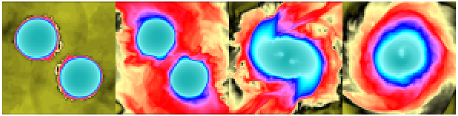
K-dynamics: Gravitational wave generation in Dark energy

Miguel Bezares Figueroa

Connecting the dots Toward: inspiral-merger-ringdown gravitational waveforms beyond general relativity

Max Planck Institute for Gravitational Physics
Albert Einstein Institute



Numerical relativity simulations in theories with kinetic screening

Miguel Bezares Figueroa

Connecting the dots Toward: inspiral-merger-ringdown gravitational waveforms
beyond general relativity

Max Planck Institute for Gravitational Physics
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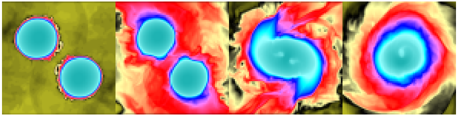
In collaboration with Ricard Aguilera, Enrico Barausse, Marco Crisostomi, Lotte ter Haar, Guillermo Lara and Carlos Palenzuela

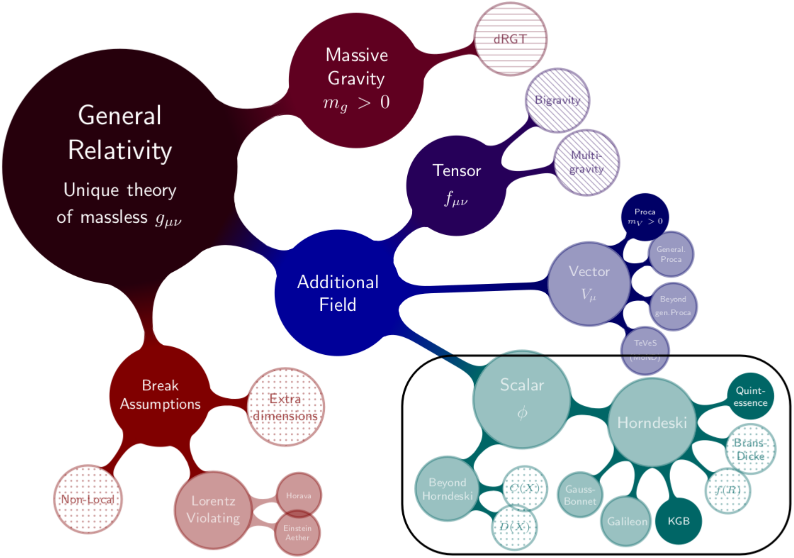


Desirable theoretical properties

- Well-motivated from Fundamental Physics: these theories would solve (in principle) some fundamental problem in physics, such as late time acceleration, or the incompatibility between quantum mechanics and General Relativity.
- Precision Tests: The theory must produce predictions that pass all Solar System, binary pulsar, cosmological and experimental tests.
- Existence of Known Solutions: The theory must admit solutions that correspond to some observed phenomena.
- Stability of Solutions: The special solutions described in property must be stable to small perturbations on timescales smaller than the age of the Universe.
- Well-posed Initial Value Formulation: It should admits a unique solution that depends continuously on the initial data.

N. Yunes, X. Siemens,*Gravitational Wave Tests of General Relativity with Ground-Based Detectors and Pulsar Timing Arrays.* Living Reviews in Relativity volume 16, 9 (2013).

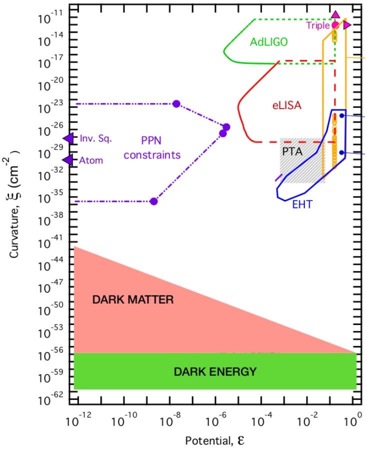
Zoo of Alternative theories of Gravity



J.M. Ezquiaga, M. Zumalacárregui, *Dark Energy in light of Multi-Messenger Gravitational-Wave astronomy*
Front. Astron. Space Sci., 21 December 2018.

How to hide the scalar field? → Screening mechanism

Courtesy Marco Crisostomi



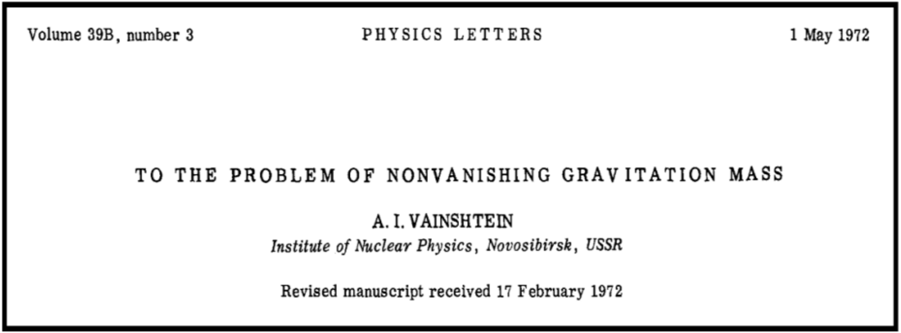
Linking Tests Of Gravity On All Scales: From The Strong-Field Regime To Cosmology. T. Baker, D. Psaltis and Constantinos Skordis. The Astrophysical Journal, Vol. 802, Number 1

$$\begin{aligned}\mathcal{L} \quad = \quad & -\frac{1}{2} Z^{\mu\nu}(\varphi,\partial\varphi,\ldots)\partial_\mu\varphi\partial_\nu\varphi \\ & -V(\varphi) + g(\varphi)\, T^{\mu}_{\nu}\end{aligned}$$

Varieties of screening:

- φ (via potential): weak coupling (symmetron), large mass (chameleon).
- $\partial_\mu\varphi$: kinetic screening.
- $\partial_\mu\partial_\nu\varphi$: Vainshtein mechanism

Beyond the Cosmological Standard Model. A. Joyce, B. Jain, J. Khoury, Mark Trodden. Phys.Rept. 568, 2015.

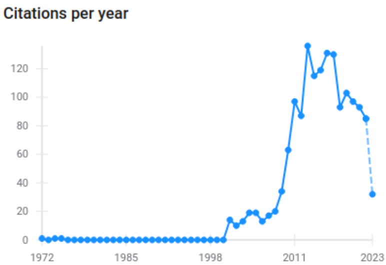


Volume 39B, number 3 PHYSICS LETTERS 1 May 1972

TO THE PROBLEM OF NONVANISHING GRAVITATION MASS

A. I. VAINSHTEIN
Institute of Nuclear Physics, Novosibirsk, USSR

Revised manuscript received 17 February 1972



1,543 cts

Potential, ε

From the zoo $\rightarrow$ K-essence $(\partial\varphi)$

K-essence action is

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{M_{\mathrm{Pl}}^2}{2}R + K(X)\right] + S_m\left[A(\Phi)g_{\mu\nu}, \Psi_m\right] \ ,$$

where $A(\Phi)$ is the conformal factor and $X \equiv \nabla_\mu\varphi\nabla^\mu\varphi$ is the standard kinetic term

- K-essence theories have been widely applied both in early and late time cosmology. They were introduced in the context of inflation (k-inflation), and then used to explain the present accelerated expansion of the Universe (self-acceleration). Cosmological relevant

  C. Armendariz-Picon, T. Damour, and V. F. Mukhanov, *k - inflation*, Phys. Lett. B458 (1999) 209218.
  T. Chiba, T. Okabe, and M. Yamaguchi, *Kinetically driven quintessence*, Phys. Rev. D62 (2000) 023511.
  C. Armendariz-Picon, V. F. Mukhanov, and P. J. Steinhardt, *A Dynamical solution to the problem of a small cosmological constant and late time cosmic acceleration*, Phys. Rev. Lett. 85 (2000) 44384441

- GW170817. K-essence remains unconstrained by the bounds on the GW speed.

  J. M. Ezquiaga, M. Zumalacarregui. *Dark Energy after GW170817: dead ends and the road ahead*. Phys. Rev. Lett. 119, 251304 (2017)
  P. Creminelli, F. Vernizzi. *Dark Energy after GW170817 and GRB170817A*. Phys. Rev. Lett. 119, 251304 (2017)
  P. Creminelli, M. Lewandowski, G. Tambalo, and F. Vernizzi, *Gravitational Wave Decay into Dark Energy*, JCAP 1812 (2018) 025.
  P. Creminelli, G. Tambalo, F. Vernizzi, and V. Yingcharoenrat, *Dark-Energy Instabilities induced by Gravitational Waves, JCAP 2005 (2020) 002.*

From the zoo → K-essence ($\partial\varphi$)

K-essence action is

where … etic term

- K- … e co … n), and th … (se

C. A … and late time

- GV … W sp…

[2] **arXiv:1710.05901 [pdf, other]** Taken from M.Zumalacarregui's talk at SISSA/IFPU

Dark Energy after GW170817
Jose María Ezquiaga (1 and 2), Miguel Zumalacárregui (2 and 3) ((1) Madrid IFT, (2) UC Berkeley, (3)
Comments: 9 pages, 3 figures
Subjects: **Cosmology and Nongalactic Astrophysics (astro-ph.CO)**; General Relativity and Quantum Cosmology (gr-qc);

[3] **arXiv:1710.05893 [pdf, other]**

Implications of the Neutron Star Merger GW170817 for Cosmological Scalar-Tensor
Jeremy Sakstein, Bhuvnesh Jain
Comments: five pages, two figures
Subjects: **Cosmology and Nongalactic Astrophysics (astro-ph.CO)**; General Relativity and Quantum Cosmology (gr-qc);

[4] **arXiv:1710.05877 [pdf, ps, other]**

Dark Energy after GW170817
Paolo Creminelli, Filippo Vernizzi
Comments: 5 pages
Subjects: **Cosmology and Nongalactic Astrophysics (astro-ph.CO)**; General Relativity and Quantum Cosmology (gr-qc);

J. M. Ezquiaga, M. Zumalacarregui. *Dark Energy after GW170817: dead ends and the road ahead*. Phys. Rev. Lett. 119, 251304 (2017)
P. Creminelli, F. Vernizzi. *Dark Energy after GW170817 and GRB170817A*. Phys. Rev. Lett. 119, 251304 (2017)
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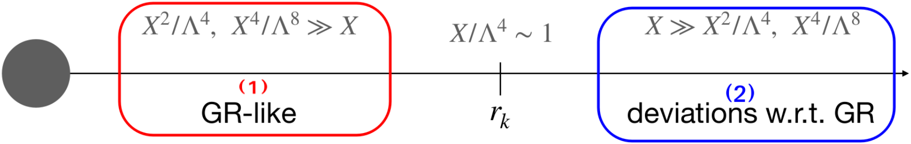
Kinetic screening

- **Kinetic screening mechanism:** allowing $\partial_\mu \varphi$ to remain unseen by local tests of gravity. It known as *K-mouflage*.

E. Babichev, C. Deffayet, R. Ziour. *k-Mouflage gravity.* Int.J.Mod.Phys. D18:2147-2154, 2009
A. Joycea B. Jain J. Khouryb M. Trodden *Beyond the cosmological standard model.*, Physics Reports Vol. 568.



(1) The non-linear terms start dominating, suppressing (or "screening") scalar effects

(2) The theory behaves as FJBD theory: only linear in X terms.

MAIN GOAL: to study the dynamics of this screening mechanism in the strong-field regime by using numerical relativity ... trying to answer the following question

Does k-mouflage survive in the strong-field regime?

We will consider neutron stars in this screening regimen, in particular, three cases:

- Stellar oscillations
- Gravitational collapse
- Binary neutron stars
- Dynamics in UV completions

The model

The K-essence action is

$$S = \int \mathrm{d}^4 x \sqrt{-g} \left[\frac{M_{\rm Pl}^2}{2} R + K(X) \right] + S_m \left[A(\varphi) g_{\mu\nu}, \Psi_m \right] \ ,$$

where $A(\varphi) = \exp\left(-\sqrt{2}\,\alpha\,\frac{\varphi}{M_{\rm Pl}}\right)$ and $X \equiv \nabla_\mu \varphi \nabla^\mu \varphi$ is the standard kinetic term of the scalar field φ.

For $K(X)$ we consider only the lowest-order terms

$$K(X) = -\frac{1}{2} X + \frac{\beta}{4\Lambda^4} X^2 - \frac{\gamma}{8\Lambda^8} X^3 + \ldots (\beta = \gamma = 0 \ \ FJBD)\,,$$

where the coefficients $\beta, \gamma \sim \mathcal{O}(1)$ are dimensionless, and Λ is the strong-coupling scale of the effective field theory.

$$\boxed{\Lambda \approx \Lambda_{\rm DE} \sim 2 \times 10^{-3}\ \mathrm{eV} \sim 10^{-12} \text{ (in units } G = c = M_\odot = 1)}$$

Equation of motion

$$(1) \qquad G_{\mu\nu} = 8\pi G\left(T^{\varphi}_{\mu\nu} + T_{\mu\nu}\right) ,$$

$$(2) \qquad \left(g^{\mu\nu} + \frac{2\,K''(X)}{K'(X)}\nabla^{\mu}\varphi\nabla^{\nu}\varphi\right)\nabla_{\mu}\nabla_{\nu}\varphi = \frac{1}{2}\mathcal{A}T$$

$$(3) \qquad \nabla_{\mu}T^{\mu\nu} = \mathcal{A}\;\nabla^{\nu}\varphi\;T ,$$

$$(4) \qquad \nabla_{\mu}(\rho_0 u^{\mu}) = \rho_0\mathcal{A}u^{\mu}\nabla_{\mu}\varphi ,$$

where $\mathcal{A} \equiv -A'(\varphi)/[2\,A(\varphi)]$

$$(5) \qquad T^{\varphi}_{\mu\nu} = K(X)g_{\mu\nu} - 2K'(X)\partial_{\mu}\varphi\partial_{\nu}\varphi ,$$

$$(6) \qquad T_{\mu\nu} = [\rho_0(1+\epsilon) + P]u_{\mu}u_{\nu} + P\,g_{\mu\nu} ,$$

being ρ_0 the rest-mass density, ϵ the specific internal energy, P the pressure and u^{μ} the fluid four-velocity.

Brief interlude about the KG equation

The scalar field equation can also be recast into a generalised Klein-Gordon equation

$$\nabla_\mu \left[K'(X)\nabla^\mu\varphi\right] = \frac{1}{2}\mathcal{A}T \Leftrightarrow \gamma^{\mu\nu}\nabla_\mu\nabla_\nu\varphi = \frac{\mathcal{A}\,T}{2\,K'(X)}\ ,$$

with an effective metric

$$\boxed{\gamma^{\mu\nu} \equiv g^{\mu\nu} + \frac{2\,K''(X)}{K'(X)}\nabla^\mu\varphi\nabla^\nu\varphi}$$

Here, we have two problems

- Caustics/shocks (even from smooth initial data)

G. N. Felder, L. Kofman, and A. Starobinsky, *Caustics in tachyon matter and other Born-Infeld scalars*, JHEP 09 (2002) 026.
H. S. Reall, N. Tanahashi, and B. Way, *Shock Formation in Lovelock Theories*, Phys. Rev. D91 no. 4, (2015) 044013.
E. Babichev, *Formation of caustics in k-essence and Horndeski theory*, JHEP 04 (2016) 129.

- Breakdown of the Cauchy problem (CP)

L. Bernard, L. Lehner, and R. Luna. *Challenges to global solutions in Horndeskis theory.* Phys. Rev. D100 no. 2, (2019) 024011
P. Figueras and T. Frana, *Gravitational Collapse in Cubic Horndeski Theories*, Classical and Quantum Gravity, Volume 37, Number 22 .

Brief interlude about the KG equation

The scalar field equation can also be recast into a generalised Klein-Gordon equation

$$\nabla_\mu \left[K'(X)\nabla^\mu\varphi\right] = \frac{1}{2}\mathcal{A}T \Leftrightarrow \gamma^{\mu\nu}\nabla_\mu\nabla_\nu\varphi = \frac{\mathcal{A}\,T}{2\,K'(X)} \ ,$$

with an effective metric

$$\boxed{\gamma^{\mu\nu} \equiv g^{\mu\nu} + \frac{2\,K''(X)}{K'(X)}\nabla^\mu\varphi\nabla^\nu\varphi}$$

Here, we have two problems

- Caustics/shocks (even from smooth initial data) change the numerical scheme!

G. N. Felder, L. Kofman, and A. Starobinsky, *Caustics in tachyon matter and other Born-Infeld scalars*, JHEP 09 (2002) 026.
H. S. Reall, N. Tanahashi, and B. Way, *Shock Formation in Lovelock Theories*, Phys. Rev. D91 no. 4, (2015) 044013.
E. Babichev, *Formation of caustics in k-essence and Horndeski theory*, JHEP 04 (2016) 129.

- Breakdown of the Cauchy problem (CP) explain in detail later

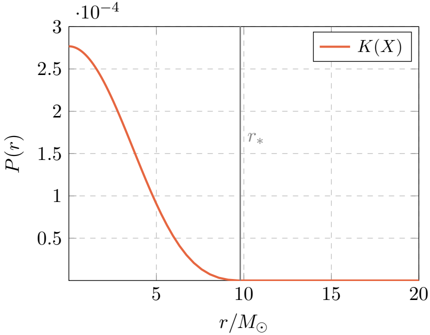
L. Bernard, L. Lehner, and R. Luna. *Challenges to global solutions in Horndeskis theory.* Phys. Rev. D100 no. 2, (2019) 024011
P. Figueras and T. Frana, *Gravitational Collapse in Cubic Horndeski Theories*, Classical and Quantum Gravity, Volume 37, Number 22 .

Stellar oscillations

Dynamics of screening in modified gravity.
Phys. Rev. Lett. 126, 091102
L. ter Haar, M. Bezares, M. Crisostomi, E. Barausse, and C. Palenzuela

Kinetic screening in nonlinear stellar oscillations and gravitational collapse
M. Bezares, L. ter Haar, M. Crisostomi, E. Barausse, and C. Palenzuela
Phys. Rev. D 104, 044022

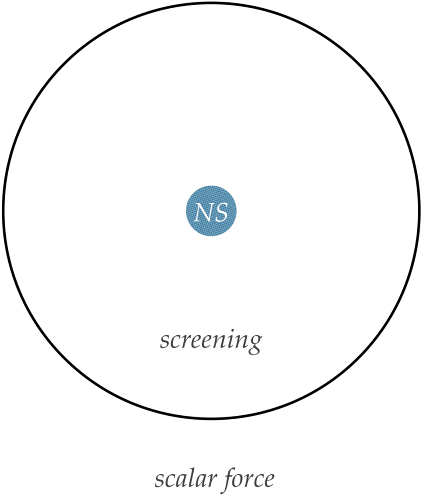
Initial data: Neutron star with screening

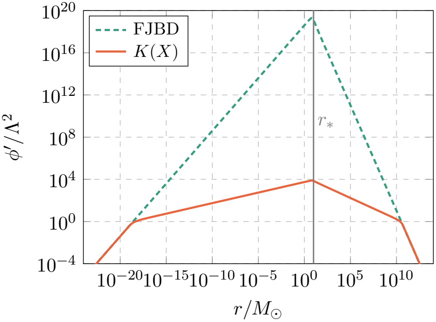


Phys. Rev. Lett. 126, 091102, *Dynamics of screening in modified gravity.*, L. ter Haar, M. Bezares, M. Crisostomi, E. Barausse, and C. Palenzuela

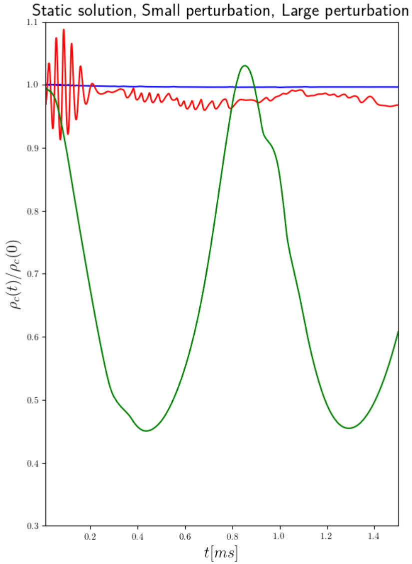
Initial data: Neutron star with screening

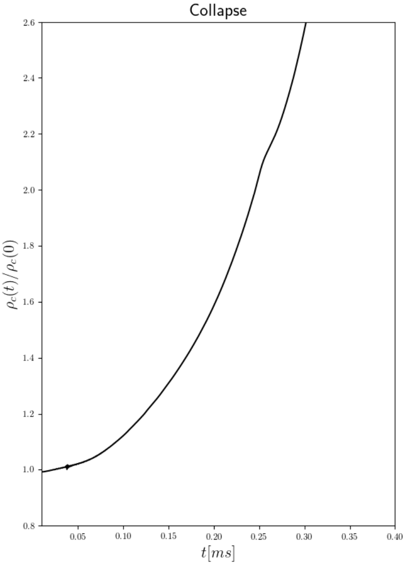
- Scalar modes ($\nabla_\mu \varphi$) are strongly suppressed near matter sources, where the non-linear terms in $K(X)$ dominates over the linear one.





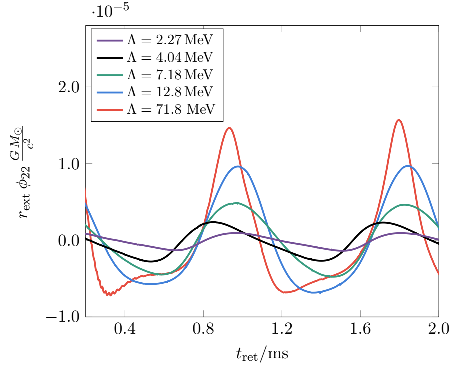
Dynamics of the screening solution-I: $\Lambda \simeq 4\ \mathrm{MeV}$

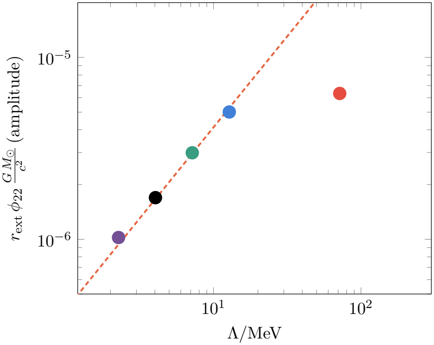




Dynamics of the screening solution-II

$$\phi_{22} \simeq -\alpha\sqrt{16\pi G}\,\partial_t^2\varphi + O\left(\frac{1}{r^2}\right)$$





$$\boxed{\varphi_c \propto \Lambda}$$

Oscillating stars: screening works!

Gravitational collapse

Kinetic screening in nonlinear stellar oscillations and gravitational collapse
M. Bezares, L. ter Haar, M. Crisostomi, E. Barausse, and C. Palenzuela
Phys. Rev. D 104, 044022

Well-posedness in a nutshell (Recall Aron's talk)

Well-posedness

Consider the first-order systems

$$u_t = P\left(t, x, \frac{\partial}{\partial x}\right)\, u, \quad t \geq t_0; u(t_0, x) = f(x).$$

This problem is well-posed if, for every t_0 and every $f \in C^\infty(x)$:

1. There exists a unique solution $u(t,x) \in C^\infty(t,x)$, and
2. The solution depends continuously on the initial data given in the problem.

Well-posedness in a nutshell (Recall Aron's talk)

Hyperbolicity

$$\partial_t u + F^i \partial_i u = S(u),$$

- Strongly hyperbolic if the principal part has real eigenvalues and complete set of eigenvectors.
- Weakly hyperbolic if the principal part has real eigenvalues and incomplete set of eigenvectors.

Well-posedness in a nutshell (Recall Aron's talk)

- Why do we have to study the hyperbolicity (characteristic structure) of our evolution system?

Weakly hyperbolic
$\Downarrow$
IBVP is ill posed
$\Downarrow$
Unstable numerical evolutions

Strongly hyperbolic
$\Downarrow$
IVBP is well posed
$\Downarrow$
Stable numerical evolution
(suitable numerical methods)

D. Hilditch, *An Introduction to Well-posedness and Free-evolution*, Int. J. Mod. Phys. A28 (2013)1340015
L. C. Evans, *Partial differential equations*. American Mathematical Society, Providence, R.I., 2010.

Breakdown of CP-I (Spherical symmetry case)

$$\nabla_\mu \left[K'(X)\nabla^\mu\varphi\right] = \frac{1}{2}\mathcal{A}T \Leftrightarrow \gamma^{\mu\nu}\nabla_\mu\nabla_\nu\varphi = \frac{\mathcal{A}\,T}{2\,K'(X)}\ .$$

The characteristic matrix for the principal part is

$$\mathbb{M} = \begin{pmatrix} 0 & \frac{\alpha}{\sqrt{g_{rr}}} \\ -\frac{\sqrt{g_{rr}}}{\alpha}\frac{\gamma^{rr}}{\gamma^{tt}} & -\frac{2\,\gamma^{tr}}{\gamma^{tt}} \end{pmatrix}. \tag{7}$$

The eigenvalues of this matrix (characteristic speed of the scalar field), $V_\pm$, read

$$V_\pm = -\frac{\gamma^{tr}}{\gamma^{tt}} \pm \sqrt{\frac{-\det(\gamma^{\mu\nu})}{(\gamma^{tt})^2}}. \tag{8}$$

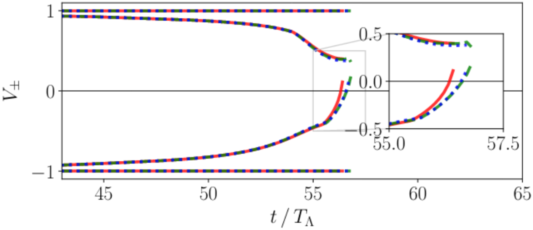
Strong hyperbolic ⇔ $V_\pm$ are real and distinct ⇔ $\det(\gamma^{\mu\nu}) < 0$

D. Hilditch, *An Introduction to Well-posedness and Free-evolution*, Int. J. Mod. Phys. A28 (2013)1340015
L. C. Evans, *Partial differential equations*. American Mathematical Society, Providence, R.I., 2010.

Tricomi-Problem

$$V_{\pm} = -\frac{\gamma^{tr}}{\gamma^{tt}} \pm \sqrt{\frac{-\det(\gamma^{\mu\nu})}{(\gamma^{tt})^2}}\,,$$

$\det(\gamma^{\mu\nu})$ may cross zero during the evolution ⇒ strong hyperbolicity would be lost



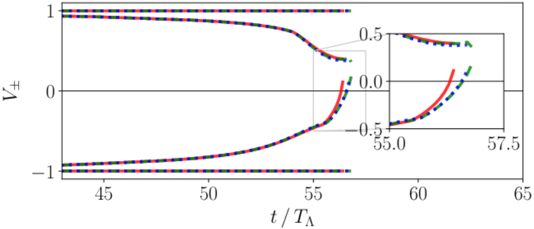
G. Lara, M. Bezares, E. Barausse, *UV completions, fixing the equations, and nonlinearities in k-essence.*, JCAP03 (2021) 072
P. Figueras and T. Franca, *Gravitational Collapse in Cubic Horndeski Theories*, Classical and Quantum Gravity, Volume 37, Number 22 .

- $\det(\gamma^{\mu\nu}) \propto \left(1 + \frac{2K''}{K'}X\right) > 0$ ⇒ Our K-essence model satisfy this condition

Tricomi-Problem

$$V_{\pm} = -\frac{\gamma^{tr}}{\gamma^{tt}} \pm \sqrt{\frac{-\det(\gamma^{\mu\nu})}{(\gamma^{tt})^2}},$$

$\det(\gamma^{\mu\nu})$ may cross zero during the evolution ⇒ strong hyperbolicity would be lost



G. Lara, M. Bezares, E. Barausse, *UV completions, fixing the equations, and nonlinearities in k-essence.*, JCAP03 (2021) 072
P. Figueras and T. Franca, *Gravitational Collapse in Cubic Horndeski Theories*, Classical and Quantum Gravity, Volume 37, Number 22 .

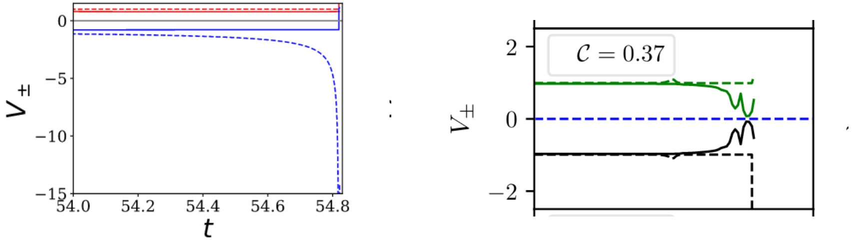
- Many alternatives theory of gravity suffer this problem!!! (see Review by J. Ripley arXiv:2207.13074)

Breakdown of CP-II (Spherical symmetry case)

Keldysh-Problem

$$V_{\pm} = -\frac{\gamma^{tr}}{\gamma^{tt}} \pm \sqrt{\frac{-\det(\gamma^{\mu\nu})}{(\gamma^{tt})^2}},$$

$\gamma^{tt} \rightarrow 0$ (dynamically) ⇒ decrease the time-step



This problem can be solved either by using a different gauge condition or the *fixing the equation*

Fixing equation

$$\nabla_\mu \left[K'(X)\nabla^\mu \varphi\right] = \frac{1}{2}\mathcal{A}T \Leftrightarrow \gamma^{\mu\nu}\nabla_\mu\nabla_\nu\varphi = \frac{\mathcal{A}\,T}{2\,K'(X)}$$

$$\Downarrow$$

introducing a new field Σ

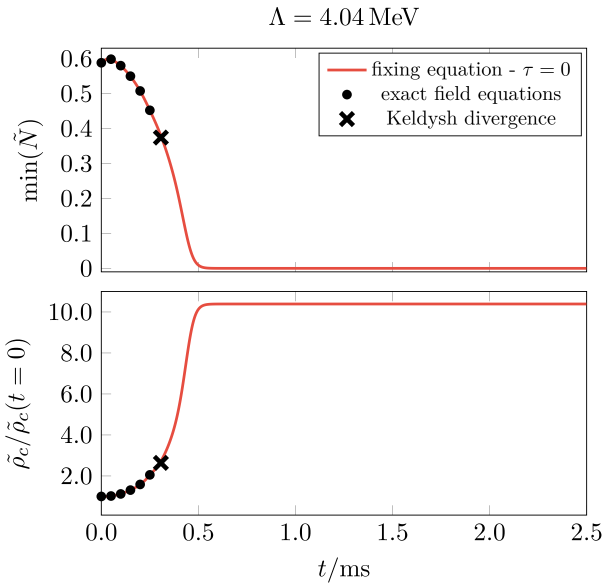
$$\Downarrow$$

$$\partial_t\left(\sqrt{-g}\Sigma\nabla^t\varphi\right) + \partial_i\left(\sqrt{-g}\Sigma\nabla^i\varphi\right) = \frac{1}{2}\sqrt{-g}\mathcal{A}T\,,$$
$$\partial_t\Sigma = -\frac{1}{\tau}(\Sigma - K'(X))\,.$$

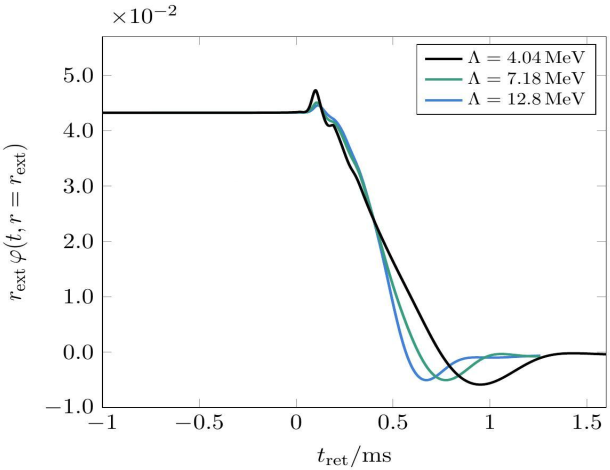
- The second equation is a driver that will force Σ to $K'(X)$ on a timescale $\tau > 0$.
- the principal part of this system takes indeed the form of a conservation law.

J. Cayuso, N. Ortiz, and L. Lehner. *Fixing extensions to general relativity in the nonlinear regime.* Phys. Rev. D 96, 084043 (2017)

Gravitational collapse



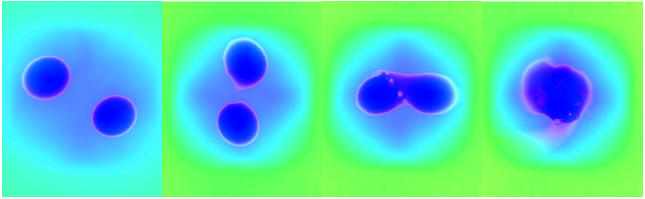
Gravitational collapse



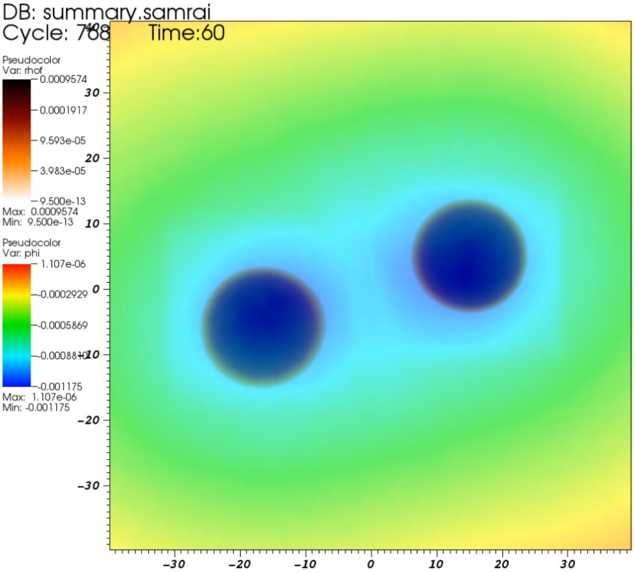
For LISA at 8 kpc,
$\mathrm{SNR}(\Lambda_{\mathrm{DE}}) \approx 30 - 40$

Gravitational collapse: screening is less efficient

Binary neutron stars

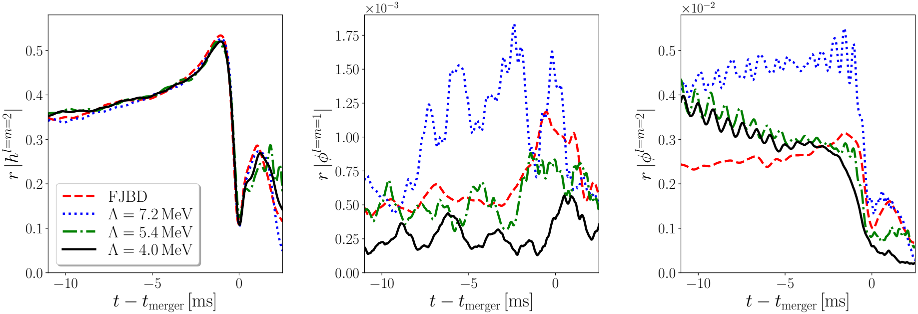


Binary NSs merger: $\Lambda \simeq 4\ \mathrm{MeV}$



Binary NSs merger

Tensor ($l = m = 2$) and scalar $l = m = 1$ and $l = m = 2$ strain



- $l = m = 1$ dipole mode shows signs of screening suppression as Λ decreases.
- $l = m = 2$ scalar quadrupole (dominant) mode is always larger than in FJBD theory

BNS: The screening is not effective in the late inspiral/merger

Non-Spherical Oscillation of neutron stars

(screening radius) $r_{sc} > \lambda_{\rm wave}$ (wavelength of scalar waves)

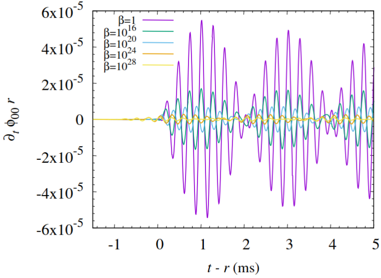
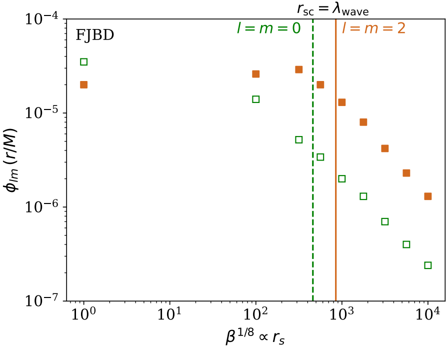


FIG. 6. Waveforms ($\partial_t \phi_{00} r$) of the monopole mode for scalar waves as functions of $t - r$ for $\beta = 1$, 10^{16}, 10^{20}, 10^{24}, and 10^{28}. The waveforms extracted at $r = 591$ km are shown together.



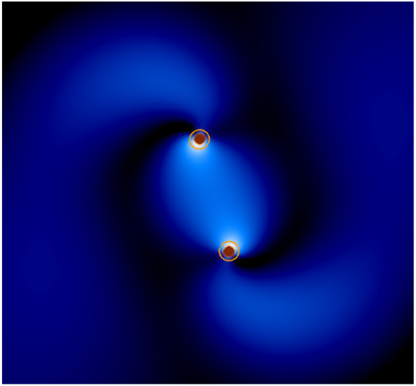
Properties of scalar wave emission in a scalar-tensor theory with kinetic screening.
Masaru Shibata and Dina Traykova. Phys. Rev. D 107, 044068, 2023

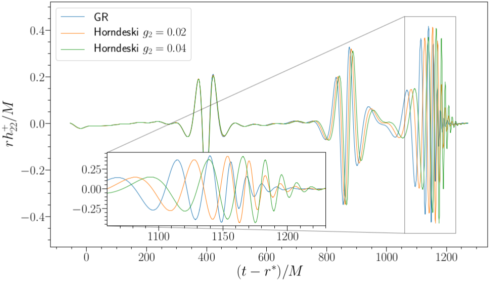
Courtesy of Dina Traykova

Binary BBH merger

Black hole binaries in cubic Horndeski theories, Pau Figueras and Tiago Frana Phys. Rev. D 105, 2022

- Cubic theory: $\mathscr{L} = R + X - V(\phi) + G_2(\phi, X) + G_3(\phi, X)\Box\phi$

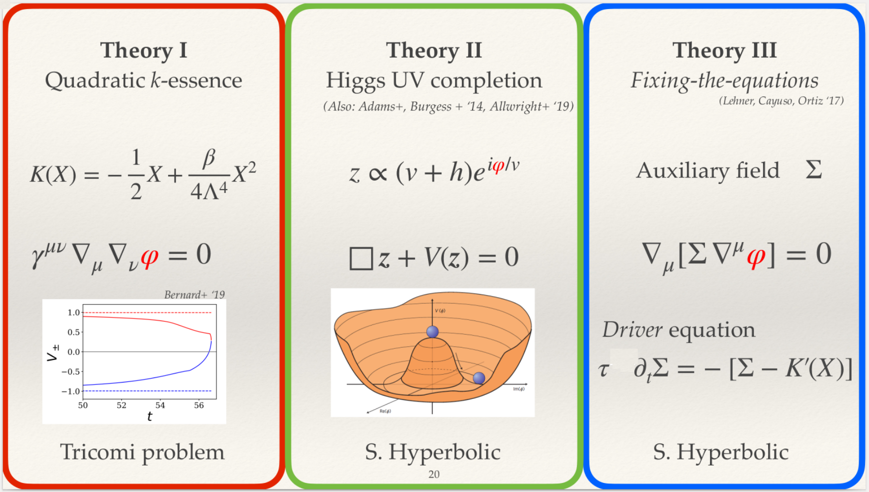




Dynamics in UV completions

UV completions, fixing the equations, and nonlinearities in k-essence.
Guillermo Lara, Miguel Bezares, and Enrico Barausse. Phys. Rev. D 105, 064058 2022

Slides from Guillermo Lara's (a.k.a Memo) talk. Frontiers in Numerical Relativity 2022



Theory I

Quadratic k-essence

$$K(X) = -\frac{1}{2}X + \frac{\beta}{4\Lambda^4}X^2$$

$$\gamma^{\mu\nu}\nabla_\mu\nabla_\nu\varphi = 0$$

Bernard+ '19

Tricomi problem

Theory II

Higgs UV completion

(Also: Adams+, Burgess + '14, Allwright+ '19)

$$z \propto (v+h)e^{i\varphi/v}$$

$$\Box z + V(z) = 0$$

S. Hyperbolic

Theory III

Fixing-the-equations

(Lehner, Cayuso, Ortiz '17)

Auxiliary field Σ

$$\nabla_\mu[\Sigma\nabla^\mu\varphi] = 0$$

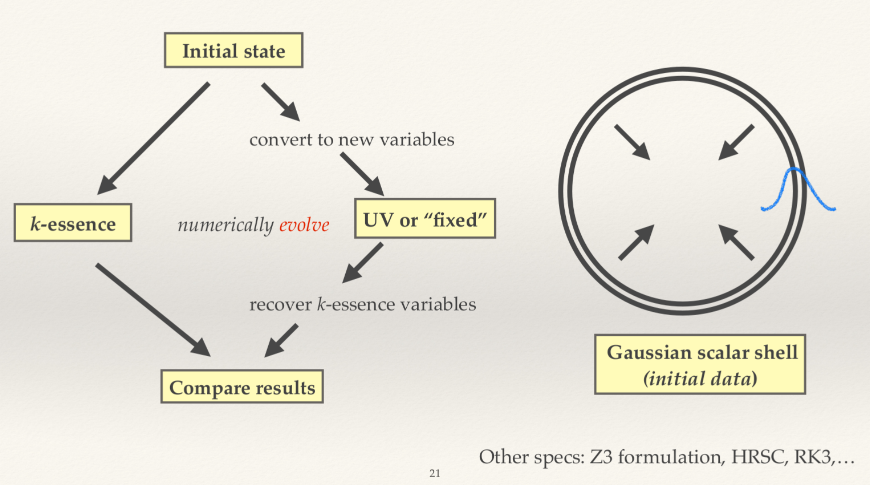
Driver equation

$$\tau \quad \partial_t\Sigma = -[\Sigma - K'(X)]$$

S. Hyperbolic

20

Slides from Guillermo Lara's (a.k.a Memo) talk. Frontiers in Numerical Relativity 2022



Initial state

convert to new variables

***k*-essence**

numerically evolve

UV or "fixed"

recover *k*-essence variables

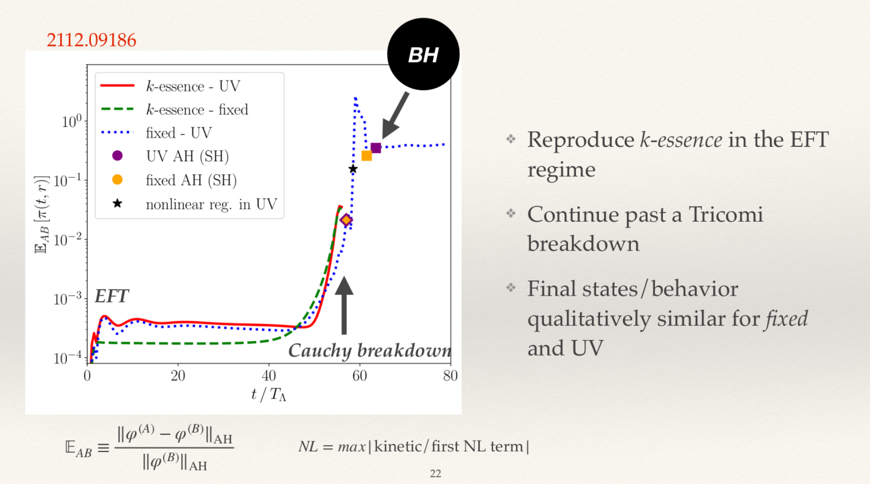
Compare results

Gaussian scalar shell
(initial data)

Other specs: Z3 formulation, HRSC, RK3,…

21

Slides from Guillermo Lara's (a.k.a Memo) talk. Frontiers in Numerical Relativity 2022



2112.09186

- Reproduce *k-essence* in the EFT regime
- Continue past a Tricomi breakdown
- Final states/behavior qualitatively similar for *fixed* and UV

$$\mathbb{E}_{AB} \equiv \frac{\|\varphi^{(A)} - \varphi^{(B)}\|_{\mathrm{AH}}}{\|\varphi^{(B)}\|_{\mathrm{AH}}}$$

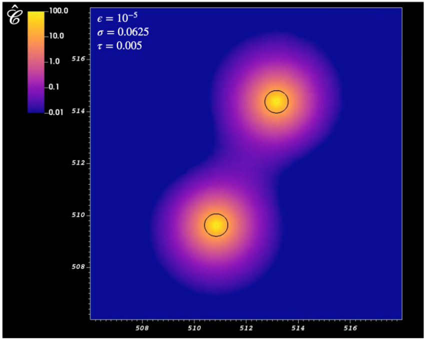
$NL = max\,|\text{kinetic/first NL term}|$

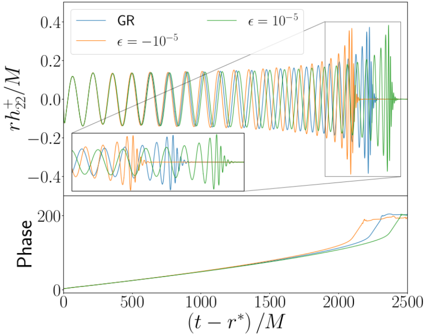
22

Fixing and BBH

- An eight-derivative theory of gravity [arXiv:2303.07246]:

$$I = \int dx^4 \sqrt{-g} \left(R - \frac{1}{\Lambda^6} \mathscr{C}^2 \right) , \qquad \mathscr{C} = R_{\mu\nu\rho\sigma} R^{\mu\nu\rho\sigma}$$





Discussion and Outlook

- Find an alternative to extrapolating our results to solve the hierarchy problem in our set-up.

$$\Lambda \approx \Lambda_{\mathrm{DE}} \sim 2 \times 10^{-3}\ \mathrm{eV}$$
$$\Downarrow$$
$$\text{To perform numerical simulations } G = c = M_{\odot} = 1$$
$$\Downarrow$$
$$\Lambda_{\mathrm{DE}} = 10^{-12};\ K(X) = -\frac{1}{2}X + \frac{\beta}{4\Lambda^4}X^2 - \frac{\gamma}{8\Lambda^8}X^3 + \dots$$

- Consider other scalar-tensor theories, such as DBI gravity.
- NS-BH binaries.
- Explore validity of the fixing program.
- We need more Arons Kovacs.

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At present, there is no experimental evidence that Boson stars exist. Nevertheless, it seems reasonable that solutions of well-tested theories, such as Einsteins GR, the Dirac equation, the Klein-Gordon equation, etc., should find their proper place in nature.

... by T.D. Lee

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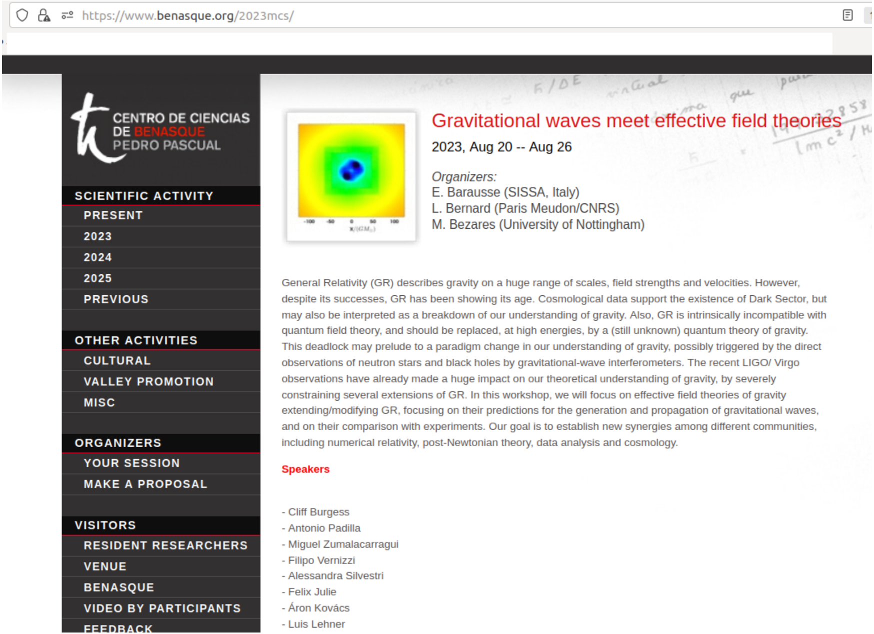
At present, there is no experimental evidence that Boson stars and alternatives theories of gravity exist. Nevertheless, it seems reasonable that solutions of well-tested (?) theories, such as Einsteins GR, the Dirac equation, the Klein-Gordon equation, etc., should find their proper place in nature.

... by T.D. Lee and M. Bezares



Gravitational waves meet effective field theories

2023, Aug 20 -- Aug 26

Organizers:
E. Barausse (SISSA, Italy)
L. Bernard (Paris Meudon/CNRS)
M. Bezares (University of Nottingham)

General Relativity (GR) describes gravity on a huge range of scales, field strengths and velocities. However, despite its successes, GR has been showing its age. Cosmological data support the existence of Dark Sector, but may also be interpreted as a breakdown of our understanding of gravity. Also, GR is intrinsically incompatible with quantum field theory, and should be replaced, at high energies, by a (still unknown) quantum theory of gravity. This deadlock may prelude to a paradigm change in our understanding of gravity, possibly triggered by the direct observations of neutron stars and black holes by gravitational-wave interferometers. The recent LIGO/ Virgo observations have already made a huge impact on our theoretical understanding of gravity, by severely constraining several extensions of GR. In this workshop, we will focus on effective field theories of gravity extending/modifying GR, focusing on their predictions for the generation and propagation of gravitational waves, and on their comparison with experiments. Our goal is to establish new synergies among different communities, including numerical relativity, post-Newtonian theory, data analysis and cosmology.

Speakers

- Cliff Burgess
- Antonio Padilla
- Miguel Zumalacarragui
- Filipo Vernizzi
- Alessandra Silvestri
- Felix Julie
- Áron Kovács
- Luis Lehner

Backup

The tool

Slides from Carlos Palenzuela's talk. Frontiers in Numerical Relativity 2022

From one computer to super-clusters

"Things don't really exist until you name them"

Formulation of equations
Numerical Schemes

MHDUET code

External open-source infrastructure

Simflowny

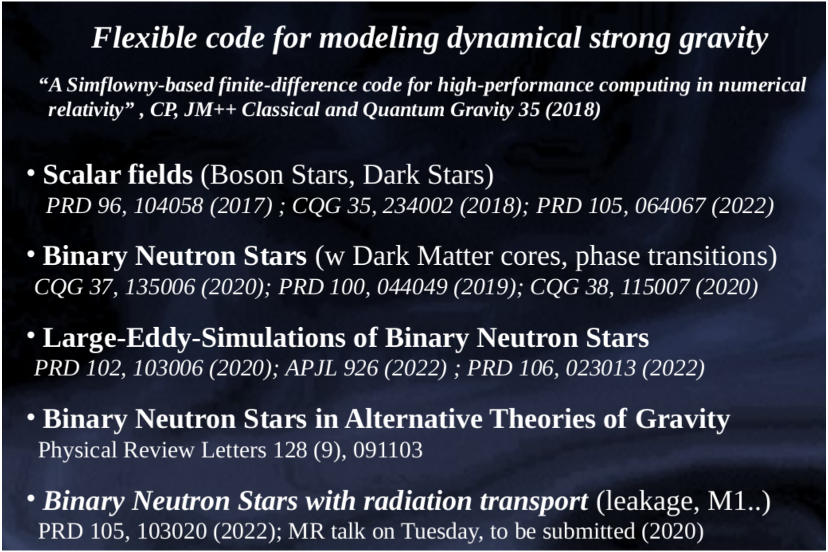
code generation

SAMRAI

parallelization & AMR

The MHDuet code

Slides from Carlos Palenzuela's talk. Frontiers in Numerical Relativity 2022



Flexible code for modeling dynamical strong gravity

"A Simflowny-based finite-difference code for high-performance computing in numerical relativity" , CP, JM++ Classical and Quantum Gravity 35 (2018)

- **Scalar fields** (Boson Stars, Dark Stars)
  PRD 96, 104058 (2017) ; CQG 35, 234002 (2018); PRD 105, 064067 (2022)
- **Binary Neutron Stars** (w Dark Matter cores, phase transitions)
  CQG 37, 135006 (2020); PRD 100, 044049 (2019); CQG 38, 115007 (2020)
- **Large-Eddy-Simulations of Binary Neutron Stars**
  PRD 102, 103006 (2020); APJL 926 (2022) ; PRD 106, 023013 (2022)
- **Binary Neutron Stars in Alternative Theories of Gravity**
  Physical Review Letters 128 (9), 091103
- ***Binary Neutron Stars with radiation transport*** (leakage, M1..)
  PRD 105, 103020 (2022); MR talk on Tuesday, to be submitted (2020)