Cosmology of gravity theories beyond General Relativity

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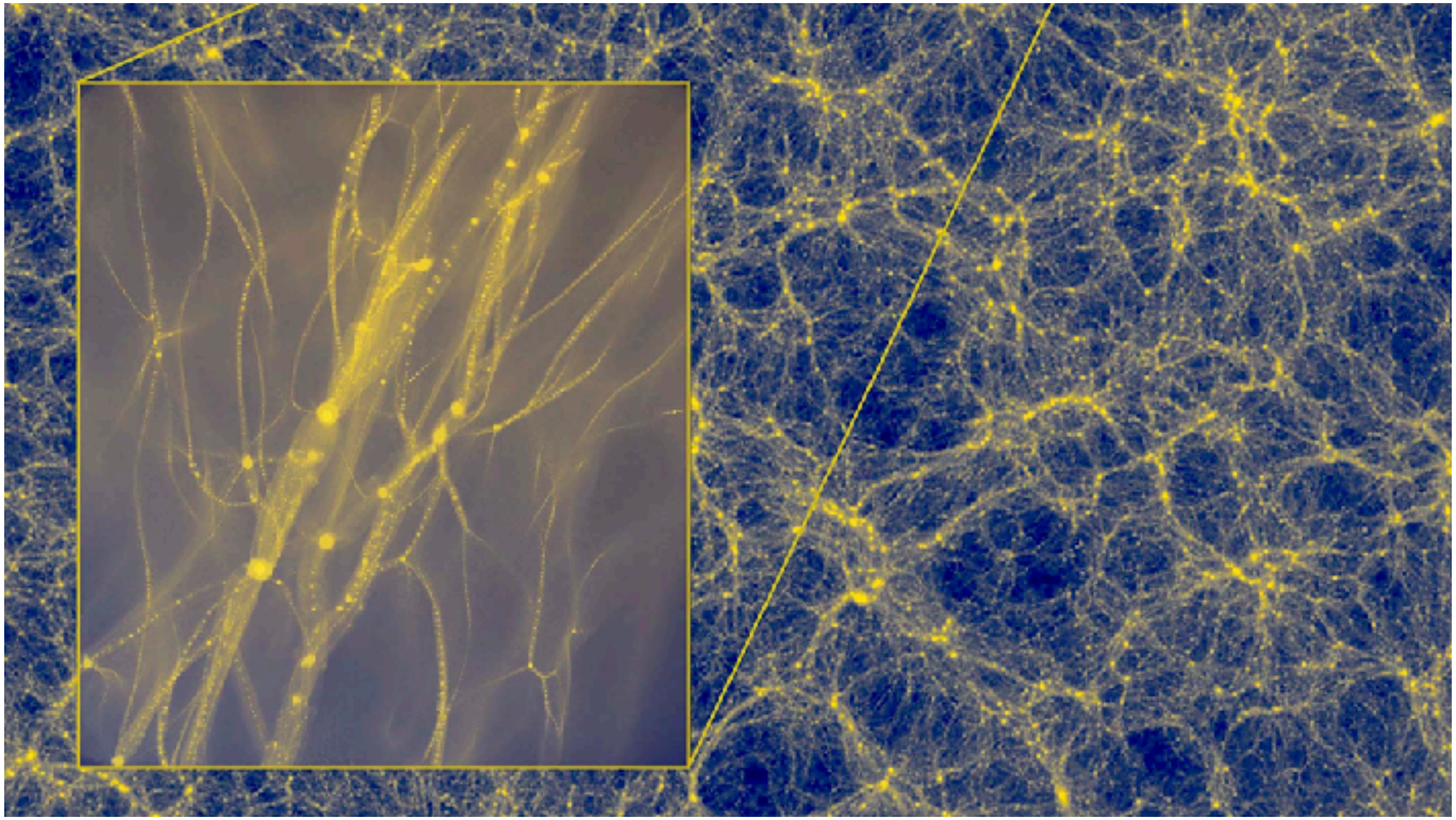
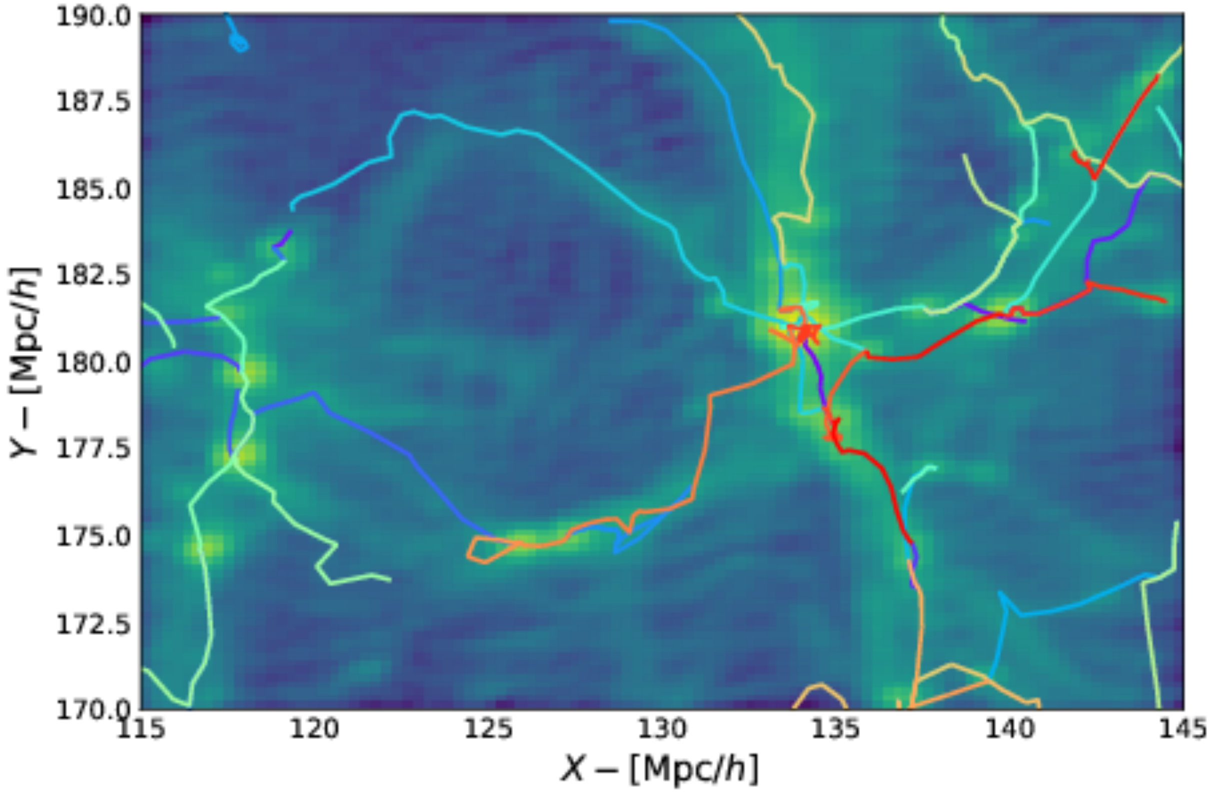
LECTURE 4

Future probes of screening mechanisms

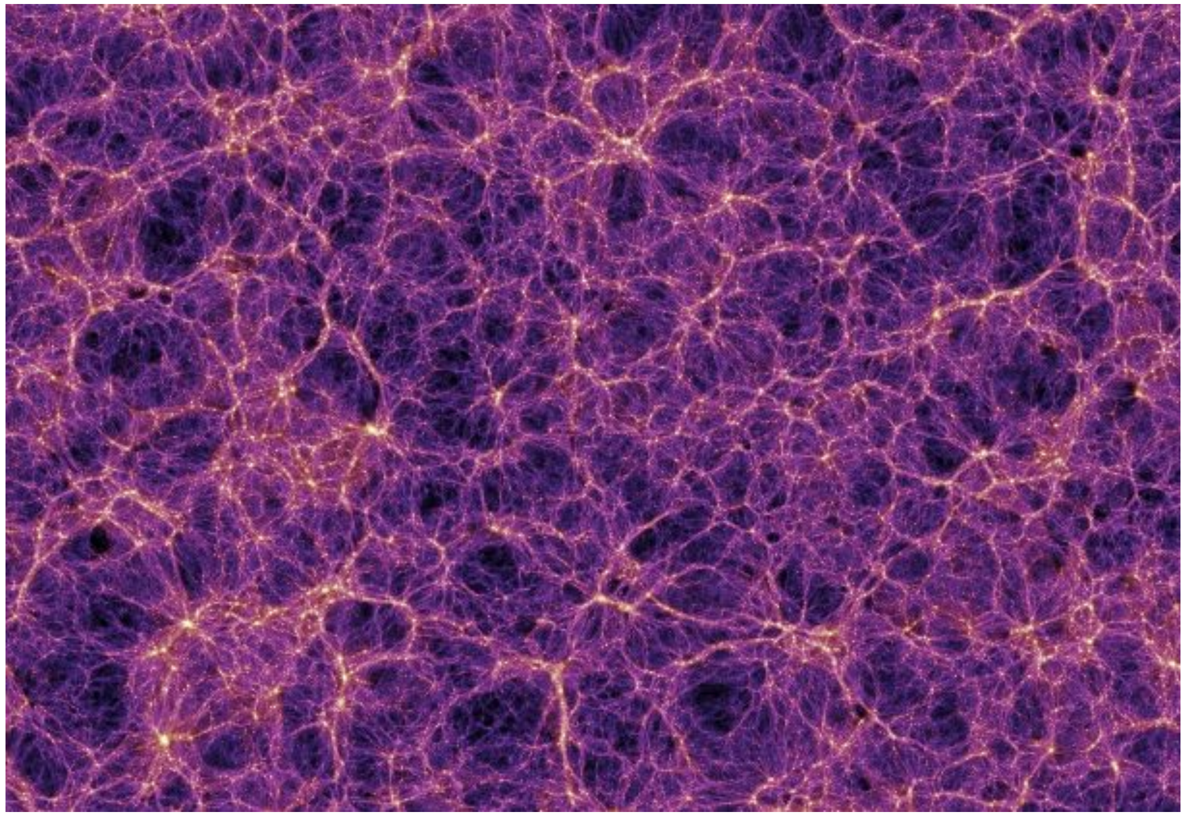
Probing Modified Gravity in Cosmic Web





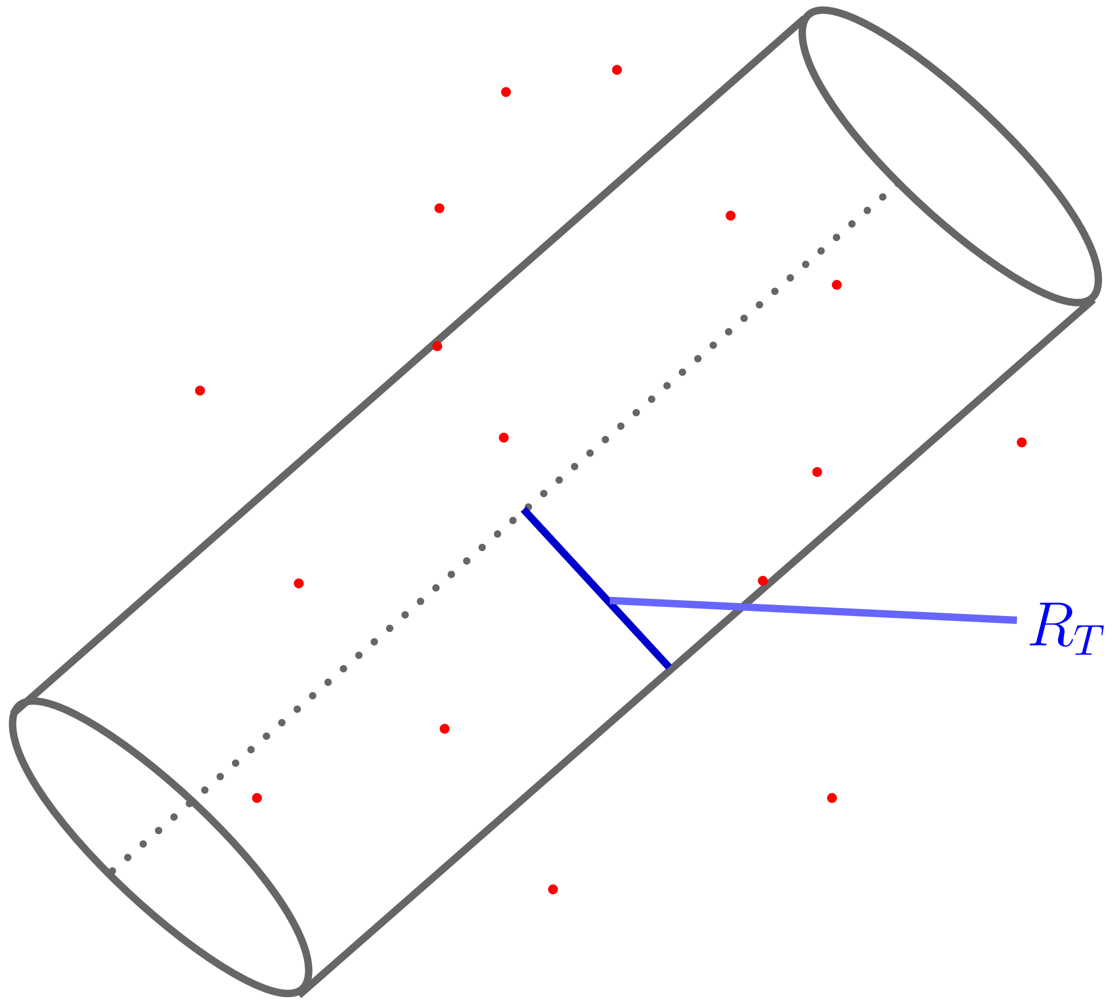
Cosmic Web

- Massive 3D distribution of matter
- Characterised by different structures
  - Halos – overdense regions
  - Voids – underdense regions
  - Filaments – connecting two high density regions
- Excellent probe of modified gravity



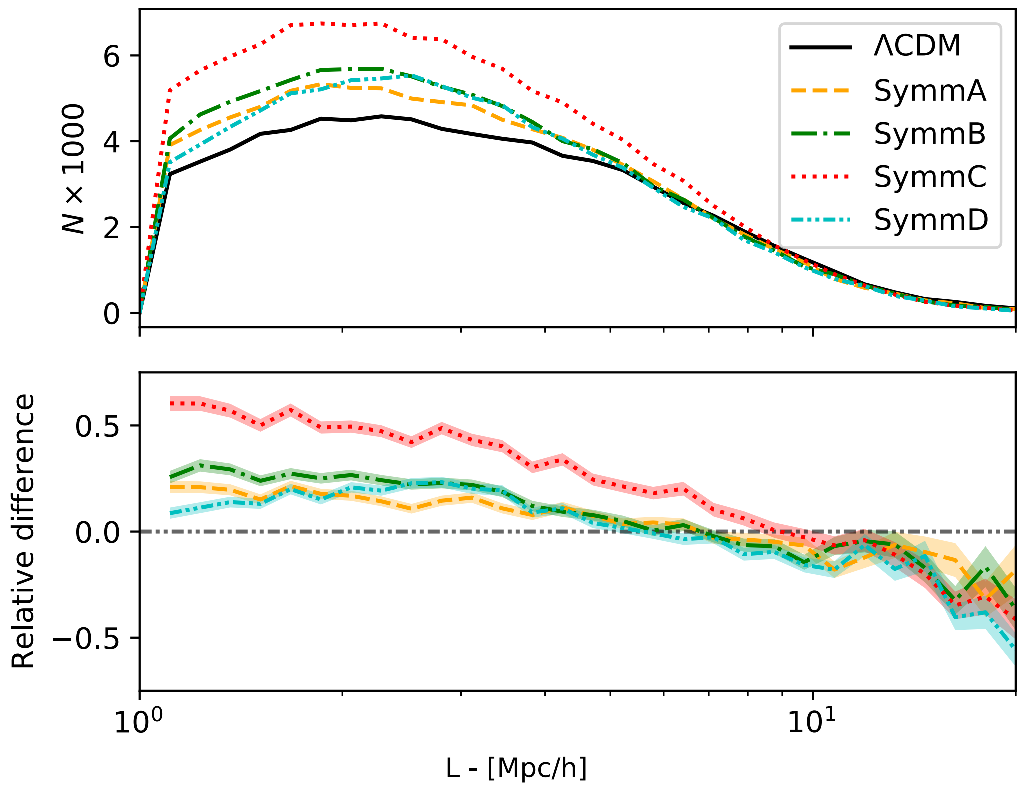
Global properties of filaments

Observed mainly using galaxies

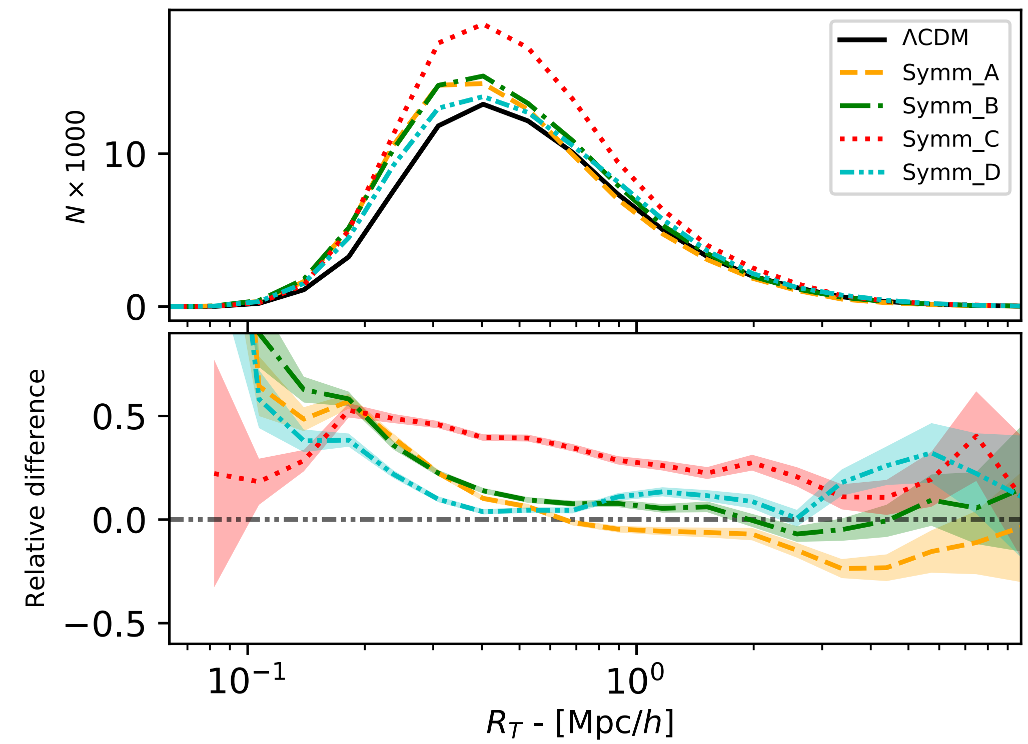


Global properties of Filaments: dependence on coupling and range

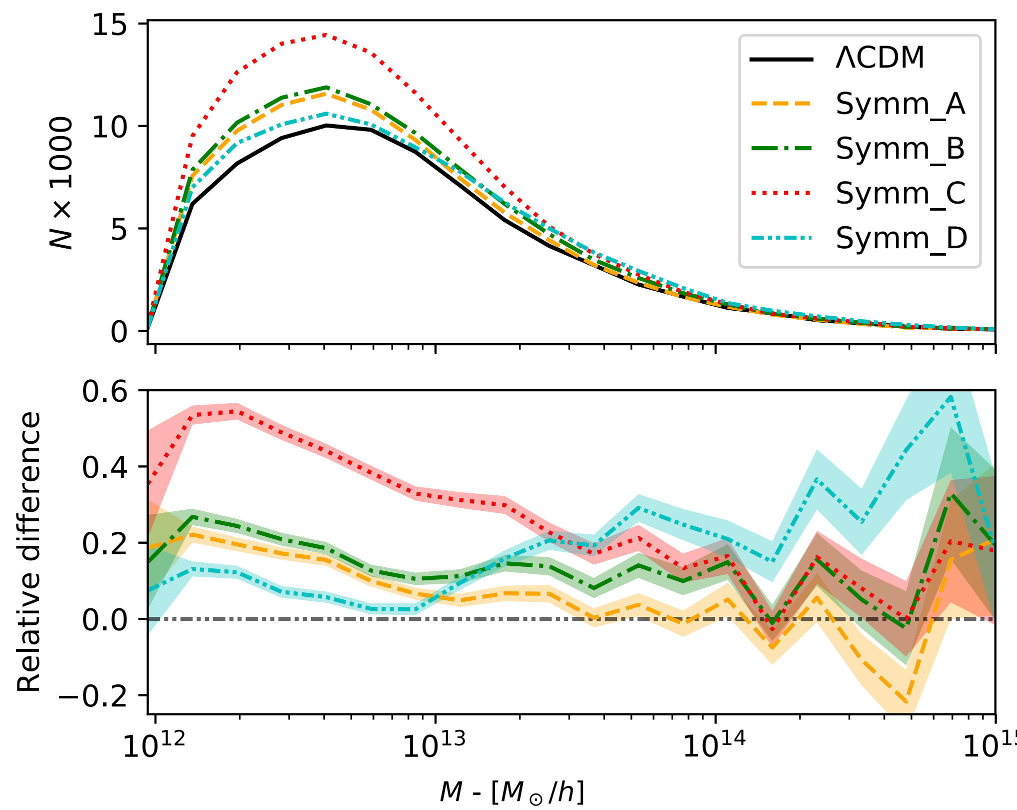
Filaments **shorter** in Modified Gravity



Filaments **thicker** in Modified Gravity



Filaments **more massive** in Modified Gravity

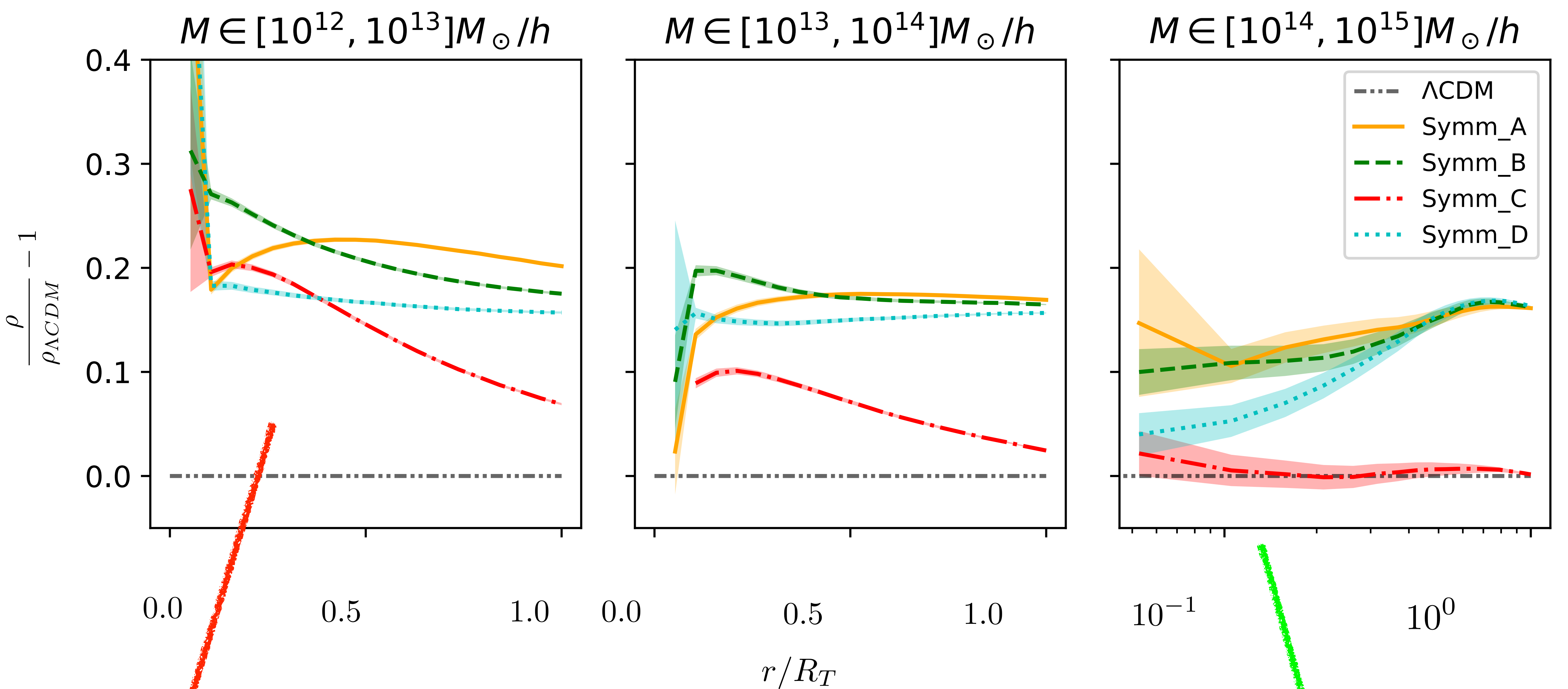


(Ho, Falck, Gronke, DFM)

Environmental dependent properties of Filaments

Density Profiles

(Ho, Falck, Gronke, DFM)



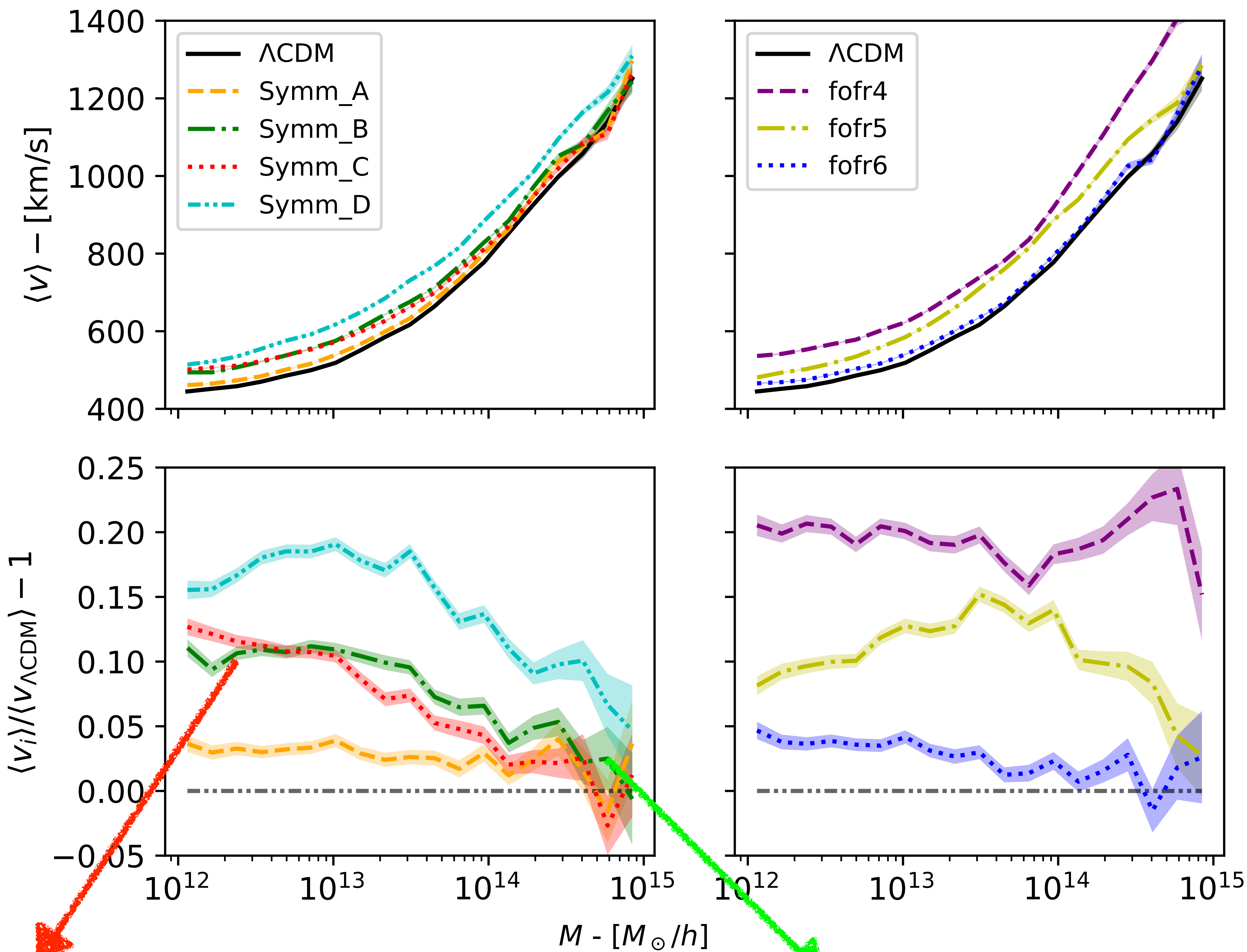
Less massive: large deviations

More massive: small deviations

Environmental dependent properties of Filaments

Velocity Profiles

(Ho, Falck, Gronke, DFM)



Less massive: large deviations

More massive: small deviations

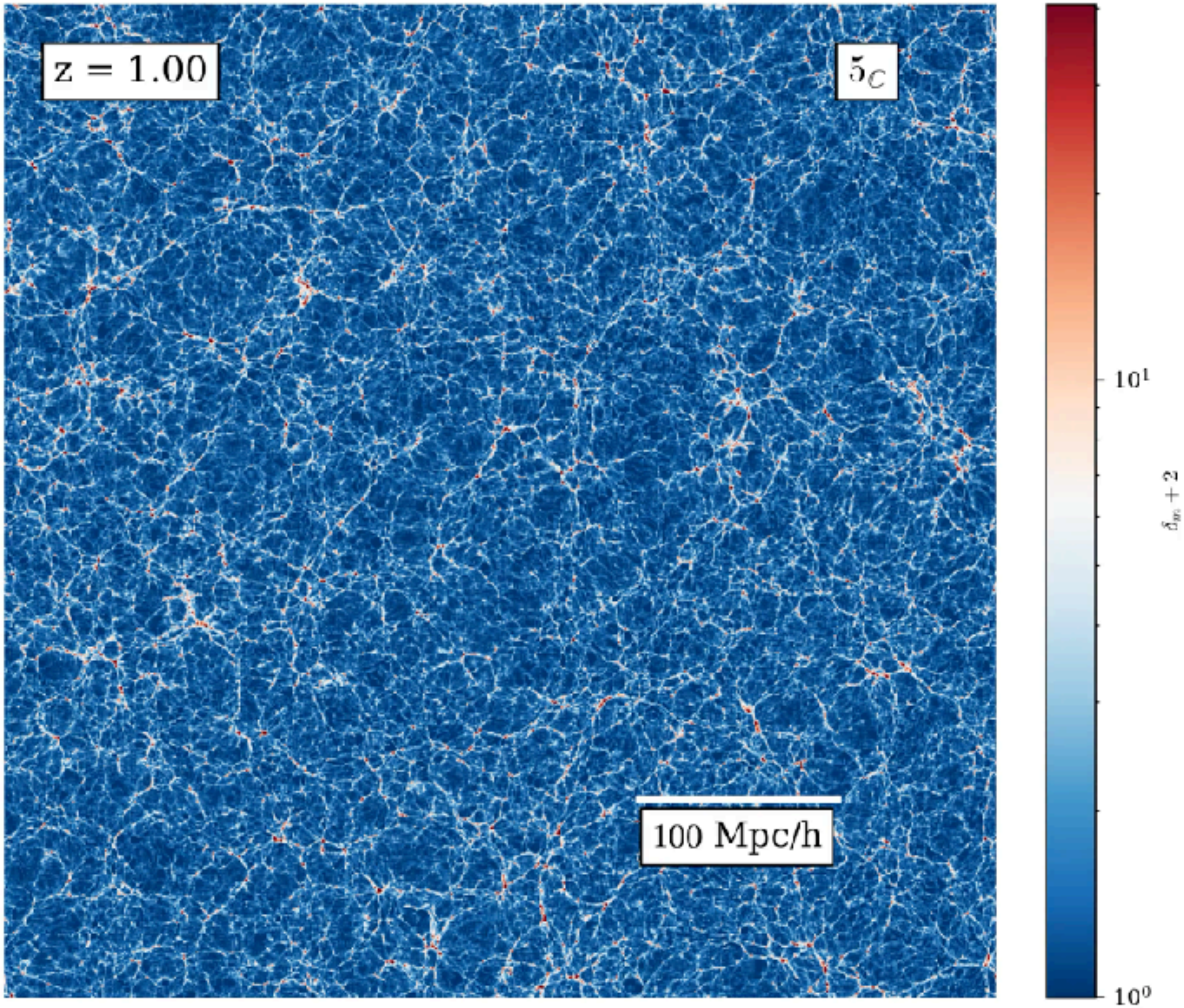
Voids as probes of Modified Gravity

(Maudland, Elgaroy, DFM, Winther)

(Voivodic, Lima, Llinares, DFM)

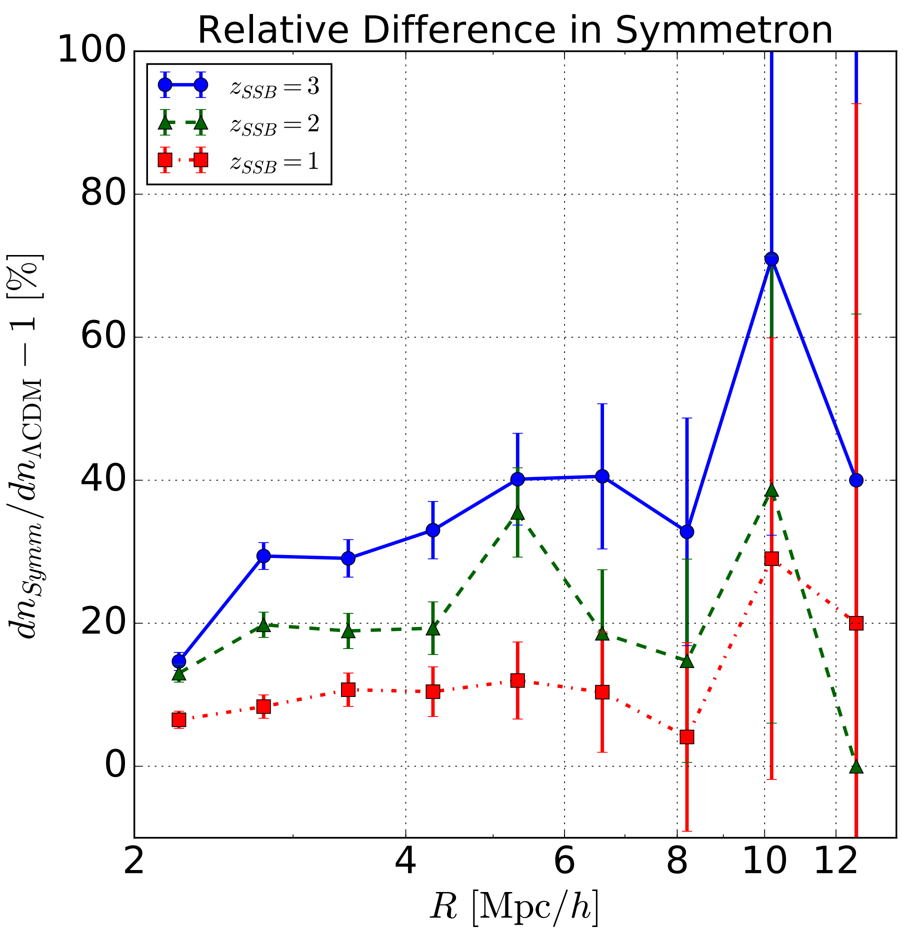
Fifth force not screened!

Observed via: galaxies, but mainly lensing

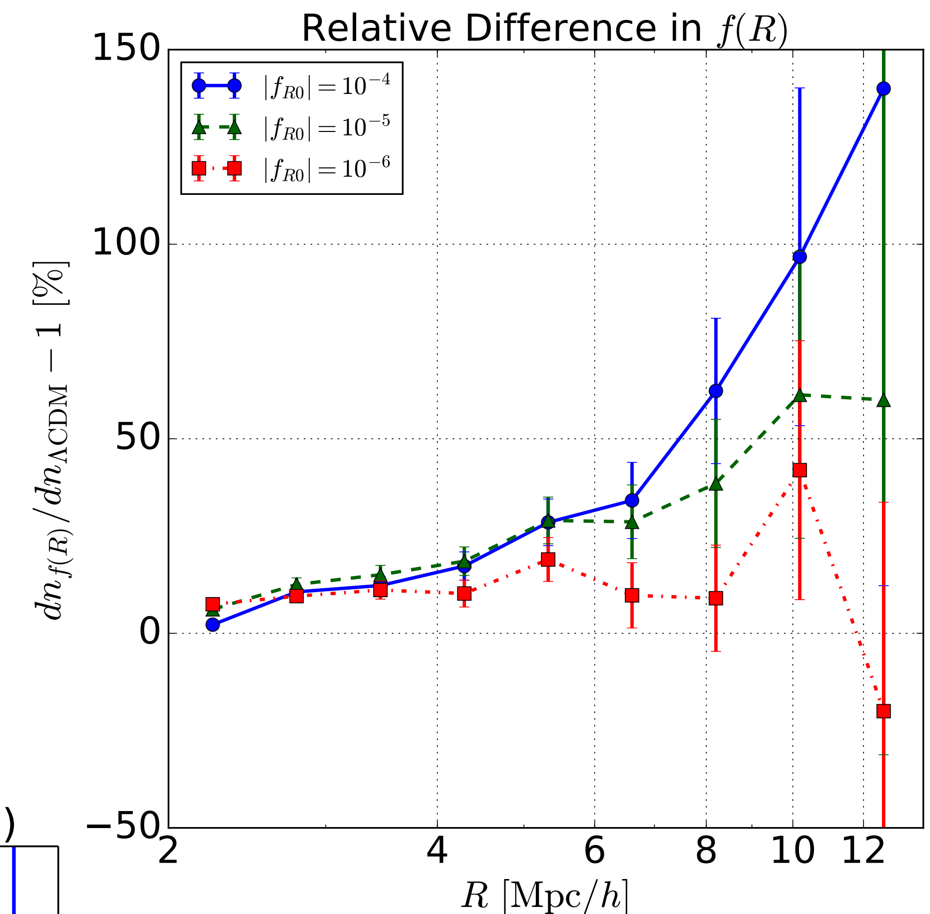


Voids abundances

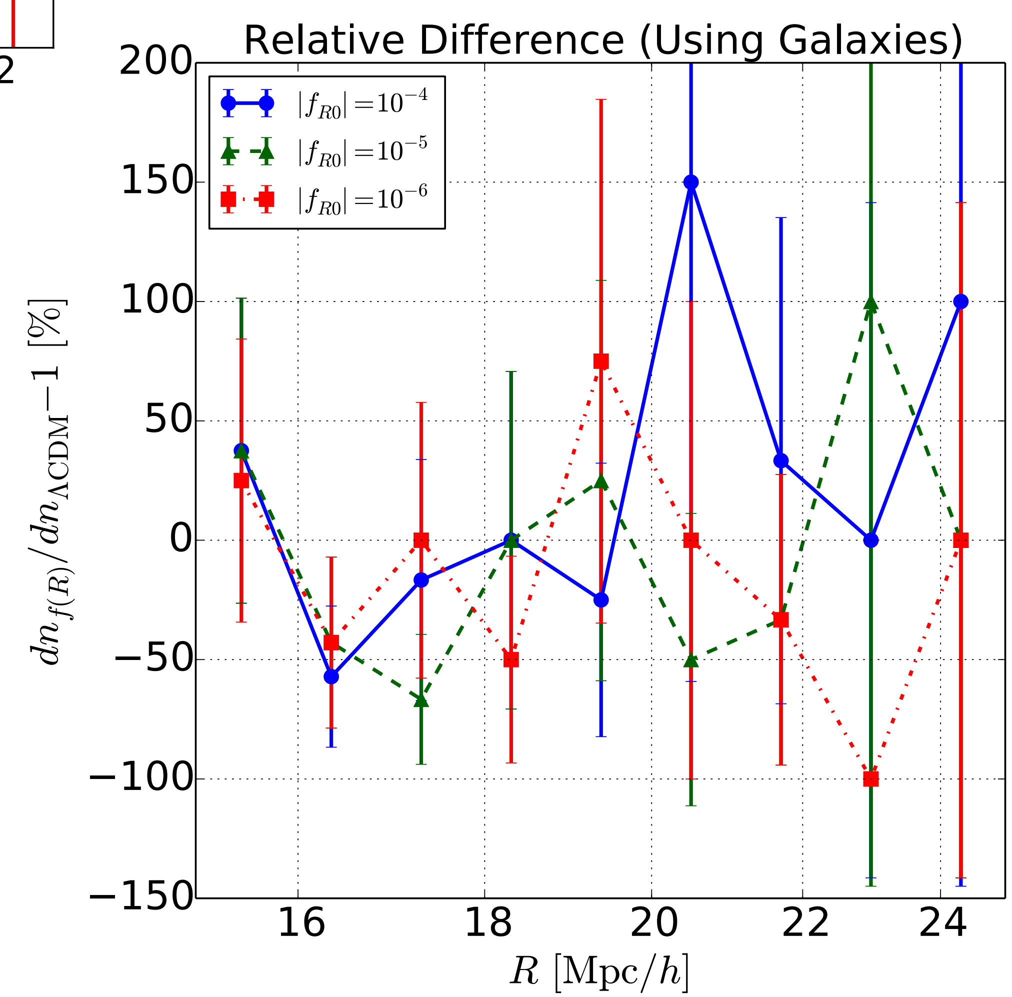
More larger voids in Modified Gravity



Dark matter probes
(Lensing)



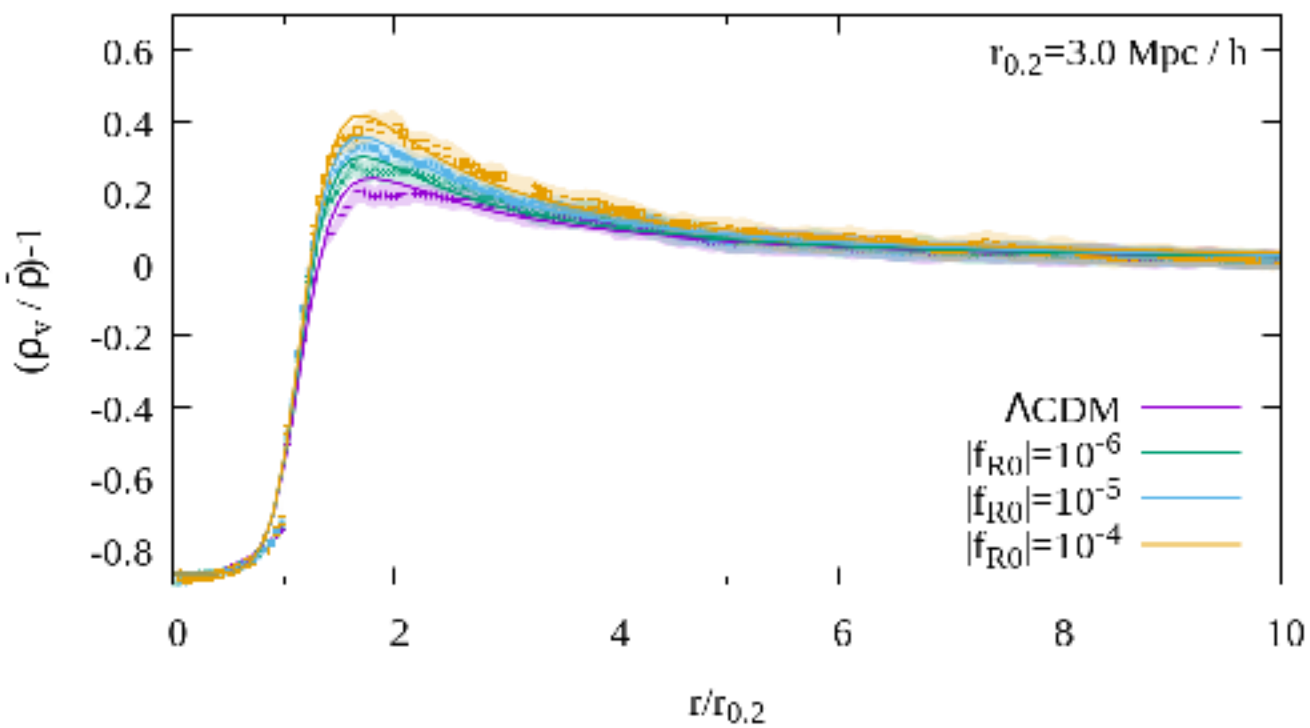
Using galaxies:
Not so promising

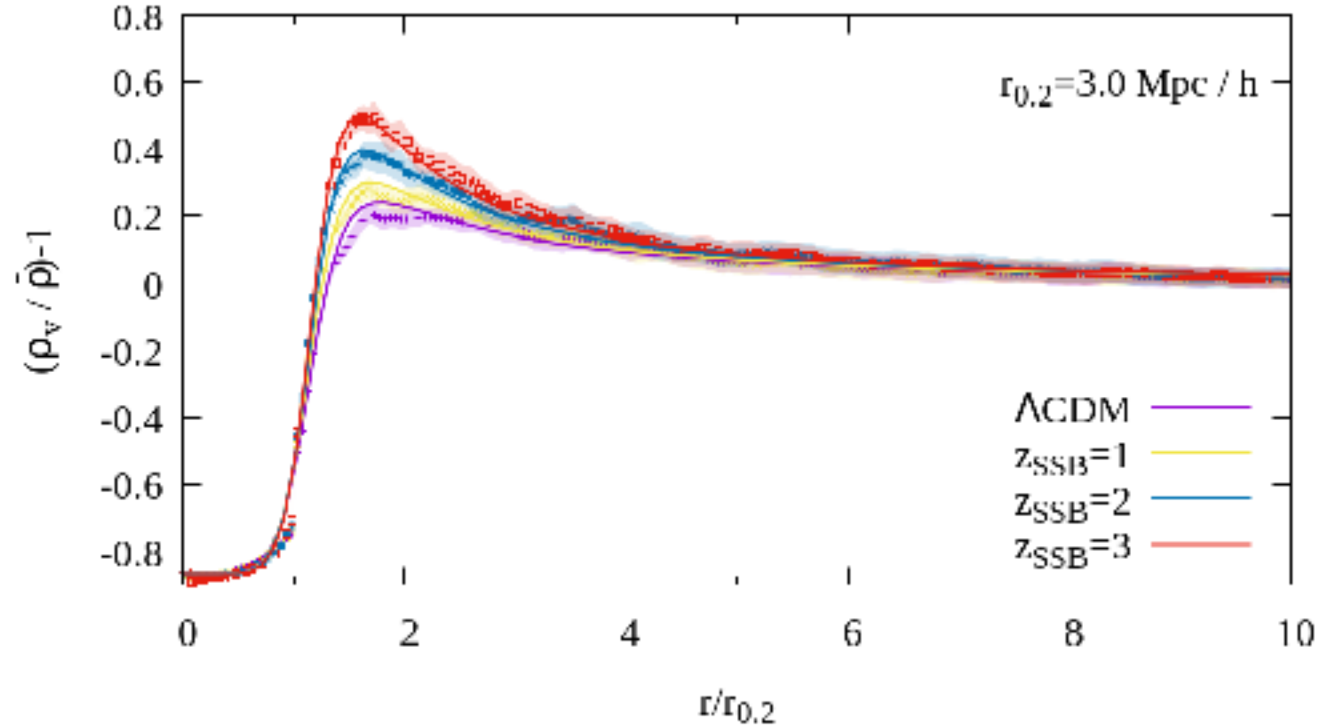


(Perico, Voivodic, Lima, DFM)
(Voivodic, Lima, Llinares, DFM)
(Maudland, Elgaroy, DFM, Winther)

Voids Profiles

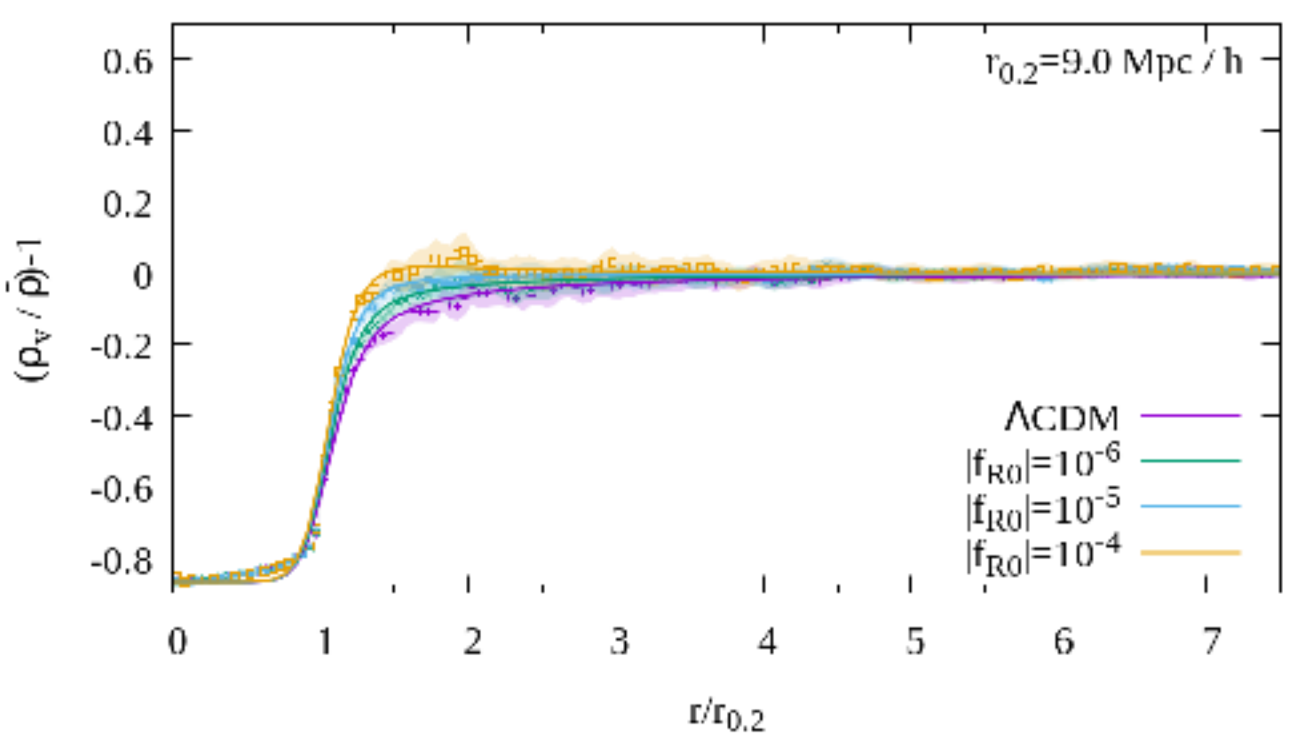
Voids are emptier in Modified Gravity

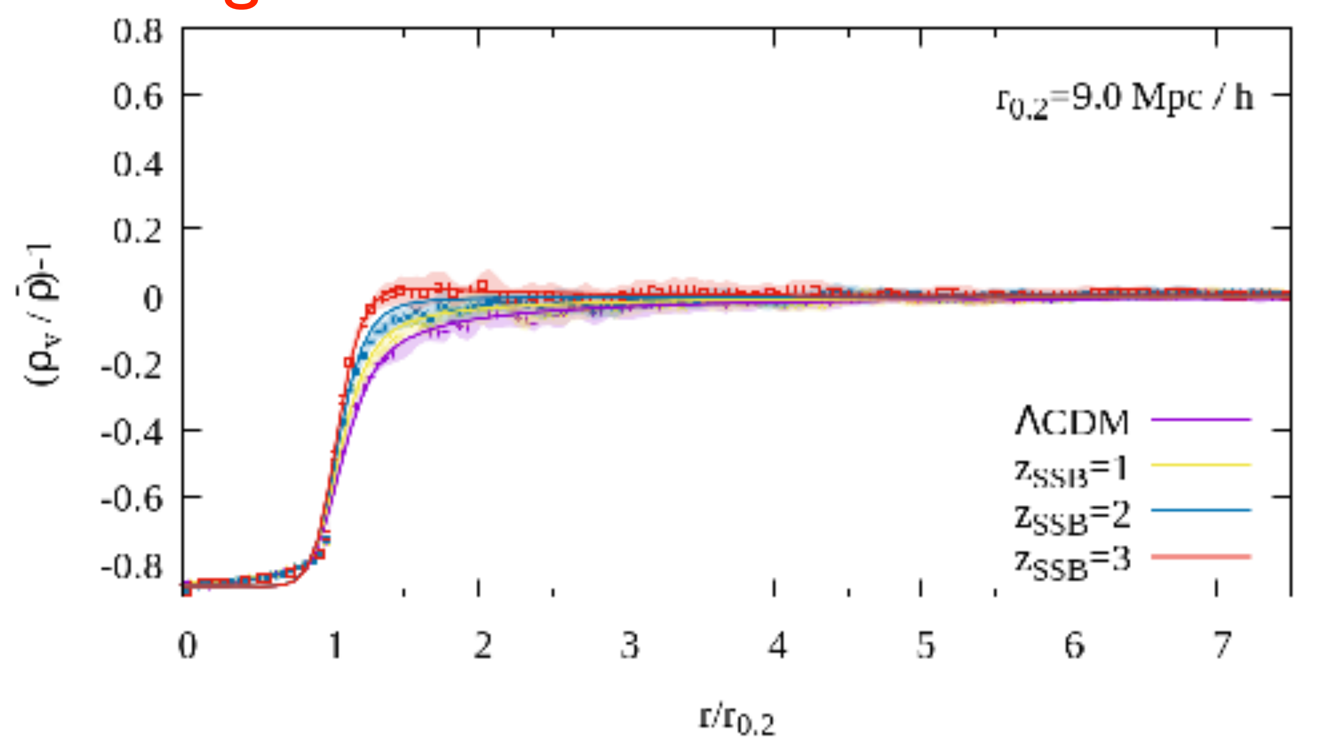




Observationally difficult both via lensing (even worst with galaxies)

Not so promising!





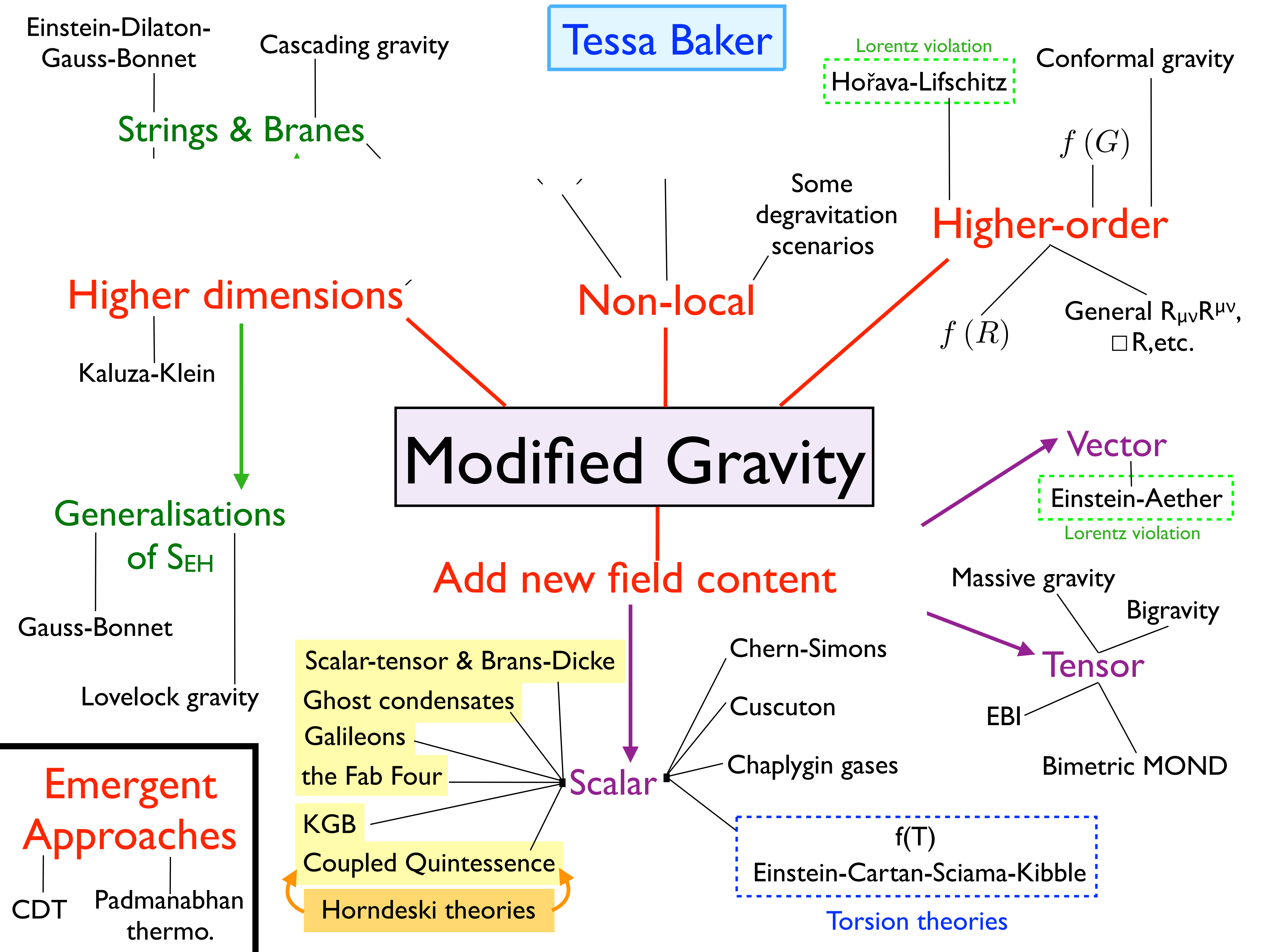
How promising are voids?

Fifth force not screened!

Observationally difficult to probe!

LECTURE 5

Are screening mechanisms viable?



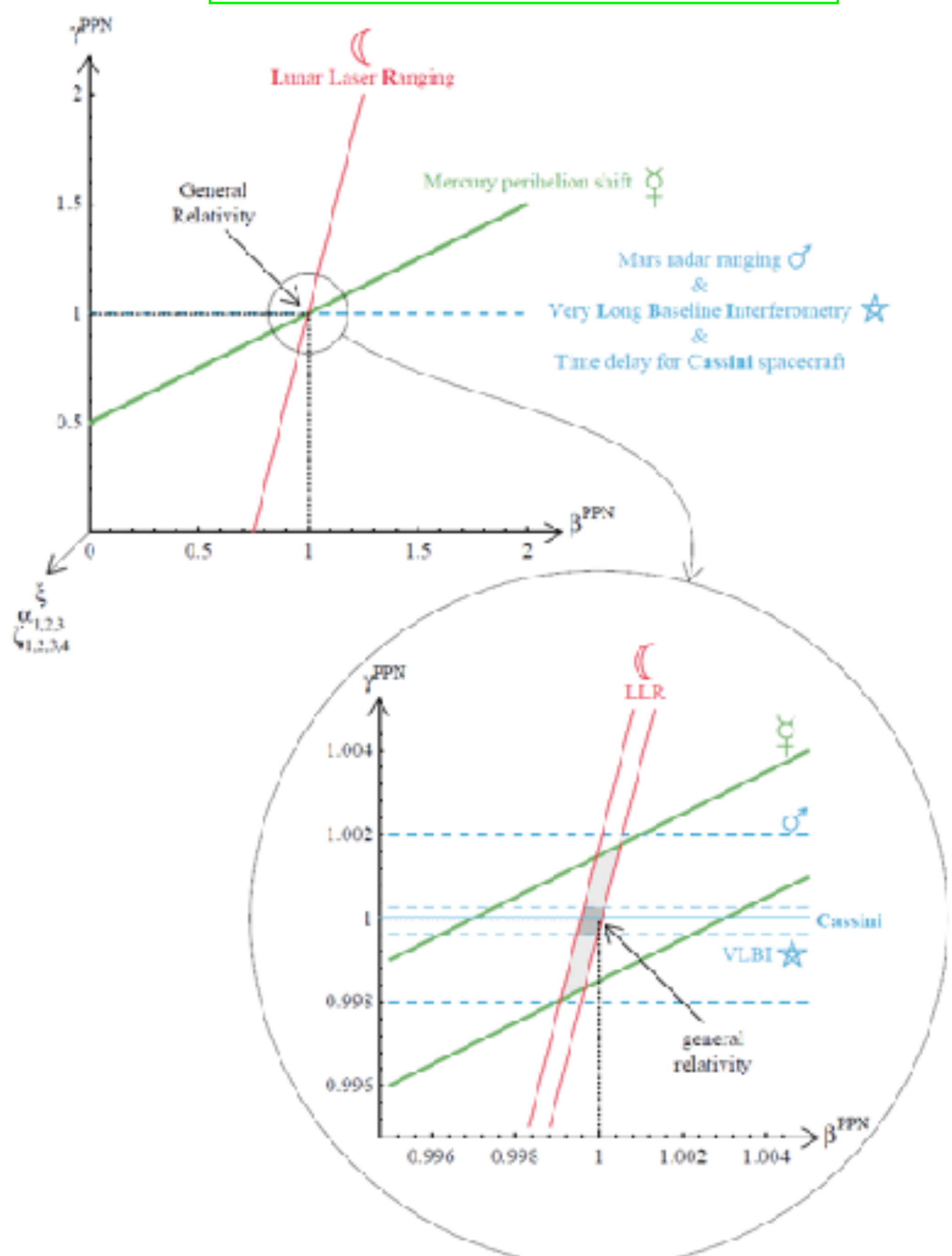
Tessa Baker
Modified Gravity
Higher dimensions
Strings & Branes
Einstein-Dilaton-Gauss-Bonnet
Cascading gravity
Kaluza-Klein
Generalisations of S_{EH}
Gauss-Bonnet
Lovelock gravity
Non-local
Some degravitation scenarios
Higher-order
Lorentz violation
Hořava-Lifschitz
Conformal gravity
$f(G)$
$f(R)$
General $R_{\mu\nu}R^{\mu\nu}$, $\Box R$,etc.
Add new field content
Vector
Einstein-Aether
Lorentz violation
Massive gravity
Bigravity
Tensor
EBI
Bimetric MOND
Scalar
Scalar-tensor & Brans-Dicke
Ghost condensates
Galileons
the Fab Four
KGB
Coupled Quintessence
Horndeski theories
Chern-Simons
Cuscuton
Chaplygin gases
f(T)
Einstein-Cartan-Sciama-Kibble
Torsion theories
Emergent Approaches
CDT
Padmanabhan thermo.

Viability of Modified Gravity

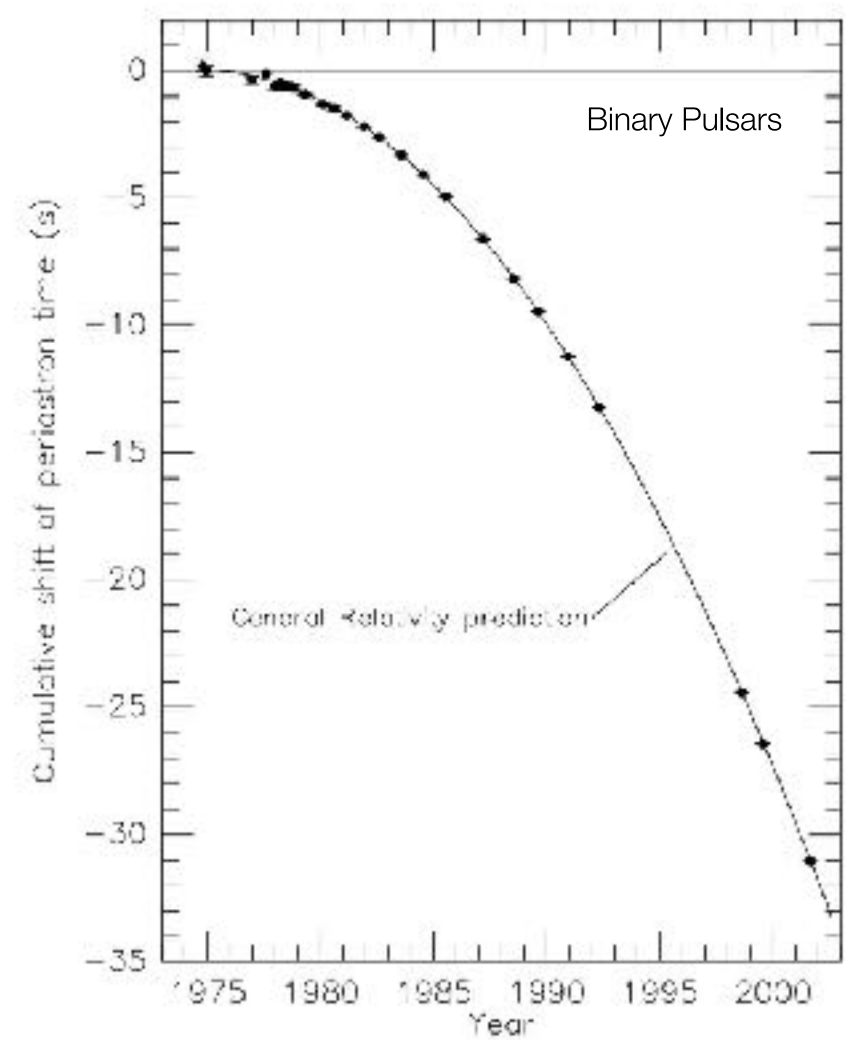
Light degree of freedom driving acceleration

Screening Mechanisms!

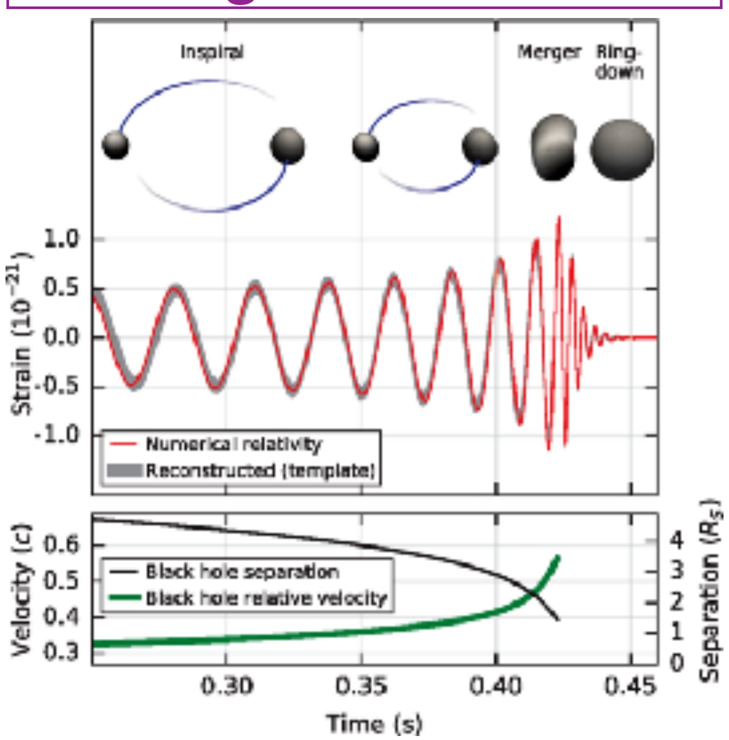
Solar System Bounds



Astrophysical Bounds



Strong field Bounds

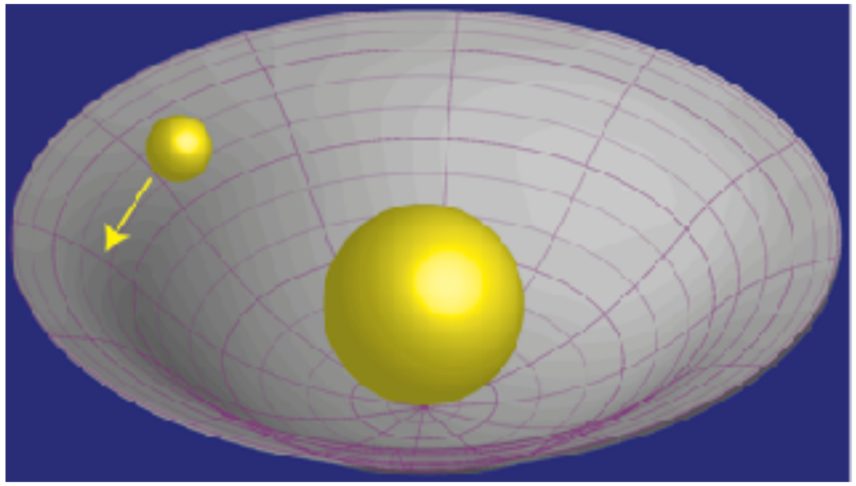


Equivalence between Bardeen potentials

$$ds^2 = a^2(\eta)\left[-d\eta^2(1+2\Phi) + (1-2\Psi)d\vec{x}^2\right]$$

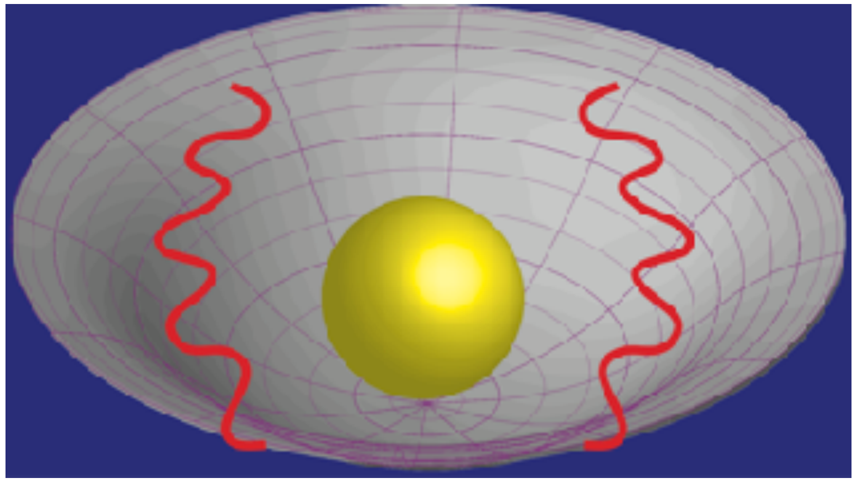
"Newtonian" potential:

$$\Phi = \delta g_{00}/2g_{00}$$



Space curvature:

$$\Psi = \delta g_{ij}/2g_{ij}$$



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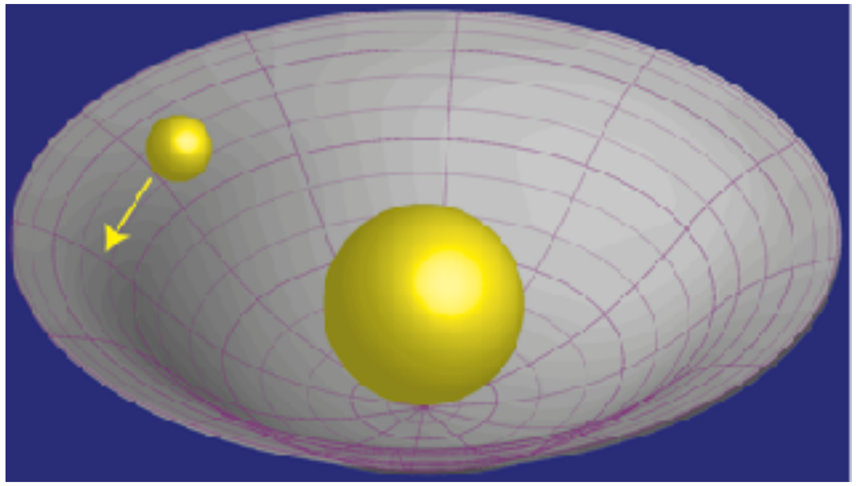
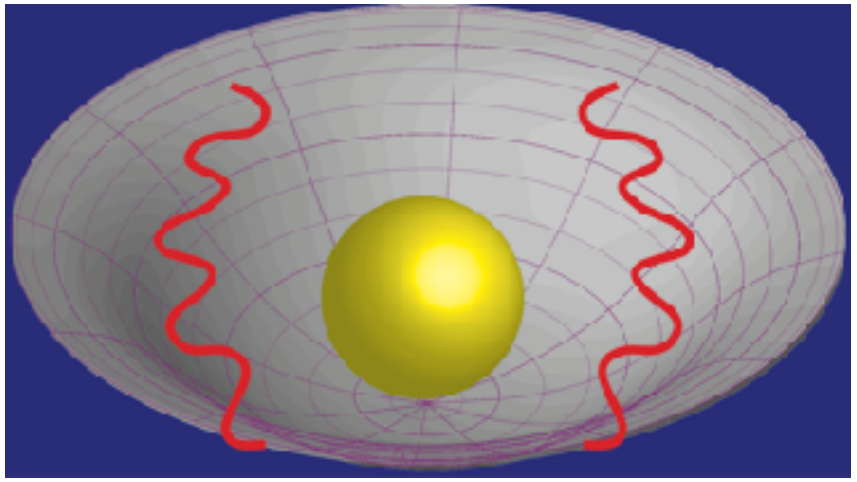




Solar System

$$\mathrm{d}s^2 = (-1 + 2\frac{GM}{r})\,\mathrm{d}t^2 + (1 + 2\ \frac{GM}{r})\,\mathrm{d}x^2$$

"How much space is curved by a unit rest mass"

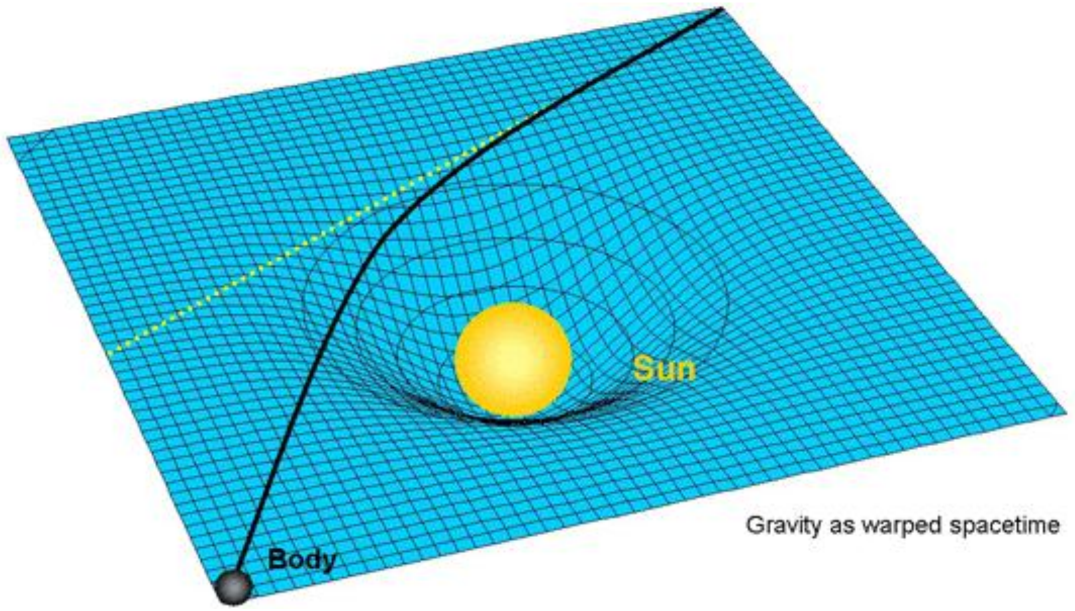
Solar System Tests

$$\mathrm{d}s^2 = (-1 + 2\frac{GM}{r})\,\mathrm{d}t^2 + (1 + 2\gamma\frac{GM}{r})\,\mathrm{d}x^2$$

- Post-Newtonian parameter

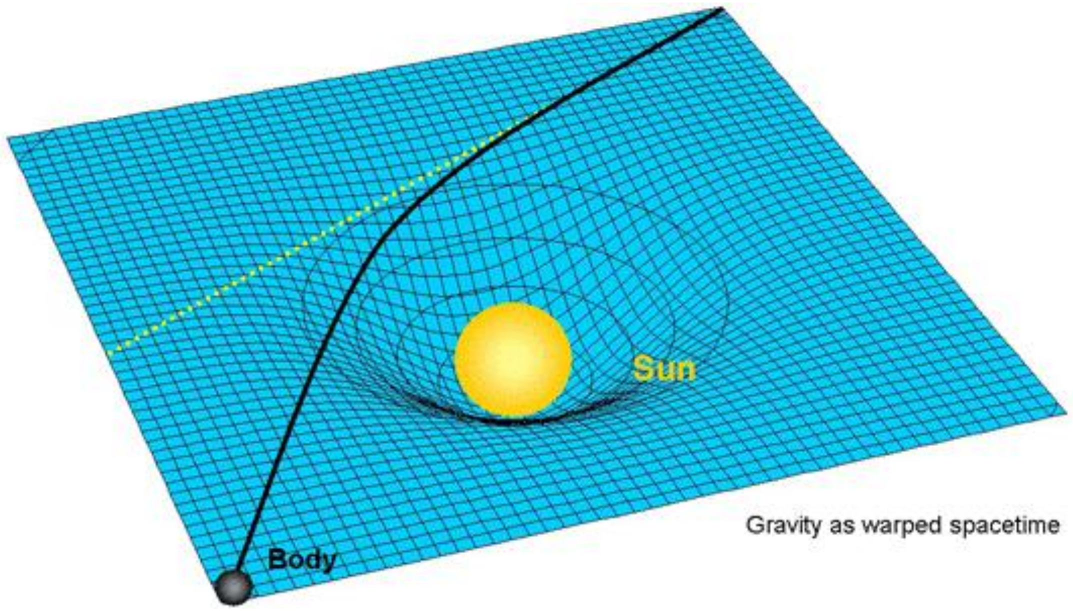
$$g_{00} = -1 + 2GU \qquad U = \frac{M}{r}$$

$$g_{ij} = \delta_{ij}(1 + 2\gamma GU)$$



Solar System Tests

$$ds^2 = (-1 + 2\frac{GM}{r})\,dt^2 + (1 + 2\gamma\frac{GM}{r})\,dx^2$$



- Post-Newtonian parameter

$$g_{00} = -1 + 2GU \qquad U = \frac{M}{r}$$

$$g_{ij} = \delta_{ij}(1 + 2\gamma GU)$$

- Bending of lights

$$\theta = 2(1+\gamma)\frac{M_\odot}{r} = \frac{1+\gamma}{2}\theta_{GR}$$

$$\gamma = 0: \text{ "Newtonian"}$$

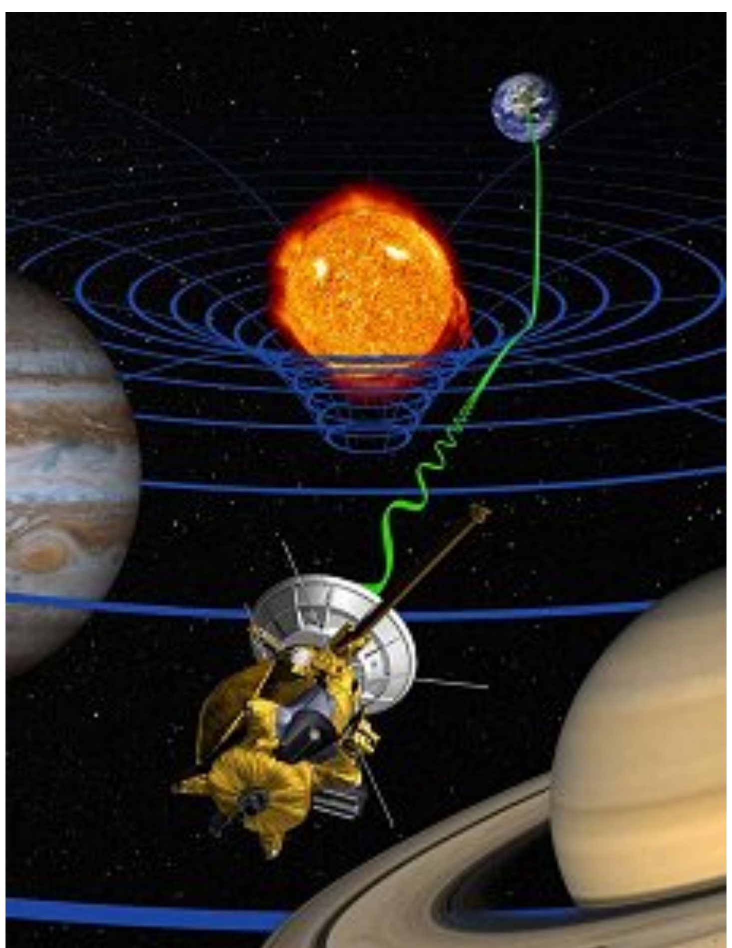
$$\gamma = 1 : \text{ GR}$$

Constrains on Modified Gravity

Post-Newtonian Parameter

$$ds^2 = (-1 + 2\frac{GM}{r})\,dt^2 + (1 + 2\gamma\frac{GM}{r})\,dx^2$$

"How much space is curved by a unit rest mass"



$$\gamma - 1 = (2.1 \pm 2.3) \times 10^{-5}$$

$$\gamma - 1 = 0, \qquad \mathrm{GR}$$

$$\gamma - 1 = -\frac{\phi^2}{M^2}\frac{2}{\frac{\phi^2}{M^2} + 2\Psi(1 + \frac{\phi^2}{M^2})}$$

Constrains on Modified Gravity

Post-Newtonian Parameter

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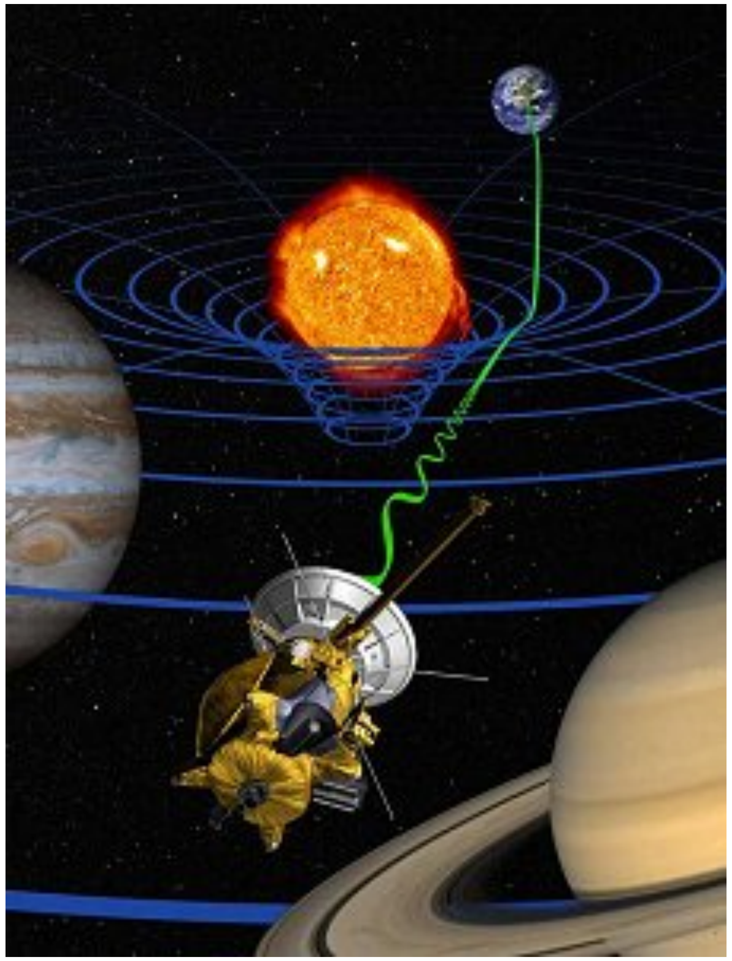
"How much space is curved by a unit rest mass"



$$\gamma - 1 = (2.1 \pm 2.3) \times 10^{-5}$$

$$\gamma - 1 = 0, \qquad \text{GR}$$

$$|\gamma - 1| \approx \frac{|\Delta f_R(r)|}{\Psi(r)}$$

Profile of field in Solar system

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

- Scalar field equation of motion

$$\ddot{\phi}+3H\dot{\phi}-\frac{1}{a^2}\nabla^2\phi= -V_{\mathrm{eff},\phi}(\rho,\phi)$$

Quasi-static approximation

Field profile does not change in virialised systems

- Scalar field equation of motion

$$\frac{1}{a^2}\nabla^2\phi = -V_{\mathrm{eff},\phi}(\rho, \phi)$$

- **Quasi-static** approximation

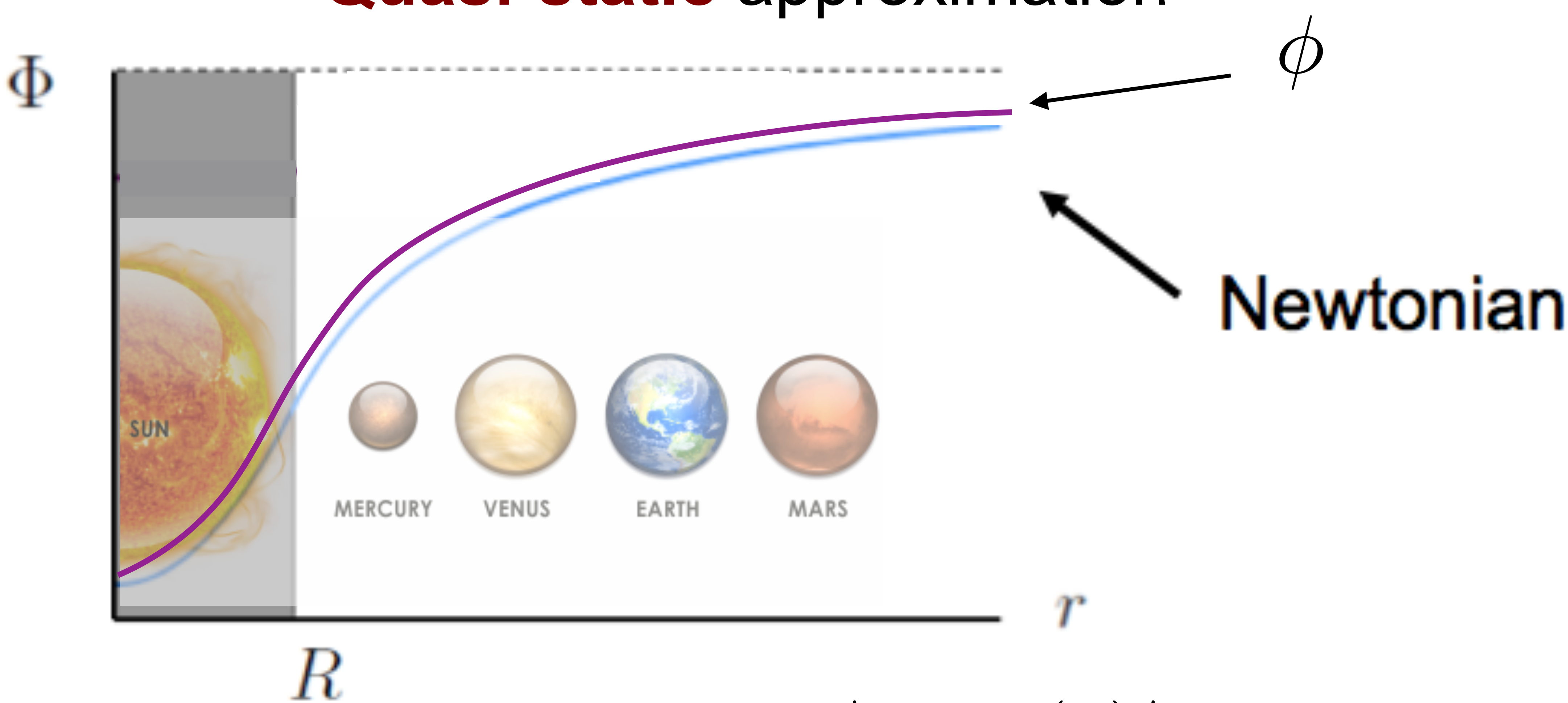
Quasi-static approximation

Field profile does not change in virialised systems

- Scalar field equation of motion

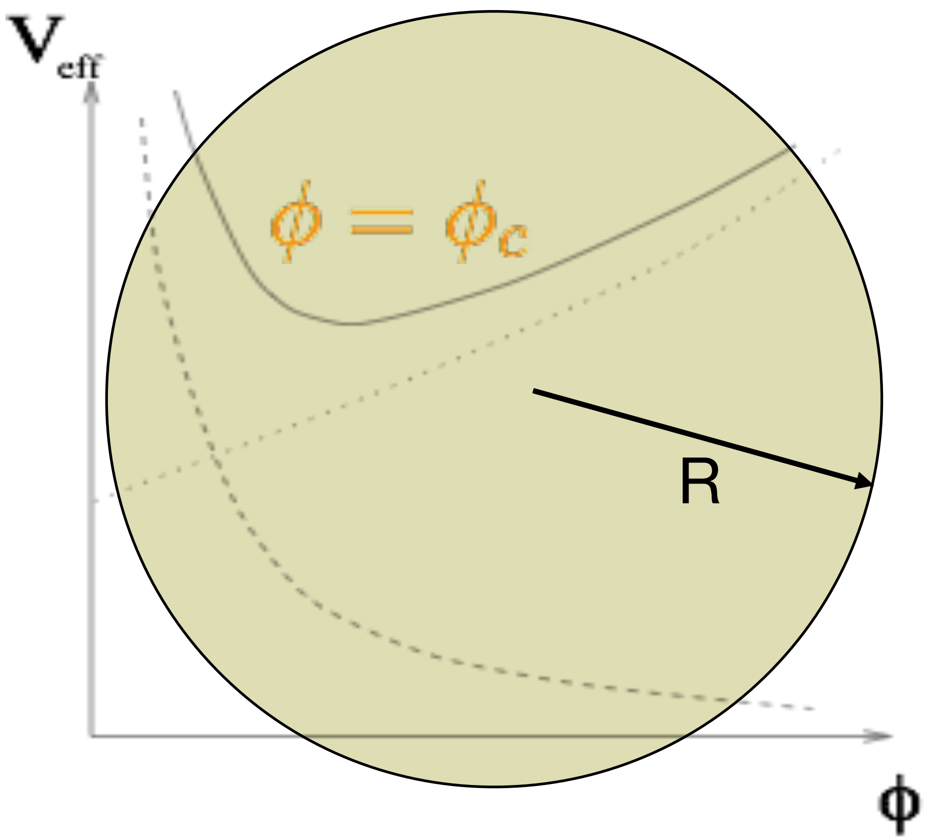
$$\frac{1}{a^2}\nabla^2\phi = -V_{\mathrm{eff},\phi}(\rho,\phi)$$

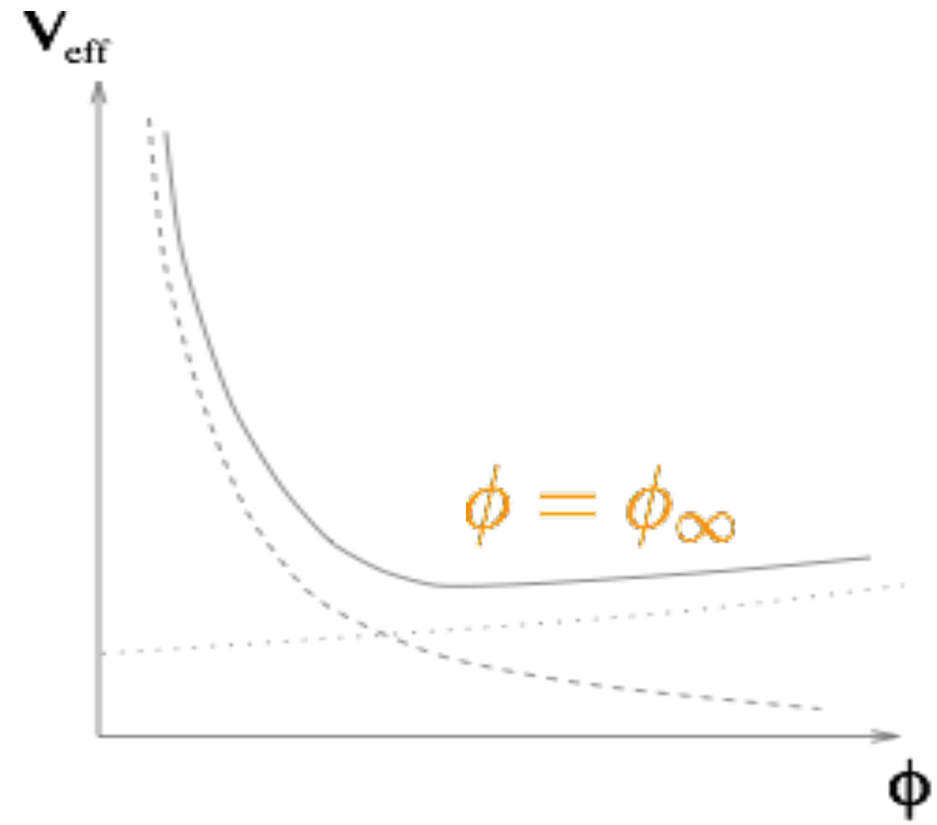
- **Quasi-static** approximation



$$|\gamma - 1| \approx \frac{|\Delta f_R(r)|}{\Psi(r)}$$

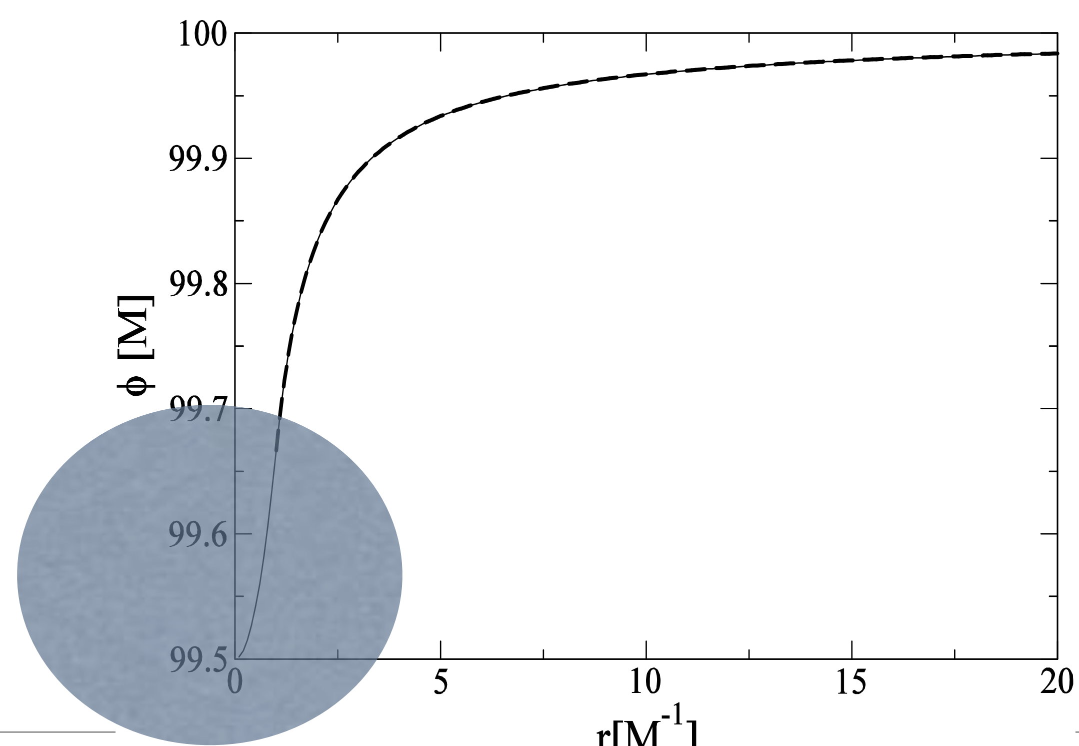
The Thin Shell Effect



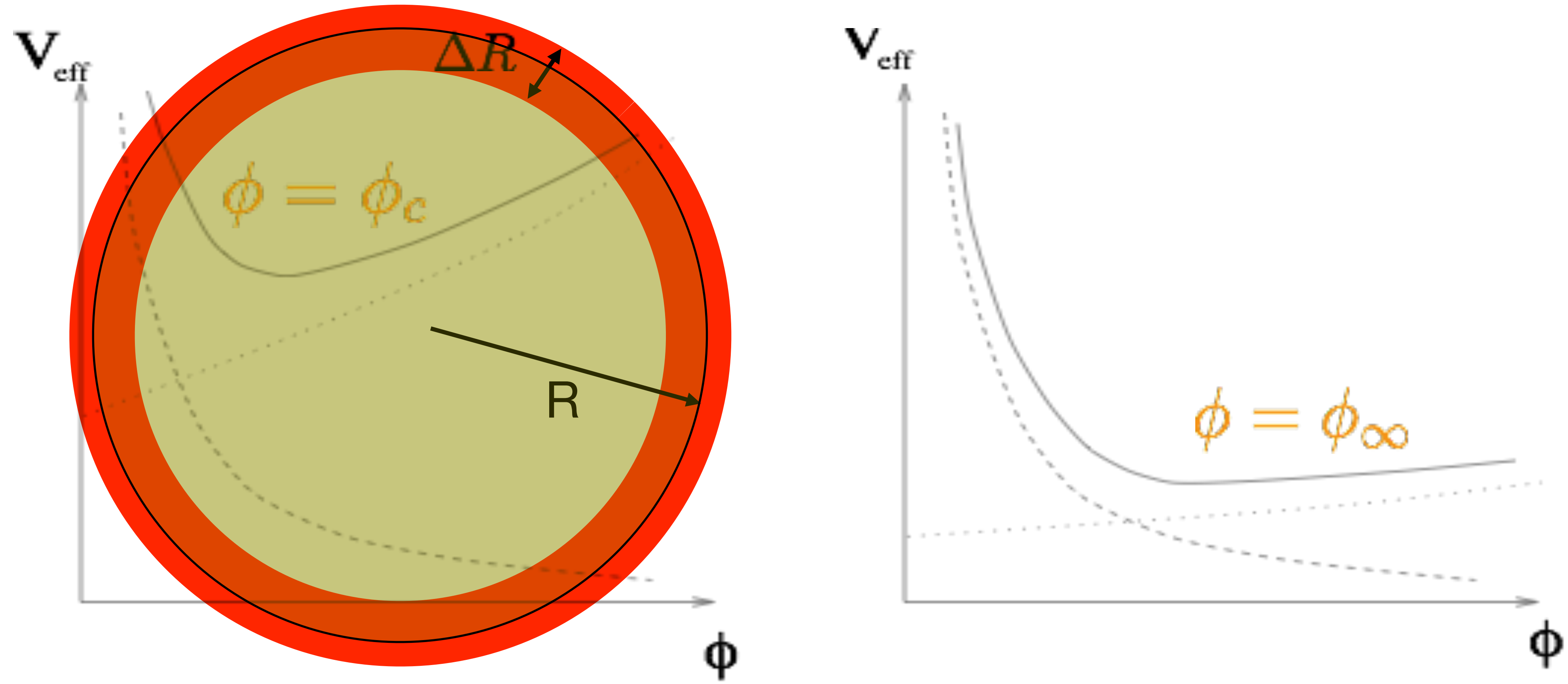


Large ρ

Small ρ

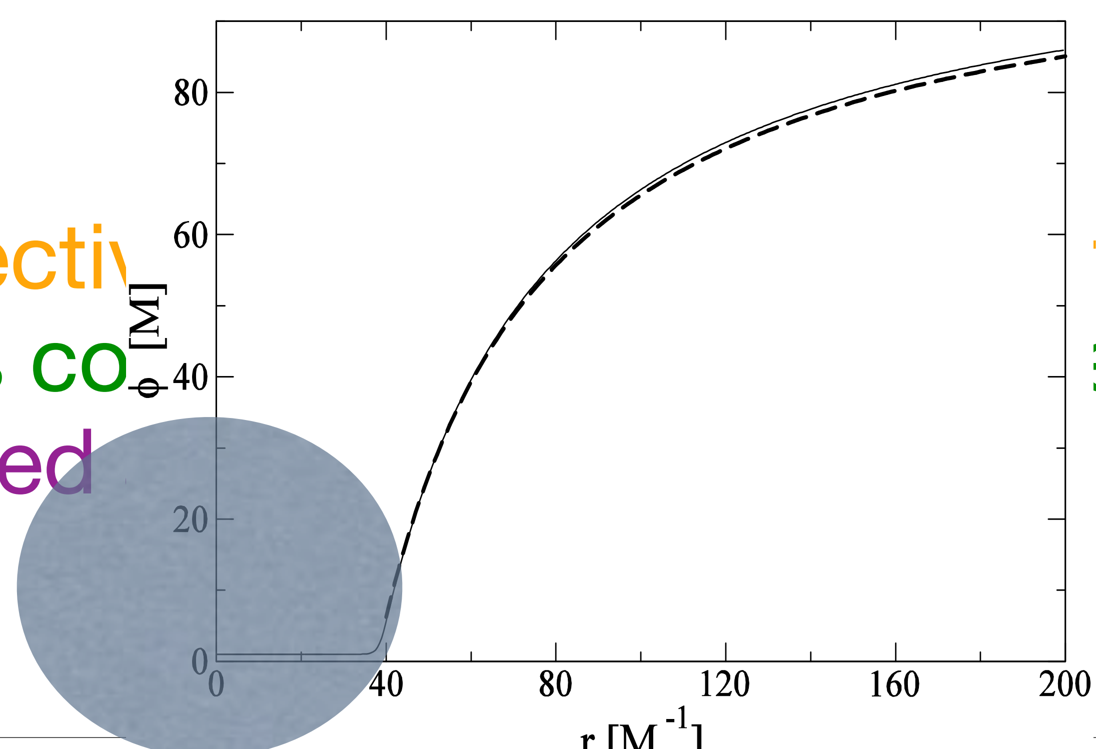


The Thin Shell Effect



Large ρ

Small ρ



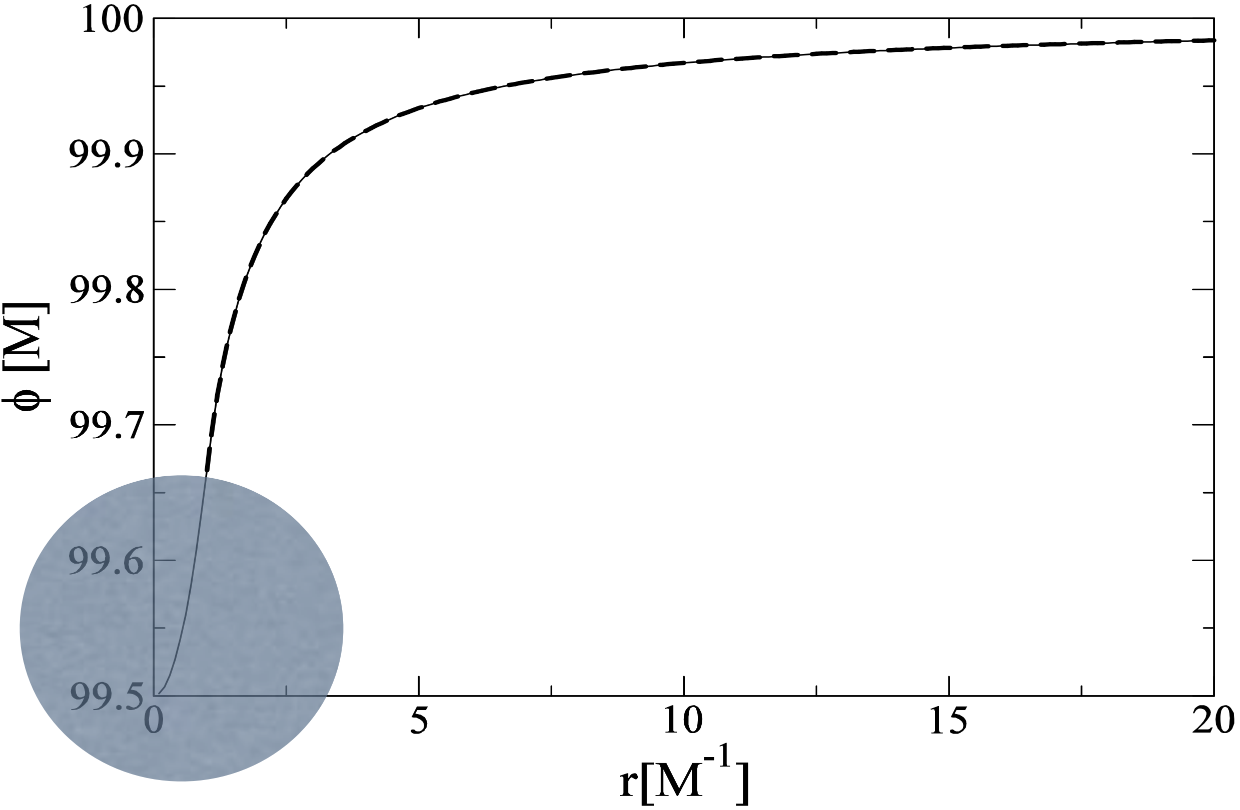
Field reaches effectiv ... ywhere in the body

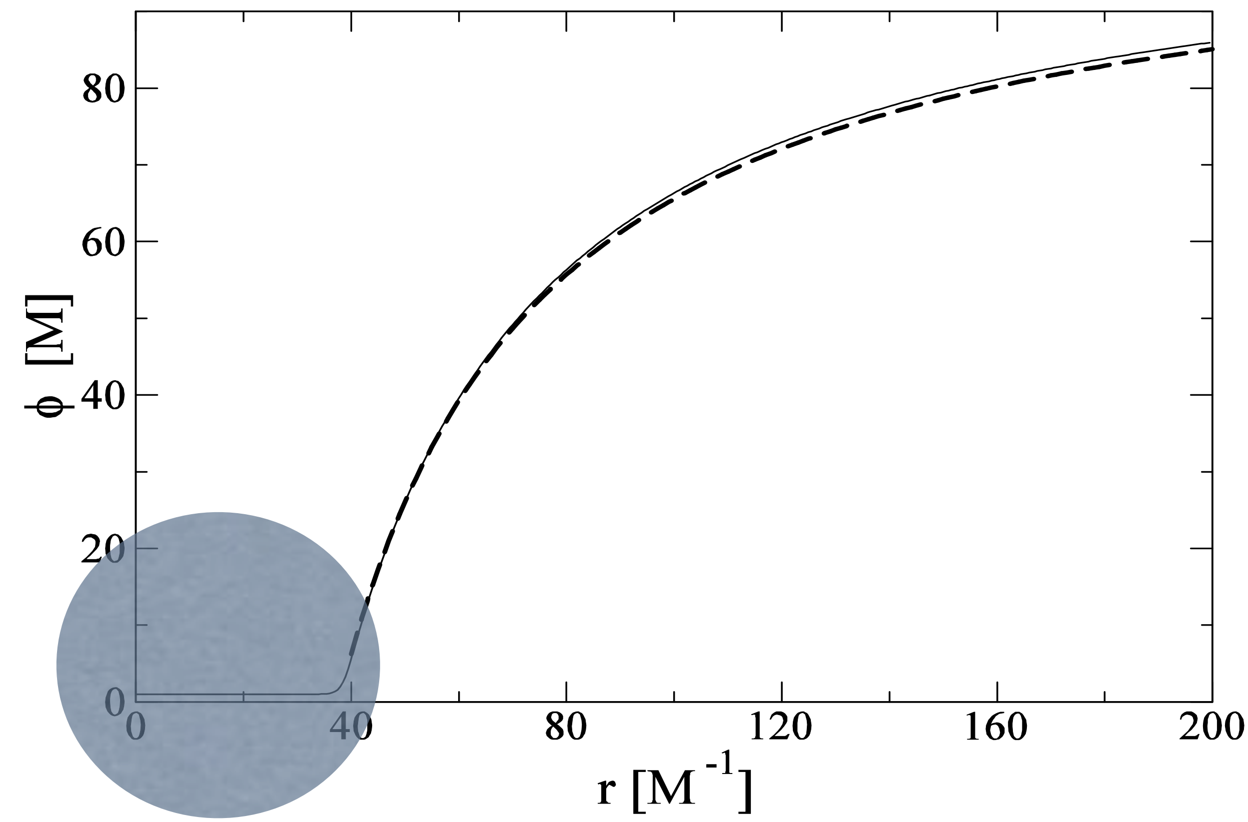
All field variations co ... ear body surface

This region is called

Fifth Force on Body with Thin-Shell

$$\vec{F}_\phi = -\frac{\beta_1}{M_{Pl}} M_1 \vec{\nabla}\phi$$





$$V(r) = -2\beta_1\beta_2 \frac{M_1 M_2}{8\pi M_{Pl}^2} \frac{e^{-r/\lambda_\infty}}{r}$$

$$V(r) = -2\beta_1\beta_2 \left(\frac{\Delta R}{R}\right) \frac{M_1 M_2}{8\pi M_{Pl}^2} \frac{e^{-r/\lambda_\infty}}{r}$$

Thin shell $\Longrightarrow$ $\beta_{eff} = \beta_1\beta_2 \frac{\Delta R}{R} \ll \beta_1\beta_2$

Fifth force produced in a body with thin-shell becomes very small

$$\frac{\Delta R}{R} \ll 1$$

Evading Gravity Constraints on Earth

$$V(\phi) = M^{4+n}\phi^{-n}$$

$$\frac{\Delta R}{R} = \frac{\phi_E - \phi_{Atm}}{6\beta M_{Pl}\Phi_E} < 10^{-7}$$

Fifth Force: $$F = (1 + \beta_{eff})F_N$$

Objects with thin-shell: $$\beta_{eff} = 2\beta_1\beta_2\frac{\Delta R}{R}$$

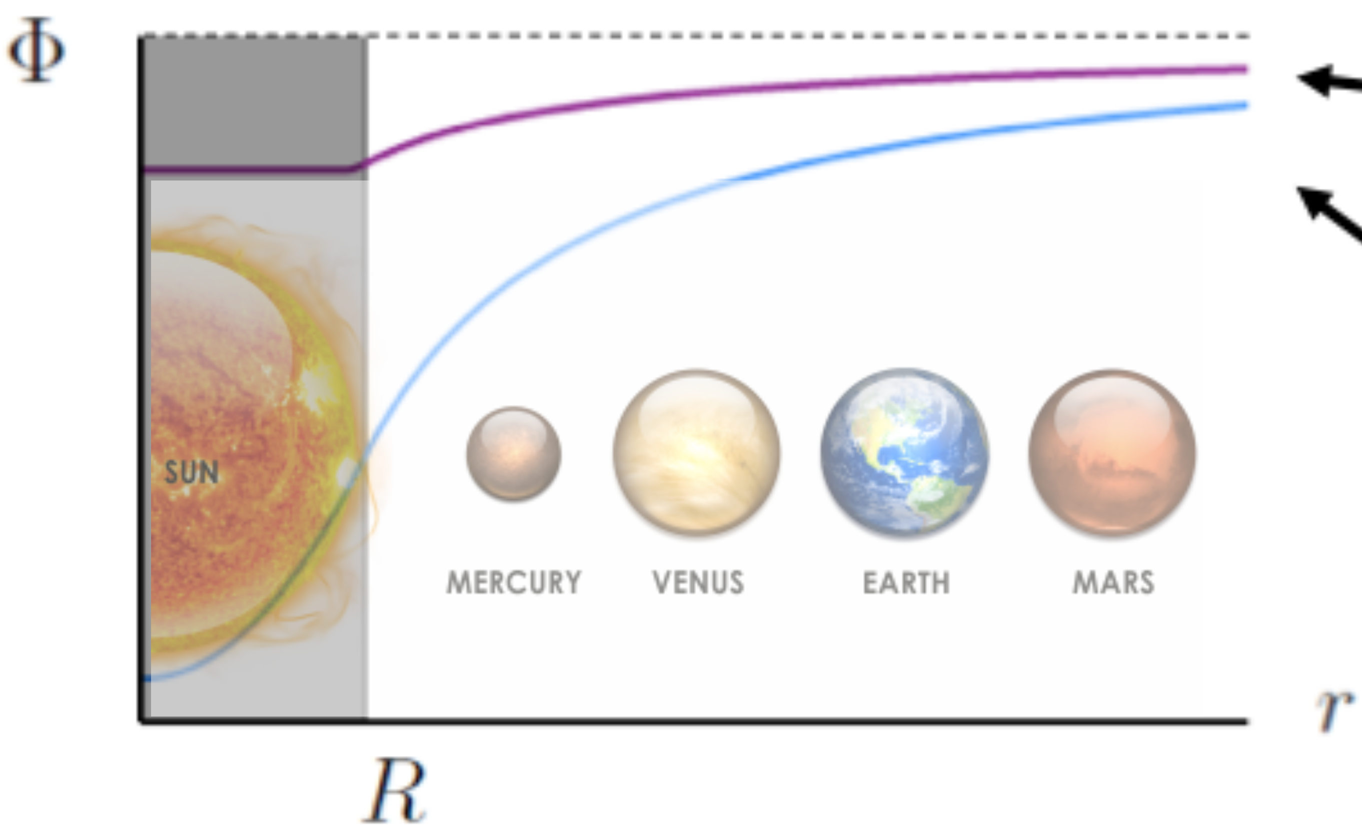
$$\beta_{eff} = 2\beta_1\beta_2 10^{-7} \ll 1 \qquad (\beta_1 \sim \beta_2 \gg 1)$$

Fifth force constraints easily evaded!

Thin shell effect

Screening mechanisms suppress value field and gradient

$$\vec{a} = -\vec{\nabla}\Phi - \frac{\mathrm{d}\ln A(\phi)}{\mathrm{d}\phi}\vec{\nabla}\phi = -\vec{\nabla}\Big(\Phi + \ln A(\phi)\Big)$$



ϕ

Newtonian potential

$$\Phi = -\frac{GM}{r}$$

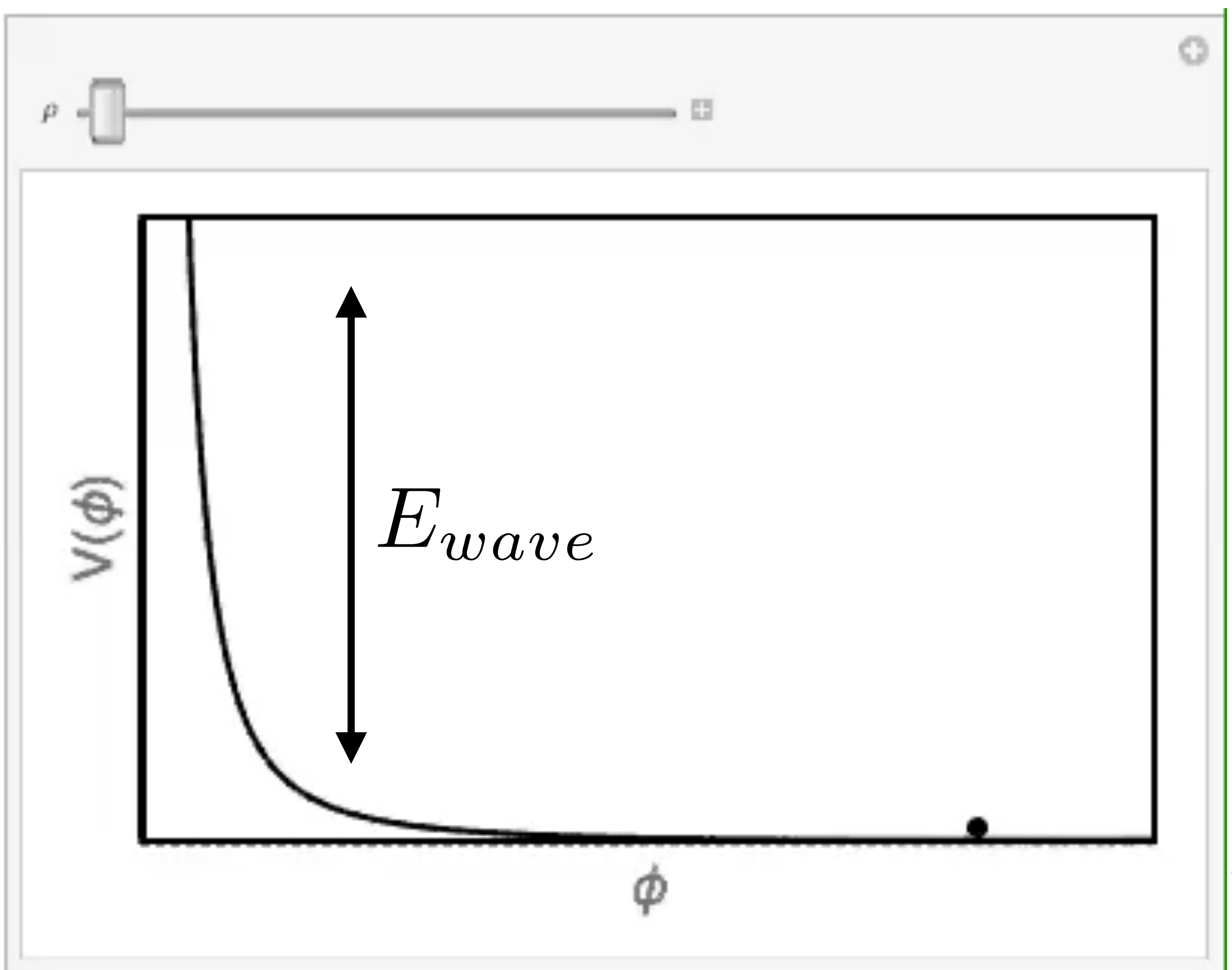
$$\boxed{F_\phi \ll F_N}$$

$$|\gamma - 1| \approx \frac{|\Delta f_R(r)|}{\Psi(r)} \ll 1$$

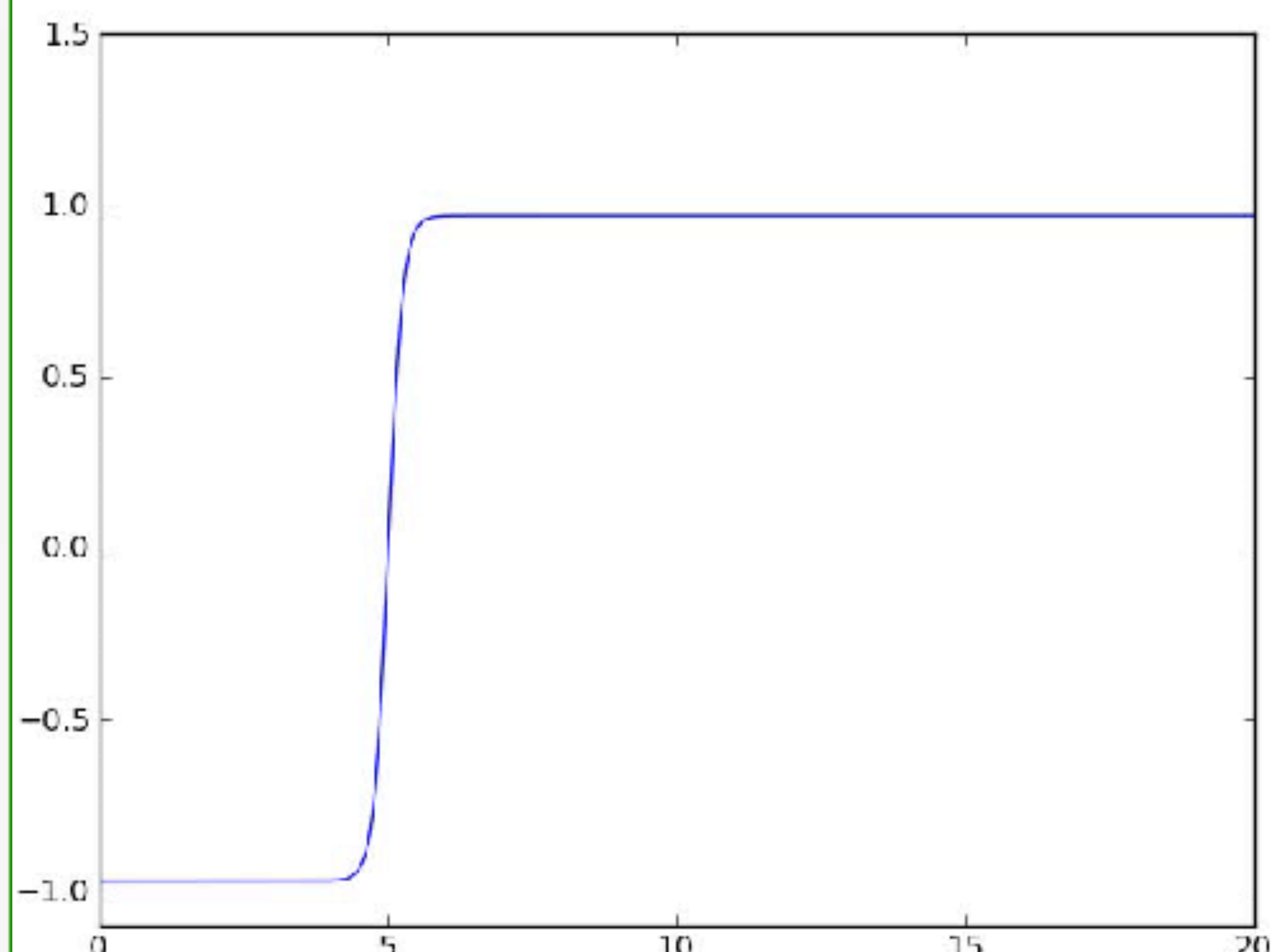
$$\boxed{\gamma - 1 = -\frac{\phi^2}{M^2}\frac{2}{\frac{\phi^2}{M^2} + 2\Psi(1 + \frac{\phi^2}{M^2})} \ll 1}$$

Waves from Supernovae

Chameleon Potential

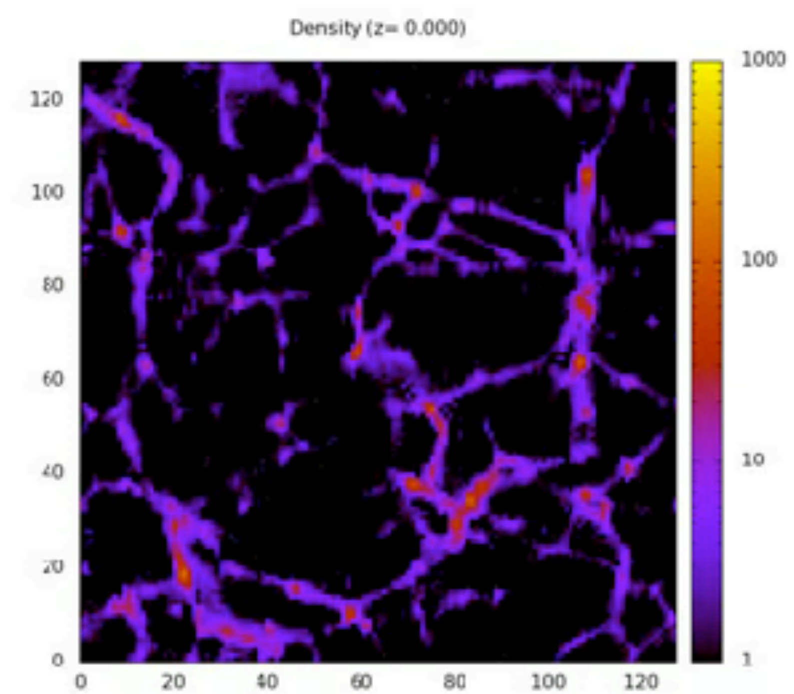


Profile of field

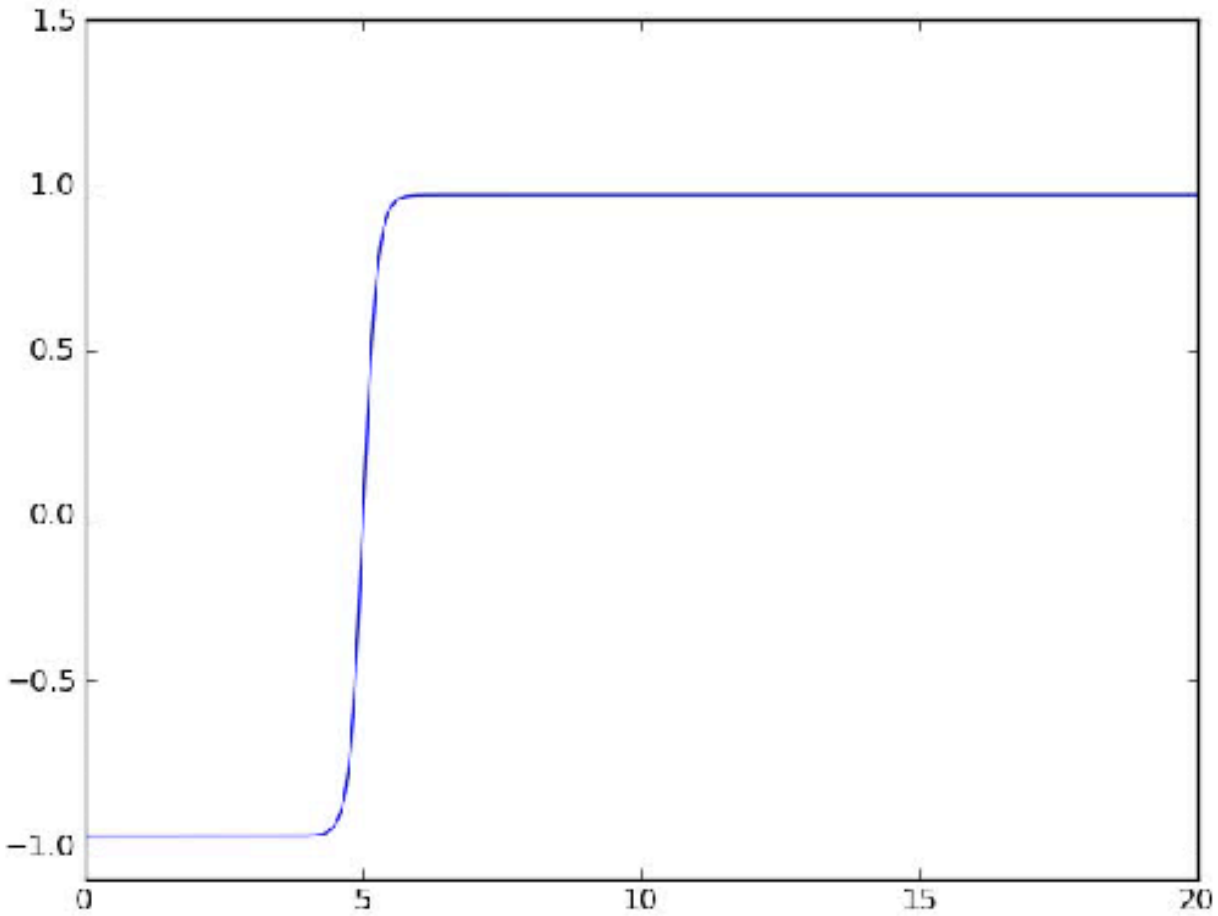


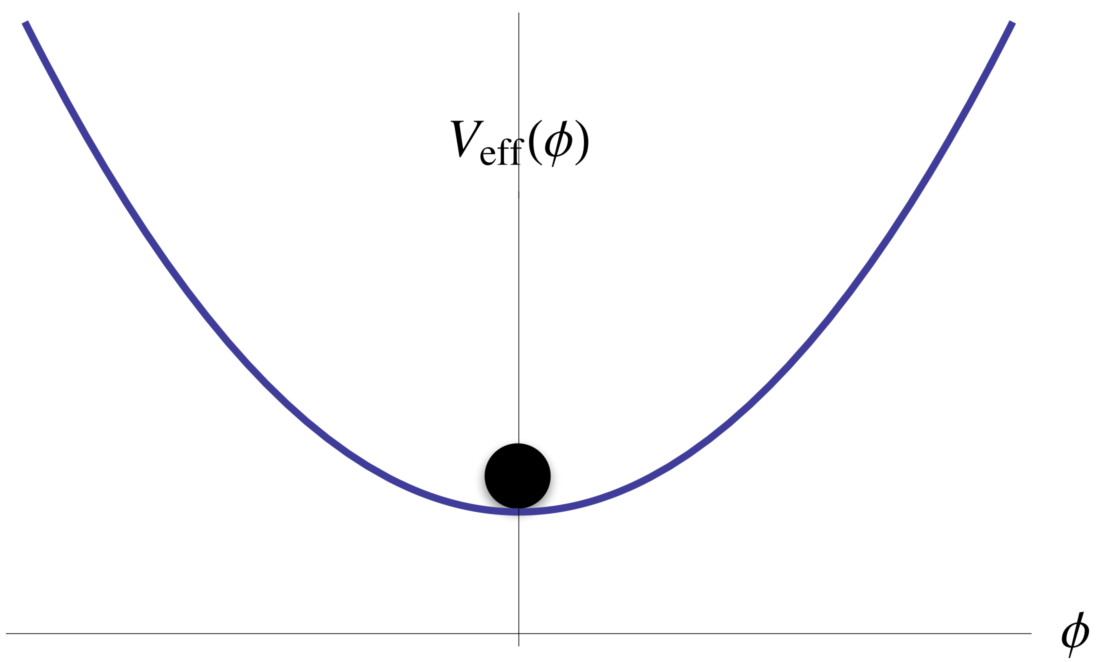
Waves from collapse of domain walls

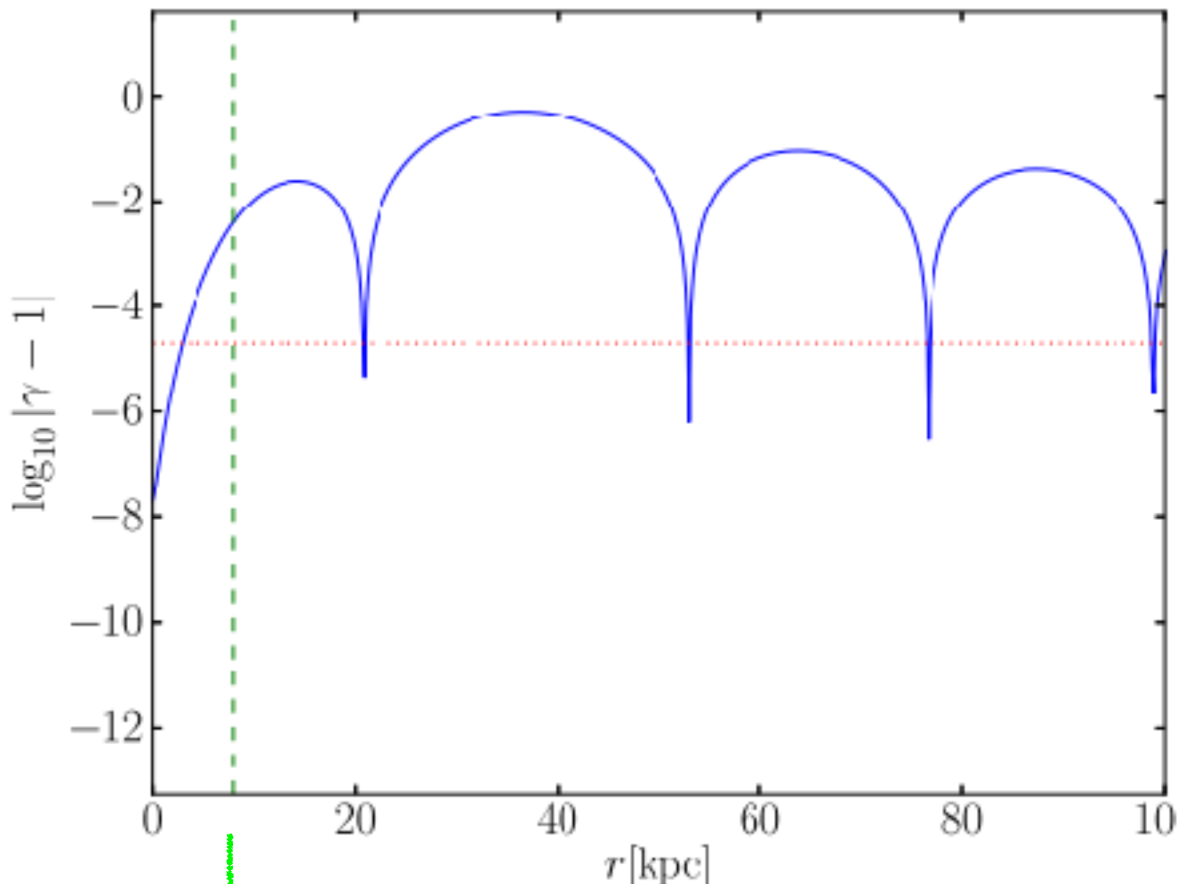
[redacted]



Profile of field [redacted]







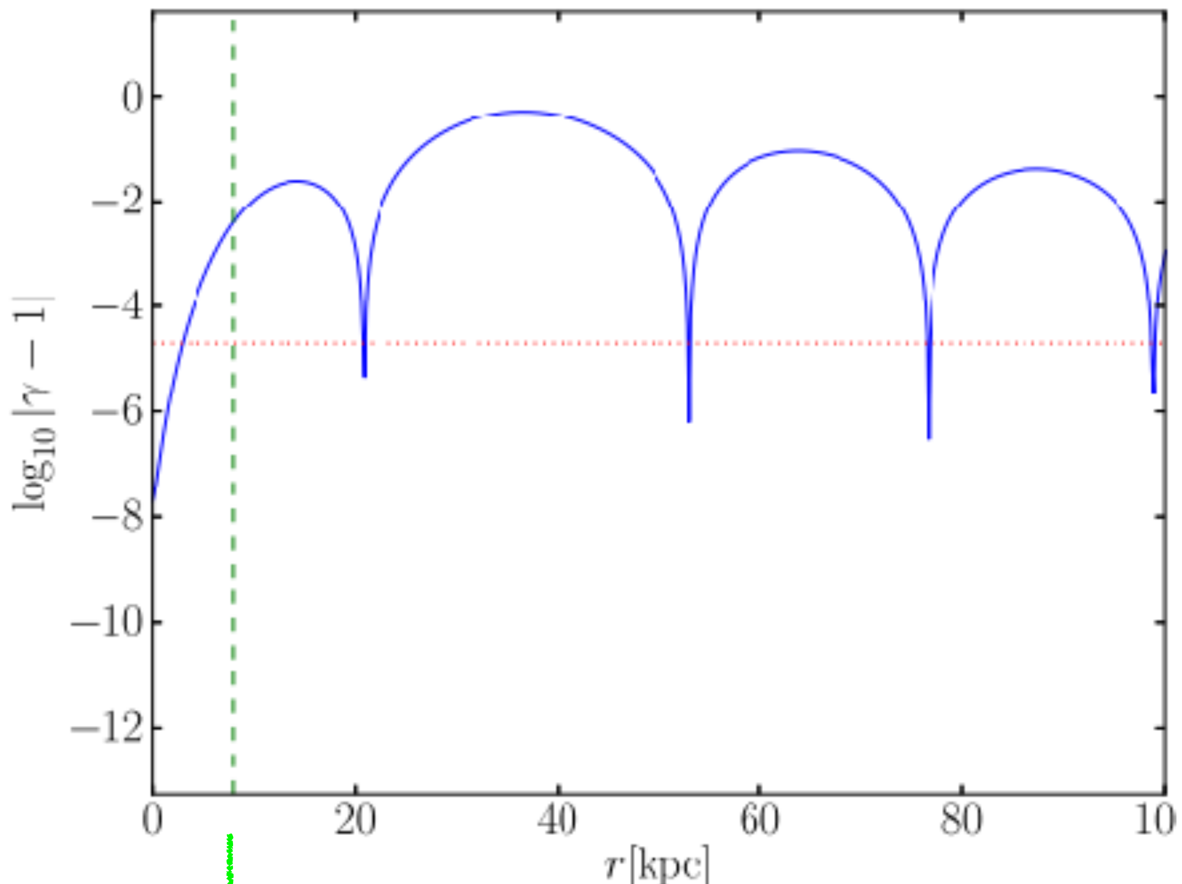
Cassini bound

$$\gamma - 1 = -\frac{\phi^2}{M^2}\frac{2}{\frac{\phi^2}{M^2} + 2\Psi(1 + \frac{\phi^2}{M^2})}$$

Distance from milky way centre

Solar System

Hagala, Llinares, DFM, PRL



Cassini bound

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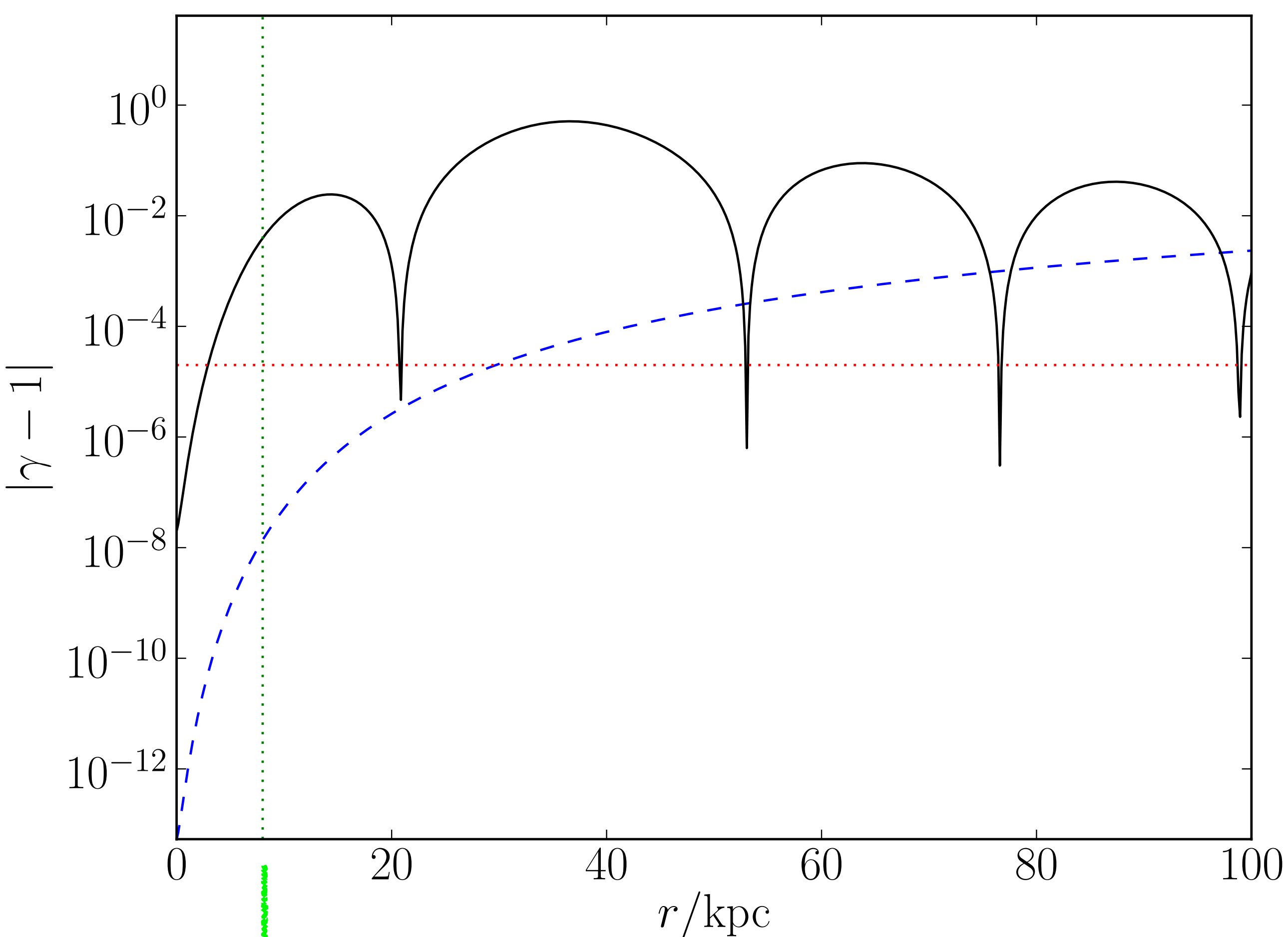
Hagala, Llinares, DFM, PRL



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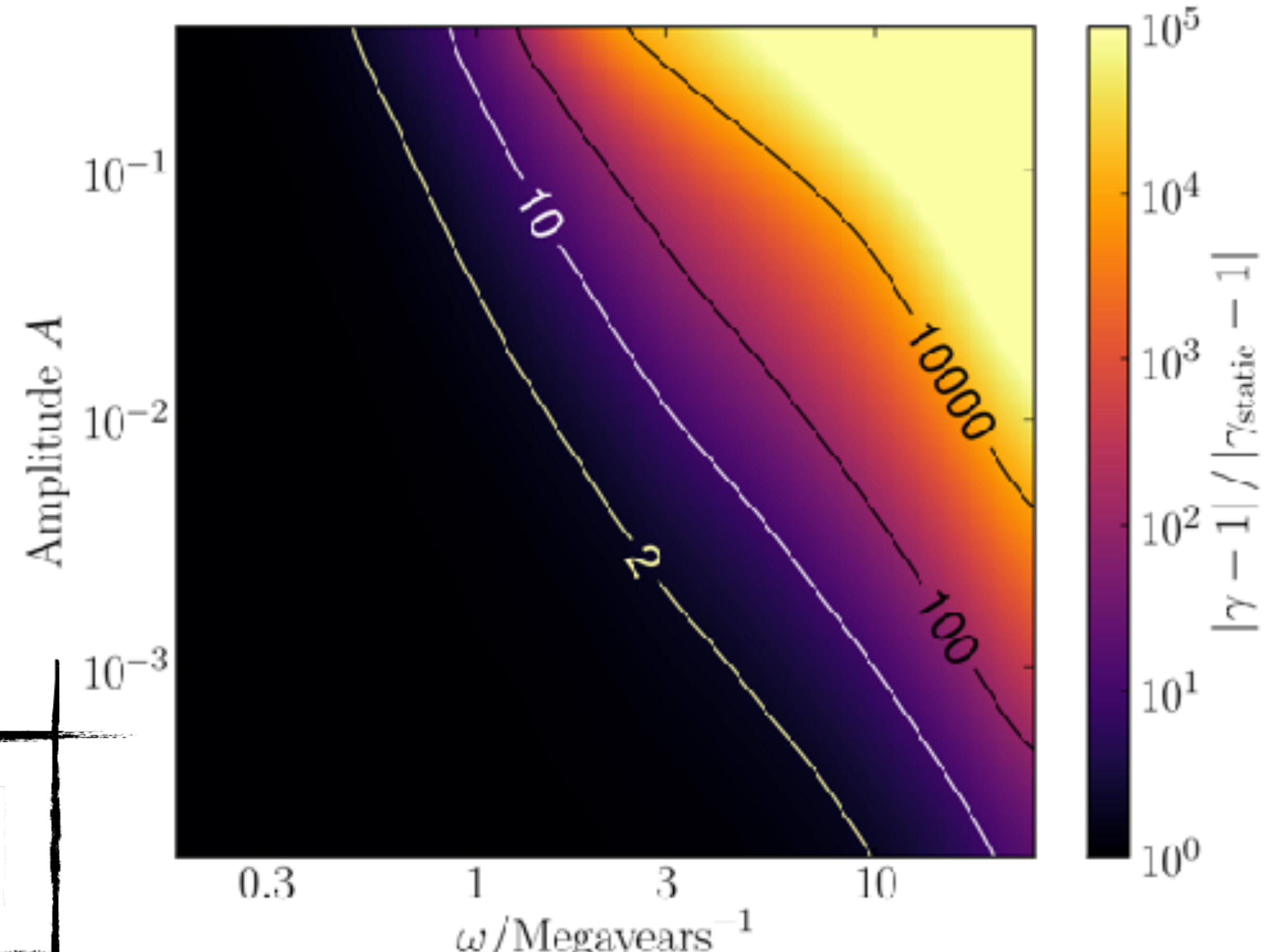

Screening disrupted!

Scalar waves increase the PPN parameter and fifth force several orders in magnitude!

Oscillations are a smoking gun!

Hagala, Llinares, DFM, PRL

Summary: Probing Screened Modified Gravity

in laboratory

in the solar system

+ perfect to test EP violations, PPN, etc
+ Direct gravity experiments
- very limited time/space/energy scales
- only probes baryonic physics

at astrophysical scales

+ probe different Screening Mechanisms
- complicated non-linear/non-gravitational effects

at cosmological scales

+ unlimited scales
+ baryons, dark matter, dark energy
+ mostly linear processes
- Does not probe screening mechanisms