Foiling ΛCDM

Wayne Hu

KICP, October 2013

foil: \fȯi(-ə)l\

v. to prevent the success of

I would really like to foil the fiendishly simple but wholly unnatural ΛCDM model

n. metal in the form of very thin sheets

True believers in alternatives use tin foil hats to to shield themselves from the signals that the Universe sends them

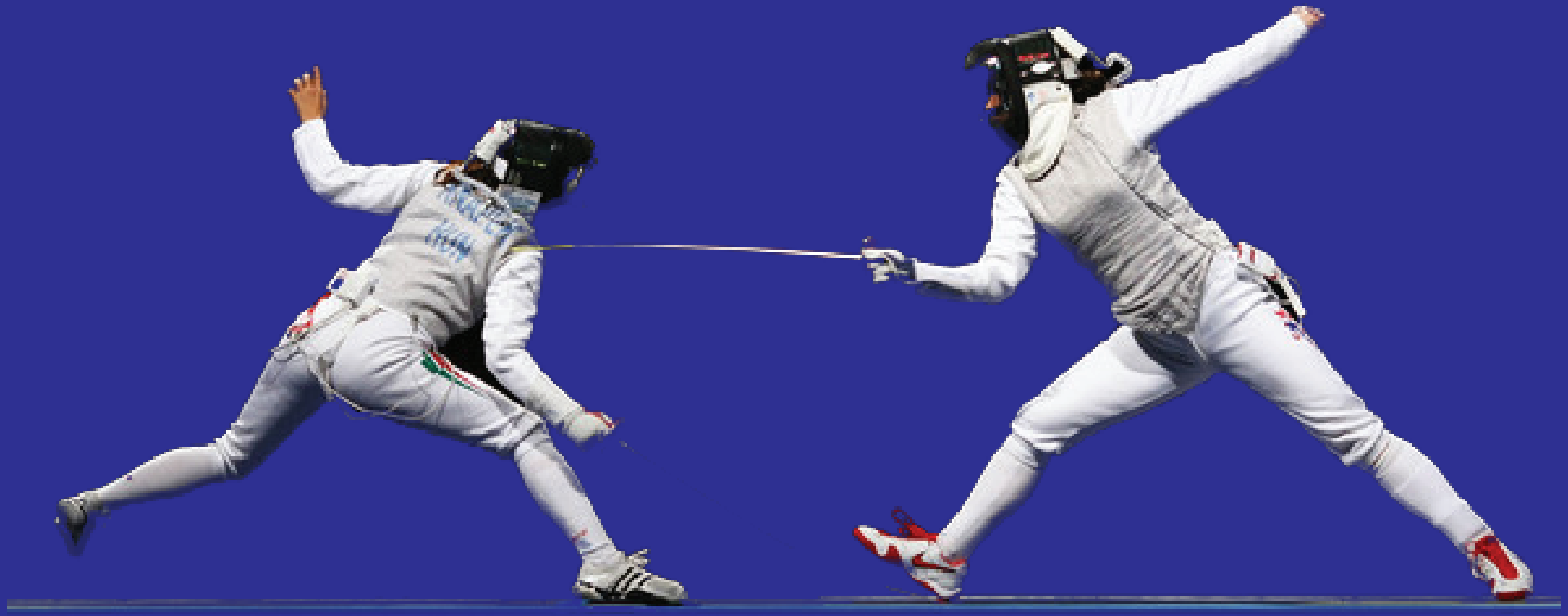
n. character who contrasts with another in order to highlight particular qualities of the other

massive neutrino DM, f(R), DGP, and massive gravity are good foils to ΛCDM

foil: \fȯi(-ə)l\

n. a light fencing sword

A foil is an instrument with which to prod graduate students…



foil: \fȯi(-ə)l\

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A foil is an instrument with which to prod graduate students…

Alexander Belikov
Cora Dvorkin
Pierre Gratia
Hector Gil
Yin Li
Marcos Lima
Lucas Lombriser
Wenjuang Fang
Vinicius Miranda
Michael Mortonson
Hiro Oyaizu
Ignacy Sawicki
Fabian Schmidt

Postdocs:

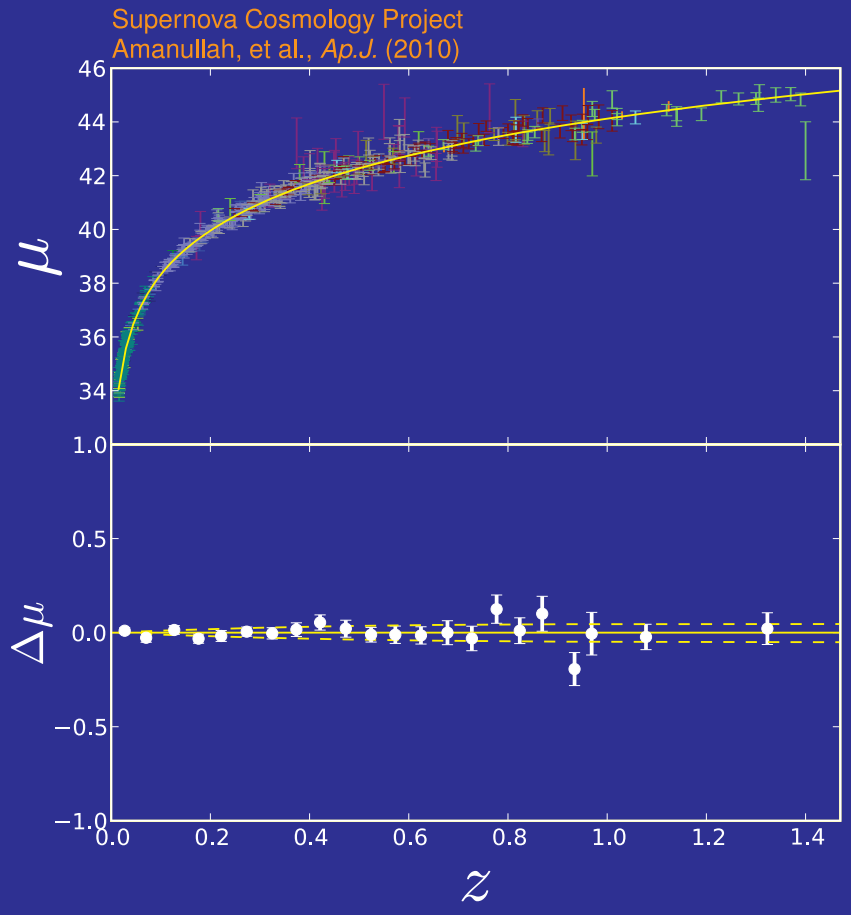
Elise Jennings
Yong Seon Song
Amol Upadhye
Ali Vanderveld
Sheng Wang
Mark Wyman

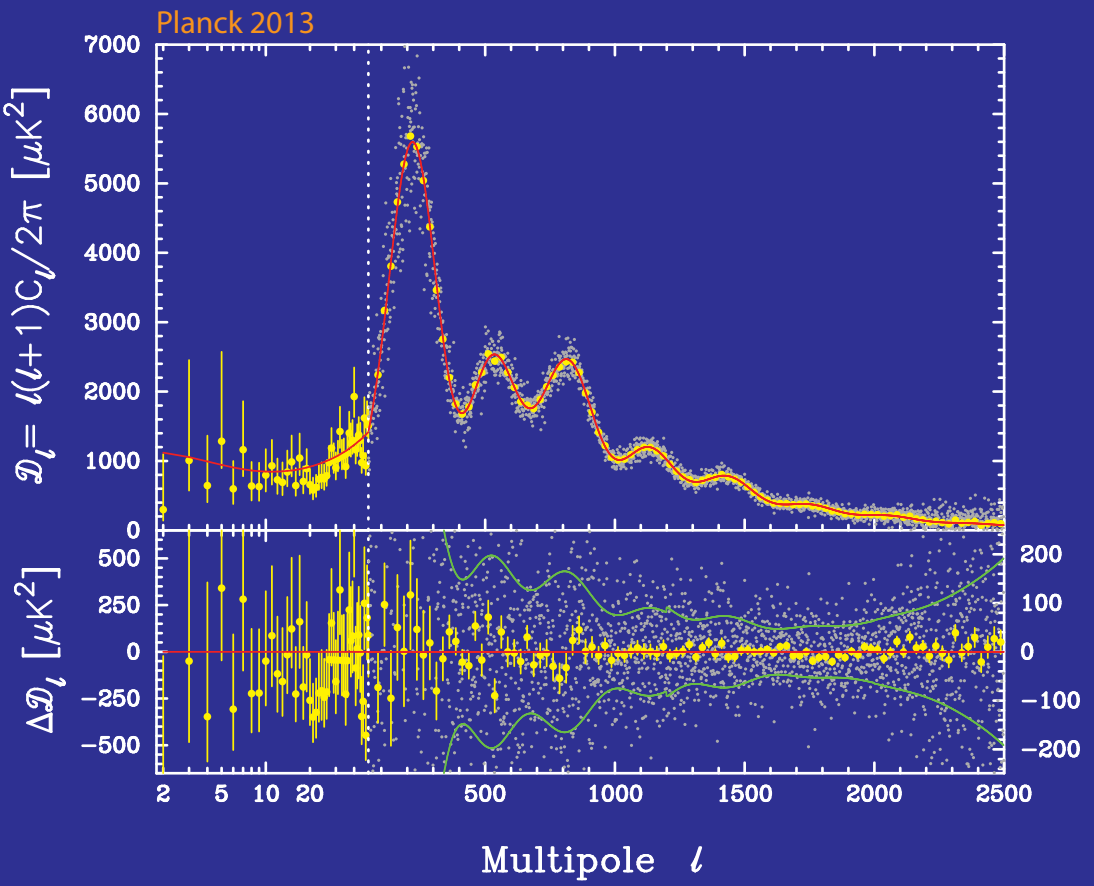
Douglas Rudd

Falsifying ΛCDM

Cosmic Acceleration

- Geometric measures of distance redshift from SN, CMB, BAO





Standard(izable) Candle

Supernovae

Luminosity v Flux

Standard(izable) Ruler

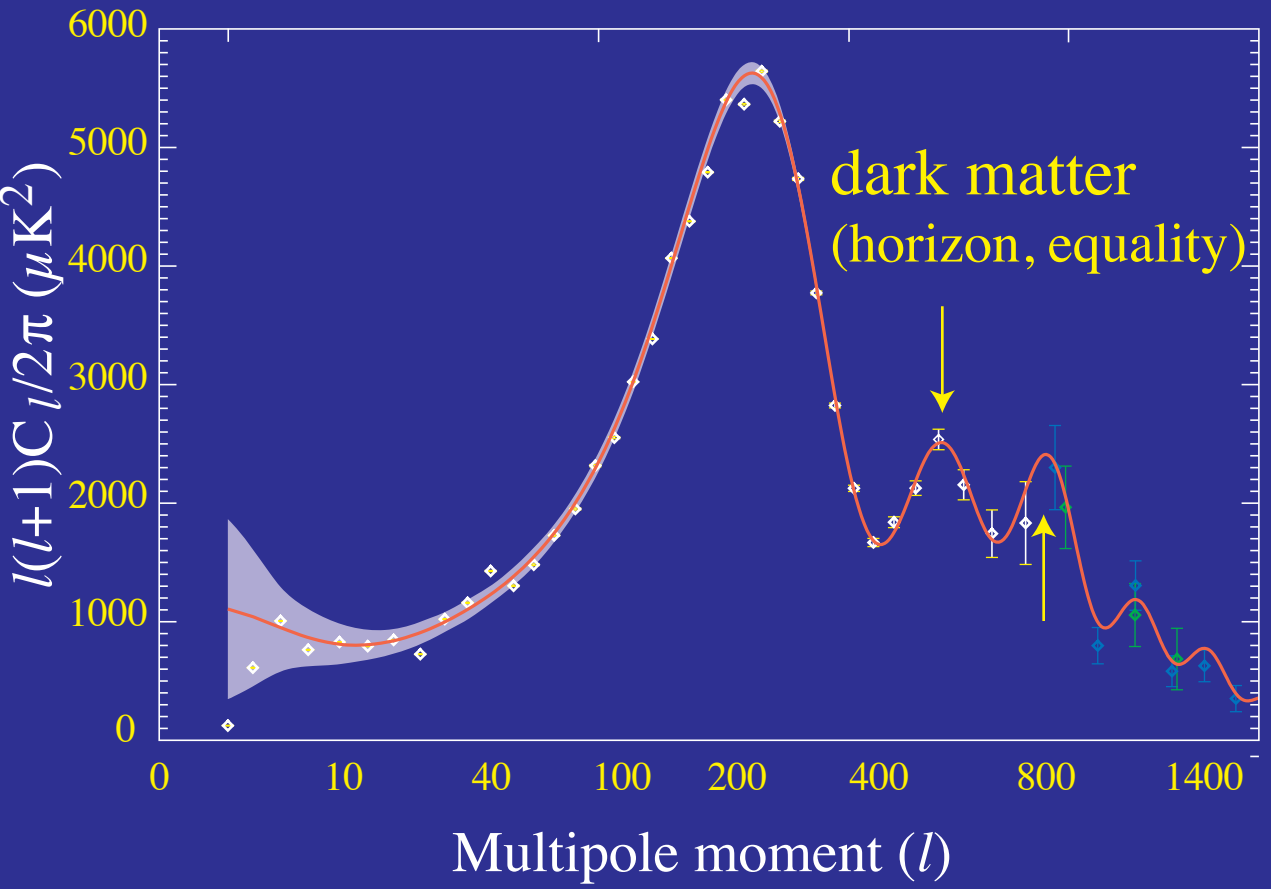
Sound Horizon

v CMB, BAO angular

and redshift separation

Calibrating the Sound Horizon

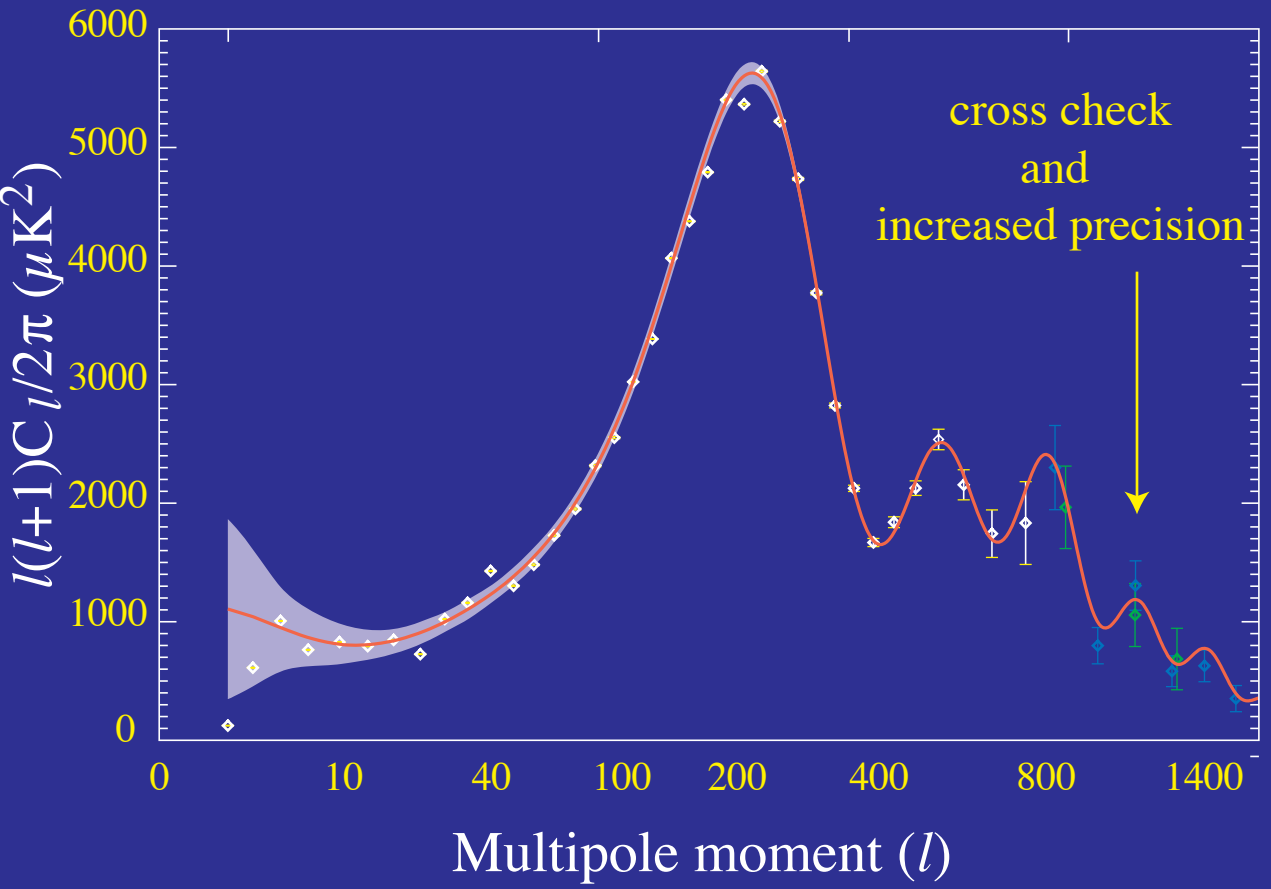
- Relative heights of the first 3 peaks calibrates the matter-radiation ratio and assuming standard neutrinos, the expansion rate and sound horizon



leading source of error!

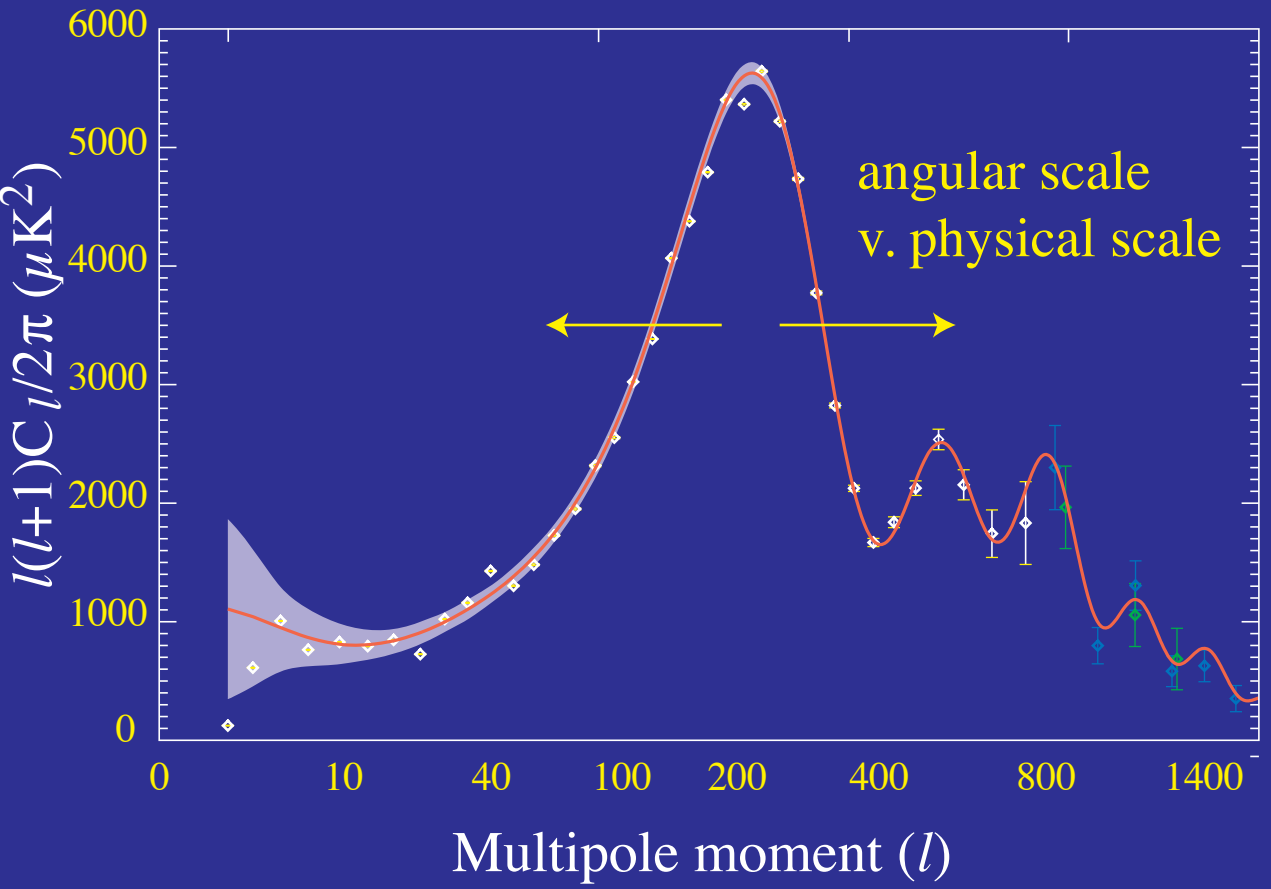
Into the Damping Tail

- Cross check with damping scale (diffusion during recombination): shifts from Planck comes from measuring damping tail



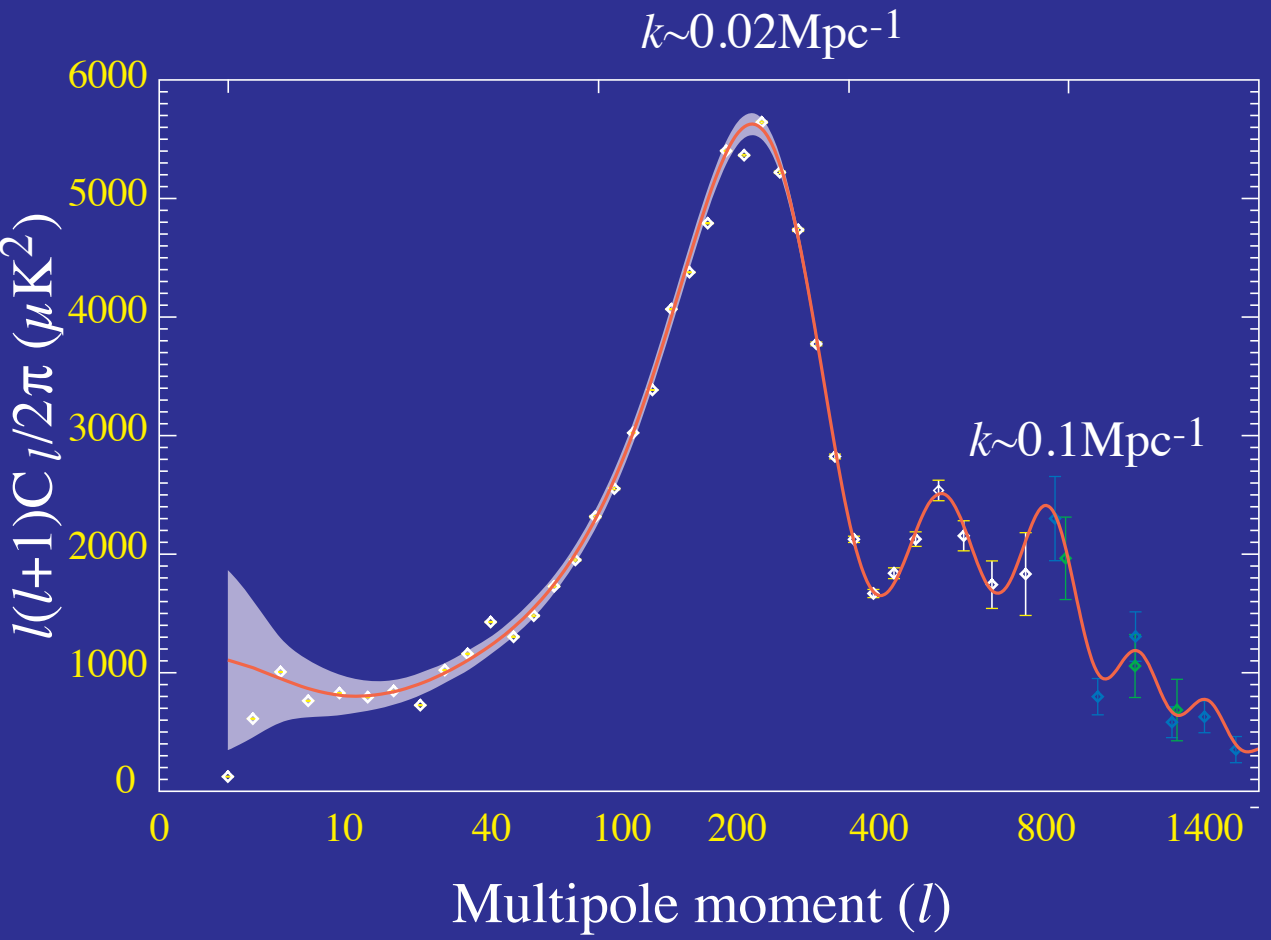
Distance to Recombination

- Sound horizon ruler and measured angular scale gives the angular diameter distance to recombination



Power of the CMB

- Standard fluctuation: absolute power determines initial fluctuations; WMAP1 best constrained 0.02 Mpc^{-1}; Planck2013 0.1 Mpc^{-1}



Falsifying ΛCDM

- CMB determination of matter density controls all determinations in the deceleration (matter dominated) epoch
- Planck: $\Omega_m h^2 = 0.1426 \pm 0.0025 \to 1.7\%$
- Distance to recombination D_* determined to $\frac{1}{4}1.7\% \approx 0.43\%$ (ΛCDM result 0.46%) Hu, Fukugita, Zaldarriaga, Tegmark (2001)

  $[-0.11\Delta w - 0.48\Delta \ln h - 0.15\Delta \ln \Omega_m - 1.4\Delta \ln \Omega_{\rm tot} = 0\,]$
- Expansion rate during any redshift in the deceleration epoch determined to $\frac{1}{2}1.7\%$
- Distance to any redshift in the deceleration epoch determined as

$$D(z) = D_* - \int_z^{z_*} \frac{dz}{H(z)}$$

- Volumes determined by a combination $dV = D_A^2 d\Omega dz/H(z)$
- Structure also determined by growth of fluctuations from z_*

Value of Local Measurements

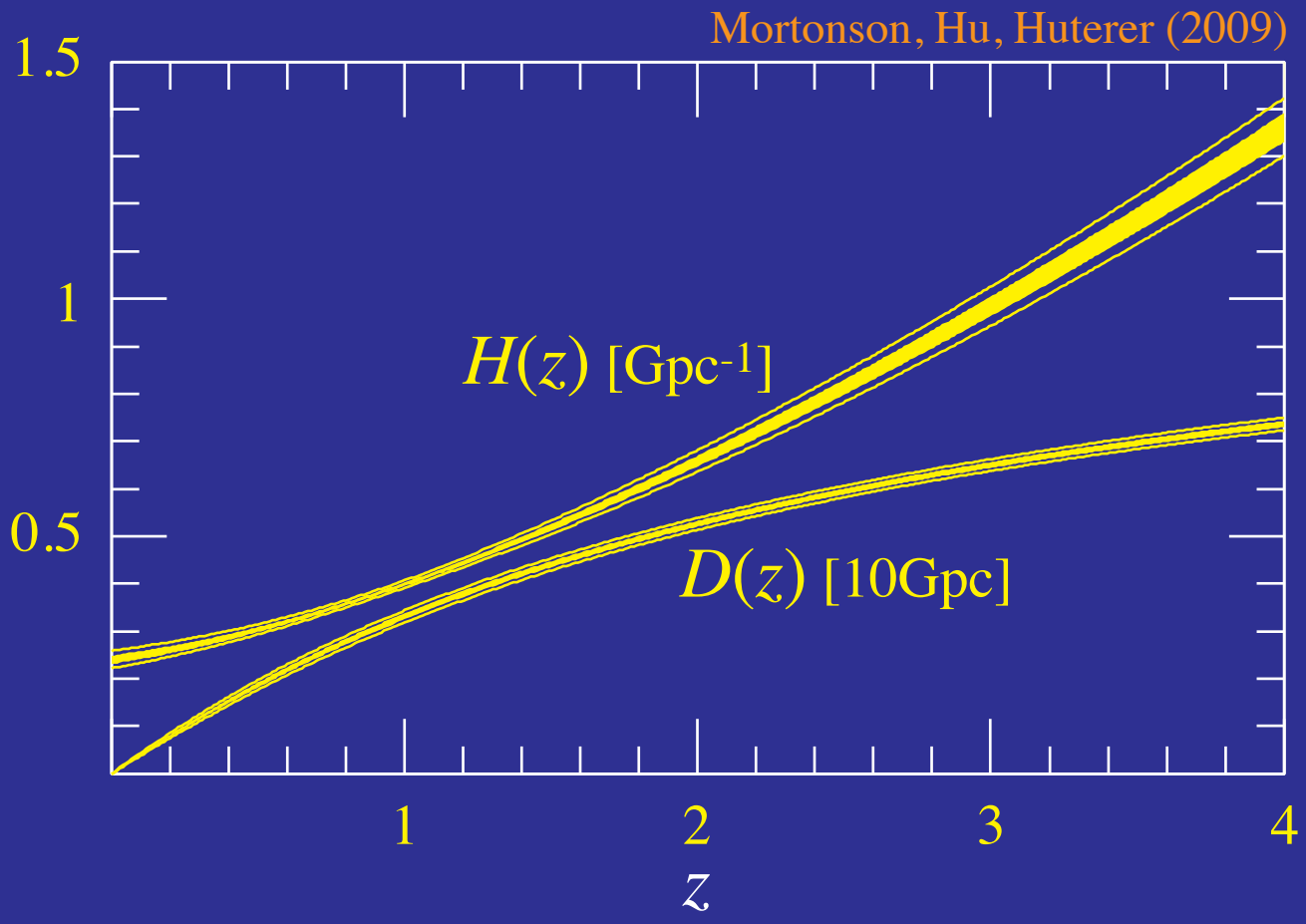
- With high redshifts fixed, the largest deviations from the dark energy appear at low redshift $z \sim 0$
- By the Friedmann equation $H^2 \propto \rho$ and difference between $H(z)$ extrapolated from the CMB $H_0 = 38$ and 67 is entirely due to the dark energy density in a flat universe
- With the dark energy density fixed by H_0, the deviation from the CMB observed D_* from the ΛCDM prediction measures the equation of state (or evolution of the dark energy density)

$$p_{\rm DE} = w\rho_{\rm DE}$$

- Likewise current amplitude of structure, e.g. local cluster abundance, tests the smooth dark energy paradigm

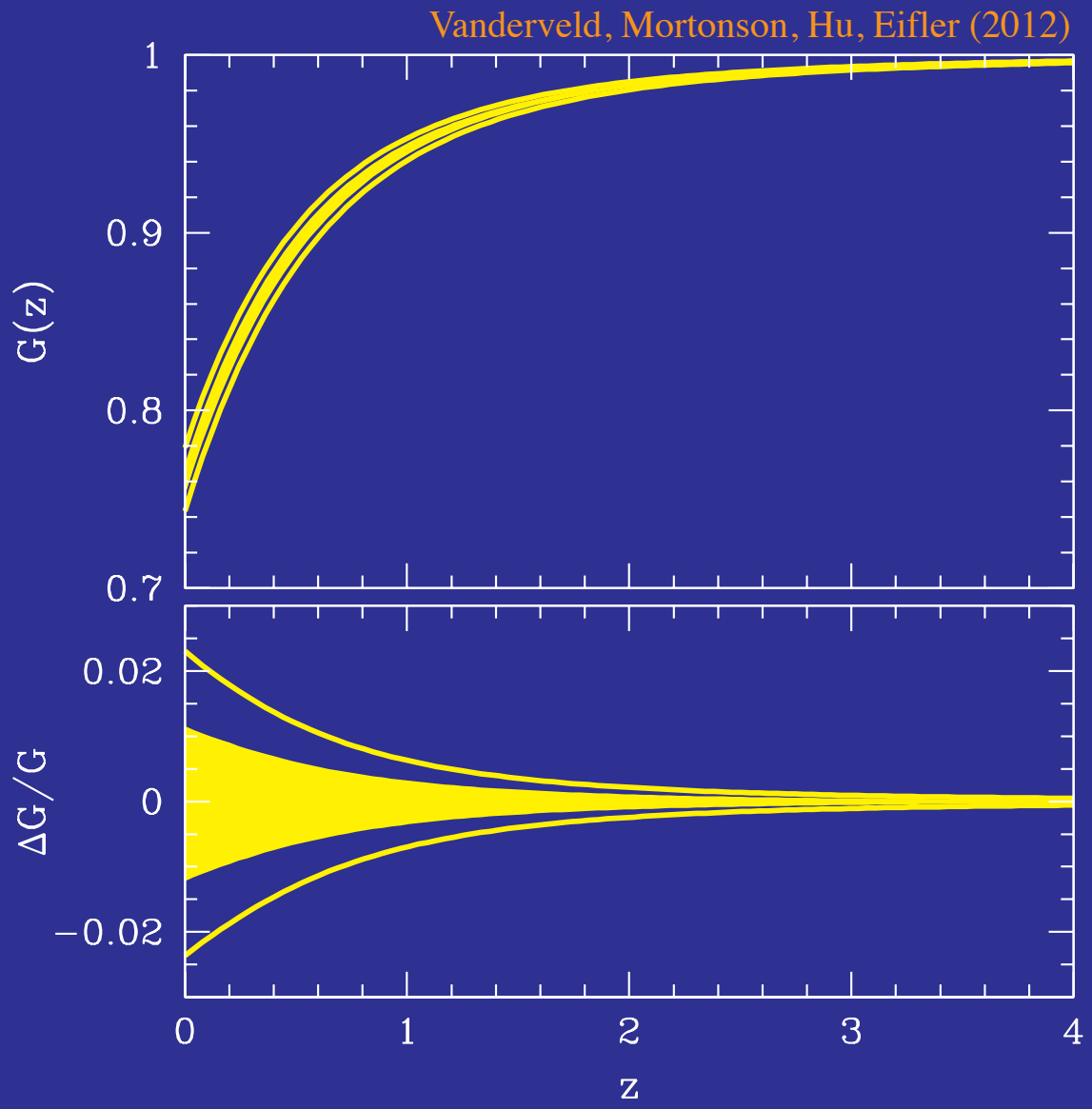
Flat ΛCDM

- CMB predicts expansion history and distance redshift relation at all redshifts to few percent precision
- Any violation falsifies flat ΛCDM
  (violation of flatness falsifies standard inflation)



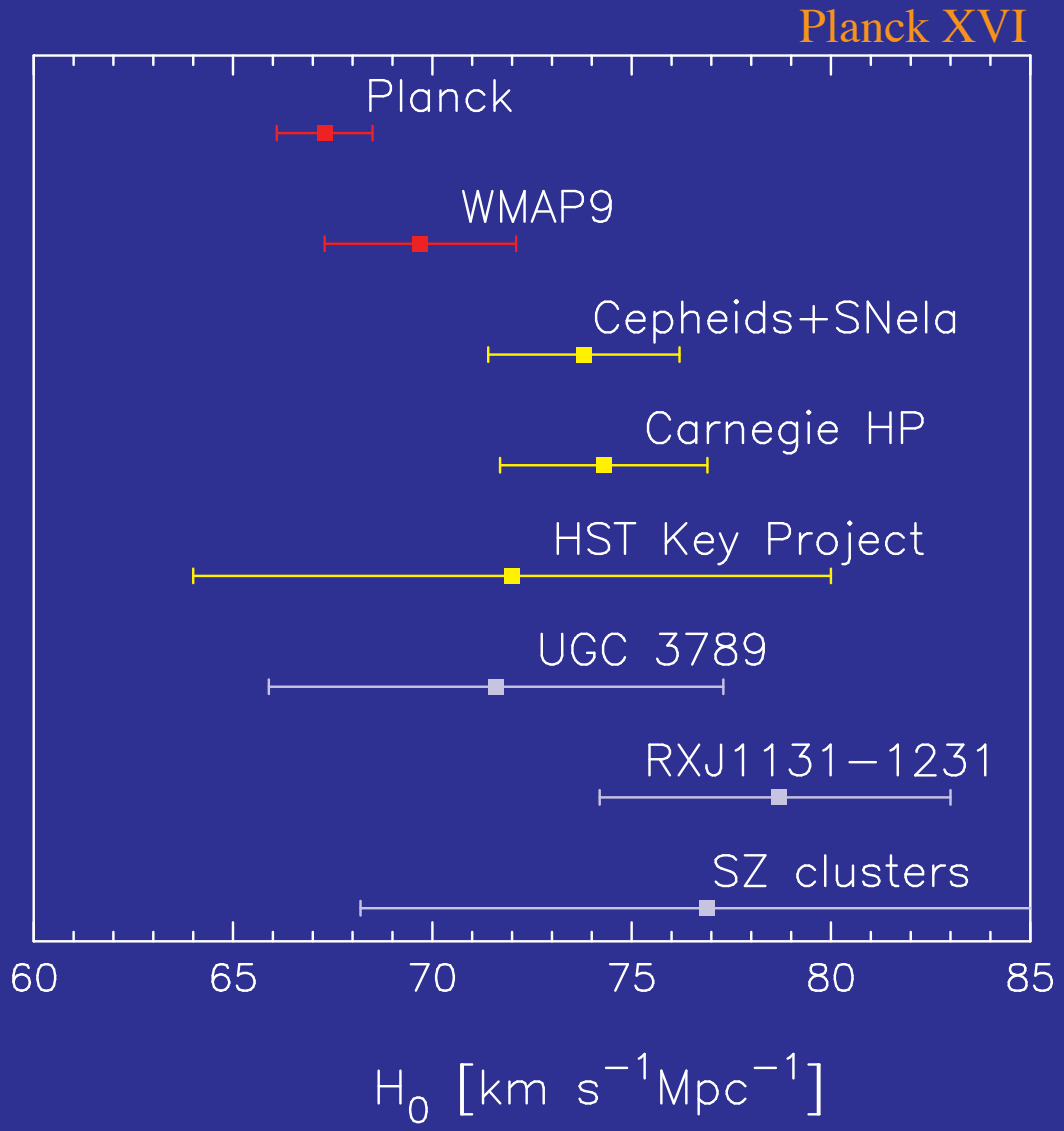
Falsifying ΛCDM

- Λ slows growth of structure in highly predictive way



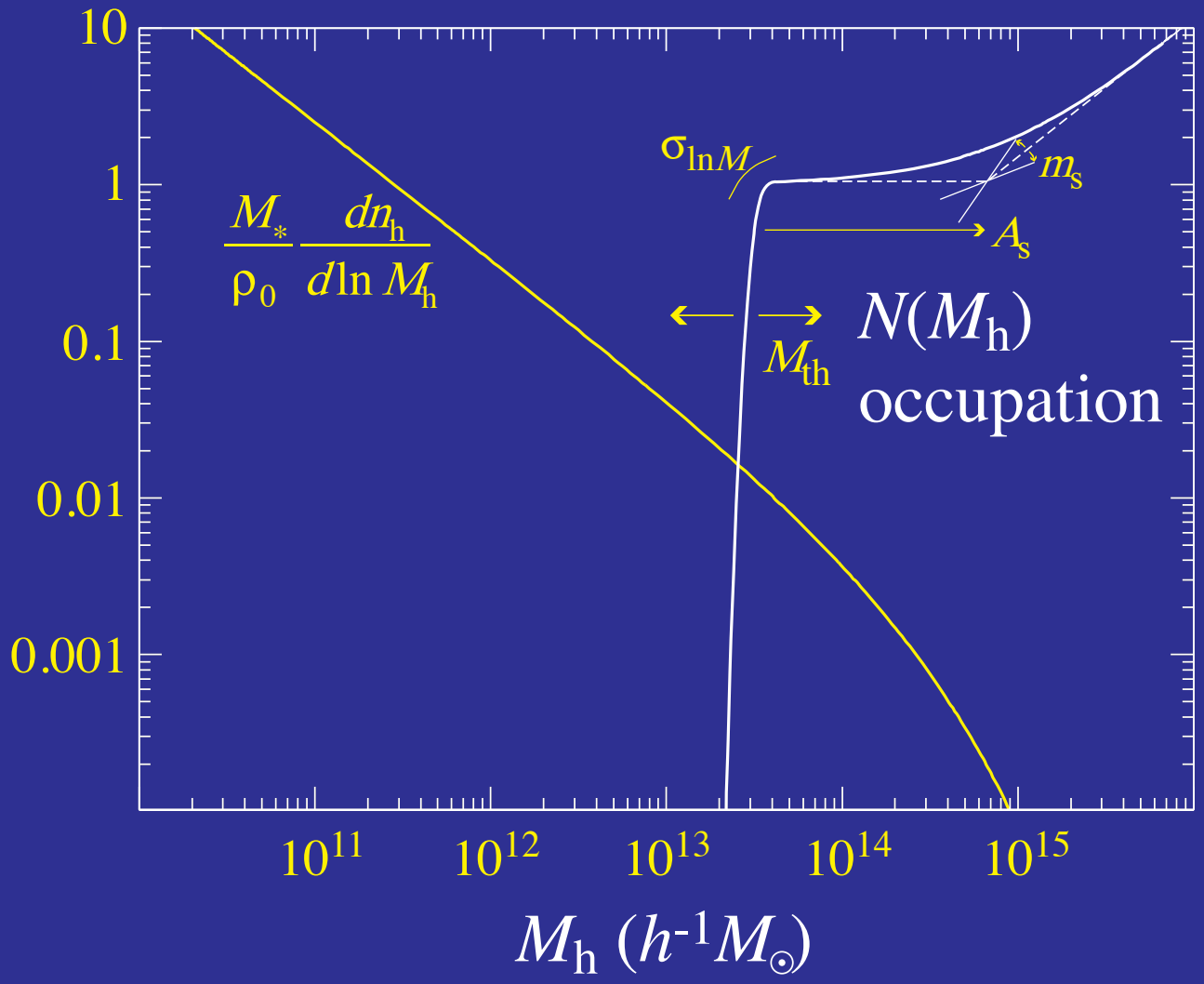
H_0 is for Hints

- Actual distance ladder measurements prefer larger value



Cluster Abundance

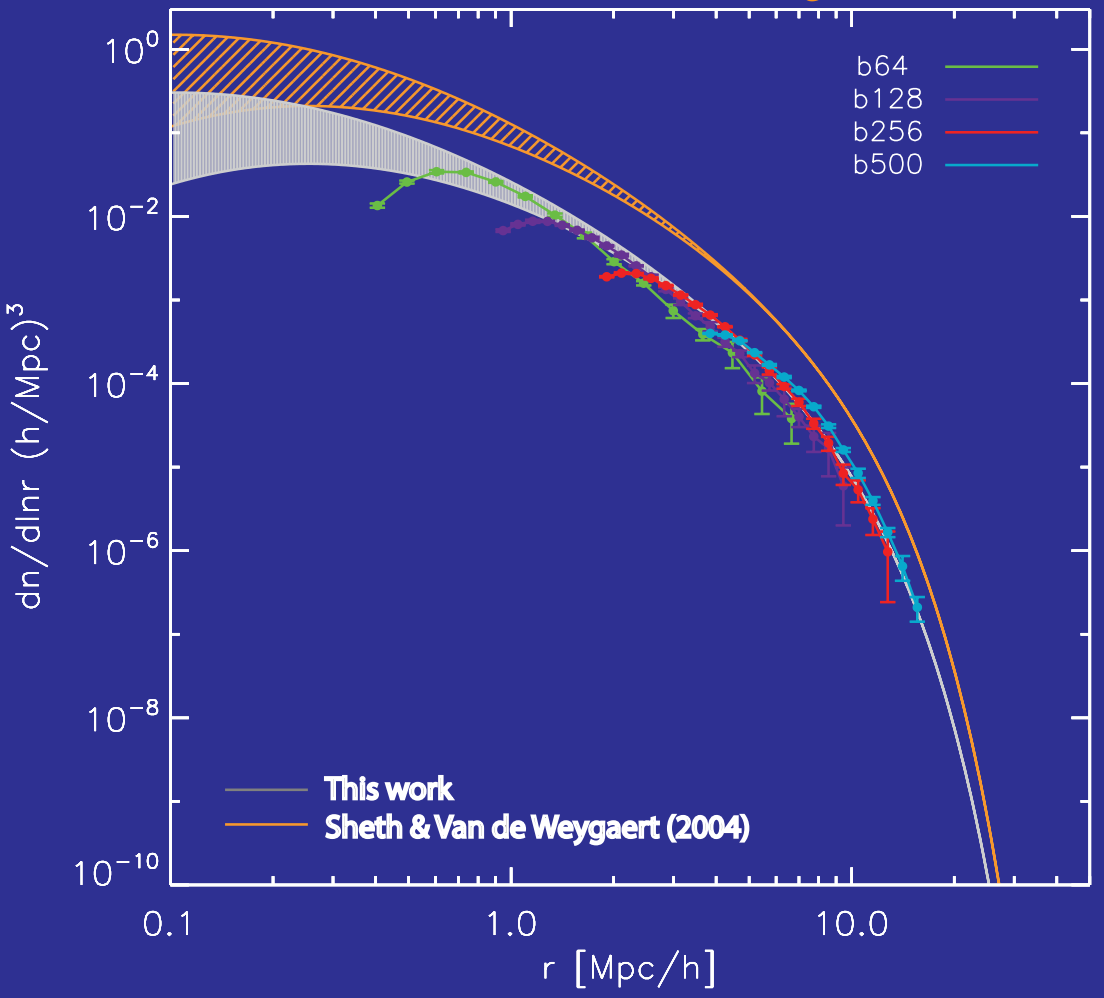
- Abundance of rare massive dark matter halos exponentially sensitive to the growth of structure
- Requires clusters to be mapped to halos of a given mass



Void Abundance

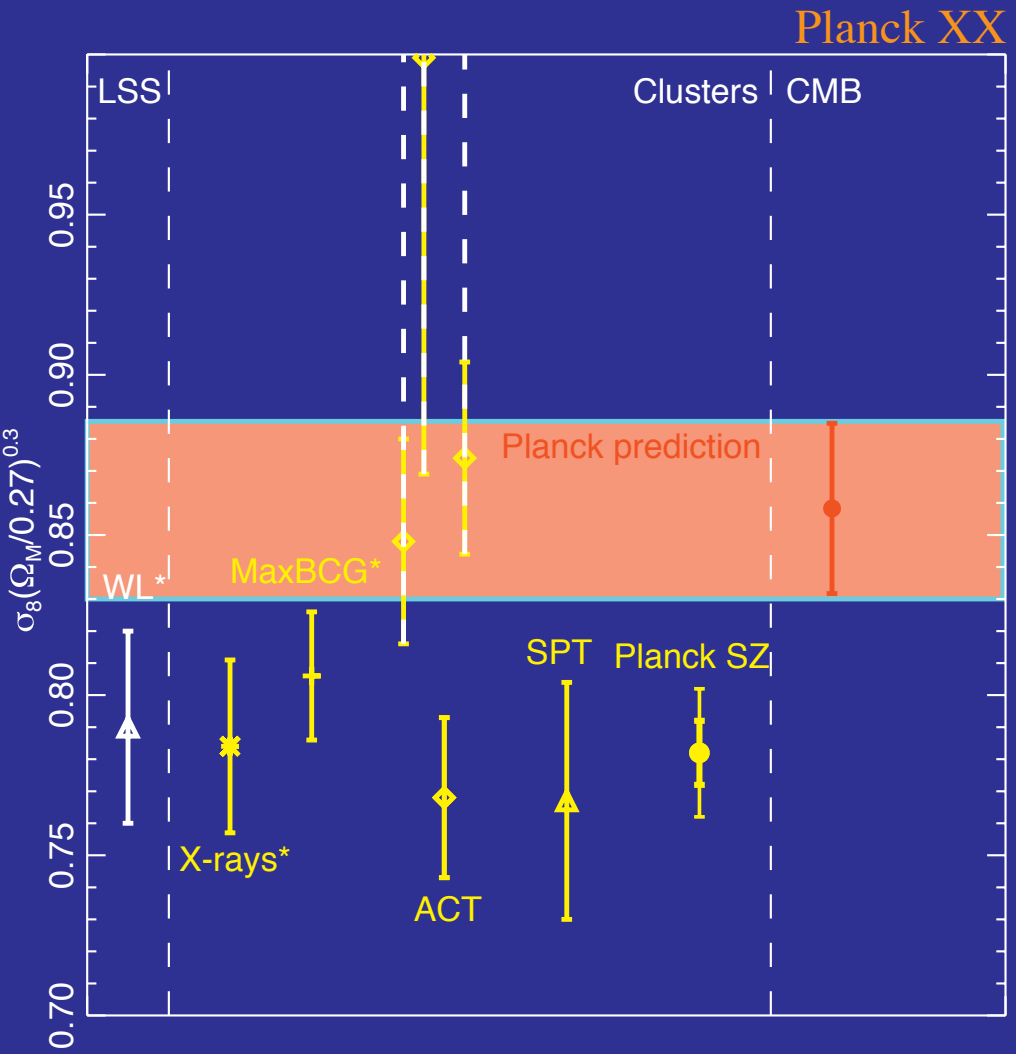
- Voids present interesting means to test gravity since they are the least screened
- Devising and quantifying statistics still lags halos Li, Koyama, Zhao (2012)

Jennings, Li, Hu (2013)



Growth and Clusters

- Growth measurements vs Planck predictions

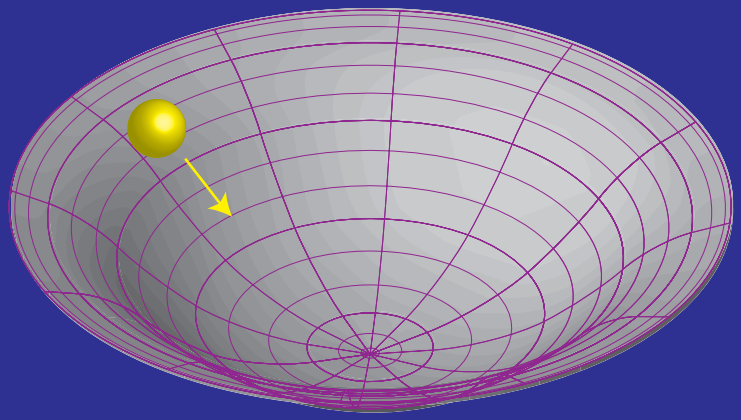


- Statistically discrepant at the ~3σ level

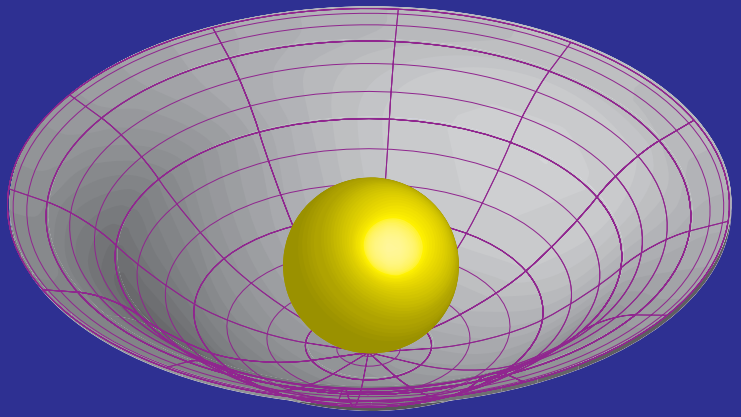
Beyond ΛCDM:
Dichotomies False and True

Mercury or Pluto?

- General relativity says Gravity = Geometry



- And Geometry = Matter-Energy



- Could the missing energy required by acceleration be an incomplete description of how matter determines geometry?

Two Potentials

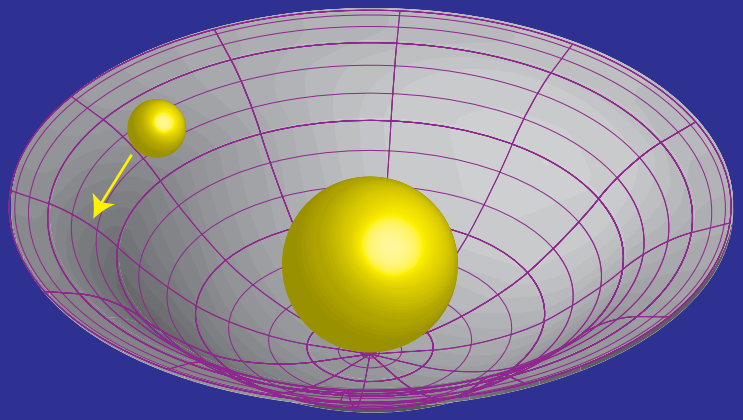
- Line Element

$$ds^2 = -(1+2\Psi)dt^2 + a^2(1+2\Phi)dx^2$$

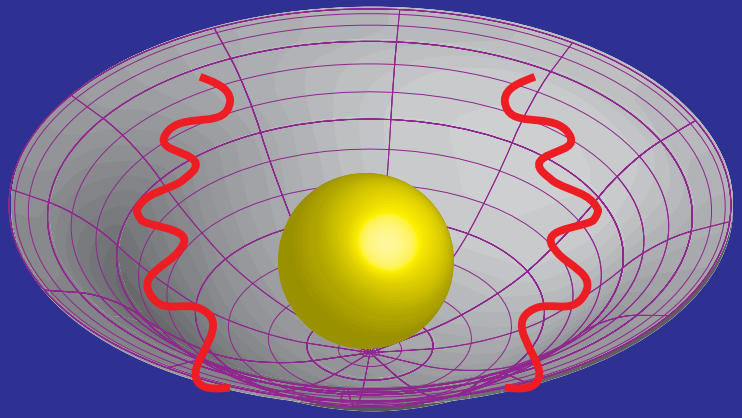
- Newtonian dynamical potential Ψ
- Space curvature potential Φ
- As in the parameterized post Newtonian approach, cosmological tests of the Φ/Ψ
- Space curvature per unit dynamical mass
- Given parameterized metric, matter falls on geodesics

Dynamical vs Lensing Mass

- Newtonian potential: $\Psi=\delta g_{00}/2g_{00}$ which non-relativistic particles feel



- Space curvature: $\Phi=\delta g_{ii}/2g_{ii}$ which also deflects photons



- Tests of space curvature per unit dynamical mass are the least model dependent

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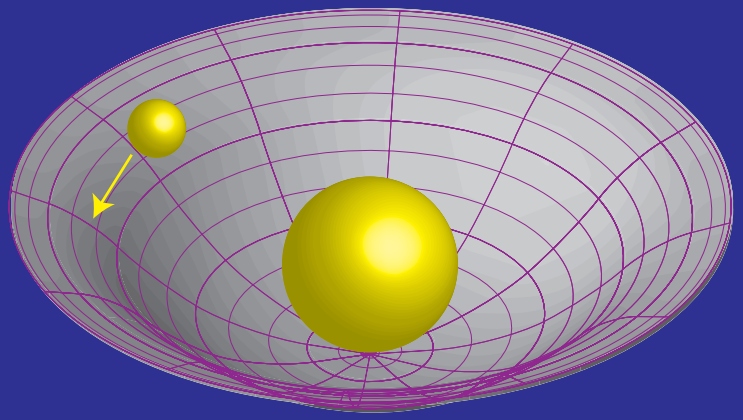

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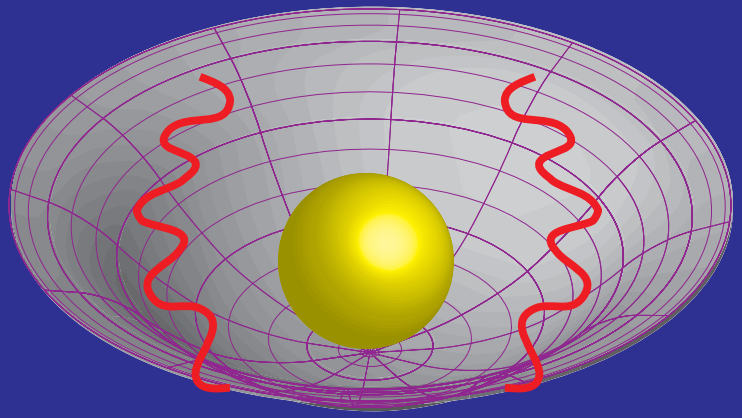


Solar system: sun
Cosmology: unknown
dark sector

- Tests of space curvature per unit dynamical mass are the least model dependent, but one suffices cosmologically combined with distance

Modified Gravity = Dark Energy?

- Solar system tests of gravity are informed by our knowledge of the local stress energy content
- With no other constraint on the stress energy of dark energy other than conservation, modified gravity is formally equivalent to dark energy

$$F(g_{\mu\nu}) + G_{\mu\nu} = 8\pi G T^{\rm M}_{\mu\nu} \qquad -F(g_{\mu\nu}) = 8\pi G T^{\rm DE}_{\mu\nu}$$
$$G_{\mu\nu} = 8\pi G [T^{\rm M}_{\mu\nu} + T^{\rm DE}_{\mu\nu}]$$

  and the Bianchi identity guarantees $\nabla^\mu T^{\rm DE}_{\mu\nu} = 0$

- Distinguishing between dark energy and modified gravity requires closure relations that relate components of stress energy tensor
- For matter components, closure relations take the form of equations of state relating density, pressure and anisotropic stress

Quintessential Dark Energy

Smooth Dark Energy

- Scalar field dark energy has $\delta p = \delta\rho$ (in constant field gauge) – relativistic sound speed, no anisotropic stress
- Jeans stability implies that its energy density is spatially smooth compared with the matter below the sound horizon

$$\begin{aligned} ds^2 &= -(1+2\Psi)dt^2 + a^2(1+2\Phi)dx^2 \\ \nabla^2\Phi &\propto \text{matter density fluctuation} \end{aligned}$$

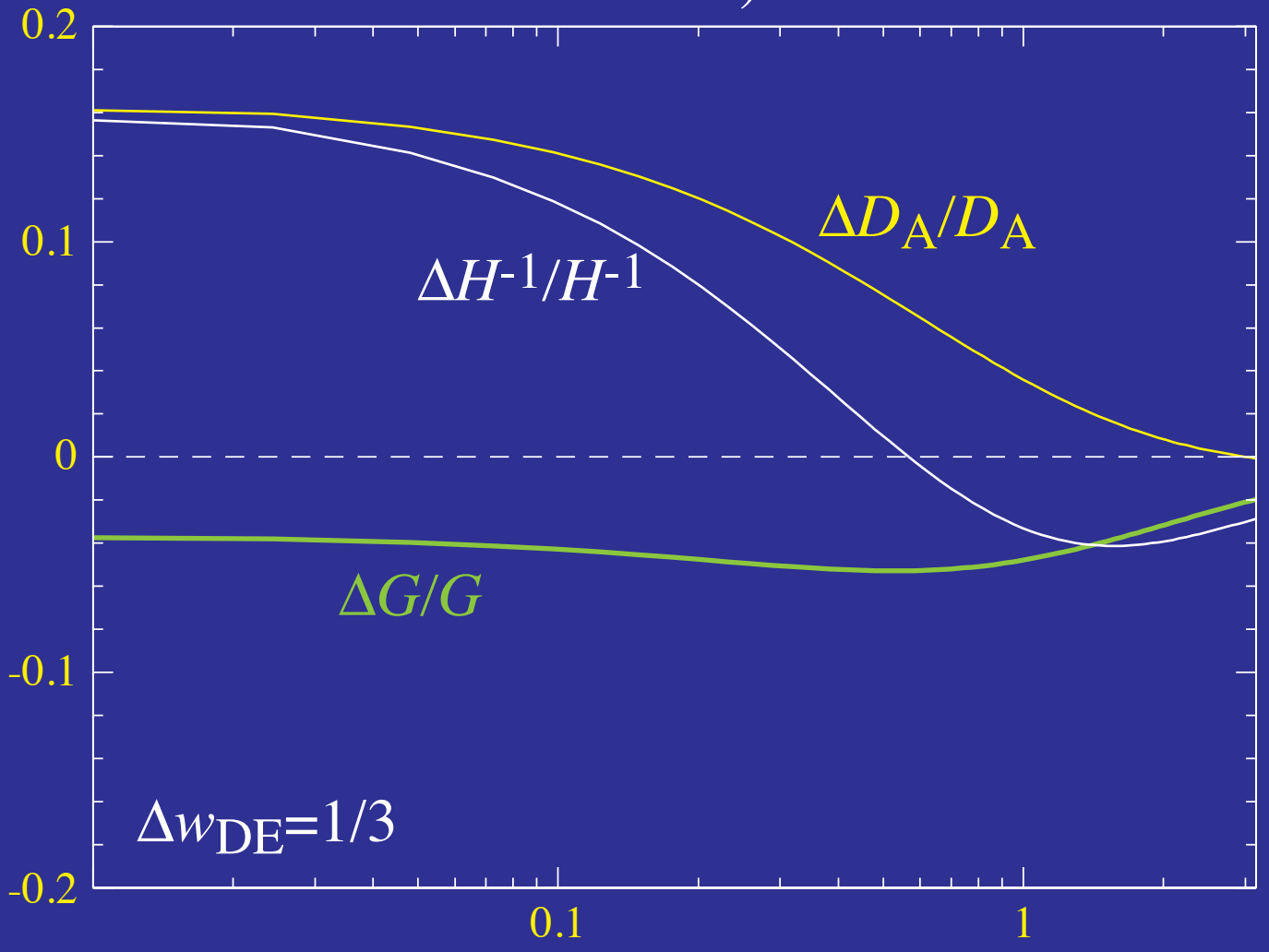
- Anisotropic stress changes the amount of space curvature per unit dynamical mass: negligible for both matter and smooth dark energy

$$\nabla^2(\Phi+\Psi) \propto \text{anisotropic stress approx } 0$$

in contrast to modified gravity or force-law models

Pinning the Past

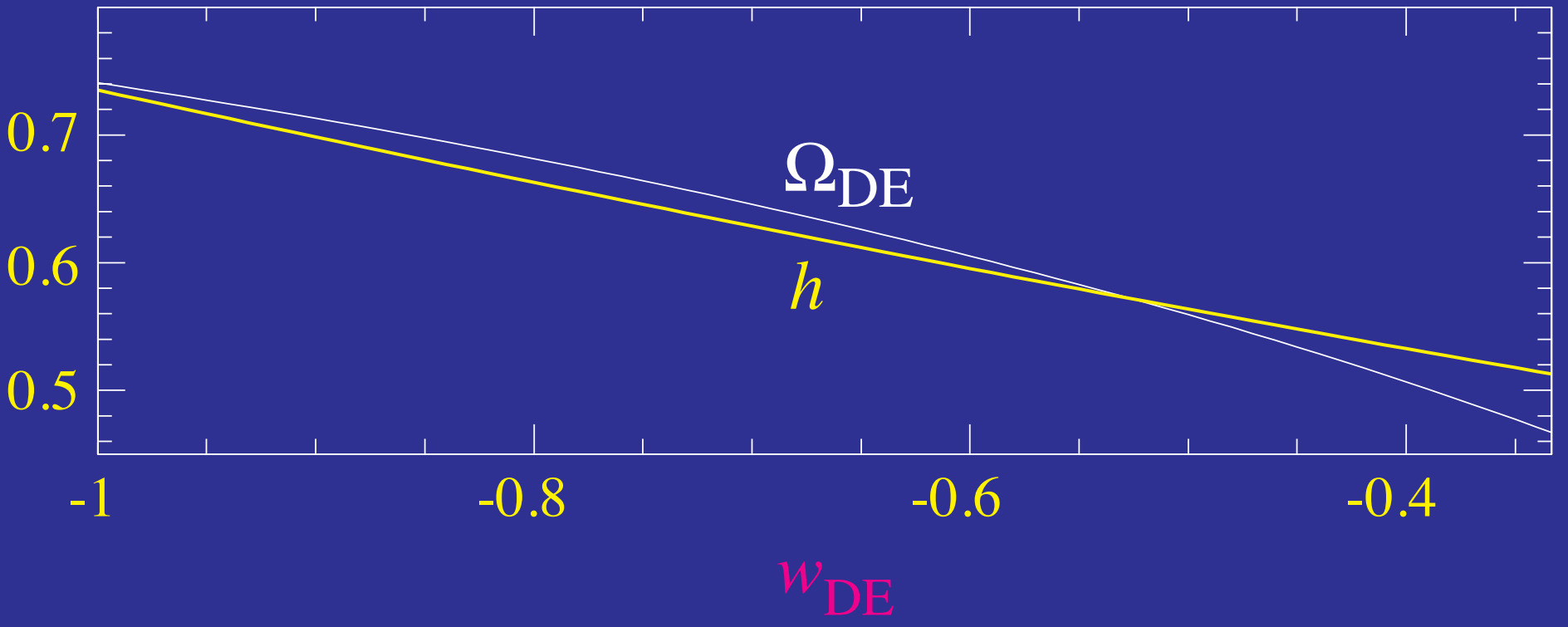
- Fixed distance to recombination $D_A(z\sim1100)$
- Fixed initial fluctuation $G(z\sim1100)$
- Constant $w=w_{DE}$; (with free functions null deviations at z=0 possible but contrived)



Hu (2004)

H_0 is Undervalued

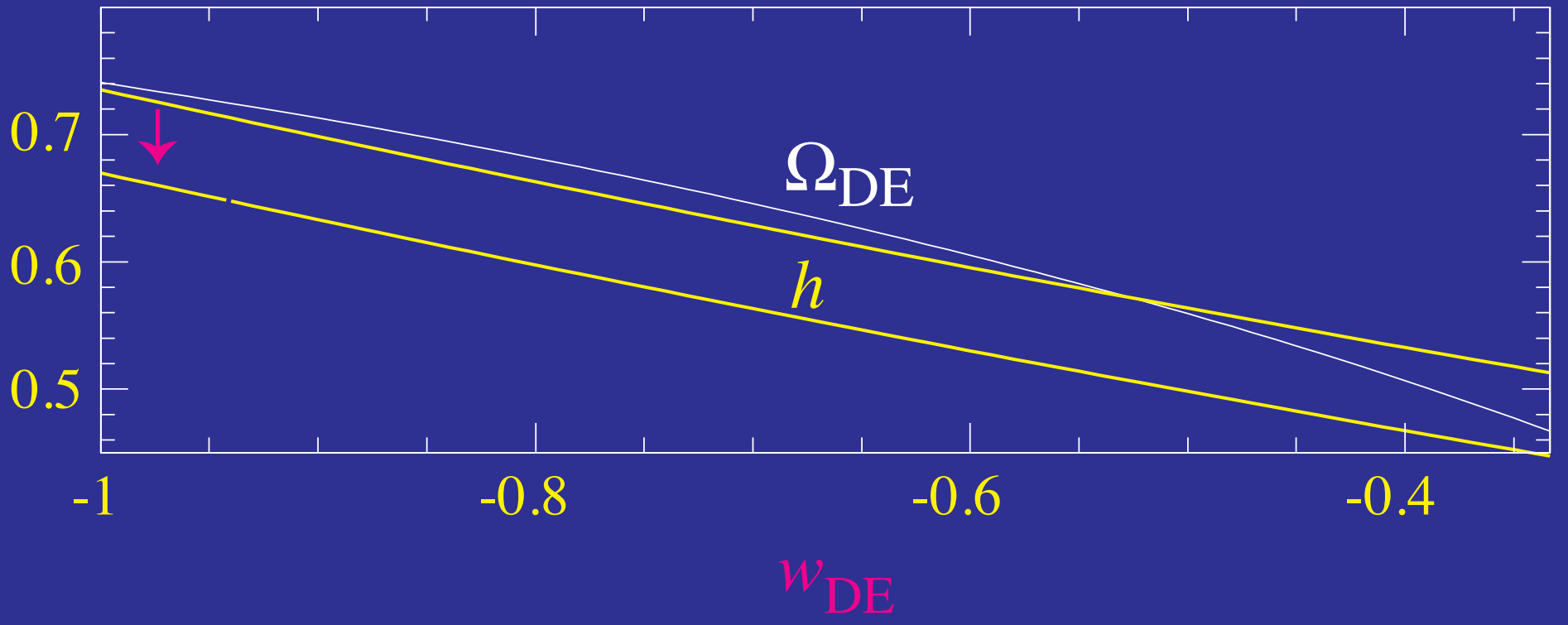
- Flat constant w dark energy model
- Determination of Hubble constant gives w to comparable precision



- For evolving w, equal precision on average or pivot w, equally useful for testing a cosmological constant

H_0 is Undervalued

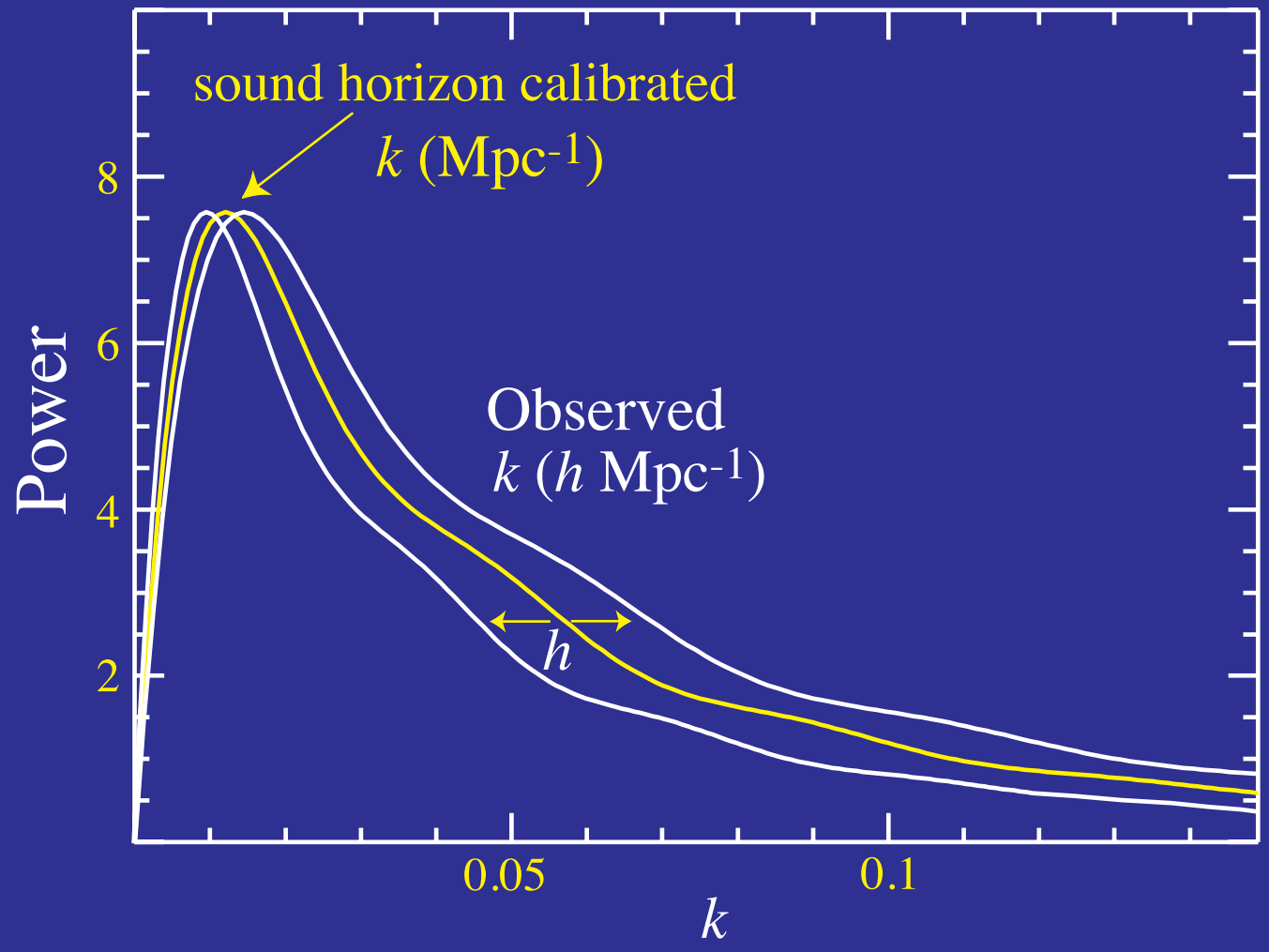
- Flat constant w dark energy model
- Determination of Hubble constant gives w to comparable precision
- At w=-1, Planck predicts h=0.673±0.012



- For evolving w, equal precision on average or pivot w, equally useful for testing a cosmological constant

Baryon Acoustic Oscillations

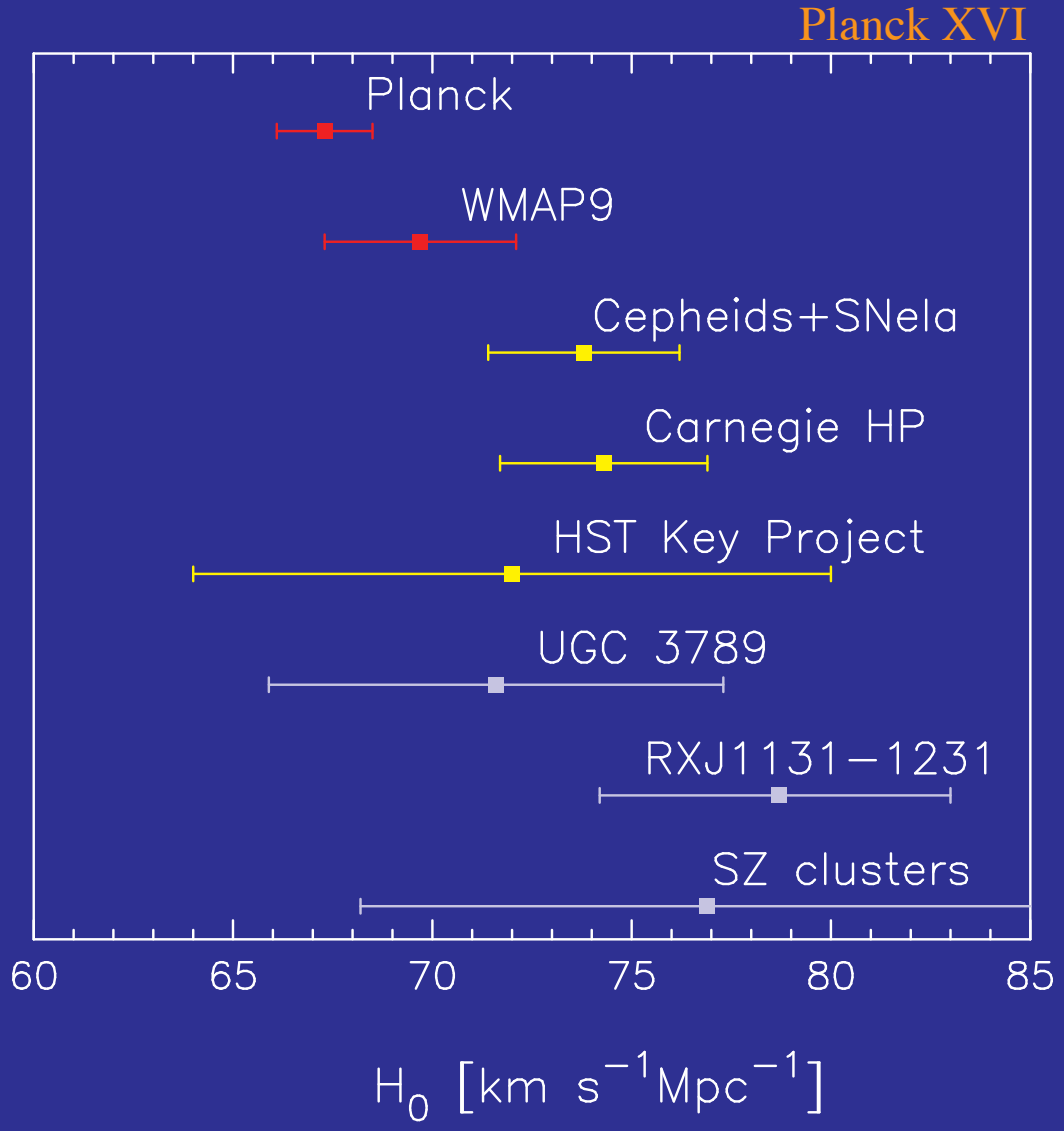
- Modes perpendicular to line of sight measure angular diameter distance, parallel $H(z)$ – at low redshift both are H_0



Eisenstein, Hu, Tegmark (1998)

H_0 is for Hints, Naught

- Actual distance ladder measurements prefer larger value

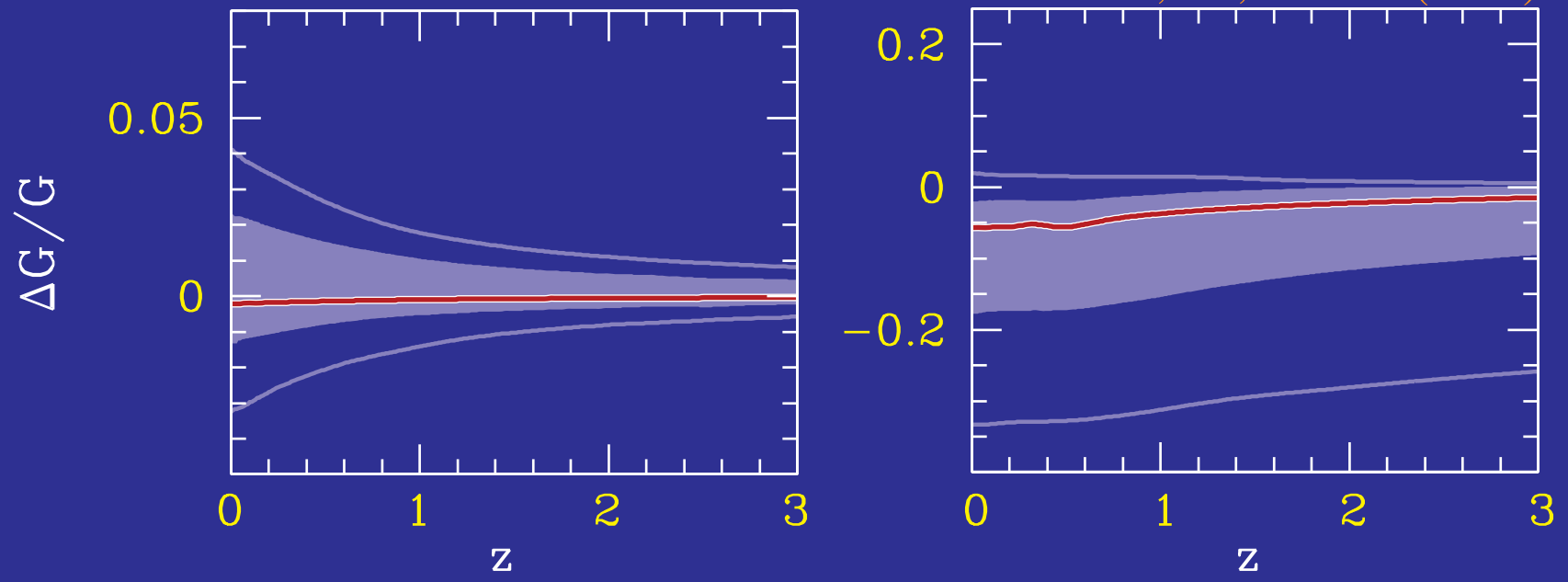


- ...but BAO inference prefers the low value 68.4±1

Falsifying Quintessence

- Dark energy slows growth of structure in highly predictive way

Mortonson, Hu, Huterer (2009)

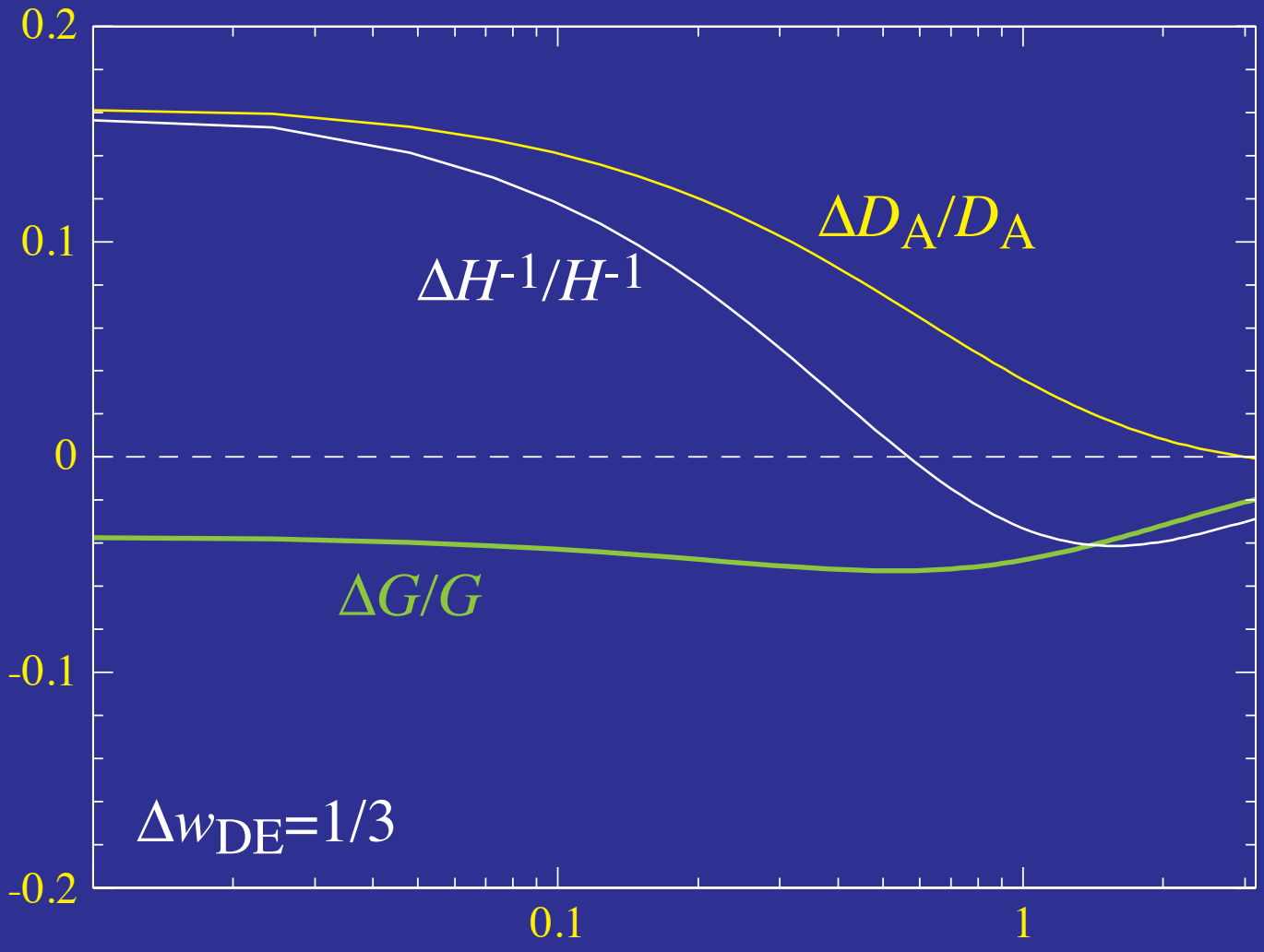


Cosmological Constant Quintessence

- Deviation significantly >2% rules out Λ with or without curvature
- Excess >2% rules out quintessence with or without curvature and early dark energy [as does >2% excess in H_0]

Phantoms & Ghosts

- High measured H_0 prefers phantom dark energy (ignoring BAO)
- If smooth, predicts more z=0 structure than ΛCDM, observations less
- Modified gravity or interacting dark sector? weakened forces=ghost?



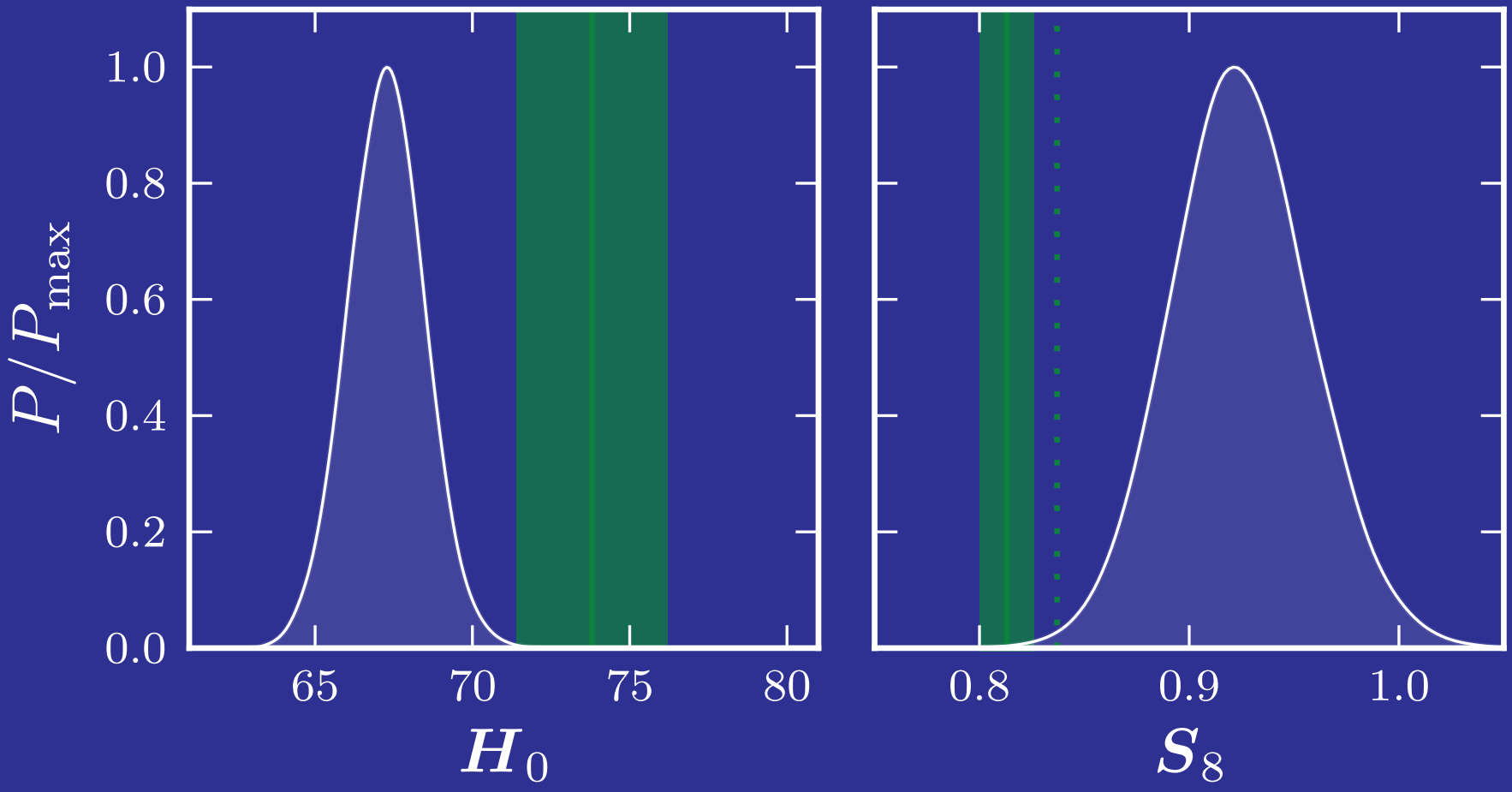
Hu (2004)

Beyond ΛCDM:
A Nu Concordance?

Neu(trino) Concordance

- Partially populated sterile, massive neutrinos change both the acoustic standard ruler and suppress structure and fixes both H_0 and clusters

Planck vs Local: ΛCDM



Wyman, Rudd, Vanderveld, Hu (2013)

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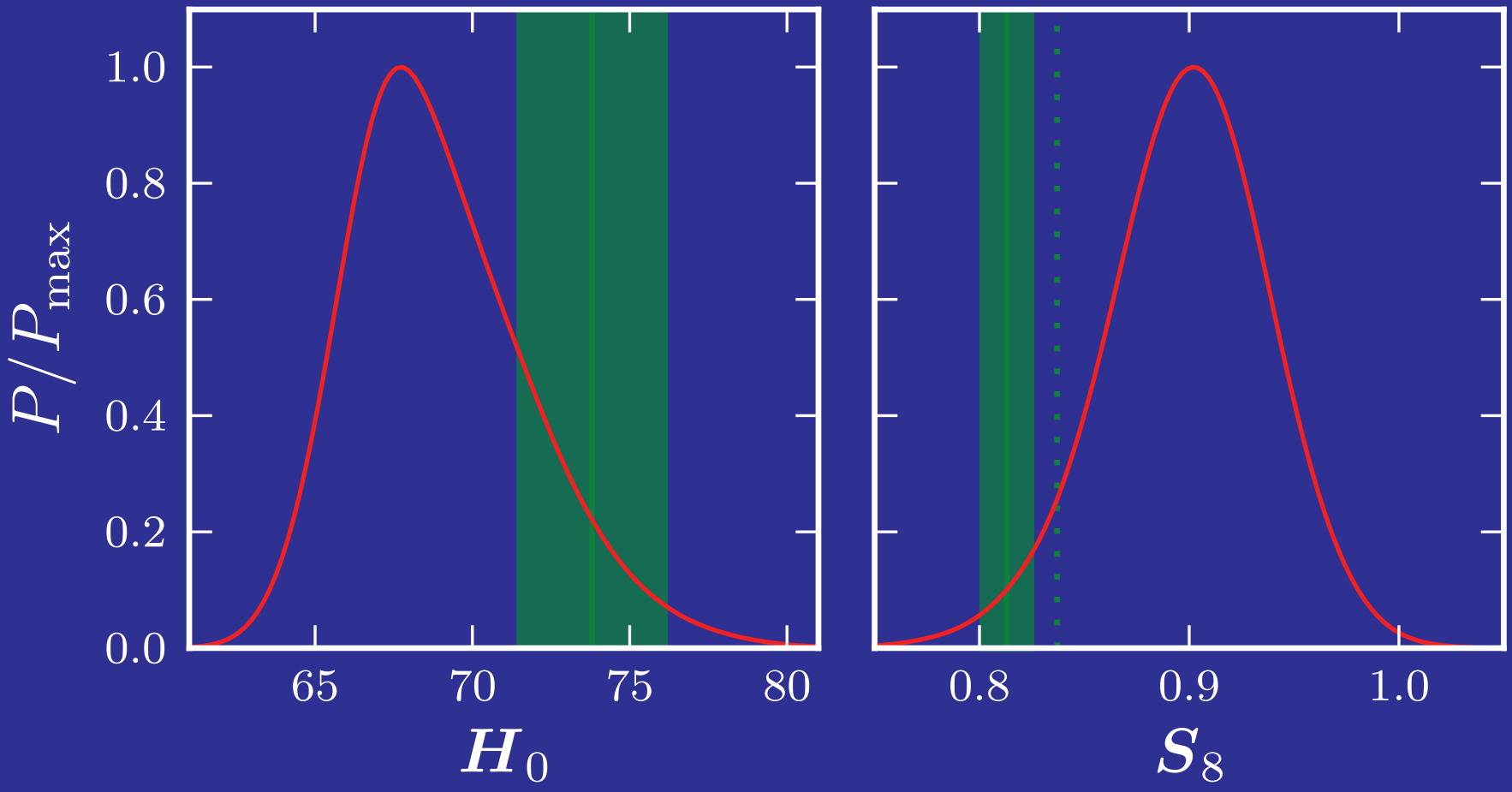

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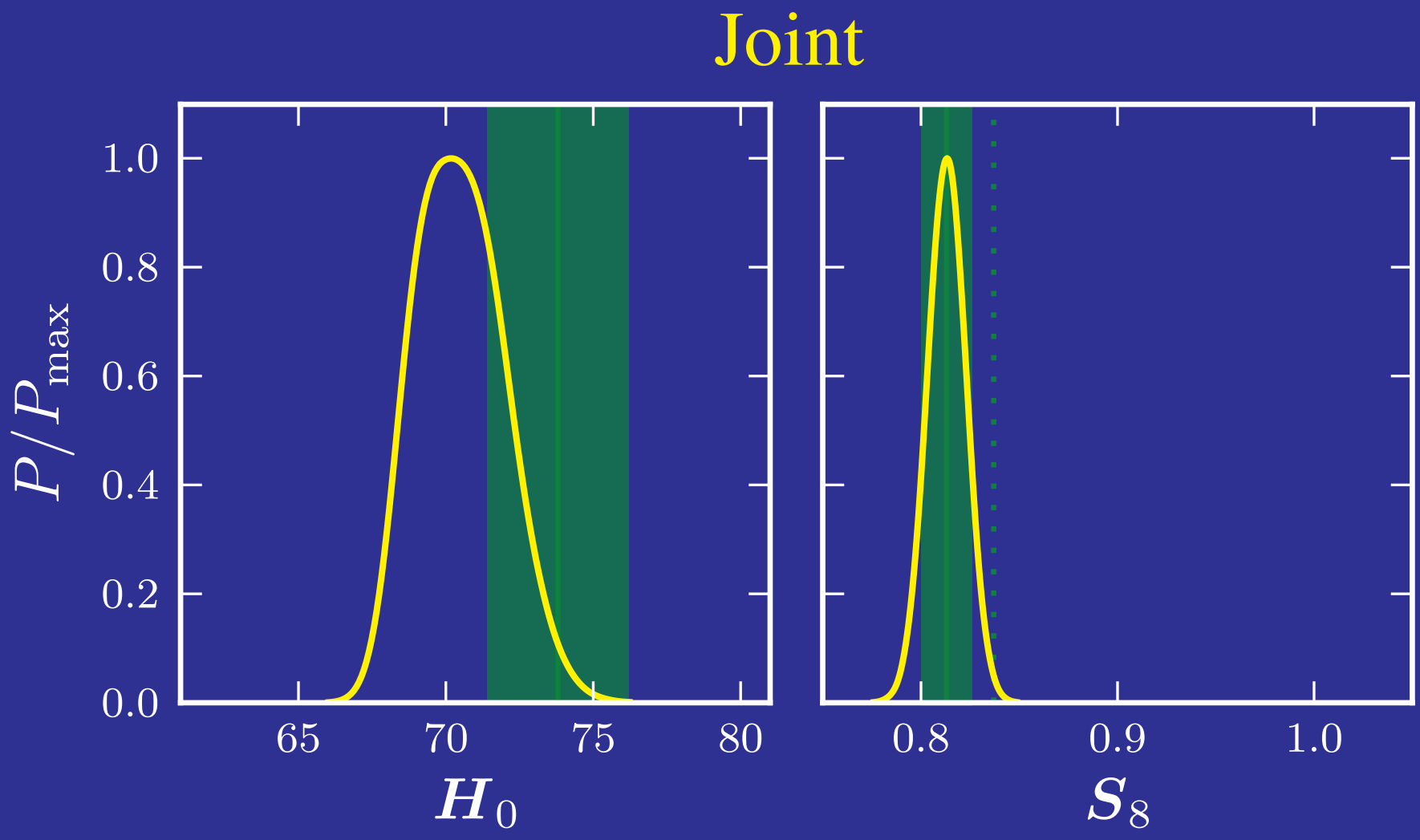

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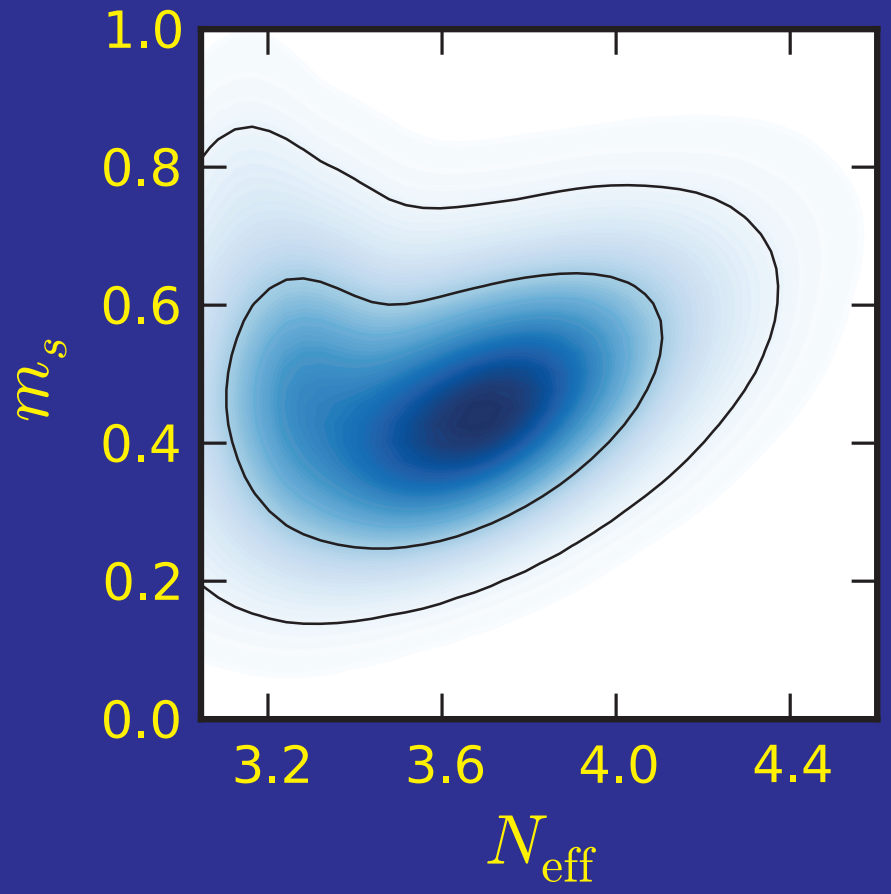
Sterile Neutrinos: >3σ stat



oscillation populated
mass=$m_s/\Delta N_{\rm eff}$ (eV)

$\Delta N_{\rm eff}$=1, 1 fully populated species

Wyman, Rudd, Vanderveld, Hu (2013)

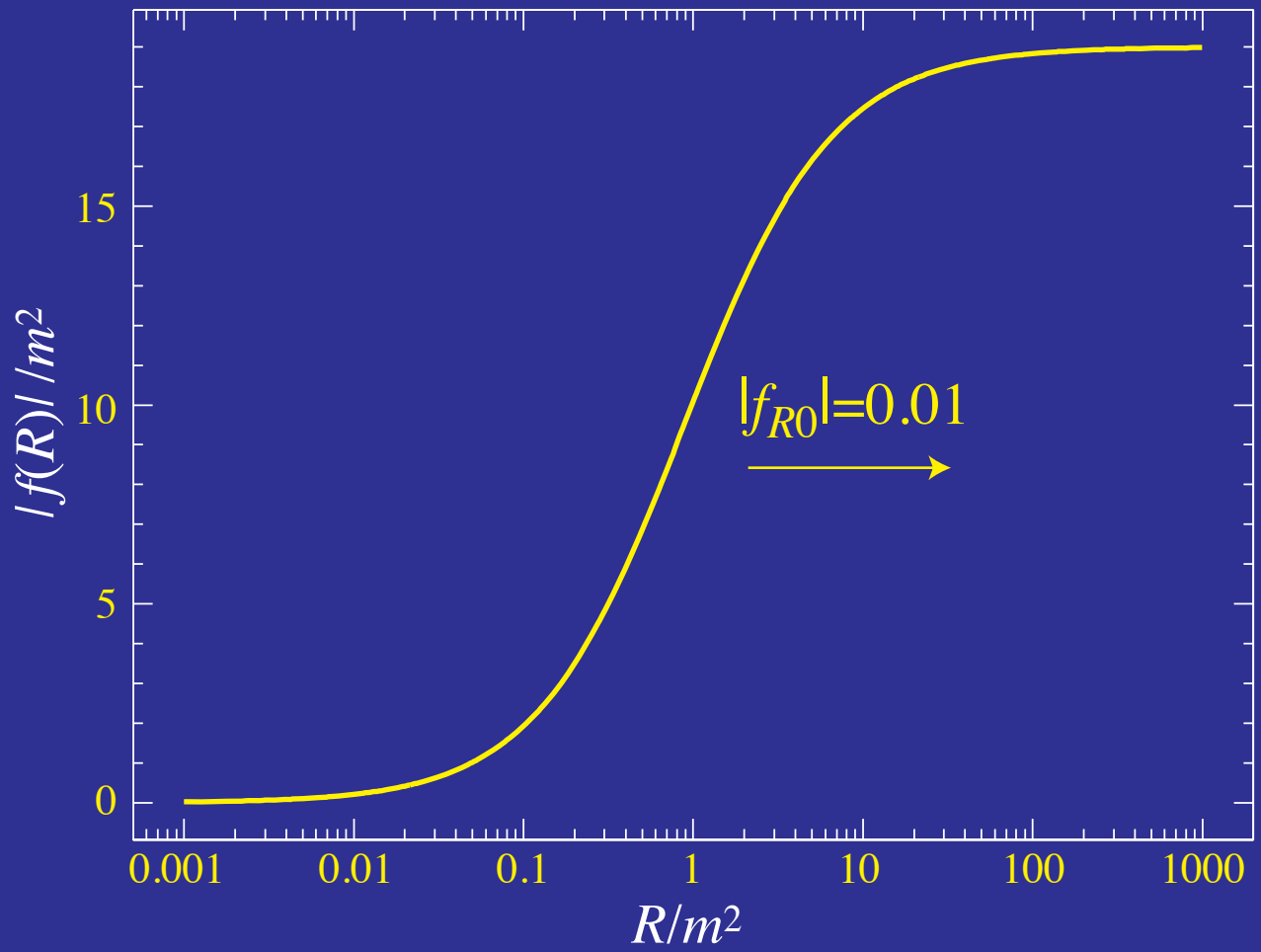
Beyond ΛCDM:
Modifying Forces and Couplings

Nonlinearly Screened DOFs

- Modifications of gravity will introduce new propagating degrees of freedom (Weinberg)
- These DOFs mediate fifth forces and may lead to ghost and tachyon instabilities
- Even attempts to modify gravity on cosmological scales (IR) will have consequences for small scales (e.g. vDVZ discontinuity)
- Fifth forces are highly constrained in the solar system and lab
- Must be screened by a nonlinear mechanism in the presence of matter source: chameleon, symmetron, Vainshtein...
- Realization in models: $f(R)$, DGP, galileon, massive gravity
- $f(R)$, DGP examples solved from horizon scales through to dark matter halo scales with N-body simulations

$f(R)$ Models

- Supplement Einstein Hilbert action with general function of Ricci scalar
- Choose function to have no c.c. at R=0, but mimic one at high R
- Propagating scalar is $df/dR=f_R$, and its value today f_{R0} controls observable deviations



Hu & Sawicki (2007)

Three Regimes

- Fully worked $f(R)$ example show 3 regimes
- Superhorizon regime: constant comoving curvature, $g(a)$
- Linear regime - closure $\leftrightarrow$ "smooth" dark energy density:

$$\begin{aligned} k^2(\Phi-\Psi)/2 &= 4\pi G a^2 \Delta\rho \\ (\Phi+\Psi)/(\Phi-\Psi) &= g(a,k) \end{aligned}$$

  In principle $G(a)$ but conformal invariance: deviations order f_R

- Non-linear regime, scalar f_R:

$$\begin{aligned} \nabla^2(\Phi-\Psi)/2 &= -4\pi G a^2 \Delta\rho \\ \nabla^2\Psi &= 4\pi G a^2 \Delta\rho + \frac{1}{2}\nabla^2 f_R \end{aligned}$$

  with non-linearity in the field equation

$$\nabla^2 f_R = g_{\rm lin}(a) a^2 \left(8\pi G\Delta\rho - N[f_R]\right)$$

Non-Linear Chameleon

- For $f(R)$ the field equation

$$\nabla^2 f_R \approx \frac{1}{3}(\delta R(f_R) - 8\pi G\delta\rho)$$

  is the non-linear equation that returns general relativity

- High curvature implies short Compton wavelength and suppressed deviations but requires a change in the field from the background value $\delta R(f_R)$

- Change in field is generated by density perturbations just like gravitational potential so that the chameleon appears only if

$$\Delta f_R \leq \frac{2}{3}\Phi\,,$$

  else required field gradients too large despite $\delta R = 8\pi G\delta\rho$ being the local minimum of effective potential

Non-Linear Dynamics

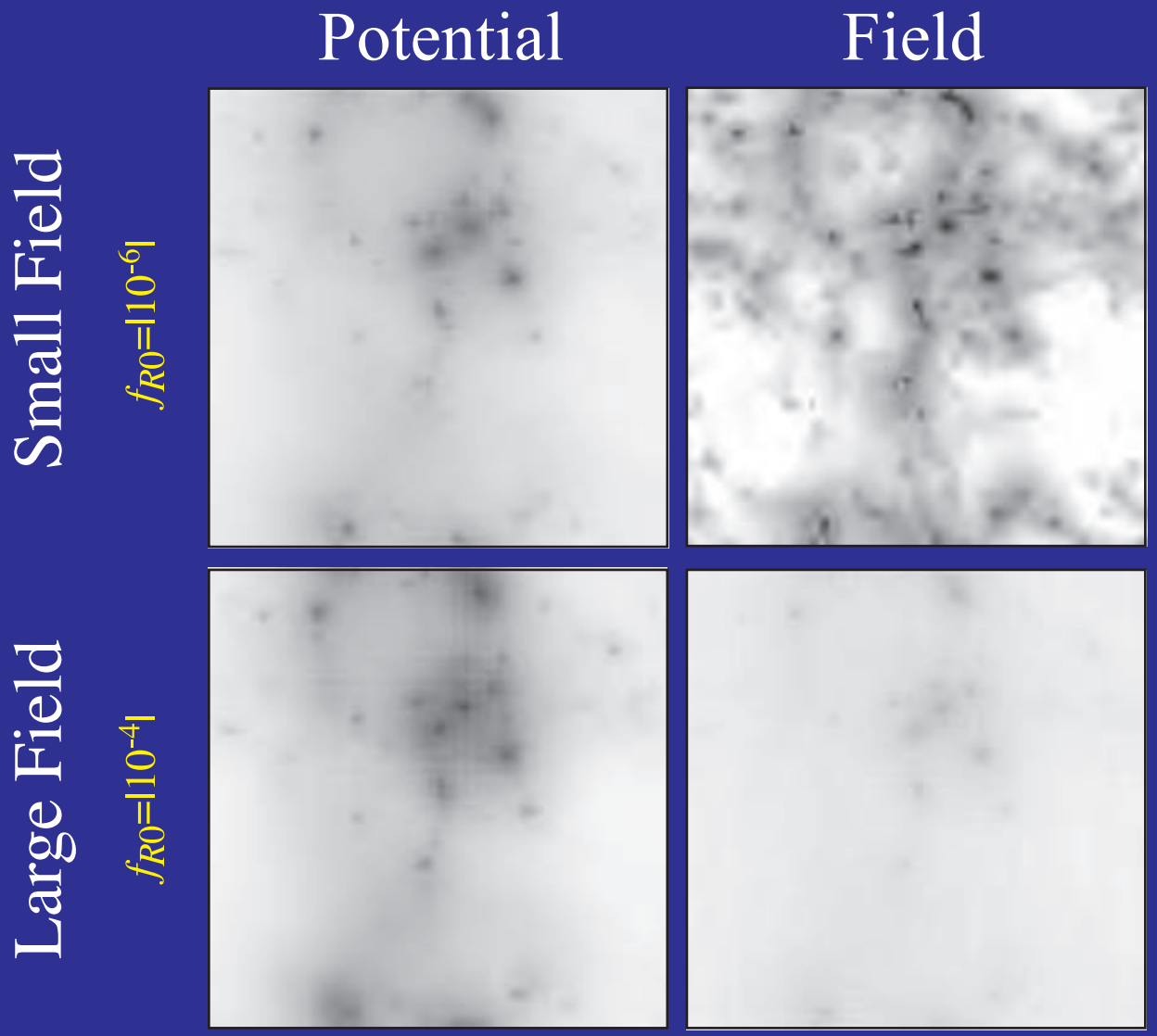
- Supplement that with the modified Poisson equation

$$\nabla^2\Psi = \frac{16\pi G}{3}\delta\rho - \frac{1}{6}\delta R(f_R)$$

- Matter evolution given metric unchanged: usual motion of matter in a gravitational potential Ψ
- Prescription for N-body code
- Particle Mesh (PM) for the Poisson equation
- Field equation is a non-linear Poisson equation: relaxation method for f_R
- Initial conditions set to GR at high redshift

Environment Dependent Force

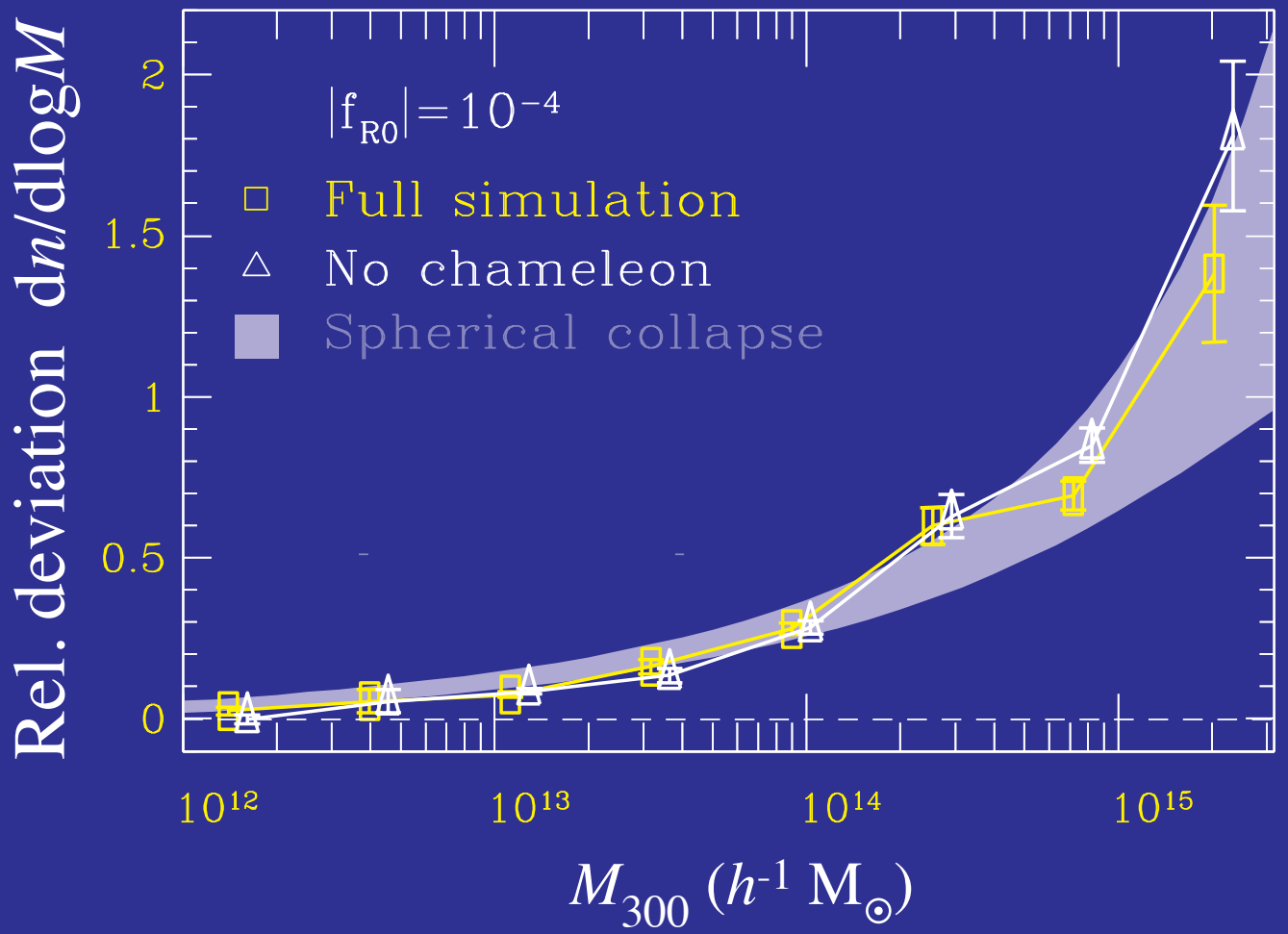
- Small background field: chameleon in cosmological structures
  Large background field: chameleon absent



Oyaizu, Lima, Hu (2008) [AMR high resolution: Zhao, Li, Koyama]

Cluster Abundance

- Enhanced abundance of rare dark matter halos (clusters) with extra force

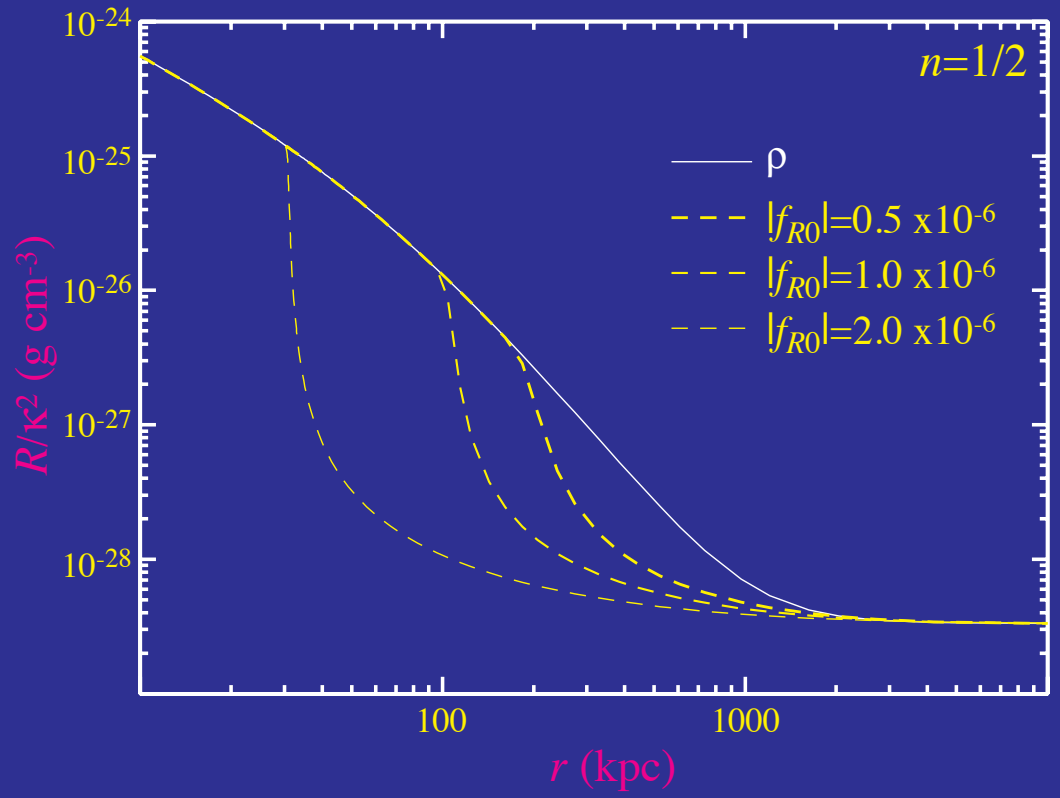


Lima, Schmidt, Oyaizu, Hu (2008)

Sun, Stars, Galaxies

- Solar system is chameleon dressed by our galaxy
- Rotation curve $v/c \sim 10^{-3}$, $\Phi \sim 10^{-6} \sim |\Delta f_R|$ limits cosmological field
- In dwarf galaxies this can reach a factor of a few lower yielding environmental differences between stellar objects of varying potential

Jain, Vikram, Sakstein (2012); Davis, Lim, Sakstein, Shaw (2011)

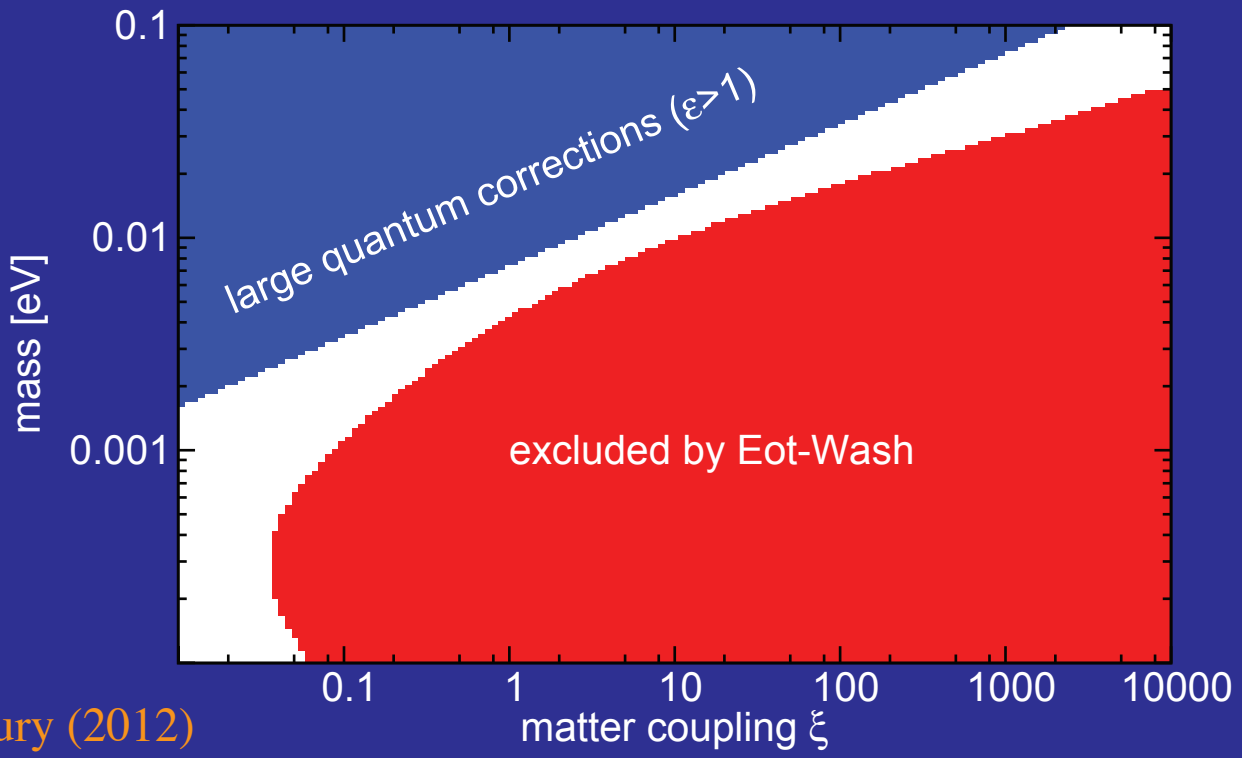


Hu & Sawicki (2007)

Solar System & Lab

- Strictly valid for solar system / lab or are beyond effective theory?
- If former, solar system $f(R)$ tests of more powerful by at least 10
  (Hu & Sawicki 2009; exosolar tests: Jain et al., Davis et al.)
- Laboratory tests: within factor of 2 of ruling out all gravitational strength chameleon models [$m < 0.0073(\xi\rho/10\text{g cm}^3)^{1/3}\text{eV}$]

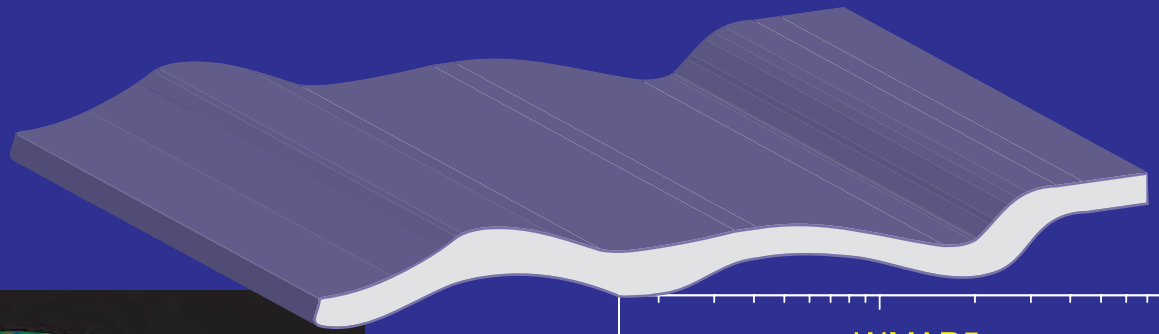
  Already exceeded the vacuum scale (1000km) and earth (1cm) of Vainshtein models (Nicolis & Rattazzi 2004)

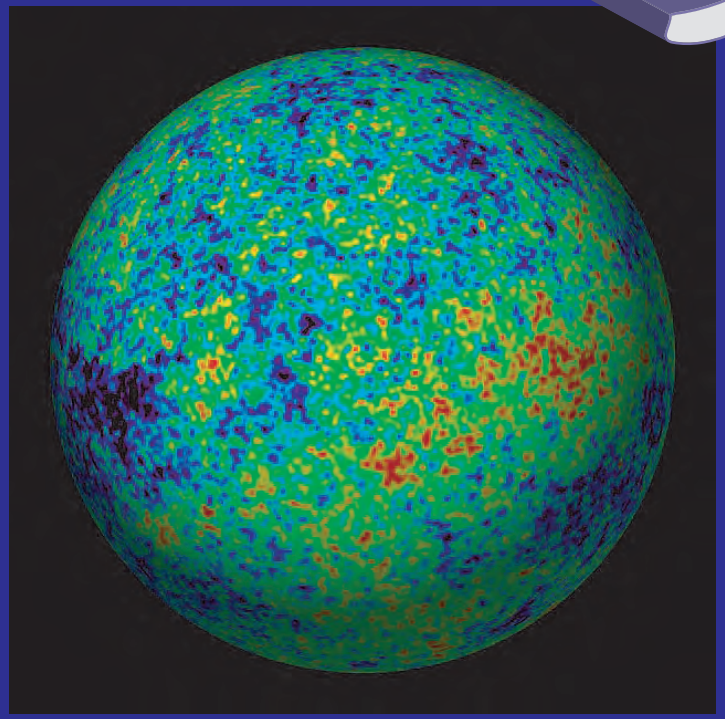


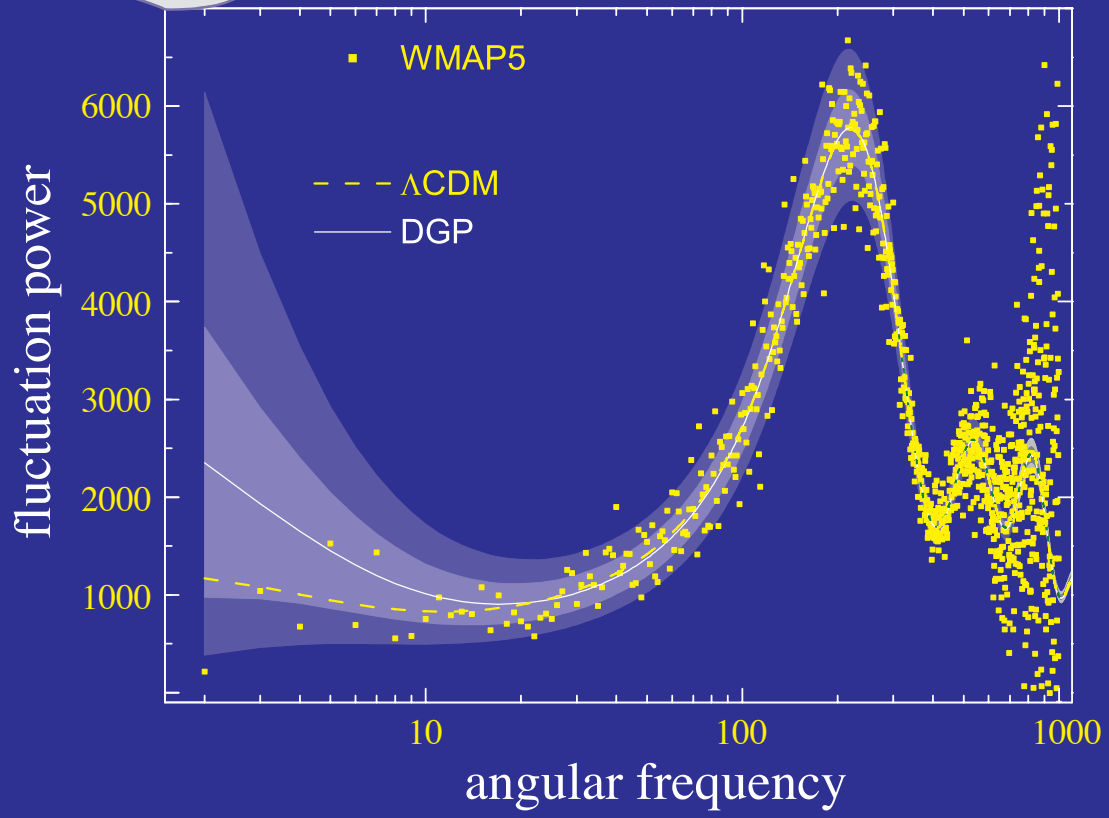
Upadhye, Hu, Khoury (2012)

DGP Braneworld Model

- Extra dimension modify gravity on large scales; self-accelerates
- Propagating scalar is position of brane, leads to unacceptable cosmo phenomenology (classically) and ghost instability (quantum)







Nonlinear Interaction

Nonlinearity in field equation recovers linear theory if $N[\phi] \to 0$

$$\nabla^2\phi = g_{\rm lin}(a)a^2\left(8\pi G\Delta\rho - N[\phi]\right)$$

- For $f(R)$, $\phi = f_R$ and

$$N[\phi] = \delta R(\phi)$$

a nonlinear function of the field

Linked to gravitational potential

- For DGP, ϕ is the brane-bending mode and

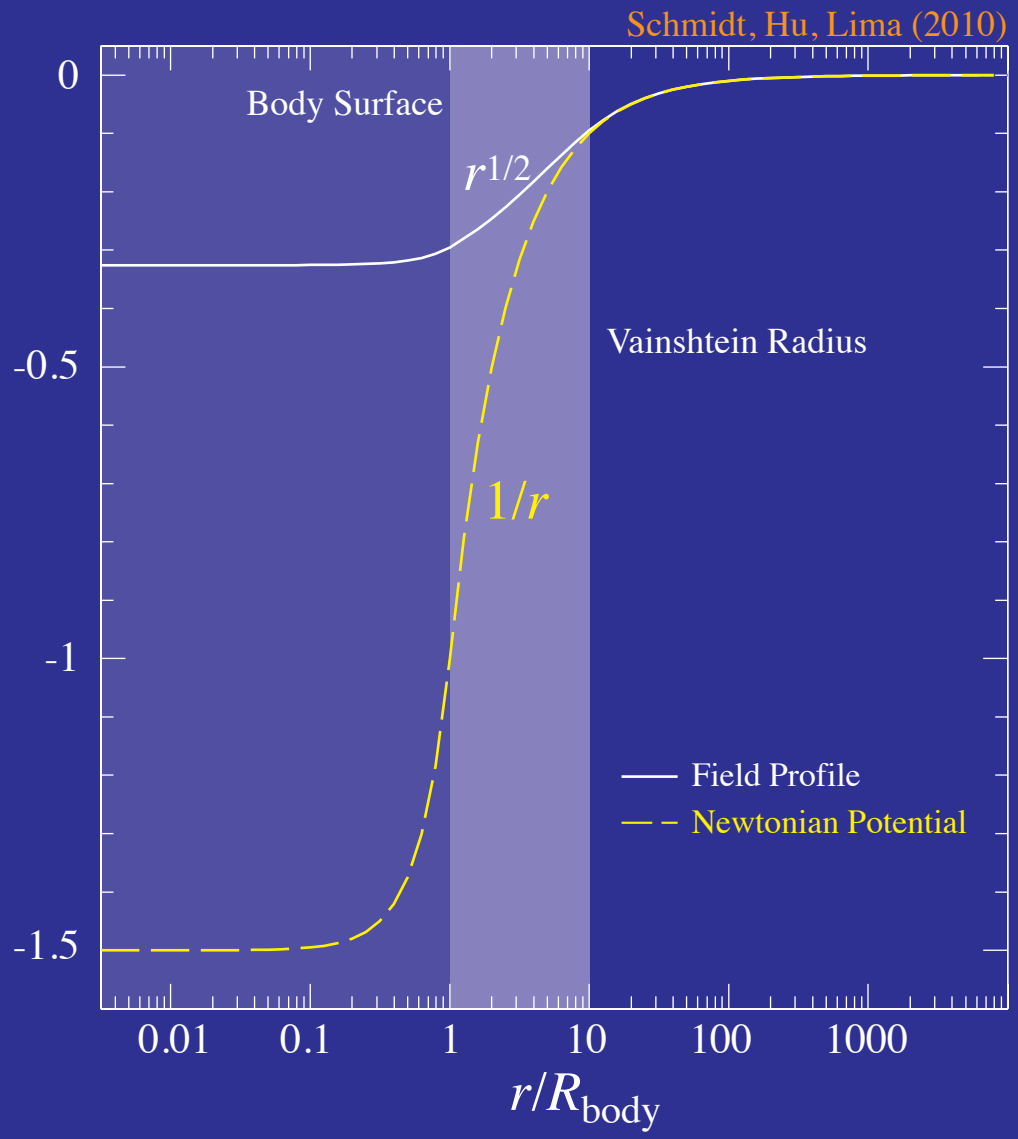
$$N[\phi] = \frac{r_c^2}{a^4}\left[(\nabla^2\phi)^2 - (\nabla_i\nabla_j\phi)^2\right]$$

a nonlinear function of second derivatives of the field

Linked to density fluctuation - Galileon invariance - no self-shielding of external forces

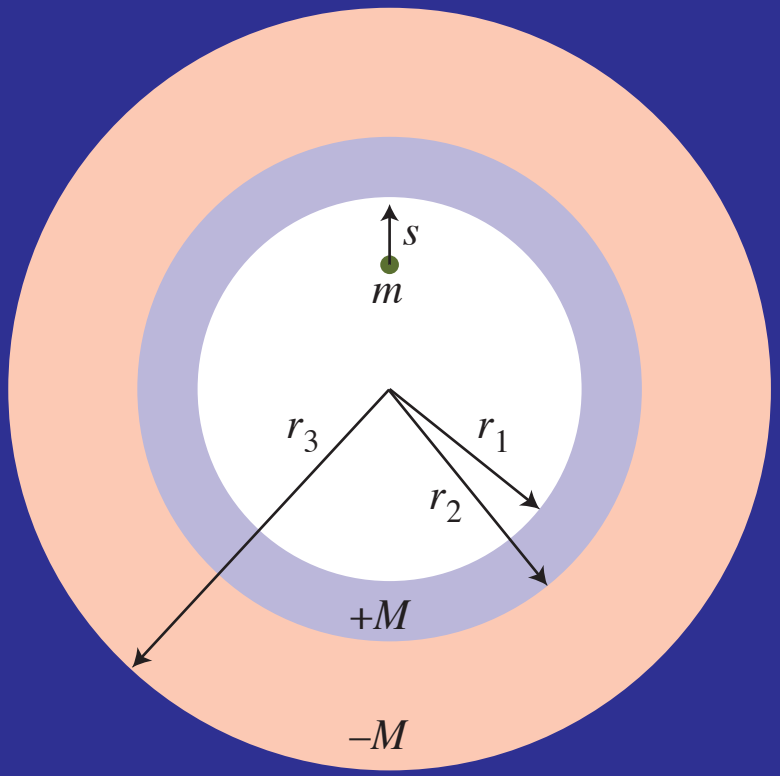
Vainshtein Suppression

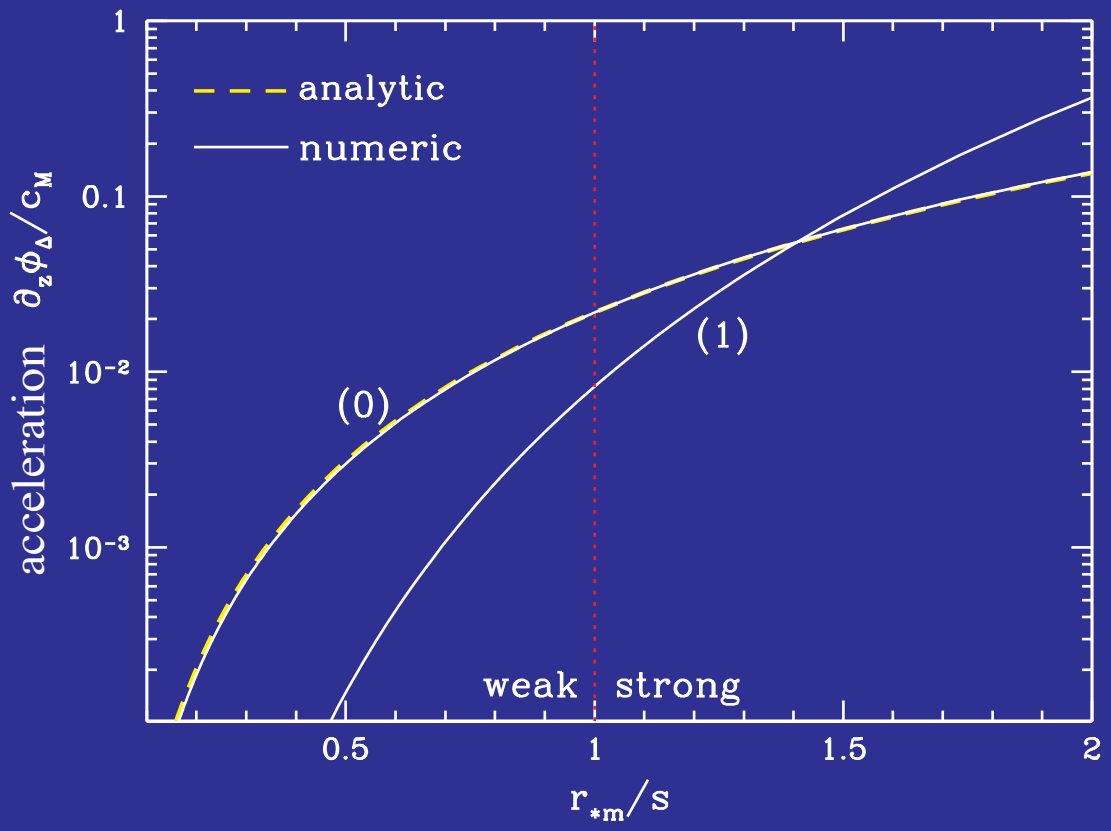
- Modification to gravitational potential saturates at the Vainshtein radius $\sim(GMr_c^2)^{1/3}$



Weak Vainshtein Screening

- Screening occurs when objects are separated by a Vainshtein radius
- Vainshtein radius depends on mass $m^{1/3}$
- Halos in compensated voids experience acceleration toward the center proportional to m

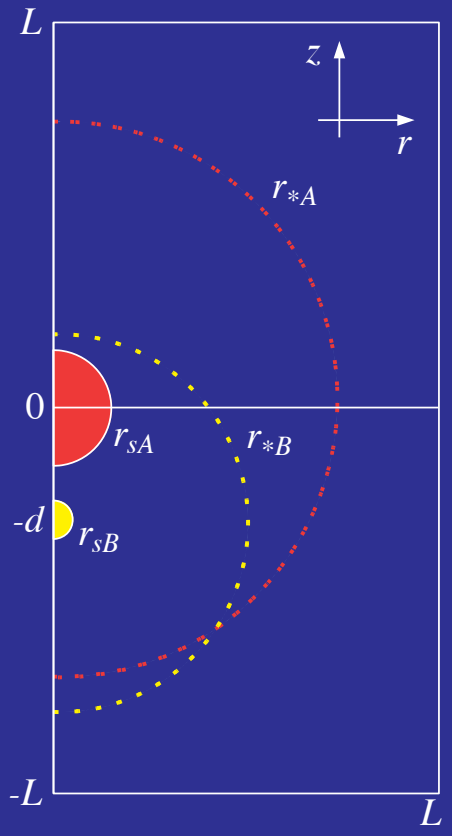


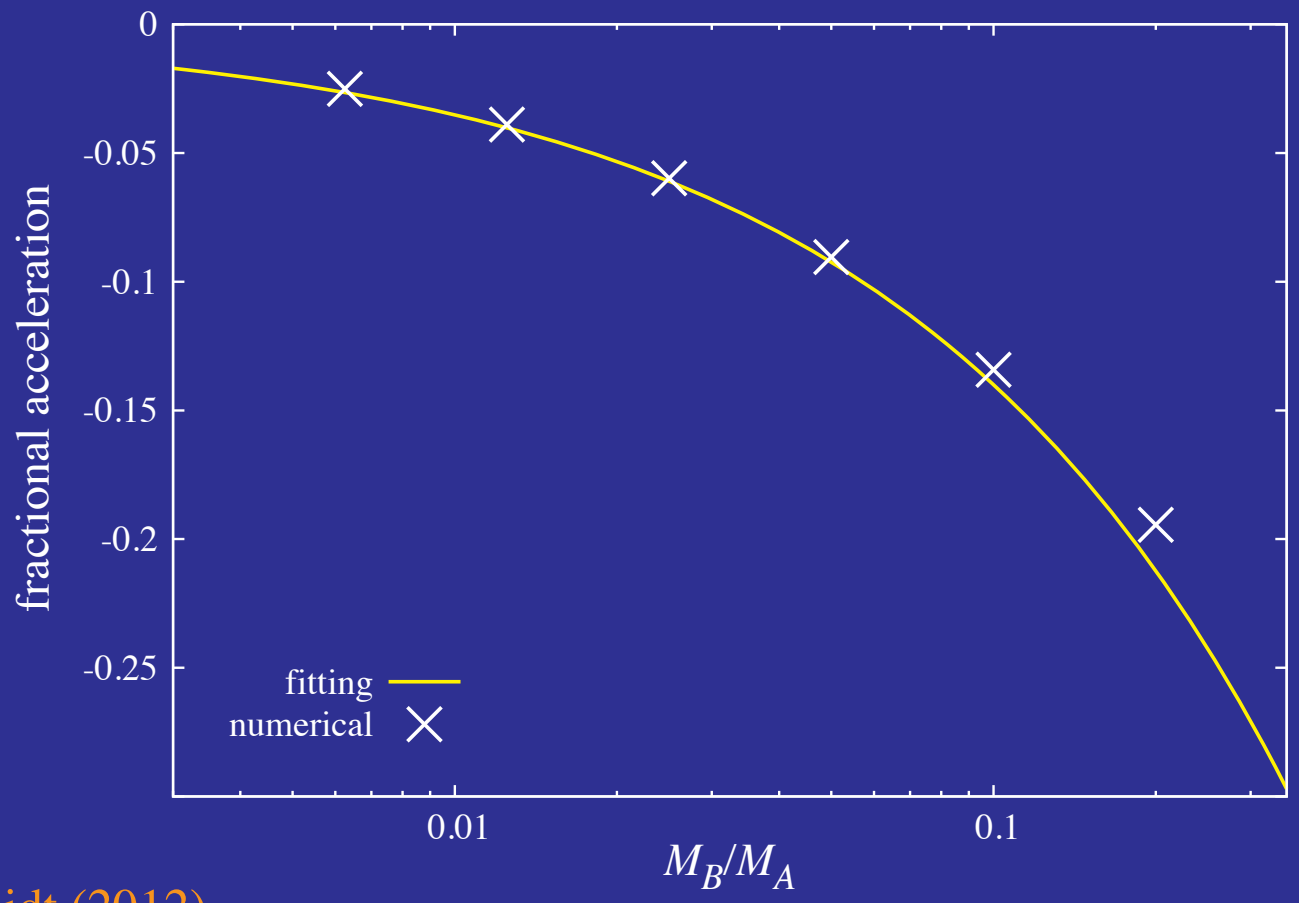


Belikov & Hu (2012)

Strong Vainshtein Screening

- Objects separated by much less than Vainshtein radius
- Screened acceleration also mass dependent due to nonlinearity
- Universal precession rate is not universal: corrections scale as $(M_B/M_A)^{3/5}$

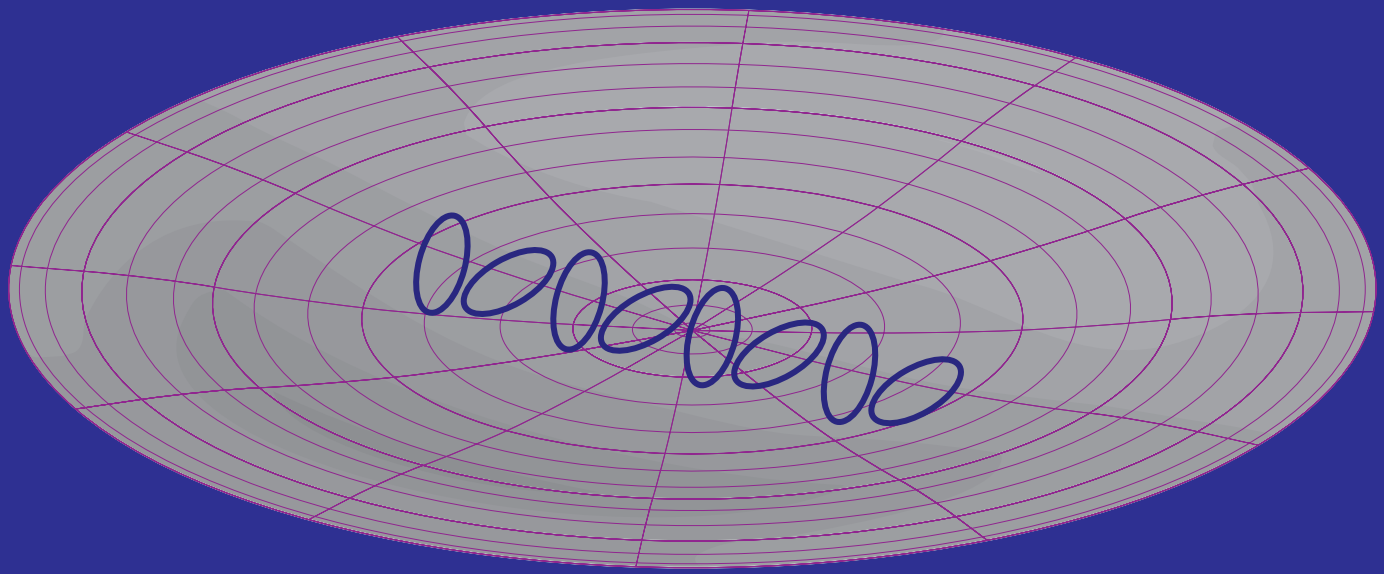




Hiramatsu, Hu, Koyama, Schmidt (2012)

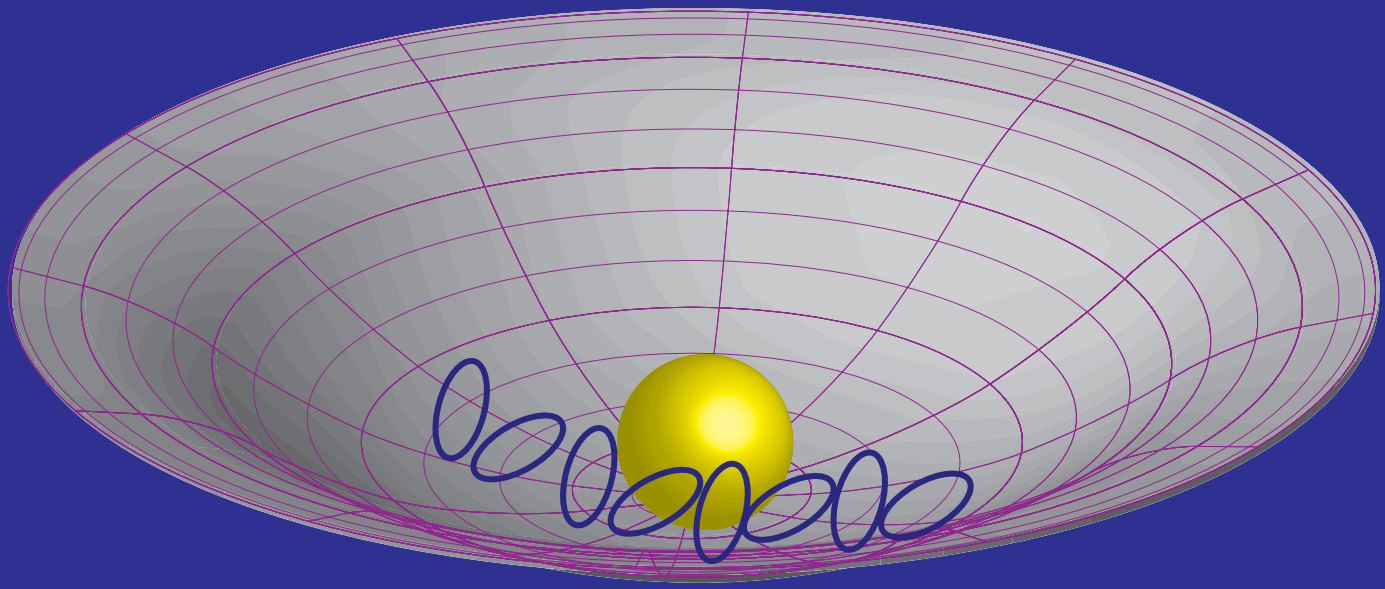
Massive Gravity

- Fierz-Pauli theory of linearized ghost-free massive gravity propagates 5 polarization states
- vDVZ discontinuity even as *m* goes to zero
- Mediates a 5th force in solar system Φ,Ψ test



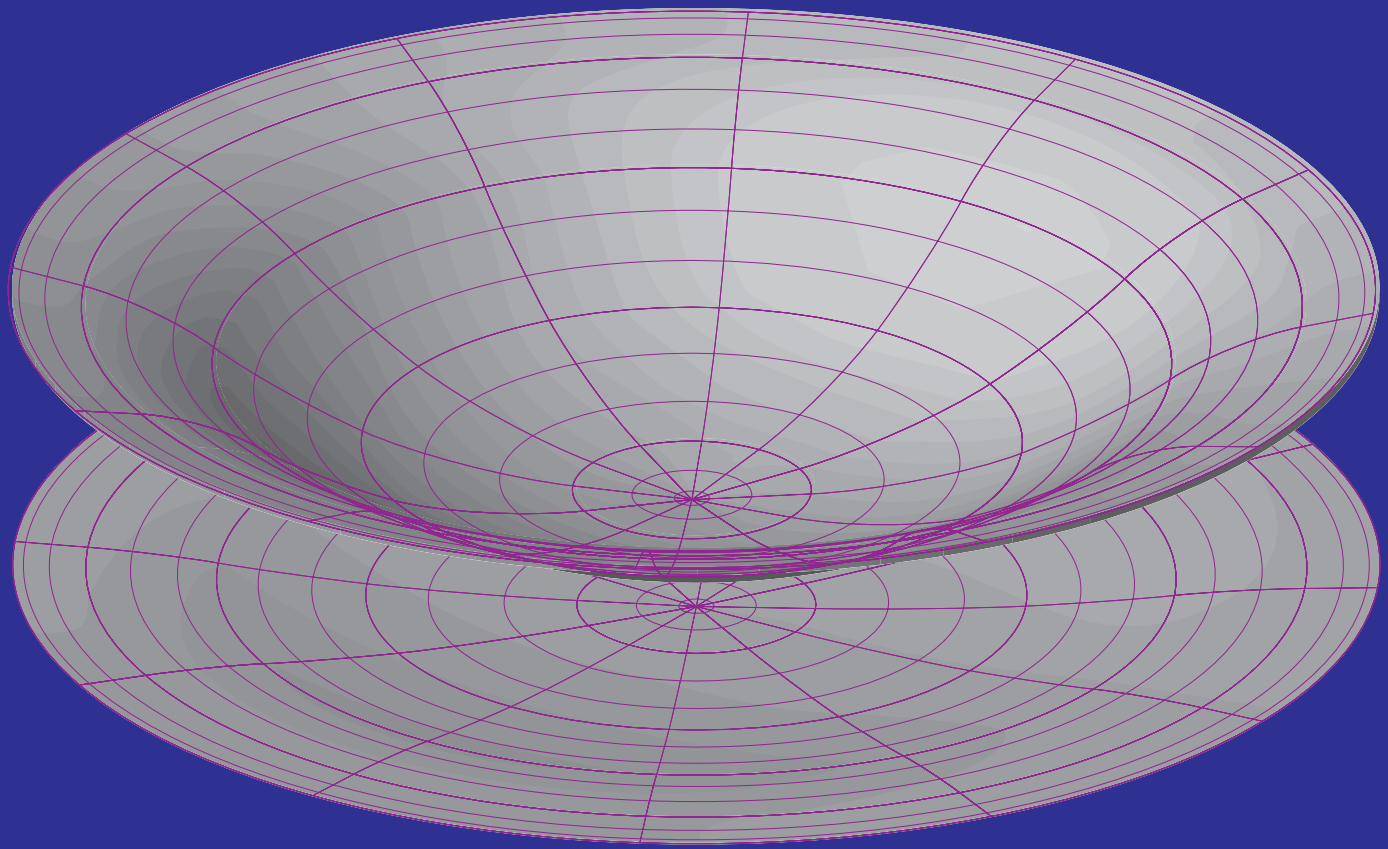
Massive Gravity

- Vainshtein showed that linear theory breaks down around massive bodies leading to screening of 5th force
- But for generic non-linear completions, the Boulware-Deser ghost returns



Massive Gravity

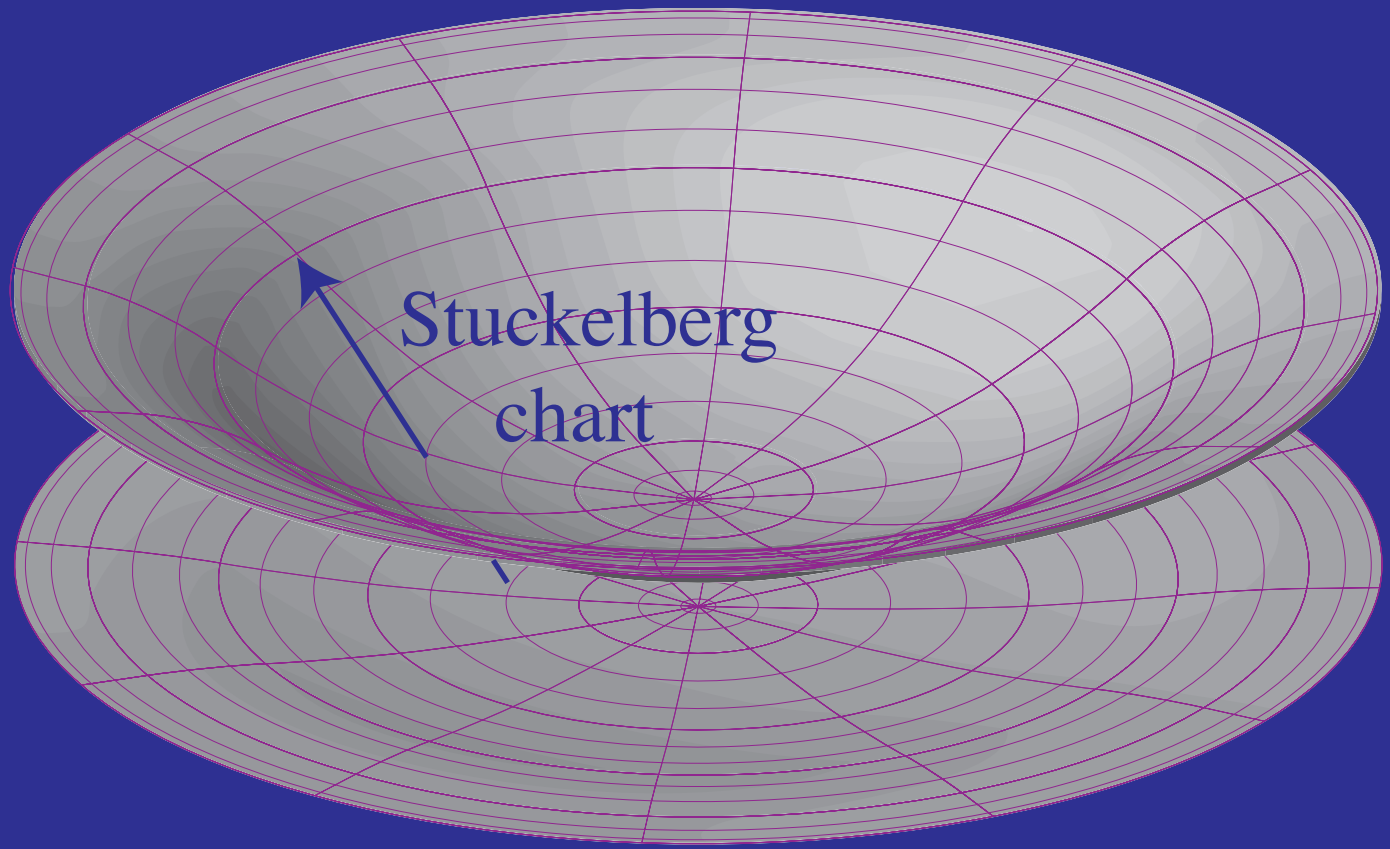
- de Rham, Gabadadze, Tolley (following Arkani-Hamed et al) constructed ghost-free effective theory
- Two metrics, spacetime metric + flat reference metric; breaks diffeomorphism (coordinate) invariance



Unitary gauge: only 1 coordinate system where reference metric standard Minkowski

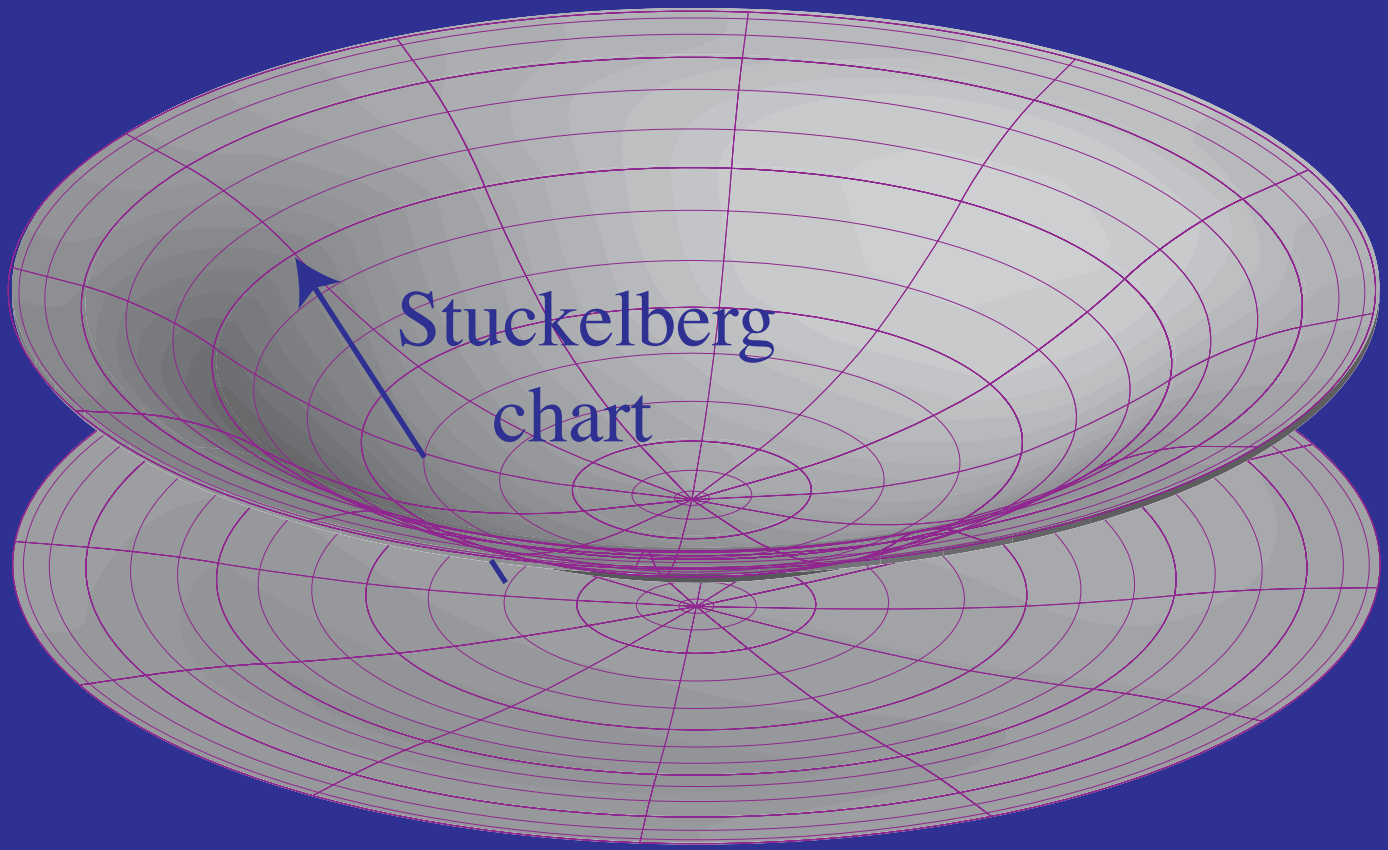
Massive Gravity

- Self-accelerates for any isotropic distribution of matter including FRW
  Koyama et al (2011); Gratia, Hu, Wyman (2012)
- Matter minimally coupled, Stuckelberg stable classically to radial perturbations Wyman, Hu, Gratia, (2012)



Massive Gravity

- Problems in having two metrics: stability to co-isotropy assumption
  Koyama et al (2012); Mukohyama et al (2012)
- Singularities from new spacetime scalars built from two metrics which persist even in bigravity generalization Gratia, Hu, Wyman (2013a,b)



dynamically evolve to no 1 to 1 map: singularity in determinant ratio

Summary

- ΛCDM alive and well but with possibly worrying growth on the "C" side (but the "A"(strophysics)-word)
- Formal equivalence between dark energy and modified gravity
- Practical inequivalence of smooth dark energy and extra propagating scalar fifth force
- Appears as difference between dynamical mass and lensing mass or dark energy anisotropic stress
- Smooth dark energy (e.g. quintessence) highly falsifiable
- Three regimes of modified gravity
- Nonlinear screening in field equations return to ordinary gravity

  Chameleon/symmetron: deep potential well

  Vainshtein: high local density

  manifest in the $f(R)$ model and DGP/galileon/massive gravity

Extras

Parameterized Post-Friedmann Approach(es)

- Parameterize cosmic acceleration sector, or whole dark sector, e.g. Hu (1998), with conserved effective stress tensor
- Equivalent to assigning equations of state for fluctuations
- Balance simplicity/efficiency with generality
- Linear regime: covariantly describe horizon and quasistatic Newtonian limits

  Anisotropic stress (slip) and effective density (Newton constant)

  Caldwell et al (1997); Hu & Sawicki (1997); Amendola et al (1997); ...

  General stress tensor Baker et al (2012); EFT Bloomfield et al (2012); EOS Battye & Pearson (2013) but massive gravity: aniso/inhom eos: Wyman, Hu, Gratia 2012
- Non-linear regime: screening mechanisms - Chameleon, symmetron, Vainstein Hu & Sawicki (1997); Li & Hu (2011); Brax et al (2012)

Massive Gravity

- DGP model motivated re-examination of massive gravity models
- Nonlinearly complete Fierz-Pauli action: Vainshtein strong coupling (restoring vDVZ continuity), no Boulware Deser ghost, effective theory out to Λ_3 Arkani-Hamed, Georgi, Schwartz (2003)
- Massive gravity action [de Rham, Gabadadze, Tolley et al, Hassan & Rosen, ... (2010-2012)]

$$S = \frac{M_p}{2}\int d^4x\sqrt{-g}\left[R - \frac{m^2}{4}\sum_{n=0}^{4}\beta_n S_n(\sqrt{\mathbf{g}^{-1}\boldsymbol{\eta}})\right]$$

where $\boldsymbol{\eta}$ is a fiducial (Minkowski) metric

- Diffeomorphism invariance can be restored by introducing Stückelberg fields (aka vierbeins of fiducial metric)

$$\mathbf{g}^{-1}\boldsymbol{\eta} \to \mathbf{g}^{-1}\mathbf{f} = g^{\mu\nu}\partial_\mu\phi^a\partial_\nu\phi^b\eta_{ab}$$

which carry transformation from unitary to arbitrary gauge

Self Acceleration

- Graviton mass $\sim H_0$ provides self-acceleration
- Generalizing results de Rham et al, Koyama et al, Mukohyama et al... for any isotropic matter a cosmological constant stress-energy is an exact solution Gratia, Hu, Wyman (2012); Volkov (2012)

$$\rho_m = -p_m = \frac{m^2 M_p^2}{2} P_0$$

  where P_0 constant given α_n
- Cosmic acceleration if $m \sim H_0$, remains constant for arbitrarily large radial matter perturbations
- Stückelberg fields are inhomogeneous in isotropic coordinates d'Amico et al (2011) - flat fiducial metric is not Minkwoski in FRW coordinates
- Stress-energy depends only on spatial Stückelberg fields, leaving a set of solutions that differ in ϕ_0 or the choice of unitary time

Self Acceleration

- Self-accelerating solution approached from arbitrary initial conditions? classically and quantum-mechanically stable?
- Field fluctuations again decouple with spatial Stückelberg field obeying first order closed equation
- Stable to radial field perturbations Wyman, Hu, Gratia (2012)

$$\delta p/\delta\rho = a\ddot{a}/3\dot{a}^2$$

e.g. de Sitter $\delta p/\delta\rho = 1/3$ - but eos generally anisotropic

- Stückelberg dynamics determined by unitary time: special cases with no dynamics, no stress energy perturbations Gumrukcuoglu et al
- Stability to anisotropic perturbations and higher order terms in action? Koyama et al; de Felice et al; d'Amico; Khosravi et al
- Effective theory to 1000km in vacuum, on earth 1cm or 1km? Burrage, Kaloper, Padilla (2012)

Singularities

- Massive gravity is bimetric theory, second metric dynamical or not
- Offers new opportunities for singularities - coordinate singularities in GR can become physical, removing in one not both
- Some static black hole solutions unphysical (reachable by dynamics?) Gruzinov & Mirbabayi (2011); Deffayet & Jacobson (2011); Nieuwenhuizen (2011); Volkov (2013) if metrics are simultaneously diagonal
- Simple example: determinant singularity dynamically generated in a recollapsing open universe Gratia, Hu, Wyman (2013a)

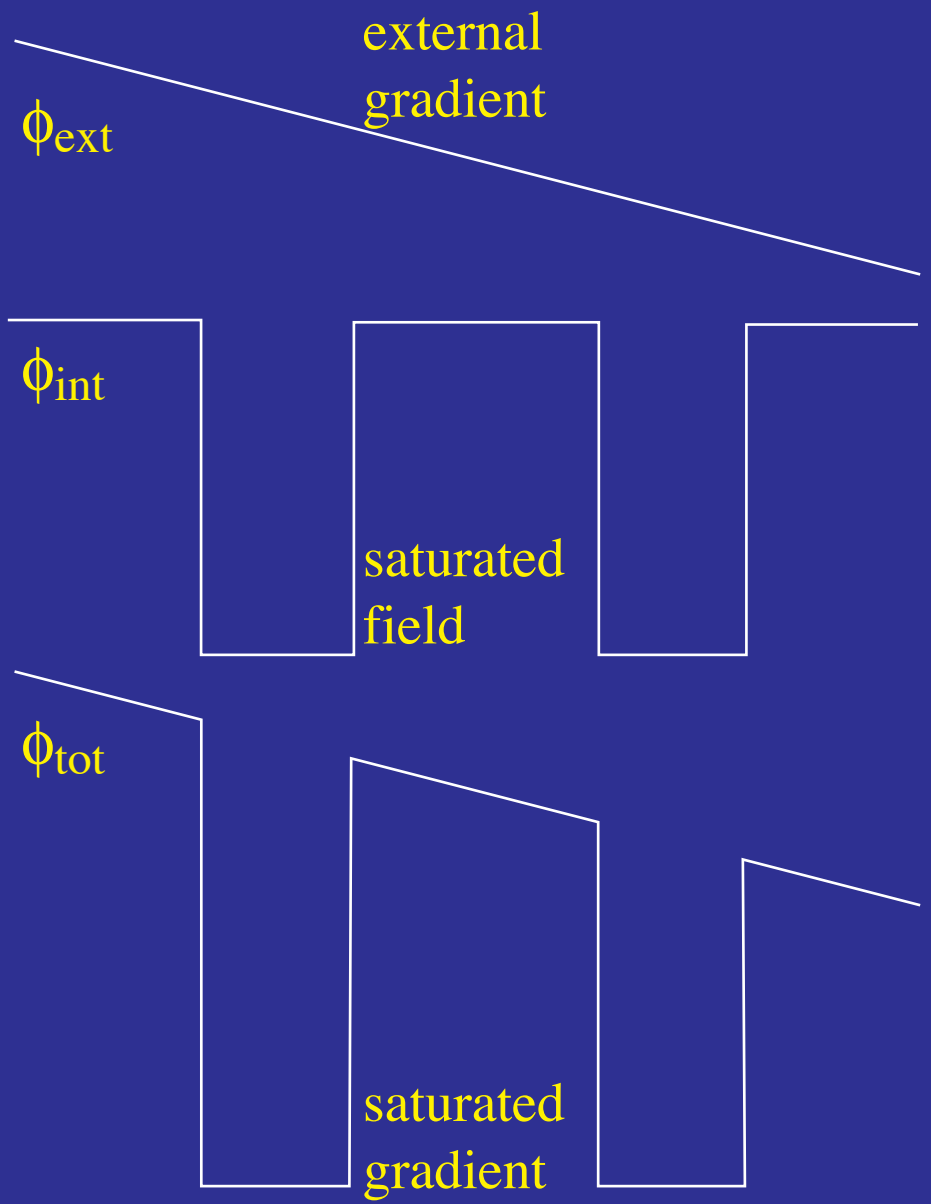
  Coordinates where fiducial metric is flat has $\tilde{t} \propto a$ - transformation singular at $\dot{a} = 0$

  Singularity in $\mathbf{g}^{-1}\mathbf{f}$ is coordinate invariant

  Non-dynamical $\mathbf{f}$ theory undefined here, non-positive definite solution continuous
- Determinant singularity persists even if $\mathbf{f}$ dynamical with two Einstein-Hilbert actions Gratia, Hu, Wyman (2013b)

Motion: Environment & Object

- Self-field of a "test mass" can saturate an external field (for $f(R)$ in the gradient, for DGP in the second derivatives)



Hui, Nicolis, Stubbs (2009)
Jain & Vanderplas (2011)
Zhao, Li, Koyama (2011)