Measuring the Cosmic Mach Number by the Sunyaev−Zeldovich effect.

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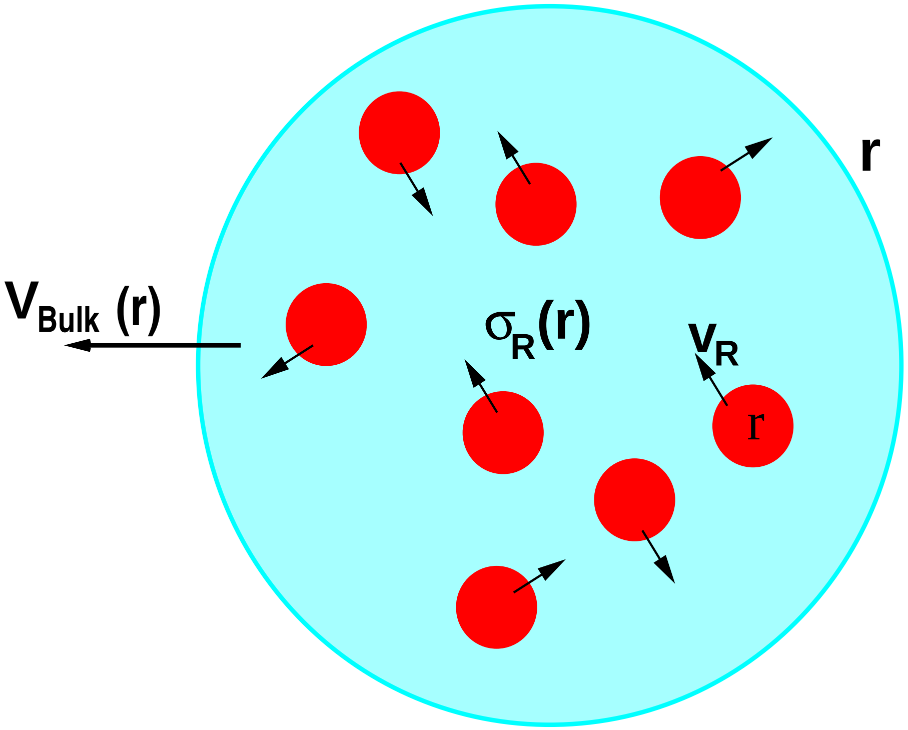
XXth IAP Colloquium, "CMB Physics and Observations", Paris

Measuring the Cosmic Mach Number (schedule)

AIP

1. *The cosmic Mach Number (definition, meaning, advantage)*
2. *The Sunyaev Zel'dovich Effect (Kinematic and thermal component)*
3. *Bulk flow velocity*
4. *Cosmic sound speed*
5. *SZ measurements and cluster redshifts*
6. *Estimation of errors; which quantities do influence the error bars?*
7. *Measuring the matter density*
8. *Summary*

The Cosmic Mach number



Bulk velocity with respect to region – r –

$$V^2_{\rm Bulk}(r) = H_0^2 f^2(\Omega_m, \Omega_\Lambda) \frac{1}{2\pi^2} \int_0^\infty P(k) W^2(kr) dk$$

Sound velocity related to objects of size R

$$C_S^2 = H_0^2 f^2(\Omega_m, \Omega_\Lambda) \frac{1}{2\pi^2} \int_0^\infty P(k)[W^2(kR) - W^2(kr)] dk$$

$$\approx H_0^2 f^2(\Omega_m, \Omega_\Lambda) \frac{1}{2\pi^2} \int_0^\infty P(k)[1 - W^2(kr)] dk$$

The Cosmic Mach Number

$$M = \frac{V_{\mathrm{Bulk}}}{C_S}$$

Independent of normalization

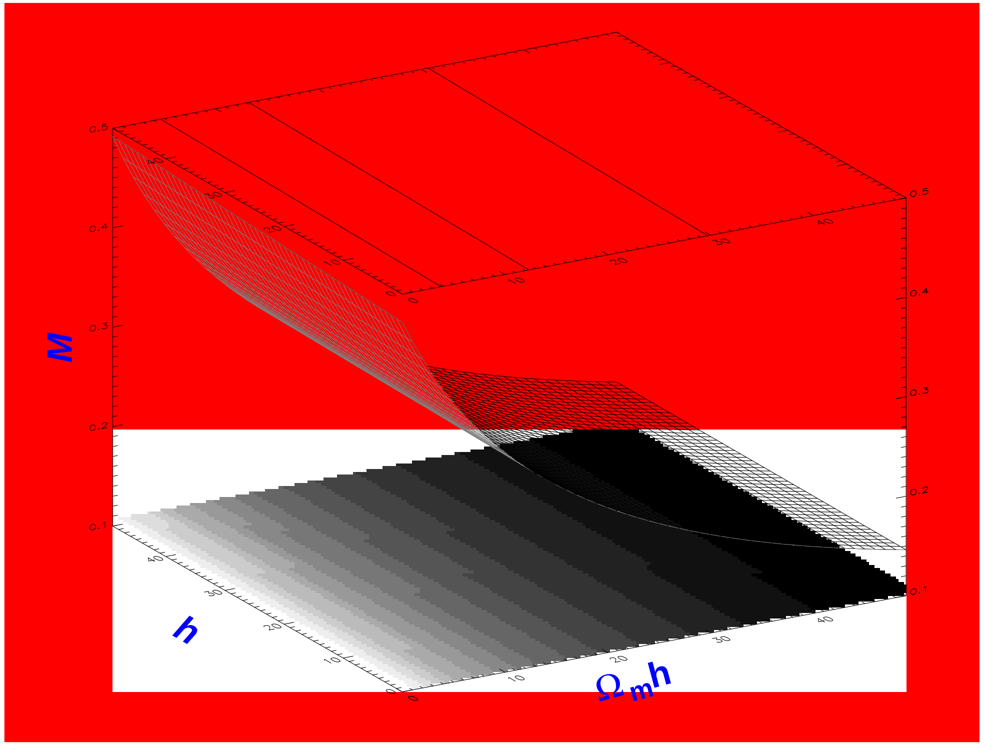
insensitive to redshift and bias in linear theory

M(R) ratio of power on scales larger than to scales smaller than considered scale R

Allows to measure the matter density
independently of CMB

The Mach Number

The dependence of the cosmic Mach number on the matter density



The mach number depends only on

$\Omega_m h$

$(\Omega_m = \Omega_b + \Omega_{cdm})$

↓

independent possibility to get information about the matter density (baryon + cdm)

The Sunyaev Zel'dovich Effect

Hot intracluster gas induces CMB temperature anisotropies

Thermal component:

$$(\frac{\Delta T}{T})_{th} = \frac{K_B T_X}{m_e c^2}\tau$$

$$\tau \propto \int n_e T_e dl$$

Kinematic component:

$$(\frac{\Delta T}{T})_{kin} = \frac{\vec{v}\vec{n}}{c}\tau$$

The temperature anisotropy at a cluster location contains the components:

$$\delta T = T_0 \tau \frac{kT_{\rm X}}{m_e c^2} G_\nu + (T_0 \tau \frac{v_{Pr}}{c} + \delta T_{\rm CMB}) H_\nu + n_\nu + f_\nu$$

Peculiar velocities for bright clusters with optical depth $\tau \sim 2 - 5 \times 10^{-3}$
are measured with an accuracy

σ_{v_p} **~ 1000 km/s**

Bulk flow velocity

The bulk flow velocity can be computed directly from the data by adding the signal of several clusters

$$V_{\rm bulk} = \sum V_{ri}$$

To this measurement an error bar can be attached:

$$\sigma_{V_{\rm bulk}} \simeq \frac{\sigma_{v_P}}{\sqrt{N_{cl}}} \sim 100 (\frac{\sigma_{v_P}}{1000 {\rm km/s}})(\frac{N_{cl}}{100})^{-1/2} {\rm km/s}$$

Cosmic sound speed

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Can be measured directly from the KSZ effect:

$$C_S^2 = \sum (V_{ri} - V_{Bulk})^2$$

The error σ_{v_p} is related to the uncertainty in δT

$$\sigma_{v_p} \approx \frac{c \cdot \sigma_{\Delta T}}{T_0 \tau}$$

Using very optimistic numbers: $\sigma_{\Delta T} \approx 10 \mu K$, $\tau \approx 10^{-3}$ we get

$$\sigma_{v_p} \approx 10^3 \left(\frac{\sigma_{\Delta T}}{10 \mu K} \right) \left(\frac{10^{-3}}{\tau} \right) km/s$$

Since σ_{vp} >> c_s the error does NOT scale as $N_{cl}^{1/2}$

Nagai, Kravtsov, Kosowsky (2003)
Diaferio, Borgani et al. (2004)

$$\sigma_{C_S^2} = \sigma_{v_P}^2 = (1000 km/s)^2$$

$\Longrightarrow$ ***the error is of the order or larger than the measurement***
HOWEVER, even with these large errors, one can get useful information

Cross−correlation of SZ measurements and redshifts

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— Clusters are choosen in shells of width Δz of mean redshift $\overline{z}$

— Cross−correlation of SZ measurements with cluster redshifts $\delta z = z - \overline{z}$ yields:

$$\frac{\langle c\delta T \cdot c\delta z\rangle}{T_o\langle\tau\rangle} = T_o < \tau > C_S \pm H_o < \tau >< V_p(d-\bar{d}) > \pm\sigma_{v_P}\frac{c\Delta z}{\sqrt{12N_{cl}}}$$

Δd , Δz and Δv_p are not independent; with $\Delta d \sim \Delta z + 2C_s$

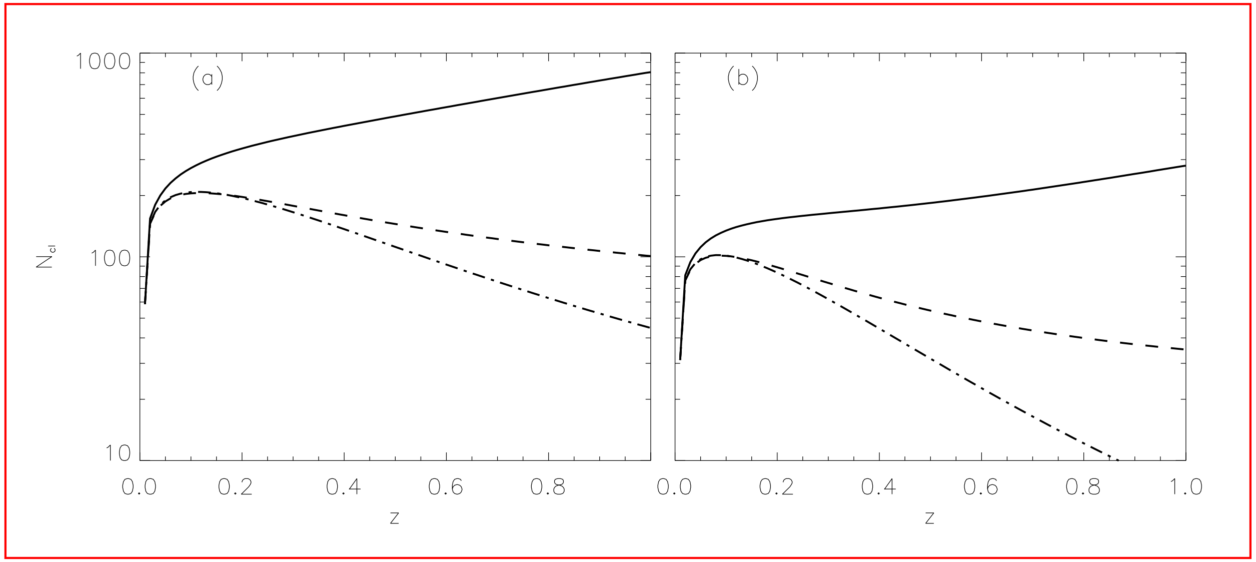
$$\frac{\langle c\delta T \cdot c\delta z\rangle}{T_o\langle\tau\rangle} = C_S^2 \pm \sigma_{v_P}\frac{c\Delta z}{\sqrt{12N_{cl}}} \pm \langle v_p\rangle\frac{(c\Delta z + 2C_S)}{\sqrt{12}}$$

If clusters are homogeneously distributed in redshift space, the error on C_S computed on a shell of width Δz is

$$\sigma_{C_S^2} = (300km/s)^2\left(\frac{\sigma_{v_P}}{1000km/s}\right)\left(\frac{\Delta z}{0.01}\right)\left(\frac{100}{N_{cl}}\right)^{1/2}$$

For the Shaply Supercluster we could estimate $\sigma_{C_S^2} = (600\ km/s)^2$

Number of Clusters



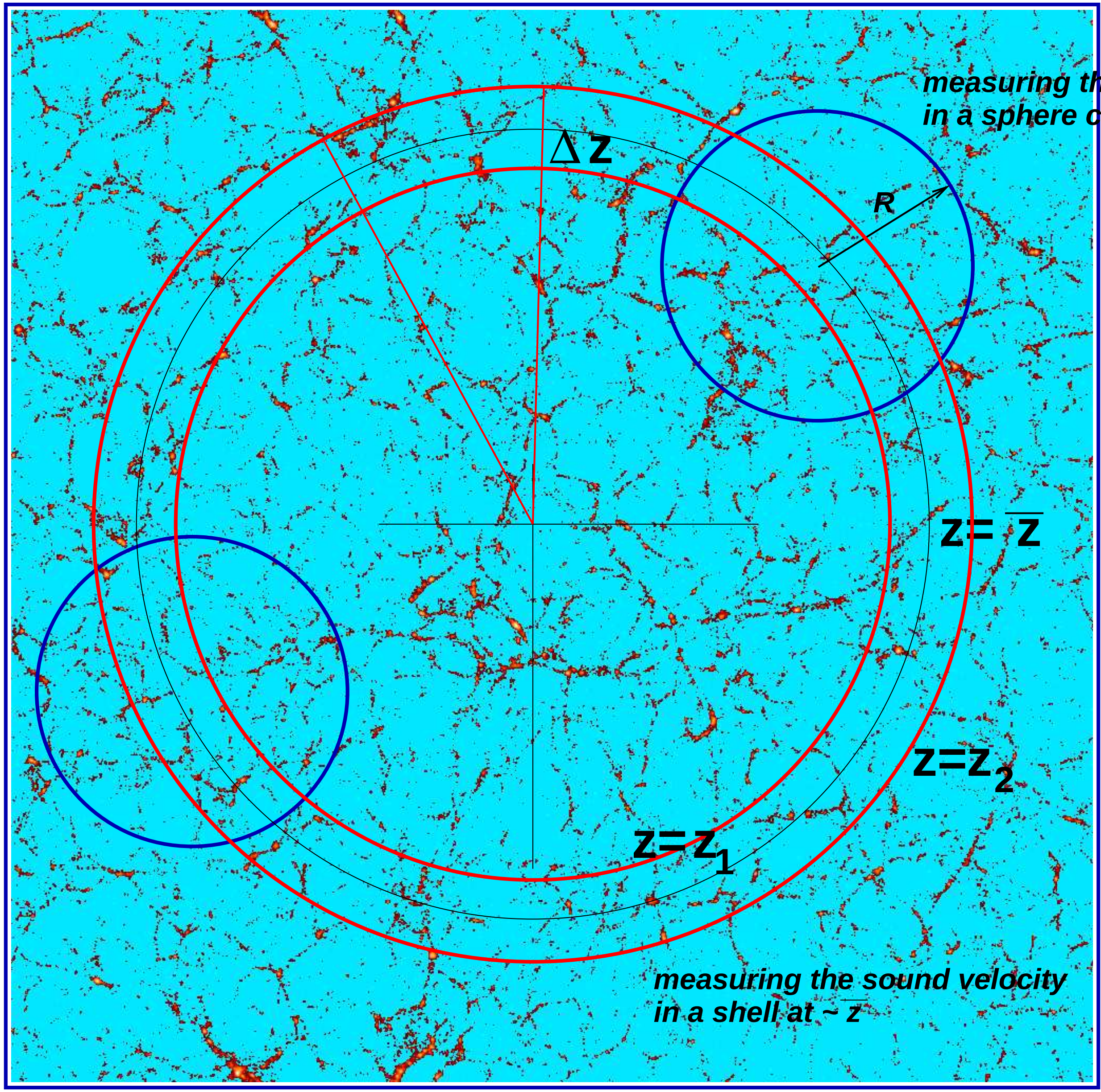
Flux variation on the CMB of ~200 mJy (a) ~400 mJy (b)

Cluster abundances: X−ray Luminosity Function (XLF) is modeled as an evolving Schechter function:

$$\phi(L,z) = \phi_o(1+z)^A L^{-\alpha} \exp(-L/L_*)$$
$$L_* = L_{*,0}(1+z)^B$$

L_*, α ***are the local XLF values***

Solid line: A = B = 0
Dashed line: A = −3, B = 0 **(RDCS)**
Dot−dashed line: A = −1, B = −2 **(EMSS)**



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from XMM Serendipitous Galaxy Cluster Survey

800 deg ^{2} on the sky

~ 7000 clusters

at z < 1

clusters in a slice from PLANCK

Slice out of a 500 h^{-1} box
red structures are of cluster size

Credit: S. Gottloeber (AIP)

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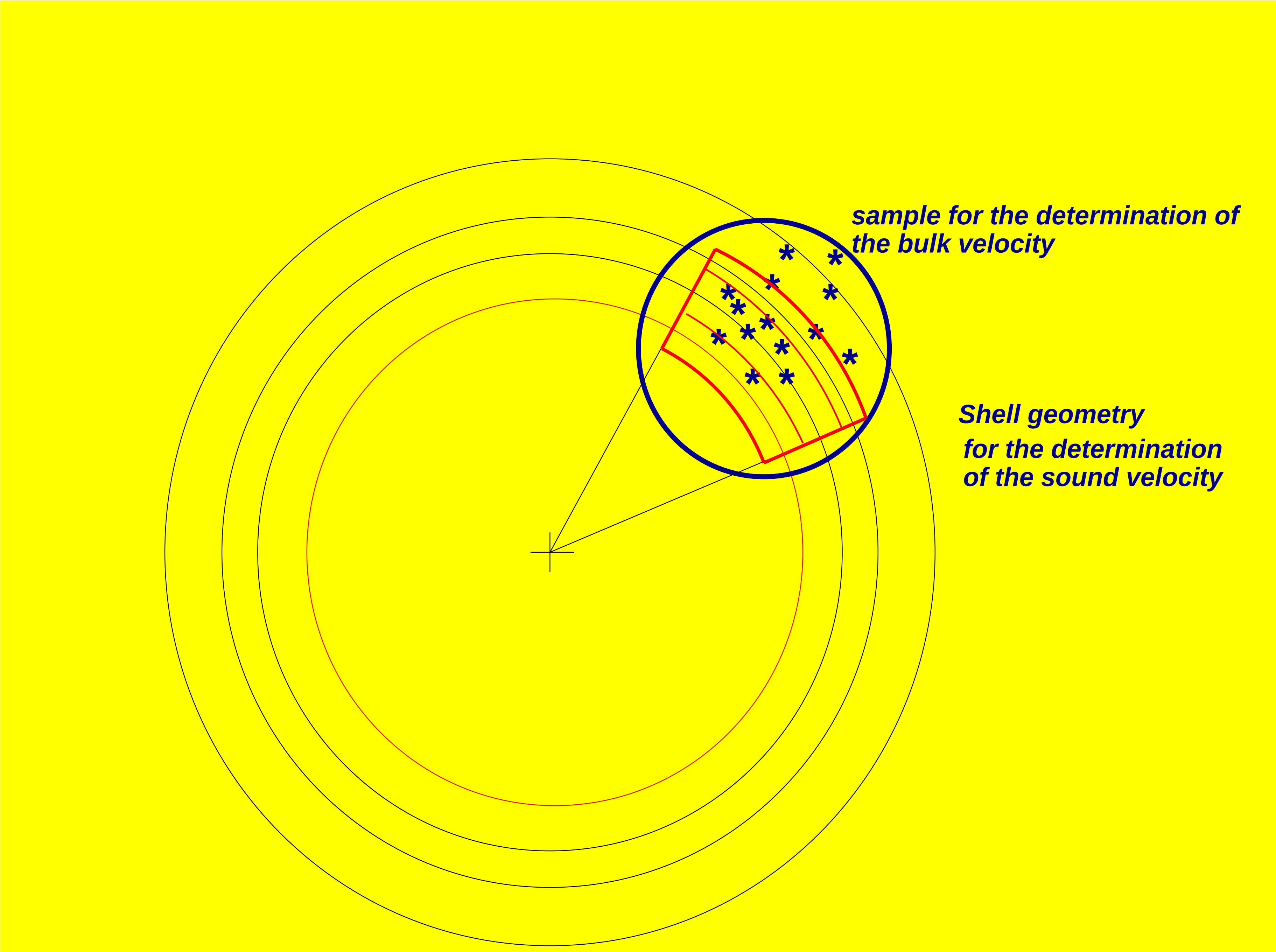
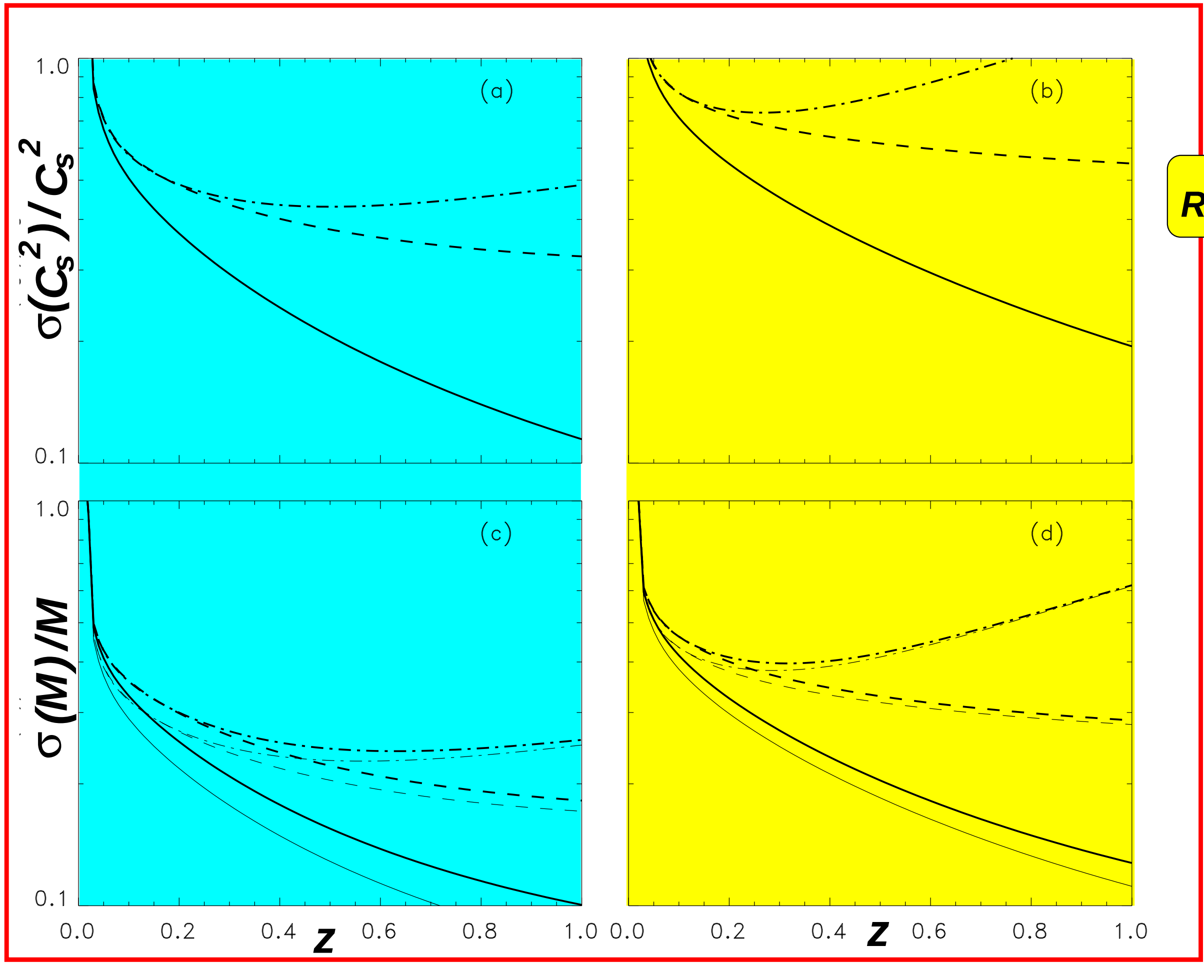

sample for the determination of
the bulk velocity
Shell geometry
for the determination
of the sound velocity

Relative error on C_s and M

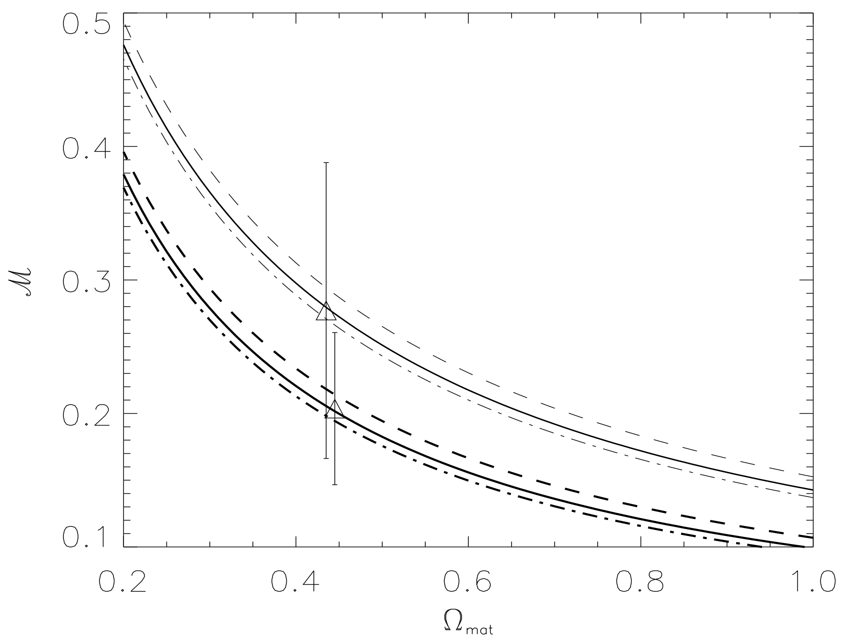


Right column: Flux limit 400 mJy

Left column: Flux limit 200 mJy

(c) and (d) Bulk flows on a sphere of 100 h^{-1}Mpc (upper curves) − and in 150 h^{-1}Mpc − (lower curves)

Measuring the matter density



– Bulk flows on a sphere of 100 (upper set) or 150 h^{-1}Mpc (lower set).

Dashed, solid and dot–dashed lines correspond to n = 0.95, 1.0 and 1.03

Ω_{matter} error bars are one–sigma

With 4 independent estimates:

$$0.25(0.21) \leq \Omega_{matter} \leq 0.37(0.47)$$

at the 68 (95) % confidence level

Summary

- *We propose a method to measure the sound speed for clusters with higher accuracy than presently available from the determination of peculiar velocities via KSZ for single clusters*

- *This allows for the determination of Mach number with sufficient accuracy in order to obtain independent limits on the cosmic matter density*

- *PLANCK will detect all clusters that produce a change in flux of about 200 mJy relative to the mean flux of the CMB [Cluster masses: $M_{200} \geq 10^{14} h^{-1} M_{\odot}$ i.e., about 10 000 clusters up to z = 1]*

  XMM will detect ~ 7000 clusters with z < 1 with KT > 4 keV in ~ 800 square degrees

  It is expected an optical follow−up to determine cluster redshifts and by ALMA a further reduction of the intrinsic CMB uncertainties

⇓

- *Determination of the cosmic matter density with increasing accuracy*