Title: Leakage into extra dimensions and cosmic acceleration.

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Abstract:

Leakage into Extra Dimensions and Cosmic Acceleration:

Differentiating dark energy from modified gravity

Arthur Lue

University of Texas at San Antonio

The Contemporary Universe

- **The New York Times** (Nov 11, 2003)

Science Times 25TH ANNIVERSARY

1. Does science matter?
2. Is war our biological destiny?
3. Will humans ever visit Mars?
4. How does the brain work?

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The Contemporary Universe

- **The New York Times** (Nov 11, 2003)

What Is **Gravity**, Really?

By DENNIS OVERBYE

"Gravity . . . it's not just a good idea. It's the Law," reads a popular bumper sticker.

Gravity is our oldest and most familiar enemy, the force we feel in our bones, the force that will eventually bury us, sagging our organs and pulling us down, but for all its intimacy, it is a mystery. What really is the law?

For most of us it's the one that Isaac Newton proclaimed in 1687 as the rule of the cosmos, describing how (but not why) two objects attract each other with a force proportional to their masses and inversely proportional to the distance between them. But it's been rewritten and physicists expect that it will be rewritten again.

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Granger Collection

Isaac Newton proclaimed his law of gravity as the rule of the cosmos in 1687.

The Contemporary Universe

- **The New York Times** (Nov 11, 2003)

Will We Ever Find **Atlantis**?

By JOHN NOBLE WILFORD

Somewhere in the imagination, at an intersection of the idealized Golden Age and mankind's descent into manifest imperfection, existed the island civilization of Atlantis. This realm of divine origin was ruled from a splendid metropolis in the distant ocean. Its empire, described by a philosopher as "larger than Libya and Asia combined," enjoyed prosperity and great power.

In time, driven by overweening ambition, a common theme in antiquity and not unheard of today, Atlantis set out to conquer lands of the Mediterranean. But in a terrible day and night of floods and earthquakes, Atlantis was swallowed by the sea, sinking into legend.

The story endures as a classic in the genre of lost worlds long vanished, the ruins

The Contemporary Universe

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Granger Collection

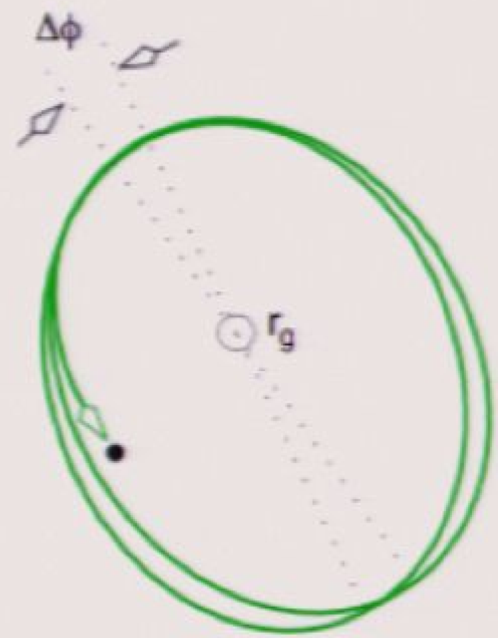
Isaac Newton proclaimed his law of gravity as the rule of the cosmos in 1687.

The Contemporary Universe

- **What do we know about gravity?**
  - Dramatic successes

Newton $r_g^{\odot} = 2GM_{\odot} = 2.95325008 \text{ km}$

$$\boxed{V_{\rm grav} = \frac{1}{2}(g_{00} - 1) = -\frac{r_g}{2r}}$$



Einstein $|\beta|,\ |\gamma| \lesssim 5 \times 10^{-4}$

$$\boxed{\frac{d}{dt}\Delta\phi_{\rm Mercury} = 430 \text{ mas/year}}$$

  - Intimate connection between matter, geometry and gravity

The Contemporary Universe

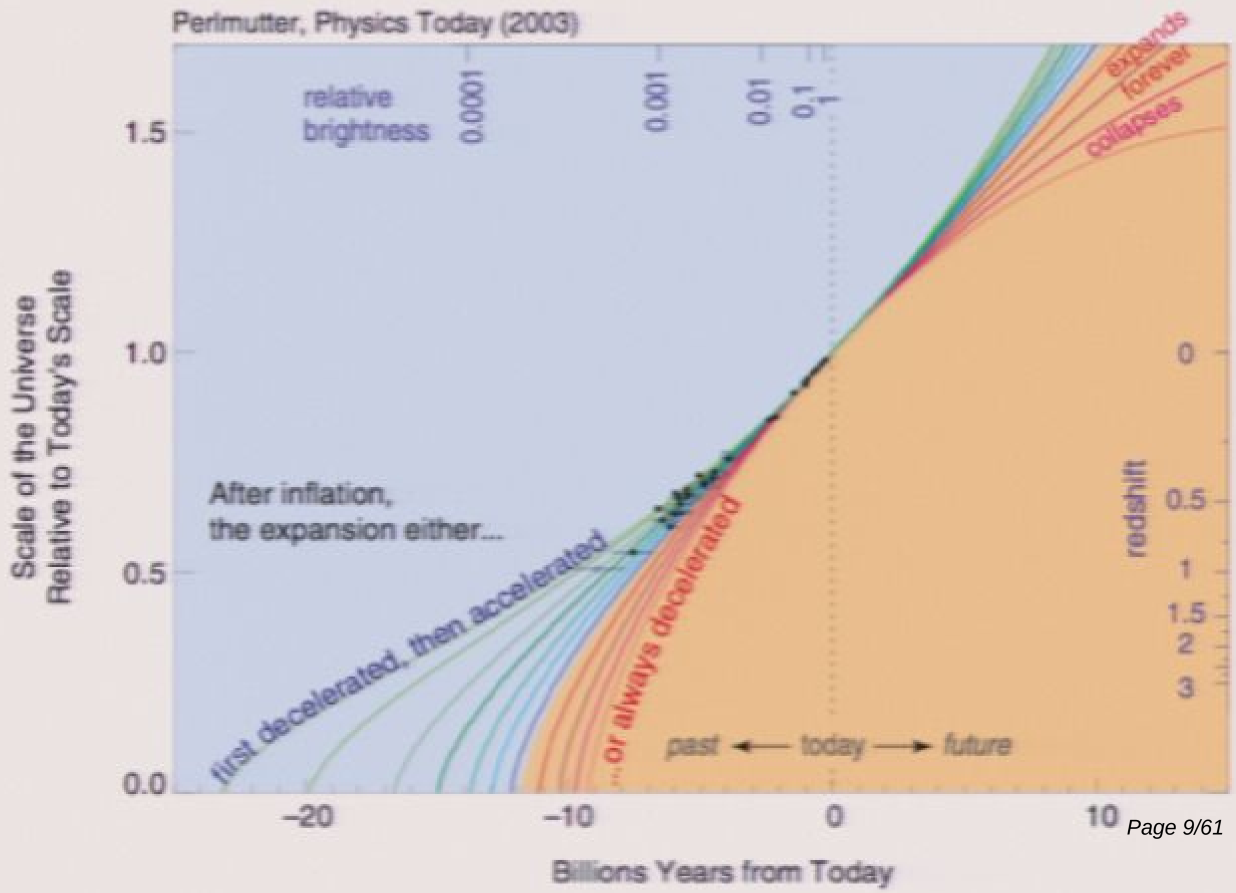
- **Hubble expansion and the Friedmann equation**

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

$$\boxed{H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\,\rho}$$

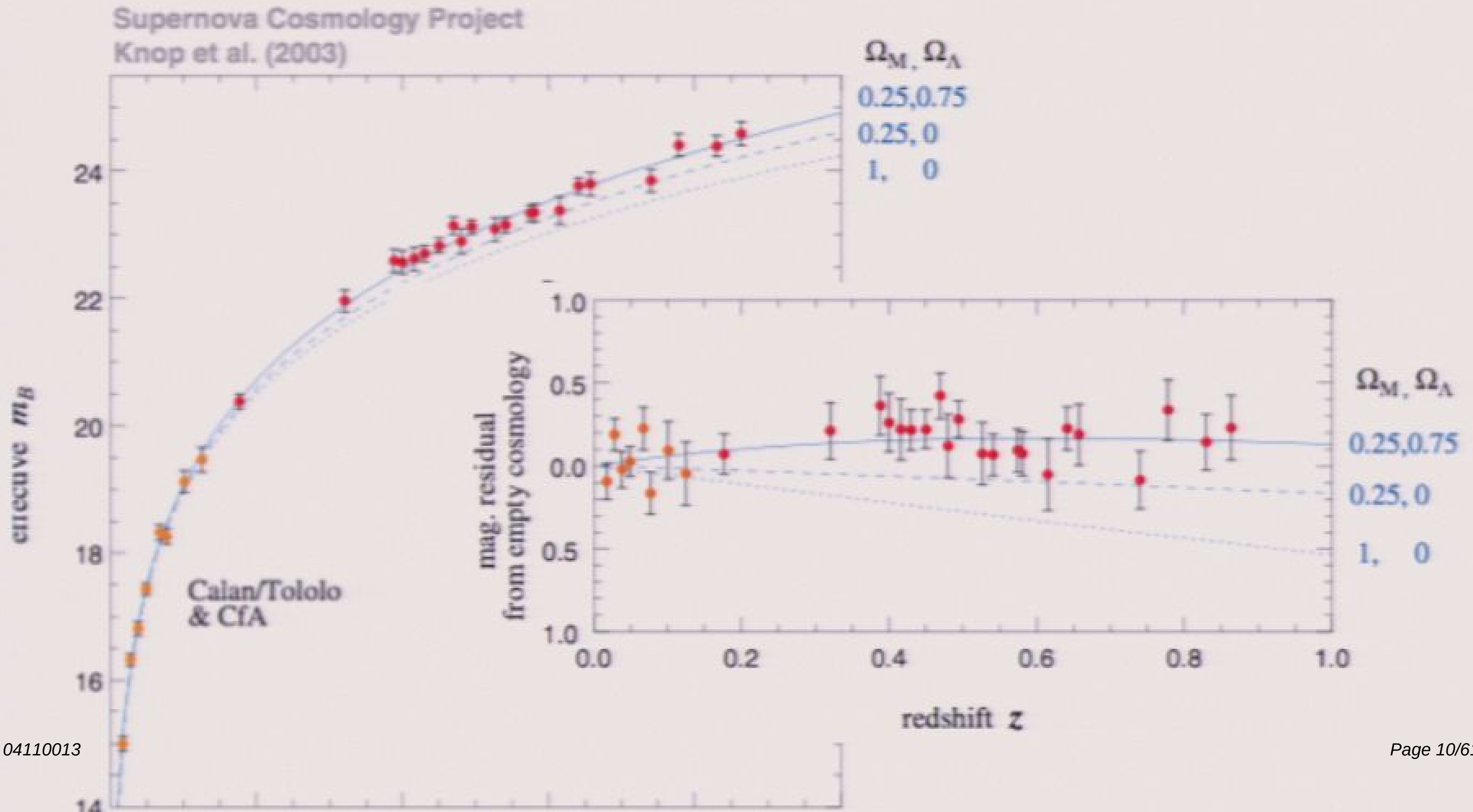
Expansion History of the Universe

Perlmutter, Physics Today (2003)



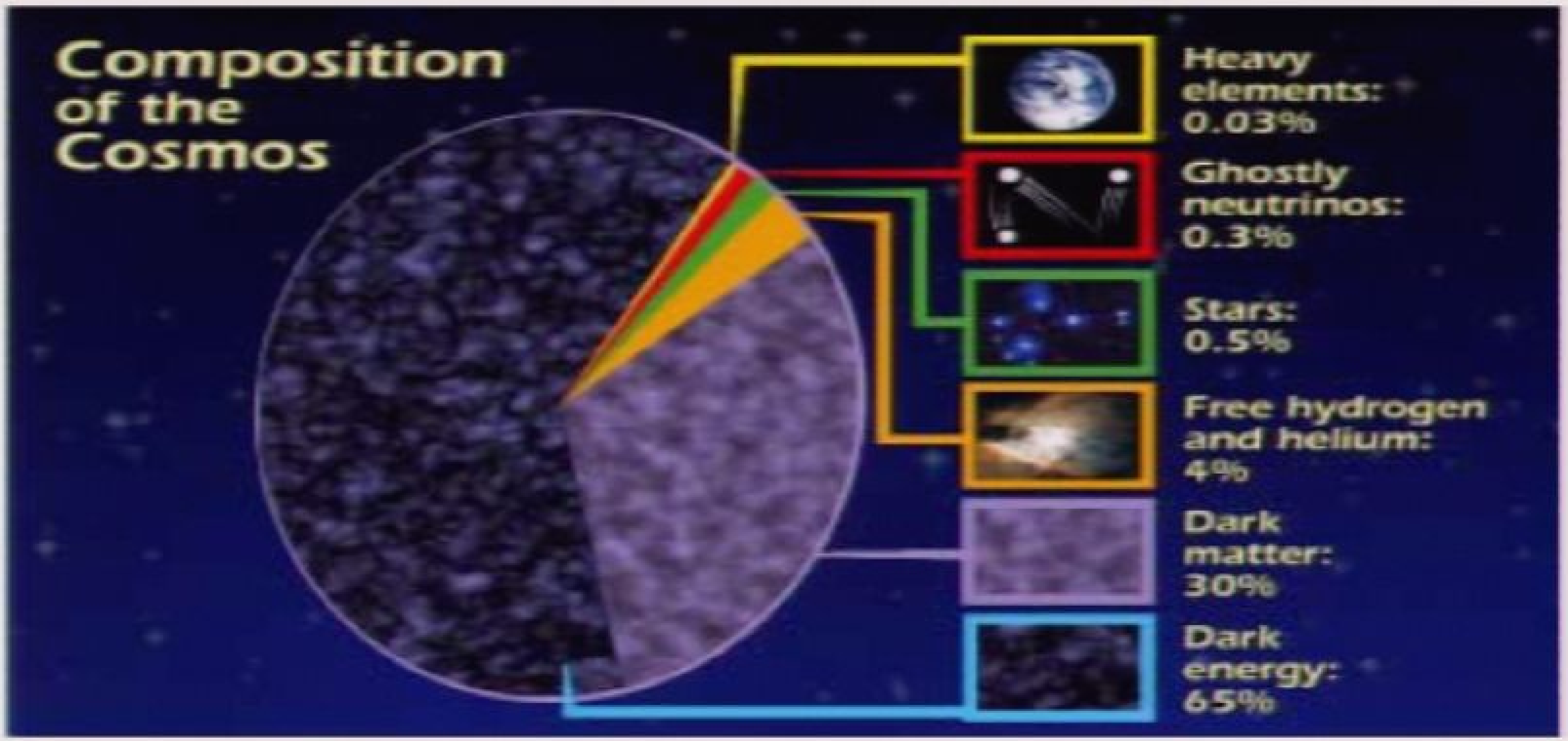
The Contemporary Universe

- The universal expansion is accelerating



The Contemporary Universe

- **Dark energy (cosmic fuel)…**
  - E.g., vacuum energy or scalar field or condensate (quintessence)



$$H^2 = \frac{8\pi G}{3}\left[\rho^{\text{baryons}} + \rho^{\text{neutrinos}} + \rho^{DM} + \boxed{\rho^{DE}} + \cdots\right]$$

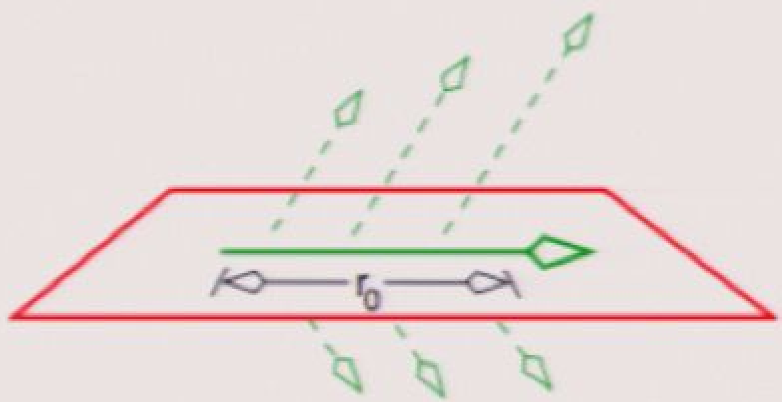
The Contemporary Universe

- **...versus modified gravity?**
  - Rather than new ingredient, treat as signal of first real lack of understanding of gravity
  - Infrared rather than ultraviolet modifications

$$G_{\mu\nu}(g_{\mu\nu}) + \boxed{\cdots} = 8\pi G\, T_{\mu\nu}$$

The Contemporary Universe

- **Many scenarios**
  - Modified Friedmann equations
  - Modified Einstein-Hilbert actions: e.g., 1/R terms, etc.
  - Braneworlds: e.g., Dvali-Gabadadze Porrati



Outline

- Phenomenology of DGP Braneworlds
- Self-accelerating Cosmology
- Tests from Local Gravity
- Cosmology and Density Perturbations
- Beyond self-acceleration

Braneworlds and Metastable Gravitons

- **Einstein gravity in 5-dimensions**

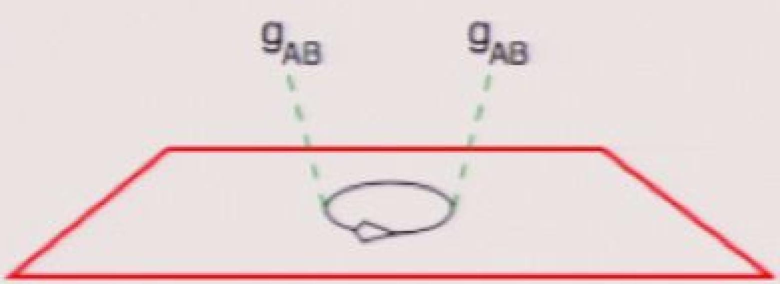
$$S_{(5)} = -\frac{1}{16\pi} M^3 \int d^5x \sqrt{-g}\, R + \int d^4x \sqrt{-g^{(4)}}\, \mathcal{L}_m + S_{GH}$$

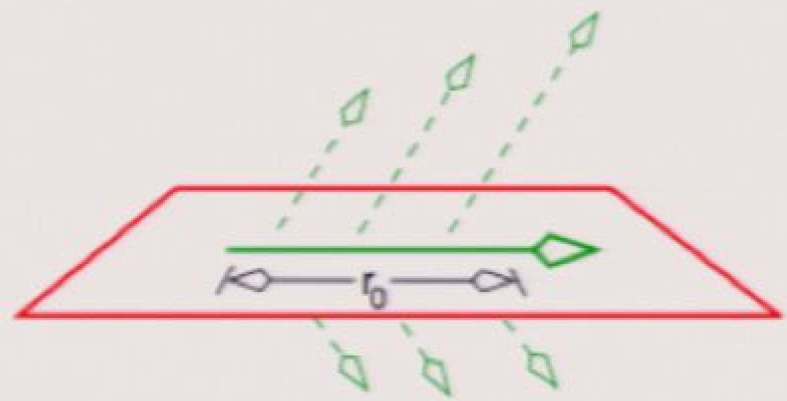
$$\boxed{g^{(4)}_{\mu\nu} = \partial_\mu X^A \partial_\nu X^B g_{AB}}$$

- **Intrinsic curvature term**

$$-\frac{1}{16\pi} M_P^2 \int d^4x \sqrt{-g^{(4)}}\, R^{(4)}$$

$$\boxed{r_0 = \frac{M_P^2}{2M^3}}$$

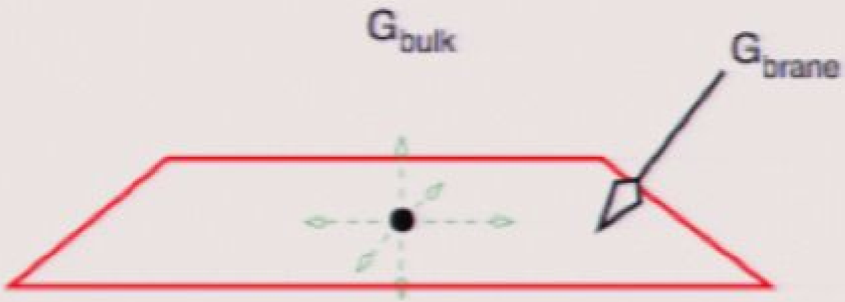




• Dvali,Gabadadze,Porrati PLB**485**:208(2000); Dvali,Gabadadze,Kolanovic,Nitti PRD**64**:084004(2001), **65**:024031(2002)

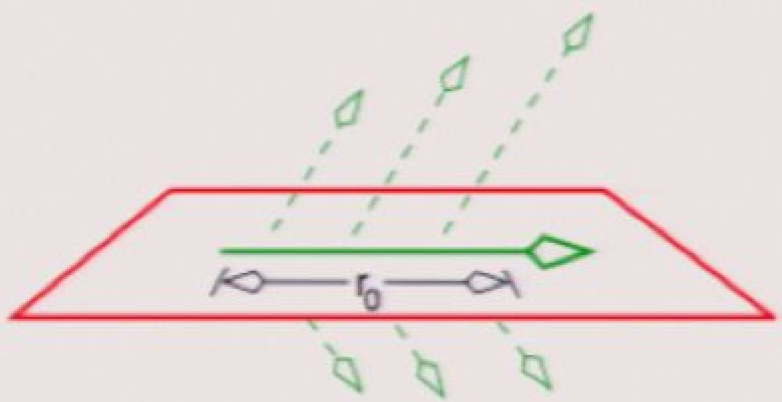
Braneworlds and Metastable Gravitons

- **Disparate gravitational strengths: brane vs. bulk**



$$\boxed{r_0 = \frac{G_{\text{bulk}}}{2G_{\text{brane}}}}$$

- **Brane gravity appears metastable**



short distances: 4-dimensional

$$V_{\text{grav}} = -\frac{G_{\text{brane}} m}{r}$$

long distances: 5-dimensional

$$V_{\text{grav}} = -\frac{G_{\text{bulk}} m}{r^2}$$

• Dvali,Gabadadze,Porrati PLB**485**:208(2000); Dvali,Gabadadze,Kolanovic,Nitti PRD**64**:084004(2001), **65**:024031(2002)

Cosmology

- **The Friedmann equation**

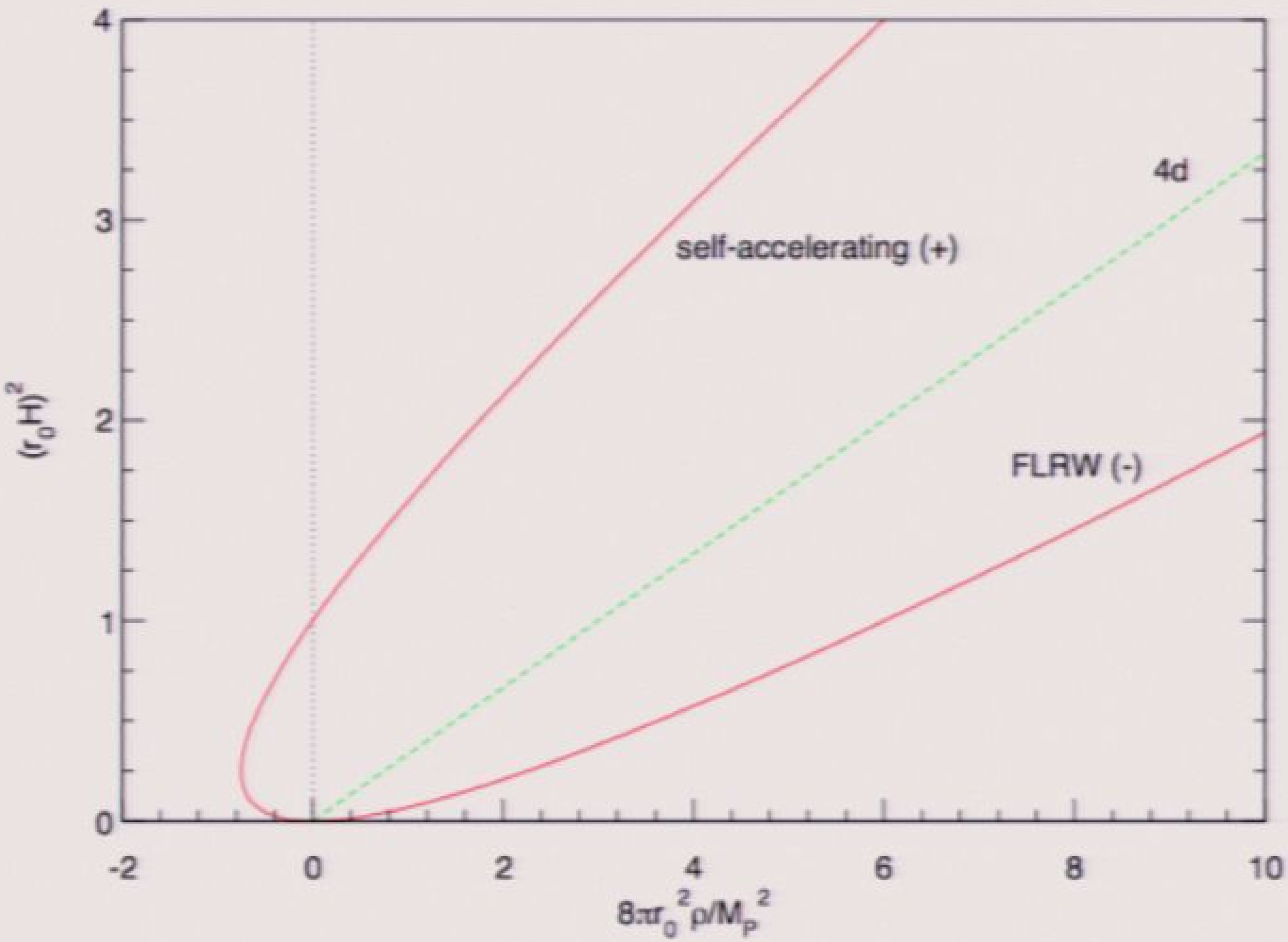
$$H^2 \pm \frac{1}{r_0} H = \frac{8\pi G}{3}\rho$$

$H \gg r_0^{-1}$	$H^2 \sim \dfrac{8\pi G}{3}\rho$	**Both phases**
$H \ll r_0^{-1}$	$H^2 \sim r_0^{-2}$	**Self-accelerating phase**
	$\sim \left(\dfrac{8\pi G}{3}\right)^2 r_0^2 \rho^2$	**FLRW phase**

• Collins, Holdom PRD**62**:105009(2000); Shtanov hep-th/0005193; Deffayet PLB**502**:199(2001)

Cosmology

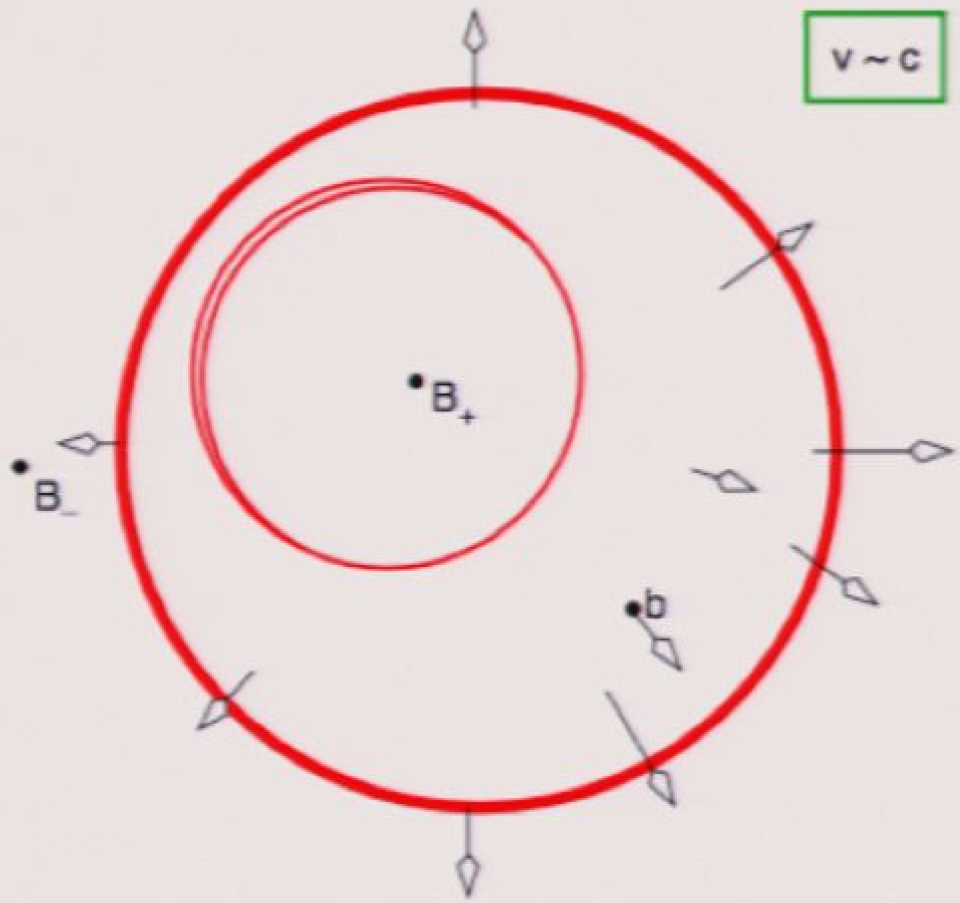
- The Friedmann equation

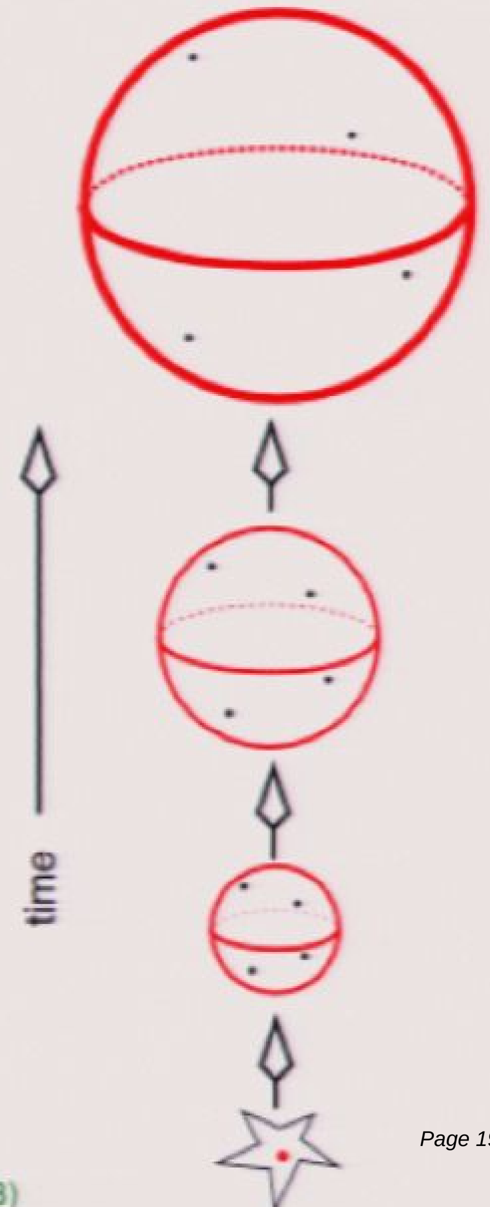


· Deffayet PLB**502**:199(2001)

Cosmology

- **Global structure**





· Deffayet PLB**502**:199(2001); Lue PRD**67**:064004(2003)

Cosmology

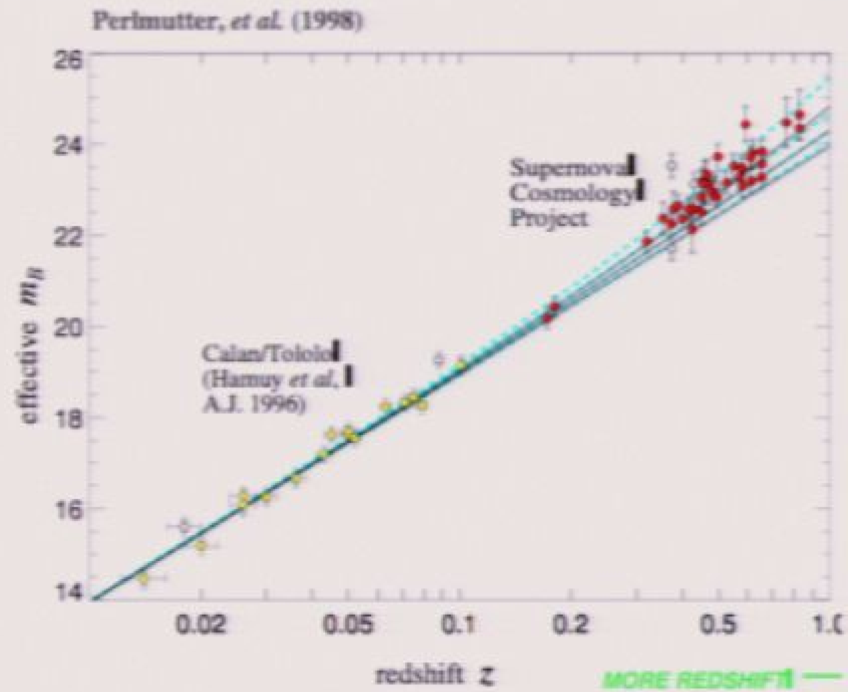
- **Constraints on r_0**

  – Friedmann equation

$$H^2 \pm \frac{1}{r_0} H = \frac{8\pi G}{3}\rho$$

  – Self-accelerating phase

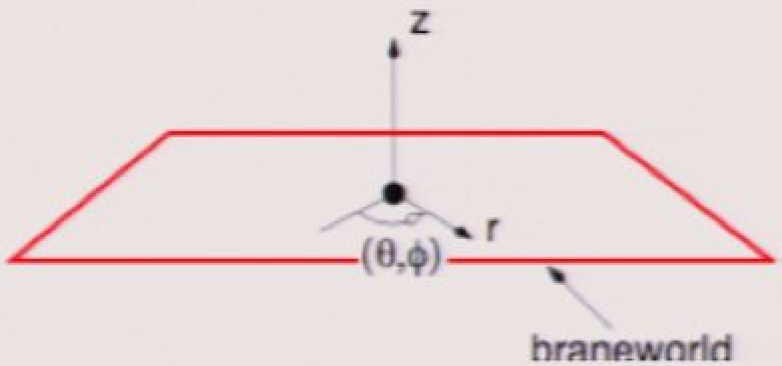
$$\boxed{r_0 = 1.21^{+0.09}_{-0.09}\, H_0^{-1} \sim 5 \text{ Gpc}}$$



• Deffayet, Dvali, Gabadadze PRD**65**:044023(2002); Deffayet,Landau,Raux,Zaldarriaga,Astier PRD**66**:024019(2002)

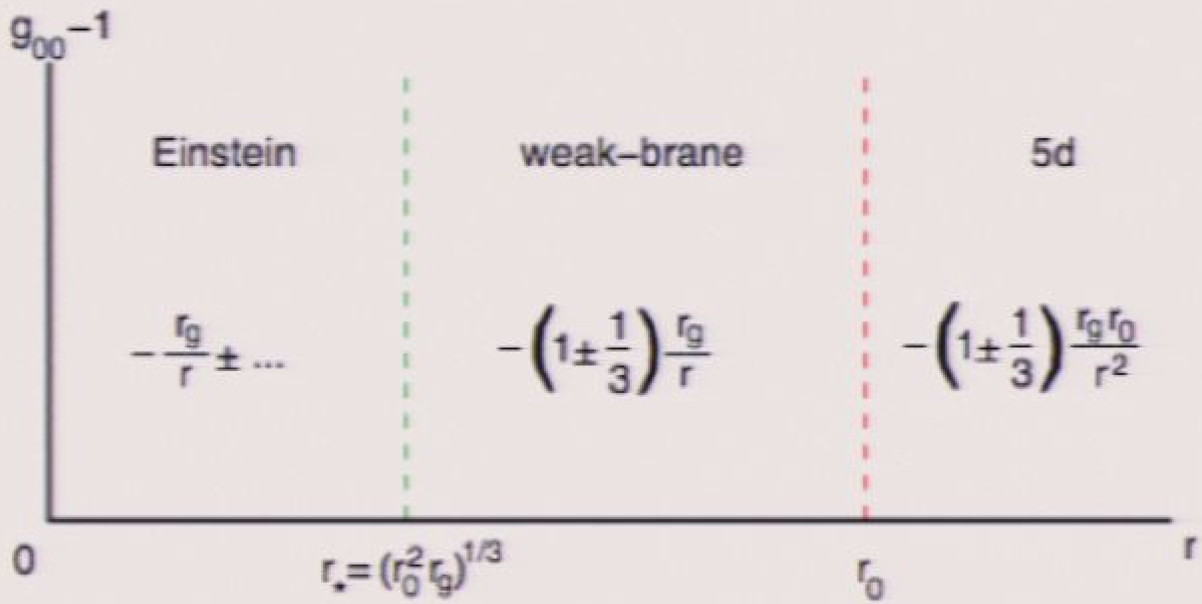
Compact Sources

- **Schwarzschild solution**



mass = m

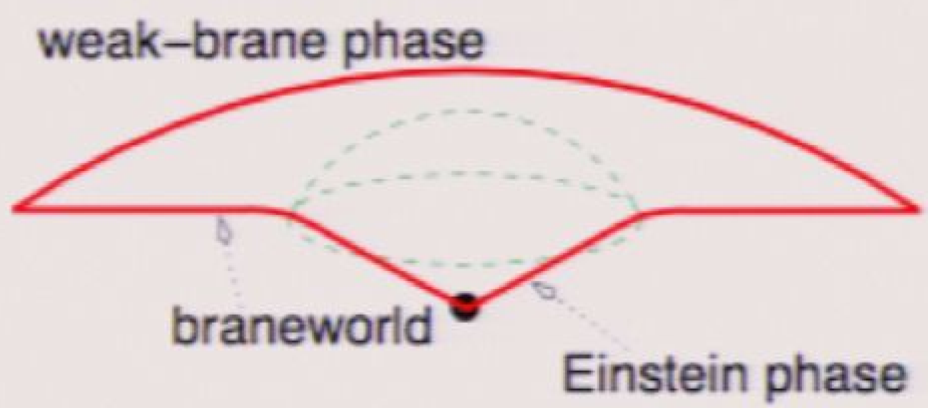
Schwarzschild radius, $r_g = 2Gm$



• Lue PRD**66**:043509(2002); Gruzinov astro-ph/0112246; Porrati PLB**534**:209(2002); Lue, Starkman PRD**67**:064002(2003)

Compact Sources

- **Strong gravity, dynamical extrinsic curvature**



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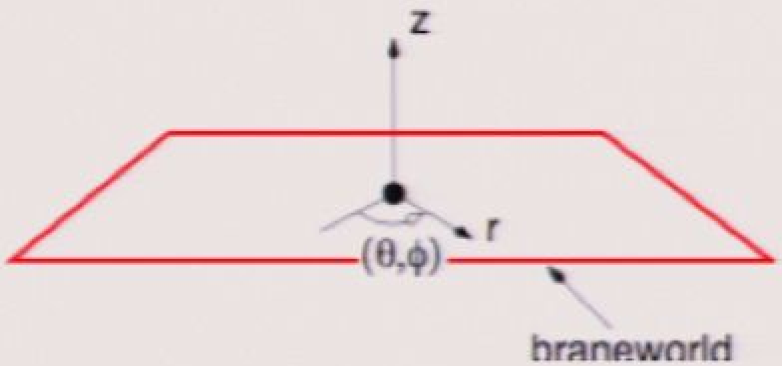

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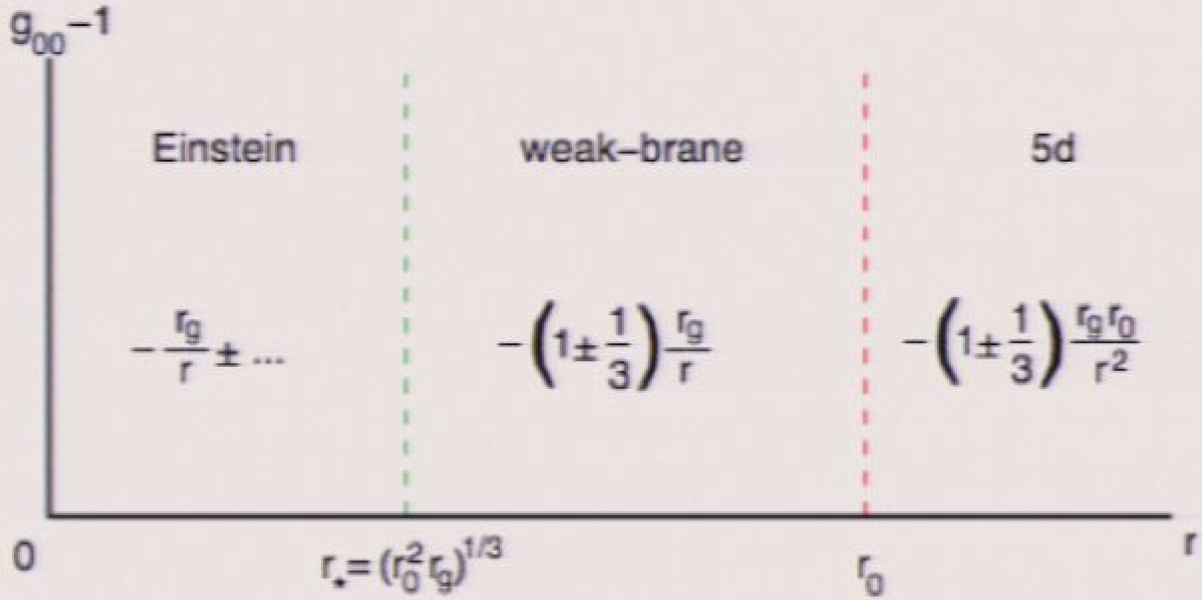

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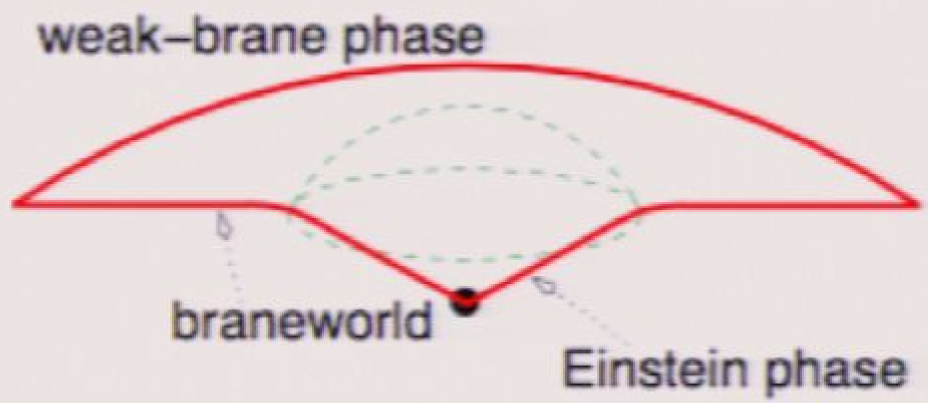


• Lue PRD**66**:043509(2002)

Compact Sources

- **Schwarzschild solution**
  - Values for $r_\star$:

Earth	**1.2 pc**
Sun	**150 pc**
Milky Way (10^{12} solar masses)	**1.2 Mpc**

• Gruzinov astro-ph/0112246; Lue, Starkman PRD**67**:064002(2003); Dvali, Gruzinov, Zaldarriaga PRD**68**:024012(2003)

Physical Considerations

- **Schwarzschild solution**
  - General expression:

$$ds^2 = g_{00}dt^2 - g_{rr}dr^2 - r^2 d\Omega$$

$$\boxed{\begin{aligned} r g_{00}'(t,r)|_{\rm brane} &= \frac{R_g}{r}\left[1+\Delta(r)\right] - 2(H^2+\dot{H})r^2 \\ g_{rr}(t,r)|_{\rm brane} &= 1 + \frac{R_g}{r}\left[1-\Delta(r)\right] + H^2 r^2 \end{aligned}}$$

• Gruzinov astro-ph/0112246; Lue, Starkman PRD**67**:064002(2003); Lue, Starkman PRD**70**:101501(2004)

Physical Considerations

- **Schwarzschild solution**
  - General expression:

$$R_g(r) = 8\pi G \int_0^r drr^2\ \delta\rho(r)$$

$$\Delta(r) = \frac{3\beta r^3}{4r_0^2 R_g}\left[\sqrt{1+\frac{8r_0^2 R_g}{9\beta^2 r^3}}-1\right]$$

$$\boxed{\beta = 1 \pm 2r_0 H\left(1+\frac{\dot{H}}{3H^2}\right)}$$

• Lue, Starkman PRD **70**:101501(2004)

Physical Considerations

- **Schwarzschild solution**
  - Einstein regime: $\boxed{r \ll r_*}$

$$\boxed{r_* = \left[\frac{r_0^2 R_g}{\beta^2}\right]^{1/3}}$$

$$\boxed{V_{\rm grav} = \frac{1}{2}(g_{00} - 1) = -\frac{r_g}{2r} \pm \sqrt{\frac{r_g r}{2r_0^2}} + \left(-\frac{1}{2}H^2 r^2 + \cdots\right)}$$

• Gruzinov astro-ph/0112246; Lue, Starkman PRD**67**:064002(2003)

Physical Considerations

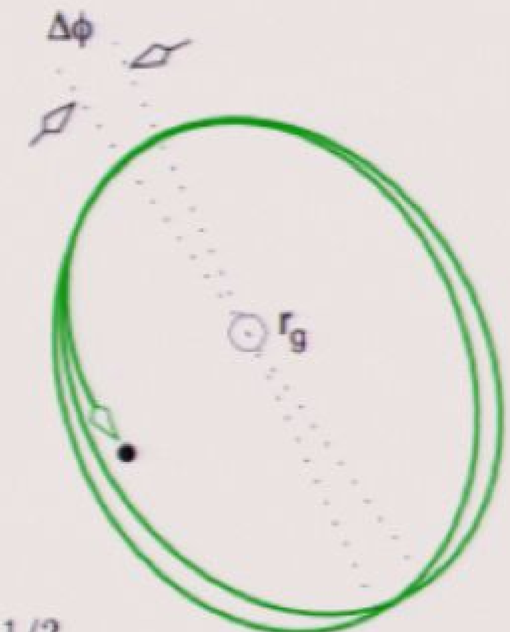
- **Orbit precession**
  - Per orbit

$$\Delta\phi = 2\pi + \frac{3\pi r_g}{r} \mp \frac{3\pi}{2}\left(\frac{r^3}{2r_0^2 r_g}\right)$$

  - Precession rate

$$\frac{d}{dt}\Delta\phi_{\mathrm{Einstein}} = \frac{3}{2}\left(\frac{r_g^3}{2r^5}\right)^{1/2}$$

$$\boxed{\frac{d}{dt}\Delta\phi_{\mathrm{DGP}} = \mp\frac{3}{8r_0} = \mp 5\ \mu\mathrm{as/year}}$$



• Lue, Starkman PRD**67**:064002(2003); Dvali, Gruzinov, Zaldarriaga PRD**68**:024012(2003)

Physical Considerations

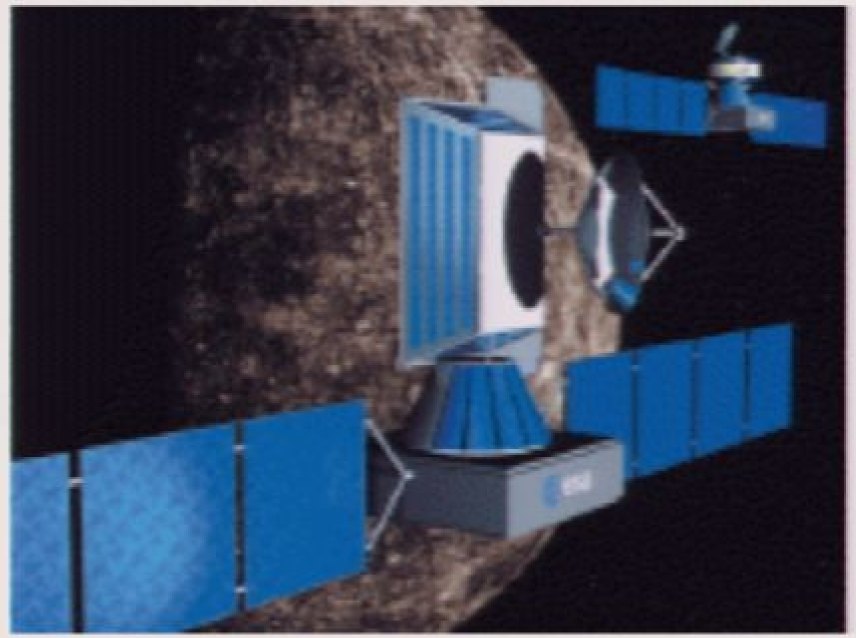
- **Orbit precession**
  - Uncertainties:

Mercury: $< 430\ \mu\text{as/year}$

$< 1\ \mu\text{as/year}$ (2009-2010)

Moon: $< 10\ \mu\text{as/year}$

Mars: $< 10\ \mu\text{as/year}$



BepiColombo (ESA)

• Nordtvedt PRD**61**:122001(2000); Will gr-qc/0103036; Milani, et al. PRD**66**:082001(2002)

Physical Considerations

- **Schwarzschild solution**

$$r_* = \left[\frac{r_0^2 R_g}{\beta^2}\right]^{1/3}$$

  - Weak-brane regime: $r \gg r_*$

$$n = -\frac{R_g}{2r}\left[1 + \frac{1}{3\beta}\right] - \frac{1}{2}(H^2 + \dot{H})r^2$$

$$a = \frac{R_g}{2r}\left[1 - \frac{1}{3\beta}\right] + \frac{1}{2}H^2 r^2$$

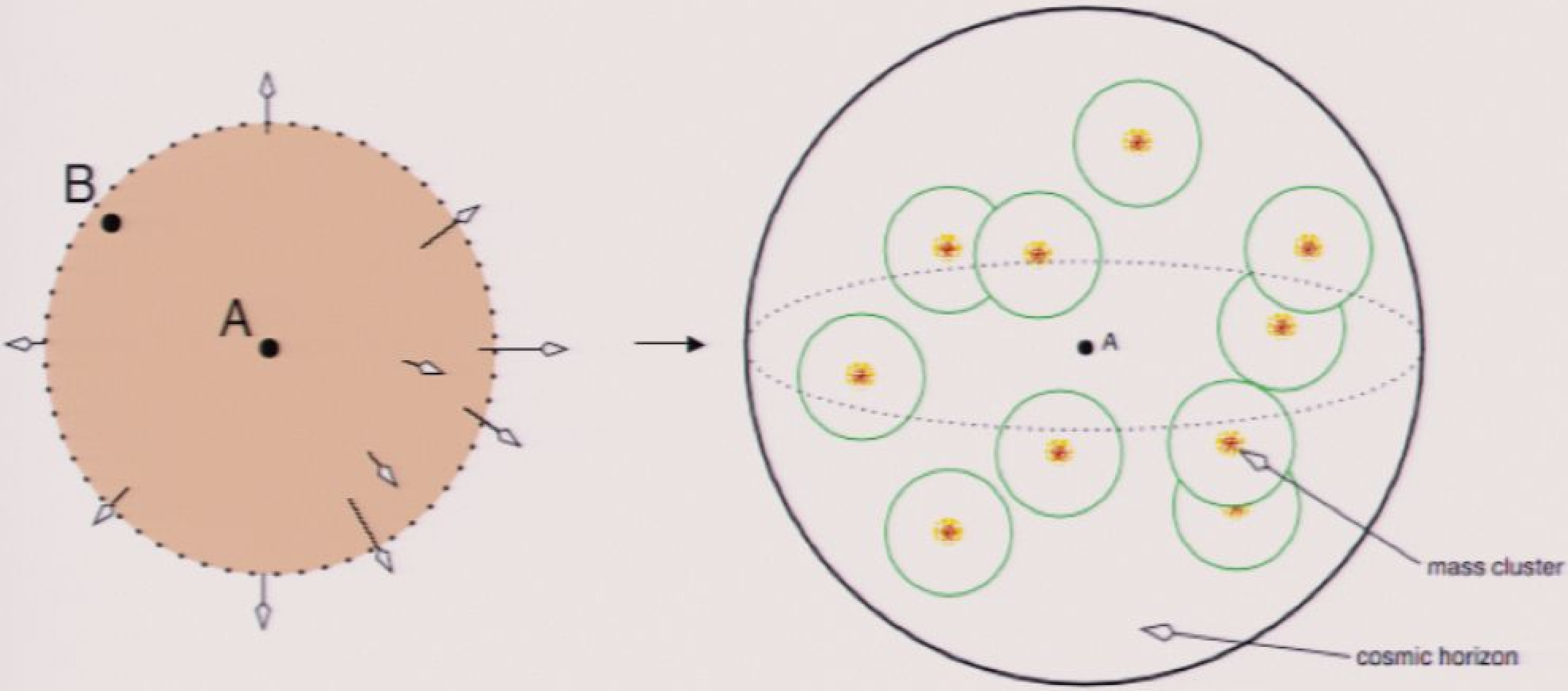
  - Brans-Dicke gravity

$$\omega = \frac{3}{2}(\beta - 1)$$

Lue, Starkman PRD**67**:064002(2003); Lue, Scoccimarro, Starkman PRD**69**:124015(2003); Lue, Starkman PRD**70**:101501(2004)

Physical Considerations

- Growth of large-scale structure



- Lue, Scoccimarro, Starkman PRD**69**:124015(2004)

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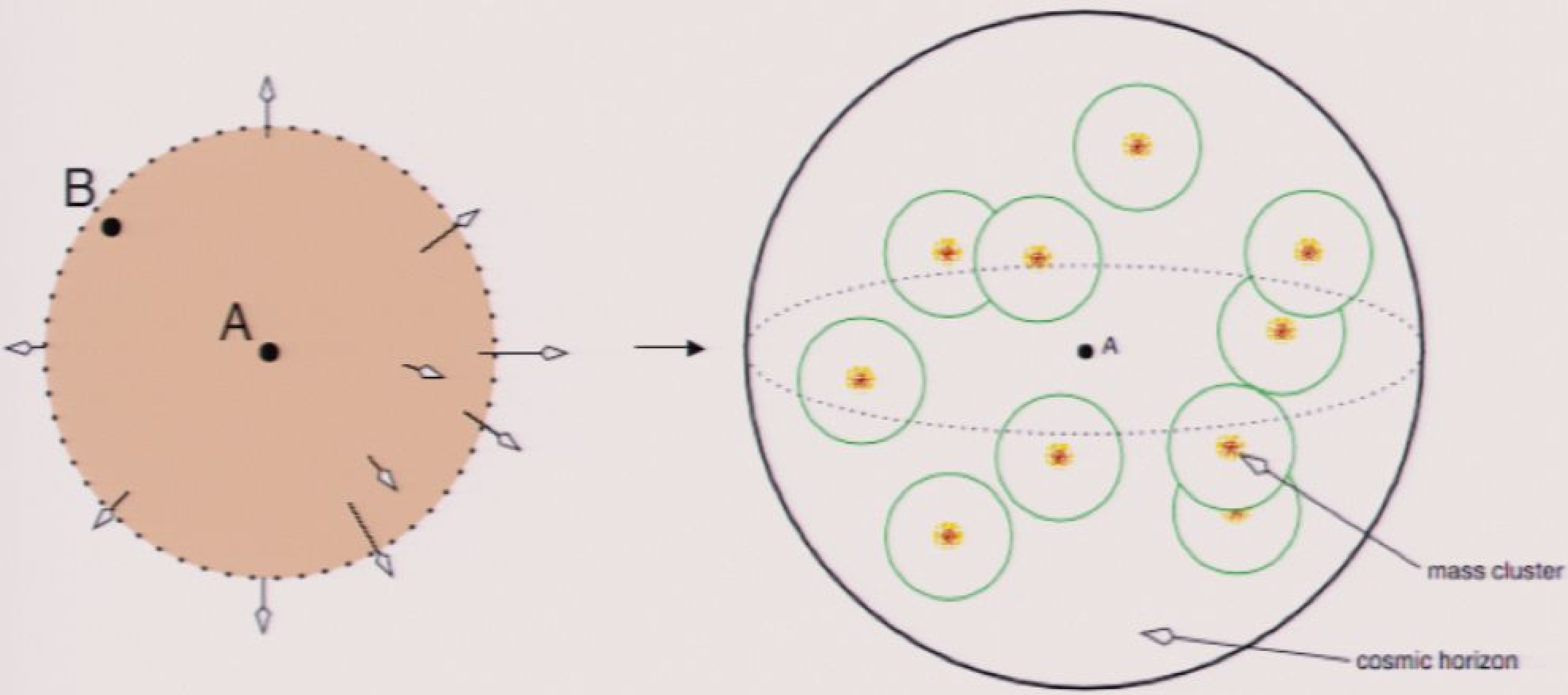


• Lue, Scoccimarro, Starkman PRD**69**:124015(2004)

Physical Considerations

- **Growth of large-scale structure**

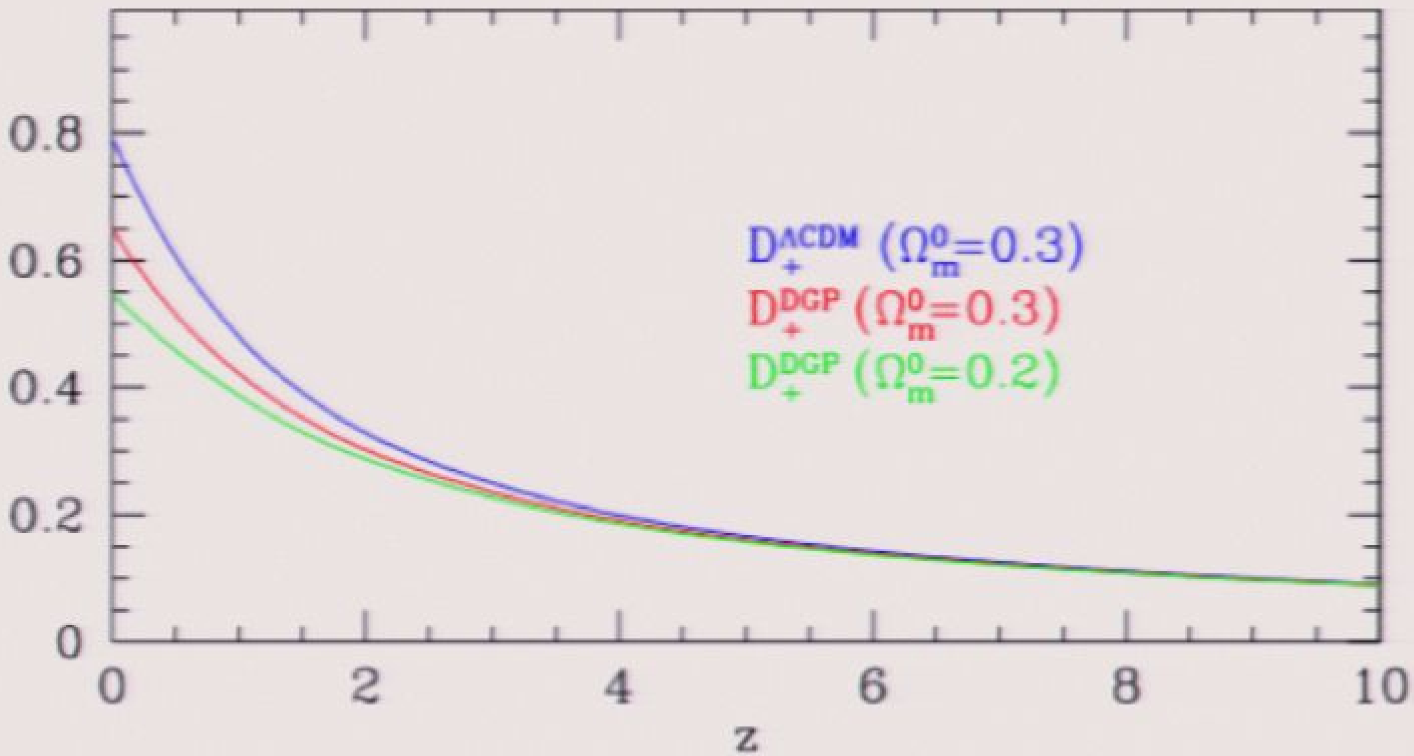
$$\ddot{\delta} + 2H\dot{\delta} = 4\pi G\rho\left(1 + \frac{1}{3\beta}\right)\delta$$

$$\boxed{G_{\rm eff} = G\left[1 + \frac{1}{3\beta}\right]}$$

• Lue, Scoccimarro, Starkman PRD**69**:124015(2004)

Physical Considerations

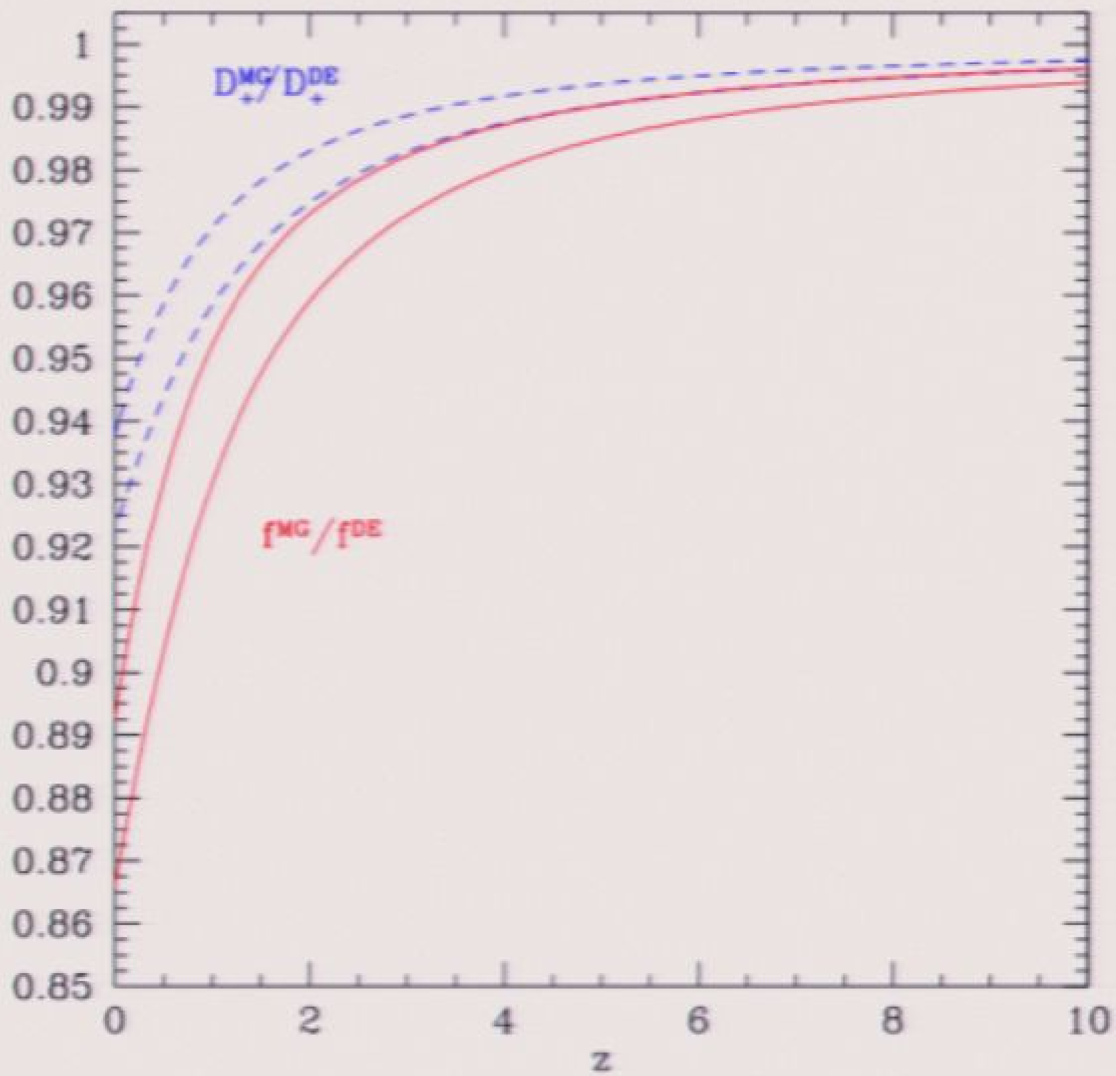
- Growth of large-scale structure



• Lue, Scoccimarro, Starkman PRD**69**:124015(2004)

Physical Considerations

- **Linear growth**



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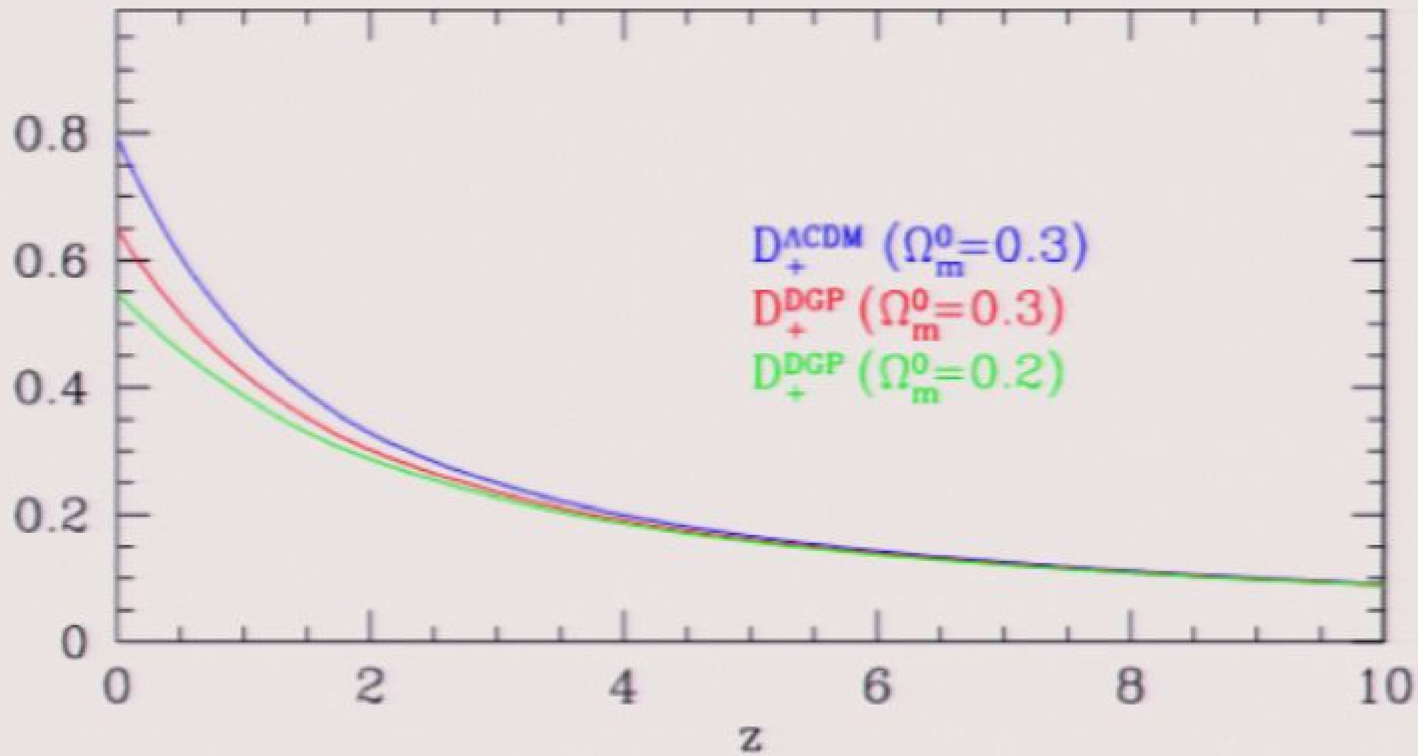

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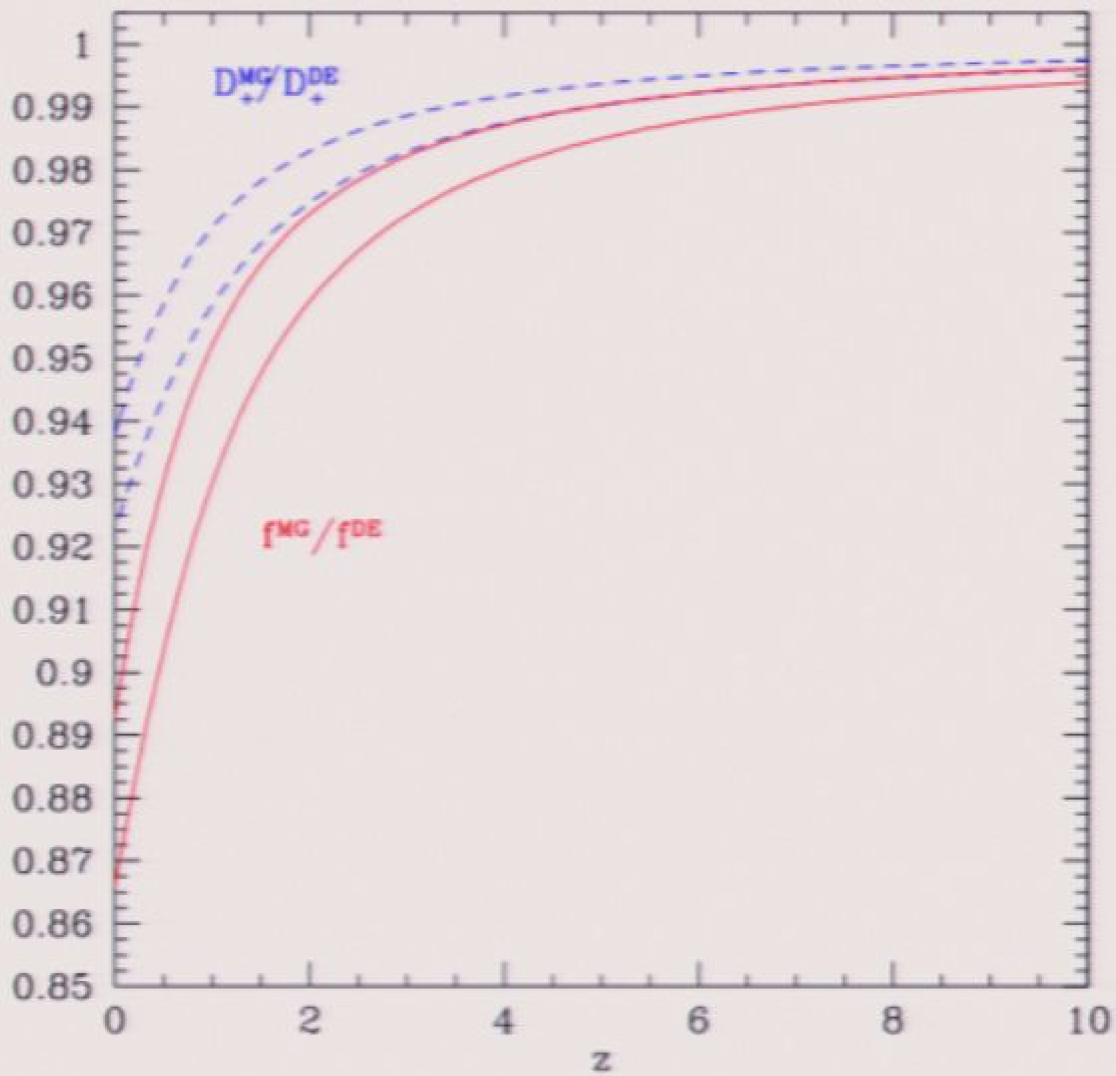

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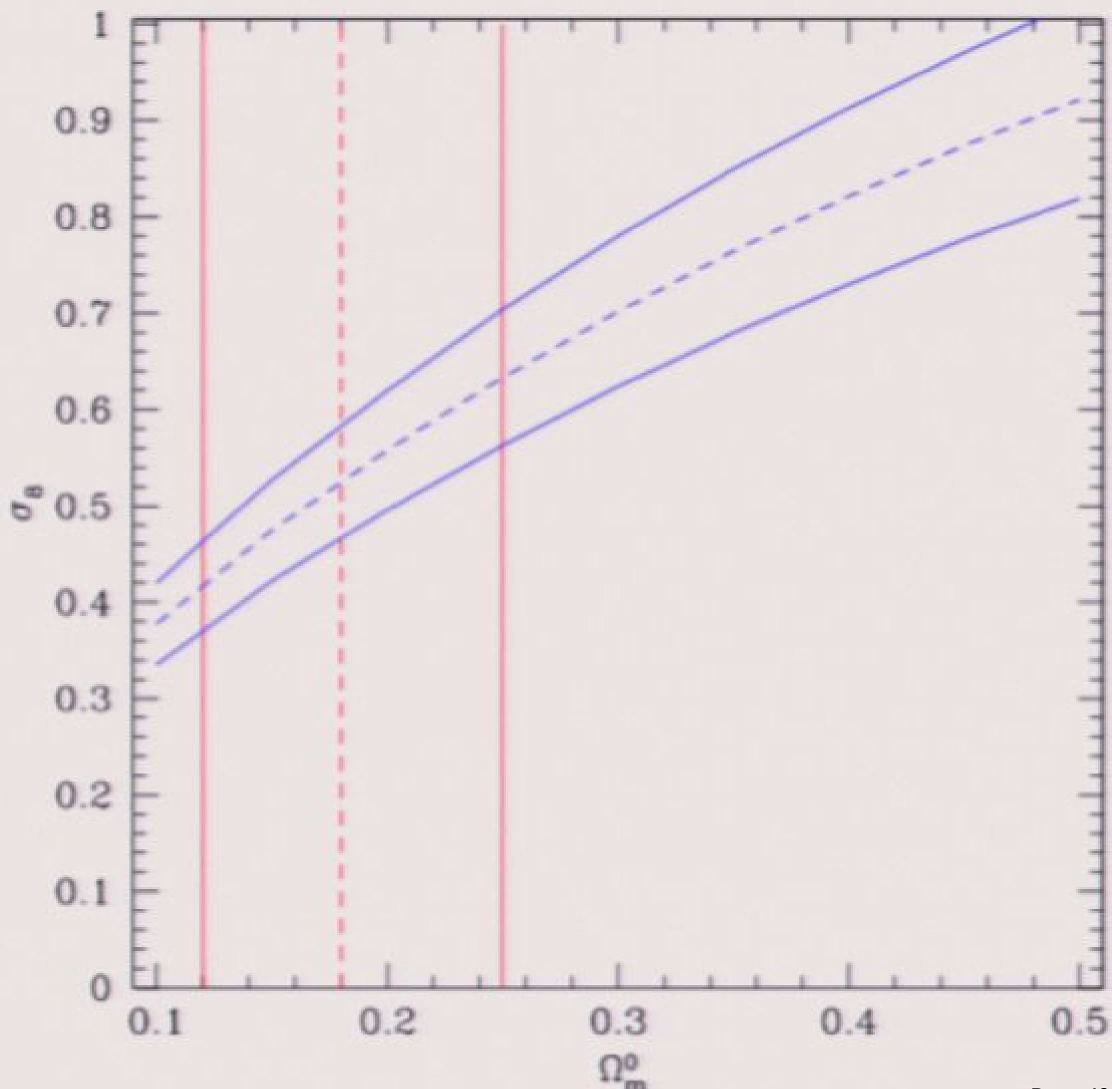
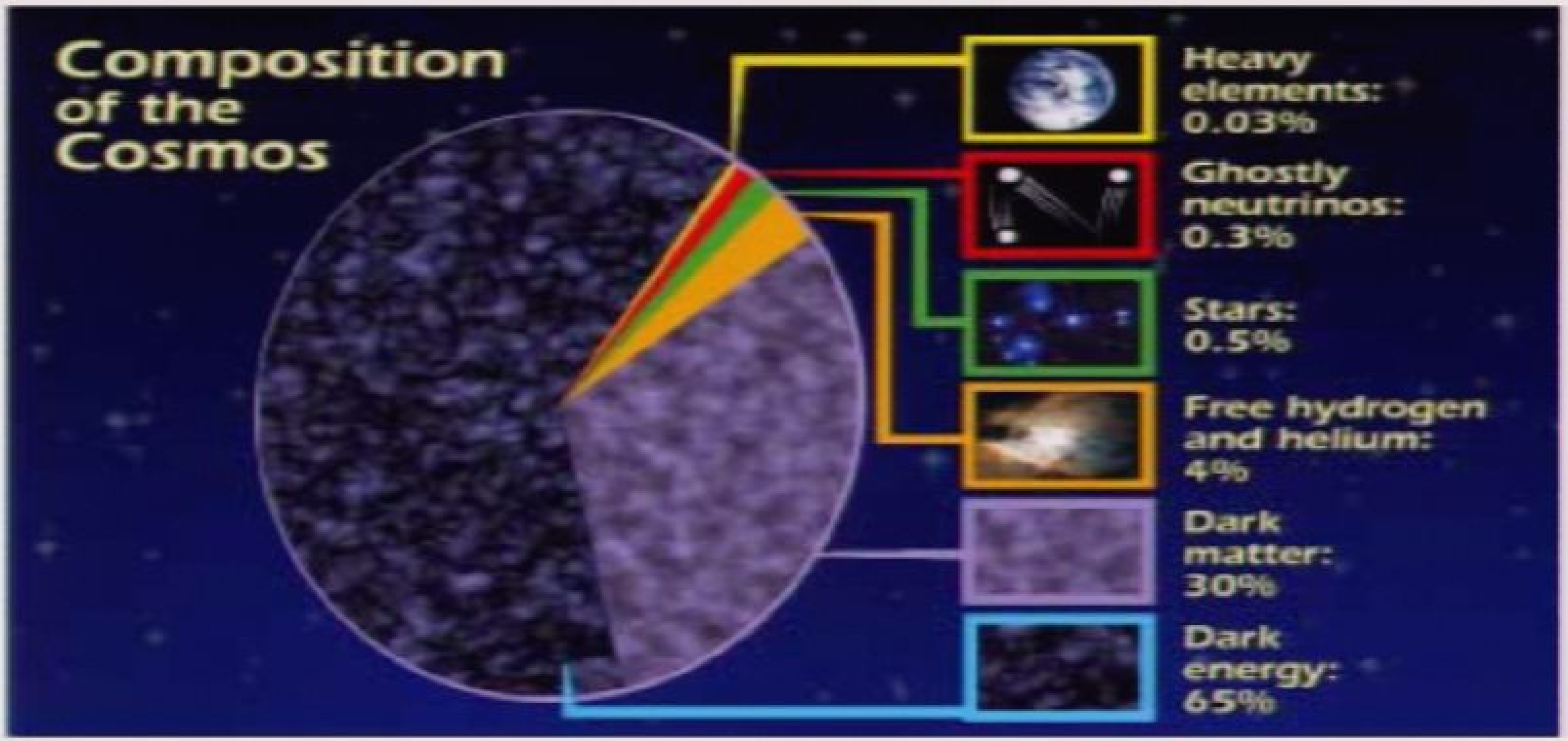


- Lue, Scoccimarro, Starkman PRD**69**:124015(2004)

Beyond Self-acceleration

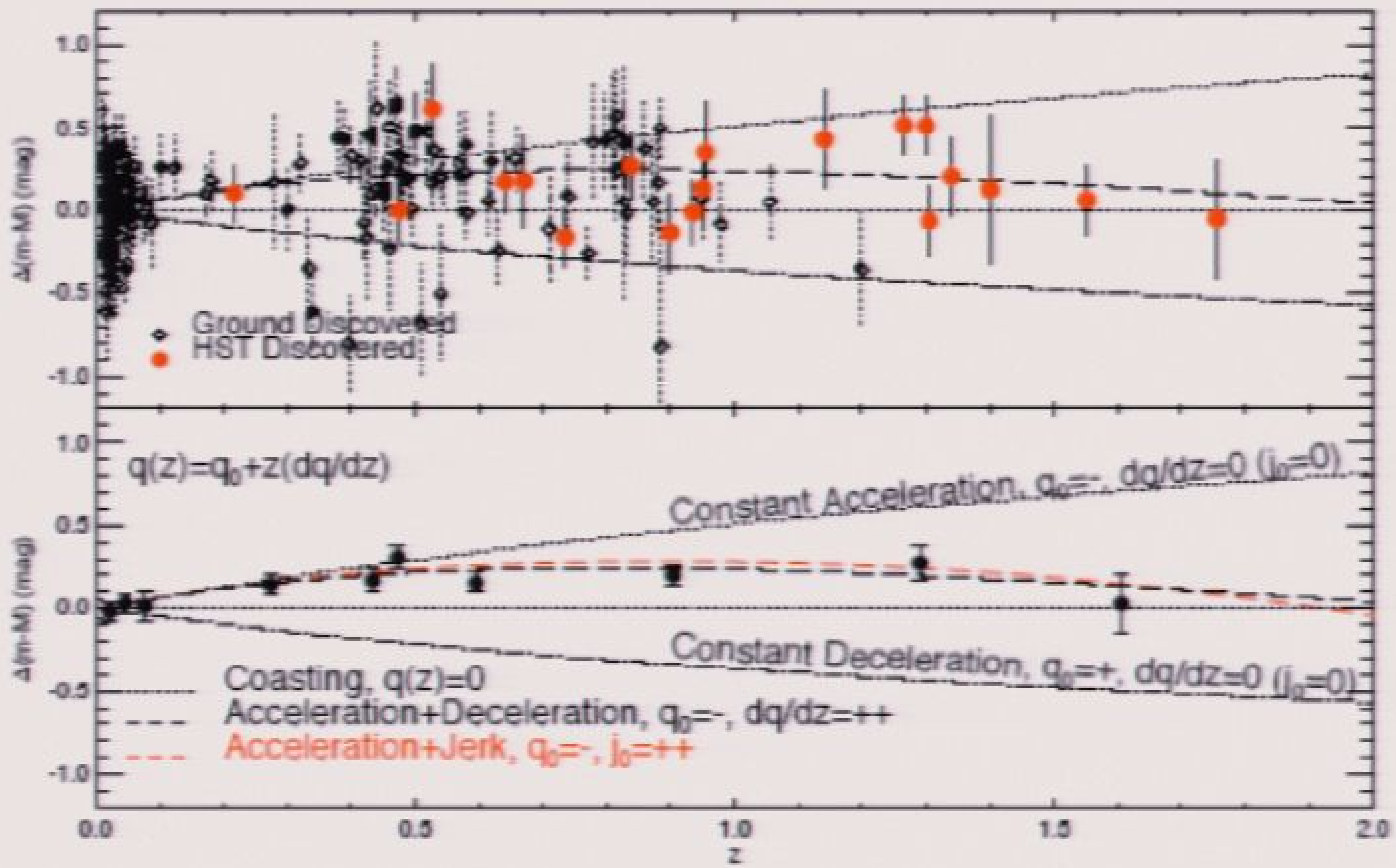
- **Dark energy (cosmic fuel)…**
  - E.g., vacuum energy or scalar field or condensate (quintessence)



$$H^2 = \frac{8\pi G}{3}\left[\rho^{\text{baryons}} + \rho^{\text{neutrinos}} + \rho^{DM} + \boxed{\rho^{DE}} + \cdots\right]$$

Beyond Self-acceleration

- Riess, et al. (2004)



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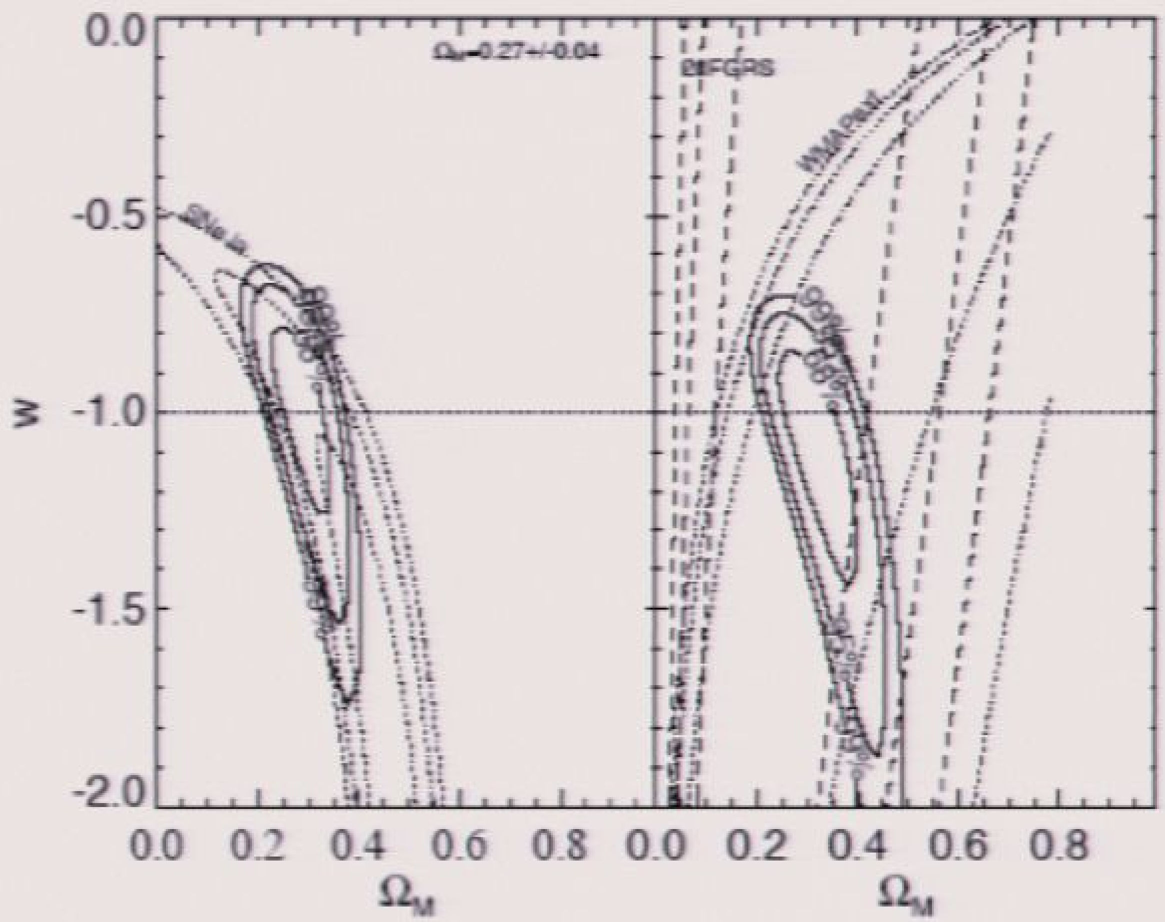


Beyond Self-acceleration

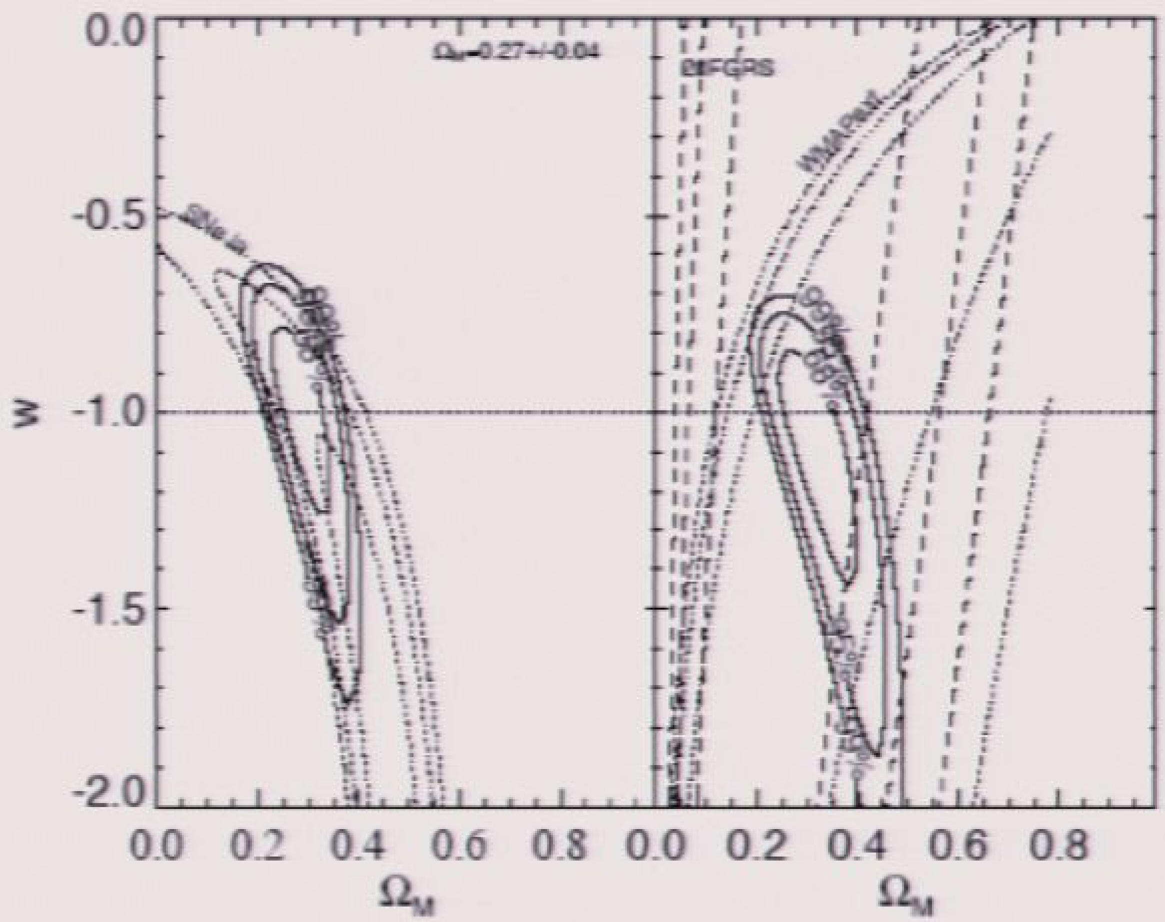
- **Superacceleration and w < -1**

$$H^2 = \frac{8\pi G}{3}\left(\rho_M + \rho_{DE}\right)$$

$$\rho_{DE}(t) = \rho^0_{DE} a^{-3(1+\mathrm{w})}$$

Beyond Self-acceleration

- Riess, et al. (2004)



Beyond Self-acceleration

- **Superacceleration and w < -1**

$$H^2 = \frac{8\pi G}{3}\left(\rho_M + \rho_{DE}\right)$$

$$\rho_{DE}(t) = \rho_{DE}^0 a^{-3(1+\mathrm{w})}$$

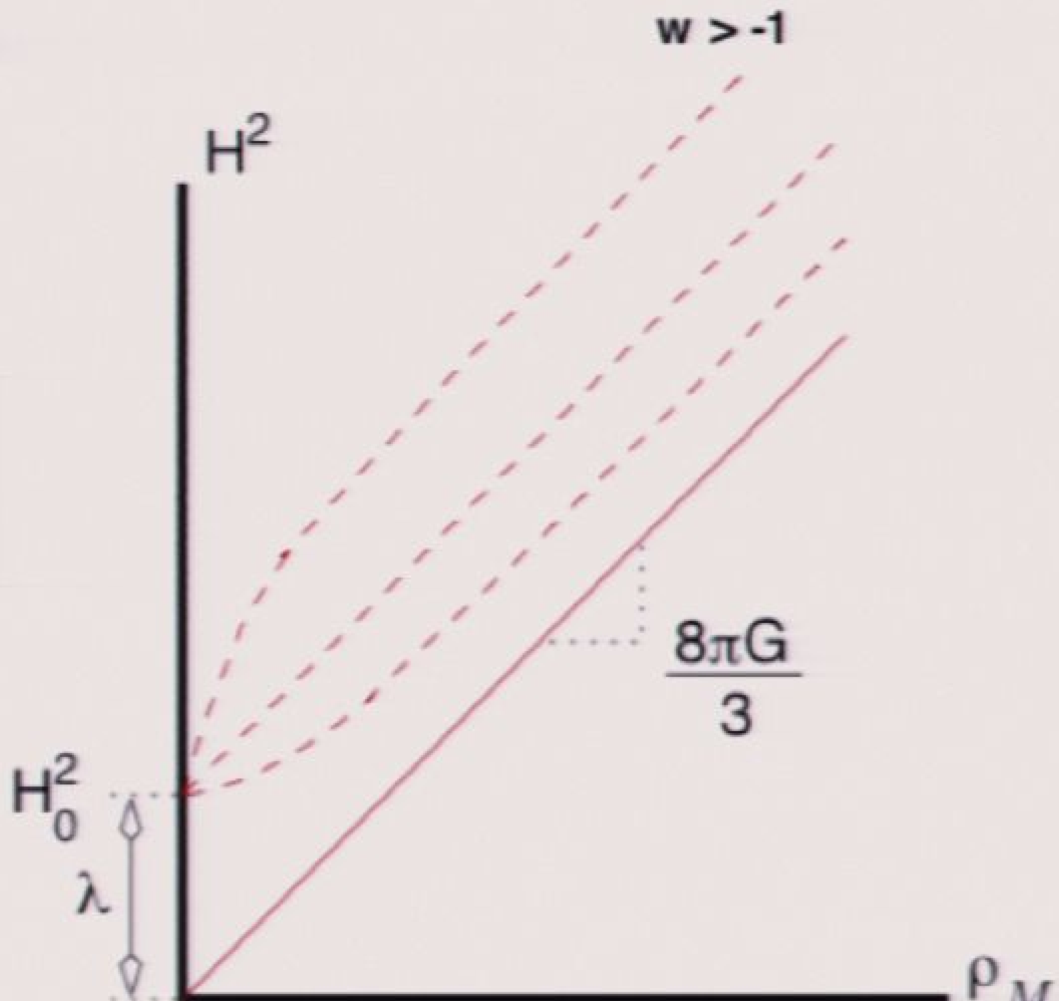
Beyond Self-acceleration

- **Superacceleration and w < -1**
  - Violation of null-energy conditions
  - Dark energy models require ghosts
  - But, again, what do we actually know about dark energy? The equation of state?

Beyond Self-acceleration

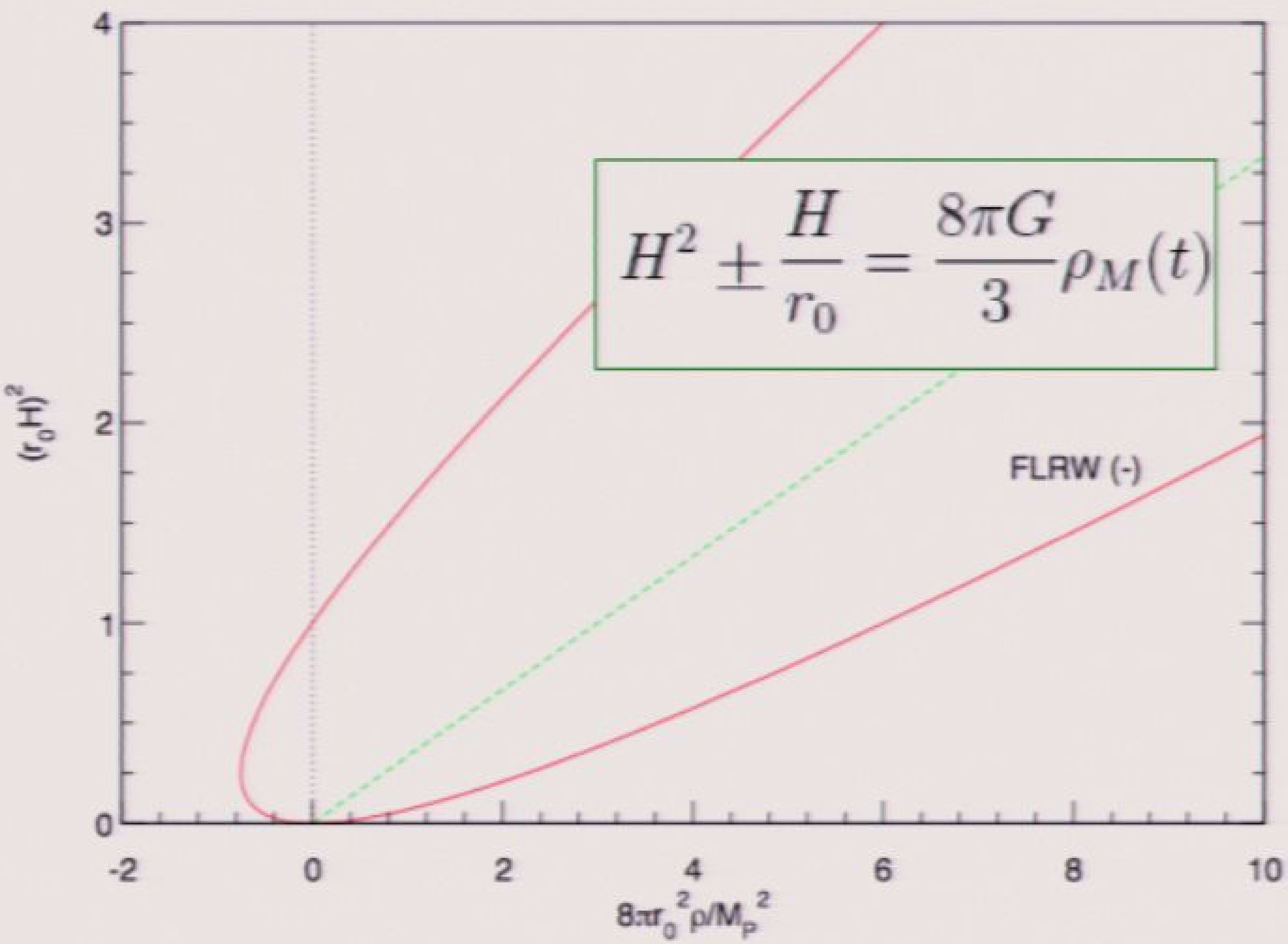
- Superacceleration and w < -1

$$H^2 = \frac{8\pi G}{3}(\rho_M + \rho_{DE})$$



Beyond Self-acceleration

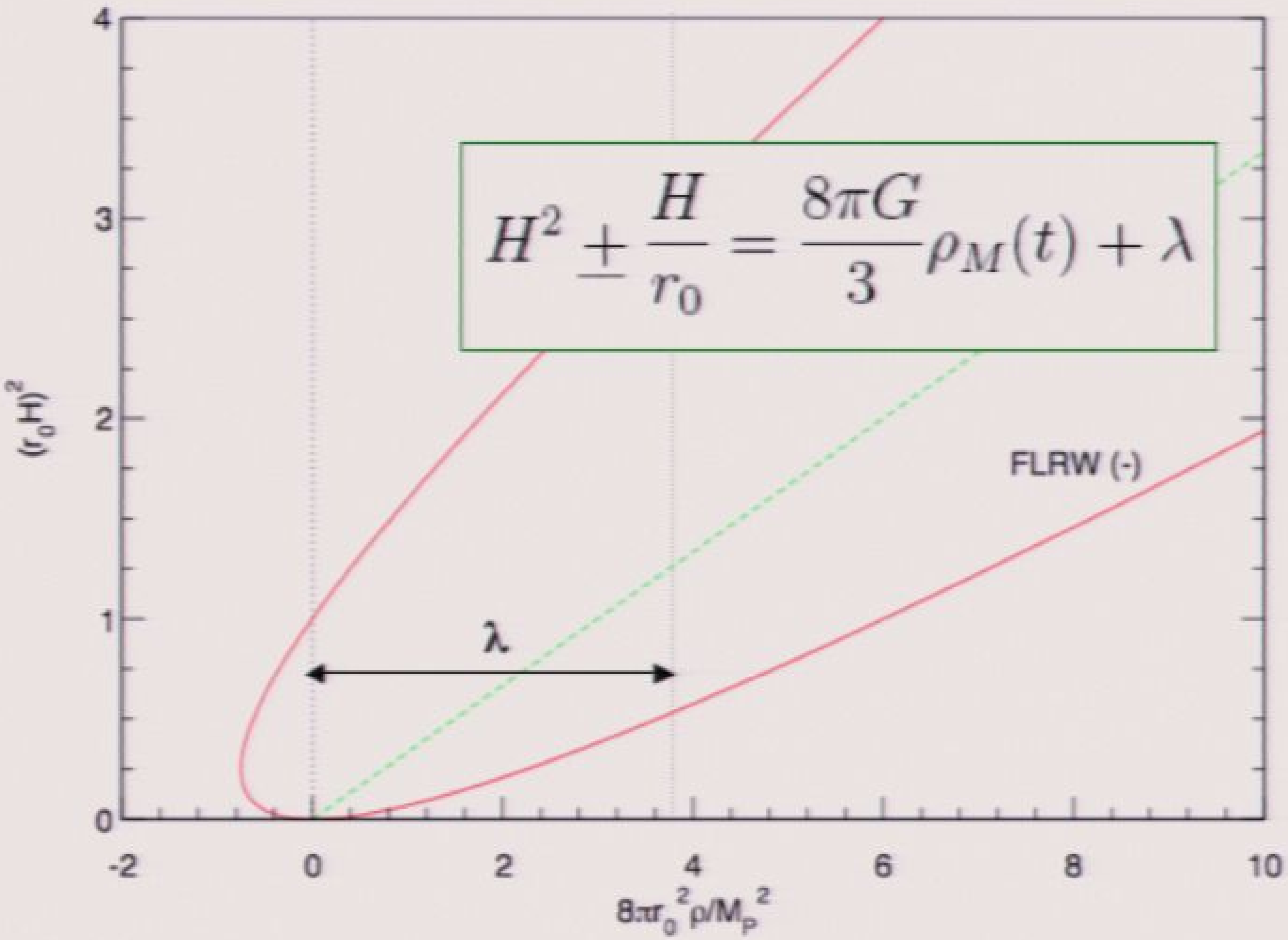
- **DGP with a brane cosmological constant**



$$H^2 \pm \frac{H}{r_0} = \frac{8\pi G}{3}\rho_M(t)$$

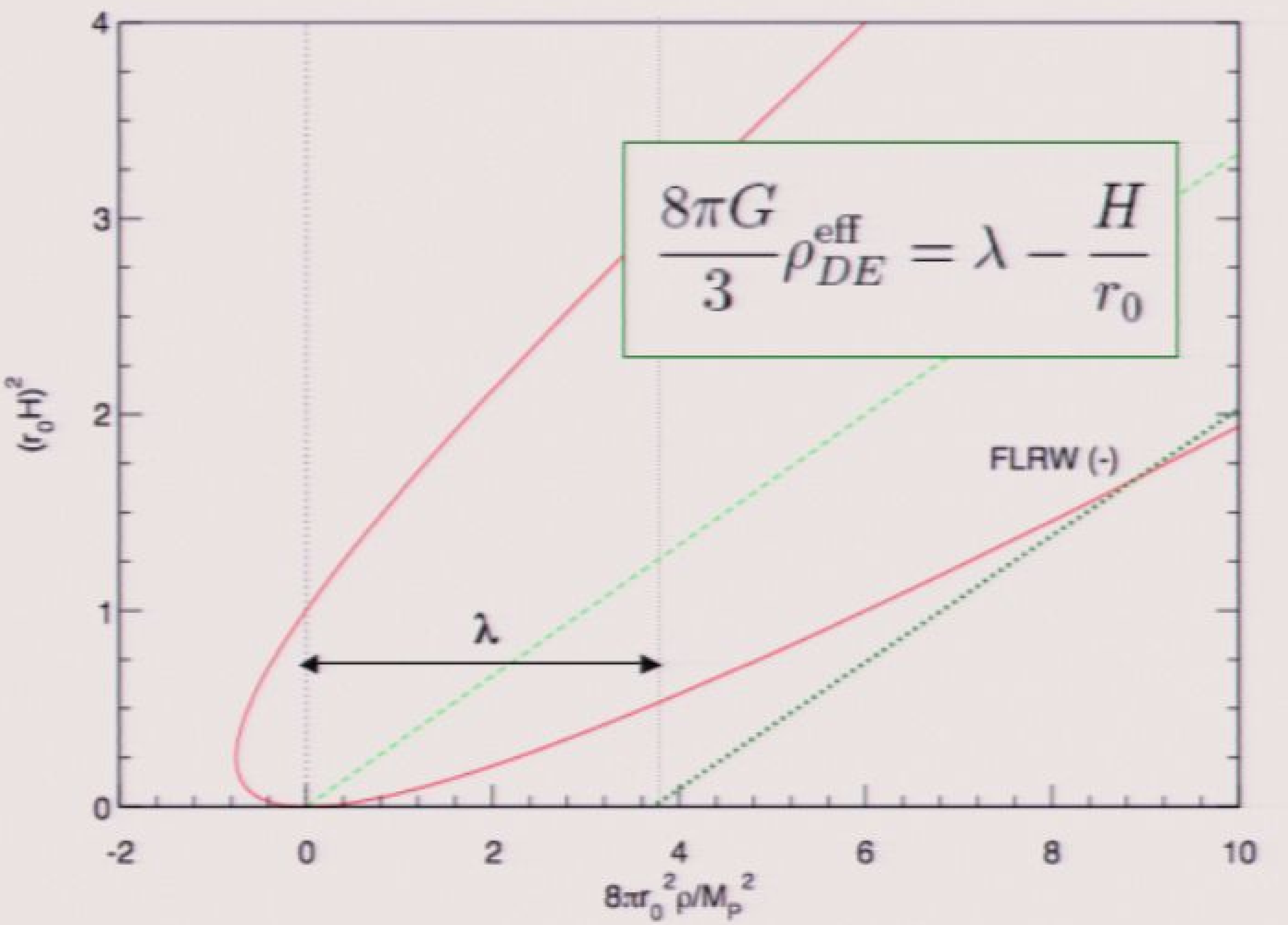
Beyond Self-acceleration

- **DGP with a brane cosmological constant**



Beyond Self-acceleration

- **DGP with a brane cosmological constant**



Beyond Self-acceleration

- **Screening of the cosmological constant**
  - Model exhibits both "dark energy" and modified gravity

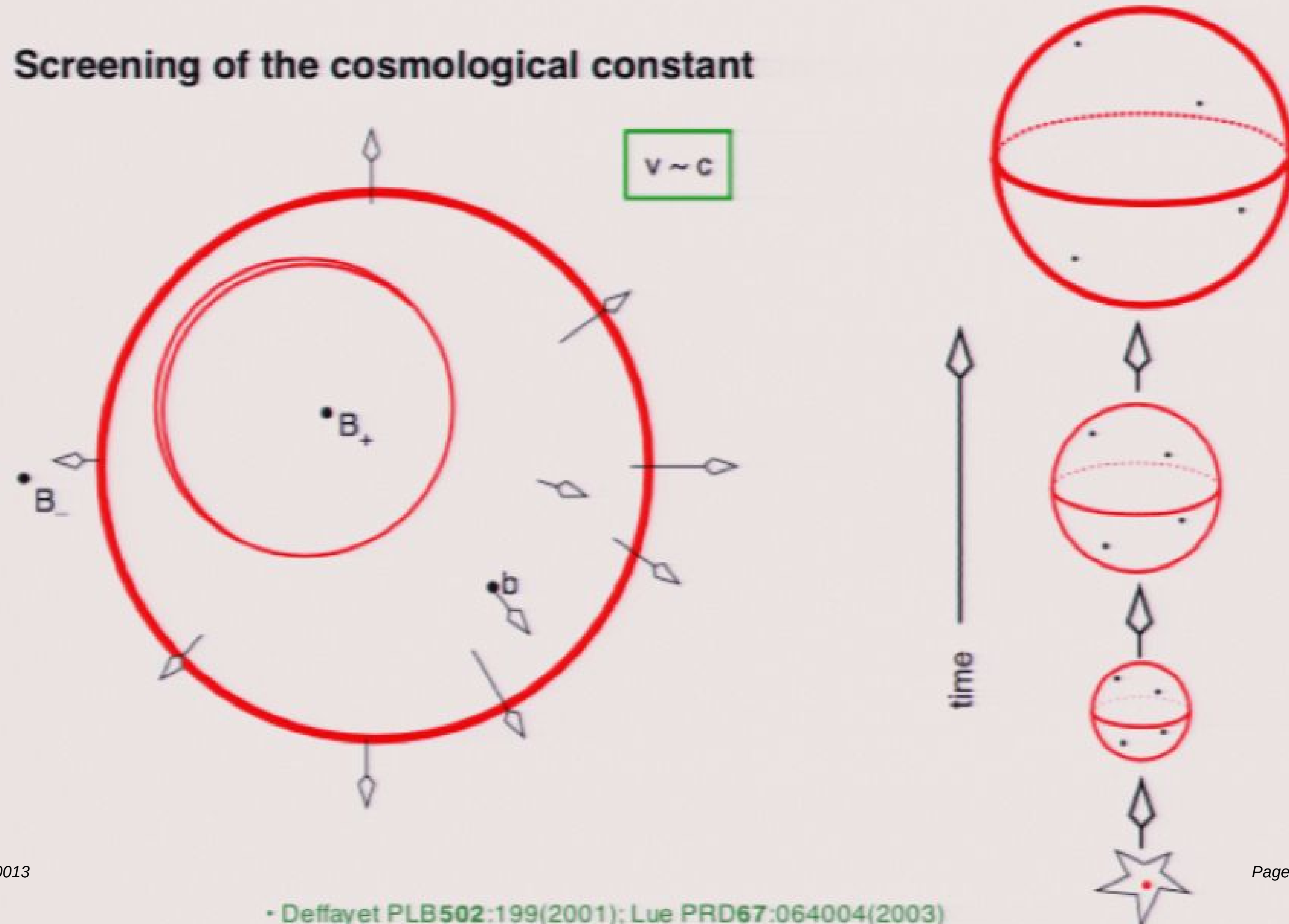
$$H^2 + \frac{H}{r_0} = \frac{8\pi G}{3}\rho_M(t) + \lambda$$

$$\boxed{\frac{8\pi G}{3}\rho_{DE}^{\text{eff}} = \lambda - \frac{H}{r_0}}$$

• Sahni, Shtanov JCAP**0311**:014(2003); Lue, Starkman PRD**70**:101501(2004)

Beyond Self-acceleration

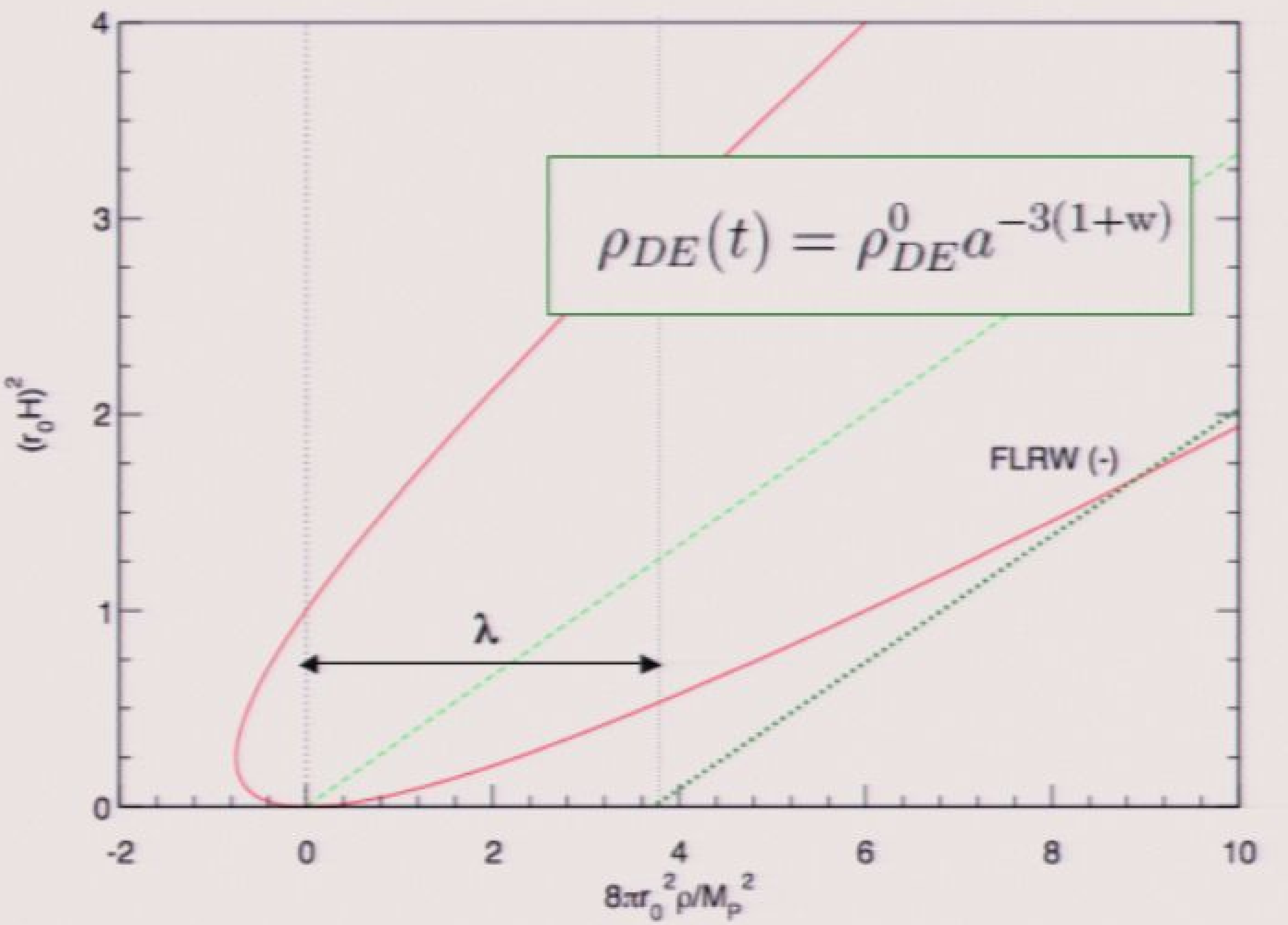
- **Screening of the cosmological constant**



· Deffayet PLB**502**:199(2001); Lue PRD**67**:064004(2003)

Beyond Self-acceleration

- w_{eff}?



Beyond Self-acceleration

- **Luminosity distance**

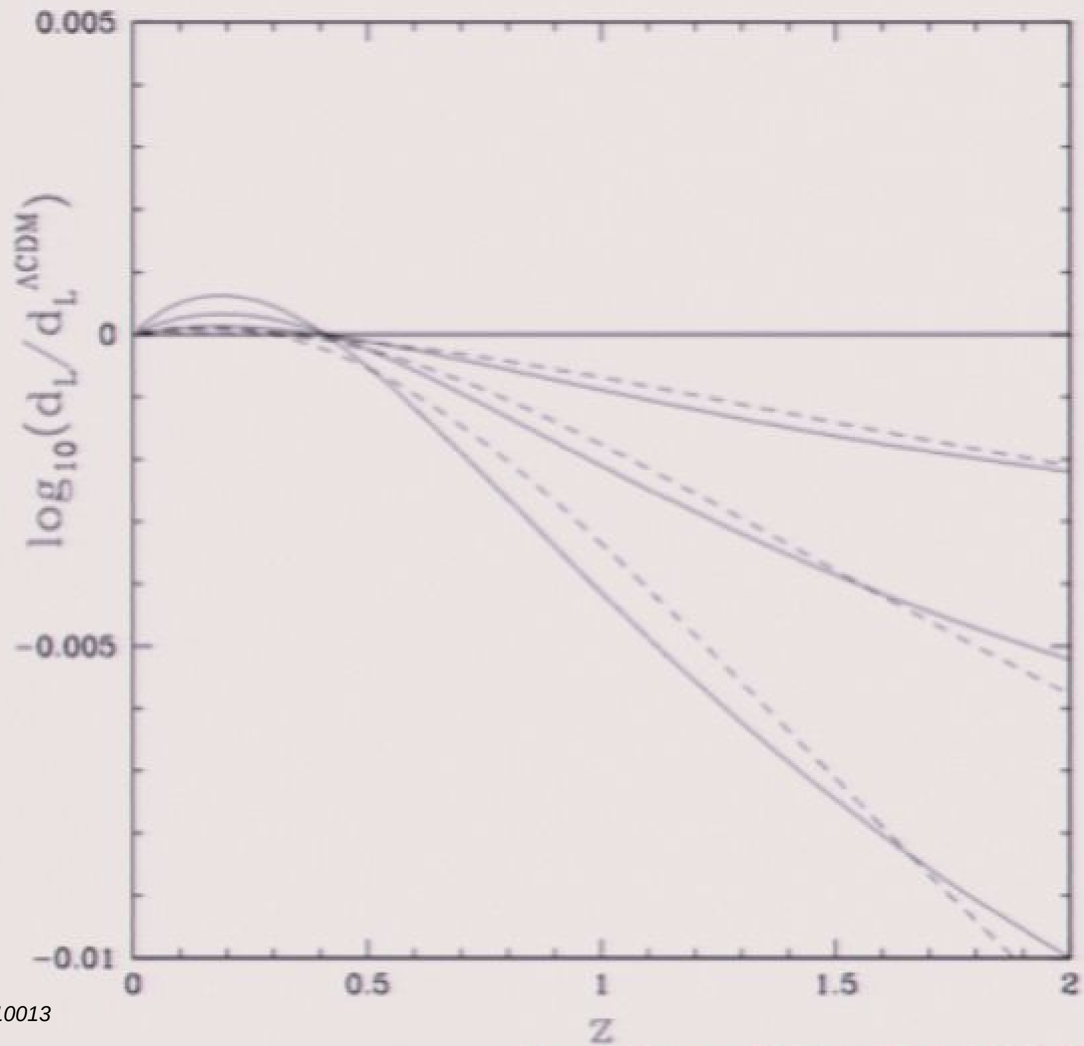
$$\frac{H(z)}{H_0} = \frac{1}{2}\left[-\frac{1}{r_0 H_0} + \sqrt{\left(2 + \frac{1}{r_0 H_0}\right)^2 + 4\Omega_M^0\left((1+z)^3 - 1\right)}\right]$$

$$\boxed{d_L^{\lambda DGP}(z) = (1+z)\int_0^z \frac{dz}{H(z)}}$$

• Sahni, Shtanov JCAP**0311**:014(2003); Lue, Starkman PRD**70**:101501(2004)

Beyond Self-acceleration

- **Luminosity distance**



(Ω_m, w)	(Ω_m, r_0H_0)
(0.28, -1.02)	(0.292, 5.9)
(0.294, -1.05)	(0.34, 1.83)
(0.316, -1.1)	(0.42, 0.86)

- Lue, Starkman PRD**70**:101501(2004)

Beyond Self-acceleration

- **Solar-system test**

$$\boxed{\frac{d}{dt}\Delta\phi = -\frac{3}{8r_0}}$$

If $r_0 H_0 = 1$, then the precession rate is about $\underline{3\ \mu\text{as/year}}$

- **Anomalous growth of structure**

(Ω_m, r_0H_0)	
(0.3, 3.77)	1.5%
(0.35, 1.41)	4.6%
(0.4, 0.87)	9.3%

This discrepancy of linear growth is roughly proportional to $1 - w_{\rm eff}$

- Lue, Starkman PRD**70**:101501(2004)

Beyond Self-acceleration

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• Lue, Starkman PRD70:101501(2004)

Remarks

- **DGP braneworlds have rich phenomenology**
  - Gravity theory with effective metastable graviton
  - Modifications to Einstein gravity occur at large (rather than short) distances
  - Provides unique environment to study alternative astrophysical and cosmological phenomena (e.g., dark energy)

Remarks

- **Modified gravity is a distinct paradigm for cosmic acceleration**
  - Distinct from dark energy paradigm
  - Subject to imminent observational discrimination

No Signal
VGA-1