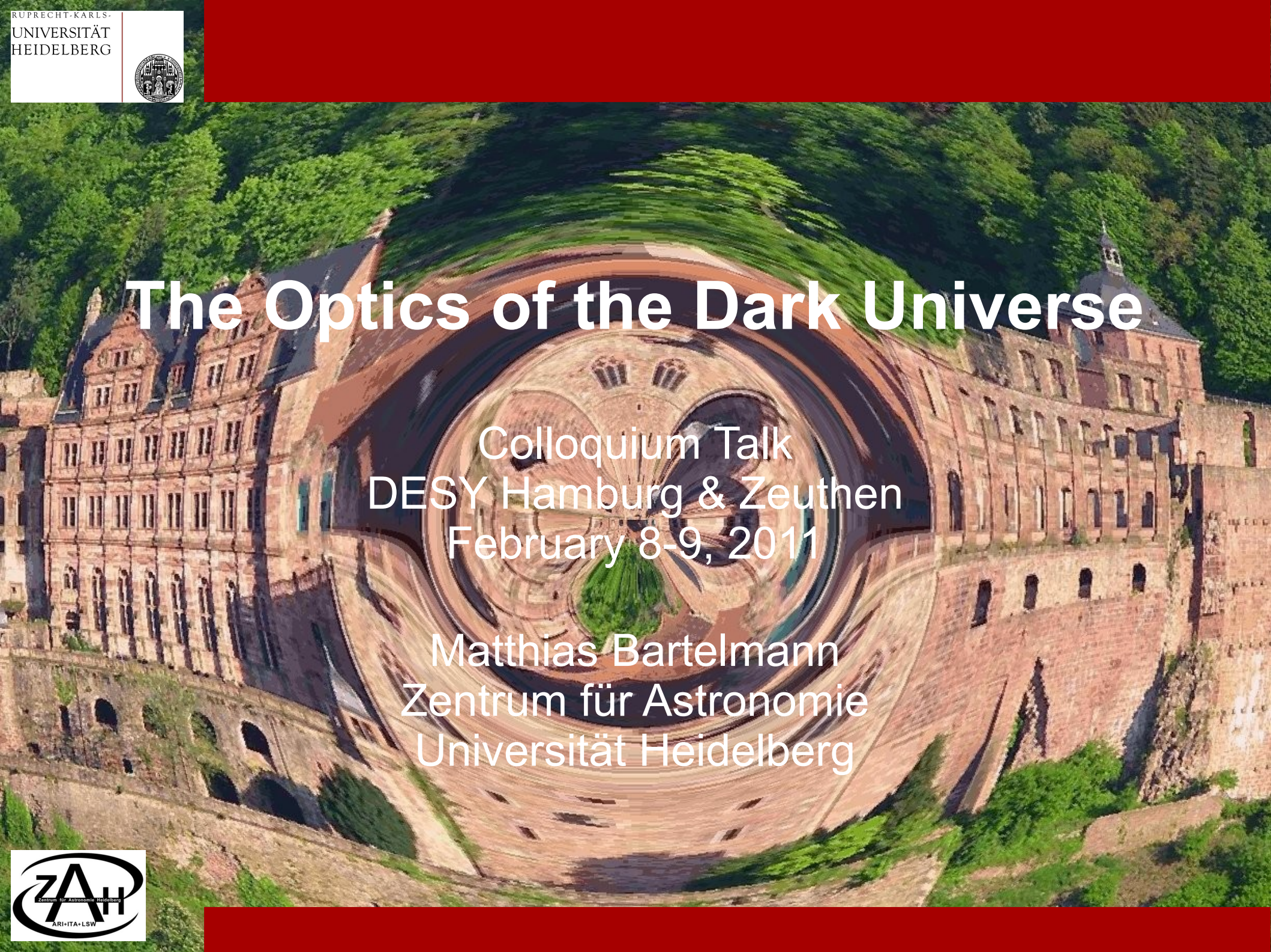
The Optics of the Dark Universe

Colloquium Talk
DESY Hamburg & Zeuthen
February 8-9, 2011

Matthias Bartelmann
Zentrum für Astronomie
Universität Heidelberg



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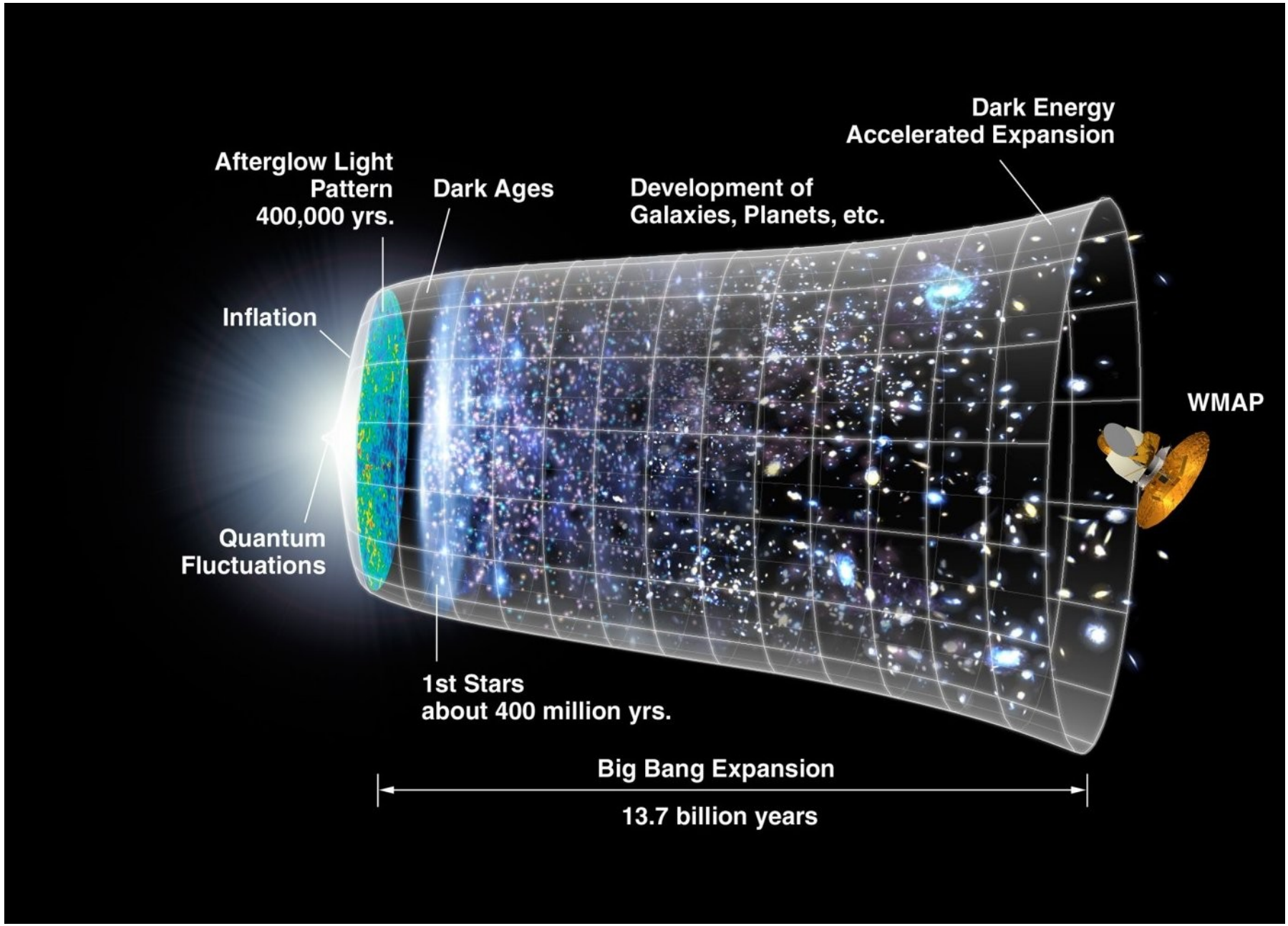
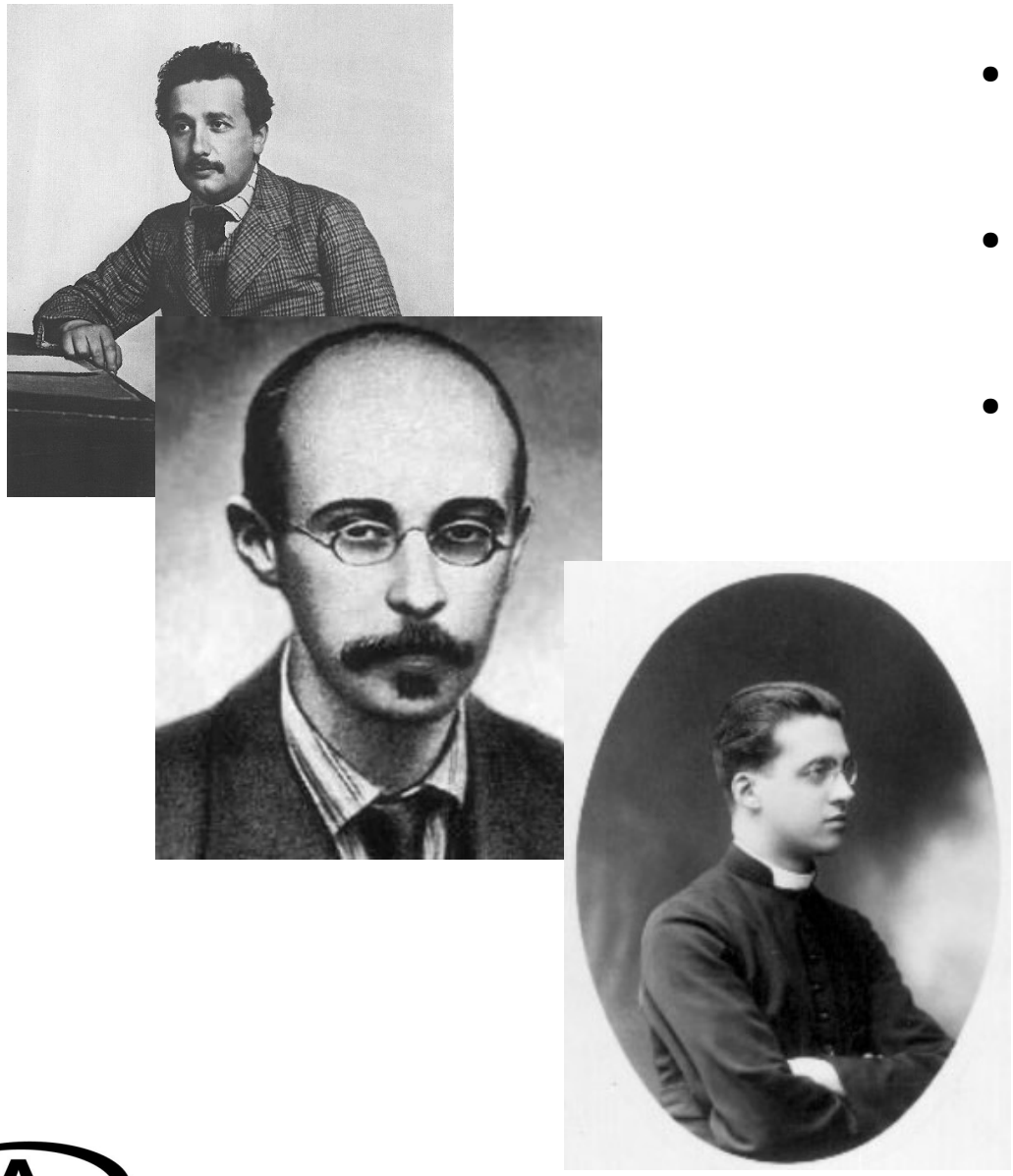
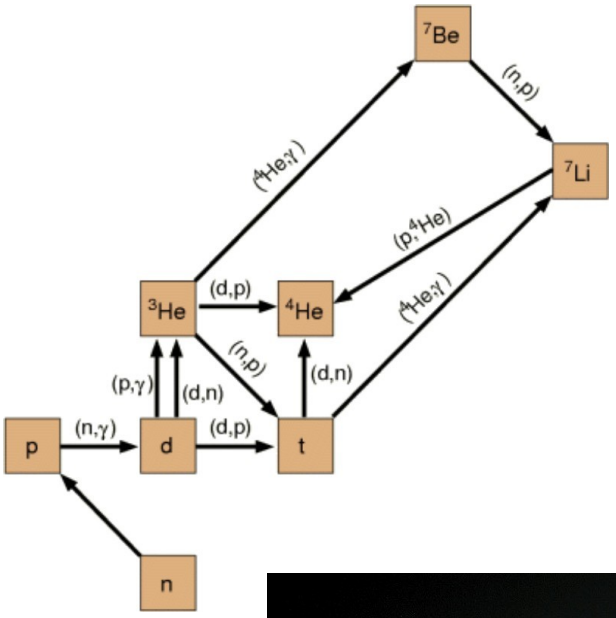


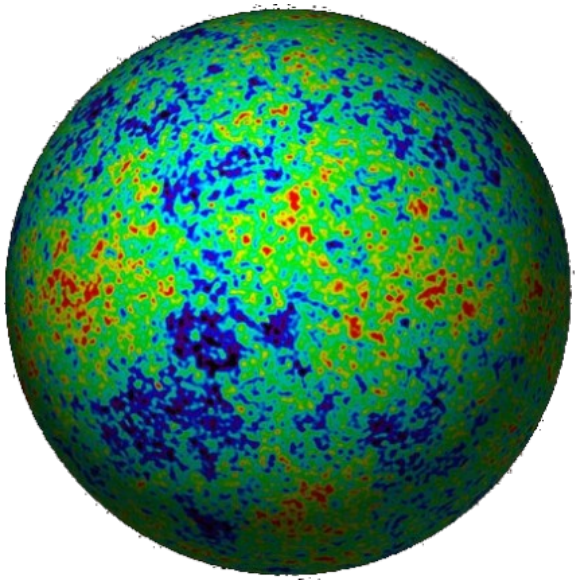
The dark universe

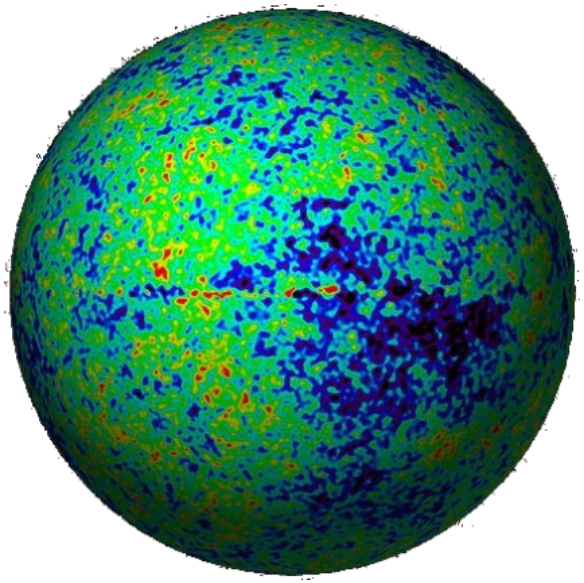


- Einstein's theory of General Relativity
- Symmetry assumptions: Friedmann-Lemaître models
- Parameters:
  - Expansion rate, H_0
  - Density contributions, Ω_i
  - Cosmological constant, Ω_Λ
  - Possible further parameters

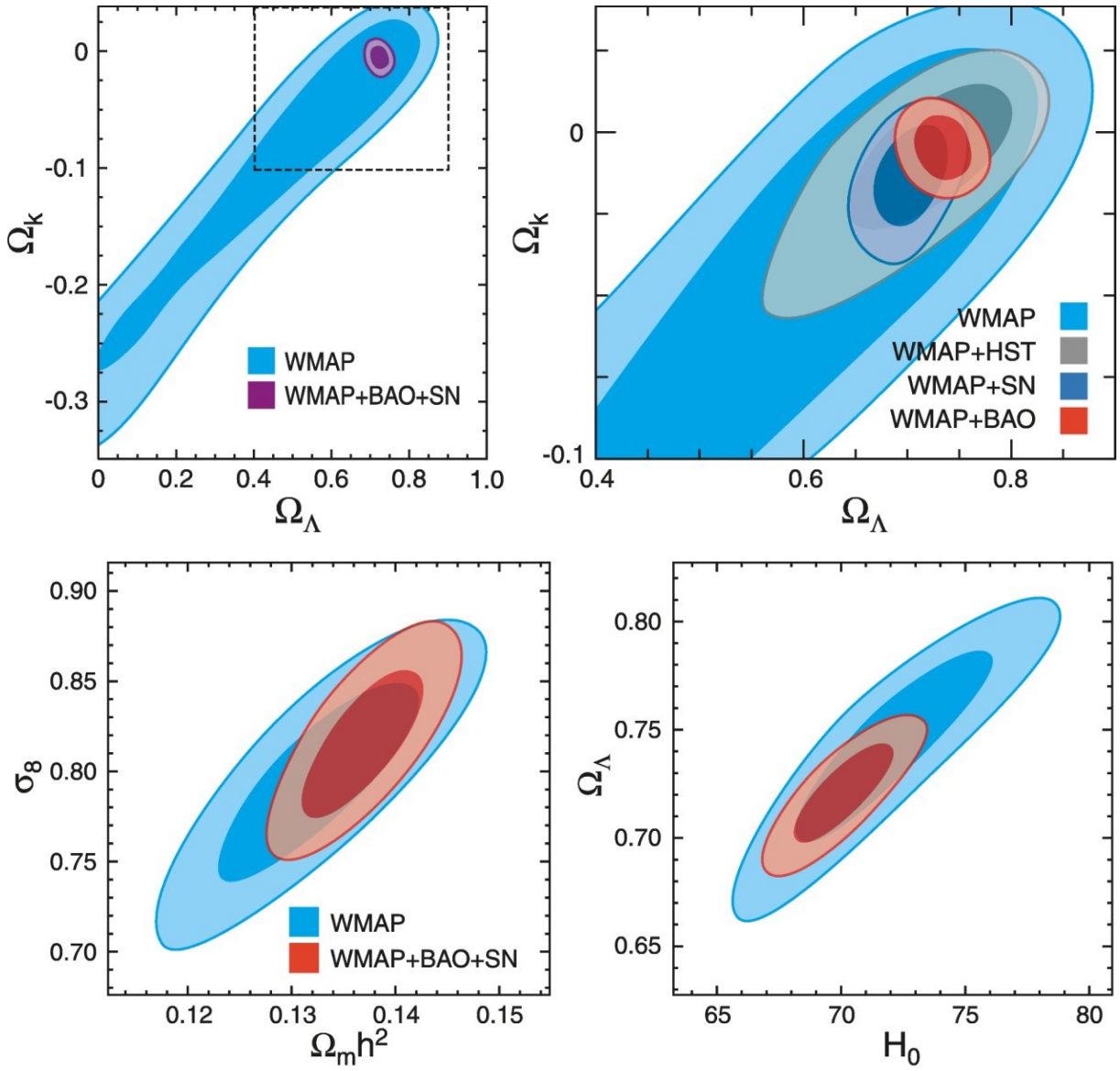
The dark universe

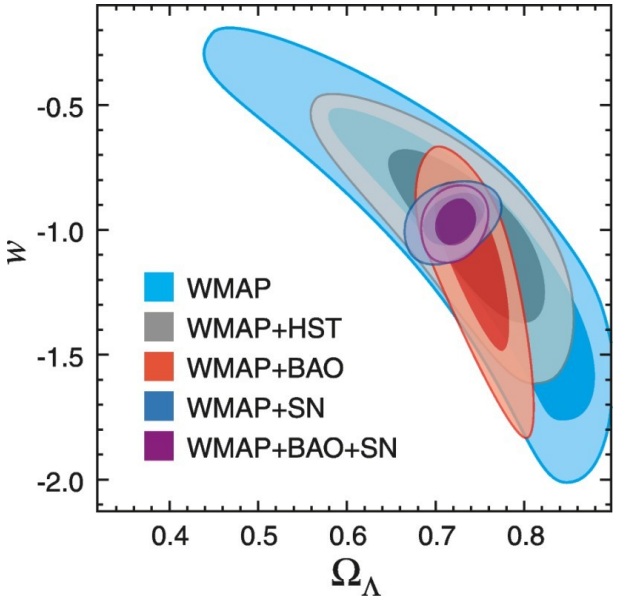






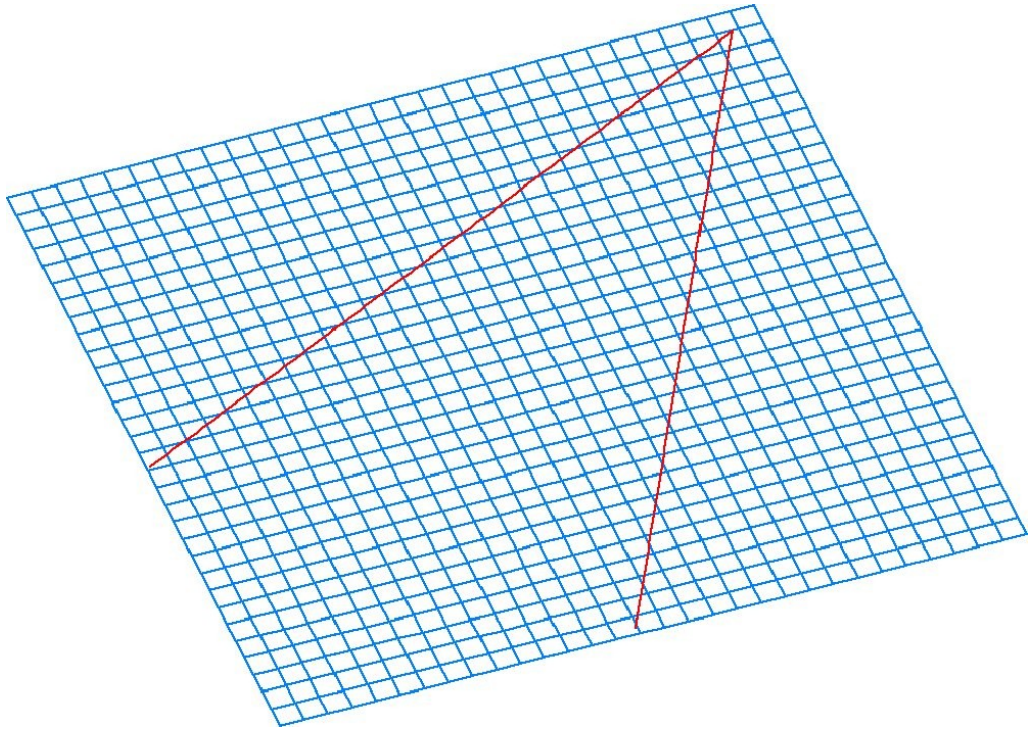
The dark universe



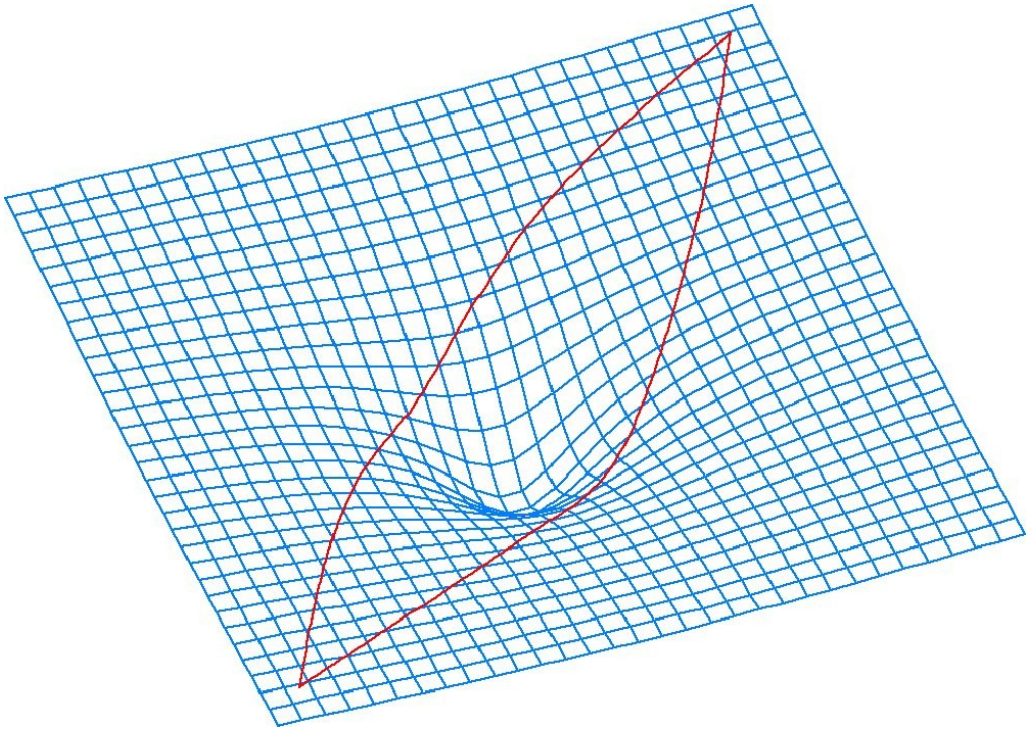


(Komatsu et al. 2008)

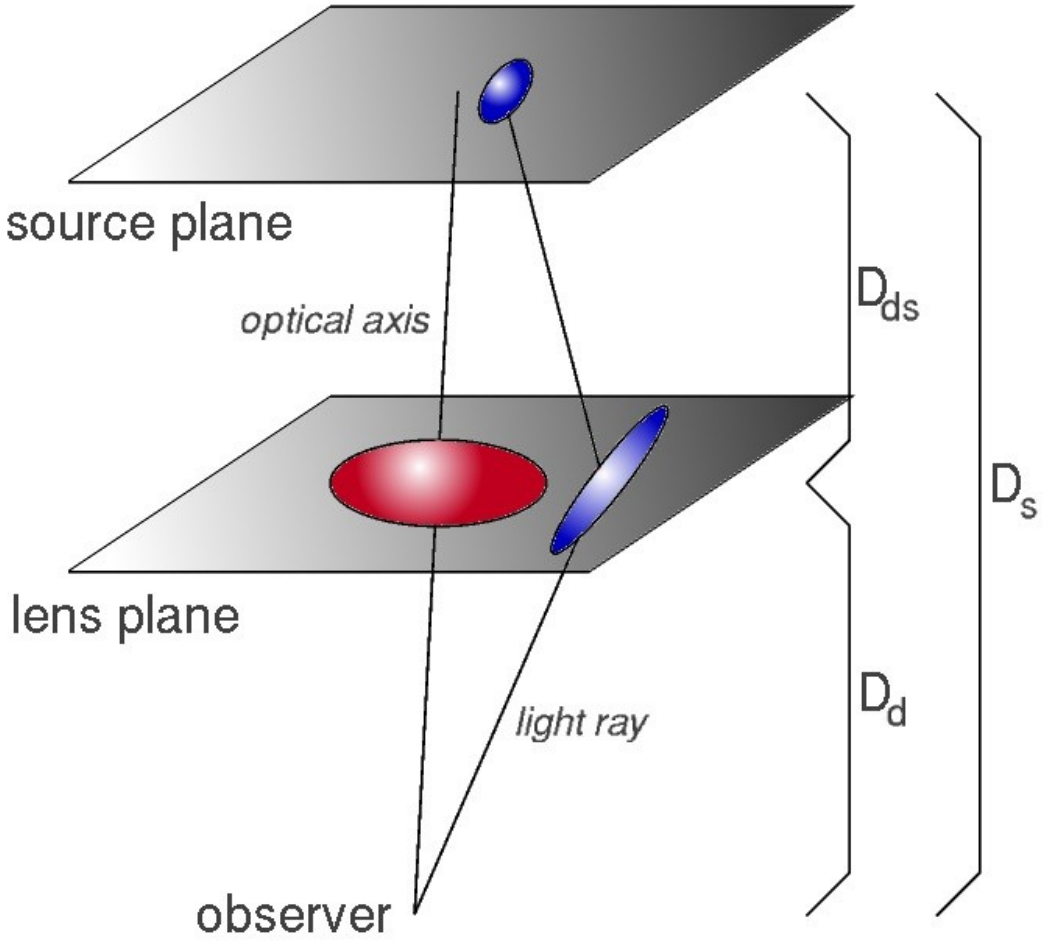
Gravitational lenses



$$n = 1 - \frac{2\Phi}{c^2} > 1$$



Gravitational lenses



Gravitational lenses

Fermat's principle

$$0 = \delta\tau = \delta\left[\int_a^b n(\vec{x})\,\frac{|\mathrm{d}\vec{x}|}{c}\right]$$

Deflection angle, lensing potential

$$\vec{\alpha} = \vec{\nabla}\psi\,, \quad \psi = \frac{2}{c^2}\frac{D_{ds}}{D_d D_s}\int \Phi\,\mathrm{d}l$$

Lens equation

$$\vec{\beta} = \vec{\theta} - \vec{\alpha}(\vec{\theta})$$

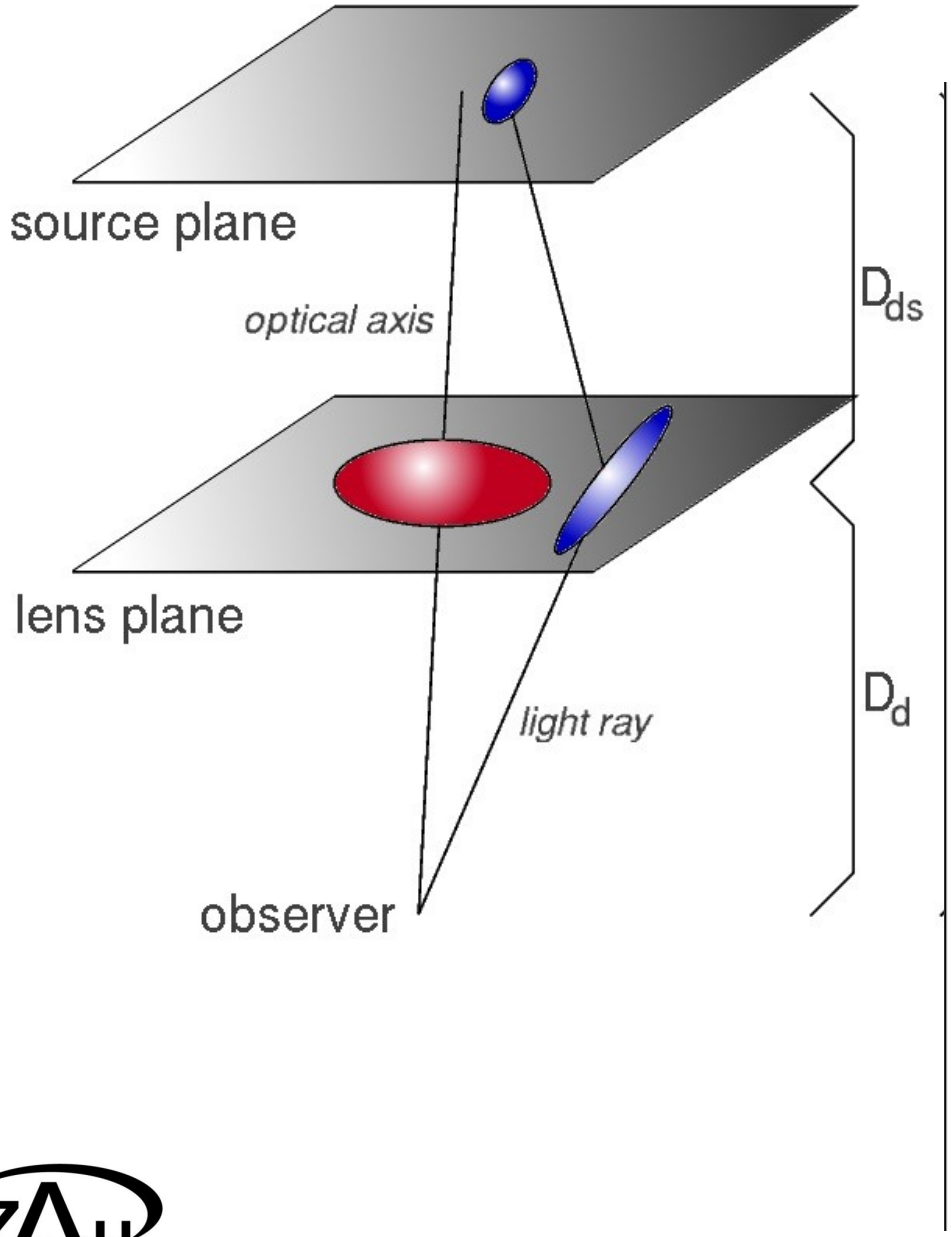
$$\mathcal{A} = \left(\frac{\partial\beta_i}{\partial\theta_j}\right) = \left(\delta_{ij} - \frac{\partial^2\psi}{\partial\theta_i\partial\theta_j}\right)$$

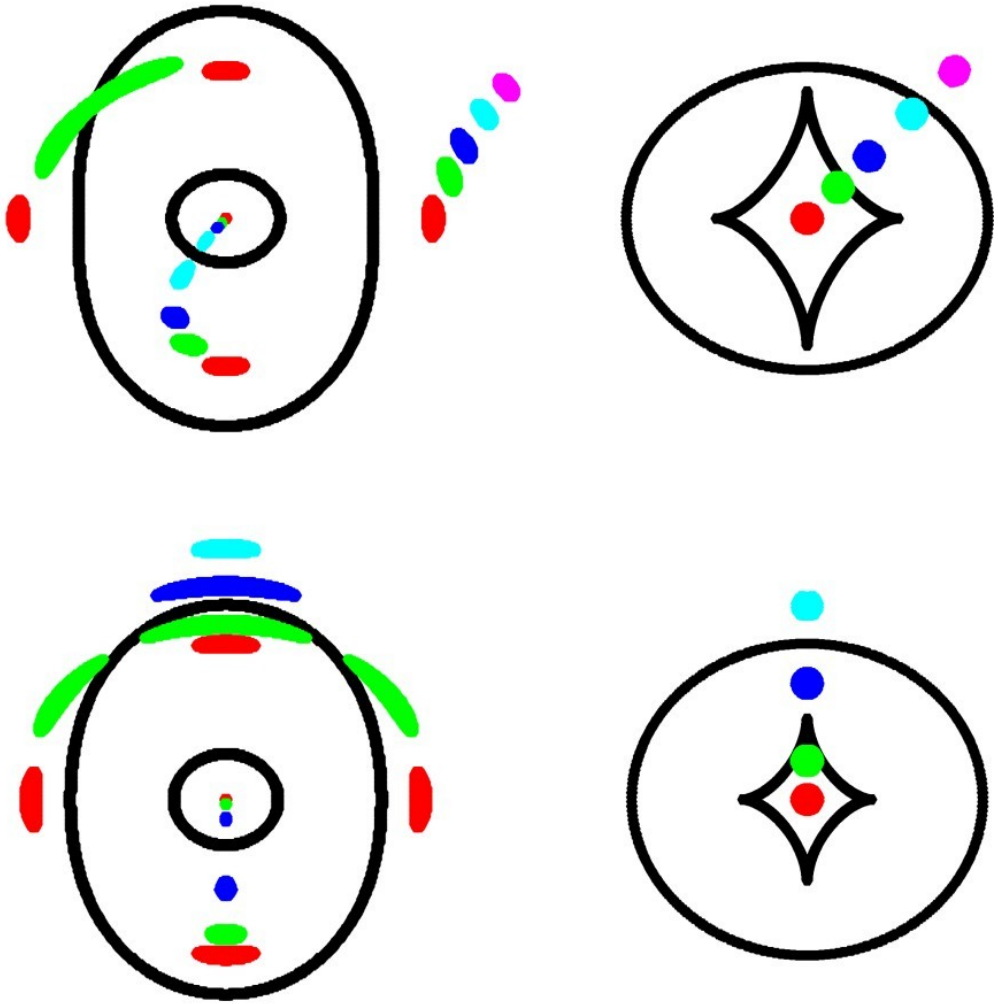
Convergence and shear

$$\partial := \partial_1 + \mathrm{i}\partial_2$$

$$\kappa = \frac{1}{2}\partial^\dagger\partial\psi\,, \quad \gamma = \frac{1}{2}\partial^2\psi$$

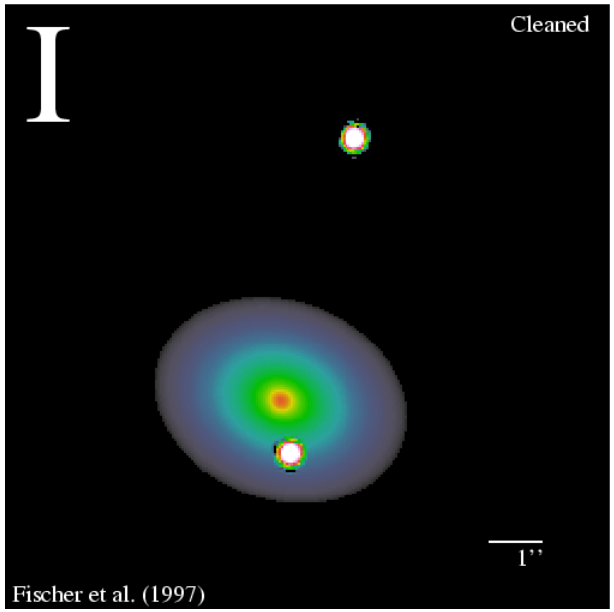
Gravitational lenses

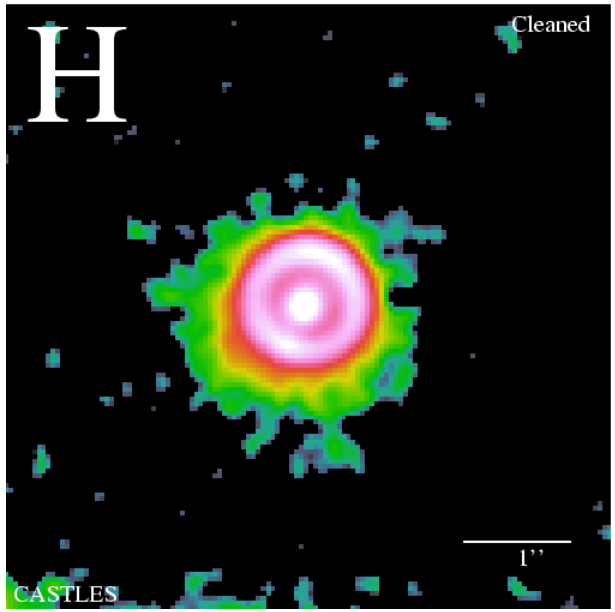


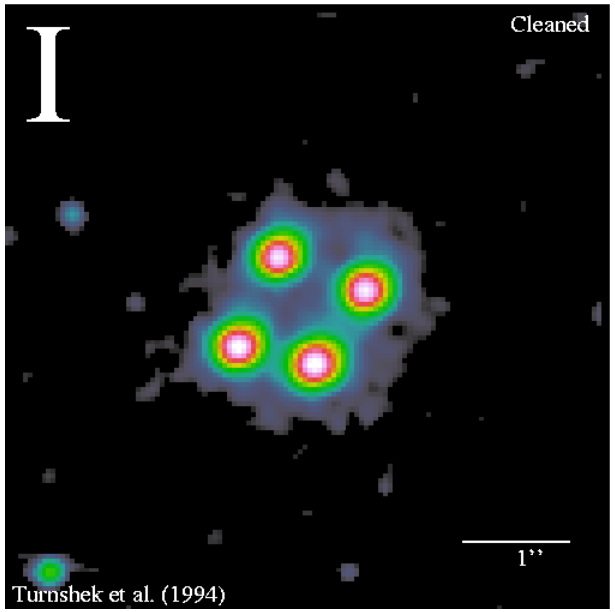


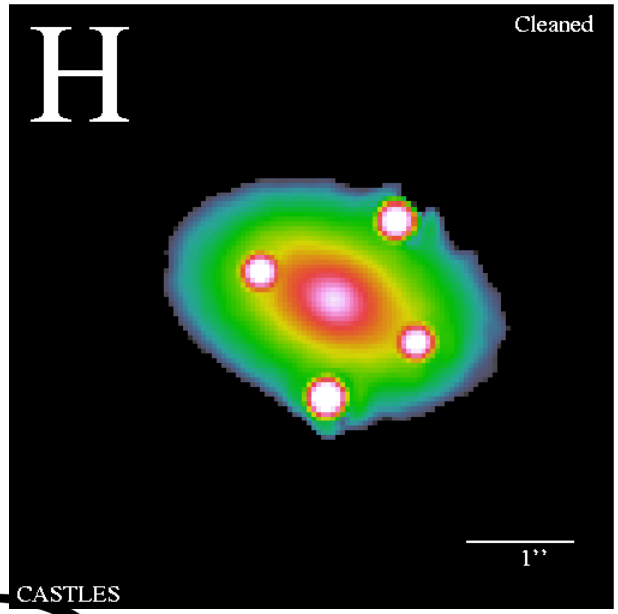
Gravitational lenses

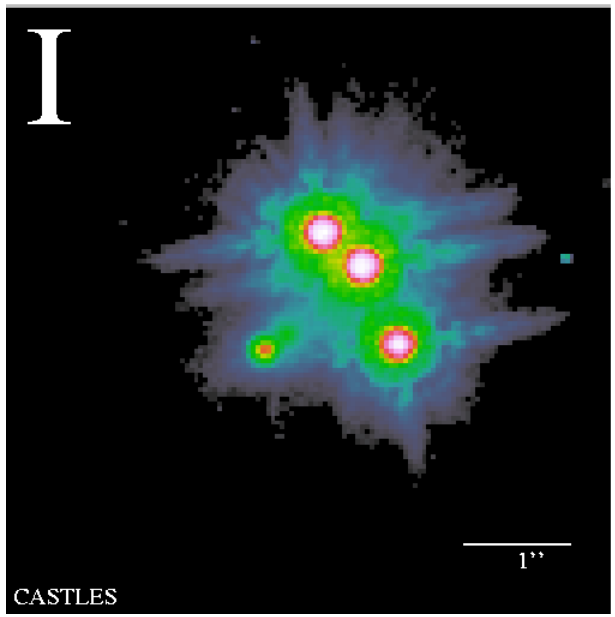
Galaxies

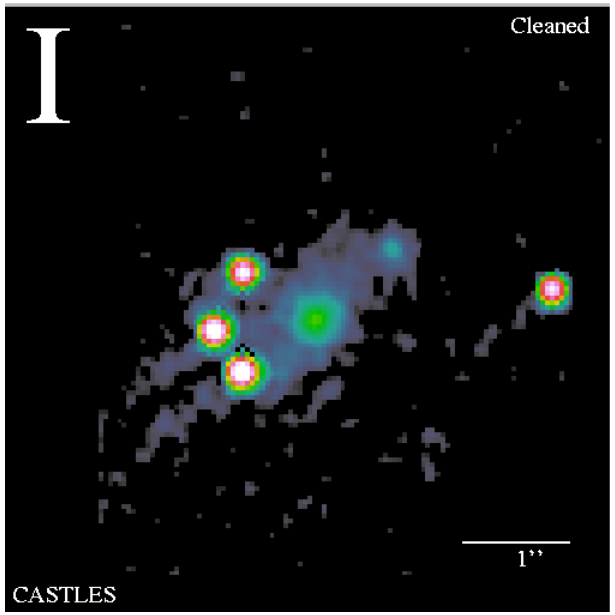






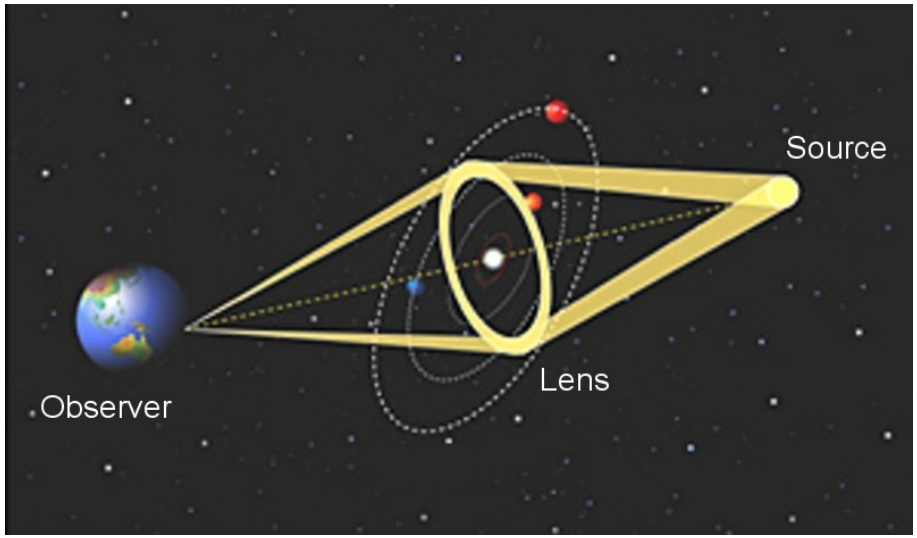


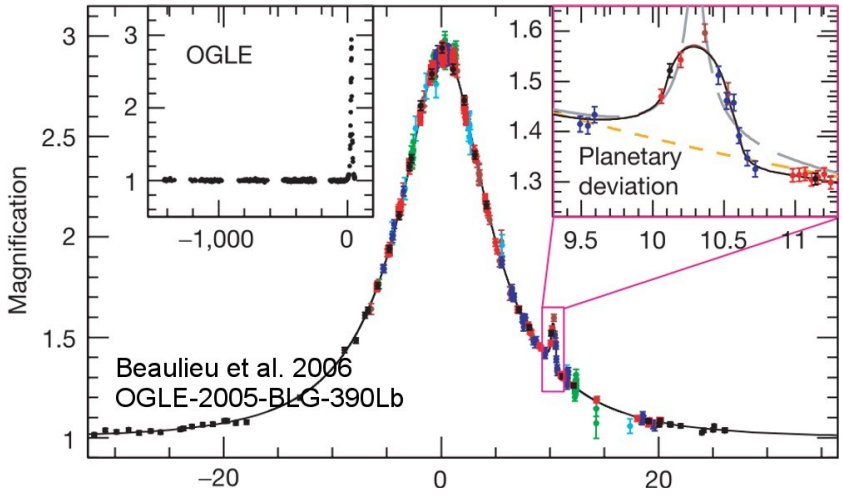


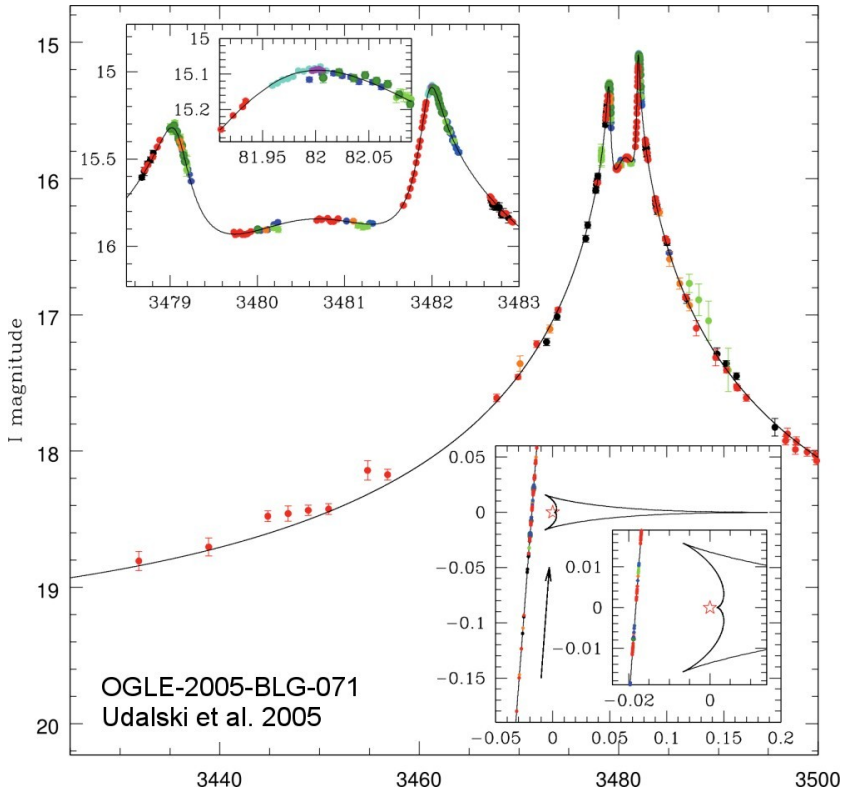


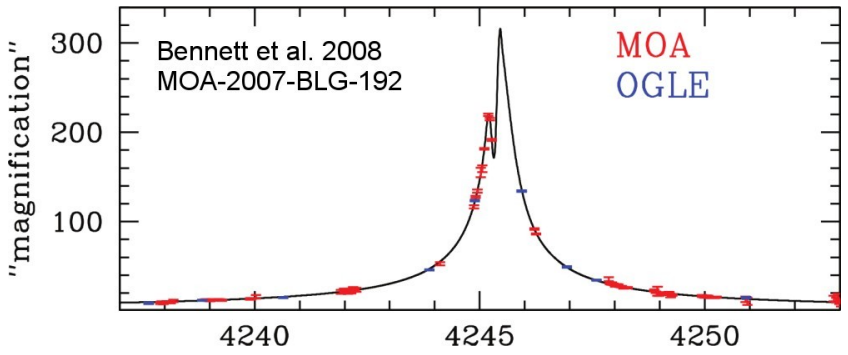
(Castles Collaboration)

Planets

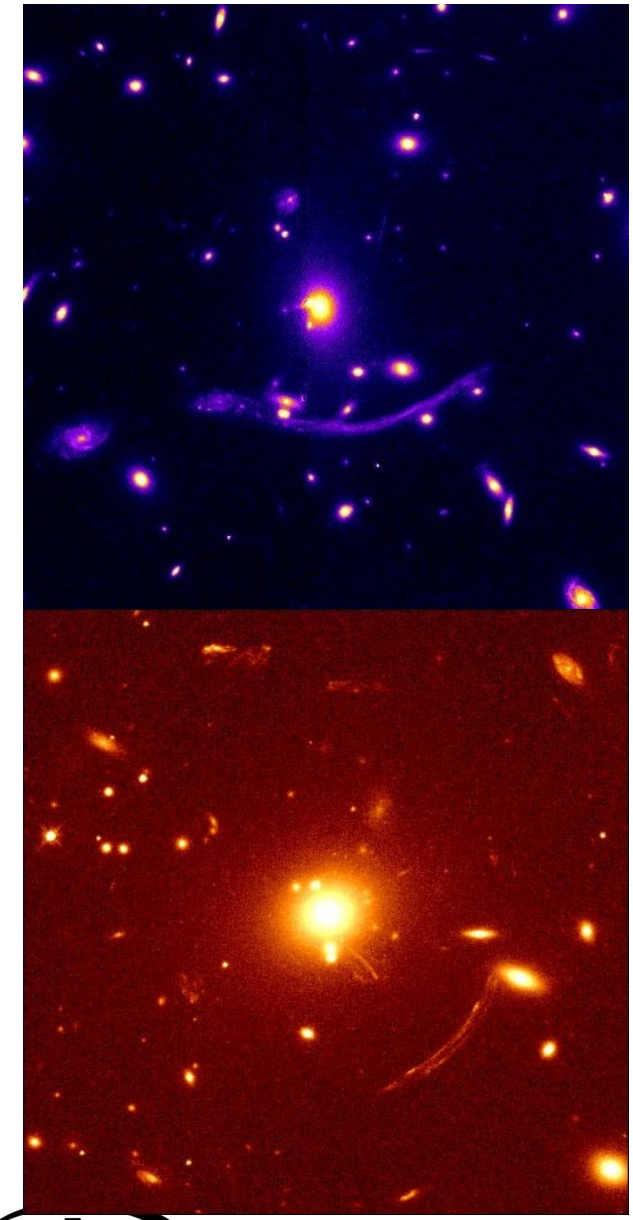

Source
Lens
Observer


OGLE
Planetary
deviation
Magnification
Beaulieu et al. 2006
OGLE-2005-BLG-390Lb


I magnitude
OGLE-2005-BLG-071
Udalski et al. 2005


"magnification"
Bennett et al. 2008
MOA-2007-BLG-192
MOA
OGLE

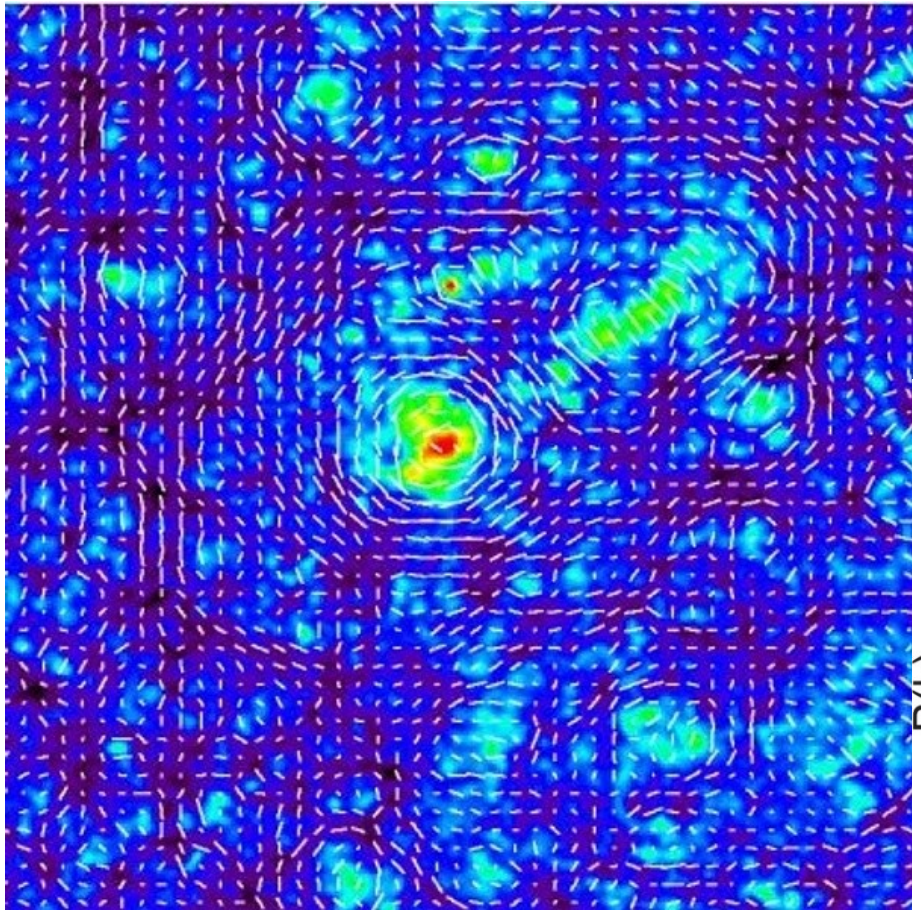
Galaxy clusters

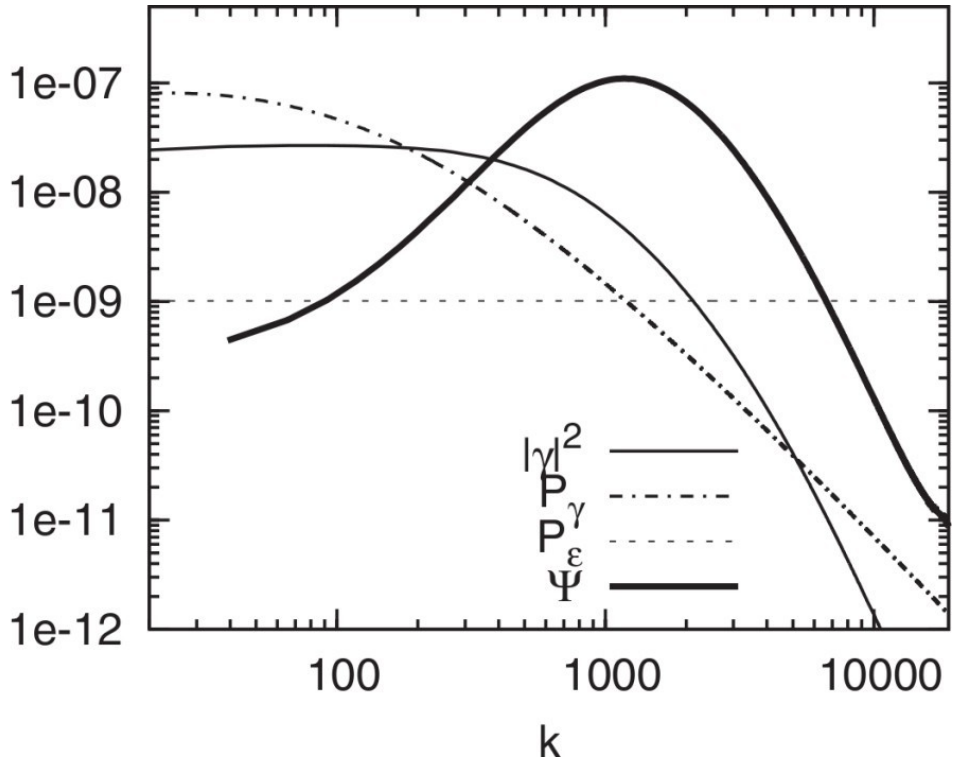


Questions

- How frequent are bound structures composed of dark matter? Do dark haloes exist? Are they connected by filaments?
- How are dark-matter haloes structured and composed? What density profiles do they have, and how substructured are they?
- How do structures grow in the universe?
  What does this imply for dark energy?

Abundance of dark-matter haloes

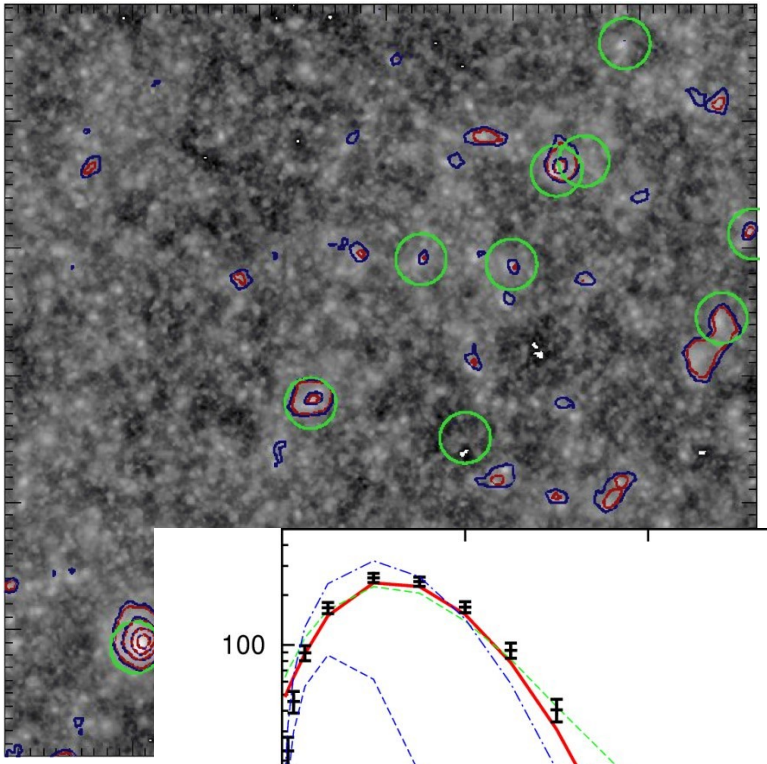




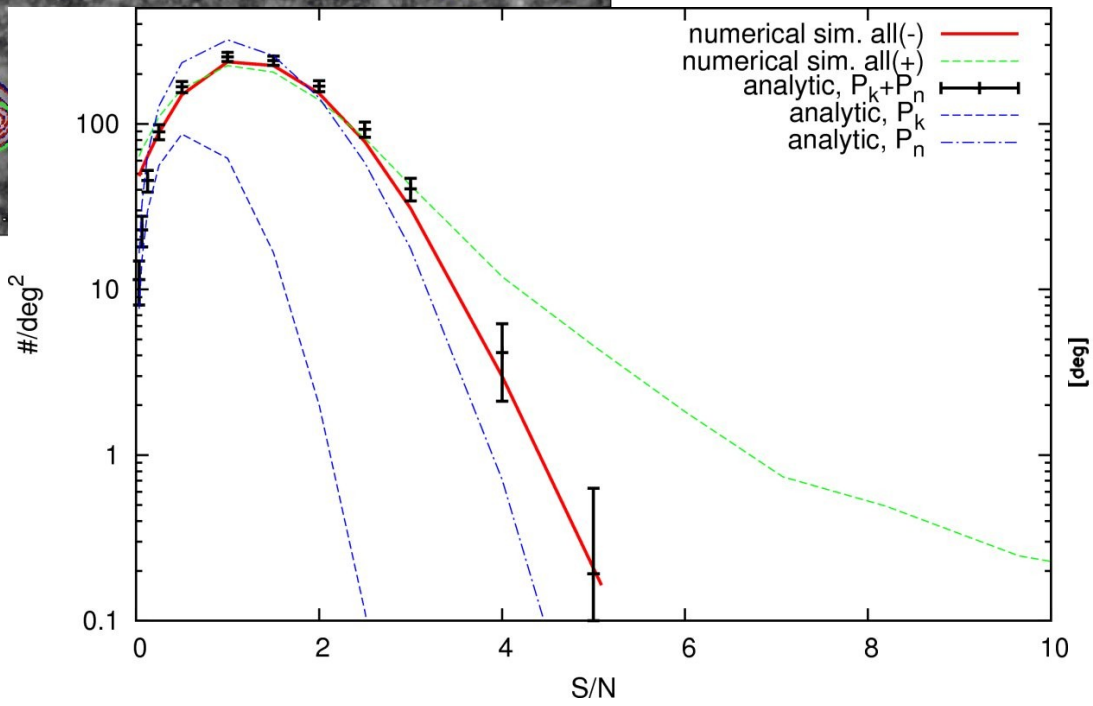
(Maturi et al. 2005)

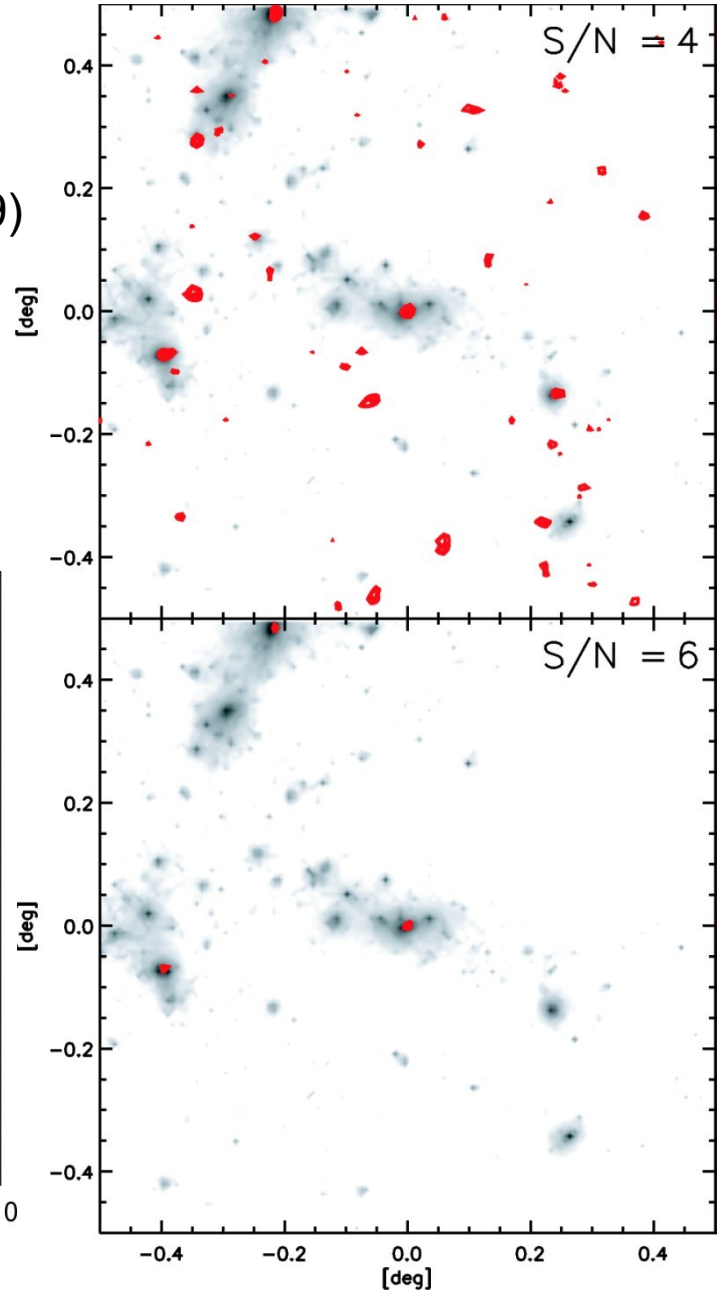
Abundance of dark-matter haloes

Abundance of dark-matter haloes



(Maturi et al. 2005
Pace et al. 2007,
Angrick et al. 2009)





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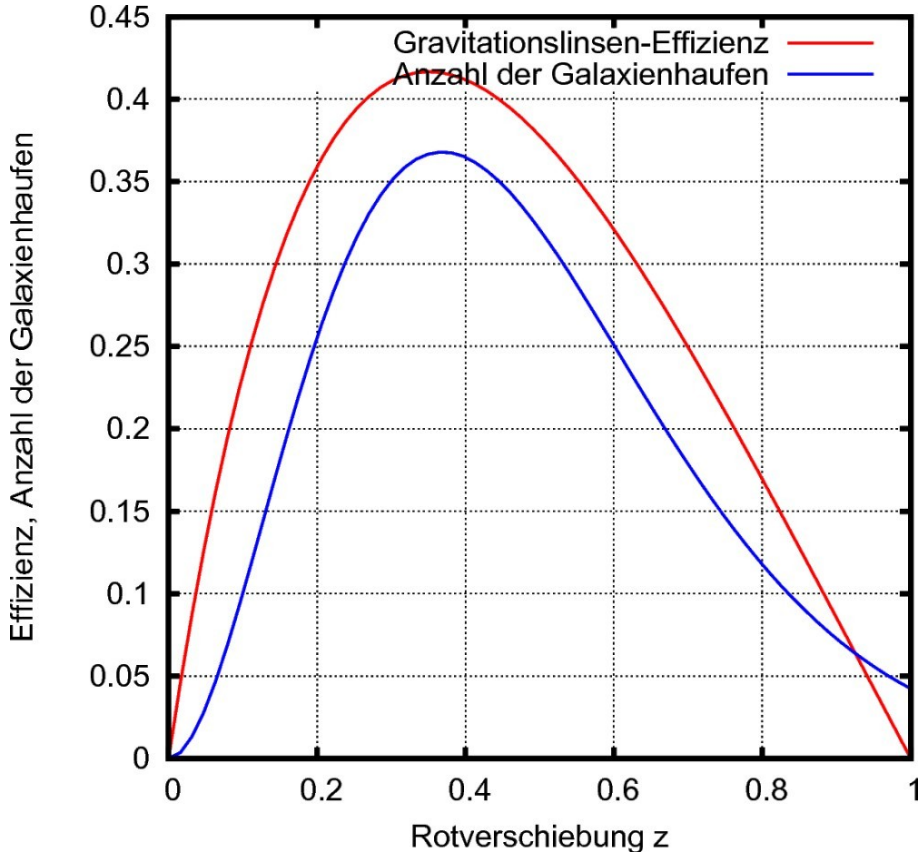

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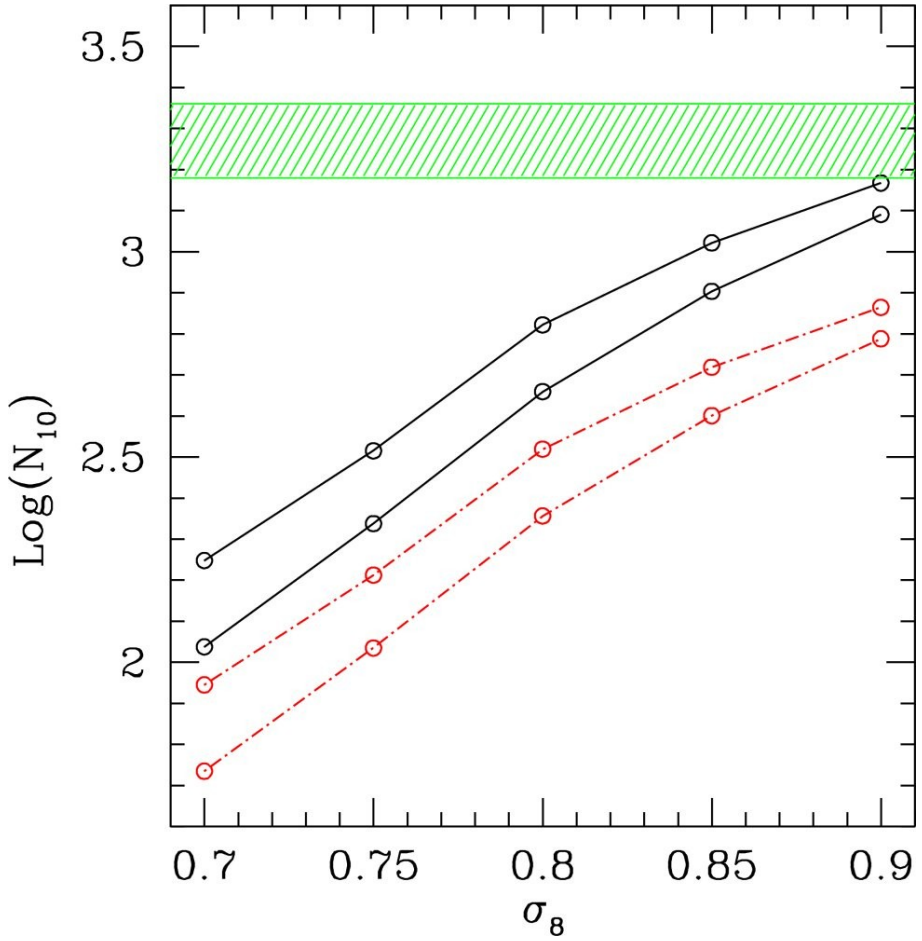
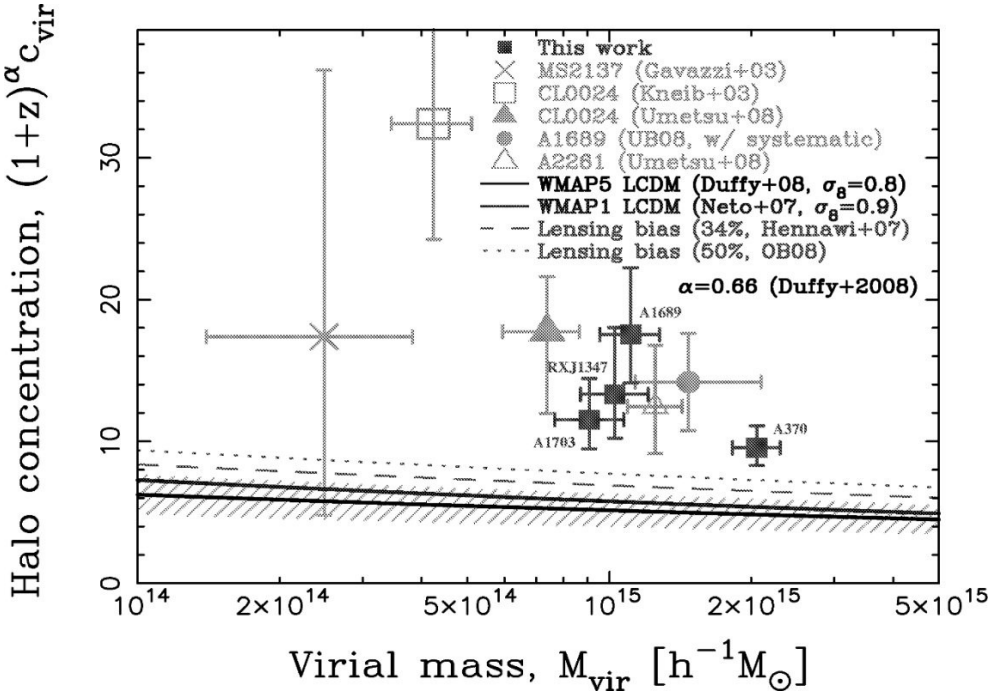


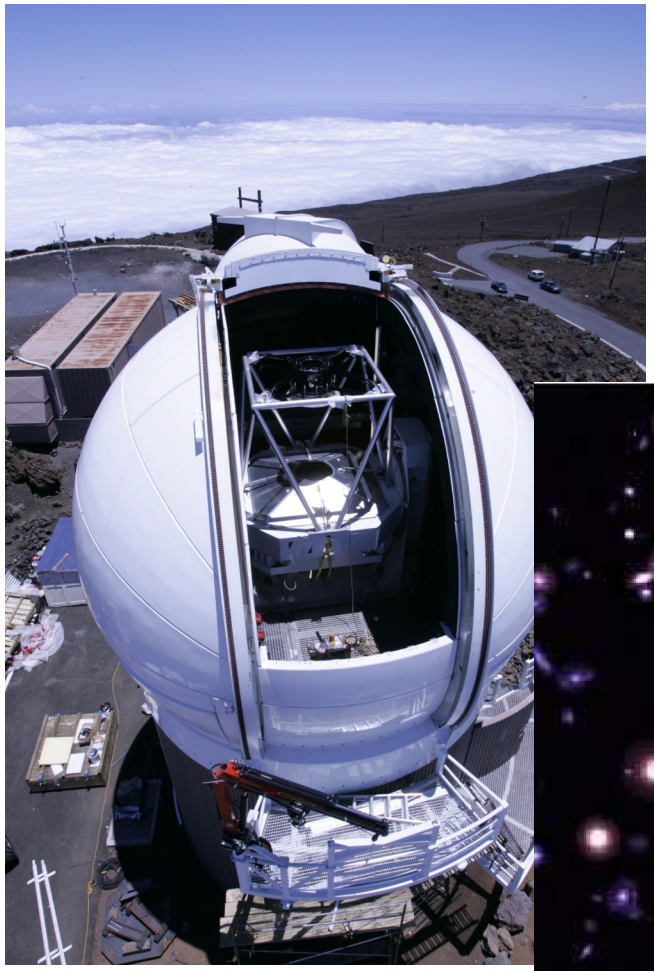
(Fedeli et al. 2006,
Fedeli et al. 2008)

Abundance of dark-matter haloes

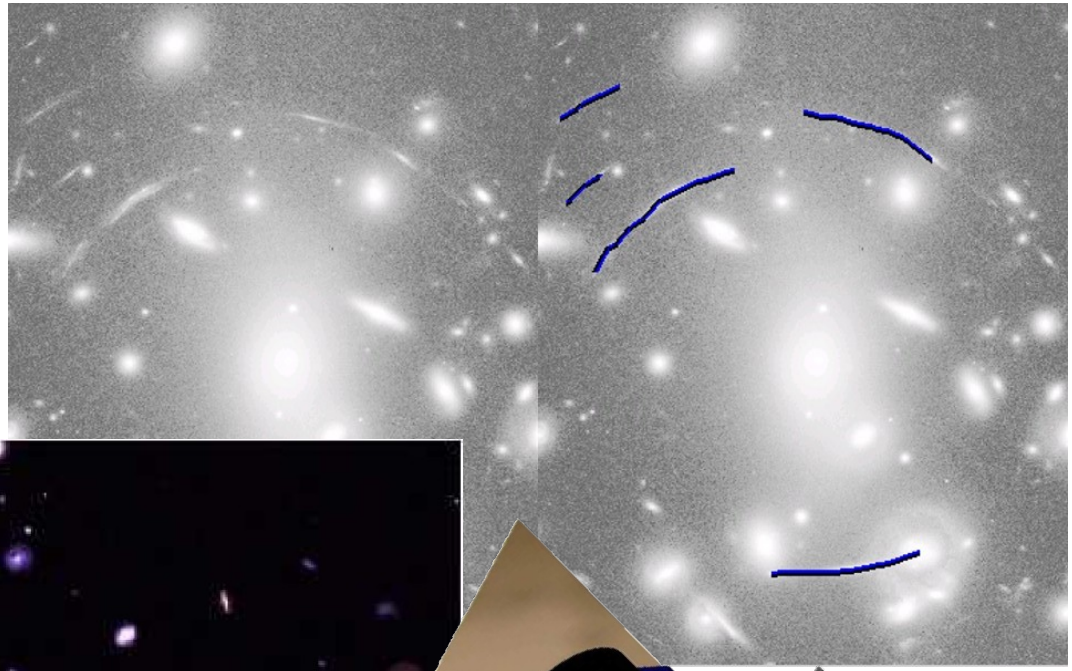


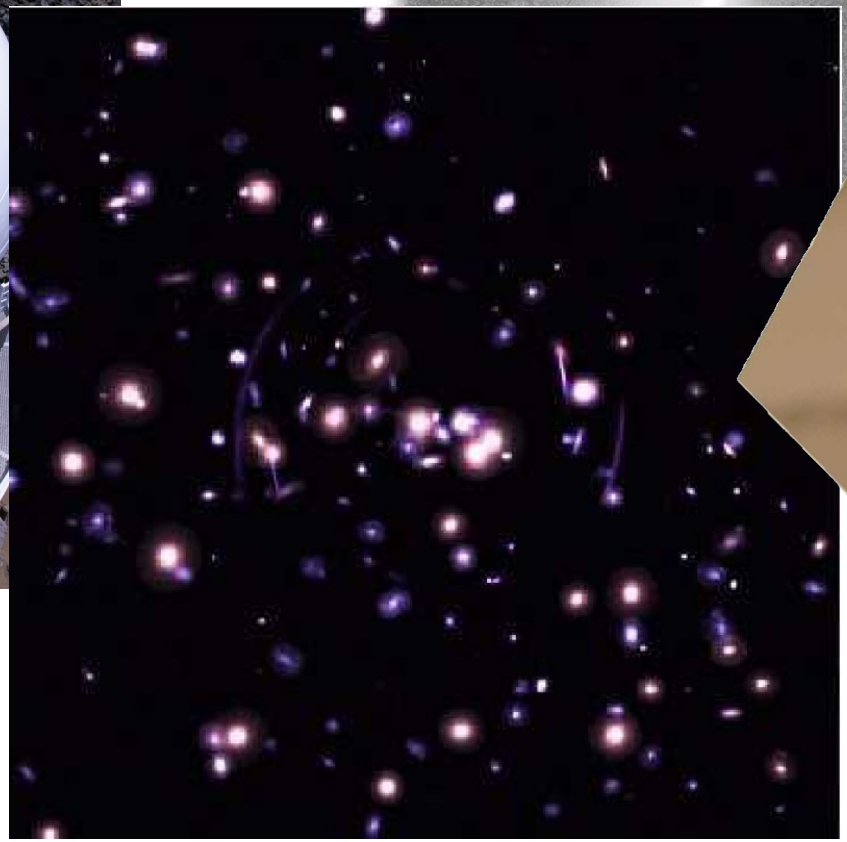
(Broadhurst et al. 2010)

Abundance of dark-matter haloes

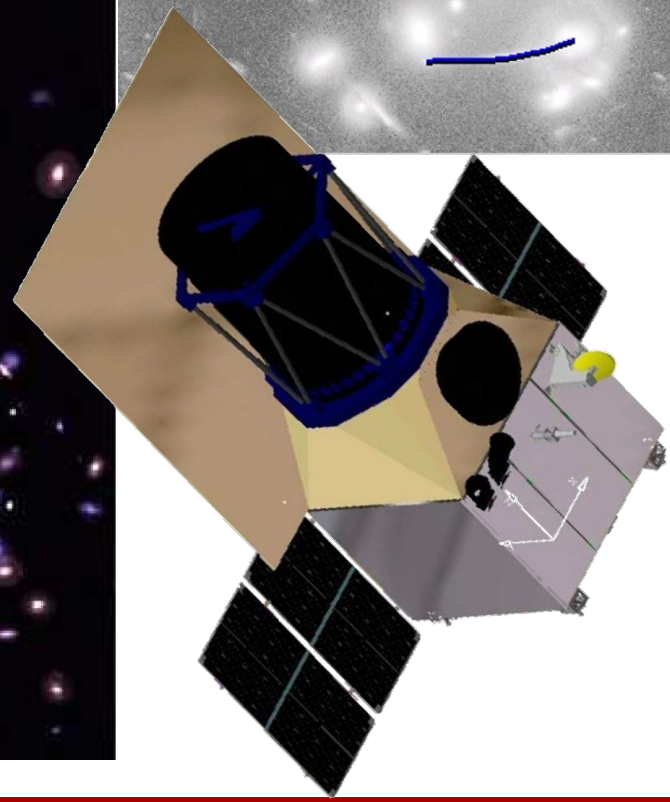


(Seidel et al. 2007)

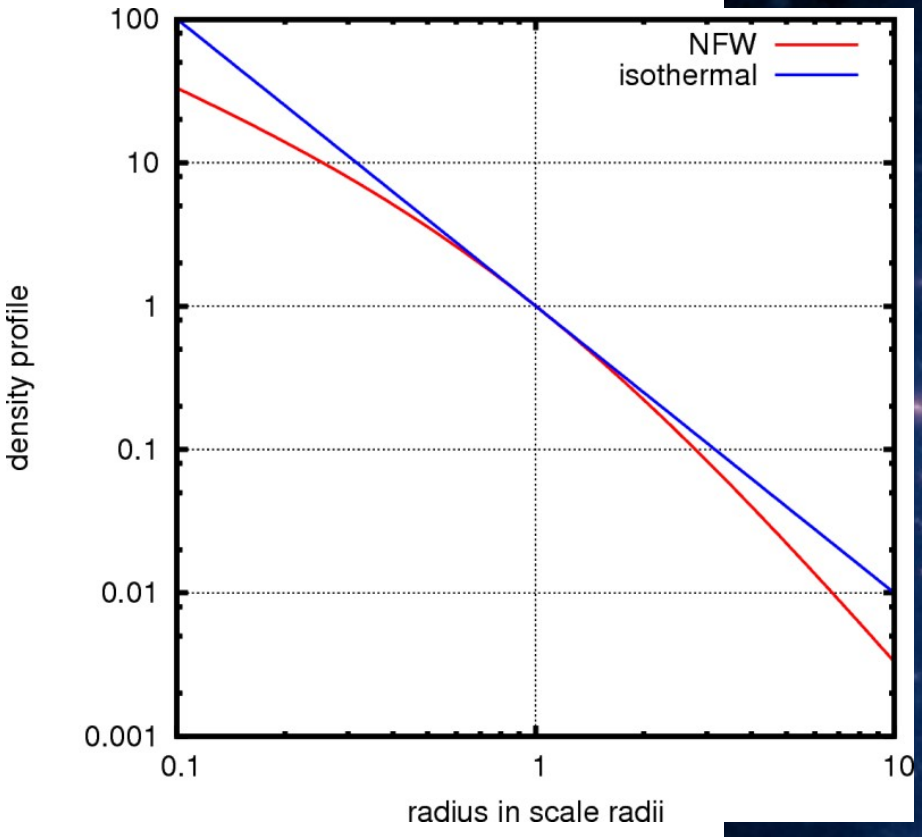


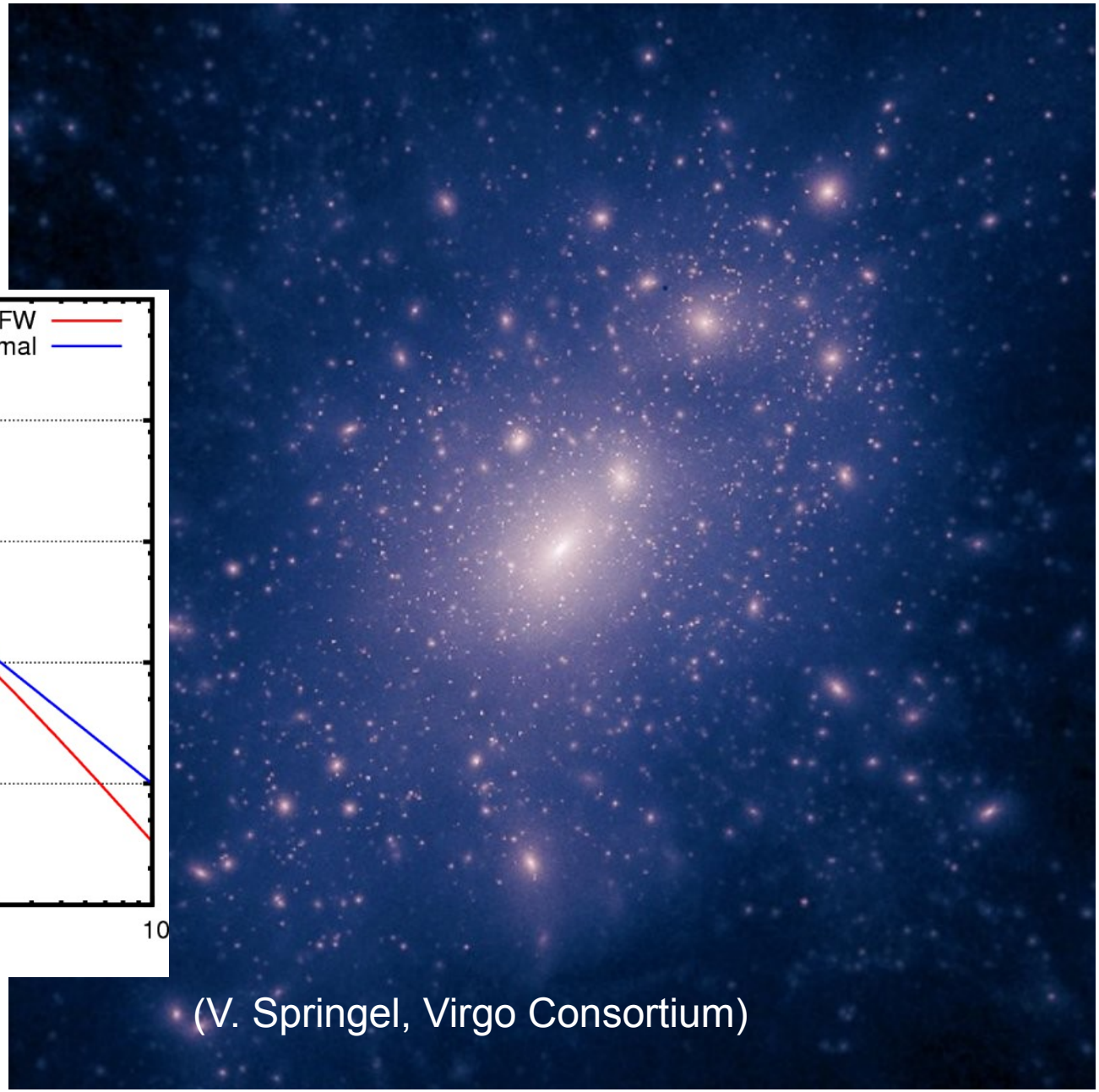


(Meneghetti et al. 2008)



Structure of dark-matter haloes

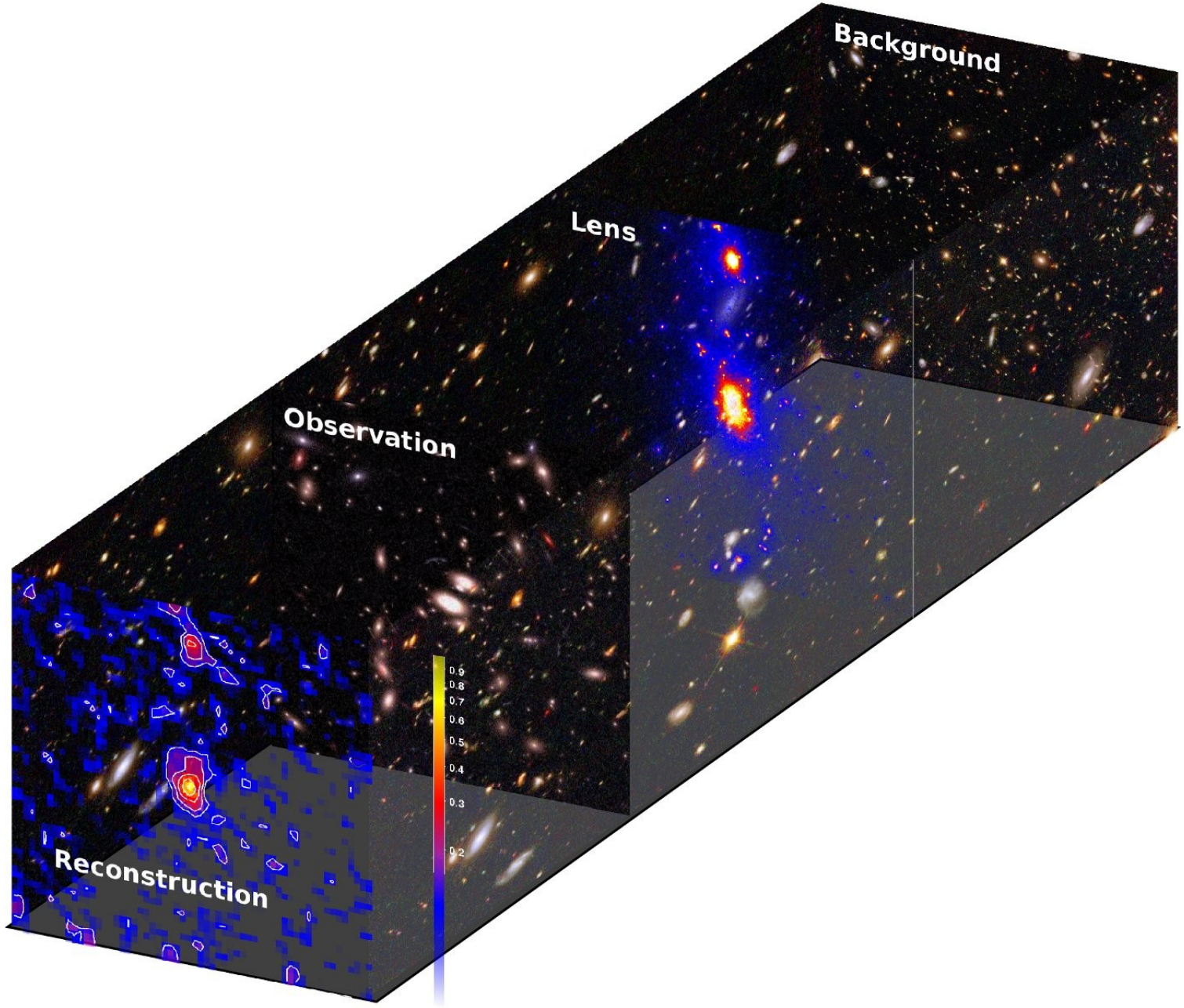




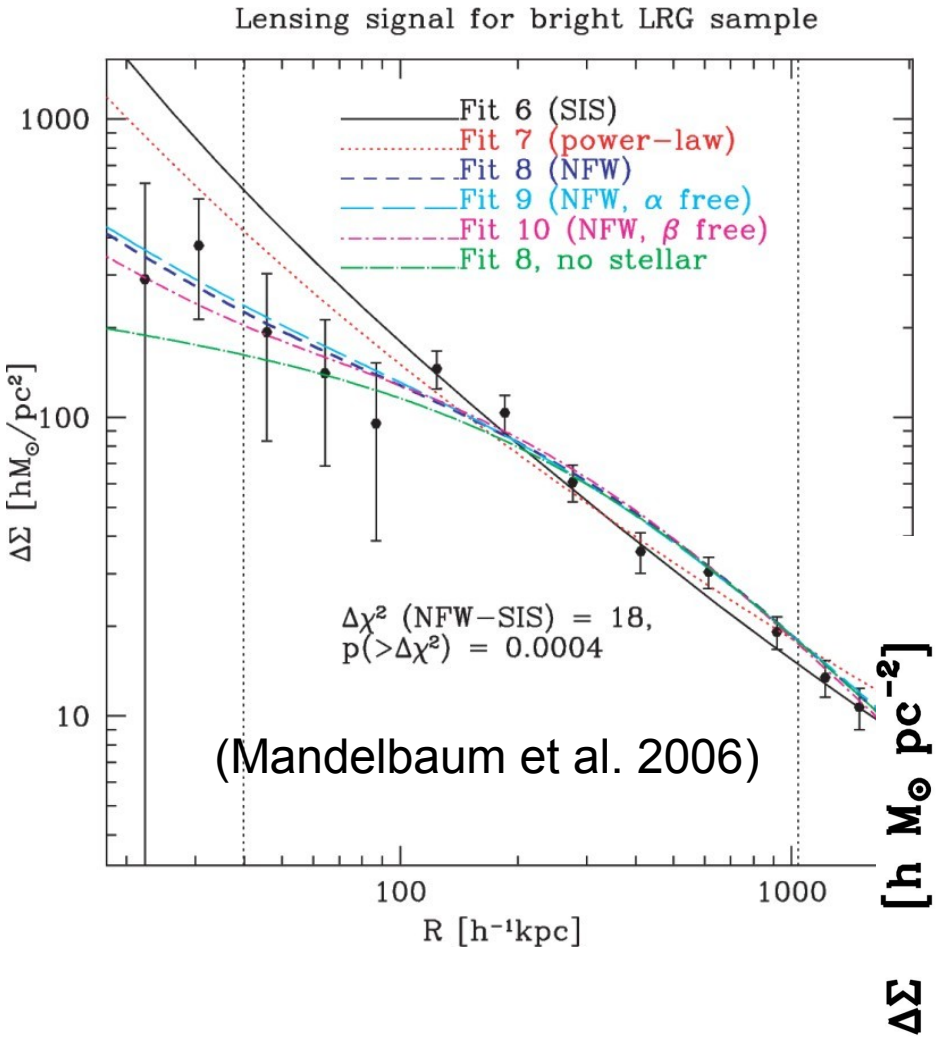
(V. Springel, Virgo Consortium)

Structure of dark-matter haloes

(Merten 2010)

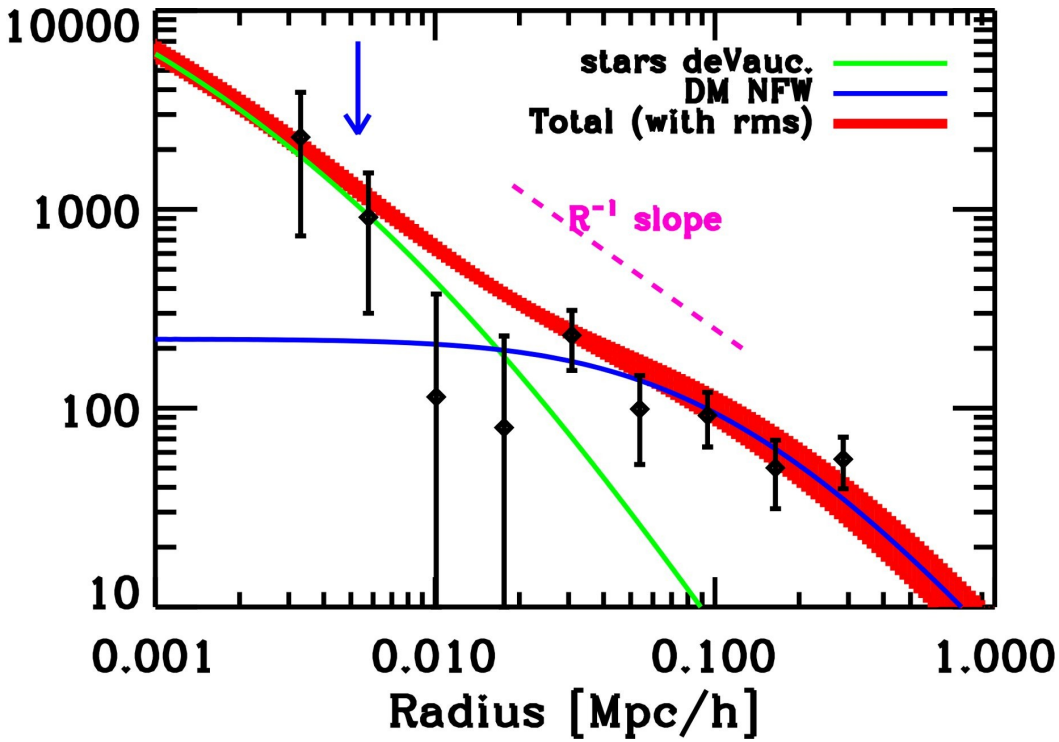


Structure of dark-matter haloes



(Mandelbaum et al. 2006)

(Gavazzi et al. 2007)



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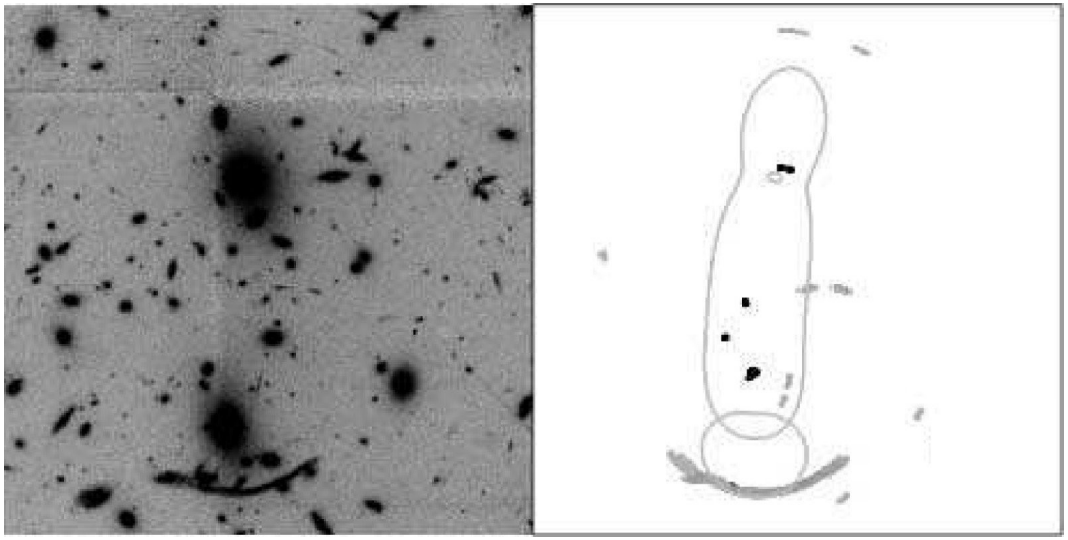
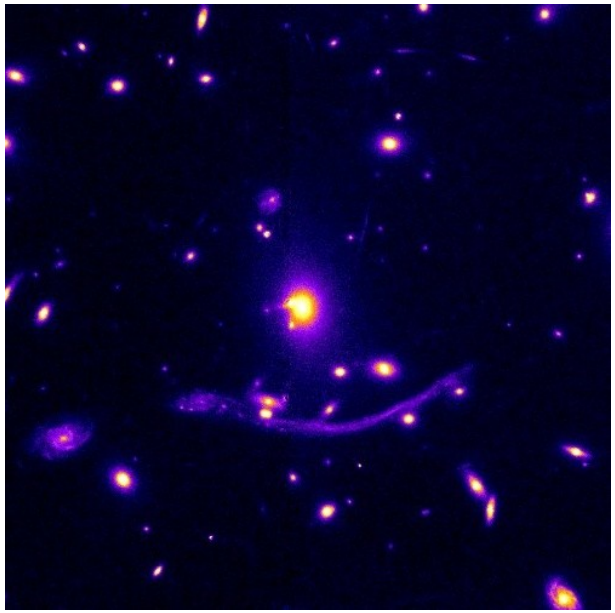
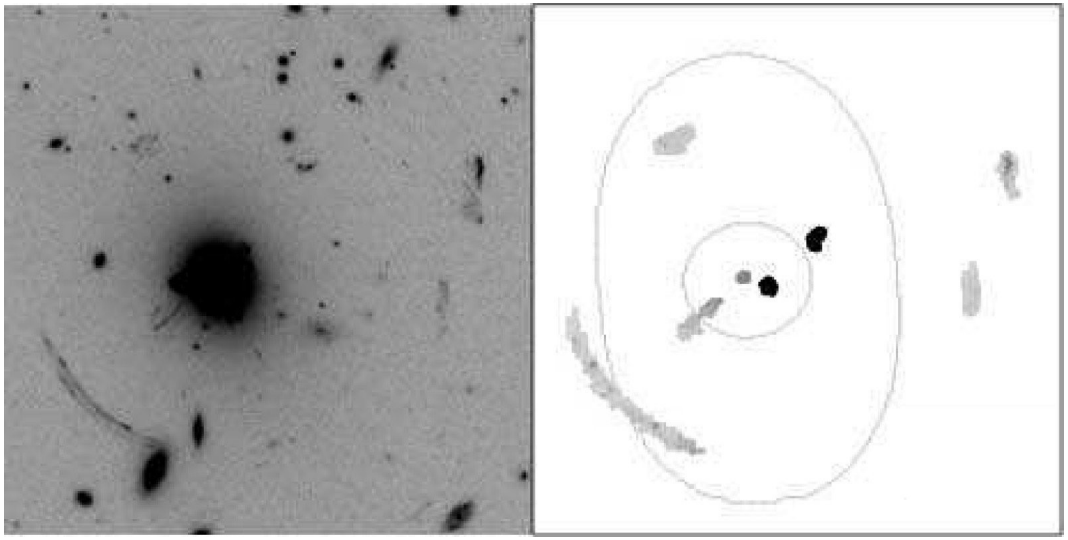
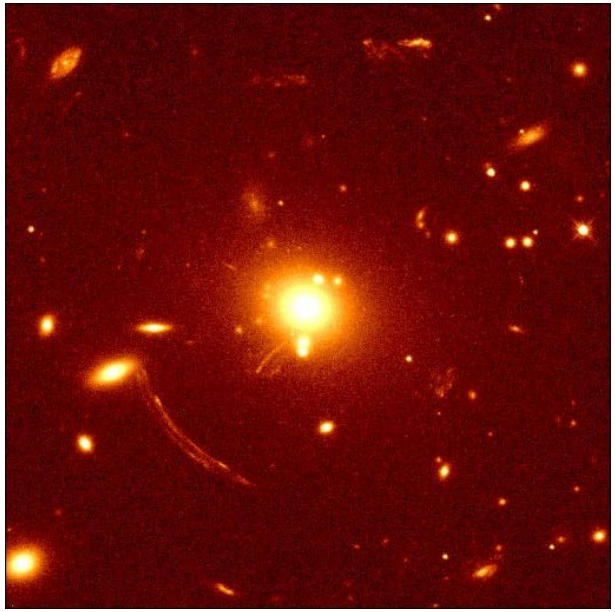


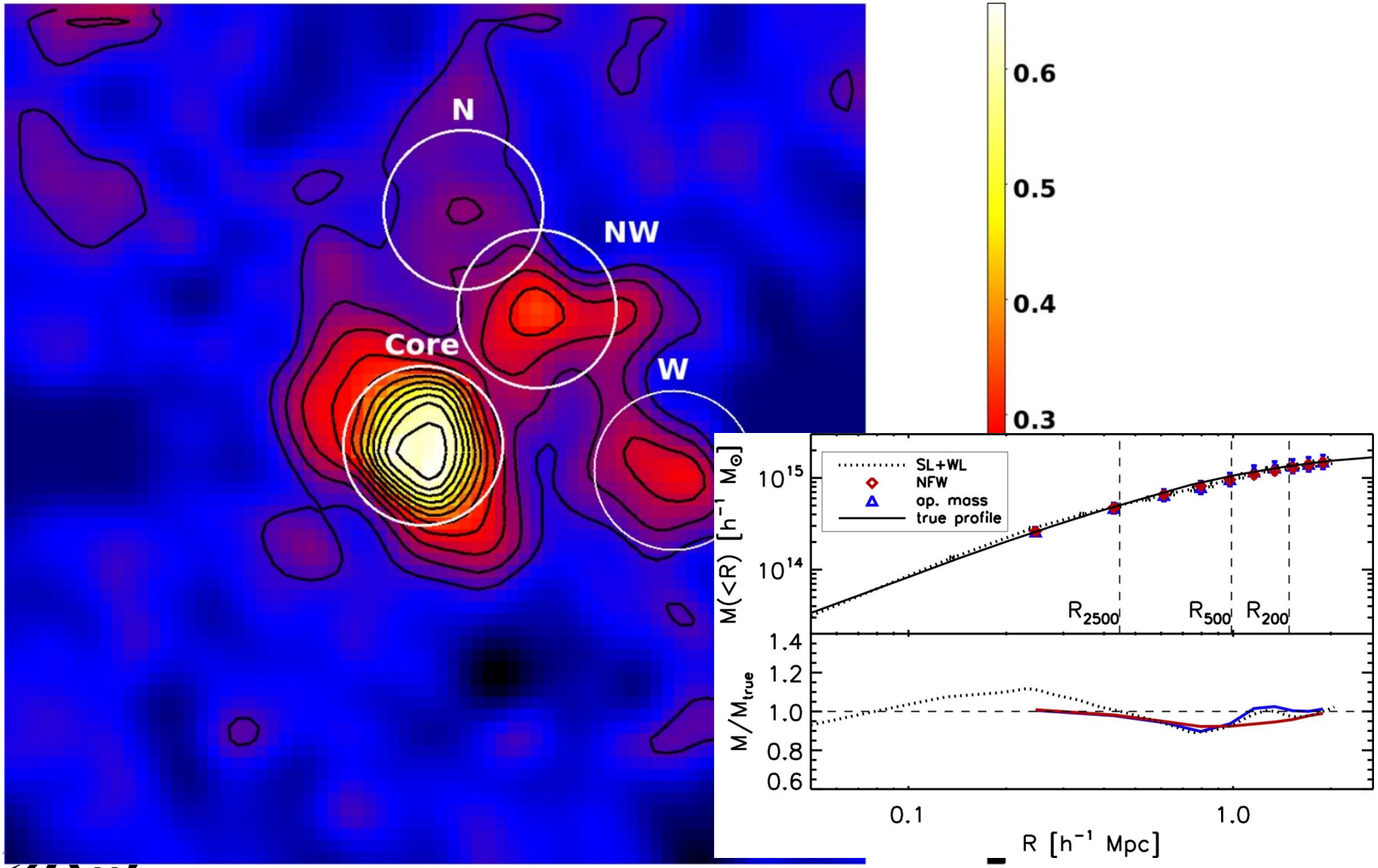




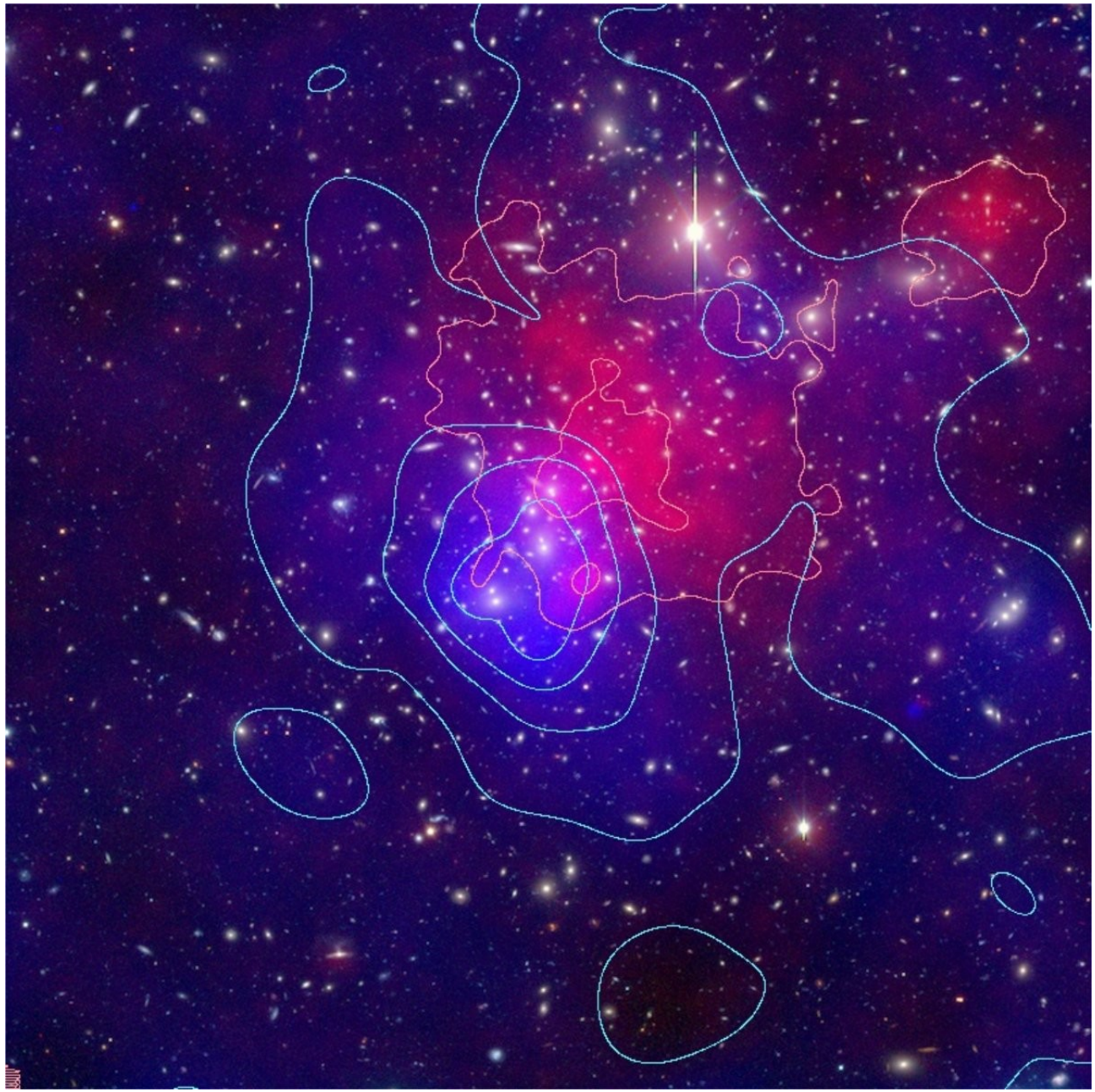


(Comerford et al. 2005)

Structure of dark-matter haloes



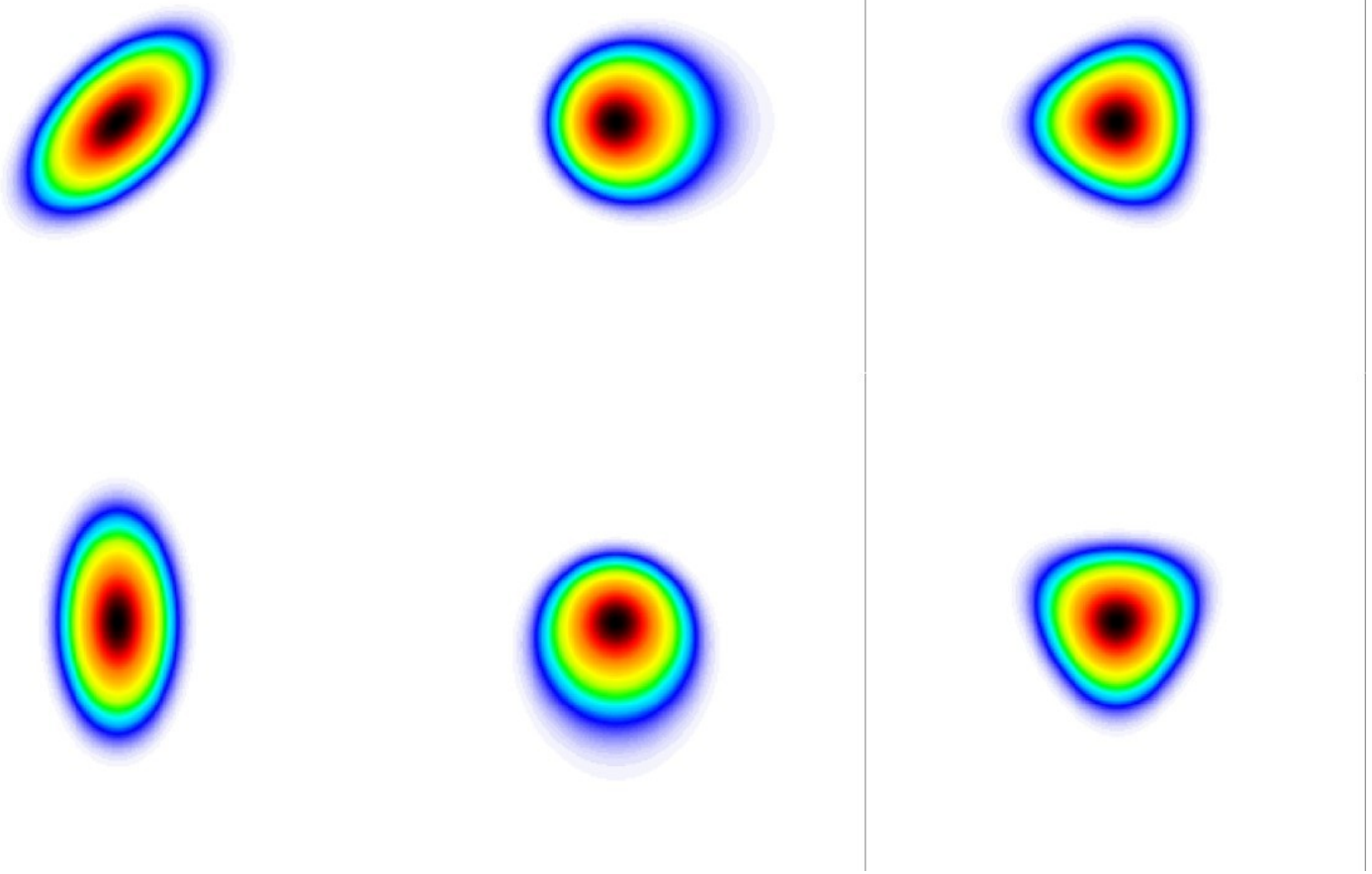
Structure of dark-matter haloes



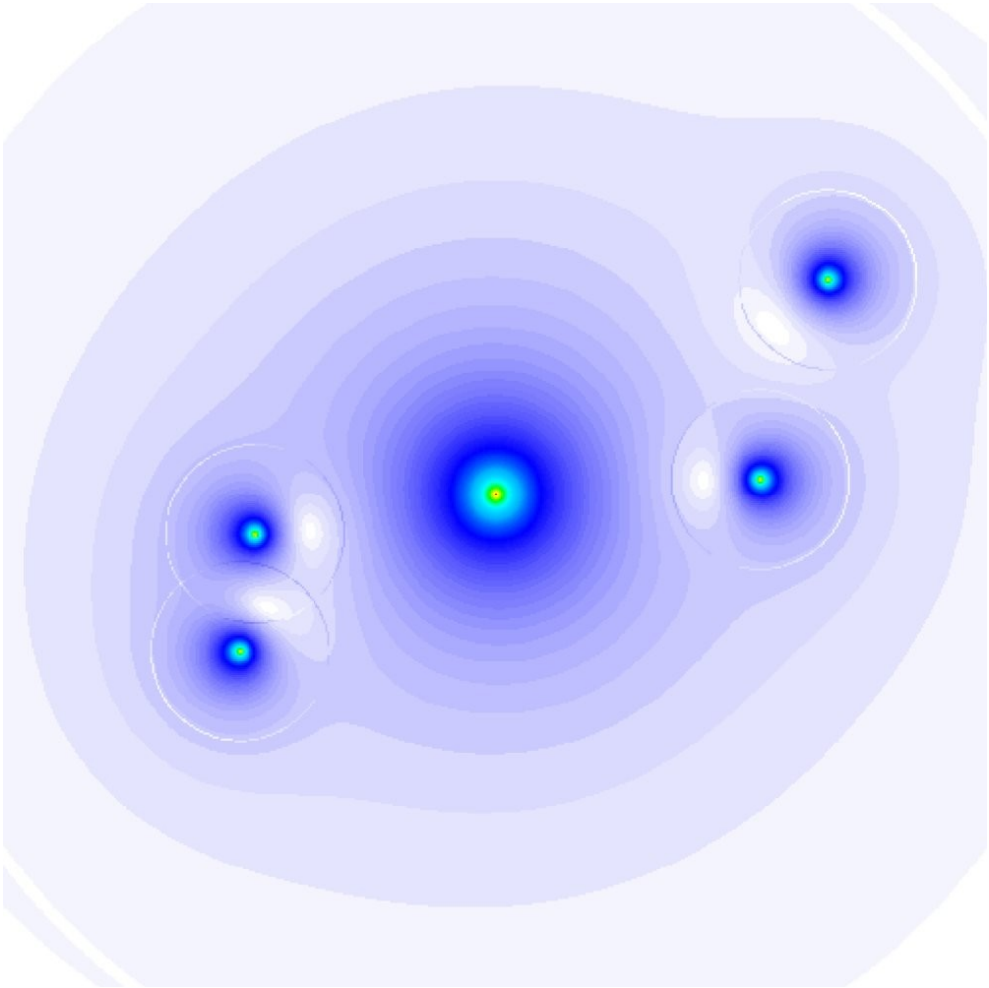
(Merten et al. 2011)

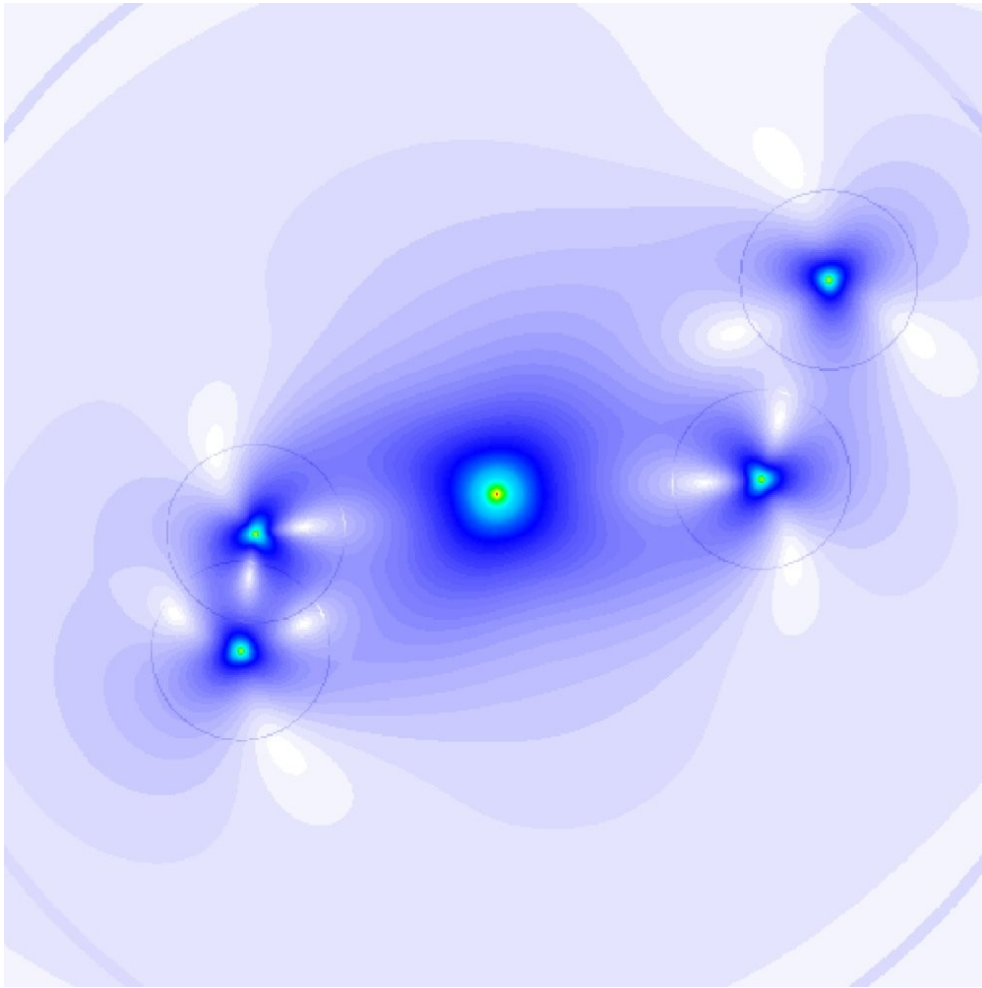
Structure of dark-matter haloes

$$\kappa = \frac{1}{2}\partial^\dagger\partial\psi\,, \quad \gamma = \frac{1}{2}\partial^2\psi \qquad F = \frac{1}{2}\partial\partial^\dagger\partial\psi\,, \quad G = \frac{1}{2}\partial^3\psi$$



Structure of dark-matter haloes

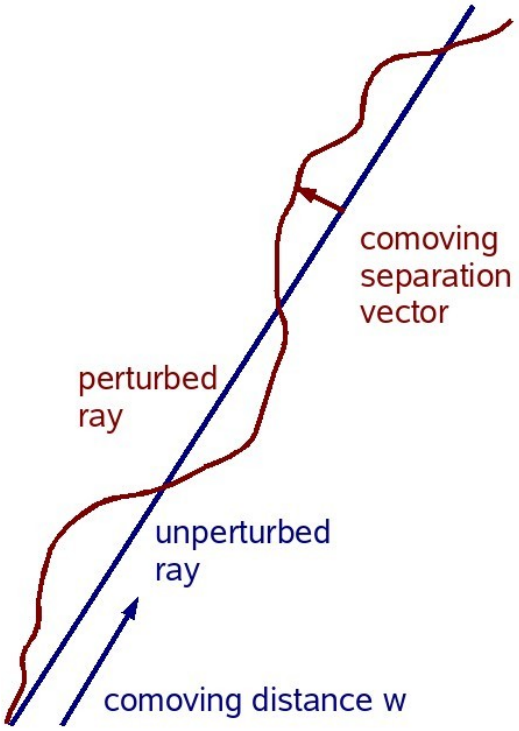


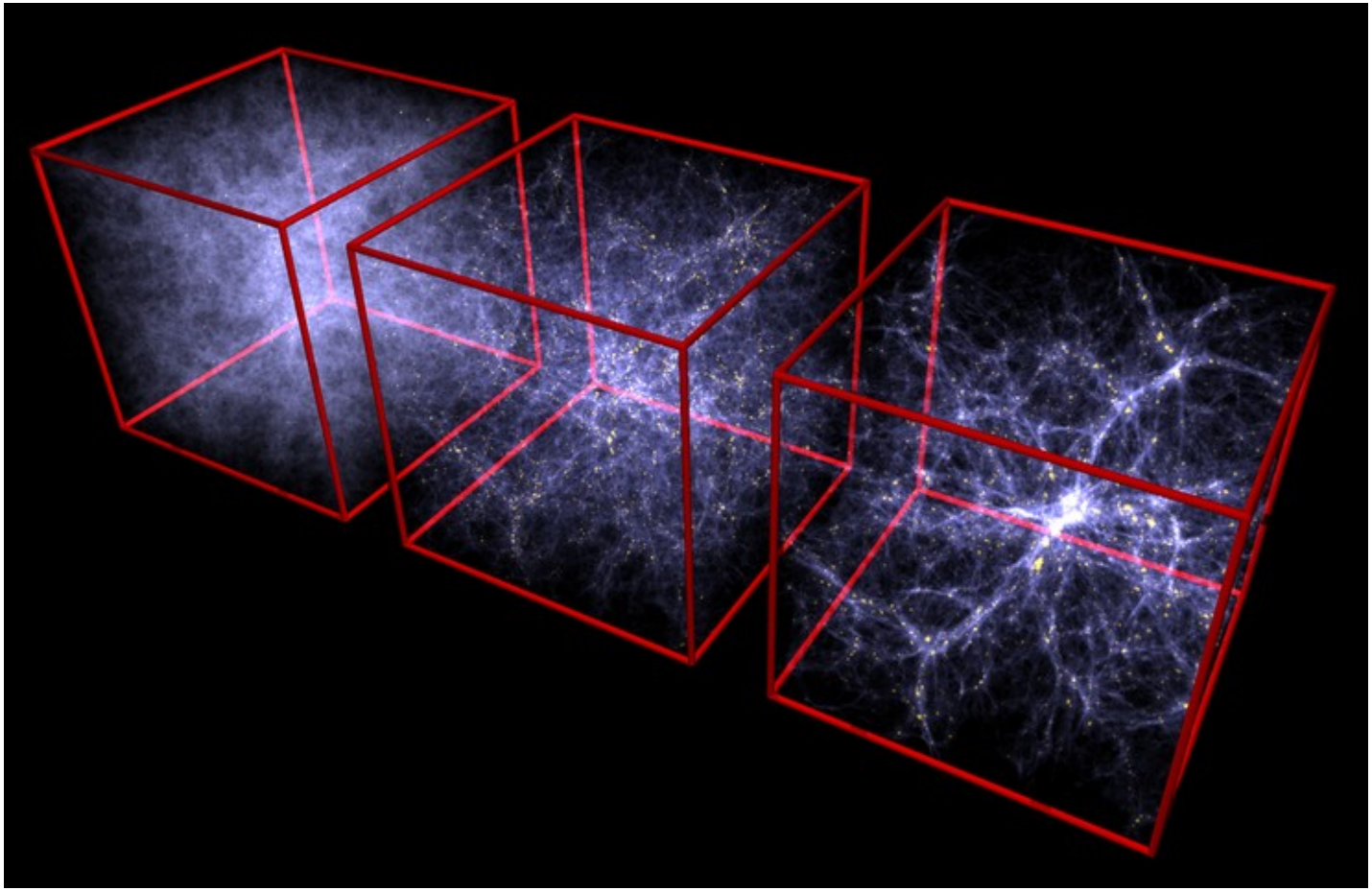


(Giocoli 2010)

Cosmic structure formation

$$\psi = \frac{2}{c^2} \int \frac{D_{ds}}{D_d D_s} \Phi \mathrm{d}z$$

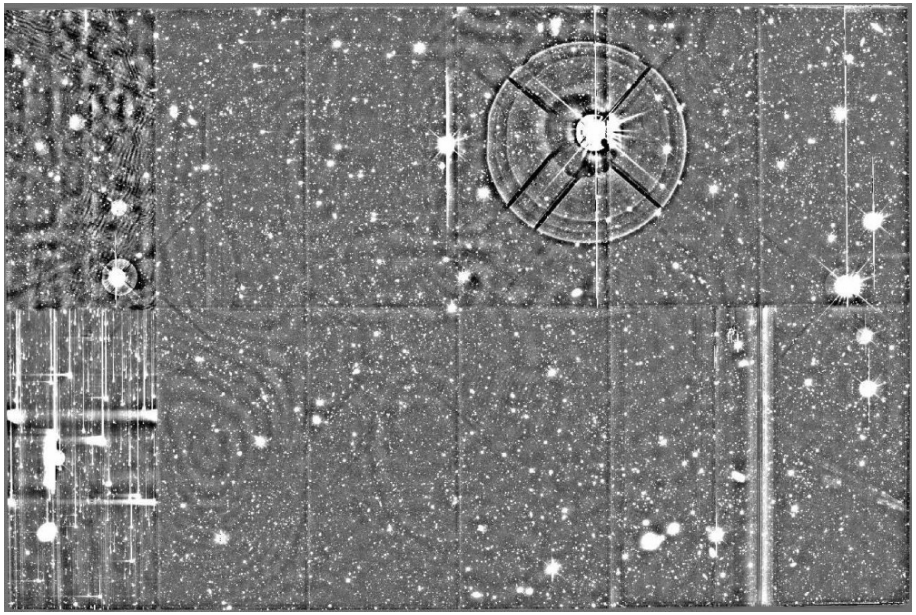


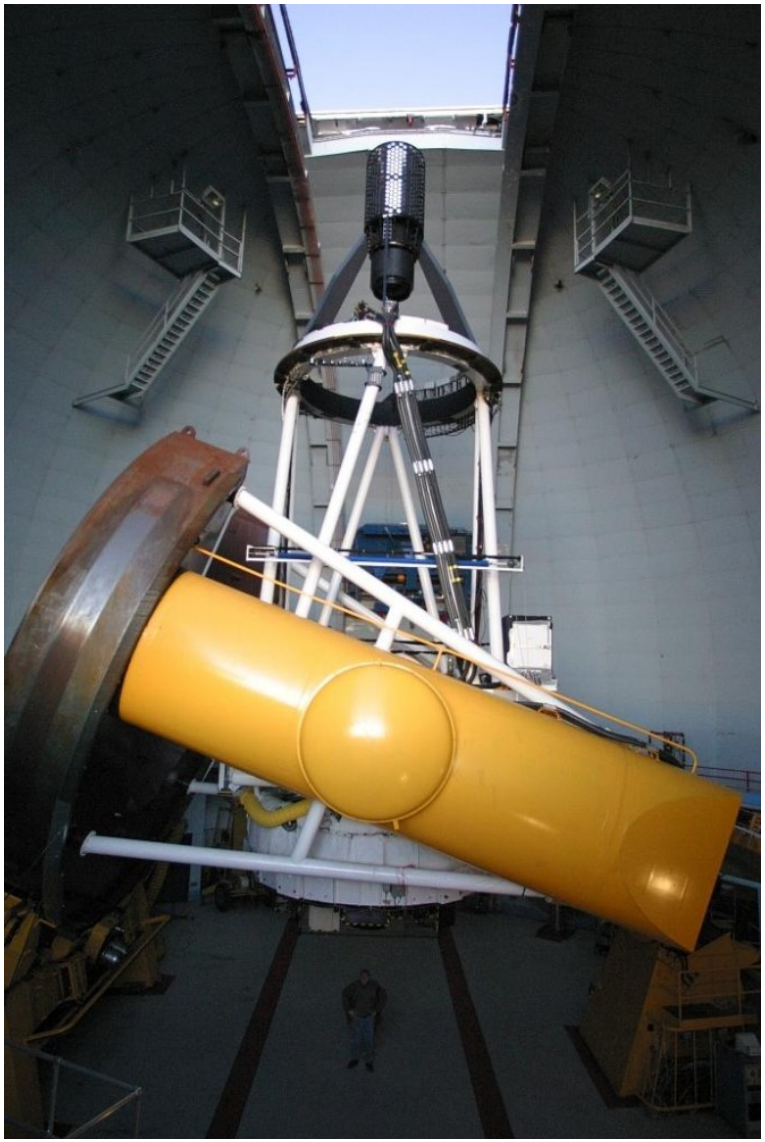


$$P_\kappa(l) = \frac{8\pi G}{c^2} \int \left(\frac{D_{ds}}{D_s}\right)^2 P_{\delta\rho}\left(\frac{l}{D_d}\right) \mathrm{d}z$$

$$\xi_\kappa(\phi) = \int_0^\infty \frac{l \mathrm{d}l}{2\pi} P_\kappa(l) J_0(l\phi)$$

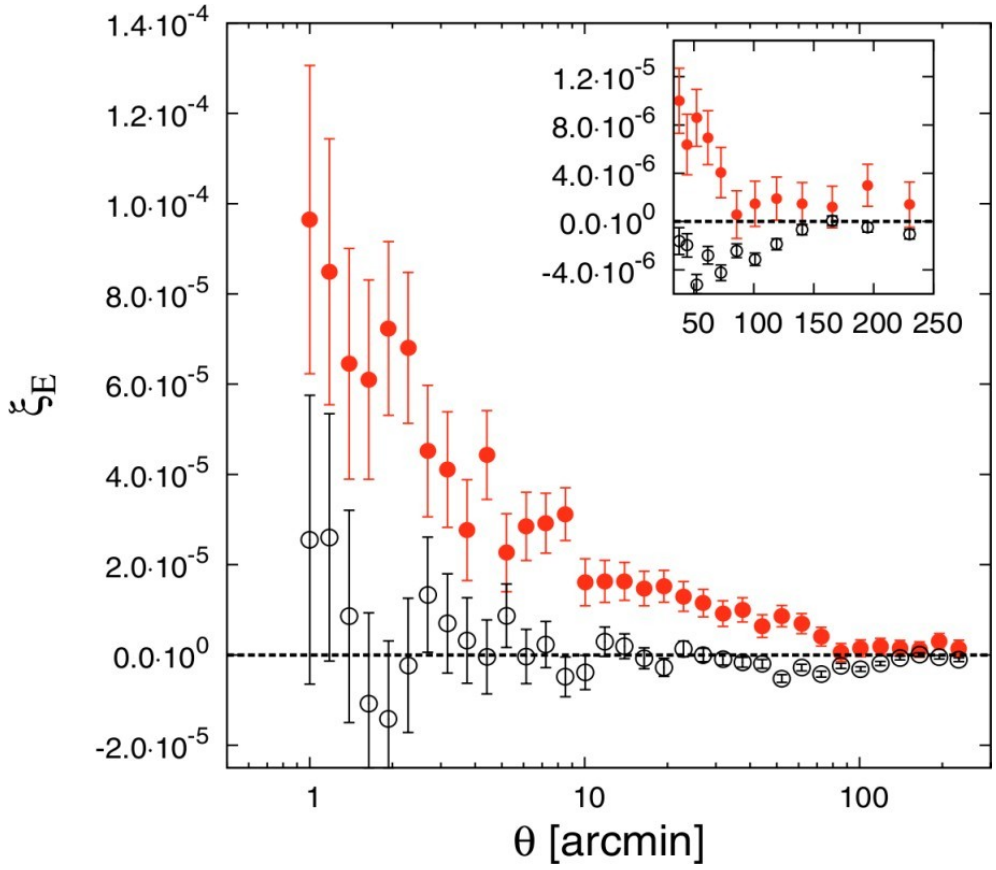
Cosmic structure formation

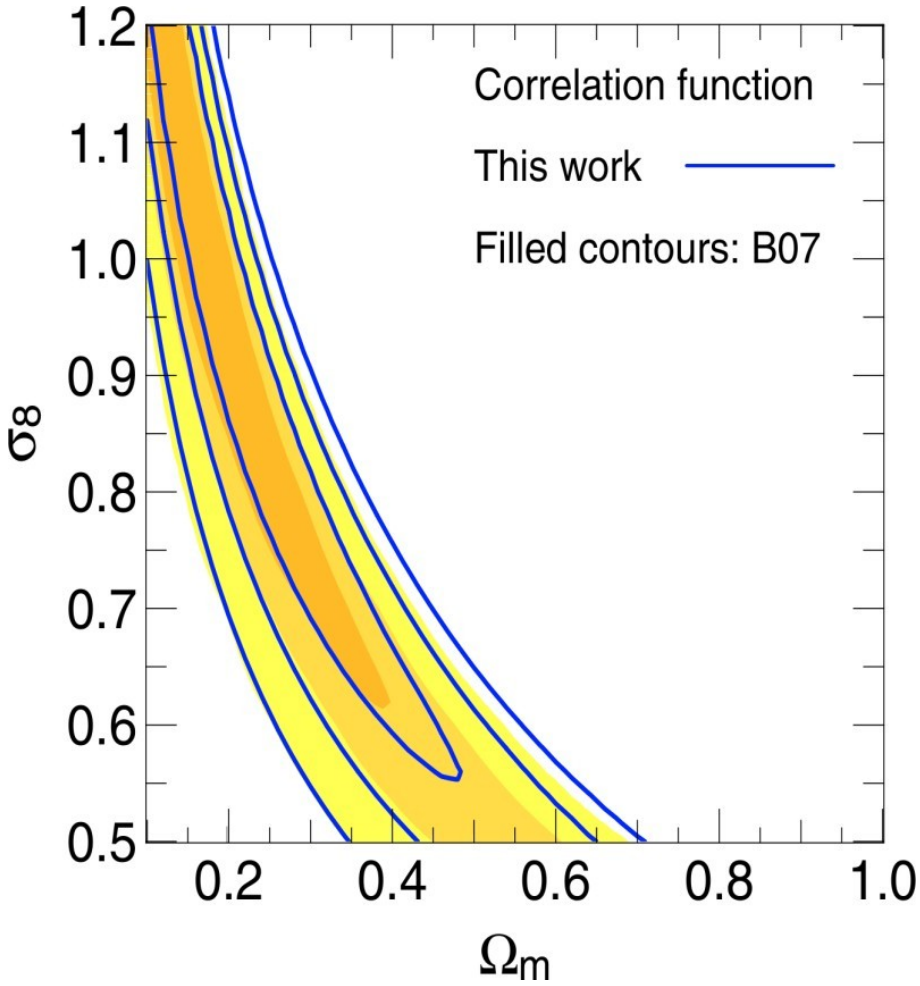




(CFHTLS, Mellier et al.)

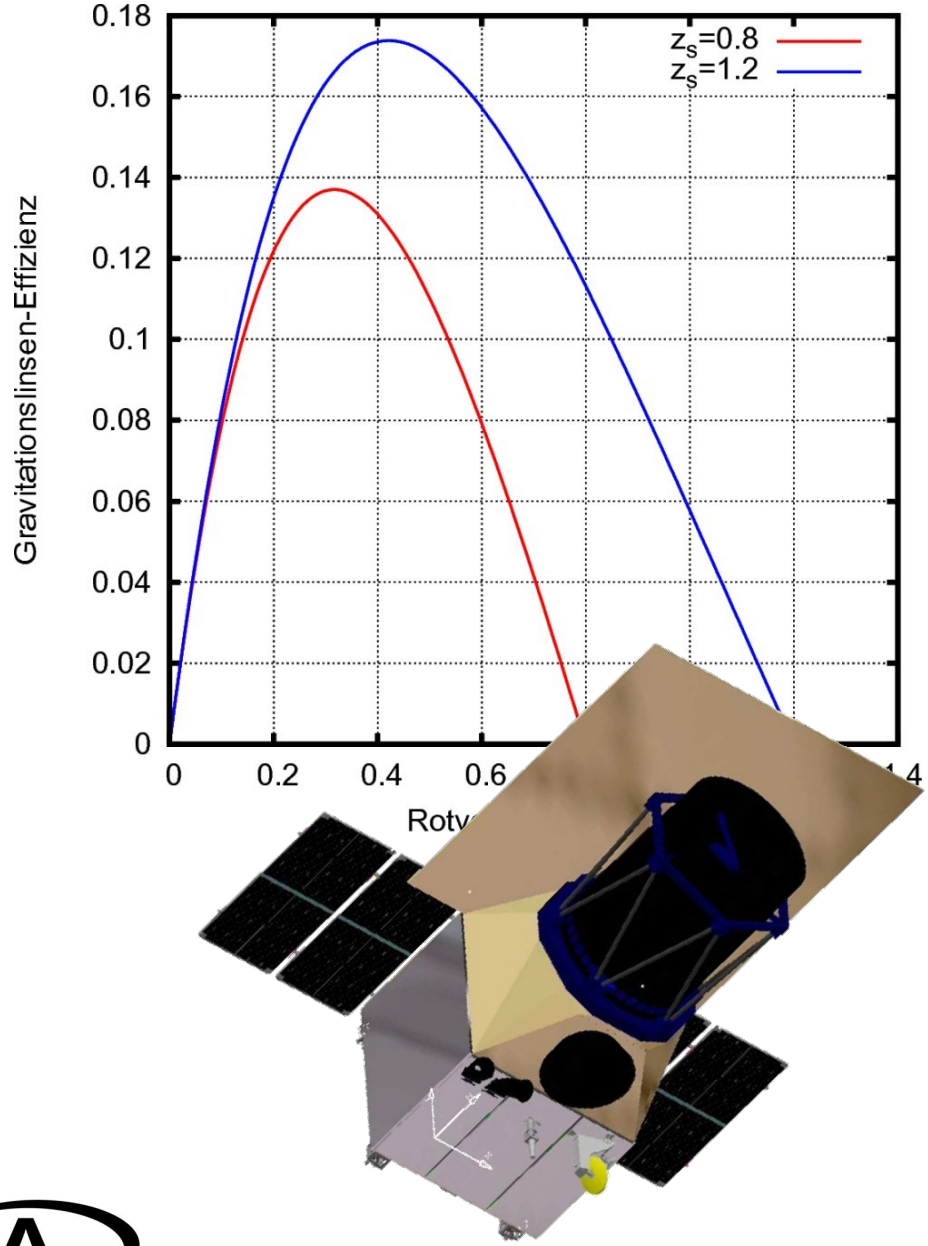
Cosmic structure formation

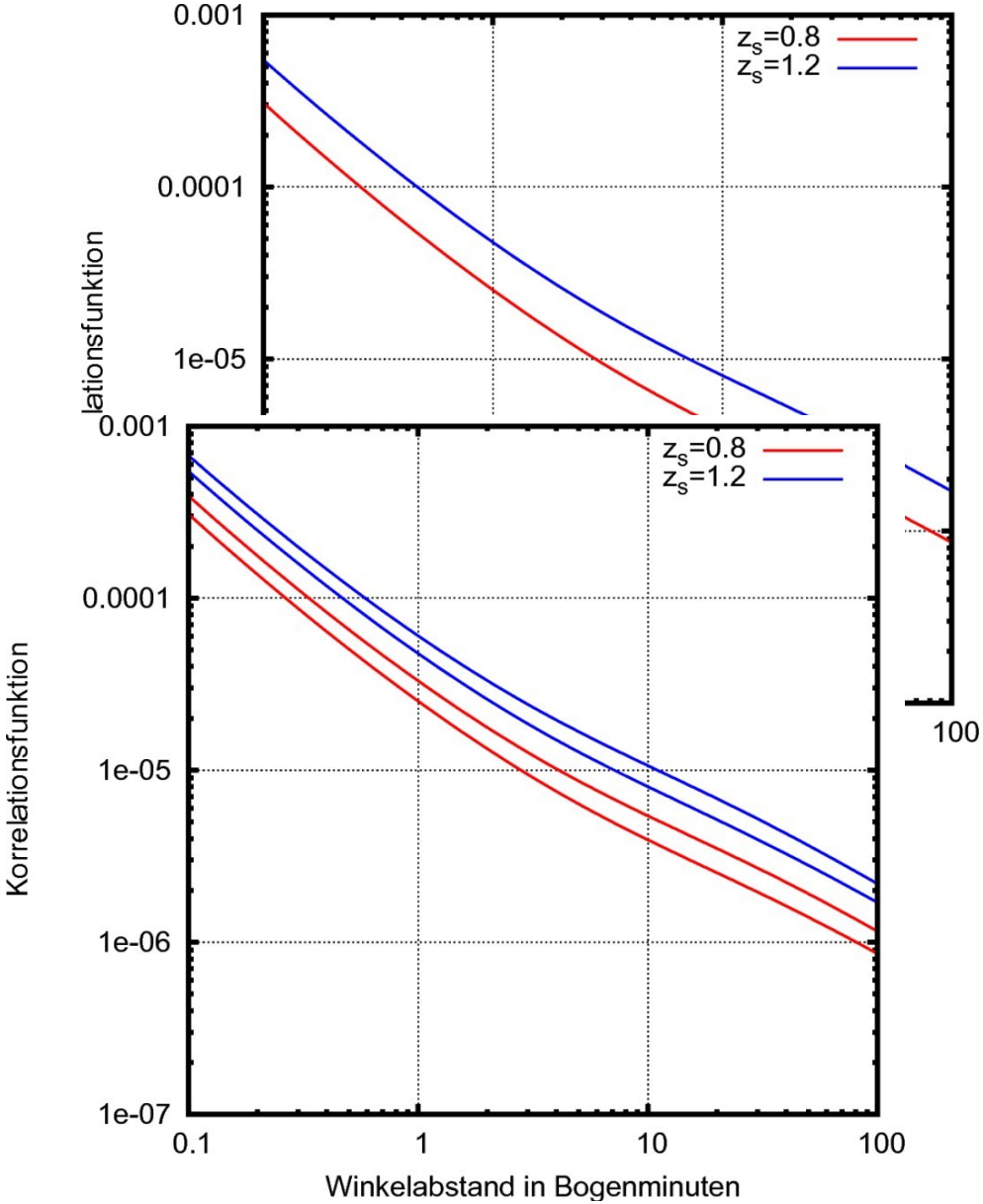




(Fu et al. 2008)

Cosmic structure formation





Cosmic structure formation

(Carbone et al. 2008)