Julian Merten

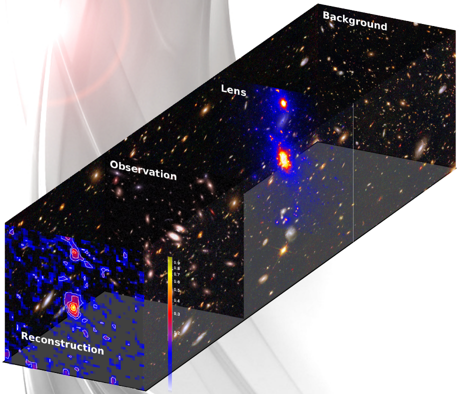
An advanced method to recover mass profiles through gravitational lensing

Institut für Theoretische Astrophysik
Zentrum für Astronomie
Universität Heidelberg
INAF - Osservatorio Astronomico di Bologna

June 1st, 2010

with: Massimo Meneghetti (OABO)
& Matthias Bartelmann (ITA)

Outline: A joint lensing reconstruction method



(Figure to appear in
625 yrs of Heidelberg University)

1. *Reconstruction method*
   - A grid based "nonparametric" approach
   - A problem of scales and a solution
2. *Implementation*
   - The basic concept of GPUs
   - GPUs in practice
3. *Applications*
   - Realistic simulations
   - Real data
4. *Great things to come*
   - CLASH (HST/MCT)
   - Solving some puzzles

The basic idea of an "inverse" method (Bartelmann96)

Spin fields

$$\beta = \theta - \alpha(\theta)$$

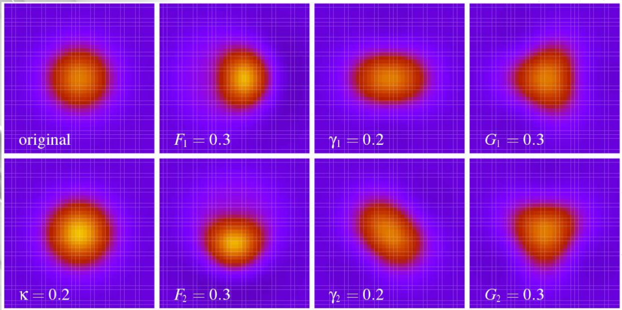
$\partial = \partial_1 + i\partial_2$	$\partial^* = \partial_1 - i\partial_2$
ψ	$\alpha = \partial\psi$
$2\gamma = \partial\partial\psi$	$2\kappa = \partial^*\partial\psi$
$2F = \partial^*\partial\partial\psi$	$2G = \partial\partial\partial\psi$

Statistical approach

$$\chi^2(\psi) = \chi_1^2 + \chi_2^2 + \chi_3^2 + \ldots$$

Possible constraints:

- Ellipticities of background sources
- Flexion (JM10 in prep.)
- Multiple image systems (Bradač05+)
- Critical curve estimates (JM09+)



The basic idea of an "inverse" method (Bartelmann96)

Spin fields

$$\beta = \theta - \alpha(\theta)$$

$$\partial = \partial_1 + i\partial_2 \qquad \partial^* = \partial_1 - i\partial_2$$

$$\psi \qquad \alpha = \partial\psi$$

$$2\gamma = \partial\partial\psi \qquad 2\kappa = \partial^*\partial\psi$$

$$2F = \partial^*\partial\partial\psi \qquad 2G = \partial\partial\partial\psi$$

Statistical approach

$$\chi^2(\psi) = \chi_1^2 + \chi_2^2 + \chi_3^2 + \ldots$$

Possible constraints:

- Ellipticities of background sources
- Flexion (JM10 in prep.)
- Multiple image systems (Bradač05+)
- Critical curve estimates (JM09+)

Other possible constraints

- Optical
  - Magnification
  - Member dynamics
- X-ray
- SZ

The basic idea of an "inverse" method (Bartelmann96)

Spin fields

$$\beta = \theta - \alpha(\theta)$$

$$\partial = \partial_1 + \mathrm{i}\partial_2 \qquad \partial^* = \partial_1 - \mathrm{i}\partial_2$$

$$\psi \qquad \alpha = \partial\psi$$

$$2\gamma = \partial\partial\psi \qquad 2\kappa = \partial^*\partial\psi$$

$$2F = \partial^*\partial\partial\psi \qquad 2G = \partial\partial\partial\psi$$

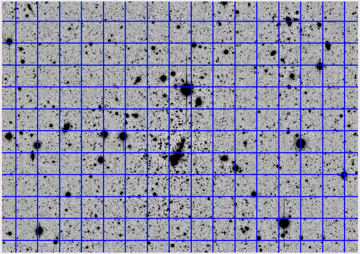
Statistical approach

$$\chi^2(\psi) = \chi_1^2 + \chi_2^2 + \chi_3^2 + \ldots$$

Possible constraints:

- Ellipticities of background sources
- Flexion (JM10 in prep.)
- Multiple image systems (Bradač05+)
- Critical curve estimates (JM09+)

The trick

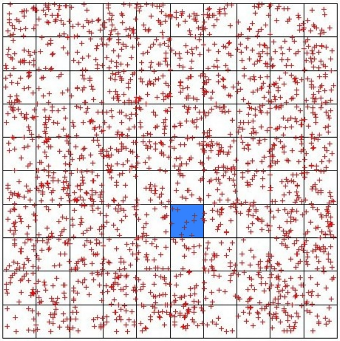


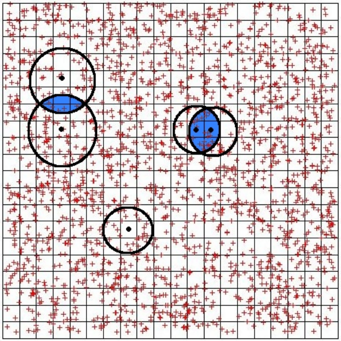
$$\frac{\partial\chi^2(\psi_\mathrm{k})}{\partial\psi_\mathrm{l}} \stackrel{!}{=} 0$$

$$\Rightarrow \mathcal{B}_{lk}\psi_k = \mathcal{V}_l$$

Example: Weak lensing

$$\chi^2_w(\psi) = \sum_{i,j} \left(\varepsilon - \frac{Z(z)\gamma(\psi)}{1 - Z(z)\kappa(\psi)} \right)_i \mathcal{C}^{-1}_{ij} \left(\varepsilon - \frac{Z(z)\gamma(\psi)}{1 - Z(z)\kappa(\psi)} \right)_j$$



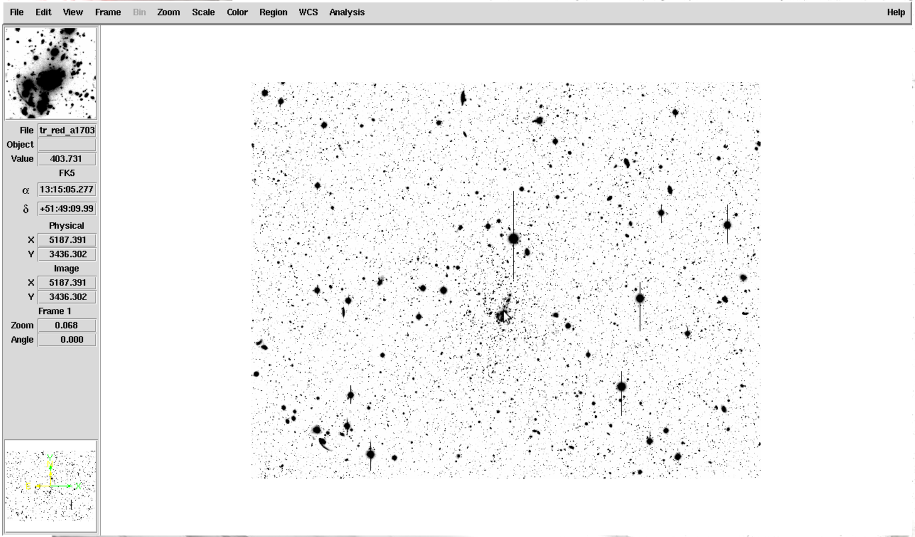


Example: Strong lensing

$$\chi_s^2(\psi) = \sum_i \frac{\left((1 - Z(z)\kappa(\psi))^2 - (Z(z)\gamma(\psi))^2\right)_i^2}{\sigma_i^2}$$

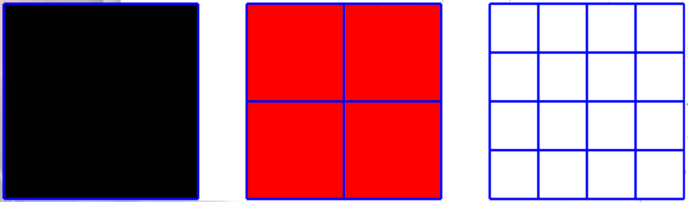
(Figure from Jullo07)

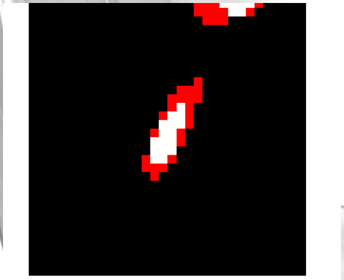
A problem of different scales

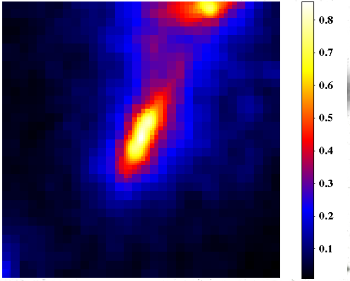


(Abell 1703 in SUBARU r-band)

Clever merging: AMR (Bradač09, JM10)

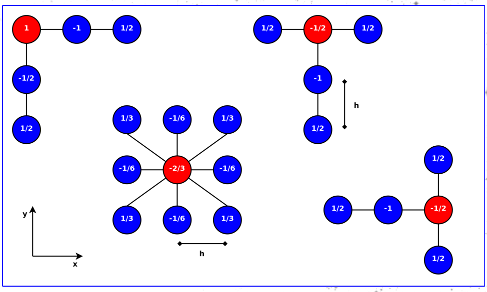






Making it all work: Numerics

- α, γ, κ, F and G can be expressed by derivatives of ψ via finite differences.
- Linearisation of the problem.
- 2-level iteration scheme with simple regularisation (Bradač05).



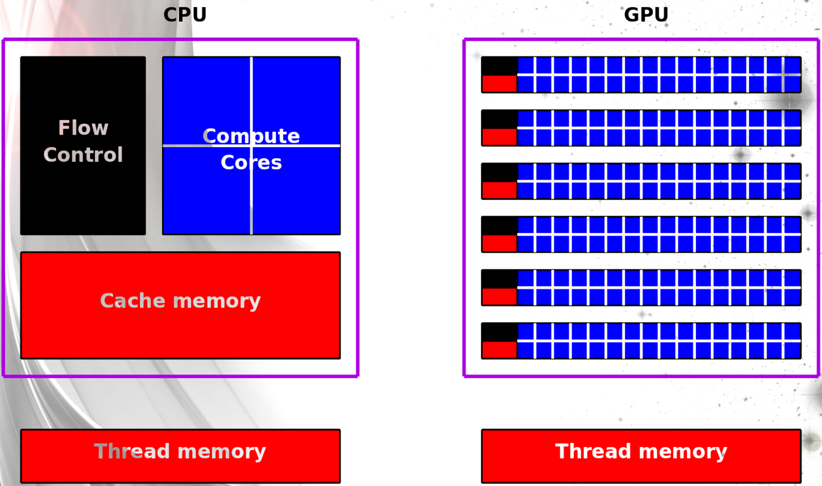
Problem Runtime

$$\mathcal{B}_{lk}\psi_k = \mathcal{V}_l$$
$$\mathcal{B}_{lk} \sim a_i b_j C_{ij} D_{il} E_{jk}$$
$$\mathcal{V}_l \sim a_i b_j C_{ij} E_{il}$$
$$l, k, i, j \sim \mathcal{O}(\text{grid\_dim}^2)$$

Geeky implementation facts

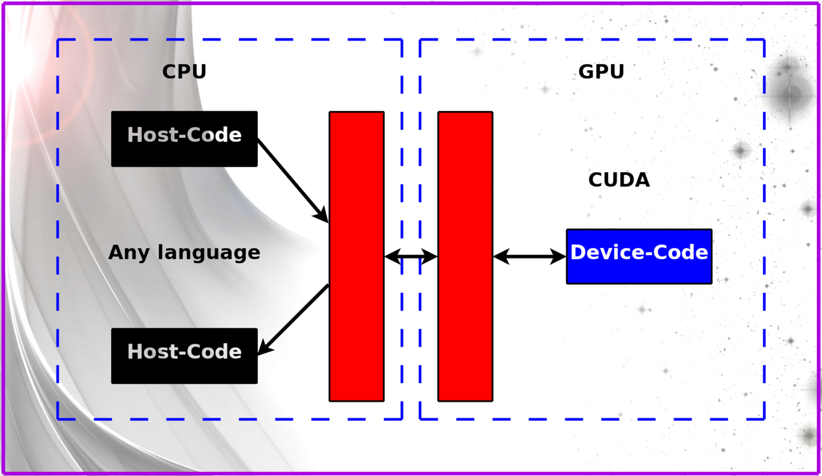
- Parallel C++ code
- medium sized $\sim$ 12000 lines
- Uses GSL, LAPACK, ATLAS, MPI
- Fully documented, including user manual
- and...`CUDA`...

Single node GPU Parallelisation



- One single GPU allows for massive parallelisation at $\sim 1/1000$ of the cost, if problem is suited for $\Rightarrow$ **Data-parallel**.

Single node GPU Parallelisation



- One single GPU allows for massive parallelisation at $\sim 1/1000$ of the cost, if problem is suited for $\Rightarrow$ **Data-parallel**.

GPUs in practice (JM10 in prep.)

NVIDIA Tesla C1060

- 240 streaming cores
- 4 GB DDR3 GPU memory
- 933 GFLOPS peak performance
- Upcoming Fermi cards

Speed-up

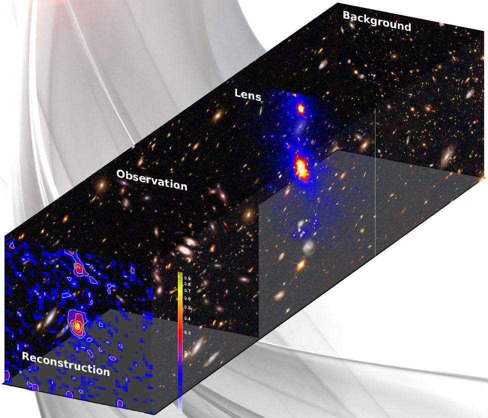
- Calculate:

$$\mathcal{B}_{lk} = a_i b_j \mathcal{C}_{ij} \mathcal{D}_{ik} \mathcal{E}_{jl}$$

- one-core CPU: 82.3 s
- 240 core GPU: 1.03 s

Realistic lensing simulations: ***SkyLens*** *(Meneghetti, JM 08/09)*

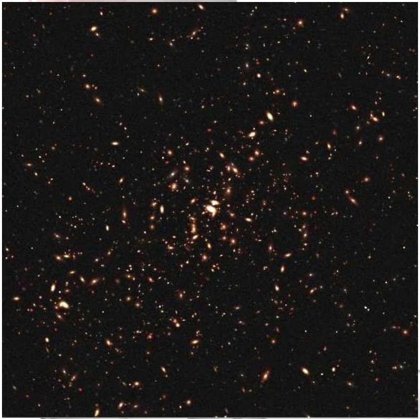
Developers: Massimo Meneghetti, Peter Melchior, Fabio Bellagamba, JM

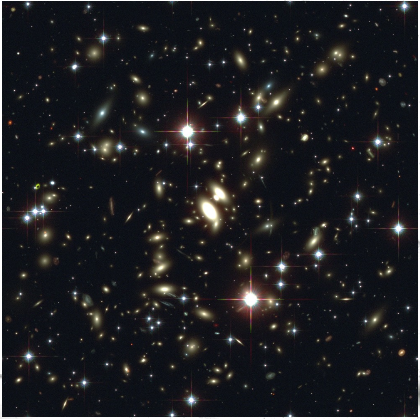


Name	Description
D	aperture diameter
g	detector gain
A_{pix}	pixel area
$F(\lambda)$	used filter
$M(\lambda)$	mirror filter curve
$O(\lambda)$	optics filter curve
$C(\lambda)$	CCD filter curve
FoV	total field-of-view
RON	detector readout-noise
f	flat-field accuracy
a	residual flat-field error
PSF	PSF model
t_{exp}	exposure time
$A(\lambda)$	atmospheric extinction
m_{a}	airmass
SED_{sky}	sky-background emission
SED_{gal}	background population
α	deflection angle map

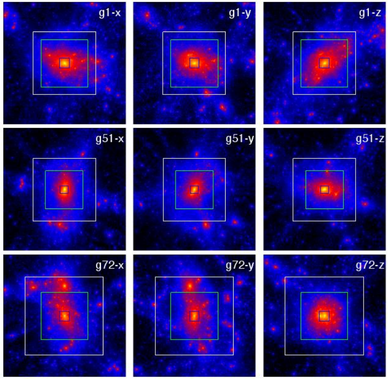
Realistic lensing simulations: **SkyLens** *(Meneghetti, JM 08/09)*

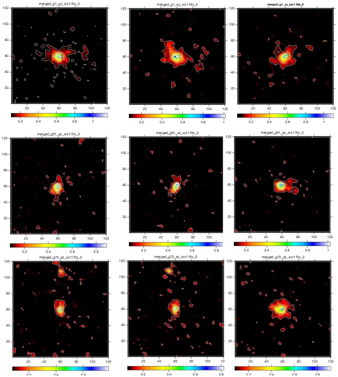
Developers: Massimo Meneghetti, Peter Melchior, Fabio Bellagamba, JM



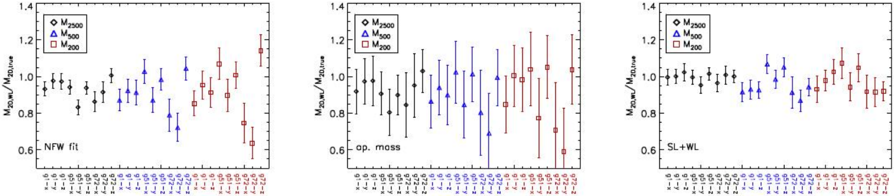


Weighing simulated galaxy clusters (Meneghetti, JM09)

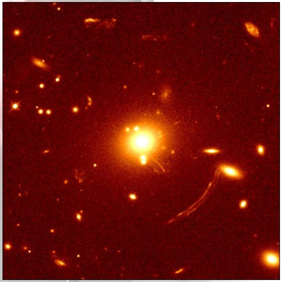


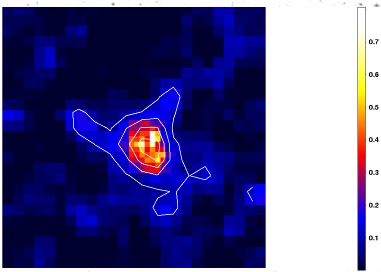


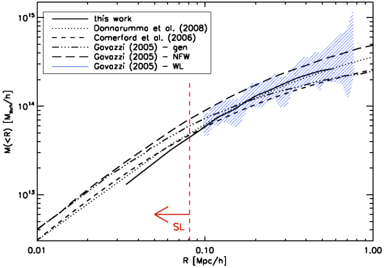
Weighing simulated galaxy clusters (Meneghetti, JM09)

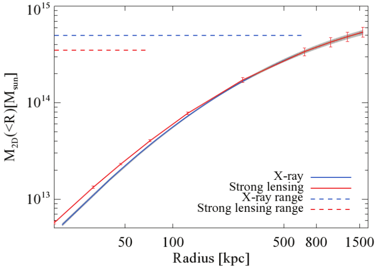


MS2137 (JM09, Donnarumma09)



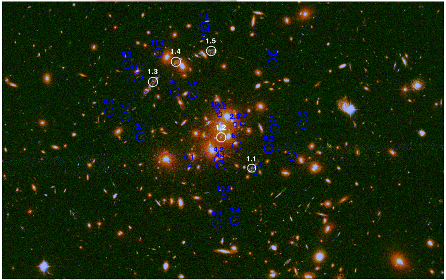


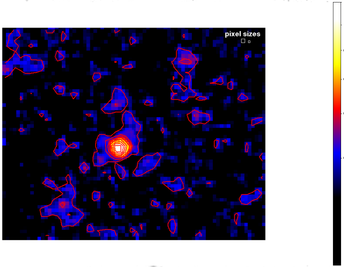


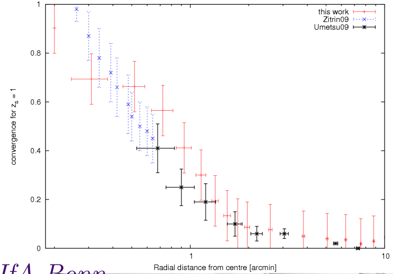


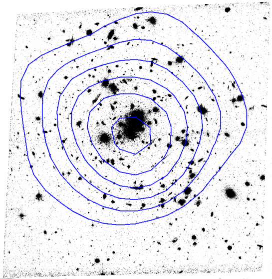
CL0024

with: T. Broadhurst, A. Zitrin, K. Umetsu



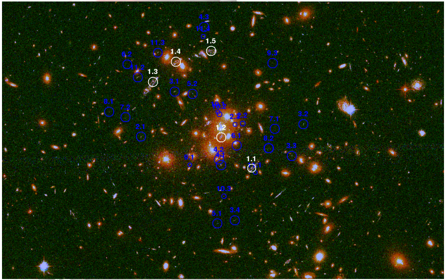


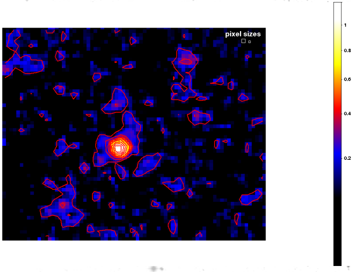


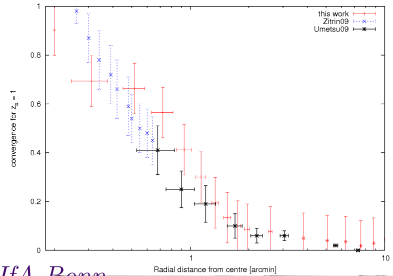


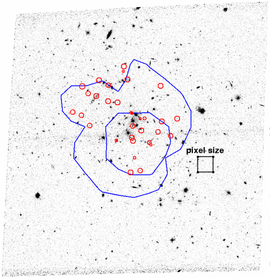
CL0024

with: T. Broadhurst, A. Zitrin, K. Umetsu



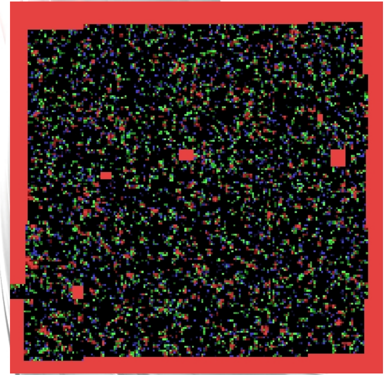




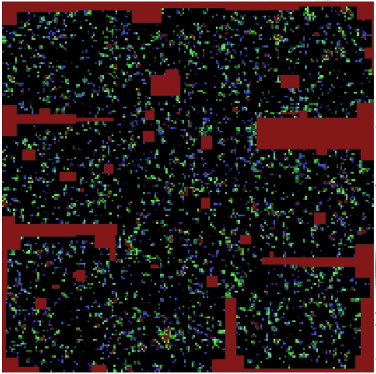


Not really official yet: COSMOS

with: M. Maturi, T.Schrabback



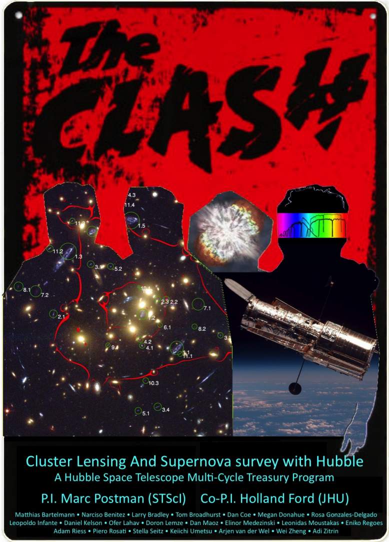
(HST/ACS, the old one)



(SUBARU)

*Great things to come: The **CLASH***

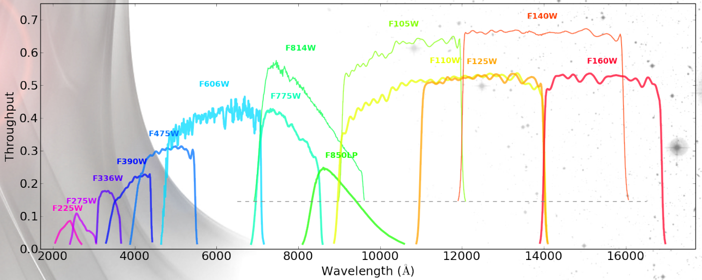
One of three HST/MCT programmes. Start September 2010 (3 cycles).



Science Drivers

- To map the dark matter in galaxy clusters
- To detect SN out to redshifts $z > 1.5$
- To detect and characterise $z > 7$ galaxies
- To study the galaxies in and behind the clusters

CLASH



CLASH Facts

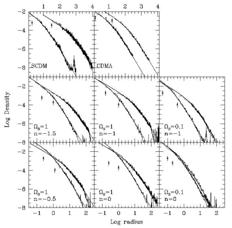
- 25 X-ray clusters
- 524 orbits
- ACS + WFC3 obs.
- 14 (16) wave bands
- wide follow-ups with SUBARU

Our contribution

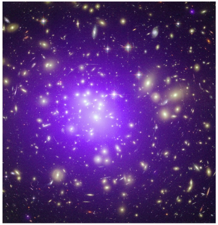
- Full pipeline calibration
- nonparametric DM profiles
- weak-lensing shapes + flexion
- magnification maps for the high-z guys

Cluster puzzles / Puzzle clusters + c.c.

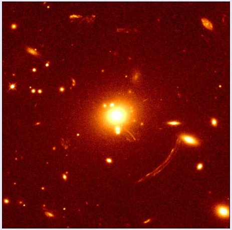
Density profile



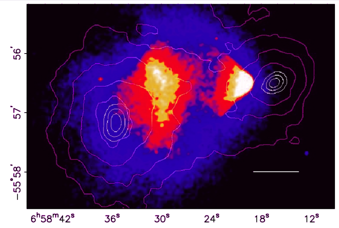
Cool cores



Strong lensing



Extreme dynamics



Are those puzzles at all?

Simulations

- State-of-the-art N-body hydro-sims
- As much physics as possible
  - Cooling
  - Star formation
  - AGN/SN feedback
  - Chemical enrichment
  - ...
- Detailed sims of individual objects
- Cluster populations from cosmological volumes

$\Leftrightarrow$

Observations

- State-of-the-art data
  - HST/ACS/WFPC3
  - SUBARU/LBT
  - KECK
  - CHANDRA / XMM / SUZAKU
- Joint reconstruction method: lensing, X-ray, dynamics, SZ (JM09+, Bradač05+, Puchwein06+)
- reliable error bars
- large cluster sample

Both sides have to be analysed with the same tools.