Dark Energy or Modified Gravity?

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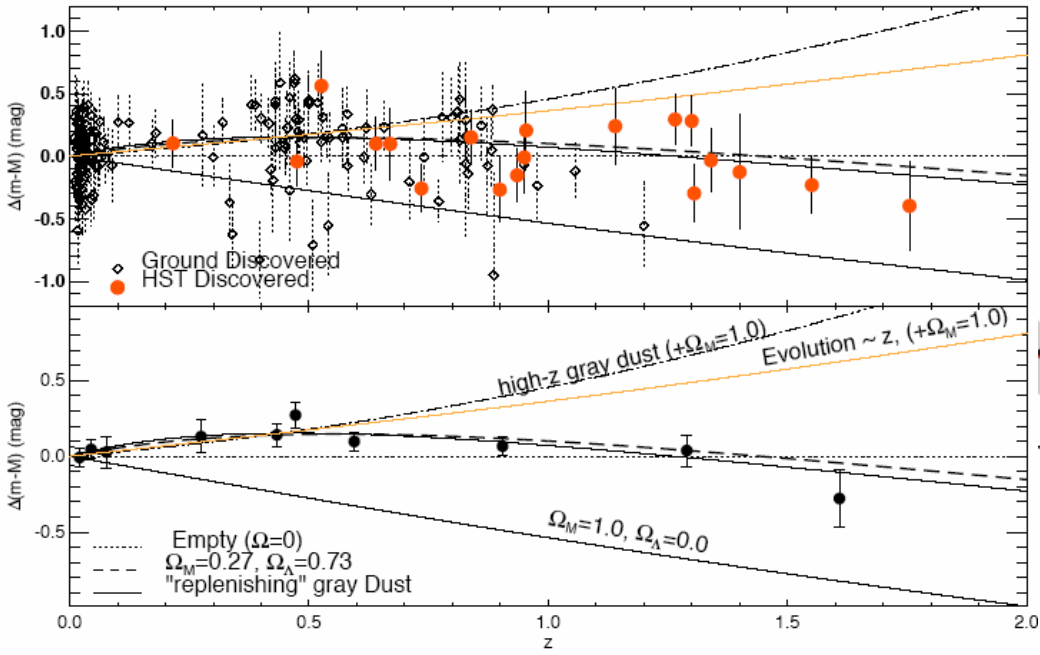
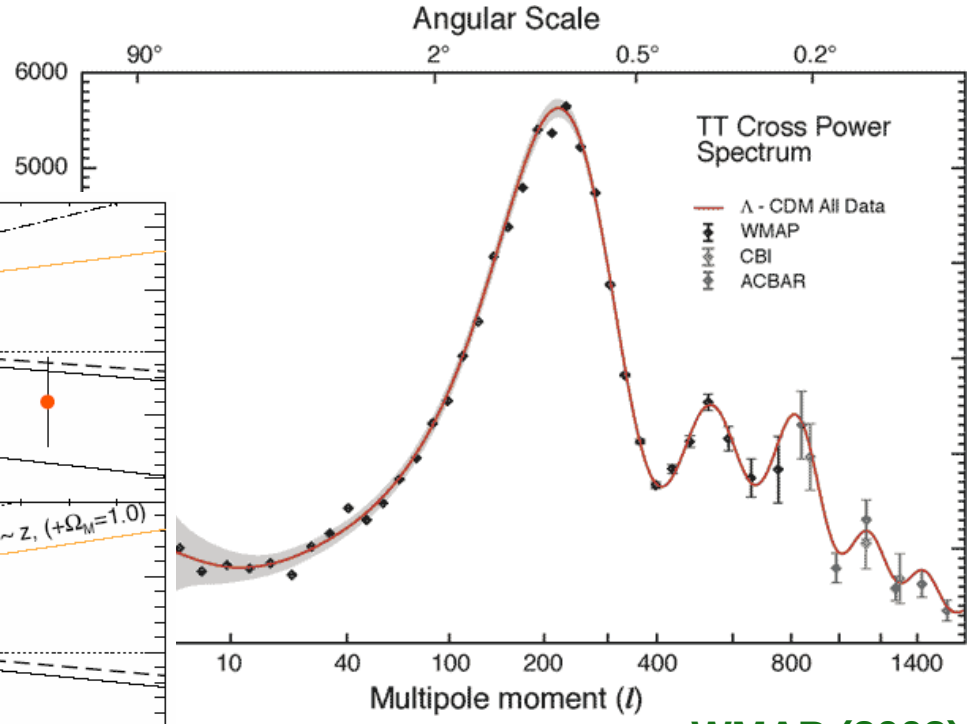
The Contemporary Universe

- **Cosmology and the Friedmann equation**
  - SNIa and cosmic acceleration
  - CMB and closure density



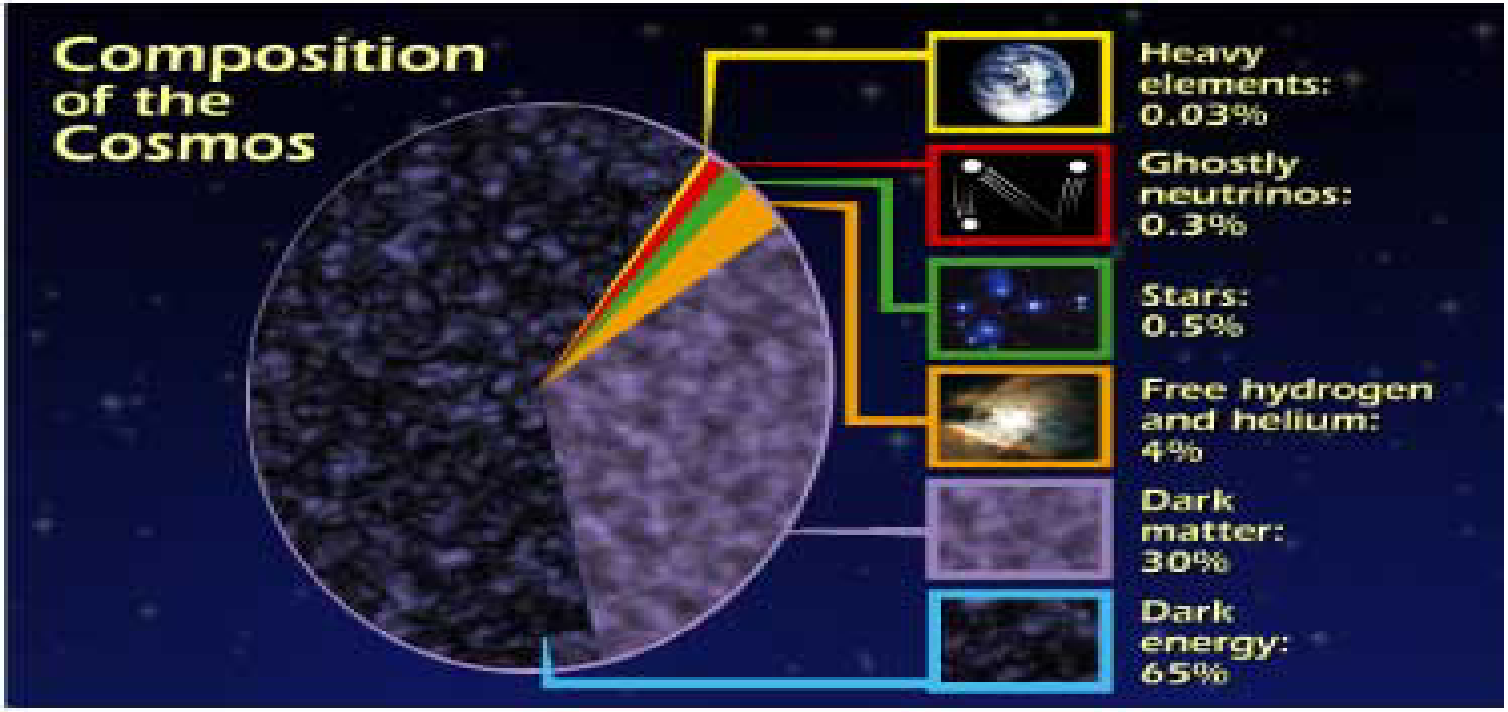
Riess, et al. (2004)



WMAP (2003)

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

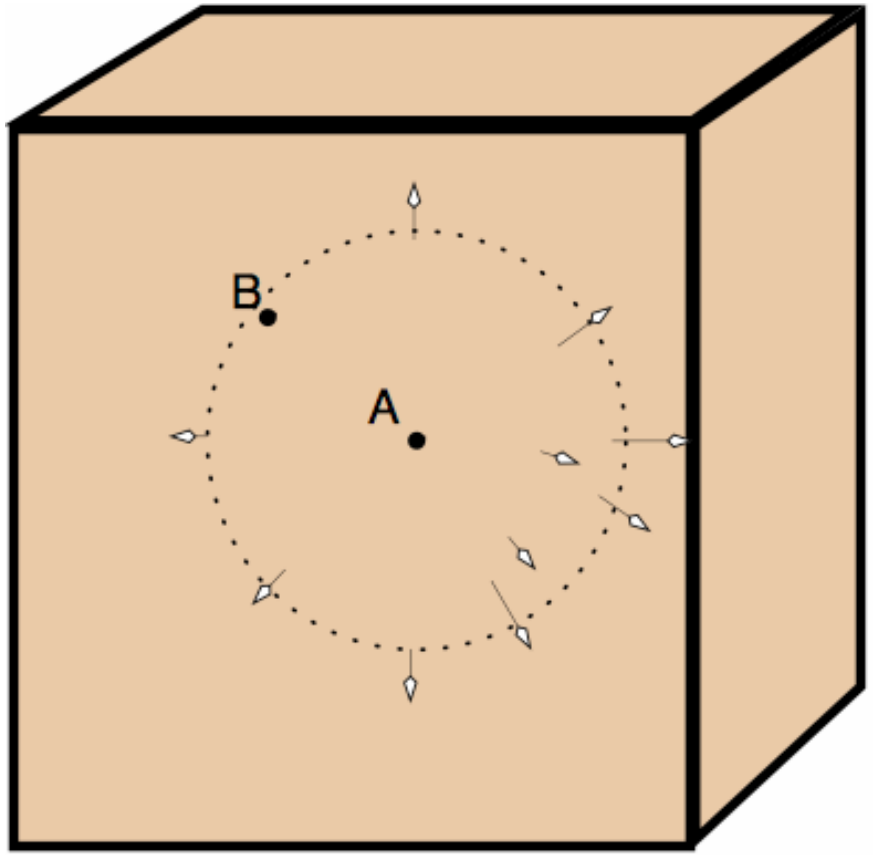
- **How to differentiate DE from MG?**
  - Powerful idea: using gravity to create local physics **and** cosmology
  - Can one deduce force law from cosmology?
  - Can one manufacture cosmological information from force law?
- **Powerful enough?**
  - Well…

The Contemporary Universe

- **Cosmology and the Friedmann equation**

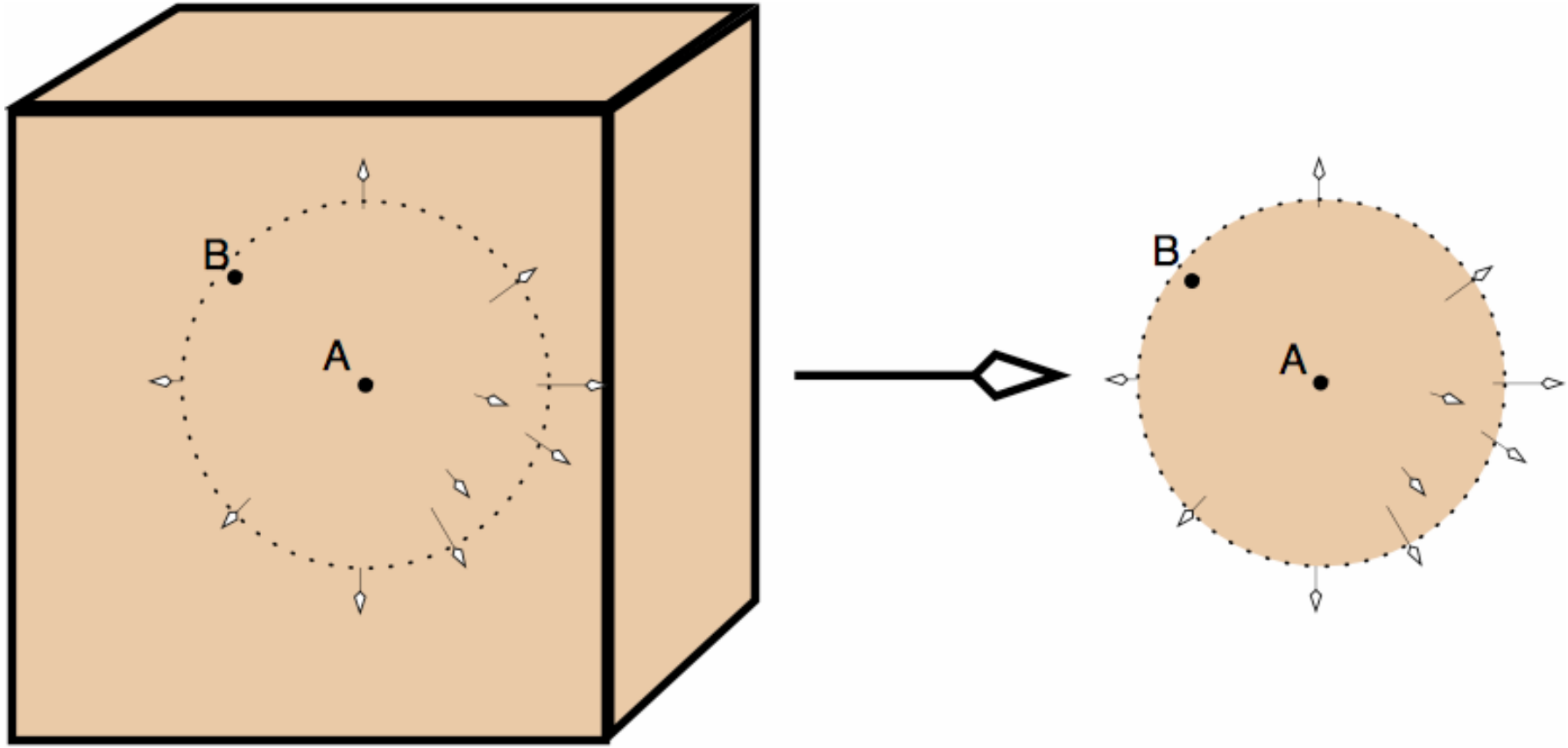
$$G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

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



The Contemporary Universe

- **Cosmology and the Friedmann equation**

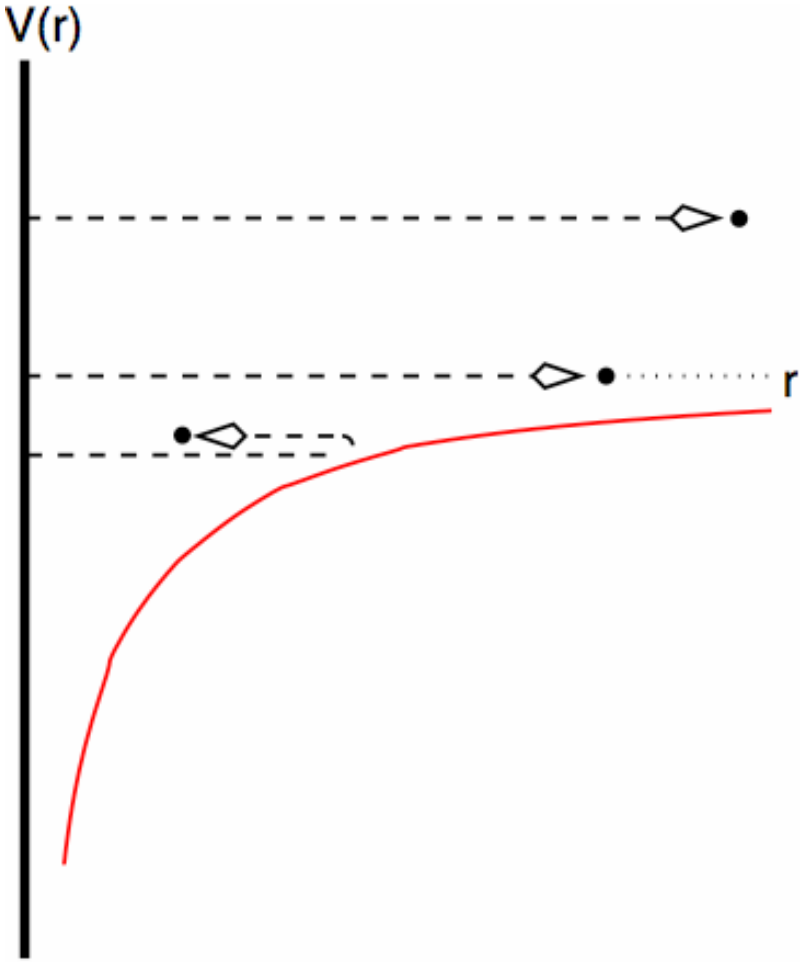


The Contemporary Universe

- **Cosmology and the Friedmann equation**
  - Pure matter domination

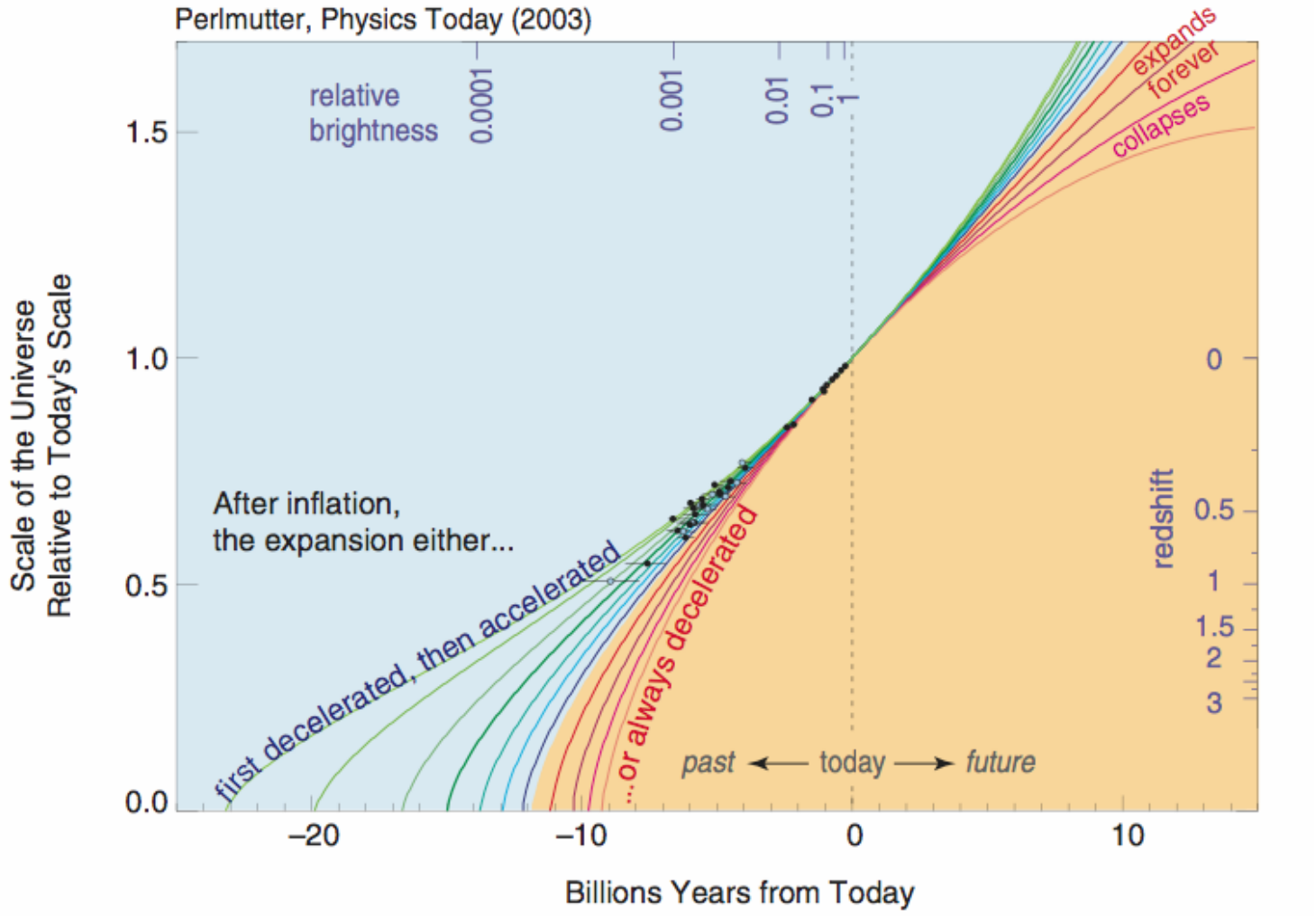
$$\frac{1}{2}\dot{r}^2 - \frac{GM}{r} = E$$

$$H^2 = \left(\frac{\dot{r}}{r}\right)^2 = \frac{8\pi G}{3}\rho + \frac{E}{r^2}$$



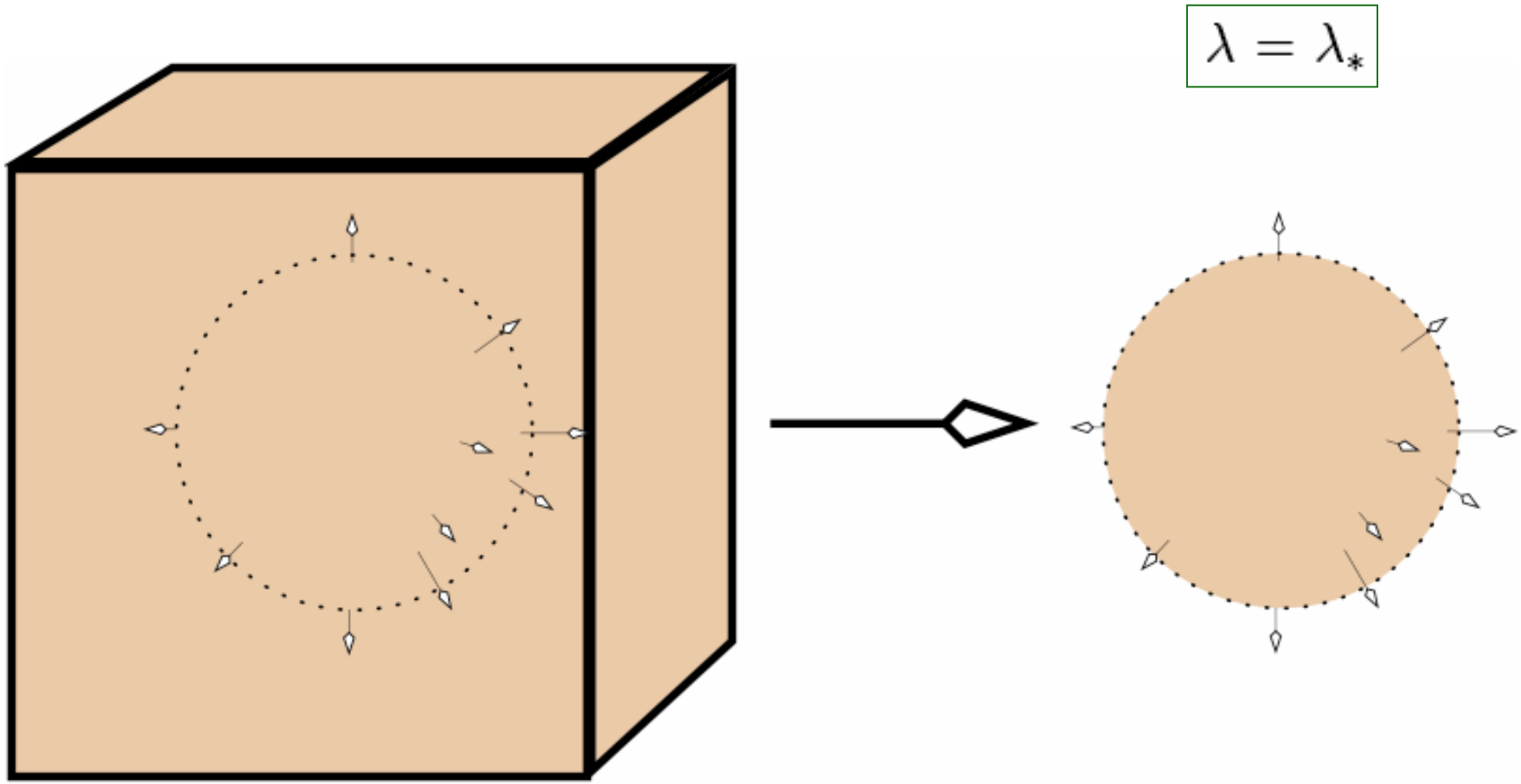
Modified Gravity

- **The picture**



Modified Gravity

- **The picture**



Modified Gravity

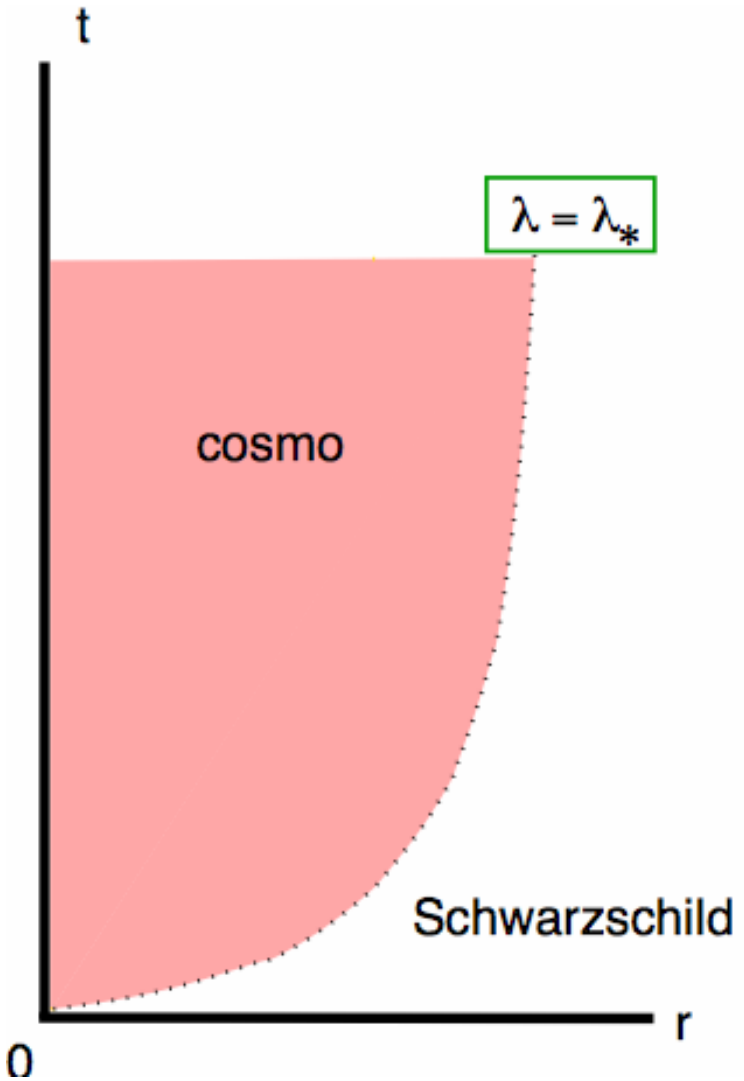
- **Matching metrics**
  - Inside $\lambda = \lambda_*$: cosmological

$$ds^2 = dt^2 - a^2(t)\ \delta_{ij} dx^i dx^j$$
$$= dt^2 - a^2(t)\left[d\lambda^2 + \lambda^2 d\Omega\right]$$

  - Outside $\lambda = \lambda_*$: Schwarzschild (empty)

$$r(t, \lambda_*) = \lambda_* a(t)$$

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

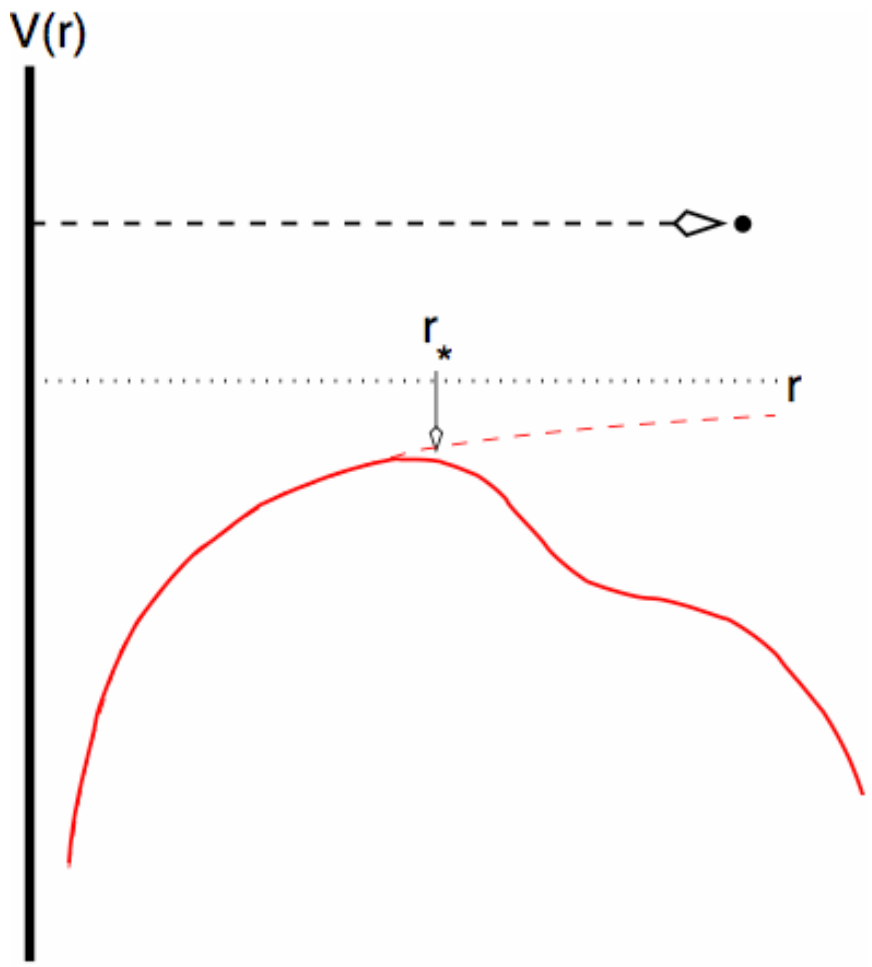


• Lue, Scoccimarro, Starkman PRD**69**:044005(2004)

Modified Gravity

- **The Schwarzschild-like metric**

$$g_{00} = E^2(1 - \lambda_*^2 \dot{a}^2)$$
$$g_{rr}^{-1} = 1 - \lambda_*^2 \dot{a}^2$$



• Lue, Scoccimarro, Starkman PRD**69**:044005(2004)

Modified Gravity

- **Governing scales**

$$r_g = 2GM$$

  - Einstein regime: $H > H_0$

$$H^2 \equiv \frac{\dot{a}^2}{a^2} = \frac{8\pi G}{3}\rho$$

  - Einstein regime: $r < r_*$

$$g_{00}(r) = g_{rr}^{-1}(r) = 1 - \frac{r_g}{r}$$

$$r_* = \left(\frac{r_g}{H_0^2}\right)^{1/3}$$

• Lue, Scoccimarro, Starkman PRD**69**:044005(2004)

Modified Gravity

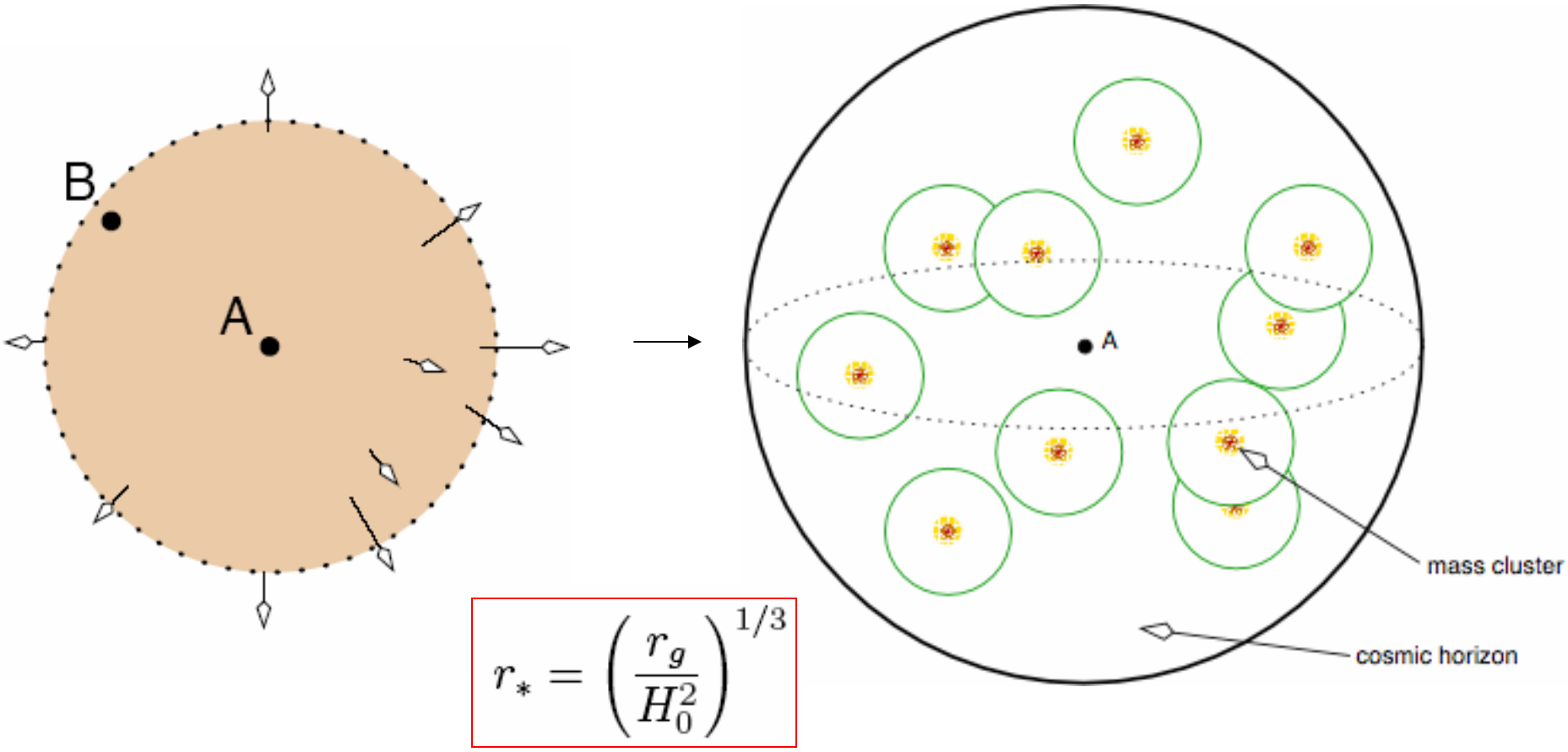
- **Modified Newton's Law**
  - Values for r_*:

Earth	**4 lightyears**
Sun	**420 lightyears**
Milky Way (10^{12} solar masses)	**4 million lightyears**

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

Modified Gravity

- **Observer's point of view**

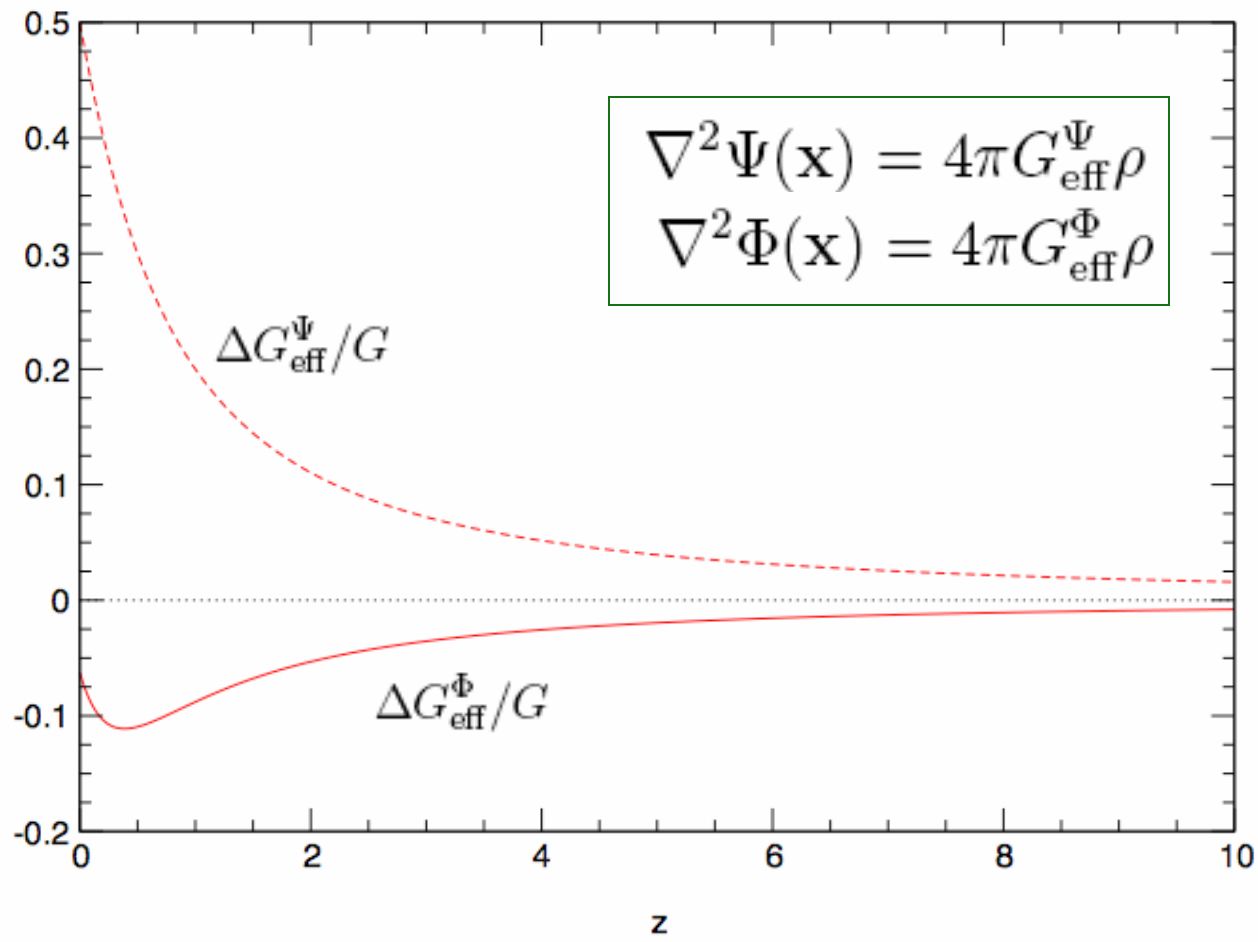


$$r_* = \left(\frac{r_g}{H_0^2}\right)^{1/3}$$

• Lue, Starkman PRD**67**:064002(2003); Lue, Scoccimarro, Starkman PRD**69**:044005(2004)

Dark Energy versus Modified Gravity

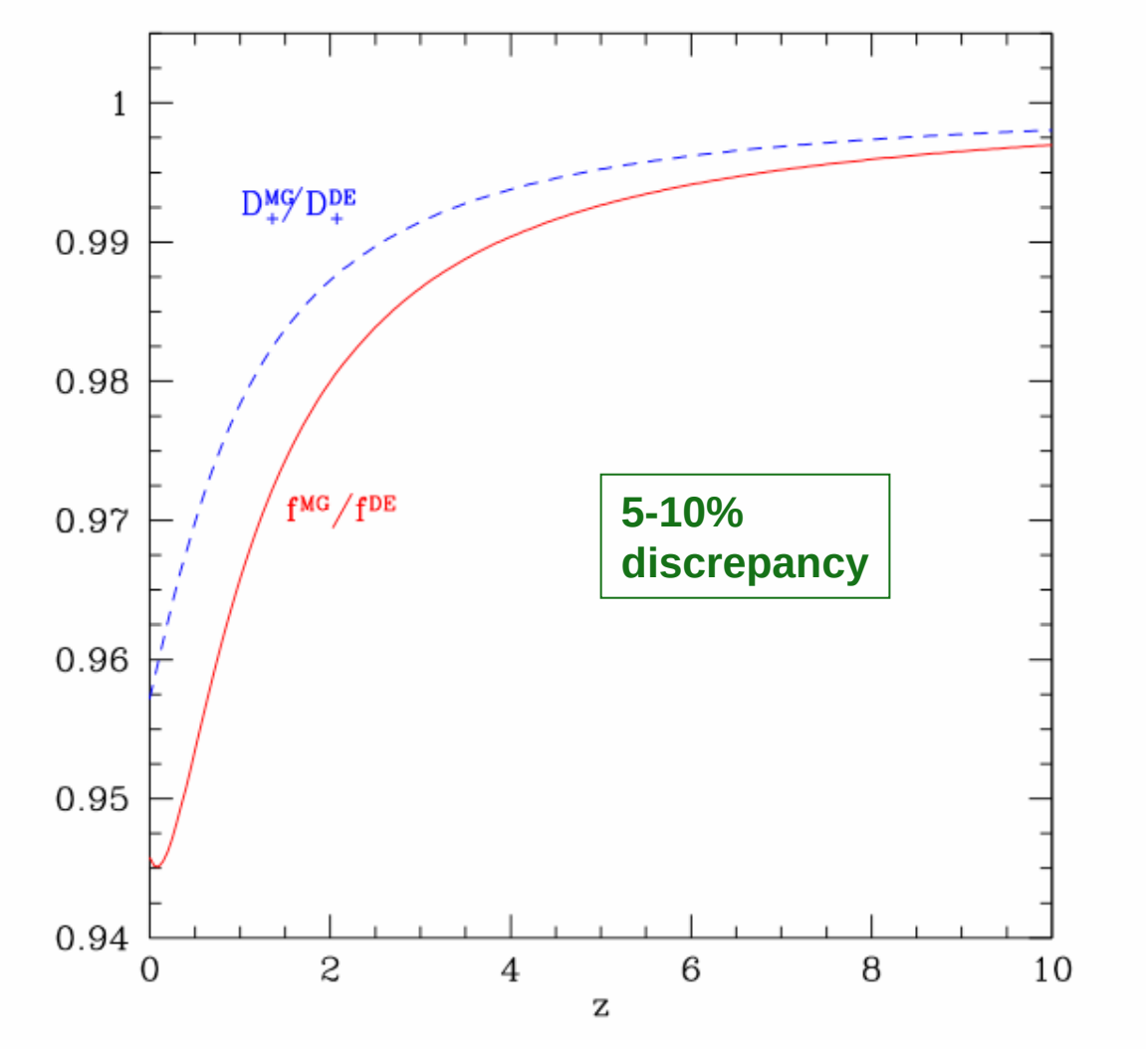
- **Effective Newton's constants** $ds^2 = [1+2\Psi(t,\lambda)]\,dt^2 - \bar{a}^2(t)\,[1+2\Phi(t,\lambda)]\left[d\lambda^2 + \lambda^2 d\Omega\right]$



• Lue, Scoccimarro, Starkman PRD**69**:044005(2004)

Dark Energy versus Modified Gravity

- **Growth of large-scale structure**

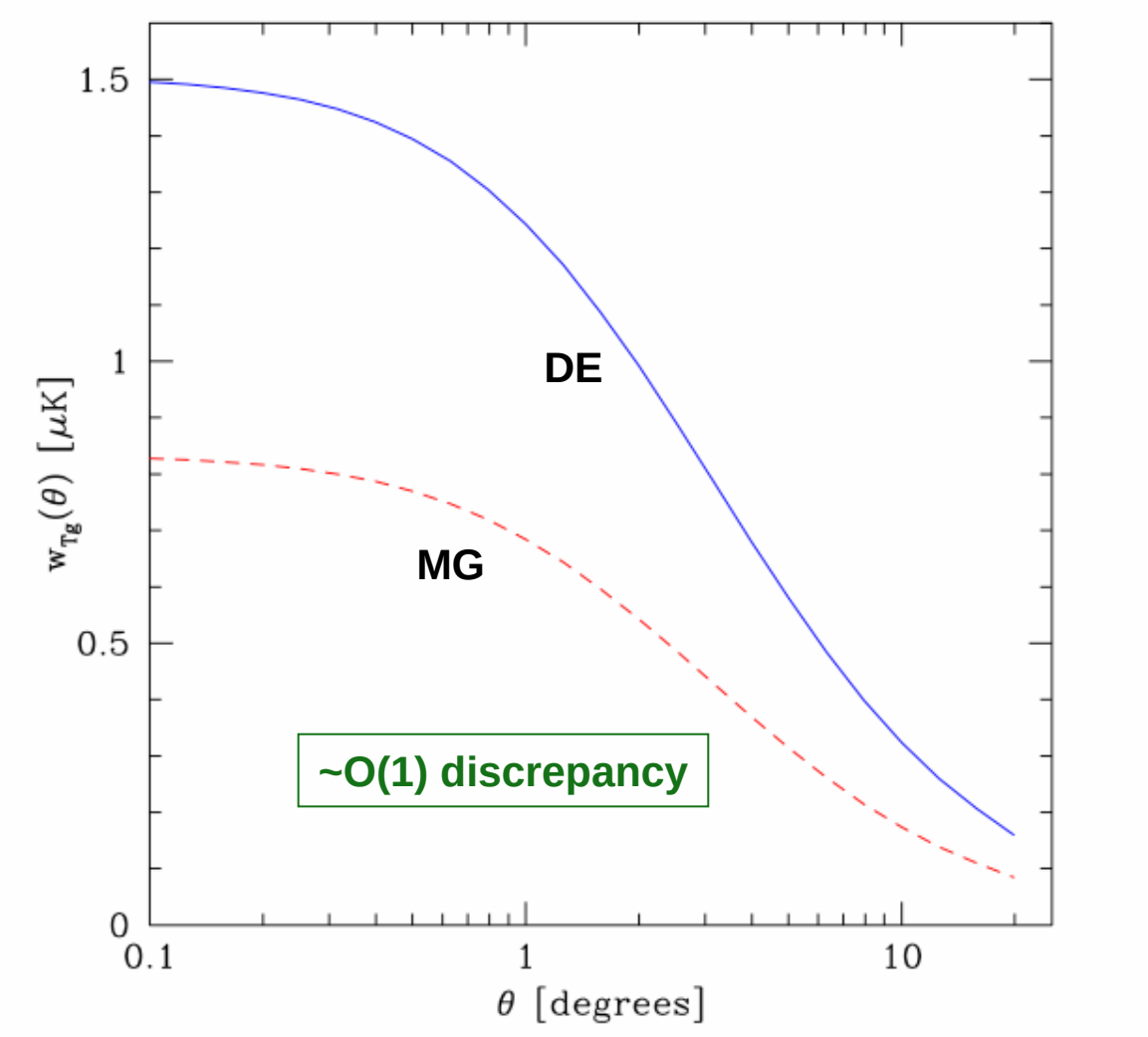


• Lue, Scoccimarro, Starkman PRD**69**:044005(2004)

Dark Energy versus Modified Gravity

- **Late-time ISW**

$$\nabla^2 \left[\Phi(\mathbf{x}) - \Psi(\mathbf{x})\right] = 4\pi \left[G_{\rm eff}^{\Phi} - G_{\rm eff}^{\Psi}\right] \rho$$



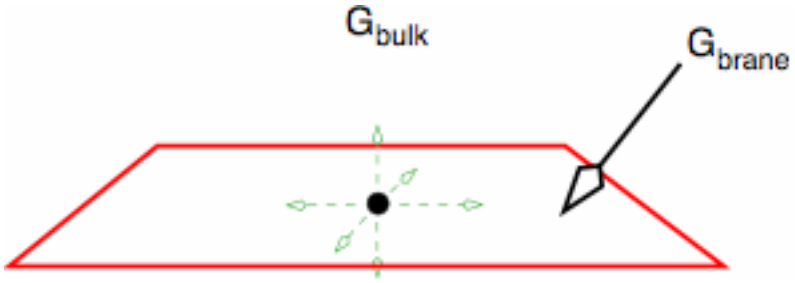
• Lue, Scoccimarro, Starkman PRD**69**:044005(2004)

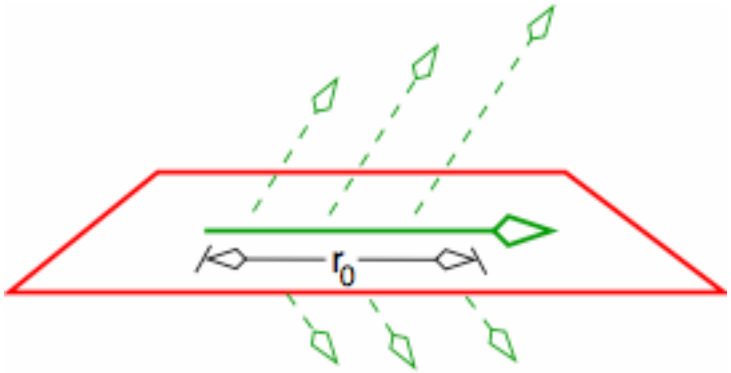
Dark Energy versus Modified Gravity

- **Differentiation between DE and MG through discrepant force-law**
- **Anomalous structure growth, even with identical expansion history**
- **Can see both in σ_8 and in late-time ISW**

Braneworlds and Modified Gravity

- **Braneworld model of Dvali, Gabadadze and Porrati**
  - Gravity theory with effective metastable graviton
  - Modifications to Einstein gravity occur at large (rather than short) distances





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

Braneworlds and Modified Gravity

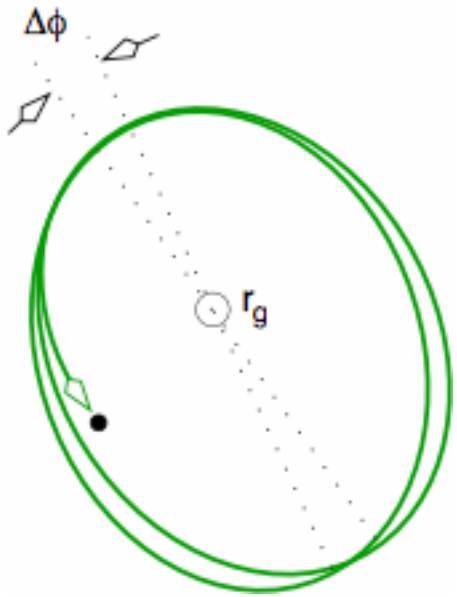
- **Braneworld model of Dvali, Gabadadze and Porrati**

  – Modification of gravity occur at r_*

  – Large-scale structure affected in analogous ways

  10% discrepancy

  – Even residual solar-system measurements (anomalous precessions)

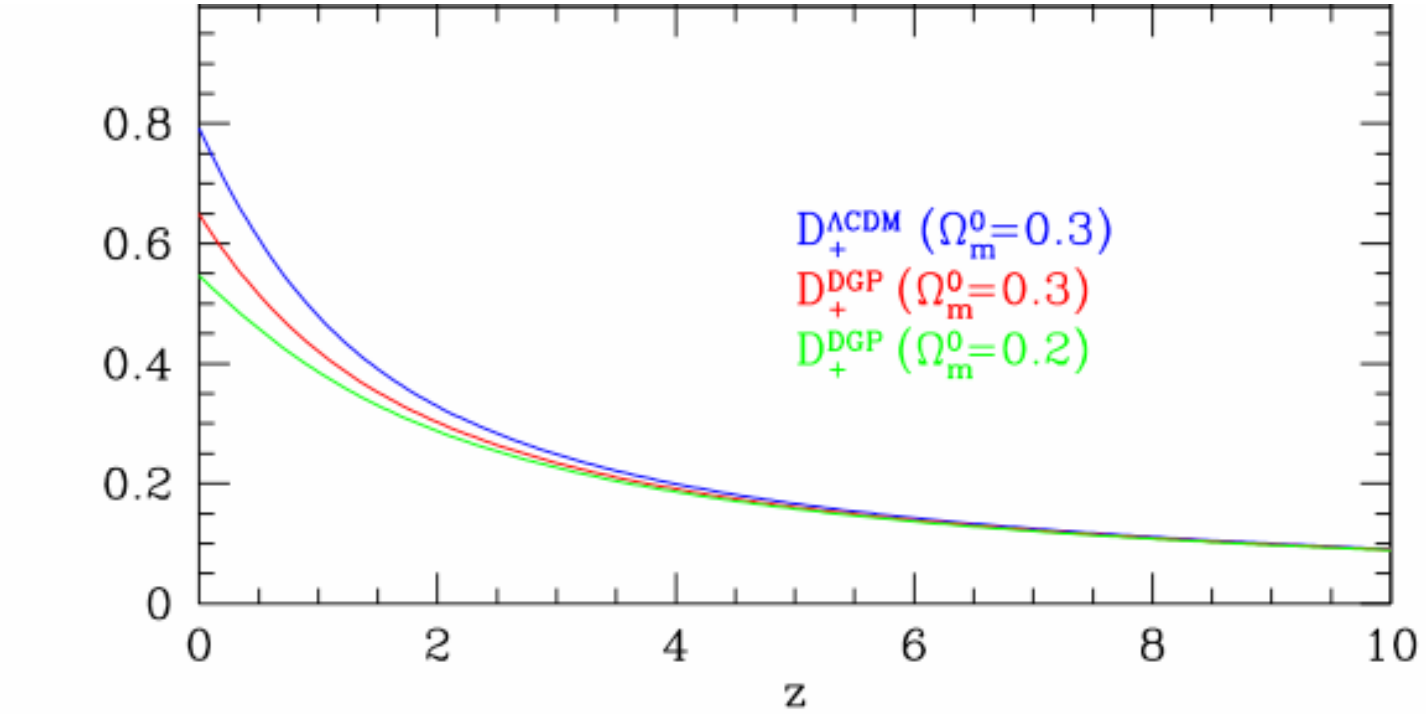


$$\frac{d}{dt}\Delta\phi_{\rm DGP} = \mp\frac{3}{8r_0} = \mp 5\ \mu{\rm as/year}$$

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

Braneworlds and Modified Gravity

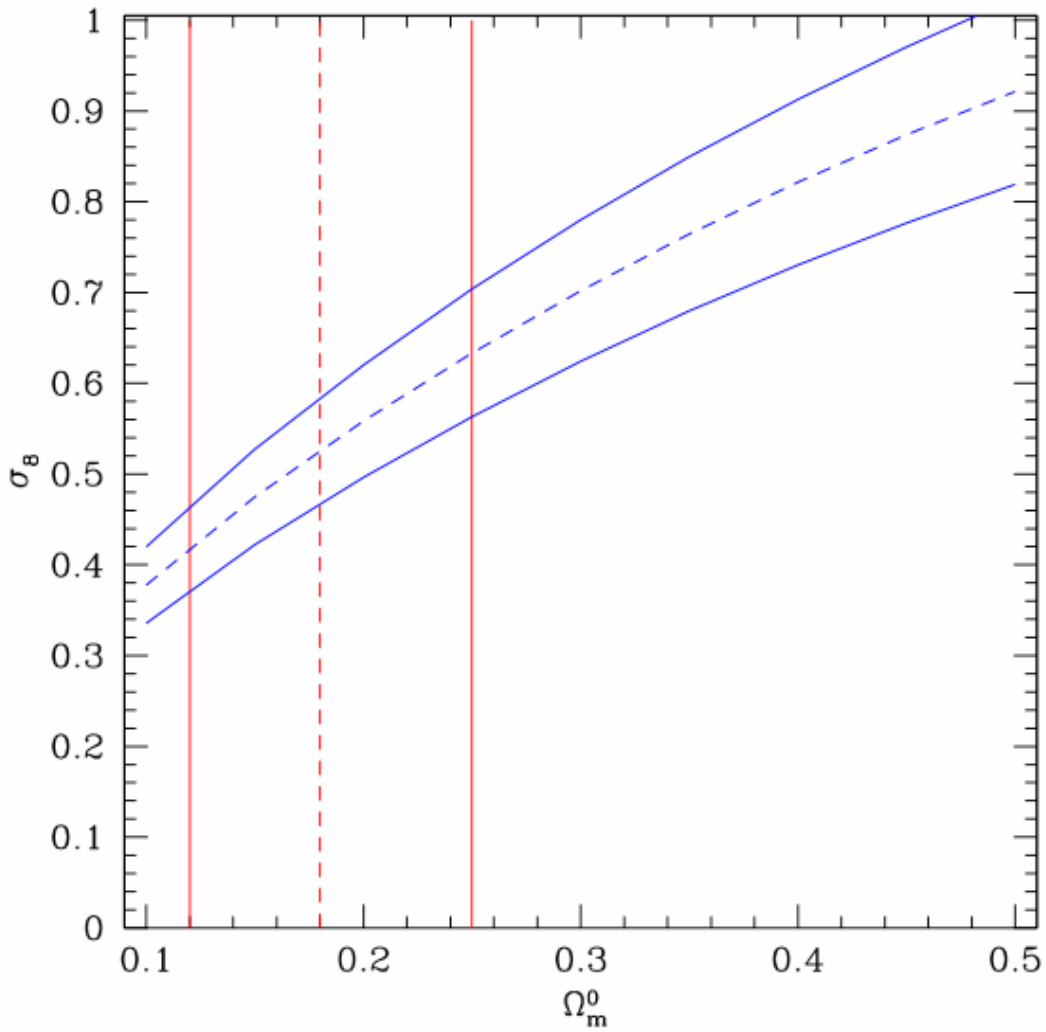
- **Growth of large-scale structure**



• Lue, Scoccimarro, Starkman astro-ph/0401515

Braneworlds and Modified Gravity

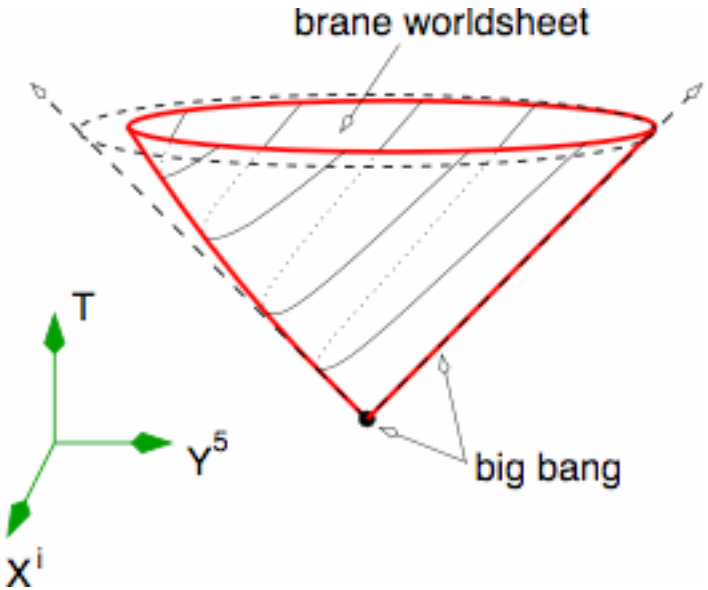
- **Linear growth**



• Lue, Scoccimarro, Starkman astro-ph/0401515

Braneworlds and Modified Gravity

- **Braneworld model of Dvali, Gabadadze and Porrati**
  - Easily accommodates $w_{eff} < -1$ through modification of Friedmann equation



• Deffayet PLB**502**:199(2001); Sahni, Shtanov JCAP**0311**:014(2003) ; Lue, Starkman astro-ph/0408246

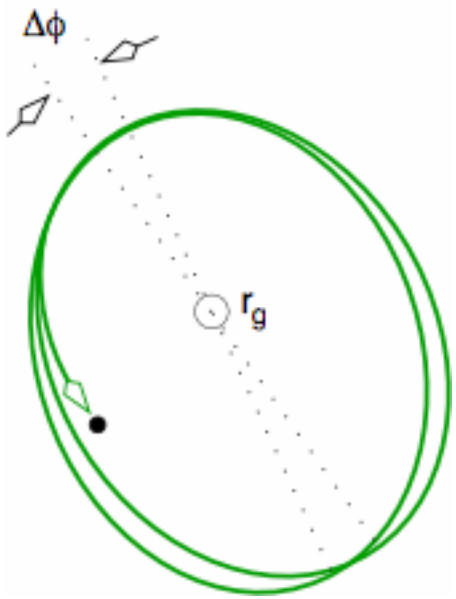
Remarks

- **Modified gravity is a distinct paradigm for cosmic acceleration**
  - Using gravity for both local attraction and cosmology a powerful idea
  - Distinct from dark energy paradigm
  - Subject to imminent observational discrimination

The Contemporary Universe

- **Actually, rather a lot…**

  – Dramatic successes



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

$$V_{\text{grav}} = \frac{1}{2}\left(g_{00} - 1\right) = -\frac{r_g}{2r}$$

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

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

  – Intimate connection between matter, geometry and gravity

Braneworlds and Modified Gravity

- **Einstein gravity in 5-dimensions**

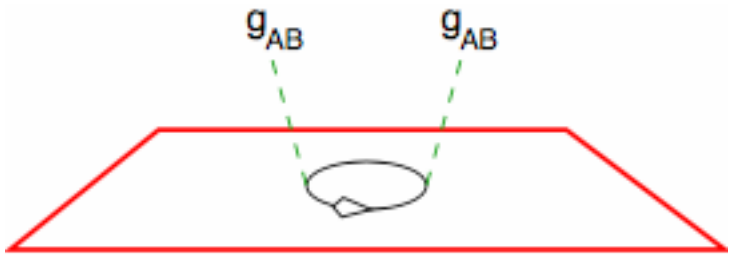
$$S_{(5)} = -\frac{1}{16\pi} M^3 \int d^5x\sqrt{-g}\ R + \int d^4x\sqrt{-g^{(4)}}\ \mathcal{L}_m + S_{GH}$$

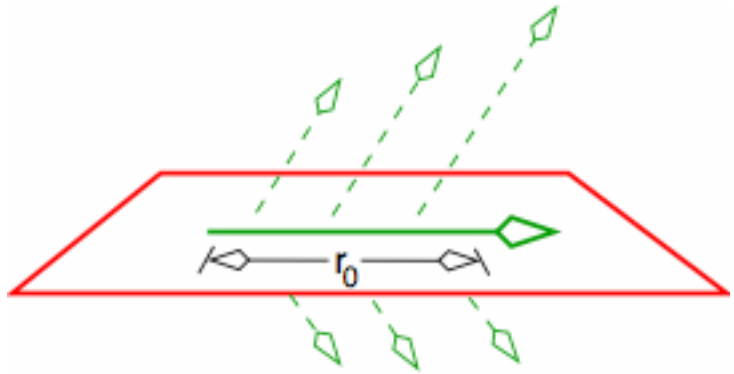
$$g^{(4)}_{\mu\nu} = \partial_\mu X^A \partial_\nu X^B g_{AB}$$

- **Intrinsic curvature term**

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

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

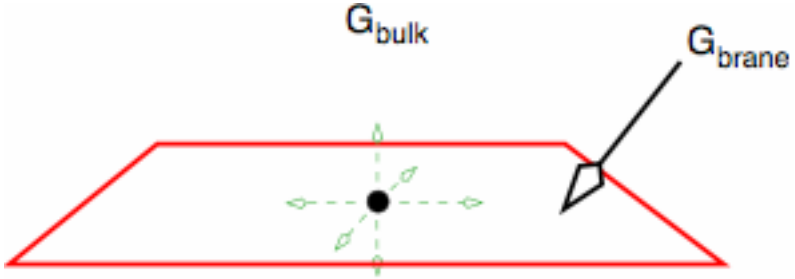




• Dvali,Gabadadze,Porrati PLB**485**:208(2000); Dvali,Gabadadze,Kolanovic,Nitti PRD**64**:084004(2001), **65**:024031(2002)

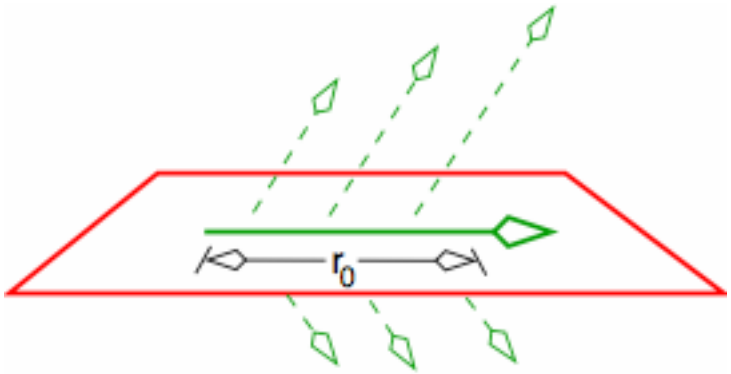
Braneworlds and Metastable Gravitons

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



$$r_0 = \frac{G_{\rm bulk}}{2G_{\rm brane}}$$

- **Brane gravity appears metastable**



short distances: 4-dimensional

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

long distances: 5-dimensional

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

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

Braneworld Cosmology

- **The Friedmann equation**

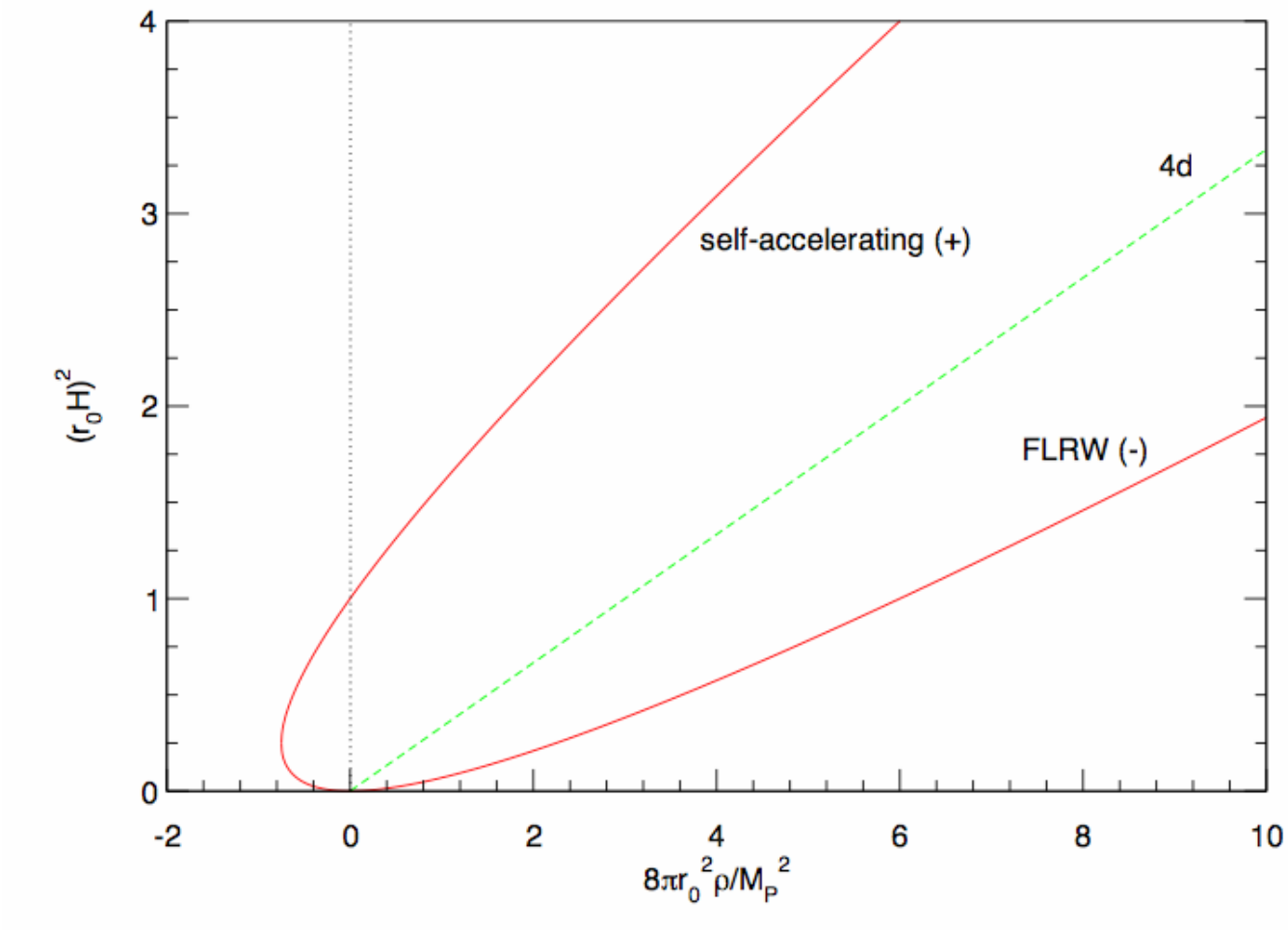
$$H^2 \pm \frac{1}{r_0} H = \frac{8\pi G}{3}\rho$$

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

• Deffayet PLB**502**:199(2001)

Braneworld Cosmology

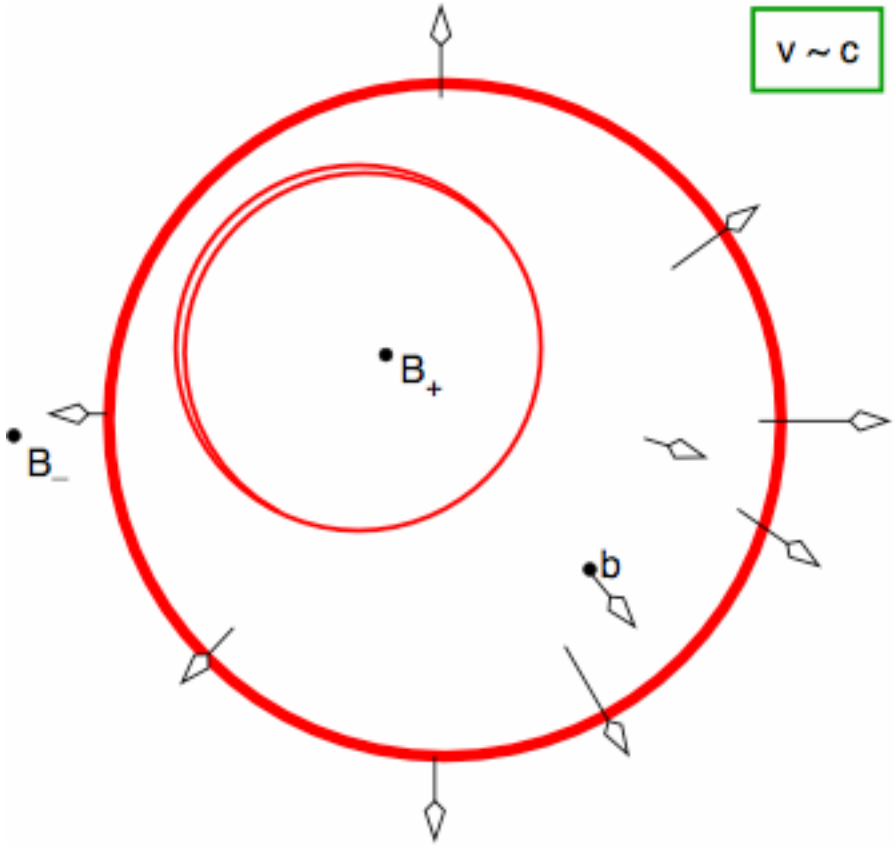
- **The Friedmann equation**

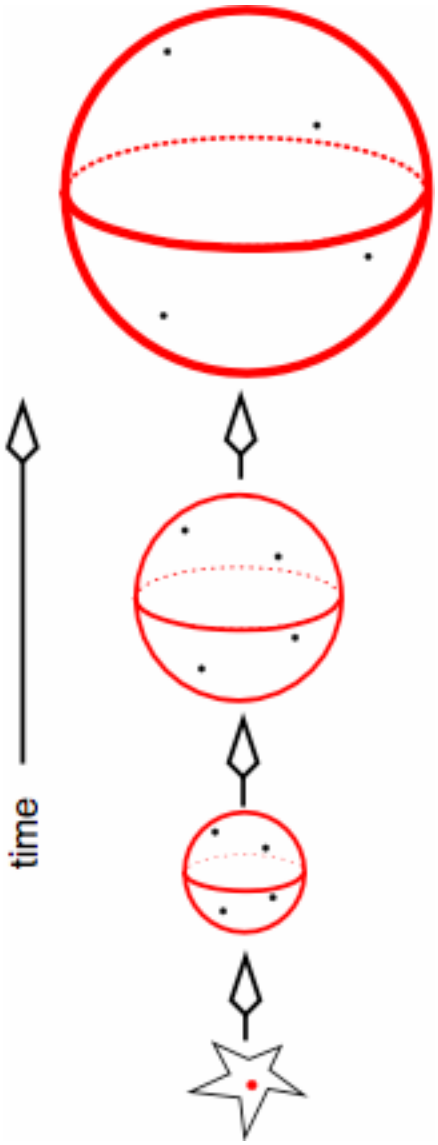


• Deffayet PLB**502**:199(2001)

Braneworld Cosmology

- **Global structure**





• Lue PRD**67**:064004(2003)

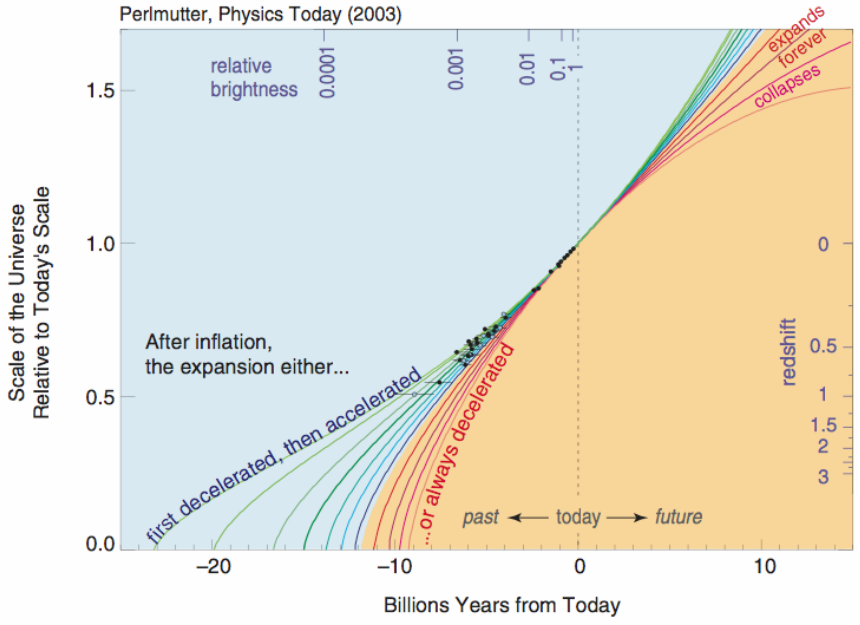
Braneworld Cosmology

- **Constraints on r_0**
  - Friedmann equation

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

  - Self-accelerating phase

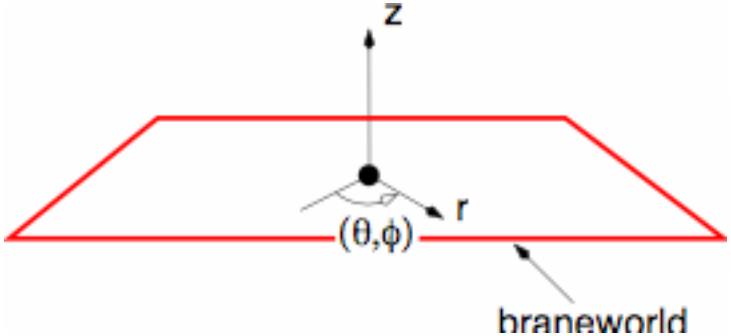
$$r_0 = 1.21^{+0.09}_{-0.09}\, H_0^{-1} \sim 5\ \mathrm{Gpc}$$



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

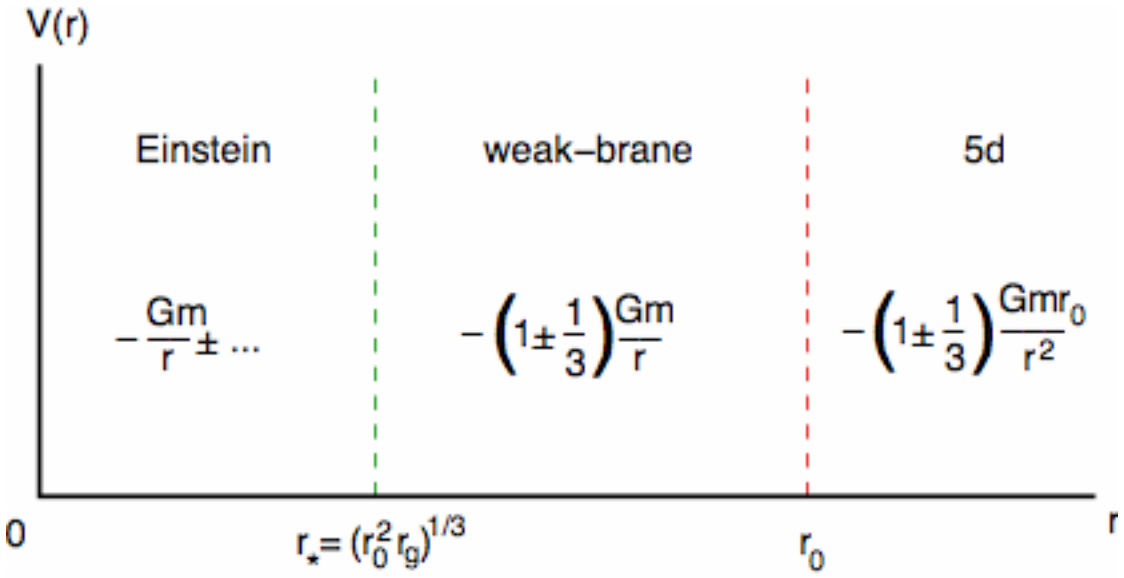
Braneworld Gravity

- **Modified Newton's law**



mass = m

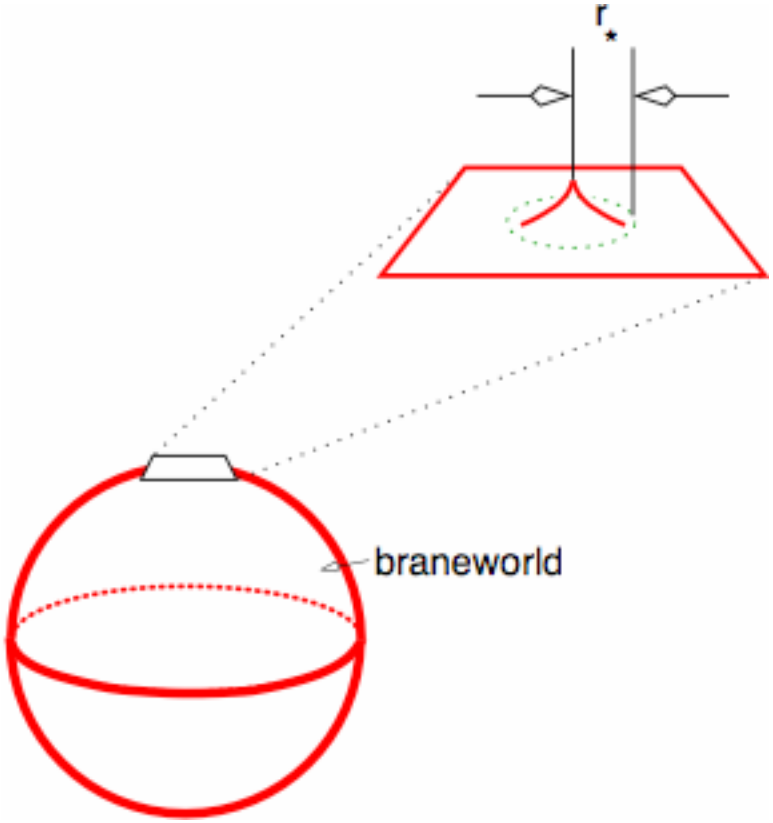
Schwarzschild radius, $r_g = 2Gm$



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

Braneworld Gravity

- **Strong gravity, dynamic extrinsic curvature**



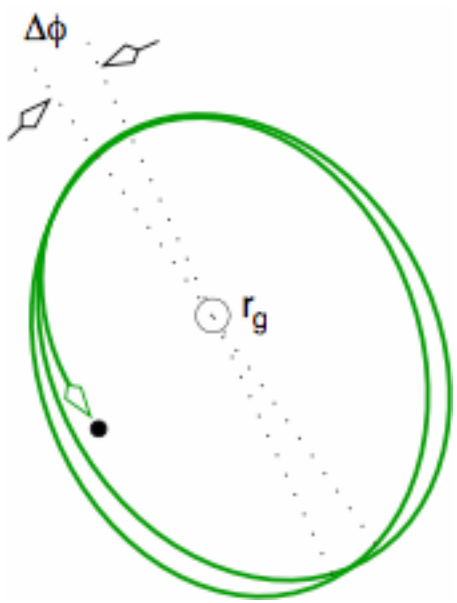
•Lue PRD**66**:043509(2002); Lue, Starkman PRD**67**:064002(2003)

Physical Considerations

- **Orbit precession**

  – Per orbit

$$\Delta\phi = 2\pi + \frac{3\pi r_g}{r} \mp \frac{3\pi}{2}\left(\frac{r^3}{2r_0^2 r_g}\right)^{1/2}$$



  – DGP anomalous precession rate

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

• Lue, Starkman PRD**67**:064002(2003)

Physical Considerations

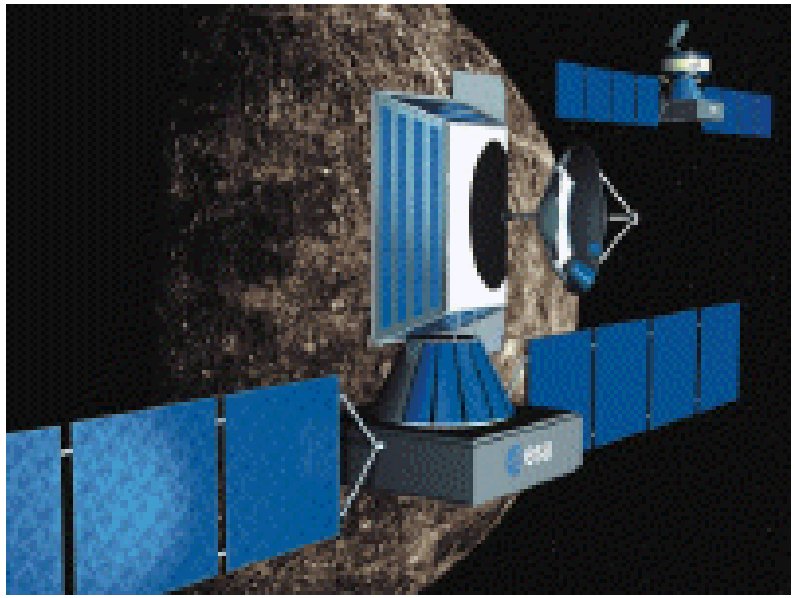
- **Orbit precession**
  - Uncertainties:

Mercury: < 430 μas/year

< 1 μas/year (2009-2010)

Moon: < 10 μas/year

Mars: < 10 μas/year

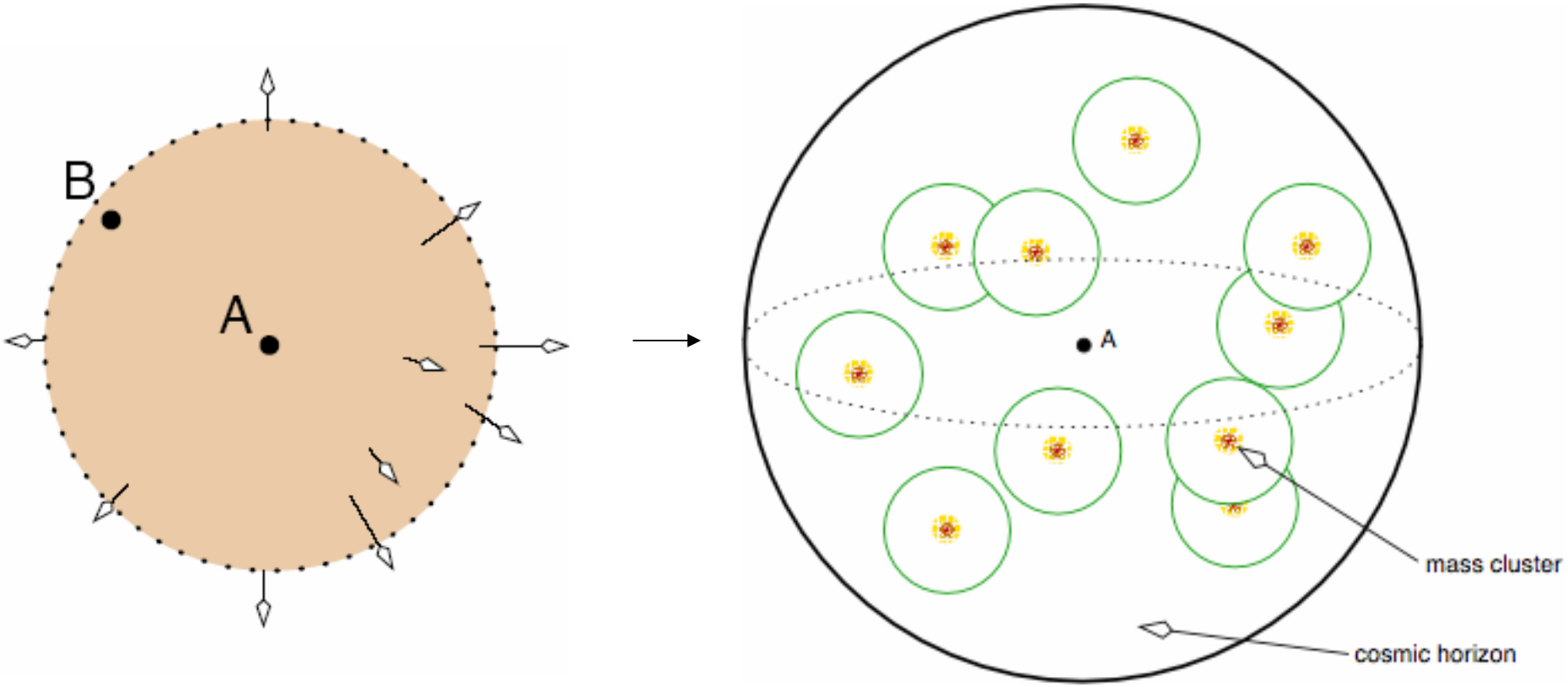


BepiColombo (ESA)

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

Physical Considerations

- **Growth of large-scale structure**



• Lue, Scoccimarro, Starkman astro-ph/0401515