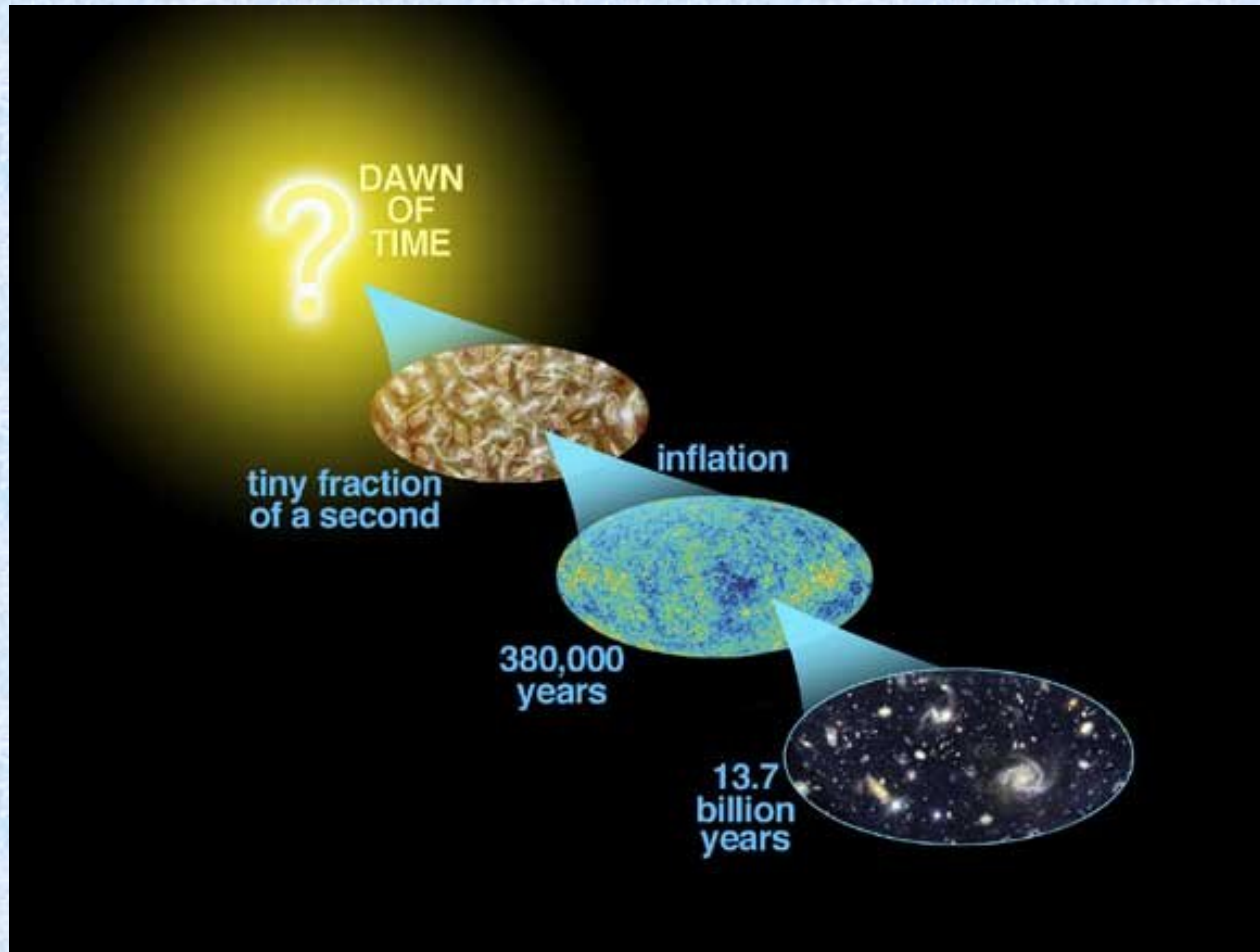


# Physics 133: Extragalactic Astronomy and Cosmology



Lecture 13; February 26 2014

## Previously

- Mass concentrations distort the images of objects in on the sky in a way similar to that of optical images.
- Strong and weak lensing provide very accurate mass maps of objects (in projection)
- Gravitational field “slows down” light.  
Strong lensing can be formulated in terms of Fermat’ s principle

# Outline:

- Cool things you can do with lensing (applications):
  - Cosmography (Hubble Constant)
- Useful link:
  - Saas Fee Lectures on gravitational lensing
  - <http://www.astro.uni-bonn.de/~peter/SaaSfee.html>
  - (Particularly the first one by Peter Schneider)

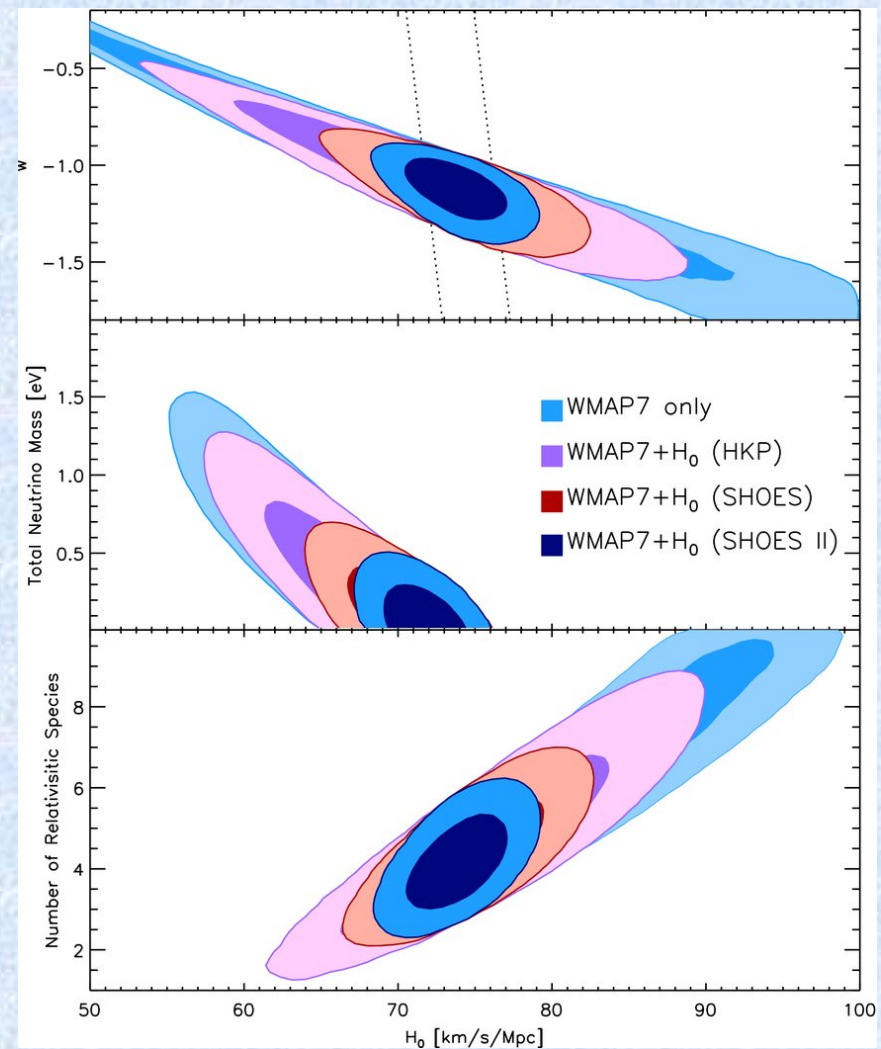
# **Cosmography with time-delays**

# Time delay distance in practice

$$\Delta t \propto D_{\Delta t}(z_s, z_d) \propto H_0^{-1} f(\Omega_m, w, \dots)$$

Steps:

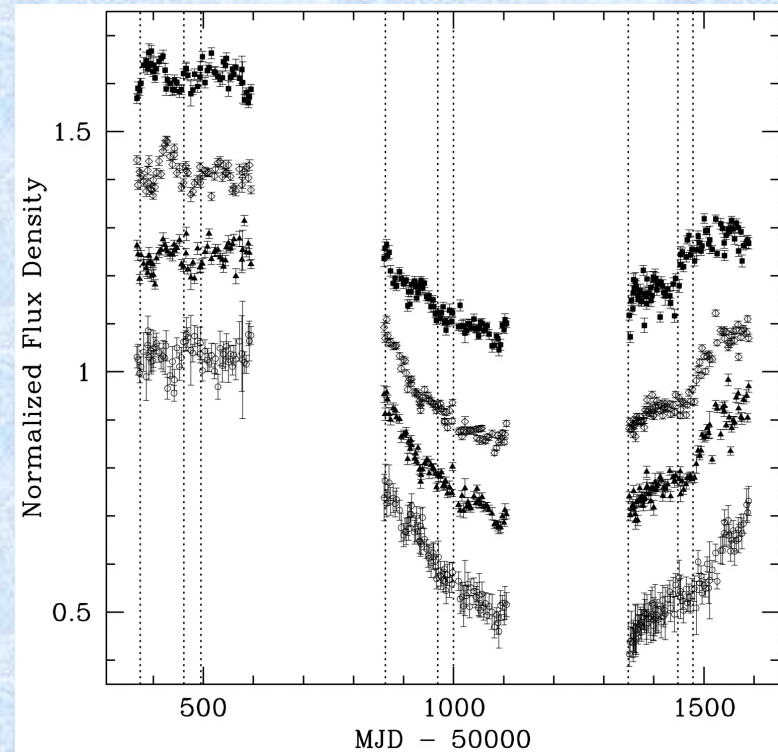
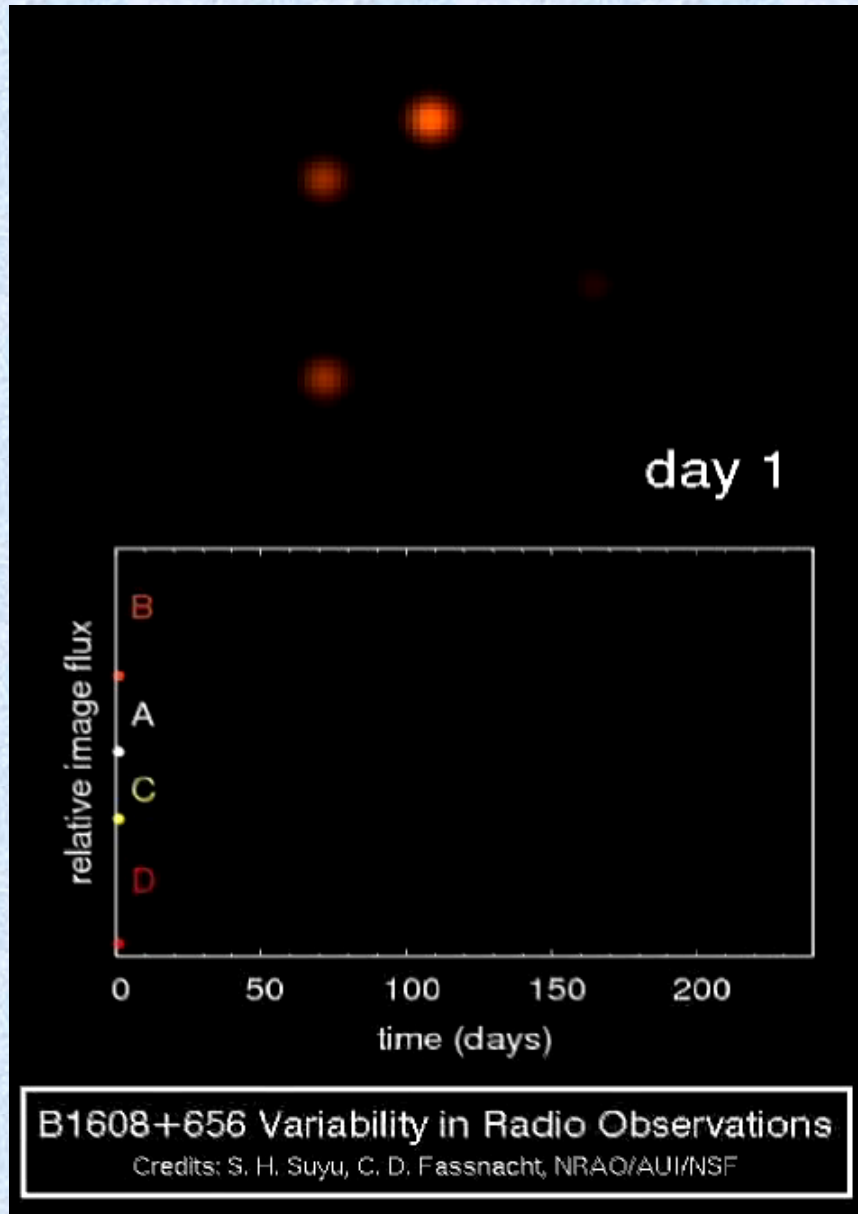
- Measure the time-delay between two images
- Measure and model the potential
- Infer the time-delay distance
- Convert it into cosmological parameters



# Cosmography with strong lenses: the 4 problems solved

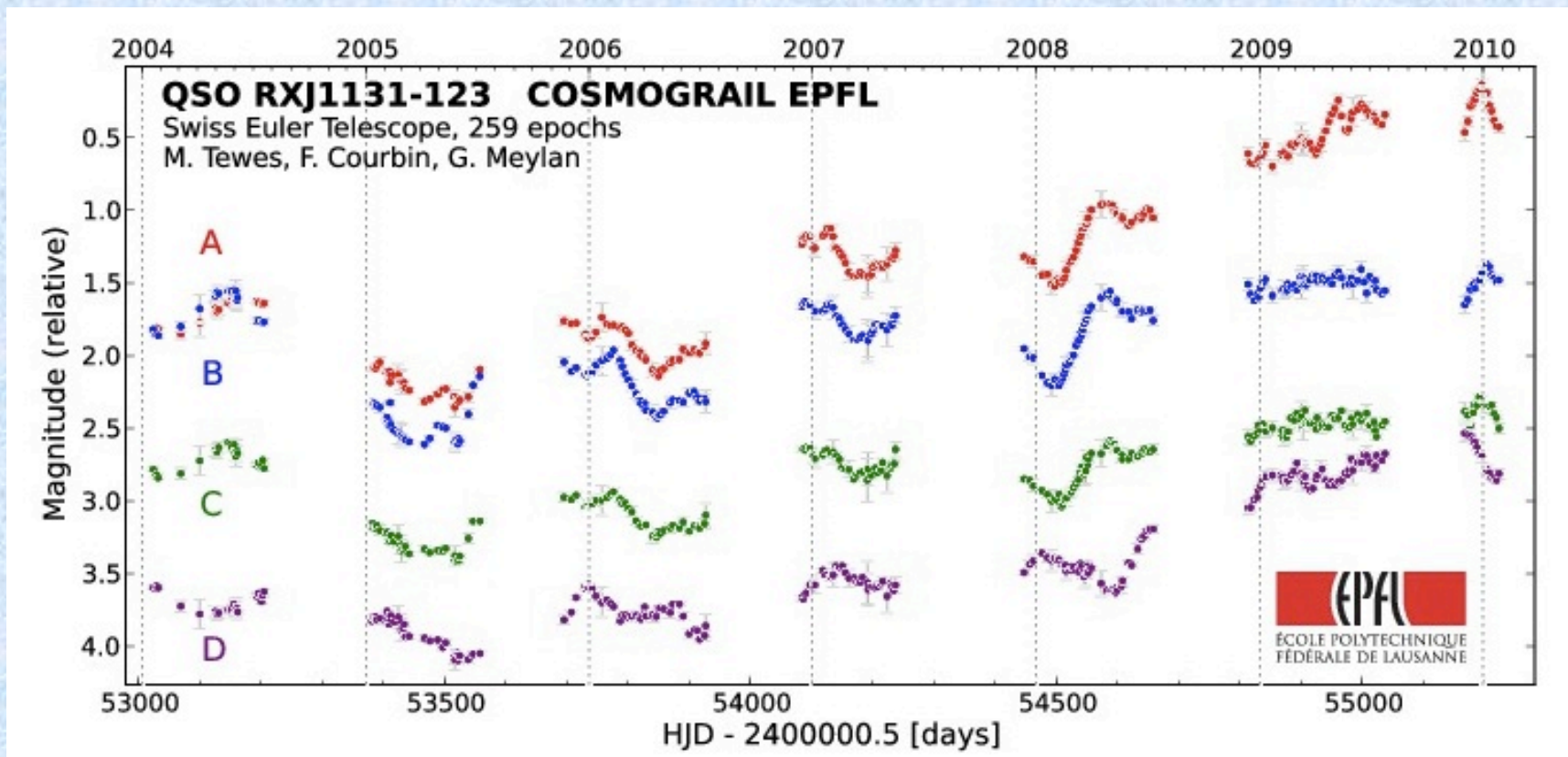
- Time delay – 2-3 %
  - Tenacious monitoring (e.g. Fassnacht et al. 2002); COSMOGRAIL (Meylan/Courbin)
- Astrometry – 10-20 mas
  - Hubble/VLA/(Adaptive Optics?)
- Lens potential (2-3%)
  - Stellar kinematics/Extended sources (Treu & Koopmans 2002; Suyu et al. 2009)
- Structure along the line of sight (2-3%) and the mass-sheet degeneracy,
  - Galaxy counts and numerical simulations (Suyu et al. 2009)
  - Stellar kinematics (Koopmans et al. 2003)

# Gravitational Lens Time Delays



# COSMOGRAIL: the COSmological MOnitoring of GRAVitational Lenses

- time delays of lensed quasars from optical monitoring
- expect to have delays with a few percent error for  $\sim 20$  lenses

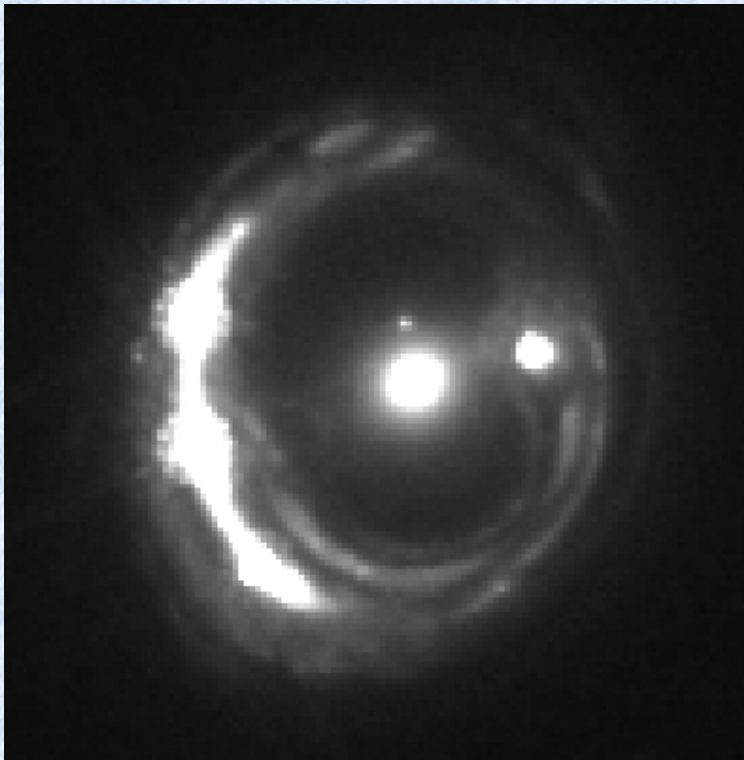


# The slope- $H_0$ degeneracy

- Uncertainty of the mass density profile of the main lens is the single largest source of uncertainty.
- If mass density profile is a power law  $\rho \sim r^{-\gamma'}$  then  $H_0(\gamma') \sim H_0(2)(\gamma' - 1)$  (Wucknitz 2002)
- Can be broken using lensing (Suyu et al. 2010) and stellar kinematic data (Treu & Koopmans 2002)
- We need to know the slope of the mass density profile to break this degeneracy!
- The degeneracy can be broken using multiple time delays, extended rings, and external information such as stellar kinematics

# Lens Model

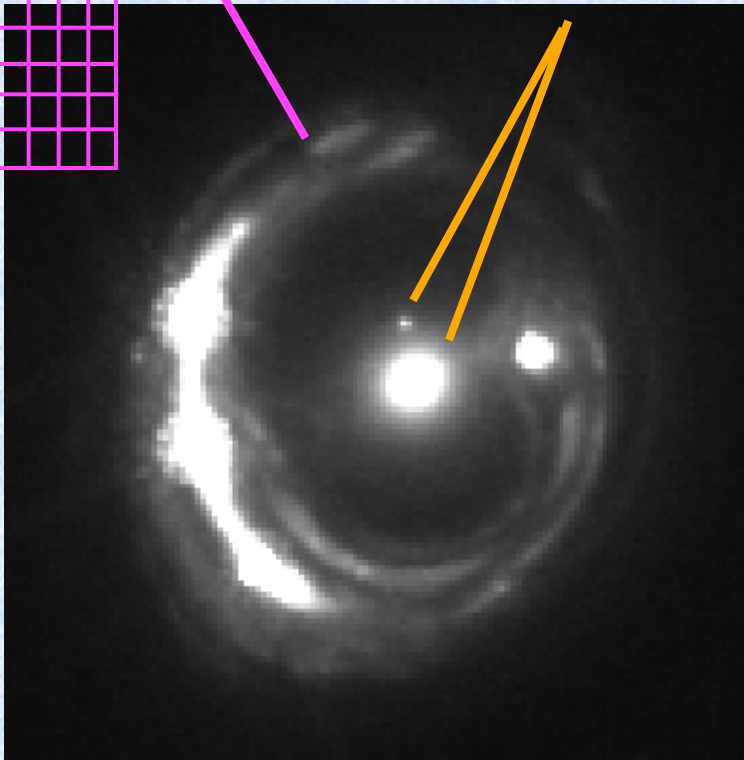
## Observed Image



# Lens Model

light distribution  
of extended source

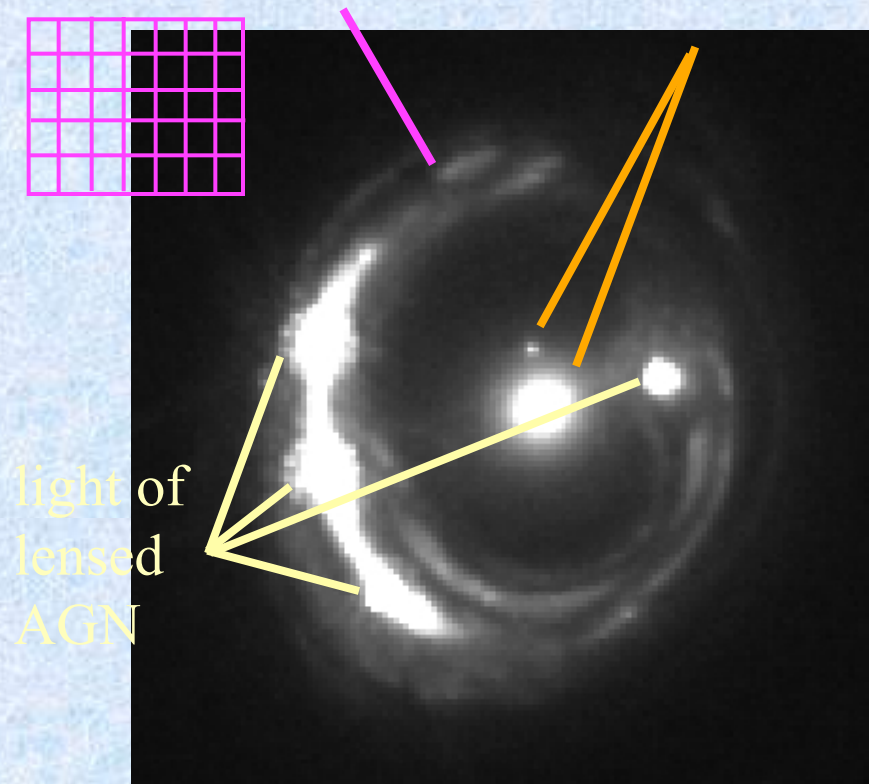
mass distribution  
of lens



# Lens Model

light distribution  
of extended source

mass distribution  
of lens



light of  
lensed  
AGN

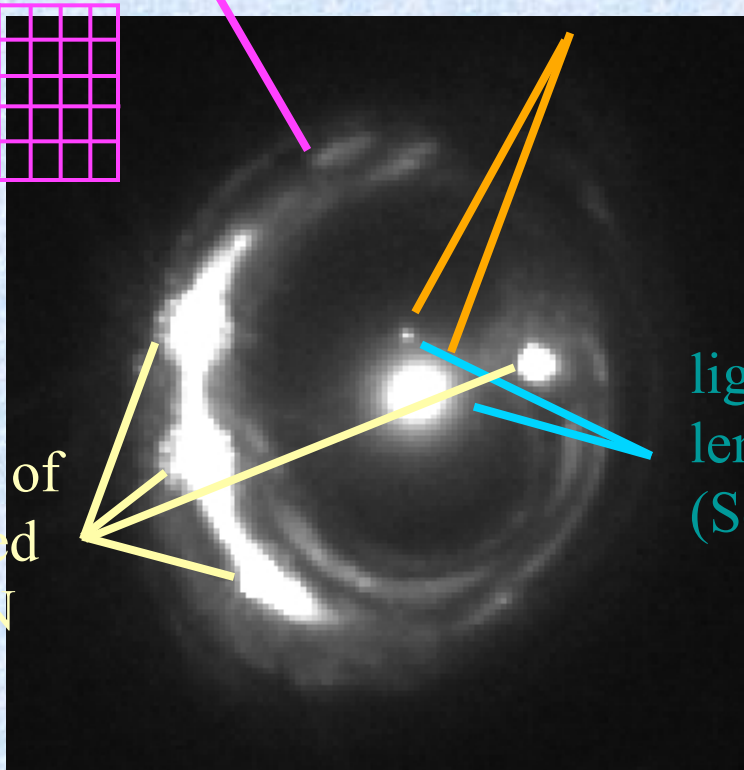
# Lens Model

light distribution  
of extended source

mass distribution  
of lens



light of  
lensed  
AGN



light of  
lens  
(Sersic)

# Lens Model

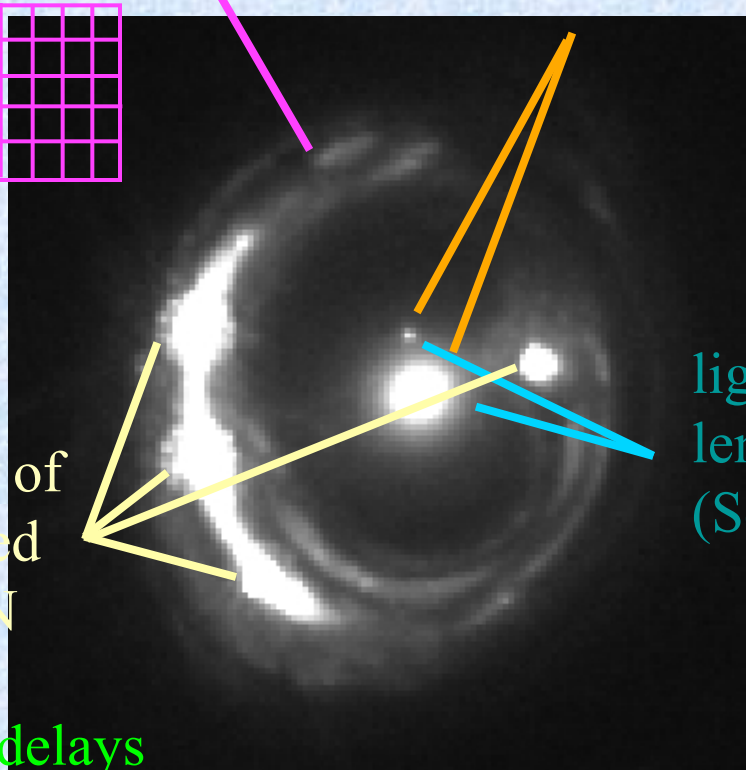
light distribution  
of extended source

mass distribution  
of lens



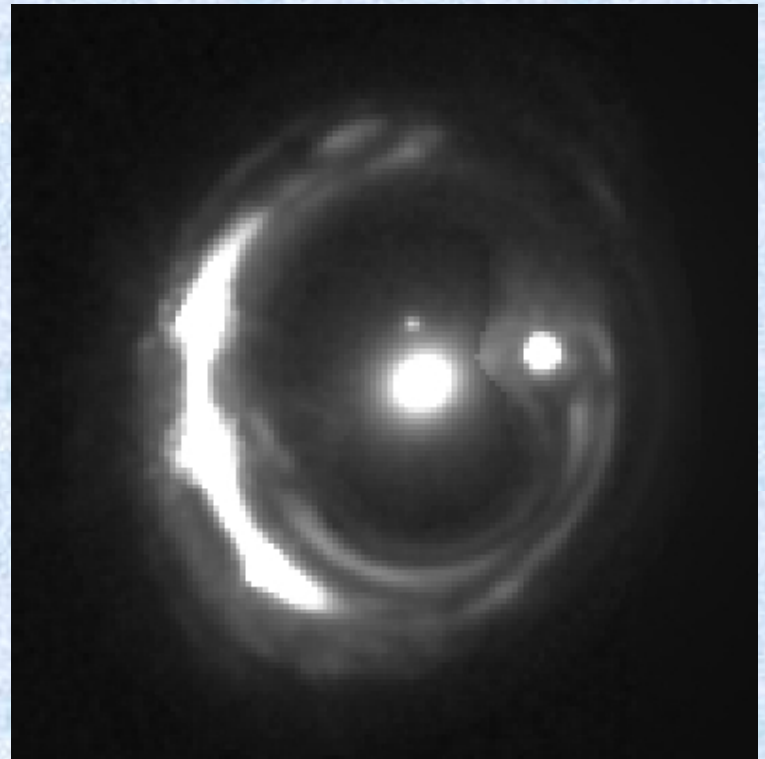
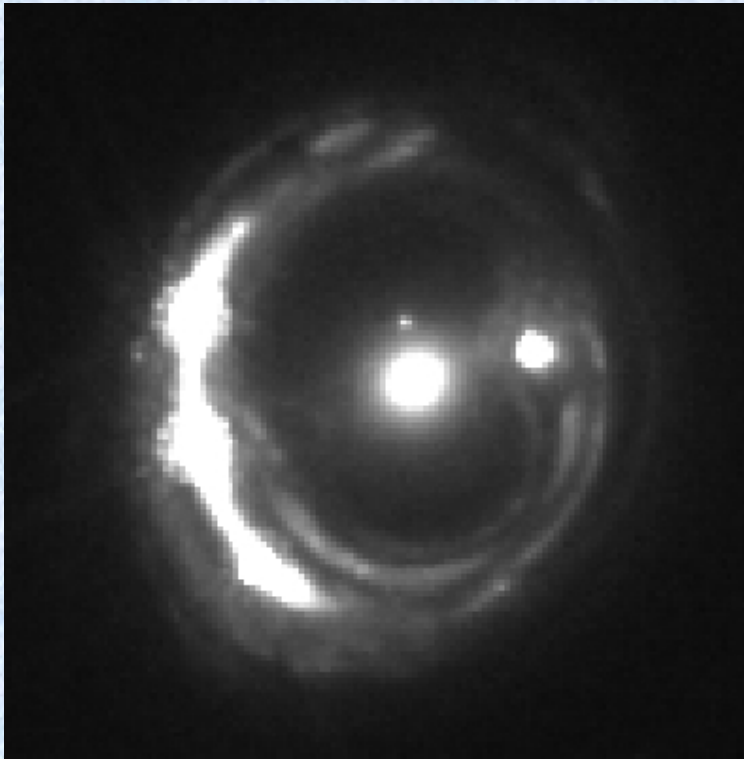
light of  
lensed  
AGN

+  
time delays



light of  
lens  
(Sersic)

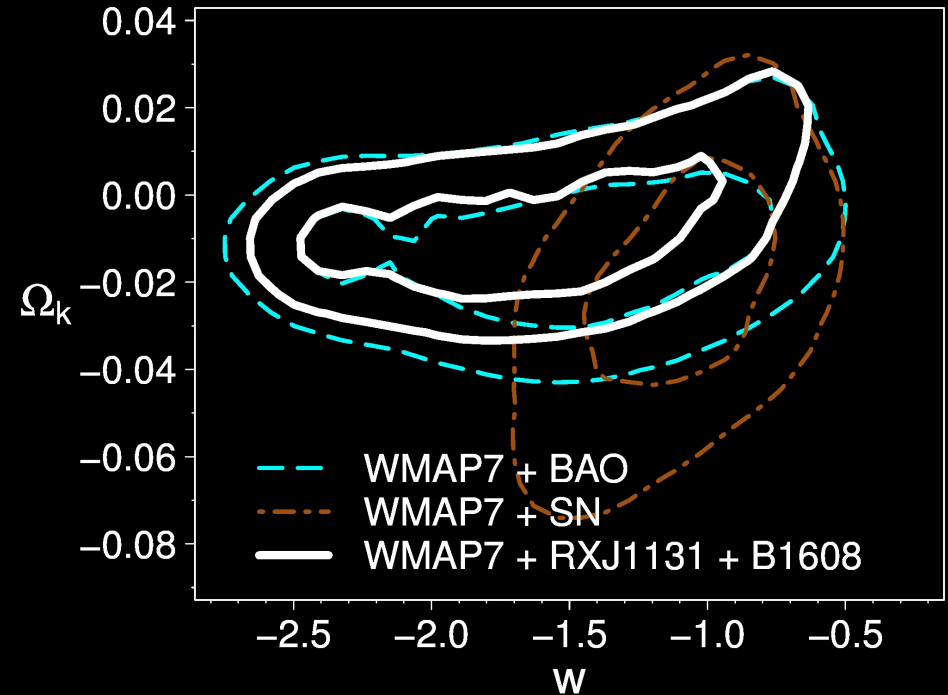
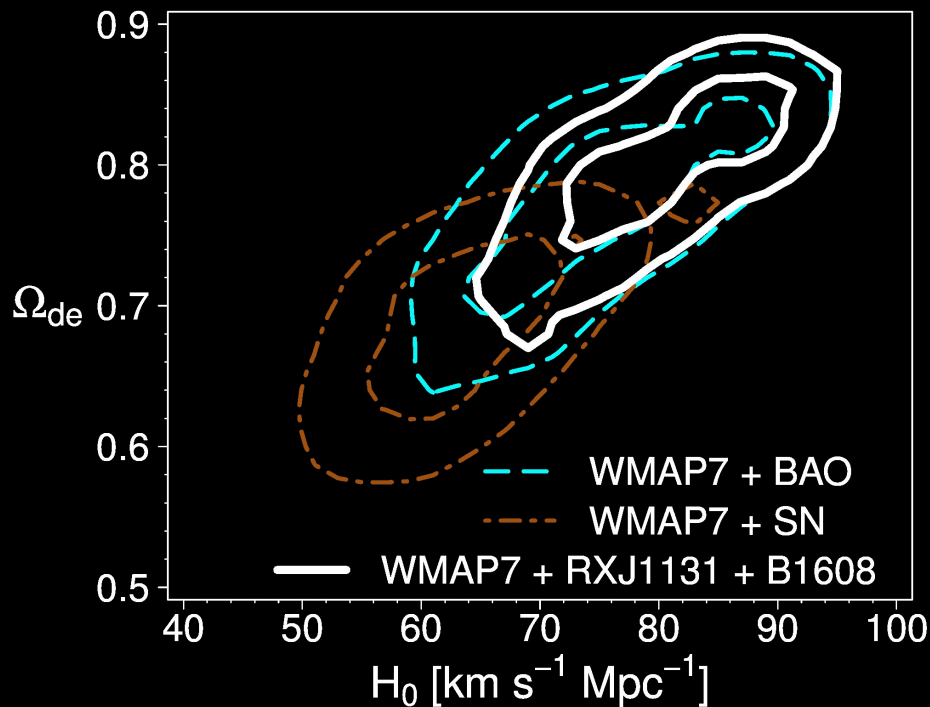
# Lens Model



# Time delays vs other probes

WMAP7 $\Lambda$ CDM prior

[Suyu et al. 2012]



- contour orientations are different: complementarity b/w probes
- contour sizes are similar: lensing is a competitive probe

# Summary. Applications of lensing

- Measure mass of galaxies, clusters planets.
- Test the cosmological model by measuring substructure
- Cosmography
- Test gravity
- Properties of dark matter

**The End**

See you on monday!