Symmetries in gravity and LSS

Lam Hui
Columbia University

Symmetries in gravity and LSS

Lam Hui
Columbia University

Outline:

1. Equivalence principle: a generic test of modified gravity
   - with Alberto Nicolis.

2. Parity in measurements of large scale structure (LSS)
   - with Camille Bonvin & Enrique Gaztanaga.

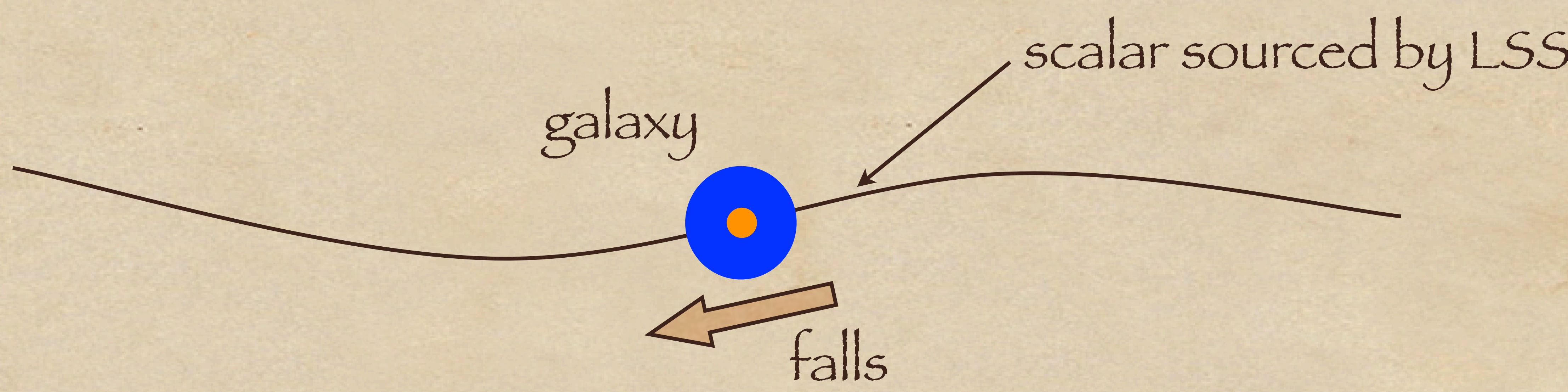
3. Spontaneously broken symmetry in the theory of LSS
   - with Kurt Hinterbichler & Justin Khoury;
     Walter Goldberger & Alberto Nicolis;
     Creminelli, Gleyzes, Simonovic &Vernizzi;
     Bart Horn & Xiao Xiao.

Idea 1: a generic test of scalar-tensor gravity

- Modifying gravity necessarily introduces new d.o.f. such as a scalar, i.e. a long range scalar force in addition to usual gravitational force (Weinberg/Deser thm.).

- Assume black holes have no scalar hair. More generally, compact objects have Q/M (scalar-charge/mass ratio) $\rightarrow$ 0. Normal stars like the Sun have Q/M ≈ 1. Thus, in the same environment a black hole and a star fall differently (Nordvedt).

- For Brans-Dicke, this is hopeless to see. Recent theories resurrect the idea.

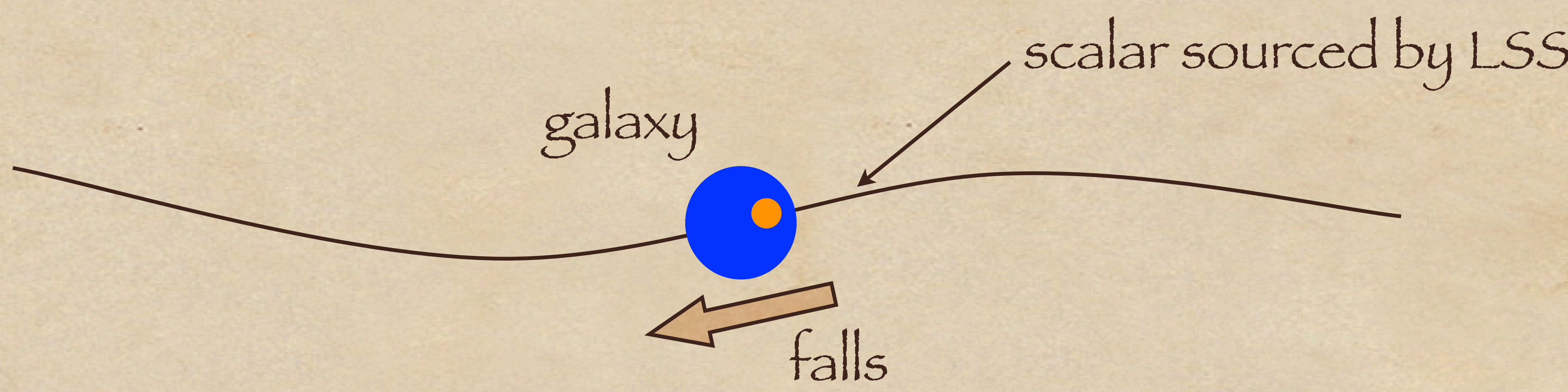


Idea 1: a generic test of scalar-tensor gravity

- Modifying gravity necessarily introduces new d.o.f. such as a scalar, i.e. a long range scalar force in addition to usual gravitational force (Weinberg/Deser thm.).

- Assume black holes have no scalar hair. More generally, compact objects have Q/M (scalar-charge/mass ratio) $\rightarrow$ 0. Normal stars like the Sun have Q/M = 1. Thus, in the same environment a black hole and a star fall differently (Nordvedt).

- For Brans-Dicke, this is hopeless to see. Recent theories resurrect the idea.

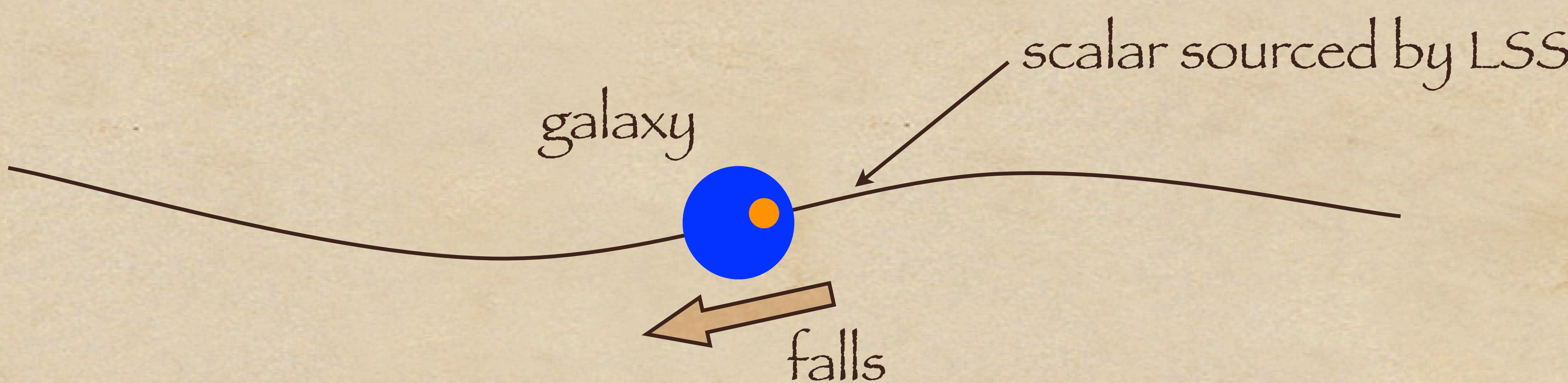


Idea 1: a generic test of scalar-tensor gravity

- Modifying gravity necessarily introduces new d.o.f. such as a scalar, i.e. a long range scalar force in addition to usual gravitational force (Weinberg/Deser thm.).

- Assume black holes have no scalar hair. More generally, compact objects have Q/M (scalar-charge/mass ratio) $\rightarrow$ 0. Normal stars like the Sun have Q/M $\approx$ 1. Thus, in the same environment a black hole and a star fall differently (Nordvedt).

- For Brans-Dicke, this is hopeless to see. Recent theories resurrect the idea.



- Black hole offset up to 100 pc (use local, small Seyfert galaxies). Known offset: 7 pc for M87; Batcheldor et al. 2010 - beware astrophys. effects.

Idea 2: ~~parity~~ in the measurement of LSS

- It is generally assumed parity is respected in measurements of LSS, for good reason:

$$\langle \delta(x_1)\delta(x_2) \rangle$$

Idea 2: ~~parity~~ in the measurement of LSS

- It is generally assumed parity is respected in measurements of LSS, for good reason:

$$\langle \delta(x_1)\delta(x_2) \rangle$$

- But how about cross-correlation between 2 different kinds of galaxies, A & B?

$$\langle \delta_A(x_1)\delta_B(x_2) \rangle$$

versus

$$\langle \delta_B(x_1)\delta_A(x_2) \rangle$$

Idea 2: ~~parity~~ in the measurement of LSS

- It is generally assumed parity is respected in measurements of LSS, for good reason:

$$\langle \delta(x_1)\delta(x_2) \rangle$$

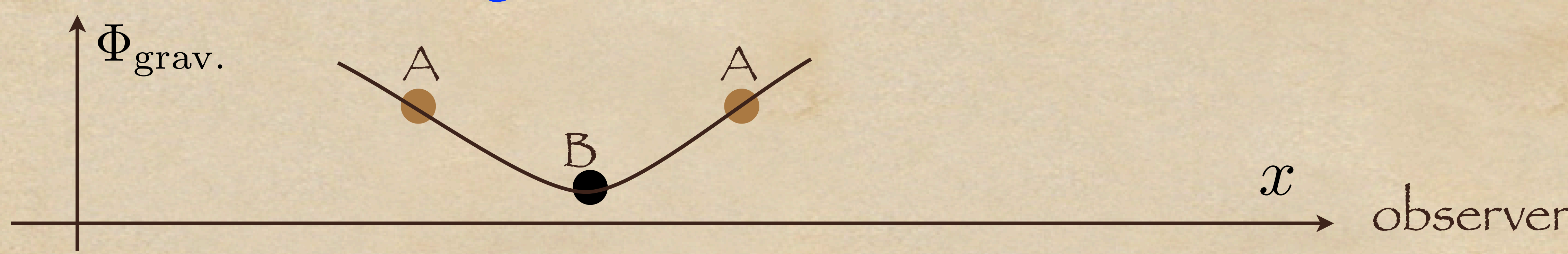
- But how about cross-correlation between 2 different kinds of galaxies, A & B?

$$\langle \delta_A(x_1)\delta_B(x_2) \rangle$$

versus

$$\langle \delta_B(x_1)\delta_A(x_2) \rangle$$

- Consider the effect of gravitational redshift:



Idea 2: ~~parity~~ in the measurement of LSS

- It is generally assumed parity is respected in measurements of LSS, for good reason:

$$\langle \delta(x_1)\delta(x_2) \rangle$$

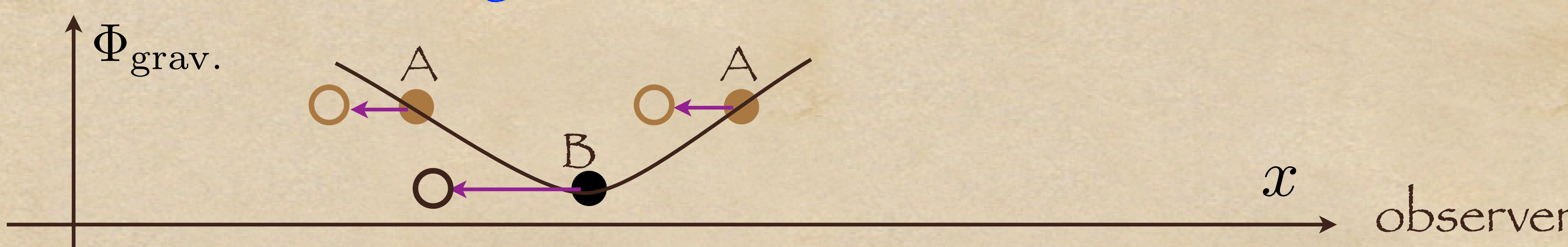
- But how about cross-correlation between 2 different kinds of galaxies, A & B?

$$\langle \delta_A(x_1)\delta_B(x_2) \rangle$$

versus

$$\langle \delta_B(x_1)\delta_A(x_2) \rangle$$

- Consider the effect of gravitational redshift:

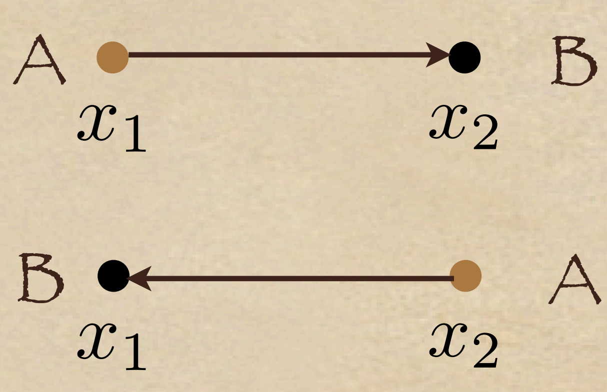


Idea 2: ~~parity~~ in the measurement of LSS

- It is generally assumed parity is respected in measurements of LSS, for good reason:

$$\langle \delta(x_1)\delta(x_2) \rangle$$

- But how about cross-correlation between 2 different kinds of galaxies, A & B?



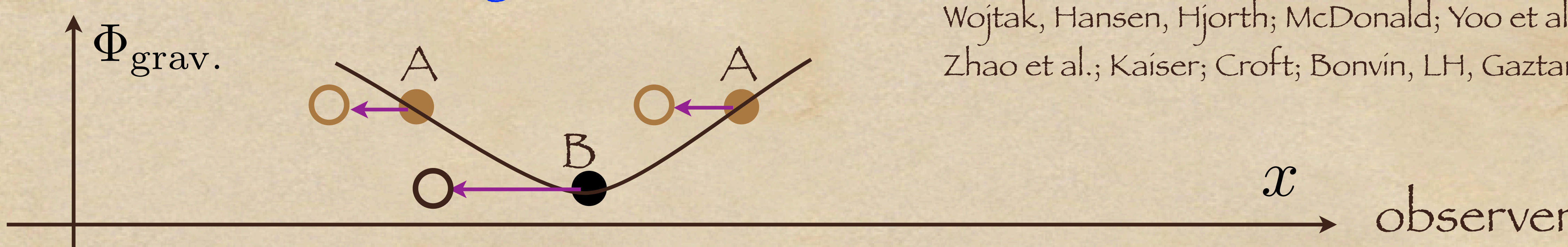
$$\langle \delta_A(x_1)\delta_B(x_2) \rangle$$

versus

$$\langle \delta_B(x_1)\delta_A(x_2) \rangle$$

- Consider the effect of gravitational redshift:

Wojtak, Hansen, Hjorth; McDonald; Yoo et al., Zhao et al.; Kaiser; Croft; Bonvin, LH, Gaztanaga

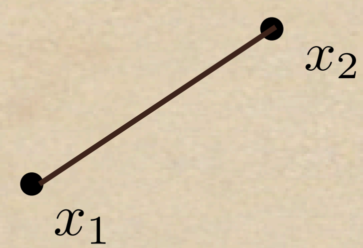


- Several additional (apparent) parity-violating effects. Possible to separate.

Idea 3: non-perturbative consistency relations in LSS

- 1. Consider a familiar example of symmetry: spatial translation.

$$x \to x + \Delta x \quad , \quad \text{where } \Delta x = \text{ const.}$$



Its consequence for correlation function is well known:

$$\langle \phi(x_1)\phi(x_2)\phi(x_3) \rangle = \langle \phi(x_1 + \Delta x)\phi(x_2 + \Delta x)\phi(x_3 + \Delta x) \rangle$$

For small Δx , we have:

$$\langle \phi(x_1 + \Delta x)\phi(x_2 + \Delta x)\phi(x_3 + \Delta x) \rangle \sim \langle \phi(x_1)\phi(x_2)\phi(x_3) \rangle + \Delta x \cdot \partial_1 \langle \phi(x_1)\phi(x_2)\phi(x_3) \rangle + \text{perm.}$$

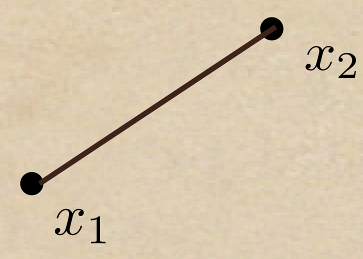
Thus, alternatively, we say:

$\langle \phi_1\phi_2\phi_3 \rangle$ is invariant under $\phi \to \phi + \Delta x \cdot \partial \phi \quad \text{i.e.} \quad \Delta x \cdot \partial_1 \langle \phi_1\phi_2\phi_3 \rangle + \text{ perm.} = 0$

Idea 3: non-perturbative consistency relations in LSS

- 1. Consider a familiar example of symmetry: spatial translation.

$$x \to x + \Delta x \quad , \quad \text{where } \Delta x = \text{const.}$$



Its consequence for correlation function is well known:

$$\langle \phi(x_1)\phi(x_2)\phi(x_3)\rangle = \langle \phi(x_1+\Delta x)\phi(x_2+\Delta x)\phi(x_3+\Delta x)\rangle$$

For small Δx, we have:

$$\langle \phi(x_1+\Delta x)\phi(x_2+\Delta x)\phi(x_3+\Delta x)\rangle \sim \langle \phi(x_1)\phi(x_2)\phi(x_3)\rangle + \Delta x \cdot \partial_1 \langle \phi(x_1)\phi(x_2)\phi(x_3)\rangle + \text{perm.}$$

Thus, alternatively, we say:

$\langle \phi_1\phi_2\phi_3\rangle$ is invariant under $\phi \to \phi + \Delta x \cdot \partial\phi \quad \text{i.e.} \quad \Delta x \cdot \partial_1 \langle \phi_1\phi_2\phi_3\rangle + \text{perm.} = 0$

- 2. Consider a different symmetry: shift in gravitational potential.

$$\phi \to \phi + c \quad , \quad \text{where } c = \text{const.}$$

For small c, we have:

$$\langle (\phi_1 + c)(\phi_2 + c)(\phi_3 + c)\rangle \sim \langle \phi_1\phi_2\phi_3\rangle + c\langle \phi_1\phi_2\rangle + c\langle \phi_2\phi_3\rangle + c\langle \phi_1\phi_3\rangle$$

Thus, saying $\langle \phi_1\phi_2\phi_3\rangle = \langle (\phi_1 + c)(\phi_2 + c)(\phi_3 + c)\rangle$ is equiv. to saying :

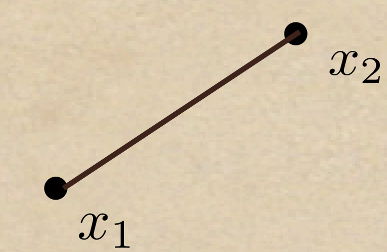
$$c(\langle \phi_1\phi_2\rangle + \langle \phi_2\phi_3\rangle + \langle \phi_1\phi_3\rangle) = 0 \longleftarrow \text{clearly false!}$$

Conclude : $\langle \phi_1\phi_2\phi_3\rangle$ is not invariant under $\phi \to \phi + c$

Idea 3: non-perturbative consistency relations in LSS

- 1. Consider a familiar example of symmetry: spatial translation.

$$x \to x + \Delta x \quad , \quad \text{where } \Delta x = \text{const.}$$



Its consequence for correlation function is well known:

$$\langle \phi(x_1)\phi(x_2)\phi(x_3)\rangle = \langle \phi(x_1 + \Delta x)\phi(x_2 + \Delta x)\phi(x_3 + \Delta x)\rangle$$

For small Δx, we have:

$$\langle \phi(x_1 + \Delta x)\phi(x_2 + \Delta x)\phi(x_3 + \Delta x)\rangle \sim \langle \phi(x_1)\phi(x_2)\phi(x_3)\rangle + \Delta x \cdot \partial_1 \langle \phi(x_1)\phi(x_2)\phi(x_3)\rangle + \text{perm.}$$

Thus, alternatively, we say:

$\langle \phi_1\phi_2\phi_3\rangle$ is invariant under $\phi \to \phi + \Delta x \cdot \partial\phi$ i.e. $\Delta x \cdot \partial_1 \langle \phi_1\phi_2\phi_3\rangle + \text{perm.} = 0$

- 2. Consider a different symmetry: shift in gravitational potential.

$$\phi \to \phi + c \quad , \quad \text{where } c = \text{const.}$$

For small c, we have:

$$\langle (\phi_1 + c)(\phi_2 + c)(\phi_3 + c)\rangle \sim \langle \phi_1\phi_2\phi_3\rangle + c\langle \phi_1\phi_2\rangle + c\langle \phi_2\phi_3\rangle + c\langle \phi_1\phi_3\rangle$$

Thus, saying $\langle \phi_1\phi_2\phi_3\rangle = \langle (\phi_1 + c)(\phi_2 + c)(\phi_3 + c)\rangle$ is equiv. to saying :

$$c(\langle \phi_1\phi_2\rangle + \langle \phi_2\phi_3\rangle + \langle \phi_1\phi_3\rangle) = 0 \longleftarrow \text{clearly false!}$$

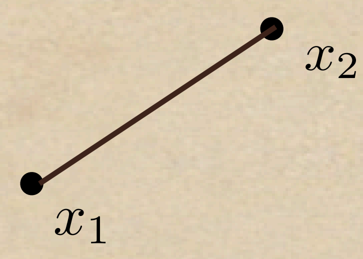
Conclude : $\langle \phi_1\phi_2\phi_3\rangle$ is not invariant under $\phi \to \phi + c$

- What makes the second case so different?

Idea 3: non-perturbative consistency relations in LSS

- 1. Consider a familiar example of symmetry: spatial translation.

$$x \to x + \Delta x \quad , \quad \text{where } \Delta x = \text{const.}$$



Its consequence for correlation function is well known:

$$\langle \phi(x_1)\phi(x_2)\phi(x_3)\rangle = \langle \phi(x_1+\Delta x)\phi(x_2+\Delta x)\phi(x_3+\Delta x)\rangle$$

For small Δx, we have:

$$\langle \phi(x_1+\Delta x)\phi(x_2+\Delta x)\phi(x_3+\Delta x)\rangle \sim \langle \phi(x_1)\phi(x_2)\phi(x_3)\rangle + \Delta x \cdot \partial_1 \langle \phi(x_1)\phi(x_2)\phi(x_3)\rangle + \text{perm.}$$

Thus, alternatively, we say:

$\langle \phi_1\phi_2\phi_3\rangle$ is invariant under $\phi \to \phi + \Delta x \cdot \partial\phi$ i.e. $\Delta x \cdot \partial_1 \langle \phi_1\phi_2\phi_3\rangle + \text{perm.} = 0$

- 2. Consider a different symmetry: shift in gravitational potential.

$$\phi \to \phi + c \quad , \quad \text{where } c = \text{const.}$$

For small c, we have:

$$\langle (\phi_1+c)(\phi_2+c)(\phi_3+c)\rangle \sim \langle \phi_1\phi_2\phi_3\rangle + c\langle\phi_1\phi_2\rangle + c\langle\phi_2\phi_3\rangle + c\langle\phi_1\phi_3\rangle$$

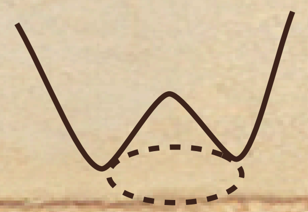
Thus, saying $\langle \phi_1\phi_2\phi_3\rangle = \langle (\phi_1+c)(\phi_2+c)(\phi_3+c)\rangle$ is equiv. to saying :

$$c(\langle\phi_1\phi_2\rangle + \langle\phi_2\phi_3\rangle + \langle\phi_1\phi_3\rangle) = 0 \longleftarrow \text{clearly false!}$$

Conclude : $\langle \phi_1\phi_2\phi_3\rangle$ is not invariant under $\phi \to \phi + c$

- What makes the second case so different? We generally choose some expectation value for ϕ e.g. $\langle\phi\rangle = 0$. The choice breaks the shift symmetry i.e. spontaneous symm. breaking.

1. Unbroken symmetries $\longrightarrow$ invariant correlation functions.
2. Spontaneously broken symmetries $\longrightarrow$ consistency relations.

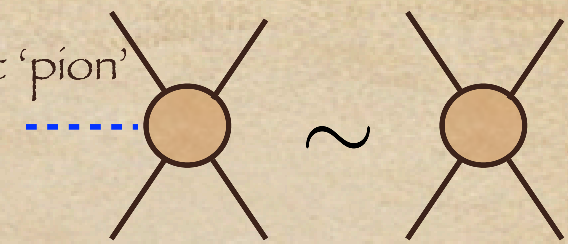


Saturday, January 17, 2015

References:

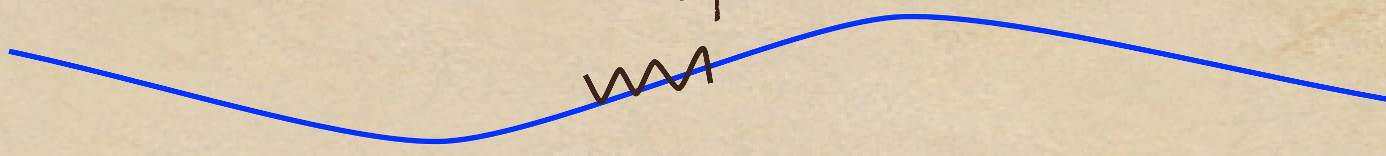
Maldacena; Creminelli & Zaldarriaga; Creminelli, Norena, Simonovic; Assassi, Baumann & Green; Flauger, Green & Porto; Pajer, Schmidt, Zaldarriaga; Kehagias & Riotto; Peloso & Pietronni; Berezhiani & Khoury; Pimentel; Creminelli, Norena, Simonovic, Vernizzi; Goldberger, LH, Nicolis; Hinterbichler, LH, Khoury; Horn, LH, Xiao.

Consistency relations from SSB

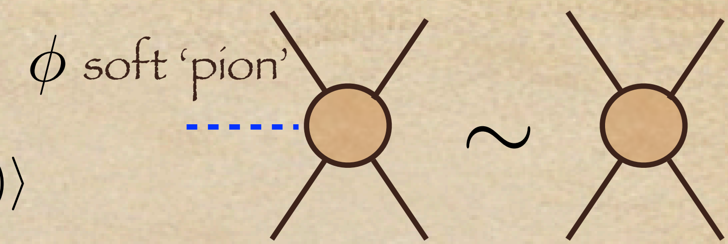


- Schematic form: $\lim_{q\to 0} \frac{1}{P_\phi(q)} \langle \phi(q)\mathcal{O}(k_1)...\mathcal{O}(k_N)\rangle \sim \langle \mathcal{O}(k_1)...\mathcal{O}(k_N)\rangle$

They are (momentum space) statements about how correlations of observables $\mathcal{O}$ behave in the presence of a long wave-mode Goldstone boson/pion.

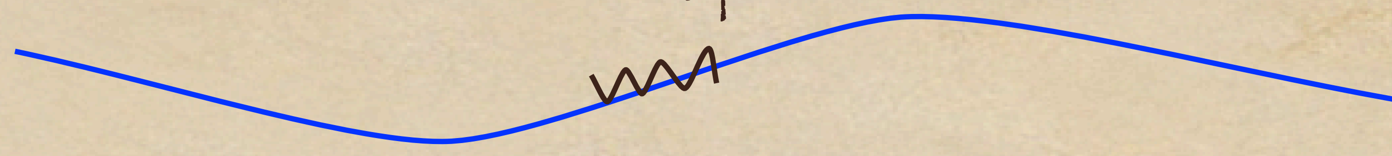


Consistency relations from SSB



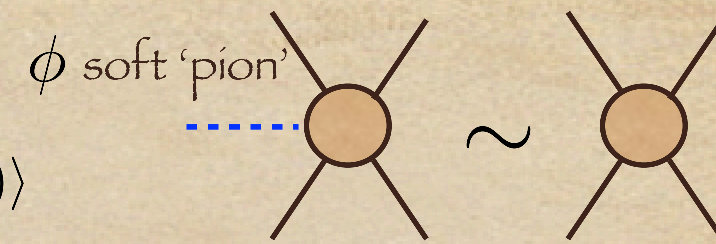
- Schematic form: $\lim_{q\to 0} \frac{1}{P_\phi(q)} \langle \phi(q) \mathcal{O}(k_1) ... \mathcal{O}(k_N) \rangle \sim \langle \mathcal{O}(k_1) ... \mathcal{O}(k_N) \rangle$

  They are (momentum space) statements about how correlations of observables $\mathcal{O}$ behave in the presence of a long wave-mode Goldstone boson/pion.



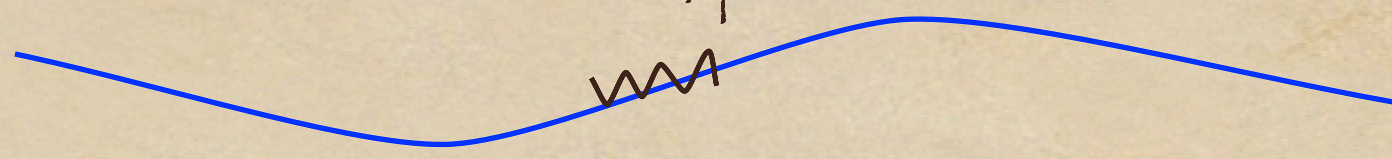
- Why are they interesting?

Consistency relations from SSB



- Schematic form: $\lim_{q \to 0} \frac{1}{P_\phi(q)} \langle \phi(q) \mathcal{O}(k_1) ... \mathcal{O}(k_N) \rangle \sim \langle \mathcal{O}(k_1) ... \mathcal{O}(k_N) \rangle$

  They are (momentum space) statements about how correlations of observables $\mathcal{O}$ behave in the presence of a long wave-mode Goldstone boson/pion.



- Why are they interesting?

1. These are symmetry statements, and are therefore exact, non-perturbative i.e. they hold even if the observables $\mathcal{O}$ are highly nonlinear, and even if they involve astrophysically complex objects, such as galaxies. The main input necessary is how they transform under the symmetry of interest (robust against galaxy mergers, birth, etc.)

2. In the fully relativistic context, there is an infinite number of consistency relations. Two of them have interesting Newtonian limits (shift and time-dependent translation).

3. Two assumptions go into these consistency relations, which can be experimentally tested (using highly nonlinear observables!): Gaussian initial condition (or more precisely, single-clock initial condition such as provided by inflation), and the equivalence principle (that all objects fall at the same rate under gravity). 10^{-4} constraint possible.

4. Non-trivial constraints on analytic models.

Outline:

1. Equivalence principle: a generic test of modified gravity
   - with Alberto Nicolis.

2. Parity in measurements of large scale structure (LSS)
   - with Camille Bonvin & Enrique Gaztanaga.

3. Spontaneously broken symmetry in the theory of LSS
   - with Kurt Hinterbichler & Justin Khoury;
     Walter Goldberger & Alberto Nicolis;
     Creminelli, Gleyzes, Simonovic &Vernizzi;
     Bart Horn & Xiao Xiao.