Testing gravity with binary pulsars, black holes and the microwave background

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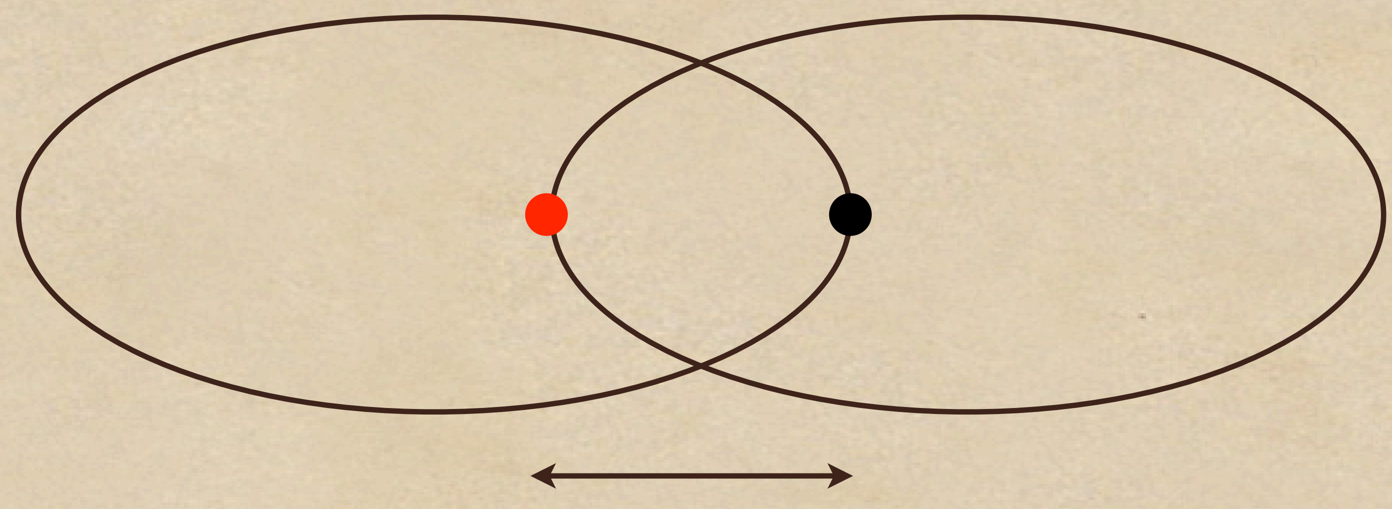
Three simple ideas (in order fantasy?):

1. on measuring gravitational waves (S. McWilliams, I-S. Yang);
2. on testing modified gravity (A. Nicolis);
3. on constraining superhorizon fluctuations (F. Schmidt).

Idea 1: a resonance detector

Weber's Bar

Hulse-Taylor binary pulsar 1913+16



periastron sep.
$1.1\,R_\odot$

orbital eccentricity: 0.6
orbital peroid P : 0.3 day
pulsar spin period: 59 milliseconds

Weisberg, Nice, Taylor 2010

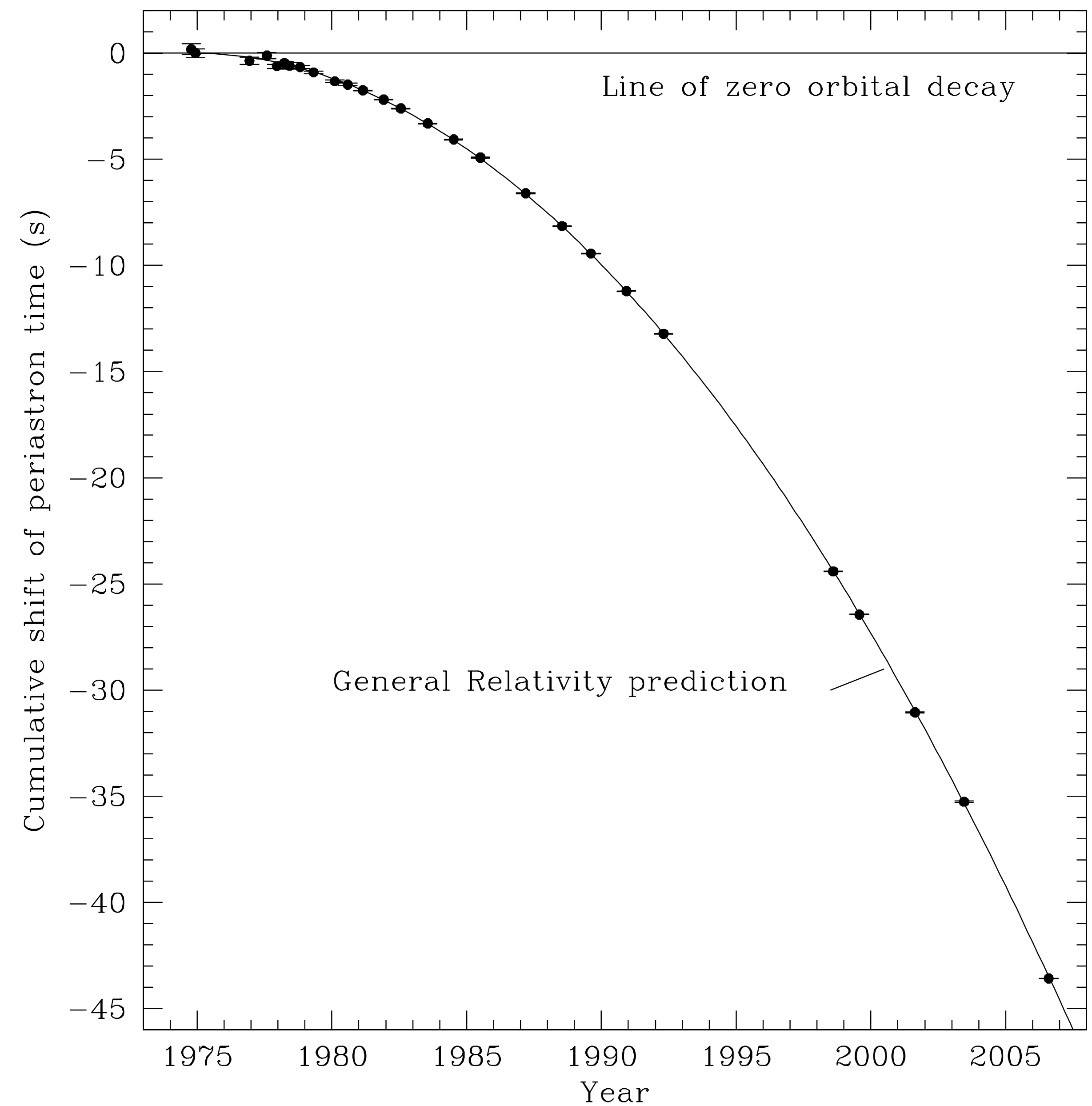


Figure 2. Orbital decay caused by the loss of energy by gravitational radiation. The parabola depicts the expected shift of periastron time relative to an unchanging orbit, according to general relativity. Data points represent our measurements, with error bars mostly too small to see.

Idea: focus instead on the scattering of a gravitational wave (GW) background by the binary. Order of magnitude estimates:

- Gravitational wave background causes the binary period to random walk. $\Delta P/P$ per period $\sim 10\,h$
- Strain h most effective at harmonics of the orbital period, $f \sim 4 \times 10^{-5}$ Hz
- Over duration $T_{\rm tot}$, accumulated rms $\Delta P/P \sim 10\,h\sqrt{T_{\rm tot}/P}$
- Accumulated rms periastron time shift $\Delta T \sim 10\,h\,T_{\rm tot}\sqrt{T_{\rm tot}/P}$

  Useful numbers: $T_{\rm tot}/P \sim 4 \times 10^4$, $T_{\rm tot} \sim 10^4$ days

- Periastron time measurement accuracy $\sim 10^{-7}$ day
- Constrain strain by $\Delta T < 10^{-7}$ day $\Longrightarrow$ $h < 5 \times 10^{-15}$

Note: h here represents the square root of the tensor power spectrum per log freq i.e. h is the rms strain.

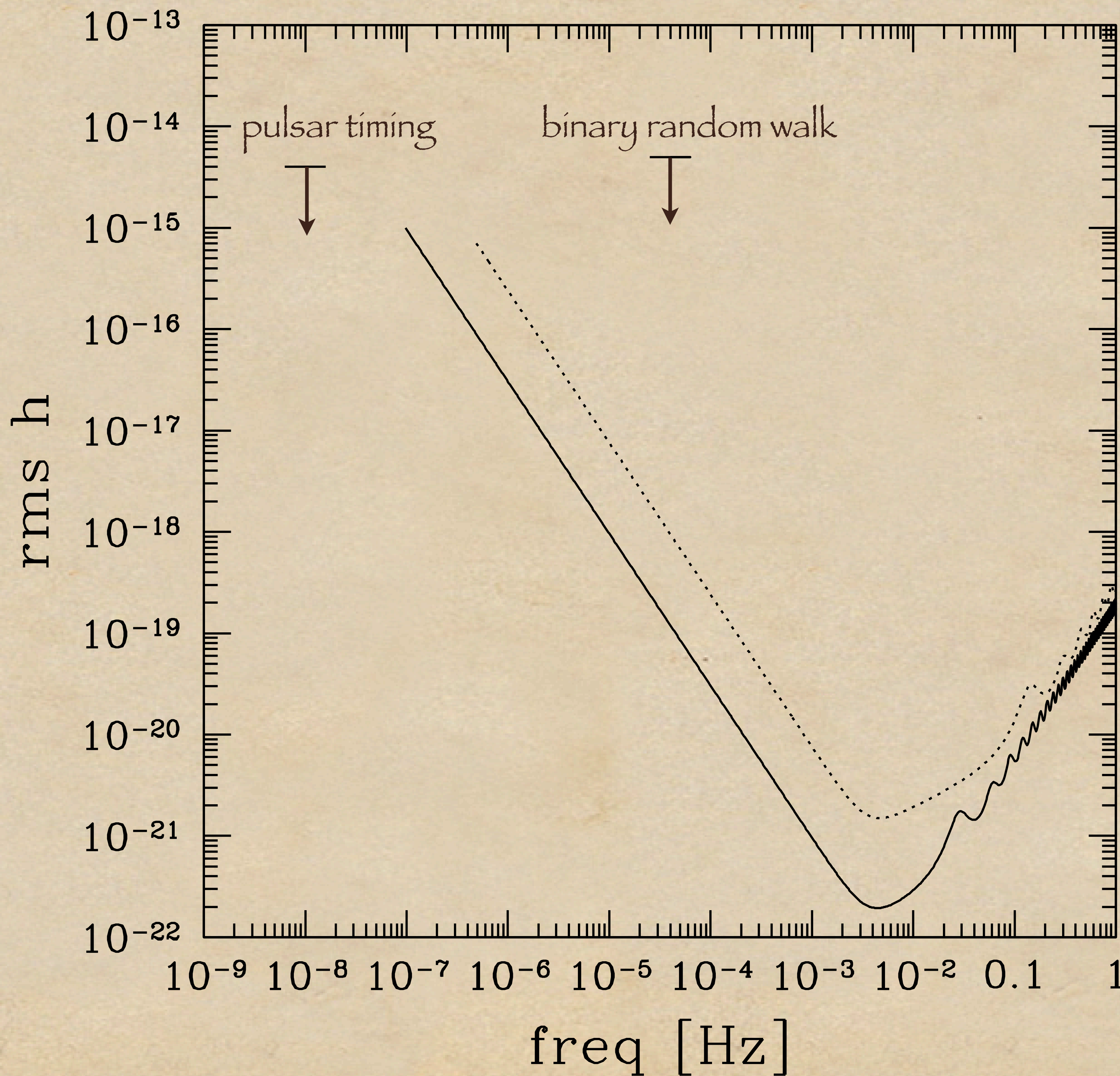
Some technical details:

- This is a stochastic process: compute two point correlation of orbital change, and relate it to the two point correlation of GW background.

$$\langle h(t)h(t')\rangle = \int \frac{df}{f}\, h_{\rm rms}^2 e^{2\pi i f(t-t')}$$

- Optimal data weighting.

- Earlier work: see Mashhoon 1978, Mashhoon, Carr, Hu 1981.



pulsar timing
binary random walk
rms h
freq [Hz]
10^-13
10^-14
10^-15
10^-16
10^-17
10^-18
10^-19
10^-20
10^-21
10^-22
10^-9
10^-8
10^-7
10^-6
10^-5
10^-4
10^-3
10^-2
0.1
1

Summary 1:

Use random walk of binary orbit to detect/constrain gravitational waves at resonance frequencies. Apply to any binaries that have been monitored for a long time with high precision.

Idea 2, on testing gravity:

- By Weinberg/Deser theorem, at low energies, a Lorentz invariant theory of a massless spin 2 particle must be general relativity (GR).
  This is why essentially all proposed long distance modifications to GR end up introducing a new particle, usually a scalar, mediating an extra long range force.
- How should we test some generic scalar-tensor theory?
- Idea: assuming black holes have no scalar hair/charge, while normal stars do, let's check for the difference in their rate of free fall.
- This effect would be hopeless to detect for classic Brans-Dicke theory, because solar system tests already tell us the Brans-Dicke scalar must be very weakly coupled i.e. the scalar force is much weaker than gravity.
- Recent versions of scalar-tensor theories (motivated by DGP/massive graviton) offer a hope: they pass solar system tests, yet have interesting O(1) effects elsewhere.

Vainshtein screening e.g. DGP

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

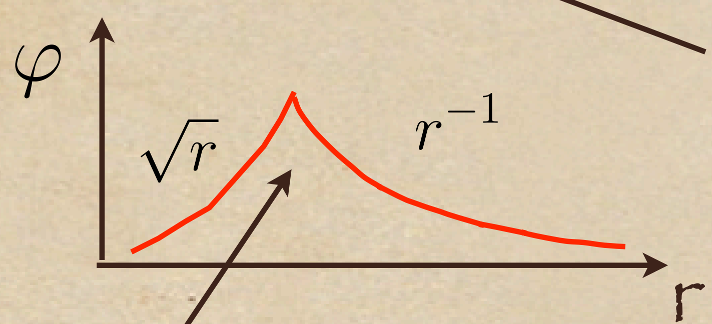
e.o.m.: $$\Box\varphi + \frac{1}{m^2}\left[(\Box\varphi)^2 - \partial^\mu\partial^\nu\varphi\partial_\mu\partial_\nu\varphi\right] \sim \alpha\rho_m$$

graviton mass

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

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

point mass solution



$r_V \sim (r_{\text{Schw}} m^{-2})^{1/3}$

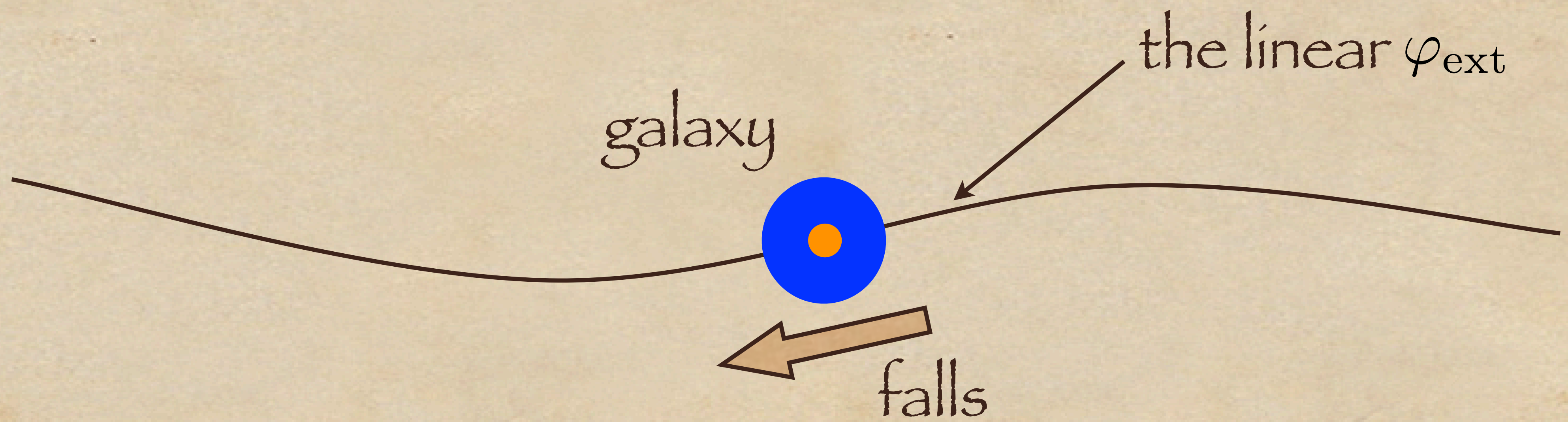
$\alpha =$ scalar-matter coupling ≈ O(1) generically

Galileon symmetry (Nicolis, Rattazzi, Trincherini): $\varphi \to \varphi + c + b_\mu x^\mu$

A problem: if Vainshtein screening is so effective, won't the scalar force be very suppressed inside a galaxy, where both black holes and stars reside?

- Numerical simulations (Chan & Scoccimarro, Schmidt, Wyman & Khoury) tell us that large scale structure produces unsuppressed scalar on large scales.

- Use the galileon symmetry to our advantage: given any nonlinear solution, adding a linear gradient gives another solution.



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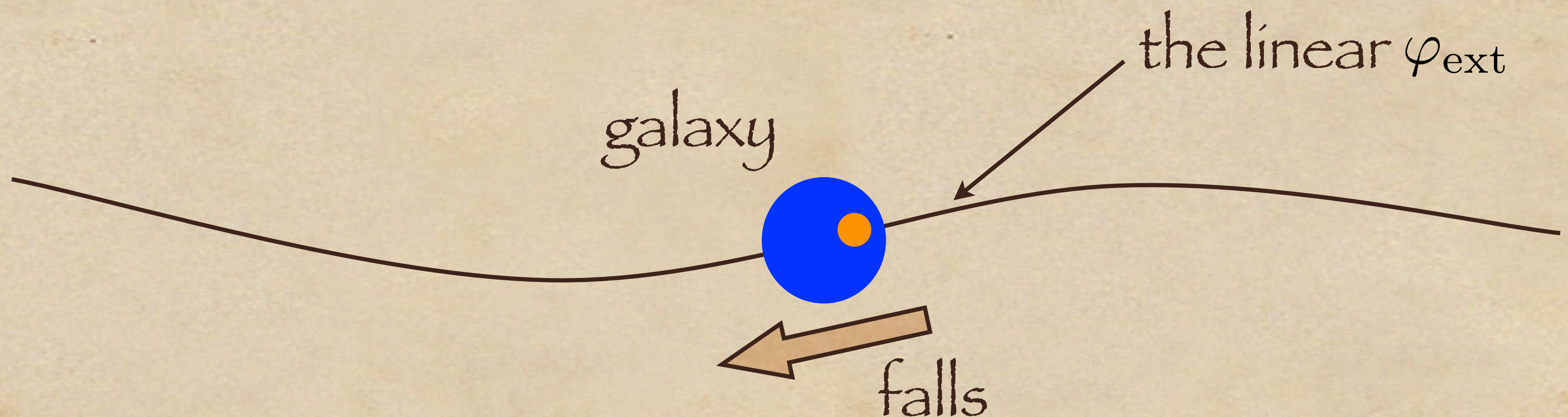

The idea is to look for the offset of massive black holes from the centers of galaxies.
The offset should be correlated with the direction of the streaming motion. The massive black holes can take the form of quasars or low luminosity galactic nuclei i.e. Seyferts.

The offset is estimated to be up to 0.1 kpc, for small galaxies.

Summary 2:

Test for presence of extra (scalar) forces by looking for off-centered black holes.

Footnote 1: No hair theorem for galileons (Babichev, Zahariade; LH, Nicolis).

Footnote 2: Analogs for chameleon mechanism (Khoury, Weltman; Hu; Jain, Vanderplas; Pourhasan, Afshordi, Mann, Davis; Cabre, Vikram, Zhao, Jain, Koyama; LH, Nicolis, Stubbs).