Julian Merten

Towards an understanding of galaxy clusters

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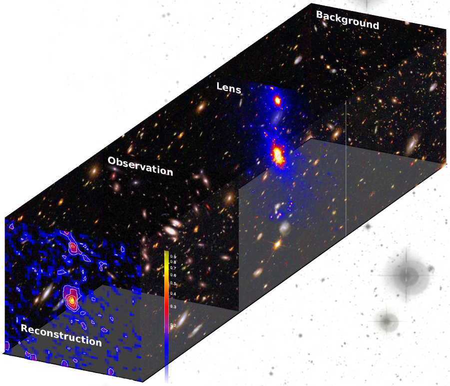
May 9th, 2011

Overview

1. Galaxy clusters
   - Cosmological probes
   - What we don't understand
   - How to pin them
2. A combined lensing method
   - Weak lensing (WL)
   - Strong lensing (SL)
   - WL + SL
   - |WL + SL| > |WL| + |SL|
   - Numerics and GPUs
3. Two applications
   - Abell 2744: Pandora's Cluster
   - The CLASH HST/MCT programme



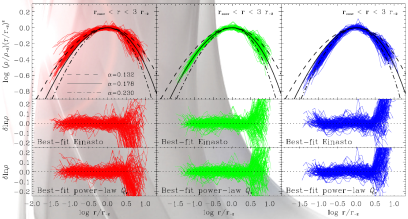
Clusters of galaxies

- Largest gravitationally bound structures in the observable Universe

  $\sim 10^{15} M_\odot$ & Mpc scale
- They appear as dark matter dominated
  (85% DM, 13% hot gas, 2% stars)
- Baryonic component is not dominant, though not negligible (e.g. Duffy10+)
- All cluster components are directly or indirectly observable in three main wavelength regimes

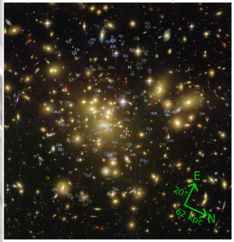
  $\Rightarrow$ Cosmic laboratories
- Powerful gravitational lenses
- We do not really understand them...

Problems with galaxy clusters

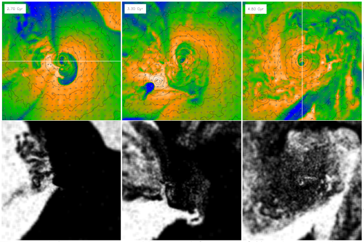


(Ludlow11+)

(Clowe06+)



(Coe10+)



(Ascasibar06+)

How to understand them better

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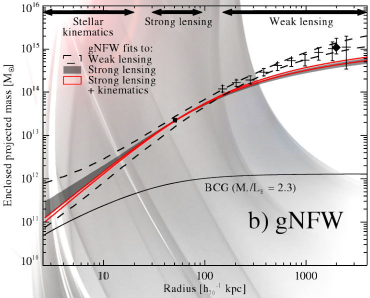

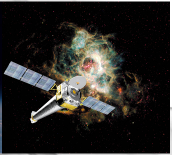

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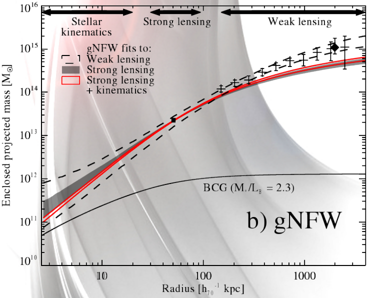

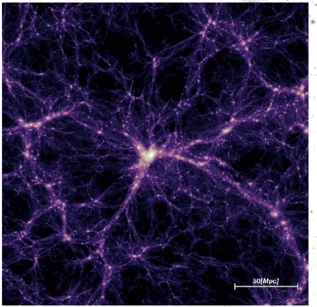

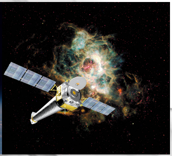

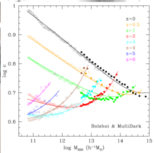

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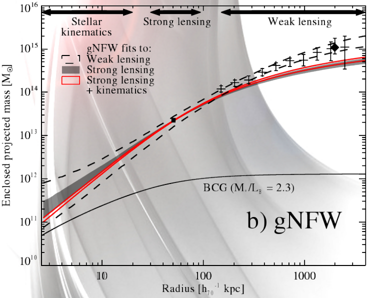
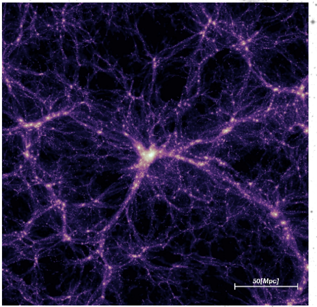
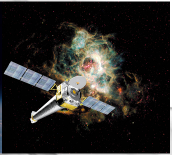


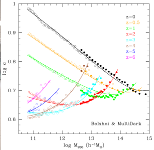
sensible

$\Longleftrightarrow$

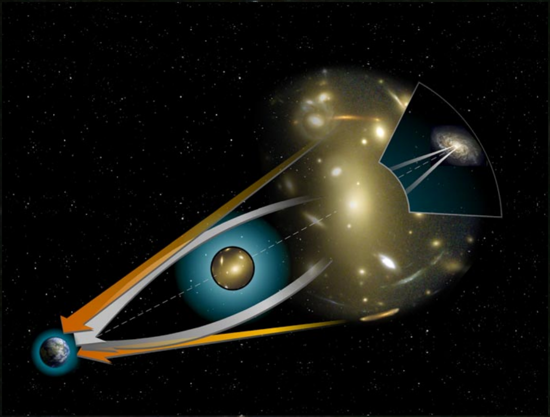
comparison







Gravitational lensing on two sketches



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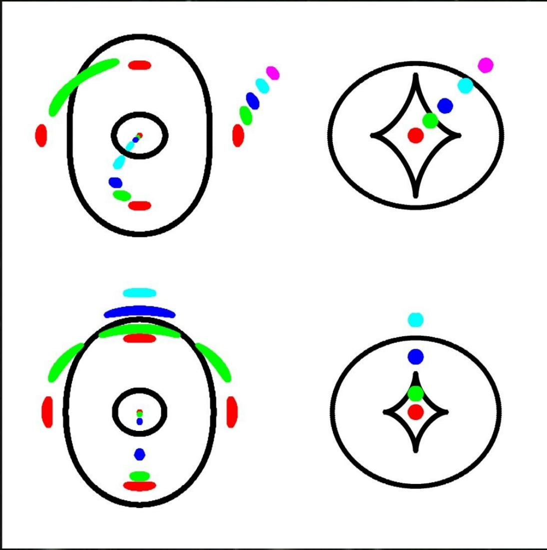


A combined lensing method: Methodology I

Cluster lensing in a box

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

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

ψ $\quad$ $\alpha = \partial\psi$

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

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

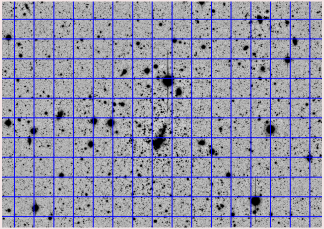
Statistical approach

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

Possible constraints:

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

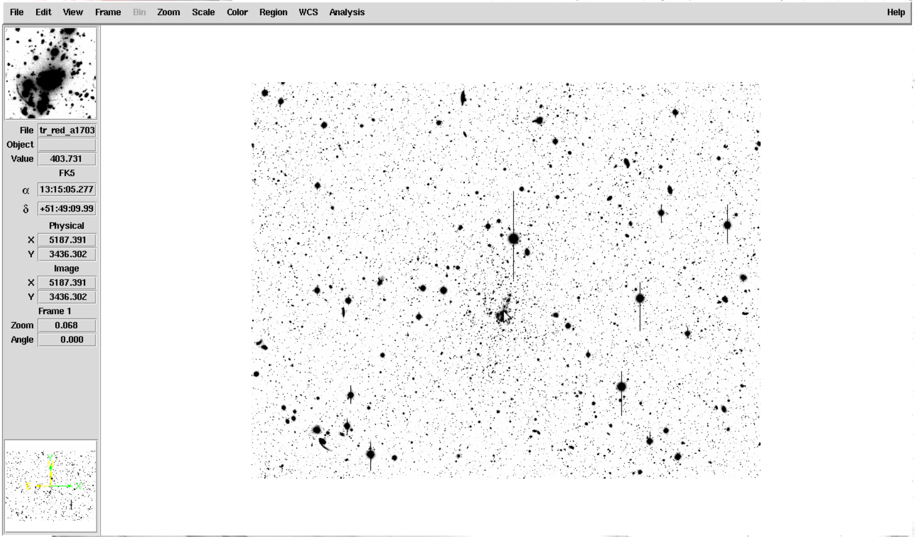
The trick



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

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

A problem of different scales *(JM10, Bradač09)*



(Abell 1703 in SUBARU r-band)

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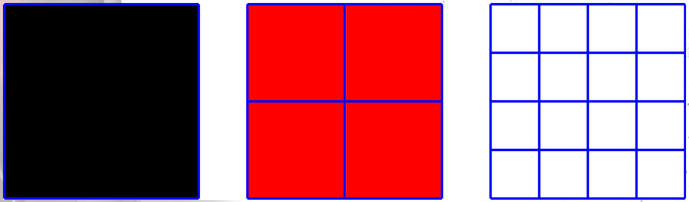
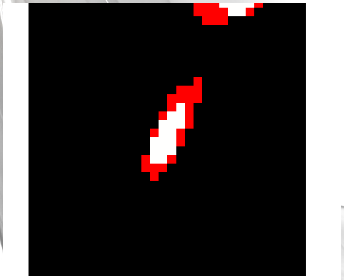
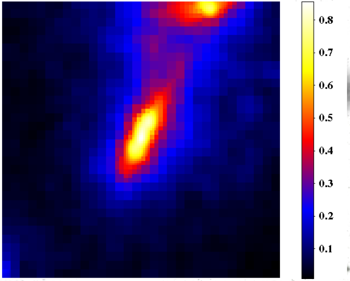
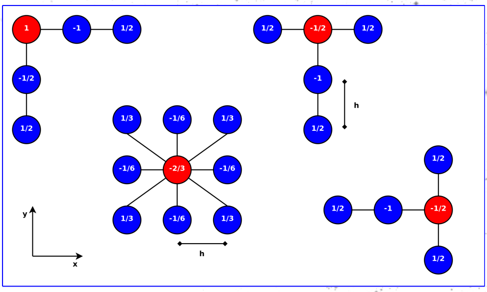






A combined lensing method: Implementation

- 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

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

$$\mathcal{B}_{lk} \sim a_i b_j C_{ij} D_{il} E_{jk}$$

$$\mathcal{V}_l \sim a_i b_j C_{ij} E_{il}$$

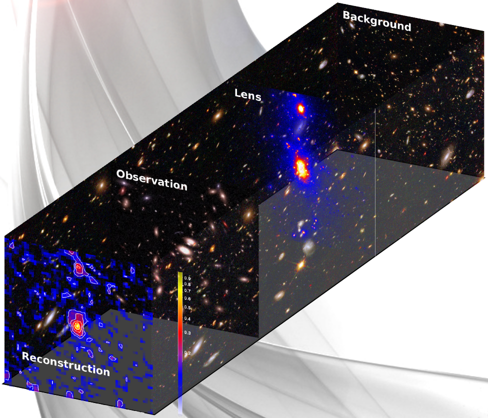
$$l, k, i, j \sim \mathcal{O}(\text{grid\_dim}^2)$$

Geeky implementation facts

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

How well does it perform? **SkyLens** *(Meneghetti, JM 08/10)*

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

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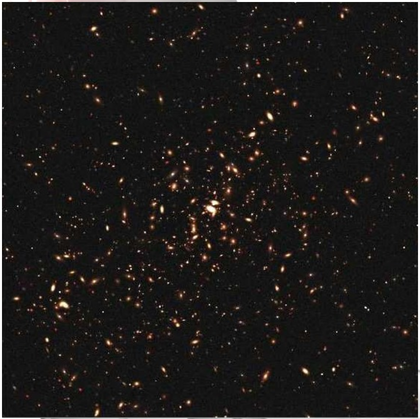

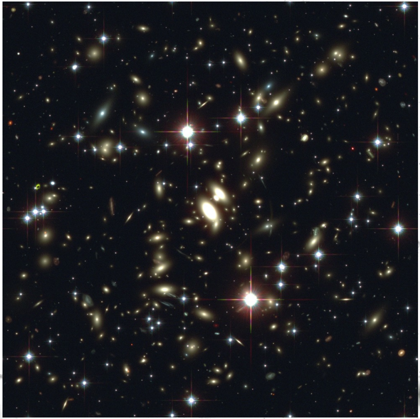

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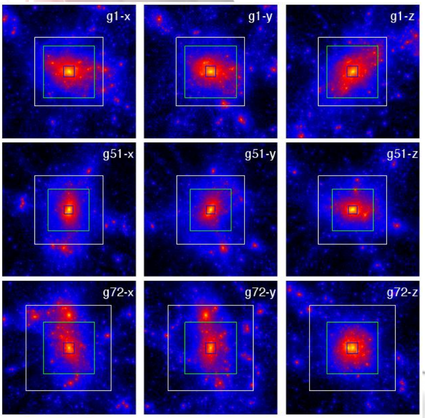

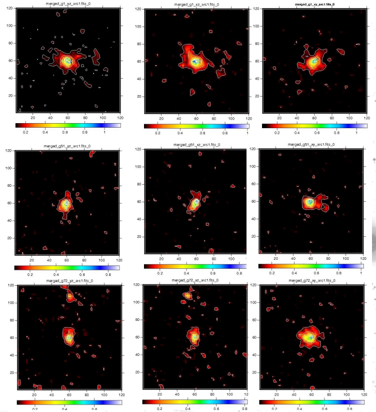

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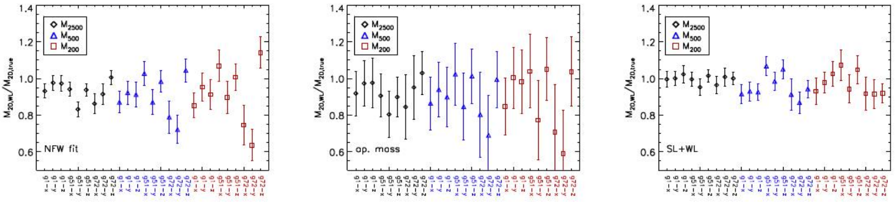
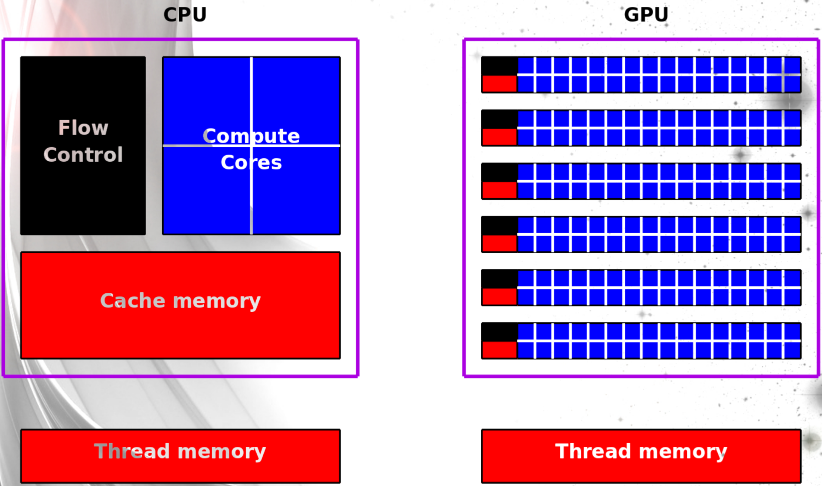


A little detour: GPU implementation



- One single GPU allows for massive parallelisation at a fraction of the cost of a CPU cluster, if problem is suited for ⇒ **Data-parallel**.

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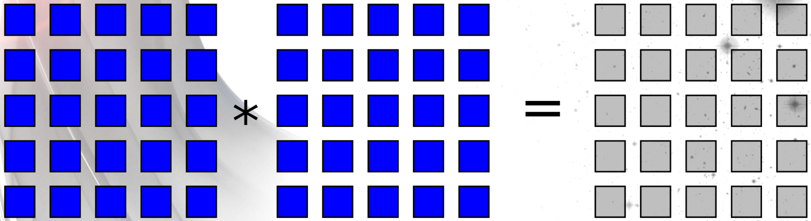

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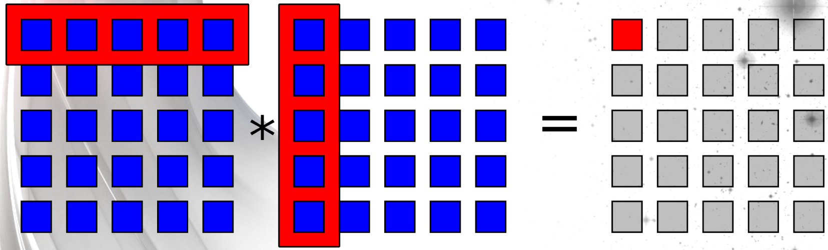

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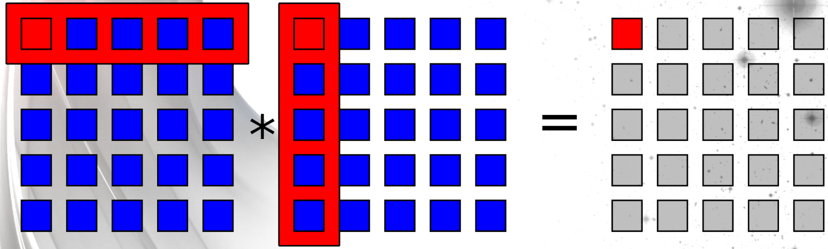

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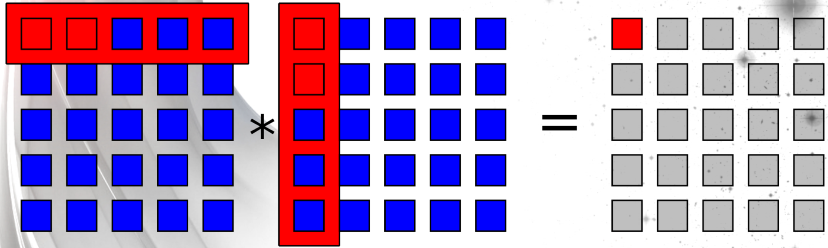

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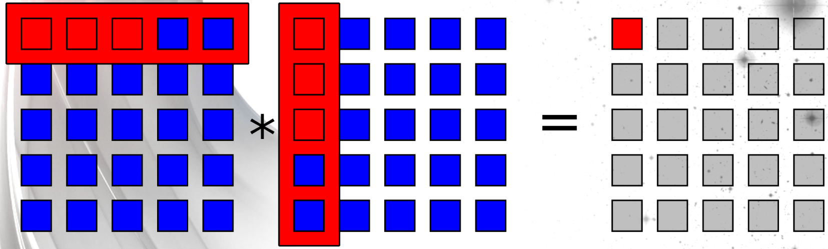

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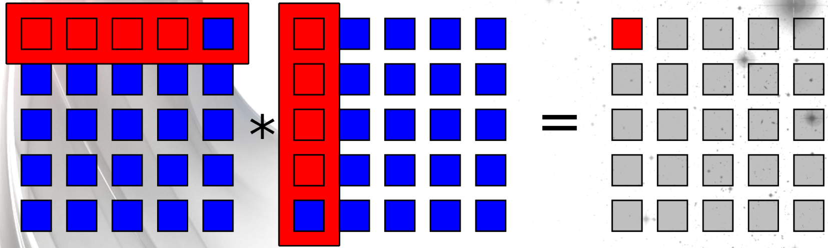

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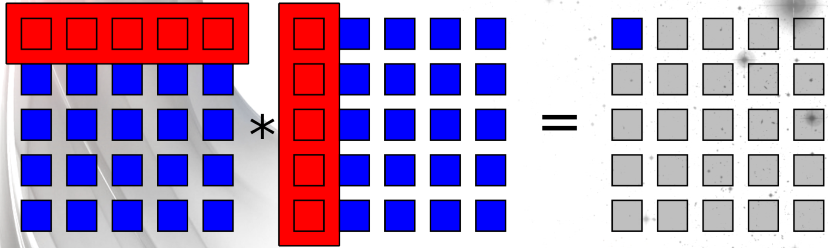

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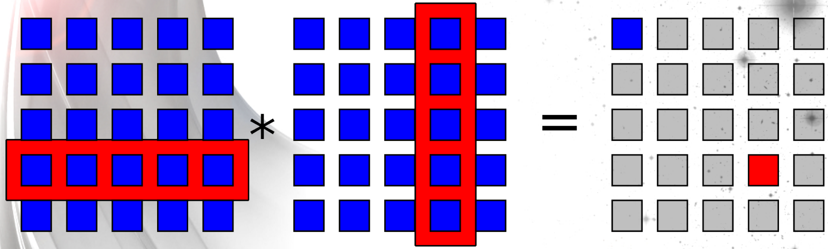

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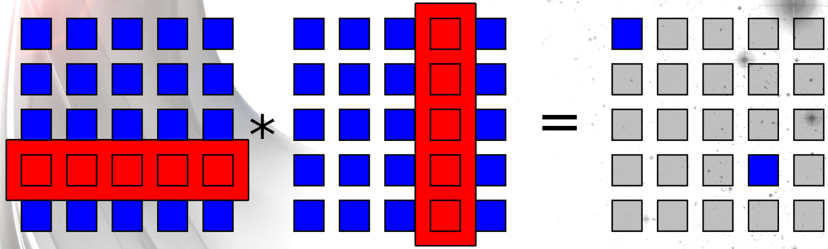

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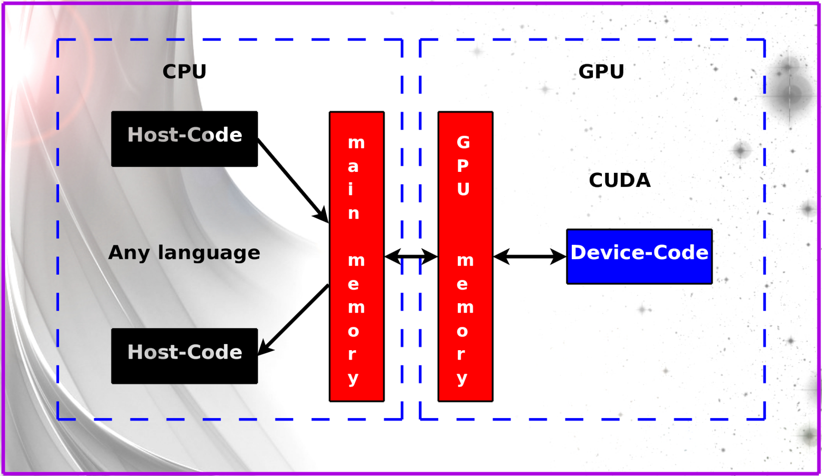

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Cluster performance under your desk

NVIDIA Tesla C2050

- 1 TFLOP peak performance (SP)
- 500 GFLOPS peak performance (DP)
- 3 GB global ECC memory
- 14 (16) multi-processors
- 448 (512) streaming cores

Workhorse: Jabba

- 2x quadcore XEON @ 2.4 GHz
- 16 GB ECC memory
- NVIDIA Tesla C1060
- NVIDIA Tesla C2050
- Cluster performance for under 5000 € .

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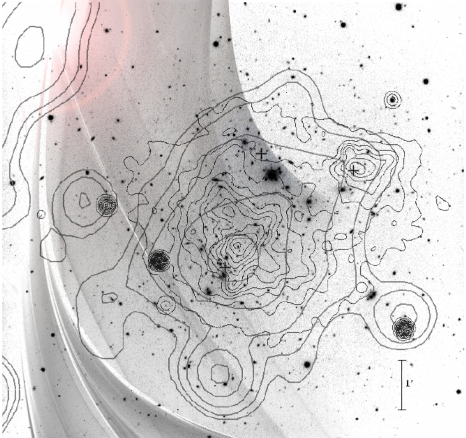
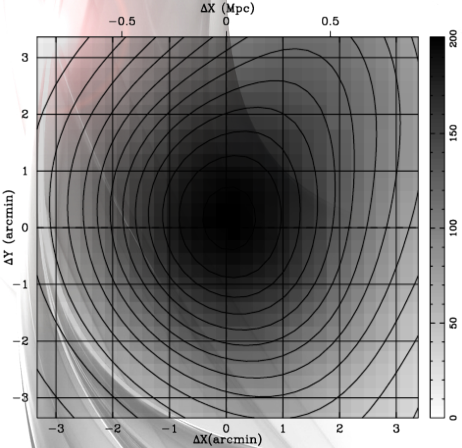
Abell 2744: Pandora's cluster I



(Owers et al. 2010, X-ray, kinematics, radio)

- A2744 ($z = 0.308$) was well known to be an interesting, merging system.
- The lensing analysis was not decisive, yet.
- We used HST/ACS (15 orbits), VLT & Subaru imaging.
- Performed a SL analysis for multiple image identification.
- Applied the presented method.



(Cypriano et al. 2004, VLT weak lensing)

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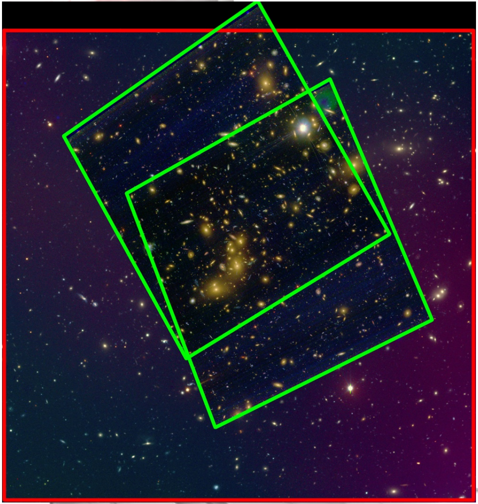

(ACS P.I.: R. Dupke)

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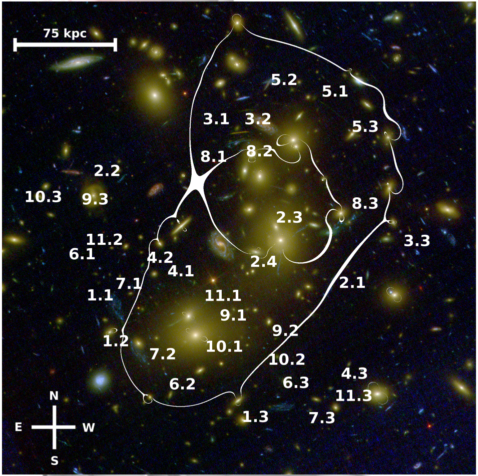

(JM, Dan Coe et al. 2011, Method: A. Zitrin (Tel Aviv))

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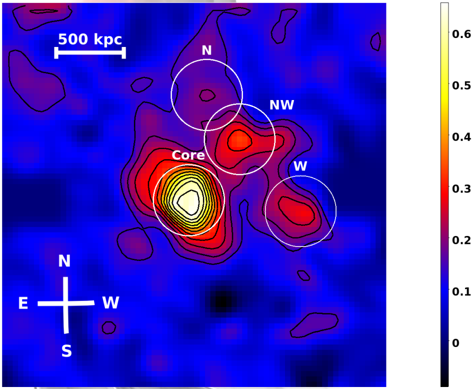

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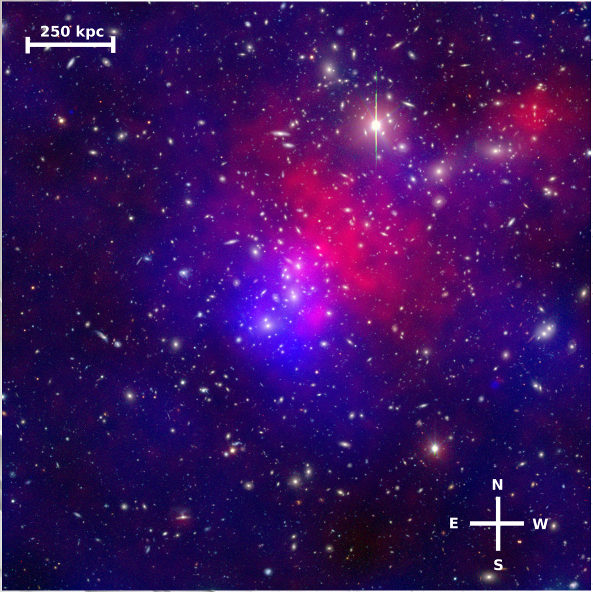
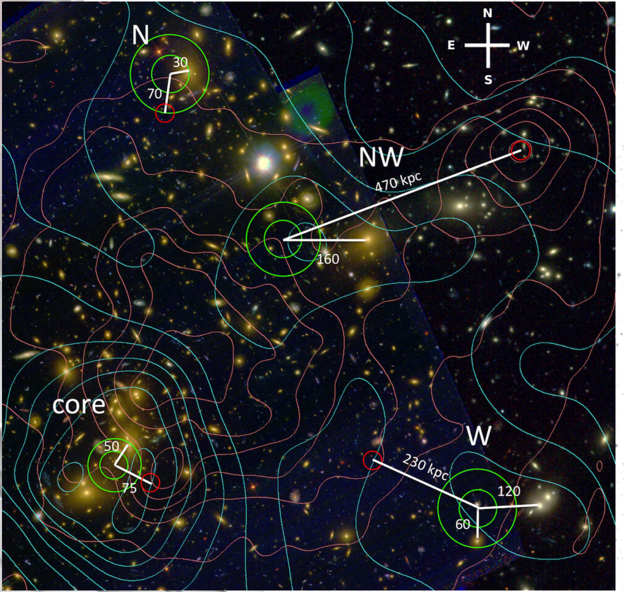
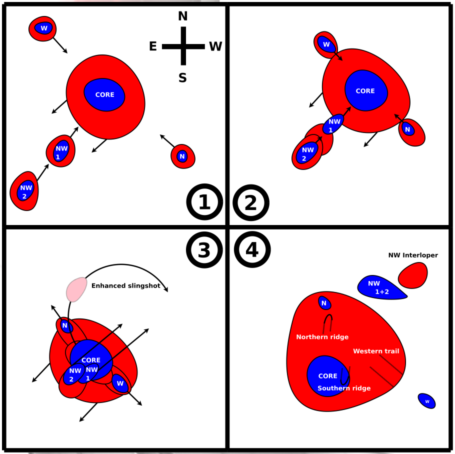
Abell 2744: Pandora's cluster II



Abell 2744: Pandora's cluster II



Abell 2744: Pandora's cluster III



(JM, Dan Coe et al. 2011)

Observations

- HST/ACS
- Chandra
- Magellan
- Gemini South

Simulations

- Together with V. Springel (Heidelberg)
- Millennium XXL
- MareNostrum Universe
- Toy models

CLASH: A HST/MCT programme

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

`http://www.stsci.edu/~postman/CLASH/`

CLASH: Team

United States

M. Postman (P.I.) (STScI) | H. Ford (Co-P.I.) (JHU) | L. Bradley (STScI) | D. Coe (STScI)
M. Donahue (Michigan) | G. Graves (UC Berkeley) | D. Kelson (Carnegie) | D. Lemze (JHU)
E. Medezinski (JHU) | L. Moustakas (JPL) | A. Riess (STScI/JHU) | W. Zheng (JHU)

Europe

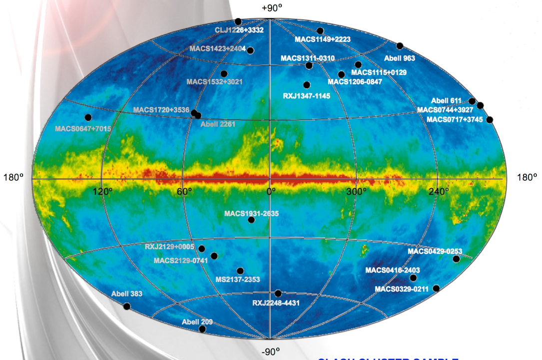
M. Bartelmann (Heidelberg) | N. Benitez (Granada) | R. Bouwens (Leiden) | T. Broadhurst (Bilbao)
R. Gonzales-Delgado (Granada) | O. Host (London) | S. Jouvel (London) | O. Lahav (London)
R. Lazkoz (Bilbao) | P. Melchior (Heidelberg) | M. Meneghetti (Bologna) | J. Merten (Heidelberg)
E. Regos (CERN) | P. Rosati (ESO) | S. Seitz (Munich)

The rest of the world

L. Infante (Santiago de Chile) | D. Maoz (Tel Aviv) | K. Umetsu (Taipei) | A. Zitrin (Tel Aviv)

Granada, September 20th, 2010

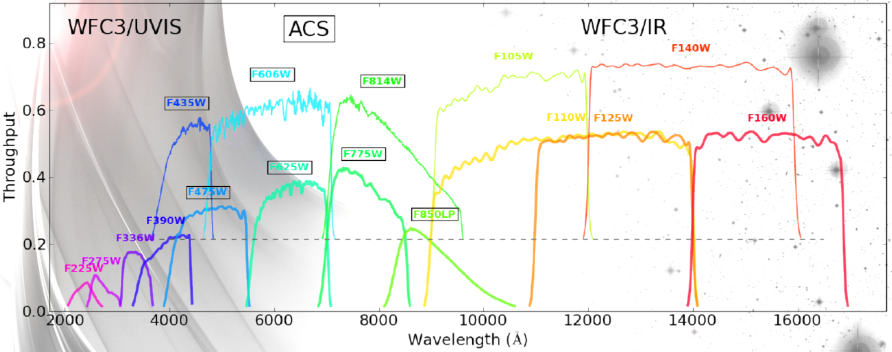
CLASH: Target



CLASH CLUSTER SAMPLE
(Galactic Coordinates)

- 25 Clusters
- $0.18 < z < 0.9$
- X-ray selected
- relaxed
- Chandra archival data

CLASH: HST observations

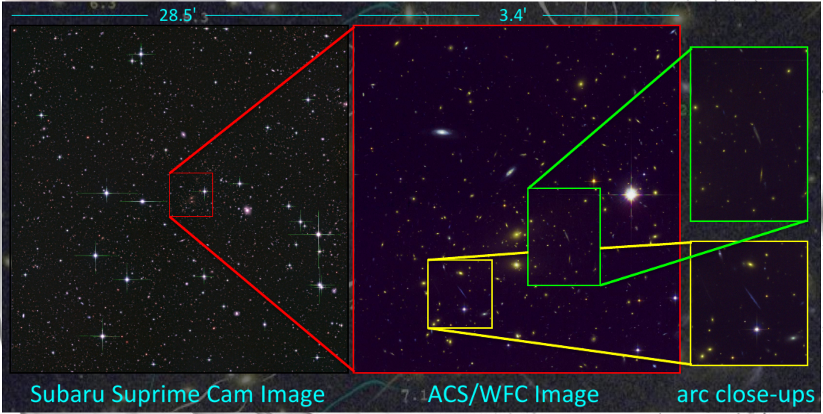


- ACS/WFC3 in parallel
- 524 orbits
- excellent photo-z determination
- near IR - near UV
- 20 orbits / cluster
- BPZ & LePhare (Hildebrandt10+)

CLASH: Parallel data

Nice sideremark: Granted Ground-based and CLASH-related observing time exceedes already the HST/MCT programme.

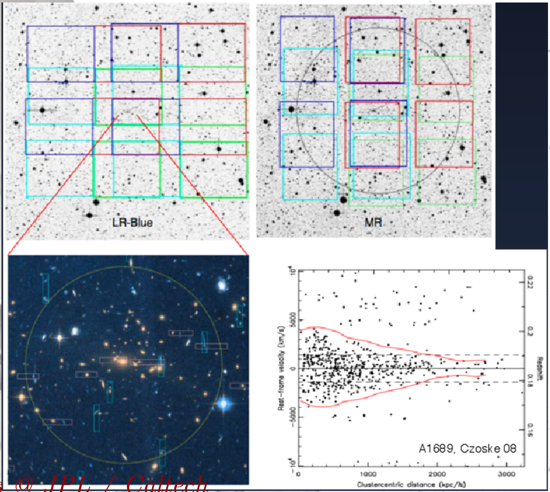
SUBARU BVRIZ weak lensing



CLASH: Parallel data

Nice sideremark: Granted Ground-based and CLASH-related observing time exceedes already the HST/MCT programme.

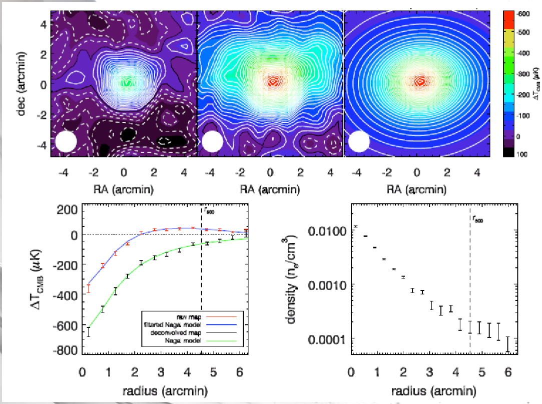
GTC/VLT/Magellan spectroscopy



CLASH: Parallel data

Nice sideremark: Granted Ground-based and CLASH-related observing time exceedes already the HST/MCT programme.

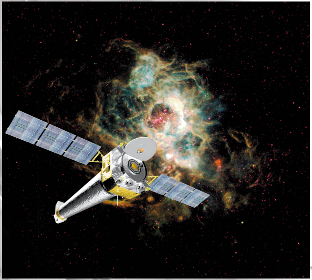
Bolocam/AMiBA/SZA/Mustang SZE observations



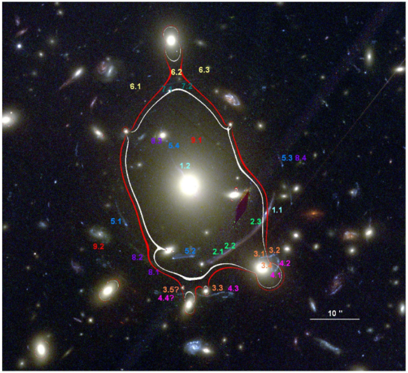
CLASH: Parallel data

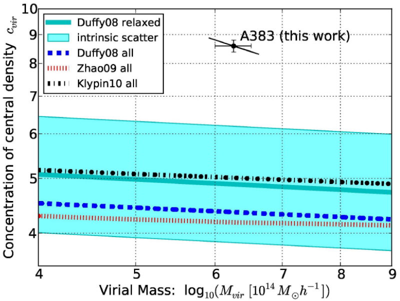
Nice sideremark: Granted Ground-based and CLASH-related observing time exceedes already the HST/MCT programme.

Chandra/XMM Newton archival data



CLASH: First results (Zitrin & CLASH team 2011)





Conclusions

1. Clusters of galaxies are ideal cosmic laboratories, though we do not really understand them.
2. Elaborate lensing methods are a powerful tool to map th mass distribution of clusters.
3. GPU computing provides cluster performance on single node machines.
4. Abell 2744 is a pearl within the known galaxy clusters: A peek into cosmic structure formation.
5. The HST/MCT programme CLASH will dissect a sample of 25 galaxy clusters. A great step towards a better understanding of galaxy clusters.