Testing the Kerr hypothesis:
universality, imitators and dynamical signatures

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Fundamental Physics with LISA
"Cosmological Frontiers in Fundamental Physics 2022 Workshop"
Solvay - APC - Perimeter Institute
27 April 2022

The Kerr hypothesis

"In my entire scientific life, extending over forty-five years, the most shattering experience has been the realization that an exact solution of Einstein's field equations of general relativity, discovered by the New Zealand mathematician, Roy Kerr, provides the absolutely exact representation of untold numbers of massive black holes that populate the Universe."

S. Chandrasekhar, in *Truth and Beauty* (1987)

Some critical skepticism:

1) are these untold numbers of massive black holes exactly represented by the Kerr metric ?

2) are these black holes all of the same type ?

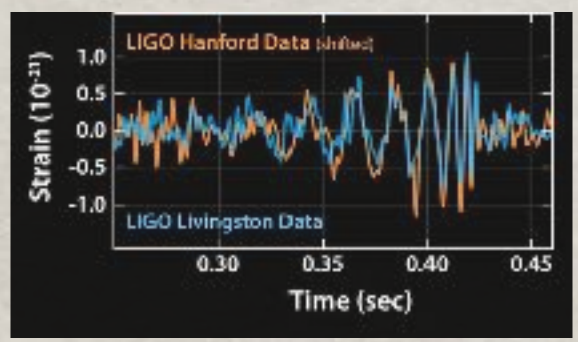
3) are these objects really black holes ?

The **Kerr hypothesis** is a very **economical** scenario:
the very same “object” spans (at least) 10 orders of magnitude!

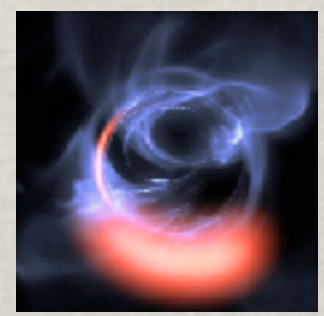
Stellar mass range

Supermassive range

0 2 4 6 8 10 $\log\left(\frac{M}{M_\odot}\right)$



LIGO-Virgo-KAGRA (LVK)



Gravity

Event Horizon Telescope

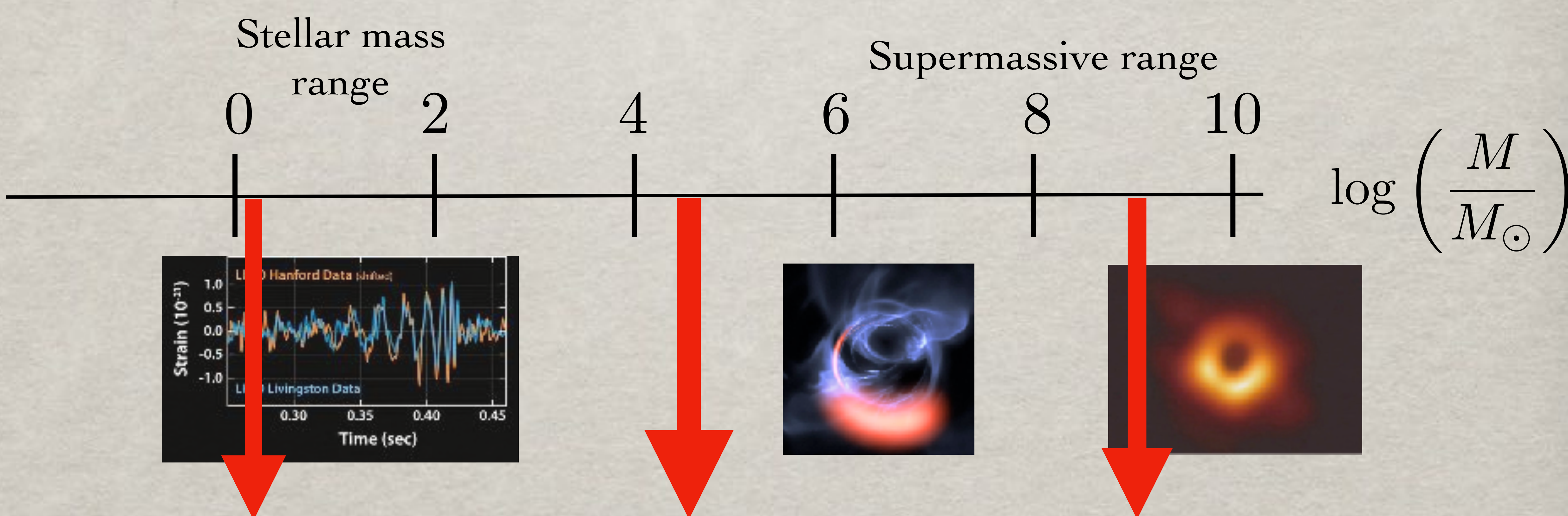
$$ds^2 = -\frac{\Delta(M,a)}{\Sigma(a)}\left(dt - a\sin^2\theta d\phi\right)^2 + \frac{\Sigma(a)}{\Delta(M,a)}dr^2 + \Sigma(a)d\theta^2 + \frac{\sin^2\theta}{\Sigma(a)}\left[a dt - (r^2+a^2)d\phi\right]^2 ,$$

The **Kerr hypothesis** is, at best, an approximation.

(singularities, UV completion of GR, dark matter…)

Typically new physics introduces new scales;

consider the possibility that non-Kerrness of astrophysical black holes may be more manifest in some particular scales.



Non-Kerrness???　　Non-Kerrness???　　Non-Kerrness???

Universality ???

"Reasonable" non-Kerr black holes/compact objects:

Theoretical criteria:

1) Appear in a well motivated and consistent physical (effective) theories;

Kerr: General Relativity

2) Have a dynamical formation mechanism;

Kerr: gravitational collapse, accretion, mergers,…

Dynamical Robustness

3) Be (sufficiently) stable.

Kerr: mode stability established (Whiting, JMP 30 (1989) 1301)

Correct phenomenology:

No clear tension between observations and the Kerr model

1) all electromagnetic observables (X-ray spectrum, shadows, QPOs, star orbits,...);

2) correct Gravitational wave (GW) templates

How much is this due to the lack of alternative detailed phenomenology?

(Incomplete)

Wish list

for testing the Kerr hypothesis with GWs
(both for LVK and LISA)

1) Obtain *extensive waveform catalogues* for reasonable non-Kerr models:
   a) From samples of *fully non-linear* numerical relativity simulations, covering inspiral, merger and ringdown;
   b) Obtaining a dense sampling of the parameter space via approximants.

2) Obtain *partial waveforms* using *perturbative methods* for reasonable non-Kerr models (where the merger may not be fully under control):
   a) Of the inspiral using Post-Newtonian or other methods in particular considering extreme mass ratio inspirals (EMRIs) relevant for LISA;
   b) Of the ringdown using black hole perturbation theory, also key for stability.

3) Obtain *parameterised post-Einsteinian (or post-Kerrian!) waveforms* in large classes of theories accommodating non-Kerr models - theory agnostic.
   Yunes and Pretorius, PRD 80 (2009) 122003

Plan - some illustrative examples:

1) Exotic Compact Objects (ECOs)
   a) Issues with ECOs;
   b) A proof of concept for new physics using GW190521;

2) Non-Kerr black holes
   a) Strict non-Kerrness vs. hybrid models (and dynamical emergence);
   b) A proof of concept for constraining new scales using GW190814;

3) Burning questions

1) Exotic Compact Objects (ECOs)

a) Issues with ECOs

Motivation:

Black holes have a horizon and (abiding energy conditions) there is a curvature singularity:

Penrose, PRL 14 (1965) 57

breakdown of the model

To avoid this difficulties, models of horizonless compact objects (black hole mimickers) have been considered:

a) "geons", realized by Boson stars (Schunck, Mielke, CQG 20 (2003) R301; Jetzer, Phys. Rept. 220 (1992) 163) and Proca stars (Brito, Cardoso, CH, Radu, PLB 752 (2016) 291); can form dynamically (Seidel, Suen, PRL 72 (1994) 2516); Perturbatively stable Gleiser and Watkins, NPB 319 (1989) 733; Lee and Pang, NPB 315 (1989) 477; Can be studied dynamically in binaries (Liebling and Palenzuela LRR 20 (2017) 5)

b) wormholes (Morris and Thorne, Am. J. Phys. 56 (1988) 395-412)

c) gravastars (Mazur and Mottola, gr-qc/0109035)

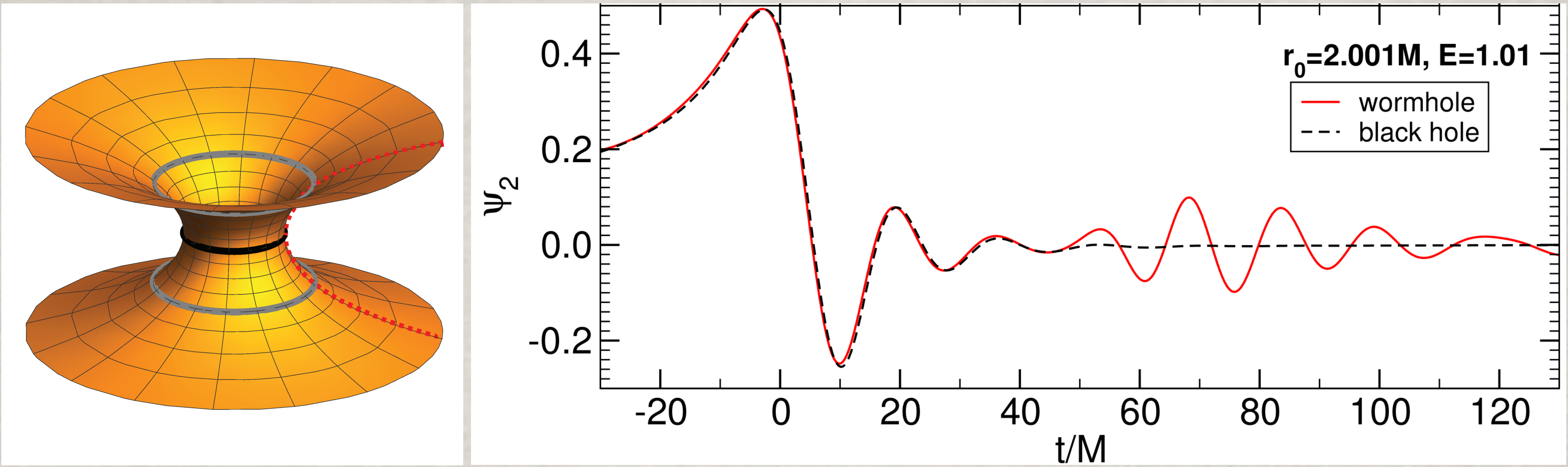
d) fuzzballs (Mathur, Fortsch. Phys. 53 (2005) 793)

Paolo Pani's talk

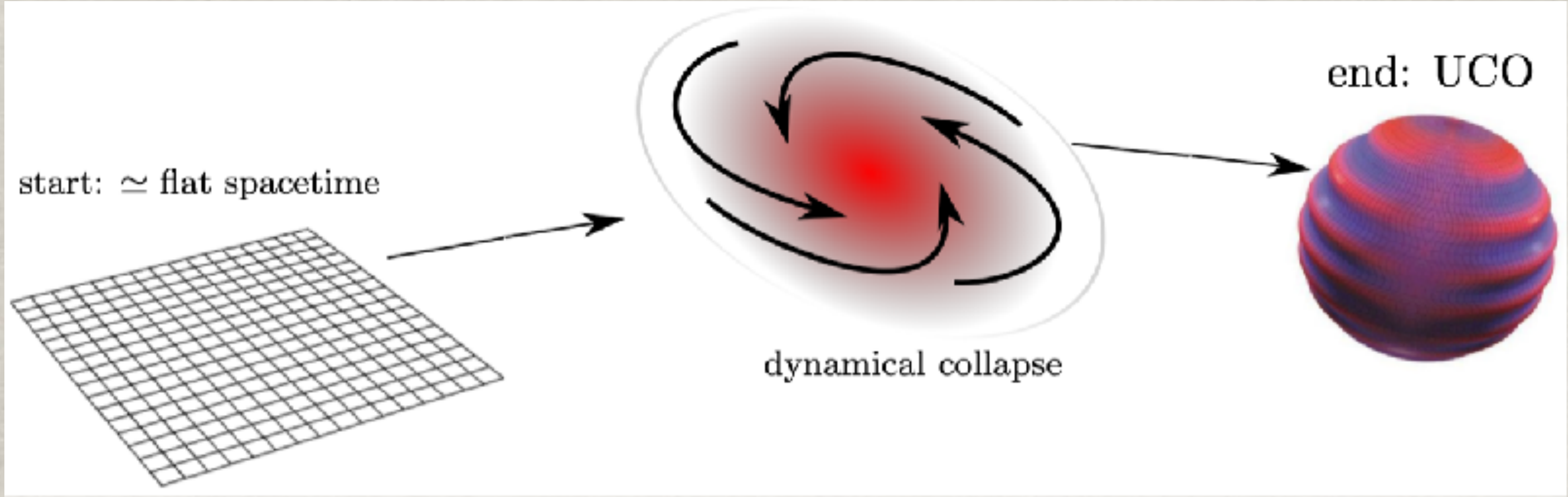
e) … See e.g. Pani and Cardoso, Nature Astron. 1 (2017) 9, 586

Does any of these (or other) ECOs models obey the previous theoretical criteria?

Can a perturbed ECO ringdown like a black hole?



- To be able to mimic (+ extra features) the GW ringdown the ECO must be ultracompact, i.e. have a light ring Cardoso, Franzin and Pani, PRL 116 (2016) 171101



- Possible issue: for ultracompact objects resulting from a smooth, incomplete gravitational collapse, light rings come in pairs and one is stable Cunha, Berti, CH, PRL 119 (2017) 251102

A (stable) light ring instability for ultracompact ECOs?

This result is based on a topological argument and uses reasonable and generic assumptions: smoothness, causality and axi-symmetry (at end point);

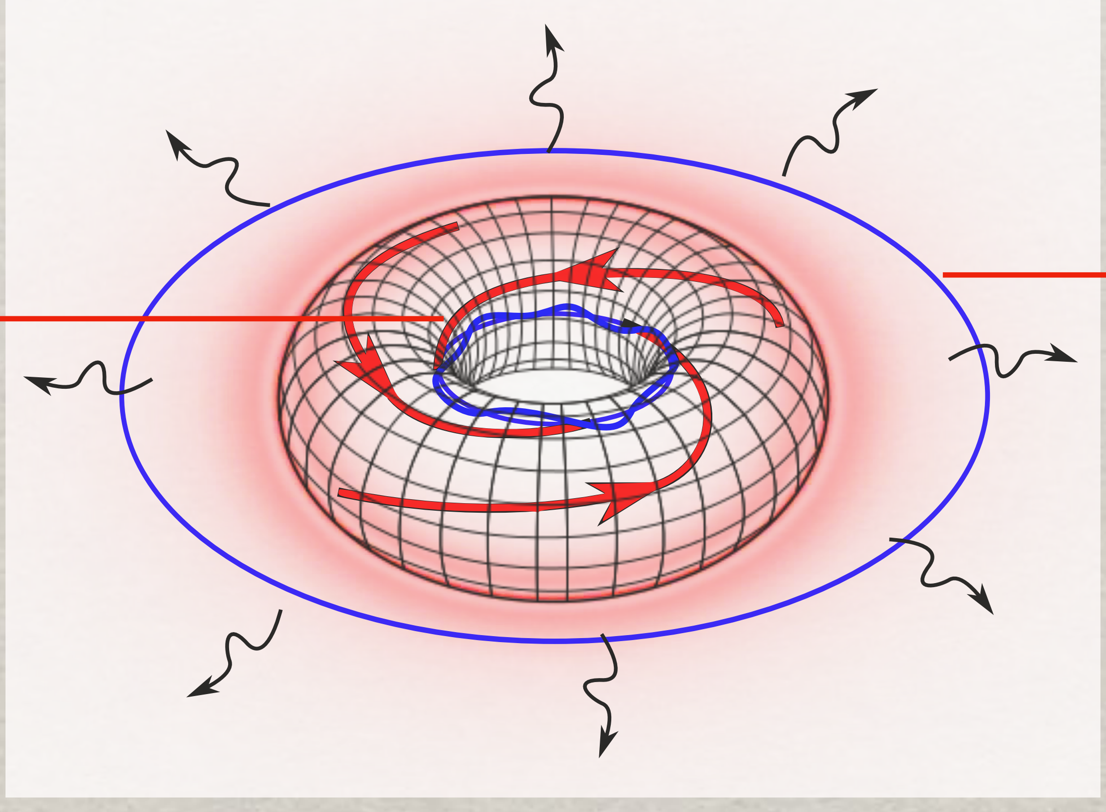
It shows for such ECOs, light-rings come in pairs and one is stable (unless NEC is violated);

Stable light rings trap radiation - this may destabilize the object (but depends on timescale)

Cardoso, Macedo, Crispino, Okawa, Pani, PRD 90 (2014) 044069; Keir, CQG 33 (2016) 135009; Benomio, 1809.07795

Stable LR

(traps null perturbations,
EMG and GW,
and may source
a spacetime instability)



Unstable LR

(allows mimic,
to some extent,
the black hole ringdown)

Can ECOs **without** LRs mimic the GW phenomenology attributed to black holes?

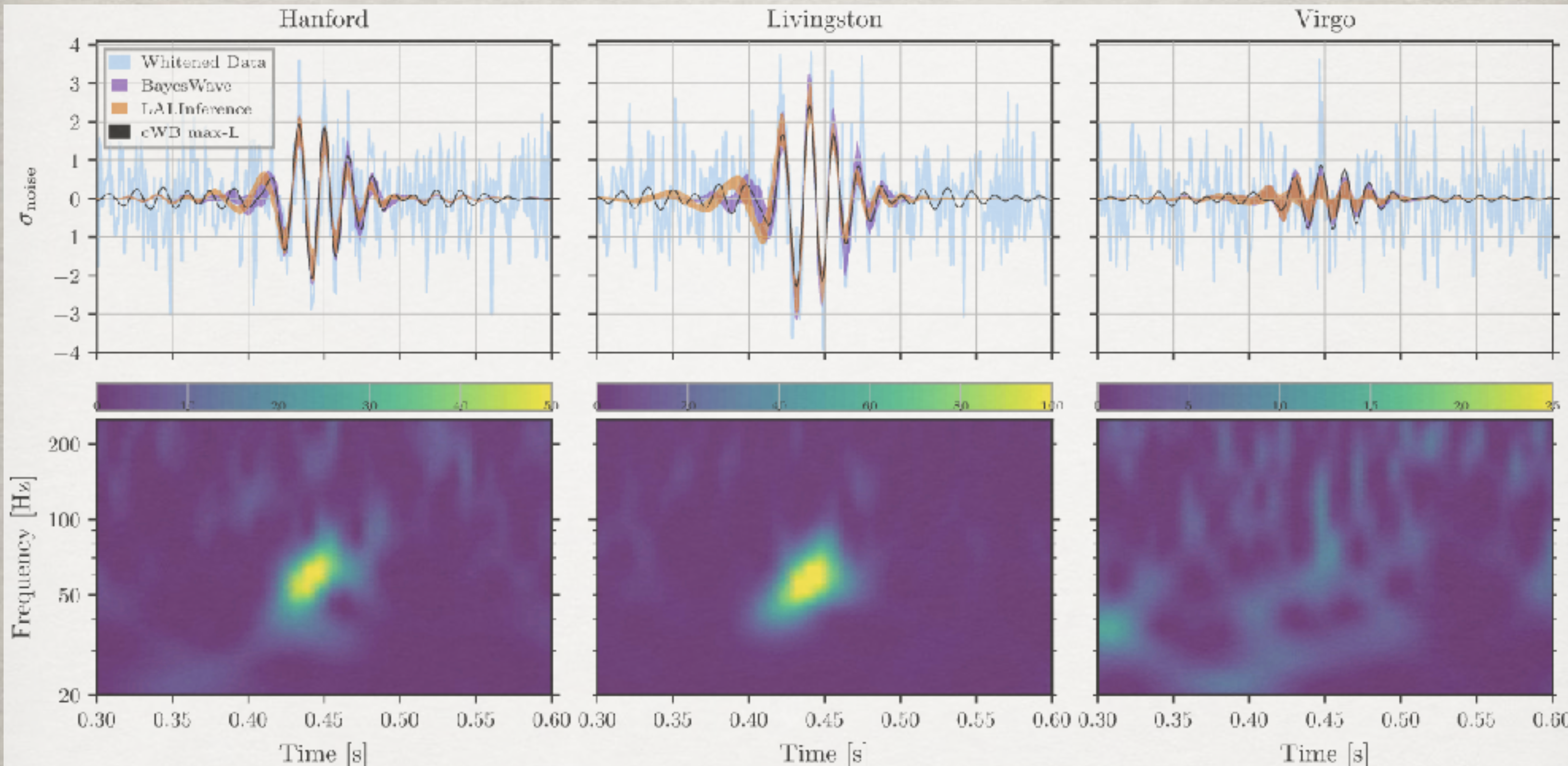
1) Exotic Compact Objects (ECOs)

b) A proof of concept for new physics using GW190521

A particular event from the O3 run

https://gracedb.ligo.org/superevents/public/O3/

GW190521 PRL 125 (2020) 10, ApJ Lett. 900 (2020) L13

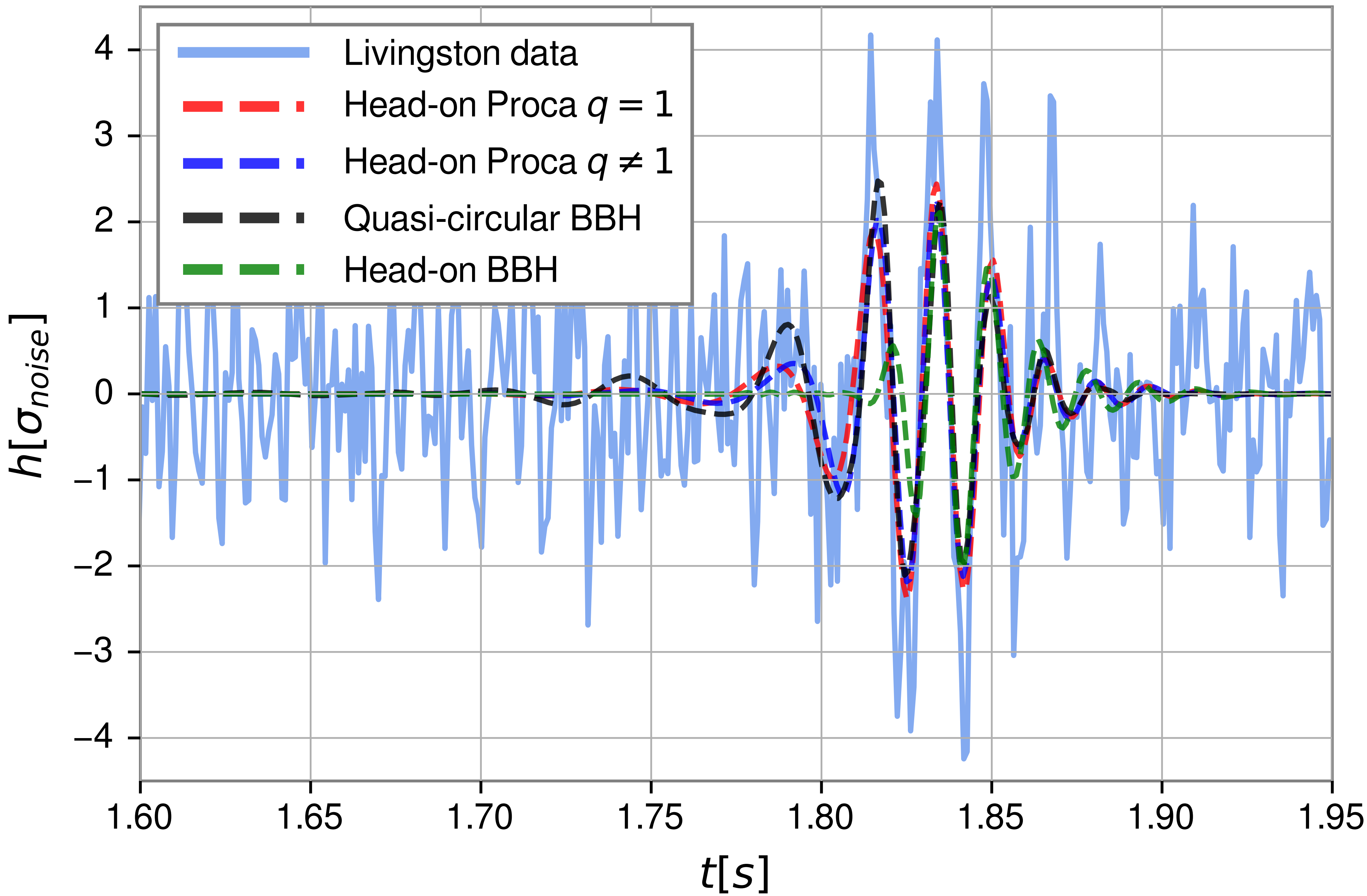


- Two most massive progenitors: $85^{+21}_{-14}M_\odot$, $66^{+17}_{-18}M_\odot$
- At least one in the pair instability supernova gap. Formation?
- Very short - no inspiral
- Final BH can be considered of intermediate mass: $142^{+28}_{-16}M_\odot$

PHYSICAL REVIEW LETTERS **126,** 081101 (2021)

GW190521 as a Merger of Proca Stars: A Potential New Vector Boson of 8.7×10^{-13} eV

Juan Calderón Bustillo,[1,2,3,4,*] Nicolas Sanchis-Gual,[5,6,†] Alejandro Torres-Forné,[7,8,9] José A. Font,[8,9] Avi Vajpeyi,[3,4] Rory Smith,[3,4] Carlos Herdeiro,[6] Eugen Radu,[6] and Samson H. W. Leong[2]



Bosonic stars (a macro perspective):

- Appear in General Relativity with simple and physically reasonable matter sources: complex massive scalar fields or vector fields, possibly with self-interactions, but certainly with a mass term.

Massive-complex-scalar-vacuum:

Scalar Boson Stars

New scale

$$\mathcal{S} = \frac{1}{4\pi}\int d^4x\sqrt{-g}\left(\frac{R}{4} - \nabla_\alpha\Phi^*\nabla^\alpha\Phi - \mu^2|\Phi|^2\right)$$

Massive-complex-vector-vacuum:

Vector Boson Stars
or
Proca Stars

New scale

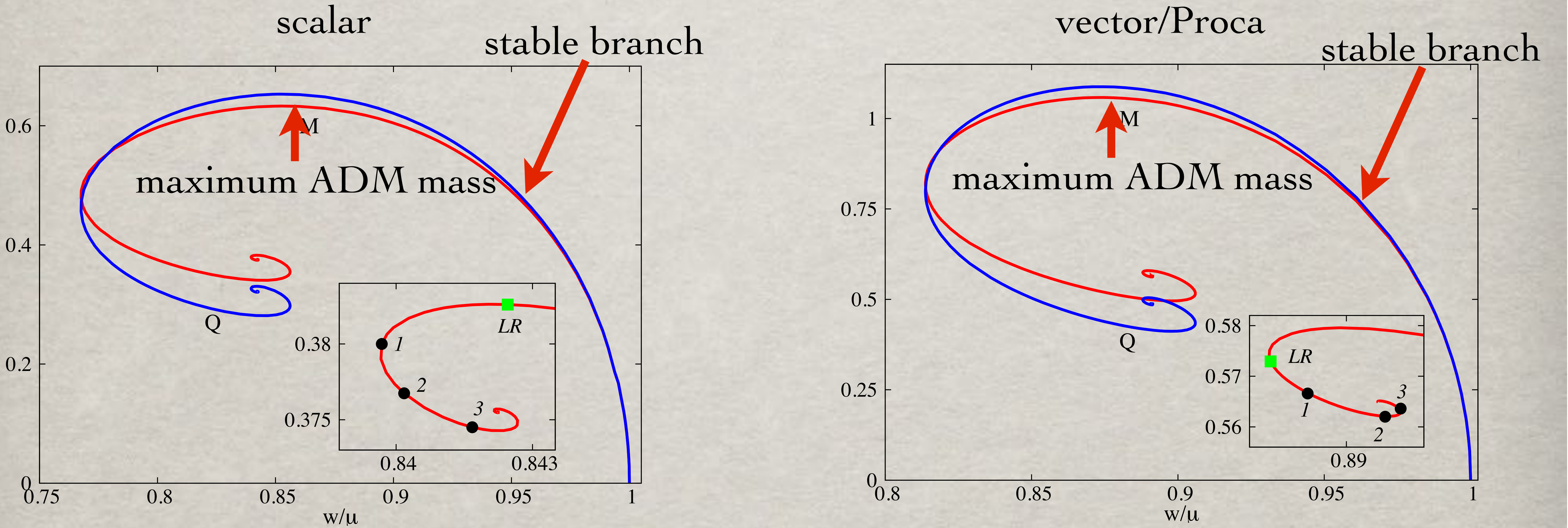
$$\mathcal{S} = \int d^4x\sqrt{-g}\left(\frac{1}{16\pi G}R - \frac{1}{4}\mathcal{F}_{\alpha\beta}\bar{\mathcal{F}}^{\alpha\beta} - \frac{1}{2}\mu^2\mathcal{A}_\alpha\bar{\mathcal{A}}^\alpha\right) .$$

Spherical bosonic stars - stability

Kaup, Phys. Rev. 172 (1968) 1331; Ruffini and Bonazzola, Phys. Rev. 187 (1969) 1767;
Brito, Cardoso, CH and Radu, PLB 752 (2016) 291; CH, Pombo, Radu, PLB 773 (2017) 654

$\Phi = \phi(r)e^{-iwt}$ $\qquad$ $\mathcal{A} = e^{-iwt}[f(r)dt + ig(r)dr]$

frequency



Studying linearized radial perturbations of the coupled system shows that an unstable mode arises precisely at the maximum of the ADM mass M. Gleiser and R. Watkins, NPB 319 (1989) 733; T. D. Lee and Y. Pang, NPB 315, 477 (1989); Brito, Cardoso, CH and Radu, PLB 752 (2016) 291.

Unstable BSs can migrate, decay into a Schwarzschild black hole or disperse entirely Seidel and Suen, PRD 42 (1990) 384; Guzman, PRD 70 (2004) 044033; Hawley and Choptuik, PRD 62 (2000) 104024; Sanchis-Gual, CH, Radu, Degollado, Font, PRD 95 (2017) 104028

Spherical Bosonic Stars - dynamical formation

Seidel and D. Suen, PRL 72 (1994) 2516 (scalar)
Di Giovanni, Sanchis-Gual, CH and Font, PRD 98 (2018) 064044 (vector)

Initial data: a coherent complex scalar field: $\Phi = 0.0025 e^{-r^2/90^2}$, $\dot{\Phi} = 0.9 i w$

Evolution:
time in units of $1/\mu$

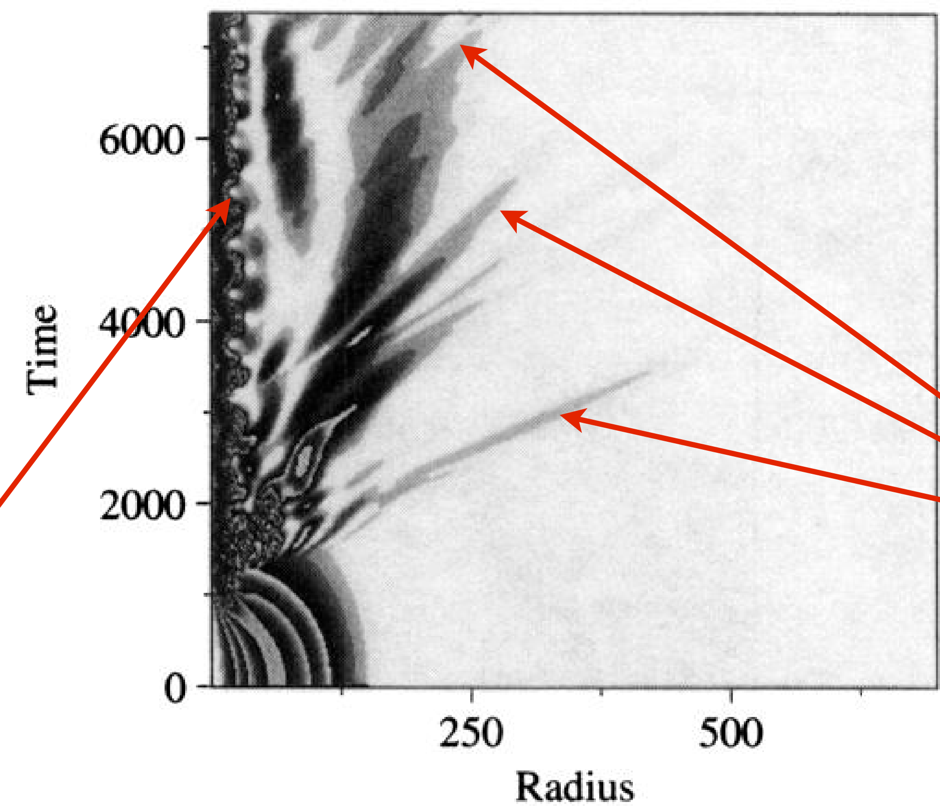


FIG. 1. The evolution of $r^2\rho$ for a massive, self-gravitating complex scalar field is shown. Because of the self-gravitation, the field collapses quickly and a perturbed boson star is formed at the center. The star oscillates and begins to settle down as scalar material is radiated through the gravitational cooling process discussed in the text.

Final state:
(perturbed) boson star with mass

$$\sim 0.56 \frac{M_{Pl}^2}{\mu}$$

Gravitational cooling:
ejected scalar field "radiation" carries excess kinetic energy
(analogous to violent relaxation in collisionless stellar systems)

$$M_i \sim 0.644 \frac{M_{Pl}^2}{\mu} > 0.633 \frac{M_{Pl}^2}{\mu}$$

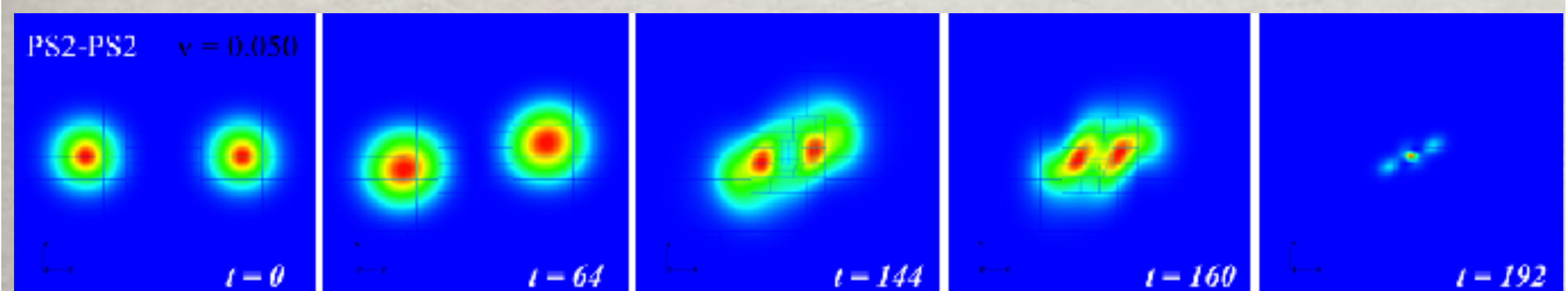
(maximal mass for boson stars in this model; without cooling a BH would form)

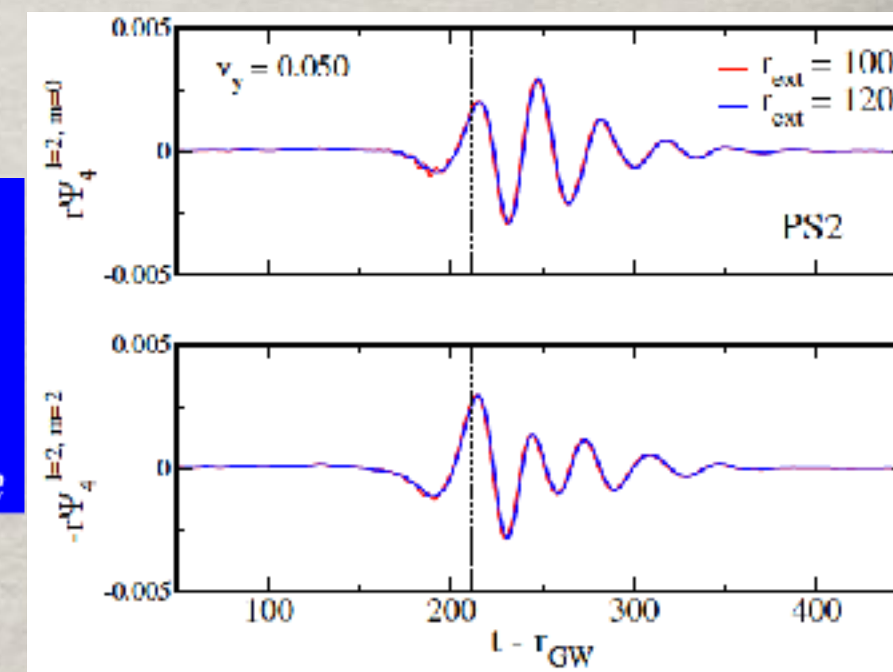
$$\frac{M_i - M_f}{M_i} \sim 0.13$$

Spherical Bosonic Stars - binary dynamics

- They started to be evolved alone or in binaries, producing waveforms.

e.g. Liebling and Palenzuela, LRR 15 (2012) 6, LRR 20 (2017) 1, 5





Stable model; apparent horizon forms at t~200

Sanchis-Gual, CH, Font, Radu and Di Giovanni, PRD 99 (2019) 024017

Certainly an excellent toy model… but… something more?

Bosonic stars (a micro perspective):

- They are a Bose-Einstein condensate of many ultralight particles in the same quantum state, thus justifying the classical description.

- The need for ultralightness comes from the existence of a (model dependent) maximal mass for the bosonic stars:

$$M_{\rm ADM}^{\rm max} \simeq \alpha_{\rm BS} \frac{M_{\rm Pl}^2}{\mu} \simeq \alpha_{\rm BS}\, 10^{-19} M_\odot \left(\frac{\rm GeV}{\mu}\right)$$

- Thus, for bosonic stars with masses in the astrophysical black holes range the fundamental bosonic particle must be ultralight:

$$M_{ADM}^{\rm max} \sim (1 - 10^{10})\ {\rm M}_\odot \quad \longleftrightarrow \quad \mu \sim (10^{-10} - 10^{-20})\ {\rm eV}$$

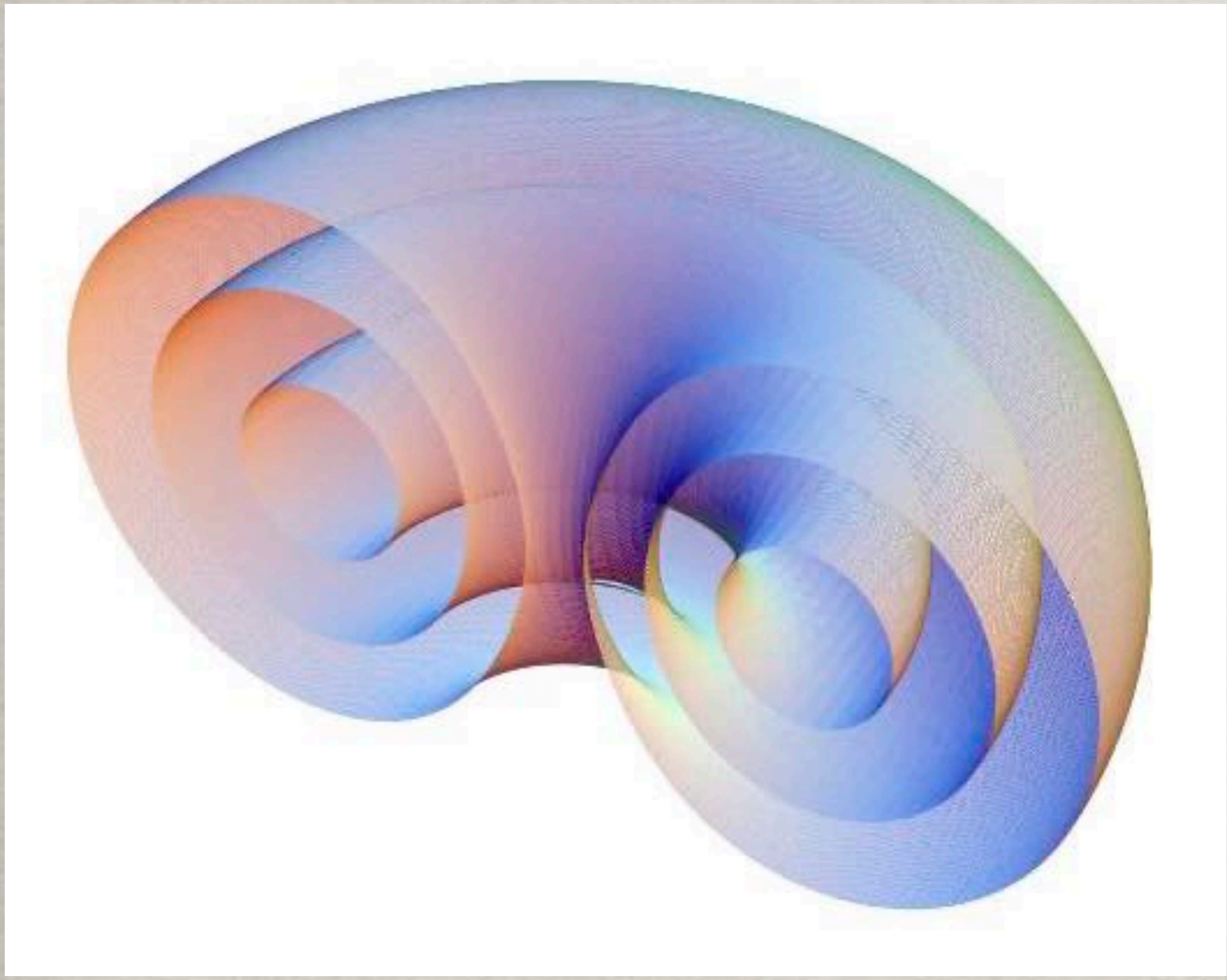
- If such hypothetical particle(s) have feeble or no-interactions with standard model constituents, they are fuzzy dark matter, only detectable gravitationally.
Suárez, Robles, Matos, 1302.0903; Hui, Ostriker, Tremain and Witten, 1610.08297

But what is their HEP origin? Axiverse? Arvanitaki et al., 0905.4720

Something else? Freitas et al. JCAP 12 (2021) 047

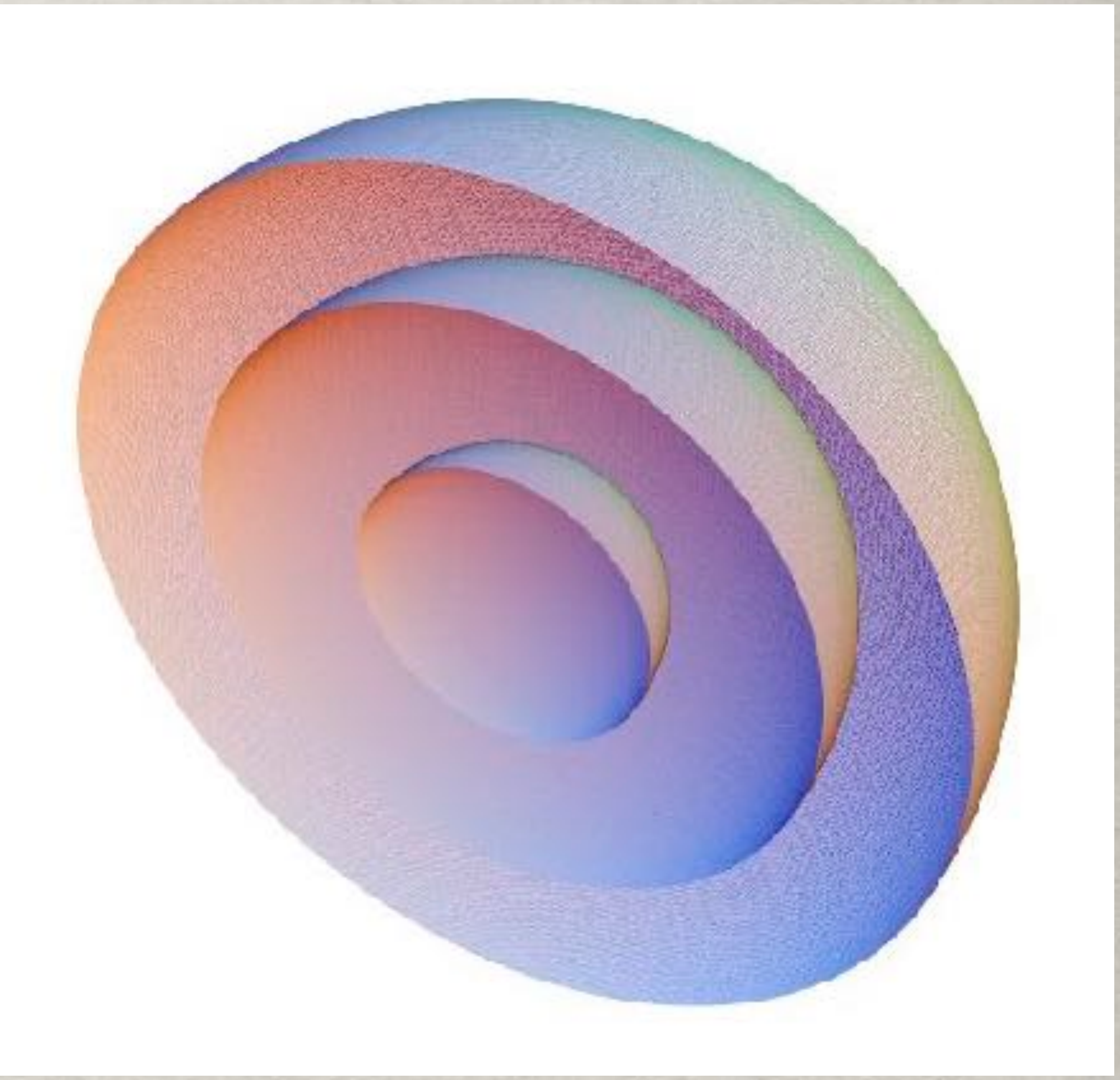
This close analogy between scalar and vector bosonic stars is broken by rotation.

Firstly, in their morphology:



Rotating boson stars

F. E. Schunck and E. W. Mielke, PLA 249 (1998) 389
S. Yoshida and Y. Eriguchi, PRD 56 (1997) 762



Rotating Proca stars

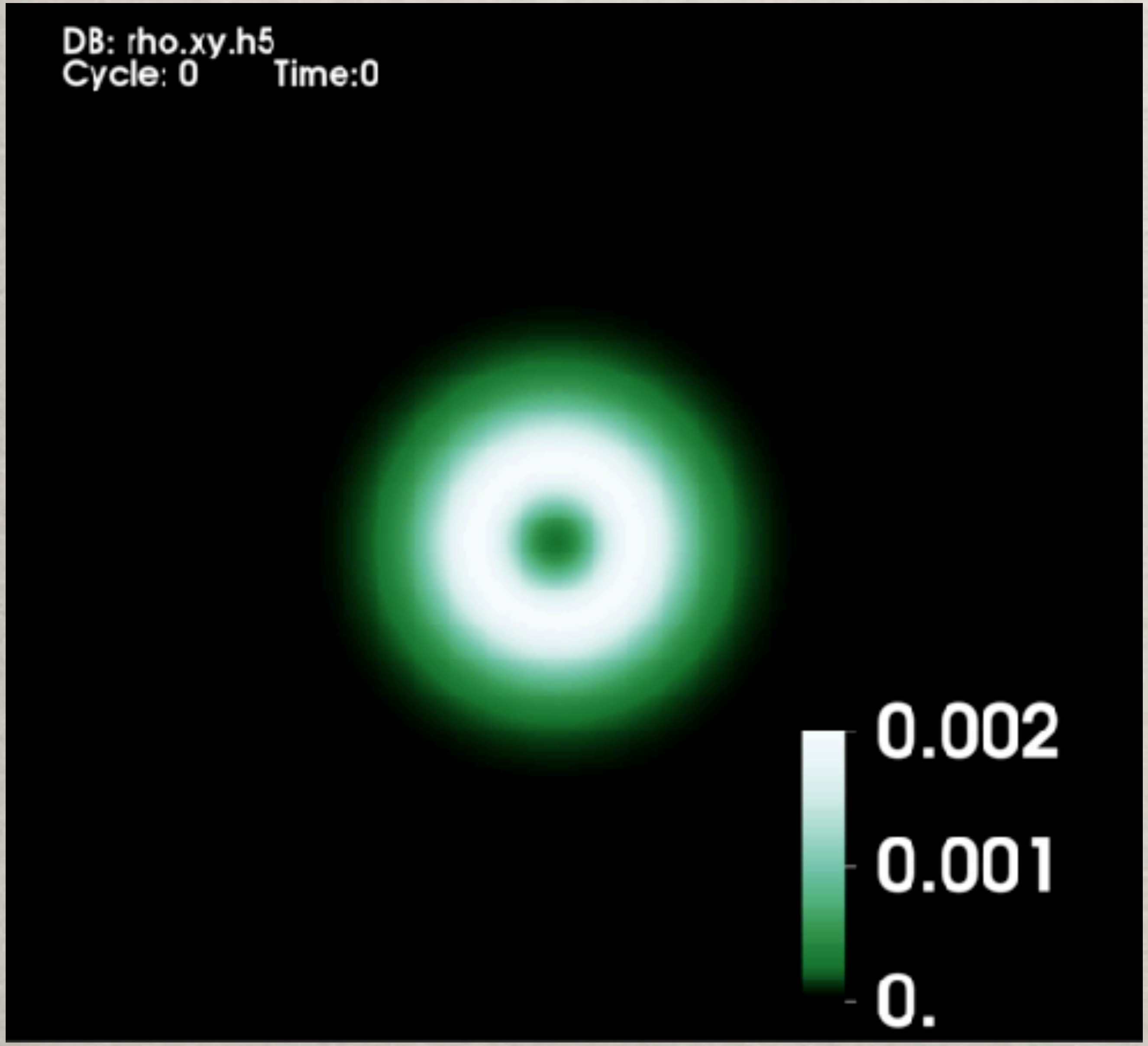
Brito, Cardoso, CH and Radu, PLB 752 (2016) 291
CH, Radu and Rúnarsson, CQG 33 (2016) 154001
CH, Perapechka, Radu and Shnir, PLB 797 (2019) 134845

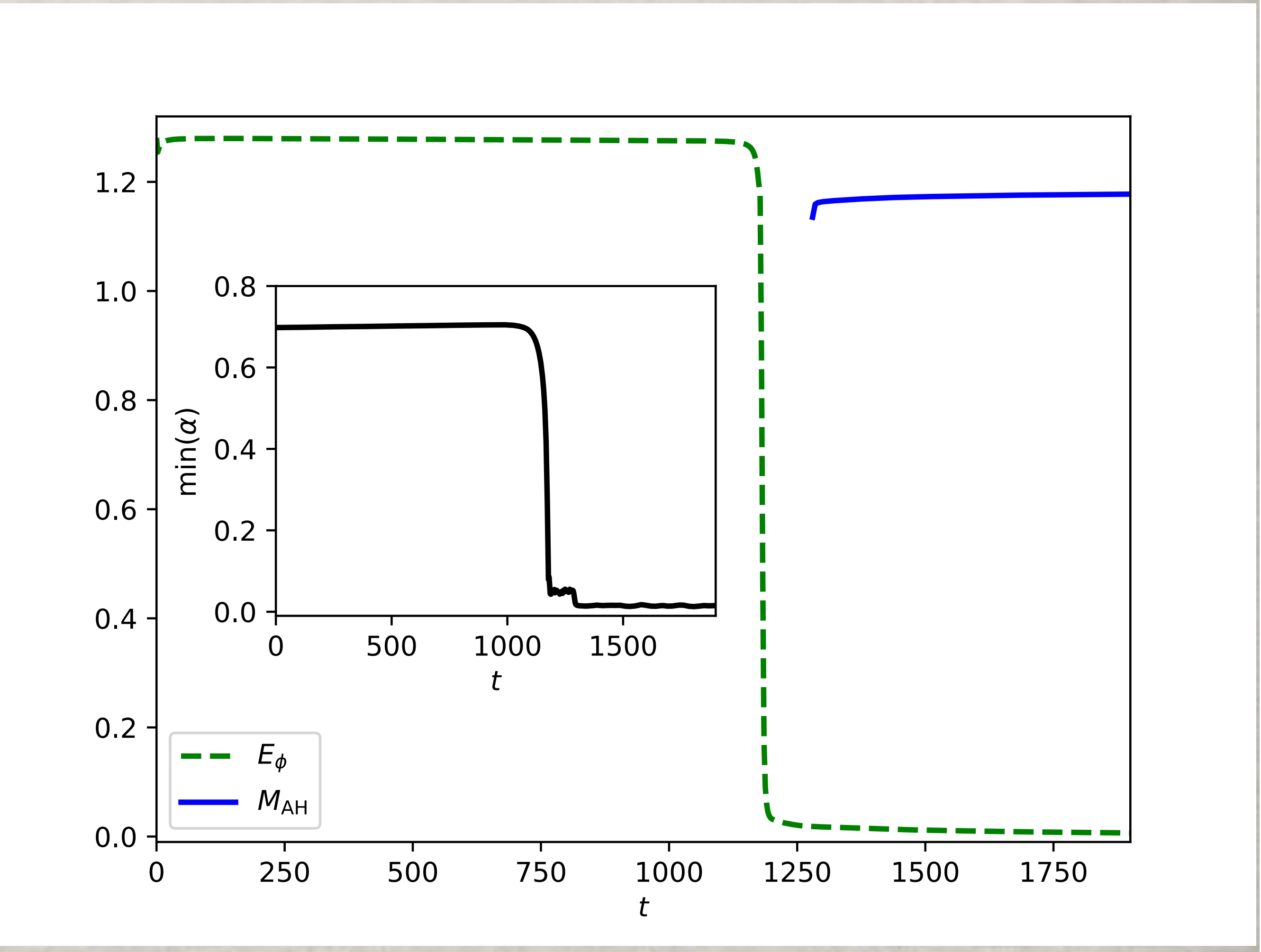
Secondly, in their stability:

Spinning scalar boson stars have a non-axisymmetric instability

Sanchis-Gual, Di Giovanni, Zilhão, CH, Cerda-Duran, Font and Radu, PRL 123 (2019) 221101

http://gravitation.web.ua.pt/node/1740



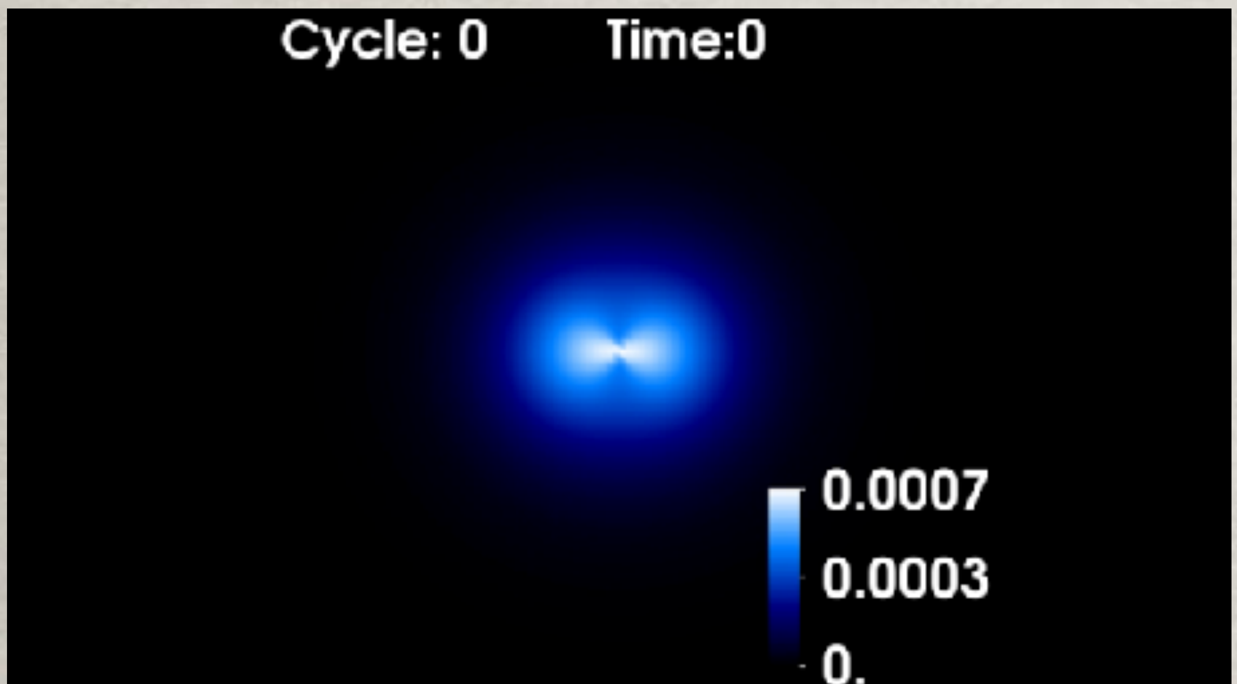


Spinning Proca stars do not exhibit such instability.

Sanchis-Gual, Di Giovanni, Zilhão, CH, Cerda-Duran, Font and Radu, PRL 123 (2019) 221101

http://gravitation.web.ua.pt/node/1740

Evolution of a perturbed spinning Proca star



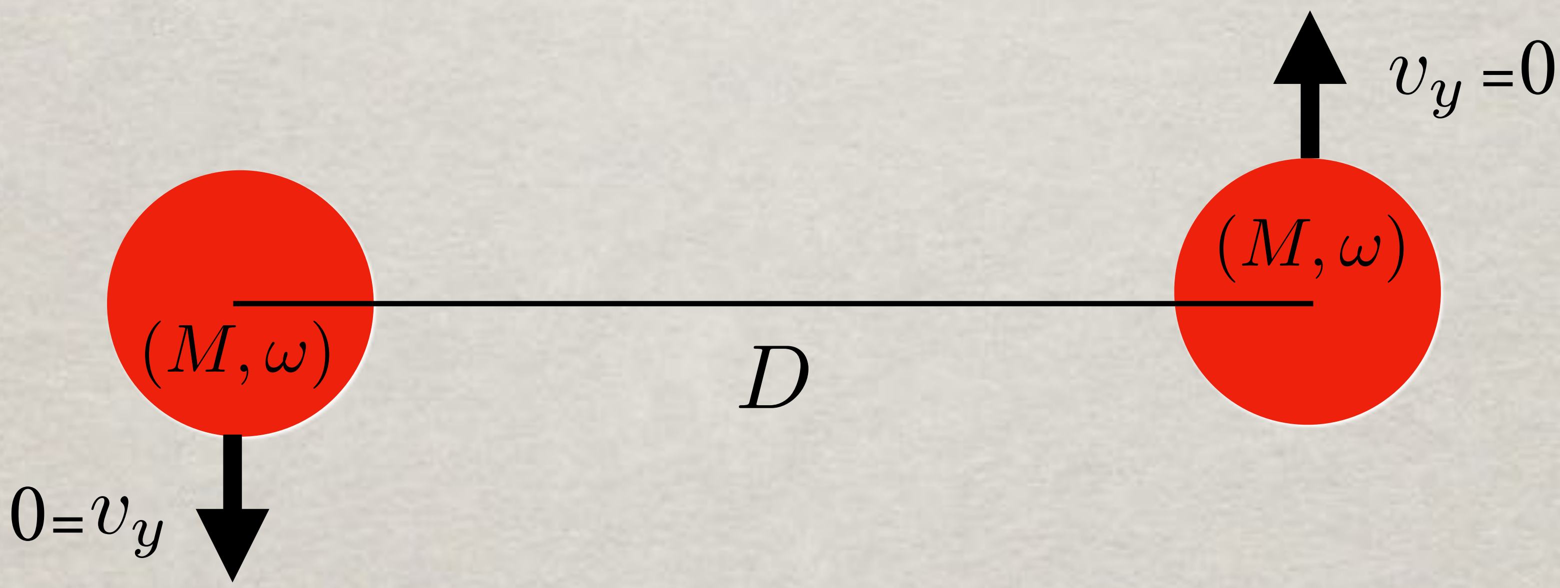
Evolution of an excited spinning Proca star

Thus, spinning Proca stars are dynamically more robust in these simplest models.

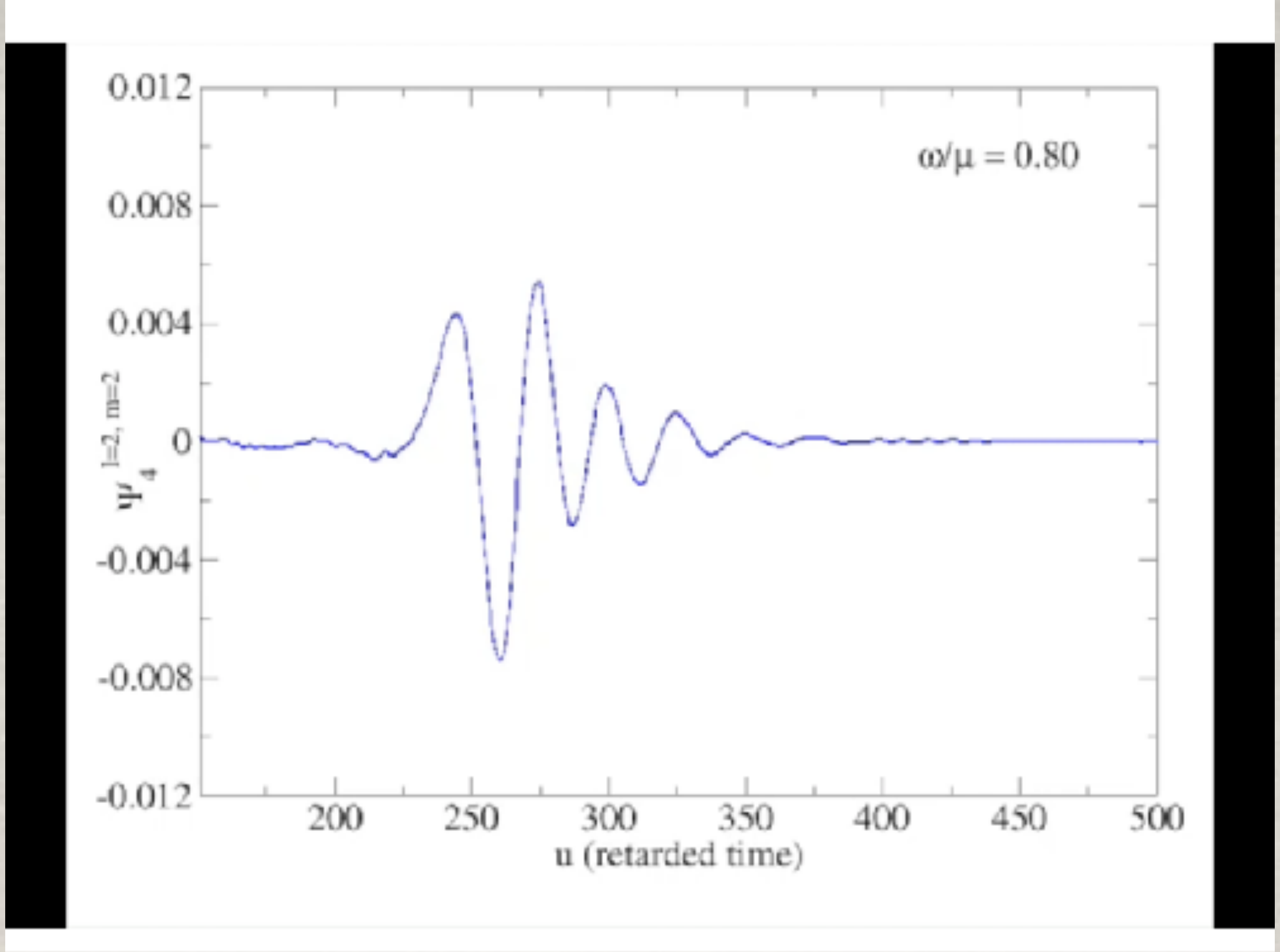
But in models with self-interactions, the spinning scalar stars instability can be mitigated.

Di Giovanni, Sanchis-Gual, Cerdan-Duran, Zilhão, CH, Font and Radu, PRD 102 (2020) 124009;
Siemonson and East, PRD 103 (2021) 044022

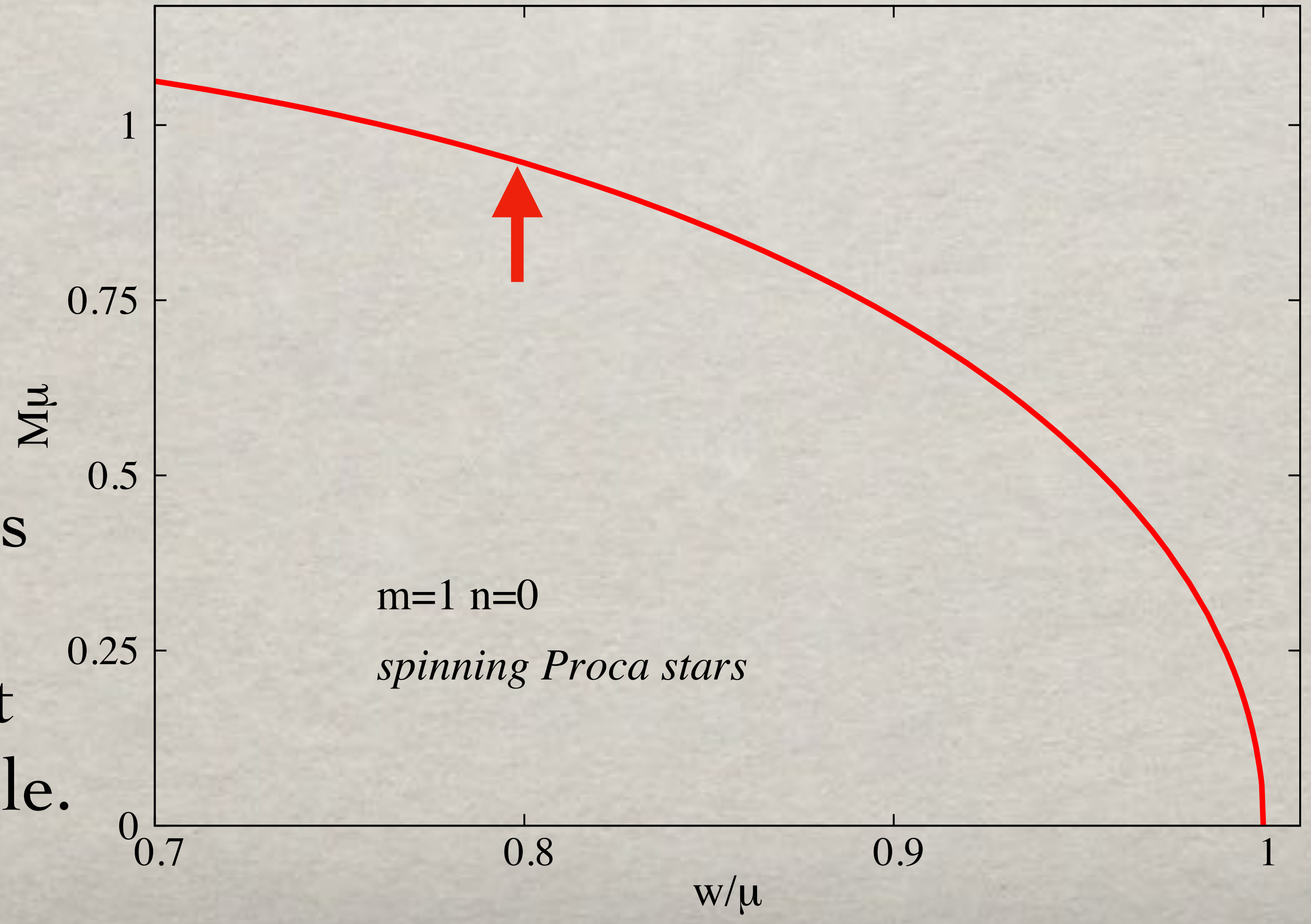
Mergers of spinning vector boson stars



Mergers of spinning vector boson stars

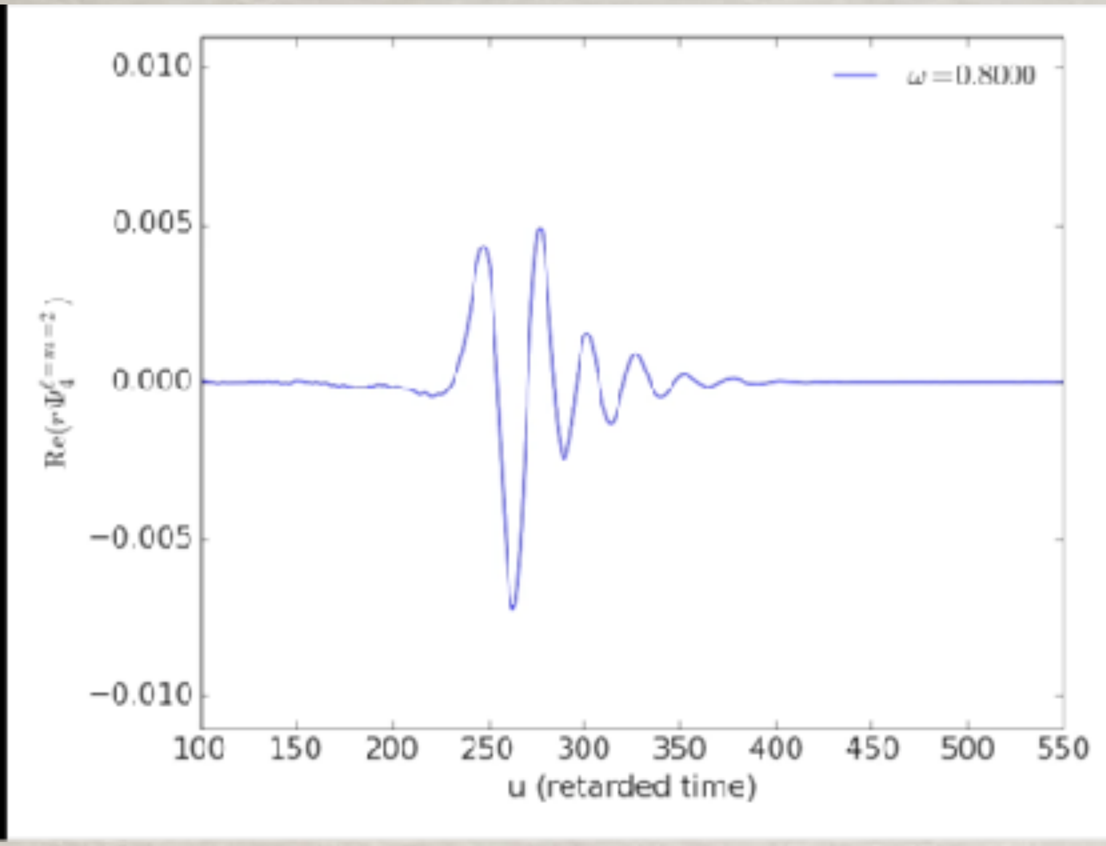


For frequencies too high the final object is not a black hole.

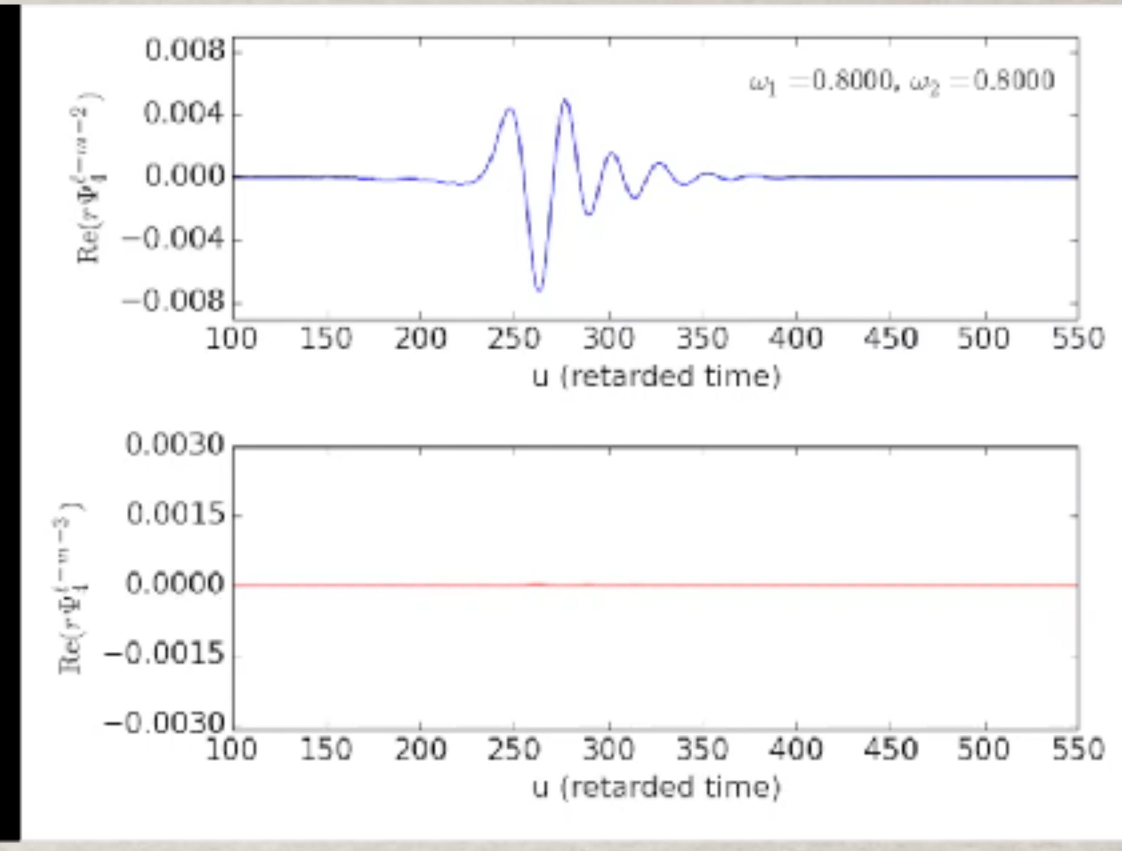


These examples are for equal masses, but we have also performed unequal mass collisions.

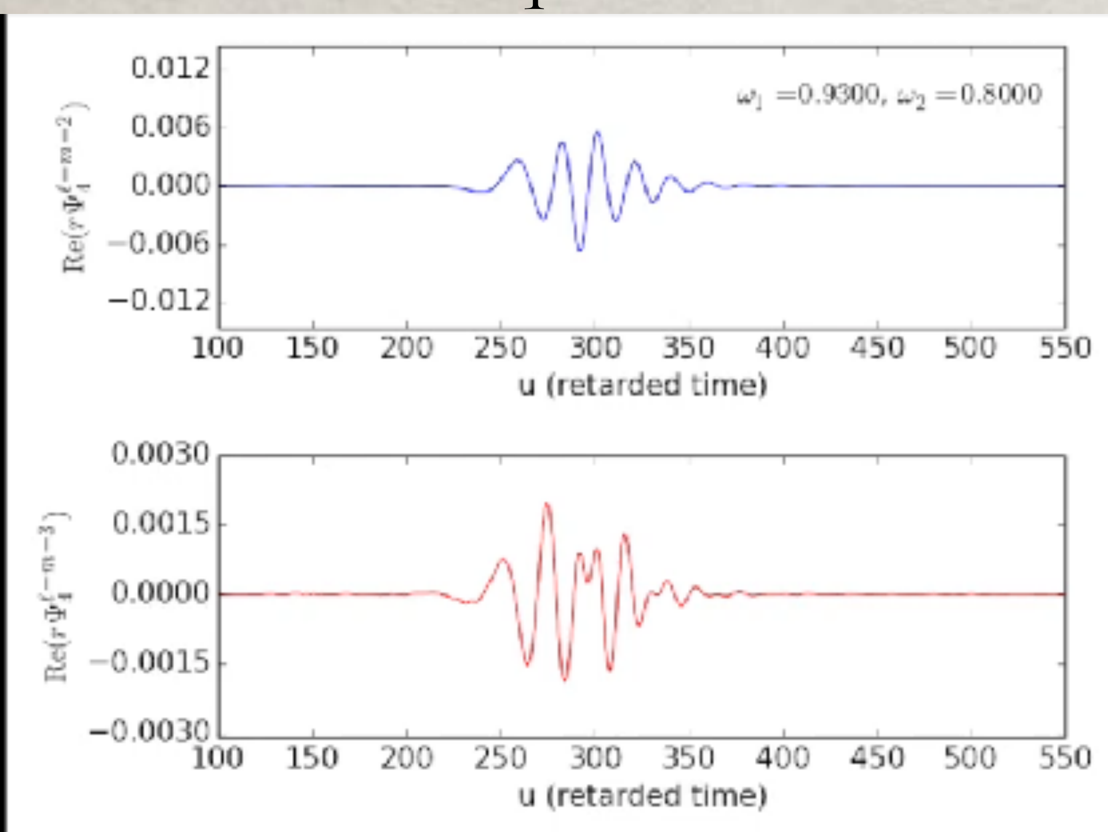
equal mass



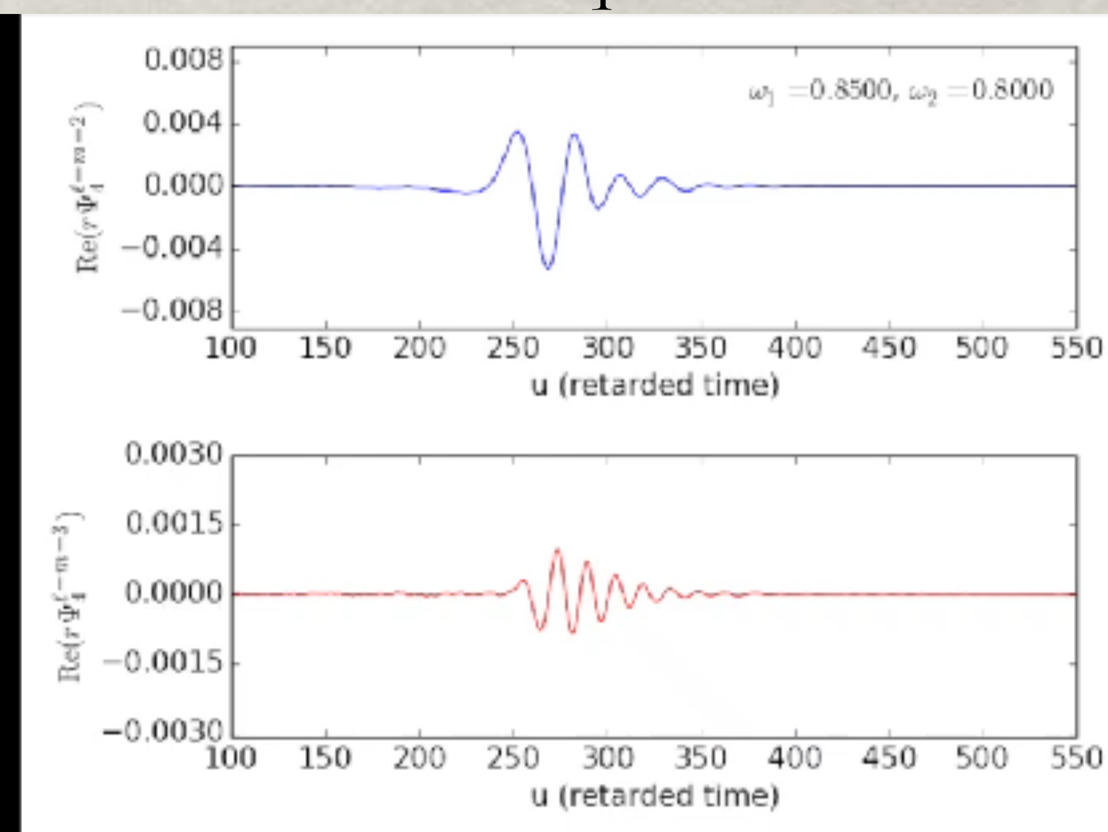
unequal mass



unequal mass



unequal mass

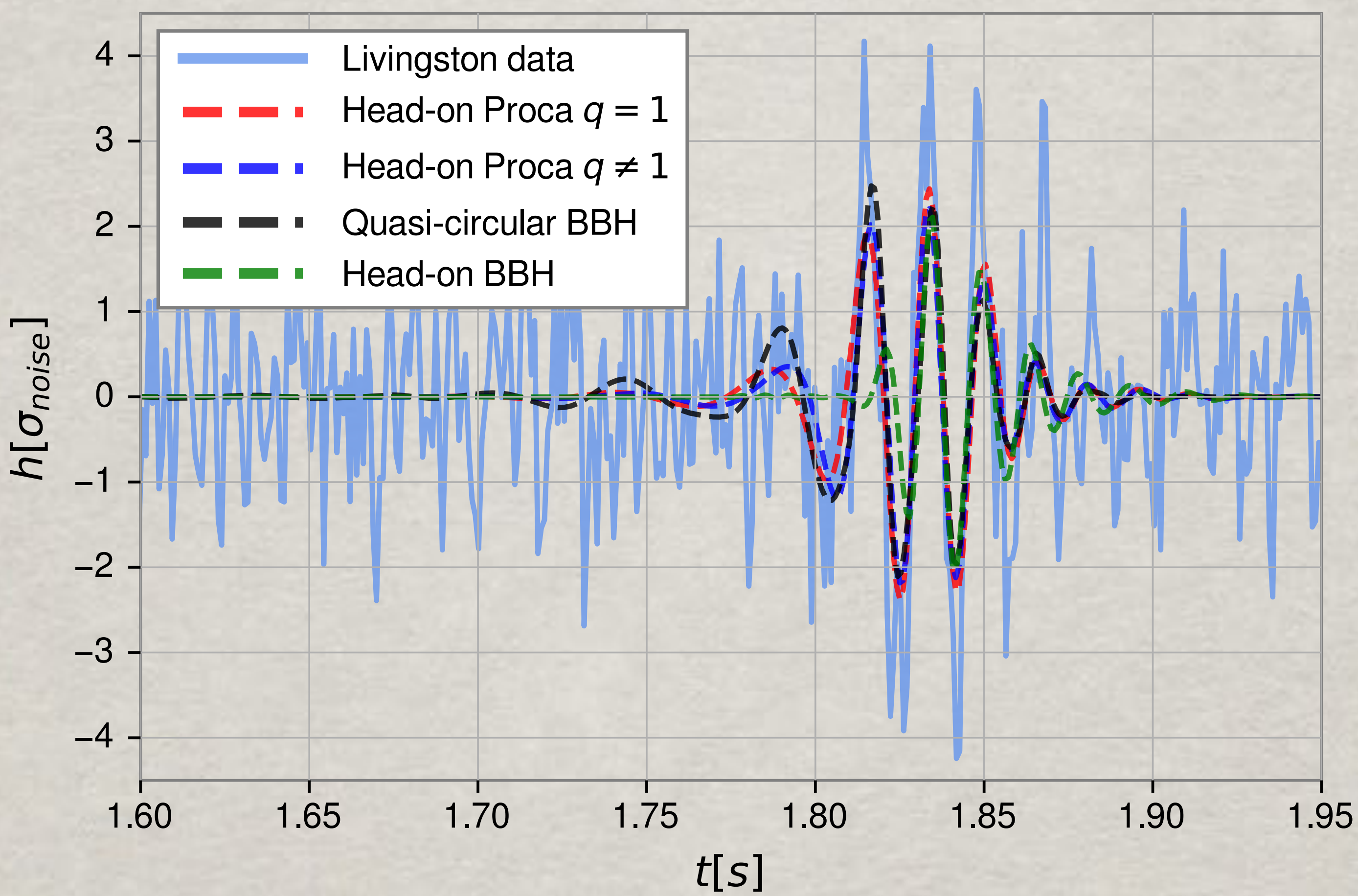


Building a catalogue of Proca star waveforms

(over 750 waveforms from NR simulations so far) Sanchis-Gual et al. to appear (2022)

Statistical Preference:

Bustillo et. al, PRL 126 (2021) 081181

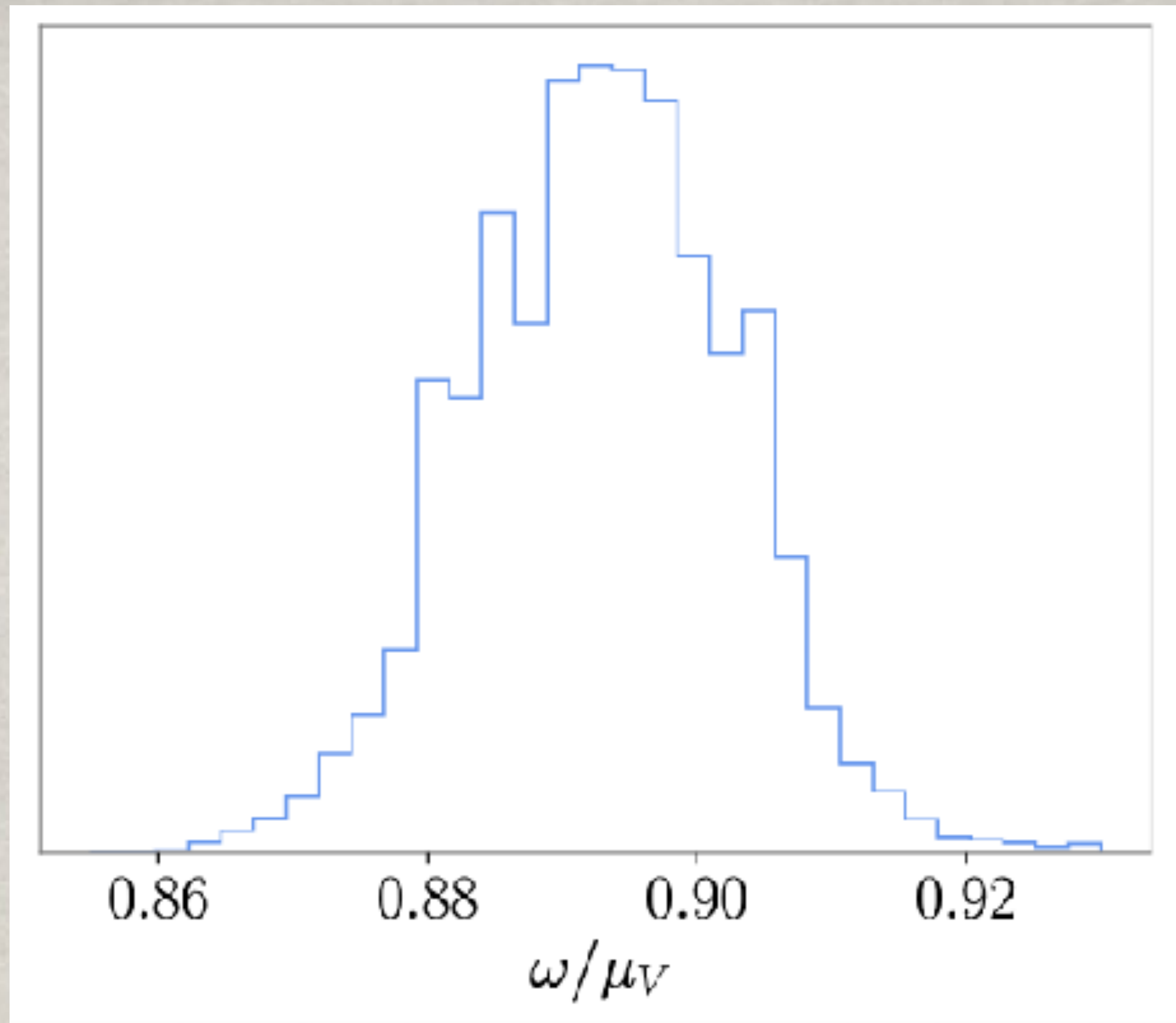


Waveform model	$\log \mathcal{B}$	$\log \mathcal{L}_{\max}$
Quasi-circular Binary Black Hole	80.1	105.2
Head-on Equal-mass Proca Stars	80.9	106.7
Head-on Unequal-mass Proca Stars	82.0	106.5
Head-on Binary Black Hole	75.9	103.2

Prior:
Uniform in co-moving volume

Waveform Model	$\log \mathcal{B}$	$\log \mathcal{L}_{Max}$
Quasi-circular Binary Black Hole	80.1	105.2
Head-on Equal-mass Proca Stars	83.5	106.7
Head-on Unequal-mass Proca Stars	84.3	106.5
Head-on Binary Black Hole	78.0	103.2

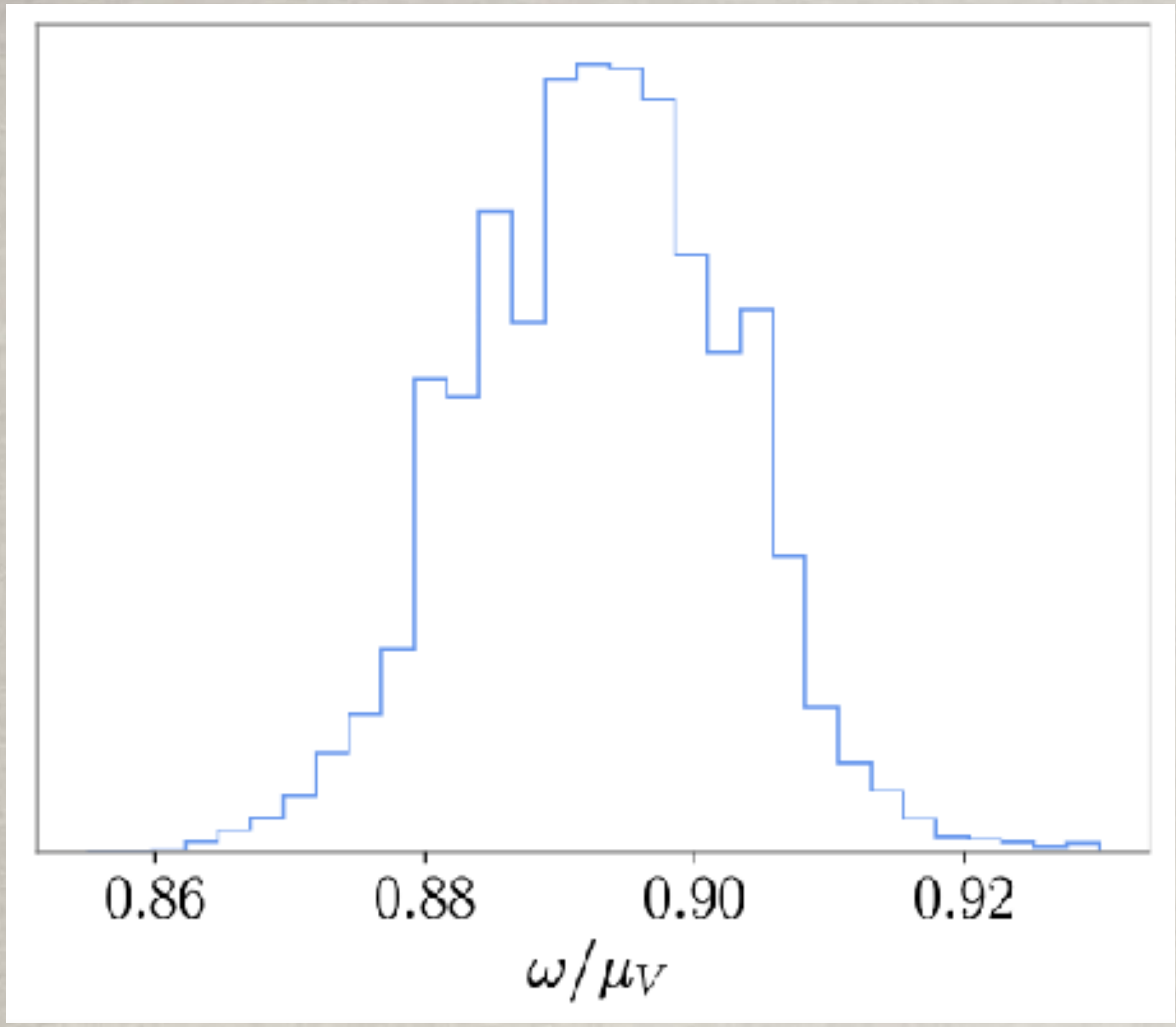
Prior:
Uniform in distance

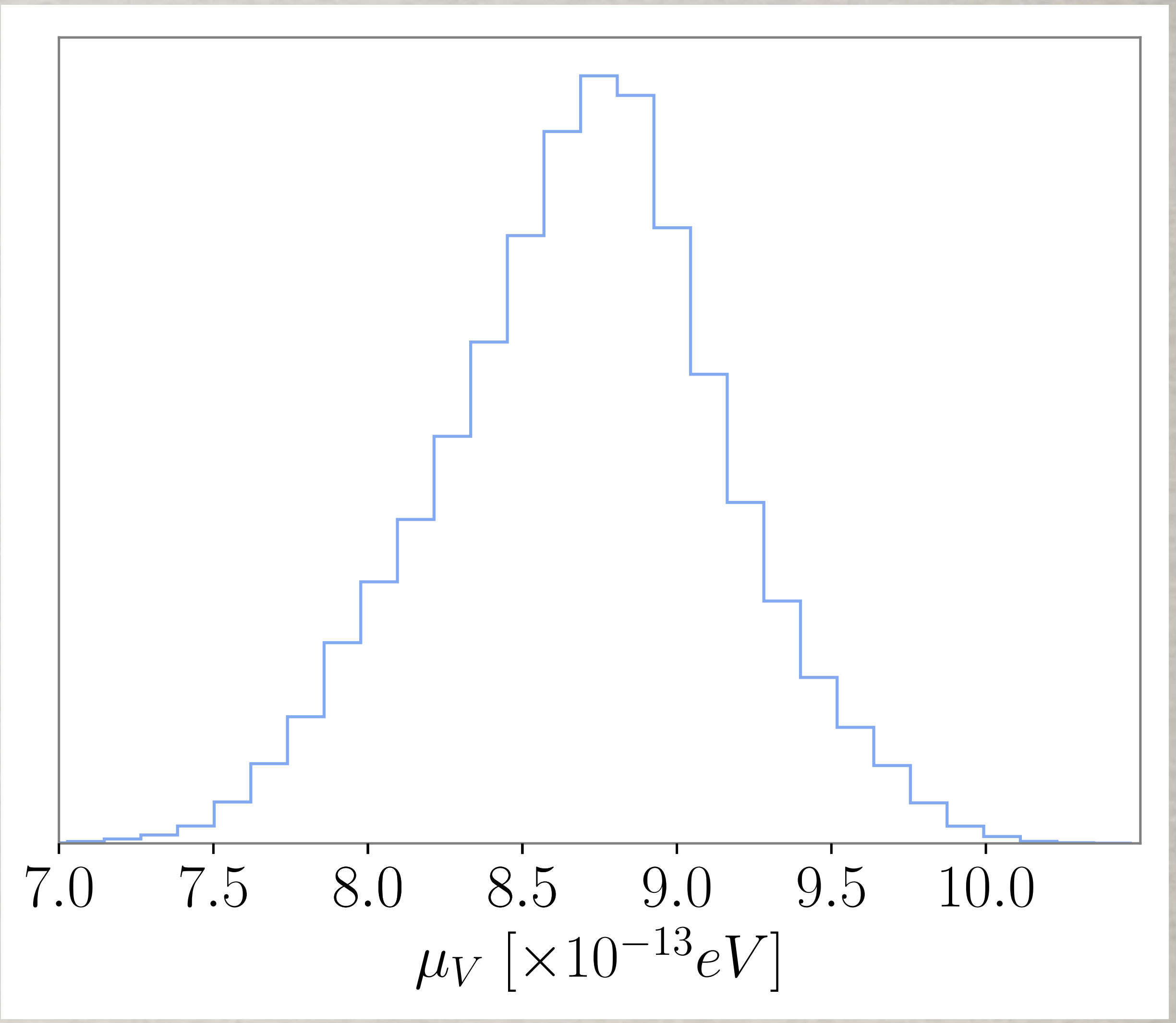


$$\omega/\mu_V = 0.893^{+0.015}_{-0.015}$$

Determines $M\mu_V$

Identifying the mass of each Proca star as half of the mass of the final black hole determines the mass of the ultralight boson.

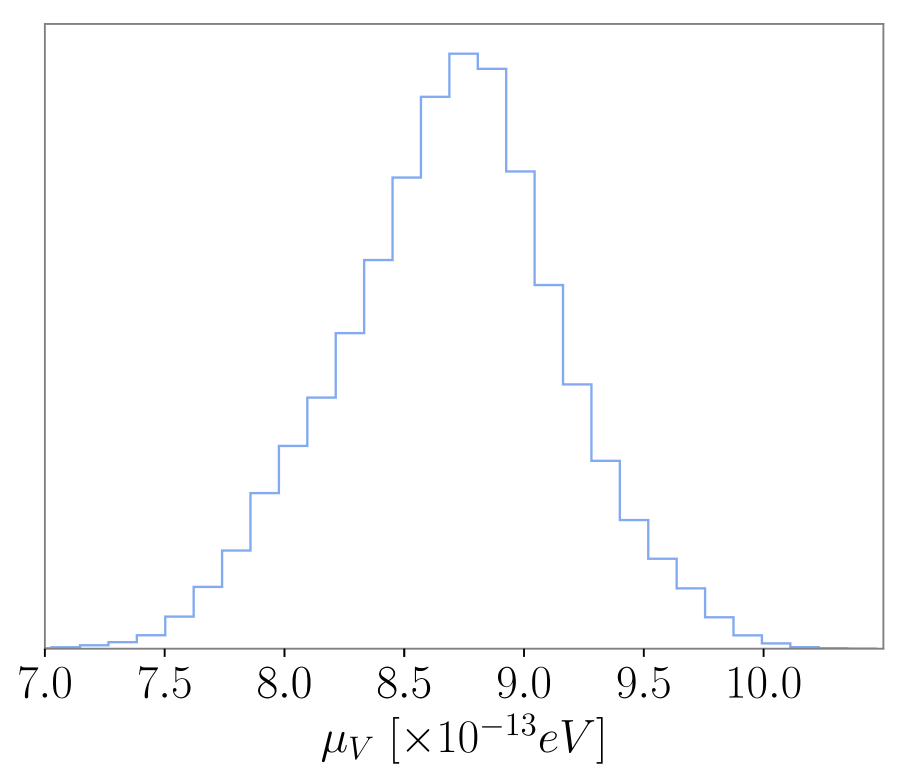




Thus we get a distribution for the mass of the ultralight boson.

Gravitating scalar/vector solitons: bosonic stars

Parameter	$q = 1$ model	$q \neq 1$ model
Primary mass	$115^{+7}_{-8}\ M_\odot$	$115^{+7}_{-8}\ M_\odot$
Secondary mass	$115^{+7}_{-8}\ M_\odot$	$111^{+7}_{-15}\ M_\odot$
Total / Final mass	$231^{+13}_{-17}\ M_\odot$	$228^{+17}_{-15}\ M_\odot$
Final spin	$0.75^{+0.08}_{-0.04}$	$0.75^{+0.08}_{-0.04}$
Inclination $\pi/2 - \lvert\iota - \pi/2\rvert$	$0.83^{+0.23}_{-0.47}$ rad	$0.58^{+0.40}_{-0.39}$ rad
Azimuth	$0.65^{+0.86}_{-0.54}$ rad	$0.78^{+1.23}_{-1.20}$ rad
Luminosity distance	571^{+348}_{-181} Mpc	700^{+292}_{-279} Mpc
Redshift	$0.12^{+0.05}_{-0.04}$	$0.14^{+0.06}_{-0.05}$
Total / Final redshifted mass	$258^{+9}_{-9}\ M_\odot$	$261^{+10}_{-11}\ M_\odot$
Bosonic field frequency ω/μ_V	$0.893^{+0.015}_{-0.015}$	$(*)0.905^{+0.012}_{-0.042}$
$\boxed{\text{Boson mass } \mu_V\ [\times 10^{-13}]}$	$\boxed{8.72^{+0.73}_{-0.82}\ \text{eV}}$	$\boxed{8.59^{+0.58}_{-0.57}\ \text{eV}}$
Maximal boson star mass	$173^{+19}_{-14}\ M_\odot$	$175^{+13}_{-11}\ M_\odot$



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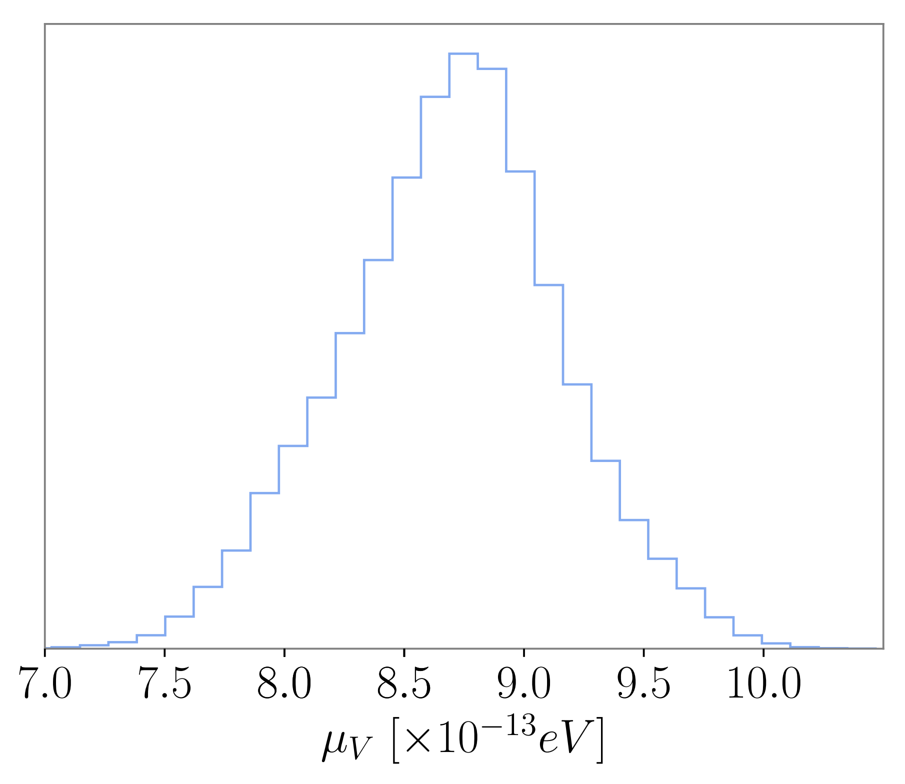
$\boxed{\text{Boson mass } \mu_V\ [\times 10^{-13}]}$	$8.72^{+0.73}_{-0.82}$ eV	$8.59^{+0.58}_{-0.57}$ eV
Maximal boson star mass	$173^{+19}_{-14}\ M_\odot$	$175^{+13}_{-11}\ M_\odot$

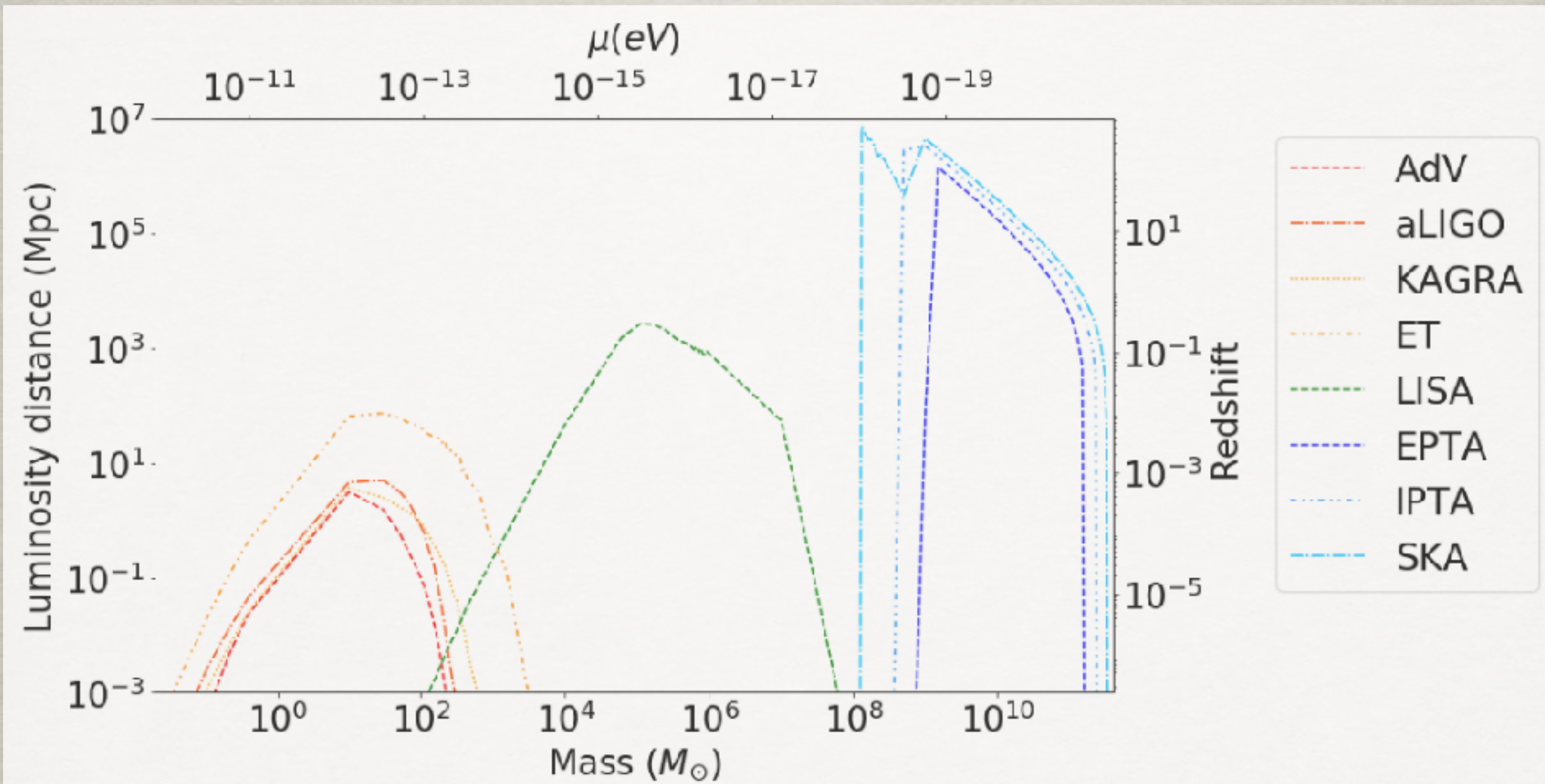


$$M_{\rm max} = 173^{+19}_{-14} M_\odot$$

No previous GW signals can be Proca star mergers.

Scalar spinning bosonic stars can *still* approximately form.
They are, however, transient due to the non-axisymmetric instability.
But the decay of these transient states generates GW emission.

Di Giovanni, Sanchis-Gual, Cerdan-Duran, Zilhão, CH, Font and Radu, PRD 102 (2020) 124009



2) Non-Kerr black holes

a) Strict non-Kerrness vs. hybrid models (and dynamical emergence);

Einstein-dilaton-Gauss-Bonnet models

(an illustration of strict-non Kerrness)

An influential example: Einstein-dilaton-Gauss-Bonnet
(arises in String Theory, second order equations of motion, etc...)

$$S = \frac{1}{16\pi}\int d^4x\sqrt{-g}\left[R - \frac{1}{2}(\partial_\mu\phi)^2 + \alpha e^{-\gamma\phi}R^2_{\rm GB}\right],$$

$$R^2_{\rm GB} = R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma} - 4R_{\mu\nu}R^{\mu\nu} + R^2$$

Schwarzschild/Kerr not solutions - new black holes which are stable in some regime

P. Kanti, N. E. Mavromatos, J. Rizos, K. Tamvakis and E. Winstanley, PRD 54 (1996) 5049; PRD 57 (1998) 6255;
P. Kanti, B. Kleihaus and J. Kunz, PRL 107 (2011) 271101

New qualitative features (minimal black hole size);

Einstein-scalar-Gauss-Bonnet models

(an illustration of a hybrid model)

There are various interesting cousin models changing the scalar-curvature coupling:

$$S = \frac{1}{16\pi}\int d^4x\sqrt{-g}\left[R - \frac{1}{2}(\partial_\mu\phi)^2 + \alpha \overset{f(\phi)}{\cancel{e^{-\gamma\phi}}} R^2_{\rm GB}\right],$$

$$R^2_{\rm GB} = R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma} - 4R_{\mu\nu}R^{\mu\nu} + R^2$$

Models admitting vacuum GR **and** scalarized black holes:

Antoniou, Bakopoulos, Kanti, PRL 120 (2018) 131102
Doneva and Yazadjiev, PRL 120 (2018) 131103
Silva, Sakstein, Gualtieri, Sotiriou, Berti, PRL 120 (2018) 131104;

$$\frac{df}{d\phi}(\phi = 0) = 0$$

Allows the *spontaneous scalarization* of vacuum GR black holes

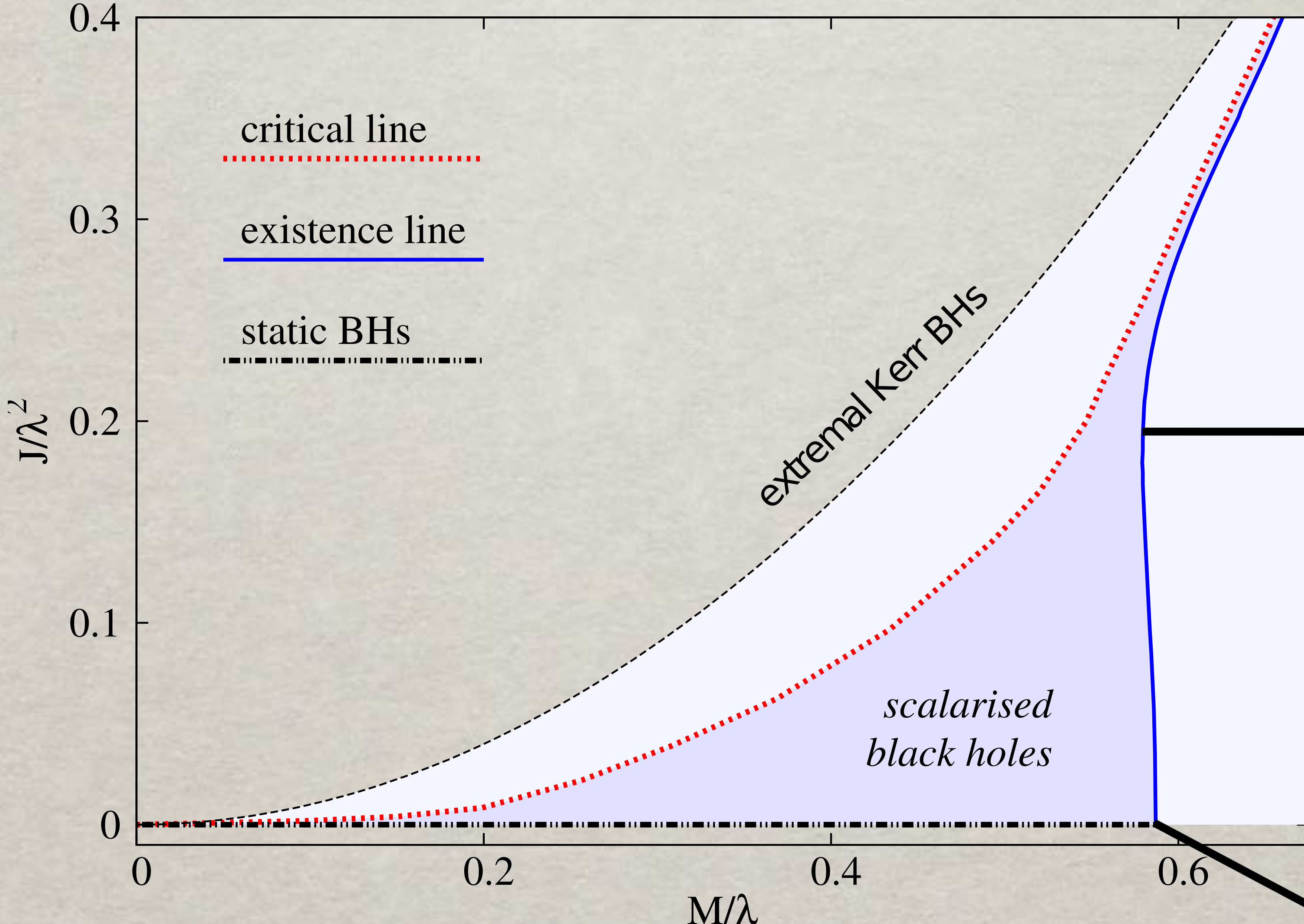
[Similar in spirit to neutron star scalarization in scalar tensor theories
Damour and Esposito-Farese, PRL 70 (1993) 2220-2223]

$$S = \frac{1}{16\pi}\int d^4x\sqrt{-g}\left[R - 2\partial_\mu\phi\partial^\mu\phi + \lambda^2 f(\phi)\left\{R^{\mu\nu\alpha\beta}R_{\mu\nu\alpha\beta} - 4R_{\mu\nu}R^{\mu\nu} + R^2\right\}\right],$$

New scale

$$f(\phi) = \frac{1}{2\beta}(1 - e^{-\beta\phi^2})$$

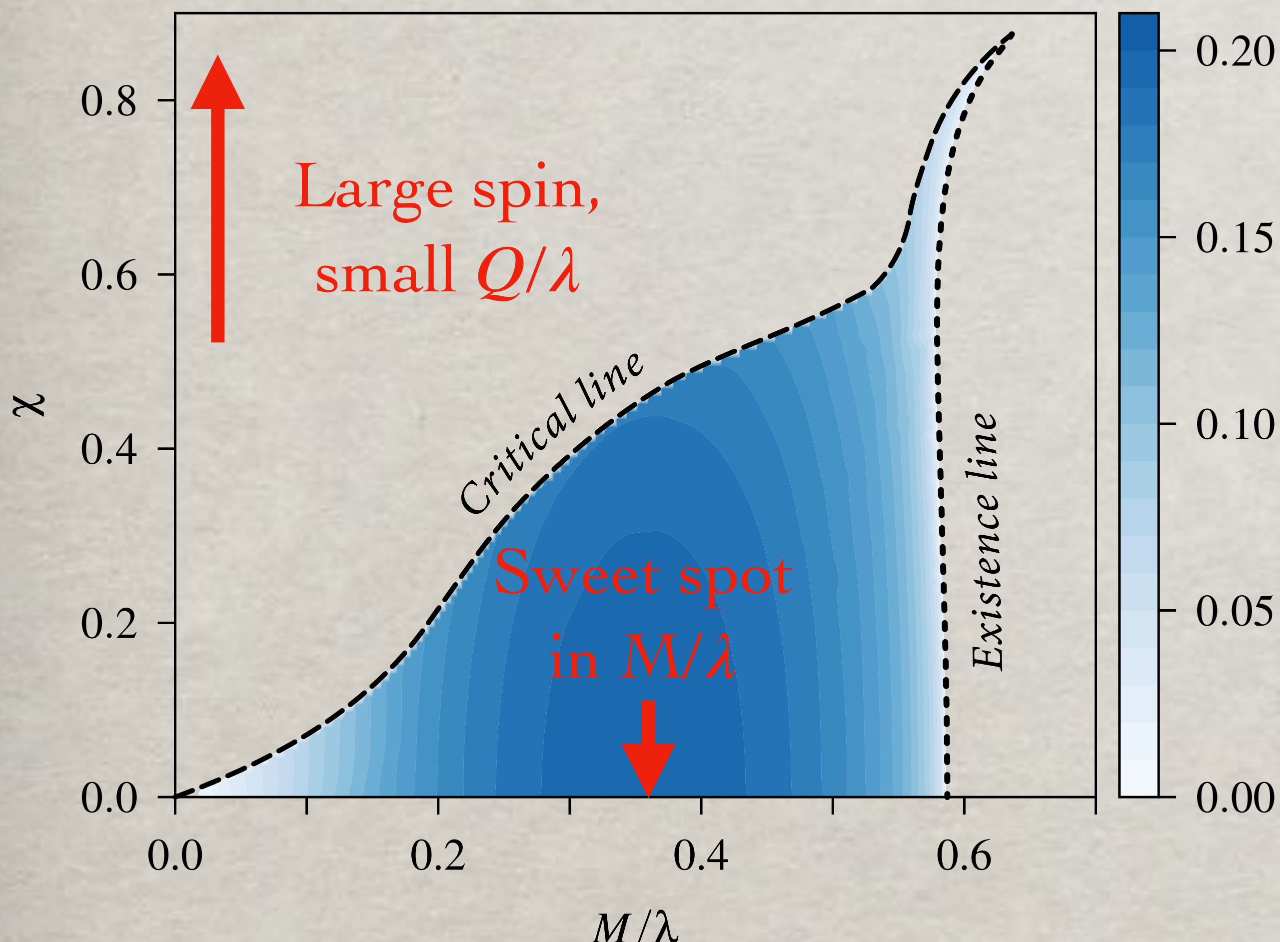
Cunha, CH, Radu, PRL 123 (2019) 011101



spin quenches GR deviations!

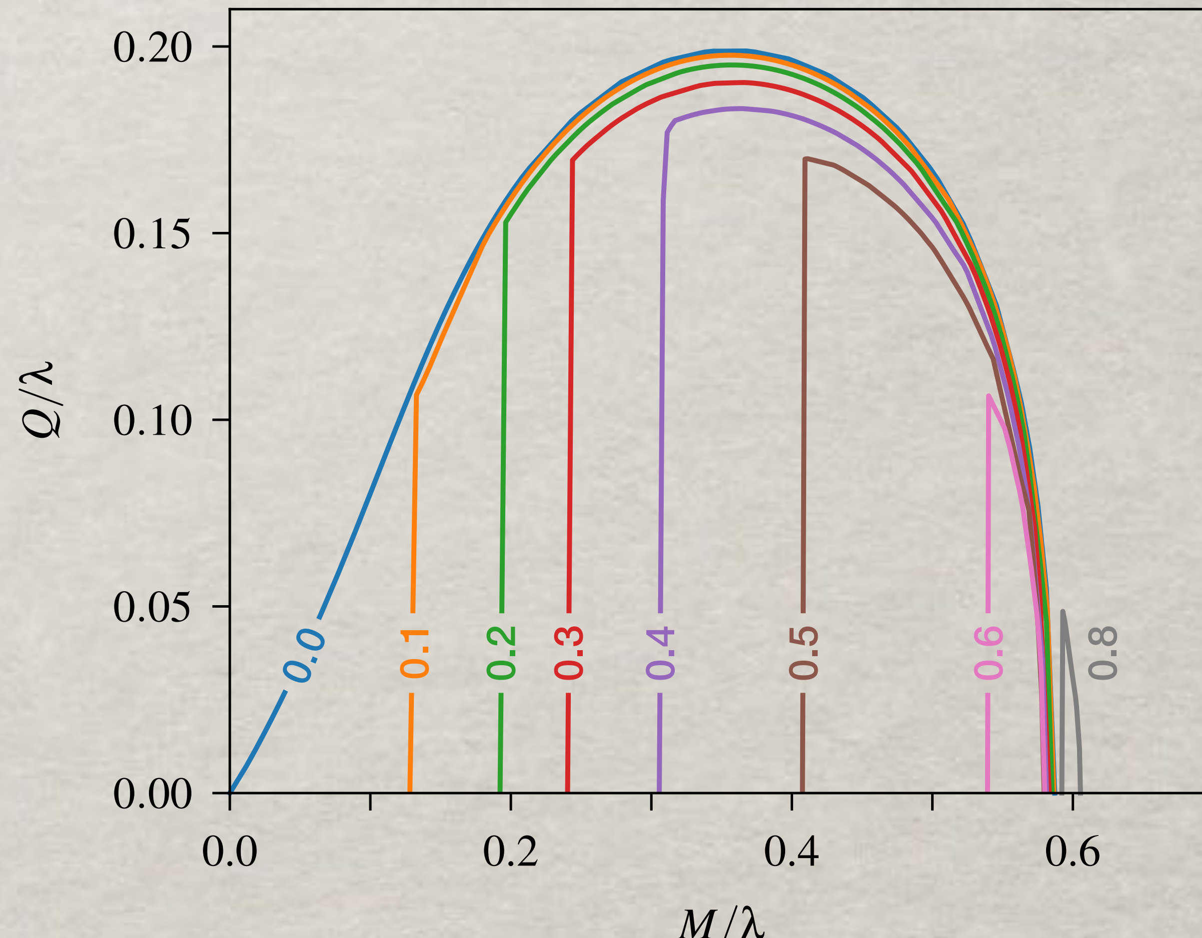
Black holes only exist below a certain M/λ

One measure of the scalarization strength is the scalar "charge" Q/λ, of the solution. This charge is suppressed increasing the dimensionless spin χ and for M/λ away from a "sweet spot". Khim Wong, CH, Radu, 2204.09083



Away from sweet spot in M/λ, small Q/λ

Magnitude of Q/λ as a function of M/λ and χ as a heat map.



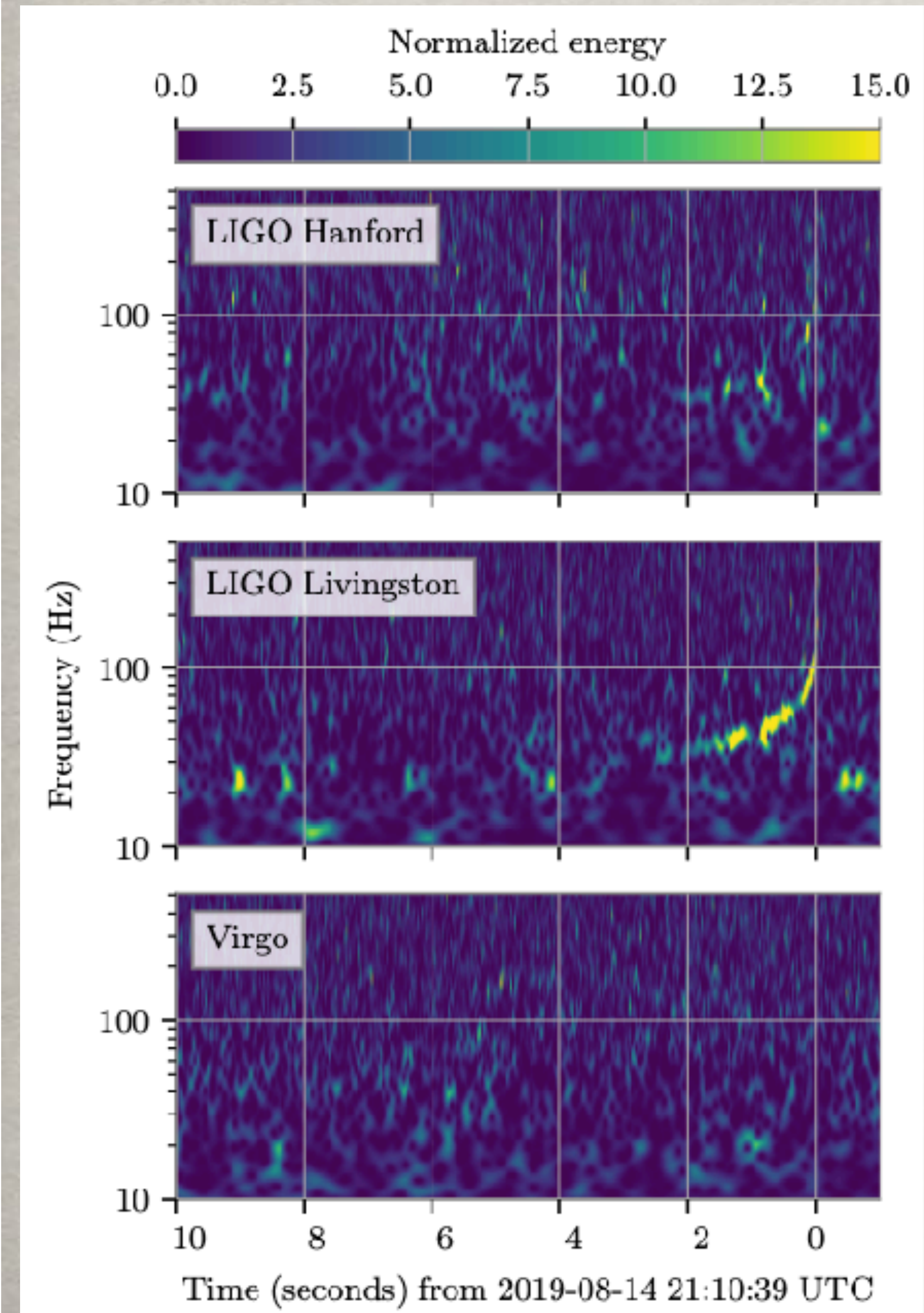
Same data: level sets of χ in M/λ - Q/λ plot

If this model were realised in nature, black holes with small spin, with mass near the new length scale, would scalarize (and effectively *only* those).

2) Non-Kerr black holes emerging dynamical at some scales

b) A proof of concept for constraining new scales using GW190814

GW190814 ApJ Lett. 896 (2020) 2, L44



- Primary: a black hole with

$$m_1 = 23.2^{+1.1}_{-1.0}\ M_\odot\ , \quad \chi_1 \leq 0.07$$

- Secondary: a black hole or neutron star with

$$m_2 = 2.59^{+0.08}_{-0.09}\ M_\odot$$

- Most unequal mass ratio reported

$$q = 0.112^{+0.008}_{-0.009}$$

- 300 cycles observed above 20Hz, (very different from GW190521)

Constraining λ using GW190814: waveform models and likelihoods

Khim Wong, CH, Radu, 2204.09083

- No complete waveforms (difficult!)

- Waveform models for inspiral as small corrections to GR:

Yunes and Pretorius, PRD 80 (2009) 122003

$$\tilde{h}_{\ell m}(f;\theta) = \tilde{h}^{(\mathrm{GR})}_{\ell m}(f;\vartheta)\, e^{-i\delta\phi_{\ell m}(f;\theta)}$$

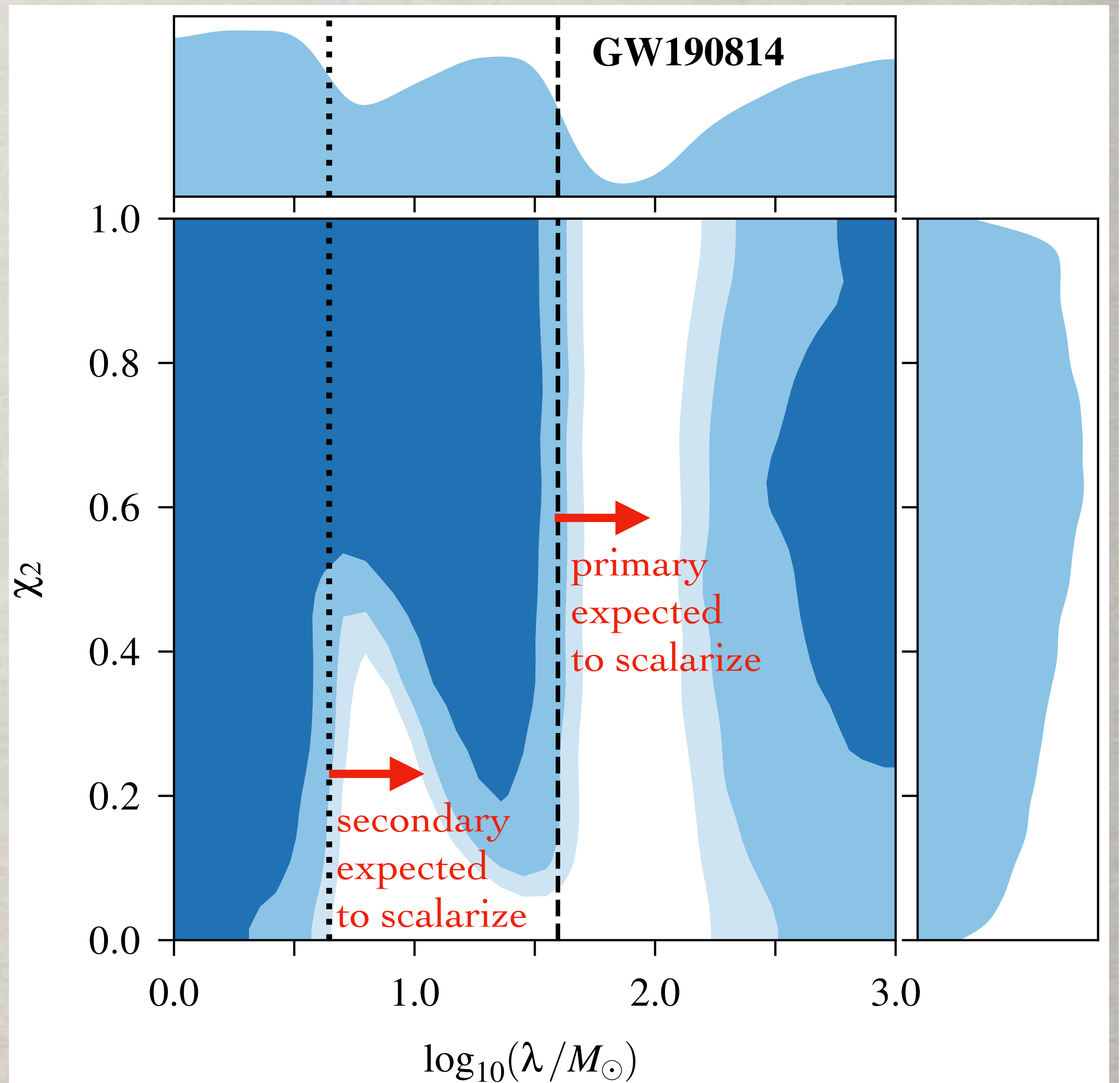
where:

Shao et al, PRX 7 (2017) 041025; …

$$\delta\phi_{\ell m}(f;\theta) = \frac{5m}{14\,336\,\eta}\left(\frac{Q_1}{M_1} - \frac{Q_2}{M_2}\right)^2 \left(\frac{2\pi M f}{m}\right)^{-7/3}$$

Constraining λ using GW190814: waveform models and likelihoods

Khim Wong, C. H., Radu, 2204.09083



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- The posterior distribution for $\log(\lambda)$ shows the expected features:

- $\lambda \in [56, 96]\ M_\odot$ strongly disfavoured with $B \leq 0.1$

- Complementary to other constraints in the same model from neutron star scalarizations Danchev, Doneva, Yazadjiev, 2112.03869

3) Burning questions

These examples illustrate reasonable theoretical possibilities, albeit with exotic physics, of alternative models to the Kerr paradigm that could manifest themselves only in **same range of scales.** They may have other caveats [*e.g.* less obvious pathologies of the models? Compatible with other constraints?]. The discussion also raises generic questions, *e.g.*:

- If the Kerr hypothesis is an approximation, is it violated for all scales similarly? Or are there sweet spots, like in the illustrations we have given?

- What are the ECO models/Non-Kerr black holes dynamically under control (concerning formation and sufficient stability)?

- For what classes of models can we hope to obtain extensive waveform catalogues of q~1 binaries (like the ongoing work for bosonic stars)? Is this a priority for LISA?

- Can dynamically robust ECOs be ultracompact? Can any ECO model mimic all phenomenology attributed to black holes? In all scales?

Final thought:

Producing detailed GW phenomenology will constrain these models and the corresponding exotic physics or, in the best case scenario, provide a smoking gun to the new physics, as the previous examples illustrate.