Voids as a Probe of Cosmology

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Voids as Probe of Cosmology

1. Standard Cosmology: ΛCDM
2. Current Efforts in cosmology
3. Voids
   - Formulation of Method
   - Forecasts
   - Systematics

Cosmology: Connecting to the rest of Physics

initial conditions (time $= t$)	Dynamical Evolution (at some early time t_i)	"final conditions" (at some time t_f)
of what variables? What conditions ? Why those conditions ?	What are the laws of long range dynamics? Interactions ?	

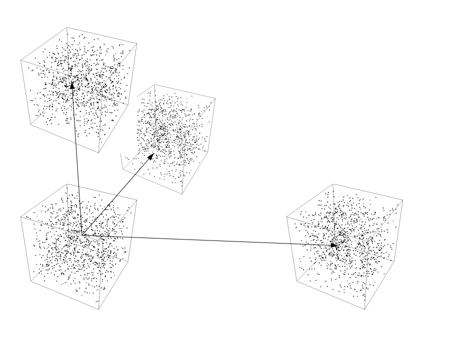
The Dynamics: General Relativity

Dynamical variable: metric $g_{\mu\nu}$

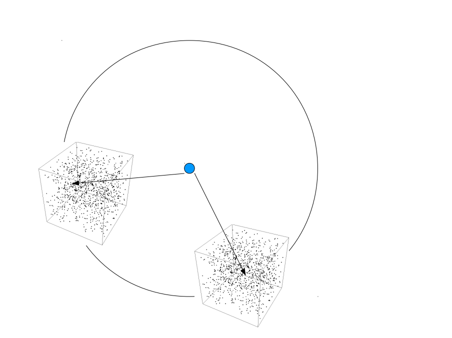
Particle motion: geodesics

Observed Approximate Symmetry

Homogeneity



isotropy

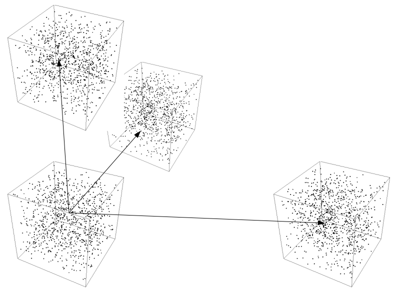


The Dynamics: General Relativity

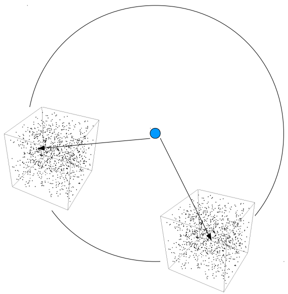
Ansatz: $g_{\mu\nu} = g_{\mu\nu}^{FRW} + \text{fluctuations}$ $\rho = \rho_{bg} + \text{fluctuations}$

Observed Approximate Symmetry

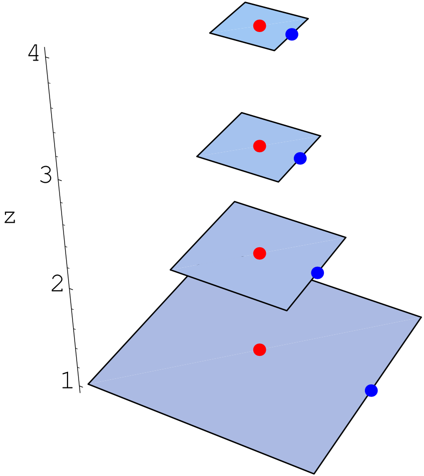
Homogeneity



isotropy



FRW: The background metric



Terminology

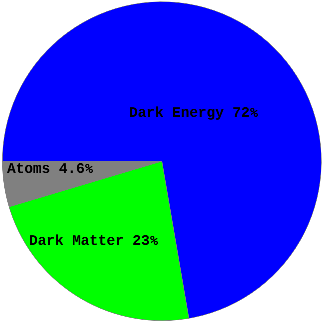
- FRW metric: only two parameters $a(t), k$

$$ds^2 = dt^2 - a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right)$$

- curvature parameter k
- Expanding universe $\implies$ $a(t)$ (scale factor) increases with time
- Redshift $z = 1/a - 1$
- $\{r, \theta, \phi\}$: "Comoving coordinates"

$$H^2(t) \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho(t) - \frac{k}{a^2}$$

The Background: Main Players



Conservation of stress tensor

- Equation of state $w = \frac{P}{\rho}$
- Determines scaling with expansion

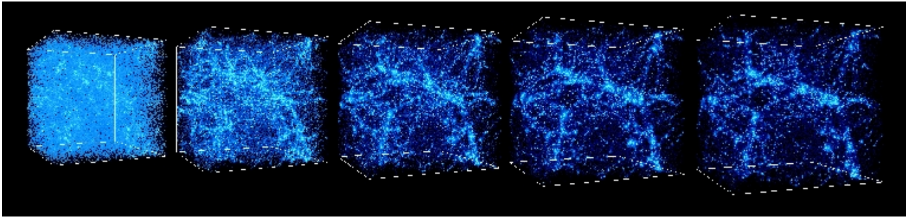
$$
\begin{aligned}
w_{dm} &= 0, \quad \rho_{dm} \sim a^{-3}, \\
w_b &= 0, \quad \rho_b \sim a^{-3} \\
w_\gamma &= 1/3; \quad \rho_\gamma \sim a^{-4} \\
w_\Lambda &= -1, \quad \rho_\Lambda \sim a^0
\end{aligned}
$$

Baryons (non-relativistic), radiation, dark matter particles (essentially collision-less today), cosmological constant

Fluctuations: the Kingmakers

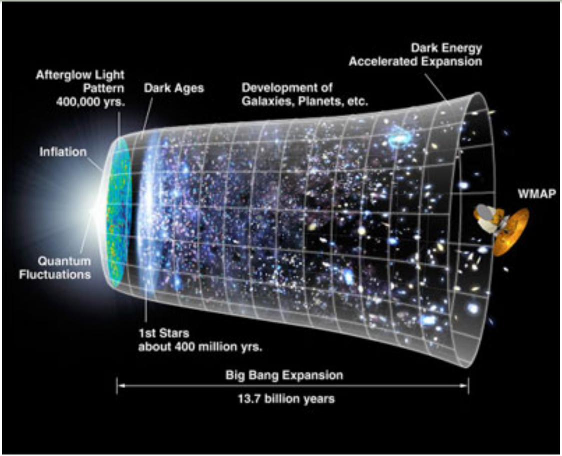
Initial Conditions

- Stochastic, not deterministic
- Seeded by inflation in Standard Model
- Homogenous and isotropic Gaussian random Field
- charactarized by the a power spectrum $P(k) = A_s \left(k/k_0\right)^{n_s - 1}$
- Grows to form large scale structure in the universe



credit: Kravtsov (UChicago) and Klypin (NM State), NCSA

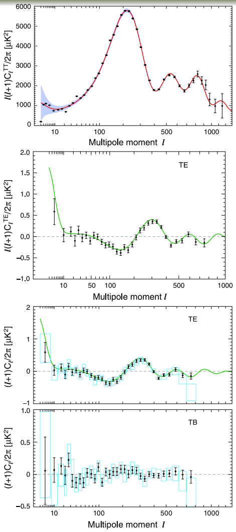
How it all fits in: The storyline



Ω_b
Ω_{cdm}
Ω_k
H_0

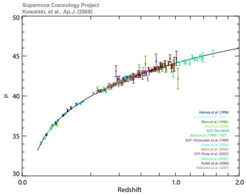
Fluctuations :
A_s or σ_8
n_s

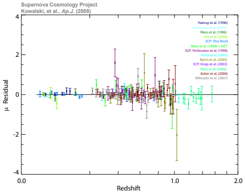
Current Status: Predicts Observations



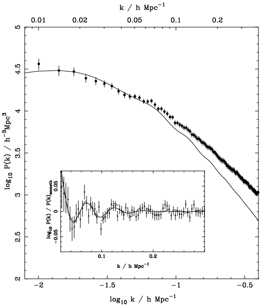
WMAP 7 year, Larson etal.

Flat ΛCDM Model : $\{\Omega_b h^2 \Omega_c h^2, H_0, z_{re}, n_s, A_s\}$





SCP, Union Data Set, Kowalski etal, 2008



SDSS, DR5, Tegmark etal.

Consistent with data: So what's next?

initial conditions (time = t)	Dynamical Evolution (at some early time t_i)	"final conditions" (at some time t_f)
of what variables? What conditions ? Why those conditions ?	What are the laws of long range dynamics? Interactions ?	

We have a simple set of answers which is consistent with current data, but it is NOT the only such set!

Λ CDM Cosmology: standard answers vs possible answers

• gravity ≡ General Relativity	• Some modified version of gravity ? Extra dimensions ? Branes?
• homogeneity, isotropy	• isometries not confirmed, Backreaction
• Dark matter (weakly interacting new particle)	• Different interactions? (Self, Dark energy ?),MOND ?
• Dark Energy (cosmological constant)	• Dynamical Field in a gravitational potential? Modified gravity?
• Nature of initial conditions (Gaussian, symmetry)	• Intrinsic Non-Gaussianity? Stochastically isotropic? Scalar and Tensor modes ? Cosmic Strings ?
• Inflation seeds fluctuations	• What kind of inflation model? Cyclic cosmology?

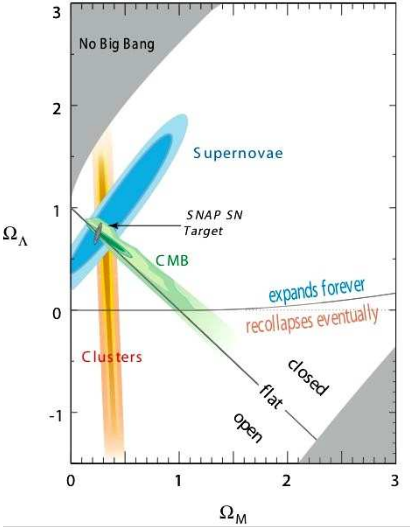
more data → select better subset of answers → Learn more about laws of physics

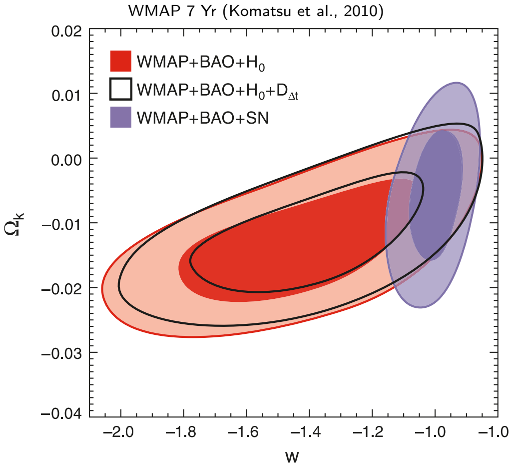
What are suitable surveys to pursue?

Dark Energy Task Force Prescription

- Generalize $w(z) = -1$ to $w(z) = w_0 + w_a \frac{z}{1+z}$
- Assume nature is really a ΛCDM model, and forecast constraints on w_0, w_a
- A good experiment is one which minimizes the size of constraints
- Rank by Figure of Merit = 1/(Area of 95% ellipse)

Motivation: Complementarity and Tension

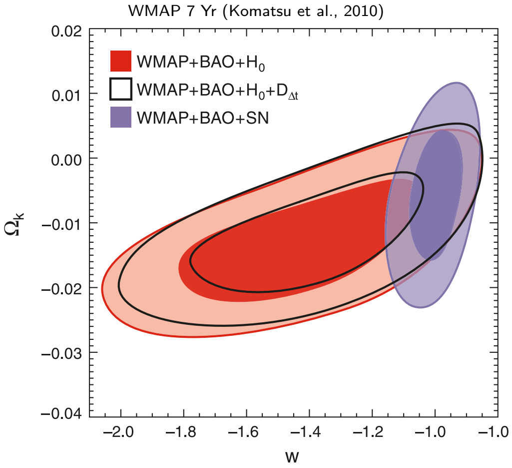




Motivation: Complementarity and Tension

Desirable Characterestics

- Probe Physics in different ways
- Have different systematics
- Sizes of Constraints should be competitive
- Independent ? Useful in breaking degeneracy?



New Probes Extremely Welcome !

Probes of Cosmology

Traditional Probes

- Cosmic Microwave Background
- Galaxy Surveys
- Supernovae

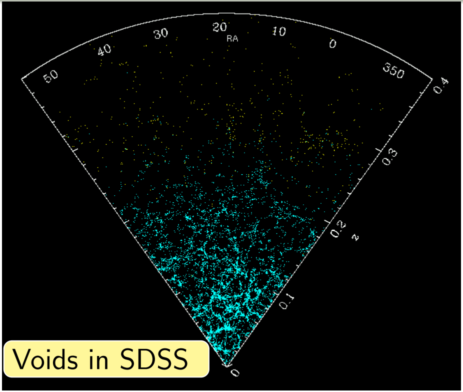
Ongoing Probes

- Weak Lensing
- Galaxy Clusters

New Probes

- Velocity Flows (eg. Redshift Distortions)
- Voids (New!)

Voids as a Probe of Cosmology



Biswas, Alizadeh & Wandelt, arXiv:1002.0014
Lavaux & Wandelt, arXiv:0906.4101, MNRAS 2010

Probe dark energy with voids

- study void 'shape' distribution
- comparison of evolution with theory constrains Dark Energy
- plausible with current and planned spectroscopic surveys
- forecasts are interesting by discussed standards

Voids as a Precision Probe for Dark Energy

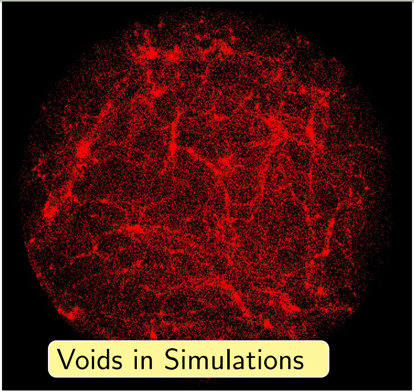
From properties of Voids to Void Finders

Use Void Properties to define a void

- Related to under-densities of the underlying dark matter fluctuations
- Under-density of galaxies
- Dynamics: Expand with time

A Void defined by one of these properties is not the same as a void defined by another property: Aspen-Amsterdam comparison (Colberg etal.)

Need to use a void-finder compatible with the property being studied

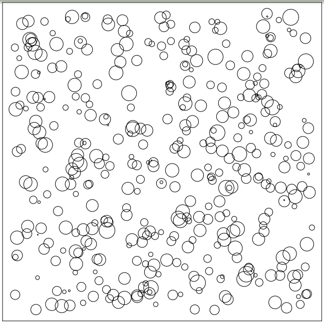


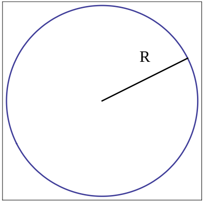
DIVA (credit: Guilhem Lavaux)

Infer Lagrangian coordinates of present galaxies

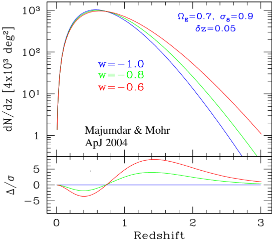
Single parameter: smoothing scale R

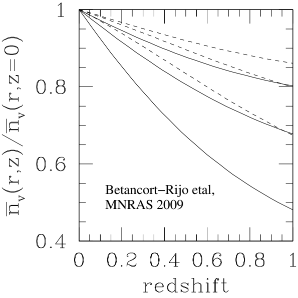
Fluctuations: Distinct Observable Properties





$n(R, z)$





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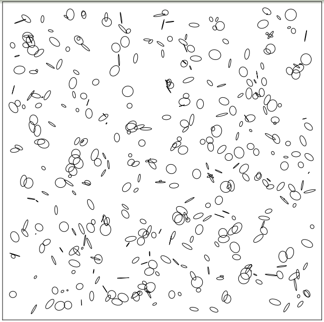
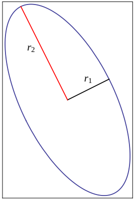
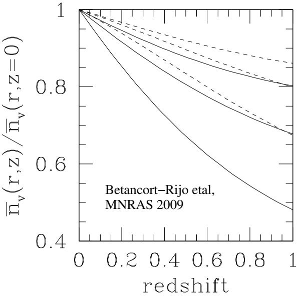


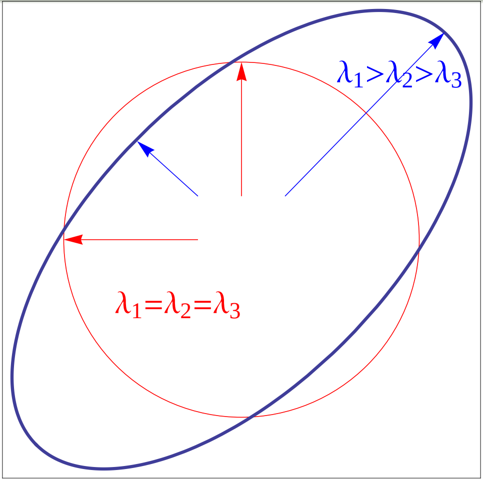


$$n(R, z), \qquad n(r_1, r_2, z)$$

Voids can probe new characterestics of fluctuations



Lagrangian Description: Displacement Field



Displacement Field $\Psi(\vec{q}, \tau)$

$$\vec{x}(\vec{q}, \tau) \equiv \vec{q} + \vec{\Psi}(\vec{q}, \tau)$$

- For spherical fluctuation, $\nabla_q \Psi(\vec{q_0}, \tau) \propto (\vec{q} - \vec{q}_0)$
- Deviation from sphericity related to elements of Tidal Field
$$T_{ij} \equiv \frac{\partial \Psi_i}{\partial q_j}$$
- Don't care about orientations; Eigenvalues $\{\lambda_1 \geq \lambda_2 \geq \lambda_3\}$

Connecting Ellipticity to Observables

$$\{\lambda_1, \lambda_2, \lambda_3\}$$

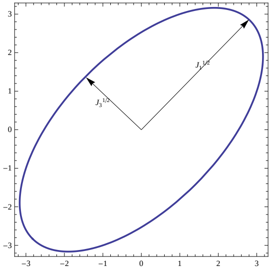
Volume Ellipticity

$$1 - \left(\frac{J_1}{J_3}\right)^{1/4}$$

Void geometry set by Tidal tensor, Park & Lee, PRL 2008

Tidal Ellipticity

$$\epsilon \equiv 1 - \left(\frac{1-\lambda_1}{1-\lambda_3}\right)^{\frac{1}{2}}$$



Reconstruct Tidal Ellipticity

- Inside voids, minimal shell crossing
- tidal ellipticity can be recovered to high accuracy. Lavaux & Wandelt, 2010

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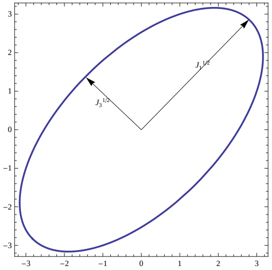
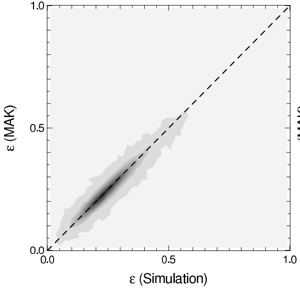
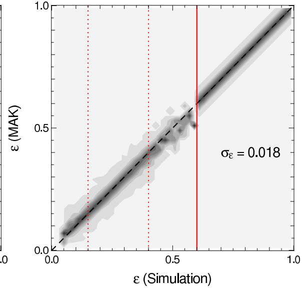






Lavaux & Wandelt, MNRAS 2010

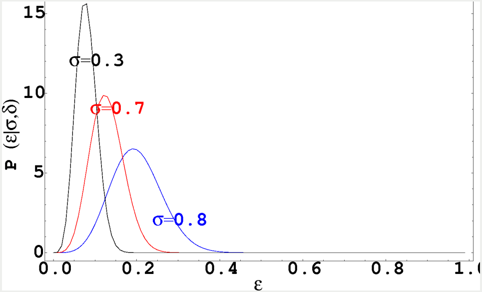
Distribution of Ellipticity

Distribution of Eigenvalues

- For smoothed Gaussian Random Fields, $P(\lambda_1, \lambda_2, \lambda_3 | \sigma_R)$ Doroshkevich, 1970
- Extend to later time through the Zeldovich approximation using linearly extrapolated overdensity δ and σ_R
- Depends on cosmology through σ_R which depends on growth of fluctuations.

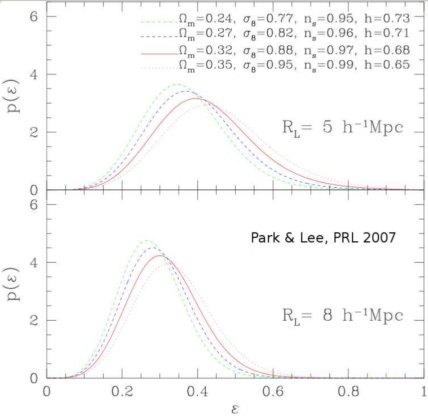
Distribution of ellipticity

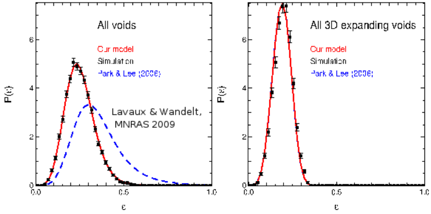
- Distribution depends on Linearly extrapolated δ and σ_R



- Observed Distributions of ϵ depend on cosmology through σ_R
- Use $P(\epsilon)$ to constrain cosmology. Park & Lee, PRL 2008

Distribution to Compare





- Need to distinguish distributions in order to discriminate between cosmological models

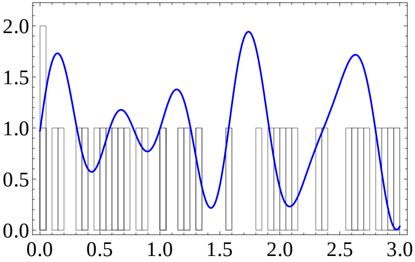
- Aim: Estimate constraints on Dark Energy parameters using void ellipticity from planned spectroscopic surveys

Linking to Surveys: How many voids?

Small voids: exponential dependence

- Number of small voids increases exponentially with decreasing size
- Void-in-Void, Void-in-cloud Problem
- A small 'void' may be due to statistics

galaxies vs galaxy field δ_g vs dark matter density δ_m



Method and Surveys

Likelihood and Fisher Matrix

- Model the random scatter $\epsilon_d(R,z) = \epsilon_s(R,z) + n, \quad n \sim G(0, \sigma_\epsilon)$
- Likelihood $L(\epsilon_d|\Theta) = \int d\epsilon_s P(\epsilon_d|\epsilon_s) P(\epsilon_s|\sigma_\epsilon, \Theta)$
- Given Likelihood compute Fisher Matrix forecasts. Depend on numbers of voids at particular redshifts
- Need to estimate number of voids for specific surveys: use Press-Schechter for voids (eg. Sheth & van de Weygaert, MNRAS 2004)
- estimating number of detectable voids: Use luminosity function

Current Surveys similar to

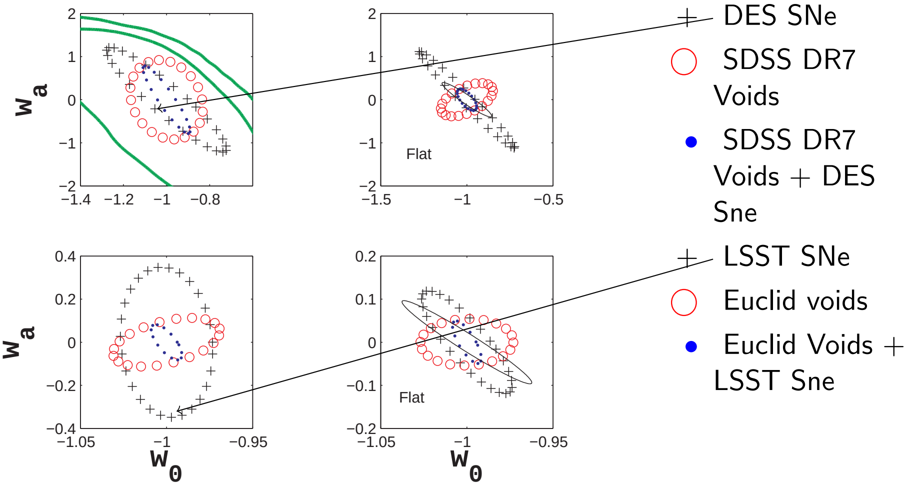
- DES SNe IA
- SDSS DR 7
- PLANCK

Futuristic Surveys similar to

- LSST SNe Ia
- EUCLID
- PLANCK

Forecasts using Void Shapes: 1 σ Constraints

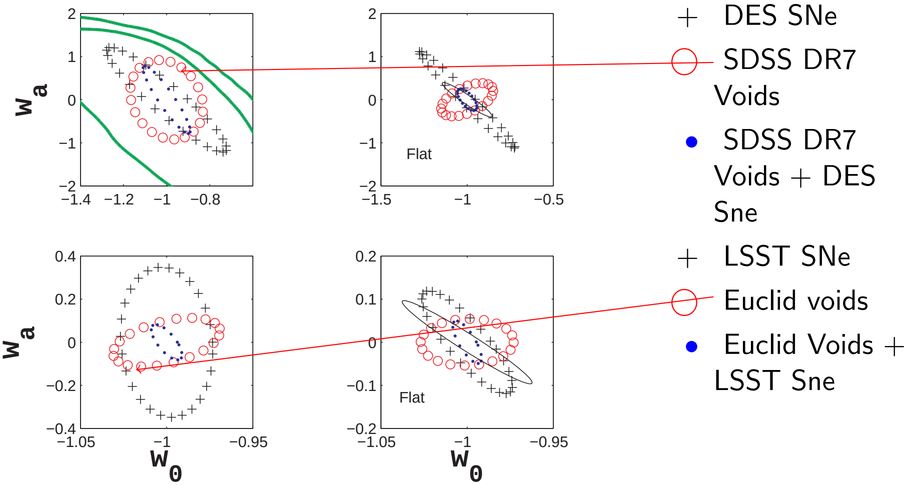
Current Surveys



Biswas, Alizadeh & Wandelt, 2010

Forecasts using Void Shapes: 1 σ Constraints

Current Surveys



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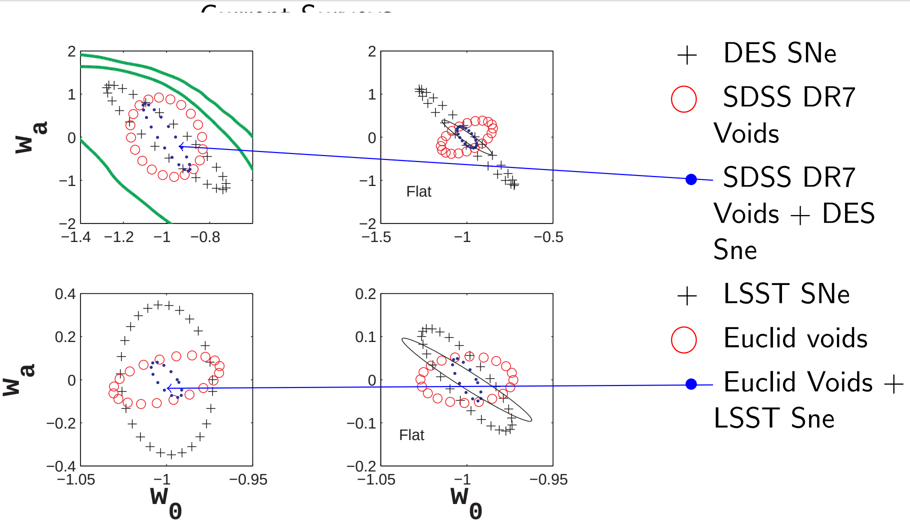

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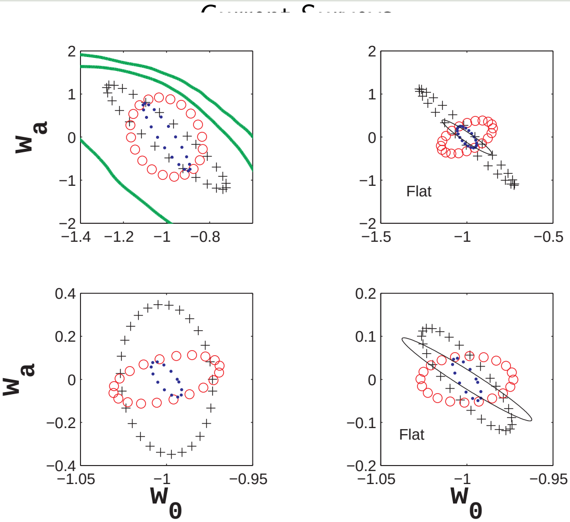
Forecasts using Void Shapes: 1 σ Constraints



Biswas, Alizadeh & Wandelt, 2010

Exciting Prospects

- Constraints using void ellipticities are competitive with supernovae constraints.
- Combining void ellipticity meaurements with supernovae improves constraints. FoM improves by factor of $\sim \mathcal{O}(10s)$ (current), $\sim \mathcal{O}(100s)$ (future)

Systematics: Modelling "Detectors"

- Formulated in terms of matter distribution inferred by Galaxy surveys observing galaxies

Effect of Shot Noise

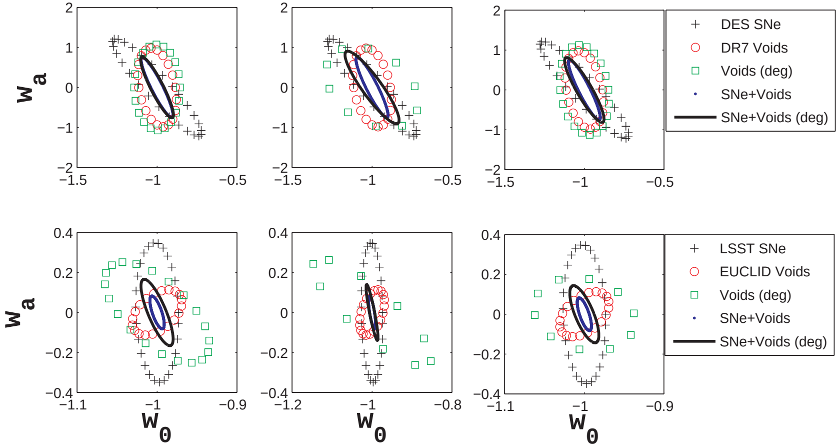
- galaxies observed as points
- Smoothed distribution $\rightarrow \delta_g$
- Given smooth distribution δ_g, how are points distributed?
- Model: Poisson process with mean δ_g
- Possible mis-identification of smaller voids ?

Effect of Galaxy Bias

- Relationship between smoothed field δ_g and δ_m (Recall $\delta = \frac{\delta\rho}{\rho}$)
- Often modelled as $\delta_g = b\delta_m$ (Linear Bias)
- Important as $P(\epsilon)$ depends on δ_m

How do these systematics impact constraints?

Systematics



Shot Noise

$l_{sep} < R_{min} < 2l_{sep}$

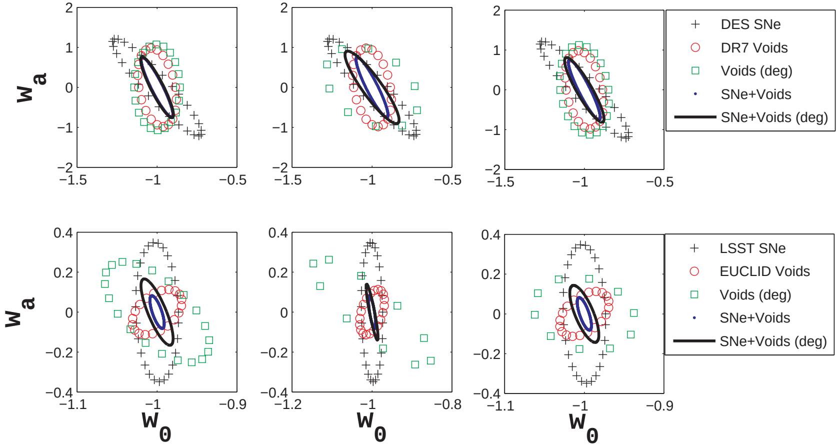
Bias

Marginalized over linear bias

Scatter

$0.1 < \sigma_\epsilon < 0.4$

Systematics



Biswas, Alizadeh & Wandelt, 2010

Constraints are interesting even accounting for systematic effects

Improvements in Figure of Merit

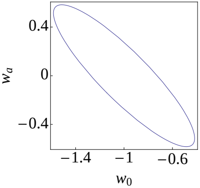


Figure of Merit, Dark Energy Task Force, Albrecht etal, 2006

- Inverse of Area of 2σ Error Ellipse determined from Fisher forecast.
- Relative Figure of Merit = FoM(interesting)/FoM(std)

Std: DES SN + PLANCK + HST

Std: LSST SN + PLANCK + HST

	SDSS+DES+HST+PLANCK		EUCLID+LSST+HST+PLANCK	
Parameters	Voids+CMB+HST	Voids + CMB+ HST +SNE	Voids+CMB+HST	Voids+CMB+HST+SNE
$A = 1, \sigma = 0.1$	1.2	16.8	8.8	331.0
$A = 2, \sigma = 0.1$	0.6	13.3	0.5	21.3
$A = 1, \sigma = 0.4$	0.5	7.7	0.7	27.6
Marginalized over b	0.2	3.3	0.2	104.5
$R_{\rm Smooth} = Min(\{R\})$	6.1	24.9	3.6	73.0
$R_{\rm Smooth} = R$	6.1	24.7	4.8	85.2

Conclusions

Summary

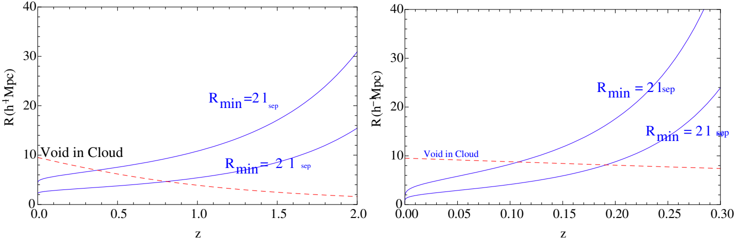
- Shapes of voids detected from spectroscopic galaxy surveys can be measured. When added to SNe, it improves FoM by ~ 10 (current) and ~ 100 (future)
- May be applied to other problems like neutrino masses, Non-Gaussianity of distributions

Issues to address in future

- Needs further checks for un-modelled effects
- Photometric surveys?

go back

Survey	f_{sky}	Freq Band	Limiting Magnitude	Number of Voids $\Delta = 0.4, \Delta = 0.1$	Number of Galaxies
SDSS DR7[1]	0.24	r	18	1292,3104	$1.7\ 10^6$
EUCLID[2]	0.48	K	22	$1.4\ 10^5$, $2.3\ 10^6$	$5.2\ 10^8$



[1] http://www.sdss.org/dr7/coverage/index.html
[2] http://hetdex.org/other_projects/euclid.php