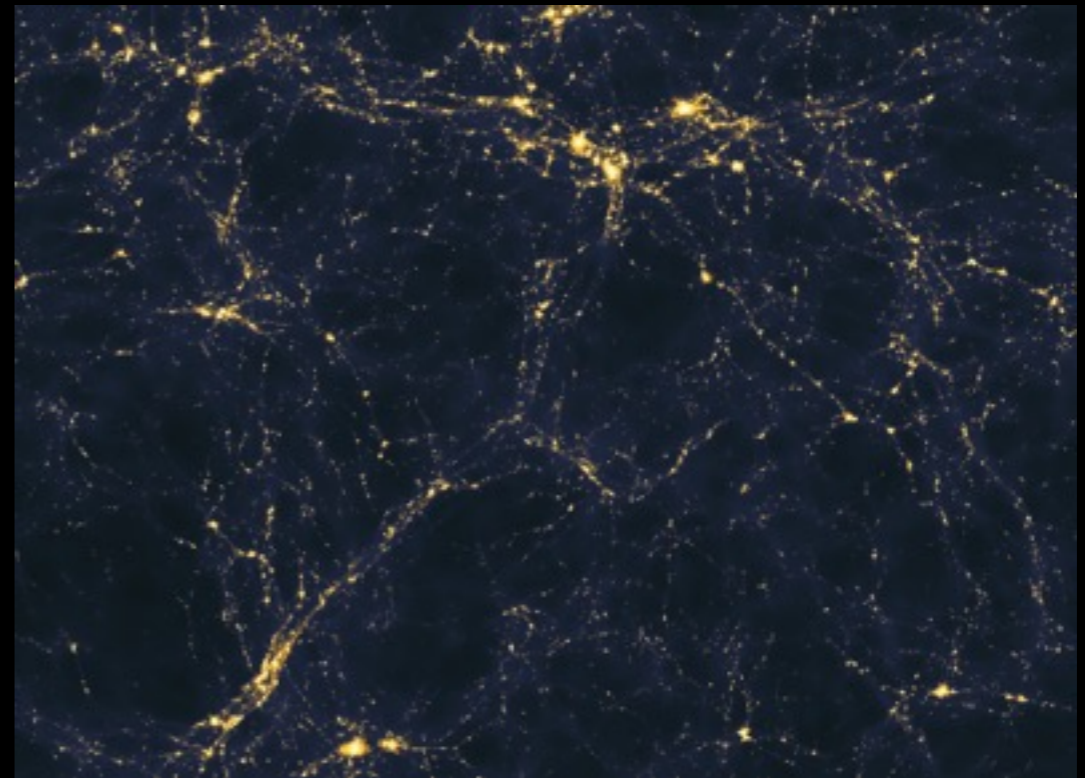
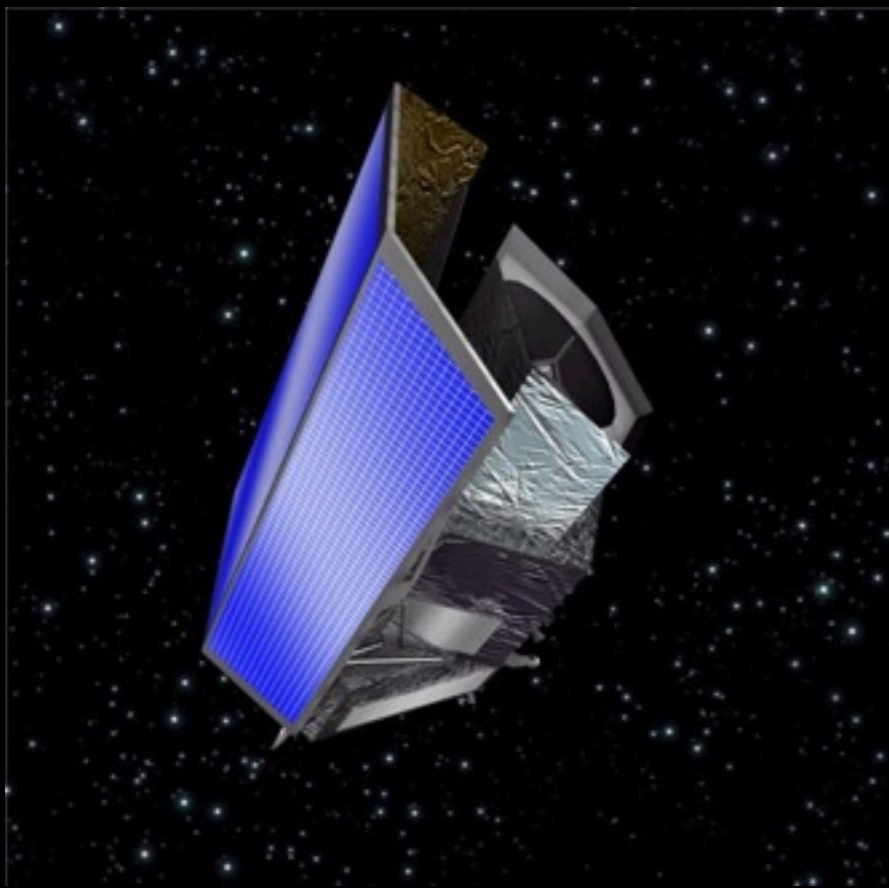


Voids Searching For Dark Energy

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M. Sahlen

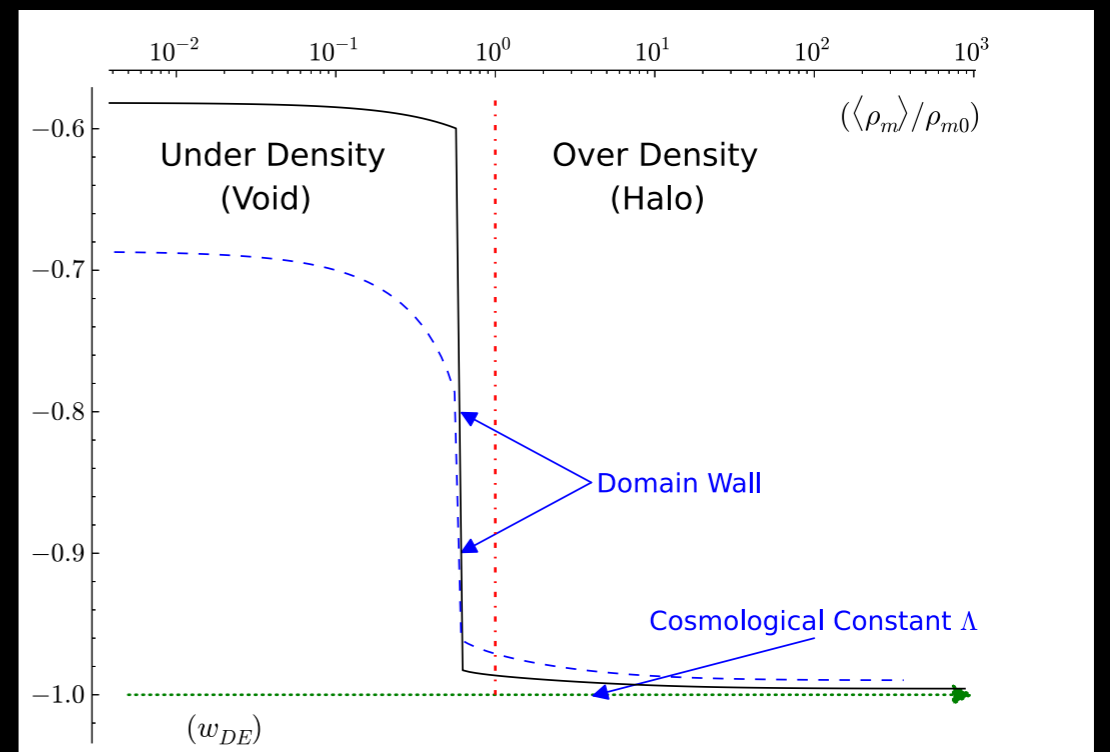
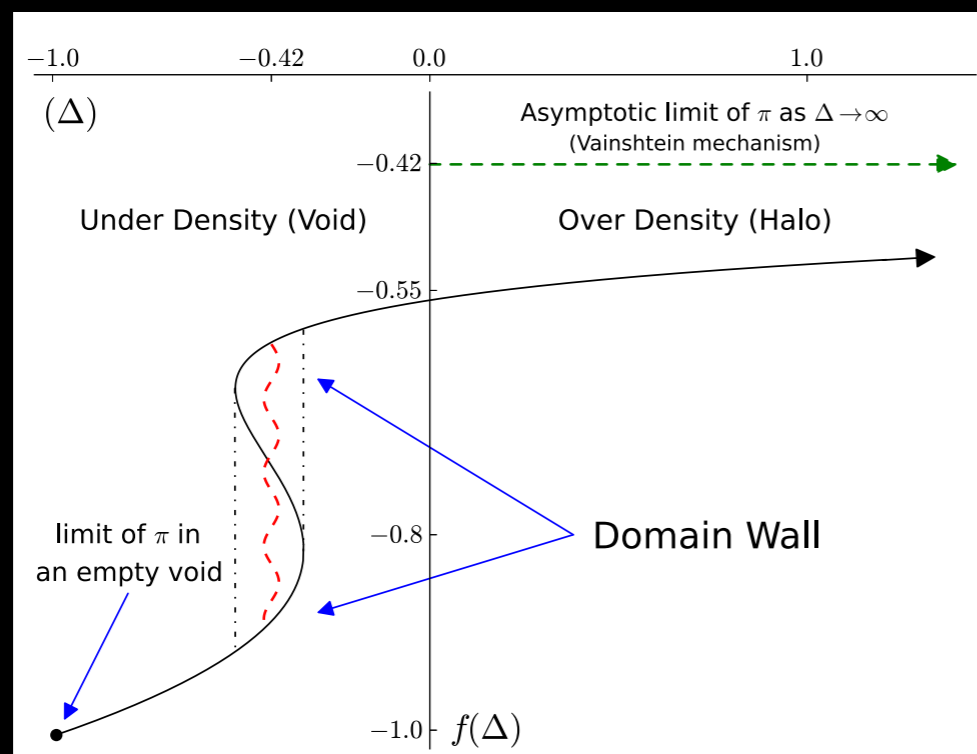


J. Silk

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

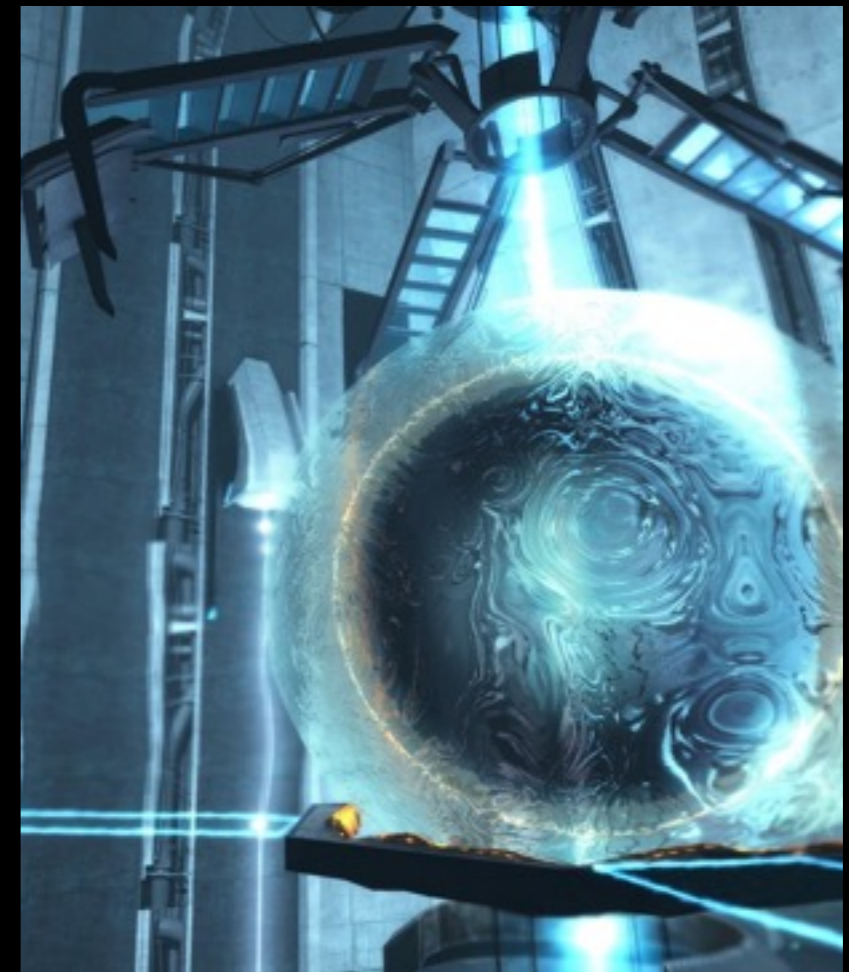
Basic Result

- 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

- Dark Energy in Brief
- Massive Gravity
- Solutions in Voids
- Euclid
- Constraints From Euclid



Massive Gravity Basics

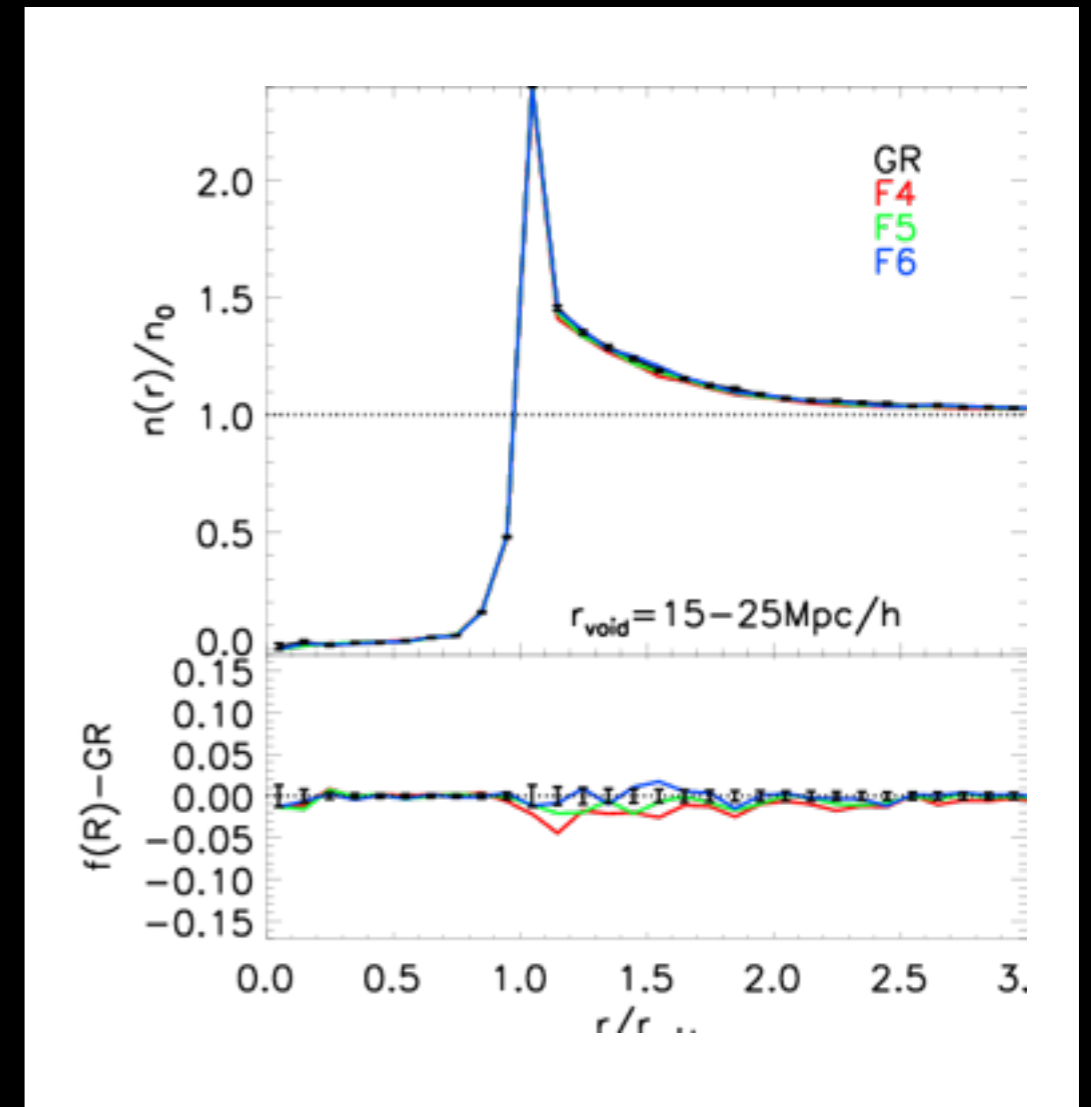
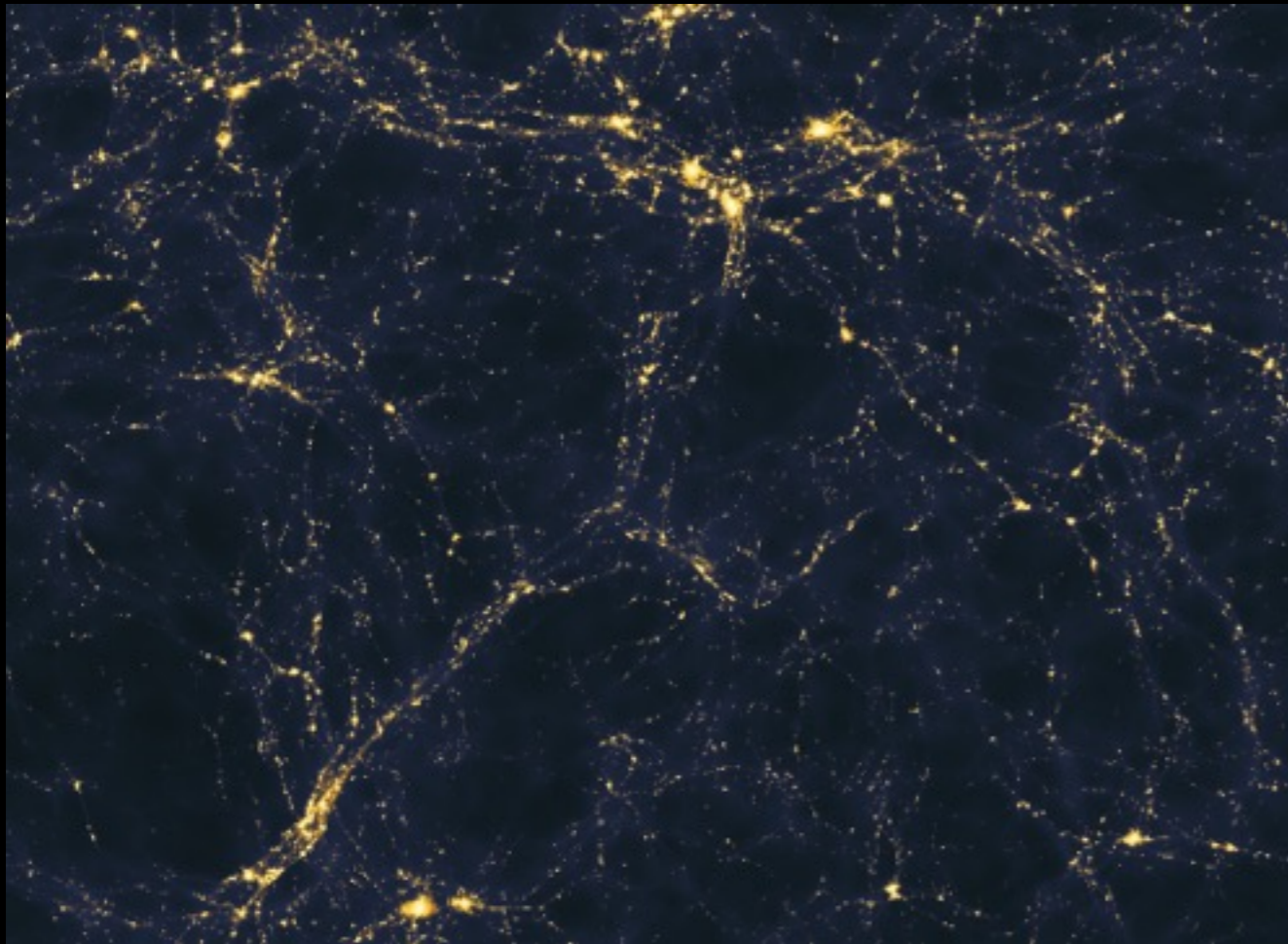


- Fierz-Pauli first introduced a mass term for linearized gravity
- The vDVZ discontinuity - Vainshtein Mechanism
 - Mass of graviton going to zero
- Boulware-Deser Ghost- General problem **Negative Kinetic energy**
 - Arkani-hamed, Georgi, Schwartz (Decoupling Limit)
 - de Rham Gabadadze and Tully gravity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

$$\Phi_N \neq \Phi_L$$

Voids why?

No Vainshtein Mechanism



Consider Spherical Symmetric Case

Voids Spotter Guide

Are the under dense region between galaxies

Voids



Basic Setup



- Well within Weak Field Limit

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

- Treat gravitation as perturbations of flat space
Newtonian gauge

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

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

- Which are instantaneous
(time independence)

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

- Also assume spherical symmetry

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

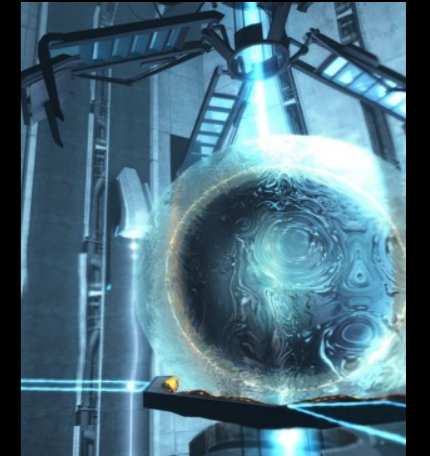
- Scales much smaller than the horizon

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

encodes the non-trivial curvature of the space time metric

- Also in the Decoupling Limit

Lagrangian



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

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

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

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

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

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

Massive Graviton

2 Tensor 2 DOF

2 vector DOF (which decouple)

1 Scalar DOF

Equation of Motion

Einstein Eq.

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

ρ_{eff}

Scalar EOM

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

p_{eff}

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

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

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

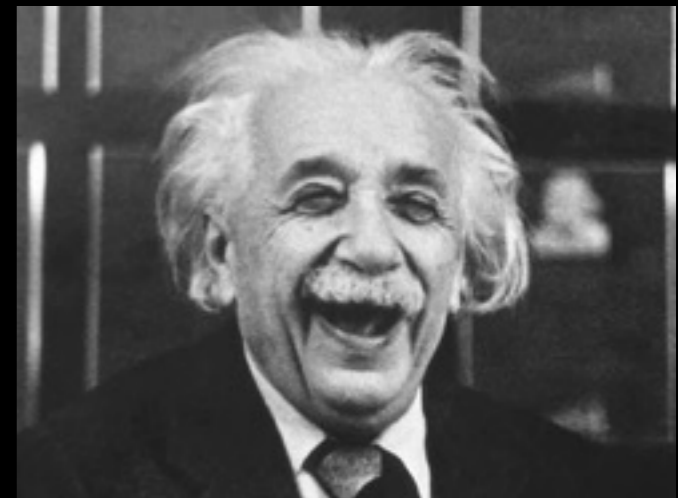
which depends upon $\langle\rho(r)\rangle$

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)

$$H^2 \rightarrow H^2 + \Psi \quad \rho \rightarrow \rho_0 + \delta\rho$$



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

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

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

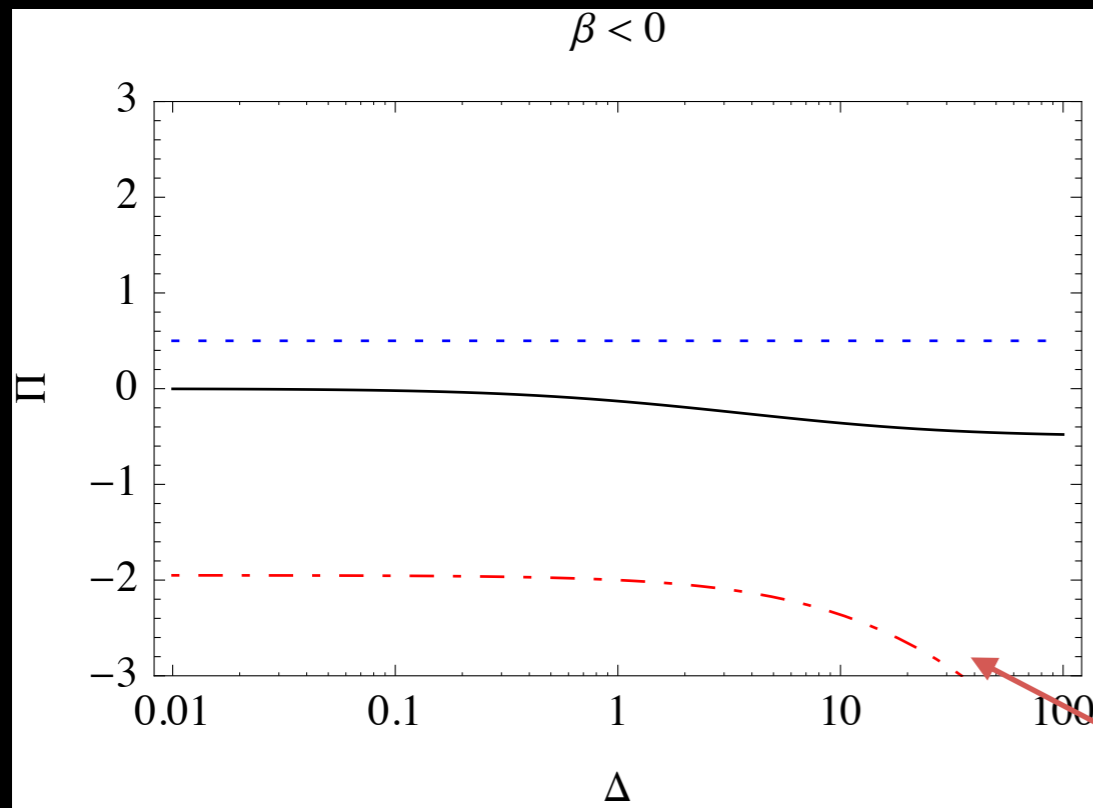
$$X_{\mu\nu}^{(3)} \equiv \epsilon_{\mu}^{\alpha\rho\gamma} \epsilon_{\nu}^{\beta\rho\sigma} \partial_{\alpha} \partial_{\beta} \pi \partial_{\rho} \partial_{\sigma} \pi \partial_{\gamma} \partial_{\delta}$$

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

Three Solutions

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

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



Density

Cosmological Solution
Self Acceleration

de Rham et al 2010

Asymptotically Flat

Chkareuli & Pirtskhalava 2011

Sörjs & Mörszell 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

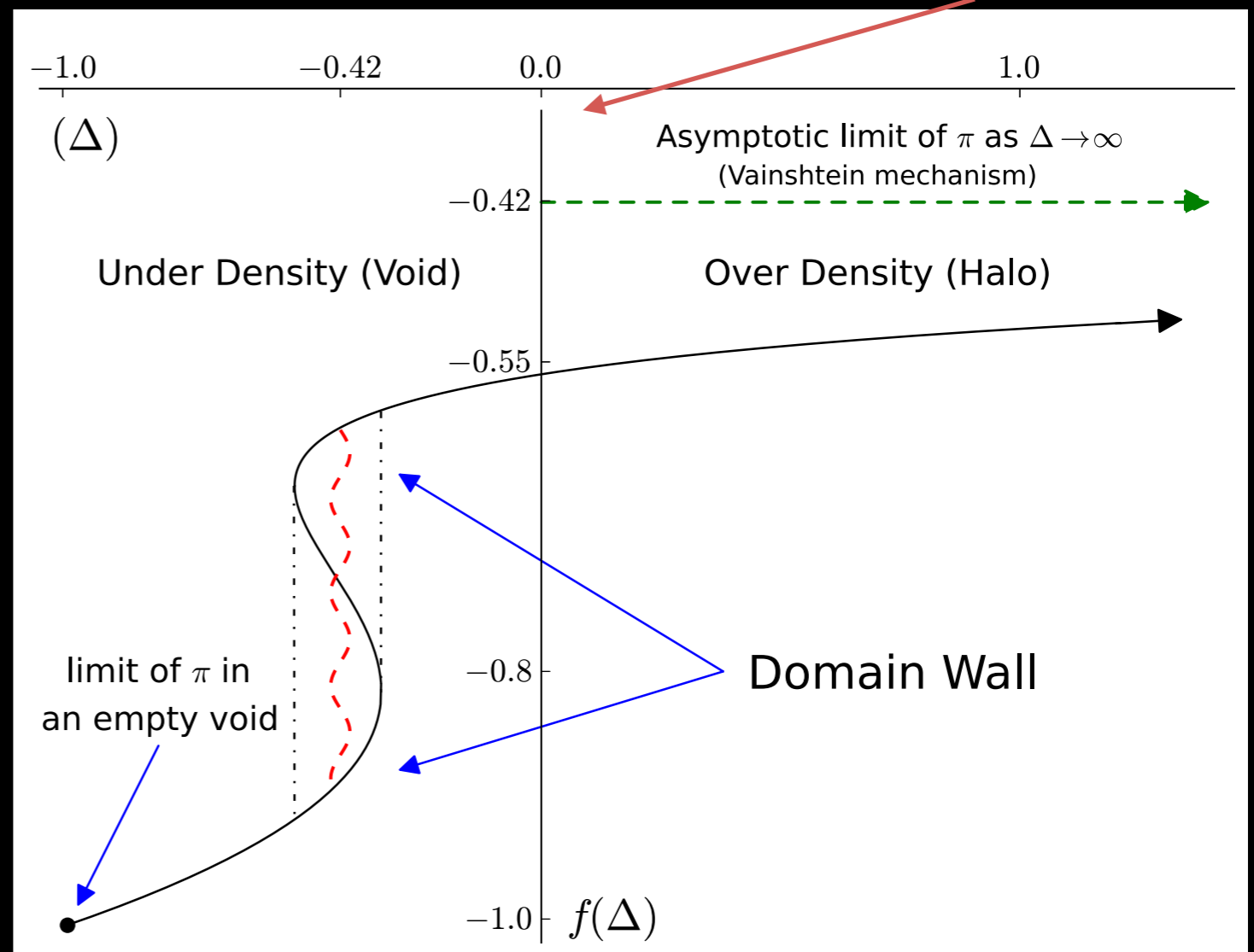
Density of Matter

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

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

cut-off Scale

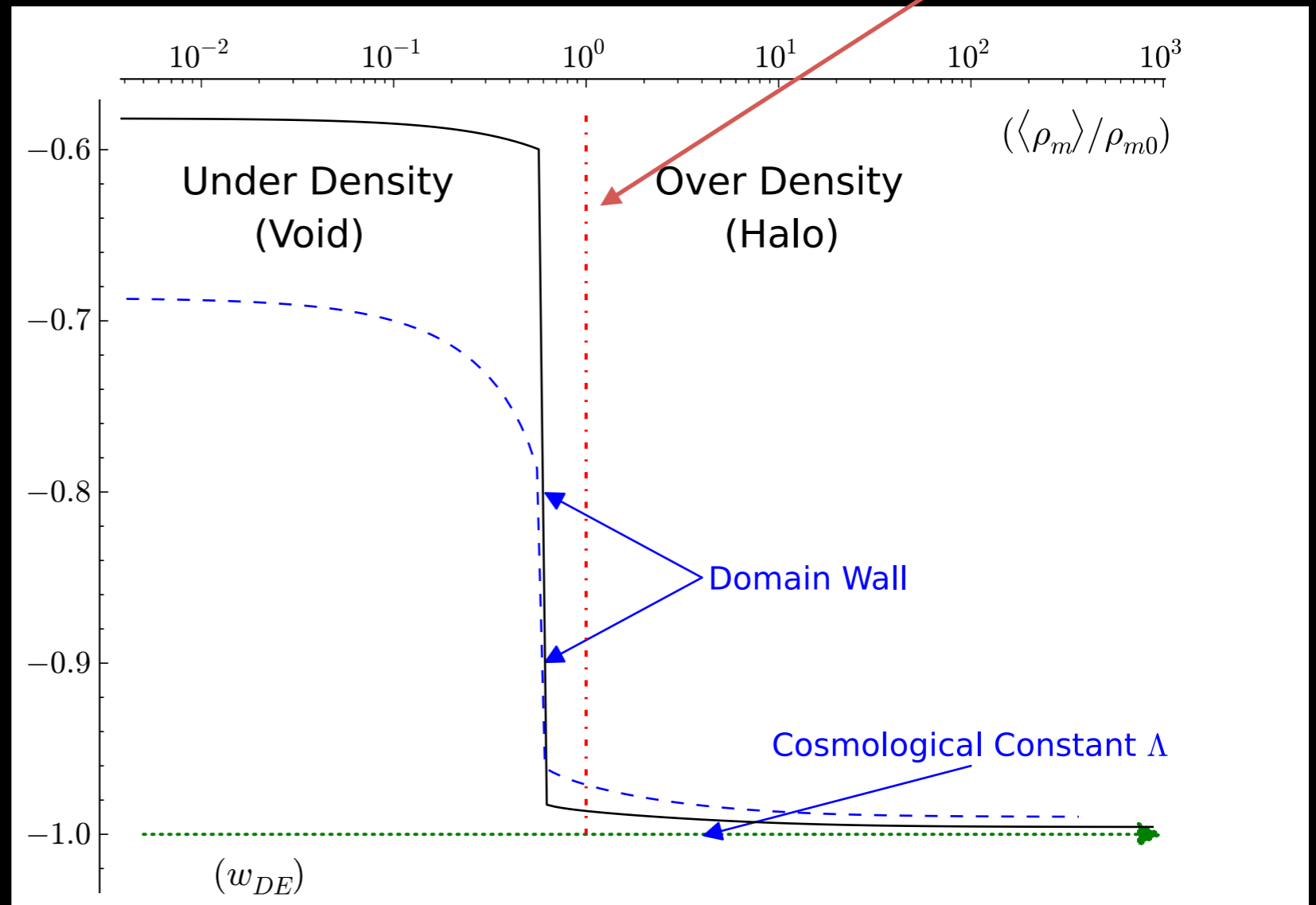
Mean Density Today



Dramatic Change in DE EOS

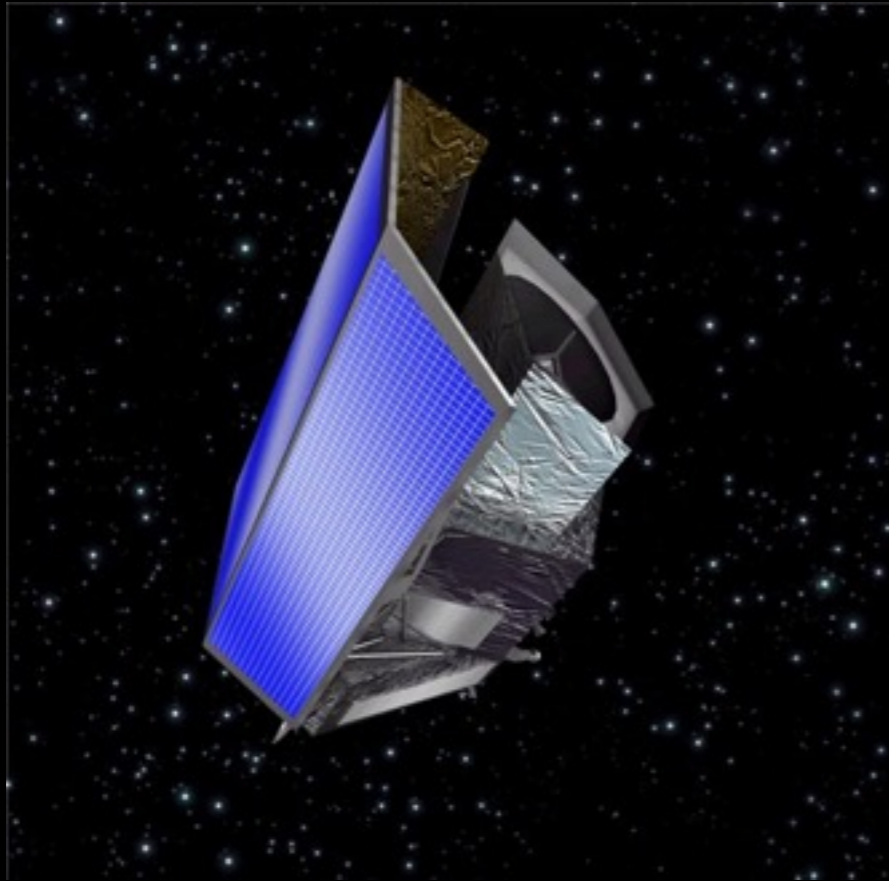
Mean Density Today

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



We already defined ρ_{eff} & p_{eff}
in Einsteins Equations

Euclid



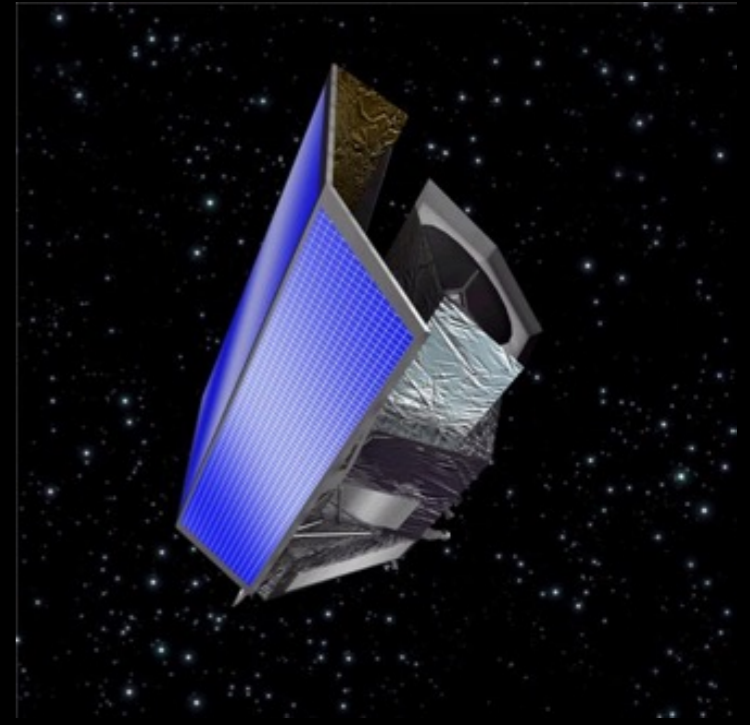
Imaging and Spectrograph

Measure BAO

Weak Lensing

Launch date 2020

Void Constraints



Stack voids should allow for the detection of modifications of gravity

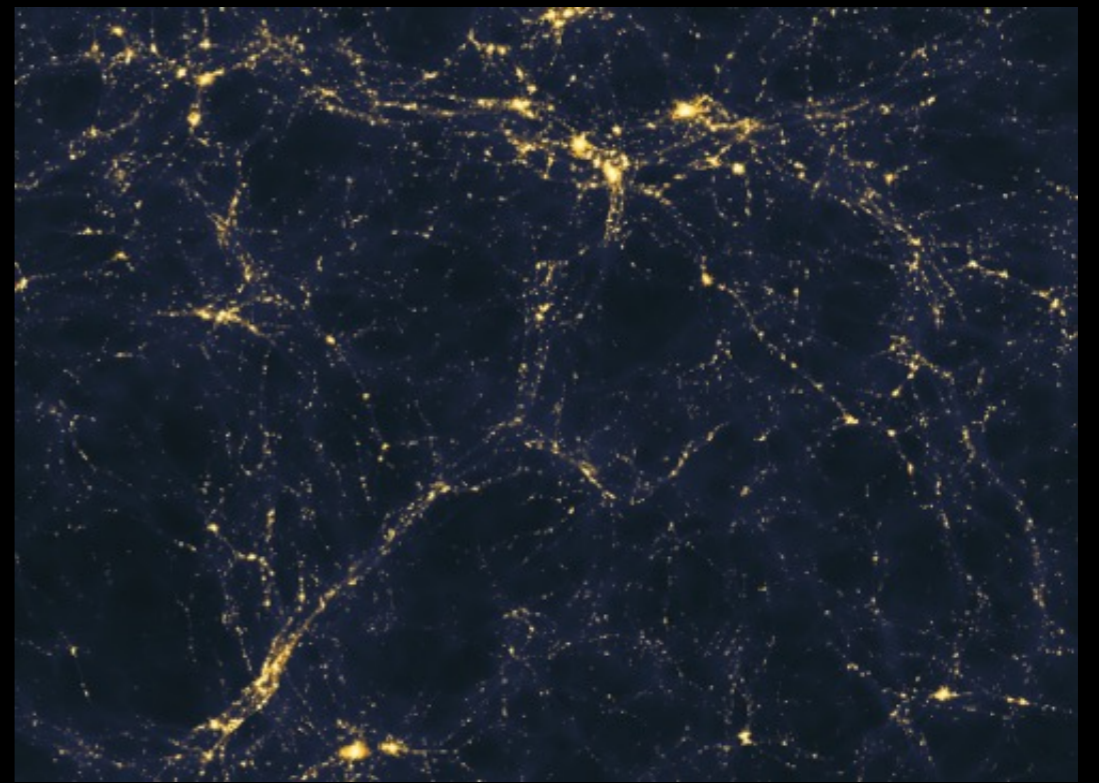
Euclid Should detect deviations of

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

A deviation of 0.3 would be highly significant

Spolyar, Sahlen, & Silk 2014
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