Testing Models of Dark Energy

IDEALS
Trieste SISSA
10th November 2011

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What is the Nature of Dark Energy?

There are many alternatives:

- **Cosmological constant Λ (vacuum energy)**
- **Scalar field (quintessence, tachyon,…)**
- **Relativistic Ether fluids (Chaplygin gas, VDE,…)**
- **Modifications of GR on UV scales (f(R), GB)**
- **Weyl gravity, Horava gravity, massive graviton**
- **Extra dimensions (DGP, KK, …)**
- **Effective interactions (Chameleon, Galileon,…)**
- **Inhomogeneous universes (backreaction, LTB large Voids,,…)**

What are the physical quantities?

- **Matter content $\Omega_m(a)$**
- **Rate of expansion $H(a)$**
- **Luminosity distance $d_L(a)$**
- **Angular diameter distance $d_A(a)$**
- **Number counts $dN/d\Omega(a)$**
- **Deceleration parameter $q(a)$**
- **Cosmic shear $\Sigma(a)$**
- **Density contrast growth function $f(a)$, $\gamma(a)$**
- **Jeans length of perturbations $c_s^2(a)$**
- **Anisotropic stresses of matter $\eta(a)$**

What are the observables?

- Matter power spectrum $P(k,a)$
- SN distance modulus $\mu(a)$
- BAO scale $\Theta_{BAO}(a)$
- Cluster number counts $dN/d\Omega(a)$
- Galaxy mass function $n(<M)$
- Lensing magnification and convergence μ, κ
- Redshift Space Distortions $\beta(a)$, bias
- CMB anisotropies $C_l(TT,TE,EE,BB)$
- Integrated Sachs-Wolfe, Sunyaev-Zeldovich
- Fractal dimension of space time

What can the different groups contribute with for a joint effort?

- **LSS : $P_{gal}(k,z)$, $\theta_{BAO}(z)$, $\Omega_m(z)$, $f_{RSD}(z)$**
- **SN : $d_L(z)$, $H(z)$, $w(z)$**
- **Lensing : $C_l(z)$, bias(z), $\Sigma(z)$**
- **Cluster : $dN/d\Omega(a)$, $n(<M)$**
- **Photo-z : systematics, covariances**
- **Simulation : validation**
- **Spectroscopy : consistencies**
- **Galaxy evolution : constraints, systematics**

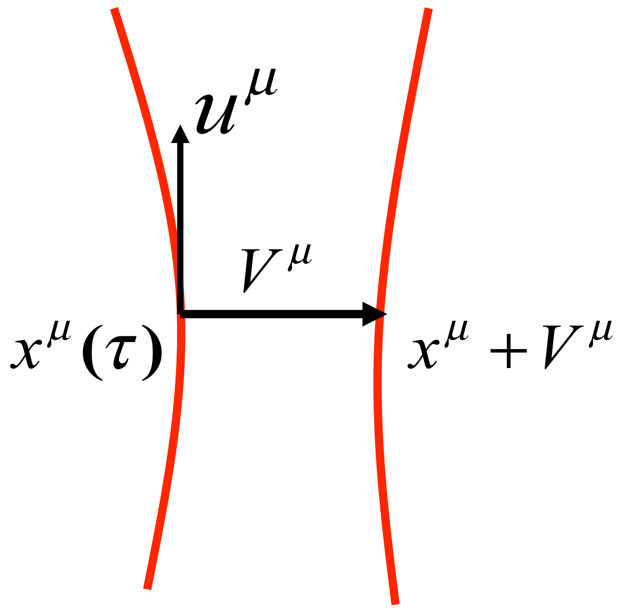
There is a limit to what we can say about the physics responsible for acceleration from observations.

- **How many parameters can we constrain?**
- **What is the optimal parametrization of the linear perturbation equations?**
- **How much can we extract from nonlinear regime?**
- **Can we interpolate between super-horizon scales, sub-horizon mildly-nonlinear and full NL scales?**
- **Can we parametrize wide classes of models?**
- **What is the role of systematics on uncertanties?**

Basic notions of Geometry

Congruence of timelike geodesics

$$\frac{DV^\mu}{d\tau} = u^\nu D_\nu V^\mu \equiv \Theta^\mu{}_\nu V^\nu$$



Describes how neighbouring geodesics deviate from remaining parallel

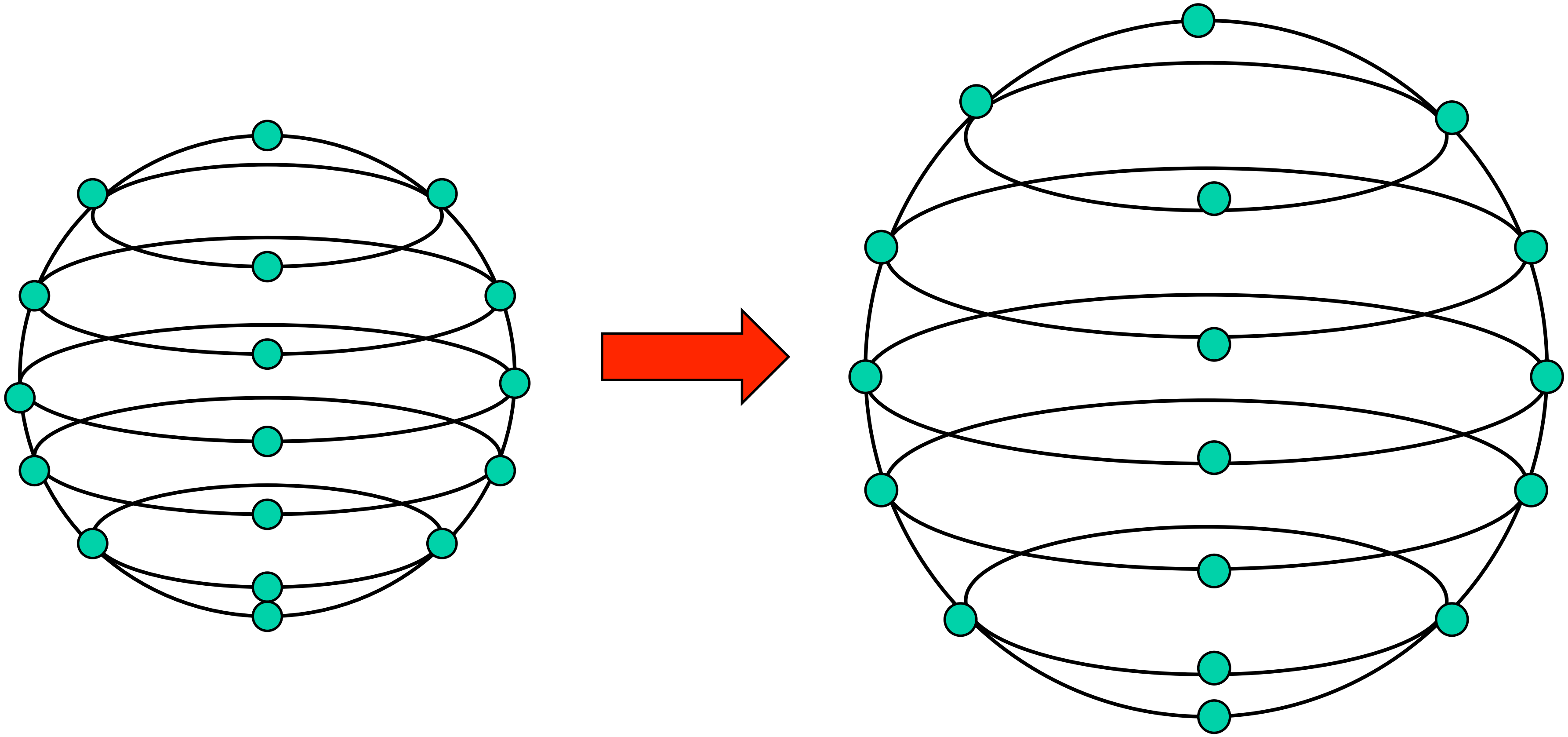
$$\Theta_{\mu\nu} = \frac{1}{3}\Theta P_{\mu\nu} + \sigma_{\mu\nu} + \omega_{\mu\nu}$$

$$\Theta = D_\mu u^\mu$$ trace

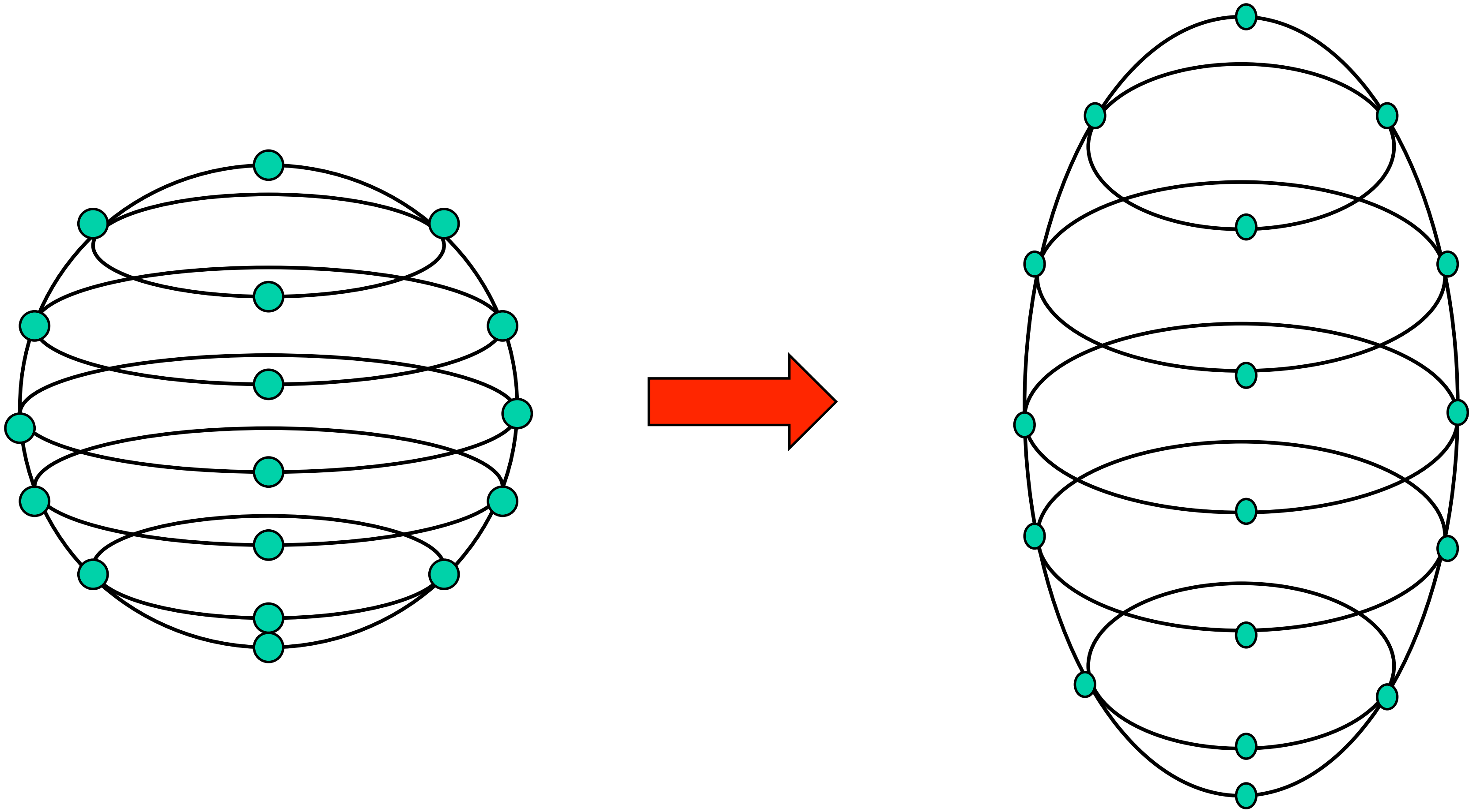
$$\sigma_{\mu\nu} = \Theta_{(\mu\nu)} - \frac{1}{3}\Theta P_{\mu\nu}$$ traceless symmetric

$$\omega_{\mu\nu} = \Theta_{[\mu\nu]}$$ antisymmetric

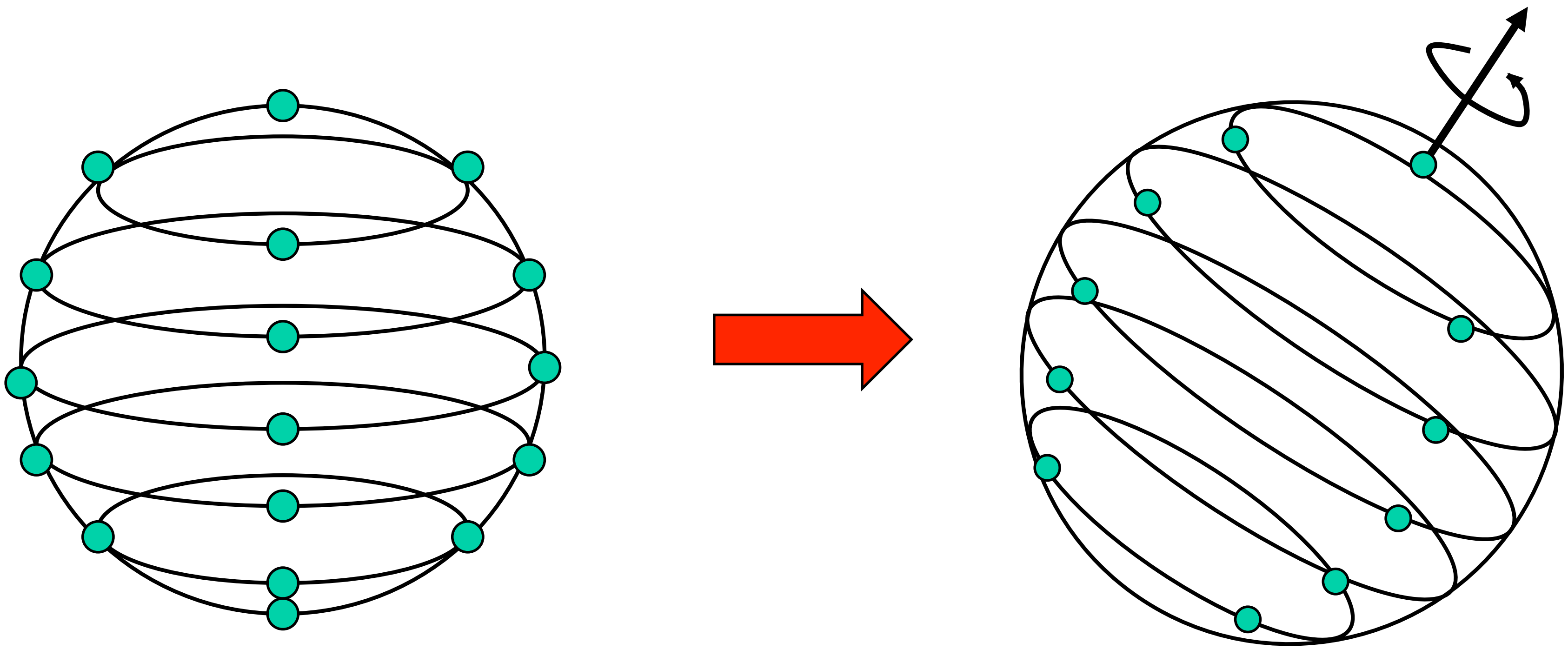
Θ expansion of congruence



$\sigma_{\mu\nu}$ shear of congruence



$\omega_{\mu\nu}$ vorticity of congruence



Evolution of Congruence

$$\frac{D}{d\tau}\Theta_{\mu\nu} = u^{\sigma} D_{\sigma} D_{\nu}\, u_{\mu} = u^{\sigma} D_{\nu} D_{\sigma}\, u_{\mu} + u^{\sigma} R^{\lambda}{}_{\mu\nu\sigma}\, u_{\lambda}$$

$$= -\Theta^{\sigma}_{\nu}\,\Theta_{\mu\sigma} - R_{\lambda\mu\sigma\nu}\, u^{\sigma} u^{\lambda}$$

Raychaudhuri Equation (trace)

Characterizes expansion's evolution

$$\boxed{\frac{d\Theta}{d\tau} = -\frac{1}{3}\Theta^{2} - \sigma_{\mu\nu}\sigma^{\mu\nu} + \omega_{\mu\nu}\omega^{\mu\nu} - R_{\mu\nu}\, u^{\mu} u^{\nu}}$$

$\sigma_{\mu\nu}\sigma^{\mu\nu} \geq 0, \quad \omega_{\mu\nu}\omega^{\mu\nu} \geq 0,$ spatial tensors

For an Expanding Universe

$$H(t,\bar{x}) = \frac{1}{3}\Theta = \frac{1}{3} D_\mu u^\mu$$ Hubble parameter

$$q = -1 - H^{-2} u^\mu D_\mu H$$ deceleration parameter

$$\text{R.E.} \Rightarrow \; qH^2 = \frac{1}{3}(\sigma_{\mu\nu}\sigma^{\mu\nu} - \omega_{\mu\nu}\omega^{\mu\nu}) + \frac{1}{3} R_{\mu\nu} u^\mu u^\nu$$

Einstein eqs. Perfect Fluid

$$R_{\mu\nu} u^\mu u^\nu \overset{\downarrow}{=} 8\pi G (T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T) u^\mu u^\nu \overset{\downarrow}{=} 4\pi G (\rho + 3p)$$

$$\boxed{-\frac{\ddot{a}}{a} = \frac{4\pi G}{3}(\rho + 3p) \quad \text{Homog.} + \text{Isotrop. Universe}}$$

Conditions for acceleration (q<0)

One of the following must be violated:

1. The Strong Energy Condition:

$$(T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T)\, u^{\mu} u^{\nu} \geq 0, \quad u^{\mu} \text{ timelike}$$

2. Gravity is described by General Relativity:

$$R_{\mu\nu} = 8\pi G\, (T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T)$$

3. The universe is homogeneous and isotropic:

$$T^{\mu\nu} = p(t) g^{\mu\nu} + [\rho(t) + p(t)]\, u^{\mu} u^{\nu}$$

Conditions for acceleration

Usually one drops assumptions 1. or 2.

1. Strong EC for a homogeneous universe:

$$(T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T) u^\mu u^\nu = \rho + 3p \geq 0$$

Dark Energy violates SEC: $p = -\rho \Rightarrow \rho + 3p < 0$

2. Modified Gravity on large scales

$$R_{\mu\nu}\, u^\mu u^\nu = f(T_{\mu\nu}, G_{\mu\nu}, D_\mu D_\nu \Phi)\, u^\mu u^\nu < 0$$

Assumption 3. is only approx. valid in the real universe, deviations are small on large scales

Five main classes of models

Model (and representative):

- **A cosmological constant (Λ)**
- **A scalar field (wCDM)**
- **Modified Gravity (f(R))**
- **Extra dimensions (DGP)**
- **Inhomogeneous universes (Gpc scale voids)**

Their background evolution does not differ much but their perturbations do!

The background equations

$$w(a) = \frac{p}{\rho} \quad \rho(a) = \rho_0 a^{-3(1+\hat{w})} \quad \hat{w}(a) = \frac{1}{\ln a}\int_1^a \frac{w(a')}{a'}\mathrm{d}a'$$

$$H^2(a) = H_0^2\left[\Omega_{\mathrm{m},0}\, a^{-3} + (1-\Omega_{\mathrm{m},0})\; a^{-3(1+\hat{w})}\right]$$

$$\Omega_{\mathrm{m}}(a) = \left(1 + \frac{1-\Omega_{\mathrm{m},0}}{\Omega_{\mathrm{m},0}} a^{-3\hat{w}}\right)^{-1}$$

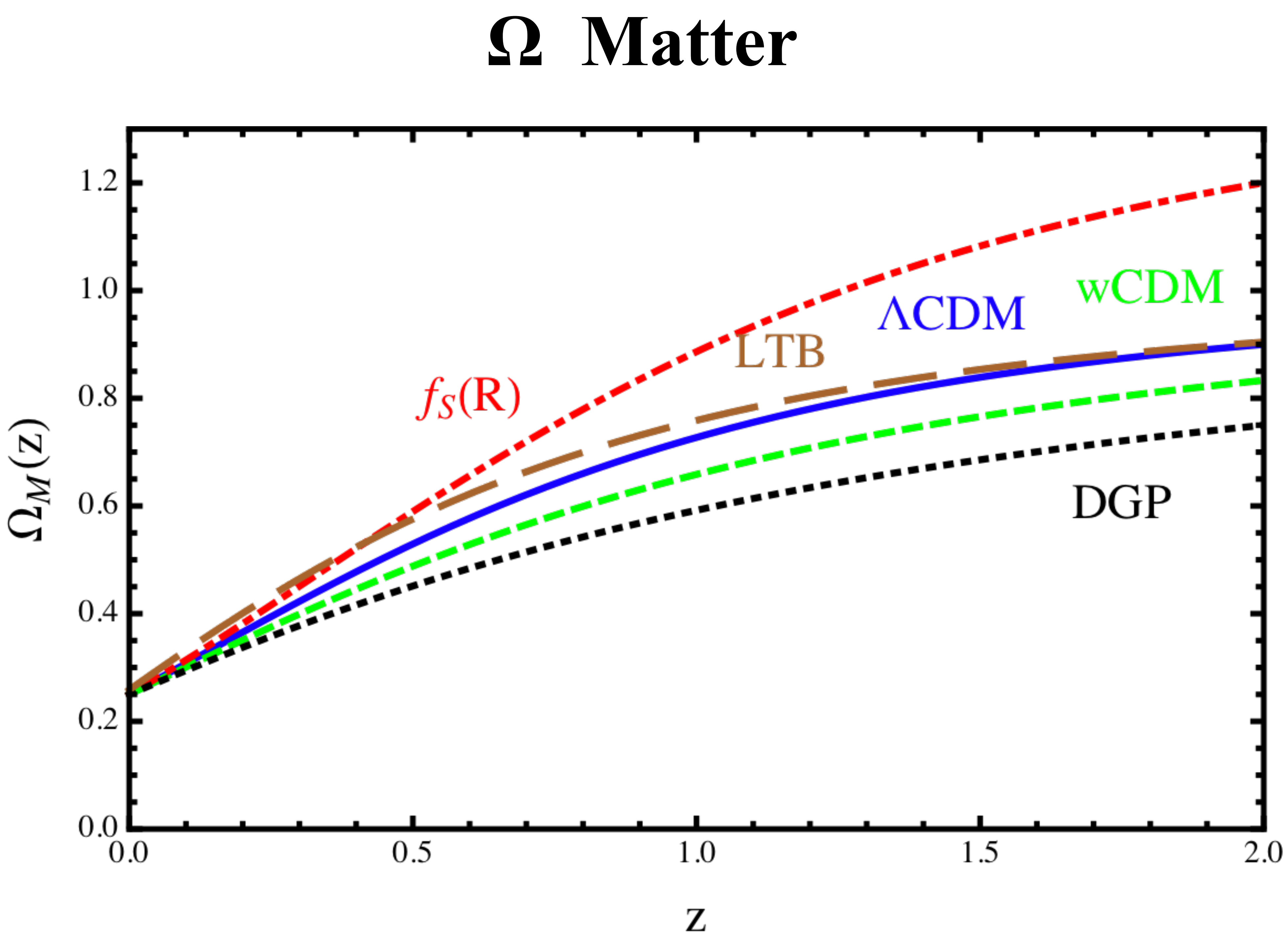
The perturbation equations

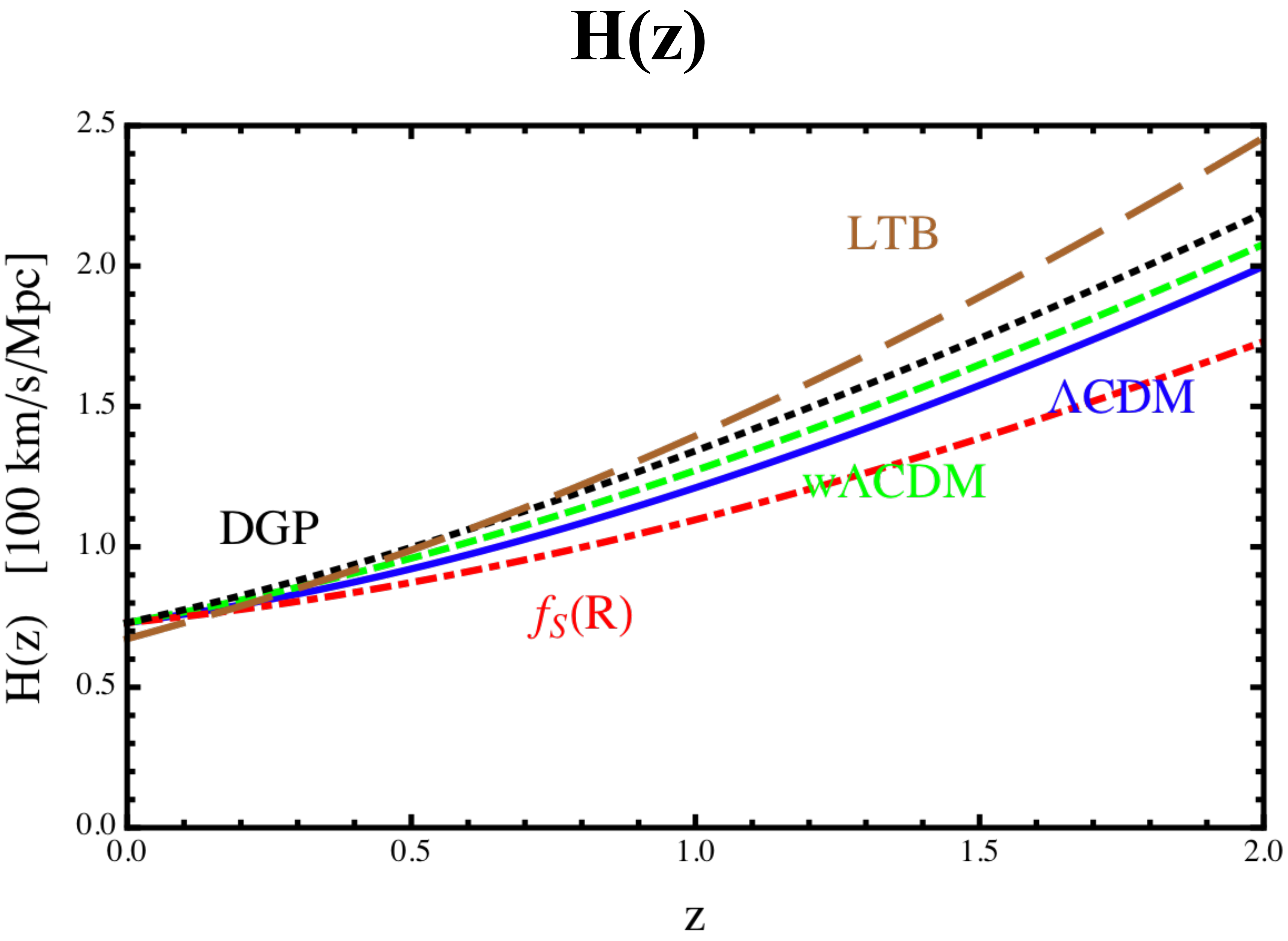
$$\mathrm{d}s^2 = a^2(\tau)\left[-(1+2\Psi)\,\mathrm{d}\tau^2 + (1-2\Phi)\,\mathrm{d}x_i\mathrm{d}x^i\right]$$

$$k^2\Phi = -4\pi G a^2 \rho_{\mathrm{m}}\left(\delta_{\mathrm{m}} + \frac{3aH}{k^2}V_{\mathrm{m}}\right) \quad \delta'_{\mathrm{m}} = -\frac{V_{\mathrm{m}}}{Ha^2},$$

$$\epsilon(a) = -d\log H(a)/d\log a \qquad V'_{\mathrm{m}} = -\frac{V_{\mathrm{m}}}{a} + \frac{k^2}{Ha^2}\Phi$$

$$a^2\delta''_m(a) + \big(3-\epsilon(a)\big)a\,\delta'_m(a) - \frac{3}{2}\Omega_m(a)\delta_m(a) = 0$$


Ω Matter
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.5
1.0
1.5
2.0
$\Omega_M(z)$
z
f_S(R)
LTB
ΛCDM
wCDM
DGP



H(z)
2.5
2.0
1.5
1.0
0.5
0.0
H(z) [100 km/s/Mpc]
LTB
ΛCDM
wΛCDM
DGP
f_S(R)
0.0
0.5
1.0
1.5
2.0
z

wΛCDM growth factor

$$a^2\delta_m''(a) + \big(3-\epsilon(a)\big)a\,\delta_m'(a) - \frac{3}{2}\Omega_m(a)\delta_m(a) = 0$$

$$\delta_m(a) = a\cdot {}_2F_1\left[\frac{w-1}{2w}, \frac{-1}{3w}, 1-\frac{5}{6w}; 1-\Omega_m^{-1}(a)\right]$$

$$f(a) \;=\; \frac{d\log\delta_m}{d\log a} \;=\; \Omega_m^{1/2}(a)\frac{P_{1/6w}^{5/6w}\left[\Omega_m^{-1/2}(a)\right]}{P_{-1/6w}^{5/6w}\left[\Omega_m^{-1/2}(a)\right]}$$

$$f(a) \;=\; \Omega_m(a)^\gamma$$

$$\boxed{\gamma(a) = \frac{1}{2} + \frac{1}{\ln\Omega_m(a)}\ln\left[\frac{P_{1/6w}^{5/6w}\left[\Omega_m^{-1/2}(a)\right]}{P_{-1/6w}^{5/6w}\left[\Omega_m^{-1/2}(a)\right]}\right]}$$

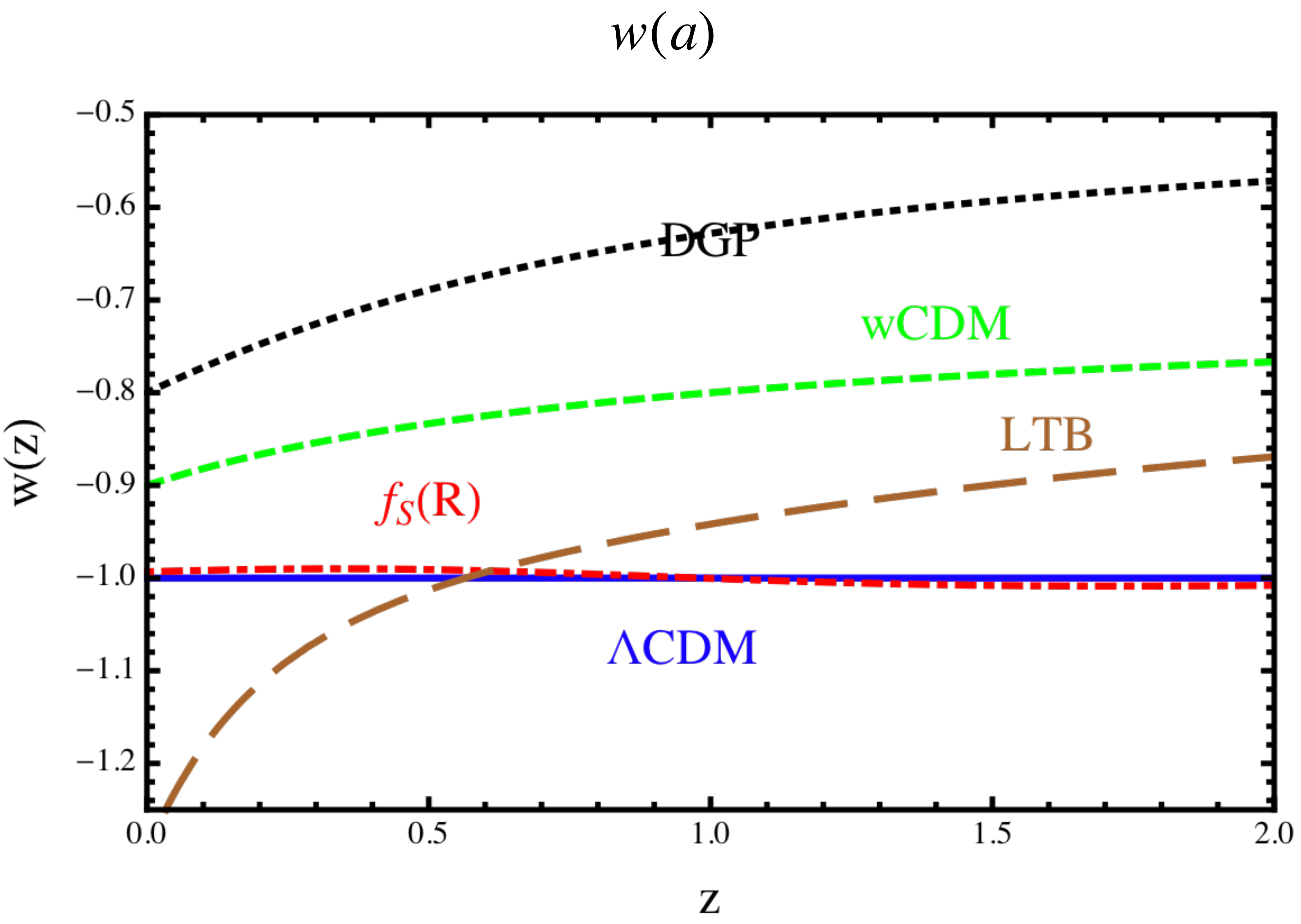
w(a)CDM growth factor

$$w(a) = w_0 + w_a\,(1-a)$$

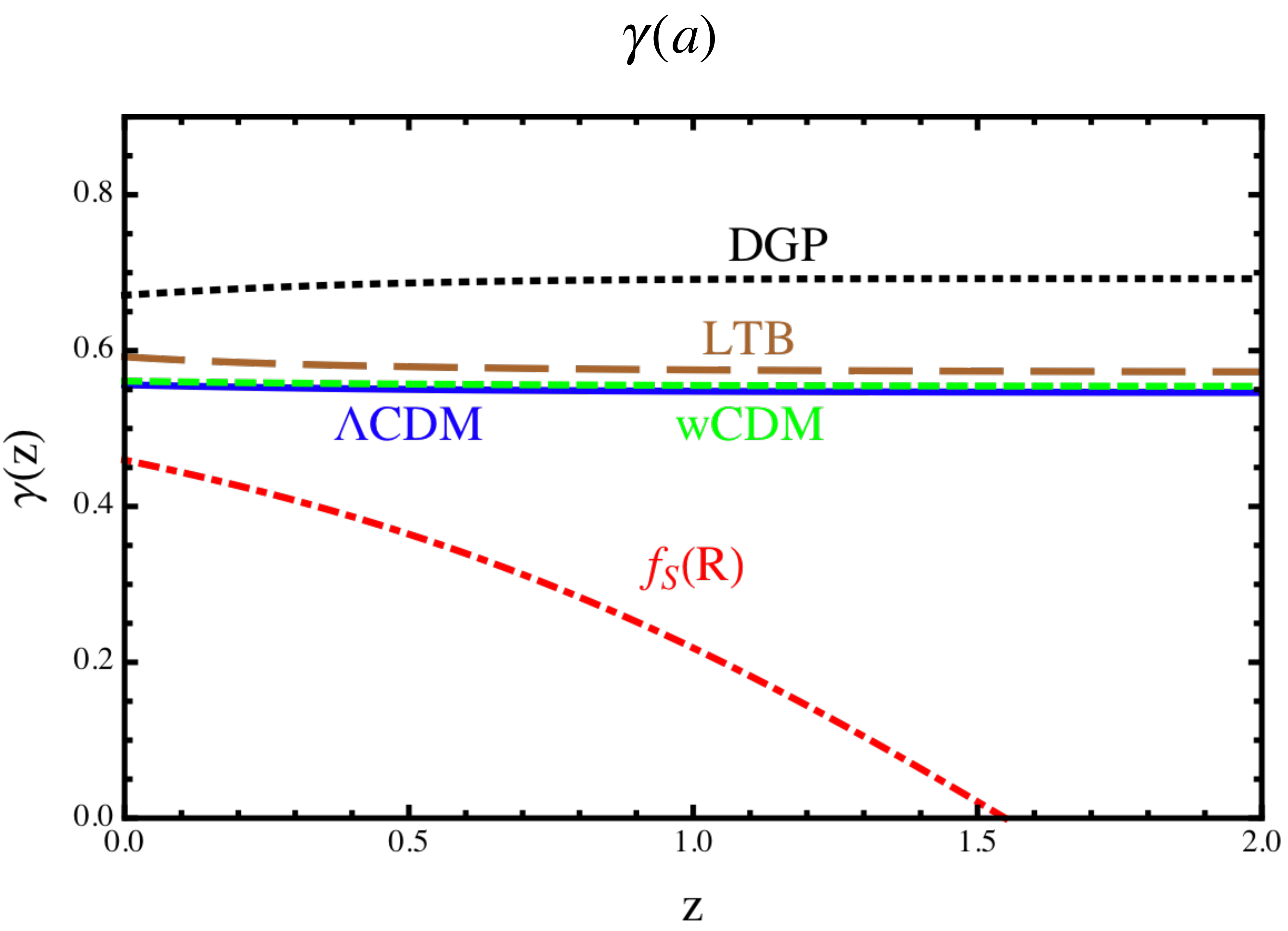
$$\Omega_m(a) = \left(1 + \frac{\Omega_{\rm de,0}}{\Omega_{\rm m,0}} a^{-3(w_0+w_a)}\, e^{3w_a(a-1)}\right)^{-1}$$

$$f(a) \;=\; \Omega_m^{1/2}(a)\, \frac{P_{1/6w(a)}^{5/6w(a)+w_a a/6w^2(a)}\left[\Omega_m^{-1/2}(a)\right]}{P_{-1/6w(a)}^{5/6w(a)+w_a a/6w^2(a)}\left[\Omega_m^{-1/2}(a)\right]}$$

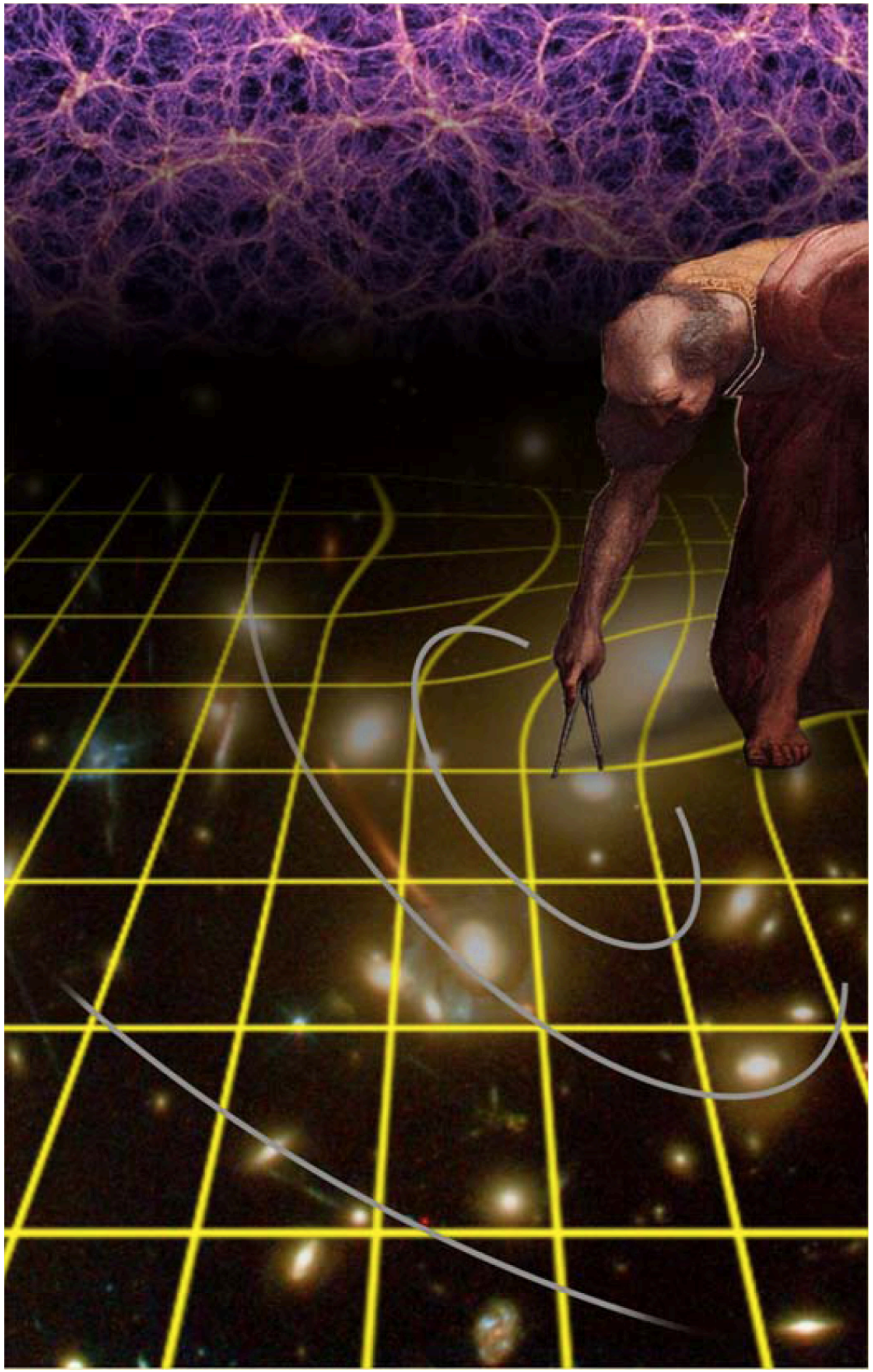
$$\boxed{\gamma(a) = \frac{1}{2} + \frac{1}{\ln \Omega_m(a)} \ln\left[\frac{P_{1/6w(a)}^{5/6w(a)+w_a a/6w^2(a)}\left[\Omega_m^{-1/2}(a)\right]}{P_{-1/6w(a)}^{5/6w(a)+w_a a/6w^2(a)}\left[\Omega_m^{-1/2}(a)\right]}\right]}$$



w(a)
DGP
wCDM
LTB
fS(R)
ΛCDM
w(z)
z
−0.5
−0.6
−0.7
−0.8
−0.9
−1.0
−1.1
−1.2
0.0
0.5
1.0
1.5
2.0



$\gamma(a)$
DGP
LTB
ΛCDM
wCDM
f_S(R)
γ(z)
z
0.0
0.2
0.4
0.6
0.8
0.5
1.0
1.5
2.0



esa

EUCLID

Spectroscopic survey

100 million galaxies
20,000 sq. deg
dz_spec = 0.001(1+z)
8 bins z range [0.5,2.1]

Imaging (photo) survey

1000 million galaxies
20,000 deg sq.
dz_photo = 0.05(1+z)
5 bins z range [0.5,3.0]

Forecasts using Fisher matrix approach

Matter power spectrum (normalized w.r.t. a ref. model)

$$P_{\rm obs}\left(z;k,\mu\right)=\frac{D_{Ar}^2(z)H(z)}{D_A^2(z)H_r(z)}G^2(z)b(z)^2\left(1+\beta\mu^2\right)^2P_{0r}(k)+P_{\rm shot}(z)$$

Growth factor Bias RSD shot noise

$$\beta(z)=\frac{\Omega_m(z)^\gamma}{b}=\frac{f(z)}{b} \qquad \mu=\vec{k}\cdot\widehat{r}/k$$

Assuming a Gaussian likelihood function

$$F_{ij}=2\pi\int_{k_{\rm min}}^{k_{\rm max}}\frac{\partial\log P\left(k\right)}{\partial\theta_i}\frac{\partial\log P\left(k\right)}{\partial\theta_j}\cdot V_{\rm eff}\cdot\frac{k^2}{8\pi^3}\cdot{\rm d}k$$

$$V_{\rm eff}=\left(\frac{\bar{n}\,P\left(k,\mu\right)}{\bar{n}\,P\left(k,\mu\right)+1}\right)^2V_{\rm survey}$$

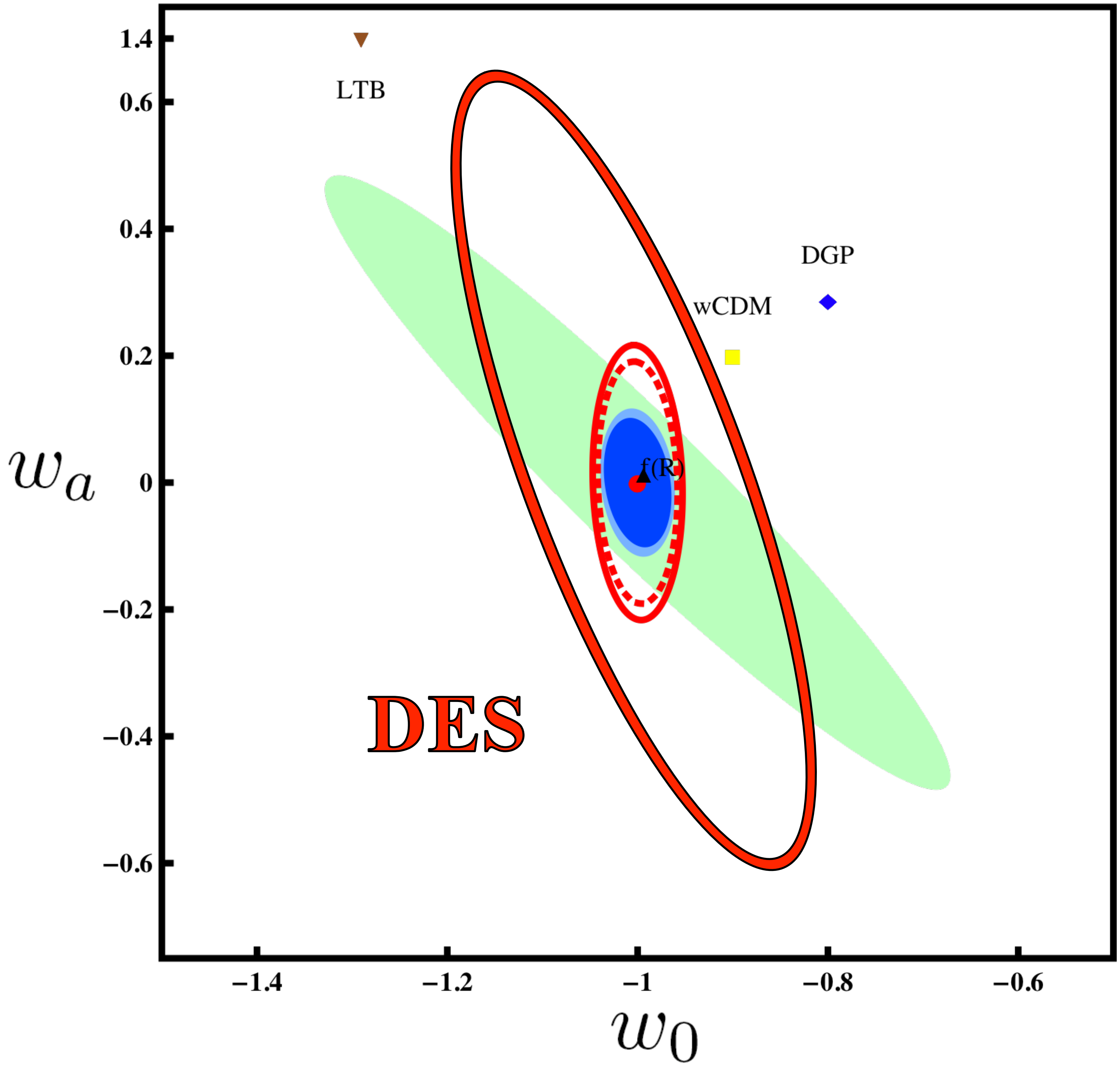
Fiducial model: our fiducial model corresponds to the ΛCDM WMAP-7yr [6]: $\Omega_{m,0}h^2 = 0.134$, $\Omega_b h^2 = 0.022$, $n_s = 0.96$, $\tau = 0.085$, $h = 0.7$, $\Omega_{m,0} = 0.275$ and $\Omega_K = 0$. For the dark energy parameters we choose $w_0 = -1$ and $w_a = 0$.

	Parameters	**P (k)**	**BAO**	**WL**
1	total matter density	$\Omega_{m_0}h^2$	$\Omega_{m_0}h^2$	$\Omega_{m_0}h^2$
2	total baryon density	$\Omega_{b_0}h^2$	$\Omega_{b_0}h^2$	$\Omega_{b_0}h^2$
3	optical thickness	τ	τ	τ
4	spectral index	n_s	n_s	n_s
5	matter density today	Ω_{m_0}	Ω_{m_0}	Ω_{m_0}
6	equation of state parameter	w_0		w_0
7	equation of state parameter	w_1		w_1
8	rms fluctuations			σ_8
For each redshift bin				
9	growth index	$\gamma(z)$ or $\{\gamma_0\,,\gamma_1\}$	$\gamma(z)$ or $\{\gamma_0\,,\gamma_1\}$	$\gamma(z)$ or γ_0
10	Hubble parameter		$\log H(z)$	
11	Angular diameter distance		$\log D_A(z)$	
12	Growth factor		$\log G(z)$	
13	z-distortion		$\log \beta(z)$	
14	shot noise	P_s	P_s	

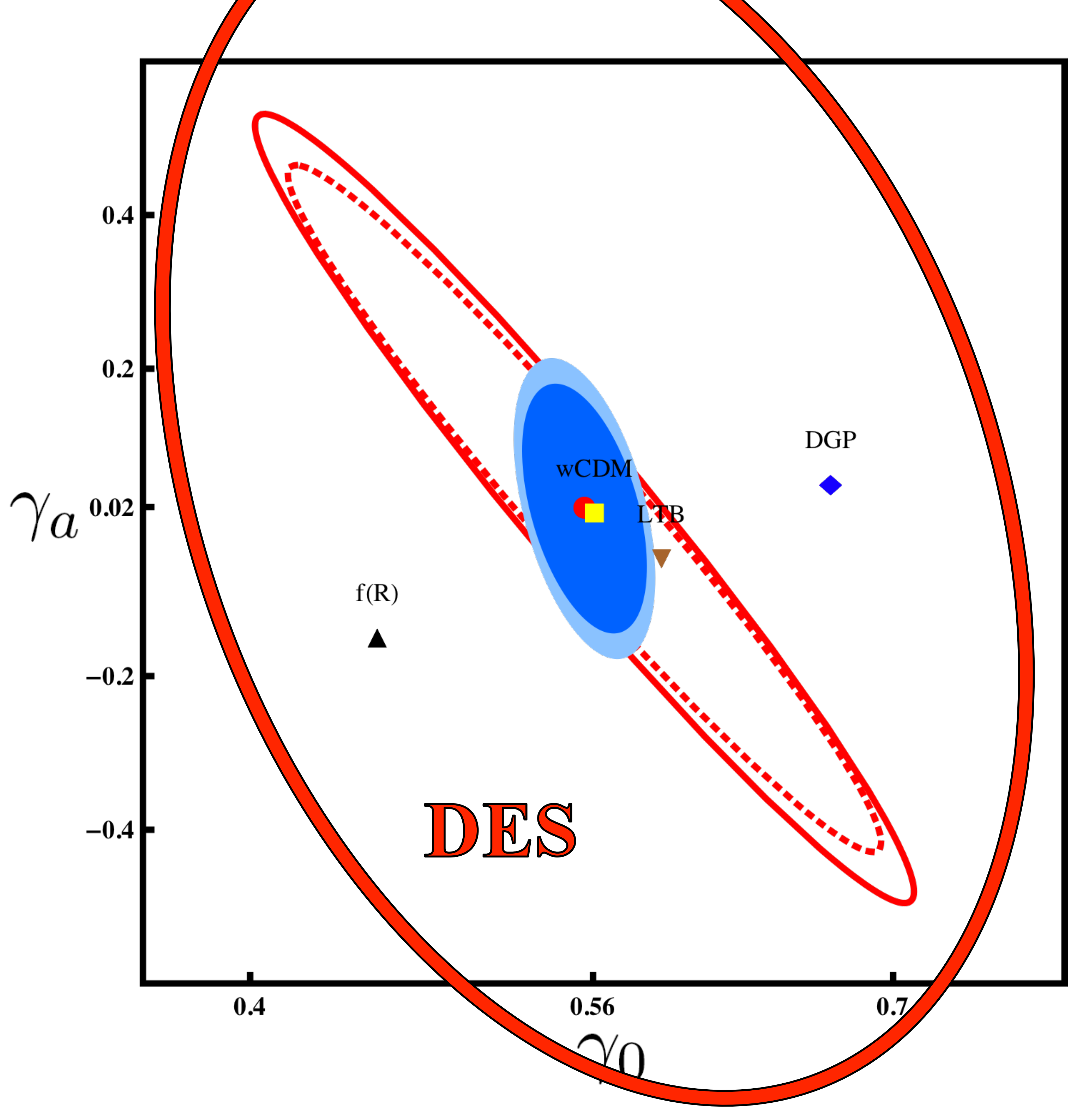
Forecast results for Euclid-like survey

$1-\sigma$ errors for w_0, w_a, γ_0 and γ_a

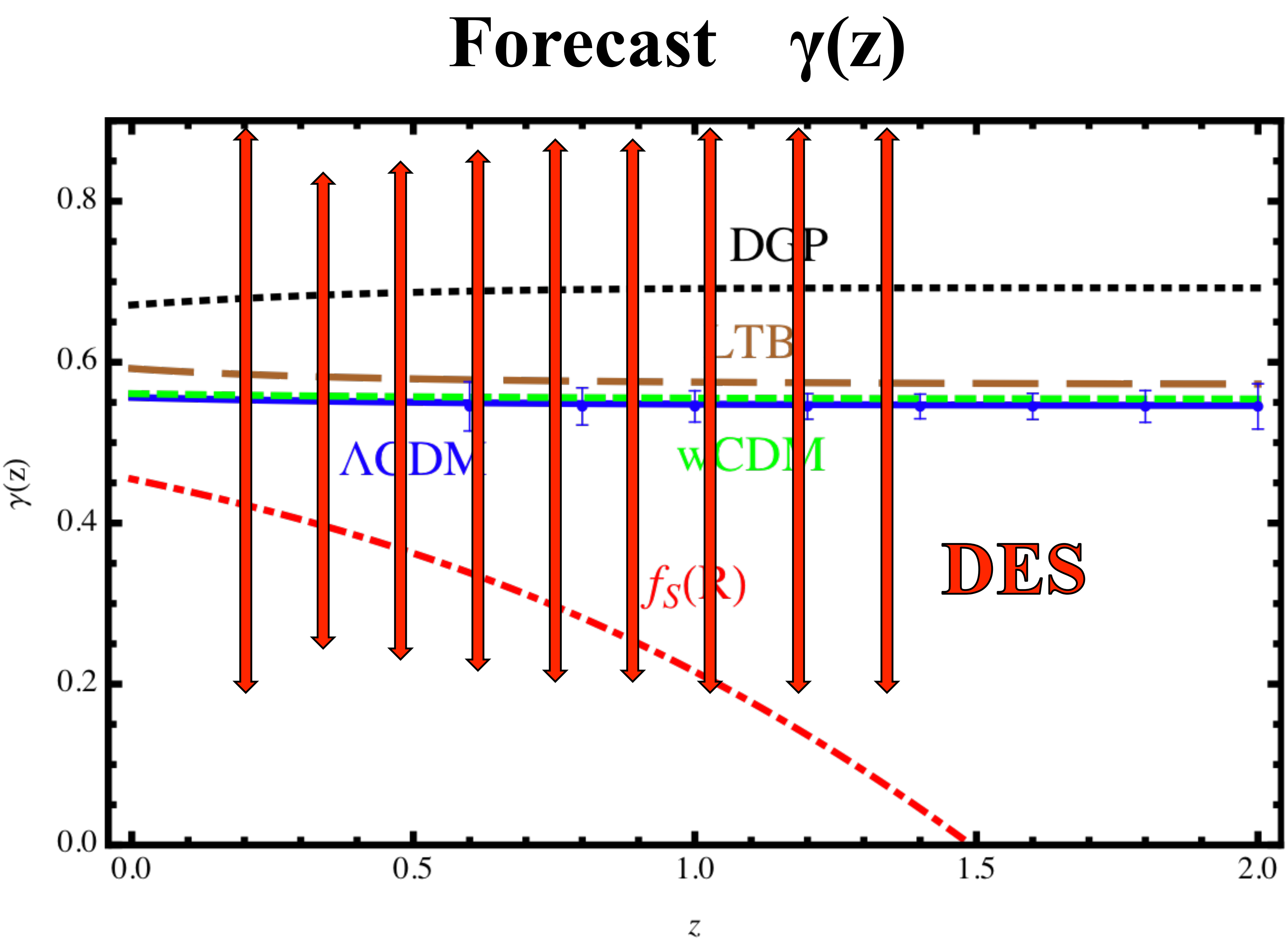
	P (k)		**BAO**		**WL**
	real.	opt.	real.	opt.	
σ_{w_0}	0.021	0.018	0.076	0.068	0.122
σ_{w_a}	0.051	0.041	0.375	0.324	0.524
σ_{γ_0}	0.022	0.020	0.102	0.092	0.075
σ_{γ_a}	0.120	0.116	0.339	0.296	



LTB
DGP
wCDM
f(R)
DES
w_a
w_0
1.4
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−1.4
−1.2
−1
−0.8
−0.6



0.4
0.2
0.02
−0.2
−0.4
γ_a
0.4
0.56
0.7
γ_0
DGP
wCDM
LTB
f(R)
DES



Forecast γ(z)
DGP
LTB
ΛCDM
wCDM
f_S(R)
DES
γ(z)
z
0.0
0.2
0.4
0.6
0.8
0.0
0.5
1.0
1.5
2.0

Discussion

- **Complete ignorance w.r.t. Nature Dark Energy.**
- **There are many alternatives, from a new state of matter and/or modifications of gravity, to extra dimensions or local spatial curvature.**
- **Background evolution can be mimicked within the dark sector among different alternatives.**
- **Cosmological perturbations are the key discriminant between theoretical models.**
- **Euclid survey has the potentiality to distinguish between Λ and a few other alternatives.**

Distinguish Large Voids from Other Models of Dark Energy

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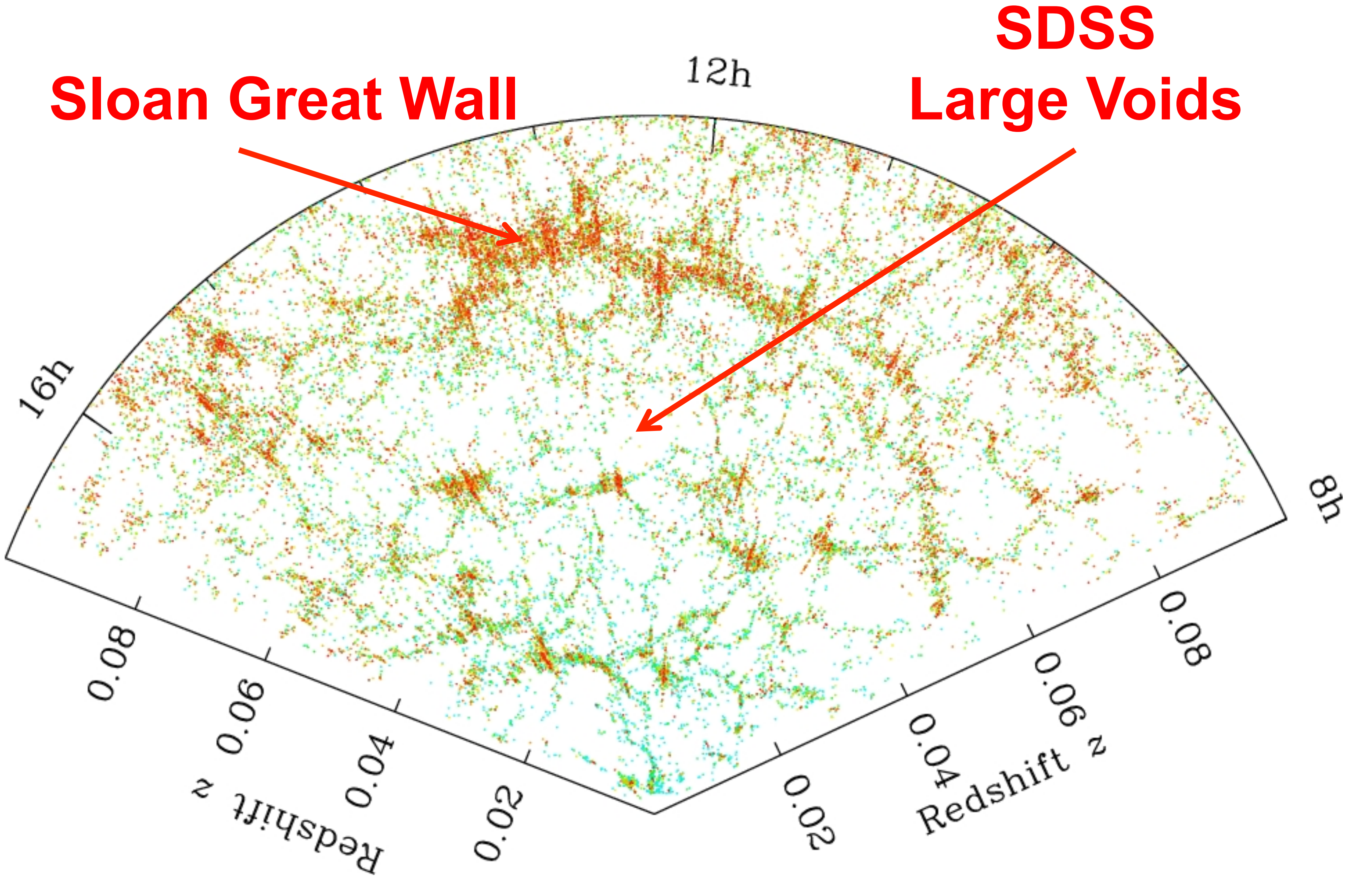
If Homogeneity and Isotropy is NOT assumed, How do we test it?

Independently of what model is behind inhomogeneity, one has several key tests:

- **Cosmic background shear**

$$\varepsilon \equiv \sqrt{\frac{3}{2}}\frac{\sigma}{\Theta} = \frac{H_T - H_L}{H_L + 2H_T}$$

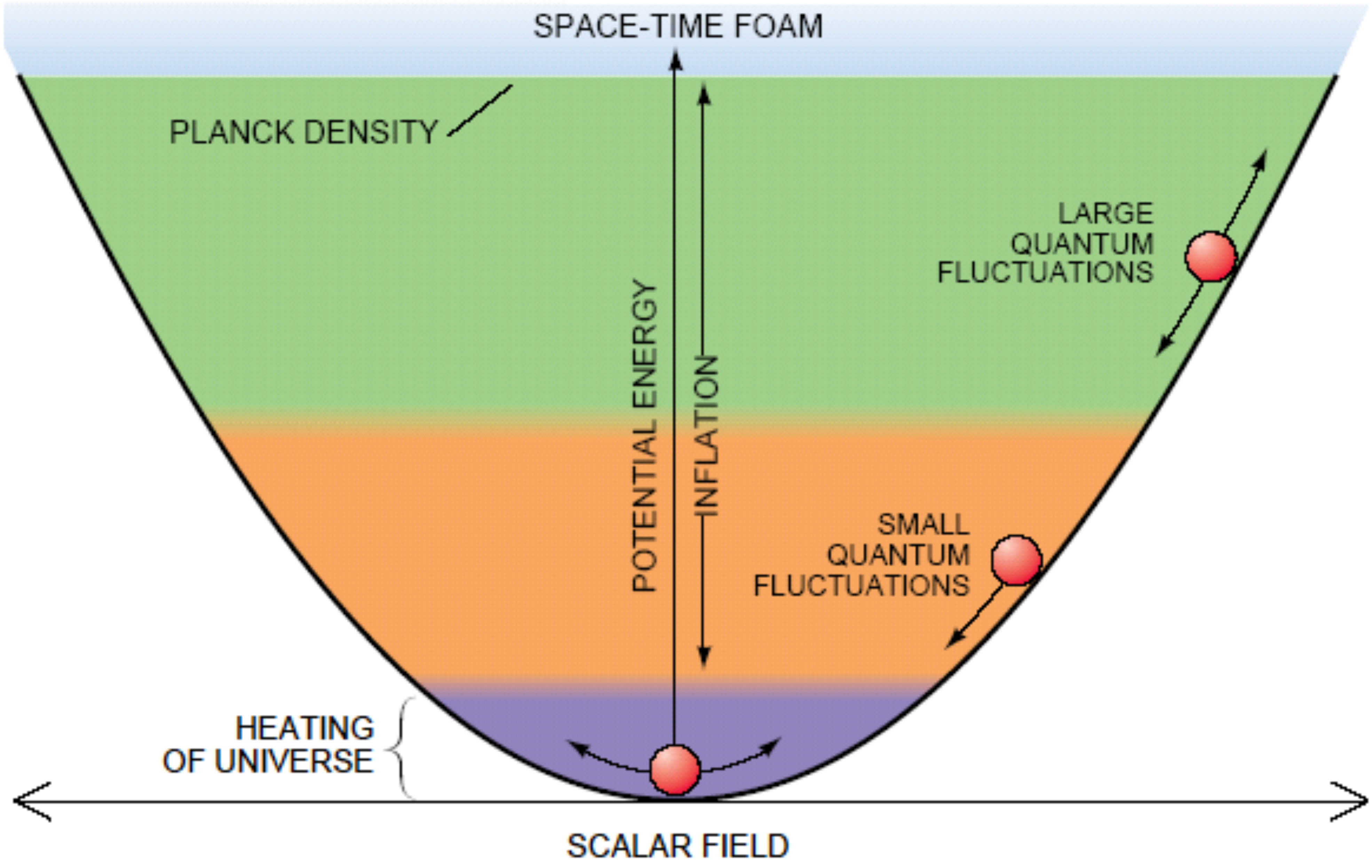
- **Growth function f(a)**
- **Bulk velocities and kSZ effect on clusters**
- **Fractal dimension dim(z)**
- **ISW effect, LSS simulations (see D.Alonso talk)**


Sloan Great Wall
SDSS
Large Voids
12h
16h
8h
0.08
0.06
0.04
0.02
Redshift z
0.02
0.04
0.06
0.08
Redshift z

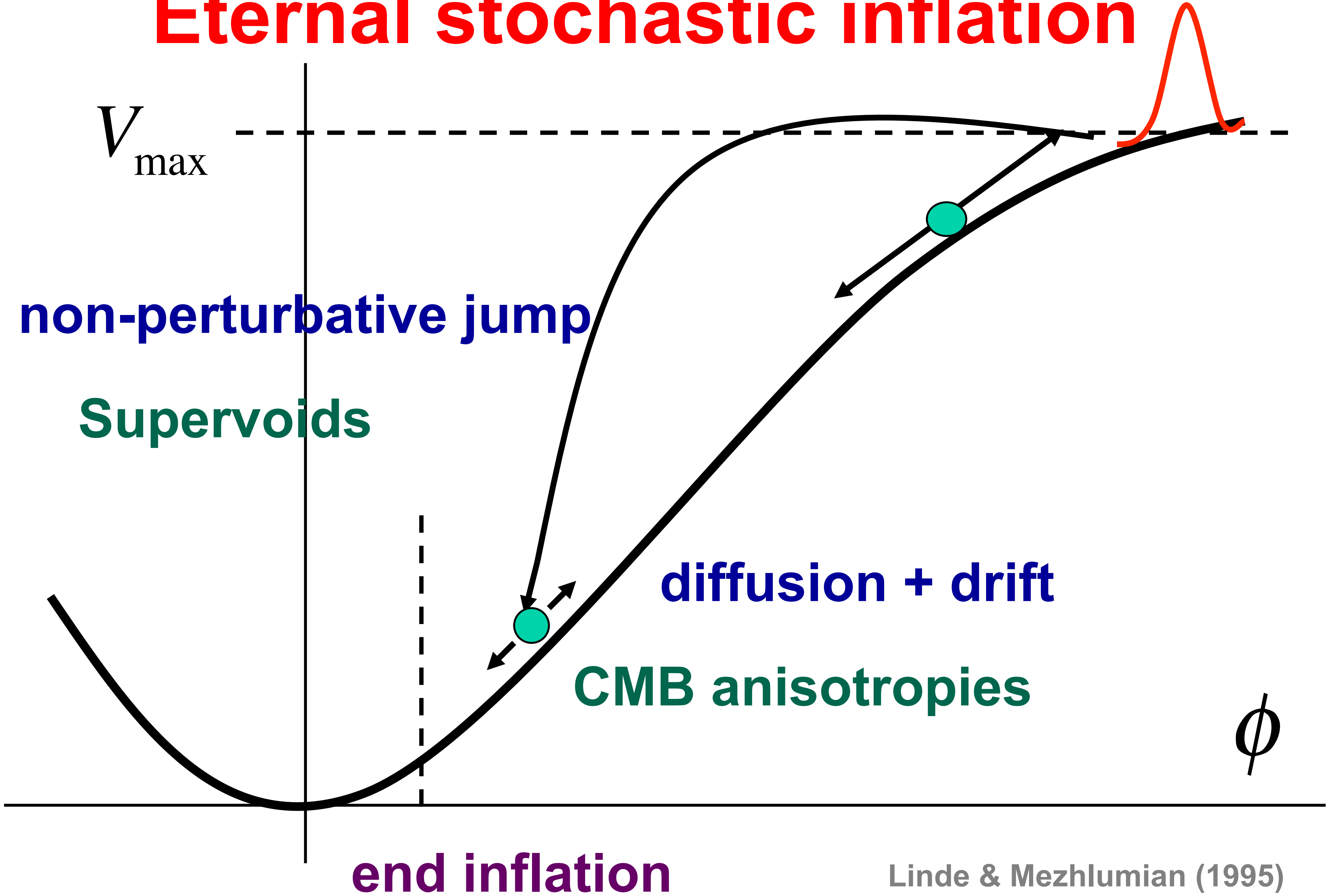
If we live in a highly inhomogeneous Universe…

what is the origin of dens. perturbations?

Chaotic Inflation

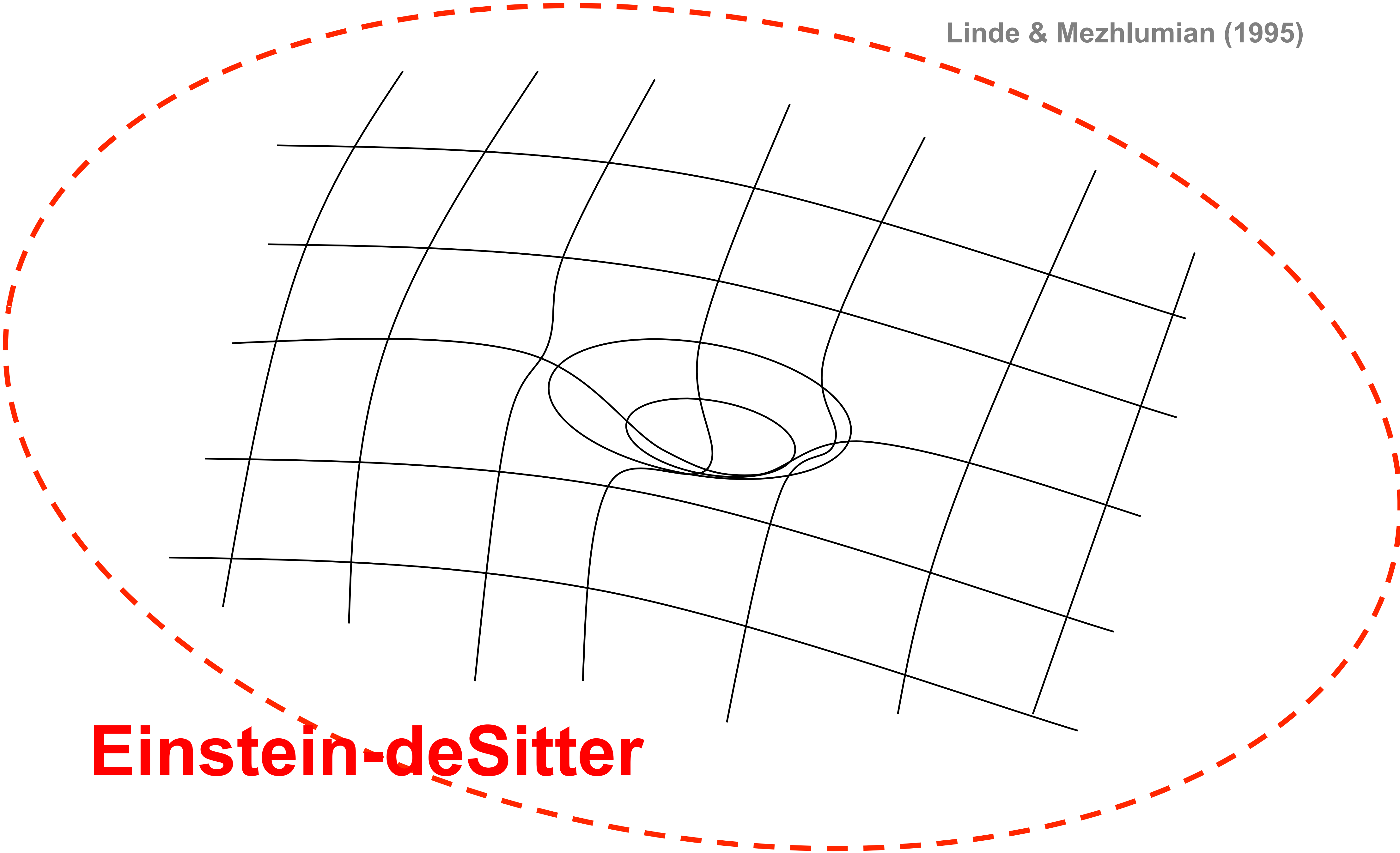


Eternal stochastic inflation

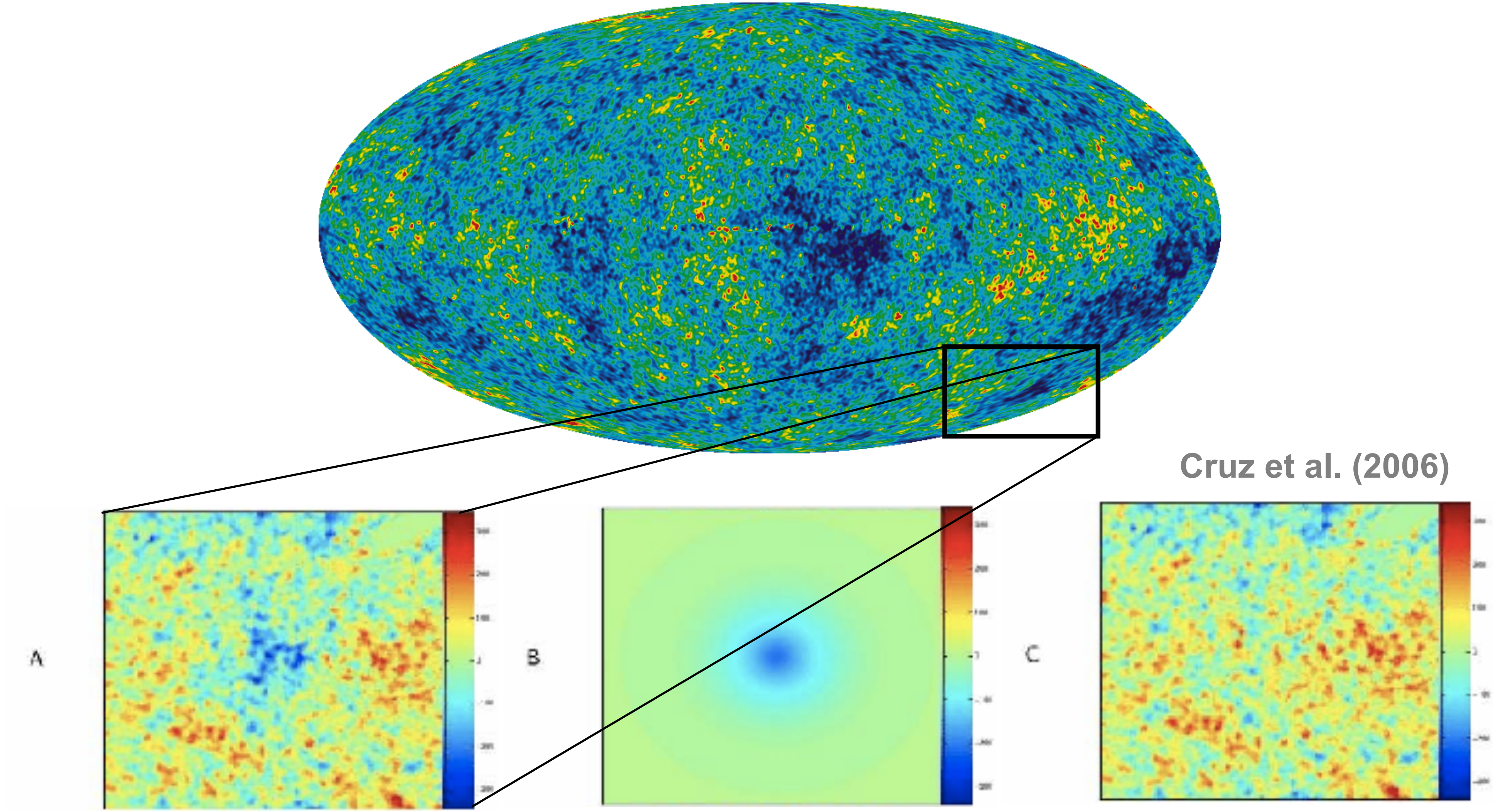


Infloid = Lemaitre-Tolman-Bondi Model

Linde & Mezhlumian (1995)



Could the Cold Spot in CMB be an “infloid” ?

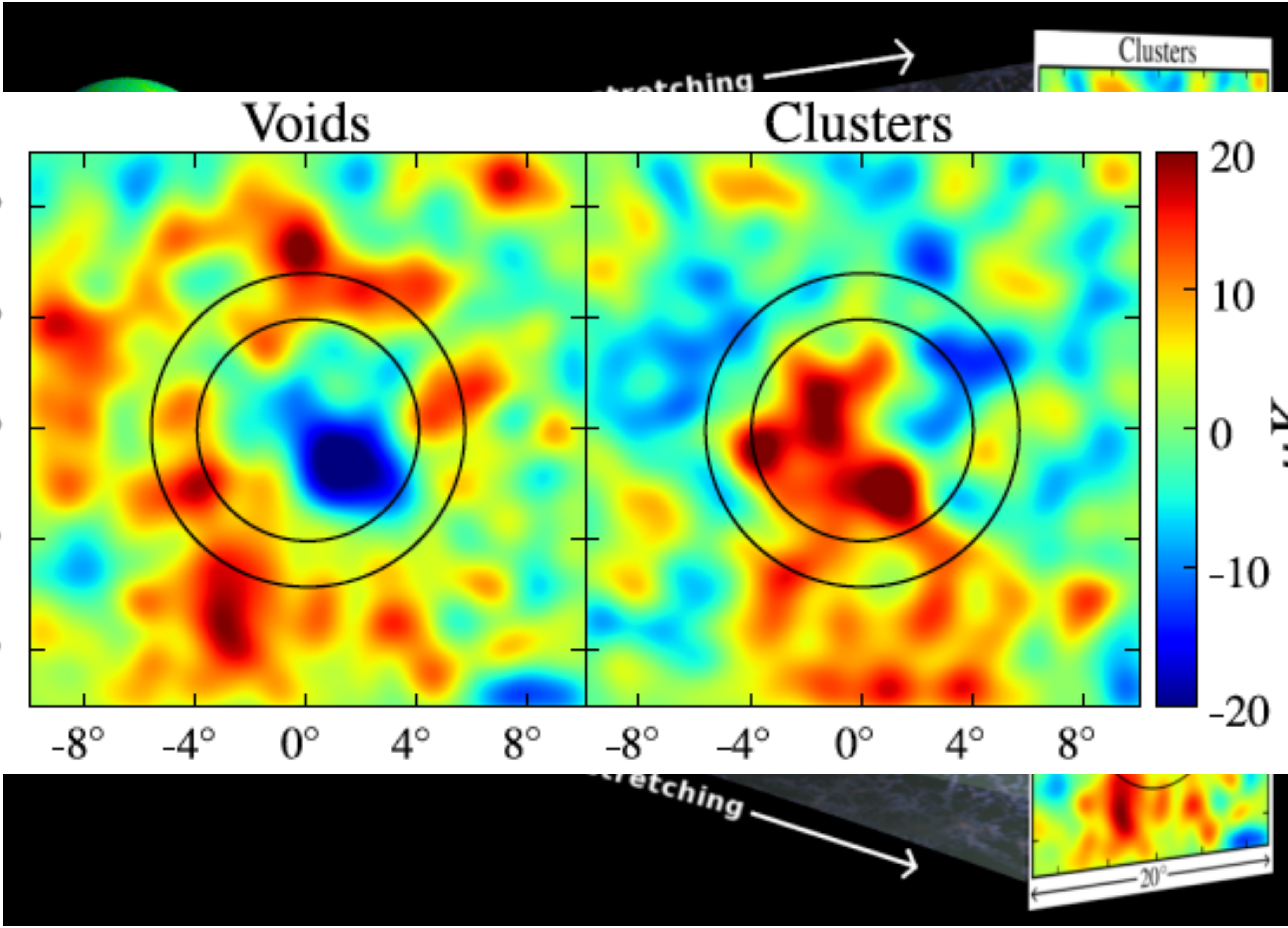


Cruz et al. (2006)

A large void, approximately 2 Gpc in size

Voids and Superclusters in SDSS

Granett et al. (2008)



The Lemaître-Tolman-Bondi Model

Celerier (1999), Tomita(2000), Moffat (2005), Alnes et al. (2005)

- Describes a space-time which has spherical symmetry in the spatial dimensions, but with time and radial dependence:

$$ds^2 = -dt^2 + X^2(r,t)\, dr^2 + A^2(r,t)\, d\Omega^2$$

- From the 0-r part of the Einstein-Equations we get:

$$X(r,t) \quad = \quad A'(r,t)/\sqrt{1-k(r)}$$

- One can recover the FRW model setting:

$$A(r,t) = a(t)\, r \qquad k(r) = k\, r^2$$

The Lemaitre-Tolman-Bondi Model

- Matter content:

$$T^{\mu}_{\nu} = -\rho_M(r,t)\,\delta^{\mu}_{0}\,\delta^{0}_{\nu}\,.$$

- The other Einstein equations give:

$$\frac{\dot{A}^2 + k}{A^2} + 2\frac{\dot{A}\dot{A}'}{AA'} + \frac{k'(r)}{AA'} = 8\pi G\,\rho_M$$

$$\dot{A}^2 + 2A\ddot{A} + k(r) = 0$$

- Integrating the last equation:

Enqvist & Mattsson(2006)

$$\frac{\dot{A}^2}{A^2} = \frac{F(r)}{A^3} - \frac{k(r)}{A^2}$$

The Lemaitre-Tolman-Bondi Model

García-Bellido & Haugbølle (2008)

- All we need to specify:

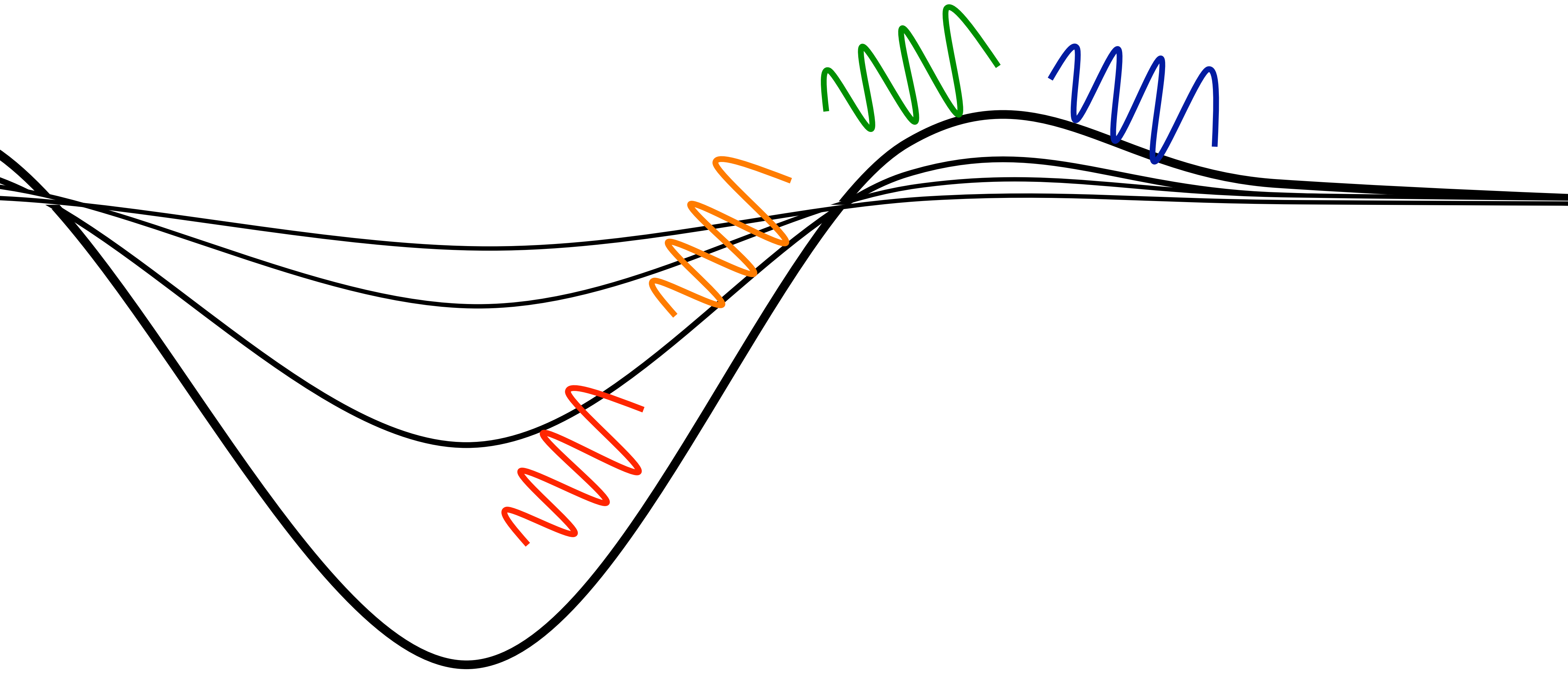
$$F(r) = H_0^2(r)\,\Omega_M(r)\,A_0^3(r)$$

$$k(r) = H_0^2(r)\Big(\Omega_M(r) - 1\Big)\,A_0^2(r)$$

- Then the Hubble rate can be integrated to give A(r,t):

$$H^2(r,t) = H_0^2(r)\left[\Omega_M(r)\left(\frac{A_0(r)}{A(r,t)}\right)^3 + (1-\Omega_M(r))\left(\frac{A_0(r)}{A(r,t)}\right)^2\right]$$

Density profile



Light Ray Propagation

- By looking at the geodesic equation, we can find the equation of motion for light rays:

$$\frac{dt}{dN} = -\frac{A'(r,t)}{\dot{A}'(r,t)} \qquad \frac{dr}{dN} = \frac{\sqrt{1-k(r)}}{\dot{A}'(r,t)}$$

where N = ln(1+z) are the # e-folds before present time.

- The various distances as a function of redshift are:

$$d_L(z) = (1+z)^2 A[r(z), t(z)]$$

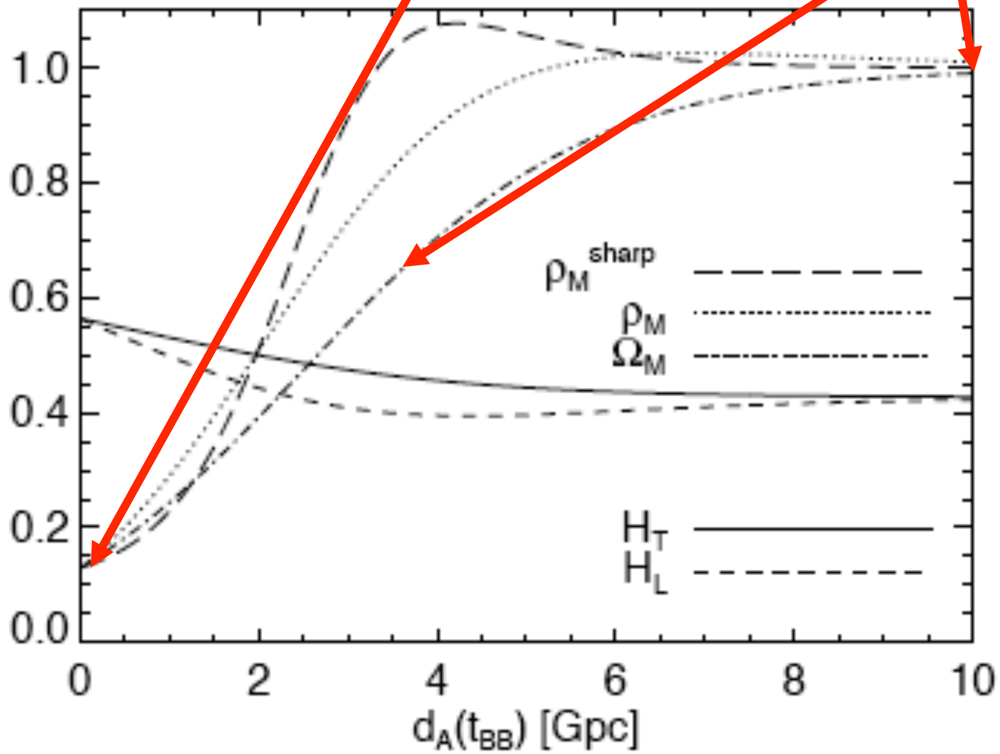
$$d_C(z) = (1+z)\,A[r(z), t(z)]$$

$$d_A(z) = A[r(z), t(z)]$$

The LTB-GBH model

$$\Omega_M(r) = \Omega_{\rm out} + \left(\boxed{\Omega_{\rm in}} - \boxed{\Omega_{\rm out}}\right)\left(\frac{1-\tanh[(r-\boxed{r_0})/2\Delta r]}{1+\tanh[r_0/2\Delta r]}\right)$$

$$H_0(r) = H_{\rm out} + \left(H_{\rm in} - H_{\rm out}\right)\left(\frac{1-\tanh[(r-r_0)/2\Delta r]}{1+\tanh[r_0/2\Delta r]}\right)$$



- If we assume asymptotic flatness, then the model has **5** parameters
- If we require a homogeneous Big Bang then the model has **4** parameters

García-Bellido & Haugbølle (2008)

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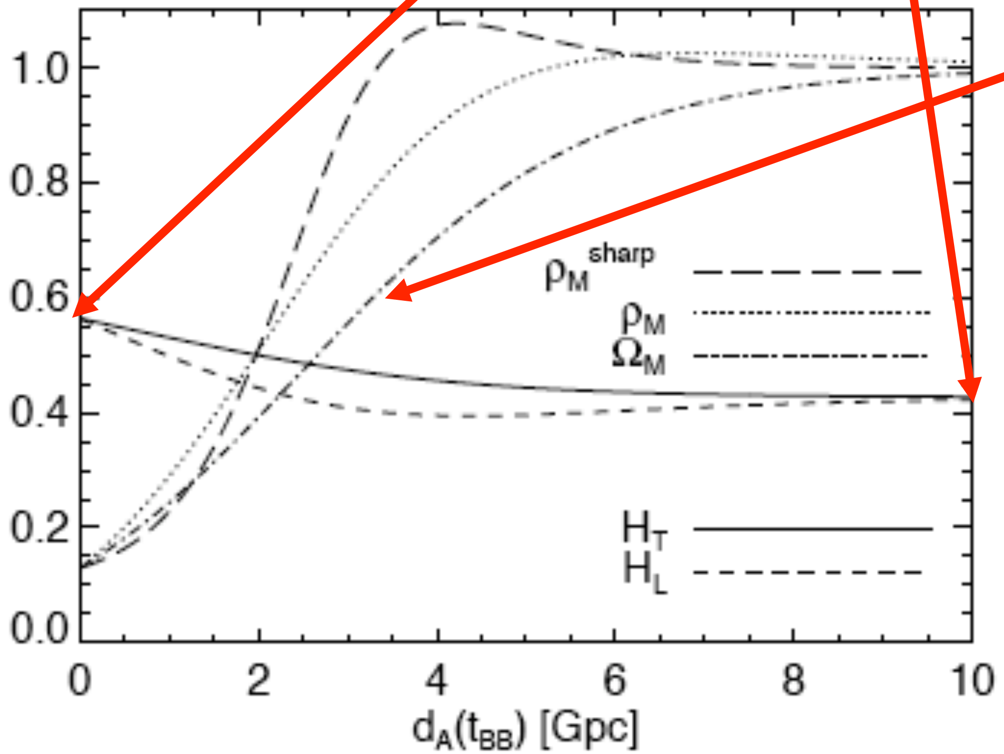

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García-Bellido & Haugbølle (2008)

A new observable: cosmic shear

García-Bellido & Haugbølle (2009)

$$\frac{d\Theta}{d\tau} = -\frac{1}{3}\Theta^2 - \sigma_{\mu\nu}\sigma^{\mu\nu} + \omega_{\mu\nu}\omega^{\mu\nu} - R_{\mu\nu}n^\mu n^\nu$$

$$\varepsilon \equiv \sqrt{\frac{3}{2}}\frac{\sigma}{\Theta} = \frac{H_T - H_L}{H_L + 2H_T}$$ normalized shear

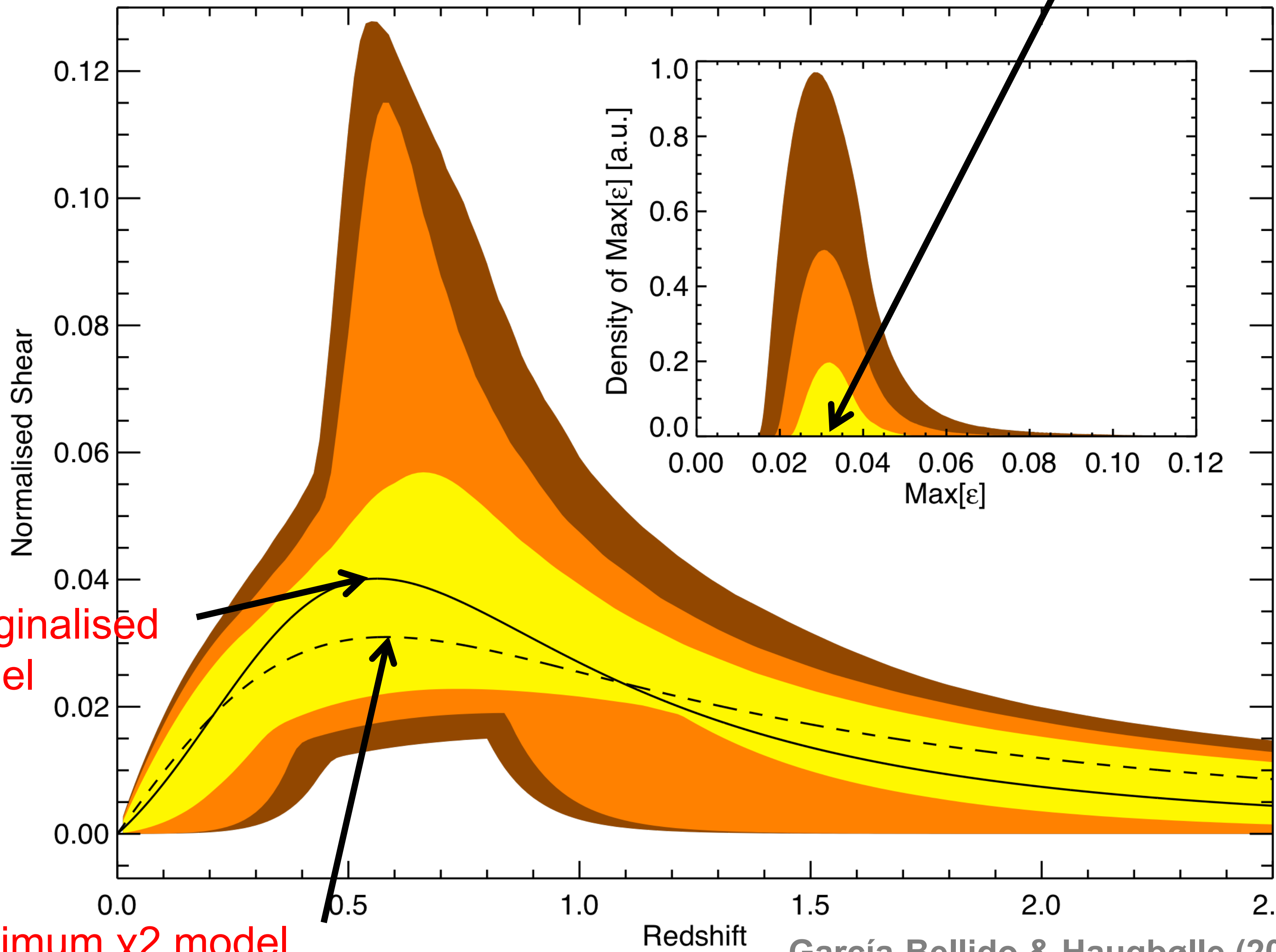
$$\boxed{\varepsilon(z) = \frac{1 - H_L(z)[(1+z)\,d_A(z)]'}{3H_L(z)d_A(z) + 2 - 2H_L(z)[(1+z)\,d_A(z)]'}}$$

FRW: $H_L = H_T = H$ shearless

$(1+z)d_A = \int dz/H(z) \qquad \varepsilon(z) = 0$

Normalized shear

ε ≈ 2 - 5% at maximum



marginalised model

minimum χ2 model

García-Bellido & Haugbølle (2009)

Constraining Cosmological Data

- Type Ia Supernovae: 307 SNIa Union Supernovae

  Simple to do since we just fit against $d_L(z)$

- Acoustic peak in the CMB: $d_C(z_{rec})$, sound horizon $r_s(z)$

3 distances

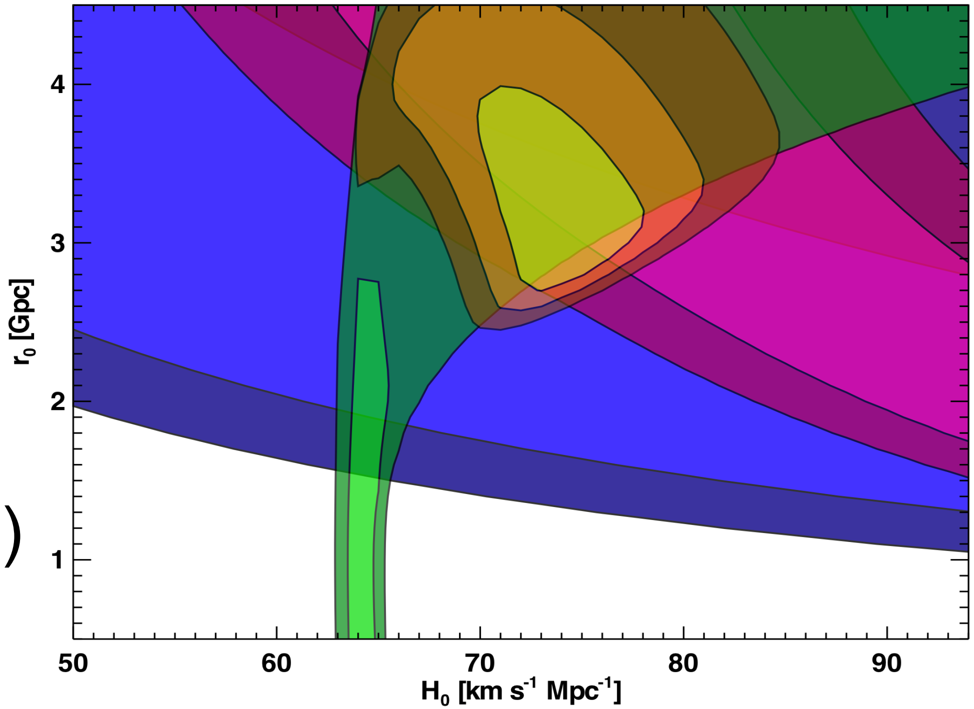
- Baryon Acoustic Oscillations:

  Sound horizon $$D_V(z) = \left[d_A^2(z)(1+z)^2 \frac{cz}{H_L(z)} \right]^{1/3}$$

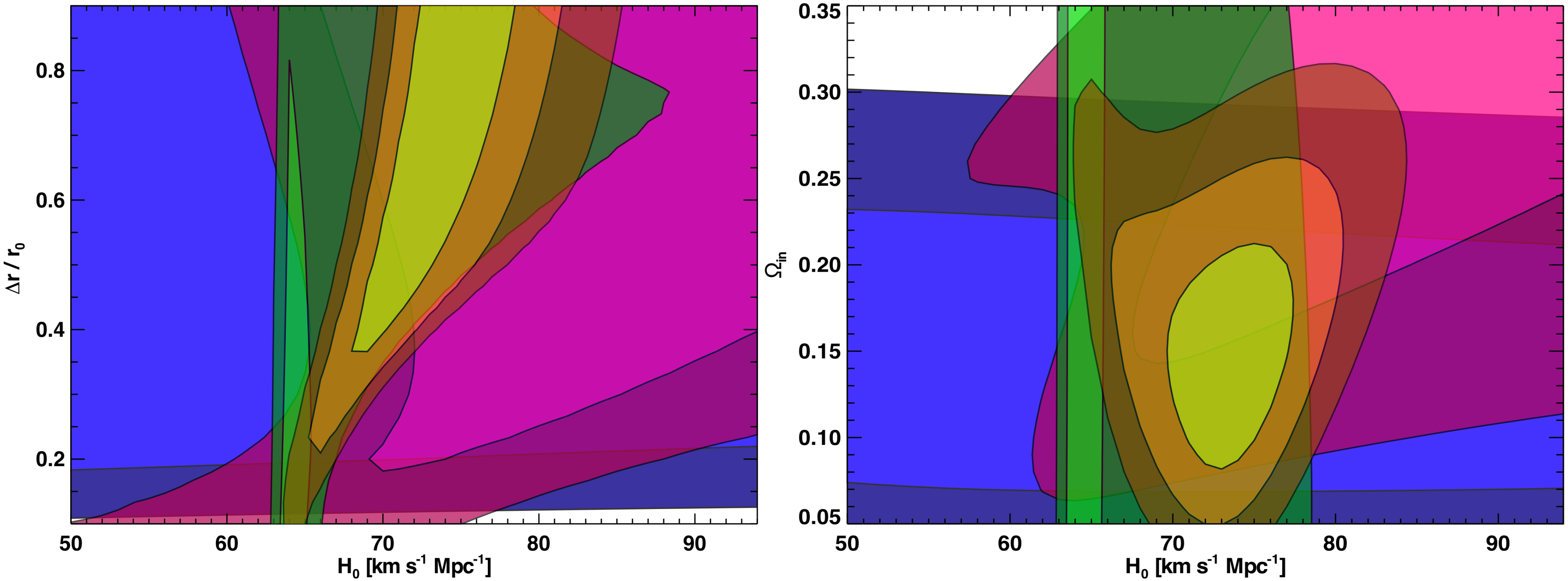
- Other constraints:
  - $f_{gas} = \rho_b / \rho_m = \omega_b / (\Omega_m h^2)$
  - HST+Cepheids (Riess): $H_0 = 74 \pm 3$ km/s/Mpc (1σ)
  - Globular cluster lifetimes ($t_{BB} > 11.2$ Gyr)

Scanning the model

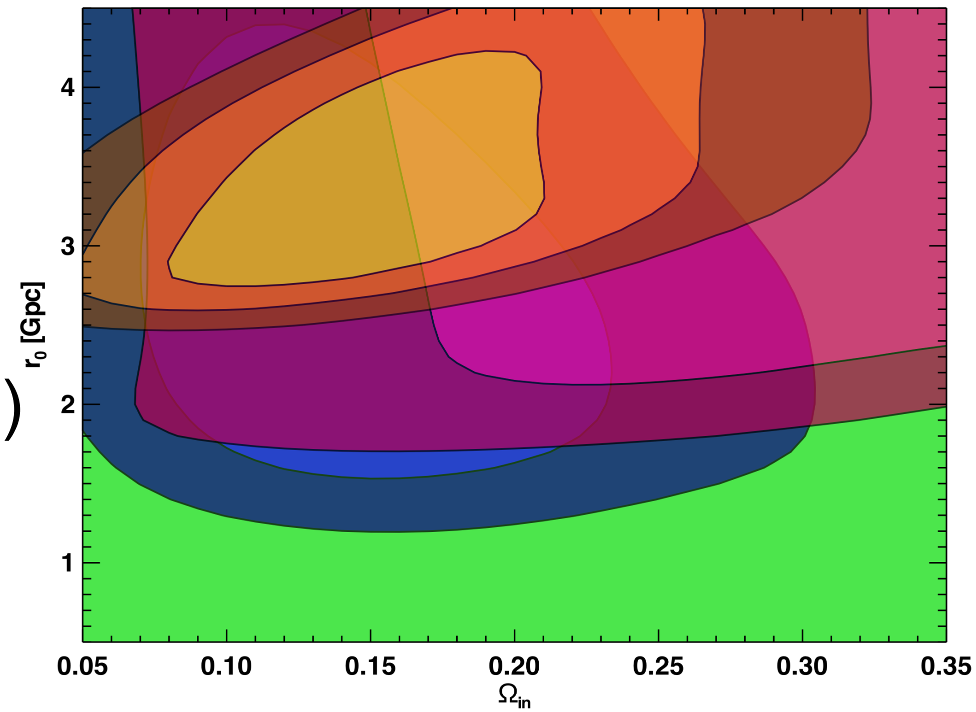
- Yellow: Everything, Blue: SNe .
- Green: CMB. Purple: BAO
- Supernovae constrain Ω_{matter}
- CMB constrains the H_0, (Ω_{out}=1)



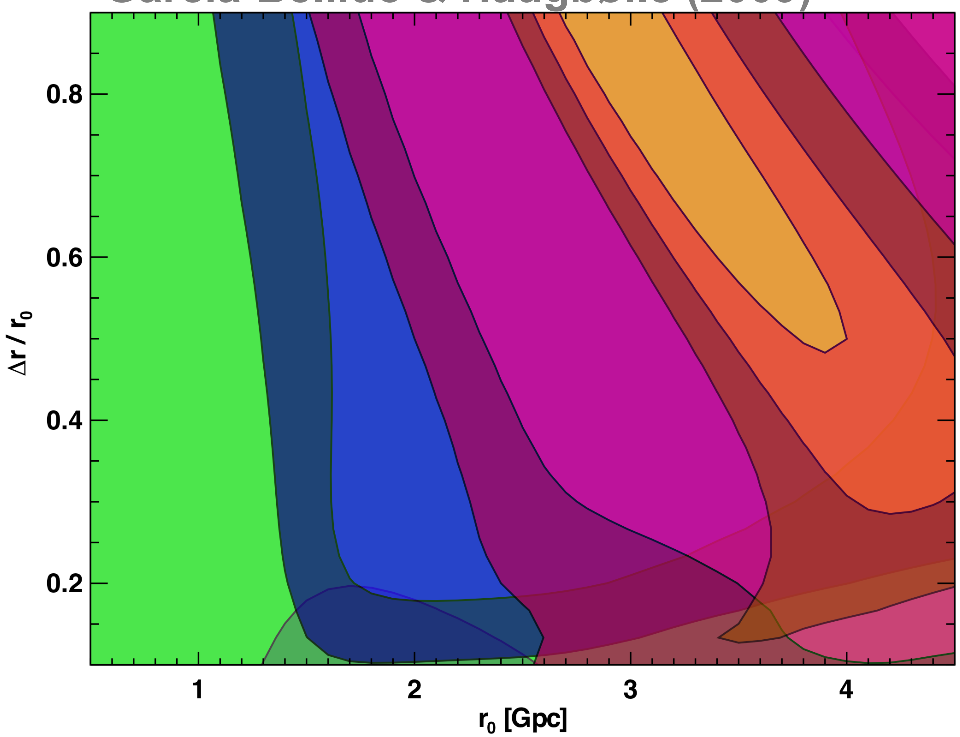
García-Bellido & Haugbølle (2009)

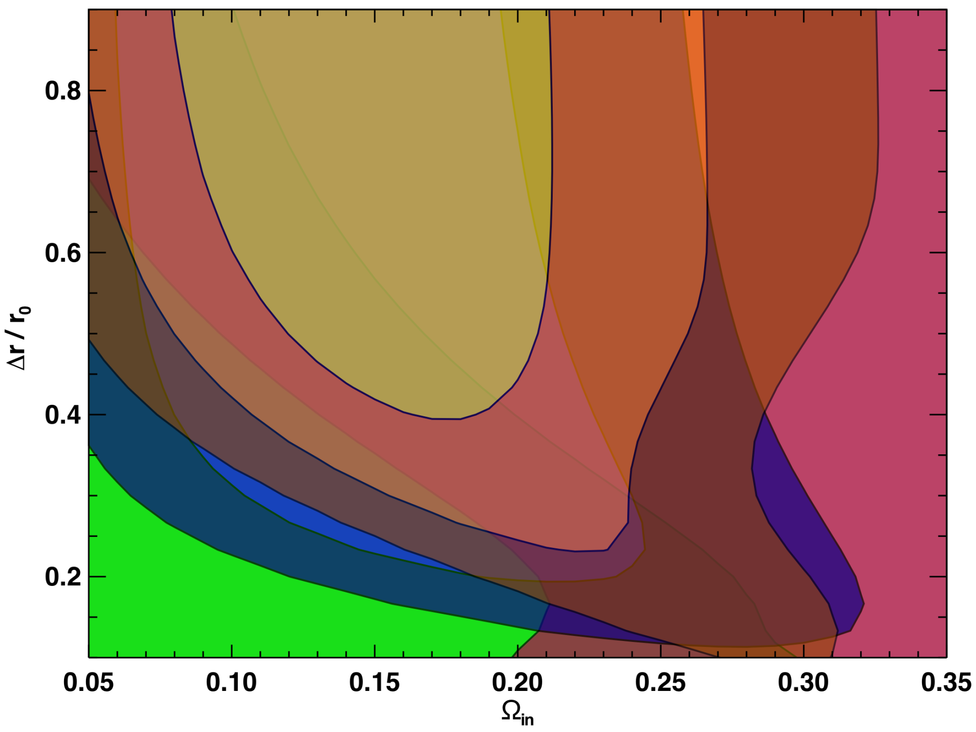


- The SNe and BAO pushes the void size to $r_0 > 1.8$ Gpc
- Some tension between RBAO and SNe (waiting for high-z SNe)
- Large degeneracy between r_0 and $\Delta r/r_0$



García-Bellido & Haugbølle (2009)





Marginalized errors

García-Bellido & Haugbølle (2009)

Model	H_0	$H_{\rm in}$	$H_{\rm out}$	$H_{\rm eff}$
units		100 km s^{-1} Mpc^{-1}		
GBH	–	0.58±0.03	0.49±0.2	0.43
Constrained	0.64±0.03	0.56	0.43	0.42

Model	$\Omega_{\rm in}$	r_0	Δr	t_{BB}
units		Gpc	r_0	Gyr
GBH	0.13±0.06	2.3±0.9	0.62(>0.20)	14.8
Constrained	0.13±0.06	2.5±0.7	0.64(>0.21)	15.3

!!

$$\chi^2_{\Lambda CDM} / d.o.f. = 1.021 \qquad \chi^2_{LTB-GBH} / d.o.f. = 1.036$$

Discussion

- Void models, observationally, appear as an alternative to the standard model. While they break away from the Copernican Principle, they do not need dark energy.
- There is no coincidence problem either: It was there always.

  The question “Why Now?” becomes “Why Here?”
- A void model with a size of ~ 2 Gpc yields a perfect fit to observations constraining the geometry of the universe.
- The final test will be comparing the model to observations:
  - Cosmic shear + bulk flows near z~0.5 (DES, PAU)
  - CMB, and matter power spectra (More theory: ISW)
  - Remote measurements of the CMB: The kinematic Sunyaev Zeldovich effect (ACT, SPT, Planck)