Weighing Clusters of Galaxies...
...from X-ray to Weak Lensing

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Dark Energy Probes

Credit: Kolb, US-DETF Report
Dark Energy Probes

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Galaxy Clusters

83% Dark Matter
2% Galaxies
15% Hot Gas

R ~ 1-10 Mpc
M ~ 10^{14} – 10^{15} M_{\text{sun}}

Dark Energy
Dark Matter
Baryonic Physics
Cluster Mass Function

Vikhlinin et al. (2009, CCCP111)

Dark Energy

No-Dark Energy

different distance-redshift relation
Weighing Galaxy Clusters...

X-ray

Hydrostatic Equilibrium + Spherical Symmetry

Mass bias sensitive to baryonic physics

(Pics: Bullet Cluster, Clowe et al., 2006)
Weighing Galaxy Clusters...

Mass bias sensitive to baryonic physics

Mass bias affected by the mass projection along the l.o.s.

Baryonic + DM

Hydrostatic Equilibrium + Spherical Symmetry

(Pics: Bullet Cluster, Clowe et al., 2006)
Weighing Galaxy Clusters...

Baryonic + DM mass bias affected by the mass projection along the l.o.s.

Benefits:
- more precise mass models
- reduction of systematic errors

Mass bias sensitive to baryonic physics

X-ray

Hydrostatic Equilibrium + Spherical Symmetry

M_X + M_{WL}

Lensing

Baryonic + DM

Mass bias affected by the mass projection along the l.o.s.

(Pics: Bullet Cluster, Clowe et al., 2006)
The 400d Cluster Survey

**CCCP**: Chandra Cluster Cosmology Project

Vikhlinin et al. (2009, CCCPII, CCCPIII)
The 400d Cluster Survey

**CCCP: Chandra Cluster Cosmology Project**

Vikhlinin et al. (2009, CCCPII, CCCPIII)

**ROSAT PSPC pointings**

*Burenin et al. (2007)*

- 242 clusters

  Median-redshift: $z \sim 0.20$

- $|b| > 25^\circ$
- $N_H < 10^{21} \text{ cm}^2$
- Total clean exposure $t_{\text{exp}} > 1 \text{ ks}$
- > $10^\circ$ away from the LMC and SMC
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- 49 low-z ($0.02 < z < 0.22$)
  - (subsample of HIFLUGCS)

- 36 high-z
  - dedicated pointings
    - with Chandra
    - (+ some XMM)

- 85 clusters

**400d Survey Cosmological Sample**

17 Jan 2013 – CotB, 2014
Weighing Clusters of Galaxies
Alberto Doria
The 400d Cluster Survey

CCCP: Chandra Cluster Cosmology Project

Credit: H. Israel
400d Cosmological Sample

Optical follow-up for Weak Lensing studies (Reiprich et al.)

- 36 Galaxy Clusters
- High Redshift: $0.35 < z < 0.9$ \(<z> = 0.5$
- $L_X > 10^{44}$ erg/s

Selection function of 400d very well known

Megacam@MMT
WFI@MPG/ESO2.2m
IMACS@Magellan
MegaCam@CFHT
ACS@HST
SuprimeCam@Subaru
FORS1-2@VLT
Precision Cosmology

- precision cosmology relies on precise and accurate cluster masses
- need of bias correction and systematics control

Vikhlinin et al. (2009, CCCPIII)

All cosmological dataset:
- $w_0 = -0.991 \pm 0.045$
- $\Omega_X = 1 - \Omega_M = 0.740 \pm 0.012$

Check assumptions for scaling relations and their evolution
Results for 8 clusters observed with MMT/Megacam

Israël et al., 2010

Israël et al., 2012
Reliable masses although bright stars are present: essential for the successful follow-up of a complete sample!

Ground-based WL works at least till $z \approx 0.8$

Israel et al., 2012
 Correction for massive foreground structures

 Instrumental effects are well under control
MMT vs CFHT

CL1701+6414

MMT – 7.5 ks
CFHT – 8.7 ks
$r'$ band

Excellent Agreement!
First Checks

Consistent with Vikhlinin et al., 2009 (CCCPIII)

PRELIMINARY!

Israel et al., in prep.
Wide Field Imager

CL0302-0423

$z = 0.35$

~30'x30'

Weighing Clusters of Galaxies
CL0302-0423

z = 0.35

Wide Field Imager

2 x 2' detail
...and also V, I, i, g bands...
Final Remarks & Outlook

➢ Control on systematic effects due to different instruments, using sophisticated methods

➢ Good mass estimates despite unfavorable physical conditions

➢ Consistency with X-ray estimates from Vikhlinin et al. 2009

➢ Tang. shear profiles and NFW cluster parameters

➢ Consistency and systematics check (for the whole sample)

➢ Growth factor comparing with HIFLUGCS

➢ Disturbances in the galaxy cluster cores

➢ Mass-luminosity scaling relation → eROSITA mission
WFI vs SUBARU

WFI - 15.0 ks  SUBARU - 2.4 ks
**THELI** pipeline for wide-field optical/IR imaging
Erben et al., 2005

- Implemented for many instruments
- Allows parallel jobs for each CCD's chip
- Encloses tools for astrometric and photometric calibration

**Optical Data Reduction**

Developed and applied an efficient method that will be easily and quickly adapted to all the clusters of the sample.
Measuring the Shear

“TS” (Schrabback et al., 2007, Hartlap et al., 2009) implementation for STEP Shear Testing Programme (Heymans+06, Massey +07) of the KSB algorithm (Kaiser et al., 1995; Erben et al., 2001)

Photometric quantities determined in 3 bands

Background galaxies – Foreground Galaxies – Cluster members