Nonlinear Cosmological probes of <u>screened</u> gravity theories beyond General Relativity

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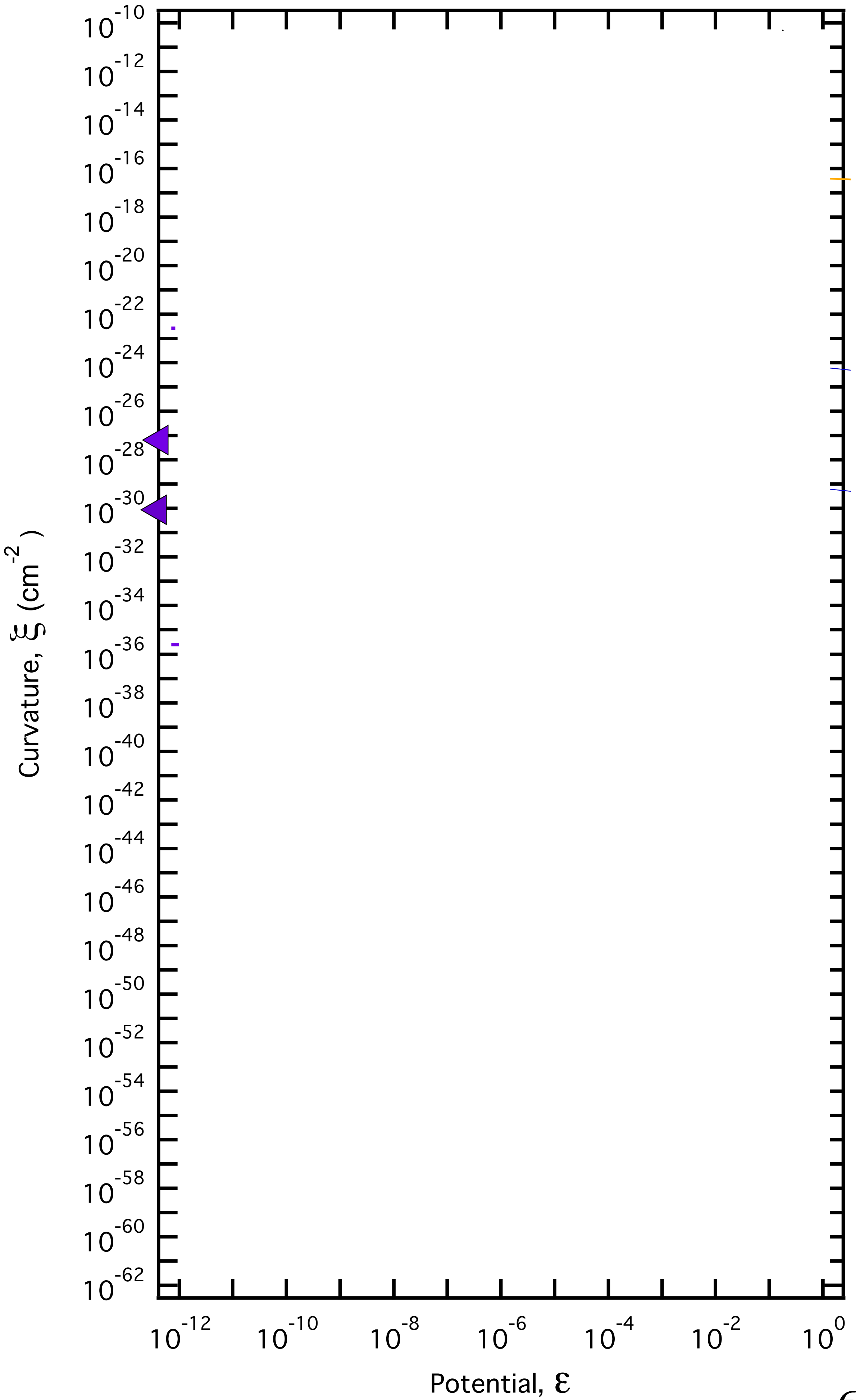
$$\xi = \frac{GM}{r^3c^2}$$

Kretschmann scalar



$$\epsilon = \frac{GM}{rc^2}$$

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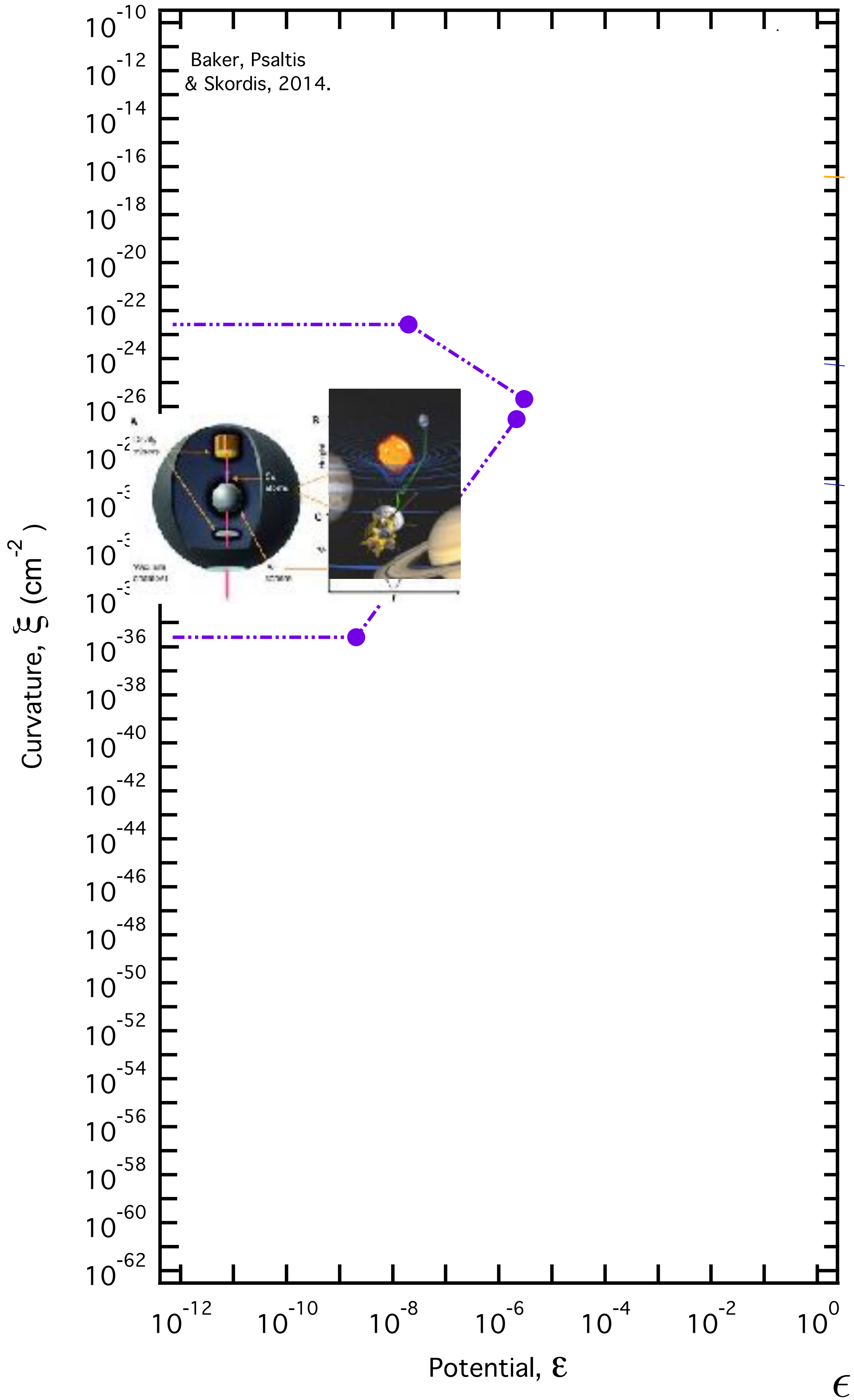
Kretschmann scalar



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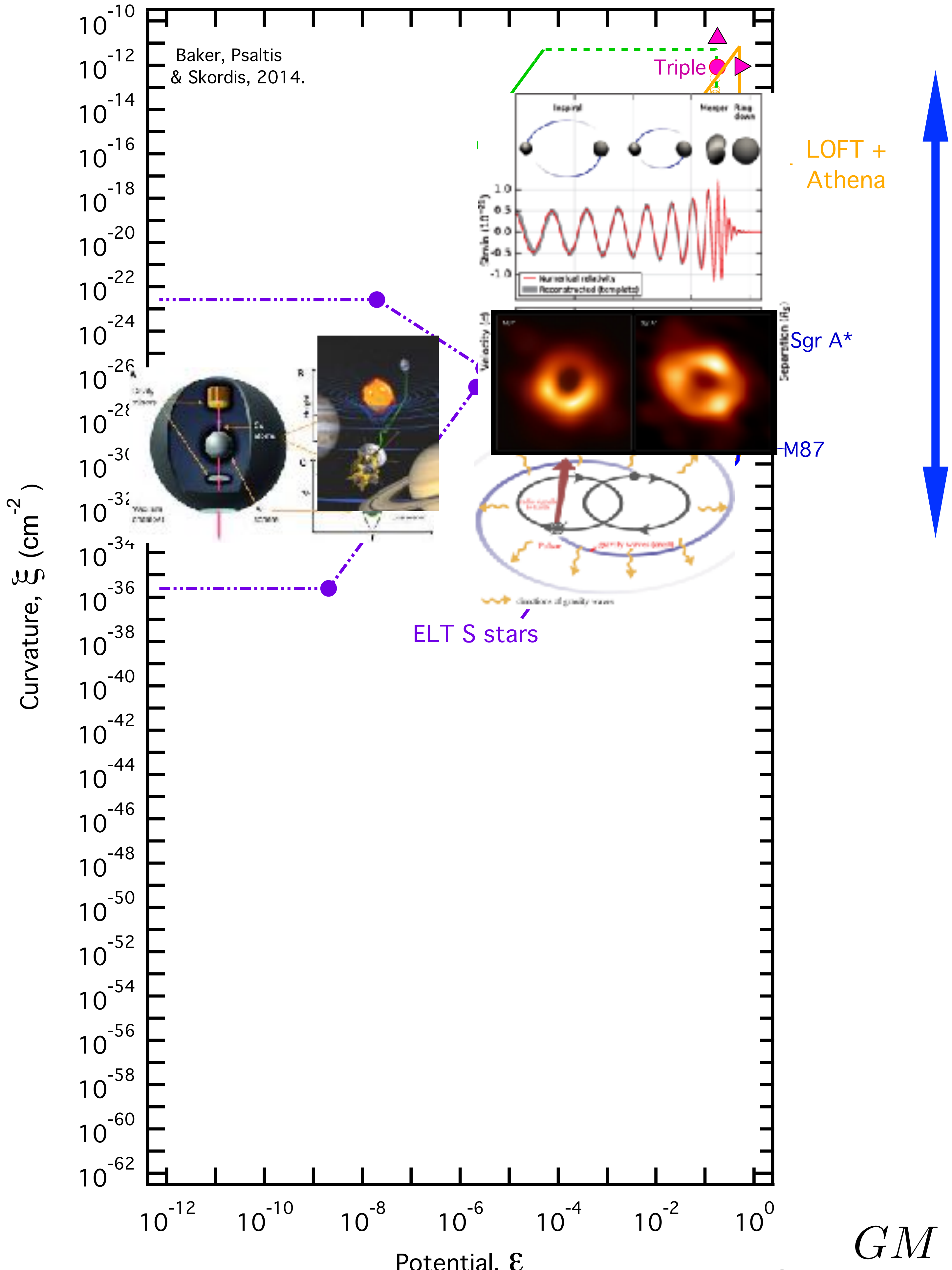

General Relativity works fine!

$$\epsilon = \frac{GM}{rc^2}$$

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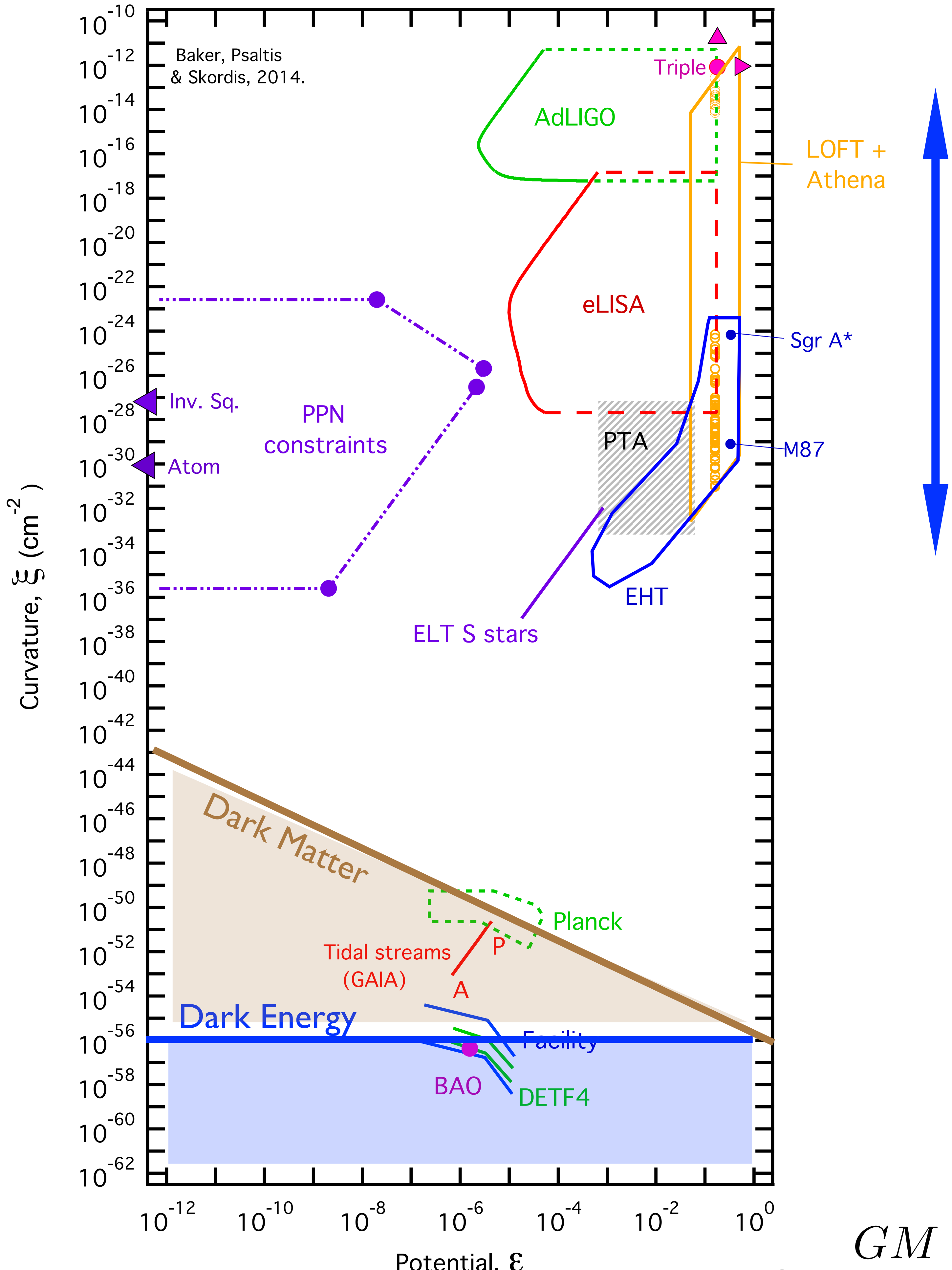

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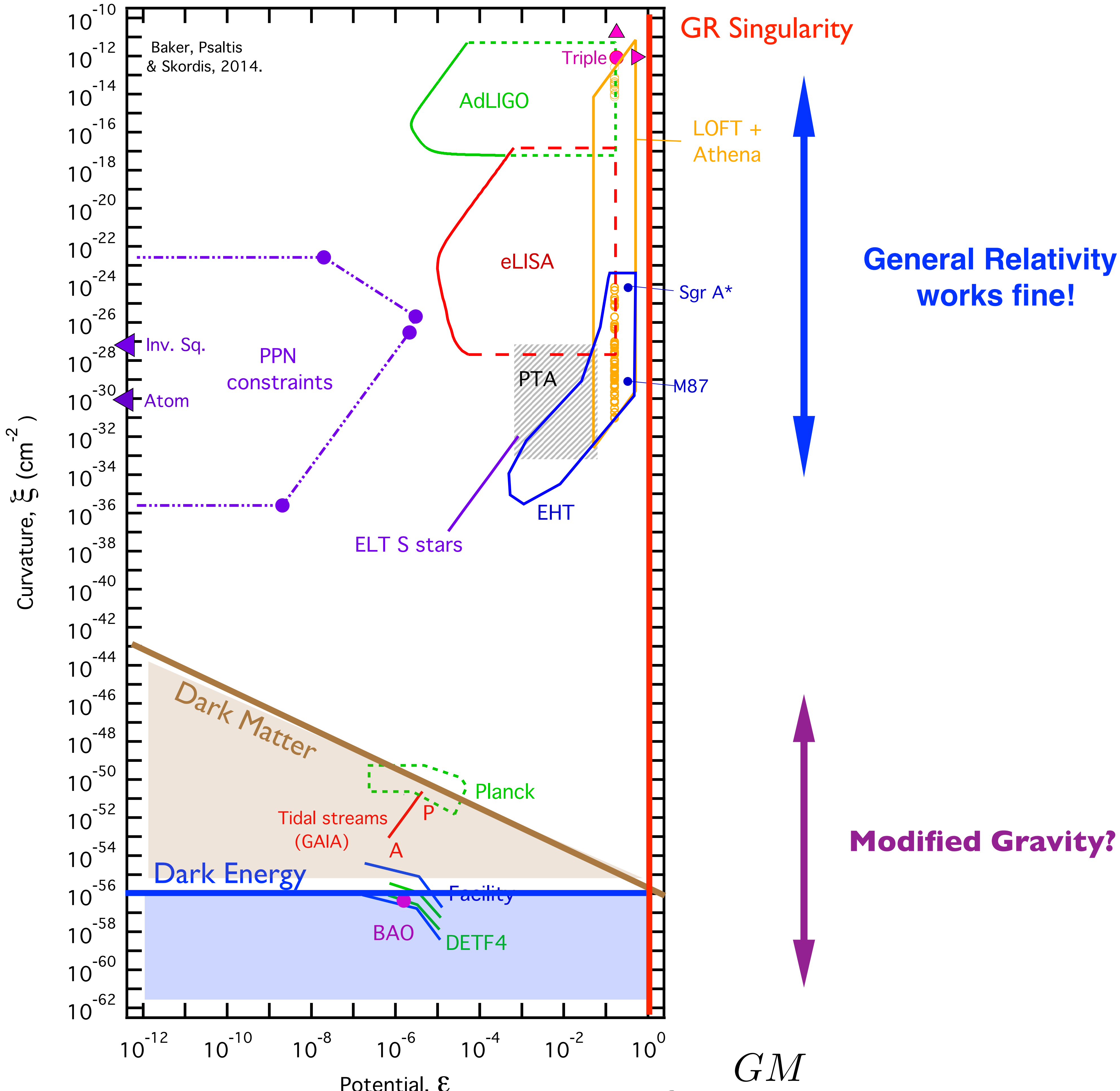
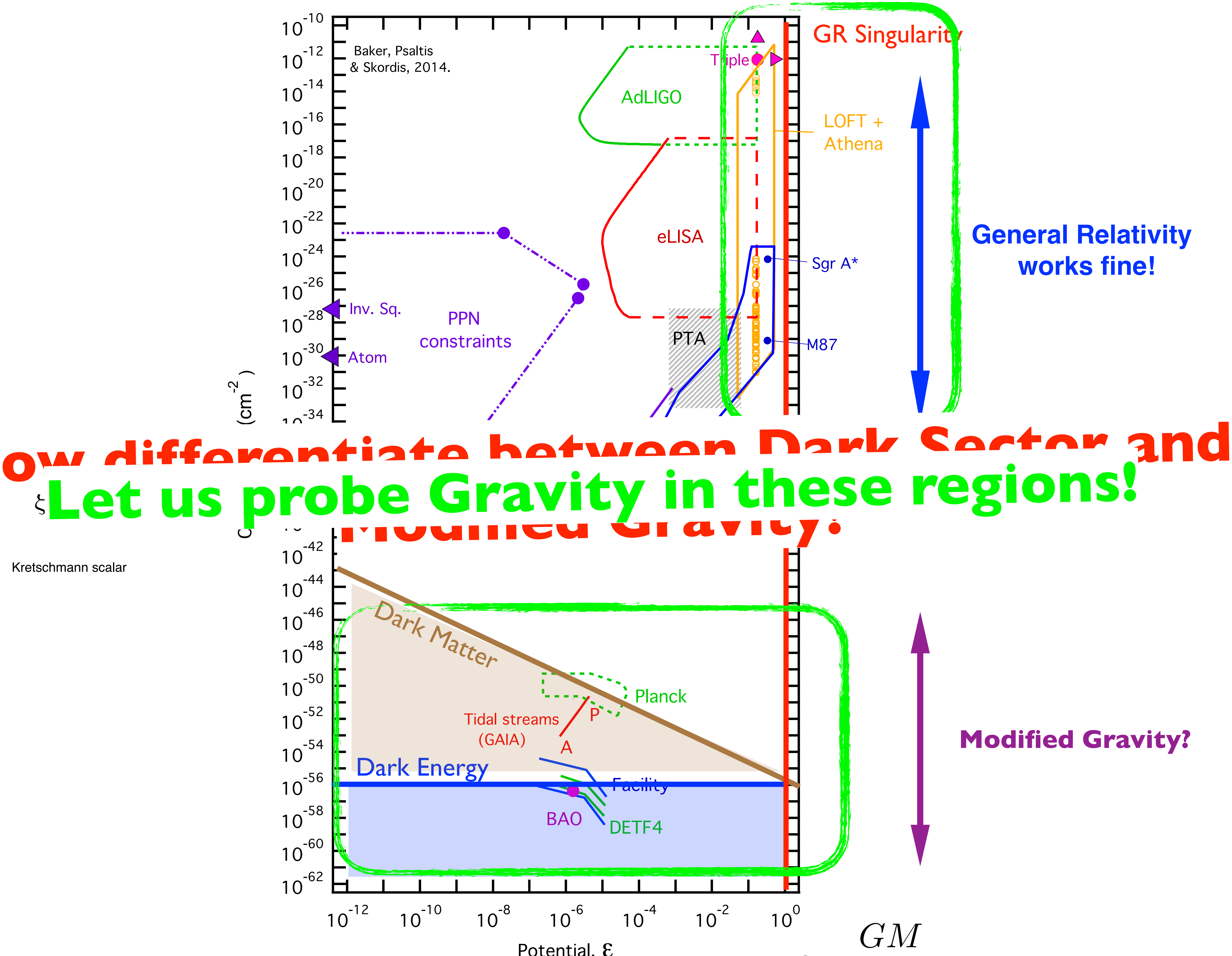


$$\epsilon = \frac{GM}{rc^2}$$



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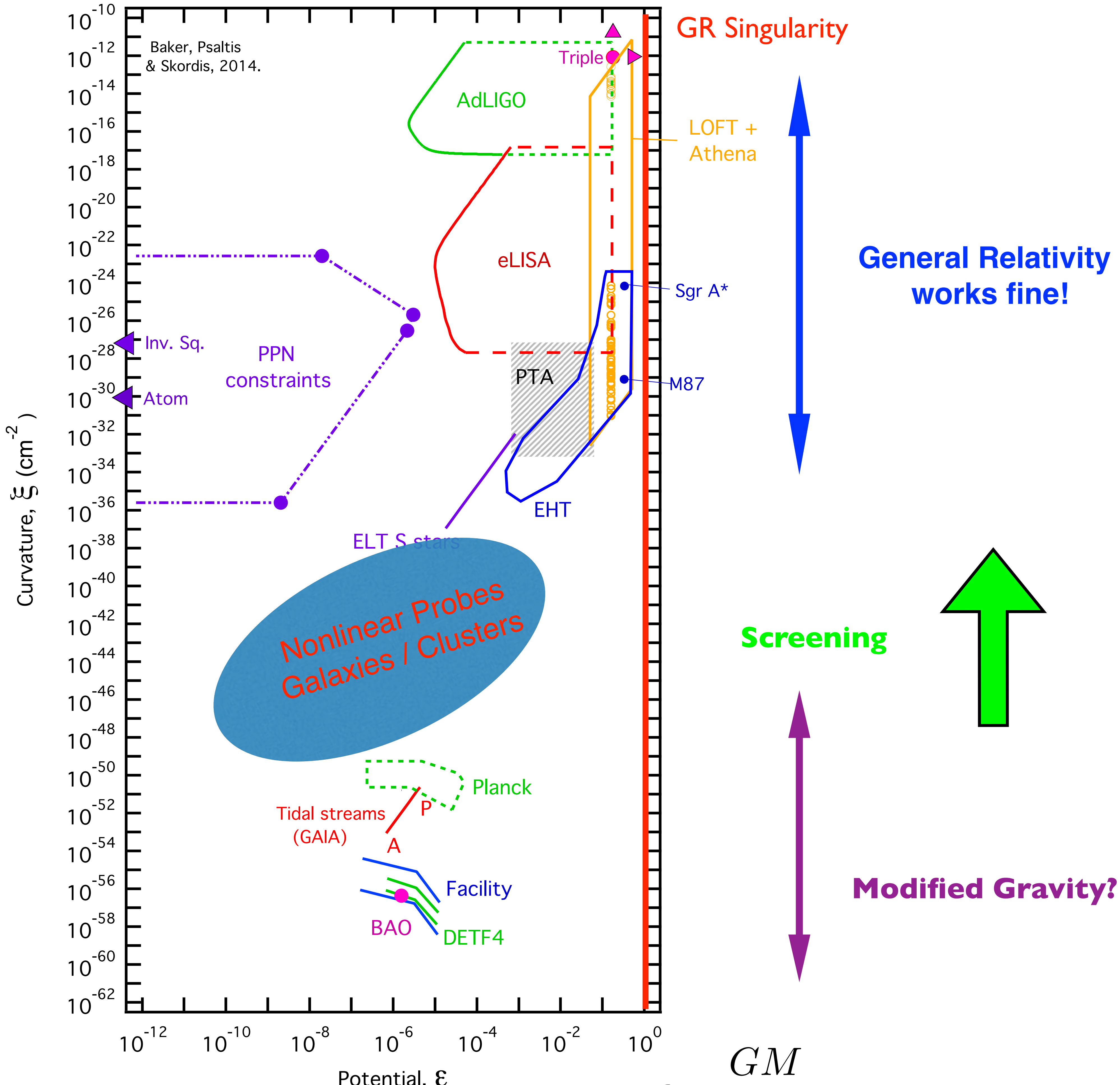
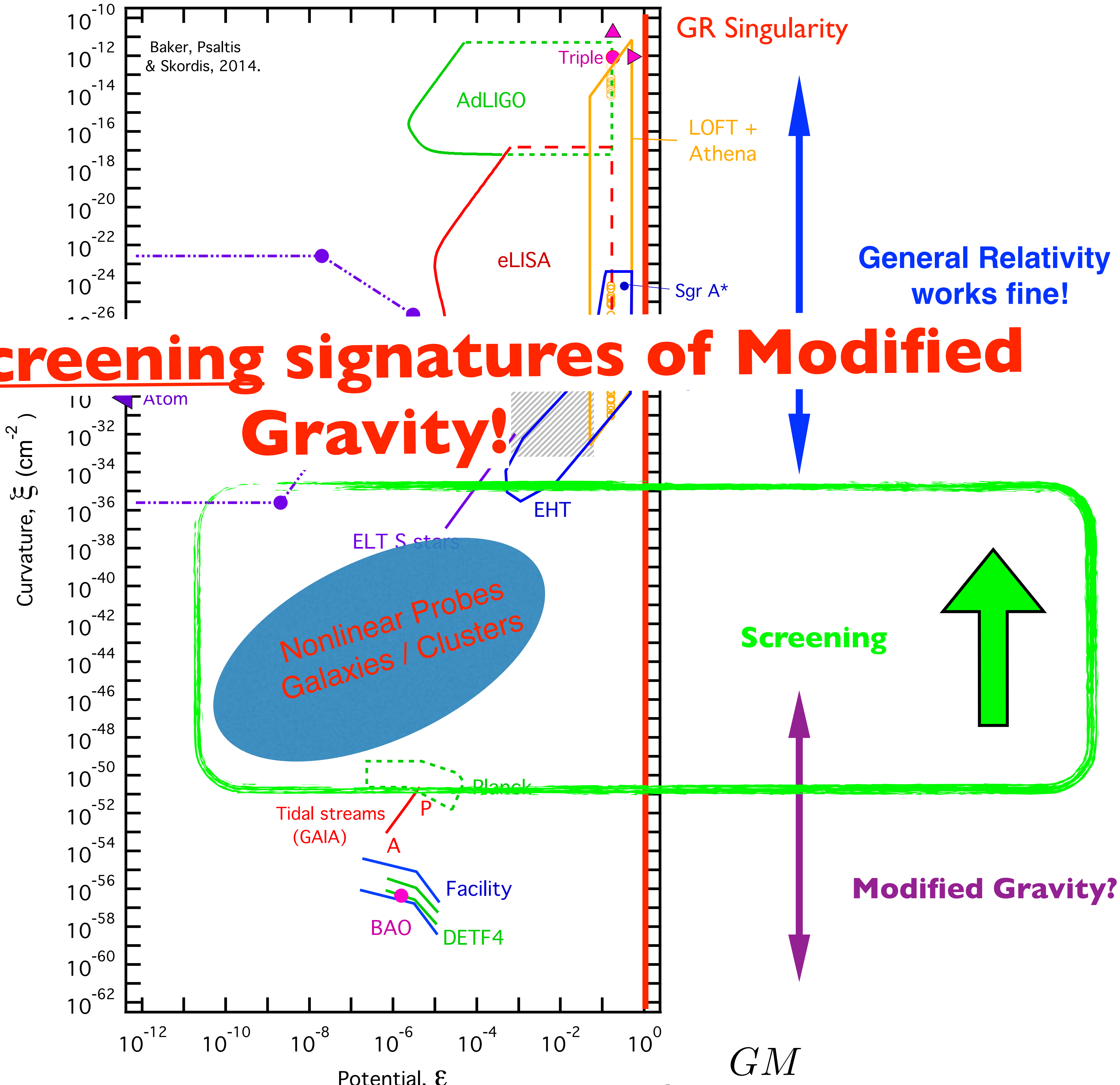


$$\epsilon = \frac{GM}{rc^2}$$

Probe Screening signatures of Modified Gravity!



$$\xi = \frac{GM}{r^3c^2}$$

Kretschmann scalar

$$\epsilon = \frac{GM}{rc^2}$$

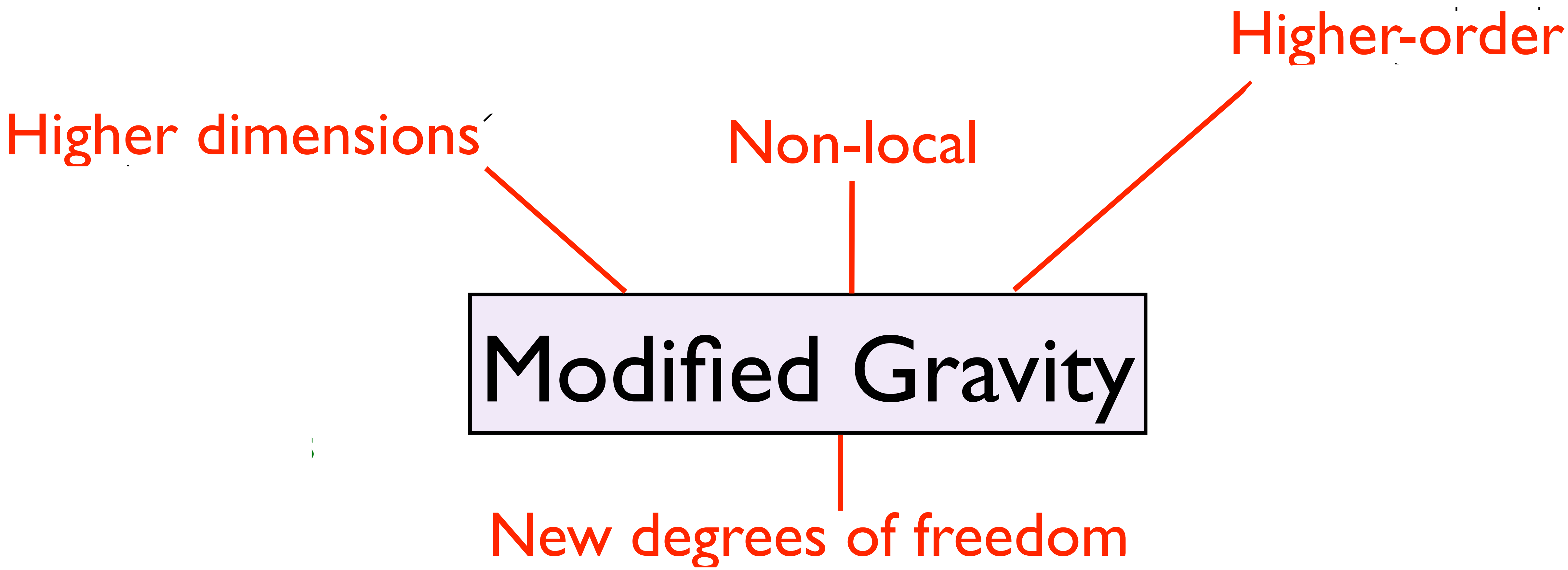
General Relativity is quite unique

Curvature

$$\frac{1}{16\pi G}\int d^4x\sqrt{-g}R(g)+\int d^4x\sqrt{-g}\mathcal{L}(g,\mathrm{matter})$$

Metric of space time

Lovelock's theorem (1971) :*"The only second-order, local gravitational field equations derivable from an action containing solely the 4D metric tensor (plus related tensors) are the Einstein field equations with a cosmological constant."*


Higher dimensions
Non-local
Higher-order
Modified Gravity
New degrees of freedom

Extra degrees of freedom in Scalar-Tensor Gravity

Fifth Force

Tensor field: $g^{\mu\nu}$
of General Relativity

+

Scalar field: Φ
Giving rise to a **5^{th} force**

Action: $S = \int d^4x \sqrt{-g} \left[\frac{M_{Pl}^2}{2} R - \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \, \partial_\nu \phi - V(\phi) \right] + \int d^4x \sqrt{-\tilde{g}} \mathcal{L}_m (\Omega_{(i)}^2(\phi) g_{\mu\nu}, \psi_m^{(i)})$

Screening Mechanisms in Scalar-Tensor Gravity

$$V = -\frac{GM}{r}(1 + \alpha e^{-mr})$$

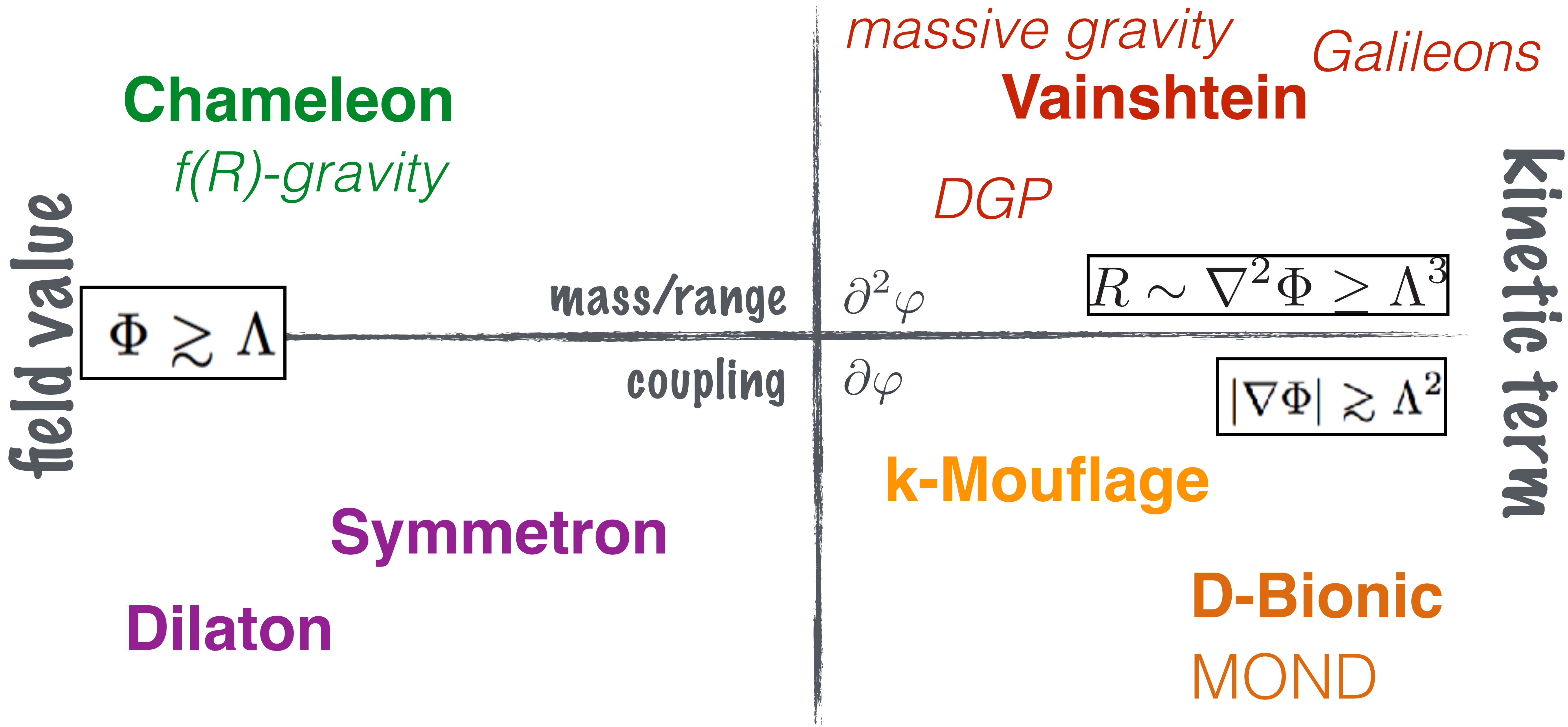
$$\mathcal{L} = -\frac{1}{2} Z^{\mu\nu}(\phi, \partial\phi, \ldots)\partial_\mu\phi\partial_\nu\phi - V(\phi) + g(\phi)T^\mu_\mu$$

$$V(r) = -\frac{g^2(\bar{\phi})}{Z(\bar{\phi})\, c_s^2(\bar{\phi})} \frac{e^{-\frac{m(\bar{\phi})}{\sqrt{Z(\bar{\phi})}\, c_s(\bar{\phi})} r}}{4\pi r} \rho \to 0$$

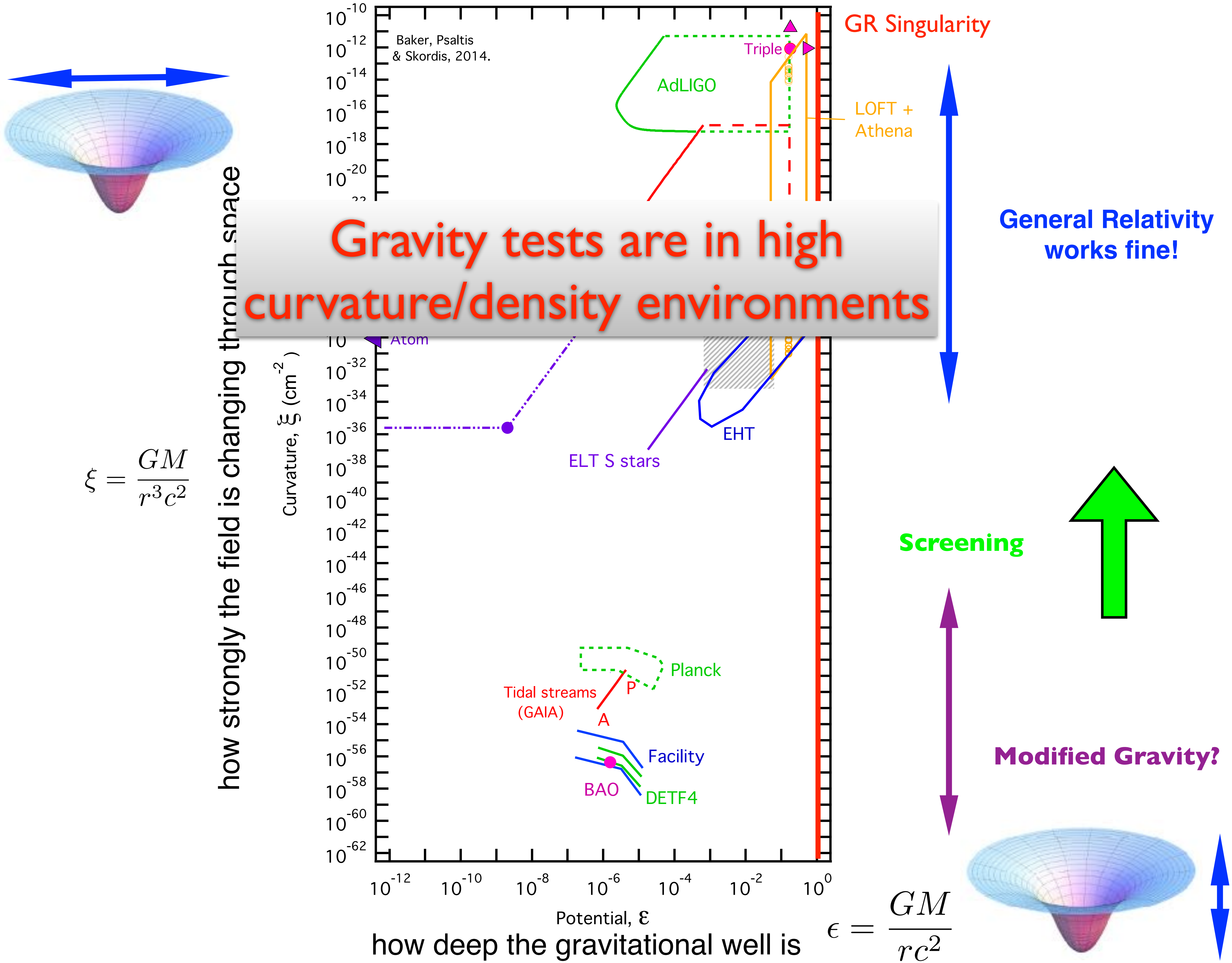
Screening mechanisms classification

$$\mathcal{L} = -\frac{1}{2} Z^{\mu\nu}(\phi, \partial\phi, \ldots)\partial_\mu\phi\partial_\nu\phi - V(\phi) + g(\phi)T^\mu_\mu$$

$$V(r) = -\frac{g^2(\bar\phi)}{Z(\bar\phi)c_s^2(\bar\phi)} \frac{e^{-\frac{m(\bar\phi)}{\sqrt{Z(\bar\phi)}c_s(\bar\phi)}r}}{4\pi r}\mathcal{M}$$



Gravity tests are in high curvature/density environments



$$\xi = \frac{GM}{r^3 c^2}$$

$$\epsilon = \frac{GM}{rc^2}$$

Symmetron Screening

Strength of fifth force depends on local density

$$S = \int d^4x \sqrt{-g}\left(\frac{M_{\rm Pl}^2}{2}R - \frac{1}{2}(\partial\phi)^2 - V(\phi)\right) + S_{\rm matter}\left[A^2(\phi)g_{\mu\nu}, \psi\right]$$

$$V = -\frac{GM}{r}\left(1 + \alpha e^{-mr}\right)$$

$$A(\phi) = 1 + \frac{1}{2M^2}\phi^2$$

coupling

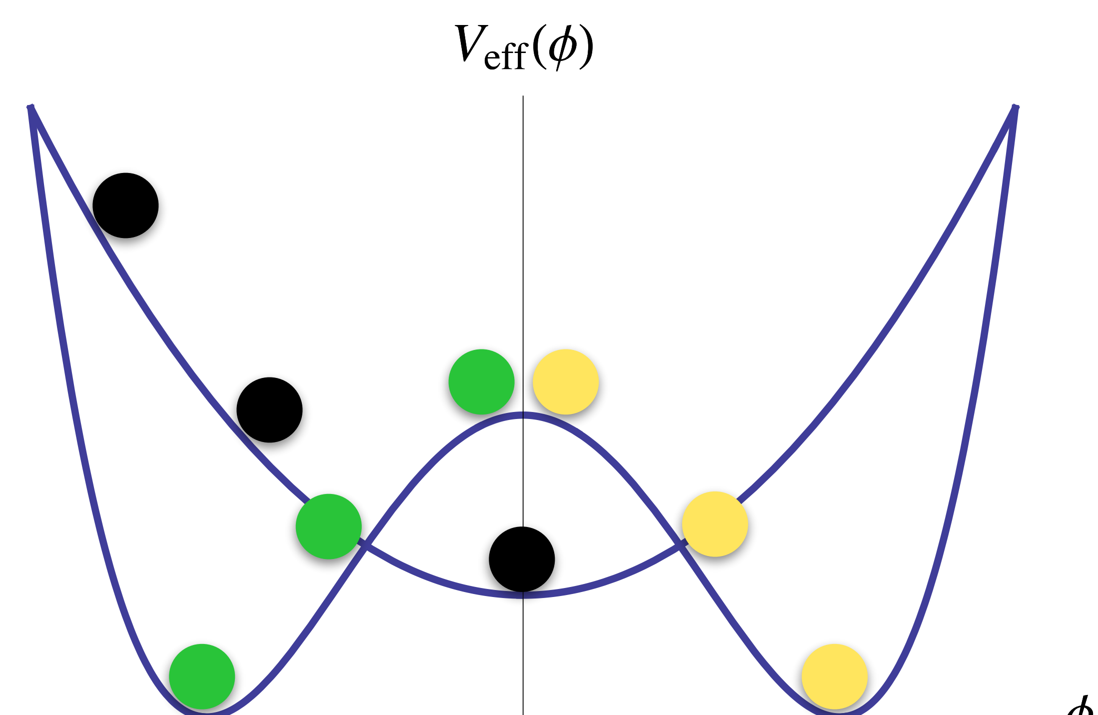
$$V_{\rm eff}(\phi) = \frac{1}{2}\left(\frac{\rho}{M^2} - \mu^2\right)\phi^2 + \frac{1}{4}\lambda\phi^4$$

(High density)

No coupling!

$$A(\phi) = 1$$

$$G_{eff} = G$$



(Low density)

coupled!

$$A(\phi) = 1 + \frac{1}{2M^2}\phi_{\rm vev}^2$$

$$G_{eff} = G(\phi)$$

Chameleon Screening

(Khoury & Weltman 2004)

Mass/Range of field depends on local density

$$S = \int \mathrm{d}^4x\sqrt{-g}\left(\frac{M_{\rm Pl}^2}{2}R - \frac{1}{2}(\partial\phi)^2 - V(\phi)\right) + S_{\rm matter}\left[A^2(\phi)g_{\mu\nu},\psi\right]$$

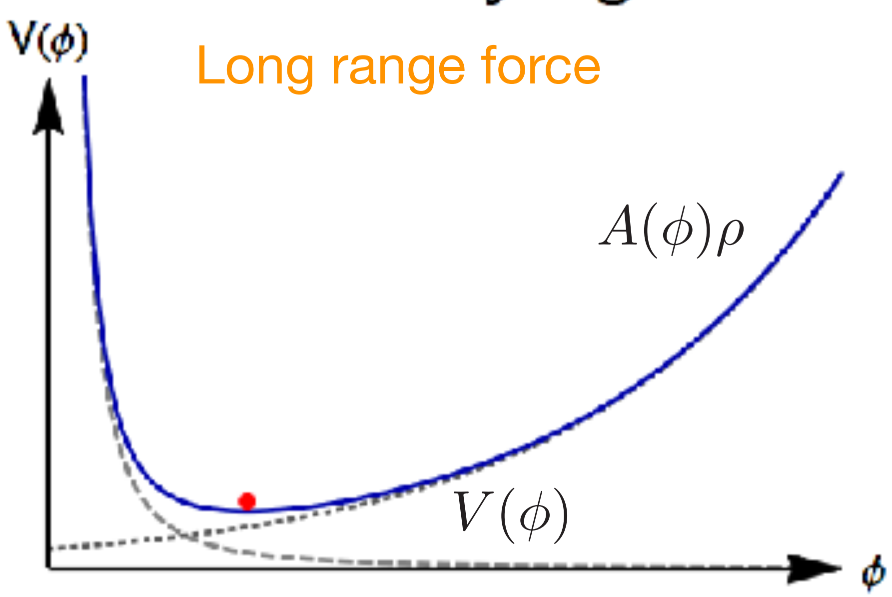
$$A(\phi) \simeq 1 + \xi\frac{\phi}{M_{\rm Pl}} \qquad V(\phi) = \frac{M^{4+n}}{\phi^n}$$

$$V = -\frac{GM}{r}(1+\alpha e^{-mr})$$

$$m_{\rm eff}^2(\bar\phi) = V^{\rm eff}_{,\phi\phi}(\bar\phi) = V_{,\phi\phi}(\bar\phi) + A_{,\phi\phi}(\bar\phi)\rho$$

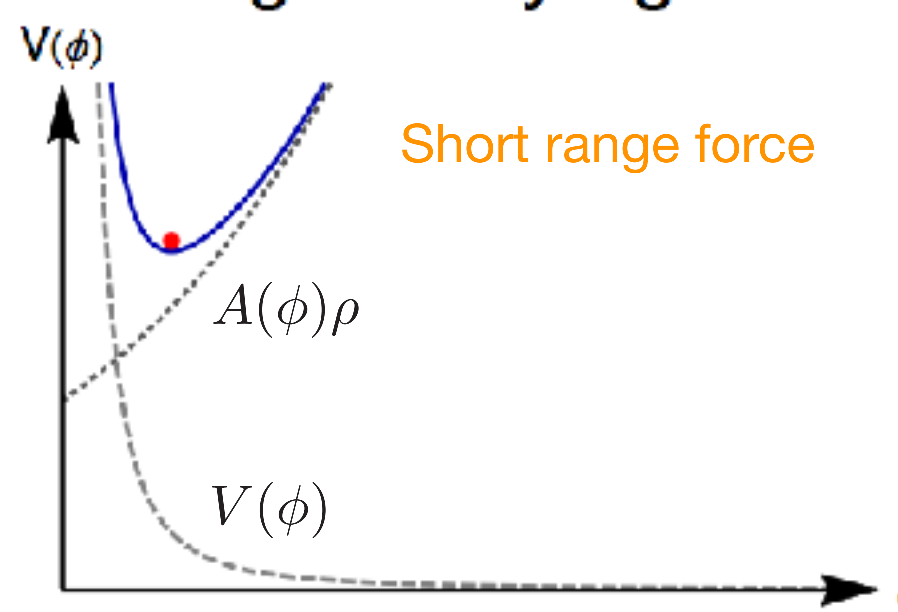
Mass

Low density region



$V''(\phi) \ll 1 \rightarrow$ Unscreened

High density region



$V''(\phi) \gg 1 \rightarrow$ Screened

Chameleon Screening

Mass/Range of field depends on local density

$$S = \int d^4x \sqrt{-g}\left(\frac{M_{\rm Pl}^2}{2}R - \frac{1}{2}(\partial\phi)^2 - V(\phi)\right) + S_{\rm matter}\left[A^2(\phi)g_{\mu\nu}, \psi\right]$$

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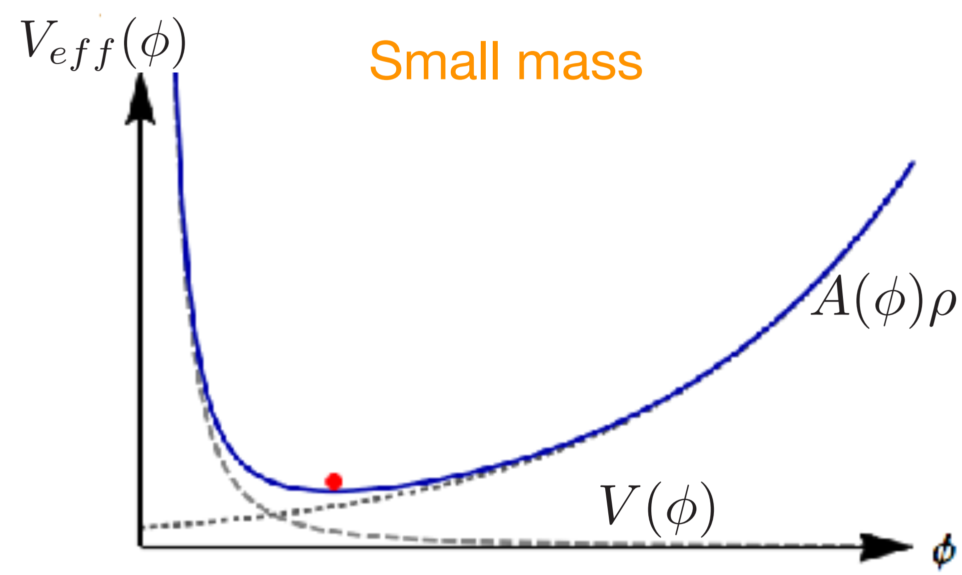
Low density region



$V''(\phi) \ll 1 \rightarrow$ Unscreened

Chameleon f(R)-gravity

$$S = \frac{M_{\rm Pl}^2}{2}\int d^4x\sqrt{-g}\Big(R + f(R)\Big) + S_{\rm matter}[g_{\mu\nu}, \psi]$$

$$f(R) = -\frac{aM^2}{1 + \left(\frac{R}{M^2}\right)^{-\alpha}}$$

Structure formation probes deviations from GR

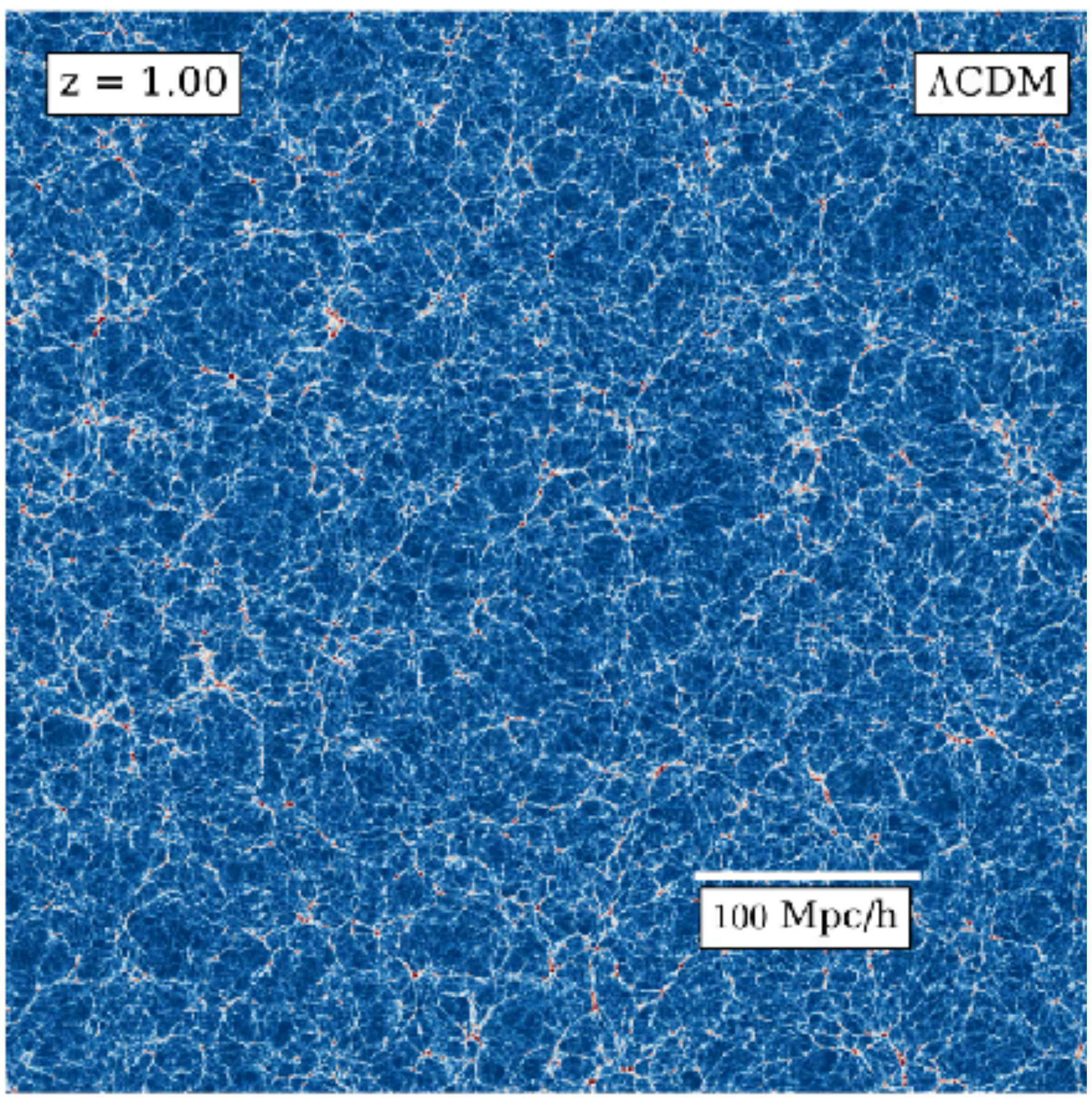
(Christiansen, Adamek, Hassani, DFM)

$$\ddot{\mathbf{x}} = -\nabla\Psi_N - f(\phi)\nabla\phi$$

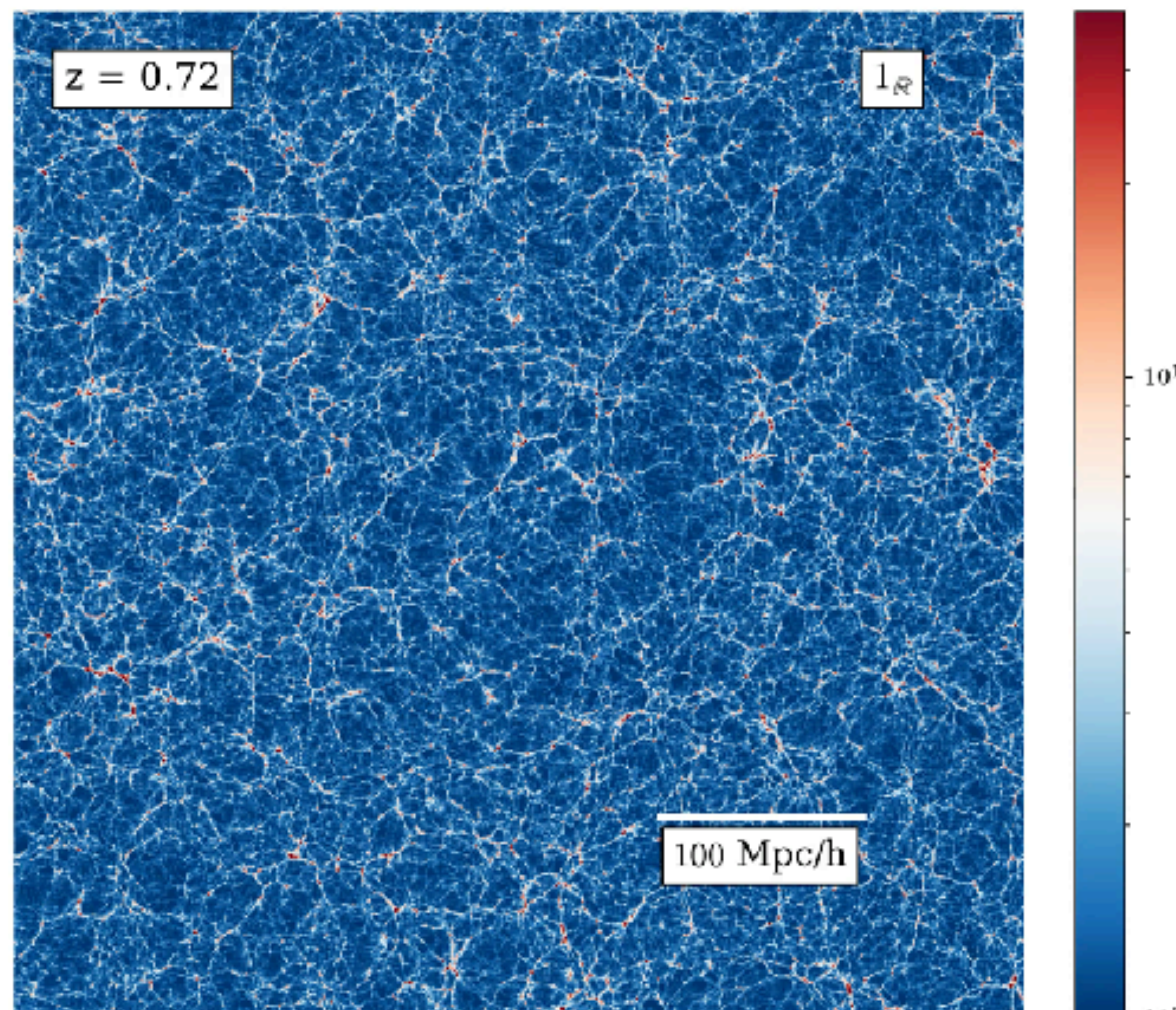
GR

Fifth Force

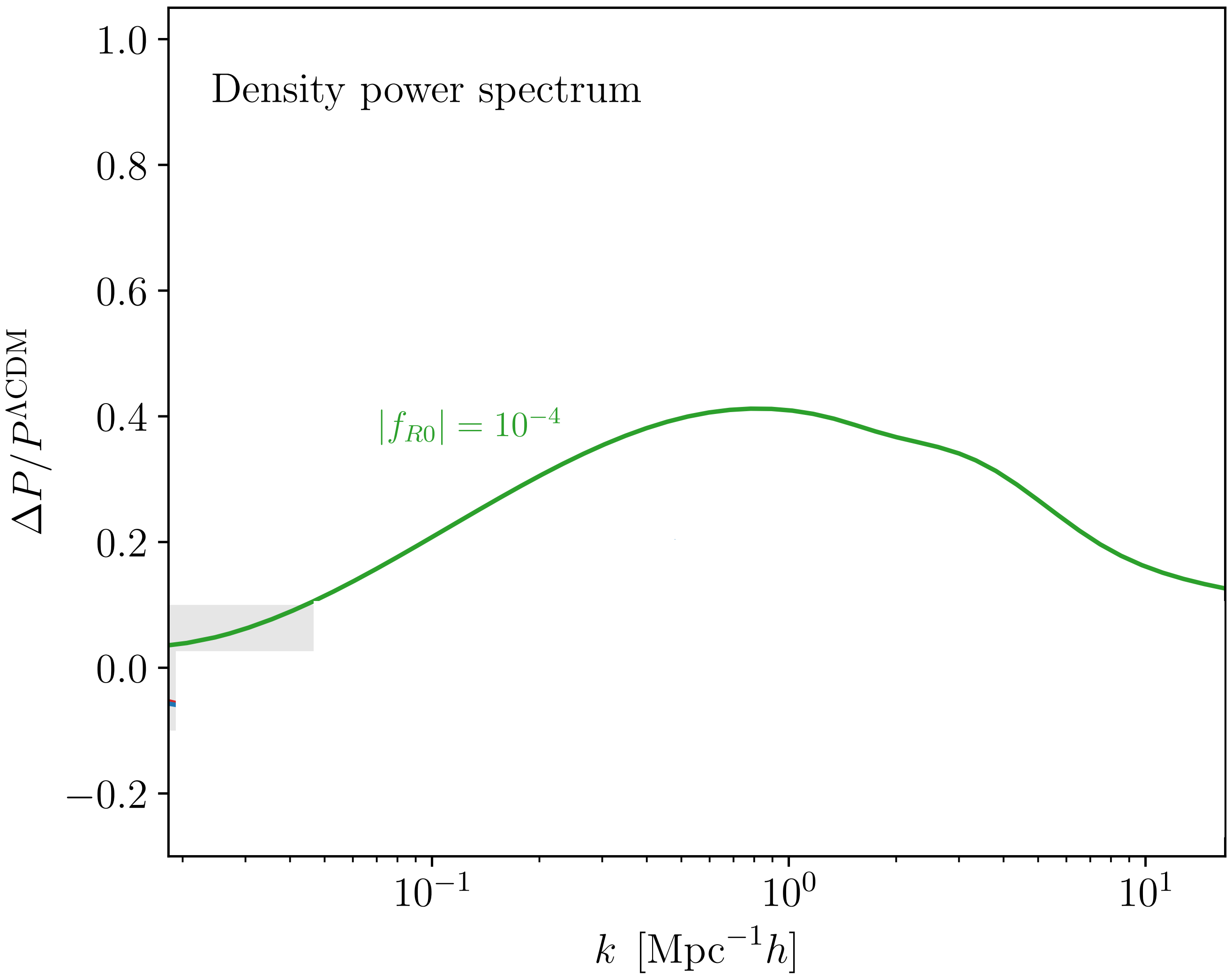
General Relativity



Modified Gravity (Symmetron)

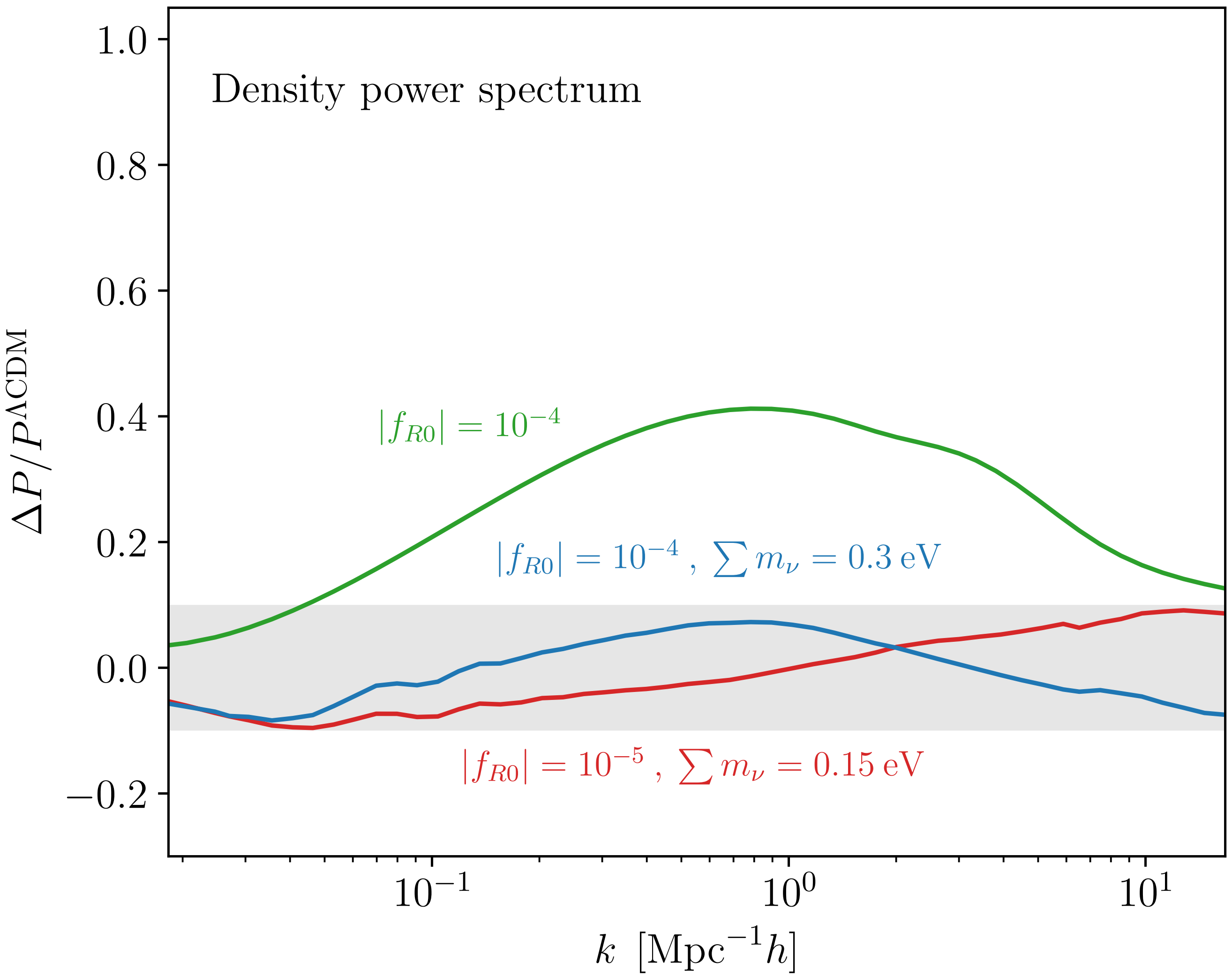


Matter Power Spectrum as a probe of Modified Gravity



Hagstotz, Gronke, DFM A&A

Neutrinos masses degenerated with Modified Gravity



Hagstotz, Gronke, DFM A&A

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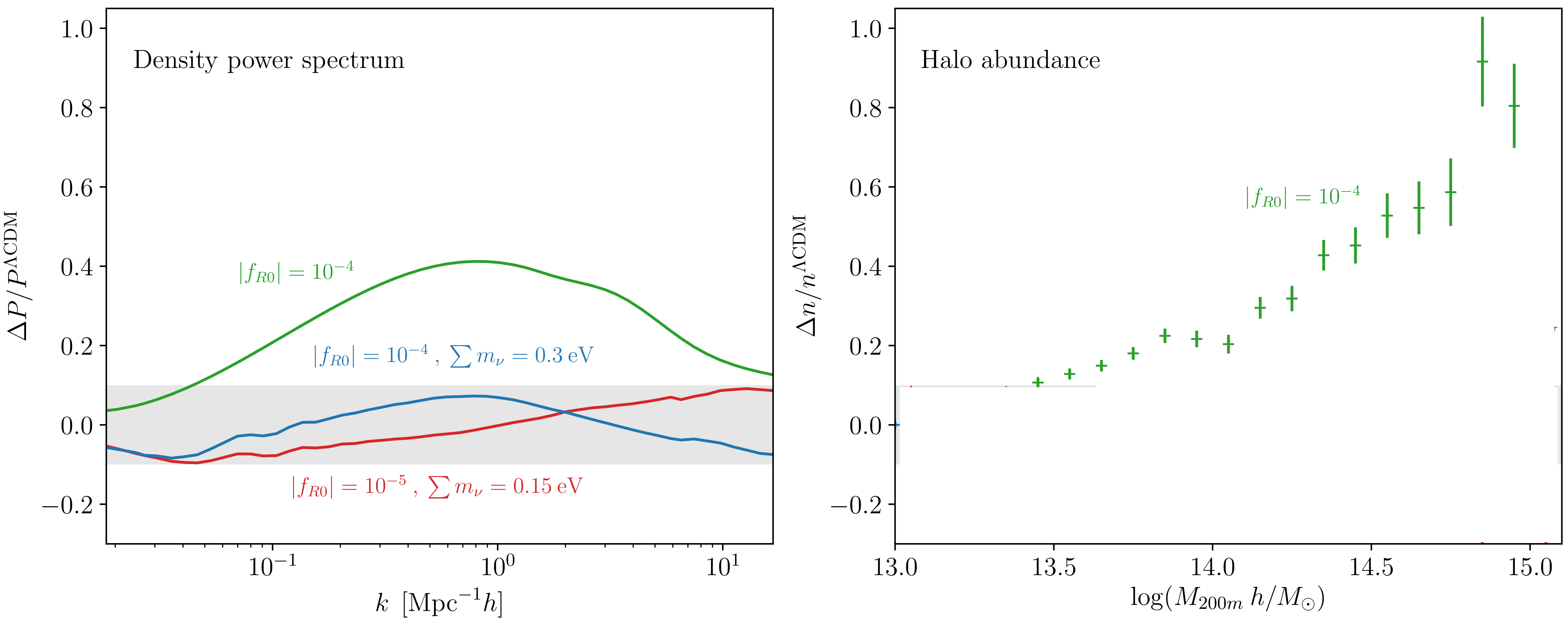
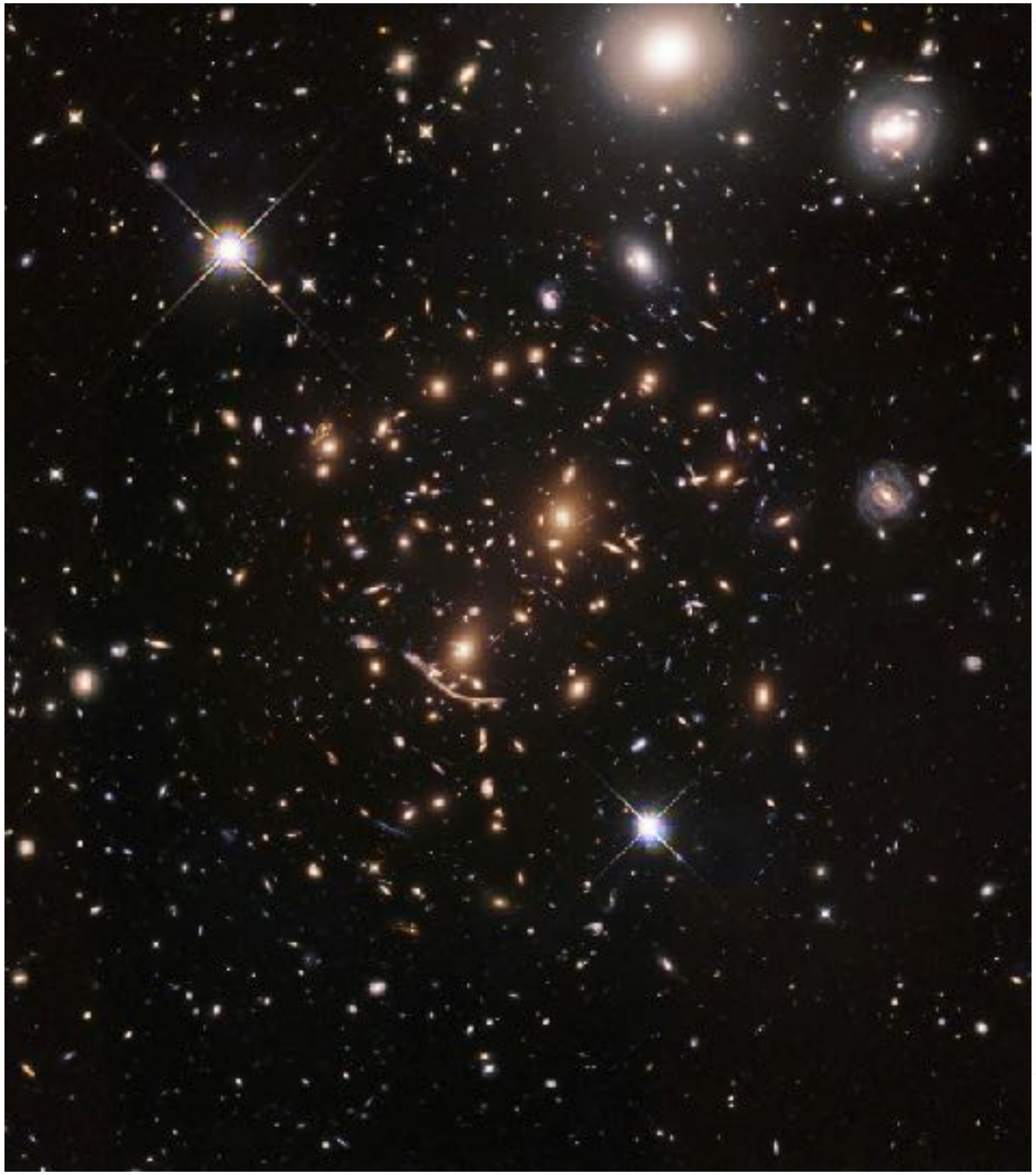
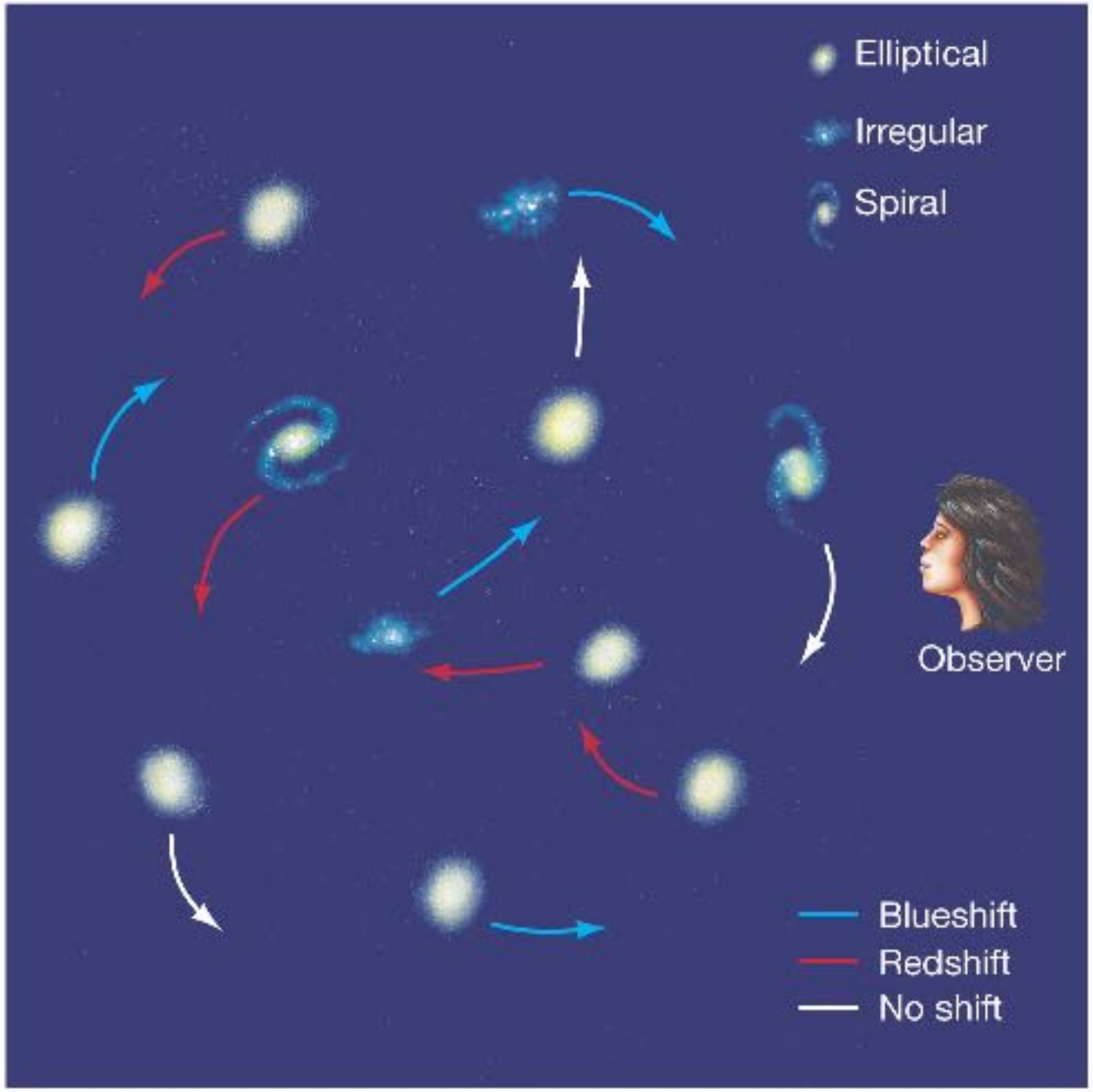


Large deviation caused by modified gravity growth counteracted by massive neutrinos

Hagstotz, Gronke, DFM A&A

Cluster Velocity Profiles

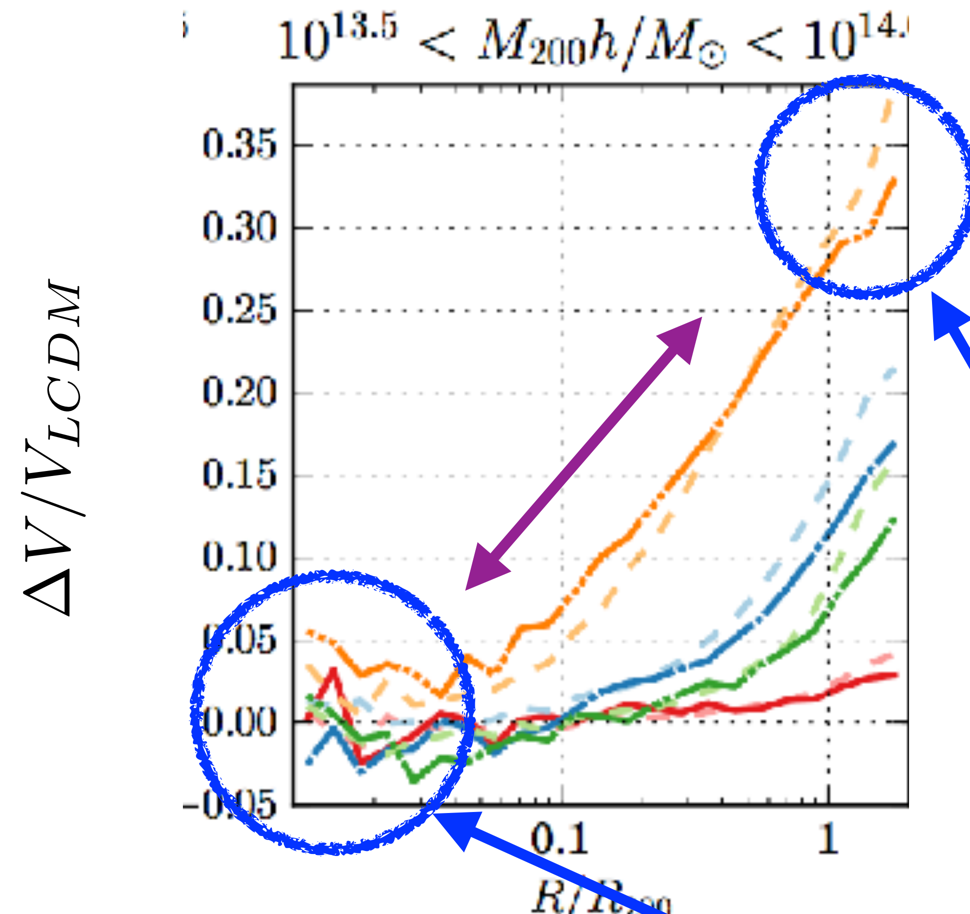


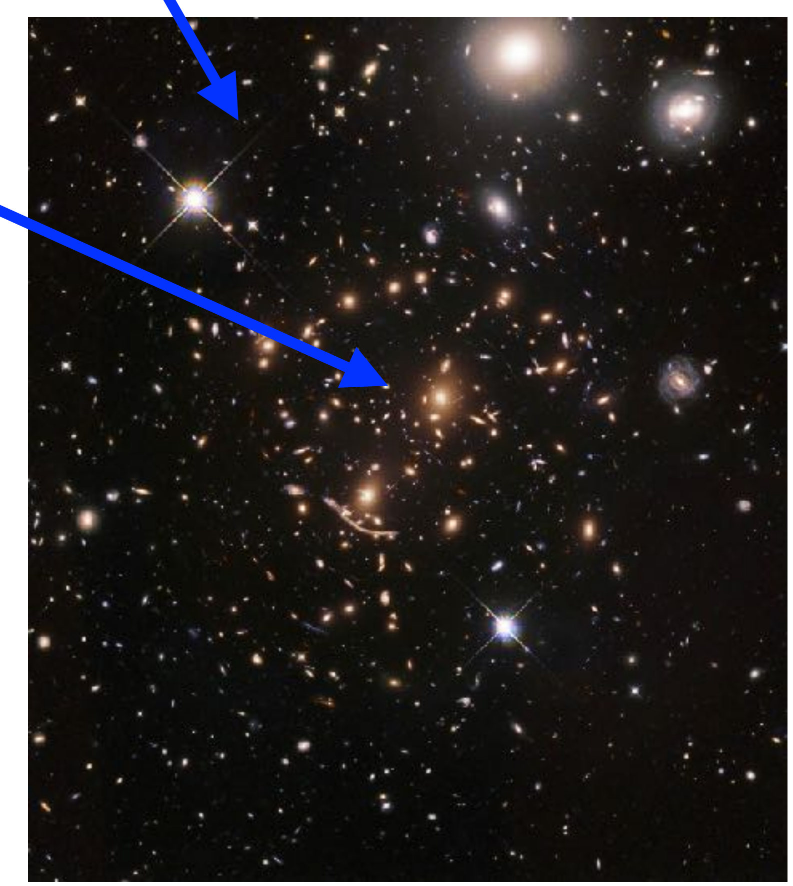


Velocity profiles

dependence on the halo mass

Gronke, Llinares, DFM, Winther

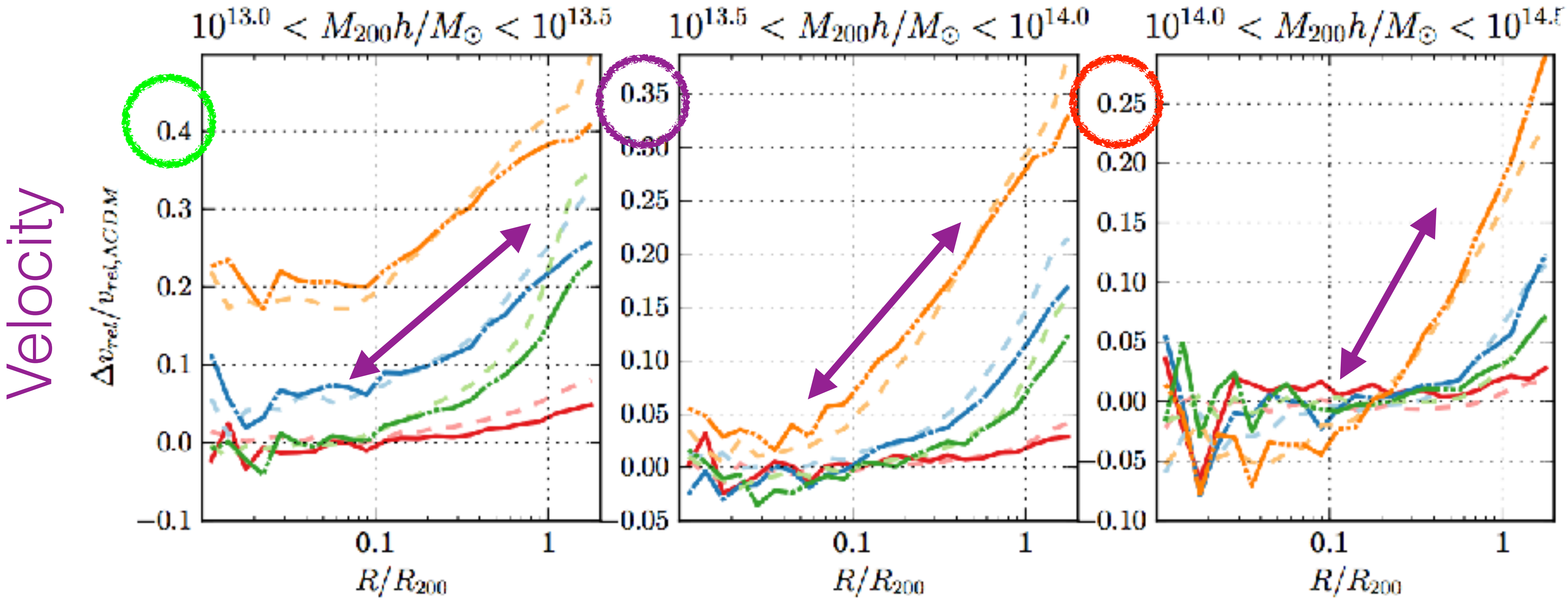


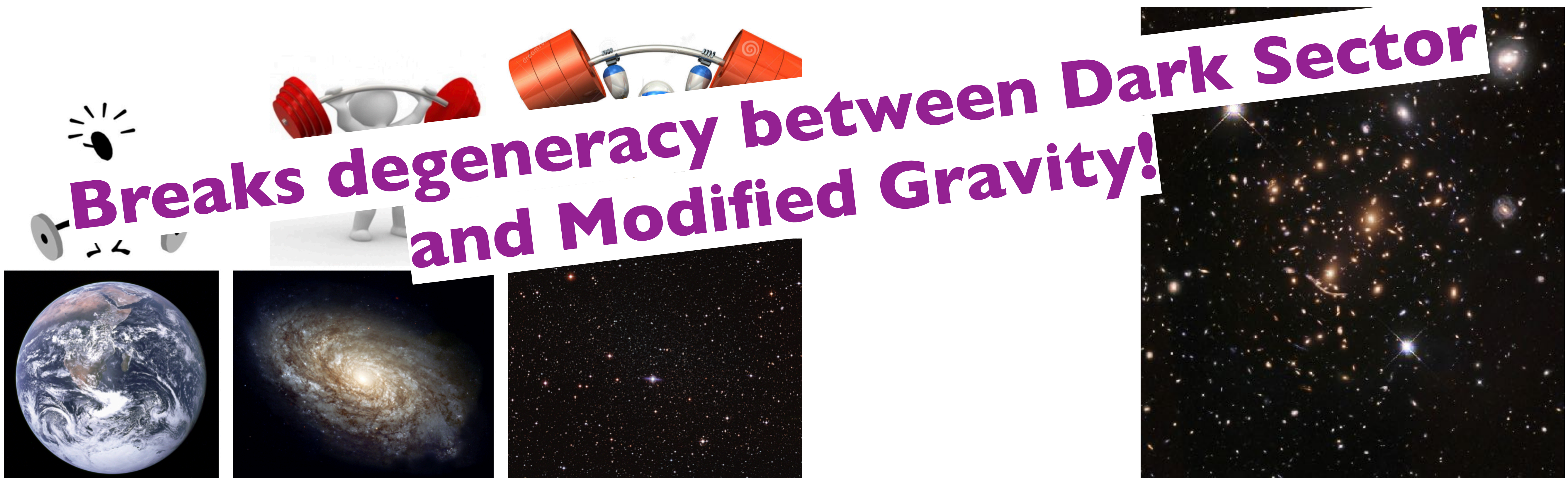


Velocity profiles

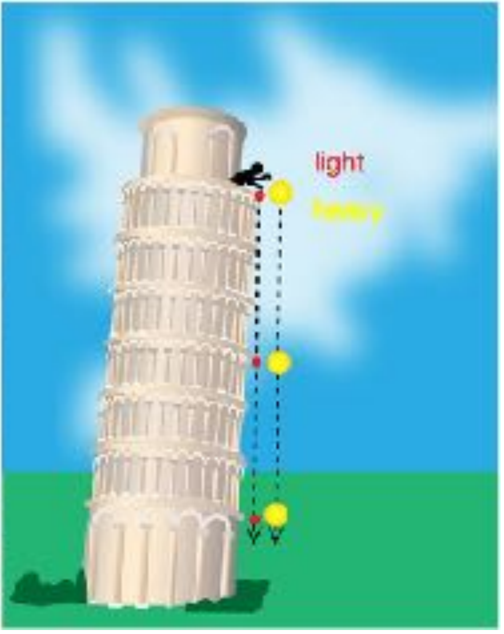
Modified Gravity smoking gun

Gronke, Llinares, DFM, Winther





Breaks degeneracy between Dark Sector and Modified Gravity!



Equivalence Principle

Inertial mass vs. Gravitational mass

- **<u>Inertial Mass</u>** - The greater the mass, the greater force it takes to change its motion (acceleration)

Inertial mass

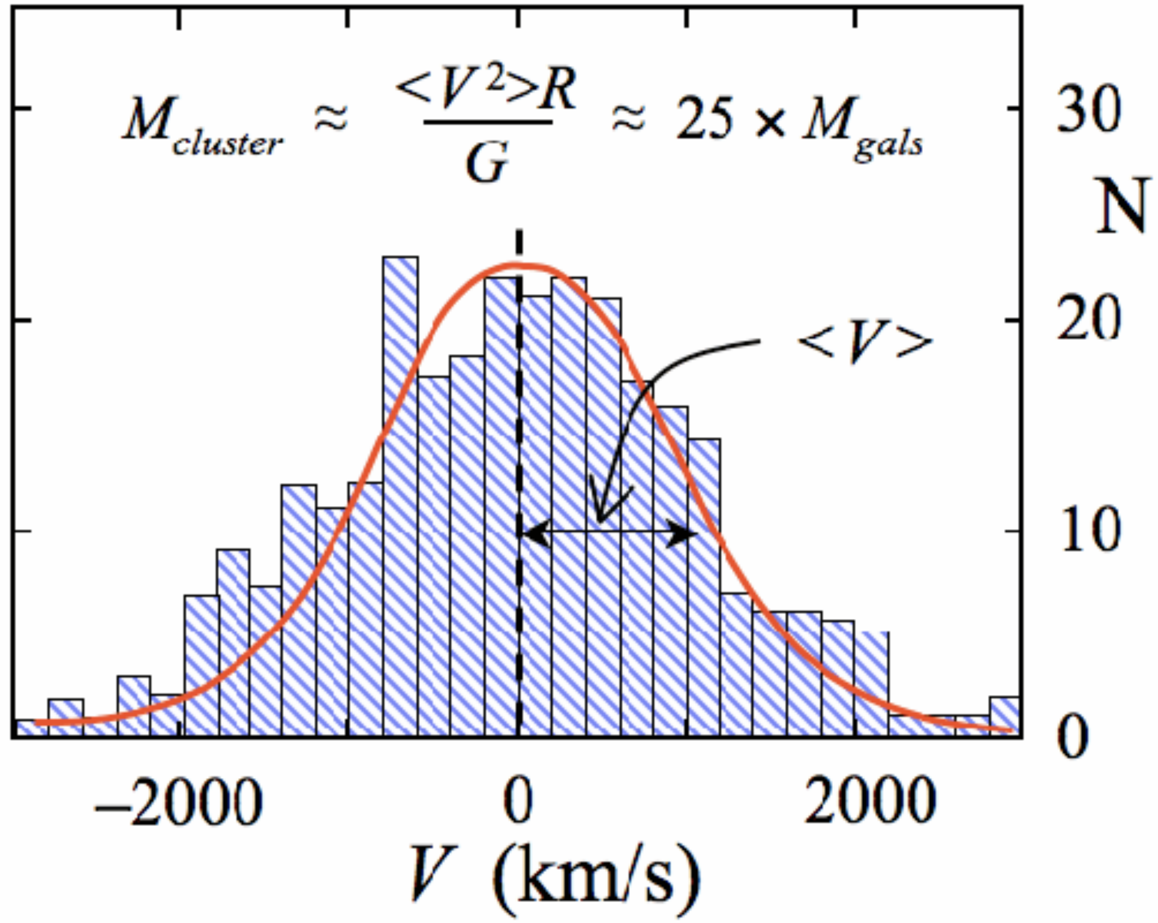
$$F = ma$$

Equivalence principle: They are the same in GR!

Kinematical Mass (Inertial mass)

from velocity dispersions of galaxies

Coma cluster (central part)

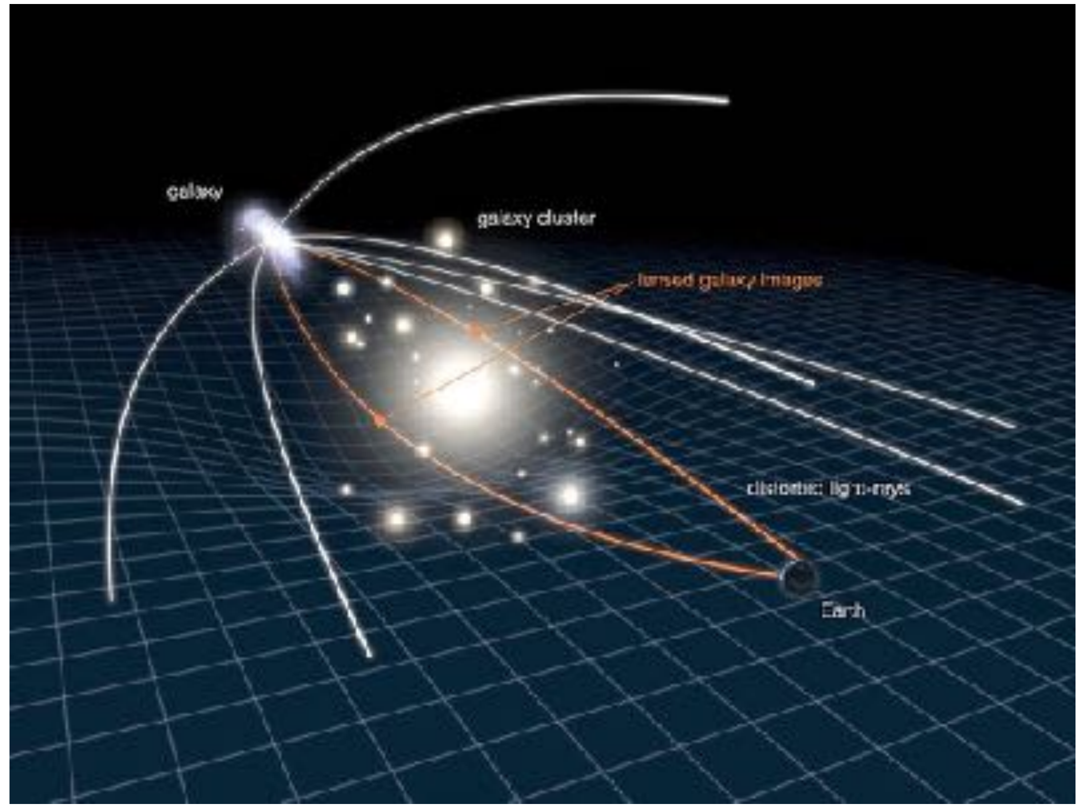


$$M_{kinematic}\frac{< V^2 >}{R} = F_N + \mathbf{F}_\phi$$

Modified Gravity <u>enhances</u> kinematical mass estimates for same velocity dispersion

Clusters Masses

Gravitational Mass: measured via lensing



Conformal Invariance: null geodesic not affected by Modified Gravity

$$\nabla^2 \Phi_+ = 4\pi G a^2 \delta\rho$$

$$\Phi_+ \equiv (\Phi + \Psi)/2$$

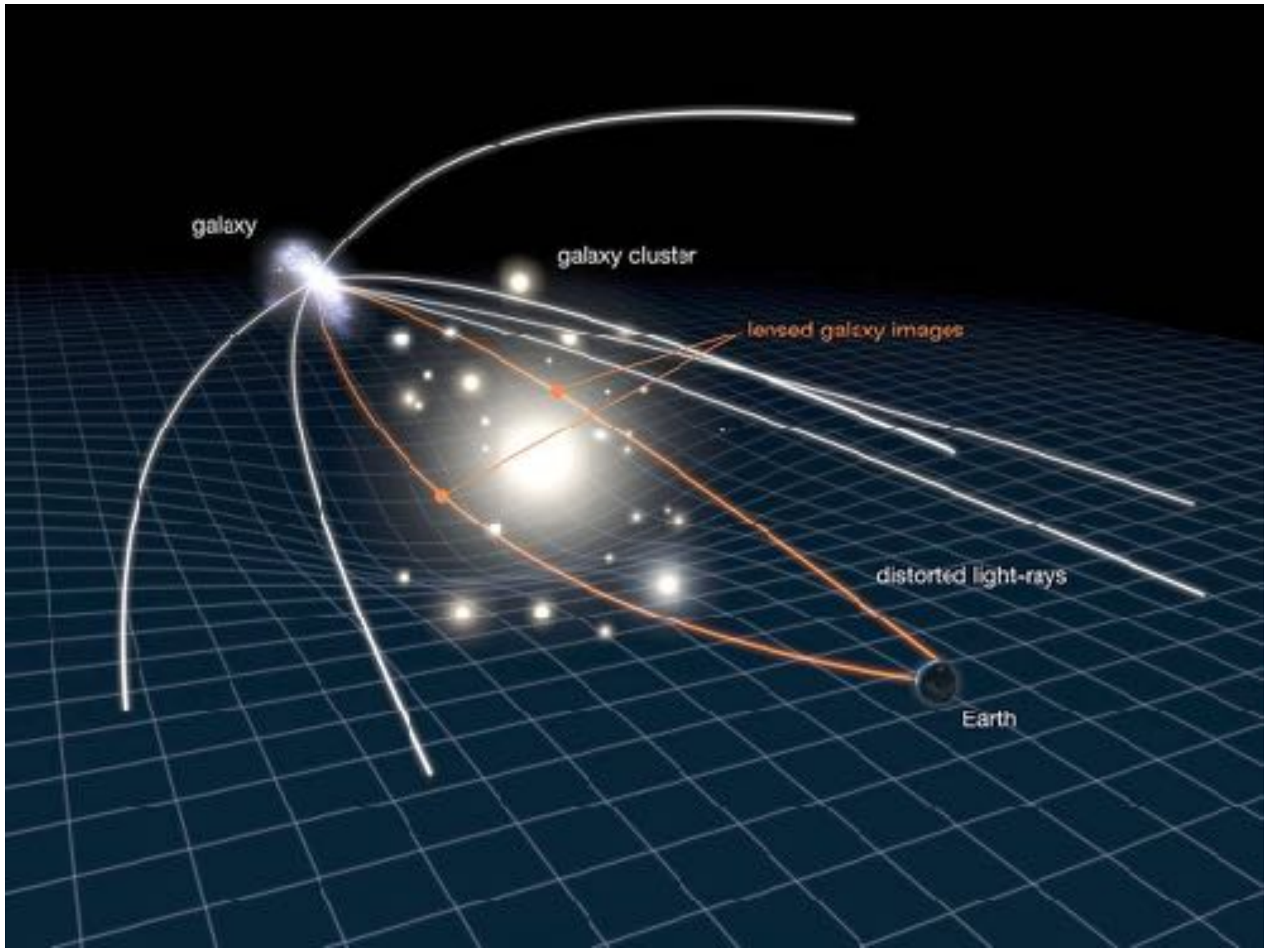
Lensing potential as in GR!

Lensing Mass in (conformal) Modified Gravity same as GR

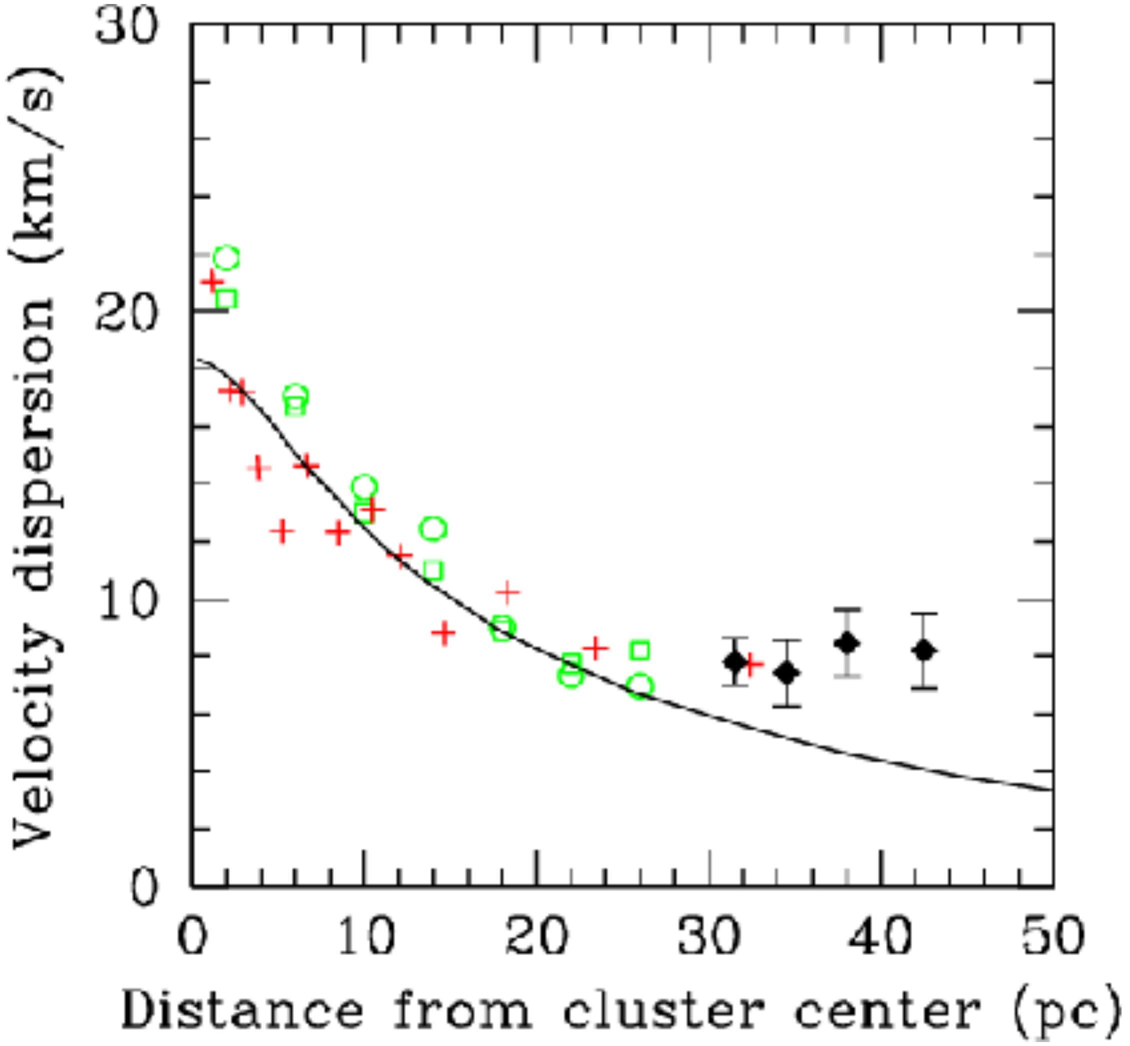
Smoking gun for Gravity beyond Einstein

Lensing Mass vs. Kinematic Mass

Lensing Mass same as in GR



Kinematic Mass depends on extra forces

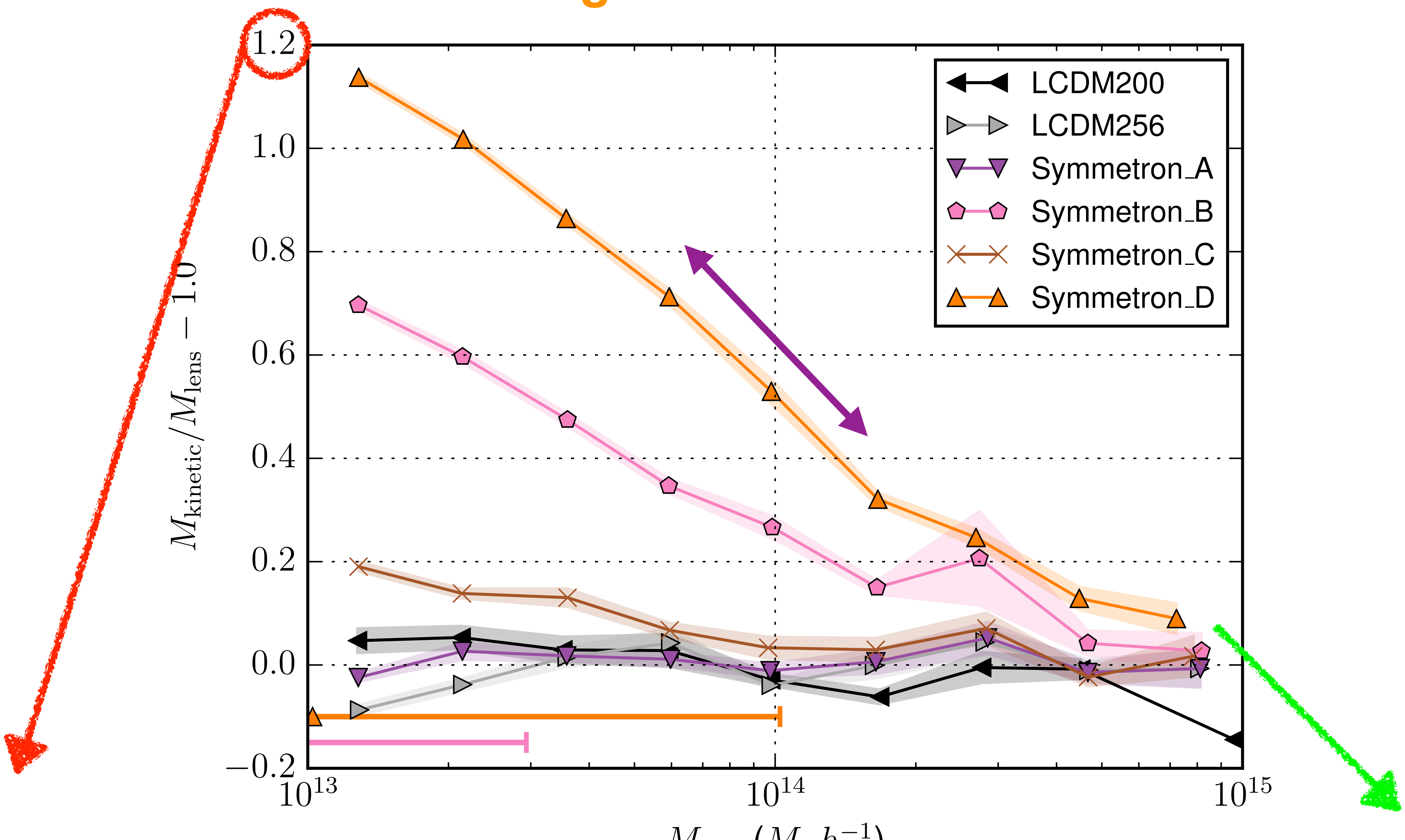


$$\Delta_M \equiv \frac{M_D}{M_L} - 1$$

Smoking gun for Modified Gravity

Lensing Mass vs. Kinematic Mass

Gronke, DFM, Winther A&A



Small halos: EP violation

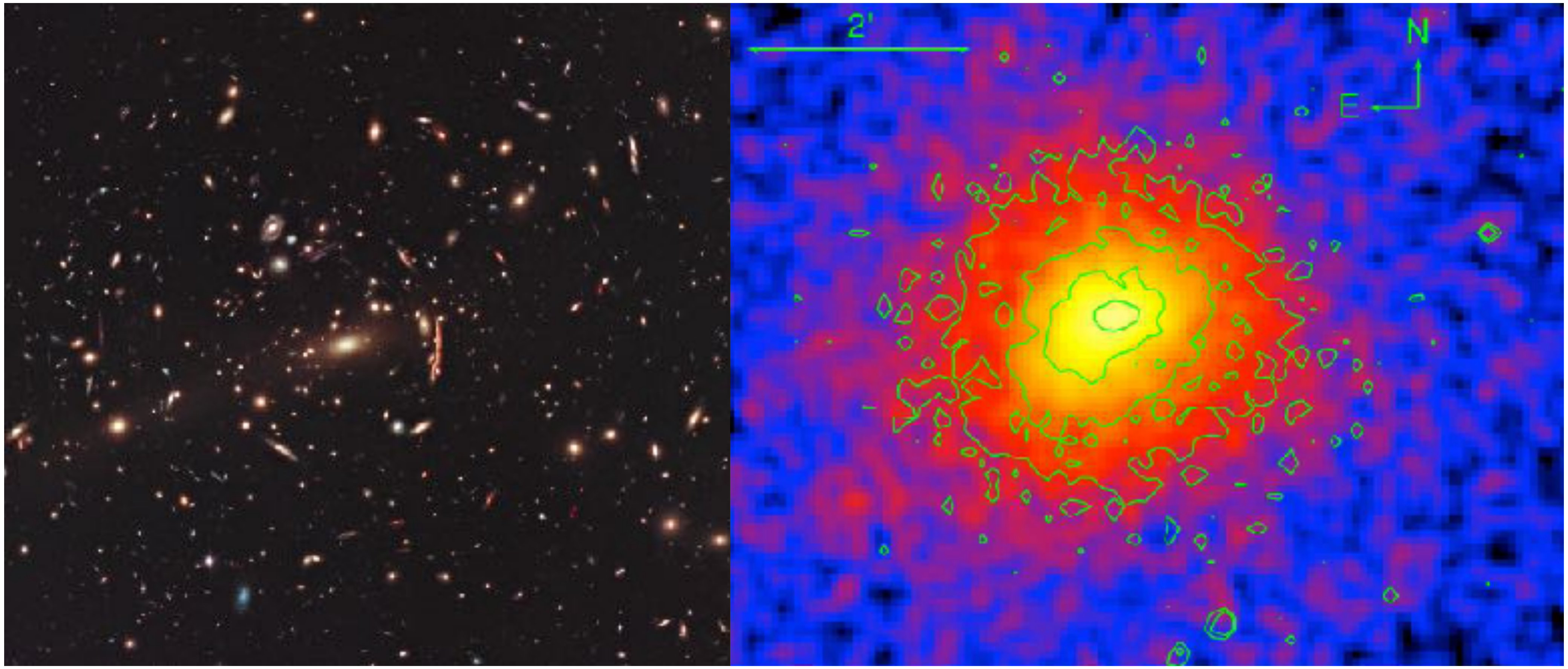
Large halos: no EP violation

Large deviations in spite of being undetected in Solar System, LSS, CMB, SNIa

Thermal Mass

from x-ray measurements of temperature and density profiles of intergalactic gas

Umetsu et al., ApJ 755, 56 (2012)



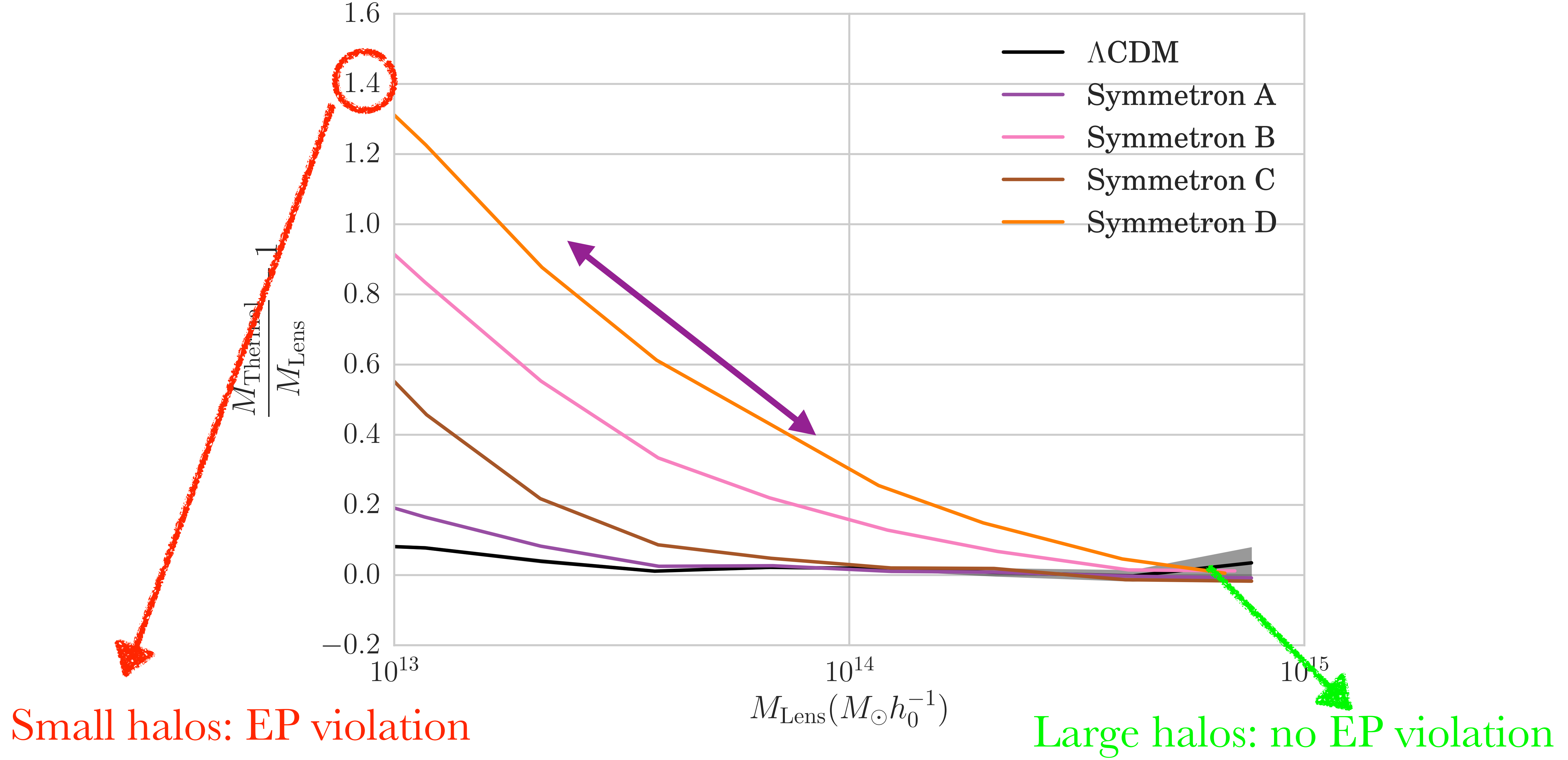
Mass holds hydrostatic equilibrium:

$$\frac{dP}{dr} = -\frac{GM(r)\rho(r)}{r^2} + F_\phi$$

Thermal mass estimates in Modified Gravity differ from GR

Smoking gun for Modified Gravity

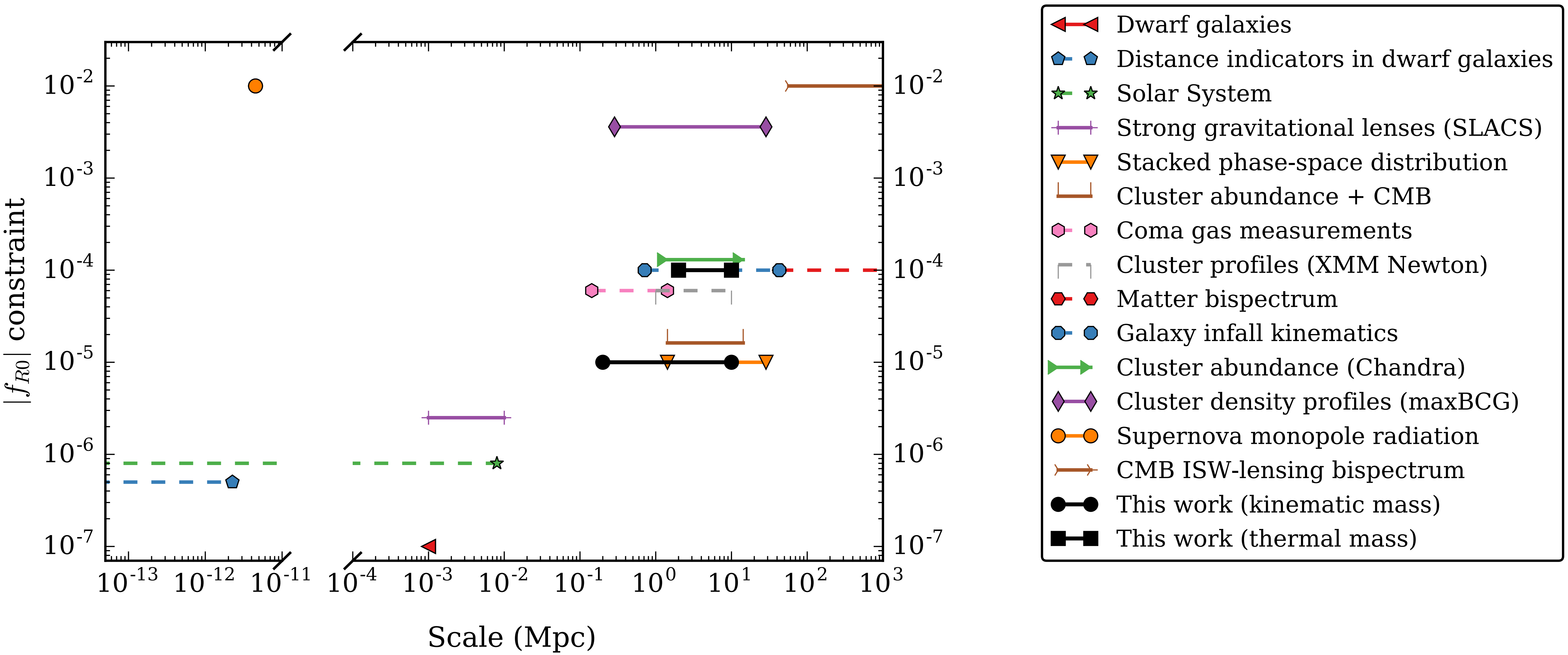
Lensing Mass vs. Thermal Mass



Large deviations in spite of being undetected in Solar System, LSS, CMB, SNIa, Black holes

Observational Constraints

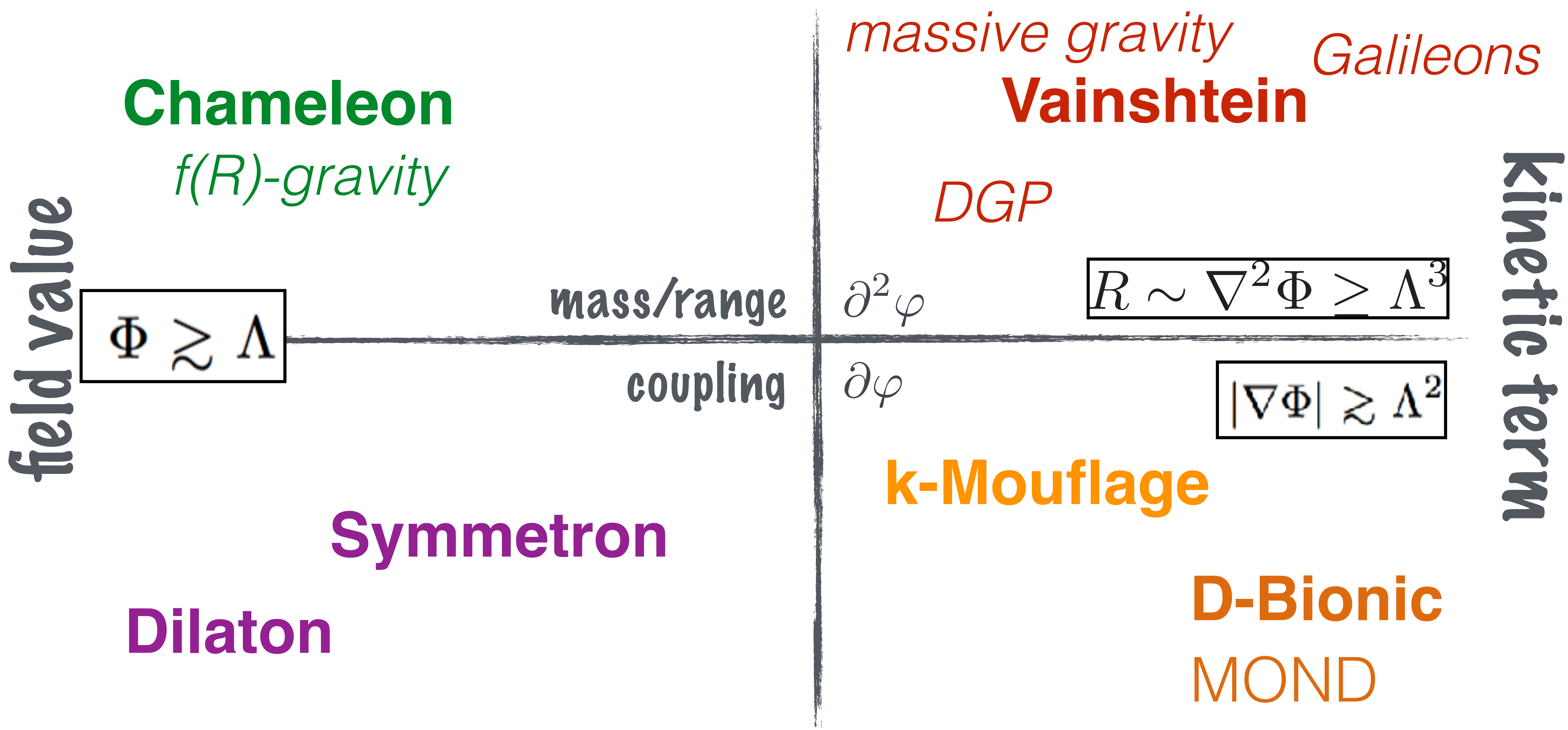
Gronke, DFM, Winther A&A



How to differentiate among Screening Mechanisms?

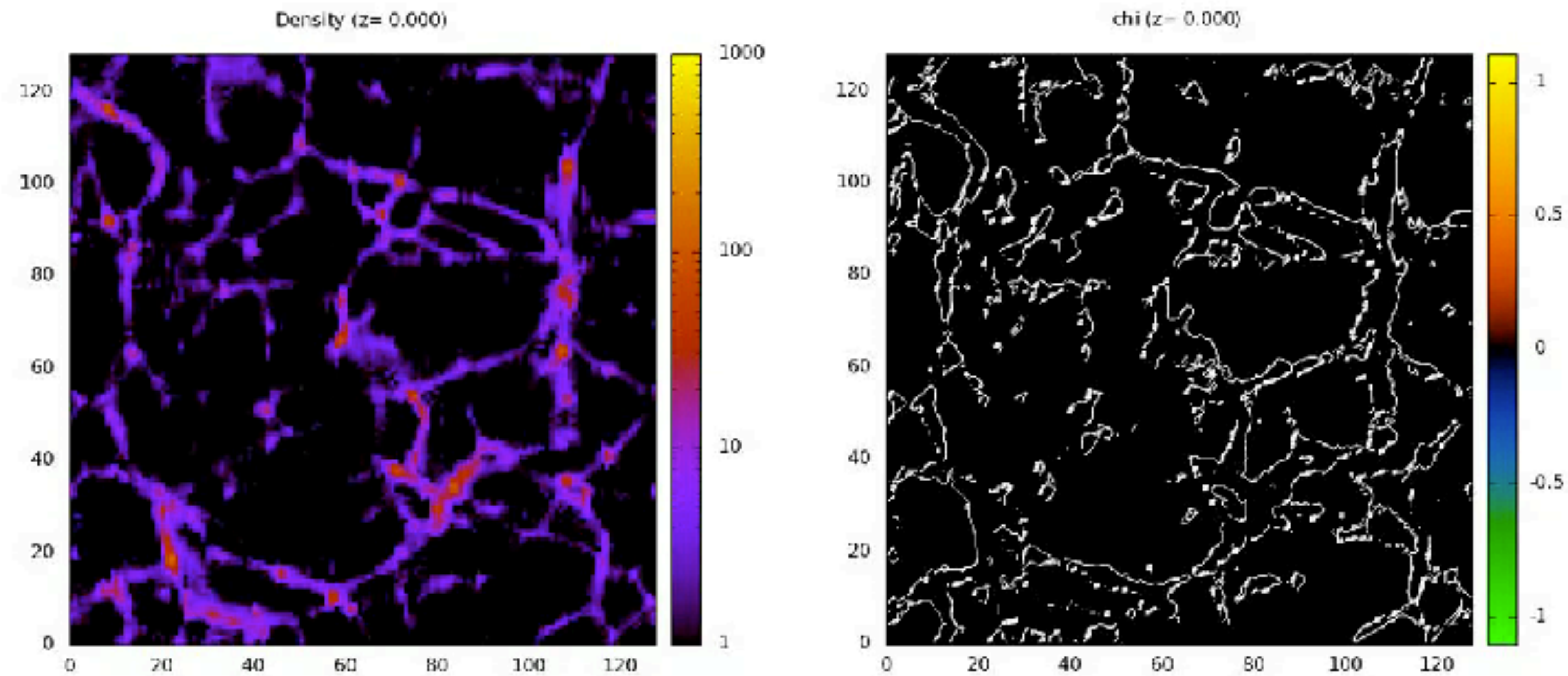
$$\mathcal{L} = -\frac{1}{2} Z^{\mu\nu}(\phi, \partial\phi, \ldots)\partial_\mu\phi\partial_\nu\phi - V(\phi) + g(\phi)T^\mu_\mu$$

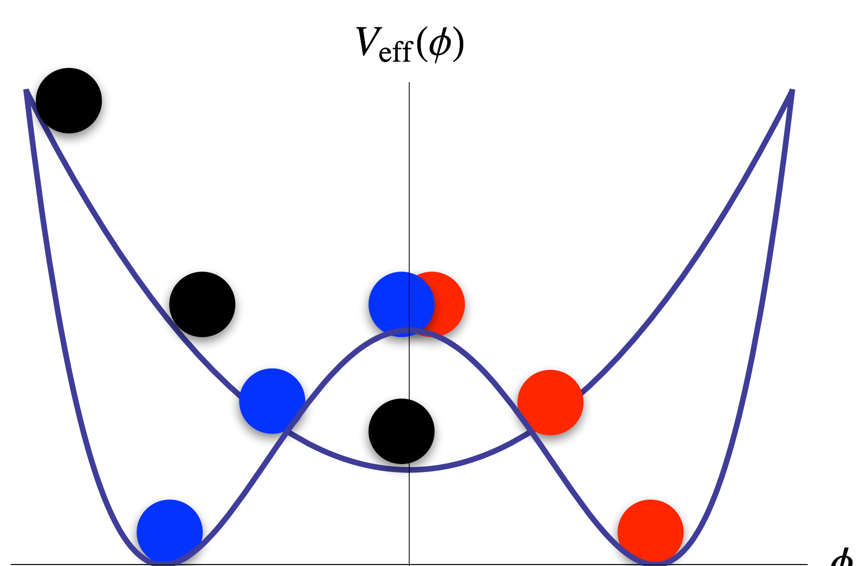
$$V(r) = -\frac{g^2(\bar{\phi})}{Z(\bar{\phi})c_s^2(\bar{\phi})} \frac{e^{-\frac{m(\bar{\phi})}{\sqrt{Z(\bar{\phi})}c_s(\bar{\phi})}r}}{4\pi r}\mathcal{M}$$



Symmetron Phase Transition

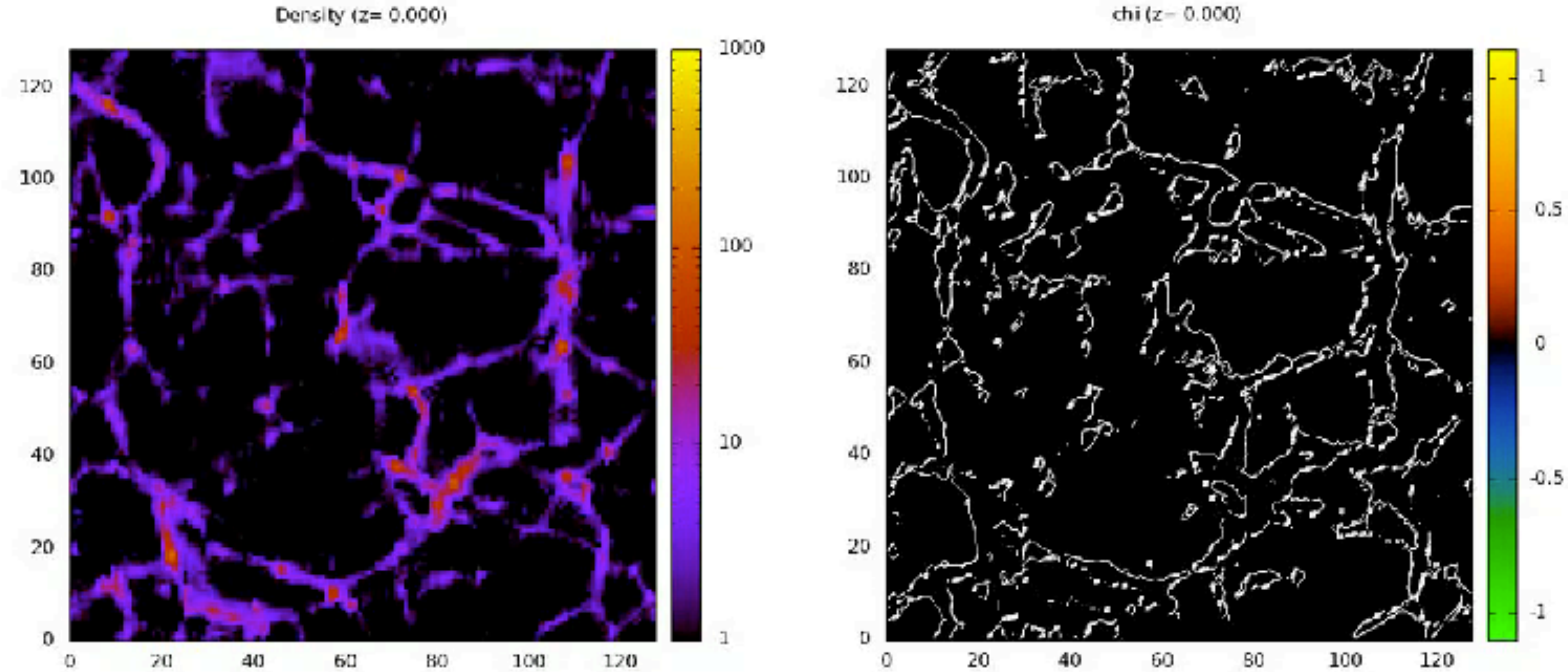
Llinares, DFM PRL

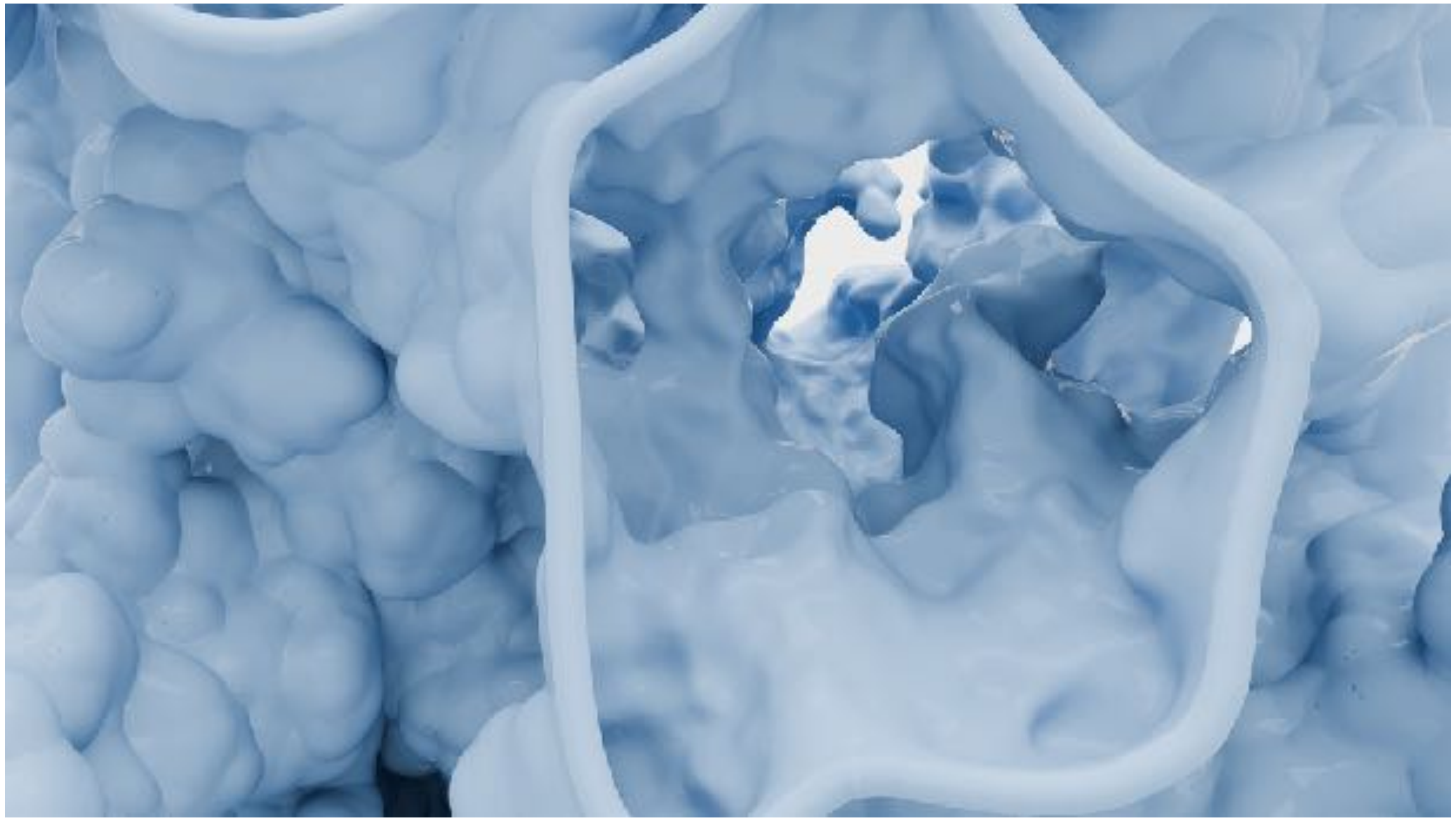




Symmetron Domain Walls

(Christiansen, DFM)

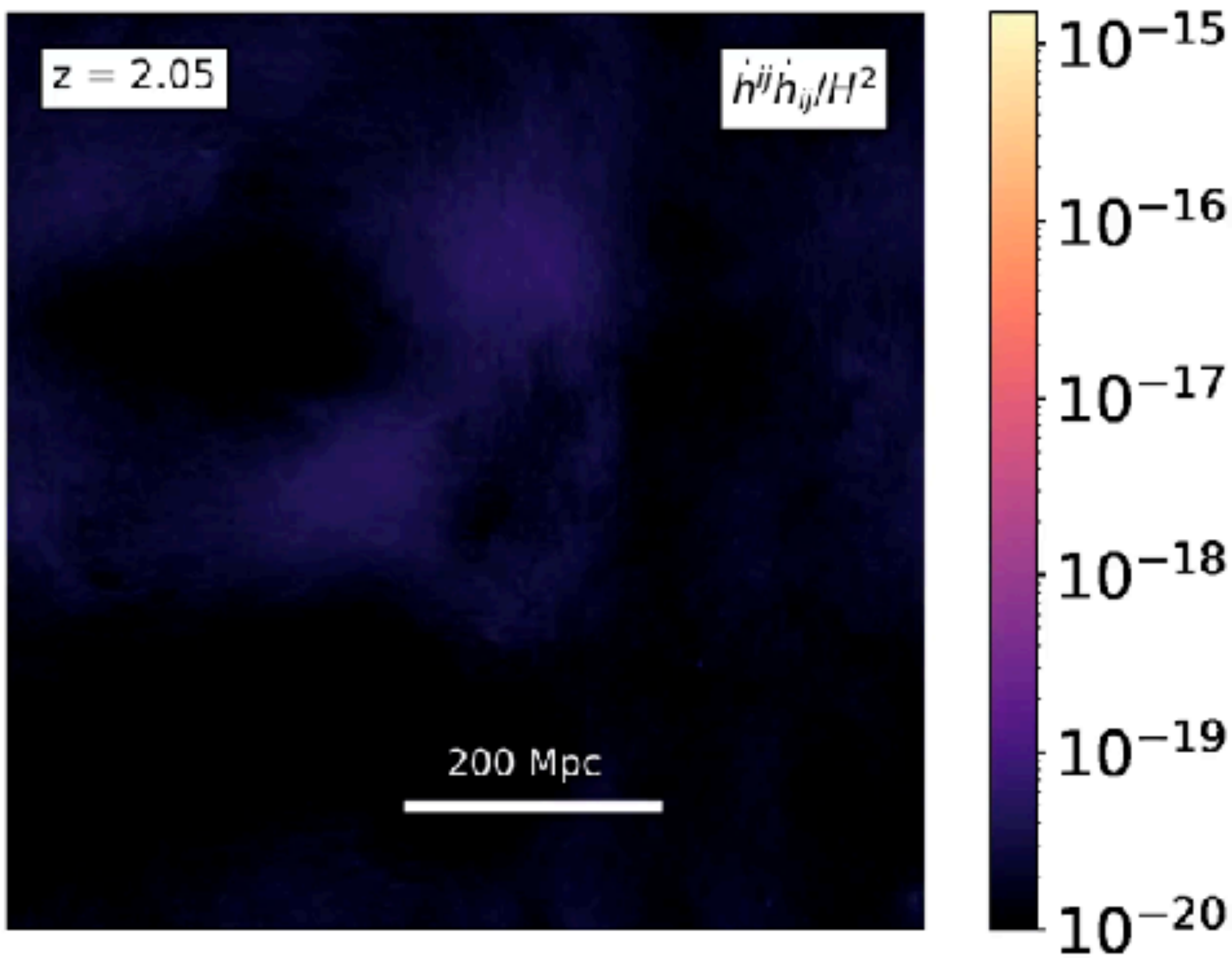


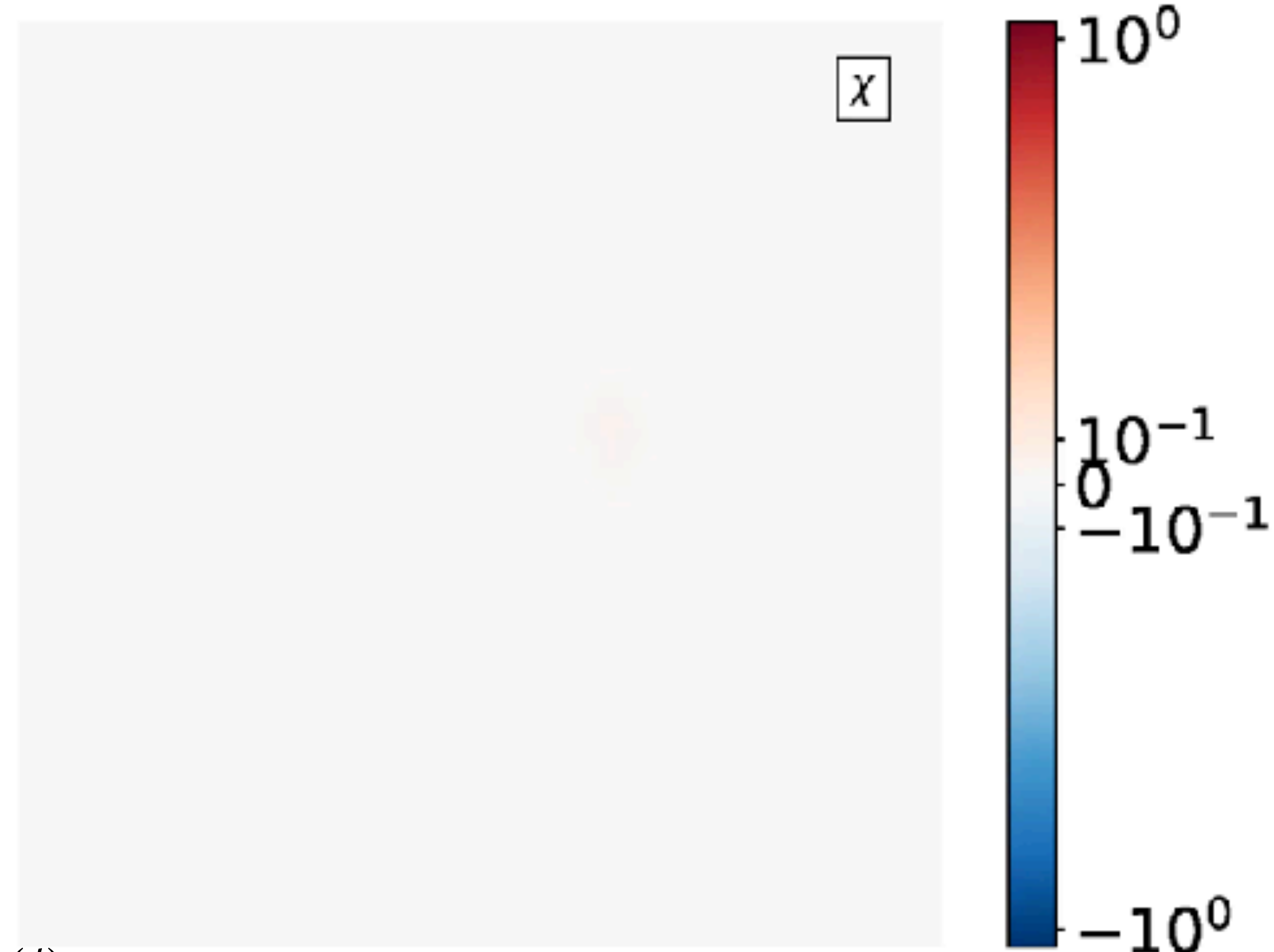


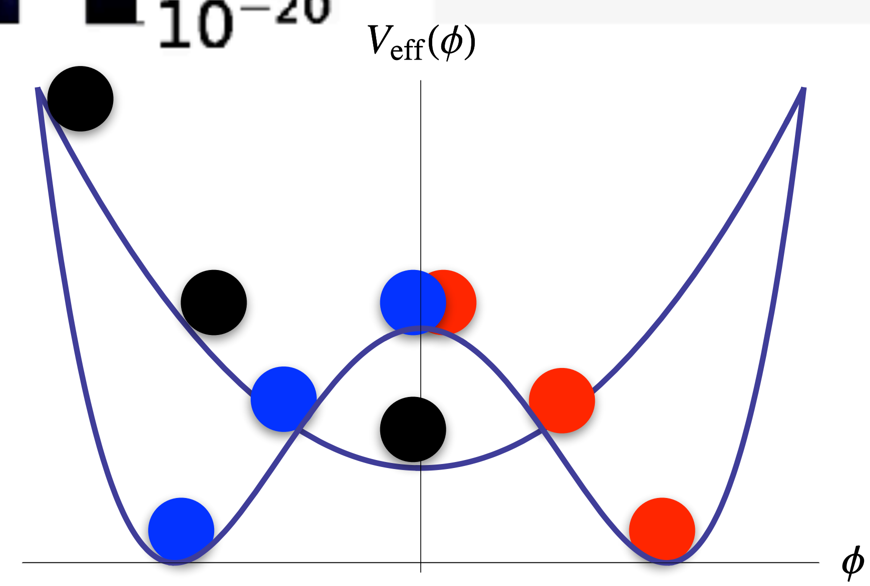
Domain Walls source Gravitational Waves

(Christiansen, Adamek, Hassani, DFM)

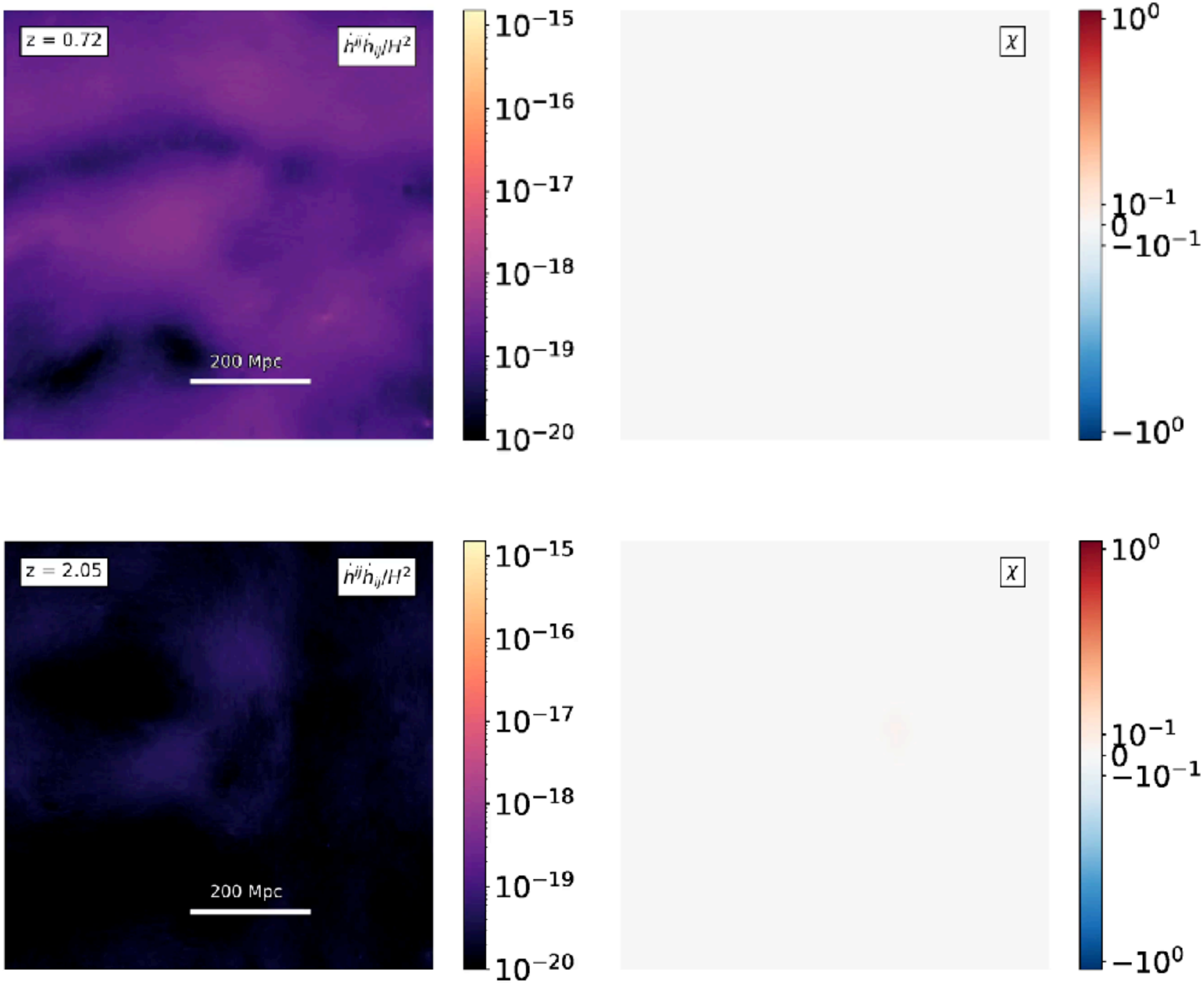
$$\tilde{h}_{ij}'' + 2\mathscr{H}\tilde{h}_{ij}' + c^2k^2\tilde{h}_{ij} = \frac{16\pi G}{c^2}\left(P_i^l P_j^m - \frac{1}{2}P_{ij}P^{lm}\right)\tilde{T}_{lm}$$







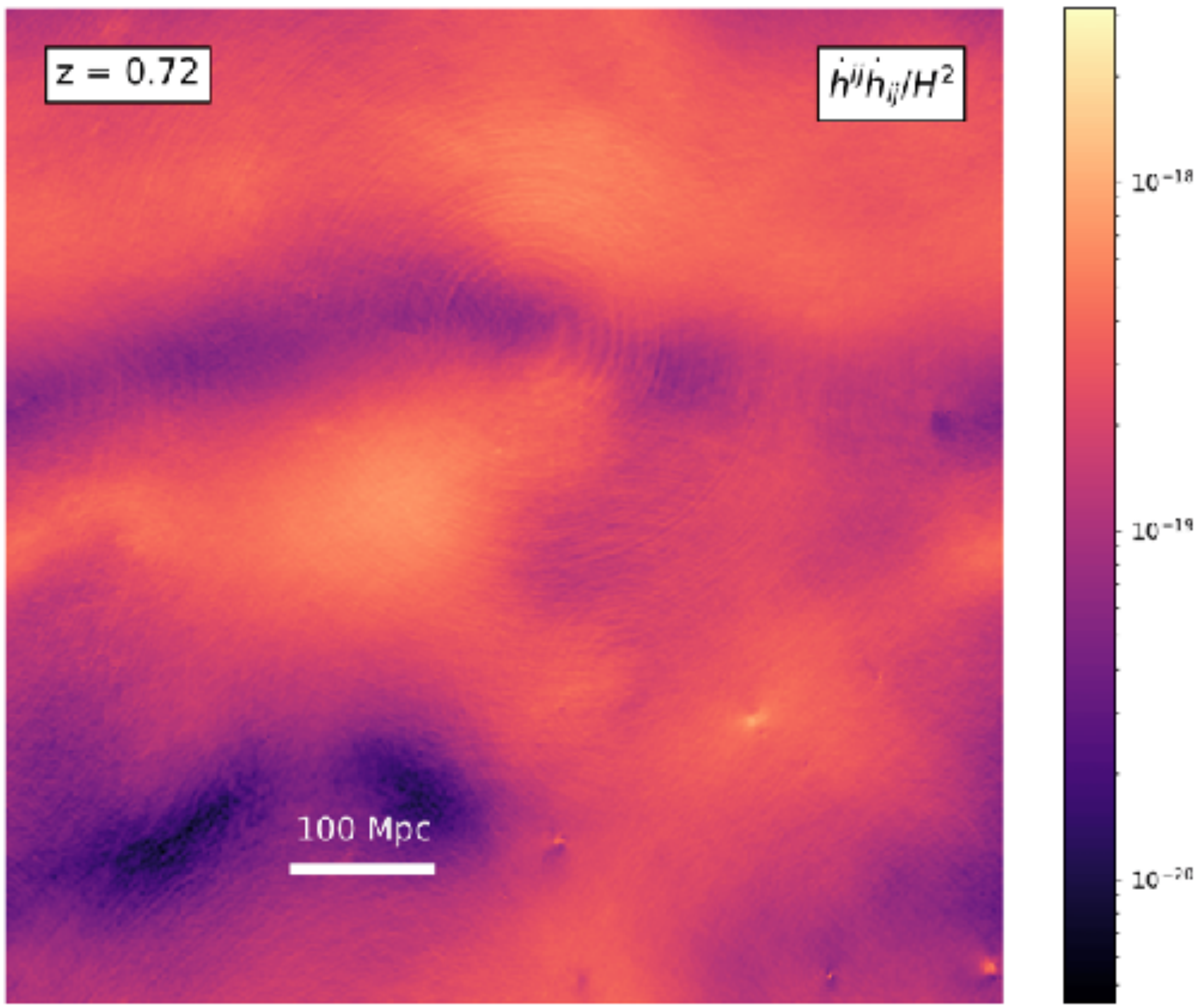
Stochastic gravitational wave background as a probe of Symmetron

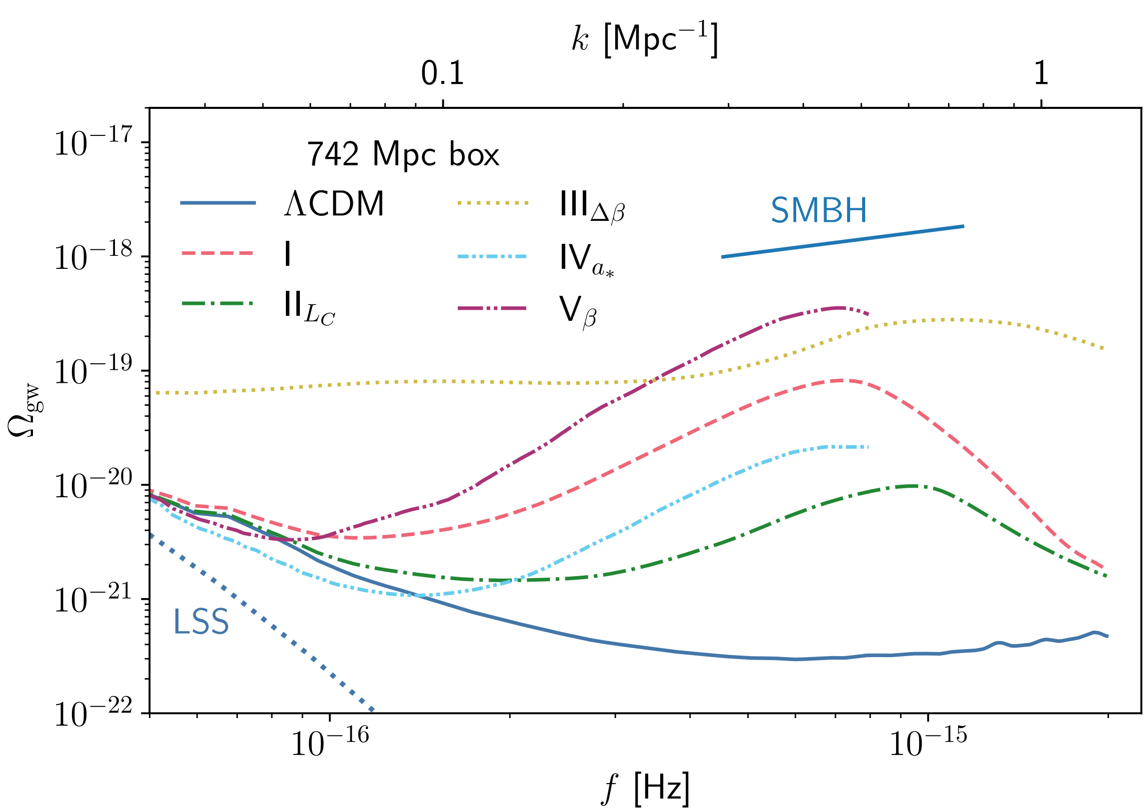


(Christiansen, Adamek, Hassani, DFM)

Stochastic gravitational wave background as a probe of Screening Mechanisms

(Christiansen, Adamek, Hassani, DFM)





k [Mpc^{-1}]

$$\tilde{h}_{ij}'' + 2\mathscr{H}\tilde{h}_{ij}' + c^2k^2\tilde{h}_{ij} = \frac{16\pi G}{c^2}\left(P_i^l P_j^m - \frac{1}{2}P_{ij}P^{lm}\right)\tilde{T}_{lm}$$

Summary

- Modified Gravity with screening affects structures in the nonlinear regime
  - Effects are stronger within the fifth force range and proportional to the coupling
- Global observables are probes of Modified Gravity
  - But local observables and environmental dependence are the best probes to break degeneracies with dark sector physics
- Measuring the mass, velocity dispersion and Gravitational Redshift of galaxy clusters can probe equivalence principle violations
  - The differences between the observed masses are environmental dependent
- Gravitational Waves are promising probes to distinguish among Screening Mechanism