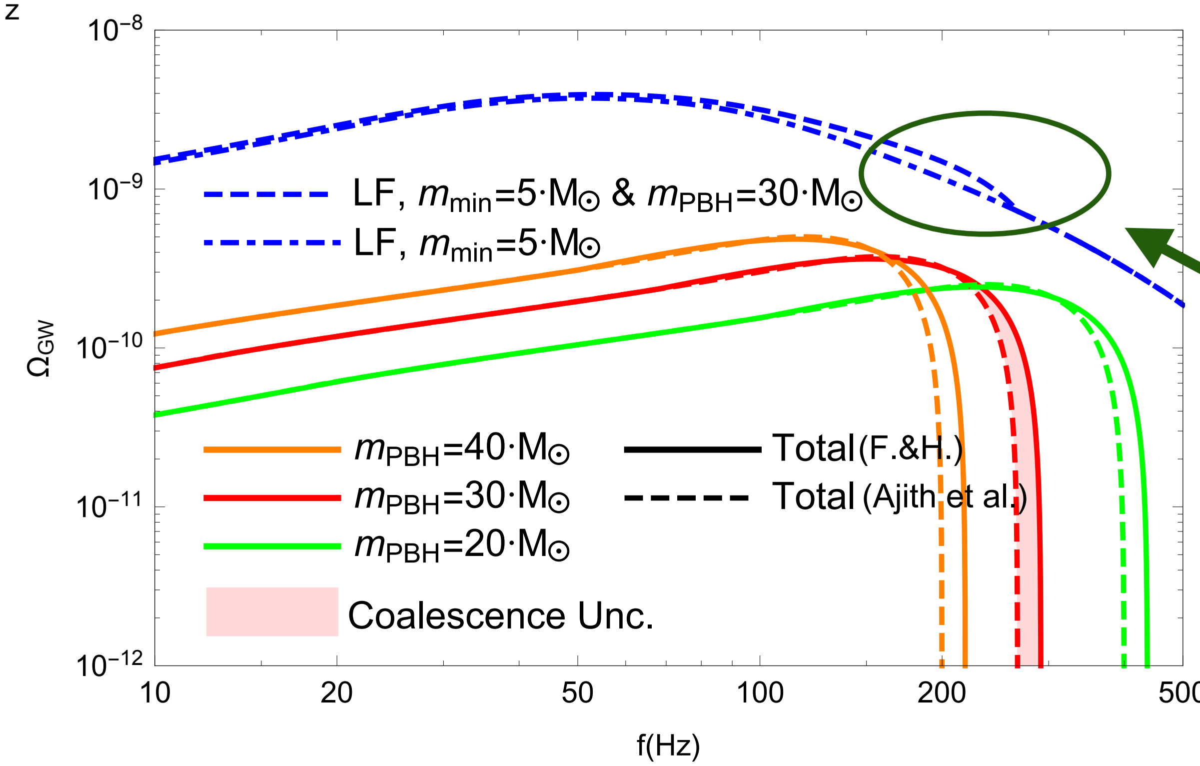
“Constant (in z) rate”: $R_m(z) = 16\, Gpc^{-3} yr^{-1}$

Updated Rates on the BH-BH mergers
(some room a PBH component to be seen in the Stoch. Background)

V. Mandic, S. Bird, I.C. (PRL accept.) arXiv:1608.06699 &
I.C. arXiv:1609.03565







With Einstein Telescope we might be able to probe the PBH model

An other future direction: Cross-Correlations with Galaxies

A. Raccanelli, E. Kovetz, S. Bird, I.C. J. Munoz
PRD 94 023516 (arXiv:1605:01405)

If the GW signal comes from BHs originating by standard astrophysical sources e.g. BH in globular clusters, then the binary systems should preferentially reside in galaxies where most of the stars are. So GW and star forming galaxy (SFG) maps would be highly correlated.

If the BH binaries are mostly populating halos with different mass range, bias, redshift and angular distributions, then the correlation with SFGs galaxies in halos of masses $\sim 10^{11} - 10^{12} M_{\odot}$ would be lower.

If the GW signal comes from PBHs that constitute the DM then their distribution will be more uniform on the sky.

We can calculate angular projections:

$$C_{\ell}^{XY} = \langle a_{\ell m}^{X} a_{\ell m}^{Y*} \rangle = 4\pi \int \frac{dk}{k} \Delta^2(k) W_{\ell}^{X}(k) W_{\ell}^{Y}(k)$$

Window functions

Window function:

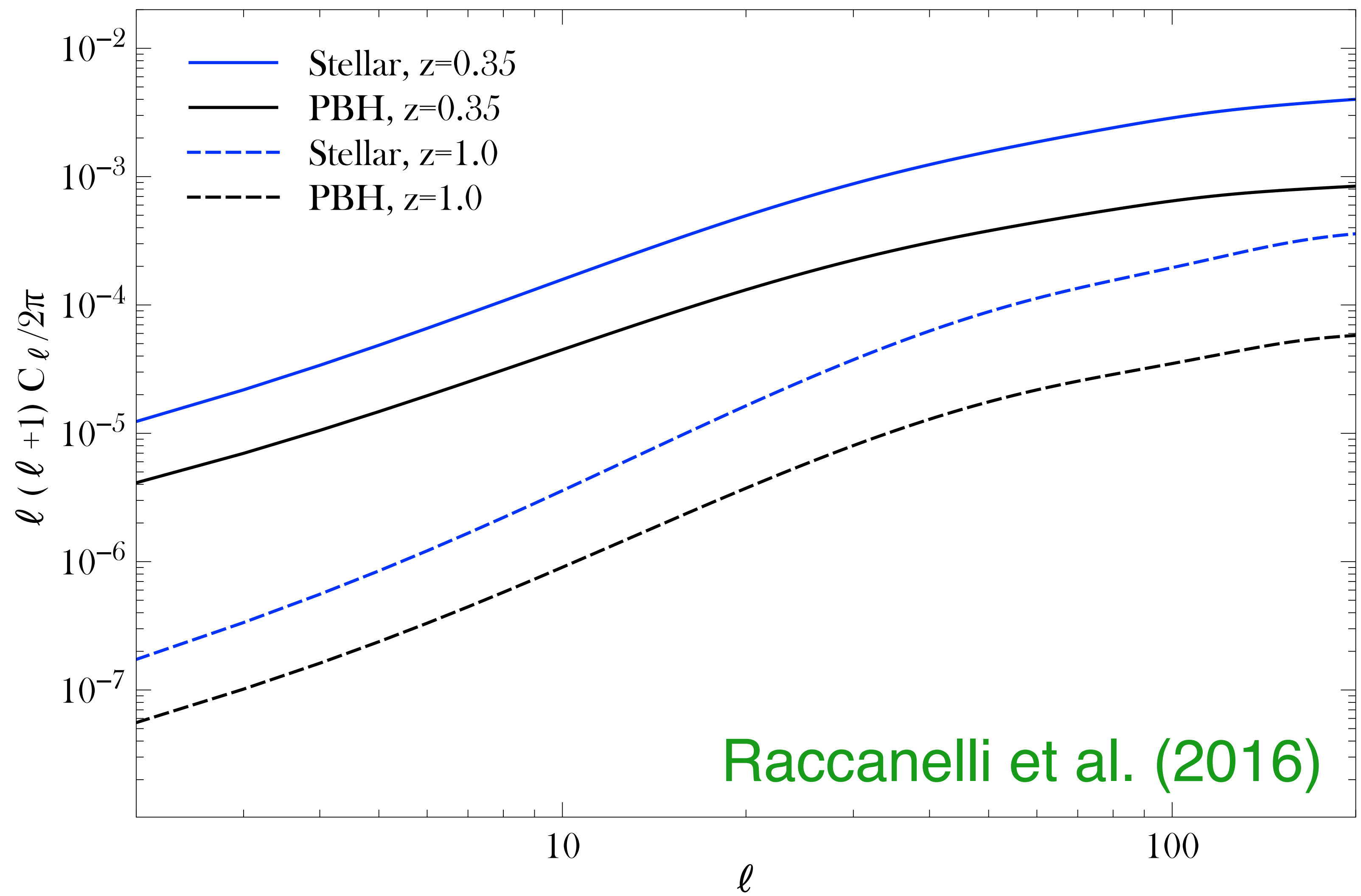
bias (progenitor infor.)

$$W_\ell^X(k) = \int N_X(z) b_X(z) j_\ell[k\chi(z)] dz$$

#/sr

co-moving distance

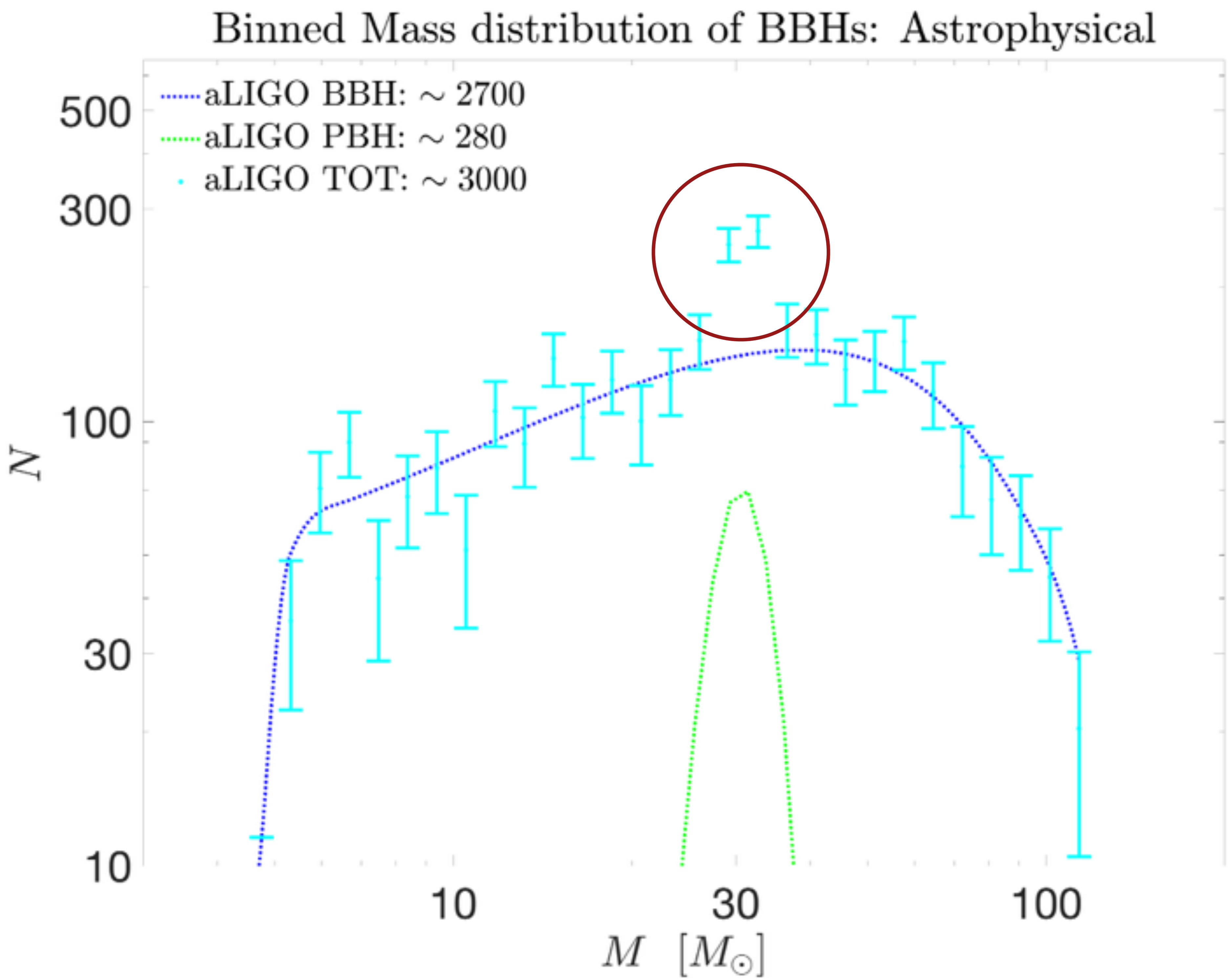
$$N_{GW}(z) = \dot{n}_{\rm GW}(z) T_{\rm obs} V(z)$$



Forecasted Cross-correlation amplitude of of Galaxies with BH-BH mergers. PBH binaries have a smaller bias b (~0.5) compared to stellar BHs (since the PBH rate is dominated by the smallest DM halos)

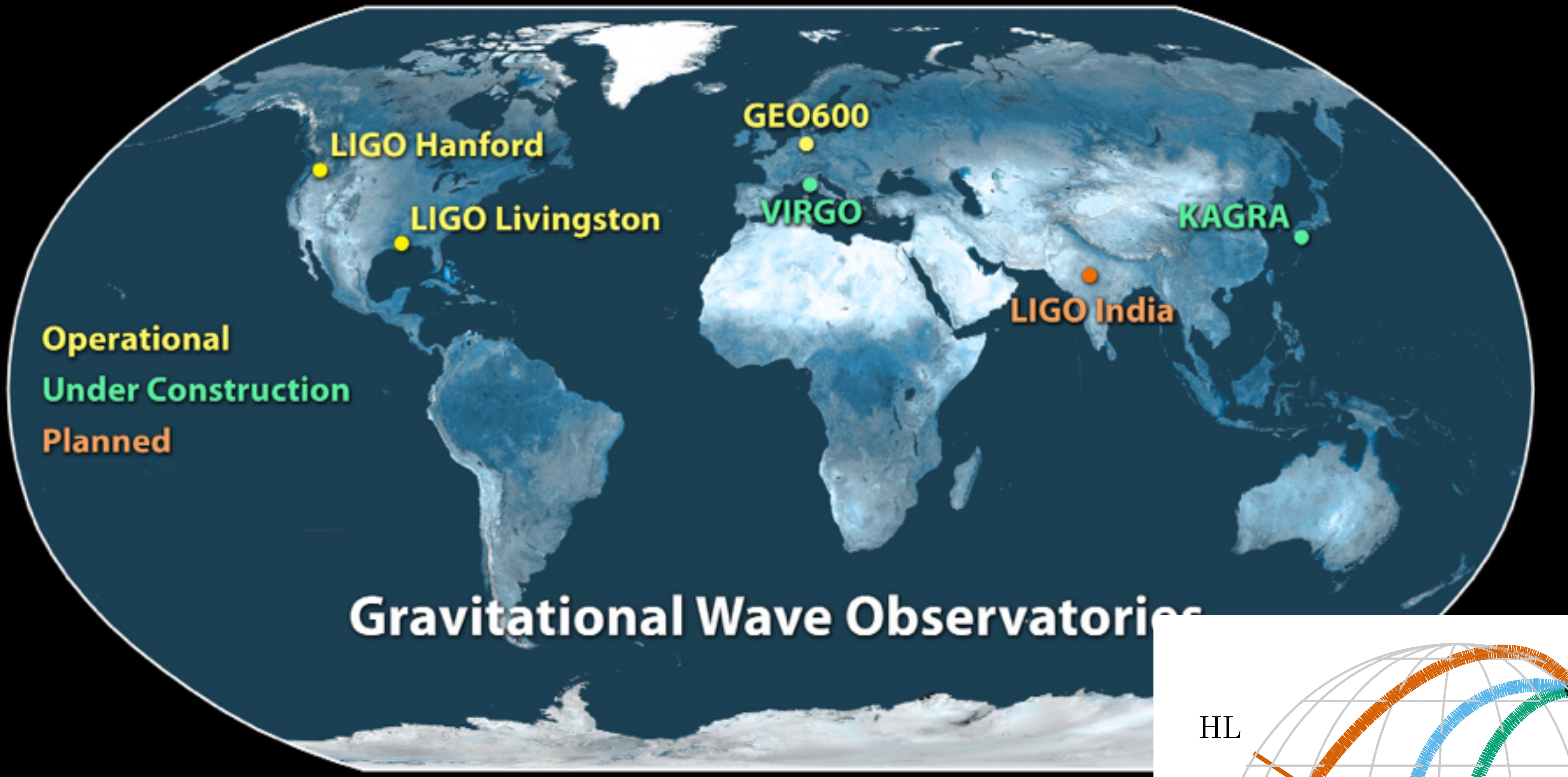
An other future possible indication: Mass-Spectrum of BH-BH binaries

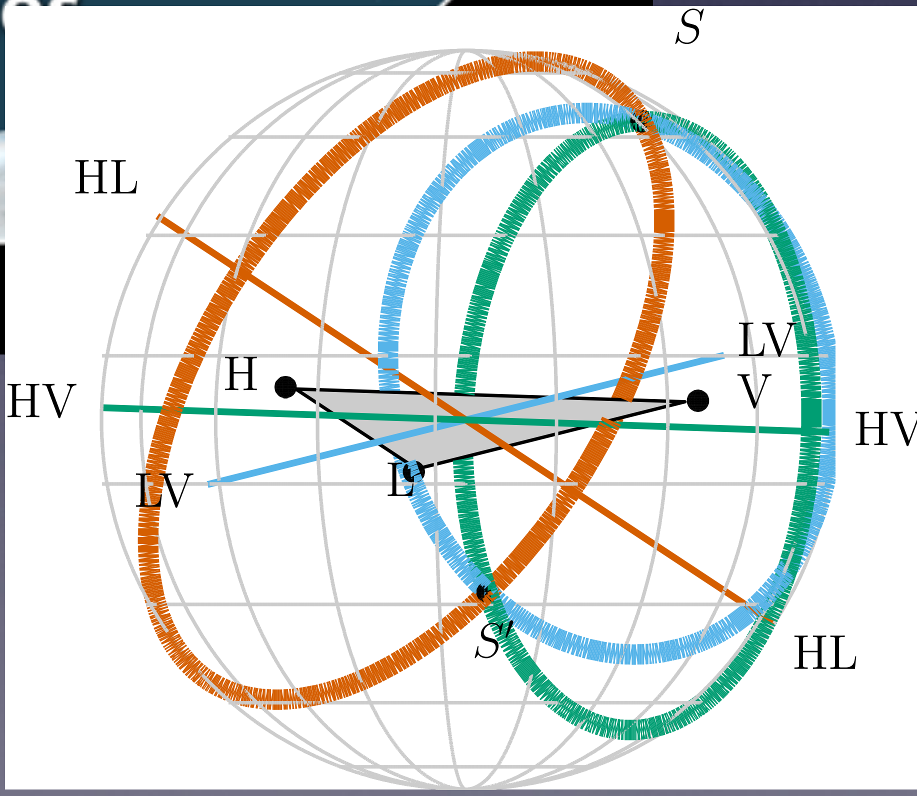
E. Kovetz, I.C., P. Breysse, M. Kamionkowski arXiv:1611:01157



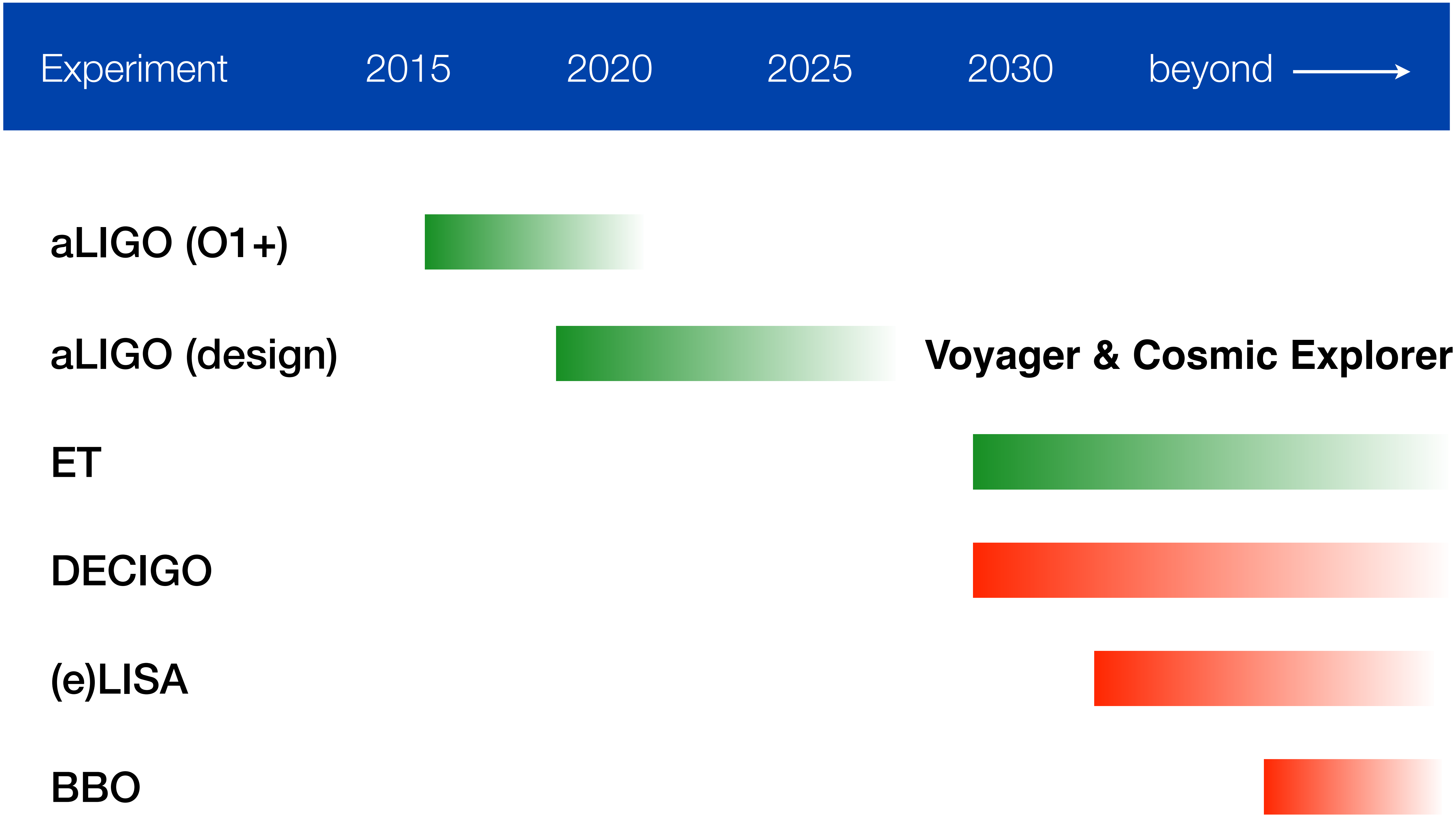
More about the future of GWs in general

The LIGO-VIRGO network



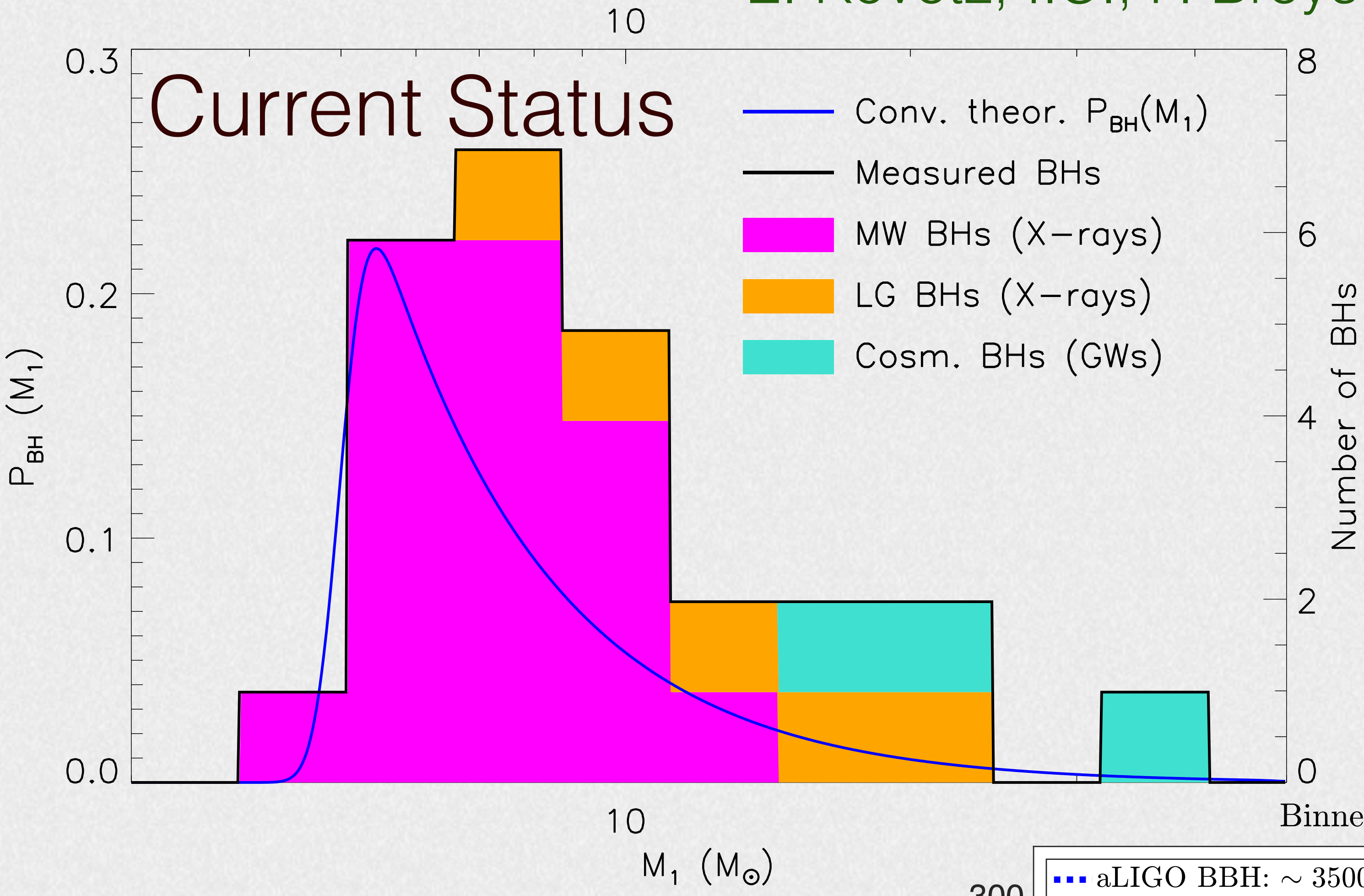


The next decades

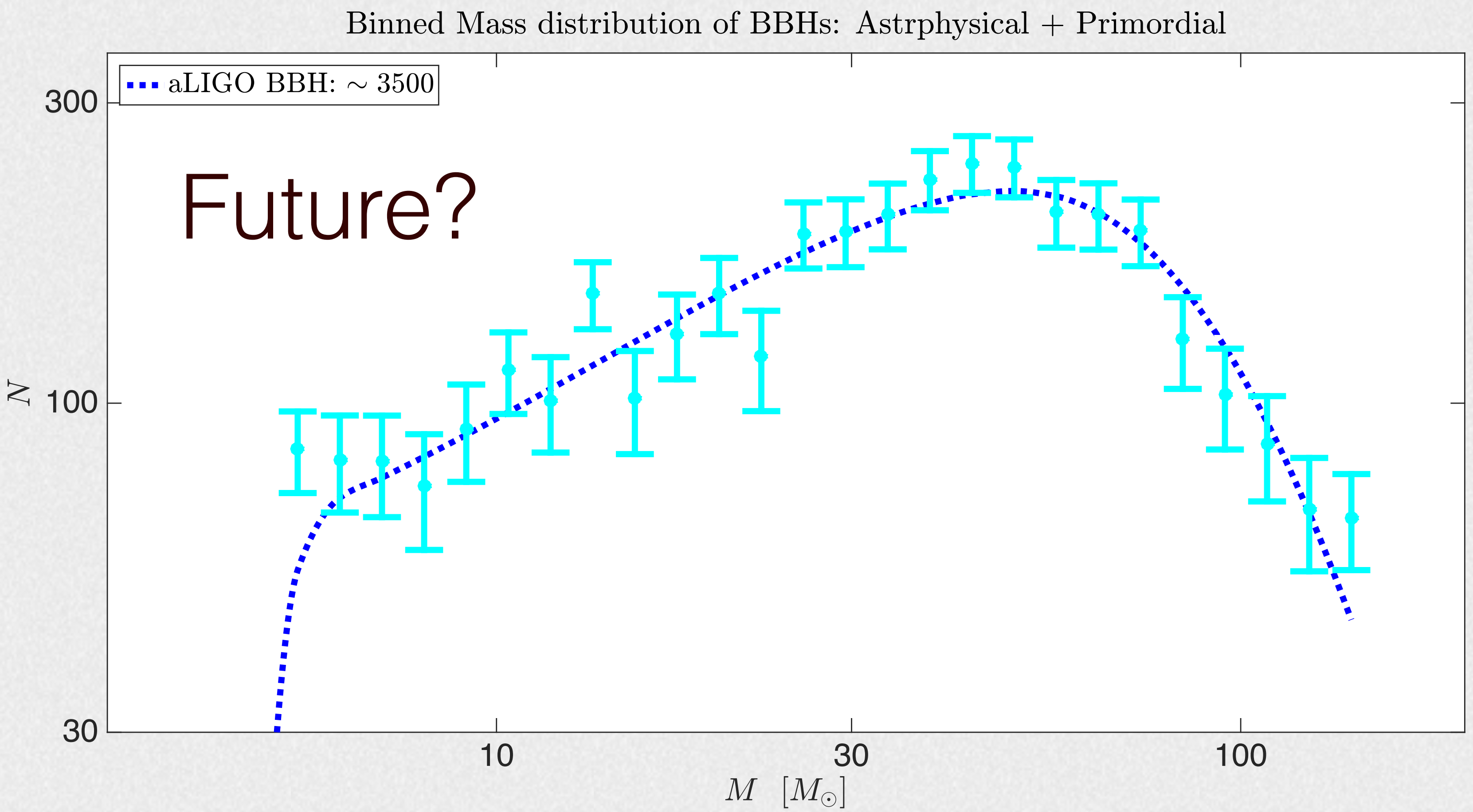


Understanding the Black Holes Mass Function

E. Kovetz, I.C., P. Breysse, M. Kamionkowski arXiv:1611:01157

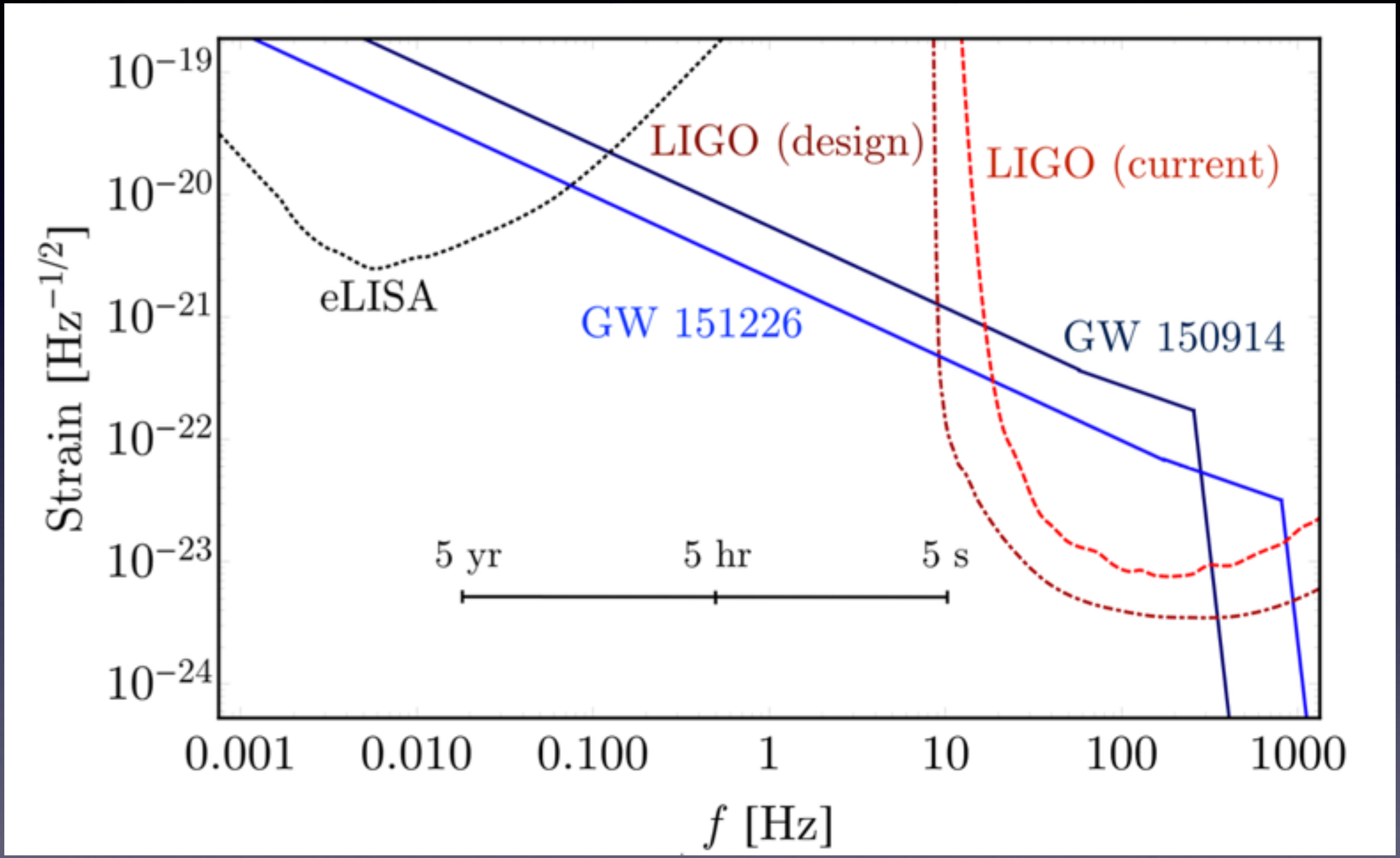


Understanding the BH mass-function can lead to understanding the progenitors of these systems



Combining space and ground-based observations

I.C. Ely Kovetz, Julian Munoz, Marc Kamionkowski (work in progress + with many extensions)



We will be able to observe the evolution of individual systems over periods of years, thus measure evolving eccentricities, masses -> progenitors.

Conclusions

- Taking the first detection of GWs we made a connection to a long standing problem, the nature of dark matter (assuming it is BHs produced at the Early Univesre).
- The rate that these BHs merge currently is of the same order of magnitude as the one observed (it could have been many orders of magnitude off) PRL 116 201031.
- These can be very short-lived objects (shorter than this presentation or the time it will take me to go through that slide). Thus with properties very unique and Testable! in the next ~decade PRD 94 084013.
- One can also search for a signal in the mass-spectrum of observed BHs in the next ten years arXiv:1611:01157 and even derive limits on PBHs from GWs (in progress).
- We can also search for a signal in the overall background GW emission PRL 117 201102 & arXiv:1609.03565 testable with the next generation of detectors (2030s).
- Make a connection with other observables as is the distributions of galaxies PRD 94 023516 (2030s++).
- Ask more general questions regarding what are the sources of the GWs and what can we learn in terms of astrophysical systems PRD 94 023516, arXiv:1609.03565 & arXiv:1611:01157.
- **A GREAT NEW PROBE TO STUDY THE COSMOS**

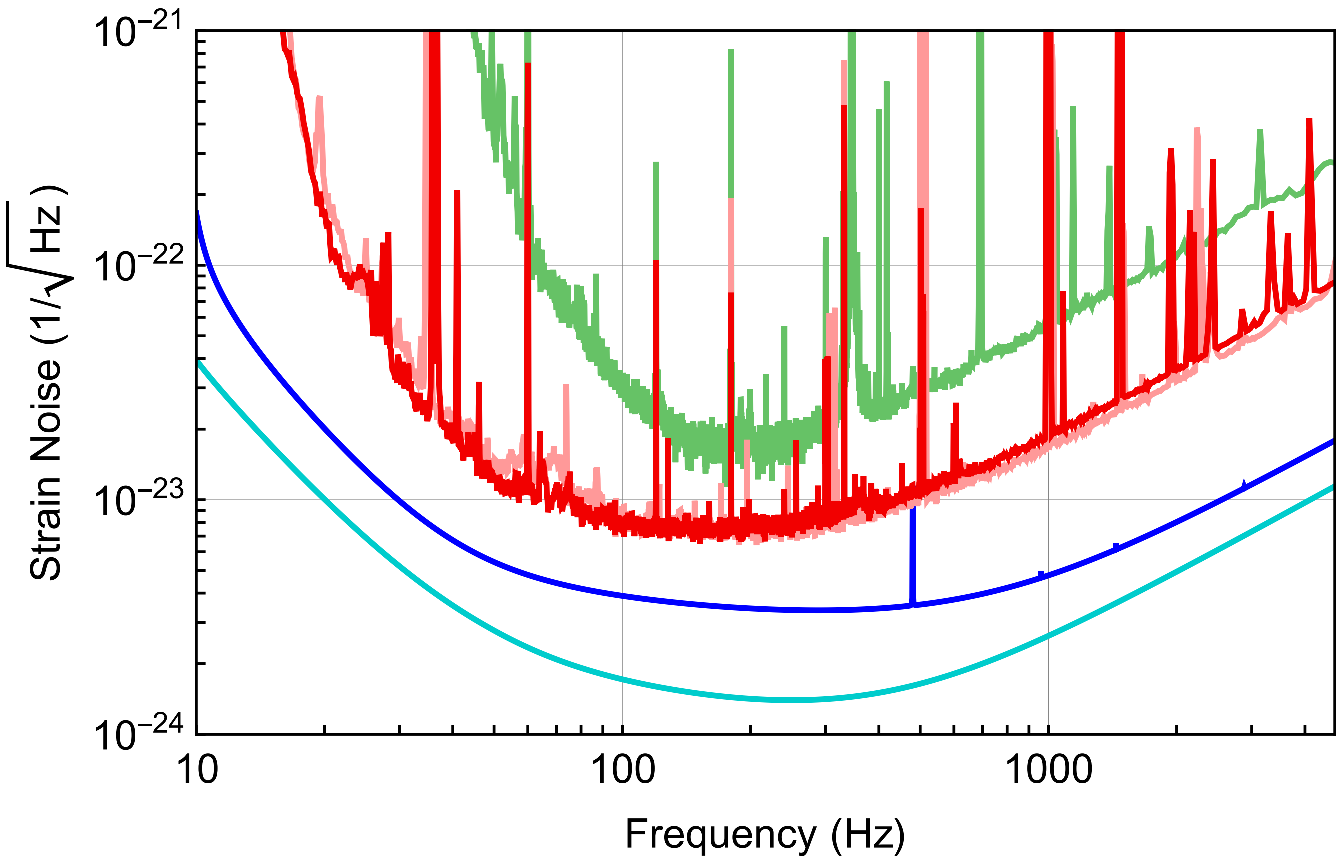
Thank you!

Additional slides

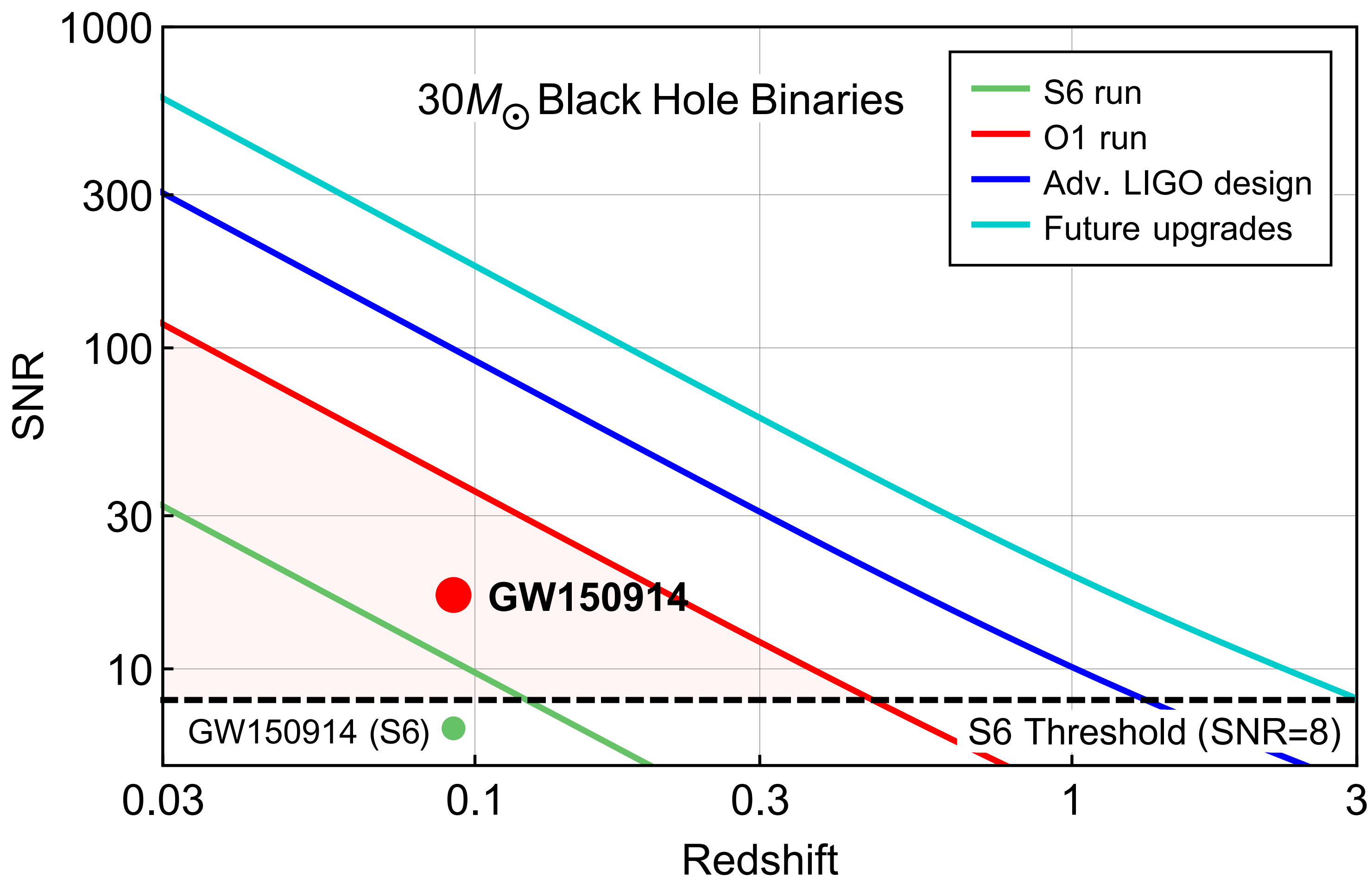
extracted parameters based on two waveform models (relying on Num. Rel. simulations)

	EOBNR	IMRPhenom	Overall
Detector-frame total mass $M/\mathrm{M}_\odot$	$70.3^{+5.3}_{-4.8}$	$70.7^{+3.8}_{-4.0}$	$70.5^{+4.6\pm0.9}_{-4.5\pm1.0}$
Detector-frame chirp mass $\mathcal{M}/\mathrm{M}_\odot$	$30.2^{+2.5}_{-1.9}$	$30.5^{+1.7}_{-1.8}$	$30.3^{+2.1\pm0.4}_{-1.9\pm0.4}$
Detector-frame primary mass $m_1/\mathrm{M}_\odot$	$39.4^{+5.5}_{-4.9}$	$38.3^{+5.5}_{-3.5}$	$38.8^{+5.6\pm0.9}_{-4.1\pm0.3}$
Detector-frame secondary mass $m_2/\mathrm{M}_\odot$	$30.9^{+4.8}_{-4.4}$	$32.2^{+3.6}_{-5.0}$	$31.6^{+4.2\pm0.1}_{-4.9\pm0.6}$
Detector-frame final mass $M_\mathrm{f}/\mathrm{M}_\odot$	$67.1^{+4.6}_{-4.4}$	$67.4^{+3.4}_{-3.6}$	$67.3^{+4.1\pm0.8}_{-4.0\pm0.9}$
Source-frame total mass $M^\mathrm{source}/\mathrm{M}_\odot$	$65.0^{+5.0}_{-4.4}$	$64.6^{+4.1}_{-3.5}$	$64.8^{+4.6\pm1.0}_{-3.9\pm0.5}$
Source-frame chirp mass $\mathcal{M}^\mathrm{source}/\mathrm{M}_\odot$	$27.9^{+2.3}_{-1.8}$	$27.9^{+1.8}_{-1.6}$	$27.9^{+2.1\pm0.4}_{-1.7\pm0.2}$
Source-frame primary mass $m_1^\mathrm{source}/\mathrm{M}_\odot$	$36.3^{+5.3}_{-4.5}$	$35.1^{+5.2}_{-3.3}$	$35.7^{+5.4\pm1.1}_{-3.8\pm0.0}$
Source-frame secondary mass $m_2^\mathrm{source}/\mathrm{M}_\odot$	$28.6^{+4.4}_{-4.2}$	$29.5^{+3.3}_{-4.5}$	$29.1^{+3.8\pm0.2}_{-4.4\pm0.5}$
Source-fame final mass $M_\mathrm{f}^\mathrm{source}/\mathrm{M}_\odot$	$62.0^{+4.4}_{-4.0}$	$61.6^{+3.7}_{-3.1}$	$61.8^{+4.2\pm0.9}_{-3.5\pm0.4}$
Mass ratio q	$0.79^{+0.18}_{-0.19}$	$0.84^{+0.14}_{-0.21}$	$0.82^{+0.16\pm0.01}_{-0.21\pm0.03}$
Effective inspiral spin parameter χ_eff	$-0.09^{+0.19}_{-0.17}$	$-0.03^{+0.14}_{-0.15}$	$-0.06^{+0.17\pm0.01}_{-0.18\pm0.07}$
Dimensionless primary spin magnitude a_1	$0.32^{+0.45}_{-0.28}$	$0.31^{+0.51}_{-0.27}$	$0.31^{+0.48\pm0.04}_{-0.28\pm0.01}$
Dimensionless secondary spin magnitude a_2	$0.57^{+0.40}_{-0.51}$	$0.39^{+0.50}_{-0.34}$	$0.46^{+0.48\pm0.07}_{-0.42\pm0.01}$
Final spin a_f	$0.67^{+0.06}_{-0.08}$	$0.67^{+0.05}_{-0.05}$	$0.67^{+0.05\pm0.00}_{-0.07\pm0.03}$
Luminosity distance $D_\mathrm{L}/\mathrm{Mpc}$	390^{+170}_{-180}	440^{+140}_{-180}	$410^{+160\pm20}_{-180\pm40}$
Source redshift z	$0.083^{+0.033}_{-0.036}$	$0.093^{+0.028}_{-0.036}$	$0.088^{+0.031\pm0.004}_{-0.038\pm0.009}$
Upper bound on primary spin magnitude a_1	0.65	0.71	0.69 ± 0.05
Upper bound on secondary spin magnitude a_2	0.93	0.81	0.88 ± 0.10
Lower bound on mass ratio q	0.64	0.67	0.65 ± 0.03
Log Bayes factor $\ln \mathcal{B}_\mathrm{s/n}$	288.7 ± 0.2	290.1 ± 0.2	—

Sensitivity evolution



An event as the GW150914 was bellow the threshold of S/N=8 to be detected by initial LIGO detectors.



The ~second Event: LVT151012

LVT: Ligo Virgo Trigger

2015, October, 12th

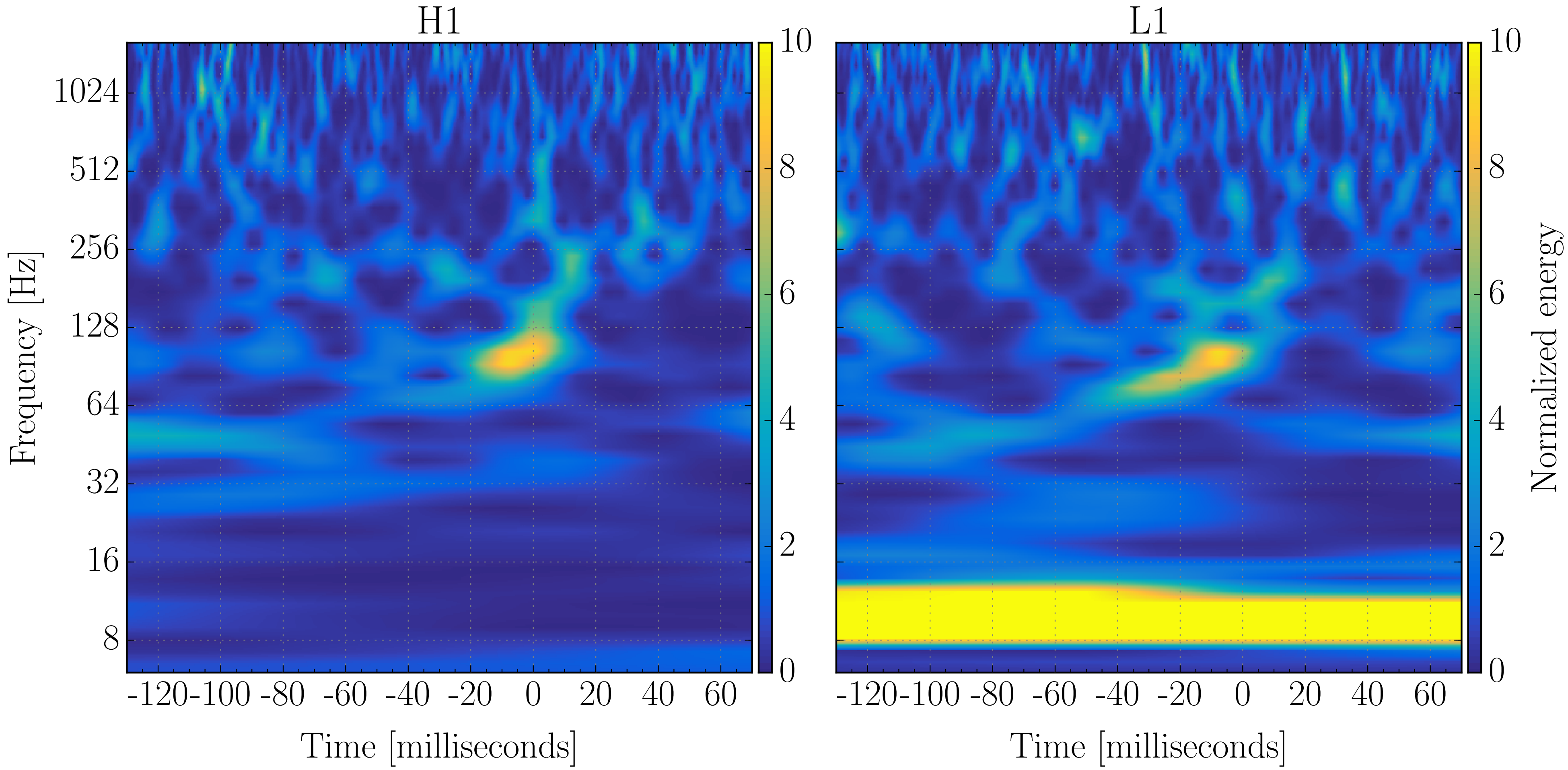
$$m_1 = 23^{+18}_{-5} M_\odot$$

$$m_2 = 13^{+4}_{-5} M_\odot$$

$$z = 0.2^{+0.1}_{-0.1}$$

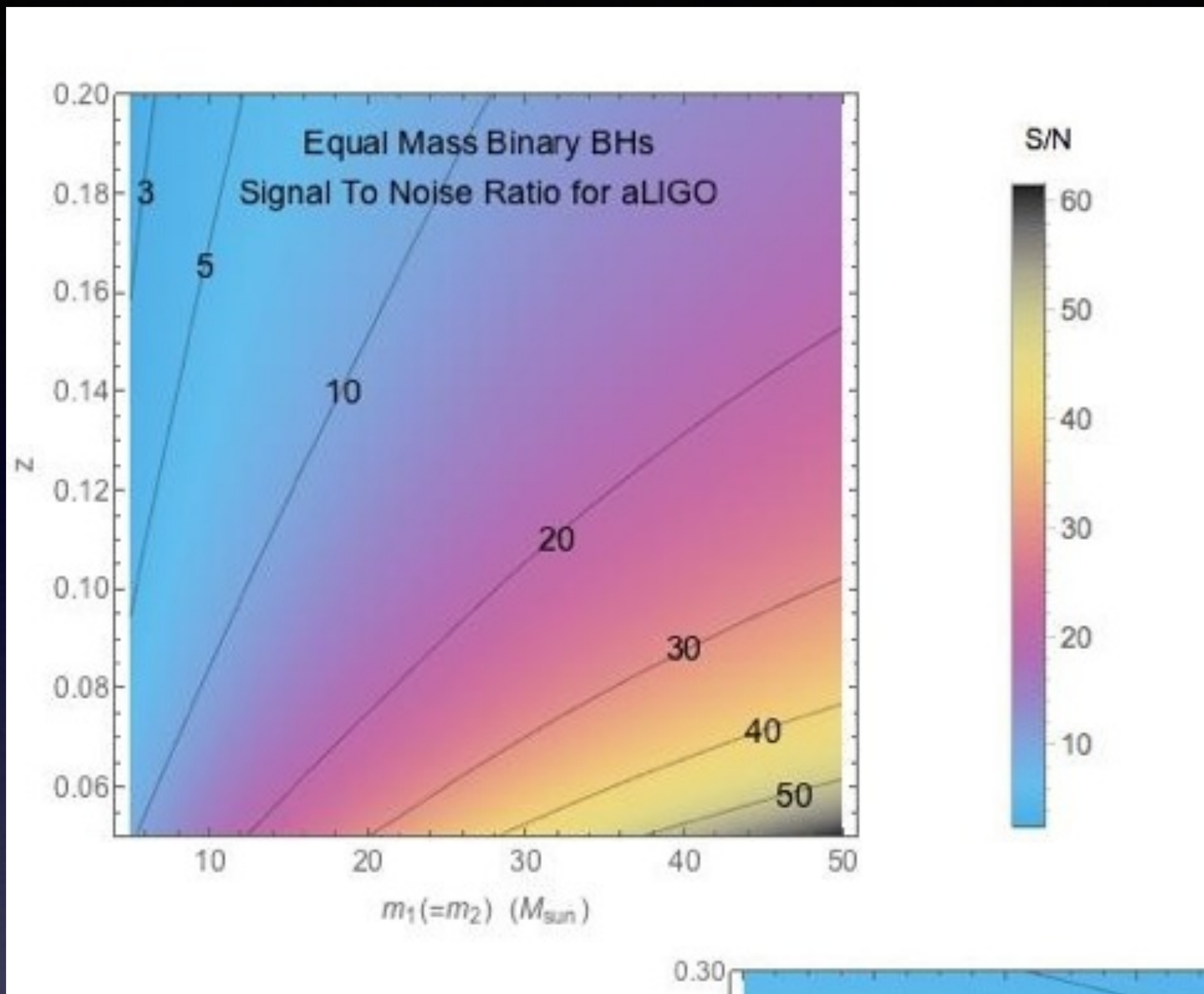
Combined S/N is 9.6 but H1 and L1 individually <8.

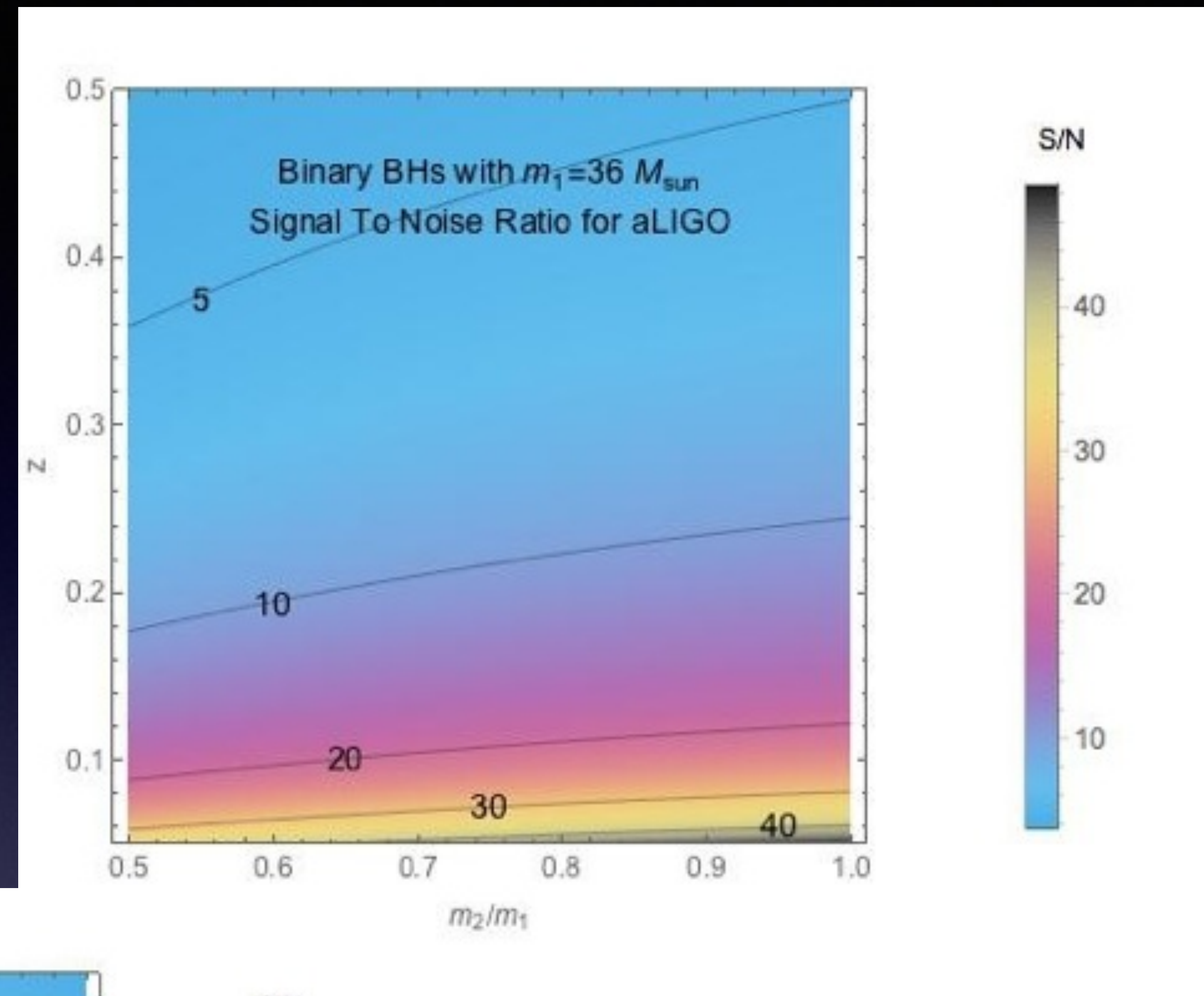
False rate 1 every 2.3 yrs (GW150914 was < 1 every 203000 yrs)



Higher Inspiral freq. -> lower masses

Sensitivity plots of current aLIGO in terms of sources parameters

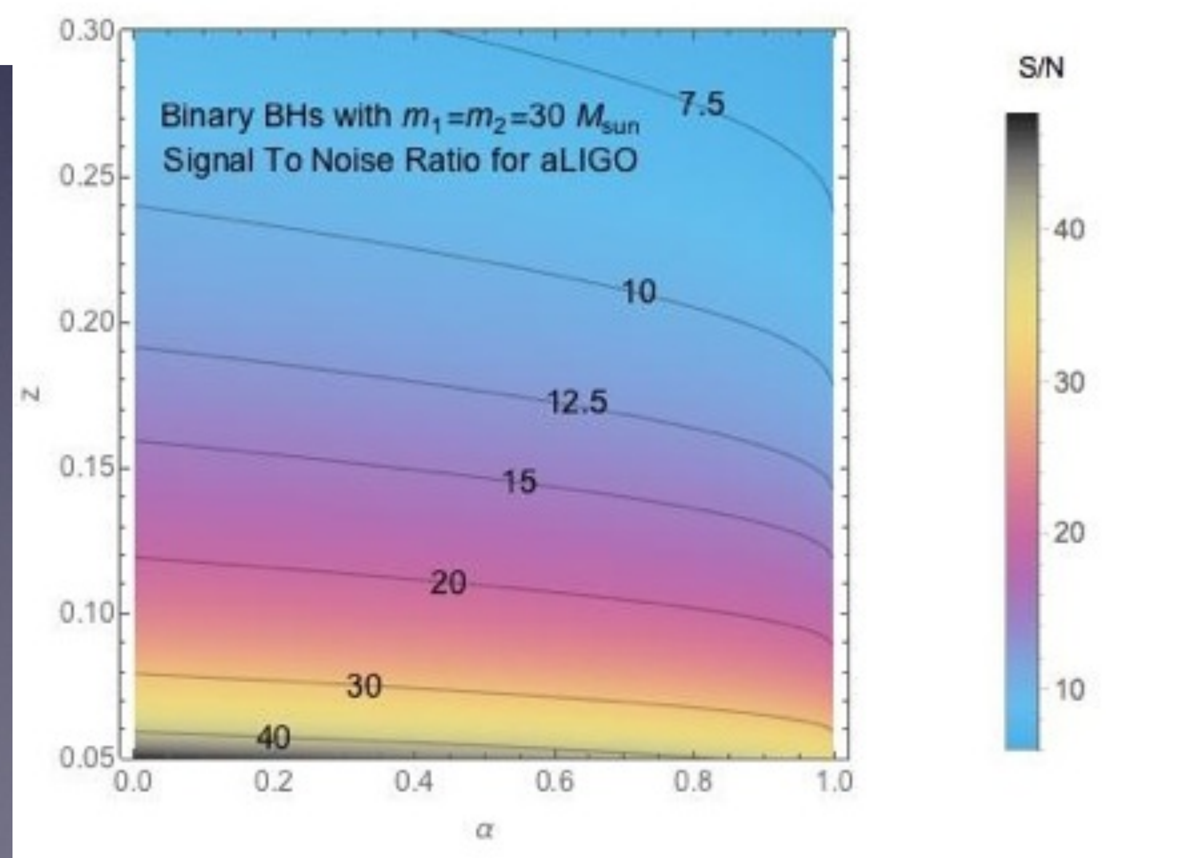




$$M_c \propto f^{-11/5}$$

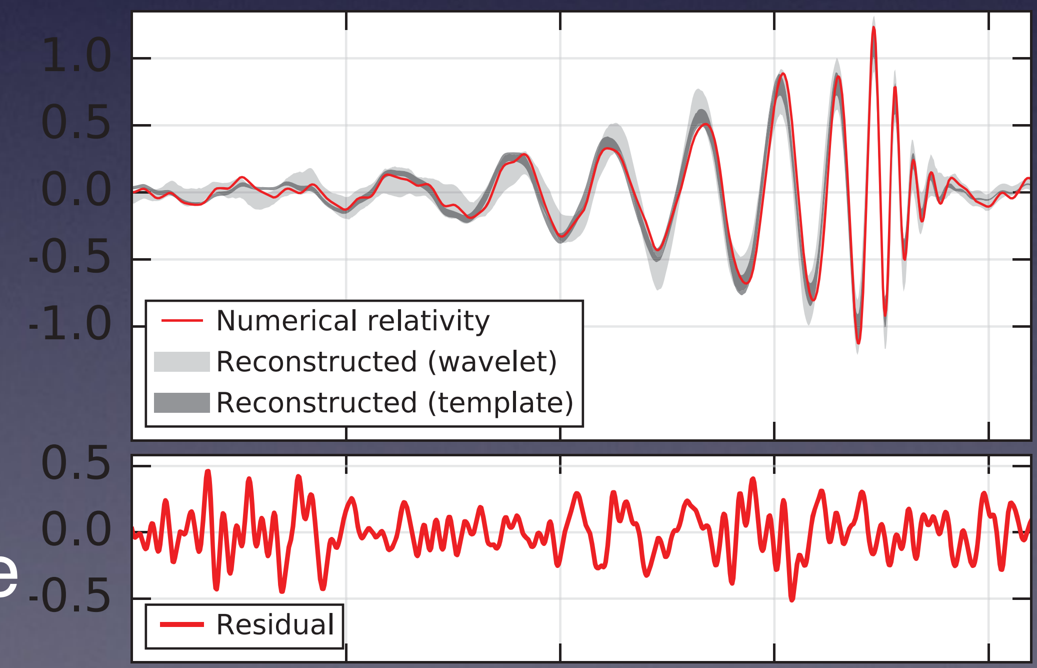
for fixed $\dot{f}$

assuming 5% of initial mass goes in GWs



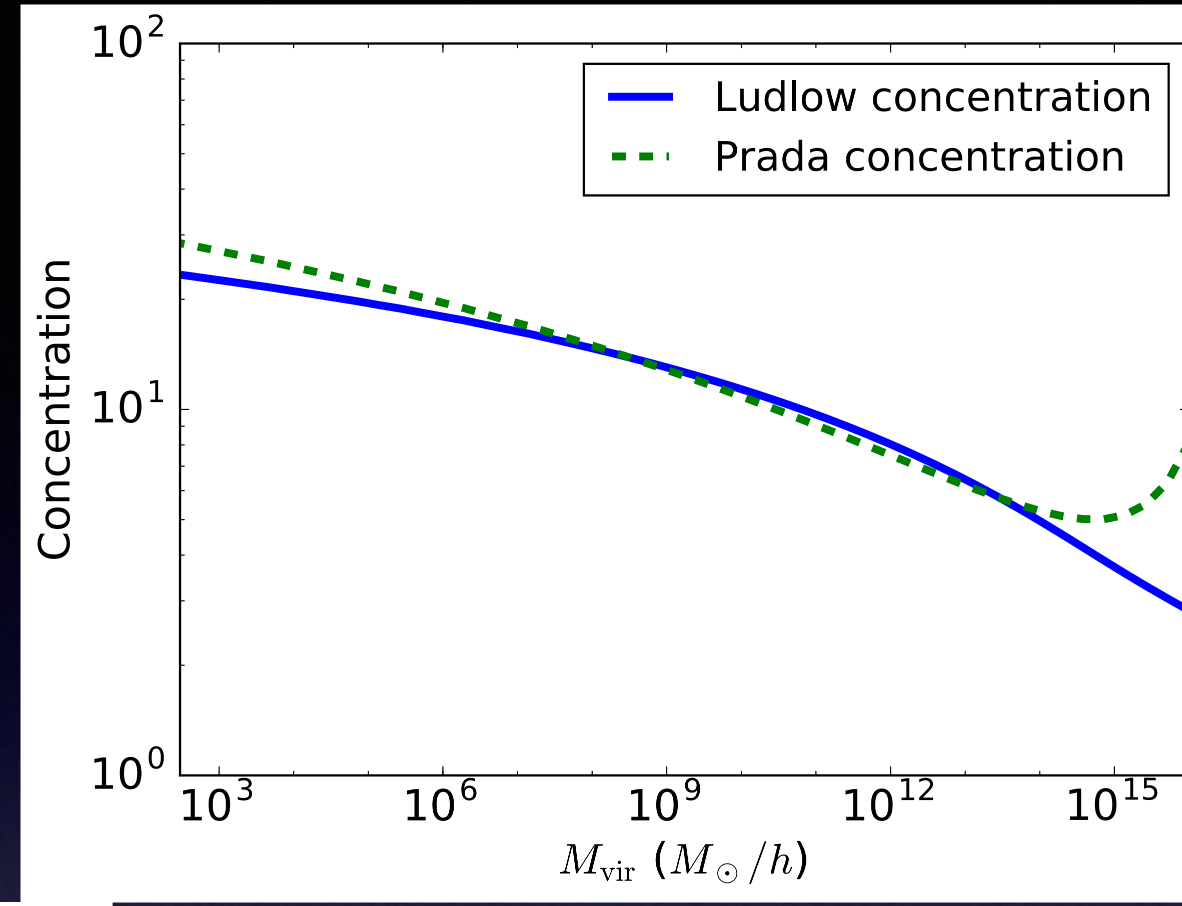
Searches for a signal

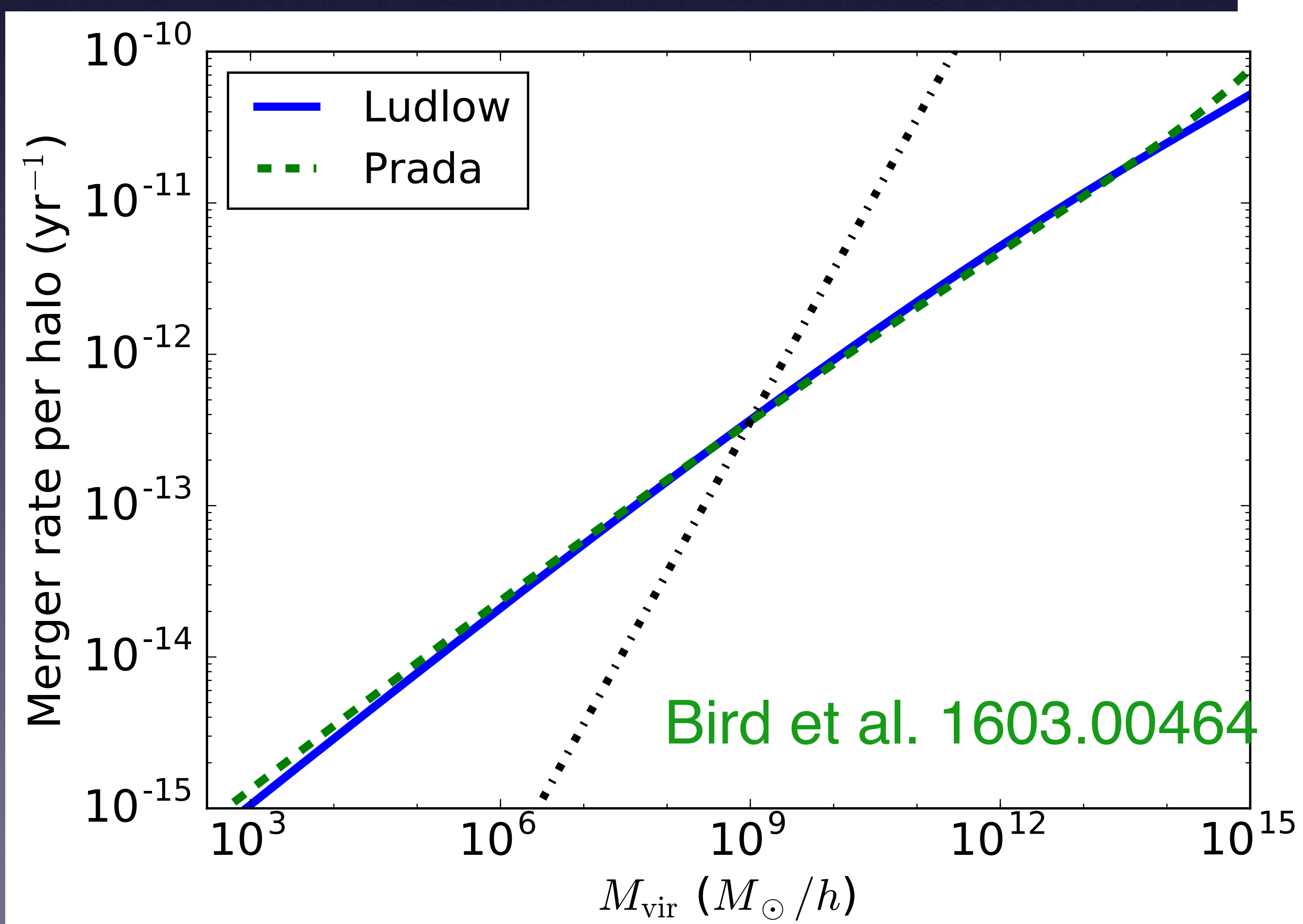
- Using waveforms (or "templates") of merging compact objects (250000 templates), $1 - 99\ M_{\odot}$ and $\alpha \epsilon (0, 0.99)$
- searching for transient signals (using linear combinations of Sine-Gaussian wavelets). GW150914 was detected by both methods.
- LIGO measures, frequency-range during the inspiral phase
- f_{merge} from the end of the inspiral phase
- $\dot{f} \equiv df/dt$ during the inspiral phase
- h_c during the inspiral and merger phases
- $f_{ring\ down}$ from the end of the merger phase



- S/N main contribution from the merger phase but also some from the insp.

Lower mass halos —>lower velocity dispersion (i.e. higher cross-section for the binary formation) and higher concentration:





But there are many more (in terms on number) low mass DM halos:

$$\frac{dn}{dM} \sim M^{-1.85}$$

Impose a cut-off at ~400 $M_\odot$