Title: Conference Talk

Speakers:

Collection: 50 Years of Horndeski Gravity: Exploring Modified Gravity

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Gravitational wave generation in effective field theories of dark energy

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Talk plan

- Beyond General Relativity (GR): why and how?
- Violations of the equivalence principle and gravitational wave (GW) generation from binary compact objects, in "plain vanilla" extensions of GR
- Collapse and binary neutron-star binaries in "non-linear" effective field theories of dark energy
- Lessons for the future

In collaboration with

Mateja Boskovic (DESY)

Lotte ter Haar (SISSA)

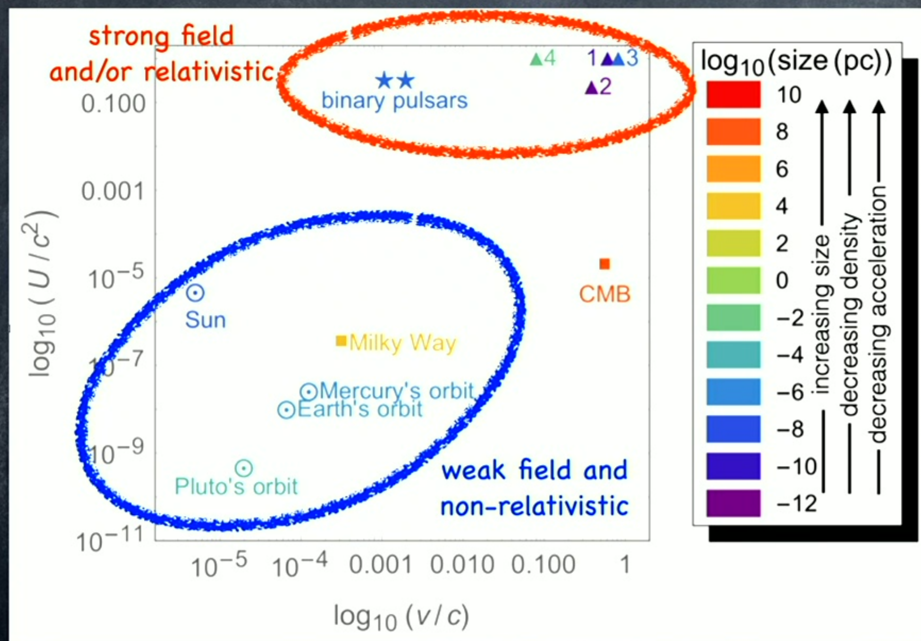
Miguel Bezares (Nottingham)

Marco Crisostomi (Caltech)

Guillermo Lara (AEI)

Ramiro Cayuso (SISSA)

Beyond GR in cosmology?



1=BH-BH systems with LIGO/Virgo/KAGRA

2=NS-NS systems with LIGO/Virgo/KAGRA,

3=BH-BH with LISA,

4=BH-BH with PTAs

- GR now testable in highly relativistic AND strong-field regime
- Evidence for Dark Sector from systems with $a < a_0 \sim 10^{-10}$ m/s^2: need screening (if modified GR is to explain cosmology)

Beyond GR: how?

Lovelock's theorem

In a 4-dimensional spacetime, the only divergence-free symmetric rank-2 tensor constructed only from the metric $g_{\mu\nu}$ and its derivatives up to second differential order, and preserving diffeomorphism invariance, is the Einstein tensor plus a cosmological term, i.e. $G_{\mu\nu} + \Lambda g_{\mu\nu}$

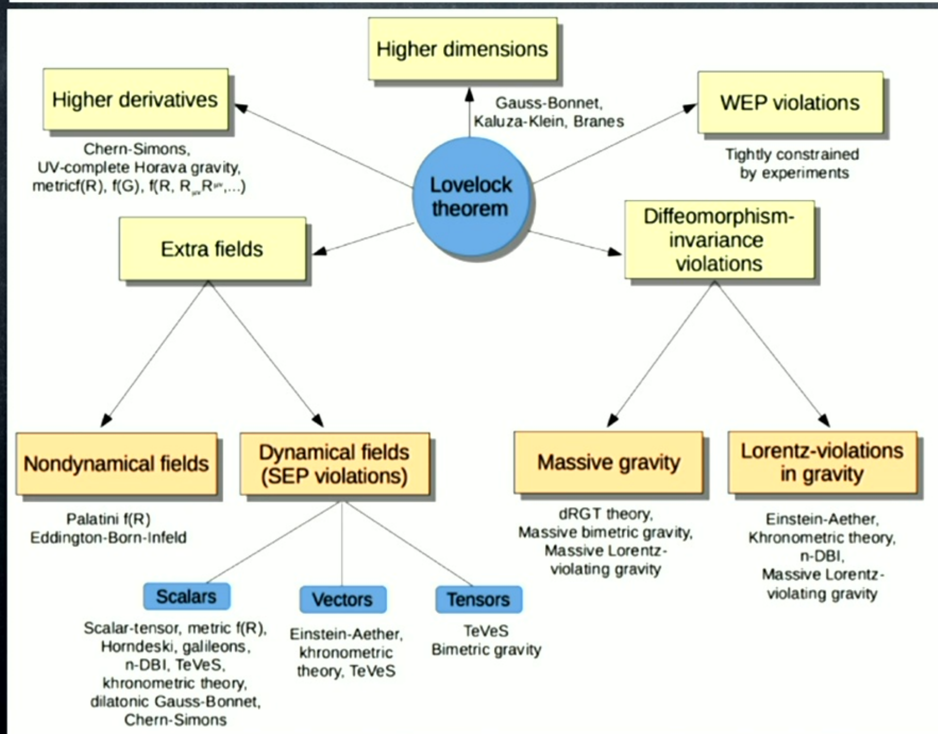


Figure adapted from Berti, EB et al 2015

Generic way to modify GR is to add extra fields!

How to couple extra fields?

- Satisfy weak equivalence principle (i.e. universality of free fall for bodies with weak self-gravity) by avoiding coupling extra fields to matter (i.e. no fifth forces at tree level)

$$S_m(\psi_{matter}, g_{\mu\nu})$$

- But extra fields usually couple non-minimally to metric, so gravity mediates effective interaction between matter and new field in strong gravity regimes (Nordtvedt effect)
- Equivalence principle violated for strongly gravitating bodies

Strong EP violations

For strongly gravitating bodies, gravitational binding energy gives large contribution to total mass, but binding energy depends on extra fields!
Examples:

- Brans-Dicke, scalar-tensor theories: $S = \int d^4x \frac{\sqrt{-g}}{2\kappa}\left[\varphi R - \frac{\omega(\varphi)}{\varphi}\partial_\mu\varphi\partial^\mu\varphi\right]$

  $G_{eff} \propto G_N/\varphi$, but φ in which star is immersed depends on cosmology, presence of other star

- Lorentz-violating gravity (Einstein-aether, Horava):
  preferred frame exists for gravitational physics ⟹
  gravitational mass of strongly gravitating bodies depends on velocity wrt preferred frame

If gravitational mass depends on fields, deviations from GR motion already at geodesics level

$$S_m = \Sigma_n \int m_n(\varphi) ds \qquad u_n^\mu \nabla_\mu (m_n u^\nu) \sim \mathcal{O}(s_n) \qquad s_n \equiv \frac{\partial m_n}{\partial \varphi}$$

sensitivities or charges or hairs,
i.e. response to change in field boundary conditions

Strong EP violations and GW emission

- Whenever strong equivalence principle is violated, monopole and dipole radiation may be produced
- In electromagnetism, no monopole radiation because electric charge conservation is implied by Maxwell eqs
- In GR, no monopole or dipole radiation because energy and linear momentum conservation is implied by Einstein eqs

e.g. $M_1 \sim \int \rho x^i d^3x$ $\qquad h \sim \frac{G\dot{M}_1}{rc^3} \sim \frac{GP}{rc^3}$ not a wave!

- In GR extensions, effective coupling matter-extra fields in strong gravity regimes ⟹ energy and momentum transfer between bodies and extra field, monopole and dipole GW emission, modified quadrupole formula

$$h \sim \frac{G\dot{M}_1}{rc^3} \sim \frac{G}{rc^3}\frac{d}{dt}(m_1(\varphi)x_1 + m_2(\varphi)x_2) \propto \frac{G}{rc^3}(s_1 - s_2)$$

Dipole emission dominant for quasi-circular systems;
1.5 PN vs 2.5 PN in GR (= -1 PN)! But effect depends on nature of bodies

Tests of dipolar emission with GWs

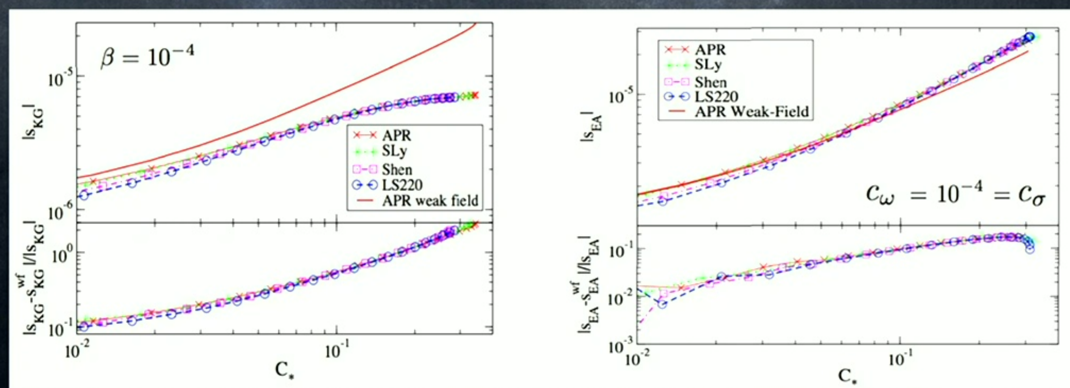
- Scalar charges/sensitivities can be extracted from scalar graviton fall off at infinity:

$$S_{\rm pp} = -\sum_A \int m_A[1+\alpha_A \delta\phi + \mathscr{O}(\delta\phi)^2]\, d\tau_A\,, \qquad \Box\phi = \frac{\partial \tilde{m}}{\partial \phi}(\phi_0)\,\delta^{(3)}(x)$$

$$\delta\phi \equiv \phi - \phi_0\,, \quad m_A \equiv \tilde{m}_A(\phi_0) = \text{const}, \quad \alpha_A \equiv \frac{1}{m_A}\frac{\partial \tilde{m}_A}{\partial \phi}(\phi_0)\Big|_{N_A,\Sigma_A} \qquad \phi = \phi_0 - \frac{\alpha m}{4\pi r} + \mathscr{O}\left(\frac{1}{r}\right)^2$$

- Calculation needs to be done exactly (no extrapolation of weak field approximation) and (for NS) for different EOS's

Example: NS sensitivities in Lorentz violating gravity (Yagi+EB+14, Ramos & EB 18; EB 19, Gupta+EB+21)



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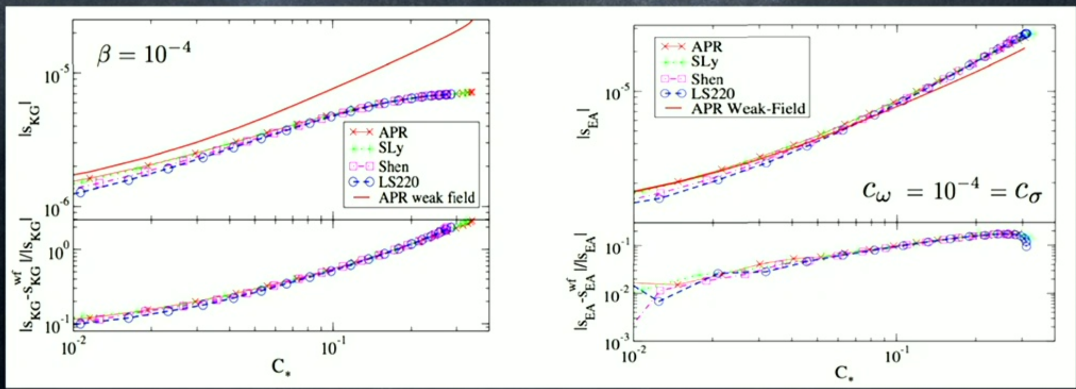
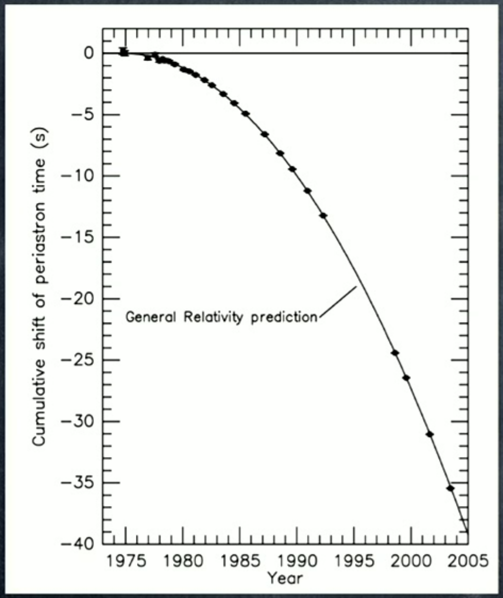
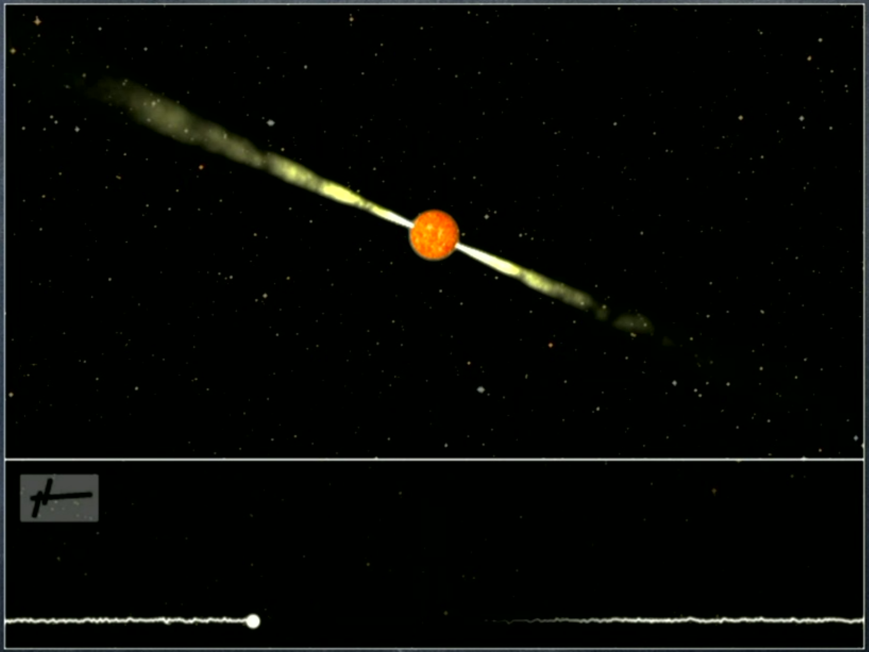


(Absence of) dipole emission in binary pulsars



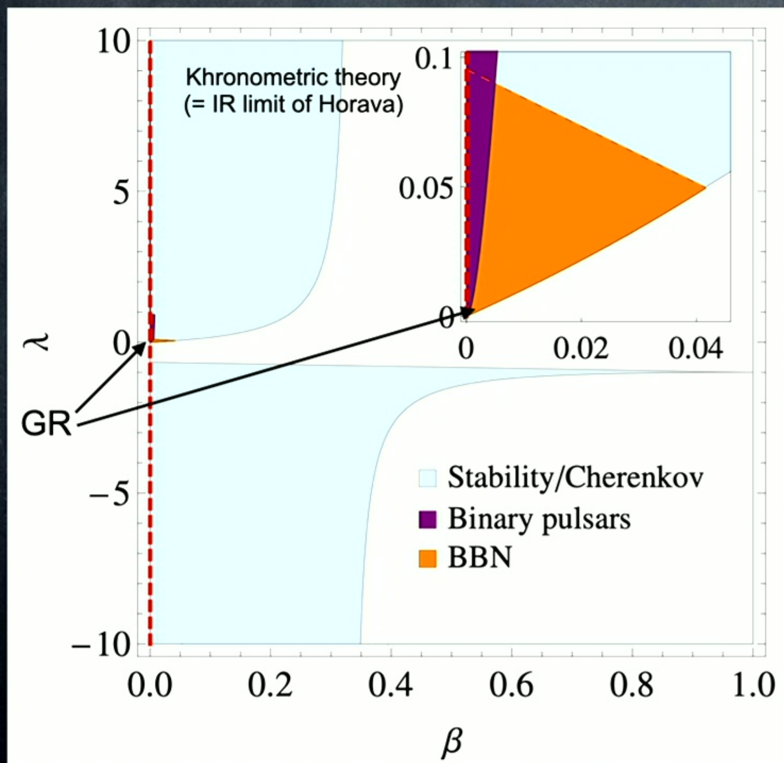


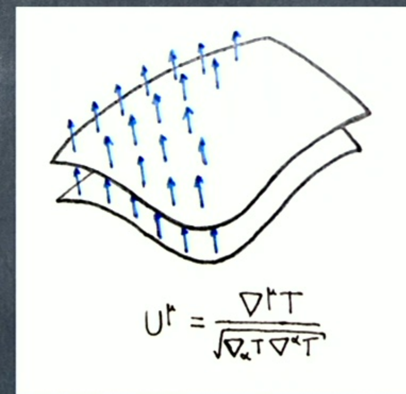
Credits: Joeri van Leeuwen

Constraints e.g. on BD-like theories, on Lorentz-violating gravity, etc

(Absence of) dipole emission in binary pulsars

An example: Lorentz-violating gravity





No ghosts+no gradient instabilities+solar system tests+absence of vacuum Cherenkov (to agree with cosmic rays)+BBN+pulsars +GW170817

Yagi, Blas, EB & Yunes 2014
Ramos & EB 2018, EB 2019,
Gupta+EB+2021

EFTs of Dark Energy

$$\mathcal{L}_\phi = \frac{\sqrt{-g}}{16\pi G}\Big\{K(\phi,X) - G_3(\phi,X)\Box\phi + G_4(\phi,X)R + \partial_X G_4(\phi,X)\left[(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)^2\right]$$
$$+G_5(\phi,X)G_{\mu\nu}\nabla^\mu\nabla^\nu\phi - \frac{1}{6}\partial_X G_5(\phi,X)\left[(\Box\phi)^3 - 3(\Box\phi)(\nabla_\mu\nabla_\nu\phi)^2 + 2(\nabla_\mu\nabla_\nu\phi)^3\right]\Big\}$$

$$X \equiv -\nabla_\mu\phi\nabla^\mu\phi/2 \quad (\nabla_\mu\nabla_\nu\phi)^2 \equiv \nabla_\mu\nabla^\nu\phi\nabla_\nu\nabla^\mu\phi \quad (\nabla_\mu\nabla_\nu\phi)^3 \equiv \nabla_\mu\nabla^\rho\phi\nabla_\rho\nabla^\nu\phi\nabla_\nu\nabla^\mu\phi$$

- Horndeski class; can be generalized to DHOST
- Model for Dark-Energy like phenomenology: screening mechanism (Vainshtein, K-mouflage, etc), self-accelerating solutions
- Constraints from GW170817, decay of propagating GWs into scalar, and scalar instabilities induced by GWs: only viable model is k-essence models with a possible conformal coupling with matter

K-essence screening
(AKA K-mouflage, kinetic screening)

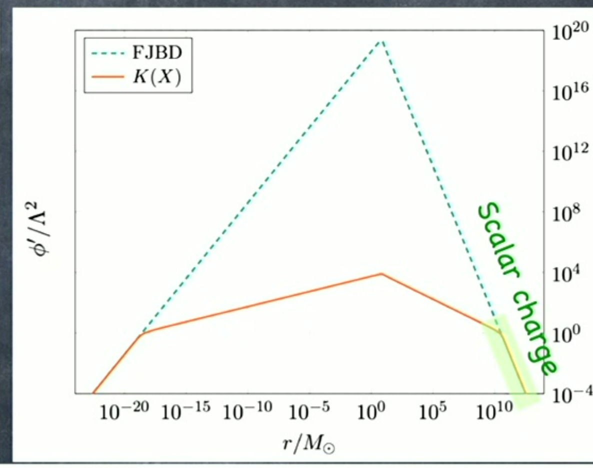
$$S = \int d^4x\sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R + K(X)\right] + S_m\left[e^{\alpha\,\phi/M_{Pl}}g_{\mu\nu}, \Psi\right]$$

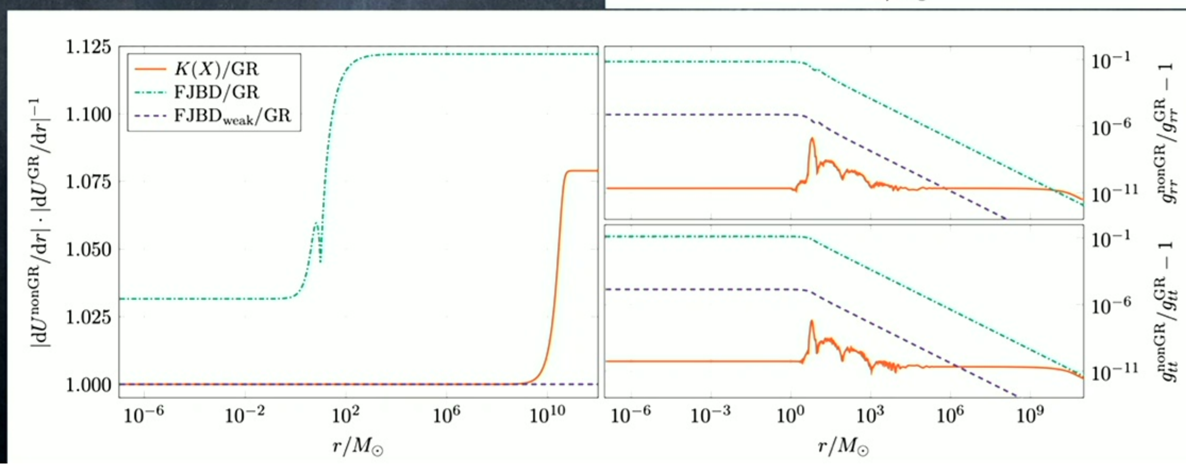
$$K(X) = -\frac{1}{2}X + \frac{\beta}{4\Lambda^4}X^2 - \frac{\gamma}{8\Lambda^8}X^3 \qquad X \equiv \nabla_\mu\phi\nabla^\mu\phi$$

$$\Lambda \sim (H_0 M_{\rm Pl})^{1/2} \sim 5\times10^{-3}\ {\rm eV}$$

$\alpha, \beta, \gamma \sim \mathcal{O}(1)$ →

$\Lambda \sim 10^{-11}$ in units $G = c = M_\odot = 1$





Ter Haar, Bezares, Crisostomi, EB & Palenzuela 2020

Compact object binaries (analytic treatment, Boskovic & EB 23)

$$G_{\mu\nu} = \frac{1}{M_{\rm Pl}^2}(T_{\mu\nu} + T^{\varphi}_{\mu\nu}),$$
$$T_{\mu\nu} = \frac{2}{\sqrt{-g}}\frac{\delta S_m}{\delta g_{\mu\nu}},$$
$$T^{\varphi}_{\mu\nu} = K(X)g_{\mu\nu} - 2K_X\partial_\mu\varphi\partial_\nu\varphi,$$
$$\nabla_\mu(K_X\nabla^\mu\varphi) = \frac{1}{2}\frac{\alpha}{M_{\rm Pl}}T,$$

$$\chi_\mu \equiv K_X\nabla_\mu\varphi$$
$$\chi^\mu\chi_\mu = K_X^2 X$$
$$\chi_\mu = -\frac{1}{2}\nabla_\mu\psi + B_\mu$$
$$\nabla_\mu B^\mu = 0.$$

$$\Box\psi = -\frac{\alpha}{M_{\rm Pl}}T$$

BD mode,
but scalar charges = 0

$$\Box B^\mu - R^\mu{}_\nu B^\nu = J^\mu,$$
$$J_\mu = 2\nabla^\nu[K_{XX}\nabla_{[\nu}X\nabla_{\mu]}\varphi]$$
$$\nabla_\mu J^\mu = 0$$

Transverse ("B") mode

For BHs, both modes are exactly zero

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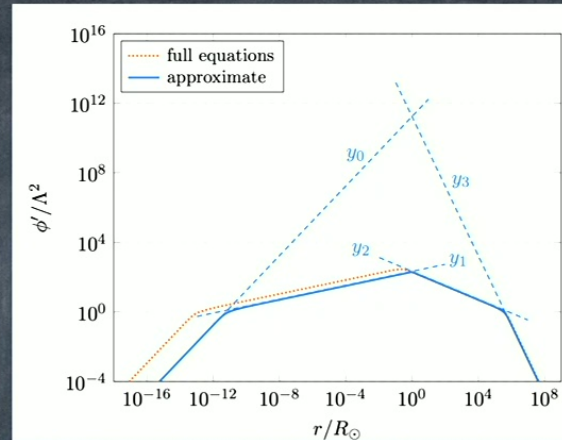
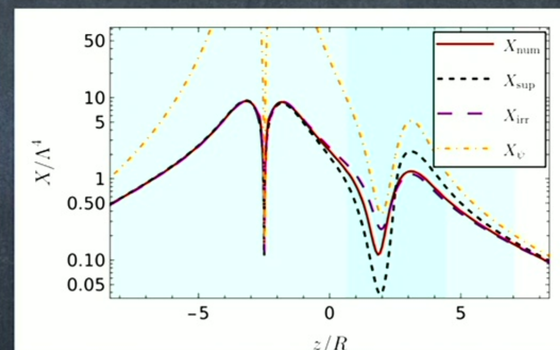
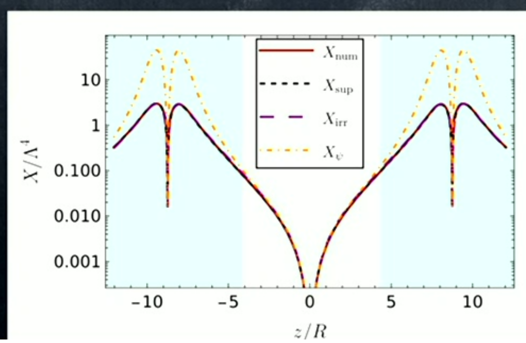
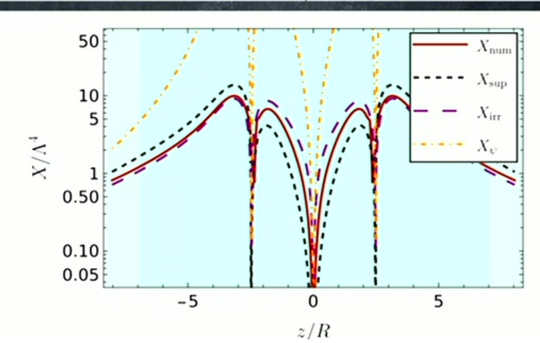
Neutron star binaries: to B or not to B

- B=0 in spherical & static symmetry and for plane waves
- B subdominant in non-relativistic binaries (Boskovic & EB 2023) and in spherical collapse (Bernard+2019)









How about GW-emitting binaries?

$$\Box\psi = -\frac{\alpha}{M_{\rm Pl}}T$$

→ If sensitivities suppressed, deviations from GR at 0PN (quadrupole), but no -1PN/ dipole

$$\Box B^\mu - R^\mu{}_\nu B^\nu = J^\mu,$$
$$J_\mu = 2\nabla^\nu[K_{XX}\nabla_{[\nu}X\nabla_{\mu]}\varphi]$$

→

$$B^t_{\rm dip}(t,\boldsymbol{x}) = \frac{1}{r}\int \partial_t \tilde{J}^t(t-r,\boldsymbol{x}')\,(\boldsymbol{x}'\cdot\boldsymbol{n})\,{\rm d}^3x' = \frac{n_i}{r}\int \tilde{J}^i(t-r,\boldsymbol{x}'){\rm d}^3x' = n_i B^i_{\rm dip}(t,\boldsymbol{x})$$
$$B^i_{\rm dip}(t,\boldsymbol{x}) = \frac{1}{r}\int \tilde{J}^i(t-r,\boldsymbol{x}'){\rm d}^3x'$$

$$\nabla_\mu J^\mu = 0$$

$B_{\rm dip} \approx 0$ when m1 ≈ m2

Can we check this with numerical relativity?

ùNeed to tackle well-posedness of Cauchy problem and separation of scales (screening radius >> binary separation)

K-essence screening
(AKA K-mouflage, kinetic screening)

$$S = \int d^4x\sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R + K(X)\right] + S_m\left[e^{\alpha\,\phi/M_{Pl}}g_{\mu\nu},\Psi\right]$$

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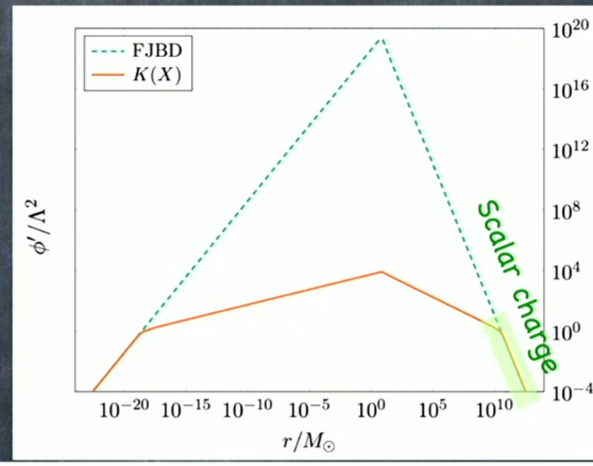
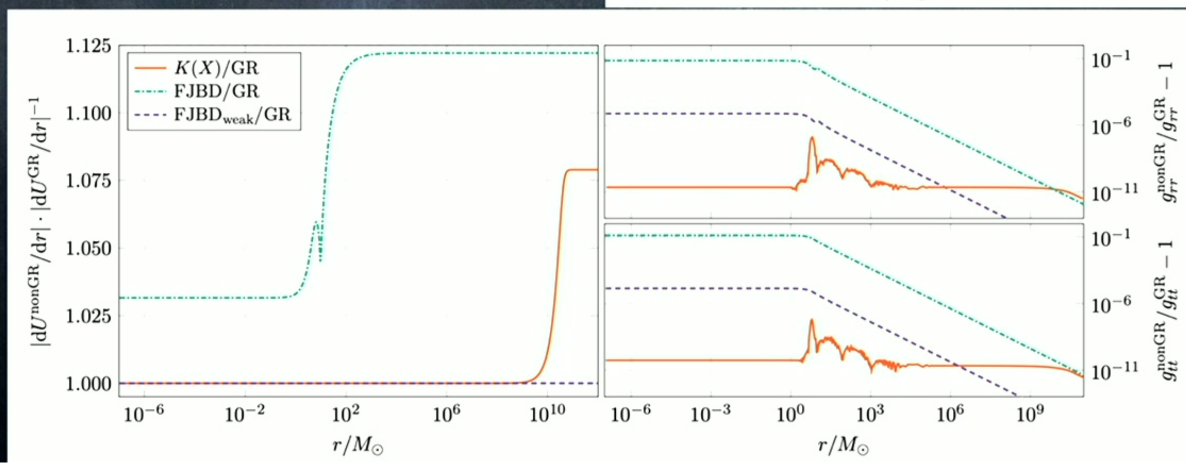




Ter Haar, Bezares, Crisostomi, EB & Palenzuela 2020

The Cauchy problem in a nutshell

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

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

$$\partial_t \boldsymbol{U} + \boldsymbol{V}\partial_r \boldsymbol{U} = \mathcal{S}(\mathbf{U})$$

$$\boldsymbol{U} \equiv (\partial_t\phi, \partial_r\phi)$$

V is the characteristic matrix
Sufficient condition for stable evolution is to have a complete set of eigenvectors and real eigenvalues

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

$$c_s = \pm\sqrt{1 + 2XK''/K'}$$

reduces to usual sound speed in flat space

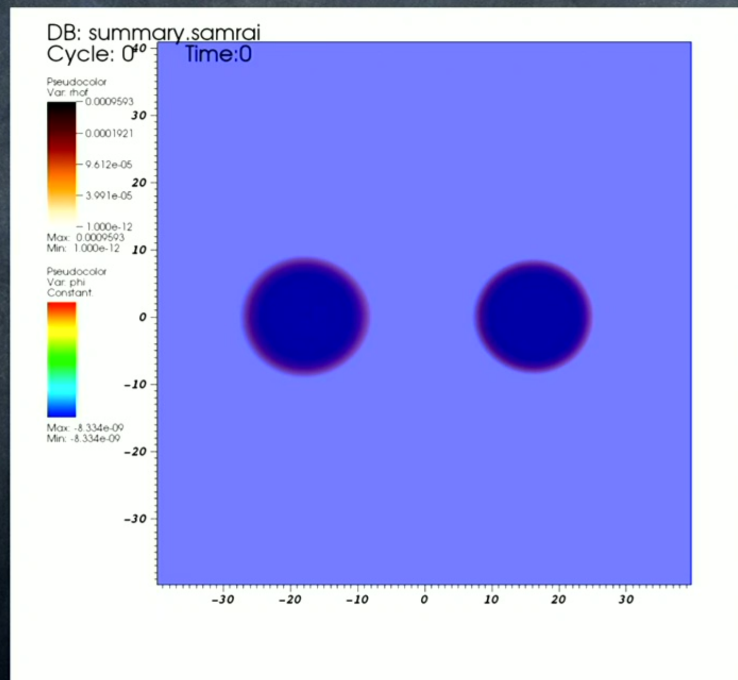
$$\det(\gamma^{\mu\nu}) = -\frac{1}{\alpha^2 g_{rr}}\left(1 + \frac{2\,K''}{K'}X\right)$$

$$1 + \frac{2\,K''(X)}{K'(X)}X > 0$$

- If $\gamma^{\mu\nu}$ changes signature, system becomes parabolic/elliptic (Tricomi behavior): avoided if K(X) includes X^3 (Bezares, Crisostomi, Palenzuela, EB 2020)
- When $\gamma^{tt} \to 0$ characteristic speeds diverge (Keldysh behaviour); avoided by "fixing the equations" (à la Cayuso & Lehner) or by choosing gauge with non-zero shift

Binary neutron star mergers

CCZ4 3+1 formulation of the Einstein equations (with 1+log slicing and Gamma-driver shift condition) leads to finite characteristic speeds (no Keldysh), no need of "fixing"



Bezares, Crisostomi, Palenzuela, EB 2021

$r_{12}/r_K \sim 1.5$

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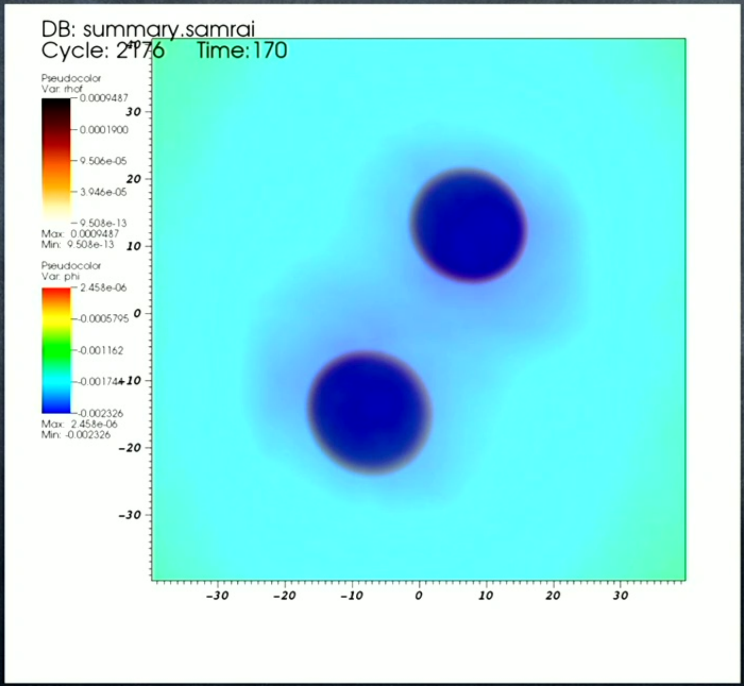

Bezares, Crisostomi, Palenzuela, EB 2021

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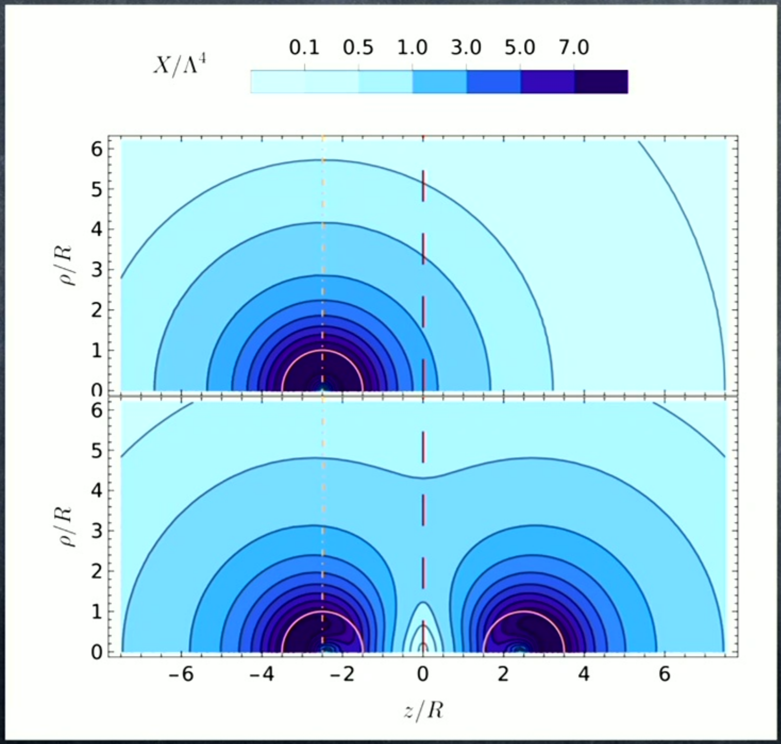
Descreening at saddle point



Boskovic & Barausse 23

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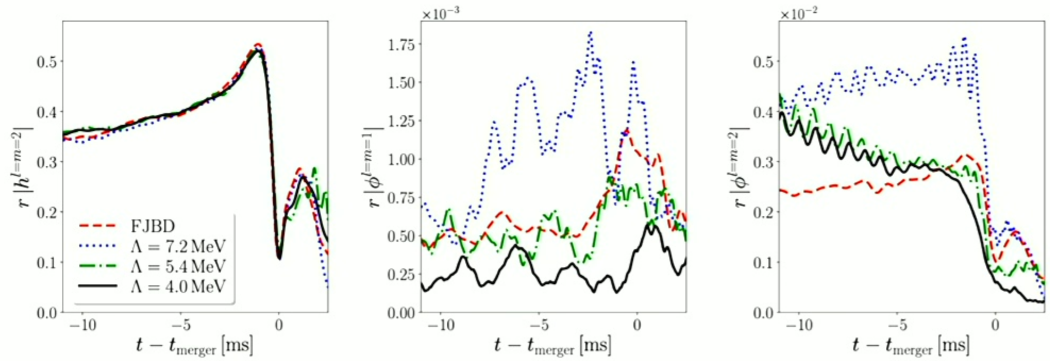


FIG. 3 – Tensor ($l = m = 2$) and scalar ($l = m = 1$ and $l = m = 2$) strain for a NS merger with $q = 0.91$, in k-essence and FJBD.

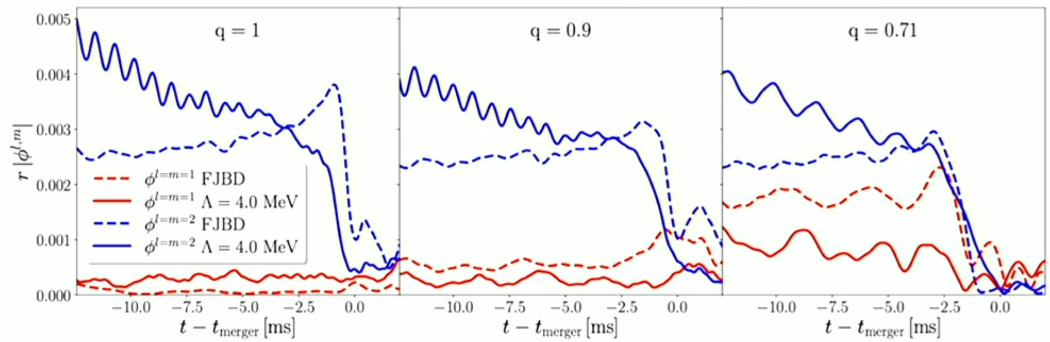
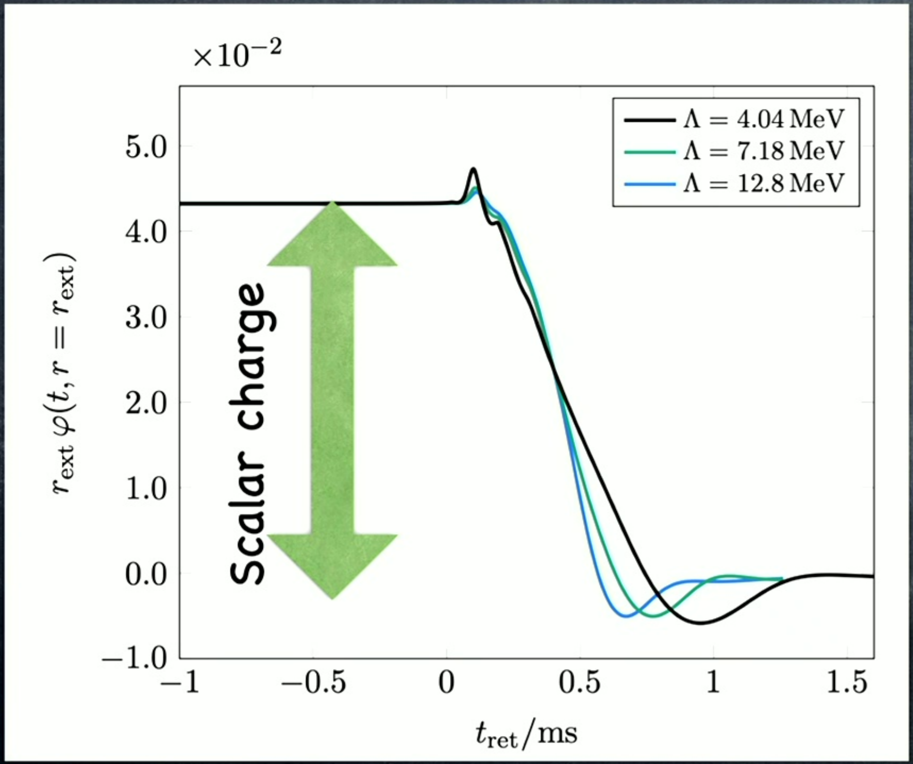


FIG. 4 – Dipole ($l = m = 1$) and quadrupole ($l = m = 2$) scalar strain for merging NS binaries of varying mass ratio, in k-essence and FJBD.

Bezares+2022

- Dipole is suppressed, but quadrupole is not (?)
- If quadrupole not screened, strong constraints from binary pulsars

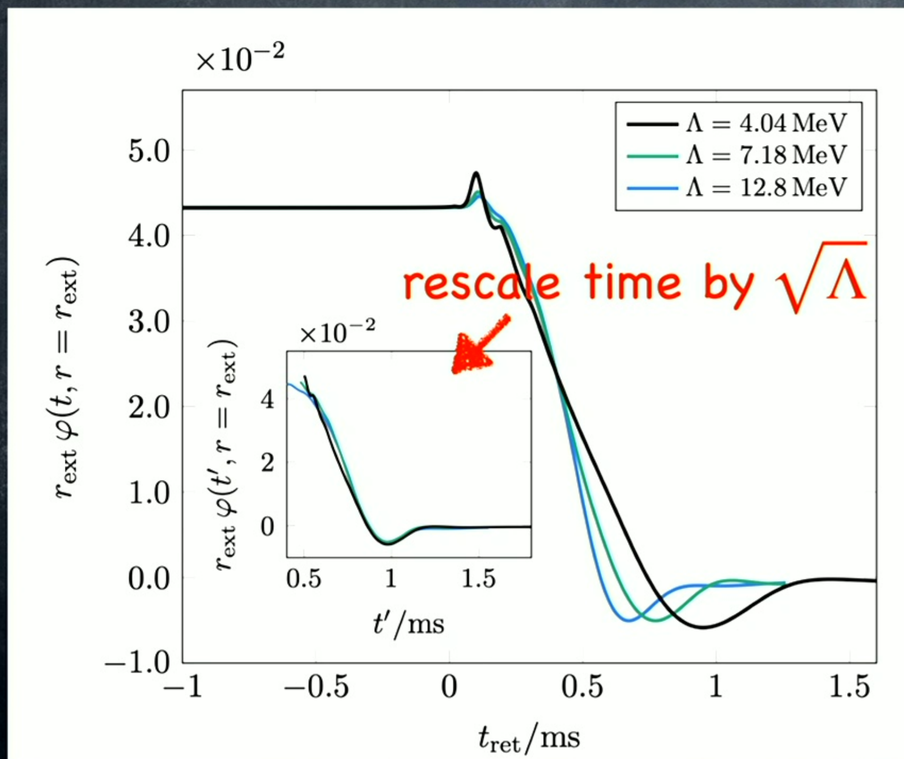
Kinetic screening in dynamical settings: neutron star collapse



Collapse radiates away scalar charge (cf BH no hair theorem)

Bezares, ter Haar, Crisostomi EB and Palenzuela 2021

Kinetic screening in dynamical settings: neutron star collapse



Observable by LISA for a supernova explosion in Milky Way (a few/century)

Bezares, ter Haar, Crisostomi EB and Palenzuela 2021

Conclusions

- GR extensions with no screening tightly constrained by solar system/binary pulsars/inspiral of LVK binaries
- Theories without screening are perturbative, i.e. "easy" to make predictions
- Screening needed to have viable EFT of Dark Energy
- Non-perturbative physics important for screening, but that makes calculations of GW generation difficult (Cauchy problem's well-posedness, breakdown of standard PN expansion and BH perturbation theory)
- Collapse and NS late inspiral (?) break screening: constraints from LISA and (possibly) binary pulsars
- Similar issues for self-interacting vectors