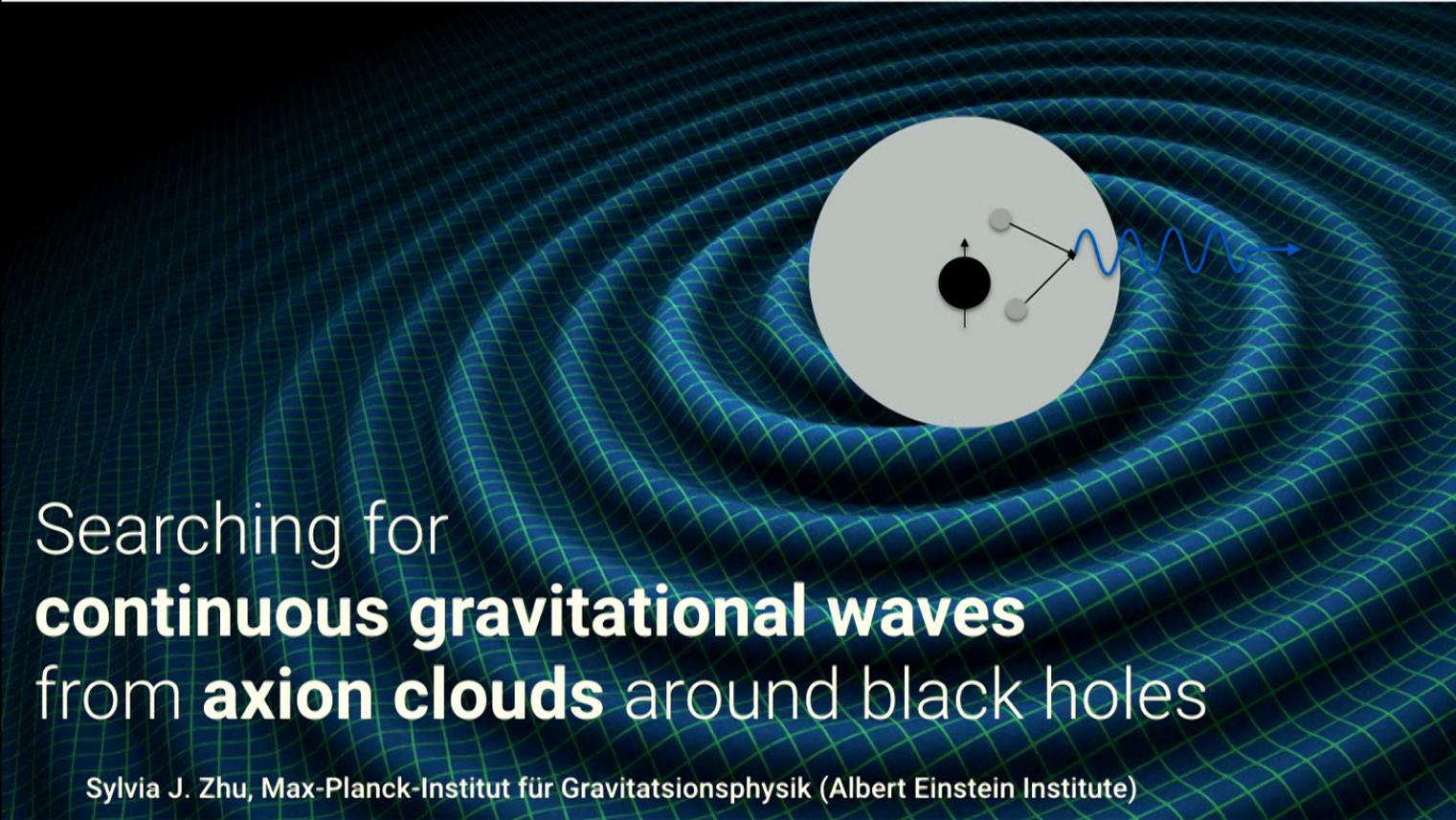


Title: Searching for continuous gravitational waves from axion clouds around black holes

Date: Dec 06, 2018 01:00 PM

URL: <http://pirsa.org/18120007>

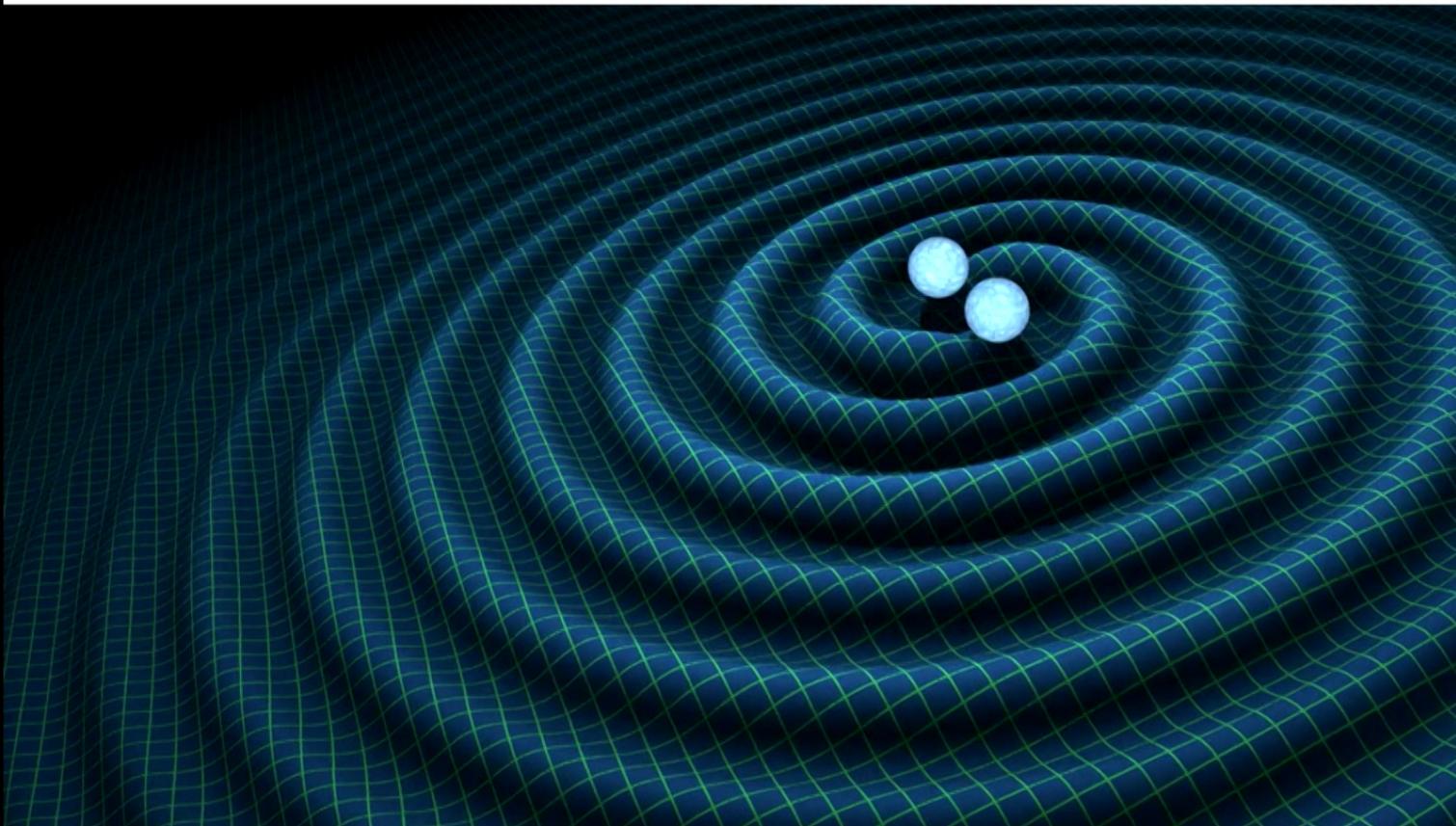
Abstract: <p>The recent gravitational-wave detections of binary mergers
 have opened a new and exciting window into observing the Universe.
 Persistent sources of gravitational waves must also exist; searches for
 continuous gravitational-wave signals generally look for signals from
 non-axisymmetric neutron stars, but are also suitable for continuous
 gravitational waves from axion annihilations in clouds around black
 holes. I will discuss the expected axion annihilations signal from an
 astrophysical standpoint, starting from the Galactic isolated black hole
 population.</p>



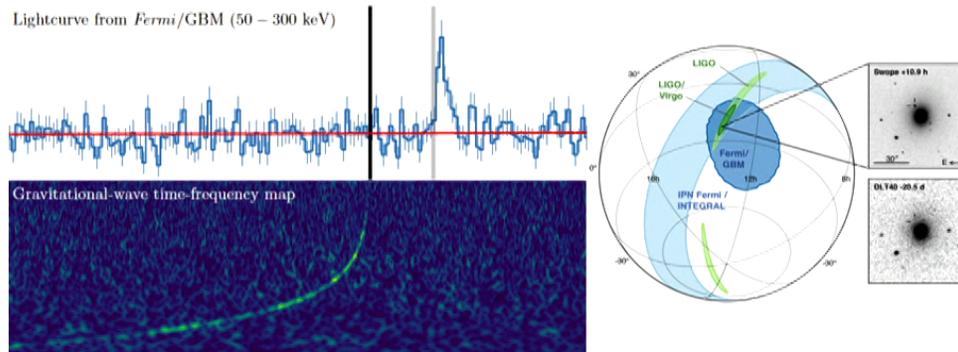
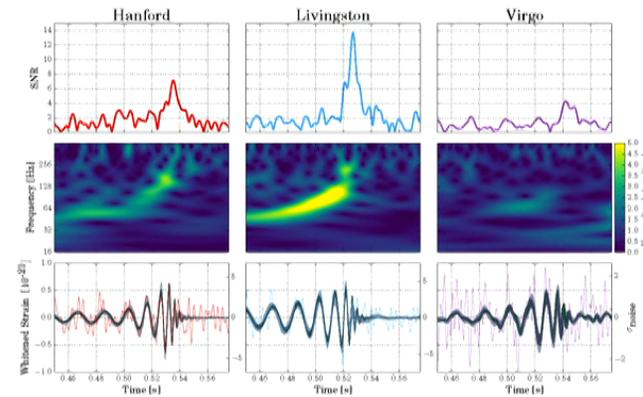
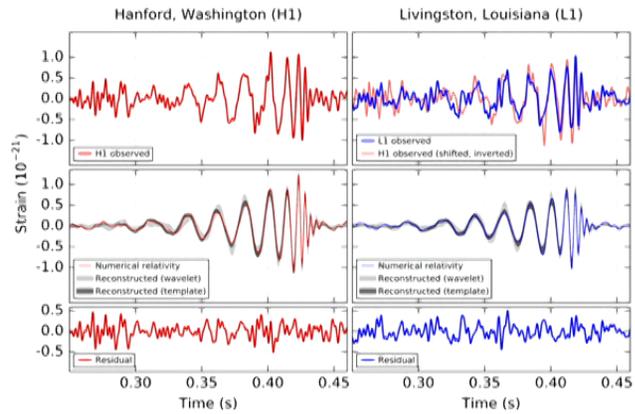
Searching for
continuous gravitational waves
from **axion clouds** around black holes

Sylvia J. Zhu, Max-Planck-Institut für Gravitationsphysik (Albert Einstein Institute)

Prologue



Prologue



[LVC, PRL 116 (2016)] [LVC, PRL 119 (2017)] [LVC et al., ApJL 848 (2017)] [LVC, Fermi-GBM, and INTEGRAL, ApJL 849 (2017)] 3 Sylvia J. Zhu, Perimeter Institute, 06 Dec 18

Prologue



GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs

<https://dcc.ligo.org/LIGO-P1800307/public>

Michael Pürrer
AEI Potsdam-Golm

On behalf of the
LIGO Scientific & Virgo Collaborations

GWPAW Dec 1, 2018



Prologue



Confident detections of GWs

- Found **four new binary black hole merger** events:
GW170729, GW170809, GW170818, GW170823
- **151012** designated as a GW event (higher significance because of improved detection pipelines)
- Not *all* events found with *all* searches

Event	UTC Time	PyCBC	FAR [y^{-1}]		cWB	Network SNR		
			GstLAL			GstLAL	GstLAL	cWB
GW150914	09:50:45.4	$< 1.53 \times 10^{-5}$	$< 1.00 \times 10^{-7}$		$< 1.63 \times 10^{-4}$	23.6	24.4	25.2
GW151012	09:54:43.4	0.17	7.92×10^{-3}		–	9.5	10.0	–
GW151226	03:38:53.6	$< 1.69 \times 10^{-5}$	$< 1.00 \times 10^{-7}$		0.02	13.1	13.1	11.9
GW170104	10:11:58.6	$< 1.37 \times 10^{-5}$	$< 1.00 \times 10^{-7}$		2.91×10^{-4}	13.0	13.0	13.0
GW170608	02:01:16.5	$< 3.09 \times 10^{-4}$	$< 1.00 \times 10^{-7}$		1.44×10^{-4}	15.4	14.9	14.1
GW170729	18:56:29.3	1.36	0.18		0.02	9.8	10.8	10.2
GW170809	08:28:21.8	1.45×10^{-4}	$< 1.00 \times 10^{-7}$		–	12.2	12.4	–
GW170814	10:30:43.5	$< 1.25 \times 10^{-5}$	$< 1.00 \times 10^{-7}$		$< 2.08 \times 10^{-4}$	16.3	15.9	17.2
GW170817	12:41:04.4	$< 1.25 \times 10^{-5}$	$< 1.00 \times 10^{-7}$		–	30.9	33.0	–
GW170818	02:25:09.1	–	4.20×10^{-5}		–	–	11.3	–
GW170823	13:13:58.5	$< 3.29 \times 10^{-5}$	$< 1.00 \times 10^{-7}$		2.14×10^{-3}	11.1	11.5	10.8

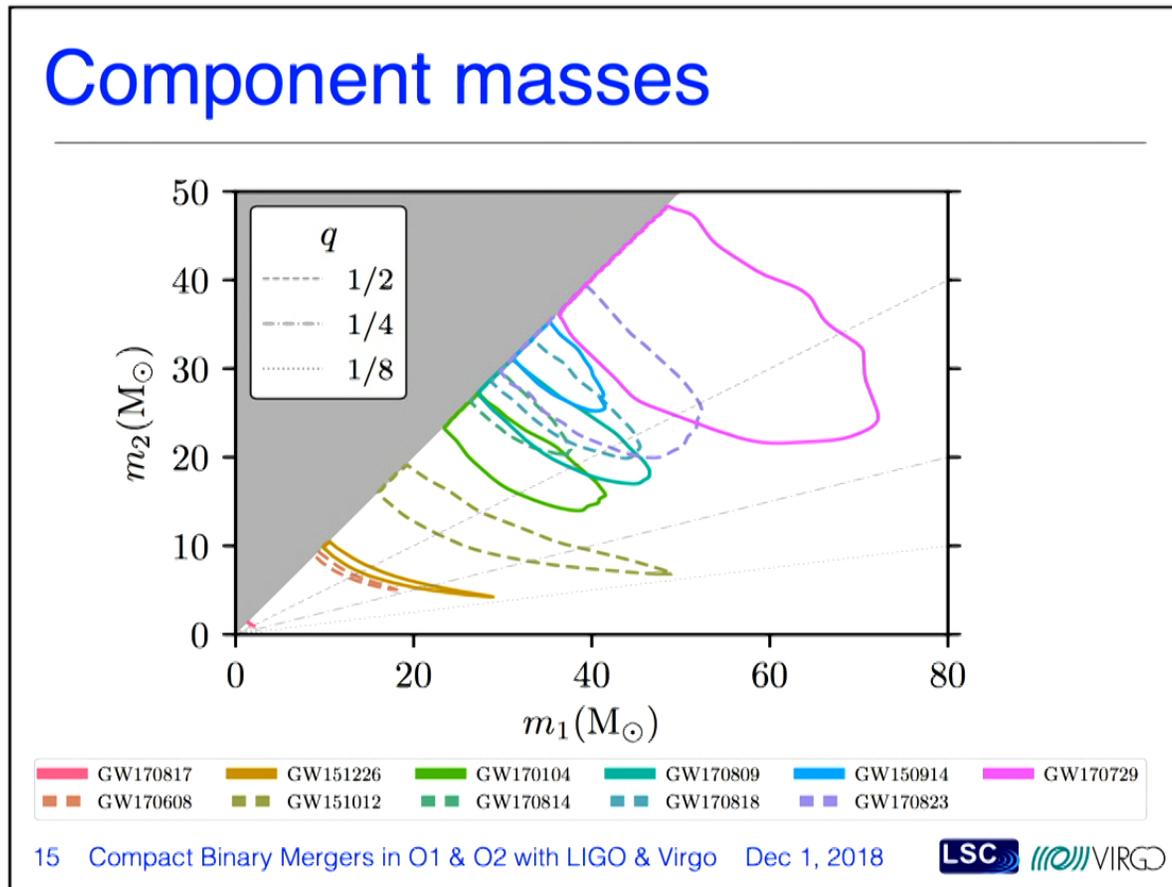
7 Compact Binary Mergers in O1 & O2 with LIGO & Virgo Dec 1, 2018



Prologue



Component masses

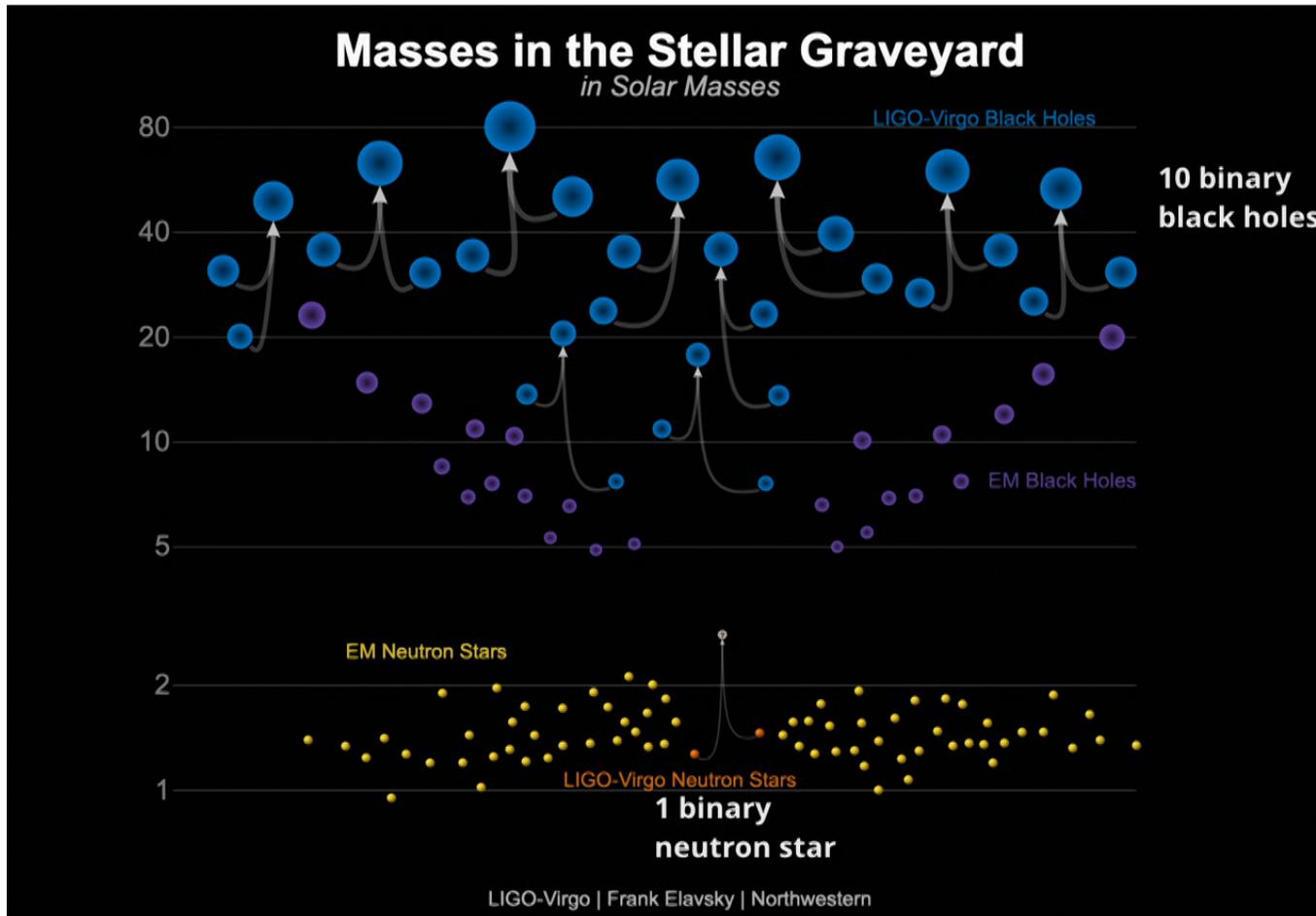


[GWPAW 2018]

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Prologue



[LIGO / Frank Elvasky / Northwestern]

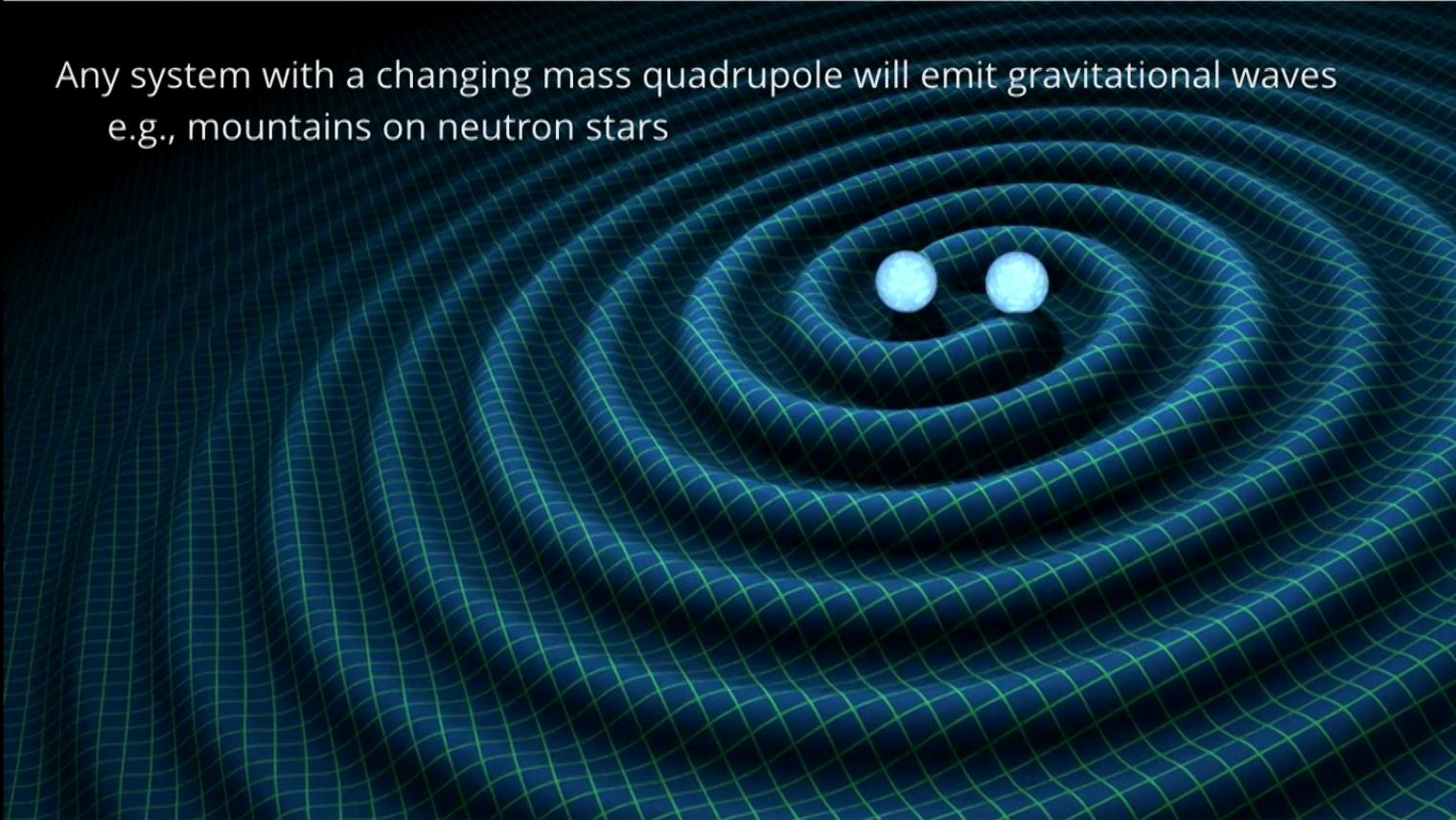
7

Sylvia J. Zhu, Perimeter Institute, 06 Dec 18

Prologue



Any system with a changing mass quadrupole will emit gravitational waves
e.g., mountains on neutron stars



Overview of this talk



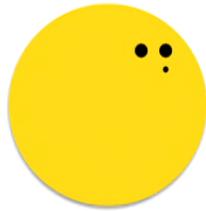
Searching for continuous
~~Detection of gravitational waves from~~
~~merging compact objects~~
isolated neutron stars

Overview of this talk



Searching for continuous
~~Detection of gravitational waves from~~
~~merging compact objects~~
~~isolated neutron stars~~
boson clouds around black holes
(with an astronomy approach)

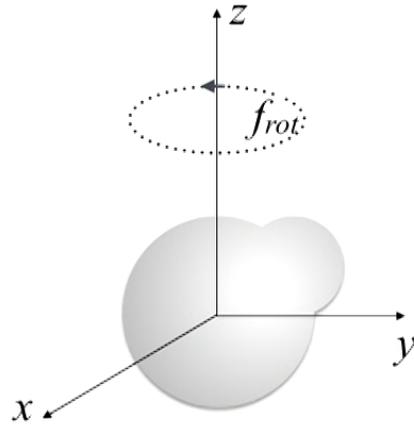
Bumpy neutron stars



(the merciless, inexorable, ceaseless passage of time)

Bumpy neutron stars

To get gravitational waves, need a **time-varying mass quadrupole**



$$h_{\mu\nu} \propto \frac{d^2 I_{\mu\nu}}{dt^2}$$

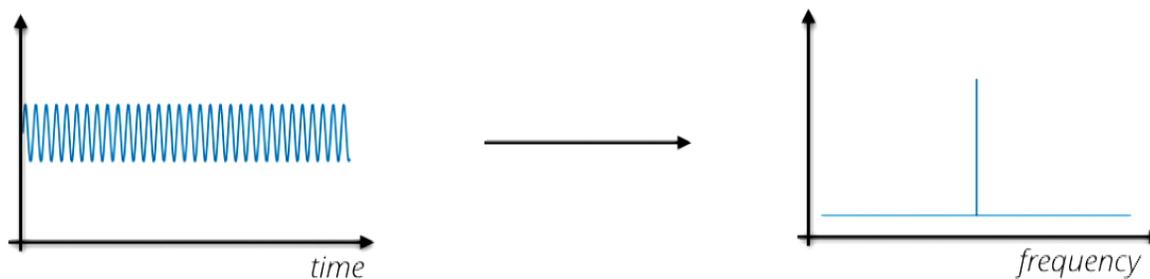
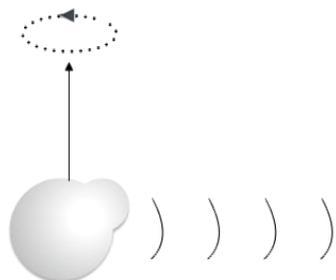
$$f_{GW} = 2f_{rot}$$

$$h_0 = \frac{4\pi G I_{zz}}{c^4} \frac{f_{GW}^2}{D} \epsilon$$

Orange arrows point from $f_{GW} = 2f_{rot}$ to f_{GW}^2 and from $\frac{|I_{xx} - I_{yy}|}{I_{zz}}$ to ϵ .

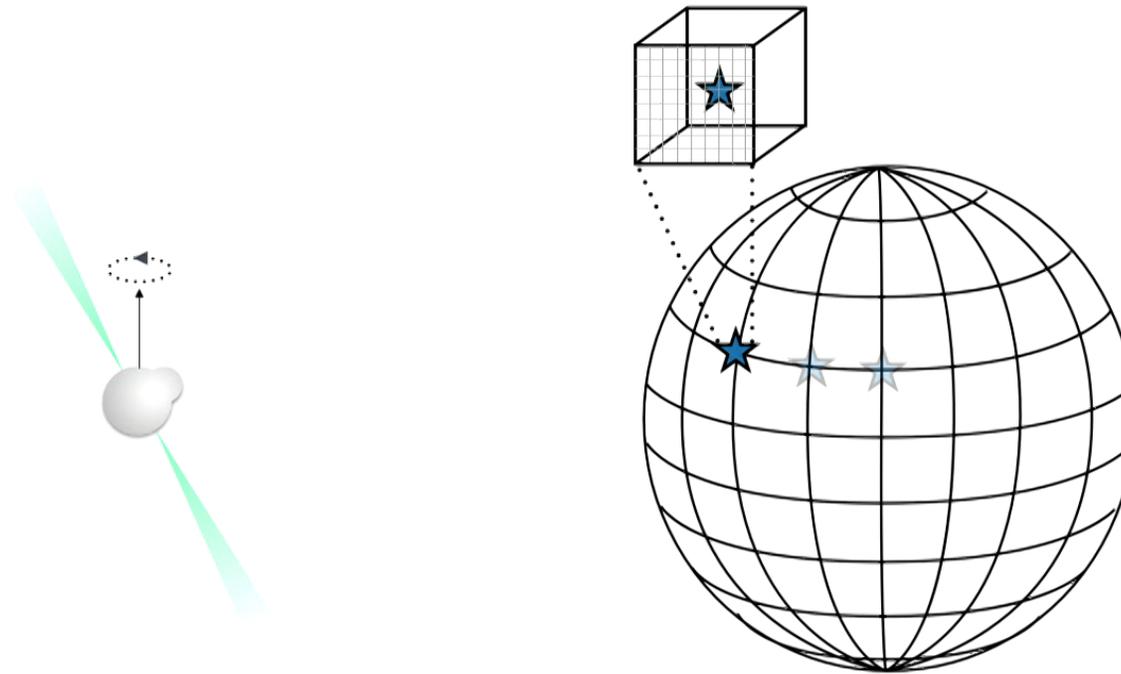
Note: There are other relevant mechanisms, but I will focus on this one

the physical waveform



frequency and frequency derivatives

scenario: known pulsar



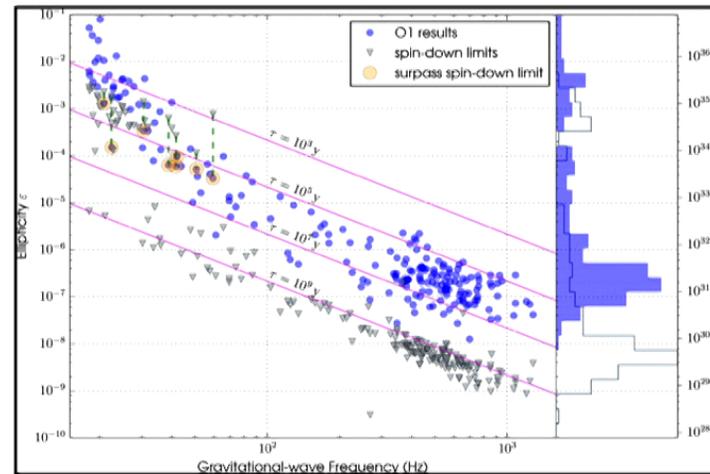
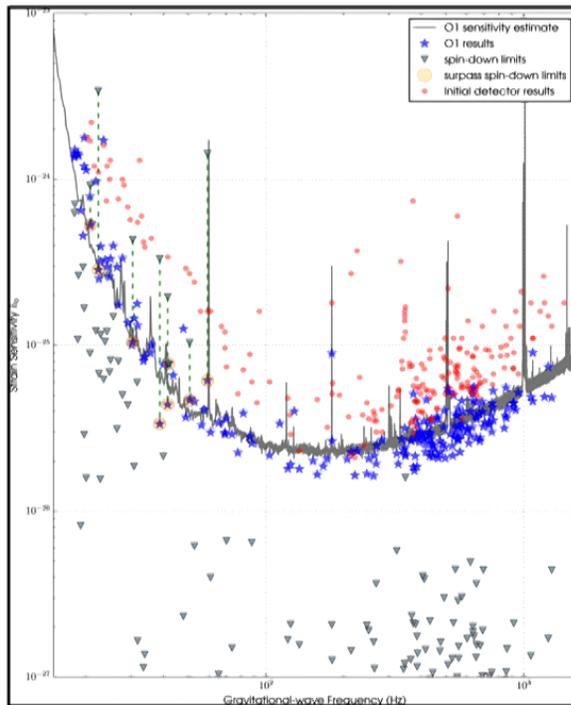
- ✓ frequency and frequency derivatives
- ✓ sky position

scenario: known pulsar

“Any gravitational-wave emission from this pulsar must be quieter than this amount”



“Any mountains on the neutron star must be smaller than this height”



[LVC, ApJ 839 (2017)]

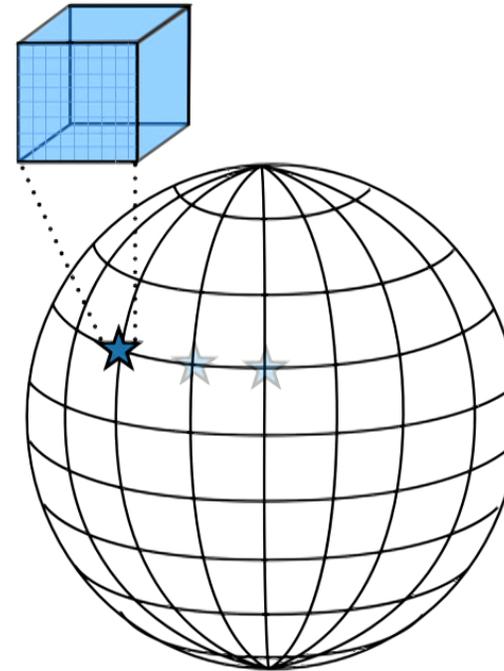
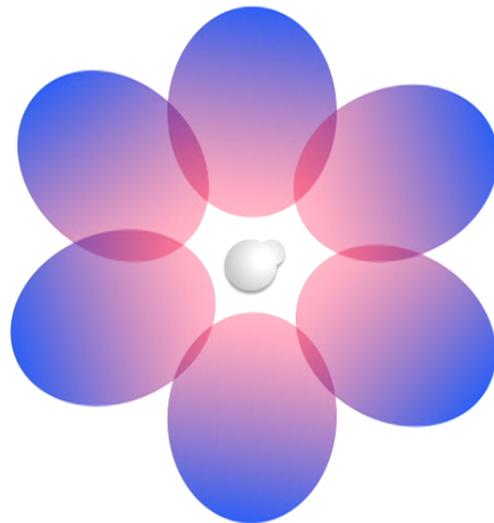
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scenario: known neutron star



compact cores of supernova remnants



- \times frequency and frequency derivatives
- \checkmark sky position

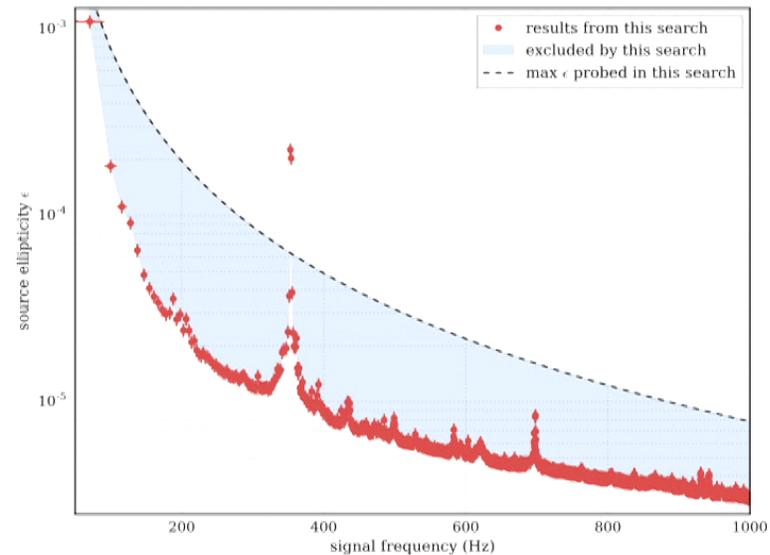
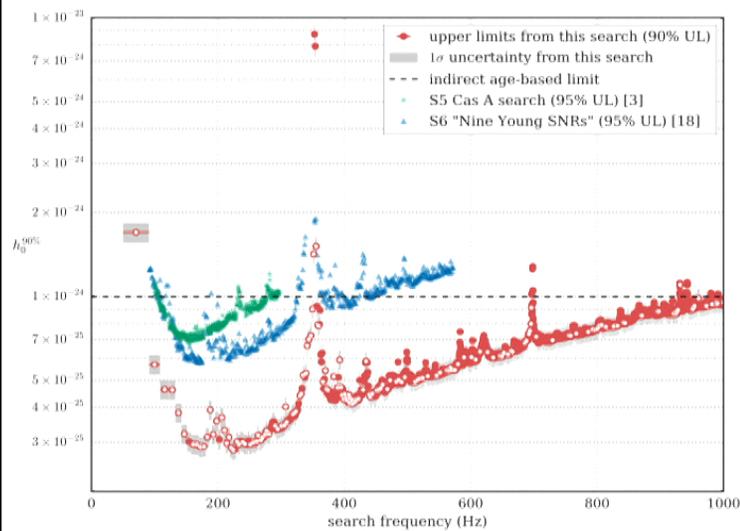
scenario: known neutron star



“Any gravitational-wave emission from this neutron star **if it were emitting at this frequency** must be quieter than this amount”



“Any mountains on this neutron star **if it were emitting at this frequency** must be smaller than this height”



[Zhu et al., PRD 94 (2016)]

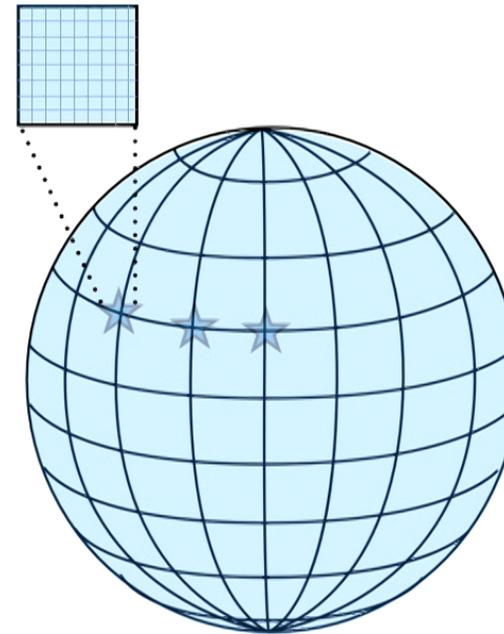
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scenario: $\sim \nu(\dot{\nu}) \sim$

$\sim \nu(\dot{\nu}) \sim$

There should be $>10^8$ NSs in the Galaxy
2500 pulsars have been discovered
 \Rightarrow 99,997,500 NSs are hidden



$\sim \nu(\dot{\nu}) \sim$ frequency and frequency derivatives
 $\sim \nu(\dot{\nu}) \sim$ sky position

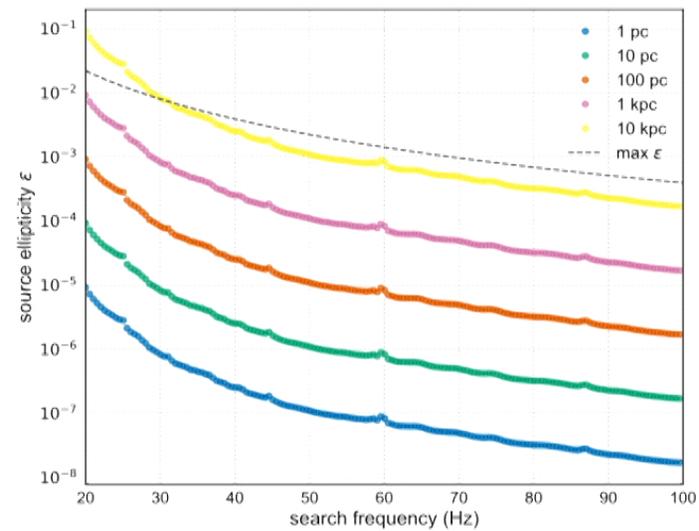
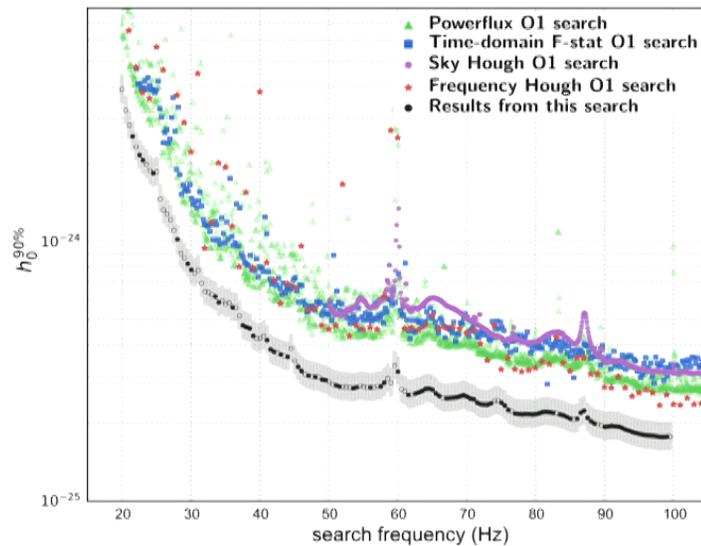
scenario: all-sky search



“Any gravitational-wave emission from **neutron stars anywhere in the sky emitting at these frequencies** must be quieter than this amount”



“Any mountains on neutron stars **that are emitting at this frequency and at this distance** must be smaller than this height”



[LVC, PRD 96 (2017)]

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scenario: all-sky search



“Any gravitational-wave emission from **boson annihilations anywhere in the sky** must be quieter than this amount”



... ?

What does the ensemble signal from all the black holes in our Galaxy look like?

Part 2: CWs from boson clouds

Disclaimer: I am going to play fast and loose with notation, terminology

boson clouds around black holes*



* from a data analyst's understanding

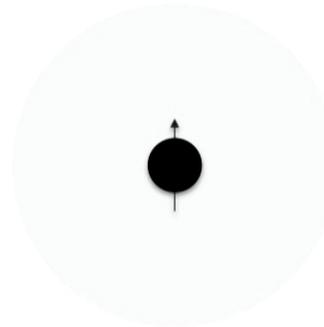
(note: we are focus on scalars)

1. BH is born



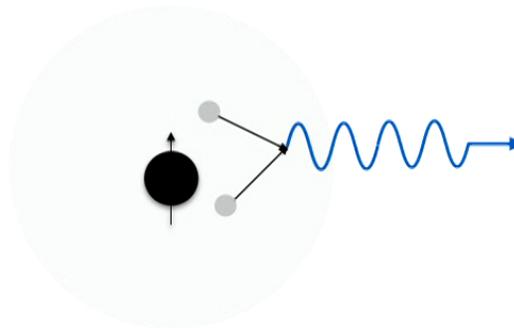
BH mass M
BH spin a_i
> minimum spin
for cloud formation

2. boson cloud builds up
via superradiance instability



BH mass $< M$
BH spin $< a_i$

3. annihilations within cloud produce
continuous gravitational waves



BH mass $< M$
BH spin $< a_i$

a few other searches



Search for the signal as a stochastic background:



**A first search for
a stochastic gravitational-wave background
from ultralight bosons**

Leo Tsukada
(RESCEU, U Tokyo)

December 2, 2018
GWPAW @ Maryland

co-authors:
Patrick Meyers, Andrew Matas, Thomas Callister

LIGO-P1800232

1/12

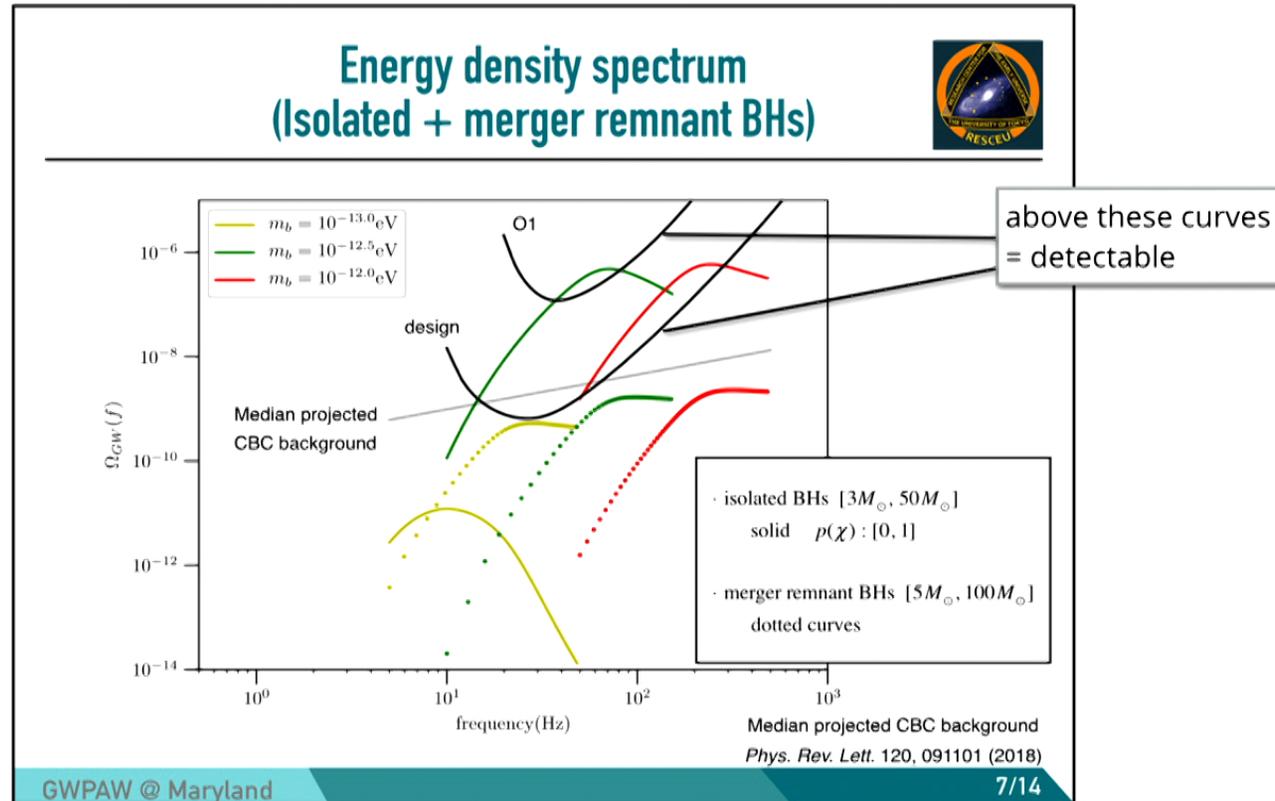
[GWPAW 2018]

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a few other searches

Search for the signal as a stochastic background:



[GWPAW 2018]

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a few other searches



All-sky search for individual signals:

A semi-coherent analysis method to search for continuous gravitational waves emitted by ultra-light boson clouds around spinning black holes

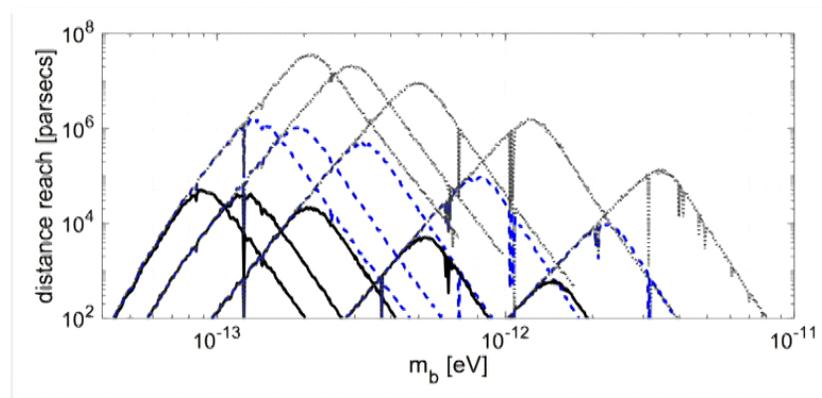
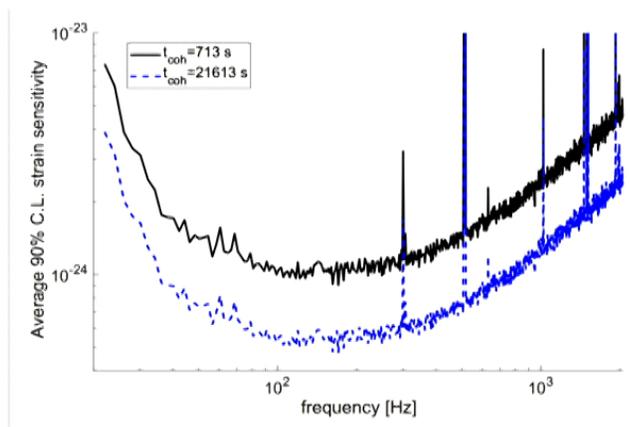
S. D'Antonio,¹ C. Palomba,² S. Frasca,^{2,3} G. Intini,^{2,3} I. La Rosa,² P. Leaci,^{2,3} S. Mastrogiovanni,^{2,3} A. Miller,^{2,3,4} F. Muciaccia,² O. J. Piccinni,^{2,3} and A. Singh²

¹*INFN, Sezione di Roma Tor Vergata, I-00133 Roma, Italy*

²*INFN, Sezione di Roma, I-00185 Roma, Italy*

³*University of Rome "La Sapienza", I-00185 Roma, Italy*

⁴*University of Florida, Gainesville, FL 32611, USA*



[D'Antonio et al., arXiv:1809.07202]

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our approach



We are taking an astronomy approach:

Use a simulation of **isolated black holes in the Galaxy** [Tsun et al., MNRAS 477 (2018)]

Calculate the expected ensemble signal from all of these BHs

Search for this

wow what a great title about CWs from boson clouds

Sylvia J. Zhu^{1,a}, Daichi Tsuna^{2,3,b}, Richard Brito^{4,c},
Maria Alessandra Papa^{1,5}, Norita Kawanaka^{6,7}, Heinz-Bernd Eggenstein¹

¹ *Max-Planck-Institut für Gravitationsphysik, Callinstraße 38, 30167, Hannover, Germany*

² *Research Center for the Early Universe (RESCEU), the University of Tokyo, Hongo, Tokyo 113-0033, Japan*

³ *Department of Physics, School of Science, the University of Tokyo, Hongo, Tokyo 113-0033, Japan*

⁴ *Max-Planck-Institut für Gravitationsphysik, am Mühlenberg 1, 14476, Potsdam-Golm, Germany*

⁵ *University of Wisconsin-Milwaukee, Milwaukee, Wisconsin 53201, USA*

⁶ *Department of Astronomy, Graduate School of Science, Kyoto*

University, Kitashirakawa Oiwake-cho, Sakyo-ku Kyoto, 606-8502, Japan

⁷ *Hakubi Center, Yoshida Honmachi, Sakyo-ku, Kyoto 606-8501, Japan*

CW signal from a single system

2 bosons \rightarrow 1 graviton

inherent CW frequency depends almost entirely on **boson mass**

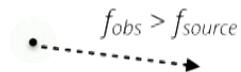
f_{source}

BHs are moving towards or away from us

observed CW frequency will be **Doppler shifted** due to BH motion

f_{obs}

$f_{obs} > f_{source}$



CW signals from all systems



2 bosons \rightarrow 1 graviton

inherent CW frequency depends almost entirely on **boson mass**

f_{source}

BHs are moving towards or away from us

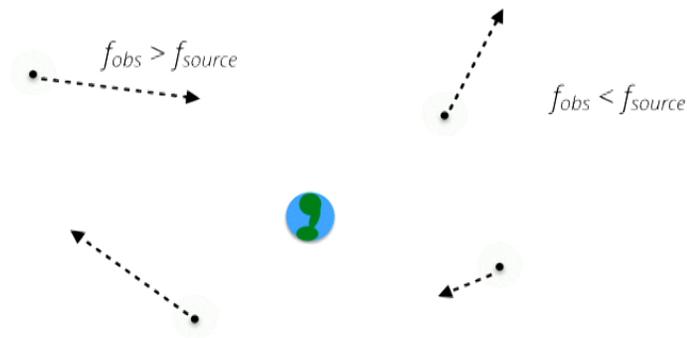
observed CW frequency will be **Doppler shifted** due to BH motion

f_{obs}

all* BHs will have clouds that emit this CW

we should be looking for the **ensemble signal** produced by all BHs

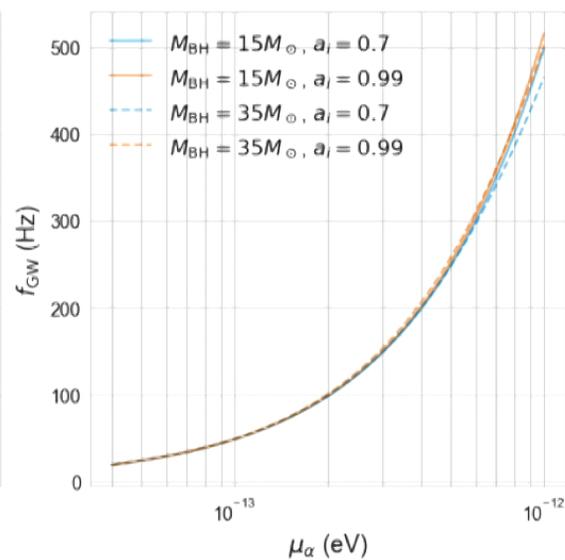
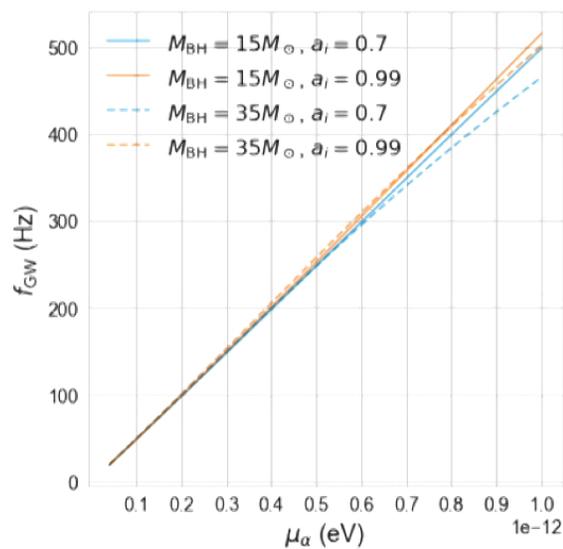
$\{f_{obs}\}$



parameter space



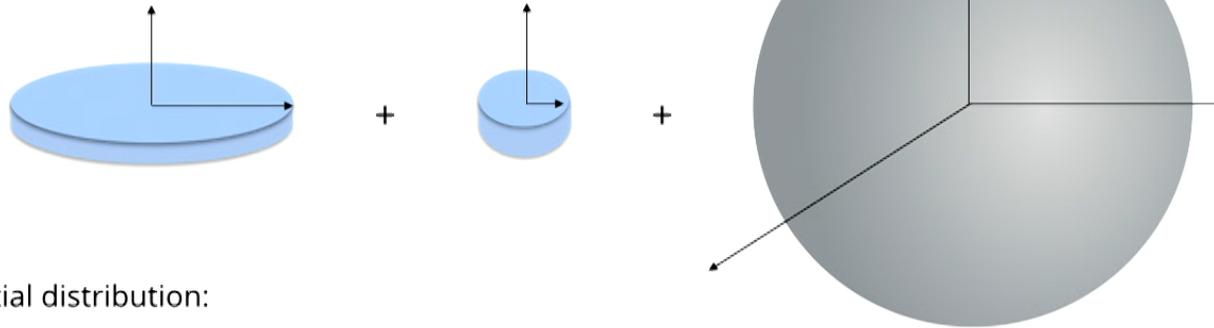
$$f_{\text{GW}} \in [20, 500] \text{ Hz} \quad \Leftrightarrow \quad \mu_\alpha \in [4\text{e-}14, 1\text{e-}12] \text{ eV}$$



Galactic isolated black holes

input:

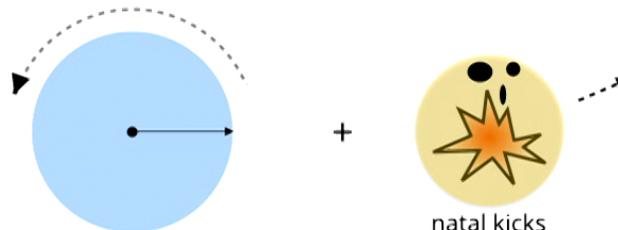
gravitational potential:



initial spatial distribution:



initial velocity distribution:



[Tsuna et al., MNRAS 477 (2018)]

face-on view of the Galaxy

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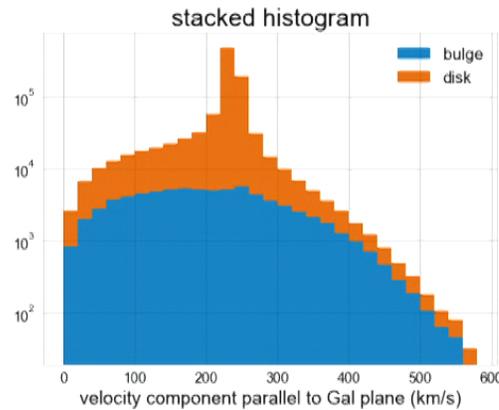
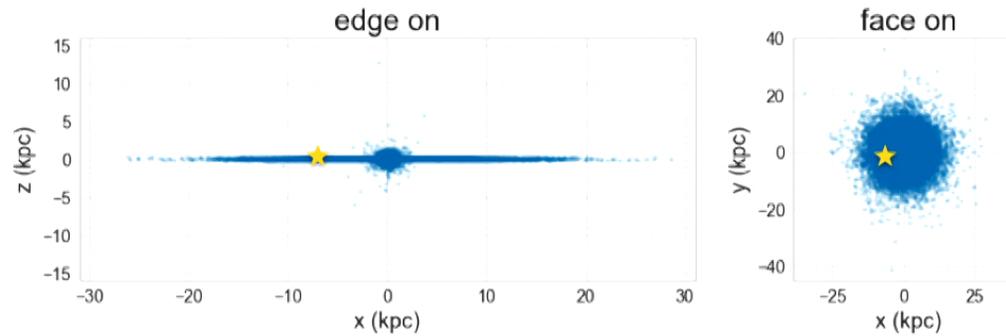
natal kicks

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Galactic isolated black holes

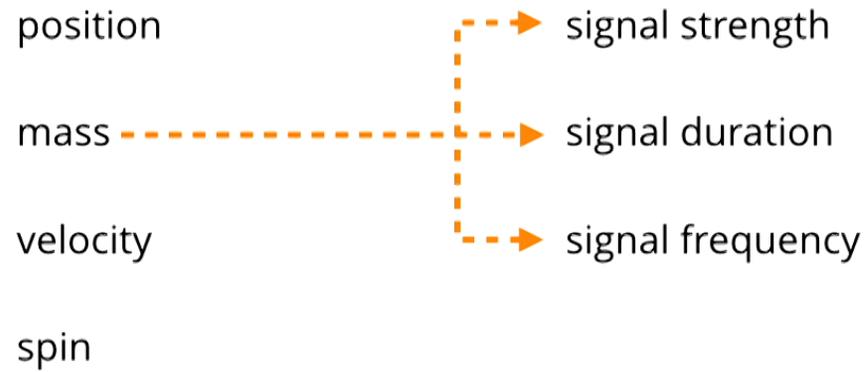


output:



bulk velocity in the plane:
~ 240 km/s

ingredients

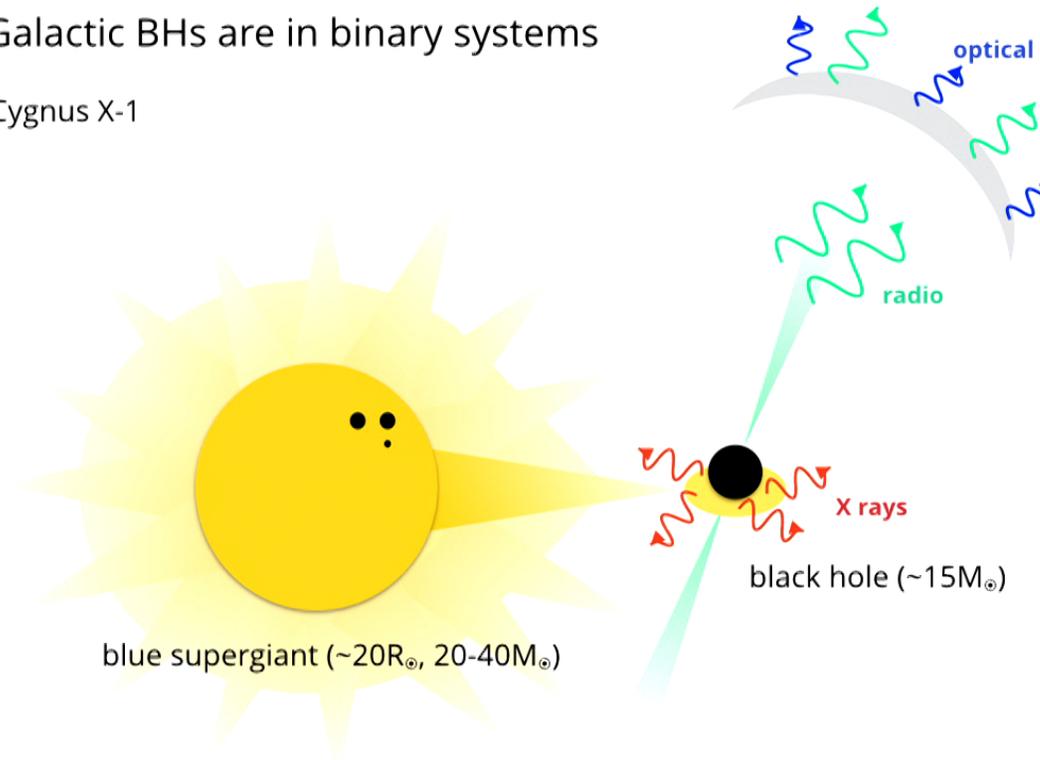


Galactic isolated black holes

What do we know about their mass distribution?

Known Galactic BHs are in binary systems

e.g., Cygnus X-1

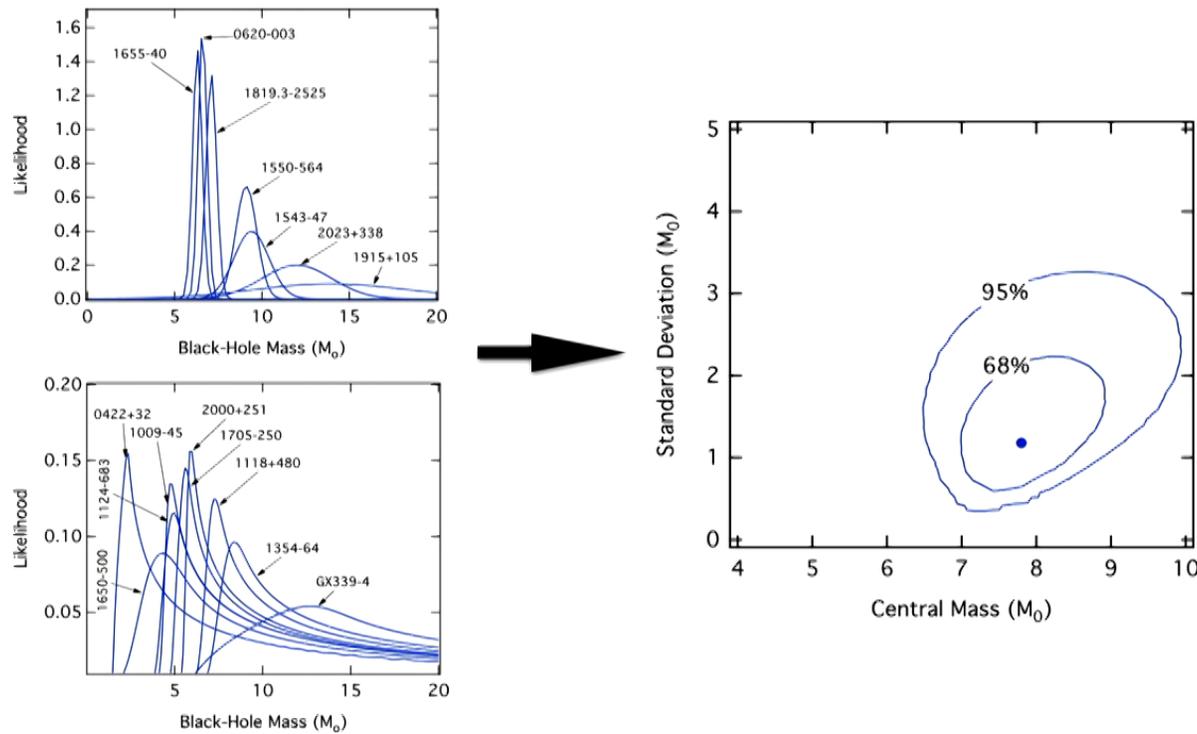


Galactic isolated black holes



What do we know about their mass distribution?

Known Galactic BHs are in binary systems: $M \sim 7.8 \pm 1.2 M_{\odot}$



[Özel et al., ApJ 725 (2010)]

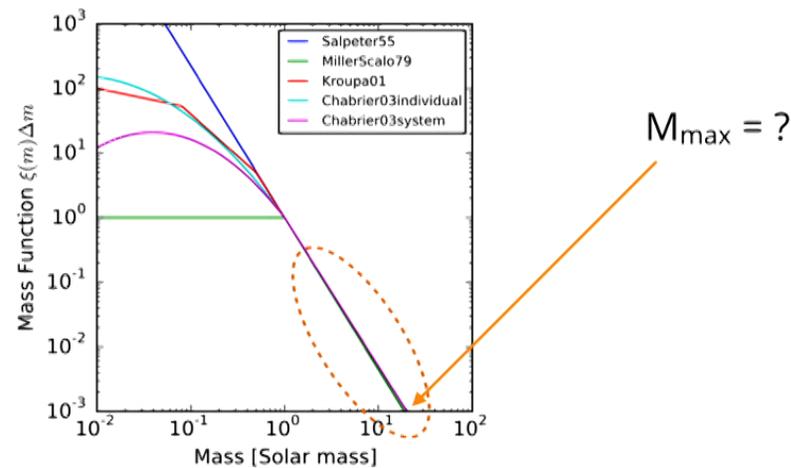
Galactic isolated black holes



What do we know about their mass distribution?

Salpeter initial mass function $\xi(M) \approx 0.03 \left(\frac{M}{M_{\odot}}\right)^{-1.35}$ from observations of stars

(It is not yet clear whether the steeper drop of ξ for masses larger than $10 M_{\odot}$ is a real effect, since in this region masses and bolometric corrections are not known very accurately and the number of such stars reasonably near the galactic plane is small.)



[Salpeter, ApJ 121 (1955)] [Wikimedia Commons]

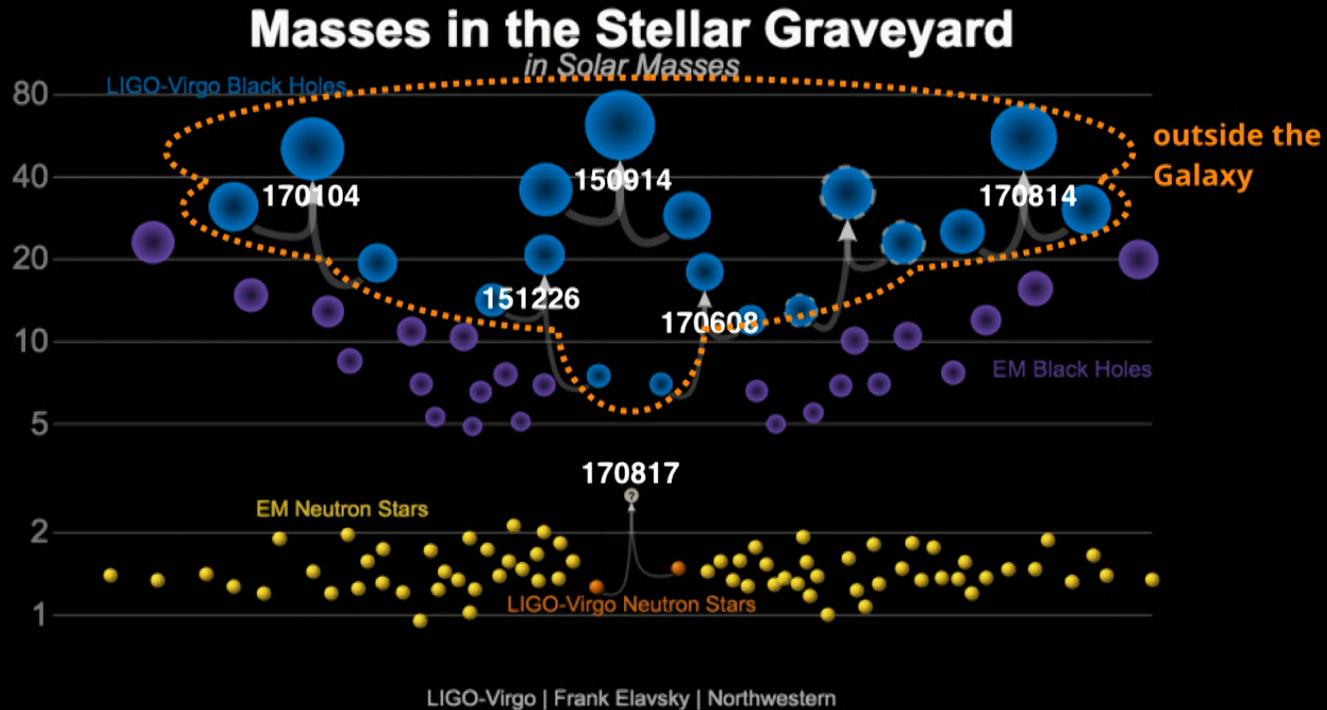
47

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Galactic isolated black holes



What do we know about their mass distribution?

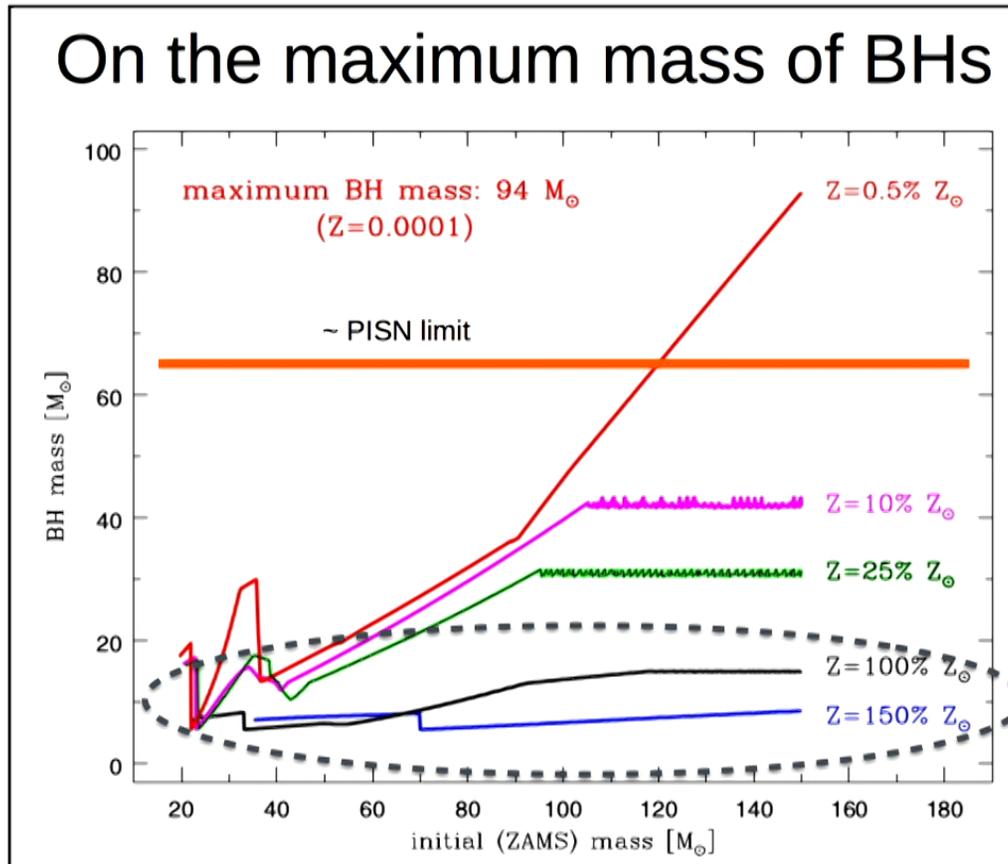


[LIGO / Frank Elvasky / Northwestern]

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Galactic isolated black holes



Z = metallicity
= percentage of
heavy elements
($>He$)

Z_{\odot} = solar metallicity
= metallicity equal to
that of our solar
system

[Tomek Bulik, GWPAAW 2018]

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Galactic isolated black holes



We will assume a couple of different mass distributions

1. Gaussian distribution from known Galactic BHs
2. $M^{-2.3}$ distribution up to some maximum M_{\max} :

Choose M_{\max} s.t. it is the smallest value that still yields a detectable signal in 10^8 BHs, $M_{\max} \geq 15M_{\odot}$

$M_{\max} = 15M_{\odot}$: completely fine

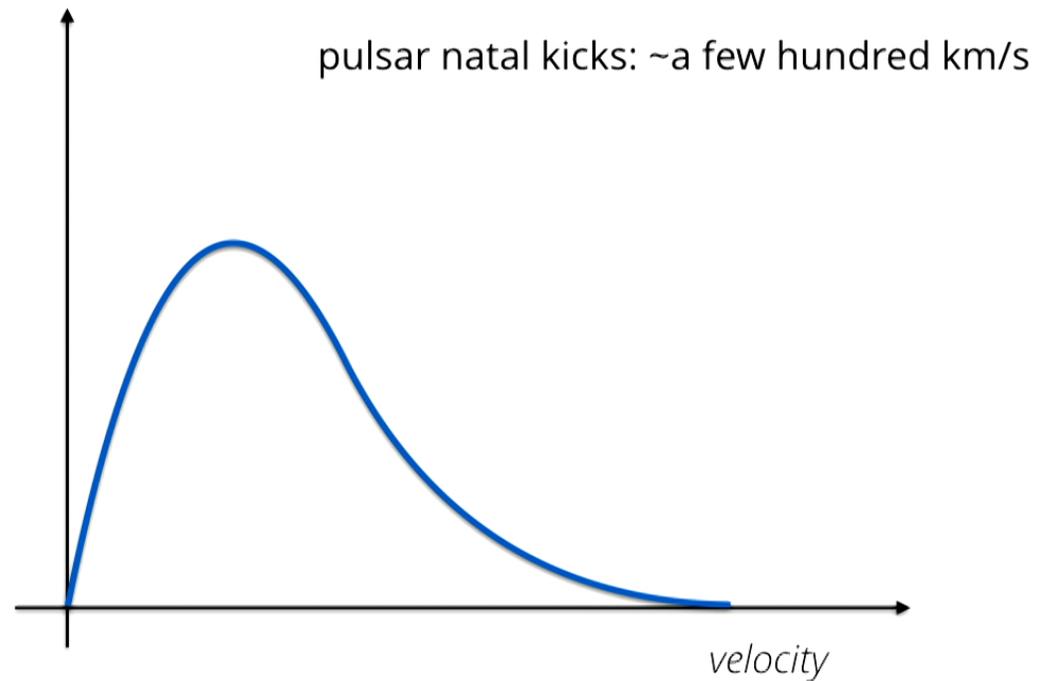
$M_{\max} = 20M_{\odot}$: reasonable

$M_{\max} = 30M_{\odot}$: astronomers get upset

Galactic isolated black holes



What do we know about their natal kicks?



Galactic isolated black holes



What do we know about their spin distribution?

$$\text{---} \backslash _ (\text{ツ}) _ / \text{---}$$

We take a uniform spin distribution between 0 and 1

signal ensemble examples



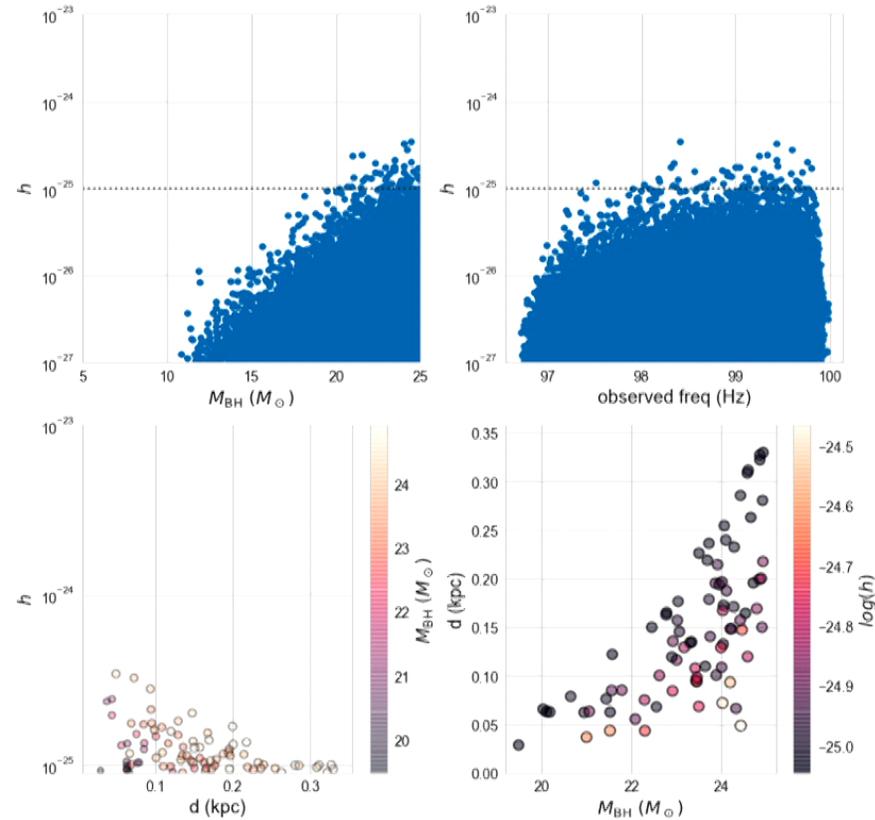
Near 100 Hz ($\mu_\alpha \sim 2e-13$), need $M_{\max} \sim 25M_\odot$

max BH mass = $25M_\odot$

All signal lifetimes are long enough
Can only detect signals from
BHs within hundreds of pc
from Earth

<100 signals over a few Hz

Obviously we can go to larger
BH masses, but we start to strain
credibility (and astronomers'
good will)



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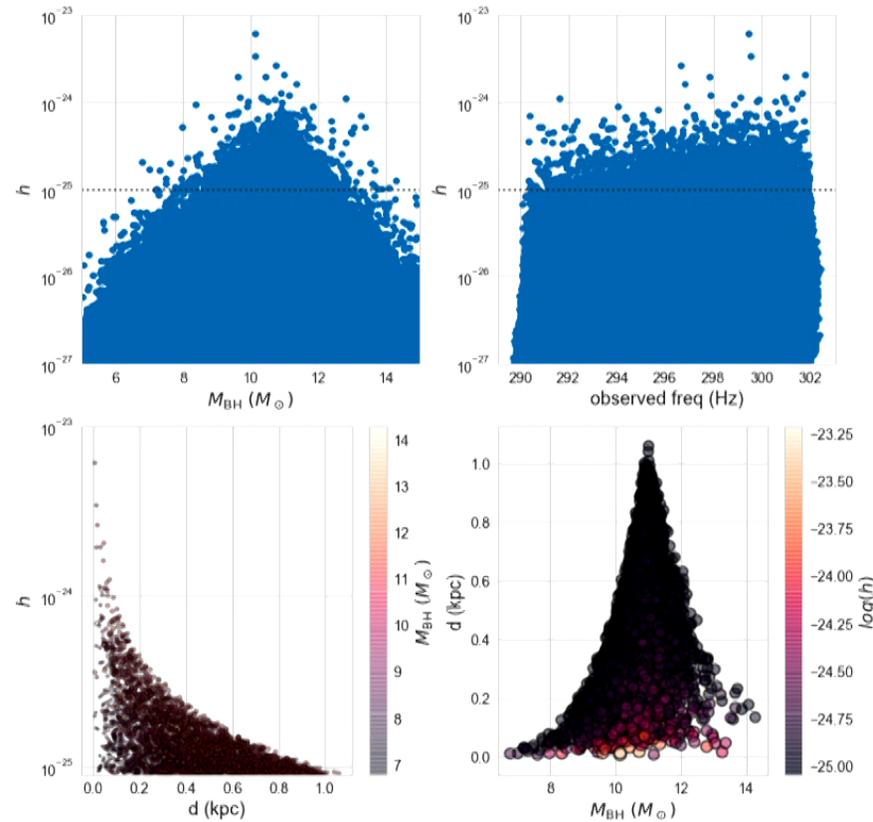
signal ensemble examples



Near 300 Hz ($\mu_\alpha \sim 6e-13$), need $M_{\max} < 15M_\odot$ max BH mass = $15M_\odot$

Only ~1% of signals are still detectable (timescales)
 Detectable signals come from within 1 kpc of Earth

~3000 signals over 12 Hz



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conclusion / future plans



The search is running; will start processing results next spring

We are finalising assumptions about the BH population