GWs and NR beyond GR

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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
- Gravitational collapse and binary compact objects in "non-linear" effective field theories of dark energy
- Lessons for the future

In collaboration with

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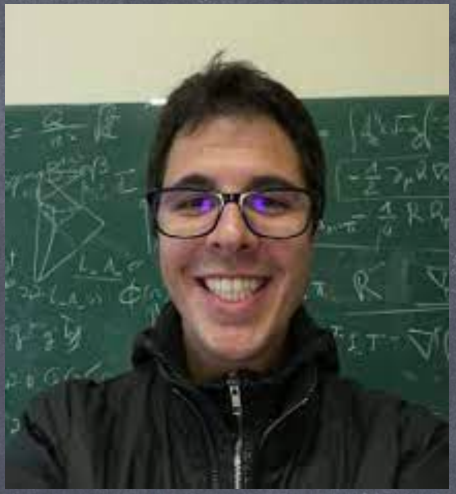

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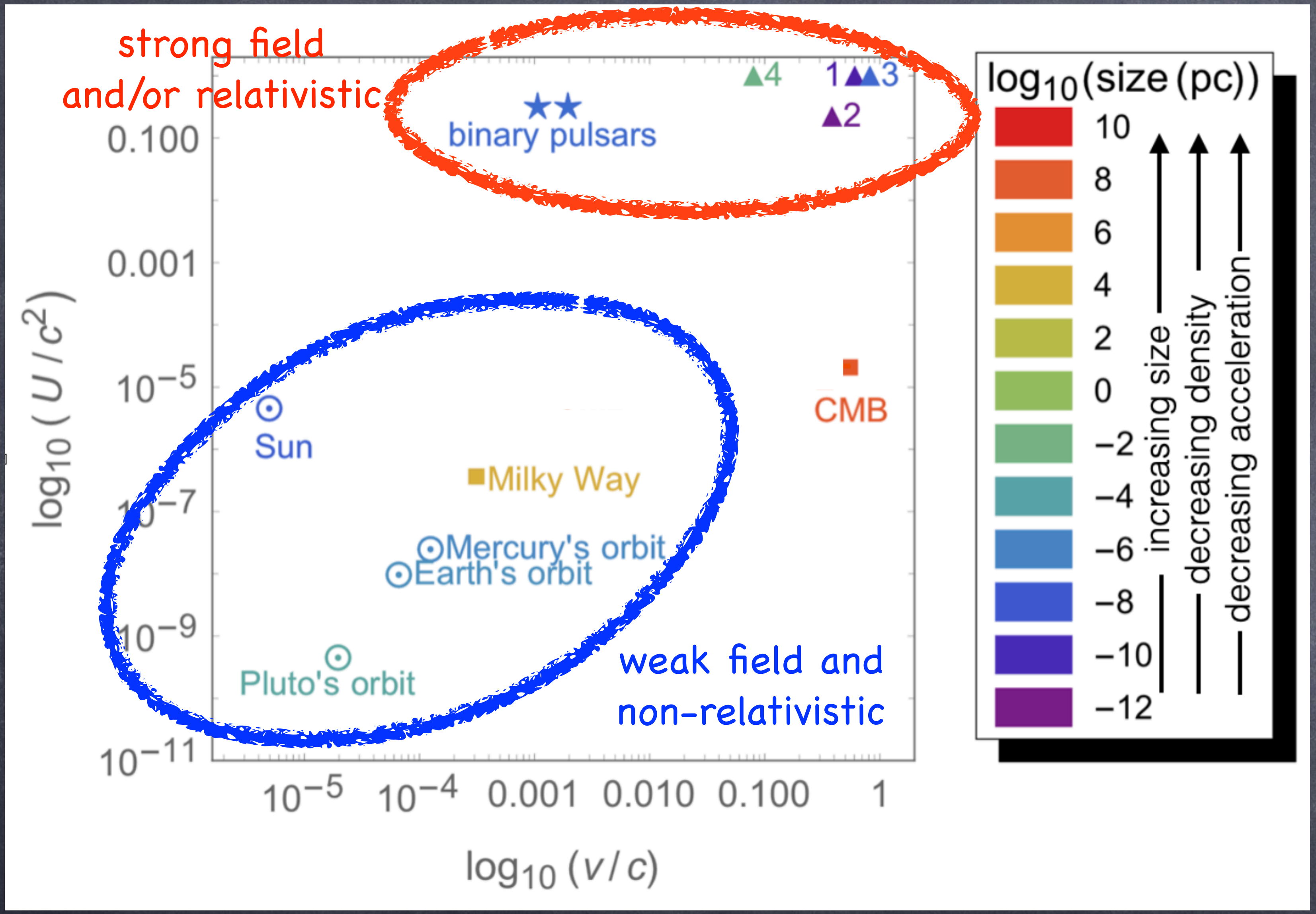
Beyond GR in the IR?



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. $G_{\mu\nu} + \Lambda\, g_{\mu\nu}$

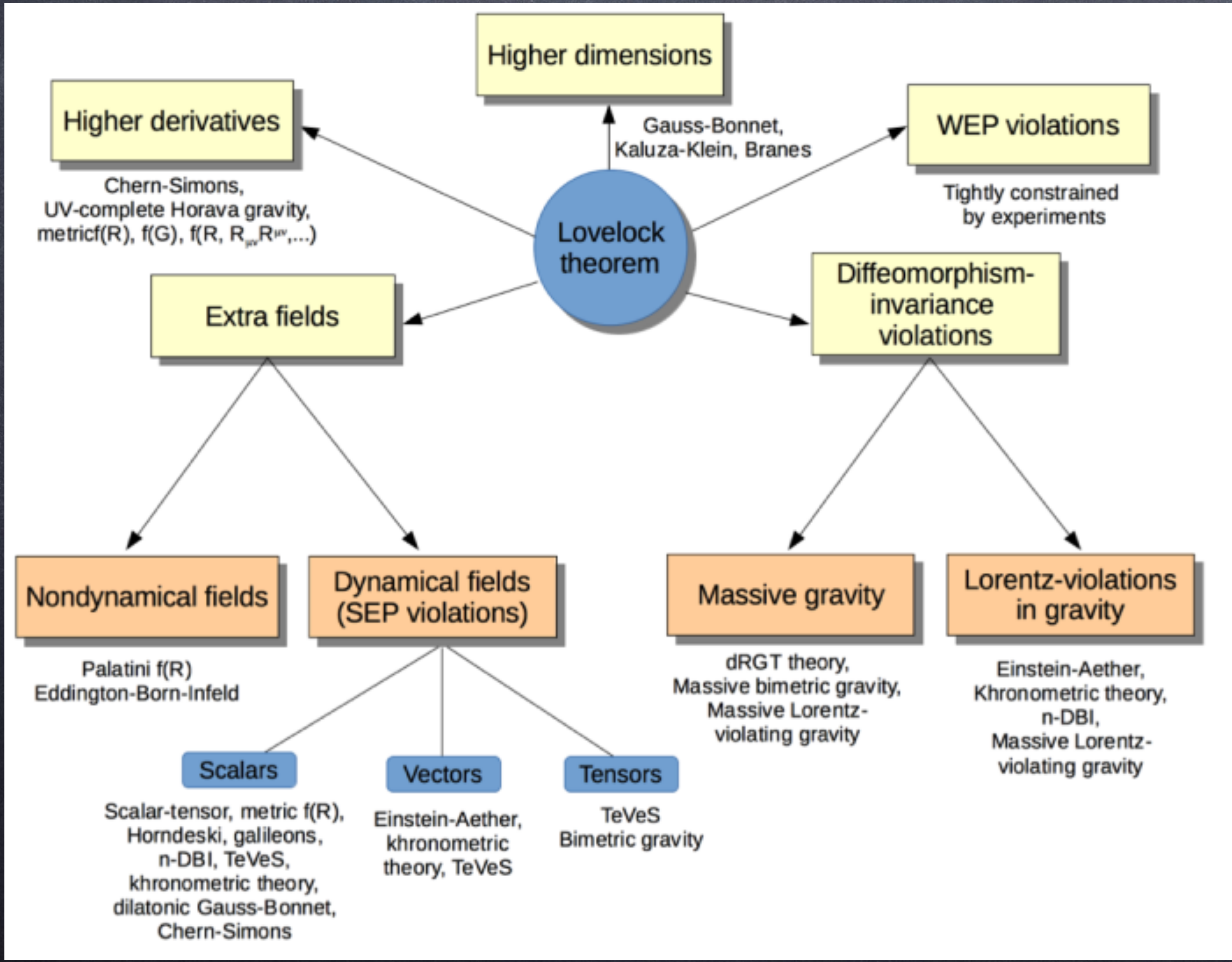


Figure adapted from Berti, EB et al 2015

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 (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

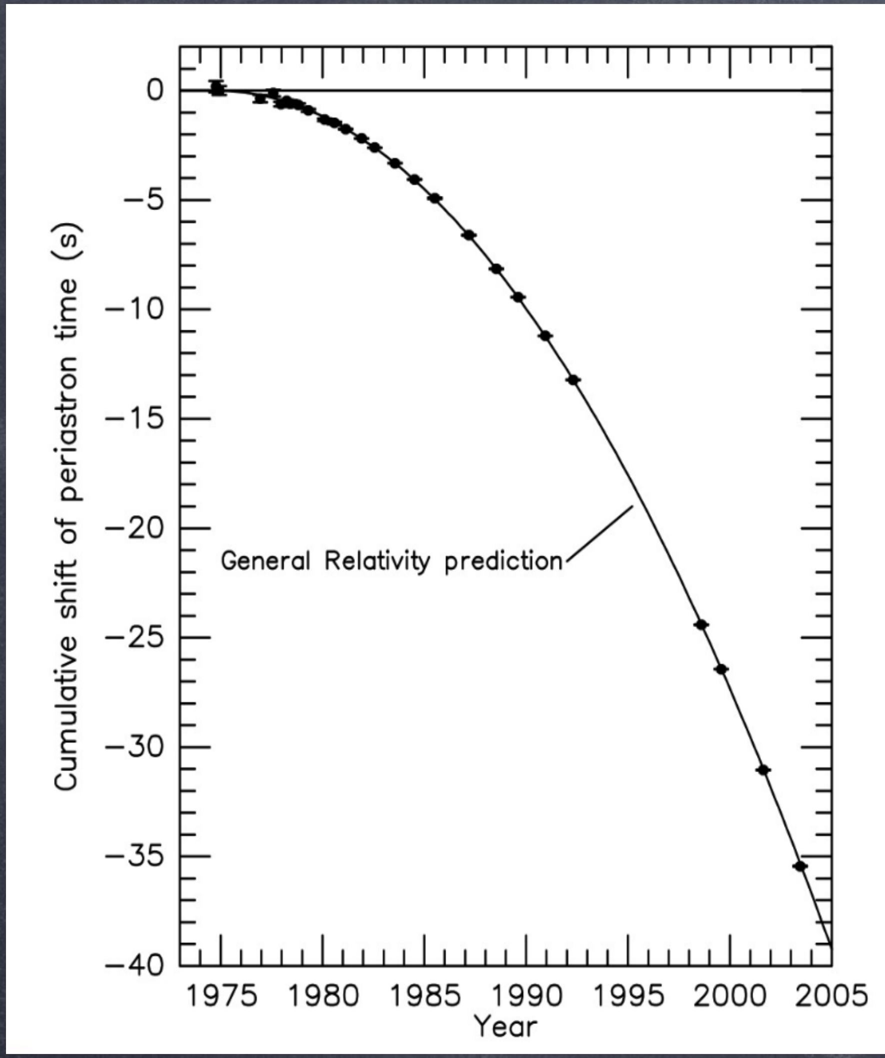
e.g. $M_1 \sim \int \rho x^i d^3x$ $\qquad h \sim \frac{G\dot{M}_1}{rc^3} \sim \frac{GP}{rc^3}$ not a wave!

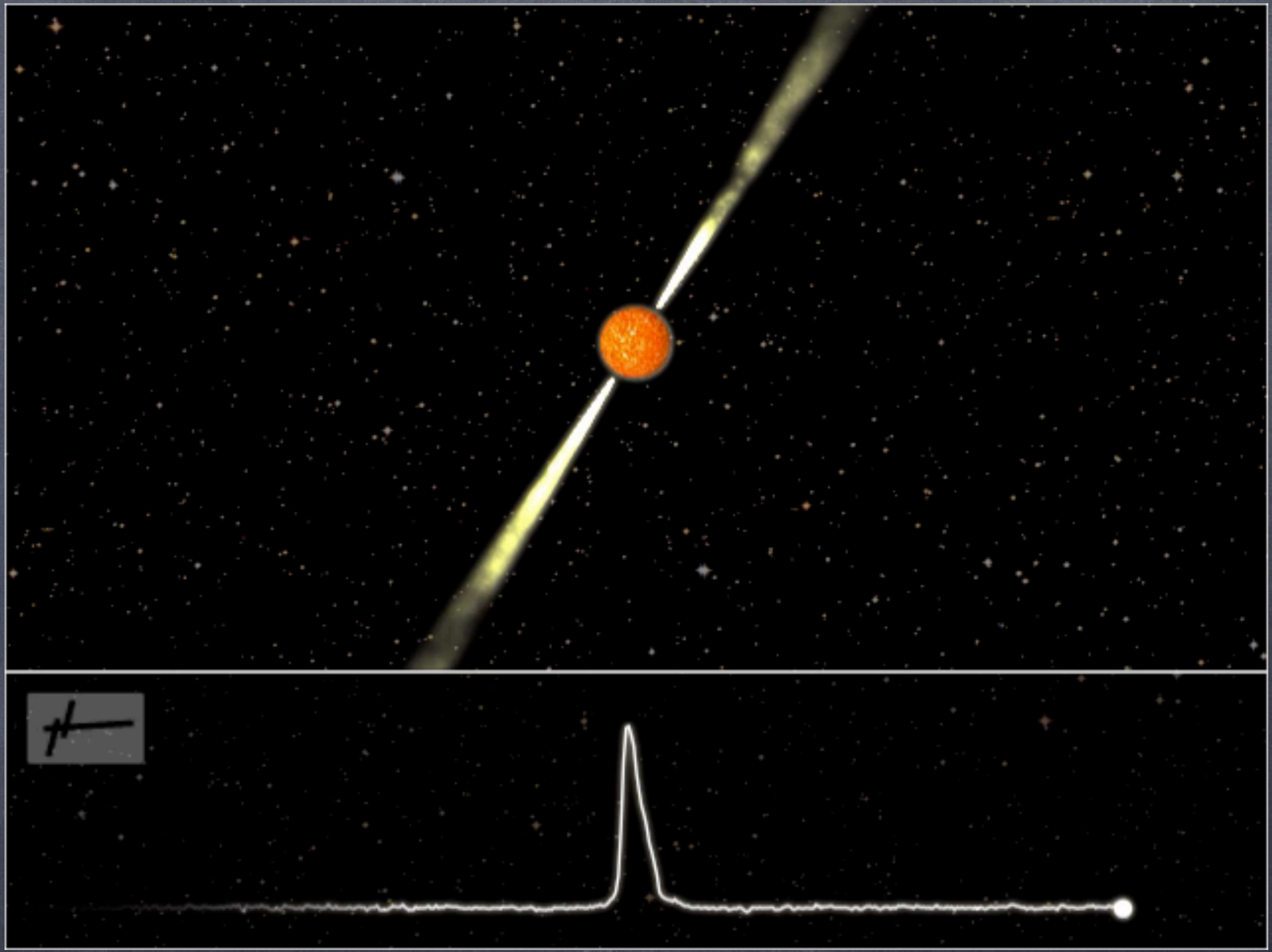
- In GR extensions, effective coupling matter-extra fields in strong gravity regimes ⟹ energy and momentum transfer between bodies and extra field, monopole and dipole GW emission, modified quadrupole formula

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

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

(Absence of) dipole emission in binary pulsars



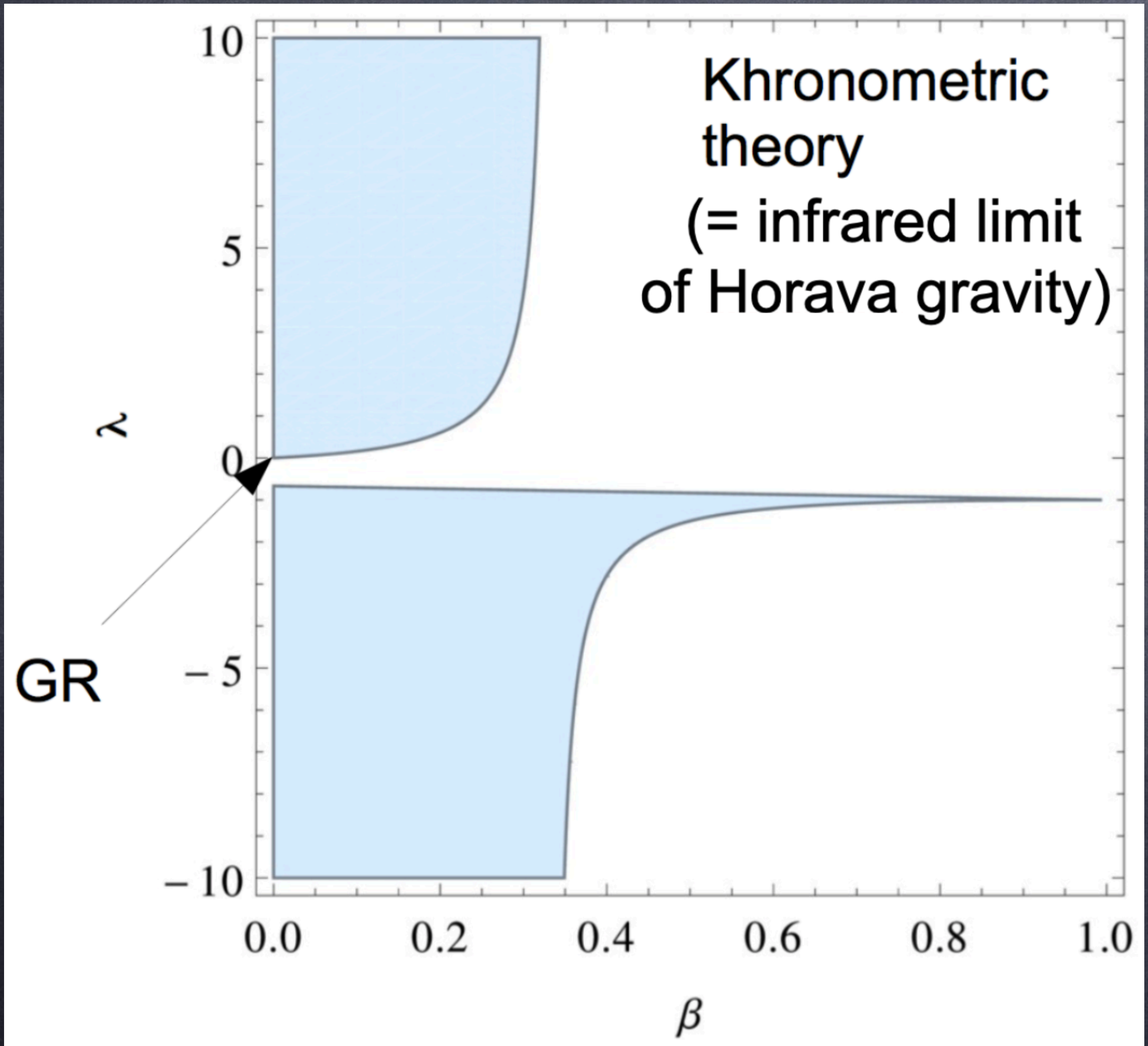


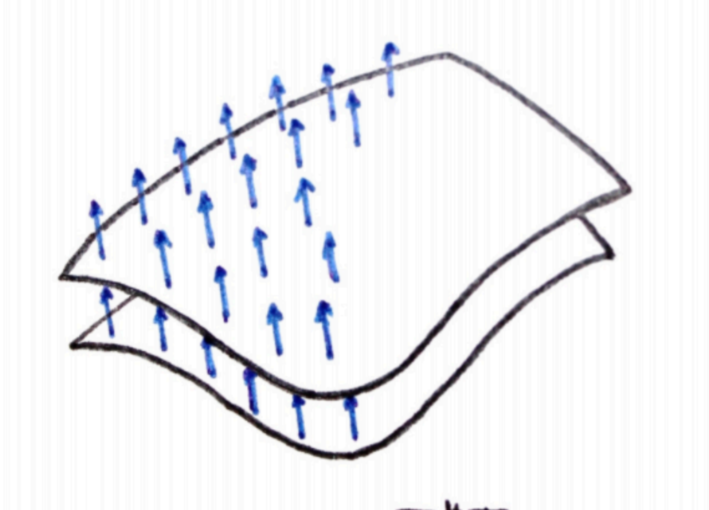
Credits: Joeri van Leeuwen

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

(Absence of) dipole emission in binary pulsars

An example: Lorentz-violating gravity





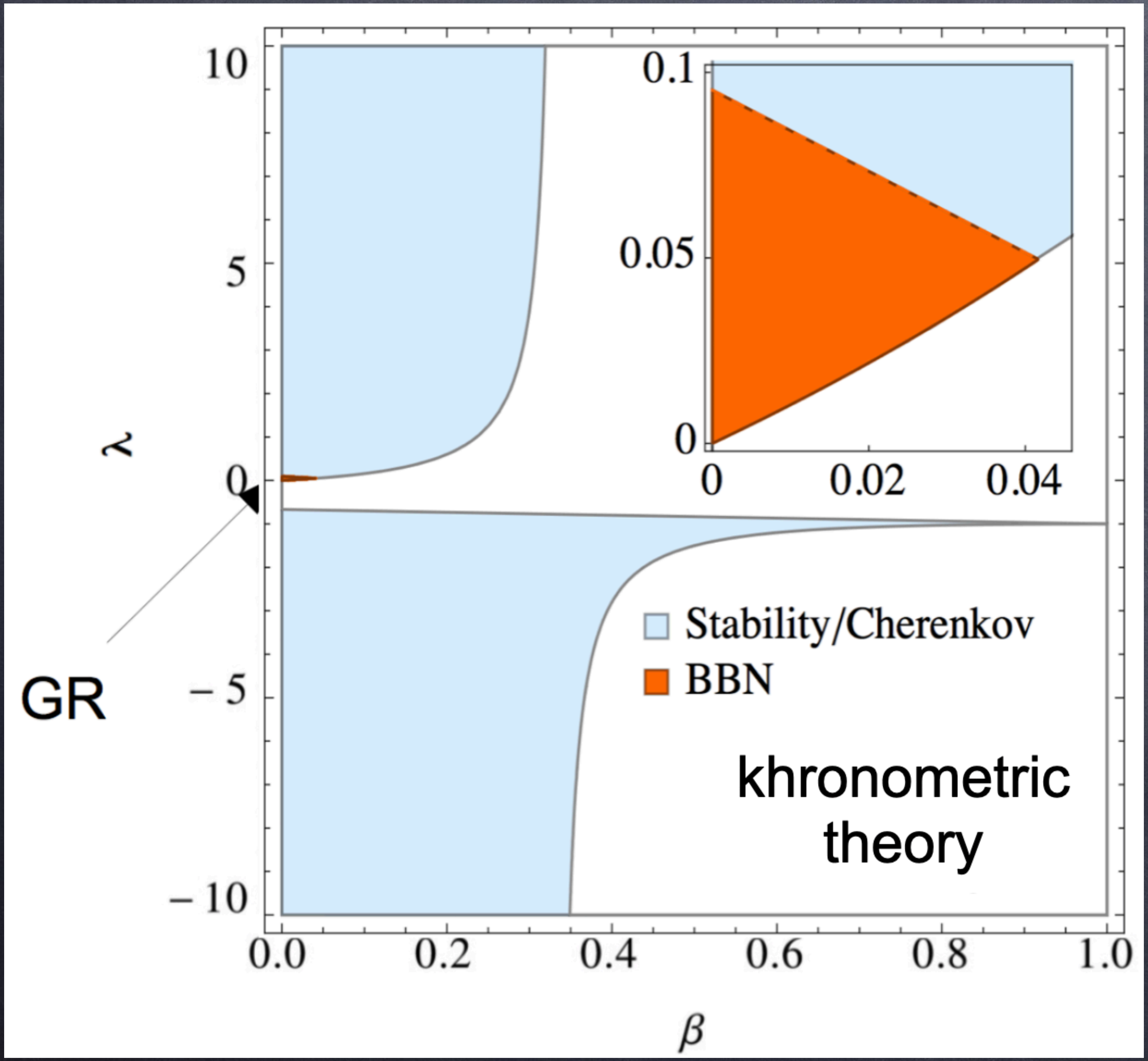
$$U^\mu = \frac{\nabla^\mu T}{\sqrt{\nabla_\alpha T \nabla^\alpha T}}$$

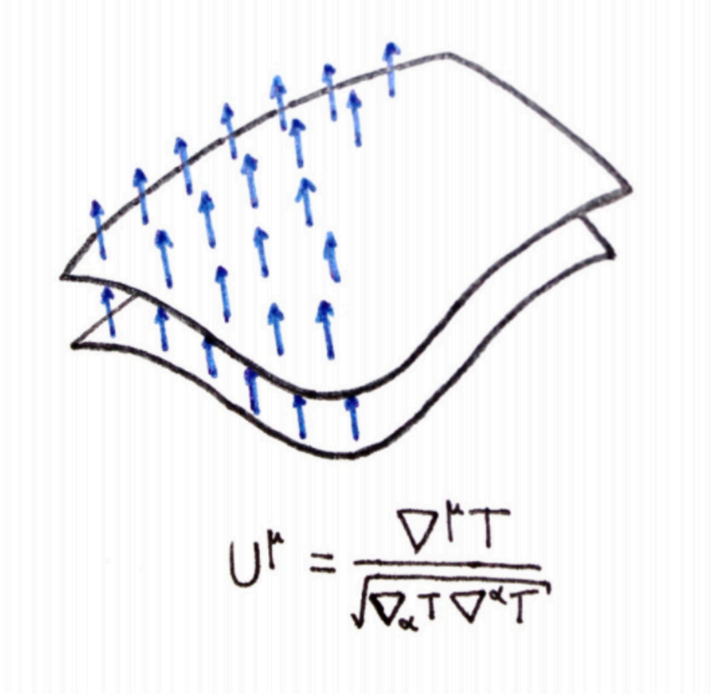
No ghosts+no gradient instabilities+solar system tests+absence of vacuum Cherenkov (to agree with cosmic rays)

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

(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

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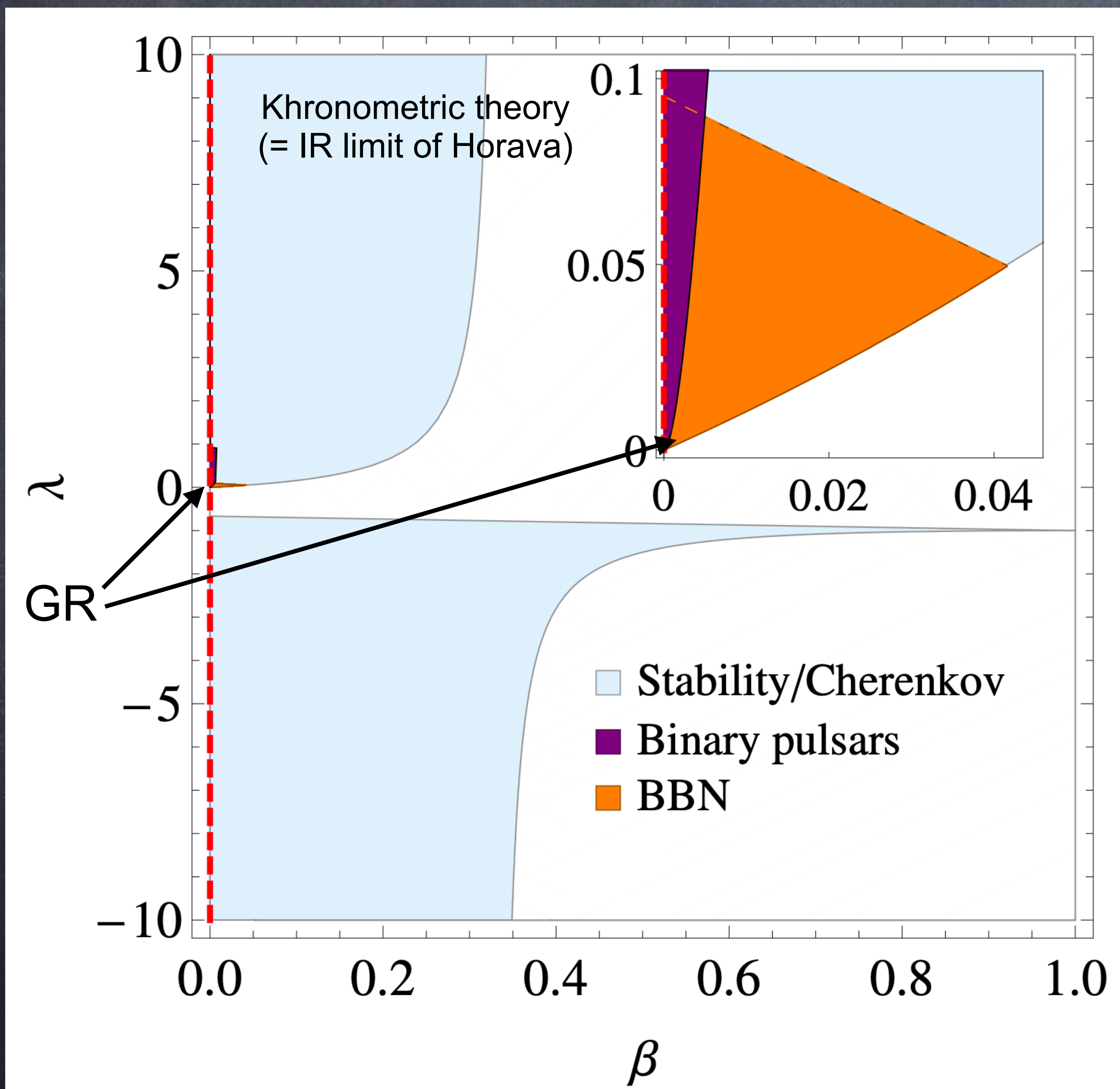
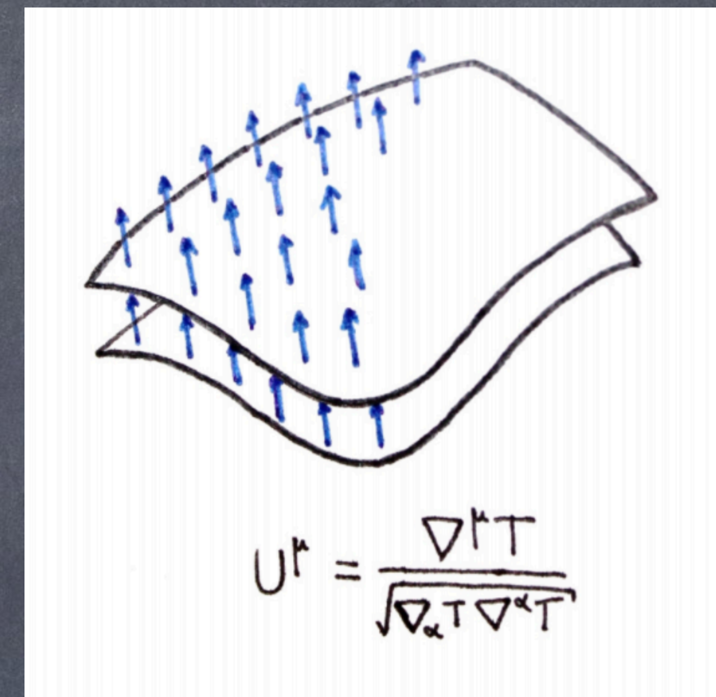
An example: Lorentz-violating gravity





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)

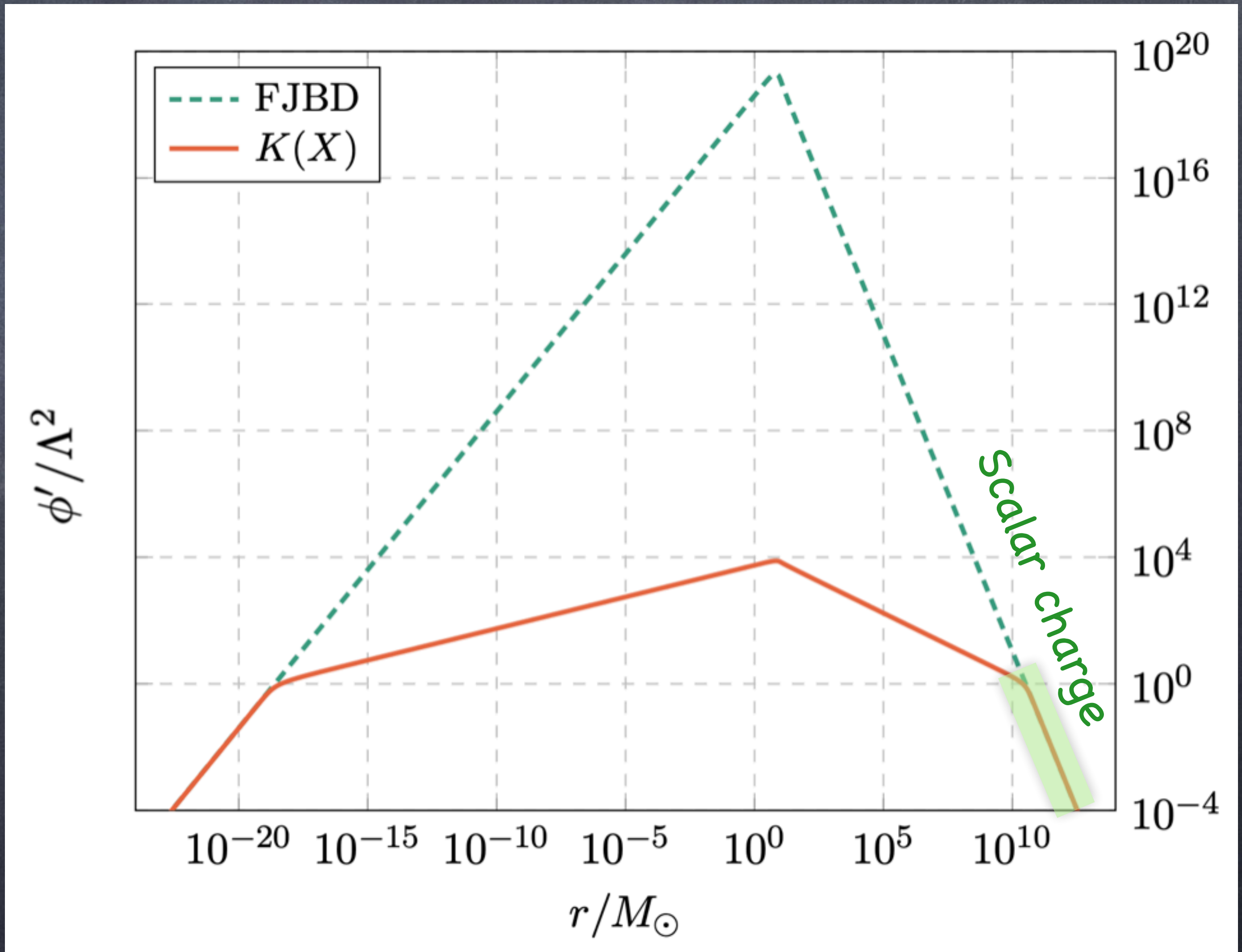
$$S = \int d^4x\sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R + K(X)\right] + S_m\left[e^{\alpha\,\phi/M_{Pl}}g_{\mu\nu}, \Psi\right]$$

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

$$\Lambda \sim (H_0 M_{\rm Pl})^{1/2} \sim 5\times 10^{-3}\ {\rm eV}$$

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

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



Ter Haar, Bezares, Crisostomi, EB & Palenzuela 2020

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

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

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

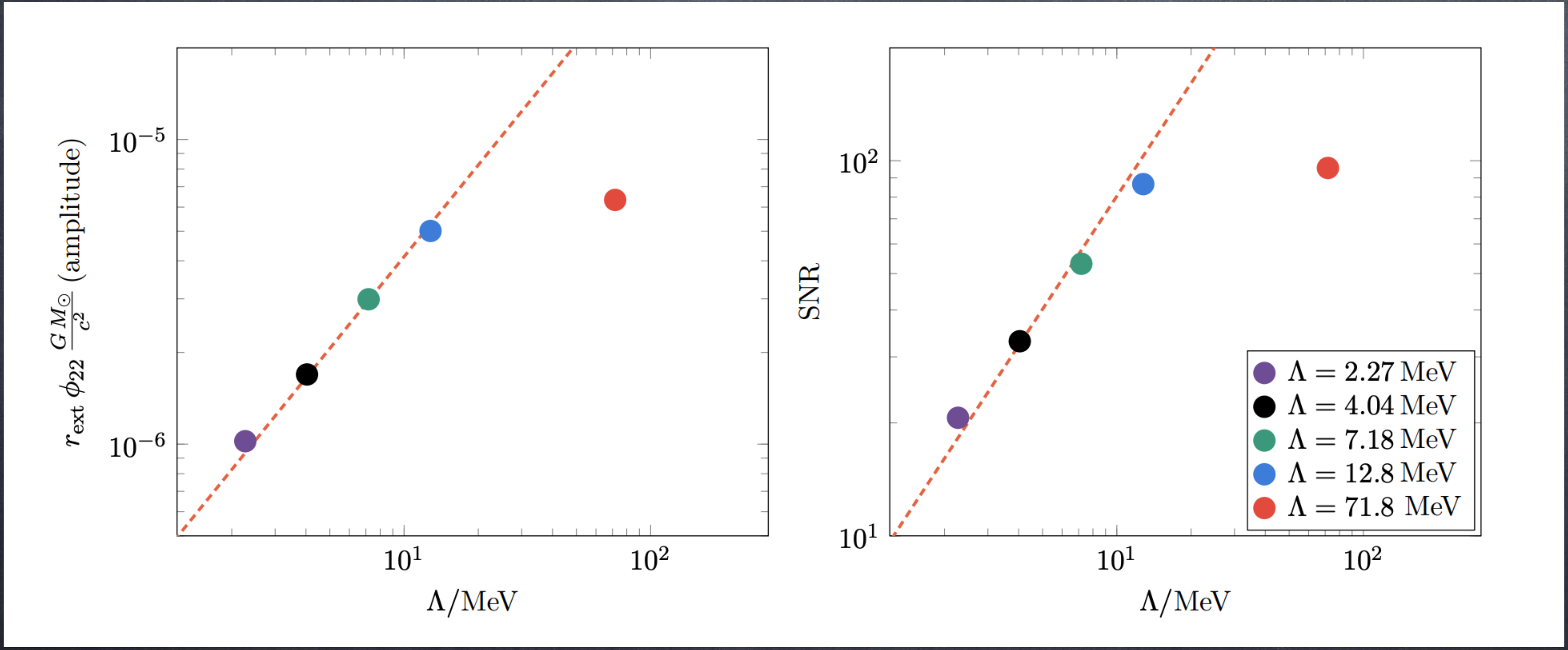
reduces to usual sound speed in flat space

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

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

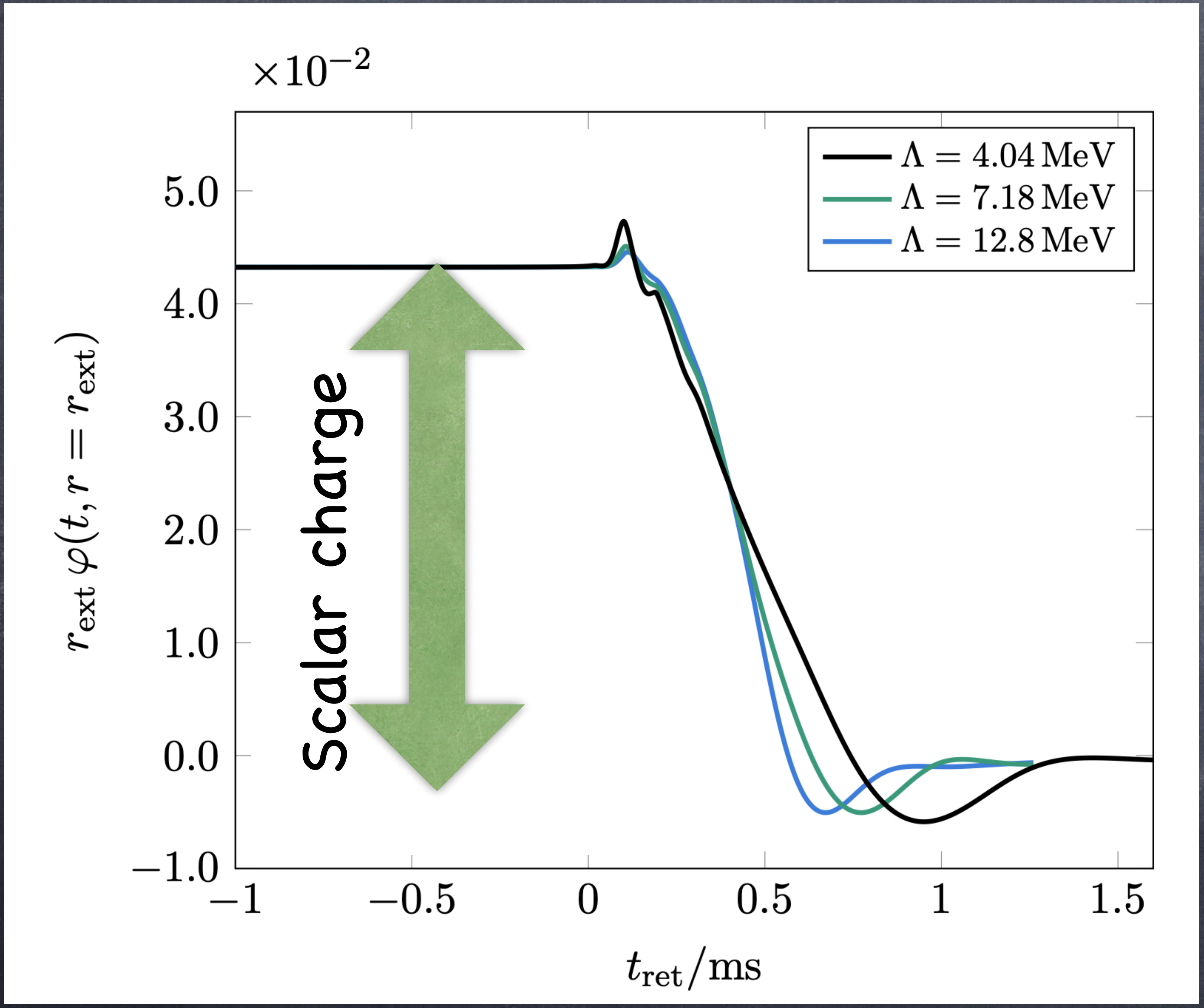
- If $\gamma^{\mu\nu}$ changes signature, system becomes parabolic/elliptic (Tricomi behavior): avoided if K(X) includes X^3 (Bezares, Crisostomi, Palenzuela, EB 2020)
- When $\gamma^{tt} \to 0$ characteristic speeds diverge (Keldysh behaviour); avoided by "fixing the equations" (à la Cayuso & Lehner)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

Kinetic screening in dynamical settings: stellar oscillations



Bezares, ter Haar, Crisostomi EB and Palenzuela 2021

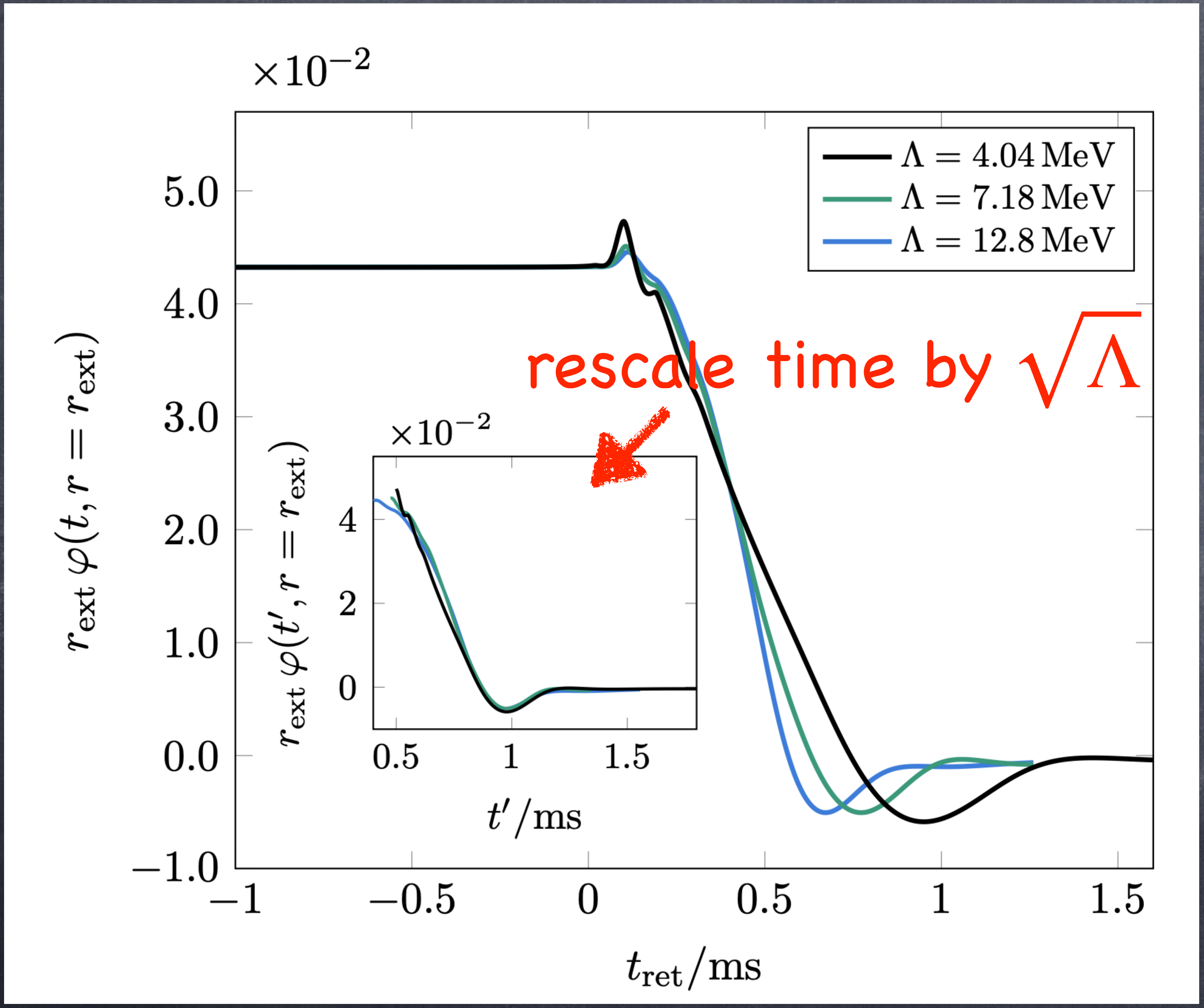
Kinetic screening in dynamical settings: neutron star collapse



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

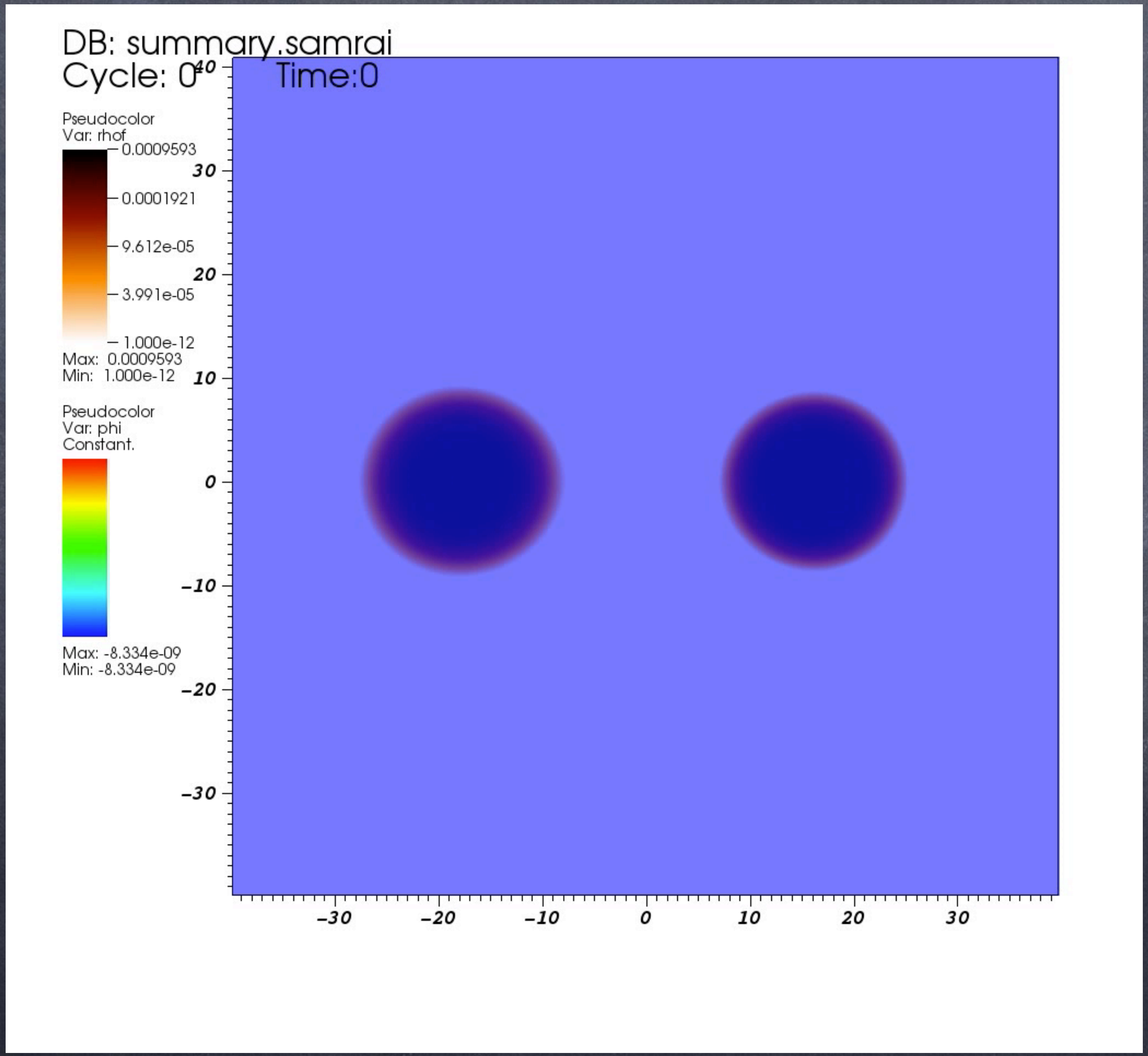


Observable by LISA for a supernova explosion in Milky Way (a few/century)

Bezares, ter Haar, Crisostomi EB and Palenzuela 2021

Binary neutron star mergers

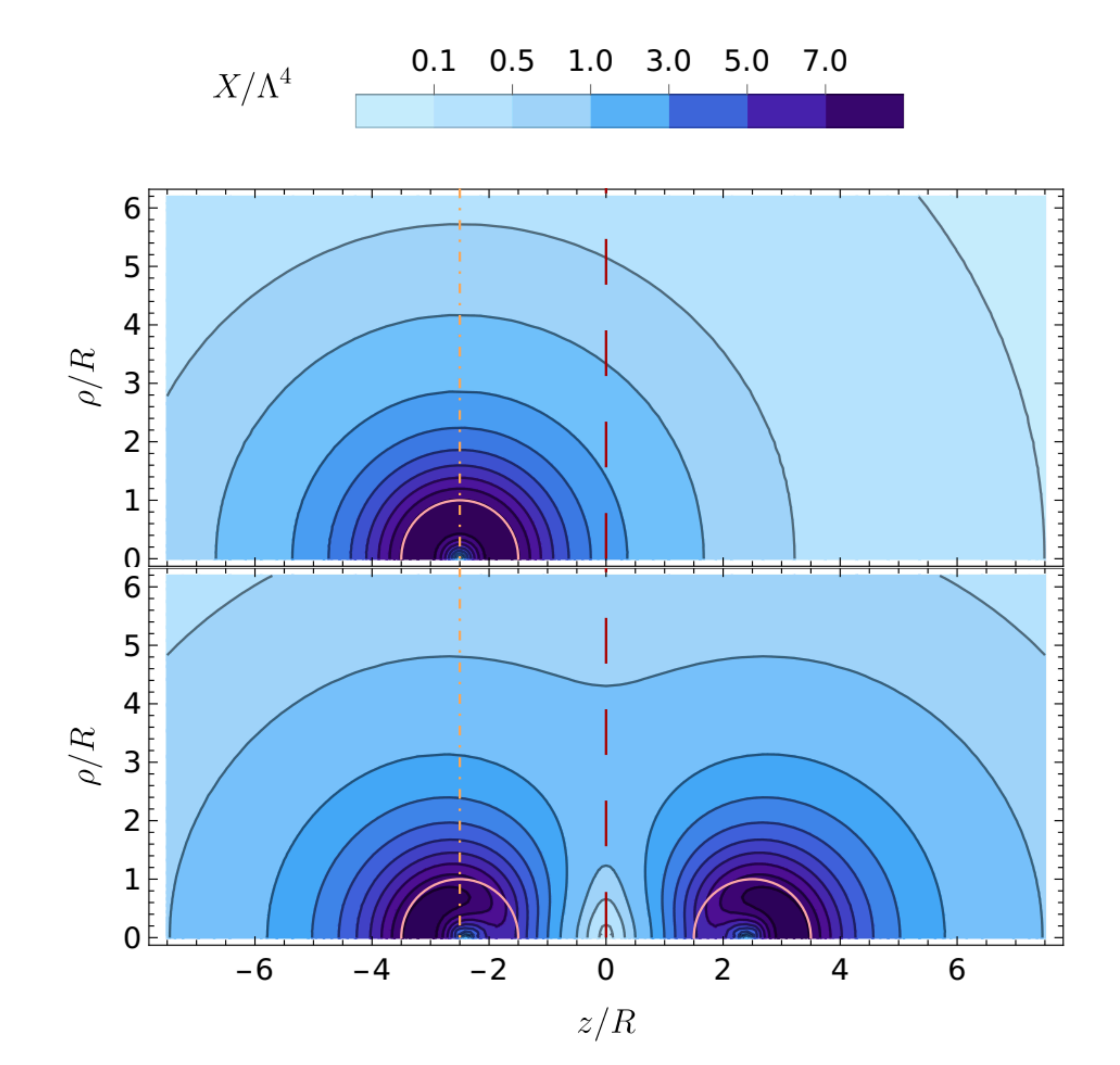
CCZ4 3+1 formulation of the Einstein equations (with 1+log slicing and Gamma-driver shift condition) leads to finite characteristic speeds (no Keldysh), no need of "fixing"



Bezares, Crisostomi, Palenzuela, EB 2021

$r_{12}/r_k \sim 1.5$

Descreening at saddle point



Boskovic & Barausse 23

Binary neutron star mergers

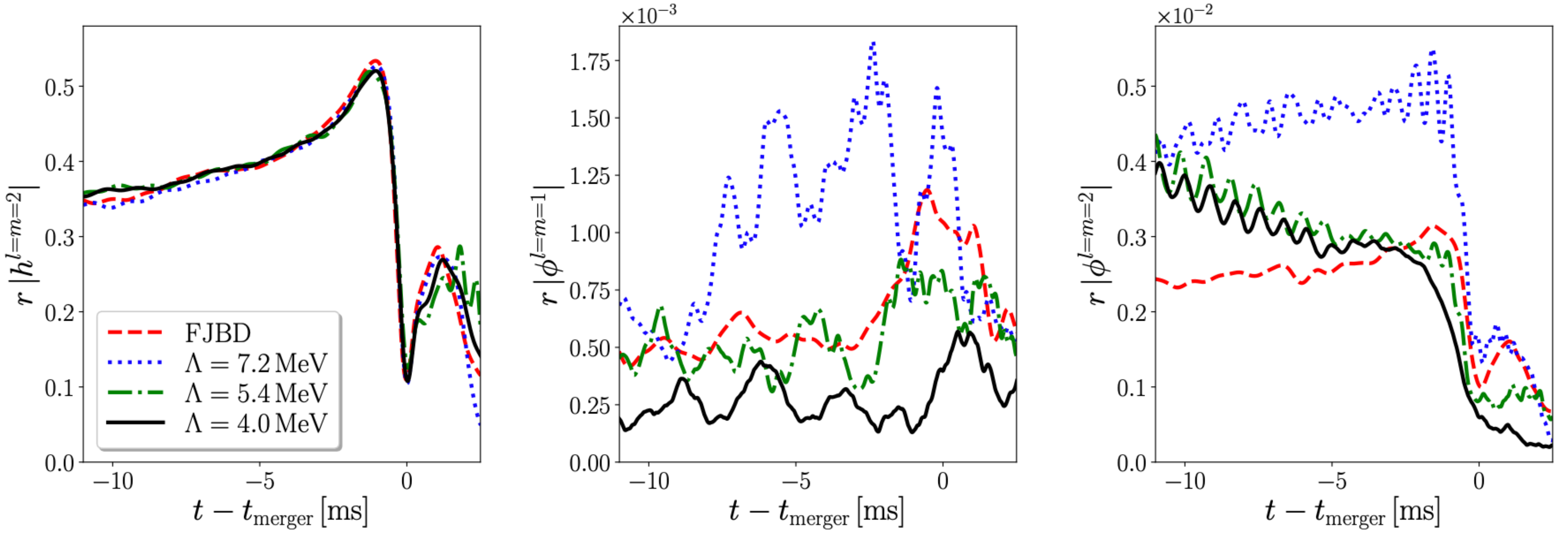


FIG. 3 – Tensor ($l = m = 2$) and scalar ($l = m = 1$ and $l = m = 2$) strain for a NS merger with $q = 0.91$, in k-essence and FJBD.

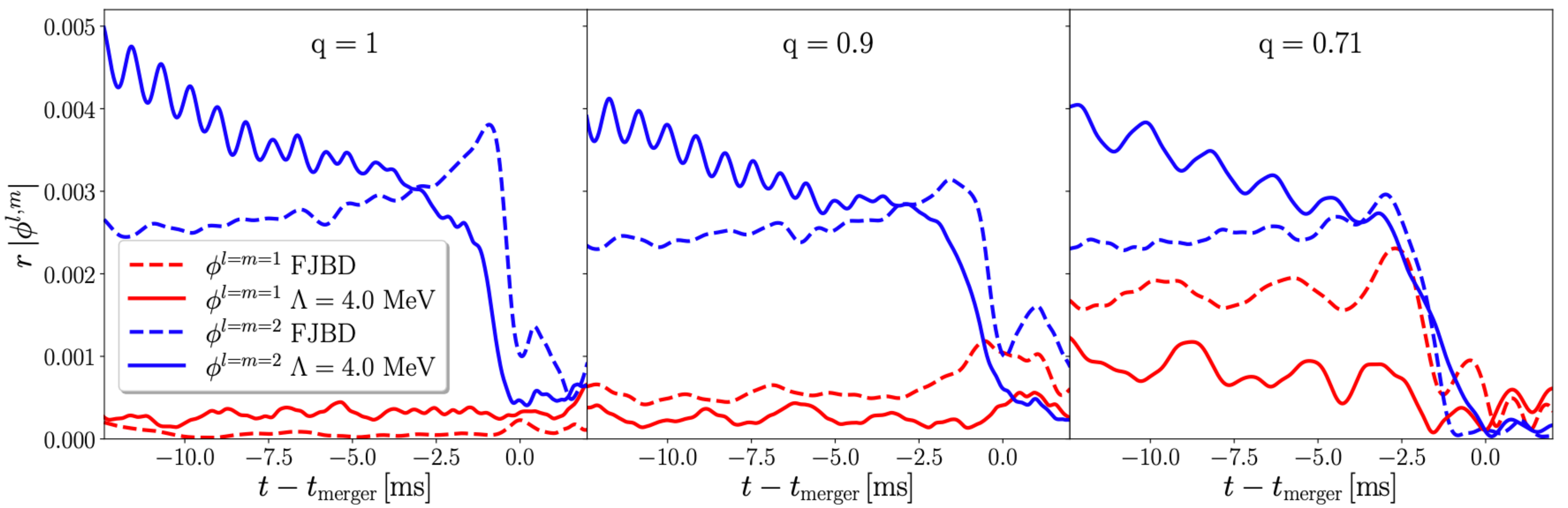
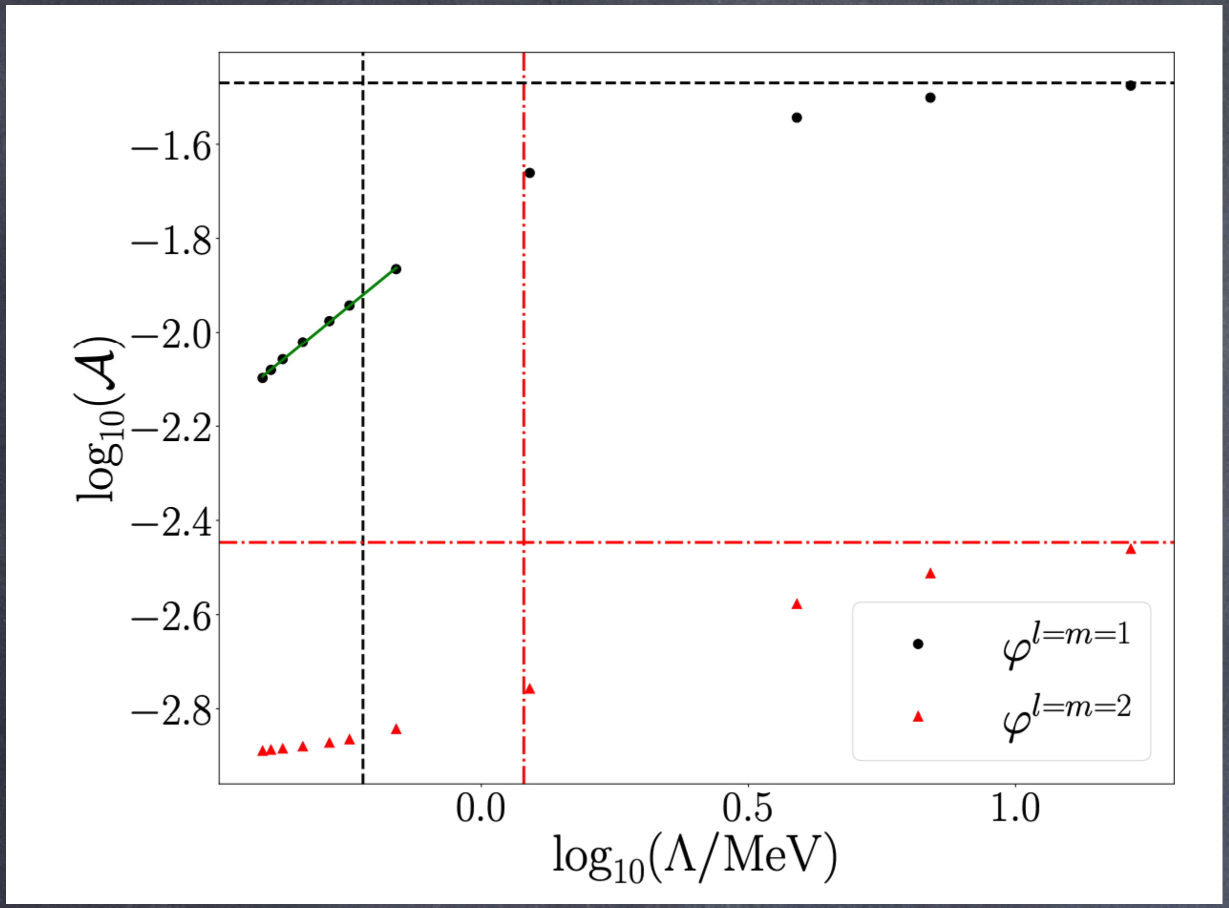


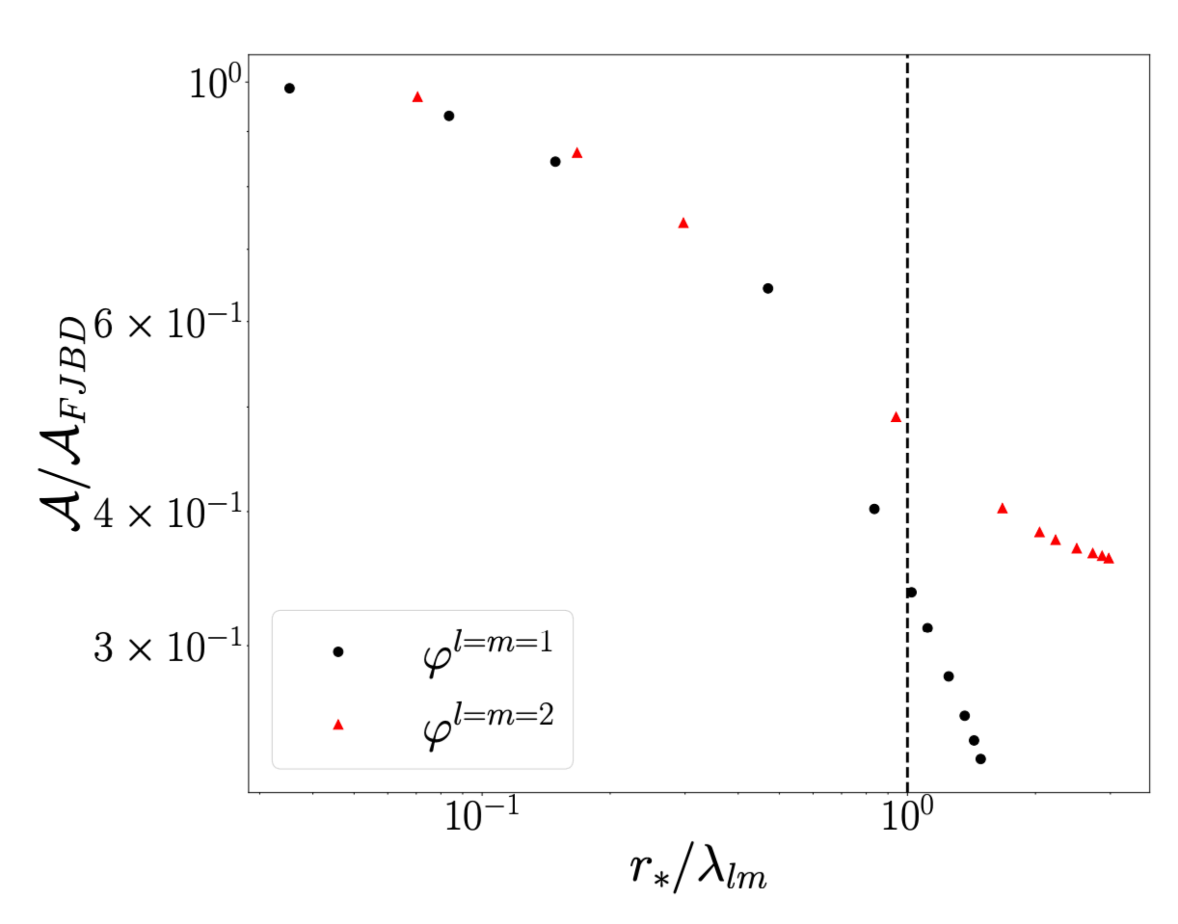
FIG. 4 – Dipole ($l = m = 1$) and quadrupole ($l = m = 2$) scalar strain for merging NS binaries of varying mass ratio, in k-essence and FJBD.

Bezares+2022

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

BH+neutron star systems





Cayuso+EB+24

- 3+1 simulations in decoupling limit (scalar dynamics only)
- Quadrupole screening suppressed wrt dipole
- Analytic solution for dipole but not for quadrupole...

$$\tilde{A}_{11\Omega} R_{11\Omega}(r) \simeq i e^{2i\pi/5} \frac{5^{3/20}}{\Gamma(7/10) 2^{17/10} 3^{1/2}} \frac{e^{i\Omega(r-0.56 r_*)}}{r} \times \frac{\alpha_{\rm NS} m_{\rm NS}}{M_{\rm P}} \frac{\Omega^{1/5}}{r_*^{4/5}} a \frac{m_{\rm BH}}{m_{\rm BH}+m_{\rm NS}}$$

Lessons for self-interacting Proca fields

$$S=\int d^4x\sqrt{-g}\left[\frac{M_{\rm P}^2}{2}R-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}\right.$$
$$\left.-\frac{1}{2}m^2A_\mu A^\mu+\lambda\left(A_\mu A^\mu\right)^2+\cdots\right]$$

- "Ghost" instabilities claimed in the literature
- Actually a Tricomi breakdown of Cauchy (EB, Bezares, Crisostomi & Lara 2022, Rubio+EB+2024), avoided by adding cubic terms or by fixing the equations

$$A_\mu\to A_\mu+\frac{1}{m}\nabla_\mu\phi$$
$$\nabla_\mu A^\mu=0.$$

$$S=\int d^4x\sqrt{-g}\left[\frac{M_{\rm P}^2}{2}R-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}\right.$$
$$\left.-\frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi+\frac{\lambda}{m^4}\left(\nabla_\mu\phi\nabla^\mu\phi\right)^2+\mathcal{O}\left(\frac{\nabla}{m}\right)^3\right]$$

at energies >> m

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

arXiv > hep-th > arXiv:1405.5213

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High Energy Physics – Theory

[Submitted on 20 May 2014 (v1), last revised 11 Nov 2014 (this version, v3)]

Riding on irrelevant operators

Claudia de Rham, Raquel H. Ribeiro

We investigate the stability of a class of derivative theories known as $P(X)$ and Galileons against corrections generated by quantum effects. We use an exact renormalisation group approach to argue that these theories are stable under quantum corrections at all loops in regions where the kinetic term is large compared to the strong coupling scale. This is the regime of interest for screening or Vainshtein mechanisms, and in inflationary models that rely on large kinetic terms. Next, we clarify the role played by the symmetries. While symmetries protect the form of the quantum corrections, theories equipped with more symmetries do not necessarily have a broader range of scales for which they are valid. We show this by deriving explicitly the regime of validity of the classical solutions for $P(X)$ theories including Dirac-Born-Infeld (DBI) models, both in generic and for specific background field configurations. Indeed, we find that despite the existence of an additional symmetry, the DBI effective field theory has a regime of validity similar to an arbitrary $P(X)$ theory. We explore the implications of our results for both early and late universe contexts. Conversely, when applied to static and spherical screening mechanisms, we deduce that the regime of validity of typical power-law $P(X)$ theories is much larger than that of DBI.

arXiv > astro-ph > arXiv:1607.01129

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Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 5 Jul 2016 (v1), last revised 7 Feb 2017 (this version, v2)]

The Quantum Field Theory of K-mouflage

Philippe Brax, Patrick Valageas

We consider K-mouflage models which are K-essence theories coupled to matter. We analyse their quantum properties and in particular the quantum corrections to the classical Lagrangian. We setup the renormalisation programme for these models and show that K-mouflage theories involve a recursive construction whereby each set of counter-terms introduces new divergent quantum contributions which in turn must be subtracted by new counter-terms. This tower of counter-terms can be constructed by recursion and allows one to calculate the finite renormalised action of the model. In particular, the classical action is not renormalised and the finite corrections to the renormalised action contain only higher derivative operators. We establish an operational criterion for classicality, where the corrections to the classical action are negligible, and show that this is satisfied in cosmological and astrophysical situations for (healthy) K-mouflage models which pass the solar system tests. We also find that these models are quantum stable around astrophysical and cosmological backgrounds. We then consider the possible embedding of the K-mouflage models in an Ultra-Violet completion. We find that the healthy models which pass the solar system tests all violate the positivity constraint which would follow from the unitarity of the putative UV completion, implying that these healthy K-mouflage theories have no UV completion. We then analyse their behaviour at high energy and we find that the classicality criterion is satisfied in the vicinity of a high energy collision implying that the classical K-mouflage theory can be applied in this context. Moreover, the classical description becomes more accurate as the energy increases, in a way compatible with the classicalisation concept.