Julian Merten

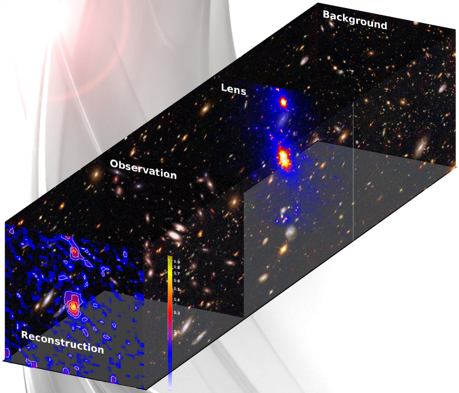
An advanced method to recover mass profiles through gravitational lensing

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

May 28th, 2010

with: Matthias Bartelmann &
Massimo Meneghetti

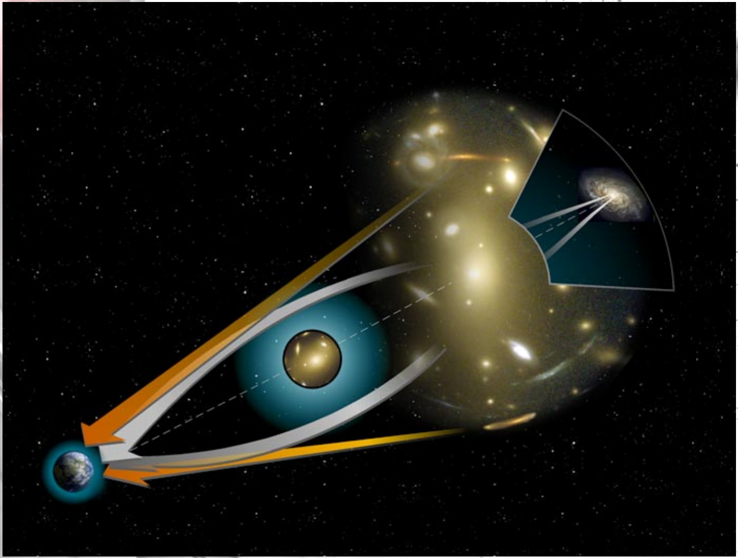
Outline: A joint lensing reconstruction method



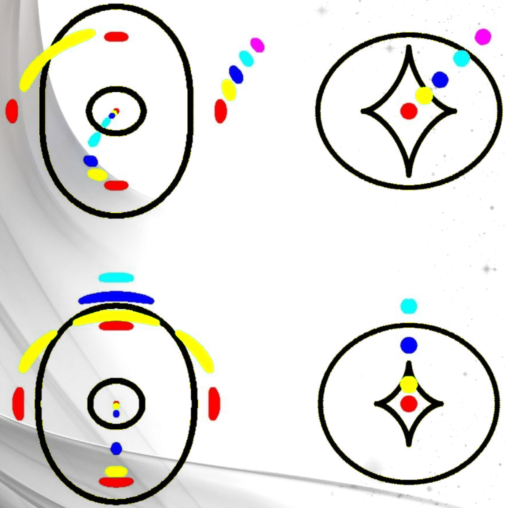
(Figure to appear in
625 yrs of Heidelberg University)

1. *Cosmological framework*
   - What lensing is about
   - Why clusters are useful
2. *A joint reconstruction method*
   - The basic idea
   - Implementation, or why video games look so cool these days
3. *Applications*
   - Realistic simulations
   - Real data
4. *Great things to come*
   - CLASH (HST/MCT)
   - Solving some puzzles

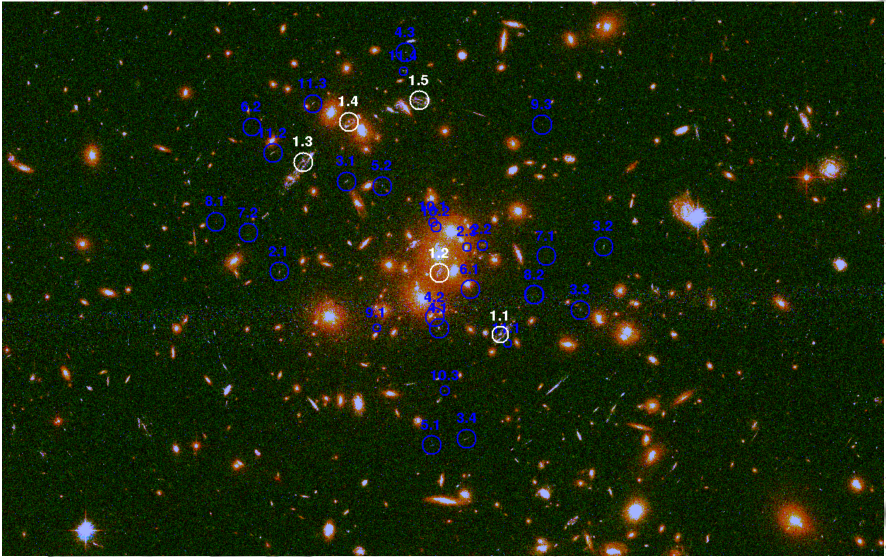
Gravitational lensing



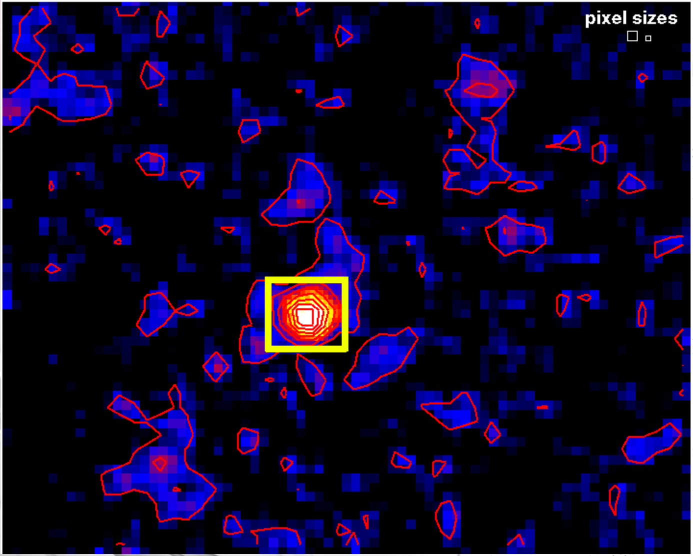
Gravitational lensing



Gravitational lensing



Gravitational lensing



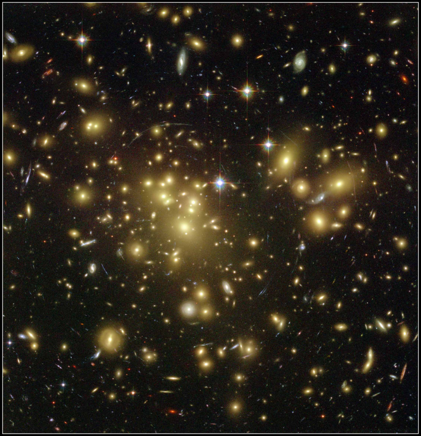
Clusters of galaxies

Cluster facts

- High-mass tail of vir. structure
- $\sim 10^{13}$-$10^{15} M_{\odot}$
- 85% DM, 15% gas, some galaxies

Describing clusters

- Observations
  - Optical (dynamics/lensing)
  - X-ray
  - Microwaves (SZ-effect)
- Simulations
  - Gas "less" important (Duffy09)
  - Draw from cosmo sims



Galaxy Cluster Abell 1689
Hubble Space Telescope • Advanced Camera for Surveys

NASA, N. Benitez (JHU), T. Broadhurst (The Hebrew University), H. Ford (JHU), M. Clampin(STScl), G. Hartig (STScl), G. Illingworth (UCO/Lick Observatory), the ACS Science Team and ESA
STScl-PRC03-01a

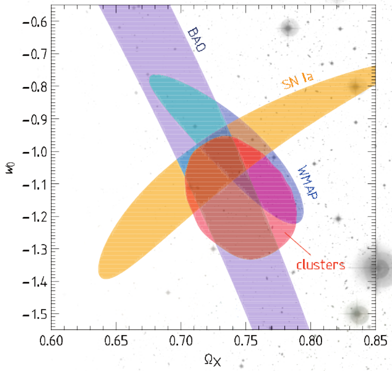
Clusters of galaxies

Cluster facts

- High-mass tail of vir. structure
- $\sim 10^{13}$-$10^{15} M_\odot$
- 85% DM, 15% gas, some galaxies

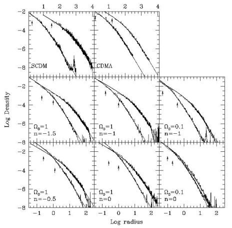
Describing clusters

- Observations
  - Optical (dynamics/lensing)
  - X-ray
  - Microwaves (SZ-effect)
- Simulations
  - Gas “less” important (Duffy09)
  - Draw from cosmo sims

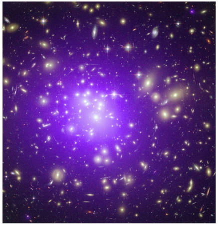


Cluster puzzles / Puzzle clusters

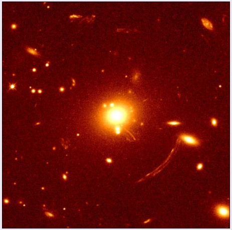
Density profile



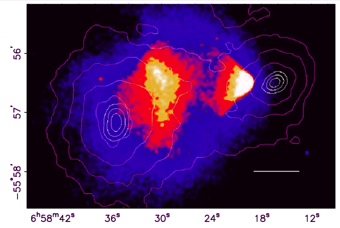
Cool cores



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

$\Leftrightarrow$

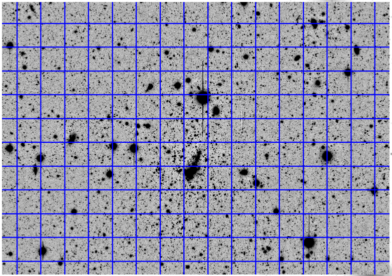
Observations

- 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.

A joint reconstruction method: **SaWLens** *(JM09+)*

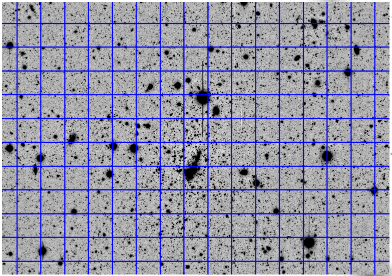
- Nonparametric and grid based.
- Connect the observables to the lensing potential in each pixel.
- χ^2-fitting of the lensing potential in each pixel.
- Possible constrains:
  - Background ellipticiti
  - Flexion (bananity me
  - Arc positions
  - Multiple image po
  - (Dynamics and IC
- Use of AMR grids
- Fast implementation necessary.



$$\chi^2(\psi) = \chi_1^2(\psi) + \chi_2^2(\psi) + \chi_3^2(\psi) + \dots \Rightarrow \mathcal{B}_{lk}\psi_k = \mathcal{V}_l$$

A joint reconstruction method: **SaWLens** *(JM09+)*

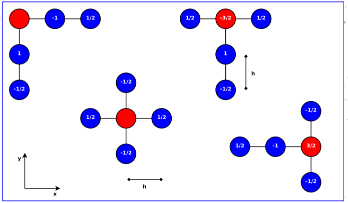
- Nonparametric and grid based.
- Connect the observables to the lensing potential in each pixel.
- χ^2-fitting of the lensing potential in each pixel.
- Possible constrains:
  - Background ellipticities
  - Flexion (bananity measure)
  - Arc positions
  - Multiple image positions
  - (Dynamics and ICM)
- Use of AMR grids
- Fast implementation necessary.

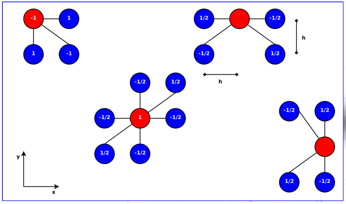


$$\chi^2(\psi) = \chi_1^2(\psi) + \chi_2^2(\psi) + \chi_3^2(\psi) + \ldots \quad \Rightarrow \mathcal{B}_{lk}\psi_k = \mathcal{V}_l$$

A joint reconstruction method: ***SaWLens*** *(JM09+)*

- Nonparametric and grid based.
- Connect the observables to the lensing potential in each pixel.
- χ^2-fitting of the lensing potential in each pixel.
- Possible constrains:
  - Background ellipticities
  - Flexion (bananity measure)
  - Arc positions
  - Multiple image positions
  - (Dynamics and ICM)
- Use of AMR grids
- Fast implementation necessary.

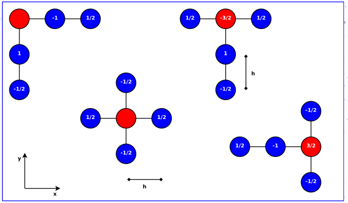


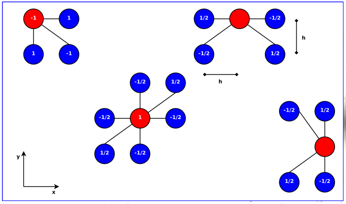


$$\chi^2(\psi) = \chi_1^2(\psi) + \chi_2^2(\psi) + \chi_3^2(\psi) + \ldots \quad \Rightarrow \mathcal{B}_{lk}\psi_k = \mathcal{V}_l$$

A joint reconstruction method: ***SaWLens*** *(JM09+)*

- Nonparametric and grid based.
- Connect the observables to the lensing potential in each pixel.
- χ^2-fitting of the lensing potential in each pixel.
- Possible constrains:
  - Background ellipticities
  - Flexion (bananity measure)
  - Arc positions
  - Multiple image positions
  - (Dynamics and ICM)
- Use of AMR grids
- Fast implementation necessary.

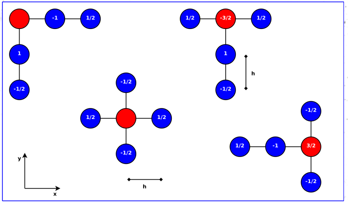


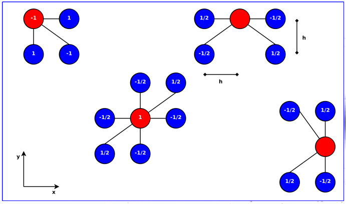


$$\chi^2(\psi) = \chi_1^2(\psi) + \chi_2^2(\psi) + \chi_3^2(\psi) + \ldots \quad \Rightarrow \mathcal{B}_{lk}\psi_k = \mathcal{V}_l$$

A joint reconstruction method: **SaWLens** *(JM09+)*

- Nonparametric and grid based.
- Connect the observables to the lensing potential in each pixel.
- χ^2-fitting of the lensing potential in each pixel.
- Possible constrains:
  - Background ellipticities
  - Flexion (bananity measure)
  - Arc positions
  - Multiple image positions
  - (Dynamics and ICM)
- Use of AMR grids
- Fast implementation necessary.

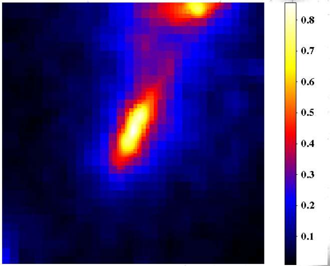




$$\chi^2(\psi) = \chi^2_1(\psi) + \chi^2_2(\psi) + \chi^2_3(\psi) + \ldots \quad \Rightarrow \mathcal{B}_{lk}\psi_k = \mathcal{V}_l$$

A joint reconstruction method: ***SaWLens*** *(JM09+)*

- Nonparametric and grid based.
- Connect the observables to the lensing potential in each pixel.
- χ^2-fitting of the lensing potential in each pixel.
- Possible constrains:
  - Background ellipticities
  - Flexion (bananity measure)
  - Arc positions
  - Multiple image positions
  - (Dynamics and ICM)
- Use of AMR grids
- Fast implementation necessary.



$$\chi^2(\psi) = \chi_1^2(\psi) + \chi_2^2(\psi) + \chi_3^2(\psi) + \ldots \quad \Rightarrow \mathcal{B}_{lk}\psi_k = \mathcal{V}_l$$

A joint reconstruction method: **SaWLens** *(JM09+)*

- Nonparametric and grid based.
- Connect the observables to the lensing potential in each pixel.
- χ^2-fitting of the lensing potential in each pixel.
- Possible constrains:
  - Background ellipticities
  - Flexion (bananity measure)
  - Arc positions
  - Multiple image positions
  - (Dynamics and ICM)
- Use of AMR grids
- Fast implementation necessary.

The complete system

When assuming that a reconstruction contains all possible contributions we find the following, total LSE

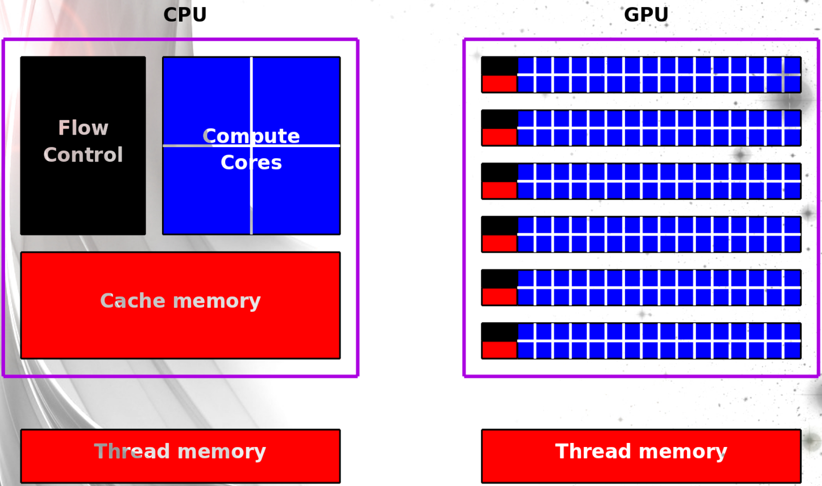
$$\begin{aligned}
\mathcal{B}_{lk} = \mathcal{P}^1_{ij}\big[&\varepsilon^1_i\varepsilon^1_j Z_i Z_j \mathcal{K}_{ik}\mathcal{K}_{jl} + \varepsilon^1_i\varepsilon^1_j Z_i Z_j \mathcal{K}_{jk}\mathcal{K}_{il} + \varepsilon^1_i Z_i Z_j \mathcal{K}_{ik} G^1_{jl} \\
&+ \varepsilon^1_i Z_i Z_j G^1_{jk}\mathcal{K}_{il} + \varepsilon^1_j Z_i Z_j \mathcal{K}_{jk} G^1_{il} + \varepsilon^1_i Z_i Z_j G^1_{ik}\mathcal{K}_{jl} \\
&+ Z_i Z_j G^1_{ik} G^1_{jl} + Z_i Z_j G^1_{jk} G^1_{il}\big] \quad \text{(Reduced shear, first comp.)} \\
+\mathcal{P}^2_{ij}\big[&\varepsilon^2_i\varepsilon^2_j Z_i Z_j \mathcal{K}_{ik}\mathcal{K}_{jl} + \varepsilon^2_i\varepsilon^2_j Z_i Z_j \mathcal{K}_{jk}\mathcal{K}_{il} + \varepsilon^2_i Z_i Z_j \mathcal{K}_{ik} G^2_{jl} \\
&+ \varepsilon^2_i Z_i Z_j G^2_{jk}\mathcal{K}_{il} + \varepsilon^2_j Z_i Z_j \mathcal{K}_{jk} G^2_{il} + \varepsilon^2_i Z_i Z_j G^2_{ik}\mathcal{K}_{jl} \\
&+ Z_i Z_j G^2_{ik} G^2_{jl} + Z_i Z_j G^2_{jk} G^2_{il}\big] \quad \text{(Reduced shear, second comp.)} \\
+\mathcal{C}^1_{ij}&\left[\mathbf{F}^1_{ik}\mathbf{F}^1_{jl} + \mathbf{F}^1_{jk}\mathbf{F}^1_{il}\right] Z_i Z_j \quad (F\text{-flexion, first comp.}) \\
+\mathcal{C}^2_{ij}&\left[\mathbf{F}^2_{ik}\mathbf{F}^2_{jl} + \mathbf{F}^2_{jk}\mathbf{F}^2_{il}\right] Z_i Z_j \quad (F\text{-flexion, second comp.}) \\
+\mathcal{C}^1_{ij}&\left[\mathrm{G}^1_{ik}\mathrm{G}^1_{jl} + \mathrm{G}^1_{jk}\mathrm{G}^1_{il}\right] Z_i Z_j \quad (G\text{-flexion, first comp.}) \\
+\mathcal{C}^2_{ij}&\left[\mathrm{G}^2_{ik}\mathrm{G}^2_{jl} + \mathrm{G}^2_{jk}\mathrm{G}^2_{il}\right] Z_i Z_j \quad (G\text{-flexion, second comp.}) \\
+\frac{2}{\sigma_2}&\left[\mathcal{D}^1_{ak}\mathcal{D}^1_{al} + \frac{1}{M}\sum_{n,m}^{M}\left(\mathcal{D}^1_{nk}\mathcal{D}^1_{al} - \mathcal{D}^1_{ak}\mathcal{D}^1_{nl} + \mathcal{D}^1_{mk}\mathcal{D}^1_{nl}\right)\right] \quad \text{(M. systems, first comp.)} \\
+\frac{2}{\sigma_2}&\left[\mathcal{D}^2_{ak}\mathcal{D}^2_{al} + \frac{1}{M}\sum_{n,m}^{M}\left(\mathcal{D}^2_{nk}\mathcal{D}^2_{al} - \mathcal{D}^2_{ak}\mathcal{D}^2_{nl} + \mathcal{D}^2_{mk}\mathcal{D}^2_{nl}\right)\right] \quad \text{(M. systems, second comp.)} \\
+Z^2_b&\left[\mathcal{K}_{bk}\mathcal{K}_{bl} - G^1_{bk}G^1_{bl} - G^2_{bk}G^2_{bl}\right]\frac{4(\det\mathcal{A})_b}{\sigma^2_b} \quad \text{(Critical curve estimator)}
\end{aligned} \tag{5.33}$$

$$\begin{aligned}
\mathcal{V}_l = \mathcal{P}^1_{ij}&\left[\varepsilon^1_i\varepsilon^1_j\mathcal{K}_{jl} + \varepsilon^1_i Z_j G^1_{jl} + \varepsilon^1_i\varepsilon^1_j Z_i\mathcal{K}_{il} + \varepsilon^1_j Z_i G^1_{il}\right] \quad \text{(Reduced shear, first comp.)} \\
+\mathcal{P}^2_{ij}&\left[\varepsilon^2_i\varepsilon^2_j\mathcal{K}_{jl} + \varepsilon^2_i Z_j G^2_{jl} + \varepsilon^2_i\varepsilon^2_j Z_i\mathcal{K}_{il} + \varepsilon^2_j Z_i G^2_{il}\right] \quad \text{(Reduced shear, second comp.)} \\
+\mathcal{C}^1_{ij}&\left[f^1_i Z_j \mathbf{F}^1_{jl} + f^1_j Z_i \mathbf{F}^1_{il}\right] \quad (F\text{-flexion, first comp.}) \\
+\mathcal{C}^2_{ij}&\left[f^2_i Z_j \mathbf{F}^2_{jl} + f^2_j Z_i \mathbf{F}^2_{il}\right] \quad (F\text{-flexion, second comp.}) \\
+\mathcal{C}^1_{ij}&\left[g^1_i Z_j \mathrm{G}^1_{jl} + g^1_j Z_i \mathrm{G}^1_{il}\right] \quad (G\text{-flexion, first comp.}) \\
+\mathcal{C}^2_{ij}&\left[g^2_i Z_j \mathrm{G}^2_{jl} + g^2_j Z_i \mathrm{G}^2_{il}\right] \quad (G\text{-flexion, second comp.}) \\
+\frac{2}{\sigma_2}&\left[-\theta^1_a\mathcal{D}^1_{al} + \frac{1}{M}\sum_{n,m}^{M}\left(\theta^1_a\mathcal{D}^1_{nl} + \theta^1_n\mathcal{D}^1_{nl} - \theta^1_m\mathcal{D}^1_{nl}\right)\right] \quad \text{(M. systems, first comp.)} \\
+\frac{2}{\sigma_2}&\left[-\theta^2_a\mathcal{D}^2_{al} + \frac{1}{M}\sum_{n,m}^{M}\left(\theta^2_a\mathcal{D}^2_{nl} + \theta^2_n\mathcal{D}^2_{nl} - \theta^2_m\mathcal{D}^2_{nl}\right)\right] \quad \text{(M. systems, second comp.)} \\
+Z_b&\mathcal{K}_{bl}\frac{4(\det\mathcal{A})_b}{\sigma^2_b} \quad \text{(Critical curve estimator).}
\end{aligned} \tag{5.34}$$

Please note some remarks. Superscripts are actually indices in the two equations above; $i, j \in [0, ..., N_{\mathrm{pix}}]$; a runs over all images in a multiple image system, furthermore it has to be summed also over the total number of multiple-image systems in the reconstruction, which has been suppressed for convenience; and b runs over all pixels in the AMR grid , which are selected to be part of the critical curve.

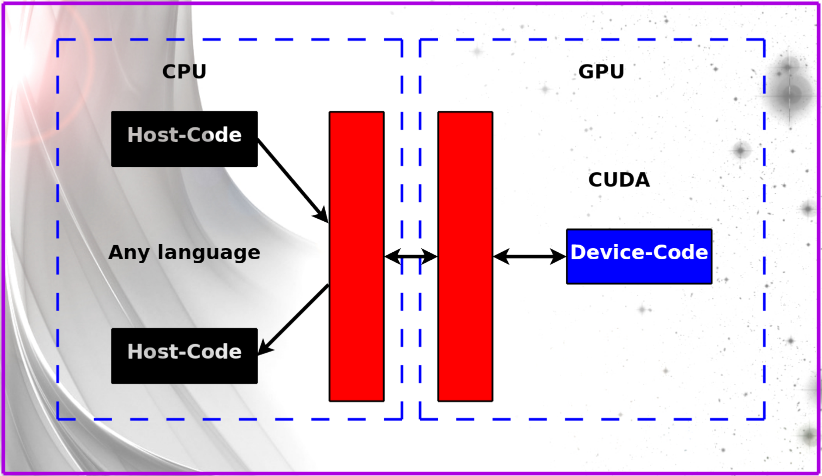
$$\chi^2(\psi) = \chi^2_1(\psi) + \chi^2_2(\psi) + \chi^2_3(\psi) + \ldots \quad \Rightarrow \mathcal{B}_{lk}\psi_k = \mathcal{V}_l$$

Single node CPU/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 CPU/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

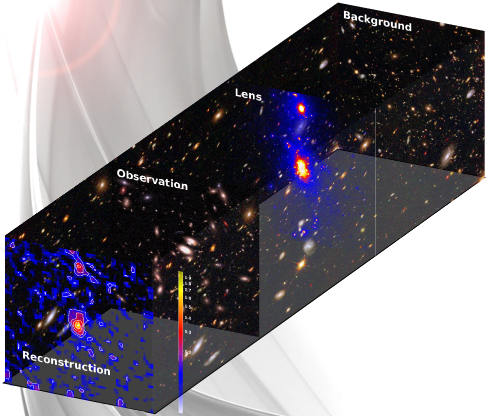
Speed-up

- Calculate:

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

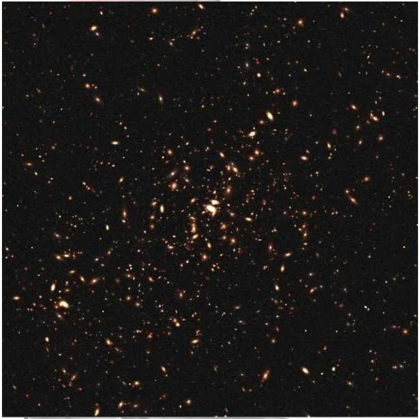
- one-core CPU: `82.3 s`
- 240 core GPU: `1.03 s`

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

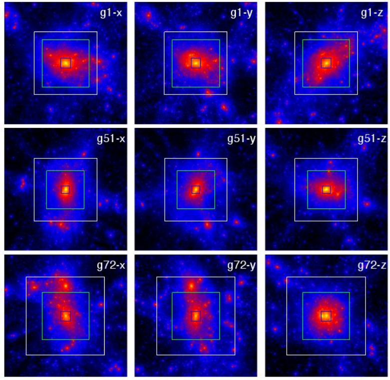


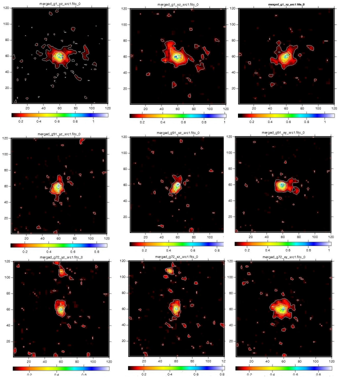
Name	Description
D	aperture diameter
g	detector gain
A_{pix}	pixel area
$F(\lambda)$	used filter
$M(\lambda)$	mirror filter curve
$O(\lambda)$	optics filter curve
$C(\lambda)$	CCD filter curve
FoV	total field-of-view
RON	detector readout-noise
f	flat-field accuracy
a	residual flat-field error
PSF	PSF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

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

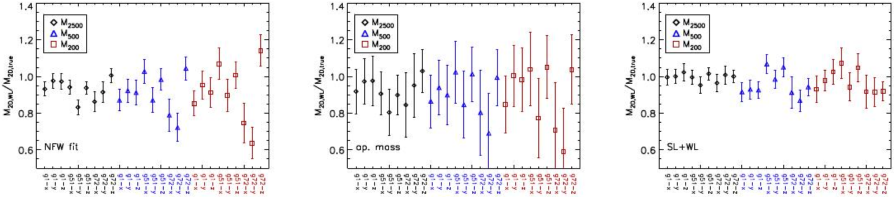


Weighing simulated galaxy clusters (*Meneghetti, JM09*)





Weighing simulated galaxy clusters *(Meneghetti, JM09)*

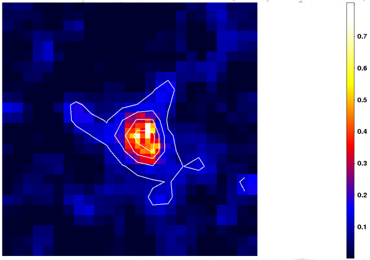


Weighing real things (JM09+)

- MS2137 (VLT)
  with: R. Gavazzi
- CL0024 (SUBARU)
  with: T. Broadhurst, K. Umetsu
- Many other clusters
  (Abell 611, full SUBARU
  sample, JM10 in prep.)
- Extreme test: COSMOS
  (SUBARU & HST)
  with: M. Maturi, T. Schrabback
  (Maturi, JM 10 in prep.)
- and...

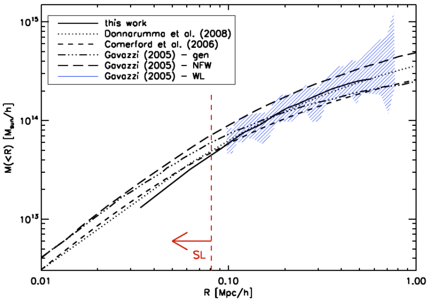
Weighing real things (JM09+)

- MS2137 (VLT)
  with: R. Gavazzi
- CL0024 (SUBARU)
  with: T. Broadhurst, K. Umetsu
- Many other clusters
  (Abell 611, full SUBARU
  sample, JM10 in prep.)
- Extreme test: COSMOS
  (SUBARU & HST)
  with: M. Maturi, T. Schrabback
  (Maturi, JM 10 in prep.)
- and...



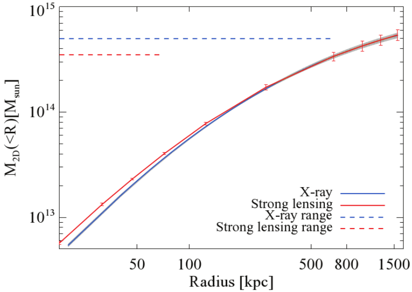
Weighing real things (JM09+)

- MS2137 (VLT)
  with: R. Gavazzi
- CL0024 (SUBARU)
  with: T. Broadhurst, K. Umetsu
- Many other clusters
  (Abell 611, full SUBARU
  sample, JM10 in prep.)
- Extreme test: COSMOS
  (SUBARU & HST)
  with: M. Maturi, T. Schrabback
  (Maturi, JM 10 in prep.)
- and...



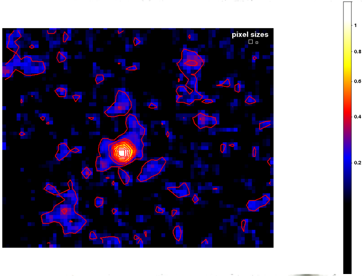
Weighing real things (JM09+)

- MS2137 (VLT)
  with: R. Gavazzi
- CL0024 (SUBARU)
  with: T. Broadhurst, K. Umetsu
- Many other clusters
  (Abell 611, full SUBARU sample, JM10 in prep.)
- Extreme test: COSMOS
  (SUBARU & HST)
  with: M. Maturi, T. Schrabback
  (Maturi, JM 10 in prep.)
- and...



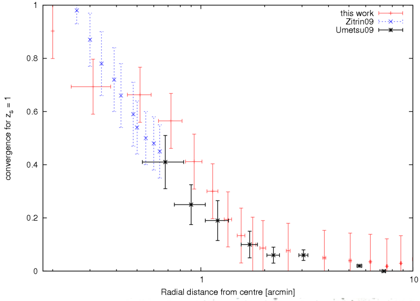
Weighing real things (JM09+)

- MS2137 (VLT)
  with: R. Gavazzi
- CL0024 (SUBARU)
  with: T. Broadhurst, K. Umetsu
- Many other clusters
  (Abell 611, full SUBARU sample, JM10 in prep.)
- Extreme test: COSMOS
  (SUBARU & HST)
  with: M. Maturi, T. Schrabback
  (Maturi, JM 10 in prep.)
- and...



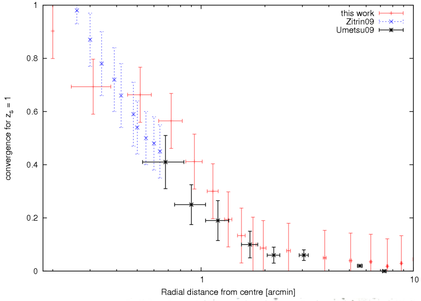
Weighing real things (JM09+)

- MS2137 (VLT)
  with: R. Gavazzi
- CL0024 (SUBARU)
  with: T. Broadhurst, K. Umetsu
- Many other clusters
  (Abell 611, full SUBARU sample, JM10 in prep.)
- Extreme test: COSMOS
  (SUBARU & HST)
  with: M. Maturi, T. Schrabback
  (Maturi, JM 10 in prep.)
- and...



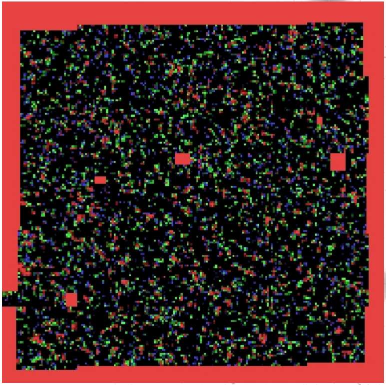
Weighing real things (JM09+)

- MS2137 (VLT)
  with: R. Gavazzi
- CL0024 (SUBARU)
  with: T. Broadhurst, K. Umetsu
- Many other clusters
  (Abell 611, full SUBARU
  sample, JM10 in prep.)
- Extreme test: COSMOS
  (SUBARU & HST)
  with: M. Maturi, T. Schrabback
  (Maturi, JM 10 in prep.)
- and...



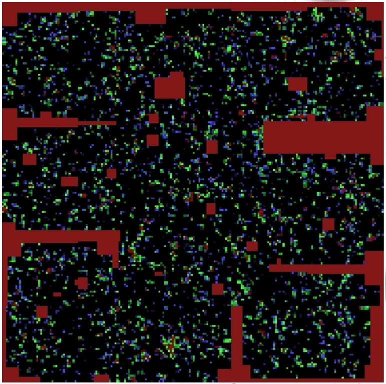
Weighing real things (JM09+)

- MS2137 (VLT)
  with: R. Gavazzi
- CL0024 (SUBARU)
  with: T. Broadhurst, K. Umetsu
- Many other clusters (Abell 611, full SUBARU sample, JM10 in prep.)
- Extreme test: COSMOS (SUBARU & HST)
  with: M. Maturi, T. Schrabback
  (Maturi, JM 10 in prep.)
- and...



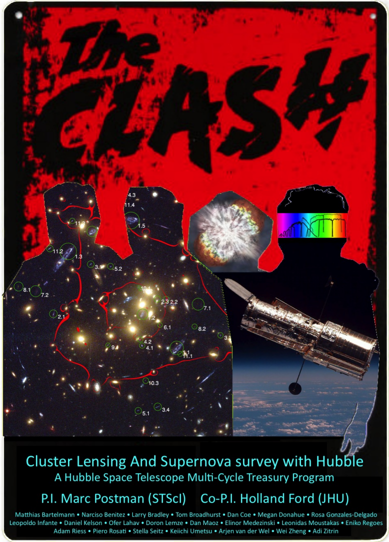
Weighing real things (JM09+)

- MS2137 (VLT)
  with: R. Gavazzi
- CL0024 (SUBARU)
  with: T. Broadhurst, K. Umetsu
- Many other clusters
  (Abell 611, full SUBARU sample, JM10 in prep.)
- Extreme test: COSMOS
  (SUBARU & HST)
  with: M. Maturi, T. Schrabback
  (Maturi, JM 10 in prep.)
- and...



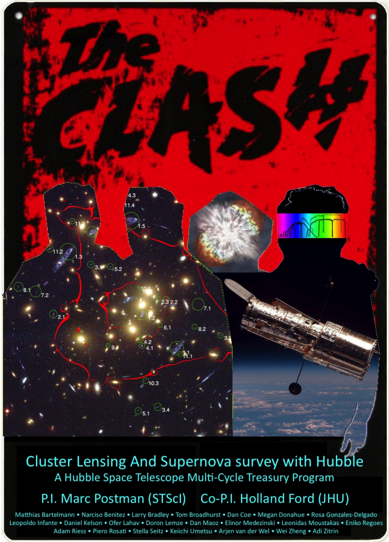
Weighing real things (JM09+)

- MS2137 (VLT)
  with: R. Gavazzi
- CL0024 (SUBARU)
  with: T. Broadhurst, K. Umetsu
- Many other clusters
  (Abell 611, full SUBARU
  sample, JM10 in prep.)
- Extreme test: COSMOS
  (SUBARU & HST)
  with: M. Maturi, T. Schrabback
  (Maturi, JM 10 in prep.)
- and...



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

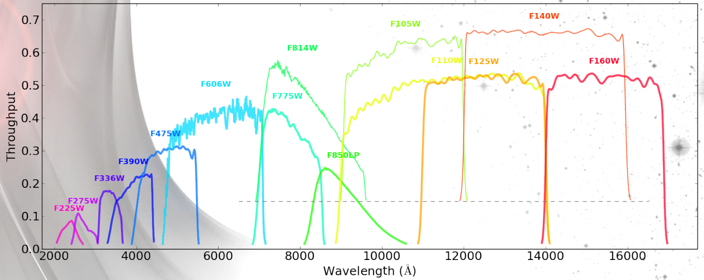
One of three HST/MCT programmes. Start September 2010 (3 cycles).



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