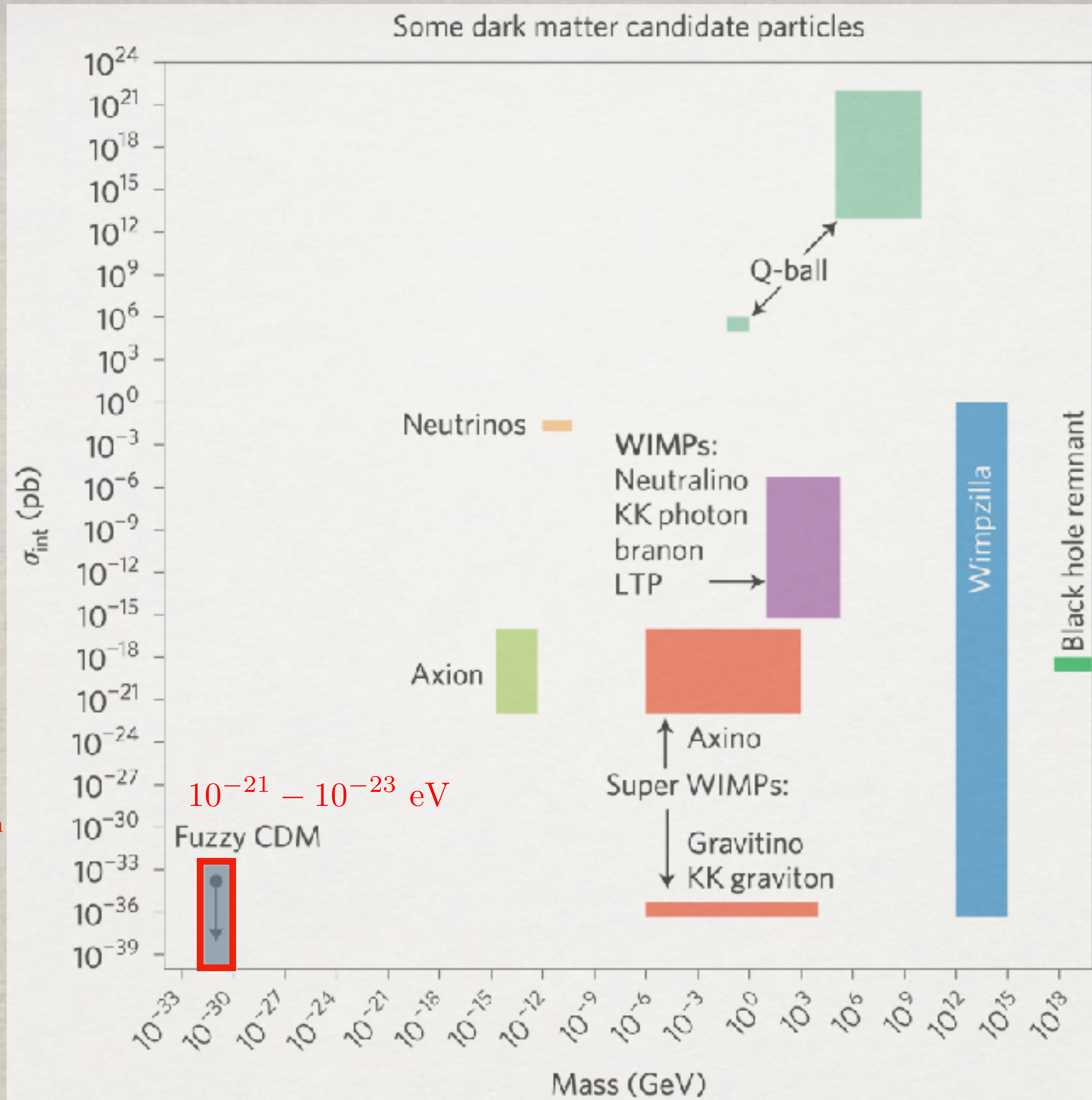
Black holes, bosonic stars and ultralight dark matter

Carlos Herdeiro
Gravitational Geometry and Dynamics Group, Aveiro University, Portugal

Lund, COST Advanced School,
Physics of Dark Matter and hidden sectors,
October 20th 2021

Suárez, Robles, Matos
ArXiv:1302.0903

Hui, Ostriker, Tremain and Witten
ArXiv:1610.08297



The Dark Matter Scientific Assessment Group (DMSAG), Report on the Direct Detection and Study of Dark Matter, 2007;
Conrad and Reimer, Nature Physics, 13 (2017) 224

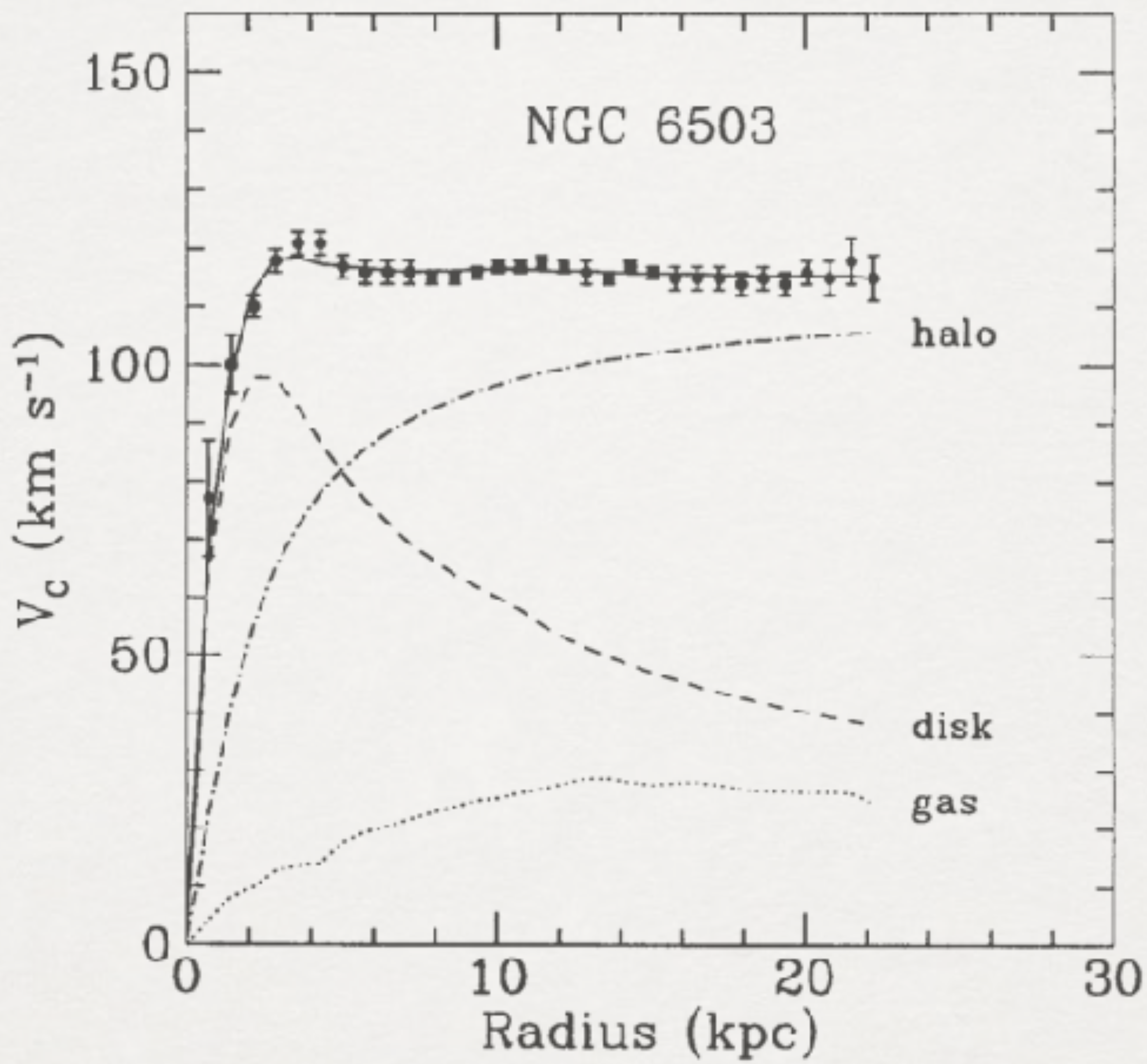
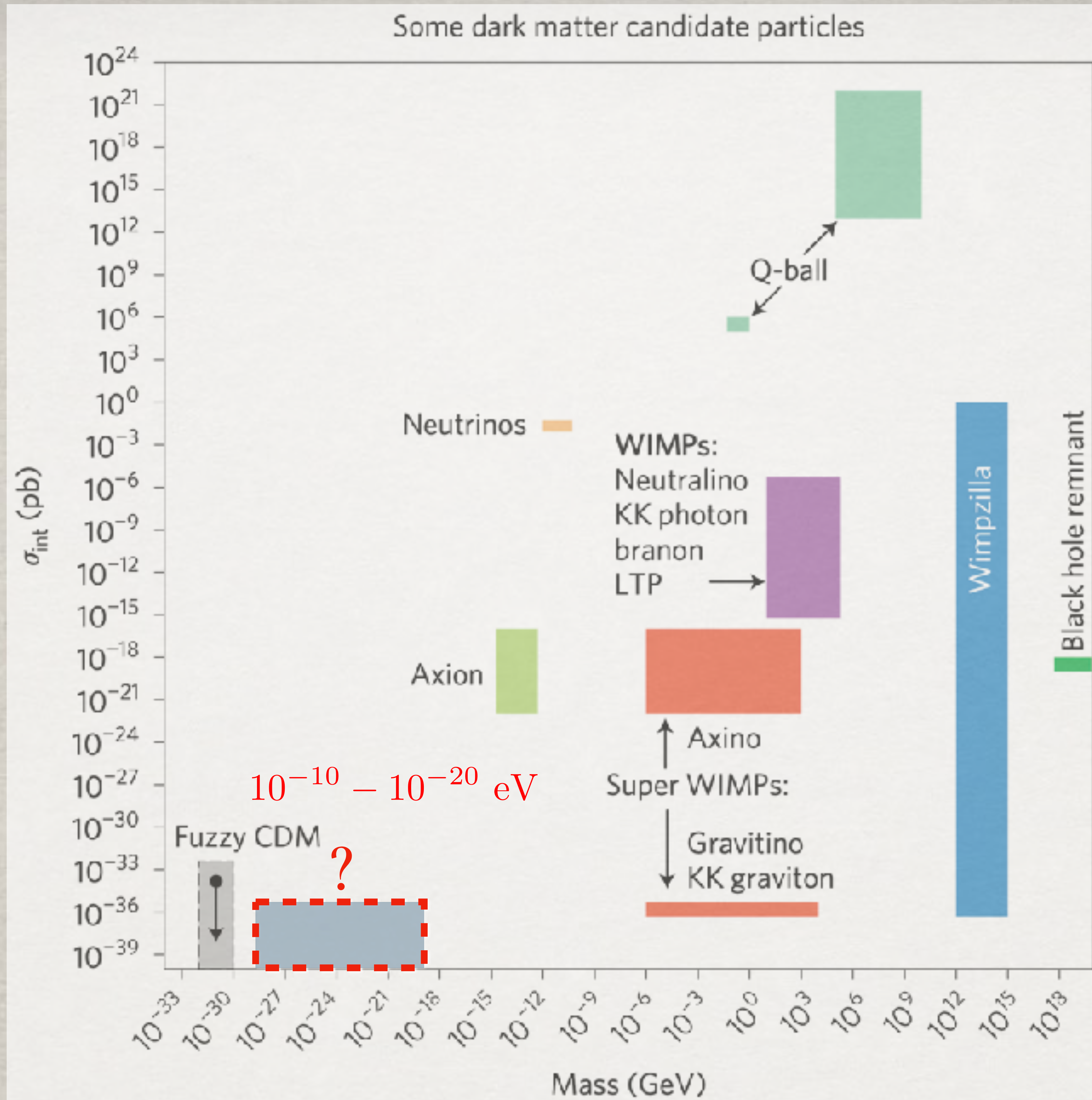


Figure 15: Galactic rotation curve[29] for NGC 6503 showing disk and gas contribution plus the dark matter halo contribution needed to match the data.

The Dark Matter Scientific Assessment Group (DMSAG), Report on the Direct Detection and Study of Dark Matter, 2007



String Axiverse

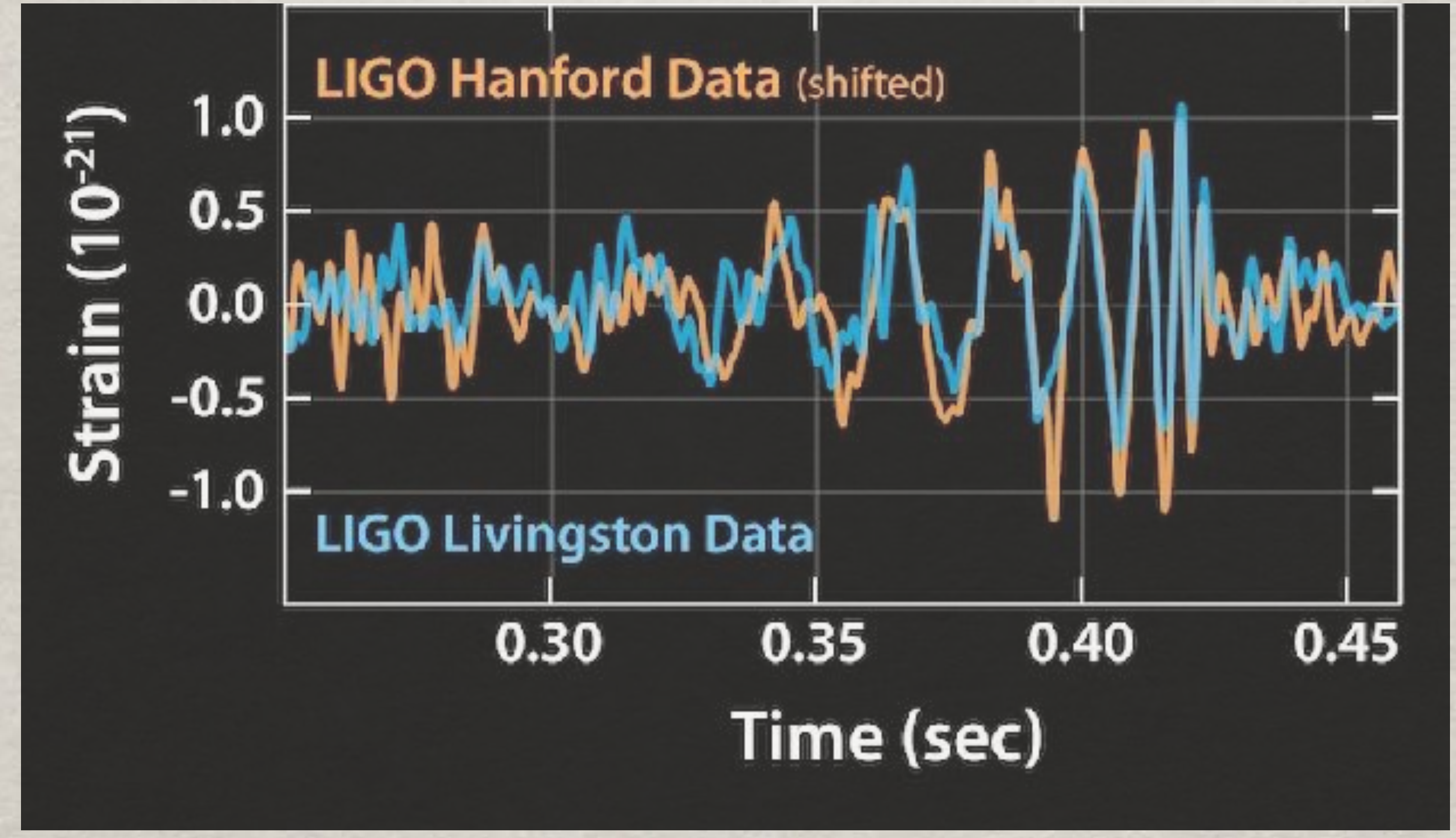
Arvanitaki et al.
ArXiv:0905.4720

The Dark Matter Scientific Assessment Group (DMSAG), Report on the Direct Detection and Study of Dark Matter, 2007;
Conrad and Reimer, Nature Physics, 13 (2017) 224

1 - Motivation

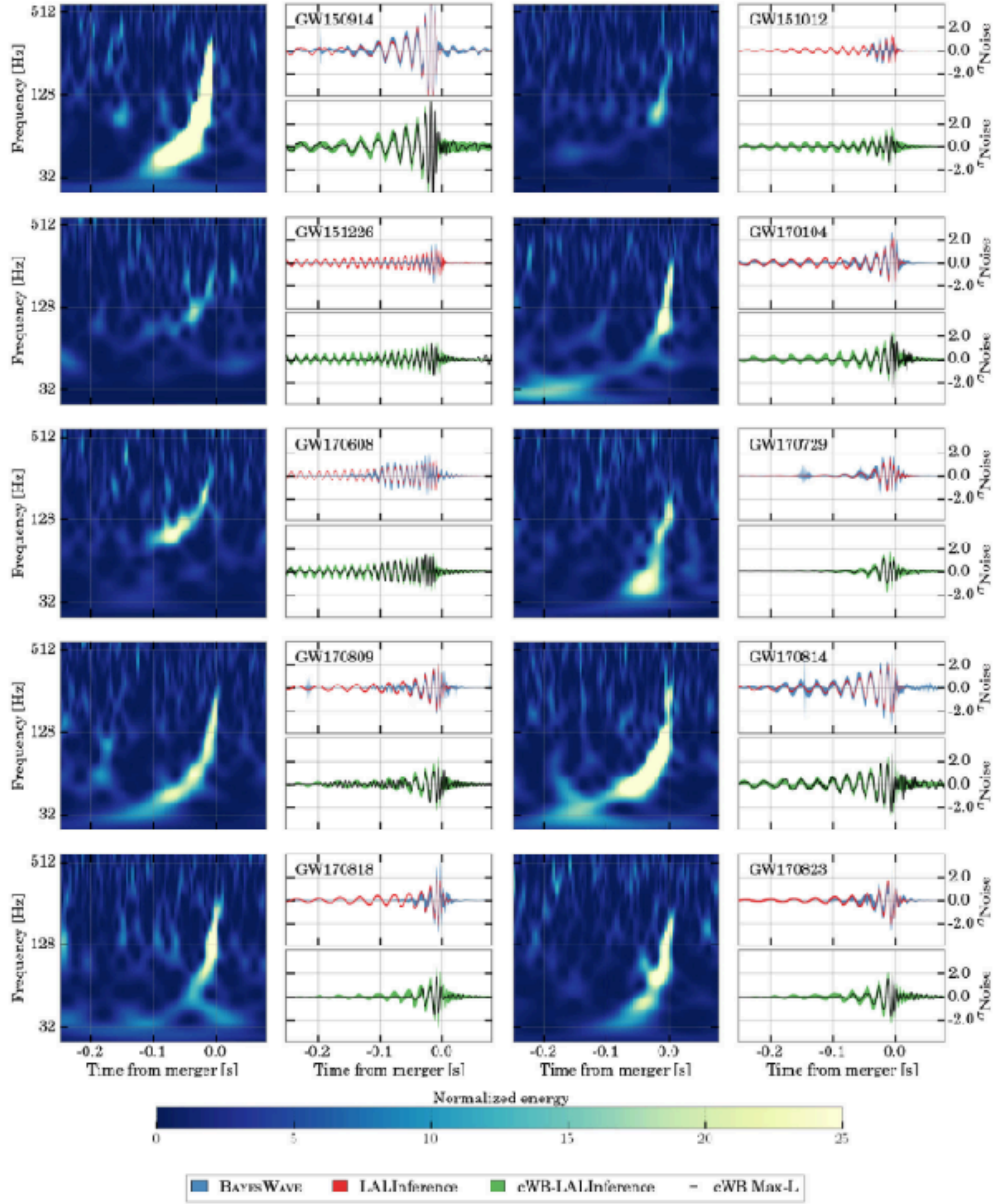
"Where shall we be looking for the unknown?"

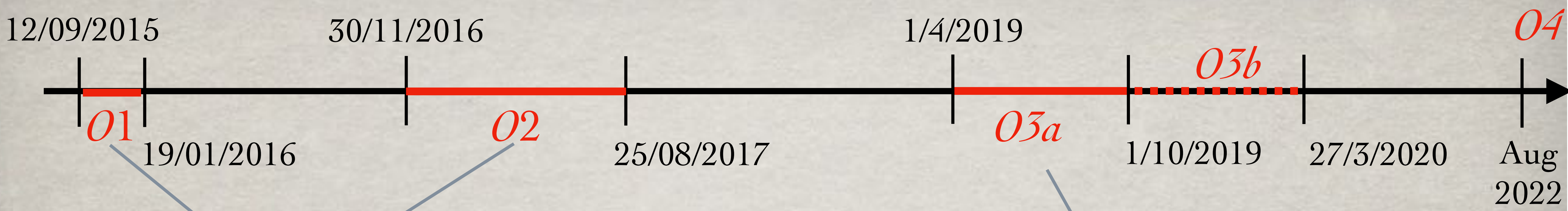
The first, epoch-making, detection



GW150914

Abbot et al., PRL 116 (2016) 061102


GW150914
GW151012
GW151226
GW170104
GW170608
GW170729
GW170809
GW170814
GW170818
GW170823
Frequency [Hz]
512
128
32
2.0
0.0
-2.0
σ_{Noise}
-0.2
-0.1
0.0
Time from merger [s]
Normalized energy
0
5
10
15
20
25
BayesWave
LALInference
cWB-LALInference
cWB Max-L



11 events (0.5 events per week)


PHYSICAL REVIEW X

Highlights Recent Subjects Accepted Collections Authors Referees Search Press About Staff

Open Access

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

B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration)
Phys. Rev. X 9, 031040 – Published 4 September 2019

39 events (1.5 events per week)


PHYSICAL REVIEW X

Highlights Recent Subjects Accepted Collections Authors Referees Search Press About Staff

Open Access

GWTC-2: Compact Binary Coalescences Observed by LIGO and Virgo during the First Half of the Third Observing Run

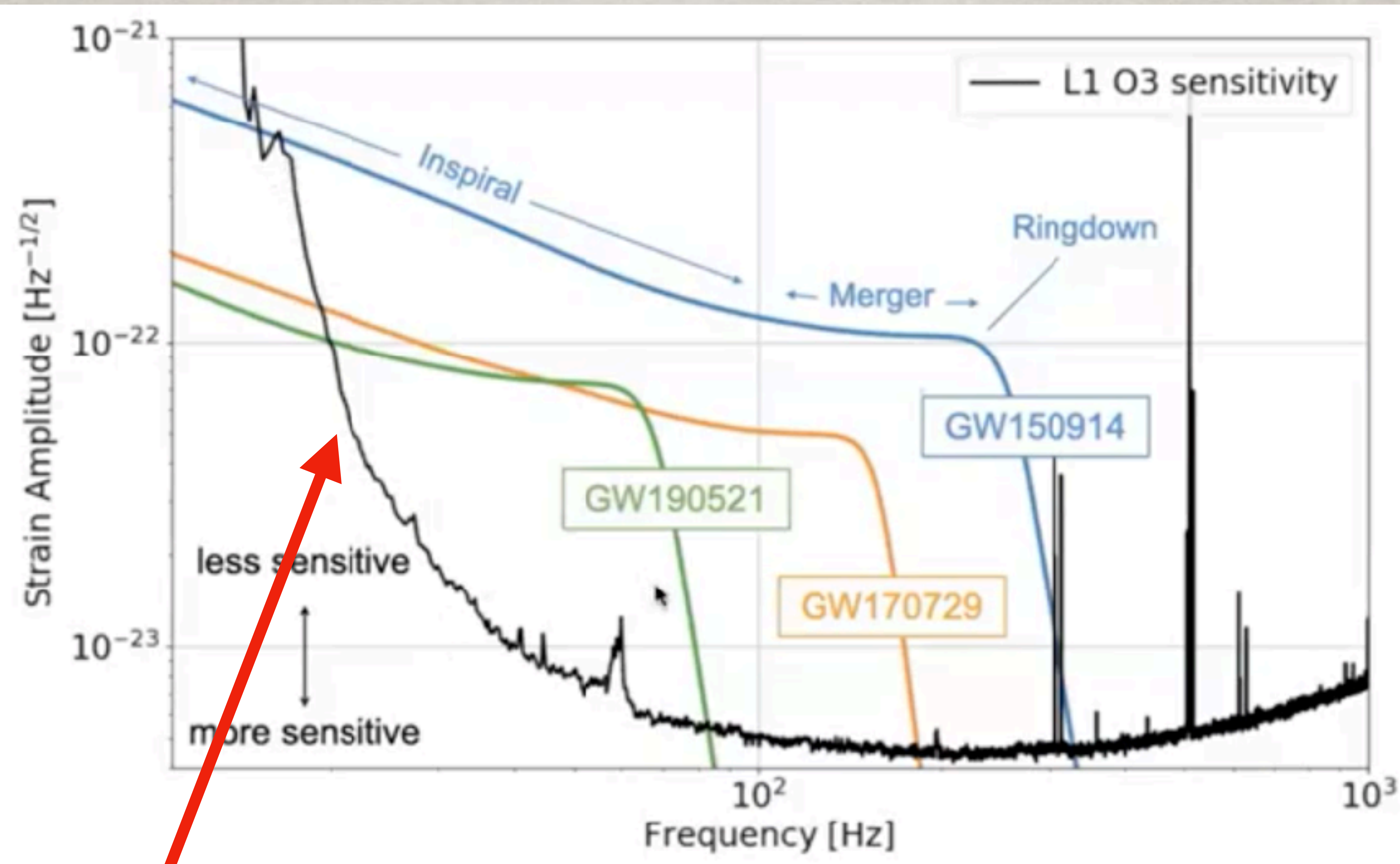
R. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration)
Phys. Rev. X **11**, 021053 – Published 9 June 2021

Gravitational waves: a particular event from the O3 run

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

GW190521 PRL125(2020)10, ApJLett.900(2020)L13

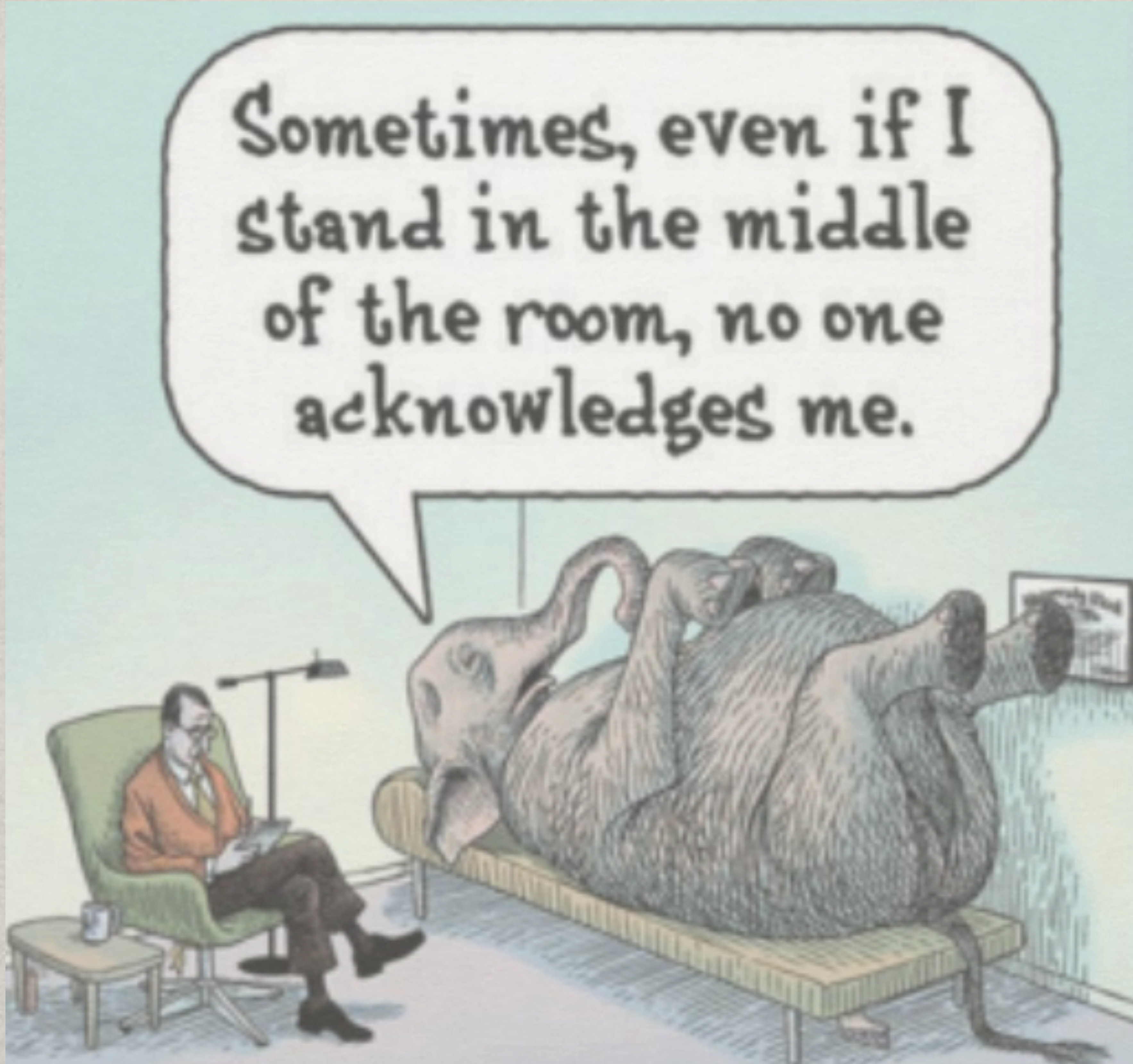
- Two most massive progenitors: $85^{+21}_{-14} M_\odot$, $66^{+17}_{-18} M_\odot$
- At least one in the pair instability supernova gap. Formation?
- Very short - no inspiral
- Final BH can be considered of intermediate mass: $142^{+28}_{-16} M_\odot$



Seismic wall

Courtesy J. Bustillo

But…


Sometimes, even if I stand in the middle of the room, no one acknowledges me.

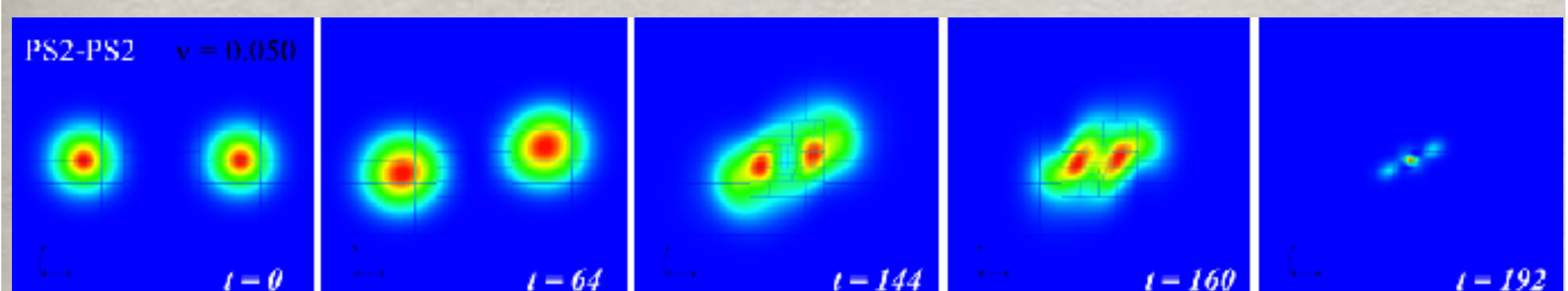
Bosonic stars (a macro perspective):

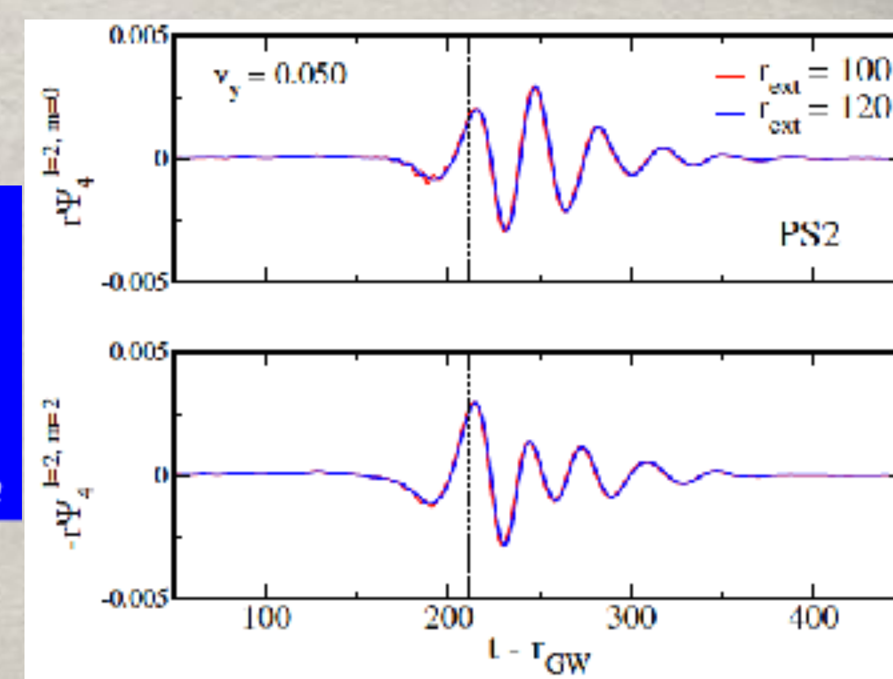
- Appear in General Relativity (GR) with simple and physically reasonable mass sources: complex massive scalar fields or vector fields, possibly with self-interactions, but certainly with a mass term.

- They can have a compactness comparable to that of black holes, making them black hole mimickers that are dynamically robust.

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

Sanchis-Gual, Herdeiro, Font, Radu and Di Giovanni, Phys. Rev. D 99 (2019) 024017





Stable model; apparent horizon forms at t~200

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:

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

- If such hypothetical particle(s) have feeble or no-interactions with standard model constituents, they are fuzzy dark matter, only detectable gravitationally.

But what is their HEP origin? Axiverse? Something else? (see A. Morais talk!)

Bosonic stars

In General Relativity, but beyond the SM

Massive-complex-scalar-vacuum:

New scale

Scalar Boson Stars

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

Massive-complex-vector-vacuum:

New scale

Vector Boson Stars
or
Proca Stars

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

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

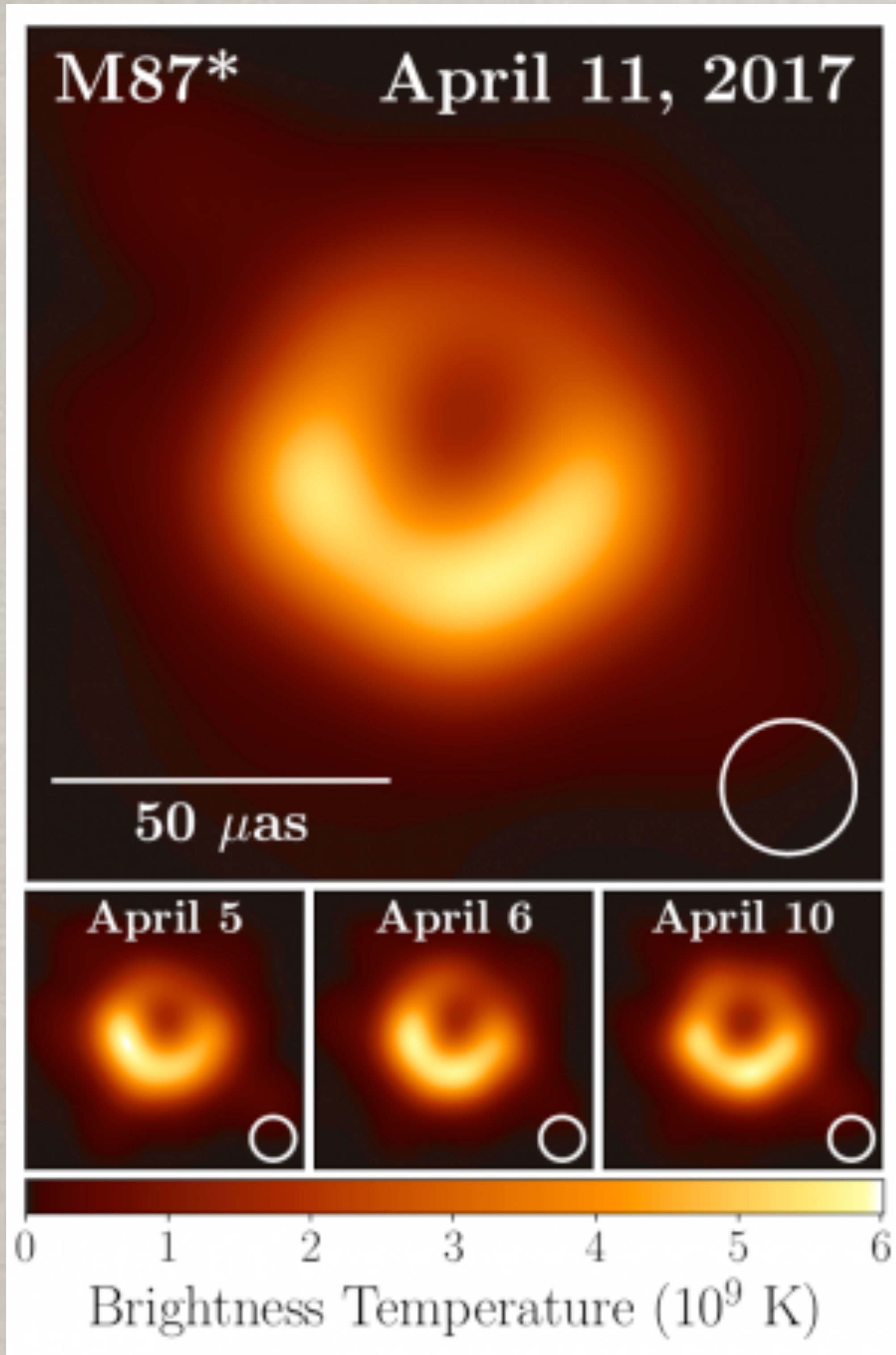
Juan Calderón Bustillo,[1,2,3,4,*] Nicolas Sanchis-Gual,[5,6,†] Alejandro Torres-Forné,[7,8,9] José A. Font,[8,9] Avi Vajpeyi,[3,4] Rory Smith,[3,4] Carlos Herdeiro,[6] Eugen Radu,[6] and Samson H. W. Leong[2]

[1]*Instituto Galego de Física de Altas Enerxías, Universidade de Santiago de Compostela, 15782 Santiago de Compostela, Galicia, Spain*
[2]*Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong*
[3]*Monash Centre for Astrophysics, School of Physics and Astronomy, Monash University, Victoria 3800, Australia*
[4]*OzGrav: The ARC Centre of Excellence for Gravitational-Wave Discovery, Clayton, Victoria 3800, Australia*
[5]*Centro de Astrofísica e Gravitação—CENTRA, Departamento de Física, Instituto Superior Técnico—IST, Universidade de Lisboa—UL, Avenida Rovisco Pais 1, 1049-001, Portugal*
[6]*Departamento de Matemática da Universidade de Aveiro and Centre for Research and Development in Mathematics and Applications (CIDMA), Campus de Santiago, 3810-183 Aveiro, Portugal*
[7]*Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Am Mühlenberg 1, Potsdam 14476, Germany*
[8]*Departamento de Astronomía y Astrofísica, Universitat de València, Dr. Moliner 50, 46100, Burjassot (València), Spain*
[9]*Observatori Astronòmic, Universitat de València, C/ Catedrático José Beltrán 2, 46980, Paterna (València), Spain*

(Received 26 September 2020; revised 20 November 2020; accepted 14 January 2021; published 24 February 2021)

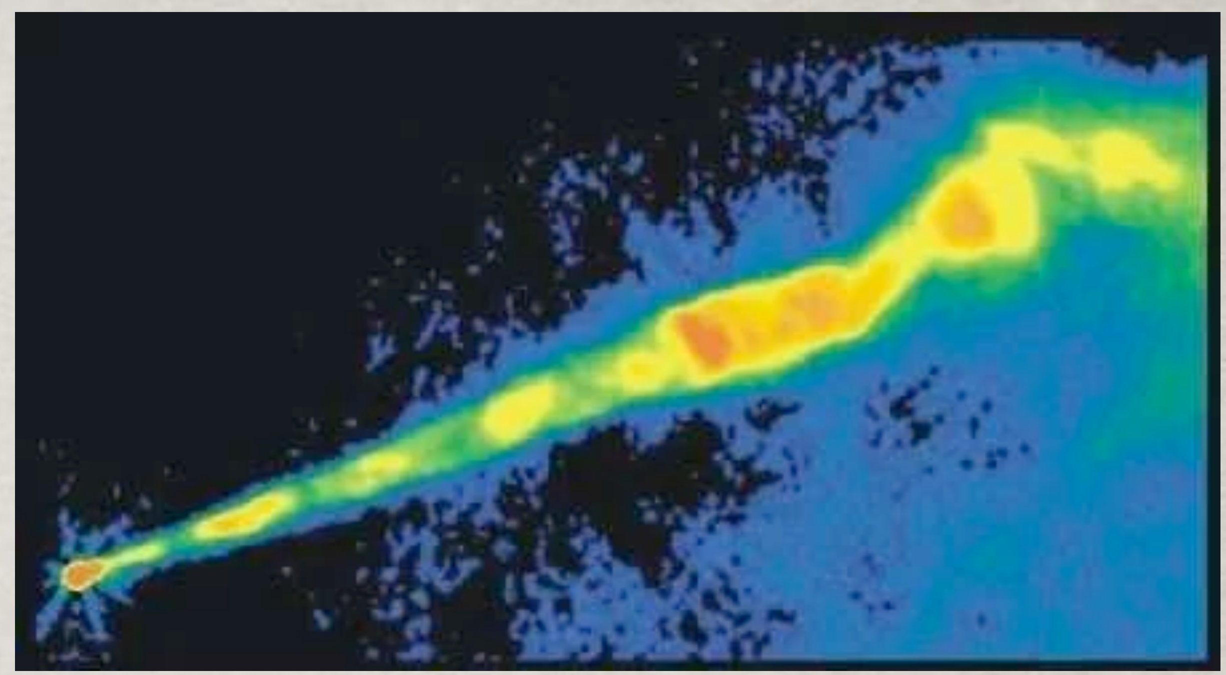
Advanced LIGO-Virgo have reported a short gravitational-wave signal (GW190521) interpreted as a quasicircular merger of black holes, one at least populating the pair-instability supernova gap, that formed a remnant black hole of $M_f \sim 142\ M_\odot$ at a luminosity distance of $d_L \sim 5.3$ Gpc. With barely visible pre-merger emission, however, GW190521 merits further investigation of the pre-merger dynamics and even of the very nature of the colliding objects. We show that GW190521 is consistent with numerically simulated signals from head-on collisions of two (equal mass and spin) horizonless vector boson stars (aka Proca stars), forming a final black hole with $M_f = 231^{+13}_{-17}\ M_\odot$, located at a distance of $d_L = 571^{+348}_{-181}$ Mpc. This provides the first demonstration of close degeneracy between these two theoretical models, for a real gravitational-wave event. The favored mass for the ultralight vector boson constituent of the Proca stars is $\mu_V = 8.72^{+0.73}_{-0.82} \times 10^{-13}$ eV. Confirmation of the Proca star interpretation, which we find statistically slightly preferred, would provide the first evidence for a long sought dark matter particle.

DOI: 10.1103/PhysRevLett.126.081101

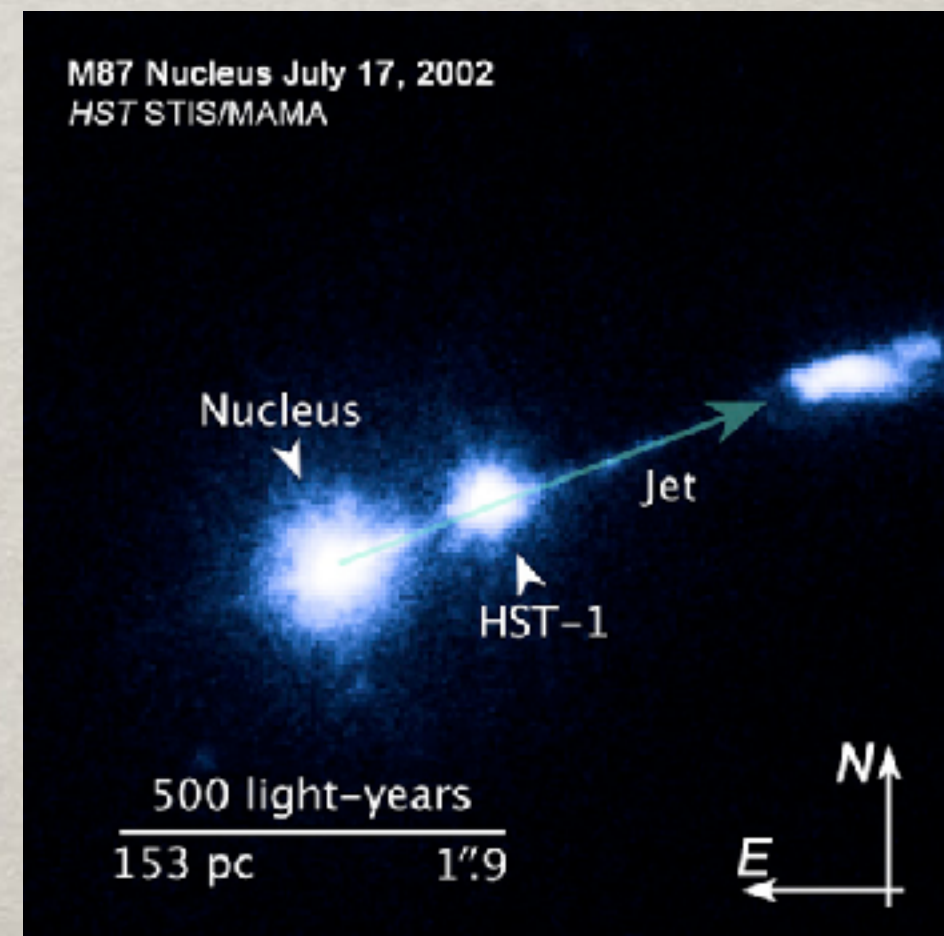


M87 supermassive black hole imaging by the EHT collaboration

ApJ Lett. 875 (2019) L1



M87 supermassive black hole jet ~17° w.r.t line of sight (radio image - Very Large Array)

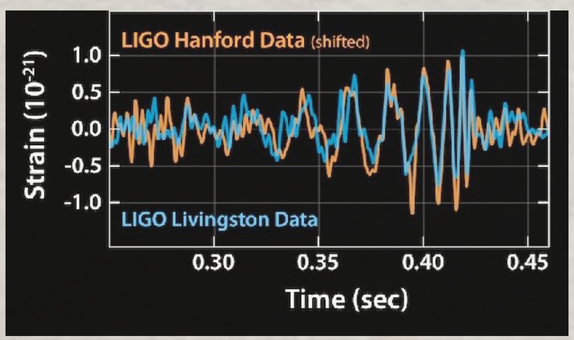


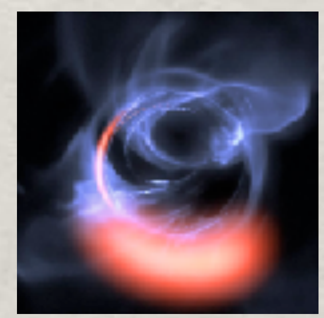
Different mass ranges:

Stellar mass range

Supermassive range

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





Sgr A*

M87*

Ultralight bosons mass range:

10^{-10} 10^{-12} 10^{-14} 10^{-16} 10^{-18} 10^{-20} μ (eV)

Alternative black holes ("hairy")

In General Relativity, but beyond the SM

Massive-complex-scalar-vacuum:

Black holes with scalar hair

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:

Black holes with Proca hair

New scale

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

2- Bosonic stars and LVK as particle detectors

Solitons in field theory

Solitons occur for non-linear field theories and the constancy of their "shape" is interpreted as a cancellation between non-linear and dispersive effects.

There is, however, a generic argument, known as *Derrick's theorem*, against the existence of stable, time-independent solutions of finite energy in a wide class of non-linear wave equations, in three or higher (spatial) dimensions G. H. Derrick, J. Math. Phys. 5 (1964) 1252 (see also R.H. Hobart, Proc. Phys. Soc. 82 (1963)201).

One way to circumvent the theorem is to considered a complex field with a harmonic time dependence, which guarantees a time-independent energy momentum tensor G. Rosen, J. Math. Phys. 9 (1968) 996:

$$\Phi(t, \mathbf{r}) = e^{-iwt}\varphi(\mathbf{r})$$

Moreover there is a global symmetry and a conserved scalar charge (typically called Q). Then, for some classes of potentials (yielding non-linear models), localized stable solutions exist, which are now known, following Coleman, as *Q-balls* S. R. Coleman, "Q Balls," Nucl. Phys. B 262 (1985) 263 [Erratum-ibid. B 269 (1986) 744]

But in the presence of gravity, no scalar non-linear interactions are required. Effectively, such non-linearities are provided by the self-gravity of the field.

Gravitating scalar/vector solitons: bosonic stars

The model (mini-boson stars):

$$S = \int d^4x\sqrt{-g}\left[\frac{R}{16\pi} - \frac{1}{2}g^{\alpha\beta}\left(\Phi^*_{,\,\alpha}\Phi_{,\,\beta} + \Phi^*_{,\,\beta}\Phi_{,\,\alpha}\right) - \mu^2\Phi^*\Phi\right],$$

The field equations:

$$G_{\alpha\beta} = 8\pi\left\{\Phi^*_{,\alpha}\Phi_{,\beta} + \Phi^*_{,\beta}\Phi_{,\alpha} - g_{\alpha\beta}\left[\frac{1}{2}g^{\gamma\delta}(\Phi^*_{,\gamma}\Phi_{,\delta} + \Phi^*_{,\delta}\Phi_{,\gamma}) + \mu^2\Phi^*\Phi\right]\right\}$$

$$\Box\Phi = \mu^2\Phi$$

The action is invariant under a U(1) global symmetry: $\Phi \to e^{i\alpha}\Phi$

This leads to a conserved current: $j^\alpha = -i(\Phi^*\partial^\alpha\Phi - \Phi\partial^\alpha\Phi^*)$

Integrating the temporal component of this 4-current on a timelike slice leads to a conserved charge - the *Noether charge* Q:

$$Q = \int_\Sigma j^t$$

The Noether charge counts the number of scalar particles. Notice that this is conserved in the sense of a local continuity equation; **there is no associated Gauss law**!

Gravitating scalar/vector solitons: bosonic stars

Spherically symmetric solutions ansatz (**three** unknown functions):

$$ds^2 = -N(r)\sigma^2(r)dt^2 + \frac{dr^2}{N(r)} + r^2(d\theta^2 + \sin^2\theta d\phi^2) \ , \quad N(r) \equiv 1 - \frac{2m(r)}{r} \ , \quad \Phi = \phi(r)e^{-iwt}$$

From a two real scalars viewpoint they are both time periodic but have opposite phases. The time dependence cancels at the level of the energy momentum tensor, being therefore compatible with a stationary metric.

The above ansatz makes the Einstein equations simpler as compared to other choices (such as isotropic coordinates). The two "essential" Einstein equations read:

$$m' = 4\pi r^2 \left(N\phi'^2 + \mu^2\phi^2 + \frac{w^2\phi^2}{N\sigma^2} \right) \ , \quad \sigma' = 8\pi\sigma r \left(\phi'^2 + \frac{w^2\phi^2}{N^2\sigma^2} \right)$$

(one further constraint equation is found, but which is a differential consequence of these).

The Klein-Gordon equation gives (thus completing **three** equations):

$$\phi'' + \frac{2\phi'}{r} + \frac{N'\phi'}{N} + \frac{\sigma'\phi'}{\sigma} - \frac{\mu^2\phi}{N} + \frac{w^2\phi}{N^2\sigma^2} = 0$$

Exercise!

Obtain these equations.

Lectures by Alexandre Pombo

(pomboalexandremira@ua.pt)

on obtaining spherical bosonic stars:

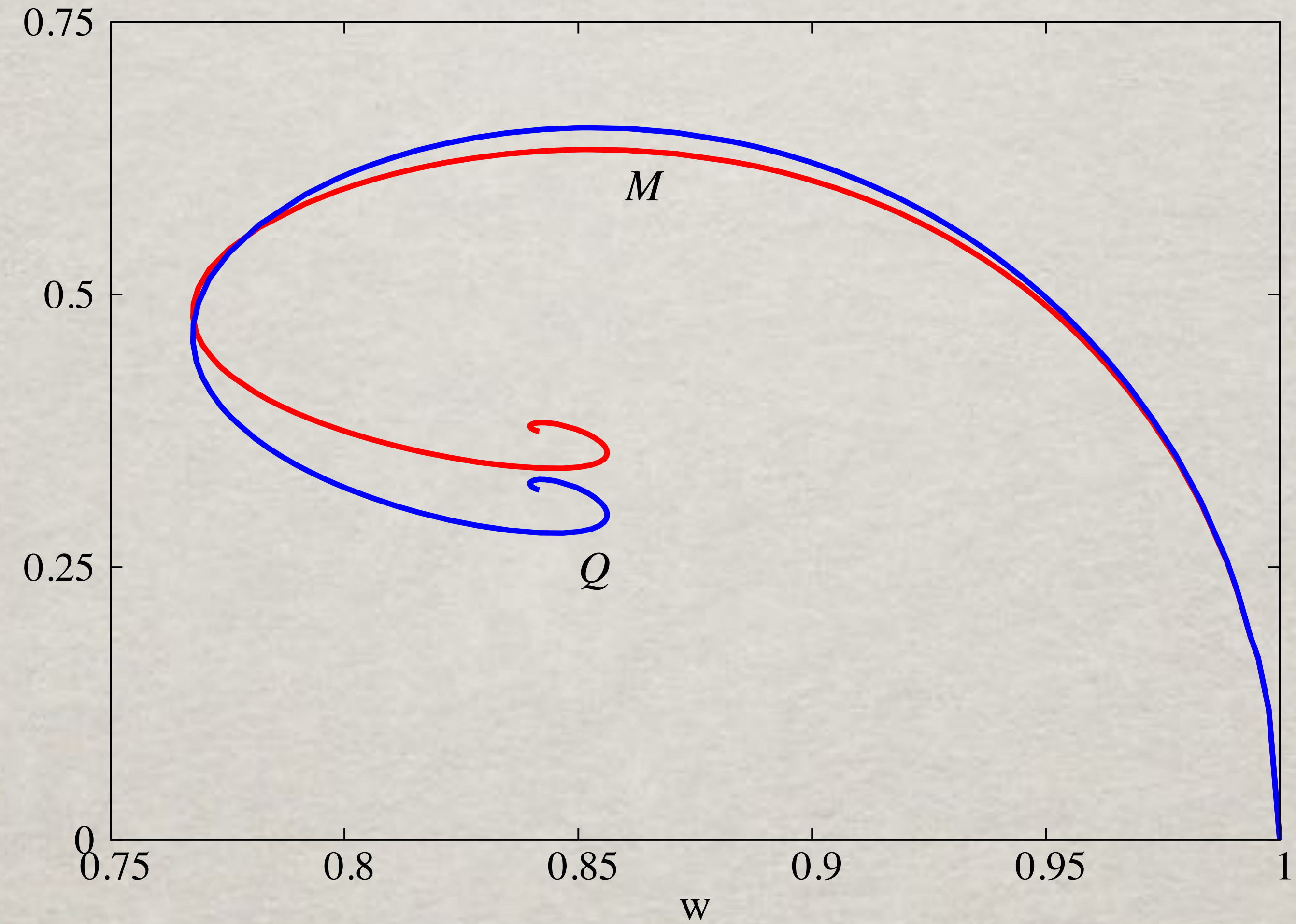
https://indico.cern.ch/event/951466/timetable/

https://indico.cern.ch/event/951466/contributions/4014172/attachments/2105845/3543310/Boson_Star_Numerics.pdf

https://www.youtube.com/watch?v=dT6hHNs-2-w

Gravitating scalar/vector solitons: bosonic stars

ADM mass M (and Noether charge Q) vs. frequency w diagram:



In units of μ

$$M\mu \to M \ , \quad w/\mu \to w$$

- Solutions only exist for a range of frequencies: $\frac{w_{\rm min}}{\mu} < \frac{w}{\mu} < 1$ $\quad w_{\rm min} \simeq 0.767\mu$

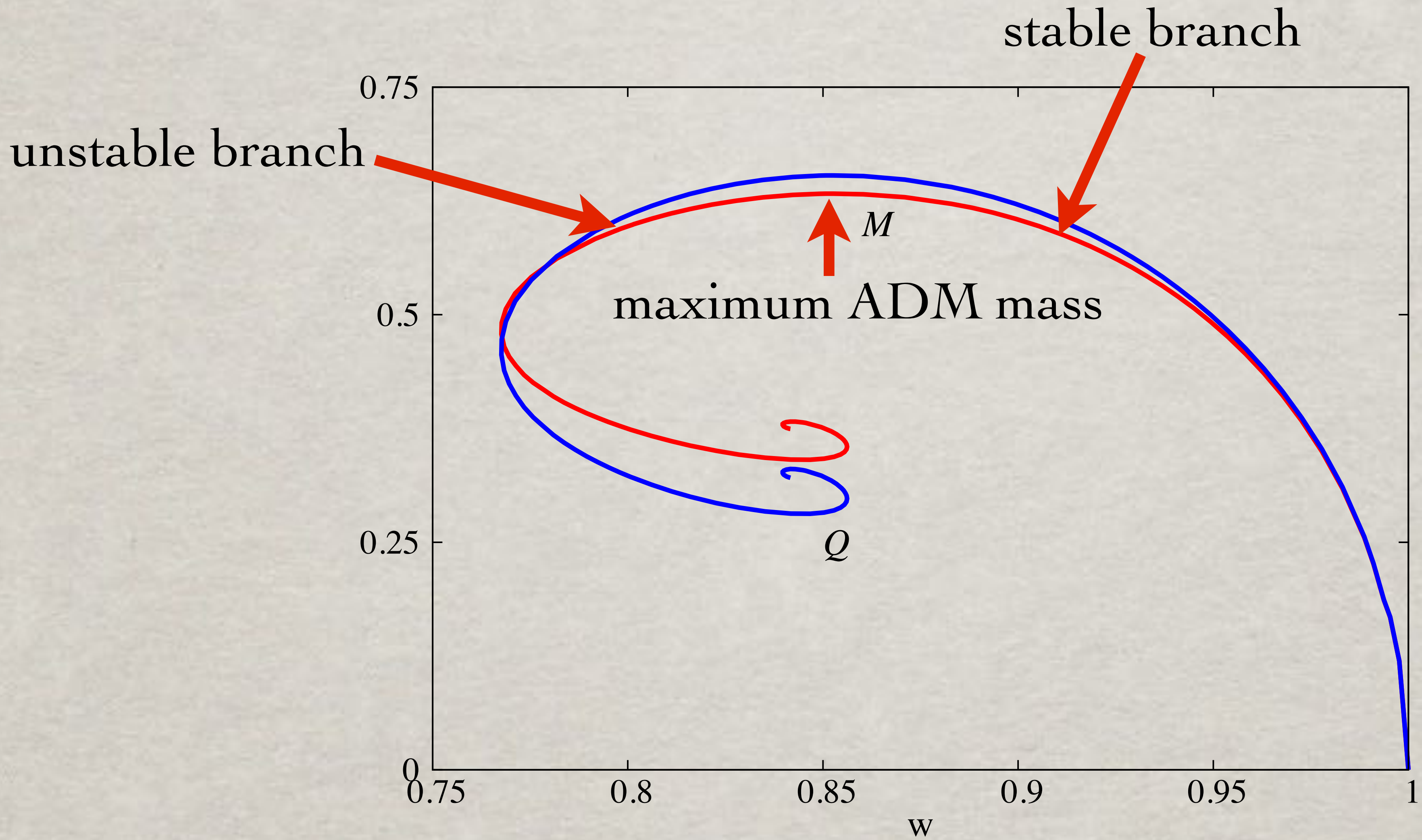
- There is a range of frequencies for which more than one solution exists. This defines the first, second, third, etc, **branches**.

- There is a maximum value for the ADM mass: $M_{\rm ADM}^{\rm max} \simeq \alpha_{\rm BS} \frac{M_{\rm Pl}^2}{\mu} \simeq \alpha_{\rm BS}\, 10^{-19} M_\odot \left(\frac{\rm GeV}{\mu}\right)$

$$\alpha_{\rm BS} = 0.633$$

Gravitating scalar/vector solitons: bosonic stars

Spherically symmetric solutions: Stability

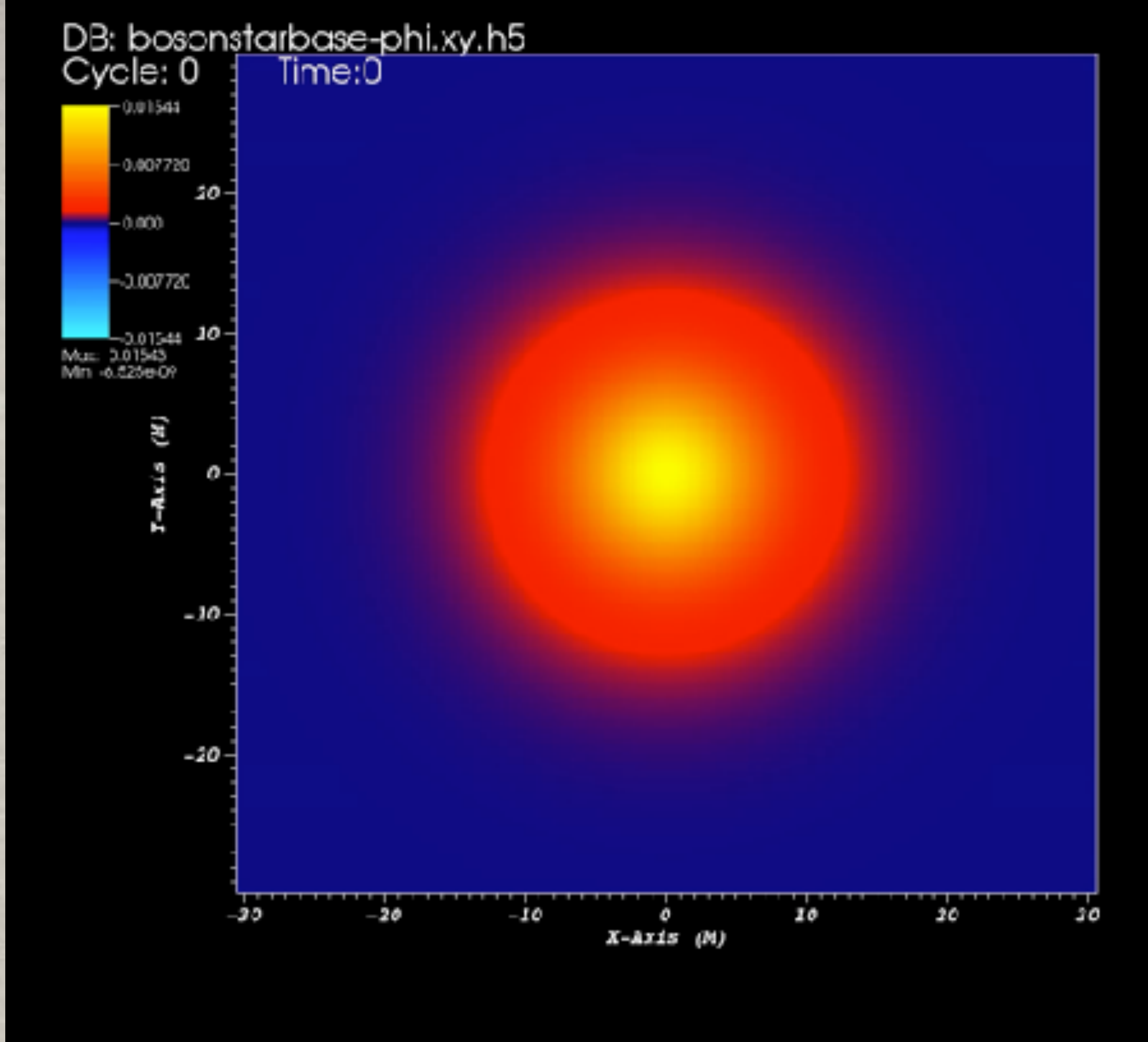


In units of μ

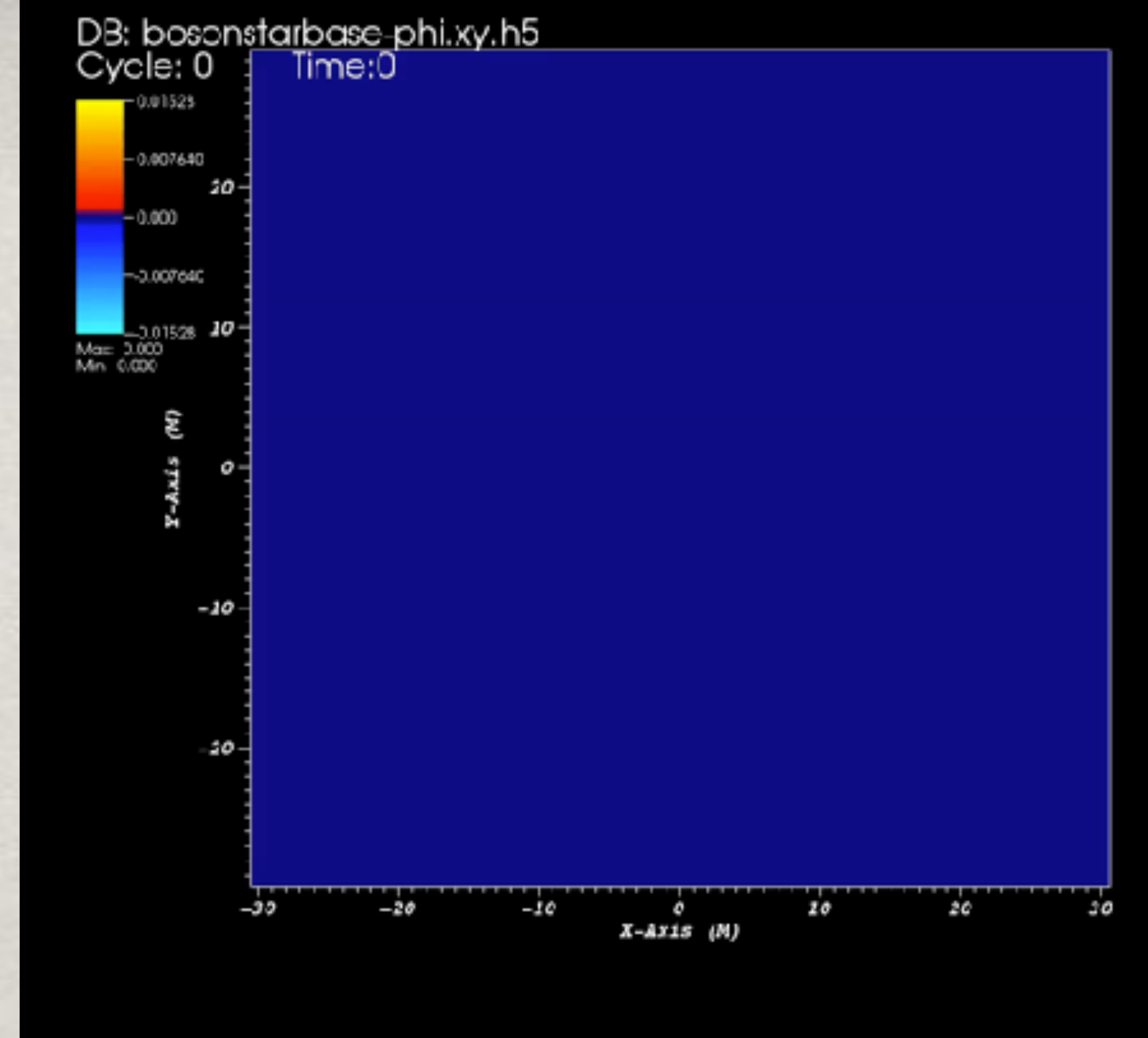
$$M\mu \to M \ , \quad w/\mu \to w$$

Studying linearized radial perturbations of the coupled metric-scalar field system shows that an unstable mode arises precisely at the maximum of the ADM mass M. Gleiser and R. Watkins, Nucl. Phys. B319 (1989) 733; T. D. Lee and Y. Pang, Nucl. Phys. B315, 477 (1989).

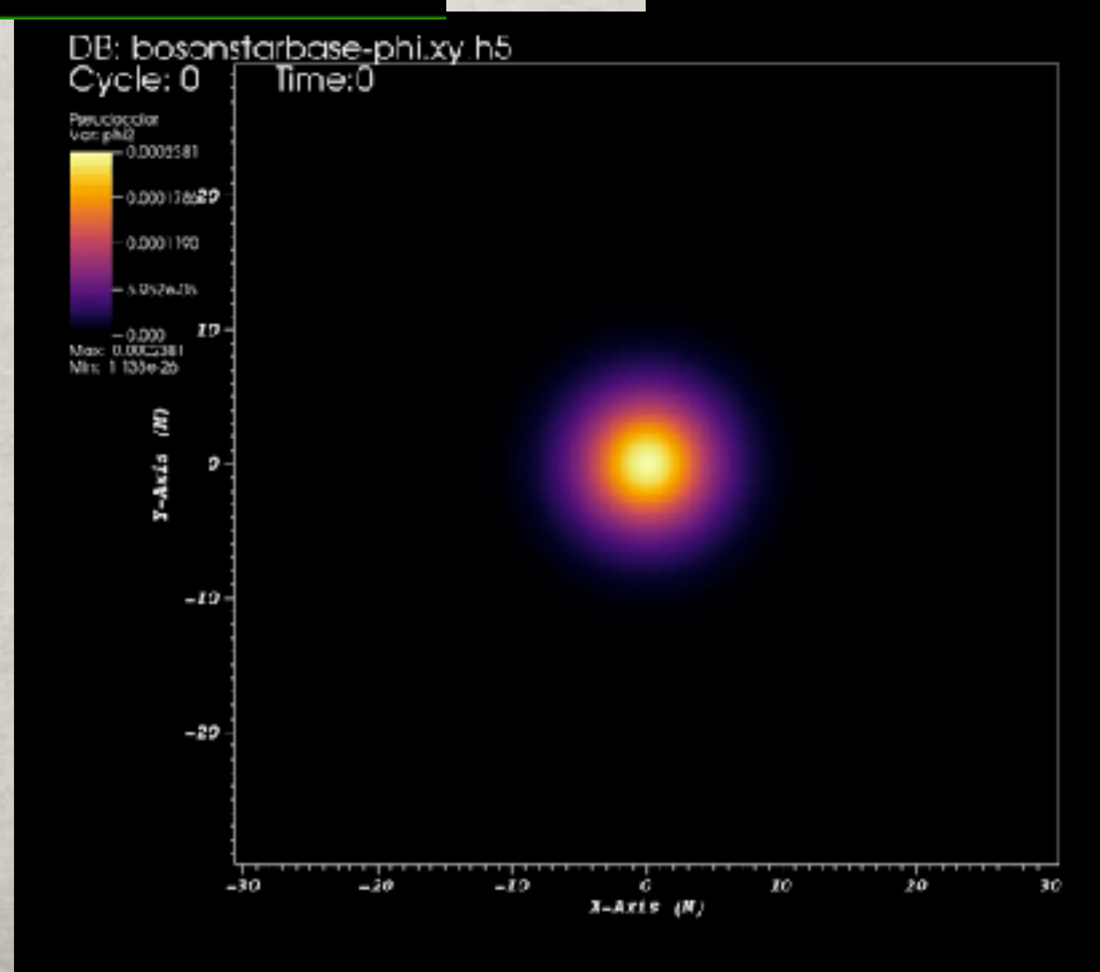
Unstable BSs can migrate, decay into a Schwarzschild black hole or disperse entirely Seidel and Suen, PRD 42 (1990) 384; Guzman, PRD 70 (2004) 044033; Hawley and Choptuik, PRD 62 (2000)104024



$\mathcal{R}(\Phi)$



$\mathcal{I}(\Phi)$



$|\Phi|^2$

w=0.95
first branch

Simulations
Zilhão (2017)

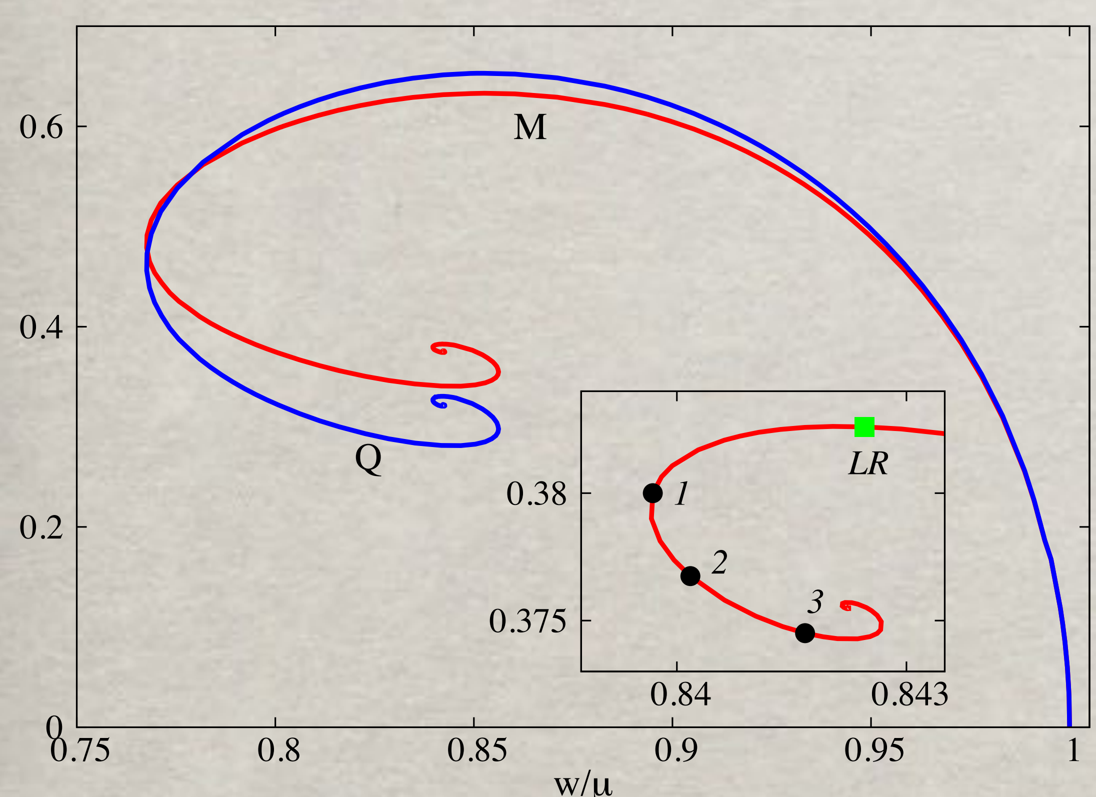
The vector cousin: spherical Proca stars

Brito, Cardoso, Herdeiro and Radu, Phys. Lett. B 752 (2016) 291

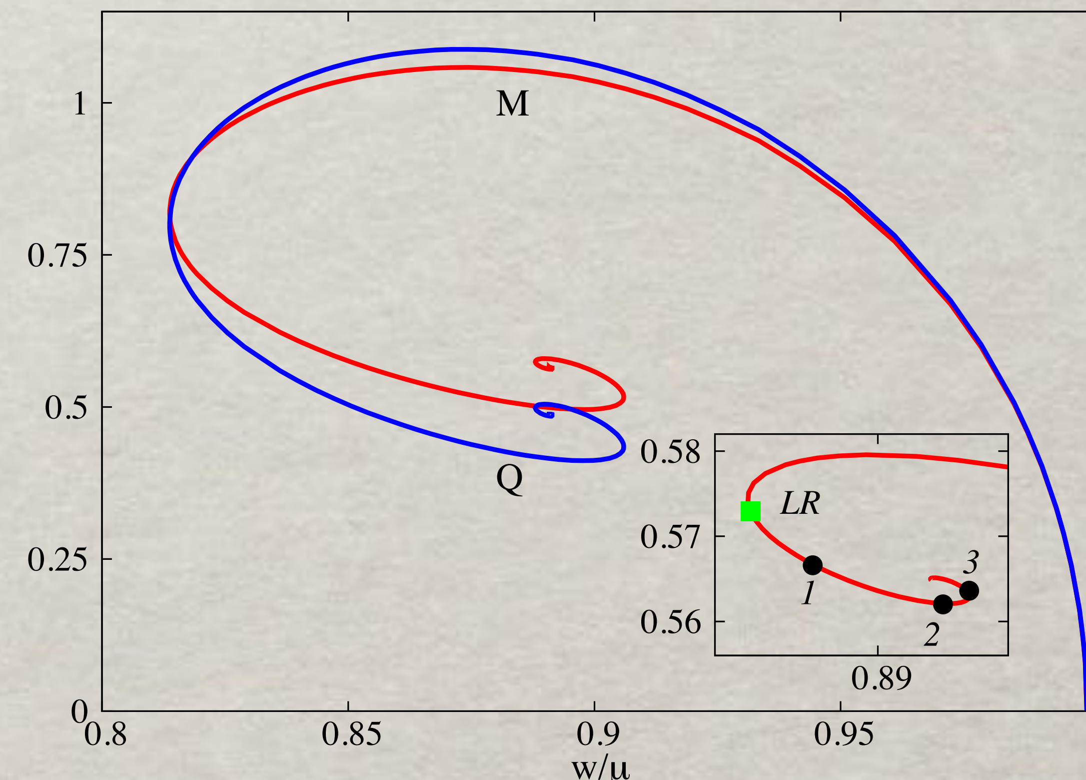
$$\mathcal{S} = \int d^4x\sqrt{-g}\left(\frac{1}{16\pi G}R - \frac{1}{4}\mathcal{F}_{\alpha\beta}\bar{\mathcal{F}}^{\alpha\beta} - \frac{1}{2}\mu^2\mathcal{A}_\alpha\bar{\mathcal{A}}^\alpha\right) .$$

A similar construction holds yielding spherical solitonic objects: spherical Proca stars

scalar



vector/Proca



Very similar domain of existence;
Dynamical stability changes at maximal mass;
Similar structure of fundamental family and excited states;
but in Proca case $\mathcal{A}_0$ has at least one node.

Dynamics of spherical Proca stars

1) As in the scalar case, vector boson stars are perturbatively stable up to the maximal mass; then they share the same three possible fates: migration, collapse or dispersion

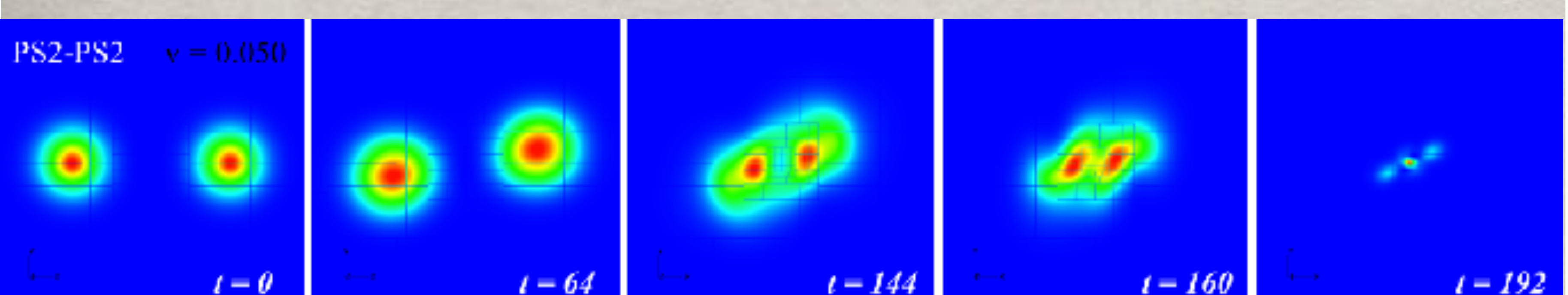
Brito, Cardoso, Herdeiro and Radu, Phys. Lett. B 752 (2016) 291

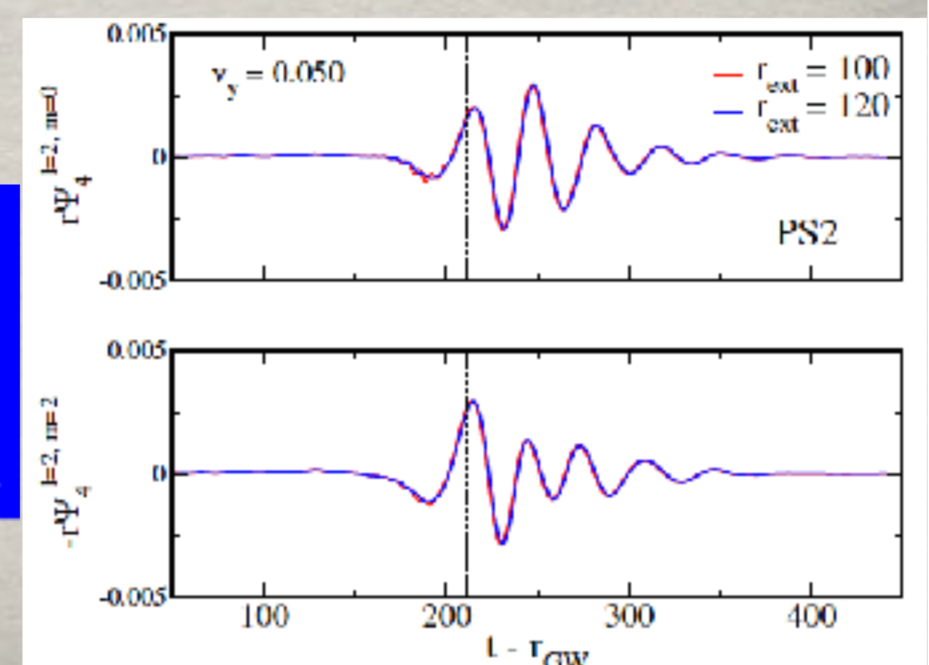
2) As in the scalar case, vector boson stars can form dynamically via gravitational cooling

Di Giovanni, Sanchis-Gual, Herdeiro and Font, PRD 98 (2018) 064044

4) As in the scalar case, one can study binaries of spherical Proca stars and their gravitational wave emission

Sanchis-Gual, Herdeiro, Font, Radu and Di Giovanni, Phys. Rev. D 99 (2019) 024017





Stable model; apparent horizon forms at t~200

Gravitating scalar/vector solitons: bosonic stars

ELSEVIER

Physics Letters B

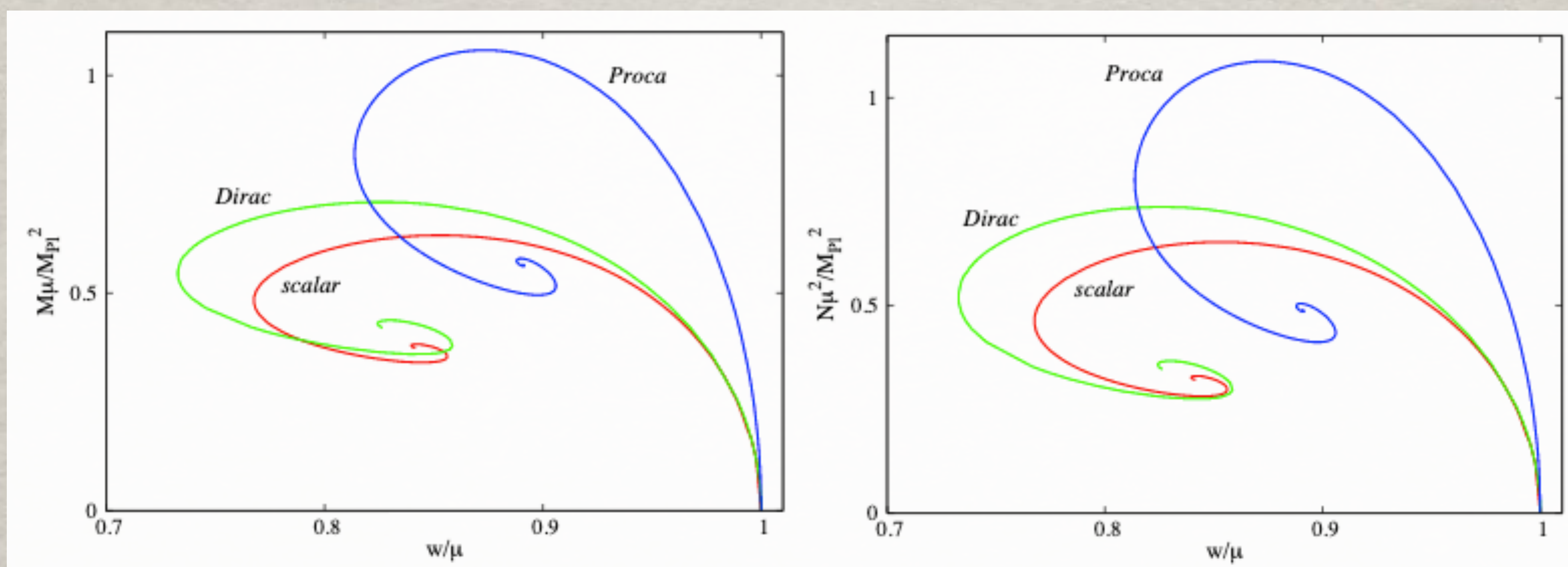
Volume 773, 10 October 2017, Pages 654-662

Asymptotically flat scalar, Dirac and Proca stars: Discrete *vs.* continuous families of solutions

Carlos A.R. Herdeiro, Alexandre M. Pombo, Eugen Radu

Show more

https://doi.org/10.1016/j.physletb.2017.09.036



Gravitating scalar/vector solitons: bosonic stars

Axially symmetric solutions ansatz (in quasi-isotropic coordinates) S.Yoshida and Y. Eriguchi, Phys. Rev. D 56 (1997) 762; F. E. Schunck and E. W. Mielke, Phys. Lett. A 249 (1998) 389:

$$ds^2 = -e^{2F_0(r,\theta)}dt^2 + e^{2F_1(r,\theta)}\left(dr^2 + r^2 d\theta^2\right) + e^{2F_2(r,\theta)}r^2\sin^2\theta\,(d\varphi - W(r,\theta)dt)^2 \qquad \Phi = \phi(r,\theta)e^{i(m\varphi - wt)}$$

The solution has three parameters: (w,m,n), but again these do not define solutions uniquely.

The Klein-Gordon plus Einstein equations yield now a system of five coupled PDEs (plus two “constraint” equations which are differential consequences of the others). To solve them:

- one performs an expansion of the unknown functions, both near the origin and asymptotically;

- the equations can be solved using a relaxation method (Newton-Raphson). For each fixed frequency w one can find various or no solutions, corresponding to different ADM masses M.

Gravitating scalar/vector solitons: bosonic stars

Klein Gordon equation:

$$\phi_{,rr} + \frac{1}{r^2}\phi_{,\theta\theta} + \phi_{,r}(F_{0,r} + F_{2,r}) + \frac{1}{r^2}\phi_{,\theta}(F_{0,\theta} + F_{2,\theta}) + \frac{2}{r}\phi_{,r} + \frac{\cot\theta}{r^2}\phi_{,\theta}$$
$$- \left(\frac{e^{-2F_2}m^2}{r^2\sin^2\theta} - e^{-2F_0}(w - mW)^2 + \mu^2\right)e^{2F_1}\phi = 0$$

The Einstein equations are combined to have second derivatives of a single function:

$$F_{1,rr} + \frac{1}{r^2}F_{1,\theta\theta} - \left(F_{0,r}F_{2,r} + \frac{1}{r^2}F_{0,\theta}F_{2,\theta}\right) - \frac{e^{-2F_0+2F_2}r^2\sin^2\theta}{4}\left(W_{,r}^2 + \frac{1}{r^2}W_{,\theta}^2\right) - \frac{F_{0,r}}{r}$$
$$+ \frac{F_{1,r}}{r} - \frac{\cot\theta F_{0,\theta}}{r^2} + 8\pi\left(\phi_{,r}^2 + \frac{1}{r^2}\phi_{,\theta}^2 + e^{2F_1}\left[e^{-2F_0}(w - mW)^2 - \frac{e^{-2F_2}m^2}{r^2\sin^2\theta}\right]\phi^2\right) = 0$$

$$F_{2,rr} + \frac{1}{r^2}F_{2,\theta\theta} + F_{2,r}^2 + \frac{1}{r^2}F_{2,\theta}^2 + F_{0,r}F_{2,r} + \frac{1}{r^2}F_{0,\theta}F_{2,\theta} + \frac{e^{-2F_0+2F_2}r^2\sin^2\theta}{2}\left(W_{,r}^2 + \frac{1}{r^2}W_{,\theta}^2\right)$$
$$+ \frac{1}{r}\left(F_{0,r} + \frac{\cot\theta F_{0,\theta}}{r}\right) + \frac{3F_{2,r}}{r} + \frac{2\cot\theta F_{2,\theta}}{r^2} + 8\pi e^{2F_1}\left(\mu^2 + \frac{2e^{-2F_2}m^2}{r^2\sin^2\theta}\right)\phi^2 = 0$$

$$F_{0,rr} + \frac{1}{r^2}F_{0,\theta\theta} + F_{0,r}^2 + \frac{1}{r^2}F_{0,\theta}^2 + F_{0,r}F_{2,r} + \frac{1}{r^2}F_{0,\theta}F_{2,\theta} - \frac{e^{-2F_0+2F_2}r^2\sin^2\theta}{2}\left(W_{,r}^2 + \frac{1}{r^2}W_{,\theta}^2\right)$$
$$+ \frac{2F_{0,r}}{r} + \frac{\cot\theta F_{0,\theta}}{r^2} + \frac{N'F_{2,r}}{2} - 8\pi e^{2F_1}\left(2e^{-2F_0}(w - mW)^2 - \mu^2\right)\phi^2 = 0$$

$$W_{,rr} + \frac{1}{r^2}W_{,\theta\theta} + (3F_{2,r} - F_{0,r})W_{,r} + \frac{1}{r^2}(3F_{2,\theta} - F_{0,\theta})W_{,\theta}$$
$$+ \frac{4}{r}\left(W_{,r} + \frac{3\cot\theta W_{,\theta}}{4r}\right) + 32\pi\frac{e^{2F_1-2F_2}m(w - mW)}{r^2\sin^2\theta}\phi^2 = 0$$

Lectures by Jorge Delgado

(jorgedelgado@ua.pt)

on obtaining spherical bosonic stars:

https://indico.cern.ch/event/951466/timetable/

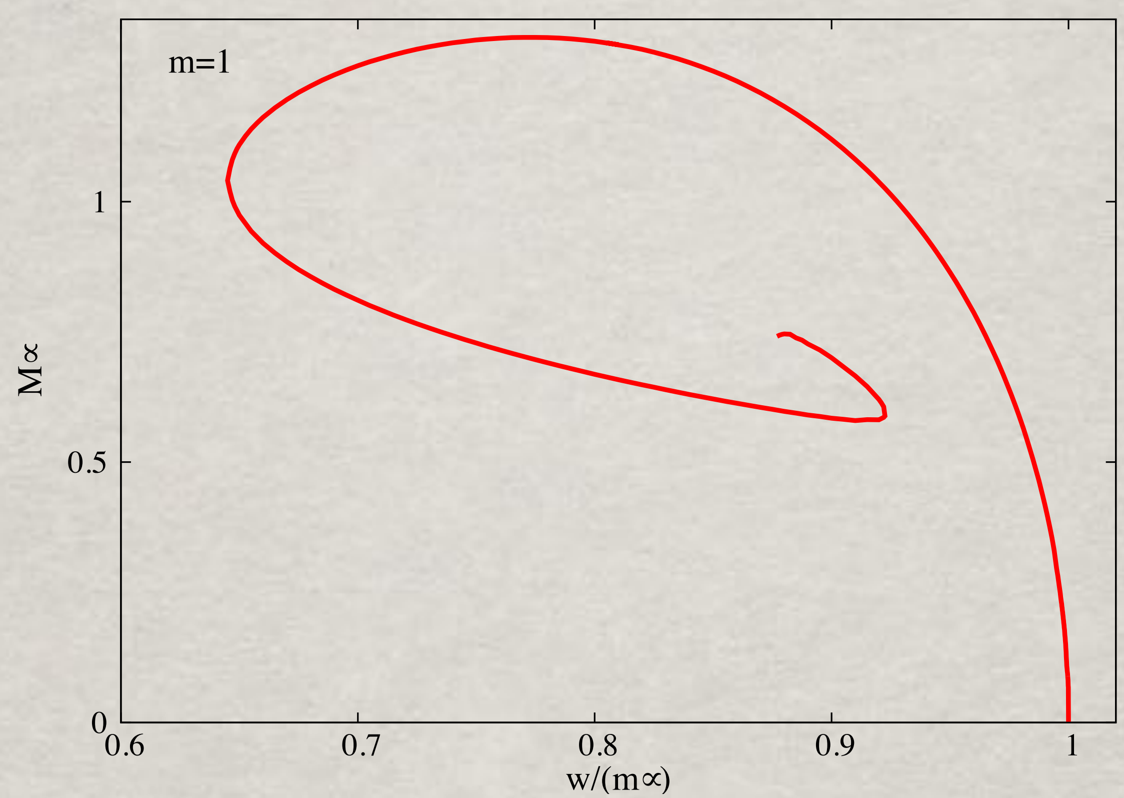
https://indico.cern.ch/event/951466/contributions/4014176/attachments/2108709/3546700/Workshop_Lecture1.pdf

https://indico.cern.ch/event/951466/contributions/4014177/attachments/2109749/3548748/Workshop_Lecture2.pdf

https://www.youtube.com/watch?v=eiIgzb5HBto&feature=youtu.be

https://www.youtube.com/watch?v=YHnxezCWH3Y&feature=youtu.be

Gravitating scalar/vector solitons: bosonic stars



The maximum value for the ADM mass increases with m:

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

m=0: $\alpha_{\rm BS} = 0.633$

m=1: $\alpha_{\rm BS} = 1.315$

S.Yoshida and Y. Eriguchi, Phys. Rev. D 56 (1997) 762

m=2: $\alpha_{\rm BS} = 2.216$

P. Grandclement, C. Somé and E. Gourgoulhon, Phys. Rev. D 90 (2014) 2, 024068 [arXiv:1405.4837 [gr-qc]].

For rotating boson stars:

F. E. Schunck and E. W. Mielke, Phys. Lett. A 249 (1998) 389

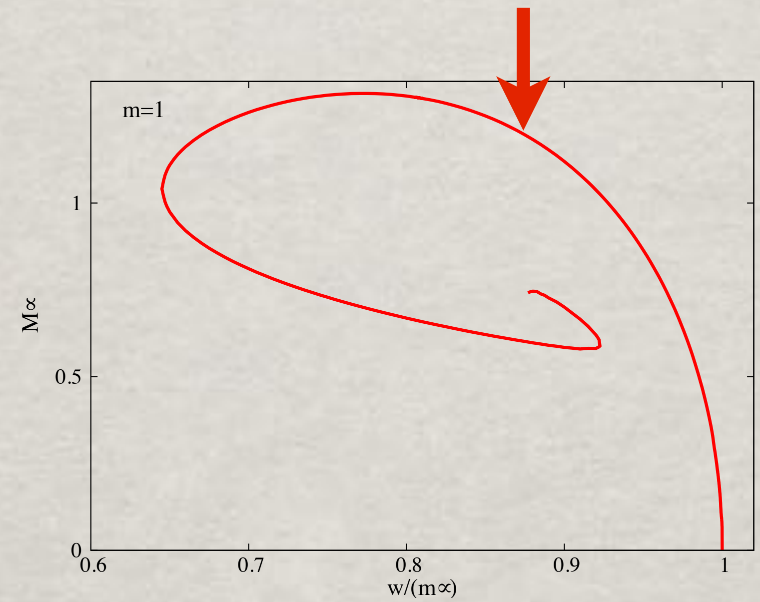
$$J = mQ$$

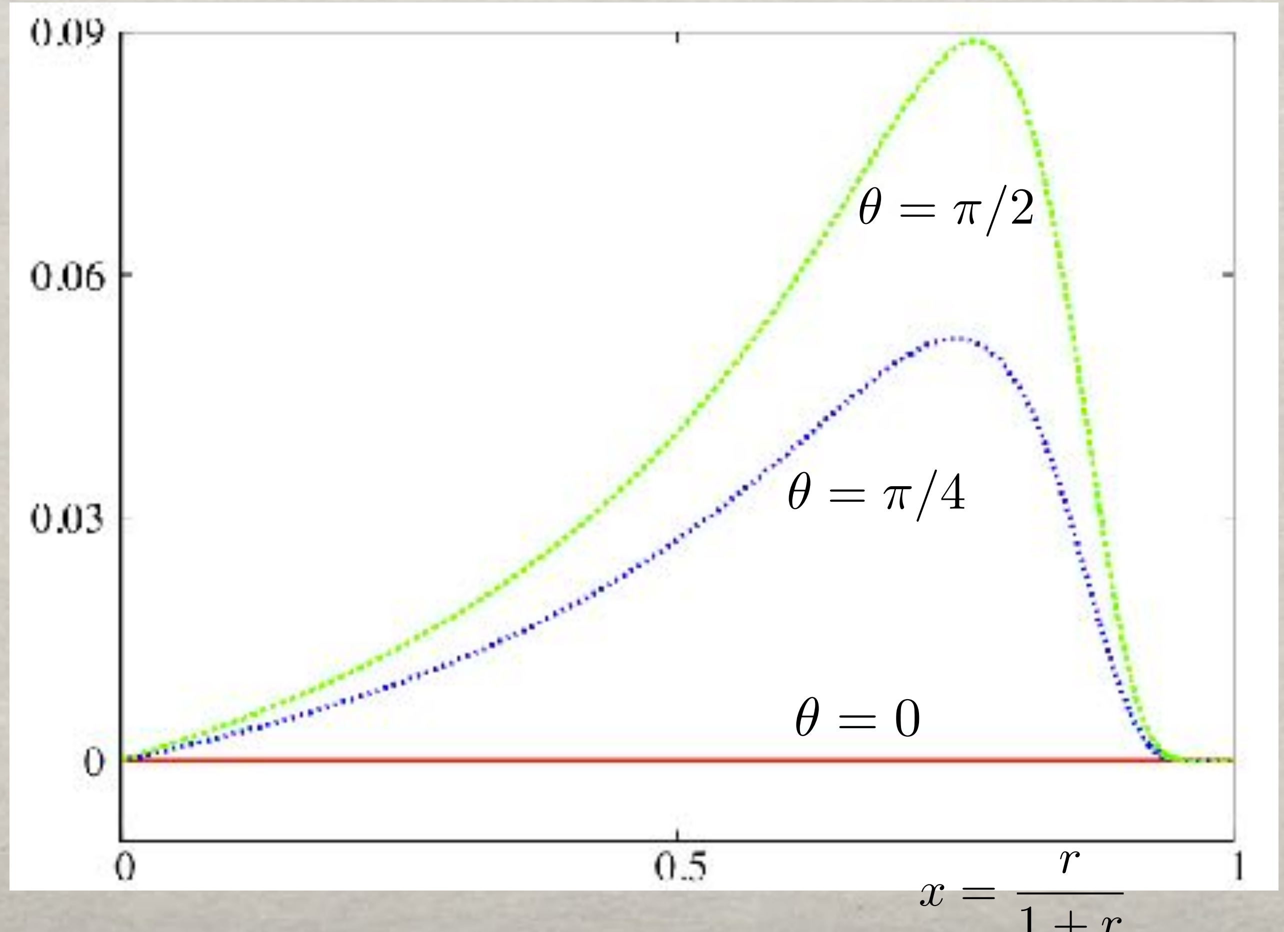
Exercise

Show this.

Gravitating scalar/vector solitons: bosonic stars

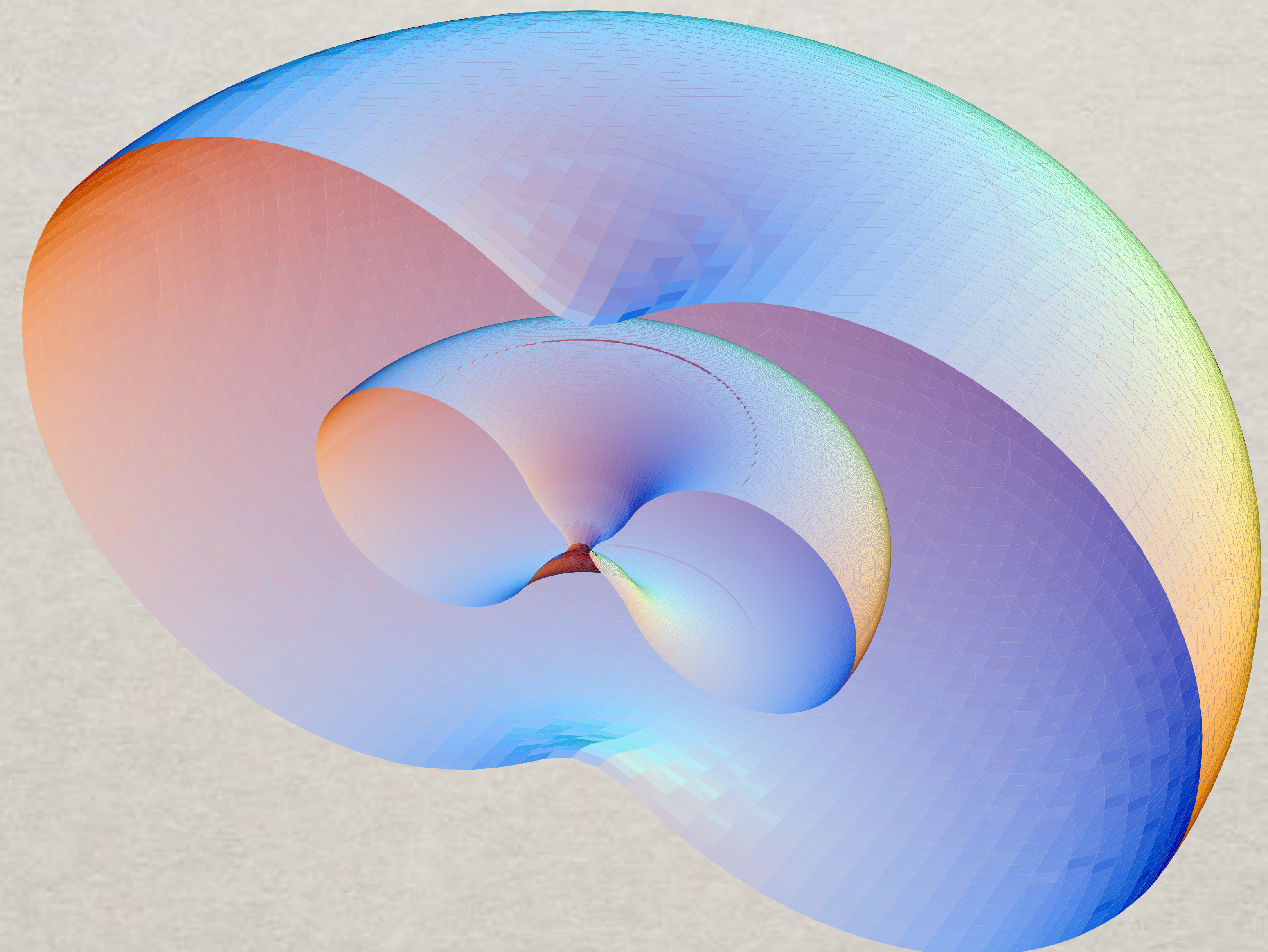
Scalar field profile (left) and for a typical rotating boson star, m=1, first branch, w=0.85:





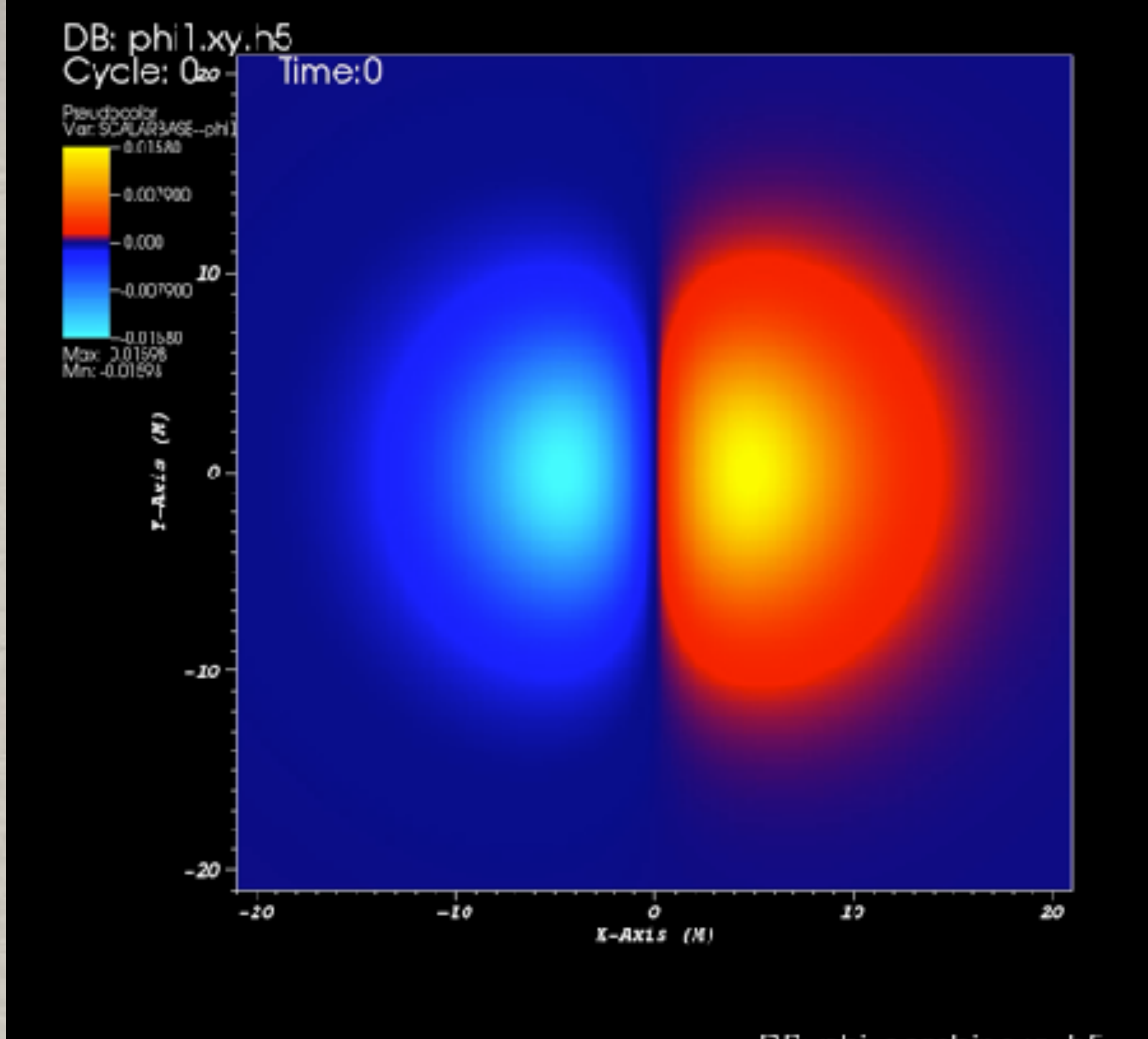
Gravitating scalar/vector solitons: bosonic stars

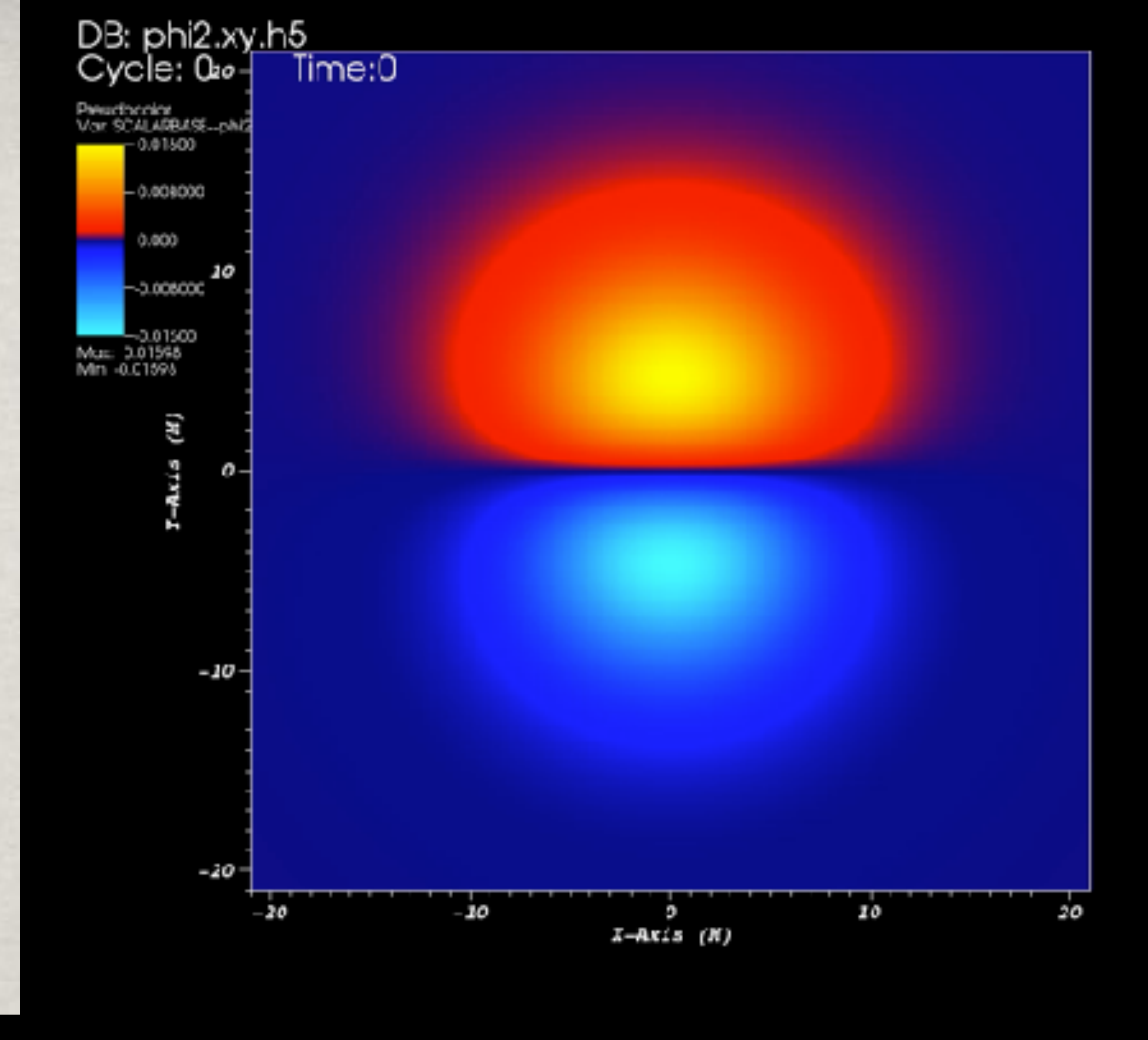
Surfaces of constant scalar energy density:



C. A. R. Herdeiro and E. Radu, Int. J. Mod. Phys. D 23 (2014) 12, 1442014 [arXiv:1405.3696 [gr-qc]]

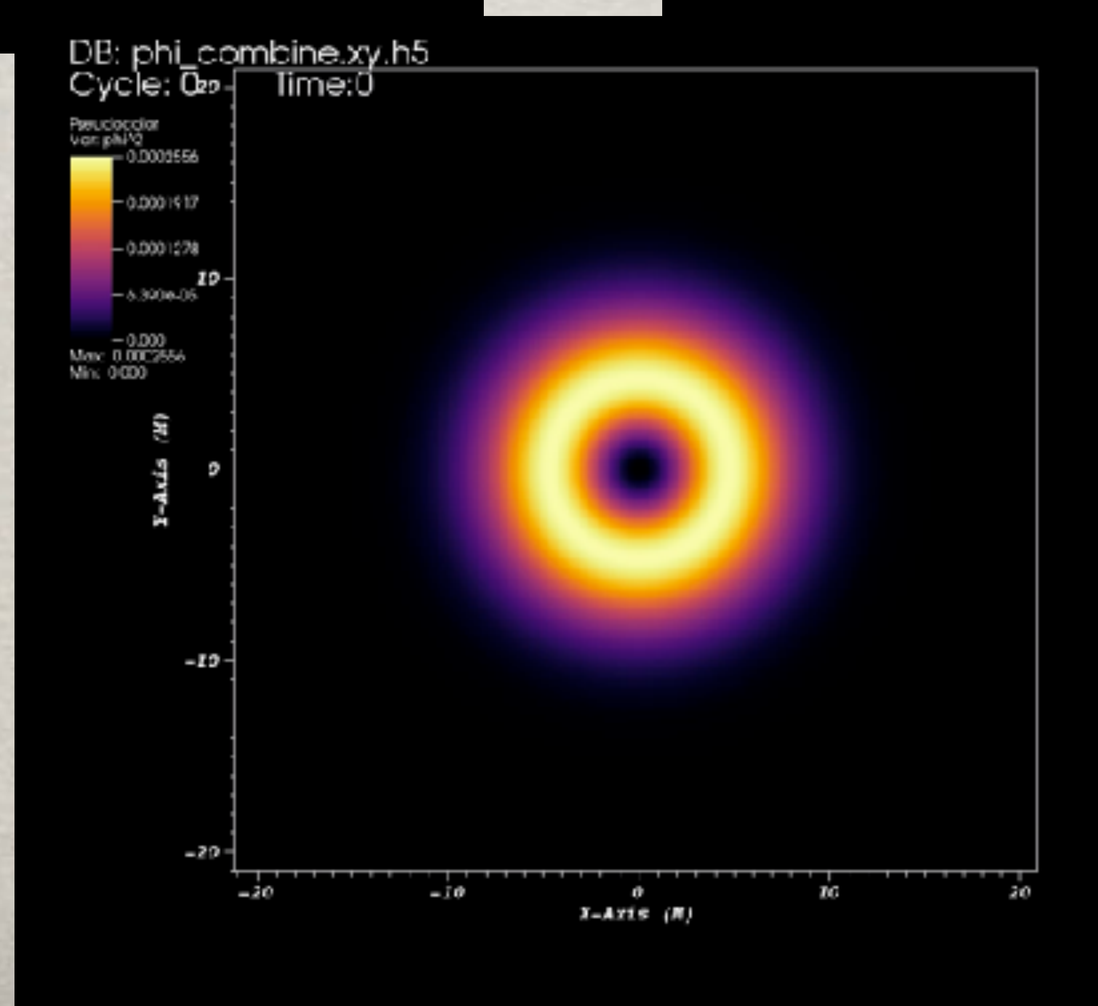
Rotating boson stars are rotating “mass” tori in GR





$\mathcal{R}(\Phi)$

$\mathcal{I}(\Phi)$



$|\Phi|^2$

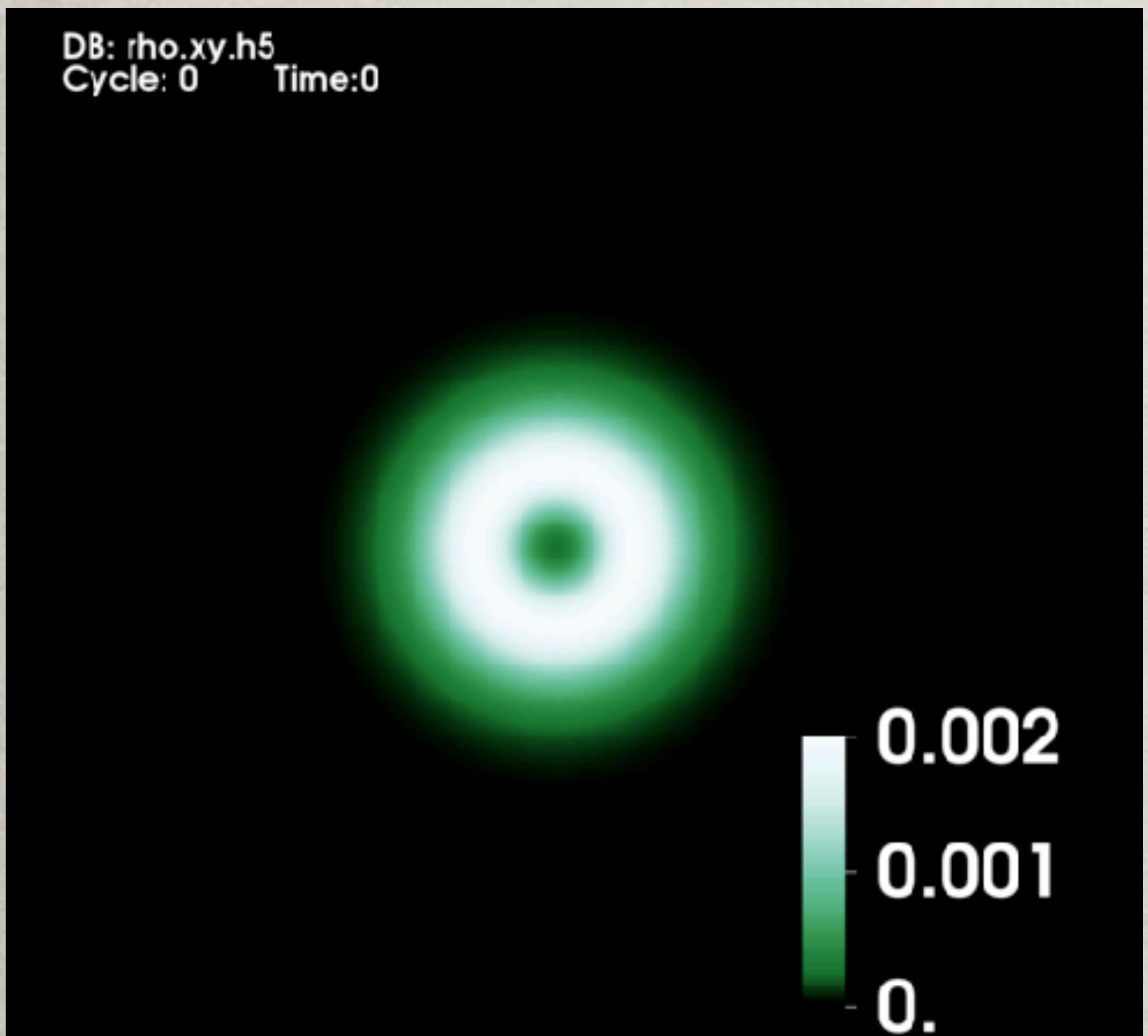
Simulations

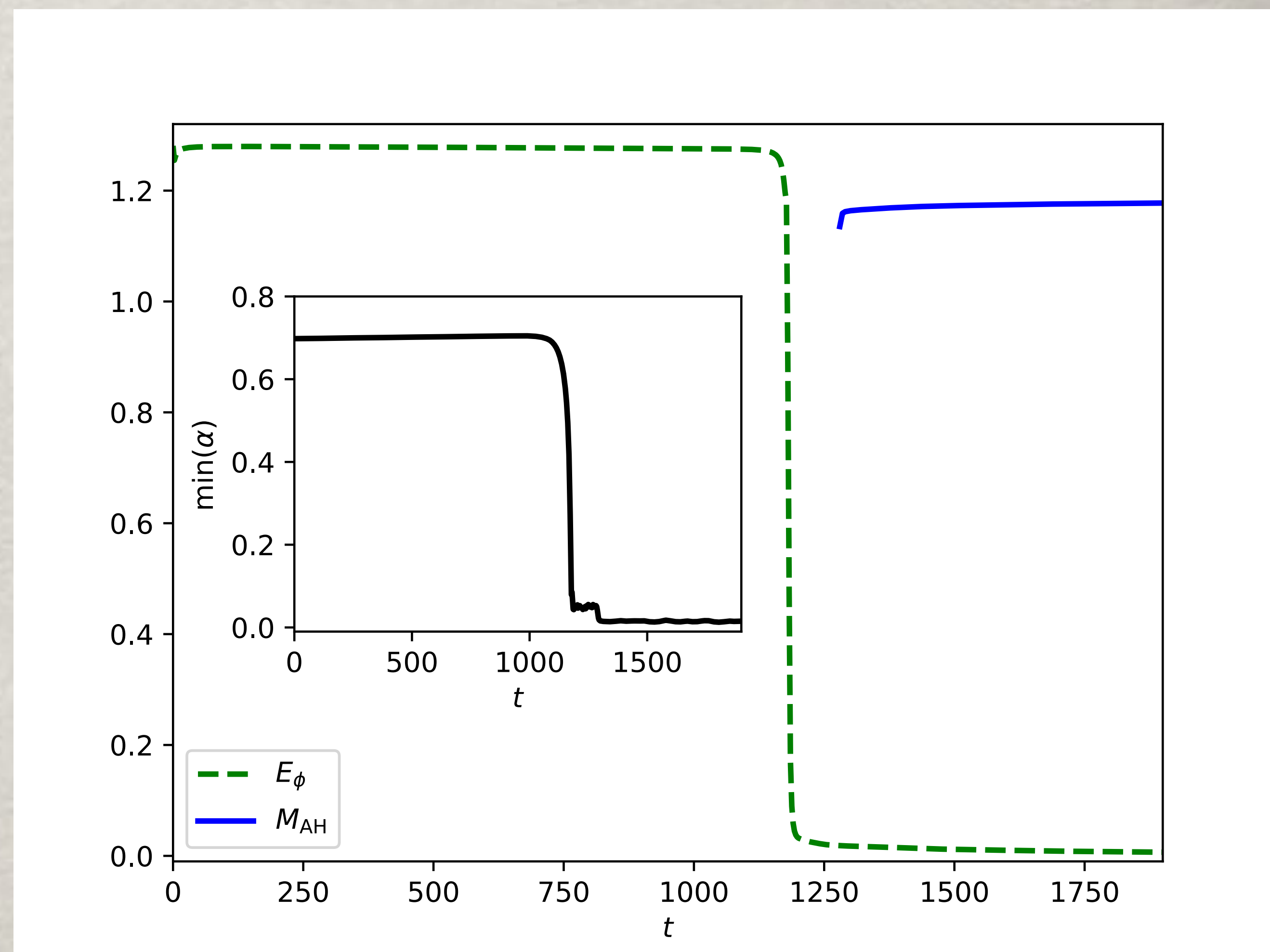
Zilhão (2017)

Spinning scalar boson stars have a non-axisymmetric instability

Sanchis-Gual, Di Giovanni, Zilhão, CH, P. Cerda-Duran, Font and Radu, Phys. Rev. Lett. 123 (2019) 221101

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

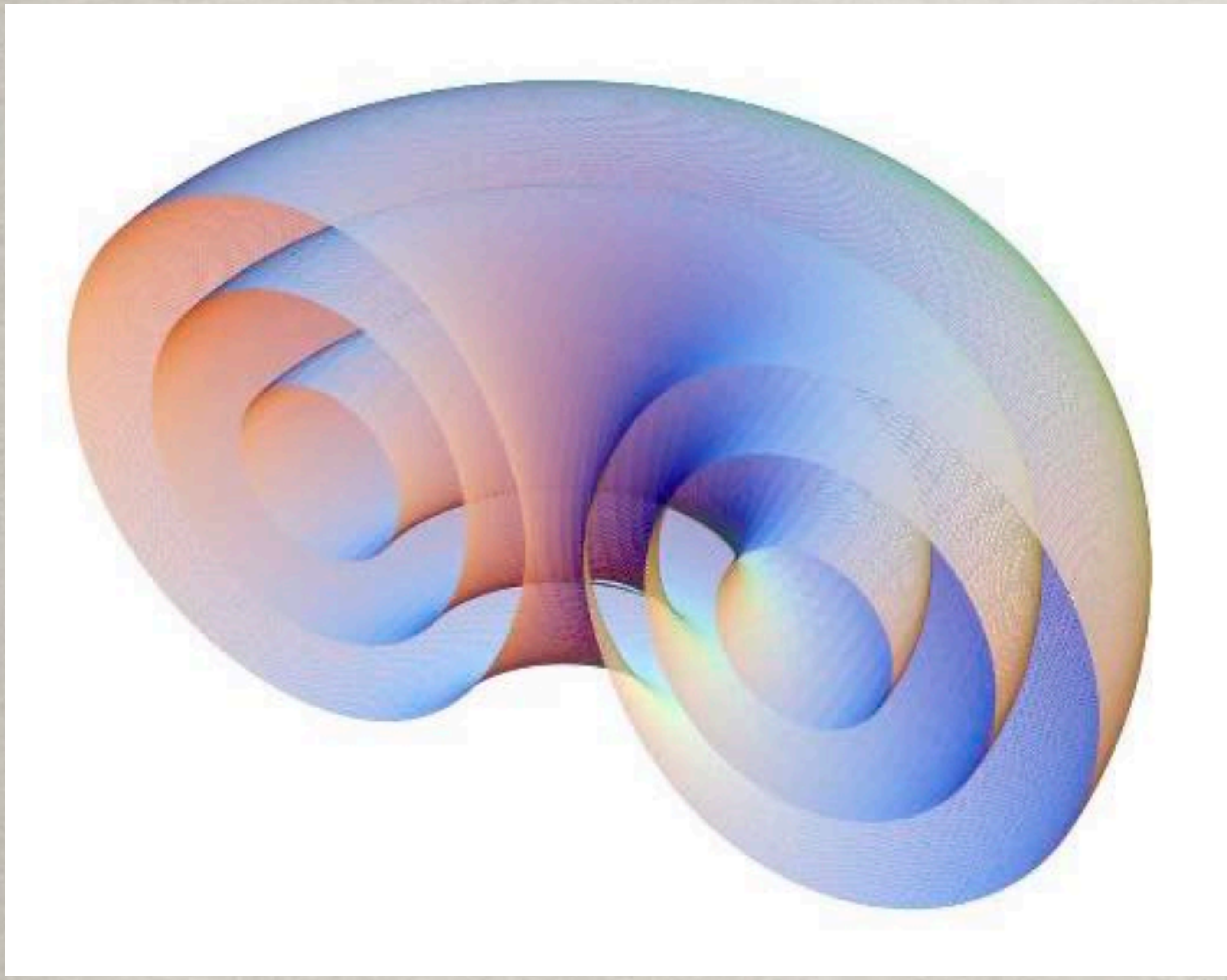




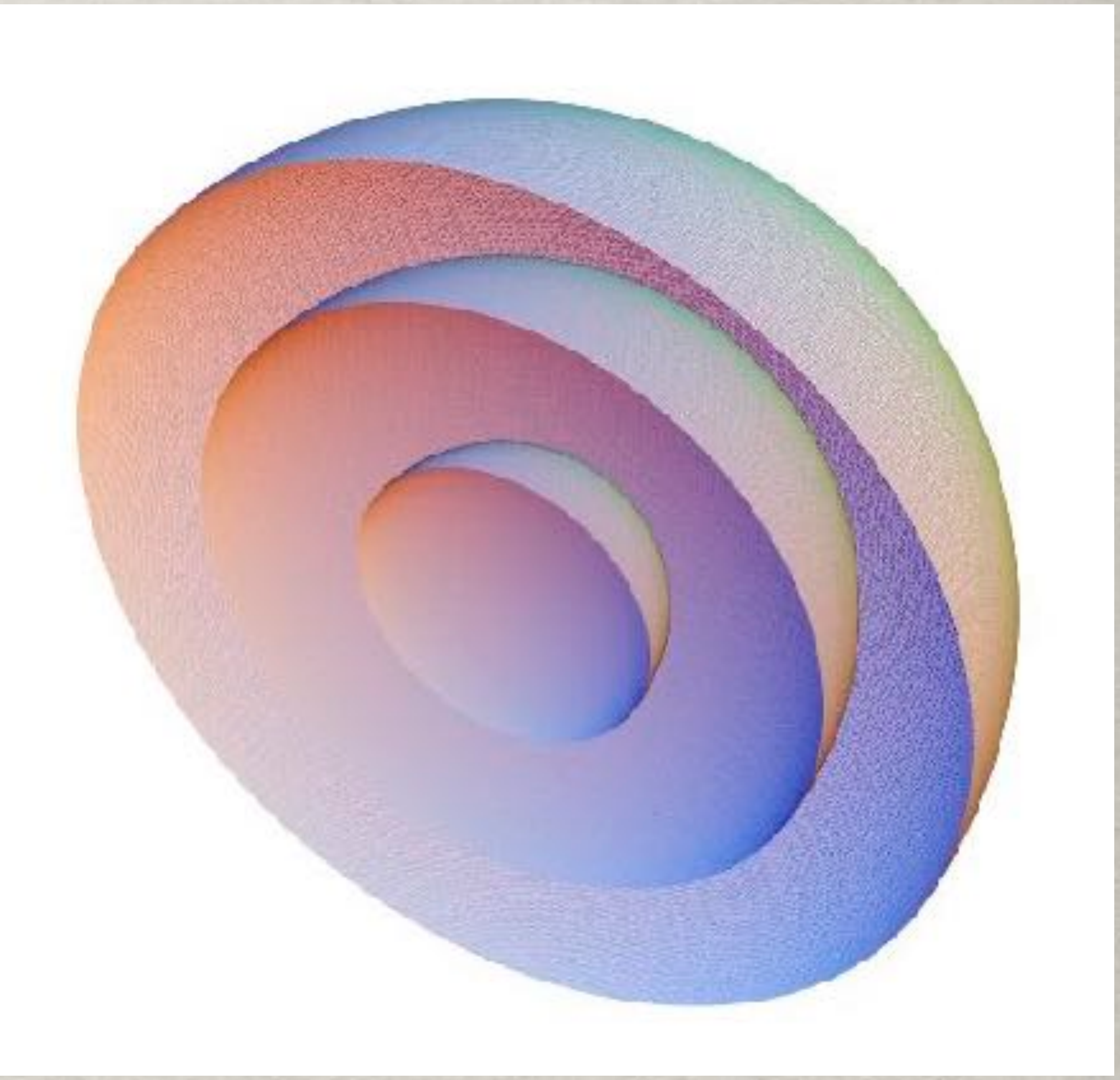
Instability may be associated to toroidal structure and is absent in cousin Proca model

Sanchis-Gual, Di Giovanni, Zilhão, CH, P. Cerda-Duran, Font and Radu, Phys. Rev. Lett. 123 (2019) 221101

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



Rotating boson stars



Rotating Proca stars

Brito, Cardoso, CH and Radu, PLB 752 (2016) 291

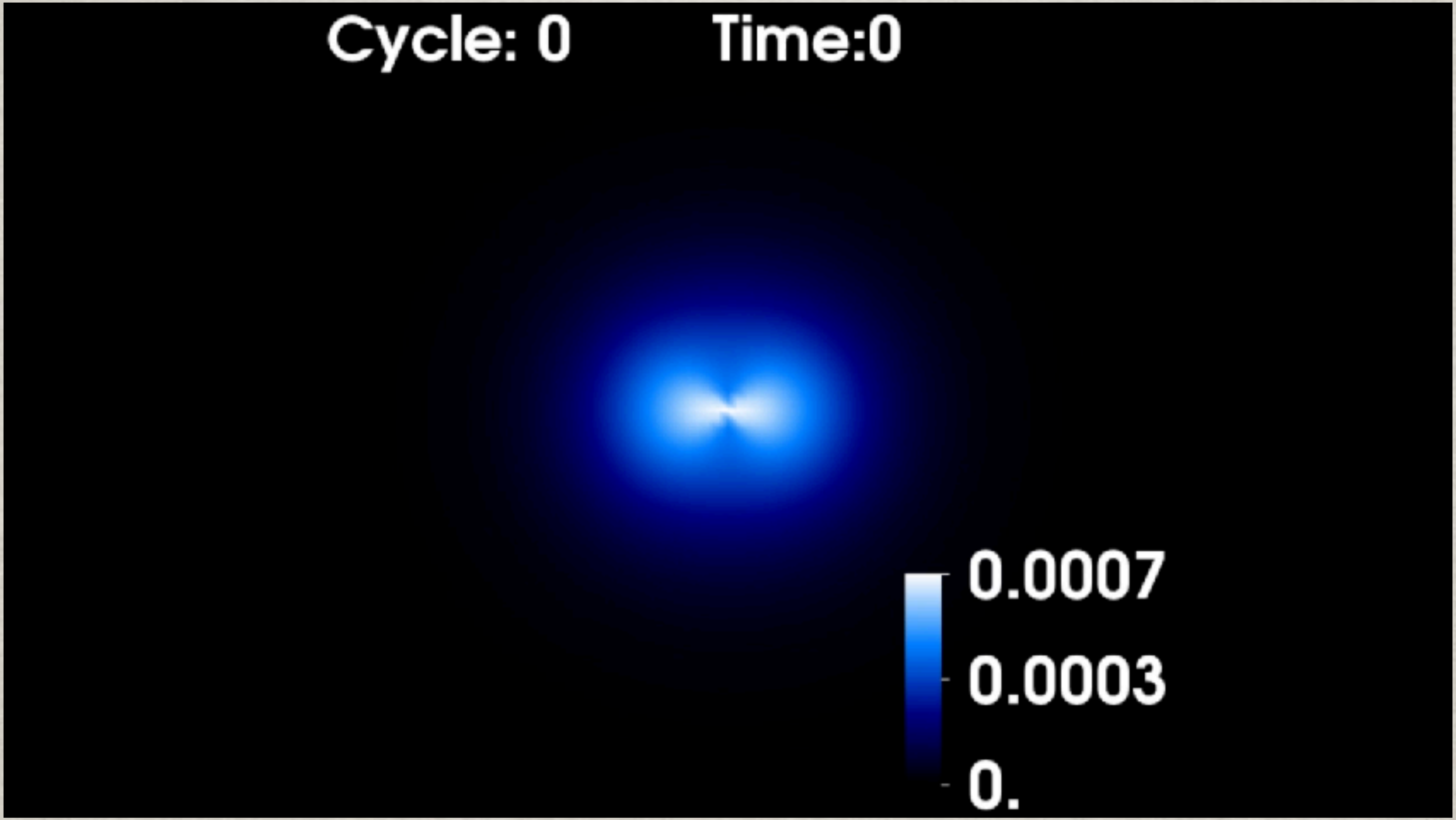
CH, Radu and Rúnarsson, CQG 33 (2016) 154001

CH, Perapechka, Radu and Shnir, PLB 797 (2019) 134845

Evolution of a perturbed spinning Proca star

Sanchis-Gual, Di Giovanni, Zilhão, Herdeiro, P. Cerda-Duran, Font and Radu, Phys. Rev. Lett. 123 (2019) 221101

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

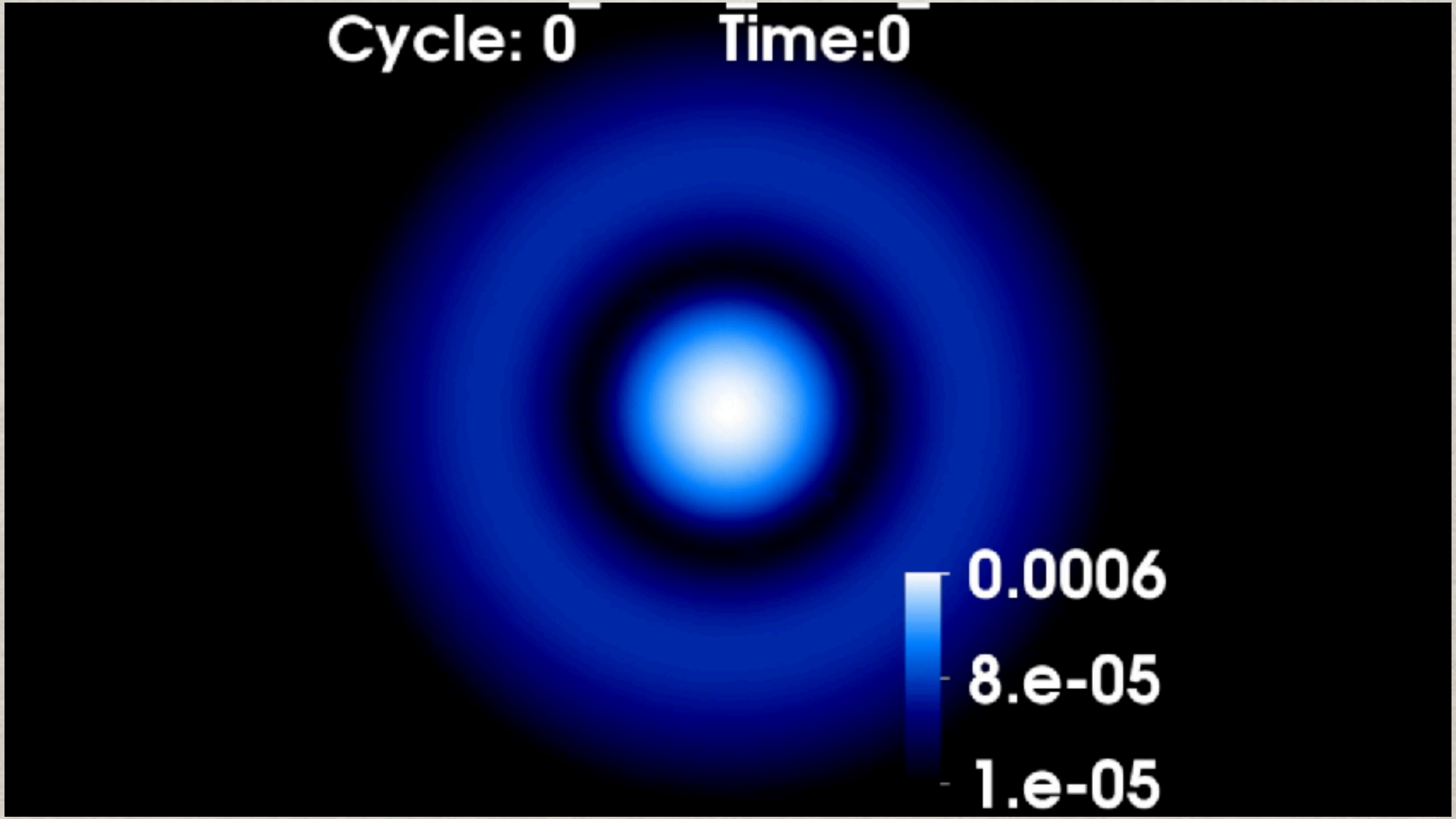


Gravitating scalar/vector solitons: bosonic stars

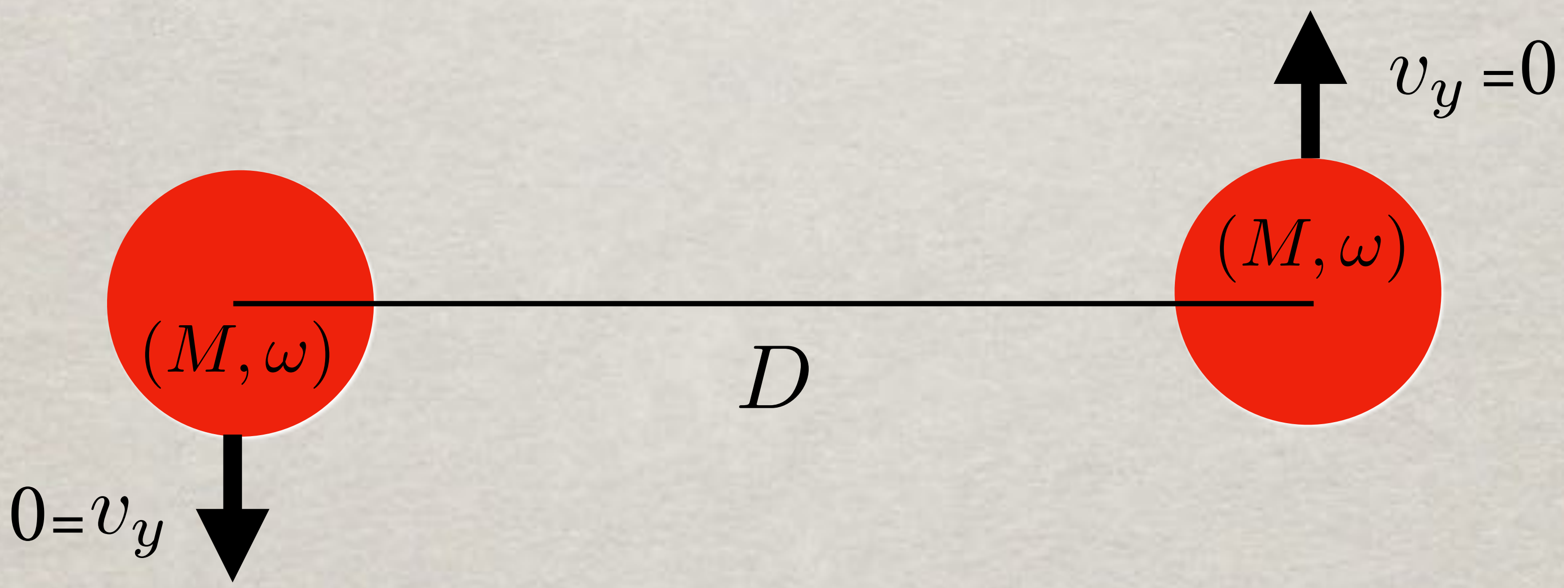
Evolution of an excited spinning Proca star

Sanchis-Gual, Di Giovanni, Zilhão, Herdeiro, P. Cerda-Duran, Font and Radu, Phys. Rev. Lett. 123 (2019) 221101

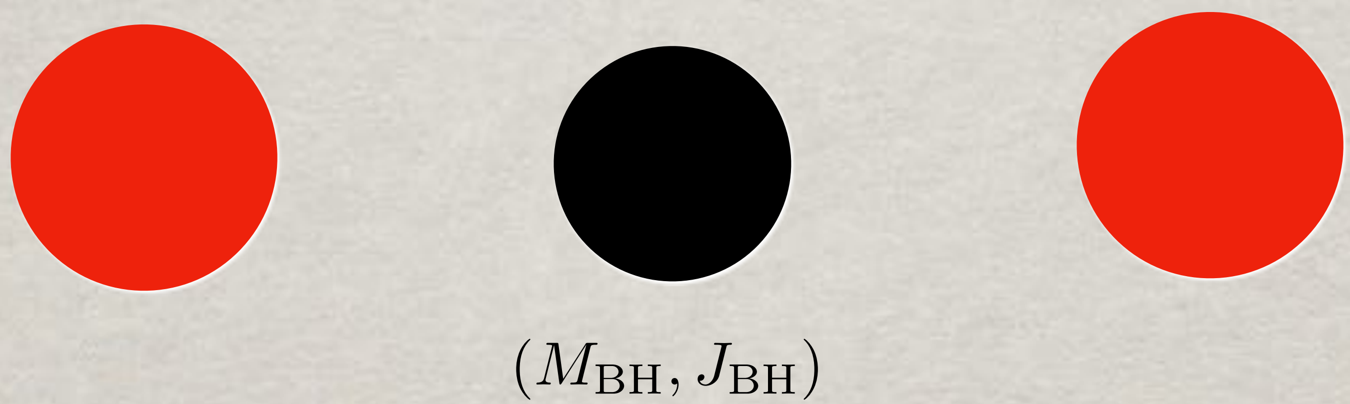
http://gravitation.web.ua.pt/node/1740

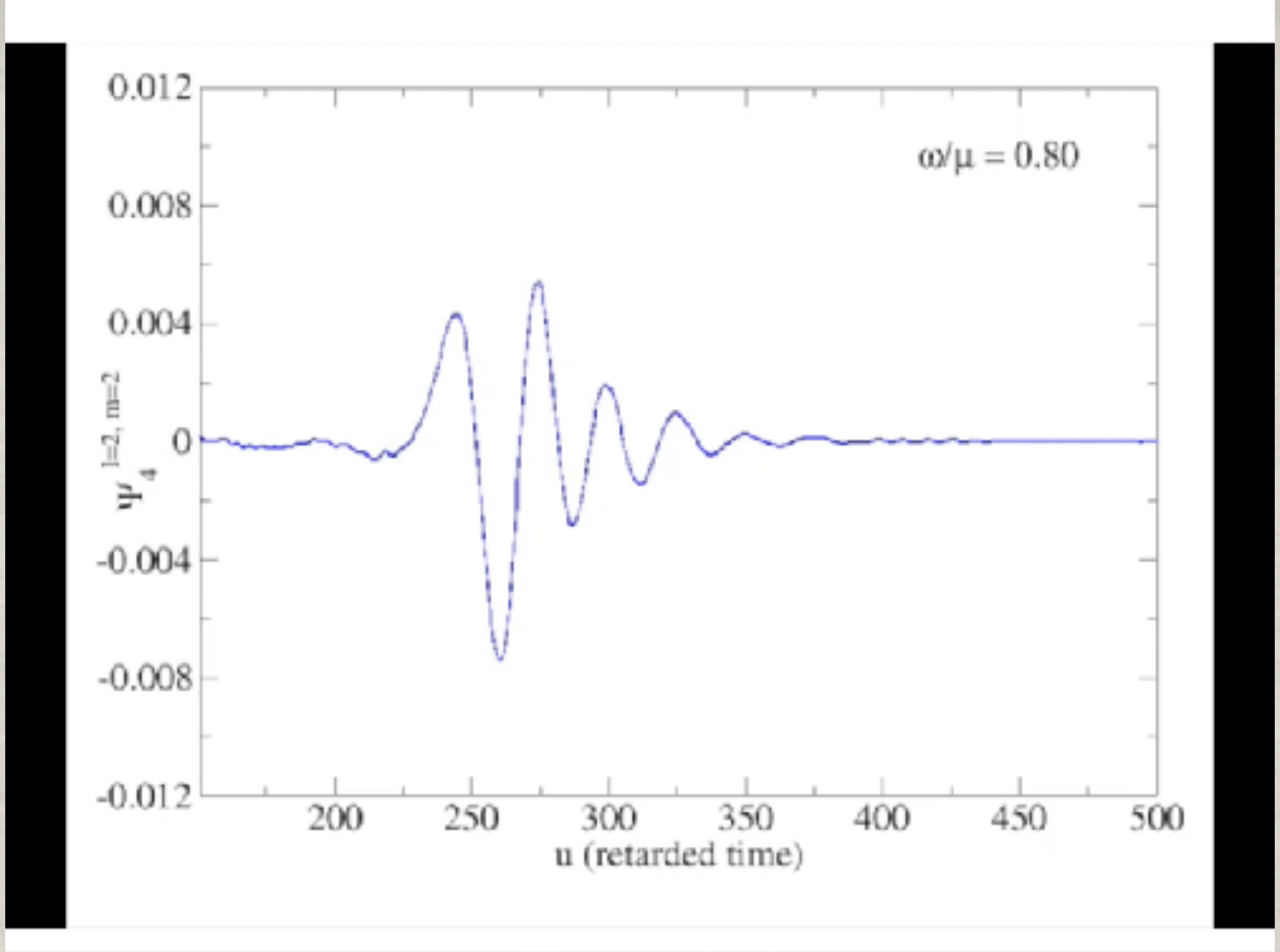


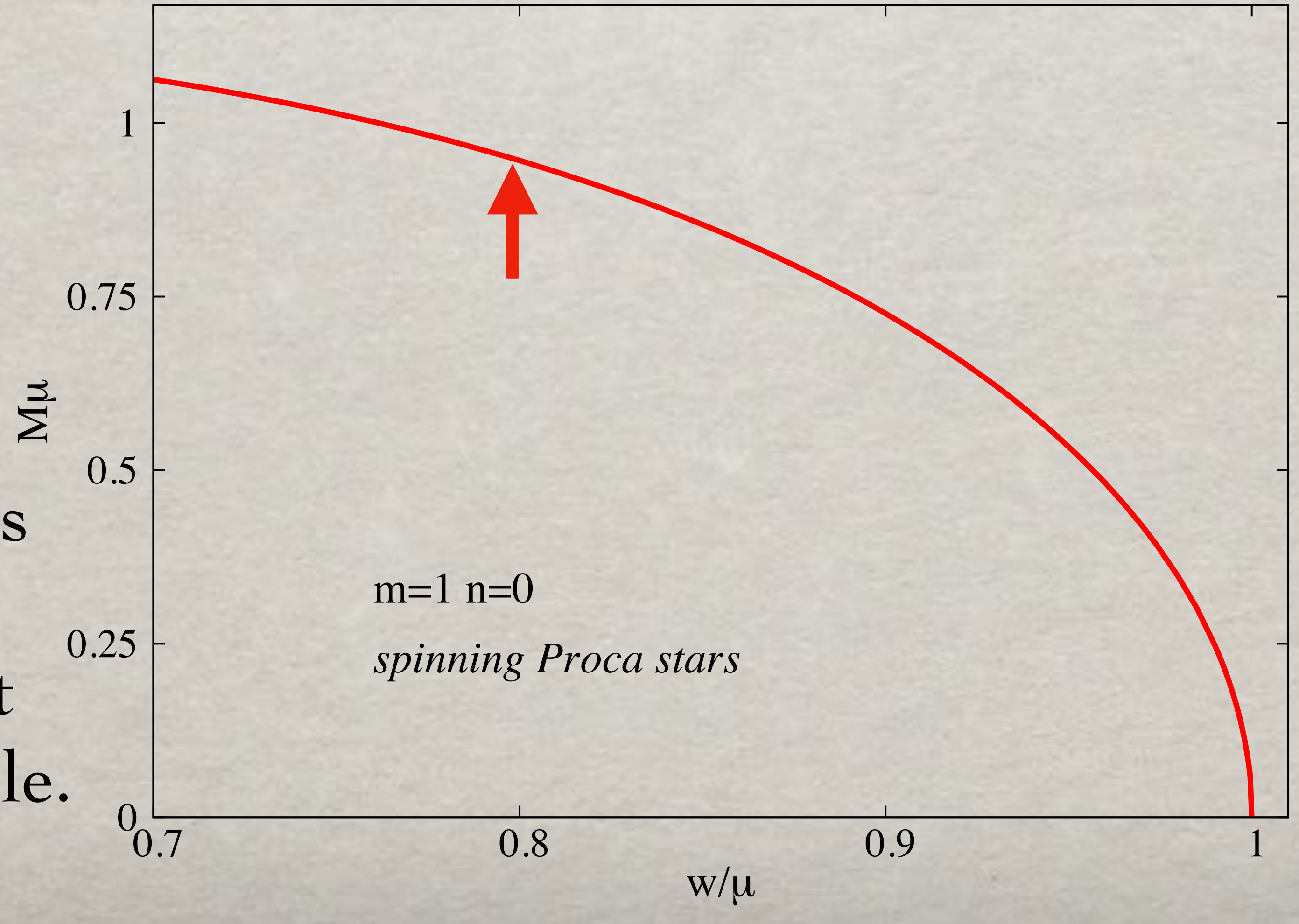
Mergers of spinning vector boson stars



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.

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]

[1]*Instituto Galego de Física de Altas Enerxías, Universidade de Santiago de Compostela, 15782 Santiago de Compostela, Galicia, Spain*
[2]*Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong*
[3]*Monash Centre for Astrophysics, School of Physics and Astronomy, Monash University, Victoria 3800, Australia*
[4]*OzGrav: The ARC Centre of Excellence for Gravitational-Wave Discovery, Clayton, Victoria 3800, Australia*
[5]*Centro de Astrofísica e Gravitação—CENTRA, Departamento de Física, Instituto Superior Técnico—IST, Universidade de Lisboa—UL, Avenida Rovisco Pais 1, 1049-001, Portugal*
[6]*Departamento de Matemática da Universidade de Aveiro and Centre for Research and Development in Mathematics and Applications (CIDMA), Campus de Santiago, 3810-183 Aveiro, Portugal*
[7]*Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Am Mühlenberg 1, Potsdam 14476, Germany*
[8]*Departamento de Astronomía y Astrofísica, Universitat de València, Dr. Moliner 50, 46100, Burjassot (València), Spain*
[9]*Observatori Astronòmic, Universitat de València, C/ Catedrático José Beltrán 2, 46980, Paterna (València), Spain*

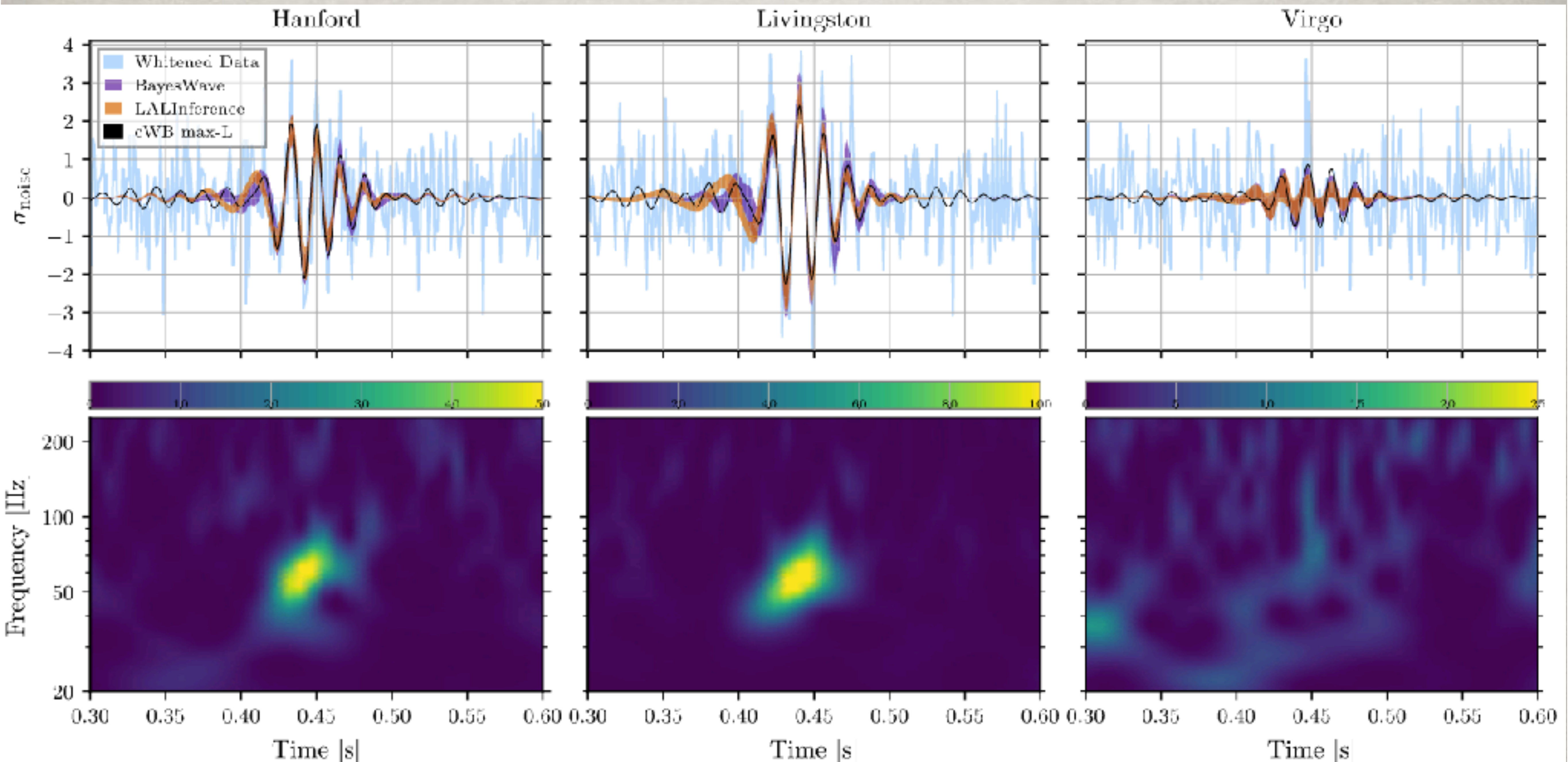
(Received 26 September 2020; revised 20 November 2020; accepted 14 January 2021; published 24 February 2021)

Advanced LIGO-Virgo have reported a short gravitational-wave signal (GW190521) interpreted as a quasicircular merger of black holes, one at least populating the pair-instability supernova gap, that formed a remnant black hole of $M_f \sim 142\ M_\odot$ at a luminosity distance of $d_L \sim 5.3$ Gpc. With barely visible pre-merger emission, however, GW190521 merits further investigation of the pre-merger dynamics and even of the very nature of the colliding objects. We show that GW190521 is consistent with numerically simulated signals from head-on collisions of two (equal mass and spin) horizonless vector boson stars (aka Proca stars), forming a final black hole with $M_f = 231^{+13}_{-17}\ M_\odot$, located at a distance of $d_L = 571^{+348}_{-181}$ Mpc. This provides the first demonstration of close degeneracy between these two theoretical models, for a real gravitational-wave event. The favored mass for the ultralight vector boson constituent of the Proca stars is $\mu_V = 8.72^{+0.73}_{-0.82} \times 10^{-13}$ eV. Confirmation of the Proca star interpretation, which we find statistically slightly preferred, would provide the first evidence for a long sought dark matter particle.

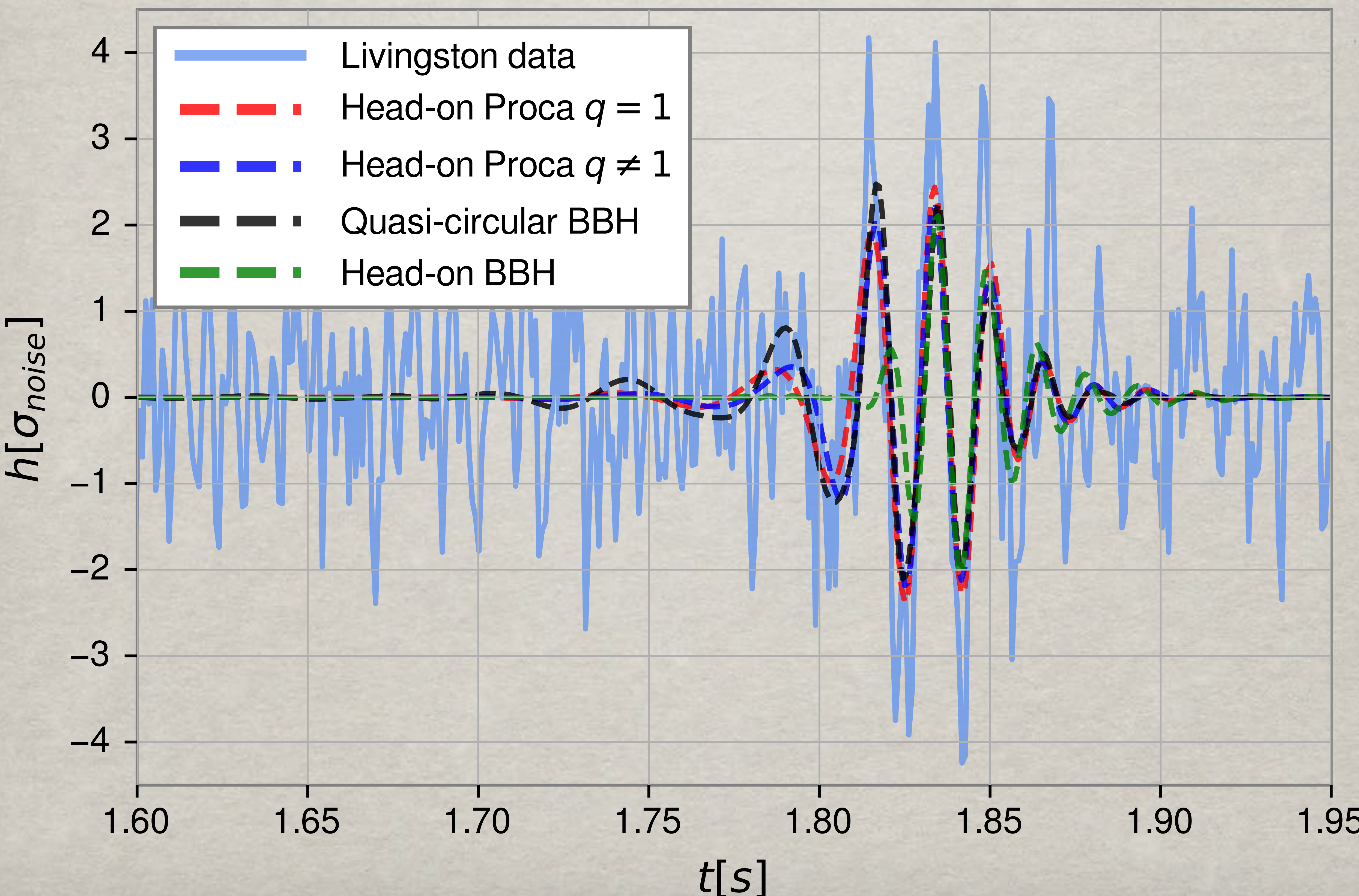
DOI: 10.1103/PhysRevLett.126.081101

GW190521

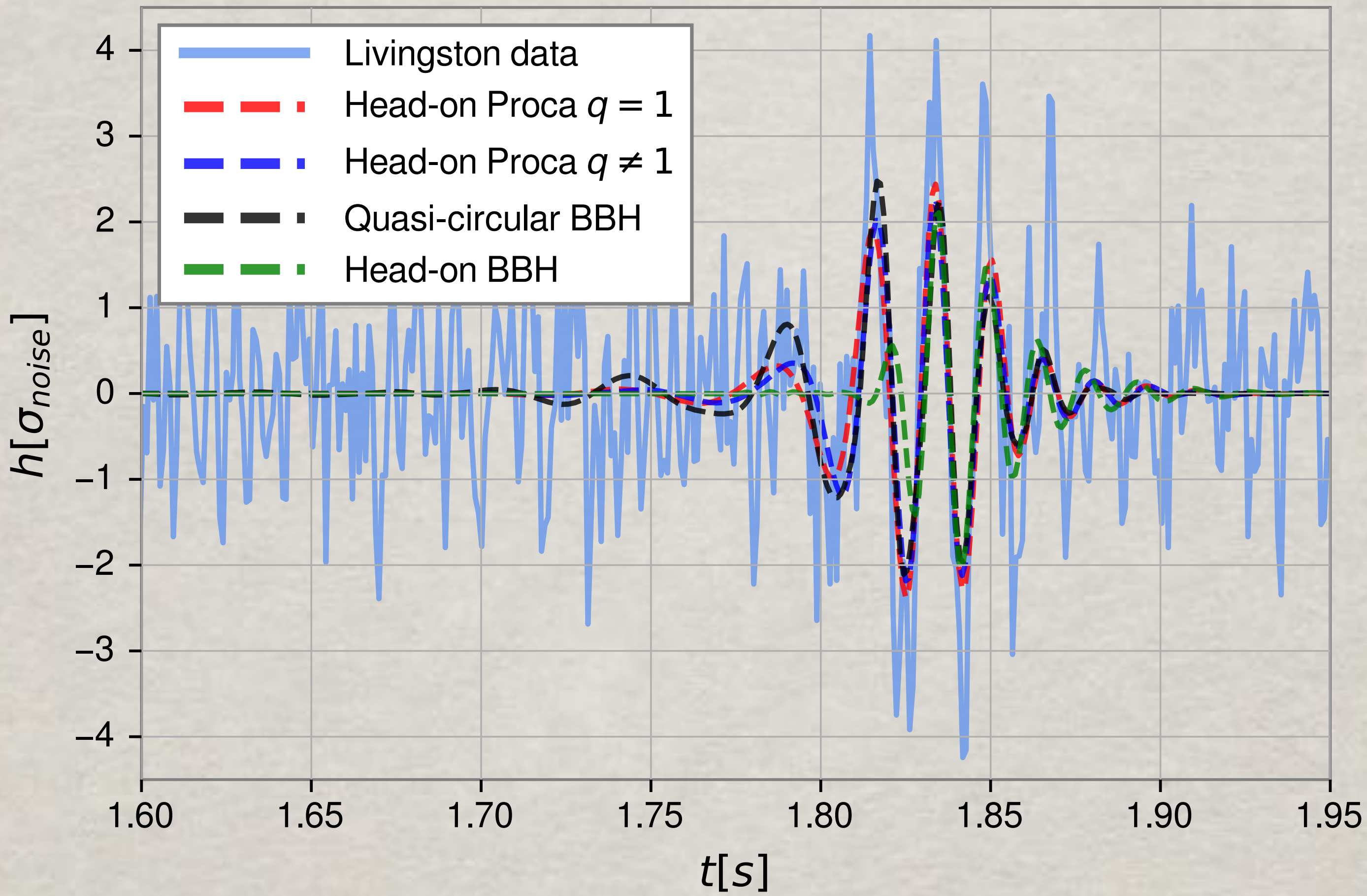
PRL125(2020)10



Gravitating scalar/vector solitons: bosonic stars



Gravitating scalar/vector solitons: bosonic stars

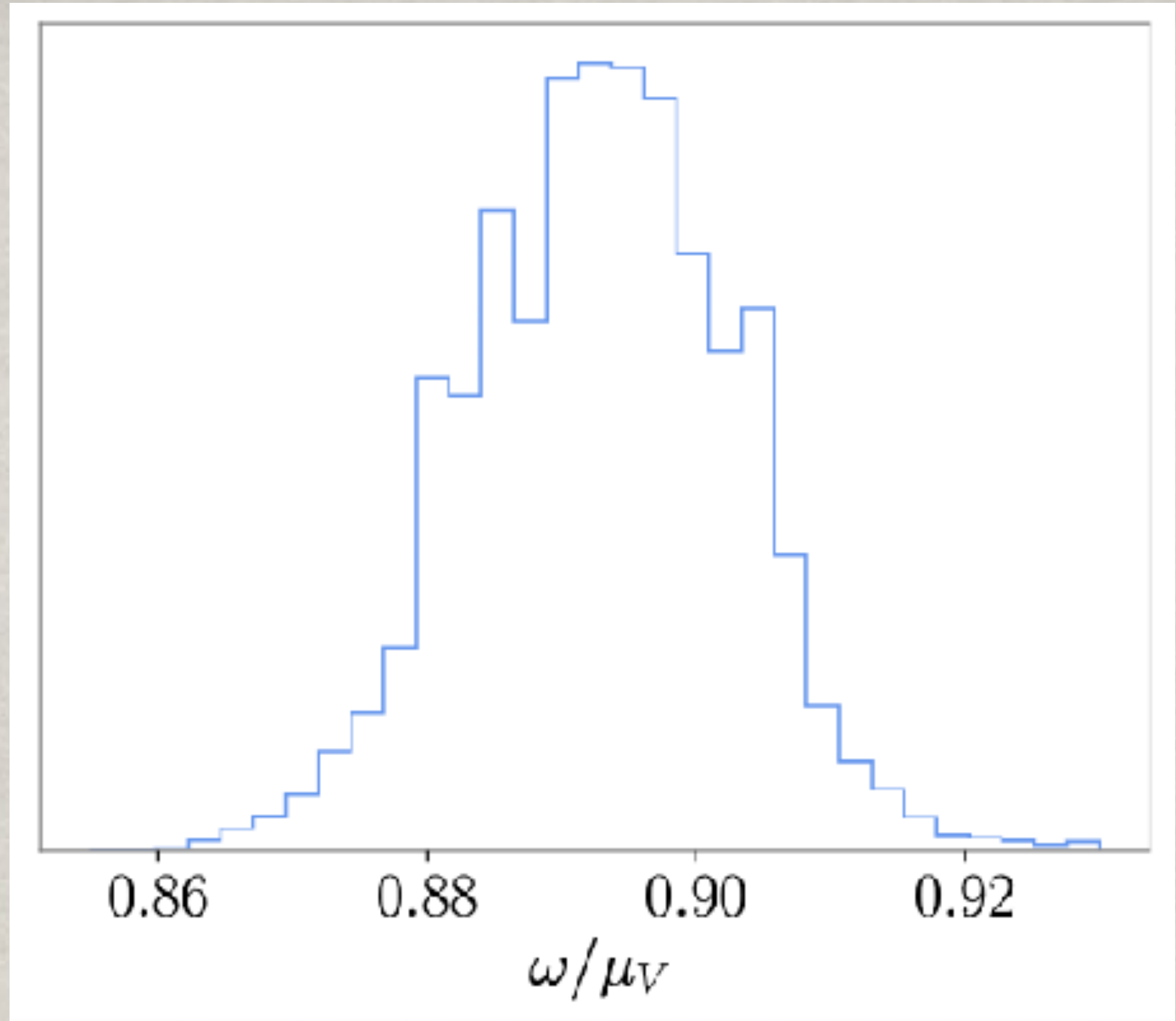


Waveform model	$\log \mathcal{B}$	$\log \mathcal{L}_{\max}$
Quasi-circular Binary Black Hole	80.1	105.2
Head-on Equal-mass Proca Stars	80.9	106.7
Head-on Unequal-mass Proca Stars	82.0	106.5
Head-on Binary Black Hole	75.9	103.2

Prior:
Uniform in co-moving distance

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

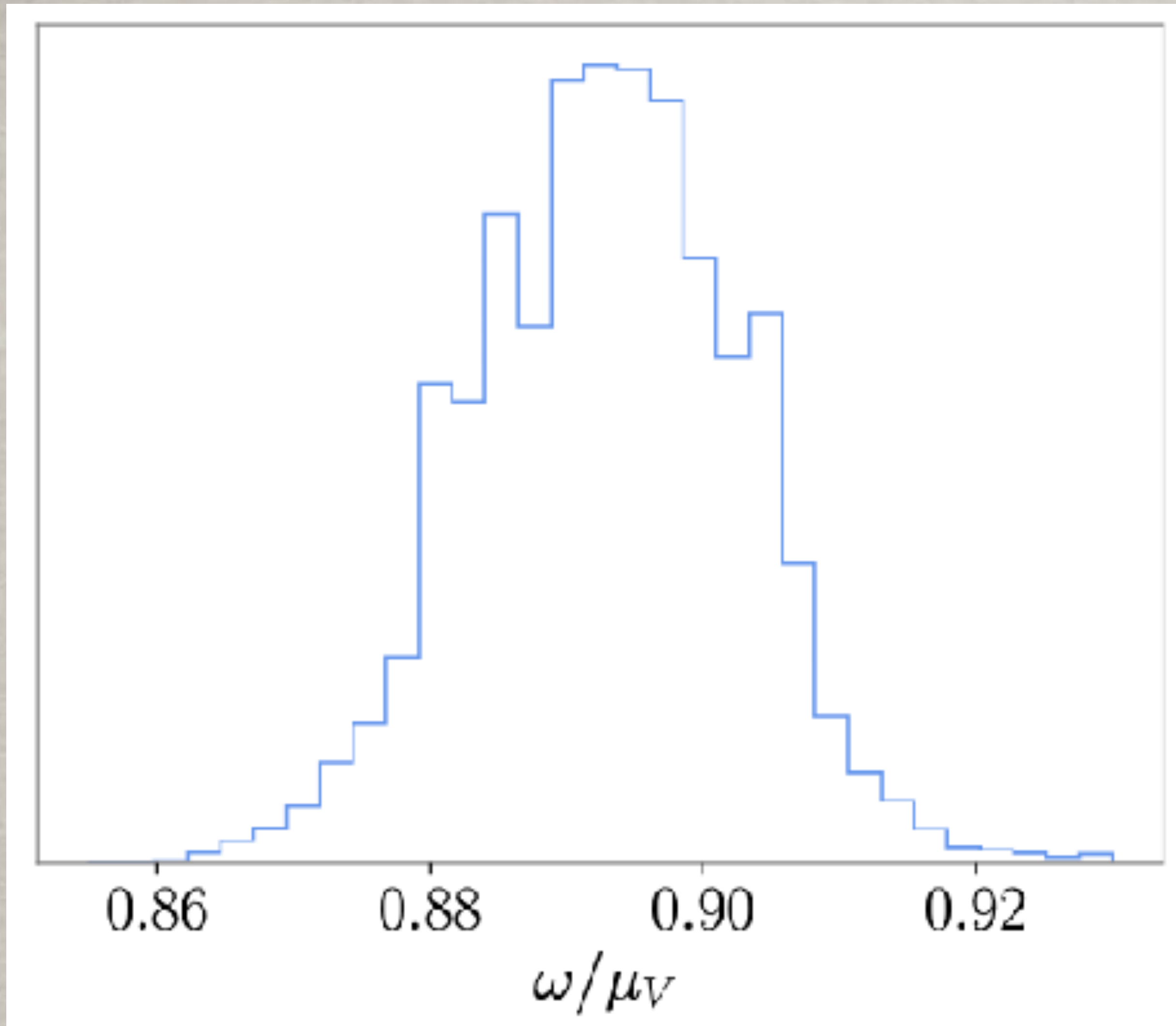
Prior:
Uniform in distance

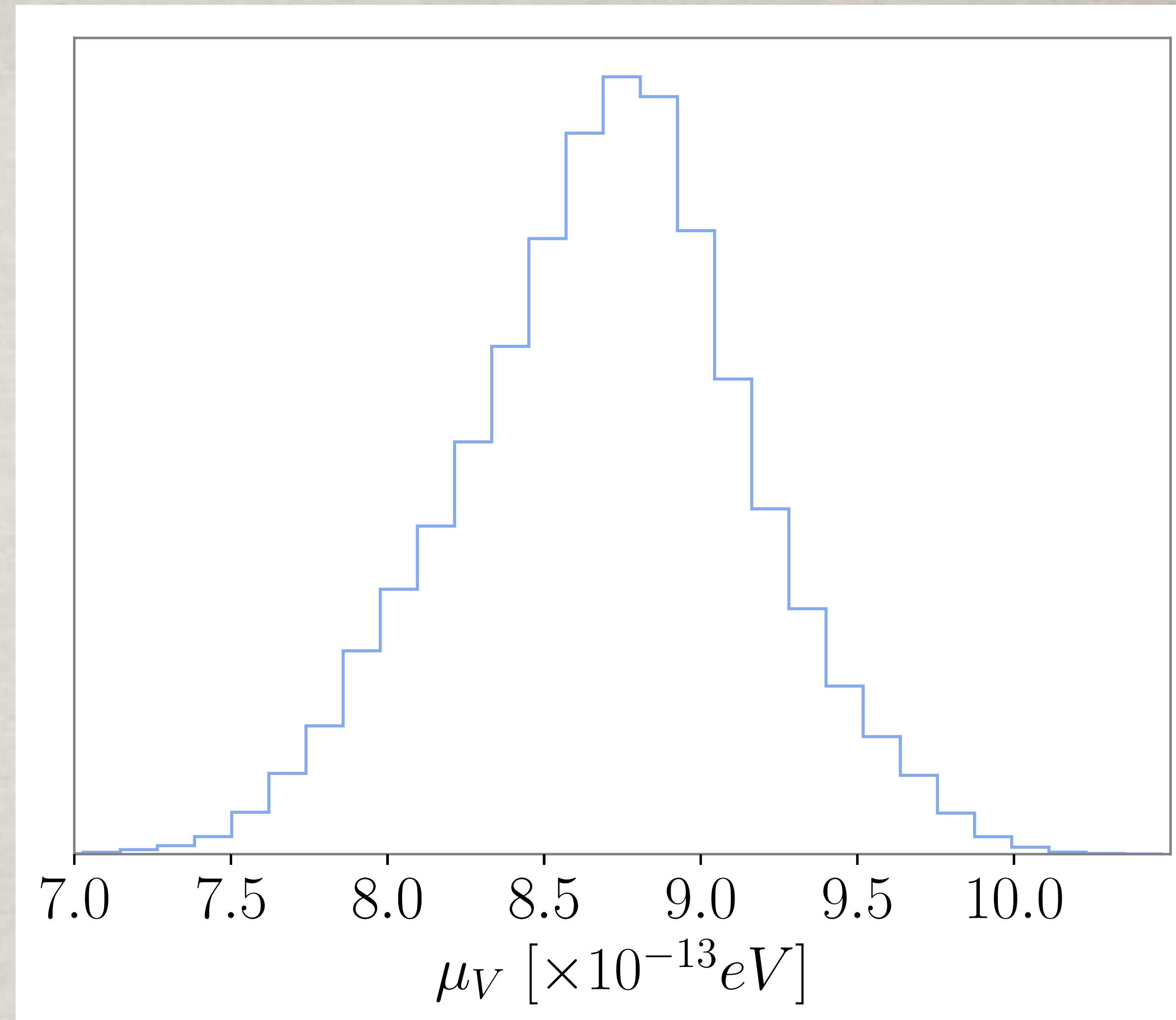


$$\omega/\mu_V = 0.893^{+0.015}_{-0.015}$$

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.

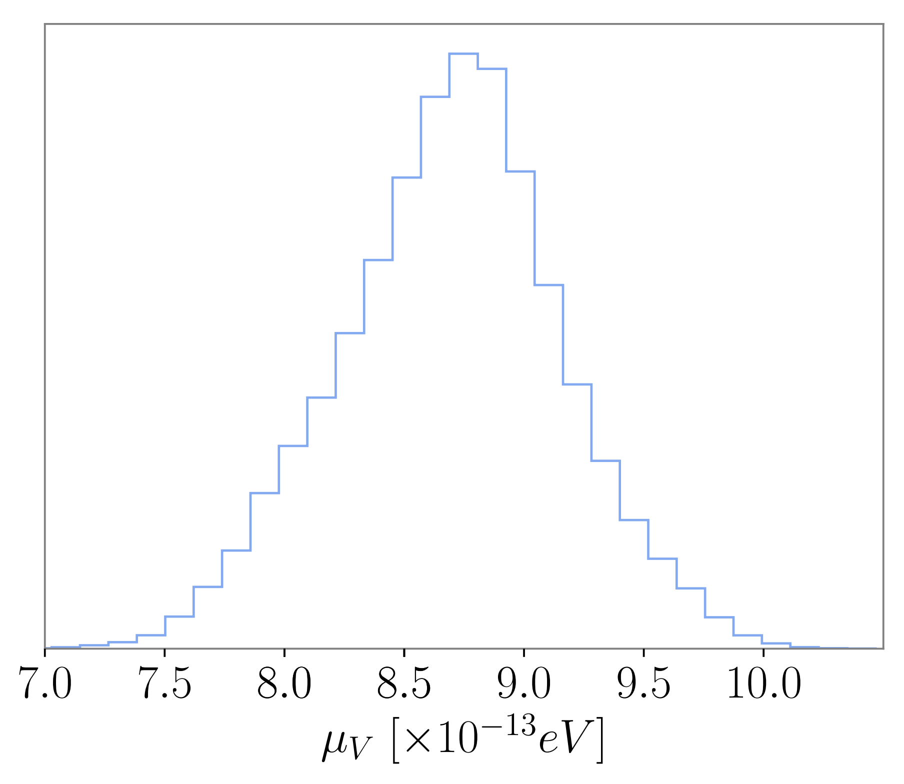




Thus we get a distribution for the mass of the ultralight boson.

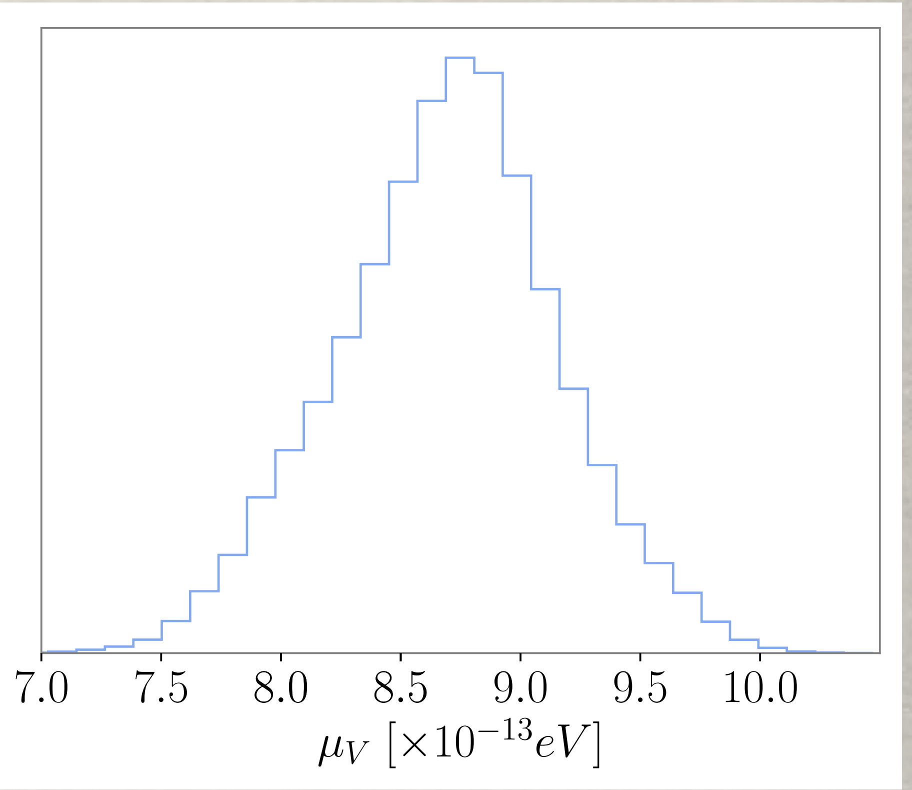
Gravitating scalar/vector solitons: bosonic stars

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	$0.893^{+0.015}_{-0.015}$	$(*)0.905^{+0.012}_{-0.042}$
Boson mass μ_V [$\times 10^{-13}$]	$8.72^{+0.73}_{-0.82}$ eV	$8.59^{+0.58}_{-0.57}$ eV
Maximal boson star mass	$173^{+19}_{-14}\ M_\odot$	$175^{+13}_{-11}\ M_\odot$



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	$0.893^{+0.015}_{-0.015}$	$(*)0.905^{+0.012}_{-0.042}$
Boson mass μ_V $[\times 10^{-13}]$	$8.72^{+0.73}_{-0.82}$ eV	$8.59^{+0.58}_{-0.57}$ eV
Maximal boson star mass	$173^{+19}_{-14}\ M_\odot$	$175^{+13}_{-11}\ M_\odot$



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

No previous GW signals can be Proca star mergers.

Masses in the Stellar Graveyard

in Solar Masses