Galileon Inflation and Non-Gaussianities

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Fermilab, October 18th, 2010

Plan

- Introduce idea of Galileon Fields - motivations Dark Energy and Light Scalar Fields
- Review how Galileons arise in context of higher dimensional models + massive gravity
- Galileon Inflation - what it is
- Non-Gaussianities in Galileon Inflation

Late Time Cosmic Acceleration potentially implies new physics

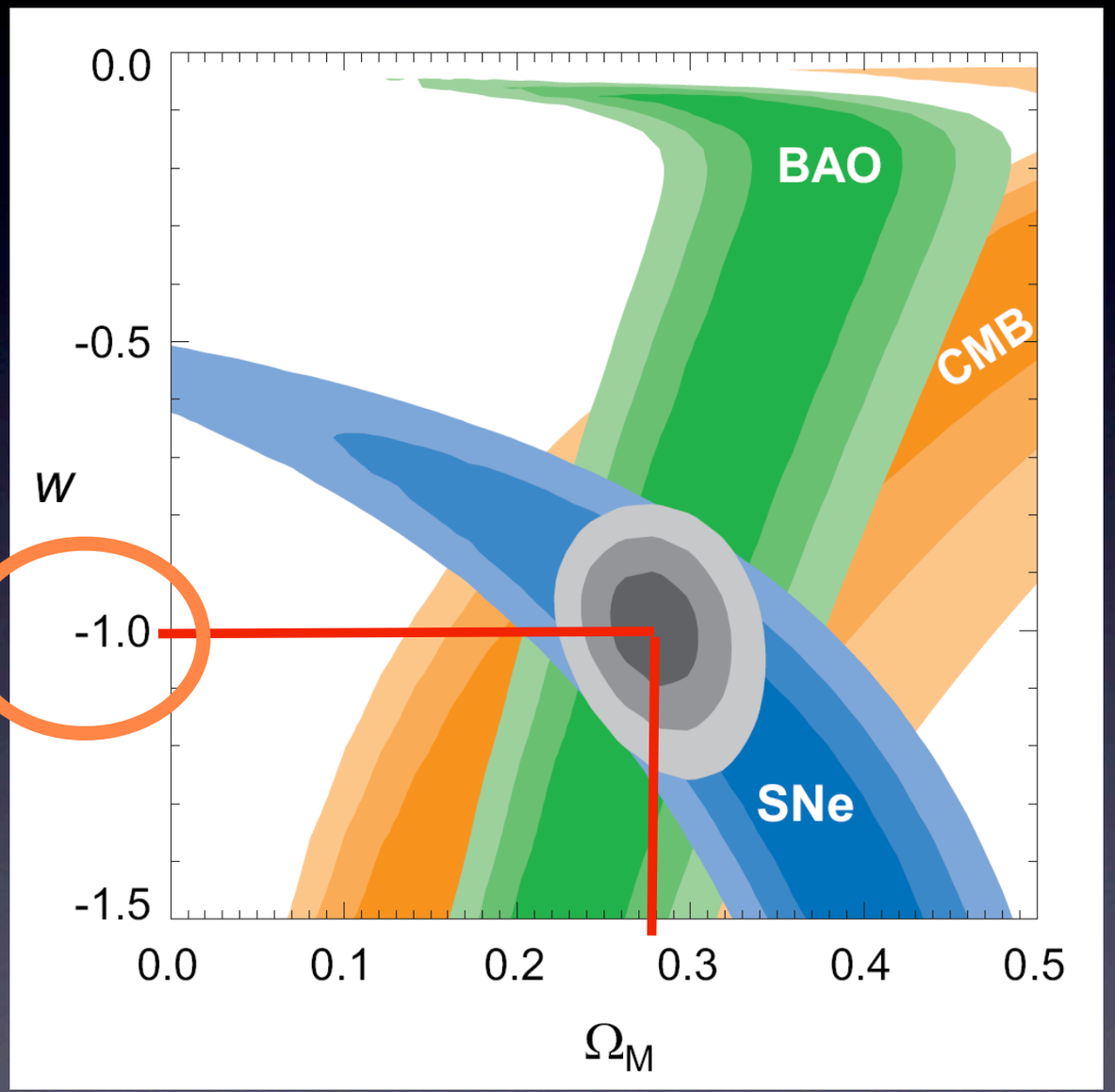
Dark Energy

The Universe is Accelerating!
Acceleration can only occur if

$$w = \frac{p}{\rho} < -1/3$$

Data points tantalizingly close to

$$w = -1$$



$$w = -0.94 \pm 0.1$$

Frieman *et al.* (2008) Ann.Rev.Astron.Astrophys

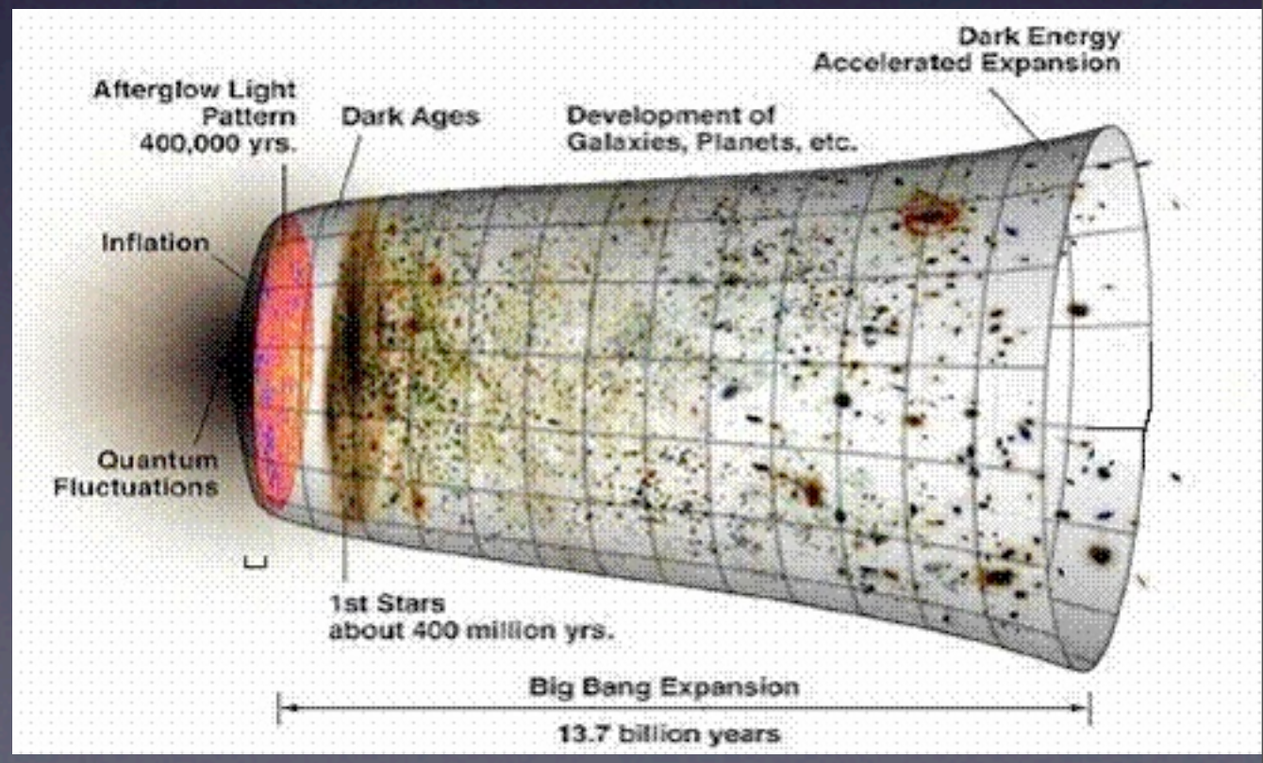
Early Time Cosmic Acceleration certainly implies new physics

Inflation

Solution of horizon/monopole/ flatness problems requires period of accelerated expansion

$$w = \frac{p}{\rho} < -1/3$$

Inflation is the most plausible mechanism for generating the seeds of cosmic structure

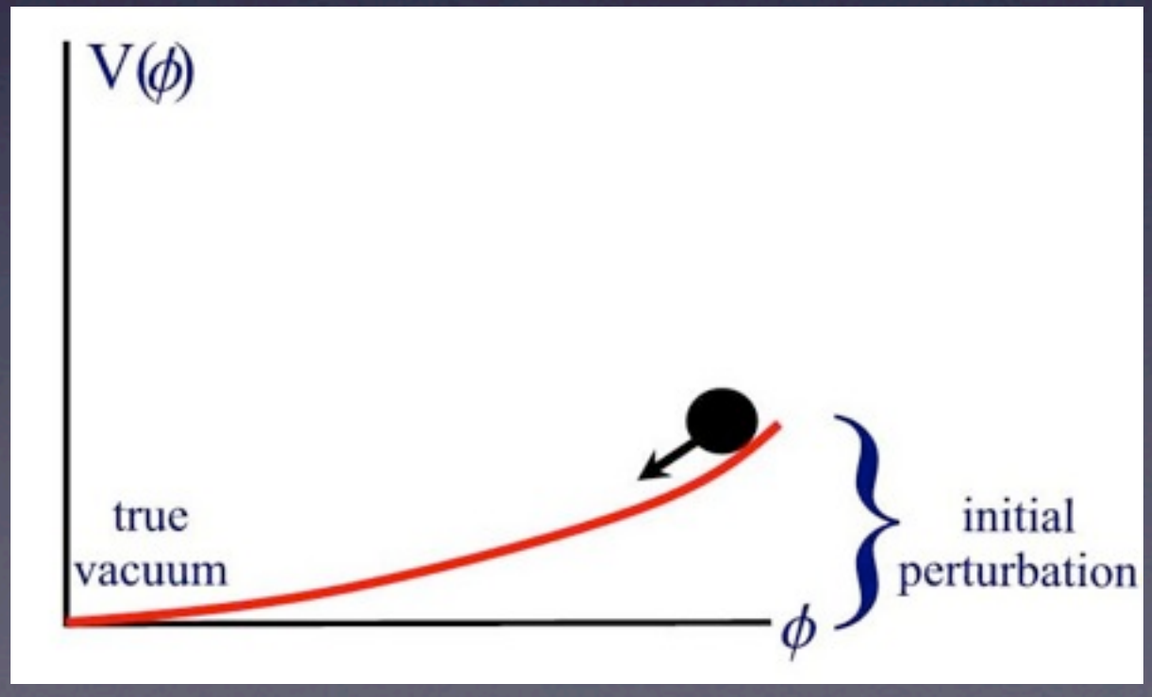


Inflation!

Common features: Existence of light scalars (fundamental or composite) which drive dynamics

- Inflaton in case of Inflation $m \ll H$
- Quintessence/chameleon/cosmon/Brans-Dicke scalar/Galileon in case of Dark Energy

$$m_{\rm d.e.} \leq 10^{-33}{\rm eV}$$



Light scalars are a problem!

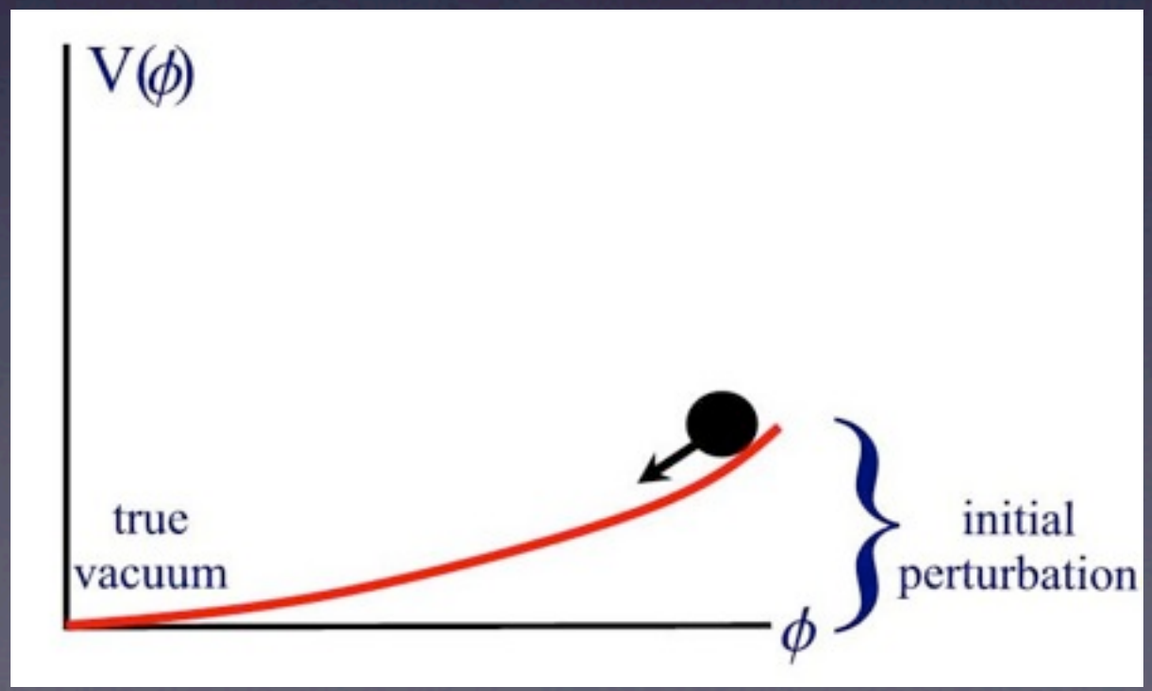
(Theoretical) Typically not technically natural (Eta problem in Inflation) - significantly worse for Dark Energy

Closely akin to Higgs mass/gauge hierarchy problem

$$\Delta V \sim V(\phi)\frac{\phi^2}{M_{\rm pl}^2}$$

dim 6 operators

mass quadratically divergent, pick up mass comparable to heaviest particle



Light scalars are a problem!

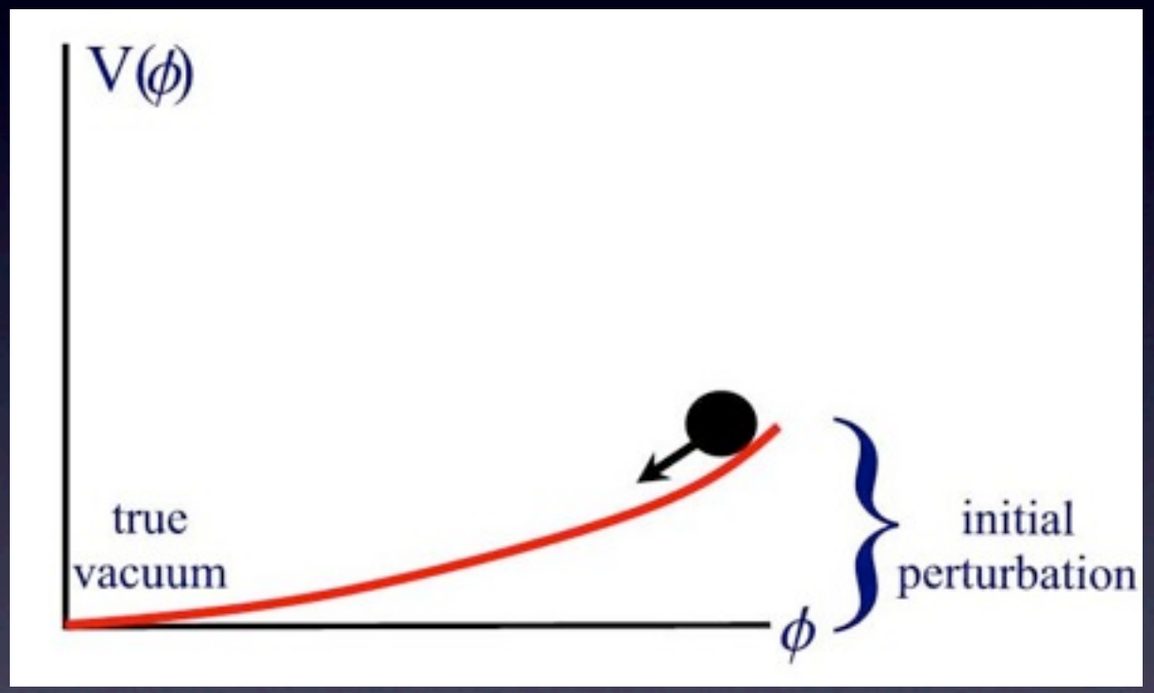
(Observational) In case of Dark Energy strong observational constraints from ....

Fifth Forces (solar system),

Binary Pulsar Timing,

Nucleosynthesis,

Equivalence Principle Tests etc.



Three Ways to Hide

Fifth Force constraints avoided if light dark energy particles ....

a. Do not couple to the SM (Quintessence)

b. Become effectively heavy near matter (eg. on earth) (Chameleon)

Khoury + Weltman, 2004

c. Are effectively weakly coupled near matter (Kinetic Chameleon – or Vainhstein mechanism)

Vainshtein, 1972

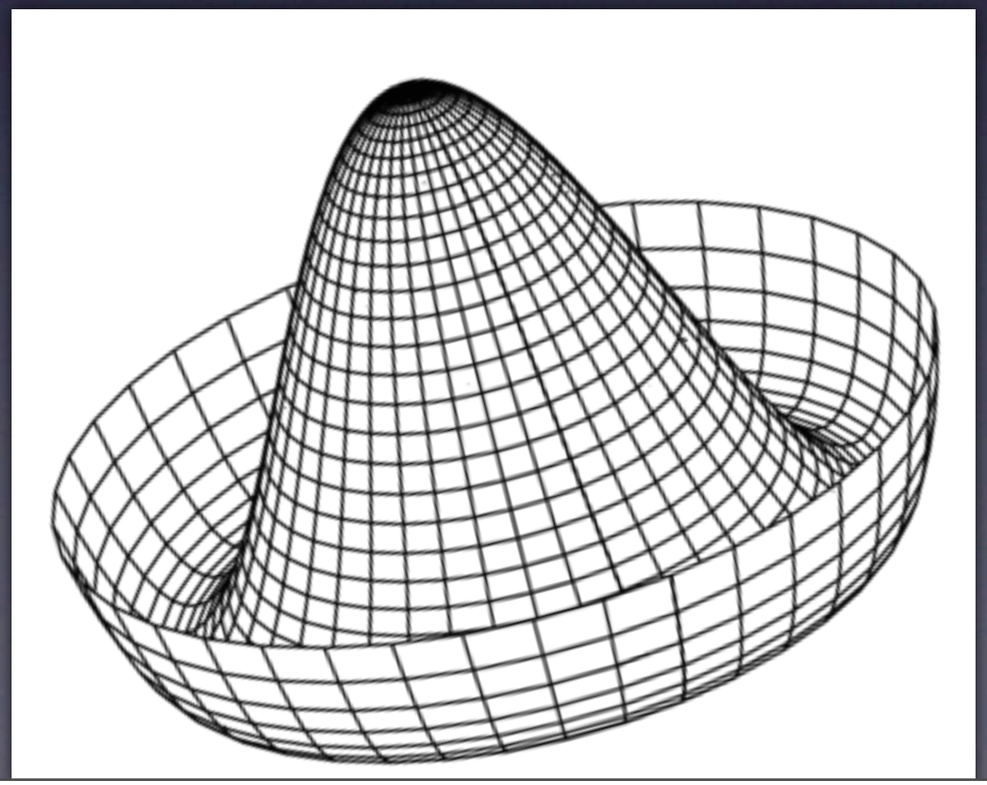
Scalars kept light by an approximate shift symmetry

- Technically natural Scalar Field arises as a *pseudo-Nambu-Goldstone* field associated with an approximately broken continuous global symmetry

$$\phi \to \phi + C$$

Explicitly broken but by a small amount

e.g. U(1) symmetry of mexican hat



Problem! All continuous broken symmetries broken at Planck scale

- Black Holes cannot carry conserved global charge - scattering processes which allow for BH creation will violate charge conservation

  Kallosh et al. 1995

- Global symmetries on string world sheet always become local symmetries in spacetime

  Polchinski

- Continuous global symmetry broken to discrete one e.g. axion models

  eg natural inflation, Freese et al. 1990

- Accept symmetry broken, suppress effects of Planck suppressed operators by other means

  Green and Baumann 2009/2010

- Global symmetry becomes local when coupled to gravity (local symmetries are protected from argument)

Only possible if global symmetry is not internal, but `mixed' with Poincare group

Full symmetry must be extension of 4d Diff group e.g. Higher Dimensional Diffeomorphisms:

↓ *decoupling limit*

4d Poincare group plus non-linearly realized *global symmetry*

Two well understood examples

- Scalar arises as goldstone mode associated with brane in higher dimensions

- Scalar arises as helicity zero mode of massive graviton - consistency of massive gravity requires existence of larger local symmetry group

Scalars arising this way exhibit Galilean symmetry

$$\pi \rightarrow \pi + C + v^{\mu} x^{\mu}$$

generalization of shift symmetry

Cascading Gravity

de Rham, Dvali, Hofmann, Khoury, Pujolas, Redi, AJT (2007)
`Cascading Gravity: Extending the Dvali-Gabadadze-Porrati model to higher dimension', PRL.199:251603,2008
de Rham, Hofmann, Khoury, AJT (2008)
`Cascading gravity and Degravitation', JCAP 0802:011,2008
de Rham, Khoury, AJT (2009)
`Flat 3-brane with Tension in Cascading Gravity', PRL.103:161691,2009
de Rham, Khoury, AJT (2010)
`Cascading Gravity is Ghost Free', PRD81:124027,2010

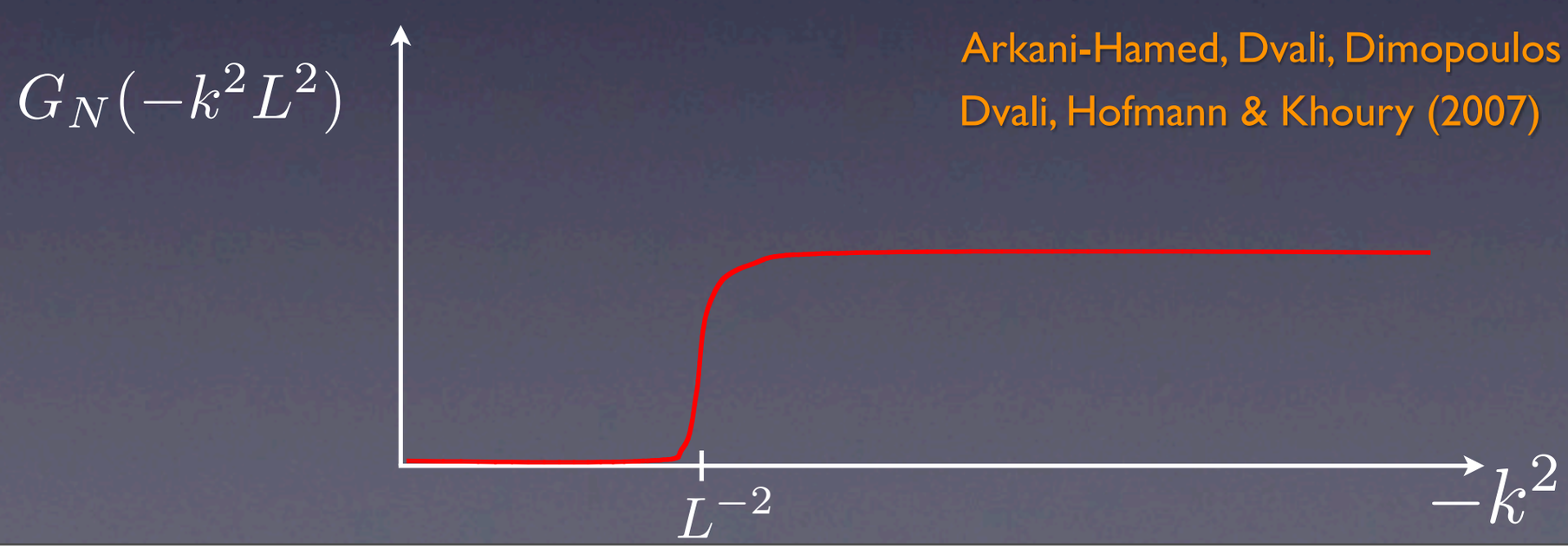
Cascading Gravity: A proposed IR modification of gravity to realize ...

DEGRAVITATION

Vacuum energy is large, as dictated by particle physics, but gravitates very weakly because graviton has mass or is resonance state

Dynamical relaxation whose timescale is set by effective 'graviton mass'

Arkani-Hamed, Dvali, Dimopoulos & Gabadadze (2002)
Dvali, Hofmann & Khoury (2007)



Massive Gravity

- The Newton's law has infinite range

$$F = -\frac{M_1 M_2 \; G_N}{r^2}$$

- If gravity was mediated by a *massive particle*, the Newton's law would "shut down" at some distance
  $L \sim m^{-1}$

$$F = \partial_r \left(\frac{M_1 M_2 \, G_N e^{-mr}}{r} \right)$$

Massive Gravity

- Filtering gravity is effectively a theory of massive gravity

$$h_{\mu\nu} \sim \frac{G_N}{\Box_4 - m^2} T_{\mu\nu} \qquad \Box = \eta^{\mu\nu}\partial_\mu\partial_\nu$$

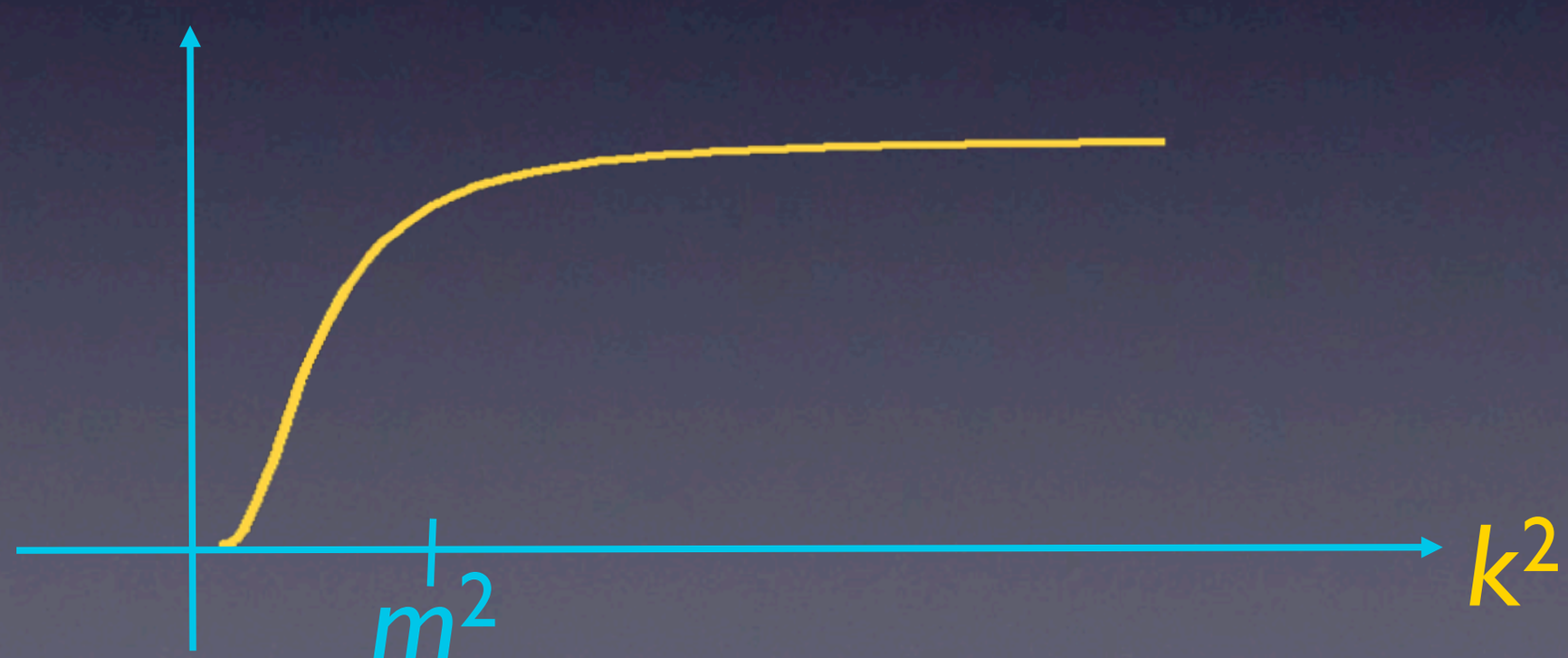
$$G_N^{\text{eff}} = \frac{k^2}{k^2 + m^2} \qquad = \frac{G_N^{\text{eff}}}{\Box}$$

Massive Gravity

- Filtering gravity is effectively a theory of massive gravity

$$\text{“}G_{\mu\nu} = 8\pi G_N^{\text{eff}} T_{\mu\nu}\text{”}$$

$$G_N^{\text{eff}} = \frac{k^2}{k^2 + m^2}$$



Tuning / Fine-tuning

- *The amount of tuning is the same*

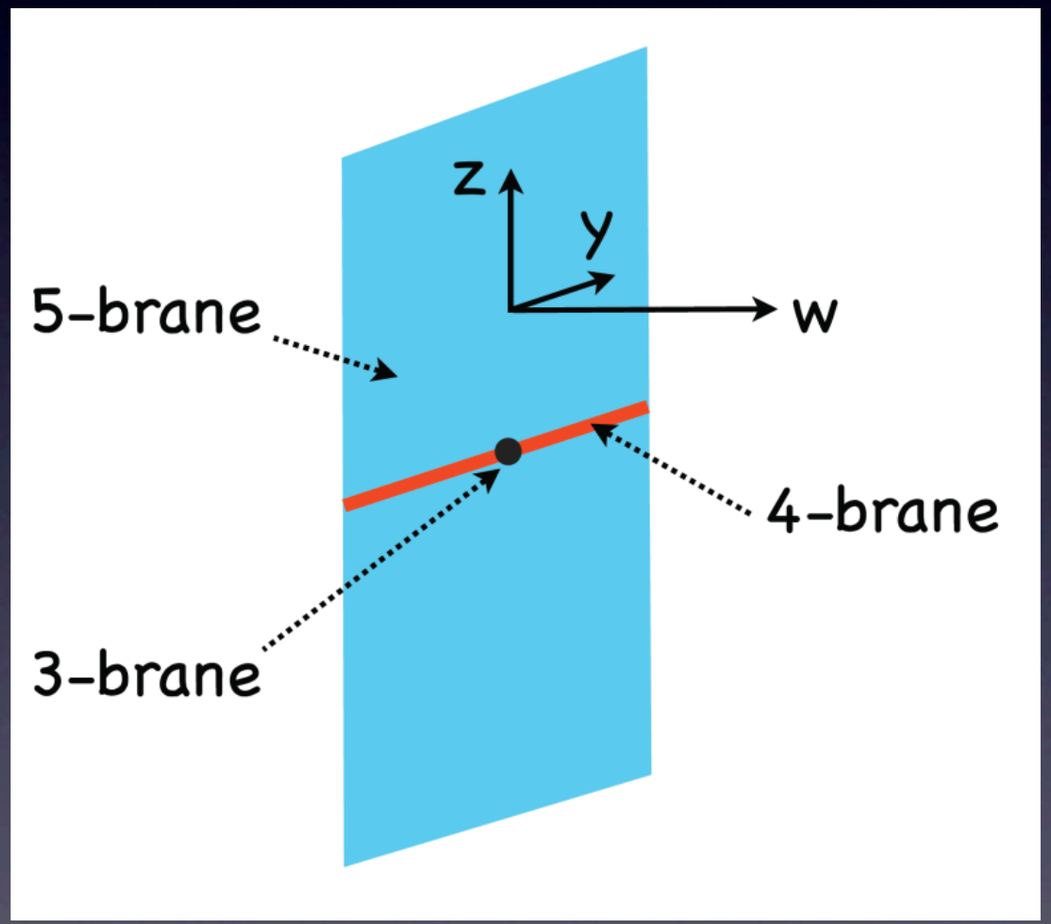
$$\frac{m^2}{M_{Pl}^2} \sim \frac{\Lambda}{M_{Pl}^4}$$

- But the graviton mass remains stable against quantum corrections
- we recover a symmetry in the limit $m \longrightarrow 0$

The theory is tuned
but technically natural

Cascading Gravity: The set up

$$S = \int d^4x\sqrt{-g_4}\left(\frac{M_4^2}{2}R_4 + \mathcal{L}_M\right) + \int d^5x\sqrt{-g_5}\left(\frac{M_3^4}{2}R_5\right) + \int d^6x\sqrt{-g_6}\left(\frac{M_6^4}{2}R_6\right)$$



Generalization of DGP idea

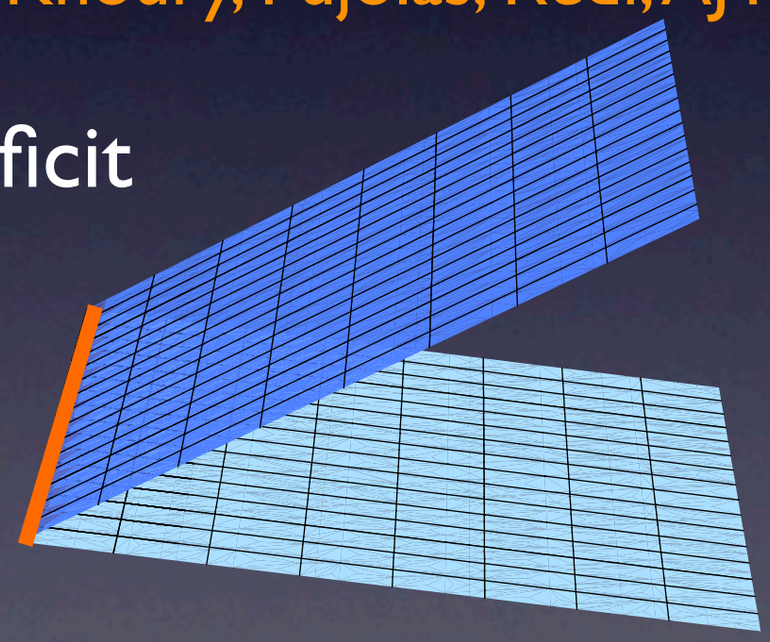
de Rham, Dvali, Hofmann, Khoury, Pujolas, Redi, AJT (2007)
de Rham, Hofmann, Khoury, AJT (2008)
de Rham, Khoury, AJT (2010)

Hiding the cosmological constant

Existence of a Minkowski vacuum solution in the presence of a cosmological constant on the 3-brane

de Rham, Dvali, Hofmann, Khoury, Pujolas, Redi, AJT (2007)

Tension creates deficit angle in bulk

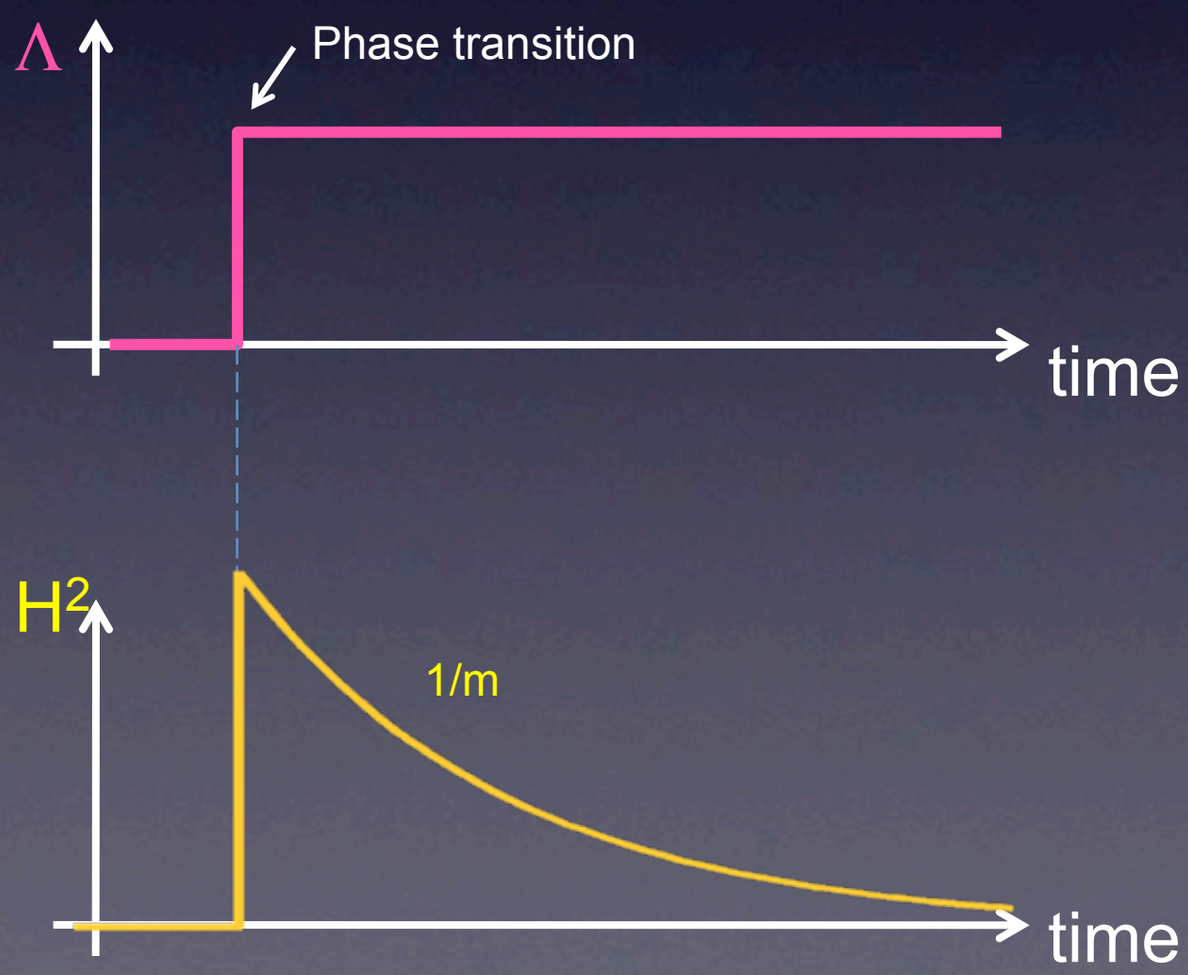


similar properties found in 7 dimensions

de Rham, Khoury, AJT (2009)

Degravitation in Real Time

Dynamical and causal process by which we can relax to this solution



At linearized level

$$G(k) = \frac{1}{k^2 + m(k)^2}$$

de Rham, Khoury, AJT (2010)

Massive Gravity leads to light scalars

- Filtering gravity is effectively a theory of massive gravity

$$h_{\mu\nu} \sim \frac{G_N}{\Box_4 - m^2} T_{\mu\nu}$$

$$2 \oplus 1 \oplus 2$$

- Massive spin-2 field, has 5 dof

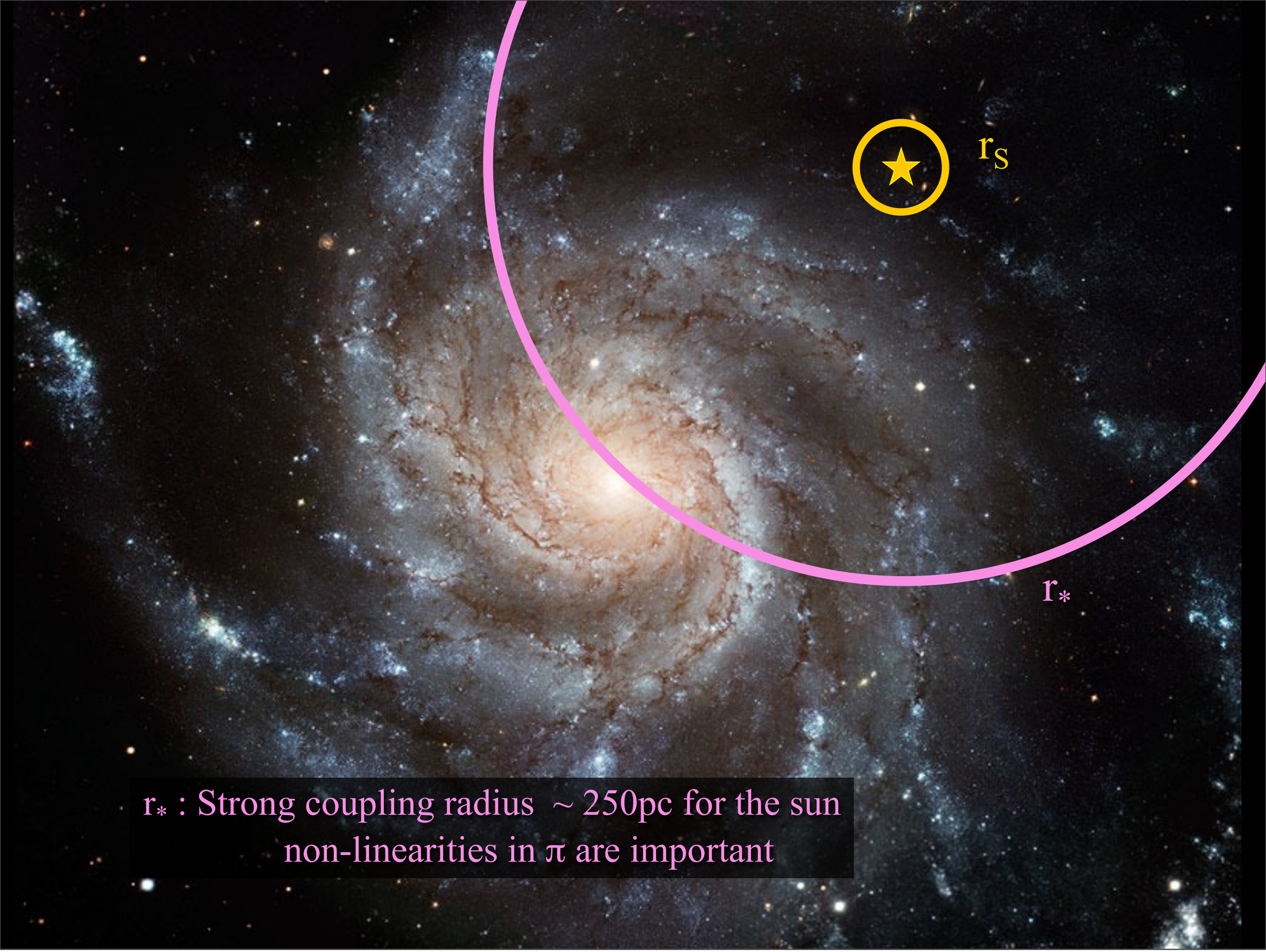
$$h_{\mu\nu} = h'_{\mu\nu} + \pi\eta_{\mu\nu}$$

Vainshtein Mechanism

r_S : Schwarzschild Radius, ~ 3km for the sun

non-linear interactions are important

both for helicity-2 and -0 modes



r_* : Strong coupling radius ~ 250pc for the sun
non-linearities in π are important

Fifth force

Higher derivative interactions are essential for the viability of this class of models.

$$\Lambda_\star = \left(M_{\rm Pl} m^2\right)^{1/3} \sim 10^{-12}{\rm eV} \sim (1000{\rm km})^{-1}$$

The interaction for the helicity-0 mode are important within the solar system !

→ Responsible for the screening of π on observational scales.

Fifth force

- Higher derivative interactions are essential for the viability of this class of models.

- Within the solar system, π reaches the scale Λ_*, yet, we are still within the regime of validity of the theory

$$\delta\hat{\pi} = \frac{\alpha_{\rm eff}(\pi_0)}{M_{\rm Pl}}\,\delta T$$

With $\alpha_{\rm eff} \ll 1$ within the solar system

Interactions

$$3\Box\hat{\pi} + \frac{1}{\Lambda^{3\beta-1}}\left[\Box\left(\Box\hat{\pi}\right)^{\beta} + \cdots\right] = -\hat{T}$$

- Close to a source, the interactions are important:

For a source $\hat{T} \sim -M_\star \frac{\delta(r)}{r^2}$

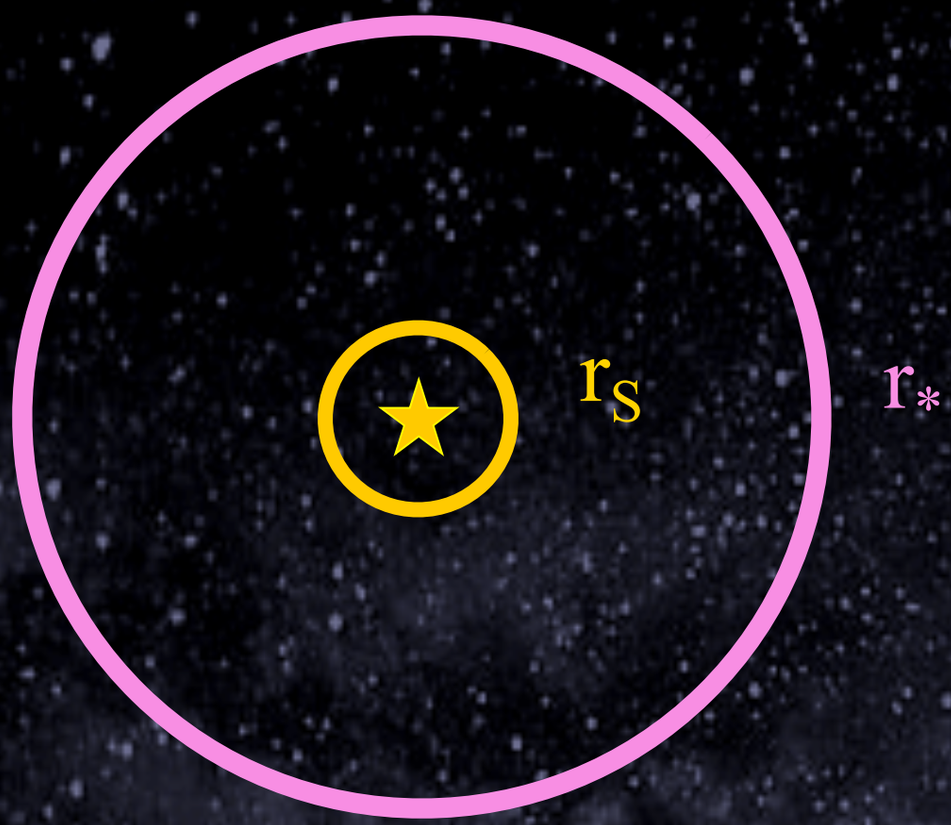
The solution is dominated by the higher interactions

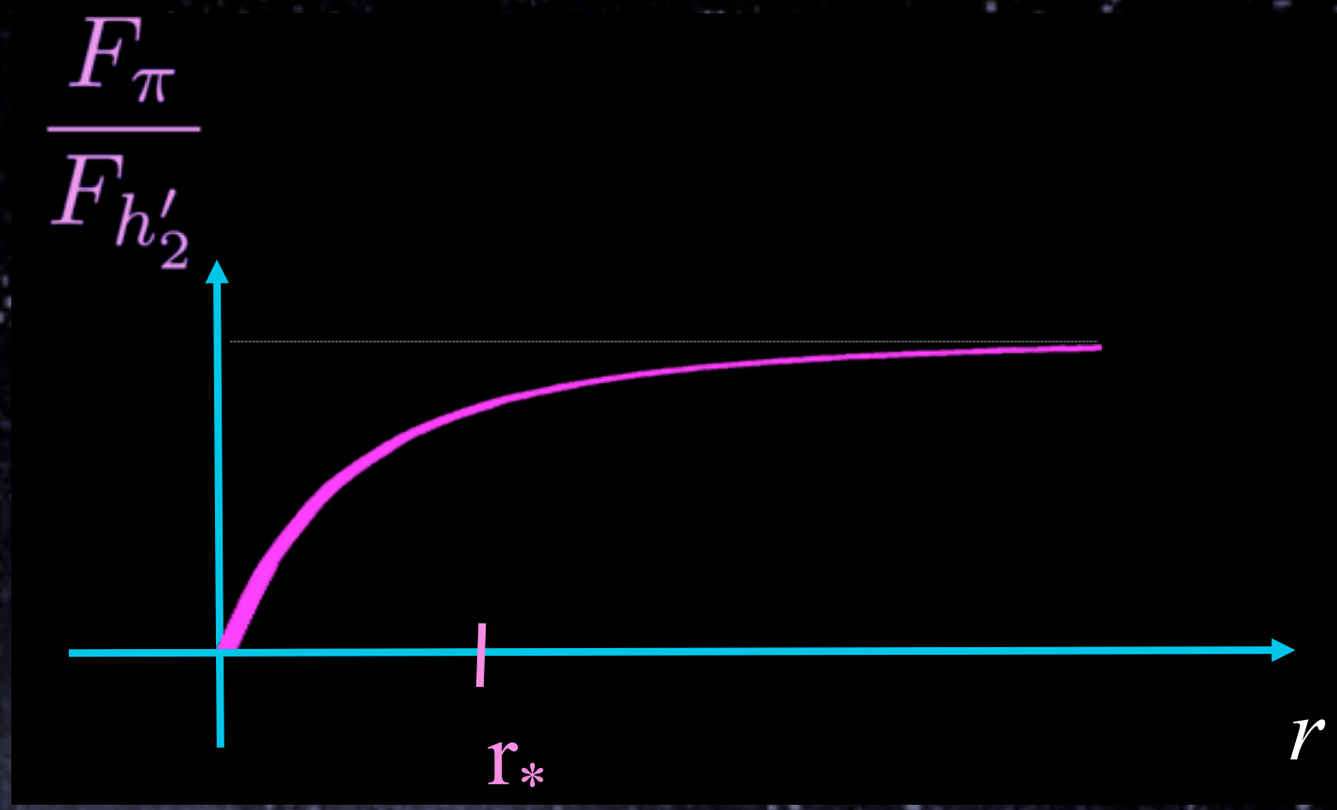
$$\pi_0(r) \sim \frac{M_\star^{1/\beta}}{r}(r\Lambda)^{3-1/\beta}$$

Perturbations are screened: (weakly coupled)

$$\Box\delta\pi \sim \alpha_{\rm eff}\delta\hat{T}$$

$$\left(3 + \frac{\Box(\Box\pi_0)^{\beta-1}}{\Lambda^{3\beta-1}}\right)\Box\delta\pi \sim \delta\hat{T} \longrightarrow \boxed{\alpha_{\rm eff} \sim \left(3 + \frac{M_\star^{1-1/\beta}}{(r\Lambda)^{3-1/\beta}}\right)^{-1}}$$





almost standard GR

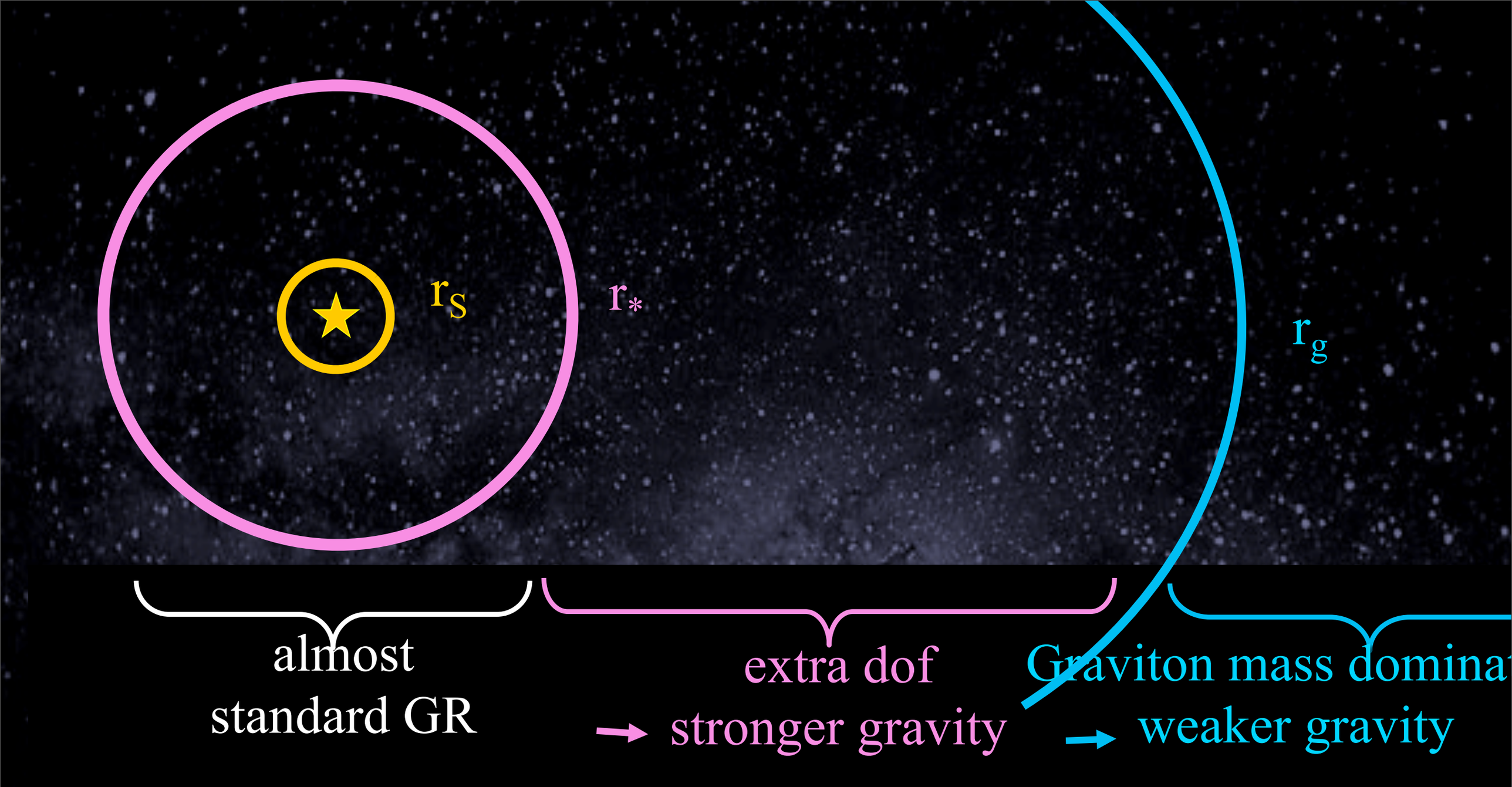
extra dof → stronger gravity

r_S : Schwarzschild Radius, ~ 3km for the sun

non-linear interactions are important

r_* : Strong coupling radius ~ 250pc for the sun

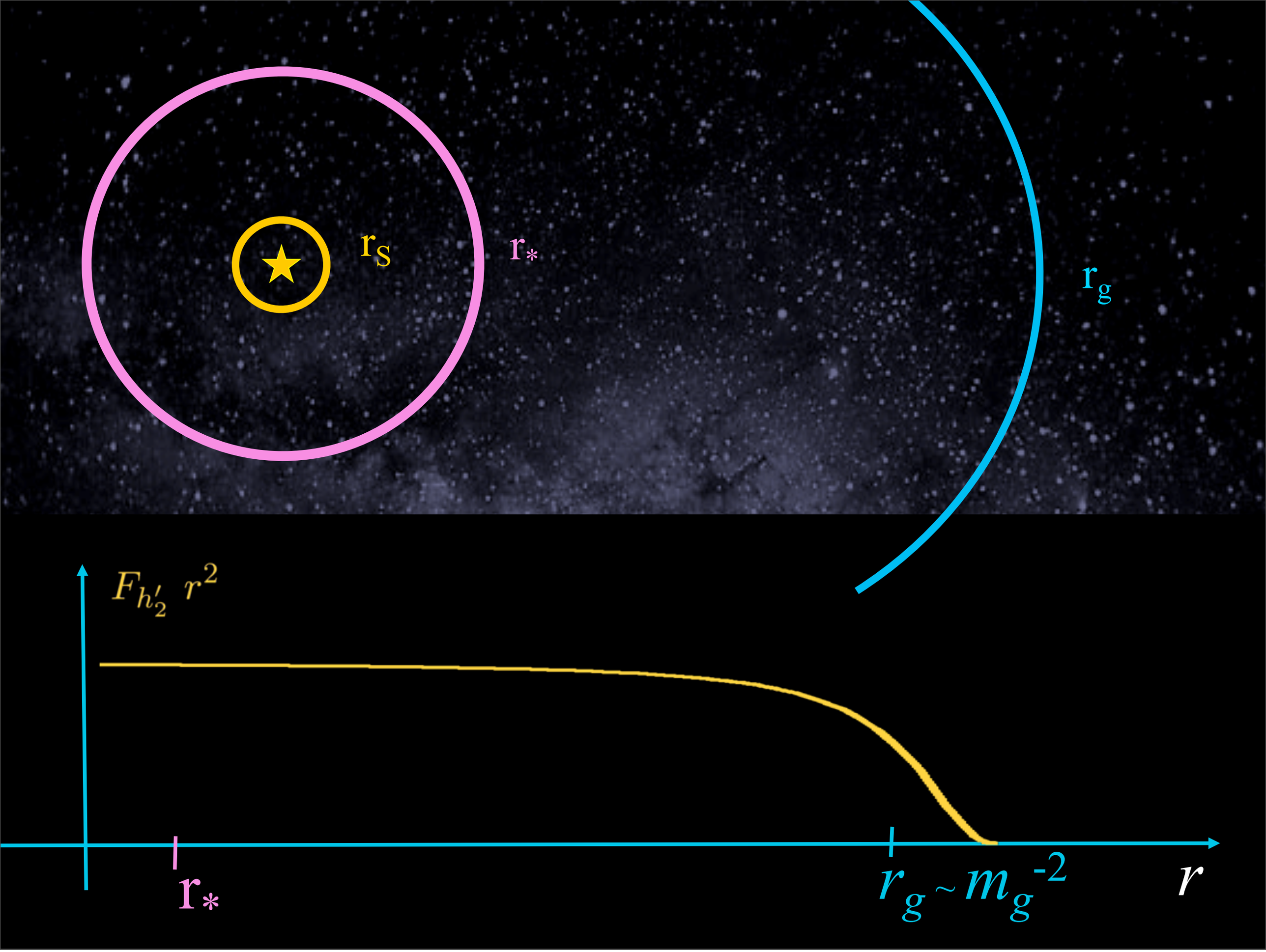
non-linearities in π are important



r_S : Schwarzschild Radius, ~ 3km for the sun

r_* : Strong coupling radius ~ 250pc for the sun

$r_g \sim 1/m_g$: gravity weakens > 300 Mpc


r_S
r_*
r_g
$F_{h_2'}\ r^2$
r_*
$r_g \sim m_g^{-2}$
r

Observations

Such models lead to specific observational signatures

Due to extra scalar dof

- Advance of the perihelion (LLR)
- Structure formation
- Pulsar monopole radiation

Modifies evolution of the Universe

- Supernovae
- CMB …

Lue, Scoccimarro & Starkman, '04
Lue & Starkman, '04
Lue, '05
Afshordi, Geshnizjani & Khoury, '08

Scoccimarro, '09
Khoury & Wyman, '09
Chan & Scoccimarro, '09
…

Perturbations

- Further work is needed to understand full effect on cosmological perturbations

Modified evolution of Inhomogeneities and Anisotropies

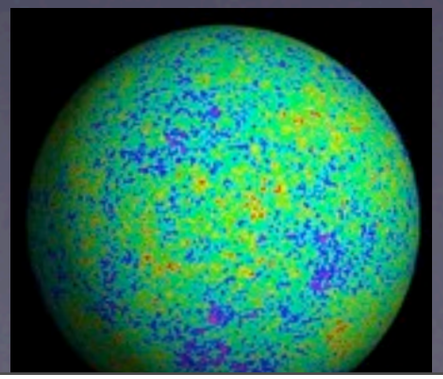
Theories where ω is a physical d.o.f. typically produce an anisotropic stress

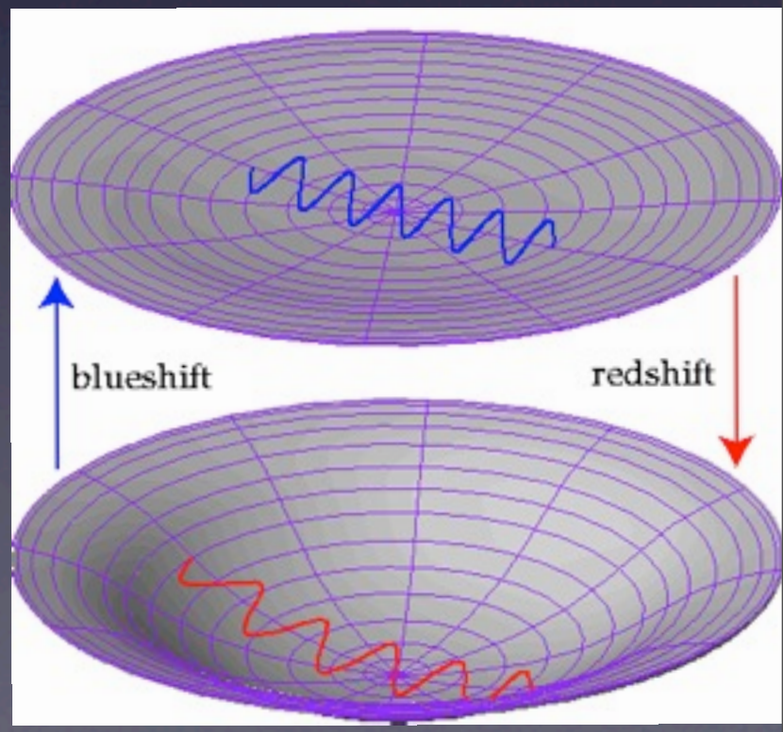
Different physics sensitive to different combinations of Newtonian potentials

Lensing, ISW $\longrightarrow$ $\phi + \psi$

Galaxy peculiar velocities $\longrightarrow$ ϕ

Nonlinear dynamics complicated because of Vainshtein mechanism





Graviton mass (hard mass)

- To give the graviton a mass, include the interactions

$$S = M_{\rm Pl}^2 \int \mathrm{d}^4x\sqrt{-g}\left(R[g] \; - \; \frac{m^2}{4}(\text{mass terms}) \right)$$

- Mass for the fluctuations around flat space-time

$$\phi^a = x^a - A^a \qquad\qquad g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

$$\phi^a = x^a - \partial^a\pi - \cancel{V^a} \qquad\qquad g_{\mu\nu} = \eta_{ab}\partial_\mu\phi^a\partial_\nu\phi^b + H_{\mu\nu}$$

$$H_{\mu\nu} = h_{\mu\nu} + 2\partial_\mu\partial_\nu\pi - \partial_\mu\partial_\alpha\pi\partial_\nu\partial^\alpha\pi$$

Graviton mass (hard mass)

$$H_{\mu\nu} = h_{\mu\nu} + 2\partial_\mu\partial_\nu\pi - \partial_\mu\partial_\alpha\pi\partial_\nu\partial^\alpha\pi$$

two derivatives acting on π

implies invariant under

$$\pi \longrightarrow \pi + C + v^\mu x^\mu$$

Ghost-free decoupling limit

Keeping this procedure to all orders,

$$\mathcal{L} = -\frac{1}{2}\hat{h}^{\mu\nu}(\mathcal{E}\hat{h})_{\mu\nu} - \hat{h}^{\mu\nu}\left(X^{(1)}_{\mu\nu} + \frac{1}{\Lambda_3^3}X^{(2)}_{\mu\nu} + \frac{1}{\Lambda_3^6}X^{(3)}_{\mu\nu} + \cdots\right)$$

with

$$X^{(1)}_{\mu\nu} = \partial_\mu\partial_\nu\hat{\pi} - \Box\hat{\pi}\eta_{\mu\nu}$$

$$X^{(2)}_{\mu\nu} \sim (\partial_\mu\partial_\nu\hat{\pi})^2 + \cdots$$

$$X^{(3)}_{\mu\nu} \sim (\partial_\mu\partial_\nu\hat{\pi})^3 + \cdots$$

de Rham, Gabadadze 2010

How do we make this fully covariant?

Decoupling limit is not fully Diff invariant, need to develop fully nonlinear theory

Attempt made by Creminelli et al. (2005)
Failed (Calculation Errors)

Attempt made by Chamseddine+ Mukhanov et al. (2010)
Initially wrote down theory with ghost, corrected but only to cubic order

We have been able to determine all interactions to all orders in perturbations to generalize previous ghost free decoupling theories

de Rham (Geneva), Gabadadze (NYU), AJT
To appear soon

Symmetries

- If hard mass gravity is consistent, must exist hidden symmetry 10+4+1 - 2*5 = 5. Work in progress looking for fundamental origin of symmetry
- In DGP/Cascading gravity, symmetry is just higher dimensional diffeomorphisms

Galileon Inflation

Burrage, de Rham, Seery, AJT (2010)
`Galileon Inflation', arXiv: 1009.2497

Similar work by Kobayashi et al (2010)
arXiv: 1008.0603

The Galileon

The decoupling limit of Cascading Gravity belongs to Galileon class of models:

$$3\Box\hat{\pi} + \frac{\alpha}{\Lambda_\star^3}\left((\Box\hat{\pi})^2 + \cdots\right) + \frac{\beta}{\Lambda_\star^6}\left((\Box\hat{\pi})^3 + \cdots\right) + \frac{\gamma}{\Lambda_\star^9}\left((\Box\hat{\pi})^4 + \cdots\right) = -\hat{T}$$

1. The theory is local
2. It possess a Galilean symmetry $\pi \to \pi + c_\mu x^\mu$
3. It has a well-defined Cauchy problem (eof remain 2nd order)

Only finite number of operators satisfying these criteria!

Nicolis, Rattazzi and Trincherini, 0811.2197

Unified DBI/Galileon

$$\mathcal{L} = \sqrt{-g}\left(-\lambda + M_4^2 R - M_5^3 K - \beta\frac{M_5^3}{m^2}\mathcal{K}_{\rm GB}\right) + \mathcal{A}(\pi)$$

$$g_{\mu\nu} = q_{\mu\nu} + \partial_\mu\pi\partial_\nu\pi$$

DBI limit

$$M_4, M_5 \to 0$$

$$\mathcal{L} = -\lambda\sqrt{1+(\partial\pi)^2} + \lambda$$

Recover the DBI action

Non-relativistic limit

$$(\partial\pi)^2 \ll 1$$

$$\mathcal{L} = (\partial\pi)^2\Big[-\lambda + M_5^3\Box\pi + M_4^2\left((\Box\pi)^2+\cdots\right) + \frac{\beta M_5^3}{m^2}\left((\Box\pi)^3+\cdots\right)\Big]$$

Recover Galileon action

de Rham, AJT (2010)
`DBI and the Galileon reunited', JCAP 1005:015,2010

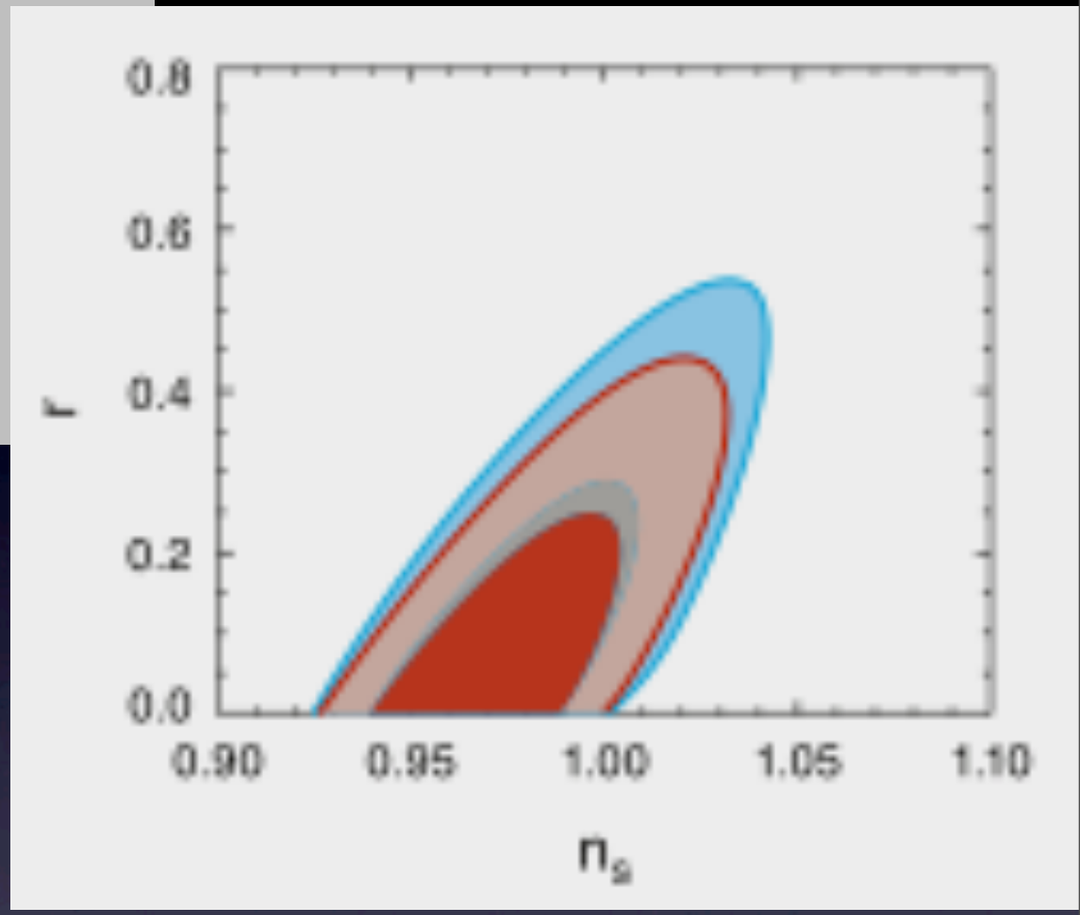
SEVEN-YEAR WILKINSON MICROWAVE ANISOTROPY PROBE (*WMAP*[1]) OBSERVATIONS: COSMOLOGICAL INTERPRETATION

MATSU[2], K. M. SMITH[3], J. DUNKLEY[4], C. L. BENNETT[5], B. GOLD[5], G. HINSHAW[6], N. JAROSIK[7], D. LARSON[5], M. R. OLTA[8], L. PAGE[7], D. N. SPERGEL[3,9], M. HALPERN[10], R. S. HILL[11], A. KOGUT[6], M. LIMON[12], S. S. MEYER[13], N. ODEGARD[6], G. S. TUCKER[14], J. L. WEILAND[11], E. WOLLACK[6], AND E. L. WRIGHT[15]

Submitted to the Astrophysical Journal Supplement Series

ABSTRACT

The combination of 7-year data from *WMAP* and improved astrophysical data rigorously tests the standard cosmological model and places new constraints on its basic parameters and extensions. By combining the *WMAP* data with the latest distance measurements from the Baryon Acoustic Oscillations (BAO) in the distribution of galaxies (Percival et al. 2009) and the Hubble constant (H_0) measurement (Riess et al. 2009), we determine the parameters of the simplest 6-parameter ΛCDM model. The power-law index of the primordial power spectrum is $n_s = 0.963 \pm 0.012$ (68% CL) for this data combination, a measurement that excludes the Harrison-Zel'dovich-Peebles spectrum by more than 3σ. The other parameters, including those beyond the minimal set, are also consistent with, and



Larson et al. WMAP7 '10

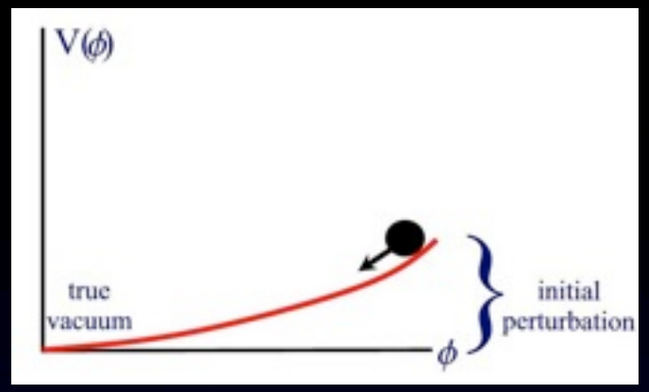
- A red spectrum
- Most models of inflation predict

$$|n_s - 1| \sim \frac{2}{N_e}$$

- Departure from scale invariance required by slow-roll paradigm but also by its alternatives!

Galileon Inflation: Central Idea

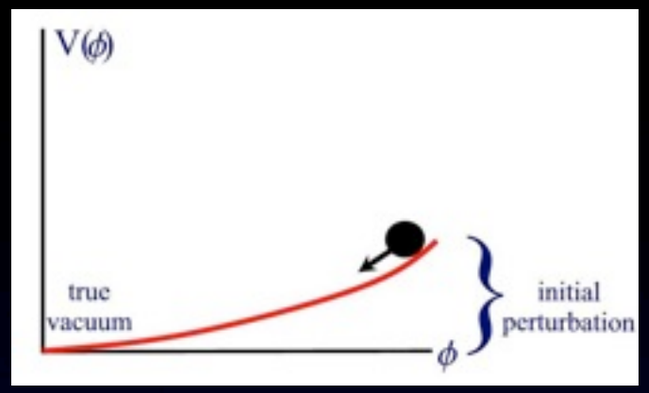
Shift symmetry protects inflationary potential to allow sufficient e-folds of inflation



$$\delta_c \ln V \sim \sqrt{\epsilon} \ll 1, \quad \text{and} \quad \delta_c^2 \ln V \sim \eta - \epsilon \ll 1,$$

$$\pi \to \pi + c/M_{\rm pl}$$

Galileon Inflation: Central Idea

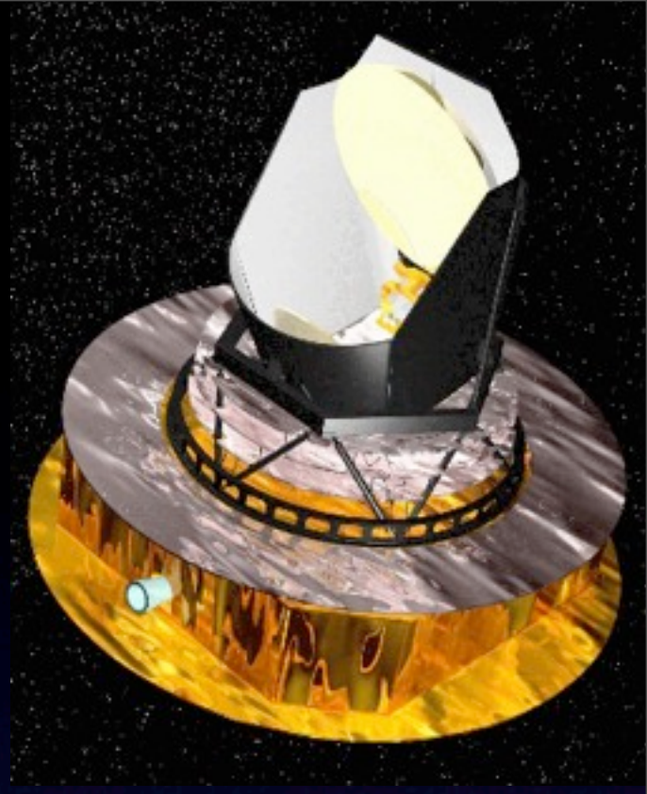


- When combined with Galilean symmetry can allow for large non-minimal kinetic terms without theory going out of control

- Non-minimal kinetic terms are principle source of single field non-Gaussianities - this inflationary models build on Galileon can have potentially observable non-Gaussianities

Non-Gaussianities + Observations

Data currently coming,
expected release 2012?



- nG's will hopefully be measured with some accuracy in future data eg PLANCK potentially getting down to

$$f_{NL} \approx 2.9$$

- Potential existence of nG's is far more significant discriminator of fundamental physics than departure from scale invariance!

There is also considerable hope of competitive constraints from Large Scale Structure

Dalal et al. 2007

Covariant Galileon

Deffayet et al 2009

$$S = \int \mathrm{d}^4x \sqrt{-g} \Bigg[-\frac{c_2}{2}(\nabla\phi)^2 + \frac{c_3}{\Lambda^3}\Box\phi(\nabla\phi)^2 - \frac{c_4}{\Lambda^6}(\nabla\phi)^2\Big\{(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)(\nabla^\mu\nabla^\nu\phi) - \frac{1}{4}R(\nabla\phi)^2\Big\}$$
$$+ \frac{c_5}{\Lambda^9}(\nabla\phi)^2\Big\{(\Box\phi)^3 - 3(\Box\phi)(\nabla_\mu\nabla_\nu\phi)(\nabla^\mu\nabla^\nu\phi) + 2(\nabla_\mu\nabla_\nu\phi)(\nabla^\nu\nabla^\alpha\phi)(\nabla_\alpha\nabla^\mu\phi) - 6G_{\mu\nu}\nabla^\mu\nabla^\alpha\phi\nabla^\nu\phi\nabla_\alpha\phi\Big\}\Bigg],$$

plus a mildly varying potential e.g.

$$V(\phi) = \frac{1}{2}m^2\phi^2$$

Galileon on de Sitter

Burrage, de Rham, Seery, AJT (2010)
`Galileon Inflation', arXiv: 1009.2497

$$S_0 = \int \mathrm{d}^4x\, a^3 \left\{ \frac{c_2}{2}\dot{\phi}^2 + \frac{2c_3 H}{\Lambda^3}\dot{\phi}^3 + \frac{9c_4 H^2}{2\Lambda^6}\dot{\phi}^4 + \frac{6c_5 H^5}{\Lambda^9}\dot{\phi}^5 + \lambda^3\phi \right\}.$$

$$\dot{\phi} \sim \frac{\lambda^3}{3H} \,.$$ (weak coupling)

$$\dot{\phi} \sim \sqrt{\frac{\Lambda^3\lambda^3}{18c_3H^2}} \,.$$ (strong coupling)

Action to cubic order in fluctuations

$$S \supseteq \int \mathrm{d}^4x\, a^3 \left[\alpha \left\{ \dot{\pi}^2 - \frac{c_s^2}{a^2}(\partial\pi)^2 \right\} + g_1 \dot{\pi}^3 + \frac{g_3}{a^2}\dot{\pi}(\partial\pi)^2 + \frac{g_4}{a^4}(\partial\pi)^2 \partial^2\pi \right],$$

comoving curvature perturbation

$$\zeta = \Phi + H\frac{\delta\phi}{\dot{\phi}} = H\pi$$

Non-Gaussianities Bispectrum

$$\langle \pi(\mathbf{k}_1,\tau)\pi(\mathbf{k}_2,\tau)\pi(\mathbf{k}_3,\tau)\rangle = (2\pi)^3\delta(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)B_\tau(k_1,k_2,k_3)$$

$$B(k_1,k_2,k_3) = \frac{6}{5}f_{\rm NL} \times \Big[P(k_1)P(k_2)+P(k_1)P(k_3)+P(k_2)P(k_3)\Big]$$

$$\zeta = \Phi + H\frac{\delta\phi}{\dot{\phi}} = H\pi$$

Non-Gaussianities Bispectrum

$$f_{\rm NL}^{\dot\pi^3} = \frac{2}{27}\frac{g_{1\star}H_\star}{\alpha_\star}\left(1+\frac{2\gamma_{\rm E}-3}{2}h_{1\star}+\frac{160\omega-2\gamma_{\rm E}-29}{2}v_\star+\frac{480\omega-98}{2}s_\star+\frac{320\omega-2\gamma_{\rm E}-63}{2}\epsilon_\star\right)$$

$$= \frac{2}{27}\frac{g_{1\star}H_\star}{\alpha_\star}\left(1-0.923h_{1\star}+1.141v_\star-0.344s_\star+0.360\epsilon_\star\right)$$

dim 6

$$f_{\rm NL}^{\dot\pi(\partial\pi)^2} = -\frac{17}{54c_{s\star}^2}\frac{g_{3\star}H_\star}{\alpha_\star}\left(1+\frac{17\gamma_{\rm E}-9}{17}h_{3\star}+\frac{32\ln\frac{3}{2}-17\gamma_{\rm E}+22}{17}v_\star+\frac{96\ln\frac{3}{2}-34\gamma_{\rm E}+40}{17}s_\star\right.$$
$$\left.+\frac{64\ln\frac{3}{2}-17\gamma_{\rm E}+18}{17}\epsilon_\star\right)$$

dim 6

$$= -\frac{17}{54c_{s\star}^2}\frac{g_{3\star}H_\star}{\alpha_\star}\left(1+0.048h_{3\star}+1.480v_\star+3.489s_\star+2.008\epsilon_\star\right)$$

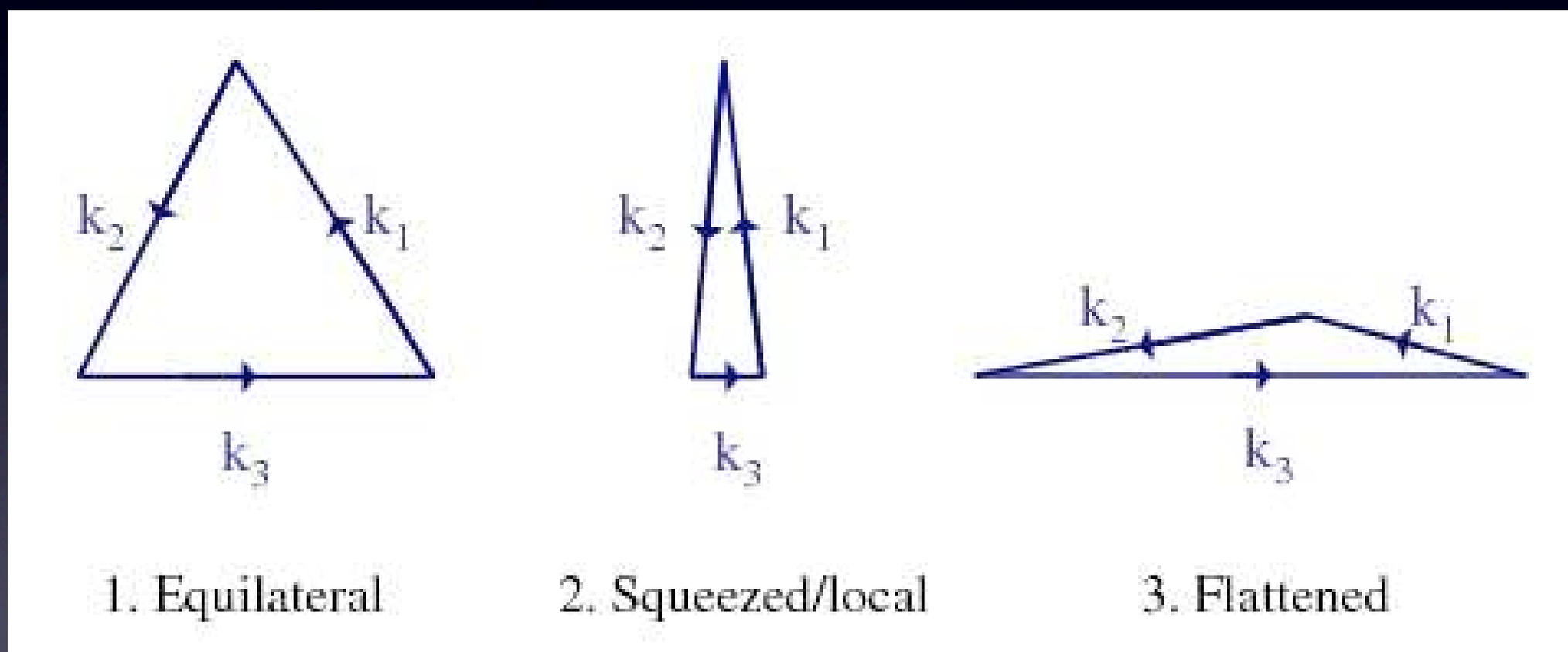
$$f_{\rm NL}^{\partial^2\pi(\partial\pi)^2} = -\frac{13}{27c_{s\star}^4}\frac{g_{4\star}H_\star^2}{\alpha_\star}\left(1+\frac{6\gamma_{\rm E}+5}{6}h_{4\star}+\frac{173-26\gamma_{\rm E}-256\ln\frac{3}{2}}{26}v_\star+\frac{733-156\gamma_{\rm E}-1152\ln\frac{3}{2}}{39}s_\star\right.$$
$$\left.+\frac{147-26\gamma_{\rm E}-256\ln\frac{3}{2}}{13}\epsilon_\star\right)$$

$$= \boxed{-\frac{13}{27c_{s\star}^4}}\frac{g_{4\star}H_\star^2}{\alpha_\star}\left(1+1.411h_{4\star}+2.084v_\star+4.509s_\star+2.169\epsilon_\star\right).$$

dim 7

Shapes

$$\langle \pi(\mathbf{k}_1,\tau)\pi(\mathbf{k}_2,\tau)\pi(\mathbf{k}_3,\tau)\rangle = (2\pi)^3\delta(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)B_\tau(k_1,k_2,k_3)$$



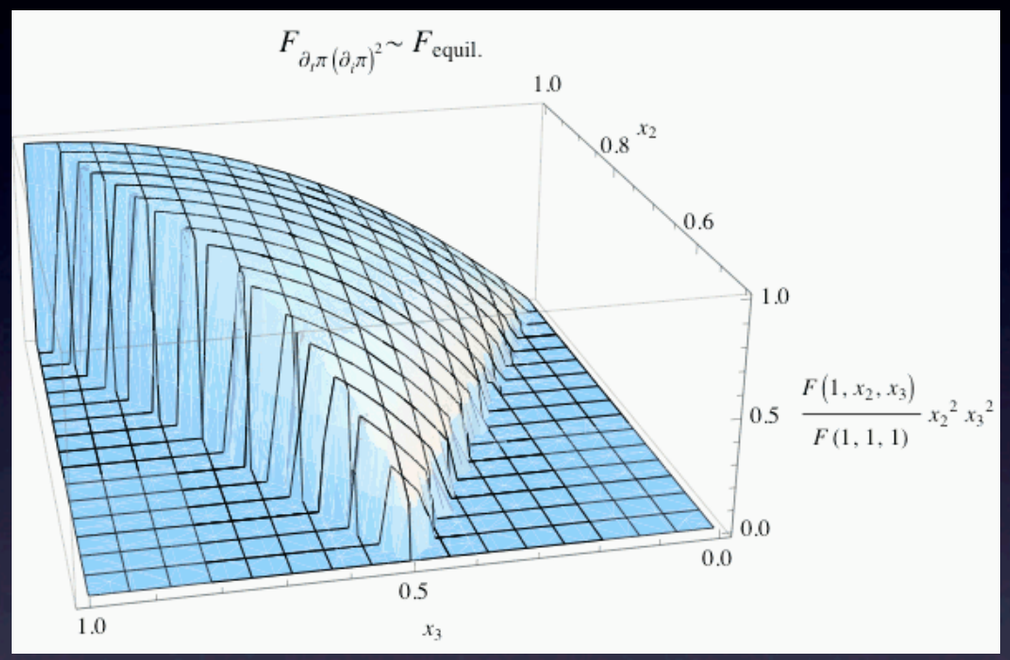
Senatore et al. 2009

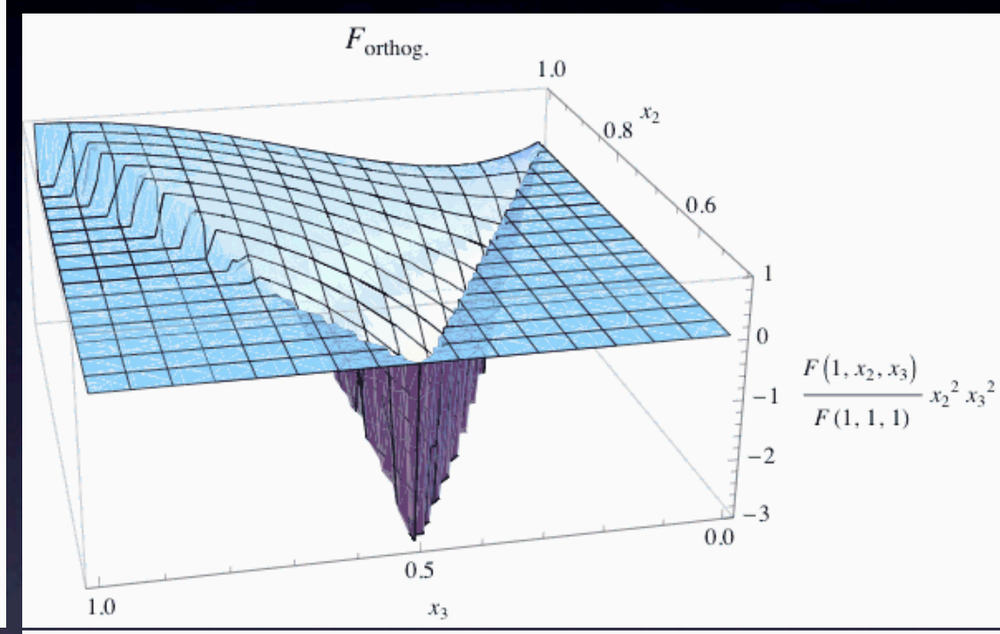
Shapes

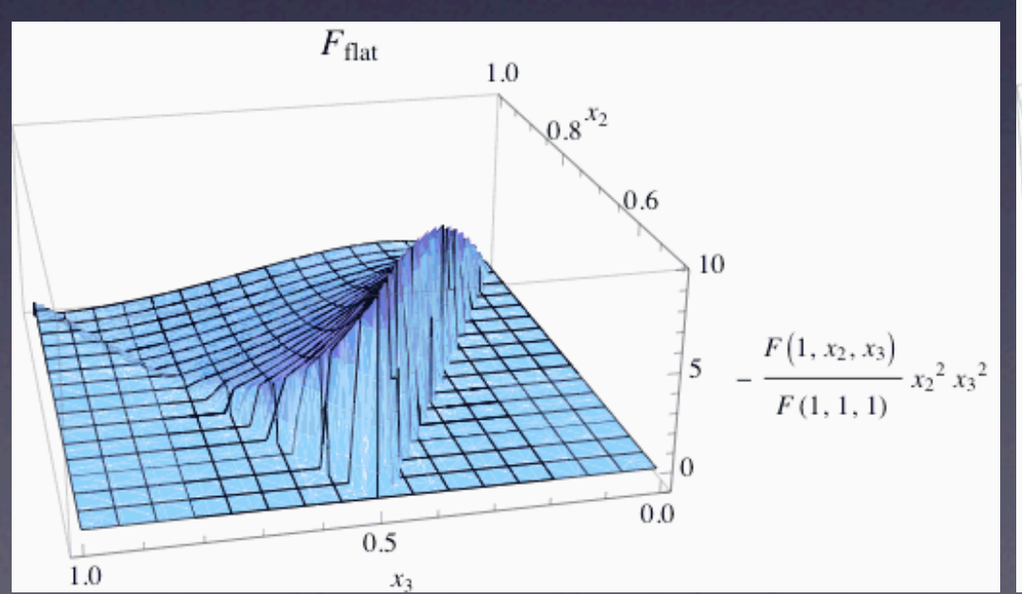
Senatore et al. 2009

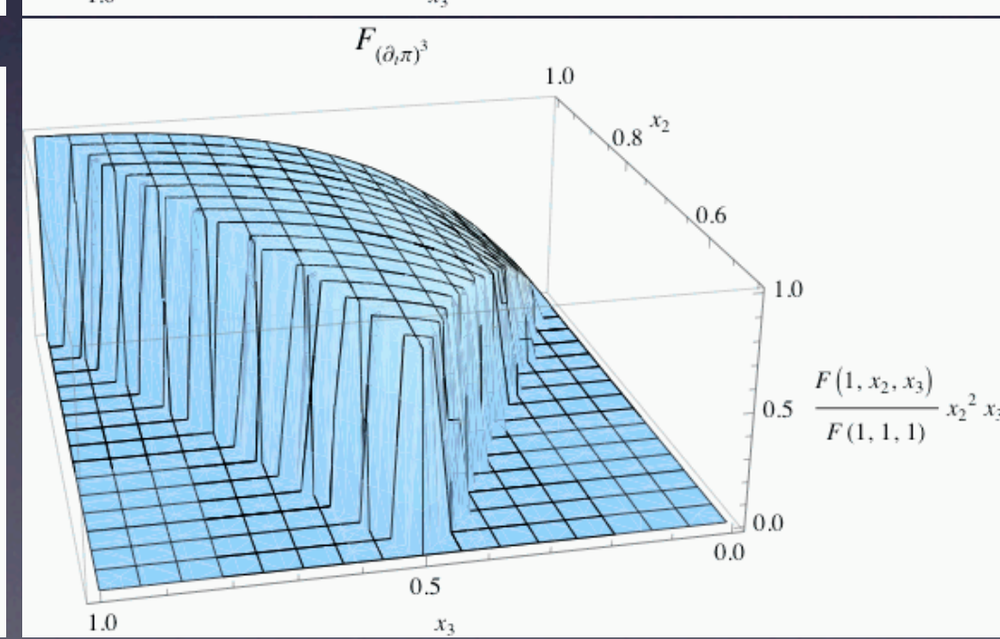
$$\langle \Phi_{\vec{k}_1} \Phi_{\vec{k}_2} \Phi_{\vec{k}_3} \rangle = (2\pi)^3 \delta^{(3)}(\sum_i \vec{k}_i) F(k_1, k_2, k_3)$$

$$\Phi = \frac{3}{5}\zeta \ ,$$









Summary

- Most plausible candidates for dynamical dark energy and inflation are fields with additional approximate global symmetries
- Consistency of coupling to gravity requires some new physics, most plausible is the global symmetry becomes local
- We are inevitably led to extra dimensional models and/or massive gravity models as consistent frameworks in which to realize local symmetry
- Models exhibit a wealth of interesting phenomenological implications

Summary

- Can produce models with large single field non-Gaussianities in a technically natural way (non-renormalization theorems)

- Only a finite number of relevant operators - highly predictive

- Non-Gaussianities no longer constrained to the form - dimension 7 operators that dominate over dimension 6 $f_{NL} \sim \frac{1}{c_s^2}$

Burrage, de Rham, Seery, AJT (2010)
`Galileon Inflation', arXiv: 1009.2497

Summary

- Generalize from Galileon inflation to DBI/Galileon inflation

Work in progress with Burrage, de Rham, Seery (Sussex)

- So far we have looked at Bispectrum predictions for CMB, natural to extend to Trispectrum .... are there any surprises? (e.g. different shapes?)

- Would like to construct in a more complete (both in IR and UV) framework e.g. higher dimensional braneworld constructions