The Ubiquity of the Fifth Force

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Constants aren’t Constants

- Higgs $\quad m\bar{\Psi}\Psi \to \lambda\phi\bar{\Psi}\Psi$
- $\Lambda \quad \Lambda \to V(\phi)$
- G $\quad ``\Box G \simeq \rho"$

$$\frac{1}{12}\alpha\phi^2 R$$

Gravity isn't (Einstein) Gravity

Curvature

$$\frac{1}{16\pi G}\int d^4x\sqrt{-g}[R(g)-2\Lambda]+\int d^4x\sqrt{-g}\mathcal{L}(g,\mathrm{matter})$$

Metric of space-time

Lovelock's theorem (1971) :*"The only second-order, local gravitational field equations derivable from an action containing solely the 4D metric tensor (plus related tensors) are the Einstein field equations with a cosmological constant."*

See also Hojman, Kuchar & Teitelboim (1976)

Gravity isn't (Einstein) Gravity

metric → add ϕ , A^{μ} ,$f_{\alpha\beta}$ etc.

4D → e.g. in 5 dimensions:

$$g_{AB} = \begin{pmatrix} g_{\alpha\beta} & A_{\alpha} \\ A_{\beta} & \phi \end{pmatrix}$$

2nd order → e.g. if $\int d^4x\sqrt{-g}f(R)$ define $\phi = \frac{df}{dR}$.

Local → e.g. $\phi = \frac{R}{\Box}$.

All transform differently under diffeomorphisms

Gravity isn't (Einstein) Gravity

$$S = \int d^4x\sqrt{-g}\left\{\sum_{i=2}^{5}\mathcal{L}_i[\phi, g_{\mu\nu}] + \mathcal{L}_M[g_{\mu\nu}, \varphi]\right\}$$

$$\begin{aligned}
\mathcal{L}_2 &= K, \\
\mathcal{L}_3 &= -G_3\Box\phi, \\
\mathcal{L}_4 &= G_4R + G_{4X}\left\{(\Box\phi)^2 - \nabla_\mu\nabla_\nu\phi\nabla^\mu\nabla^\nu\phi\right\}, \\
\mathcal{L}_5 &= G_5G_{\mu\nu}\nabla^\mu\nabla^\nu\phi - \frac{1}{6}G_{5X}\left\{(\nabla\phi)^3 - 3\nabla^\mu\nabla^\nu\phi\nabla_\mu\nabla_\nu\phi\Box\phi\right. \\
&\quad \left.+2\nabla^\nu\nabla_\mu\phi\nabla^\alpha\nabla_\nu\phi\nabla^\mu\nabla_\alpha\phi\right\}.
\end{aligned}$$

where $X = \frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi$

Horndeski 1974

Deffayet et al 2009

Fifth Force

Define $M^2 = -\frac{\alpha}{6}\phi^2$

to get

$$S_{BD} = -\int d^4x\sqrt{-g}\left[\frac{M^2}{2}R + \frac{\omega_{BD}}{M^2}\partial^\mu M^2 \partial_\mu M^2 + V + L_m\right]$$

Einstein-Hilbert recovered when $\omega_{\rm BD} \sim 1/\alpha \to \infty$

Brans & Dicke 1961

Fifth Force

$$(1-\alpha)\left[\Box\phi + \frac{\nabla_\mu\phi\nabla^\mu\phi}{\phi}\right] + V - 4\phi\frac{dV}{d\phi} = \frac{\rho+3P}{\phi}$$

"Newtonian Limit": $\phi = \phi_0 + \delta\phi$

$$(1-\alpha)\nabla^2\delta\phi + m_\phi^2\delta\phi = -\frac{\rho}{\phi_0} \longrightarrow \delta\phi \sim \frac{M}{r}e^{-m_\phi r}$$

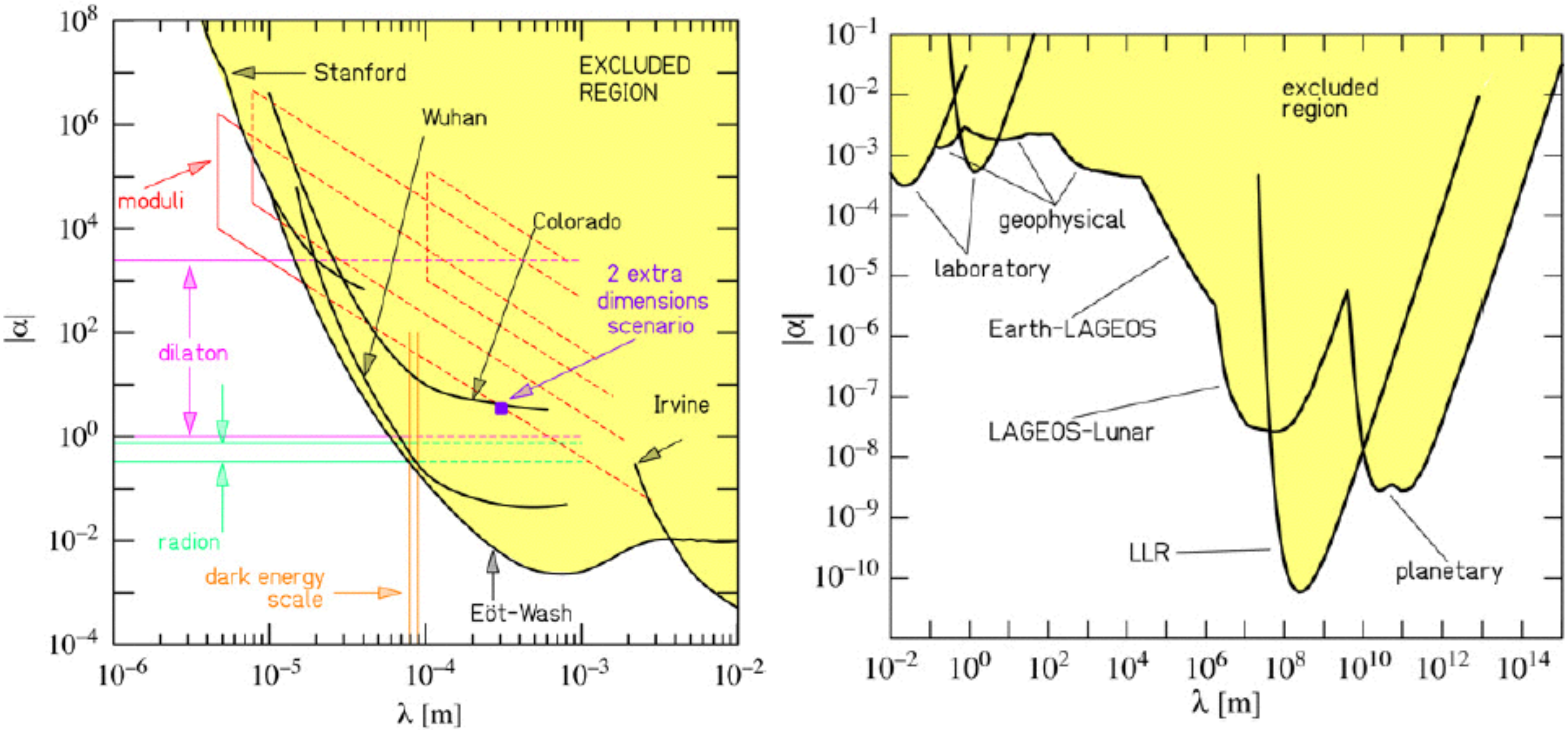
Modified Newtonian Force:

$$F = -\underbrace{\nabla\Phi}_{F_N} - \nabla\delta\phi$$

$$m_\phi^2 \sim \frac{d^2V}{d\phi_0^2}$$

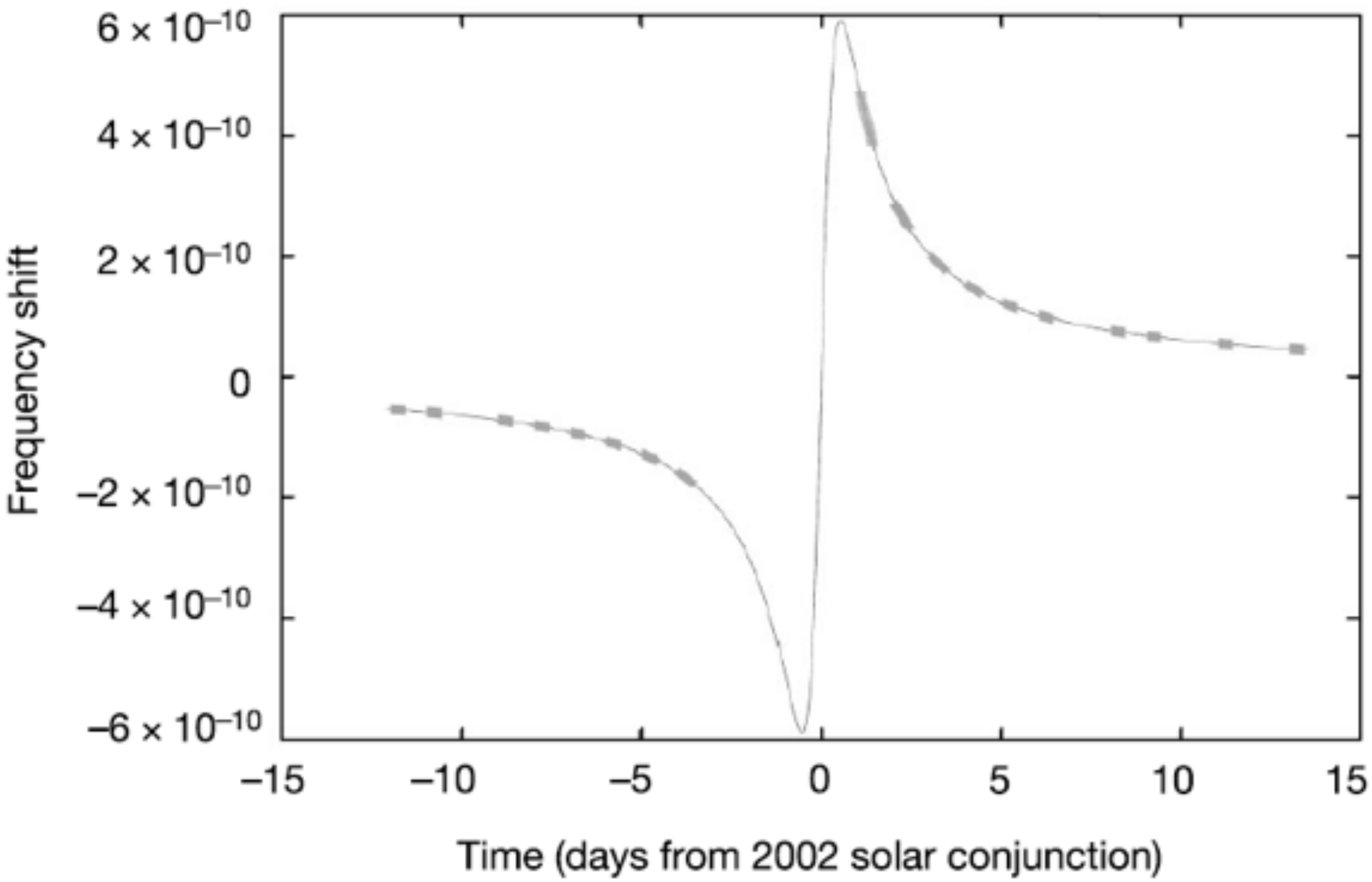
Fifth Force

Adelberger++ (2009)



$$V(r) = -G\frac{m_1 m_2}{r}[1 + \alpha e^{-r/\lambda}]$$

Fifth Force



Bertotti et al 2003

Impact parameter

$$\text{Frequency shift} = -(1 \times 10^{-5}\text{s})(1+\gamma)\frac{d\ln b}{dt}$$

$$\gamma = \frac{2\alpha - 3}{4\alpha - 3} \qquad \gamma = 1 + (2.1 \pm 2.3) \times 10^{-5}$$

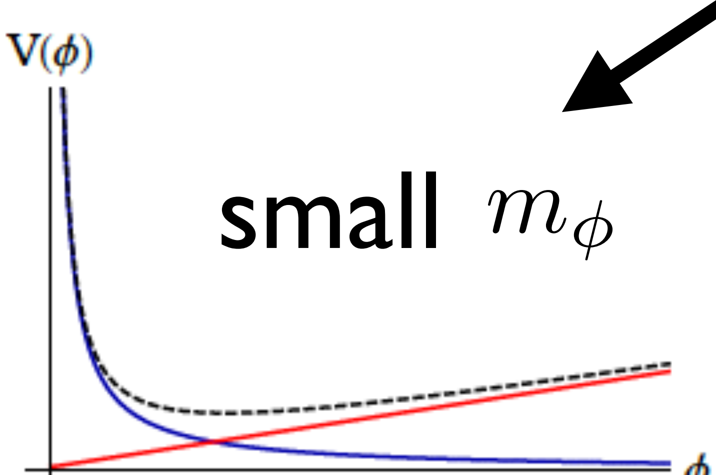
Gravitational Screening

Consider a cosmological background: ρ_0

$$V_{eff} = V + \rho_0 \ln\left[\frac{M^2(\phi)}{M_{\mathrm{Pl}}}\right]^2$$

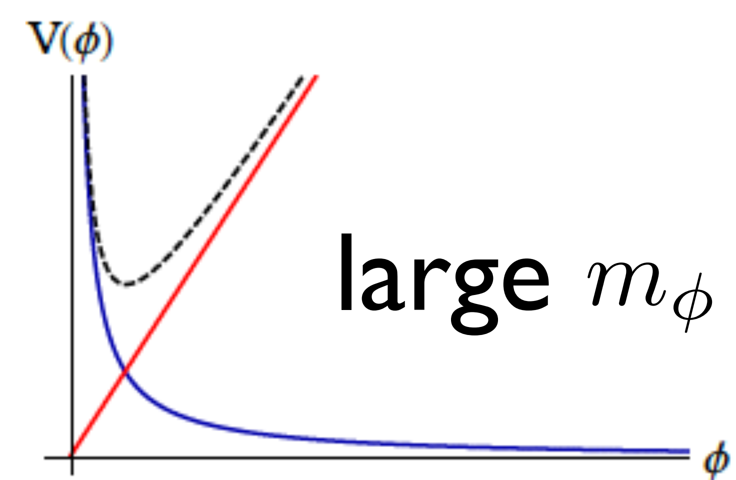
Khoury & Weltman 2003

$$m_\phi^2 = \frac{d^2 V_{eff}}{d\phi^2}$$



small m_ϕ

Chameleon



large m_ϕ

Burrage & Sakstein 2017

Gravitational Screening

Vainshtein Mechanism:

$$\left[1+\frac{c_3}{\Lambda^3}\nabla^2\phi_0\right]\nabla^2\delta\phi = -\frac{\rho}{M}$$

Rescale: $\delta\tilde{\phi} \simeq \left[1+\frac{c_3}{\Lambda^3}\nabla^2\phi_0\right]^{1/2}\delta\phi$

So $\quad \nabla^2\delta\tilde{\phi} \simeq -\frac{1}{[1+(c_3/\Lambda^3)\nabla^2\phi_0]^{1/2}}\frac{\rho}{M}$

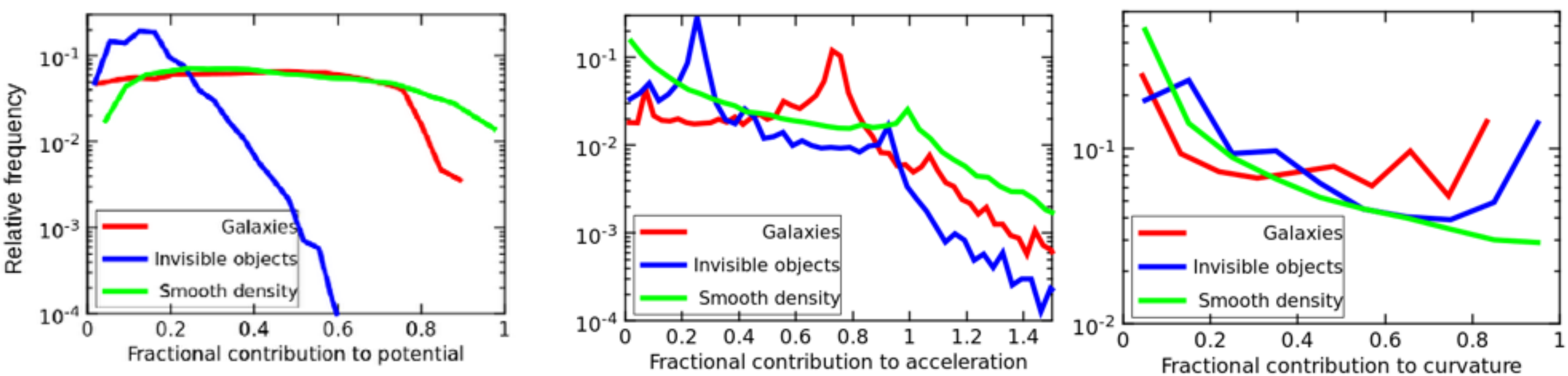
Coupling to matter $\longrightarrow$ 0 near sources

Vainshtein 1972 Nicolis++ 2007

Gravitational Screening

Construct gravitational maps of the Universe

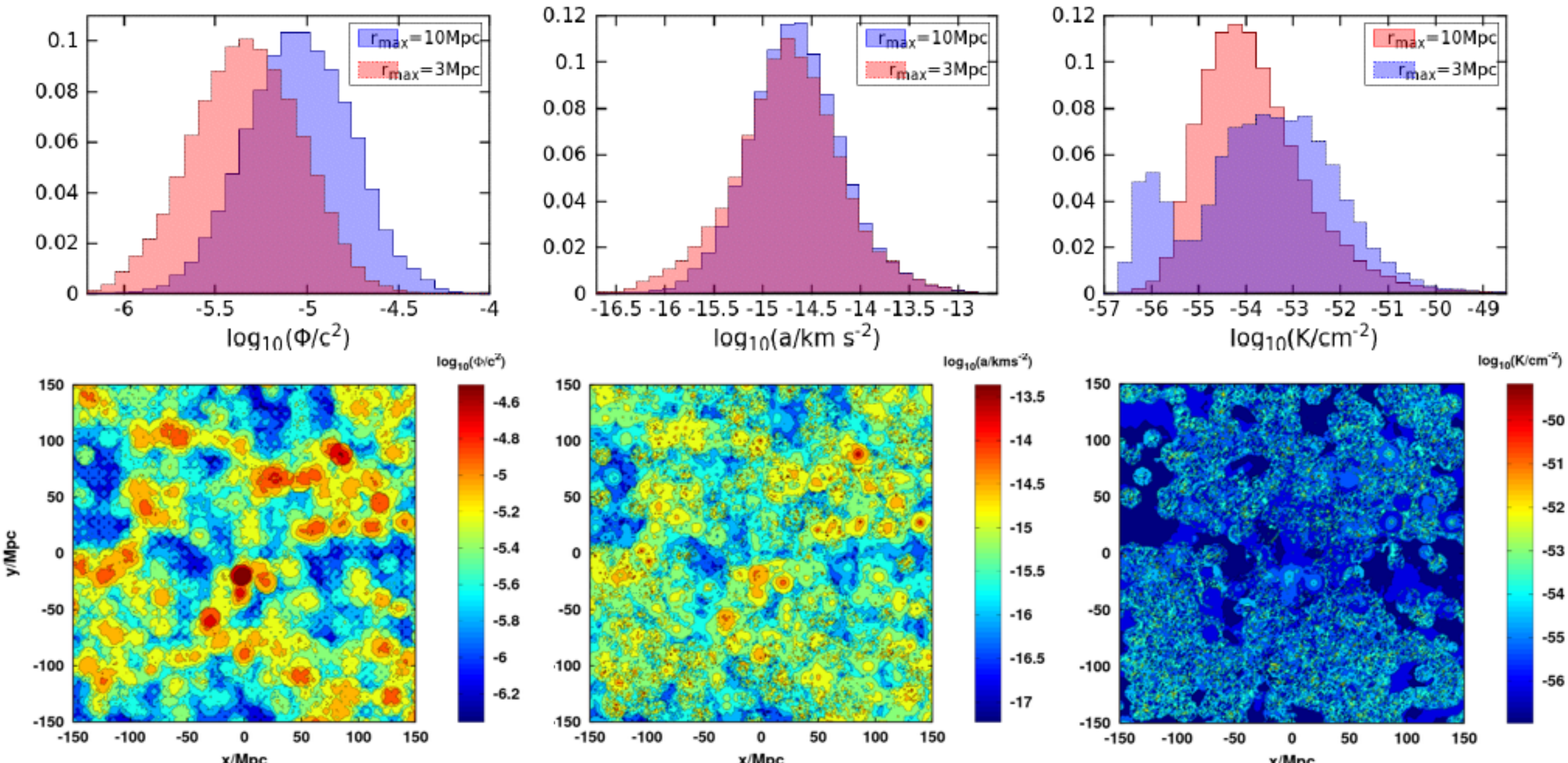
- Mass in smoothed density field
- Halo mass associated with 2M++ galaxies
- Halos hosting galaxies too faint to see



Desmond, Ferreira, Lavaux, Jasche 2017

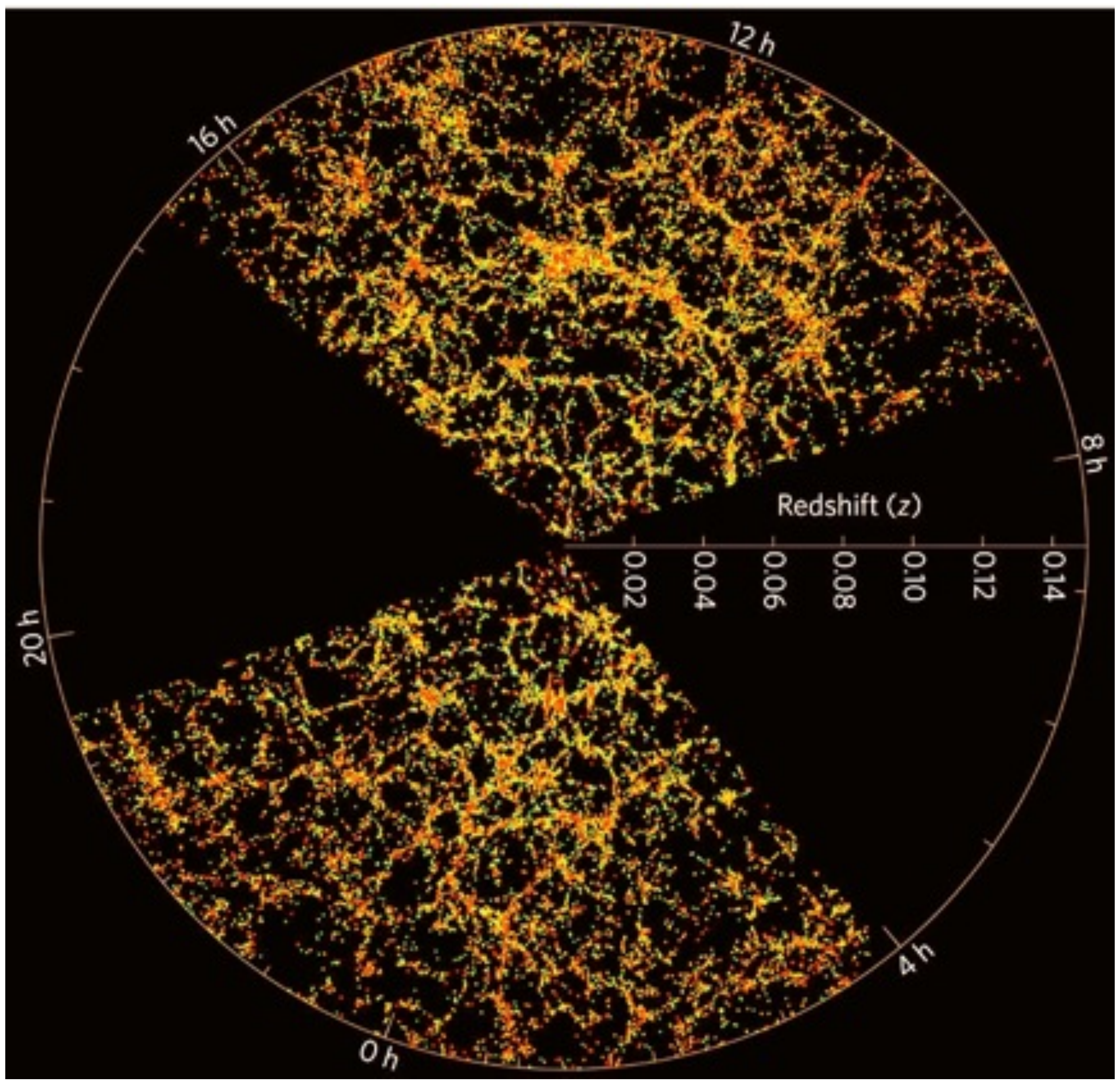
Gravitational Screening

Construct gravitational maps of the Universe



Desmond, Ferreira, Lavaux, Jasche 2017

Large Scale Structure



Large Scale Structure

Most surveys very sub-horizon $\simeq 3000h^{-1}\mathrm{Mpc}$

Newtonian potentials: $h_{\alpha\beta} = 2\begin{pmatrix} \Phi & 0 \\ 0 & a^2\Psi\delta_{ij} \end{pmatrix}$

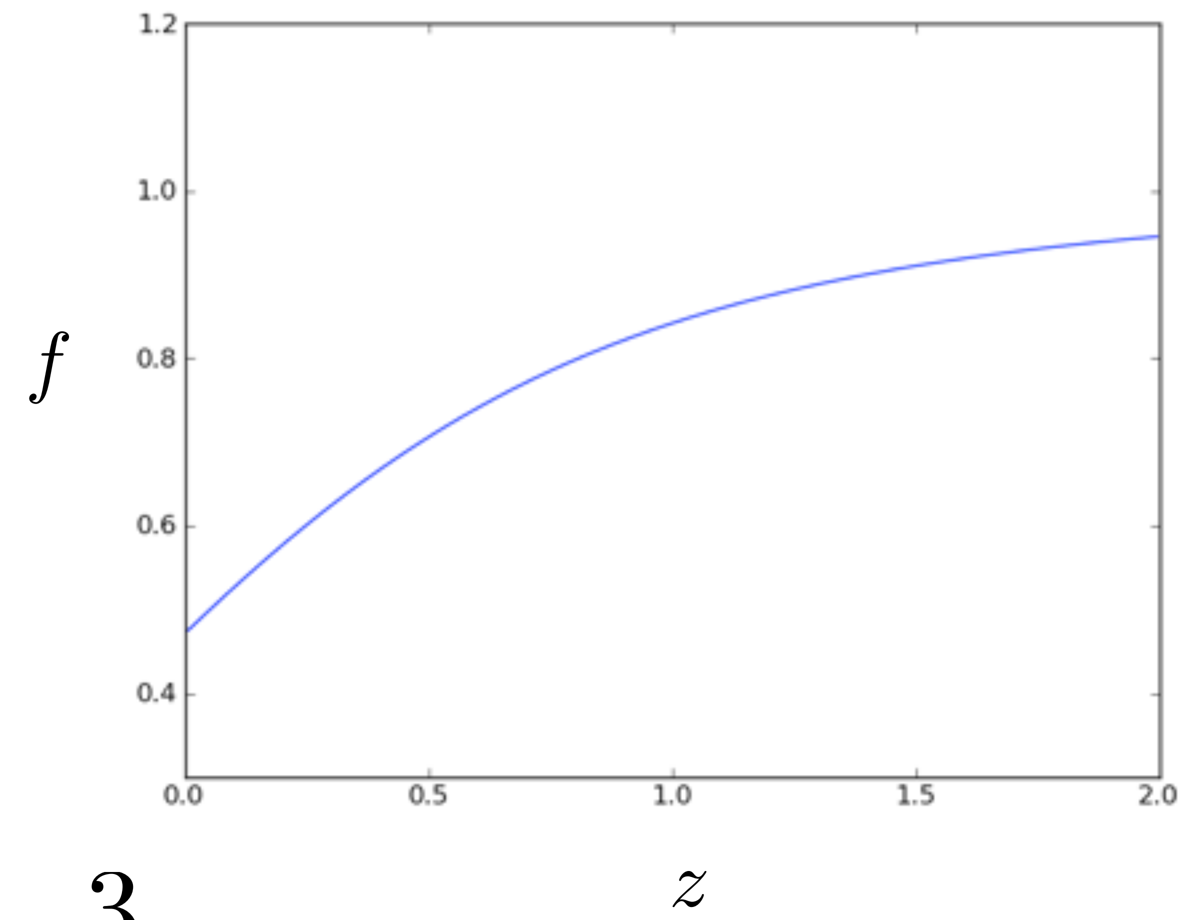
Fifth force absorbed in redefinition of field equations:

$$-k^2\Phi = 4\pi G\underline{\mu}a^2\rho\Delta \qquad \underline{\gamma}\Psi = \Phi$$

Large Scale Structure

Growth rate

$$f(k,a) = \frac{d\ln\delta_M(k,a)}{d\ln a}$$



f satisfies a simple ODE

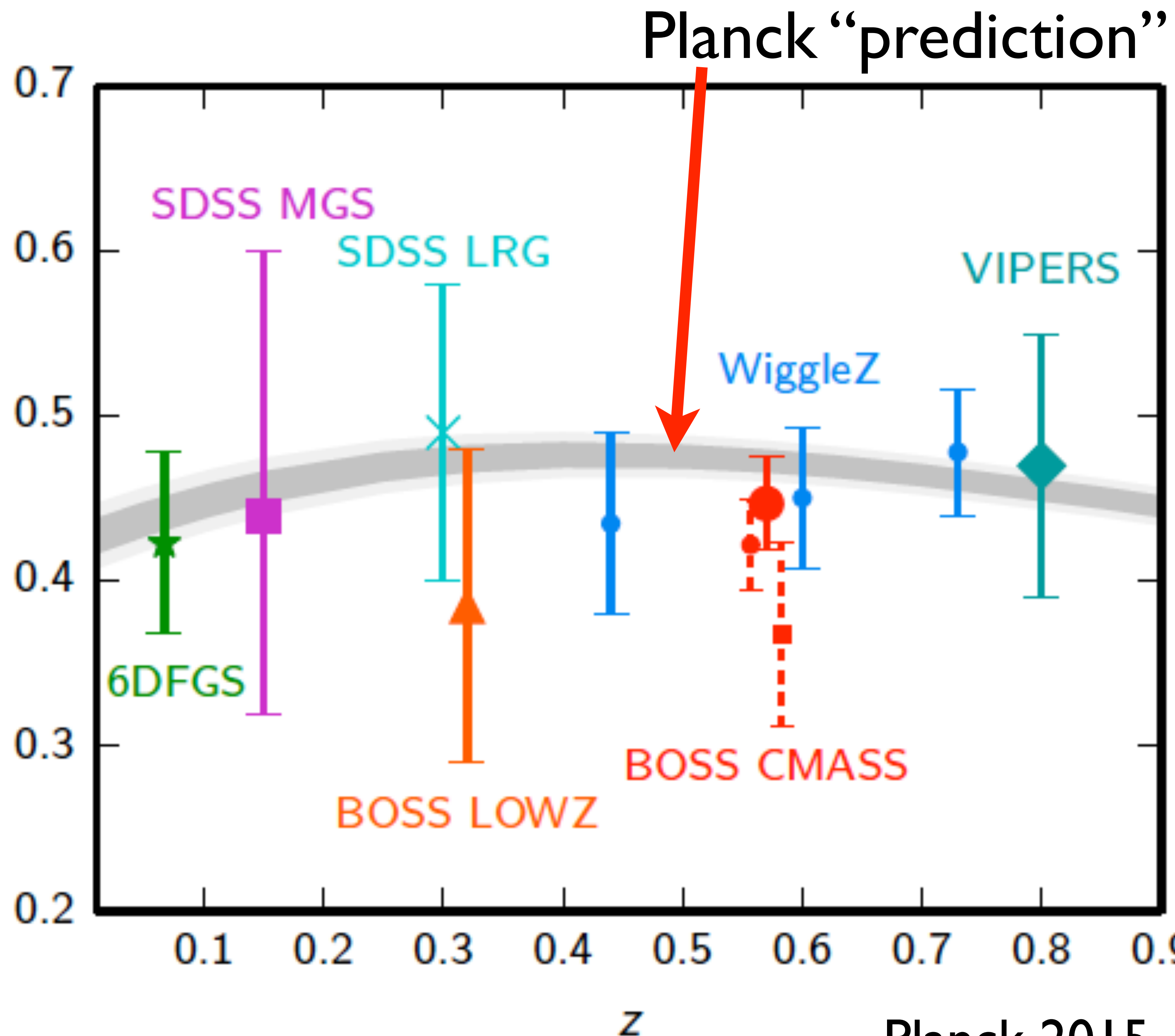
$$\frac{df}{d\ln a} + qf + f^2 = \frac{3}{2}\Omega_M \xi$$

with $q = \frac{1}{2}[1 - 3w(1-\Omega_M)]$ and $\xi = \frac{\mu}{\gamma}$

Large Scale Structure

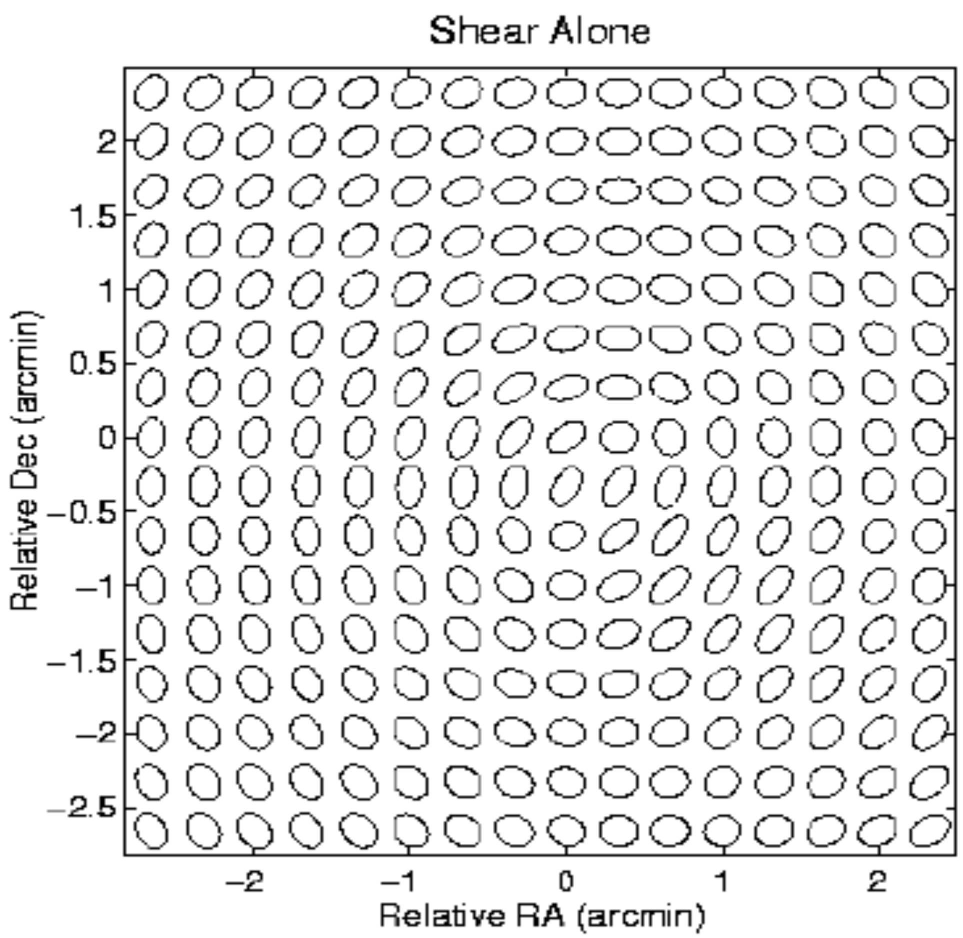
“growth rate of structure”

$$f\sigma_8 \propto \frac{d\delta}{d\ln a}$$



Planck 2015

Large Scale Structure



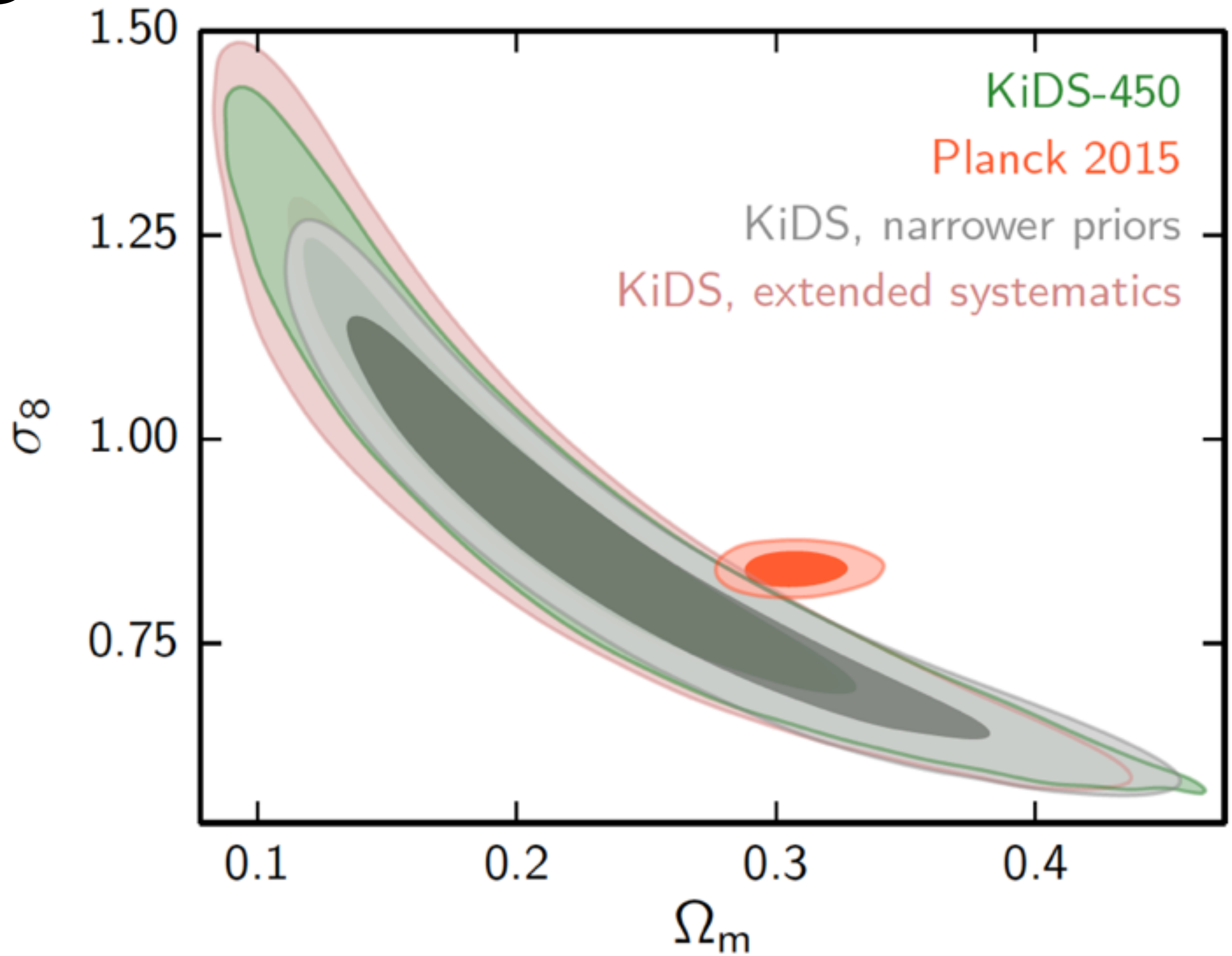
shear $\simeq \int_0^{\chi} \nabla_\perp^2 [\Phi + \Psi](\chi') \left[\chi' \left(1 - \frac{\chi'}{\chi}\right)\right] d\chi'$

shear $\sim \Sigma \equiv \mu \left(1 + \frac{1}{\gamma}\right)$

Sarah Bridle lectures (2003)

Large Scale Structure

“amplitude of clustering at 8 h^{-1} Mpc”

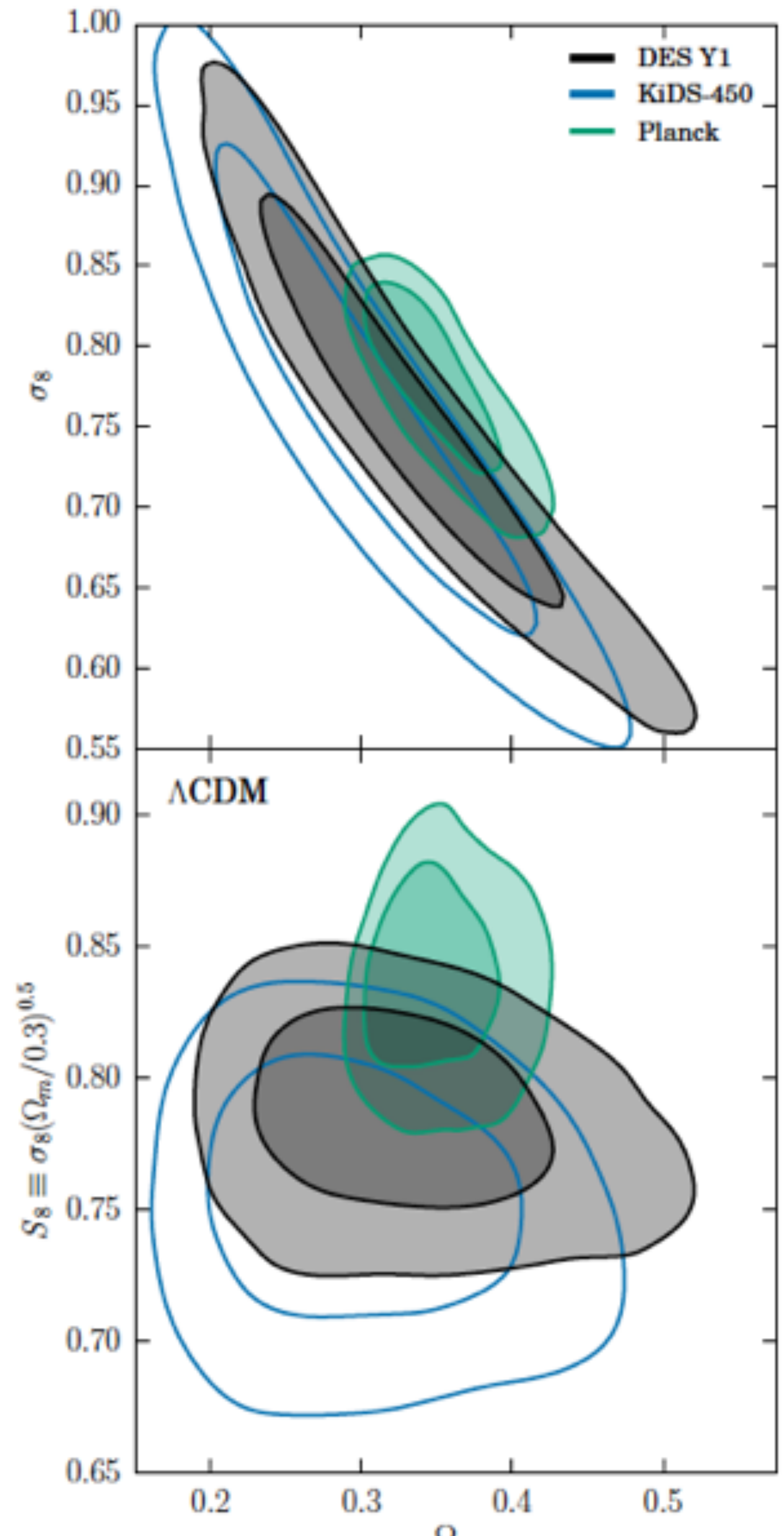


Joudaki et al 2016

“matter density”

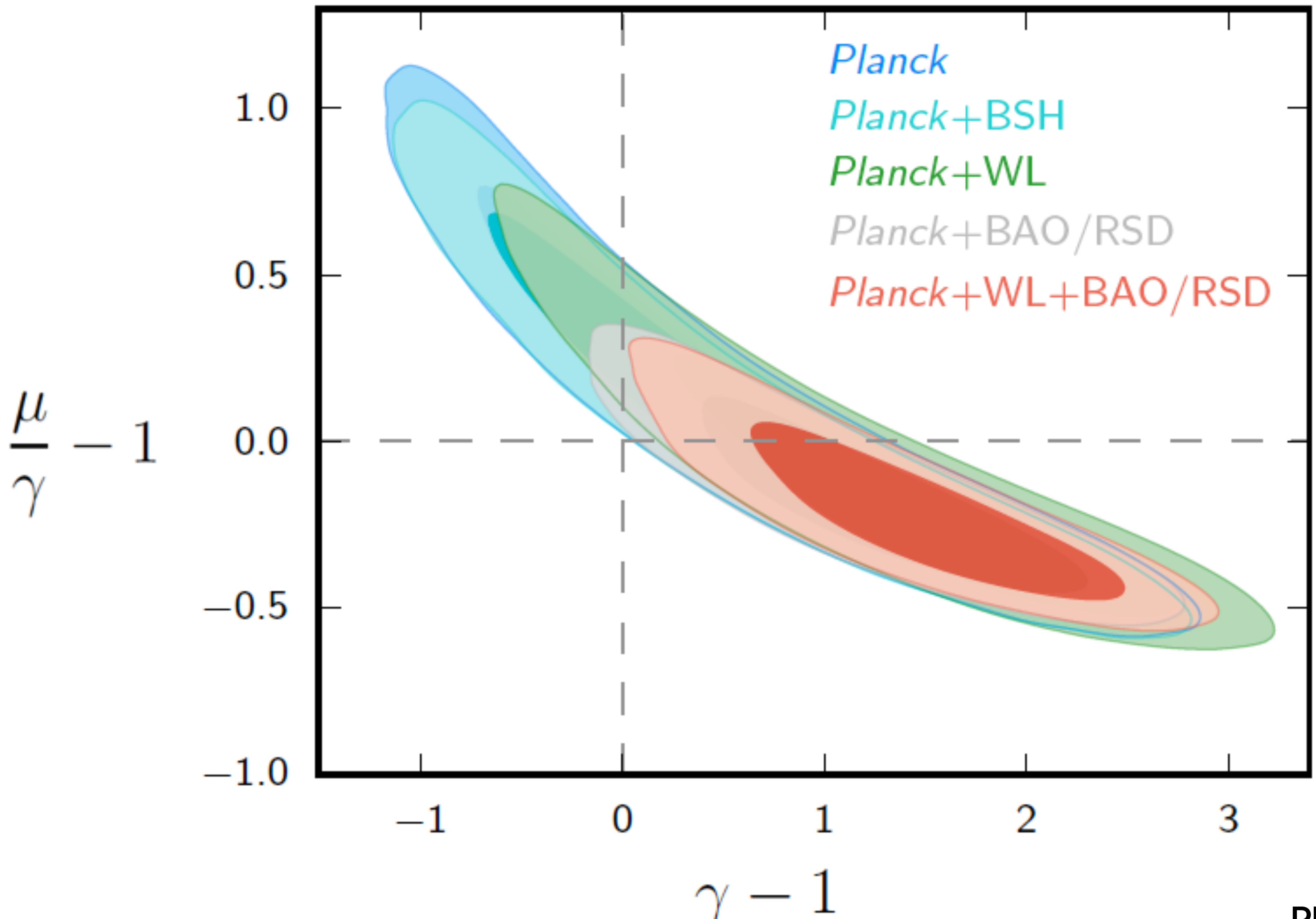
Large Scale Structure

"amplitude of clustering at 8 h^{-1} Mpc"



Troxel et al 2017

Large Scale Structure



Planck 2015

Large Scale Structure

Data Type	Now	Soon	Future
Photo-z:LSS (weak lensing)	DES, RCS, KIDS	HSC	LSST, Euclid, SKA, WFIRST
Spectro-z (BAO, RSD, ...)	BOSS	DESI,PFS,HETDEX, Weave	Euclid, SKA
SN Ia	HST, Pan-STARRS, SCP, SDSS, SNLS	DES, J-PAS	JWST,LSST
CMB/ISW	WMAP, Planck	AdvACT	Simons Array, Stage IV, LiteBird
sub-mm, small scale lensing, SZ	ACT, SPT,Planck, ACTPol,SPTPol,	PolarBear,Spider, Vista	CCAT, SKA
X-Ray clusters	ROSAT, XMM, Chandra	XMM, XCS, eRosita	
HI Tomography	GBT	Meerkat, Baobab, Chime, Kat 7	SKA

Large Scale Structure

One free parameter

$$S_{BD} = -\int d^4x\sqrt{-g}\left[\frac{M^2}{2}R + \frac{\omega_{BD}}{M^2}\partial^\mu M^2 \partial_\mu M^2 + V + L_m\right]$$

Cassini (Bertotti et al 2003)	$\omega_{\rm BD}$	$>$	$40,000$
Planck (Avilez & Skordis 2015)	$\omega_{\rm BD}$	$>$	$1,000$
LSST+SKA+S4 (Alonso et al 2016)	$\omega_{\rm BD}$	$>$	$20,000$

Gravitational Waves

Extra fields can function as a medium

$$g_{\alpha\beta} = \eta_{\alpha\beta} + h_{\alpha\beta}$$

Minkowski

$$S_h = \frac{1}{2} \int d^3x dt M_*^2 [\dot{h}_{\times,+}^2 - c_T^2 (\nabla h_{\times,+})^2]$$

Speed of gravitational waves: $c_T^2 = 1 + \alpha_T$

In General Relativity

$$\alpha_T = 0$$

$$M_* = M_{\mathrm{Pl}}$$

Gravitational Waves

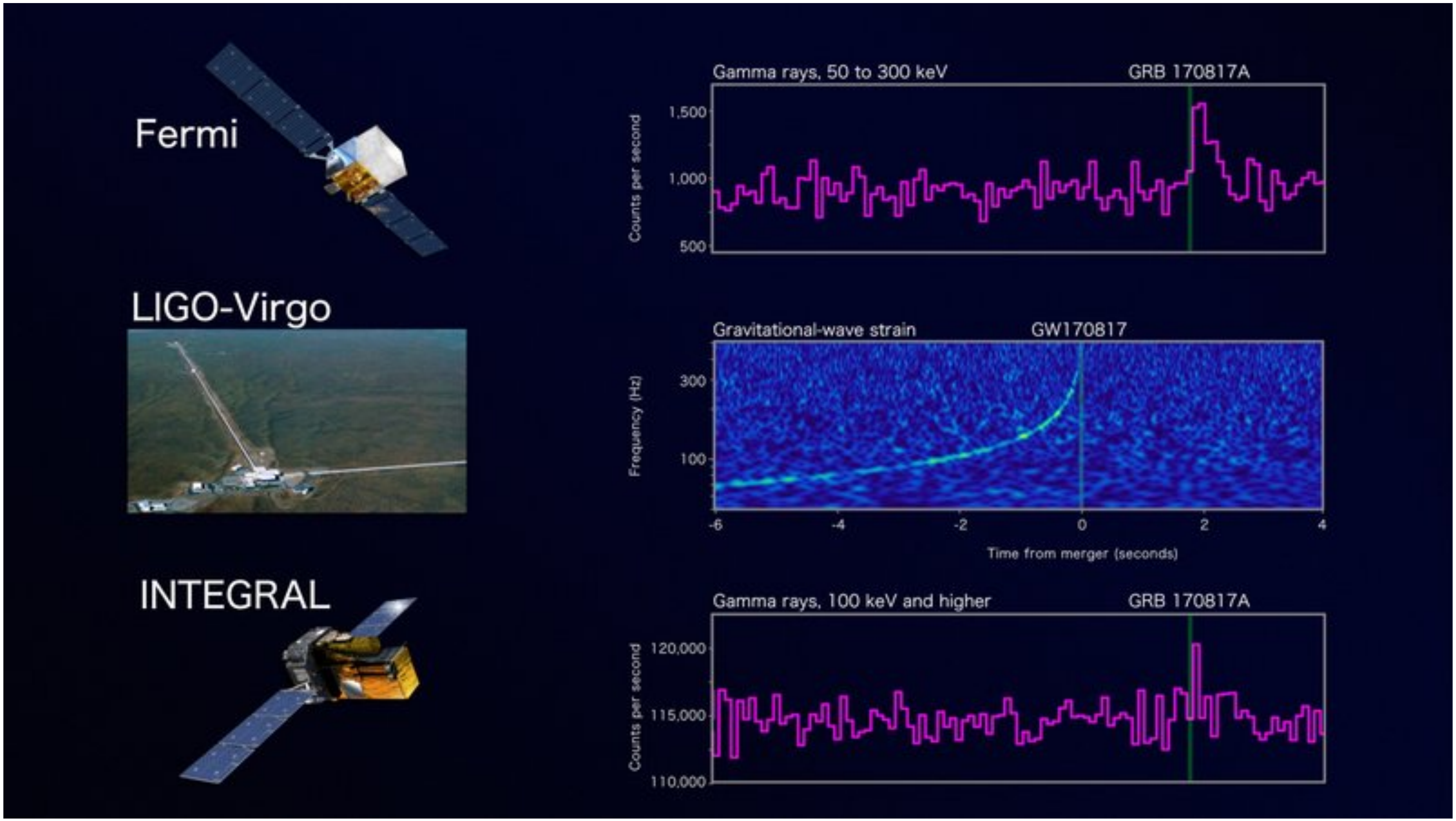
α_T deeply connected to underlying theory

For example: $$\int d^4x\sqrt{-g}\,\frac{M^2(\phi,X)}{2}R$$

where $$X=\frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi$$

gives us $$\alpha_T=\frac{\frac{dM^2}{d\ln X}}{M^2-2\frac{dM^2}{d\ln X}}$$

Gravitational Waves



$$\alpha_T \simeq 2\Delta t / d_s$$

$$d_s \simeq 40 \text{ Mpc}$$
$$\Delta t \simeq 1.7 \text{ s}$$

$$|\alpha_T| \lesssim 1 \times 10^{-15}$$

Gravitational Waves

$$S = \int d^4x\sqrt{-g}\left\{\sum_{i=2}^{5}\mathcal{L}_i[\phi, g_{\mu\nu}] + \mathcal{L}_M[g_{\mu\nu}, \varphi]\right\}$$

$$\begin{aligned}
\mathcal{L}_2 &= K, \\
\mathcal{L}_3 &= -G_3\Box\phi, \\
\mathcal{L}_4 &= G_4R + G_{4X}\left\{(\Box\phi)^2 - \nabla_\mu\nabla_\nu\phi\nabla^\mu\nabla^\nu\phi\right\}, \\
\mathcal{L}_5 &= G_5G_{\mu\nu}\nabla^\mu\nabla^\nu\phi - \frac{1}{6}G_{5X}\left\{(\nabla\phi)^3 - 3\nabla^\mu\nabla^\nu\phi\nabla_\mu\nabla_\nu\phi\Box\phi \right. \\
&\quad \left. +2\nabla^\nu\nabla_\mu\phi\nabla^\alpha\nabla_\nu\phi\nabla^\mu\nabla_\alpha\phi\right\}.
\end{aligned}$$

Baker et al 2017

Creminelli et al 2017

Sakstein et al 2017

Ezquiaga et al 2017

$$\alpha_T = 0 \quad \Big\downarrow$$

$$\mathcal{L} = f(\phi)R + K(\phi, X) + G_3(\phi, X)\Box\phi$$

Gravitational Waves

$$\mathcal{L}_4 = G_4(X)R + G_{4,X}(X)\left[(\nabla_\mu A^\mu)^2 + c_2 \nabla_\rho A_\sigma \nabla^\rho A^\sigma - (1+c_2)\nabla_\rho A_\sigma \nabla^\sigma A^\rho\right]$$

$$\mathcal{L}_5 = G_5(X)G_{\mu\nu}\nabla^\mu A^\nu - \frac{1}{6}G_{5,X}(X)[(\nabla_\mu A^\mu)^3 - 3d_2\nabla_\mu A^\mu \nabla_\rho A_\sigma \nabla^\rho A^\sigma - 3(1-d_2)\nabla_\mu A^\mu \nabla_\rho A_\sigma \nabla^\sigma A^\rho + (2-3d_2)\nabla_\rho A_\sigma \nabla^\gamma A^\rho \nabla^\sigma A_\gamma + 3d_2 \nabla_\rho A_\sigma \nabla^\gamma A^\rho \nabla_\gamma A^\sigma]$$

$$\xrightarrow{\alpha_T = 0}$$

Baker et al 2017

$$\mathcal{L}_4 \propto R \qquad \mathcal{L}_5 \propto G_{\mu\nu}\nabla^\mu A^\nu$$

No Fifth Force

Brans-Dicke with a quartic potential

$$S = -\int d^4x\sqrt{-g}\left[-\frac{\alpha}{12}\phi^2 R + \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + \lambda\phi^4\right]$$

is invariant under scale transformations

$$g_{\alpha\beta} \to \Omega^2 g_{\alpha\beta}$$

$$\phi \to \phi/\Omega$$

$$x^\alpha \to \Omega x^\alpha$$

where Ω is a constant.

No Fifth Force

Consider FRW metric $g_{\alpha\beta} = (-1, a^2\delta_{ij})$

Integrate the Noether current to get

$$\phi^2 = \phi_0^2 + c\int \frac{dt}{a^3}$$

Fixed point: ϕ_0

generates two mass scales:

$$\begin{cases} M^2 = -\dfrac{\alpha}{6}\phi_0^2 \\ H^2 = -\dfrac{2\lambda\phi_0^2}{\alpha} \end{cases}$$

No Fifth Force

A spontaneously broken, continuous symmetry will lead to the existence of a massless boson which is derivatively coupled to any sources.

Goldstone 1961

In this case

symmetry $\longrightarrow$ scale (or Weyl) invariance

boson $\longrightarrow$ dilaton

but then

derivatively coupled $\longrightarrow$ suppressed fifth force!

In fact: <u>no coupling!</u>

No Fifth Force

Is the universe scale invariant?

$$\left\{\begin{array}{l}\text{scalars} \longrightarrow \text{inflaton, Brans-Dicke field, Higgs, ...}\\ \text{vectors} \longrightarrow \text{gauge fields}\\ \text{tensors} \longrightarrow \text{metric}\end{array}\right.$$

$$S = -\int d^4x\sqrt{-g}\left[-\frac{1}{12}\sum_i^N \alpha_i\phi_i^2 R + \frac{1}{2}\sum_i^N \partial_\mu\phi_i\partial^\mu\phi_i - W(\vec{\phi})\right]$$

$$+\frac{i}{2}\bar{\psi}(\overrightarrow{\nabla\!\!\!/} - \overleftarrow{\nabla\!\!\!/})\psi - g'\bar{\psi}\psi h \longrightarrow +\frac{i}{2}\bar{\psi}'(\overrightarrow{\nabla\!\!\!/} - \overleftarrow{\nabla\!\!\!/})\psi' - g'\bar{\psi}'\psi'\hat{h}$$

If Higgs mass spontaneously generated, then yes!

Wetterich 1528 Shaphoshnikov & Zenhausern 2009 Ferreira, Hill & Ross 2017

Summary

- Extra fields are inevitable and ubiquitous.
- Extra fields lead to fifth forces.
- They are tightly constrained in the lab and in space.
- Fifth forces can be hidden (screened).
- We can find unscreened regions of the universe.
- Fifth forces will affect cosmological observables.
- Cosmological constraints will become very tight.
- Extra fields affect the speed of gravitational waves.
- They are tightly constrained by GW170817A.
- We can evade constraints by invoking scale symmetry.