Some thoughts on equivalence principle and bubble collisions on cosmic scales

E.P. collaborators: Alberto Nicolis, Chris Stubbs

Bubble collaborators: Richard Easther, Tom Giblin, Eugene Lim, I-Sheng Yang

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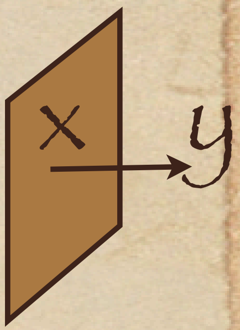
Outline

- Long distance modification of gravity - the generic nature of scalar-tensor theory.
- 2 screening mechanisms - mandatory suppression of scalar on small scales.
- The problem of motion - how do things move? Do they really all fall at the same rate under gravity (i.e. equivalence principle)?
- Observational tests - look for O(1) violations.

Examples of IR modification of GR - relation to scalar-tensor theories:



- f(R) and generalizations - scalar-tensor (Chiba).
- DGP - brane bending mode (Luty, Porrati, Rattazzi).
- massive gravity - Stueckelberg (Arkani-Hamed, Georgi, Schwartz).
- resonance gravity/filtering/degravitation - Stueckelberg (Dvali, Hofmann, Khoury).
- ghost condensate (Arkani-Hamed, Cheng, Luty, Mukohyama; Dubovsky).
- galileon (Nicolis, Rattazzi, Trincherini).
- cucuston (Afshordi, Chung, Geshnizjani).

Weinberg's theorem: at low energy, a Lorentz invariant theory of massless spin-2 particle must be GR.

Therefore, to modify gravity, either add new degrees of freedom (e.g. scalar) or make the graviton massive (which via Stueckelberg also contains scalar) or violate Lorentz invariance (e.g. ghost condensate).

Some form of scalar-tensor theory seems generic.

Also: modified gravity is in a sense no more exotic than quintessence. Absent symmetries, quintessence should be coupled to matter at gravitational strength i.e. scalar-tensor theory yet again (Carroll).

We don't at the moment know what precise form a compelling modified gravity model might take (if it exists). Let us therefore focus on generic consequences of a scalar-tensor theory.

Screening

We generally want the scalar to be alive on large scales i.e. induce $O(1)$ modification on Hubble scale.

But the scalar must be screened on small scales to match solar system tests (recover GR).

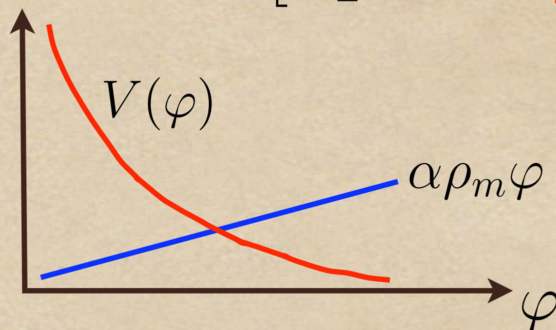
Two known screening mechanisms:
chameleon and strong coupling/Vainshstein.
Both make use of scalar self-interactions, one uses potential, the other uses derivatives.

Chameleon screening:

Khoury & Weltman

$$S_{\rm scalar} \sim \int d^4x \left[-\frac{1}{2}(\partial\varphi)^2 - \underline{V(\varphi)} + \alpha\varphi T_m{}^\mu{}_\mu \right]$$

(Einstein frame)



e.o.m.:

$$\Box\varphi \sim [V + \alpha\rho_m\varphi]_{,\varphi} \qquad (T_m{}^\mu{}_\mu \sim -\rho_m)$$

(φ dimensionless, $M_P = 1$)

Vainshtein screening:

e.g. DGP

$$S_{\rm scalar} \sim \int d^4x \left[-\frac{1}{2}(\partial\varphi)^2 - \underline{\frac{1}{m^2}(\partial\varphi)^2\Box\varphi} + \alpha\varphi T_m{}^\mu{}_\mu \right]$$

(Einstein frame)

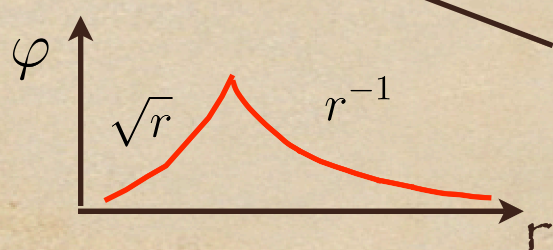
e.o.m.: $\Box\varphi + \frac{1}{m^2}\left[(\Box\varphi)^2 - \partial^\mu\partial^\nu\varphi\partial_\mu\partial_\nu\varphi\right] \sim \alpha\rho_m$

$\varphi \propto \frac{1}{r}$ large r

$\varphi \propto \sqrt{r}$ small r

graviton mass

point mass solution



key in both: nonlinear interaction

$\alpha =$ universal scalar-matter coupling = O(1) generically

How do objects move under these screening mechanisms?

- One would think the answer is simple: objects move on geodesics in Jordan frame, where matter is minimally coupled to metric.

$$S_{\text{matter}} \sim \int d^4x\, \tilde{h}_{\mu\nu}\, {T_m}^{\mu\nu} \sim \int d^4x\, \left[h_{\mu\nu} + \eta_{\mu\nu}\alpha\varphi\right] {T_m}^{\mu\nu}$$

Jordan   Einstein

$\tilde{h}_{\mu\nu}$ = Jordan metric pert. $h_{\mu\nu}$ = Einstein metric pert. $\eta_{\mu\nu}$ = Minkowski metric

- Not so fast: this might be true for infinitesimal test particles, but is it true for extended objects?

Even in Newtonian gravity, extended objects do not necessarily move like a test particle.
They only do if we ignore tides.

e.g. the Earth's motion is well approximated by that of a test particle because the Earth is small compared to the scale on which the Sun's grav. field varies (Principia).

We will work within the same zero-tide approximation.

Intuitive reasoning in Einstein frame:

$$S_{\rm matter} \sim \int d^4x \, [h_{\mu\nu} + \eta_{\mu\nu}\alpha\varphi] \, T_m{}^{\mu\nu}$$

Scalar mediates a fifth force.

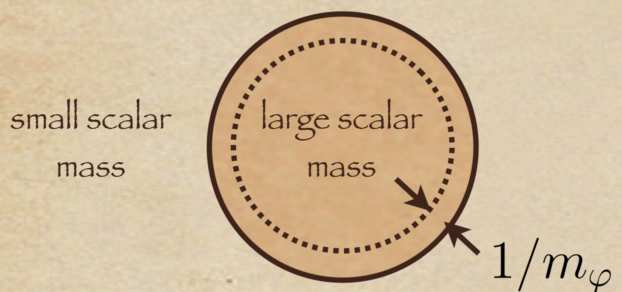
- Scalar is universally coupled (coupling constant α indep. of particle species): no apparent equivalence principle violation in microscopic action (counter e.g. Frieman & Gradwohl).
- Macroscopic object interacts with scalar via charge:

$$S_{\rm int} \sim \alpha Q \int d\tau \varphi$$

- A well-known effect (Nordvedt): $Q \sim \int d^3x \, T_m{}^\mu{}_\mu$
  Therefore, relativistic or compact object has Q/M $\longrightarrow$ 0.
  A black hole and a star would therefore fall at different rates because star has Q/M=1, while black hole has Q/M = 0 (no hair).

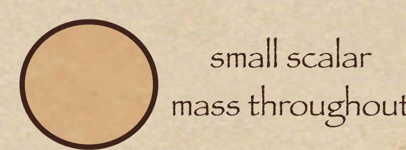
- Nordvedt effect is $O(1/c^2)$ in the sense of post-Newtonian expansion i.e. (1 - Q/M) is roughly equal to the fraction of the object mass M from gravitational binding energy.
- Chameleon screening adds a new twist: an O(1) equivalence principle violation, from classical renormalization of Q.

$$\frac{\varphi}{\alpha} < |\Phi_{\rm grav}|$$



Screened object: Q/M $\rightarrow$ 0 by Yukawa suppression.

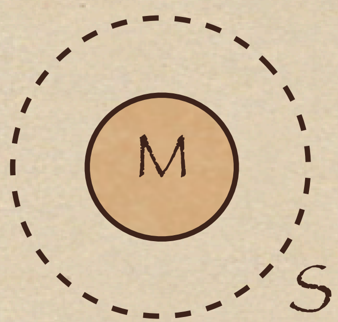
$$\frac{\varphi}{\alpha} > |\Phi_{\rm grav}|$$



Unscreened object: Q/M = 1.

- Screened and unscreened objects have O(1) difference in Q/M, and therefore O(1) equivalence principle violation.

Motion of an extended object - a more precise argument:



momentum $P_i = \int d^3x \, t_i{}^0$

momentum flux

$$\dot{P}_i = \int d^3x \, \partial_0 t_i{}^0 = - \int d^3x \, \partial_j t_i{}^j = - \oint dS \hat{x}_j t_i{}^j$$

where $t_\mu{}^\nu$ = pseudo energy-momentum

Trick: choose S so that $h_{\mu\nu}$ is small at S, but not necessarily at object. Advantage: perturbative at S and bypass consideration of self-forces. Works in both Einstein and Jordan frame.

Einstein, Hofmann, Infeld; Damour

Jordan frame summary for chameleon:

$$M\ddot{X}_i = -M\left[\frac{1+2\epsilon\alpha^2}{1+2\alpha^2}\right]\partial_i\Phi_{\text{ext}}$$

$\epsilon \sim 1$ for unscreened objects and $\epsilon \sim 0$ for screened objects

$(\,\varphi/\alpha > |\Phi_{\text{object}}|\,)$ $(\,\varphi/\alpha < |\Phi_{\text{object}}|\,)$

grav. mass = inertial mass grav. mass ≠ inertial mass

Generically $\alpha \sim 1$, so expect O(1) violation of equivalence principle between screened and unscreened objects.

Only unscreened objects move on Jordan frame geodesics.

E.g. f(R): $\alpha = 1/\sqrt{6}$, unscreened/screened grav. mass = 4/3.

Note: f(R)'s special α is not protected against quantum corrections.

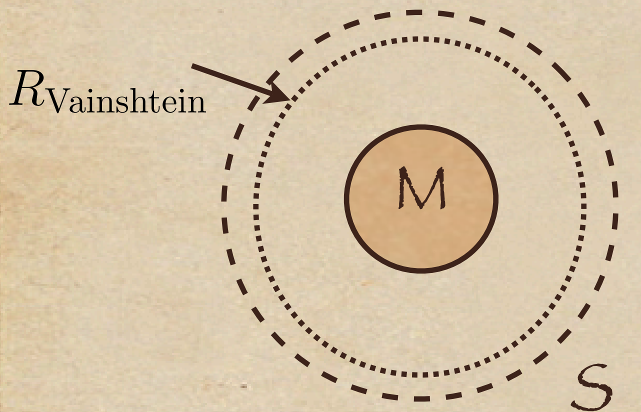
Important parameters: α & $\dfrac{\varphi}{\alpha}$

scalar-matter coulping:
controls e.p. violation level

controls screening

Interestingly, for Vainshtein mechanism , there's no such O(1) violation of equivalence principle.

Eqt for φ : $\partial_\mu J^\mu \sim \frac{\rho_m}{M_P^2}$ where $J^\mu \sim \partial^\mu \varphi + \frac{1}{m^2}\partial^\mu\varphi\partial^2\varphi$



Scalar charge is conserved.

Reason: shift symmetry.

Note: conclusion is unchanged whether S is outside or inside the Vainshtein radius.

Also: $O(1/c^2)$ Nordvedt effect remains.

Side remark:

Question: how robust is the universal scalar-matter coupling?

$$S_{\rm matter} \sim \int d^4x \, [h_{\mu\nu} + \underline{\eta_{\mu\nu}\alpha\varphi] \, T_m{}^{\mu\nu}}$$

Answer: it is stable against renormalizations from the matter sector, but not from the scalar (e.g. subject of this talk) and the graviton (e.g. black holes).

Note 1: a universal scalar-matter coupling, while technically natural in a limited sense, is not mandatory (unlike that between the graviton and matter).

Note 2: protons still have Q = M.

Alberto Nicolis, LH

Jordan frame summary for chameleon:

$$M\ddot{X}_i = -M\left[\frac{1+2\epsilon\alpha^2}{1+2\alpha^2}\right]\partial_i\Phi_{\rm ext}$$

Milky way & Sun has $|\Phi_{\rm object}| \sim 10^{-6}$
$\longrightarrow \quad \varphi/\alpha \lesssim 10^{-6}$

$\epsilon \sim 1$ for unscreened objects and $\epsilon \sim 0$ for screened objects

$(\varphi/\alpha > |\Phi_{\rm object}|)$ $\quad$ $(\varphi/\alpha < |\Phi_{\rm object}|)$

grav. mass = inertial mass $\quad$ grav. mass ≠ inertial mass

Generically $\alpha \sim 1$, so expect O(1) violation of equivalence principle between screened and unscreened objects.
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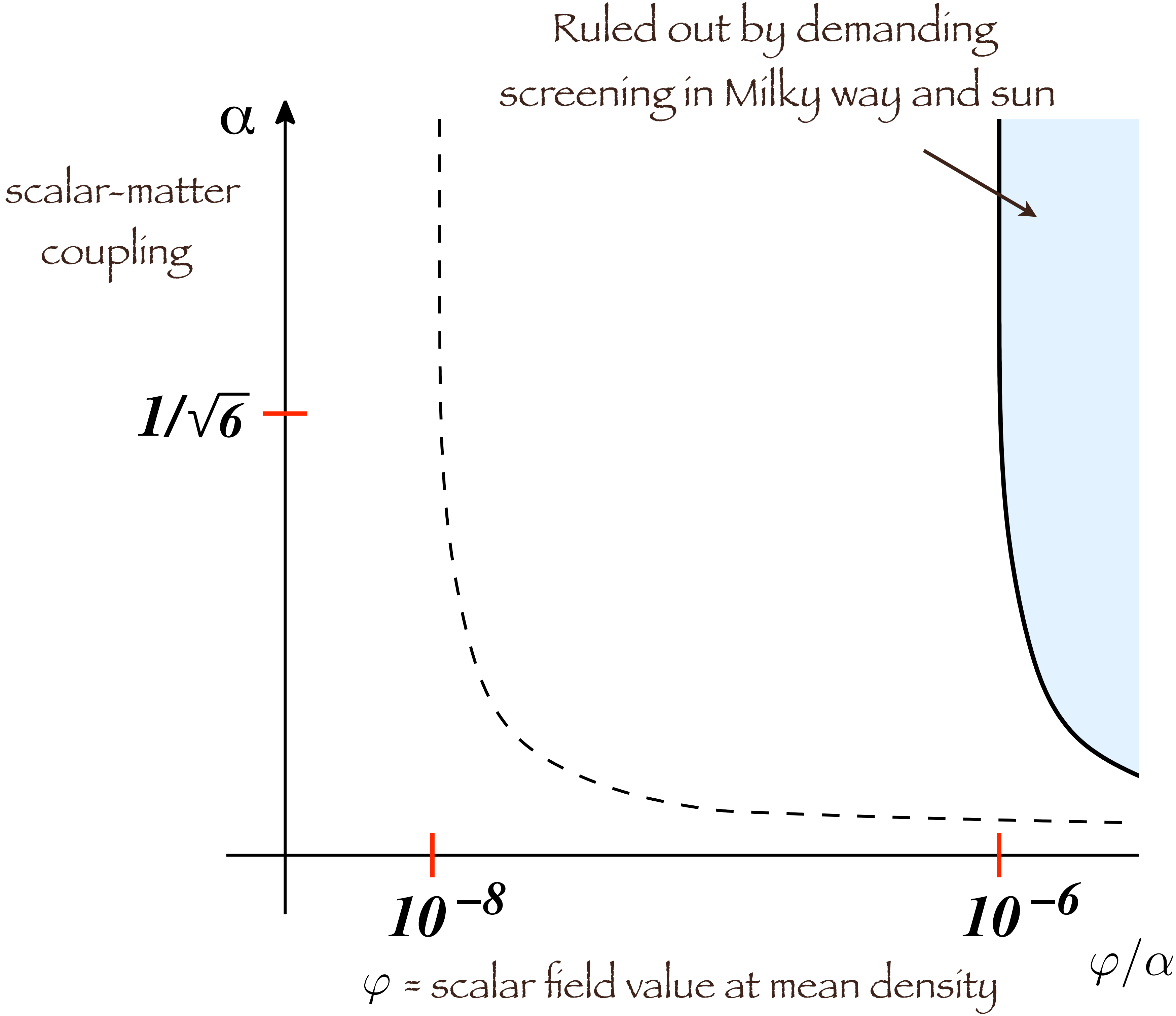
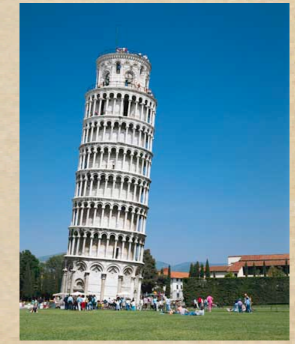


Ruled out by demanding
screening in Milky way and sun
α
scalar-matter
coupling
$1/\sqrt{6}$
10^{-8}
10^{-6}
φ/α
φ = scalar field value at mean density

Bulk motion tests:

Idea - unscreened small galaxies, screened large galaxies.

1. Small galaxies should move faster than large galaxies (i.e. an effective velocity bias - redshift distortion needs to be reworked) in unscreened environments.   Beware: Yukawa suppression.
2. Small galaxies should stream out of voids faster than large galaxies creating larger than expected voids defined by small galaxies (see Nusser & Peebles).

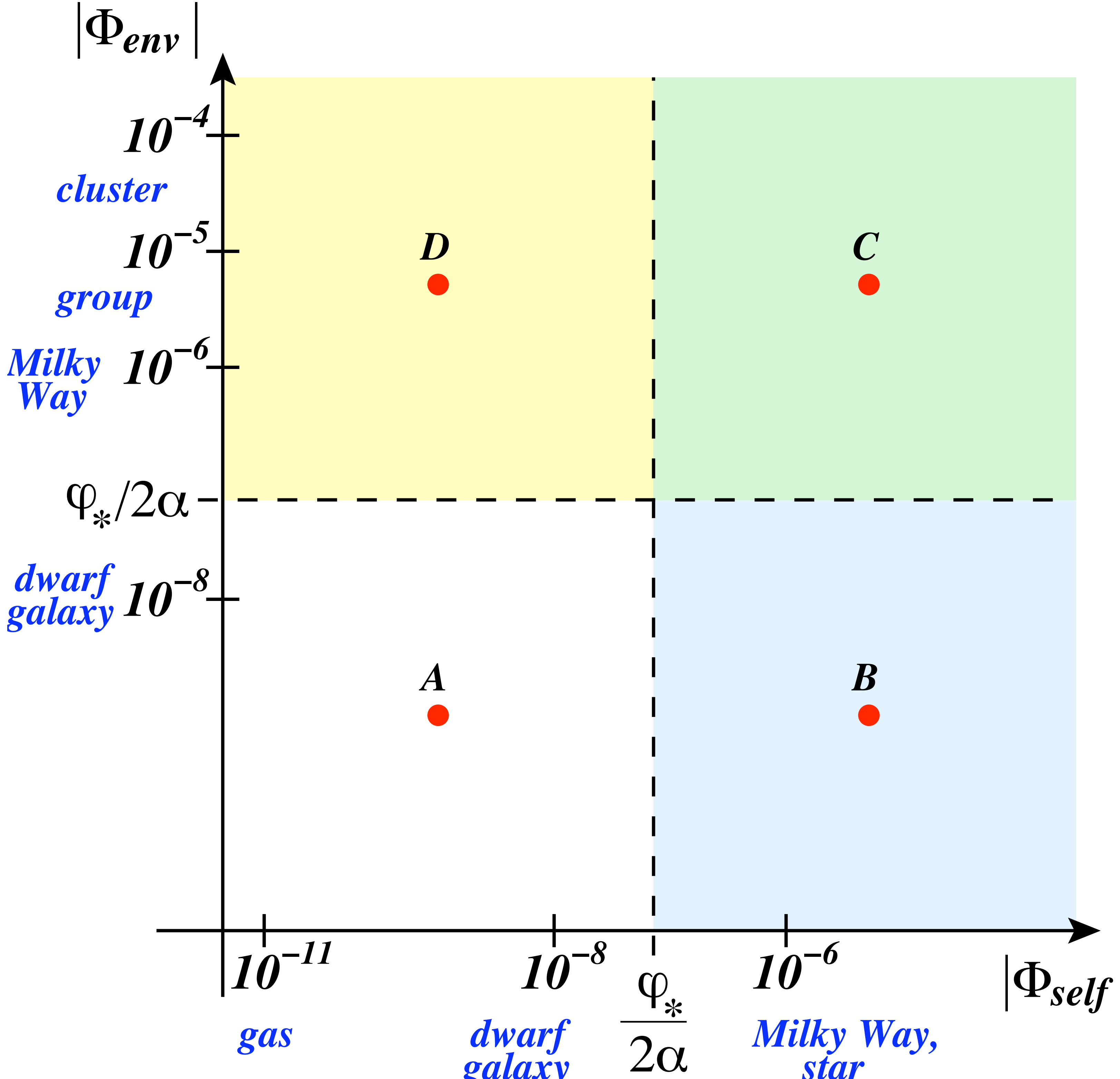


Internal motion tests:

Idea - unscreened HI gas clouds, screened stars.

3. Diffuse gas (e.g. HI) should move faster than stars in small galaxies even if they are on the same orbit. Beware: asymmetric drift.
4. Gravitational lensing mass should agree with dynamical mass from stars, but disagree with that from HI in small galaxies.

Key: avoid blanket screening.



|Φ_env|
10^−4
cluster
10^−5
D
C
group
Milky Way
10^−6
φ_*/2α
dwarf galaxy
10^−8
A
B
10^−11
10^−8
10^−6
|Φ_self|
φ_*/2α
gas
dwarf galaxy
Milky Way, star