

Gravitational waves beyond General Relativity

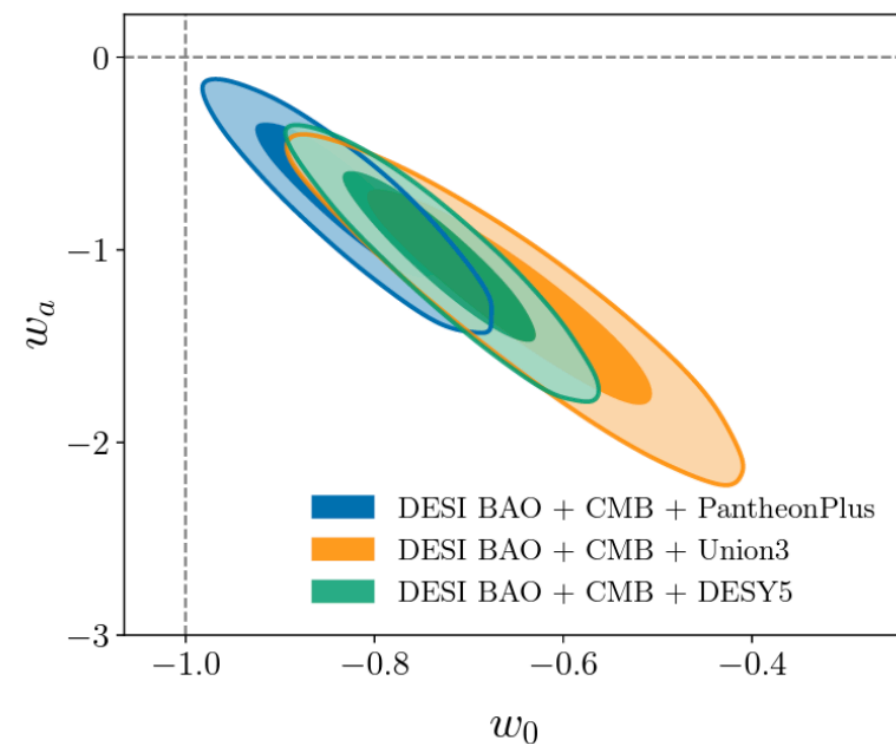
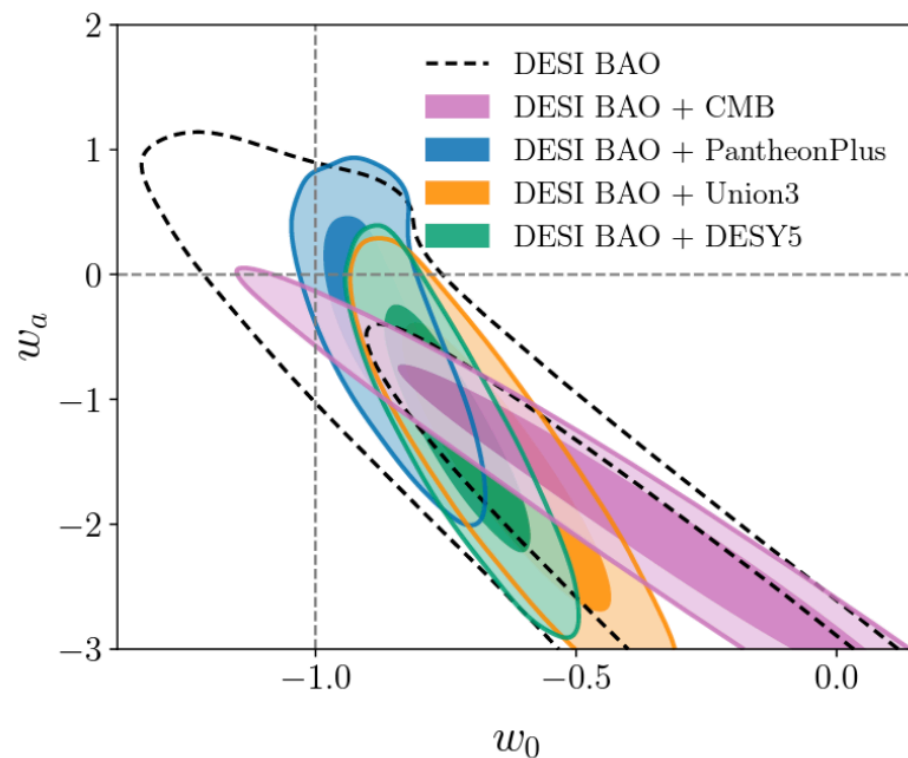
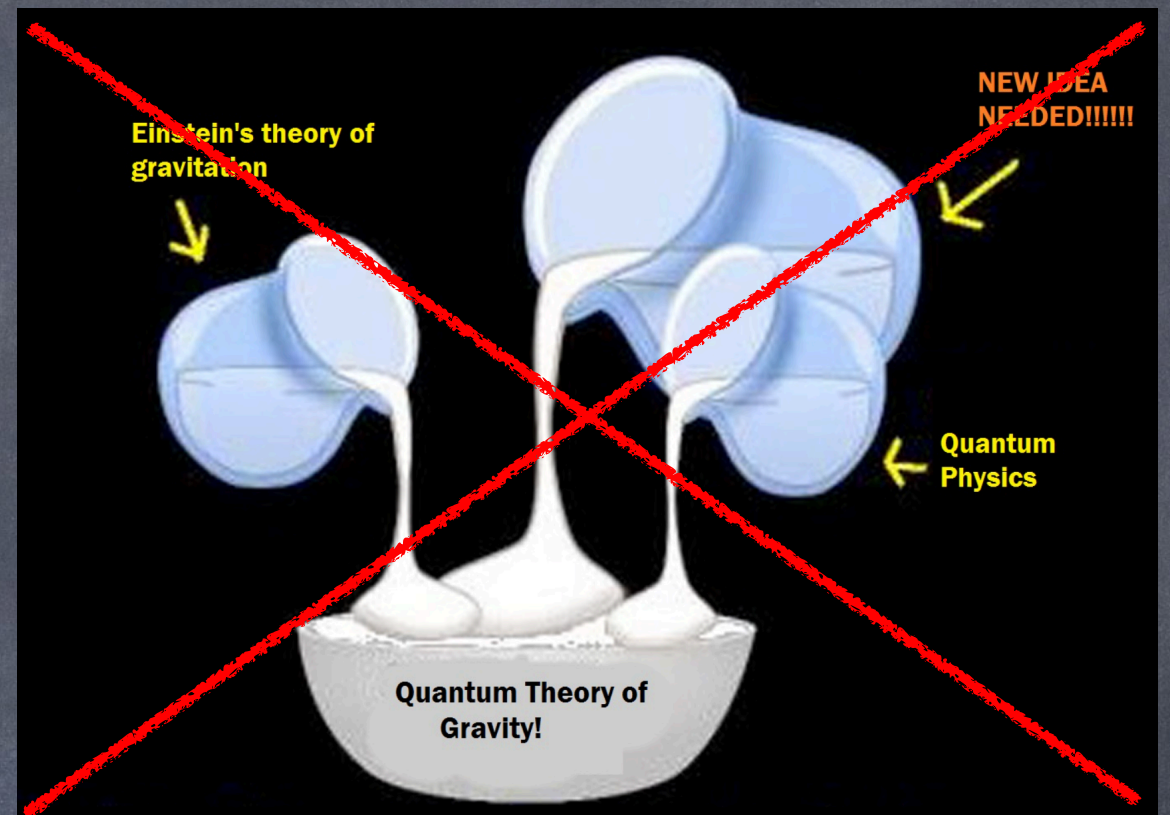
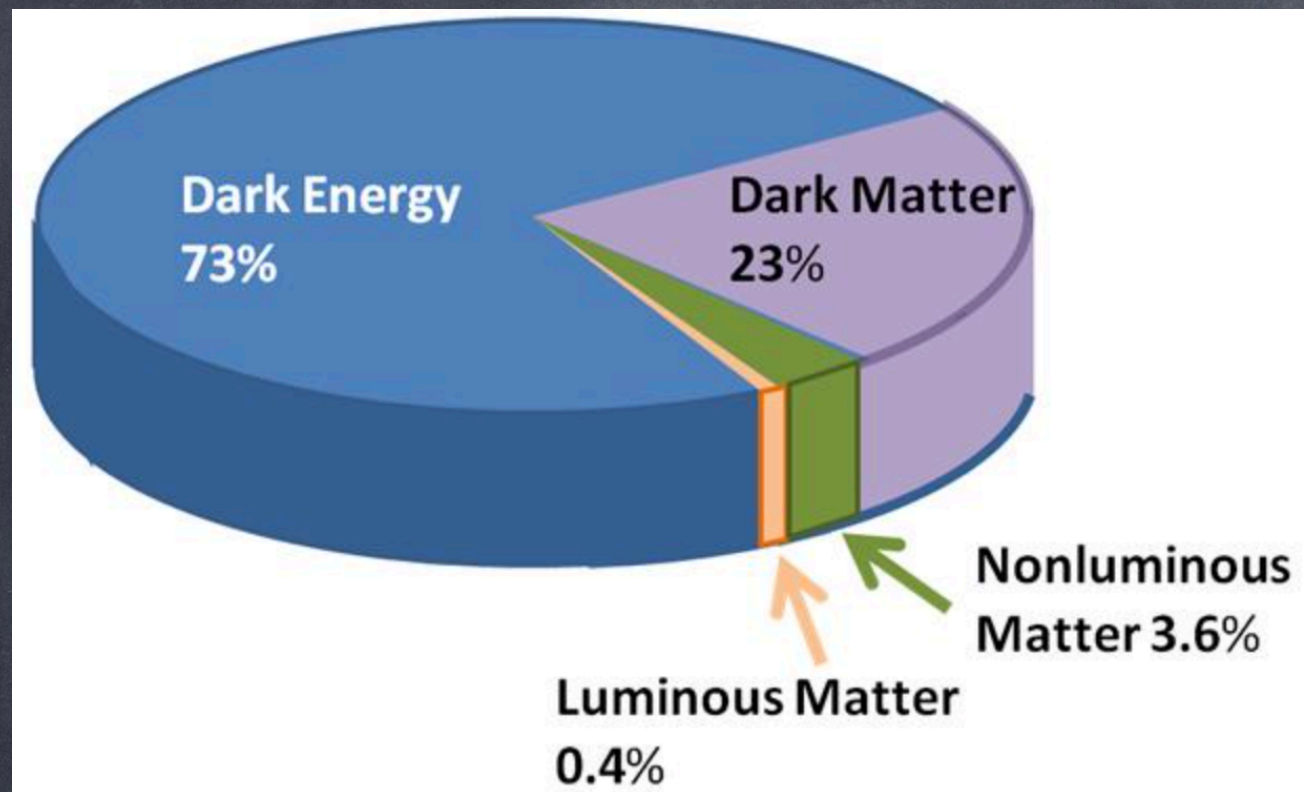
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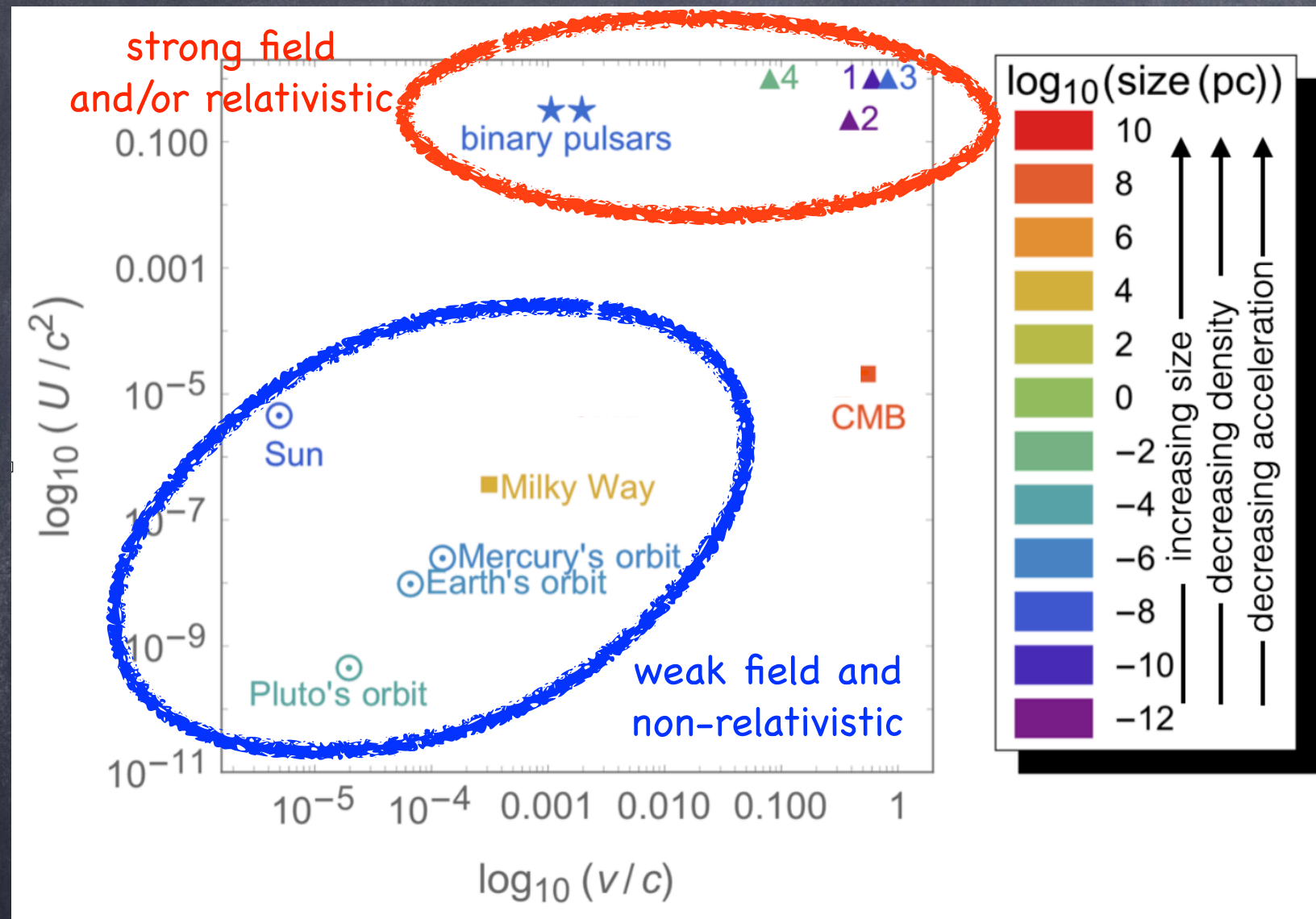
Talk plan

- 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
- Constraints on light fields

Beyond GR: why?



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 $a < a_0 \sim 10^{-10} \text{ m/s}^2$: need screening (if modified GR is to explain cosmology)

Motion of bodies beyond GR

- Non-GR gravitons must satisfy weak equivalence principle (no couplings to matter at tree level)

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

- Non-GR gravitons couple non-minimally to metric, so tensors mediate effective interaction between matter and non-GR gravitons in strong gravity regimes (strong equivalence principle violations)

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

$G_{\text{eff}} \propto G_N/\varphi$, but φ in which star is immersed depends on cosmology, presence of other star. Renormalization of binding energy and mass for strongly gravitating bodies

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

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 equations
- In GR, no monopole or dipole radiation because energy and linear momentum conservation is implied by Einstein equations

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

- In GR extensions, effective coupling of matter to non-GR fields in strong gravity regimes  energy and momentum transfer between bodies and non-GR fields, 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

EFTs of Dark Energy

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

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

- 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 with a possible conformal coupling to matter

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

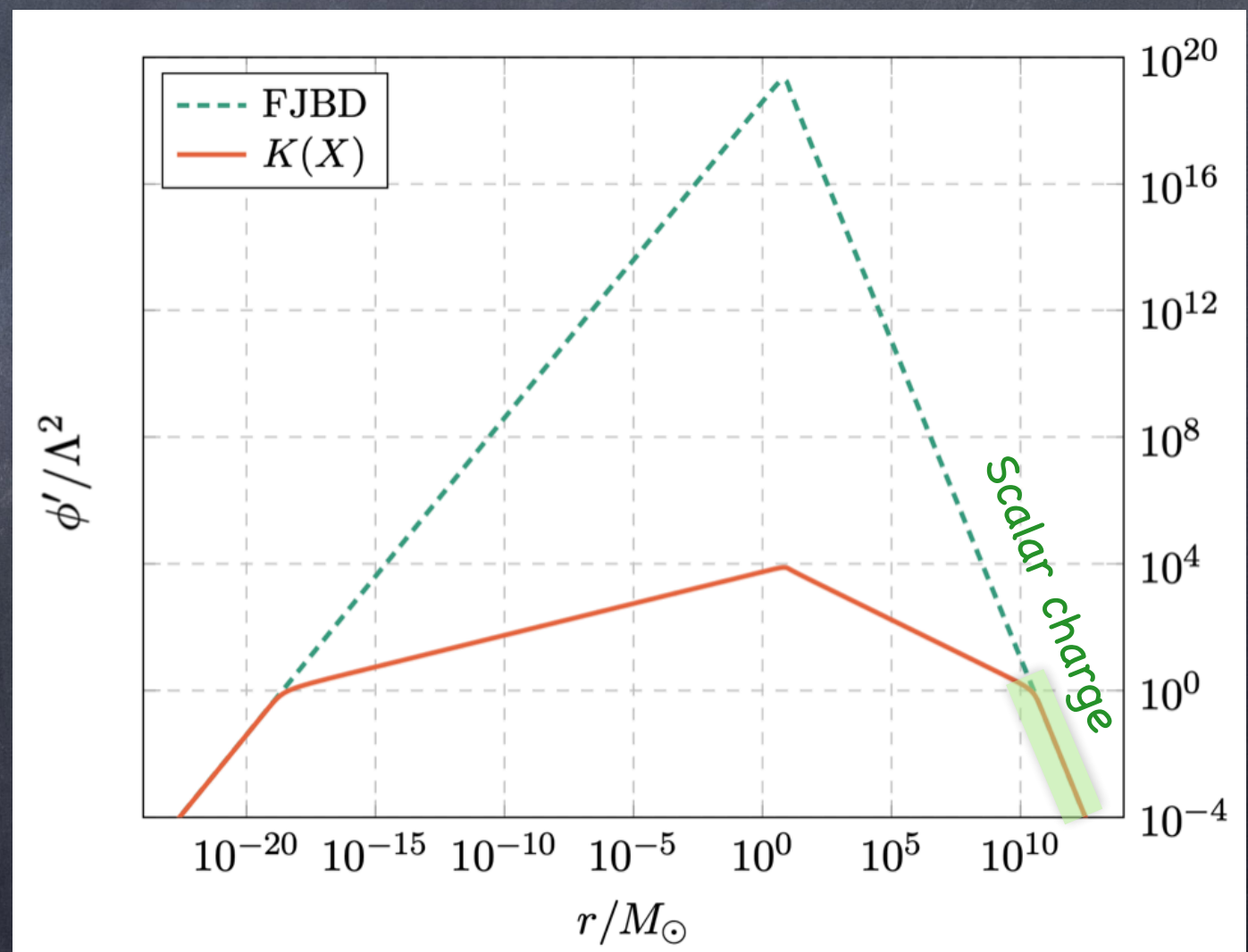
$$S = \int d^4x \sqrt{-g} \left[\frac{M_{\text{Pl}}^2}{2} R + K(X) \right] + S_m \left[e^{\alpha \phi / M_{\text{Pl}}} g_{\mu\nu}, \Psi \right]$$

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

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

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

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



The Cauchy problem in a nutshell

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

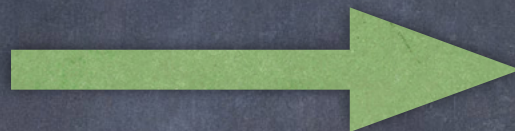
$$\gamma^{\mu\nu} \equiv g^{\mu\nu} + \frac{2K''(X)}{K'(X)} \nabla^\mu \phi \nabla^\nu \phi$$

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

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

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

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



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

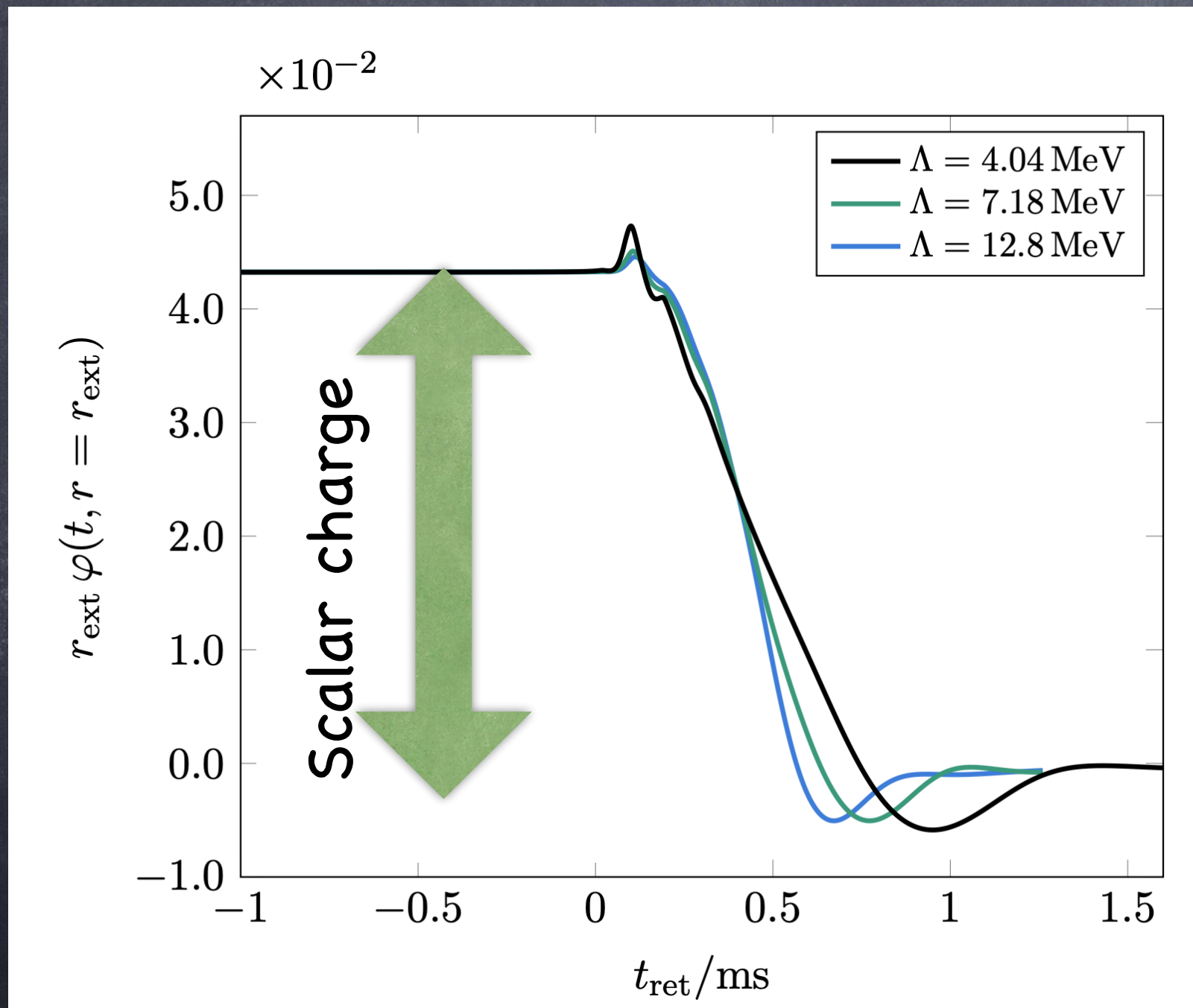
reduces to usual sound speed
in flat space

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

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

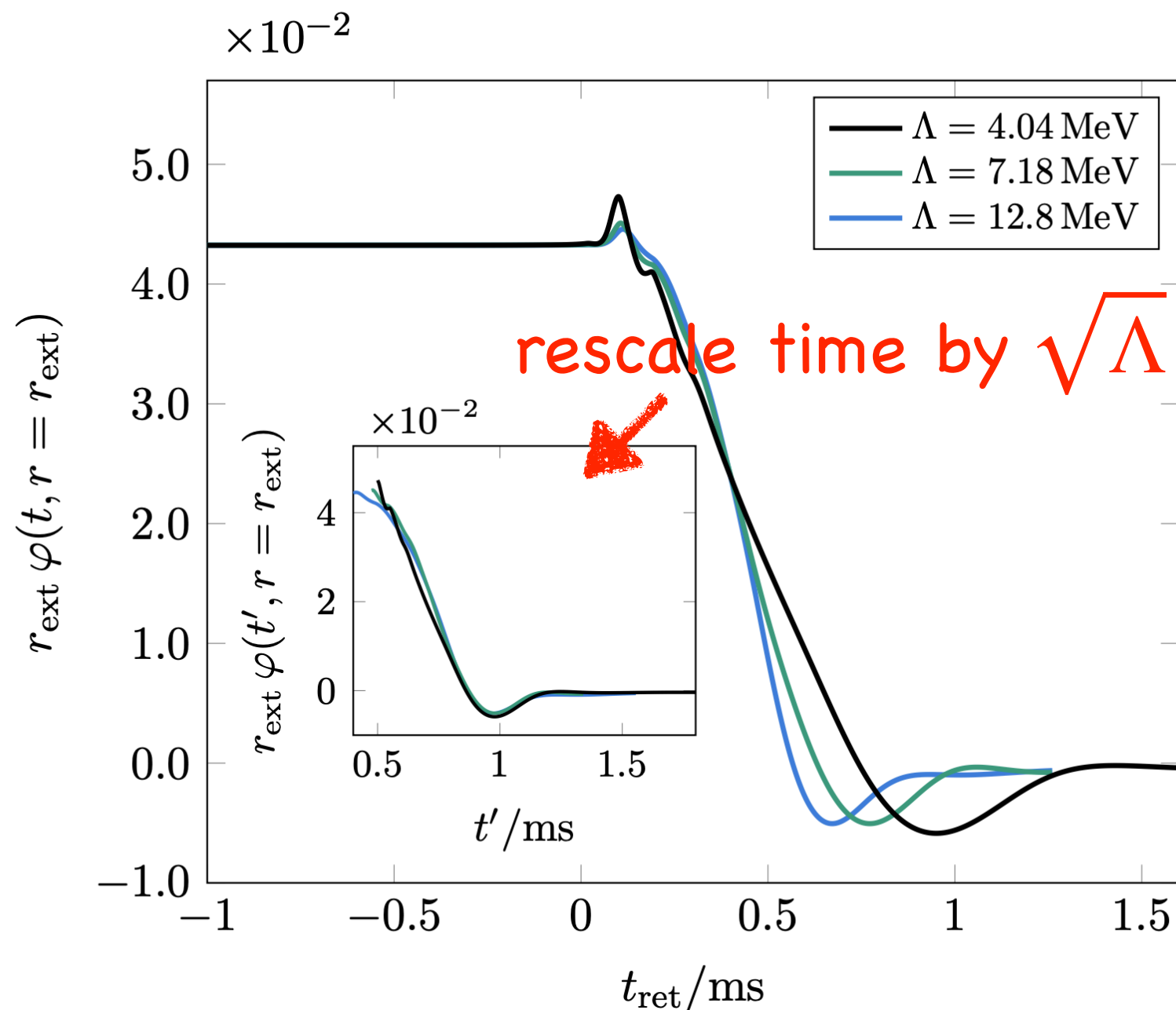
- If $\gamma^{\mu\nu}$ changes signature, system becomes parabolic/elliptic (Tricomi behavior): avoided if $K(X)$ includes X^3 (Bezares, Crisostomi, Palenzuela, EB 2020)
- When $\gamma^{tt} \rightarrow 0$ characteristic speeds diverge (Keldysh behaviour); avoided by “fixing the equations” (à la Cayuso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

Kinetic screening in dynamical settings: neutron star collapse



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

Kinetic screening in dynamical settings: neutron star collapse



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

Binary neutron star mergers

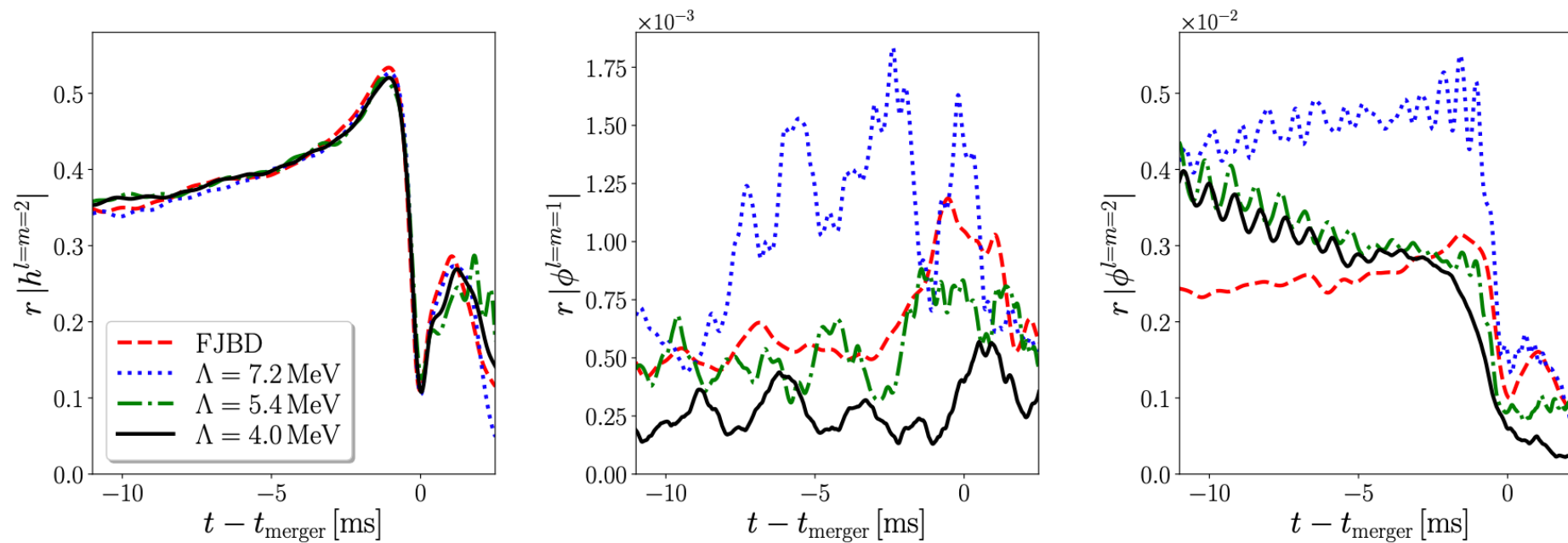


FIG. 3 – Tensor ($l = m = 2$) and scalar ($l = m = 1$ and $l = m = 2$) strain for a NS merger with $q = 0.91$, in k -essence and FJBD.

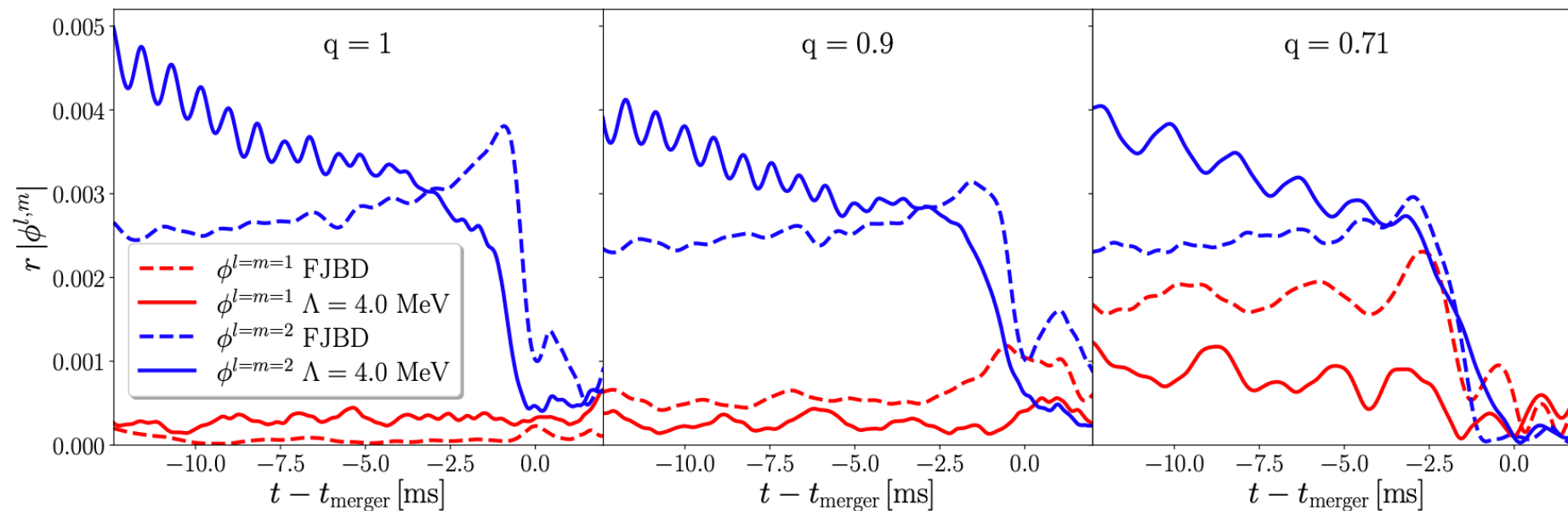
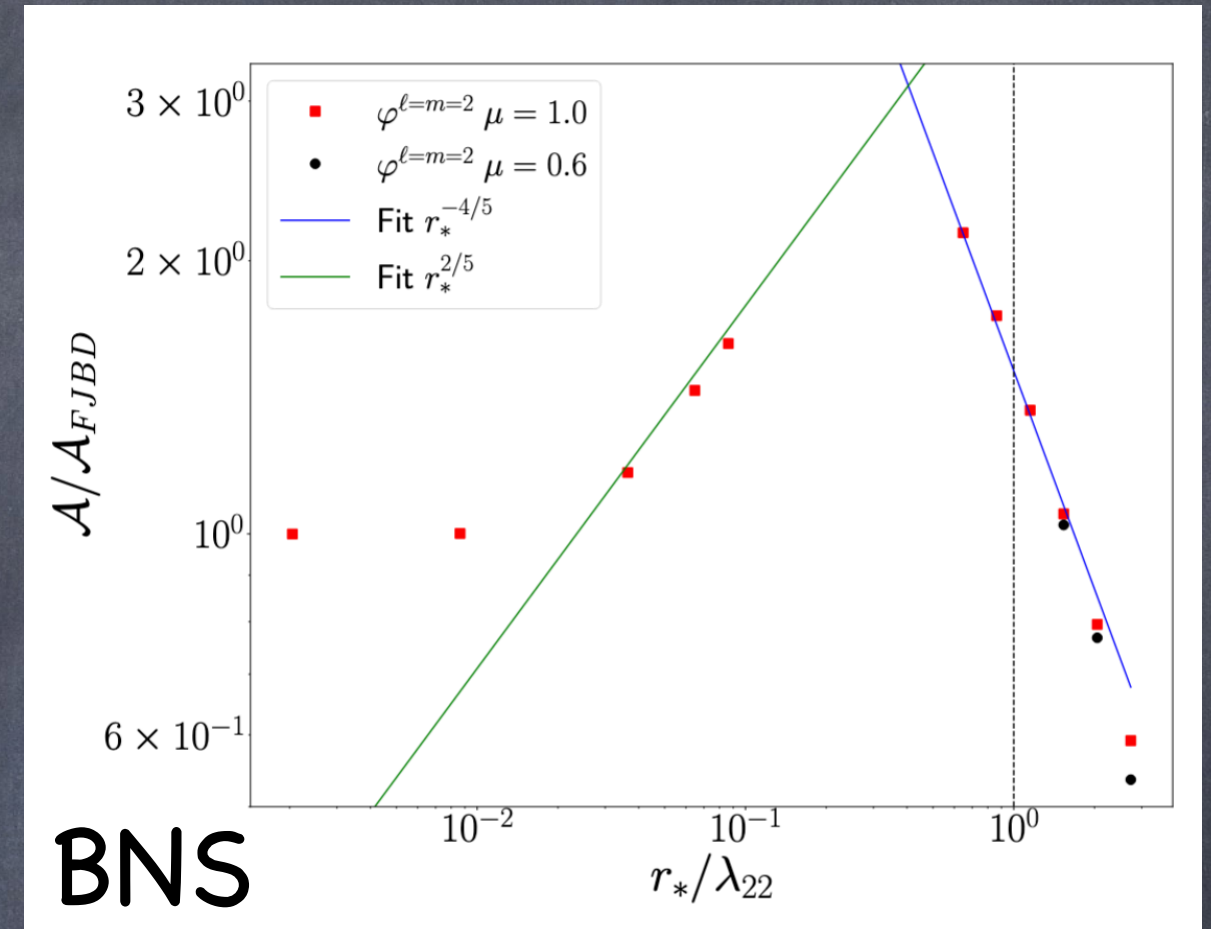
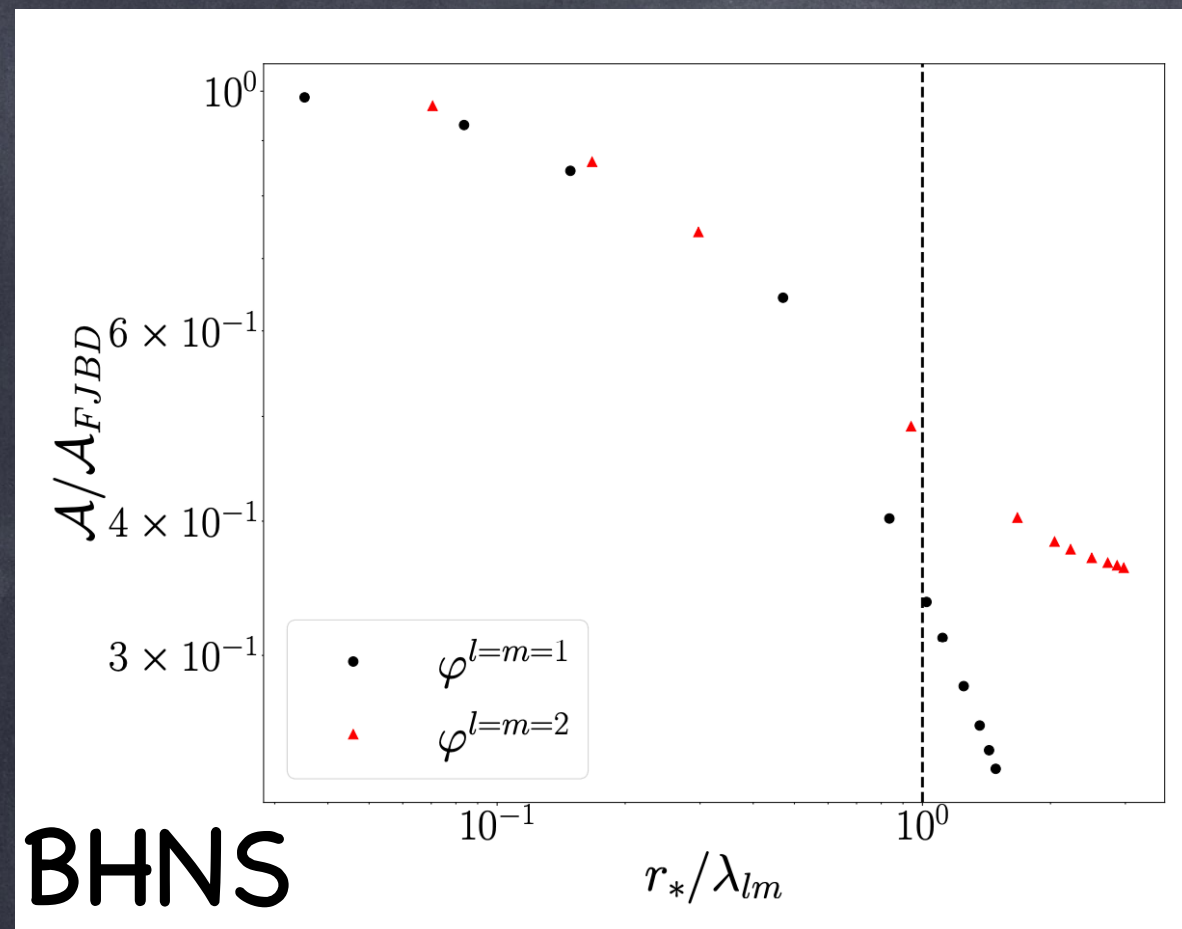


FIG. 4 – Dipole ($l = m = 1$) and quadrupole ($l = m = 2$) scalar strain for merging NS binaries of varying mass ratio, in k -essence and FJBD.

Bezares+2022

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

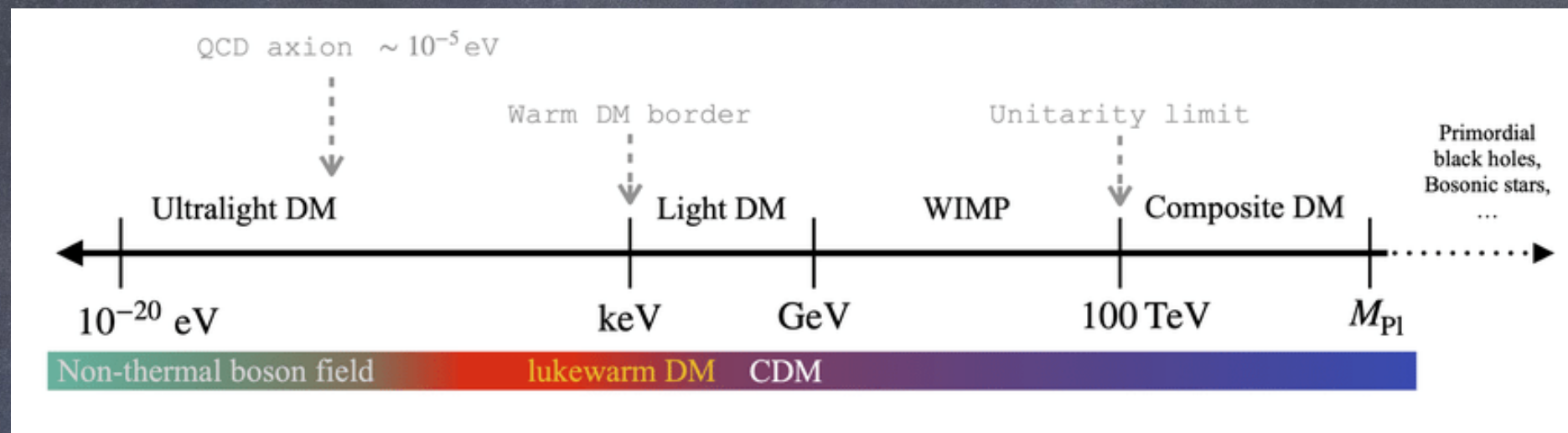
Binaries in decoupling limit



Cayuso+EB+24, 26

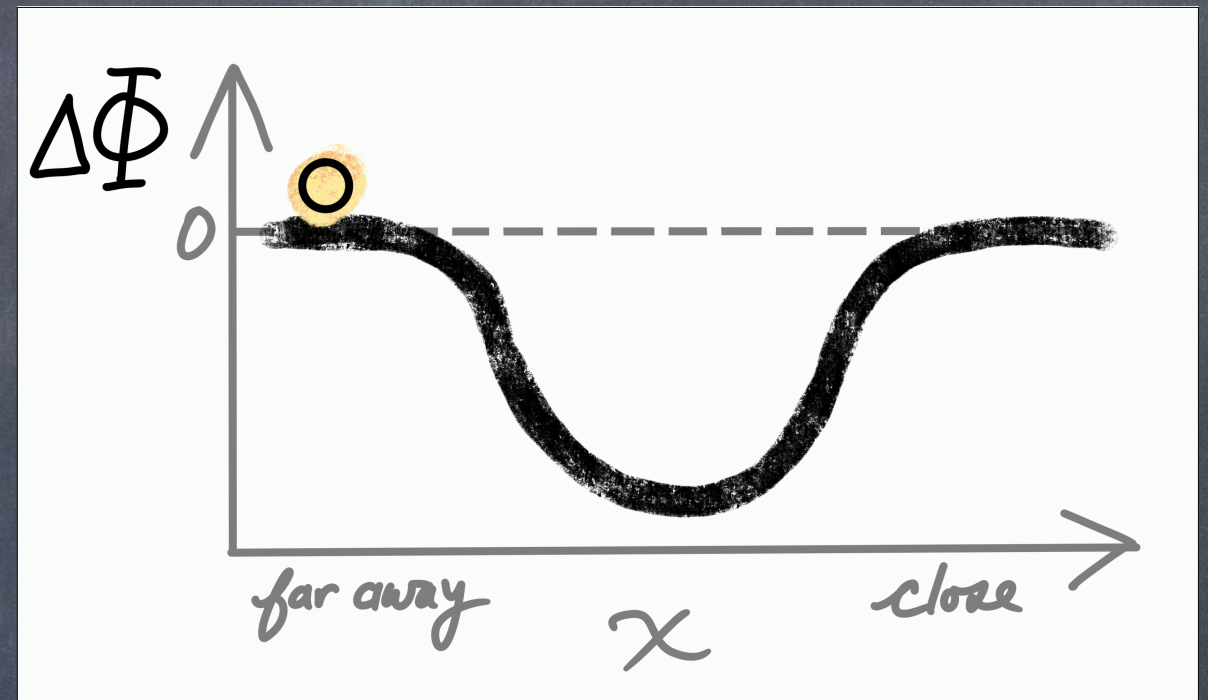
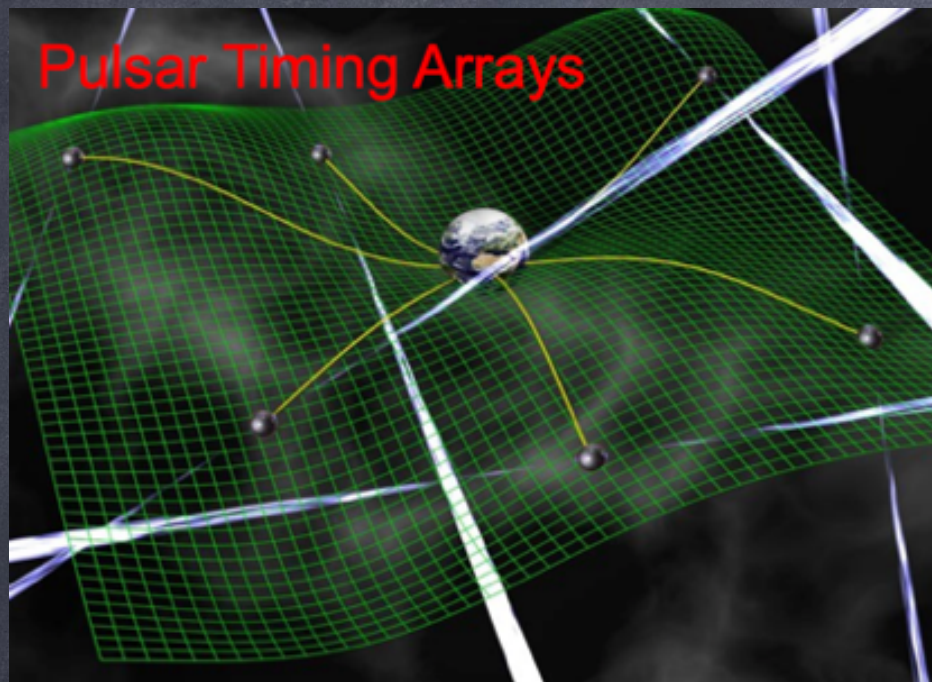
- 3+1 simulations with scalar dynamics only
- Dipole screened
- Quadrupole also screen but less so/non-monotonically
- Analytic solutions
- Screening may be imperfect for binary pulsars
(wavelength of $1e9$ km vs screening radius of $1e11$ km)

Ultralight boson fields



- Classical wave in galaxies due to high occupation numbers
- Recovers LCDM on large scales
- Solve small scale problems of CDM if mass is $1e-22$ eV

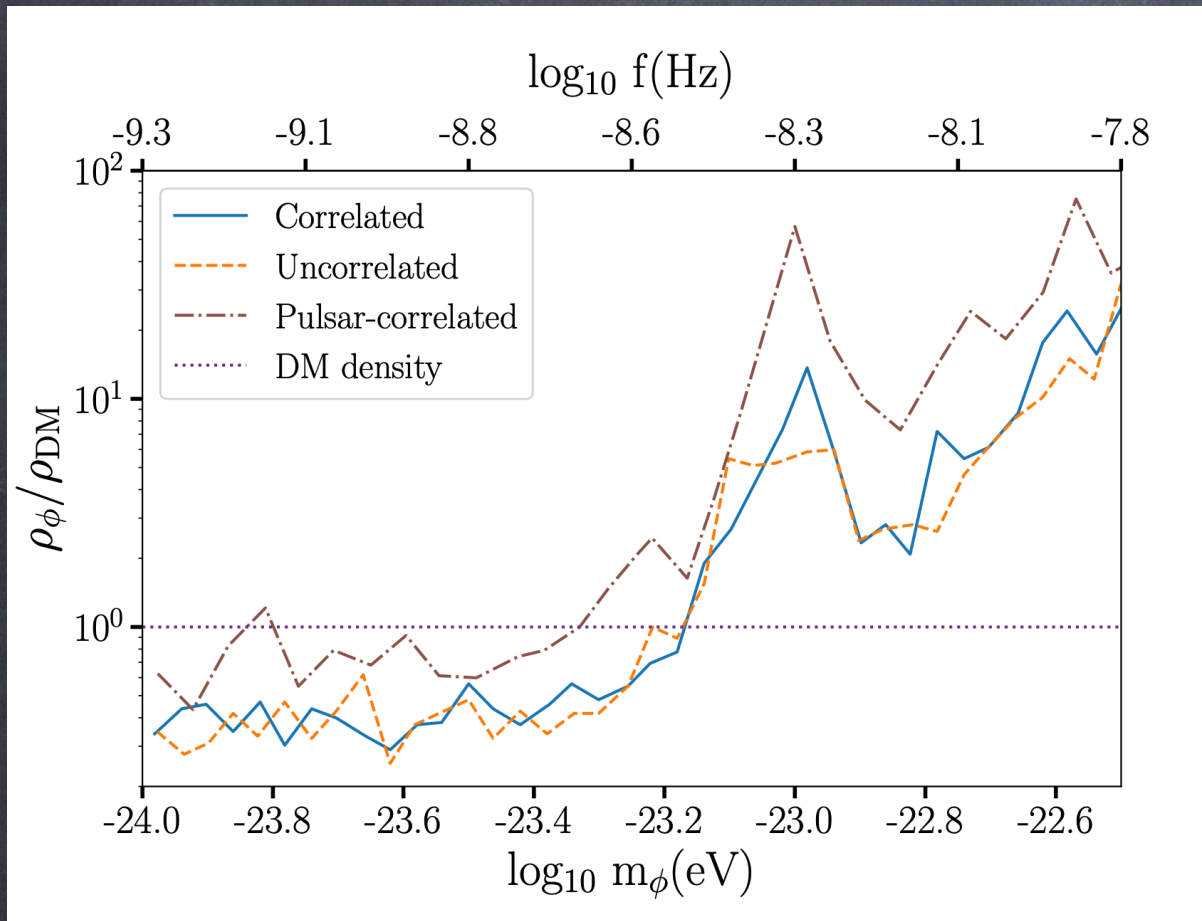
The Khmelnitsky-Rubakov effect



$$\square \phi = m^2 \phi \Rightarrow \phi \approx \frac{\sqrt{\rho}}{m M_p} \exp[i(mt + \gamma(x))]$$

- Boson field with mass m oscillates on timescale $1/m$ within the Galaxy
- $\nabla^2 U = 4\pi G \rho_\phi$: Newtonian potential also oscillates
- Photons redshifted/blueshifted (integrated Sachs-Wolfe effect)
- Mass $1e-22$ – $1e-23$ eV [$1/m=O(\text{yr})$]: detectable by PTAs

EPTA constraints on Khmelnitsky–Rubakov



- No coupling to matter (except through gravity)
- Need to model all other effects (including GW background)
- Ultralight DM cannot be 100% of DM below $1e^{-23.2}$ eV

Smarra+EB+ (EPTA) PRL 131, 171001 (2023)

$$\ell_c \simeq \frac{2\pi}{m_\phi v_\phi} \sim 0.4 \text{ kpc} \left(\frac{10^{-22} \text{ eV}}{m_\phi} \right),$$

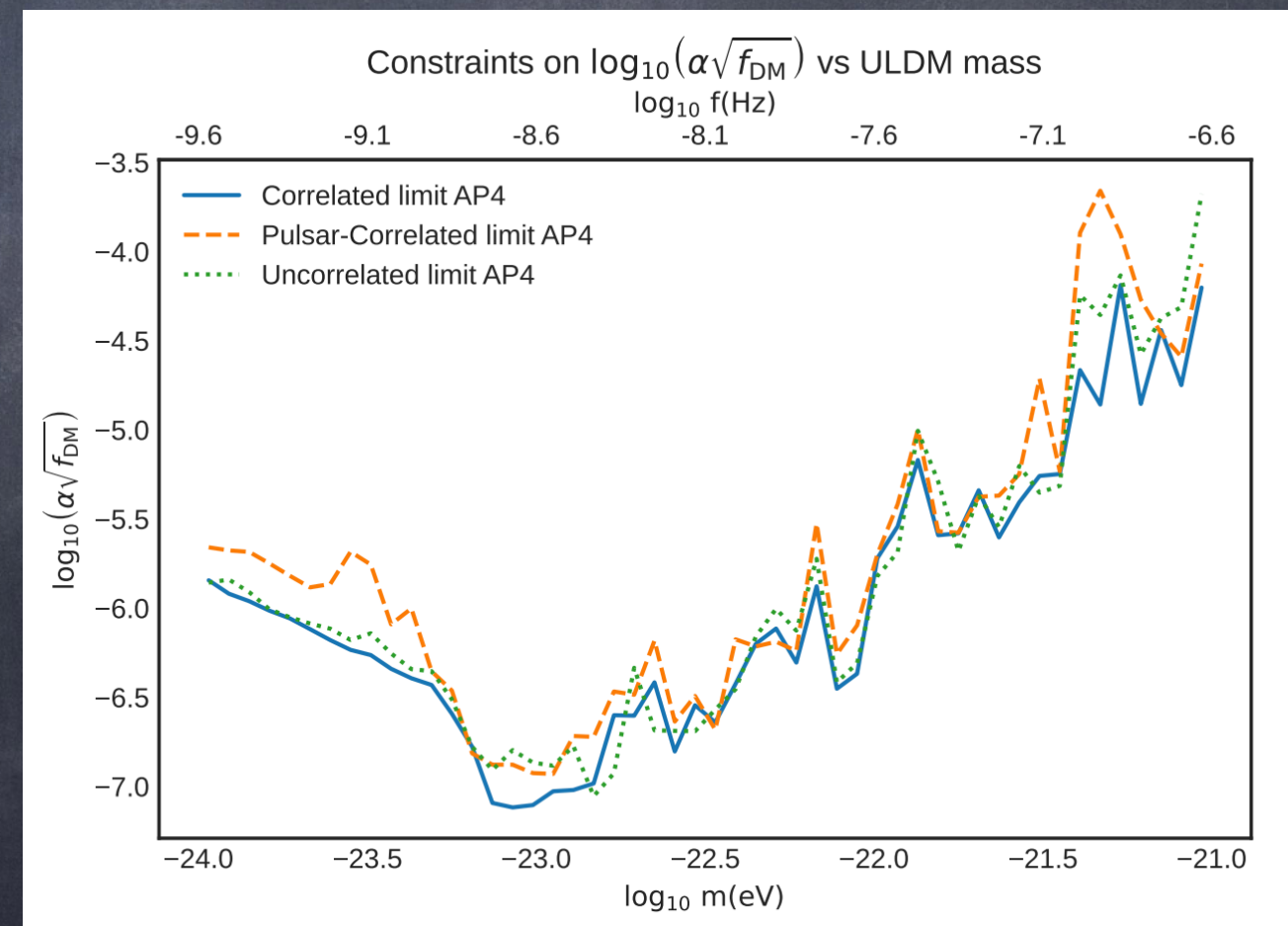
$$\delta t_{\text{DM}} = \frac{\Psi_c(\vec{x})}{2m_\phi} \left[\hat{\phi}_E^2 \sin(2m_\phi t + \gamma_E) - \hat{\phi}_P^2 \sin(2m_\phi t + \gamma_P) \right]$$

Universal (conformal) coupling to SM

$$S = M_{\text{P}}^2 \int d^4x \sqrt{-g} \left(\frac{R}{2} - g^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi \right) + S_m[\psi_m, \tilde{g}_{\mu\nu}] \quad \tilde{g}_{\mu\nu} = A^2(\varphi) g_{\mu\nu}$$

$$S = M_{\text{P}}^2 \int d^4x \sqrt{-\tilde{g}} A^{-2}(\varphi) \left[\frac{\tilde{R}}{2} - (1 - 3\alpha^2(\varphi)) \tilde{g}^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi \right] + S_m[\psi_m, \tilde{g}_{\mu\nu}] \quad \alpha(\varphi) = A'(\varphi)/A(\varphi)$$

- Pulsar moment of inertia and rotational velocity change if local scalar field changes: $\omega = S/I(\varphi)$
- Scalar field oscillations on timescale $1/m$
- Constraints with EPTA (Kuntz & EB 24, Smarra, Kuntz, EB+24): more stringent than Solar system/ neutron star binaries

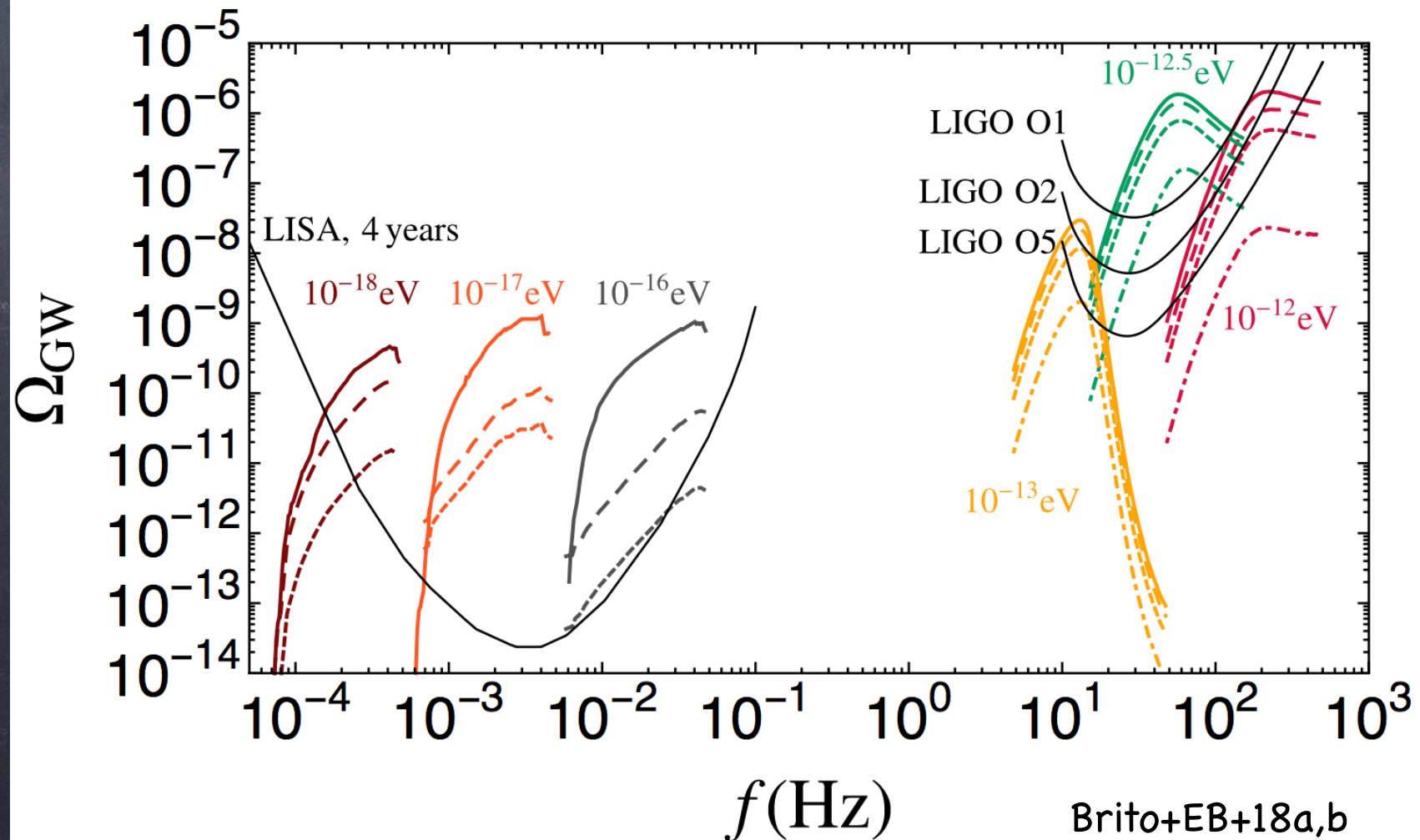
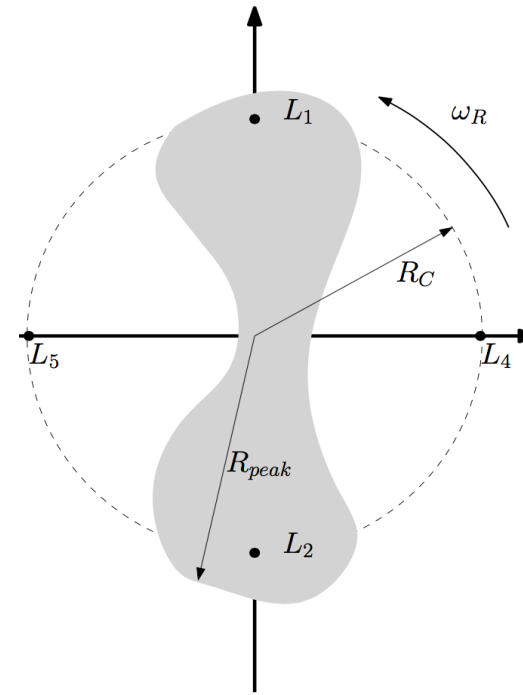
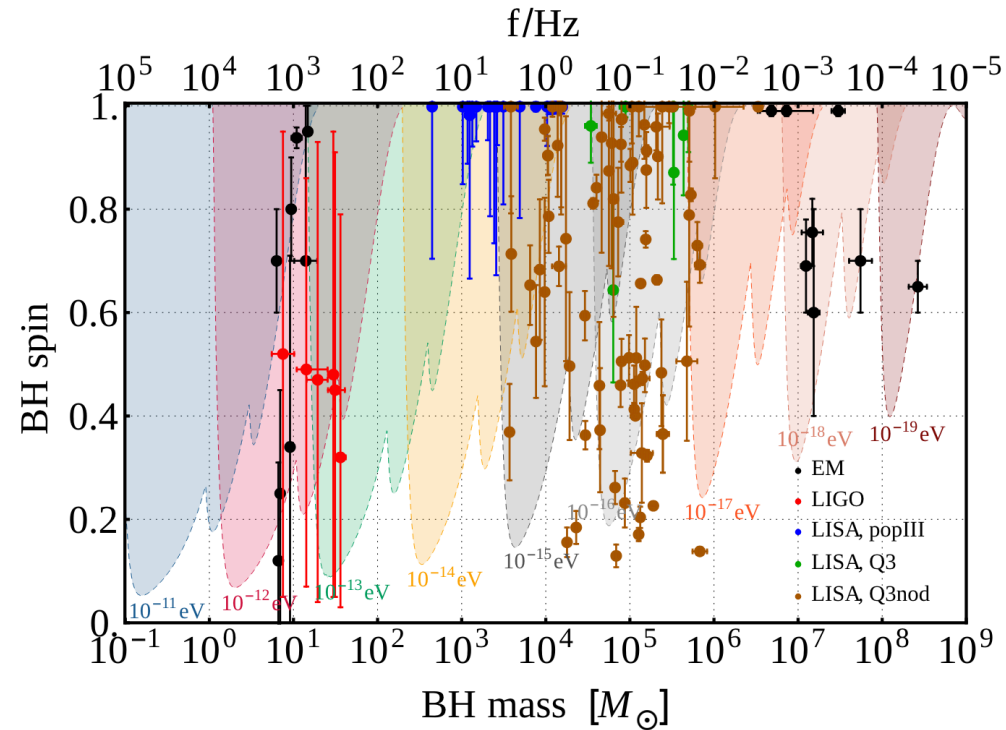


BH+boson condensates

- Isolated spinning BH + light scalar fields with Compton wavelength comparable to event horizon radius are unstable under super-radiance
- Mass and (mostly) angular momentum are transferred from BH to scalar condensate surrounding BH on instability timescale; condensate then emits almost monochromatic waves on timescale
- Observable by LVK/LISA as stochastic background and resolved sources; effect on EMRIs, etc

$$\tau_{\text{inst}} \sim 0.07 \chi^{-1} \left(\frac{M}{10 M_{\odot}} \right) \left(\frac{0.1}{M_{\mu}} \right)^9 \text{ yr},$$

$$\tau_{\text{GW}} \sim 6 \times 10^4 \chi^{-1} \left(\frac{M}{10 M_{\odot}} \right) \left(\frac{0.1}{M_{\mu}} \right)^{15} \text{ yr}.$$



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 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
- Bounds on ultralight boson fields from PTAs/LVK/LISA

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.

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.