Advanced Techniques and Future Opportunities

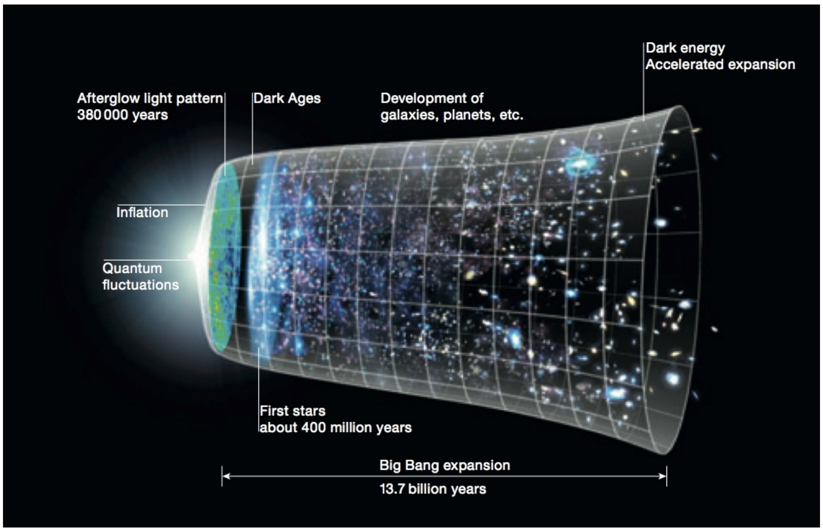
Overview

- Science drivers
- Emerging technologies
- Next generation telescopes
- Gravitational lensing

Science Drivers

- Dawn of galaxy formation
- Dark matter and dark energy
- Black holes and galaxies
- Earth-like extra-solar planets

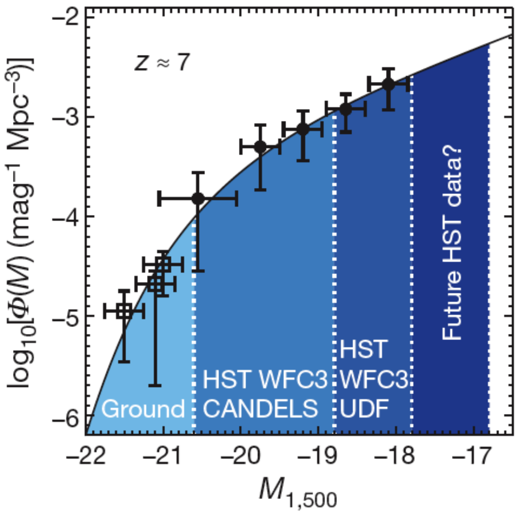
Cosmic History



Dawn of Galaxy Formation

How big would the Milky Way appear in the UDF if it was at z=10?

Dawn of Galaxy Formation

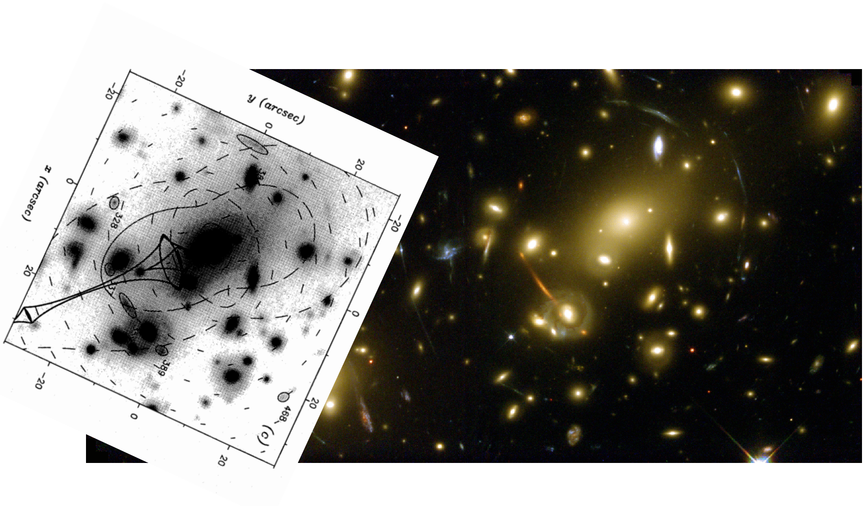


How do we convert absolute magnitudes to apparent magnitudes?

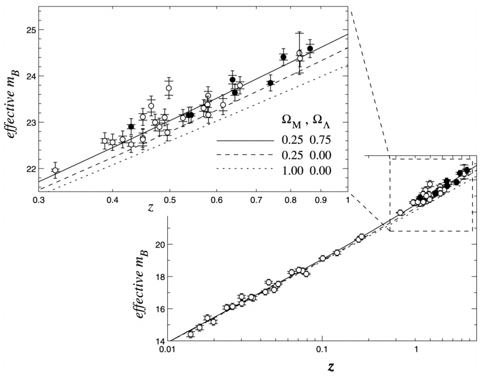
What observed wavelength does rest-frame 1500A correspond to?

Dark Matter

Dark Matter



Dark Energy



Supernovae (standard candles) are fainter and thus further away than expected.

Something is pushing galaxies away from us!

We call it "dark energy".

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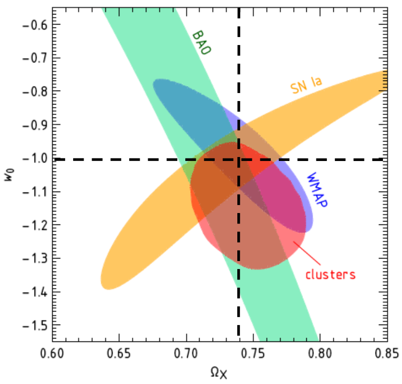
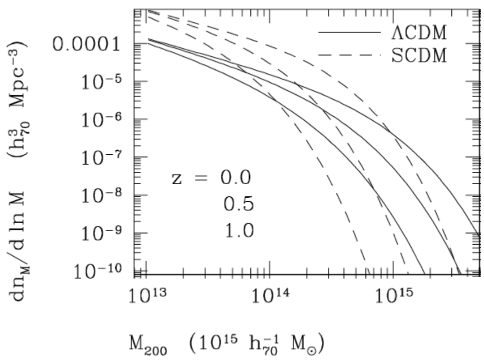
Dark Energy



Vikhlinin et al., 2009, ApJ, 692, 1060



Voit, 2005, RvMP, 77, 207

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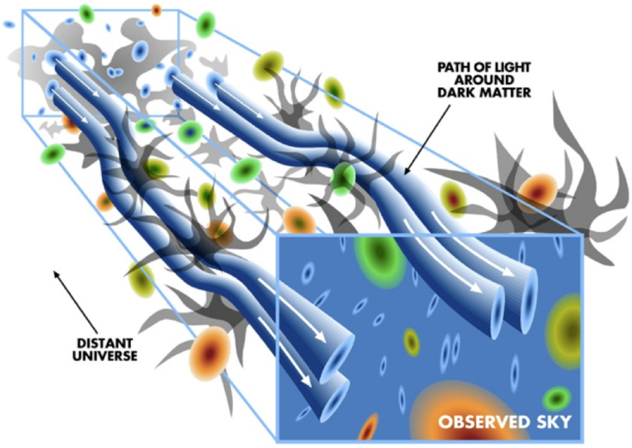
Dark Energy



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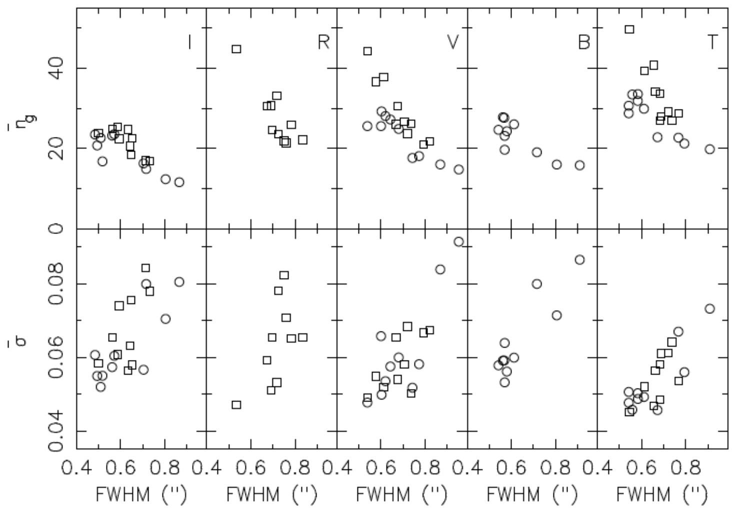
Dark Energy



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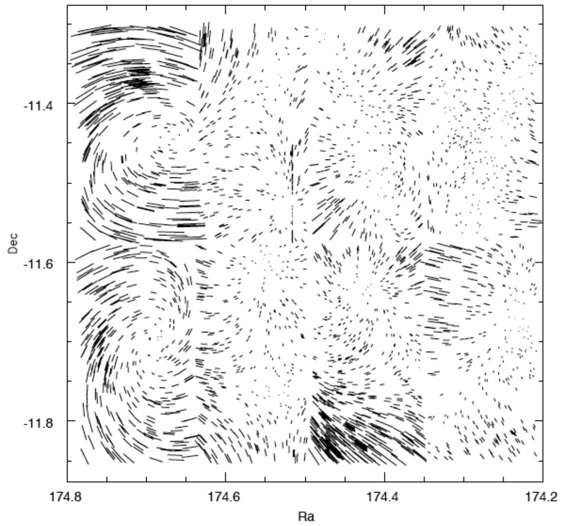
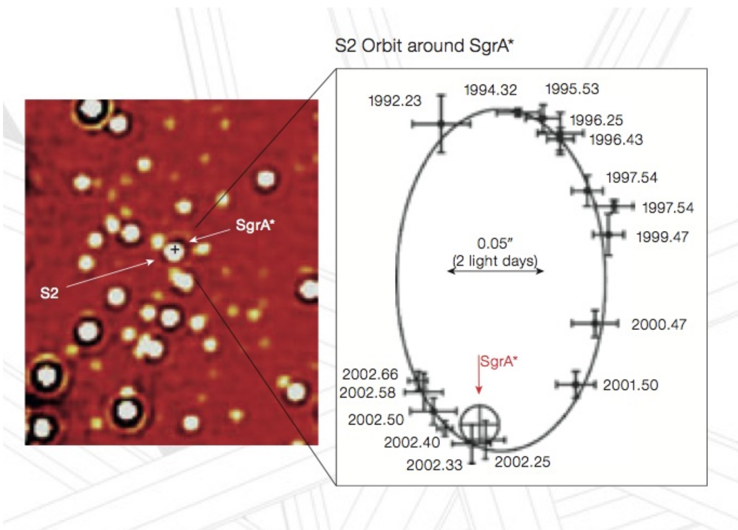
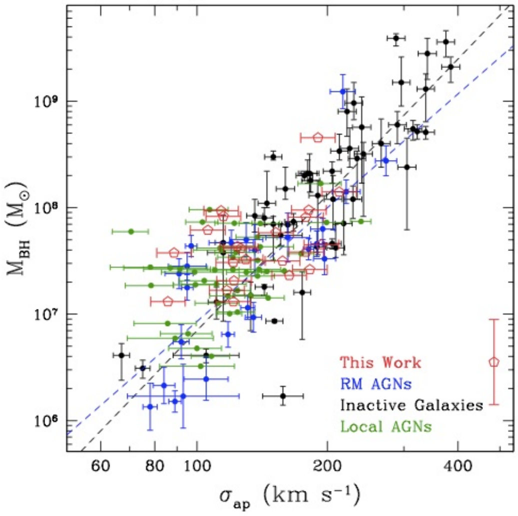
Dark Energy



Black Holes



Black Holes and Galaxies



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Design Requirements

- Dawn of galaxy formation
  - Very deep near-IR imaging and spectroscopy (30th mag)
  - ~10 milli-arcsecond image quality
- Dark matter and dark energy
  - Very wide-field high cadence imaging (~PI sr)
  - Sub-arcsecond image quality across wide-fields
- Black holes and galaxies
  - High signal-to-noise spectroscopy
  - ~10 milli-arcsecond image quality
- Earth-like extra-solar planets

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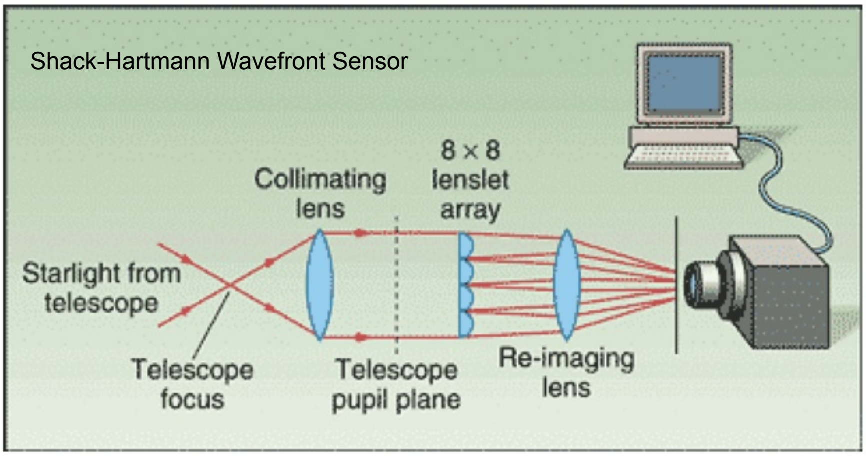
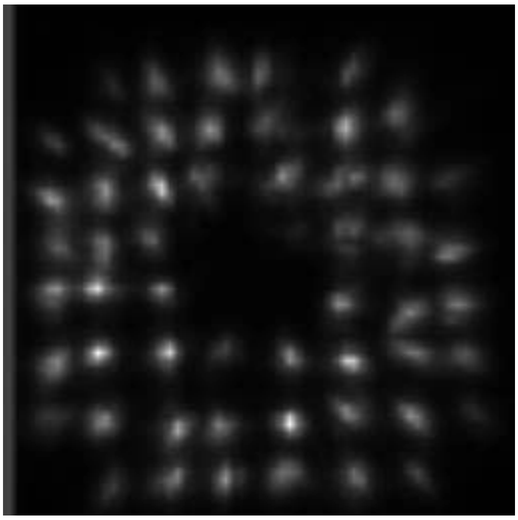
Emerging Technologies

- Adaptive optics
- OH suppression
- Integral-field spectroscopy
- Wide-field CCDs

Adaptive Optics



Adaptive Optics



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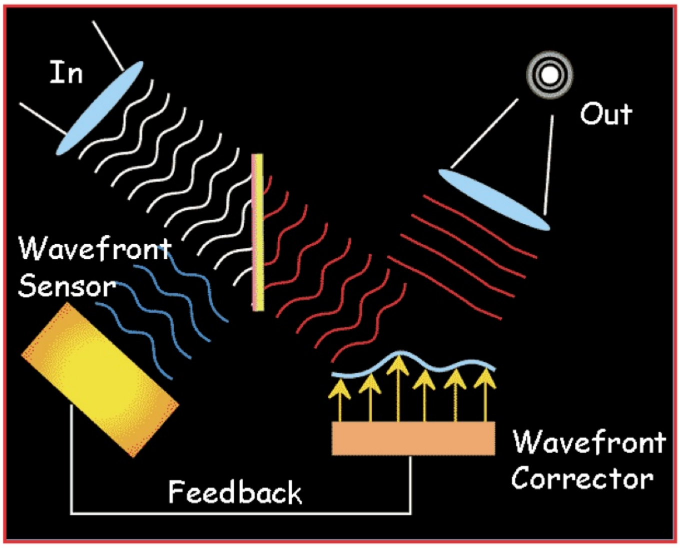
Adaptive Optics



The sampling rate is 100kHz.

What implications does this have for the CCD equation?

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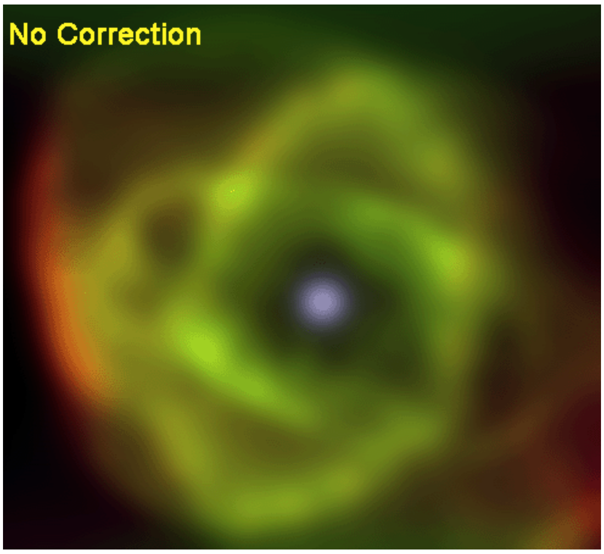
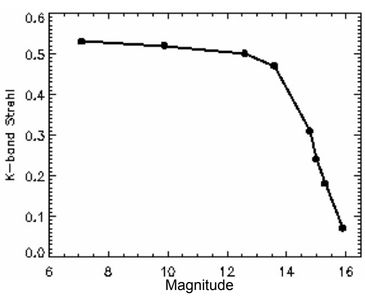
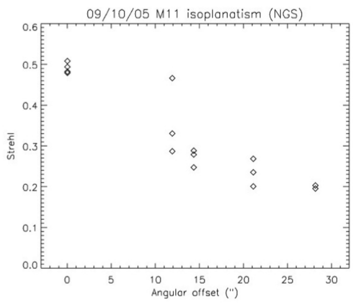
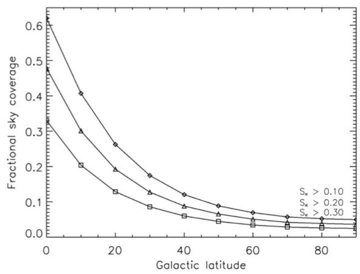
Adaptive Optics



Adaptive Optics





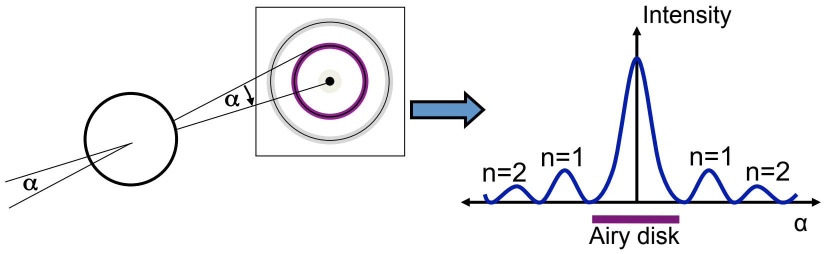


$$\text{Strehl} = \frac{I_{\text{peak}}^{\text{Actual}}}{I_{\text{peak}}^{\text{Limit}}}$$

Reminder

Resolving Power

Huygens Principle



- The constructive and destructive interference patterns are described according to Huygen's Principle
- For a telescope with diameter D and light with wavelength λ, minima occur at positions given by:

$$\sin\alpha_n = \frac{m_n \lambda}{D}$$

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Laser Guide Stars

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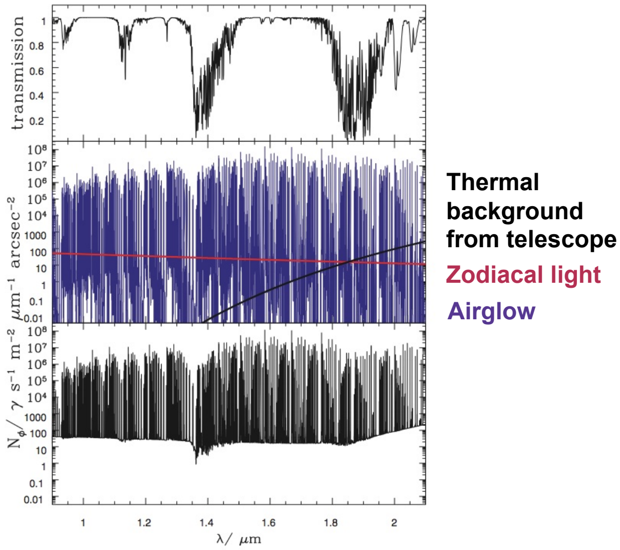
OH Suppression



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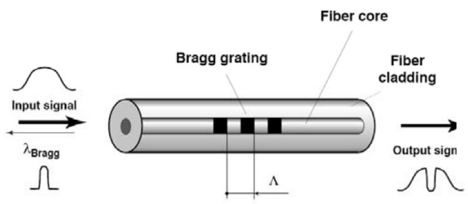
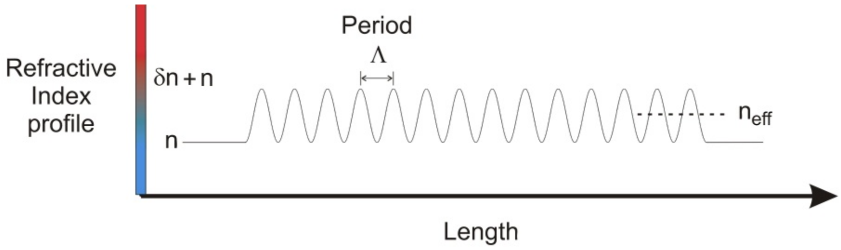
OH Suppression



$$\lambda_B \cdot m = 2 \cdot n_{eff} \cdot \Lambda$$



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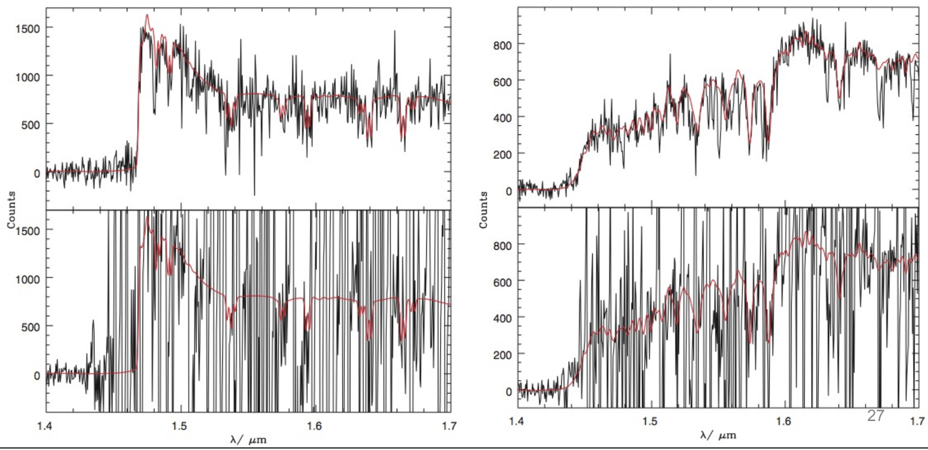
OH Suppression

H=24.6 (Vega); QSO at z=11;
70 hours; R=1000

H=23 (Vega); Galaxy at z=3;
8 hours; R=1000



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Next generation telescopes

- James Webb Space Telescope
- Large Synoptic Survey Telescope
- European Extremely Large Telescope
- Square Kilometre Array
- e-ROSITA
- …

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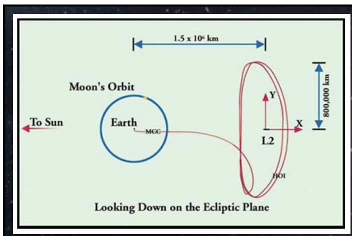
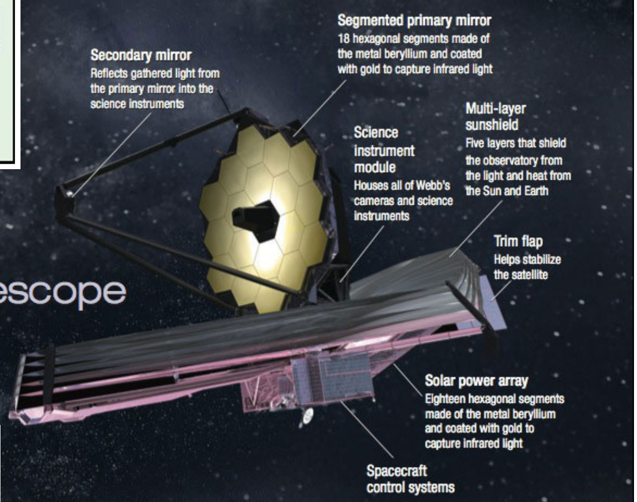
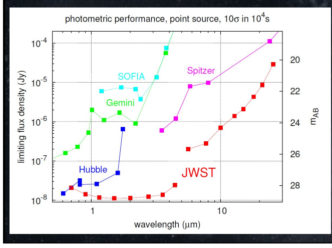


The James Webb Space Telescope





F-ratio = 20 D = 6.57m

What science discussed earlier is JWST well-suited to?

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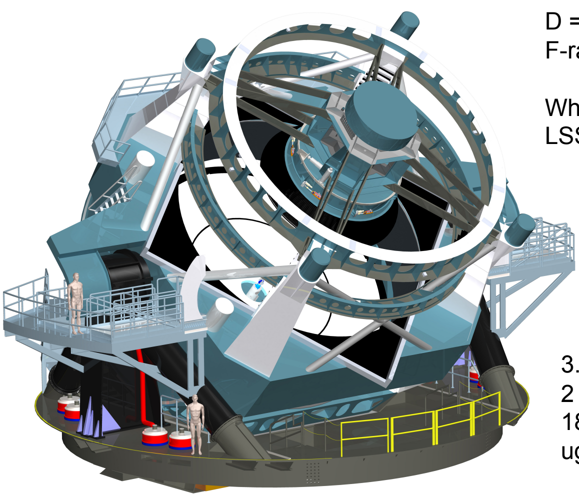
Large Synoptic Survey Telescope



D = 8.4m
F-ratio = 1.23

What science discussed earlier is LSST well-suited to?

3.5degree field of view
2 seconds per read out
189 4k x 4k CCDs
ugrizY filters

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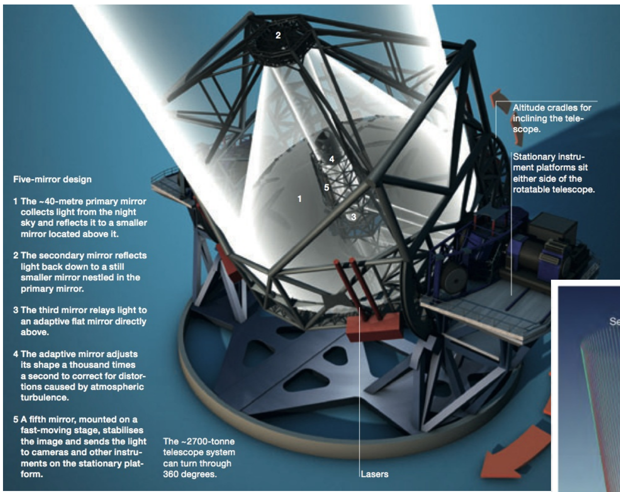
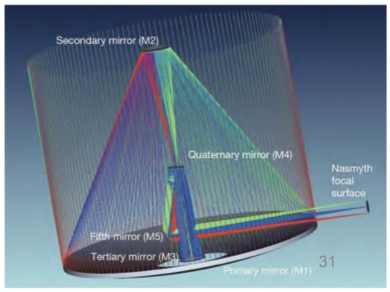
European Extremely Large Telescope



D = 39.3m
F-ratio = 0.88
798 segments
6 laser guide stars
At Nasmyth: f-ratio=17.8

What science discussed earlier is E-ELT well-suited to?



10 x 10 arcmin field of view

Summary

- Science drivers
  - Cosmic re-ionization, dark matter, dark energy, black holes, exoplanets
  - Angular resolution, near-infrared sensitivity, wide-field of view, high cadence imaging
- Emerging technologies
  - Adaptive optics, OH suppression, integral field spectroscopy
- Next generation telescopes
  - JWST, LSST, E-ELT, SKA, e-ROSITA
- Gravitational lensing
  - A glimpse of tomorrow, today …

Gravitational Lensing

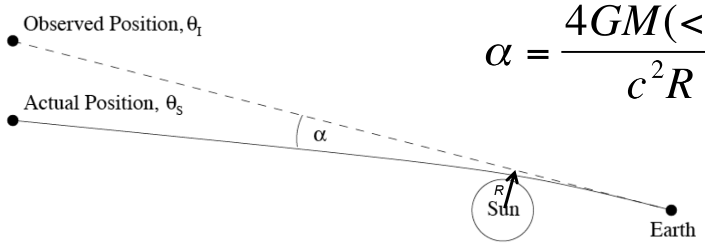
Overview

- What is gravitational lensing?
- What is lensing good for?
- The lens equation
- Gravitational magnification
- Galaxy clusters as gravitational telescopes

Deflection of Light by Mass

- Early speculation based on Newtonian physics (Newton 1704, Soldner 1804)
- Einstein (1915) predicted that deflection by a point mass is double the Newtonian prediction
- Eddington (1920) confirmed Einstein's prediction during a solar eclipse

$$\alpha = \frac{4GM(< R)}{c^2 R}$$



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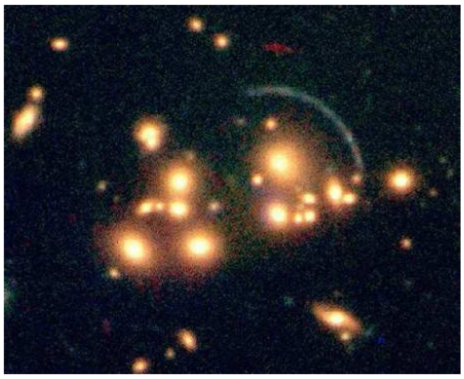
Early Extragalactic Observations

- If the density of the lens is high enough it is possible to form multiple images of source
- Multiple-imaging first observed by Walsh, Carswell, Weymann (1979)
- Multiple-imaging first observed in a cluster of galaxies by Soucail et al. (1987)



Cl2244-02
z_{arc}=2.24
Highest redshift galaxy known in 1987!

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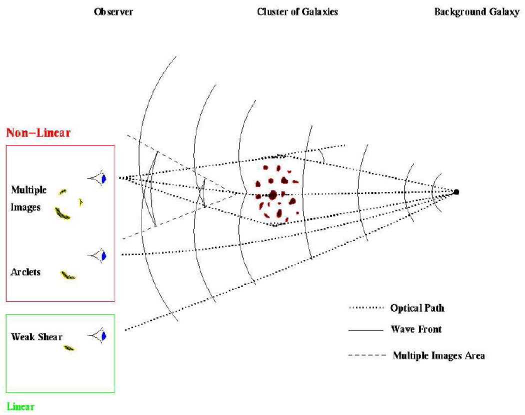
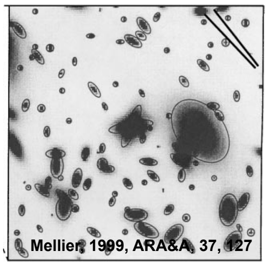
Non-linear and Linear Lensing





Mellier, 1999, ARA&A, 37, 127

What is lensing good for?

- Growth of structure probe of dark energy
  – Cluster mass function
  – Cosmic shear
- Testing alternative dark matter candidates
  – Cold dark matter
  – Warm dark matter
- Gravitational magnification of distant galaxies
- Testing gravity theory on large scales
- One of several tools for Exoplanet searches

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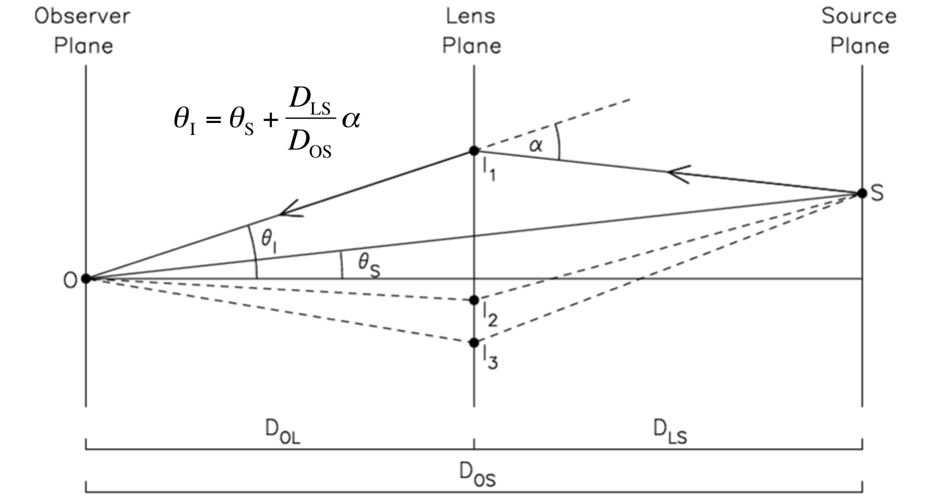

Working Assumptions

- Lens is small perturbation in isotropic+homogeneous universe
- Lens (R_{vir}~1Mpc) is thin compared to light paths (~1Gpc)
- Weak ($|\Phi| \ll c^2$), stationary ($v_{peculiar} \ll c$) gravitational field
- Small angle approximation applies (e.g. $\sin\theta_I = \tan\theta_I = \theta_I$)
- Geometrical optics applies ($\lambda \ll \theta_I D_{OL}$)

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Gravitational Magnification

lensing is an achromatic coordinate transformation

- Consider an infinitesimal source of surface brightness I_ν and solid angle $d\omega_S$
- The monochromatic flux of the source in the absence of lensing is: $S_{\nu,S} = I_\nu d\omega_S$
- If this source is viewed through a gravitational lens, the solid angle is modified, and the surface brightness is unchanged
- The monochromatic flux of the lensed image is: $S_{\nu,I} = I_\nu d\omega_I$
- Magnification is therefore: $|\mu| = \frac{S_{\nu,I}}{S_{\nu,S}} = \frac{d\omega_I}{d\omega_S}$

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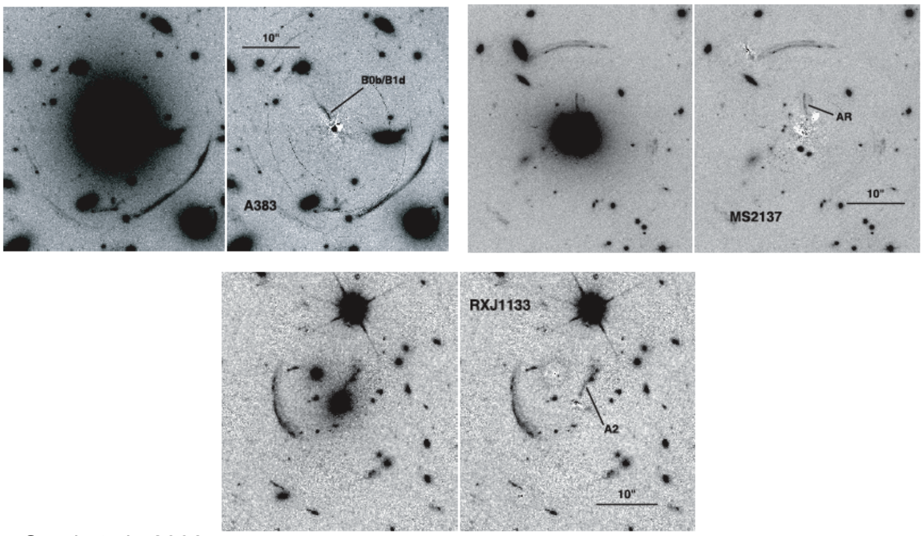
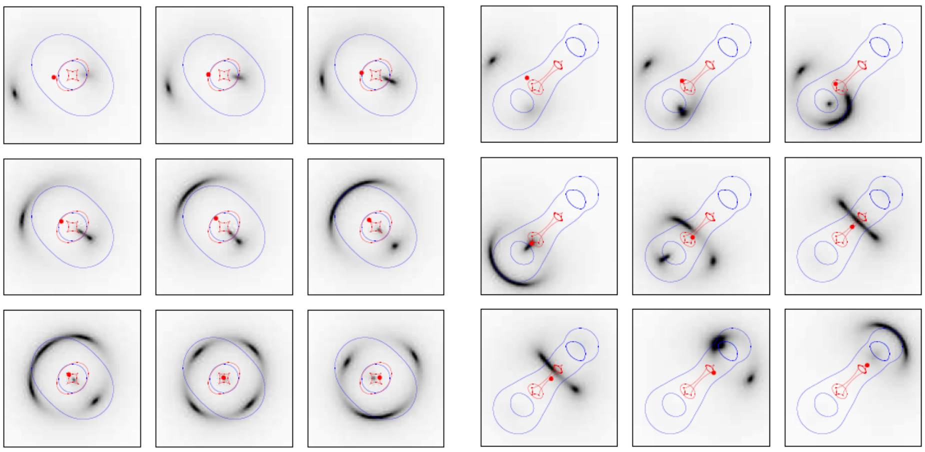
Example Gravitational Arcs

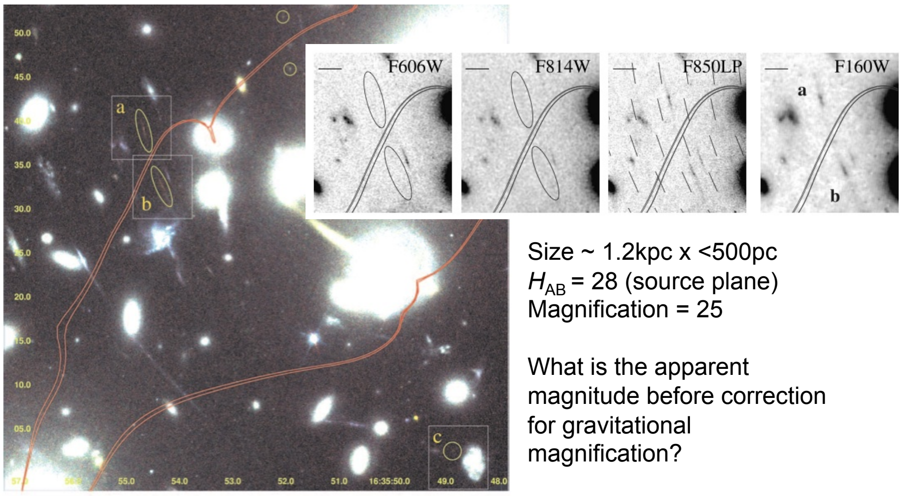


Sand et al., 2008

Critical Curves in Asymmetric Lenses



A Magnified Galaxy at z~7

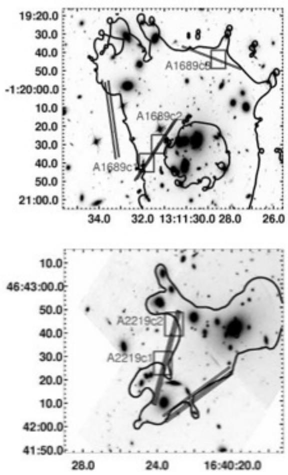


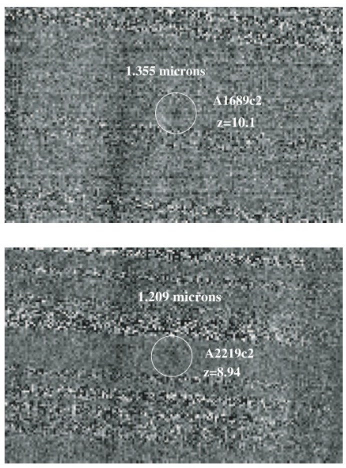
Size ~ 1.2kpc x <500pc
H_{AB} = 28 (source plane)
Magnification = 25

What is the apparent magnitude before correction for gravitational magnification?

Kneib et al., 2004

Critical line mapping





Stark et al., 2007

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Summary

- Gravitational lensing magnifies our view of distant galaxies:
  - Surface brightness is conserved
  - Solid angle is increased (for most images)
  - Angular resolution is improved
- Massive galaxy clusters can boost the light collecting power of man-made telescopes
- Lensing also a powerful tool for studying dark matter, dark energy, exo-planets