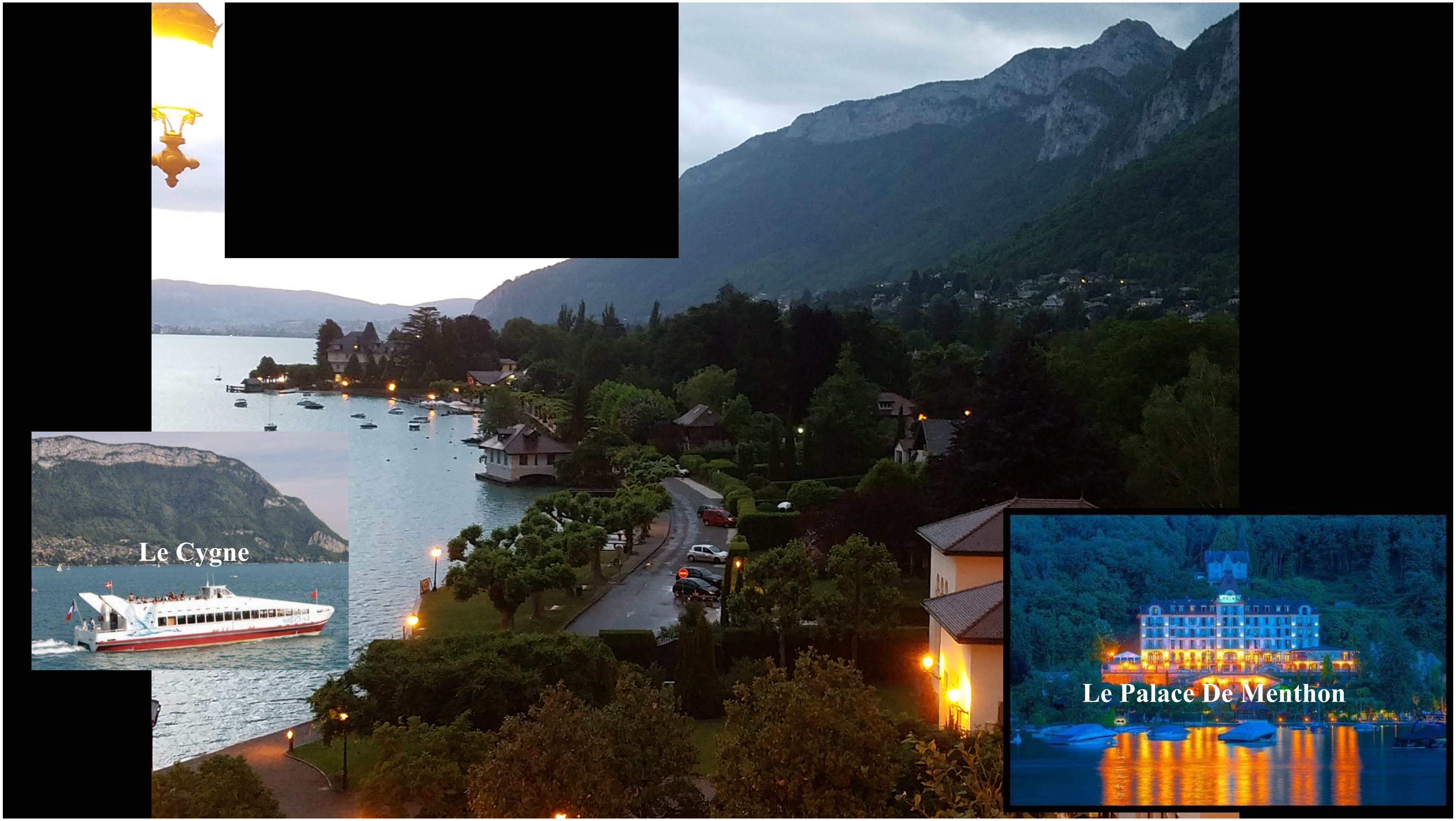
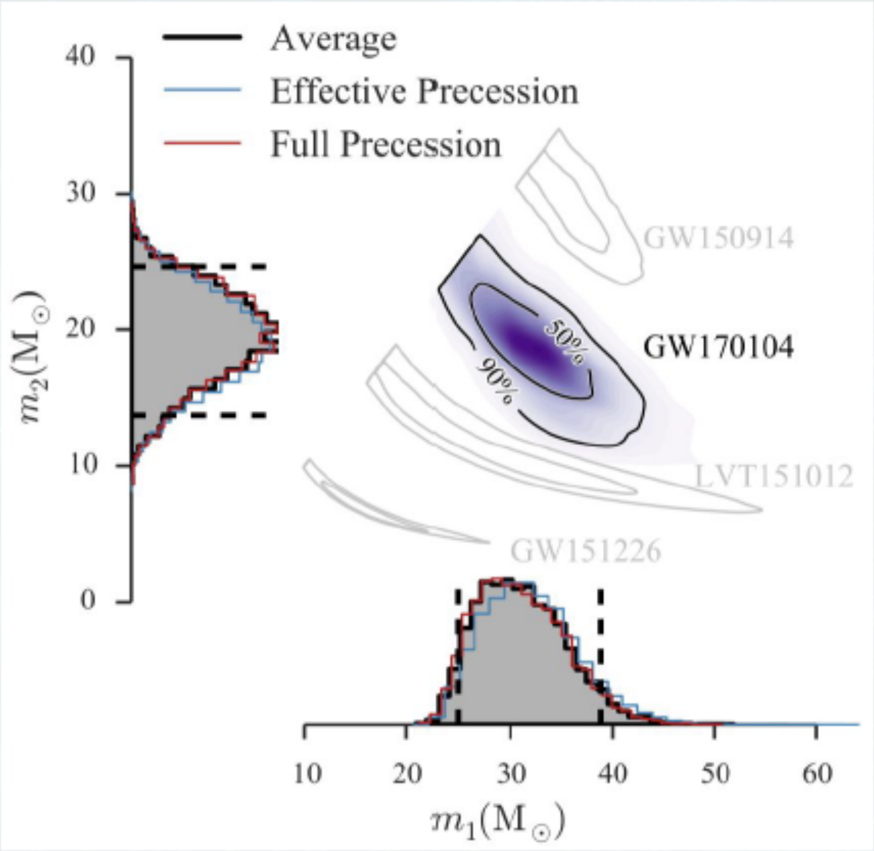
Some highlights from GWPAW 2017 Annecy, France

Alan Weinstein, Caltech & LIGO Laboratory

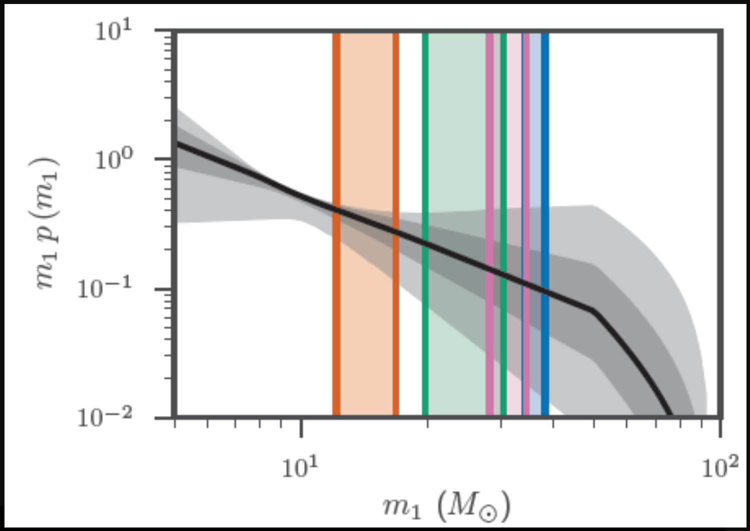

Le Cygne
Le Palace De Menthon

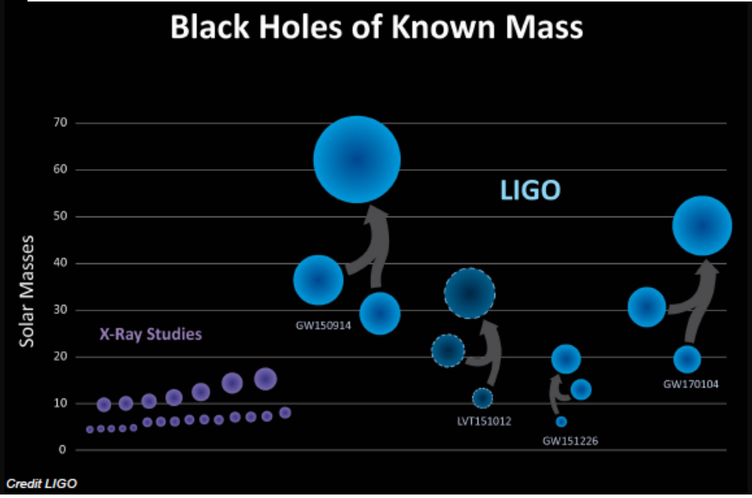
Introducing GW170104



LIGO Scientific Collaboration and Virgo Collaboration to appear in PRL

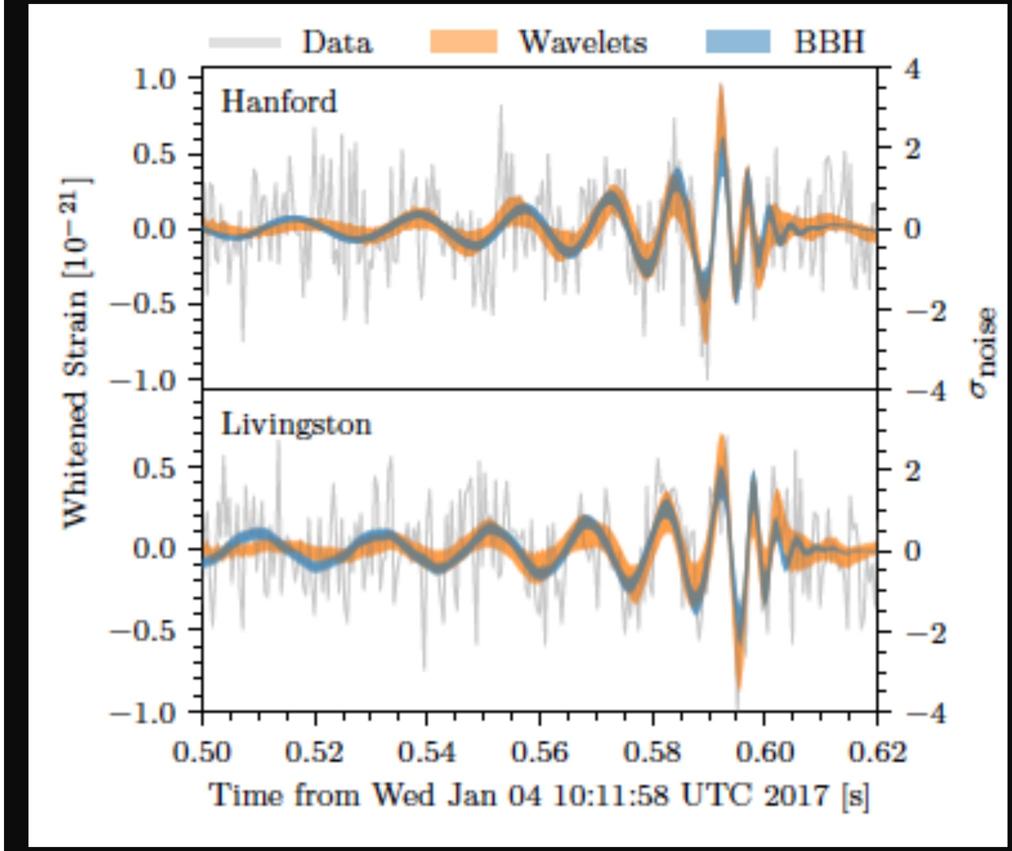
Filling in the spectrum of BH masses



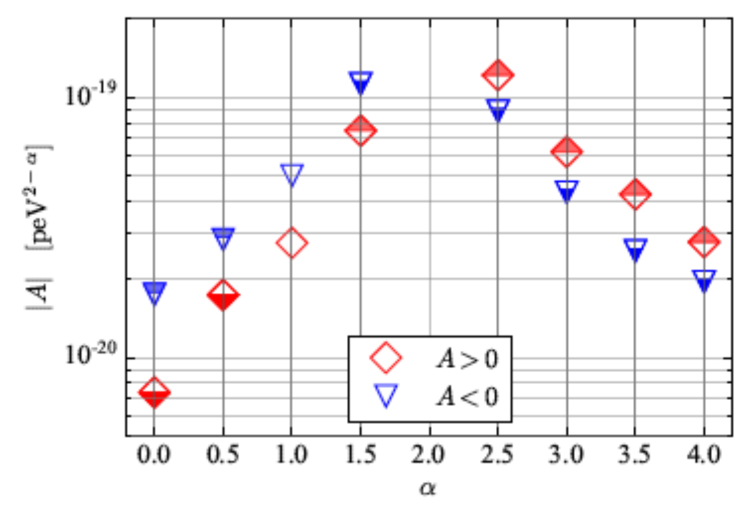


Credit LIGO

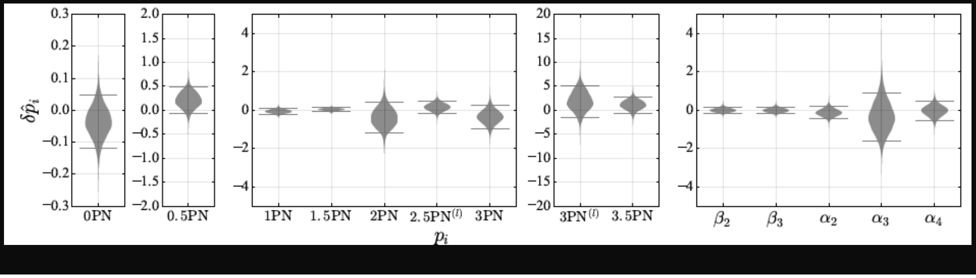
Excellent agreement with waveforms based on General Relativity



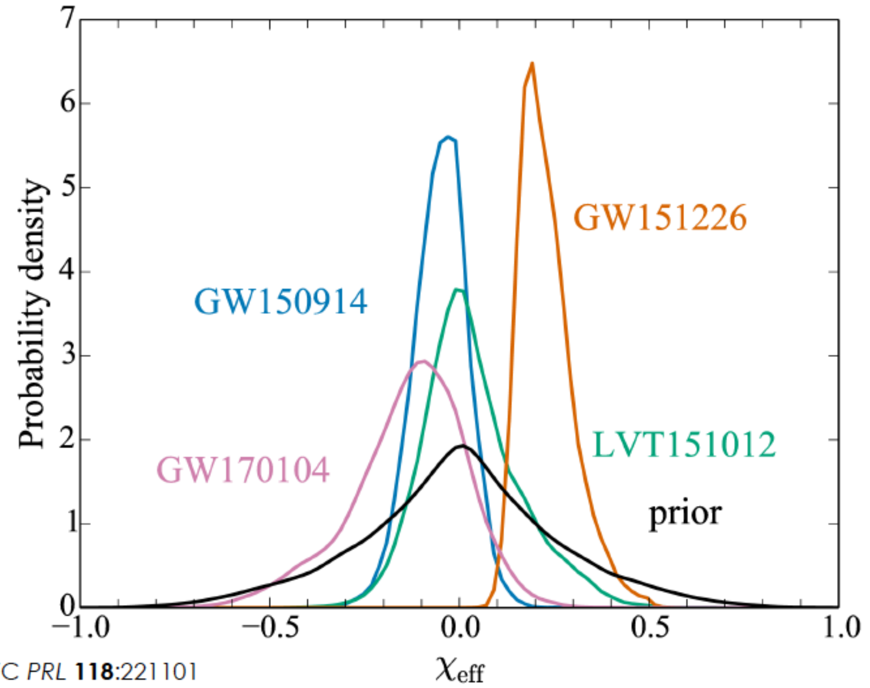
No evidence for exotic dispersion relation in propagation



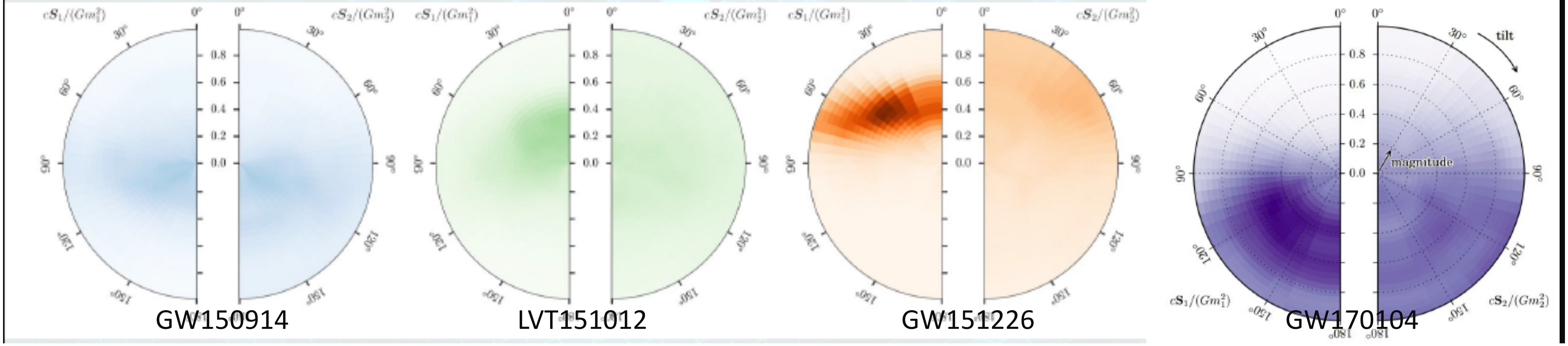
No deviation from GR in inspiral, merger, ringdown



GW170104 Primary BH spin suggestive of anti-alignment with respect to orbital angular momentum



LVC *PRL* **118**:221101

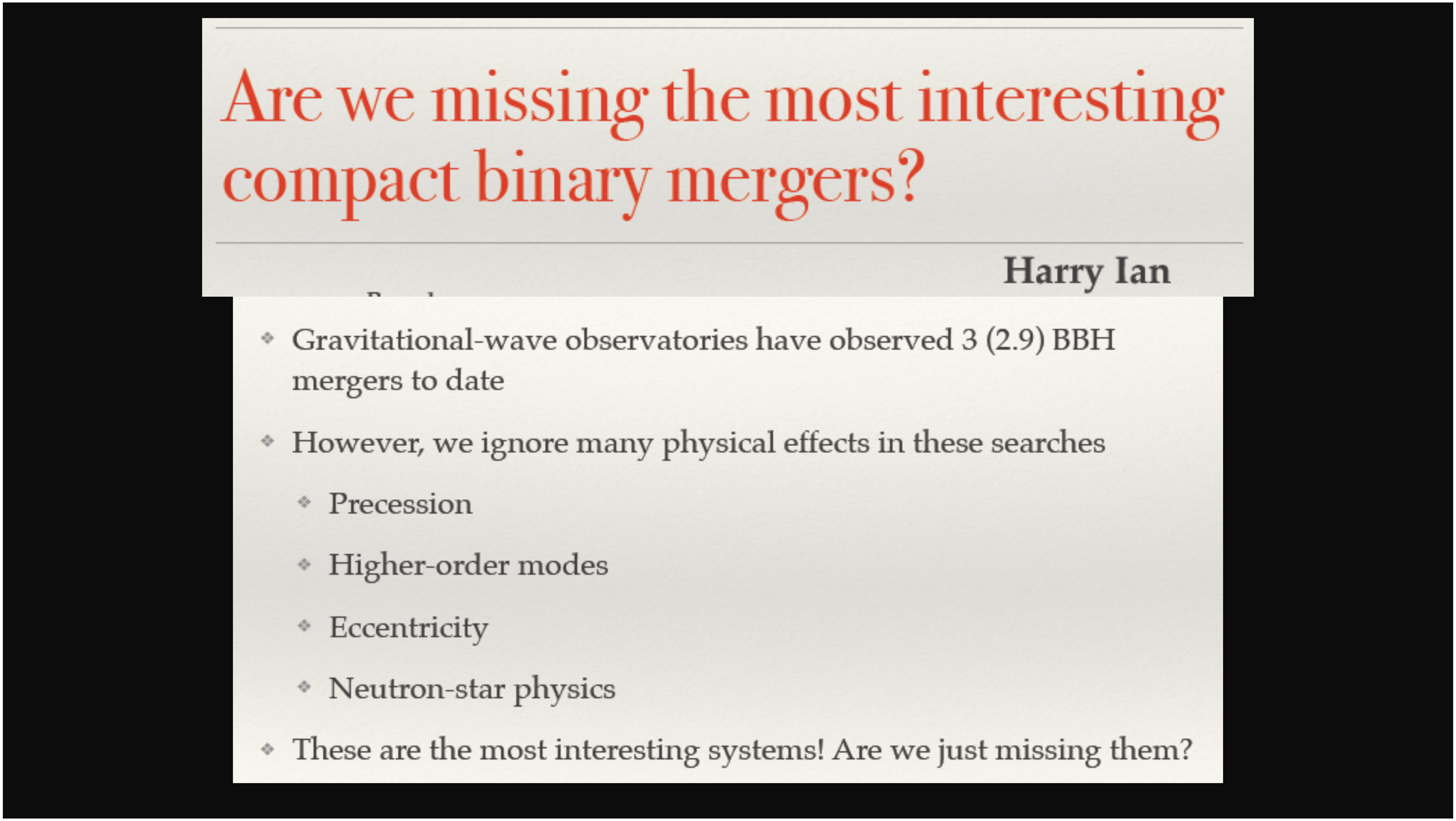


GW150914

LVT151012

GW151226

GW170104



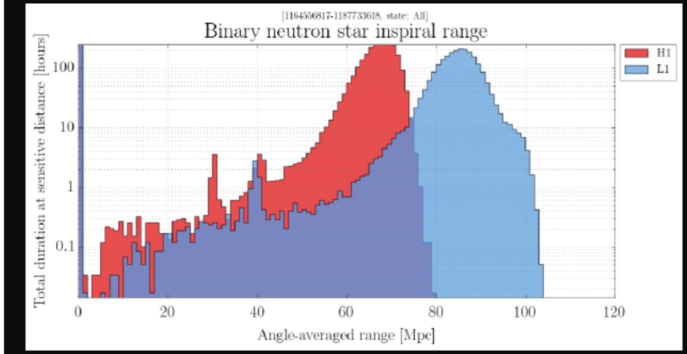
Are we missing the most interesting compact binary mergers?

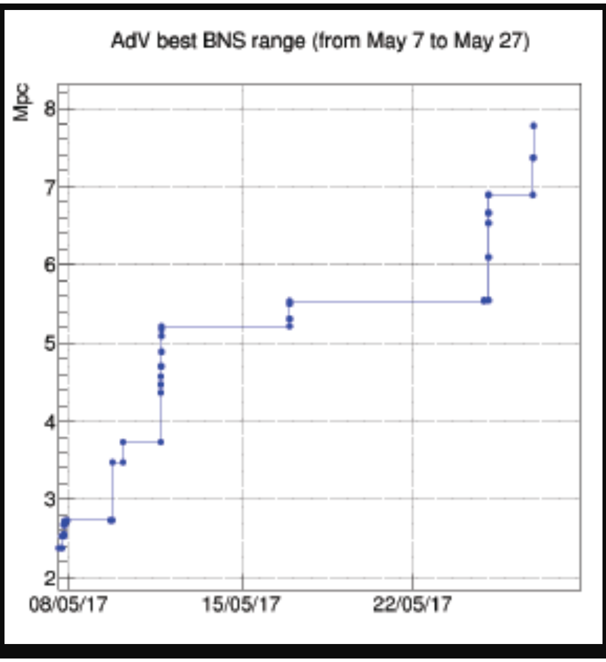
Harry Ian

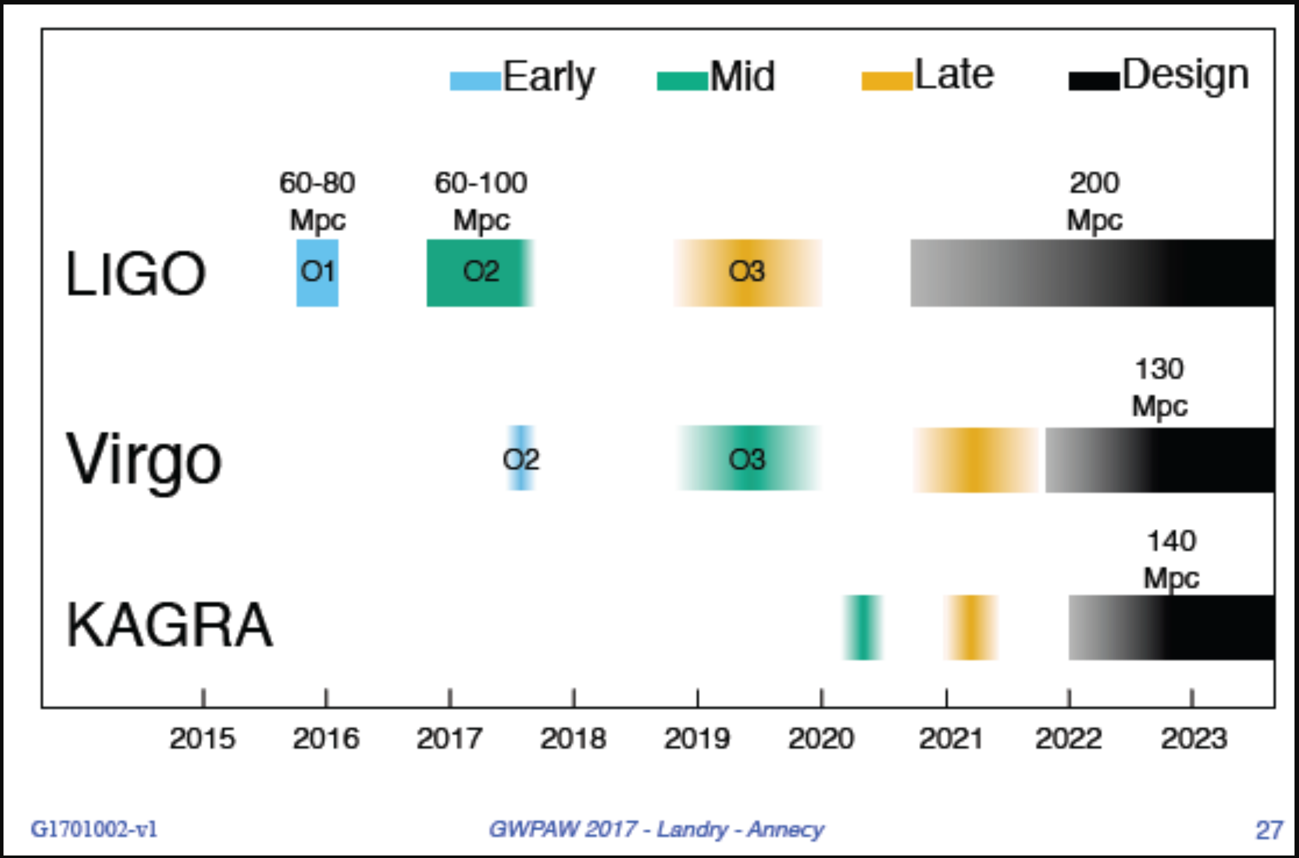
- Gravitational-wave observatories have observed 3 (2.9) BBH mergers to date
- However, we ignore many physical effects in these searches
  - Precession
  - Higher-order modes
  - Eccentricity
  - Neutron-star physics
- These are the most interesting systems! Are we just missing them?

Status of Advanced LIGO, GEO 600, Advanced Virgo

Mike Landry



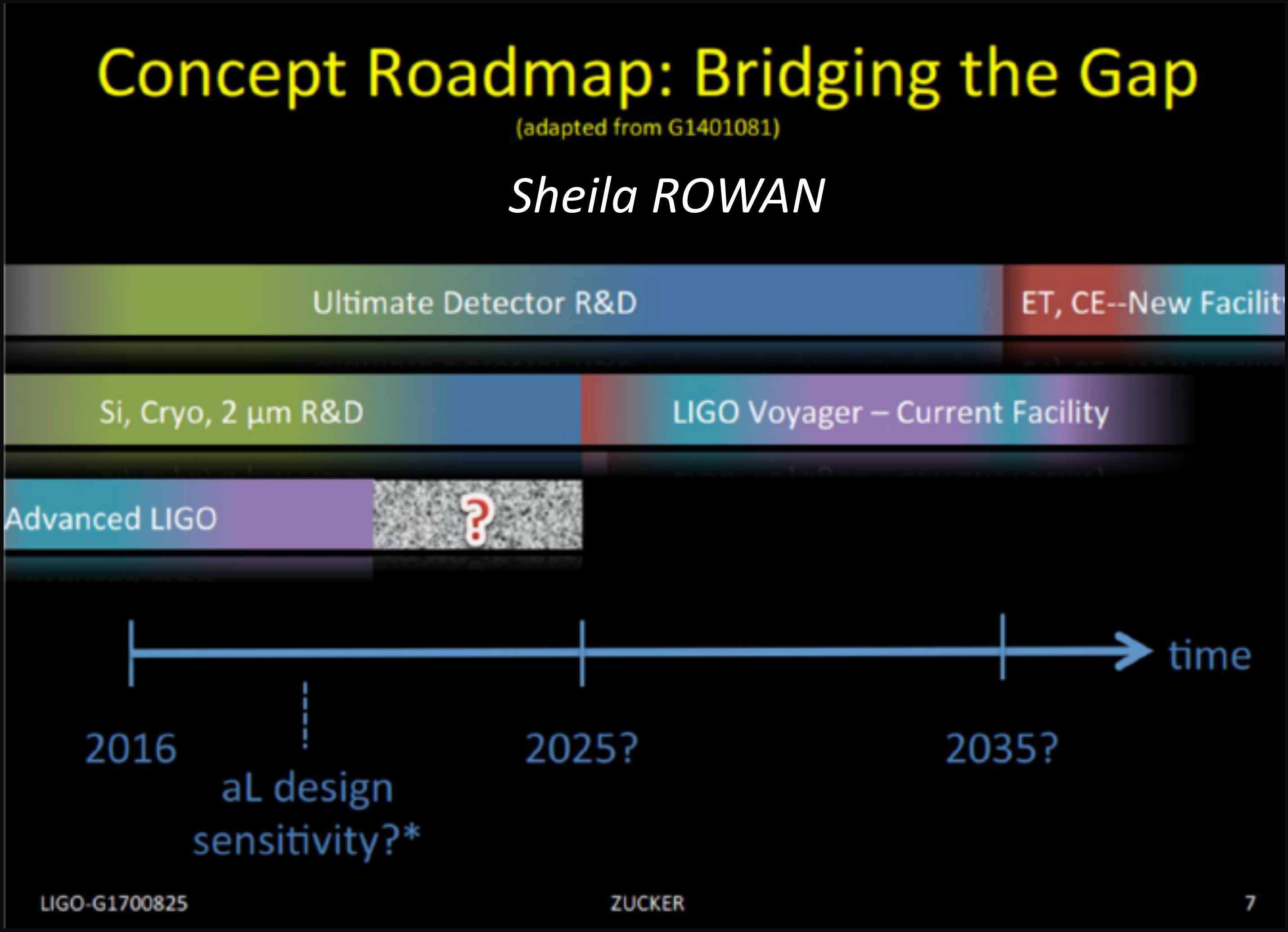




G1701002-v1

GWPAW 2017 - Landry - Annecy

27



Concept Roadmap: Bridging the Gap

(adapted from G1401081)

Sheila ROWAN

Ultimate Detector R&D

ET, CE--New Facilit

Si, Cryo, 2 µm R&D

LIGO Voyager – Current Facility

Advanced LIGO

?

time

2016

aL design sensitivity?*

2025?

2035?

GW Spectrograms from 3D-GR models with strong SASI vs. weak SASI activity

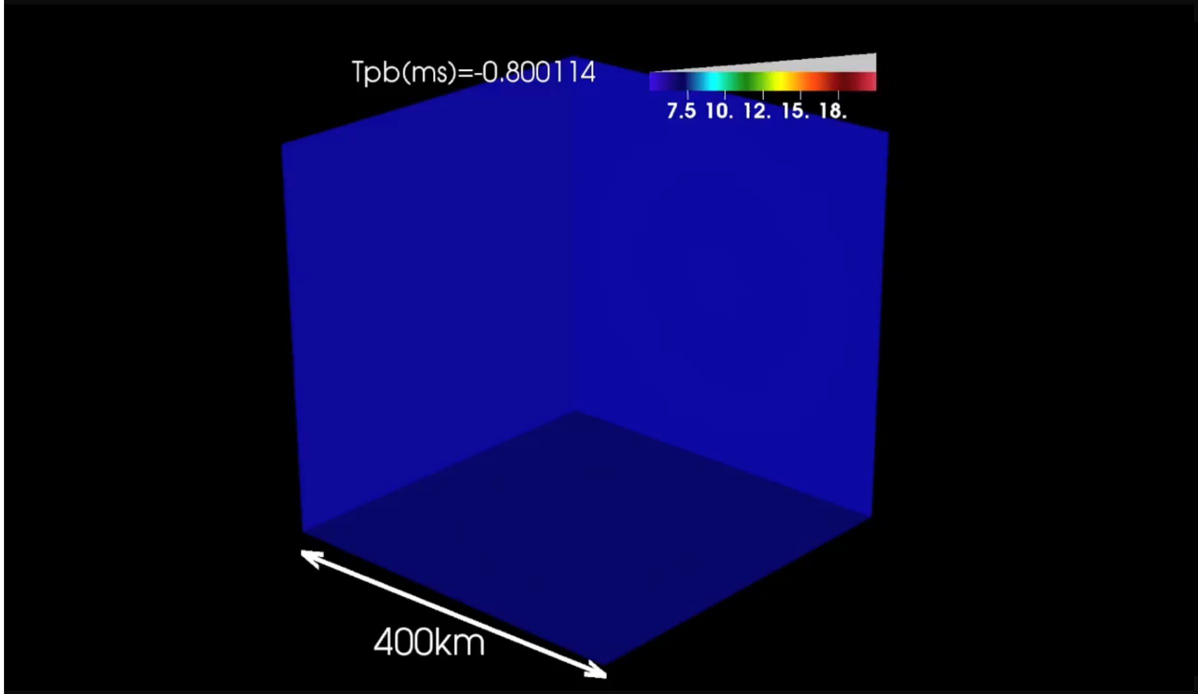
(from **Kuroda, KK, & Takiwaki ApJL (2016),** see also Andresen et al. (2016))

Kei KOTAKE

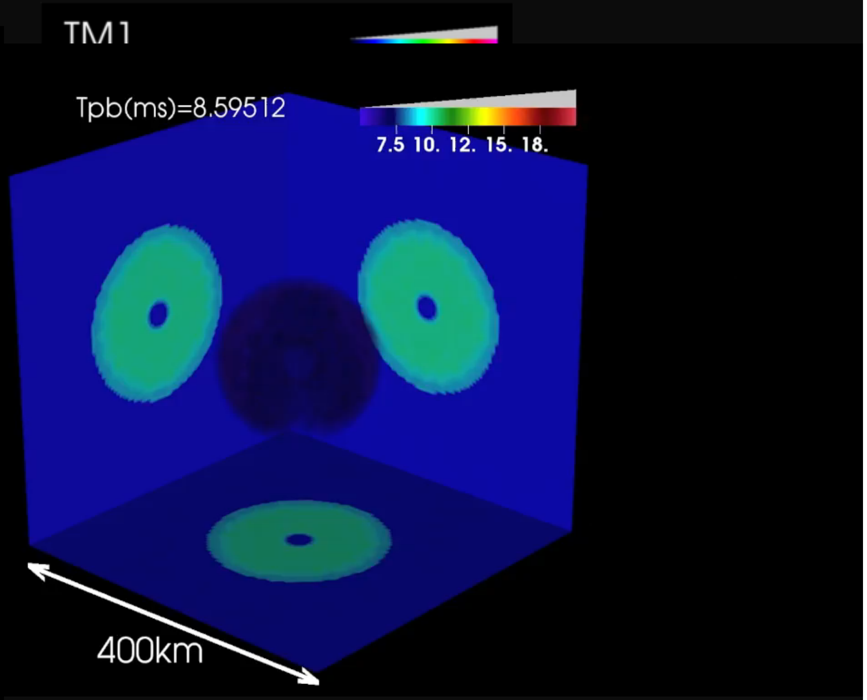
✓ Two EOSs → SFHx (Steiner et al. (2013), fits well with experiment/NS radius,Steiner+(2011)),
HS(TM1) (Shen et al. (1998)).

✓ 15 M_{sun} star (Woosley & Weaver (1995))

SFHx :softer



TM1 :stiffer



✓ **SASI activity higher for softer EOS** (due to shorter growth rate, e.g., Foglizzo et al. ('06)).

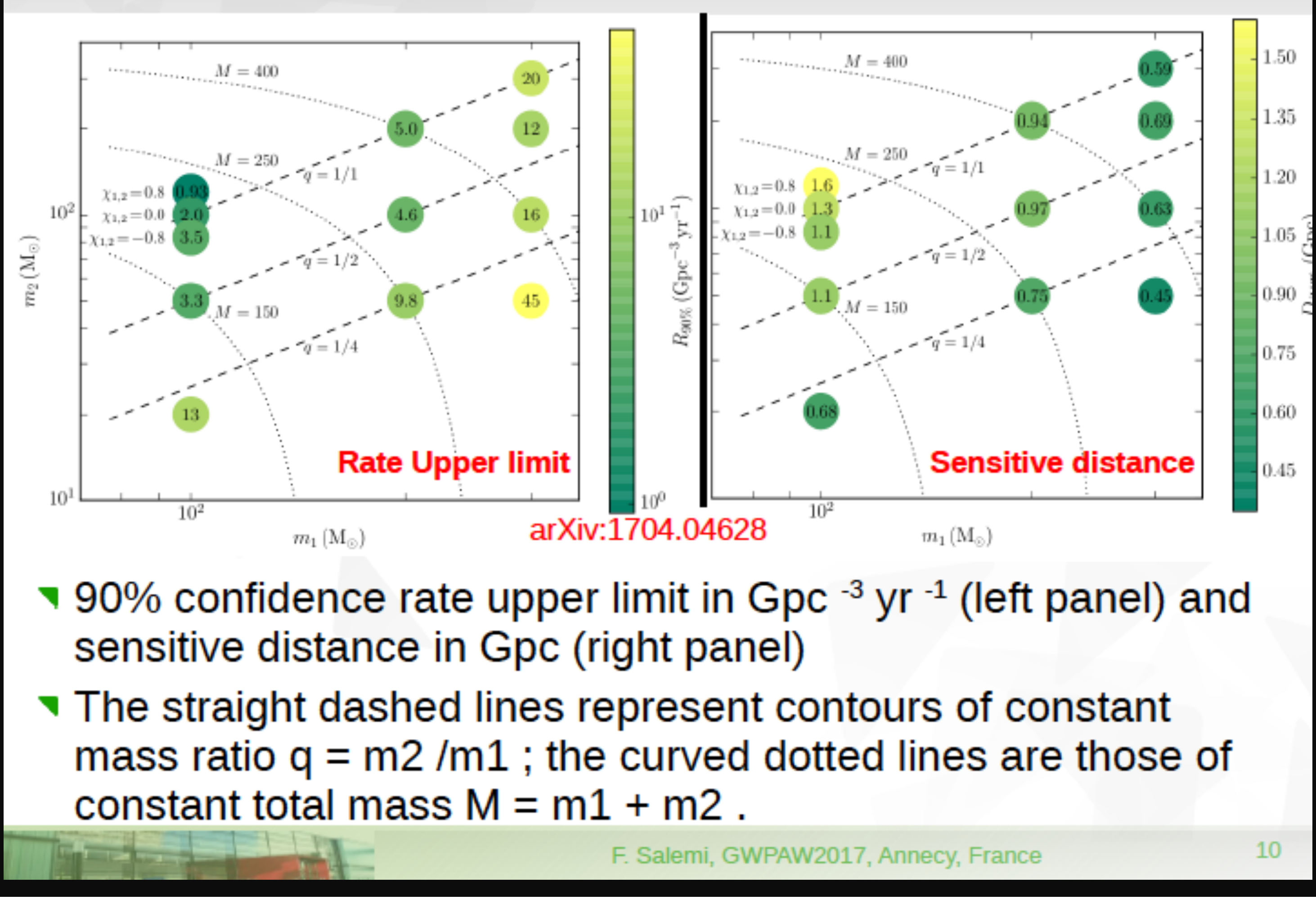
Summary

Kei KOTAKE

	Neutrino mechanism	MHD mechanism
Progenitor	Non- or slowing- rotating star $(\Omega_0 < \sim 0.1 \text{ rad/s})$	Rapidly rotating star with strong B fields $(\Omega_0 > \sim\pi \text{ rad/s}, B_0 > \sim 10^{11} \text{ G})$
Main GW signatures	**Three generic phases:** **Prompt convection, neutrino-driven convection & SASI, and explosion**	**Rotating bounce (< 20 ms p.b.) and non-axisymmetric instabilities (< ? ms)**
Detection Prospect	**✓Requires 3rd generation detector to see <u>every</u> Galactic event (with high SNR).** **✓Closeby events (2~3kpc) detectable by LIGO-class detectors.** **✓ Circular polarization with SASI-dominated models** **✓ If detected, critical information about SN engine (convection-dominant vs. SASI dominant) can be obtained.**	**✓ Bounce GW signal: horizon of LIGO, depending on Ω_0, can cover our Milky way and beyond.** **✓ GWs from non-axisymmetric instabilities: "quasi-periodicity" enhances chance of detection.** **✓ Circular polarization: probe of rotation (Talk by Hayama!)** **✓ Clear directionality of GW and neutrino signals**

Advanced LIGO (O1) Search for IMBHB's

Francesco SALEMI



Rate Upper limit

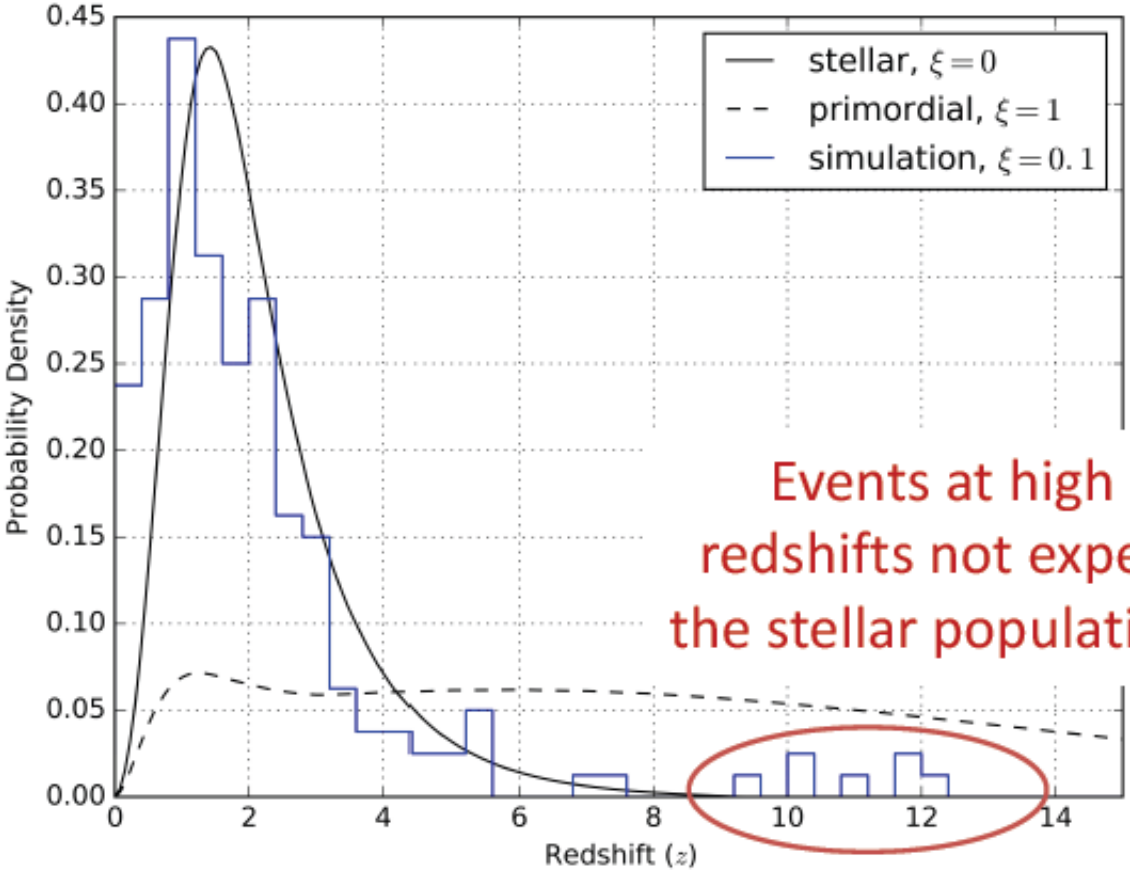
Sensitive distance

arXiv:1704.04628

- 90% confidence rate upper limit in Gpc $^{-3}$ yr $^{-1}$ (left panel) and sensitive distance in Gpc (right panel)
- The straight dashed lines represent contours of constant mass ratio q = m2 /m1 ; the curved dotted lines are those of constant total mass M = m1 + m2 .

PBH signature

Letizia SAMMUT



Events at high enough redshifts not expected from the stellar population models!

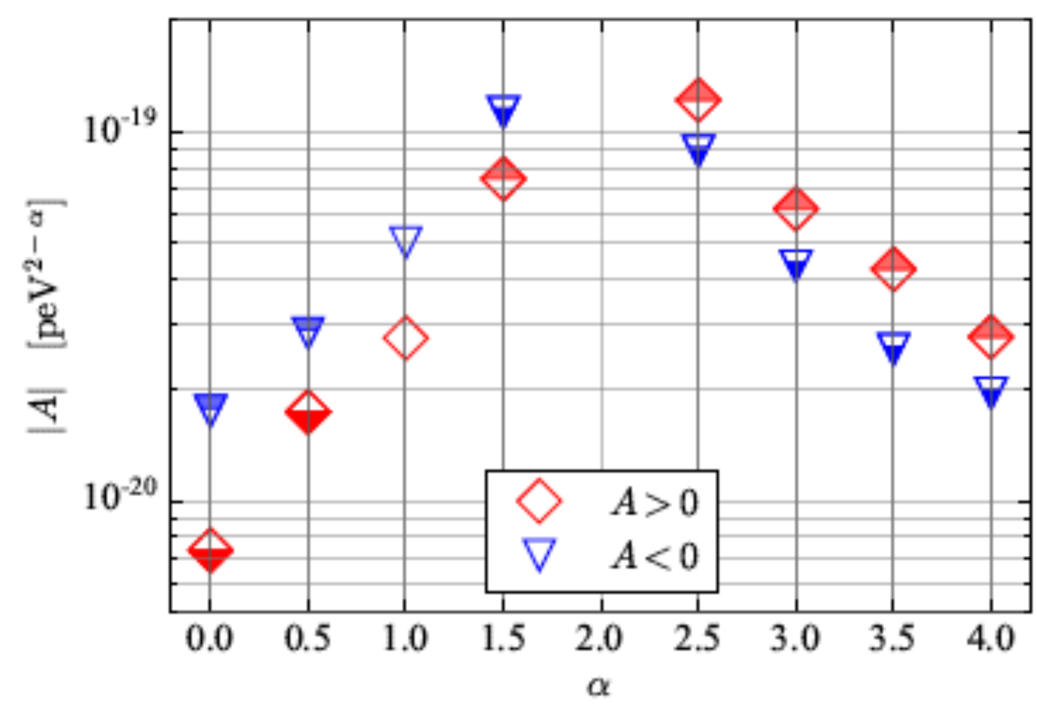
GW in alternative gravity

- Alternative to GR can introduce extra-fields, curvature terms, challenge GR pillars, …
- Almost no full solution in non-GR known
- GW phase is modified:
  - non-GR action (extra fields, higher curvature, …): no full non-linear description, only post-Newtonian
  - Propagation (Lorentz violations, graviton mass, …): GR-like BBH dynamics, but modified GW propagation (see Samajdar's talk)
  - non-GR BHs (extra-fields, exotic objects):
    - tidal deformability
    - ringdown spectrum (see London, Cabero and Ghosh's talks)
    - Echoes (see Nielsen and Abedi talks)

Generic dispersion relation for GW propagation

Anuradha SAMAJDAR
Chris VAN DEN BROCK

- With a modified dispersion,

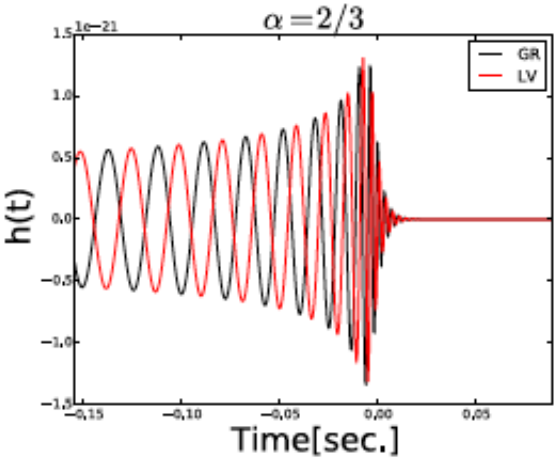


of Lorentz violating GWs.

$$E^2 = p^2c^2 + \mathbb{A}p^\alpha c^\alpha$$

Mirshekari et al., 2012

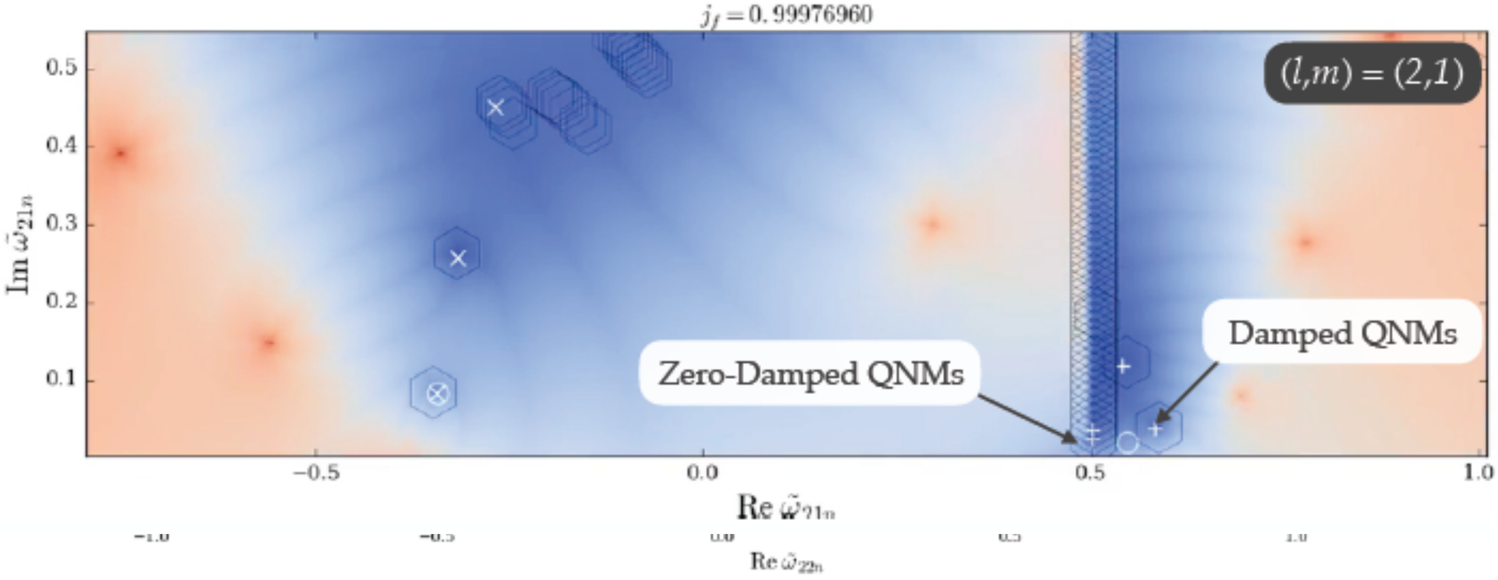
$\mathbb{A}$, α: Lorentz violating parameters.



Lionel LONDON

Review: Structure of QNM Solution Space

Nontrivial behavior in the limit extremal BH spin (j_f~ 1):
solution branching, and nonzero / **zero damping**



Zero-Damped QNMs

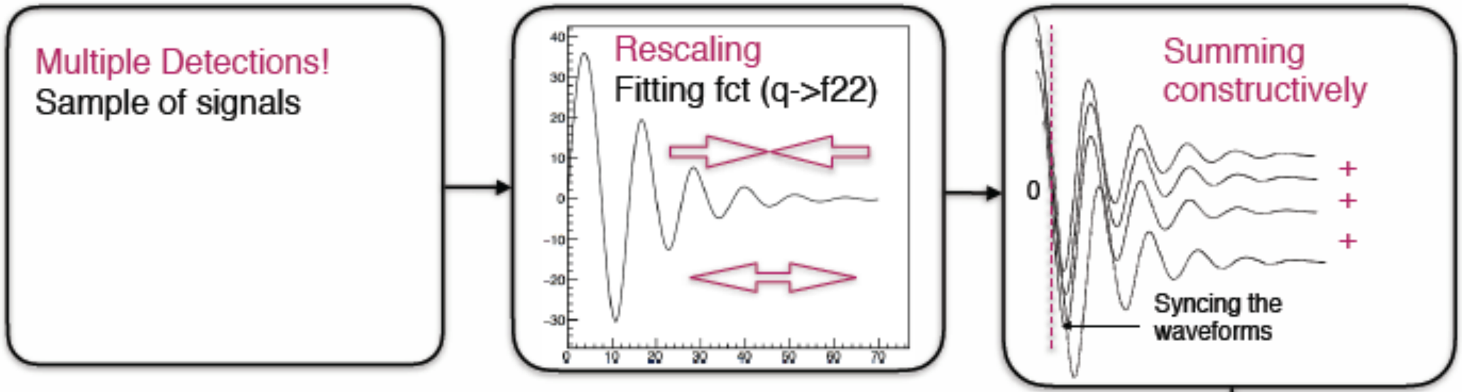
Damped QNMs

Example: **Blue** (Low work function values), **Red** (High). Using Berti's approximation for the separation constants allows 2D visualization of QNM solution space

Method/ Constructively sum up QNM

Carlos Filipe DA SILVA COSTA

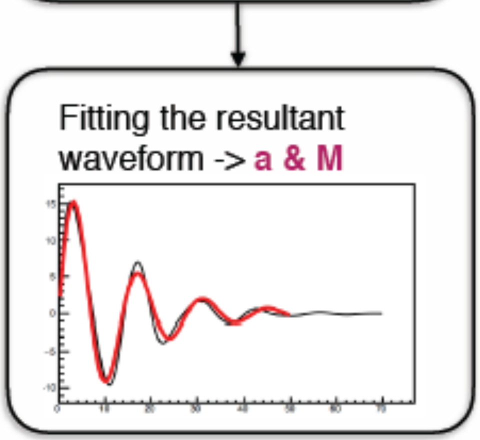
We tested the following method
Four main steps:


Multiple Detections!
Sample of signals

Rescaling
Fitting fct (q->f22)

Summing
constructively

Syncing the
waveforms

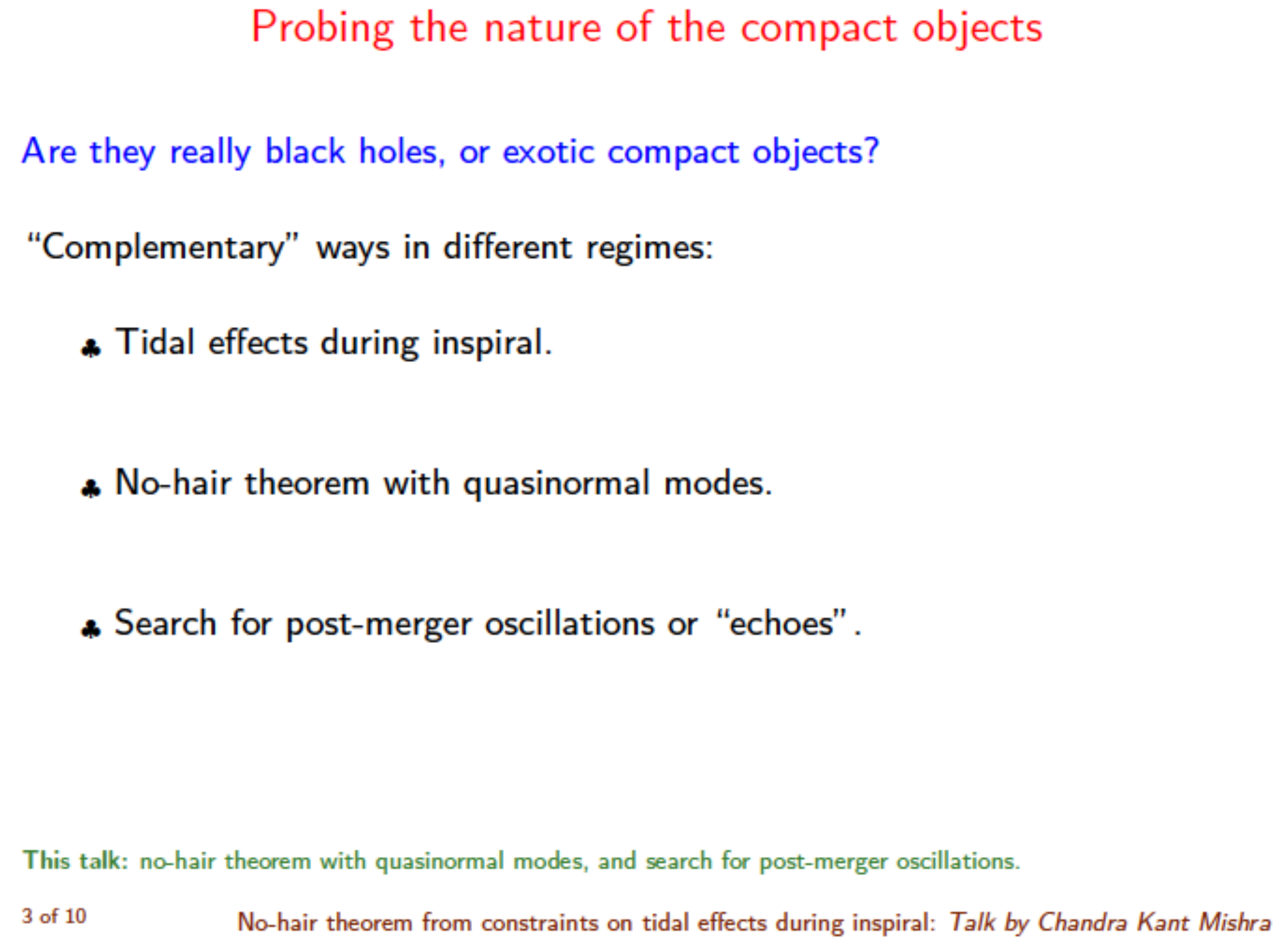

Fitting the resultant
waveform -> **a & M**

In this project, we considered:
- non charged BHs,
- non spinning initial BHs,
- mass ratio $m_1/m_2=q=$ 1, 1.5, 2, 3. (above for tests)
  (Present detections q=1-2)
- Face on

Caveats:
1) When do QNMs start?
2) How to rescale any signal?
3) Can the modes be constructively summed?
4) How well the SNR is improved?

Ringdown and echoes as probes of strong-field dynamics of GR

Archisman GHOSH



Probing the nature of the compact objects

Are they really black holes, or exotic compact objects?

“Complementary” ways in different regimes:

- ♣ Tidal effects during inspiral.
- ♣ No-hair theorem with quasinormal modes.
- ♣ Search for post-merger oscillations or “echoes”.

This talk: no-hair theorem with quasinormal modes, and search for post-merger oscillations.

No-hair theorem from constraints on tidal effects during inspiral: *Talk by Chandra Kant Mishra*

Testing the no-hair theorem with quasinormal modes

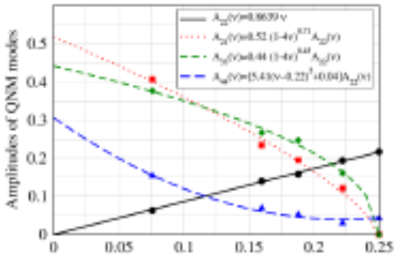
Archisman GHOSH

Even where it is not possible to measure the ω_{lmn} and τ_{lmn} directly, by combining information from multiple events, systematic departures from their GR values ($\delta\omega_{lmn}$ and $\delta\tau_{lmn}$) can be constrained.

$$\omega_{lmn} = \omega_{lmn}^{GR}(1 + \delta\omega_{lmn}), \; \tau_{lmn} = \tau_{lmn}^{GR}(1 + \delta\tau_{lmn})$$

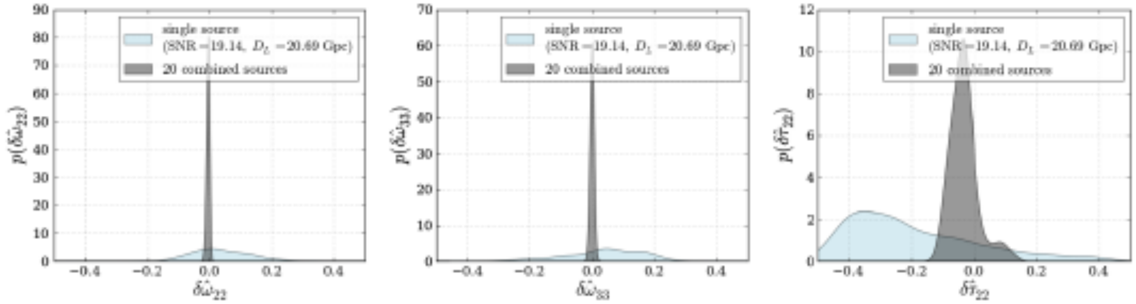
à la parameterized deformations

NR fits: Kamaretsos *et al* (2012)
Implementation: Gossan *et al* (2012)



$$\{\delta\omega_{220}, \delta\omega_{330}, \delta\tau_{220}\}$$

ET, 20 sources, masses: 500–1000 $\mathrm{M}_\odot$, ringdown SNR $\sim$ 20:



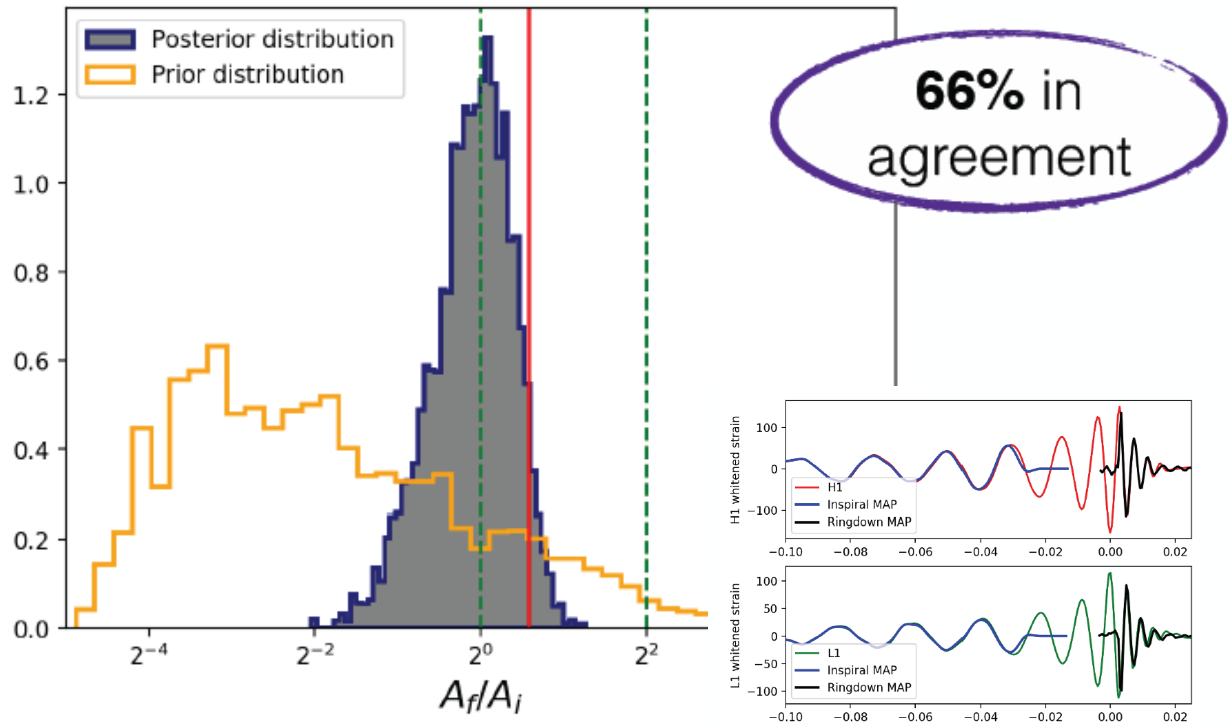
Results from: Meidam *et al* (2014)

Testing the area theorem

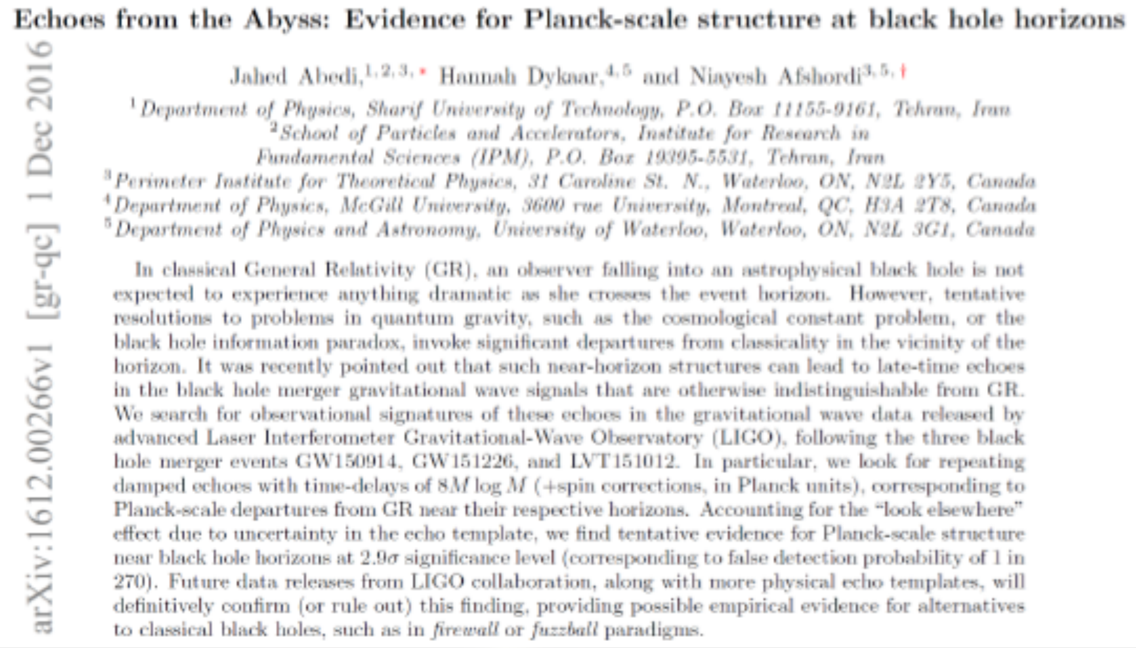
Miriam CABERO MUELLER

It is thrilling to see predictions I made over 40 years ago such as the black hole area and uniqueness theorems being observed within my lifetime. -SH

Area theorem: Violation ← → Agreement



66% in agreement



arXiv:1612.00266v1 [gr-qc] 1 Dec 2016

Echoes from the Abyss: Evidence for Planck-scale structure at black hole horizons

Jahed Abedi,[1,2,3,*] Hannah Dykaar,[4,5] and Niayesh Afshordi[3,5,†]
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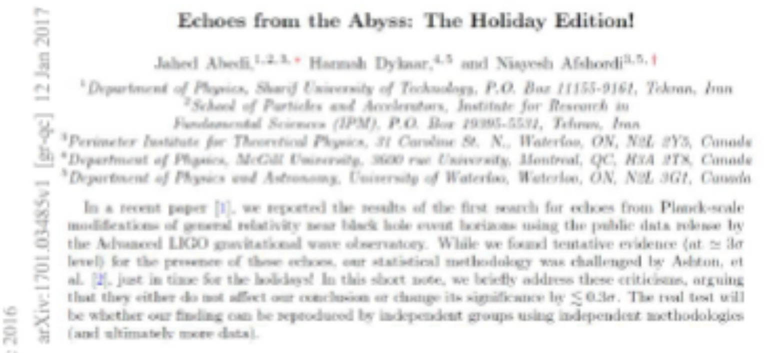
[2]*School of Particles and Accelerators, Institute for Research in Fundamental Sciences (IPM), P.O. Box 19395-5531, Tehran, Iran*
[3]*Perimeter Institute for Theoretical Physics, 31 Caroline St. N., Waterloo, ON, N2L 2Y5, Canada*
[4]*Department of Physics, McGill University, 3600 rue University, Montreal, QC, H3A 2T8, Canada*
[5]*Department of Physics and Astronomy, University of Waterloo, Waterloo, ON, N2L 3G1, Canada*

In classical General Relativity (GR), an observer falling into an astrophysical black hole is not expected to experience anything dramatic as she crosses the event horizon. However, tentative resolutions to problems in quantum gravity, such as the cosmological constant problem, or the black hole information paradox, invoke significant departures from classicality in the vicinity of the horizon. It was recently pointed out that such near-horizon structures can lead to late-time echoes in the black hole merger gravitational wave signals that are otherwise indistinguishable from GR. We search for observational signatures of these echoes in the gravitational wave data released by advanced Laser Interferometer Gravitational-Wave Observatory (LIGO), following the three black hole merger events GW150914, GW151226, and LVT151012. In particular, we look for repeating damped echoes with time-delays of $8M \log M$ (+spin corrections, in Planck units), corresponding to Planck-scale departures from GR near their respective horizons. Accounting for the "look elsewhere" effect due to uncertainty in the echo template, we find tentative evidence for Planck-scale structure near black hole horizons at 2.9σ significance level (corresponding to false detection probability of 1 in 270). Future data releases from LIGO collaboration, along with more physical echo templates, will definitively confirm (or rule out) this finding, providing possible empirical evidence for alternatives to classical black holes, such as in *firewall* or *fuzzball* paradigms.



arXiv:1701.03485v1 [gr-qc] 12 Jan 2017

Echoes from the Abyss: The Holiday Edition!

Jahed Abedi,[1,2,3,*] Hannah Dykaar,[4,5] and Niayesh Afshordi[3,5,†]
[1]*Department of Physics, Sharif University of Technology, P.O. Box 11155-9161, Tehran, Iran*
[2]*School of Particles and Accelerators, Institute for Research in Fundamental Sciences (IPM), P.O. Box 19395-5531, Tehran, Iran*
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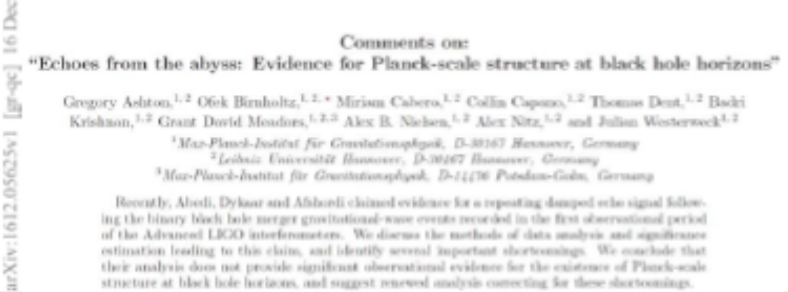
[4]*Department of Physics, McGill University, 3600 rue University, Montreal, QC, H3A 2T8, Canada*
[5]*Department of Physics and Astronomy, University of Waterloo, Waterloo, ON, N2L 3G1, Canada*

In a recent paper [1], we reported the results of the first search for echoes from Planck-scale modifications of general relativity near black hole event horizons using the public data release by the Advanced LIGO gravitational wave observatory. While we found tentative evidence (at $\simeq 3\sigma$ level) for the presence of these echoes, our statistical methodology was challenged by Ashton, et al. [2], just in time for the holidays! In this short note, we briefly address these criticisms, arguing that they either do not affect our conclusion or change its significance by $\lesssim 0.3\sigma$. The real test will be whether our finding can be reproduced by independent groups using independent methodologies (and ultimately more data).



arXiv:1612.05625v1 [gr-qc] 16 Dec 2016

Comments on:
"Echoes from the abyss: Evidence for Planck-scale structure at black hole horizons"

Gregory Ashton,[1,2] Ofek Birnholtz,[1,2,*] Miriam Cabero,[1,2] Collin Capano,[1,2] Thomas Dent,[1,2] Badri Krishnan,[1,2] Grant David Meadors,[1,2,3] Alex B. Nielsen,[1,2] Alex Nitz,[1,2] and Julian Westerweck[1,2]
[1]*Max-Planck-Institut für Gravitationsphysik, D-30167 Hannover, Germany*
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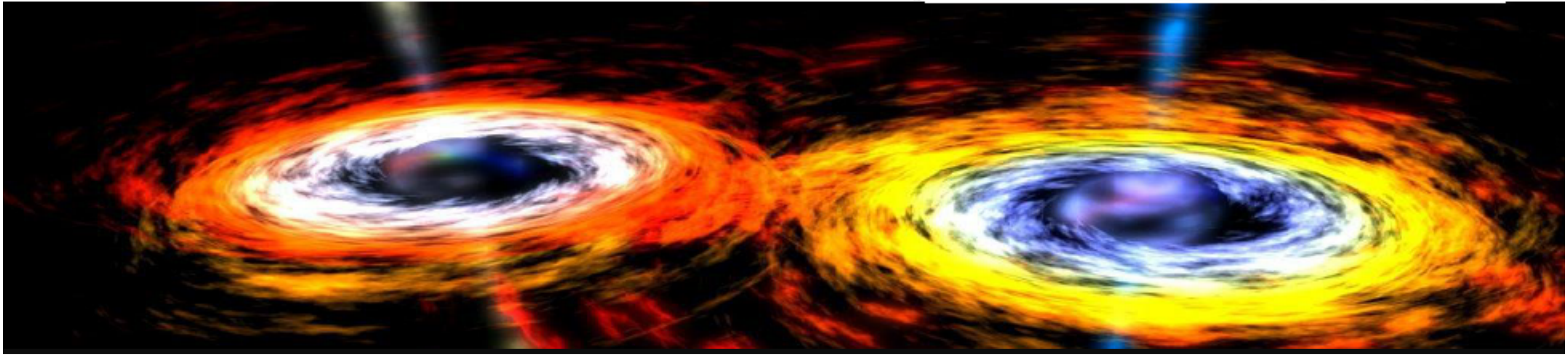
Recently, Abedi, Dykaar and Afshordi claimed evidence for a repeating damped echo signal following the binary black hole merger gravitational-wave events recorded in the first observational period of the Advanced LIGO interferometers. We discuss the methods of data analysis and significance estimation leading to this claim, and identify several important shortcomings. We conclude that their analysis does not provide significant observational evidence for the existence of Planck-scale structure at black hole horizons, and suggest renewed analysis correcting for these shortcomings.



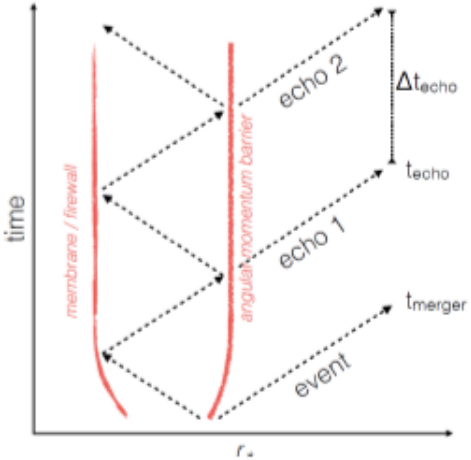
Echoes from the ABYSS

Jahed ABEDI

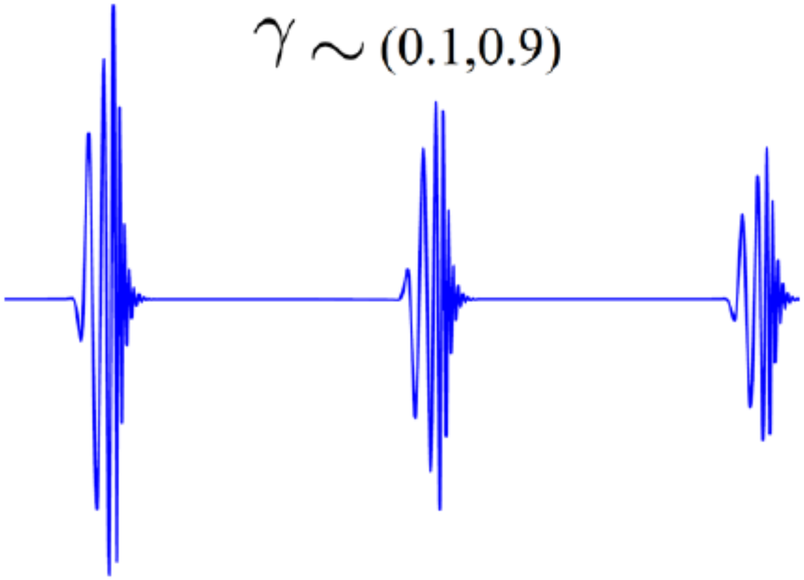
$$t_{0,GW150914} \sim (-0.03s, 0)$$

$$t_{0,GW151226} \sim \frac{\Delta t_{pred,GW151226}}{\Delta t_{pred,GW150914}} \times t_{0,GW150914} = (-0.0104s, 0)$$

$$t_{0,LVT151012} \sim \frac{\Delta t_{pred,LVT151012}}{\Delta t_{pred,GW150914}} \times t_{0,GW150914} = (-0.0182s, 0)$$



$$\gamma \sim (0.1{,}0.9)$$



$$\mathcal{M}_{T,I}(t,t_0) \equiv \Theta_I(t,t_0)\mathcal{M}_I(t).$$

$$M_{TE,I}(t) \equiv$$

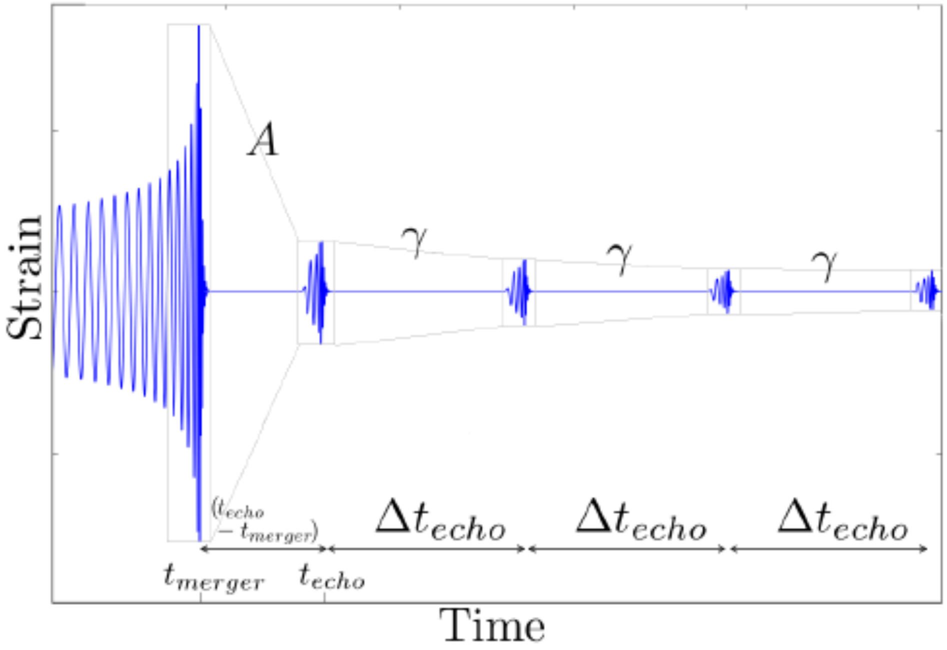
$$A\sum_{n=0}^{\infty}(-1)^{n+1}\gamma^n\mathcal{M}_{T,I}(t + t_{\rm merger} - t_{\rm echo} - n\Delta t_{\rm echo}, t_0)$$

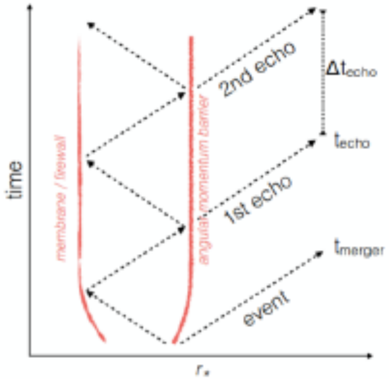
Echoes from AEI

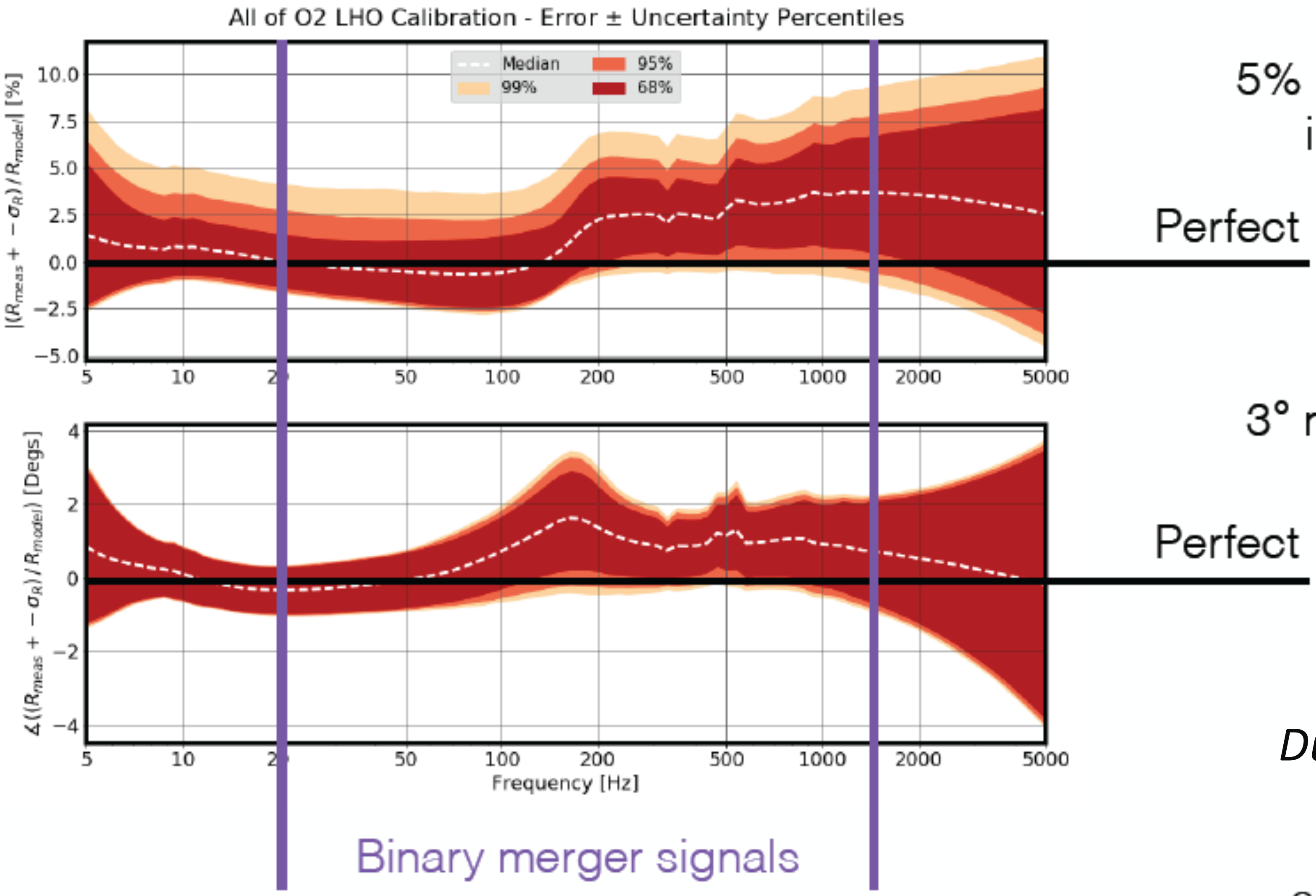
Alex NIELSEN

- We repeat the analysis of Abedi, Dykaar and Afshordi (ADA) from arXiv: 1612.00266.
- We use the same model templates as ADA but a modified background estimate from arXiv: 1612.05625.

Our combined significance estimate for these signals is ~1.3σ (p-value 0.104).







5% max uncertainty
in magnitude

Perfect

3° max uncertainty
in phase

Perfect

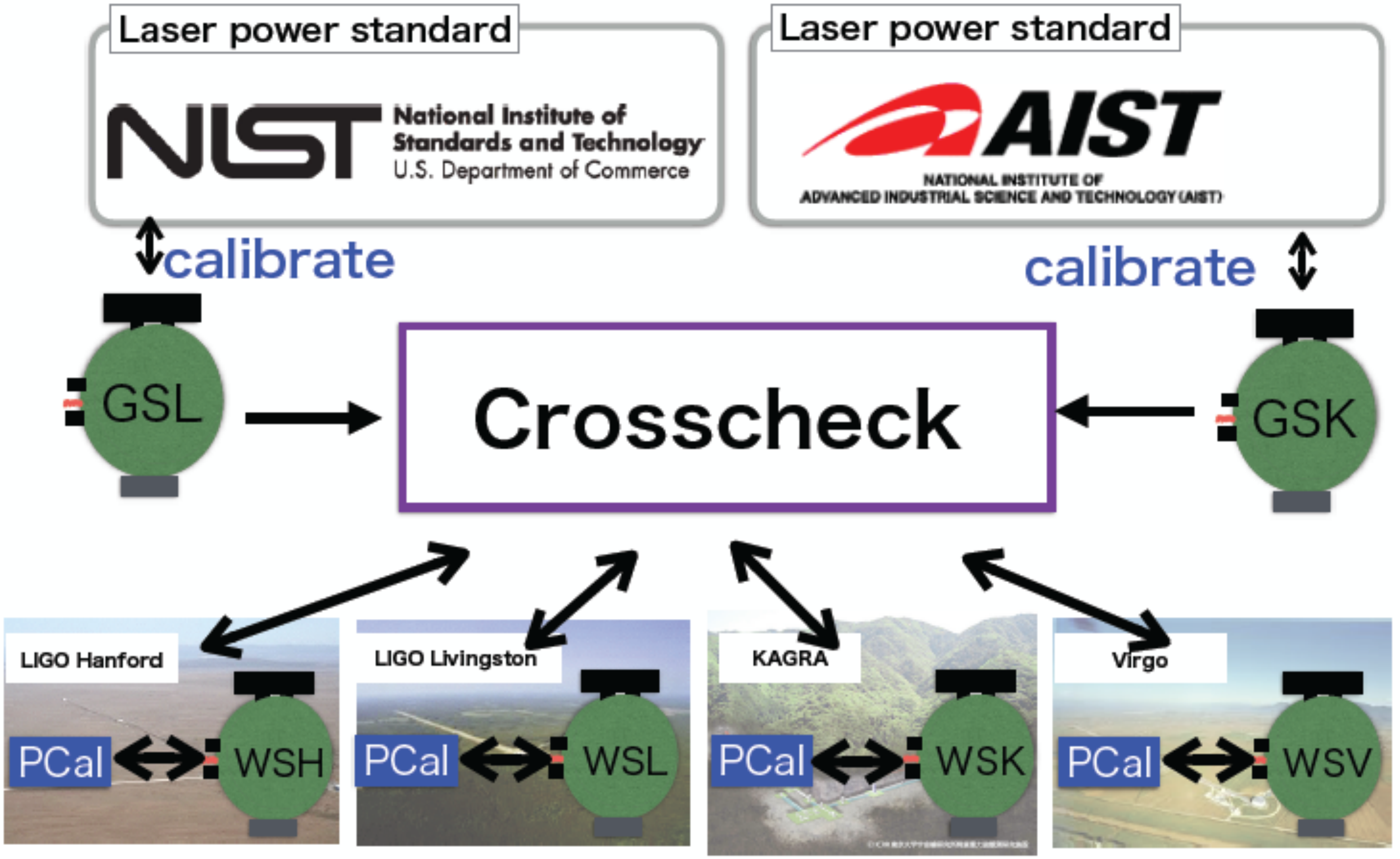
Binary merger signals

Duncan BROWN

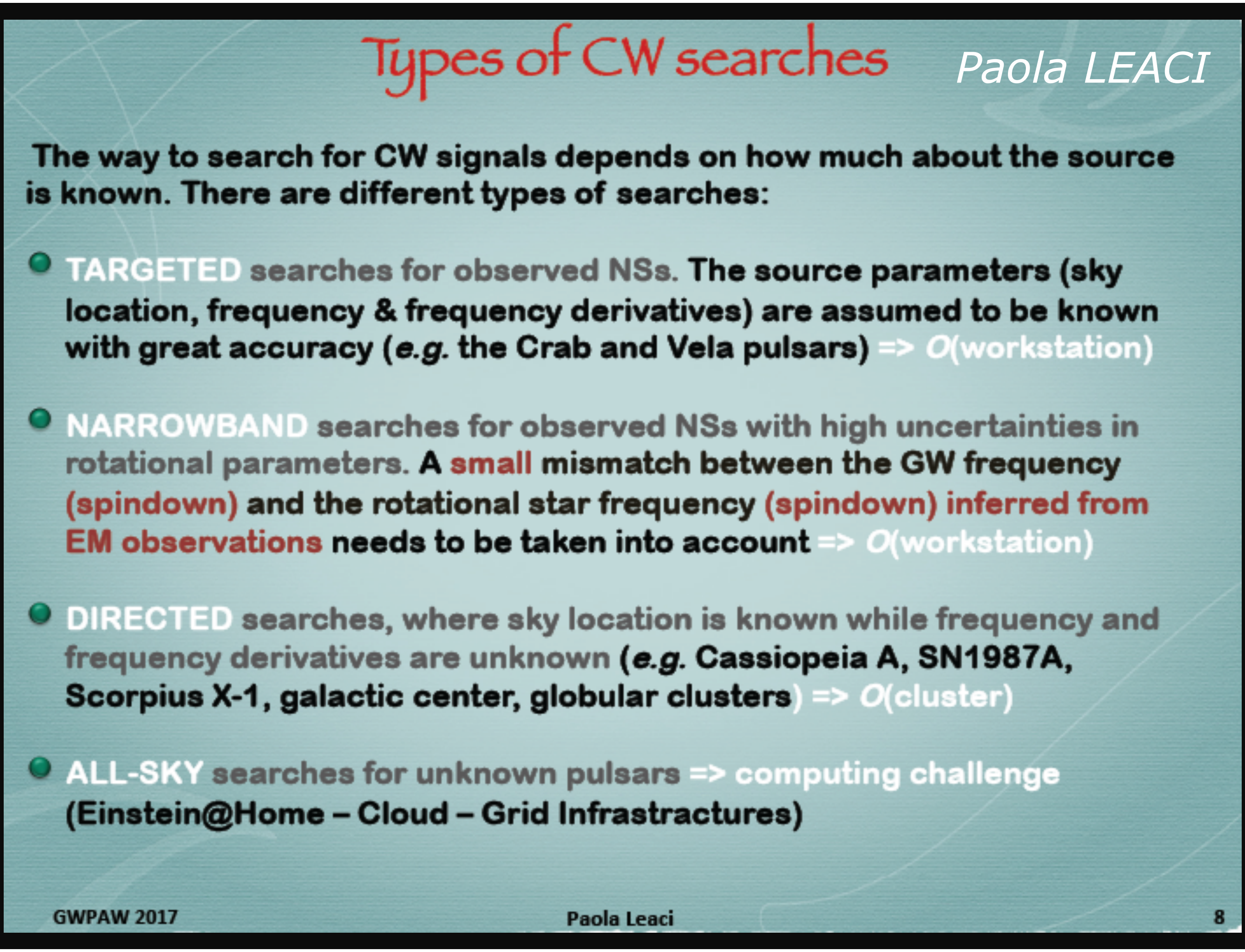
Cahillane et al. (in prep)

Calibration standard (More future)

Yuki INOUE



We plan to make GSK for crosschecking

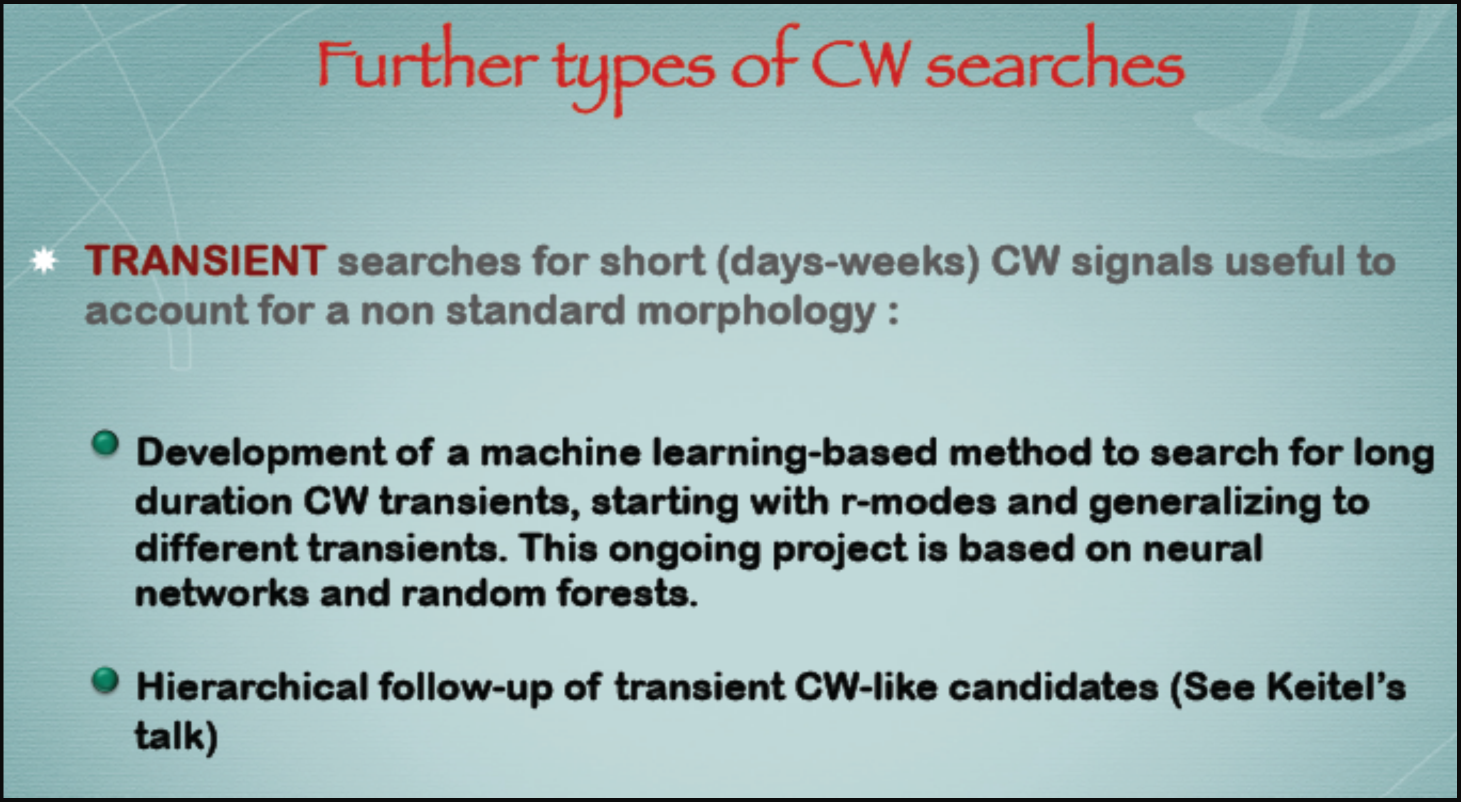


Types of CW searches

Paola LEACI

The way to search for CW signals depends on how much about the source is known. There are different types of searches:

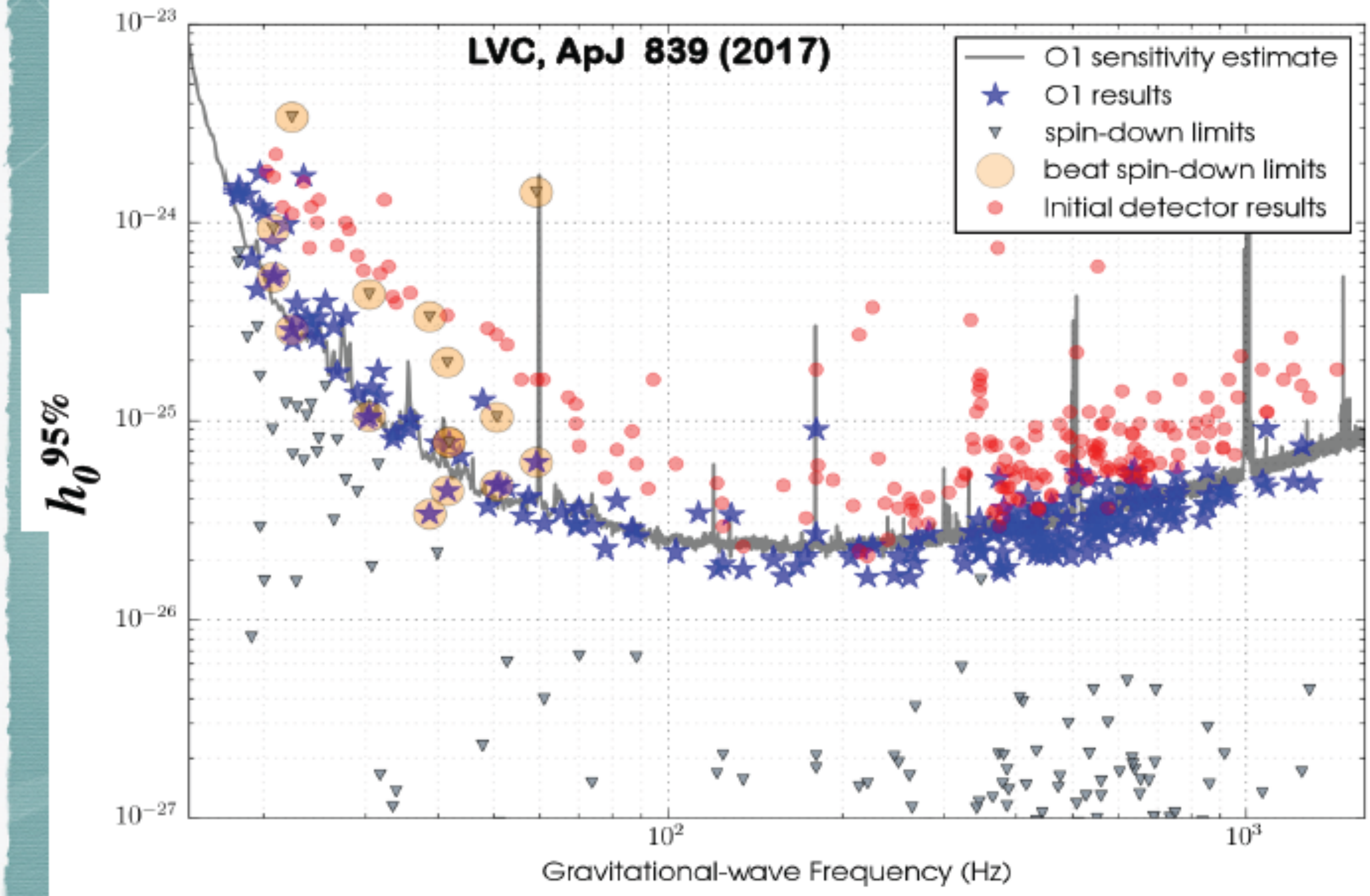
- **TARGETED** searches for observed NSs. The source parameters (sky location, frequency & frequency derivatives) are assumed to be known with great accuracy (*e.g.* the Crab and Vela pulsars) => *O*(workstation)
- **NARROWBAND** searches for observed NSs with high uncertainties in rotational parameters. A small mismatch between the GW frequency (spindown) and the rotational star frequency (spindown) inferred from EM observations needs to be taken into account => *O*(workstation)
- **DIRECTED** searches, where sky location is known while frequency and frequency derivatives are unknown (*e.g.* Cassiopeia A, SN1987A, Scorpius X-1, galactic center, globular clusters) => *O*(cluster)
- **ALL-SKY** searches for unknown pulsars => computing challenge (Einstein@Home – Cloud – Grid Infrastructures)



Further types of CW searches

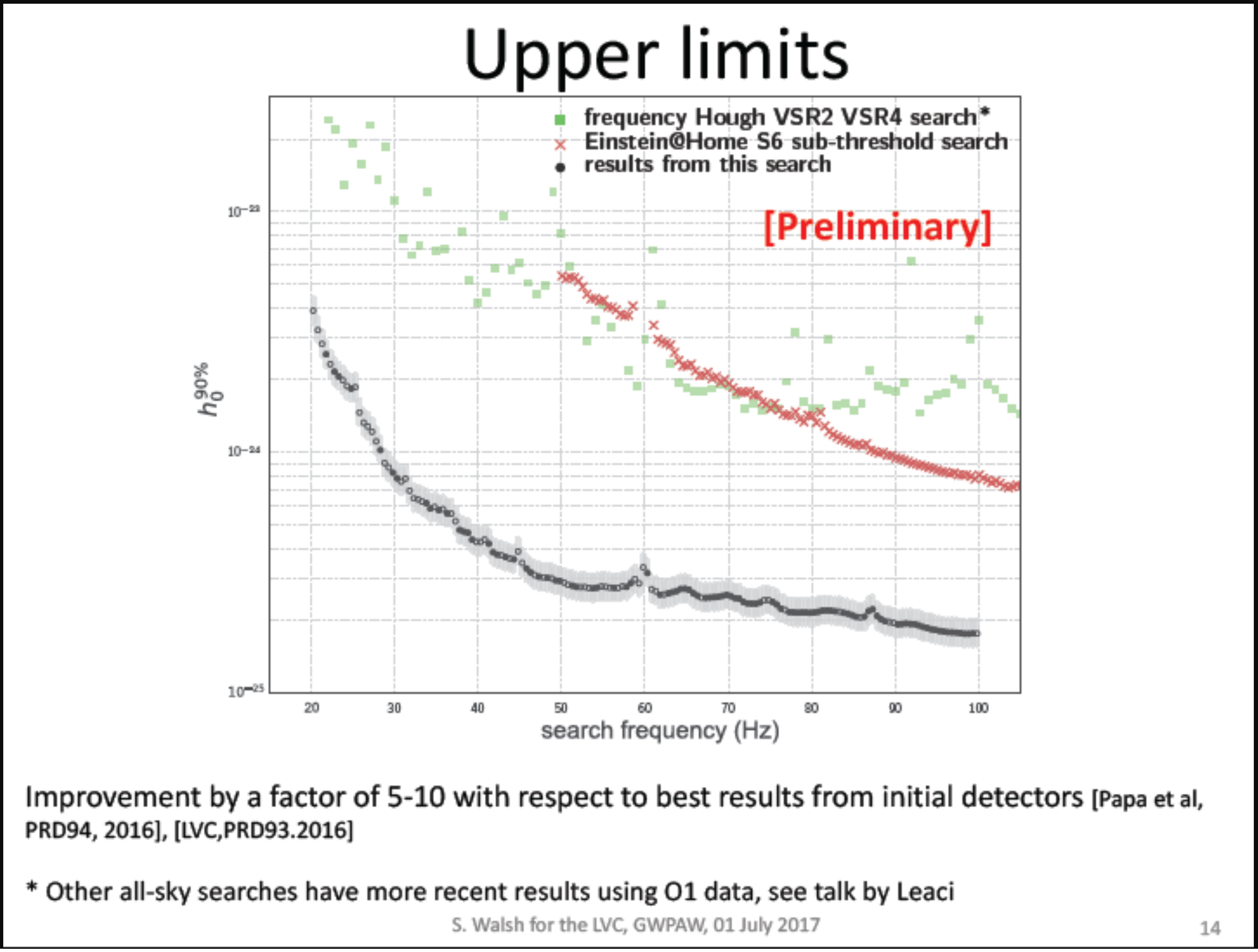
- **TRANSIENT** searches for short (days-weeks) CW signals useful to account for a non standard morphology :
  - Development of a machine learning-based method to search for long duration CW transients, starting with r-modes and generalizing to different transients. This ongoing project is based on neural networks and random forests.
  - Hierarchical follow-up of transient CW-like candidates (See Keitel's talk)

Highlights from targeted searches 2



Einstein@Home all-sky search

Sinead WALSH



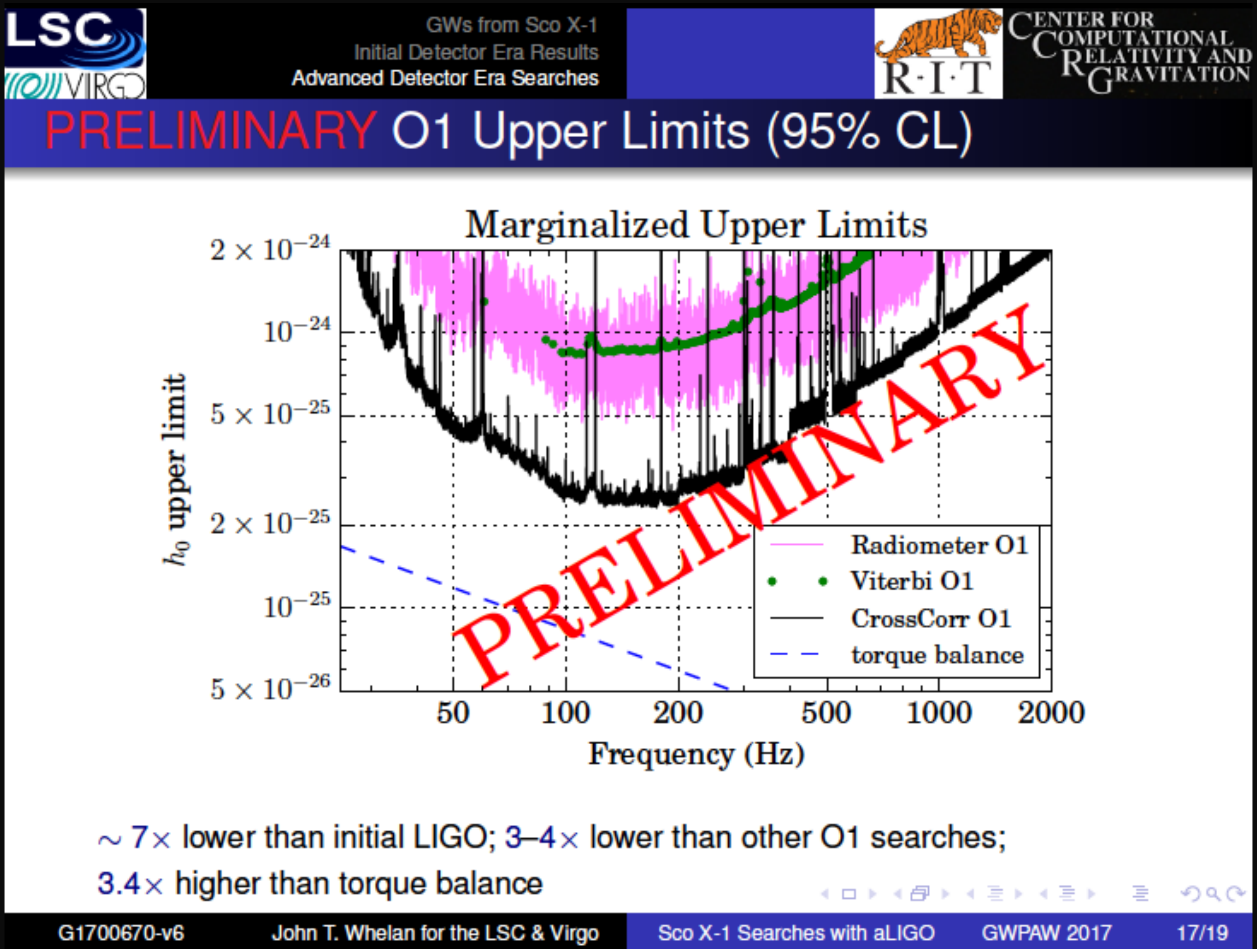
Upper limits

Improvement by a factor of 5-10 with respect to best results from initial detectors [Papa et al, PRD94, 2016], [LVC,PRD93.2016]

* Other all-sky searches have more recent results using O1 data, see talk by Leaci

Directed searches for CWs from Sco X-1

John WHELAN



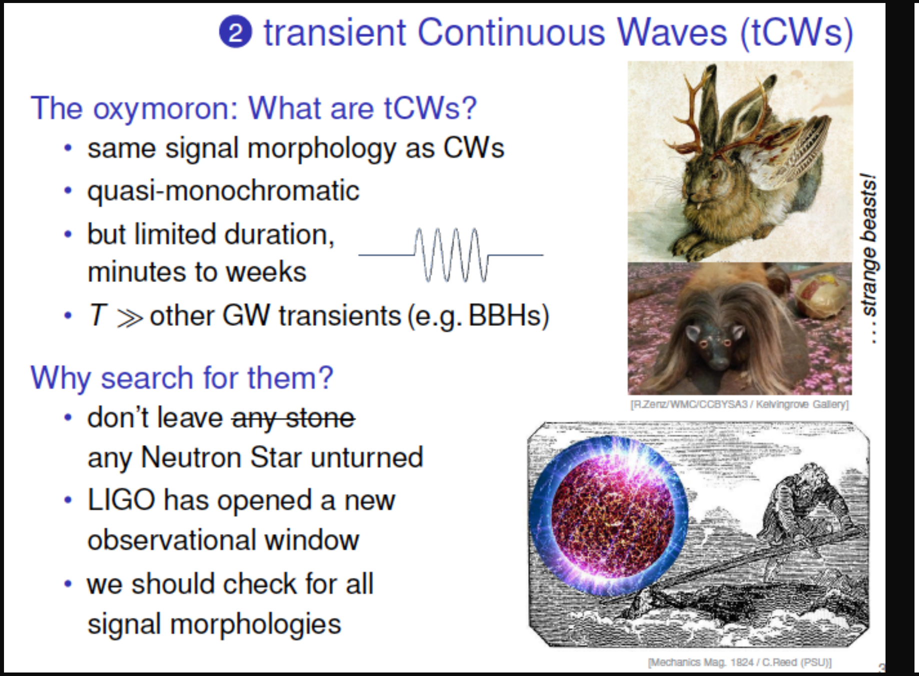
GWs from Sco X-1
Initial Detector Era Results
Advanced Detector Era Searches

PRELIMINARY O1 Upper Limits (95% CL)

∼ 7× lower than initial LIGO; 3–4× lower than other O1 searches; 3.4× higher than torque balance

The oxymoronic transient CWs

David KEITEL



② transient Continuous Waves (tCWs)

The oxymoron: What are tCWs?

- same signal morphology as CWs
- quasi-monochromatic
- but limited duration, minutes to weeks
- $T \gg$ other GW transients (e.g. BBHs)

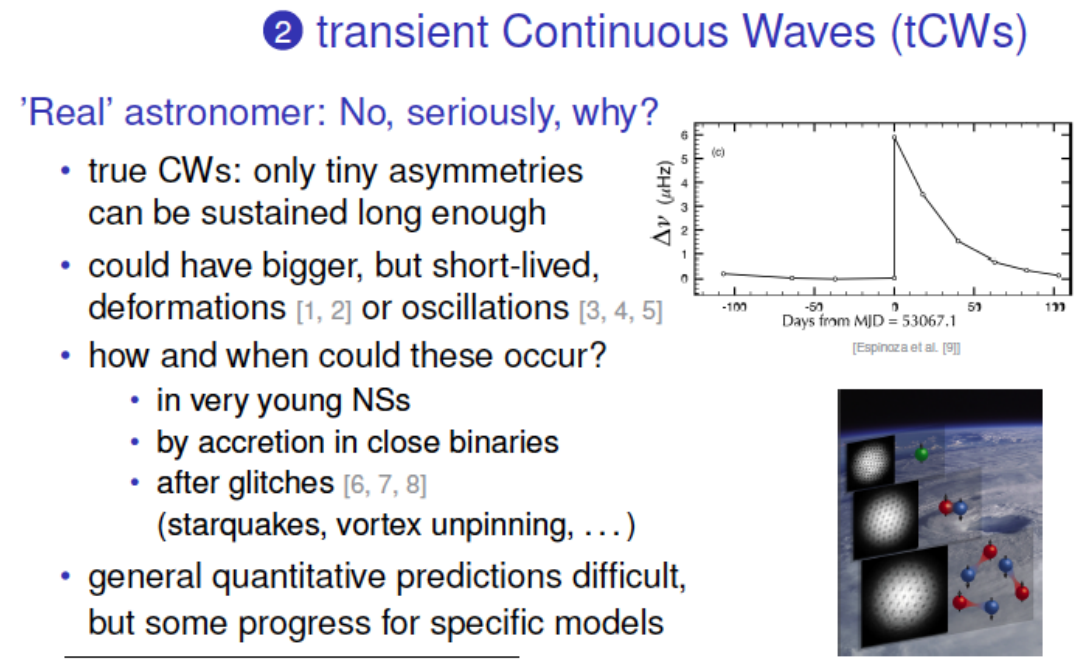
Why search for them?

- don't leave ~~any stone~~ any Neutron Star unturned
- LIGO has opened a new observational window
- we should check for all signal morphologies

. . . strange beasts!

[R.Zenz/WMC/CCBYSA3 / Kelvingrove Gallery]

[Mechanics Mag. 1824 / C.Reed (PSU)]



② transient Continuous Waves (tCWs)

'Real' astronomer: No, seriously, why?

- true CWs: only tiny asymmetries can be sustained long enough
- could have bigger, but short-lived, deformations [1, 2] or oscillations [3, 4, 5]
- how and when could these occur?
  - in very young NSs
  - by accretion in close binaries
  - after glitches [6, 7, 8] (starquakes, vortex unpinning, . . .)
- general quantitative predictions difficult, but some progress for specific models

[Espinoza et al. [9]]

Stochastic Gravitational-wave Background

Nelson CHRISTENSEN

Spectral index α	Frequency band with 99% sensitivity	Amplitude Ω_α	95% CL upper limit	Previous limits [36]
0	20 – 85.8 Hz	$(4.4 \pm 5.9) \times 10^{-8}$	1.7×10^{-7}	5.6×10^{-6}
2/3	20 – 98.2 Hz	$(3.5 \pm 4.4) \times 10^{-8}$	1.3×10^{-7}	–
3	20 – 305 Hz	$(3.7 \pm 6.5) \times 10^{-9}$	1.7×10^{-8}	7.6×10^{-8}

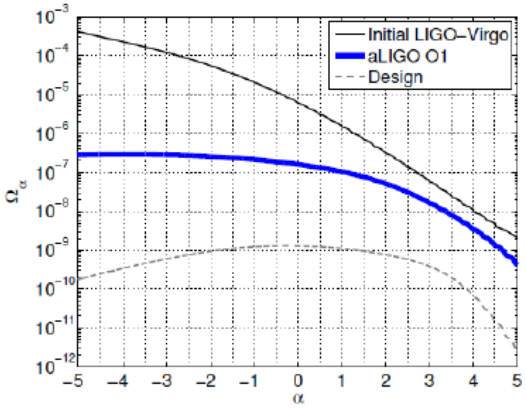


FIG. 2. Following [52], we present 95 % confidence contours in the $\Omega_\alpha - \alpha$ plane. The region above these curves is excluded at 95% confidence. We show the constraints coming from the final science run of Initial LIGO-Virgo [36] and from O1 data. Finally, we display the projected (not observed) design sensitivity to Ω_α and α for Advanced LIGO and Virgo [54].

(LSC-Virgo) PRL.118.121101 (2017)

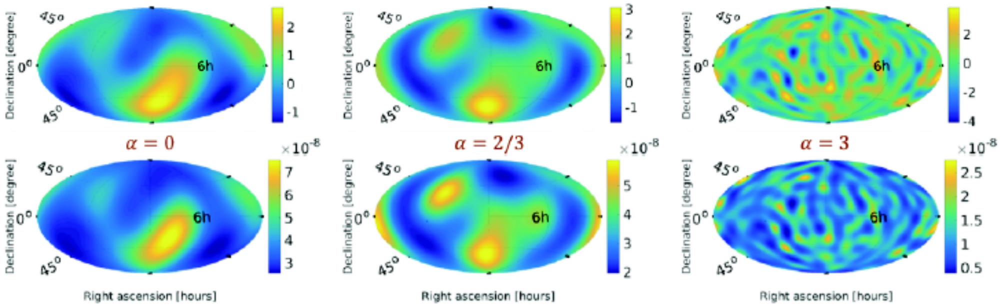
O1 Directional – Extended Sources

Spherical Harmonics (SHD)

All-sky (broadband) Results

						Max SNR (% p-value)		Upper limit range	
α	$\Omega_{\rm gw}$	$H(f)$	f_α (Hz)	θ (deg)	$l_{\max}$	BBR	SHD	BBR ($\times 10^{-8}$)	SHD ($\times 10^{-8}$)
0	constant	$\propto f^{-3}$	52.50	55	3	3.32 (7)	2.69 (18)	10 – 56	2.5 – 7.6
2/3	$\propto f^{2/3}$	$\propto f^{-7/3}$	65.75	44	4	3.31 (12)	3.06 (11)	5.1 – 33	2.0 – 5.9
3	$\propto f^{3}$	constant	256.50	11	16	3.43 (47)	3.86 (11)	0.1 – 0.9	0.4 – 2.8

SNR maps



Upper Limit maps [$\Omega_{\rm gw}$ sr^{-1}]

(LSC-Virgo) PRL.118.121102 (2017)

HOW NEIL GERHELS CHANGED THE FIELD OF TRANSIENT ASTRONOMY

Paul O'Brien
University of Leicester

(with thanks to the Swift team)

Neil Gehrels
1952-2017

As the last speaker, it is my privilege to say
merci beaucoup to the organizers:
Frederique Marion
Benoit Mours
Damir Buskulic
and the rest of the L.A.P.P. team
for an extremely well-organized
and fascinating meeting
in a lovely venue
here in this beautiful city of Annecy!