Looking for deviations in the large scale structure

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The large scale structure

(Very) tentative definition :

"*Everything above galaxy scale that is sensitive to gravitational instability.*"

2dFGRS (2002) :

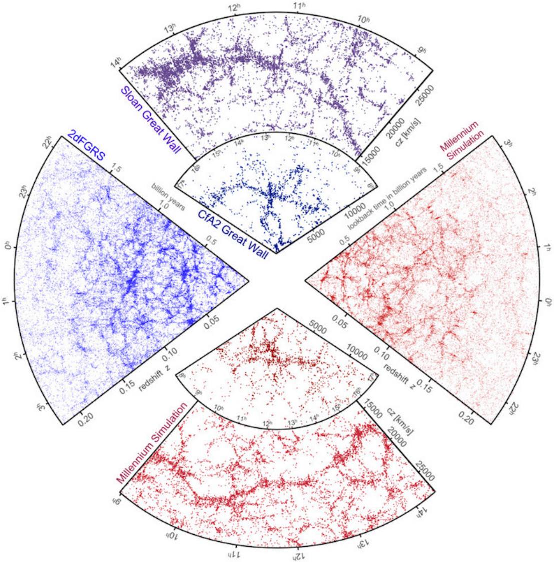
- 2.5 Gly depth on 2 slices
- $\sim$ 1500 sqdeg area
- spectra for $\sim$ 250k objects
- http ://www.2dfgrs.net/

Millennium Run (2005) :

- 10 G particles
- 2 Gly box
- $\sim$ 20 M galaxies

Sloan Digital Sky Survey :

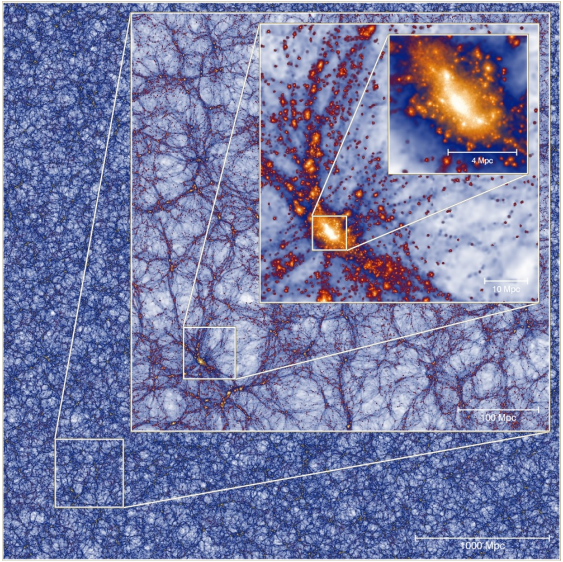
- 3 M spectra
- $\sim$ 35% of the sky



Millennium-XXL (2010)

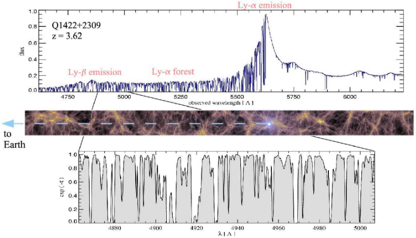
- 300 billion particles
  whole Univ. to $z \sim 0.72$
- goal 1 : relation between optical richness, lensing mass, X-ray luminosity and thermal Sunyaev-Zeldovich (tSZ) signal from CMB
- goal 2 : mass of extreme galaxy **clusters**
- **useful for other probes :** BAOs, redshift space distortions (RSD), cluster number counts, weak gravitational lensing (WL), integrated Sachs-Wolfe (ISW) effect.
- halo mass function, power spectrum
- gives optical, lensing, X-ray, tSZ maps, galaxy clusters catalogues

See Angulo *et al.* 2013.

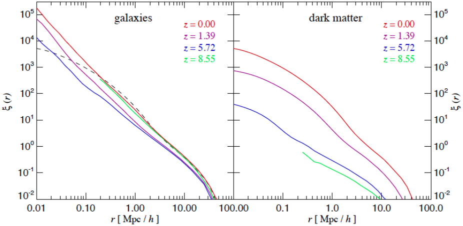


Examples of probes

- Intergalactic H absorption lines in quasar spectra $\Rightarrow$ Lyman-α forest.



- 2pt-correl. (of galaxies or DM) $\Leftrightarrow$ Power spectrum $P_g(\mathbf{k}) = b^2 P_m(\mathbf{k})$



Source of images : Springel, Frenk, White 2006

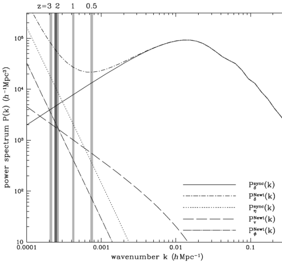
Two aspects of this talk

- **RELATIVISTIC CORRECTIONS DUE TO THE LSS :** *how does the LSS affects cosmological observables, how we can use adapted coordinates which actually simplify calculations.*

- **COMPARING STANDARD CANDLES AND GALAXY CATALOGUES IN OUR LOCAL UNIVERSE :** *what can we learn by comparing these probes, what it can say about the H_0 tension, supernovae or galaxy catalogues.*

PART I
RELATIVISTIC CORRECTIONS DUE TO THE LSS

Relativistic corrections to LSS



Context : Perturbations around a FLRW background.

Galaxy clustering (Yoo, Fitzpatrick, Zaldarriaga '09, Yoo '10) :

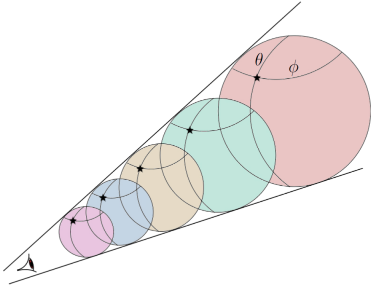
- $\delta_g = b\,\delta_m$ is affected by relativistic corrections.
- δ_m and $b(k)$ are both **gauge dependent** quantities.
- gauge effects appear near horizon and at large z (where Newt. approx. is not valid) $\Rightarrow$ **Test of GR !**
- total number of observed galaxies is affected by matter perturbations.

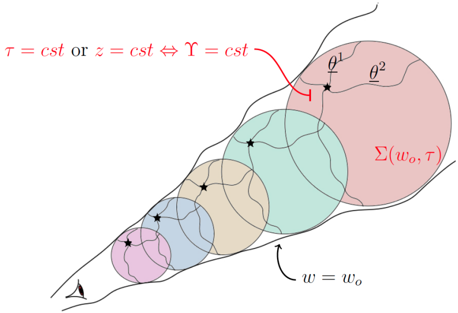
Generalization of **Kaiser formula** (valid at small scales) relating redshift-space power spectrum $P_s(\mathbf{k}, \mu_k)$ and $P_m(\mathbf{k})$ (Montanari, Durrer '12, Bertacca *et al.*'12, Yoo, Seljak '13).

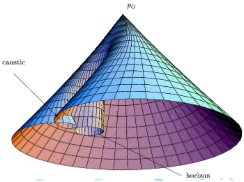
Impact of relativistic corrections : luminosity distance (Hubble diagram), redshift, angles (gravitational lensing), volumes (number counts).

Geodesic Light Cone coordinates (GLC)

Adapted coordinates : Simplify relativistic calculations by working in coordinates defined from observable (gauge-invariant) quantities.







History : Temple 1938, Joseph '58, Saunders '68, Maartens '84, Gasperini, Marozzi, N., Veneziano 2011.

$$ds^2_{\mathrm{GLC}} = \Upsilon^2 \mathrm{d}w^2 - 2\Upsilon \mathrm{d}w\mathrm{d}\tau + \gamma_{ab}(\mathrm{d}\underline{\theta}^a - U^a \mathrm{d}w)(\mathrm{d}\underline{\theta}^b - U^b \mathrm{d}w)$$
$$\text{(6 arbitrary functions } : \Upsilon,\ U^a,\ \gamma_{ab})$$

w is a null coordinate, $\partial_\mu \tau$ defines a geodesic flow (from $g^{\tau\tau}_{GLC} = -1$), photons travel at $(w, \underline{\theta}^a) = \overrightarrow{cst}$ $\perp$ to $\Sigma(w, z)$.

Υ is like an **inhomogeneous scale factor** (lapse function), U^a is a **shift-vector** and γ_{ab} the **metric inside the 2-sphere** $\Sigma(\tau, w)$.

$$\text{FLRW}: \quad w = \eta + r\ ,\ \tau = t\ ,\ (\underline{\theta}^1, \underline{\theta}^2) = (\theta, \phi)\ ,$$
$$\Upsilon = a(t)\quad,\quad U^a = 0\quad,\quad \gamma_{ab} = a^2 r^2 \mathrm{diag}(1, \sin^2\theta)\quad.$$

Residual gauge freedoms : relabeling light cones/rays ; reparametrizing light rays ; conformal transformations (Fleury, N., Fanizza '16, Scaccabarozzi, Yoo '17)

⇒ **Redshift perturbation** :

$$\boxed{(1+z_s) = \frac{(k^\mu u_\mu)_s}{(k^\mu u_\mu)_o} = \frac{(\partial^\mu w \partial_\mu \tau)_s}{(\partial^\mu w \partial_\mu \tau)_o} = \frac{\Upsilon(w_o, \tau_o, \underline{\theta}^a)}{\Upsilon(w_o, \tau_s, \underline{\theta}^a)} \equiv \frac{\Upsilon_o}{\Upsilon_s}}$$

where $u_\mu = -\partial_\mu \tau$ is the peculiar velocity of the **comoving** observer/source and $k_\mu = \partial_\mu w$ is the photon momentum.

⇒ **(exact) Angular distance** (with homogeneous observer neighborhood) :

$$\boxed{d_A = \gamma^{1/4} \left(\sin \underline{\theta}^1\right)^{-1/2} \quad \text{with} \quad \gamma \equiv \det(\gamma_{ab}) = |\det(g_{\mathrm{GLC}})|/\Upsilon^2}$$

which, combined with redshift, gives the **distance-redshift relation**.

⇒ expressions of **luminosity distance** $d_L = (1+z)^2 d_A$ and **distance modulus** $\mu = 5\log_{10}(d_L) + \mathrm{cst}$.

Distance-redshift relation at $\mathcal{O}(2)$

- Define scalar perturbations in the Newtonian gauge :

$$ds^2_{NG} = a^2(\eta)\left(-(1+2\Phi)\mathrm{d}\eta^2 + (1-2\Psi)(\mathrm{d}r^2 + \gamma^{(0)}_{ab}\mathrm{d}\theta^a\mathrm{d}\theta^b)\right)$$

with $\gamma^{(0)}_{ab} = r^2 \mathrm{diag}\left(1, \sin^2\theta\right)$, $\Phi = \psi + \frac{1}{2}\phi^{(2)}$, $\Psi = \psi + \frac{1}{2}\psi^{(2)}$, and taking $\psi^{(2)}, \phi^{(2)} \propto \nabla^{-2}(\partial_i\psi\partial^i\psi)$, $\partial_i\psi\partial^i\psi$ (cf. Bartolo, Matarrese, Riotto, 2005)

- Establish transformation between GLC and NG at second order in PT :
$(\tau, w, \widetilde{\theta}^1, \widetilde{\theta}^2) = f(\eta, r, \theta, \phi) \quad \Rightarrow \quad (\Upsilon, U^a, \gamma^{ab}) = f(\psi, \psi^{(2)}, \phi^{(2)})$

- Use $d_L = (1+z)^2\, d_A = (1+z)^2\,\gamma^{1/4}\left(\sin\tilde{\theta}^1\right)^{-1/2}$ up to $\mathcal{O}(2)$ to get :

$$d_L(z_s, \underline{\theta}^a) = d_L^{FLRW}(z_s)\left(1 + \delta^{(1)}_S(z_s, \underline{\theta}^a) + \delta^{(2)}_S(z_s, \underline{\theta}^a)\right)$$

- Details in 1104.1167, 1209.4326, 1506.02003, contributors : Ben-Dayan, Fanizza, Gasperini, Marozzi, N., Veneziano, in qualitative agreement with Umeh, Clarkson and Maarten '14, Bonvin, Clarkson, Durrer, Maartens, Umeh '15, Kaiser, Peacock '15, and recently Yoo, Scaccabarozzi '16 !

At $\mathcal{O}(1)$:

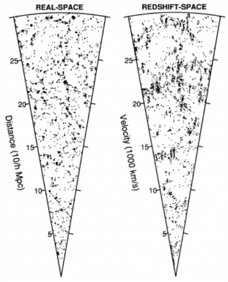
$$\delta_S^{(1)}(z_s,\theta^a) \sim \mathrm{SW} + \mathrm{ISW} + \mathrm{Doppler} - \left(\psi_s^{(1)} + \int_{\eta_+}^{\eta_-} \mathrm{d}x\ \psi\right) - \mathrm{Lensing}^{(1)}$$

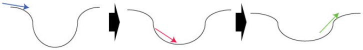
$$\mathrm{Lensing}^{(1)} = \frac{1}{2}\nabla_a\theta^{a(1)} = \int_{\eta_s^{(0)}}^{\eta_o} \frac{d\eta}{\Delta\eta}\ \frac{\eta-\eta_s^{(0)}}{\eta_o-\eta}\Delta_2\psi(\eta,\eta_o-\eta,\bar{\theta}^a)$$

$$\mathrm{Doppler} = \left(1-\frac{1}{\mathcal{H}_s\Delta\eta}\right)(\mathbf{v}_o-\mathbf{v}_s)\cdot\hat{n} \quad , \quad \mathbf{v}\equiv\int_{\eta_{\rm in}}^{\eta}\mathrm{d}\eta'\,\frac{a(\eta')}{a(\eta)}\nabla\psi(\eta',r,\theta^a)$$

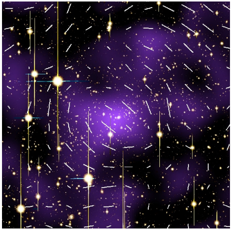
At $\mathcal{O}(2)$, full calculation :

- **Dominant terms** : $(\mathrm{Doppler})^2$, $(\mathrm{Lensing})^2$!!!
- Combinations of $\mathcal{O}(1)$-terms : ψ_s^2, $([\mathrm{I}]\mathrm{SW})^2$, $[\mathrm{I}]\mathrm{SW} \times \mathrm{Doppler}$, $(\psi_s, \int_{\eta_+}^{\eta_-} dx\ \psi)\times$ (Lensing, [I]SW, Doppler) ...
- Genuine $\mathcal{O}(2)$-terms : $\psi_s^{(2)}$, $\mathrm{Lensing}^{(2)} = \frac{1}{2}\nabla_a\theta^{a(2)}$, $Q_s^{(2)}$...
- A LOT of other contributions : New integrated effects, Angle deformations, Redshift perturbations($\subset$ transverse peculiar velocity), Lens-Lens coupling, corrections to Born approximation, ... *See 1209.4326, also Umeh 1402.1933*.





Gravitational well of galaxy supercluster - the depth shrinks as the universe (and cluster) expands



4.2. DETAILED EXPRESSION FOR $D_L(Z, \theta^A)$

$$
\begin{aligned}
\bar{\delta}^{(2)}_{path} = \; & \Xi_s \Bigg\{ -\frac{1}{4}\left(\phi^{(2)}_s - \phi^{(2)}_o\right) + \frac{1}{4}\left(\psi^{(2)}_s - \psi^{(2)}_o\right) + \frac{1}{2}\left(\psi_s - \psi_o\right)^2 - \psi_o J_2^{(1)} \\
+ \; & (\psi_o - \psi_s - J_2^{(1)})[\partial_+ Q]_s + \frac{1}{4}(\gamma_0^{ab})_s \partial_a Q_s \partial_b Q_s + Q_s\left(-[\partial_+^2 Q]_s + [\partial_+\psi]_s\right) + \frac{1}{\mathcal{H}_s}(\psi_o + [\partial_+ Q]_s)[\partial_\eta \psi]_s \\
- \; & \frac{1}{2}\int_{\eta_{in}}^{\eta_s^{(0)}} d\eta' \frac{a(\eta')}{a(\eta_s^{(0)})}\partial_r \left[\phi^{(2)} - \psi^2\right](\eta', \Delta\eta, \tilde{\theta}^a) + \frac{1}{2}\int_{\eta_{in}}^{\eta_o} d\eta' \frac{a(\eta')}{a(\eta_o)}\partial_r\left[\phi^{(2)} - \psi^2\right](\eta', 0, \tilde{\theta}^a) \\
+ \; & \frac{1}{4}\int_{\eta_s^{(0)+}}^{\eta_s^{(0)-}} dx \; \partial_+ \left[\hat{\phi}^{(2)} + \hat{\psi}^{(2)} + 4\hat{\psi}\;\partial_+ Q + \hat{\gamma}_0^{ab}\;\partial_a Q\;\partial_b Q\right](\eta_s^{(0)+}, x, \tilde{\theta}^a) \\
- \; & \frac{1}{2}\partial_a(\psi_o + \partial_+ Q_s)\left(\int_{\eta_s^{(0)+}}^{\eta_s^{(0)-}} dx \; \left[\hat{\gamma}_0^{ab}\;\partial_b Q\right](\eta_s^{(0)+}, x, \tilde{\theta}^a)\right)\Bigg\} \\
- \; & \frac{1}{2}\psi_s^{(2)} - \frac{1}{2}\psi_s^2 - K_2 + \psi_s J_2^{(1)} + \frac{1}{2}(J_2^{(1)})^2 + (J_2^{(1)} - \psi_o)\frac{Q_s}{\Delta\eta} - \frac{1}{\mathcal{H}_s\Delta\eta}\left(1 - \frac{\mathcal{H}_s'}{\mathcal{H}_s^2}\right)\frac{1}{2}(\psi_o + [\partial_+ Q]_s)^2 \\
- \; & \frac{2}{\mathcal{H}_s\Delta\eta}\psi_s(\psi_o + [\partial_+ Q]_s) + \frac{1}{2}\partial_a\left(\psi_s + J_2^{(1)} + \frac{Q_s}{\Delta\eta}\right)\left(\int_{\eta_s^{(0)+}}^{\eta_s^{(0)-}} dx \; \left[\hat{\gamma}_0^{ab}\;\partial_b Q\right](\eta_s^{(0)+}, x, \tilde{\theta}^a)\right) \\
+ \; & \frac{1}{4}\partial_a Q_s \; \partial_+ \left(\int_{\eta_s^{(0)+}}^{\eta_s^{(0)-}} dx \; \left[\hat{\gamma}_0^{ab}\;\partial_b Q\right](\eta_s^{(0)+}, x, \tilde{\theta}^a)\right) \\
+ \; & \frac{1}{16}\partial_a\left(\int_{\eta_s^{(0)+}}^{\eta_s^{(0)-}} dx \; \left[\hat{\gamma}_0^{bc}\;\partial_c Q\right](\eta_s^{(0)+}, x, \tilde{\theta}^a)\right)\partial_b\left(\int_{\eta_s^{(0)+}}^{\eta_s^{(0)-}} dx \; \left[\hat{\gamma}_0^{ad}\;\partial_d Q\right](\eta_s^{(0)+}, x, \tilde{\theta}^a)\right) \\
- \; & \frac{1}{4\Delta\eta}\int_{\eta_s^{(0)+}}^{\eta_s^{(0)-}} dx \; \left[\hat{\phi}^{(2)} + \hat{\psi}^{(2)} + 4\hat{\psi}\;\partial_+ Q + \hat{\gamma}_0^{ab}\;\partial_a Q\;\partial_b Q\right](\eta_s^{(0)+}, x, \tilde{\theta}^a) \\
+ \; & \frac{1}{\mathcal{H}_s}(\psi_o + [\partial_+ Q]_s)\left\{-[\partial_\eta\psi]_s + [\partial_r\psi]_s + \frac{1}{\Delta\eta^2}\int_{\eta_s^{(0)}}^{\eta_o} d\eta' \Delta_2\psi(\eta', \eta_o - \eta', \tilde{\theta}^a)\right\} \\
+ \; & Q_s\Bigg\{[\partial_r\psi]_s + \partial_+\left(\int_{\eta_s^{(0)+}}^{\eta_s^{(0)-}} dx \frac{1}{(\eta_s^{(0)+} - x)^2}\int_{\eta_s^{(0)+}}^{x} dy \Delta_2\hat{\psi}(\eta_s^{(0)+}, y, \tilde{\theta}^a)\right) \\
+ \; & \frac{1}{2\Delta\eta^2}\int_{\eta_s^{(0)}}^{\eta_o} d\eta' \Delta_2\psi(\eta', \eta_o - \eta', \tilde{\theta}^a)\Bigg\} + \frac{1}{16\sin^2\tilde{\theta}}\left(\int_{\eta_s^{(0)+}}^{\eta_s^{(0)-}} dx \; \left[\hat{\gamma}_0^{1b}\;\partial_b Q\right](\eta_s^{(0)+}, x, \tilde{\theta}^a)\right)^2 \quad , \qquad (4.67)
\end{aligned}
$$

$$
\begin{aligned}
\bar{\delta}^{(2)}_{pos} = \; & \frac{\Xi_s}{2}\Bigg\{([\partial_r P]_s - [\partial_r P]_o)^2 + (\gamma_0^{ab})_s \partial_a P_s \, \partial_b P_s - \lim_{r\to 0}\left[\gamma_0^{ab}\partial_a P \, \partial_b P\right] \\
- \; & \frac{2}{\mathcal{H}_s}([\partial_r P]_s - [\partial_r P]_o)\left(\mathcal{H}_s[\partial_r P]_s + [\partial_r^2 P]_s\right) \\
- \; & \int_{\eta_{in}}^{\eta_s^{(0)}} d\eta' \frac{a(\eta')}{a(\eta_s^{(0)})}\partial_r\left[(\partial_r P)^2 + \gamma_0^{ab}\partial_a P \, \partial_b P\right](\eta', \Delta\eta, \tilde{\theta}^a) \qquad (4.68) \\
+ \; & \int_{\eta_{in}}^{\eta_o} d\eta' \frac{a(\eta')}{a(\eta_o)}\partial_r\left[(\partial_r P)^2 + \gamma_0^{ab}\partial_a P \, \partial_b P\right](\eta', 0, \tilde{\theta}^a)\Bigg\} - \frac{1}{2\mathcal{H}_s\Delta\eta}\left(1 - \frac{\mathcal{H}_s'}{\mathcal{H}_s^2}\right)([\partial_r P]_s - [\partial_r P]_o)^2 \quad ,
\end{aligned}
$$

$$
\begin{aligned}
\bar{\delta}^{(2)}_{mixed} = \; & \Xi_s\Bigg\{\left(2\psi_o - \psi_s + \partial_+ Q_s - \frac{Q_s}{\Delta\eta}\right)[\partial_r P]_o - ([\partial_r P]_s - [\partial_r P]_o)\left(\frac{1}{\mathcal{H}_s}[\partial_\eta\psi]_s - J_2^{(1)}\right) \\
- \; & (\gamma_0^{ab})_s\partial_a Q_s \partial_b P_s + \frac{1}{\mathcal{H}_s}(\psi_o + [\partial_+ Q]_s)[\partial_r^2 P]_s + Q_s\,[\partial_r^2 P]_s \\
+ \; & \frac{1}{2}\partial_a([\partial_r P]_s - [\partial_r P]_o)\left(\int_{\eta_s^{(0)+}}^{\eta_s^{(0)-}} dx \; \left[\hat{\gamma}_0^{ab}\;\partial_b Q\right](\eta_s^{(0)+}, x, \tilde{\theta}^a)\right)\Bigg\} \\
+ \; & \frac{1}{\Delta\eta}([\partial_r P]_s - [\partial_r P]_o)\left\{\frac{1}{\mathcal{H}_s}\left(1 - \frac{\mathcal{H}_s'}{\mathcal{H}_s^2}\right)(\psi_o + [\partial_+ Q]_s) + \frac{2}{\mathcal{H}_s}\psi_s + Q_s\right\} \\
+ \; & \frac{1}{\mathcal{H}_s}([\partial_r P]_s - [\partial_r P]_o)\left\{[\partial_\eta\psi]_s - [\partial_r\psi]_s - \frac{1}{\Delta\eta^2}\int_{\eta_s^{(0)}}^{\eta_o} d\eta' \Delta_2\psi(\eta', \eta_o - \eta', \tilde{\theta}^a)\right\} \quad . \qquad (4.69)
\end{aligned}
$$

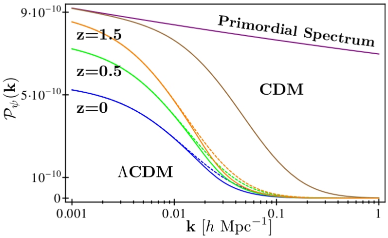
Stochastic average of inhomogeneous realizations

Inhomogeneities :

$$\psi(\eta,\vec{x}) = \int \frac{\mathrm{d}^3 k}{(2\pi)^{3/2}}\; e^{i\vec{k}\cdot\vec{x}}\psi_k(\eta)E(\vec{k})$$

with E a hom. and gaussian unit R.V..

Spectrum : $|\psi_k(\eta)|^2 = 2\pi^2\mathcal{P}_\psi(k)/k^3$



Light-cone average is combined with a stochastic average. In CDM :

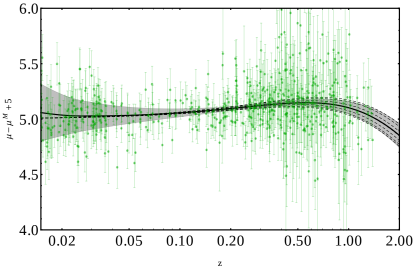
$$\langle S\rangle_{w_o,\tau_s} = \frac{\int d^2\underline{\theta}\,\sqrt{\gamma(w_o,\tau_s,\underline{\theta}^a)}\,S(w_o,\tau_s,\underline{\theta}^a)}{\int d^2\widetilde{\theta}\sqrt{\gamma(w_o,\tau_s,\underline{\theta}^a)}} \quad\Rightarrow\quad \boxed{\overline{\langle d_L\rangle} = \int_0^\infty \frac{\mathrm{d}k}{k}\mathcal{P}_\psi(k)C(k\Delta\eta)}$$

We do the same $\forall$ terms in $\overline{\left\langle \delta_S^{(1)}\right\rangle}$ and $\overline{\left\langle \delta_S^{(2)}\right\rangle}$ in ΛCDM... with approximations.

Kaiser & Peacock 2015 for precise discussion on 'directional' / 'source' averaging.

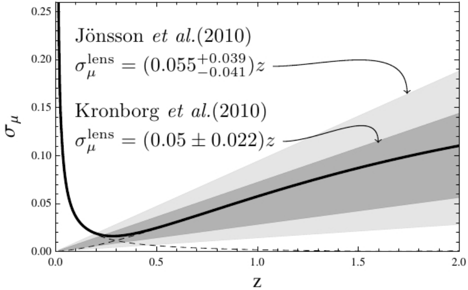
The averaged modulus $\overline{\langle\mu\rangle}$ depends on $\overline{\left\langle\left(d_L^{(1)}/d_L^{(0)}\right)^2\right\rangle}$ while the standard deviation $\sigma_\mu = \sqrt{\overline{\langle\mu^2\rangle} - \overline{\langle\mu\rangle}^2} = 10(\log_{10} e)\sqrt{\overline{\left\langle\left(d_L^{(1)}/d_L^{(0)}\right)^2\right\rangle}}$ with

$$\overline{\left\langle\left(d_L^{(1)}/d_L^{(0)}\right)^2\right\rangle} \sim \overline{\langle(\text{Doppler})^2\rangle} + \overline{\left\langle\left(\text{Lensing}^{(1)}\right)^2\right\rangle}$$



With the Union 2 dataset :

- small z : Velocities explain quite well the scatter.
- large z : Lensing is too weak to explain data's scatter ($\sim\%\,\Omega_{\Lambda 0}$).



- The total effect is well approximated by Doppler ($z \leq 0.2$) + Lensing ($z > 0.3$),
- Lensing prediction is in great agreement with experiments so far !

See also Fleury, Clarkson, Maartens '17

Other GLC applications

- Evaluate **galaxy number counts** at $\mathcal{O}(2)$ in perturbations (Di Dio, Durrer, Marozzi, Montanari 1407.0376, 1510.04202) ⇒ Bispectrum !

- **Inhomogeneous spacetime :** Lemaître-Tolman-Bondi with off-center observer and no curvature (*Fanizza, Nugier 2014*, 1408.1604), **lensing quantities** for over/under dense regions.

- Application to an **Anisotropic Bianchi I spacetime** *Fleury, Nugier, Fanizza 2016*, 1602.04461). ⇒ we find that the **anisotropy of the Bianchi I spacetime violates** $\langle \mu^{-1} \rangle_\Omega = 1$ **!**

- Application to the **time-of-flight of UR particles** (*Fanizza,Gasperini,Marozzi,Veneziano*, 1512.08489).

- Relation between GLC and **double-null coordinates**. (Unrealistic) application to **static black holes** (Nugier 2016).

Number counts with GLC

Number counts of galaxies in volume $\mathrm{d}\mathcal{V} = (\mathrm{d}z, \mathrm{d}\Omega)$, defining the fluctuation $\Delta(\mathbf{n}, z) = \frac{N(\mathbf{n},z) - \langle N \rangle(z)}{\langle N \rangle(z)}$ with $N(\mathbf{n}, z) = \rho(\mathbf{n}, z) V(\mathbf{n}, z)$ (neglecting bias), computing perturbations of density, redshift, angles, and **volume** :

$$\mathrm{d}V \equiv \sqrt{-g}\epsilon_{\mu\nu\alpha\beta}u^\mu \mathrm{d}x^\nu \mathrm{d}x^\alpha \mathrm{d}x^\beta = \sqrt{|\gamma|}\frac{\Upsilon_s^2}{\Upsilon_o \partial_\tau \Upsilon_s}\mathrm{d}z\mathrm{d}\theta_o\mathrm{d}\phi_o \quad .$$

Bispectrum is given by $\langle \Delta(\mathbf{n}_1, z_1)\Delta(\mathbf{n}_2, z_2)\Delta(\mathbf{n}_3, z_3)\rangle$ at $\mathcal{O}(2)$ and the expressions can be applied to most modified gravity models. See Di Dio, Durrer, Marozzi, Montanari, 1407.0376, 1510.04202. Hundreds of terms !

Higher-order lensing terms in **CMB lensing** can have impact on the **tensor-to-scalar ratio** of $\sim \mathcal{O}(10^{-3})$ and affect the effective number of **relativistic species** N_{eff} (see Marozzi, Fanizza, Di Dio, Durrer '17).

Also : Biern and Yoo '17 compute the **luminosity distance correlation** function $\langle \delta D_L(z_1, \mathbf{n}_1)\delta D_L(z_2, \mathbf{n}_2)\rangle$.

$\Rightarrow$ SUB-PERCENT COSMOLOGY NEEDS THESE CORRECTIONS.

PART II
COMPARING STANDARD CANDLES AND GALAXY CATALOGUES IN OUR LOCAL UNIVERSE

Motivations

Collaboration with Hsu-Wen Chiang (蔣序文),
Enea Romano, Pisin Chen (陳丕燊).
1706.09734

- Estimate how **standard candles** can probe the **local density contrast**.
- Investigate on H_0 as *Riess 2016* re-evaluates $H_0 = 73.24 \pm 1.74\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$, raising the **tension to 3.4** σ against $66.93 \pm 0.62\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ from Planck.
- We know that being inside an **underdensity** region may alleviate tension (see Ben-Dayan, Durrer, Marozzi, Schwarz '14 and Romano '16).
- Isotropic inhomogeneity extending very far should not exist, but anisotropic inhomogeneity may. Keenan, Barger, Cowie '13 find a **super-void** extending to $z \sim 0.07$ ($\sim 300\, h_{70}^{-1}\mathrm{Mpc}$).

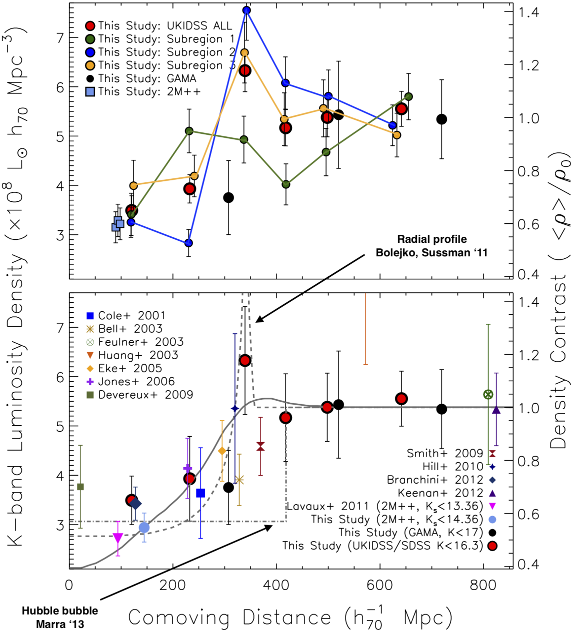
Keenan '13, Fig. 11

Comparison with density maps obtained from luminosity density of Keenan et al. 2013.

K13 uses UKIDSS, analyses K-selected catalog of 35,000 gal. ($b = 1$).

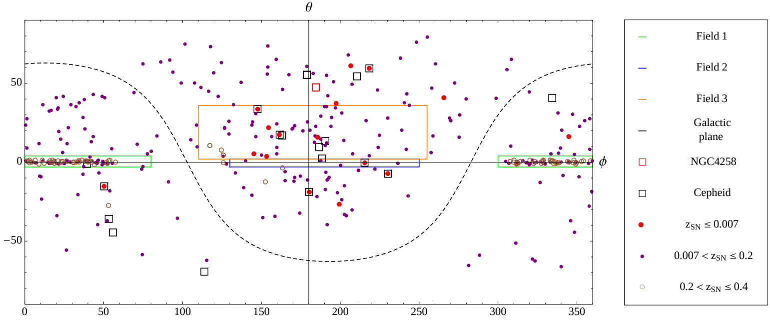
- Green : Field 1
- Blue : Field 2
- Orange : Field 3

Keenan '13 agree with 2M++ **density constrast** ~ 0.6.



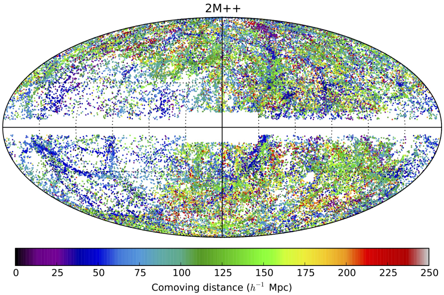
Standard Candles data

- **Cepheids** from *Riess 2016* (z_{host} from NED) and **SNe Ia** from UNION 2.1 (with **z less than 0.2 or 0.4** and positions from SIMBAD).
- Use of 7 host galaxies common to $\mathcal{R}16$ Cepheids and UNION 2.1 SNe to rescale SNe Ia such that $\mu(\mathcal{R}16) = \mu(\text{Union 2.1}) - 5\log_{10}(73.24/70)$.

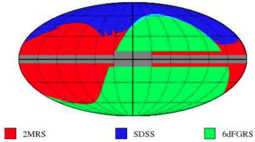


- **Velocity dispersion :** $250\ \mathrm{km\,s^{-1}}$ for SNe, $0, 40, 250\ \mathrm{km\,s^{-1}}$ for Cepheids. Implies a change in μ by $\Delta\mu_{\mathrm{v.d.}} \approx \frac{5}{\log 10}\frac{\Delta v}{cz}$.

2M++ (Lavaux & Hudson 2011, Carrick *et al.* 2015)



Redshifts are from 2MRS, SDSS-DR7, and 6dFGRS.

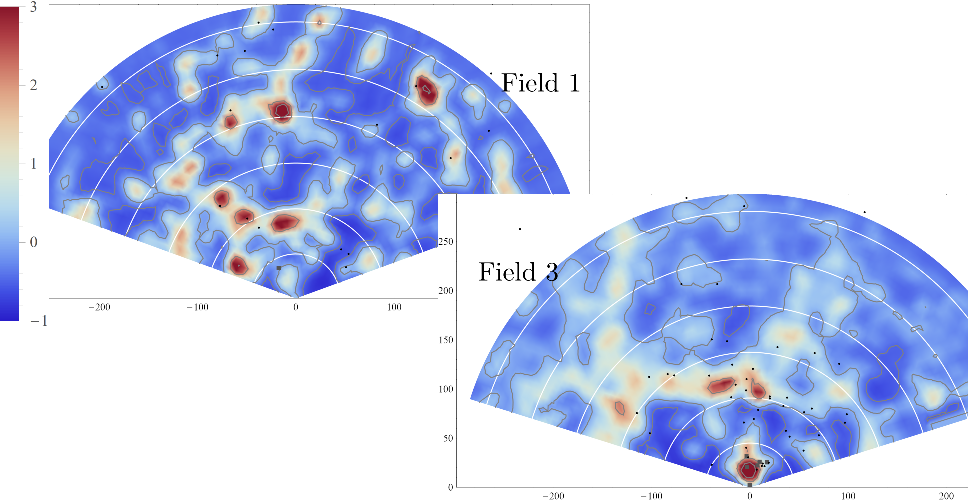


Peculiar velocity corrections (PVC) obtained from the galaxy density :

$$\vec{v}(\vec{r}) = \frac{\beta^*}{4\pi} \int_0^{R_{\rm max}} \mathrm{d}^3\vec{r}'\, \delta_g^*(\vec{r}') \frac{\vec{r}'}{r'^3} \quad , \quad \bar{z} = z_{\rm obs} - \vec{v}\cdot\vec{n}$$

where $\beta^* = 0.43$ is a best fit value and the upper limit of integration is the **depth of the survey :** $R_{\rm max} = 200\, h^{-1}\mathrm{Mpc}$, i.e. $z = 0.067$.

$\Rightarrow$ limited to **200** h^{-1}Mpc + **an external bulk flow** (that we remove).



Comparison with 2M++ density map (averaged along declination direction in ICRS coordinates).

White arcs correspond to $z = 0.01, 0.02, \ldots, 0.06$, gray contours indicate iso-density lines of $\delta_C = -0.5, 0, 2, 4$.

1D Fitting

Fits of the distance modulus data $(z_i, \mu_i, \Delta\mu_i)$ by minimizing χ^2 of the deviation from a homogeneous model :

$$\chi^2 = \sum_i \left(\frac{f\left(z_i\right) - \left(\mu_i - \mu^{\text{Planck}}\left(z_i\right)\right)}{\Delta\mu_i} \right)^2 \quad , \quad f(z) = \left(\mu^{\text{obs}} - \mu^{\text{Planck}}\right)(z)$$

where $\mu^{\text{Planck}}(z)$ is the ΛCDM theoretical value of distance modulus at z.

Model independent by decomposing the fitting function $f(z)$ wrt a set of *radial basis functions* (RBFs NN) :

$$f(z) = w_0 + w_{-1}\, z + \sum_{m=1}^{N_{\text{NL}}} w_m\, \Phi\left(|z - p_m|\right)$$

where Φ are chosen to be $\Phi(r) = r^3$ (N_{NL} RBFs), p_m are the **non-linear parameters** or “centers” of the RBFs, w_m the linear parameters, w_0 (intercept) and/or w_{-1} (slope) parameters.

Best fit and confidence bands

- **Linear parameters w** $\equiv (w_{-1}, \ldots, w_{N_{\rm NL}})$ **:** we use the simple Moore-Penrose pseudo-inverse method.
- **Non-linear parameters p** $\equiv (p_1, \ldots, p_{N_{\rm NL}})$ **:** we use a Monte Carlo (MC) random sampling method and a LO algorithm (Gauss-Newton).
- **To speed up the MC process and fill up confidence band** we use a MCMC algorithm to explore the non-linear parameter space.

A **fitting model** is classified by a set of parameters $(N_0, N_{-1}, N_{\rm NL})$.

We use a F-test to determine the **best model parameters**.

\+ **Inversion** in each field based on Lemaître-Tolman-Bondi (LTB) in 1D (neglecting transverse shear) to reconstruct the local radial density profile (assuming Planck background). See Romano, Chiang and Chen, 2013.

$\Rightarrow$ **Density contrast :**

$$\delta_C = \Omega_{m0}^{-0.55} \left(\frac{\rho_{\rm inv}\left(D_L, z\right)}{\rho_{\rm inv}\left(D_L^{\rm Planck}, z\right)} - 1 \right) \quad .$$

Full sky fitting

Applying PVC from 2M++ and velocity dispersion (VD) of 250 $\mathrm{km\,s^{-1}}$ for SNe.

VD = 250 $\mathrm{km\,s^{-1}}$ for Cepheids (like Riess 2016) :

$\Rightarrow$ Preferred model is **(1,0,0)** : $f(z) = w_0$, i.e. homogeneous with :

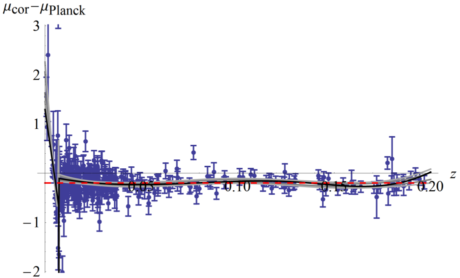
$$H_0^{\text{loc}} \equiv H_0^{\text{Planck}} 10^{-f(z=0)/5} = H_0^{\text{Planck}} 10^{-w_0/5} = 10^{-w_0/5}(\,66.93\ \mathrm{km\,s^{-1}\,Mpc^{-1}})\,.$$

We find : $H_0^{\text{loc}} = 73.06 \pm 1.61\,(\text{stat.})\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$, in good agreement with $73.24 \pm 1.61\,(\text{stat.}) \pm 0.66\,(\text{sys.})\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ of Riess 2016 (we have $\chi_R^2 = 1.49$).

VD = 40 $\mathrm{km\,s^{-1}}$ for Cepheids :
(see Tully 2007)

Best fit is a $(0,1,7)$ model!
$\chi_R^2 = 4.18$

$\Rightarrow$ there seems to be structure not accounted for by 2M++.

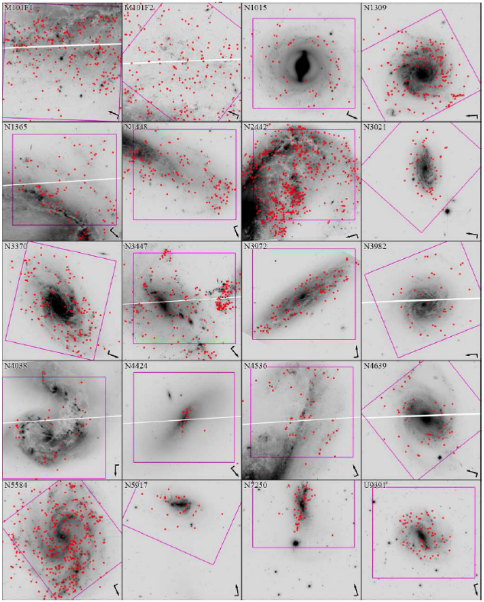


Cepheid hosts

We decide to give more importance to the Cepheid hosts and assume : **VD** $= \mathbf{0}\ \mathrm{km\,s^{-1}}$.

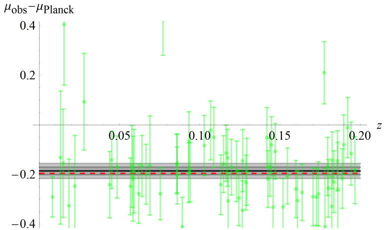
Could NGC 4536 be biased ?

See Hoffmann '16 for more information about Cepheids.



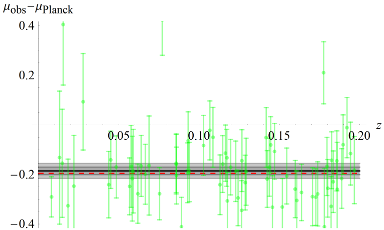
Directional fitting in F1

With PVC from 2M++ :



- **best fit** we get is a **(1,0,0) model** with $H_0^{loc} = 72.89 \pm 0.50$ km s^{-1} Mpc^{-1} and $\chi_R^2 = 1.05$,
- next best fit (Threshold < 33%) is given by a $(0, 1, 5)$ model with $\chi_R^2 = 0.88$.

Without PVC from 2M++ :



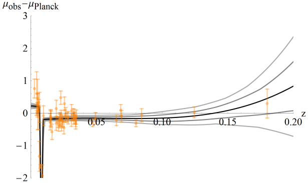
- **best fit model is (1,0,0)** with $H_0^{loc} = 72.90 \pm 0.51$ km s^{-1} Mpc^{-1} with F-test *Threshold* > 36% and $\chi_R^2 \sim 1.07$,
- second best model is an inhomogeneous $(1, 1, 13)$ model with $\chi_R^2 \sim 0.59$ but low threshold.

Directional fitting in F3 with PVC

Applying PVC from 2M++ and **VD** of 250 $\mathrm{km\,s^{-1}}$ for SNe Ia (host rotation) and no VD for Cepheids.

Use a F-test *Threshold* $\sim 95\%$ to compare models.

$z_{\max} = 0.2$			
χ^2_R	*Threshold* (%)	*Param.*	Removal
19.5	Not Preferred	76.40 ± 2.90	
1.59	$81 \sim 100$	$(0, 1, 6)$	
5.92	$95.8 \sim 100$	$(0, 0, 0)$	NGC 4536
2.06	$90.7 \sim 95.7$	$(0, 1, 3)$	Same
2.05	$73 \sim 100$	70.56 ± 0.93	+NGC 4424



$z_{\max} = 0.4$			
χ^2_R	*Threshold* (%)	*Param.*	Removal
17.9	Not Preferred	76.36 ± 2.75	
1.60	$74 \sim 100$	$(0, 1, 6)$	
5.58	$96.9 \sim 100$	$(0, 0, 0)$	NGC 4536
2.03	$85 \sim 96.8$	$(0, 1, 3)$	Same
2.00	$72 \sim 100$	70.65 ± 0.91	+NGC 4424

Based on no-PVC (but similar)

$\Rightarrow$ Necessary to remove some “outliers” to have invertible fits !

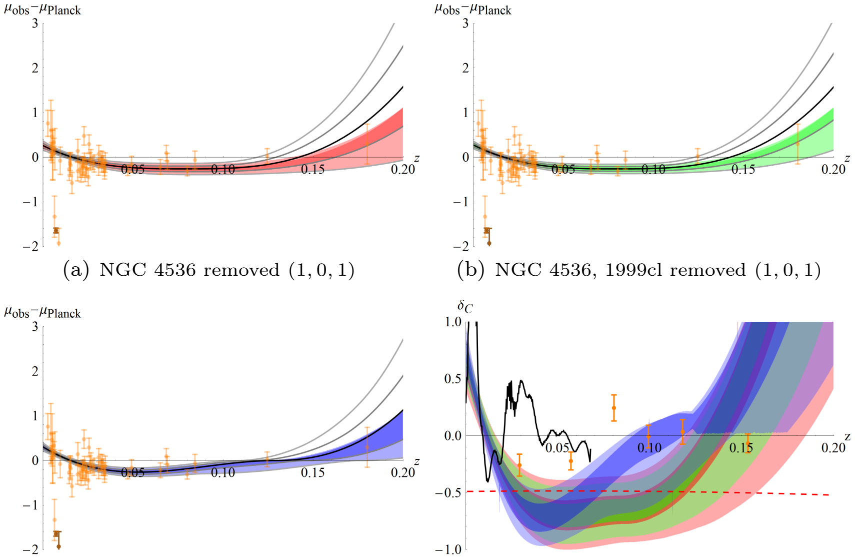
Directional fitting in F3 without PVC

We don't apply PVC since we want to see the whole contribution from SNe Ia and Cepheids.

Just apply a VD of 250 $\mathrm{km\,s^{-1}}$ for SNe Ia (host rotation).

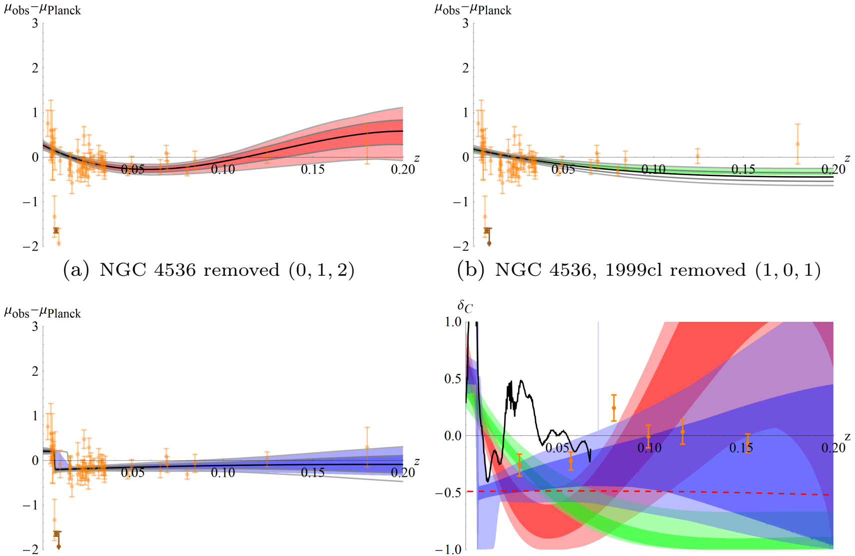
$z_{\rm max} = 0.2$			
χ^2_R	*Threshold* (%)	*Param.*	Removal
1.40	$39 \sim 100$	$(0, 0, 5)$	
3.45	$97.5 \sim 100$	$(0, 0, 0)$	NGC 4536
2.26	$89 \sim 97.4$	$(1, 0, 1)$	Same
2.88	$99.5 \sim 100$	$(0, 0, 0)$	+1999cl
1.55	$94.1 \sim 99.4$	$(1, 0, 1)$	Same
1.47	**$47 \sim 94.0$**	**(0, 0, 2)**	**Same**

$z_{\rm max} = 0.4$			
χ^2_R	*Threshold* (%)	*Param.*	Removal
1.43	$38 \sim 100$	$(0, 1, 5)$	
3.31	$92.6 \sim 100$	$(0, 0, 0)$	NGC 4536
2.20	$92.1 \sim 92.5$	$(0, 1, 2)$	Same
2.80	$96.3 \sim 100$	$(0, 0, 0)$	+1999cl
1.96	$89 \sim 96.2$	$(1, 0, 1)$	Same
1.37	**$76 \sim 88$**	**(0, 0, 4)**	**Same**



(a) NGC 4536 removed $(1,0,1)$
(b) NGC 4536, 1999cl removed $(1,0,1)$
(c) **NGC 4536, 1999cl removed $(\mathbf{0},\mathbf{0},\mathbf{2})$**
(d) Inverted density

FIGURE: Distance modulus best fit models are plotted for F3 with $z_{\rm max} = 0.2$, without peculiar velocity corrections and with a 250 $\rm km\,s^{-1}$ velocity dispersion for SNe.



(a) NGC 4536 removed $(0, 1, 2)$

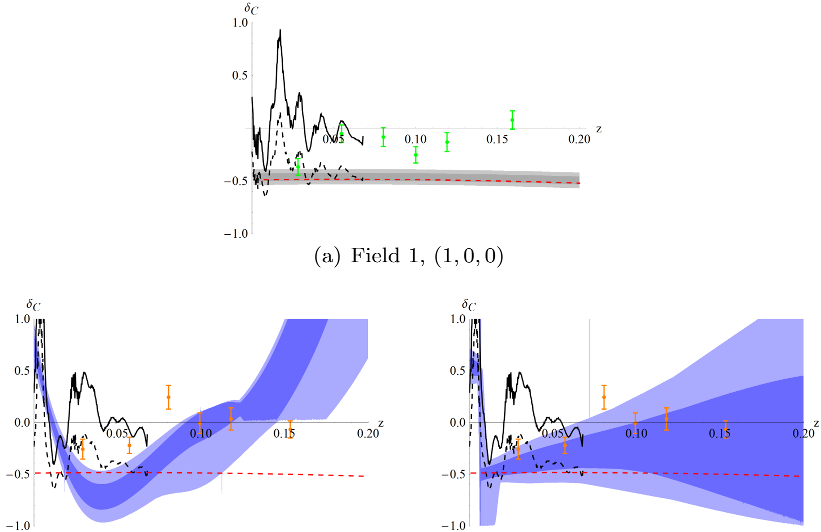
(b) NGC 4536, 1999cl removed $(1, 0, 1)$

(c) **NGC 4536, 1999cl removed** $(\mathbf{0}, \mathbf{0}, \mathbf{4})$

(d) Inverted density

FIGURE: Distance modulus best fit models are plotted for F3 with $z_{max} = 0.4$, without peculiar velocity corrections and with a 250 $\mathrm{km\,s^{-1}}$ velocity dispersion for SNe.

Main results



(a) Field 1, $(1, 0, 0)$

(b) Field 3, $z_{\max} = 0.2$ with NGC 4536 and 1999cl removed $(0, 0, 2)$

(c) Field 3, $z_{\max} = 0.4$ with NGC 4536 and 1999cl removed $(0, 0, 4)$

Rescaling 2M++

- 2M++ is normalized wrt the average within its depth $\Rightarrow$ its normalization can be wrong if 2M++ is embedded in a larger structure.
- Same with Keenan 2013 with background equal to the averaged luminosity density over the data set.
- **Our reconstructed density profile is normalized wrt the background** since we are assuming cosmological background parameters obtained from large scale observations (Planck).

If we take $\mathcal{K}13$ background density we would have to rescale 2M++ as

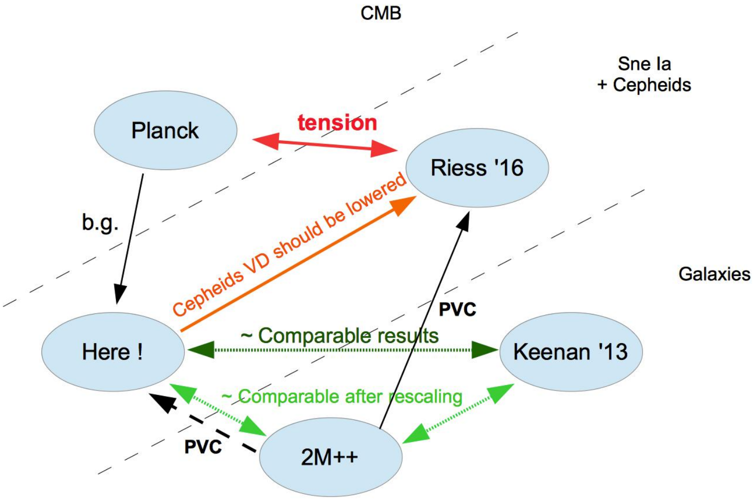
$$\delta_C^{\rm cor} = \frac{\tilde{\rho}_{\rm 2M++}}{\tilde{\rho}_{\mathcal{K}13}}(1+\delta_C) - 1,$$

where $\delta_C^{\rm cor}$ is the rescaled density contrast, while $\tilde{\rho}_{\rm 2M++}$ and $\tilde{\rho}_{\mathcal{K}13}$ are the assumed background density of 2M++ and $\mathcal{K}13 \Rightarrow$ **factor 0.6 rescaling**.

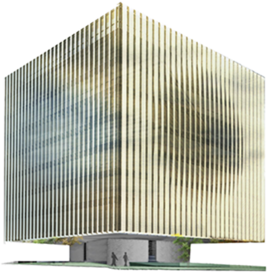
Summary

- SNe + Cepheids hosts appear to independently confirm the existence of **inhomogeneities**,
- to some extent in qualitative agreement with Keenan 2013 (claiming ~ 300 Mpc void), but **normalization of background seems crucial**,
- based on **1D fit** in windows of the sky, **LTB inversion** model, with SNe Ia and Cepheids data $\Rightarrow$ different sources of uncertainty,
- SNe Ia could be useful to **correctly normalize density maps** from galaxy surveys with respect to the average density of the Universe,
- **could clarify apparent tension** between local and large scale estimations of H_0 (especially between Planck and Riess which uses 2M++).

Summary picture



どうも ありがとう ござい ます。



LeCosPA @ NTU has new building, please come give a seminar ! :-)

I) The **large scale structure** sources **relativistic corrections** to all cosmological observables, important for **percent accuracy** in cosmology.
Adapted coordinates are useful !

II) The **local structure** needs careful studying, with precise data. It may contain the solution of the **critical H_0 tension** !

Thank You!