Test of the equivalence principle using the odd multipoles of the NPCF

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Arxiv:2011.05876

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January 15, 2021

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Outline

- A short video introduction to equivalence principle
- History of free-fall experiments for particles of different masses
- Equivalence principle for fluids in general relativity
- Violations of the equivalence
- How to detect the violations using the large scale structure.

Free fall experiments

Year	Investigator	Sensitivity	Method
500?	Philoponus[14]	"small"	Drop tower
1585	Stevin[15]	5×10^{-2}	Drop tower
1590?	Galileo[16]	2×10^{-2}	Pendulum, drop tower
1686	Newton[17]	10^{-3}	Pendulum
1832	Bessel[18]	2×10^{-5}	Pendulum
1908 (1922)	Eötvös[19]	2×10^{-9}	Torsion balance
1910	Southerns[20]	5×10^{-6}	Pendulum
1918	Zeeman[21]	3×10^{-8}	Torsion balance
1923	Potter[22]	3×10^{-6}	Pendulum
1935	Renner[23]	2×10^{-9}	Torsion balance
1964	Dicke, Roll, Krotkov[10]	3×10^{-11}	Torsion balance
1972	Braginsky, Panov[24]	10^{-12}	Torsion balance
1976	Shapiro, et al.[25]	10^{-12}	Lunar laser ranging
1981	Keiser, Faller[26]	4×10^{-11}	Fluid support
1987	Niebauer, et al.[27]	10^{-10}	Drop tower
1989	Stubbs, et al.[28]	10^{-11}	Torsion balance
1990	Adelberger, Eric G.; et al.[29]	10^{-12}	Torsion balance
1999	Baessler, et al.[30][31]	5×10^{-14}	Torsion balance
2017	MICROSCOPE[32]	10^{-15}	Earth orbit

MICROSCOPE: Similarity of free-fall for two bodies

- MICROSCOPE:: 300 kg Satellite operated by National Centre for Space Studies
- Aim: To test the universality of free-fall with a precesion to the order 10^{15}, 100 times more precess that what could be achieved on earth
- Two masses with different neutron-proton ratios
  - Platinum-Rhodium alloy
  - Titanium-Aluminium-Vanadium ally

Equivalence principle

"A little reflection will show that the law of the equality of the inertial and gravitational mass is equivalent to the assertion that the acceleration imparted to a body by a gravitational field is independent of the nature of the body. For Newton's equation of motion in a gravitational field, written out in full, it is:

$$\begin{aligned}&(\text{Inertial mass}) \cdot (\text{Acceleration}) \\ &= (\text{Intensity of the gravitational field}) \cdot (\text{Gravitational mass}).\end{aligned}$$

It is only when there is numerical equality between the inertial and gravitational mass that the acceleration is independent of the nature of the body"

"How I created the theory of relativity "

by

Albert Einstein

Free-fall in curved spacetime

- Consider the action of particle free from all external, non-gravitational forces etc

$$S = \int_A^B ds = \int_A^B \sqrt{-g_{\mu\nu}(x)\, dx^\mu\, dx^\nu} = \int_A^B \sqrt{-g_{\mu\nu} \frac{dx^\mu}{d\tau} \frac{dx^\nu}{d\tau}}\, d\tau$$

- The Euler-Lagrange equation leads to a geodesic equation

$$\frac{d^2 x^\beta}{d\tau^2} + \Gamma^\beta{}_{\alpha\nu} \frac{dx^\alpha}{d\tau} \frac{dx^\nu}{d\tau} = 0$$

- Promote to fluids(fields): Imagine a family of curves and a define an average tangent vector to the family of curves

$$u^\mu = \frac{dx^\mu}{d\tau} \longrightarrow u^\nu \nabla_\nu u^\mu = 0$$

Equivalence principle: General relativity

- Consider.a standard Einstein-Hilbert action with no funny fields or coupling

$$S = S_{\rm EH}[g_{\mu\nu}] + S_{\rm SM}[g_{\mu\nu}] + S_{\phi}[\phi, g_{\mu\nu}] + S_{\rm DM}[\varphi, g_{\mu\nu}]$$

- For this action, you can write down

$$T_I^{\mu\nu} \equiv \frac{-2}{\sqrt{-g}} \frac{\delta(\sqrt{-g}\mathcal{L}(g_{\mu\nu}))}{\delta g^{\mu\nu}} = (\rho_I + P_I) u_I^\mu u_I^\nu + P_I g^{\mu\nu} .$$

- I = baryons, dark matter, etc

$$\nabla^\mu T_{\mu\nu} = (P_I + \rho_I) u_I^\mu \nabla_\mu u_I^\nu + g^{\mu\nu} \nabla_\nu P_I + u_I^\nu \left[\nabla_\mu (P_I + \rho_I) u_I^\mu\right] = 0$$

- Relativistic Euler equation

$$(P_I + \rho_I) \cancel{u_I^\mu \nabla_\mu u_I^\nu} + \left(g^{\mu\nu} + u_I^\mu u_I^\nu\right) \nabla_\nu P_I = 0$$

Unverse at late-time

- We consider metric perturbations

$$ds^2 = a^2 \left(-(1+2\Phi)\, d\eta^2 + (1-2\Psi)\, \delta_{ij} dx^i dx^j\right) \,,$$

- The perturbation of the temporal and spatial components of its 4-velocity is given by

$$\begin{aligned} u_I^0 &= 1 - \Phi^{(1)} + \frac{1}{2}\left[3[\Phi^{(1)}]^2 - \Phi^{(2)} + \partial_i v_I^{(1)} \partial^i v_I^{(1)}\right] \,, \\ u_I^i &= \partial^i v_I^{(1)} + \frac{1}{2}\partial^i v_I^{(2)} \,, \end{aligned}$$

- In the limit of vanishing pressure: $I = b, c, m$

$$\partial^i {v_I}^{(1)\prime} + \mathcal{H}\partial^i {v_I}^{(1)} + \partial^i \Phi^{(1)} = 0 \,,$$

- Note that $v_{bc} = v_b - v_c = 0$.

- Zero relative velocity due to the equivalence principle

Late-time violations of the equivalence principle

- Recombination: tight coupling between baryons and photon

- Violation of the local Lorentz invariance (existence of a preferred frame, e.g Einstein-aether theory)

- Gravity contains degrees of freedom that couple differently to various matter fields (Scalar-Tensor theory)

Scalar-Tensor theory with interaction in the dark sector

- Consider the following action

$$S = S_{\rm EH}[g_{\mu\nu}] + S_{\rm M}[g_{\mu\nu}] + S_{\phi}[\phi, g_{\mu\nu}] + S_{\rm DM}[\varphi, \tilde{g}_{\mu\nu}]$$

- The dark matter field φ sees the metric $\tilde{g}_{\mu\nu}$.
- The two metrics $\tilde{g}_{\mu\nu}$ and $g_{\mu\nu}$ are related according to

$$\tilde{g}_{\mu\nu} = C(\phi) g_{\mu\nu} + D(\phi)\partial_\mu\phi\partial_\nu\phi\,.$$

- Couplies to the ϕ field through $C(\phi)$ and $D(\phi)$
- Energy-momentum conservation equations become

$$\begin{aligned}\nabla^\mu T^{\rm sm}_{\mu\nu} &= 0 \\ \nabla^\mu T^{\rm DM}_{\mu\nu} &= Q\left(\phi, u^\mu\nabla_\mu\phi, \rho_{\rm c}\right)\nabla_\nu\phi\end{aligned}$$

Velocities in the CDM/dark energy interacting universe

- Baryon peculiar velocity

$$\partial^i v_b^{(1)\prime} \quad + \quad \mathcal{H}\partial^i v_b^{(1)} + \partial^i \Phi^{(1)} = 0 \, ,$$

- CDM peculiar velocity

$$\partial^i v_c^{(1)\prime} \quad + \quad \mathcal{H} \left[1 + \Theta_1\right] \partial^i v_c^{(1)} + \left[1 + \Theta_2\right] \partial^i \Phi^{(1)} = 0 \, ,$$

- Baryon-CDM relative velocity $v_{bc} = v_b - v_c$

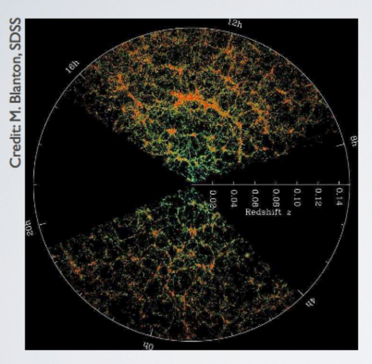
$$v_{bc}^{(1)\prime} \quad = \quad -\mathcal{H} \left(v_{bc}^{(1)} - \Theta_1 v_c^{(1)} \right) + \Theta_2 \Phi^{(1)} \, .$$

- Equivalence principle violation!

Can we test these in a model independent way in the universe?

Distribution of structures in the Universe

A typical galaxy survey

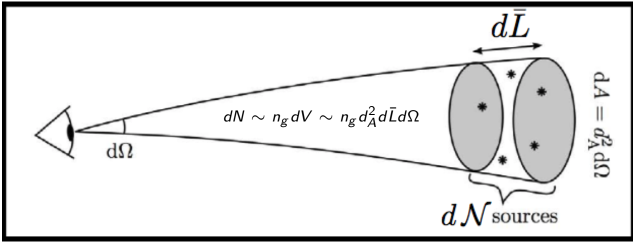


How structures are distributed in the Universe is determined by:

- The theory of gravity
- The matter content of the universe
- The initial conditions/origin

To extract these pieces of information we need to understand exactly what we are measuring.

Theory of what observation measures



Original proposals

- *Kristian, J and Sachs, R. K, Observations in Cosmology, Texas Symposium, (1969)*
- *Ellis, G. F. R, Relativistic cosmology, Varenna Lectures, (1969)*

Relativistic Number count fluctuations proposals

- *Yoo,+, Phys. Rev. D* **80**, *083514 (2009)*
- *Challinor:, +, Phys. Rev. D* **84**, *043516 (2011)*
- *Bonvin:, +, Phys. Rev. D* **84**, *063505 (2011)*

Number count of sources

- Flux-limited number count of sources

$$\frac{\mathrm{dN^{obs}}(z,\hat{\mathbf{n}},F)}{\mathrm{dz\,d}\Omega_o} = \mathcal{N}_g(z,\hat{\mathbf{n}},F)\, d_A^2(z,\hat{\mathbf{n}})\,[k_\mu u^\mu]_o \left|\frac{d\lambda}{dz}\right|,$$

- The observed number density is dependent on the flux-cut

$$\mathcal{N}_g(z,\hat{\mathbf{n}},F) = \int_{\ln L(F)}^{\infty} d\ln L\; n_g(z,\hat{\mathbf{n}},\ln L)\,.$$

- The luminosity of the source is related to its flux by

$$L = 4\pi F d_L^2 = 4\pi F(1+z)^4 d_A^2$$

.

Evolution and flux constraint

- Flux-limited proper number density of galaxy

$$\mathcal{N}_g(z, \hat{\mathbf{n}}, \bar{L}) \;=\; \bar{\mathcal{N}}_g(z, \bar{L})\left[1 + \delta_g + b_e\Delta_z + \mathcal{Q}\Delta_{d_L} + \frac{\partial \delta_g}{\partial \ln \bar{L}}\Delta_{d_L}\right],$$

- Parametrize these effects:
  - The Evolution bias

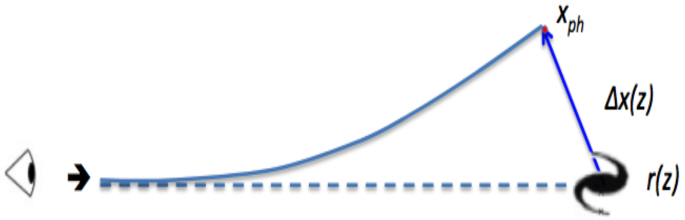
$$b_e(z, \bar{L}) = \frac{\partial \ln\left[\bar{\mathcal{N}}_g(z, >\bar{L})\right]}{\partial \ln a}$$

  - The Magnification bias

$$\mathcal{Q}(z, \bar{L}) = -\frac{\partial \ln\left[\bar{\mathcal{N}}_g(z, >\bar{L})\right]}{\partial \ln \bar{L}} = \frac{2}{5}s(z, \bar{L})$$

Galaxy positions are distorted by inhomogeneities.

- We infer source position



- Radial and angular distortions

$$\mathbf{s}_{\rm obs} = \mathbf{x}_{\rm phy} + \Delta\mathbf{x}(z) = \mathbf{x}_{\rm phy} + \Delta x_{\parallel}\hat{\mathbf{n}} + \Delta\mathbf{x}_{\perp} \, ,$$

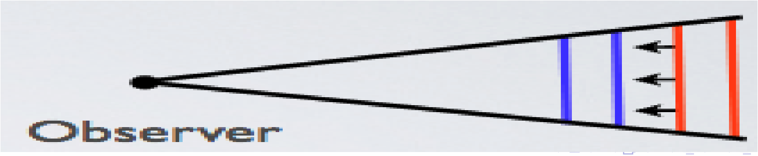
- Radial distortions $\Delta x_{\parallel}\hat{\mathbf{n}} \sim \delta z/\mathcal{H} + \delta x_{\parallel}$
- Angular distortions $\Delta\mathbf{x}_{\perp}$

Radial distortions by inhomogeneities

- Radial displacement of the source position at leading order

$$
\Delta x_{\parallel} = -\frac{1}{\mathcal{H}_s}\left[(\partial_{\parallel} v_s - \partial_{\parallel} v_o) - \Phi_s - \int_0^{\chi_s}(\Phi' + \Psi')\mathrm{d}\chi\right] - \int_0^{\chi_s}(\Phi + \Psi)\,\mathrm{d}\chi\,,
$$

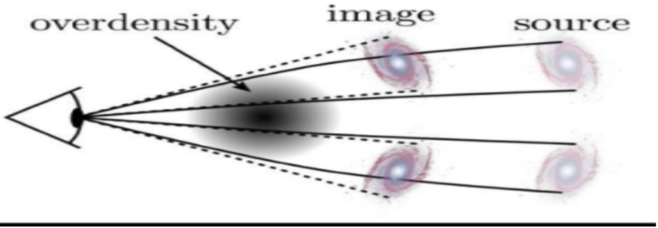
  - Doppler effect
  - Sachs-Wolfe effect (gravitational potential
  - Integrated Sachs-Wolfe effects
  - Time delay effect



Angular distortions by inhomogeneities

- Angular displacement of the image position AKA lensing

$$\Delta x^i_\perp \quad = \quad - \int_0^\chi d\chi' \left[(\chi - \chi') \frac{\chi'}{\chi} \partial^i_\perp (\Phi + \Psi) \right],$$



- Cosmic magnification

$$\Delta_{d_A} = \frac{1}{2} \left[\frac{1}{\chi_s} \Delta x_\parallel + \nabla_{\perp I} \Delta x^I_\perp \right] \propto \frac{1}{\chi_s} \Delta x_\parallel - \kappa$$

Redshift drift and Kaiser approximation

- Jacobian: Map from real to redshift space

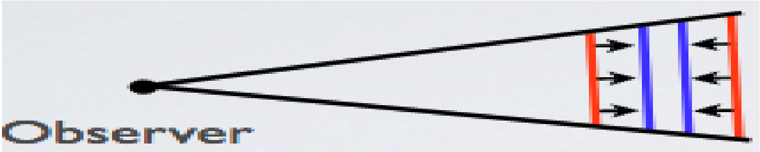
$$\left|\frac{d\lambda}{dz}\right| = \frac{a(z_s)^3}{\mathcal{H}(z_s)}\left[1 + \frac{1}{\mathcal{H}_s}\frac{d\delta z}{d\lambda} - \delta k^0 + \left(2 - \frac{\mathcal{H}'_s}{\mathcal{H}_s^2}\right)\delta z\right]$$

- Redshift modification

$$\delta z \;=\; (\partial_\parallel v_s - \partial_\parallel v_o) - (\Phi_s - \Phi_o) - \int_0^{\chi_s}(\Phi' + \Psi')\mathrm{d}\chi\,,$$

- Redshift drift and Kaiser approximation

$$\frac{d\delta z}{d\lambda} \approx \partial_\parallel v' - \partial_\parallel^2 v + \partial_\parallel \Phi \approx -\partial_\parallel^2 v$$



Operational approximation

- We neglect all integrations terms
- Weak-field approximation: we neglect all terms that become important only on super-Horizon scales. i.e

$$\Phi, \quad v, \quad v\partial_{\|}\Phi, \quad \partial_i\Phi\partial^i\Phi$$

- We keep terms like $\delta_m \propto \partial^2\Phi$, $\partial_{\|}v \sim \partial_{\|}\Phi$, $\Phi\partial_{\|}\delta_m$
  - First order:

$$\begin{aligned} \Delta_g^{(1)} &= \Delta_{\partial^2}^{(1)} + \Delta_{\partial^1}^{(1)} + \Delta_{\partial^0}^{(1)} \\ &\approx \Delta_{\partial^2}^{(1)} + \Delta_{\partial^1}^{(1)} = \Delta_{\mathrm{N}}^{(1)} + \Delta_{\mathrm{D}}^{(1)} \end{aligned}$$

  - Second order

$$\begin{aligned} \Delta_g^{(2)} &= \Delta_{\partial^4}^{(2)} + \Delta_{\partial^3}^{(2)} + \Delta_{\partial^2}^{(2)} + \Delta_{\partial^1}^{(2)} + \Delta_{\partial^0}^{(2)} \\ &\approx \Delta_{\partial^4}^{(2)} + \Delta_{\partial^3}^{(2)} = \Delta_{\mathrm{N}}^{(2)} + \Delta_{\mathrm{D}}^{(2)} \end{aligned}$$

Gravity theory independent number count fluctuations

- Newtonian limit at linear order(Kaiser limit)

$$\Delta_{\rm N}^{(1)} = \delta_g^{(1)} - \frac{1}{\mathcal{H}}\partial_\parallel^2 v_g{}^{(1)}$$

- General relativistic corrections at linear order

$$\begin{aligned}\Delta_{\rm D}^{(1)} &= \partial_\parallel v_g{}^{(1)} + \frac{1}{\mathcal{H}}\left(\partial_\parallel v_g{}^{(1)\prime} + \partial_\parallel \Phi^{(1)}\right) \\ &\quad + \left[b_e - 2\mathcal{Q} - \frac{2(1-\mathcal{Q})}{\chi\mathcal{H}} - \frac{\mathcal{H}'}{\mathcal{H}^2}\right]\partial_\parallel v_g{}^{(1)}\end{aligned}$$

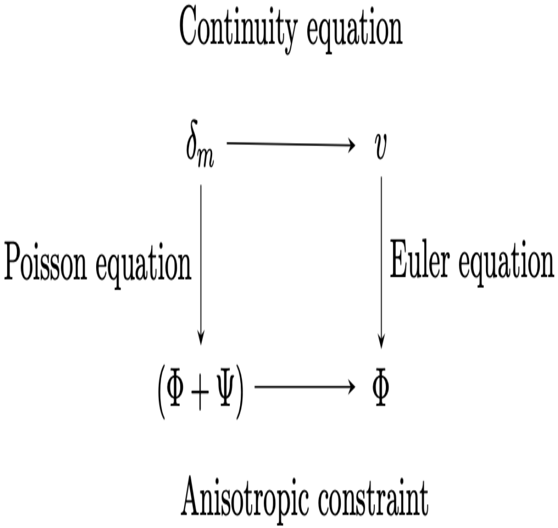
- Newtonian limit at second order

$$\begin{aligned}\Delta_{\rm N}^{(2)} &= \delta_g^{(2)} - \frac{1}{\mathcal{H}}\partial_\parallel^2 v_g{}^{(2)} - \frac{2}{\mathcal{H}}\left[\delta_g^{(1)}\partial_\parallel^2 v_g{}^{(1)} + \partial_\parallel v_g{}^{(1)}\partial_\parallel \delta_g^{(1)}\right] \\ &\quad + \frac{2}{\mathcal{H}^2}\left[\left(\partial_\parallel^2 v_g{}^{(1)}\right)^2 + \partial_\parallel v_g{}^{(1)}\partial_\parallel^3 v_g^{(1)}\right]\end{aligned}$$

Gravity theory independent number count fluctuations

$$\begin{aligned}
\Delta_{\rm D}^{(2)} &= \left[1+b_e-2\mathcal{Q}-\frac{2(1-\mathcal{Q})}{\chi\mathcal{H}}-\frac{\mathcal{H}'}{\mathcal{H}^2}\right]\partial_\| {v_g}^{(2)} \\
&+\frac{1}{\mathcal{H}}\left(\partial_\| {v_g}^{(2)\prime}+\partial_\|\Phi^{(2)}\right)+\frac{2}{\mathcal{H}}\Phi^{(1)}\left[\partial_\|\delta_g^{(1)}-\frac{1}{\mathcal{H}}\partial_\|^3 {v_g}^{(1)}\right] \\
&+\frac{2}{\mathcal{H}}\left[\delta_g^{(1)}-\frac{2}{\mathcal{H}}\partial_\|^2 {v_g}^{(1)}\right]\left[\partial_\| {v_g}^{(1)\prime}+\partial_\|\Phi^{(1)}\right] \\
&+4\partial_\| {v_g}^{(1)}\left(1-\frac{1}{\chi\mathcal{H}}\right)\frac{\partial\delta_g^{(1)}}{\partial\ln L}-\frac{2}{\mathcal{H}}\nabla_{\perp i} {v_g}^{(1)}\nabla_\perp^i\partial_\| {v_g}^{(1)} \\
&+2\partial_\| {v_g}^{(1)}\delta_g^{(1)}\left[1+b_e-2\mathcal{Q}-\frac{2(1-\mathcal{Q})}{\chi\mathcal{H}}-\frac{\mathcal{H}'}{\mathcal{H}^2}\right] \\
&+\frac{2}{\mathcal{H}}\partial_\| {v_g}^{(1)}\left[\delta_g^{(1)\prime}-\frac{2}{\mathcal{H}}\partial_\|^2 {v_g}^{(1)\prime}-\frac{1}{\mathcal{H}}\partial_\|^2\Phi^{(1)}\right] \\
&+\frac{2}{\mathcal{H}}\partial_\| {v_g}^{(1)}\partial_\|^2 {v_g}^{(1)}\left[-2-2b_e+4\mathcal{Q}+\frac{4(1-\mathcal{Q})}{\chi\mathcal{H}}+3\frac{\mathcal{H}'}{\mathcal{H}^2}\right] .
\end{aligned}$$

Imprint of theory of gravity



Prior from the solar system test

- Baryons obey the Equivalence principle

$$\partial^i {v_b}^{(1)\prime} + \mathcal{H}\partial^i {v_b}^{(1)} + \partial^i \Phi^{(1)} = 0\,,$$

- Leads to a velocity difference

$$\begin{aligned} \Delta_{\rm D}^{(1)} &= \partial_\| {v_g}^{(1)} - \partial_\| {v_b}^{(1)} + \frac{1}{\mathcal{H}}\left(\partial_\| {v_g}^{(1)\prime} - \partial_\| {v_b}^{(1)\prime}\right) \\ &+ \left[b_e - 2\mathcal{Q} - \frac{2\,(1-\mathcal{Q})}{\chi\mathcal{H}} - \frac{\mathcal{H}'}{\mathcal{H}^2}\right]\partial_\| {v_g}^{(1)} \end{aligned}$$

- Parametrise as

$$v_g^{(1)} - v_b^{(1)} = v_{gb}^{(1)} \equiv \Upsilon_1 v_g^{(1)},$$

- Conformal time derivative

$${v_g}^{(1)\prime} - {v_b}^{(1)\prime} = v_{gb}^{(1)\prime} = \beta_1 v_g^{(1)\prime},$$

Prior from the solar system test

- Euler equation for baryons at second order

$$\partial_i v_b^{(2)\prime} \quad + \quad \mathcal{H}\partial_i v_b^{(2)} + \partial_i \Phi^{(2)} + 2\partial_i\partial_j v_b^{(1)}\partial^j v_b^{(1)} = 0\,.$$

- Parametrise the velocity diffference

$$v_g^{(2)} - v_b^{(2)} = v_{gb}^{(2)} \equiv \Upsilon_2 v_g^{(2)}\,.$$

- The conformal time derivative

$$v_g{}^{(2)\prime} - v_b{}^{(2)\prime} = v_{gb}^{(2)\prime} = \beta_2 v_g^{(2)\prime}\,.$$

Odd multipoles of the galaxy power spectrum

- Multipoles of the cross-power spectrum
$P_g^{AB}(k,\mu) = P_{\rm N}^{AB}(k,\mu) + iP_{\rm D}^{AB}(k,\mu)$

$$P_\ell^{AB}(k) = \frac{(2\ell+1)}{2}\int_{-1}^{1} d\mu\, P_D^{AB}(k,\mu)\mathcal{L}_\ell(\mu)\,,$$

- Dipole:

$$\begin{aligned} P_1^{AB}(k) &= (-i)\Bigg[(b_1^B - b_1^A)\left[\frac{2}{\chi\mathcal{H}} + \frac{\mathcal{H}'}{\mathcal{H}^2} - \Upsilon_1 - \beta_1 X_{g1}\right] \\ &+ \left(1 - \frac{1}{\chi\mathcal{H}}\right)\left[3f_g(s^A - s^B) + 5(b_1^B s^A - b_1^A s^B)\right] \\ &+ \frac{3}{5}f_g\left(b_e^B - b_e^A\right) + \left(b_1^A b_e^B - b_1^B b_e^A\right)\Bigg] f_g\frac{\mathcal{H}}{k}P_m(k) \end{aligned}$$

- Octupole:

$$P_3^{AB}(k) = 2\left[\frac{1}{5}(b_e^A - b_e^B) - \left(1 - \frac{1}{\chi\mathcal{H}}\right)(s^A - s^B)\right] f_g^2\frac{\mathcal{H}}{k}P_m(k)$$

Galaxy bispectrum

- Galaxy bispectrum in the Newtonian limit

$$B_{g\mathrm{N}}(\boldsymbol{k}_1, \boldsymbol{k}_2, \boldsymbol{k}_3) = \mathcal{K}_{\mathrm{N}}(\boldsymbol{k})\, \mathcal{K}_{\mathrm{N}}(\boldsymbol{k}_2)\mathcal{K}^{(2)}_{\mathrm{N}}(\boldsymbol{k}_1, \boldsymbol{k}_2, \boldsymbol{k}_3)\, P(k_1)P(k_2) + 2 \text{ c. p.},$$

- We expand in spherical harmonics

$$B_g(k_1, k_2, k_3, \mu_1, \phi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} B_g^{\ell m}(k_1, k_2, k_3) Y_{\ell m}(\mu_1, \phi),$$

- Leads to even multipoles only $\ell = 0, 2, 4, 6, 8$.

- Adding relativistic Doppler corrections, generate $\ell = 1, 3, 5, 7$

Parametrization

- Redshift independent parametrization

$$\Upsilon_{1,2}(z) = \frac{1-\Omega_m(z)}{1-\Omega_m}\gamma_{1,2}\,,$$

- Its derivative wrt redshift

$$\beta_{1,2}(z) = \left[\frac{1-\Omega_m(z)}{1-\Omega_m}\right]'\gamma_{1,2}$$

Equivalence principle, cosmological and Astrophysical parameters

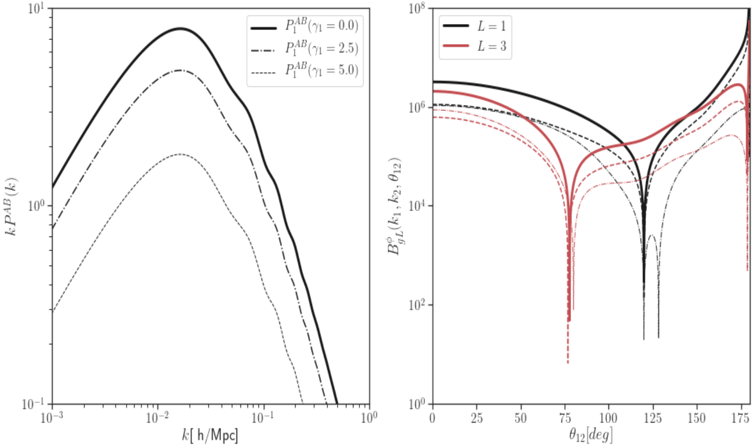
- Equivalence principle parameters $= \{\gamma_1, \gamma_2\}$.
- Cosmological parameters $= \{D_m, f_g, \Omega_m, P_{\mathcal{O}}(k)\}$.
- Astrophysical parameters $= \left\{b_1, b_2, b_{s^2}, b_e, \mathcal{Q}, \frac{\partial b_1}{\partial \ln \bar{L}}\right\}$.

Future surveys

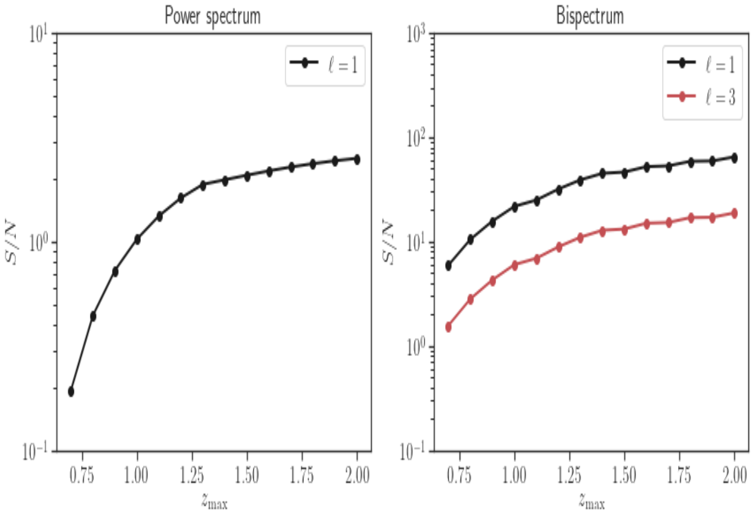
- Hα emission line galaxies

- HI intensity mapping survey

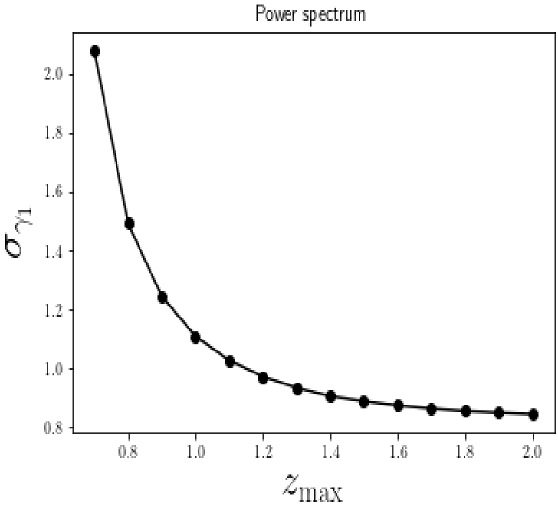
Multipoles of the cross-power spectrum and bispectrum



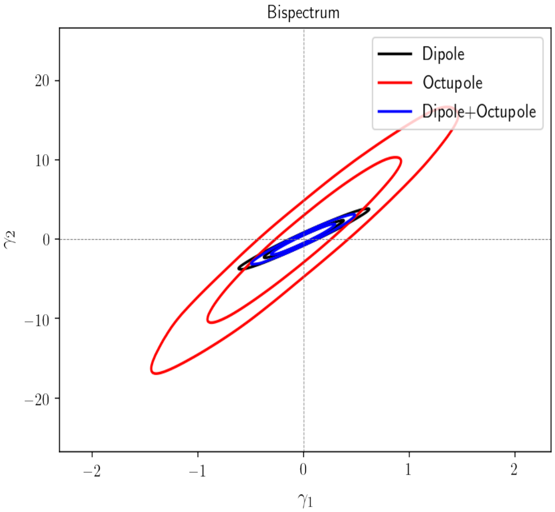
Detectability of the multipole moments



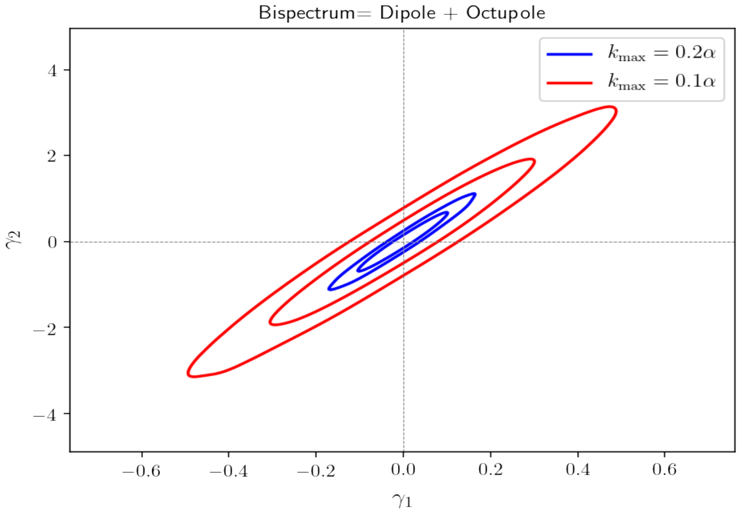
Power spectrum sensitive to γ_1



Bispectrum is senstive to both $\gamma_{1,2}$



Importance of modelling small scales well



$$\alpha = (1+z)^{(2/(2+n_s))}[h/\mathrm{Mpc}].$$

Conclusion

- Equivalence principle is the bedrock of general relativity, this is an opportunity to test it on cosmological scales
- This is a unique window to probe interacting dark sector
- Current surveys will be able to actually test this!

References

1. R. Maartens, S. Jolicoeur, **O. Umeh**, E. M. De Weerd and C. Clarkson, "Local primordial non-Gaussianity in the relativistic galaxy bispectrum," [arXiv:2011.13660 [astro-ph.CO]]
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