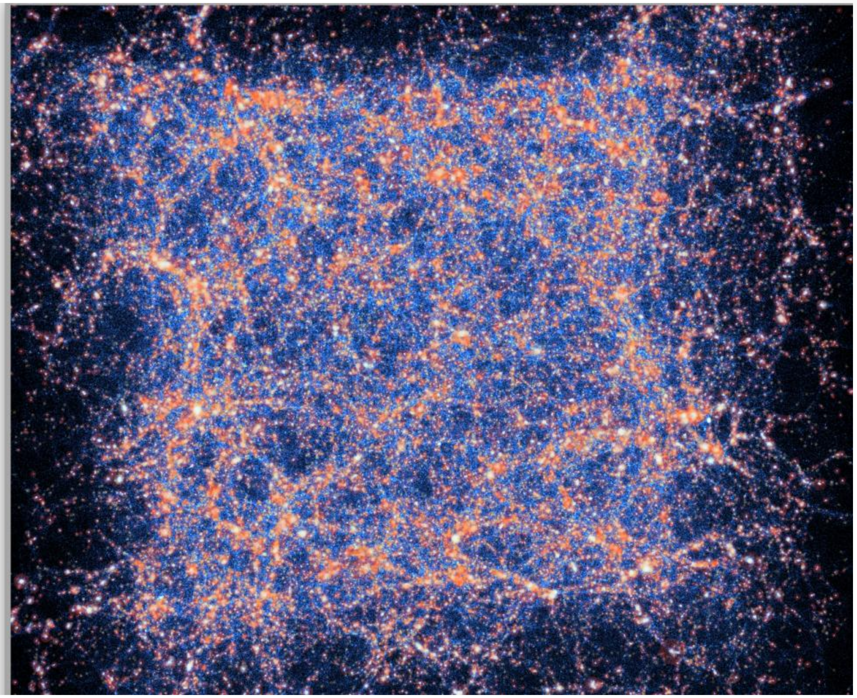
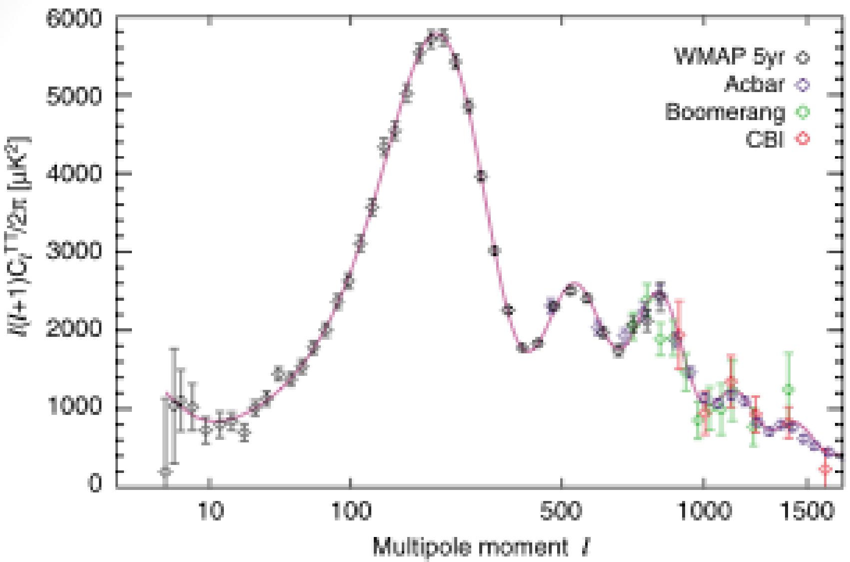
New techniques to measure the velocity field in Universe.



Suman Bhattacharya.
Los Alamos National Laboratory

Collaborators: Arthur Kosowsky, Andrew Zentner, Jeff Newman (University of Pittsburgh)

Constituents of the Universe



Komatsu et. al. 2008

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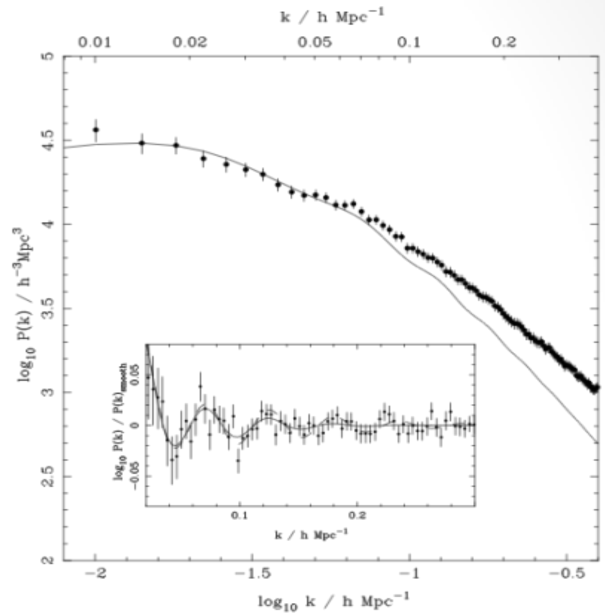

Percival et. al. 2007

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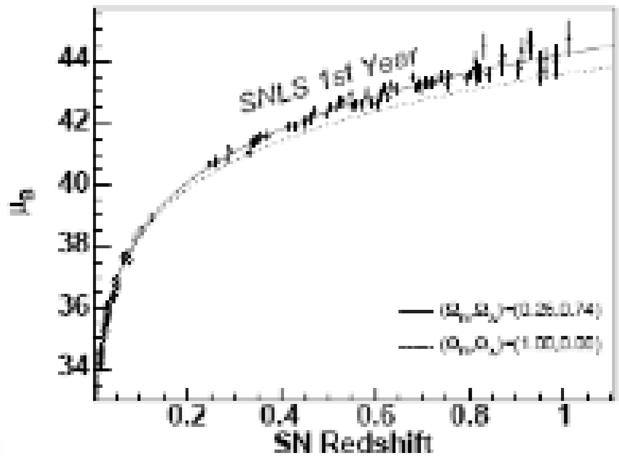
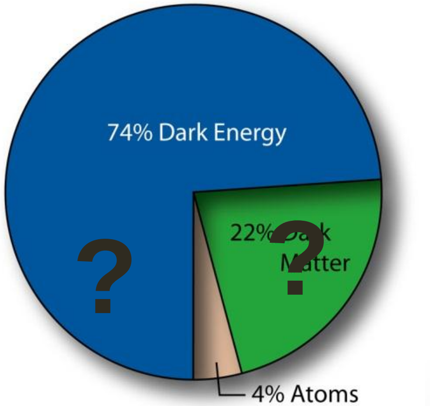


Astier et al 2006

=



Credit: NASA

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What is Dark Energy?

- Cosmological Constant (constant with time)
- Scalar field evolving with time.
- Current approach to study dark energy is largely phenomenological: consider dark energy a fluid
- -> characterized by three quantities:

$$w_{DE} = \frac{p_{DE}}{\rho_{DE}}$$ → **Equation of state**

$$c^2_{a,DE} = \frac{\dot{p}_{DE}}{\dot{\rho}_{DE}}$$ → **Speed of sound**

$$\Gamma_{DE} = \frac{\delta p_{DE}}{p_{DE}} - \frac{c^2_{a,DE}}{w_{DE}}\delta_{DE}$$ → **Entropy perturbation**

Current observations suggest w_{DE} ~[-0.8, -1.2] (consistent with cosmological constant!) and ρ_{DE} ~ [0.7, 0.8]

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Dark Energy Probes:

- 1. SNIa distance measures
- 2. BAO
- 3. Galaxy clusters
- 4. Weak lensing

velocity

Dark energy task Force report

Future goal is to constrain dark energy parameters with 1-2% accuracy.

Need to understand observational and theoretical uncertainties with similar accuracy

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Peculiar velocity

- The velocities with which objects are moving have an "extra" component other than just Hubble expansion. We call it *peculiar velocities*.
- **Why study velocity?** Velocity measurement provides information about the dynamics of structures.
- **Cosmic complementarity:**
- FRW universe + continuity equation relates density and velocity as

$$\frac{\partial \delta(\mathbf{x})}{\partial t} + \frac{\nabla \mathbf{v}(\mathbf{x})}{a} = 0,$$

Velocity power spectrum is related to density power spectrum as

$$P_{vv}(k) = \left(H(z) \frac{dD_\delta(z)}{dz} \right)^2 \frac{P_m(k)}{k^2}.$$

- where D(z) is the density growth rate

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How do we measure velocities?

- Typical velocities ~300 km/s.

1. Traditional redshift based surveys: subtract Hubble flow from measured redshift.

- Biases introduced in calibrating the distances.
- Error increases with z. Typically ~15-20 % of distance.
- Velocity as a cosmology probe limited to near redshift z~0.024 (Bridle et al 2001).
- Velocity of ~5000 nearby galaxies measured with error ~300-500 km/s. (SFI++ survey)

2. Redshift space distortions(distortions due to motion seen in galaxy power spectrum): good measurements (z<1), theoretical modeling issues exist. For z> 1 need space based mission (e.g., Euclid)

3. CMB distortion: error do not increase with redshift, other measurement errors exist, target massive clusters-> easier to model than galaxies.

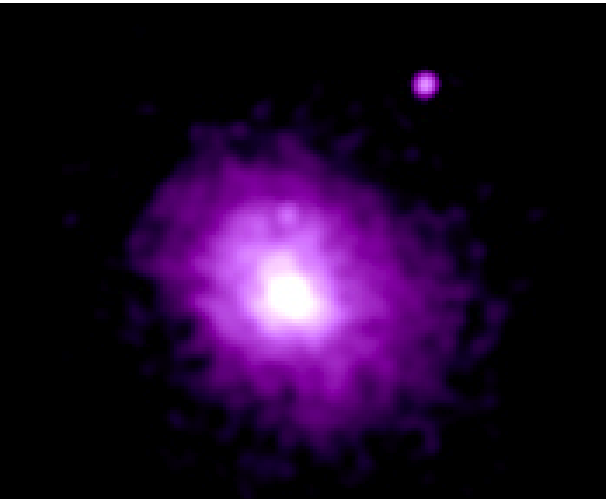
Current measurement of 15 cluster velocities exist but error ~1500 km/s (Benson et al 01)

Galaxy clusters:

-> Largest virialized objects in the universe .

-> typical properties: mass~ $10^{14} – 10^{15}$ solar mass, T~ 1-10 keV, L_x ~ 10^{44} ergs/sec, CMB temperature distortion~ 10^{-6} , formed around z~0.5-1.0 (youngest!), numbers vary from 10,000-100,000.

- Detected as i) bright spots in CMB maps: Sunyaev-Zeldovich effect ⟶ scattering of CMB photons off the hot electrons in clusters, ii) X-ray emission and iii) Counting galaxies in optical wavebands or as lensing of background matter.



X-ray emission

CMB shadows on top of galaxies

Telescopes/surveys: Chandra, XMM-Newton, eROSITA, ACT, SPT, Planck, SDSS, DES, LSST,…

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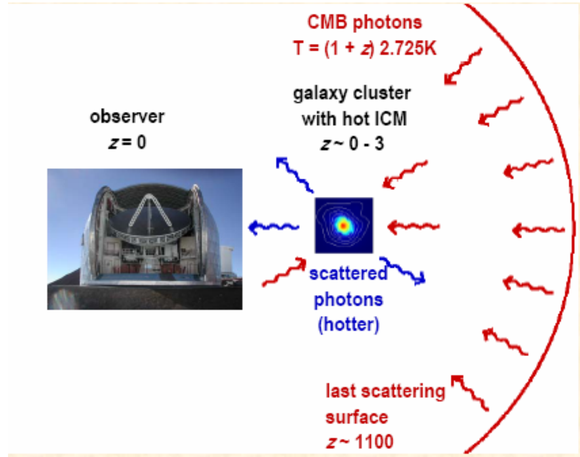
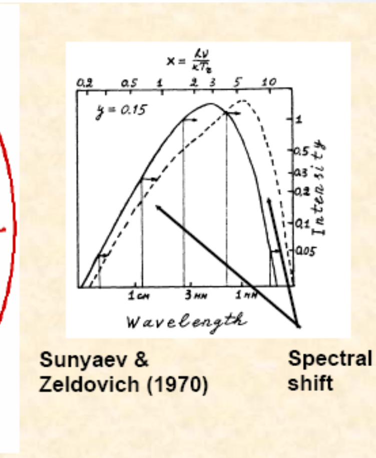
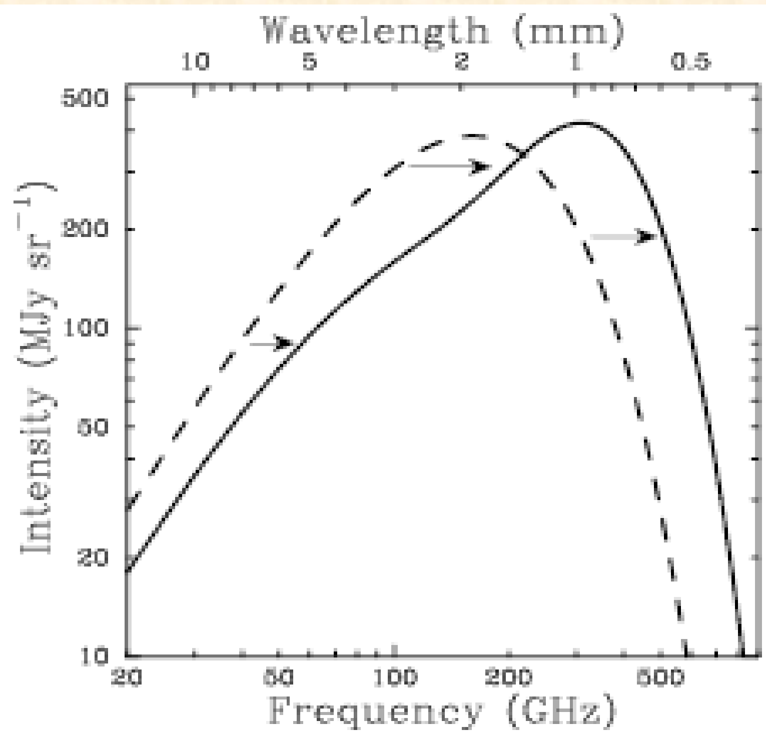
CMB distortions: Sunyaev-Zel'dovich Effect:

- CMB photons passing through galaxy clusters undergo collisions with electrons present within clusters causing a change in the spectrum (Thermal SZ effect).

- proportional to optical depth X Gas temperature.

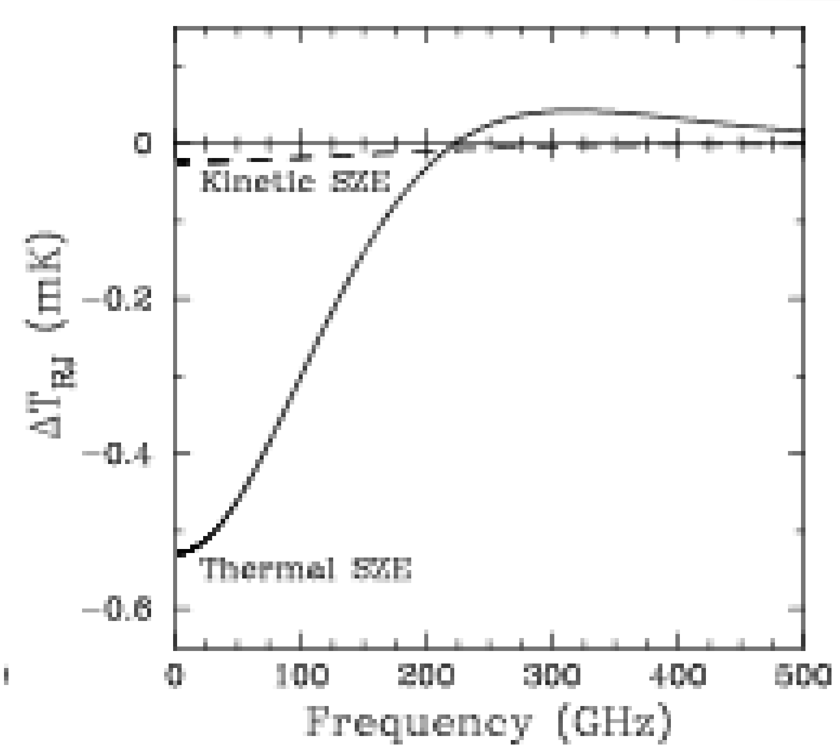






Kinetic SZ effect:

- This is due to scattering of photons off gas with bulk motion.
- Being Doppler shift, (approx.) spectrum of kSZ is still blackbody unlike tSZ.
- This effect is proportional to radial peculiar velocity X optical depth.
- Typically kSZ (~ 10 μK) << tSZ (~ 100 μK) in clusters of galaxies.



Credit: Carlston et al 2002

Ongoing SZ measurements

- ACT (150 sq deg); (Kosowsky(2003);

Fowler et al (2005)).

- SPT (4000 sq deg) (Ruhl et al (2004) designed to scan the microwave sky with very high sensitivity and arc minute resolution.

- Planck

- nominal sensitivity (2-10 μK) to measure kSZ.

Current ACT/SPT operational sensitivity ~ 20-30 μK

SZ -> cluster velocity

- Need at least 3 frequency channels and arc minute resolution.

- Get cluster parameters (T_e , v, optical depth)-> actually linear combinations from rel SZ flux from 3 frequency channels with 3-10 μk sensitivity. (Sehgal , Kosowsky & Holder 2005)

->Need x-ray follow-up. If ΔT_x =2 KeV then σ_v =100 km/s for a 3 KeV (or 2 x 10^{14} solar mass).

- A moderate X-ray follow-up is needed.

- Alternately, scaling relation like Y-T_e (scatter: 10-20%) can be used to break the degeneracy between velocity and temperature.

Modeling Errors:

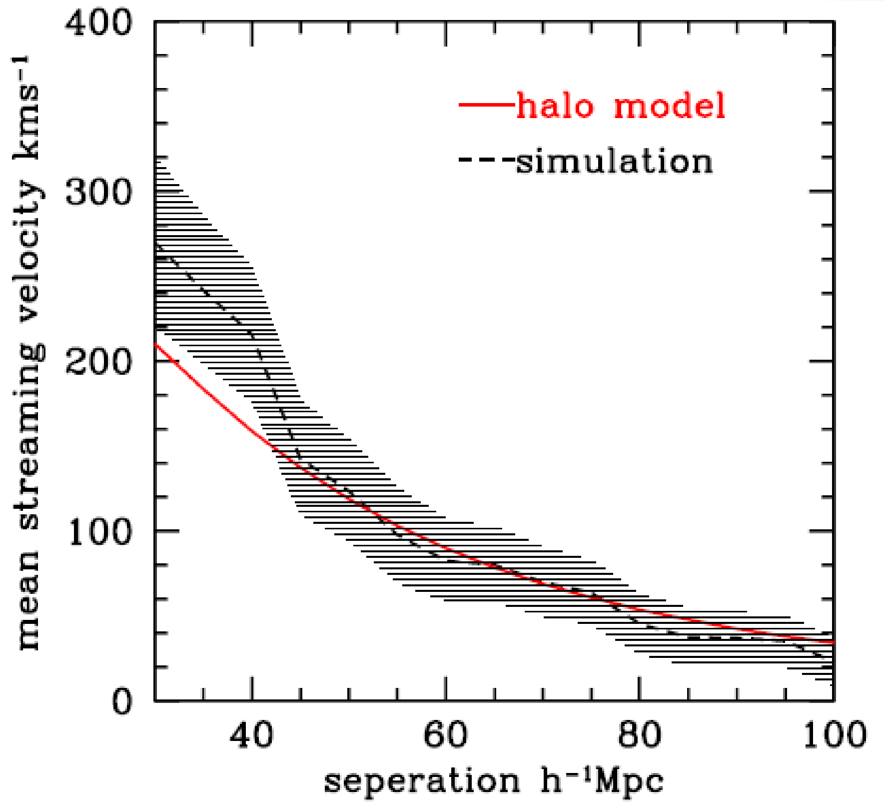
- Internal dispersion (100-130 km/s). (Nagai, Kravtsov & Kosowsky 2002; Diaferio et al 2004)
- Inaccuracy in mass or T_x : 20-30% of v_{rms} (=330 kmps)~ 60 km. (Diaferio et al 2004)
- Residual primary CMB +rel tSZ ~ unbiased few µk. (Hernandez-Monteagudo et al 2005; Forse & Aghanim 2004)
- Still don't know what extent IR point sources are correlated- some preliminary works suggests velocity error of 200 km/s including point souces, radio galaxies and lensing. (Knox, Holder & Church 2004)
- We assume velocity errors are normal distribution with σ_v = 200, 300, 400, 500 km/s…

Velocity statistics: mean pairwise velocity

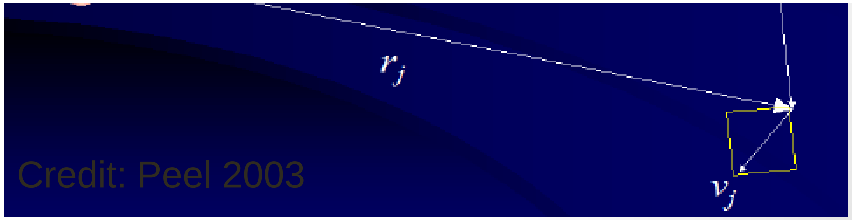
- Mean streaming velocity: average relative velocity of all clusters at a fixed separation along the line joining them.

  $V_{12}(r) = < (V_1 - V_2) . r >$

- Plots shows mean streaming velocity at redshift =0.1 as a function of separation.

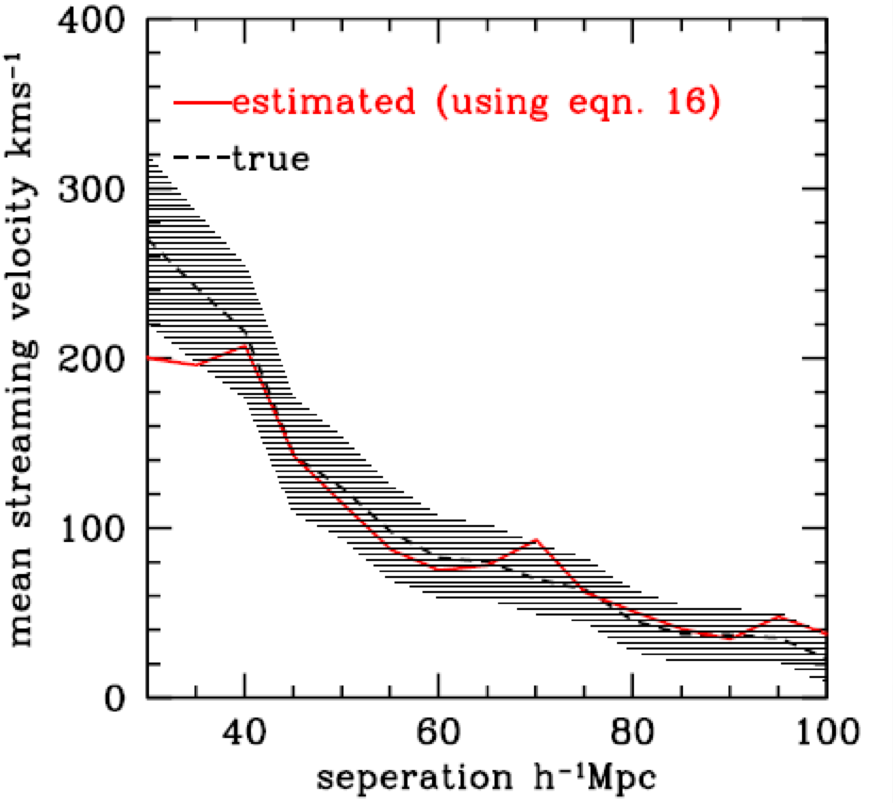


shaded-> 1σ error (shot noise + cosmic variance + measurement error).

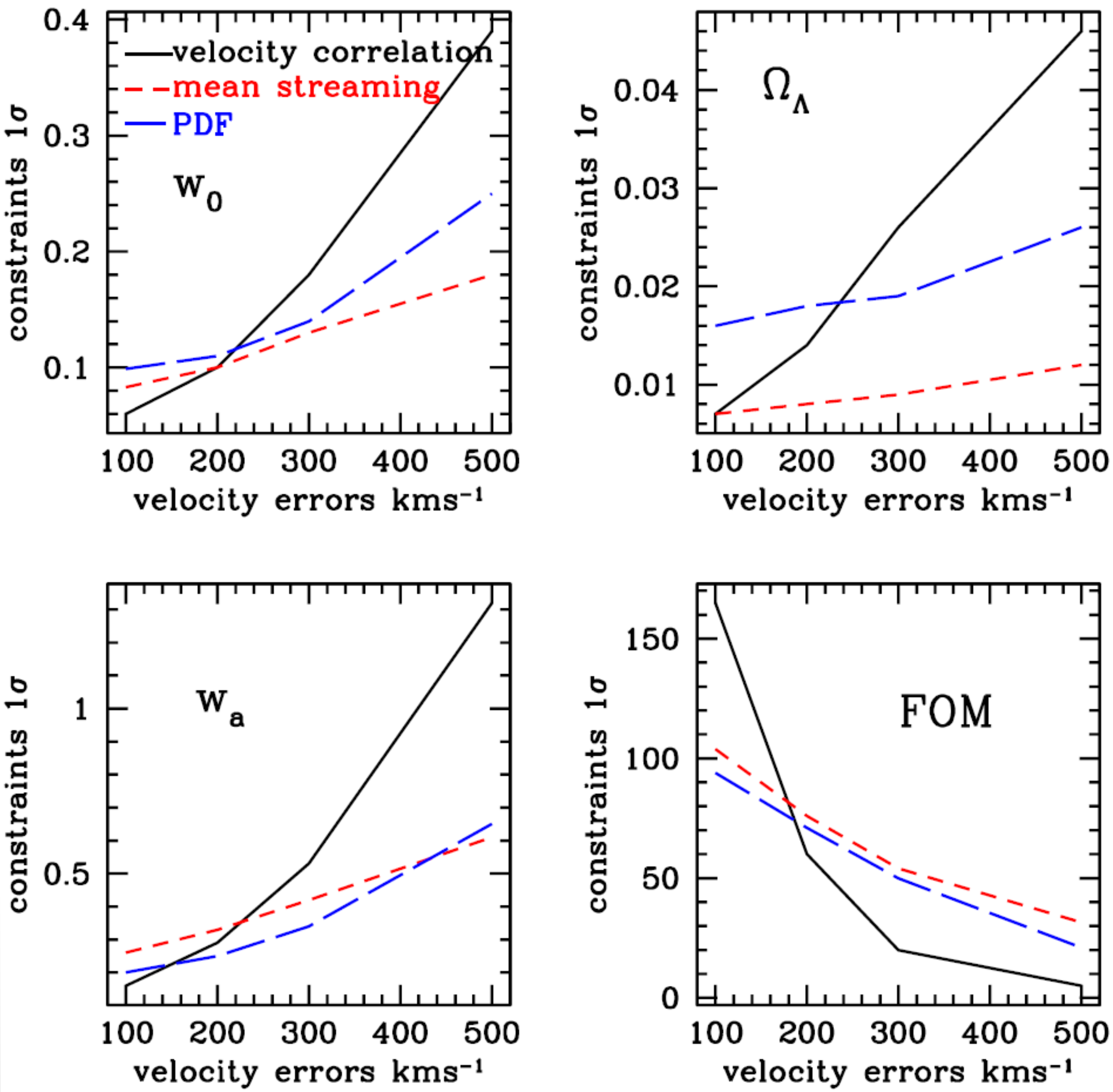


1D-> 3D

- However this is a 3D statistics and we only know radial component -> so need an estimator.
- Using a simple X^2-technique (Ferreira et al 1999), we can obtain an estimator that calculates $V_{12}(r)$ from radial velocities.
- Plot shows $V_{12}(r)$ true (red) and estimated (blue).



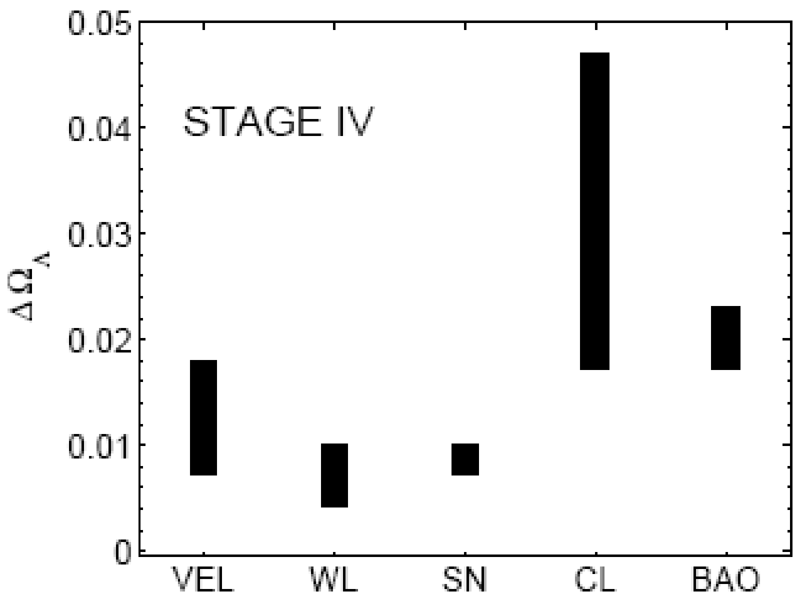
Effect of velocity errors on DE parameters:

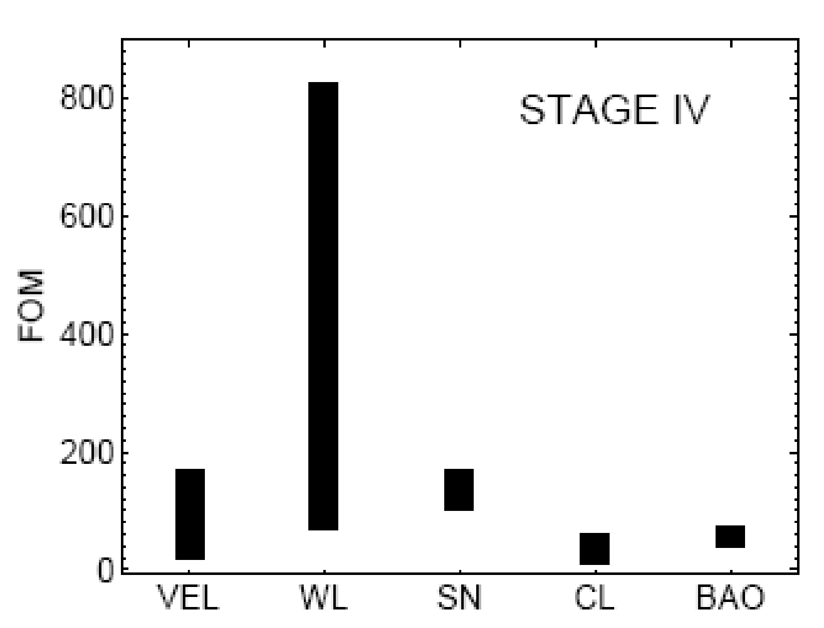


FOM=area of ellipse in w_a-w_0 space = 1/[σ(w_p) x σ(w_a)] where w_p is the pivot point where w is most constrained.

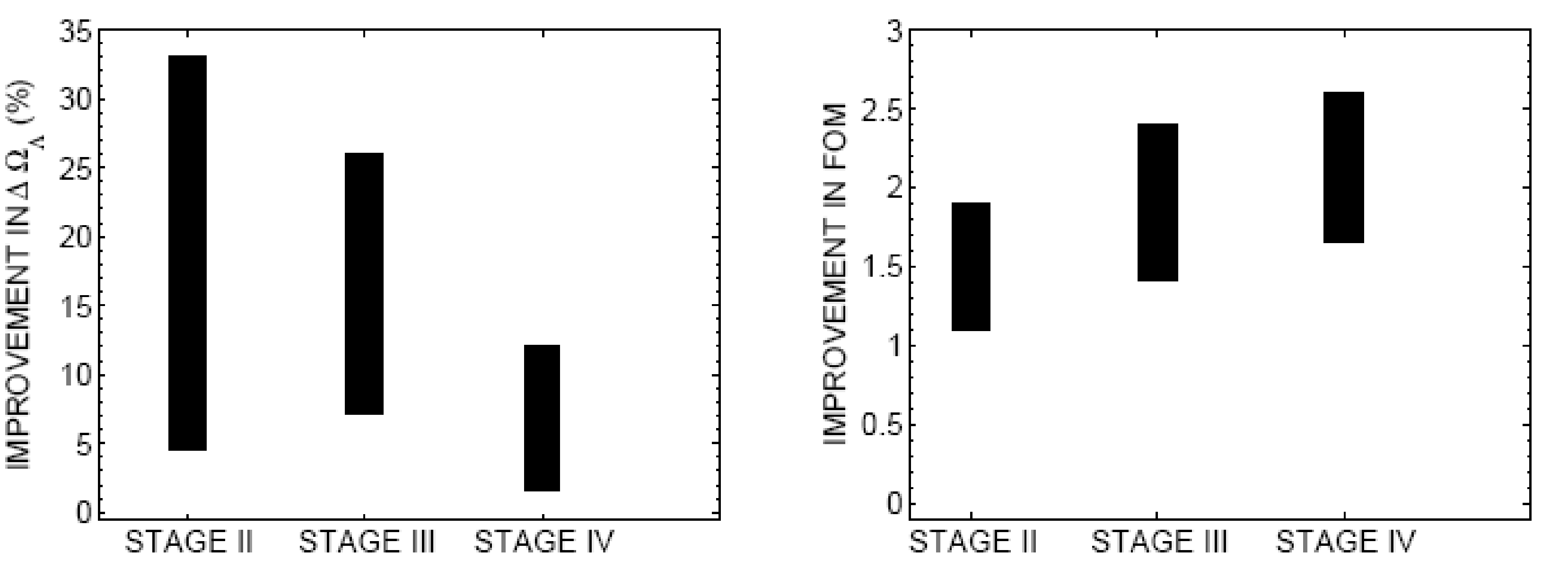
Bhattacharya & Kosowsky 2007

Prospects of stage IV velocity experiments (compared with other stage IV experiments)





Improvement at various stages when velocity added as a DE probe compared to when not added:



Bhattacharya and Kosowsky 07

Velocity as a probe of gravity

- While lensing probes the growth factor , velocity measurement probes the rate of growth.

(Jain & Zhang 2007)

- Redshift space distortions is one possible way but requires better modeling (Scoccimarro 2004) and accurate measurement of galaxy bias (Linder 2007, Jain & Zhang 2007).
- Write the velocity growth factor as $f = \Omega_m(a)^{\gamma}$
- Ω_m (a) is the matter density at scale factor a and γ is the gravitational growth index (Linder 2007)

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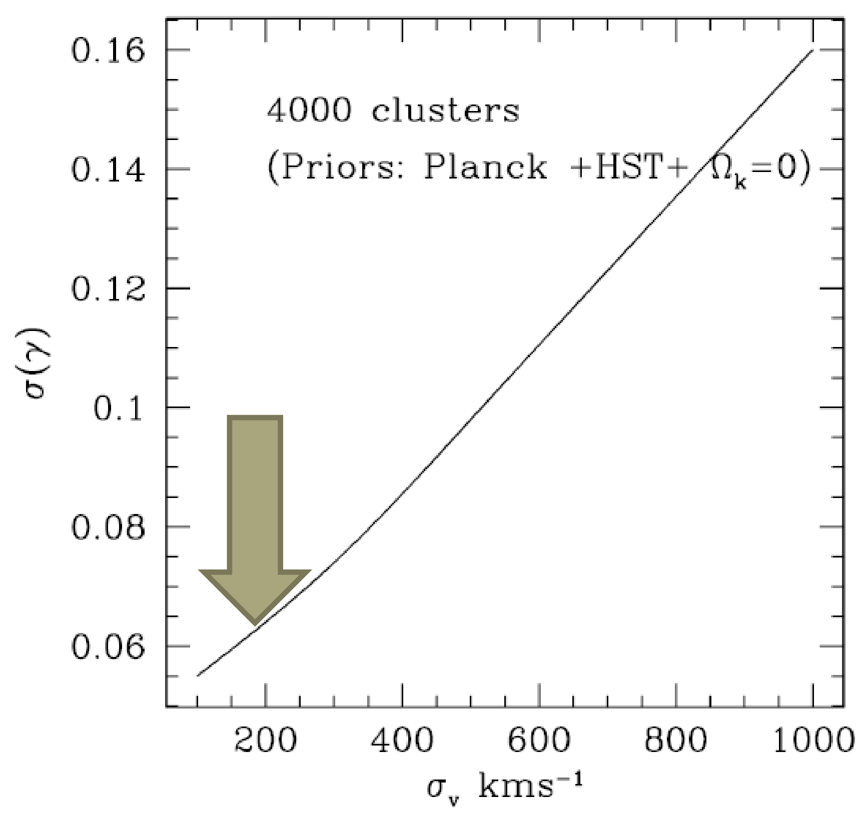
Constraint on gravitational growth index from cluster velocities:

- The difference in growth index between GR and DGP scenario is

$$\Delta\gamma = 0.13.$$

(Linder 2007)

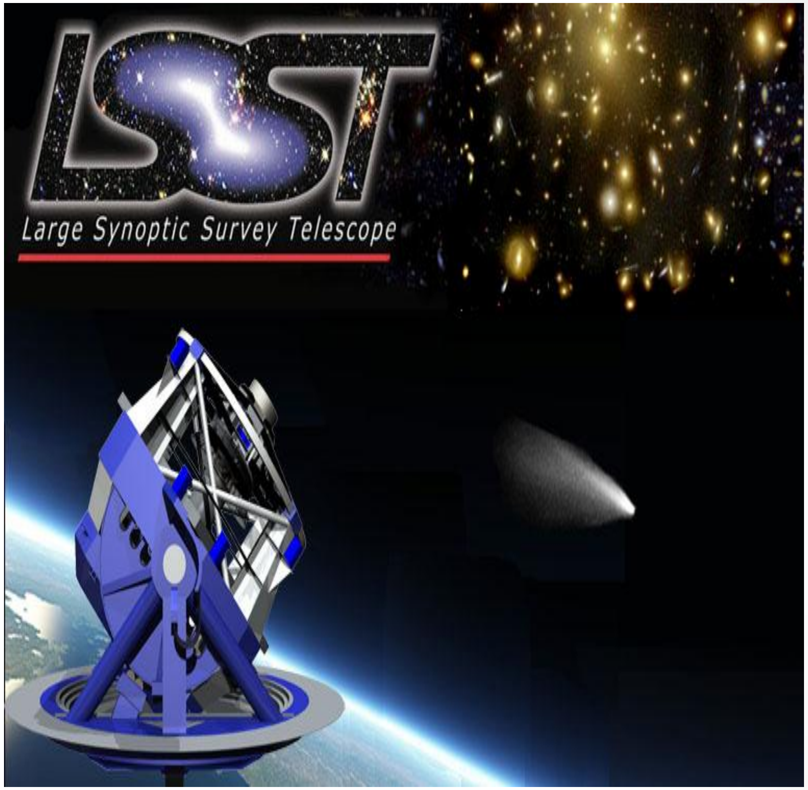
- With 4000 clusters and σ_v =200 km/s, GR and DGP can be distinguished > 2 σ level.



Kosowsky & Bhattacharya 2009, JCAP

LSST supernovae survey

- LSST is going to detect a large sample of supernovae over 10 year time period.
- Distance measurement provides dark energy constraints.
- Another possible science goal could be measuring peculiar velocity over cosmological volume at no extra observational effort.



velocities from supernovae

- SNe Ia are standard candles, so flux measurement tells us how far away they are.

- Peculiar velocity of the host galaxy is

$$v_{\rm los} = \frac{cz(\mu) - cz_{\rm meas}}{1 + z_{\rm meas}},$$

(Hogg 2000)

z_{obs} is obtained through photo-z follow-up.

z_{cos} is obtained through magnitude-$d_L(z)$ relation.

where magnitude of SNIa and luminosity distance is related as:

$$\mu = 2.17 \ln\left(\frac{d_L}{\rm Mpc}\right) + 25.$$

with luminosity distance :

$$d_L(z) = (1+z)d_C(z) = (1+z)c\int_0^z \frac{dz'}{H(z')},$$

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cosmological dependence

- Pair conservation gives

$$v_{ijgal}(r) = \frac{2}{3} H(z)\Omega_m(z)^{0.55+0.05(1+w_0)} D(z)^2 b_{gal} r \bar{\xi}_{DM}(r,0)$$

in the large scale limit. (Sheth et al 2001)

measurable

measurable

Calculated accurately

assume galaxy bias: $b_{gal}(z)$= 1.0 +0.6z

- Measurement error at z: $N \approx c\frac{z}{(1+z)}(\sigma_m/2.13 + \sigma_z/z)$

where σ_m is the intrinsic dispersion of SNIa and σ_z is the photo-z error

- For $\sigma_m = 0.1 \& \sigma_z = 0.01(1+z), N \approx 8000 kms^{-1}$ at z=0.5.
- Typical v~300 kms^{-1}, S/N per SNIa ~0.04.
- Noise in v_{ijgal} (r) measurement at redshift z~ √2N(z)/ nSN(z)

survey requirements

- Density of SNe Ia matters, not the total number.
- Area > 300 deg^2 to suppress sample variance effect.
- Total ~300,000 SNe Ia with intrinsic magnitude error $\sigma_m = 0.1$ => 1000 per deg^2. (DETF LSST optimistic, Albrecht et al 2006)
- Rate of SNIa ~ $\frac{d^3 n}{d\Omega\, dz\, dt} \propto \begin{cases} \exp(3.12 z^{2.1}) - 1, & z \leq 0.5, \\ \left(\exp(3.12 z^{2.1}) - 1\right) \exp(-12.2(z-0.5)^2), & z > 0.5. \end{cases}$

(Zhan et al 2008)

- Photoz error: $\sigma_z = \sigma_{z0}(1+z)$, $\sigma_{z0} = 0.01$
  (DETF LSST optimistic, Albrecht et al 2006)
- Current measured SNe Ia rate ~ $1.2^{+2}_{-1} \times 10^{-4}\, \mathrm{yr}^{-1}\, h^3\, \mathrm{Mpc}^{-3}$
  (Neill et al 2007)
- Needs ~5-10 years of LSST observation to achieve the rate.

error budget

- ***statistical error:***
- 1. dispersion in SNIa magnitude.
- 2. photoz dispersion.
- 3. dispersion due to lensing.
- 4. sample variance

- ***systematic error:***
- arise due to redshift evolution of SNIa properties (or SNIa not being perfect standard candles!).

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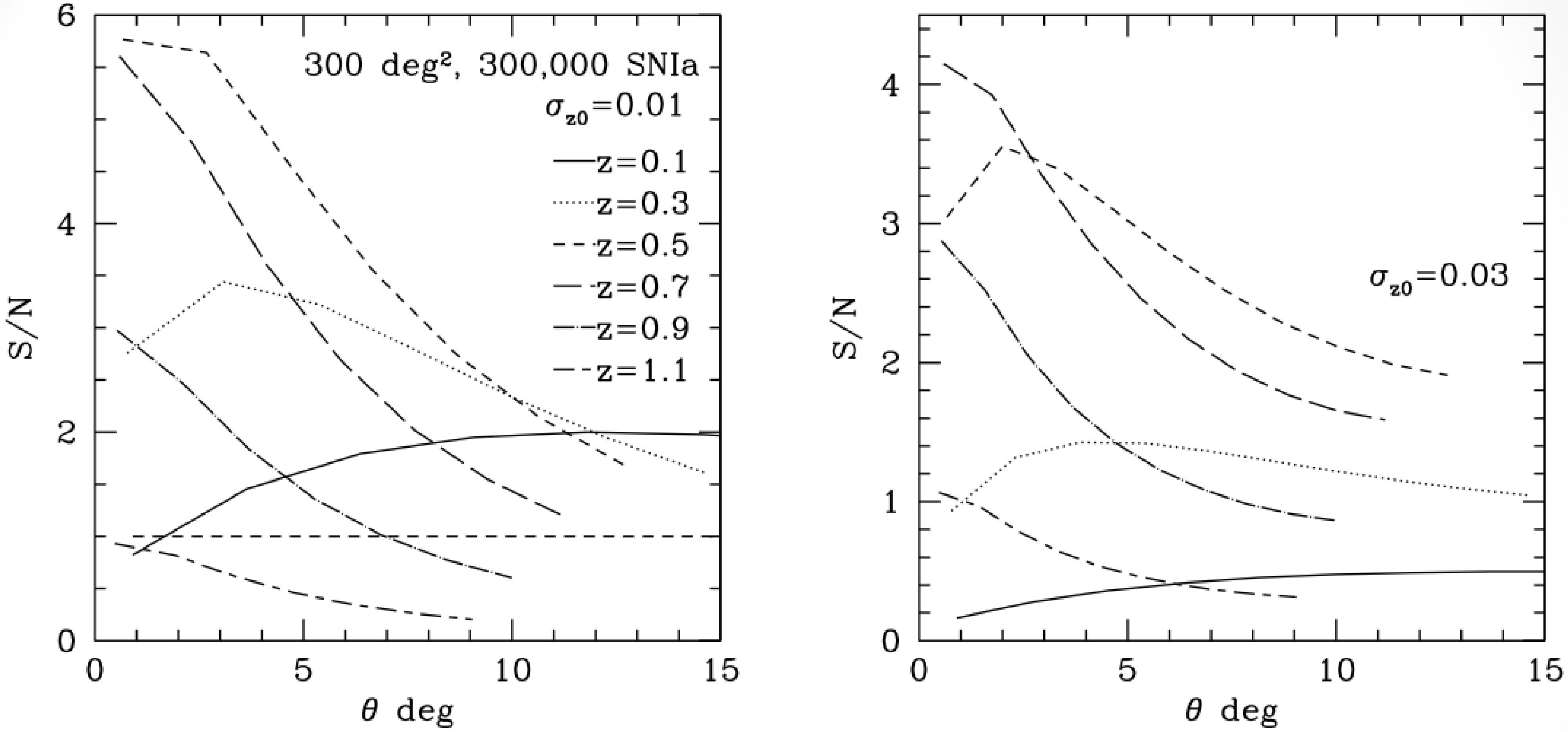
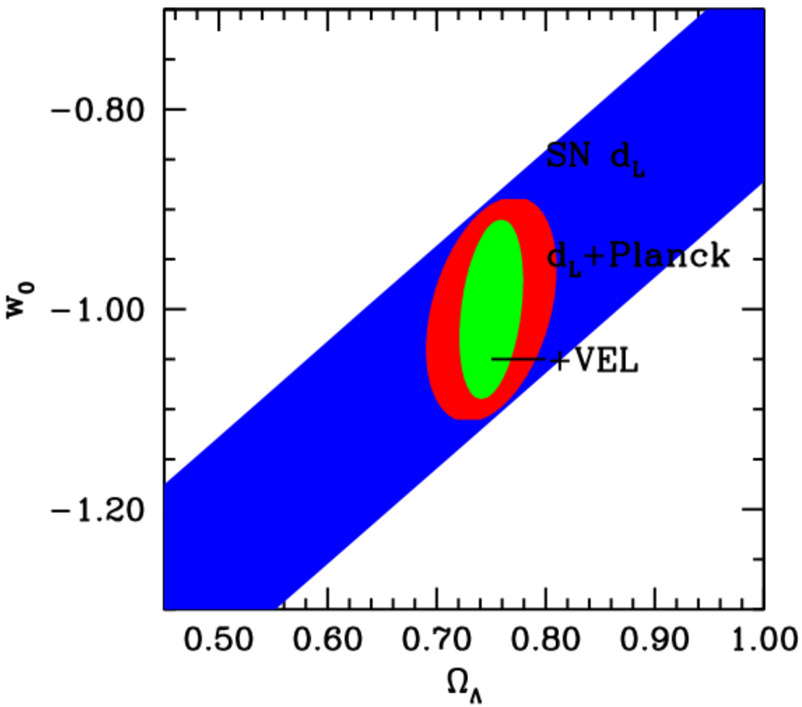
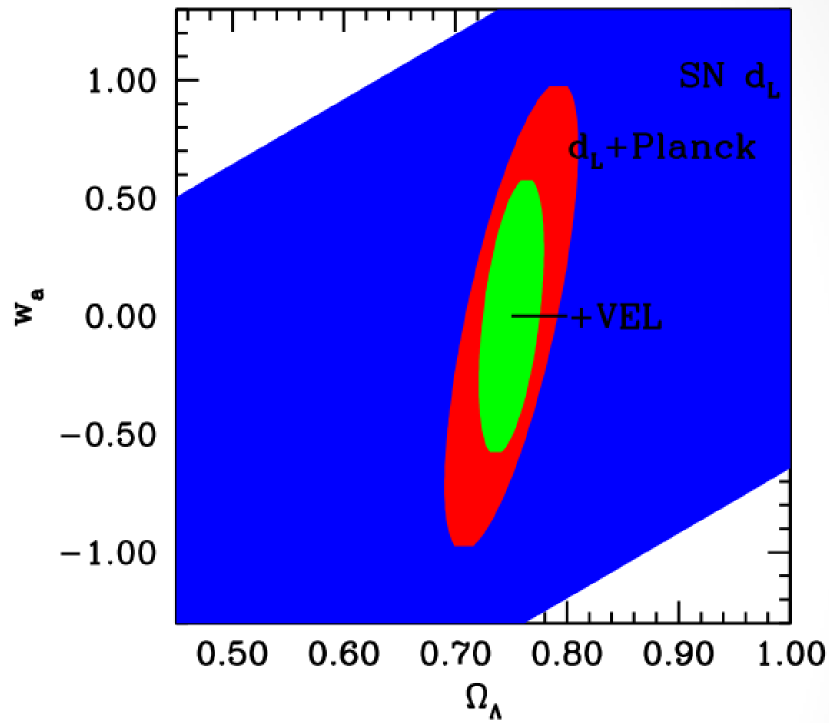
signal to noise (statistical)



Bhattacharya, Kosowsky, Newman and Zentner 10, PRD

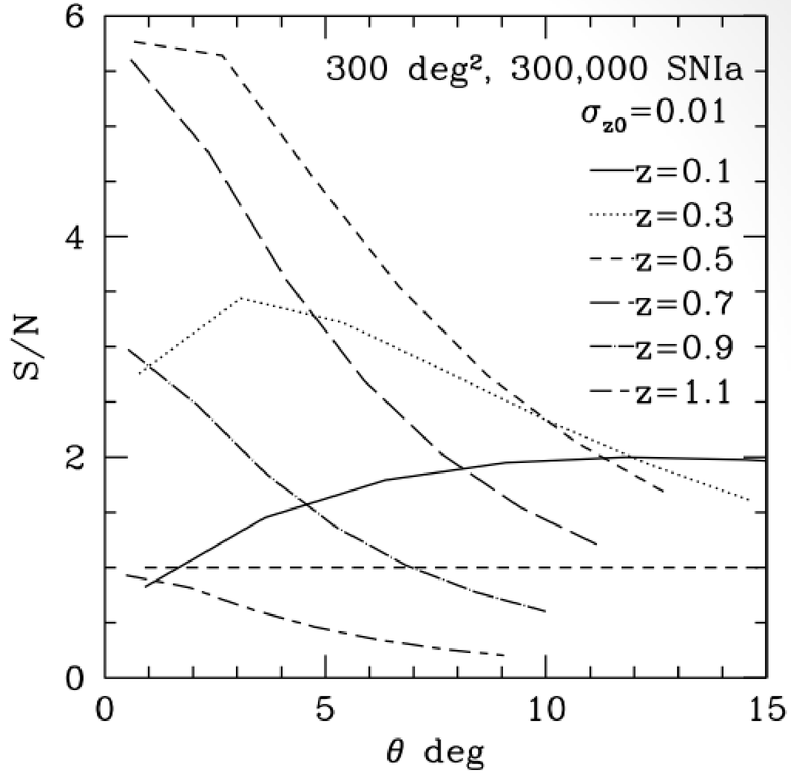
velocity from supernovae as a DE probe





- Constraints on $\Omega_\Lambda \sim 2.5\%$, $w_0 \sim 20\%$ and $w_a \sim 0.31$ from velocity only.
- Figure of Merit for DE (inverse of area of the ellipse in $w_0 - w_a$) improves by factor 2.1 when VEL added to SN d_L + Planck + HST prior.

testing GR:



-> assume measurements at 5 separation bin per z with S/N ~ 4 per bin
in each z.

-> This gives measurement on d log D/d log a ~ 0.25/√5= 0.11

-> $$\frac{d\,\log\mathrm{D}}{d\,\log\mathrm{a}} = \Omega_m(z)^\gamma => \gamma = 25 - 50\%\ \mathrm{per\ z\ bin}$$

Summary:

- SZ effect can be used to measure the velocities of galaxy clusters
- Such a dataset can be used to probe dark energy parameters.
- A unique feature of velocities is to test any deviation from General Relativity.
- Future LSST surveys detecting ~ million SNe can be used to measure velocities of host galaxies.

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Cosmological Parameter space

$\Omega_{m(DM+b)} = 0.29 - 0.34.$

- Matter density (CDM +Baryons).

$n = 0.93 – 0.96.$

- power spectrum index.

$\sigma_8 = 0.68 – 0.79.$

- Amplitude of fluctuations

$h = 0.7-0.76.$

- Hubble parameter

$w = 0.9 – 1.15$

(include w_a as well)

- Dark Energy equation of state.

Current constraints from WMAP3 Spergel et al 2006

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Constraining DE parameters using velocity statistics:

- Use fisher matrix ->

$$F_{\alpha\beta} = \sum_{k,l} \frac{\partial \phi(x_k, z_l)}{\partial p_\alpha} \frac{1}{\sigma_\phi^2} \frac{\partial \phi(x_k, z_l)}{\partial p_\beta}$$

- Marginalize over other parameters to constrain DE parameters.
- Use HST +Planck priors+ flat priors to compare with the dark energy task force (Albrecht et al 2006) proposed observations (WL, SnIa, Cl, BAO)
- DETF FOM=area of ellipse in w_a-w_0 space = 1/[σ(w_p) x σ(w_a)] where w_p is the pivot point where w is most constrained.

from theory to observation

- 3D vij in real space-> vij in photoz space.
- project 3D velocity to 2D (projected)

$$\tilde{v}(\theta, a) = \int_0^{\pi_{\max}} d\pi_t P(\pi_t|\theta, a) v(r, a), \quad P(\pi_t|\theta, a) = \frac{1 + \xi^{\rm gal}(r, a)}{\int_0^{\pi_{\max}} d\pi_t \left[1 + \xi^{\rm gal}(r, a)\right]}$$

$$r = \sqrt{\theta^2 d_M(a)^2 + \pi_t^2},$$

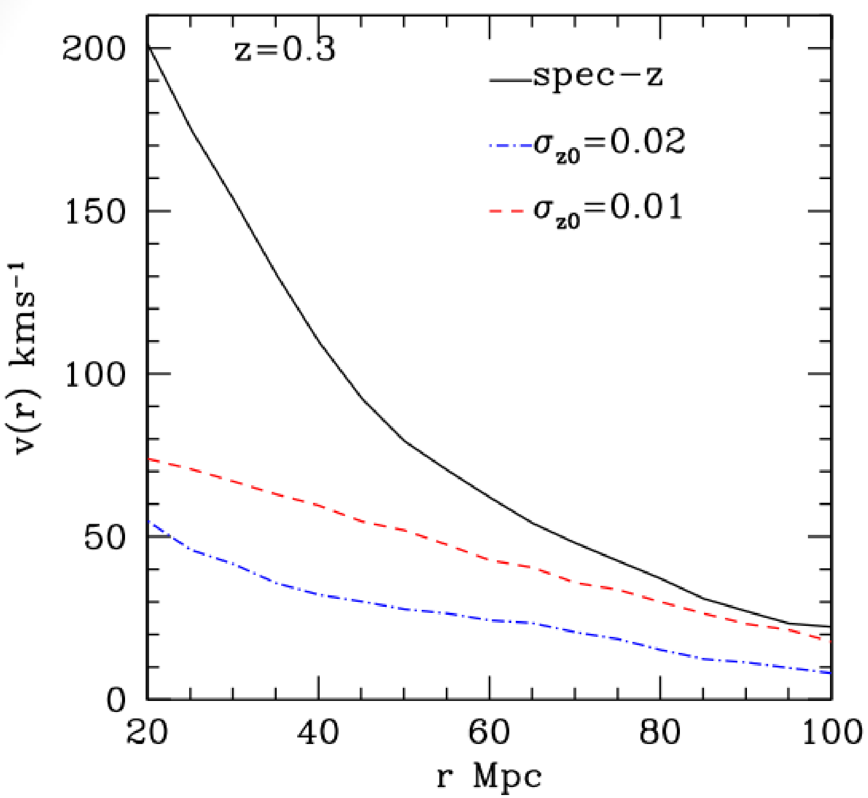
- redshift not perfectly known-> need to include photometric redshift error distribution

$$P(z_p|z, \sigma_z) = \frac{1}{\sqrt{2\pi\sigma_z^2}} \exp[-(z - z_p)^2/(2\sigma_z^2)].$$

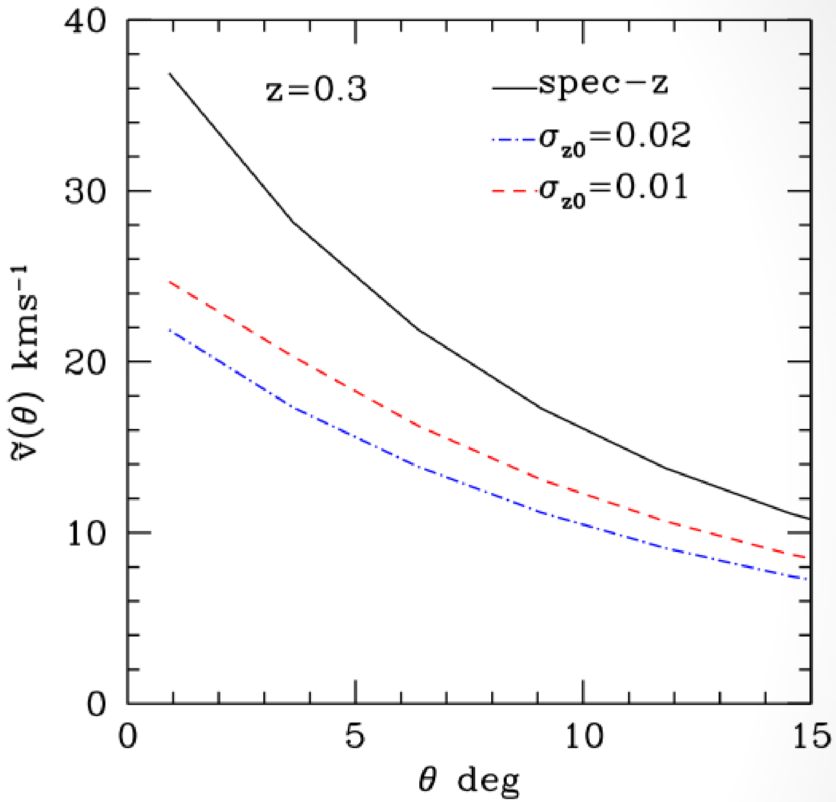
- projected vij in photoz space:

$$\tilde{v}(\theta, a|\sigma_\pi(a)) = \int_0^{\pi_{\max}} d\pi_t \int_0^{\infty} d\pi_{\rm obs} P(\pi_t|\theta, a) P(\pi_{\rm obs}|\pi_{\rm t}, \sigma_\pi(a))\, v((\theta^2 d_C(a)^2 + \pi_t^2)^{1/2}, a).$$

effect of photoz errors



3D statistics



Projected vij

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