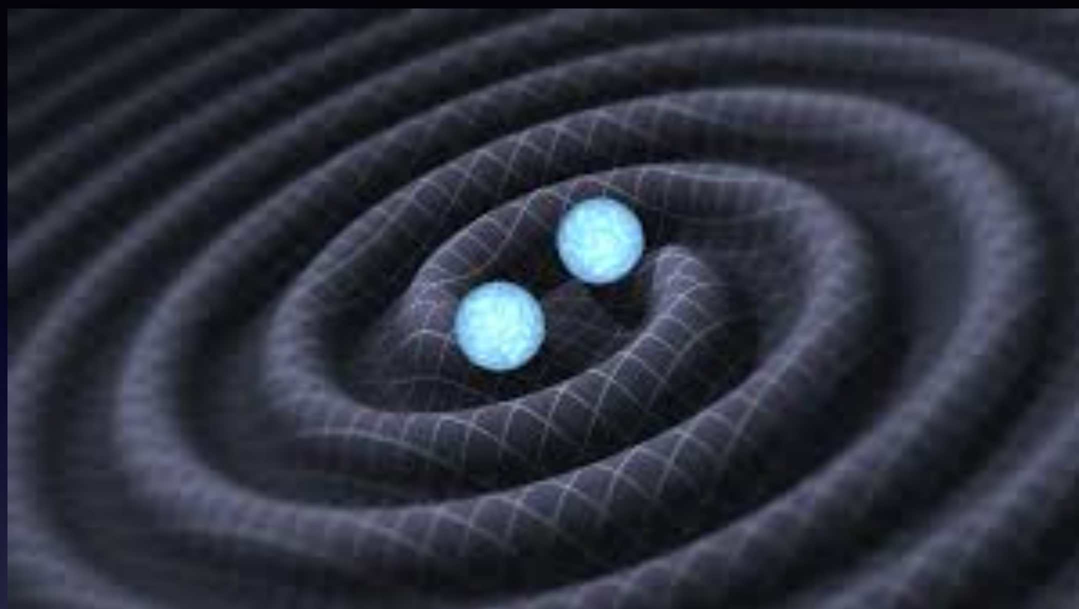
Searching for Dark Matter in Gravitational Waves



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)

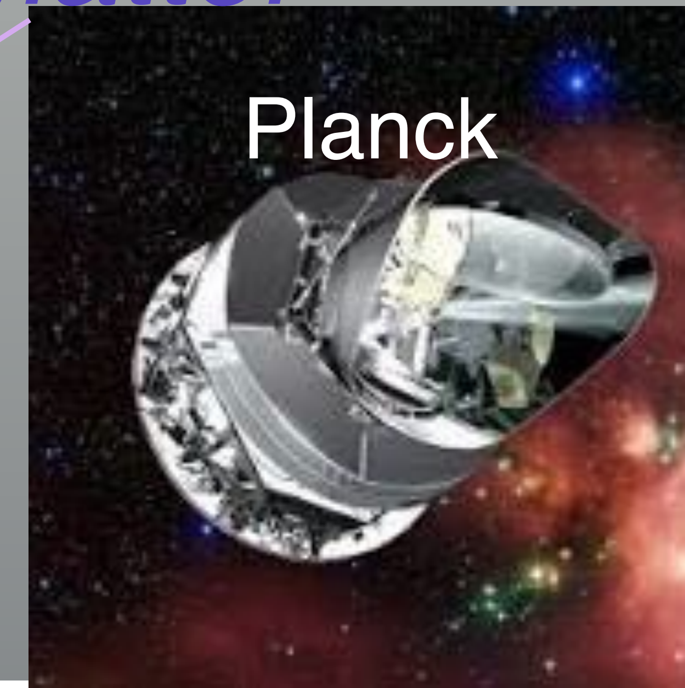
V. Mandic, S. Bird, I.C. PRL 117.201102 (arXiv:1608.06699)

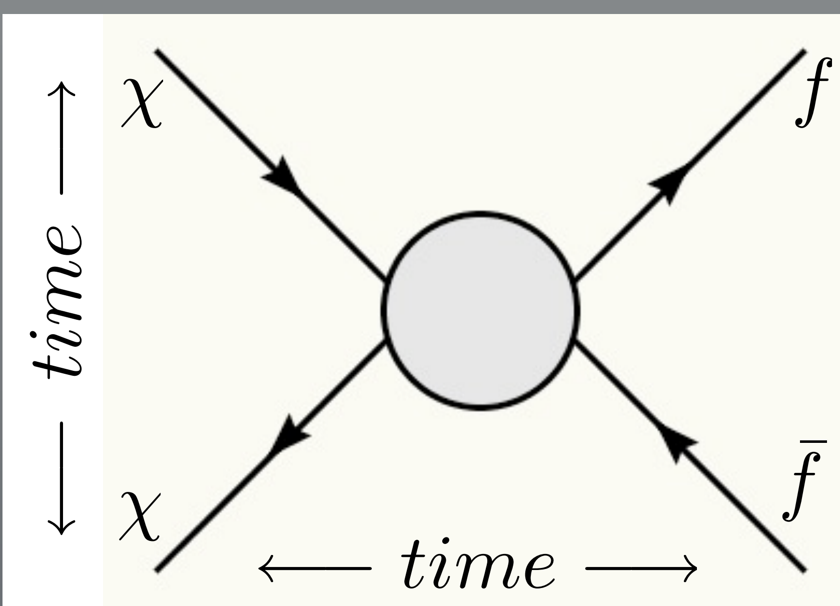
I.C. JCAP 06 037 2017 (arXiv:1609.03565), E. Kovetz, I.C., P. Breysse, M. Kamionkowski PRD 95 103010 (arXiv:1611.01157)

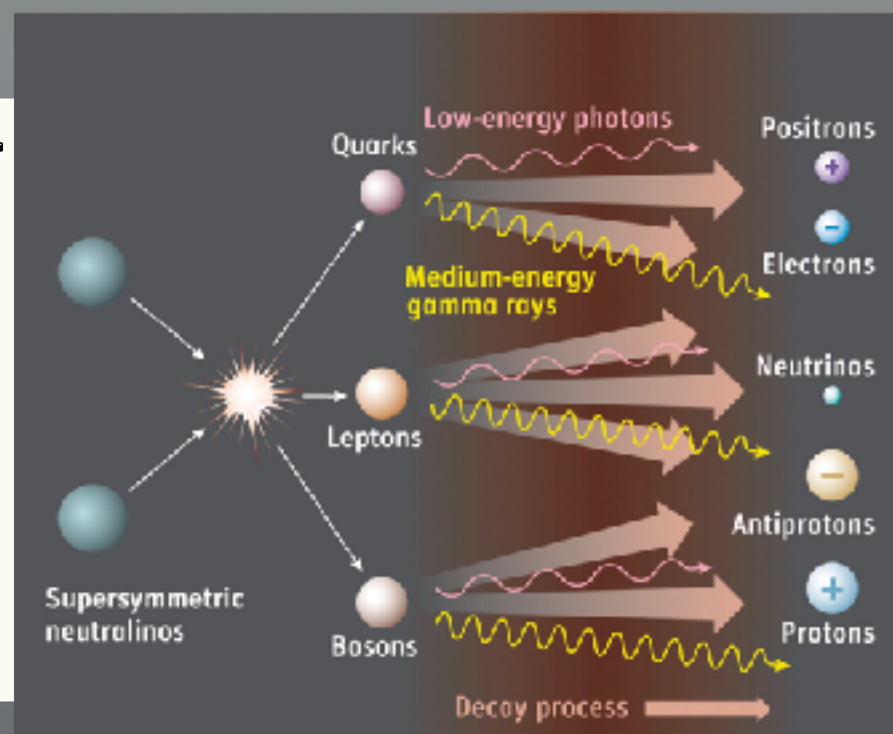
Ilias Cholis 11/14/2017

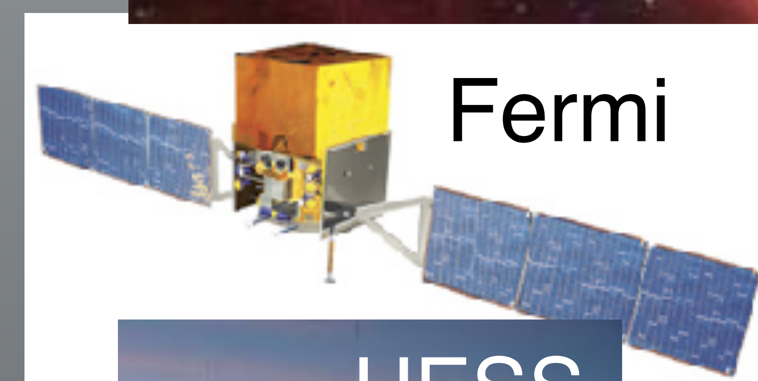
Searches for Particle Dark Matter

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





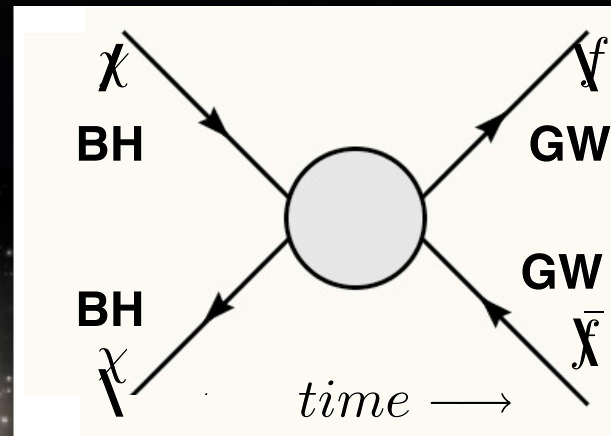


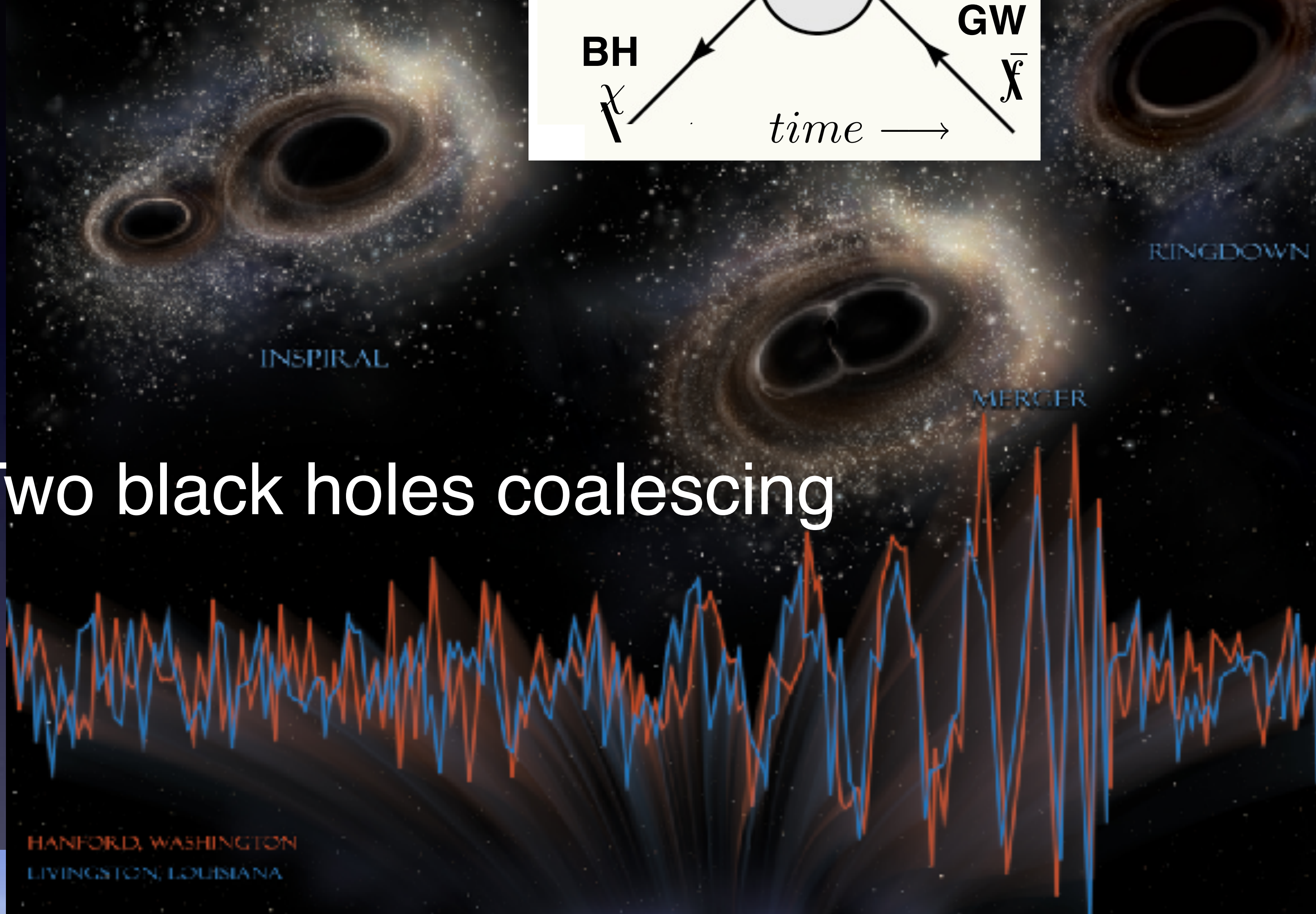


Indirect detection: annihilation into gamma-rays, cosmic rays, neutrinos

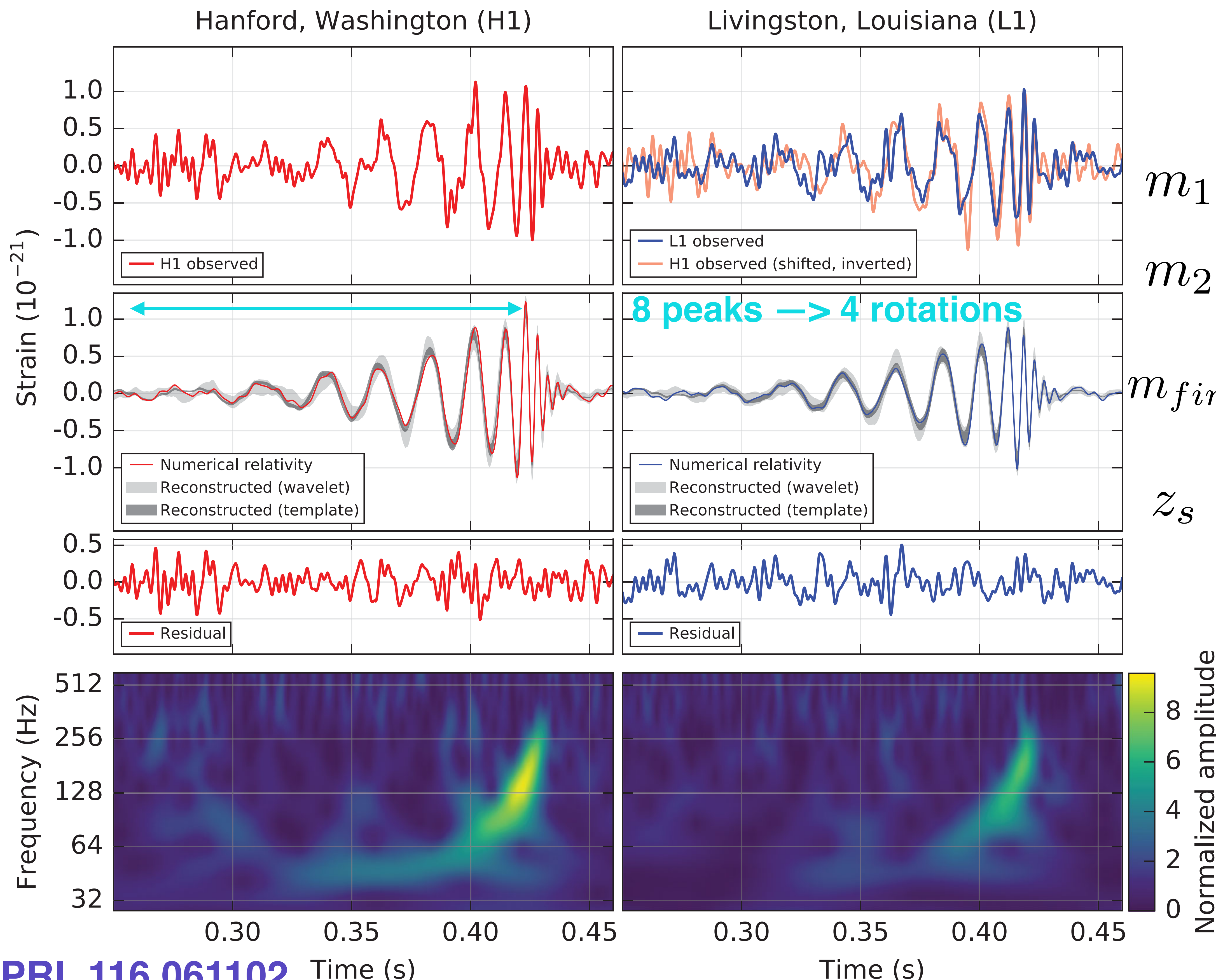
Dark matter production at colliders

What about Gravitational Waves?





The GW150914 event



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

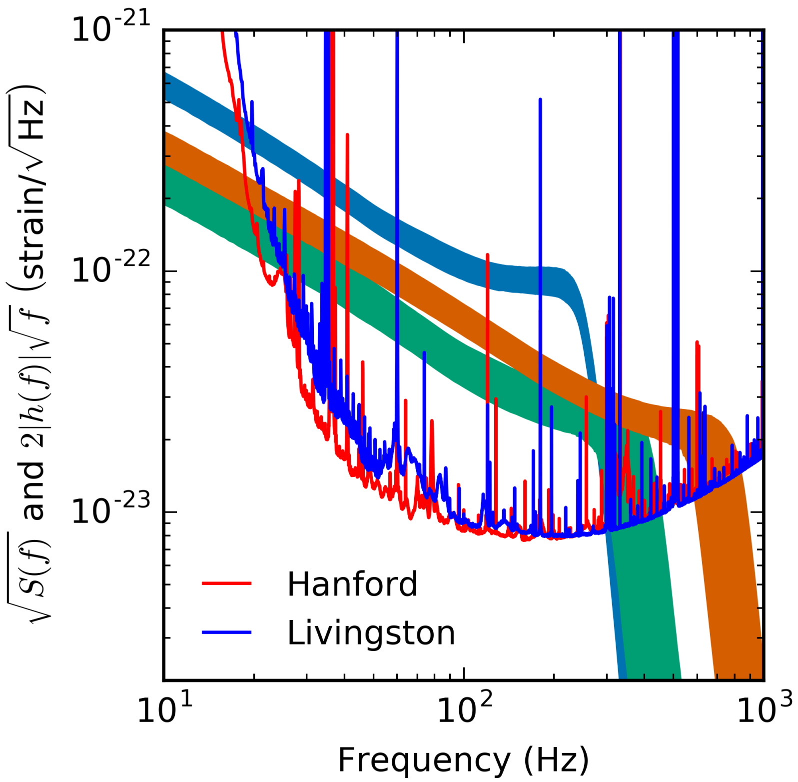
$$m_2 = 29^{+4}_{-4} M_\odot$$

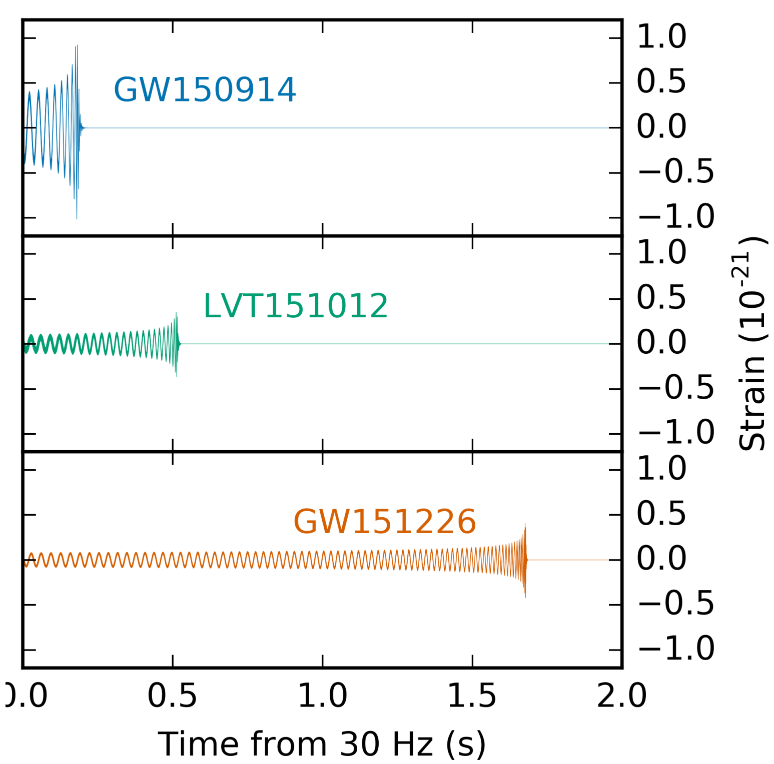
$$m_{final} = 62^{+4}_{-4} M_\odot$$

$$z_s = 0.09^{+0.03}_{-0.04}$$

PRL 116.061102

LIGO's full 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

How fast do two BHs form a binary?

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

G. D. Quinlan and S. L. Shapiro, ApJ 1989

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:

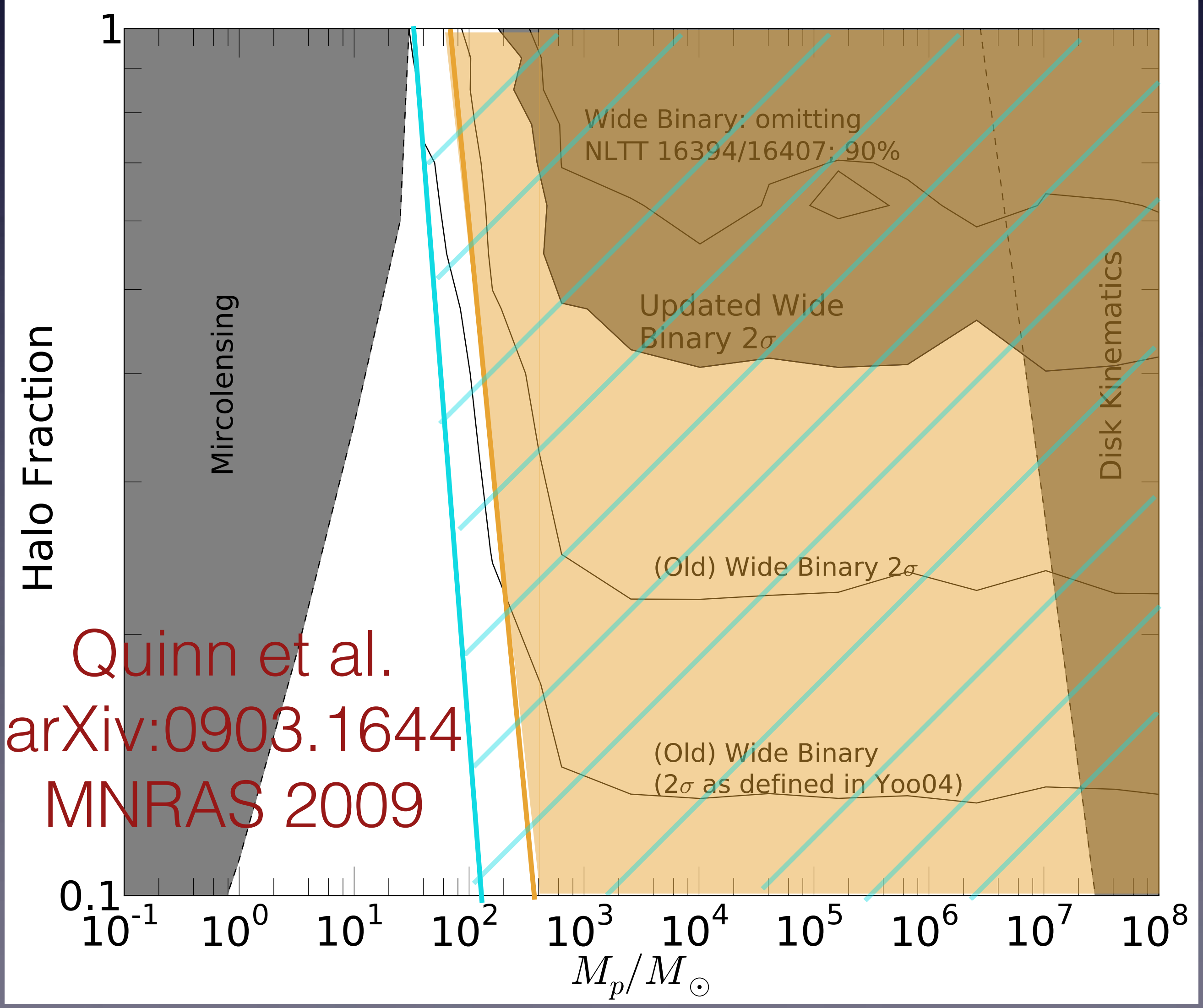
$$\mathcal{R} = 4\pi \int_0^{R_{\mathrm{vir}}} r^2 \frac{1}{2}\left(\frac{\rho_{\mathrm{nfw}}(r)}{M_{\mathrm{pbh}}}\right)^2 \langle \sigma v_{\mathrm{pbh}} \rangle \, dr$$

Making a connection with DM

Bird, IC, Munoz, Ali-Haimoud, Kamionkowski, Kovetz, Raccanelli and Riess (JHU) PRL 116.201031

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 $M_\odot$

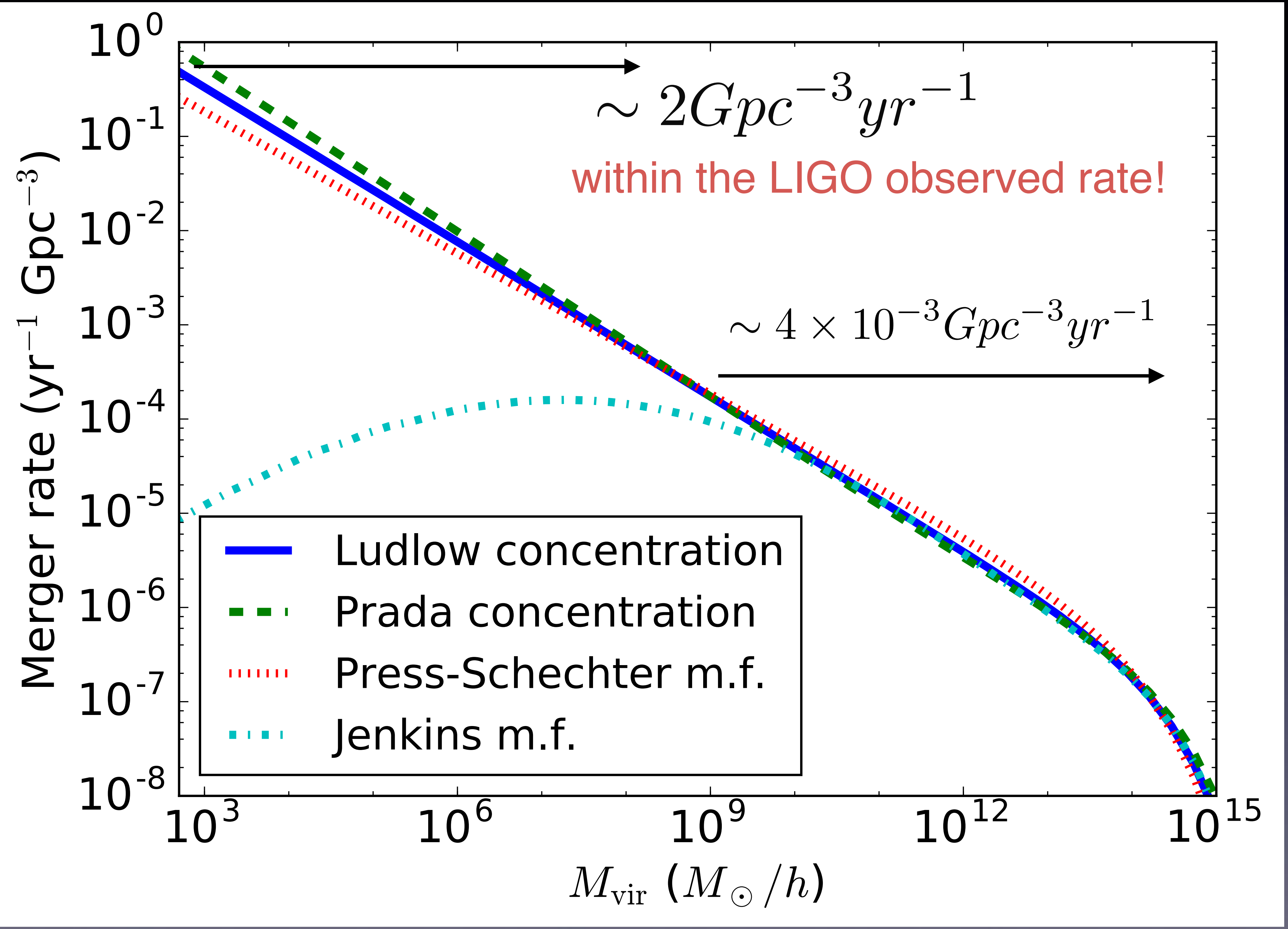
Limits on the CMB anisotropies from the observed temperature and polarization power-spectra are efficient above 100 $M_\odot$

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.

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 100s of events from PBHs (if they compose 100% of DM) by 2025.

All will 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.

Also work from:
S. Class and J. Garcia-Bellido (Phys. Dark Univ. 15 2017) for many mergers leading to generations of PBHs,
H. Nishikawa et al. 2017 on the enhancement from posible DM spikes.

One “small”  in the room:

Primordial black hole scenario for the gravitational wave event GW150914

Misao Sasaki[a], Teruaki Suyama[b], Takahiro Tanaka[c], and Shuichiro Yokoyama[d]

[a] *Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan*

[b] *Research Center for the Early Universe (RESCEU), Graduate School of Science, The University of Tokyo, Tokyo 113-0033, Japan*

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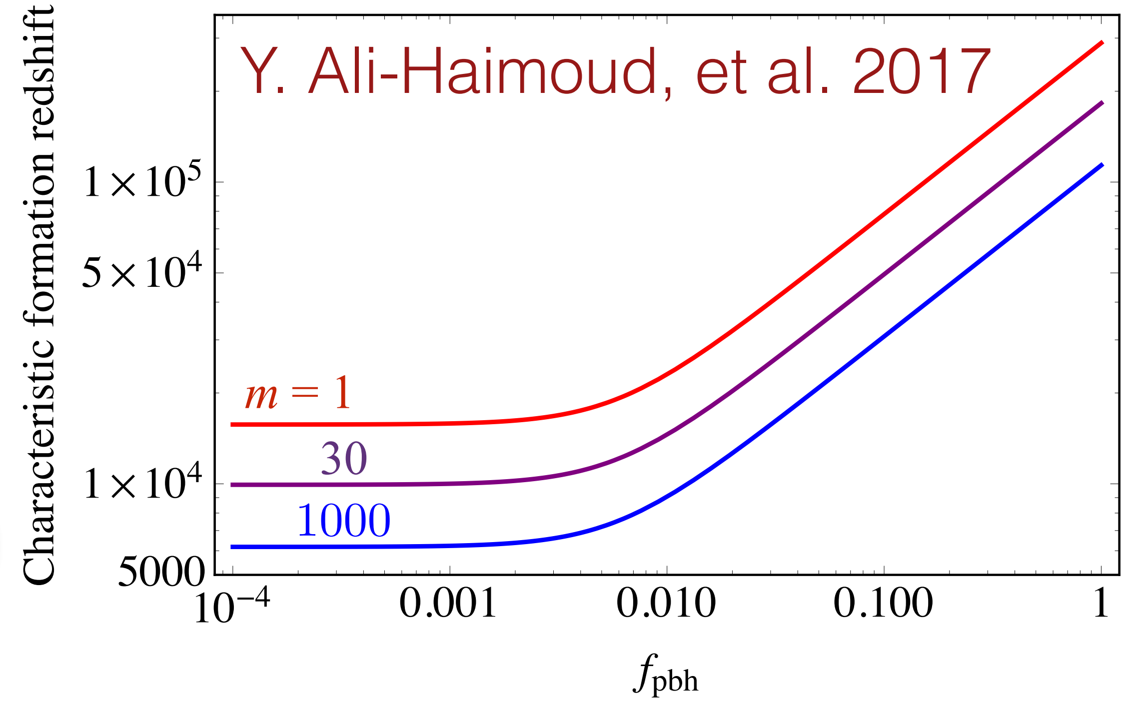
[d] *Department of Physics, Rikkyo University, Tokyo 171-8501, Japan*

Abstract

We point out that the gravitational wave event GW150914 observed by the LIGO detectors can be explained by the coalescence of primordial black holes (PBHs). It is found that the expected PBH merger rate would exceed the rate estimated by the LIGO scientific collaboration and Virgo collaboration if PBHs were the dominant component of dark matter, while it can be made compatible if PBHs constitute a fraction of dark matter. Intriguingly, the abundance of PBHs required to explain the suggested lower bound on the event rate, > 2 events/year/Gpc^3, roughly coincides with the existing upper limit set by the non-detection of the CMB spectral distortion. This implies that the proposed PBH scenario may be tested in the not-too-distant future.

~All PBH form binaries form early on
(~ matter radiation equality or earlier):



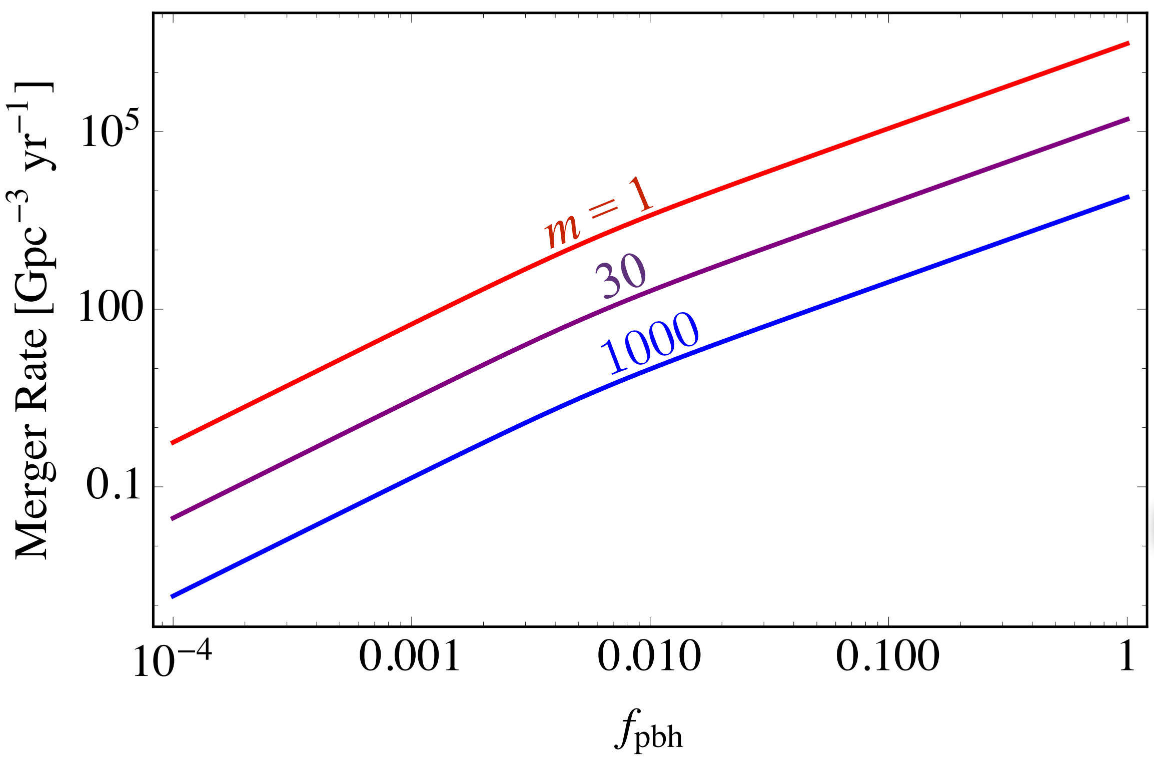


FIG. 5. PBH binary merger rate, as a function of PBH fraction $f_{\rm pbh}$ and mass $m = M/M_\odot$.

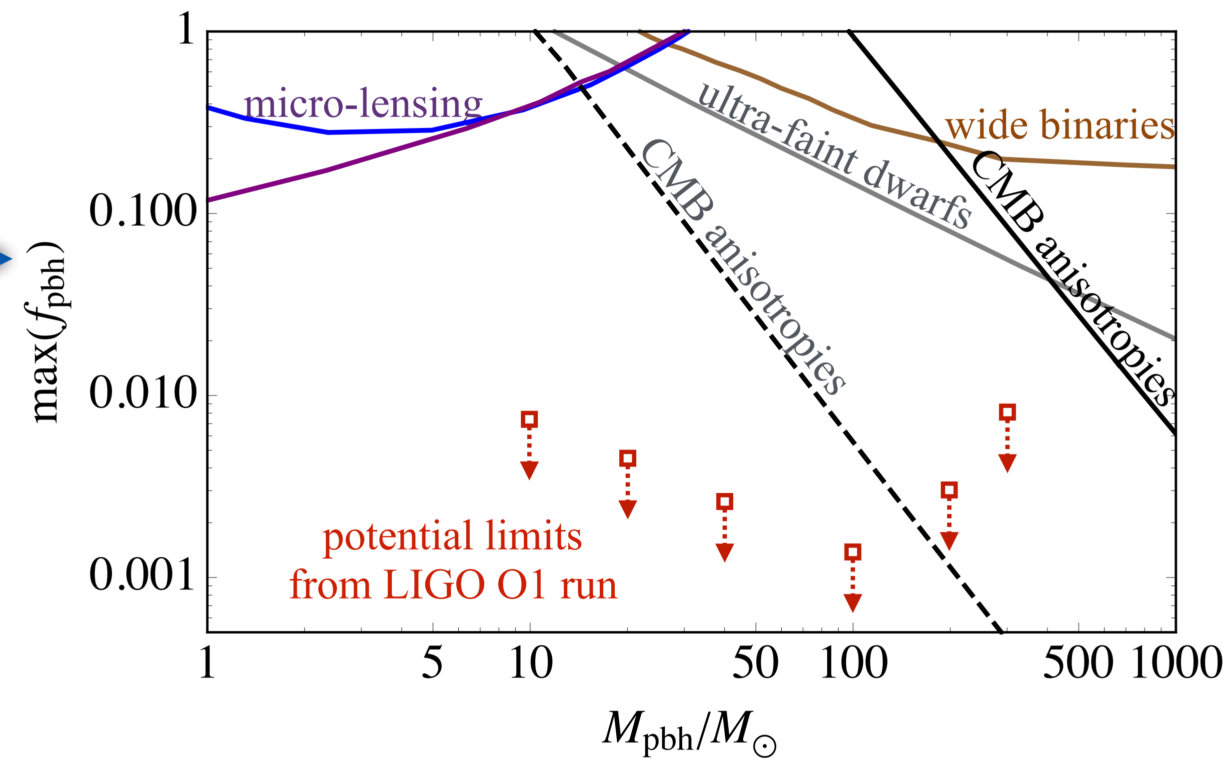
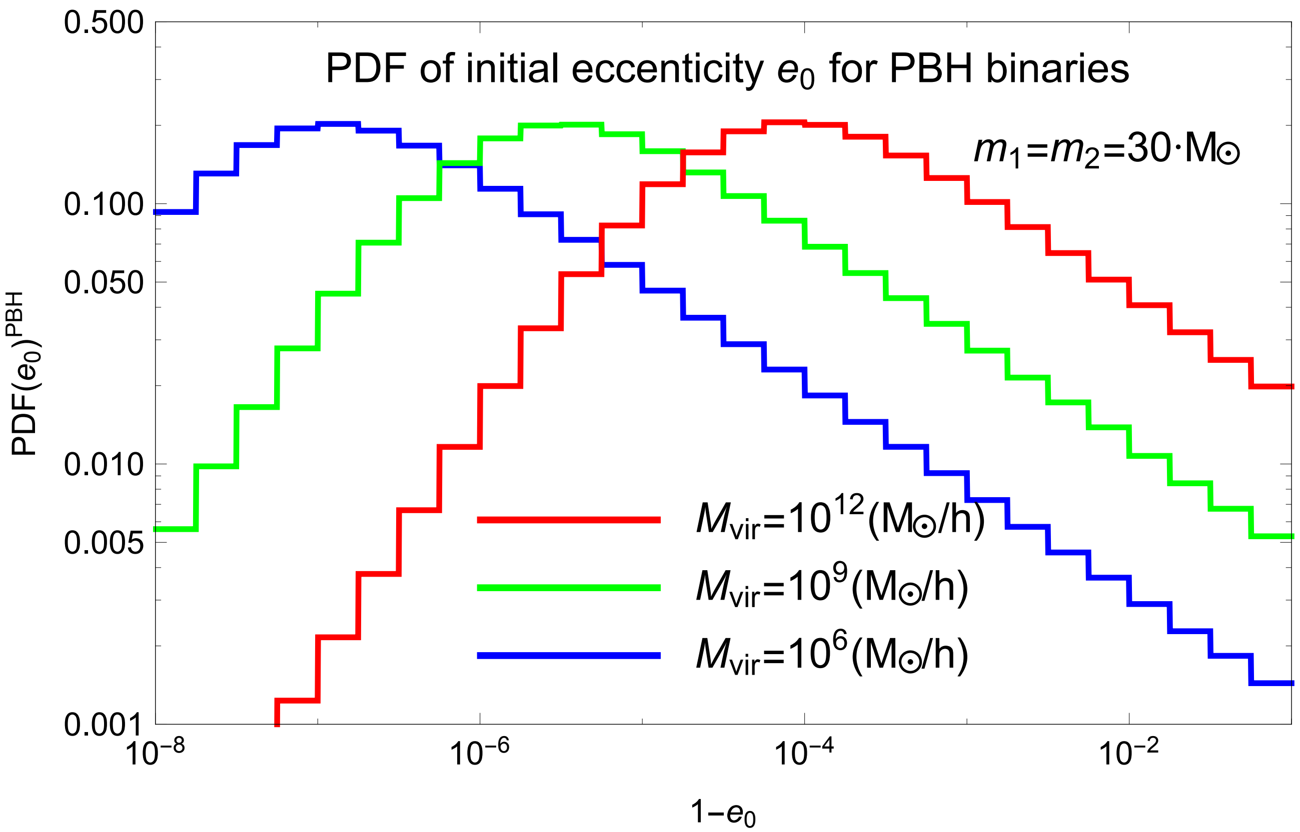


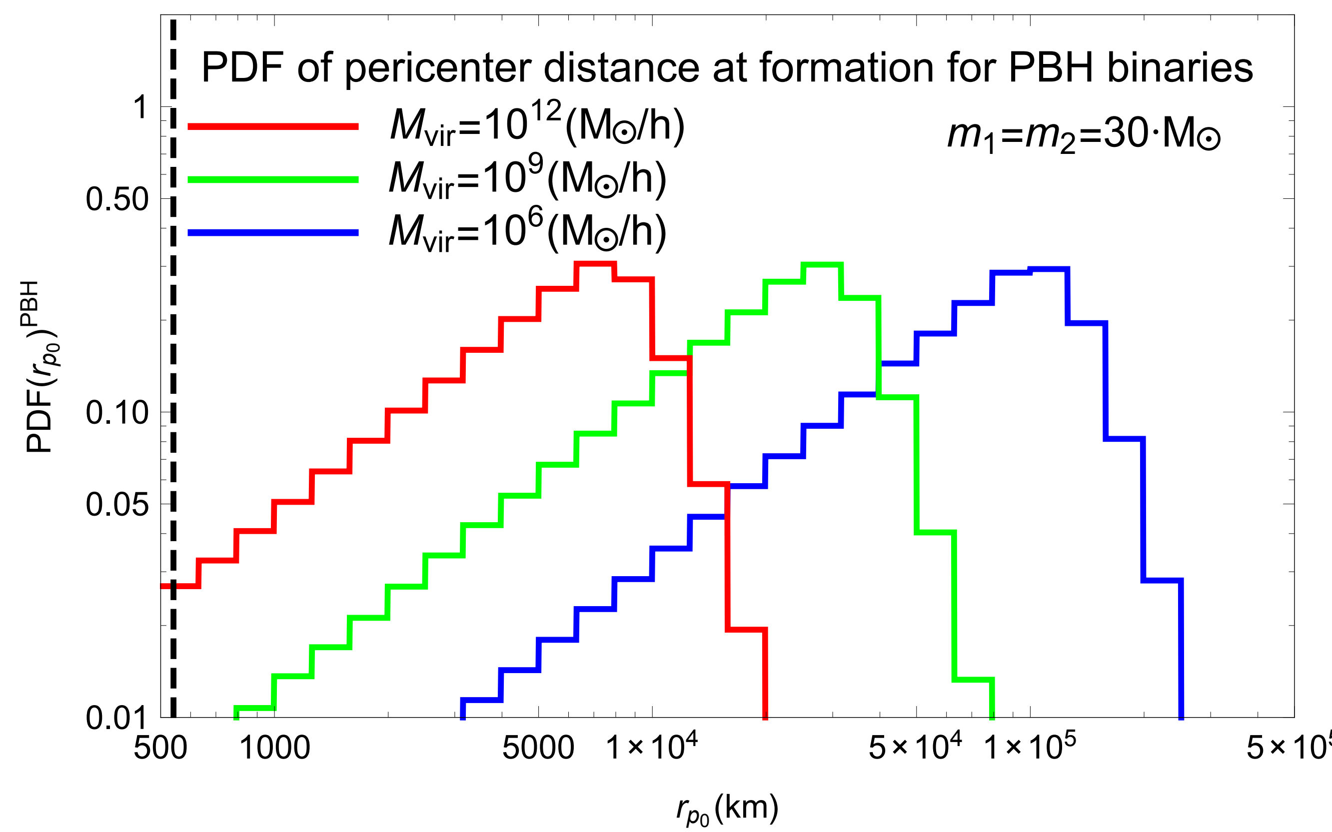
FIG. 7. Potential upper bounds on the fraction of dark matter in PBHs as a function of their mass, derived in this paper (red arrows), and assuming a narrow PBH mass function. These bounds need to be confirmed by numerical simulations. For

Large Uncertainties pertaining to the
i) formation of the first DM halos and how they affect the binaries and
ii) impact of gas accreted into the BH binaries (especially circum-binary disks)

Future directions for DM by PBHs

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





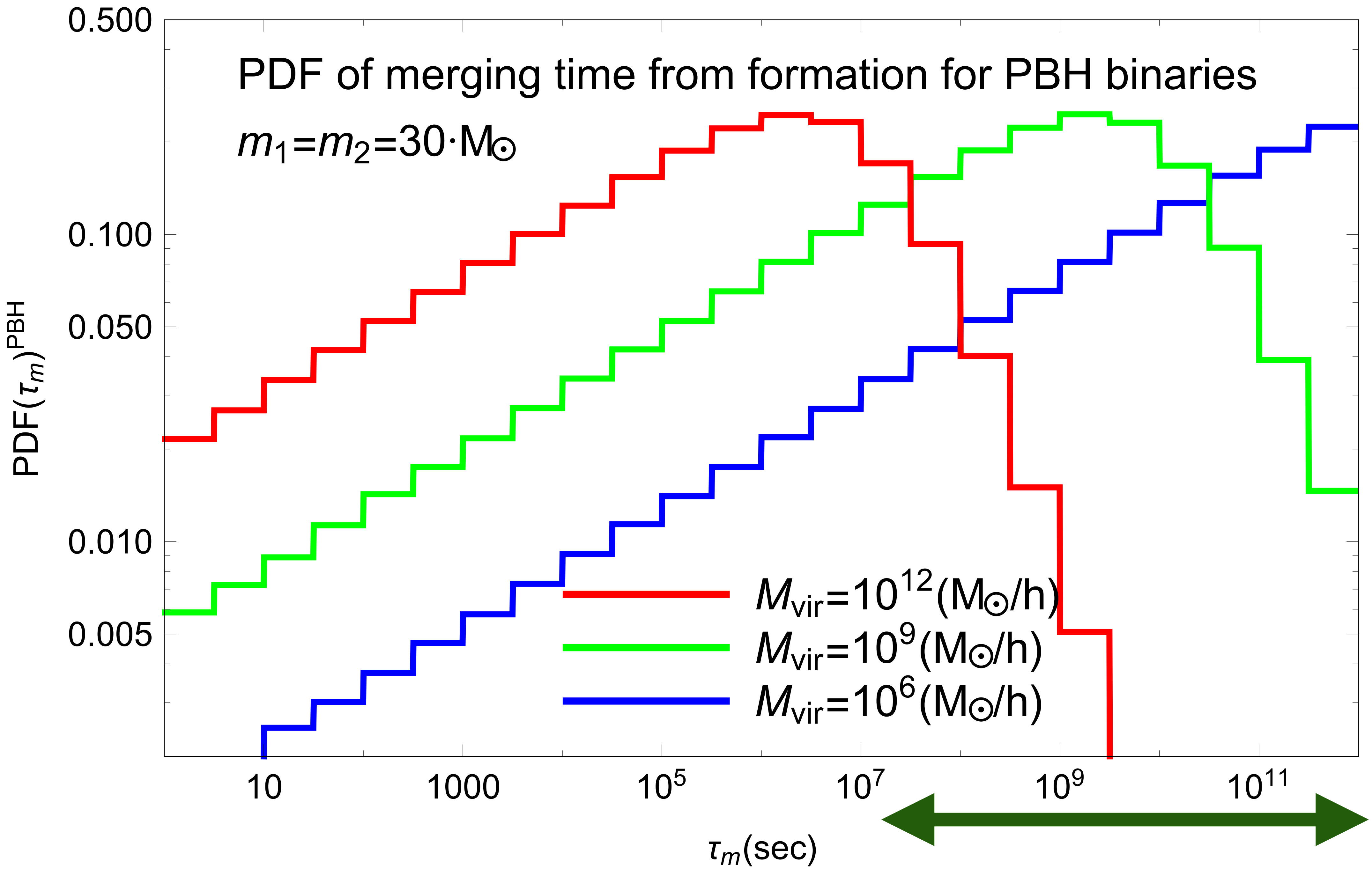
PDFs of the PBH formed binaries

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

$$r_{p_0} \simeq 2\times 10^4 km (v_{DM}/20km/s)^{-4/7} \qquad w \simeq 2/20/200\ km/s$$

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 have dramatically different timescales until merger:

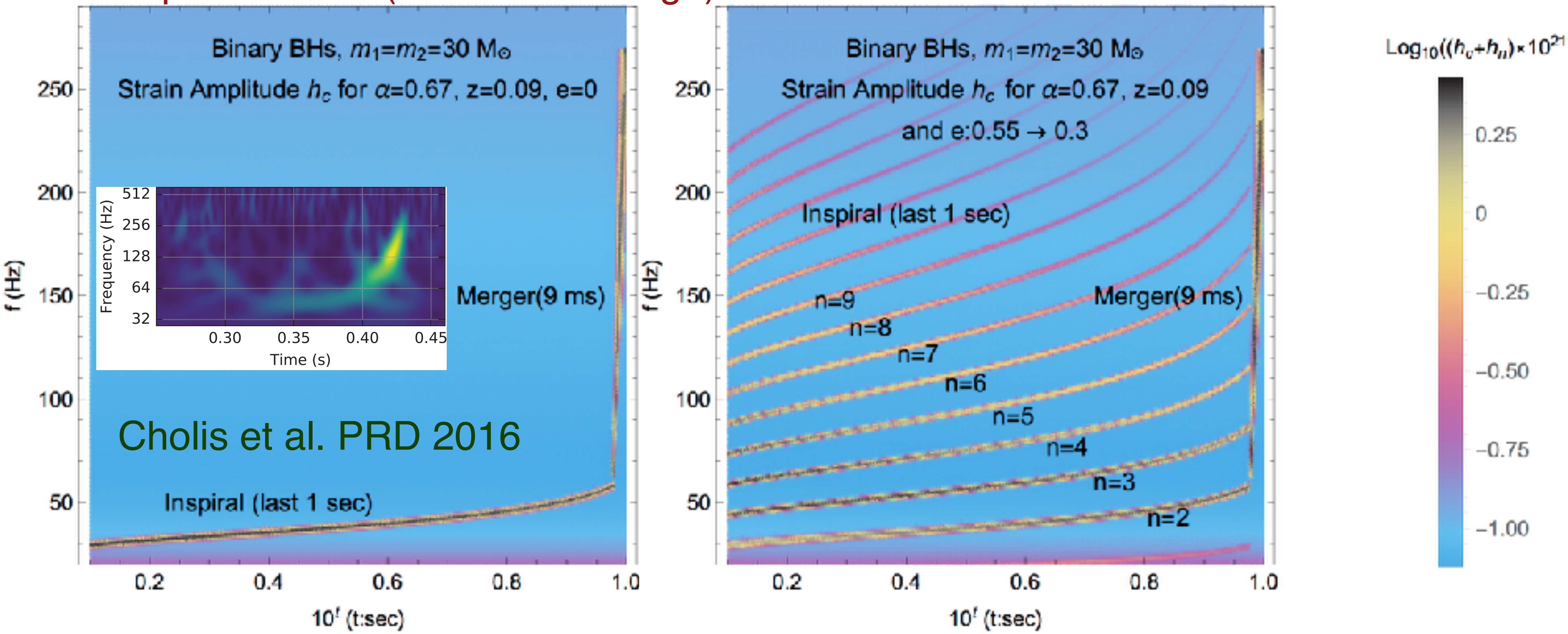


$$\tau_m = \frac{3}{85}\frac{a_0^4}{m_{tot}^3\eta}(1-e_0)^{7/2}$$

By the time of LIGO observation fully circularized.

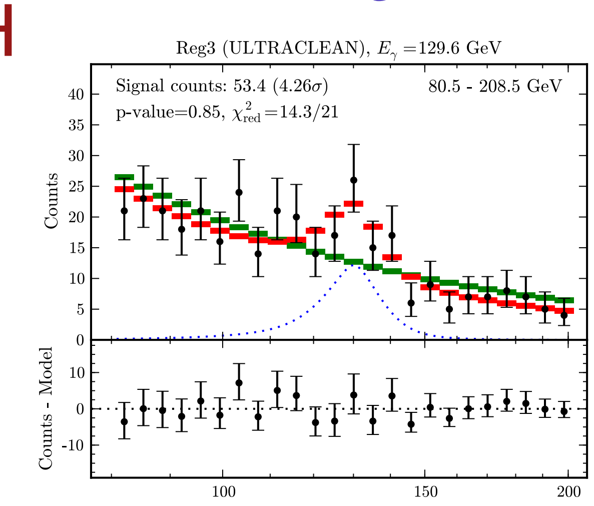
A rare case? (see many more modes of grav. waves)

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.

~ a gamma-ray line

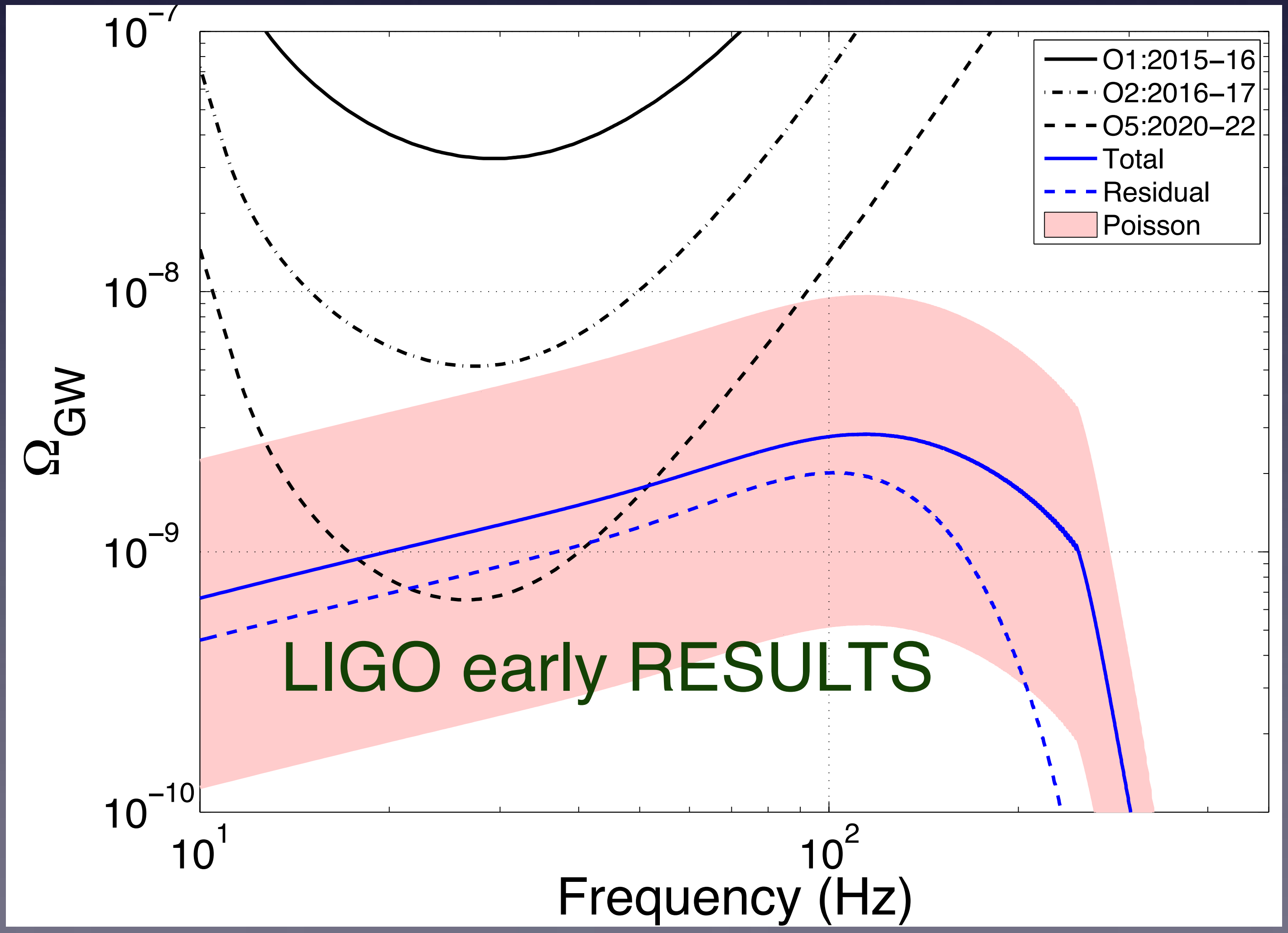


The stochastic GW background

There are many more too distant or not powerful enough to be resolved above the threshold. These create a “stochastic” grav. wave background.

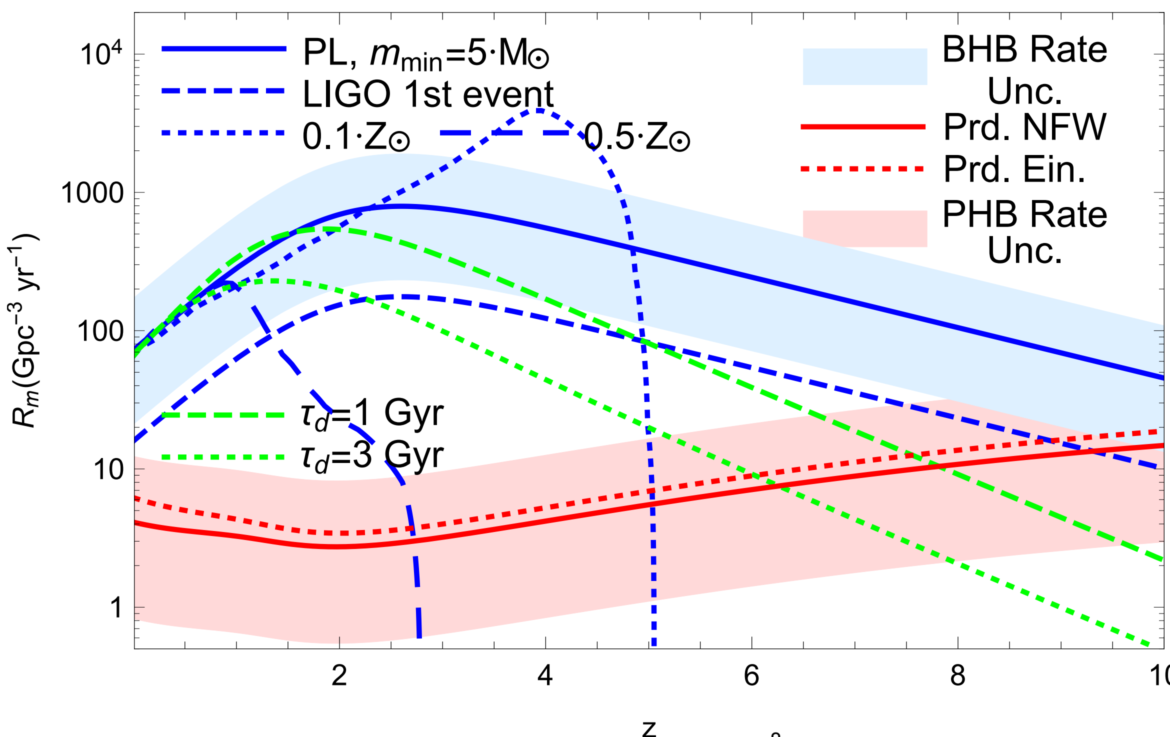
$$\Omega_{GW} = \frac{f}{\rho_c}\frac{d\rho_{GW}}{df}$$ <— energy density between f and f+df

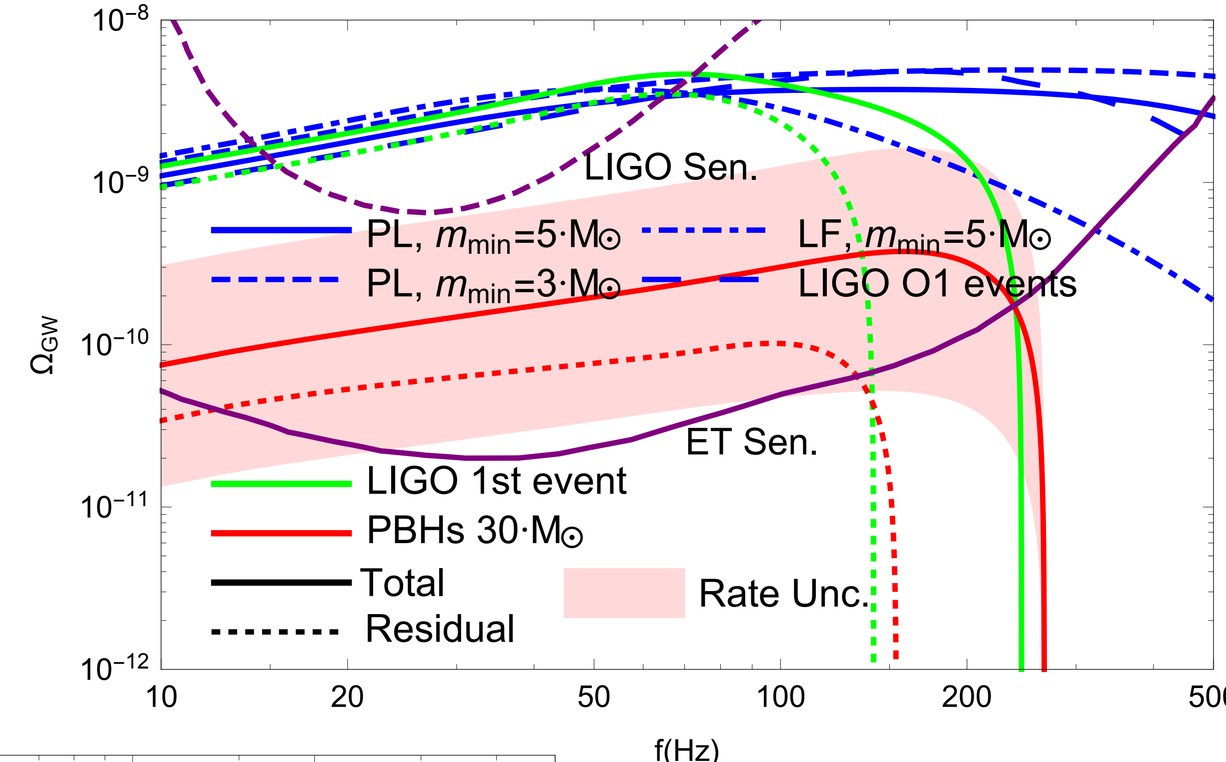
Measuring the stock. back will probe the GW sources and it is a measurable quantity within the next 5-10 years.

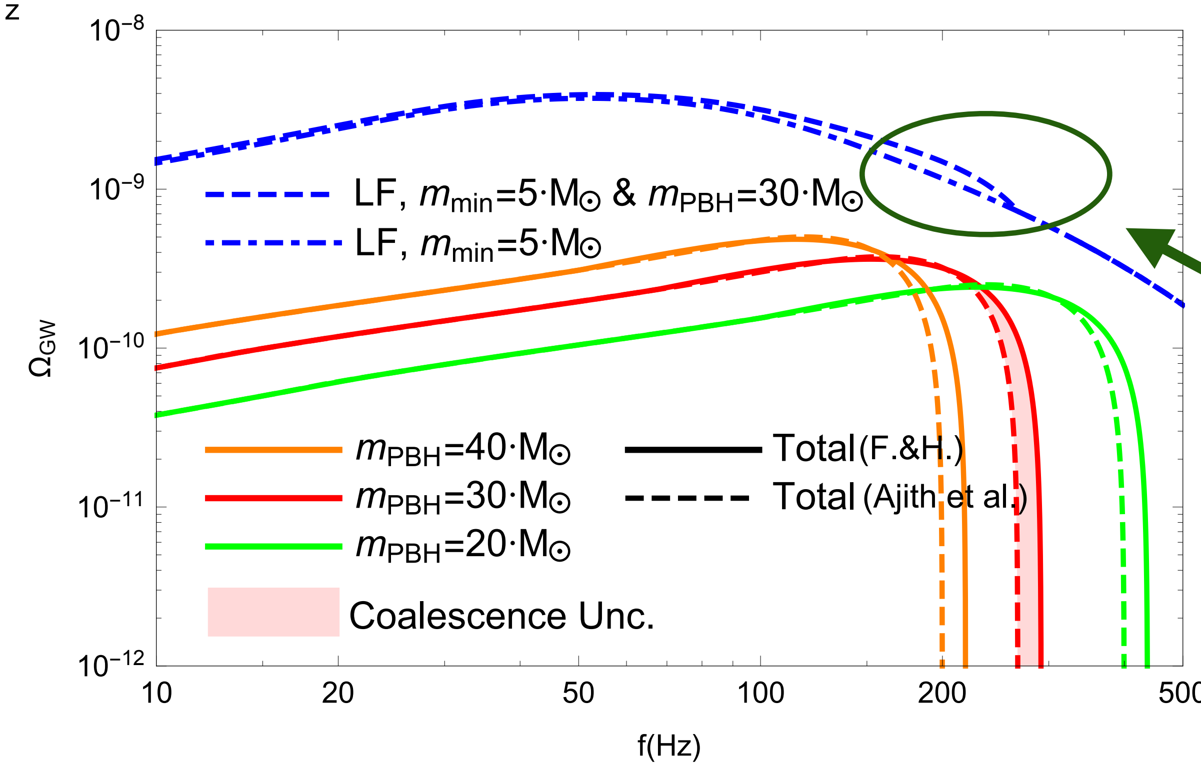


Updated Rates on the BH-BH mergers
(some room a PBH component to be seen in the Stoch. Background)

V. Mandic, S. Bird, I.C. (PRL 117.201102) arXiv:1608.06699 &
I.C. (JCAP 06 037 2017) arXiv:1609.03565





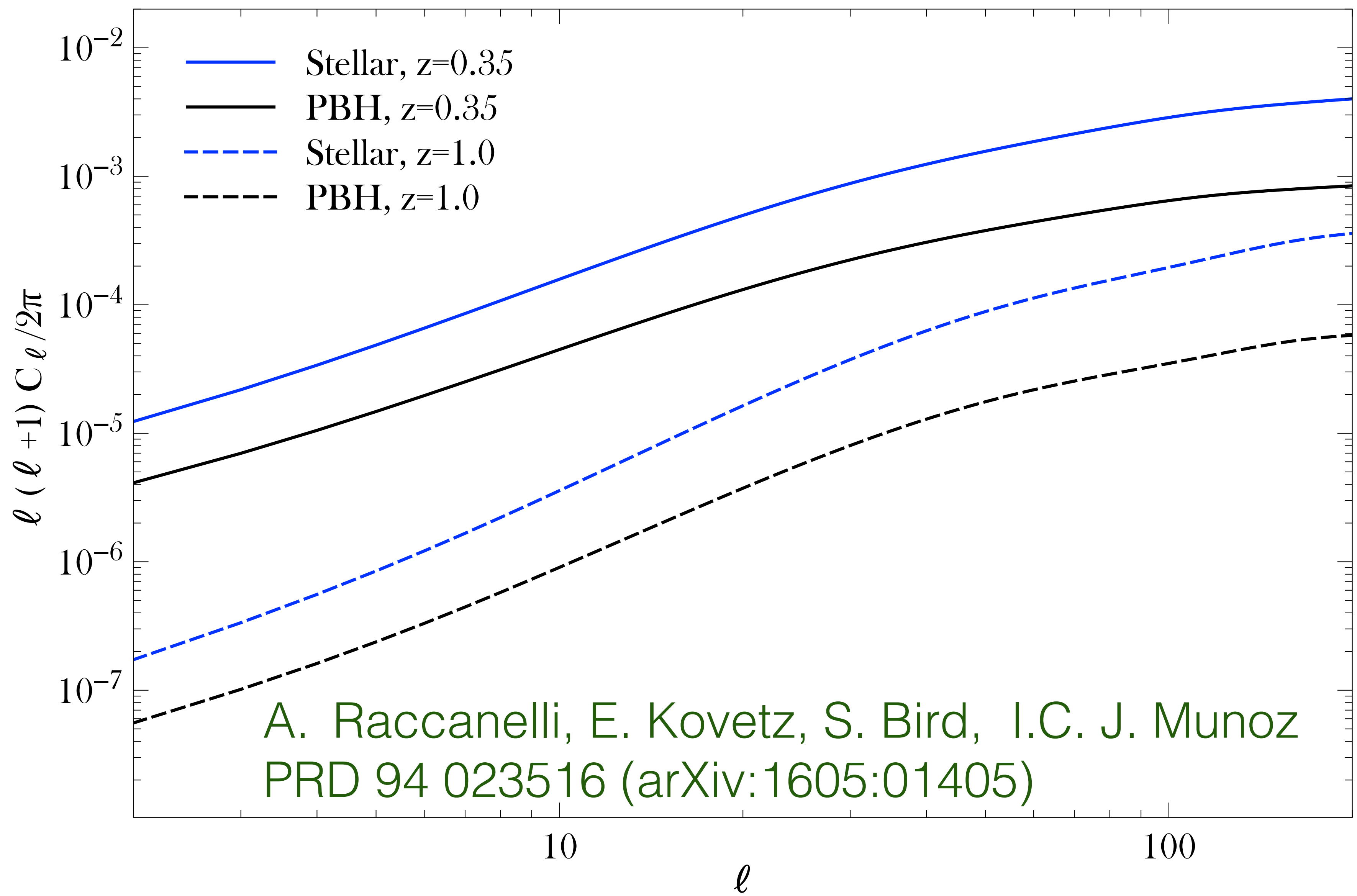


With Einstein Telescope we might be able to probe the PBHs

Another future direction:Cross-Correlations with Galaxies

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.

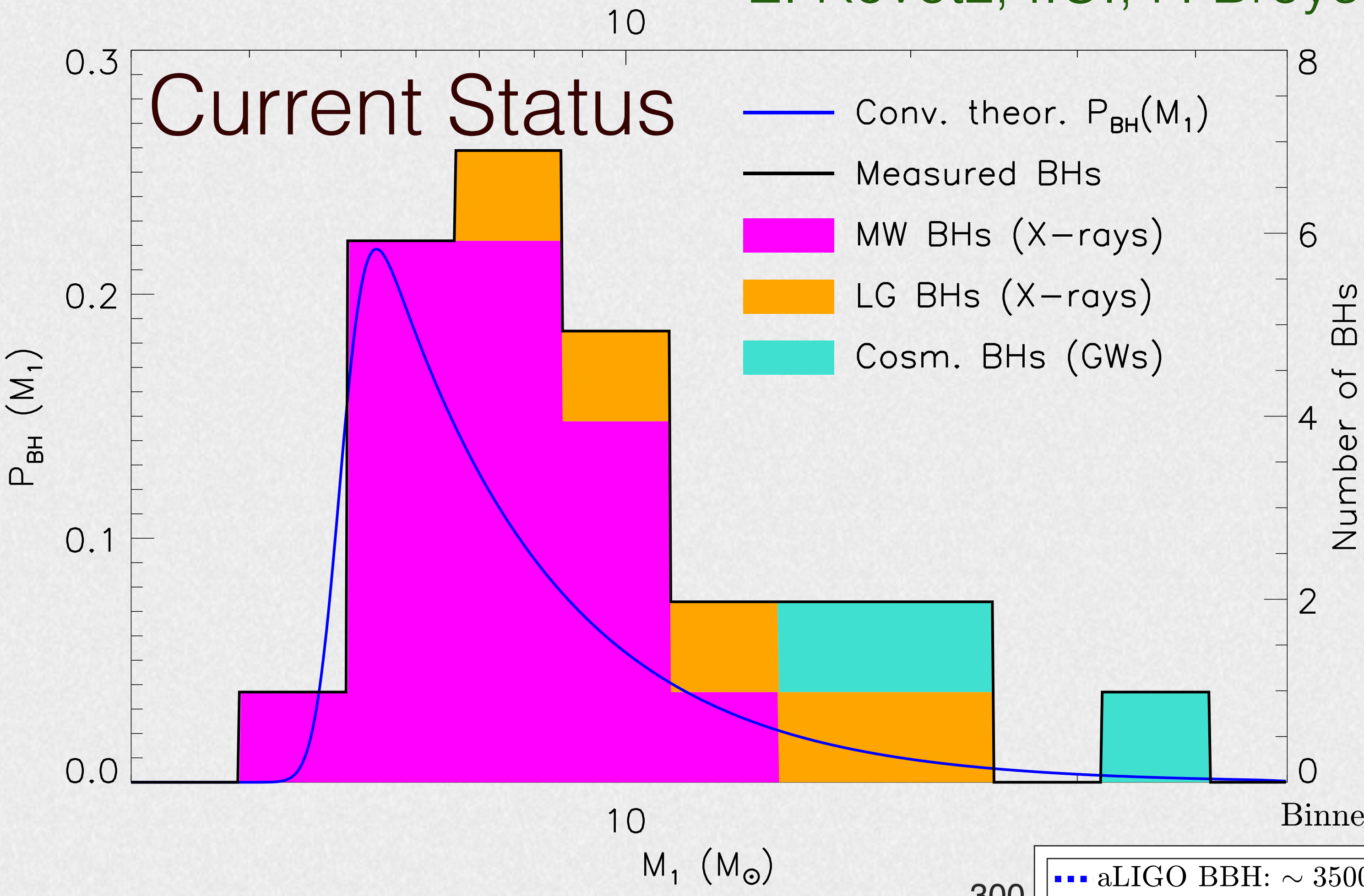
If the GW signal comes from PBHs that constitute the DM then their distribution will be more uniform on the sky.



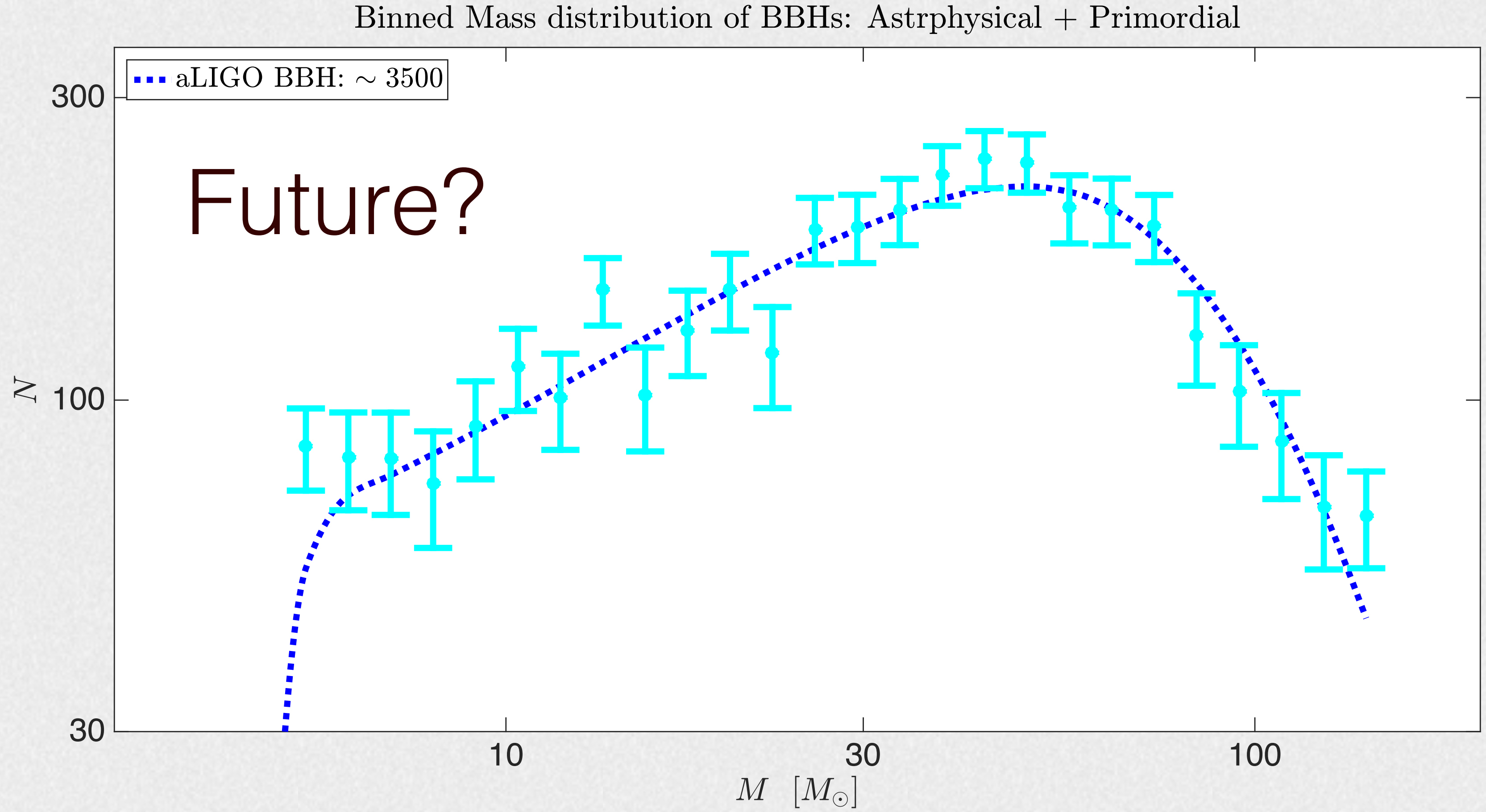
Forecasted Cross-correlation amplitude of of Galaxies with BH-BH mergers. PBH binaries have a smaller bias b (~0.5) compared to stellar BHs (since the PBH rate is dominated by the smallest DM halos)

Understanding the Black Holes Mass Function

E. Kovetz, I.C., P. Breysse, M. Kamionkowski PRD 2017

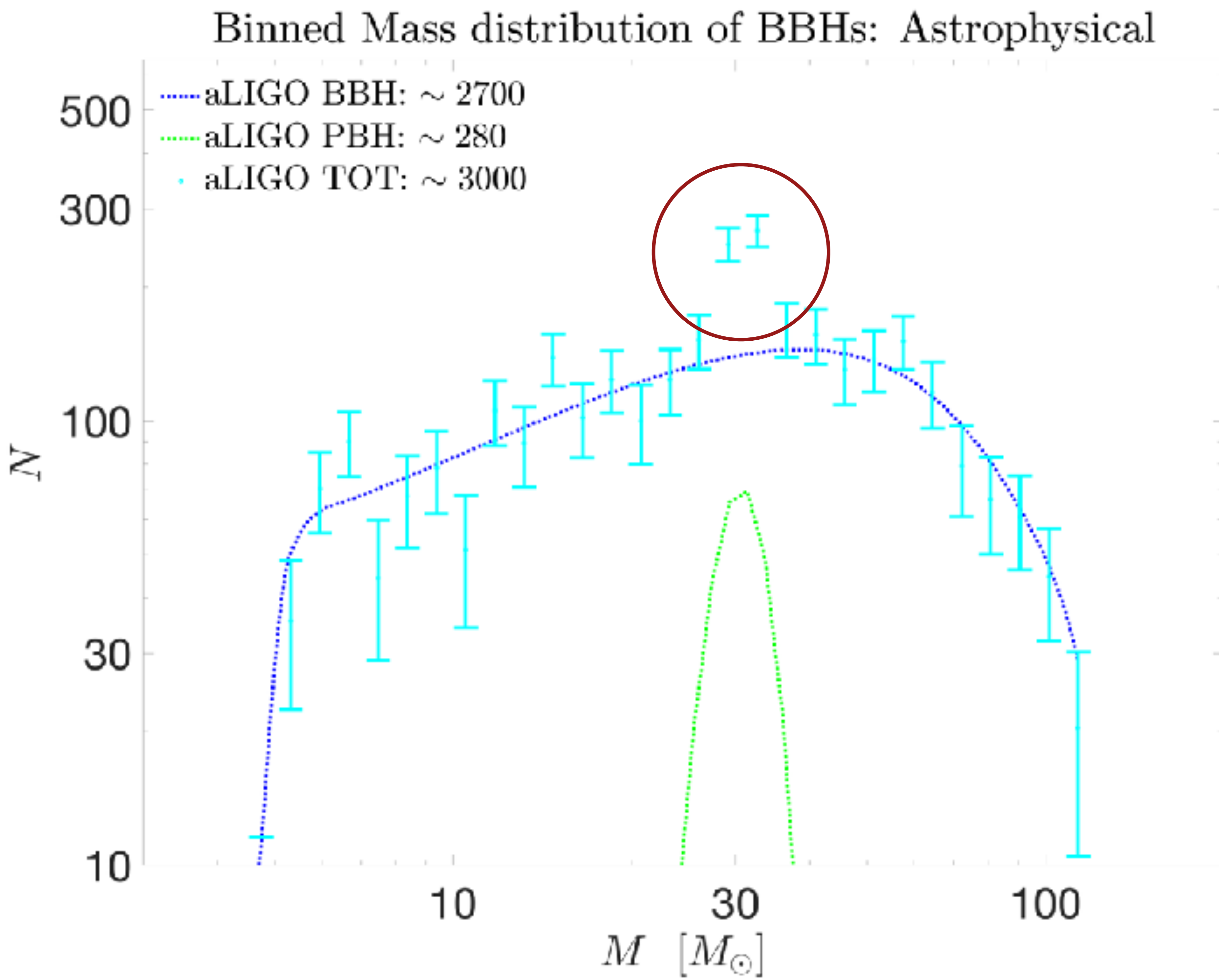


Understanding the BH mass-function can lead to understanding the progenitors of these systems

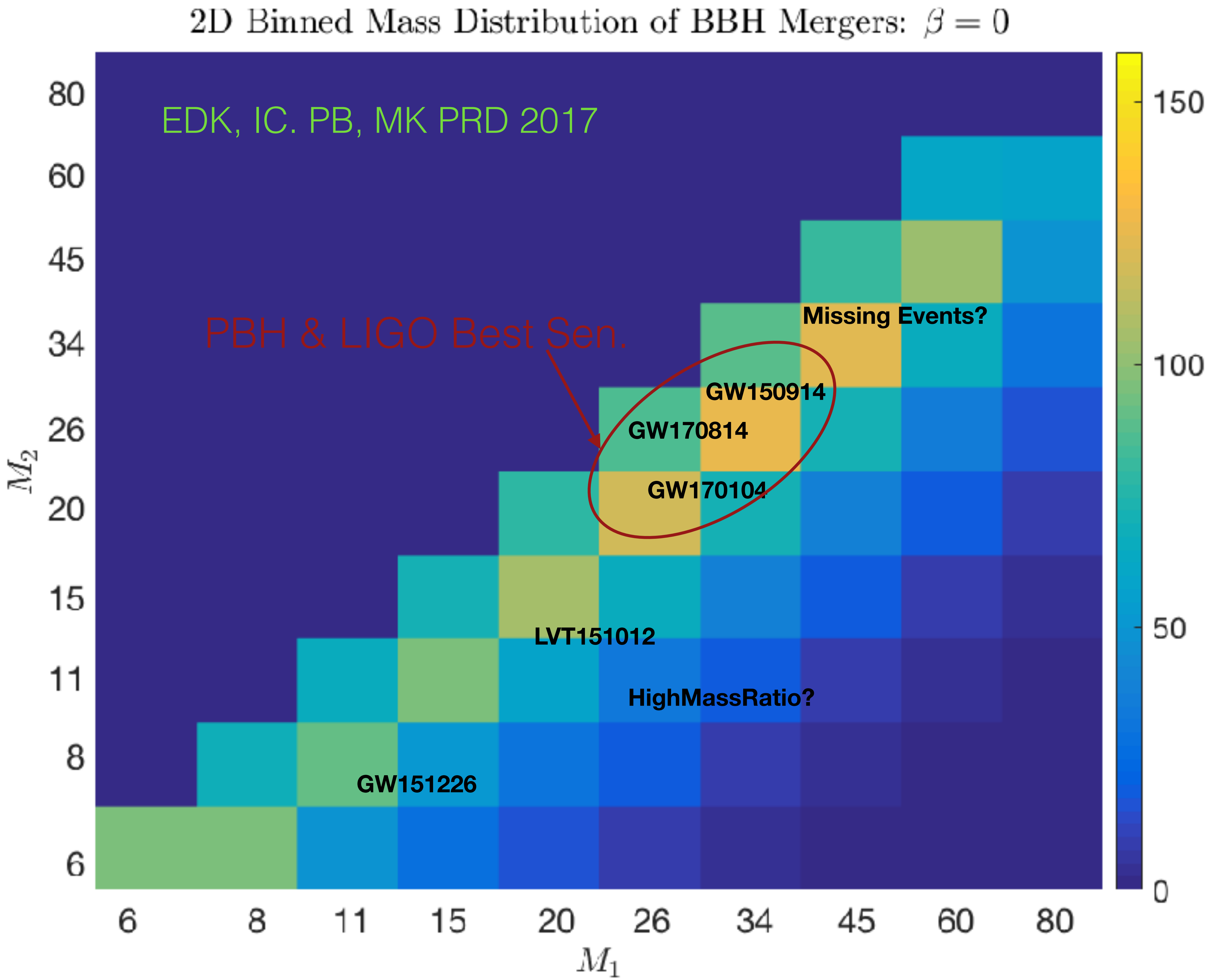


Another future possible indication for PBH: Mass-Spectrum of BH-BH binaries

E. Kovetz, et al. PRD 2017

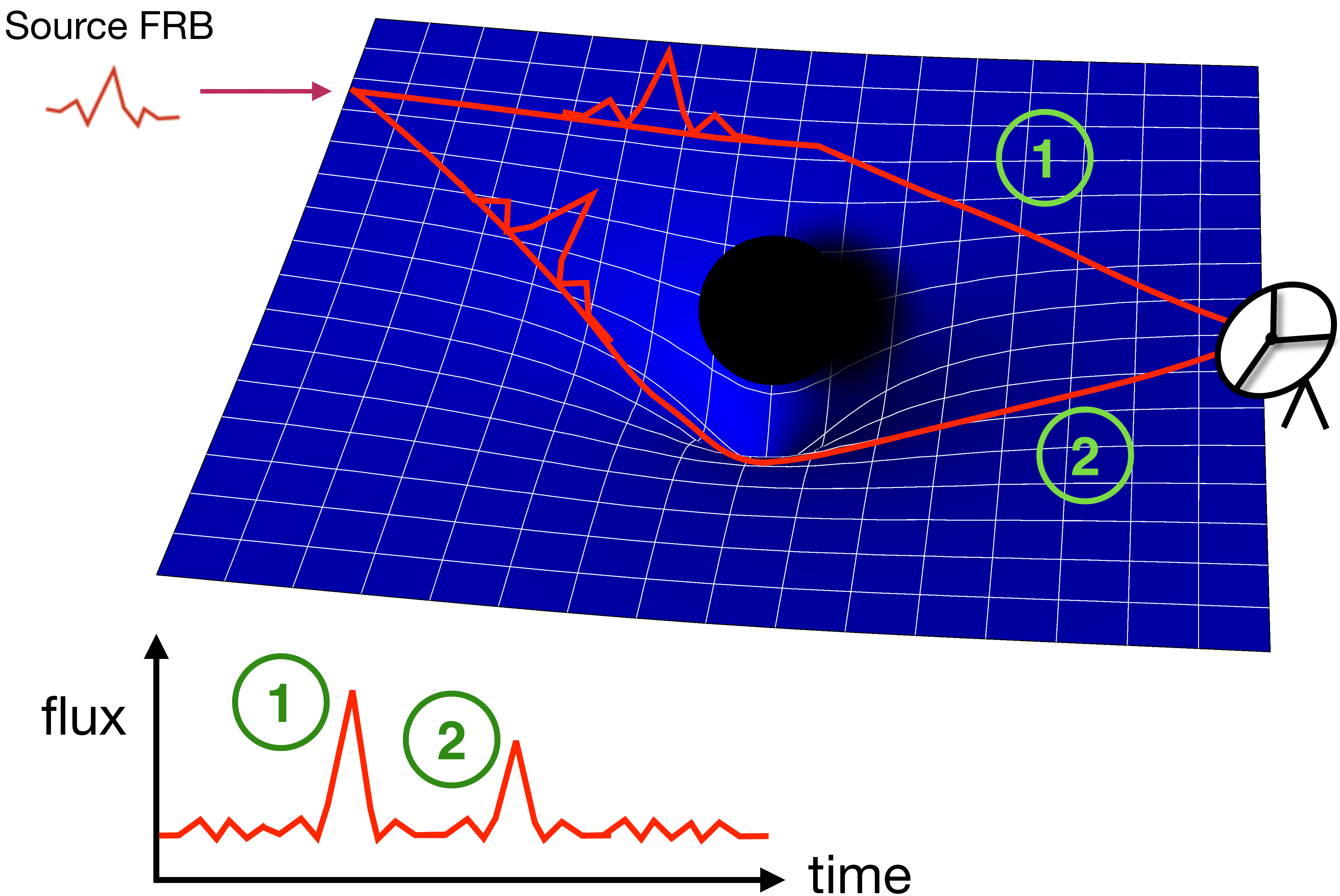


With LIGO Run 1 & 2:

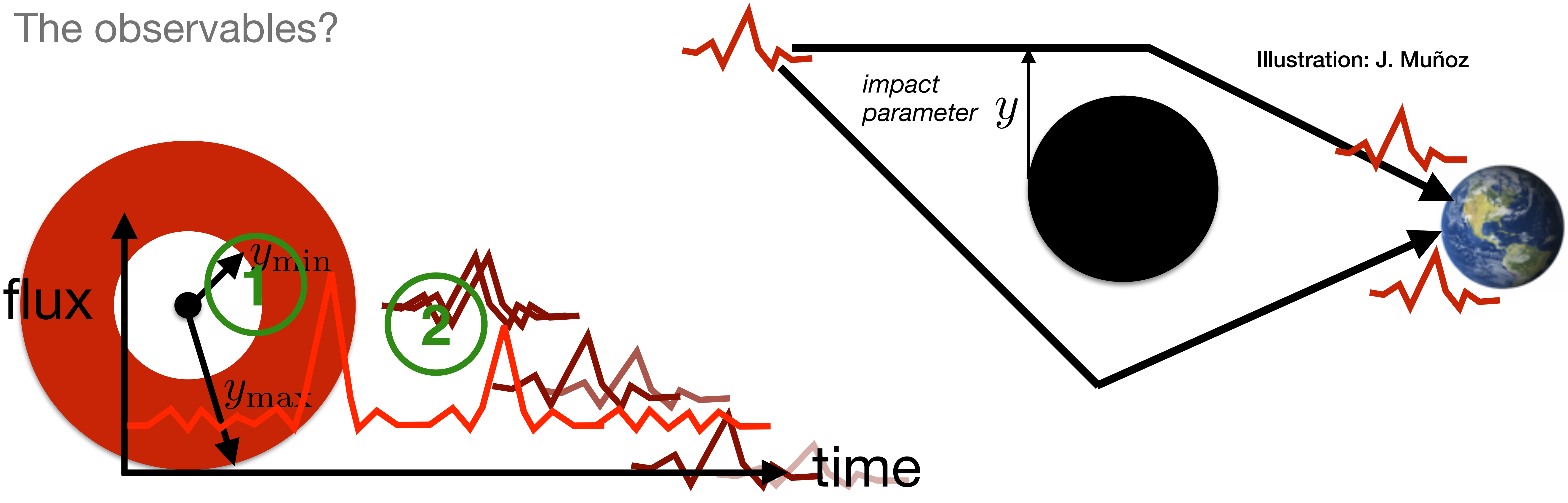


Constraining MACHO Dark Matter: FRB Lensing

(Muñoz, EDK, Dai, Kamionkowski, PRL 117 (2016))



The observables?



Flux ratio $\frac{F_1}{F_2} = g(y)$ $\longrightarrow$ $y < y_{\rm max}$ (both images need be detectable)

Time delay $\boldsymbol{\Delta t} = 4M_L f(y) \sim 1\,\mathrm{ms} \times \frac{\mathrm{M_L}}{30\,\mathrm{M}_\odot}$ $\xrightarrow{>\Delta t_{\rm int}}$ $y > y_{\rm min}(M_L, z_s)$

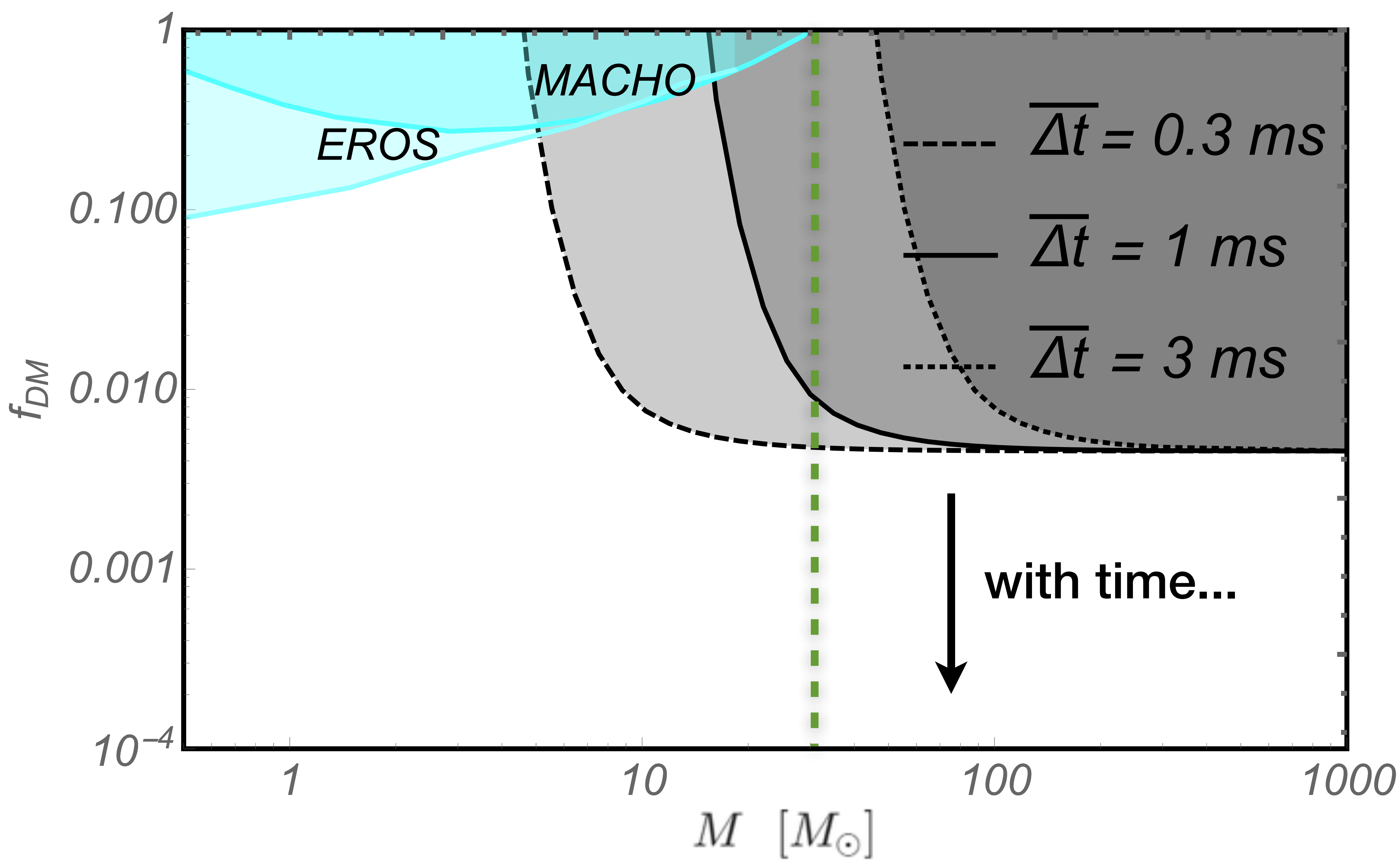
Constraining MACHO Dark Matter: FRB Lensing

(Muñoz, EDK, Dai, Kamionkowski, PRL 117 (2016))

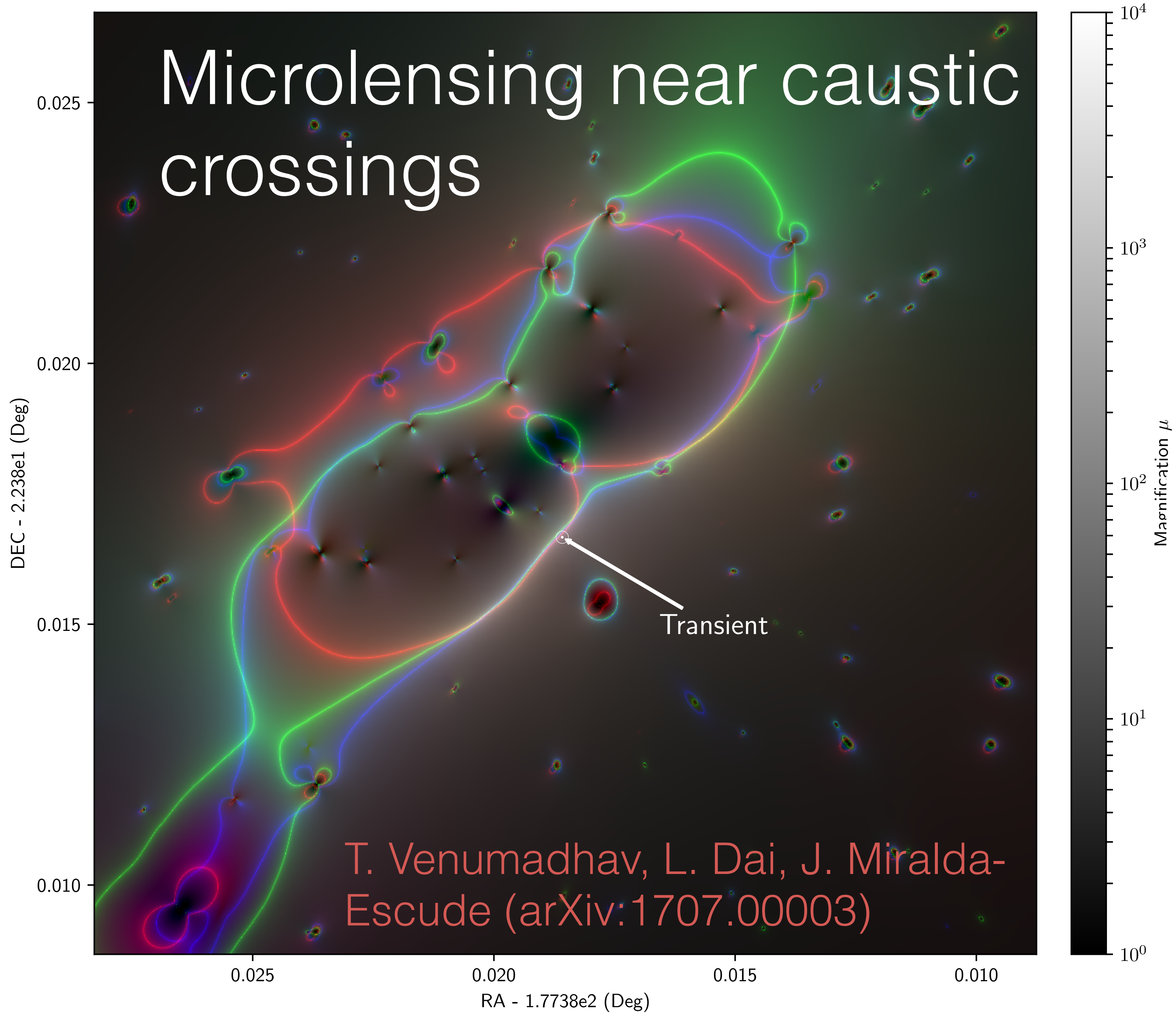
CHIME experiment: expected rate of $\mathcal{O}(10^4)$ FRBs per year

$$N_{\rm lensed} = \bar{\tau} N_{\rm FRB} \xrightarrow{\bar{\tau} \sim 1\%} N_{\rm lensed} = 10 - 100\ {\rm yr}^{-1}$$

A null detection will close the “window”:



Other ideas on how to constrain PBH DM:



Radio and X-ray emission from gas accretion in the Galactic Center

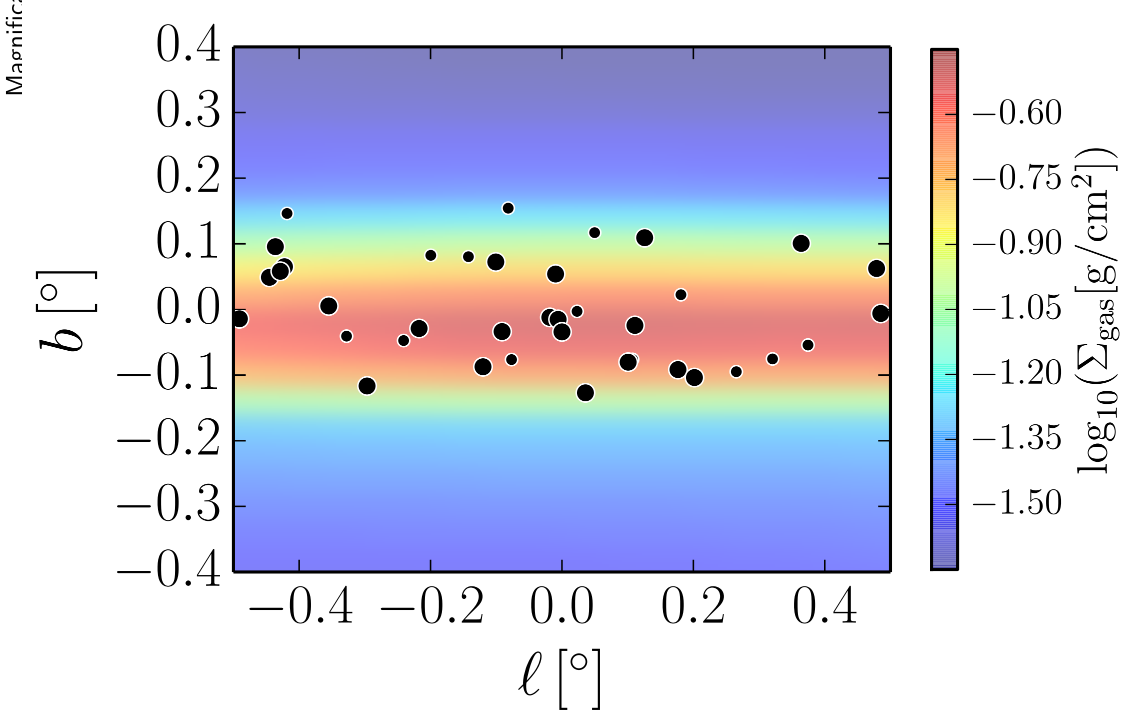
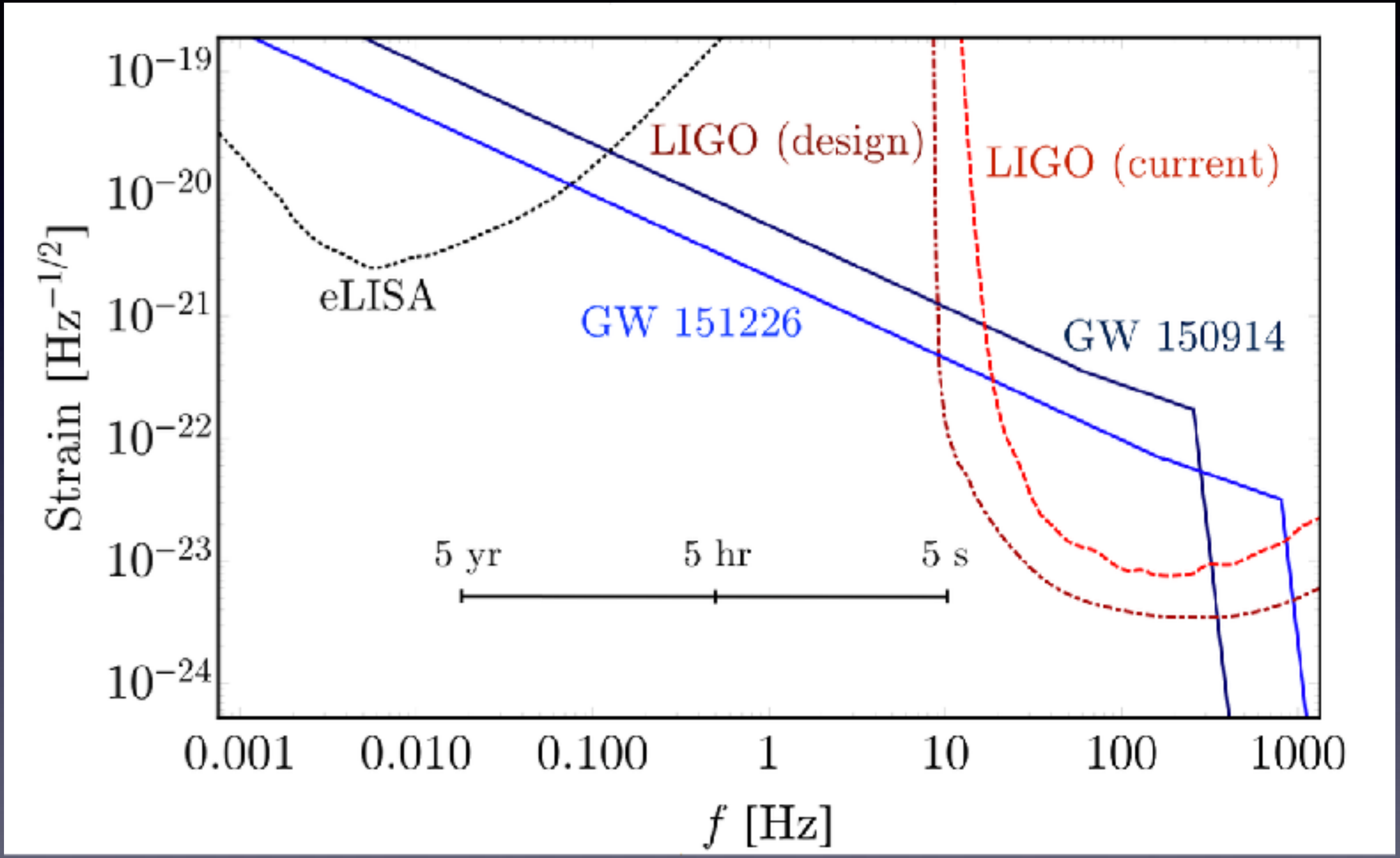


FIG. 2. Example of the distribution of 30 $M_\odot$ PBHs detectable by VLA in the ROI, for one Monte Carlo realization. The colored background depicts the column gas density. The size of the black points is proportional to the PBH velocity in the range $0.3 - 3$ km/s (for detectable PBHs).

D. Gaggero, G. Bertone, F. Calore et al. PRL 2017

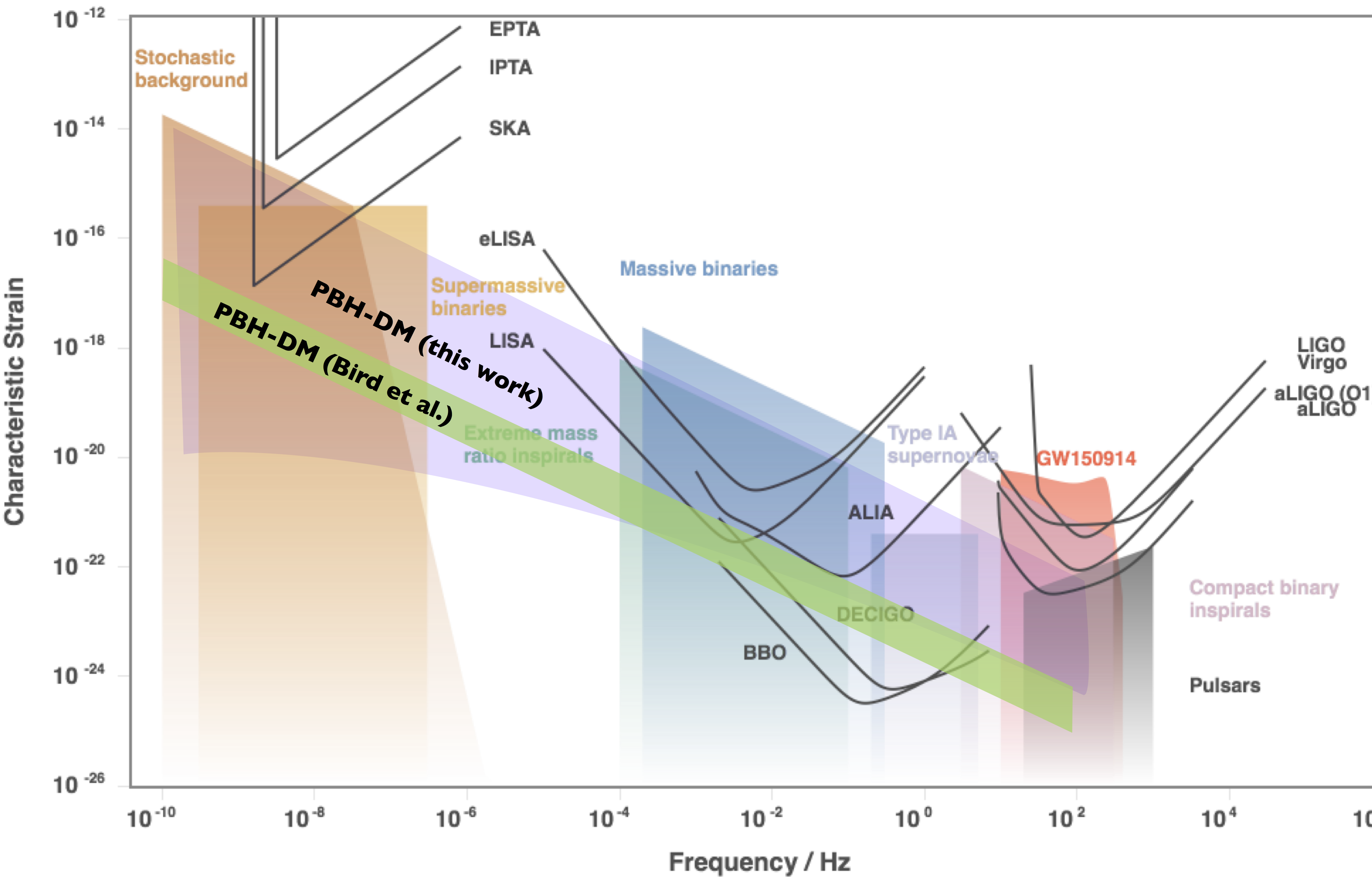
Combining space and ground-based observations

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



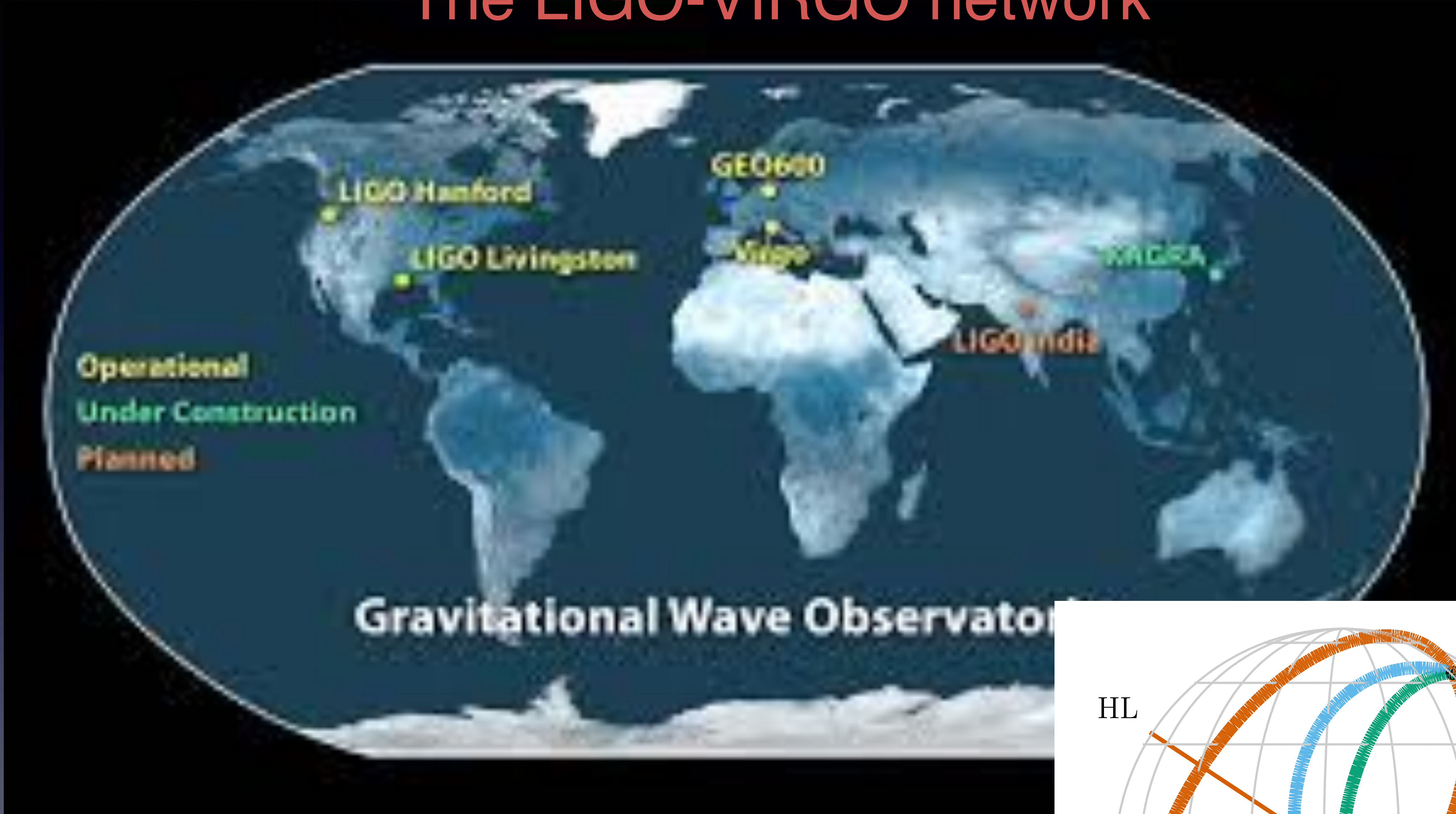
We will be able to observe the evolution of individual systems over periods of years, thus measure the evolving eccentricities, masses.

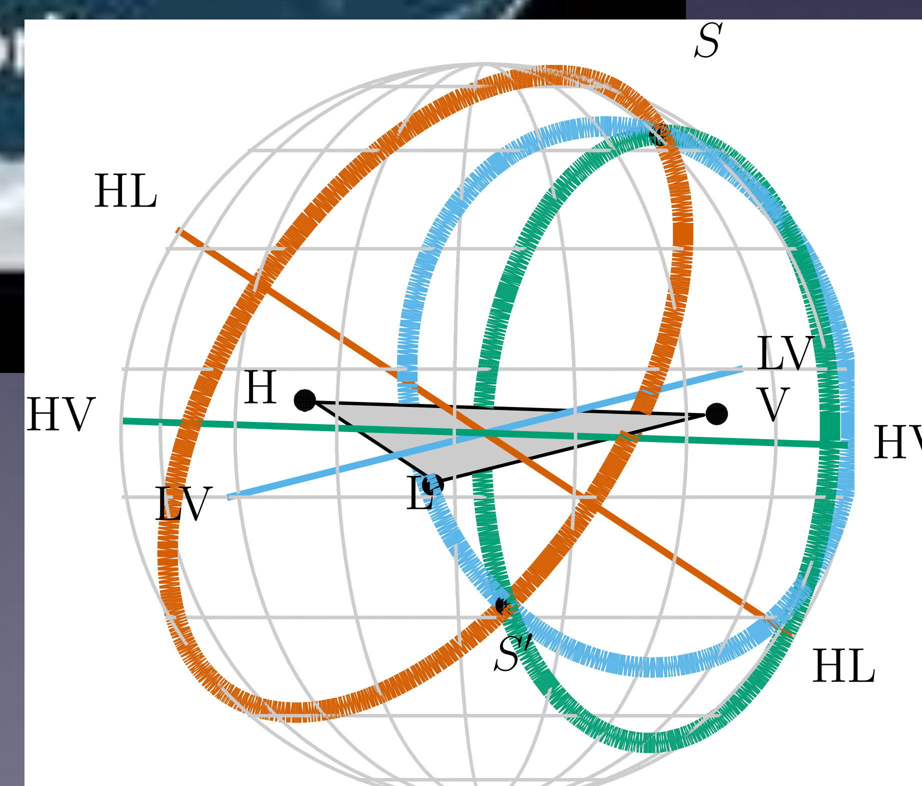
And at even lower-frequencies:



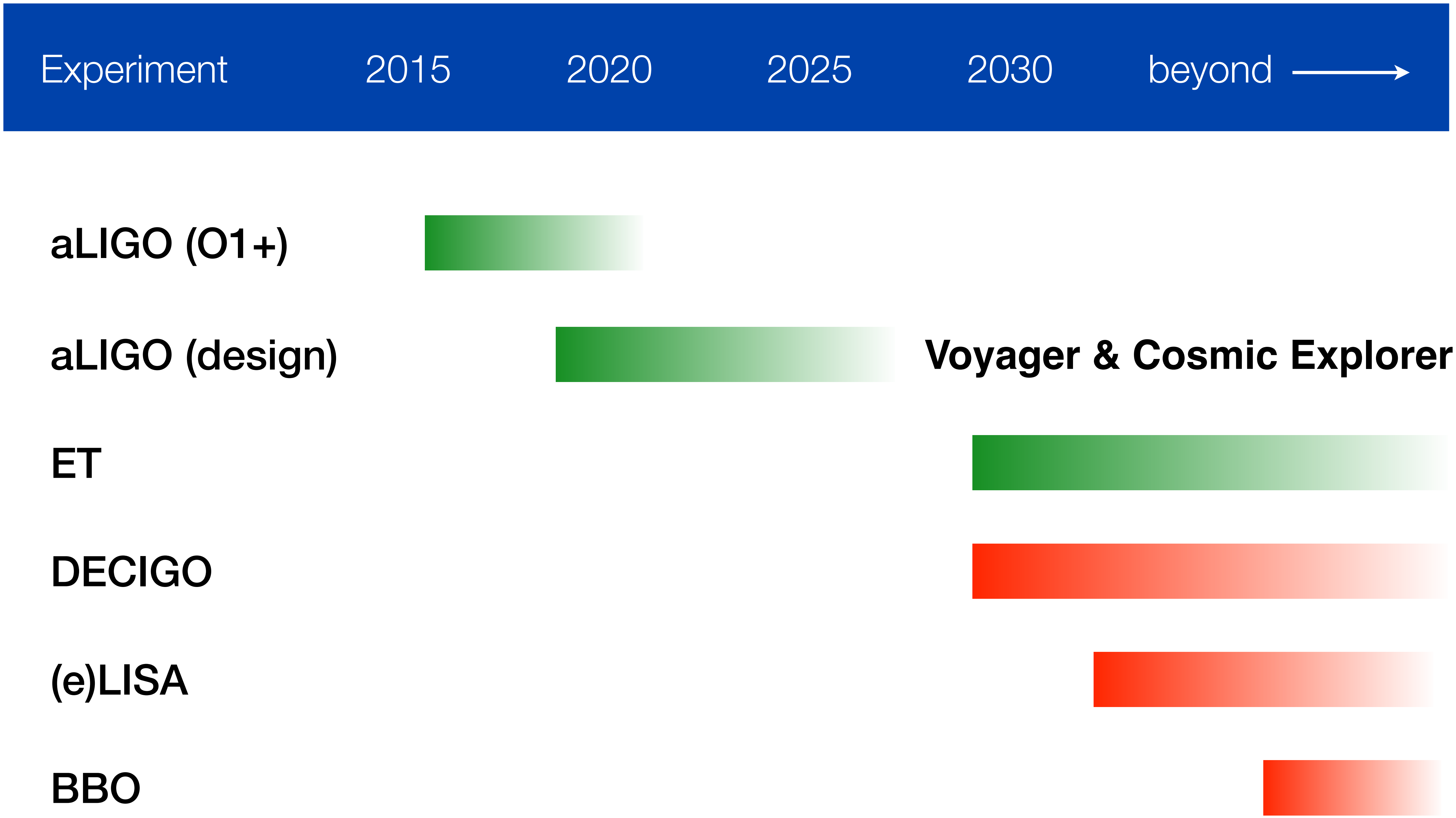
Clesse & Garcia-Bellido (Phys. Dark Univ. 18 2017)

The future of GWs with ground-based
The LIGO-VIRGO network





And the next decades

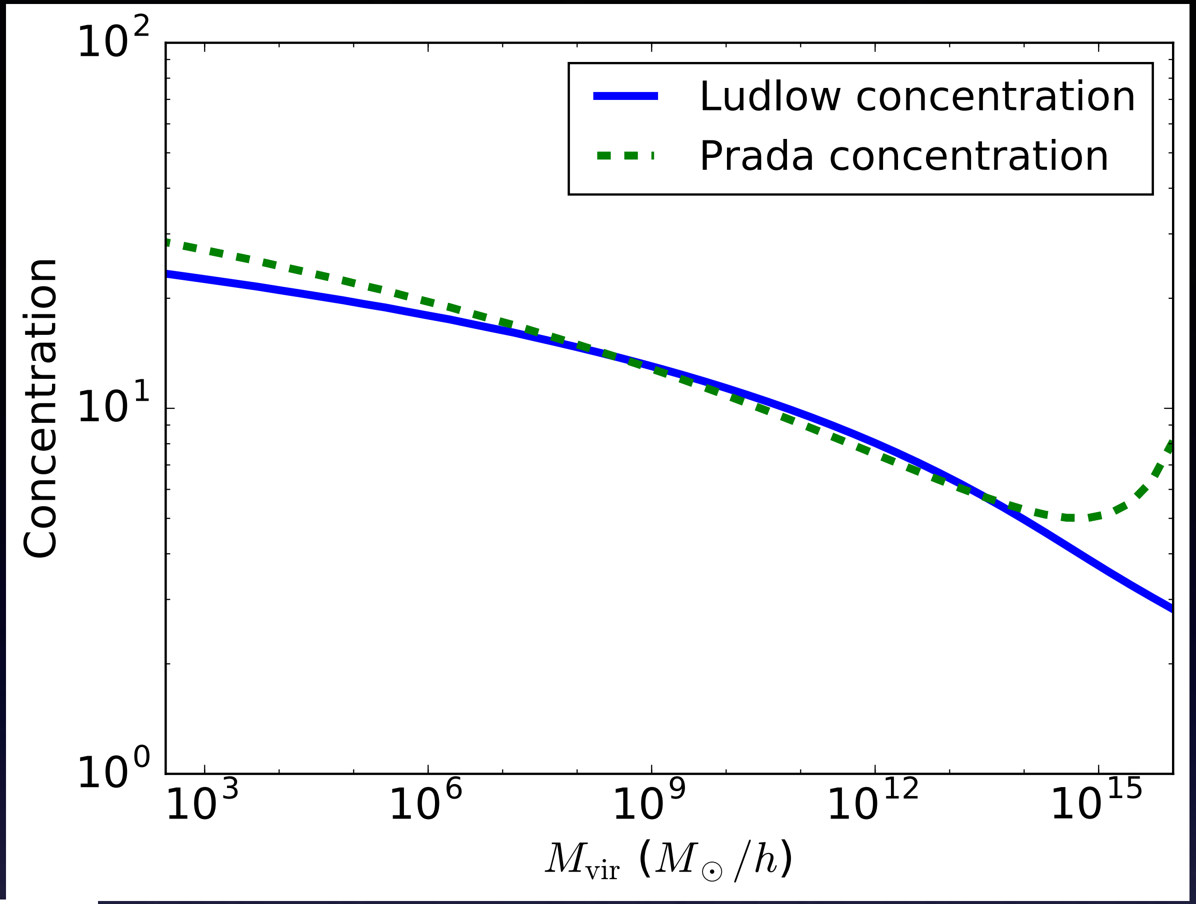


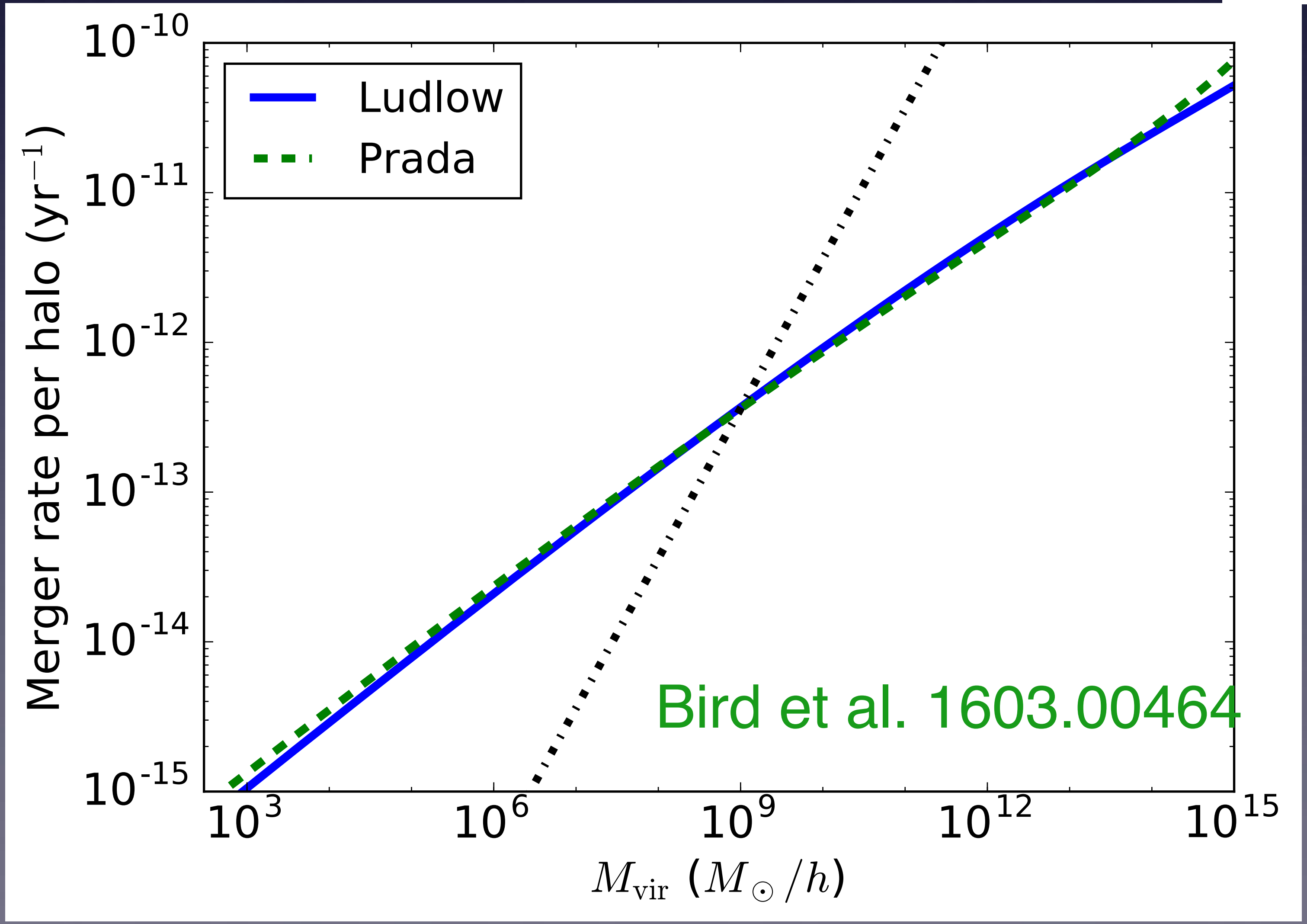
Conclusions

- Taking the first detection of GWs we can make a connection to a long standing problem, the nature of dark matter (assuming it is BHs produced at the Early Universe).
- 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, see though Sasaki et al.
- 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 PRD 95 103010 and even derive limits on PBHs from GWs (e.g. Kovetz 2017).
- We can also search for a signal in the overall GW emission PRL 117 201102 & JCAP 06 037 2017, Clesse&Garcia-Bellido, 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 these astrophysical systems PRD 94 023516, JCAP 06 037 2017 & PRD 95 103010.
- **A GREAT NEW PROBE TO STUDY THE COSMOS : A NEW INDIRECT DM PROBE.**

Thank you!

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

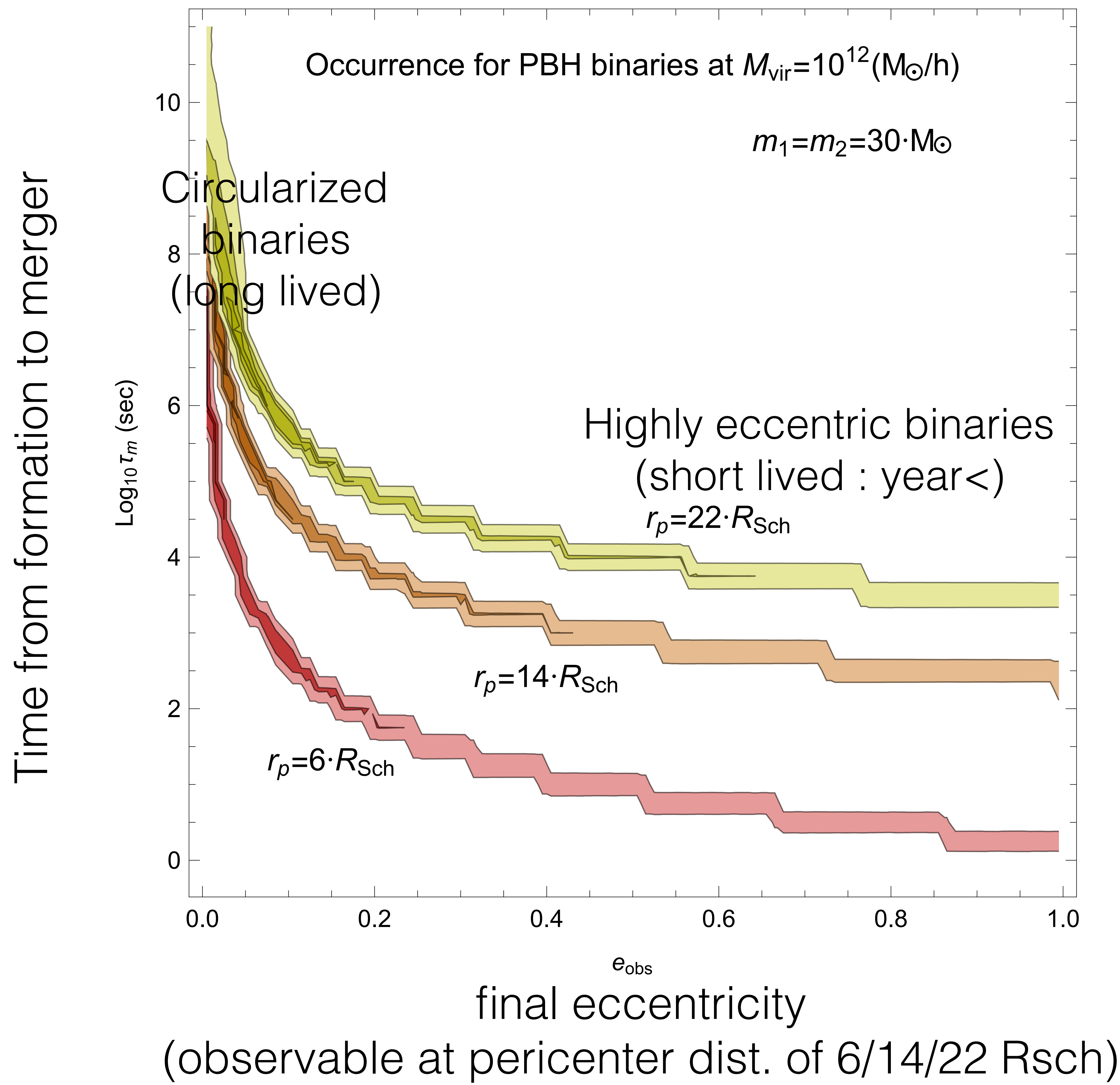




But there are many more (in terms on number) low mass DM halos:

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

Impose a cut-off at 500 $M_\odot$



Occurrence for PBH binaries at $M_{vir}=10^{12}(M_\odot/h)$
$m_1=m_2=30\cdot M_\odot$
Circularized binaries (long lived)
Highly eccentric binaries (short lived : year<)
$r_p=22\cdot R_{Sch}$
$r_p=14\cdot R_{Sch}$
$r_p=6\cdot R_{Sch}$
Time from formation to merger
$Log_{10}\,\tau_m$ (sec)
10
8
6
4
2
0
0.0
0.2
0.4
0.6
0.8
1.0
e_{obs}
final eccentricity
(observable at pericenter dist. of 6/14/22 Rsch)

Another 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:

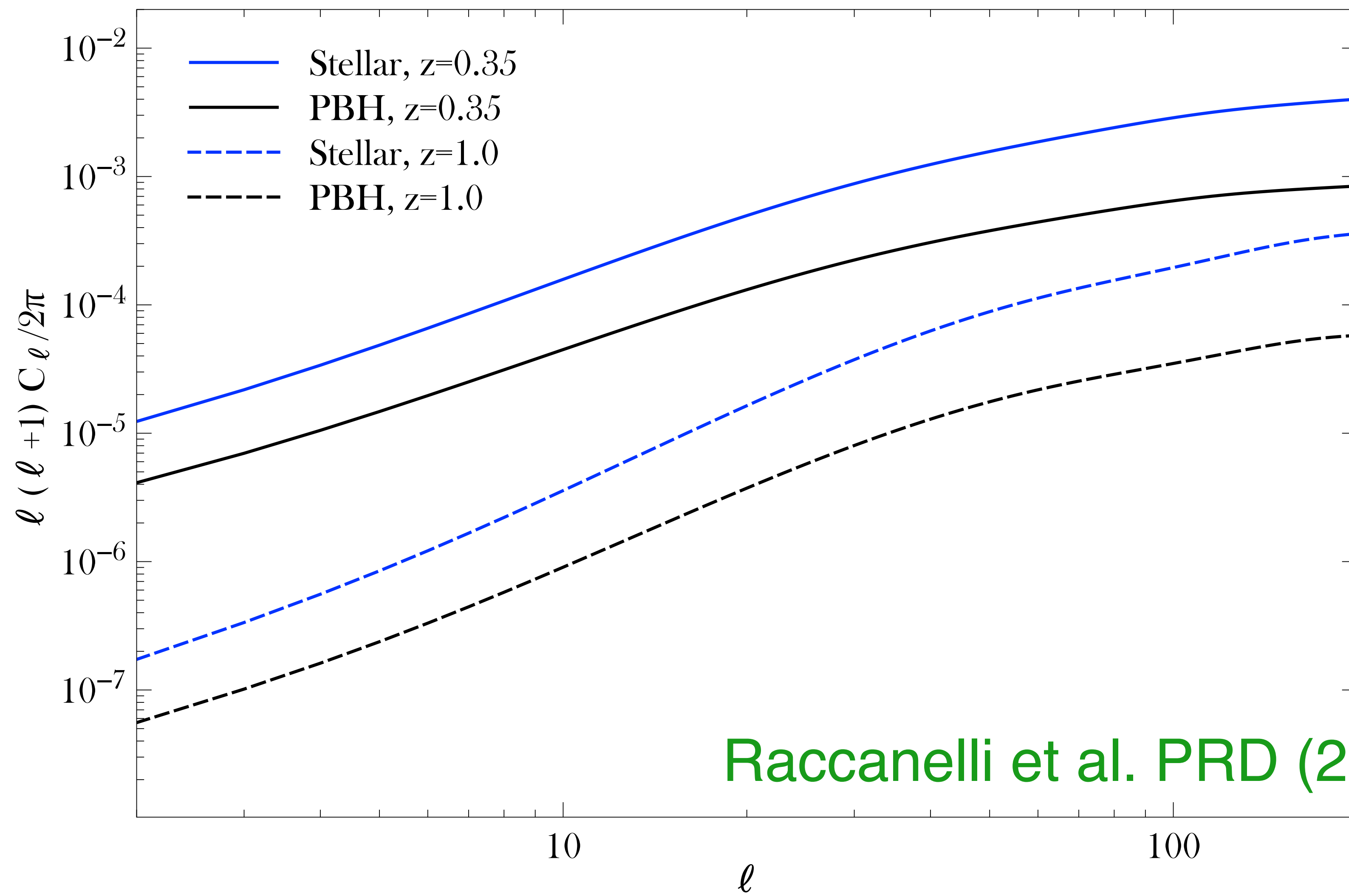
bias (progenitor infor.)

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

#/sr

co-moving distance

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



Raccanelli et al. PRD (2016)

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)