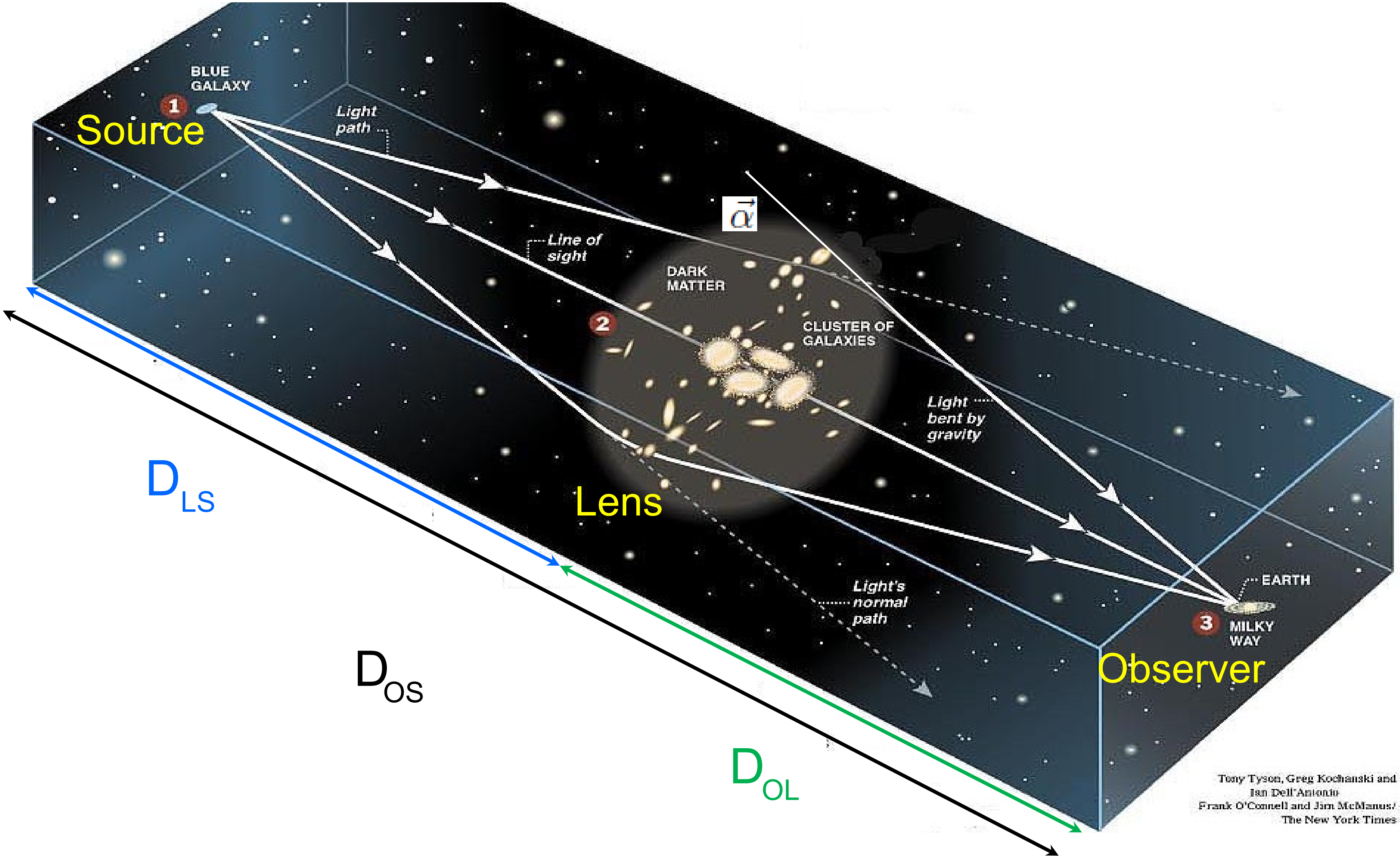
Gravitational Lensing

Y. Mellier - IAP

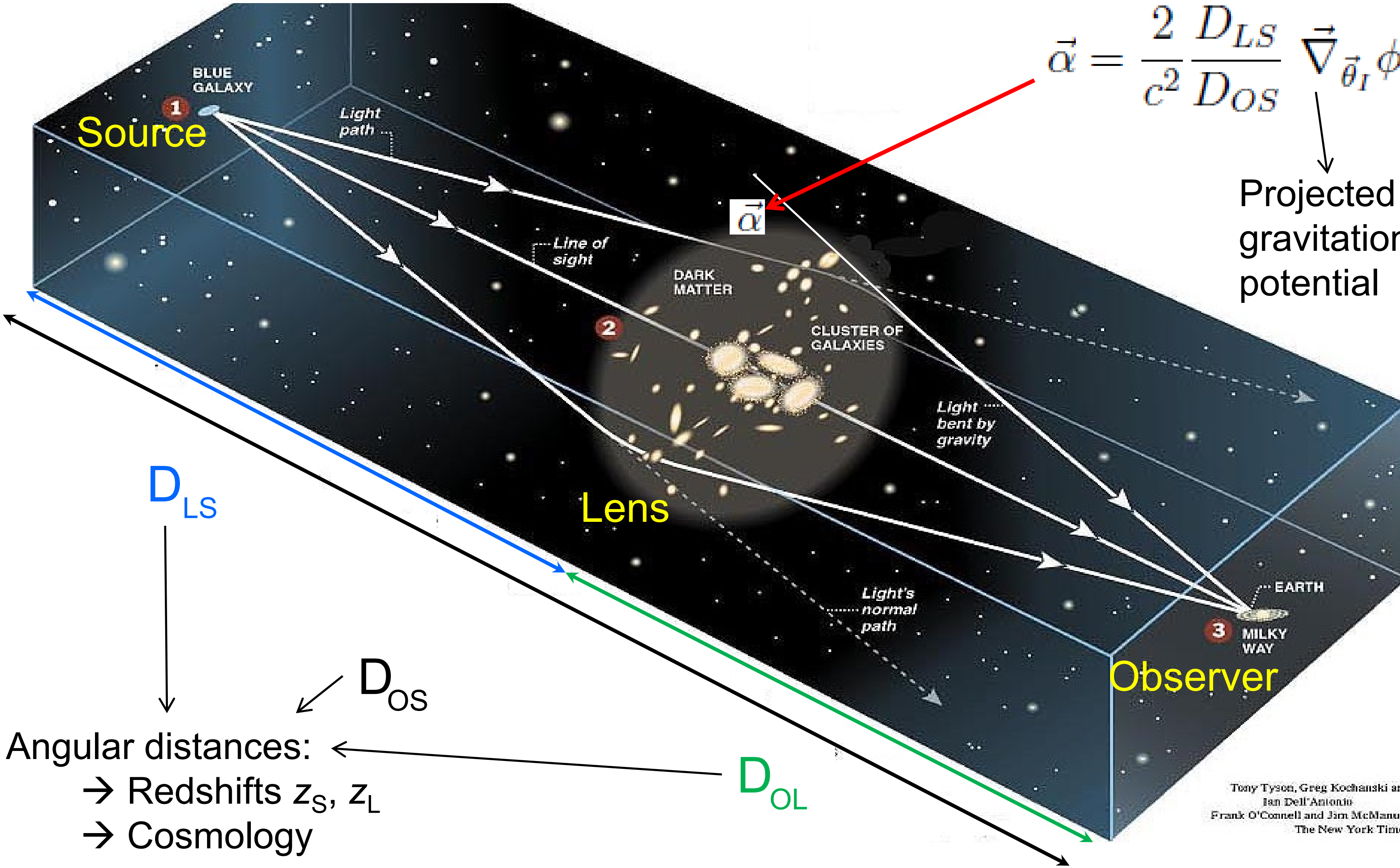
Gravitational deflection of light



Gravitational deflection of light

$$\vec{\alpha} = \frac{2}{c^2}\frac{D_{LS}}{D_{OS}}\vec{\nabla}_{\vec{\theta}_I}\phi_N^{2D}$$

Projected gravitational potential

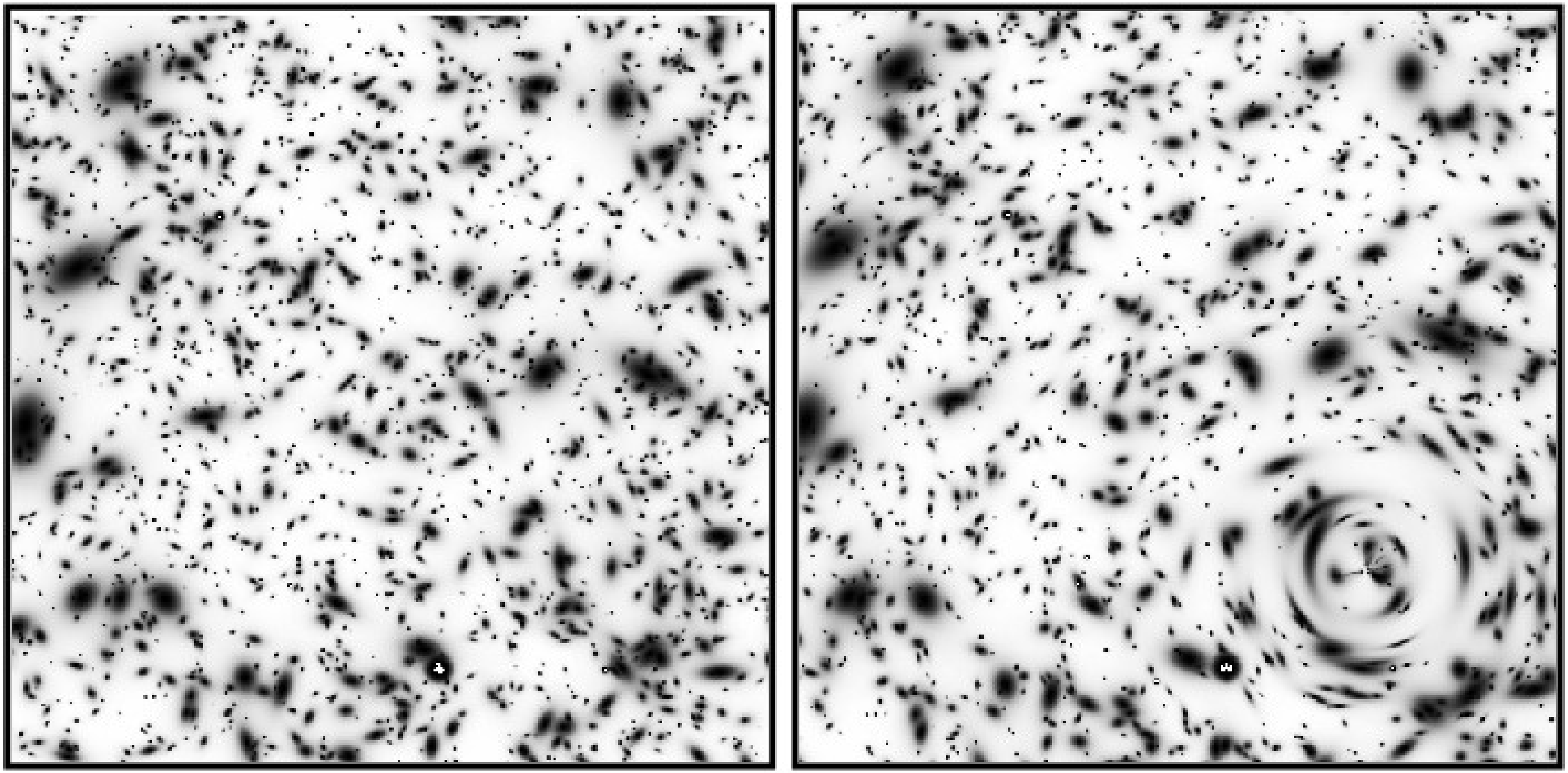


Angular distances:

→ Redshifts z_S, z_L

→ Cosmology

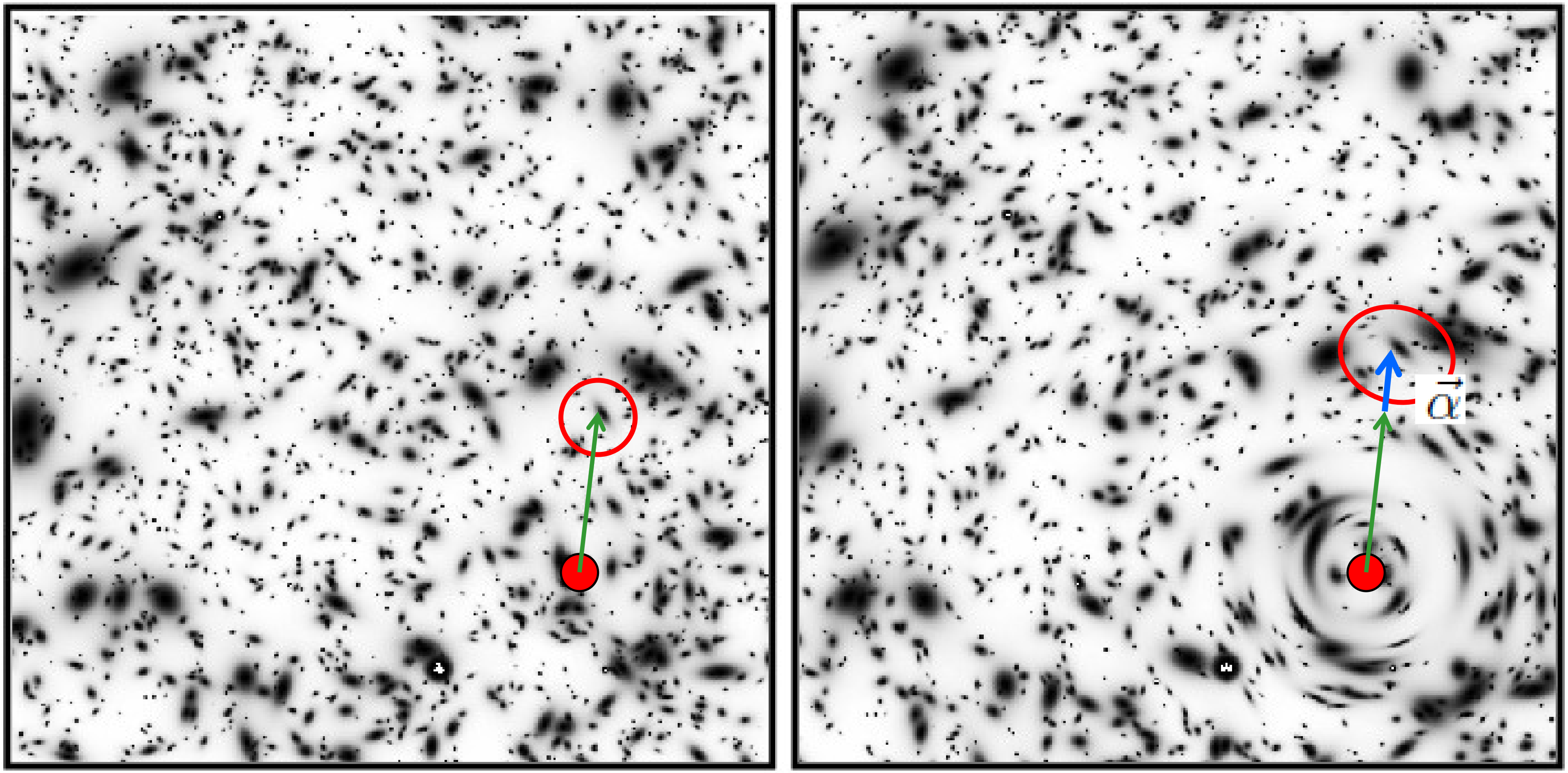
Gravitational lensing effects on lensed sources



Mellier 1999

Gravitational lensing effects on lensed sources

- Image multiplication
  → image parity, time delay, flux ratios
- Magnification (size)
- Image distortion (shear)



Mellier 1999

Astrophysics with gravitational lenses

- **Properties of Halos**:
  - Total mass, mass profile, mass function, internal structures, clustering and evolution with redshifts of:
    - → galaxies, groups, clusters of galaxies, superclusters, filaments.
  - Relation(s) between baryonic and dark matters in structure formation processes, biasing;
- **Cosmology**:
  - Expansion rate and growth rate of structure in the Universe
  - Test dark matter, dark energy, gravity models
  - Measure H_0 with time delays in multiply imaged sources
- **Gravitational telescope -High- z universe**: magnified sources

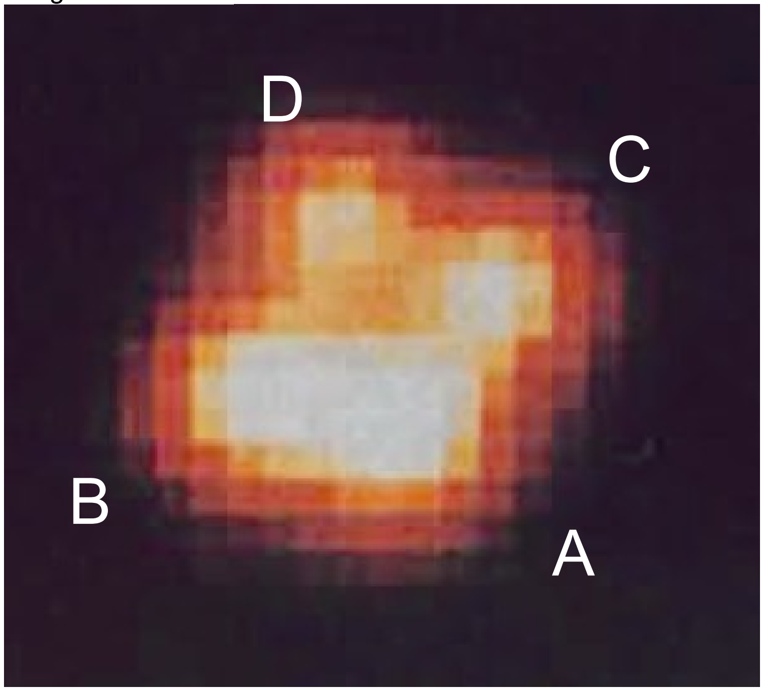
- **Exoplanets** with micro-lensing

50 yrs of gravitational lensing@ESO: some highlights

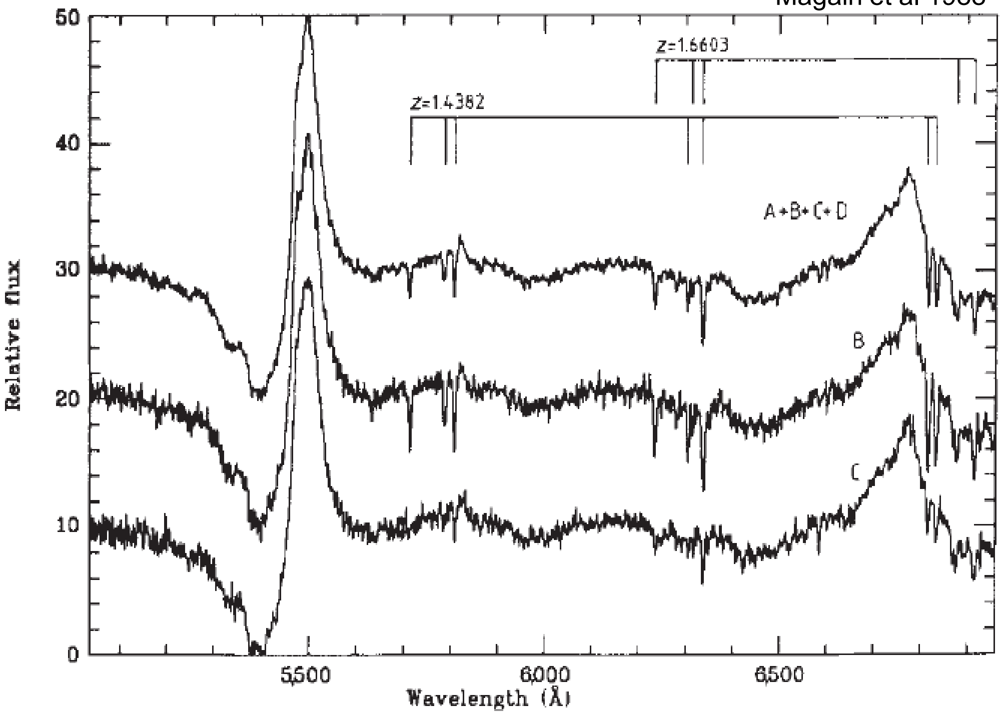
ESO Key Programmes: finding « golden » lenses:

Multiply imaged QSOs for time delays/Ho/mass models of galaxy-scale lenses

Magain et al 1988



Magain et al 1988

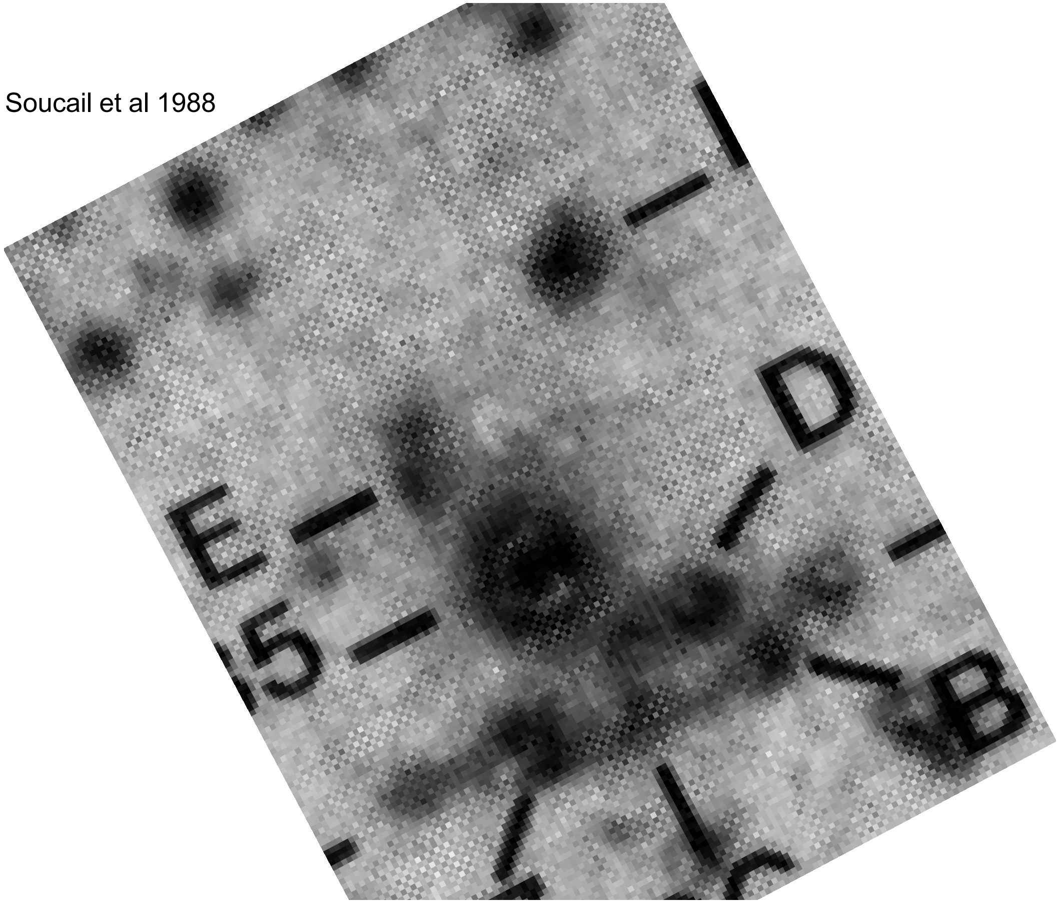


1988 ESO 2.2 m: discovery of the quadrupled imaged quasar ESO GL2 « *Cloverleaf* »=H1413+117

1988 ESO 3.60 m/EFOSC: confirmation that spectra are identical → same QSO with 4 lensed images.

Giant gravitational arcs

Soucail et al 1988



6 Sept. 1985 - A370 arc discovery
Very 1st image at CFHT Cass. focus
RCA 512x320 CCD 0.8’’ /pixel,
10mn R-band , seeing 0.8’’

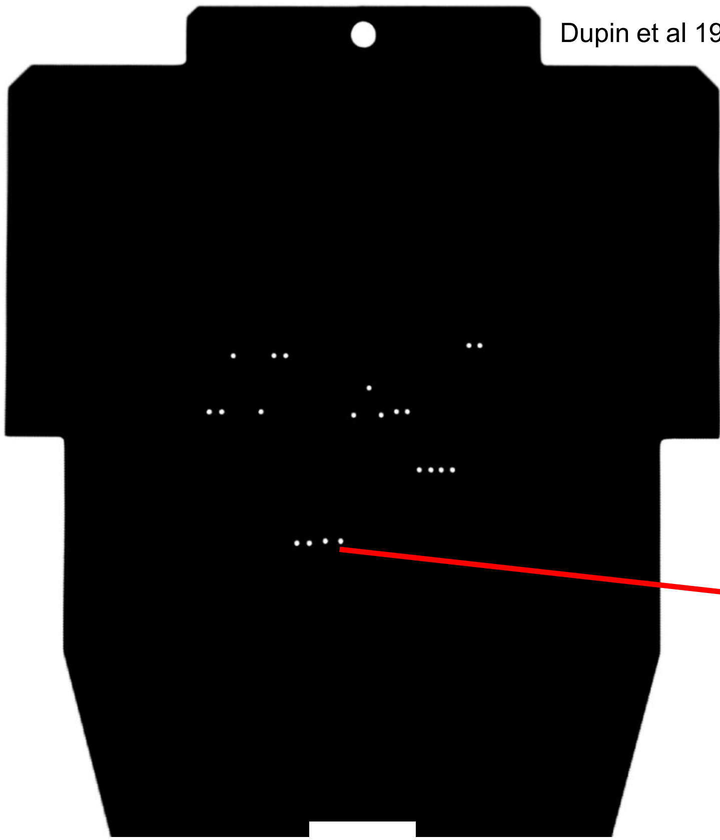
Abell 370, HST/ACS ; credit NASA/ESA

- Space telescope best for imaging
- Ground based facilities

→
  - NIR imaging follow up (AO)
  - VIS/NIR spectroscopy follow up (AO)
  - Statistics: wide field

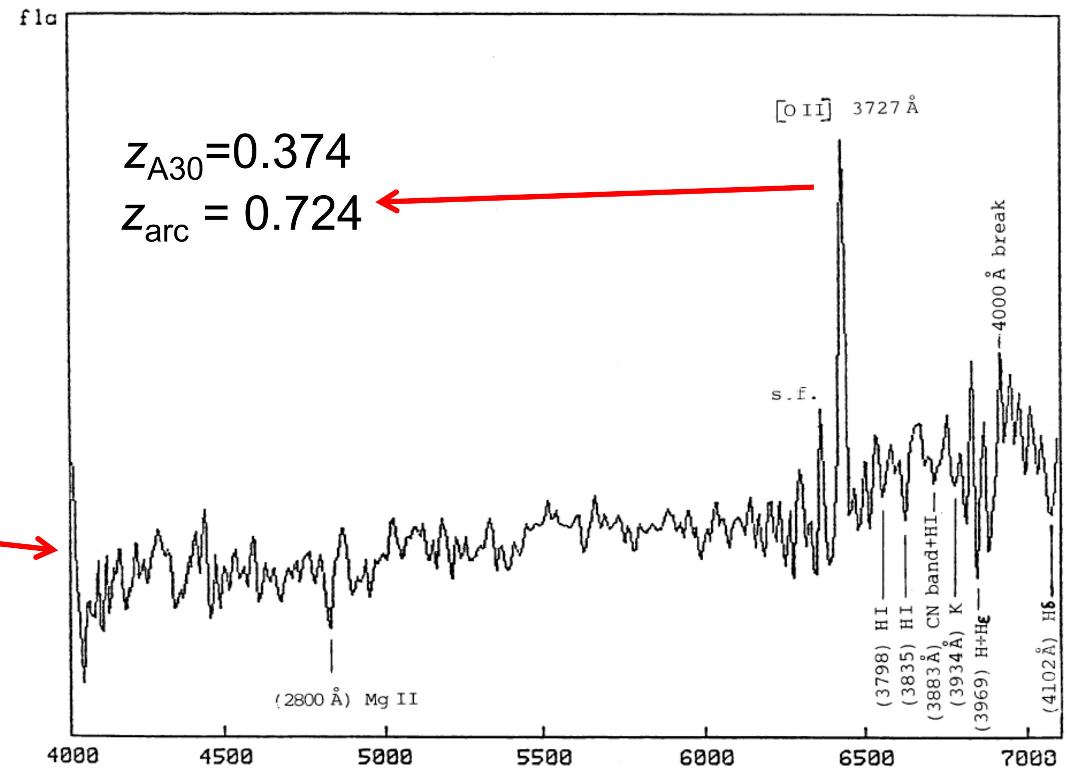
The birth of gravitational distortion astrophysics

ESO 1987: first demonstration of the gravitational lensing nature of giant arcs



Dupin et al 1988

Soucail et al 1988

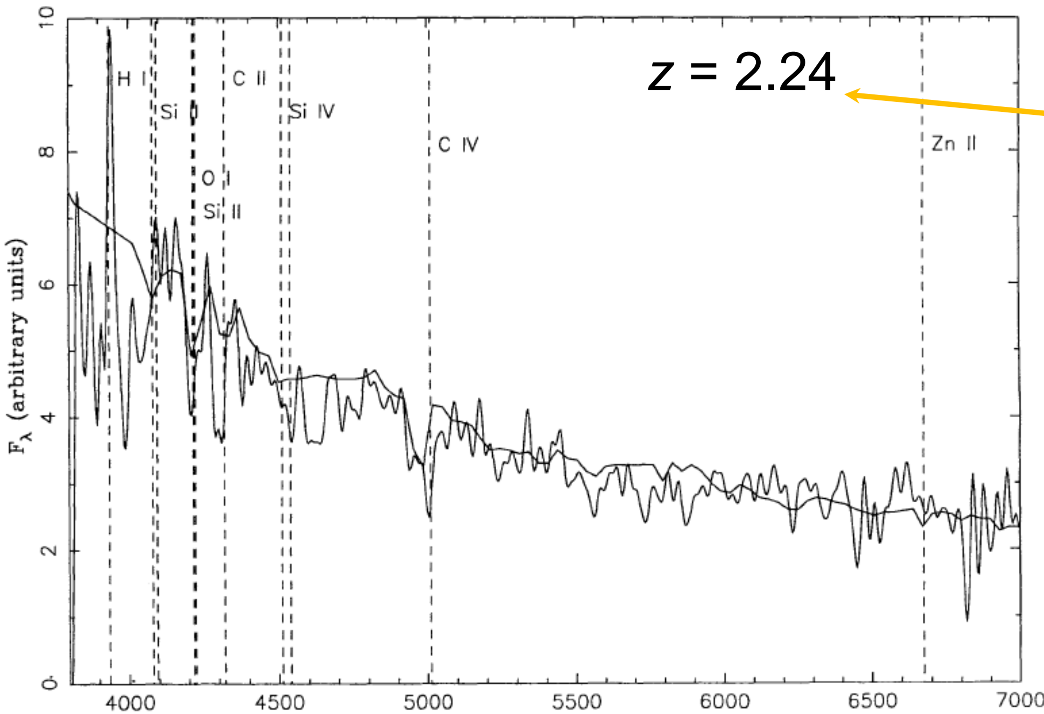


ESO **1987** A370:

spectrum of the giant arc with the MOS PUMA2-v1.0 punching machine on 3.60m/EFOCS1

ESO/EFOSC1 pioneered deep spectroscopic observations of very high-z lensed galaxies

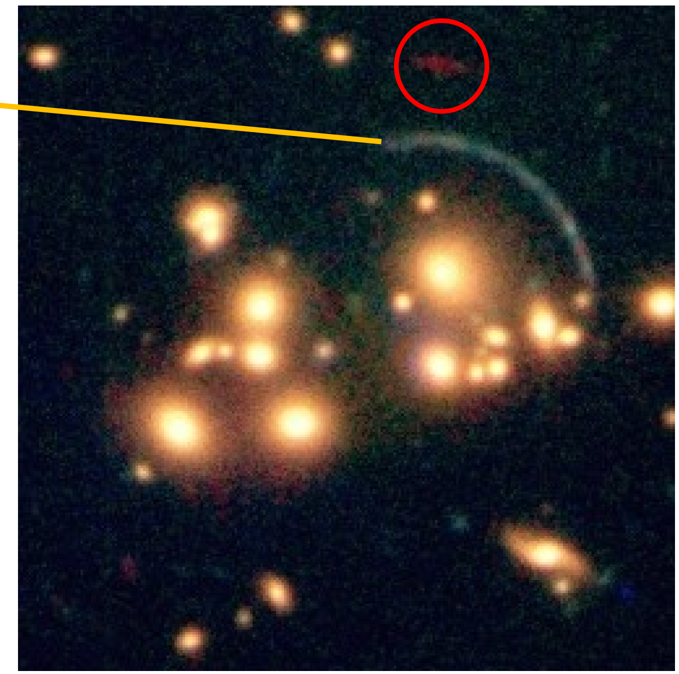
Mellier et al 1991



1987-1988: ESO 3.60m/EFOSC1 : redshfit of the giant arc Cl2244-02

ESO PR 1998

z > 3.5

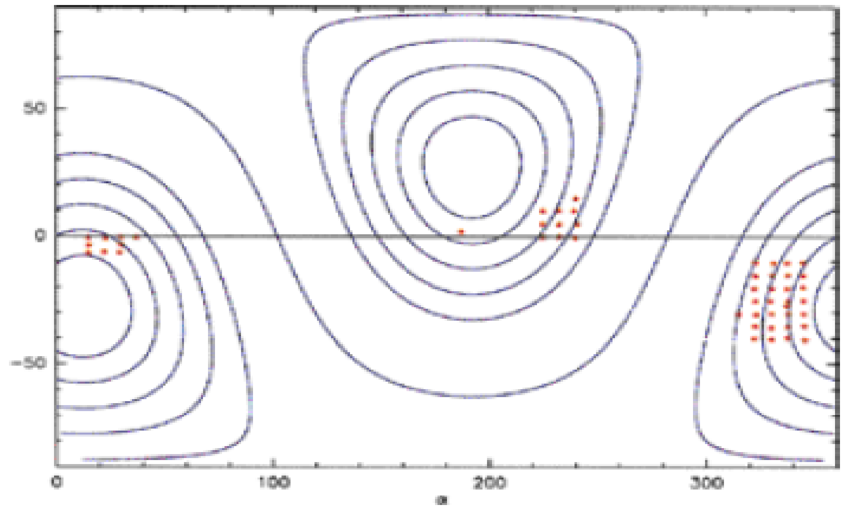


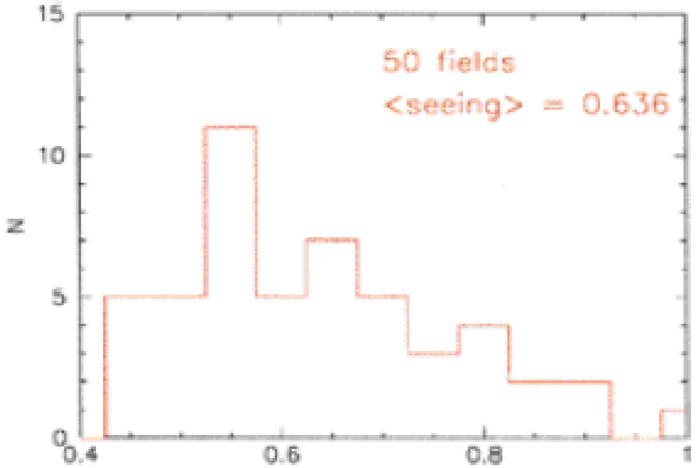
ESO 1998: Giant arc in Cl2244-02: UT1/ISAAC in Ks + (V,R) with VLT test camera

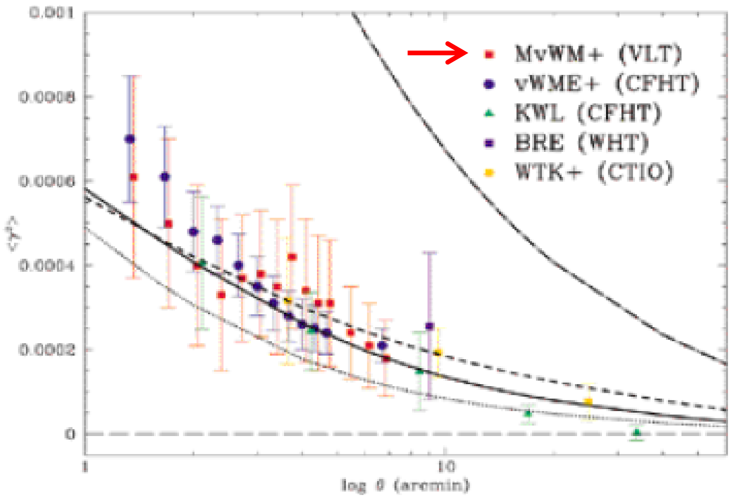
Cosmic shear@ESO → service mode with the VLT

for imaging with critical IQ requirements

Maoli et al (2000, 2001)







- VLT/FORS Large Programme on Cosmic Shear
- A different approach : many small independent « *empty* » fields with FORS randomly selected over the whole sky
- A use case for service mode: superb seeing sample

ESO spectroscopy: whatever the lens and lensing configurations

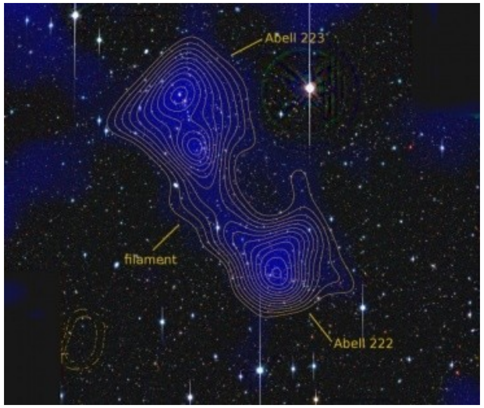
HST/ACS credit NASA/ESA

Galaxy halos

HST/ACS; credit NASA/ESA

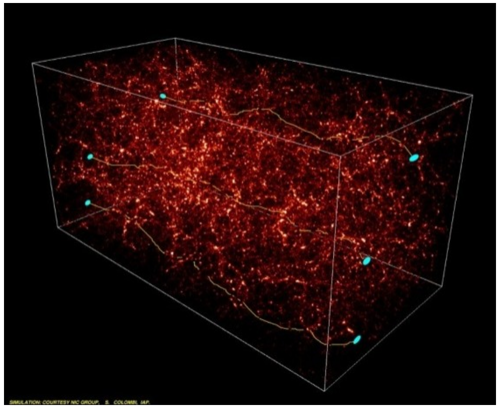
Clusters of galaxies

Dietrich et al 2012



Filaments between clusters

Colombi/Mellier



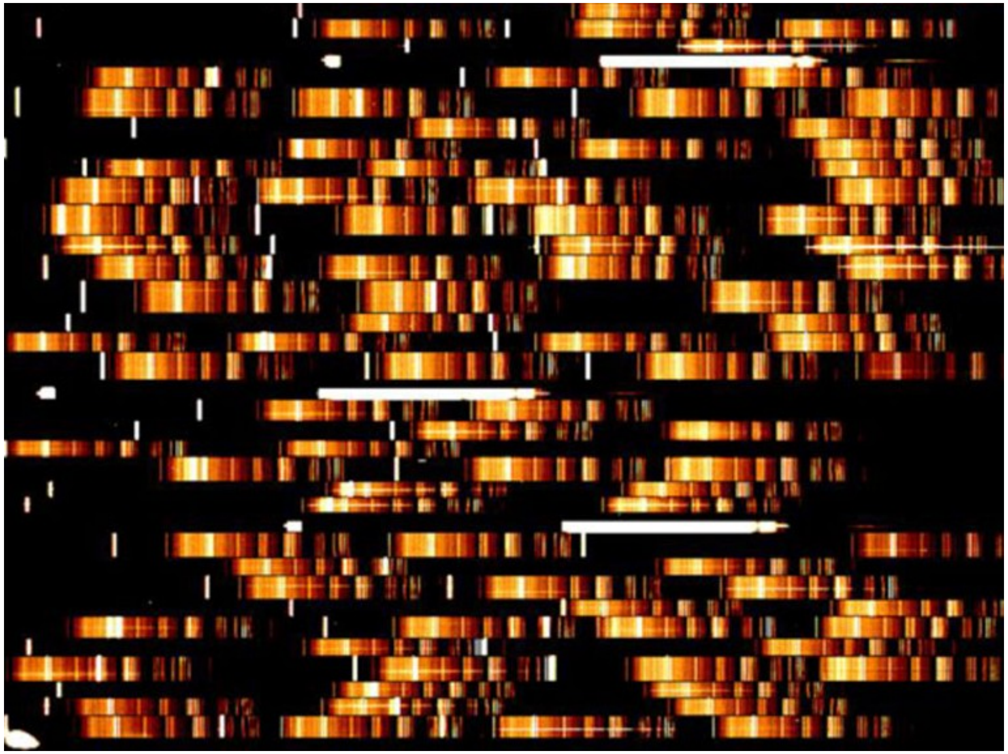
Cosmic shear

$$\vec{\alpha} = \frac{2}{c^2}\frac{D_{LS}}{D_{OS}}\vec{\nabla}_{\vec{\theta}_I}\phi_N^{2D}$$

Redshifts of sources and lenses are needed

ESO spectroscopic surveys for weak lensing surveys

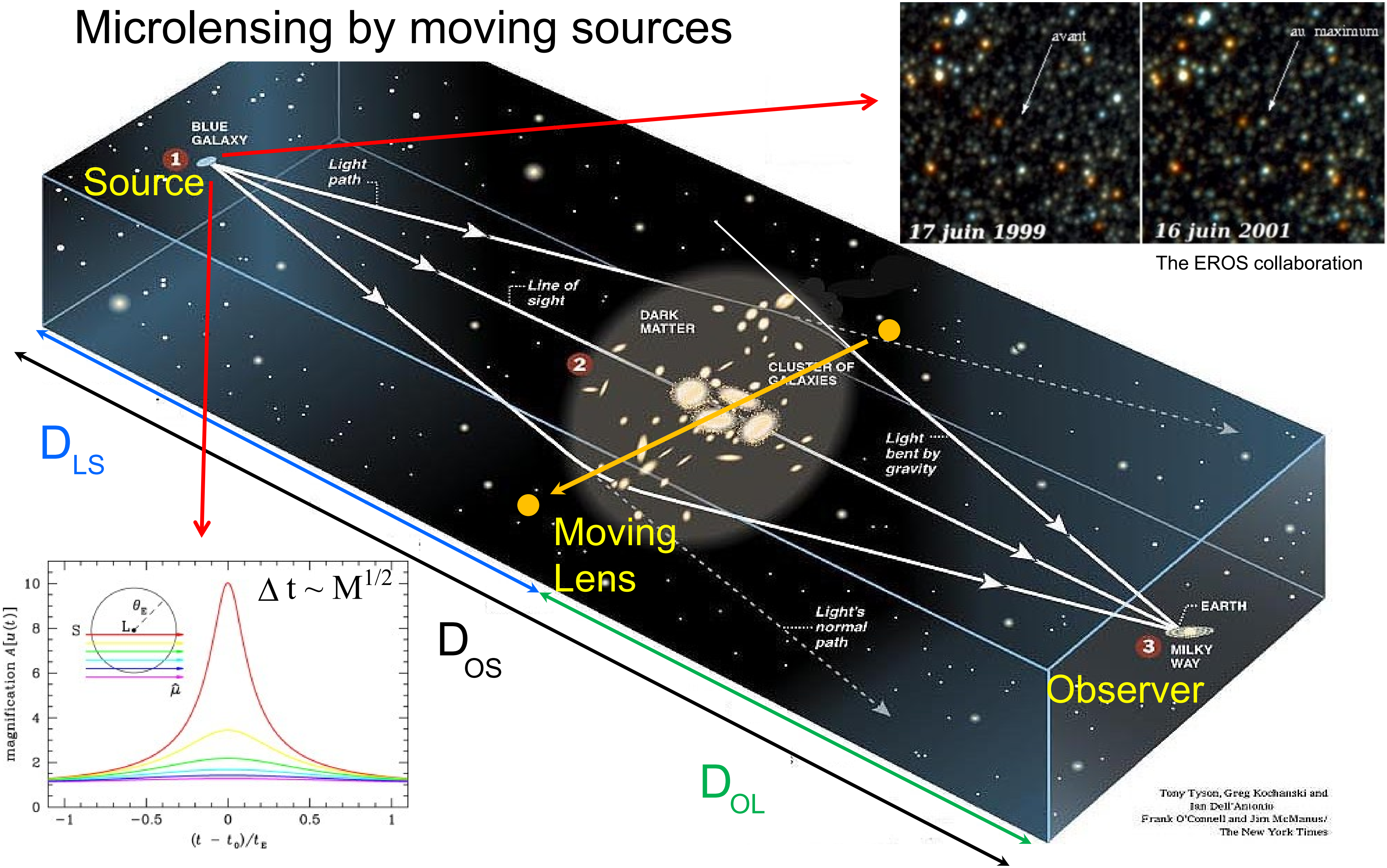
ESO PR, Le Fèvre et al 2006



2000-2012 VLT/VMOS: weak lensing analysis of CFHTLS and COSMOS fields impossible without these data.

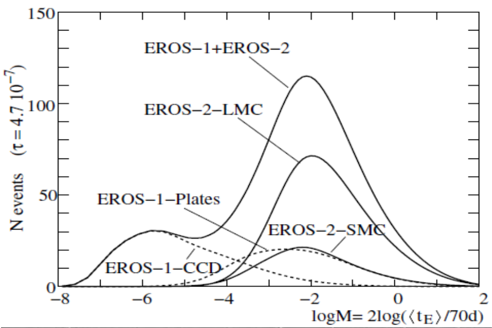
- **CFHTLS : VVDS** with VMOS,
  - 32,000 redshifts to I=22.5 over ~15 deg^2, (Garilli et al 2008)
  - 15,000 to I=24 over ~1 deg^2 (Le Fèvre et al 2005)
  - 1000 redshifts 23<I<24.75 over 0.15 deg^2 (Le Fèvre et al 2012)
- **CFHTLS : VIPERS** with VMOS: ~100,000 redshifts to I=22.5 over 25 deg^2 (Guzzo et al 2012)
- **COSMOS : z-Cosmos** with VMOS:
  - ~ 20,000 redshifts to I=22.5 over 1.7 deg^2 (Lilly et al 2009)
  - ~10,000 redshiifts B<25.25 color selected, over 0.9 deg^2

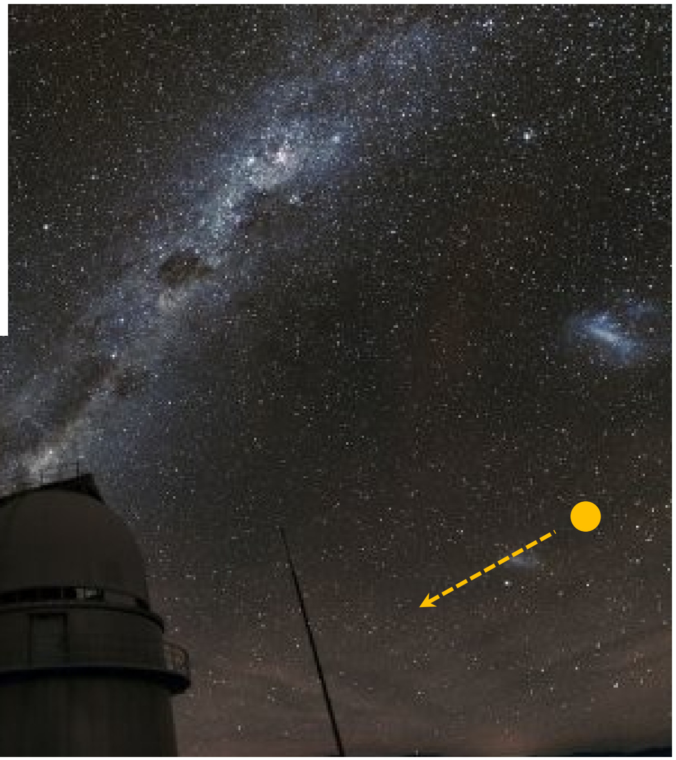
Microlensing by moving sources

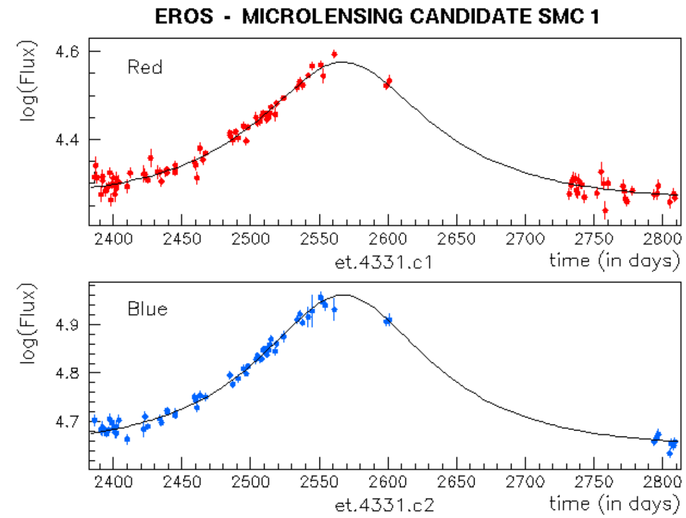


The EROS collaboration

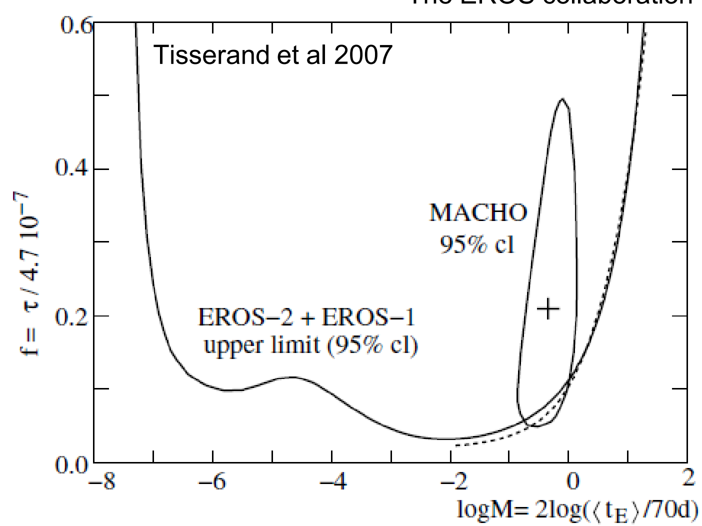
1990-1997: ESO as support to a major micro-lensing project: La Silla facilities to the EROS collaboration







The EROS collaboration



- 380 photographic B,R plates from the 1.0m ESO Schmidt telescope
- Installation of the Marly telescope at La Silla

The future of gravitational lensing@ESO

The future for gravitational lensing@ESO in the context of JWST, Euclid: resolution, sensitivity, multiplex

The future for gravitational lensing@ESO in the context of JWST, Euclid: resolution, sensitivity, multiplex

- **Very high redshift Universe**: faint/ultra-faint sources, high spatial resolution, mid-spectral resolution (AO+IFU+NIR – SINFONI, MUSE, ALMA, E-ELT)
- **Sub-halos** : modelling lenses/ sources (VLT, E-ELT)
- **Redshift of faint/ultra-faint arcs/rings** and lenses: scale total mass (VLT, ELT): magnified and also ***demagnified*** images

- **Wide field for cosmic shear**: wide field faint spectroscopic surveys → VMOS/PILMOS, 4 MOST , MOONS

- **Time domain**: mu-lens, exoplanets, times delays: Danish VST, ESO 4-m class telescopes (?)

The future for gravitational lensing@ESO in the context of JWST, Euclid: resolution, sensitivity, multiplex

Depend on lens models

- **Very high redshift Universe**: faint/ultra-faint sources, high spatial resolution, mid-spectral resolution (AO+IFU+NIR – SINFONI, MUSE, ALMA, E-ELT)
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Magnification: the high-z universe with gravitational telescopes

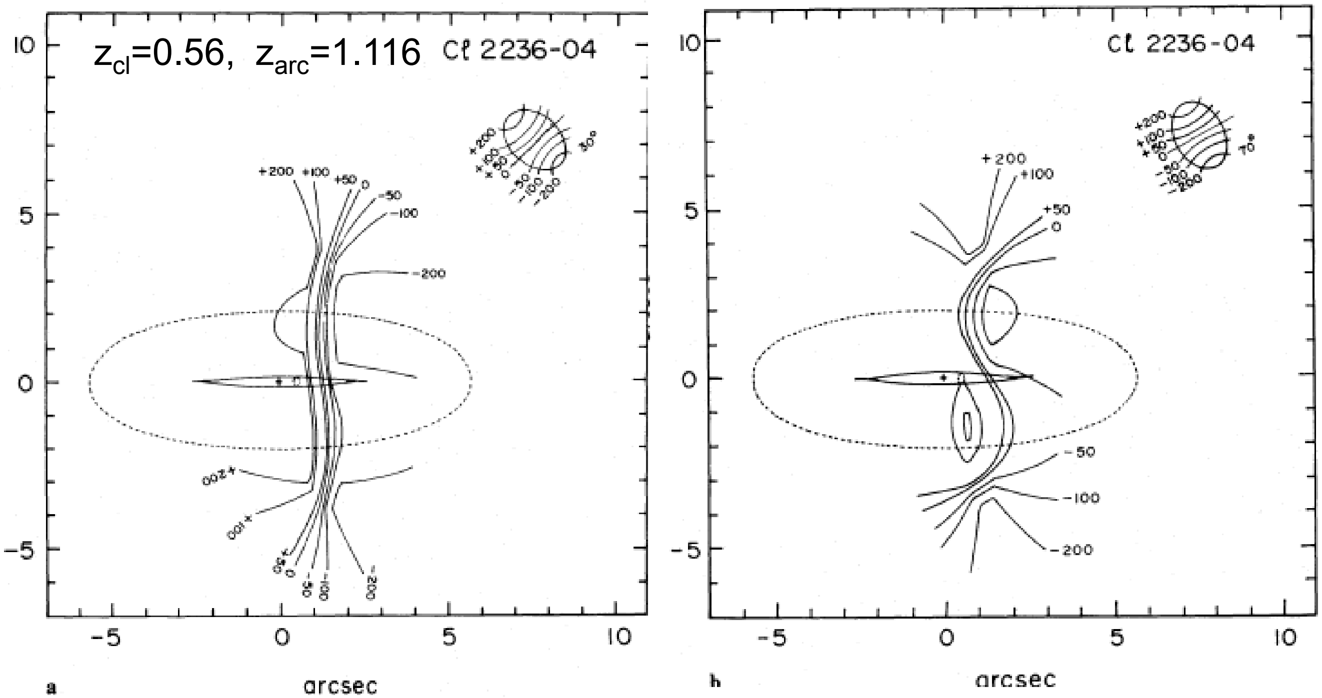
Abell 370, HST/ACS ; credit NASA/ESA

A spiral structure resolved at z=0.724

Stretched rotation curved resolved at z=0.724

Constraining mass model of lenses and model of lensed sources with IFU observations of arcs

Narasimha & Chitre 1993



Gravitational arc in the cluster Cl2236-04:

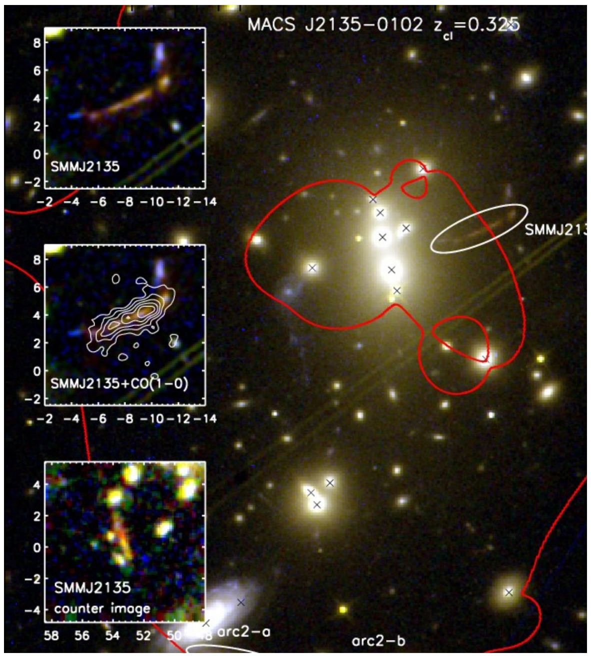
- Discovery: Melnick et al (1993) with ESO 3.60m /EFOSC1.
- Redshift measured by Kneib et al (1994) with ESO/NTT/EMMI

Narasimha and Chitre in 1993:
Use together high resolution imaging (HST) and observation of magnified rotation curve of the source to constrain models of lens/source.

Gravitational magnification + ALMA

understanding the dynamics and halos properties of high-z galaxies

Swinbank et al 2011

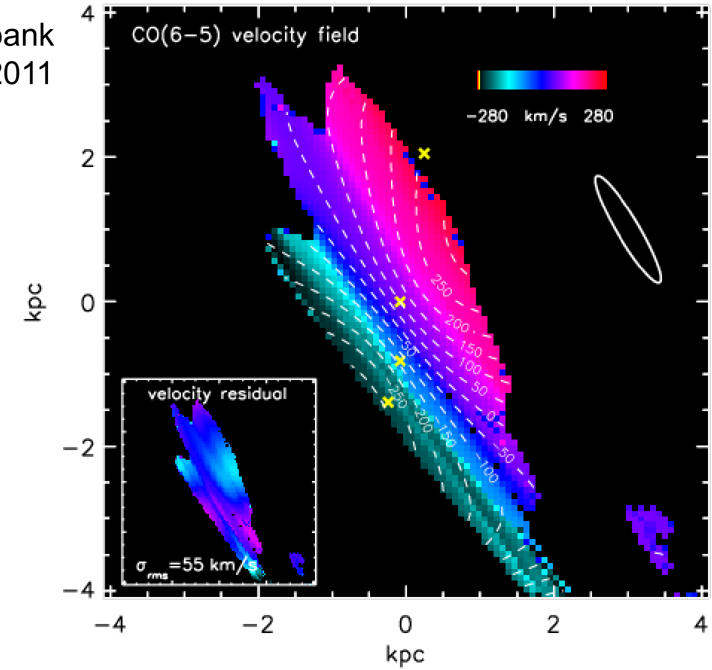


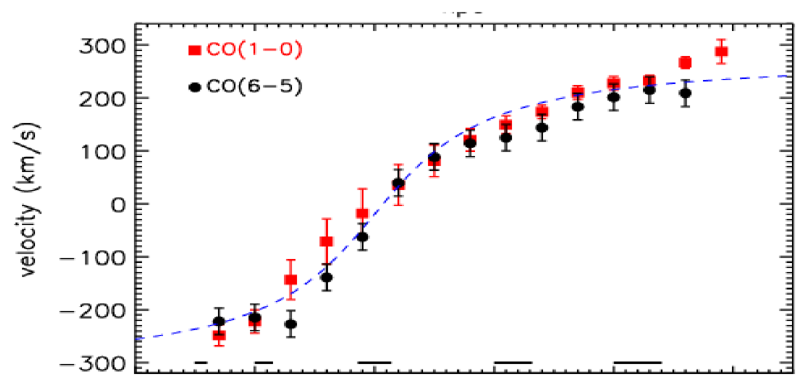
MACS J2135-0102: the *Cosmic Eyelash*

z_{cl}=0.325, $z_{SMM2125}$=2.3

Swinbank et al 2011

HST
+ IRAM
+ EVLA

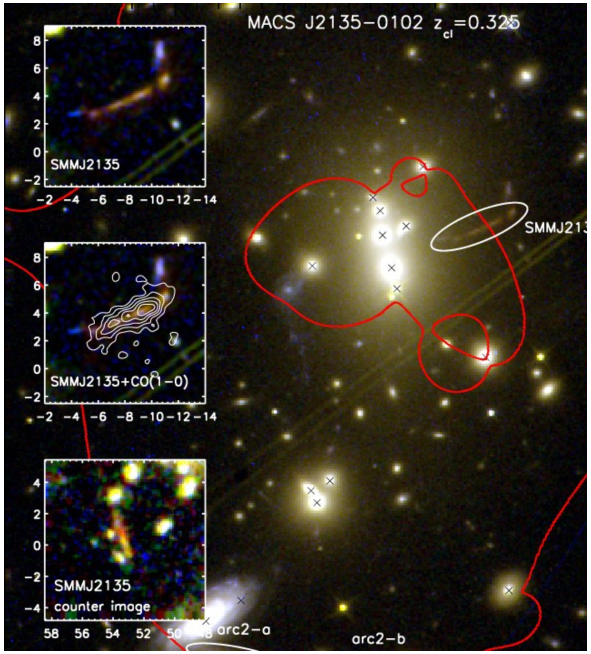




Gravitational magnification + ALMA

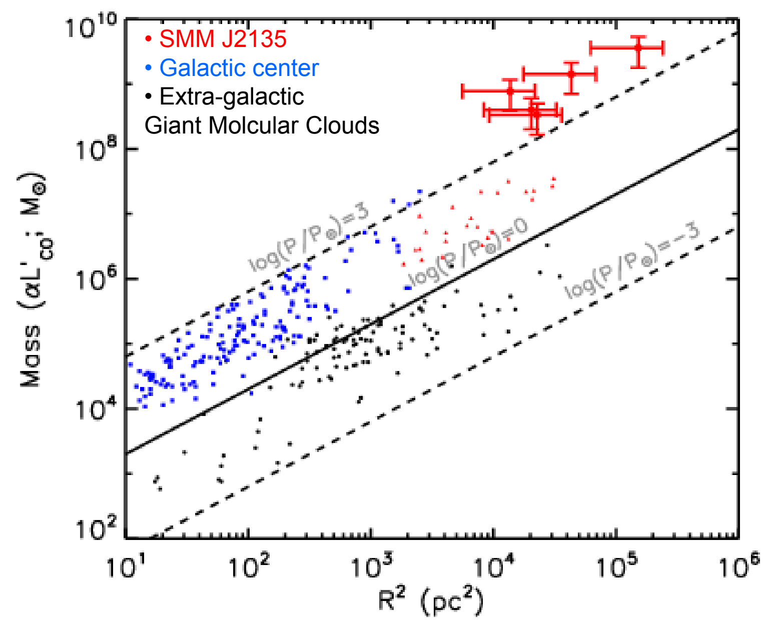
dissecting the content and physical properties of gas in high-z galaxies

Swinbank et al 2011



Swinbank et al 2011

HST + IRAM + EVLA



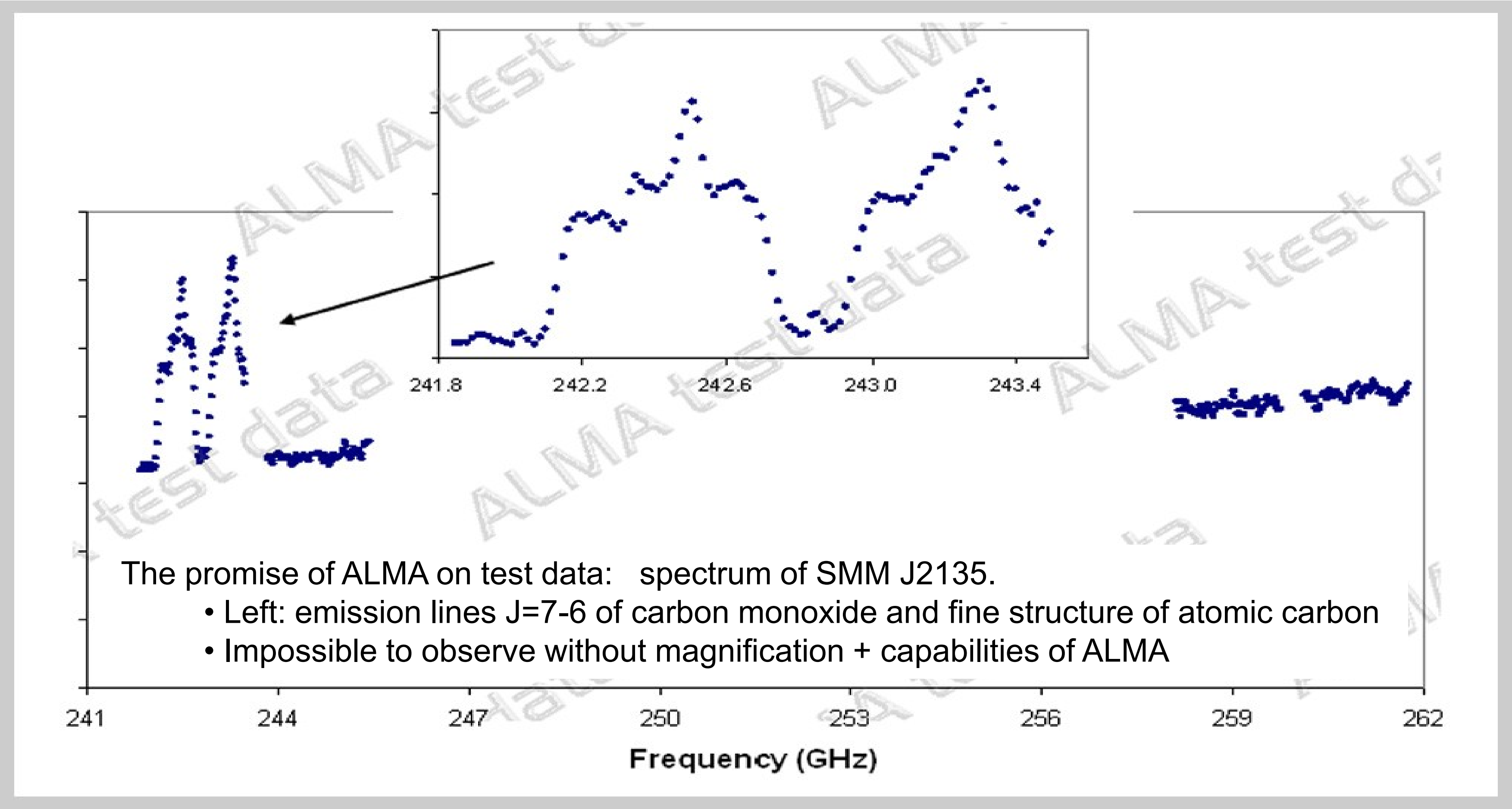
Swinbank et al 2011: « *Only ALMA will be capable of verifying the true pressure-induced offsets in distant forming galaxies by probing scales < 100pc…. This will be possible for strongly lensed starburst systems such as SMM J2135, allowing an unprecedented insight into key quantities characterising the turbulent molecular gas in star forming systems at high redshifts.* »

←

M(H2)-R2 relation.
The molecular star forming regions in SMM J2135 lie on a line corresponding to very high turbulent pressure

Gravitational magnification of SMM J2135 + ALMA

dissecting content and physical properties of gas in high-z galaxies



Swinba
true pre
scales
starbur
dented insight into key quantities charactersing the turbulent molecular gas in star forming systems at hIgh redshifts. »

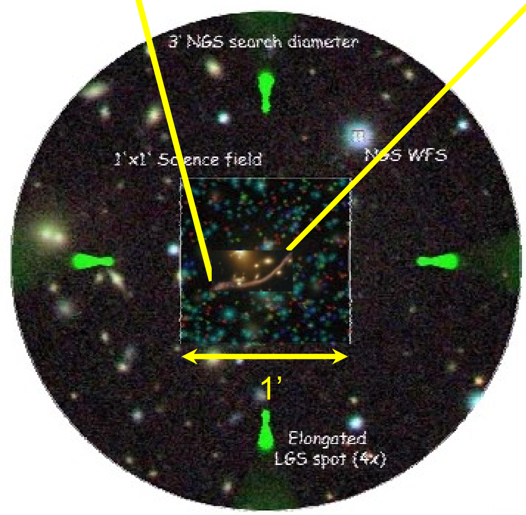
http://www.almaobservatory.org/visuals/images

Gravitational magnification + ESO AO spectro-imaging

dissecting the content, physical properties and dynamics of high-z galaxies

Observational Parameters	
Spectral range (simultaneous)	0.465-0.93 μm
Resolving power	2000@0.46 μm
	4000@0.93 μm
Wide Field Mode (WFM)	
Field of view	1x1 $arcmin^2$
Spatial sampling	0.2x0.2 $arcsec^2$
Spatial resolution (FWHM)	0.3-0.4 arcsec
Gain in ensquared energy within one pixel with respect to seeing	2
Condition of operation with AO	70%-ile
Sky coverage with AO	70% at Galactic Pole
Limiting magnitude in 80h	I_{AB} = 25.0 (R=3500)
	I_{AB} = 26.7 (R=180)
Limiting Flux in 80h	3.9 $10^{-19} erg.s^{-1}.cm^{-2}$
Narrow Field Mode (NFM)	
Field of view	7.5x7.5 $arcsec^2$
Spatial sampling	0.025x0.025 $arcsec^2$
Spatial resolution (FWHM)	0.030-0.050 arcsec
Strehl ratio	10-30%
Limiting Flux in 1h	2.3 $10^{-18} erg.s^{-1}.cm^{-2}$
Limiting magnitude in 1h	R_{AB} = 22.3
Limiting surface brightness in 1h	R_{AB} = 17.3 $arcsec^{-2}$

A370, HST/ACS ; NASA/ESA



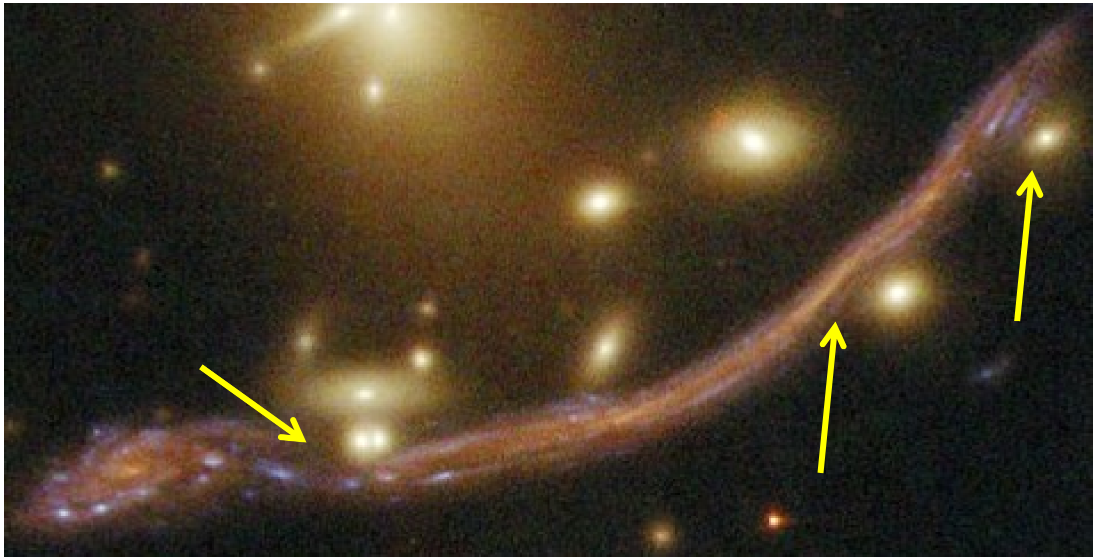
Synergy HST/JWST with ground based AO+IFU (SINFONI / MUSE):

Dissecting high-z magnified galaxies with MUSE+Galacsi

Gravitational magnification + ESO AO spectro-imaging

Exploring sub-halos with lensing models coupled with MUSE or ALMA

Abell 370, HST/ACS ; credit NASA/ESA



Models are now so accurate that properties of bright/dark halos can be derived from anomalies to predictions of simple models:

Kassiola et al 1992 (Cl0024+1654), Mellier et al 1993 (MS2137-23),Falco et al 1997 and Keeton et al 1997 (MS0440+0534), Mao & Schneider 998 and Bradac et al 2002 (B1422+231)

→« milli-lensing » effects can be detected - perturbations to large halo models:

- Change flux ratios
- Change source/lenses image positions
- May create extra-images
- Change time delays

Bright halos: AO/IFU is a tool to constrain mass/size of visible halos

Dark halos: probed by lensing effects

Gravitational magnification + ESO AO spectro-imaging

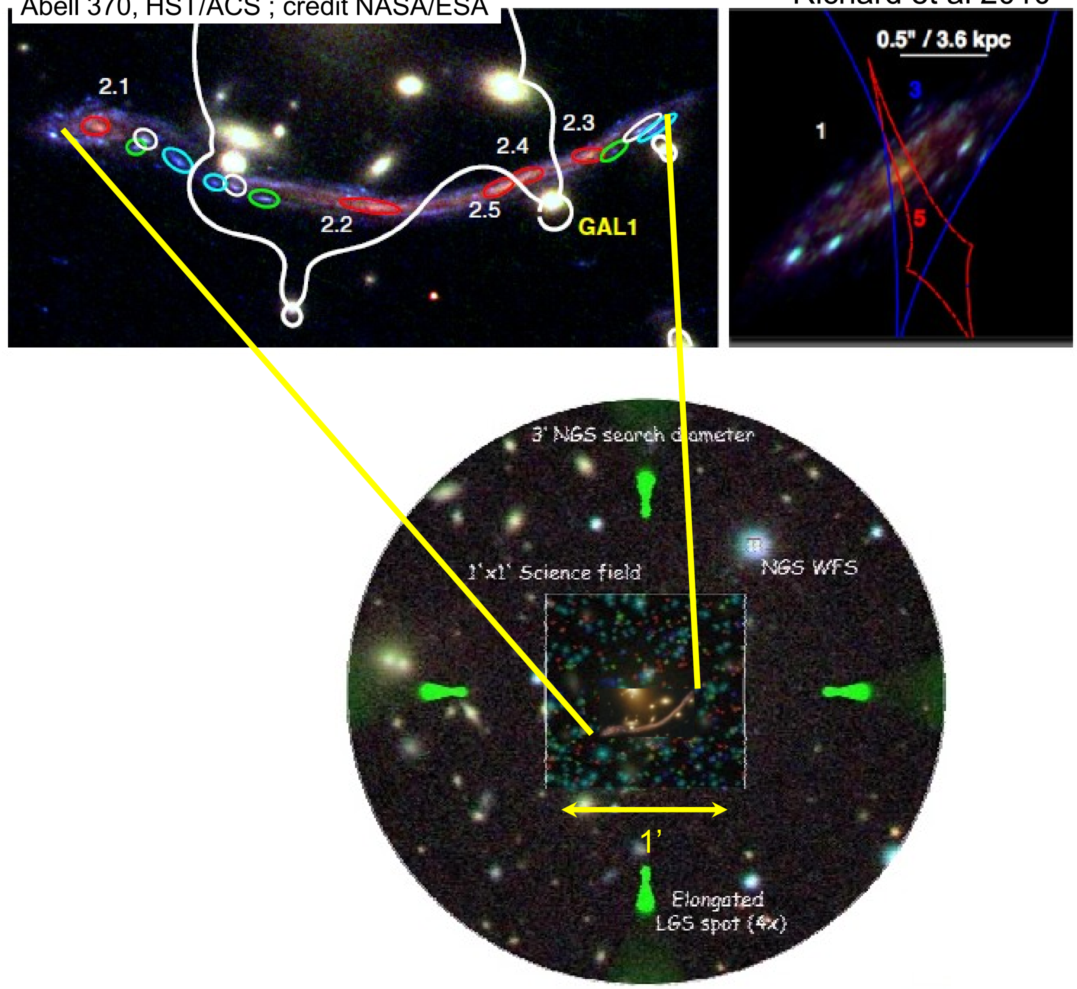
Exploring sub-halos with lensing models coupled with MUSE or ALMA

Synergy HST/JWST with ground based facilities:

- AO+IFU + deep AO NIR:
  - Dynamical properties of magnified galaxy halos with MUSE+Galacsi
  - Monitoring time delays in lensed galaxies/QSOs with multiple images

Abell 370, HST/ACS ; credit NASA/ESA

Richard et al 2010



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- **Wide field for cosmic shear**: KIDS/VIKING, wide field faint spectroscopic surveys → VMOS/PILMOS, 4 MOST , MOONS

- **Time domain**: mu-lens, exoplanets, times delays: Danish, VST, ESO 4-m class telescopes (?)

ESO and wide fields weak lensing surveys

VST / VISTA – KIDS / VIKING

Courtesy: K. Kuijken

- 9-band u-K survey with VST+VISTA (photo-z)
- 1500 deg^2 (CFHTLS = 150 deg^2)
- 2 mag. deeper than SDSS, but x2 sharper
- 1 mag. shallower than CFHTLS: spectro follow up easier
- Started Oct. 15, 2011

ESA/ESO synergy: Euclid

Weak Lensing and BAO surveys to probe dark energy

Euclid: ESA mission - Launch date : 2020 - Survey: 6 yrs

	Area (deg2)	Description
Wide Survey	**15,000 deg²**	Step and stare with 4 dither pointings per step.
Deep Survey	**40 deg²**	In at least 2 patches of > 10 deg² 2 magnitudes deeper than wide survey

PAYLOAD

Telescope	1.2 m Korsch, 3 mirror anastigmat, f=24.5 m				
Instrument	VIS	NISP			
Field-of-View	0.787×0.709 deg²	0.763×0.722 deg²			
Capability	Visual Imaging	NIR Imaging Photometry			NIR Spectroscopy
Wavelength range	550– 900 nm	Y (920-1146nm),	J (1146-1372 nm)	H (1372-2000nm)	1100-2000 nm
Sensitivity	24.5 mag 10σ extended source	24 mag 5σ point source	24 mag 5σ point source	24 mag 5σ point source	$3\ 10^{-16}$ erg cm-2 s-1 3.5σ unresolved line flux
	Shapes + Photo-z of *n* = 1.5 x10⁹ galaxies				***z* of *n*=5x10⁷ galaxies**

Laureijs et al 2011

Euclid : ~ 300,000 strong galaxy lensing, ~ 5000 giant arcs, ~ 30 z=8 QSOS

ESA/ESO synergy: Euclid and ESO

- Ground based visible (u-band) imaging for Euclid photo-z: VST? (no next gen. wide field visible imaging at ESO ?)

- Need for spectroscopic follow up of Euclid galaxies:
  - 10^5 redshifts to I_{AB}=24.5:
    - Shear galaxy sample, control completeness, calibration of photo-z of galaxies used for shape measurement.
    - BAO (emission line) galaxy redshift samples: very high completeness, purity well understood, high uniformity

→ Wide field and ultra-deep spectroscopic surveys : ESO next generation wide field faint MOS/high multiplex is needed.

→ Euclid deep field: E-ELT spectroscopic follow up of Euclid discoveries: very high-z galaxies, z~8 QSOs, cool stars

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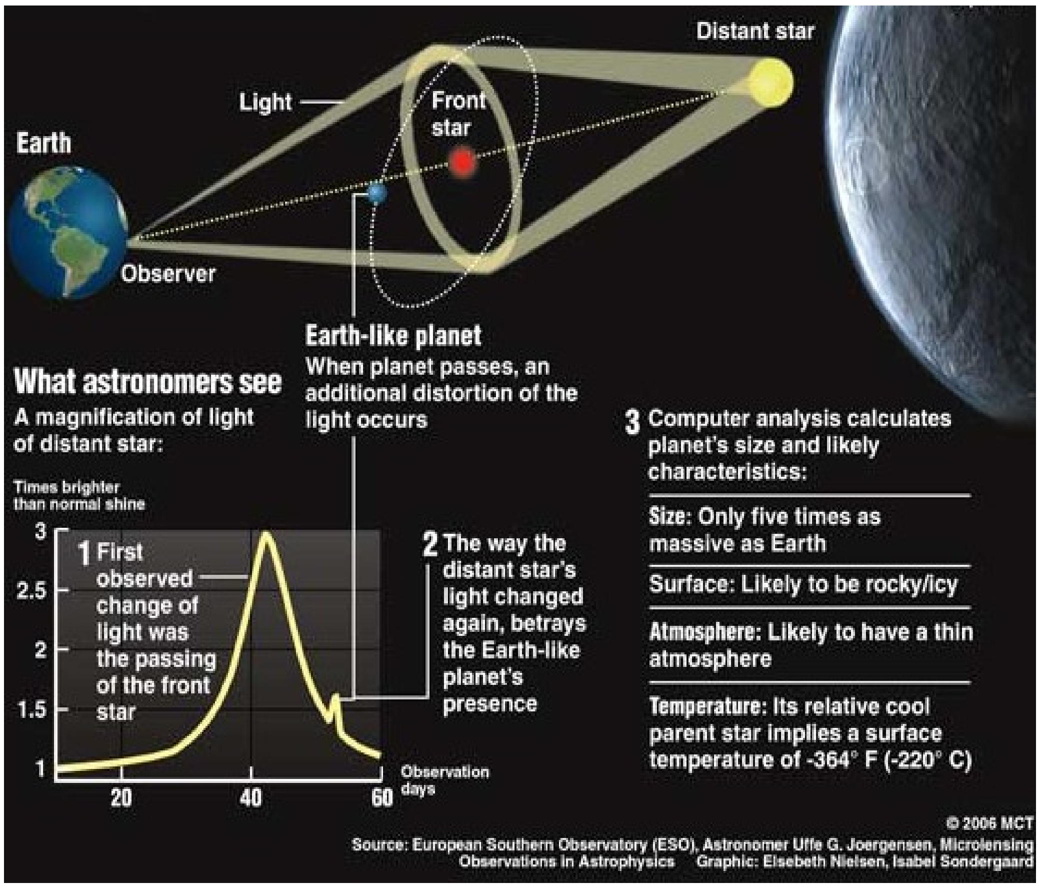
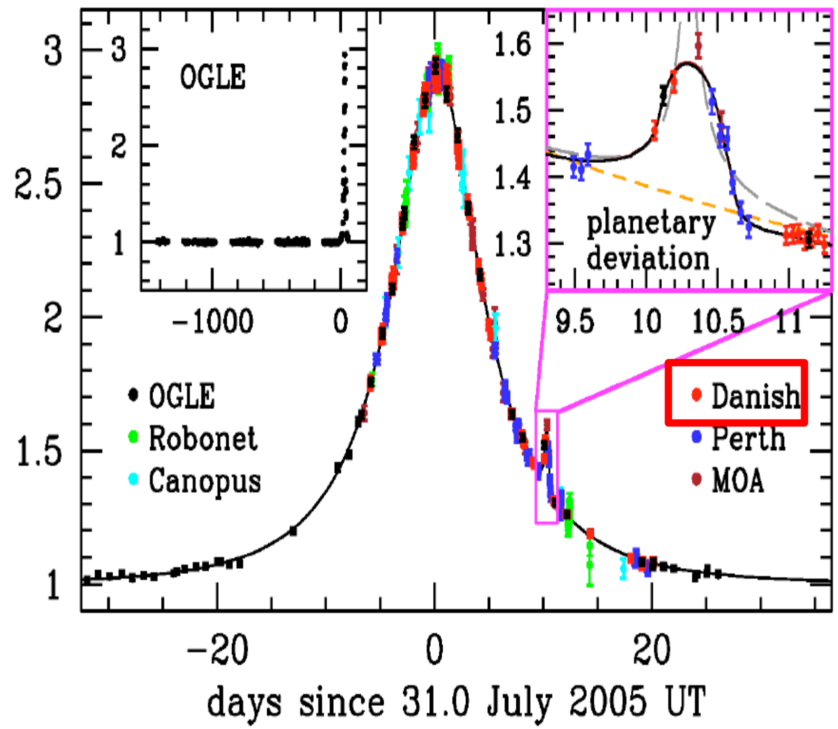
- **Time domain:** mu-lens, exoplanets, times delays: Danish, VST, ESO 4-m class telescopes (?), E-ELT spectro follow up.

2002-2012: La Silla as support to the micro-lensing PLANET collaboration

(an example of planetary research project reported by Alvio)

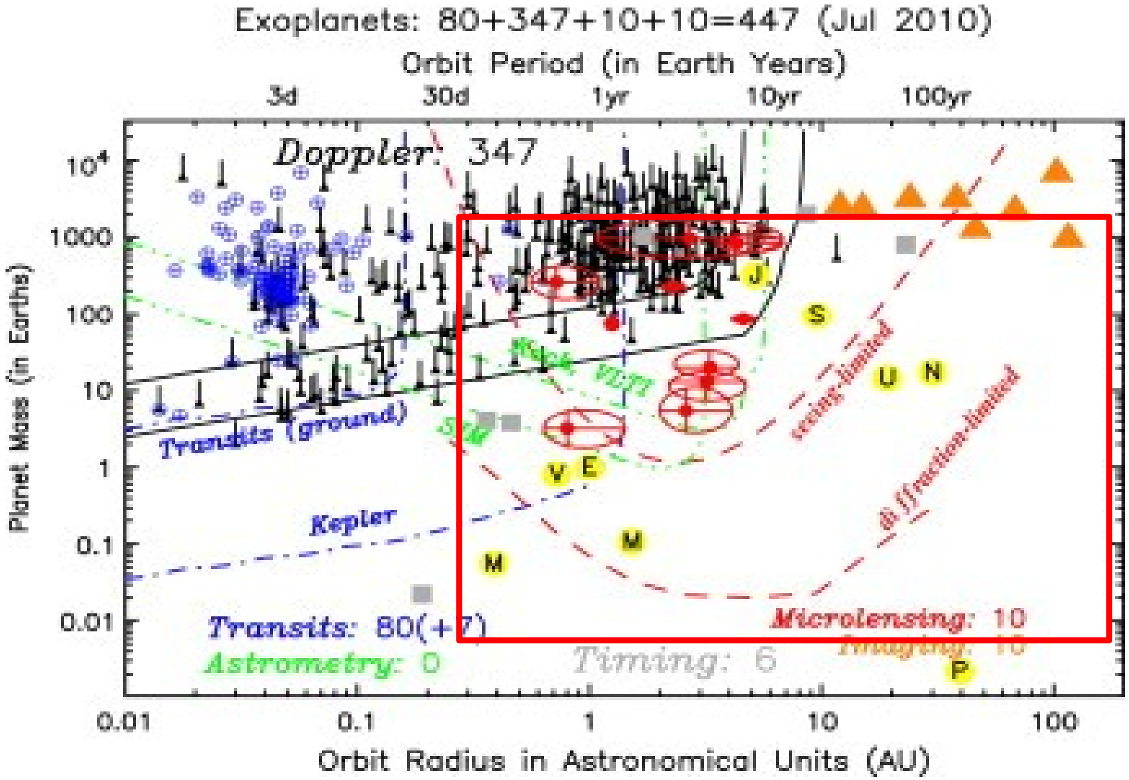


Beaulieu et al 2006



A 5.5 Earth mass cool planet

Cassan et al 2012: 1.6 planets/star in the Milky Way? Most inspiring for the future.



- ESO facilities for detecting/monitoring mu-lens events and
- VLT , E-ELT for follow up

So… ESO and gravitational lensing?.

- Major impacts on (S+W) lensing, mu-lensed QSOs and exo-planets

- Considerable contribution on spectro weak lensing surveys
    - CFHTLS and COSMOS, (KIDS/VIKING)
    - Lensing clusters surveys (VLT-CLASH)
- Imaging:VST/VISTA (Collaboration with non-ESO visible surveys?)

- E-ELT: spectra very-high-z magnified (z> 8) + *demagnified* images

- Space/Ground synergy obvious on
    - Magnified sources:HST/JWST→AO/IFU on VLT/E-ELT
    - Euclid: VLT (MOS wide field) and E-ELT follow up

- Exoplanets: detection and follow up a niche for E-ELT

So… ESO and gravitational lensing?.

- Major impacts on (S+W) lensing, mu-lensed QSOs and exo-planets

- Considerabl … urveys
    - CFHTLS
    - Lensing
- Imaging:VS … veys data?)

- E-ELT: spec … *ified* images

- Space/Grou

100 Years 1962-2062

…the next review will be interesting…

- Exoplanets: detection and follow up a niche for E-ELT