GW generation in dark energy EFTs

Marco Crisostomi

SISSA

European Research Council
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GWs meet EFTs
Benasque 23/08/23

Based on:

arXiv:2008.07546 (JCAP)

arXiv:2009.03354 (PRL)

arXiv:2105.13992 (PRD)

arXiv:2107.05648 (PRL)

arXiv:2207.00443 (JCAP)

arXiv:2207.03437 (PRD)


Enrico Barausse


Miguel Bezares

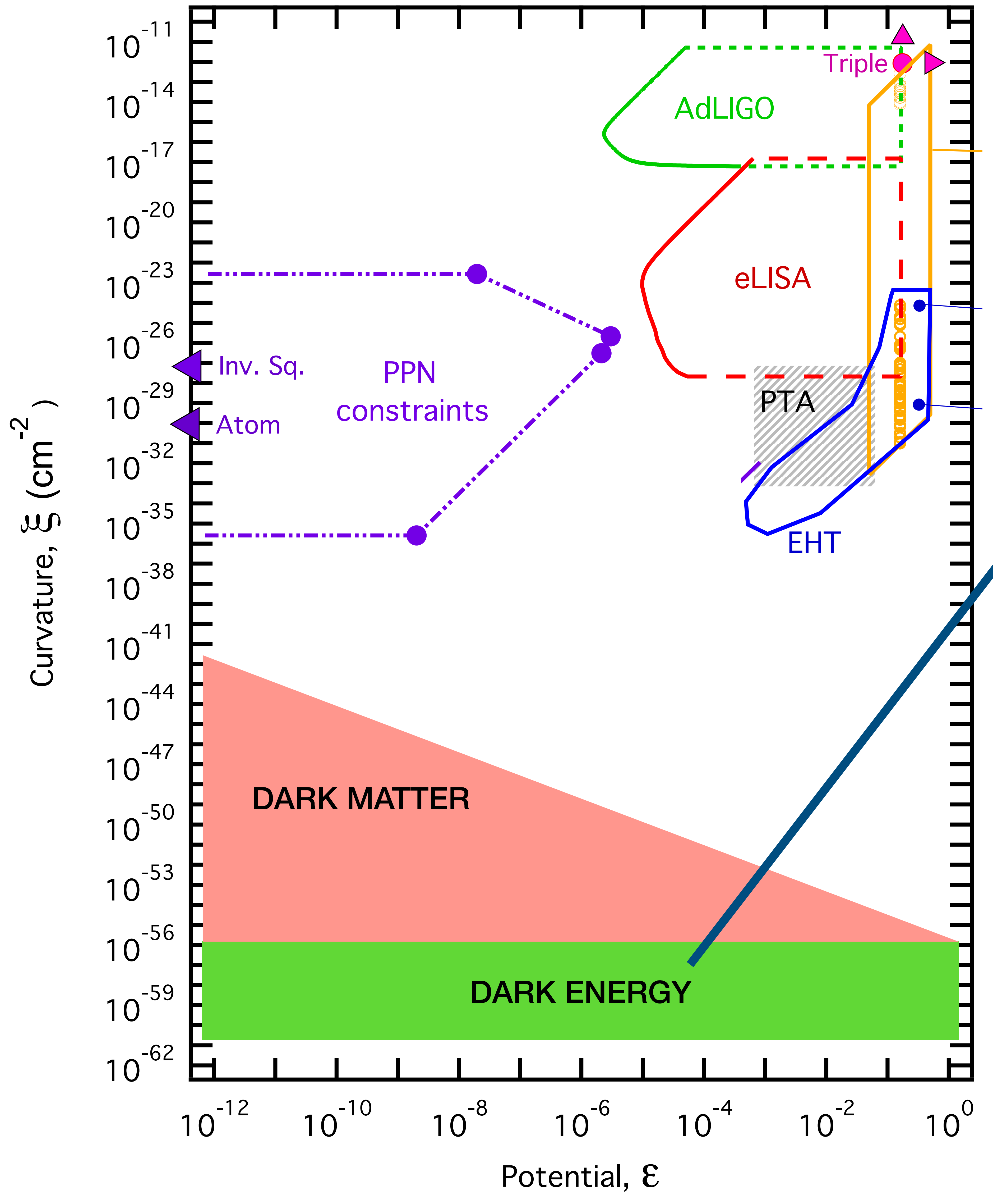

Lotte ter Haar


Carlos Palenzuela


Guillermo Lara


Ricard Aguilera-Miret

Tests of Gravity

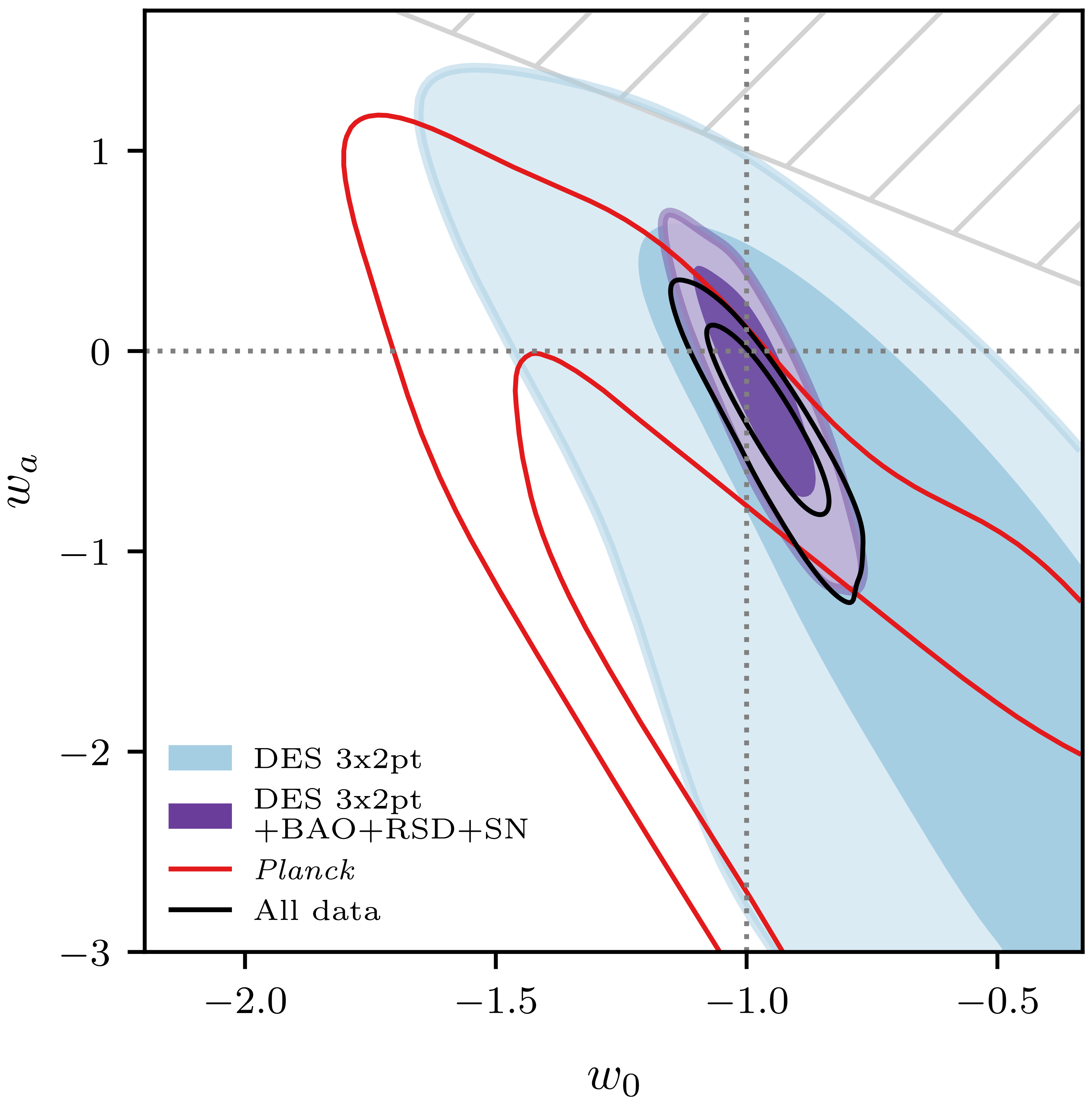


Baker, Psaltis, Skordis '15

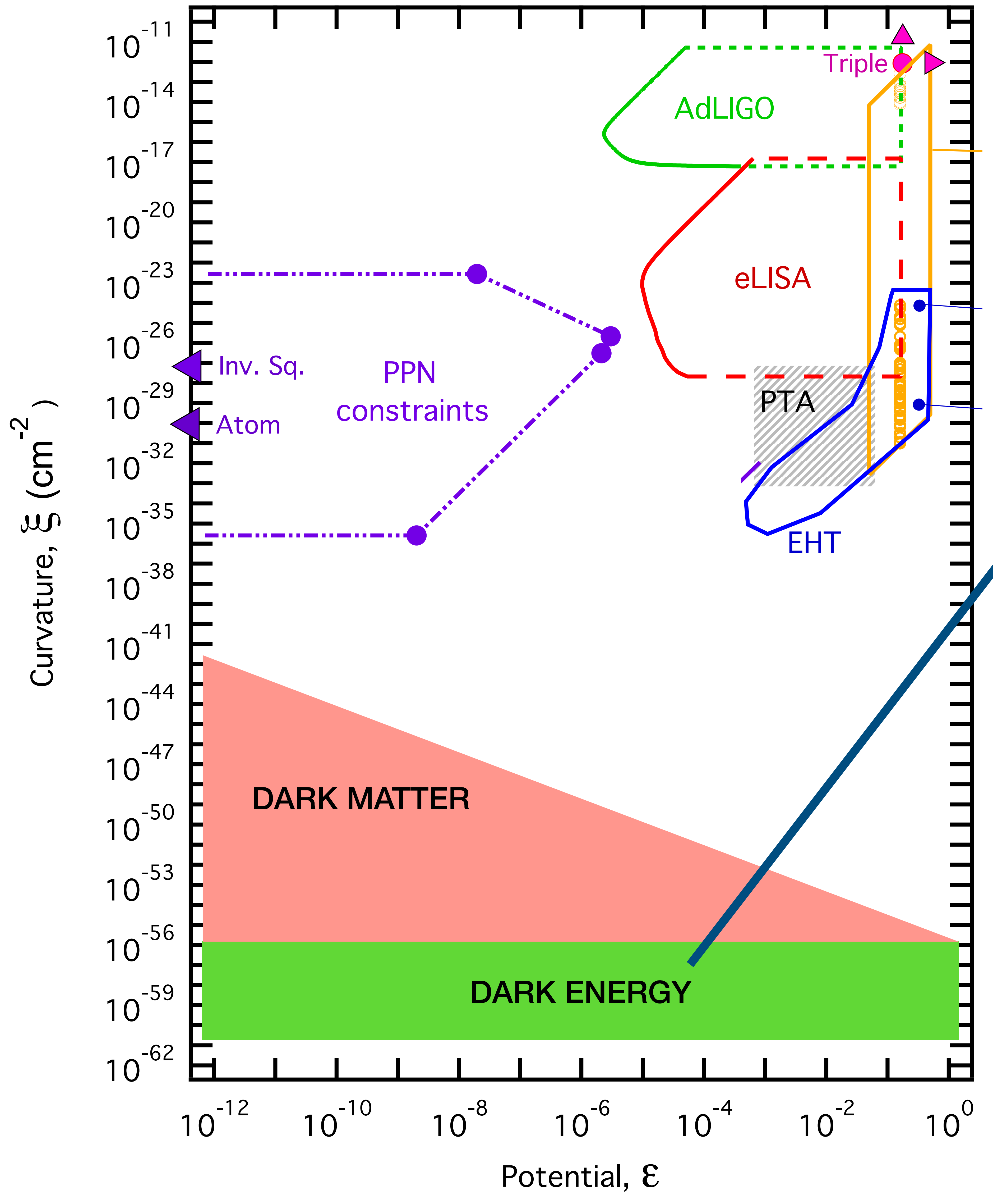
EUCLID
DESI
SKA
Vera Rubin Obs. (LSST)

$$w_{DE}(a) = w_0 + w_a(1-a)$$

Dark Energy Survey
Year 3 Results



Tests of Gravity



Baker, Psaltis, Skordis '15

EUCLID
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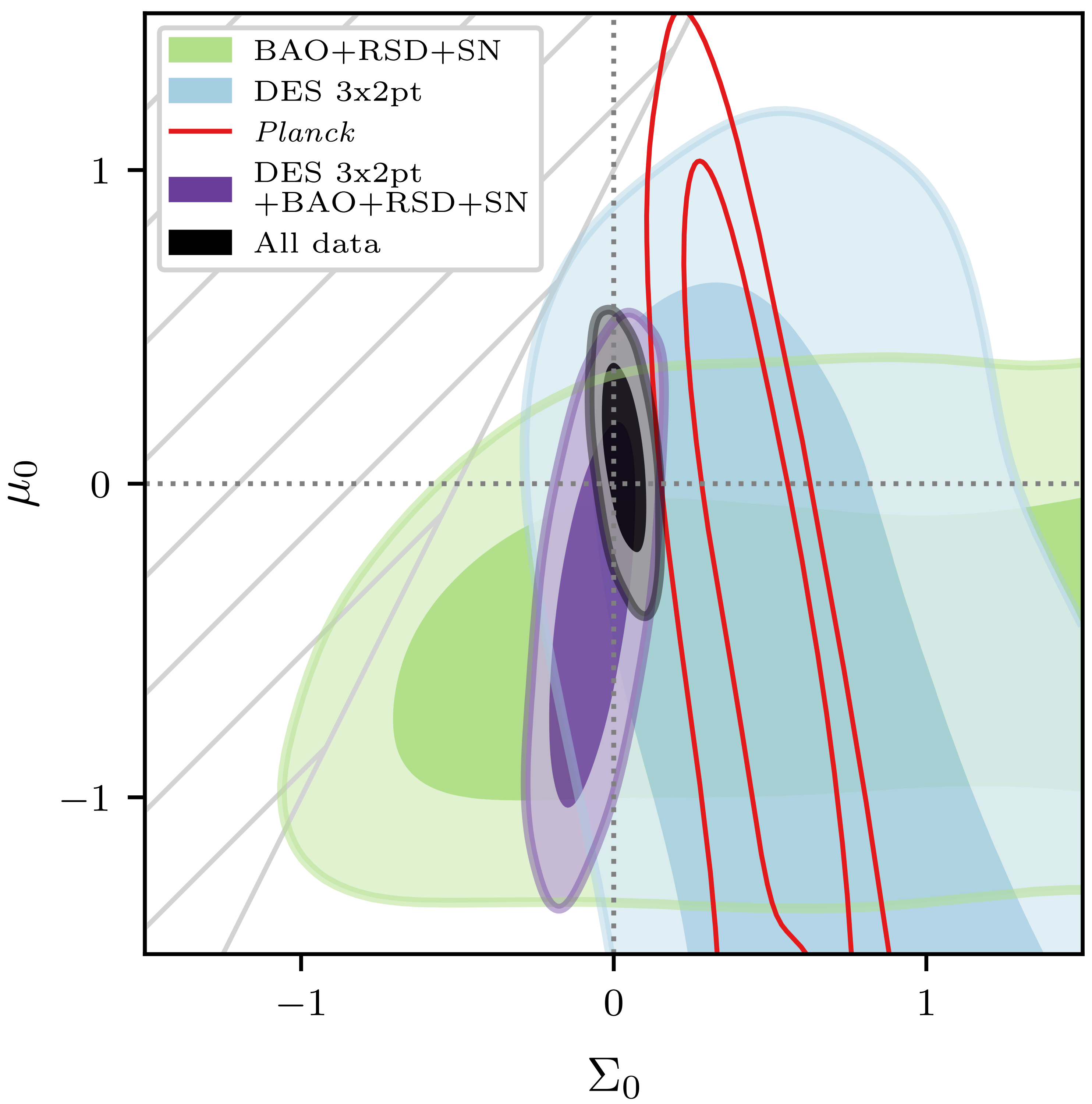
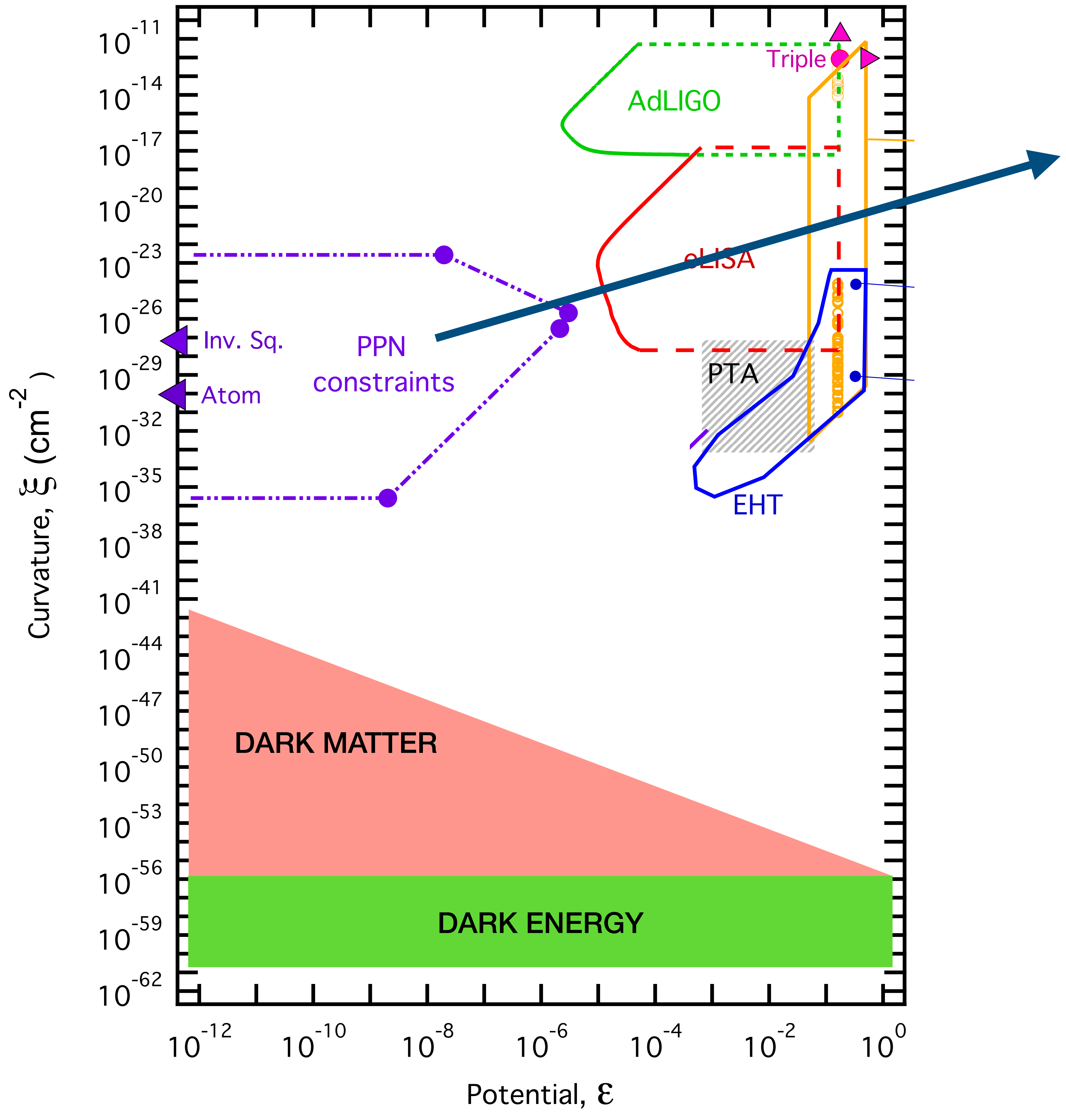
$$k^2\Psi = -4\pi G a^2(1+\mu(a))\rho\delta$$
$$k^2(\Psi+\Phi) = -8\pi G a^2(1+\Sigma(a))\rho\delta$$

Dark Energy Survey

Year 3 Results



Tests of Gravity

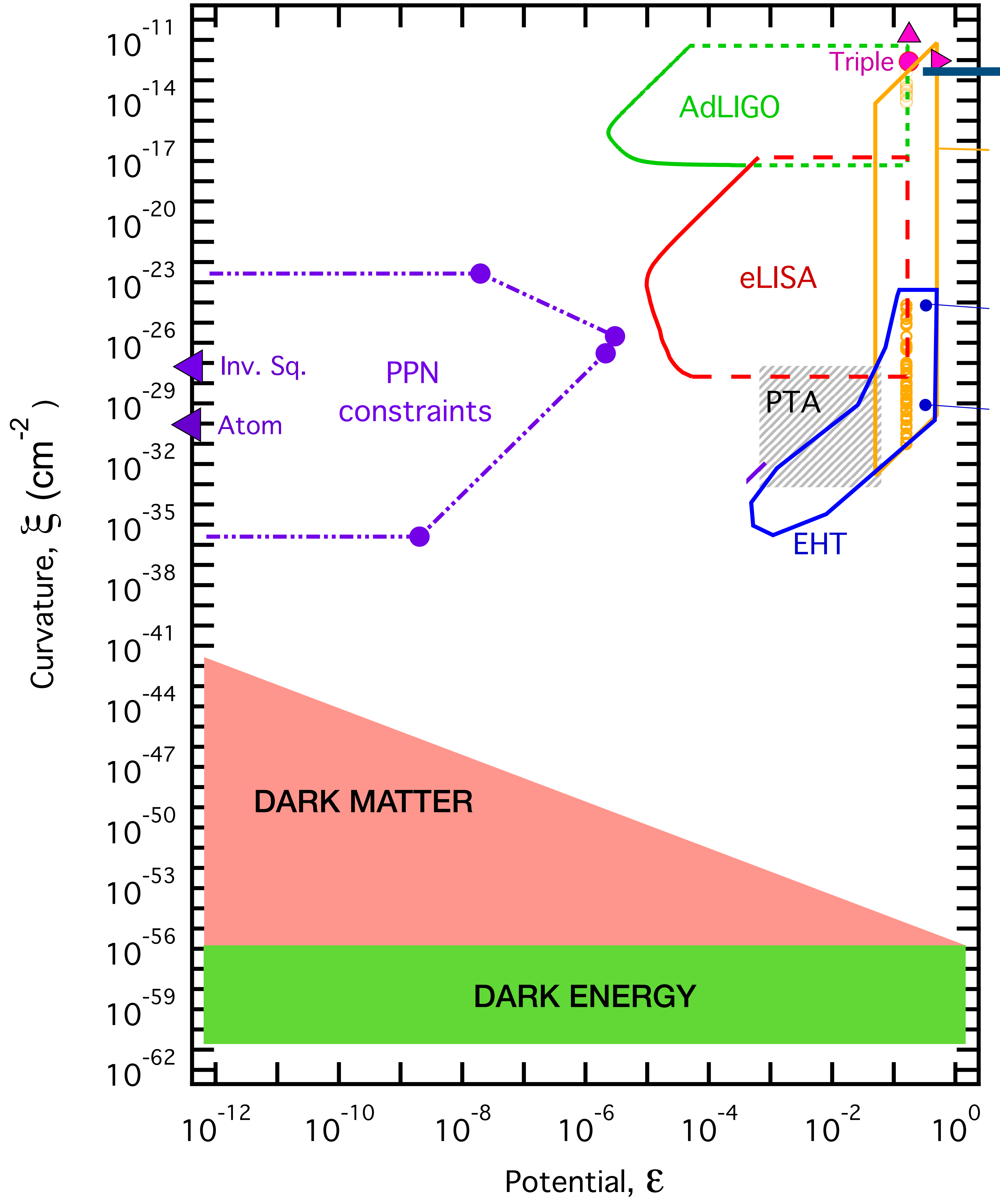


Baker, Psaltis, Skordis '15

Parameter	Effect	Limit	Remarks
$\gamma - 1$	time delay	2.3×10^{-5}	Cassini tracking
	light deflection	2×10^{-4}	VLBI
$\beta - 1$	perihelion shift	8×10^{-5}	$J_{2\odot} = (2.2 \pm 0.1) \times 10^{-7}$
	Nordtvedt effect	2.3×10^{-4}	$\eta_N = 4\beta - \gamma - 3$ assumed
ξ	spin precession	4×10^{-9}	millisecond pulsars
α_1	orbital polarization	10^{-4}	Lunar laser ranging
		4×10^{-5}	PSR J1738+0333
α_2	spin precession	2×10^{-9}	millisecond pulsars
α_3	pulsar acceleration	4×10^{-20}	pulsar $\dot{P}$ statistics
ζ_1	—	2×10^{-2}	combined PPN bounds
ζ_2	binary acceleration	4×10^{-5}	$\ddot{P}_p$ for PSR 1913+16
ζ_3	Newton's 3rd law	10^{-8}	lunar acceleration
ζ_4	—	—	not independent [see Eq. (73)]

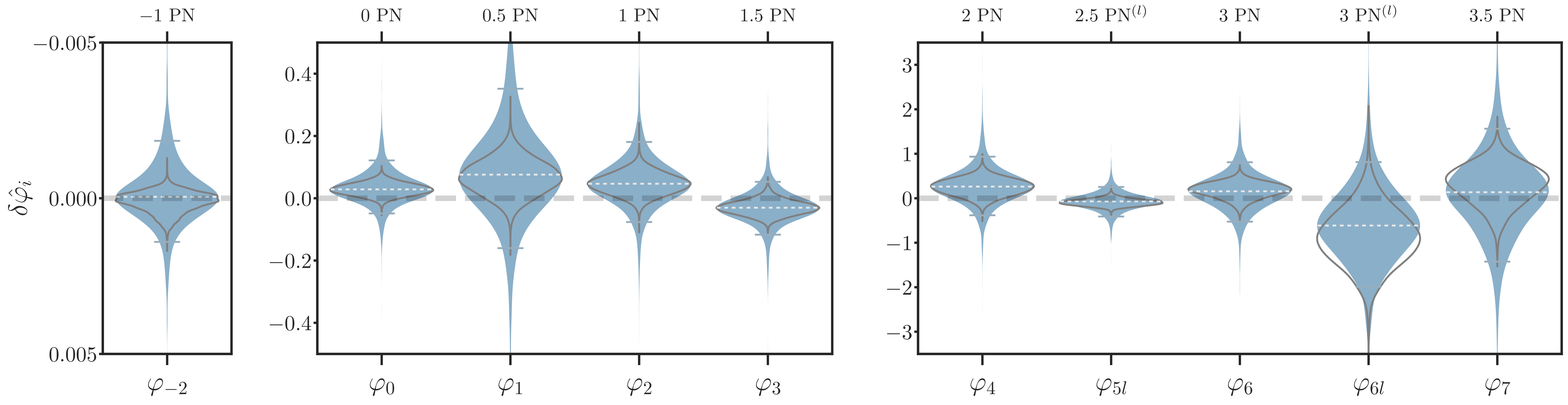
C. Will LLR '14

Tests of Gravity



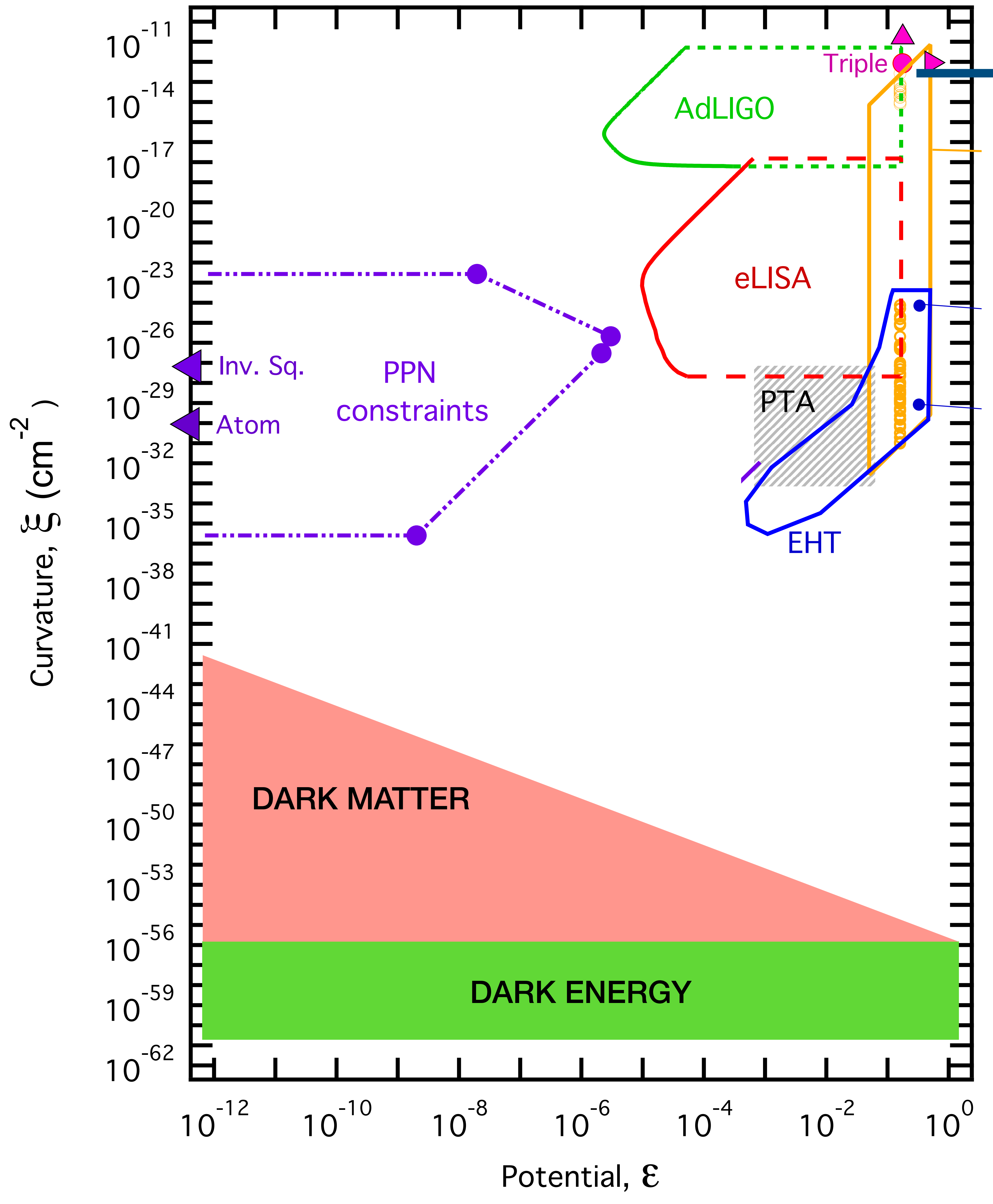
~ 65 BBH detected

LIGO/Virgo Dec. '21



Baker, Psaltis, Skordis '15

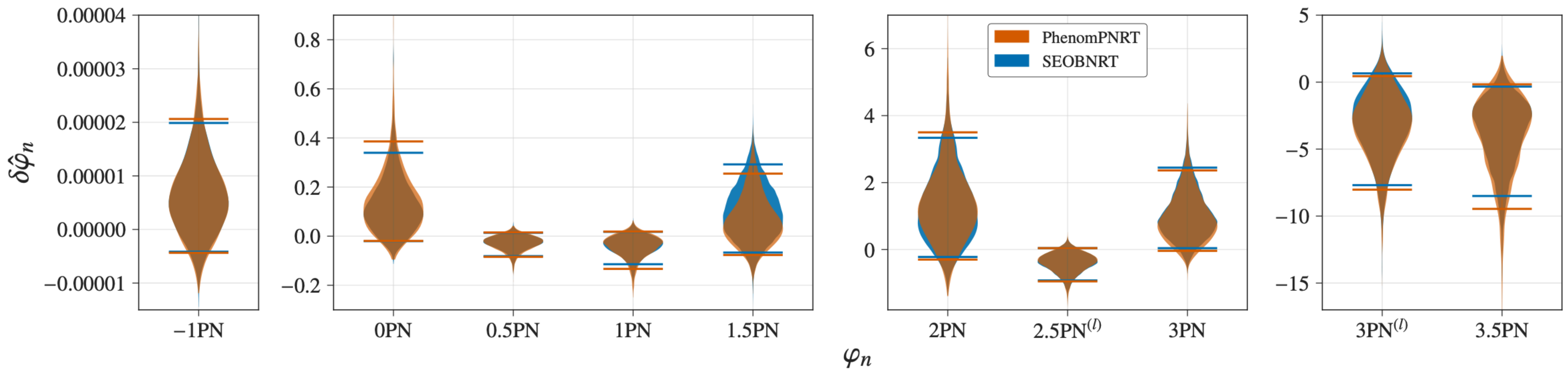
Tests of Gravity



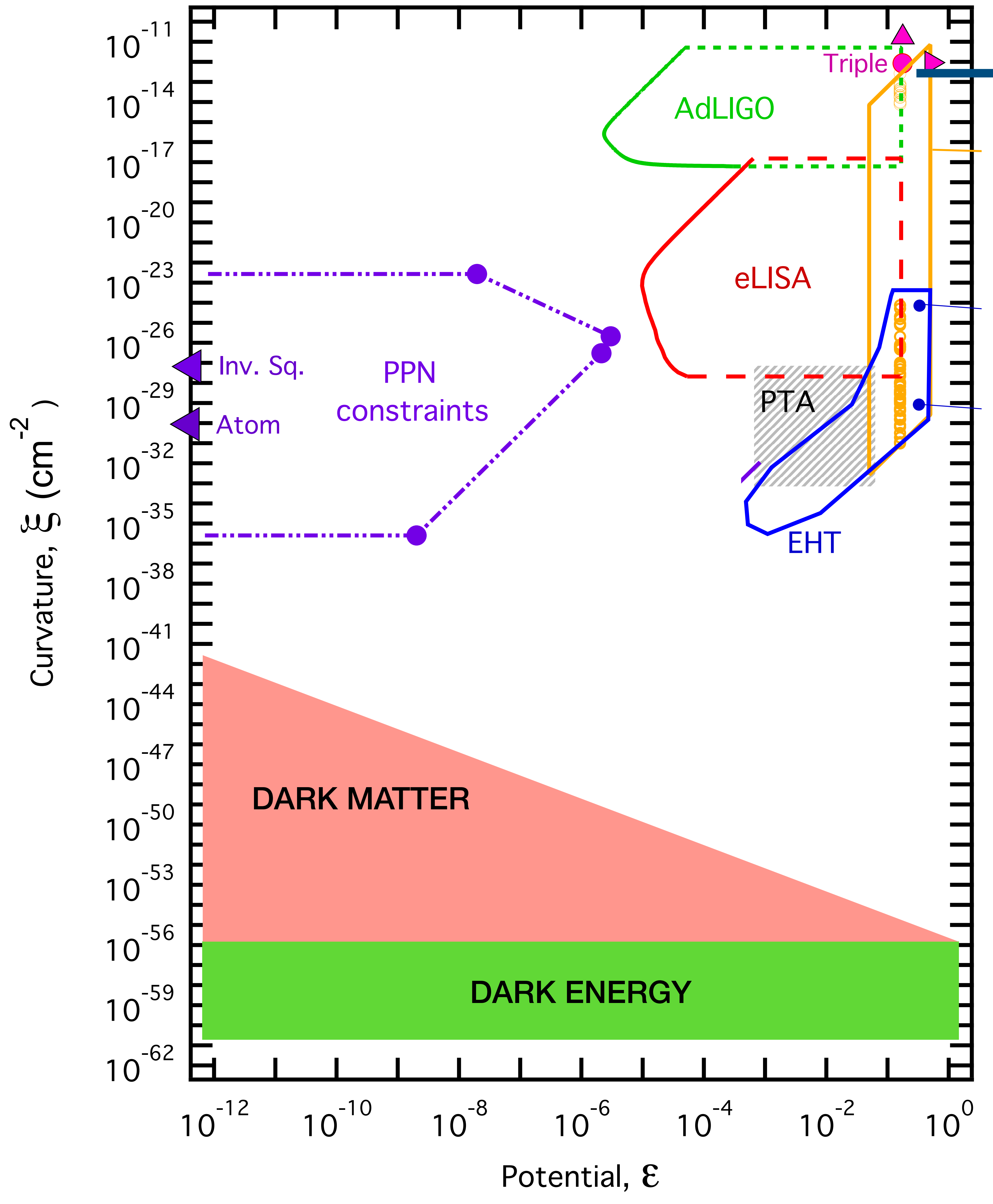
Baker, Psaltis, Skordis ‘15

BNS GW170817

LIGO/Virgo ‘18



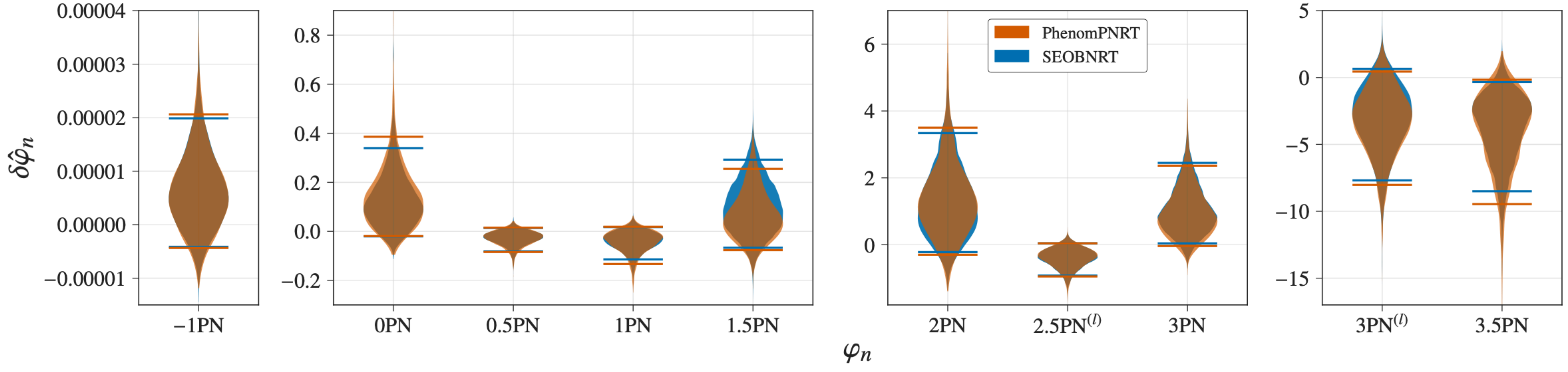
Tests of Gravity



Baker, Psaltis, Skordis ‘15

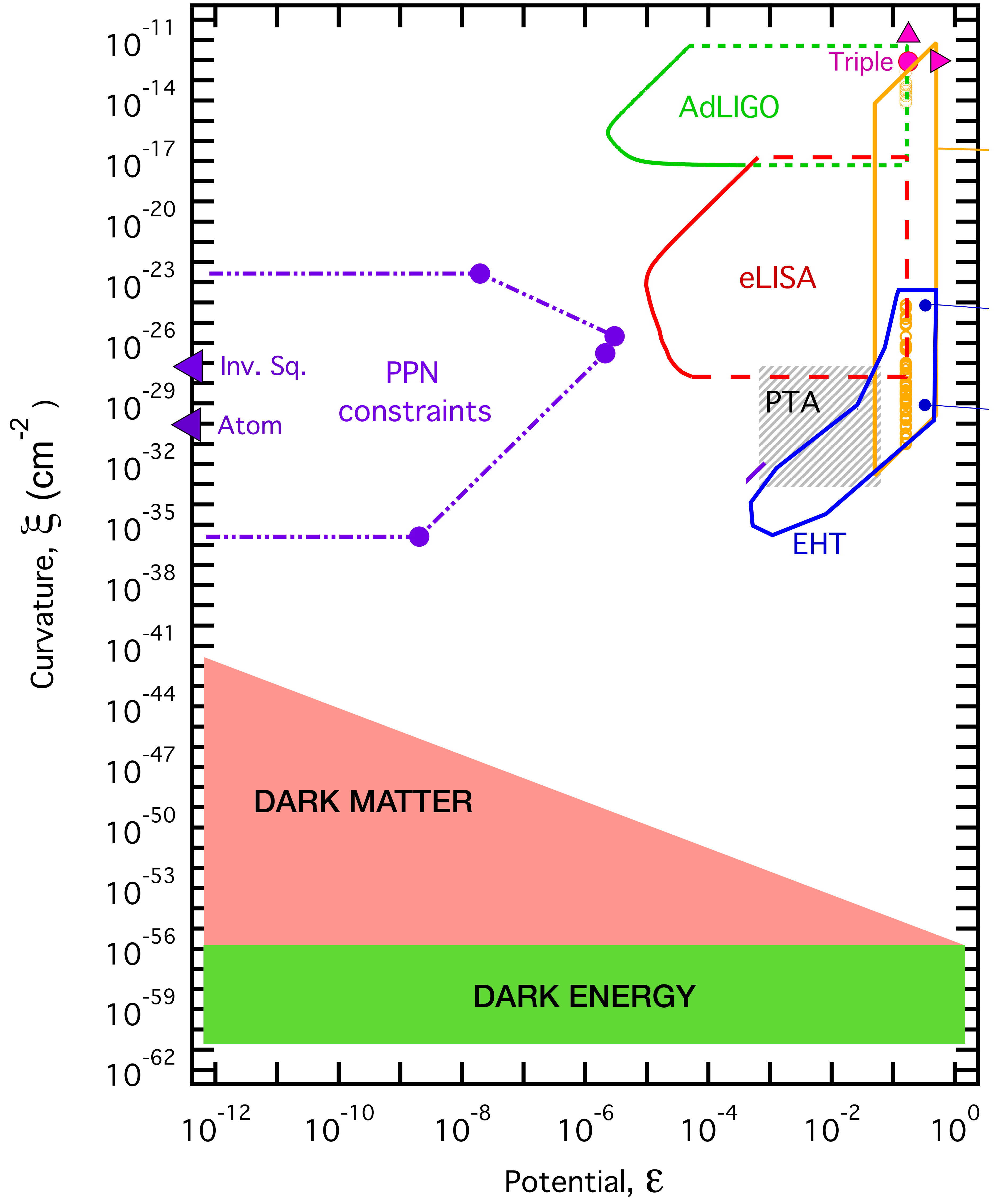
BNS GW170817

LIGO/Virgo ‘18



We find no evidence in support of physics beyond general relativity

Screening Mechanisms



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

Baker, Psaltis, Skordis '15

Large distances modification and screening

1) We do want a sizeable modification at cosmological scales

$$L = M_{Pl}^2 R - \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2$$

$\Longrightarrow$ Very light mode $\quad H^2 \sim m^2$

$$L = M_{Pl}^2 R - \frac{1}{2}(\partial\phi)^2 + \frac{\beta}{4\Lambda^4}(\partial\phi)^4 \qquad M_{Pl}^2 H^2 \sim \Lambda^4$$

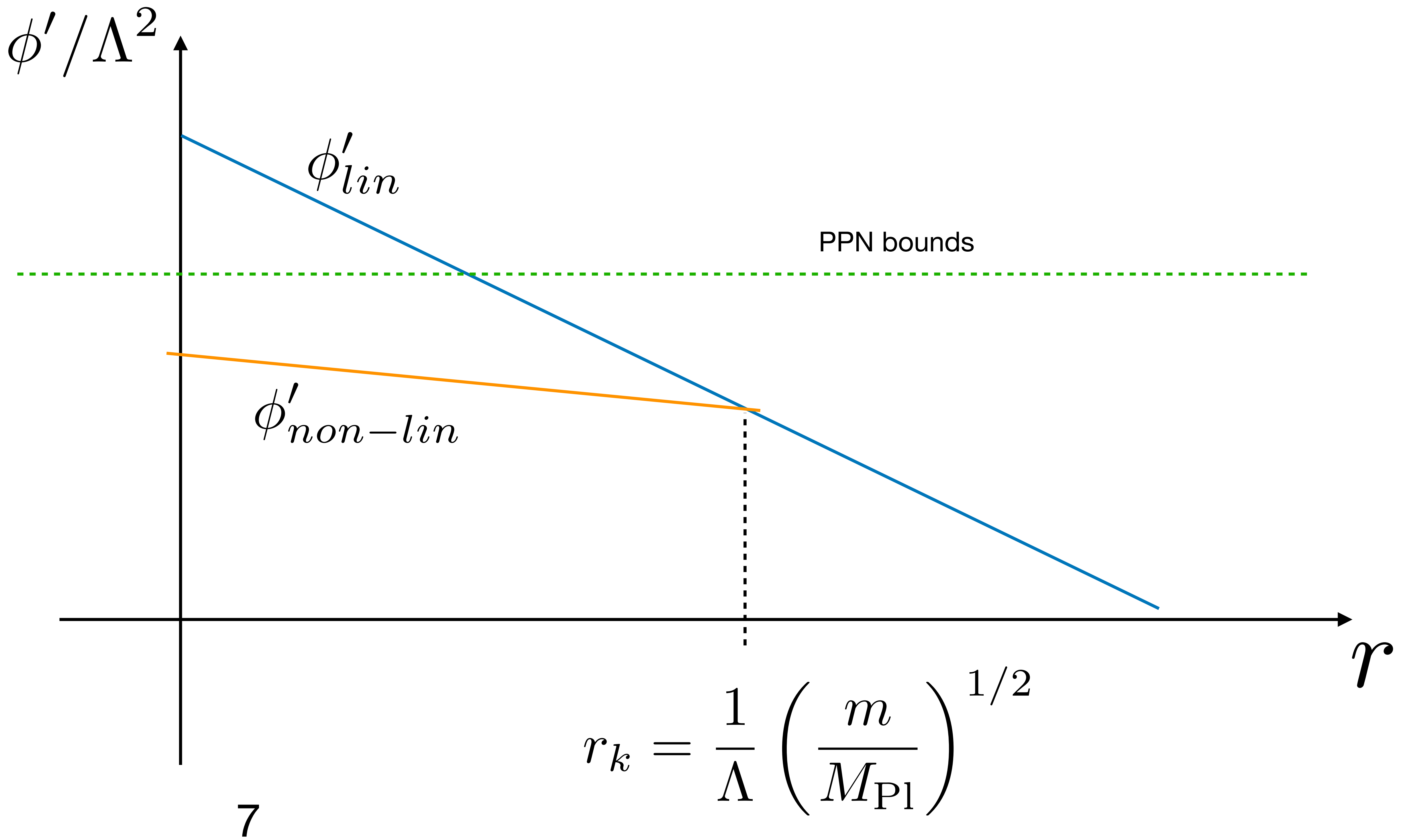
Large distances modification and screening

2) We do not want a modification at short scales

$$L = -\frac{1}{2}(\partial\phi)^2 + \frac{\beta}{4\Lambda^4}(\partial\phi)^4 + \frac{a}{M_{\rm Pl}}\phi T$$

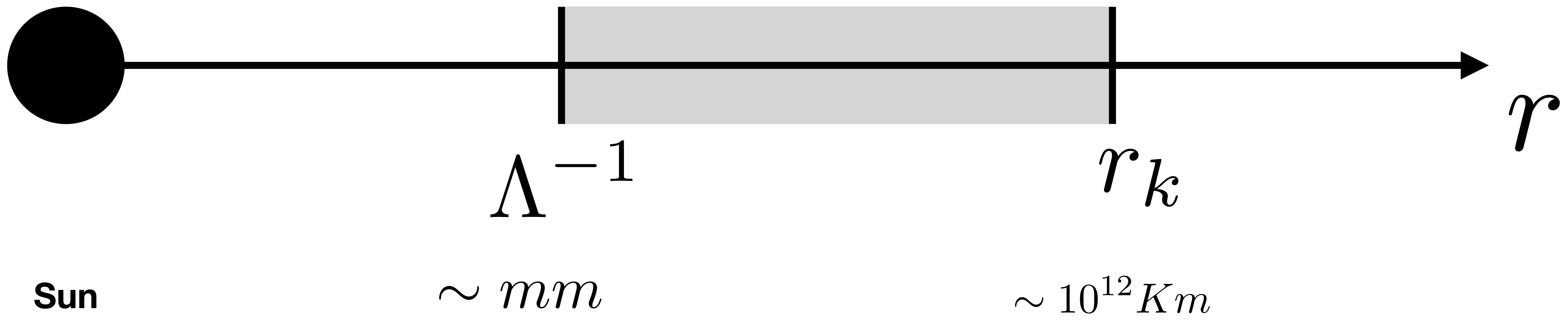
$$\phi'_{lin} \sim \frac{1}{r^2}$$

$$\phi'_{non-lin} \sim \frac{1}{r^{2/3}}$$



Large distances modification and screening

Summary



Nicolis & Rattazzi ’04
De Rham & Ribeiro ’14
Brax & Valageas ‘14

Well-posedness ?

Cauchy problem

Unique solution that depends continuously on the initial data

$$\partial_t \, \mathbf{u} + \mathbf{A}^k \, \partial_k \, \mathbf{u} = \mathbf{S}(\mathbf{u})$$

$\mathbf{A}^k$ → Characteristic matrix

Strong hyperbolicity $\Rightarrow$ well-posedness

↓

Complete set of eigenvectors and real eigenvalues

Weak hyperbolicity $\not\Rightarrow$ well-posedness

↓

Real eigenvalues but incomplete set of eigenvectors

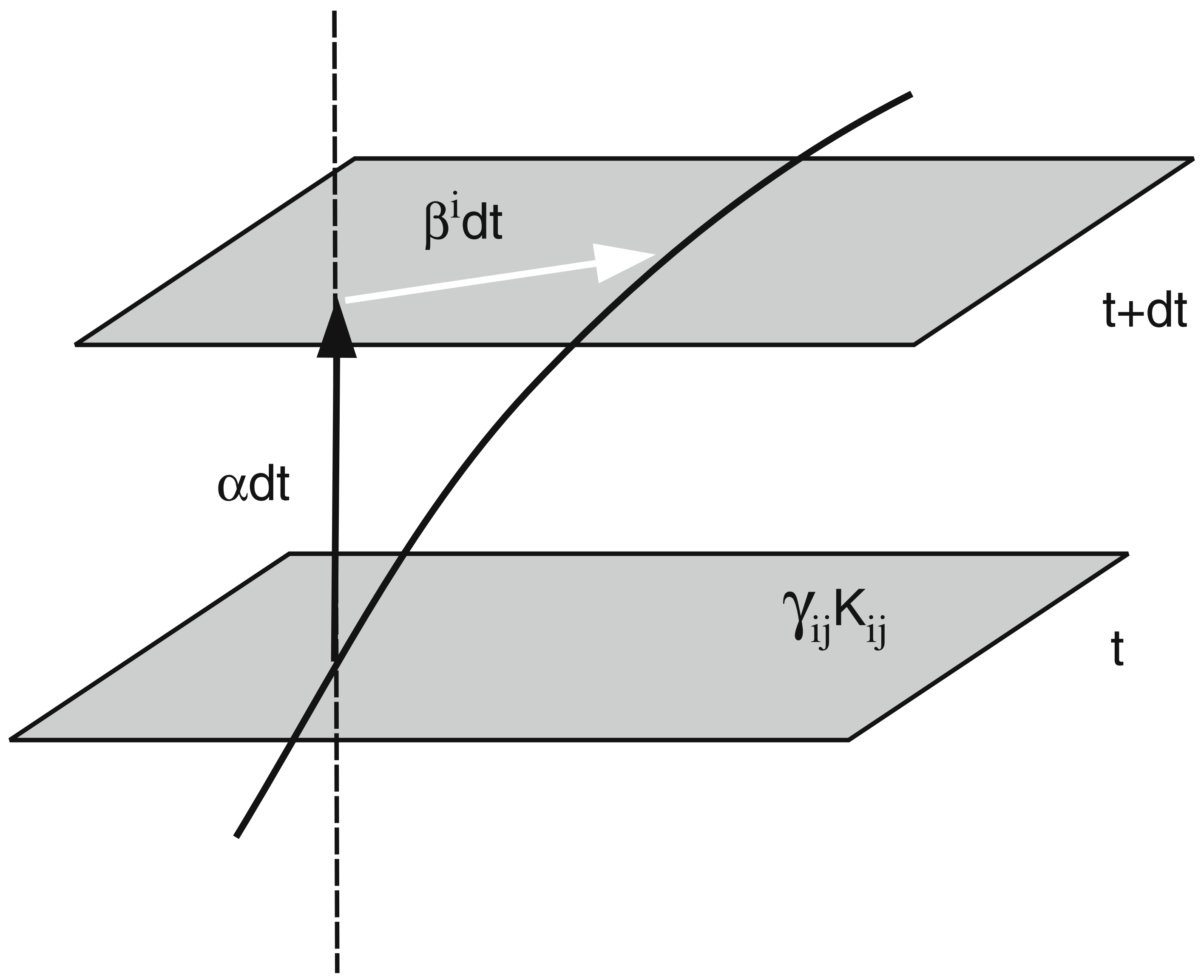
Well-posedness ?

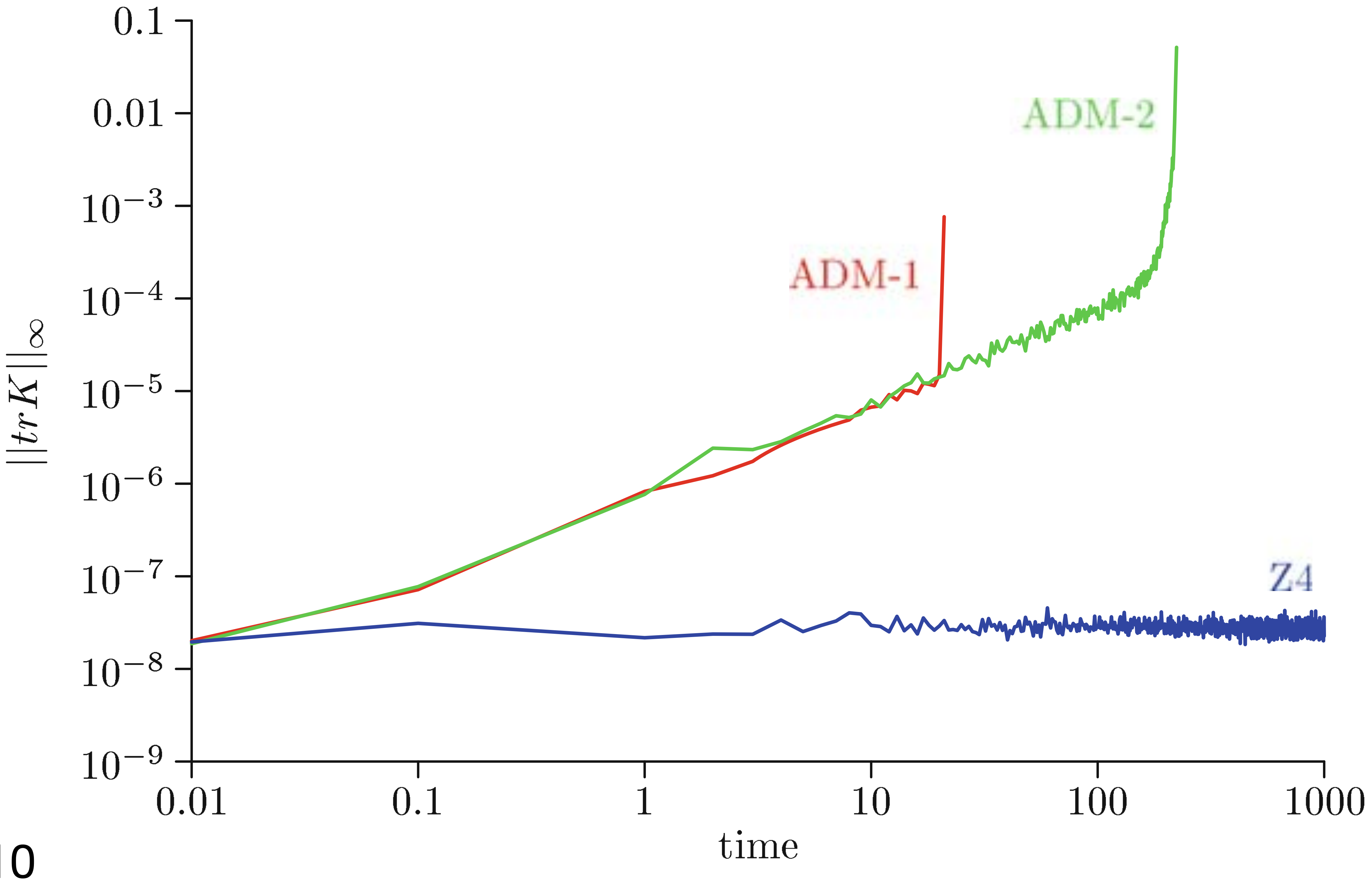
Cauchy problem

Unique solution that depends continuously on the initial data

GR in ADM formulation is not well-posed!

$$ds^2 = -\alpha^2 dt^2 + \gamma_{ij}\left(dy^i + \beta^i dt\right)\left(dy^j + \beta^j dt\right)$$





Well-posedness ?

CCZ4 formalism

$$R_{ab} + \nabla_a Z_b + \nabla_a Z_b = 8\pi \left(T_{ab} - \frac{1}{2} g_{ab}\, trT \right) + \kappa_z \, (n_a Z_b + n_b Z_a - g_{ab} n^c Z_c)$$

$$\partial_t \tilde{\gamma}_{ij} = \beta^k \partial_k \tilde{\gamma}_{ij} + \tilde{\gamma}_{ik}\, \partial_j \beta^k + \tilde{\gamma}_{kj} \partial_i \beta^k - \frac{2}{3} \tilde{\gamma}_{ij} \partial_k \beta^k - 2\alpha \Big(\tilde{A}_{ij} - \frac{\lambda_0}{3} \tilde{\gamma}_{ij}\, tr\tilde{A} \Big) - \frac{\kappa_c}{3} \alpha \tilde{\gamma}_{ij} \ln \tilde{\gamma},$$

$$\partial_t \tilde{A}_{ij} = \beta^k \partial_k \tilde{A}_{ij} + \tilde{A}_{ik} \partial_j \beta^k + \tilde{A}_{kj} \partial_i \beta^k - \frac{2}{3} \tilde{A}_{ij} \partial_k \beta^k - \frac{\kappa_c}{3} \alpha\, \tilde{\gamma}_{ij}\, tr\tilde{A}$$
$$+ \chi \Big[\alpha \left({}^{(3)}R_{ij} + \nabla_i Z_j + \nabla_j Z_i - 8\pi\, S_{ij} \right) - \nabla_i \nabla_j \alpha \Big]^{\mathrm{TF}} + \alpha \Big(tr\hat{K}\, \tilde{A}_{ij} - 2 \tilde{A}_{ik} \tilde{A}^k{}_j \Big),$$

$$\partial_t \chi = \beta^k \partial_k \chi + \frac{2}{3} \chi \left[\alpha (tr\hat{K} + 2\,\Theta) - \partial_k \beta^k \right],$$

$$\partial_t tr\hat{K} = \beta^k \partial_k tr\hat{K} - \nabla_i \nabla^i \alpha + \alpha \left[\frac{1}{3} (tr\hat{K} + 2\Theta)^2 + \tilde{A}_{ij} \tilde{A}^{ij} + 4\pi (\tau + trS) + \kappa_z \Theta \right]$$
$$+ 2\, Z^i \nabla_i \alpha,$$

$$\partial_t \Theta = \beta^k \partial_k \Theta + \frac{\alpha}{2} \left[{}^{(3)}R + 2 \nabla_i Z^i + \frac{2}{3} tr^2 \hat{K} + \frac{2}{3} \Theta \Big(tr\hat{K} - 2\Theta \Big) - \tilde{A}_{ij} \tilde{A}^{ij} \right] - Z^i \nabla_i \alpha$$
$$- \alpha \left[8\pi\, \tau + 2\kappa_z\, \Theta \right],$$

$$\partial_t \hat{\Gamma}^i = \beta^j \partial_j \hat{\Gamma}^i - \hat{\Gamma}^j \partial_j \beta^i + \frac{2}{3} \hat{\Gamma}^i \partial_j \beta^j + \tilde{\gamma}^{jk} \partial_j \partial_k \beta^i + \frac{1}{3} \tilde{\gamma}^{ij} \partial_j \partial_k \beta^k$$
$$- 2 \tilde{A}^{ij} \partial_j \alpha + 2\alpha \left[\tilde{\Gamma}^i{}_{jk} \tilde{A}^{jk} - \frac{3}{2\chi} \tilde{A}^{ij} \partial_j \chi - \frac{2}{3} \tilde{\gamma}^{ij} \partial_j tr\hat{K} - 8\pi\, \tilde{\gamma}^{ij}\, S_i \right]$$
$$+ 2\alpha \left[-\tilde{\gamma}^{ij} \left(\frac{1}{3} \partial_j \Theta + \frac{\Theta}{\alpha}\, \partial_j \alpha \right) - \frac{1}{\chi} Z^i \left(\kappa_z + \frac{2}{3} \left(tr\hat{K} + 2\Theta \right) \right) \right],$$

$$\partial_t \alpha = \beta^i \partial_i \alpha - \alpha^2\, f\, tr\hat{K},$$

$$\partial_t \beta^i = \beta^j \partial_j \beta^i + g\ B^i,$$

$$\partial_t B^i = \beta^j \partial_j B^i - \eta B^i + \partial_t \hat{\Gamma}^i - \beta^j \partial_j \hat{\Gamma}^i,$$

1+log slicing

Gamma-driver shift condition

O(20) equations with Thousands terms

Well-posedness ?

$$S = \int d^4x\sqrt{-g}\left[\frac{R}{16\pi G} + K(X)\right]$$

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

$$X \equiv \nabla_\mu\phi\nabla^\mu\phi$$

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

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

$$V_\pm = -\frac{\gamma^{tr}}{\gamma^{tt}} \pm \sqrt{\frac{-\det(\gamma^{\mu\nu})}{(\gamma^{tt})^2}} \quad < 0 \quad \neq 0$$

$$\partial_t\ \mathbf{u} + \mathbf{A}^k\ \partial_k\ \mathbf{u} = \mathbf{S}(\mathbf{u})$$

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

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

Well-posedness ?

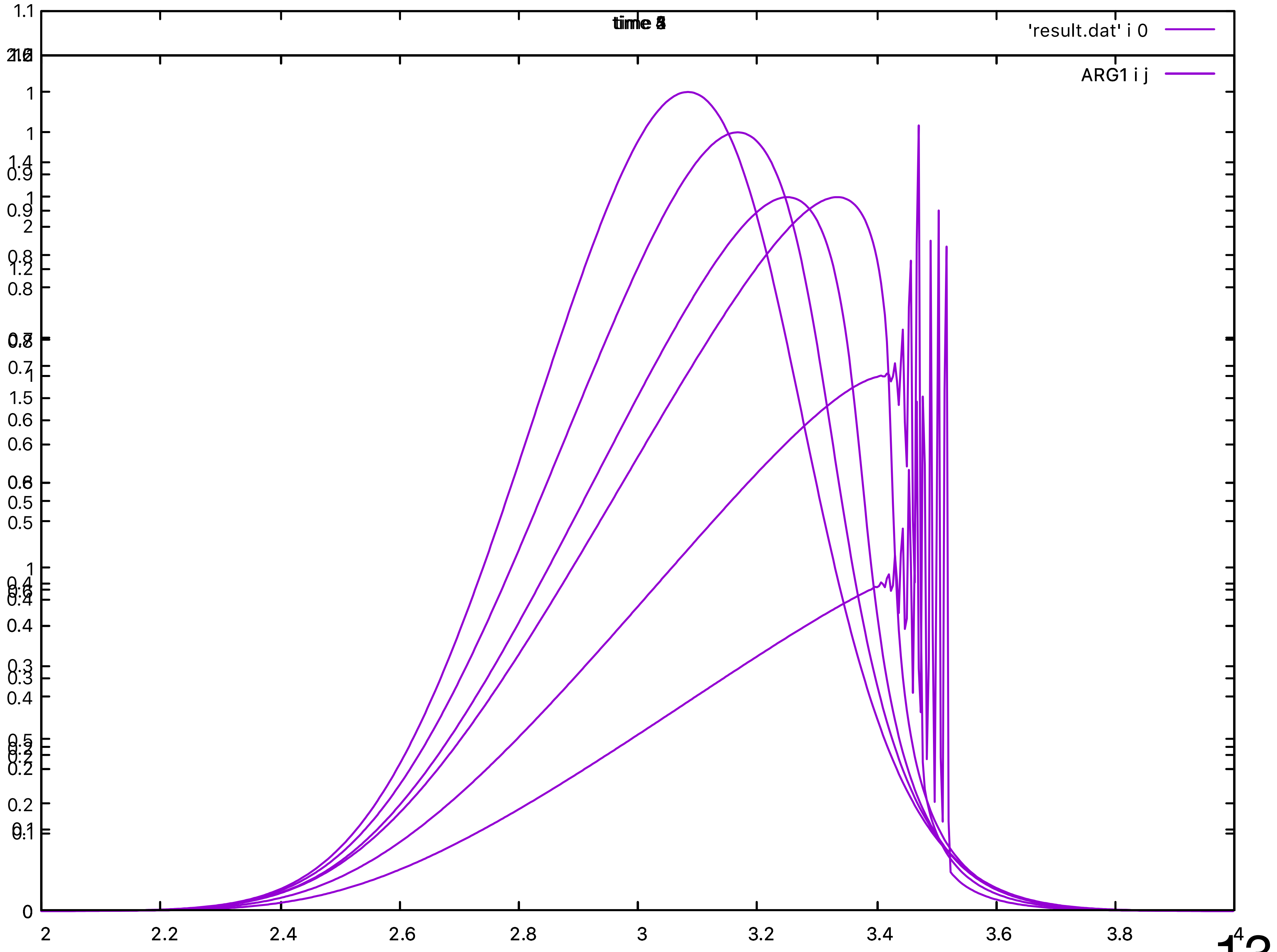
Caustics / shocks

$$\partial_t \ \mathbf{u} + \mathbf{A}^k \ \partial_k \ \mathbf{u} = \mathbf{S}(\mathbf{u}) \quad \rightarrow \quad \partial_t \ \mathbf{u} + \partial_k \mathbf{F}^k(\mathbf{u}) = \mathbf{S}(\mathbf{u})$$

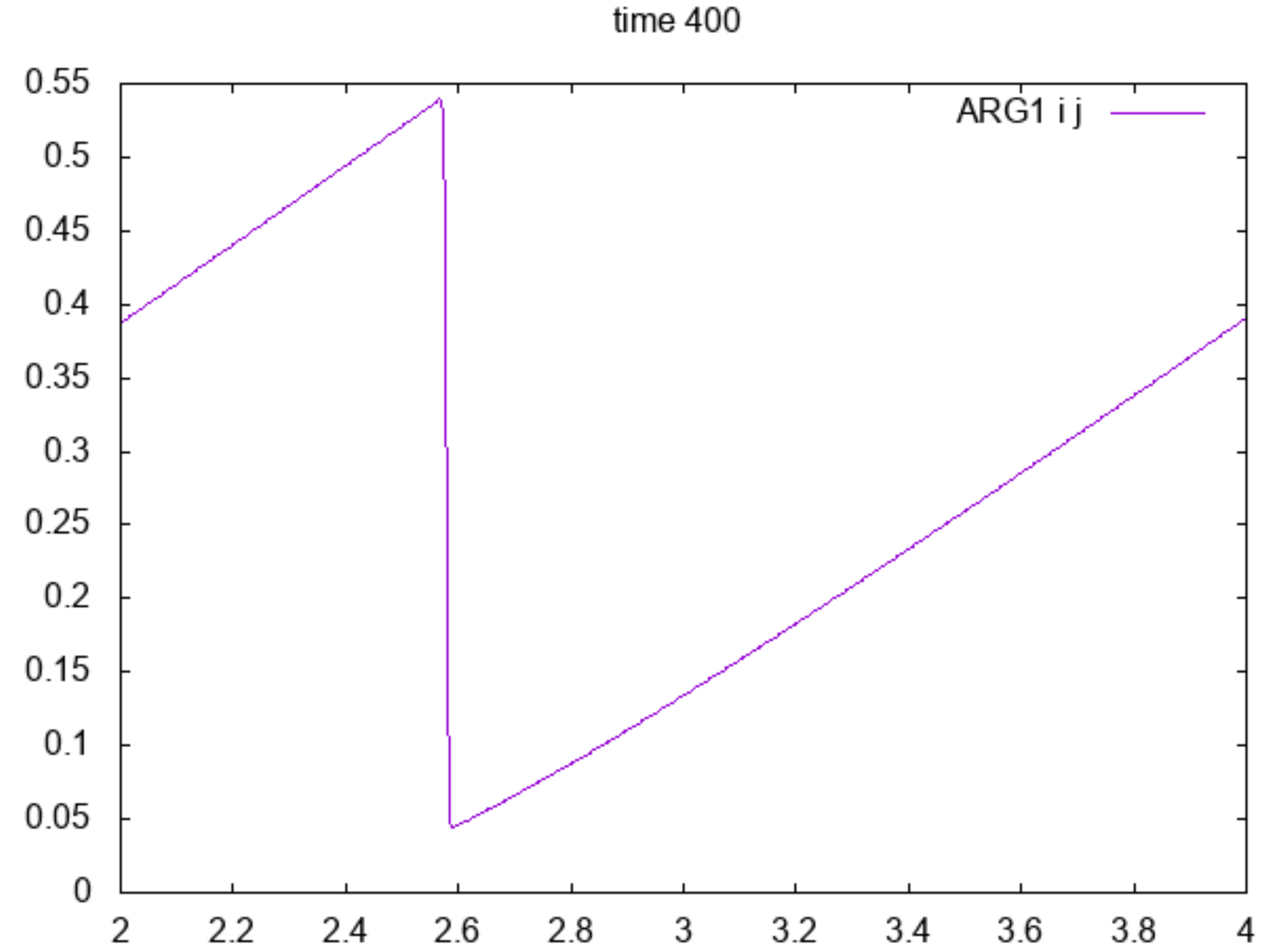
Burgers equation

$$\partial_t u + u \partial_x u = 0 \qquad u = h(p) \qquad p = x - ut \qquad \partial_t u + \frac{1}{2} \partial_x u^2 = 0$$

Finite difference

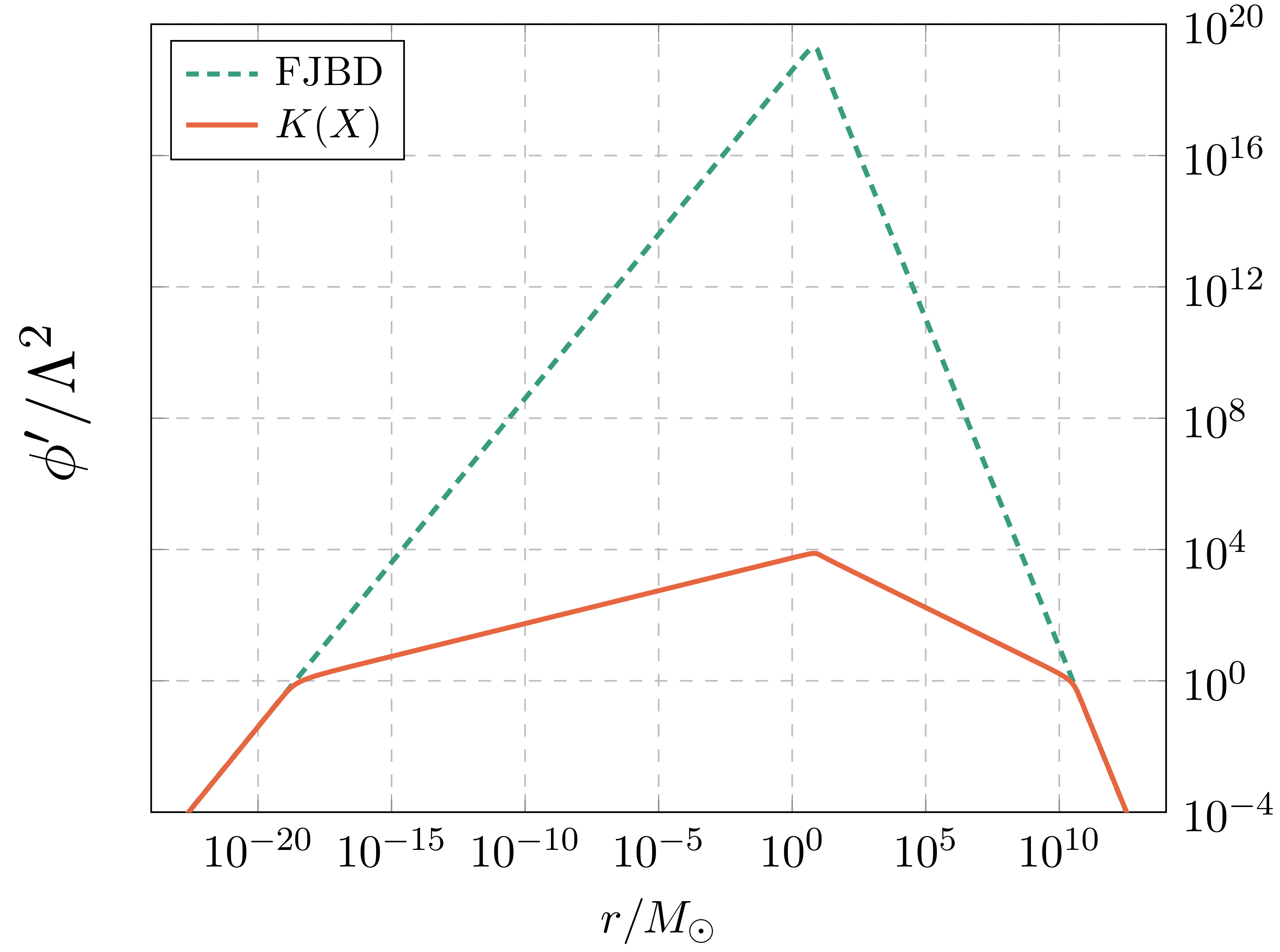


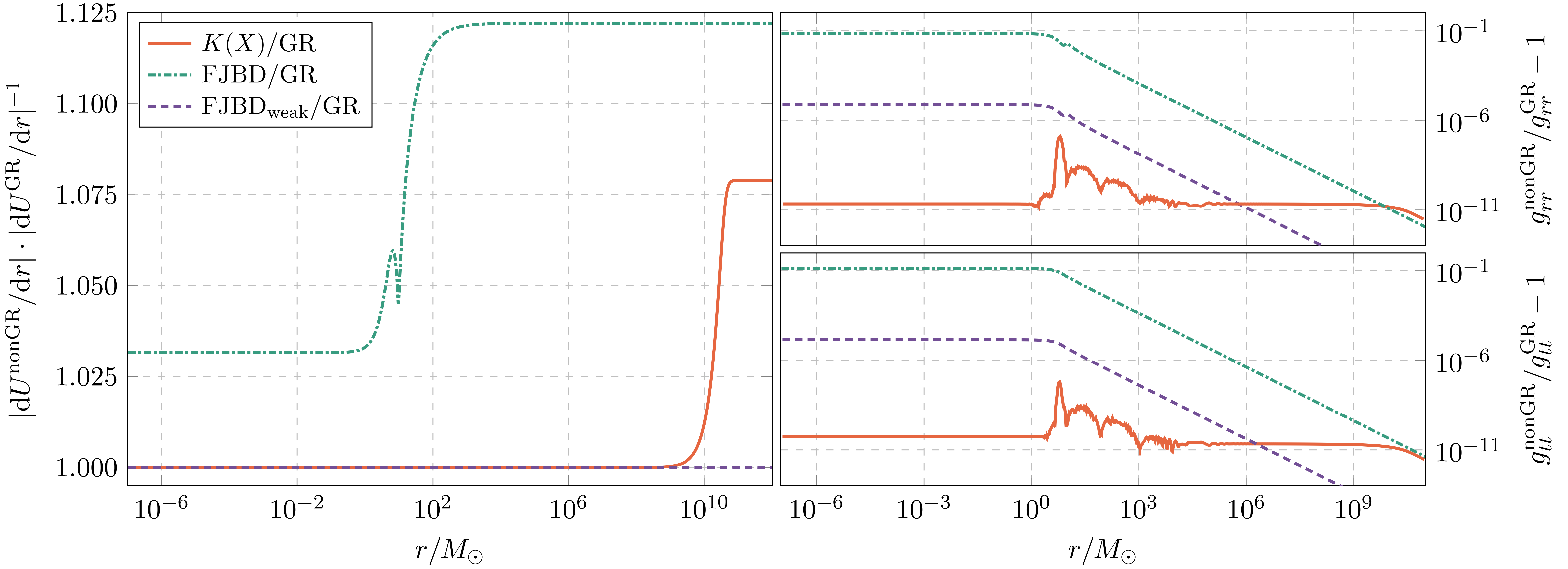
HRSC



Screened NS

Initial data: TOV solution



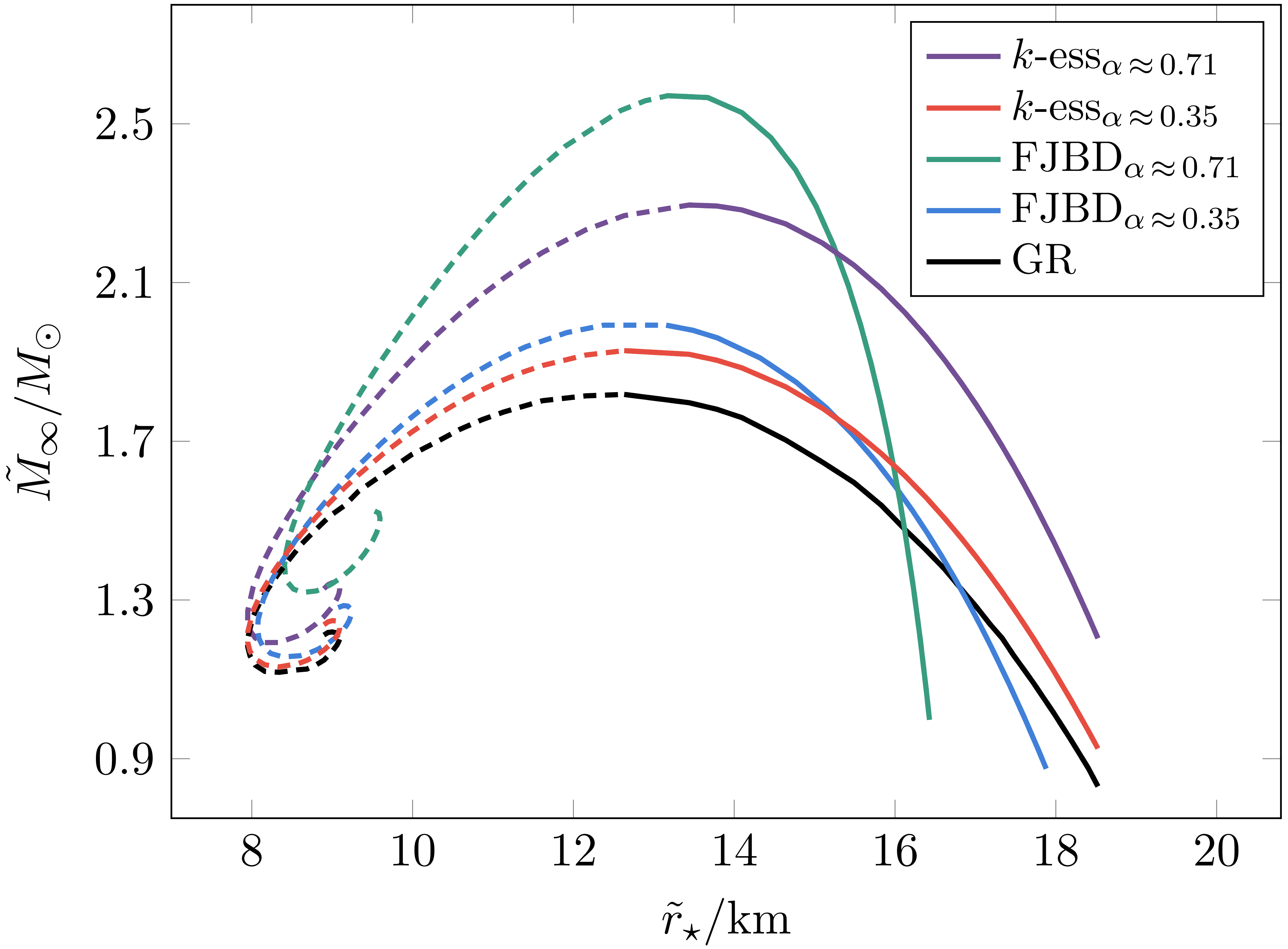


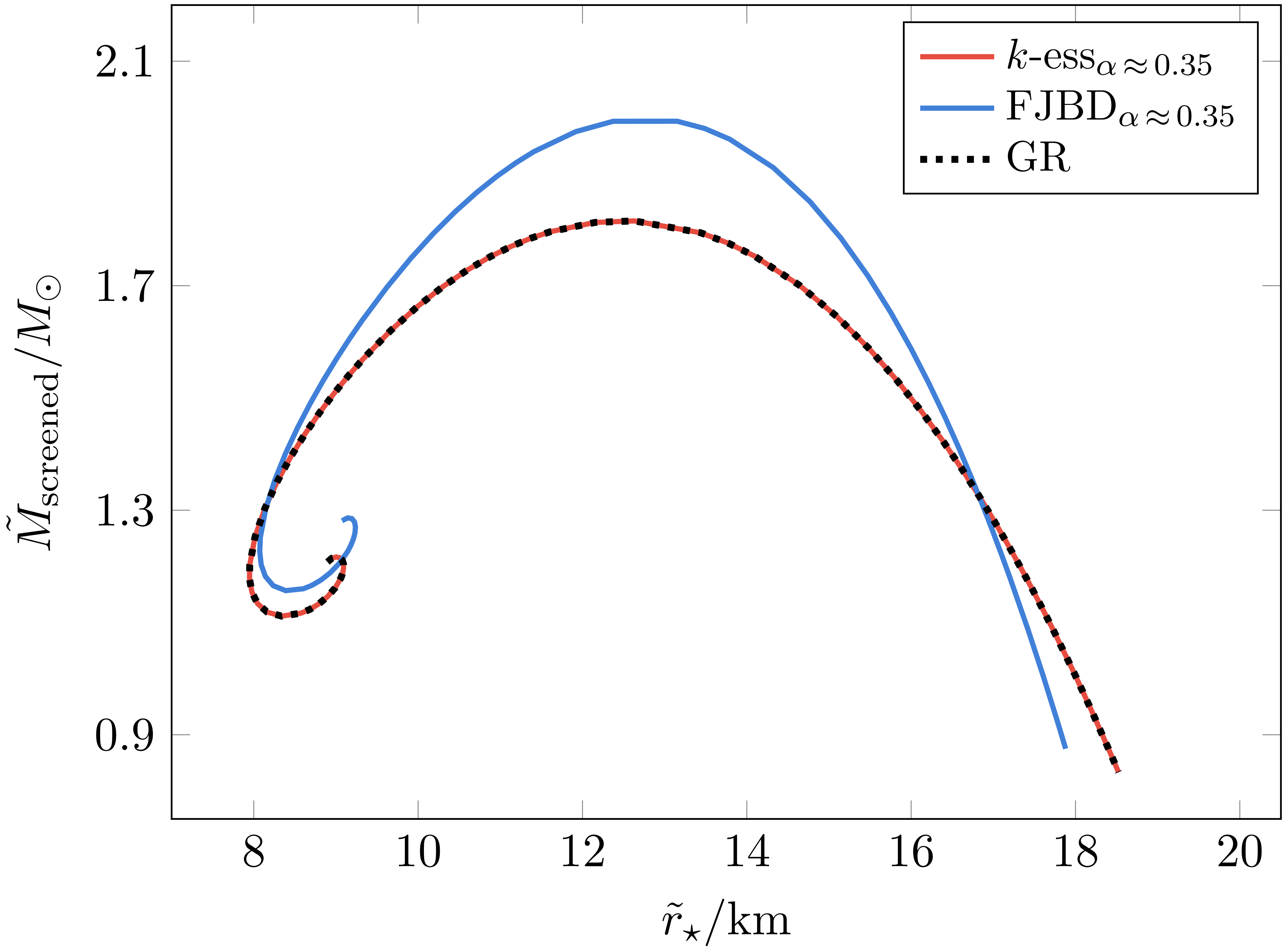
$$\gamma^{\mathrm{PPN}} - 1 = (-2.98 \pm 1.38) \times 10^{-12}\,,$$

$$\beta^{\mathrm{PPN}} - 1 = (1.10 \pm 0.764) \times 10^{-10}\,,$$

Screened NS

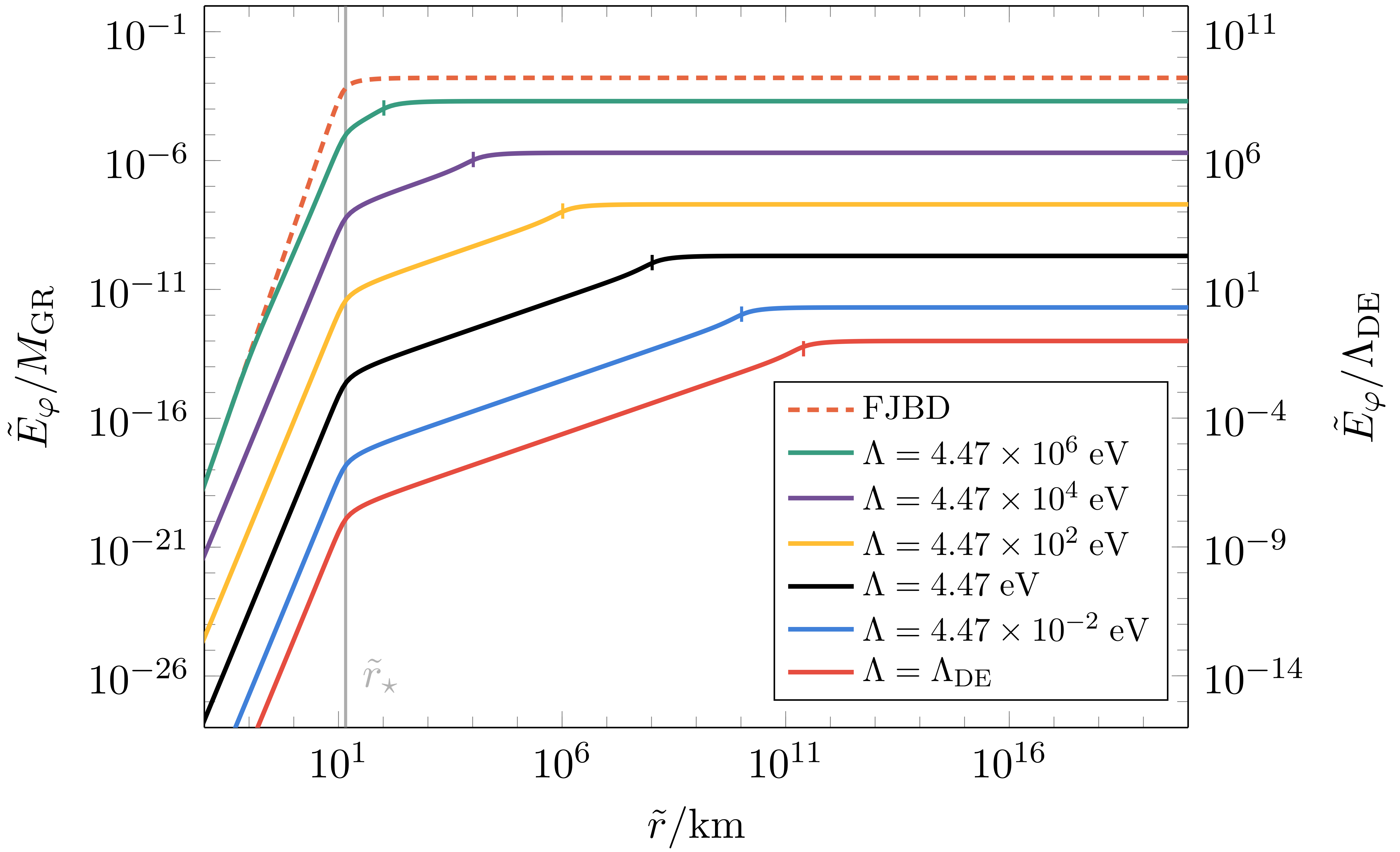
Mass-Radius curves





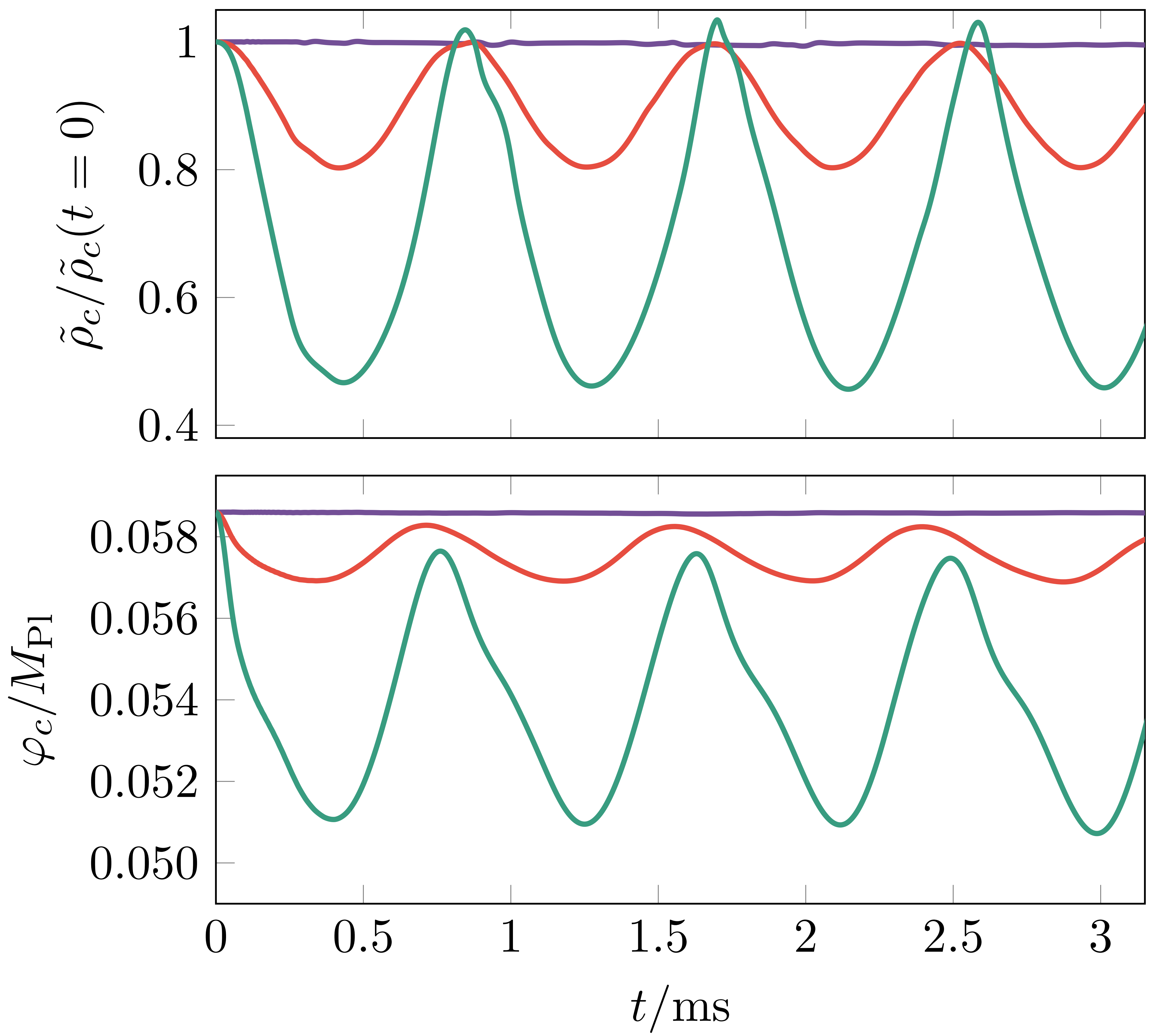
Screened NS

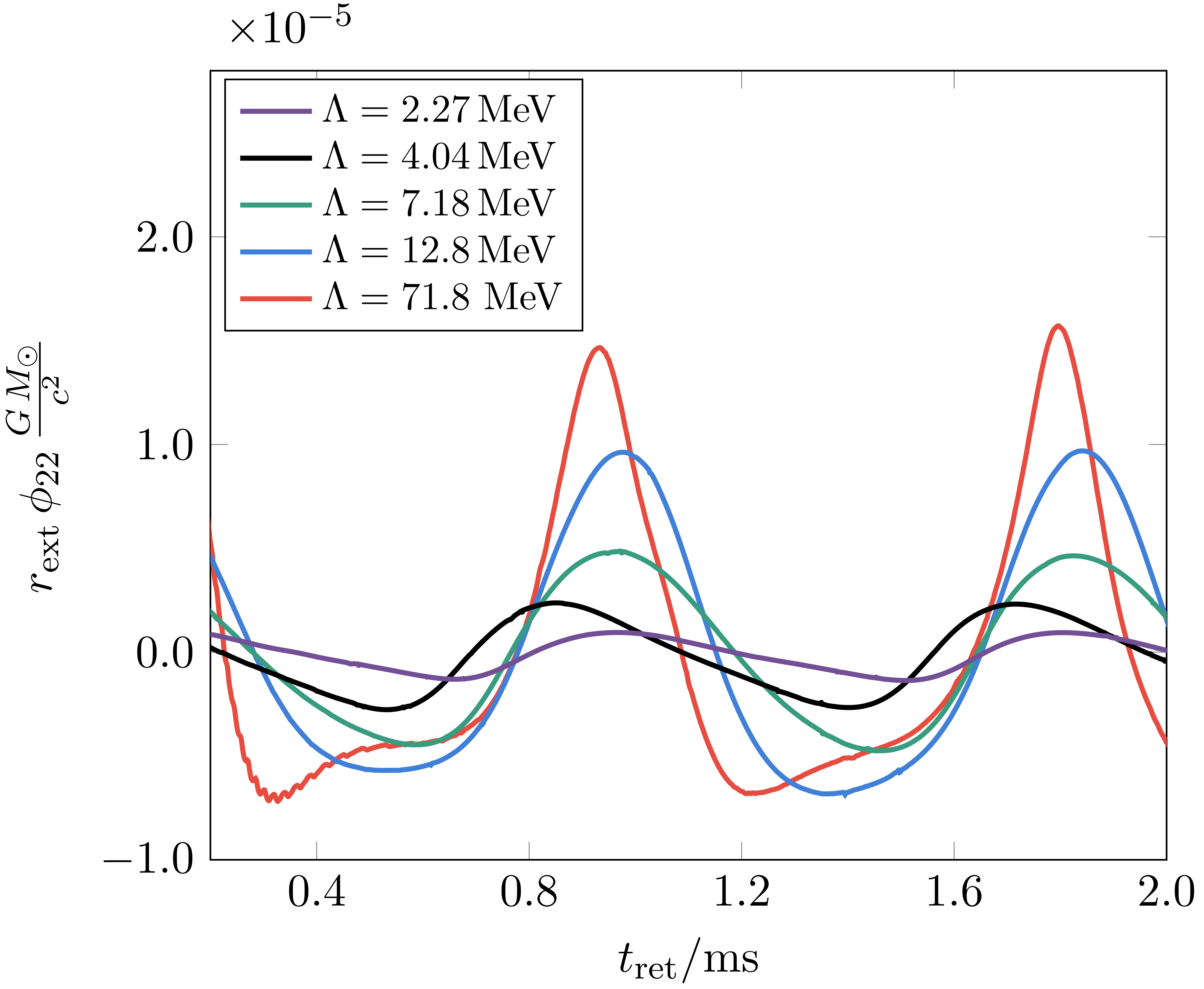
Scalar field energy



Dynamics of Screened NS

Evolution: stellar oscillations

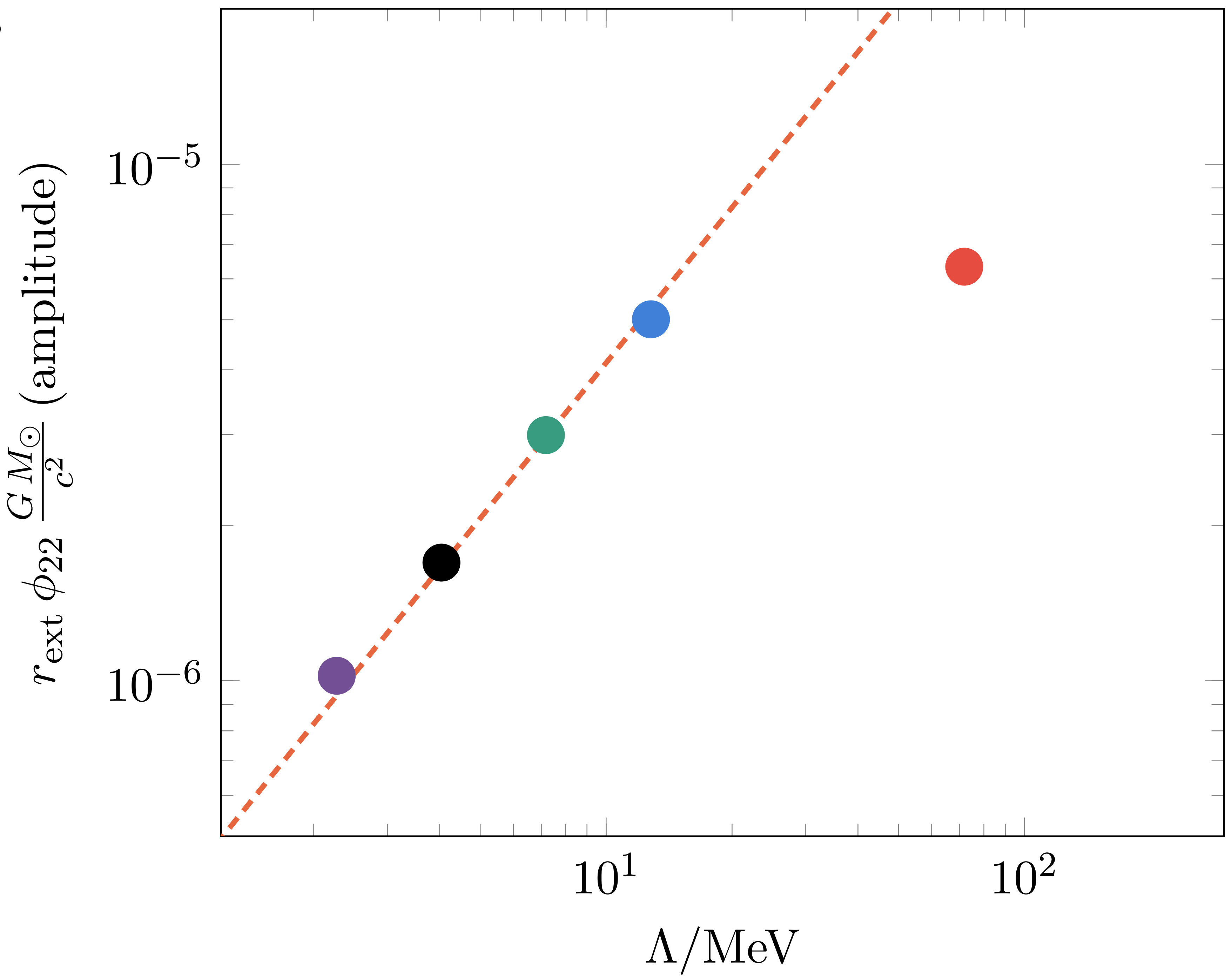


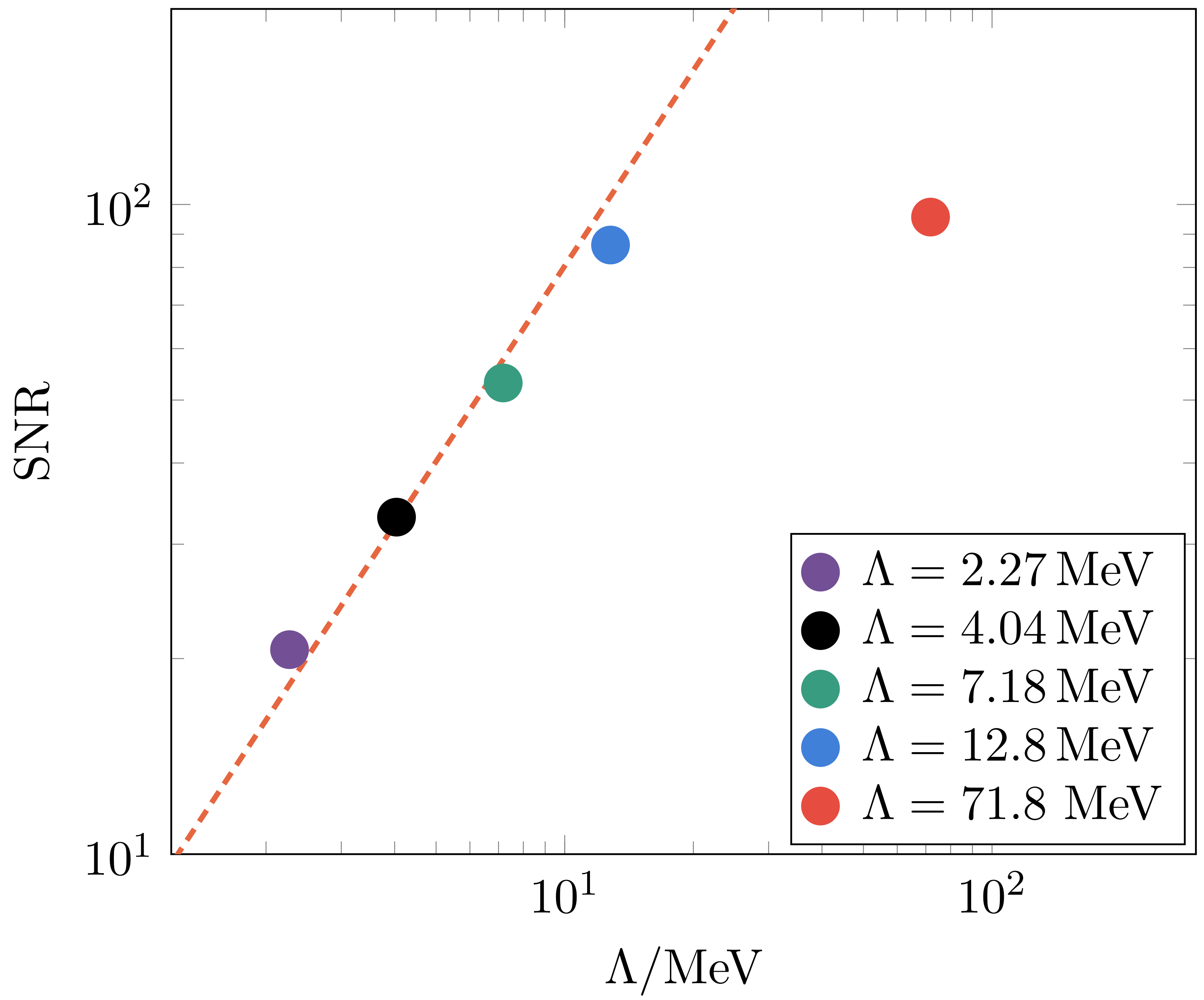


$$\phi_{22} \simeq -\alpha\sqrt{16\pi G}\partial_t^2\varphi + O\left(\frac{1}{r^2}\right)$$

Dynamics of Screened NS

Evolution: stellar oscillations





$$\phi_{22} \quad , \quad \mathrm{SNR} \quad \propto \Lambda$$

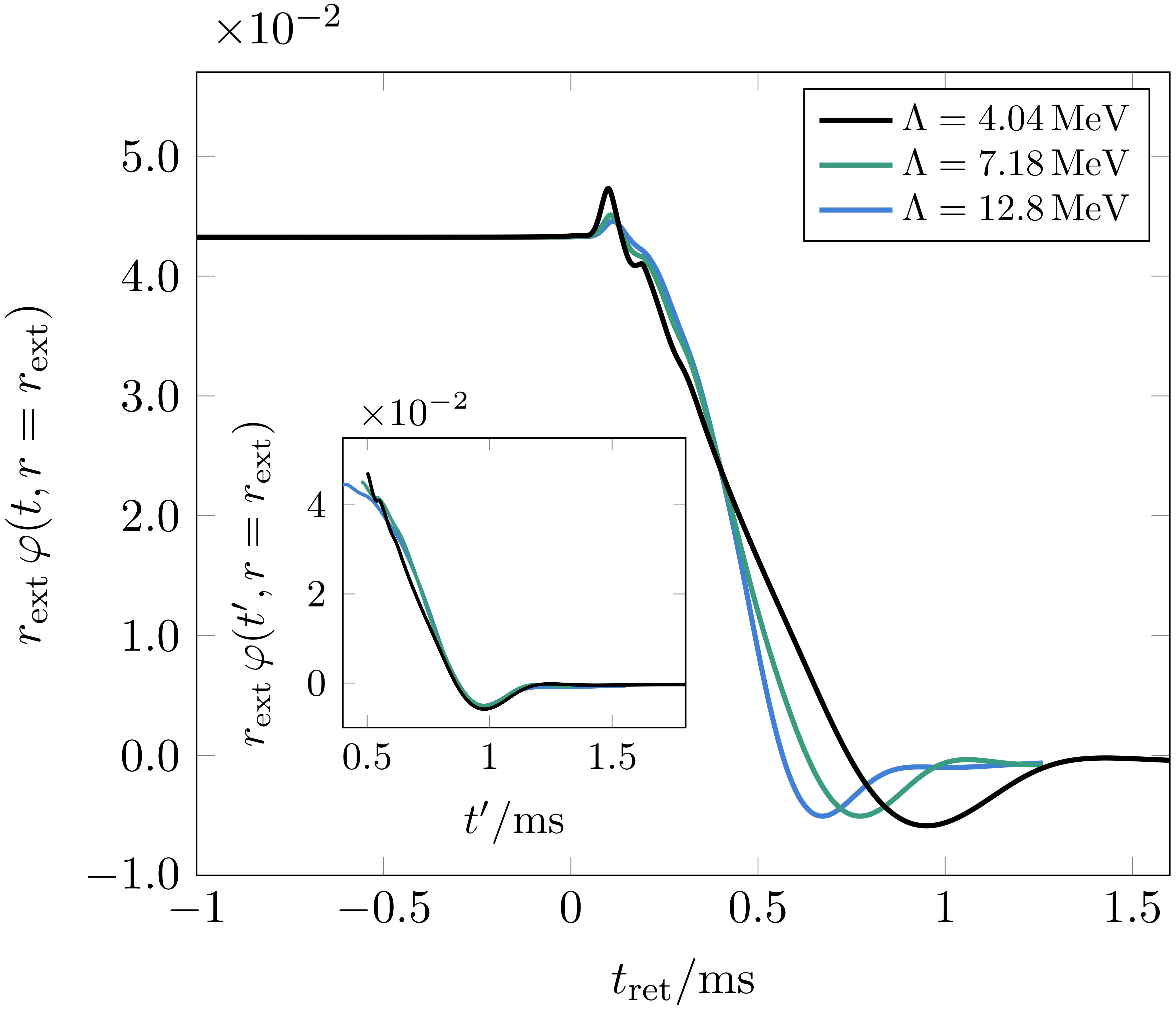
For Ad LIGO at 8 kpc

Dynamics of Screened NS

Evolution: collapse in a BH

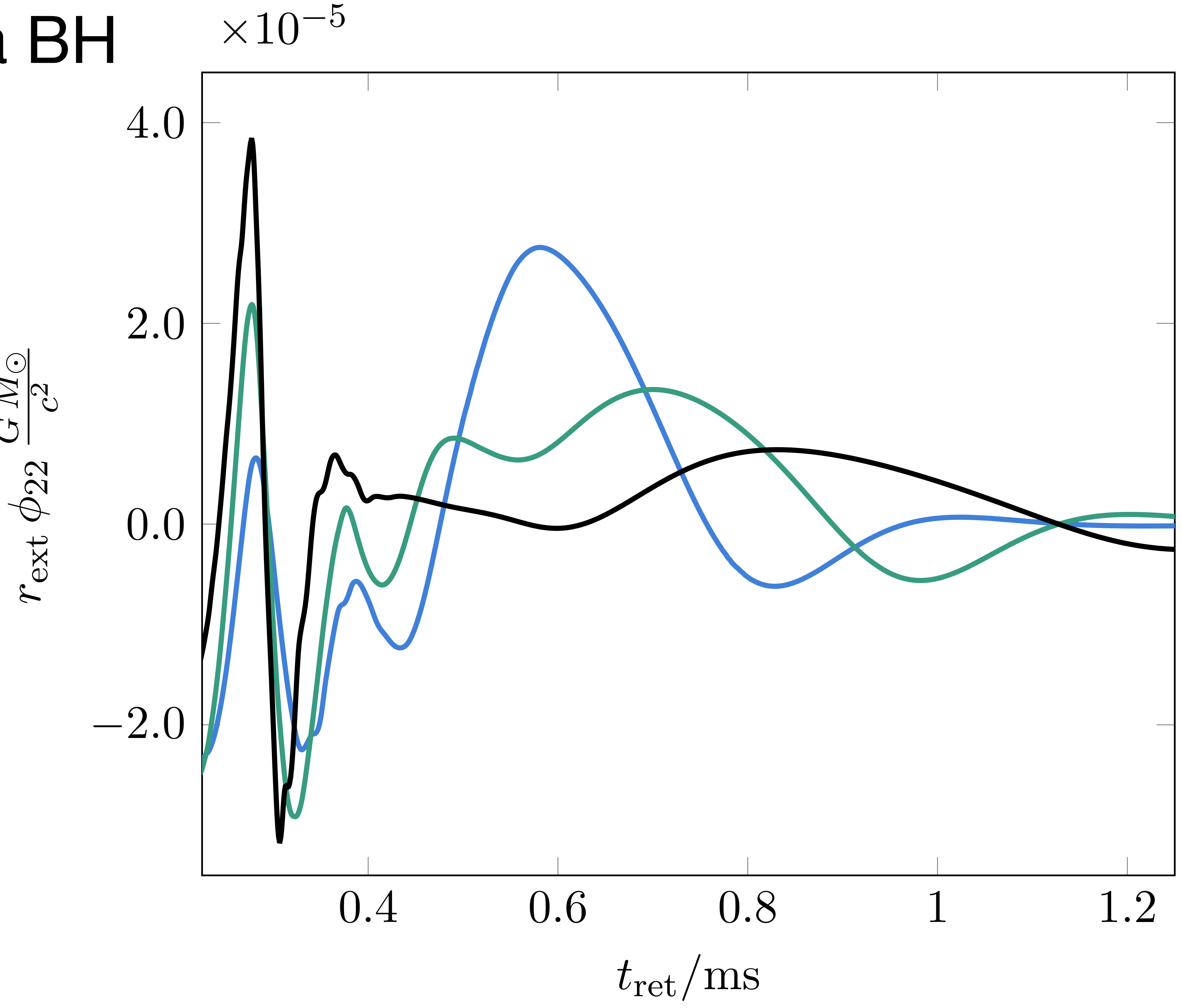
$$f \propto \sqrt{\Lambda}$$

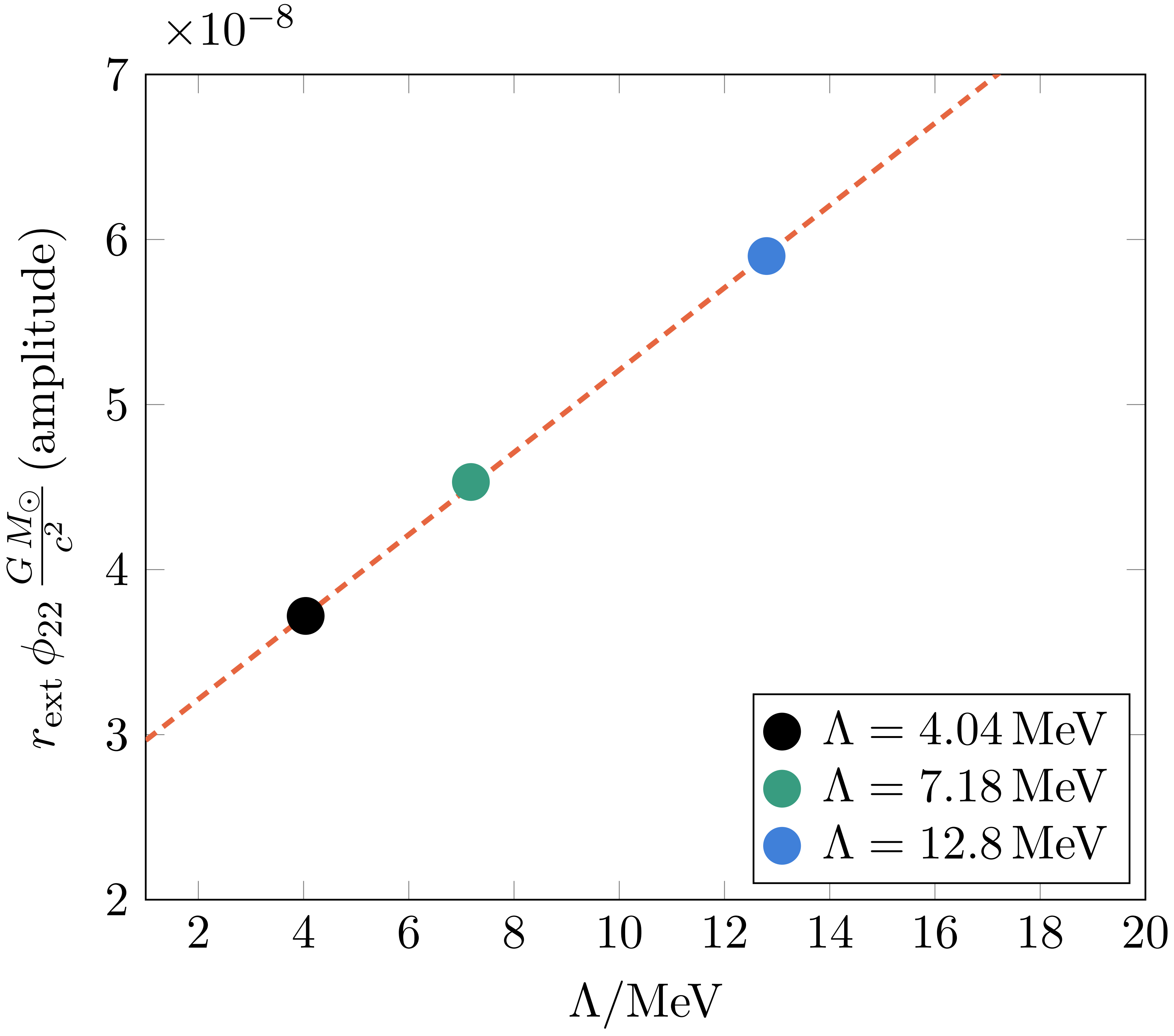
$$\phi_{22} \propto (2\pi f)^2 \varphi \propto \Lambda$$



Dynamics of Screened NS

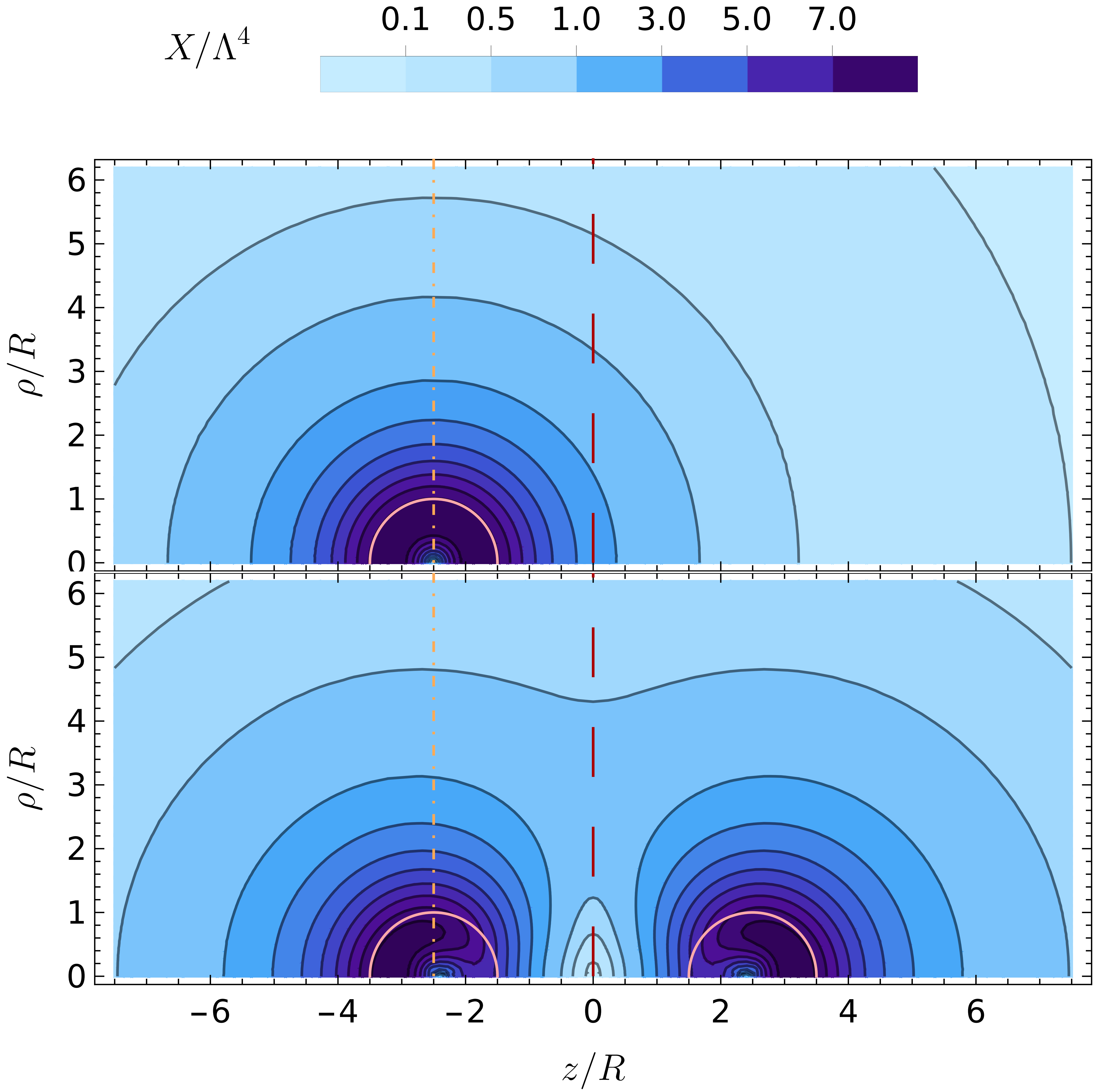
Evolution: collapse in a BH





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

2 body problem



Boskovic & Barausse ‘23

3D simulations

Simflowny

Source
Commits
Branches
Pull requests
Pipelines
Deployments
Jira issues

IAC3 UIB / Simflowny project / Simflowny

Wiki

Clone wiki

Simflowny / Home

View History

Simflowny

Generates parallel code
for 3+1 simulations

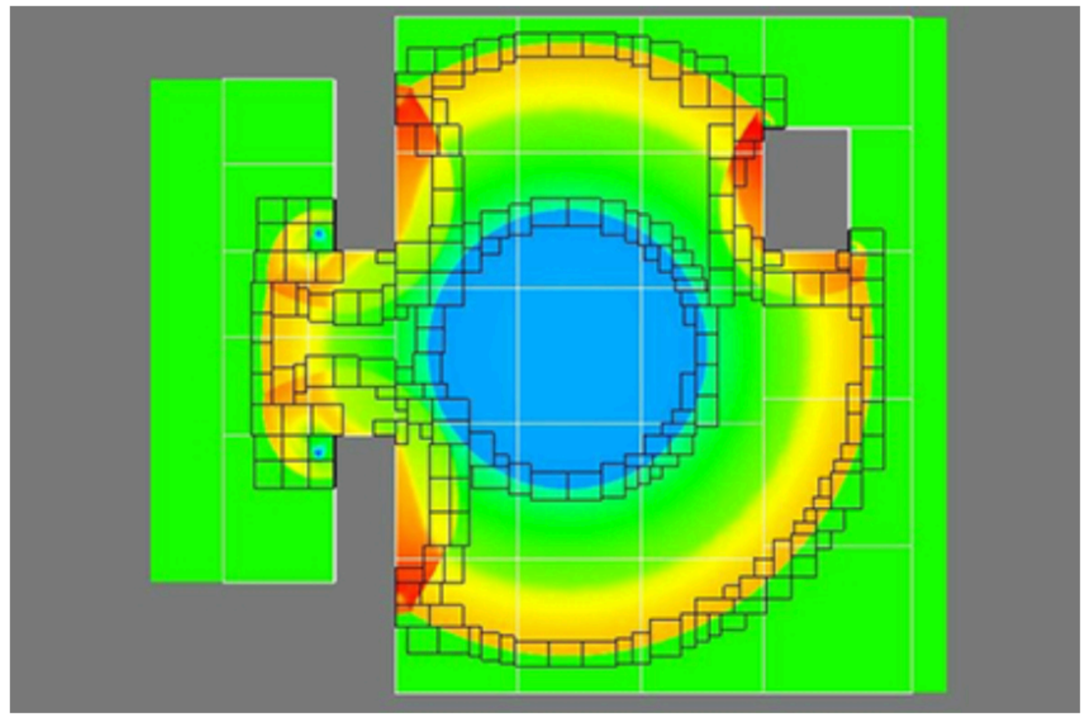
Simflowny: open scientific models

Simflowny is a cloud-based open environment for scientific dynamical models, composed by a semantic Domain Specific Language and a friendly Integrated Development Environment, which automatically generates parallel code for simulation frameworks.

SAMRAI: Structured Adaptive Mesh Refinement Application Infrastructure

AMR

Exploring application, numerical, parallel computing, and software issues associated with structured adaptive mesh refinement



LORENE

Langage Objet pour la REativité NumériquE

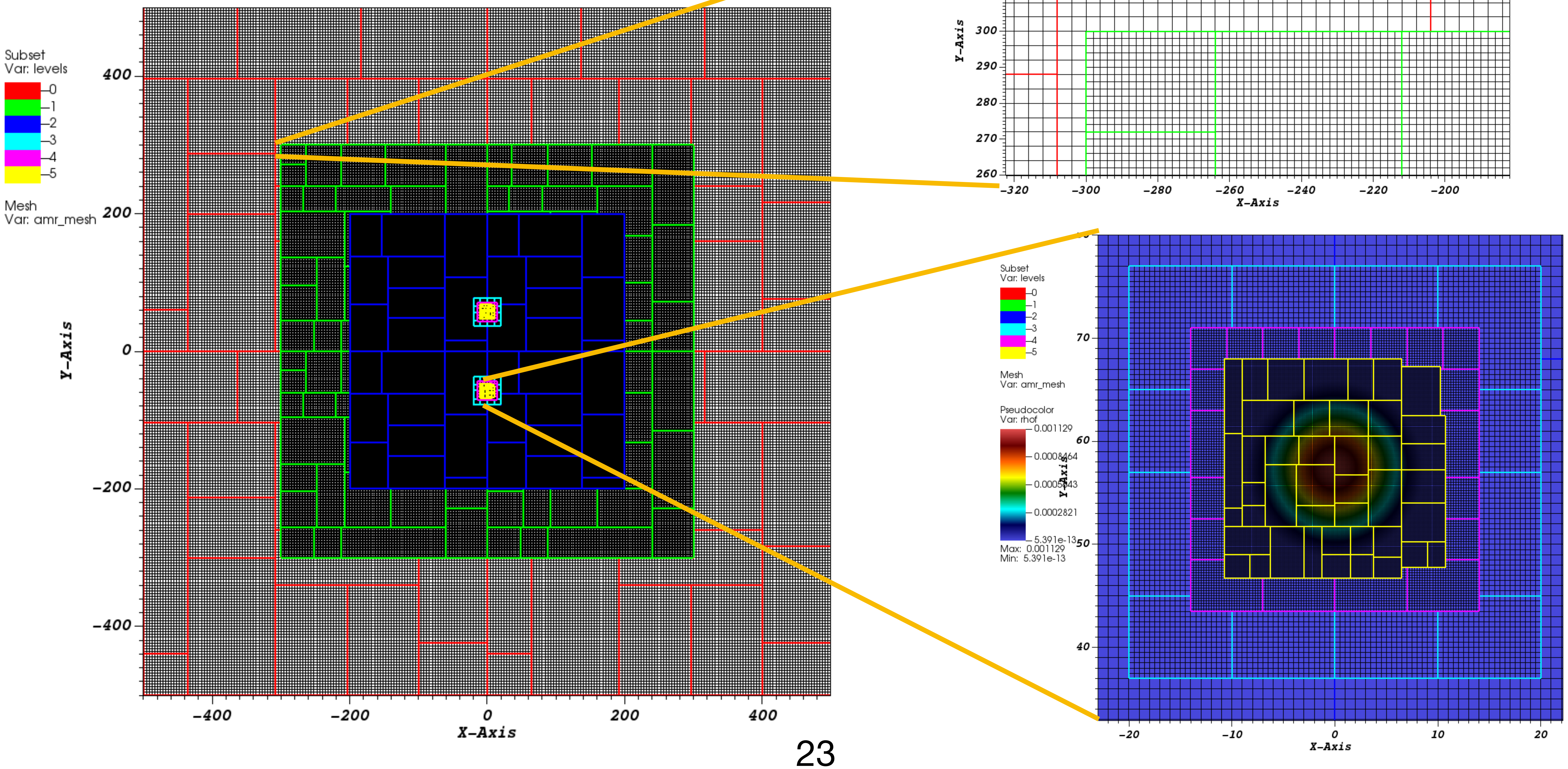
Initial Data

3D simulations

SAMRAI

- Parallelization: divide the domain in patches to be evolved in parallel in different processors → faster simulations
- Adaptive mesh refinement

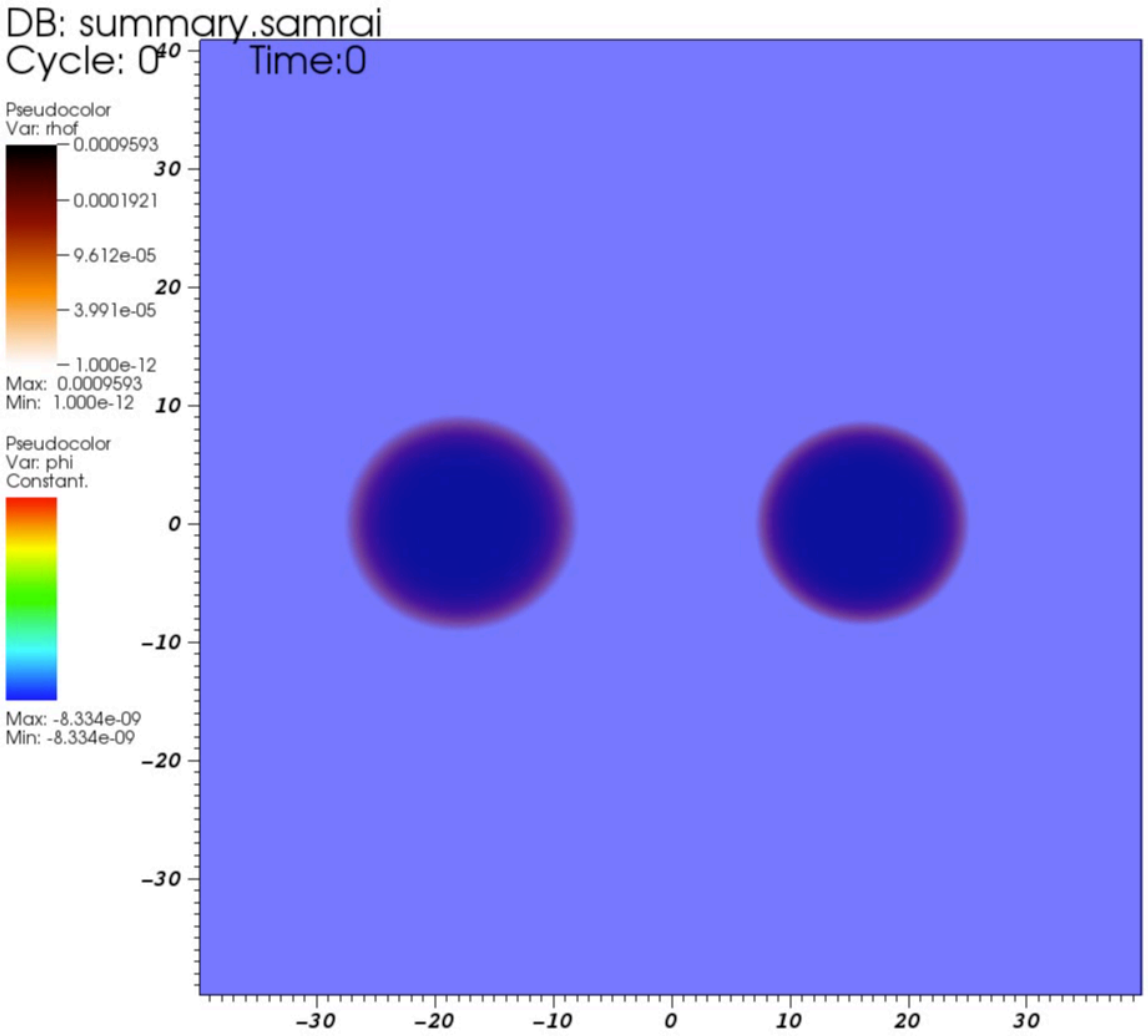
$[-1500, 1500]^3$ km

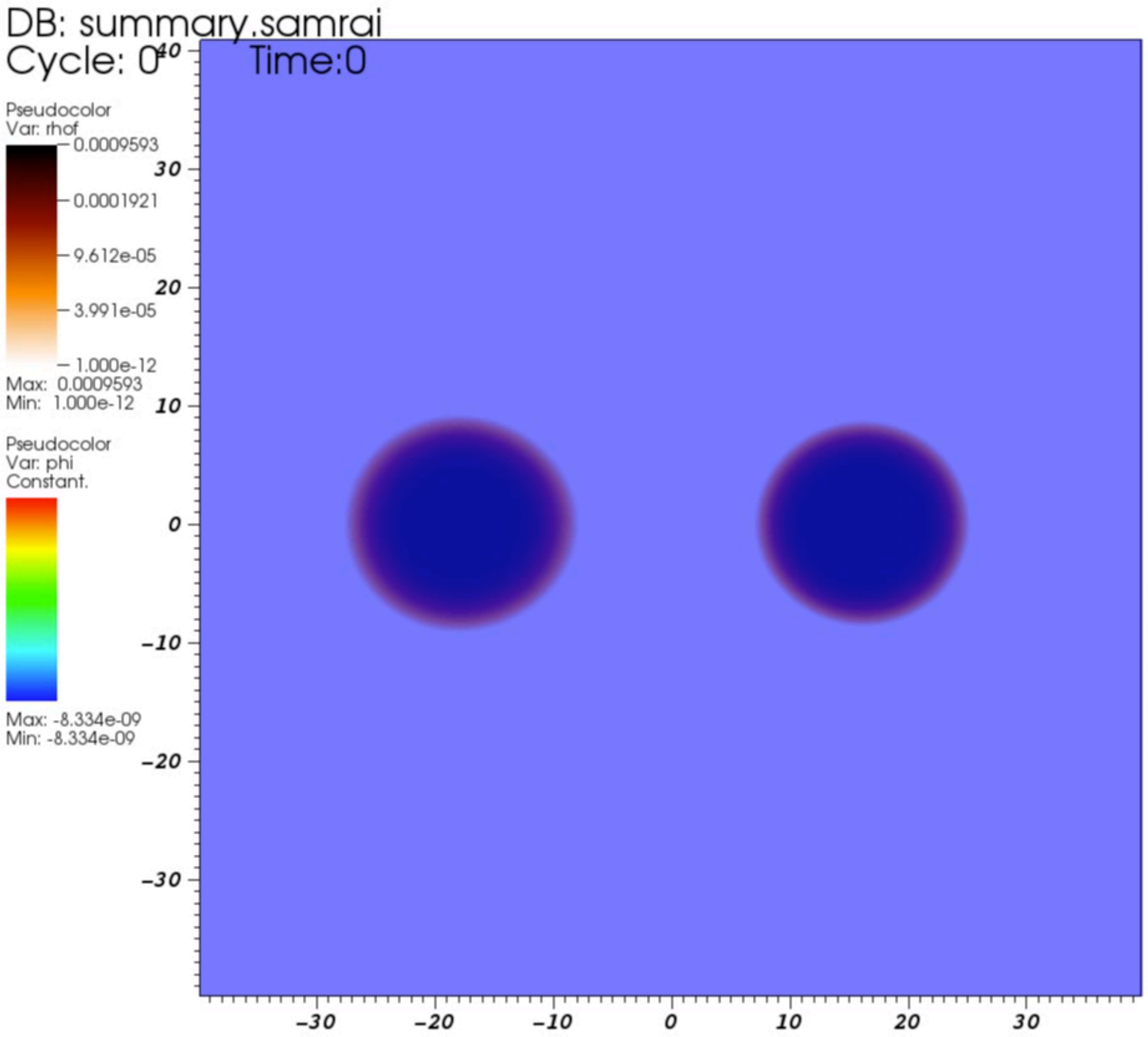


6 levels of refinement

$\Delta x = 300$ m

Binary NSs merger





Binary NSs merger

Binary NSs merger

Conclusions

- Screening mechanisms allow to reconcile large and short distances
- Test them in the dynamical regime of binary mergers
- Long overdue
- Interesting deviations from GR