# Power Counting & Gravity

*The power of counting*
*in gravity & cosmology*

*Cliff Burgess*

*R Holman, L Leblond, H.-M. Lee, S Shandera and M. Trott*

# On the shoulders of giants

*With thanks to Ulf Danielsson*

J. Conlon, L. McAllister, E. Silverstein, S. Kachru, J. Polchinski, R. Brandenberger, A. Salam, E. Sezgin, H. Nishino,G. Gibbons, S. Kachru E. Silverstein, R. Guven, C. Pope, K. Maeda, M. Sasaki, V. Rubakov, R. Gregory, I. Navarro, J. Santiago, S. Carroll, C. Guica, C. Wetterich, S. Randjbar-Daemi, F. Quevedo, Y. Aghababaie, S. Parameswaran, J. Cline, J. Matias, G. Azuelos, P-H. Beauchemin, A. Albrecht, C. Skordis, F. Ravndal, I. Zavala, G. Tasinato, J. Garriga, M. Porrati, H.P. Nilles, A. Papazoglou, H. Lee, N. Arkani-Hamad, S. Dimopoulos, N. Kaloper, R. Sundrum, D. Hoover, A. Tolley, C. de Rham, S. Forste, Z. Lalak, S. Lavingnac, C. Grojean, C. Csaki, J. Erlich, T. Hollowood, H. Firouzjahi, J. Chen, M. Luty, E. Ponton, P. Callin, D. Ghilencea, E. Copeland, O. Seto, V. Nair, S. Mukhoyama, Y. Sendouda, H. Yoshigushi, S. Kinoshita, A. Salvio, J. Duscheneau, J. Vinet, M. Giovannini, M. Graesser, J. Kile, P. Wang, P. Bostok, G. Kofinas, C. Ludeling, A. Nielsen, B. Carter, D. Wiltshire. C. K. Akama, S. Appleby, F. Arroja, D. Bailin, M. Bouhmadi-Lopez, M. Brook, R. Brown, C. Byrnes, G. Candlish, A. Cardoso, A. Chatterjee, D. Coule, S. Creek, B. Cuadros-Melgar, S. Davis, B. de Carlos, A. de Felice, G. de Risi, C. Deffayet, P. Brax, D. Easson, A. Fabbri, A. Flachi, S. Fujii, L. Gergely, C. Germani, D. Gorbunov, I. Gurwich, T. Hiramatsu, B. Hoyle, K. Izumi, P. Kanti, S. King, T. Kobayashi, K. Koyama, D. Langlois, J. Lidsey, F. Lobo, R. Maartens, N. Mavromatos, A. Mennim, M. Minamitsuji, B. Mistry, S. Mizuno, A. Padilla, S. Pal, G. Palma, L. Papantonopoulos, G. Procopio, M. Roberts, M. Sami, S. Seahra, Y. Sendouda, M. Shaeri, T. Shiromizu, P. Smyth, J. Soda, K. Stelle, Y. Takamizu, T. Tanaka, T. Torii, C. van de Bruck, D. Wands, V. Zamarias, H. Ziaeepour

# Outline

- Loopy gravity
  - Quantifying quantum effects
- Relevance to gravity
  - Inflation
  - de Sitter space
  - Naturalness issues
- Conclusions

# Outline

- Loopy gravity
  - Quantifying quantum effects
- Relevance to gravity
  - Inflation
  - de Sitter space
  - Naturalness issues
- Conclusions

# Outline

- Loopy gravity
  - Quantifying quantum effects
- Relevance to gravity
  - Inflation
  - de Sitter space
  - Naturalness issues
- Conclusions

# Quantifying Quantum Effects

- Gravity as an effective field theory

- How does matter change things?

# Quantifying Quantum Effects

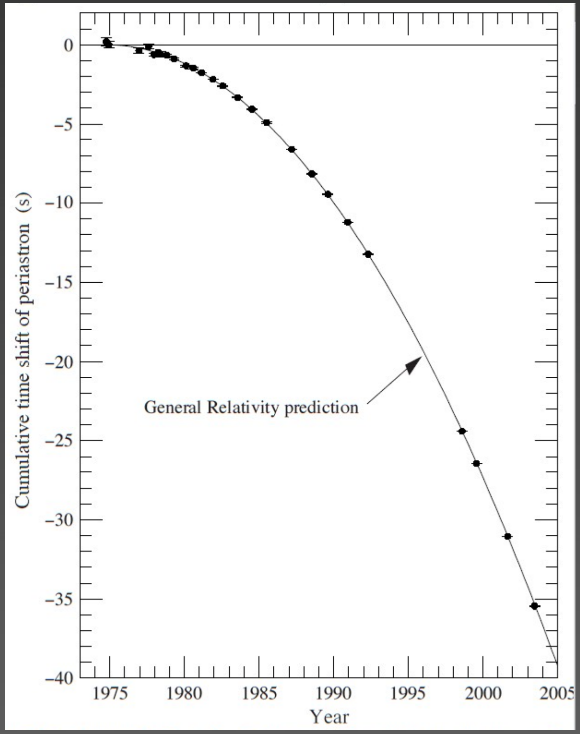
- Gravity as an effective field theory

- How does matter change things?

# Quantifying Quantum Effects

- Gra
  fiel
- Ho
  cha

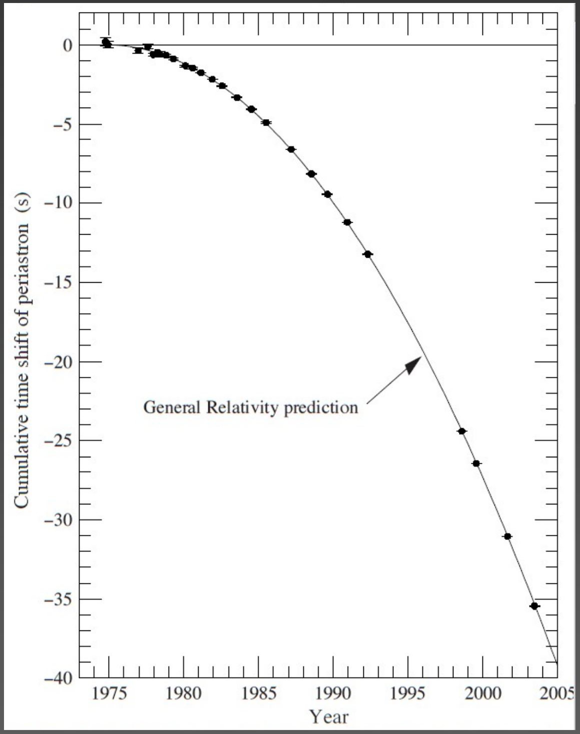
General relativity is a precision science

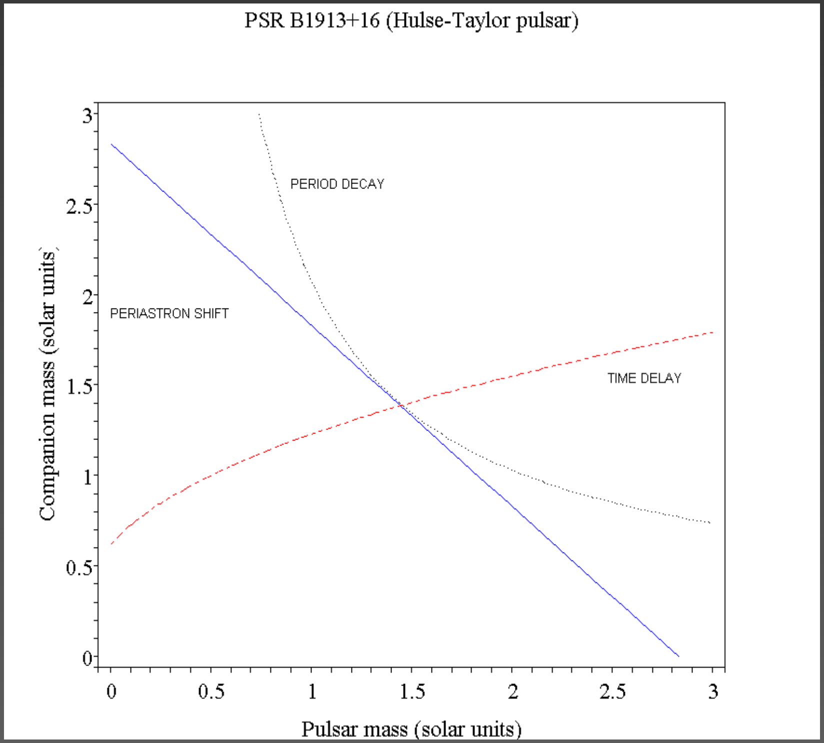


# Quantifying Quantum Effects

- Gra
  fiel
- Ho
  cha

## General relativity is a precision science



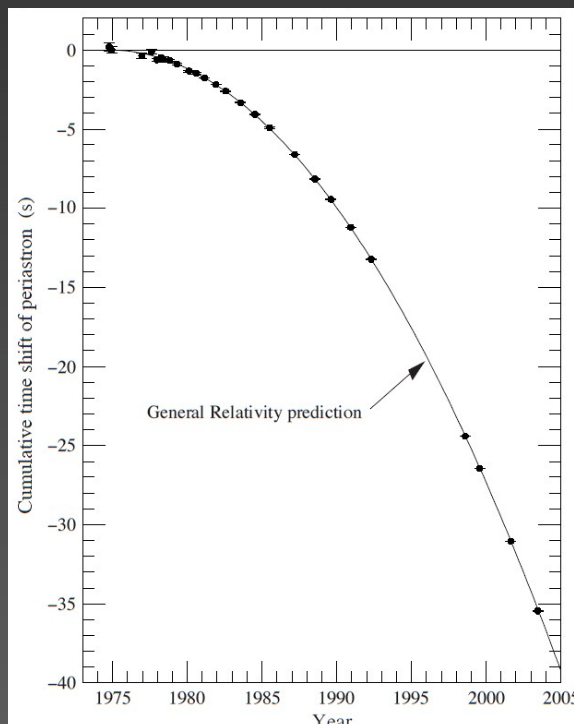



# Quantifying Quantum Effects

- Gra
fiel

- Ho
cha

General relativity is a precision science




Theoretical predictions use the classical equations of motion

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = 8\pi\, G\, T_{\mu\nu}$$

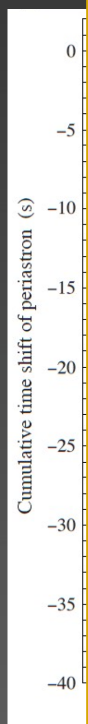
usually in weak-field regime

$$R_{\mu\nu\lambda\rho} R^{\mu\nu\lambda\rho} \approx \left( \frac{GM}{r^3} \right)^2$$

# Quantifying Quantum Effects

- Gra
  fiel
- Ho
  cha

C



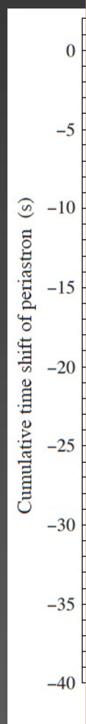

Meaningful comparison with experiment requires a quantification of theoretical errors

*PPN corrections, plasma effects, loops,…*

# Quantifying Quantum Effects

- Gra
  fiel
- Ho
  cha

C




Meaningful comparison with experiment requires a quantification of theoretical errors

*PPN corrections, plasma effects, loops,…*

# Quantifying Quantum Effects

- Gra
  fiel

- Ho
  cha

How can quantum effects be estimated without a theory of quantum gravity, since General Relativity is not renormalizable?

QED

$$L_{\text{int}} = e A_\mu \psi \gamma^\mu \psi$$

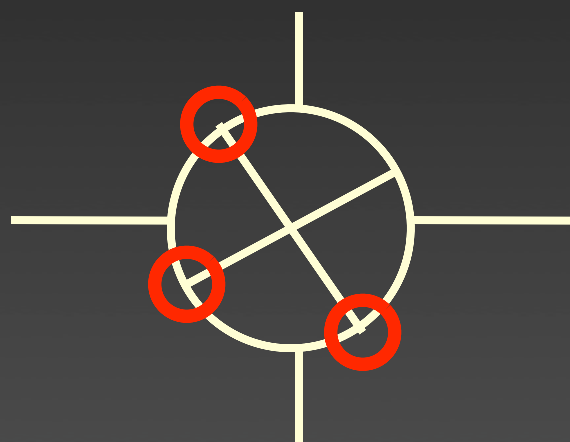
GR

$$L_{\text{int}} = \frac{1}{M_p} h_{\mu\nu} \psi \gamma^\mu \partial^\nu \psi$$

# Quantifying Quantum Effects

- Gra
  fiel
- Ho
  cha

How can quantum effects be estimated without a
y, since General Relativity



$$A_4 \approx \left( \frac{\Lambda}{M_p} \right)^{nL}$$

GR

$$L_{int} = \frac{1}{M_p} h_{\mu\nu} \psi \gamma^{\mu} \partial^{\nu} \psi$$

# Quantifying Quantum Effects

- G… fi… a …vity
- H… ch… ψ

In the 60's this was regarded as a major disaster:

| Left Brain: $G = 0$ | Right Brain: $h = 0$ |
| --- | --- |
| *Precision quantum world in which gravity does not exist.* | *Precision gravity world in which quantum mechanics does not exist.* |

# Quantifying Quantum Effects

- G … a
  fi … vity
- H …
  ch … ψ

In the 60’s this w… as a major disaster:

Left Brain: G

*Precision … uantum world in … ich gravity does not e…*

Right … ain: $h = 0$

*Precis… gravity world … which … mechanics d… ot exist.*

If true, uncontrolled theoretical errors…

# Quantifying Quantum Effects

- Gra
fiel

- Ho
cha

Progress: abandon gravitational exceptionalism

Soft pions

$$L_{\text{int}} = \frac{1}{F_\pi} \partial_\mu \pi (\psi \gamma^\mu \gamma_5 \psi)$$

Fermi theory

$$L_{\text{int}} = G_F (\psi \gamma^\mu \gamma_L \psi)(\psi \gamma_\mu \gamma_L \psi)$$

# Quantifying Quantum Effects

- Gra
  fiel
- Ho
  cha

Progress: abandon gravitational exceptionalism

Soft pions

$$L_{\text{int}} = \frac{1}{F_\pi} \partial_\mu \pi \, (\psi \gamma^\mu \gamma_5 \psi)$$

Fermi theory

$$L_{\text{int}} = G_F \, (\psi \gamma^\mu \gamma_L \psi)(\psi \gamma_\mu \gamma_L \psi)$$

QCD

$$E < 4\pi F_\pi$$

Standard Model

$$E < M_W \approx (\alpha / G_F)^{1/2}$$

# Quantifying Quantum Effects

- Gra
  fiel

- Ho
  cha

Precise rules for calculations:

Must include all possible interactions allowed by particle content and symmetries, to any given order in *1/M*

$$L_{eff} = f^2 M^2 \sum_{ik} \frac{c_{ik}}{M^{d_k}} O[\partial^k (\varphi / v)^i]$$

Only a finite number of these appear in observables to any fixed order in *E/M: but which ones?*

# Quantifying Quantum Effects

- Gra… fiel…
- Ho… cha…

Precise rules for calculations:

$$L_{eff} = f^2 M^2 \sum_{ik} \frac{c_{ik}}{M^{d_k}} O[\partial^k (\varphi / v)^l]$$

*M, f and v* are (possibly related) high scales whose presence must be tracked in arbitrary processes

# Quantifying Quantum Effects

- Gra
  fiel

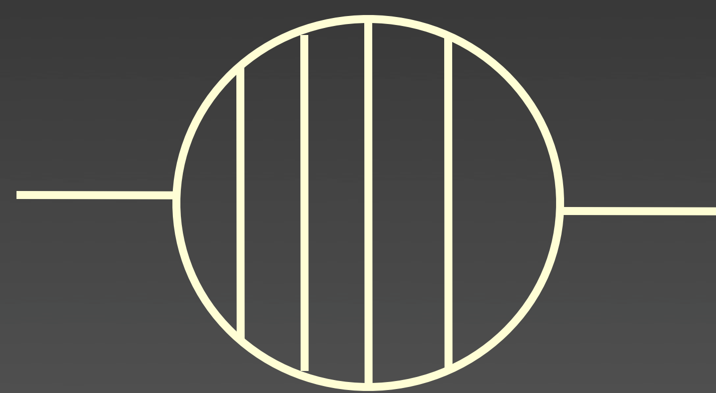
Preci

- Ho
  cha

*M, f*

prese

*eg* for an amplitude at energy $E << M, f, v$



# Quantifying Quantum Effects

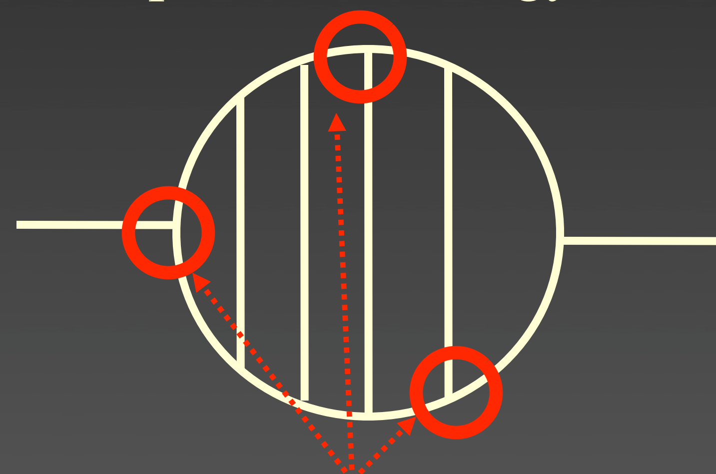
- Gra
  fiel
- Ho
  cha

Preci

*M, f*

prese

*eg* for an amplitude at energy $E << M, f, v$



*dependence on M, f and v easily tracked,*

# Quantifying Quantum Effects

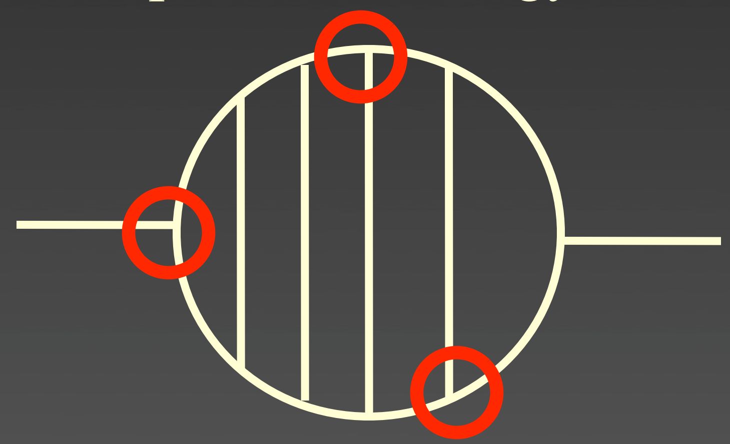
- Gra
  fiel
- Hov
  cha

Preci

*M, f*

prese

*eg* for an amplitude at energy $E << M, f, v$



*dependence on M, f and v easily tracked,*

*dependence on E often follows dimensionally*

# Quantifying Quantum Effects

- Gra
  fiel
- Ho
  cha

Preci

*M, f*
prese

*dependence on E often follows dimensionally:*

This could be *(but need not be)* obtained in momentum space

$$A(E) \approx \iiint \frac{d^n k_i}{\left(k_i^2 + E^2\right)^p} \approx E^{n-2p}$$

with UV divergences regulated and renormalized using dimensional regularization

# Quantifying Quantum Effects

Notice that cutoff regularizations are much less useful for these purposes because:

Cutoffs appear as large scales in intermediate steps (such as regularized integrals)

but cutoffs ultimately cancel once these divergences are renormalized, and so do not appear in the final result

# Quantifying Quantum Effects

Notice that cutoff regularizations are much less useful for these purposes because:

$$e^{i\Gamma(\varphi)} = \int D\phi_{E<\Lambda} D\phi_{E>\Lambda}\, e^{iS(\varphi+\phi)}$$

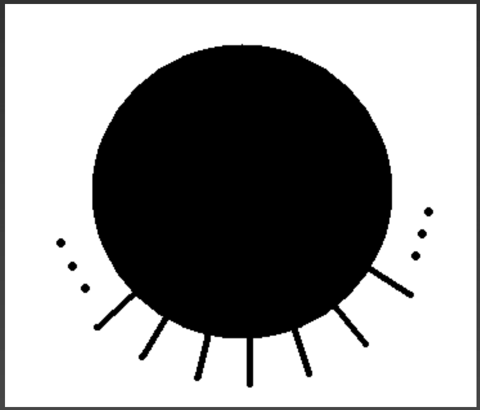
$$= \int D\phi_{E<\Lambda}\, e^{iS_\Lambda(\varphi,\phi)}$$

# Quantifying Quantum Effects

- Gra
  fiel
- Ho
  cha

*eg:* $N$-point amplitude

$N$: external lines
$L$: loops
$V_{ik}$: vertices with $i$ fields, $k$ derivs
$E$: external energy



$$A_N(E) \propto \left(\frac{f^4 E^2}{M^2 v^N}\right)\left(\frac{ME}{4\pi f^2}\right)^{2L}\prod_{ik} c_{ik}\left(\frac{E}{M}\right)^{(k-2)V_{ik}}$$

# Quantifying Quantum Effects

- Gra
  fiel

- Ho
  cha

Regarding GR as the leading term at low-energies:

$$\frac{\mathcal{L}}{\sqrt{-g}} = \lambda + \frac{M_p^2}{2} R + c_1 R^2 + c_2 R_{\mu\nu} R^{\mu\nu} + \frac{c_3}{m^2} R^3 + \ldots$$

Low-dimension operators are enhanced by the largest scales integrated out to that point (like $M_p$)

High-dimension operators are suppressed by the lowest scales integrated out to that point (like $1/m_e$)

# Quantifying Quantum Effects

*N*-point amplitude

$$A_N(E) \propto \left(\frac{E^2}{M_p^{N-2}}\right)\left(\frac{E}{4\pi M_p}\right)^{2L} \prod_{i;k>2}\left(\frac{E}{M_p}\right)^{2V_{ik}} \left(\frac{E}{m}\right)^{(k-4)V_{ik}}$$

# Quantifying Quantum Effects

- 

*N*-point amplitude

$$A_N(E) \propto \left(\frac{E^2}{M_p^{N-2}}\right)\left(\frac{E}{4\pi M_p}\right)^{2L} \prod_{i;k>2}\left(\frac{E}{M_p}\right)^{2V_{ik}} \left(\frac{E}{m}\right)^{(k-4)V_{ik}}$$

- 

*Leading contribution: L = 0 and $V_{ik}$ = 0 for all k > 2 ie: classical GR*

# Quantifying Quantum Effects

*N*-point amplitude

$$A_N(E) \propto \left(\frac{E^2}{M_p^{N-2}}\right)\left(\frac{E}{4\pi M_p}\right)^{2L}\prod_{i;k>2}\left(\frac{E}{M_p}\right)^{2V_{ik}}\left(\frac{E}{m}\right)^{(k-4)V_{ik}}$$

*Leading contribution: L = 0 and* $V_{ik} = 0$ *for all k > 2 ie: classical GR*

*Next-to-leading: L = 1 and* $V_{ik} = 0$ *for all k > 2*

*or L = 0 and* $V_{i4} = 1$ *and* $V_{ik} = 0$ *for k > 4*

# Quantifying Quantum Effects

•

*N*-point amplitude

$$A_N(E) \propto \left(\frac{E^2}{M_p^{N-2}}\right)\left(\frac{E}{4\pi M_p}\right)^{2L} \prod_{i;k>2}\left(\frac{E}{M_p}\right)^{2V_{ik}} \left(\frac{E}{m}\right)^{(k-4)V_{ik}}$$

*Divergences in these are renormalized by these*

*$L = 0$ and $V_{ik} = 0$ for all $k >$*

*2 ie. classical GR*

*Next-to-leading: $L = 1$ and $V_{ik} = 0$ for all $k > 2$*

*or $L = 0$ and $V_{i4} = 1$ and $V_{ik} = 0$ for $k > 4$*

# Quantifying Quantum Effects

- Gravity as an effective field theory
- How does matter change things?

# Quantifying Quantum Effects

- Gra
fiel

- Hov
cha

For scalar fields

$$L = L_{GR} + G_{ab}(\phi)\,\partial\phi^a\,\partial\phi^b + V(\phi) + \ldots$$

General dimensional arguments go through if no new scales are introduced by the matter (such as non-relativistic sources)

Scalar potential involves no derivatives so can dominate at low energies, making terms like $M^2\varphi^2$ or $M\,\varphi^3$ potentially dangerous

# Outline

- Loopy gravity
  - Quantifying quantum effects
- Relevance to gravity
  - Inflation
  - de Sitter space
  - Naturalness issues
- Conclusions

# Relevance to gravity

- Inflation
- de Sitter space
- Naturalness issues

# Relevance to gravity

- Inflation
- de Sitter space
- Naturalness issues

# Relevance to gravity

- Infl
- de
- Nat

*Old idea:* inflation requires a scalar, and the Standard Model has one (the Higgs). Can one scalar do both jobs?

# Relevance to gravity

- Infl
- de
- Nat

*Old idea:* inflation requires a scalar, and the Standard Model has one (the Higgs). Can one scalar do both jobs?

*Old Answer:* No, even though a slow roll is possible for $V \sim \lambda_H \phi^4$ *if* $\phi \gg M_p$

$$\varepsilon \approx \eta \approx \left( \frac{M_p}{\phi} \right)^2$$

*Problem:* one parameter, $\lambda_H$, must satisfy contradictory requirements

$$m_H \approx \lambda_H v,$$

$$\left( \frac{\delta\rho}{\rho} \right)^2 \propto \lambda_H$$

# Relevance to gravity

*Bezrukov, Gormunov,*
*& Shaposhnikov*

- Infl
- de
- Nat

*New idea:* Higgs inflation might yet work if we take $L_{SM} + L_{GR} \rightarrow L_{SM} + L_{GR} + \xi R \phi^2$ term added to the SM lagrangian.

*In the spirit of effective lagrangian to add all possible terms: this is only one missing to dim 4.*

*New parameter, ξ, can set δρ/ρ without ruining* $m_H$

Can potentially obtain predictions for other observables – $n_s$ etc – in terms of $\lambda_H$, and so $m_H$.

# Relevance to gravity

*Spokoiny; Salopek, Bond & Bardeen; Steinhardt*

- Infl
- de
- Nat

Potential can still produce a slow roll at large $\phi$. After Weyl rescaling the action to Einstein frame $(M_p^2 + \xi\,\phi^2)\,R \;\rightarrow\; M_p^2\,R$, get a scalar potential:

$$V = \frac{(m_H^2\phi^2 + \lambda_H\phi^4)}{\Omega^2} \qquad \Omega = 1 + \frac{\xi\,\phi^2}{M_p^2}$$

which approaches a constant for $\phi \gg M_p/\sqrt{\xi}$.

$$H \approx \frac{\sqrt{\lambda_H}\,M_p}{\xi}$$

# Relevance to gravity

- Infl
- de
- Nat

To use standard inflationary formulae should also redefine the inflaton to canonical kinetic energy:

$$\frac{d\chi}{d\phi} = \left[\frac{\Omega + 6\xi^2\phi^2/M_p^2}{\Omega^2}\right]^{1/2} \qquad \Omega = 1 + \frac{\xi\phi^2}{M_p^2}$$

so

$$\phi \approx \frac{M_p}{\sqrt{\xi}} \exp\left(\frac{\chi}{\sqrt{6}M_p}\right)$$

and

$$V \approx \frac{\lambda_H M_p^4}{\xi^2}\left(1 - Ae^{-a\chi/M_p}\right) + \ldots$$

# Relevance to gravity

*Bezrukov, Gormunov, & Shaposhnikov*

- Infl
- de
- Nat

Amplitude of primordial perturbations requires $\xi \sim 10^4$ since

$$\frac{\delta\rho}{\rho} \approx \frac{\sqrt{V/\varepsilon}}{M_p^2} \approx \frac{\sqrt{\lambda_H}}{\xi}$$

*Everything else predictable in terms of parameters linked to Higgs physics!*

# Relevance to gravity

- Inf
- de
- Nat

Question: is this large a dimensionless coupling a problem?

# Relevance to gravity

- Infl
- de
- Nat

Question: is this large a dimensionless coupling a problem?

At first blush, no: the relative size of higher curvature terms is small, even if these are systematically proportional to ξ:

$$1+\frac{\xi R}{M_p^2}\approx 1+\frac{\xi \phi^2}{M_p^2}\approx 1+\frac{\lambda_H}{\xi}\approx 1$$

# Relevance to gravity

*CB, Lee & Trott*

- Infl
- de
- Nat

BUT: there are two kinds of problems:

1. Parameters are on the very edge of the domain of validity of the classical approximation, which is controlled only at energies low compared with $\Lambda = M_p/\xi$.

# Relevance to gravity

*CB, Lee & Trott;*
*Espinosa & Barbon*

- Infl
- de
- Nat

BUT: there are two kinds of problems:

1. Parameters are on the very edge of the domain of validity of the classical approximation, which is controlled only at energies low compared with $\Lambda = M_p/\xi$.

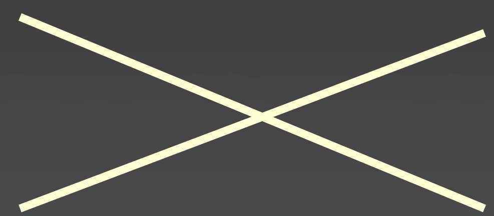
2. $V$ and $f(\phi)\ R$ are usually understood only for small fields: for $\phi$ *smaller* than $\Lambda$.

# Relevance to gravity

*CB, Lee & Trott; Herzberg*

- Inf
- de
- Nat

To see one symptom of the first problem consider higgs scattering in Einstein frame:



$$L_{\rm int} = \frac{\xi^2}{M_p^2} \phi_i \phi_j \, \partial\phi^i \partial\phi^j + \mathrm{L}$$

# Relevance to gravity

*CB, Lee & Trott; Herzberg*

- Infl
- de
- Nat

To see one symptom of the first problem consider higgs scattering in Einstein frame:

$$\sigma(E) \approx \left(\frac{\xi E}{M_p^2}\right)^2 > \sigma_{unitarity} \approx \frac{1}{E^2}$$

for $E > \Lambda \sim M_p/\xi \sim H/\sqrt{\lambda}$.

Quantum corrections can be dangerous since *H* is not systematically small compared with Λ.

# Relevance to gravity

*Espinosa & Barbon*

- Infl
- de
- Nat

To see the second problem, suppose that before going to Einstein frame we consider:

$$L \approx \left( m_H^2 \phi^2 + \lambda_H \phi^2 + c\frac{\phi^6}{M^2} + \ldots \right) + \left( \xi \phi^2 + c' \frac{\phi^4}{M^2} + \ldots \right) R + \ldots$$

for some *M*.

*But: for small* $\phi$*, we have* $\phi = \chi(1+\xi\, \chi^2/M_p^2 + ..)$
*so* $\lambda\, \phi^4 = \lambda\, \chi^4 (1 + \xi\, \chi^2/M_p^2 + ..)$

*so in the Einstein frame* $M < \Lambda = M_p/\xi$.

# Relevance to gravity

- Inflation
- de Sitter space
- Naturalness issues

# Relevance to gravity

- Inf
- de
- Nat

Interacting scalar field in de Sitter space is notoriously IR sensitive once $m << H$.

$$L = M_p^2 R + (\partial\phi)^2 + \lambda + m^2\phi^2 + g\phi^4$$

Field profiles become dominated by large fluctuations from one Hubble patch to the next

$$\langle \phi^2 \rangle \approx \frac{3H^4}{8\pi^2 m^2}$$

# Relevance to gravity

- Inf
- de
- Na

This situation is reminiscent of IR sensitivity of thermal fluctuations near a critical point

$$L = (\partial\phi)^2 + \lambda + m^2\phi^2 + g\phi^4$$

$$\rho = \exp(-\beta H)$$

for which Bose-Einstein distribution functions, $n(k) \sim 1/(e^{\beta k}-1) \sim T/k$ enhance the IR singularities

# Relevance to gravity

- Inf
- de
- Na

Can power count how amplitudes diverge in the IR

$$A_N(T) \propto \left(\frac{gT}{4\pi^2 m}\right)^L$$

so if $m_{eff}^2(T) \propto \frac{gT^2}{4\pi}$ then $A_N(T) \propto \left(\frac{g}{4\pi}\right)^{L/2}$

but if $m_{eff}^2(T) = 0$ then mean-field methods completely break down

# Relevance to gravity

*CB, Holman, Leblond & Shandera*

- Inf
- de
- Nat

Similarly scalar fields in de Sitter have IR behaviour

$$\langle \phi^2 \rangle \propto \left( \frac{gH^2}{4\pi^2 m^2} \right)^L$$

so might also expect mean-field (ie semiclassical) methods to completely break down for $m^2 < g\, H^2$

# Relevance to gravity

- Inflation
- de Sitter space
- Naturalness issues

# Relevance to gravity

- Inf
- de
- Nat

Power counting reinforces the problems with light scalars: since scalar masses are UV sensitive, light scalars generically require some explanation.

# Relevance to gravity

- Inf
- de
- Nat

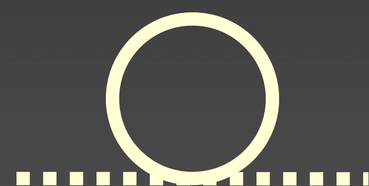
Power counting reinforces the problems with light scalars: since scalar masses are UV sensitive, light scalars generically require some explanation.

For instance, inferences about microscopic properties (like supersymmetry or extra dimensions) through classical reasoning applied to astrophysical observables (like dark energy) is generically suspect.

*Since small masses are required, classical conclusions are likely dominated by quantum effects.*

# Relevance to gravity

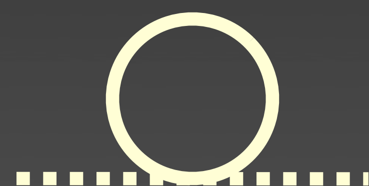
Searches for light scalars are nonetheless interesting provided the relevant quantum effects are included

$$L_{eff} \approx g\phi^2\psi^2$$

# Relevance to gravity

Searches for light scalars are nonetheless interesting provided the relevant quantum effects are included

$$L_{eff} \approx g\phi^2\psi^2$$

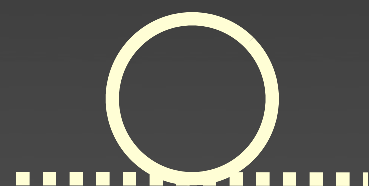
$$\delta m^2 \approx g\int \frac{d^4k}{(k^2+m^2)} \approx g\Lambda^2$$

# Relevance to gravity

- I
- d
- N

s

Searches for light scalars are nonetheless interesting provided the relevant quantum effects are included

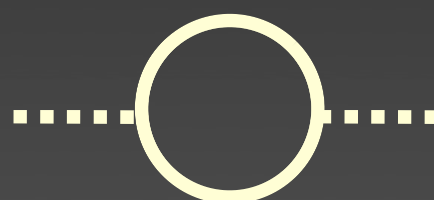
$$L_{eff} \approx g\phi^2\psi^2$$

$$\delta m^2 \approx g\int\frac{d^4k}{(k^2+m^2)} \approx g\Lambda^2$$

$$\delta m^2 \approx g\int\frac{d^4k}{(k^2+m^2)} \approx gm^2$$

# Relevance to gravity

Searches for light scalars are nonetheless interesting provided the relevant quantum effects are included

$$L_{eff} \approx gM\,\phi\psi^2$$

$$\delta m^2 \approx g^2 M^2 \int \frac{d^4k}{(k^2+m^2)^2} \approx g^2 M^2$$

Power UV divergences are proxies for sensitivity to heavy physical masses

# Relevance to gravity

- Inf
- de
- Nat

Are radiative corrections smaller when the gravity scale is hierarchically smaller than $M_p$?

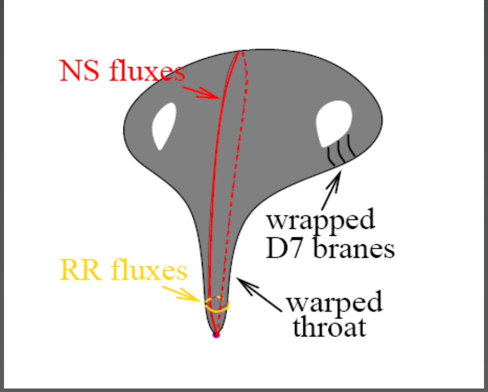
# Relevance to gravity

*Balasubramanian, Bergland, Conlon & Quevedo*

- Inf
- de
- Nat

Are radiative corrections smaller when the gravity scale is hierarchically smaller than $M_p$?

Example: *Large-Volume string compactifications of Type IIB vacua*




$$K = -2\ln V + \frac{\xi}{V} + K_{loop} + \ldots$$

$$W = W_0 + A_1 e^{a_1 T_1} + A_2 e^{a_2 T_2}$$

# Relevance to gravity

*Balasubramanian, Bergland, Conlon & Quevedo*

- Inf…
- de …
- Nat…

Are radiative corrections smaller when the gravity scale is hierarchically smaller than $M_p$?

Example: *Large-Volume string compactifications of Type IIB vacua*

These stabilize moduli at exponentially large volumes

$$V = \left(\frac{L}{l_s}\right)^6 \approx \exp(c\tau_s) \qquad \tau_s \approx \frac{1}{g_s}$$

# Relevance to gravity

*Balasubramanian, Bergland, Conlon & Quevedo*

- Inf
- de
- Nat

Are radiative corrections smaller when the gravity scale is hierarchically smaller than $M_p$?

Example: *Large-Volume string compactifications of Type IIB vacua*

They also predict a rich hierarchy of 4D scalar masses

$$M_s \propto \frac{M_p}{V^{1/2}} \qquad M_{KK} \propto \frac{1}{L} \approx \frac{M_p}{V^{2/3}}$$

$$M_{3/2} \approx M_{\text{mod}} \approx \frac{M_p}{V} \qquad M_V \propto \frac{M_p}{V^{3/2}}$$

# Relevance to gravity

- 4D Planck scale
- String scale
- Kaluza Klein scale
- Moduli and gravitino mass scales
- Volume modulus mass scale

String scale and Kaluza Klein scale: 10D sugra description

Moduli and gravitino mass scales: 4D sugra description

# Relevance to gravity

- Inf
- de
- Nat

How stable are these against quantum corrections?

Example: *moduli masses*

$$M_{\text{mod}} \approx \frac{M_p}{V}$$

# Relevance to gravity

*Conlon & Quevedo*

- Inf
- de
- Nat

How stable are these against quantum corrections?

Example: *moduli masses*

$$M_{\mathrm{mod}} \approx \frac{M_p}{V}$$

String loops: *generate α' corrections to 10D sugra*

$$L_D \approx \frac{1}{g_s^2} \sqrt{-g}\, g^{\mu\nu} R_{\mu\nu} \left[ 1 + \alpha'^3 \left( g^{mn} R_{mn} \right)^3 \right] + \ldots$$

# Relevance to gravity

$$L_{eff} \approx \frac{1}{M_s^2}\phi^3$$

- …ese against quantum corrections?

*…i masses*

$$M_{\text{mod}} \approx \frac{M_p}{V}$$

- *…erate α' corrections to 10D sugra*

10D sugra loops: *generate* KK *scale corrections*

$$\delta m^2 \approx \frac{1}{M_s^4}\int \frac{d^{10}k}{(k^2+m^2)^2} \approx \frac{m^6}{M_s^4}$$

- Nat…

$$m \approx M_s \longrightarrow \delta m \approx \left(\frac{m}{M_s}\right)^3 M_s \approx M_s \approx \frac{M_p}{V^{1/2}}$$

# Relevance to gravity

- Inf
- de

How stable are these against quantum corrections?

Example: *moduli masses*

$$M_{\text{mod}} \approx \frac{M_p}{V}$$

String loops: *generate* $\alpha'$ *corrections to 10D sugra*

10D sugra loops: *generate* KK *scale corrections*

$M_s$ is the cutoff, so is already included in string loop part.

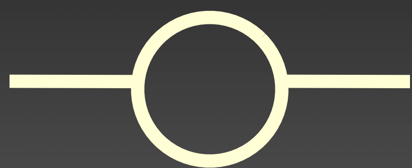
$$\delta m^2 \approx \frac{1}{M_s^4}\int \frac{d^{10}k}{(k^2+m^2)^2} \approx \frac{m^6}{M_s^4}$$

$$m \approx M_s \longrightarrow \delta m \approx \left(\frac{m}{M_s}\right)^3 M_s \approx M_s \approx \frac{M_p}{V^{1/2}}$$

# Relevance to gravity

- …ese against quantum corrections?

  *…i masses*



$$L_{eff} \approx \frac{1}{M_s^2}\phi^3$$

$$M_{\mathrm{mod}} \approx \frac{M_p}{V}$$

- *…erate $\alpha'$ corrections to 10D sugra*

  10D sugra loops: *generate* KK *scale corrections*

$$\delta m^2 \approx \frac{1}{M_s^4}\int \frac{d^{10}k}{(k^2+m^2)^2} \approx \frac{m^6}{M_s^4}$$

$$m \approx m_{KK} \longrightarrow \delta m \approx \left(\frac{m}{M_s}\right)^3 M_s \approx \left(\frac{1}{V^{1/6}}\right)^3 \frac{M_p}{V^{1/2}} \approx \frac{M_p}{V}$$

- Nat…

# Relevance to gravity

- ese against quantum corrections?

$$L_{eff} \approx M\phi^3$$

*i masses*

$$M_{\rm mod} \approx \frac{M_p}{V}$$

- *erate α' corrections to 10D sugra*

4D loops: *cutoff is $M_{KK}$, largest mass is $M_{mod}$*

$$\delta m^2 \approx M^2 \int \frac{d^4 k}{(k^2 + m^2)^2} \approx M^2$$

These are deadly for any $M$ bigger than $M_{mod}$, but in LV models they are forbidden by 4D susy

- Nat

# Relevance to gravity

- ...ese against quantum corrections?
- ... *masses*

$$M \sim M_{3/2} \sim M_{mod}$$

$$M_{\rm mod} \approx \frac{M_p}{V}$$

- ...*erate α' corrections to 10D sugra*

4D loops: *cutoff is* $M_{KK}$, *largest mass is* $M_{mod}$

$$\delta m^2 \approx M^2 \int \frac{d^4k}{(k^2+m^2)^2} \approx M^2$$

- Nat...

These are deadly for any $M$ bigger than $M_{mod}$, but in LV models they are forbidden by 4D susy

# Relevance to gravity

- Inf
- de
- Nat

How stable are these against quantum corrections?

Example: *moduli masses*

$$M_{\text{mod}} \approx \frac{M_p}{V}$$

Upshot: loops are generically dangerous but can be adequately suppressed by susy. No new miracles

For volume modulus, classical prediction is likely too low, with radiative corrections lifting its mass

# Outline

- Loopy gravity
  - Quantifying quantum effects
- Relevance to cosmology
  - Inflation
  - de Sitter space
- Conclusions

# Conclusions

- *Quantum effects including gravity are well understood at sufficiently low energies*

# Conclusions

- *Quantum effects including gravity are well understood at sufficiently low energies*
- *For most inflationary models, these quantum effects are controllably small, but for some inflation occurs at the edges of the semiclassical regime*

# Conclusions

- *Quantum effects including gravity are well understood at sufficiently low energies*
- *For most inflationary models, these quantum effects are controllably small, but for some inflation occurs at the edges of the semiclassical regime*
- *Large fluctuations for massless scalars in de Sitter space might invalidate semiclassical methods in some circumstances.*

# Conclusions

- *Quantum effects including gravity are well understood at sufficiently low energies*
- *For most inflationary models, these quantum effects are controllably small, but for some inflation occurs at the edges of the semiclassical regime*
- *Large fluctuations for massless scalars in de Sitter space might invalidate semiclassical methods in some circumstances.*
- *Light scalars are notoriously difficult to achieve, but unusual combinations of supersymmetry and extra dimensions may yet surprise us*