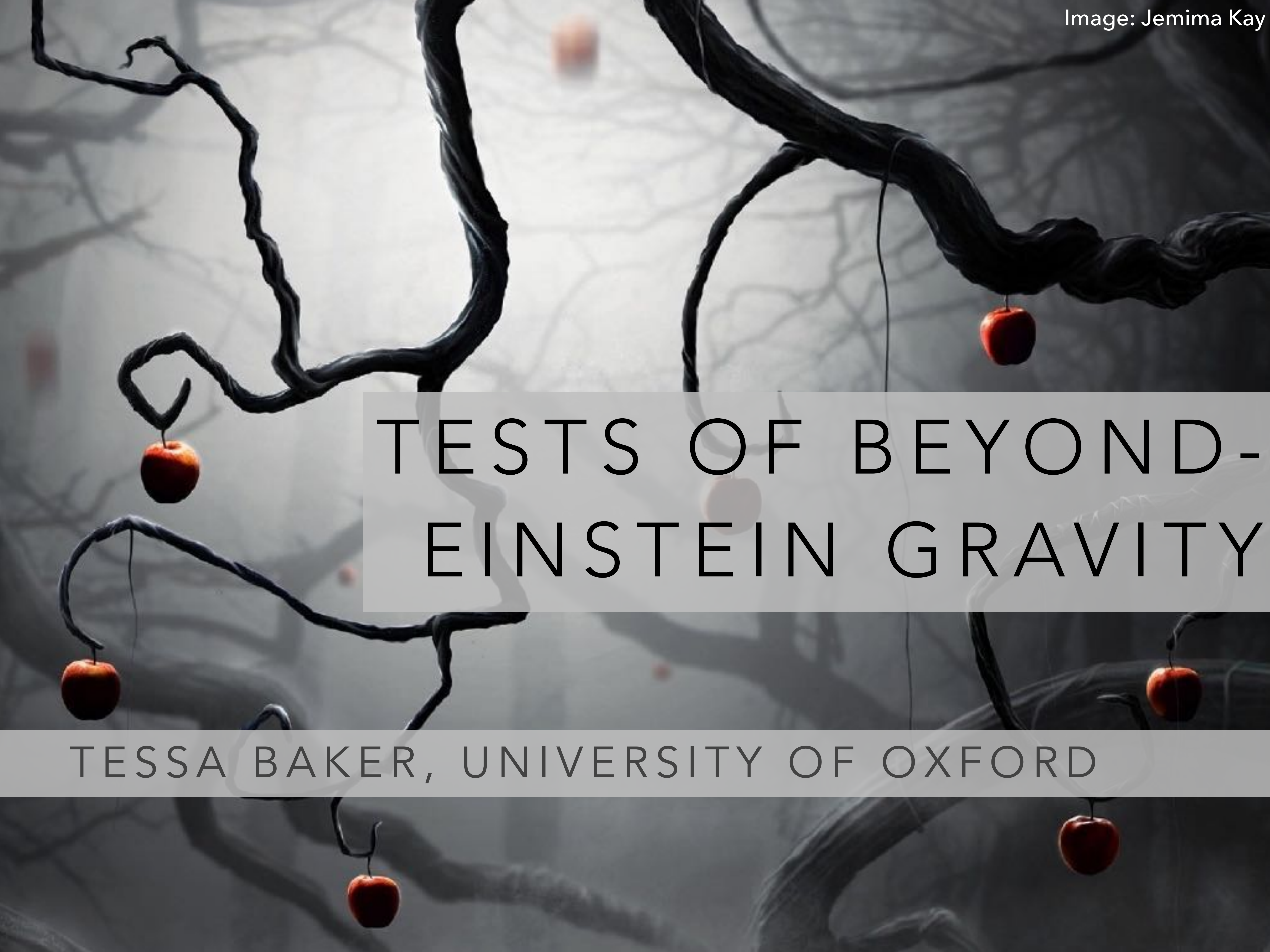


Image: Jemima Kay

TESTS OF BEYOND-EINSTEIN GRAVITY

TESSA BAKER, UNIVERSITY OF OXFORD

OUTLINE

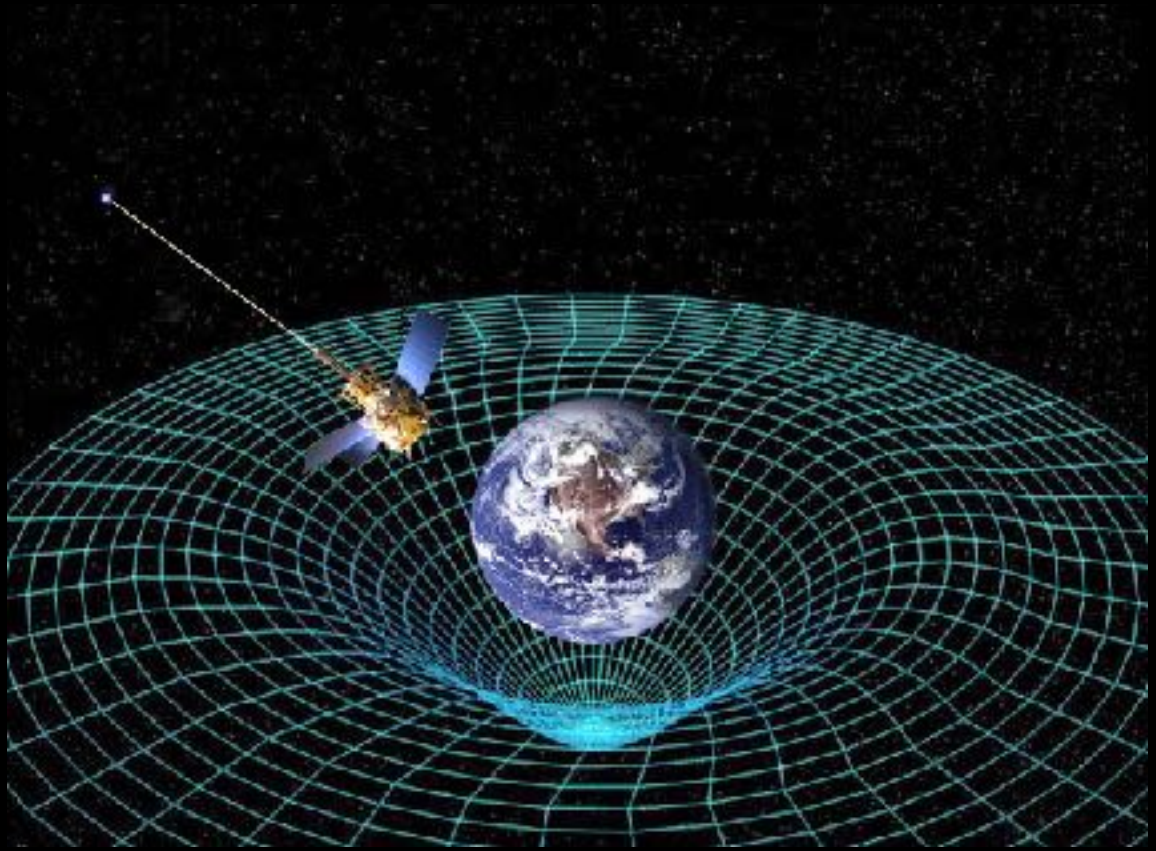
- Overview: the landscape of modified gravity.
- Details: parameterised tests.
  - ➡ theory
  - ➡ observations

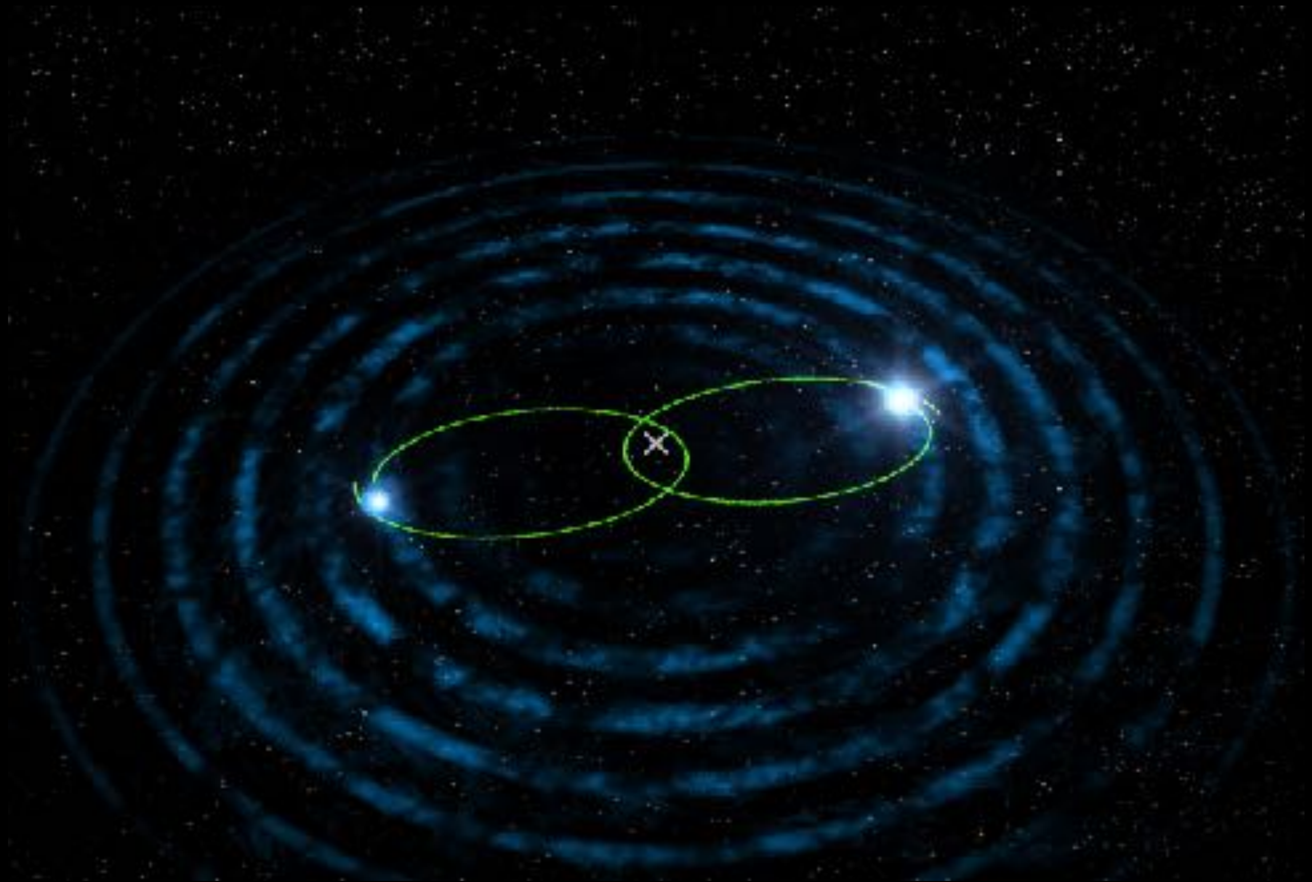
1.THE GRAVITY LANDSCAPE

WHY TEST GRAVITY?

- Cosmic acceleration, i.e. dark energy.
  Replace / explain the cosmological constant?

- Cosmological scales >> scales of precision tests.
  Test extrapolation over 16 orders of magnitude(!)

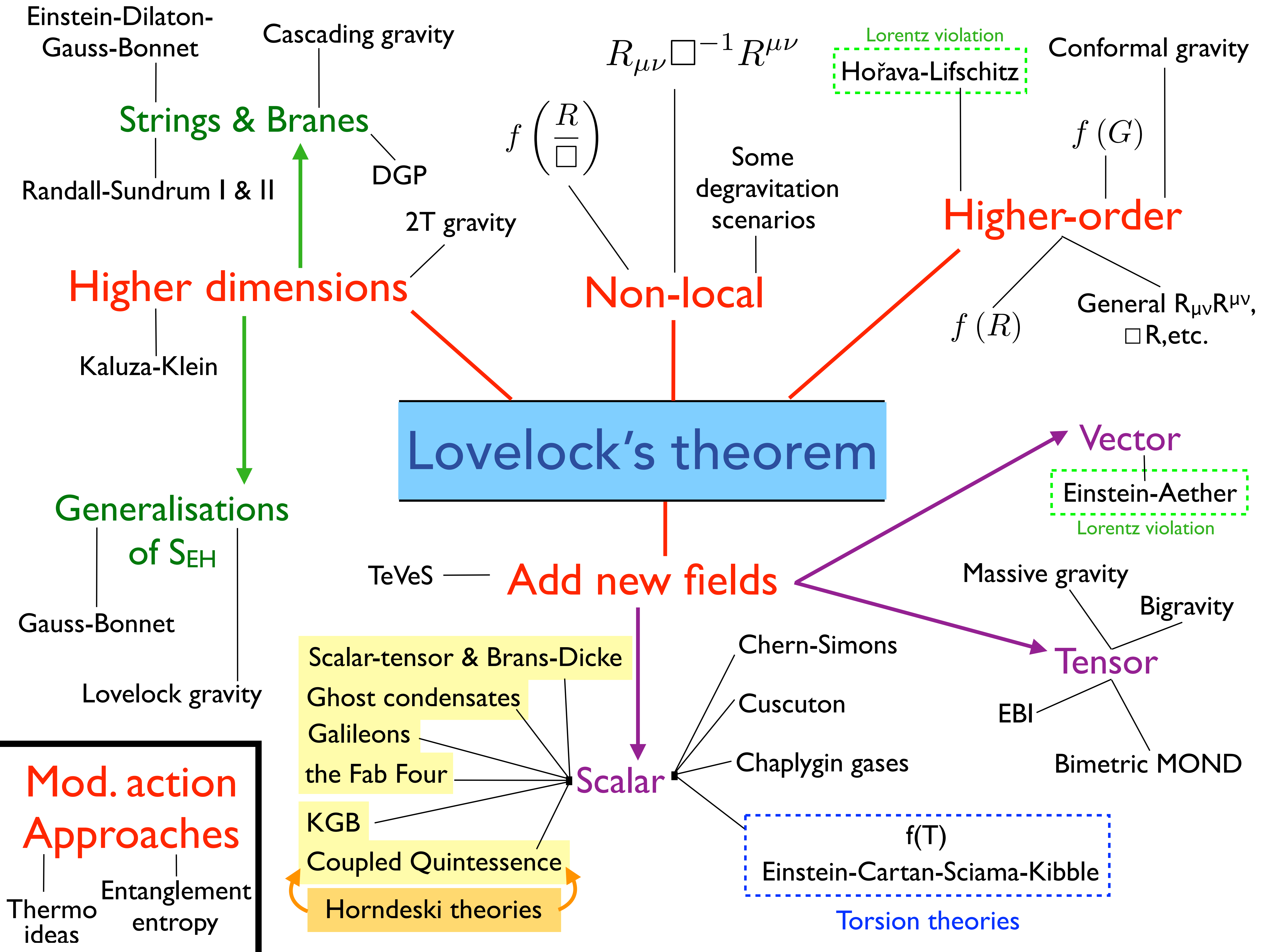




Images: NASA, Norbert Bartel.

LOVELOCK'S THEOREM (CLIFTON VERSION)

"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."



Einstein-Dilaton-Gauss-Bonnet
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Add new fields
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Ghost condensates
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Scalar
Mod. action Approaches
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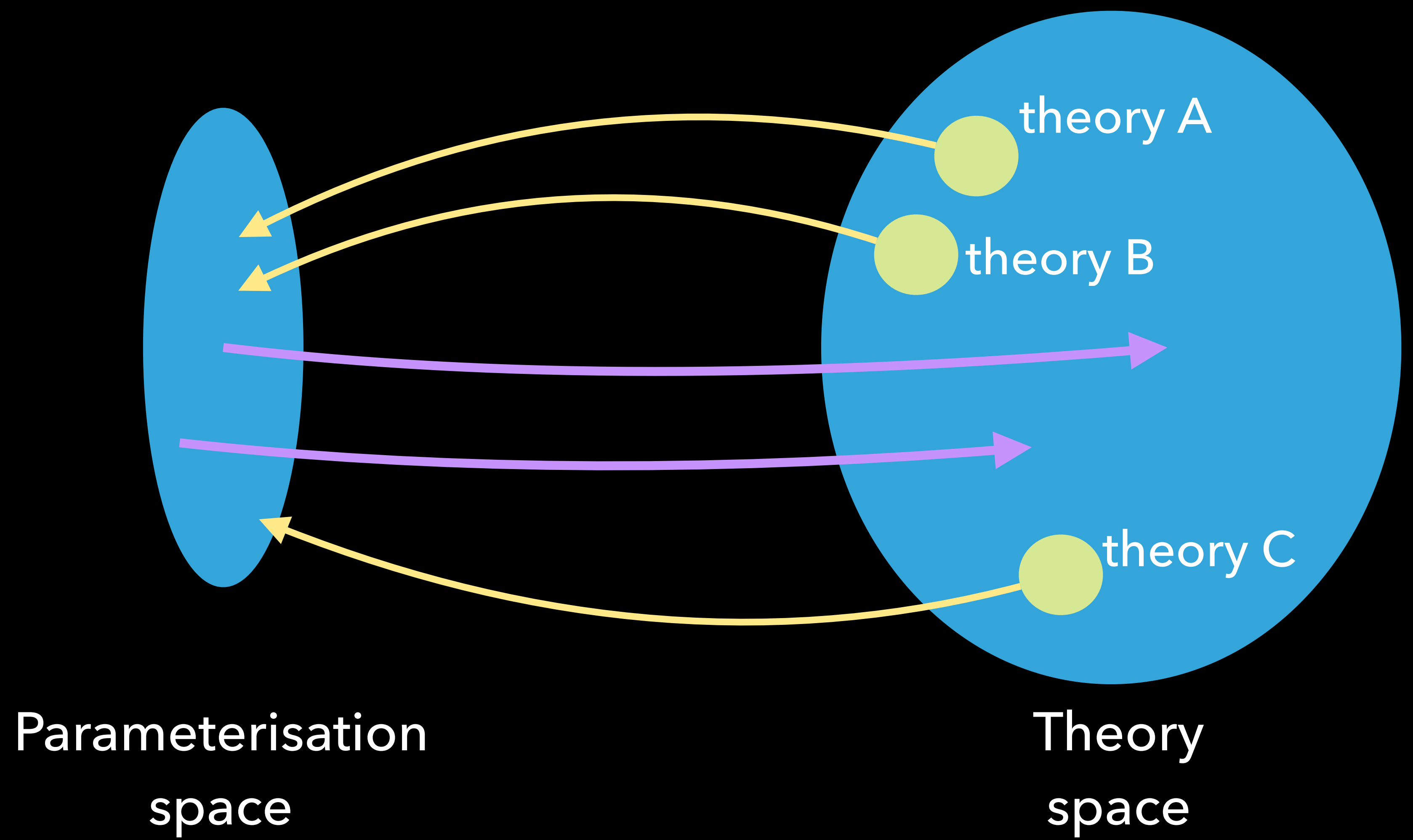
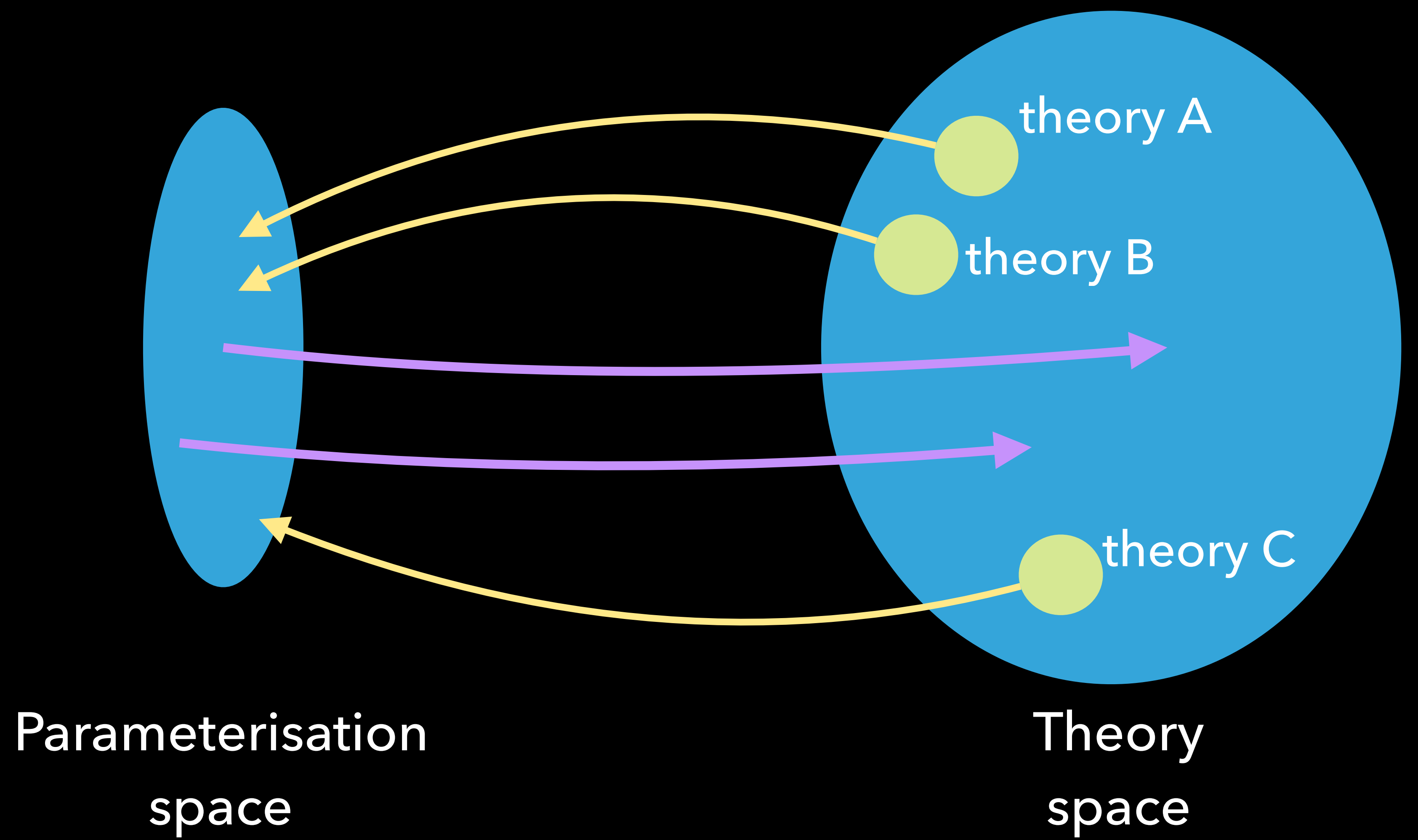
Horndeski theories
Thermo ideas
Entanglement entropy
Torsion theories

PARAMETERISING GRAVITY



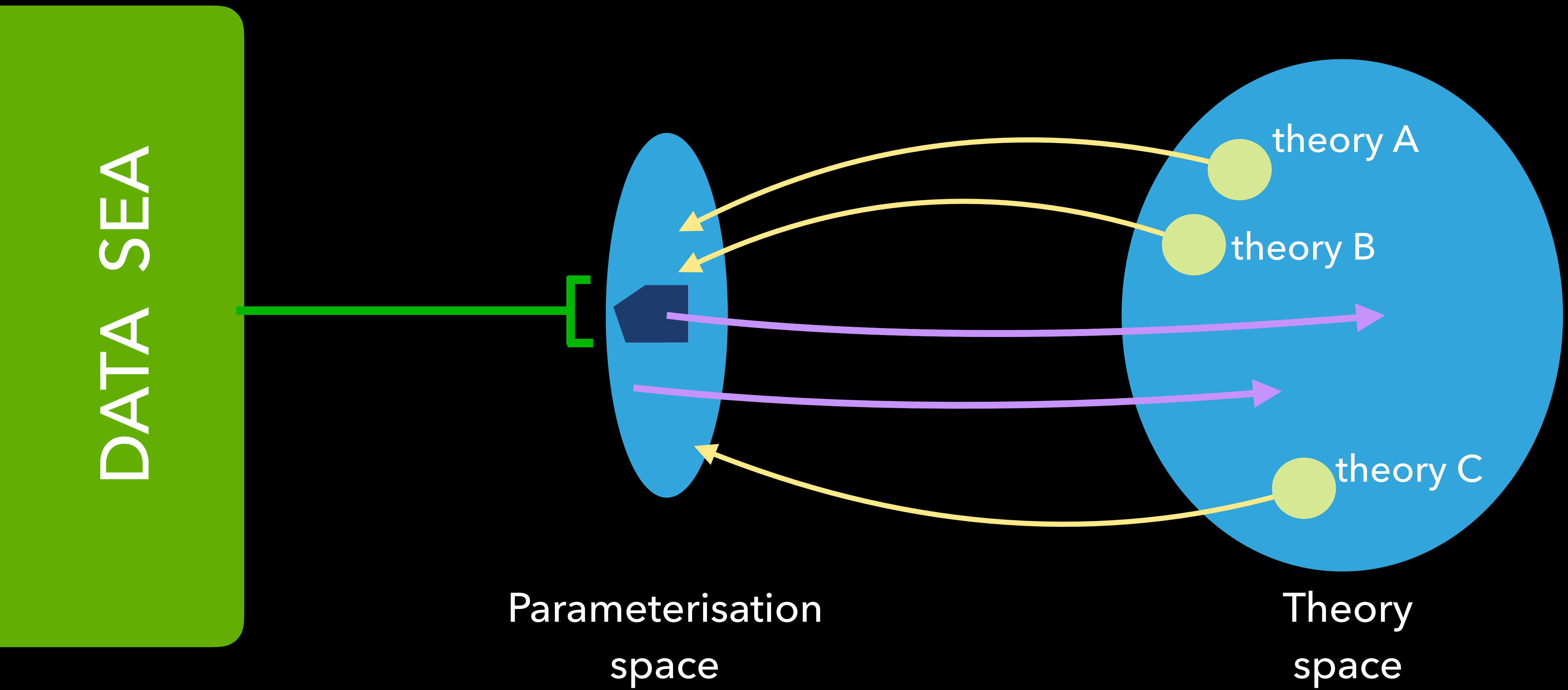
Gleyzes, Langlois & Vernizzi (2014)
Lagos, Baker ++ (2016)

PARAMETERISING GRAVITY



Gleyzes, Langlois & Vernizzi (2014)
Lagos, Baker ++ (2016)

PARAMETERISING GRAVITY



Gleyzes, Langlois & Vernizzi (2014)
Lagos, Baker ++ (2016)


Image: George Johnson

2. PARAMETERISED METHODS

PARAMETERISED ACTIONS

1. Determine a sensible set of 'building blocks':

$$\vec{\Theta} = \left(g_{\mu\nu}\,,\; \phi,\, \vec{A},\, q_{\mu\nu} \right)$$

metric — new fields

2. Taylor expand the gravitational Lagrangian:

$$L \simeq \bar{L} + L_{\Theta_a}\,\delta\Theta_a + \frac{1}{2} L_{\Theta_a \Theta_b}\delta\Theta_a \delta\Theta_b + \ldots$$

$$\frac{\partial L}{\partial \Theta_a}$$

Gives us linearised grav. field equations.

PARAMETERISED ACTIONS — THEORY

3. Write down an action containing all possible combinations of the building blocks ⇒ ~ 70 terms!

   Each term comes with an unknown coefficient.

$$\delta_2 S = \int d^4x \sqrt{-g} \Big[L_{gg}(t)\; \delta g^i_j \, \delta g^j_i \; + \; \ldots$$

$$+ \; L_{g\,\partial g}(t)\, \delta g_{ij}\, \partial^i \delta g^{0j} + L_{\dot{g}\,\dot{g}}(t)\; \delta \dot{g}_{00}\, \delta \dot{g}^{00} \; + \; \ldots$$

$$+ \; L_{\partial\phi\partial\phi}(t)\, \partial^i \delta\phi\, \partial_i \delta\phi \; + \; L_{\phi R}(t)\, \delta\phi\, \delta R \; + \; \ldots$$

$$+ \; \text{usual fluid matter sector} \quad \Big]$$

PARAMETERISED ACTIONS — THEORY

4. The action must be coordinate-invariant + a few other physical restrictions.

$\Rightarrow$ Enforce linear diff symmetry: $x^\mu \to x^\mu + \epsilon^\mu$

$$\epsilon^\mu = (\pi,\ \partial^i \epsilon)$$

$$\Rightarrow \quad \delta_2 S \to \delta_2 S + \left[\begin{array}{l}\text{terms linear in} \\ \delta\varphi,\ \delta g_{00},\ \delta g_{ij}\ \text{etc.}\end{array}\right] \times \ (\pi \ \text{ or } \ \epsilon)$$

must vanish

Invariance of action under a ***non-dynamical*** symmetry gives a set of constraint relations.

PARAMETERISED ACTIONS — THEORY

Write down an action containing all possible combinations of the building blocks ⇒ ~ 70 terms!

Each term comes with an unknown coefficient.

$$\delta_2 S = \int d^4x \sqrt{-g} \Big[L_{gg}(t)\, \delta g^i_j \, \delta g^j_i + \ldots$$

$$+ L_{g\,\partial g}(t)\, \delta g_{ij}\, \partial^i \delta g^{0j} + L_{\dot{g}\,\dot{g}}(t)\, \delta \dot{g}_{00}\, \delta \dot{g}^{00} + \ldots$$

$$+ L_{\partial\phi\partial\phi}(t)\, \partial^i \delta\phi\, \partial_i \delta\phi + L_{\phi R}(t)\, \delta\phi\, \delta R + \ldots$$

$+$ usual fluid matter sector $\Big]$

SIMPLEST CASE — HORNDESKI THEORY

$$\delta_2 S = \int d^3x\, dt\; a^3 \frac{M(t)^2}{2} \left[R^{(4D)} + \alpha_T(t)\, \delta_2\left(\sqrt{h} R/a^3\right) \right.$$

$$\left. + \alpha_K(t) H^2 \delta N^2 + 4\alpha_B(t) H \delta K \delta N \right]$$

← just pieces of metric

$\alpha_T(t)$: speed of gravitational waves, $c_T^2 = 1 + \alpha_T$.

$\alpha_K(t)$: kinetic term of scalar field.

$\alpha_B(t)$: `braiding' – mixing of scalar + metric kinetic terms.

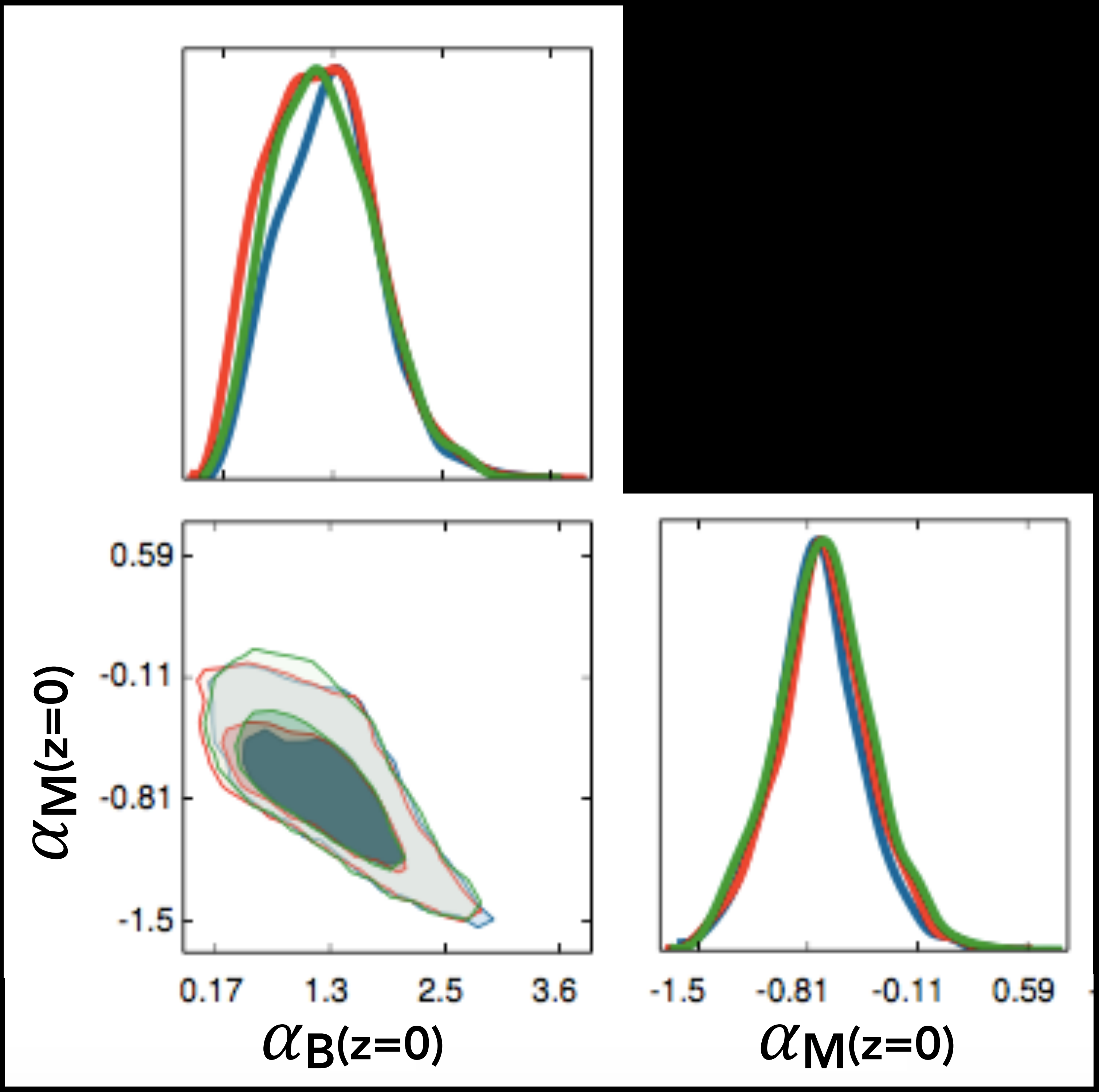
$\alpha_M(t) = \dfrac{1}{H} \dfrac{d \ln M^2(t)}{dt}$: running of effective Planck mass.

THE ALPHA PARAMETERS

Model Class		α_K	α_B	α_M	α_T
ΛCDM		***0***	***0***	***0***	***0***
cuscuton ($w_X \neq -1$)	[71]	0	0	0	0
quintessence	[1, 2]	$(1-\Omega_m)(1+w_X)$	0	0	0
k-*essence*/perfect fluid	[45, 46]	$\frac{(1-\Omega_m)(1+w_X)}{c_s^2}$	0	0	0
kinetic gravity braiding	[47–49]	$\frac{m^2(n_m+\kappa_\phi)}{H^2 M_{Pl}^2}$	$\frac{m\kappa}{HM_{Pl}^2}$	0	0
galileon cosmology	[57]	$-\frac{3}{2}\alpha_M^3 H^2 r_c^2 e^{2\phi/M}$	$\frac{\alpha_K}{6}-\alpha_M$	$\frac{-2\dot{\phi}}{HM}$	0
BDK	[26]	$\frac{\dot{\phi}^2 K_{,\dot{\phi}\dot{\phi}} e^{-\kappa}}{H^2 M^2}$	$-\alpha_M$	$\frac{\dot{\kappa}}{H}$	0
metric $f(R)$	[3, 72]	0	$-\alpha_M$	$\frac{B\dot{H}}{H^2}$	0
MSG/Palatini $f(R)$	[73, 74]	$-\frac{3}{2}\alpha_M^2$	$-\alpha_M$	$\frac{2\dot{\phi}}{H}$	0
f(Gauss-Bonnet)	[52, 75, 76]	0	$\frac{-2H\dot{\xi}}{M^2+H\dot{\xi}}$	$\frac{\dot{H}\dot{\xi}+H\ddot{\xi}}{H(M^2+H\dot{\xi})}$	$\frac{\ddot{\xi}-H\dot{\xi}}{M^2+H\dot{\xi}}$

Bellini & Sawicki (2014)

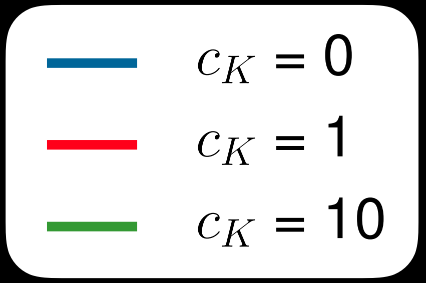
THE CURRENT STATE OF PLAY



2σ constraints:

$0.24 < \alpha_B < 2.32$

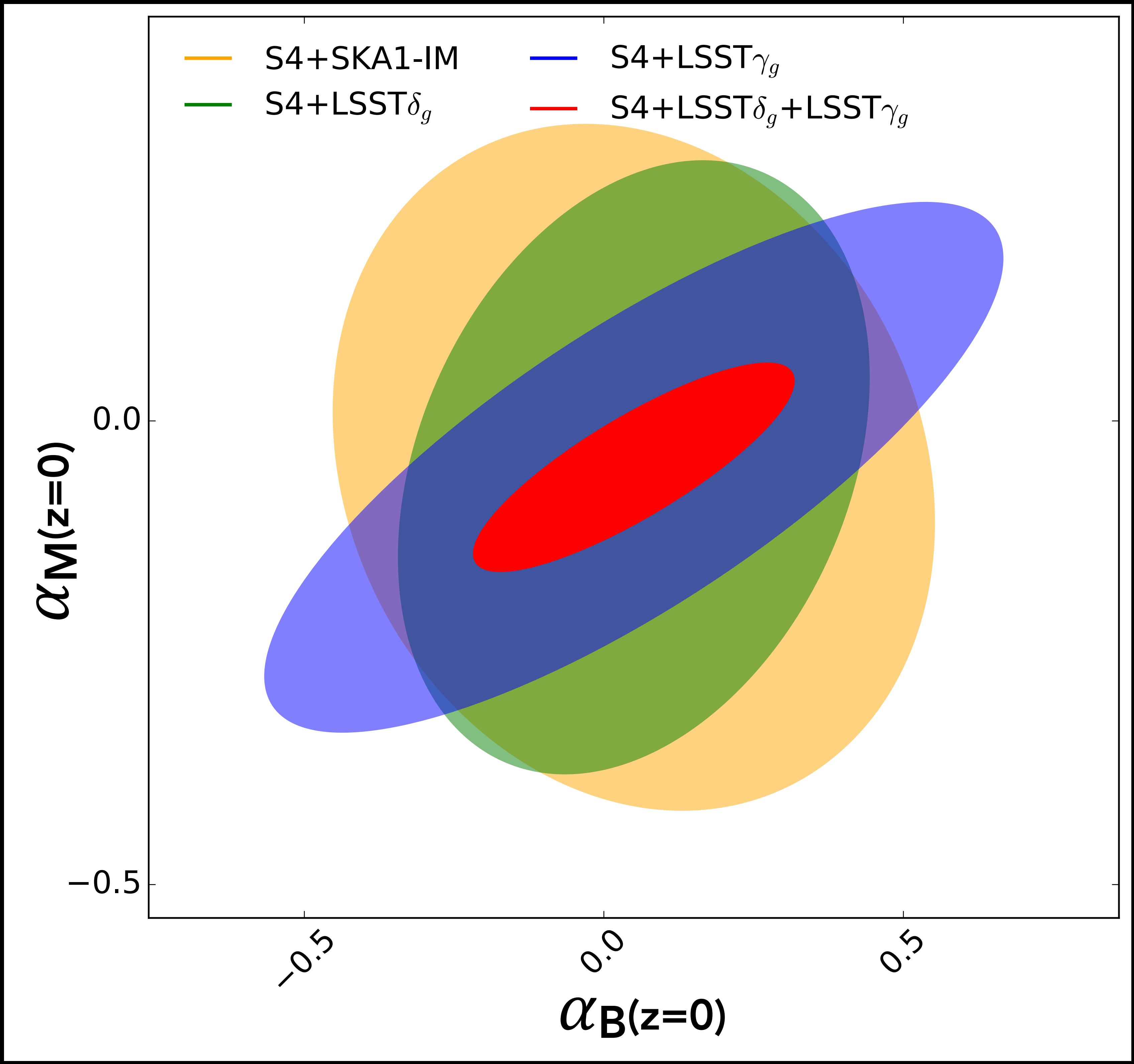
$-1.36 < \alpha_M < -0.13$



Bellini et al., 2015.

ONGOING & FUTURE EXPERIMENTS

FUTURE CONSTRAINTS



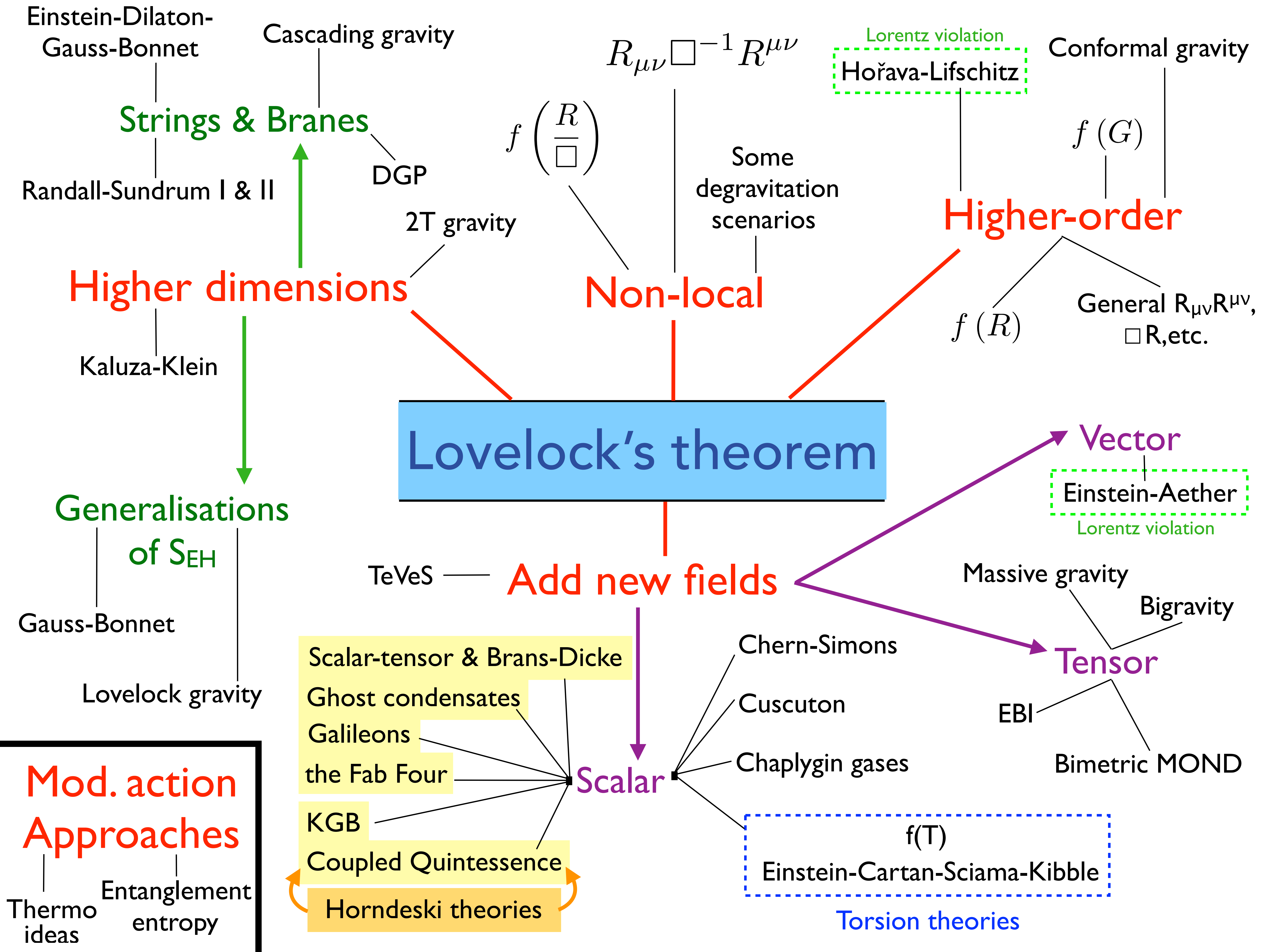
S4 = CMB experiment.

LSSTδ_g = galaxy clustering

LSSTγ_g = weak lensing

IM = intensity mapping (radio emission survey)

Alonso et al. (2017)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`CONCLUSIONS'

1. Method applies beyond scalar-field models.

Fields	# True free functions	Theory family
$g_{\mu\nu}$	1	GR
$g_{\mu\nu},\ \phi$	5	Horndeski
$g_{\mu\nu},\ A^{\mu}$	9	Vector-tensor
$g_{\mu\nu},\ A^{\mu},\ \lambda$	4	Einstein-Aether
$g_{\mu\nu},\ q_{\mu\nu}$	5	Massive Bigravity

Lagos, Baker, Ferreira & Noller (2016)

Lagos, Baker et al. in prep. (2017)

tessa.baker@physics.ox.ac.uk

`CONCLUSIONS'

1. Method applies beyond scalar-field models.

2. We have codes!

xIST – **Mathematica** routines for **l**inear **S**calar **T**ensor theories.

Available from https://github.com/noller/xIST .

We're working on a version of:

Zumalacarregui et al. (2016).

Lagos, Baker, Ferreira & Noller (2016)

Lagos, Baker et al. in prep. (2017)

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