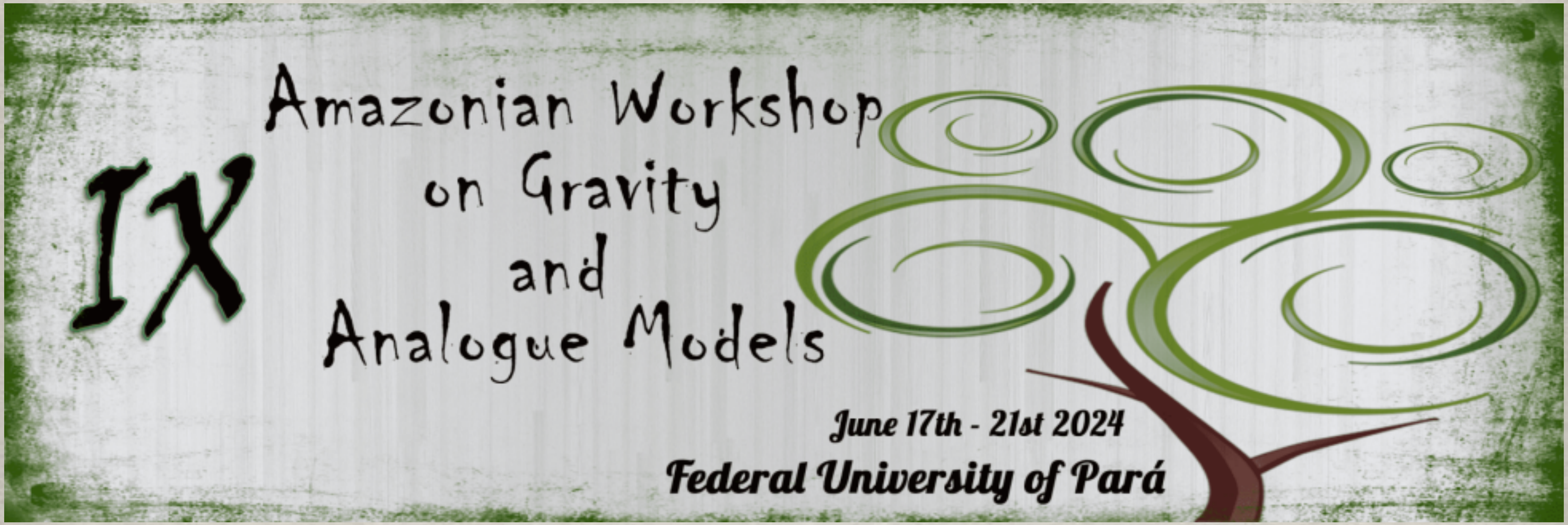
The wonderful world of compact objects with bosonic fields in GR



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

IX Amazonian Workshop on Gravity and Analogue Models

June 17, 2024

in collaboration with M. Brito, R. Brito, V. Cardoso, P. Cerda-Duran, P. Cunha, E. Costa-Filho, J. Degollado, J. Font, F. di Giovanni, J. Kunz, A. Morais, I. Parapechka, E. Radu, N. Sanchis-Gual, N. Santos, Y. Shnir, M. Zilhão,…

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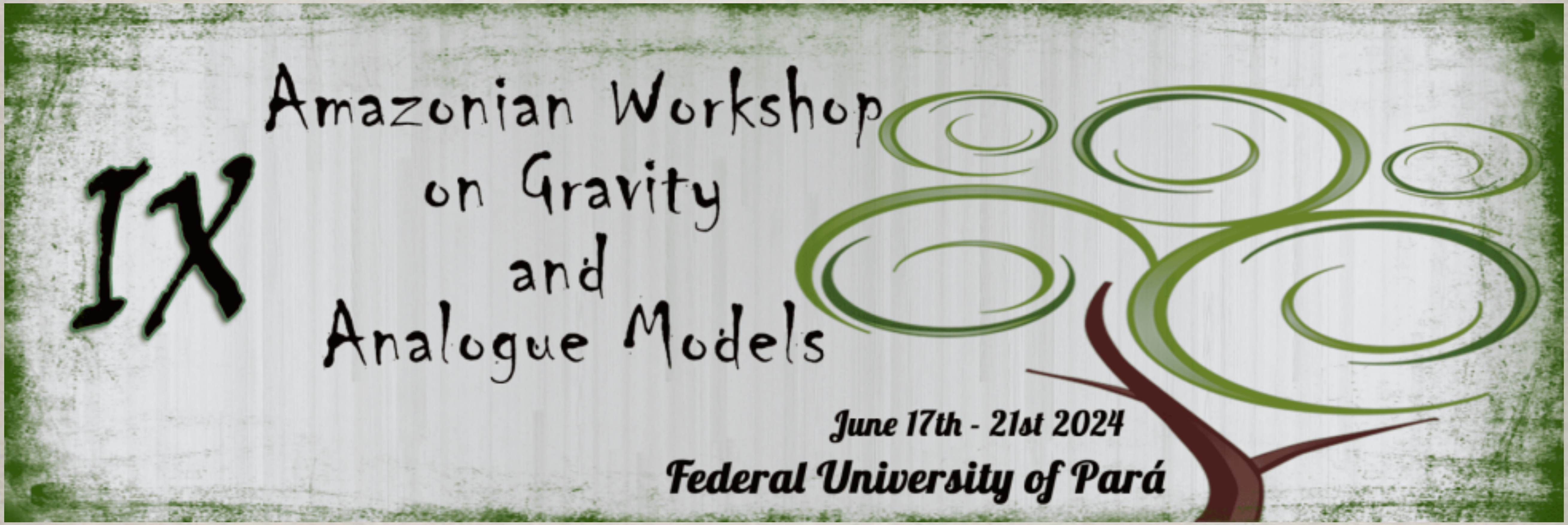

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The paradigms and "tunnel vision"

Our understanding of the most compact objects in the Universe, in particular black holes, is **b(i)ased** by our paradigmatic models.

Einstein-Maxwell:

- Integrable (with symmetry):
  analytic solutions;

- No solitons;

- No-hair for black holes (BHs):
  uniqueness of Kerr-Newman BHs;

- No balanced neutral 2-BH systems
  (asymptotically flat);

The paradigms and “tunnel vision”

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Einstein-(multi) Maxwell:
Einstein-(complex) Maxwell:

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TODAY!!

Einstein-(massive, complex) Maxwell
Einstein-(massive, complex) Klein-Gordon:

- No integrable structure known: numerical solutions;

- Landscape of solitons: bosonic stars (BSs) with some dynamical surprises;

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- Hairy BHs and non-uniqueness; deep relations to superradiance and BSs;

PRL **112,** 221101 (2014) PHYSICAL REVIEW LETTERS week ending 6 JUNE 2014

Kerr Black Holes with Scalar Hair

Carlos A. R. Herdeiro and Eugen Radu
Departamento de Física da Universidade de Aveiro and I3N, Campus de Santiago, 3810-183 Aveiro, Portugal
(Received 13 March 2014; revised manuscript received 23 April 2014; published 2 June 2014)

We present a family of solutions of Einstein's gravity minimally coupled to a complex, massive scalar field, describing asymptotically flat, spinning black holes with scalar hair and a regular horizon. These hairy black holes (HBHs) are supported by rotation and have no static limit. Besides mass M and angular momentum J, they carry a conserved, continuous Noether charge Q measuring the scalar hair. HBHs branch off from the Kerr metric at the threshold of the superradiant instability and reduce to spinning boson stars in the limit of vanishing horizon area. They overlap with Kerr black holes for a set of (M, J) values. A single Killing vector field preserves the solutions, tangent to the null geodesic generators of the event horizon. HBHs can exhibit sharp physical differences when compared to the Kerr solution, such as $J/M^2 > 1$, a quadrupole moment larger than J^2/M, and a larger orbital angular velocity at the innermos stable circular orbit. Families of HBHs connected to the Kerr geometry should exist in scalar (and othe models with more general self-interactions.

DOI: 10.1103/PhysRevLett.112.221101 PACS numbers: 04.70.Bw, 03.50.-

E. Radu's and L. Leite's talks

Hairy BHs in GR with matter obeying all important energy conditions which have a physical formation mechanism.

The paradigms and "tunnel vision"

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- Balanced neutral black holes (asymptotically flat)

PHYSICAL REVIEW LETTERS **131,** 121401 (2023)

Editors' Suggestion

Two Spinning Black Holes Balanced by Their Synchronized Scalar Hair

Carlos A. R. Herdeiro and Eugen Radu
Departamento de Matemática da Universidade de Aveiro and CIDMA, Campus de Santiago, 3810-183 Aveiro, Portugal

(Received 30 May 2023; accepted 8 August 2023; published 21 September 2023)

General relativity minimally coupled to a massive, free, complex scalar field, is shown to allow asymptotically flat solutions, nonsingular on and outside the event horizon, describing two spinning black holes (2sBHs) in equilibrium, with coaxial, aligned angular momenta. The 2sBHs configurations bifurcate from solutions describing dipolar spinning boson stars. The BHs emerge at equilibrium points diagnosed by a test particle analysis and illustrated by a Newtonian analog. The individual BH "charges" are mass and angular momentum only. Equilibrium is due to the scalar *environment*, acting as a (compact) dipolar field, providing a lift against their mutual attraction, making the 2sBHs (h)airborne. We explore the 2sBHs domain of solutions and its main features.

DOI: 10.1103/PhysRevLett.131.121401

C. Macedo's talk

The hair can provide a physical mechanism to balance two neutral asymptotically flat spinning black holes, without conical singularities, which was an old problem in GR.

Plan of this talk:

Einstein-(multi) Maxwell:
Einstein-(complex) Maxwell:

- Integrable (with symmetry):
  analytic solutions;

- No solitons;

- No-hair for black holes (BHs):
  uniqueness of Kerr-Newman BHs;

- No balanced neutral black holes
  (asymptotically flat);

Einstein-(massive, complex) Maxwell
Einstein-(massive, complex) Klein-Gordon:

- No integrable structure known:
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I) Landscape of solitons: bosonic stars (BSs)
with some dynamical surprises;

II) Hairy BHs and non-uniqueness; deep relations to superradiance and BSs;

III) Balanced neutral black holes
(asymptotically flat)

I) Landscape of solitons:
bosonic stars (BSs) with some dynamical surprises

G. Raposo's course

and

G. Olmo's talk

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:

New scale

Scalar Boson Stars

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

"Reference models"

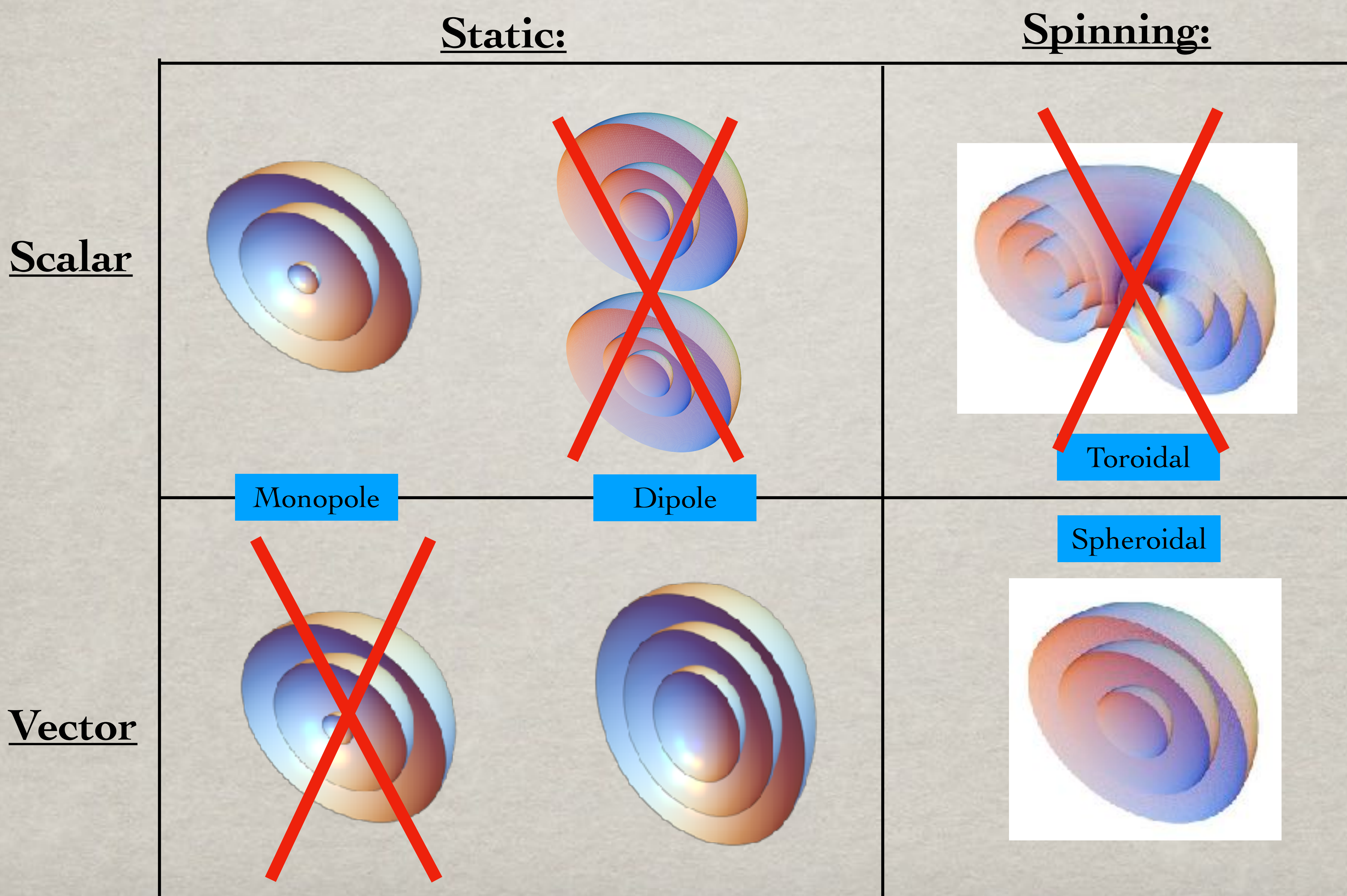
Massive-complex-vector-vacuum:

New scale

Vector Boson Stars
or
Proca Stars

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

A surprising (dynamically) different picture:



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. CH, Radu, 2205.05395

- 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

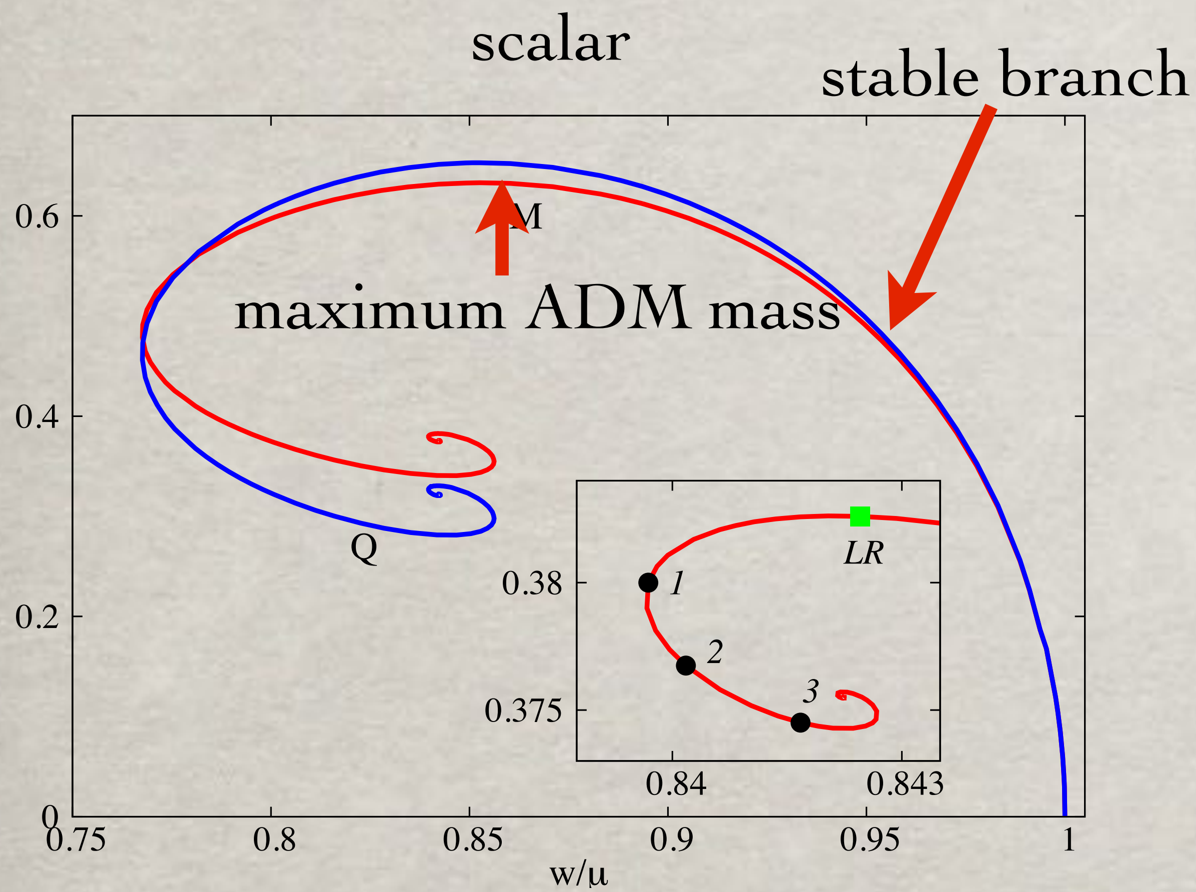
But what is their HEP origin? Axiverse? Arvanitaki et al., 0905.4720
Something else? Freitas et al. JCAP 12 (2021) 047

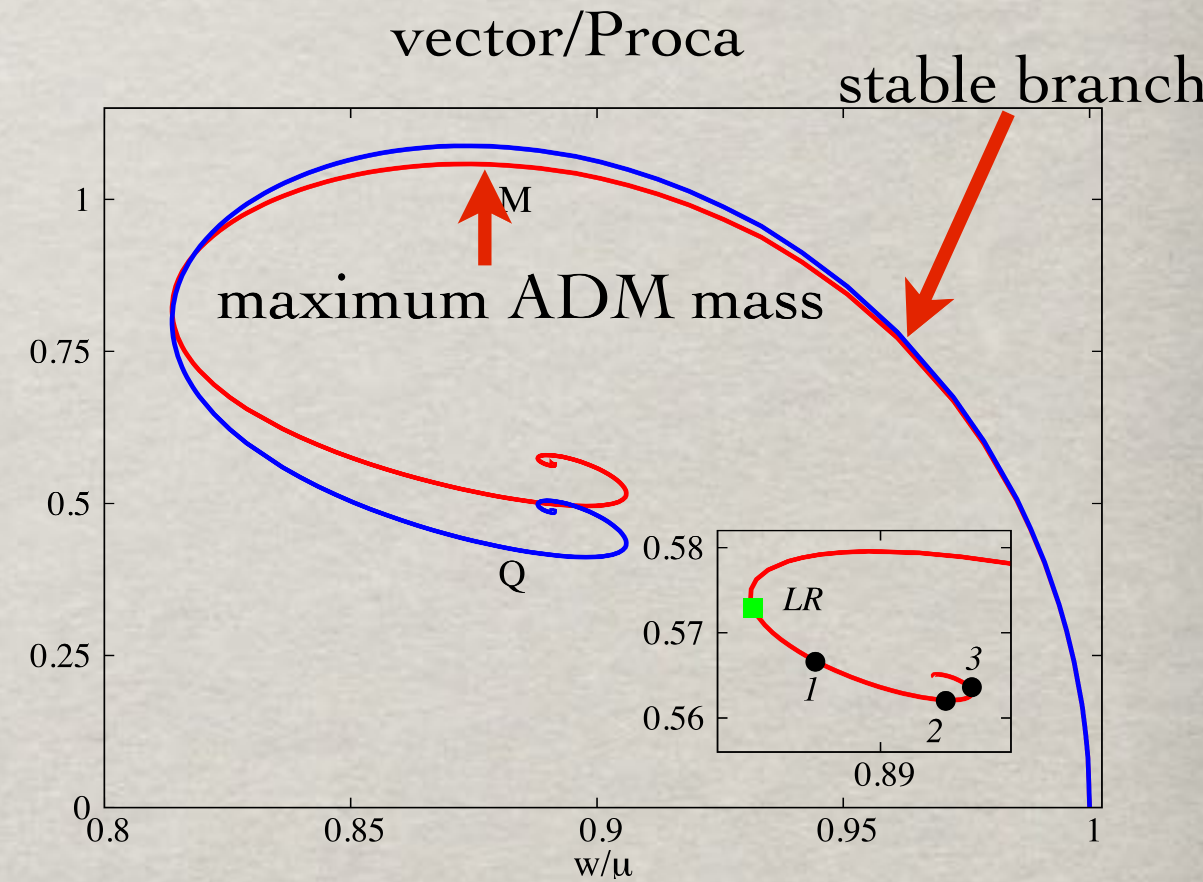
Spherical bosonic stars - stability

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

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

frequency



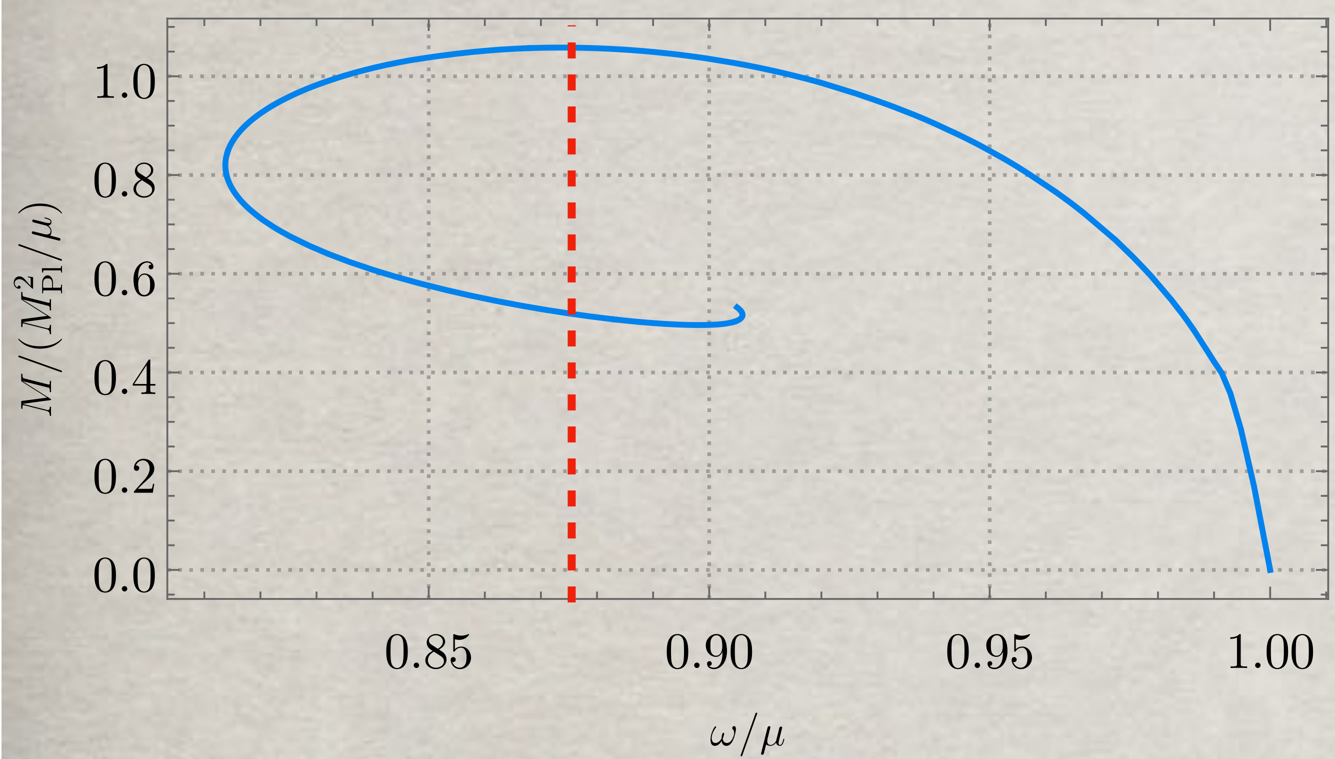


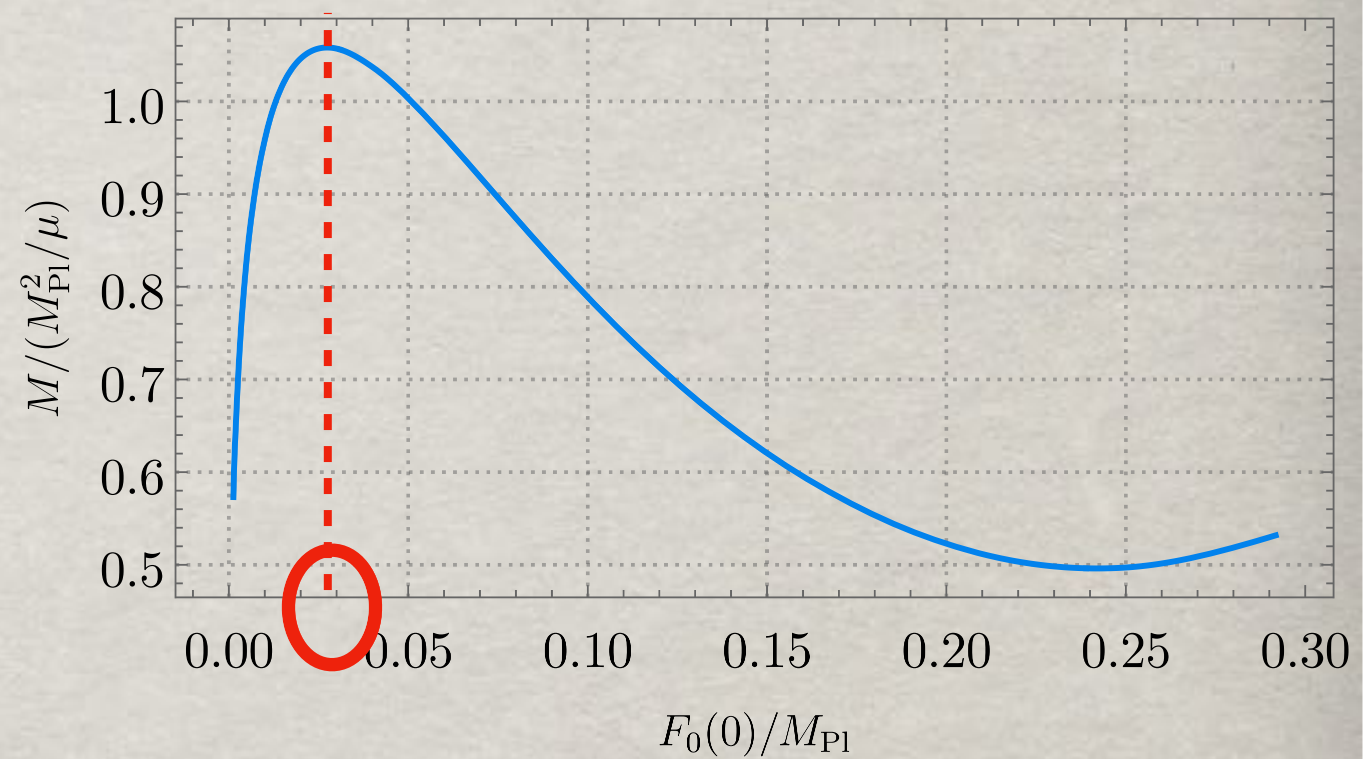
Studying linearized radial perturbations of the coupled system shows that an unstable mode arises precisely at the maximum of the ADM mass M. Gleiser and R. Watkins, NPB 319 (1989) 733; T. D. Lee and Y. Pang, NPB 315, 477 (1989); Brito, Cardoso, CH and Radu, PLB 752 (2016) 291.

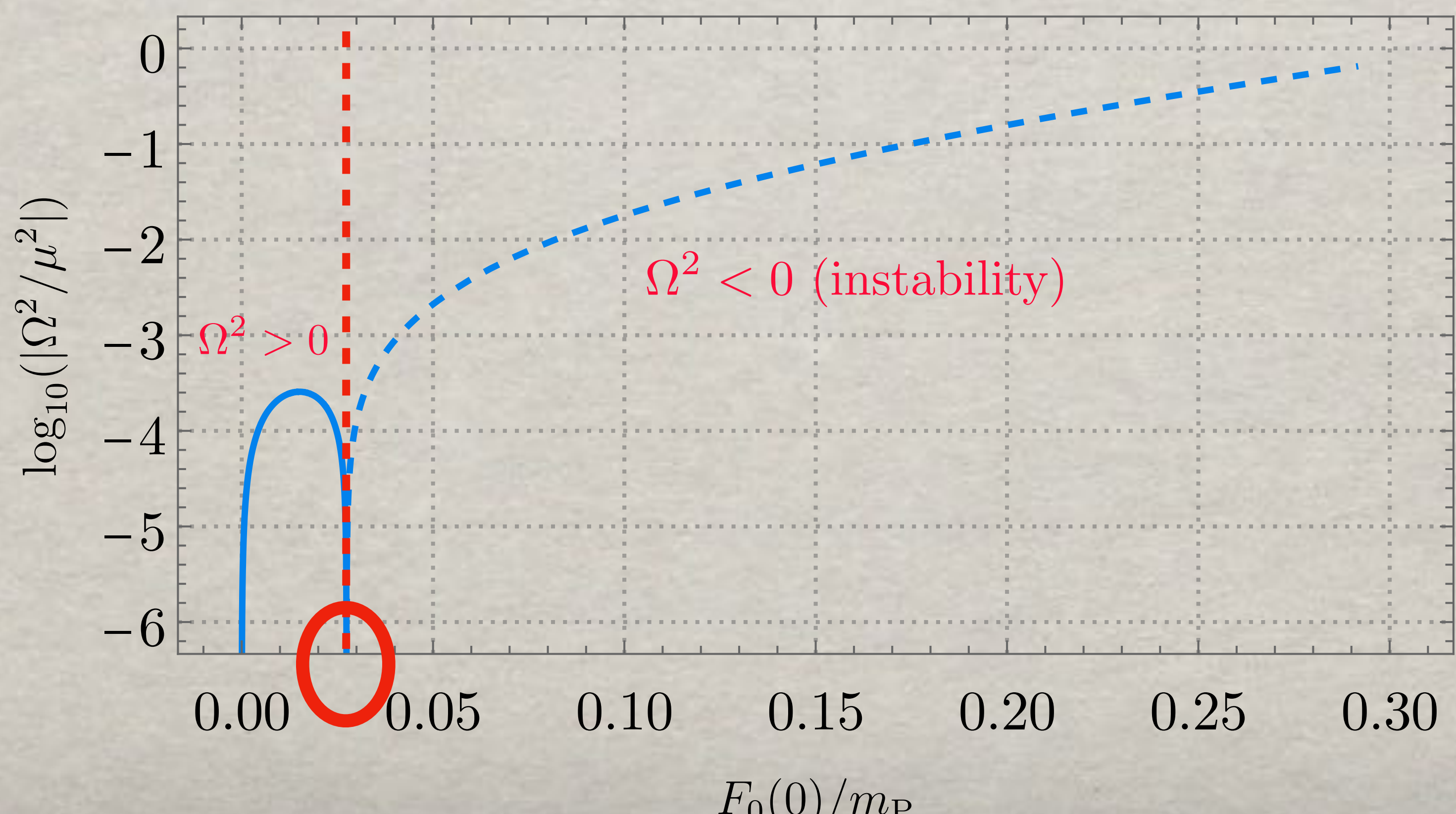
Unstable BSs can migrate, decay into a Schwarzschild black hole or disperse entirely Seidel and Suen, PRD 42 (1990) 384; Guzman, PRD 70 (2004) 044033; Hawley and Choptuik, PRD 62 (2000) 104024; Sanchis-Gual, CH, Radu, Degollado, Font, PRD 95 (2017) 104028

Spherical perturbation theory of mini-Proca stars:

Santos, Benone and CH (2404.07257)







C. Benone's talk

Spherical mini-PSs are unstable against a **non-spherical** perturbation

Costa, CH, Radu, Sanchis-Gual and Santos, 2311.14800

Bosonic stars can have a multipolar distribution

CH, Kunz, Parapechka, Radu, Shnir, PLB 812 (2021) 136027

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

$$\Phi = e^{-iwt}\sum_{\ell,m} R_\ell(r)Y_{\ell m}(\theta,\varphi)$$

$$R_\ell(r) = \frac{c}{\sqrt{r}}K_{\frac{1}{2}+\ell}(r\sqrt{\mu^2-\omega^2})$$

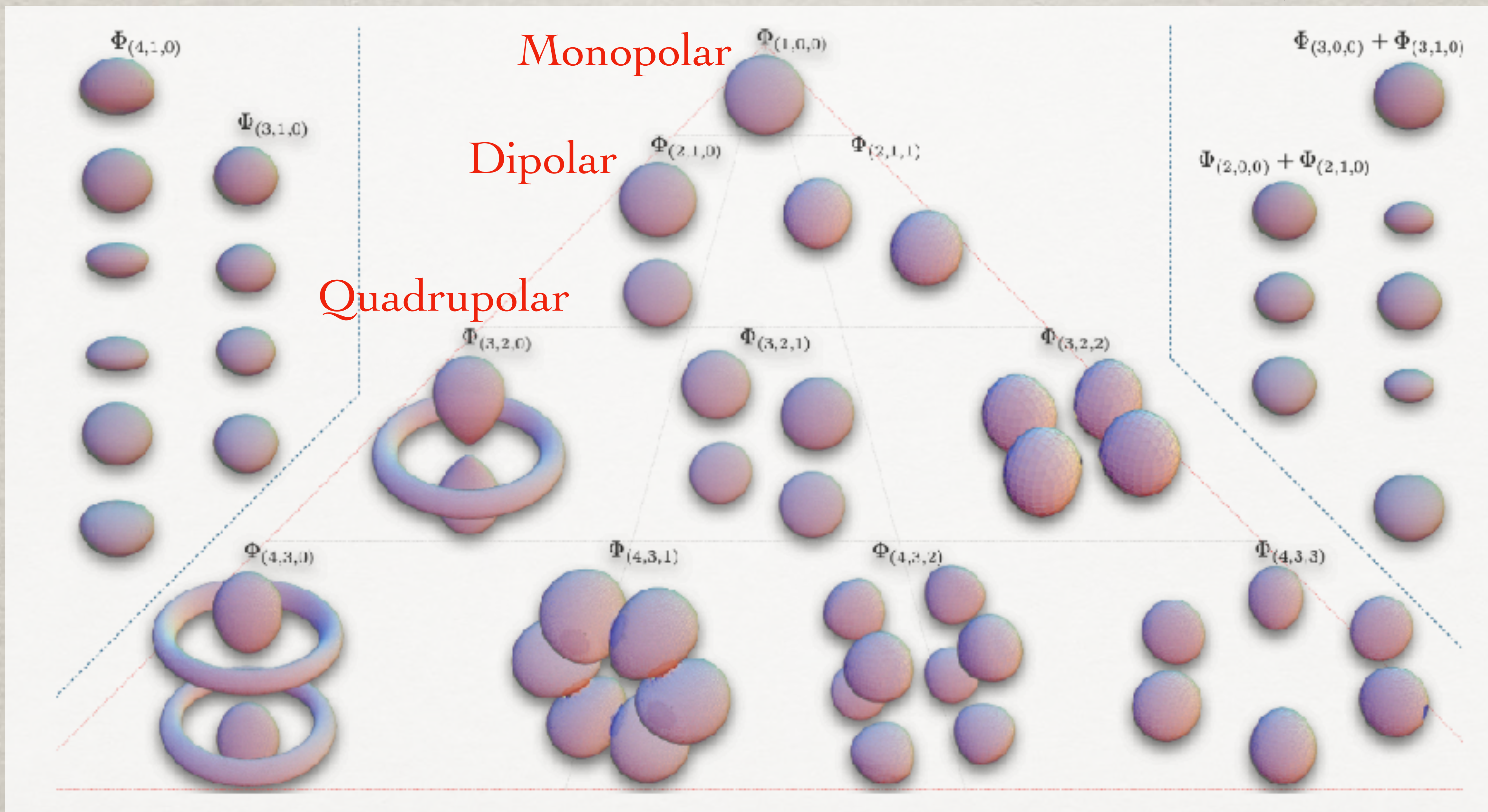


FIG. 3. Surfaces of constant energy density for a selection of $\Phi_{(N,\ell,m)}$. The hydrogen orbitals-like morphology is unmistakable, see *e.g.* [2].

Spherical mini-PSs are unstable against a **non-spherical** perturbation

Costa, CH, Radu, Sanchis-Gual and Santos, 2311.14800

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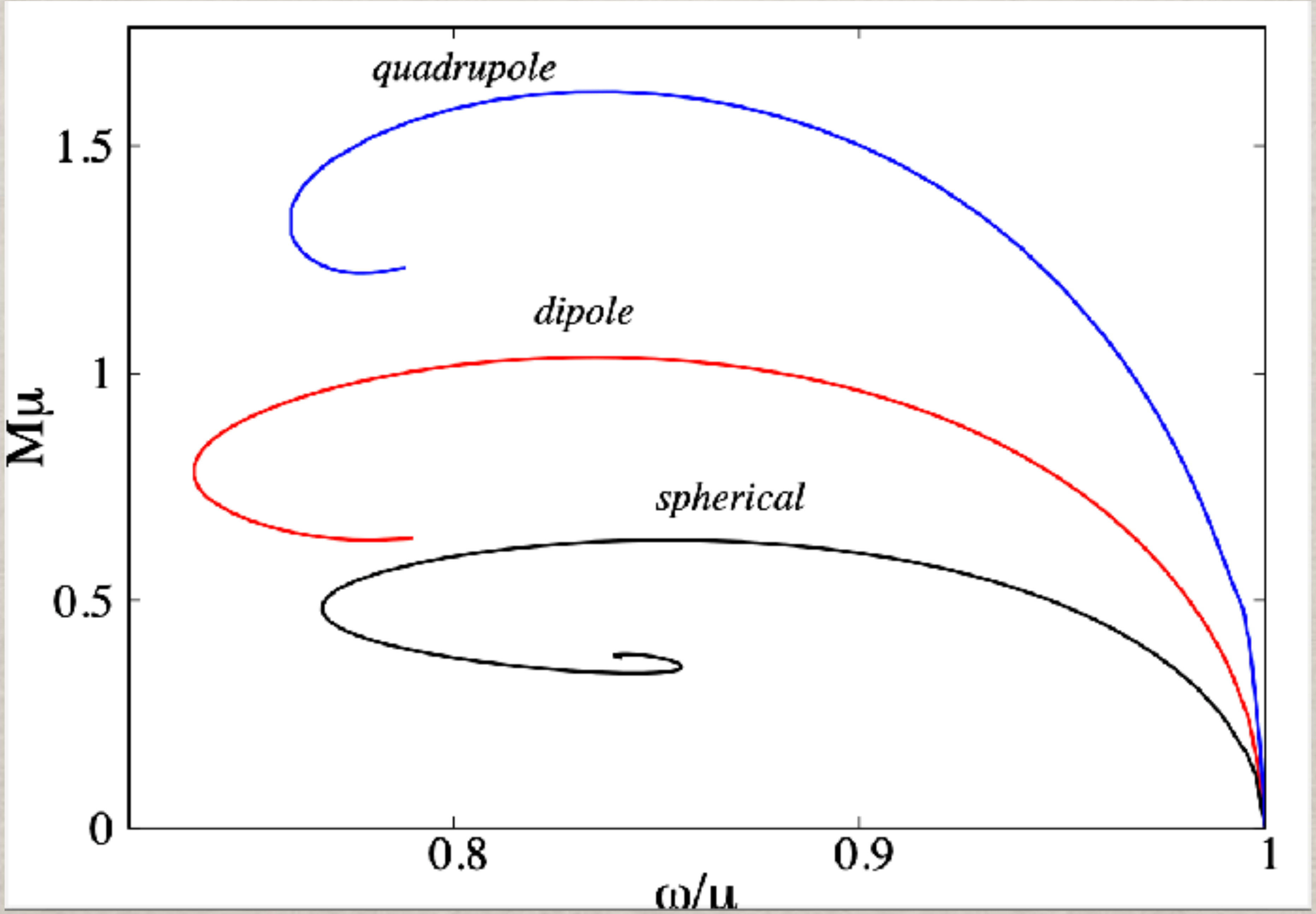
CH, Kunz, Parapechak, Radu, Shnir, PLB 797 (2019) 134845

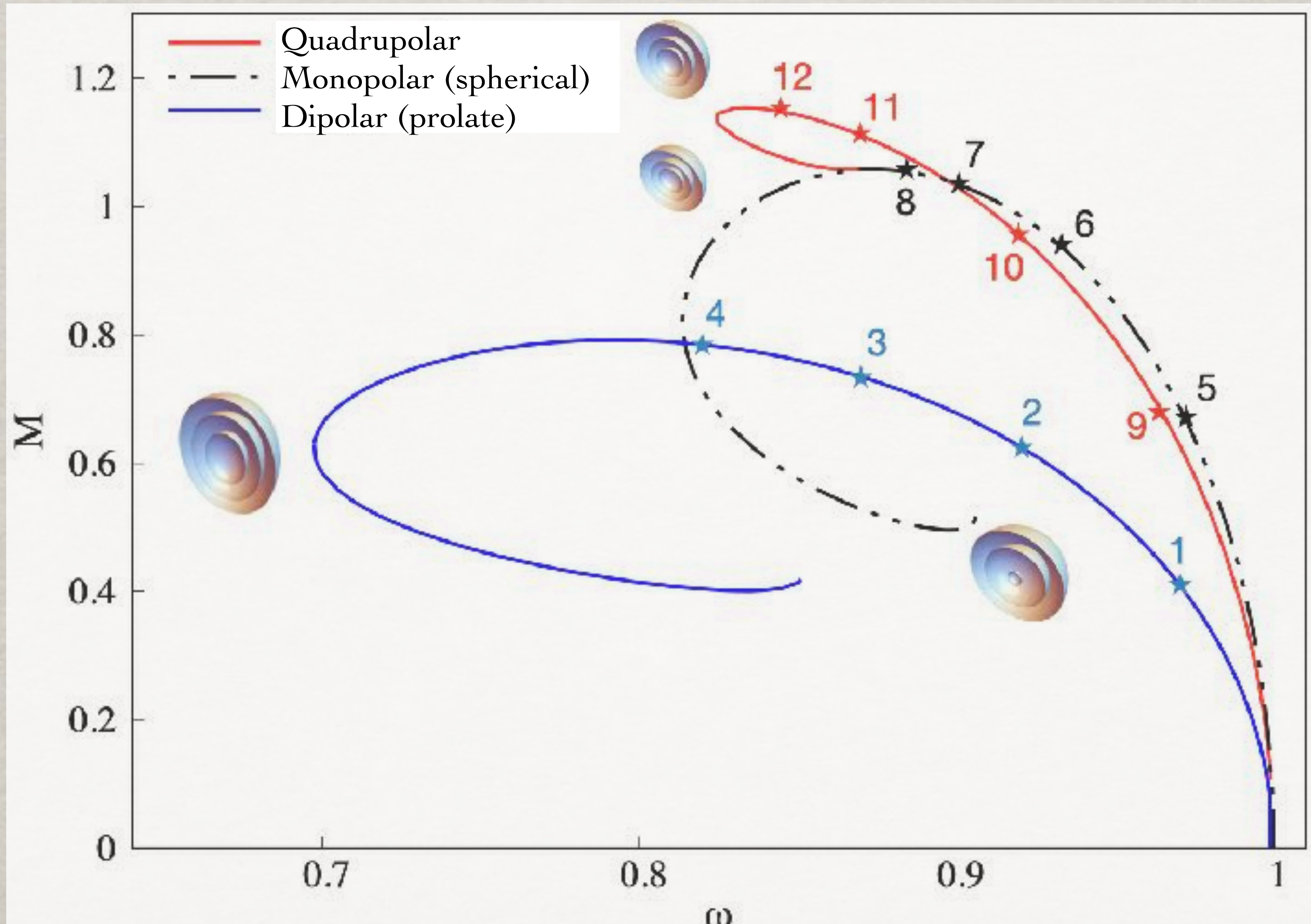


Cunha, CH, Kunz, Radu, Shnir, PRD 106 (2022) 124039

Spherical mini-PSs are unstable against a **non-spherical** perturbation

Costa, CH, Radu, Sanchis-Gual and Santos, 2311.14800

Evidence 1: - energetics (the ground state)



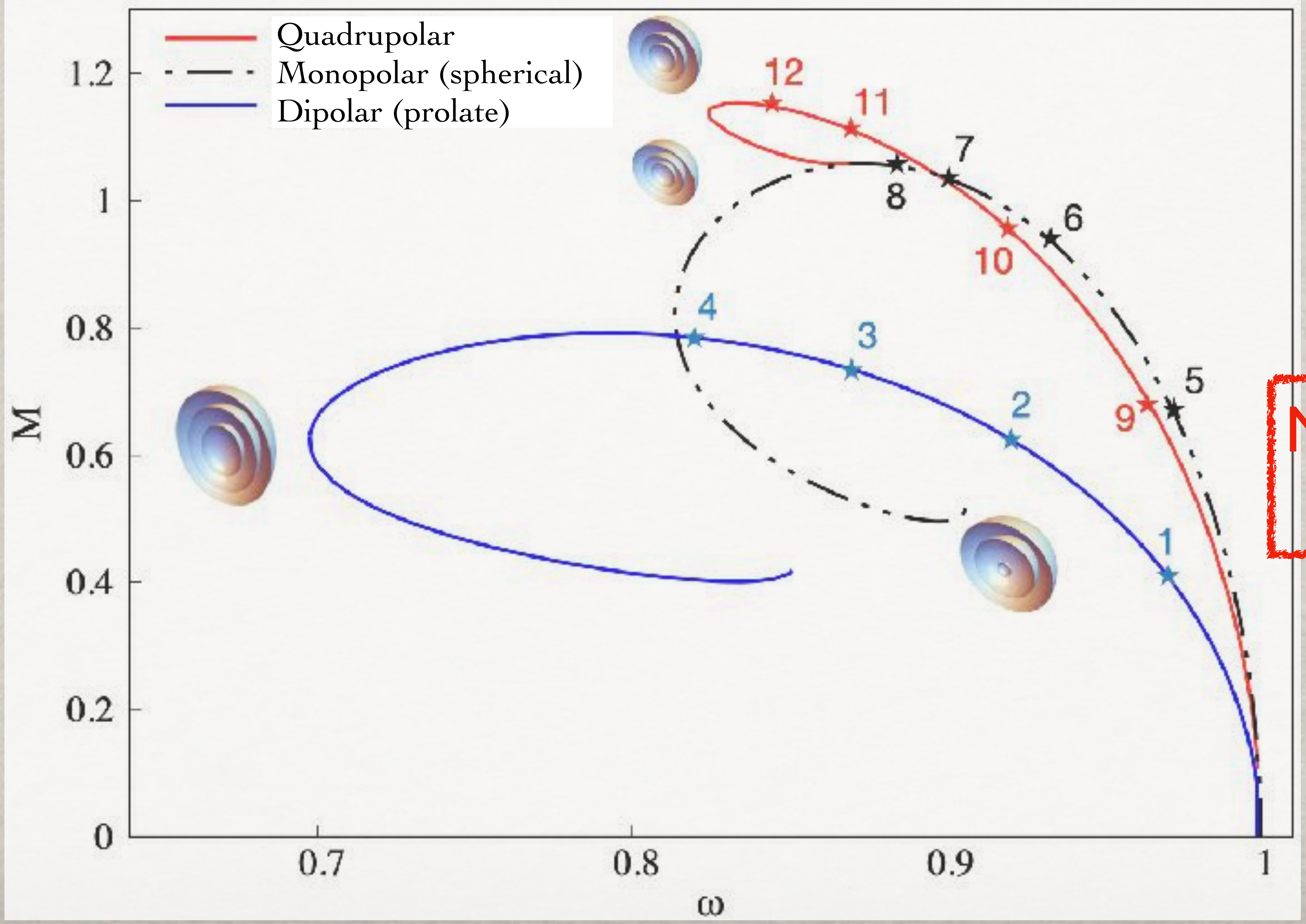
Spherical mini-PSs are unstable against a **non-spherical** perturbation

Costa, CH, Radu, Sanchis-Gual and Santos, 2311.14800

Evidence 2: - dynamics (using 3D NR simulations)

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

Q1) if the dipolar Proca stars are the ground state, are they stable in a long term numerical evolution?



M. Zilhão's course

Spherical mini-PSs are unstable against a **non-spherical** perturbation

Costa, CH, Radu, Sanchis-Gual and Santos, 2311.14800

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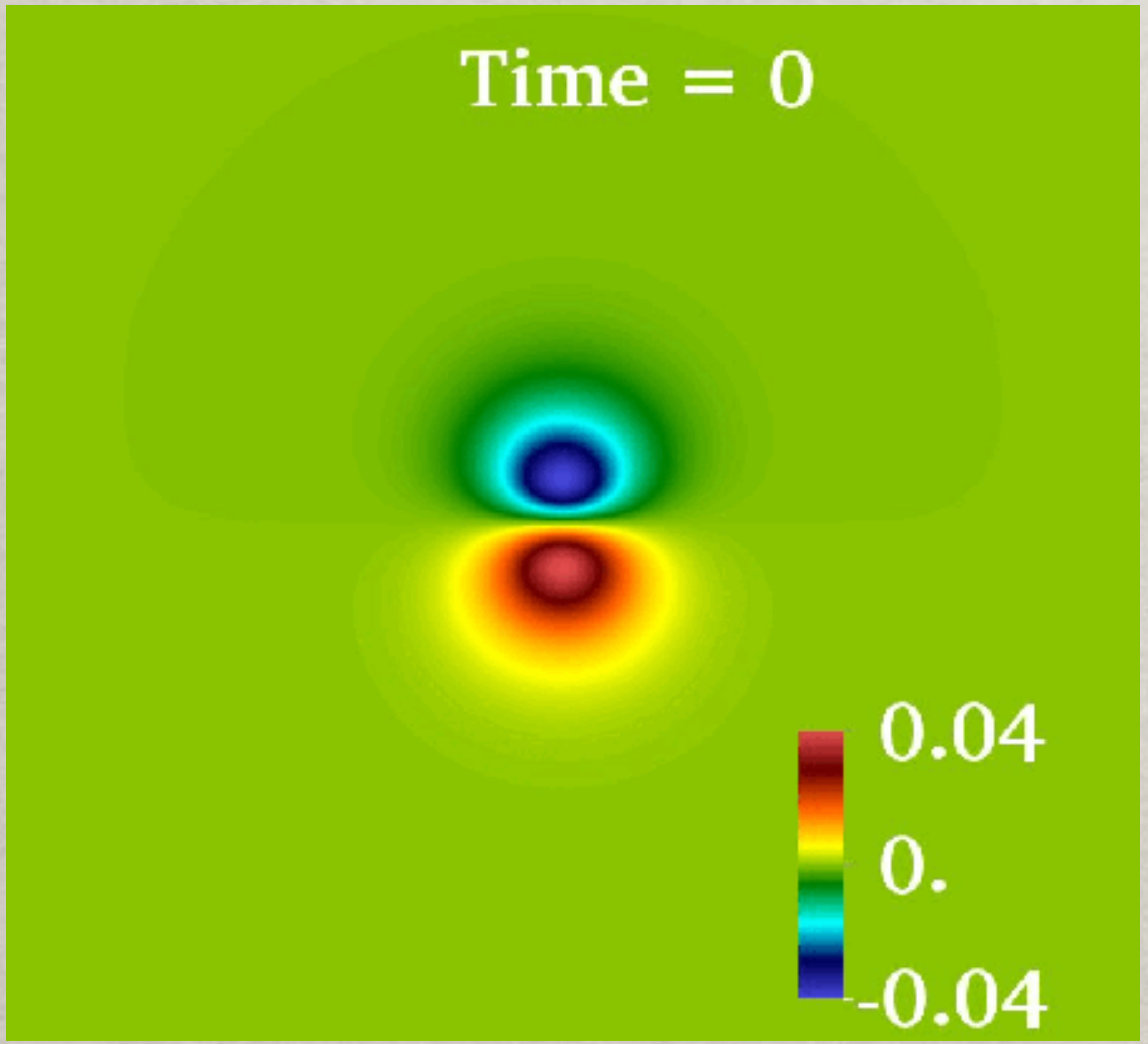
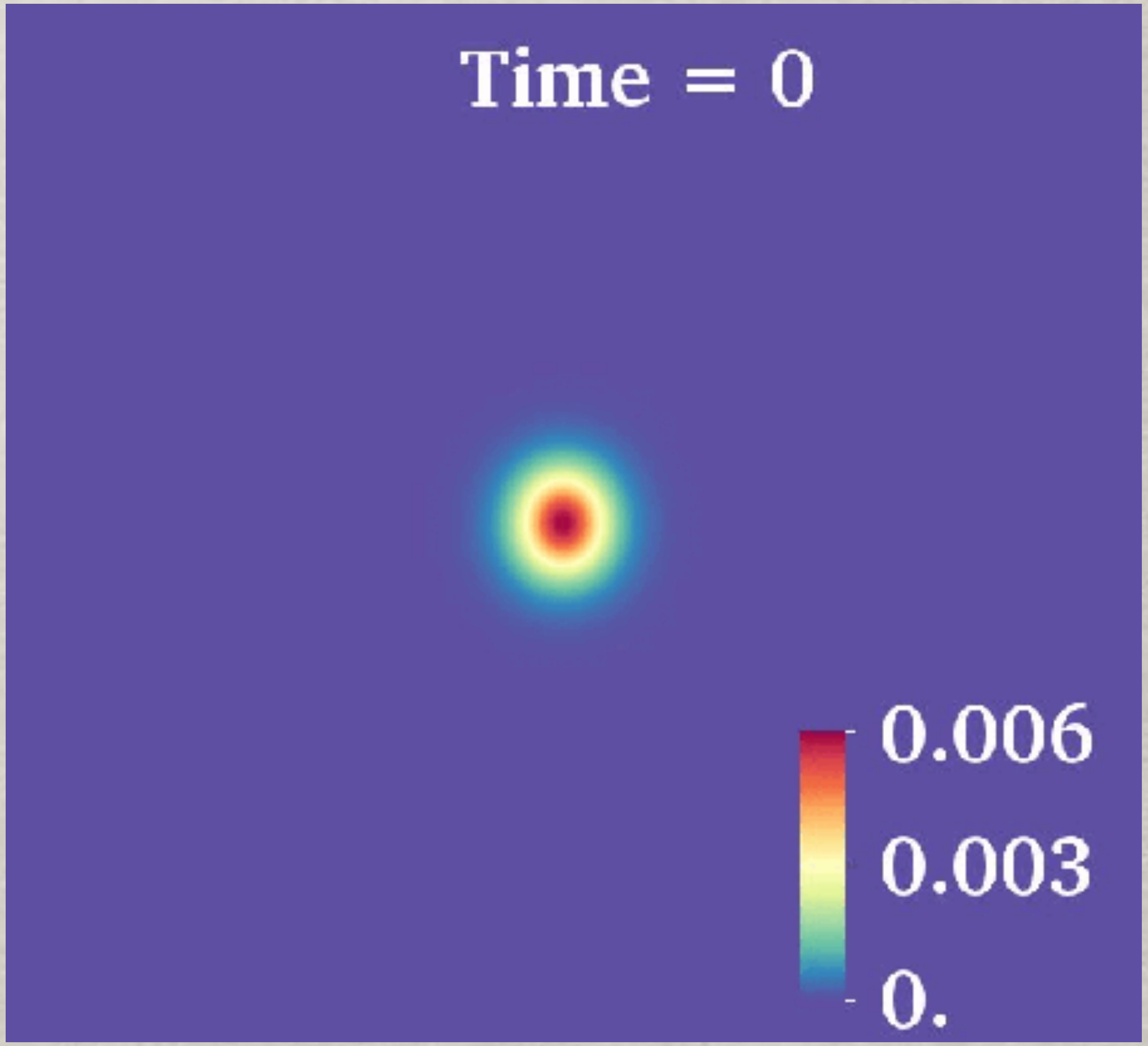


Proca (scalar) potential x-z plane



Energy density x-z plane

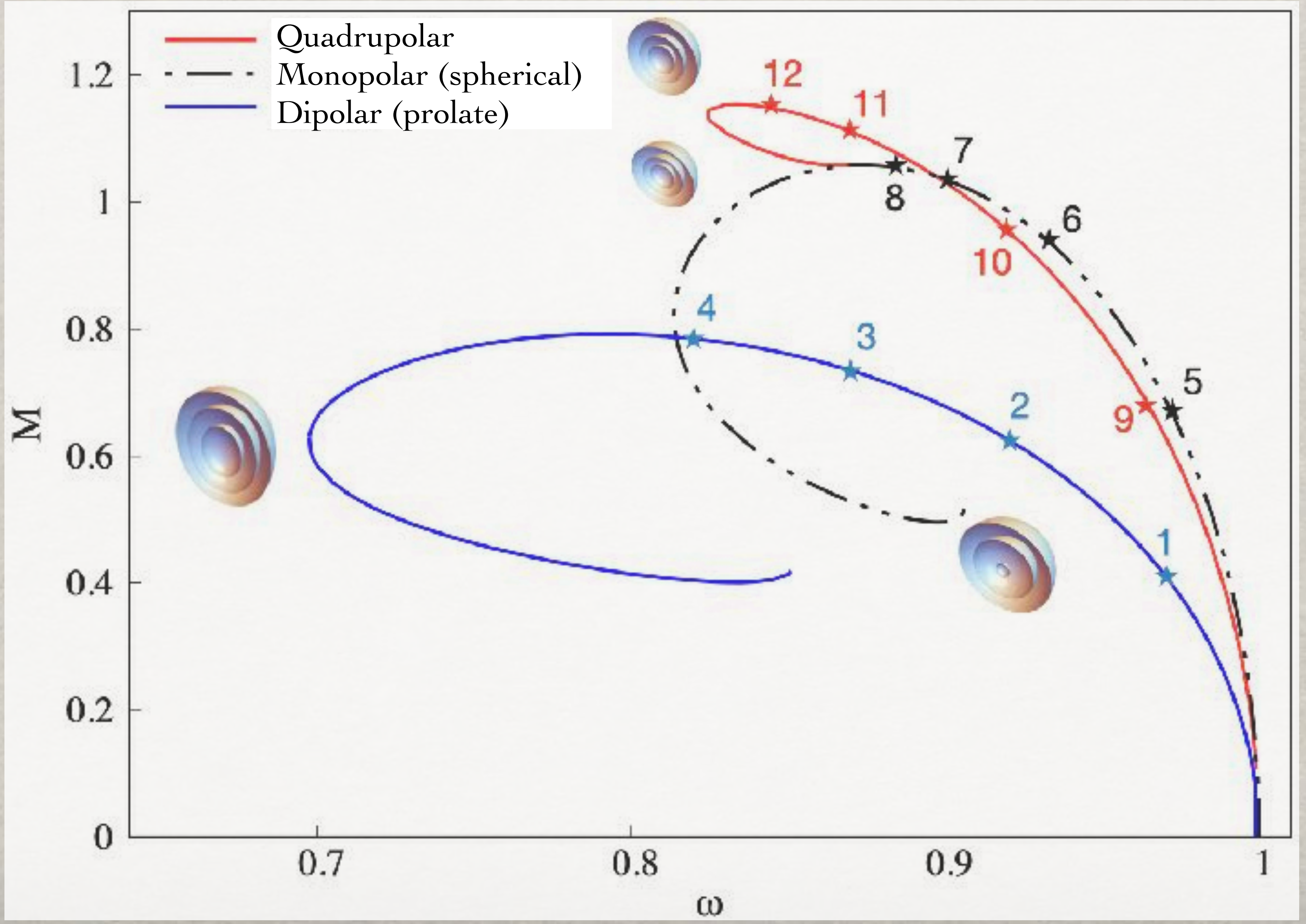
Spherical mini-PSs are unstable against a **non-spherical** perturbation

Costa, CH, Radu, Sanchis-Gual and Santos, 2311.14800

Evidence 2: - dynamics (using 3D NR simulations)

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

Q2) if the dipolar Proca stars are the ground state, are spherical stars unstable?



Spherical mini-PSs are unstable against a **non-spherical** perturbation

Costa, CH, Radu, Sanchis-Gual and Santos, 2311.14800

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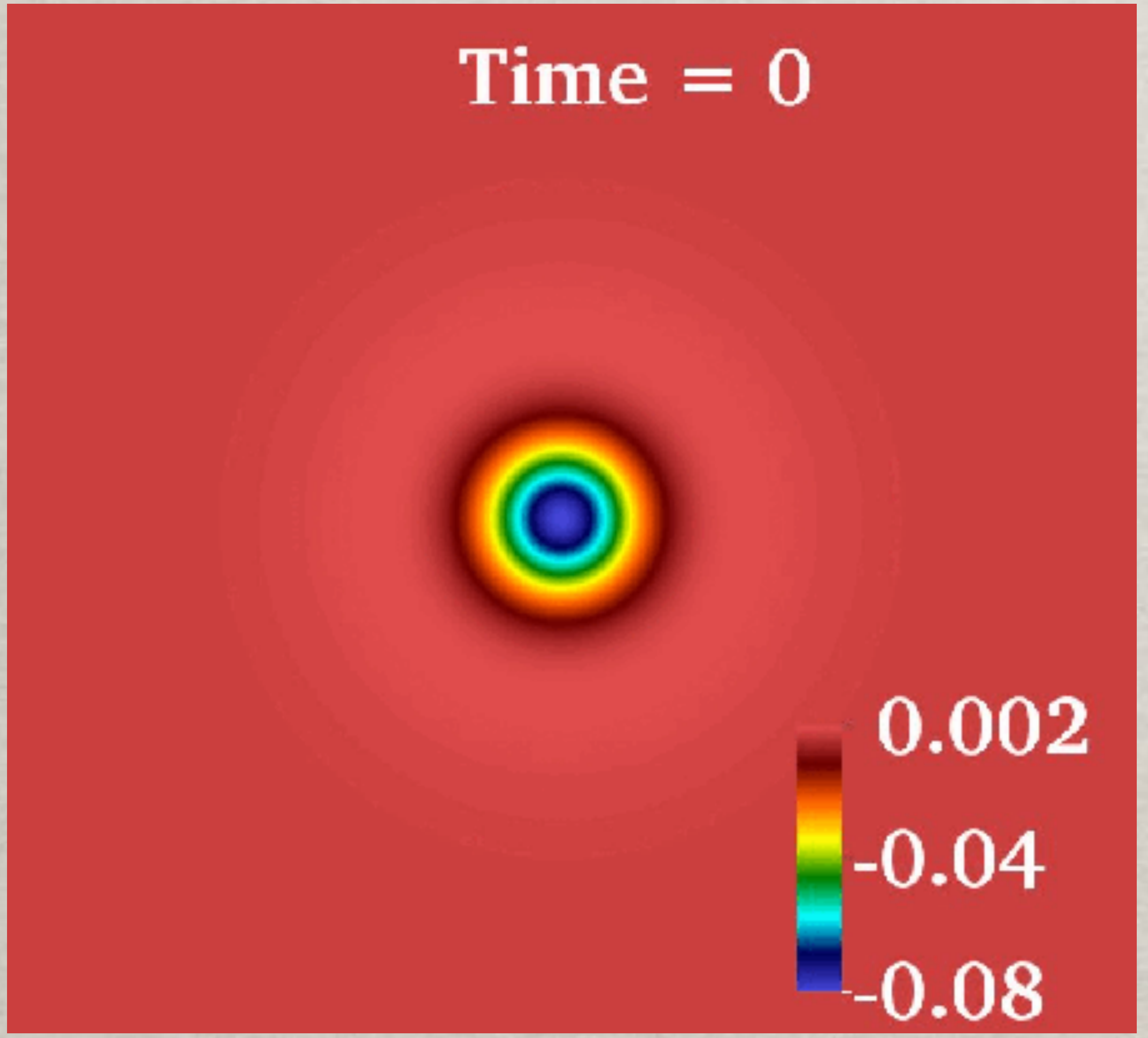

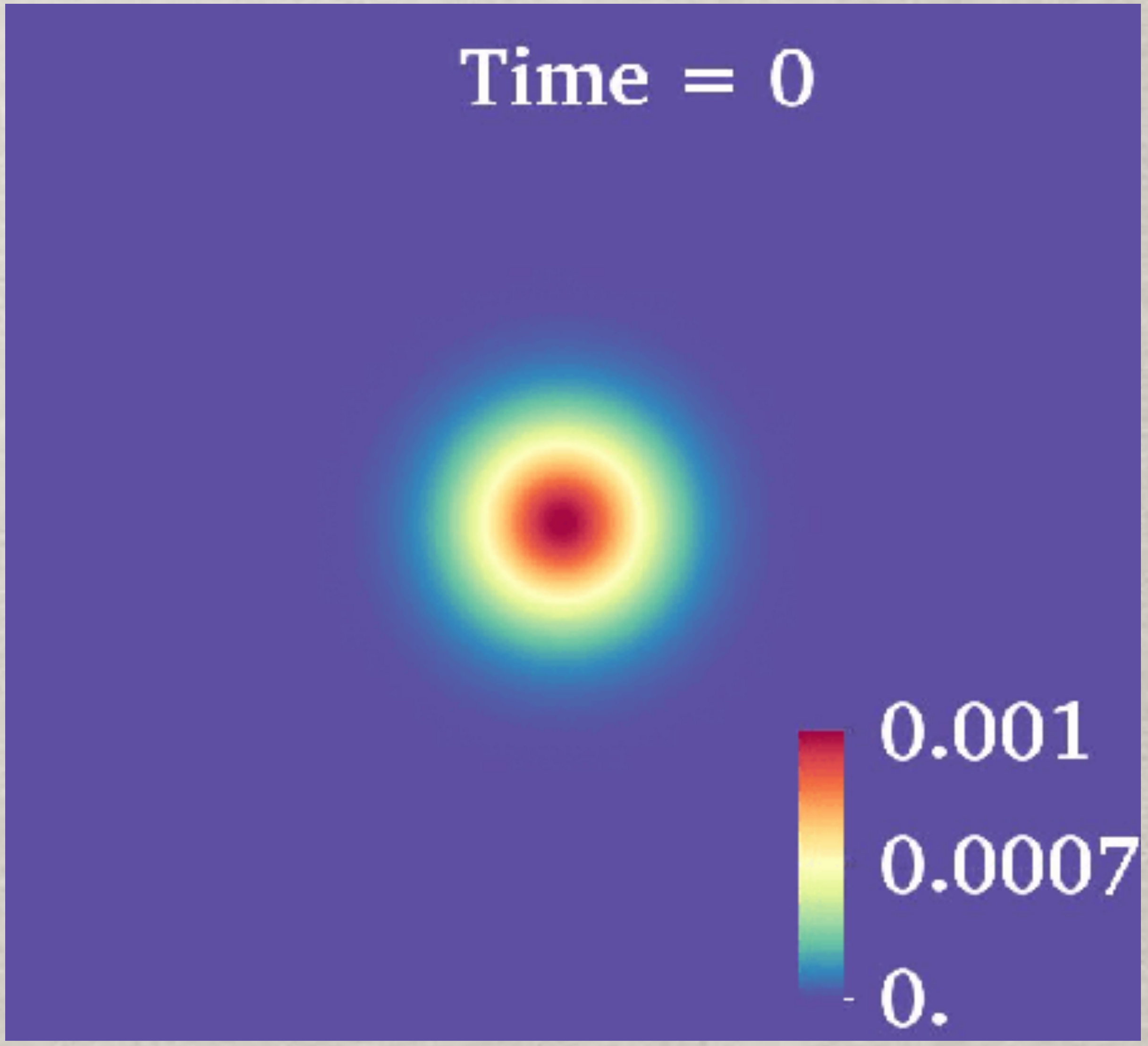

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Prolate (P)	Spherical (S)	Quadrupolar (Q)
1-(0.970,0.4124) *Stable*	**5**-(0.970,0.6928) $S \to P$; $[\mathbb{Z}_2]$	**9**-(0.965,0.6928) $Q \to P$; $[\mathbb{Z}_2]$ *Stable*
2-(0.920,0.6261) *Stable*	**6**-(0.936,0.9245) $S \to P$; $[\mathbb{Z}_2]$ $S \to Q \to P$	**10**-(0.920,0.9549) $Q \to P$; $[\mathbb{Z}_2]$ *Stable*
3-(0.870,0.7346) *Stable*	**7**-(0.900,1.035) $S \to P$; $[\mathbb{Z}_2]$ $S \to Q \to P$	**11**-(0.870,1.1108) $Q \to BH$; $[\mathbb{Z}_2]$ *Stable*
4-(0.820, 0.7846) *Stable*	**8**-(0.885,1.054) $S \to P$; $[\mathbb{Z}_2]$ $S \to Q$	**12**-(0.845,1.1478) $Q \to BH$; $[\mathbb{Z}_2]$ *Stable*

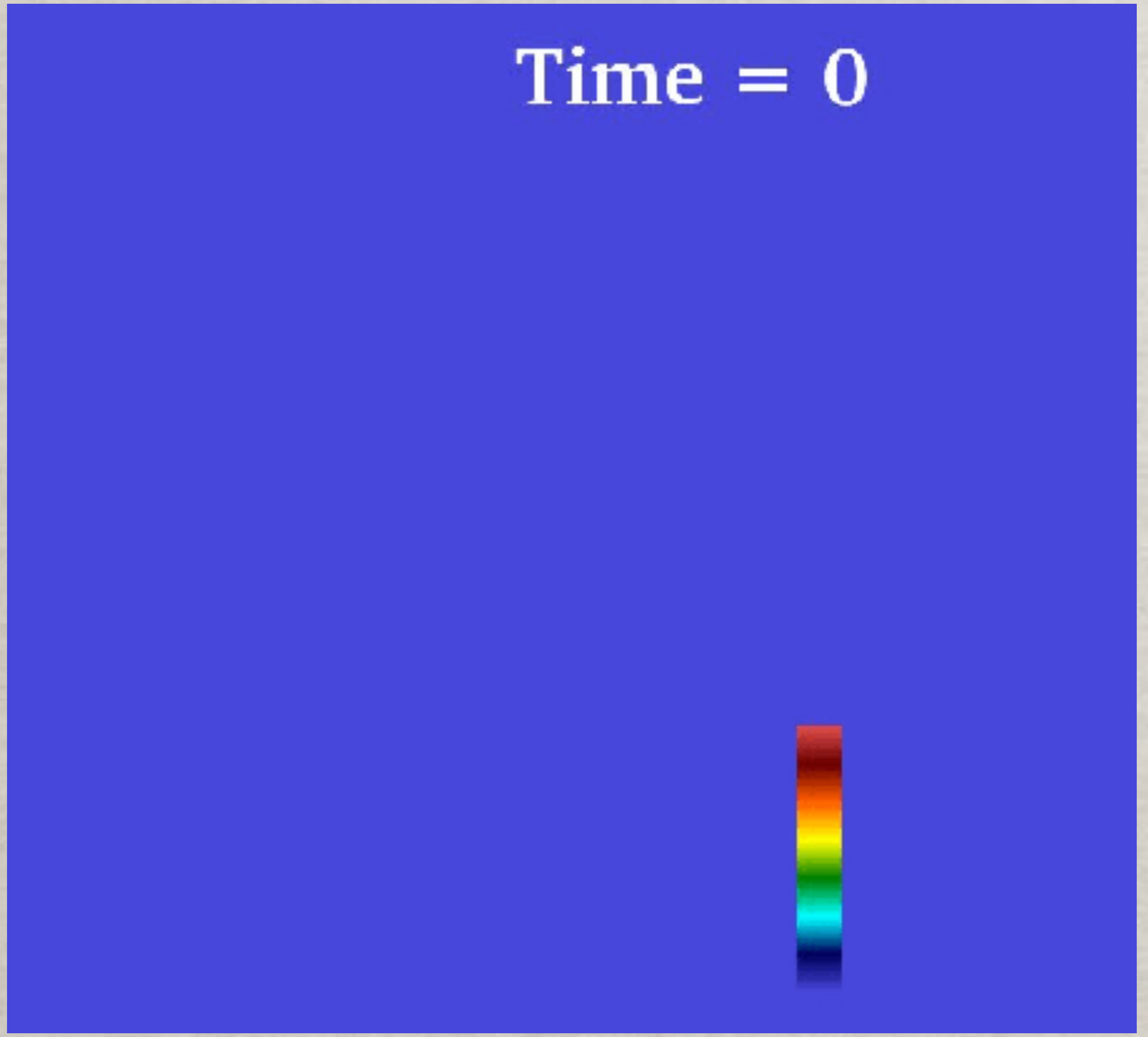
Spherical mini-PSs are unstable against a **non-spherical** perturbation

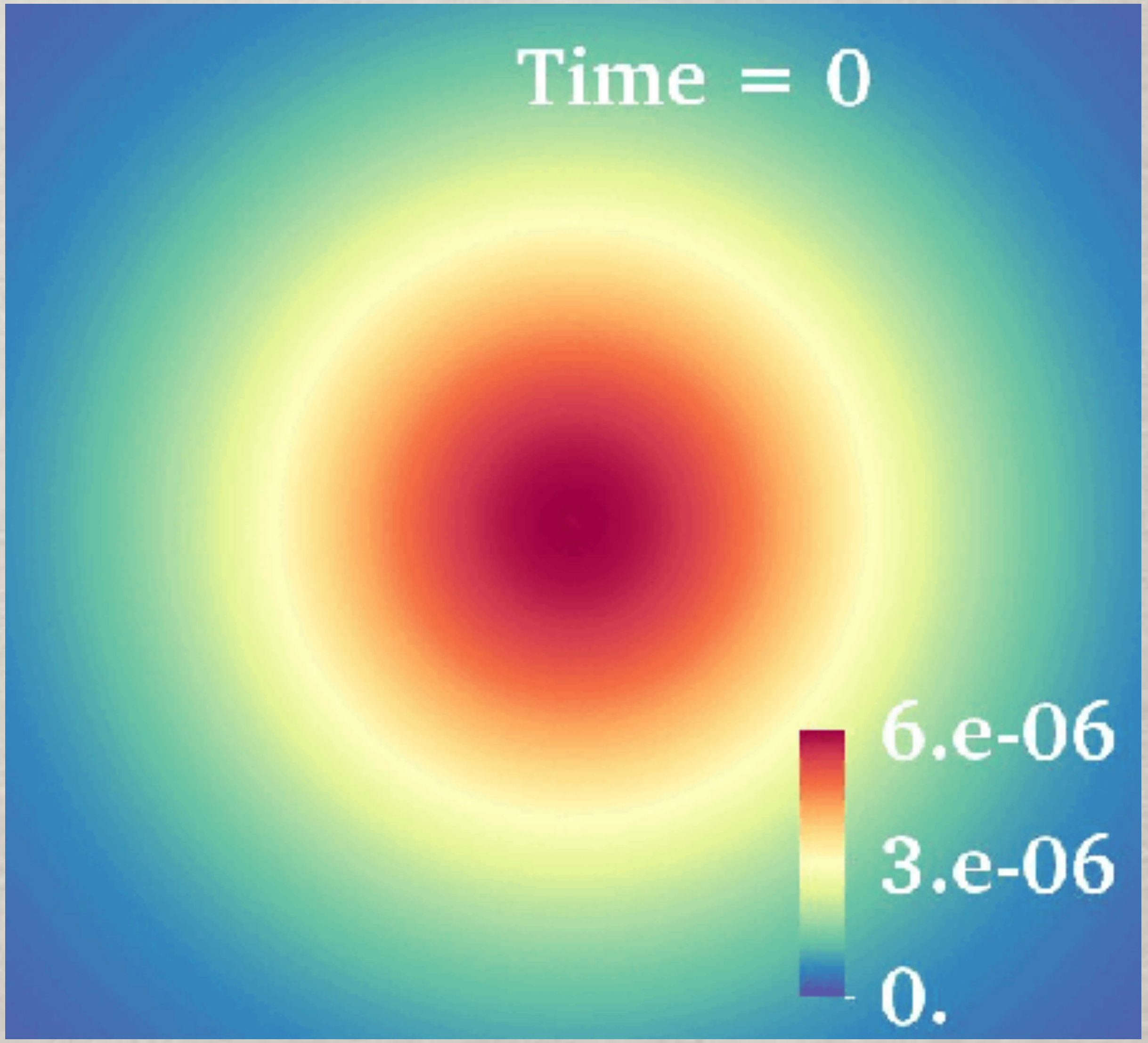
Costa, CH, Radu, Sanchis-Gual and Santos, 2311.14800

Evidence 3: - dynamics (formation scenario)

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

Q3) what happens if we evolve a dilute cloud of spherical Proca field?





Spherical mini-PSs are unstable against a **non-spherical** perturbation

Costa, CH, Radu, Sanchis-Gual and Santos, 2311.14800

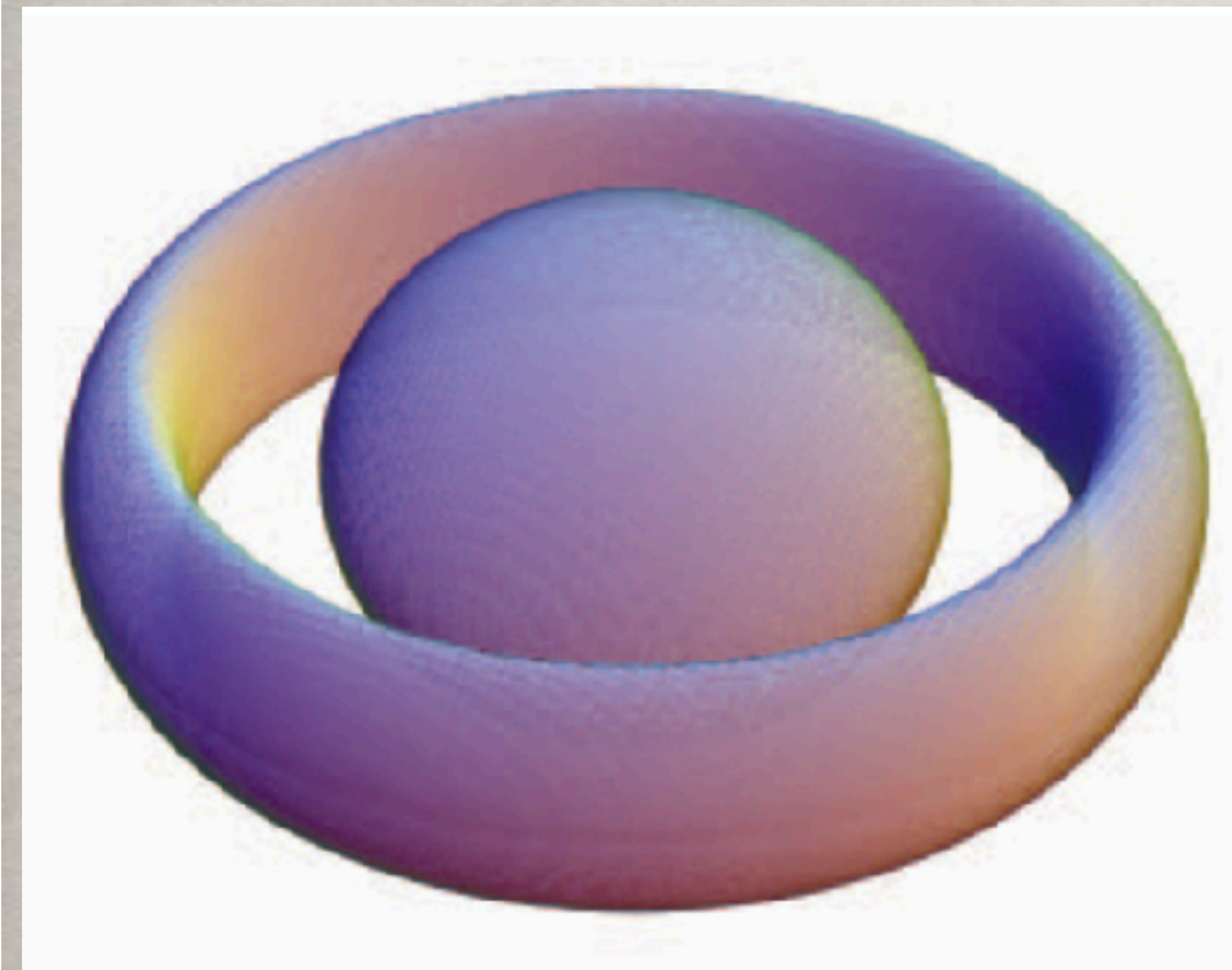
Comments:

- The prolateness (rather than spherical symmetry) of the ground state gives an example of a *static*, strong gravity system (which can reach a compactness comparable to that of black holes) that is not spherical;

- The instability of spherical Proca stars was missed in previous works because it was tacitly assumed that perturbative spherical stability was enough, and NR simulations were either too short or (inadvertedly) imposed symmetries quenching/mitigating the instability;

- There are other interesting systems where a spherical configuration decays into a non-spherical one (e.g. a charged liquid drop).

Impact for rotating Proca stars?



First rotating Proca stars reported

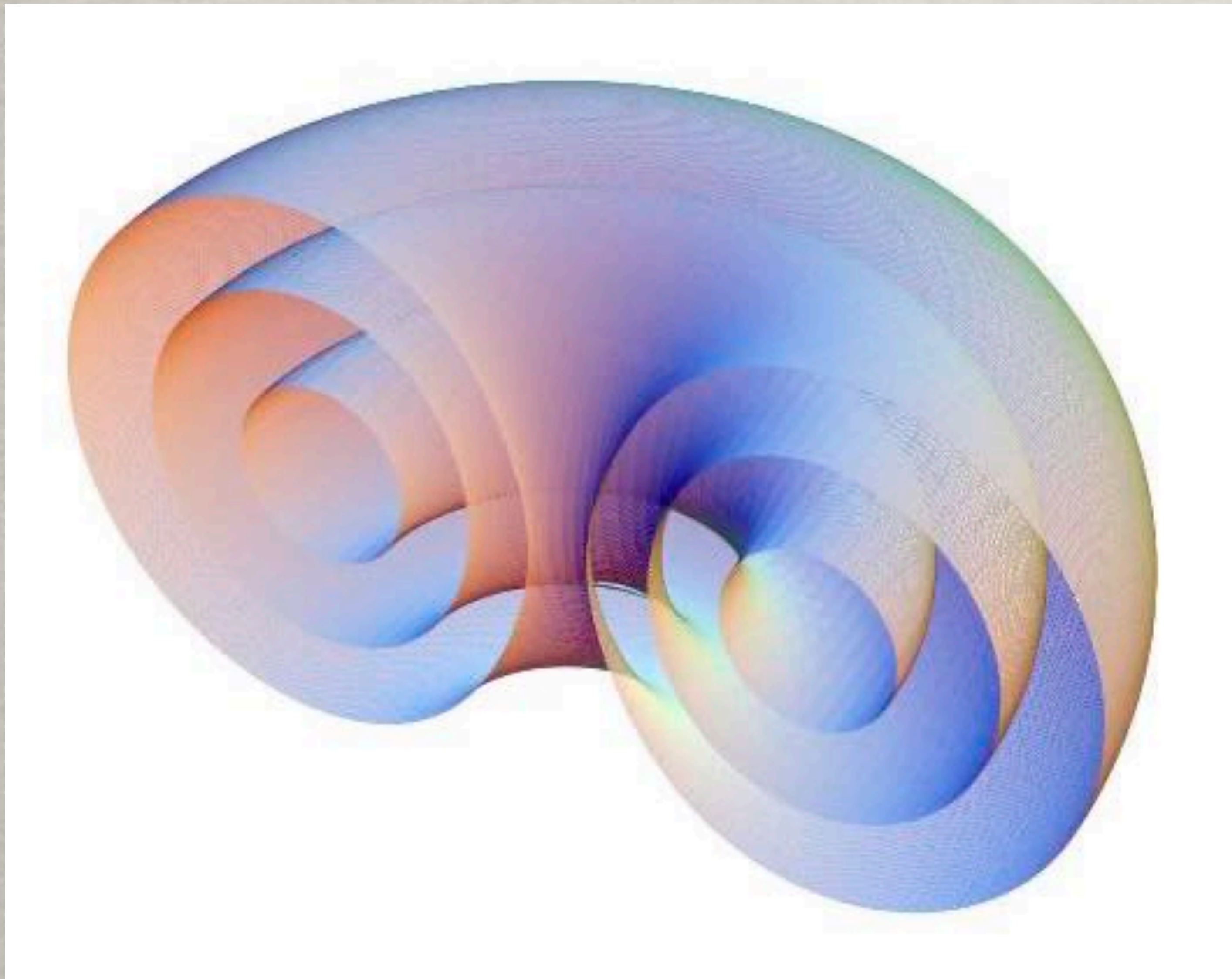
Brito, Cardoso, CH and Radu, PLB 752 (2016) 291
CH, Radu and Rúnarsson, CQG 33 (2016) 154001

Rotating Proca stars without nodes

CH and Radu, PRL 119 (2017) 261101
CH, Perapechka, Radu and Shnir, PLB 797 (2019) 134845

In fact, these are known to be dynamically more robust than spinning (scalar) boson stars

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



Rotating (scalar) boson stars

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

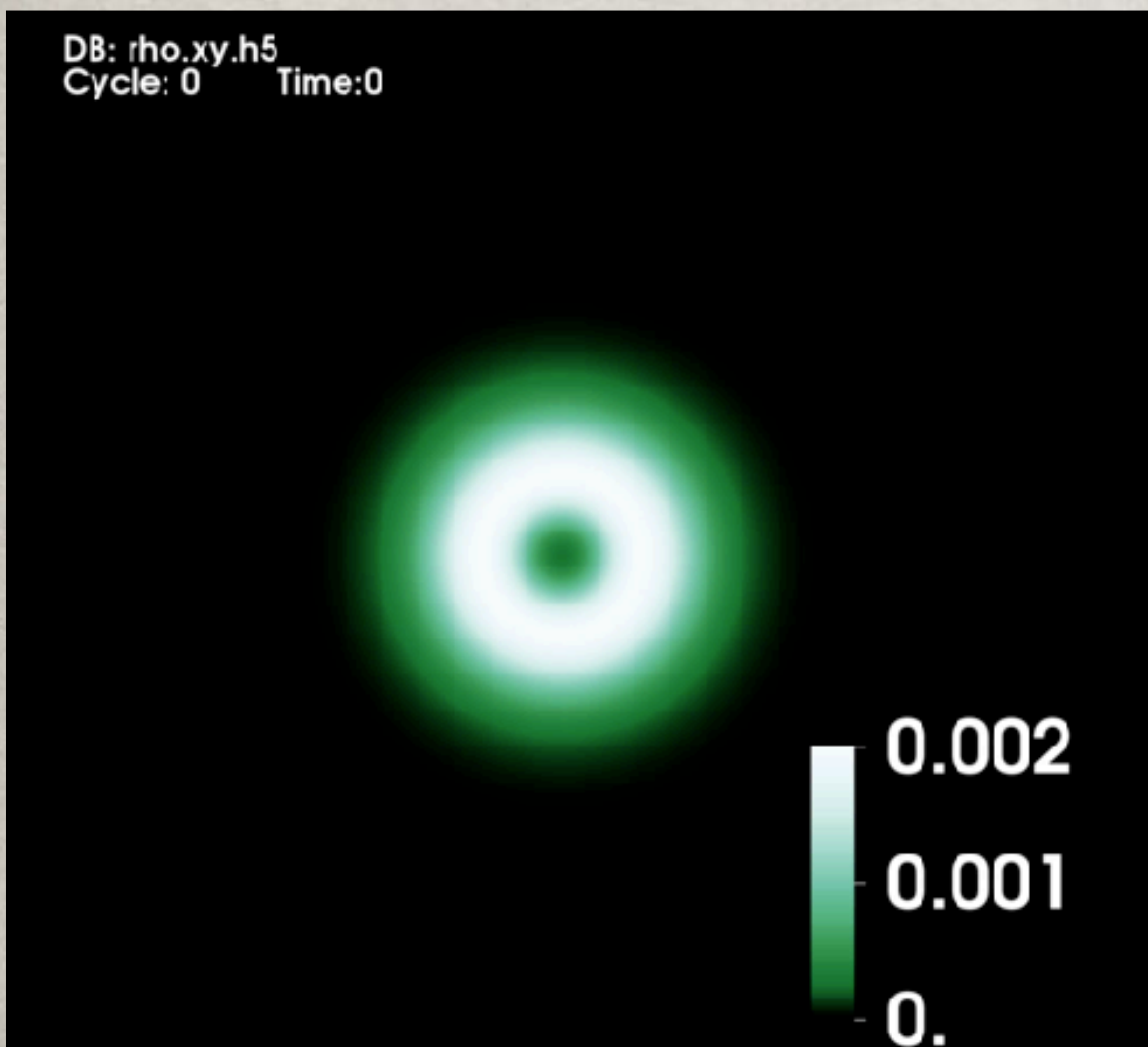
Rotating Proca stars without nodes

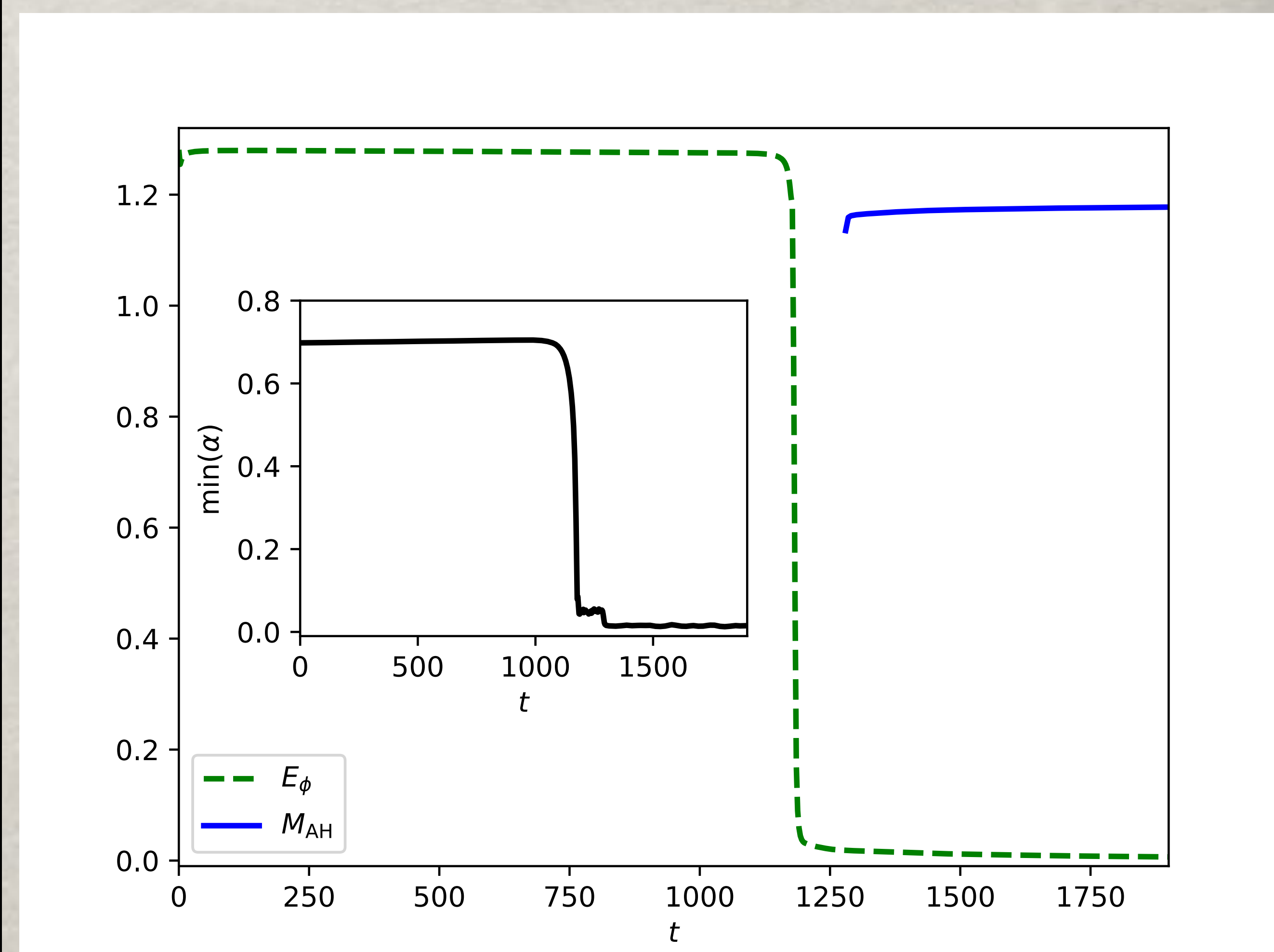
CH and Radu, PRL 119 (2017) 261101
CH, Perapechka, Radu and Shnir, PLB 797 (2019) 134845

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

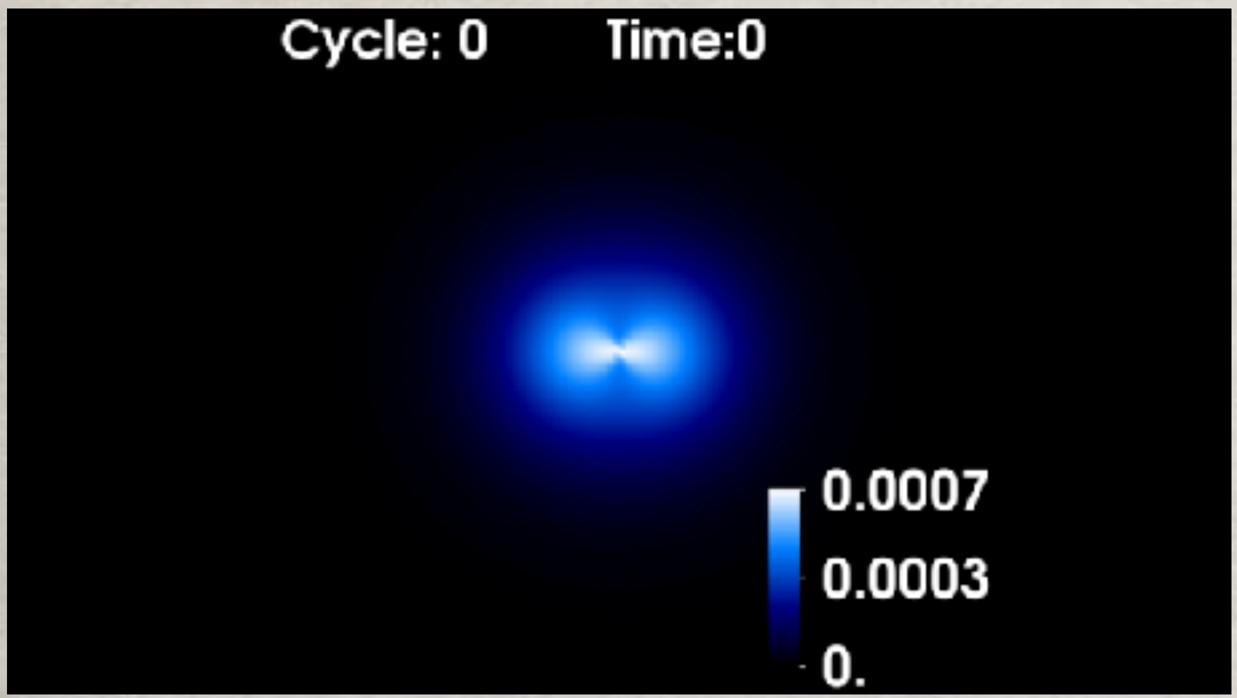




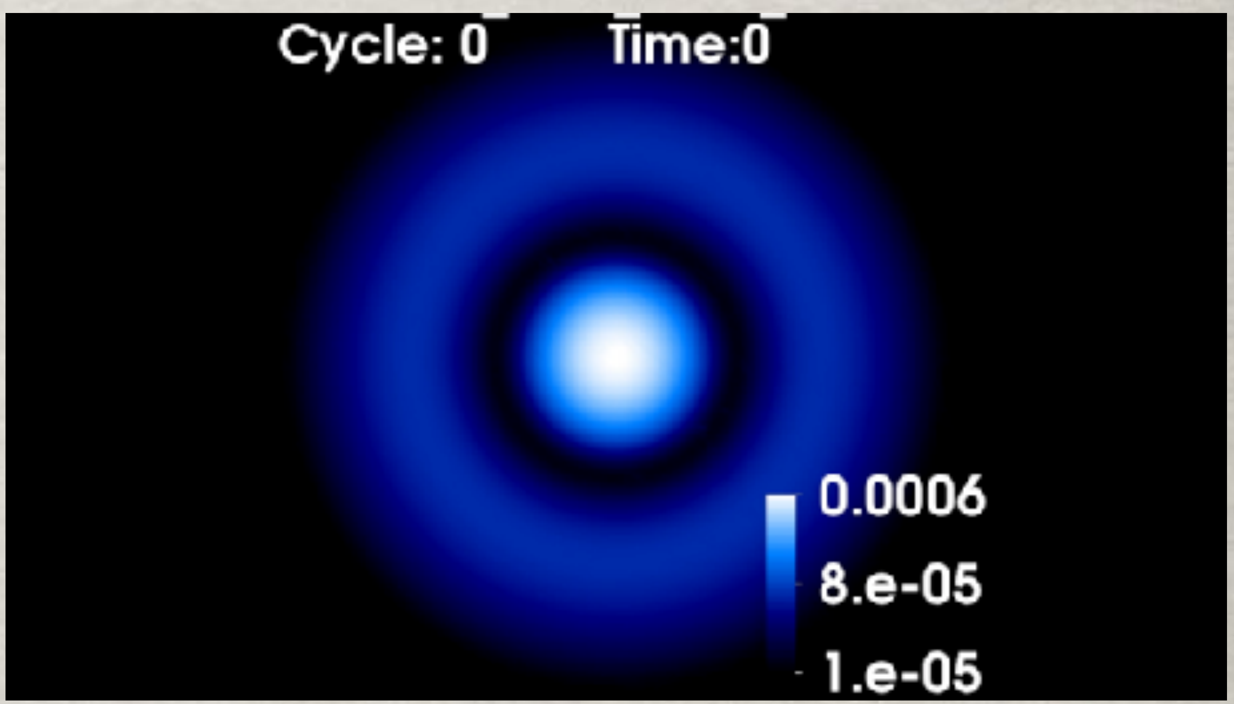
Spinning Proca stars do not exhibit such instability.

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



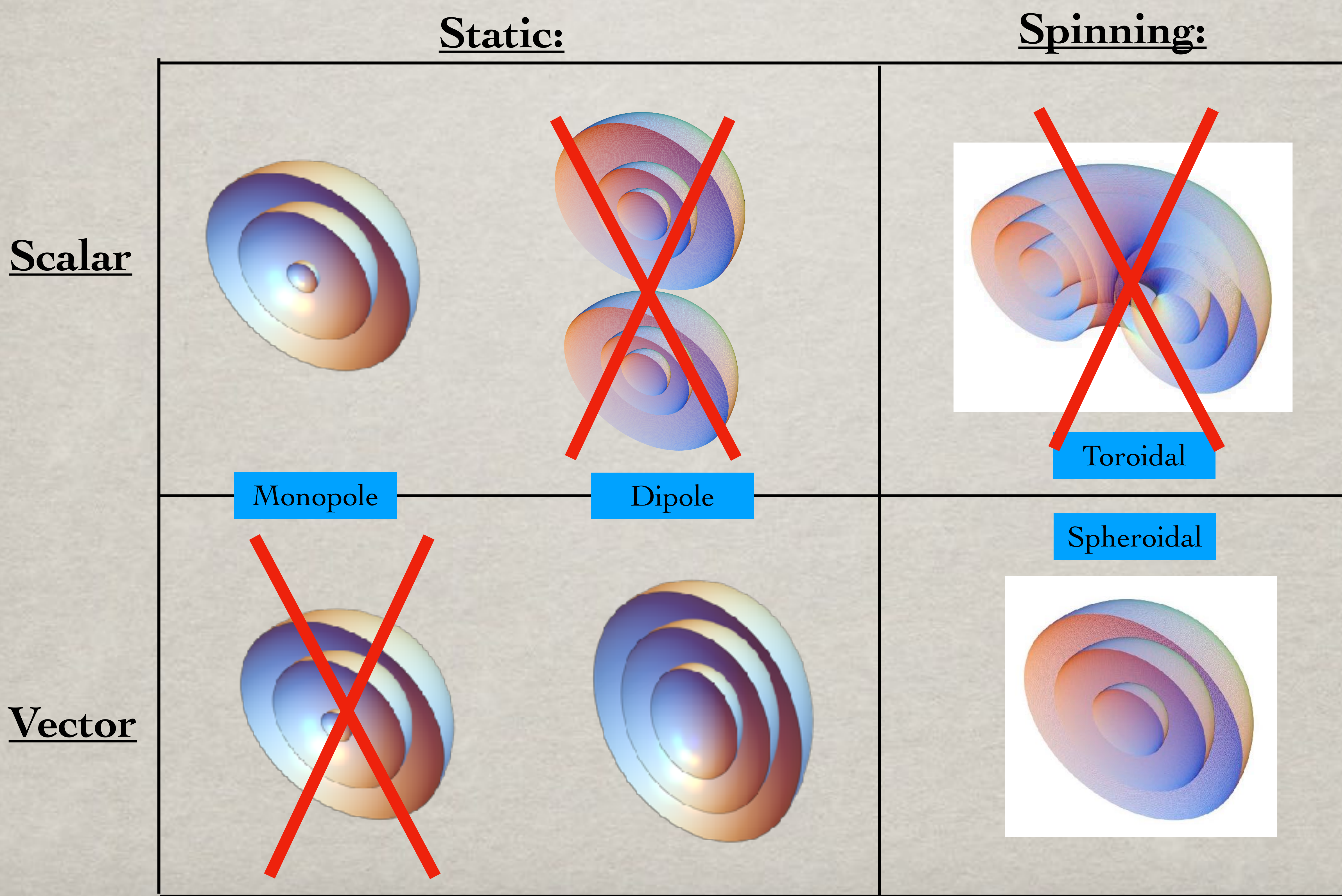
Thus, spinning Proca stars are dynamically more robust in these simplest models.

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

A surprising (dynamically) different picture:

Costa, CH, Radu, Sanchis-Gual and Santos, 2311.14800



Composite stars (multi-state, multi-frequency):

Matos, Urena-Lopez, GRG 39 (2007) 1279; Bernal, Barranco, Alic, Palenzuela, PRD 81 (2010) 044031; Urena-Lopez and Bernal, PRD 82 (2010) 123535; Alcubierre, Barranco, Bernal, Degollado, Diez-Tejedor, Megevand, Nunez, Sarbach, CQG 35, 19LT01 (2018); Di Giovanni, Fakhry, Sanchis-Gual, Degollado, and Font, PRD 102 (2020) 084063; F. S. Guzmán and L. A. Ureña López, PRD 101 (2020) 081302(R); F. S. Guzmán, Astron. Nachr. 342 (2021) 398

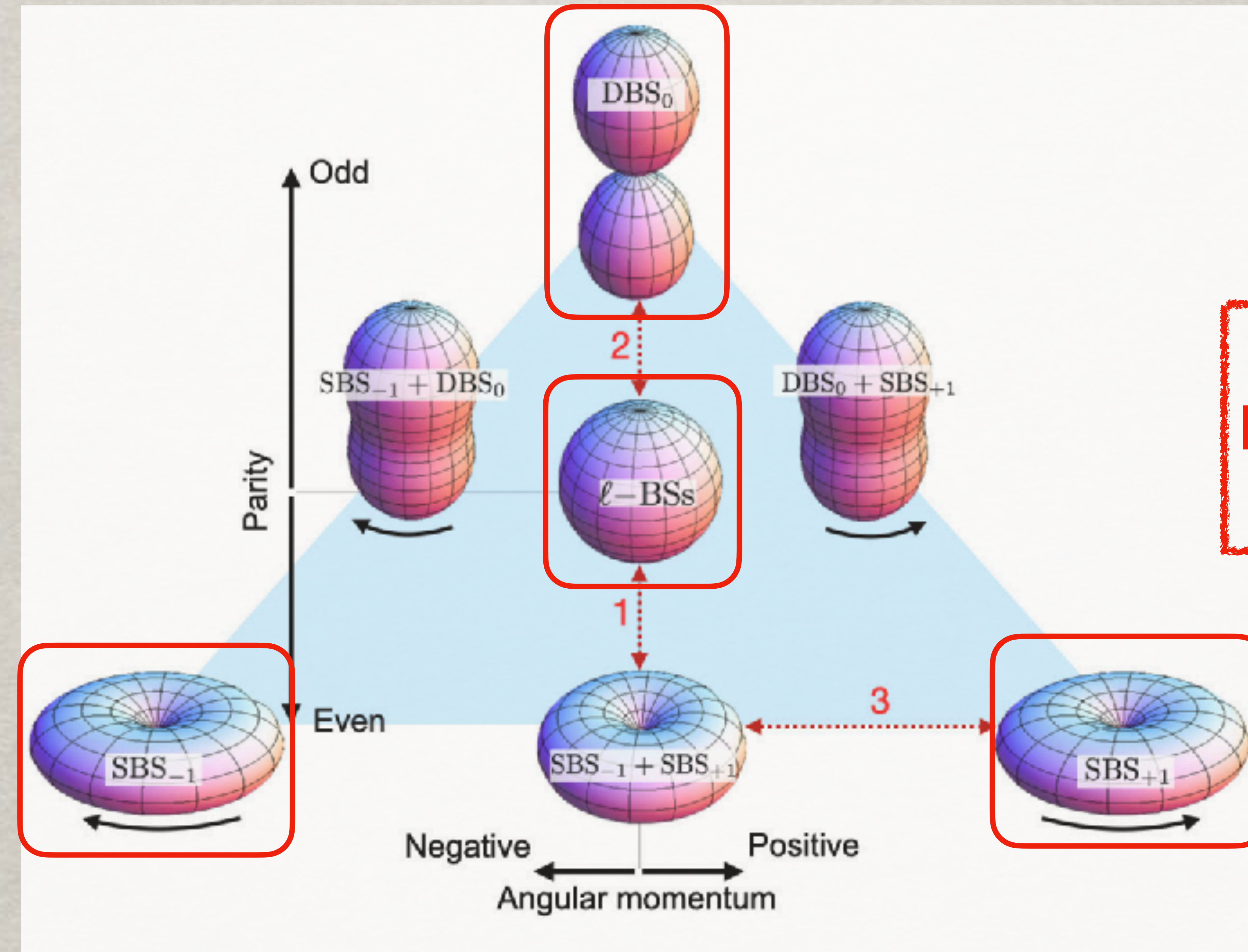


FIG. 1. $\ell = 1$ BSs family.

J. C. Degollado's talk

Sanchis-Gual, Di Giovanni, CH, Radu, Font, PRL 126 (2021) 241105

II) Some phenomenology
(and the imitation game)

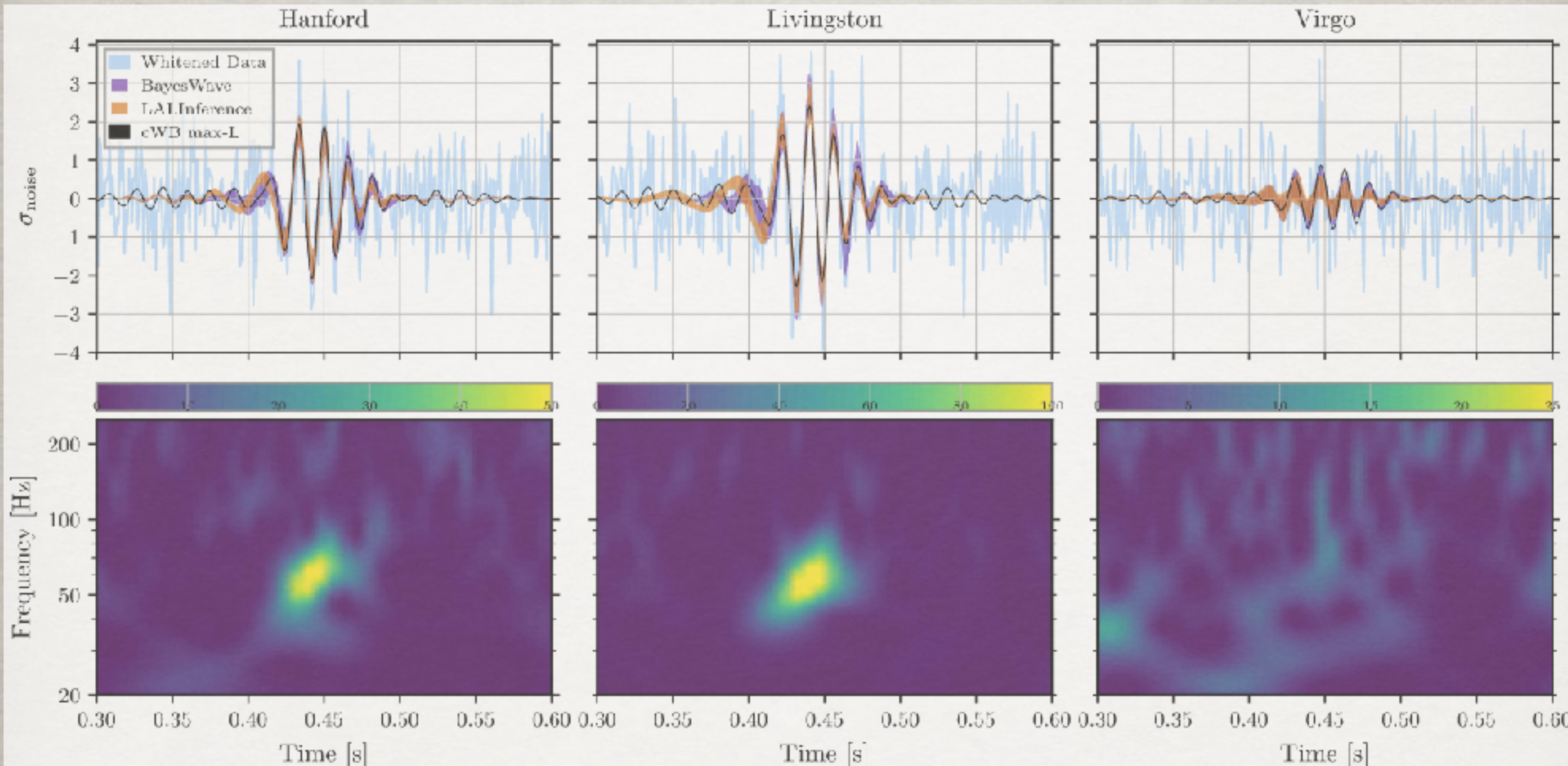
The imitation game

a) Mimicking a gravitational wave event

A particular event from the O3 run

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

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

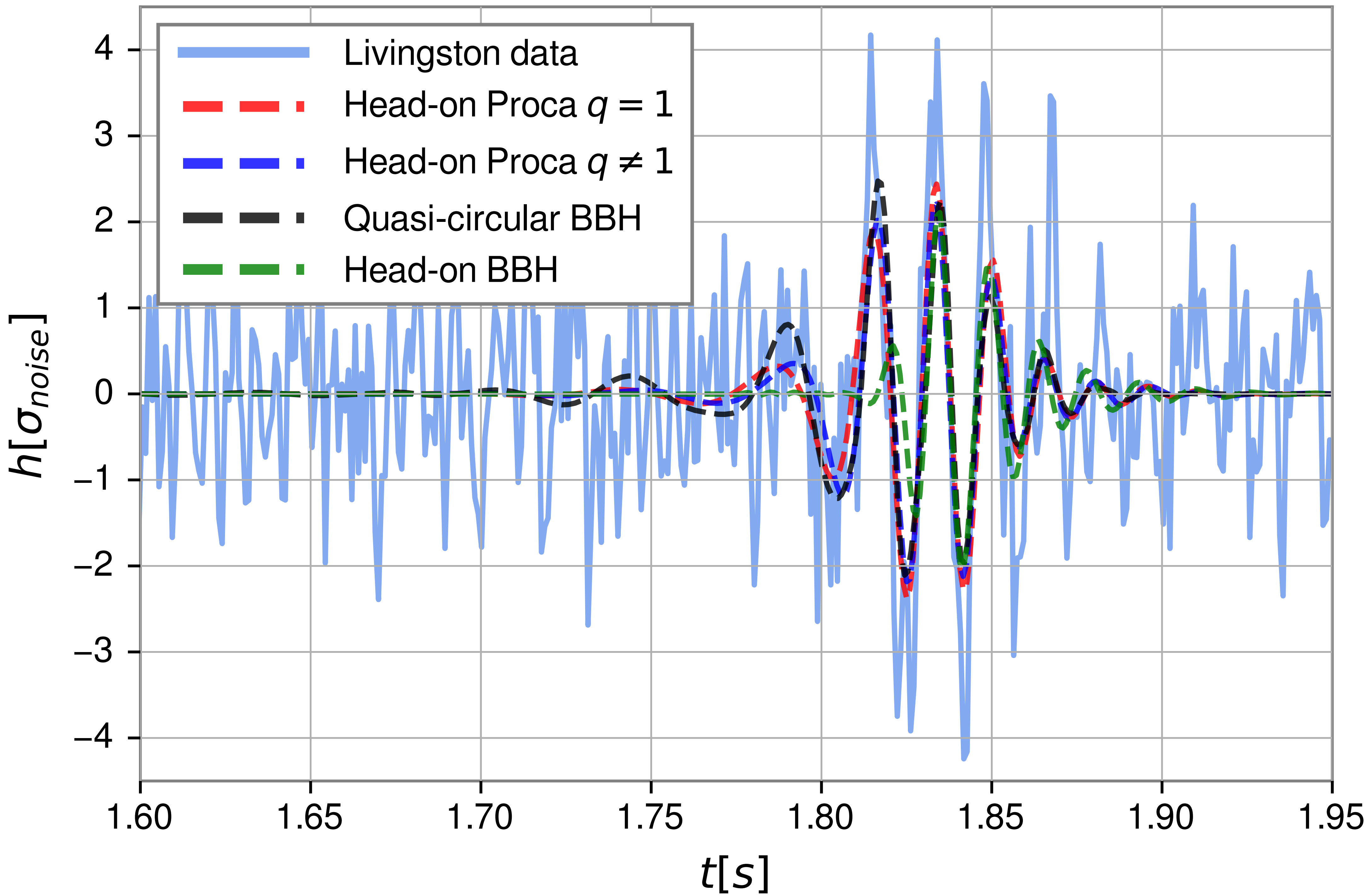


- Two most massive progenitors: $85^{+21}_{-14} M_\odot$, $66^{+17}_{-18} M_\odot$
- At least one in the pair instability supernova gap. Formation?
- Very short - no inspiral
- Final BH can be considered of intermediate mass: $142^{+28}_{-16} M_\odot$

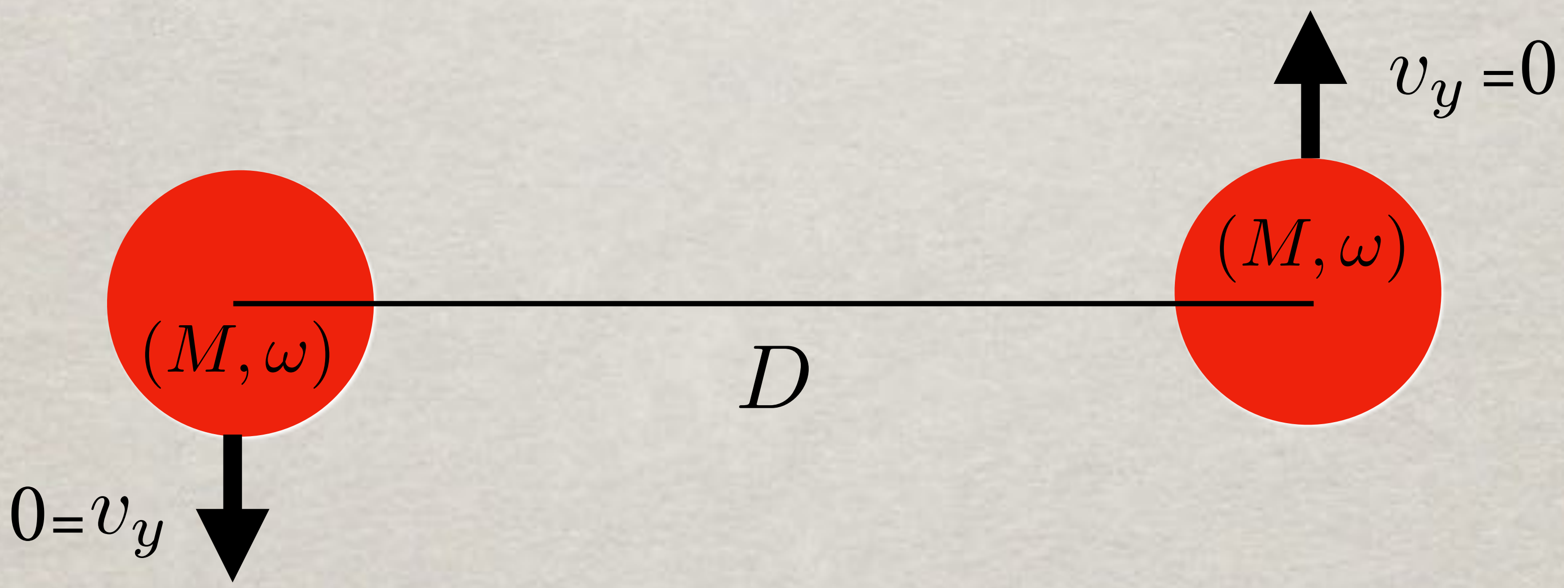
PHYSICAL REVIEW LETTERS 126, 081101 (2021)

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

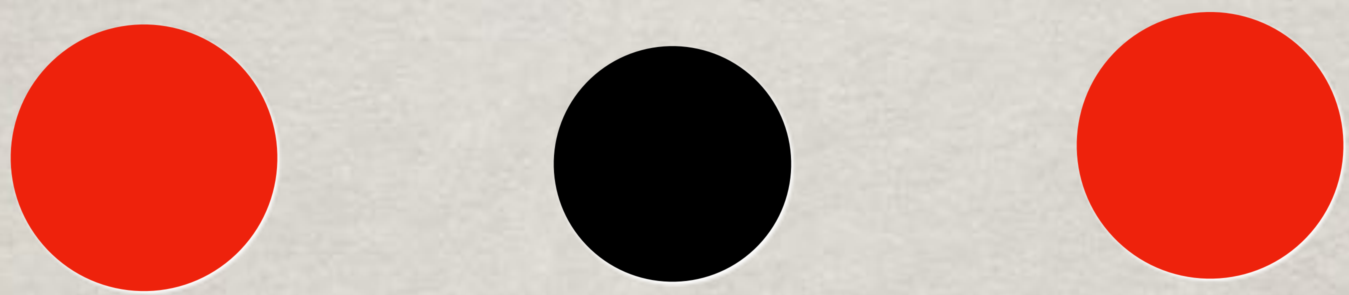
Juan Calderón Bustillo,[1,2,3,4,*] Nicolas Sanchis-Gual,[5,6,†] Alejandro Torres-Forné,[7,8,9] José A. Font,[8,9] Avi Vajpeyi,[3,4] Rory Smith,[3,4] Carlos Herdeiro,[6] Eugen Radu,[6] and Samson H. W. Leong[2]



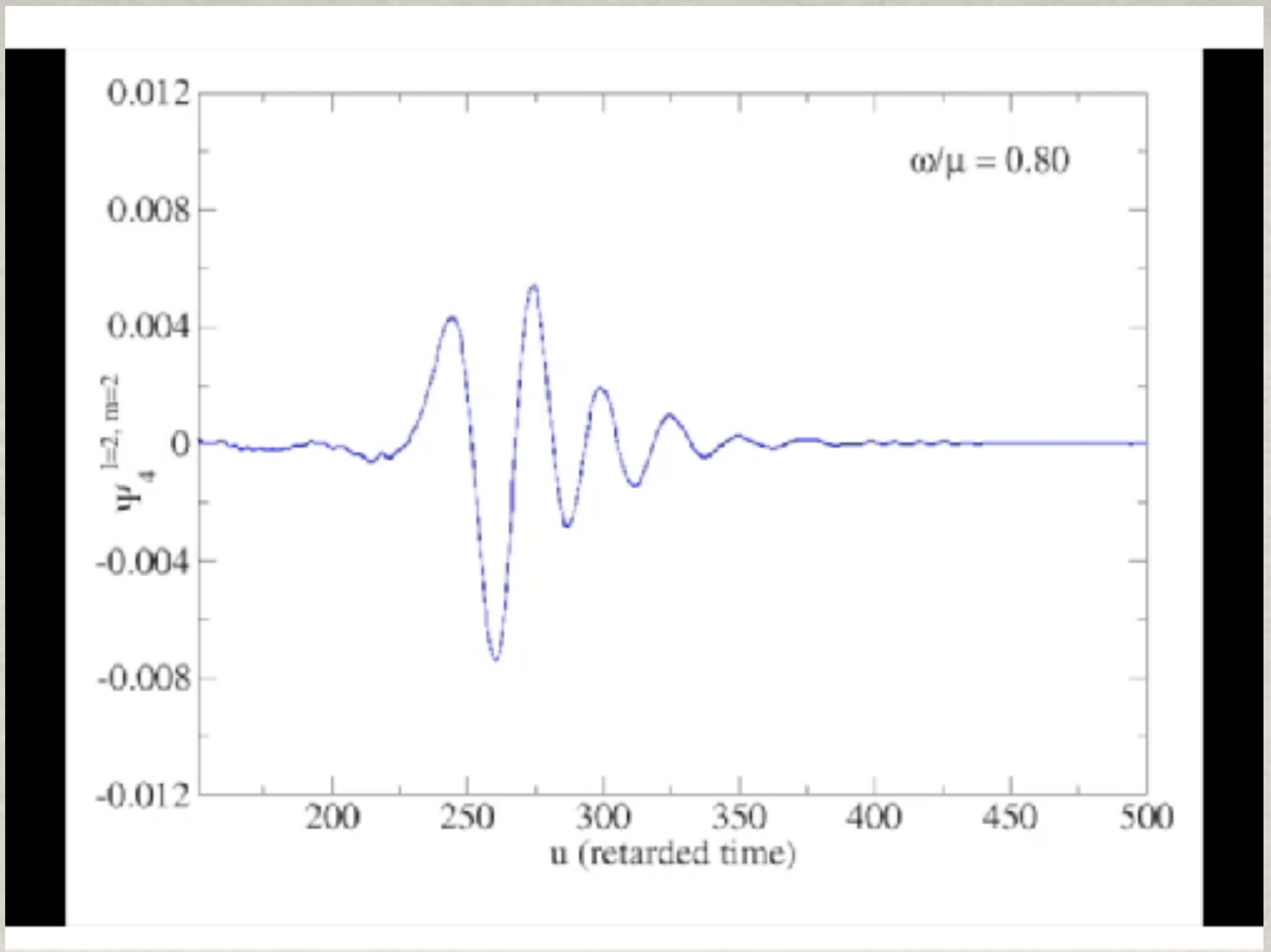
Mergers of spinning vector boson stars

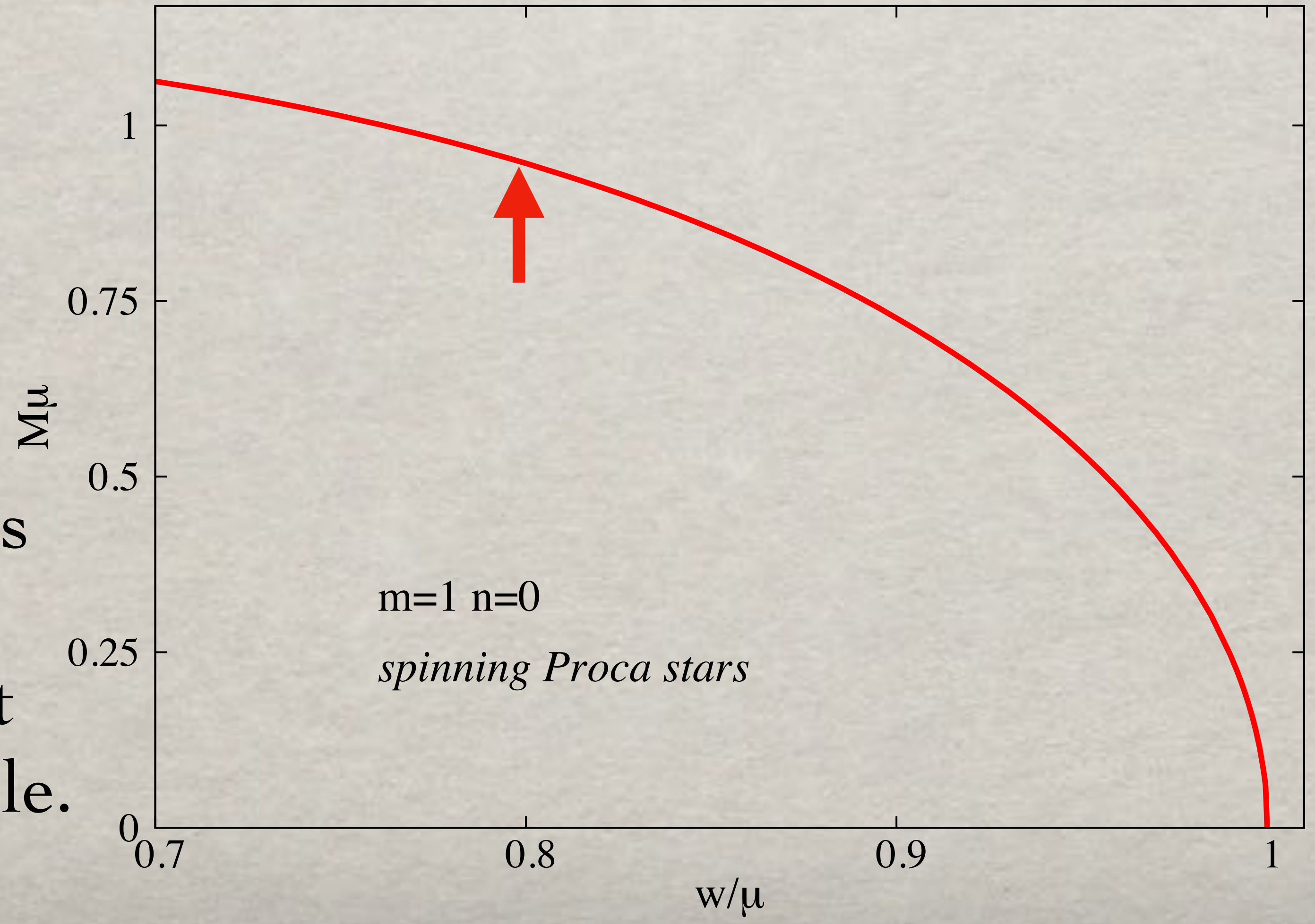


Mergers of spinning vector boson stars



$(M_{\mathrm{BH}}, J_{\mathrm{BH}})$

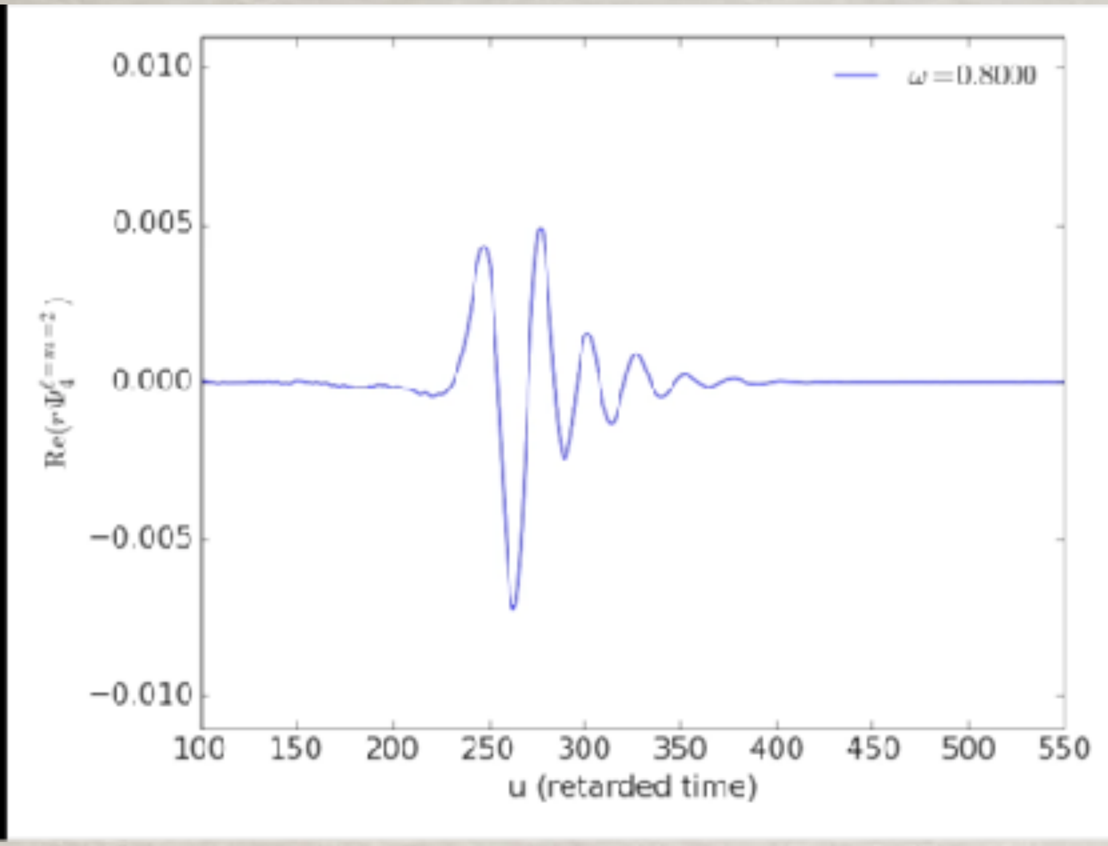




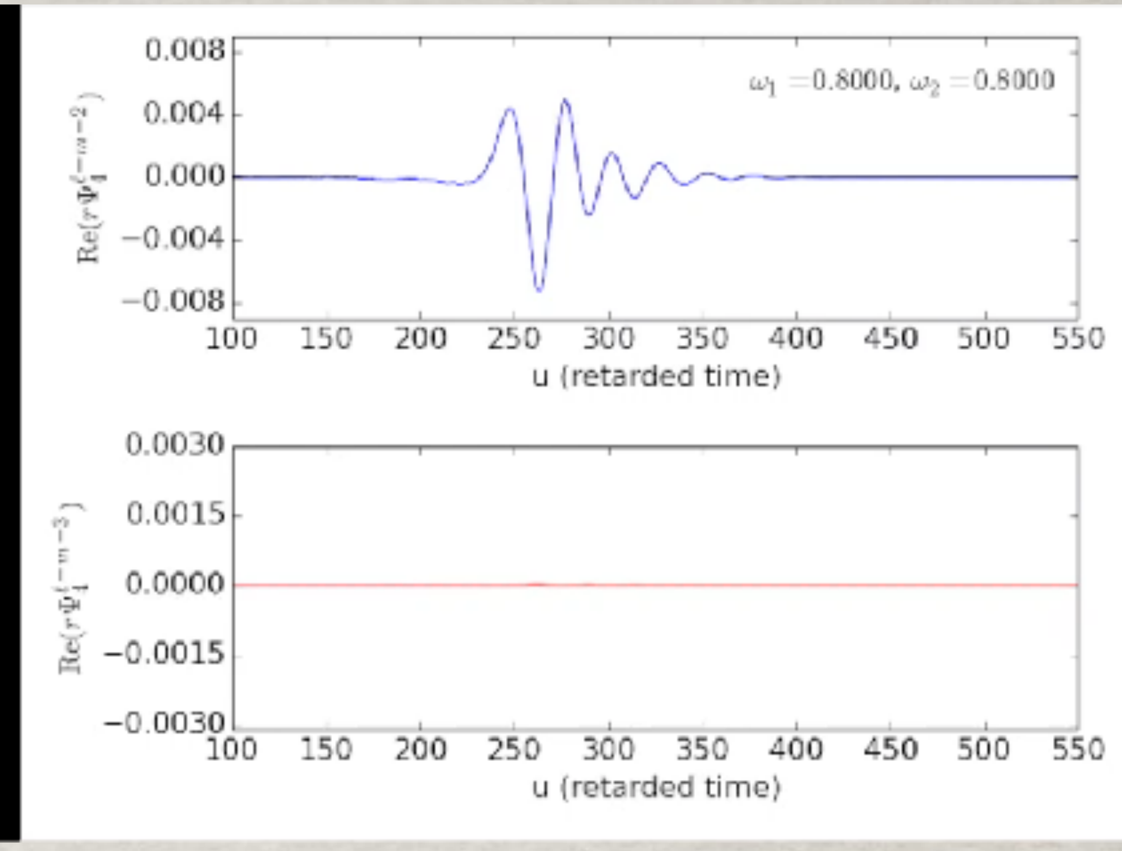
For frequencies too high the final object is not a black hole.

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

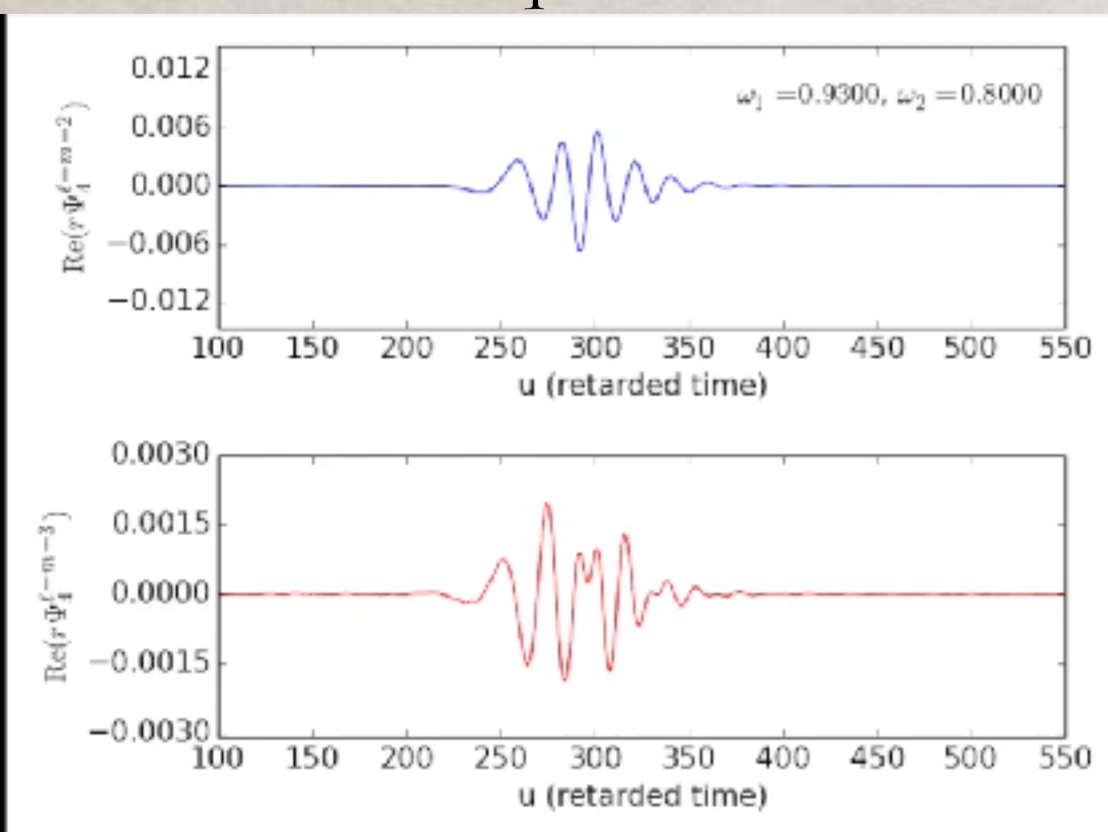
equal mass



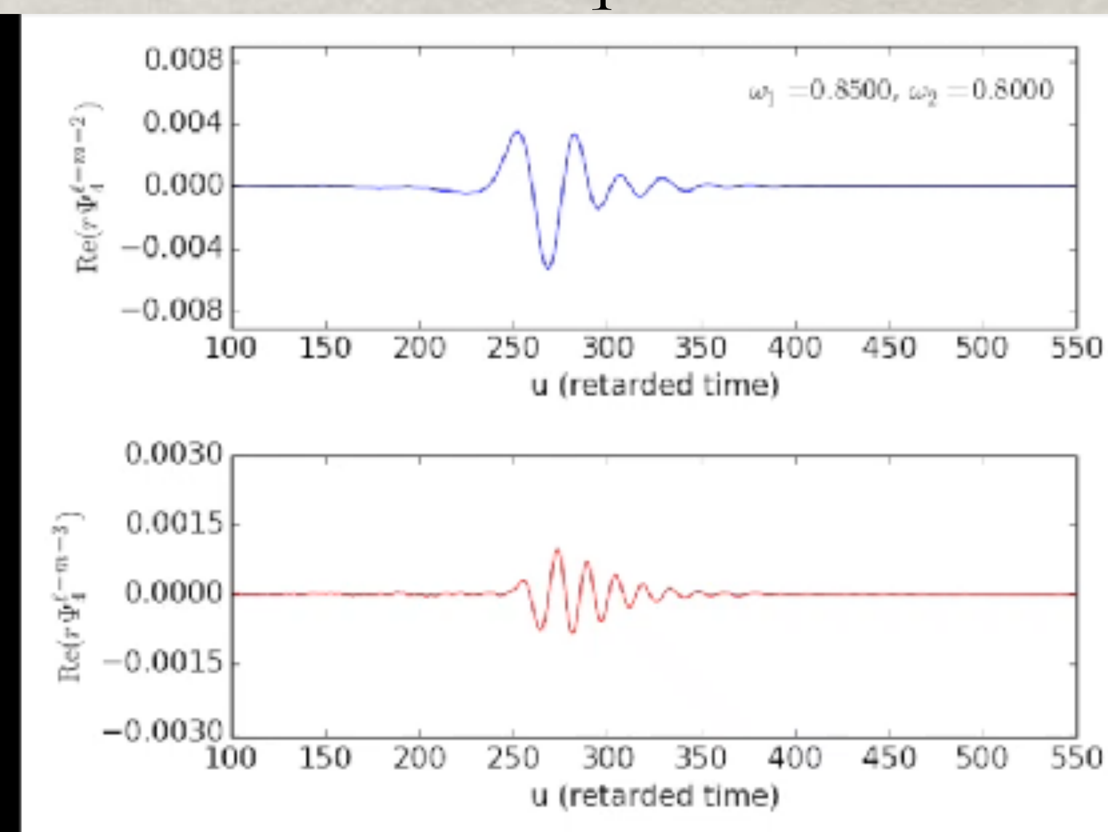
unequal mass



unequal mass



unequal mass

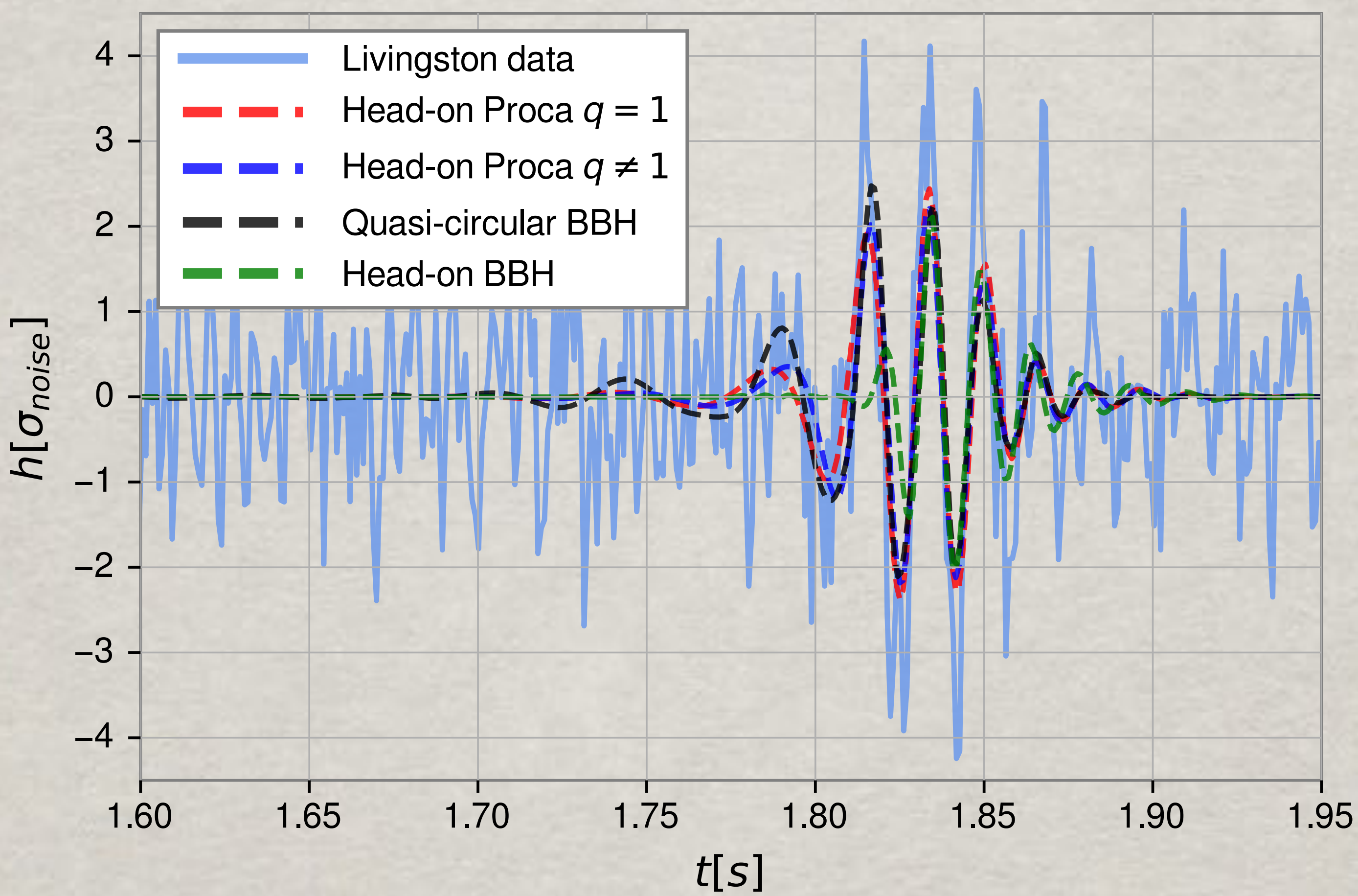


Building a catalogue of Proca star waveforms

(over 750 waveforms from NR simulations so far) Sanchis-Gual+ 2208.11717

Statistical Preference:

Bustillo et. al, PRL 126 (2021) 081181

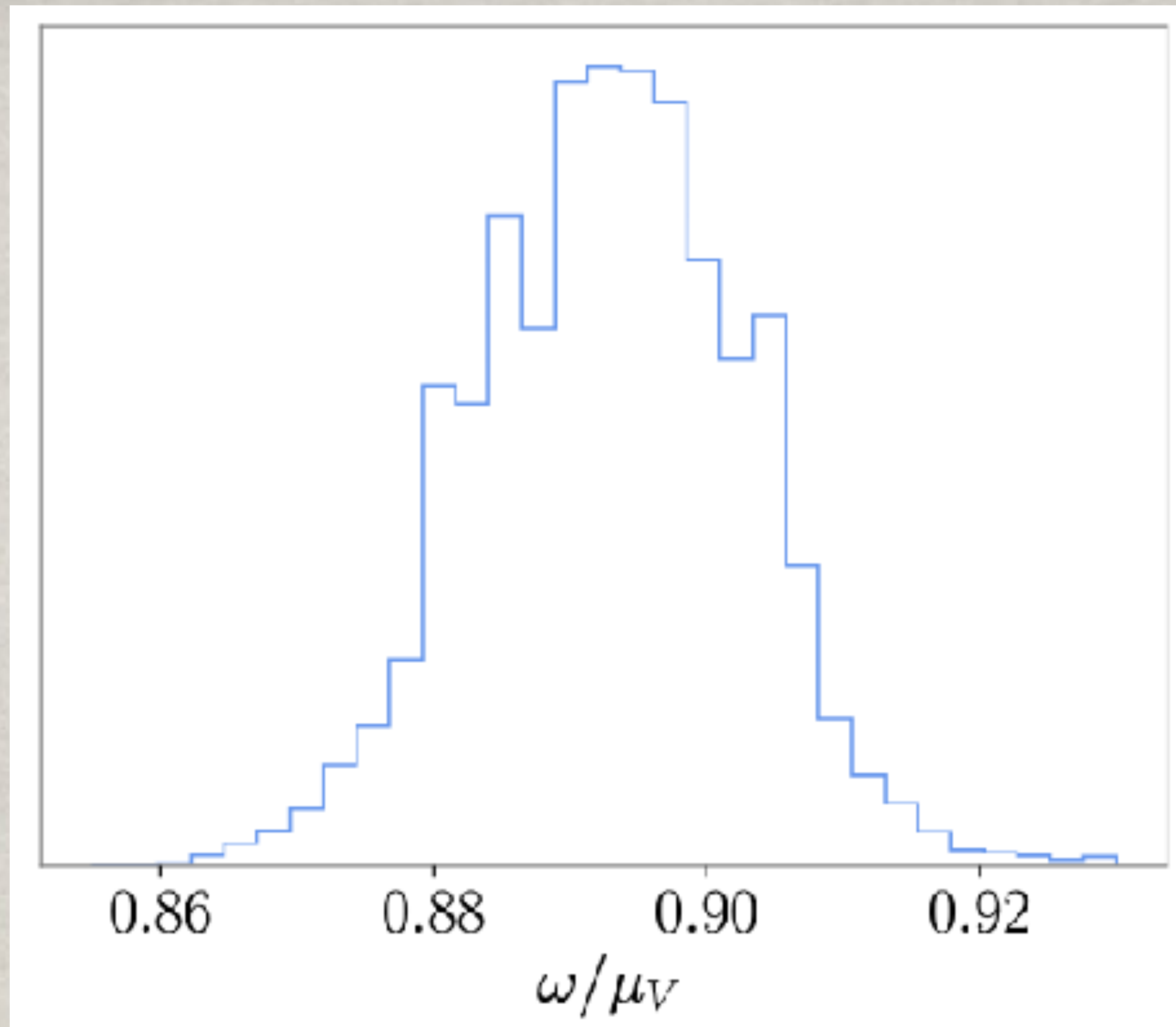


Waveform model	$\log \mathcal{B}$	$\log \mathcal{L}_{\max}$
Quasi-circular Binary Black Hole	80.1	105.2
Head-on Equal-mass Proca Stars	80.9	106.7
Head-on Unequal-mass Proca Stars	82.0	106.5
Head-on Binary Black Hole	75.9	103.2

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

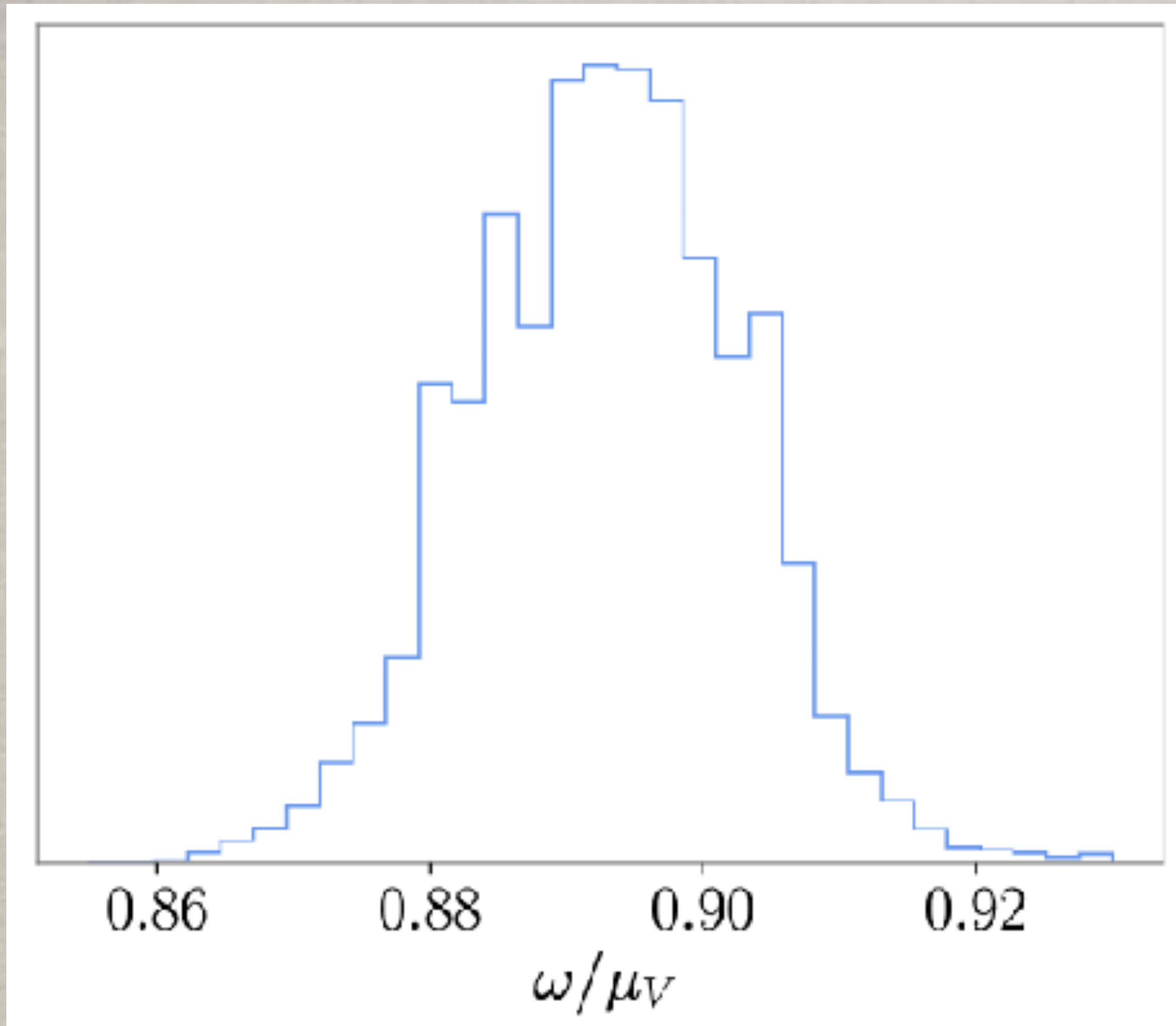
Prior:
Uniform in distance

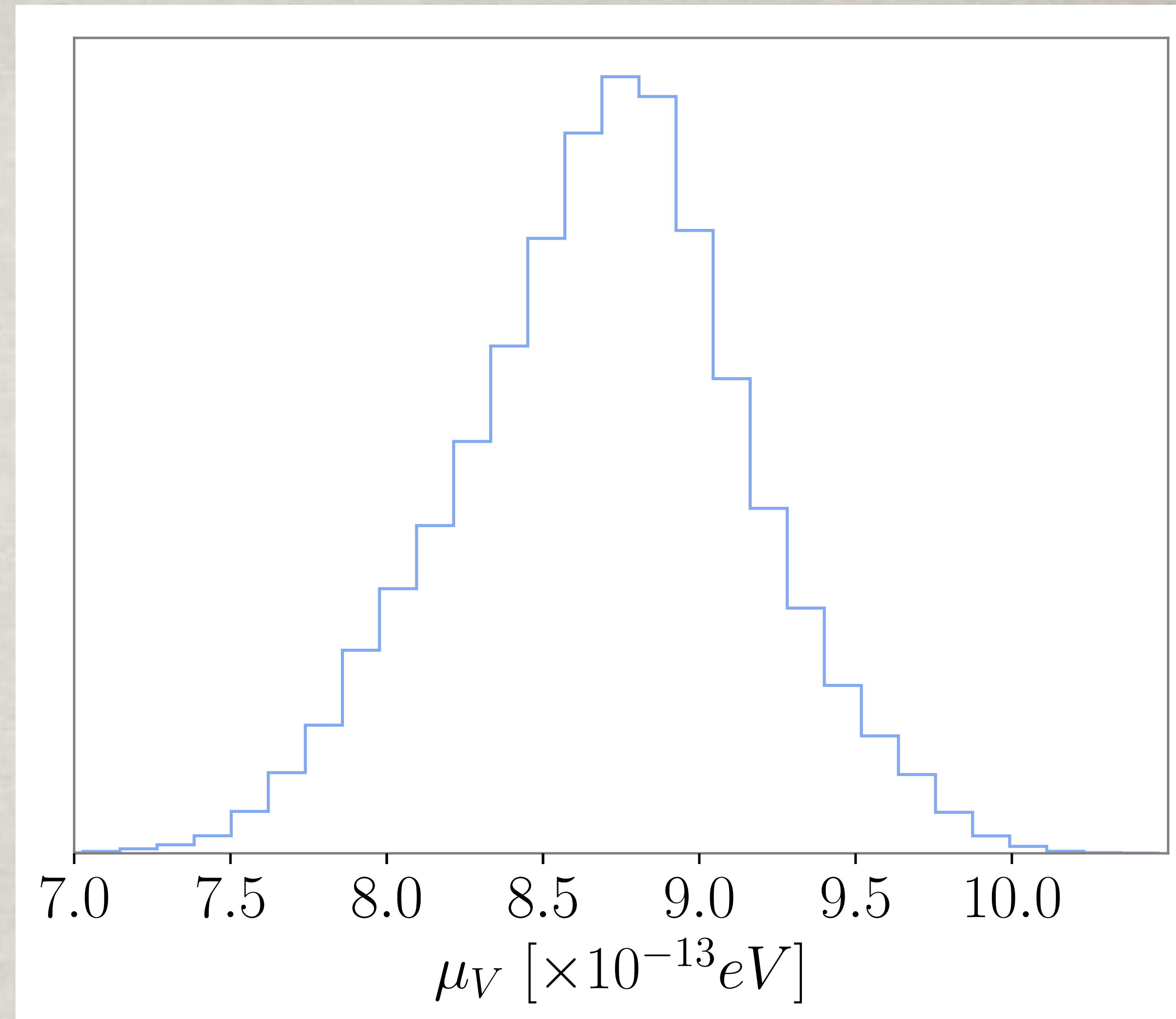


$$\omega/\mu_V = 0.893^{+0.015}_{-0.015}$$

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.

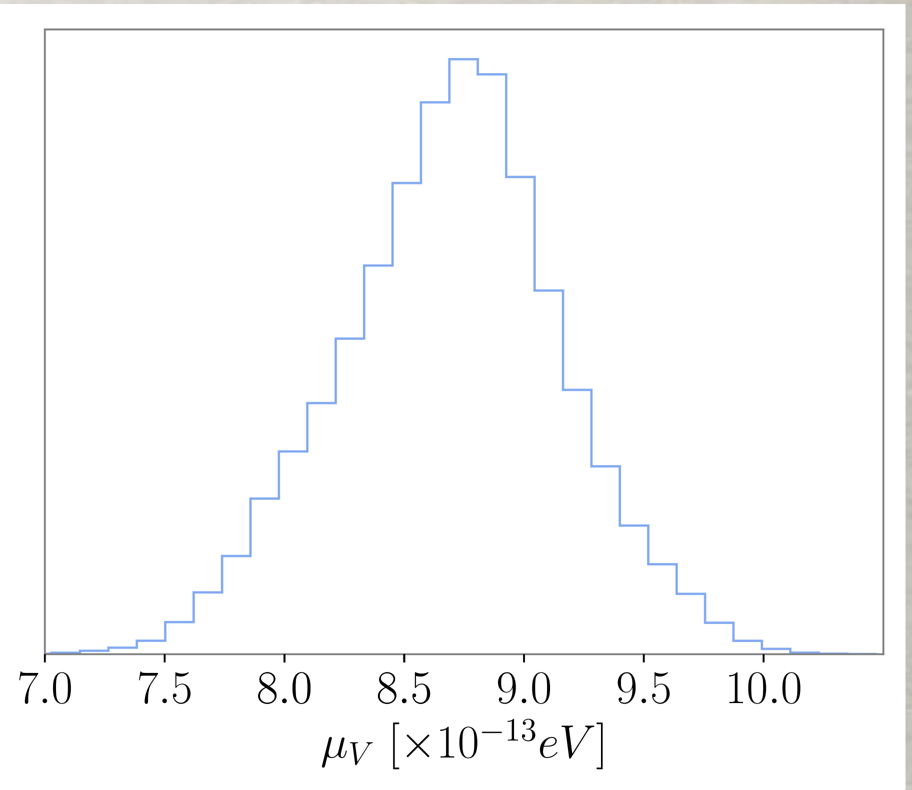




Thus we get a distribution for the mass of the ultralight boson.

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	$0.893^{+0.015}_{-0.015}$	$(*)0.905^{+0.012}_{-0.042}$
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	$173^{+19}_{-14}\ M_\odot$	$175^{+13}_{-11}\ M_\odot$



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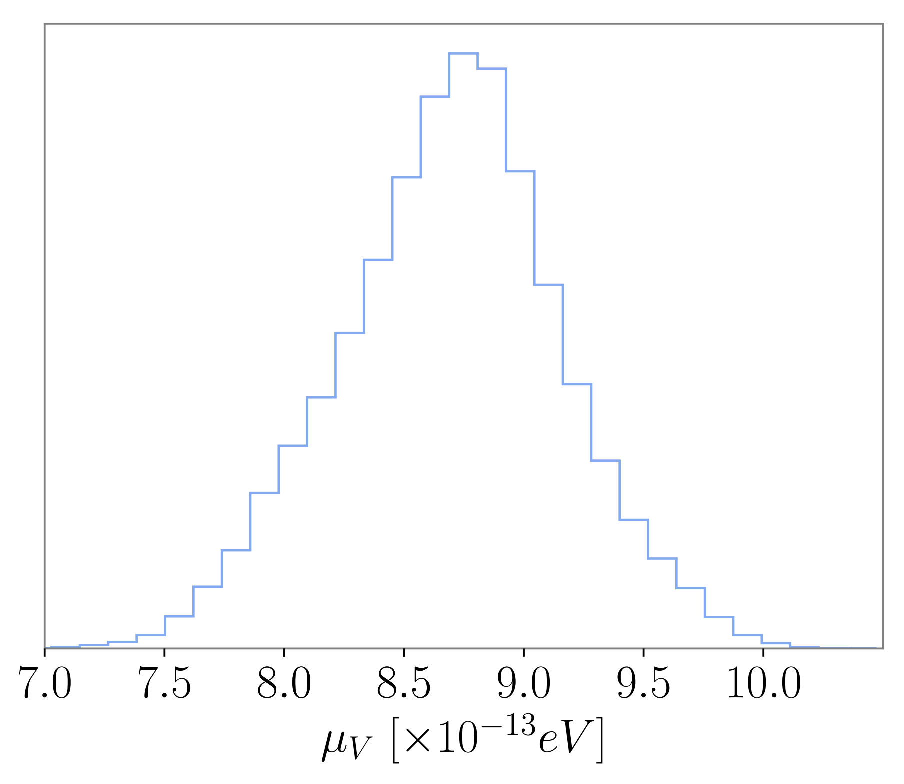


$$M_{\rm max} = 173^{+19}_{-14} M_\odot$$

No previous GW signals can be Proca star mergers.

The imitation game

b) Mimicking a black hole shadow without light rings

P. Cunha's

H. Lima Junior's

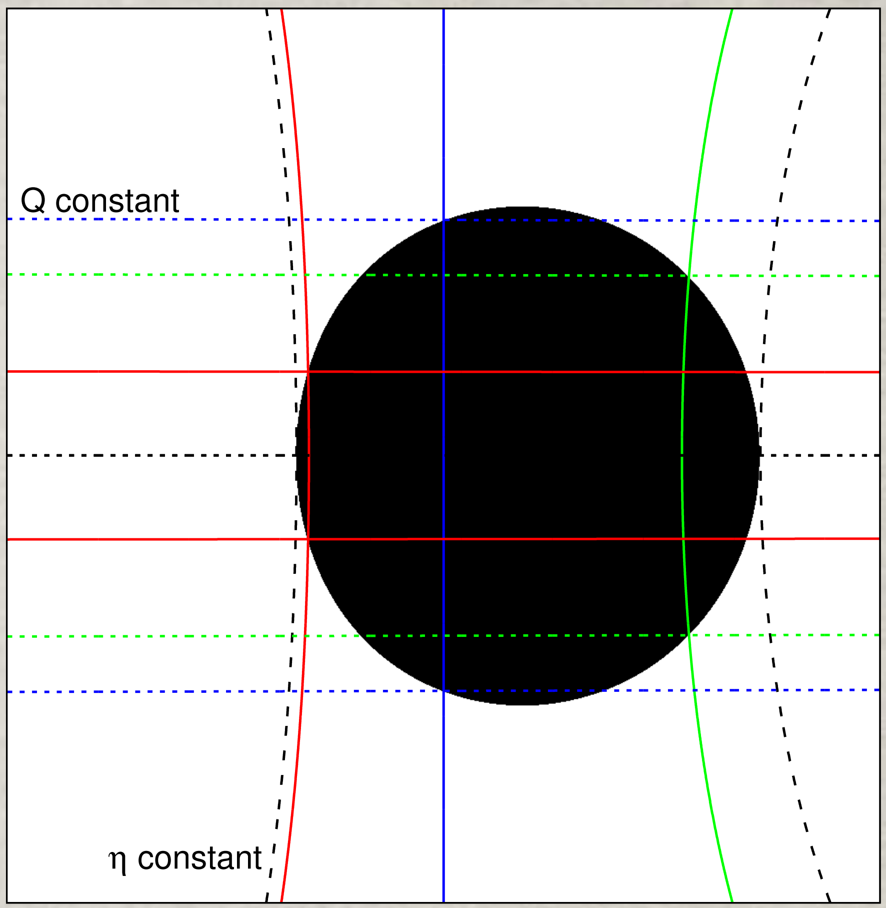
S. Dolan's
talks

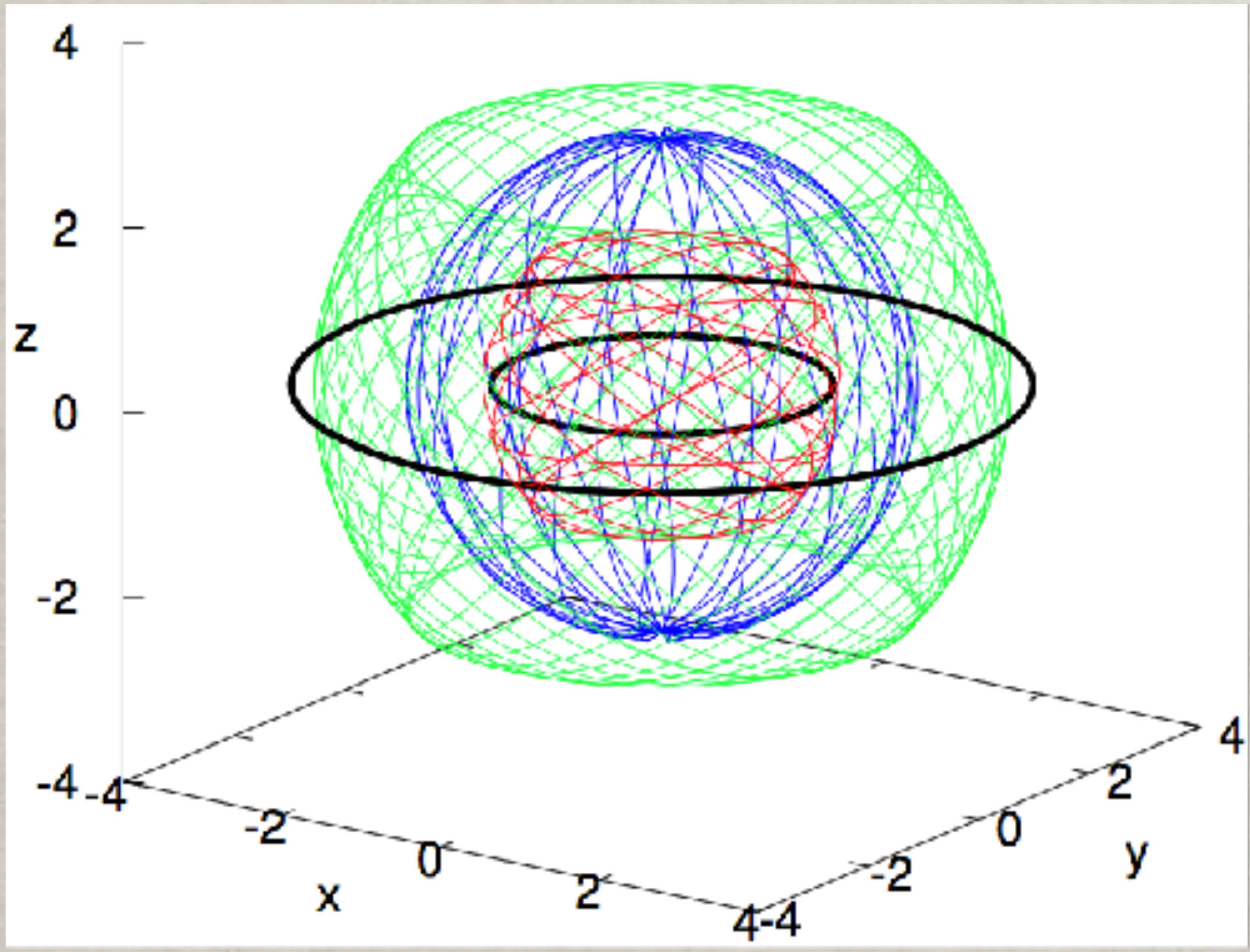
j~0.82

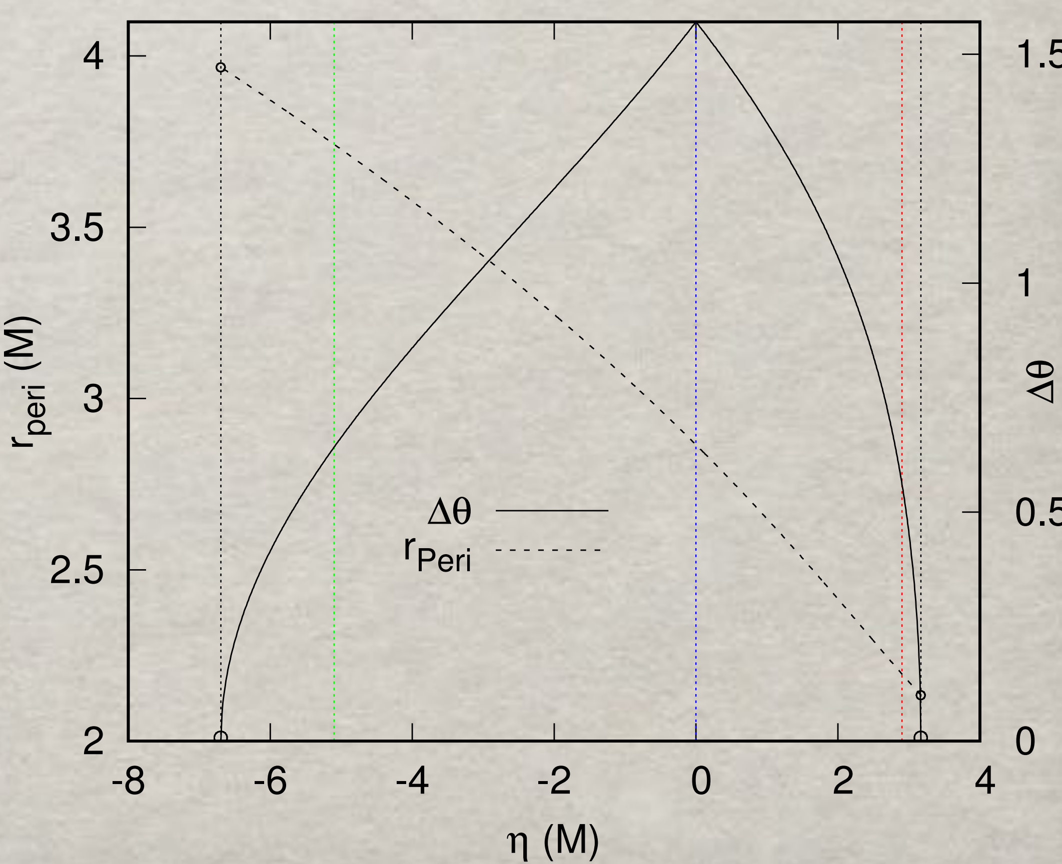
The edge of the shadow is determined by the
Fundamental Photon Orbits
Cunha, C.H., Radu, PRD 96 (2017) 024039

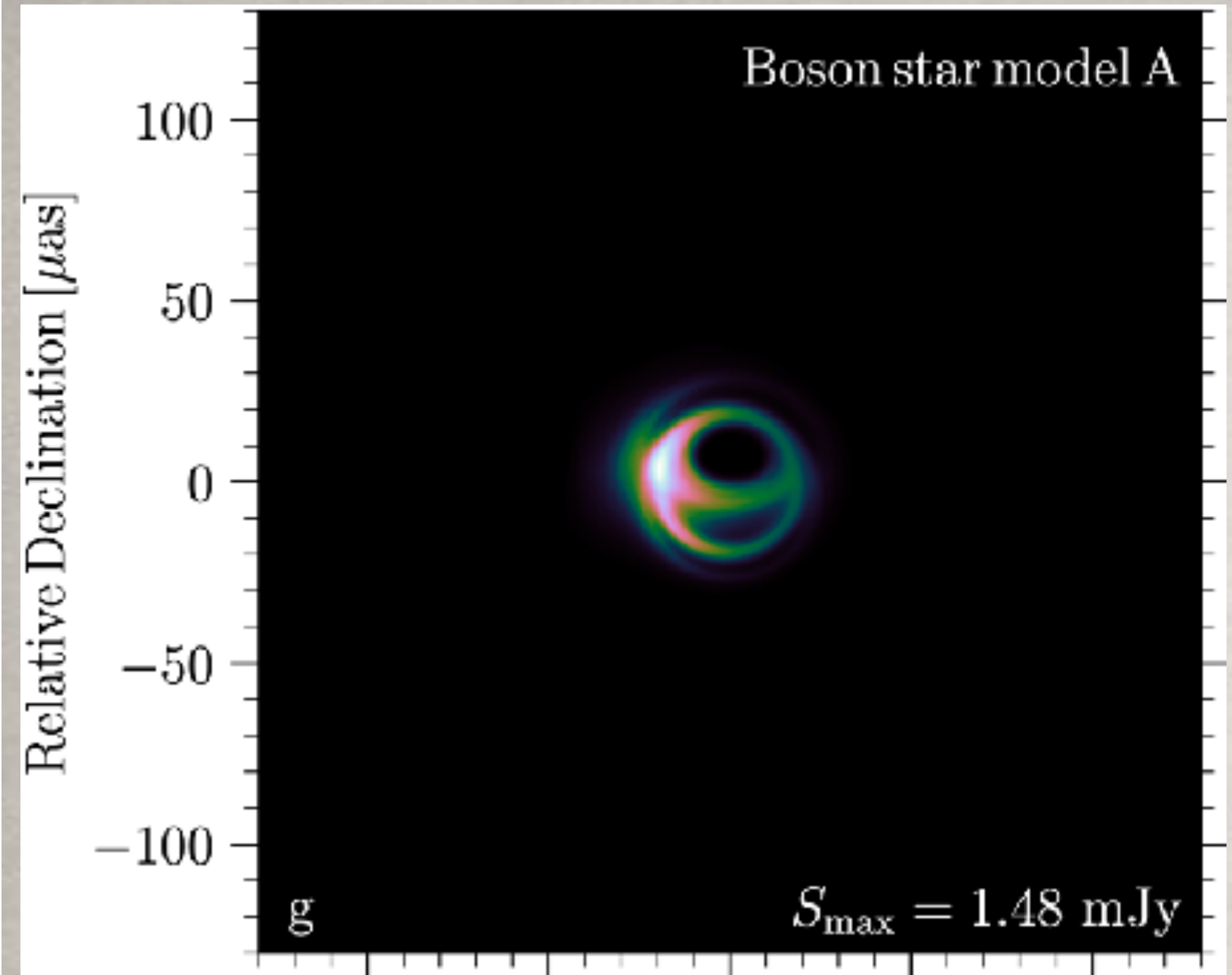
Called spherical orbits in Kerr case
Teo, GRG 35 (2003) 1909

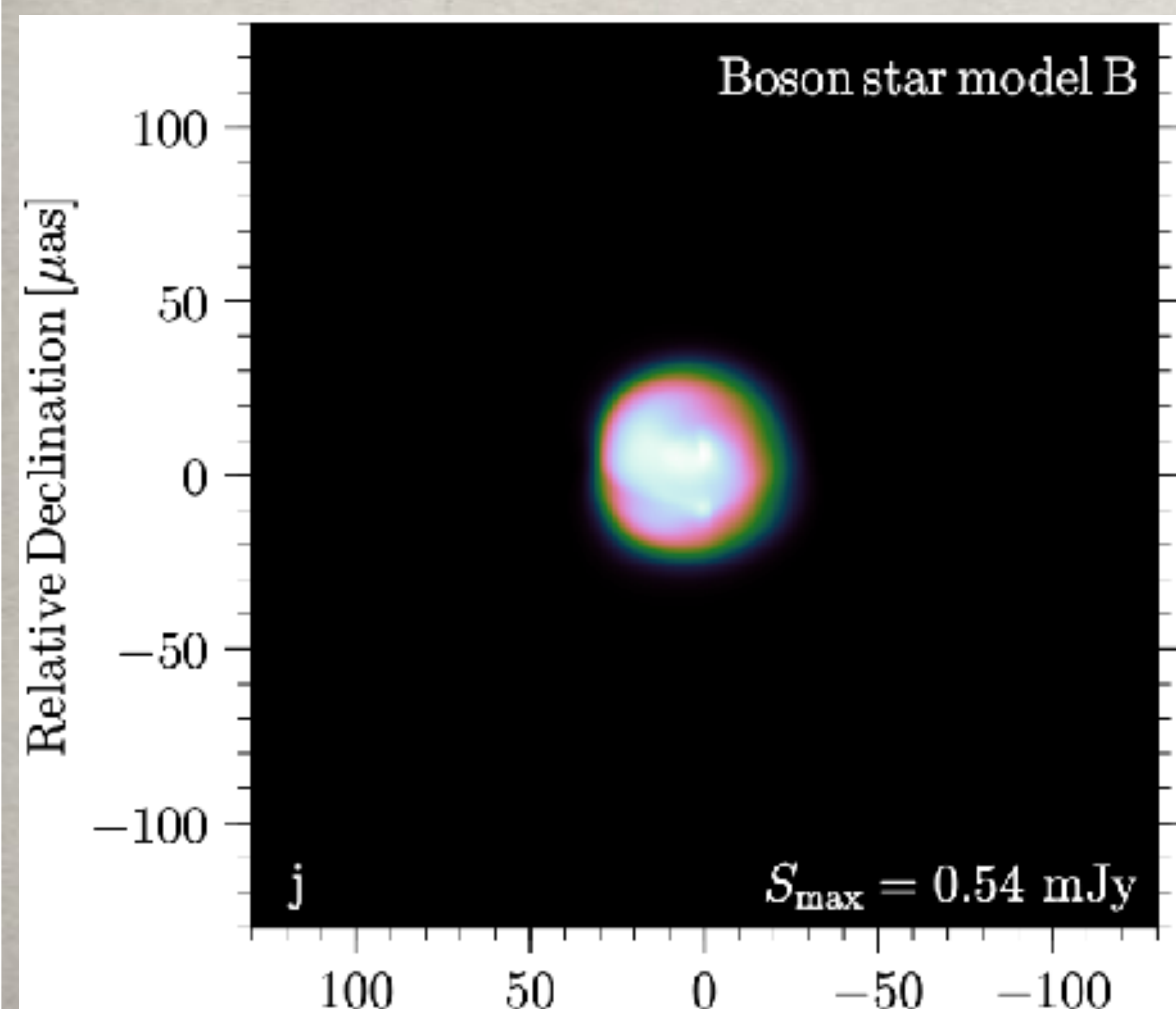
Relate to quasi-normal ringing
Goebel, Astrophys. J. 172 (1972) L95
Cardoso, Franzin and Pani, PRL 116 (2016) 171101

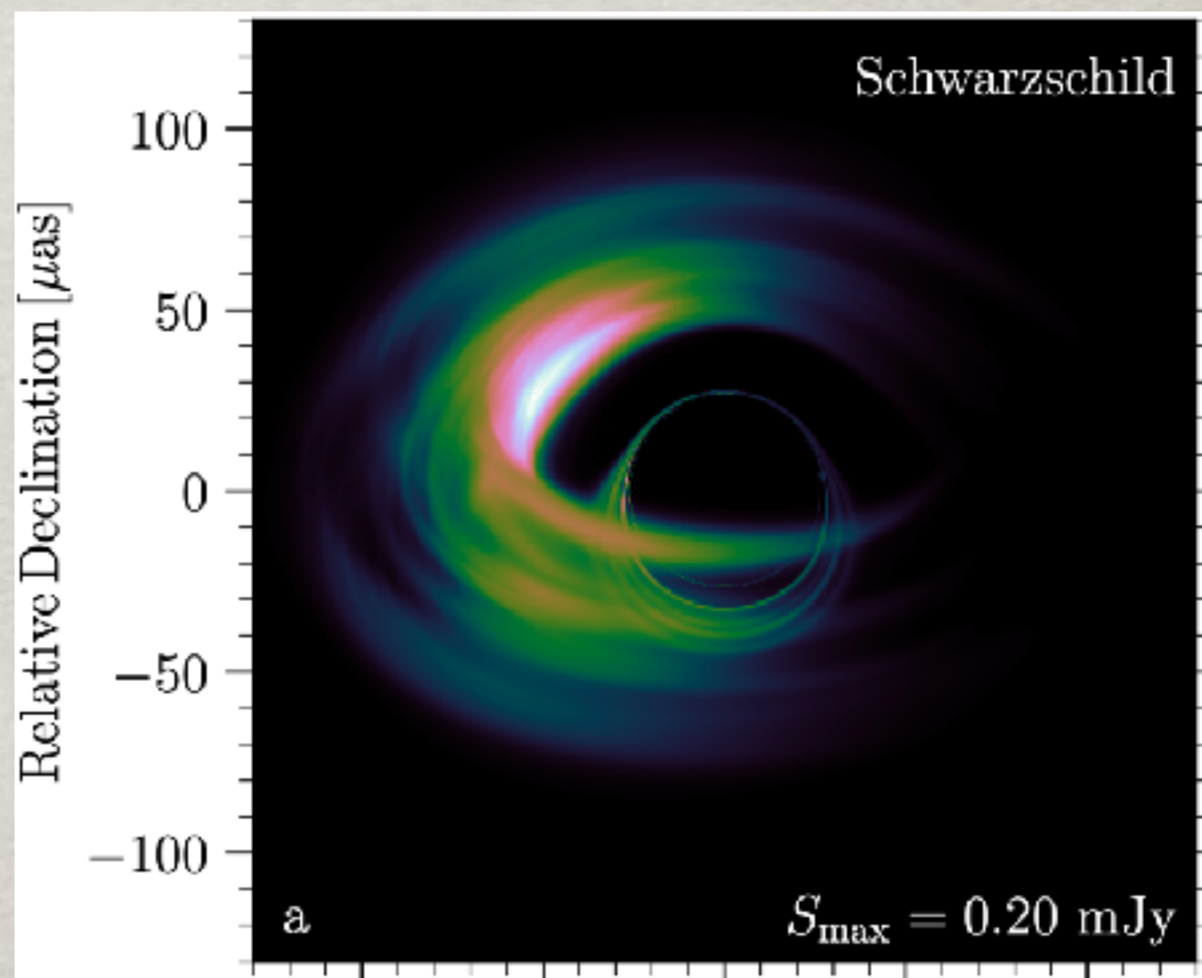






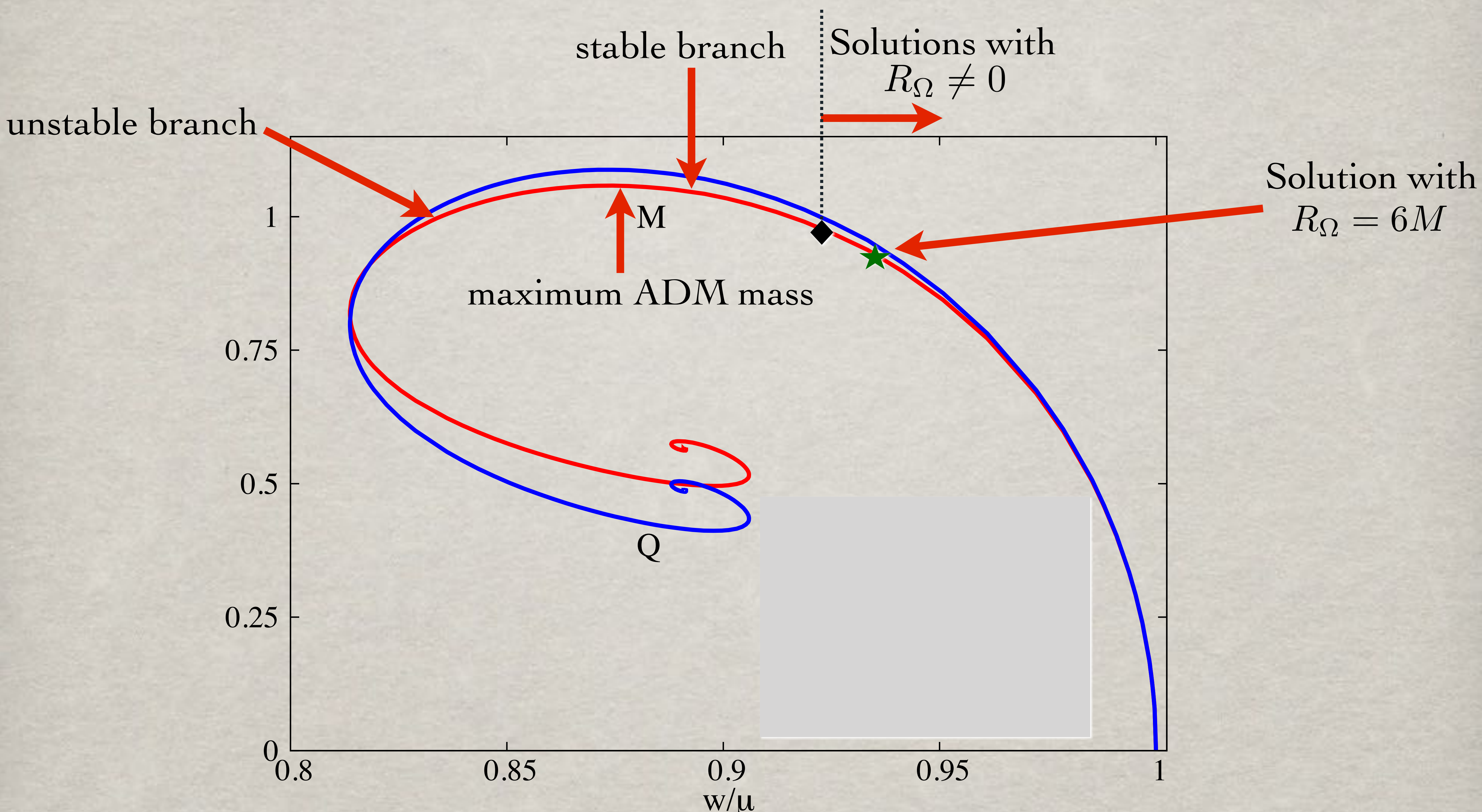






Olivares, Younsi, Fromm, De Laurentis, Porth, Mizuno, Falcke, Kramer, Rezzolla, Mon. Not. Roy. Astron. Soc. 497 (2020) 521

Spherical Proca stars domain of existence

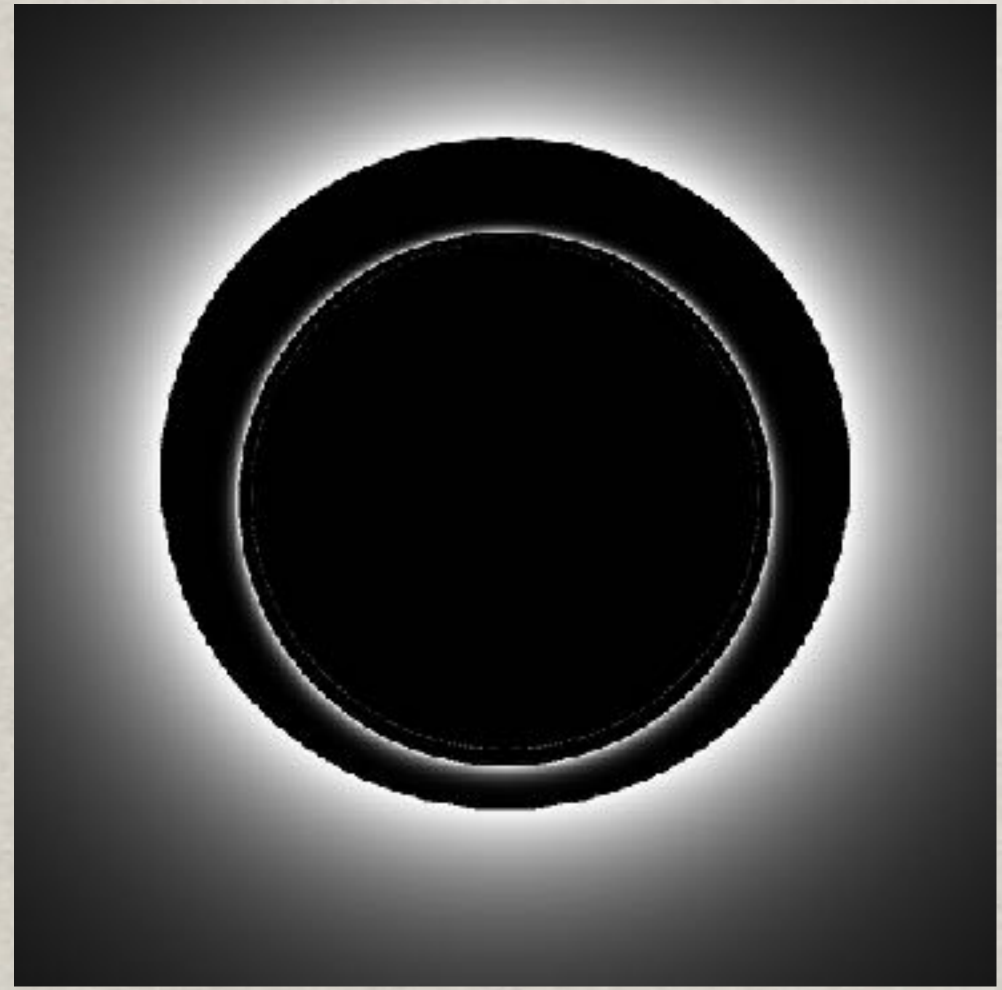


CH, Pombo, Radu, Cunha, Sanchis-Gual
ArXiv: 2102.01703

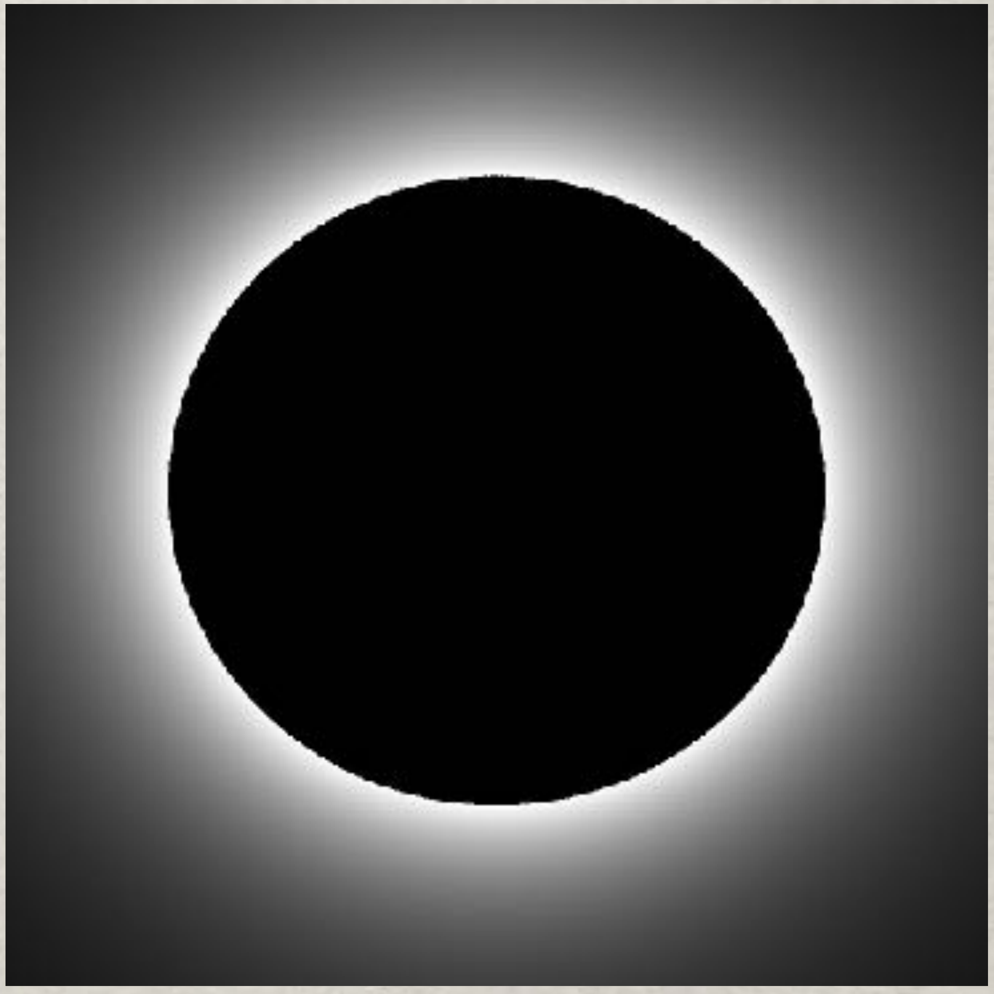
Almost polar observation

$\theta_{\rm obs} = 17^{\rm o} \qquad r_{\rm obs} = 100M$

Schwarzschild BH



Proca star



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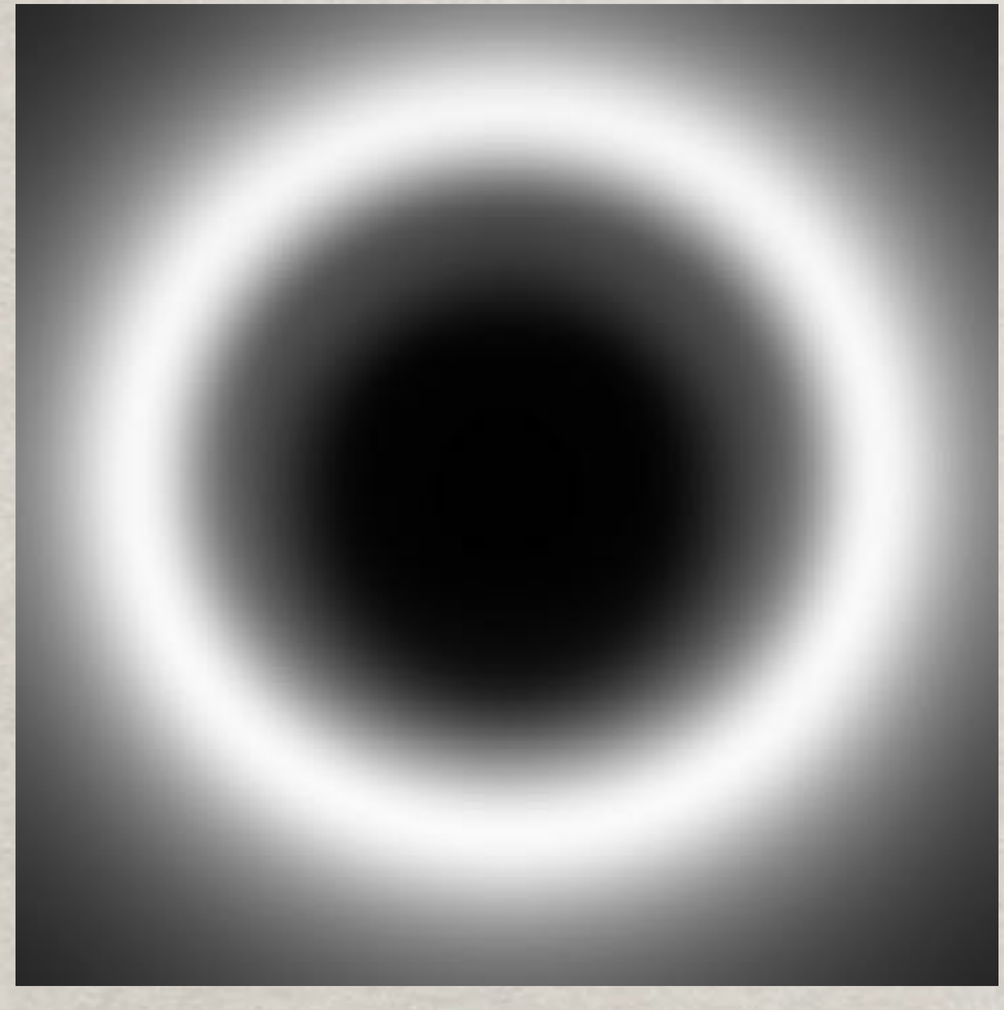
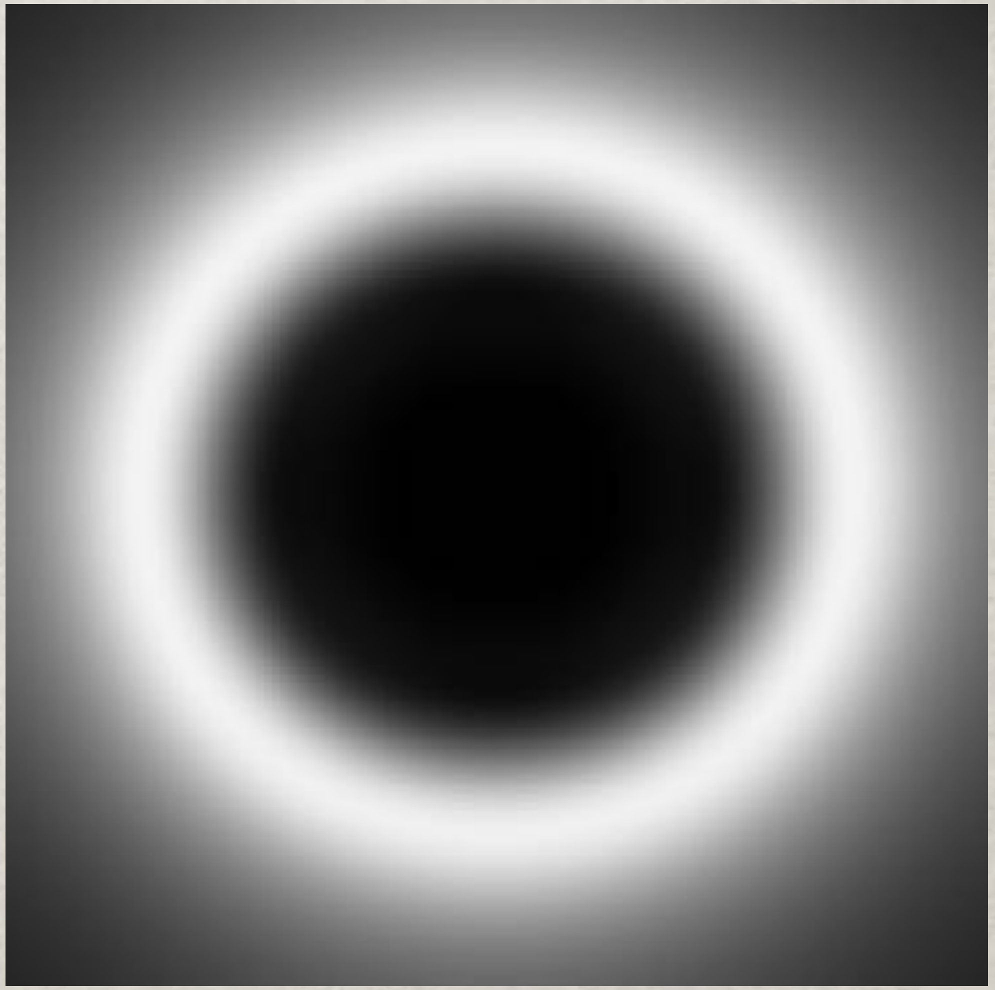
Schwarzschild BH



Proca star

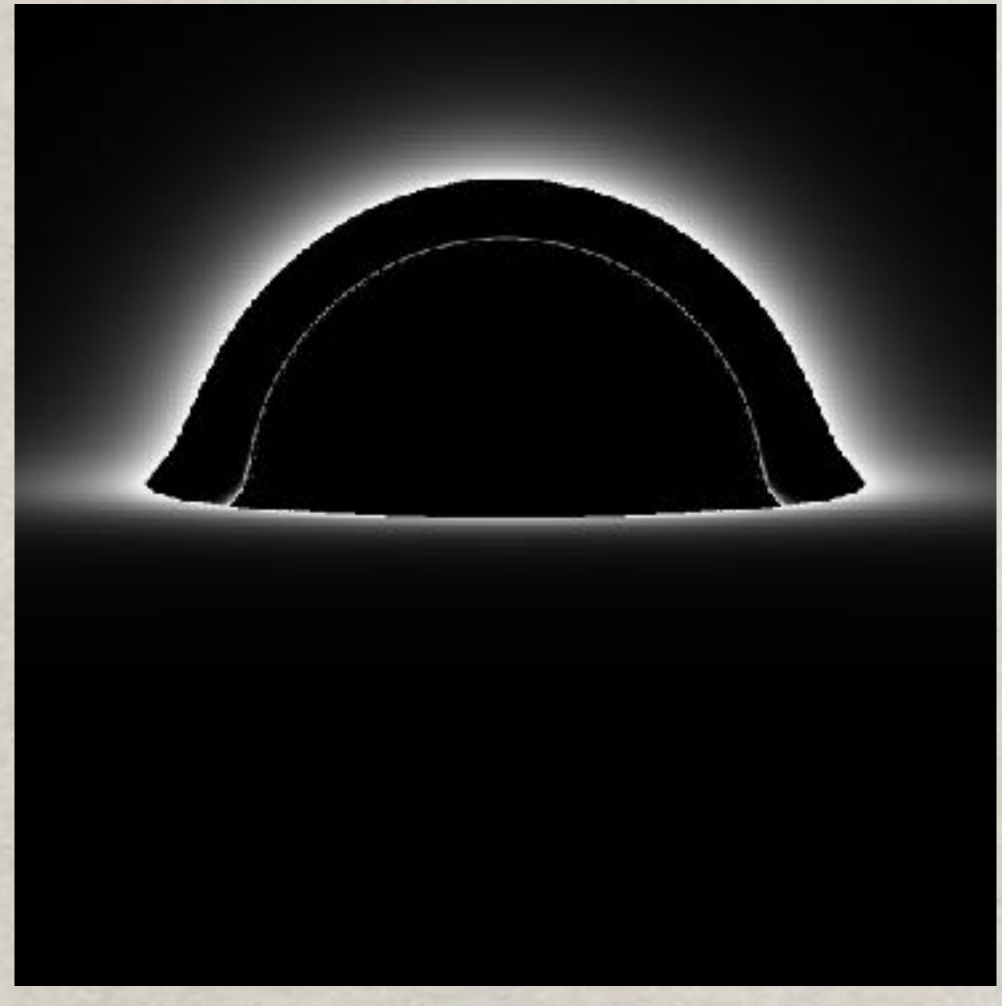


Applying a Gaussian blurring filter

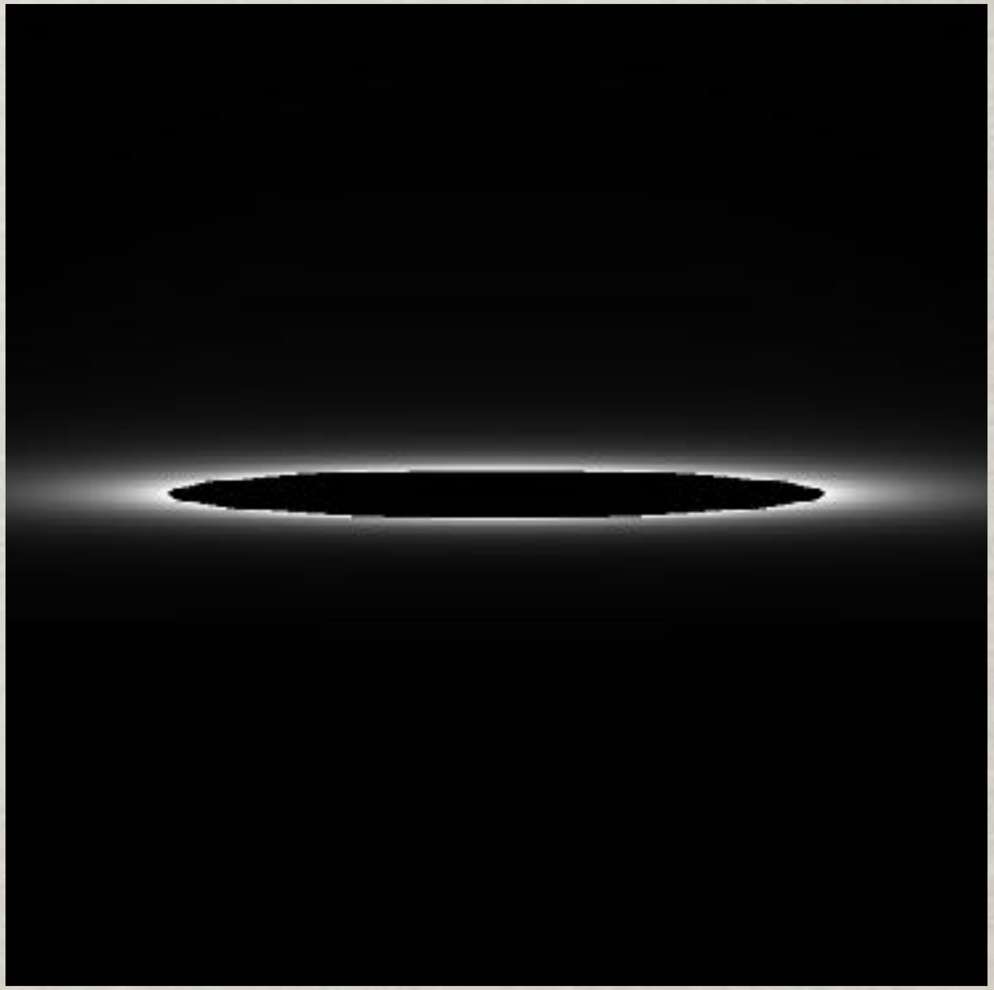
Almost equatorial observation

$\theta_{\rm obs} = 86^{\rm o} \quad r_{\rm obs} = 100M$

Schwarzschild BH



Proca star



Almost equatorial observation

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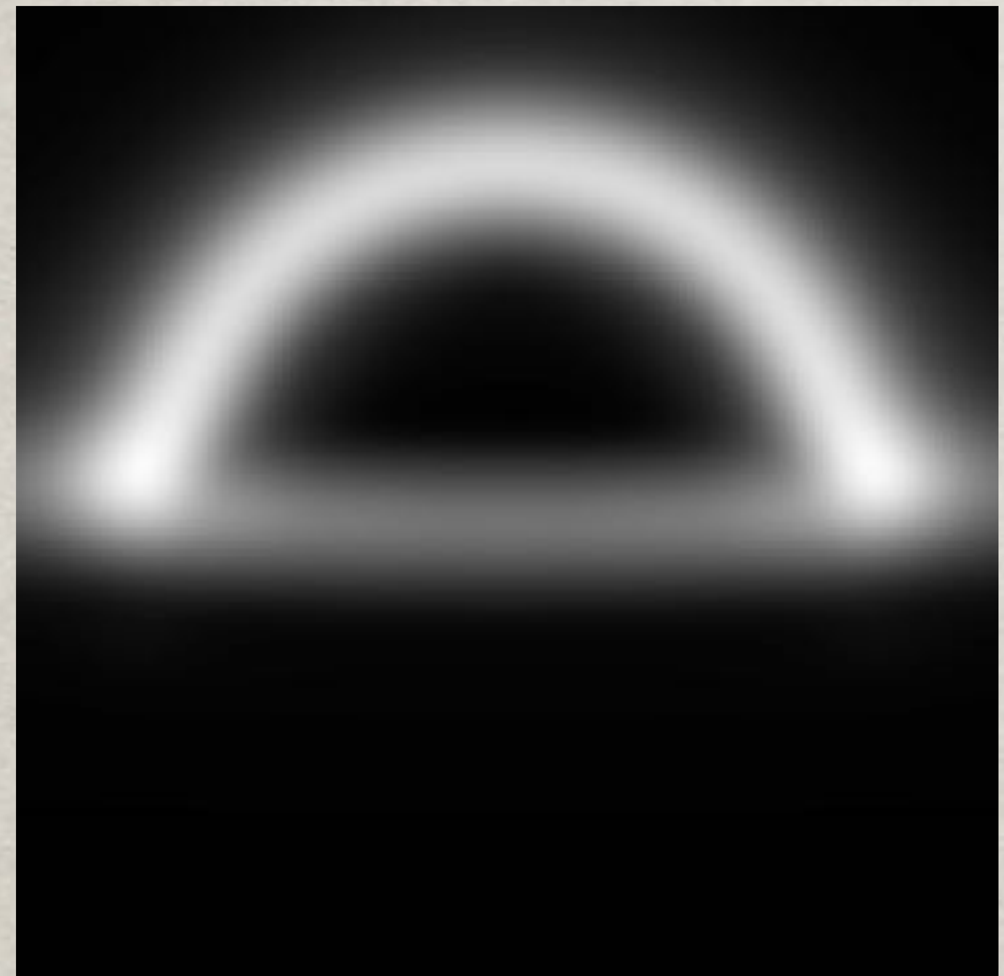
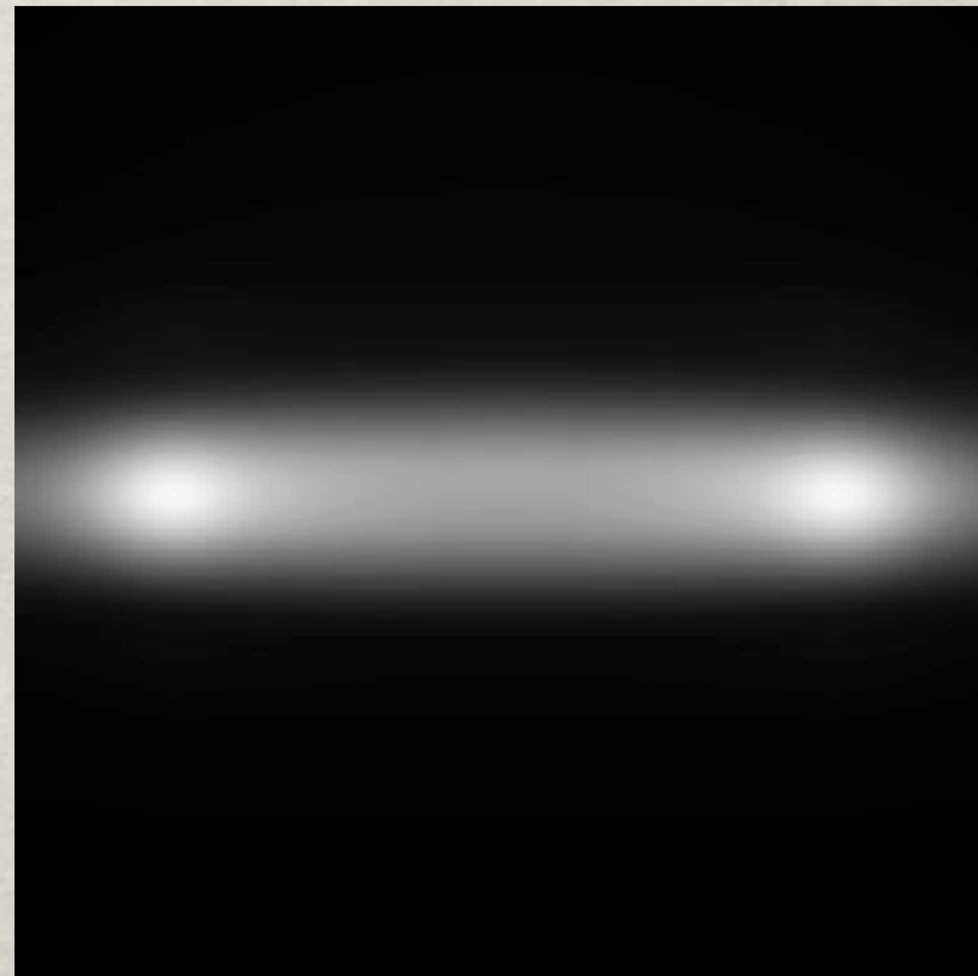


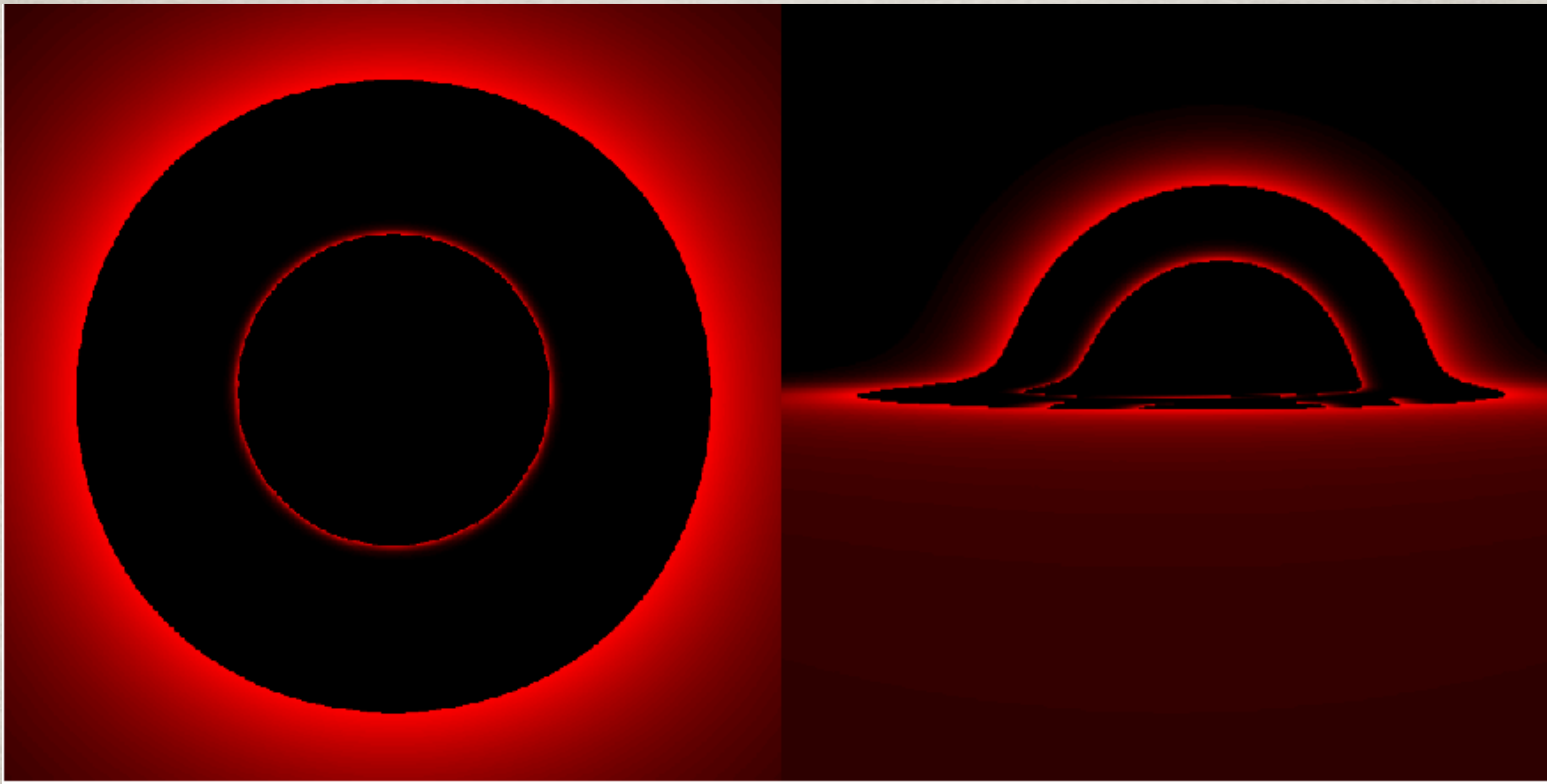
Proca star



Applying a Gaussian blurring filter

The imitation game reloaded

Sengo, Cunha, CH, Radu,
ArXiv: 2402.14919 (to appear in JCAP)



(a) $\theta = 5^o$ (b) $\theta = 88^o$

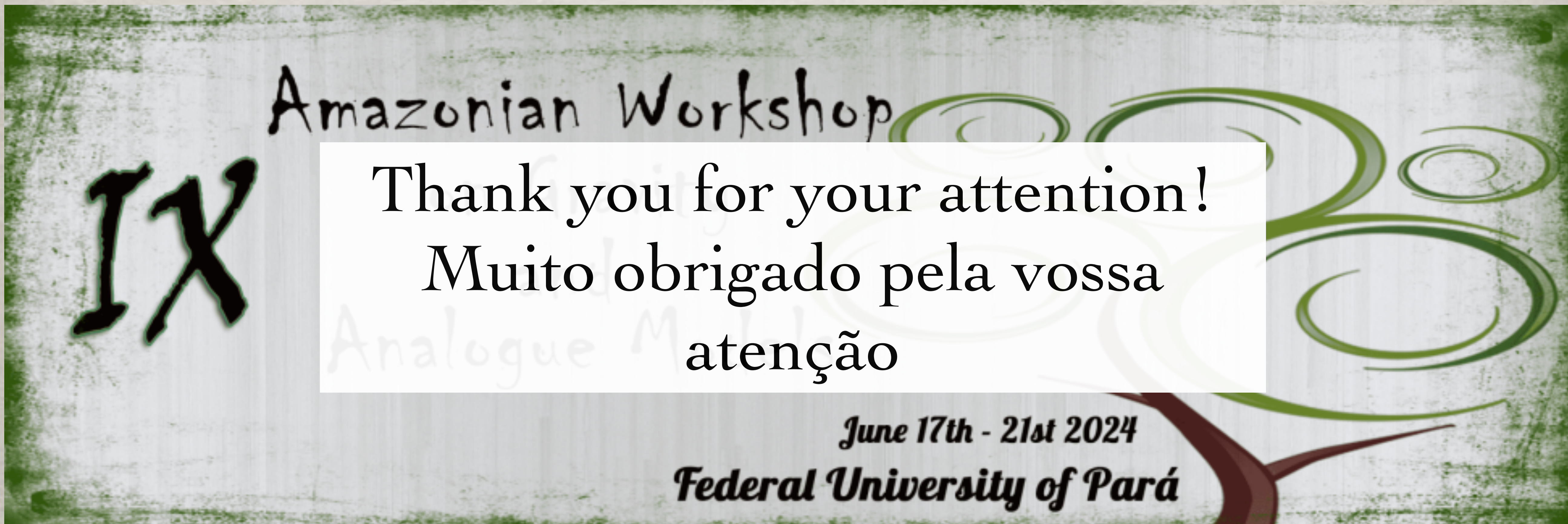
Concluding remark:

Bosonic stars illustrate theoretical possibilities of **dynamically robust** black hole imitators that could manifest themselves only **at some specific scales**.

Producing detailed phenomenology will constrain the model and the corresponding (exotic) physics or, in the best case scenario, provide a smoking gun to this new physics.

R. Bernar's
and
A. Higuchi
talk's

The wonderful world of compact objects with bosonic fields in GR



Thank you for your attention!
Muito obrigado pela vossa atenção

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

IX Amazonian Workshop on Gravity and Analogue Models

June 17, 2024

in collaboration with M. Brito, R. Brito, V. Cardoso, P. Cerda-Duran, P. Cunha, E. Costa-Filho, J. Degollado, J. Font, F. di Giovanni, J. Kunz, A. Morais, I. Parapechka, E. Radu, N. Sanchis-Gual, N. Santos, Y. Shnir, M. Zilhão,…