3D mapping of the invisible universe

Journées des doctorants de l'Irfu, 2 et 3 Juillet 2014

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2^{nd} year PhD Student, under the supervision of Jean-Luc Starck

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Irfu

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energie atomique • energies alternatives

Layout

Introduction

3D Weak Gravitational Lensing

- Gravitational Lensing
- Probing the Universe in 3D
- State of the art 3D weak lensing reconstruction methods

GLIMPSE: sparsity based 3D density reconstruction

- Sparse regularisation of inverse problems
- The GLIMPSE Algorithm
- Assessing the performance of the algorithm

Education

2008-2011 :

- **Supélec** Gif-Sur-Yvette/Metz, specialisation in Robotics
- L3, M1 in Fundamental Physics, Paris 11
- M2 Research in Fundamental Mathematics, Metz

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Motivations for the PhD

Why am I doing a PhD in astrophysics ?

- Always wanted to work in physics/astrophysics
- Irfu's **Master's Days** $\Rightarrow$ NPAC then PhD

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Master's day, January 2011

PhD subject

Gravitational shear estimation and reconstruction of the dark matter mass map

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- **Invisible matter** that accounts for 85% of all the matter in the universe
- Only detected indirectly through its gravitational effects

PhD subject

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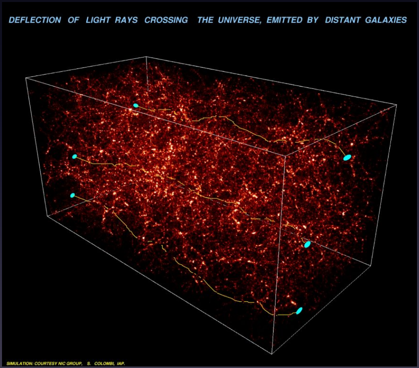

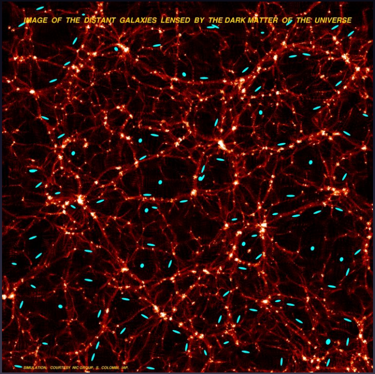

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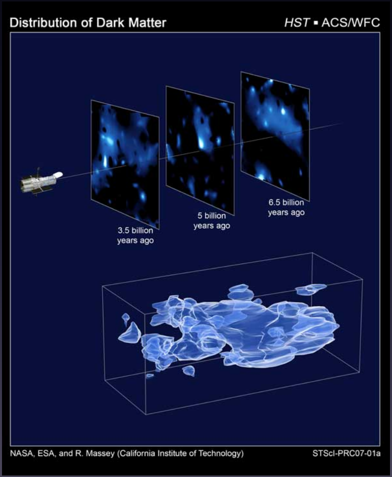

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The 2 regimes of gravitational lensing:

- Strong Lensing
  - near massive clusters
  - presence of arcs and rings

Galaxy Cluster Abell 2218 HST • WFPC2
NASA, A. Fruchter and the ERO Team (STScI, ST-ECF) • STScI-PRC00-08

- Weak Lensing
  - generated by large scale structures (filaments, halos, ...)
  - **slight** deformation of galaxy shapes and sizes

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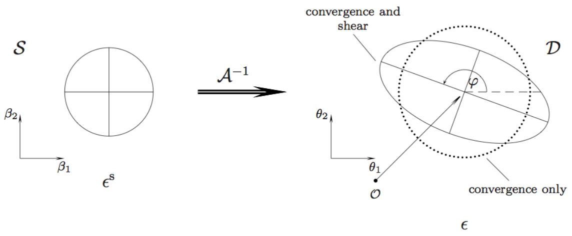
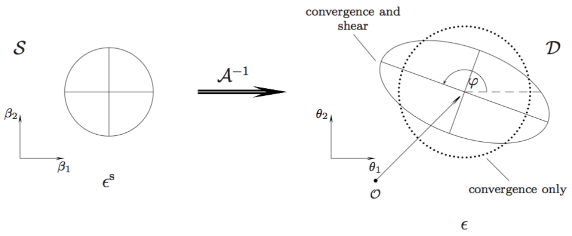
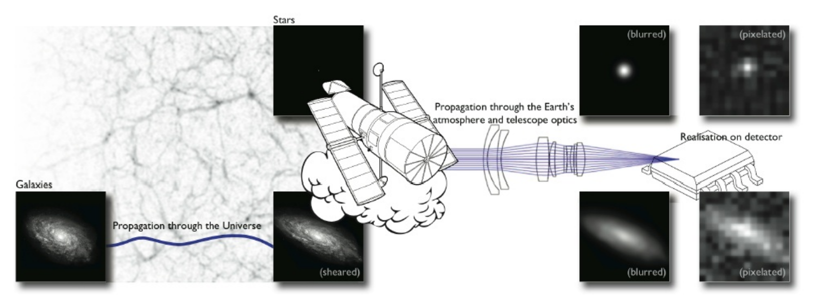
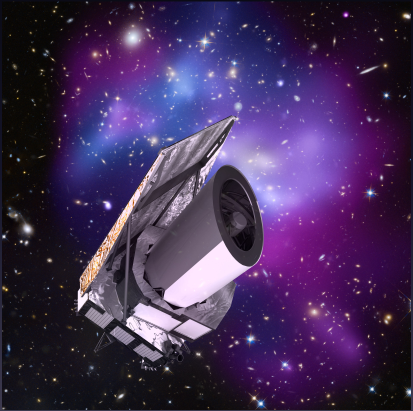

convergence and
shear
$\mathcal{S}$
$\mathcal{D}$
$\mathcal{A}^{-1}$
φ
β_2
β_1
θ_2
θ_1
ϵ^s
$\mathcal{O}$
convergence only
ϵ





Kitching et al. (2010)

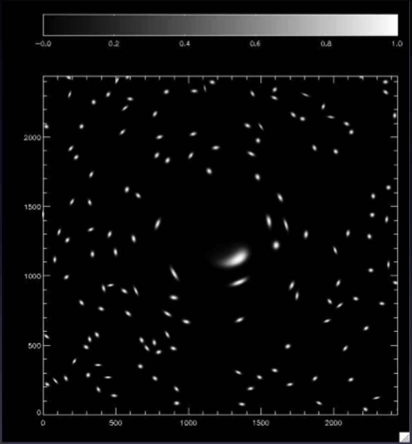
The ESA Euclid mission:



An artist view of the Euclid Satellite – © ESA

- 1.2 m mirror
- 2 instruments:
  - Visible imager (VIS)
  - Near infrared photometer and spectrograph (NISP)
- Wide survey: 15,000 deg^2
- Shape measurement of over a billion galaxies
- Photometric and spectroscopic **redshift measurements**

What are we trying to do ?



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From measurements:

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- redshift

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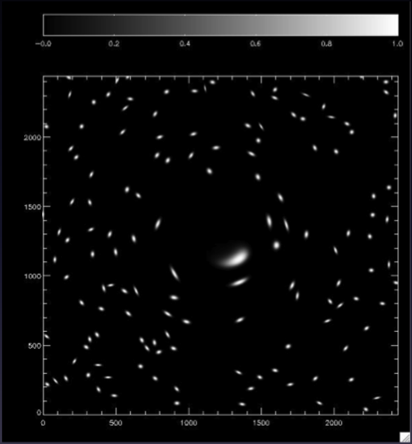

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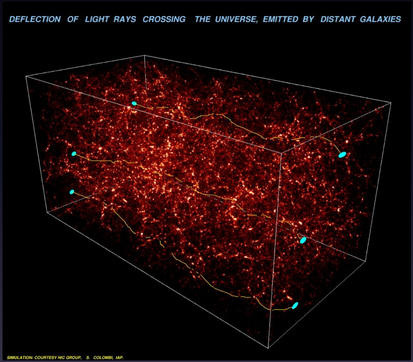

From measurements:

- shear
- redshift

Infer the **3D distribution** of dark matter

- **The 3D Reconstruction Problem:**

$$\underbrace{\gamma}_{\text{shear}} = \mathbf{P} \quad \mathbf{Q} \quad \underbrace{\delta}_{\text{overdensity}} + \underbrace{n}_{\text{noise}}$$

P and Q are the **tangential** and **line of sight** lensing operators

Where the complications begin:

- **ill-posed** inverse problem, some of the information is lost
- extremely noisy shears
- **photometric redshifts** errors
- missing data

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Where the complications begin:

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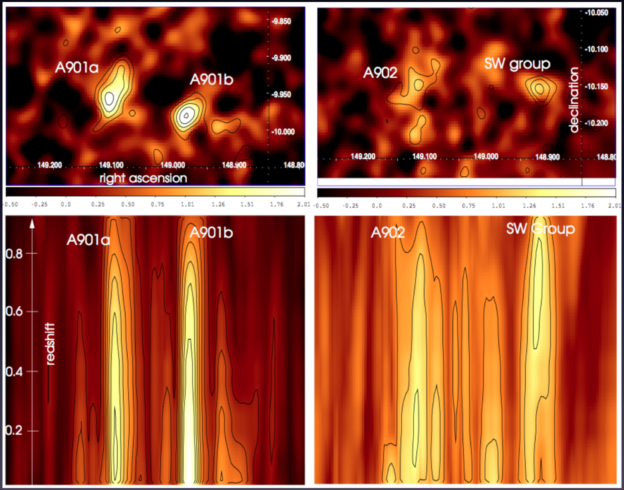
- 2 **linear methods** where introduced to address the inversion problem:
  - Wiener filtering, *Simon et al.* (2009)
  - SVD regularisation, *VanderPlas et al.* (2011)

- In both cases:
  - very poor redshift accuracy (structures are smeared in l.o.s.)
  - systematic bias in reconstructed redshift
  - overall noisy reconstructions

- With standard methods, the results have very limited applications.

Wiener filter reconstruction of the STAGES Abell A901/2 superclusters, from *Simon et al.* (2012)



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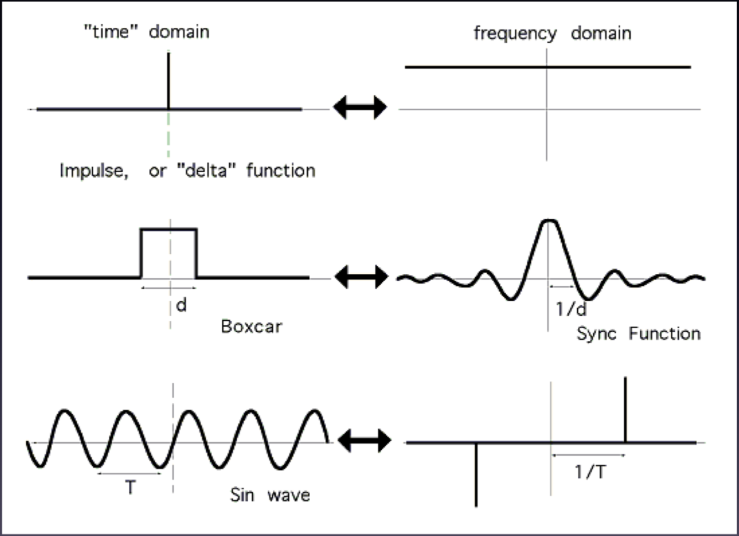
- The 3D dark matter mapping problem is specific but the underlying **linear inverse problem is very generic**
- A very active field in **image and signal processing**
- We transpose a very robust method based on the notion of **sparsity** to the 3D reconstruction problem

Sparsity

A signal $y = \Phi\alpha$ is sparse in the dictionary Φ if most of its coefficients α are 0

Example in the Fourier domain:



Considering a general linear problem of the form:

$$Y = \mathbf{A}X_0 + N$$

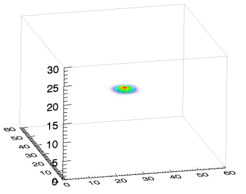
An approximation of X_0 can be recovered by imposing a sparsity promoting penalty on the solution in a dictionary Φ.

$$\boxed{\min_{\alpha} \frac{1}{2} \parallel Y - \mathbf{A\Phi}\alpha \parallel_2^2 + \lambda \parallel \alpha \parallel_1} \qquad \text{with } \tilde{X} = \Phi\alpha$$

Simple example: **Deblurring**

The 2 ingredients of the **GLIMPSE** reconstruction technique:

- a **wavelet based dictionary** adapted to dark matter halos.



- a **Fast Iterative Soft Thresholding Algorithm** to solve the optimisation problem:

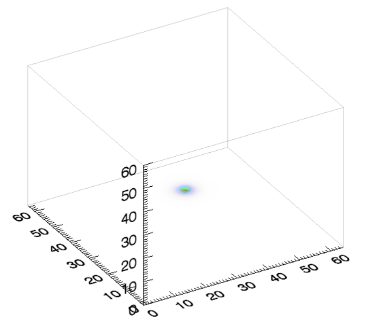
$$\min_{\alpha} \frac{1}{2} \underbrace{\| \boldsymbol{\Sigma}^{-1/2} \left[\gamma - \mathbf{PQ\Phi}\alpha \right] \|_2^2}_{\text{Data fidelity}} + \underbrace{\lambda \| \alpha \|_1}_{\text{Sparsity constraint}}$$

Leonard, **Lanusse** & Starck (2014)

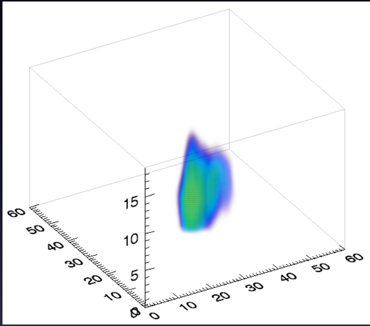
The algorithm in action on an N-body simulation:

(Loading Video...)

Comparison to previous methods on a single halo field:



(a) Input **simulated density contrast** for an NFW halo



(b) **SNR map** thresholded at 4.5σ using **Transverse Wiener Filtering**

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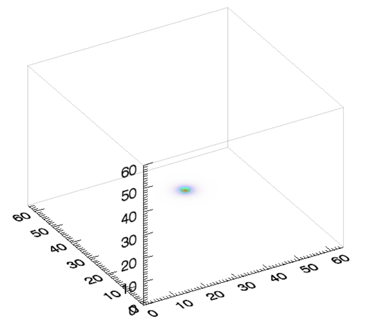

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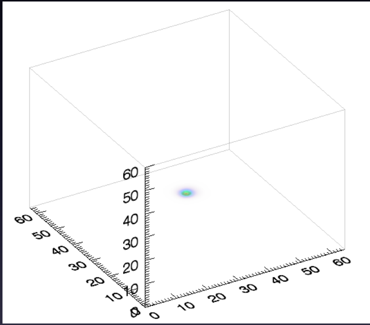


(b) **Density contrast** reconstruction using **GLIMPSE**

Improvement over linear methods:

- GLIMPSE reconstructs the value of **density contrast**
- No redshift bias
- No smearing of structures
- No bias in amplitude of the reconstructed density.

Single halo simulations

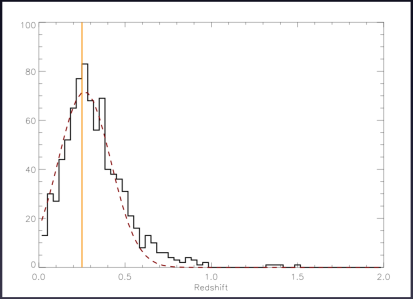
- One NFW profile at the center of a 60x60 arcmin field
- Noise and redshift errors corresponding to an Euclid-like survey
- Mass varying between 3.10^{13} and 1.10^{15} $h^{-1}M_{\odot}$
- Redshifts between 0.05 and 1.55

We ran 1000 noise realisations on each of the 96 fields.

Redshift Estimation

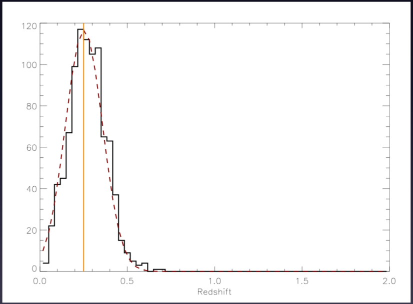
Example of 2 NFW halos at z=0.25

$m_{vir} = 4.10^{14} h^{-1} M_{\odot}$



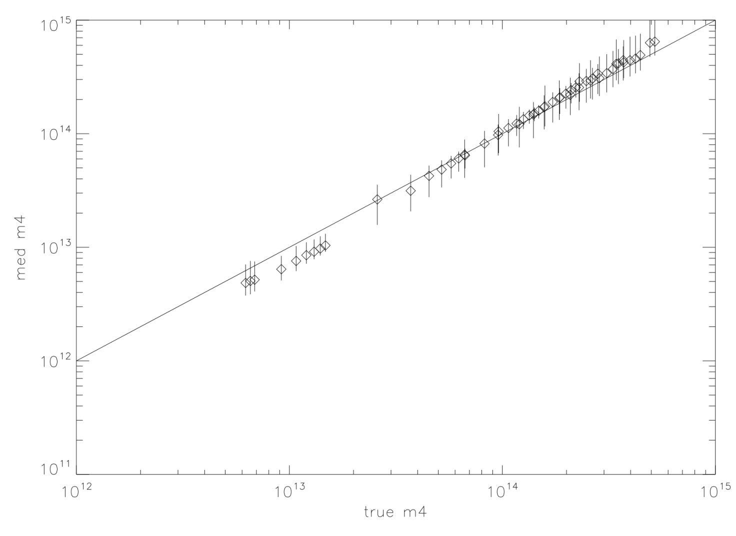
$\sigma_z = 0.15$

$m_{vir} = 8.10^{14} h^{-1} M_{\odot}$



$\sigma_z = 0.1$

Mass estimation:



Summary of the analysis:

- Detection of clusters of mass $< 10^{15}\ h^{-1} M_\odot$ up to $z = 0.75$.
- Unbiased estimator for the redshift. The incertitude on the redshift decreases as the mass increases.
- The quality of reconstructed density is sufficient to start constraining the mass of halos.
- This technique can potentially be used to probe the high mass end of the halo mass function $n(M, z)$.

Progress of the project

- A first paper on the method has been published:
  - *GLIMPSE : Accurate 3D weak lensing reconstructions using sparsity*, A. Leonard, **F. Lanusse** and J.-L. Starck, MNRAS, 2014

- We are now working on three goals:
  - Apply the method to real data (CFHTLenS, STAGES)
  - Fully characterise the method on realistic N-body simulations
  - Investigate the use this new method to constrain cosmology

- Upcoming papers:
  - *Weak lensing reconstructions in 2D & 3D: implications for cluster studies*, A. Leonard, **F. Lanusse** and J.-L. Starck, in prep.
  - *Combined flexion and shear 2D mass mapping*, **F. Lanusse**, A. Leonard and J.-L. Starck, in prep.

Conclusion

- We have proposed a new 3D dark matter mapping technique from weak lensing
- For the first time the reconstruction can be used to make meaningful measurements (mass and redshifts)
- We hope to develop this technique as a new, complementary way to constrain cosmology

List of publications:

- *Spherical 3D Isotropic Wavelets*, **F. Lanusse** et al., A&A (2012)
- *3D Sparse Representations*, **F. Lanusse** et al., chapter in AIEP 2013
- *GLIMPSE : Accurate 3D weak lensing reconstructions using sparsity*, A. Leonard, **F. Lanusse** and J.-L. Starck, MNRAS (2014)
- *PRISM: Sparse Recovery of the Primordial Power Spectrum*, P. Paykari, **F. Lanusse** et al., A&A (2014)
- *PRISM: Recovery of the primordial spectrum from Planck data*, **F. Lanusse** et al., submitted to A&A
- *3D Galaxy Clustering with Future Wide-Field Surveys: Advantages of a Spherical Fourier-Bessel analysis*, **F. Lanusse** et al., submitted to A&A