Primordial Black Holes as Gravitational Wave Sources

JOHNS HOPKINS UNIVERSITY

Bird, IC, Munoz, Ali-Haimoud, Kamionkowski, Kovetz, Raccanelli and Riess (JHU) PRL 116.201031,
IC, Kovetz, Ali-Haimoud, Bird, Kamionkowski, Munoz, Raccanelli PRD 94 084013
Raccanelli, Kovetz, Bird, IC, Munoz PRD 94 023516
Mandic, Bird, IC PRL 117.201102, IC JCAP 06 037 2017
Kovetz, IC, Breysse, Kamionkowski PRD 95 103010

Kovetz, IC, Kamionkowski, Silk arXiv: 1803.00568

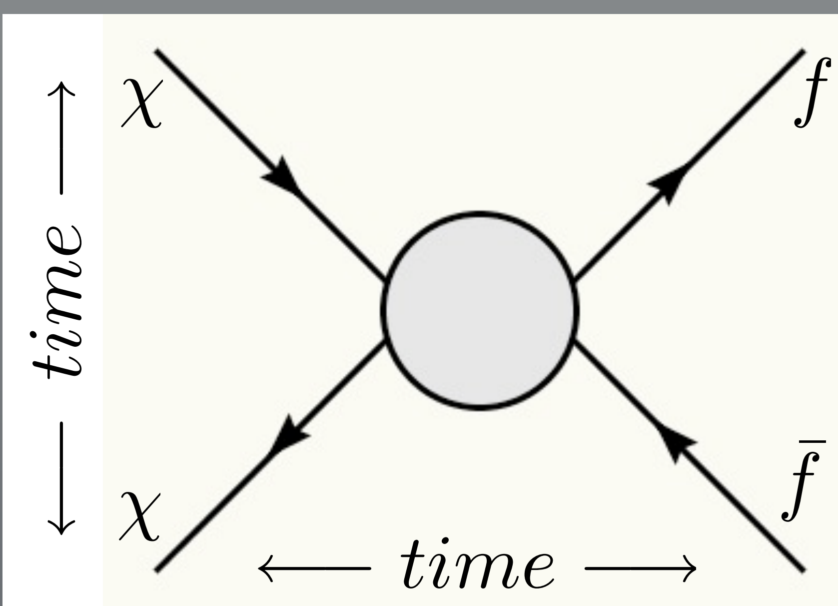
APS physics

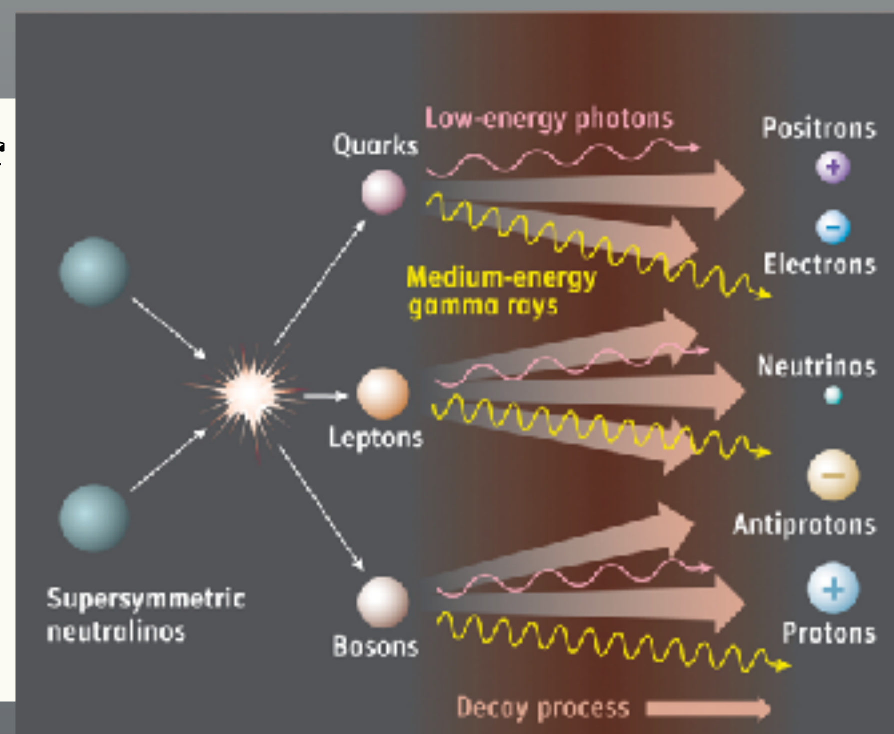
APS April Meeting

Ilias Cholis 04/16/2018

Searches for Particle Dark Matter

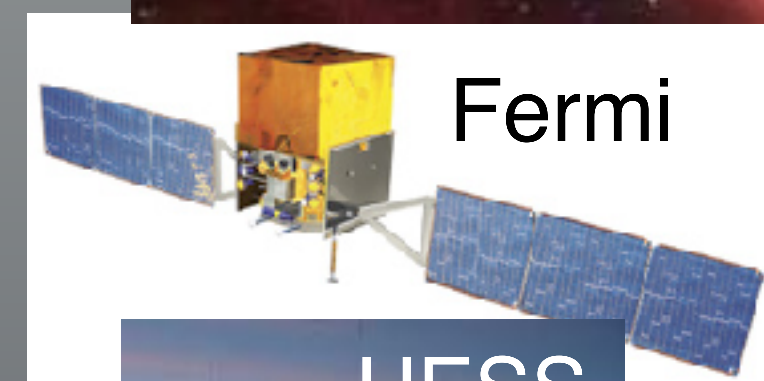
Direct Detection scattering off normal matter, Xe, Ar, Ge, Si:

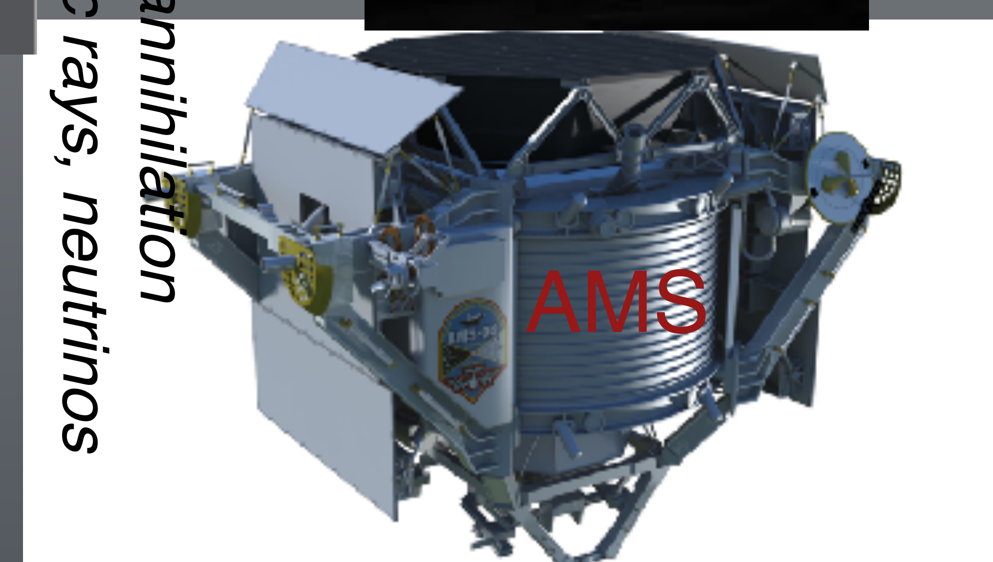




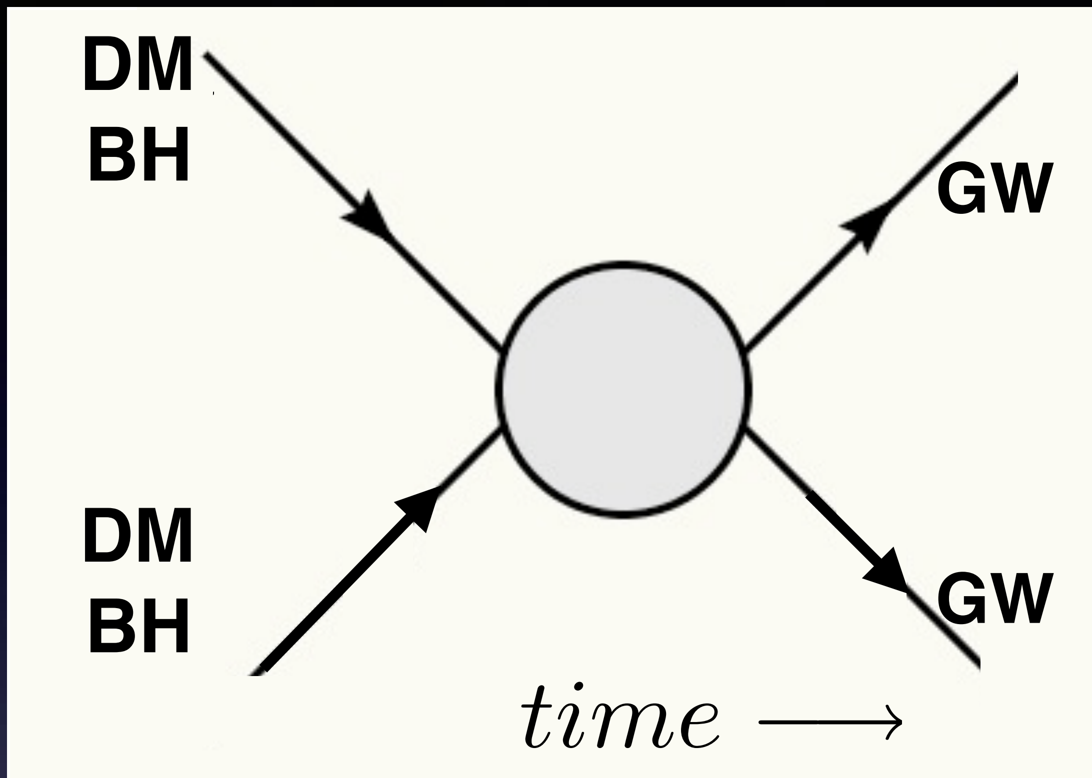
Dark matter production at colliders

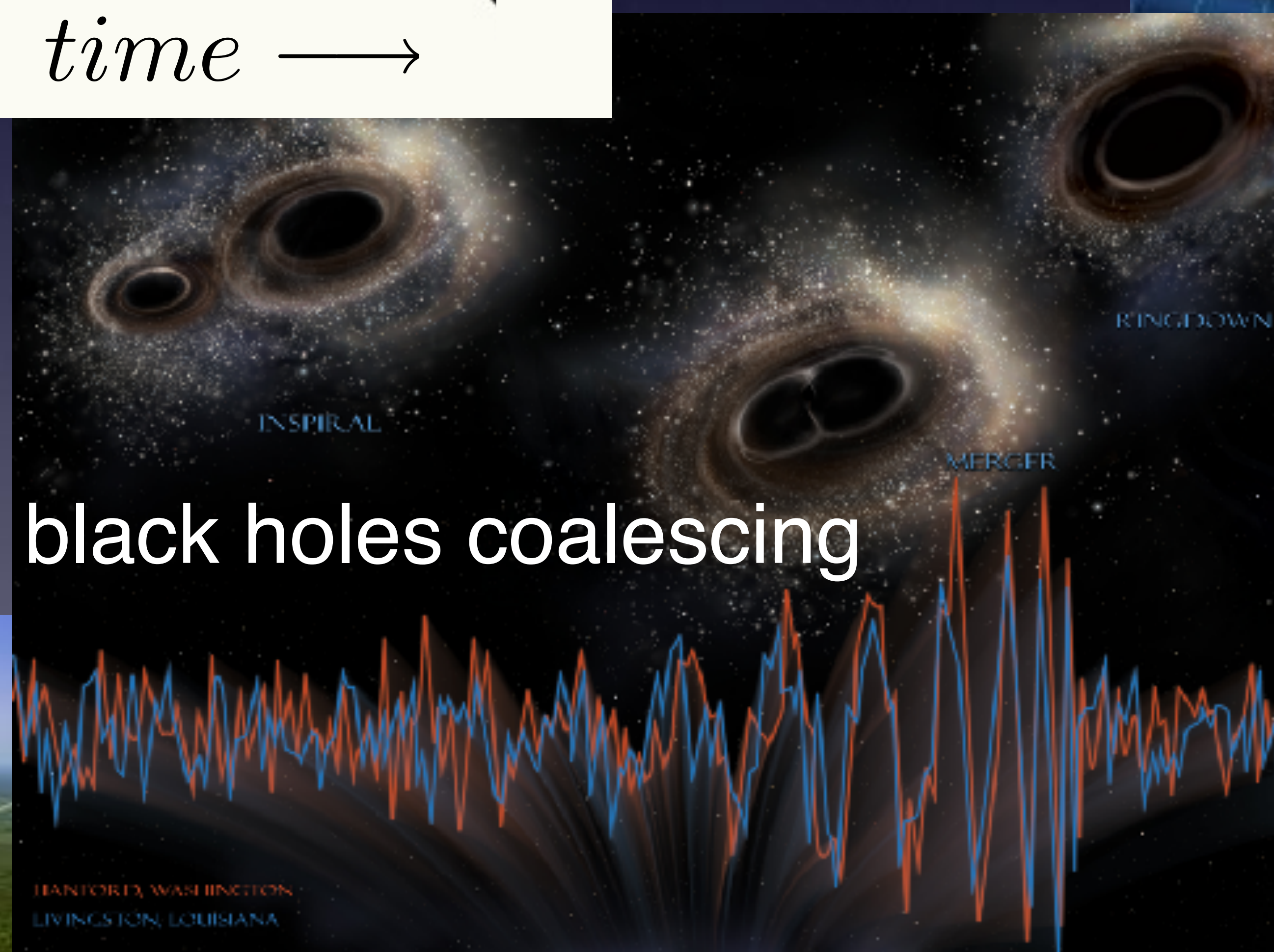
Indirect detection: annihilation into gamma-rays, cosmic rays, neutrinos

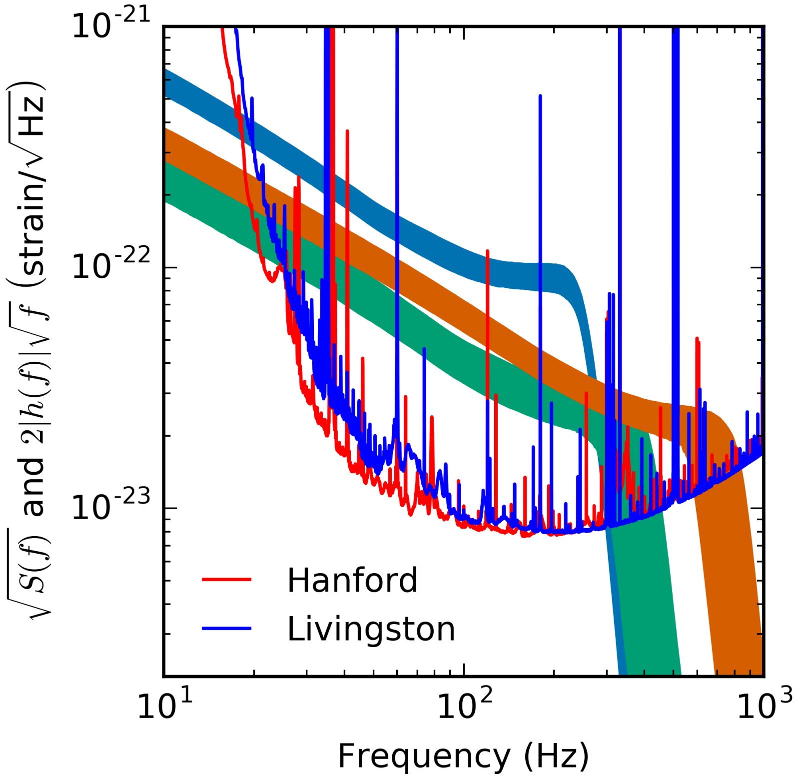


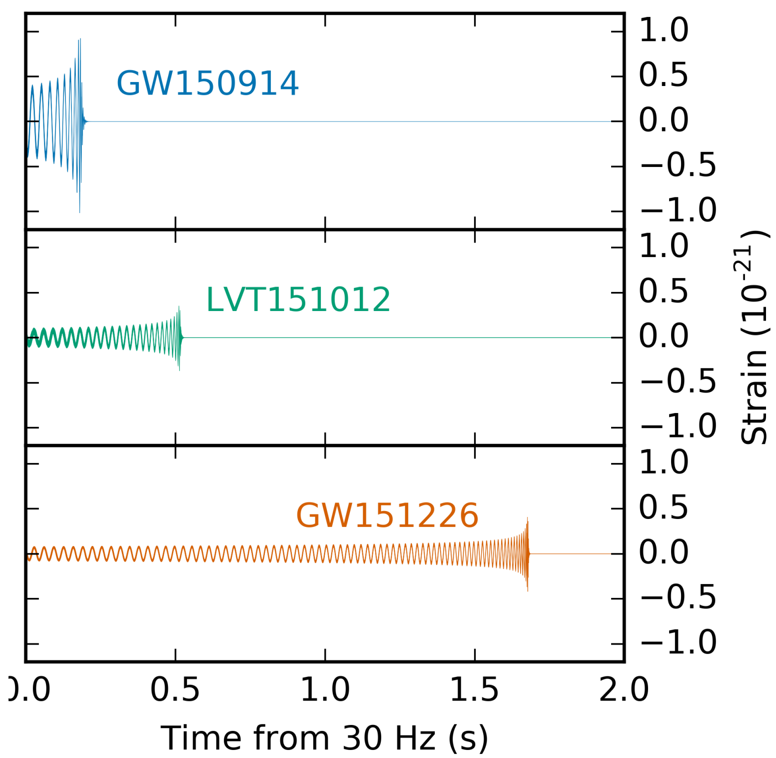


What about Gravitational Waves?









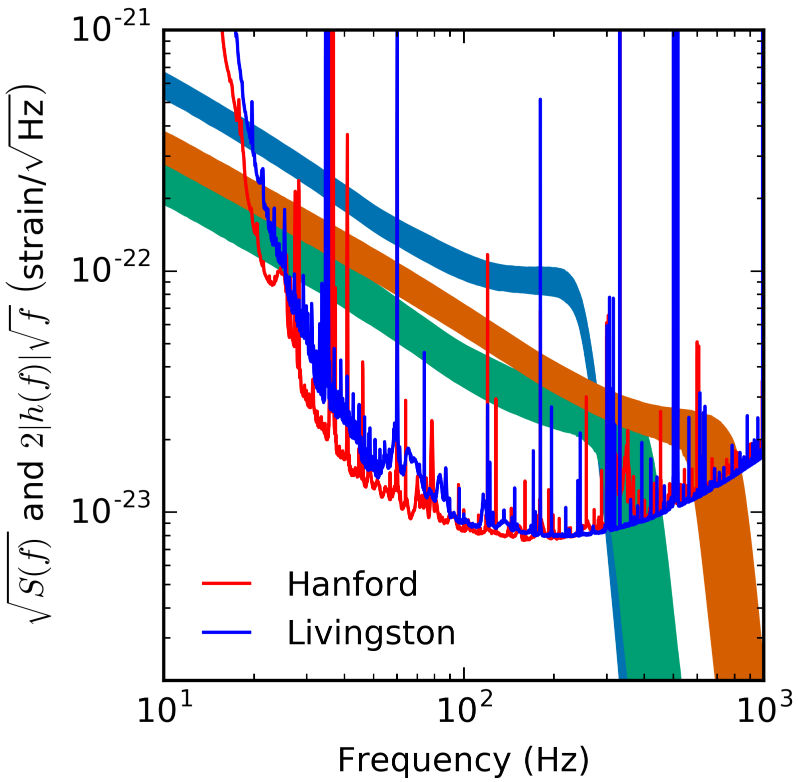
LIGO's full O1 (2015-16) run:

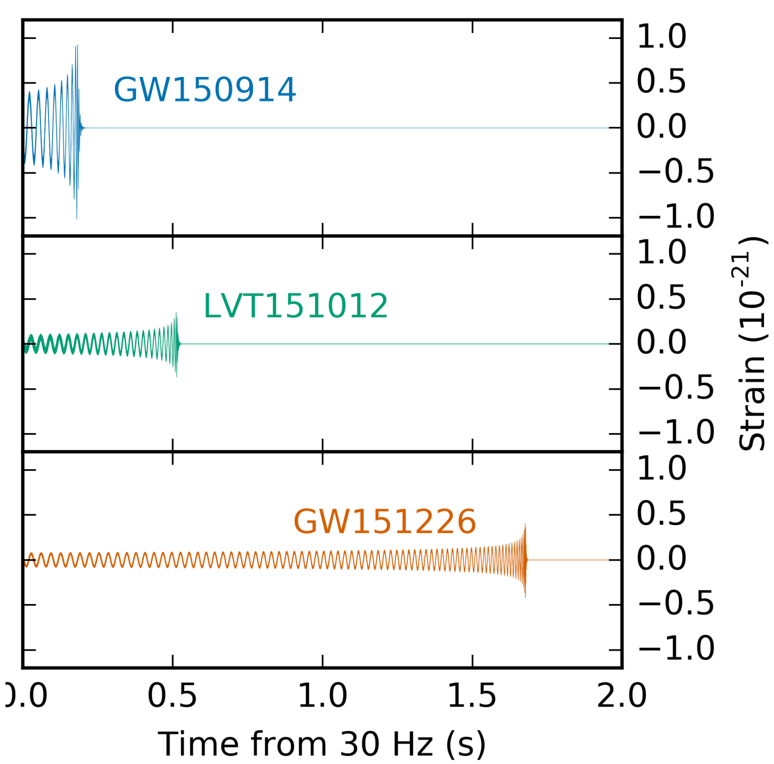
TABLE II. Rates of BBH mergers based on populations with masses matching the observed events, and astrophysically motivated mass distributions. Rates inferred from the PyCBC and GstLAL analyses independently as well as combined rates are shown. The table shows median values with 90% credible intervals.

	$R/(\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1})$		
Mass distribution	PyCBC	GstLAL	Combined
	Event based		
GW150914	$3.2^{+8.3}_{-2.7}$	$3.6^{+9.1}_{-3.0}$	$3.4^{+8.8}_{-2.8}$
LVT151012	$9.2^{+30.3}_{-8.5}$	$9.2^{+31.4}_{-8.5}$	$9.1^{+31.0}_{-8.5}$
GW151226	35^{+92}_{-29}	37^{+94}_{-31}	36^{+95}_{-30}
All	53^{+100}_{-40}	56^{+105}_{-42}	55^{+103}_{-41}
	Astrophysical		
Flat in log mass	31^{+43}_{-21}	29^{+43}_{-21}	31^{+42}_{-21}
Power law (−2.35)	100^{+136}_{-69}	94^{+137}_{-66}	97^{+135}_{-67}

LIGO Coll., Phys Rev X, 2016

Different estimates on the coalescence rates come from different astrophysical assumptions





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DM?

LIGO Coll., Phys Rev X, 2016

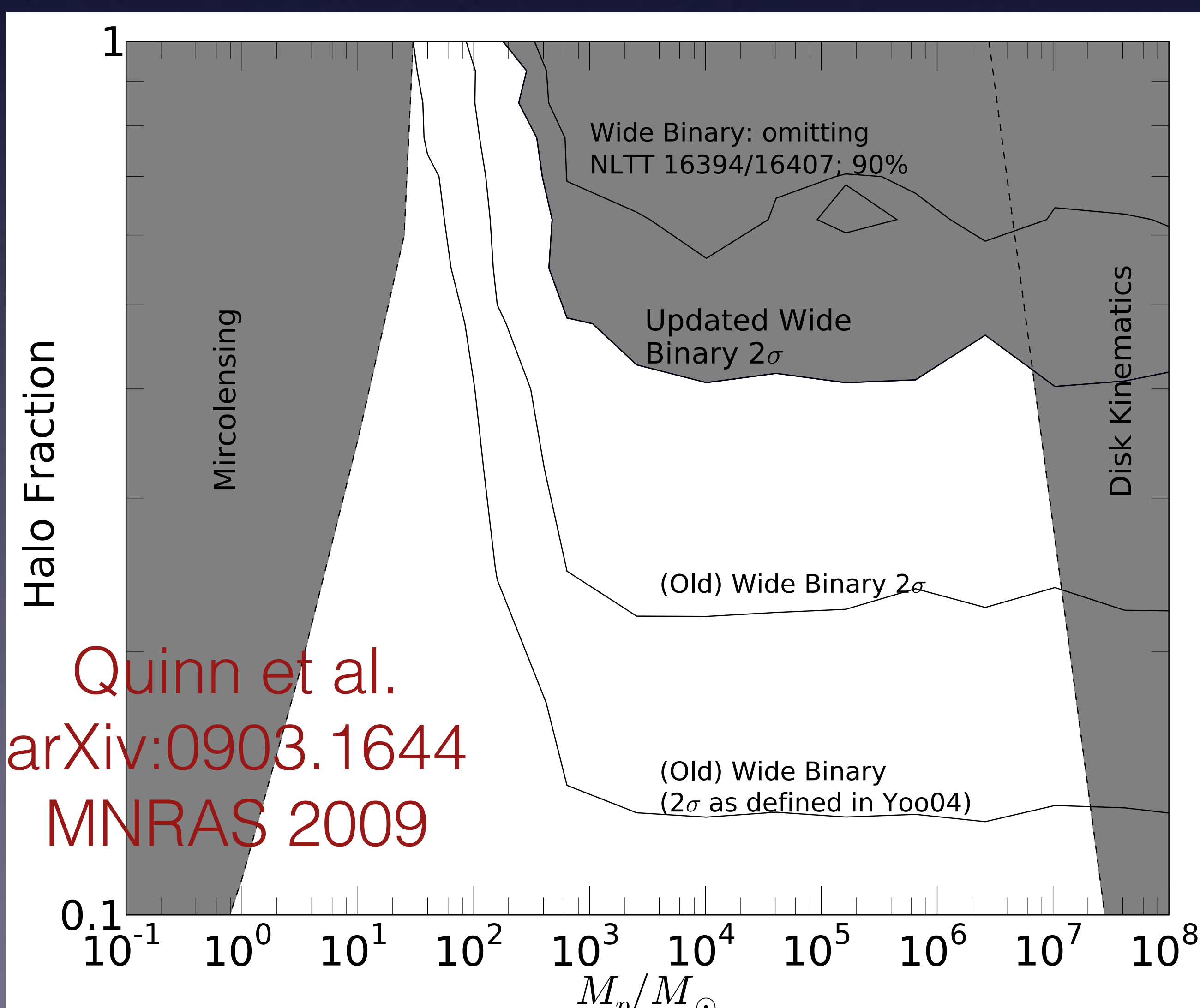
Different estimates on the coalescence rates come from different astrophysical assumptions

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 $M_{\odot}$



Quinn et al.
arXiv:0903.1644
MNRAS 2009

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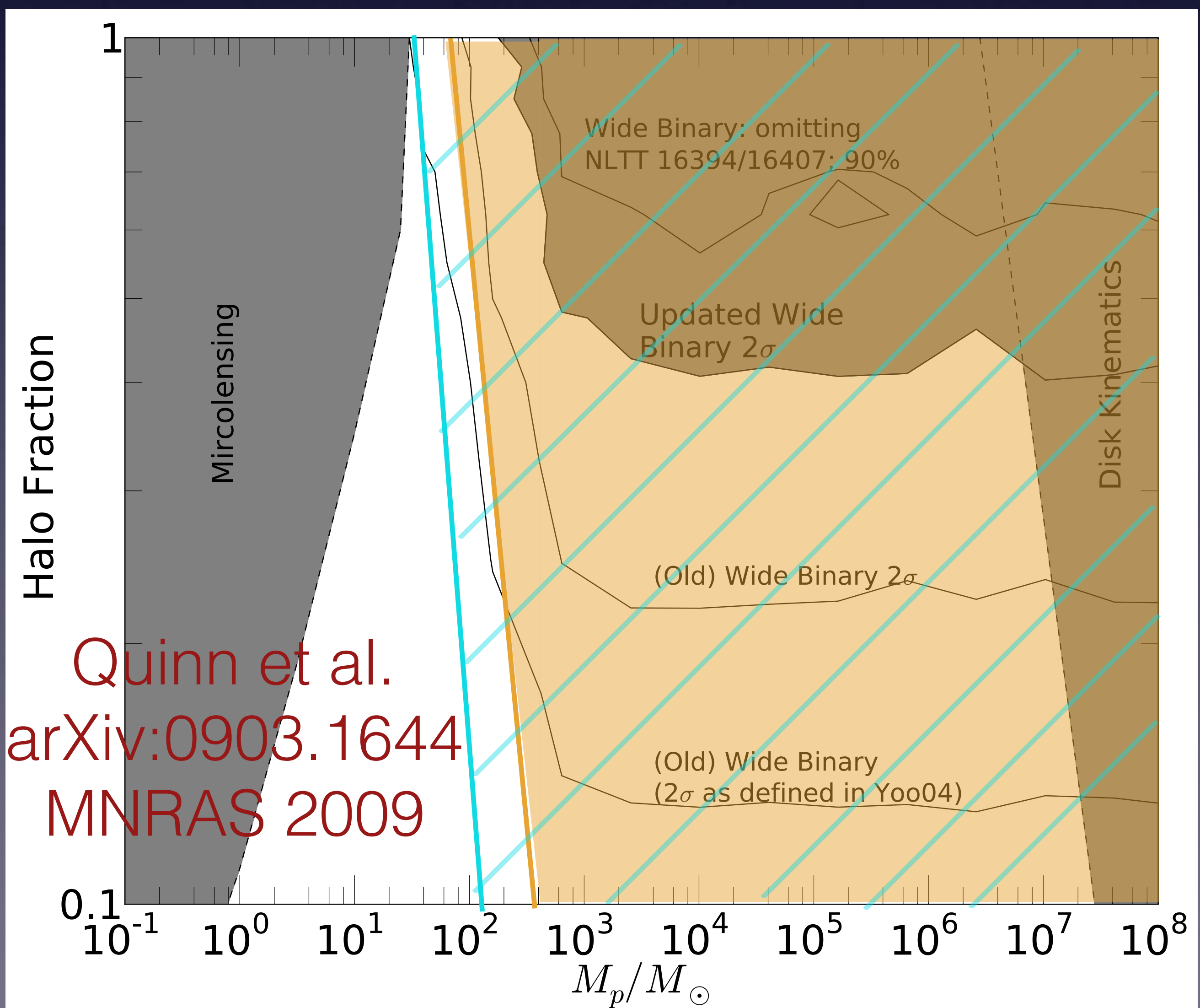


For the remainder I will assume that all DM is composed of PBHs and set their mass to 30 $M_\odot$

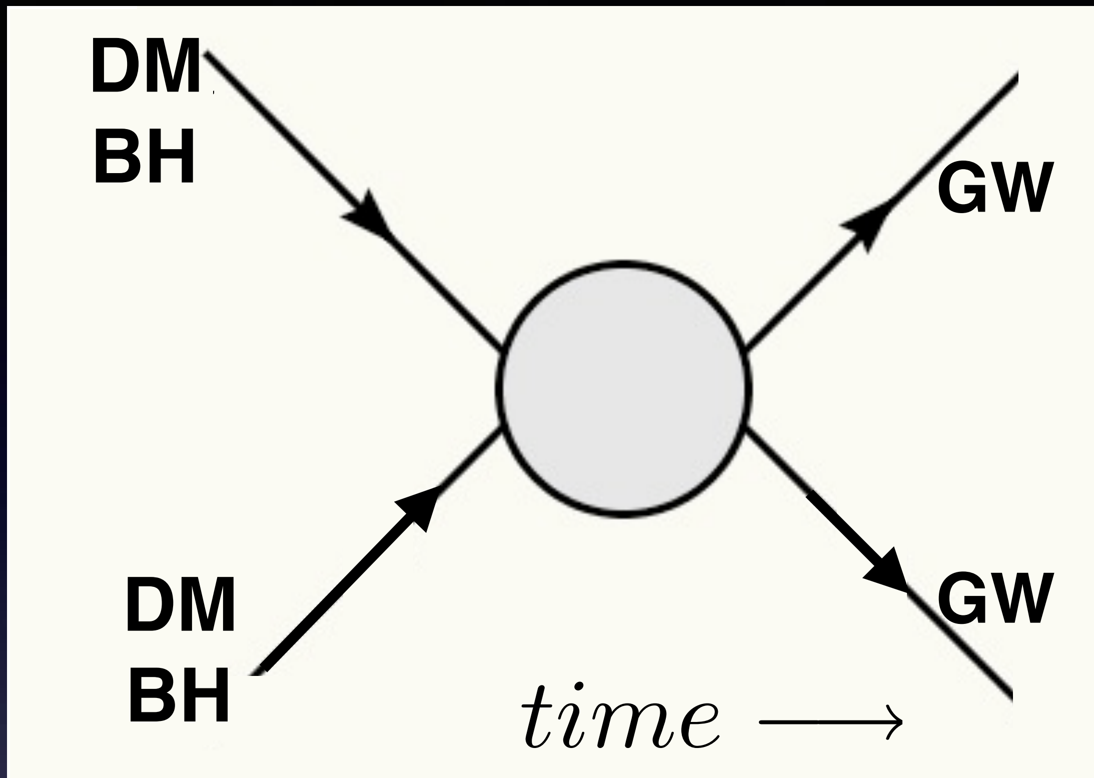
Limits on the CMB anisotropies from the observed temperature and polarization power-spectra are efficient above 100 $M_\odot$

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.

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

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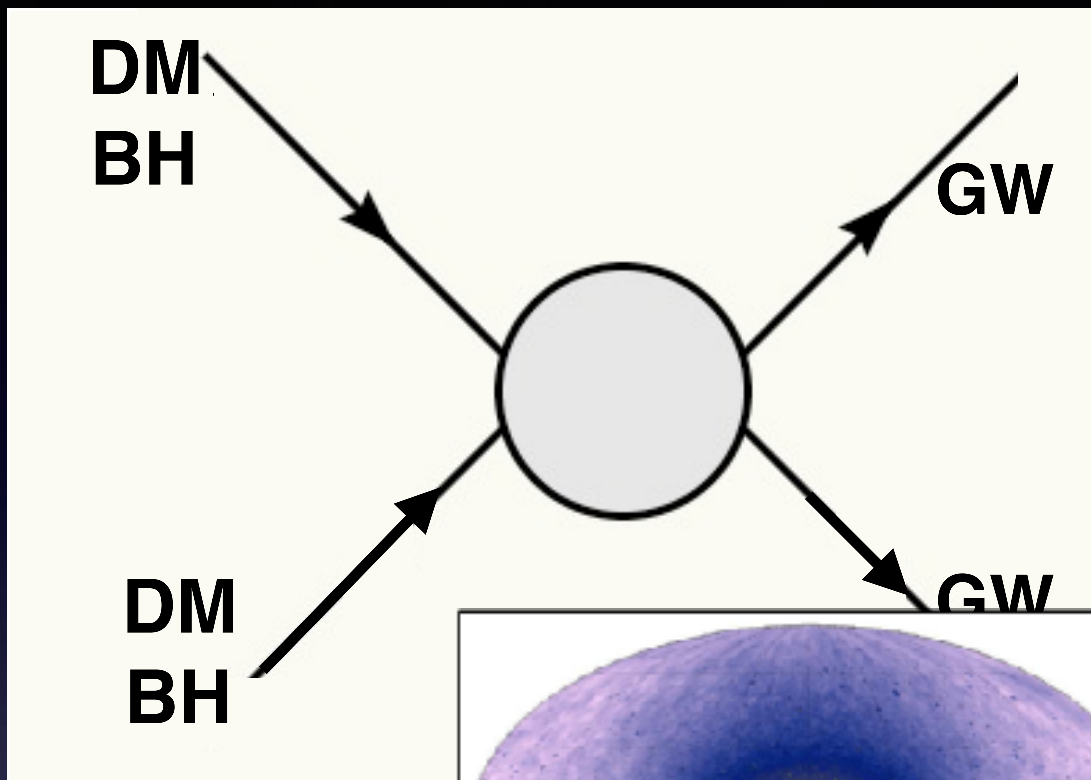

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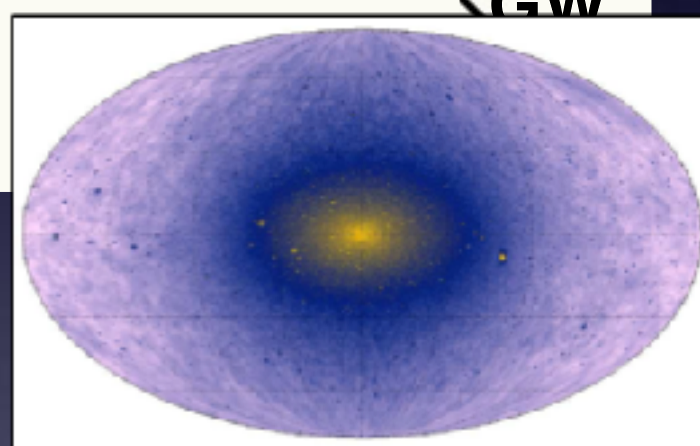


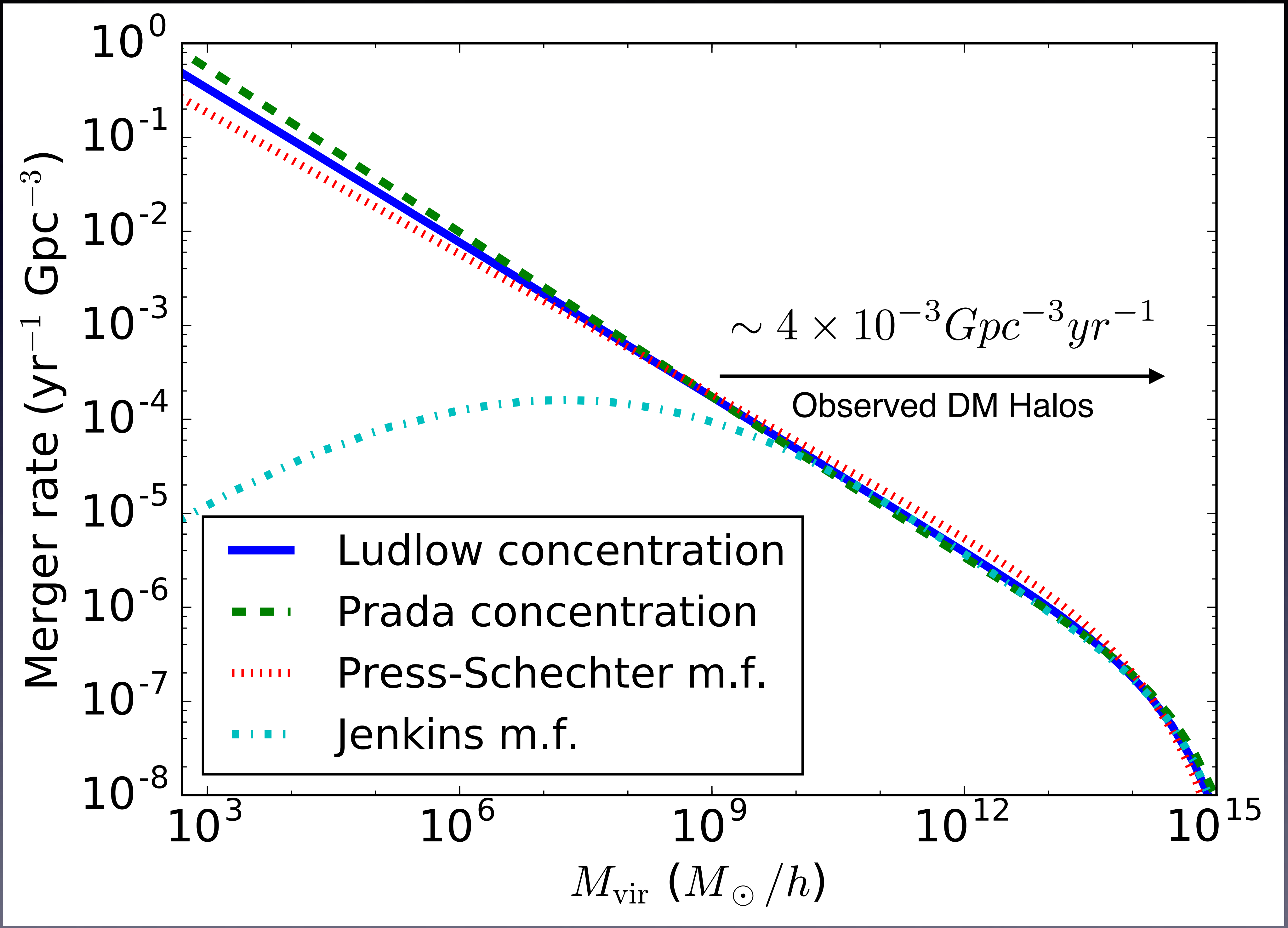
Assuming an NFW profile for the PBHs:

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

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 different DM halos properties (concentration, and velocity dispersions) and effects on the smallest DM halos:



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

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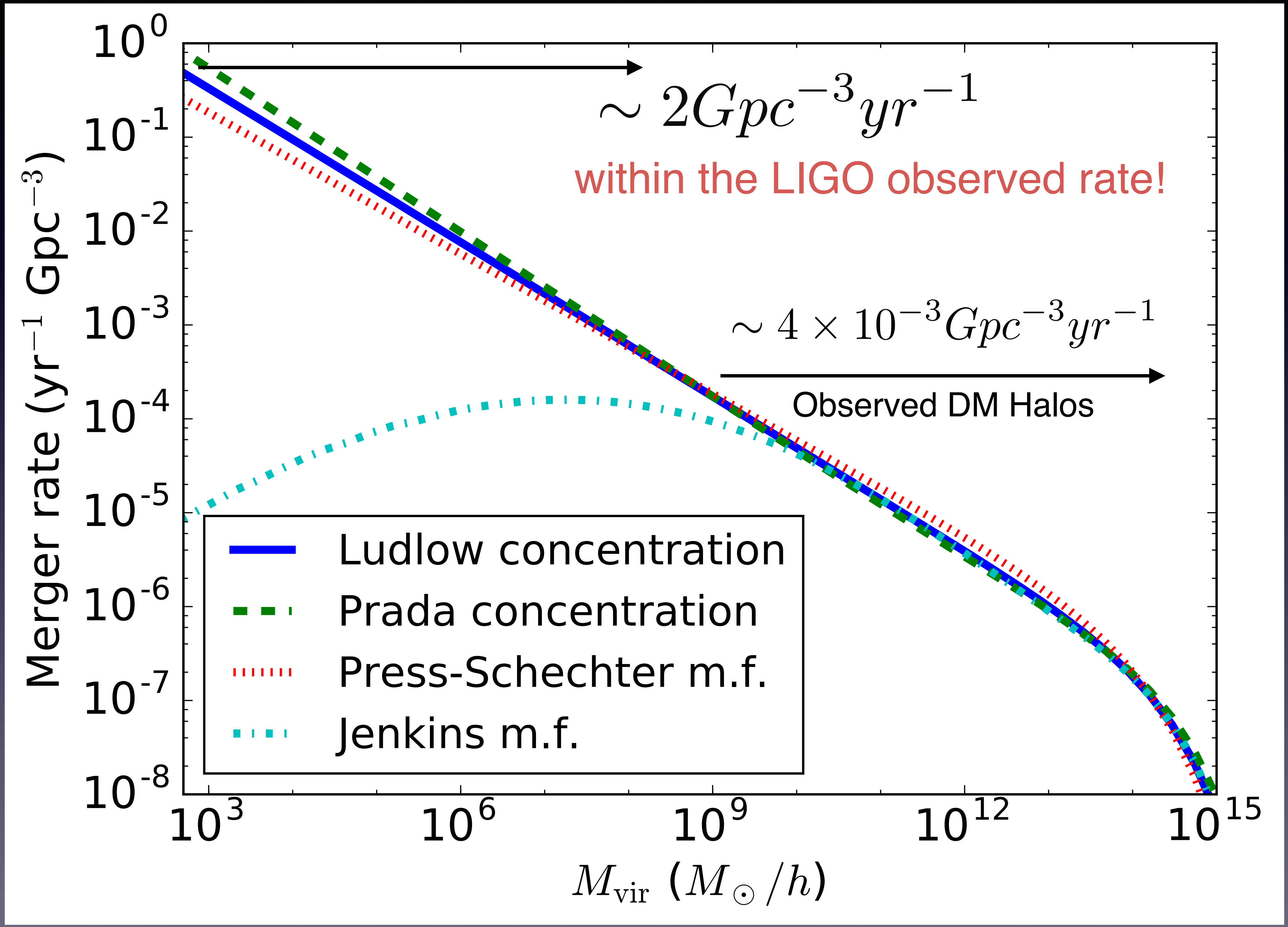


S. Bird, IC, J. Munoz et al. (2016)

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

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*

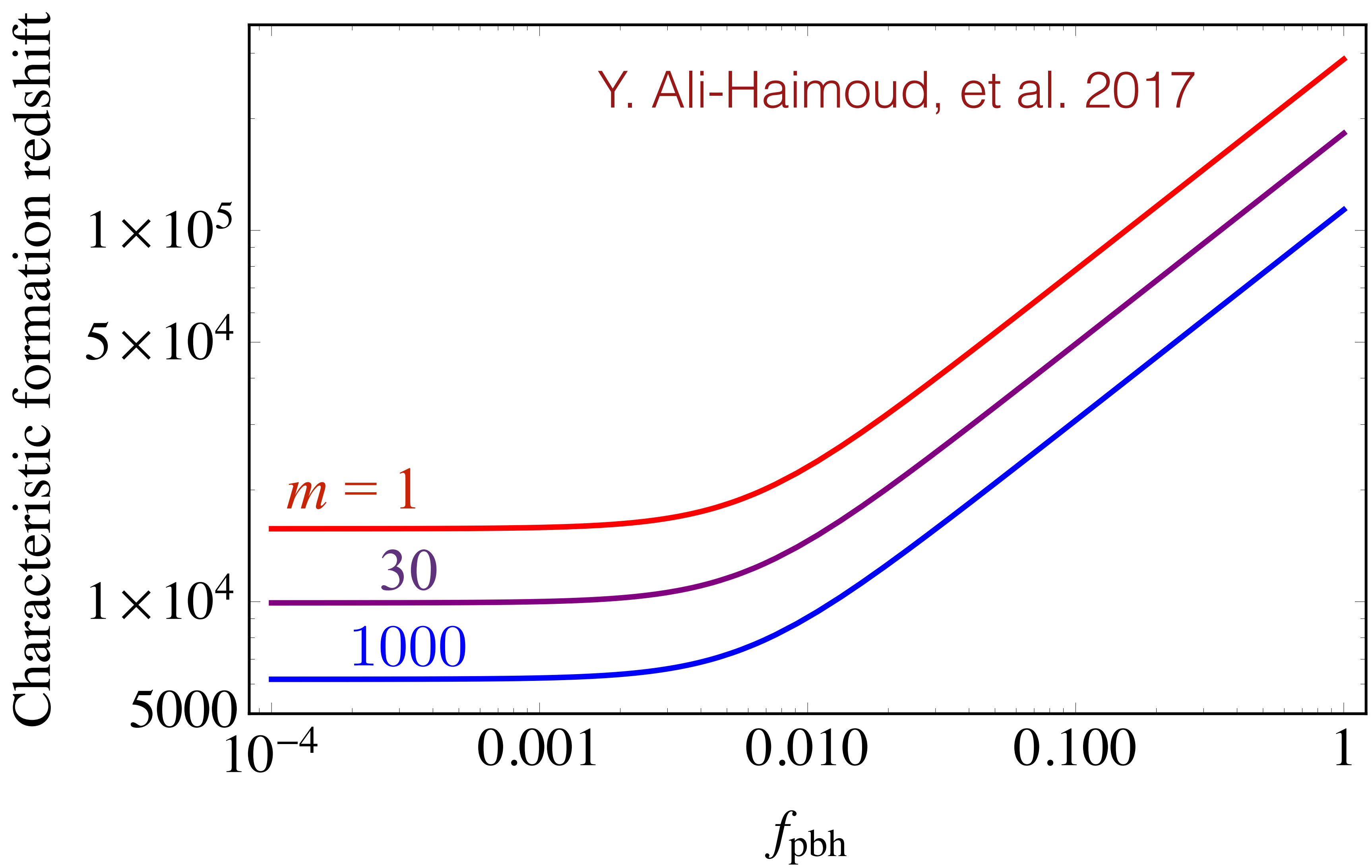
[c] *Department of Physics, Kyoto University, Kyoto 606-8502, Japan*

[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 early on
(~ matter radiation equality or earlier):



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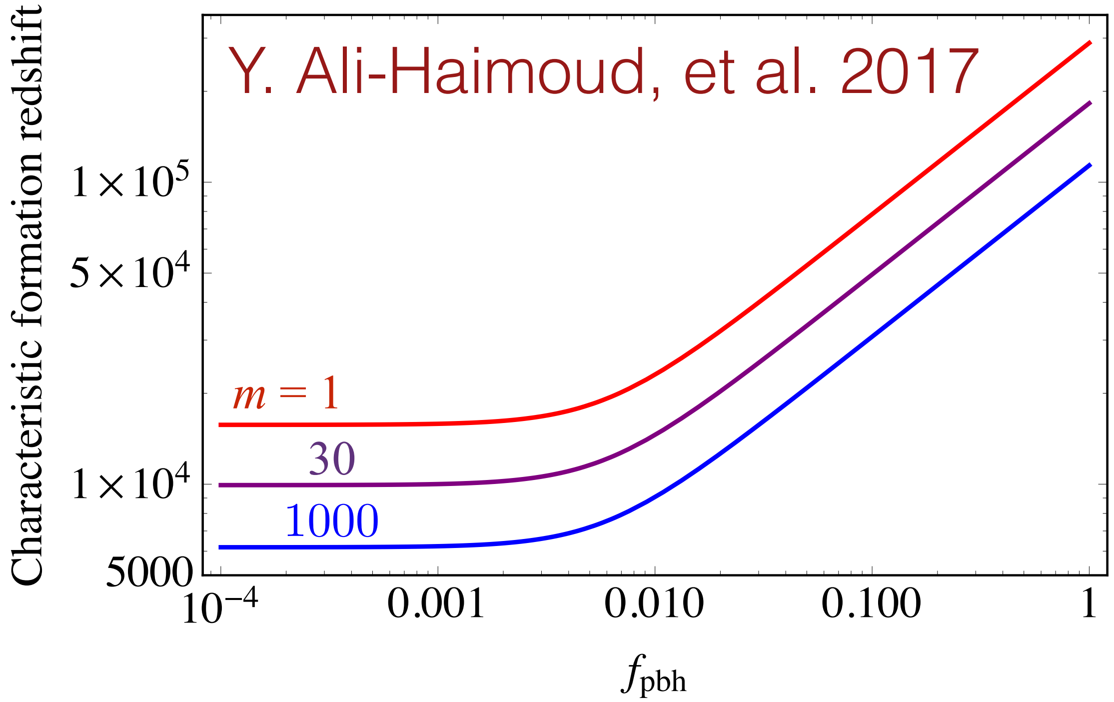

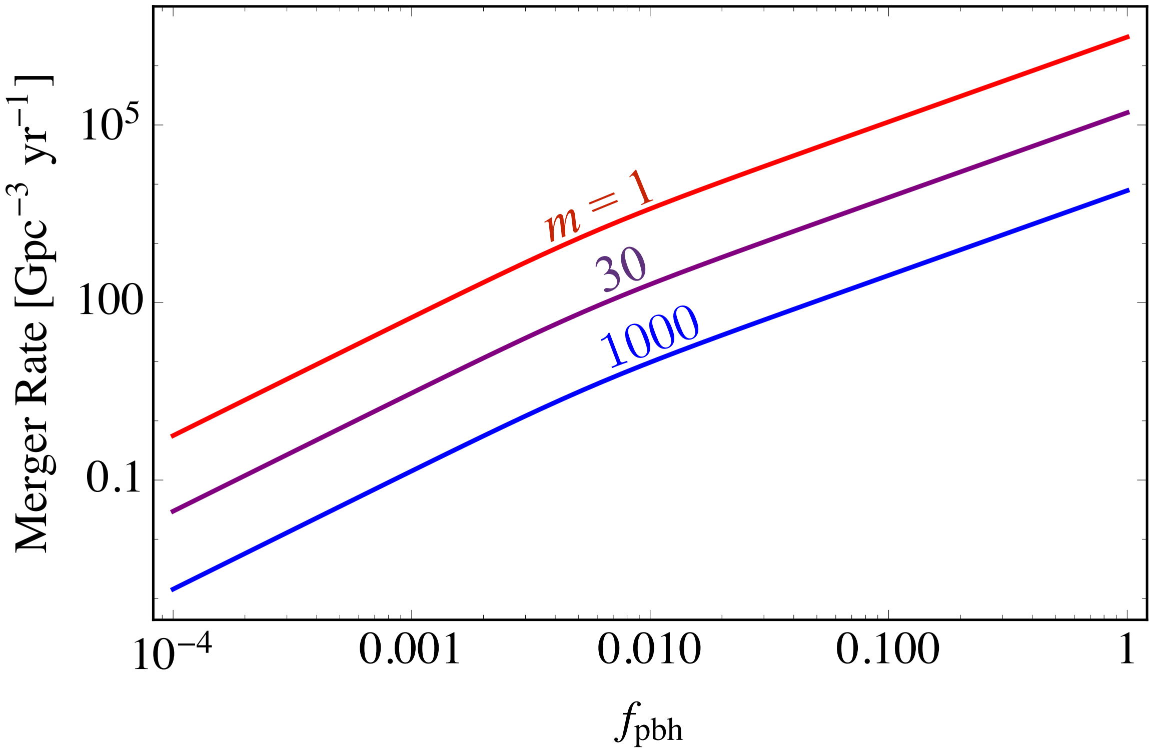

FIG. 5. PBH binary merger rate, as a function of PBH fraction $f_{\rm pbh}$ and mass $m = M/M_\odot$.

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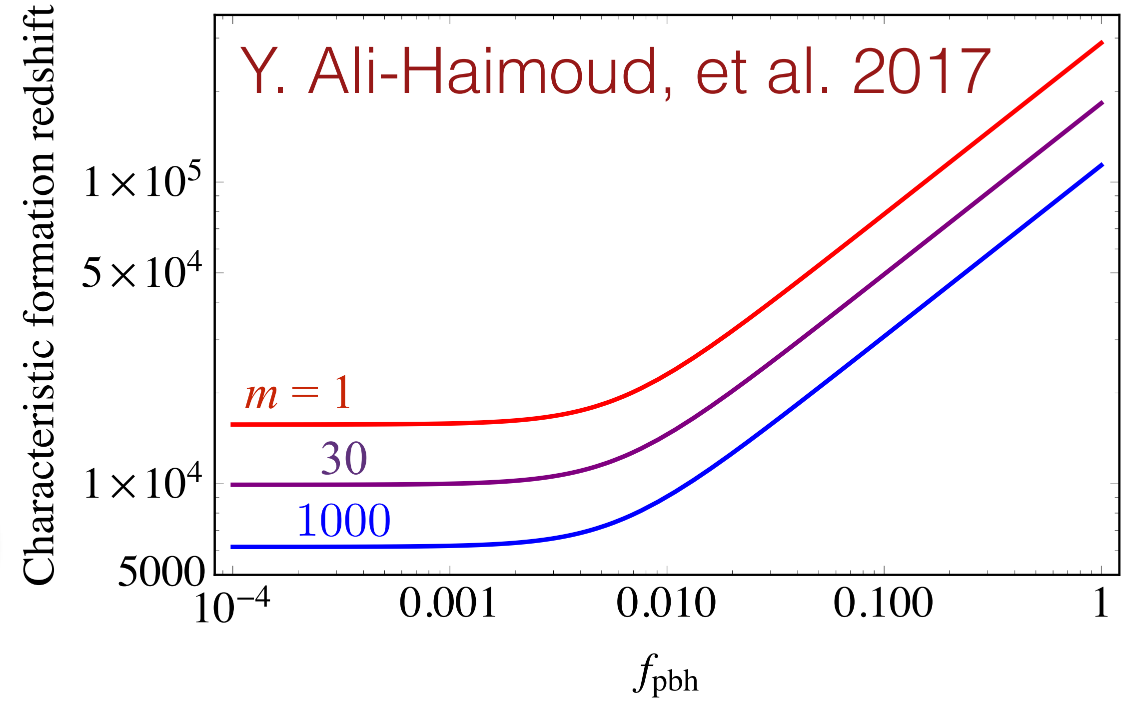

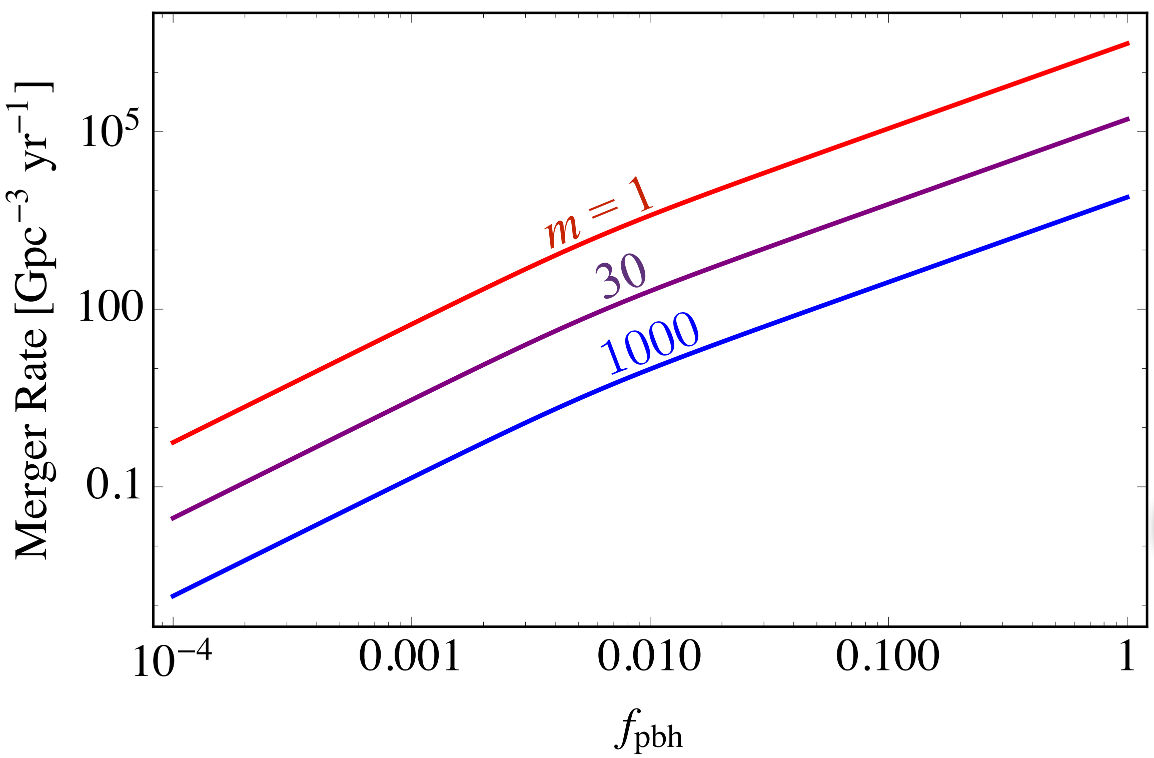

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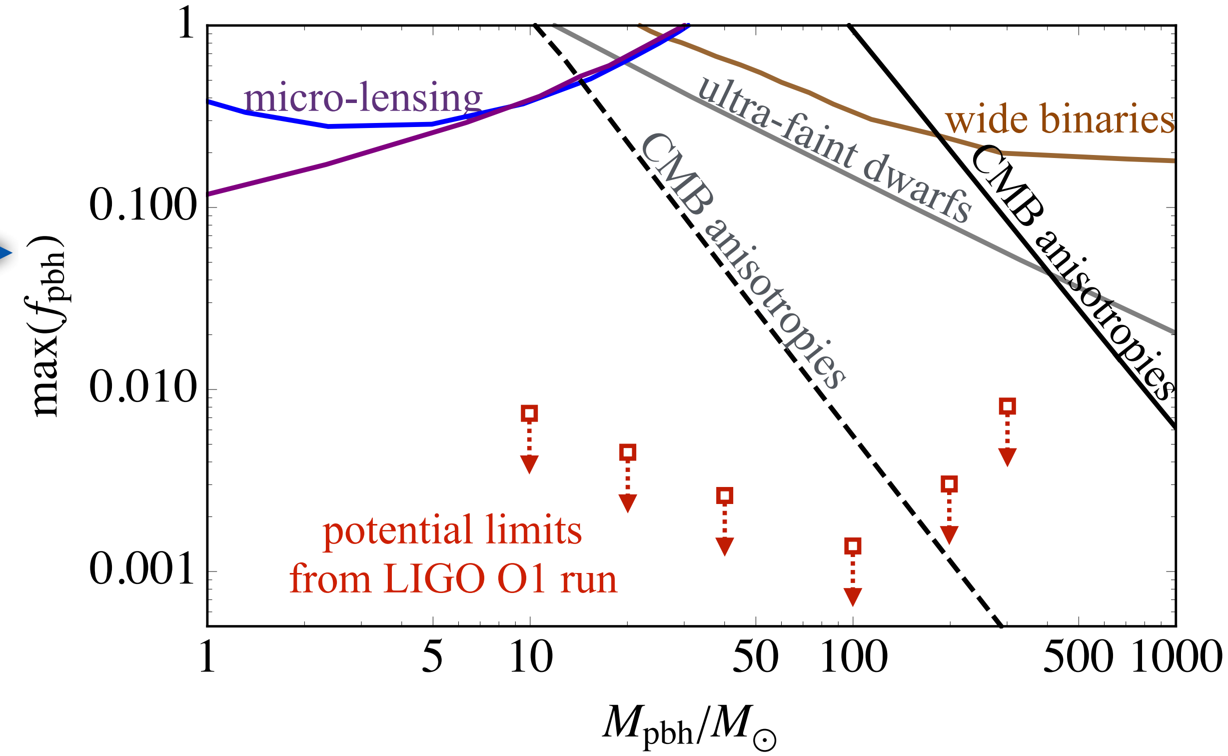


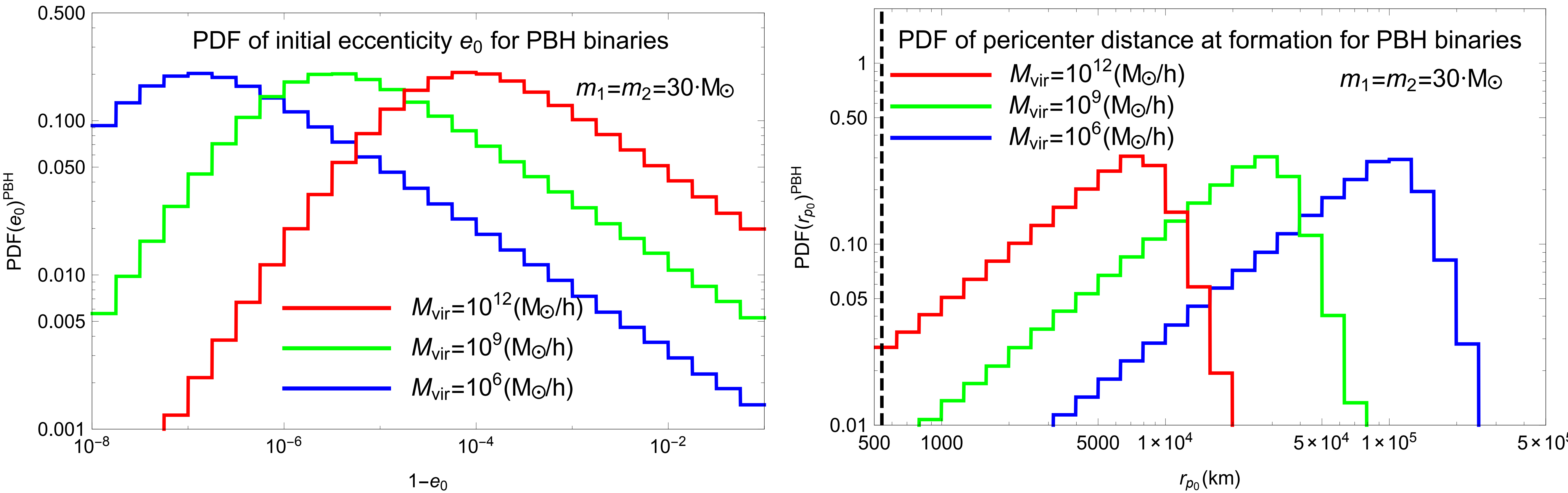
FIG. 7. Potential upper bounds on the fraction of dark matter in PBHs as a function of their mass, derived in this paper (red arrows), and assuming a narrow PBH mass function. These bounds need to be confirmed by numerical simulations. For

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)

How to differentiate DM BH binaries
from
regular astrophysical BH-BH binaries
with future observations.

I) Orbital properties of DM PBH binaries

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



PDFs of the PBH formed binaries

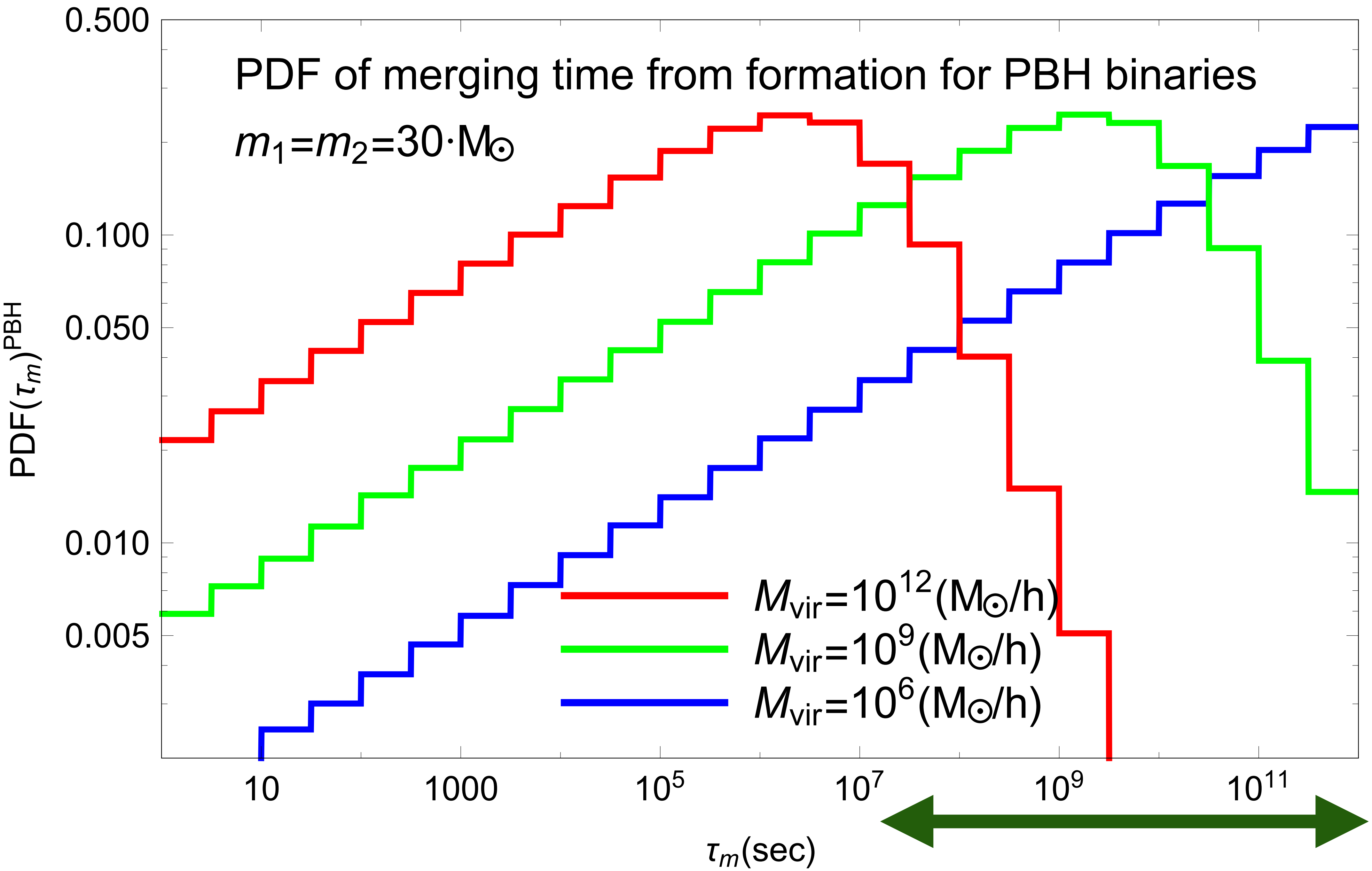
$$(1-e_0)^{\rm peak} \simeq 2.6\xi\eta^{2/7}(w/c)^{10/7}$$

$\xi \simeq 1, \eta = 1/4$ for equal BH masses

$$w \simeq 2/20/200\ km/s$$

IC, Kovetz, Ali-Haimoud, Bird, Kamionkowski, Munoz and Raccanelli
PRD 94 084013

Which in turn have dramatically different timescales until merger:

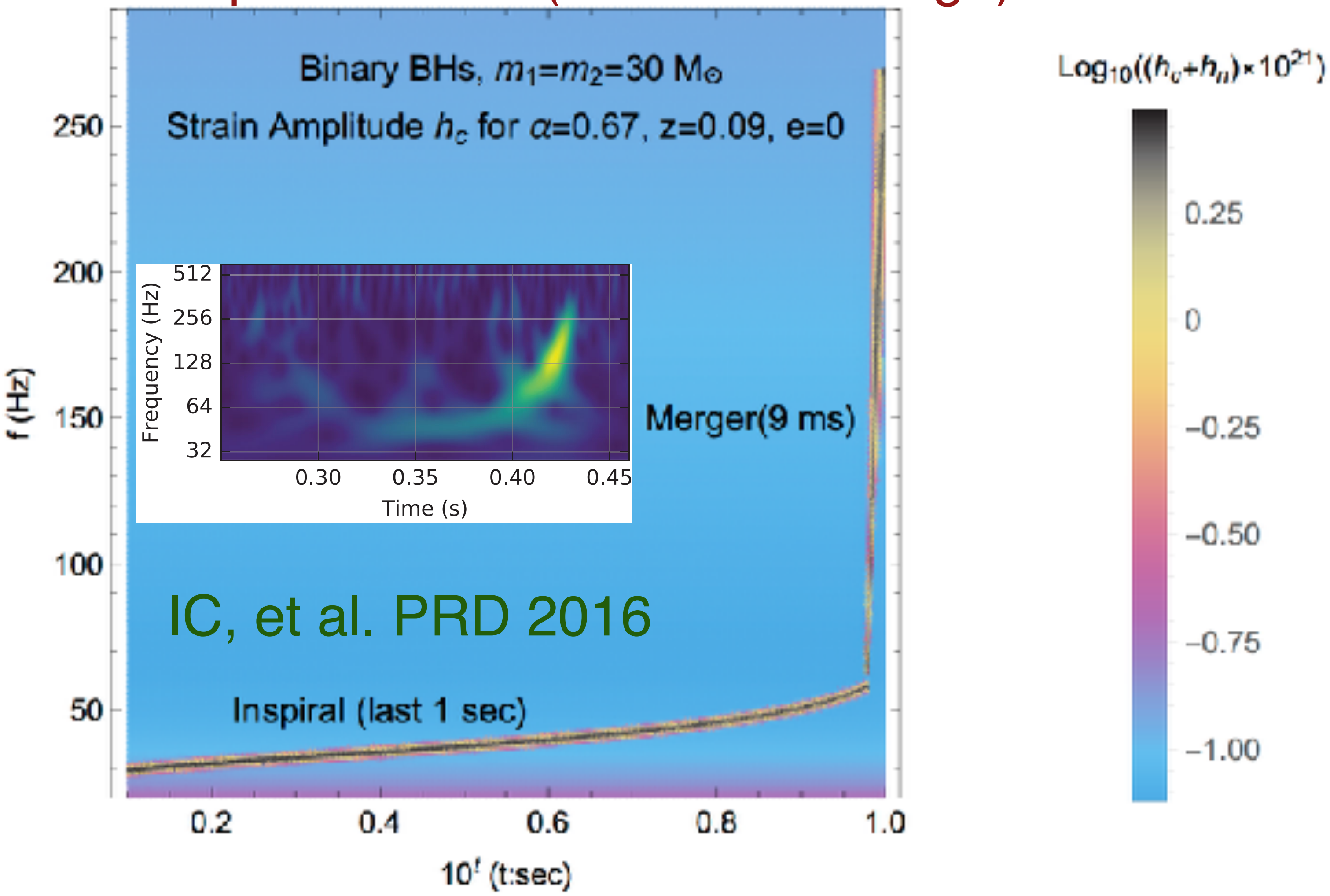


$$\tau_m = \frac{3}{85}\frac{a_0^4}{m_{tot}^3\eta}(1-e_0)^{7/2}$$

By the time of LIGO observation fully circularized.

An outlier!

simplified noise (LIGO final design)



An outlier! See many more modes of grav. waves.

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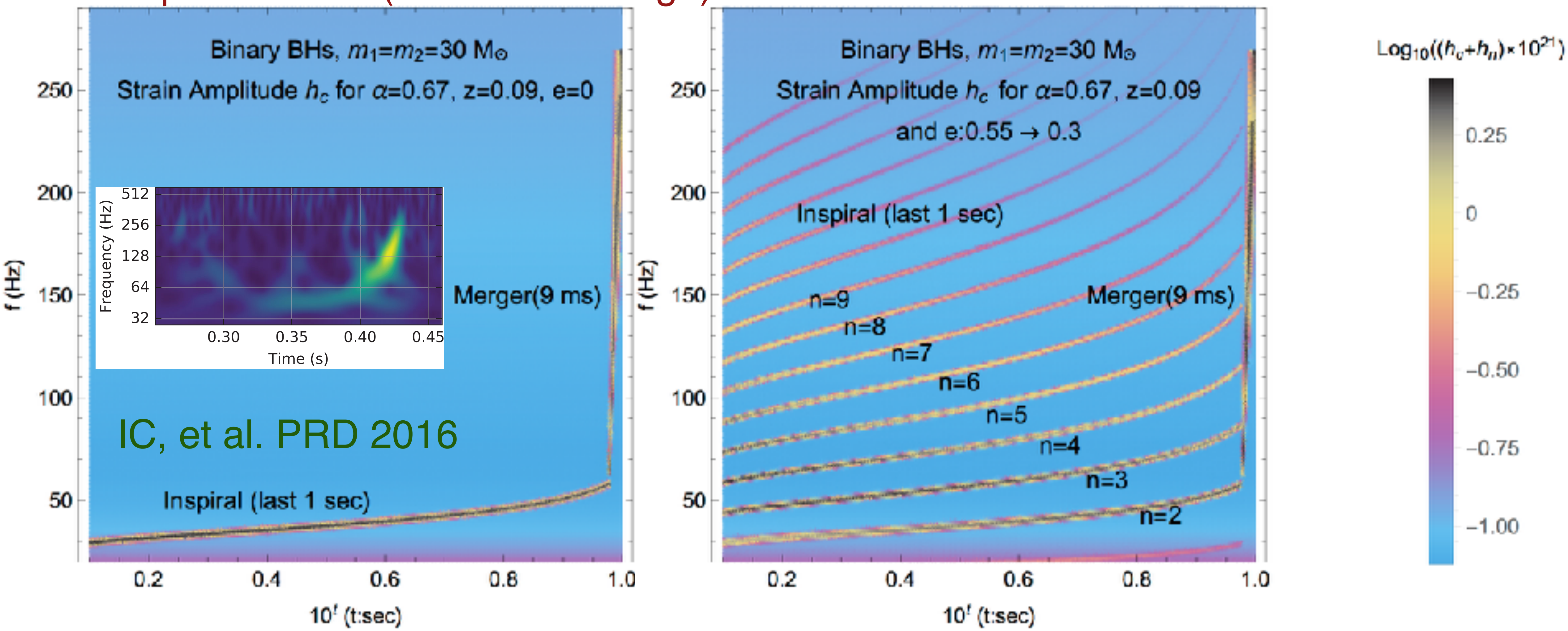

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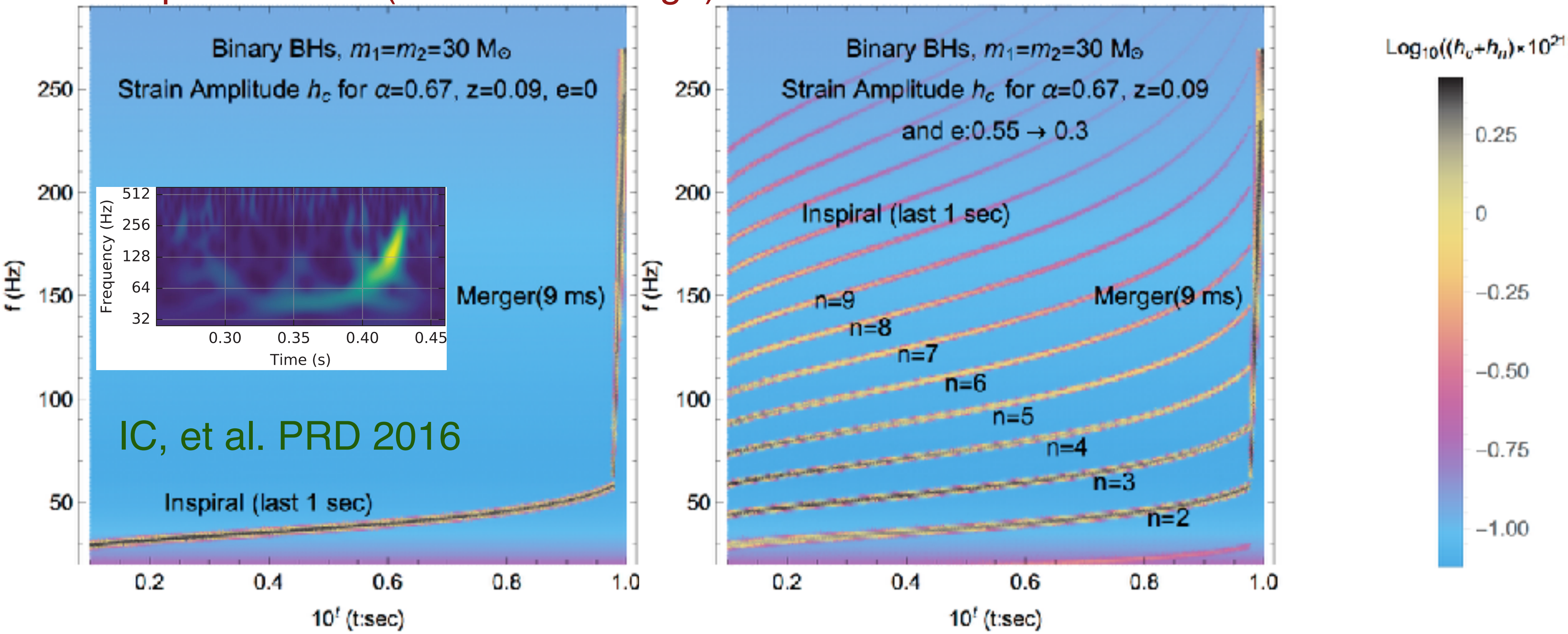
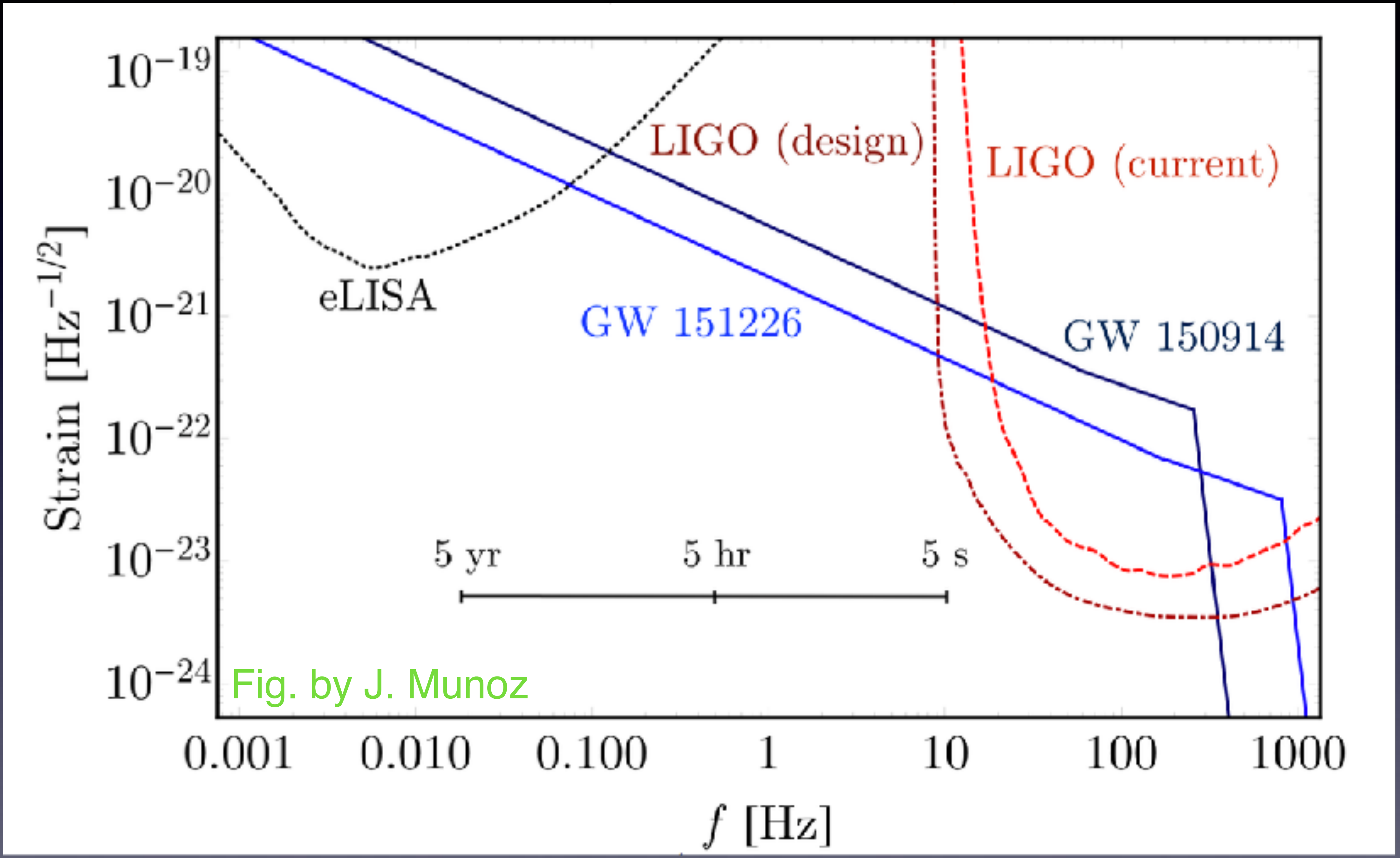


With LIGO we expect O(1) events while with the Einstein Telescope we expect O(10) events with multiple modes detected from PBH binaries.

Other astrophysical mechanisms for Binary BHs have typical time-scales of evolution that is ~Myrs-Gyrs.

II) Combining space and ground-based observations

FUTURE: Berti, IC, Kovetz, Wong in prep 2018



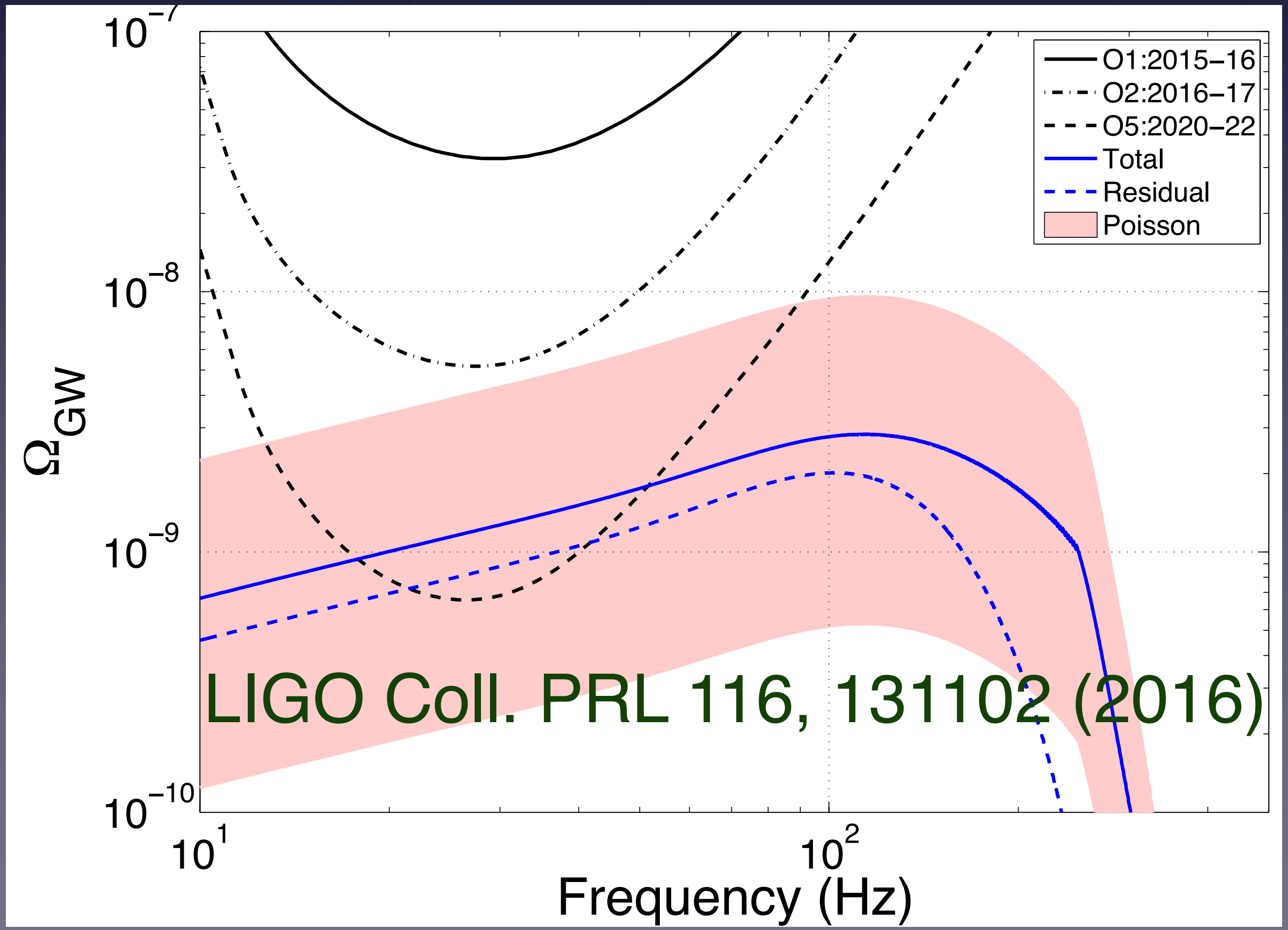
With Future LISA we will also be able to trace back some PBH systems to earlier stages (days-years before the merger event) and thus observe the binaries at even higher eccentricities. That is true for all progenitor models.

III) The stochastic GW background & High Redshifts

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

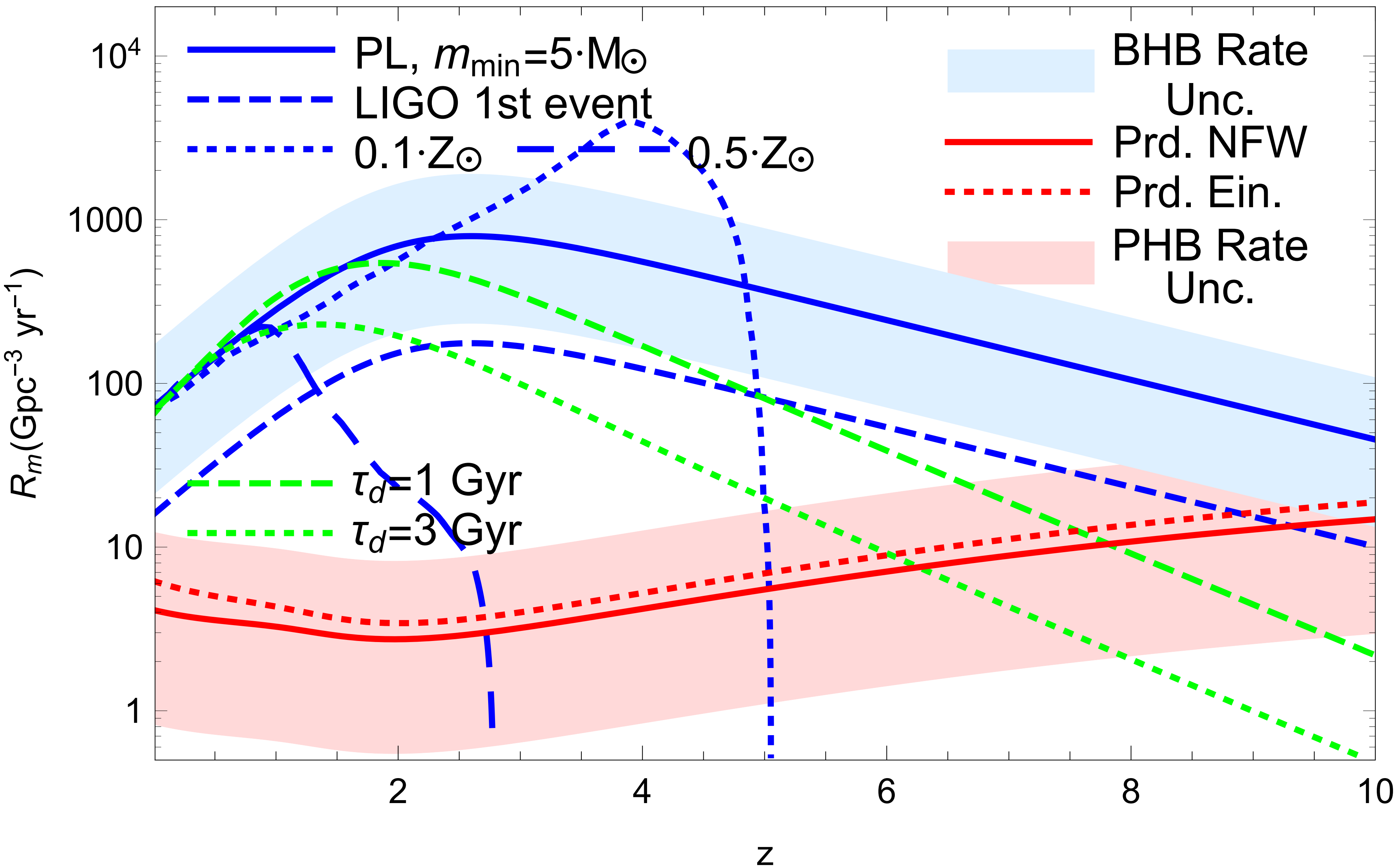
$$\Omega_{GW} = \frac{f}{\rho_c}\frac{d\rho_{GW}}{df}$$ <— energy density between f and f+df

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



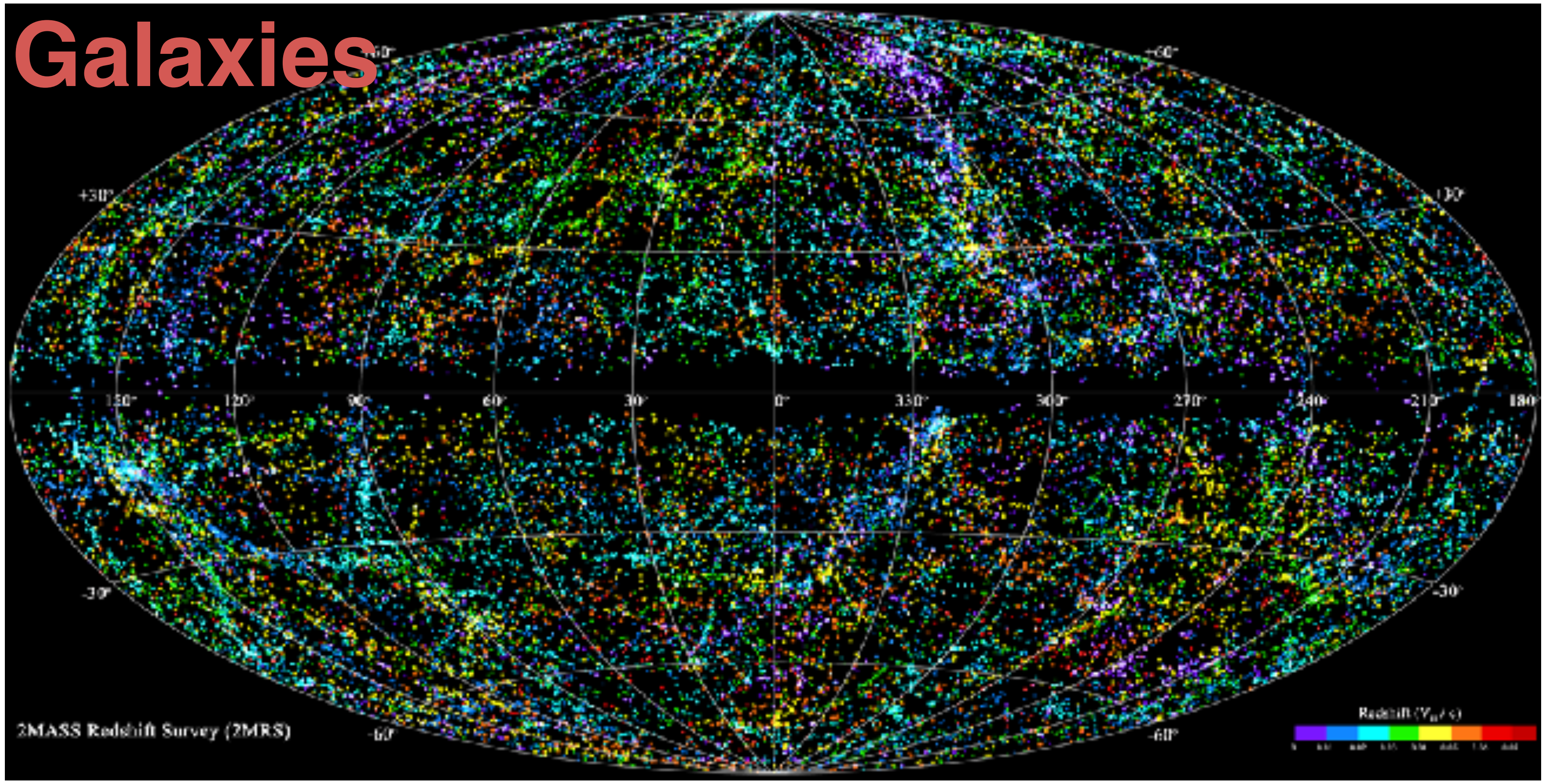
Rates on the BH-BH mergers
(some room a PBH component to be seen in the Stoch. Background)

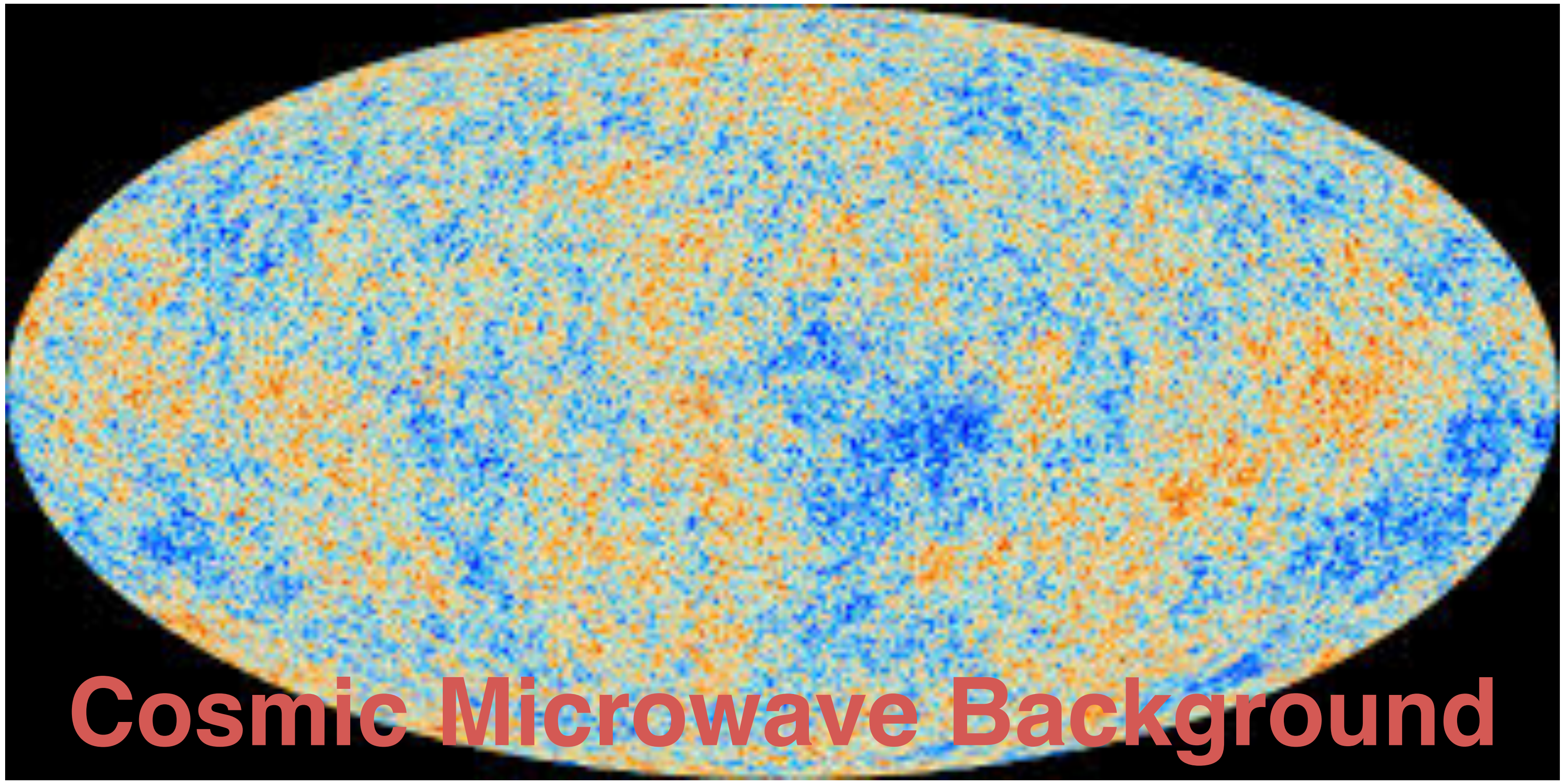
Mandic, Bird, IC (PRL 117.201102) &
Cholis (JCAP 06 037 2017)



With Einstein Telescope/Cosmic Explorer will be able to probe the PBHs at High Redshift and Better Understand Stoch. Back.

IV) Far future direction: Cross-Correlations with Galaxies





IV) Far future direction: Cross-Correlations with Galaxies

Raccanelli, Kovetz, Bird, IC, Munoz PRD 94 023516

If the GW signal comes from BHs originating by standard astrophysical sources, then the binary systems should preferentially reside in galaxies where most of the stars are.

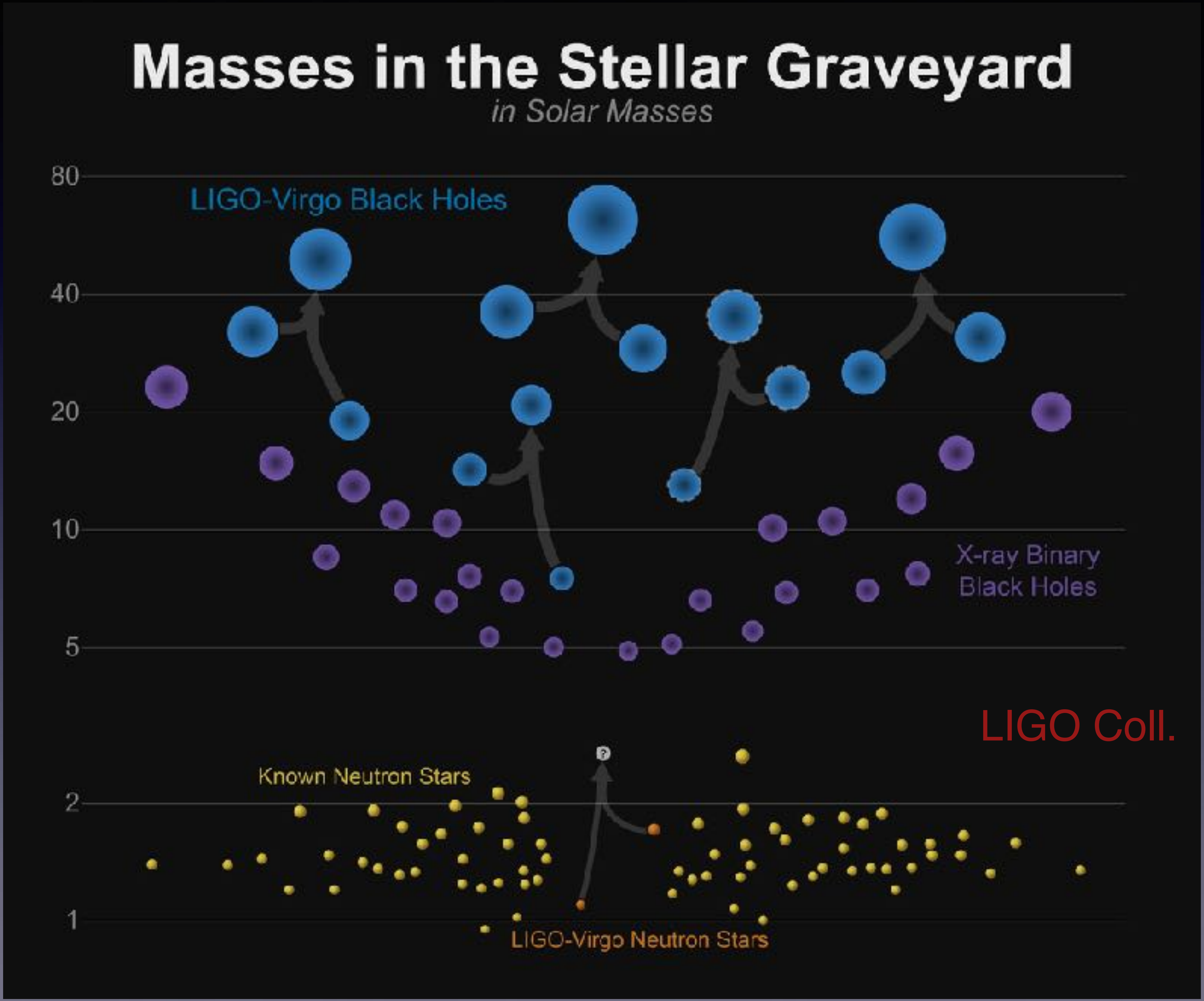
The GW and star forming galaxy (SFG) maps would be highly correlated.

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

The GW map will not be highly correlated to the star forming galaxy maps.

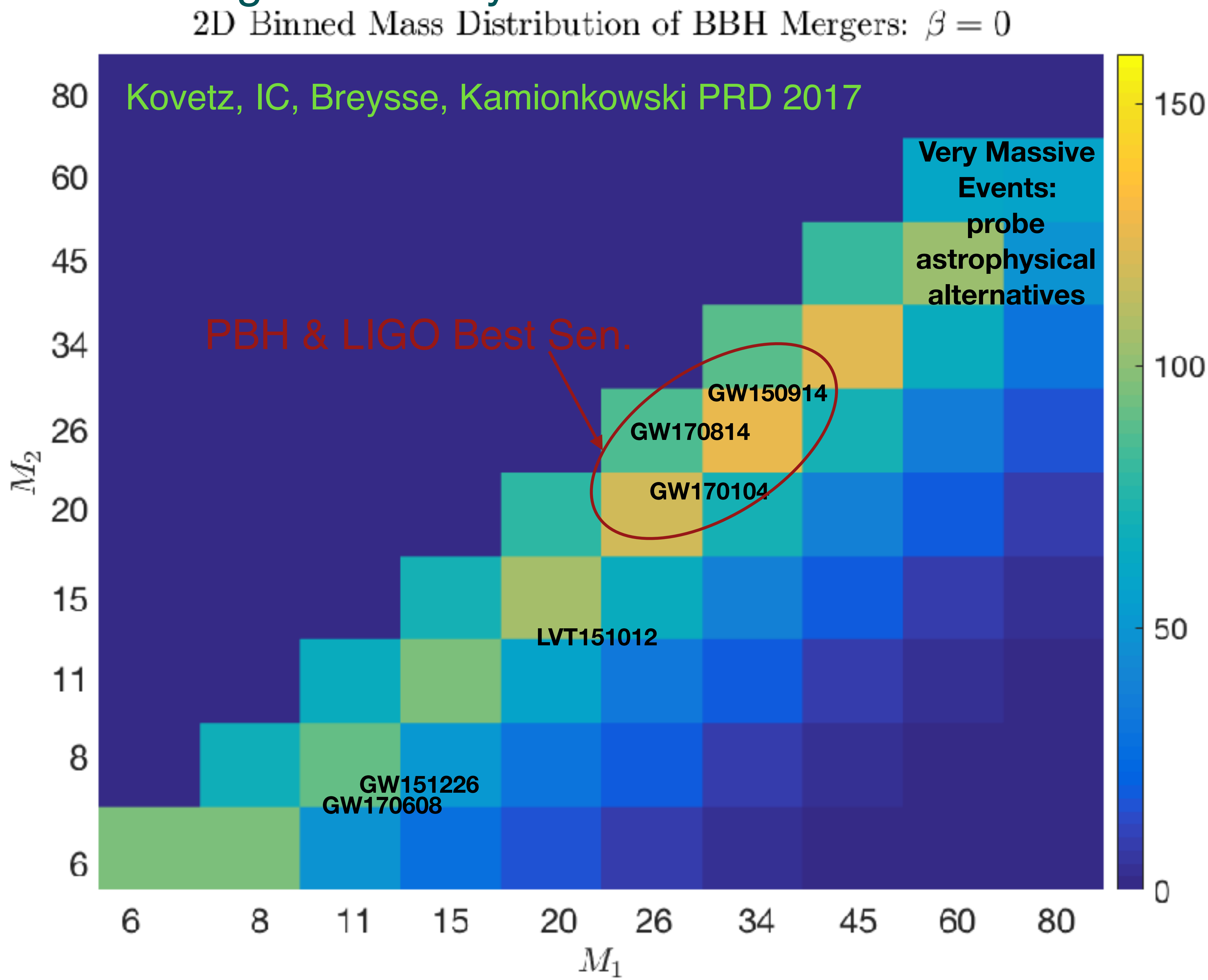
We will have to wait up to 2030+ for that test.

V) Understanding the Black Holes Mass Function



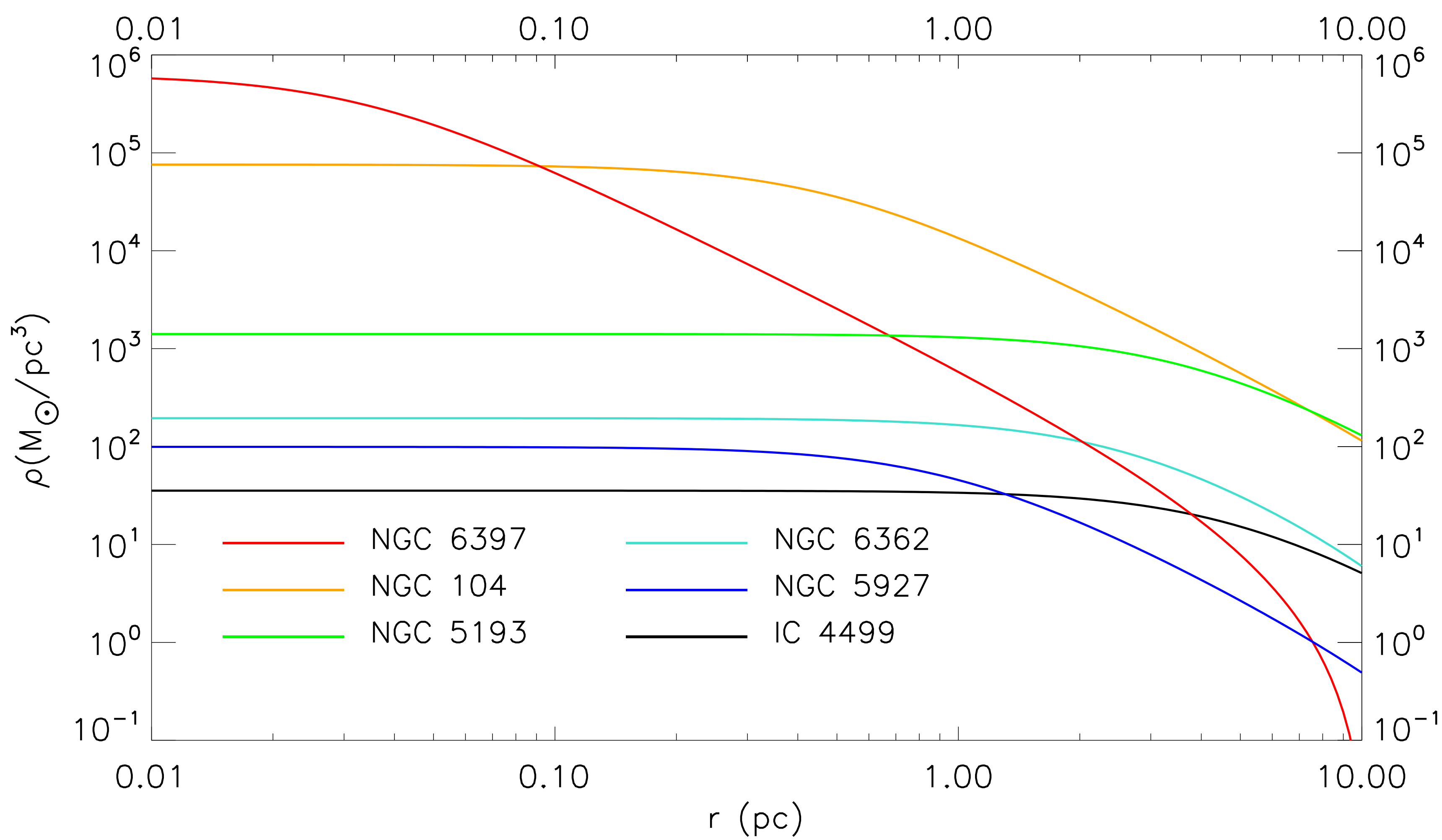
LIGO Coll.

With aLIGO design sensitivity



An Astrophysical Alternative: The Centers of Globular Clusters

Six Observed Globular Clusters of the Milky Way:

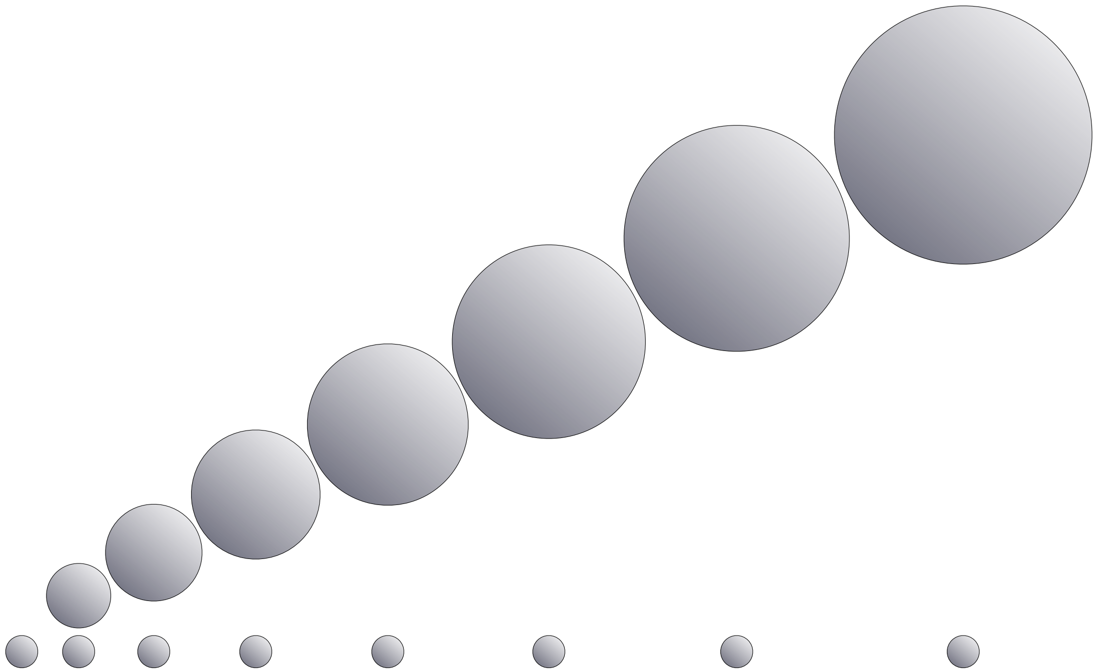


Kovetz, IC, Kamionkowski, Silk arXiv:1803.00568

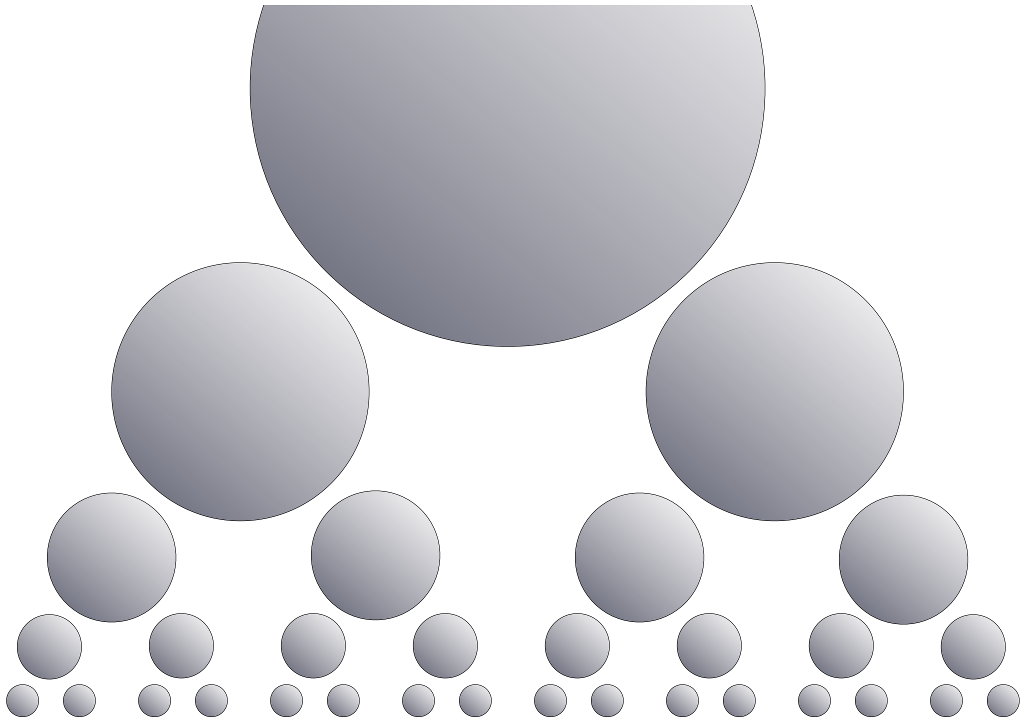
If GCs are the birthplaces of merging BHs—> GWs, then for a ~10% of these systems we expect to have a runaway process.

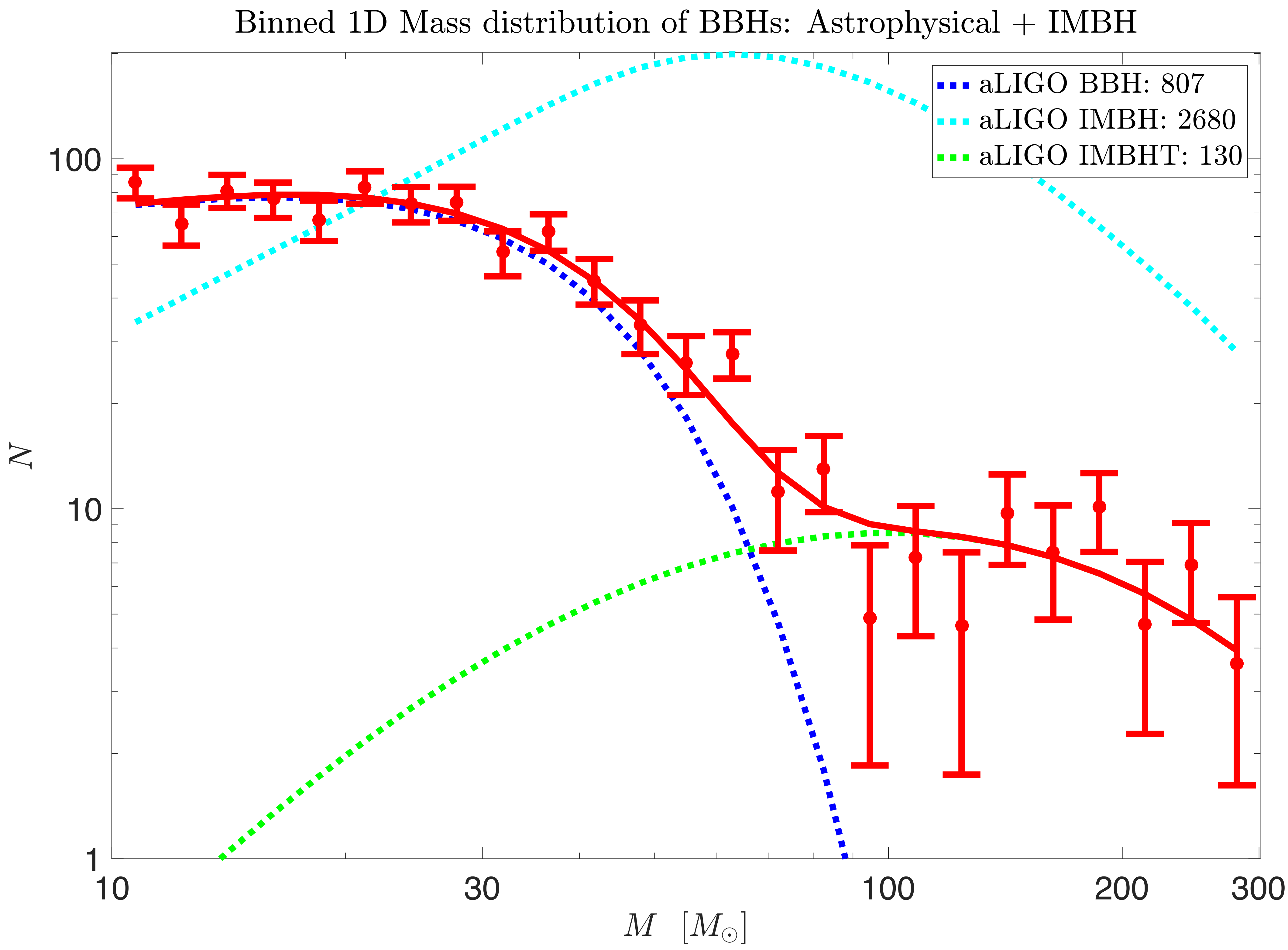
Kovetz, IC, Kamionkowski, Silk, arXiv: 1803.00568
IC, Kovetz, Kamionkowski in prep 2018

Slowest:



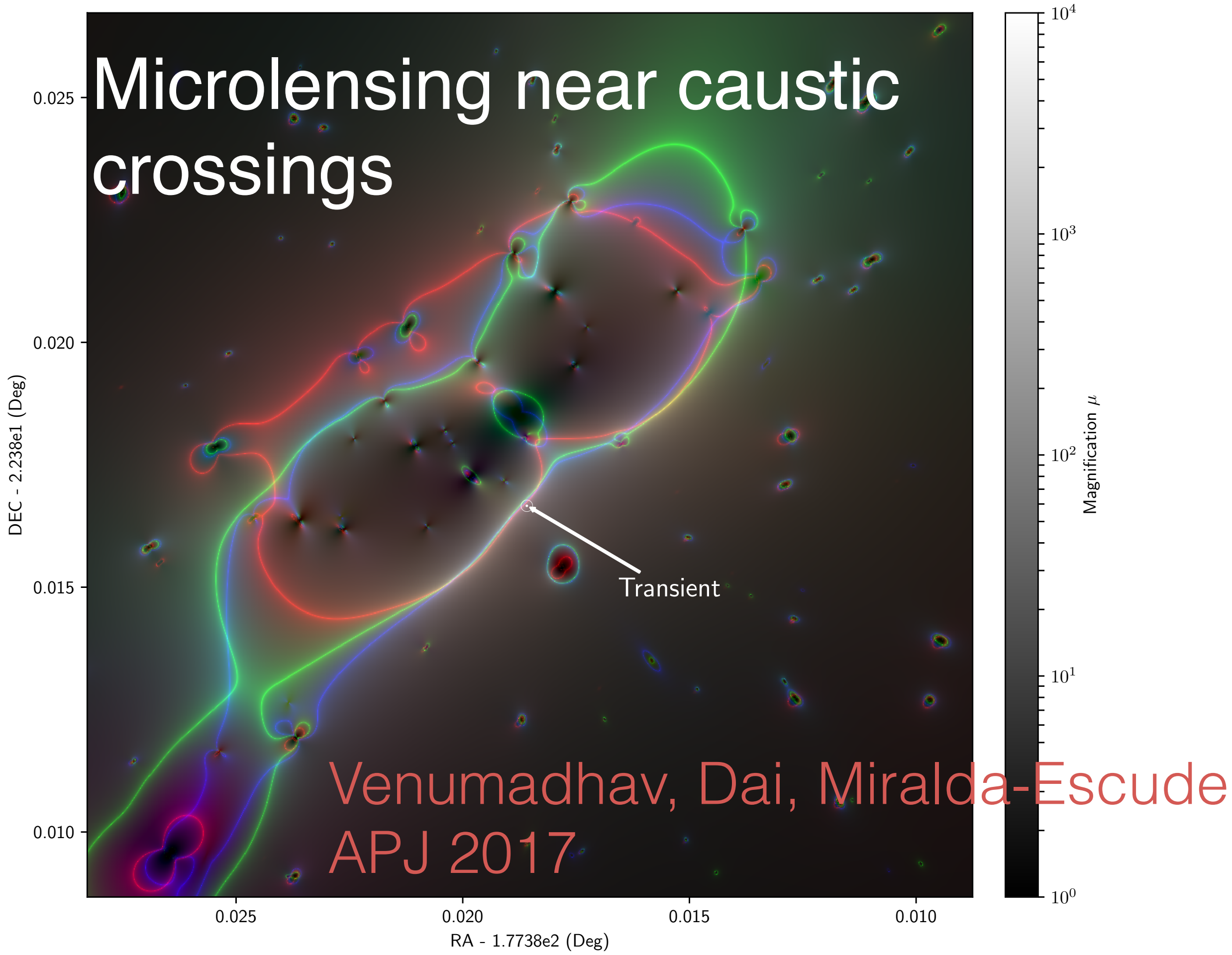
Most Fast:



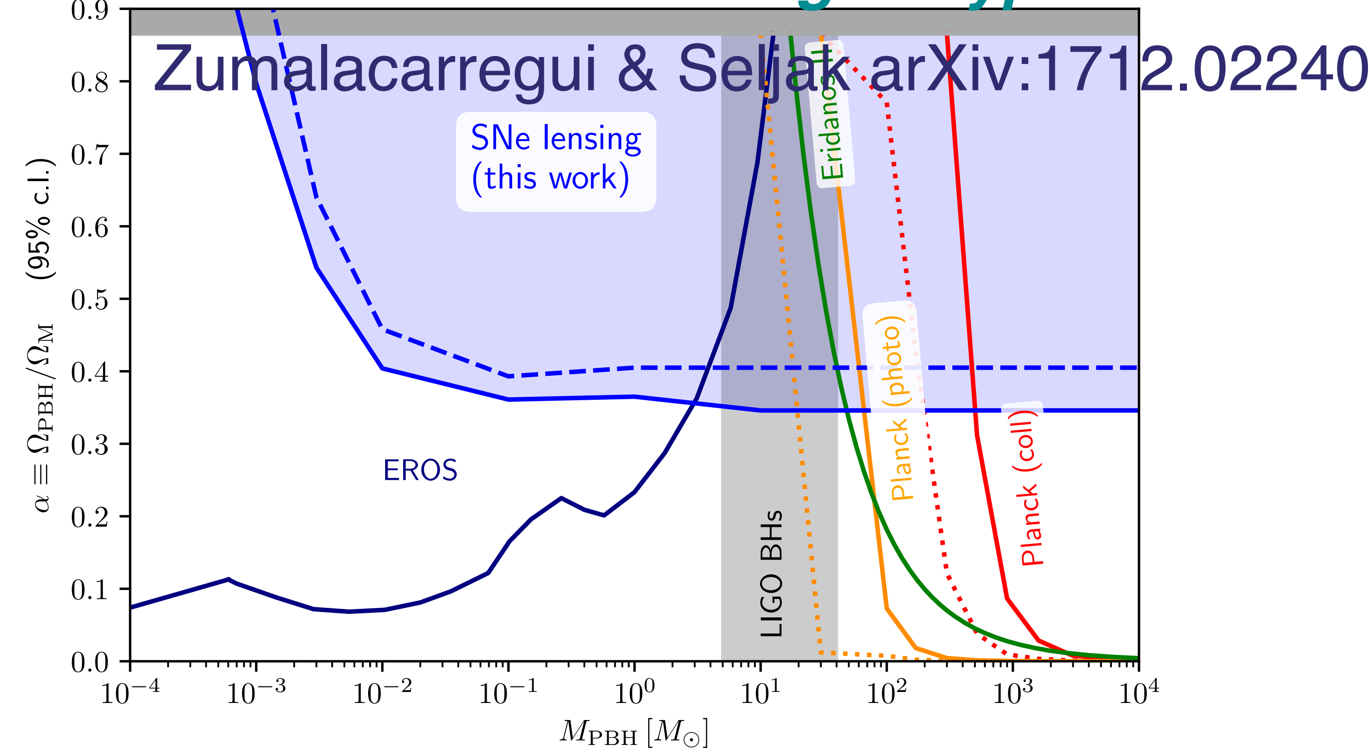


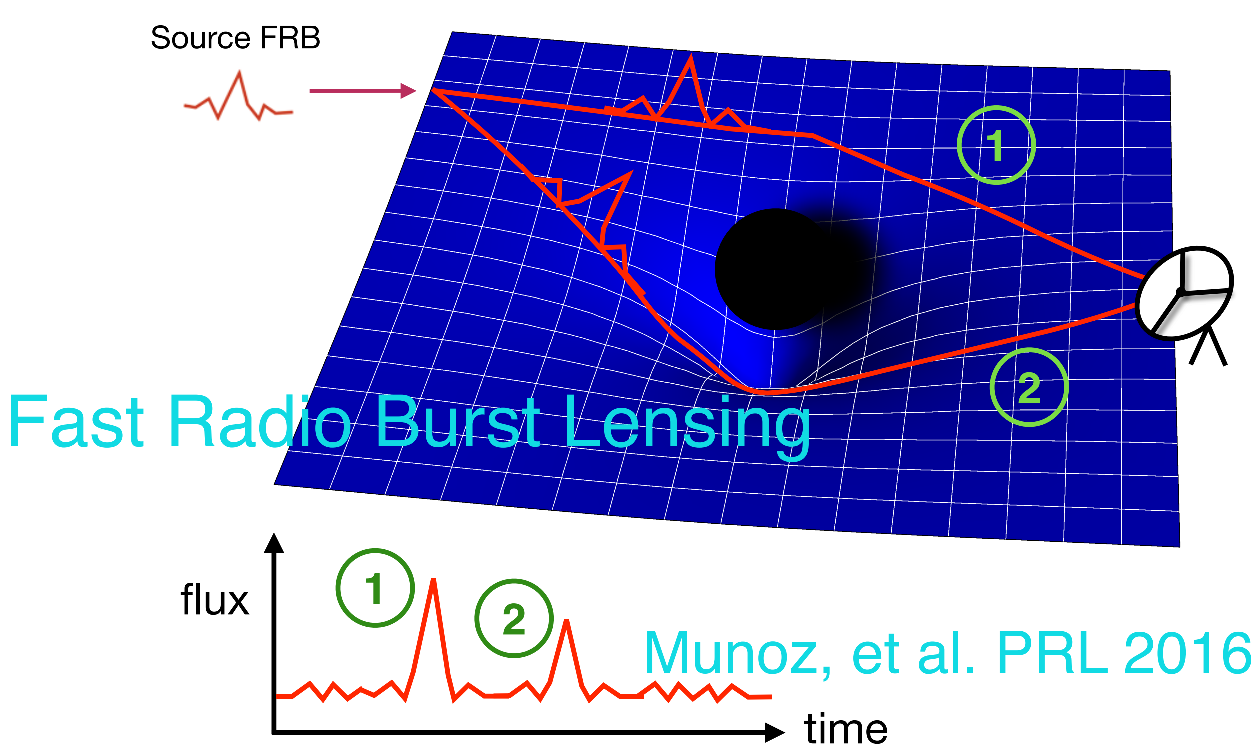
Kovetz, IC, Kamionkowski, Silk arXiv:1803.00568

New Ideas on how to constrain PBH DM:

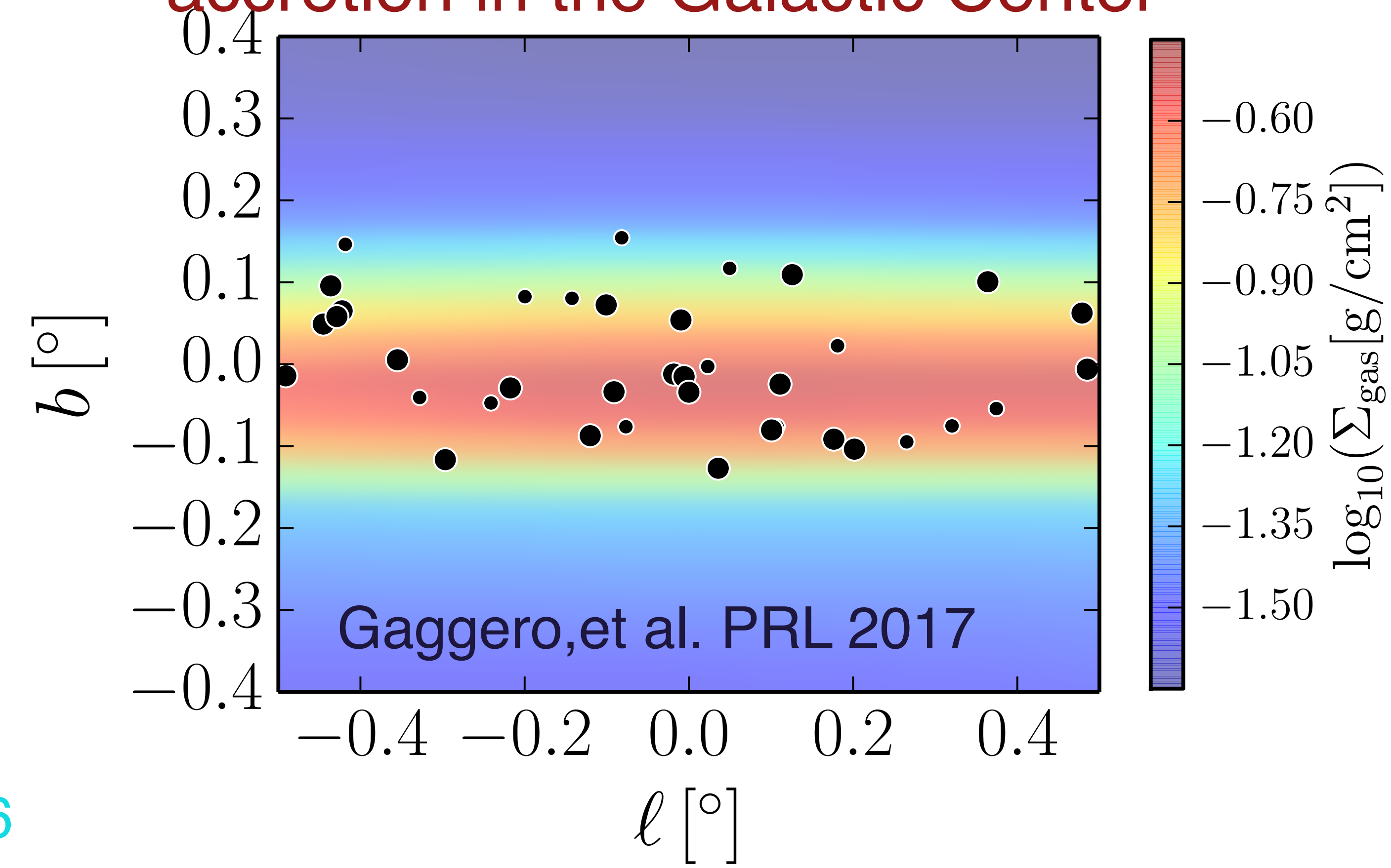


From Lensing of Type Ia SN

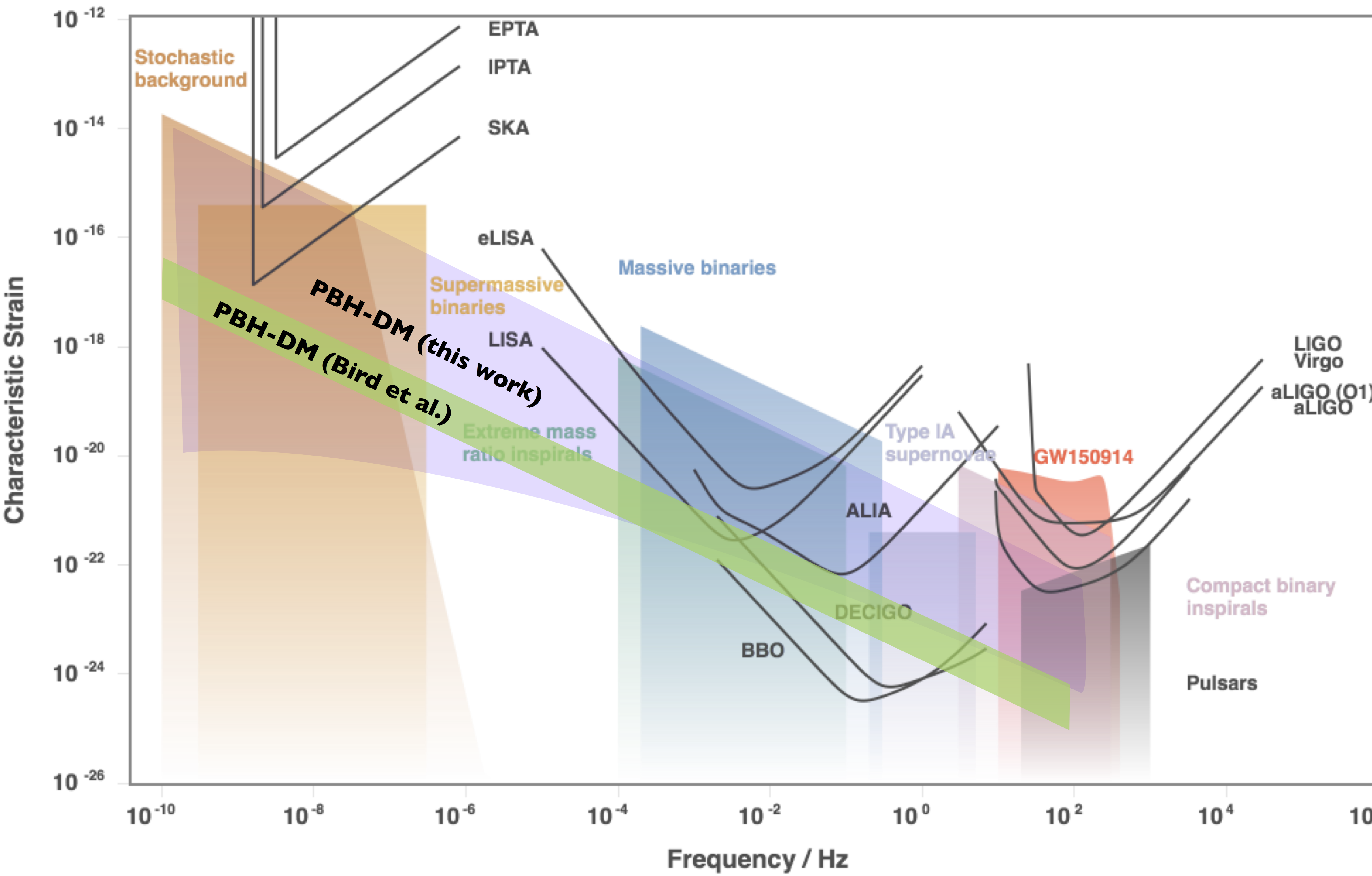




Radio and X-ray emission from gas accretion in the Galactic Center



And at even lower-frequencies:



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

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).
- These can be very short-lived systems (shorter than this presentation). Thus with properties very unique and Testable! in the next ~decade.
- One can also search for a signal in the mass-spectrum of observed BHs in the next ten years and even derive limits on PBHs from GWs.
- We can also search for a signal in the overall GW emission, testable with the next generation of detectors (2030s).
- Make a connection with other observables as is the distributions of galaxies(2030s++).
- **A GREAT NEW PROBE TO STUDY THE COSMOS : A NEW INDIRECT DM PROBE.**