Voids Searching For Dark Energy

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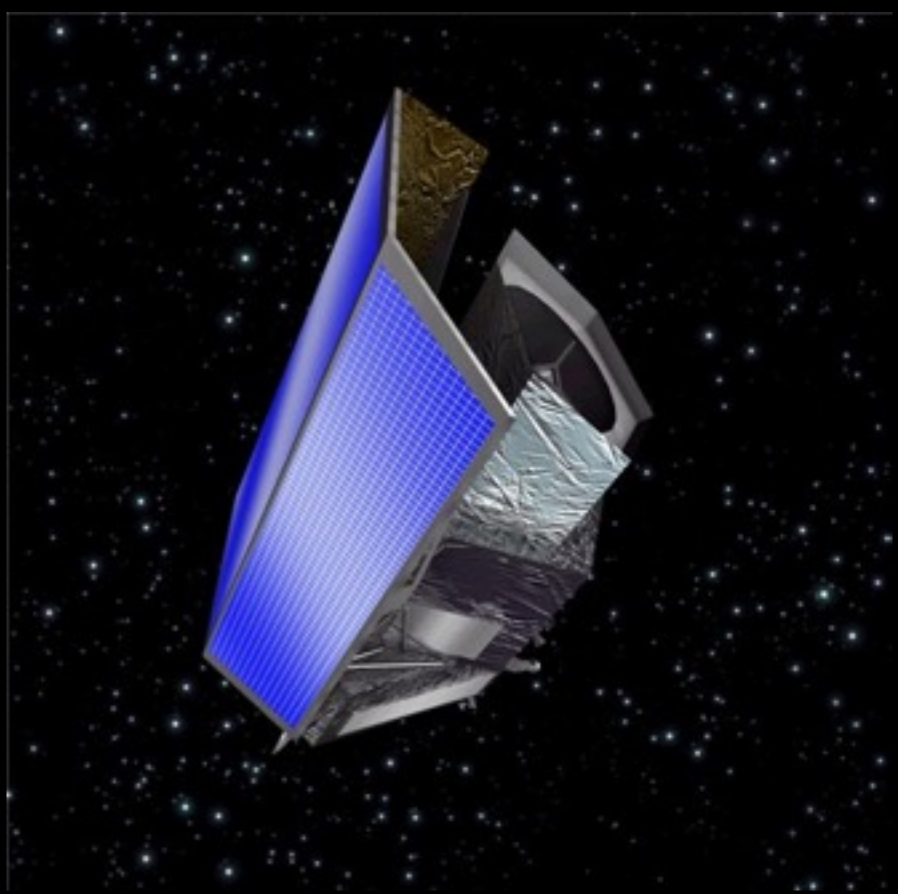

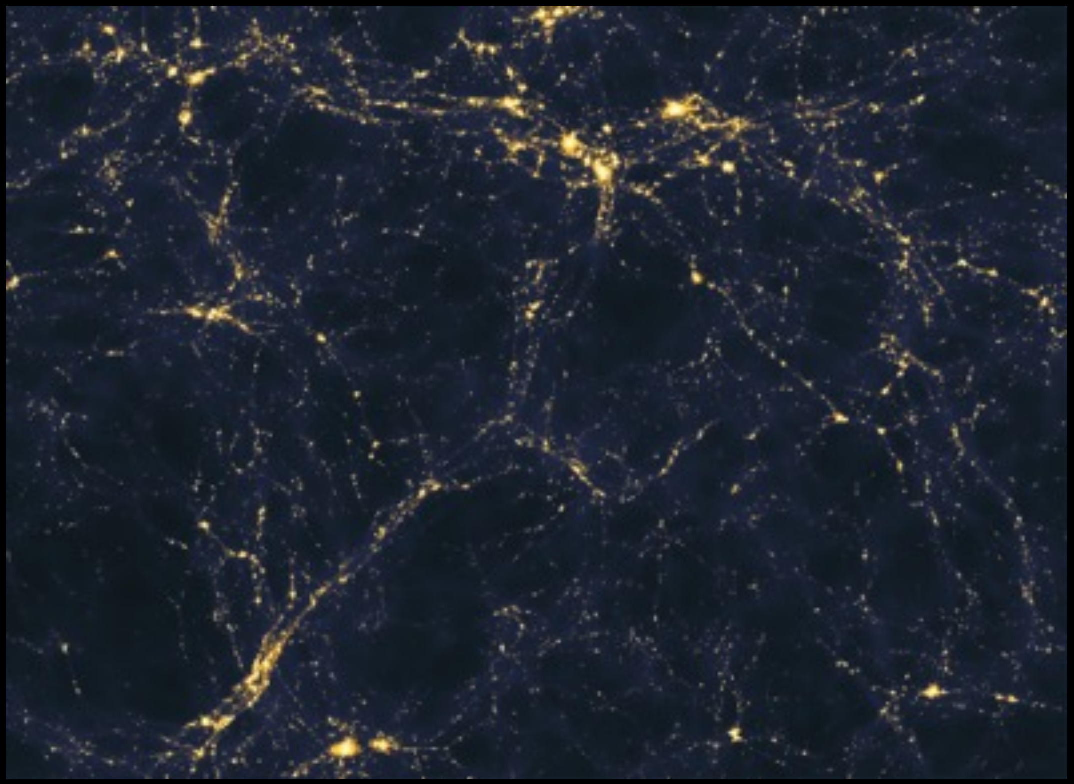

Collaborators

M. Sahlen

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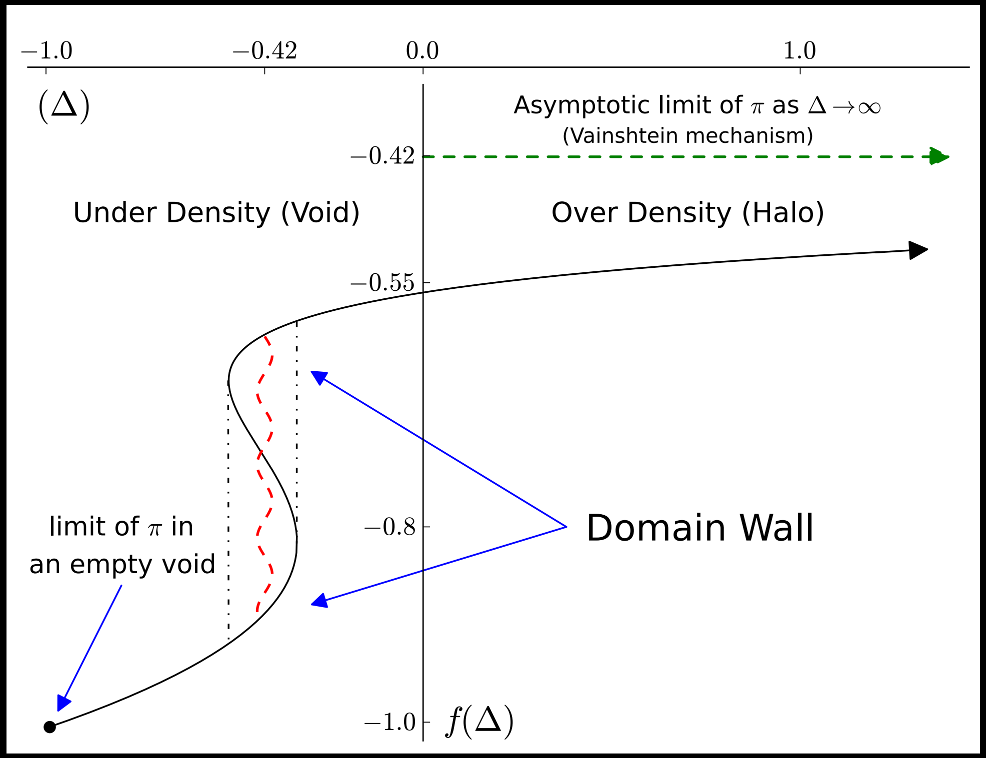
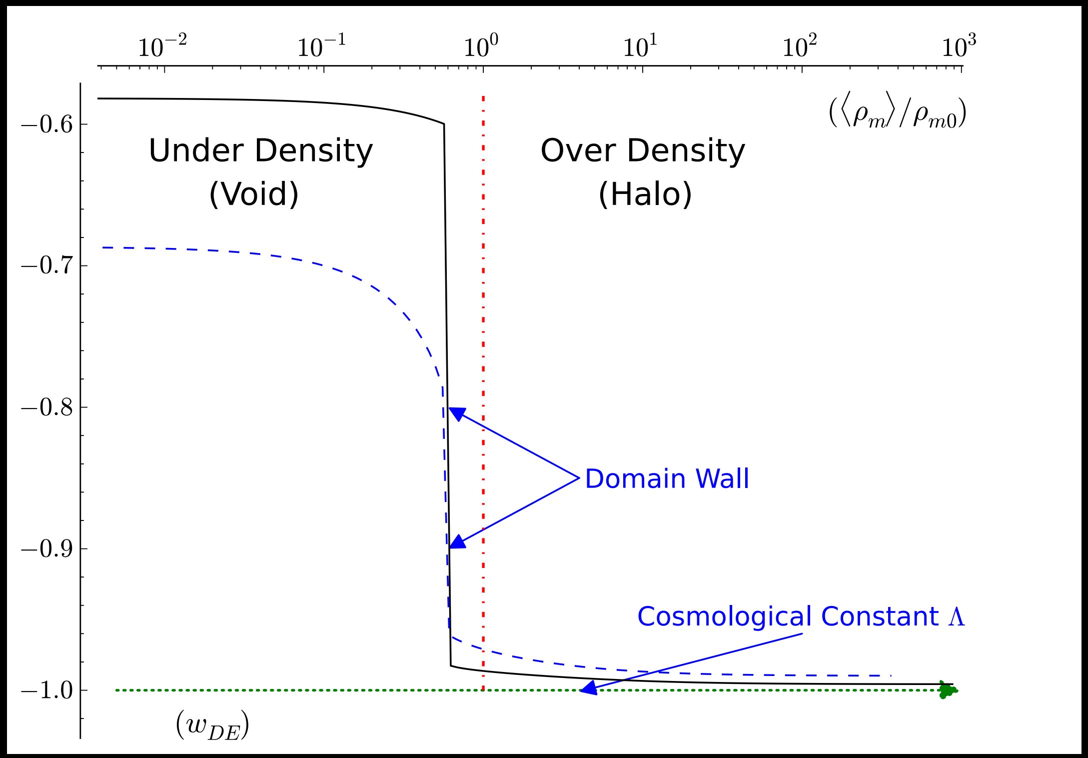
D. Spolyar, M. Sahlen, J. Silk
Phys.Rev.Lett. 111 (2013) 24, 241103

Basic Result

- No Vainshtein Mechanism-No Screening
- Massive Gravity can dramatically modify the equation of state of dark energy in voids
- In fact the extra scalar degree of freedom can generate a domain wall





The Plot

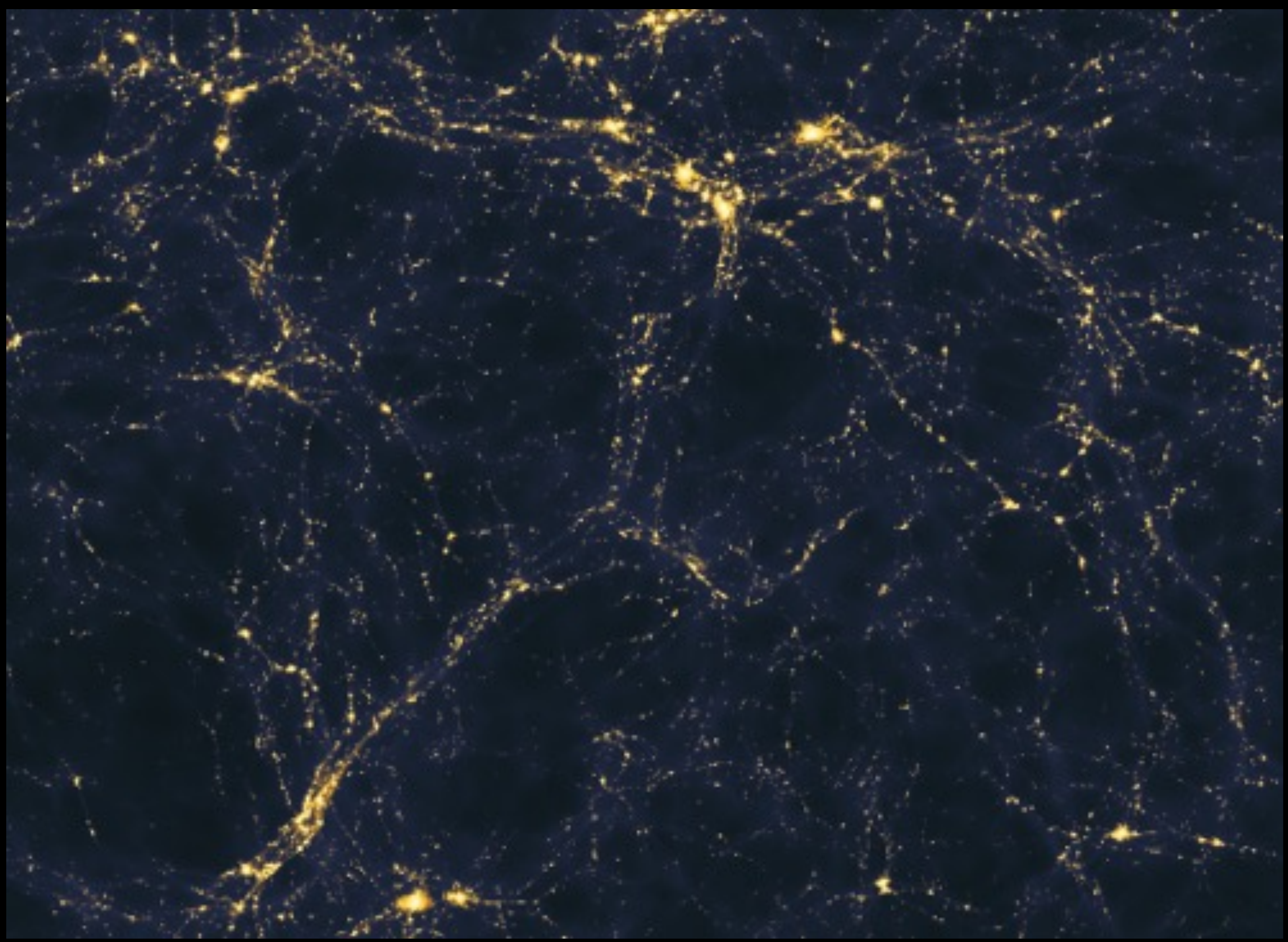
- Massive Gravity
- Solutions in Voids
- Euclid
- Constraints From Euclid

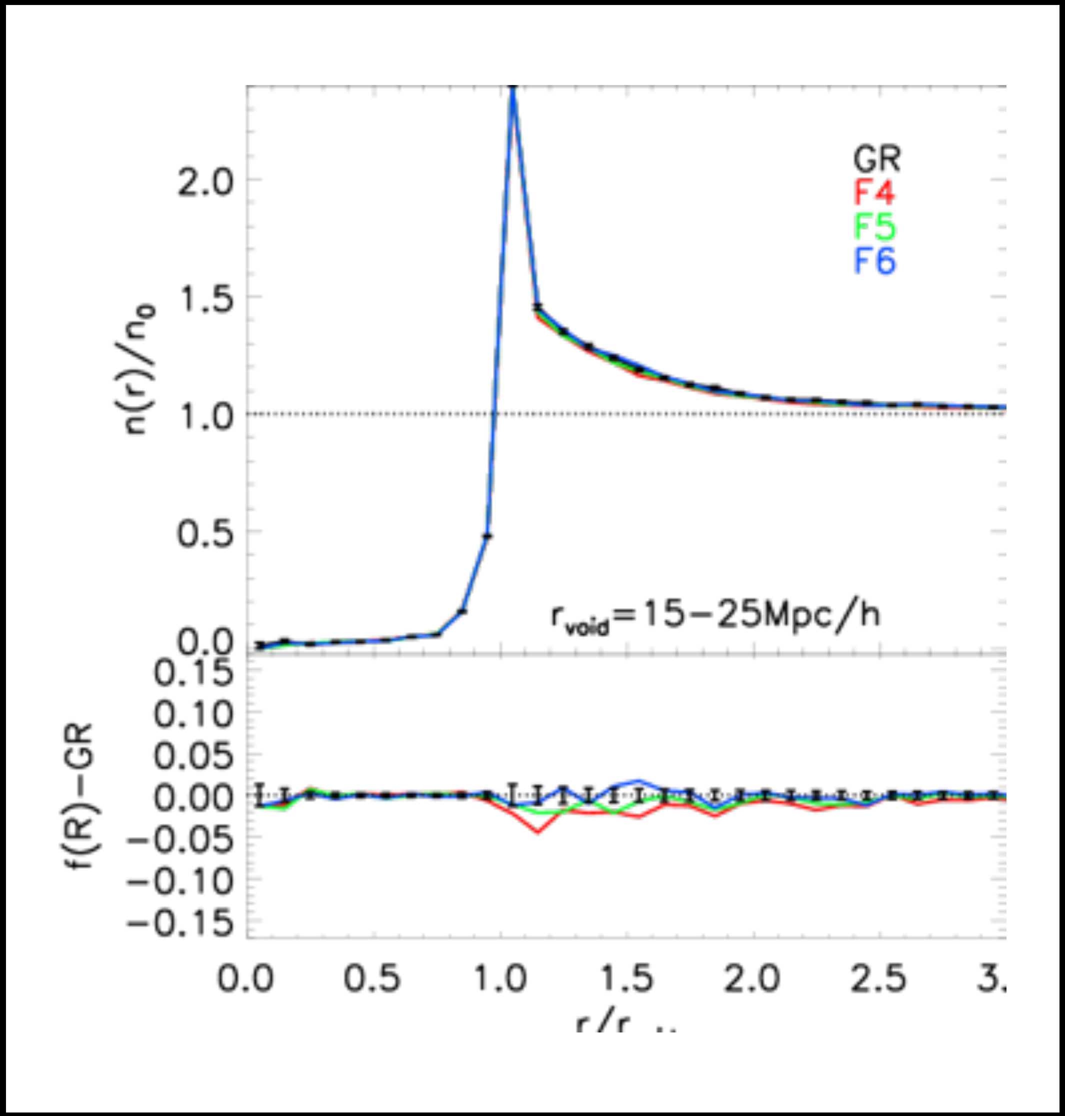
Massive Gravity Basics

- Fierz-Pauli first introduced a mass term for linearized gravity
- The vDVZ discontinuty - Vainshtein Mechanism
    - Mass of graviton going to zero
- Boulware-Deser Ghost- General problem
    - Arkani-hamed, Georgi, Schwartz (Decoupling Limit)
    - de Rham Gabadadze and Tully gravity and Bi-Gravity (Hassan &Rosen)
        - (Relativistic Extensions)

Voids why?

No Vainshtein Mechanism





Consider Spherical Symmetric Case

Technical points

- Well with in Weak Field Limit
  - Treat gravitation as perturbations of flat space Newtonian gauge
    - Which are instantaneous (time independence)
    - Also assume spherical symmetry
    - Scales much smaller than the horizon
- Also in the Decoupling Limit

$$ds^2 = -(1+2\Phi(r))dt^2 + (1-2\Psi(r))d\vec{r}^2$$

$$\Phi = \Phi_{FC} + \Phi_{loc}$$

$$\Psi = \Psi_{FC} + \Psi_{loc}$$

$$\Psi \rightarrow \Psi_{FC} \quad \text{for } r_v < r < \mathrm{H}^{-1}$$

$$\Phi \rightarrow \Phi_{FC} \quad \text{for } r_v < r < \mathrm{H}^{-1}$$

Via fermi coordinates Ψ_{FC} and Φ_{FC}

encodes the no-trivial curvature of the space time metric

Lagrangian

Decoupling Limit $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$

$$\mathcal{L} = h^{\mu\nu}\left(-\frac{1}{2}\,\mathcal{E}^{\alpha\beta}_{\mu\nu} h_{\alpha\beta} + \frac{1}{m_{pl}}\,\mathcal{T}_{\mu\nu} + \mathcal{L}(\pi)_{\mu\nu}\right)$$

$$\mathcal{L}(\pi)_{\mu\nu} = \alpha\, X^{(1)}_{\mu\nu} + \frac{\beta}{\Lambda_3^3}\, X^{(2)}_{\mu\nu} + \frac{\gamma}{\Lambda_3^6}\, X^{(3)}_{\mu\nu}$$

$$X^{(1)}_{\mu\nu} \equiv \epsilon_\mu{}^{\alpha\rho\sigma}\epsilon_\nu{}^{\beta}{}_{\rho\sigma}\,\partial_\alpha\partial_\beta\,\pi \ ,$$

$$X^{(2)}_{\mu\nu} \equiv \epsilon_\mu{}^{\alpha\rho\gamma}\epsilon_\nu{}^{\beta\sigma}{}_{\gamma}\,\partial_\alpha\partial_\beta\,\pi\,\partial_\rho\partial_\sigma\,\pi \ ,$$

$$X^{(3)}_{\mu\nu} \equiv \epsilon_\mu{}^{\alpha\rho\gamma}\epsilon_\nu{}^{\beta\rho\sigma}\,\partial_\alpha\partial_\beta\,\pi\,\partial_\rho\partial_\sigma\,\pi\,\partial_\gamma\partial_\delta\,\pi$$

Equation of Motion

Einstein Eq.

$$2\nabla^2\Psi = 8\pi G\langle\rho\rangle + \boxed{\frac{6\,\alpha}{\mathrm{m_{pl}}}\frac{\pi'}{r} + \frac{6\,\beta}{\mathrm{m_{pl}}\Lambda^3}\frac{(\pi')^2}{r^2} + \frac{6\,\gamma}{\mathrm{m_{pl}}\Lambda^6}\frac{(\pi')^3}{r^3}} \quad (3)$$

ρ_{eff}

$$(\nabla^2 - \partial_i^2)(\Phi - \Psi) = 8\pi G\langle p\rangle \boxed{- \frac{4\,\alpha}{\mathrm{m_{pl}}}\frac{\pi'}{r} - \frac{2\,\beta}{\mathrm{m_{pl}}\Lambda^3}\frac{(\pi')^2}{r^2}} \quad (4)$$

p_{eff}

Scalar EOM

$$\alpha\nabla^2(2\Psi - \Phi) + \frac{2\,\beta}{\Lambda^3}\frac{\pi'}{r}\nabla^2(\Psi - \Phi) - \frac{3\,\gamma}{\Lambda^6}\frac{(\pi')^2}{r^2}\nabla^2\Phi = 0 \quad (5)$$

$\pi(r)$ is only a function of r.

Scalar EOM becomes a quintic constraint Eq.for $\pi(r)$

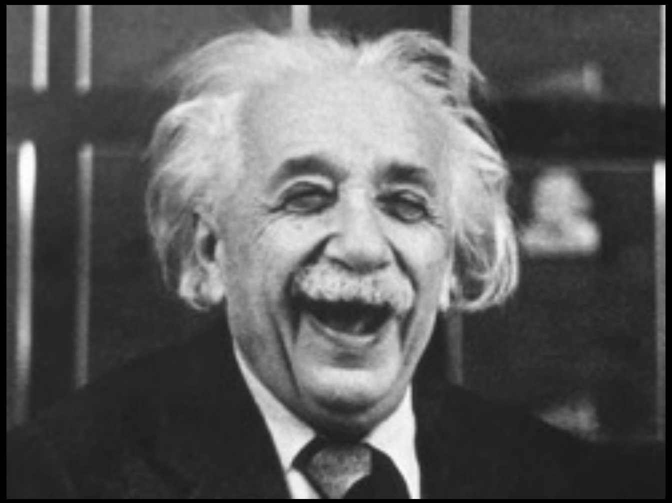
which depends upon $\langle\rho(r)\rangle$

Three real solutions!

Which solution to pick?

In GR, the perturbed Friedman equations are linear in the metric perturbations and density or radiation perturbations (schematically)

$$\mathrm{H}^2 -> \mathrm{H}^2 + \Psi \qquad \rho \to \rho_0 + \delta\rho$$



Then one can subtract off the background solution. The perturbed solution evolves independently of the background

Different in MG

Again look for perturbed solutions but now can not separate background from the perturbed solutions

$$\pi \rightarrow \pi + \delta\pi$$

The system of equations are nonlinear
NOT SEPERABLE

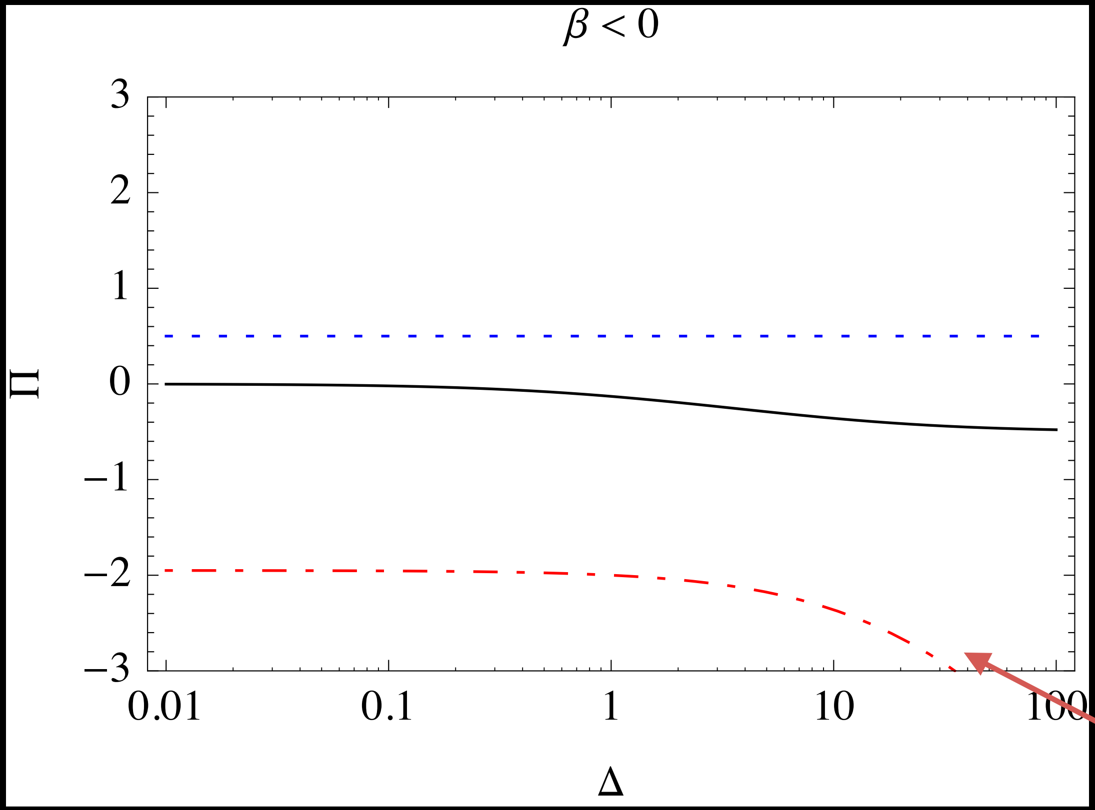
$$X^{(1)}_{\mu\nu} \equiv \epsilon_{\mu}{}^{\alpha\rho\sigma}\epsilon_{\nu}{}^{\beta}{}_{\rho\sigma}\,\partial_\alpha\partial_\beta\,\pi\ ,$$
$$X^{(2)}_{\mu\nu} \equiv \epsilon_{\mu}{}^{\alpha\rho\gamma}\epsilon_{\nu}{}^{\beta\sigma}{}_{\gamma}\,\partial_\alpha\partial_\beta\,\pi\,\partial_\rho\partial_\sigma\,\pi\ ,$$
$$X^{(3)}_{\mu\nu} \equiv \epsilon_{\mu}{}^{\alpha\rho\gamma}\epsilon_{\nu}{}^{\beta\rho\sigma}\,\partial_\alpha\partial_\beta\,\pi\,\partial_\rho\partial_\sigma\,\pi\,\partial_\gamma\partial_\delta$$

Need to pick the branch which gives the correct behavior outside of the local perturbation

Three Solutions

$$\Psi \to \Psi_{FC} \qquad \text{for } r_v < r < \mathrm{H}^{-1}$$

$$\Phi \to \Phi_{FC} \qquad \text{for } r_v < r < \mathrm{H}^{-1}$$



Density

Cosmological Solution
Self Acceleration

de Rham et al 2010

Asymptotically Flat

Chkareuli &Pirtskhalava 2011 Sörjs &Mörstell 2011

Degravitating Solution

de Rham et al 2010

$$\kappa \equiv \frac{\gamma}{\beta^2} = -\frac{2}{3}$$

Rethink Lensing &Dynamics

Previous authors have looked
at the asymptotically flat solution
but due to nonlinearities one
needs to look at the branch which
is related to self acceleration.

Work In progress

More General Solution

- Instead of just treating the case of self acceleration, we could also look at what happens when we include a CC.

Δ is a normalized

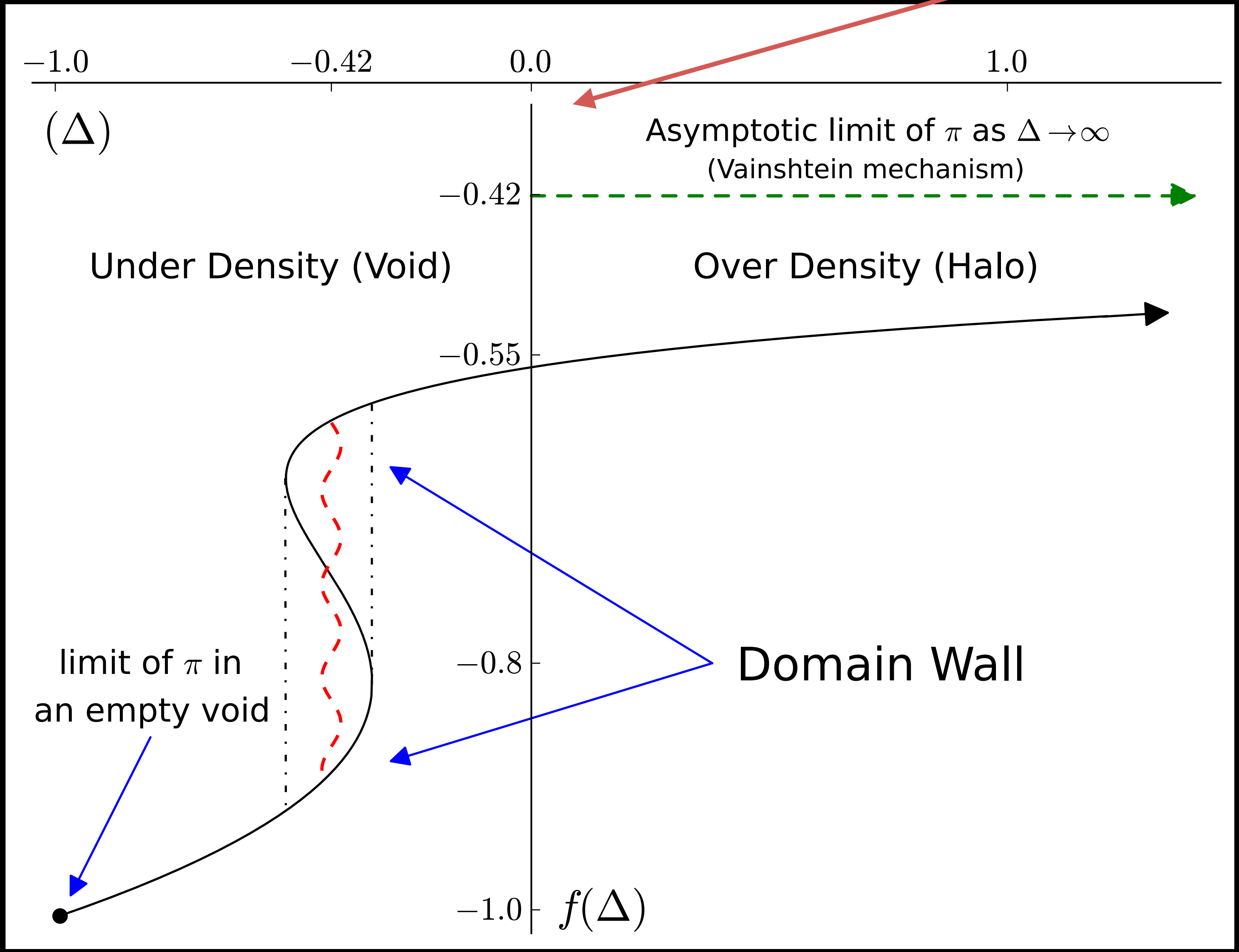
Density of Matter

$$\pi'/r = f(\Delta)\Lambda^3$$

$$\Lambda^3 = (m_{pl} m_g^2)$$

cut-off Scale

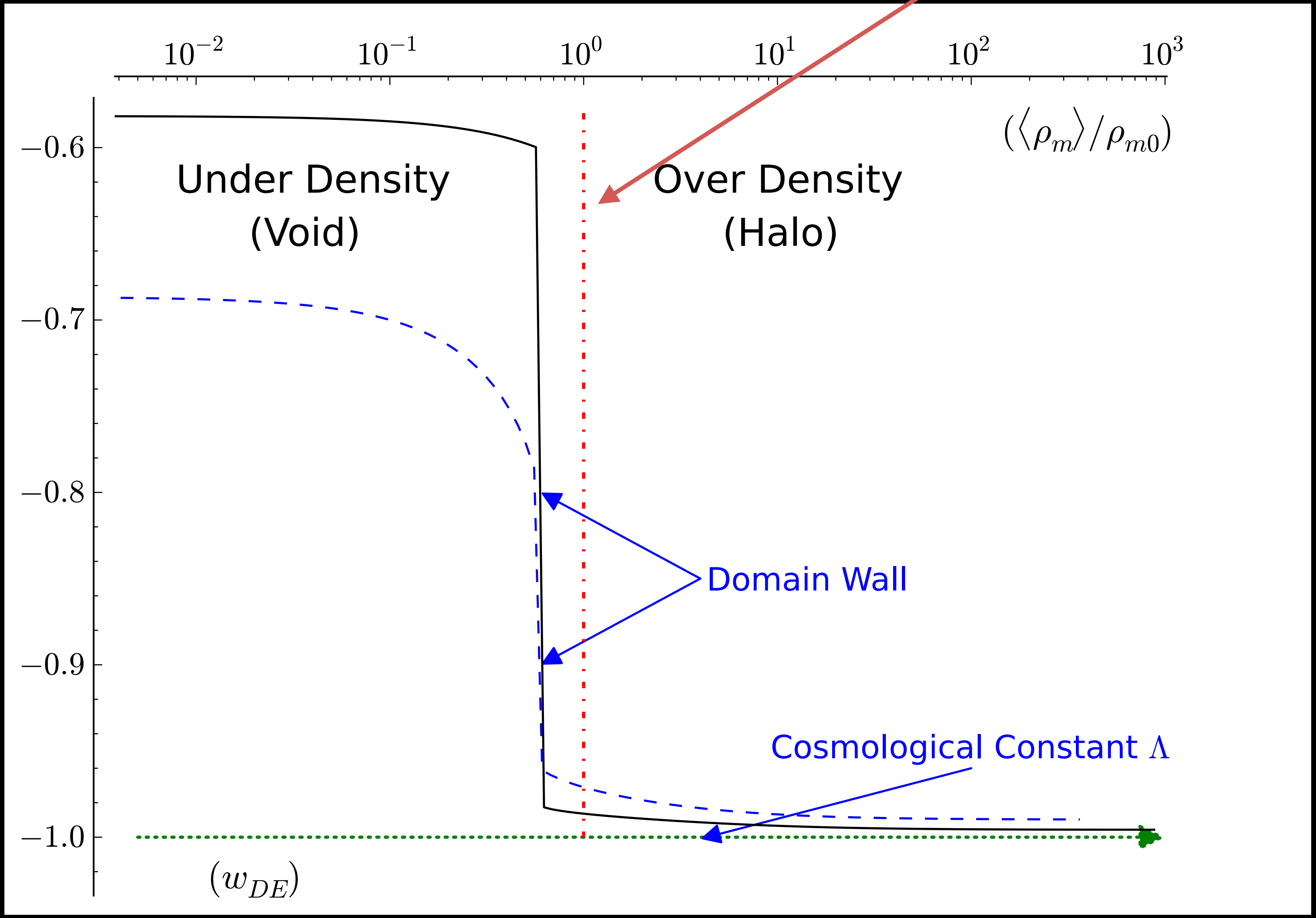
Mean Density Today



Dramatic Change in DE EOS

Mean Density Today

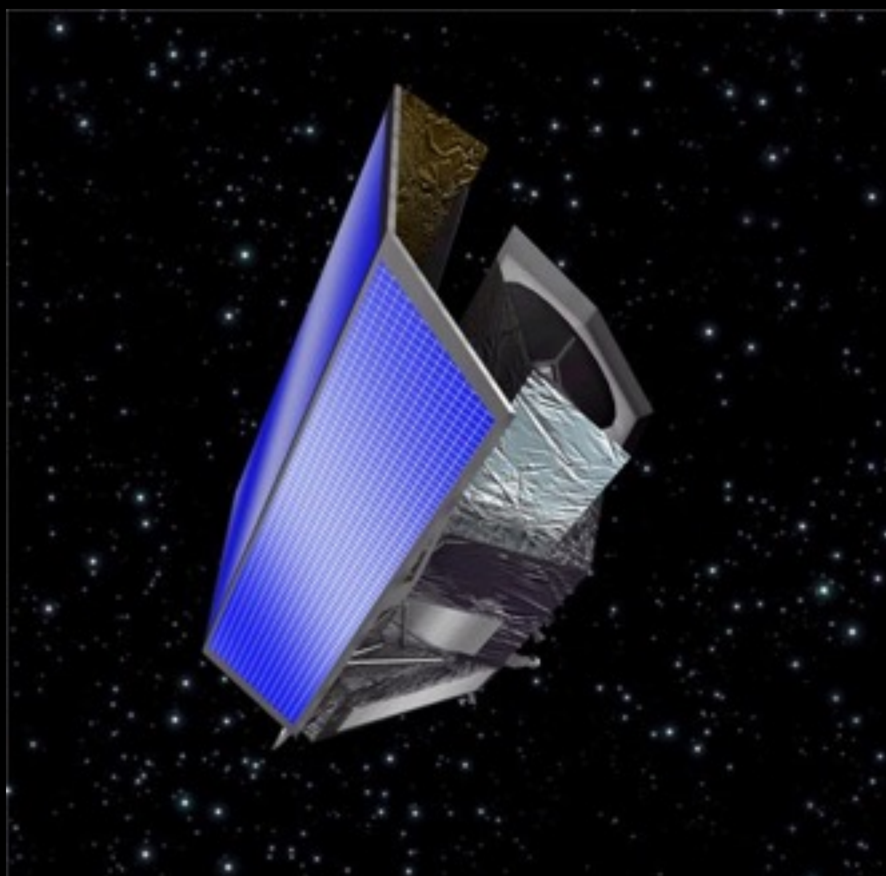
$$w_{eff} = \frac{p_{eff} - \Lambda_{cc}}{\rho_{eff} + \Lambda_{cc}}$$



We already defined ρ_{eff} & p_{eff}

in Einsteins Equations

Euclid



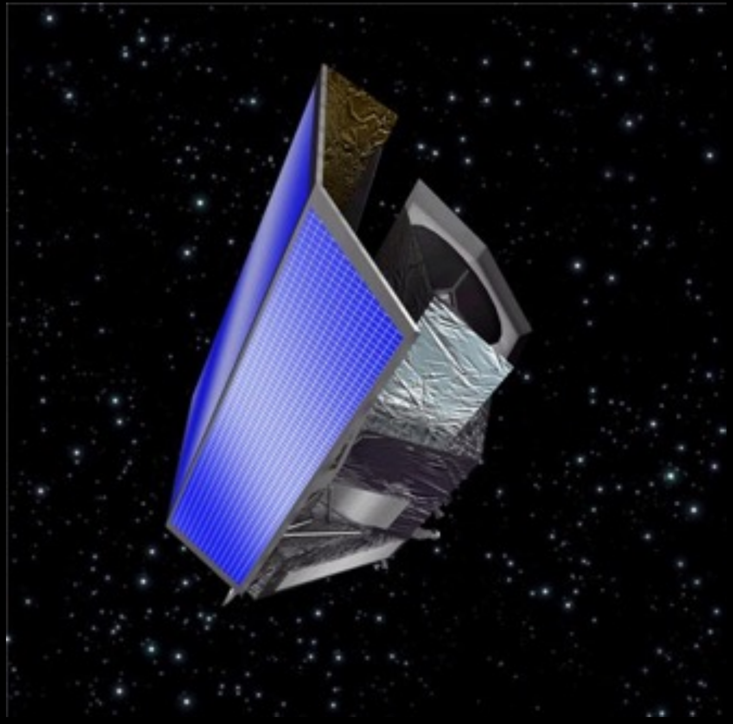
Imaging and Spectrograph

Measure BAO

Weak Lensing

Launch date 2020

Void Constraints



Stack voids should allow for the detection of modifications of gravity

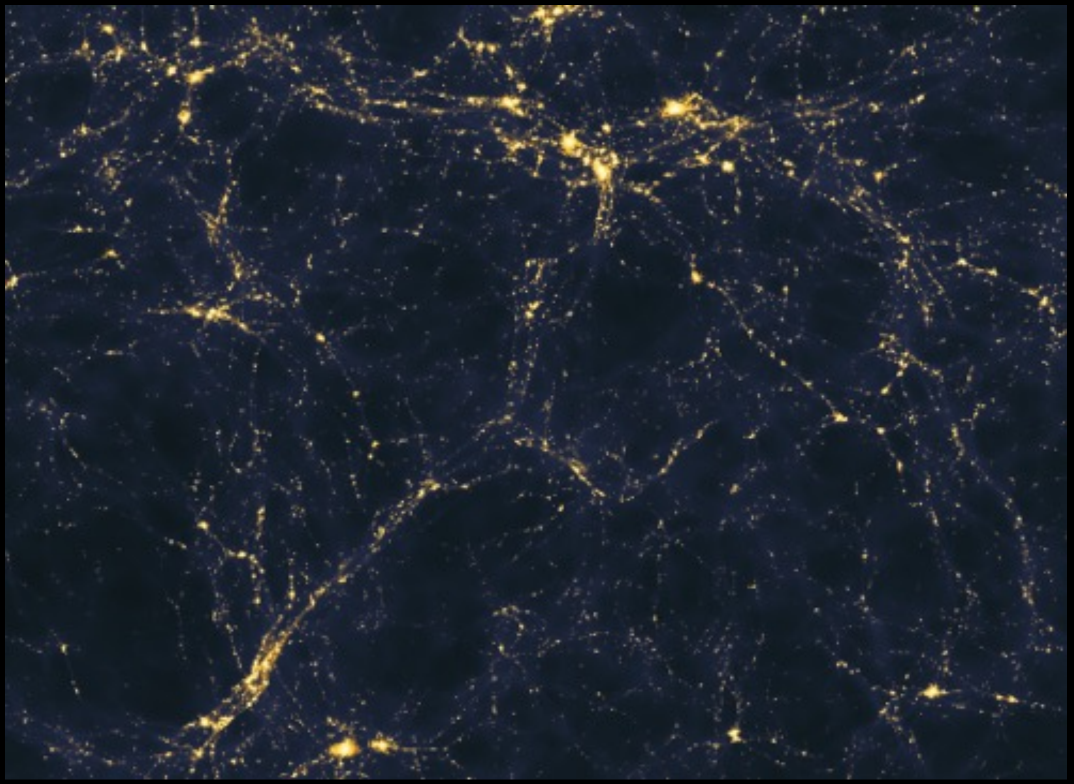
Euclid Should detect deviations of

$|\Delta w_{DE}| > 0.1$ At 95% confidence level

A deviation of 0.3 would be highly significant

Lavaux & Wandelt 2012

Take Away Message



- Topological defects are solutions of the extra degrees of freedom found in massive gravity

- One needs to carefully choose the correct massive gravity solution when looking at lensing and dynamics of voids

- Euclid could make voids an interesting testing ground for massive gravity