Testing Gravity at Cosmological Scales

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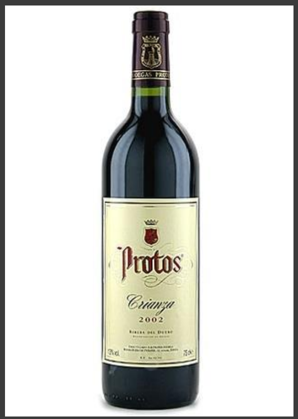
Testing gravity on Earth is tough



- Gravitational effects become dominant only at high volumes
  - Non-local aspects: screening/memory effects
  - Lack of sensitivity to initial conditions
- At lower volumes, gravitational oscillations subdominant to non-perturbative jet physics
  - UV/IR mixing
    turbulence
- Exotic generations improve signal to noise, but at significant cost

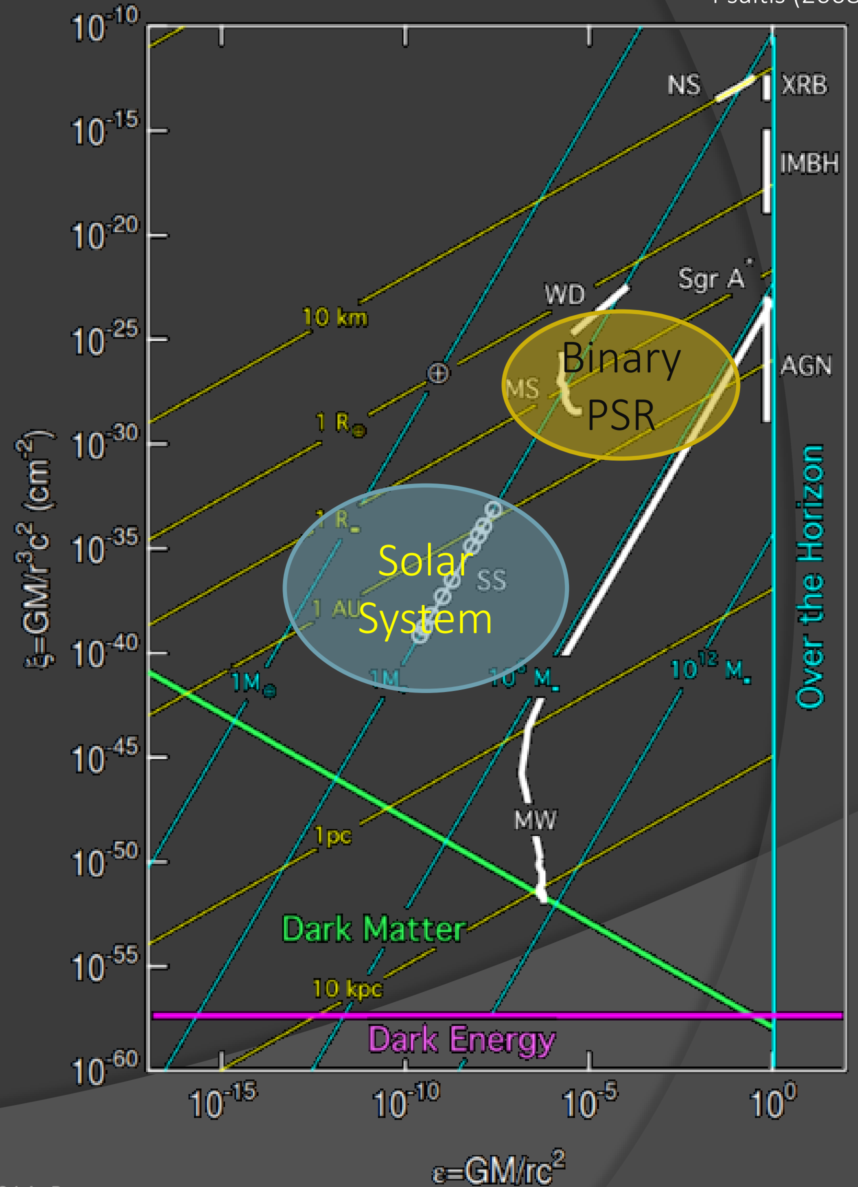
The Gist

- Model-independent observables:
  - *Both* background and LSS are probes of *geometry*
  - Saying more requires a model for gravity
- How to parameterise modifications of GR
  - Linear perturbations fully determined by functions of time only incl. superhorizon

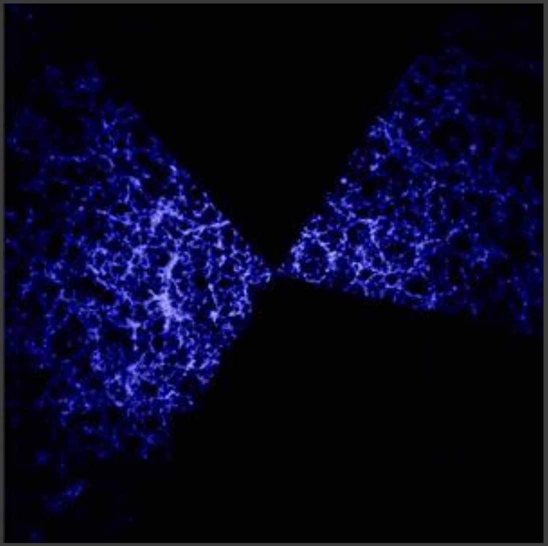
What do we know about gravity?

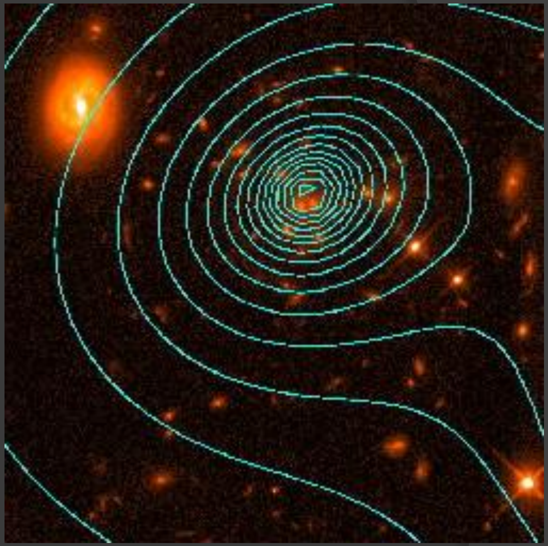
- Λ, famously, is too small
  - Only solution would probably be anthropic
- Alternatives to Λ dynamical
  - *Must* introduce a d.o.f.
- Dynamics imply ***time- and scale-dependent deviations***
- No dynamics means we effectively have Λ

Psaltis (2008)



Our Limited Eyes





Supernovae: d_{L}

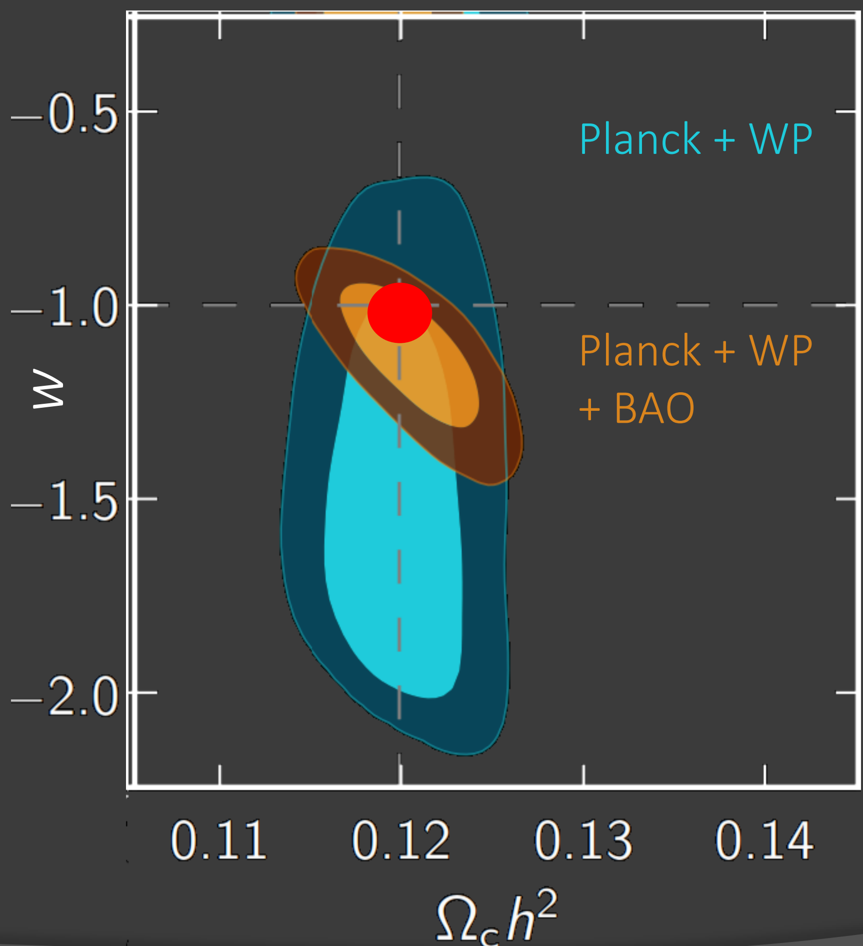
Galaxy Counts

Galaxy Shapes/ Brightness

We are constraining the EoS. Or?

$$w \equiv {}^{p}/_{\rho}$$

Planck: Ade et al. (2013)



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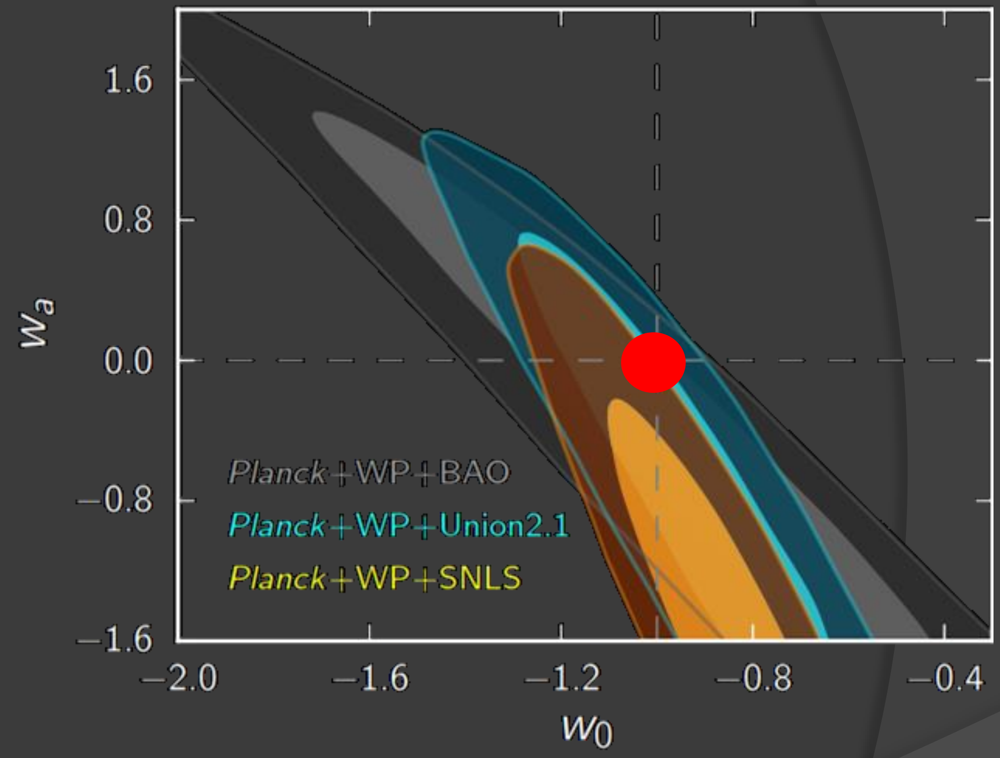


$$w \equiv w_0 + w_a(1-a)$$

Amendola, Kunz, Motta, Saltas, **IS** (2012)

But *w* is *not* an observable

- Distances only depend on

$$D = \int \frac{dz\, H_0}{H(z)}$$

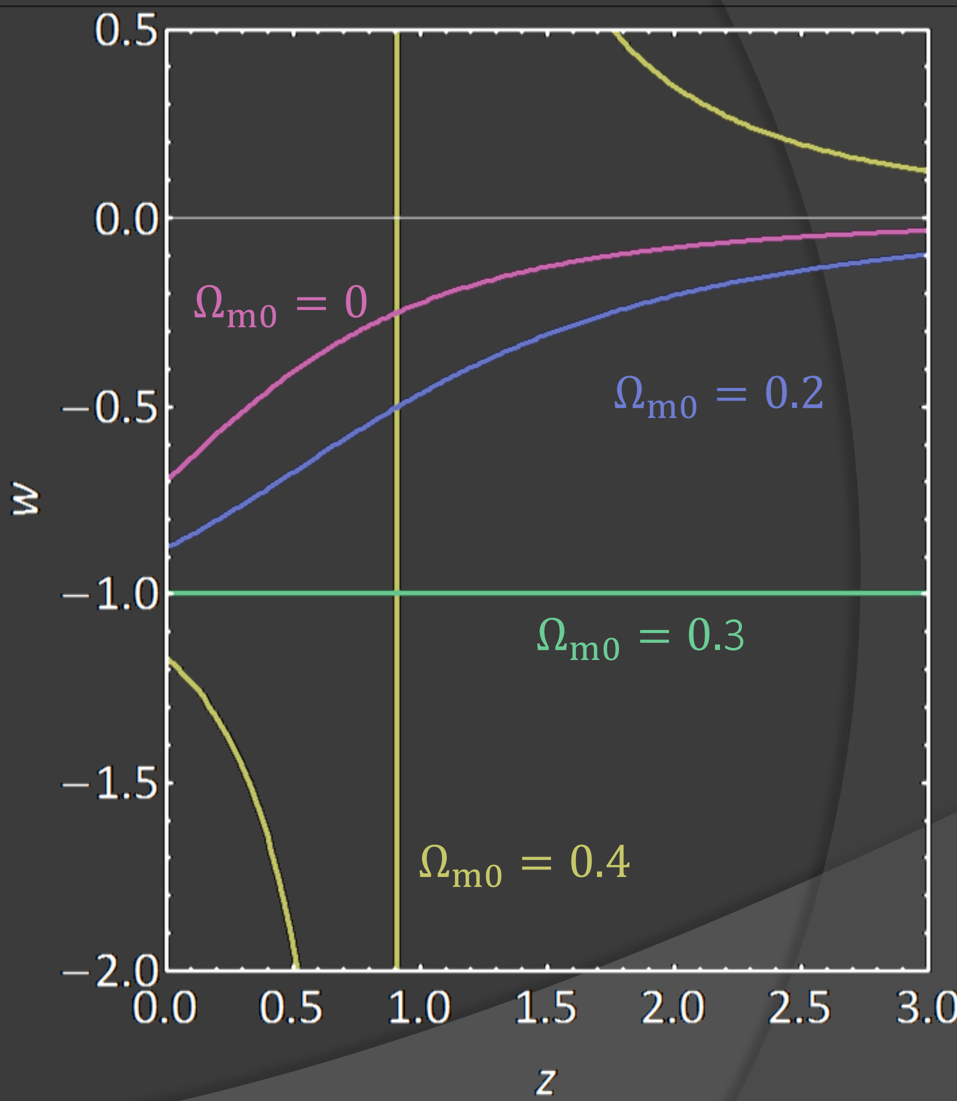
  - We measure *geometry* only
  - Including Ω_k, by comparing ⊥ and ∥ BAO

- DM/DE split is *ambiguous*

$$H^2 = H_0^2(\Omega_{m0} a^{-3} + \Omega_\Lambda)$$

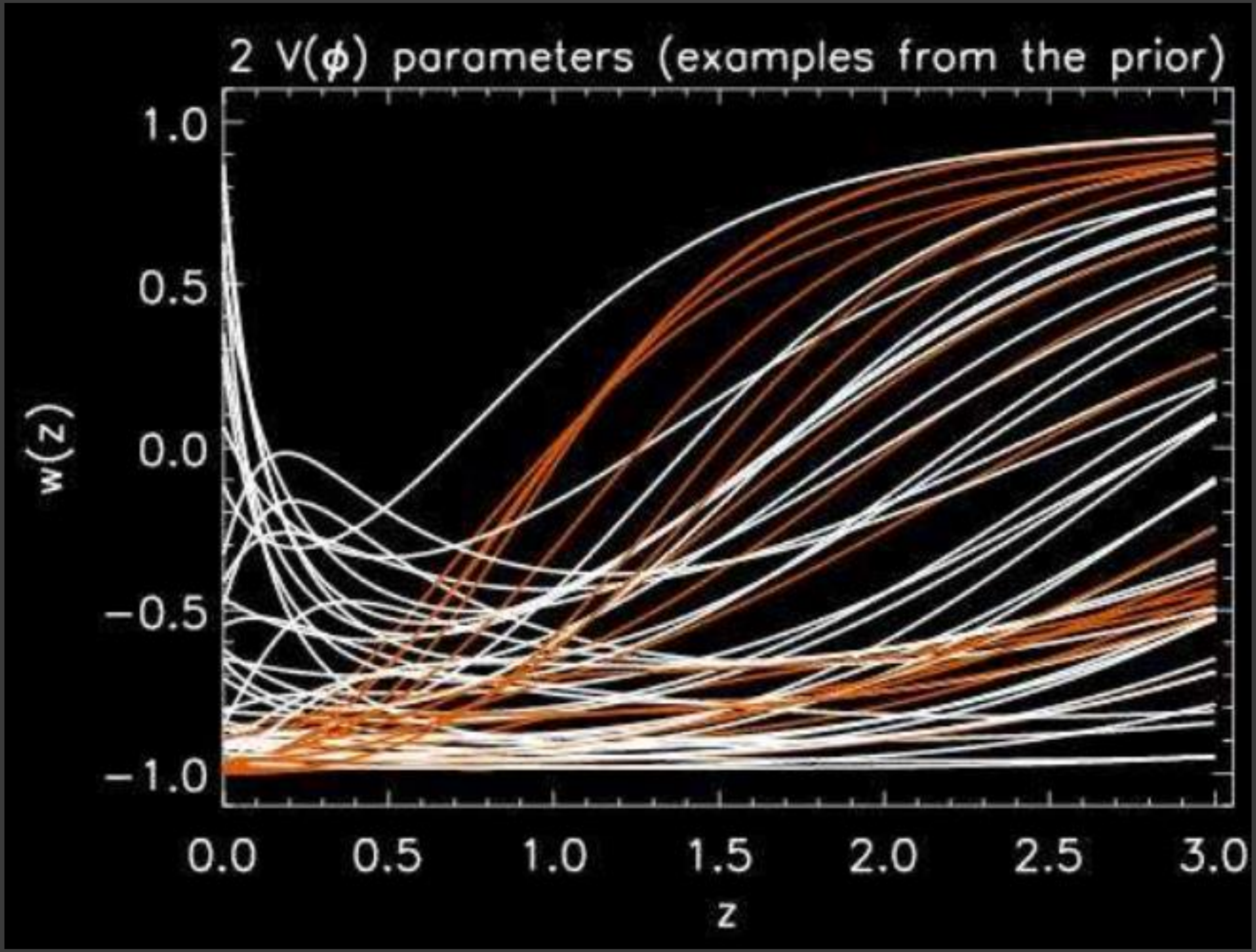
$$H^2 = H_0^2\left(\tilde{\Omega}_{m0} a^{-3} + \tilde{\Omega}_{DE}\, a^{-3(1+w)}\right)$$

- Ω_{m0} can *only* be measured using LSS



Natural EoS for Quintessence

Huterer and Peiris (2006)



$$w = w_0 + w_a(1 - a)?$$

Is dark energy smooth?

- $\eta = 1$
- $\mu = 1$

Λ:
of course

- $c_s^2 = 1$
- $\eta = 1$
- $\mu \to 1 + \frac{\alpha}{c_s^2 k^2}$

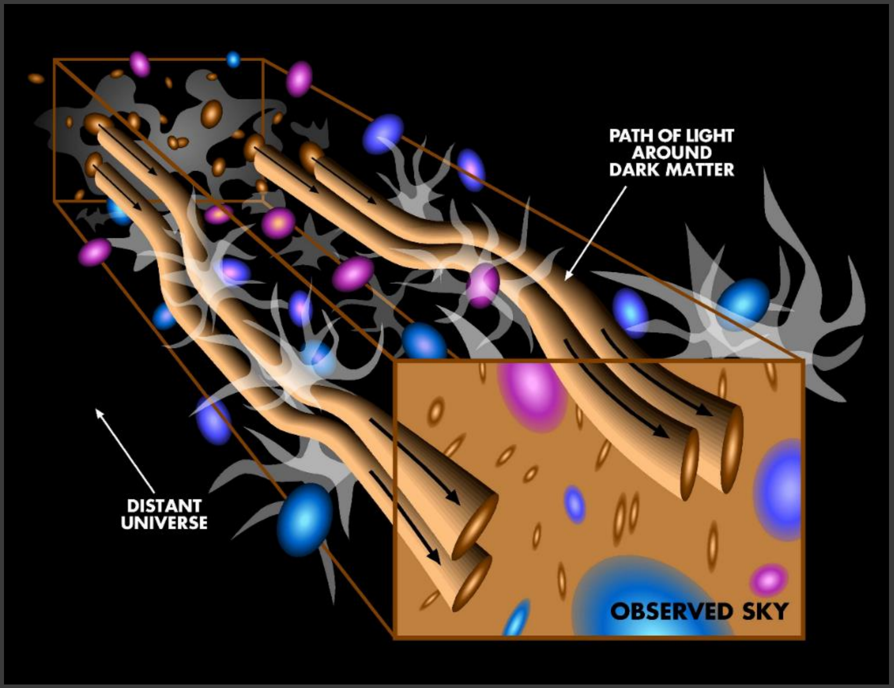
Quintessence:
more or less

- $c_s^2 = 1$
- $\eta = \frac{1}{2}$
- $\mu = \frac{2}{3}$

$f(R)$:
not at all

$$\delta\rho_X = -\frac{1}{3}\delta\rho_{\mathrm{m}}$$

Galaxy Shapes



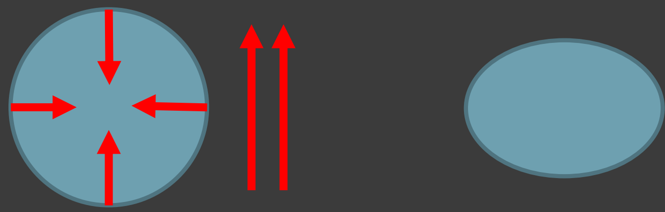
$$\sigma_{ij} = \int_{z_s}^{z_o} \mathrm{d}z\, \partial_i \partial_j (\Psi + \Phi) K(z)$$

- Weak lensing
  - Gravity from DM *and DE* changes light geodesics, distorting galaxy shapes
  - Shear tomography measures lensing potential

$$L = k^2(\Phi + \Psi)$$

- Measure distribution of *potential* not of DM

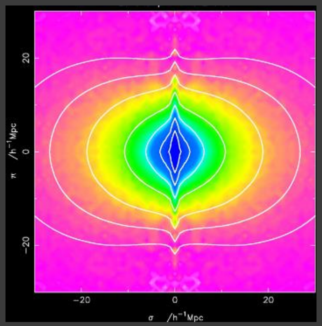
Galaxy Counts



Real space

Redshift space

Hawkins et al (2002)



2D power spectrum

$$\delta^{z}_{\mathrm{gal}}(k, z, \cos^2\alpha\ ) = \delta_{\mathrm{gal}}(k, z) - \cos^2\alpha \frac{\theta_{\mathrm{gal}}(k, z)}{H}$$

$\delta_{\mathrm{gal}} = b(a, k)\delta_{\mathrm{m}}?$
$\delta_{\mathrm{gal}} = b(a, k)k^2\Psi?$

$\theta_{\mathrm{gal}} \approx \theta_{\mathrm{m}} = f\sigma_8$

A question of bias

Biagetti, Desjacques et al (2014)

Density Bias

- $\delta_{\text{gal}} = b(z,k) \cdot ?$
- Need two things
  - Understand when halos form
  - Understand what galaxies form inside
- In DE have extra degree of freedom

$$\delta_{\text{gal}} = b_1 k^2 \Phi + b_2 k^2 \Psi + b_3 \delta_{\text{m}}$$

- Stellar evolution sensitive to corrections to GR (AC Davis et al (2011))
  - Screening depends on environment
  - Effect on galaxy luminosity?

Velocity Bias

- Velocity bias is a *purely statistical* effect
  - Effective force on galaxies modified

$$\Psi_{\text{eff}} = \Psi + R_v^2 k^2 \Psi$$
$$R_v \sim 10\ \text{Mpc}$$

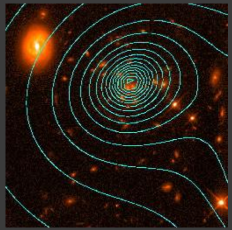
- *No bias* at large scales

LSS *also* only probes *geometry*

Motta, **IS,** Saltas, Amendola, Kunz (2013)

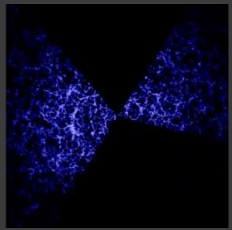
$$ds^2 = -(1+2\Psi)dt^2 + a^2(1-2\Phi)d\boldsymbol{x}^2$$

We want:	Two functions of time and *space* $\eta(z,k) \equiv \Psi/\Phi \qquad Z(z,k) \equiv -k^2\Phi/\rho_m\delta_m$



Galaxy shapes

$\sigma_{ij}(z_s, \hat{\boldsymbol{n}})$ → $\phi_l = \Psi + \Phi$



Galaxy counts

$\theta_{gal}(z_s, k)$ → $\Psi = \left(a^2\theta_{gal}\right)' k^{-2}$

$$\eta(z,k) = \Psi/\Phi$$
$$\Gamma(z,k) = \Psi'/\Psi$$

b, Z σ_8, f	*Cannot* measure without specifying *DE perturbations*

Local Null Tests of ΛCDM Geometry

Motta, **IS,** Saltas, Amendola, Kunz (2013)

- We can in principle reconstruct ***without DE model assumption***

$$\eta(z,k) = \Psi/\Phi \qquad \Gamma(z,k) = \Phi'/\Phi$$

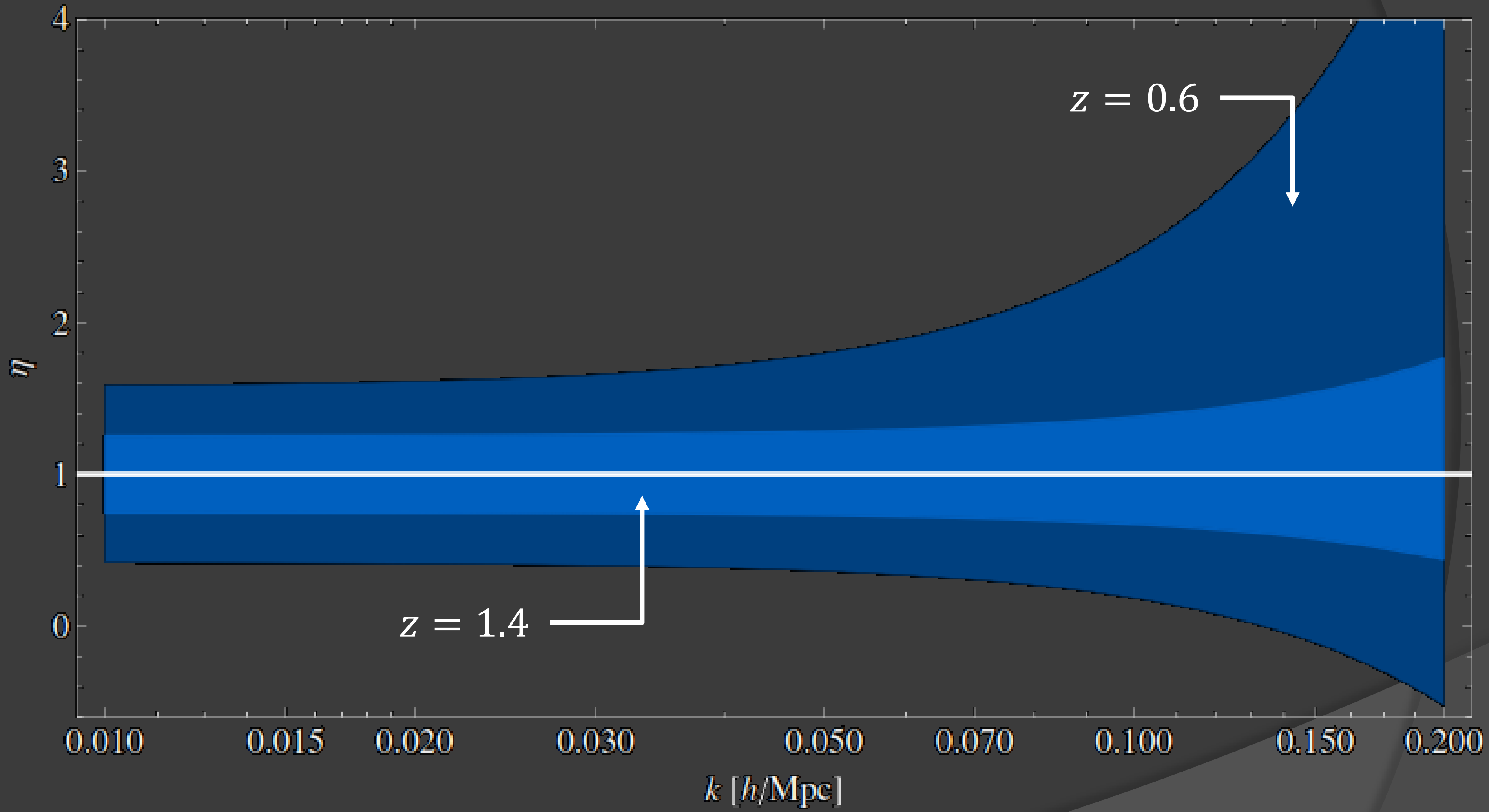
- In ΛCDM predictions ***fixed***

$$\eta = 1 \qquad \Gamma = (1+z)^3 \; {}_2F_1\left(a, b, c, -\frac{1-\Omega_{m0}}{\Omega_{m0}(1+z)^3}]\right)$$

- These are ***local*** and not integrated quantities
  - Avoids signal cancellation due to mixing scales and times
  - No IC dependence
- Can build similar null tests for other models:
  - typically scale-dependent
  - Can test by studying ***one redshift?***

Scale-dependent η

Amendola et al. (2013)



Should we parameterise…

$$ds^2 = -(1+2\Psi)dt^2 + a^2(1-2\Phi)d\boldsymbol{x}^2$$

We want:	In principle, two functions of time and *space* $\eta(z,k) \equiv \Psi/\Phi \qquad Z(z,k) \equiv -k^2\Phi/\delta_m$

$$\eta = \eta(z)$$
$$Z = Z(z)$$

- Simple
- Realistic?
- Bad at horizon

Time-Dependent

$$\mu = Z\eta = h_1\left(\frac{1+k^2h_3}{1+k^2h_5}\right), \eta = h_2\left(\frac{1+k^2h_4}{1+k^2h_5}\right)$$

- Quite general
- Assumes DE follows dust
- Bad at horizon

Quasi-Static

Amendola et al. (2012)
Silvestri, Pogosian, Buniy (2013)

Are these even consistent models?

…or test model by model?

- Quintessence

$$\ddot{\phi} + 3H\dot{\phi} = V'$$

  - Pick $V(\phi)$ and iteratively guess acceptable ICs
- Linear

$$\delta\ddot{\phi} + 3H\delta\dot{\phi} + V''\delta\phi + \frac{k^2}{a^2}\delta\phi = \cdots$$

  - Evolution specified given ICs
- But
  - How to pick $V(\phi)$?
  - symmetry and redundancy: $\tilde{\phi} \equiv \tilde{\phi}(\phi)$ etc.
  - *How do you compare this with other models?*

What do (I think) we actually want?

- Like a perfect fluid

$$\dot{\delta} + (1+w)(\theta - 3\,\dot{\Phi}) + 3H\left({}^{\delta p}/_{\rho} - w\delta\right) = 0$$

$$\dot{\theta} + H(2 - 3c_{\mathrm{a}}^2)\theta + \frac{k^2}{a^2}\Psi + \frac{k^2}{a^2}\frac{\delta p/\rho}{1+w} = 0$$

- *Any* $K(X,\phi)$
  - ${}^{\delta p}/_{\rho} = c_{\mathrm{s}}^2\delta + (c_{\mathrm{s}}^2 - c_{\mathrm{a}}^2)\theta/k^2$
  - Everything determined by $w(z)$, $c_{\mathrm{s}}^2(z)$ and Ω_{m}
  - No loss of information

- Dependence on $V(\phi)$ *disappeared*!
  - Background, sound speed and pert. ICs determine *everything*

Bellini & IS (2014)

Scalar-Tensor: EFT-like Approach

$$\mathcal{L} \sim K(X,\phi) + G_3(X,\phi)\Box\phi + \\ +G_4(X,\phi)[\nabla_\mu\nabla_\nu\phi \dots]^2 + G_5(X,\phi)[\nabla_\mu\nabla_\nu\phi \dots]^3$$

$$\mathcal{L}_2 \sim H^2\left(\alpha_{\rm K}(t) + \frac{3}{2}\alpha_{\rm B}^2(\rm t)\right)\left(\dot{\zeta}^2 - c_s^2(\partial_i\zeta)^2\right) \\ +M_*^2(t)\left(\dot{h}^2 - \left(1+\alpha_{\rm T}(t)\right)(\partial_i h)^2\right)$$

- Use ***observed*** background $H(z)$ as ***input*** (or specify arbitrary)
- Perts, with ***no loss*** of information, determined by:
  1. $\Omega_{\rm m0}$ (this is a perturbation variable!)
  2. 4 $\alpha_i\ (z)$ define physical properties

  ($\alpha_{\rm H}(z)$ new third-diff terms)

c.f. EFT — Gubitosi, Gleyzes, Piazza, Vernizzi (2013); Bloomfield et al. (2013)

Zumalacàrregui & Garcìa-Bellido (2013)
Gleyzes, Langlois, Piazza, Vernizzi (2013, 2014)

Bellini & IS (2014)

Linear-Property Functions

$\alpha_{\rm M}$: Planck-Mass Run Rate

$$\alpha_{\rm M} = H^{-1}\frac{\mathrm{d}M_*^2}{\mathrm{d}\ln a}$$

- From G_4 and G_5
- Switches on η
- Non-conservation of matter

$$\dot{\rho} + 3H(\rho + p) = -\alpha_{\rm M} H\rho$$

$\alpha_{\rm T}$: Tensor Speed Excess

$$c_{\rm T}^2 = 1 + \alpha_{\rm T}$$

- From G_4 and G_5
- Switches on η

$\alpha_{\rm B}$: Braiding

- From G_3, G_4 and G_5
- Kinetic mixing of graviton and scalar
- Allows for dark energy clustering
  - $Z \neq 1$ at small scales

$\alpha_{\rm K}$: Kineticity

- From all operators
- Perfect fluid: $\alpha_K = \Omega_{\rm DE}(1+w)/c_s^2$
- Suppresses sound speed
- Controls transition scale for Z and η

$$k_{\rm B}^2 \sim \Omega_{\rm DE}(1+w)\frac{\alpha_K}{\alpha_B^2} + \frac{9}{2}\Omega_{\rm m}$$

- Guaranteed that a Horndeski model exists for *any choice* of $H(z)$, $\Omega_{\rm m0}$, $\alpha_i(z)$
- There is *nothing* beyond this at linear order in Horndeski

All Models Become Nested

Model	α_{K}	α_{B}	α_{M}	α_{T}
ΛCDM	**0**	**0**	**0**	**0**
Quintessence	$\Omega_{\mathrm{DE}}(1+w)$	0	0	0
K-essence	$\Omega_{\mathrm{DE}}(1+w)/c_s^2$	0	0	0
$f(R)$	0	$-\alpha_{\mathrm{M}}$	$B\dot{H}/H^2$	0
KGB	$m^2 n_m$	$m\kappa/H$	0	0
$f(G)$	0	X	X	X

- Parameterise the $\alpha_i = \Omega_{\mathrm{DE}} * \mathrm{const}$
- If all $\alpha_i \ll \Omega_{\mathrm{DE}}$ it is mostly just Λ

Saltas, **IS**, Amendola, Kunz (2014)

$\eta \neq 1$: Modified GW *Propagation*

$$\ddot{h}_{ij} + (3+\alpha_{\mathrm{M}})H\dot{h}_{ij} + (1+\alpha_{\mathrm{T}})\frac{k^2}{a^2}h_{ij} + m^2 h_{ij} = \Gamma\gamma_{ij}$$

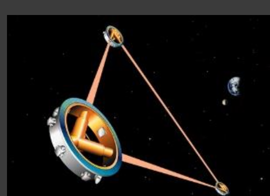
Massive Gravity

Luminosity distance to standard sirens

Cutler & Holz (2009)

Time separation of GW and ν

Nishizawa & Nakamura (2014)



GWO

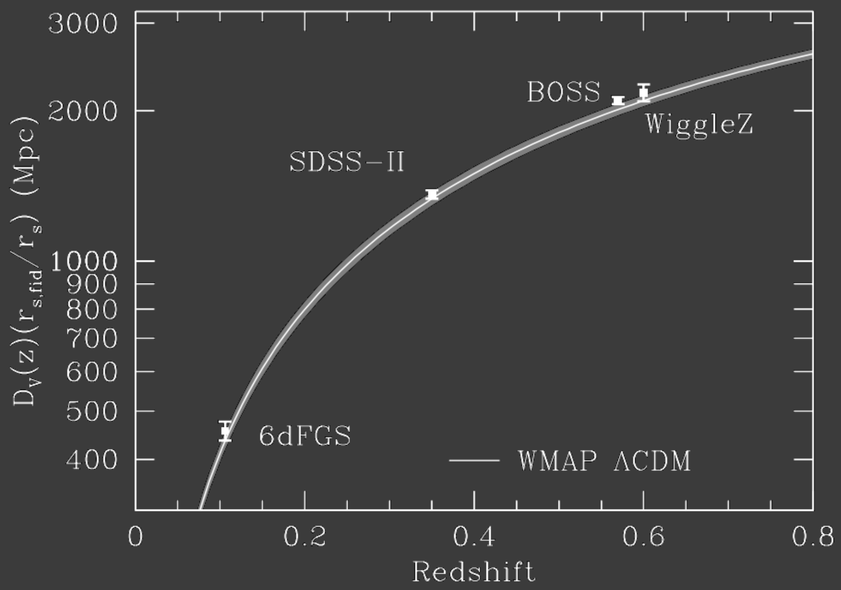
h_{ij}

$\eta \neq 1$

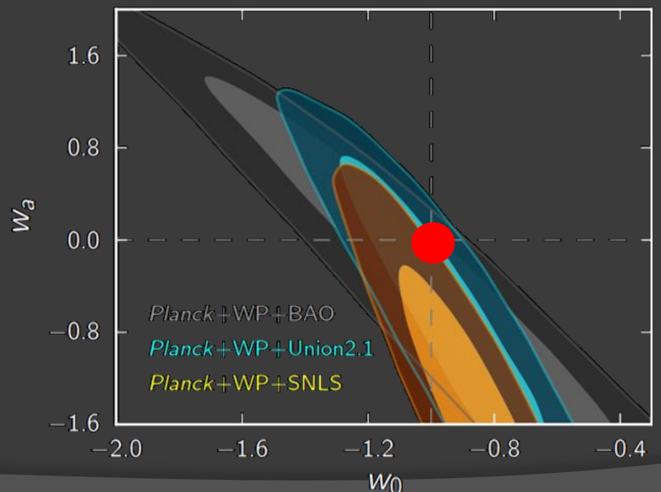
z_{cosmo}

How important is *w*?

Anderson et al. (2012)



Planck: Ade et al. (2013)



- Large *w* on errors since *w* is irrelevant in the past
- EFT formulation only contains

$$2\dot{H} \approx -3H^2\Omega_{\mathrm{m}}$$

The Take Away

- Cosmological probes only see *geometry*
  - *Both* background and LSS
  - To get more, must *specify* DE/MG model or calculate bias
  - But: $\eta = \Psi/\Phi$ is a direct observable
  - Can build null tests for ΛCDM structure and more
- $\eta(z,k), \mu(z,k)$ parameterisation *too wide*
  - Use *unambiguously* observed background $H(z)$ as *input*
  - Dynamically consistent model described by just *functions of time*
  - Horndeski is just 4 α_i and Ω_{m0}
  - All models *nested*, ΛCDM is $\alpha_i = 0$
- GW provide a completely *independent probe* of the same parameters

Thank you!