Dark Energy

massive gravity

quintessence

k-essence

barotropic fluids

modified gravity

Theory

coupled quintessence

frustrated defects

Wayne Hu

SUSY, August 2011

Outline

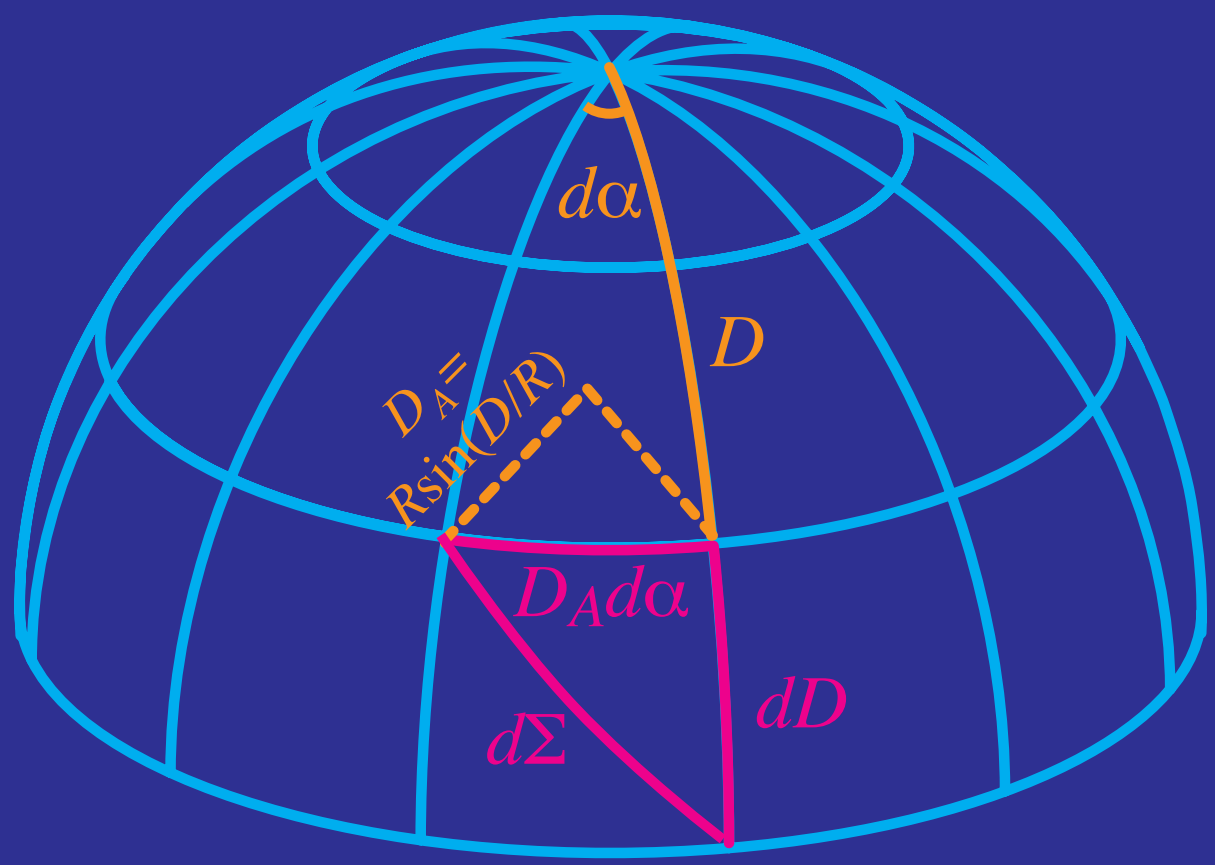
- Accelerating expansion history
- Dark energy phenomenology
- Cosmological constant
- Quintessence
- Couplings, modified forces
- Modified gravity

Homogeneity & Isotropy

- Homogeneity and isotropy $\rightarrow$ FRW line element

$$ds^2 = -dt^2 + a^2(t)\left[dD^2 + D_A^2 d\alpha^2\right]$$

$$d\alpha^2 = d\theta^2 + \sin^2\theta d\phi^2$$



Distance-Redshift

- Photons travel on null-geodesics

$$D = \int \frac{dt}{a} = \int \frac{da}{aH} = \int \frac{dz}{H}$$

where the expansion rate $H = \dot{a}/a$ and redshift $(1+z) = a^{-1}$

- Given a measure of distance D (which measures time t)

  to an object at redshift z (which measures size a)

  infer the expansion history of universe $a(t)$

Acceleration

- Relative distance between high and low z supernovae are further $H_0 D = \int dz (H_0/H)$ than expected in a matter only universe $\rightarrow$ expansion rate

  does not increase with redshift

  does not decrease with expansion a

  as quickly

- If expansion rate drops with a as $H \propto a^{-3(1+w)/2}$ then

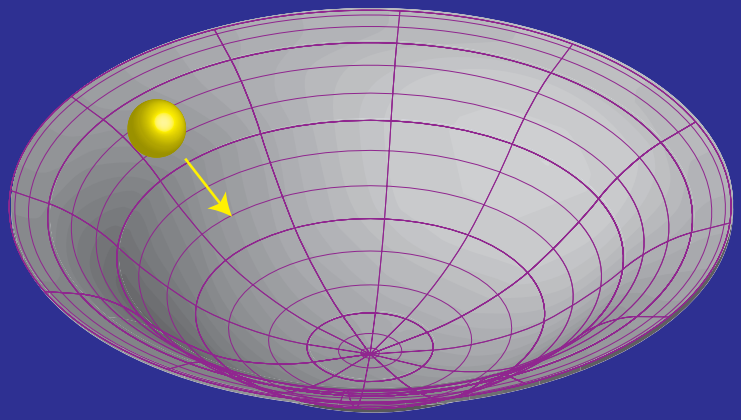
$$\frac{\ddot{a}}{a} \propto -(1+3w)a^{-3(1+w)}$$

  acceleration if $w < -1/3$ or expansion rate falls slower than $H \propto a^{-1}$

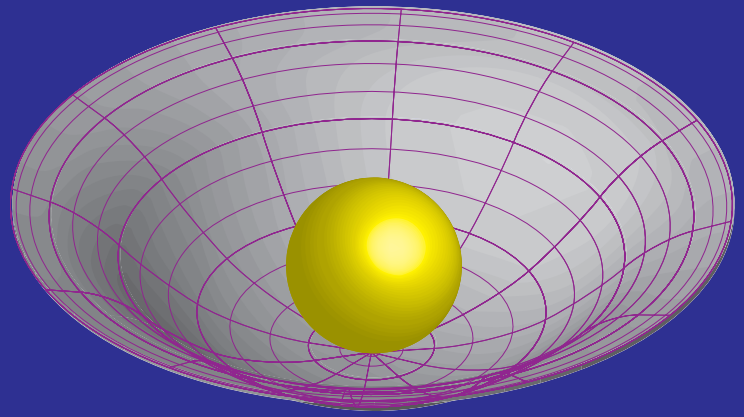
- Purely geometric so far, inference about missing dark energy requires Friedmann equation (Einstein equations)

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?

Dark Energy

- Under the Einstein equations

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

and the FRW metric, 00 and ii give the Friedmann equations

$$H^2 = \frac{8\pi G}{3}(\bar{\rho} + \rho_K)$$
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\bar{\rho} + 3\bar{p})$$

where $\bar{\rho}$ and $\bar{p}$ are the average energy density and pressure and are the only things allowed in $T_{\mu\nu}$ by symmetry

- The index $w = \bar{p}/\bar{\rho}$ is known as the equation of state parameter

$w \neq$ Equation of State

- $w = \bar{p}/\bar{\rho}$ is a relationship between average energy density and pressure not local energy density and pressure
- Consider a barotropic fluid $p(\rho)$

$$\bar{p} = w\bar{\rho} \rightarrow \nabla p = w \nabla \rho$$

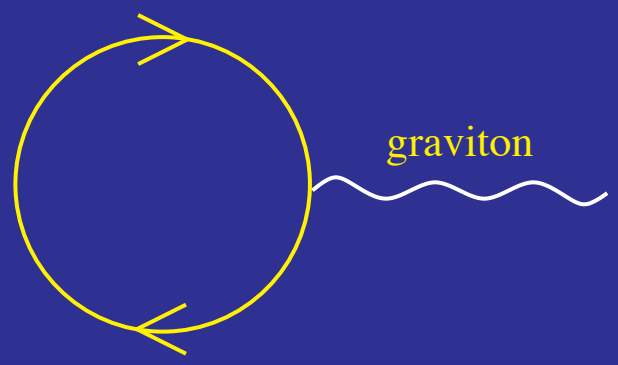
  which for $0 < w < -1$ is an imaginary sound speed and violently unstable
- The only baryotropic equation of state that is allowed and accelerates the expansion is

$$p(\rho) = f(\rho - \text{const}) - \text{const.}$$

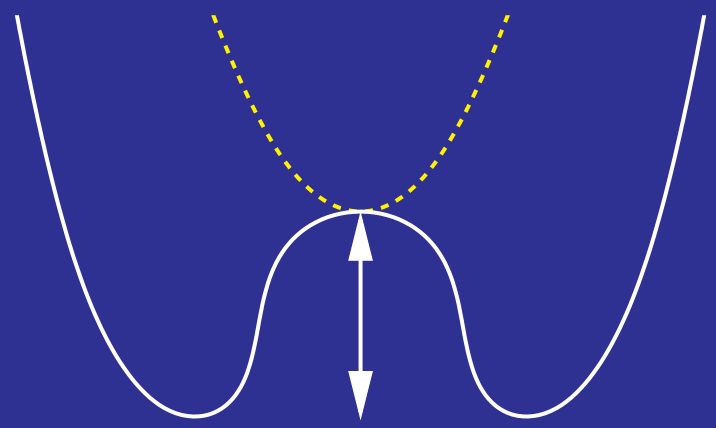
  with $f' > 0$ – "Chaplygyn gas" models RIP
- Even more generally beyond $p(\rho)$: one non-dynamical dominant piece, zero or more subdominant dynamical piece

Cosmological Constant

- Simplest possibility, consistent with all data to date, is a constant: Einstein's Cosmological Constant
- Particle physics provides sources for such a constant



Zero Point Energy



Phase Transitions

- But the energy scales associated with particle physics scale cutoffs and transitions give energy densities ($\rho \sim E^4$) at least ~60 orders of magnitude too large
- For a bare CC to cancel these contributions would seem to require exquisite fine tuning

String Landscape?

- String landscape provides ~10^{500} metastable vacua
  [Kachru, Kallosh, Linde, and Trivedi 2003]
- At some of these, this cancellation is achieved [so if they can be populated and selected anthropically...]

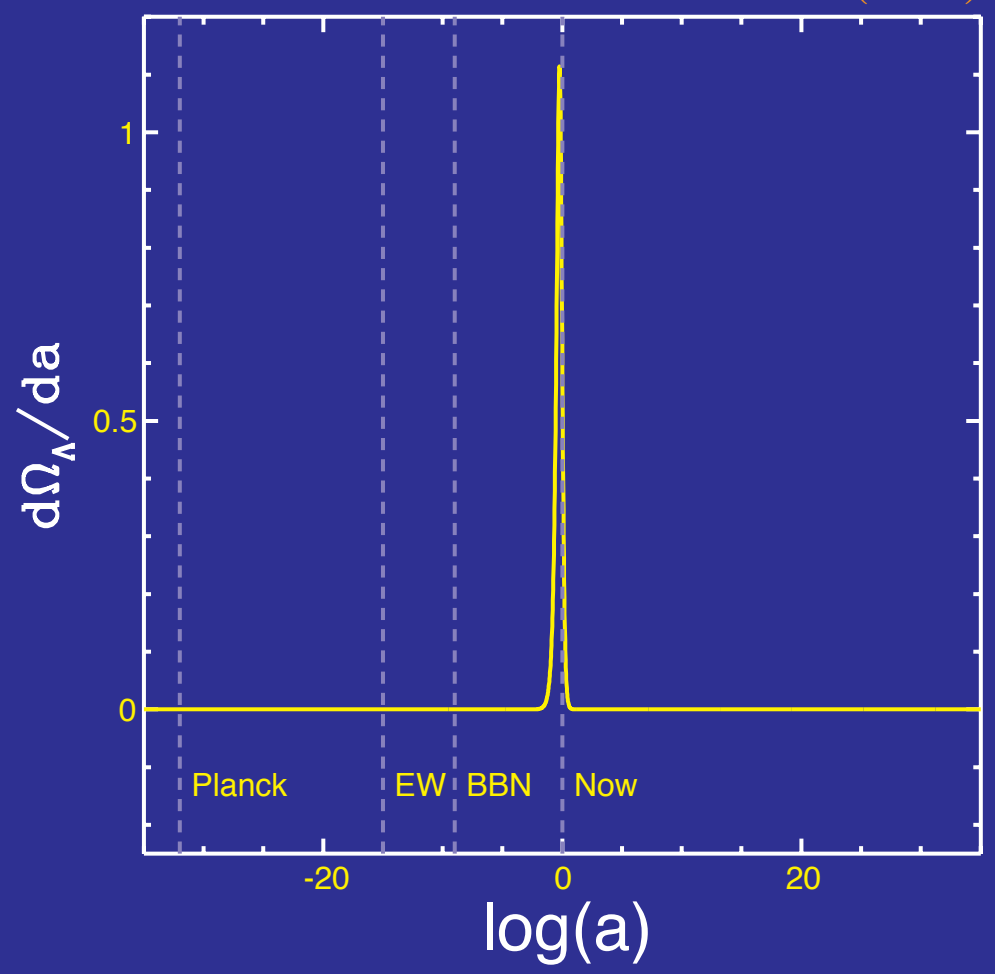
String Landscape?

- String landscape provides ~10^{500} metastable vacua
  [Kachru, Kallosh, Linde, and Trivedi 2003]
- Meets some resistance from people with flat backgrounds who think landscapes are artificial!

Coincidence

- Anthropic arguments attempt to address coincidence problem:
  matter/radiation dilutes with expansion
  dark energy constant or slowly diluting
  only comparable today

Carroll (2001)



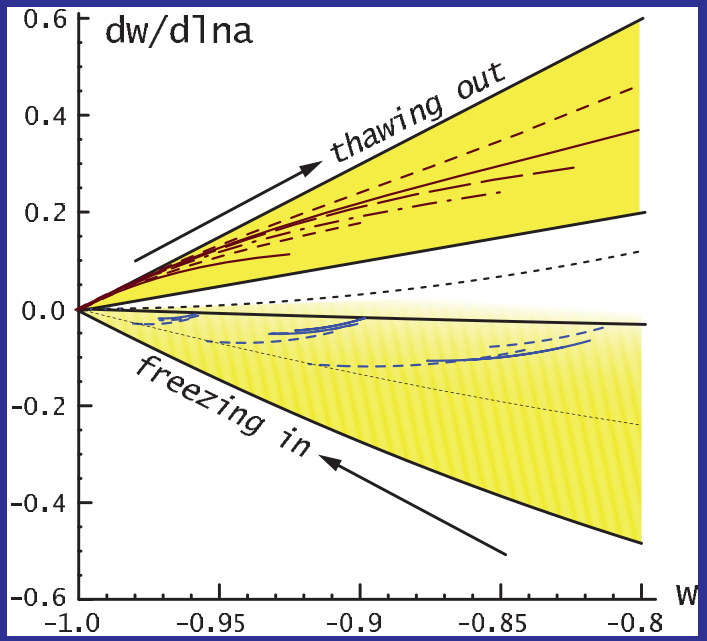
Quintessence

- Perhaps the true cosmological constant is zero and we are rolling in a (very!) flat direction of a landscape like inflation
  [but what protects a $m \sim H_0 \sim 10^{-33}$eV mass and small couplings?]

Quintessence

- Perhaps the true cosmological constant is zero and we are rolling in a (very!) flat direction of a landscape like inflation
  [but what protects a $m \sim H_0 \sim 10^{-33}$eV mass and small couplings?]
- Two degrees of freedom:
  potential energy (driving acceleration)
  kinetic energy (associated with rolling)
  dynamical dark energy
- Typical models:
  thawing -
  frozen by Hubble drag,
  released to roll
  freezing
  rolling/tracking early
  on and slowing to potential domination
  [possibly trading coincidence with features in potential]

Caldwell & Linder (2005)



Beyond *w*

- Hallmark of cosmological constant / quintessence spatial smoothness relative to matter

  for quintessence, sound speed of kinetic contribution $c_S = 1$ - smooth inside the horizon

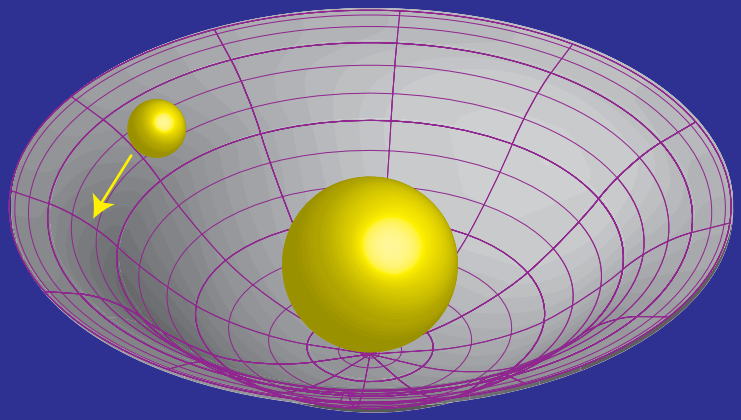
- Beyond a minimally coupled light scalar field: self-interactions, coupling to dark matter or baryons etc.
- From the matter standpoint these look like changes to the (gravitational) force law

- Currently, strongest evidence for acceleration is from expansion history

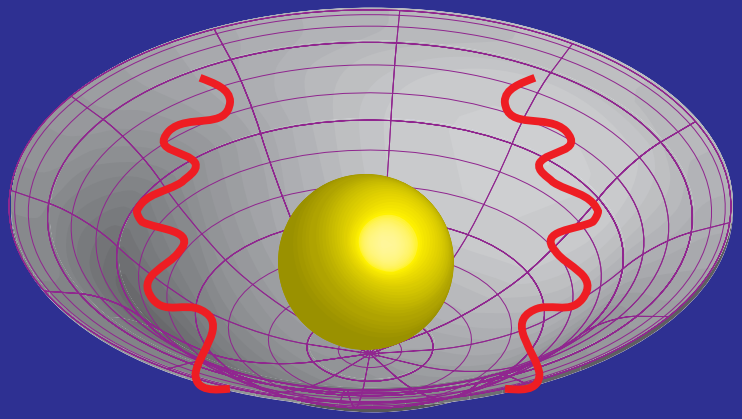
- Tests of growth of structure are starting to be incisive and can confirm or refute predictions of the paradigm

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



- Most of the incisive tests of gravity reduce to testing the space curvature per unit dynamical mass

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

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

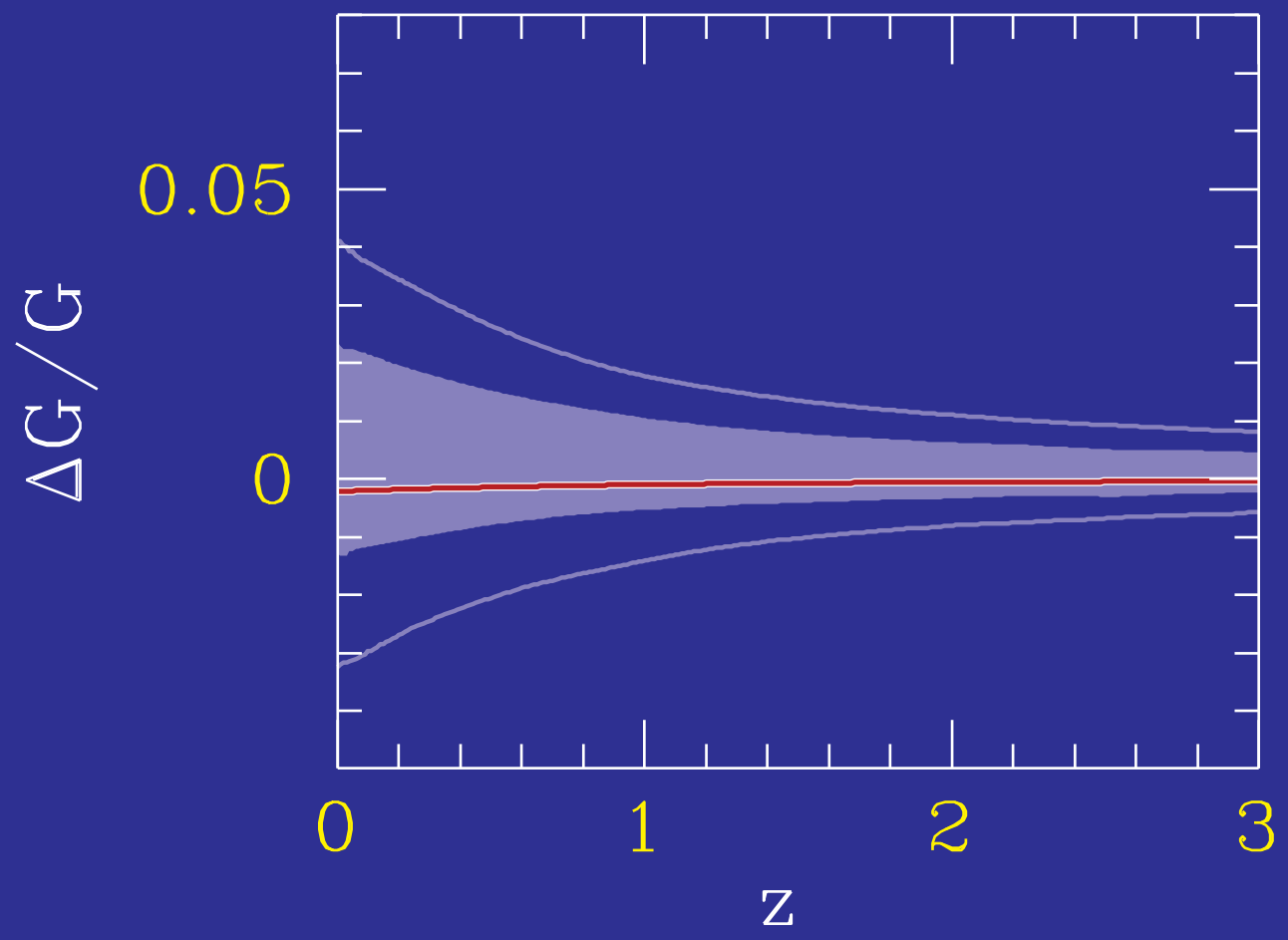
$$G_{\mu\nu} = 8\pi G [T^{\rm M}_{\mu\nu} + T^{\rm DE}_{\mu\nu}]$$

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

Falsifying ΛCDM

- Λ slows growth of structure in highly predictive way

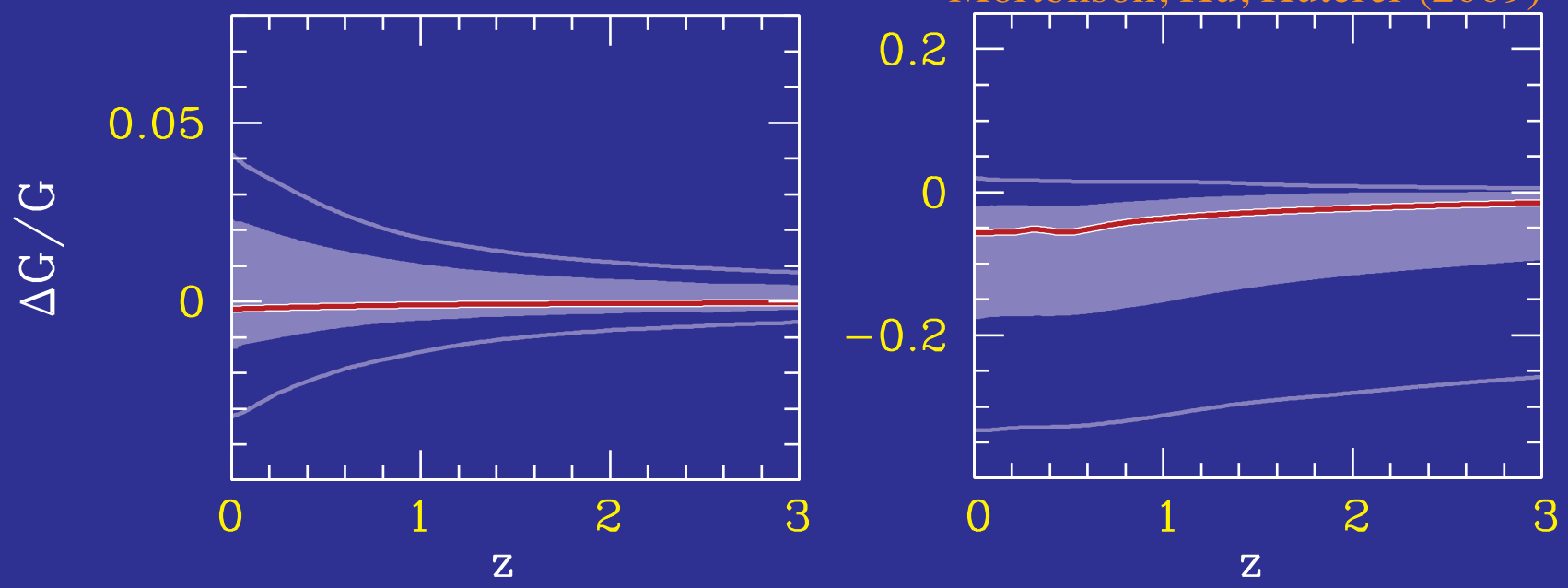


Cosmological Constant

Falsifying Quintessence

- Dark energy slows growth of structure in highly predictive way

Mortonson, Hu, Huterer (2009)



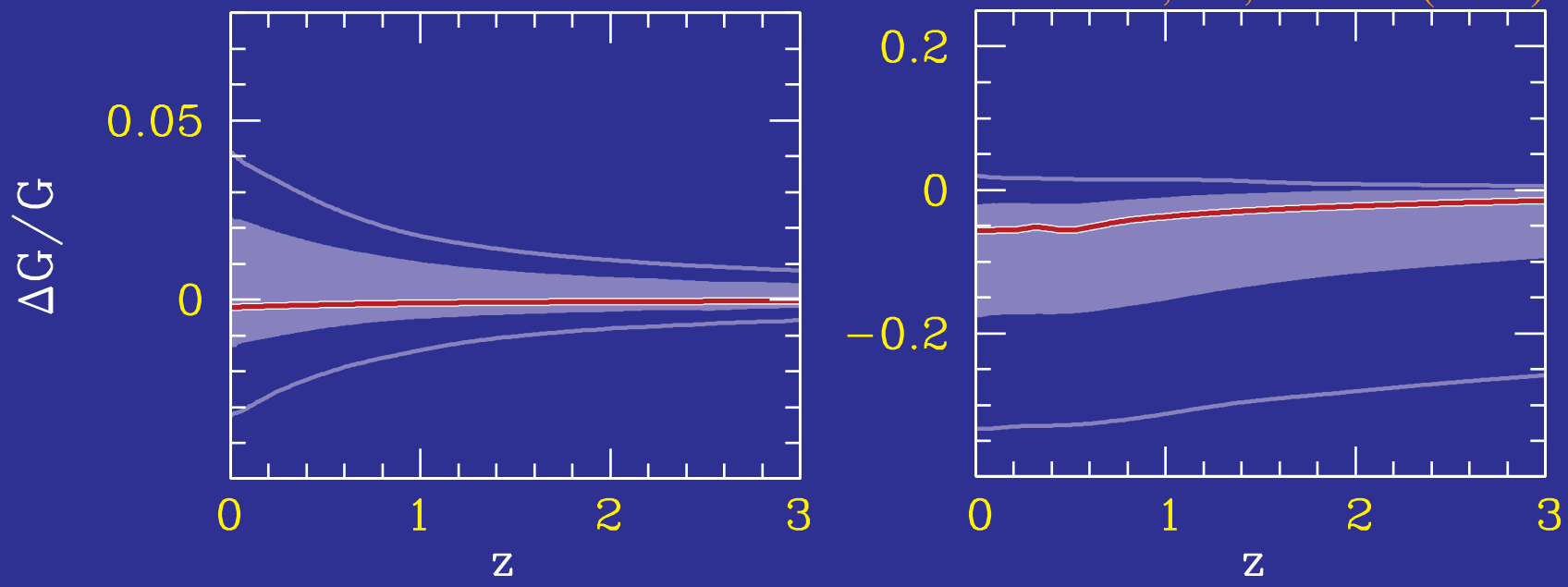
Cosmological Constant Quintessence

- 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]

Dynamical Tests of Acceleration

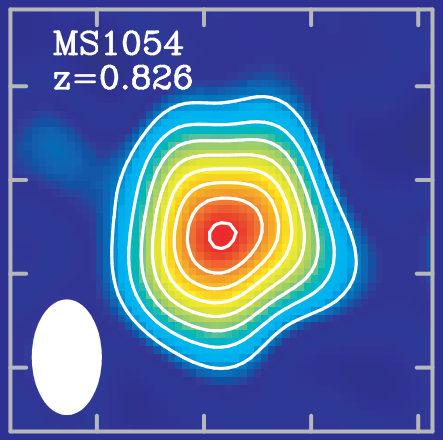
- Dark energy slows growth of structure in highly predictive way

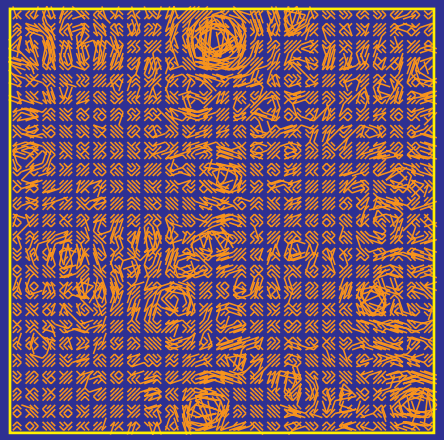
Mortonson, Hu, Huterer (2009)

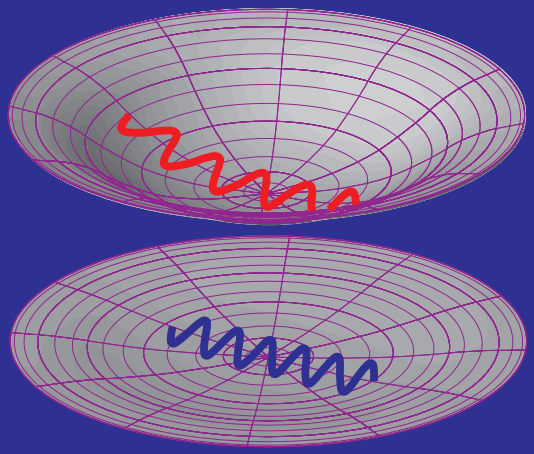


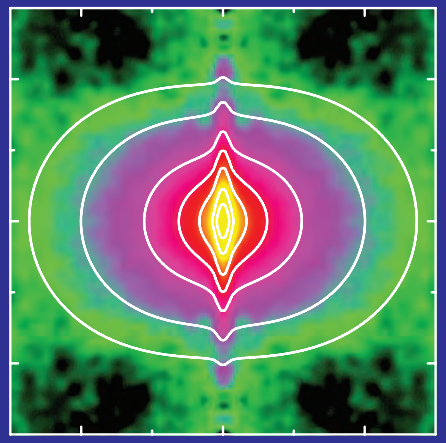
Cosmological Constant

Quintessence









Modified Forces

- Extra scalar propagating degree of freedom
- Cosmological IR modification hidden from local constraints on gravity and fifth forces $\rightarrow$ non-linear mechanism (strong interactions or changes in the potential or coupling)

  Chameleon mechanism (running mass or coupling)

  Vainshtein mechanism (strong coupling, derivative interactions)
- Concrete (but toy) models that exhibit these

  Modified Action $f(R)$

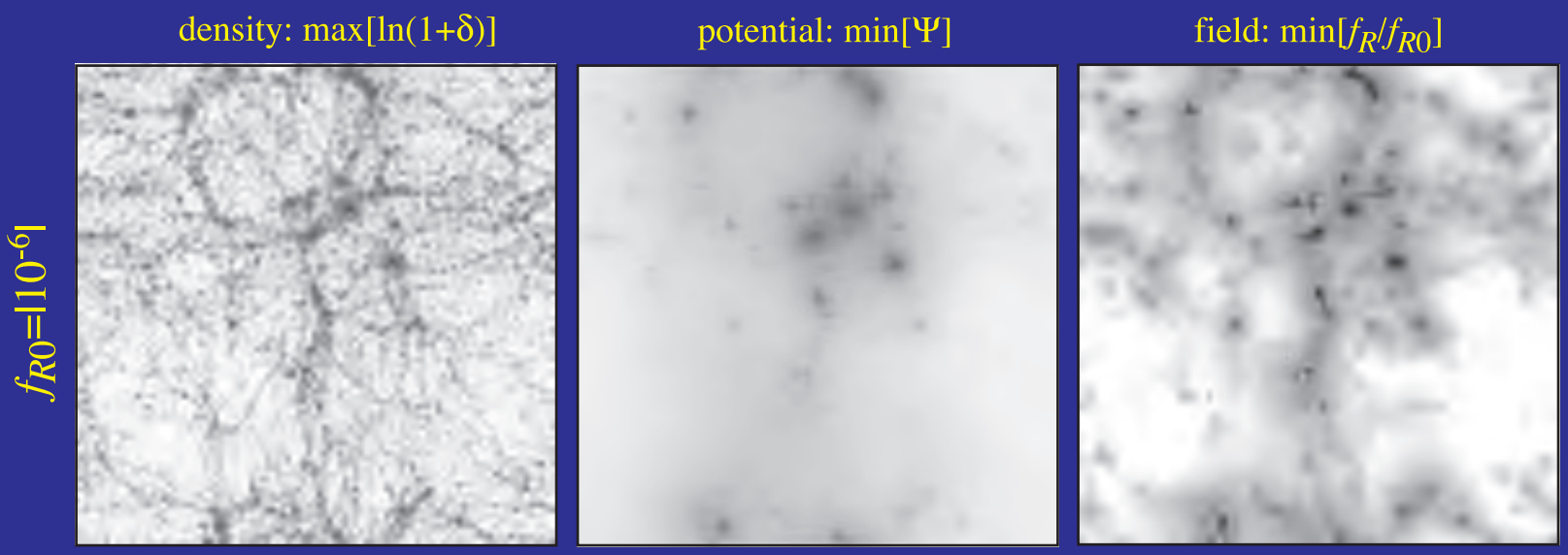
$$S = \int d^4x\sqrt{-g}\left[\frac{R + f(R)}{16\pi G} + \mathcal{L}_{\rm m}\right]$$

  Dvali-Gabadadze-Porrati (DPG) Braneworld

$$S = \int d^5x\,\sqrt{-g}\left[\frac{{}^{(5)}R}{2\kappa^2} + \delta(\chi)\left(\frac{{}^{(4)}R}{2\mu^2} + \mathcal{L}_m\right)\right]$$

Environment Dependent Force

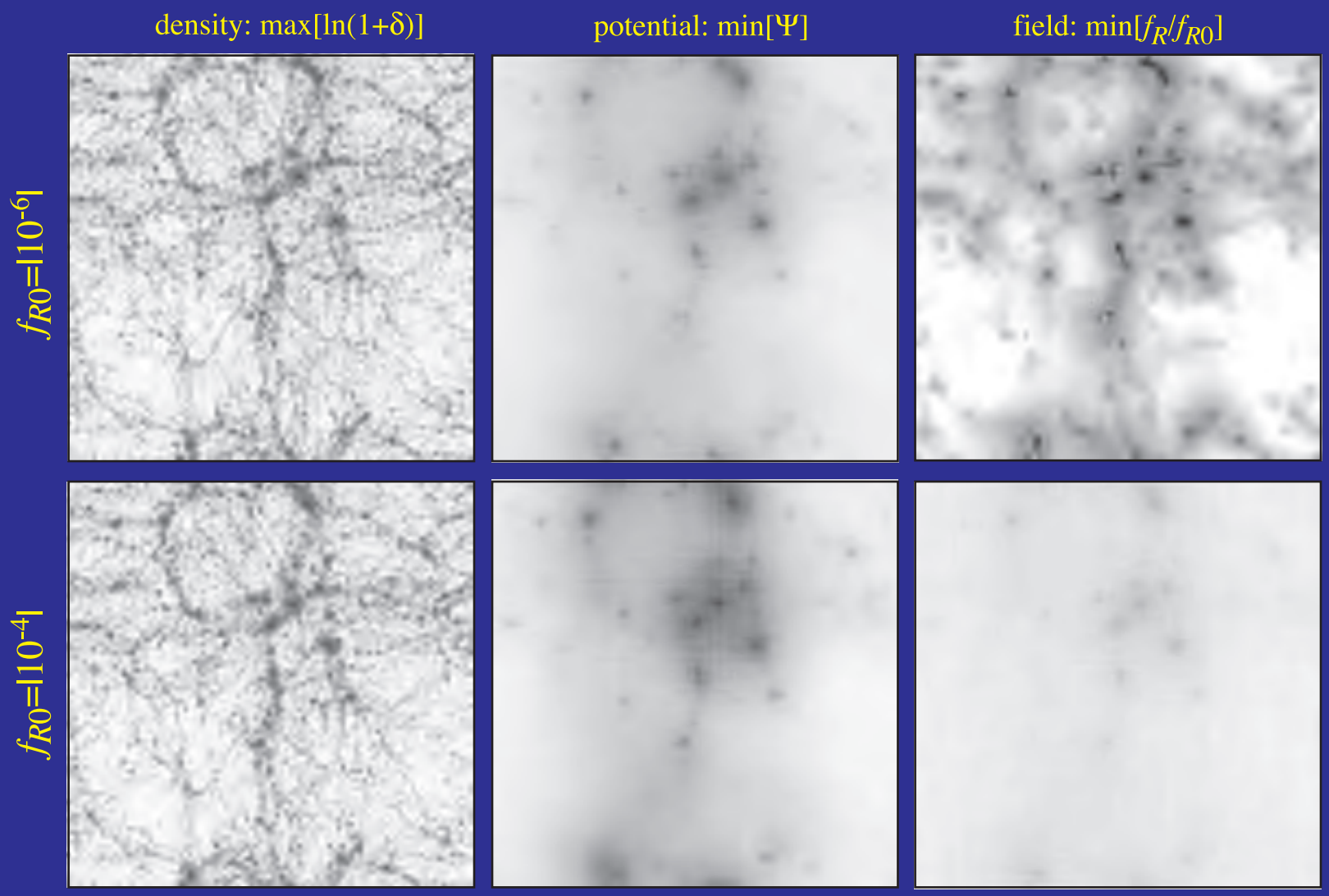
- Chameleon suppresses extra force (scalar field) in high density, deep potential regions



Oyaizu, Lima, Hu (2008)

Environment Dependent Force

- For large background field, gradients in the scalar prevent the chameleon from appearing



Oyaizu, Lima, Hu (2008)

Massive Gravity

- DGP model motivated re-examination of massive gravity models [de Rham, Gabadadze, et al, Koyama et al (2010-2011)]
- Graviton mass $\sim H_0$ provides self-acceleration

$$H^2 = m^2 + \frac{8\pi G}{3}\rho$$

  while also not seeing the cosmological constant contribution "degravitation"
- Key: add extra terms to the Fierz-Pauli action that make it non-linearly ghost free, exhibit Vainshtein coupling (Galileon symmetry, restoring vDVZ continuity)
- Much progress in the last year! stay tuned...

Summary

- Strong evidence for cosmic acceleration from distance-redshift or geometric probes
- Einstein/Friedmann equations imply negative pressure component $\bar{p}/\bar{\rho} < -1/3$
- Dark energy looks like const (+ small dynamical component) - must look phenomenologically like cosmological constant
- Why small but finite cosmological constant? string landscape?
- Quintessence: dynamics of minimally coupled, very light, slowly rolling scalar field
- Couplings $\rightarrow$ fifth forces, difficult to hide - Chameleon, Vainshtein
- Fifth forces subset of "modified gravity" explanations
- Recent progress on making massive gravity explain acceleration, cosmological constant problem...